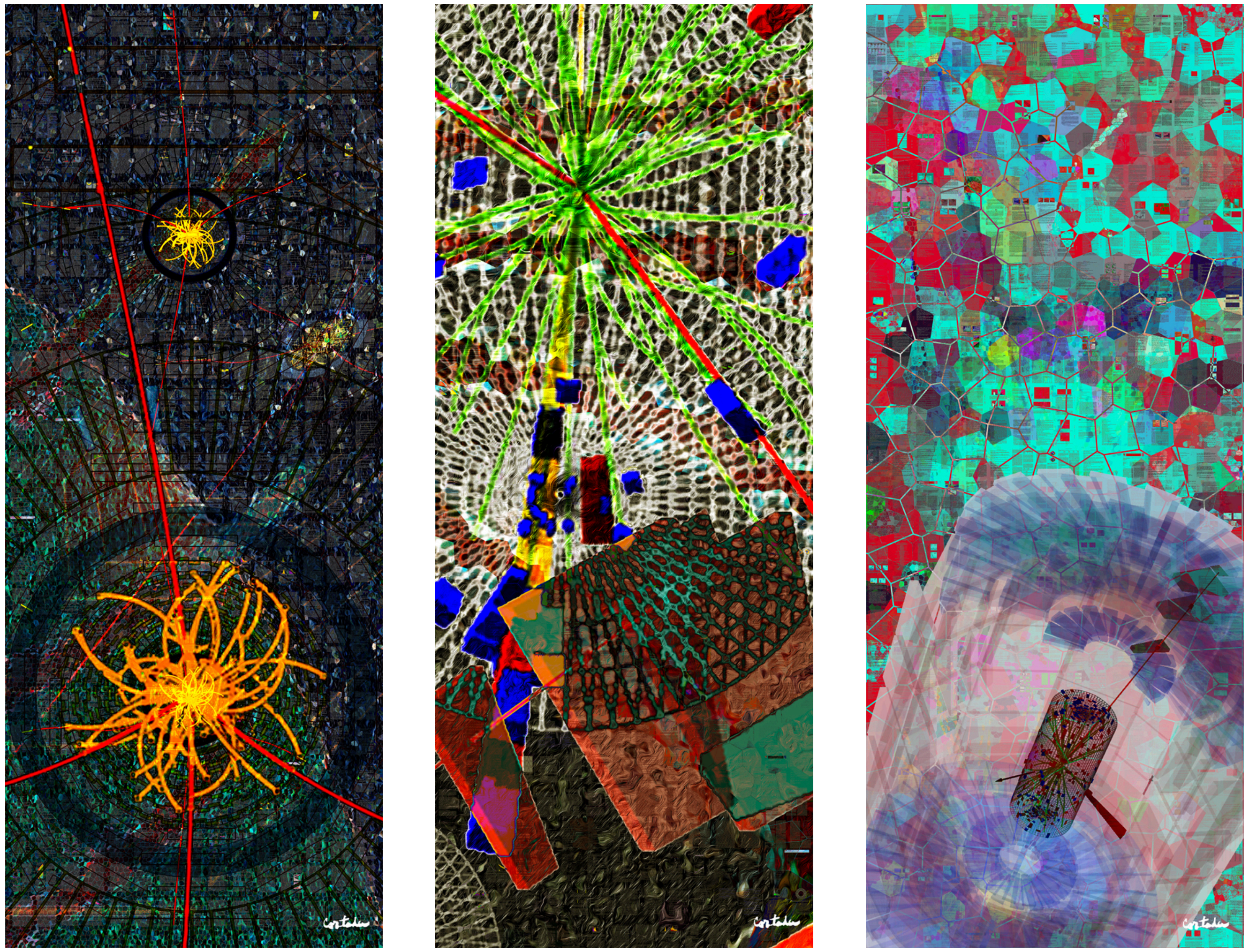
Higgs sector: a perspective

Konstantinos Nikolopoulos
University of Birmingham

UNIVERSITY OF BIRMINGHAM

European Research Council
Established by the European Commission



X. Cortada, "In search of the Higgs boson" (2013)

6^{th} IDPASC/LIP PhD Students Workshop
June 25-27, Coimbra, Portugal

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement no 714893 (ExclusiveHiggs)

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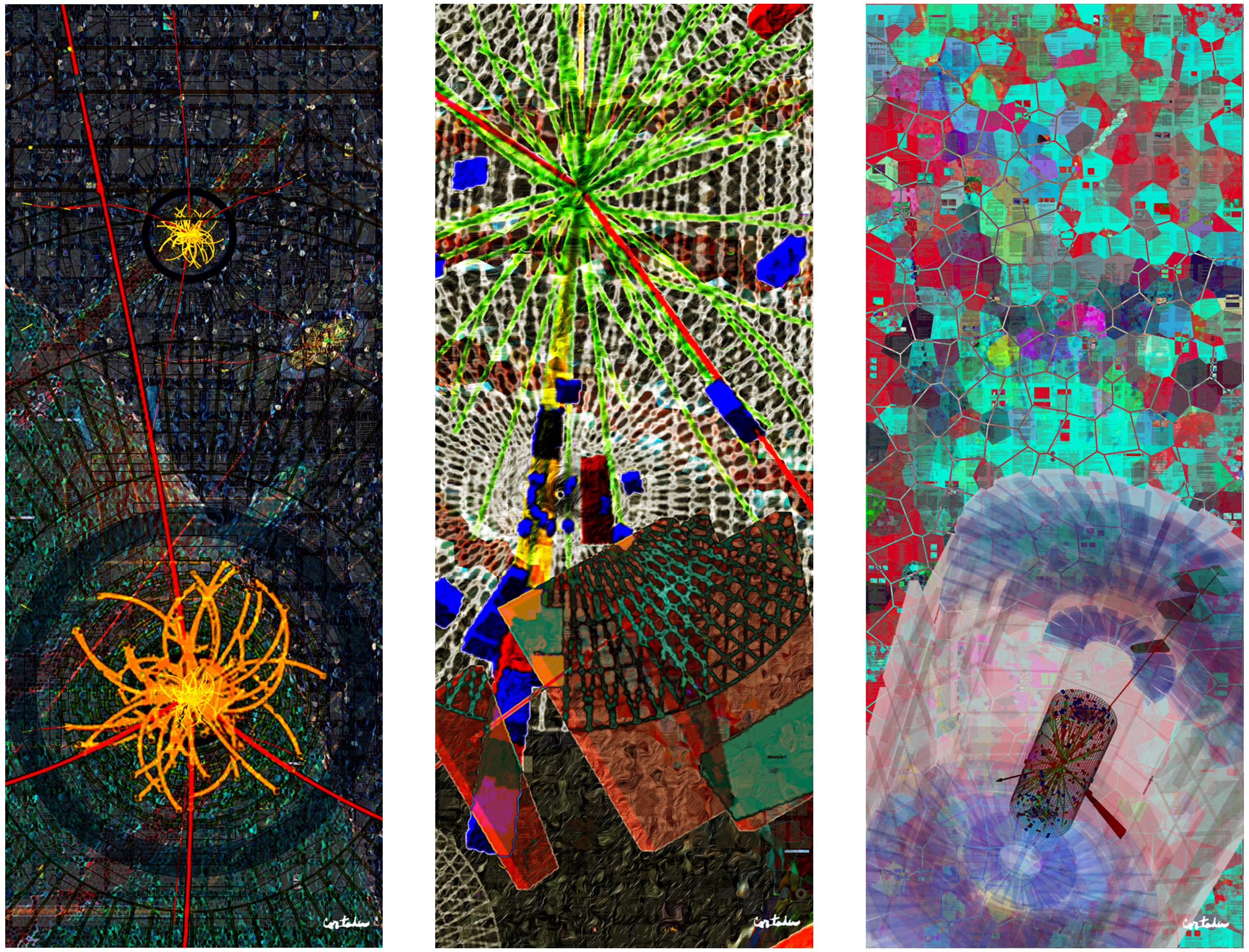

X. Cortada, "In search of the Higgs boson" (2013)

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Higgs sector: a brief perspective

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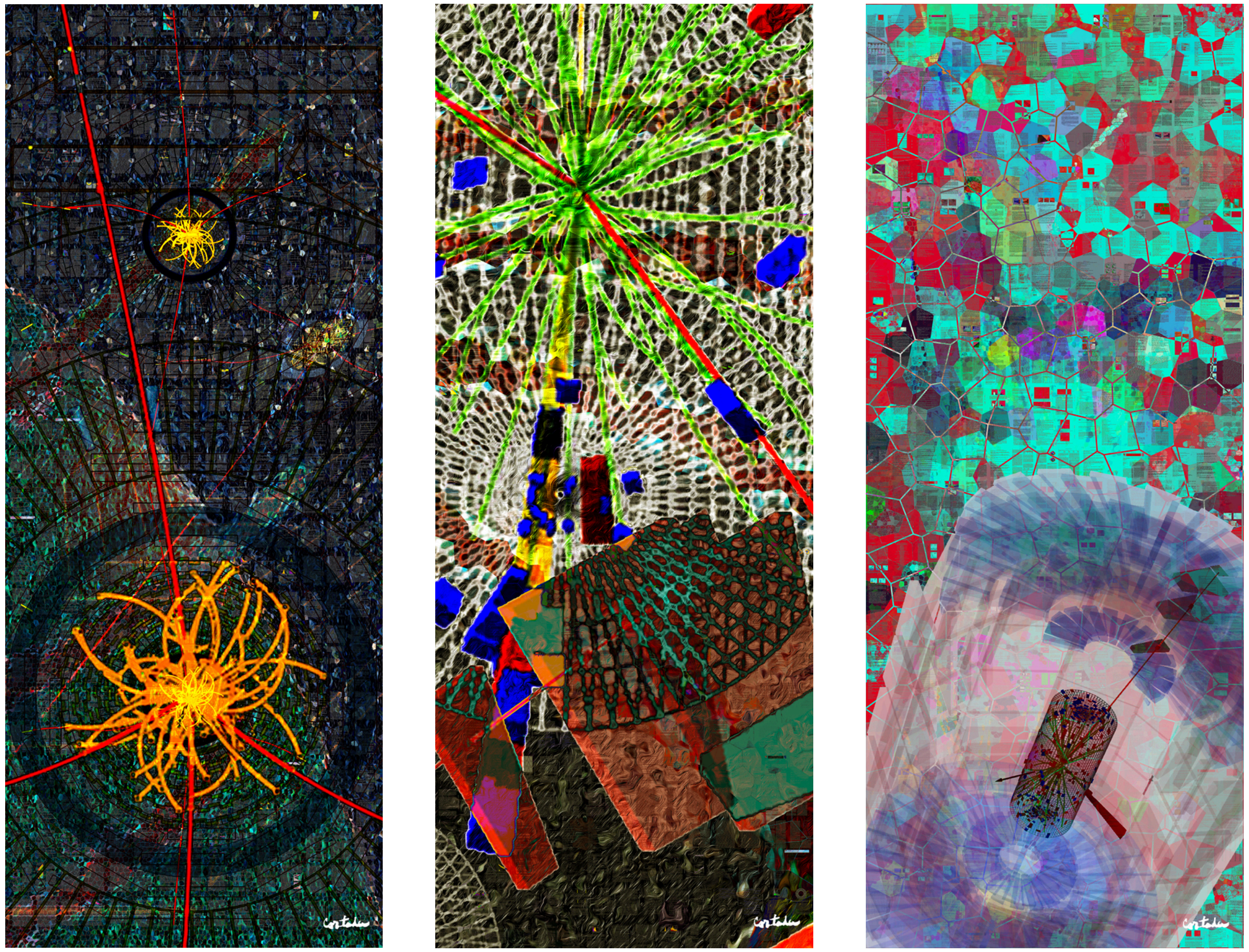

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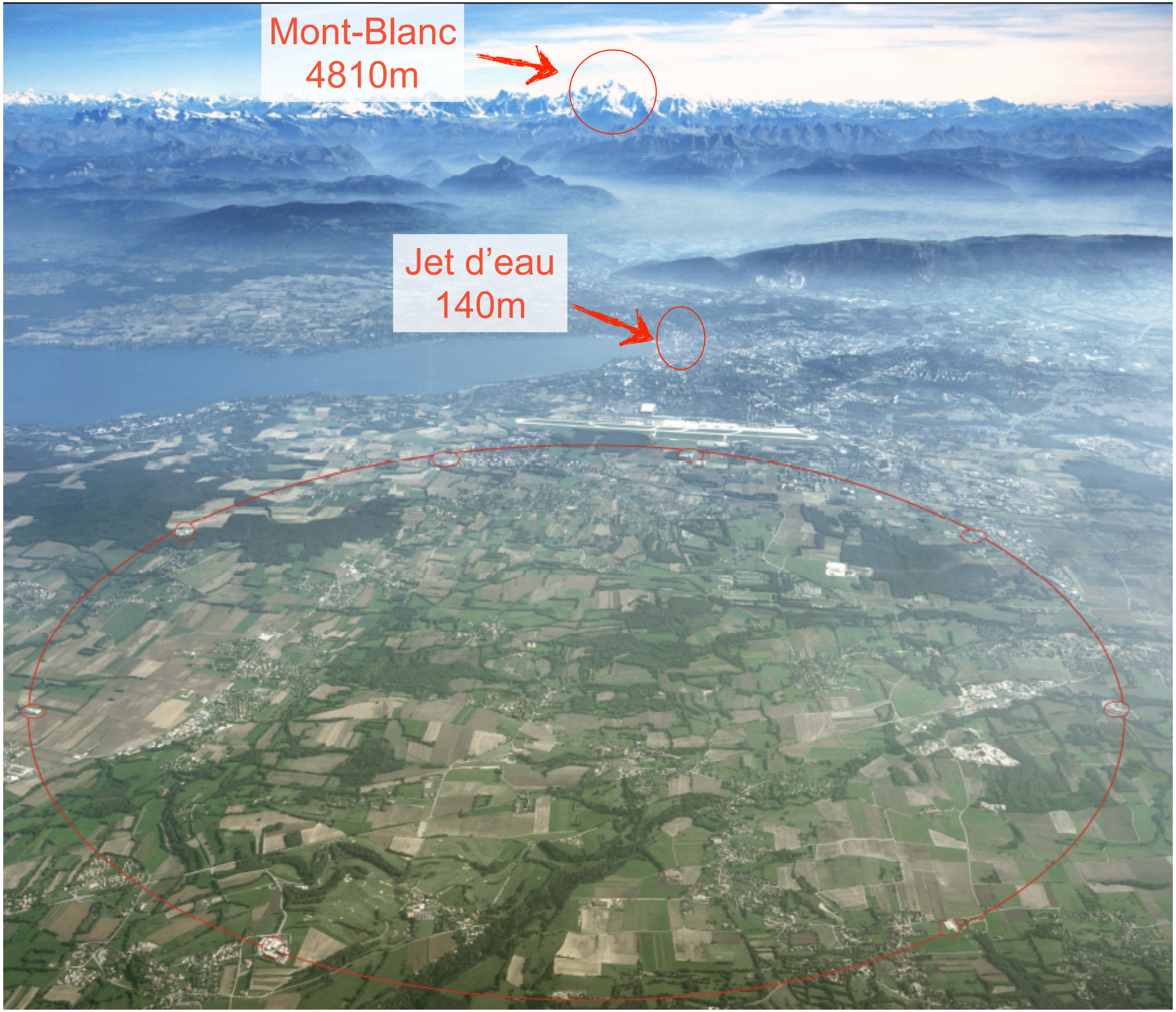
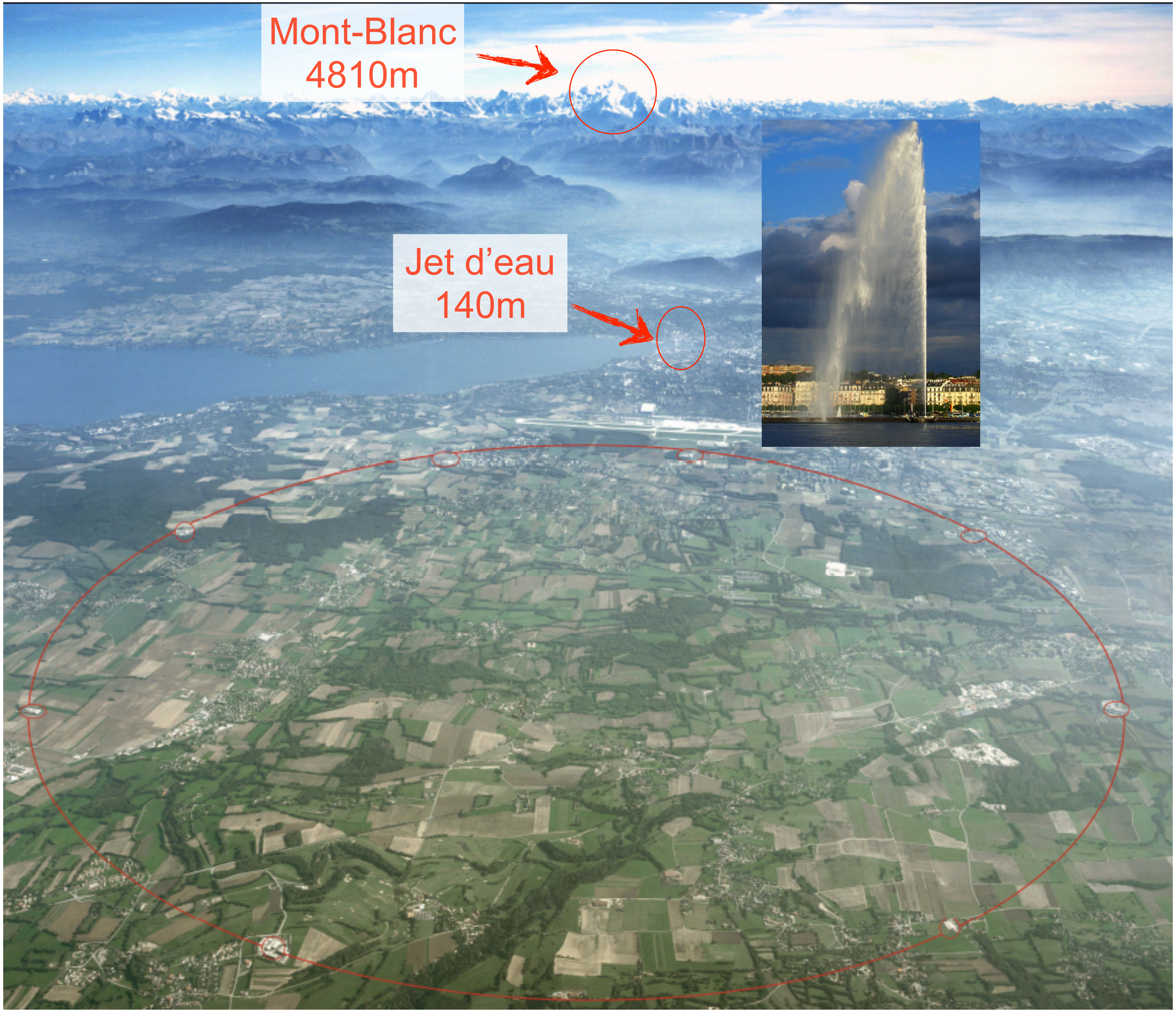
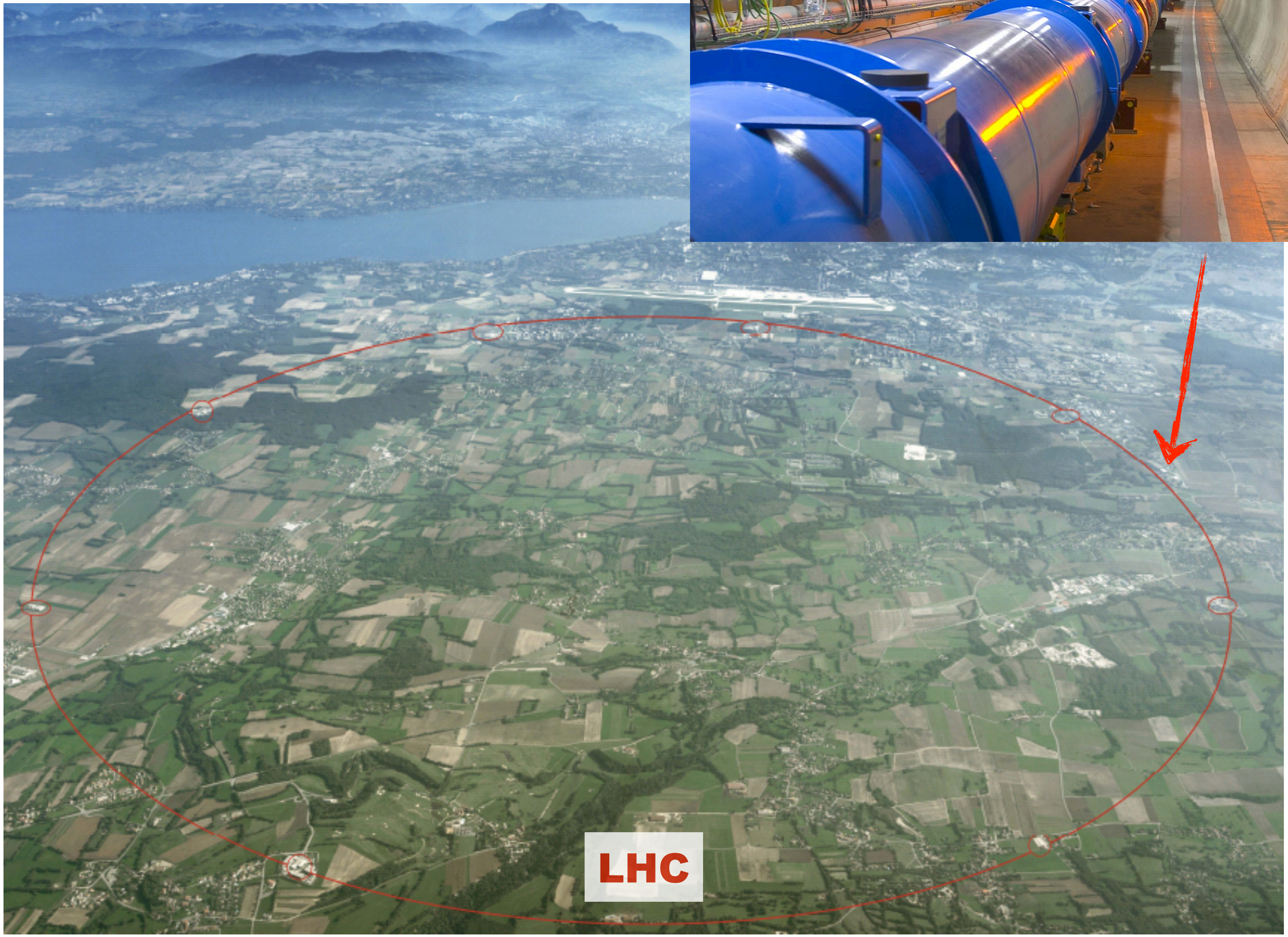
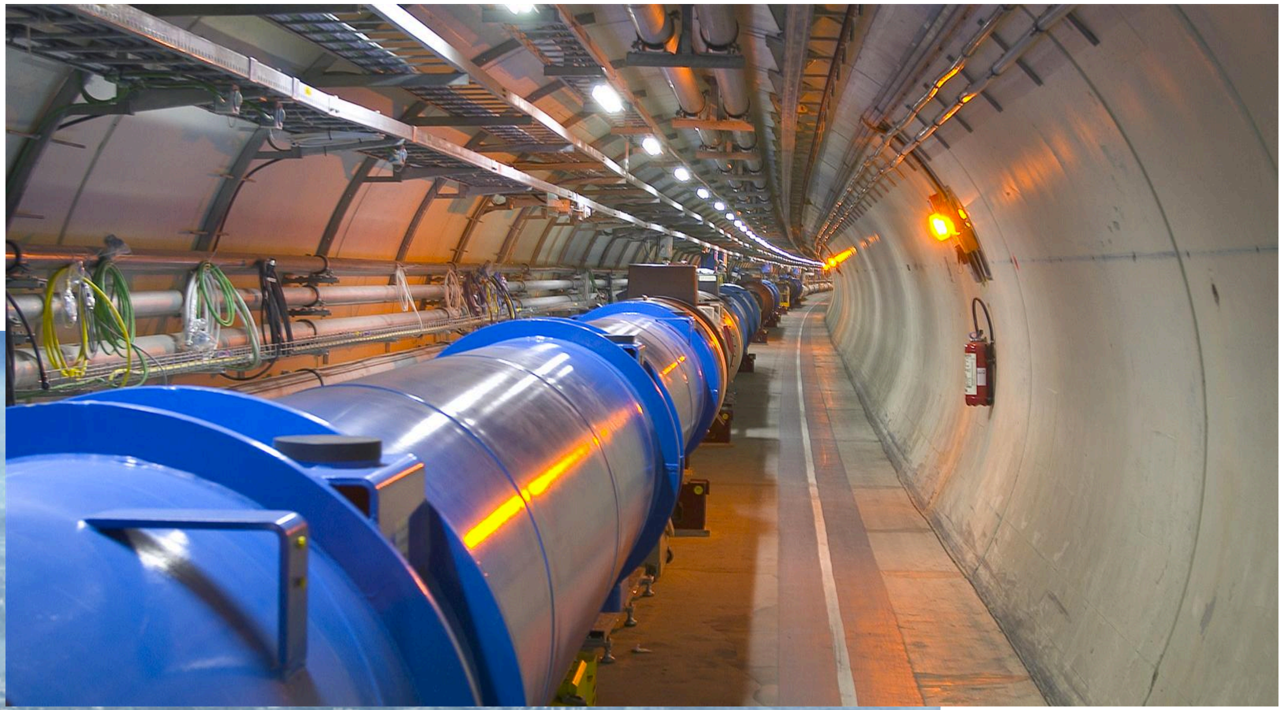
Mont-Blanc
4810m


Mont-Blanc
4810m
Jet d'eau
140m


Mont-Blanc
4810m
Jet d'eau
140m

- 1232 superconducting dipoles
  - magnetic field of 8.3T
  - operating at 1.9K





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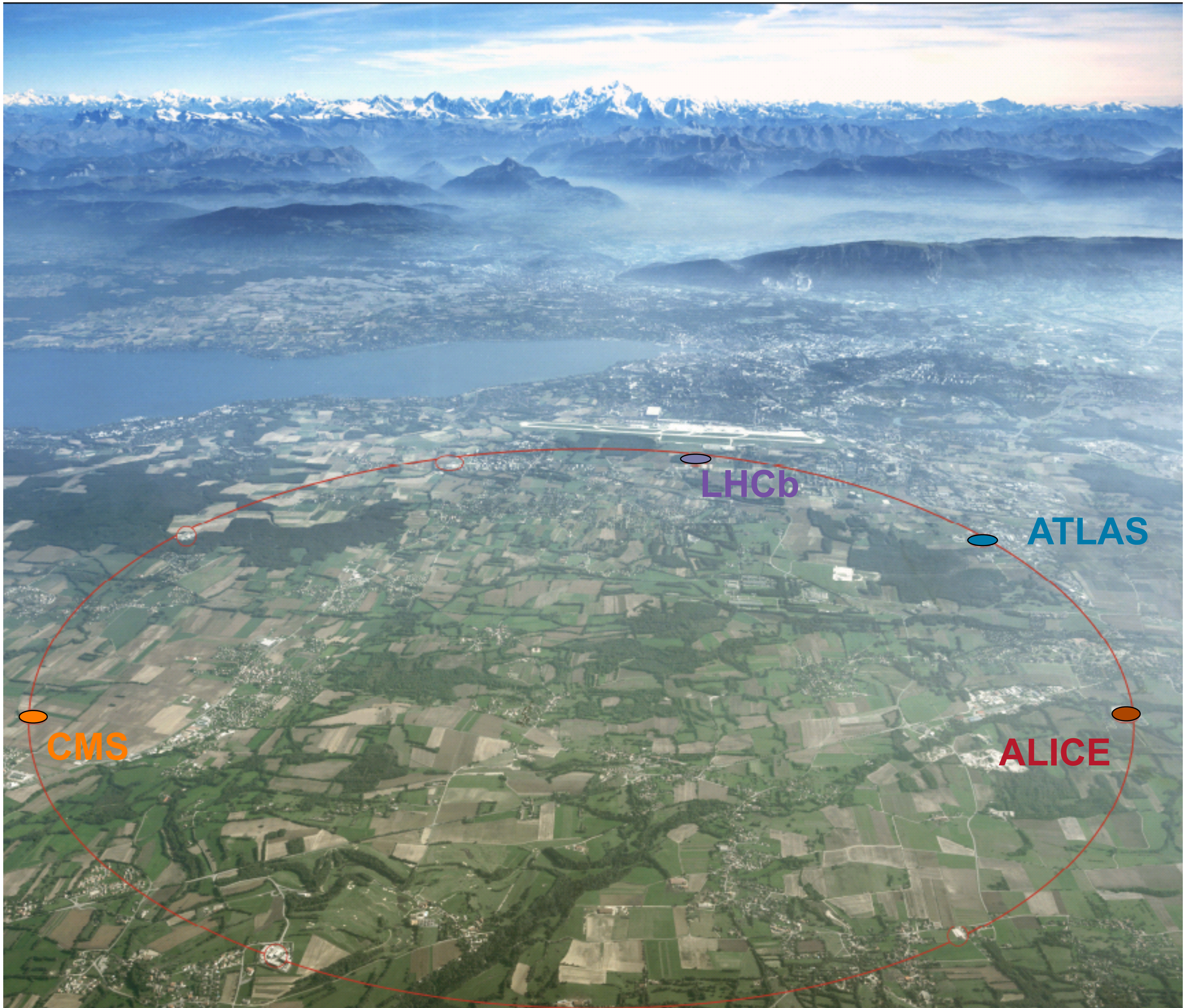
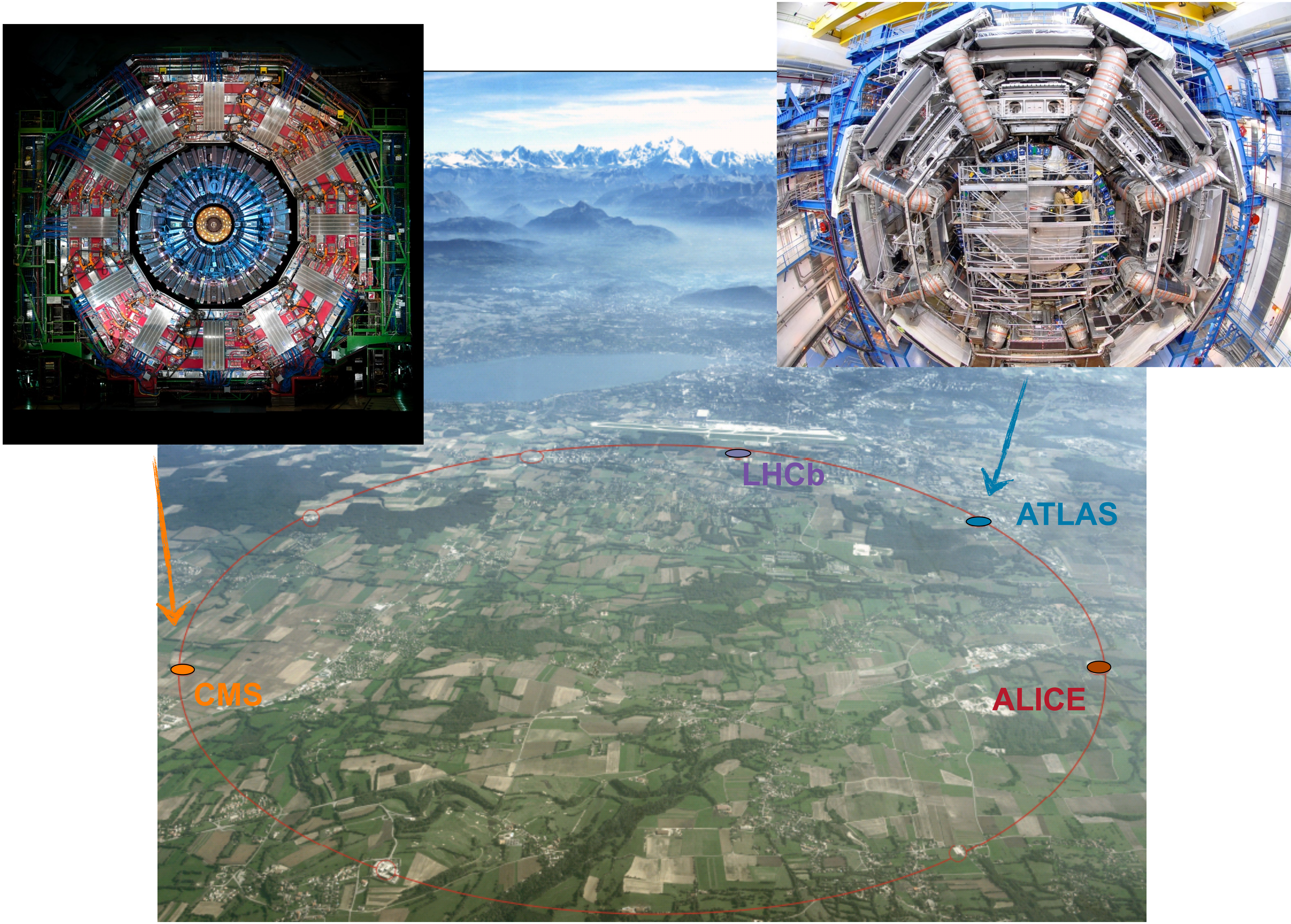
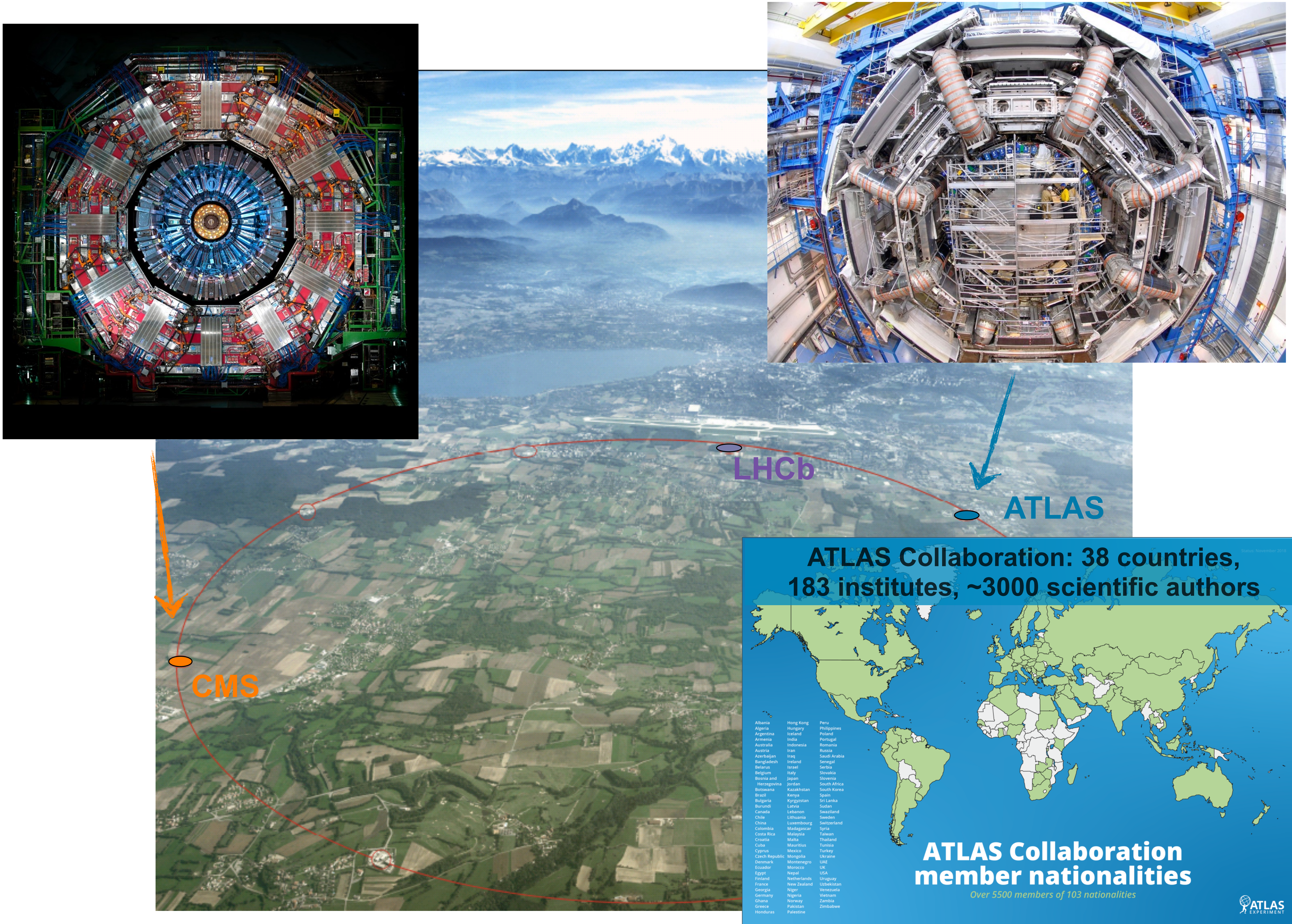
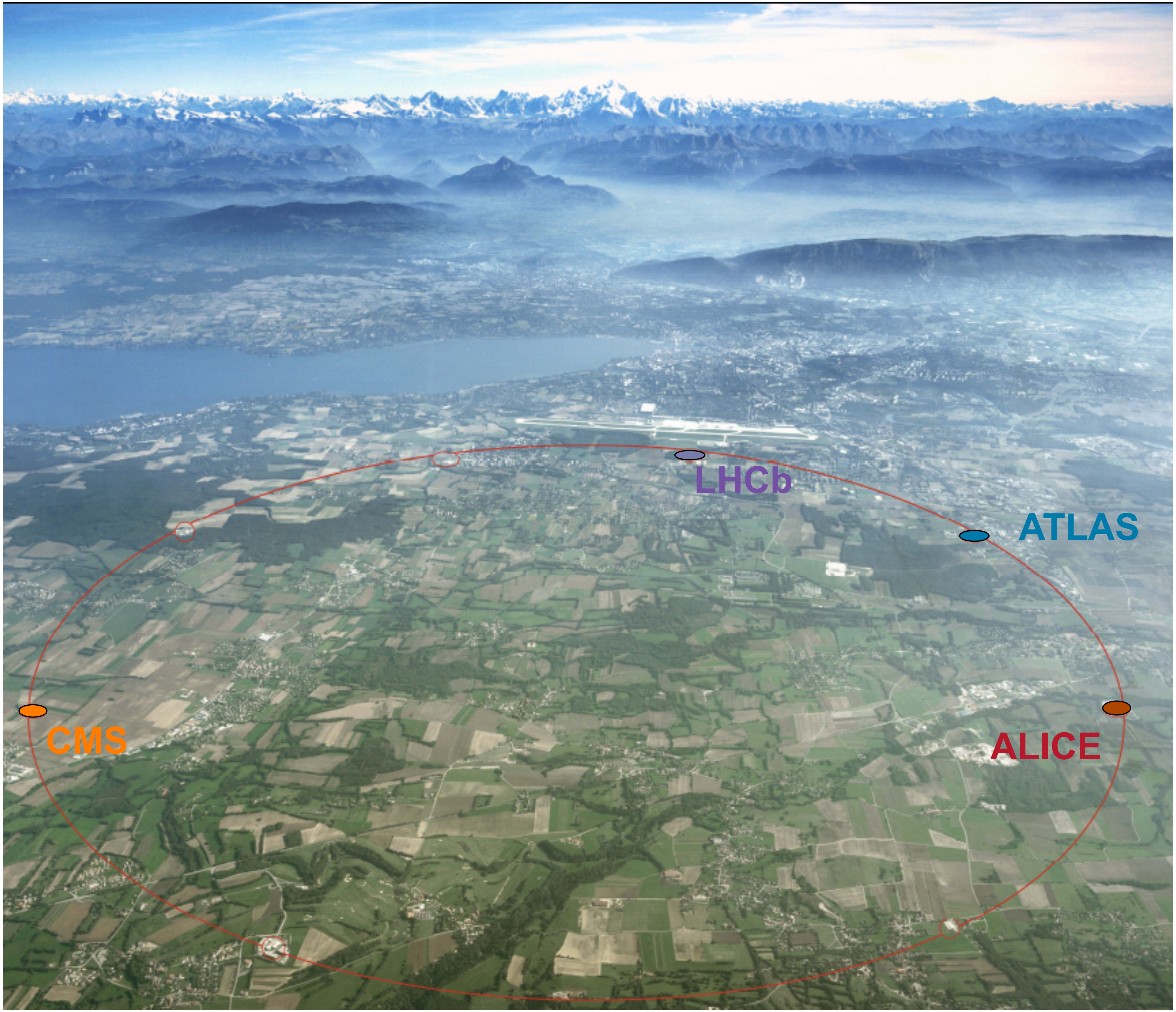
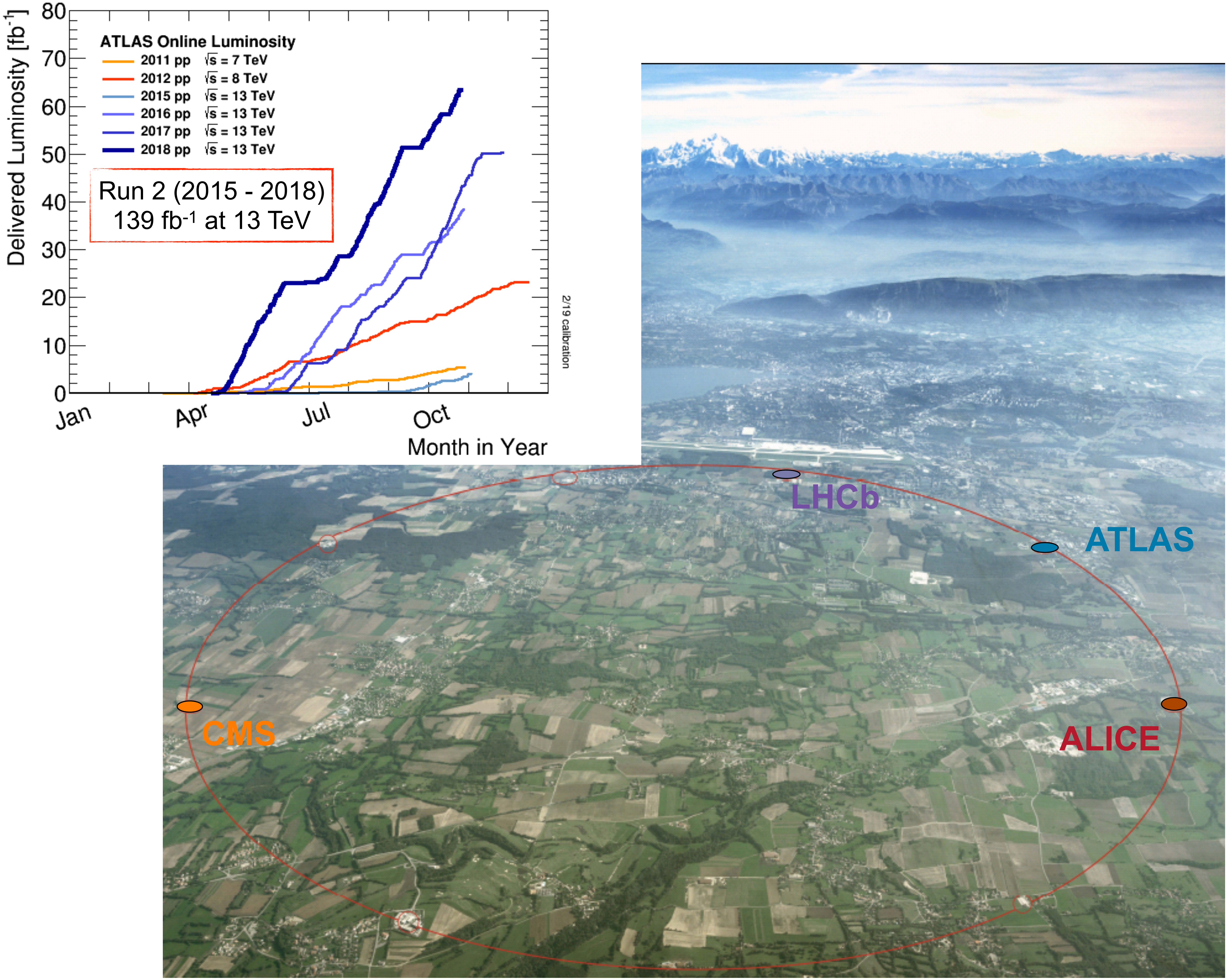

LHCb
ATLAS
CMS
ALICE

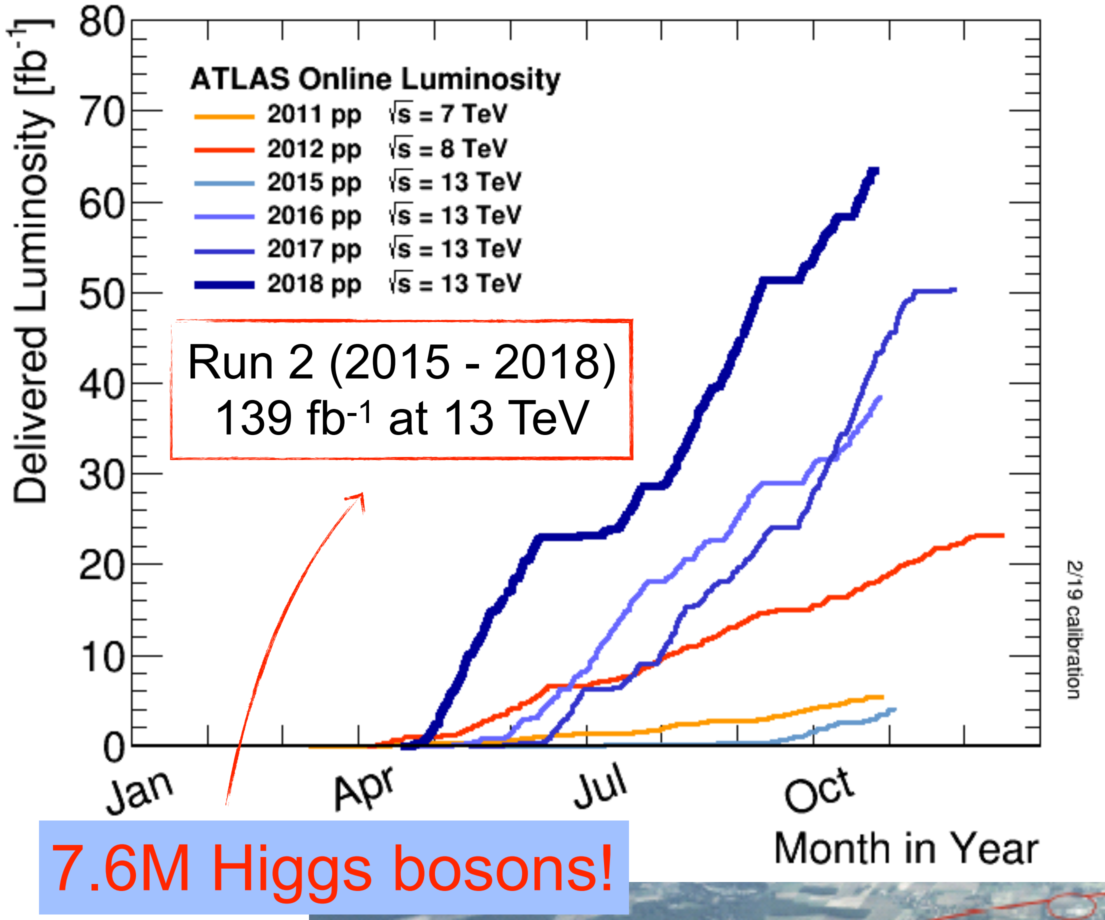

LHCb
ATLAS
CMS
ALICE


LHCb
ATLAS
CMS
ATLAS Collaboration: 38 countries,
183 institutes, ~3000 scientific authors
ATLAS Collaboration
member nationalities
Over 5500 members of 103 nationalities
ATLAS EXPERIMENT


LHCb
ATLAS
CMS
ALICE



ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
2018 pp √s = 13 TeV
Run 2 (2015 - 2018)
139 fb-1 at 13 TeV
Delivered Luminosity [fb-1]
Month in Year
Jan
Apr
Jul
Oct
2/19 calibration
LHCb
ATLAS
CMS
ALICE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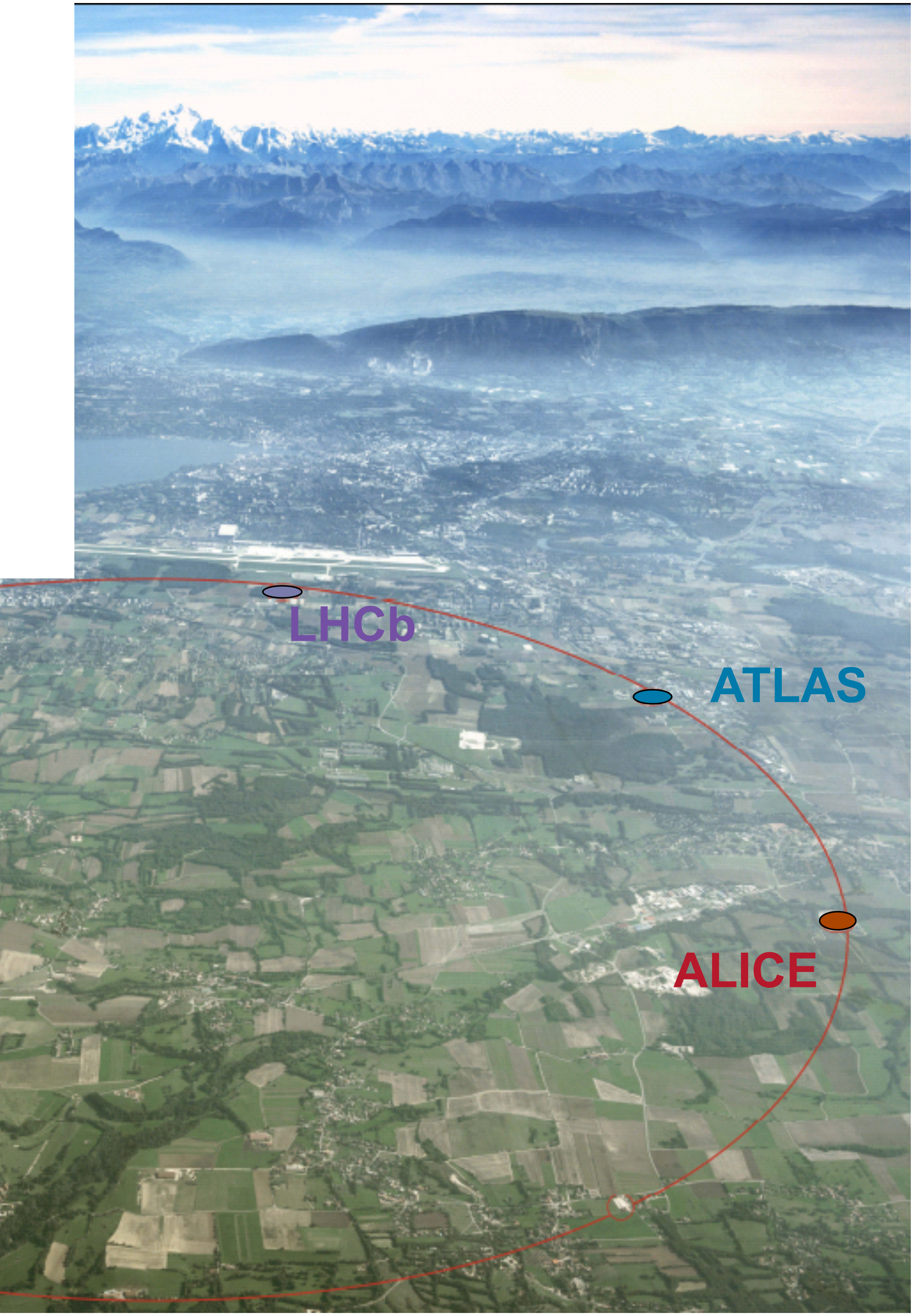
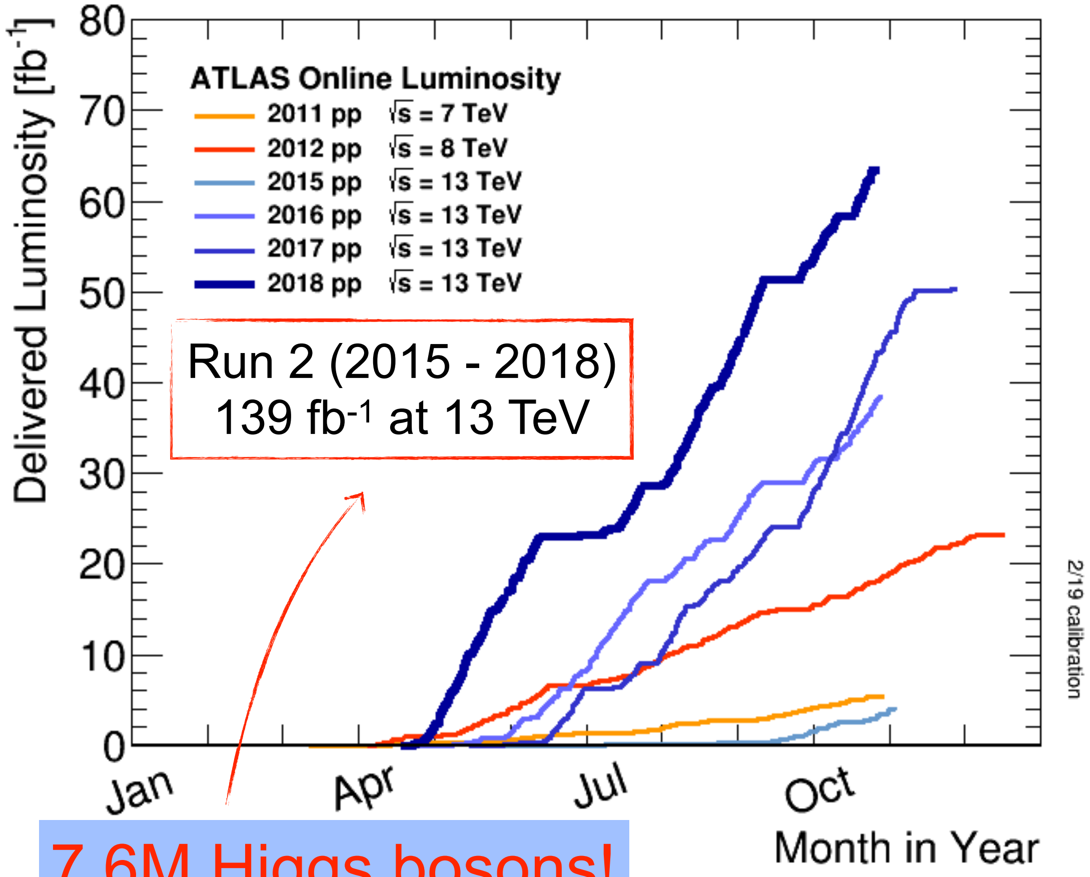
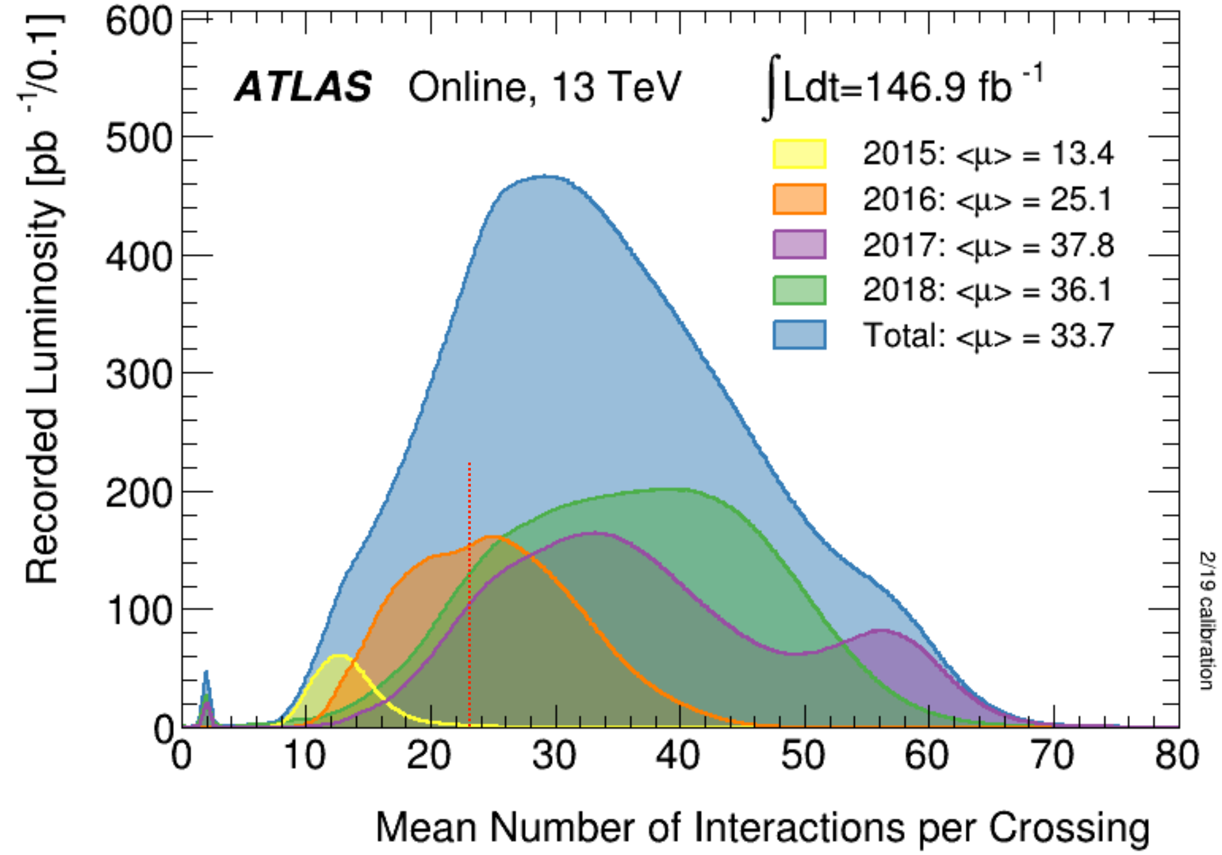
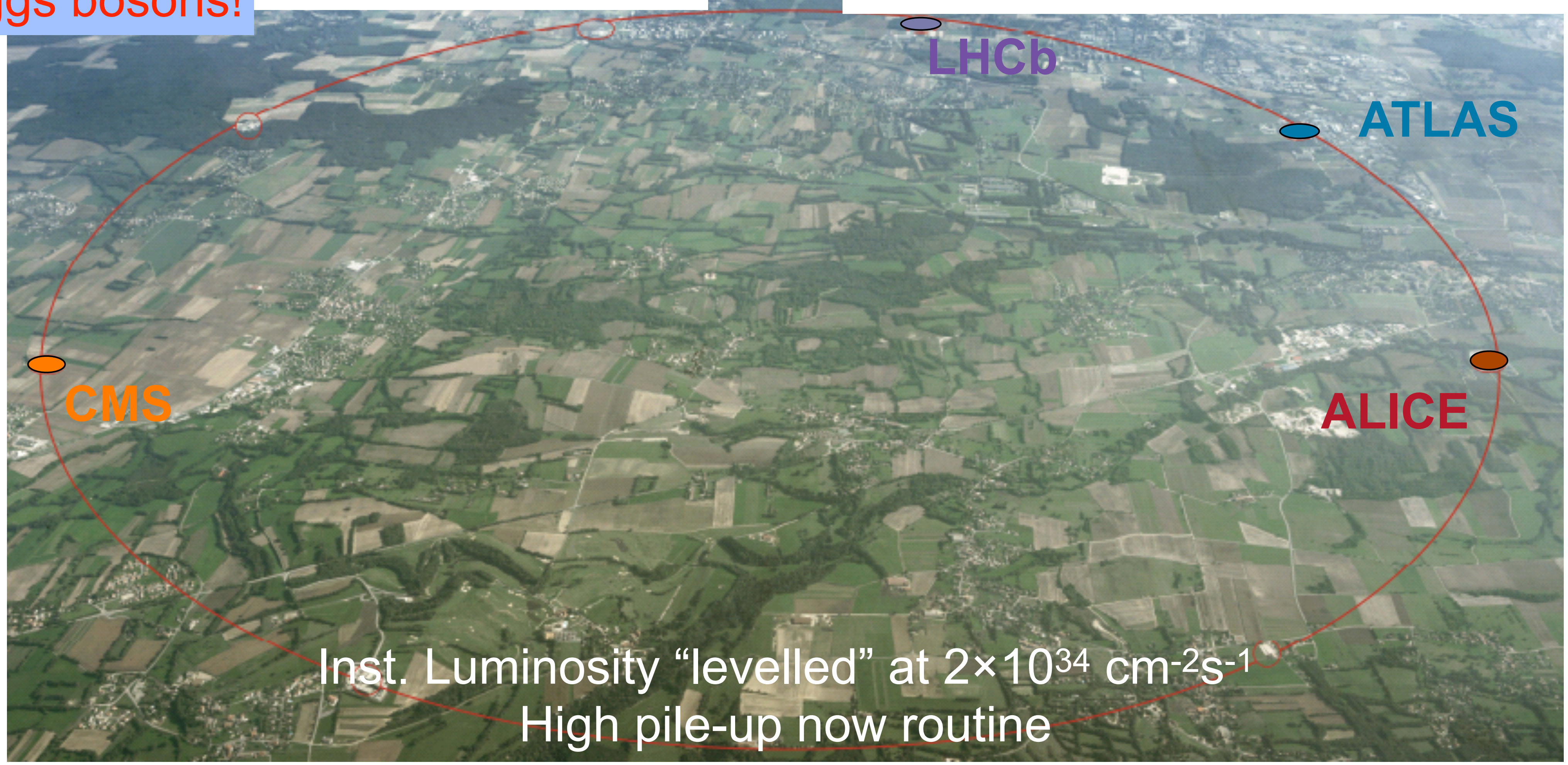
2018 pp √s = 13 TeV
Delivered Luminosity [fb-1]
Month in Year
Jan
Apr
Jul
Oct
2/19 calibration
Run 2 (2015 - 2018)
139 fb-1 at 13 TeV
7.6M Higgs bosons!


LHCb
ATLAS
CMS
ALICE

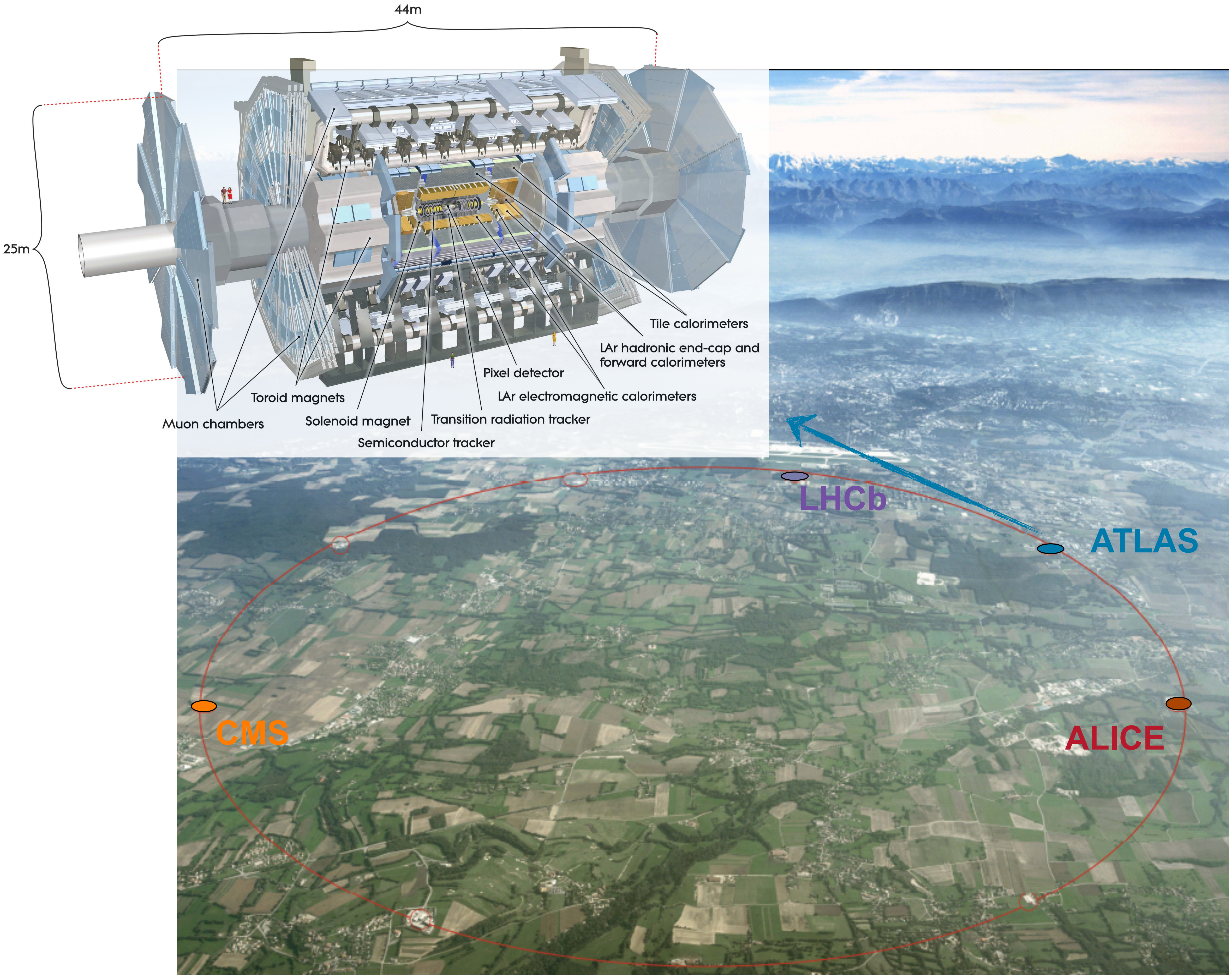


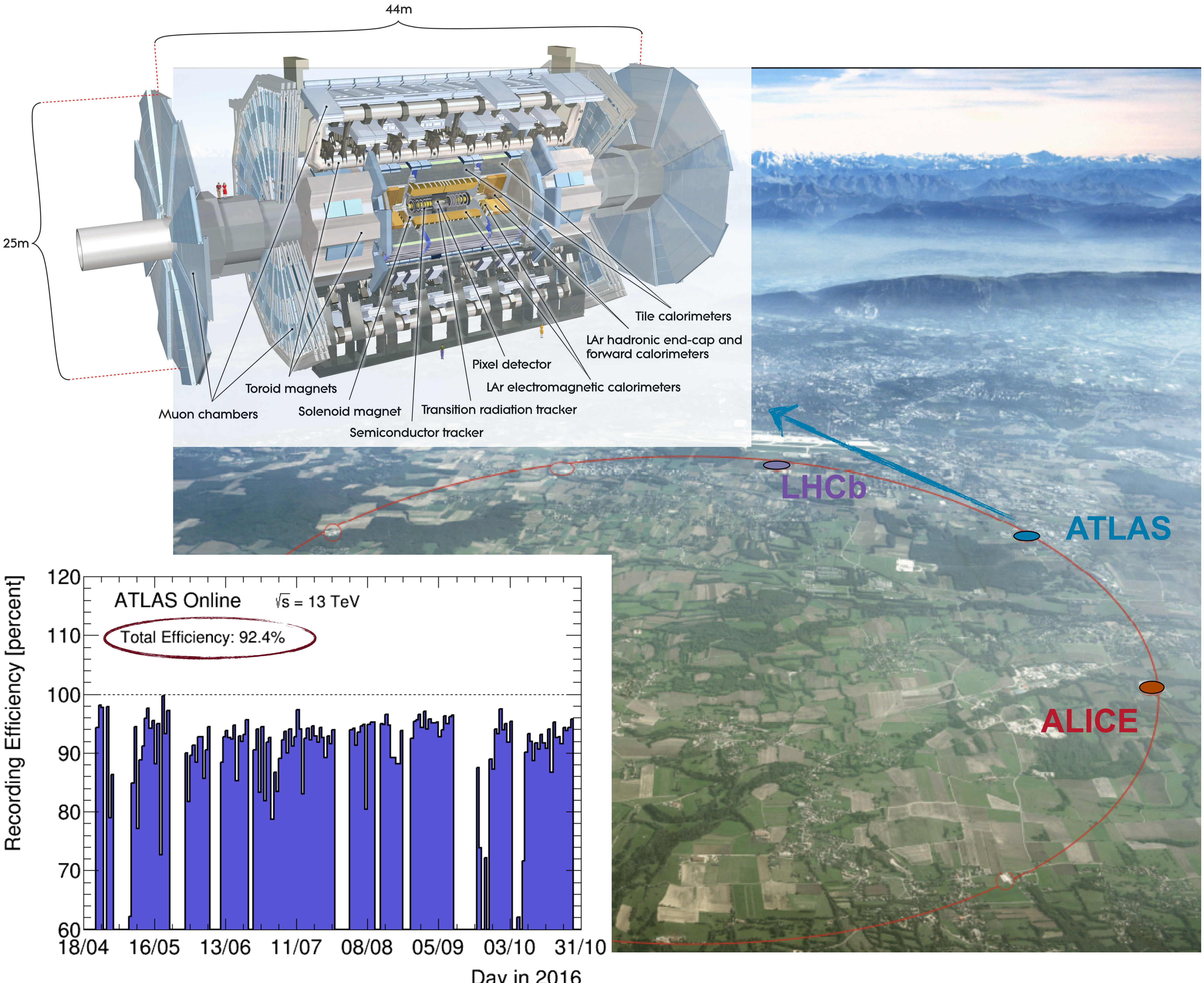
7.6M Higgs bosons!





Inst. Luminosity "levelled" at 2×10^{34} cm^{-2}s^{-1}
High pile-up now routine


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker
LHCb
ATLAS
CMS
ALICE


44m
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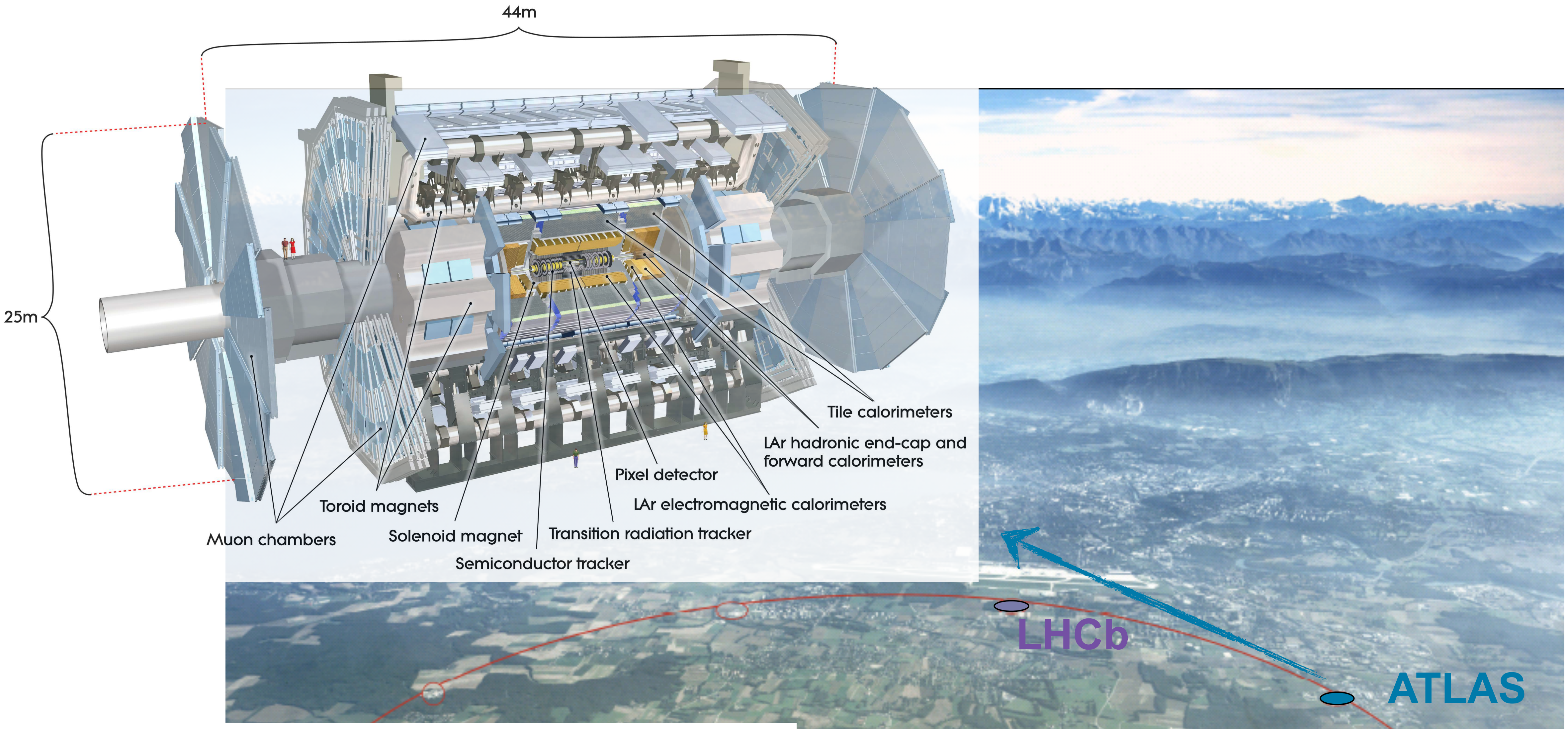
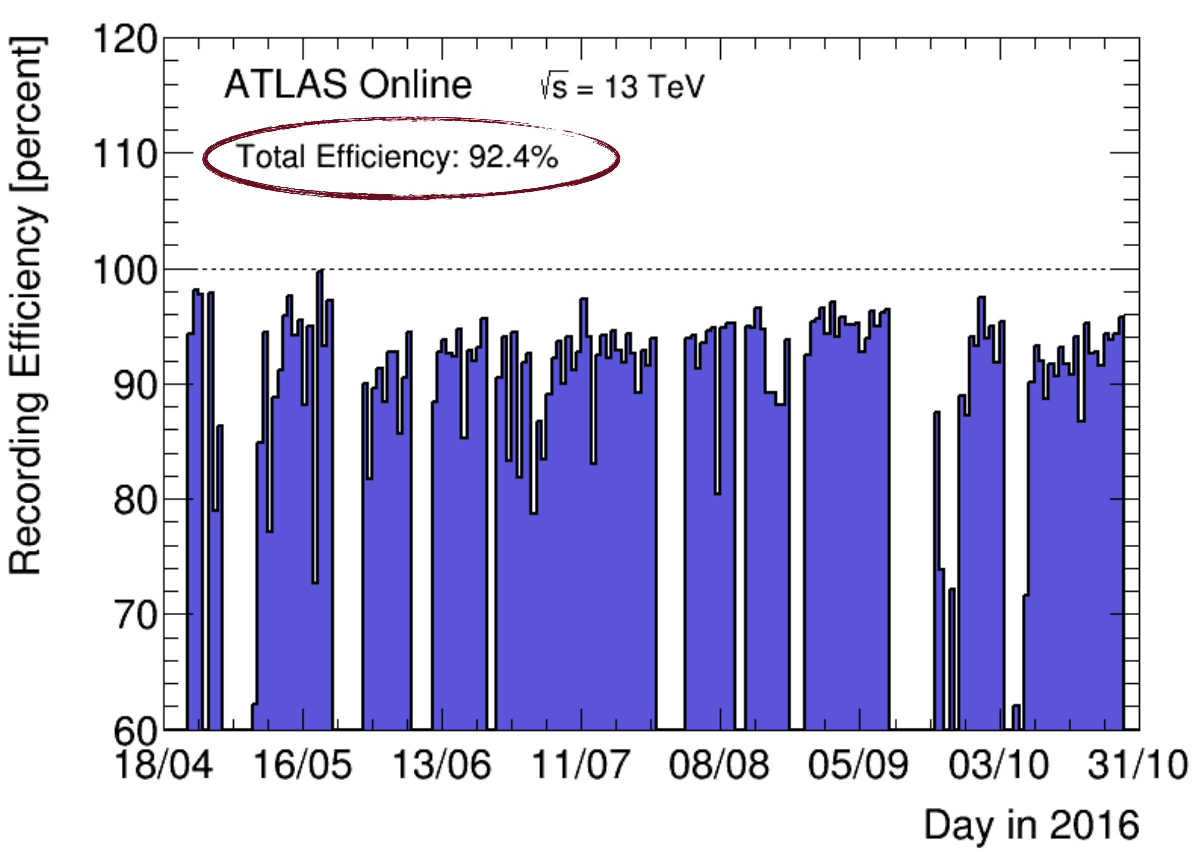
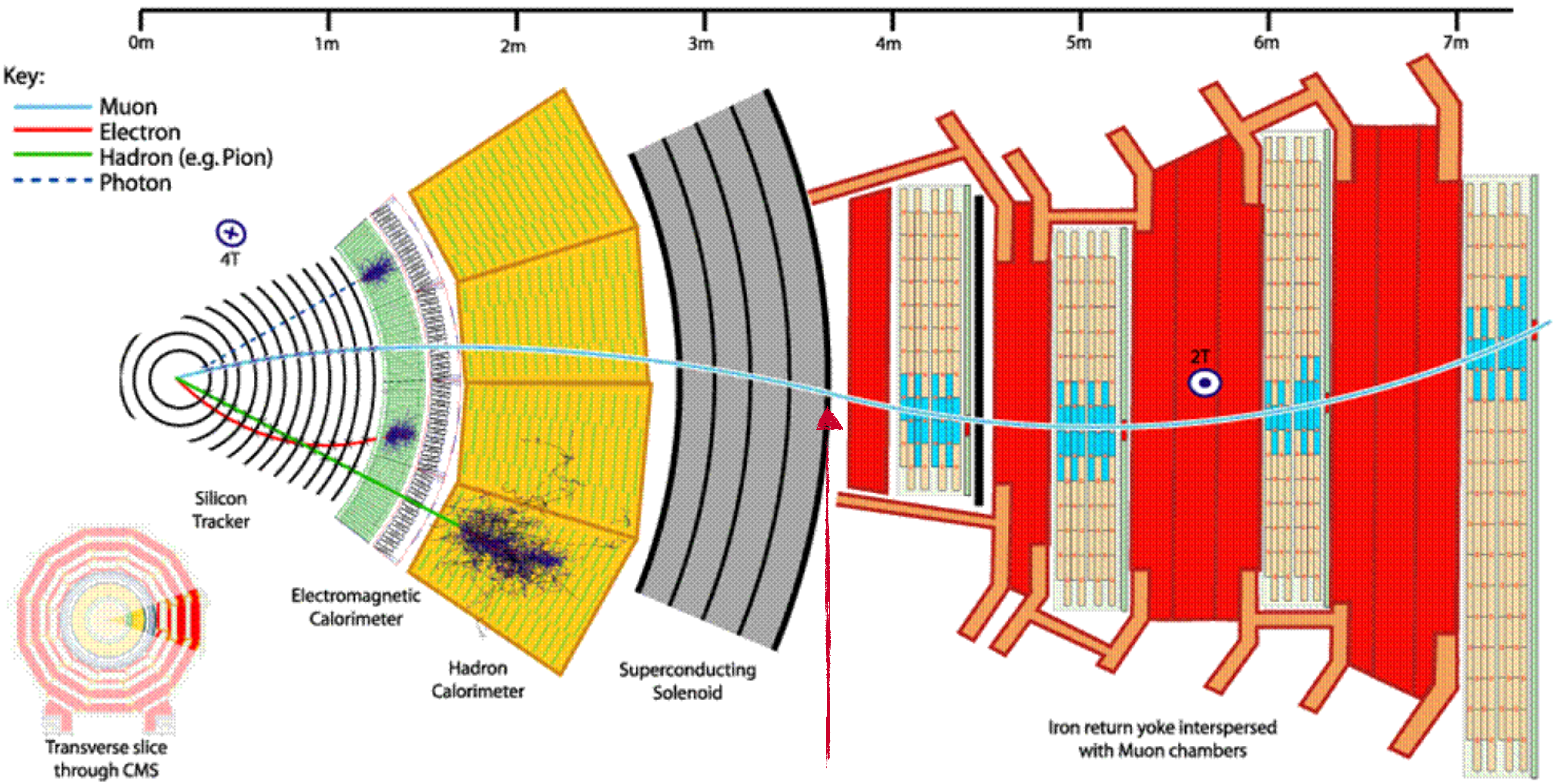
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker
LHCb
ATLAS
ALICE
ATLAS Online
$\sqrt{s}$ = 13 TeV
Total Efficiency: 92.4%
Recording Efficiency [percent]
120
110
100
90
80
70
60
18/04
16/05
13/06
11/07
08/08
05/09
03/10
31/10
Day in 2016



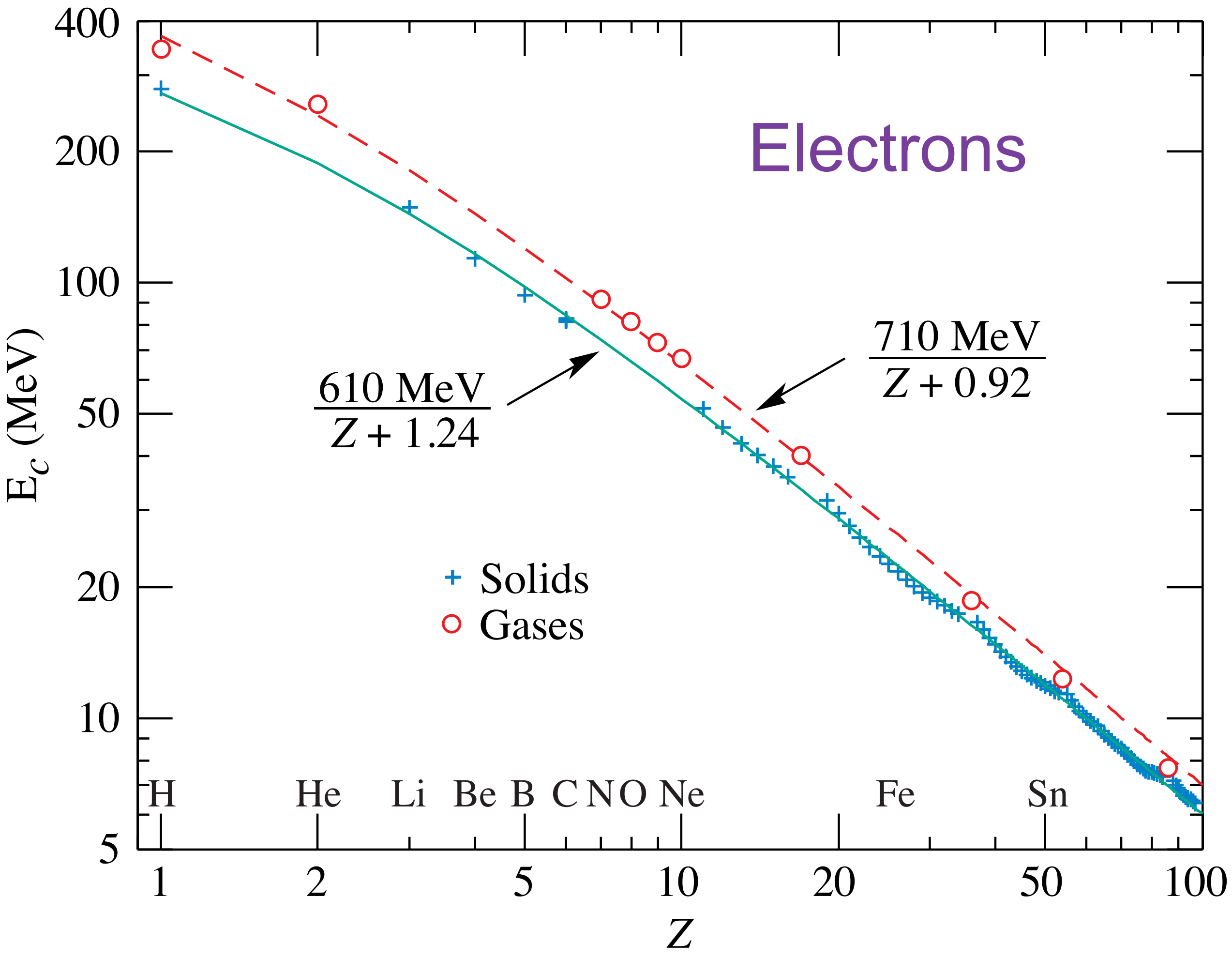


ATLAS pp Run-2: July 2015 – October 2018										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.5	99.9	99.7	99.6	99.7	99.8	99.6	100	100	99.8	98.8
Good for physics: 95.6% (139 fb^{-1})										

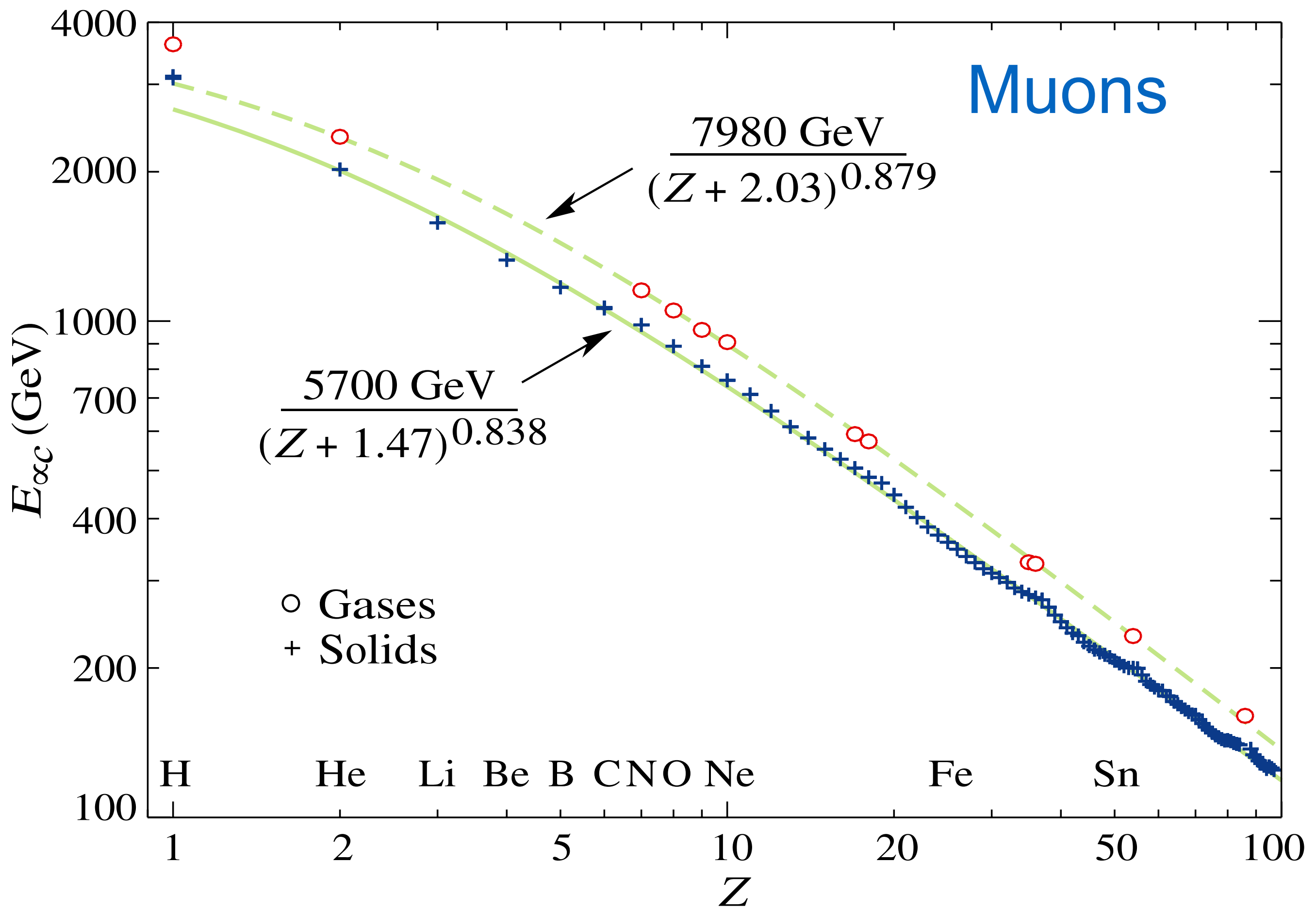
Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collision physics runs with 25 ns bunch-spacing at √s=13 TeV for the full Run-2 period (between July 2015 – October 2018), corresponding to a delivered integrated luminosity of 153 fb^{-1} and a recorded integrated luminosity of 146 fb^{-1}. Runs with specialized physics goals are not included. Dedicated luminosity calibration activities during LHC fills used 0.6% of recorded data in 2018 and are included in the inefficiency. Trigger-specific data quality problems (0.4% inefficiency at Level-1) are included in the overall inefficiency. When the stable beam flag is raised, the tracking detectors undergo a so-called "warm start", which includes a ramp of the high-voltage and turning on the pre-amplifiers for the Pixel system. The inefficiency due to this, as well as the DAQ inefficiency, are not included in the table above, but accounted for in the ATLAS data taking efficiency.

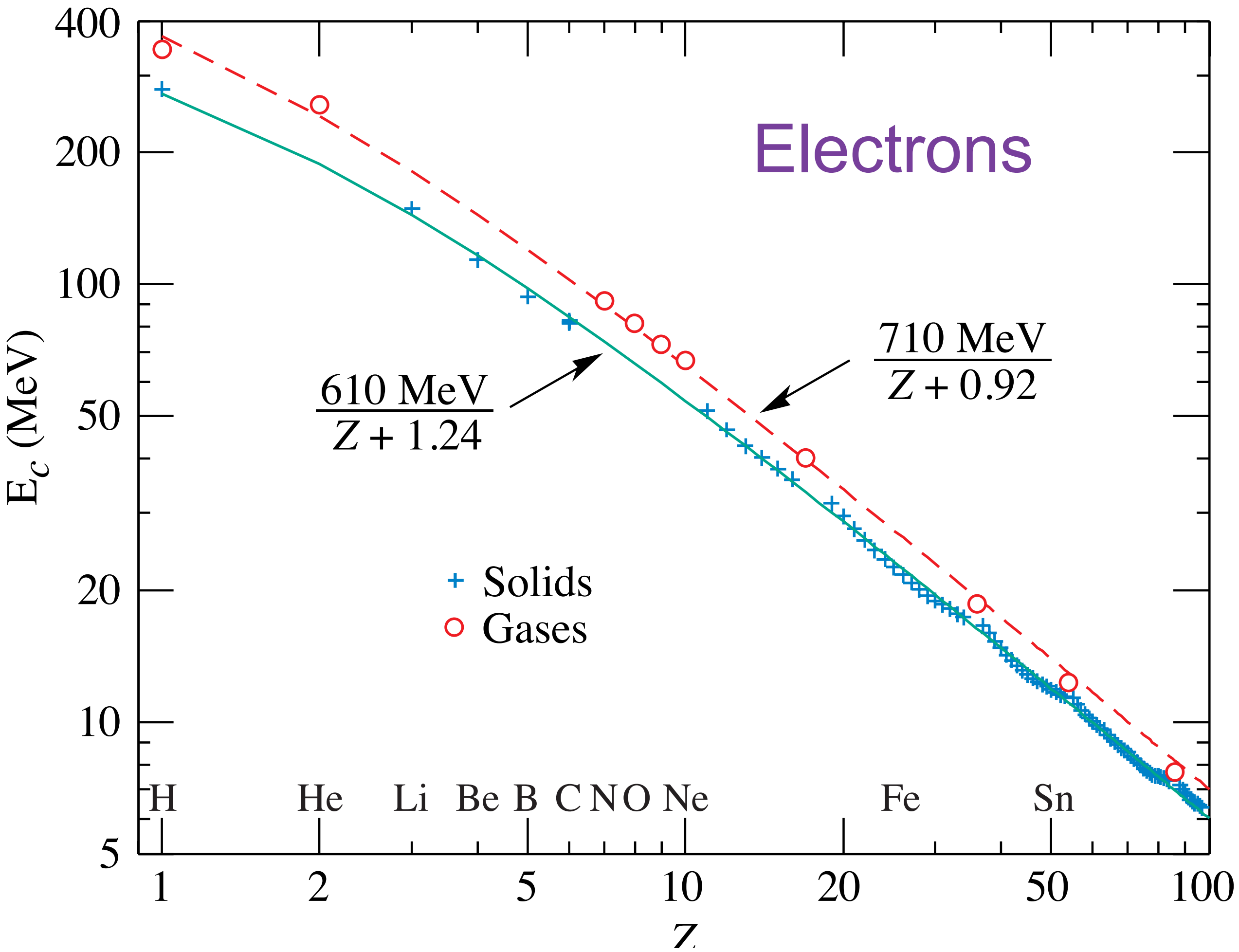


Muons are the "cleanest" physics objects to be reconstructed



Radiative energy losses important for **electrons** from O(30 MeV), for **muons** from O(500 GeV)!





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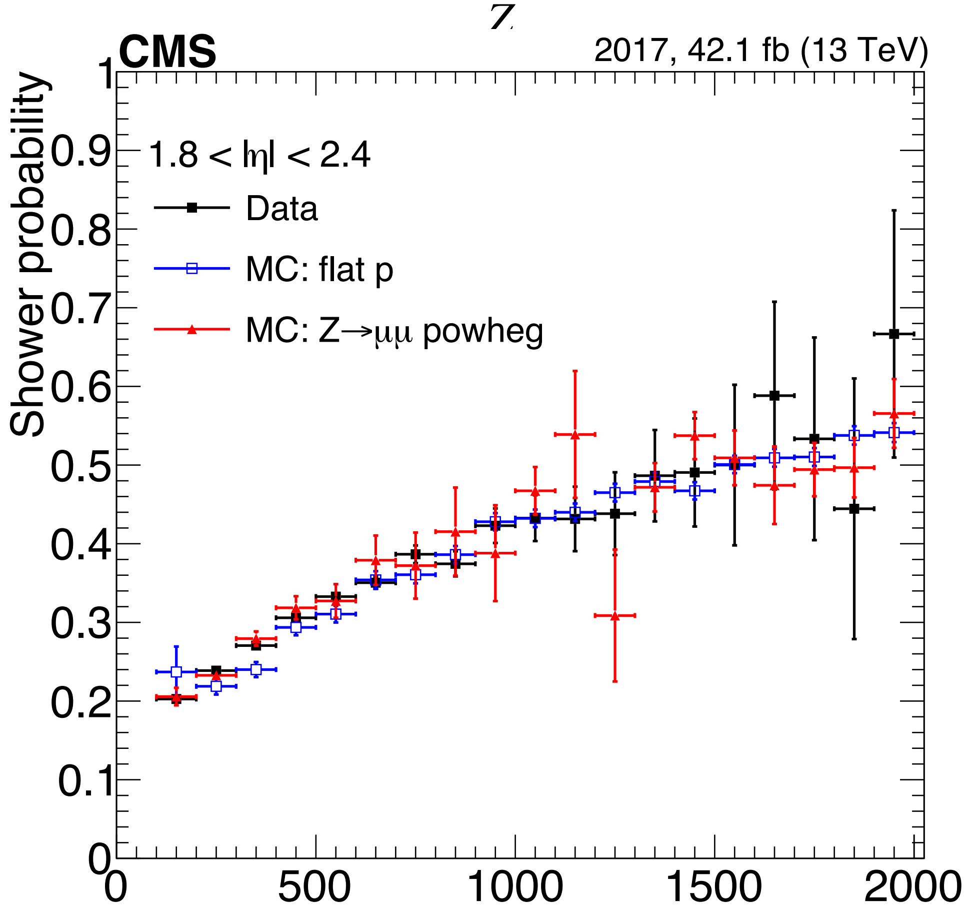
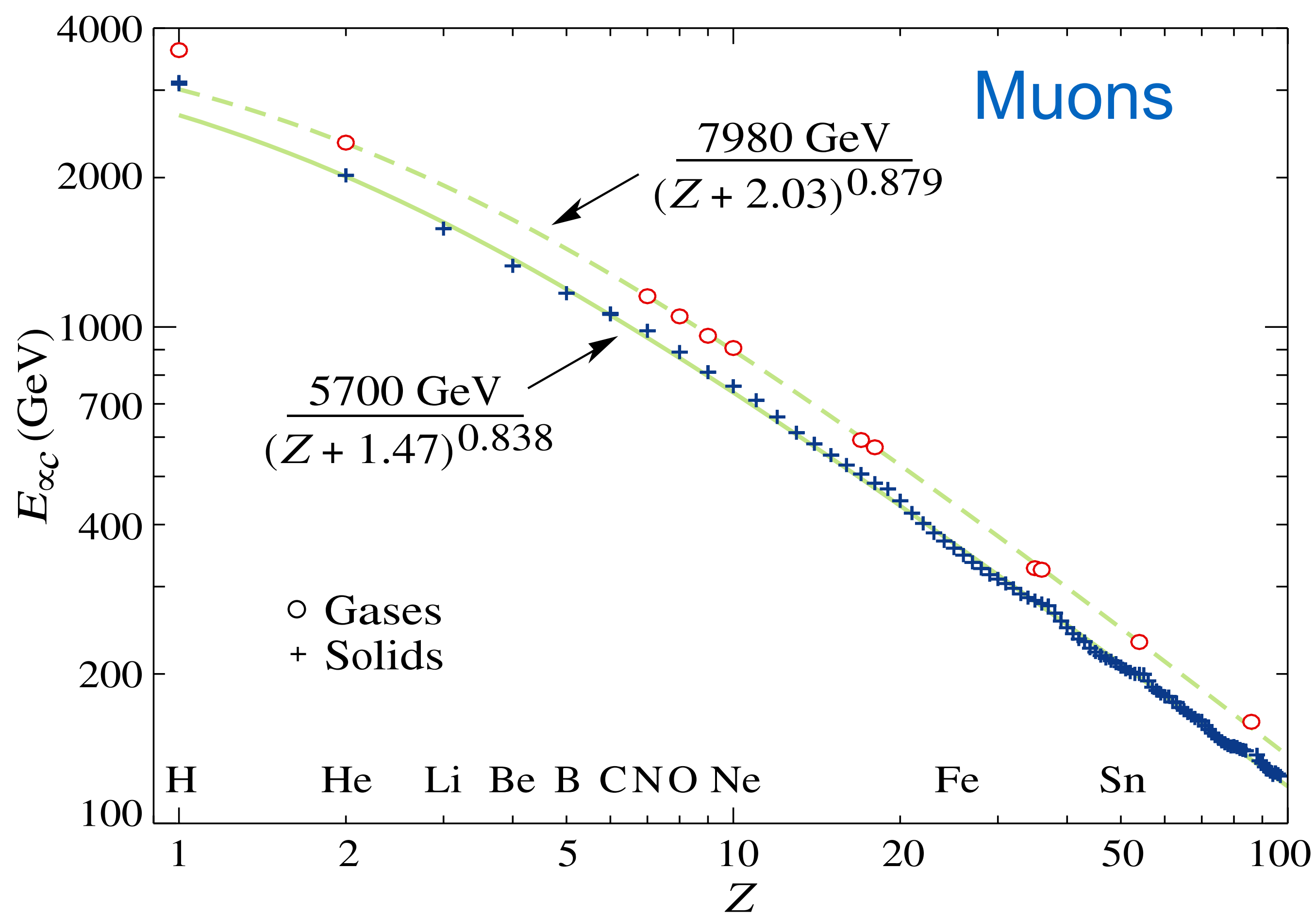
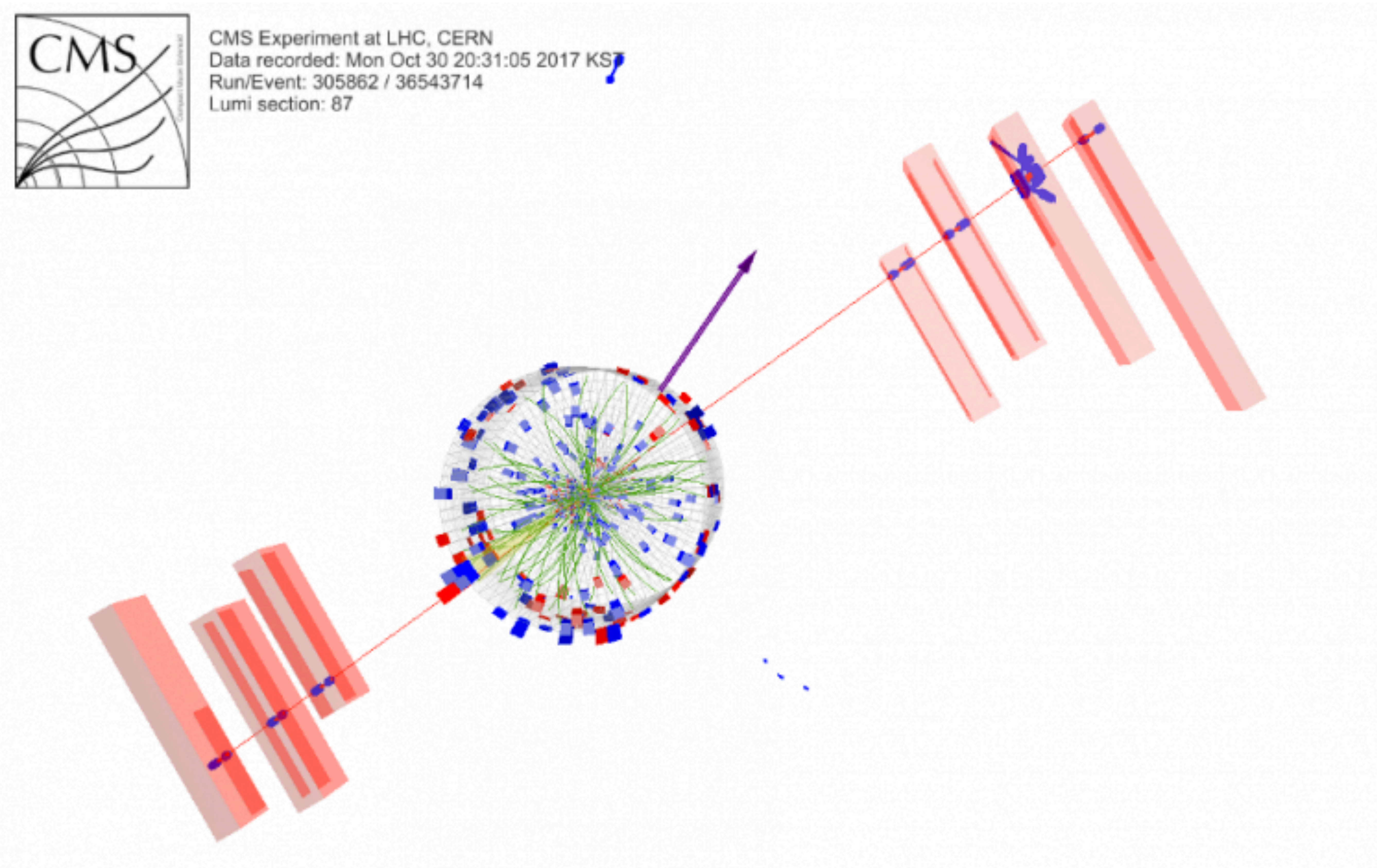
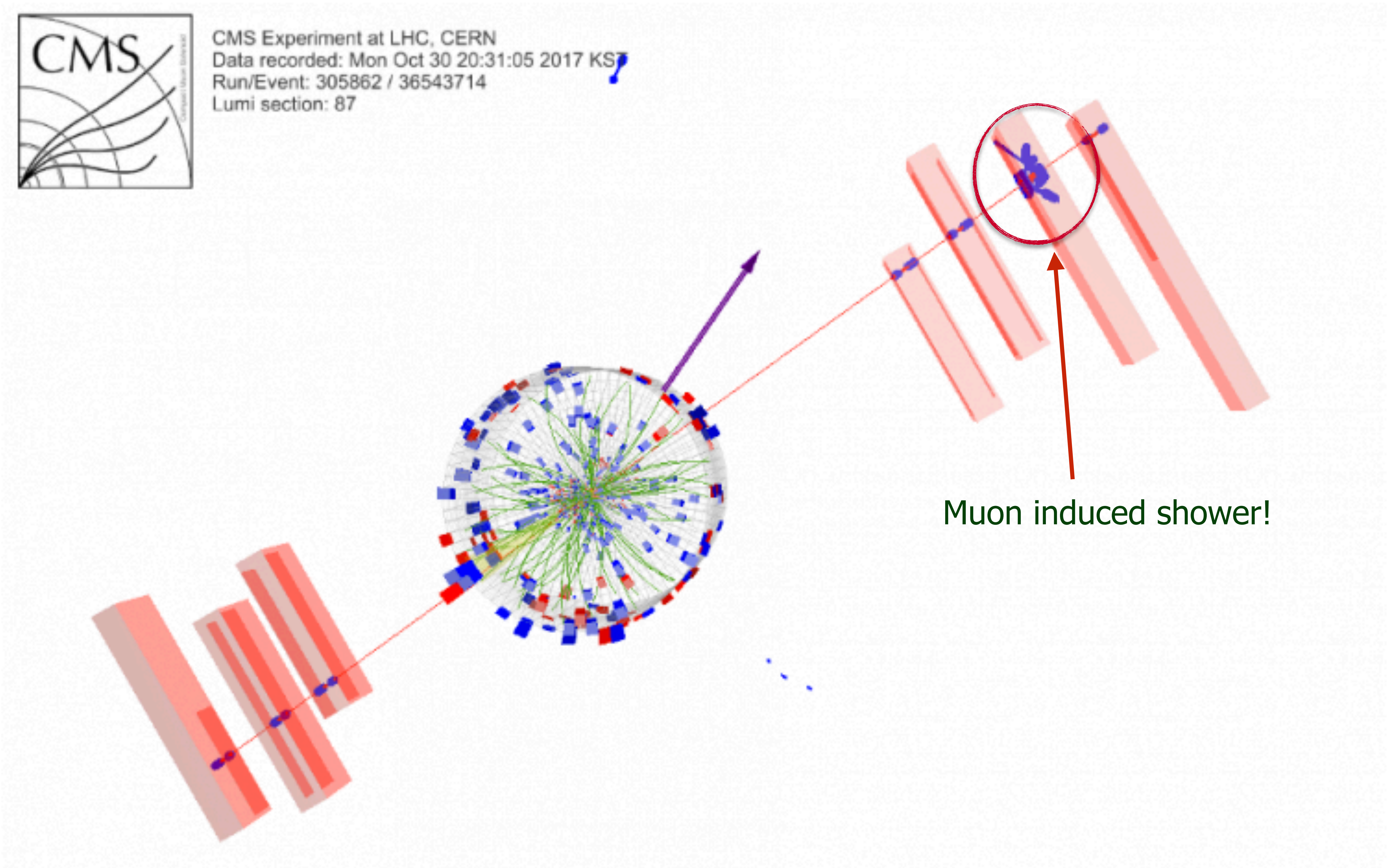
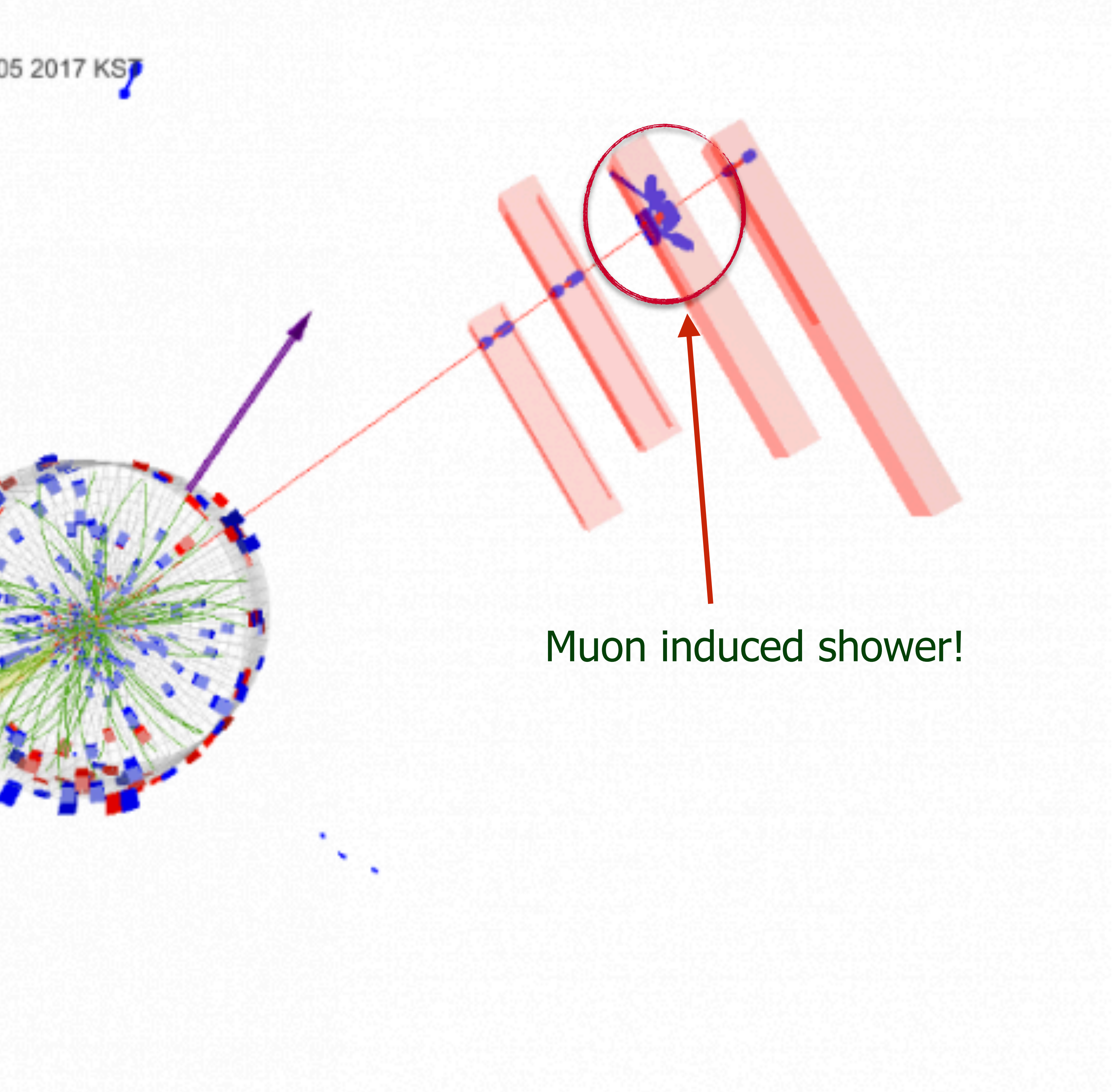


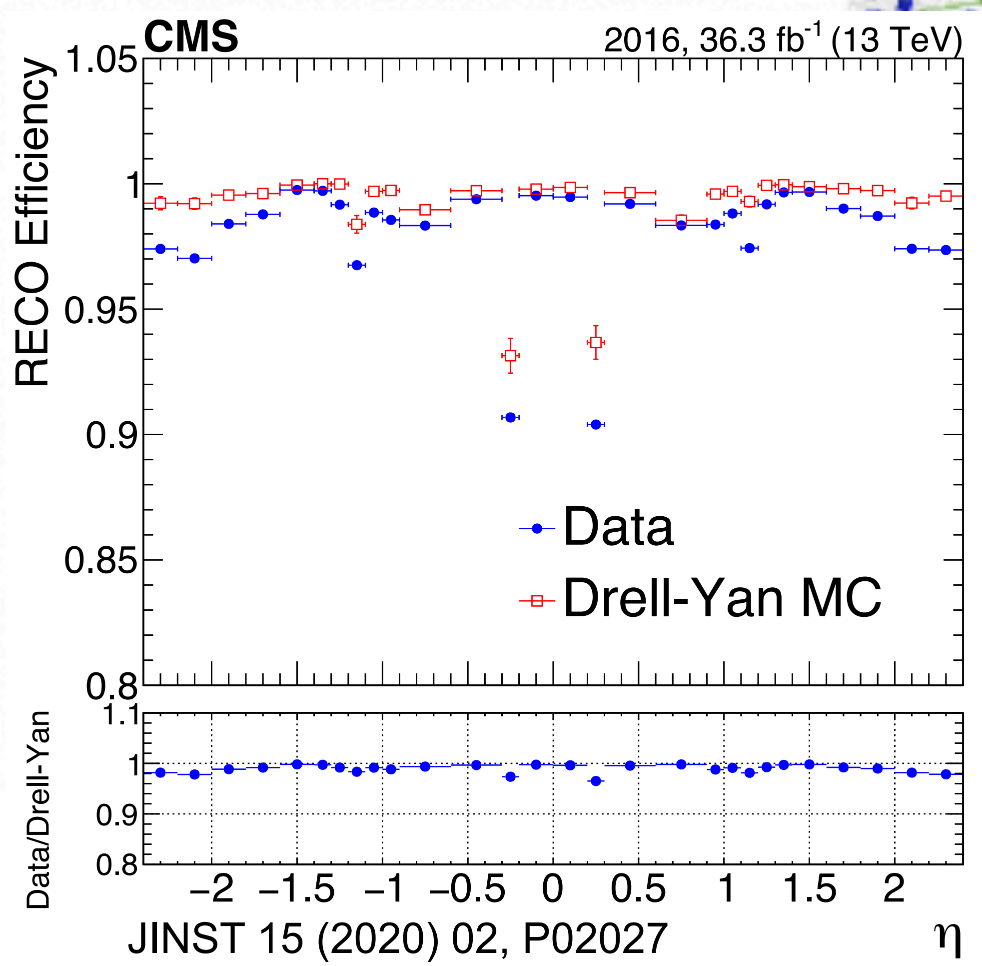
JINST 15 (2020) 02, P02027



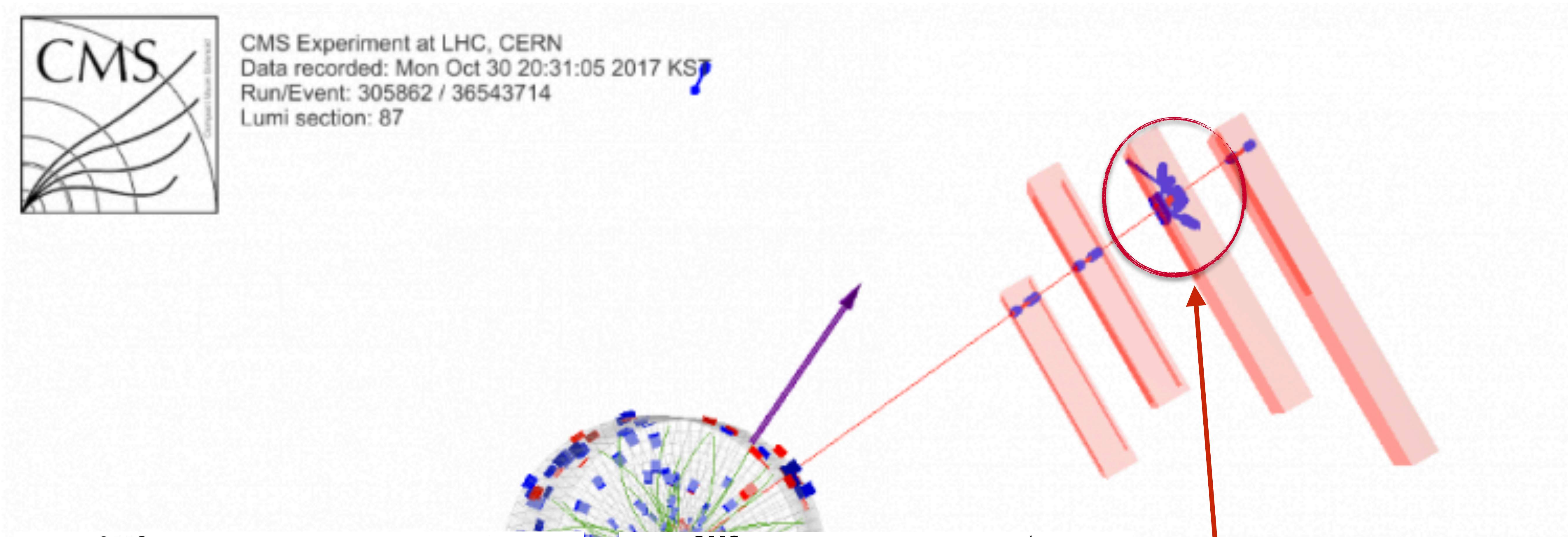

CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Oct 30 20:31:05 2017 KST
Run/Event: 305862 / 36543714
Lumi section: 87


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Oct 30 20:31:05 2017 KST
Run/Event: 305862 / 36543714
Lumi section: 87
Muon induced shower!

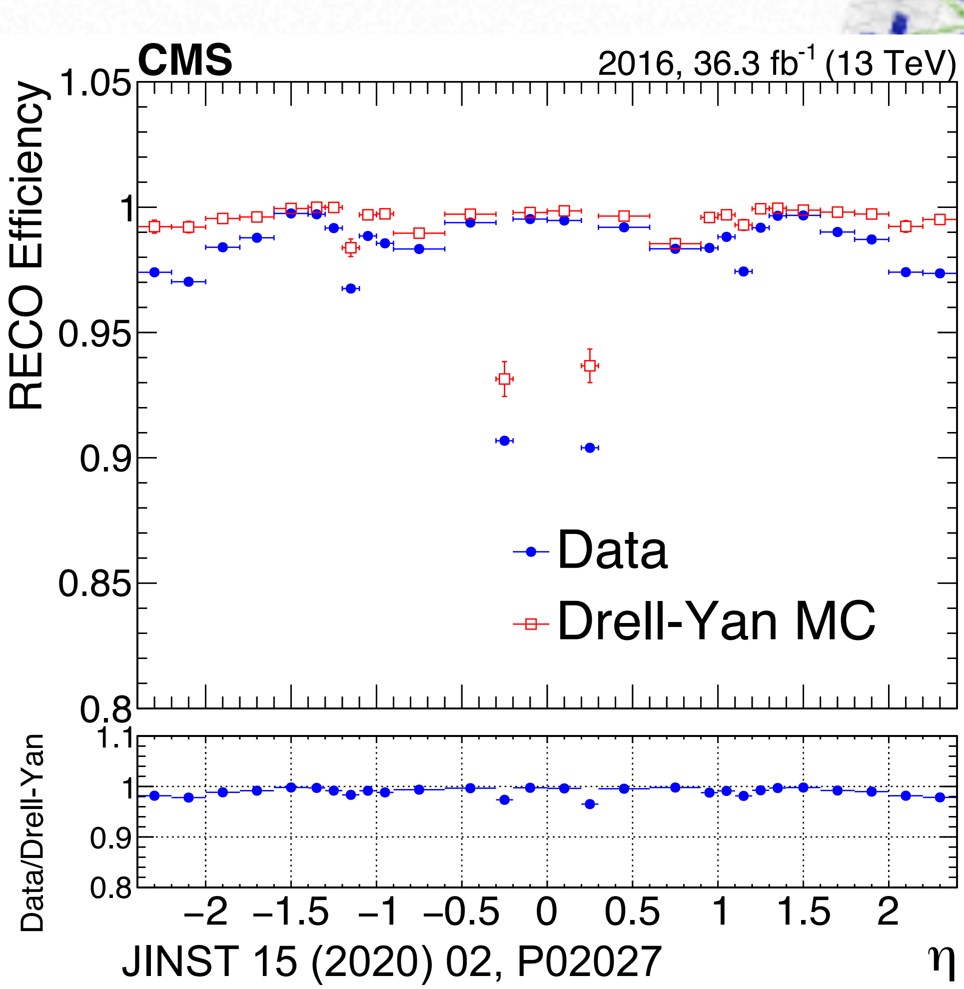


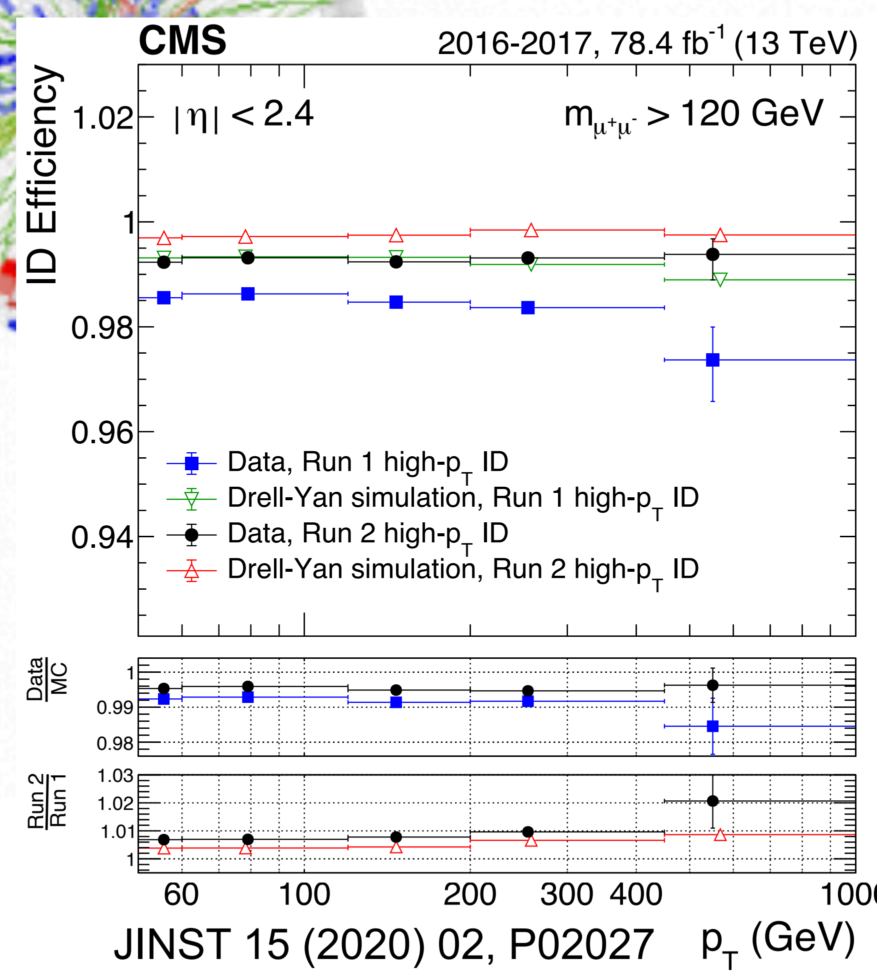


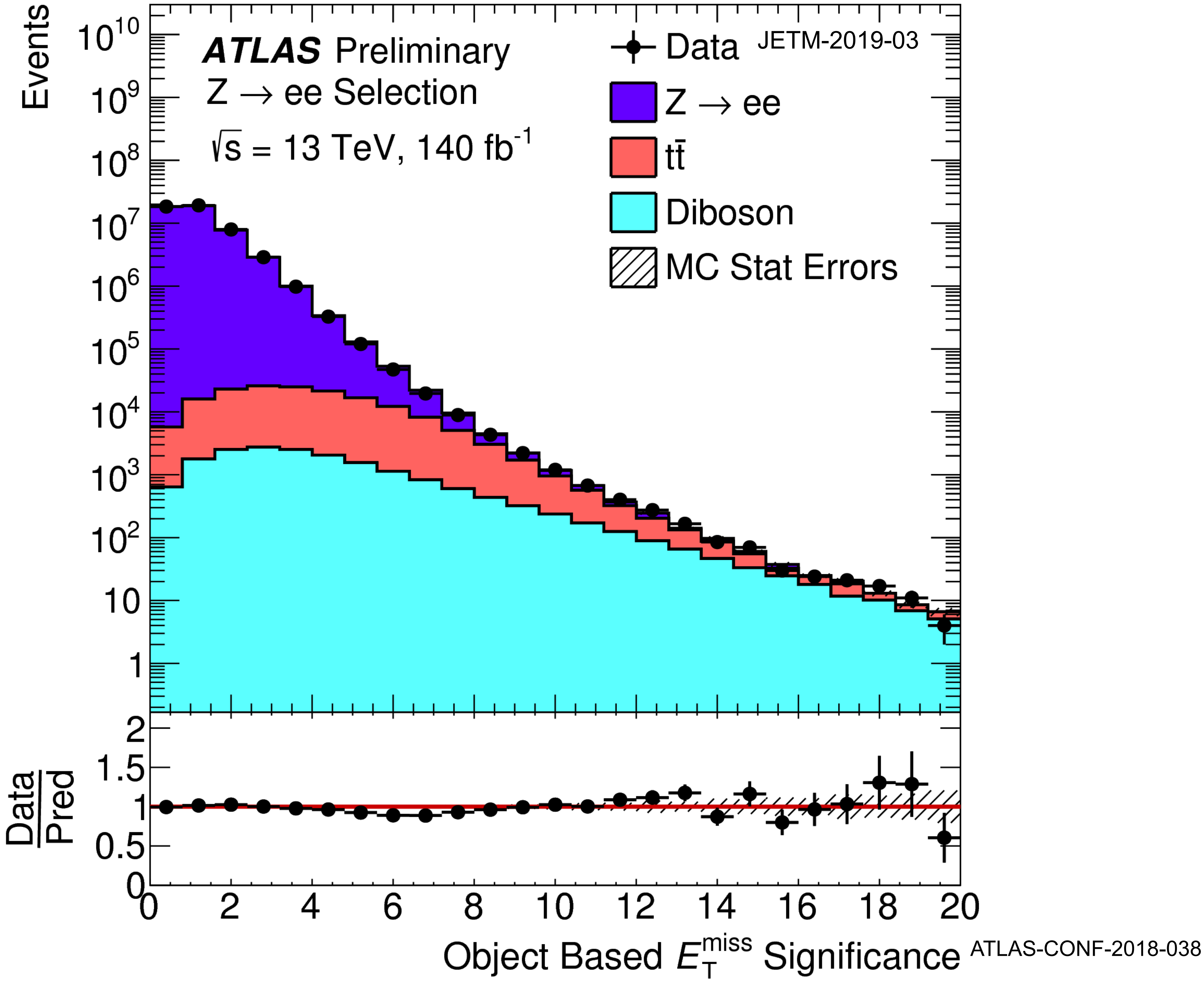
JINST 15 (2020) 02, P02027

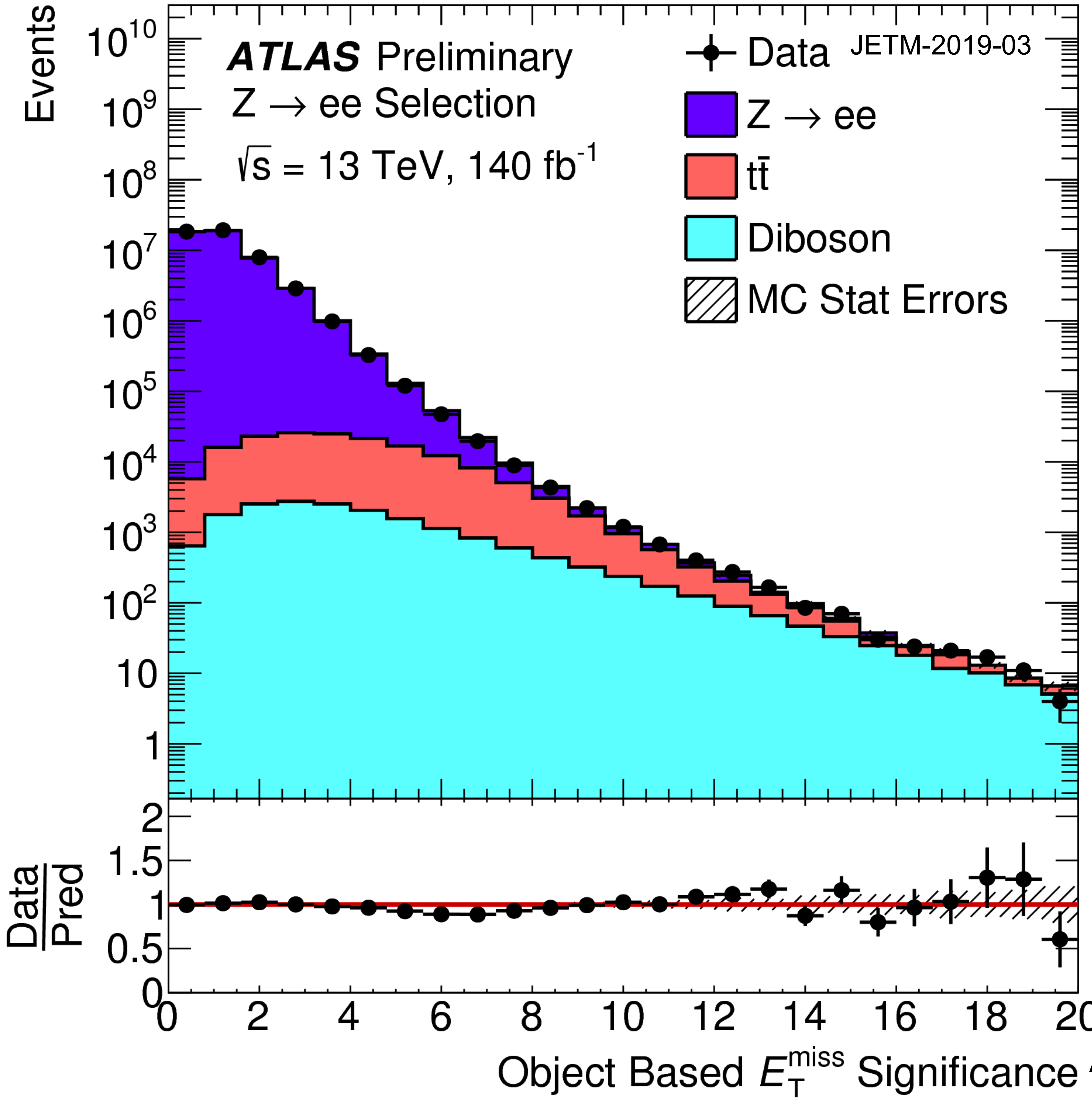


on induced shower!






ATLAS Preliminary
Z → ee Selection
√s = 13 TeV, 140 fb-1
Data
JETM-2019-03
Z → ee
tt̄
Diboson
MC Stat Errors
Events
Data/Pred
Object Based E_T^{miss} Significance
ATLAS-CONF-2018-038

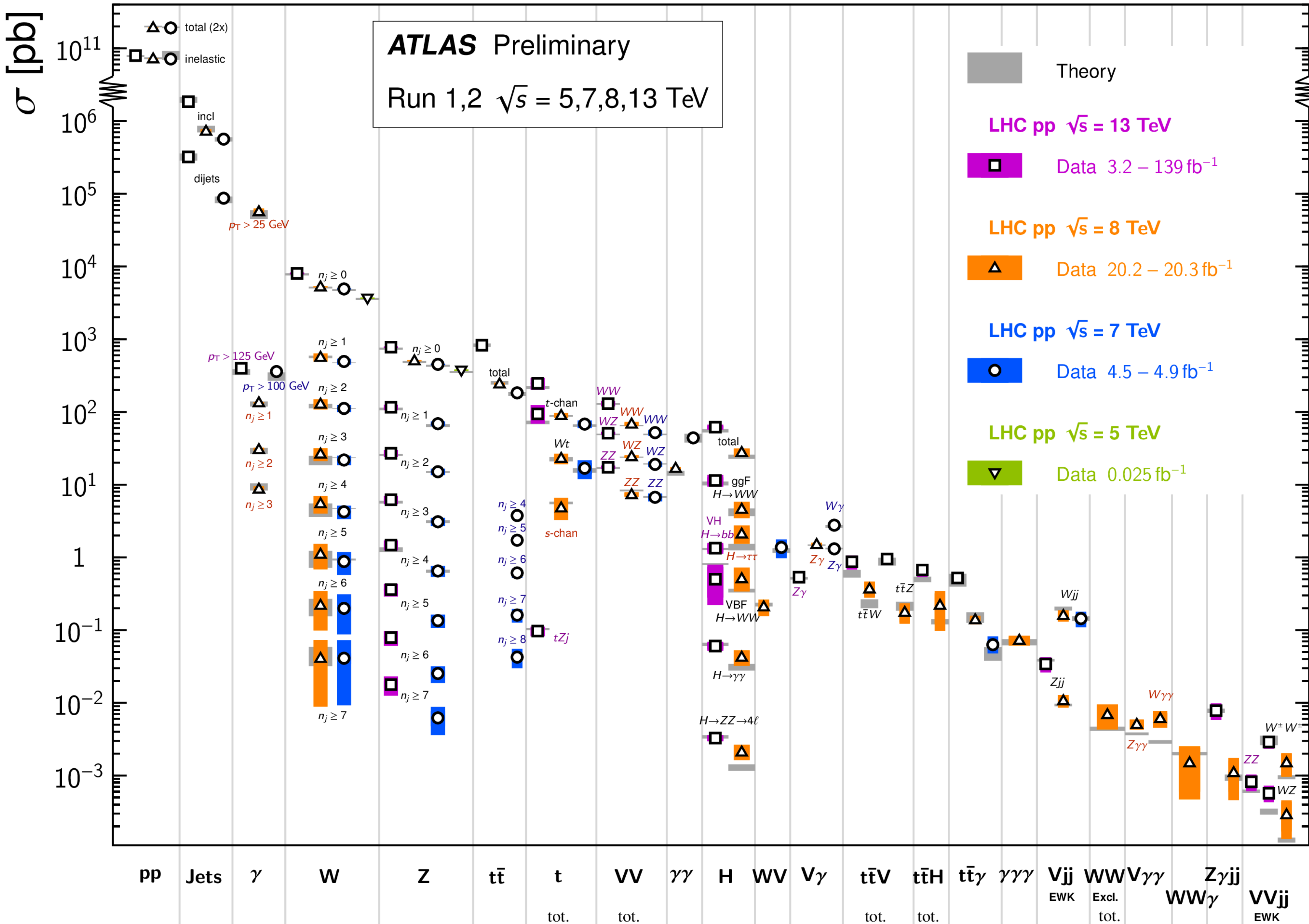


ATLAS-CONF-2018-038

$$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} = \underbrace{\underbrace{- \sum_{\substack{\text{selected}\\ \text{electrons}}} \mathbf{p}_{\mathrm{T}}^{e}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},e}} \underbrace{- \sum_{\substack{\text{accepted}\\ \text{photons}}} \mathbf{p}_{\mathrm{T}}^{\gamma}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\gamma}} \underbrace{- \sum_{\substack{\text{accepted}\\ \tau\text{-leptons}}} \mathbf{p}_{\mathrm{T}}^{\tau_{\mathrm{had}}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\tau_{\mathrm{had}}}} \underbrace{- \sum_{\substack{\text{selected}\\ \text{muons}}} \mathbf{p}_{\mathrm{T}}^{\mu}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\mu}} \underbrace{- \sum_{\substack{\text{accepted}\\ \text{jets}}} \mathbf{p}_{\mathrm{T}}^{\mathrm{jet}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss,jet}}}}_{\text{hard term}} \underbrace{\underbrace{- \sum_{\substack{\text{unused}\\ \text{tracks}}} \mathbf{p}_{\mathrm{T}}^{\mathrm{track}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss,soft}}}}_{\text{soft term}}$$

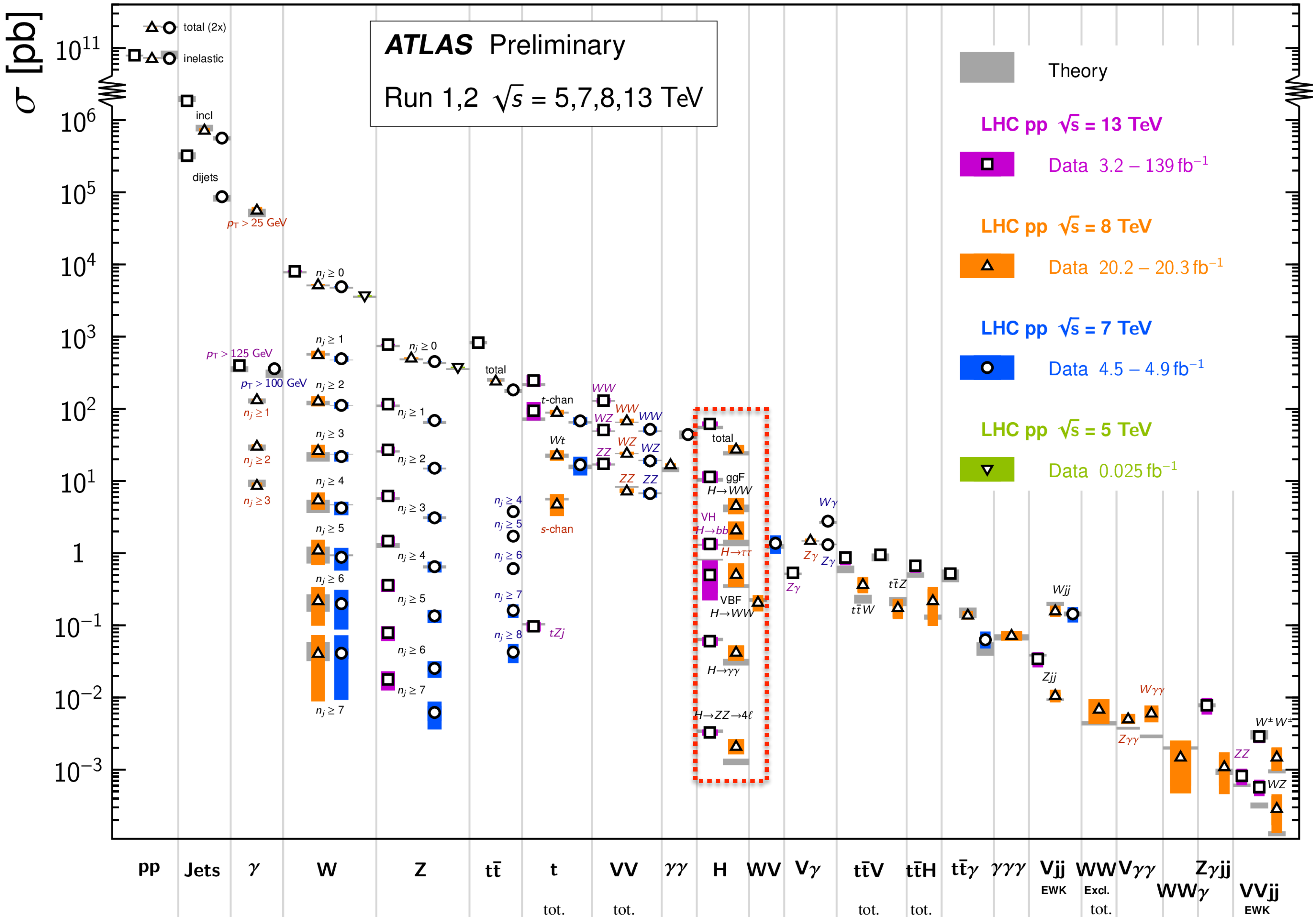
Standard Model Production Cross Section Measurements

Status: May 2020



Standard Model Production Cross Section Measurements

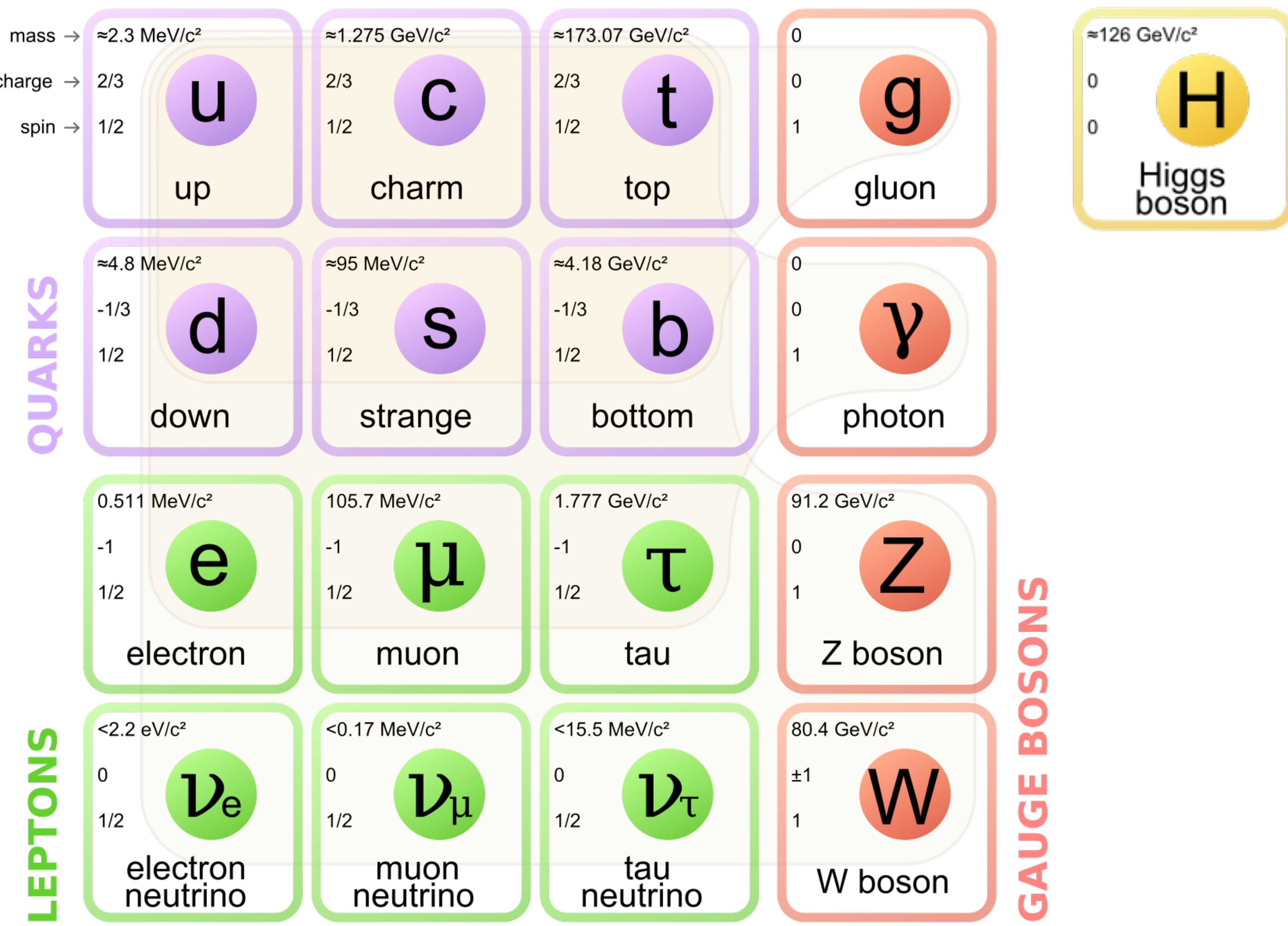
Status: May 2020



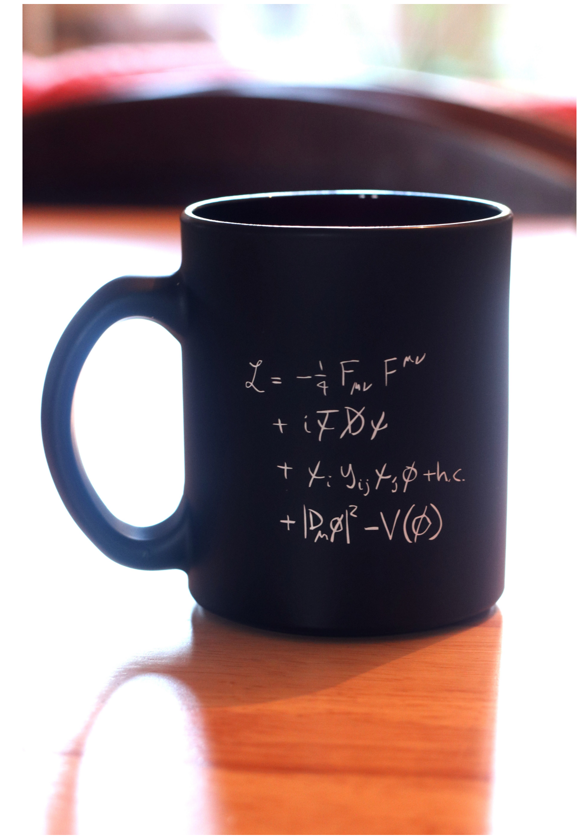
The Standard Model of Particle Physics

The Standard Model describes the **matter particles** and their **interactions**, and the **Higgs boson**

Matter Particles **Force Particles**



1st 2nd 3rd
Generations



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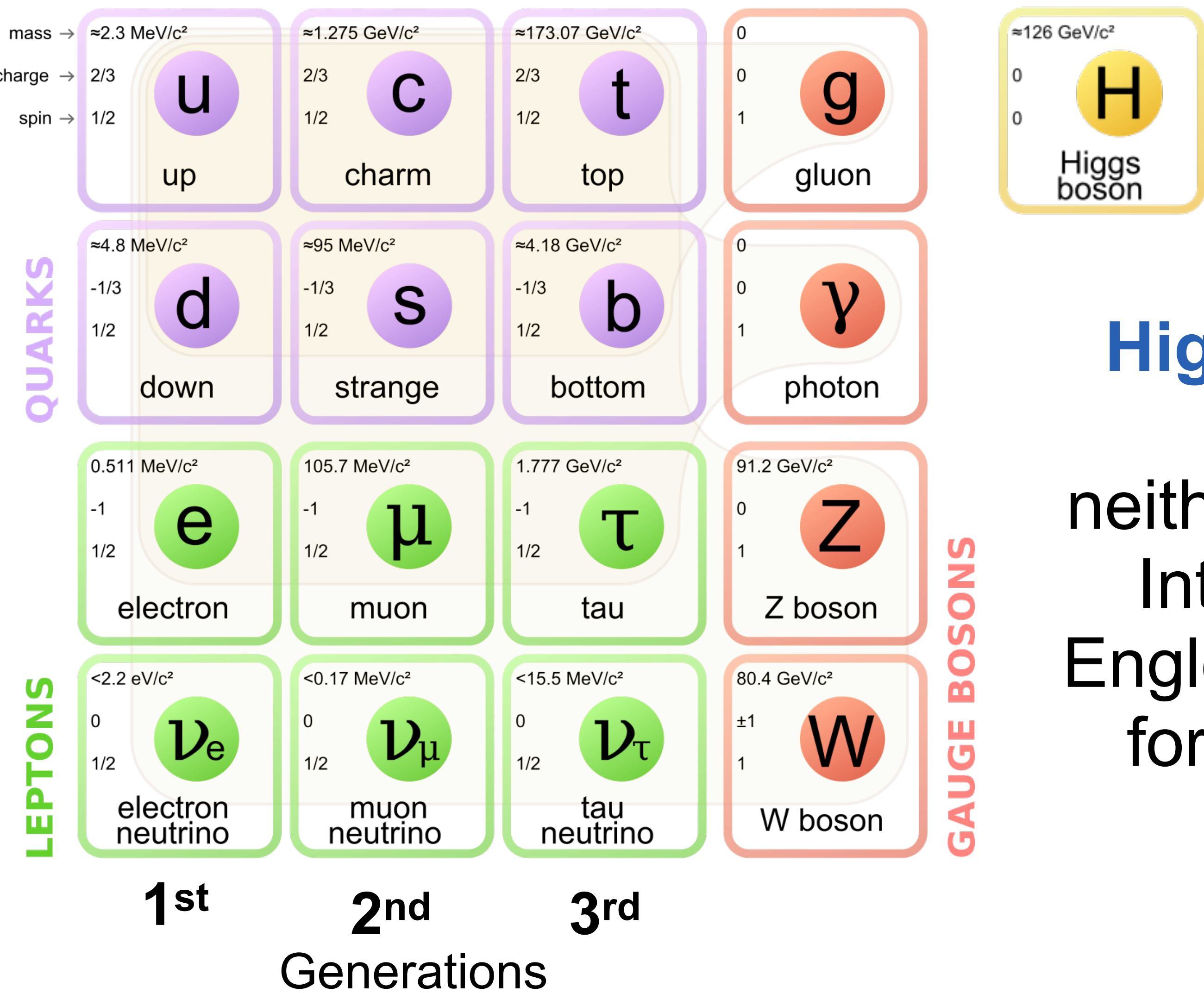
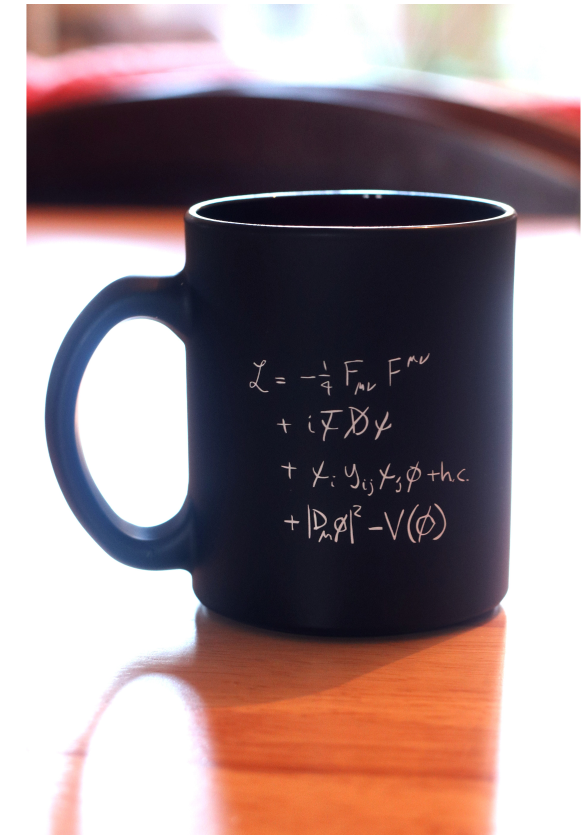


Higgs boson is a new kind of particle

neither **Matter** nor **Force**.
Introduced via Brout-Englert-Higgs mechanism for **W±/Z boson** mass generation



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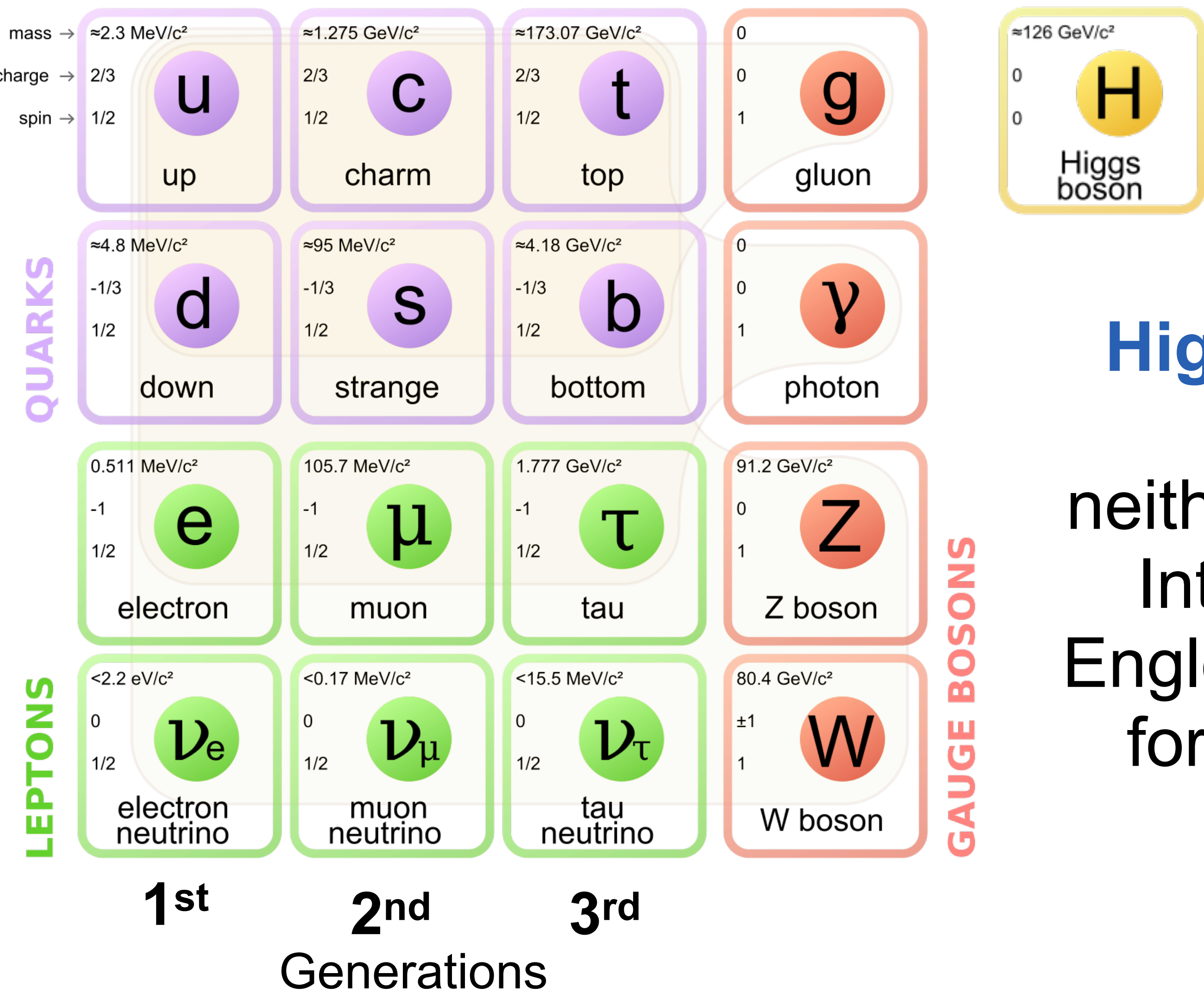
Matter Particles **Force Particles**



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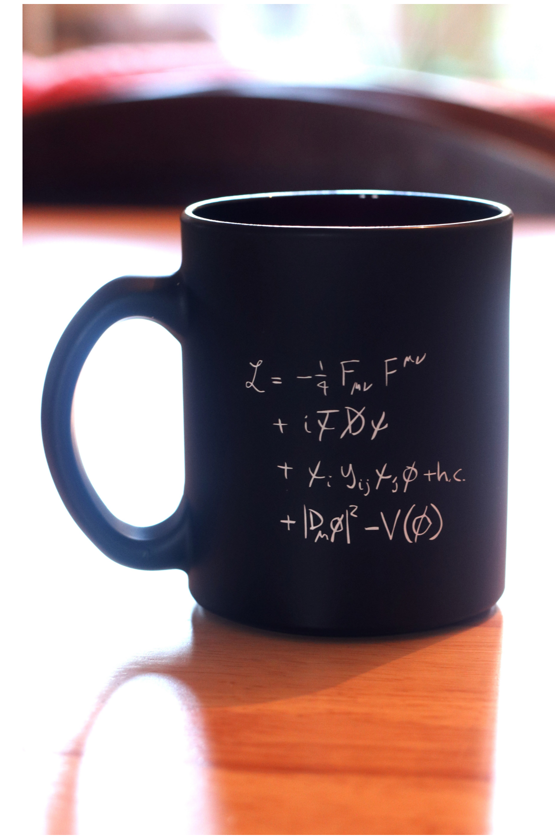
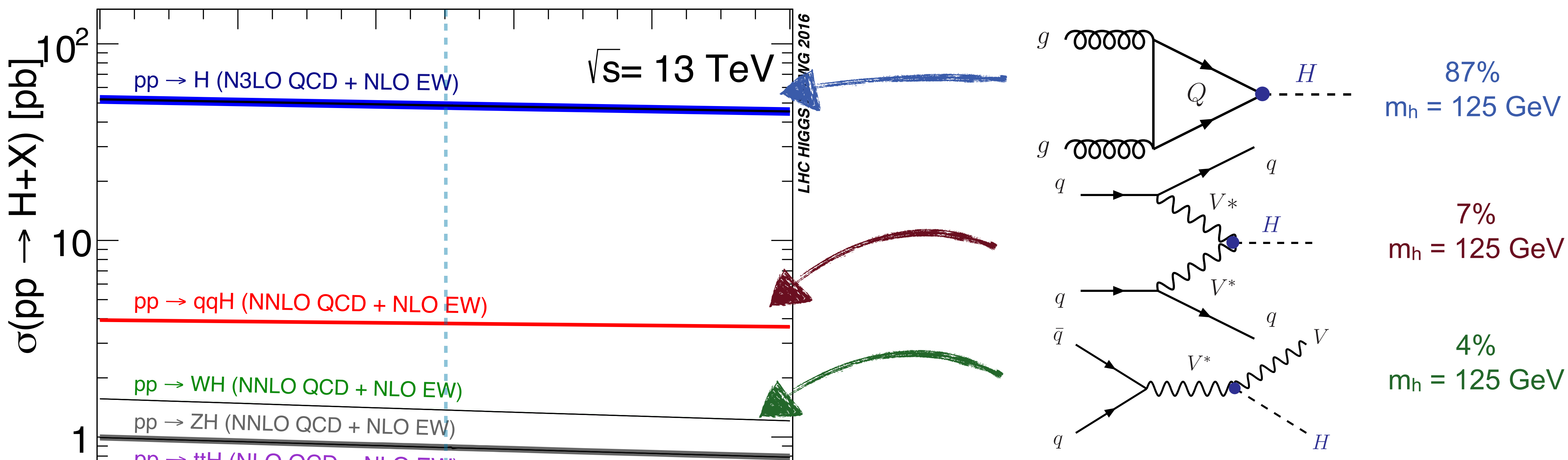
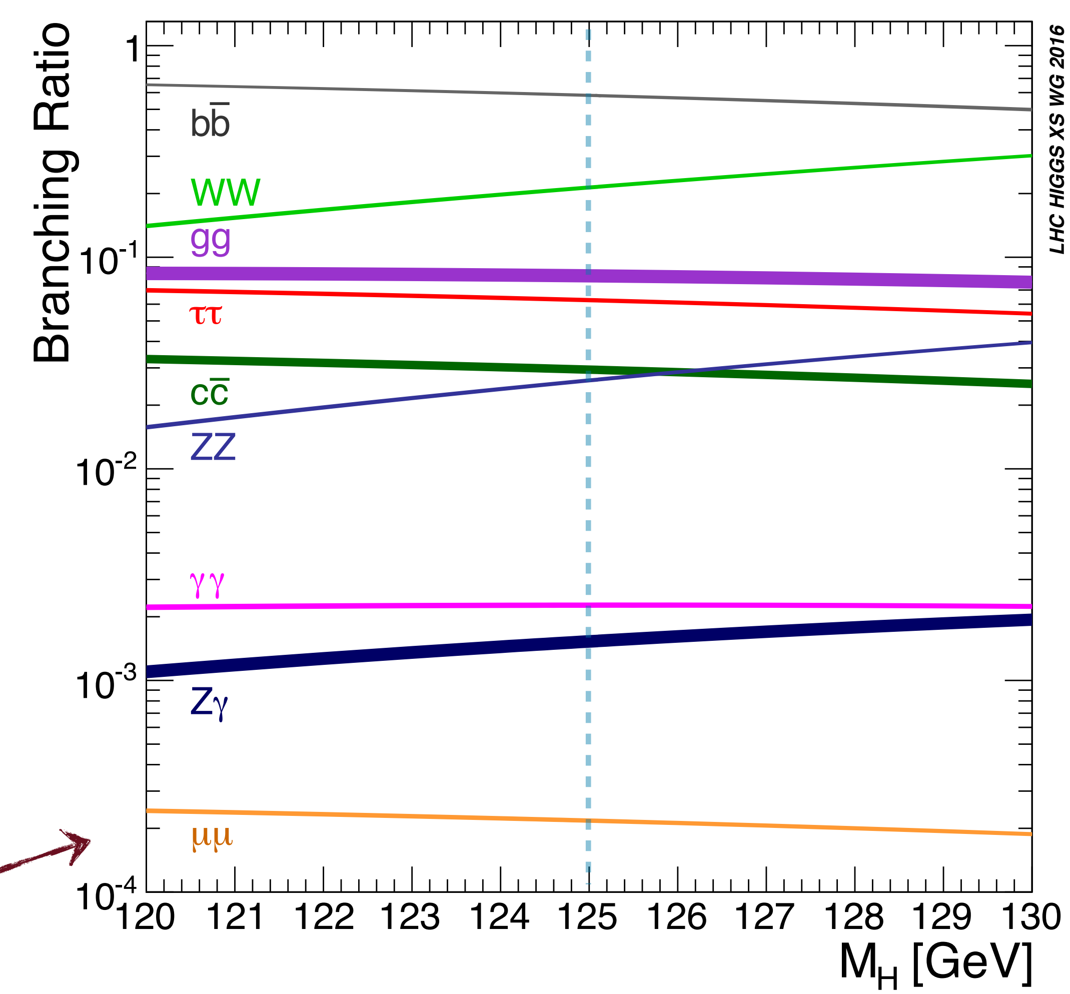


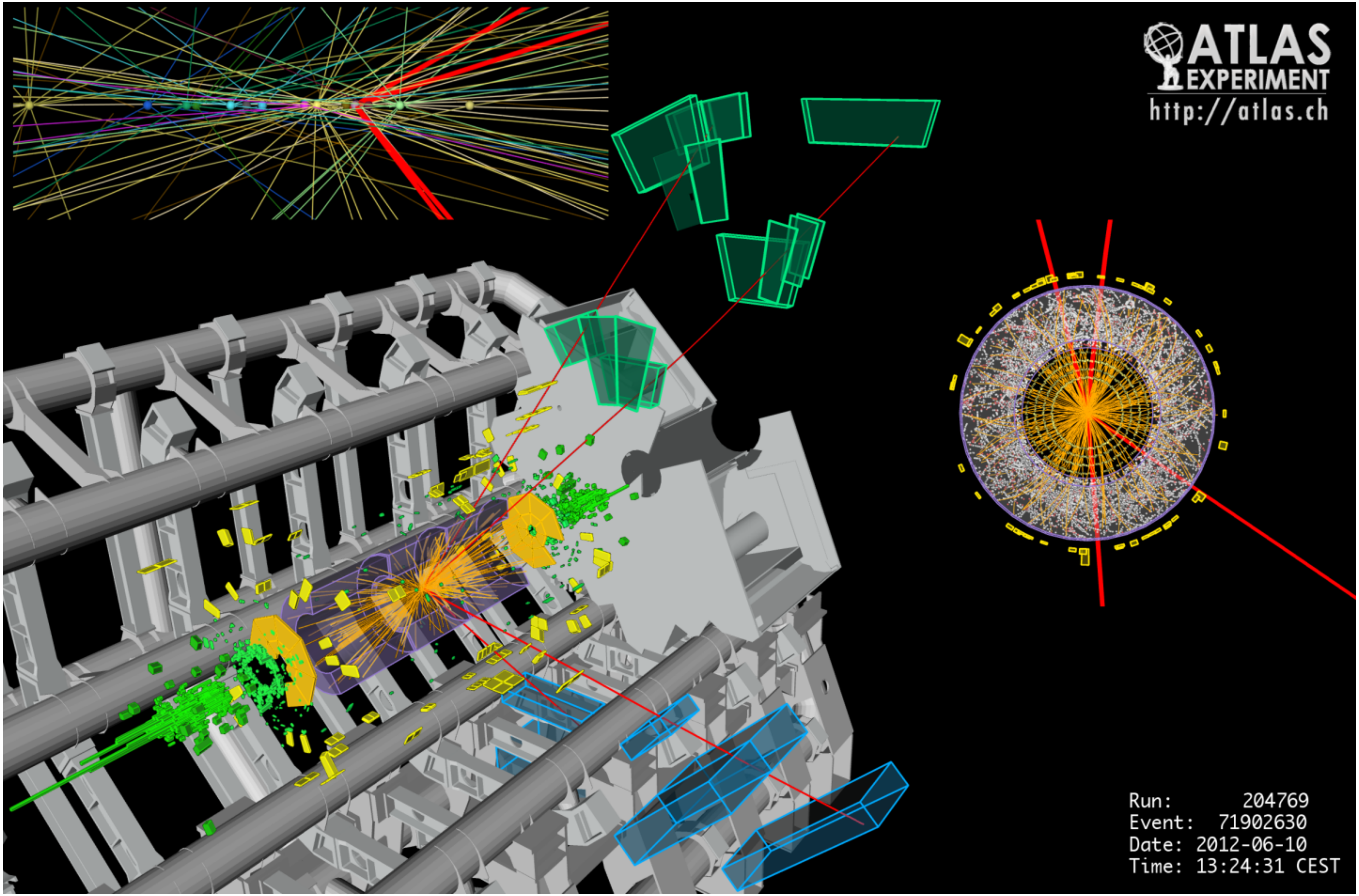
The **Higgs boson** was the last particle of the SM to be discovered → **July 2012**

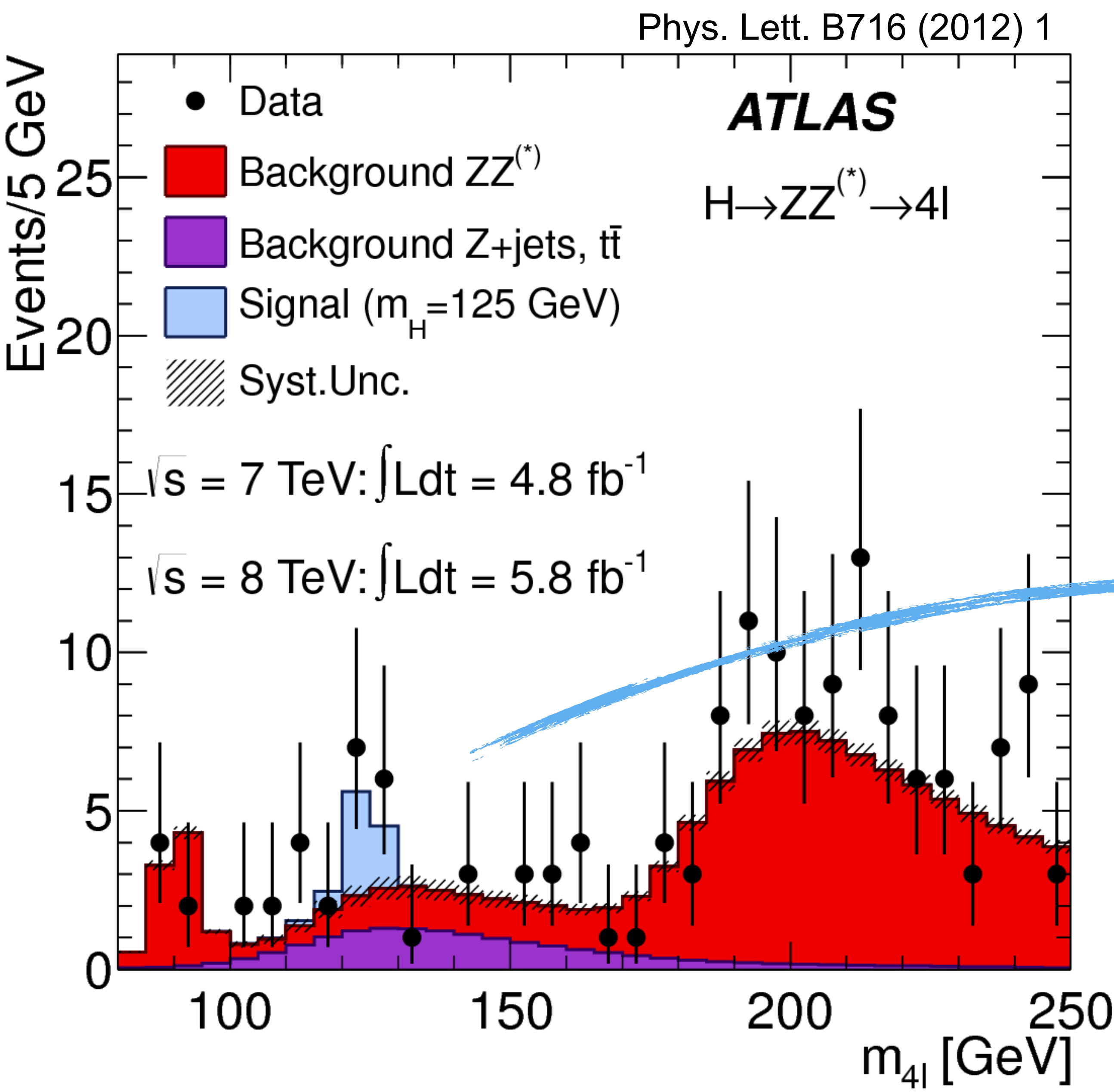
SM Higgs boson production and decay

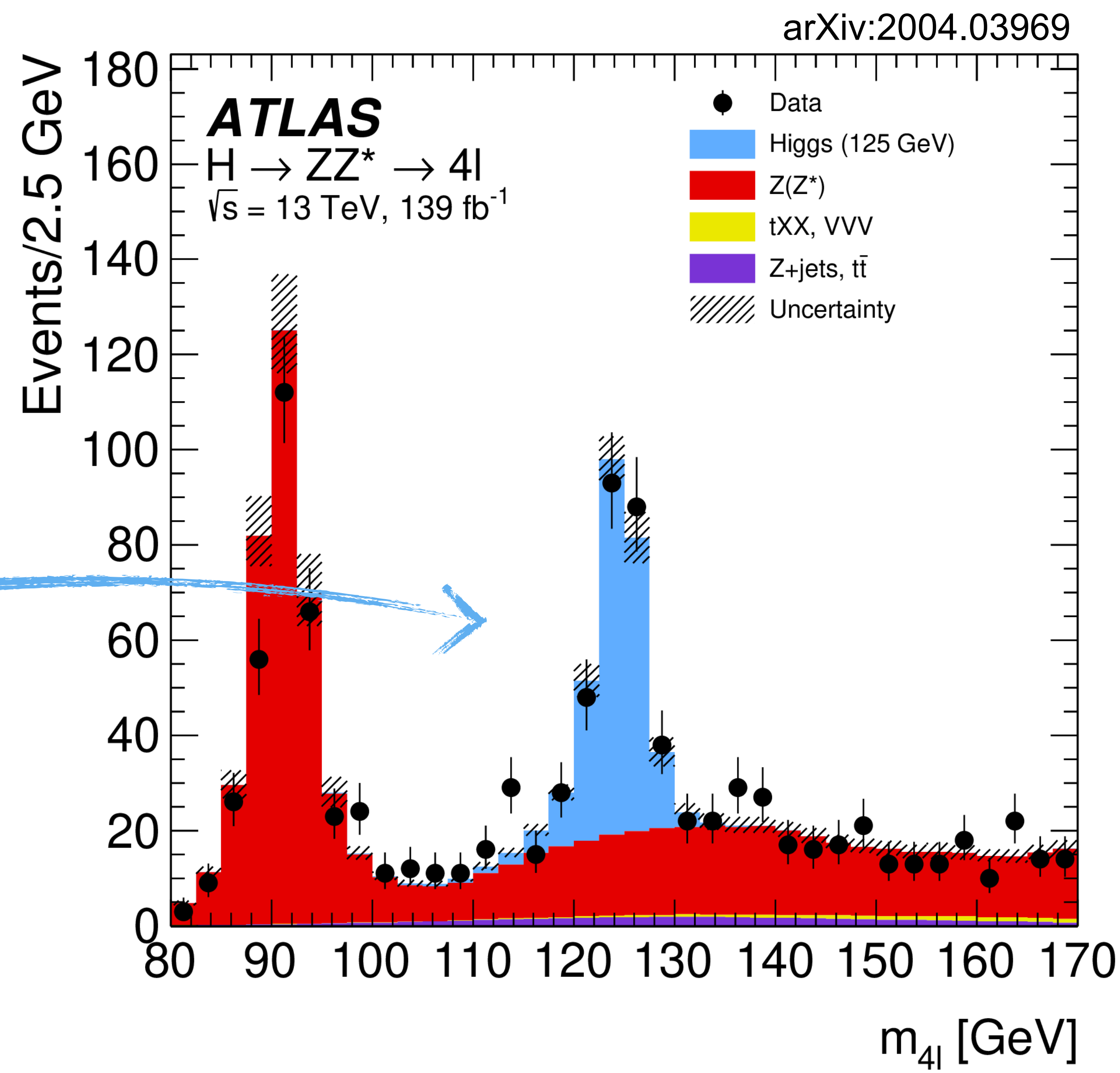




m_h~125 GeV gives access to several decay channels

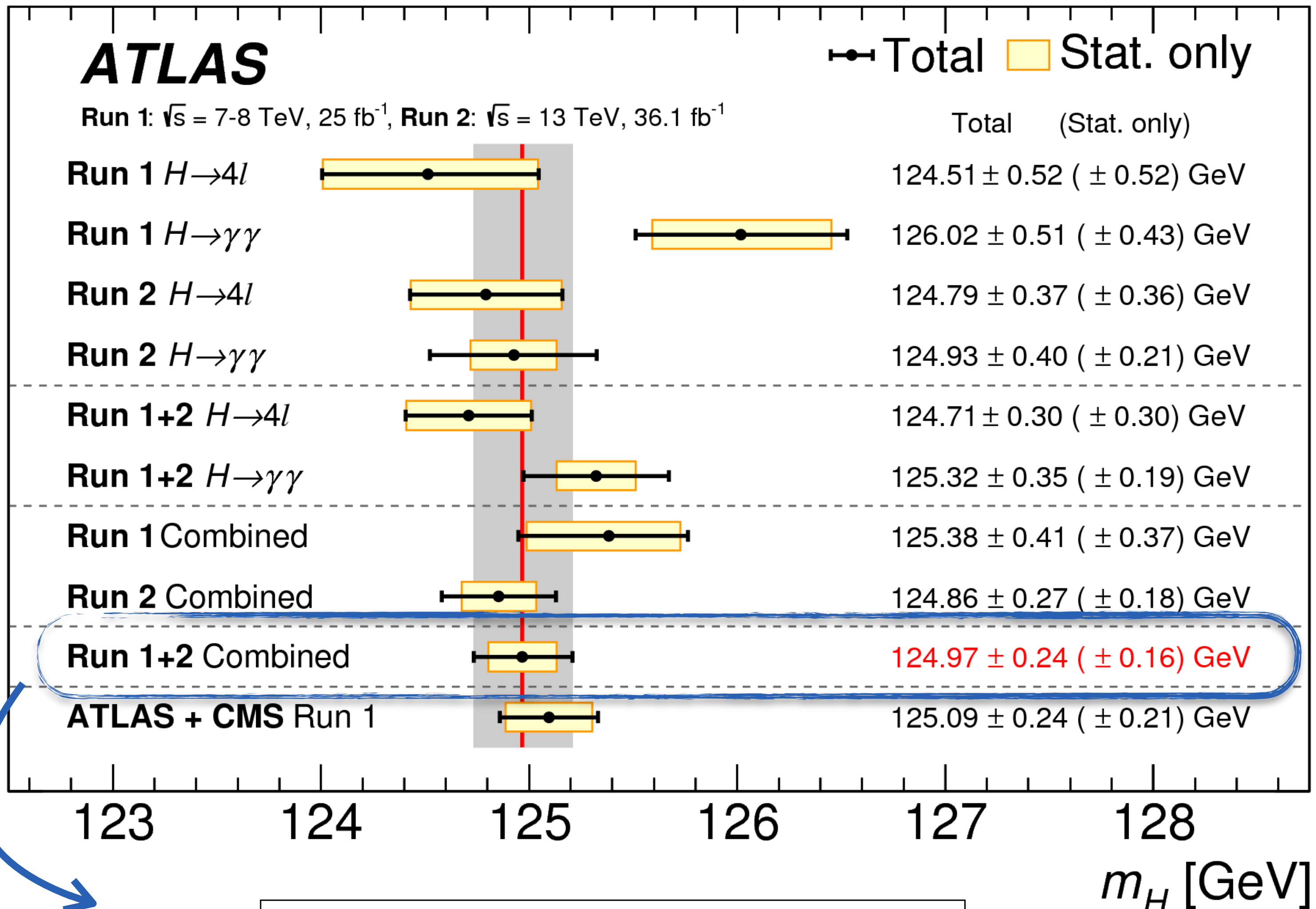

ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

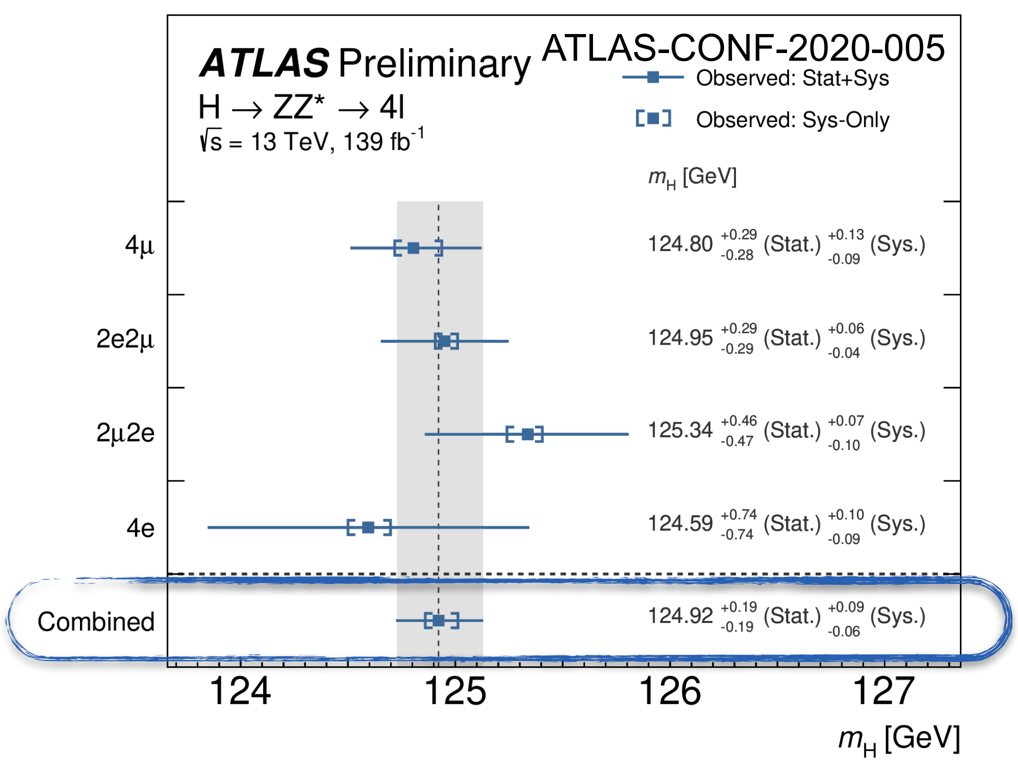

Phys. Lett. B716 (2012) 1
ATLAS
H→ZZ(*)→4l
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (mH=125 GeV)
Syst.Unc.
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
m4l [GeV]


arXiv:2004.03969
ATLAS
H → ZZ* → 4l
√s = 13 TeV, 139 fb-1
Data
Higgs (125 GeV)
Z(Z*)
tXX, VVV
Z+jets, tt̄
Uncertainty
Events/2.5 GeV
m4l [GeV]

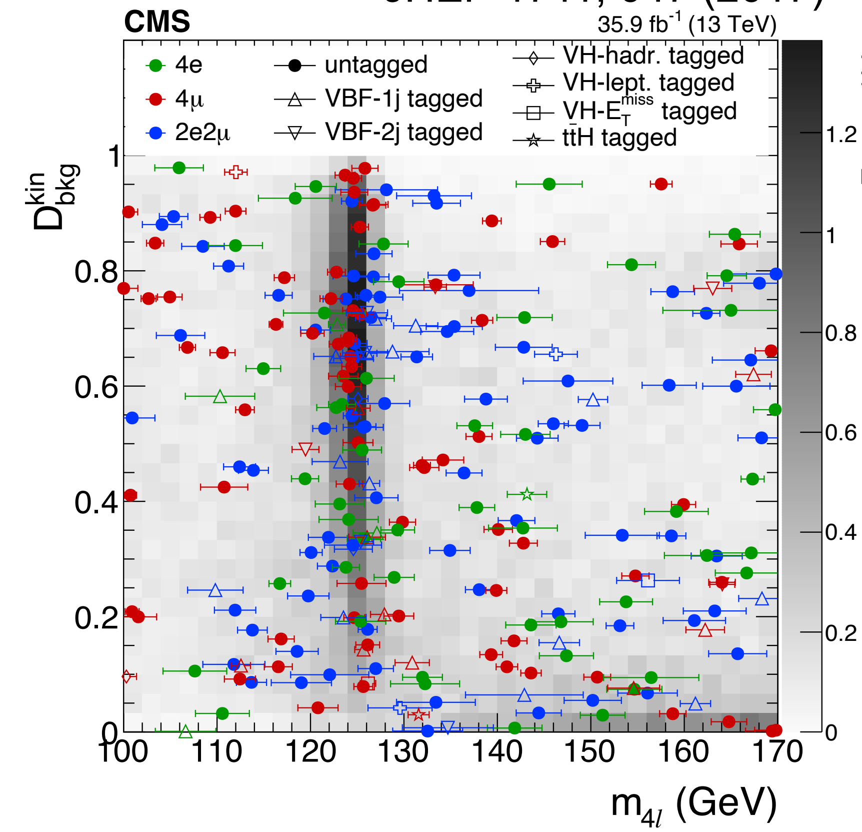
The Higgs boson mass was the last free parameter of the Standard Model

Phys. Lett. B 784 (2018) 345



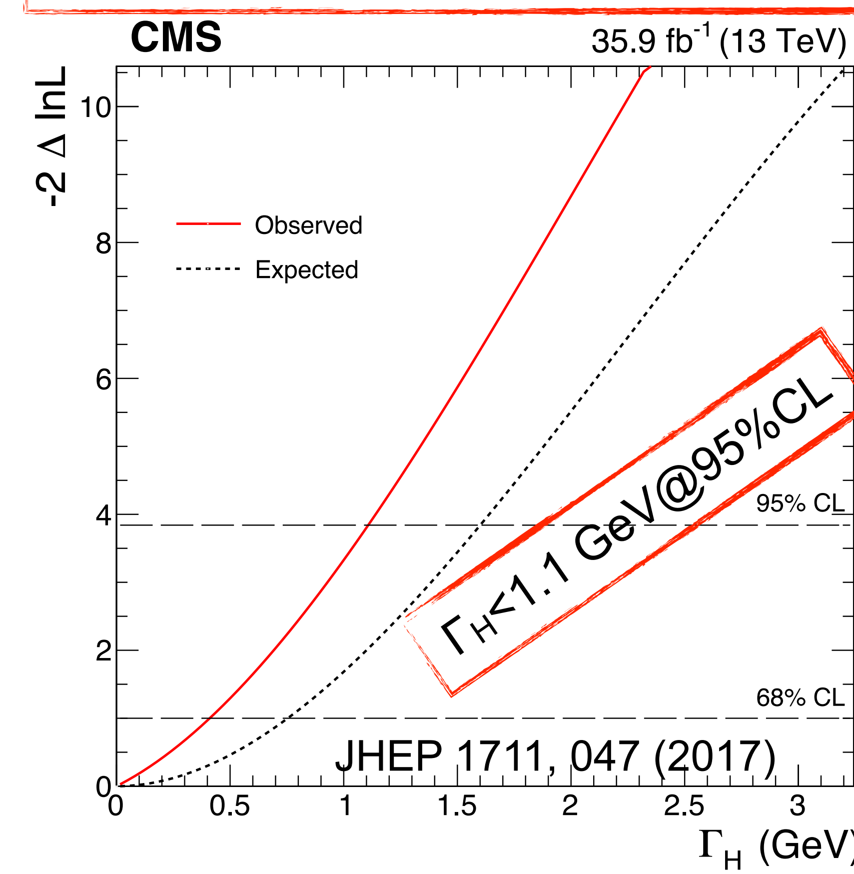


JHEP 1711, 047 (2017)



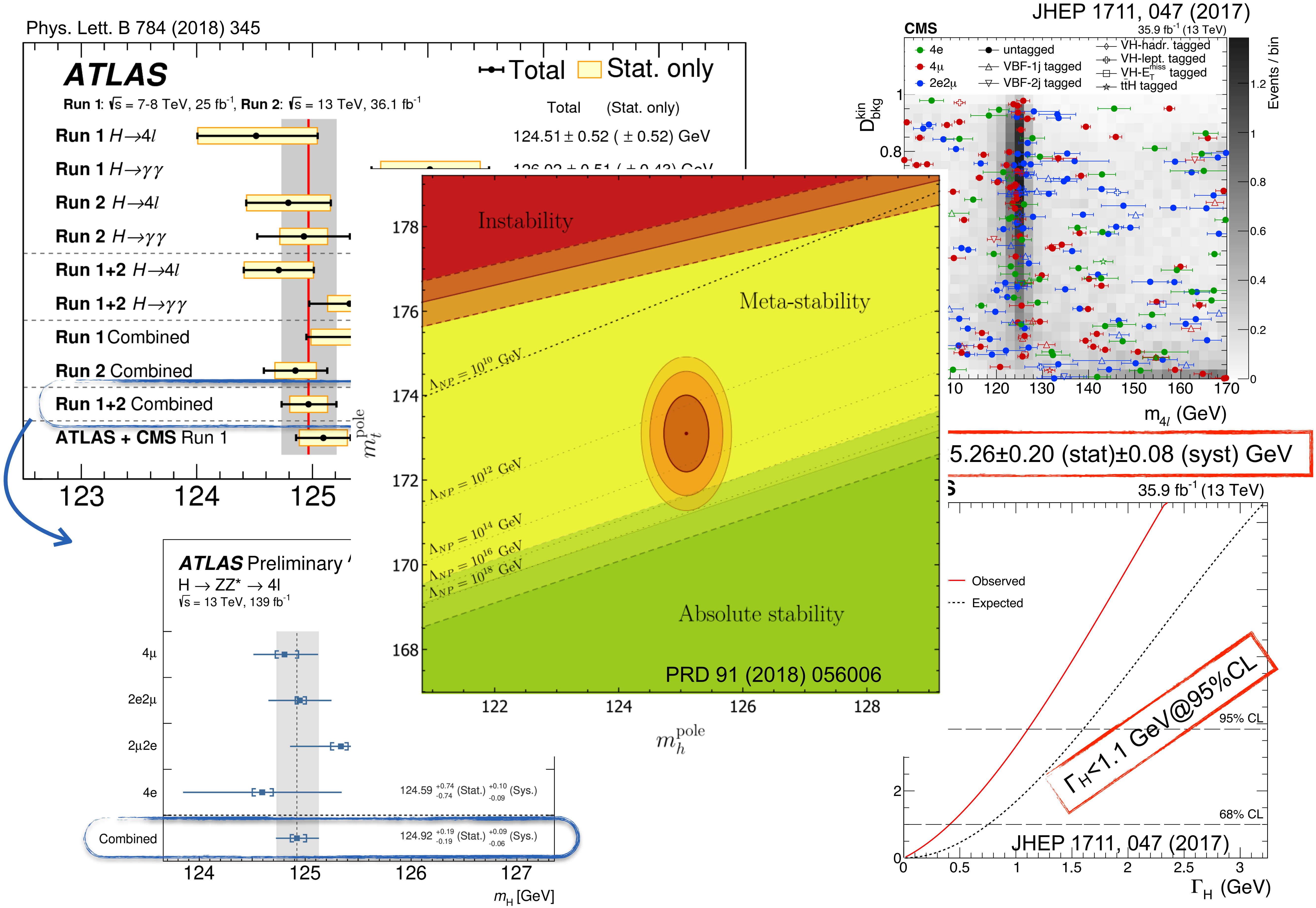
m_H=125.26±0.20 (stat)±0.08 (syst) GeV

δm/m~0.16%



Direct width measurement. Indirect method more precise but with theory assumptions

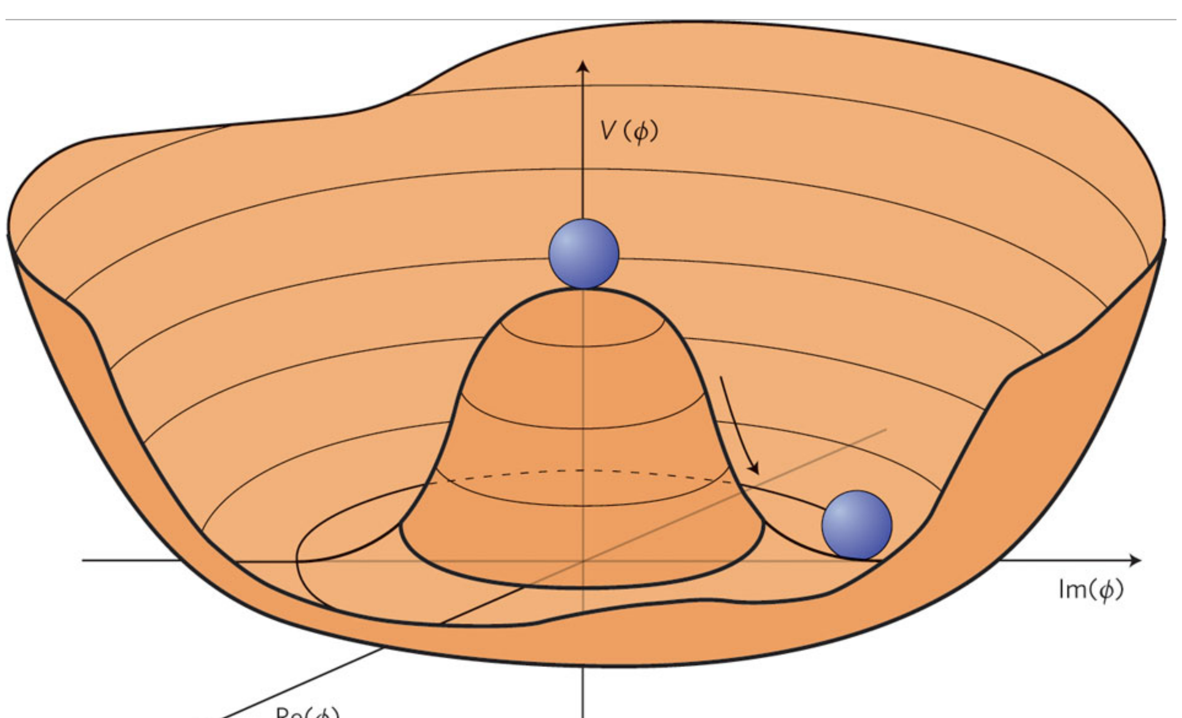
The Higgs boson mass was the last free parameter of the Standard Model



Direct width measurement. Indirect method more precise but with theory assumptions

Higgs mechanism and the Higgs boson

- $SU(2)_L \otimes U(1)_Y$ local gauge symmetry; electro-weak unification: massless carriers
- Symmetry spontaneously broken by Higgs field
  - 4 degrees of freedom (d.o.f)
- Higgs field obtains non-zero vacuum expectation value
  - 3 d.o.f of Higgs field become longitudinal polarisations of $W^{\pm}/Z$ bosons
  - 1 d.o.f of Higgs field becomes the physical Higgs boson
- **Higgs interactions to vector bosons:** defined by symmetry breaking



VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

Volume 12, number 2 PHYSICS LETTERS 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

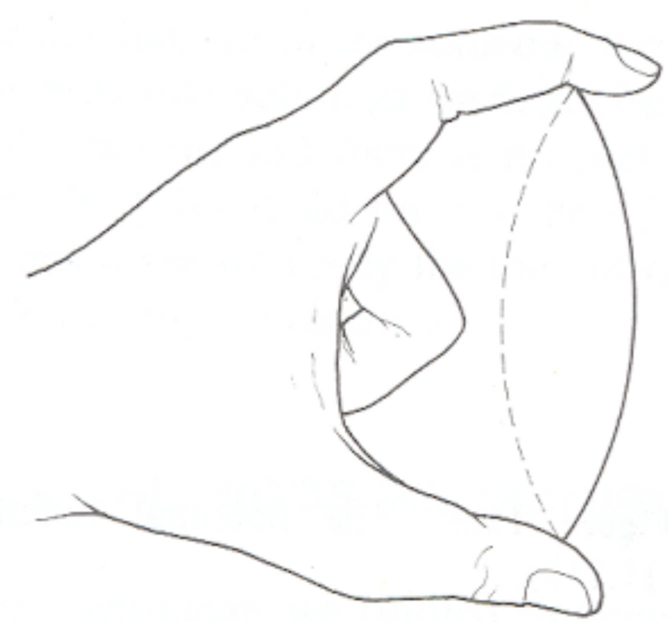
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)



Higgs mechanism and the Higgs boson

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  electro-weak unification: m
- Symmetry spontaneously
  - 4 degrees of freedom (c
- Higgs field obtains non-ze
  expectation value
  - 3 d.o.f of Higgs field bec
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  - 1 d.o.f of Higgs field bec
    Higgs boson
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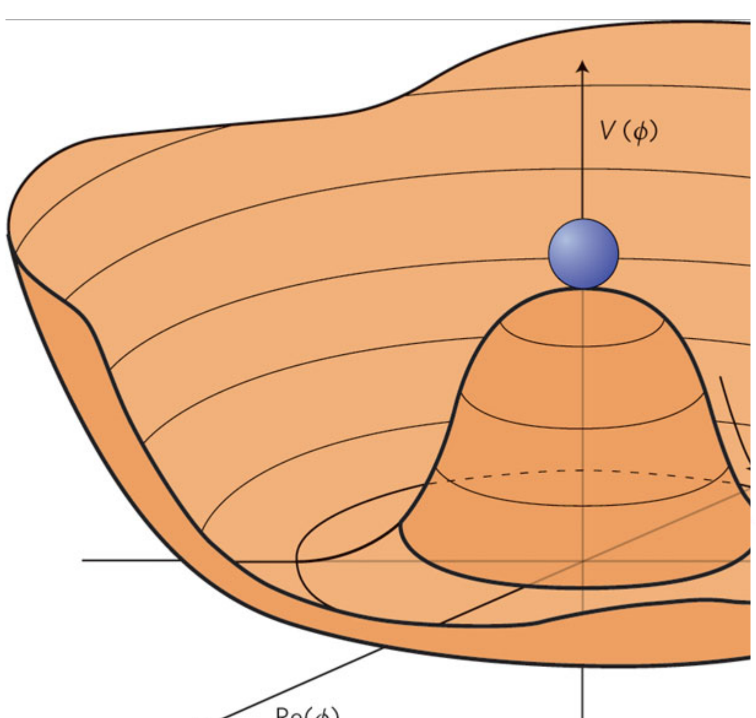

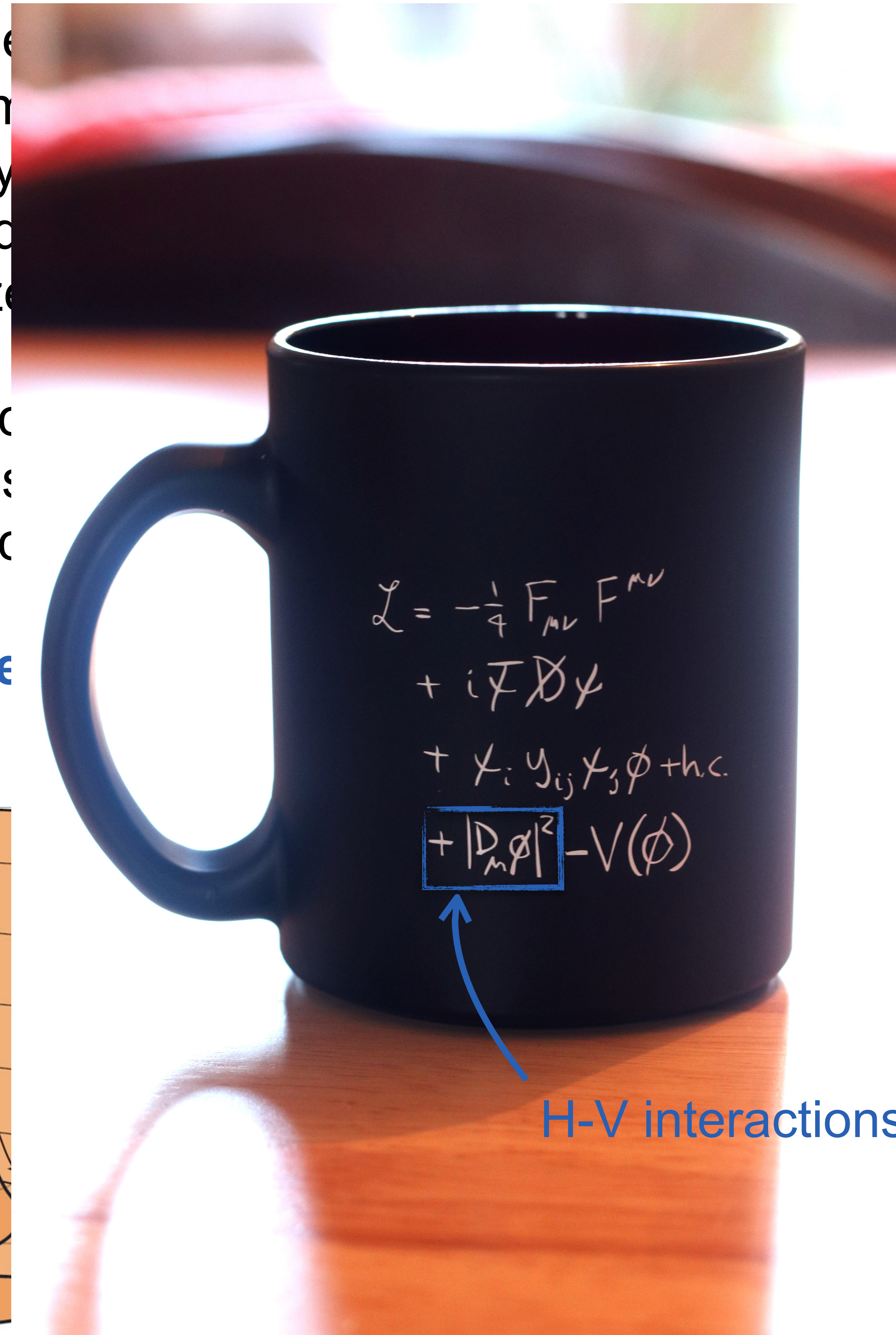

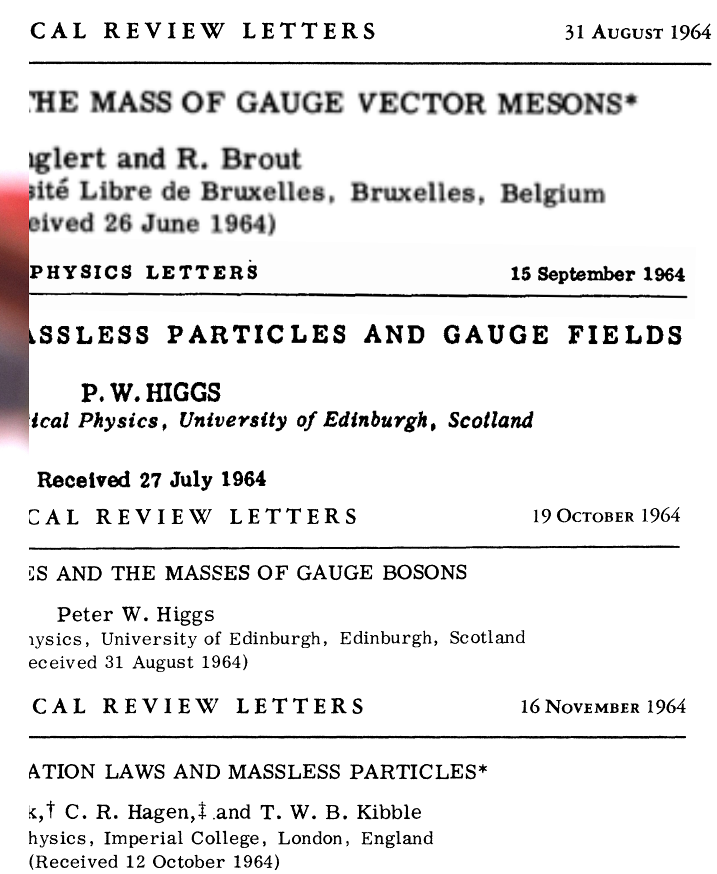
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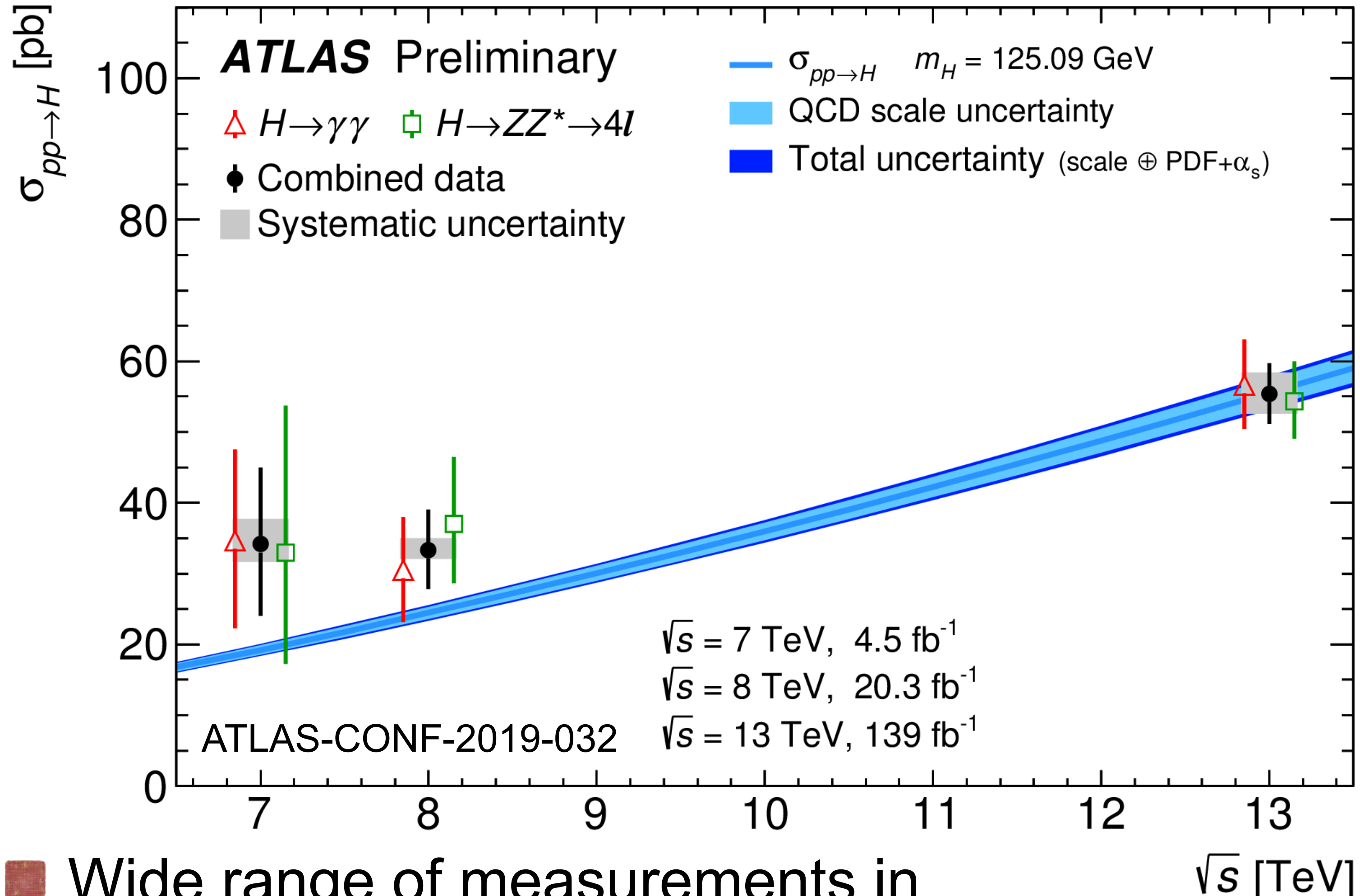
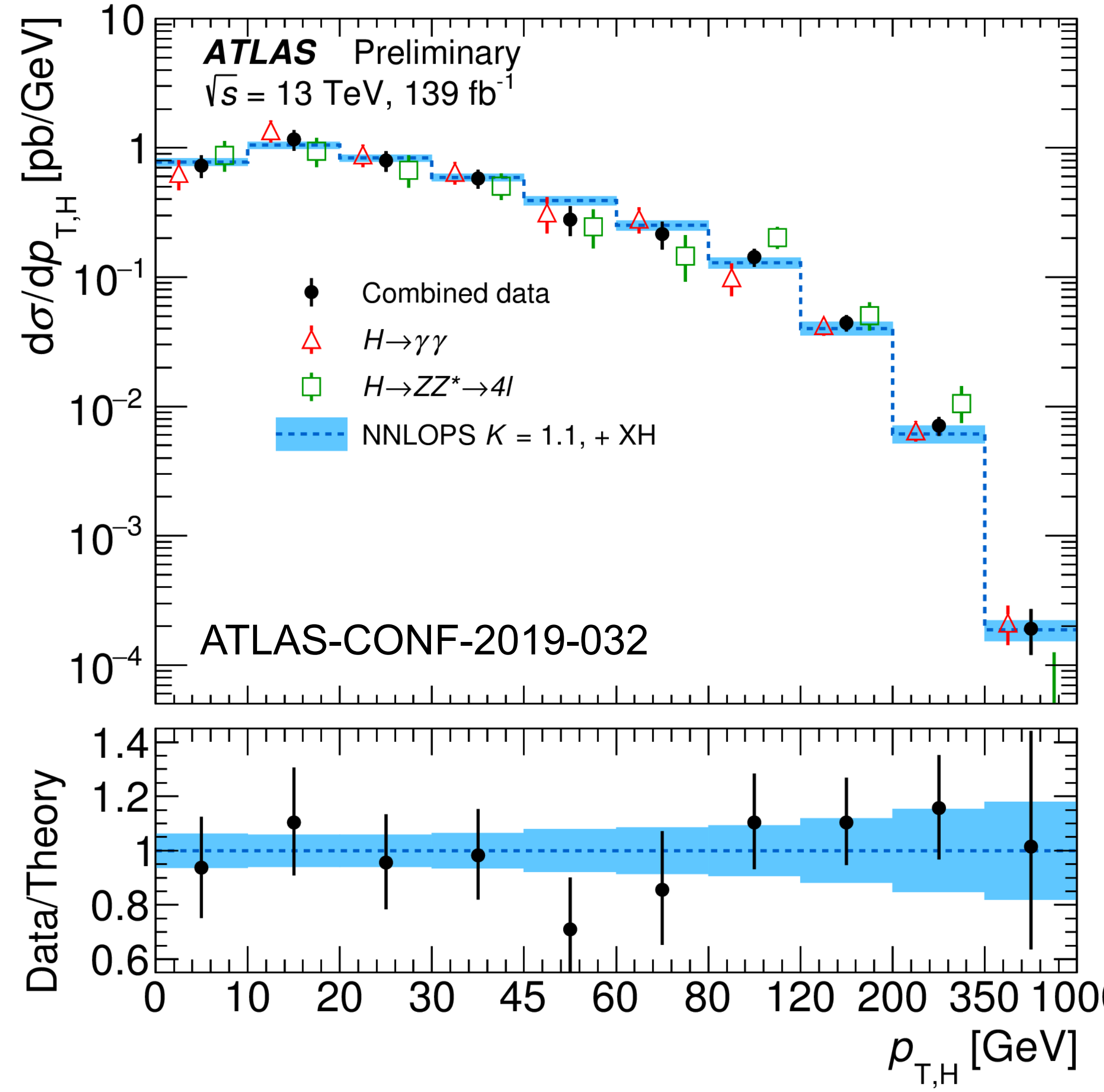
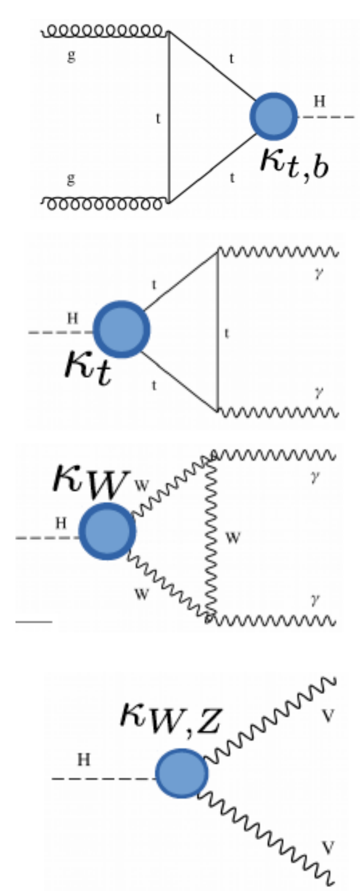
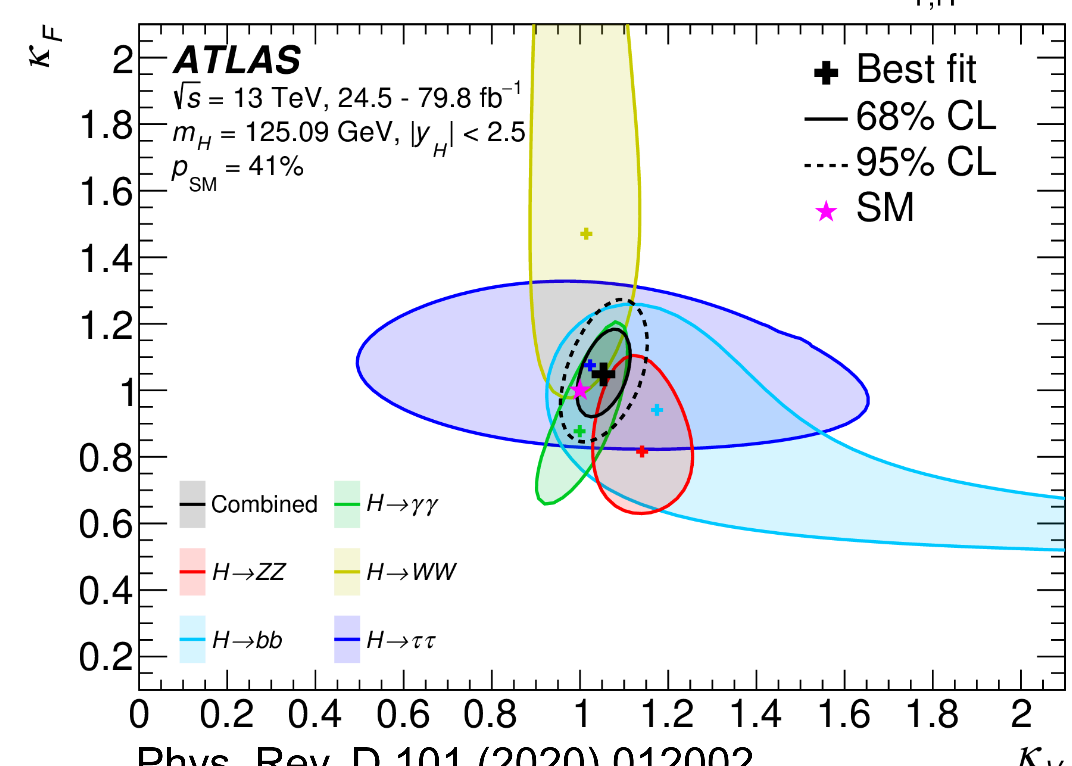


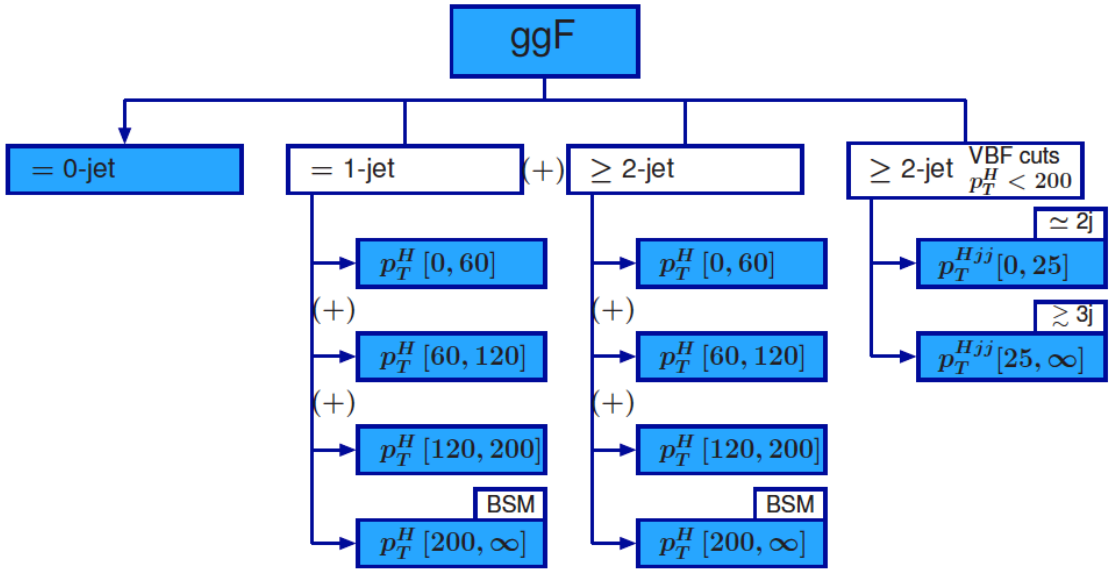


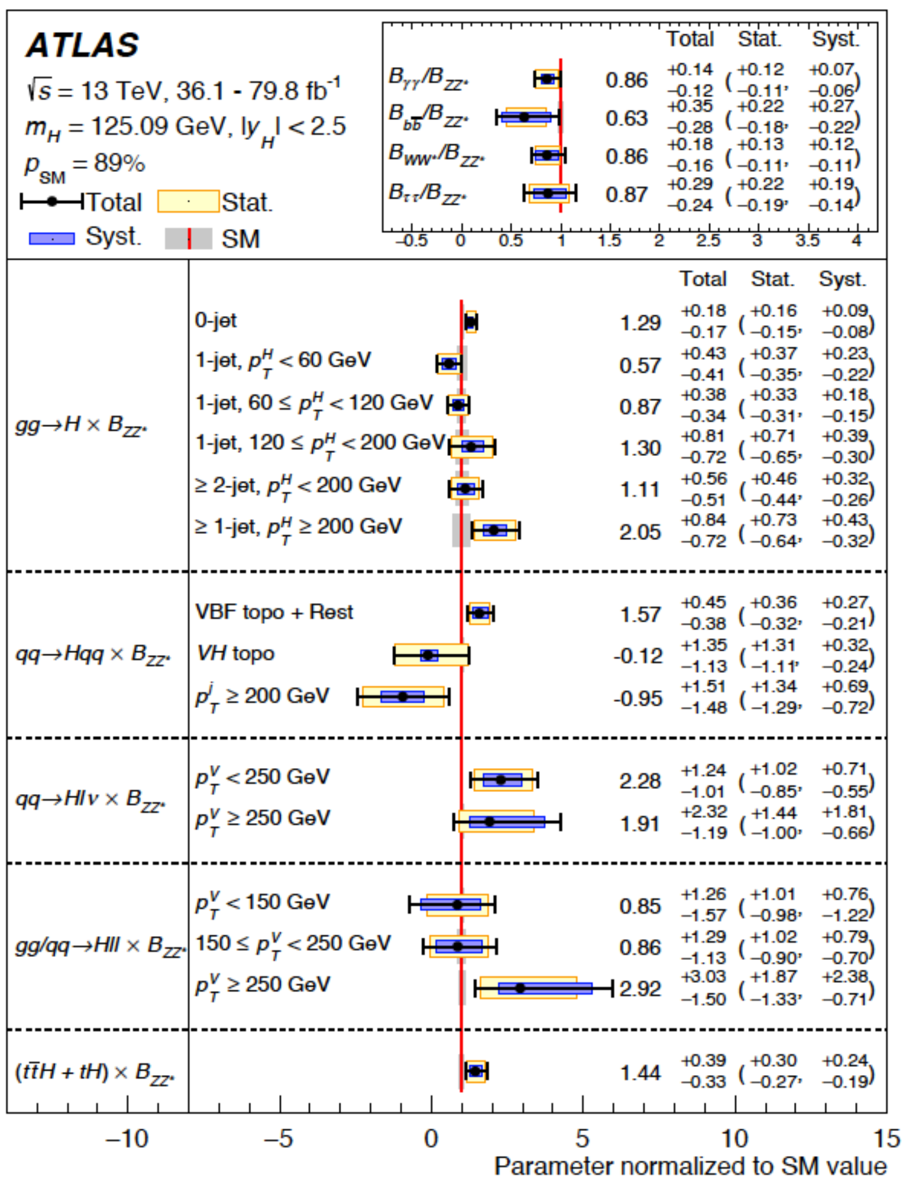
- Wide range of measurements in Higgs couplings to vector bosons
  - Total/fiducial cross-sections
  - Differential cross-sections
- Several modes of interpretation
  - κ-framework
    - Only accounts for rates
    - Leading Order framework
    - Higgs specific
  - Simplified template cross-sections
  - Effective Field Theory



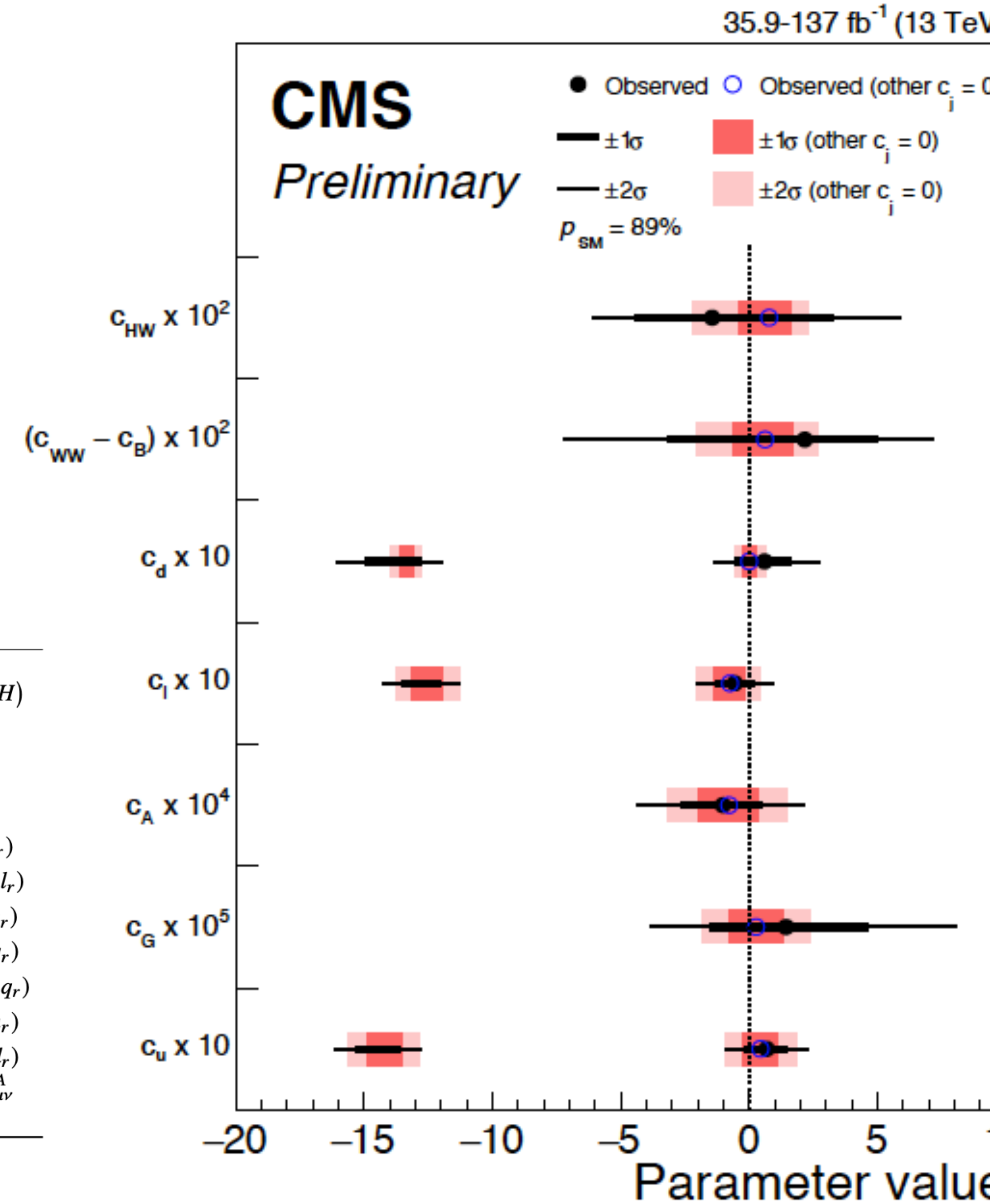


Phys. Rev. D 101 (2020) 012002





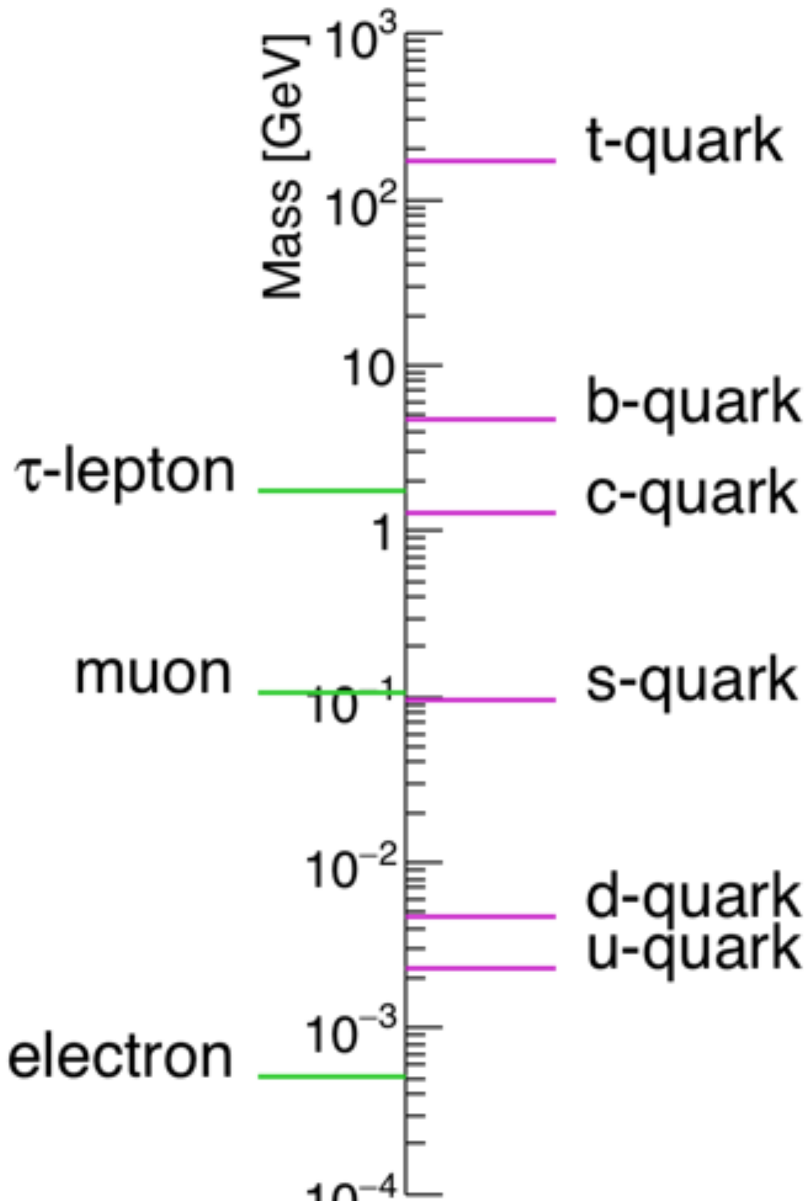
Wilson coefficient	Operator
c_{Hbox}	$(H^\dagger H)\square(H^\dagger H)$
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
c_{Hl1}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
c_{Hl3}	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
c_{Hq1}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
c_{Hq3}	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$\lvert c_{uG}\rvert$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
c_{ll1}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$



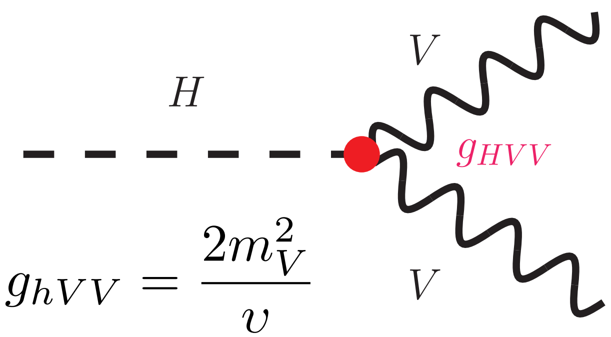
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

Higgs-fermion interactions: Yukawa couplings

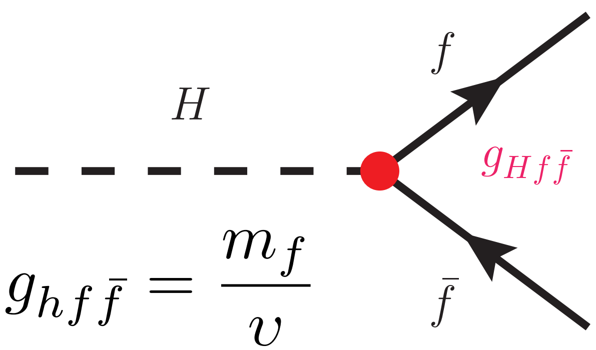
- **Higgs interactions to vector boson:** defined by symmetry breaking
- **Higgs interactions to fermions:** ad-hoc hierarchical Yukawa couplings $\propto m_f$



$$\frac{m_e}{m_t} \approx 3 \times 10^{-6}$$



$$g_{hVV} = \frac{2m_V^2}{v}$$



$$g_{hf\bar{f}} = \frac{m_f}{v}$$

- Yukawa couplings **not** imposed by fundamental principle
- Modified Higgs-fermion couplings in BSM scenarios
- Probing fermion mass generation scale→independent task
  - Fermion mass generation scale from **unitarity bounds**:

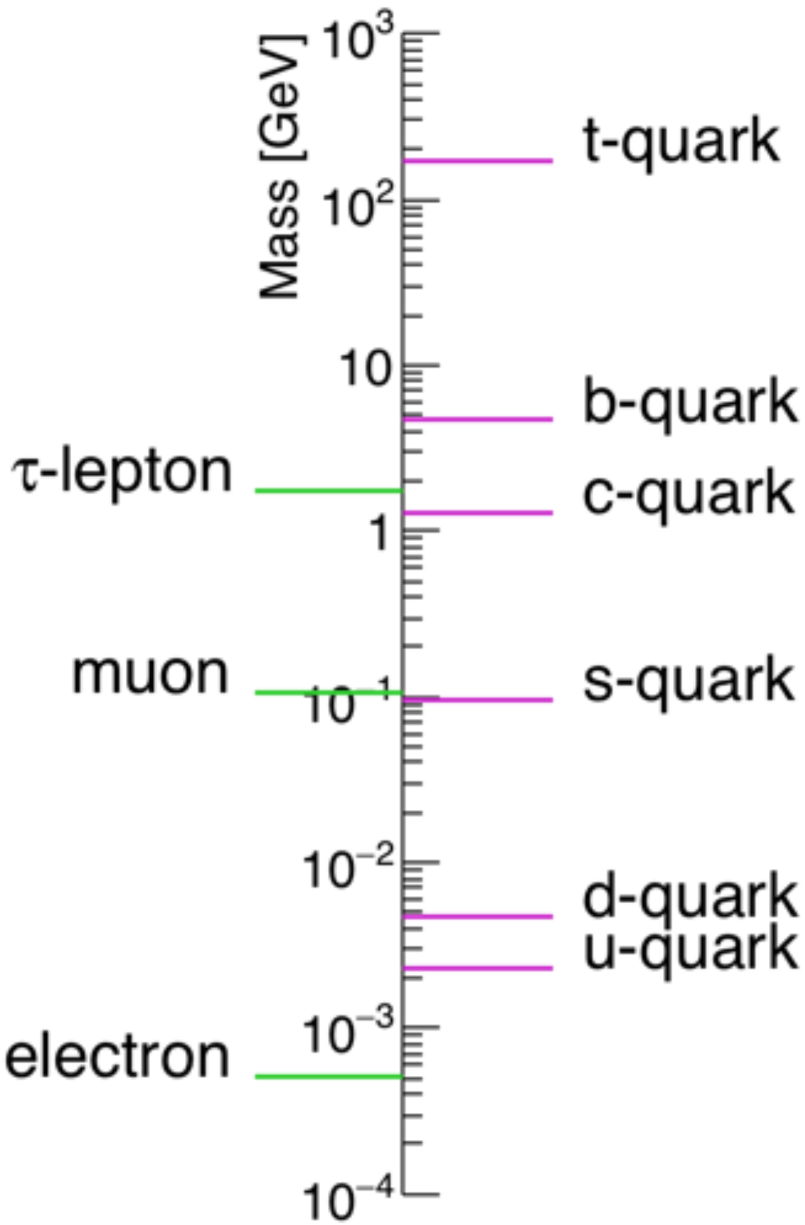
$$\Lambda \approx 3.5, 23, 32, 52, 77, 84 \text{ TeV (t, b,c,s,d,u)}$$

[Phys. Rev. Lett. 59, 2405 (1987); Phys.Rev. D71 (2005) 093009]

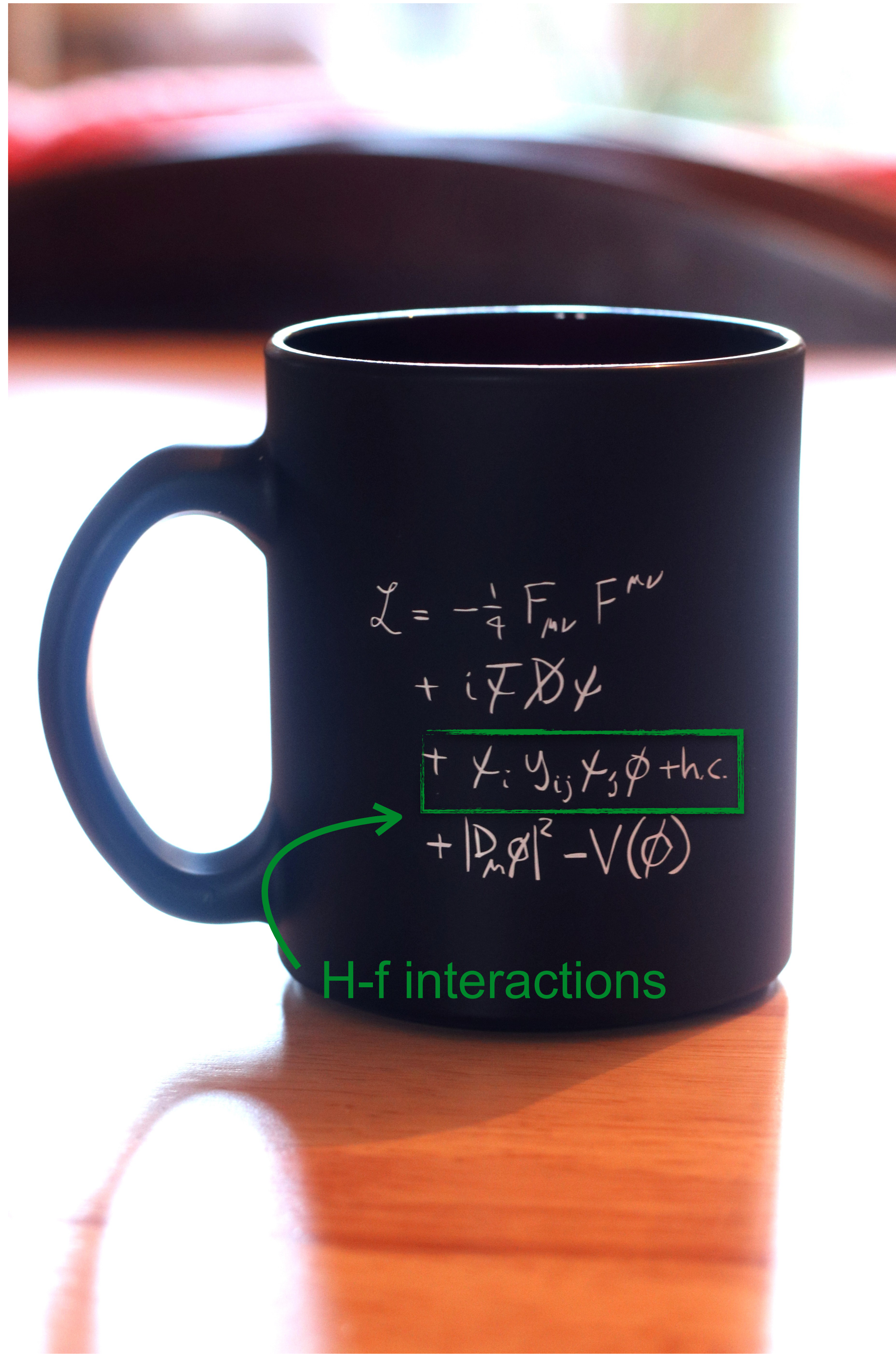
Standard Model successful
but matter particle mass hierarchy unexplained!

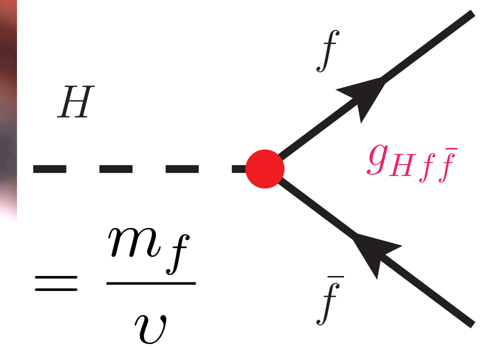
Higgs-fermion interactions: Yukawa couplings

- Higgs interactions to ... ɔreaking
- Higgs interactions to ... a couplings ∝ m_f



$$\frac{m_e}{m_t} \approx 3 \times 10^{-6}$$



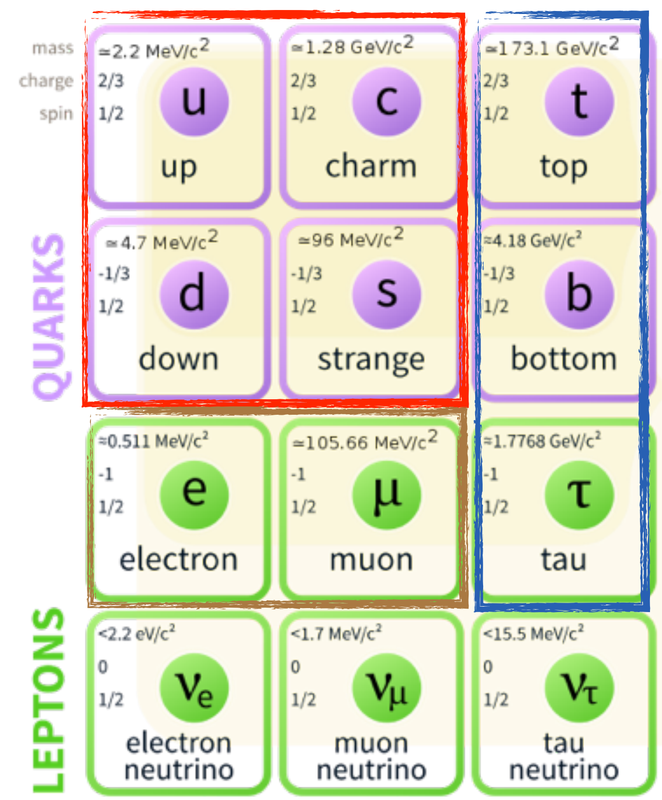


fundamental principle
BSM scenarios
ɔcale→independent task
ɾom **unitarity bounds**:
TeV (t, b,c,s,d,u)
/. D71 (2005) 093009]

ɔdel successful
ɔarticle mass
ɹnexplained!

Higgs-fermion interactions: The story so far

[in a nutshell]



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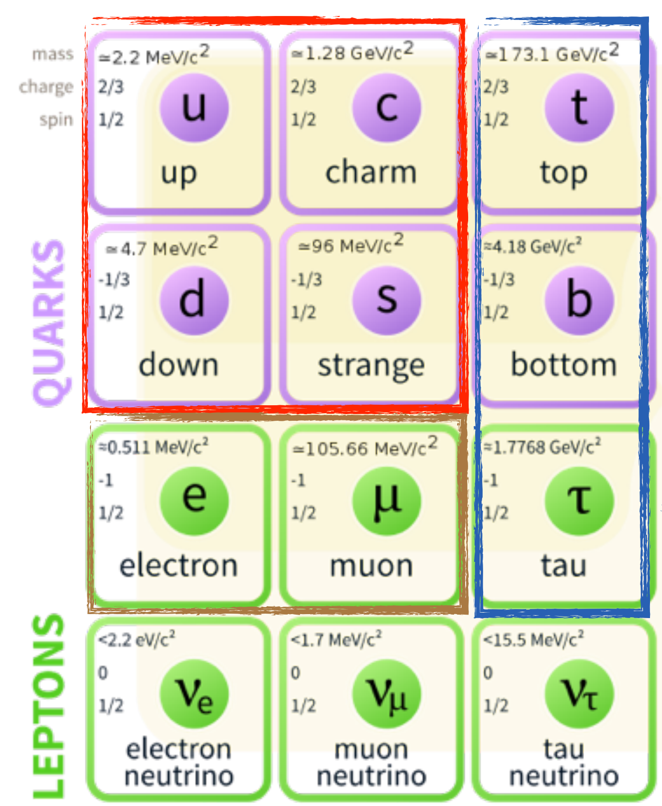

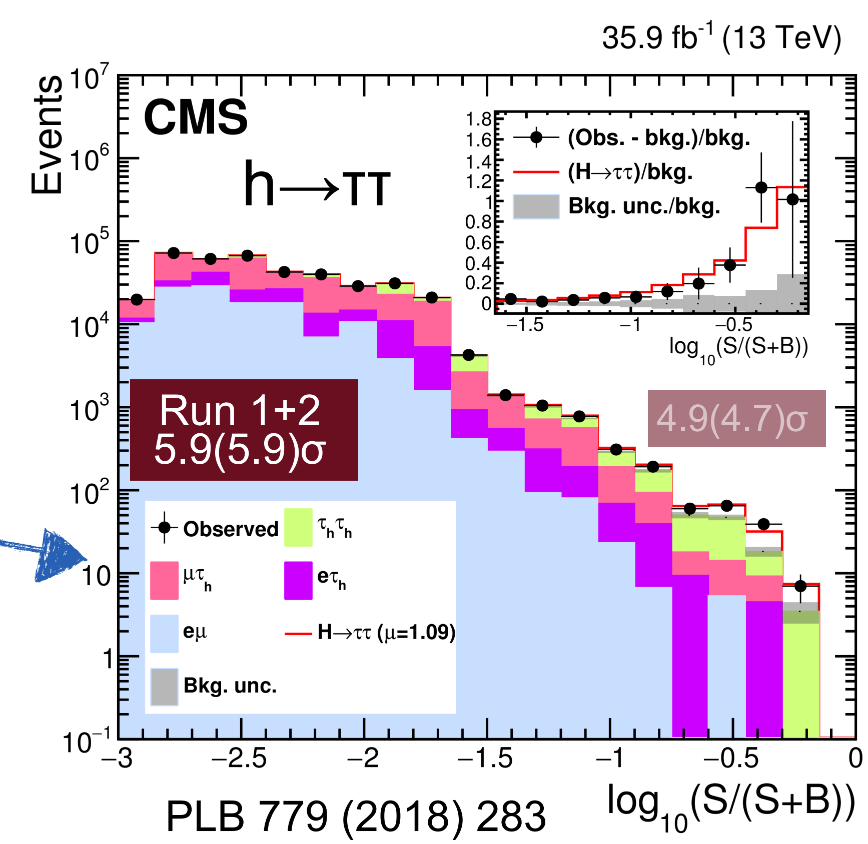

PLB 779 (2018) 283

Higgs-fermion interactions: The story so far

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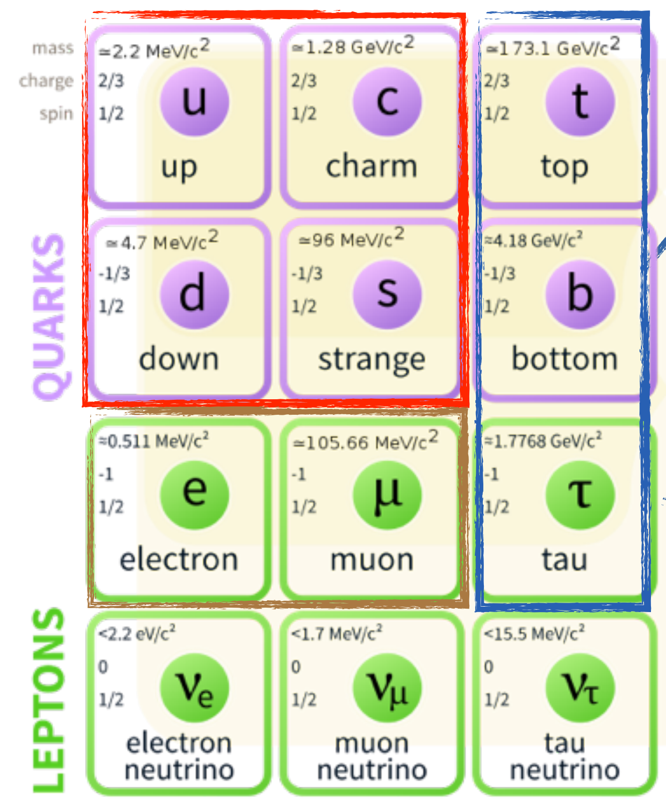
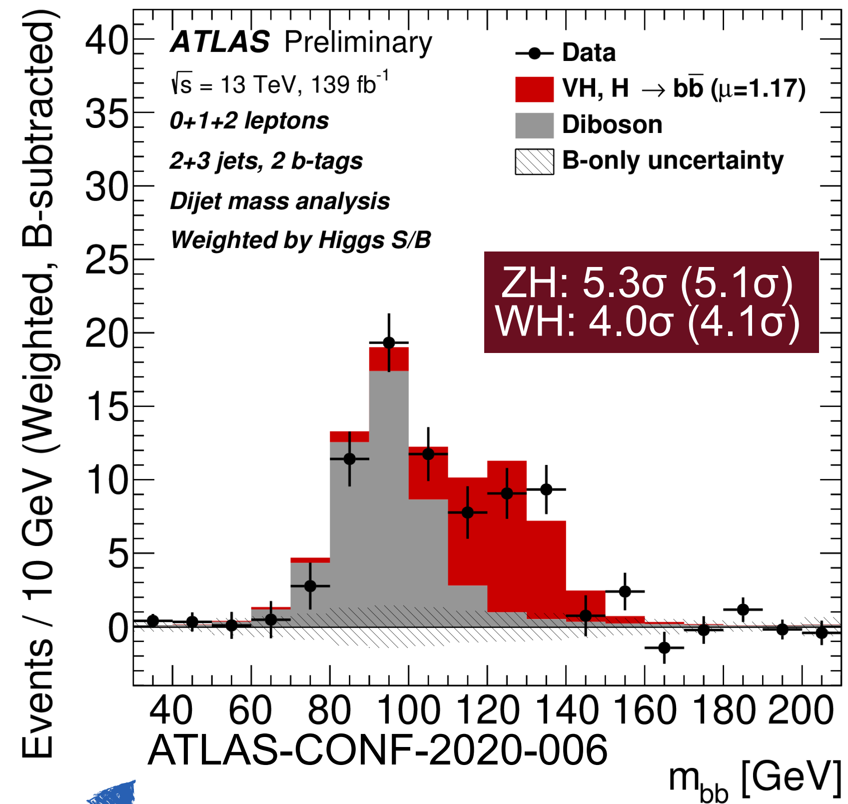
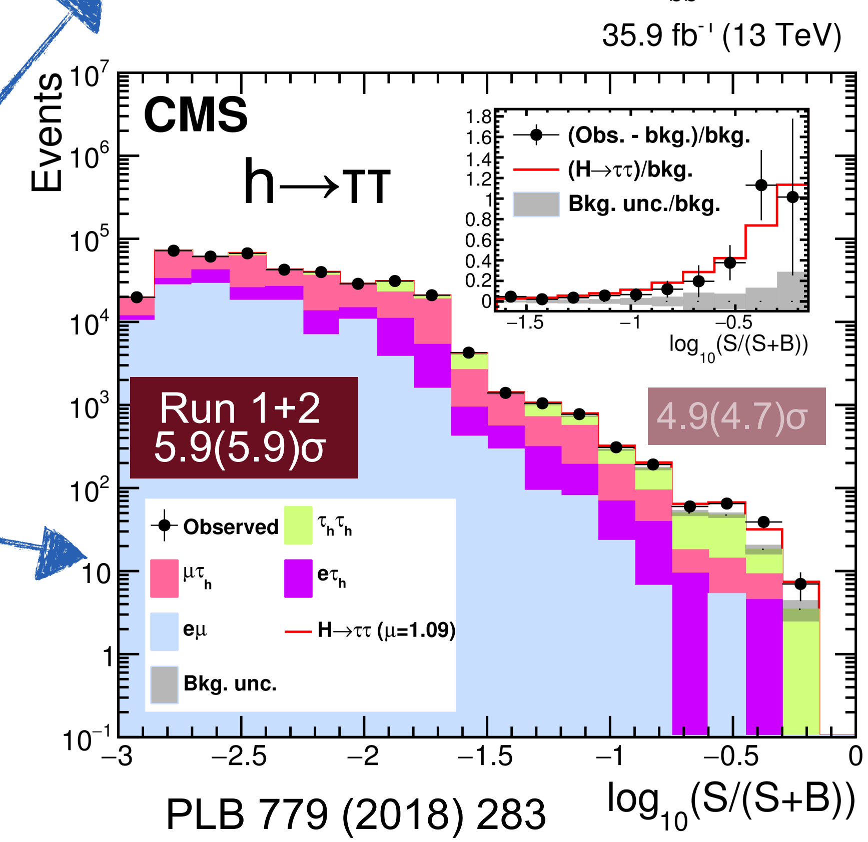




ATLAS-CONF-2020-006



PLB 779 (2018) 283

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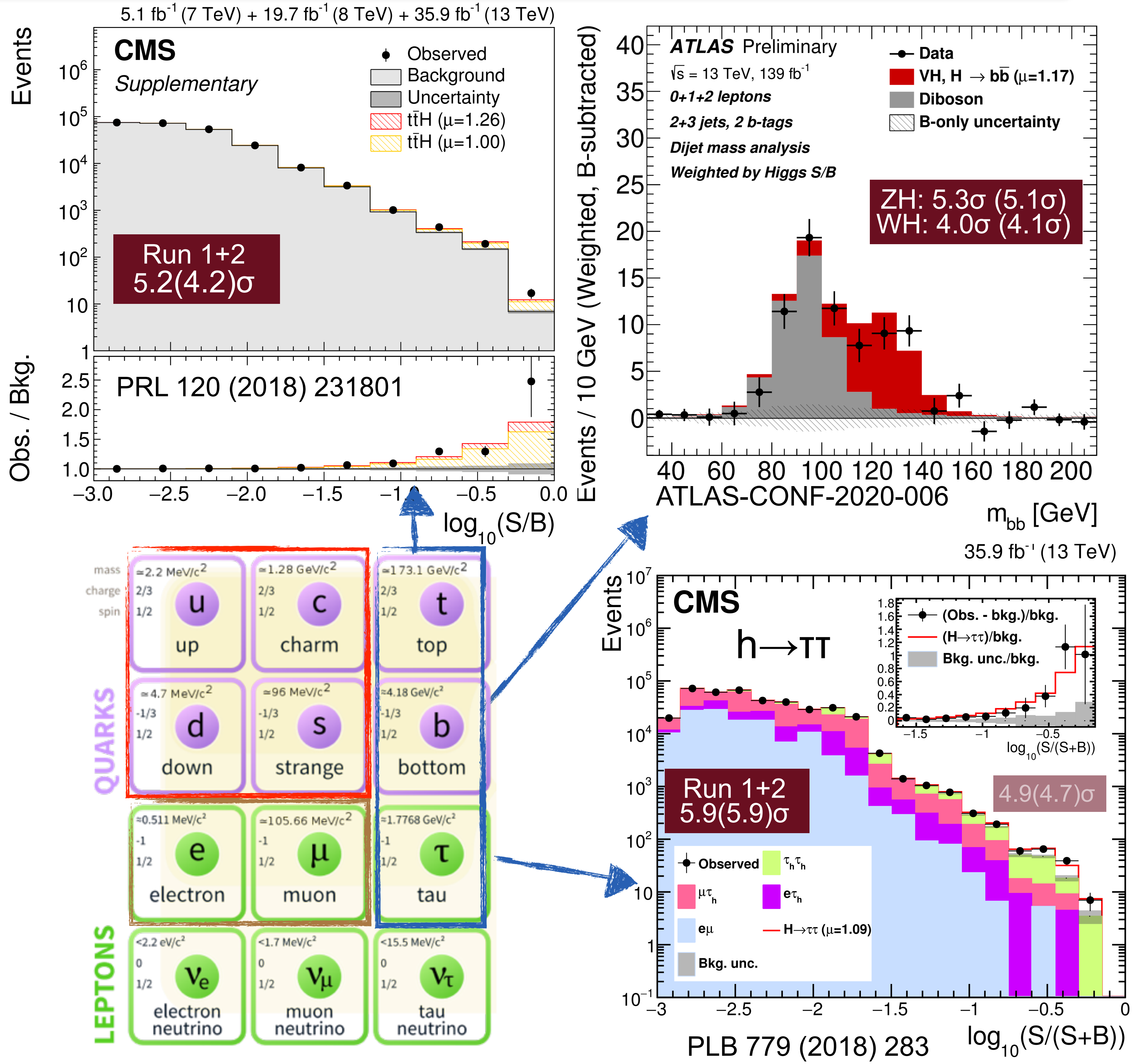

Higgs-fermion interactions: The story so far

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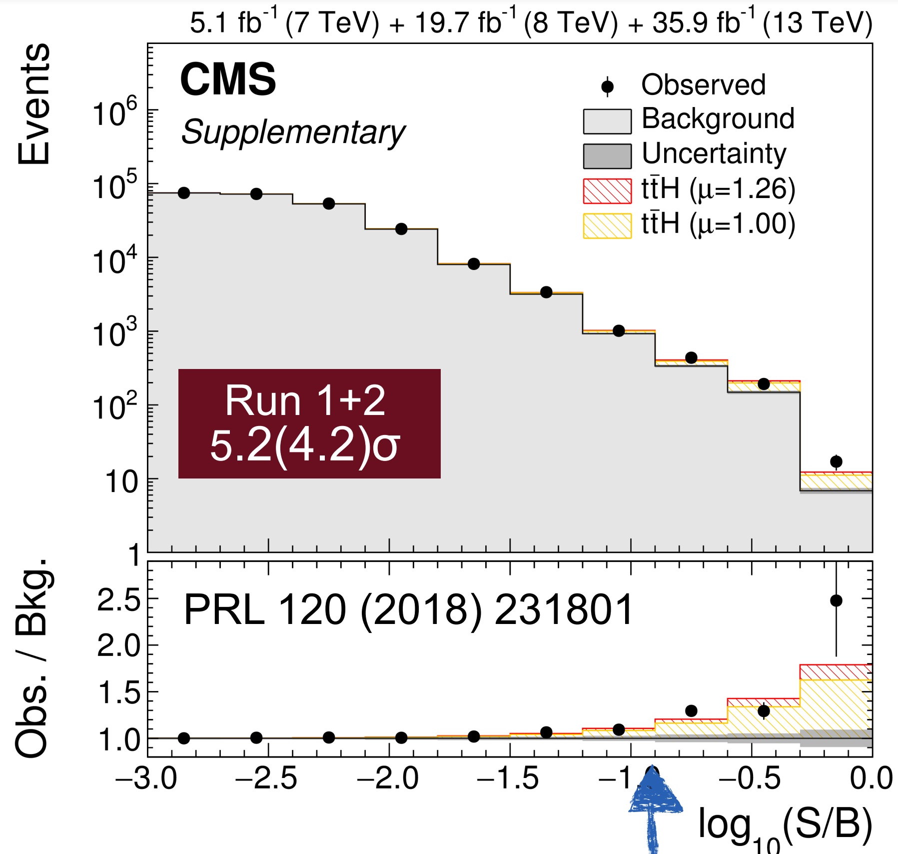
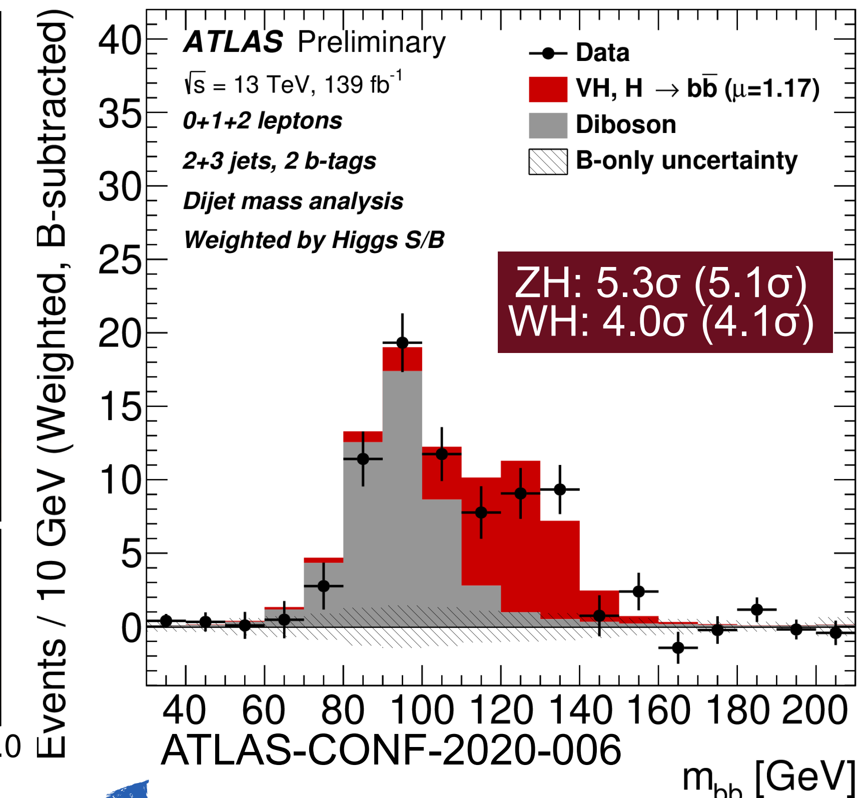
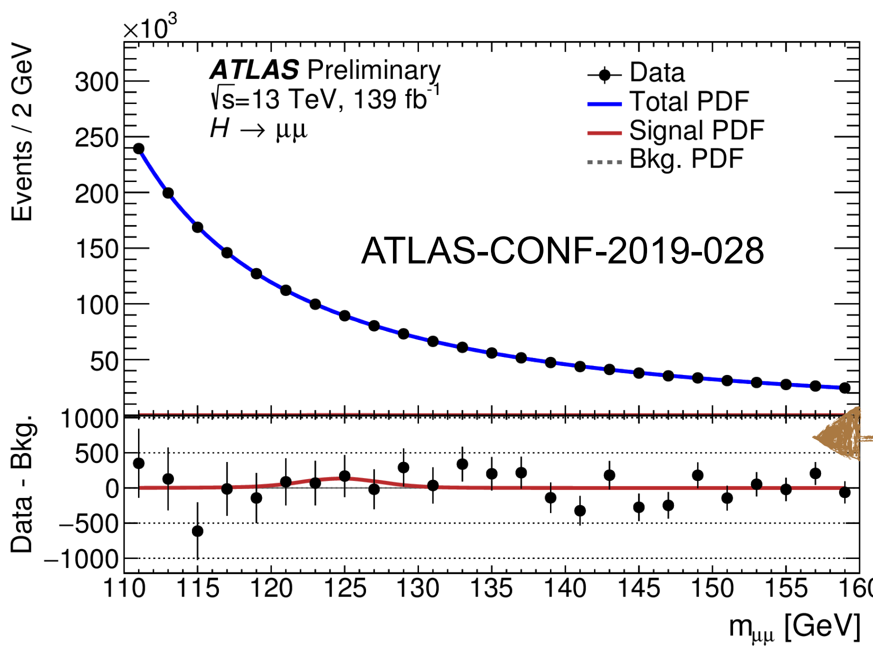
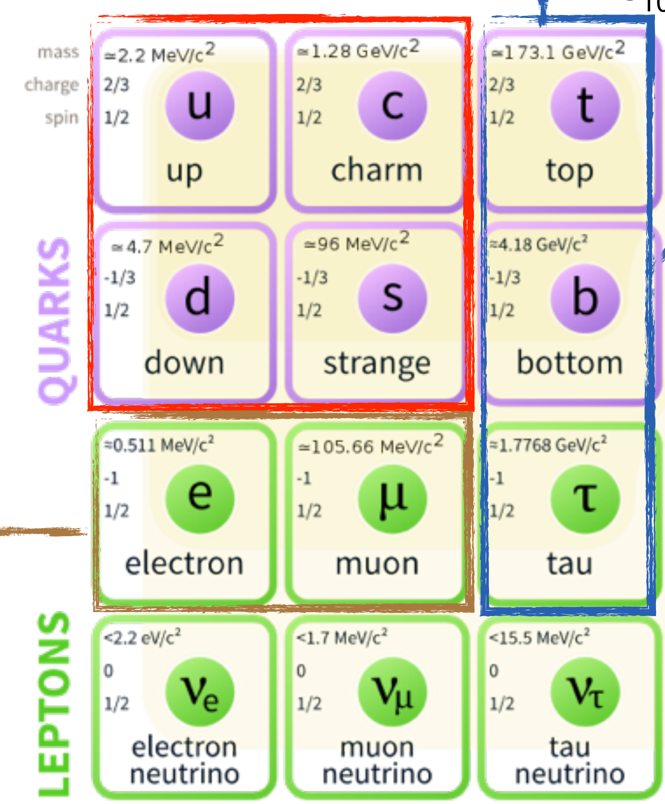
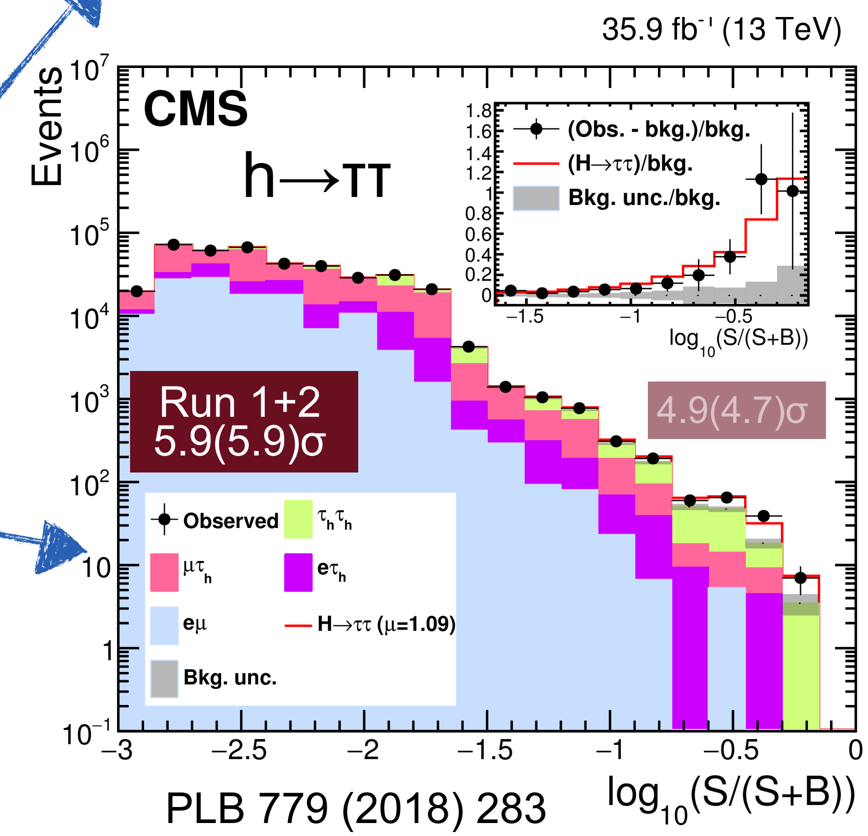






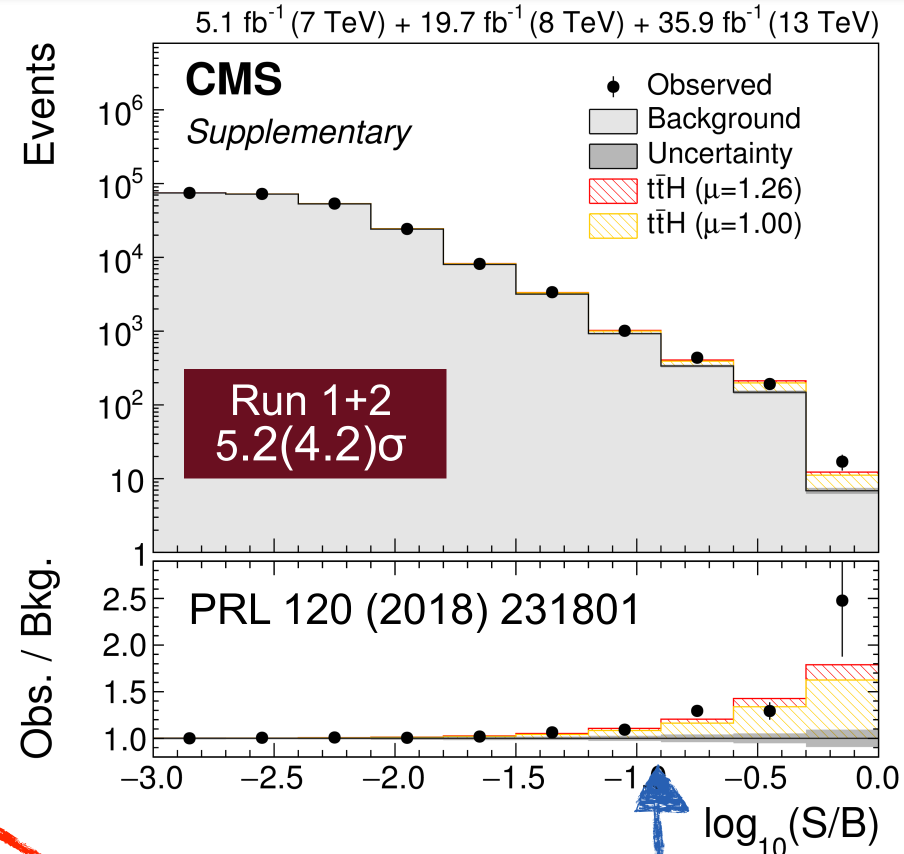


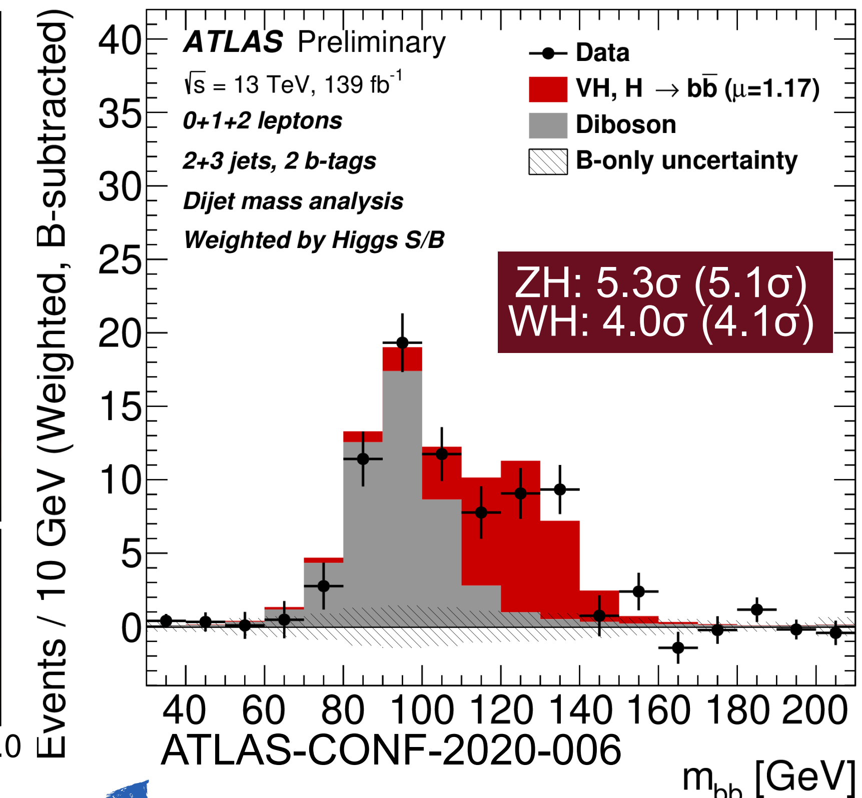


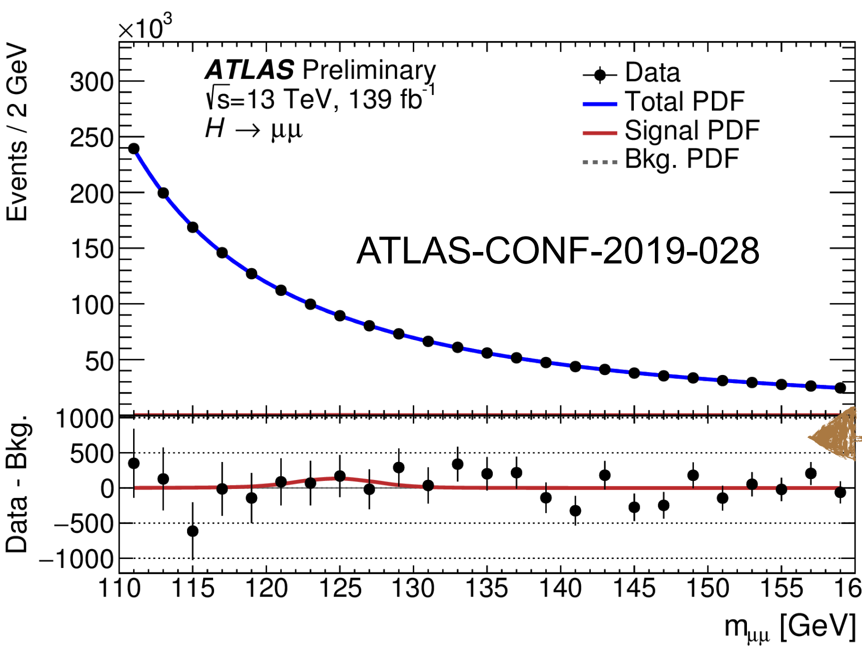
- established non-universality
- h→μμ: feasible in LHC (Run III)

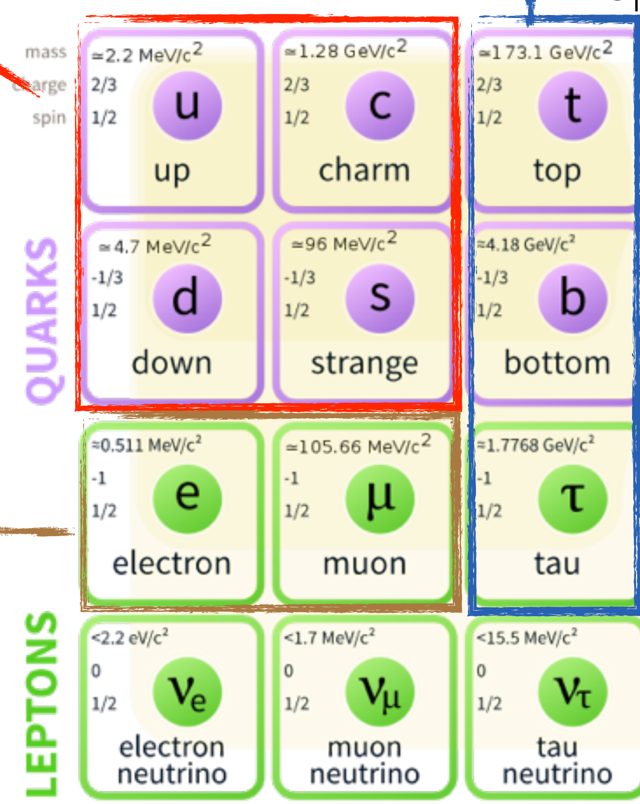
Higgs-fermion interactions: The story so far

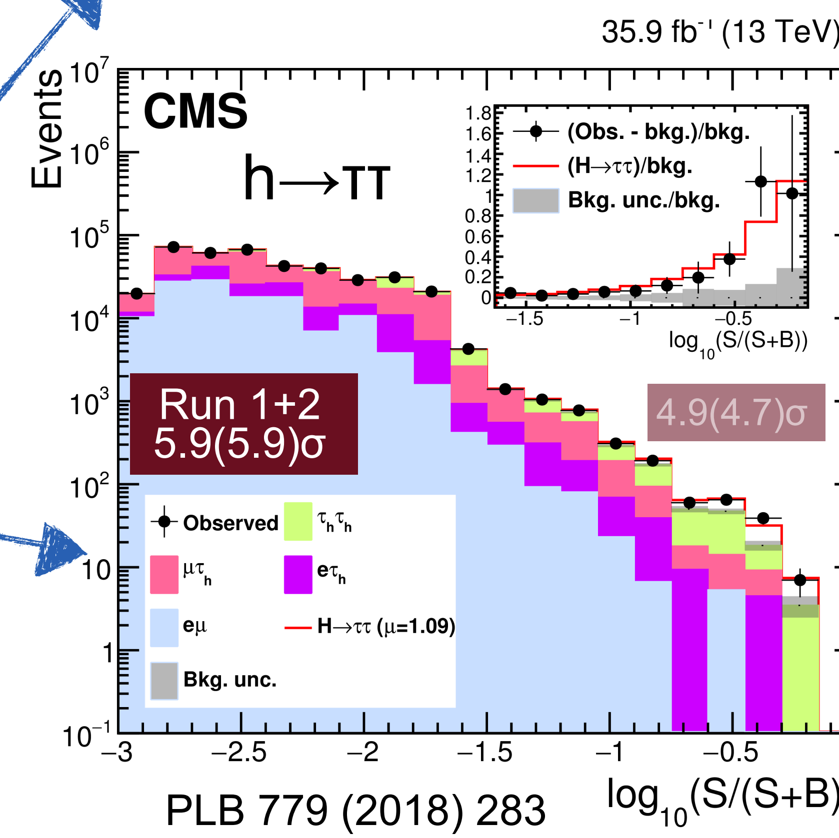
[in a nutshell]











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Higgs-fermion interactions: The story so far

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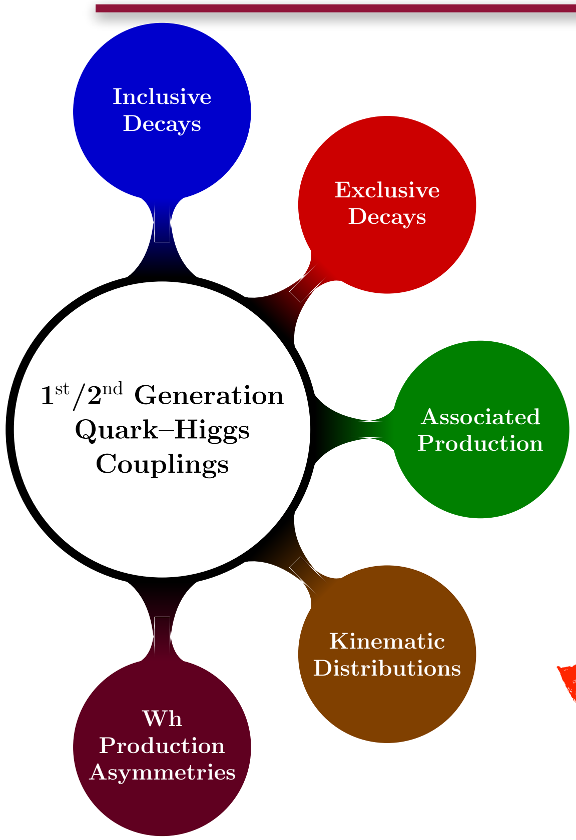

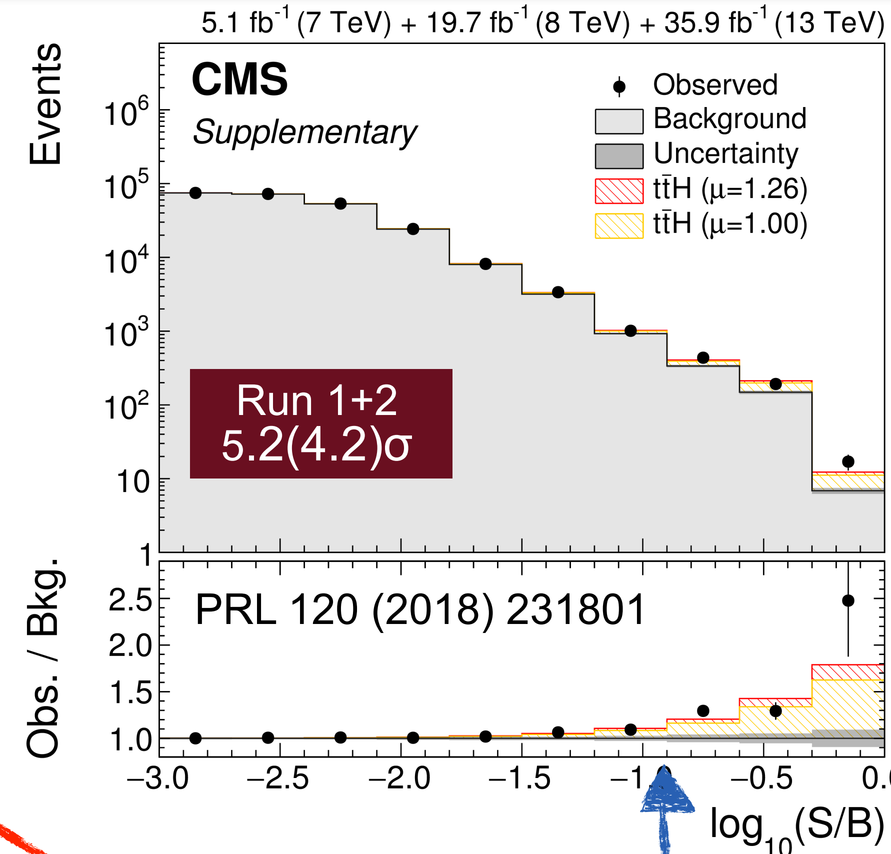

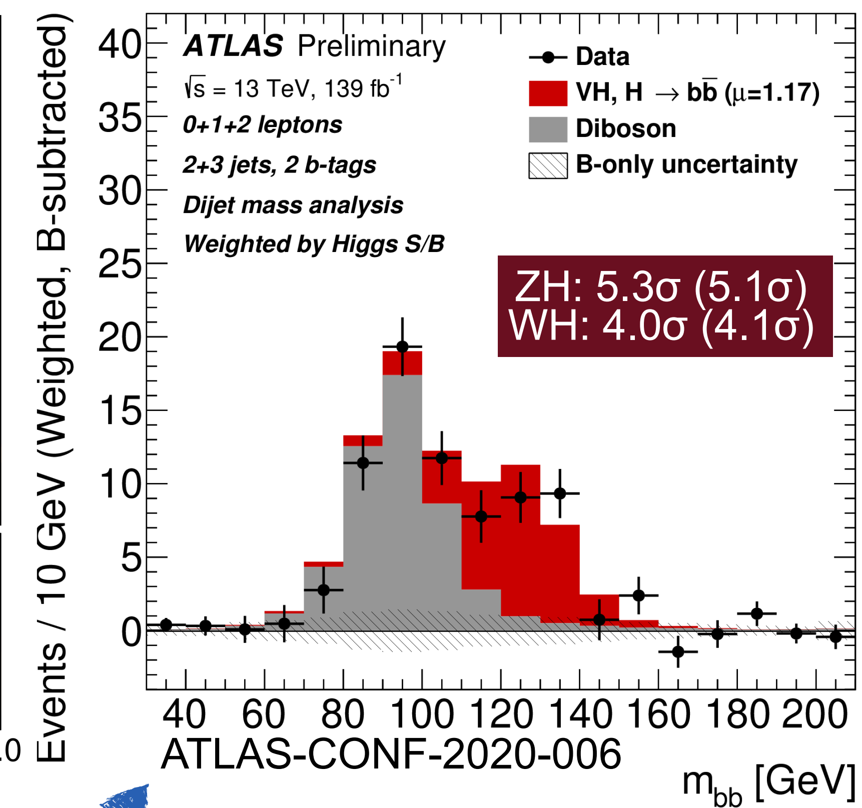

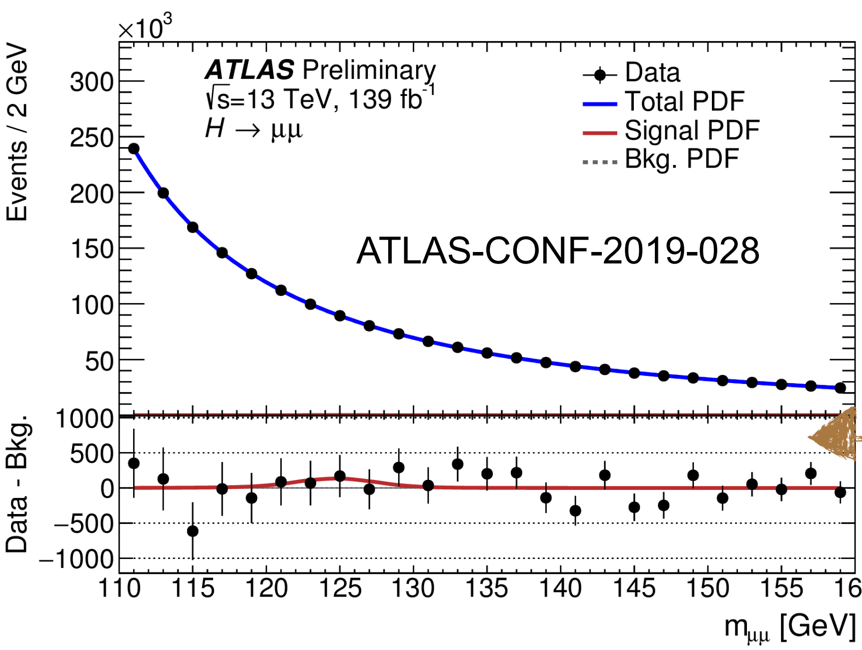

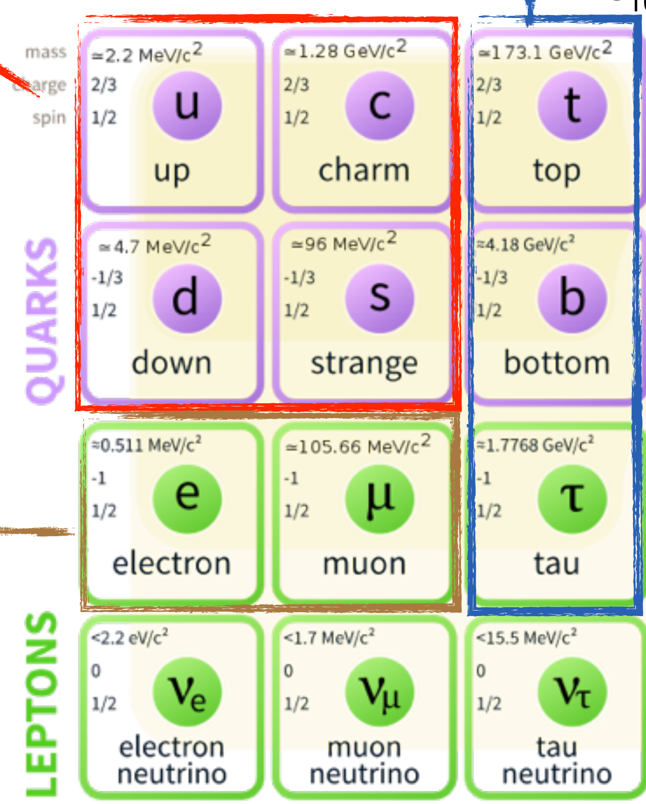

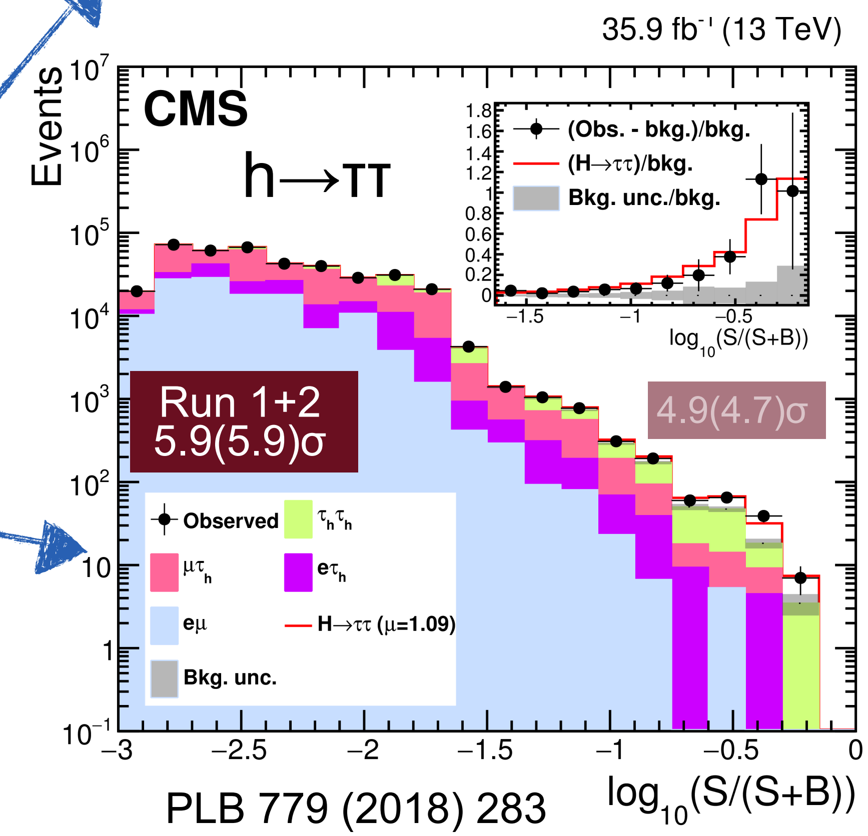

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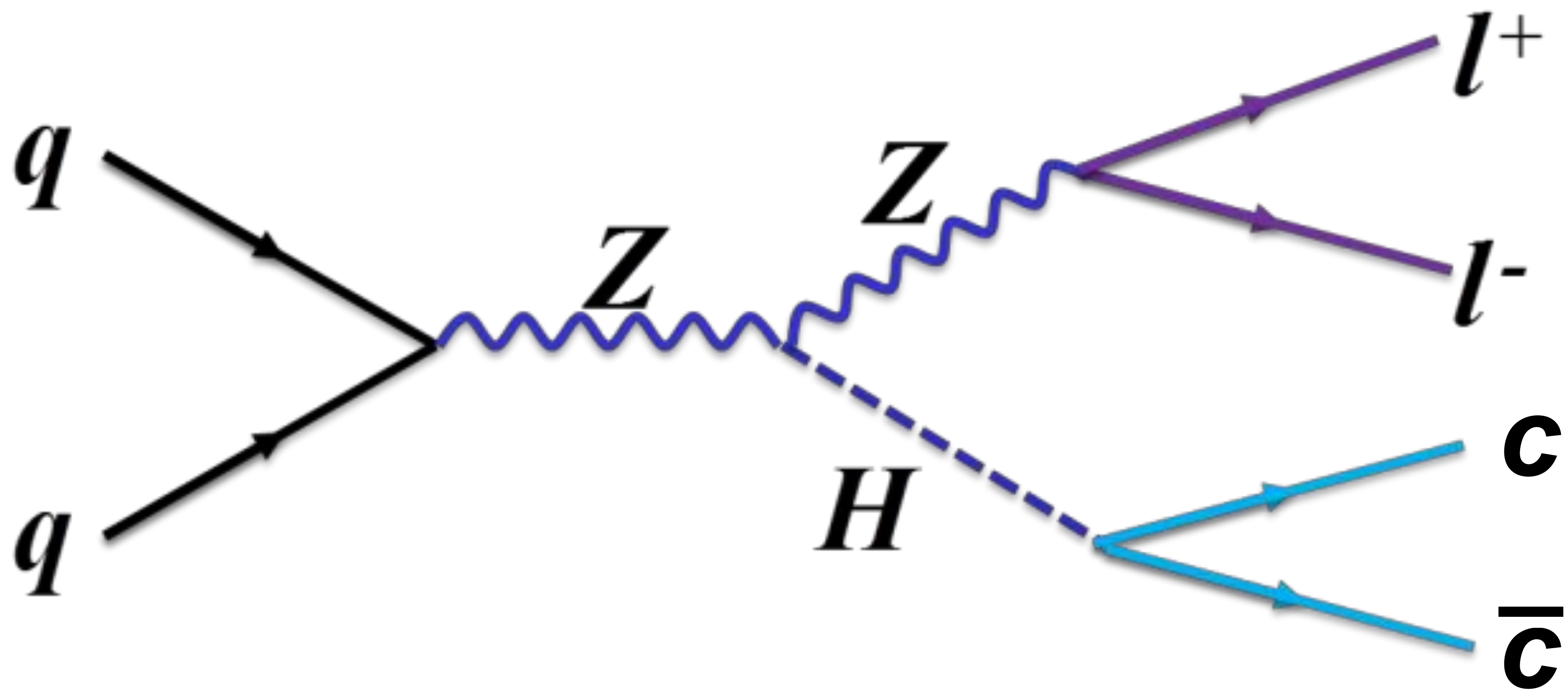
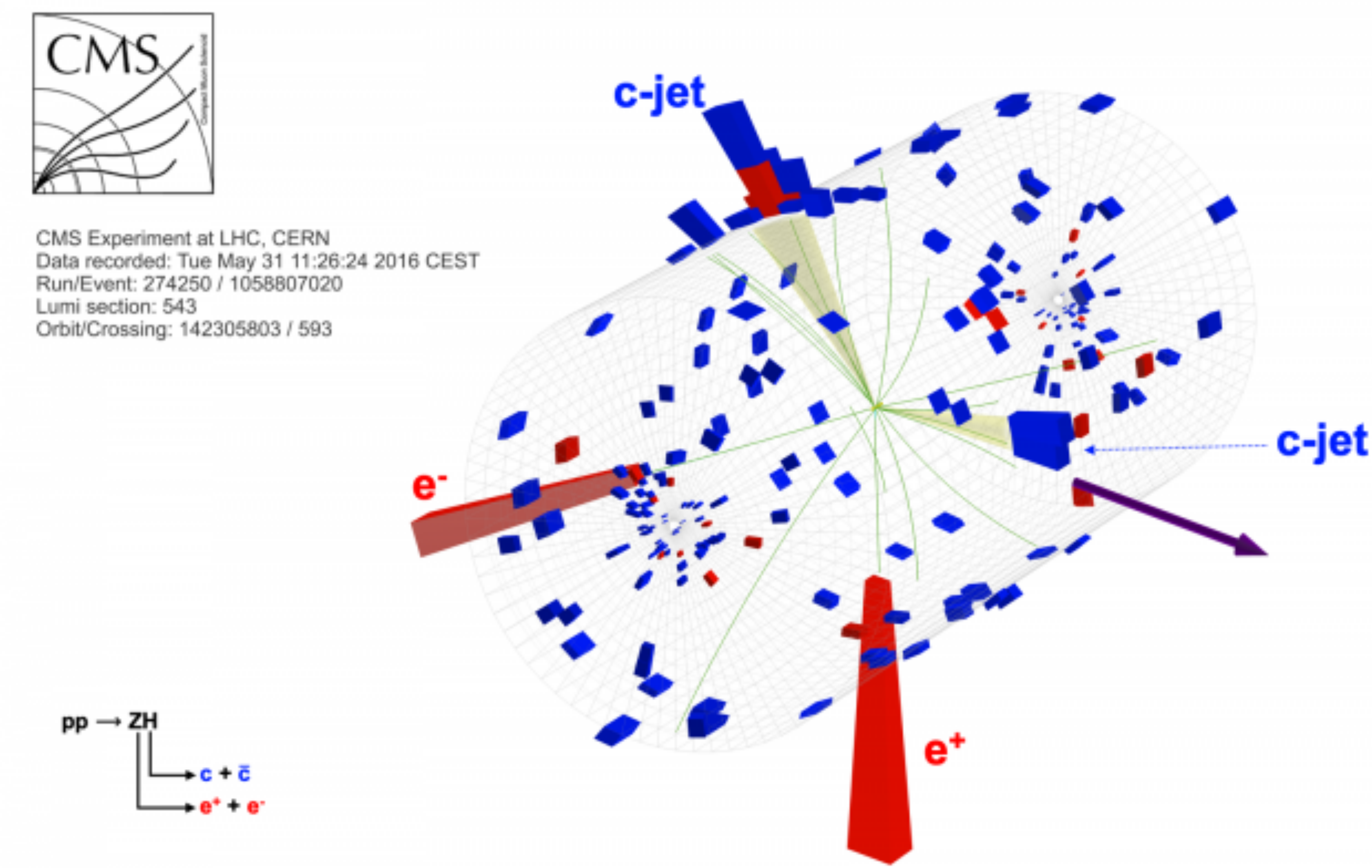
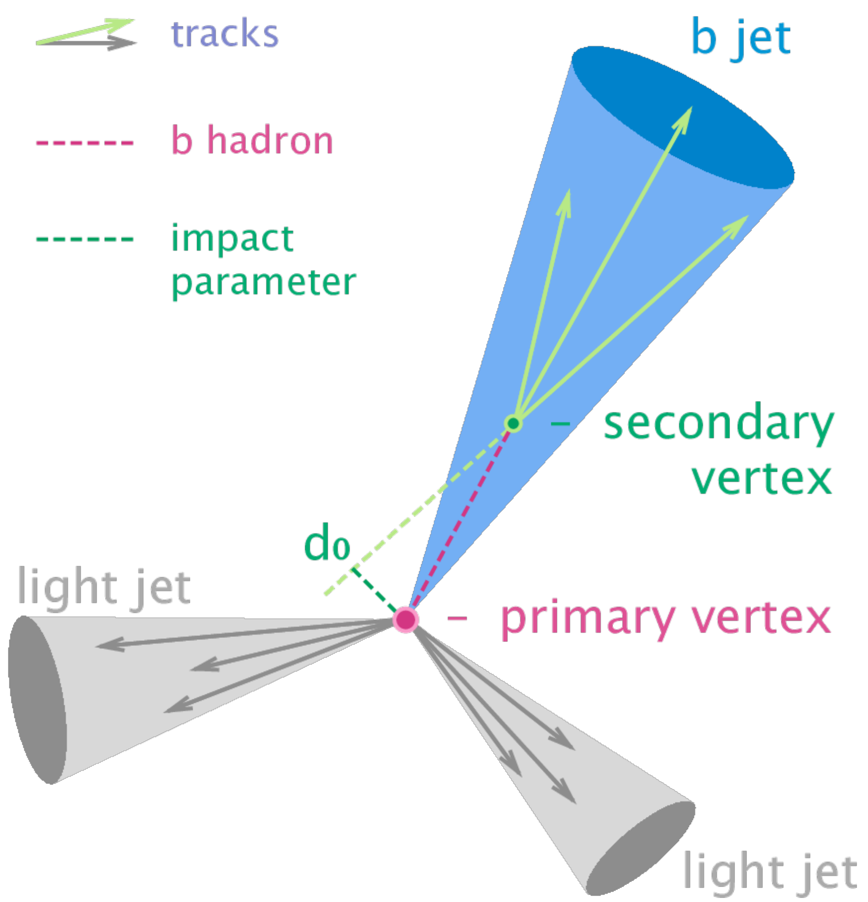

q
q
Z
Z
H
l+
l-
c
c̅

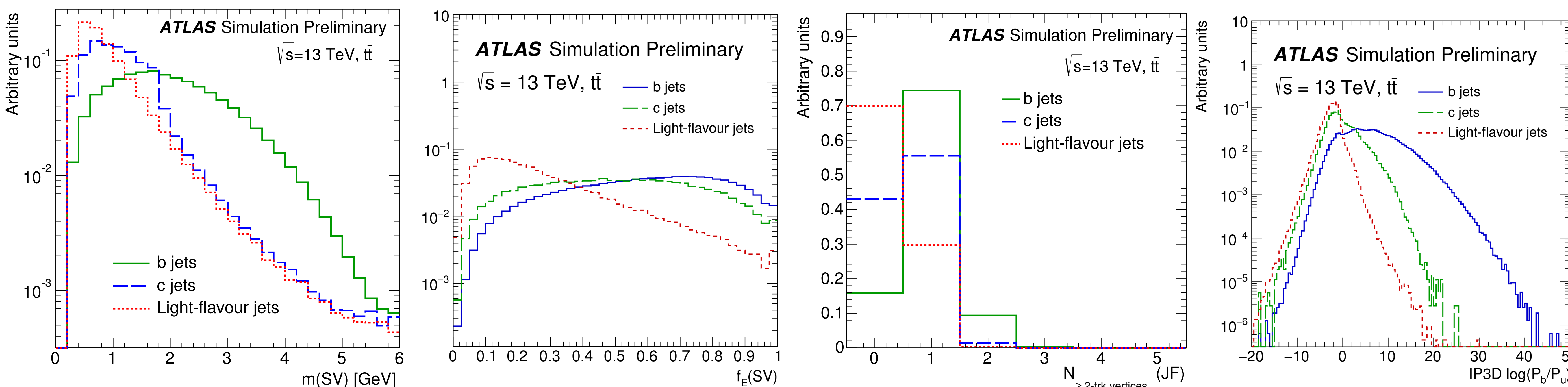

CMS
CMS Experiment at LHC, CERN
Data recorded: Tue May 31 11:26:24 2016 CEST
Run/Event: 274250 / 1058807020
Lumi section: 543
Orbit/Crossing: 142305803 / 593
c-jet
c-jet
e-
e+
pp → ZH
c + c̄
e+ + e-

Higgs boson-charm quark coupling

- **First search** for exclusive Zh→llcc decays, l=e, μ
- Search for **inclusive** h→cc decays, similar to h→bb
  - SM BR(h→bbbar) ~ 20 x BR(h→ccbar)
- **c-tagging** algorithm
  - c-jets less distinct than b-jets; e.g. ×3.5 less displacement
  - First used **Run 1** for search for s-charm

[Phys.Rev.Lett. 114 (2015) 161801]

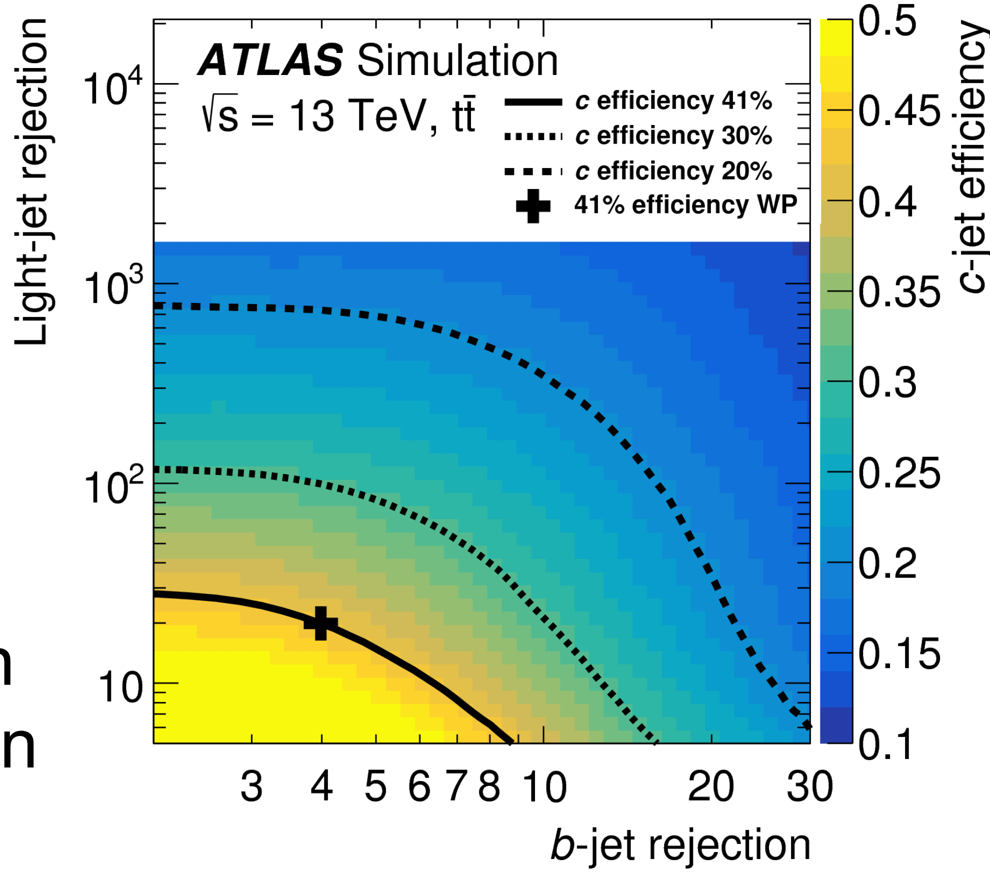




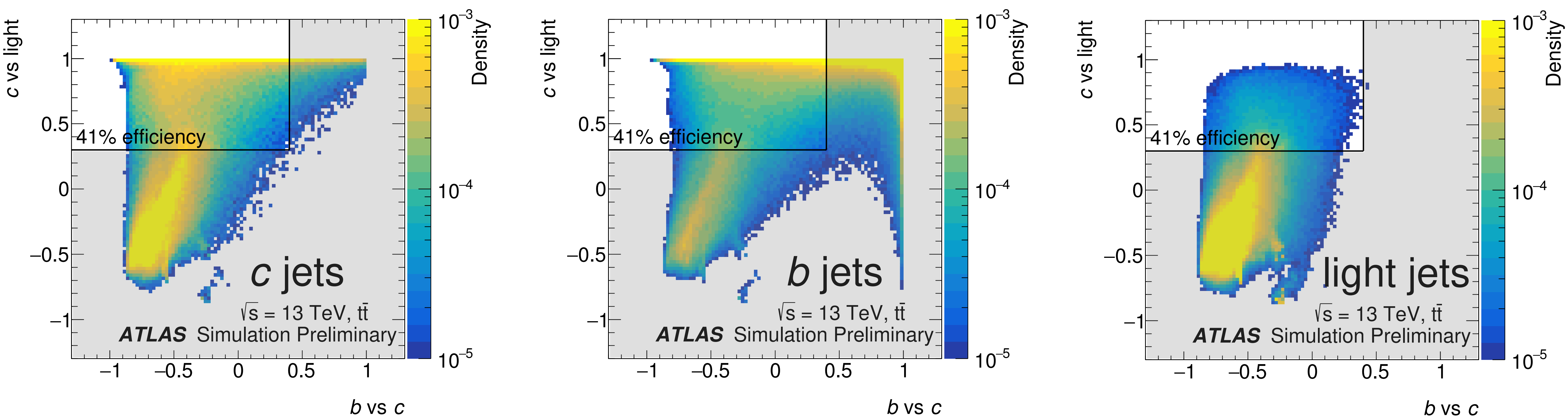
Higgs boson-charm quark coupling

- **Run 2** new "inclusive" c-tagging
  - "Low level" taggers:
    - Track Impact Parameter
    - Secondary Vertices
    - JetFitter: b/c-jet decay chain fit
  - "High level" tagger obtained with BDT

- c-tagging: 41% c-jet eff; 4×b-jet & 20×light jet rejection
- b-tagging: 77% b-jet eff; 6×c-jet &134×light jet rejection



***c*-jets** ***b*-jets** **light flavour (u, d, s, g) jets**



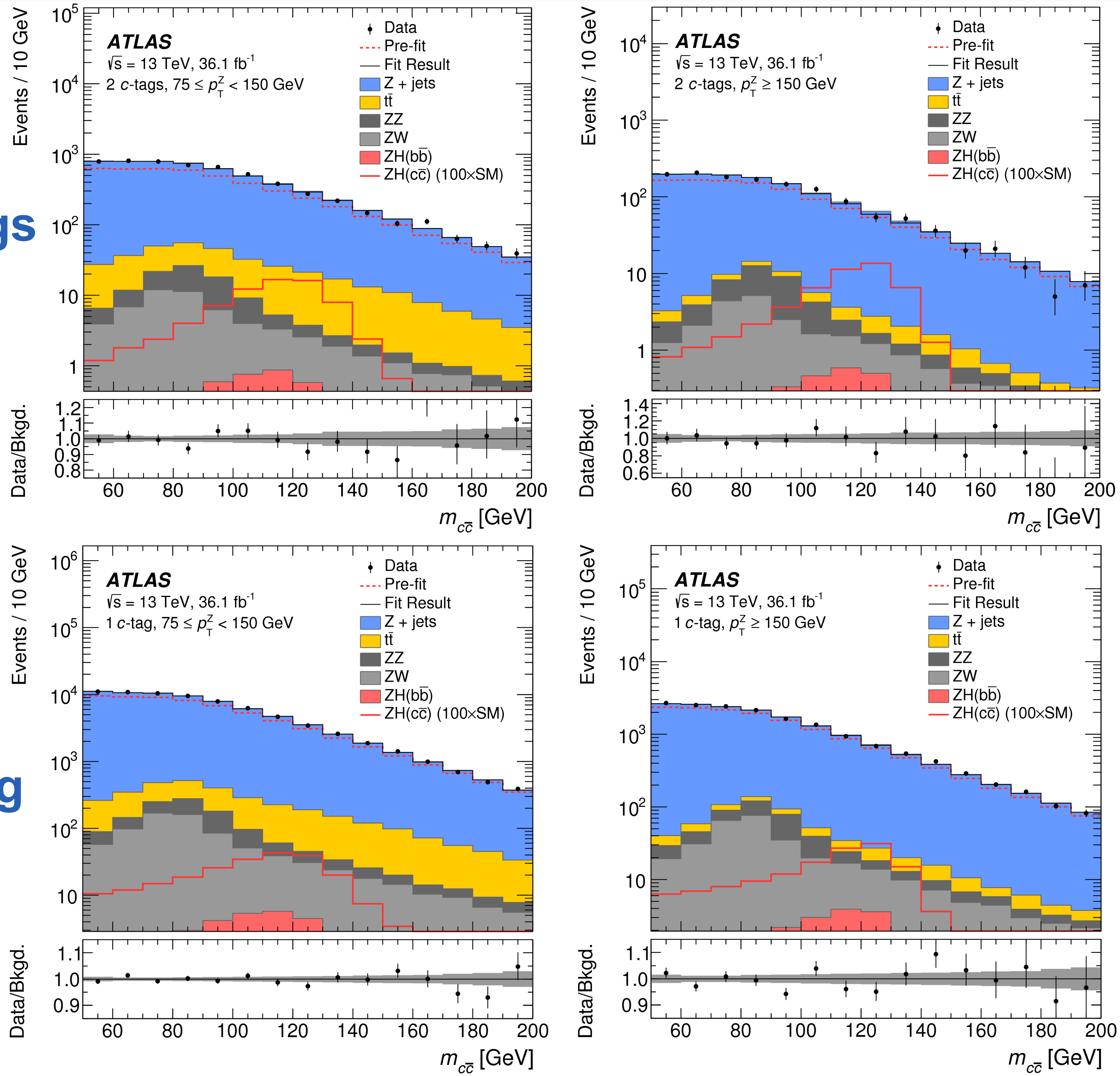
ATLAS-CONF-2017-078

Zh(→cc): Results

PRL120 (2018) 211802

2 c-tags

1 c-tag



75< p_TZ < 150 GeV

p_TZ > 150 GeV

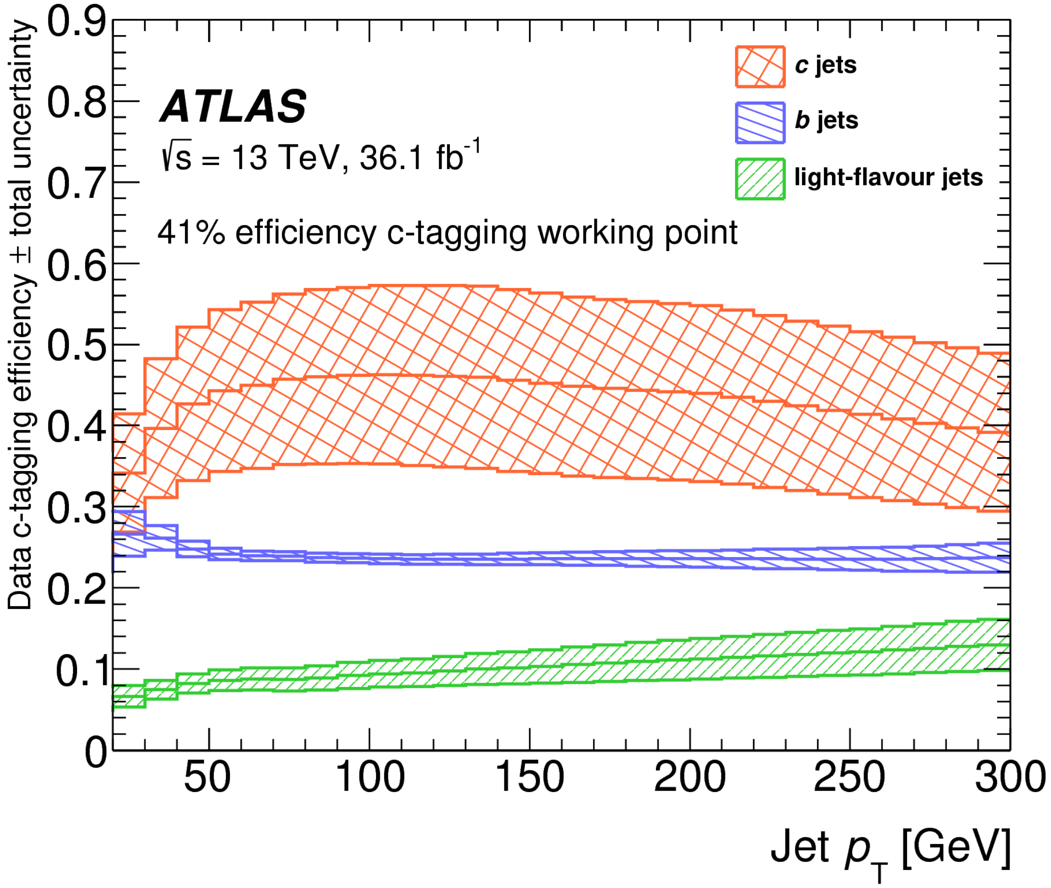
- **No evidence** for Zh(→cc)
- 95% CL_s upper limit:110×SM (150^{+80}_{-40})
- Prospects of reaching (a few×) SM sensitivity at the end of LHC physics programme

Zh(→cc):Results

- **No evidence** for Zh(→cc) production with current dataset
- 95% CL_s upper limit:110×SM (150^{+80}_{-40})

PRL120 (2018) 211802

Source	$\sigma/\sigma_{\text{tot}}$
Statistical	**49%**
Floating Z + jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%



- Single tagging working point constrains linear combination of h→cc/h→bb
  - Analysis in conjunction with h→bb; account for cross-contamination
- Key to future is control of systematic uncertainties
  - Phenomenological analysis (2×3000 fb^{-1}) indicates $|\kappa_c|\lesssim 2.5$-5.5 at 95% CL depending on the c-tagging scenario [Phys.Rev. D93 (2016) 013001]
  - ATLAS HL-LHC projection for Z(ll)H(cc) alone μ<6.3 [ATL-PHYS-PUB-2018-016]

Zh(→cc):Results from CMS

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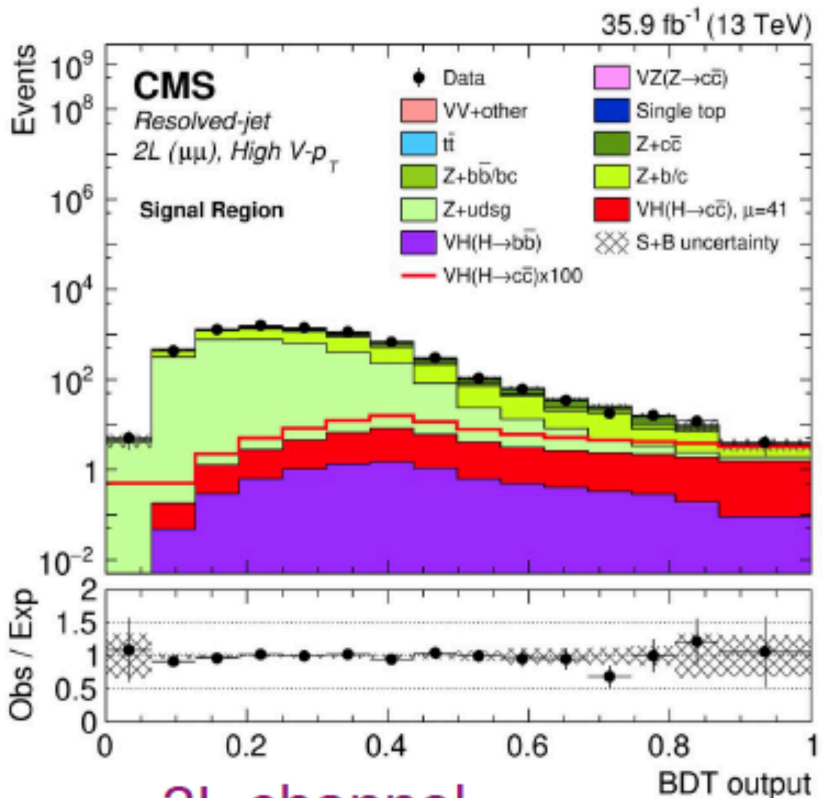
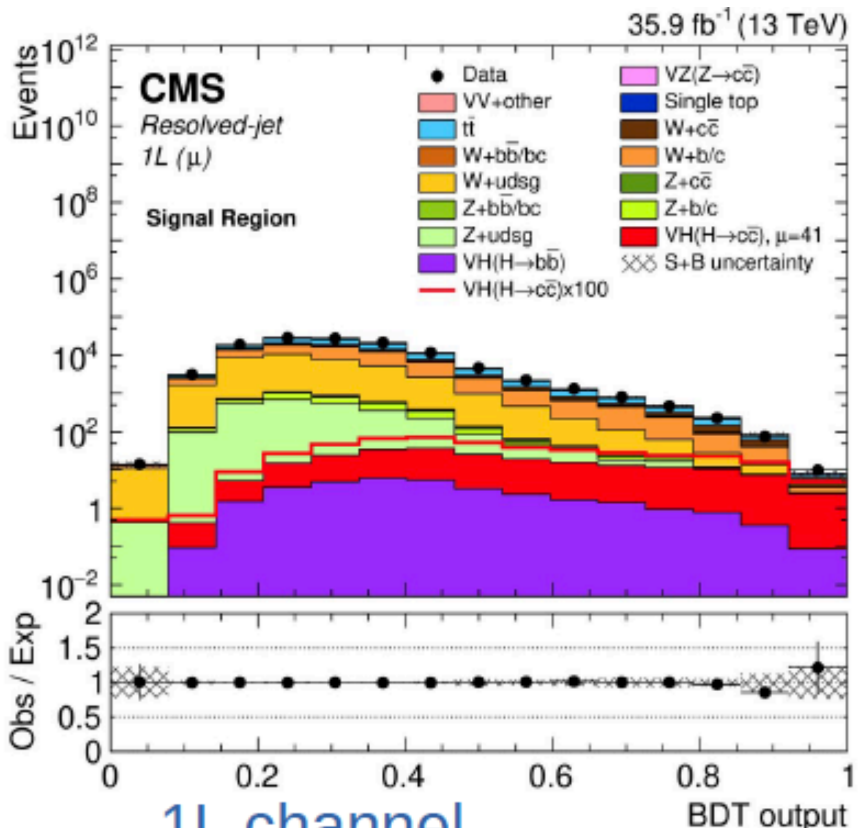
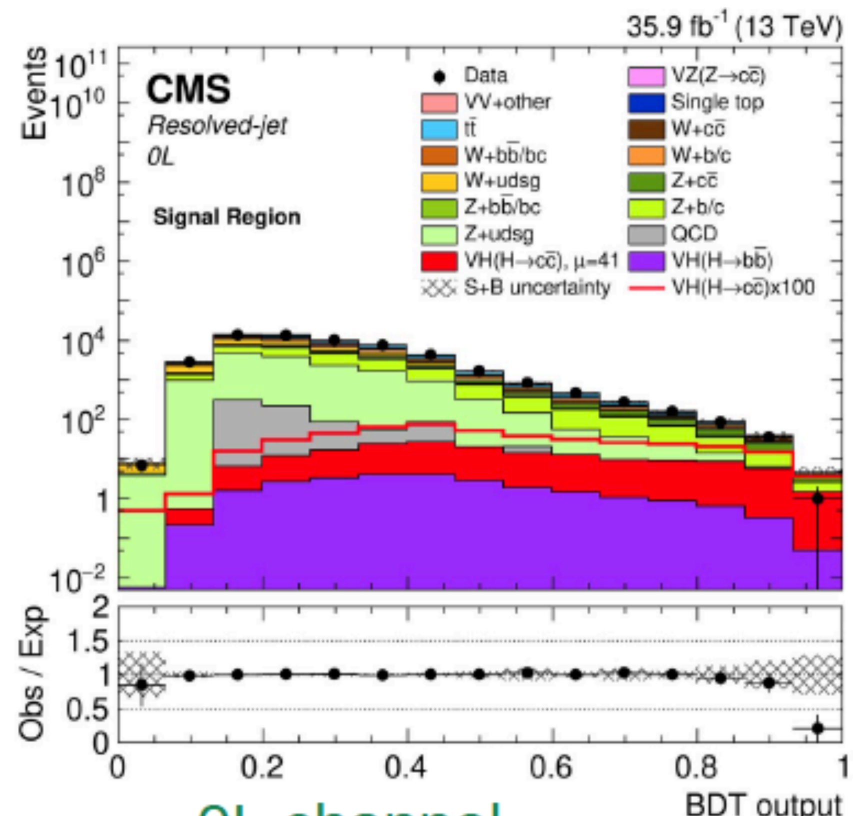


2L channel



1L channel



0L channel

95%CL upper limit on σ/σ_{SM}

	Resolved-jet (inclusive)			
	0L	1L	2L	All channels
Expected UL	84^{+35}_{-24}	79^{+34}_{-23}	59^{+25}_{-17}	38^{+16}_{-11}
Observed UL	66	120	116	75

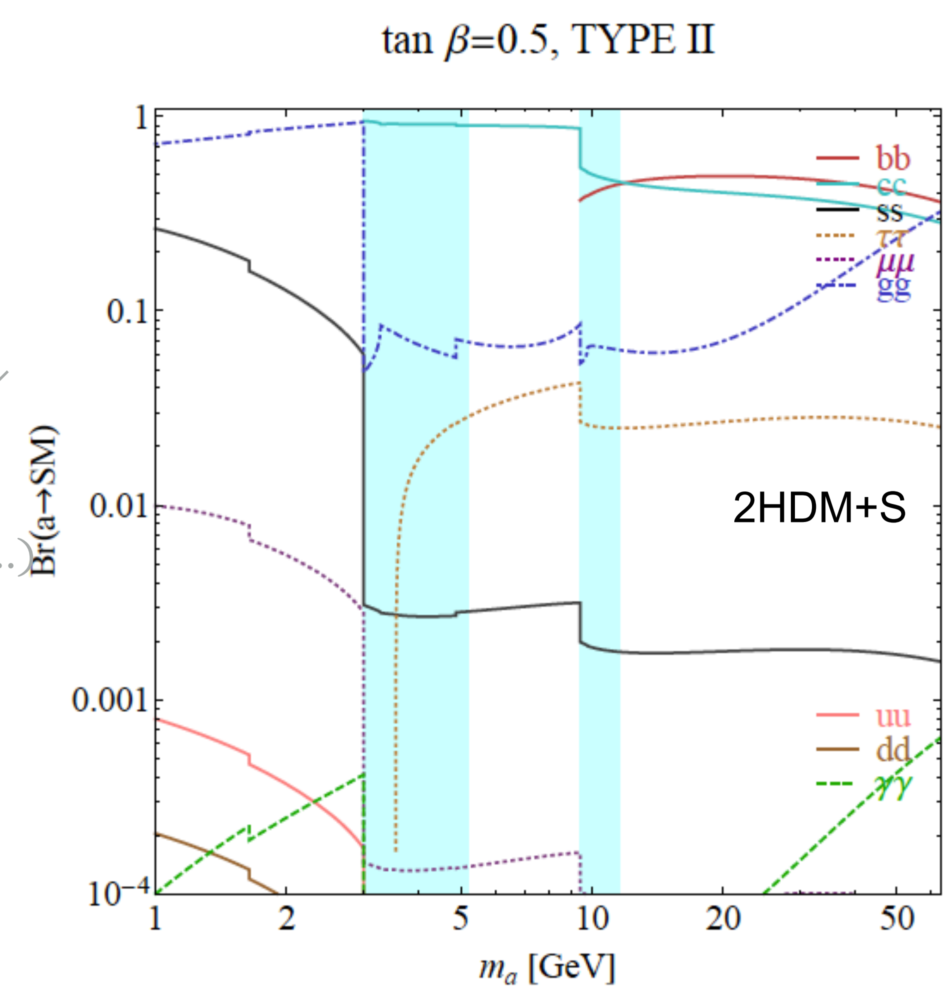
Higgs sectors beyond the SM

- The SM Higgs sector is not the only possible
  - Merely the simplest one
  - Extended Higgs boson sectors can be constructed
    - Possible answers to open questions
    - With additional $SU(2)_L$ scalars, doublets, triplets,..
  - The ρ parameter puts tight constraints on model viability

$$\frac{M_W^2}{M_Z^2 c_W^2} = \frac{\sum_i \left[T_i(T_i+1) - \frac{1}{4}Y_i^2\right] v_i^2}{\frac{1}{2}\sum_i Y_i^2\, v_i^2} \overset{\text{doublets}}{=} \frac{\sum_i \left[\frac{3}{4} - \frac{1}{4}\right] v_i^2}{\frac{1}{2}\sum_i v_i^2} = 1$$

For SM ρ=1 (plus small corrections)
and was measured precisely at LEP!
(ρ=1.00039±0.00019)

- V(φ1,φ2,...)



arXiv:1312.4992

- SM+Singlet, 2HDM, 2HDM+S, …
  - Extending the Higgs sector → more Higgs bosons
  - e.g. 2HDM has 5 Higgs bosons: h, H, A, $H^{\pm}$
- Rich phenomenology
  - Provided they are kinematically possible, Higgs boson decays to other Higgs bosons are allowed

Higgs sectors beyond the SM

- The SM Higgs sector is n
  - Merely the simplest one
  - Extended Higgs boson s
    - Possible answers to op
    - With additional $SU(2)_L$ s
  - The ρ parameter puts tig

$$\frac{M_W^2}{M_Z^2 c_W^2} = \frac{\sum_i \left[T_i(T_i+1) - \frac{1}{4}Y_i^2\right] v}{\frac{1}{2}\sum_i Y_i^2 v_i^2}$$

For SM ρ=1 (plus small
and was measured preci
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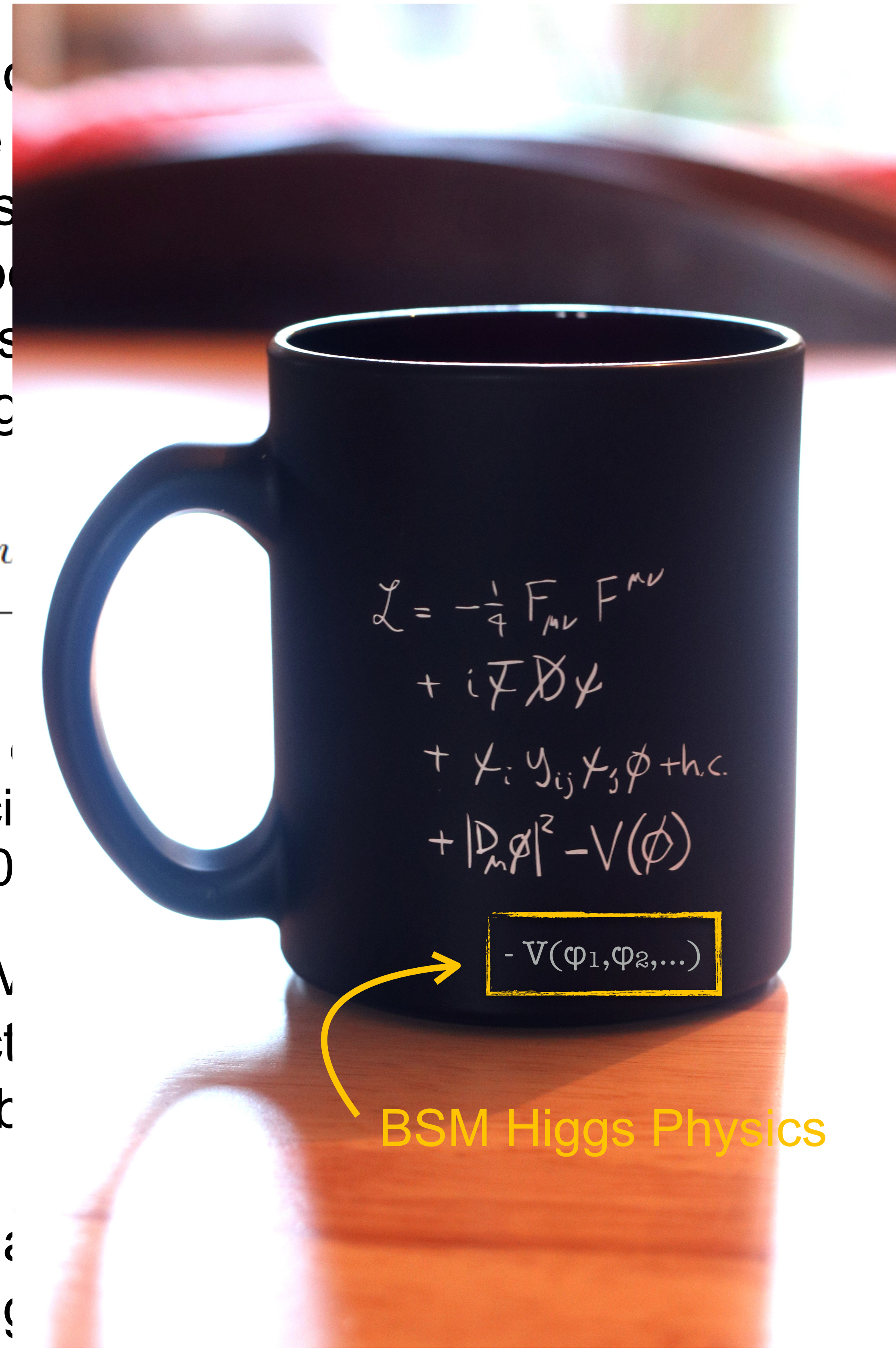

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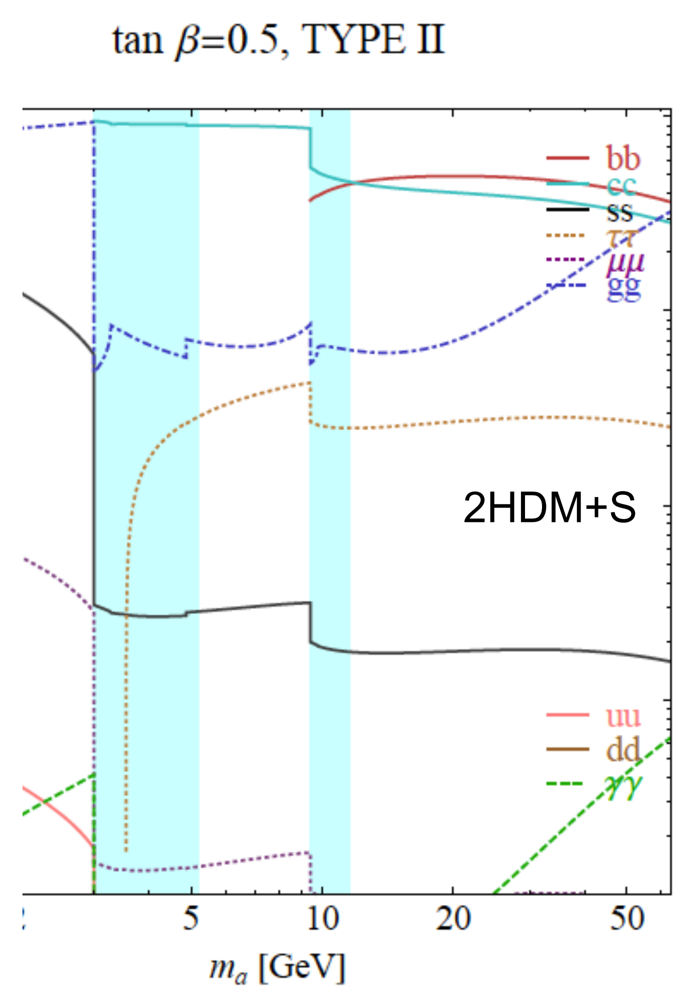
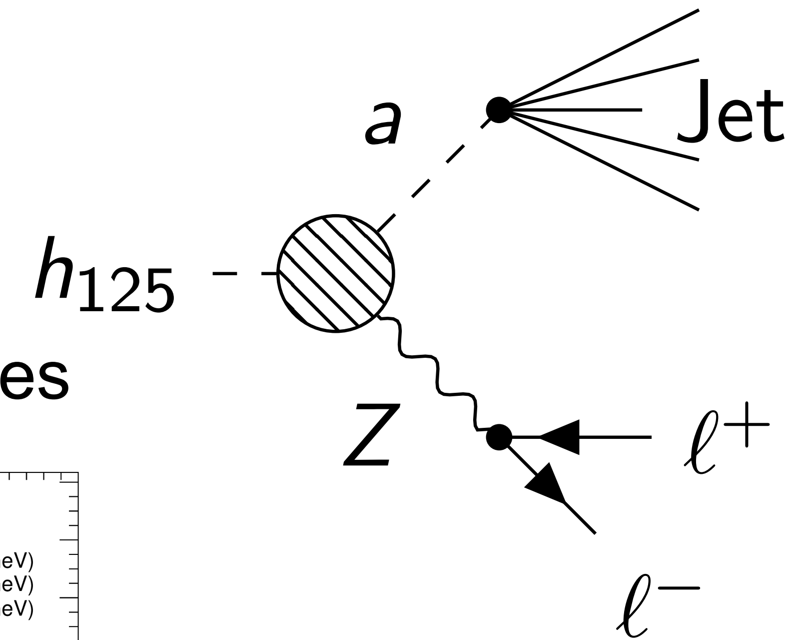
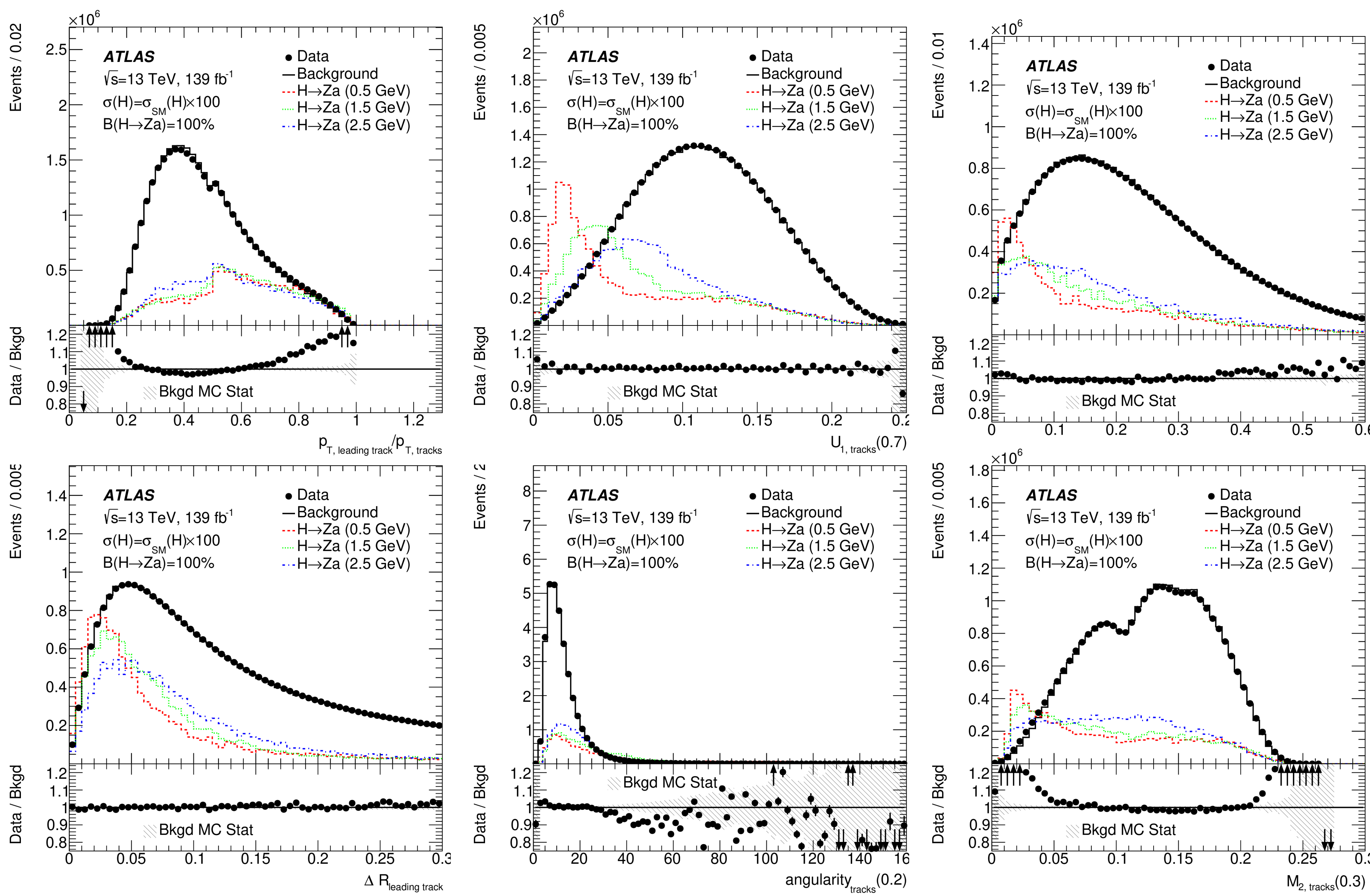


arXiv:1312.4992

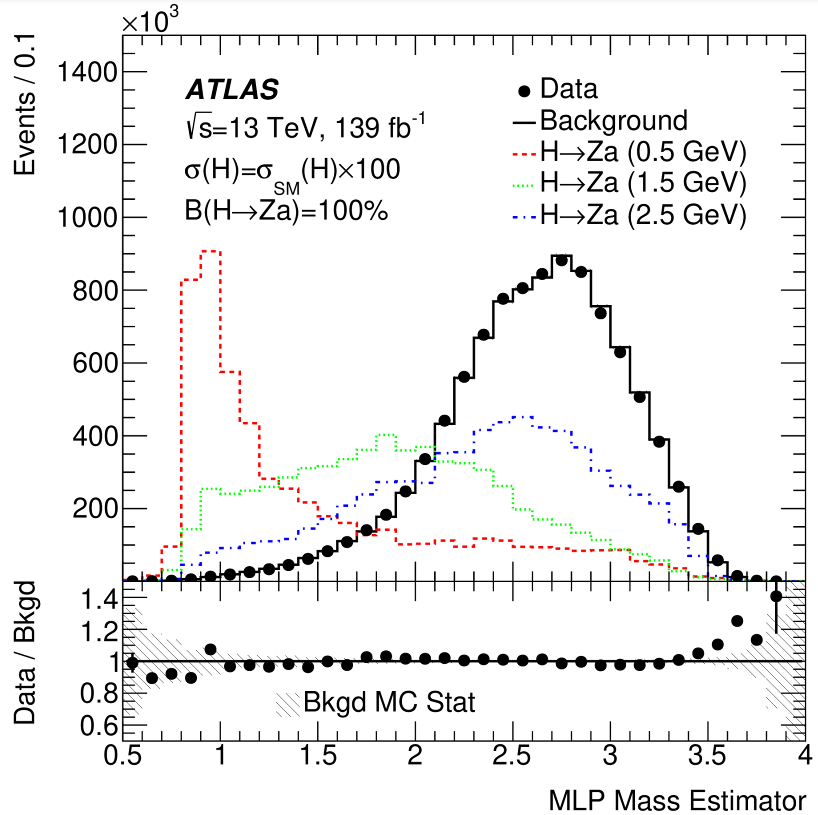
h→Za→ll+jet

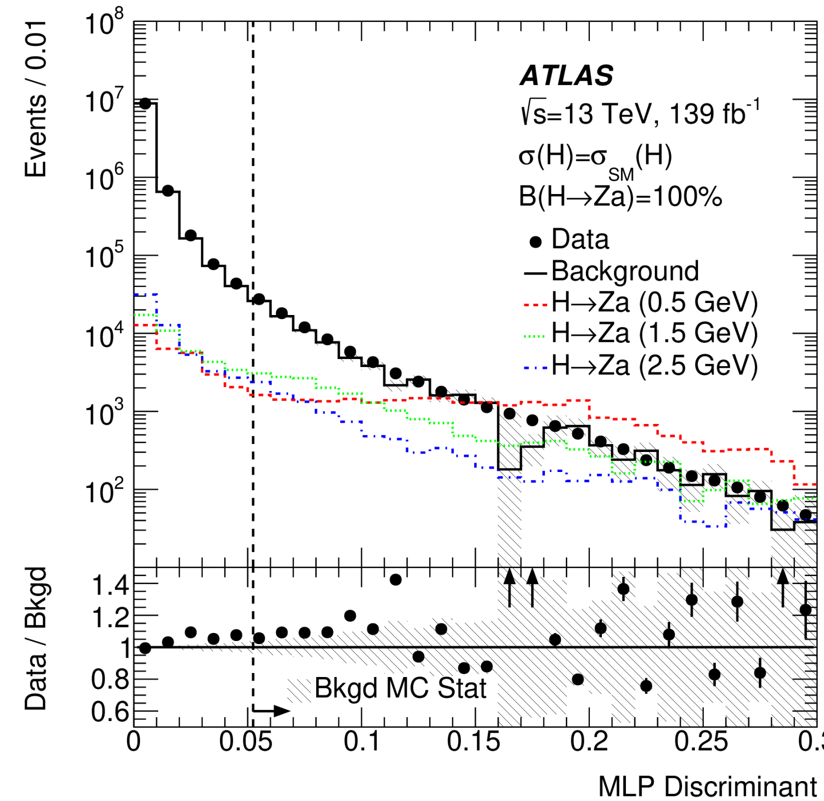
- Experimentally, searches mostly focus on:
  - h→aa
  - a decays to down-type fermions
- Novel search: h→Za with a→hadrons
  - Major challenge: overwhelming Z + jets background
  - a→hadrons reconstruction using sub-structure techniques

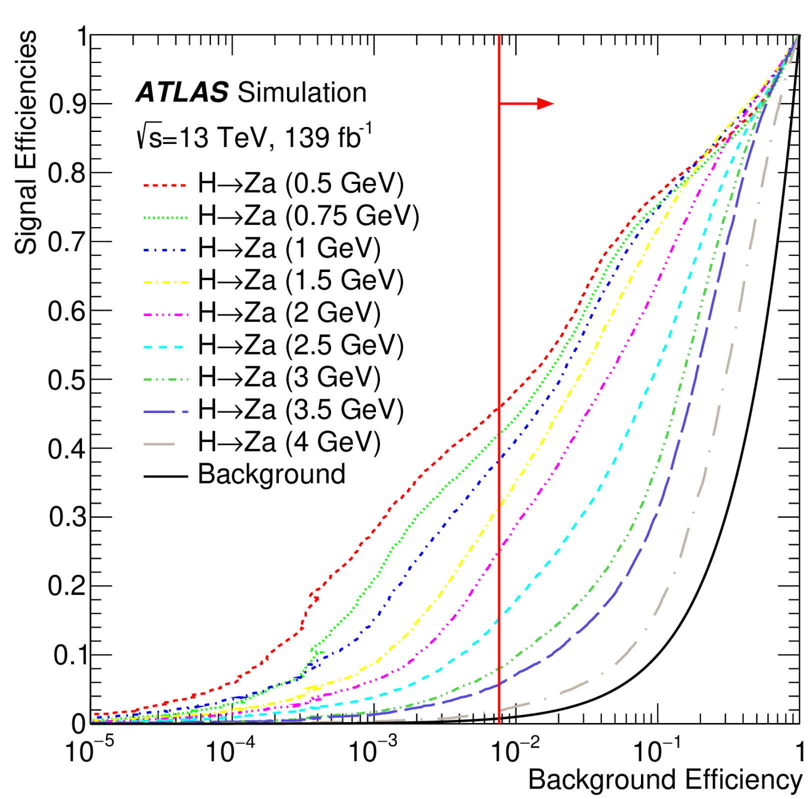


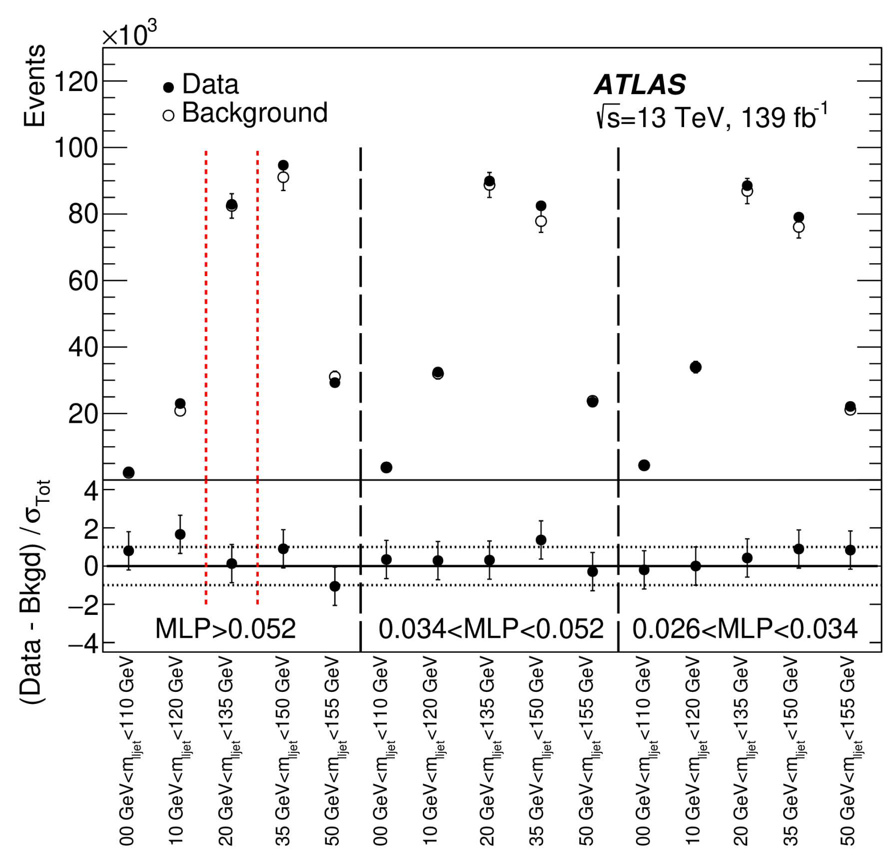


h→Za→ll+jet

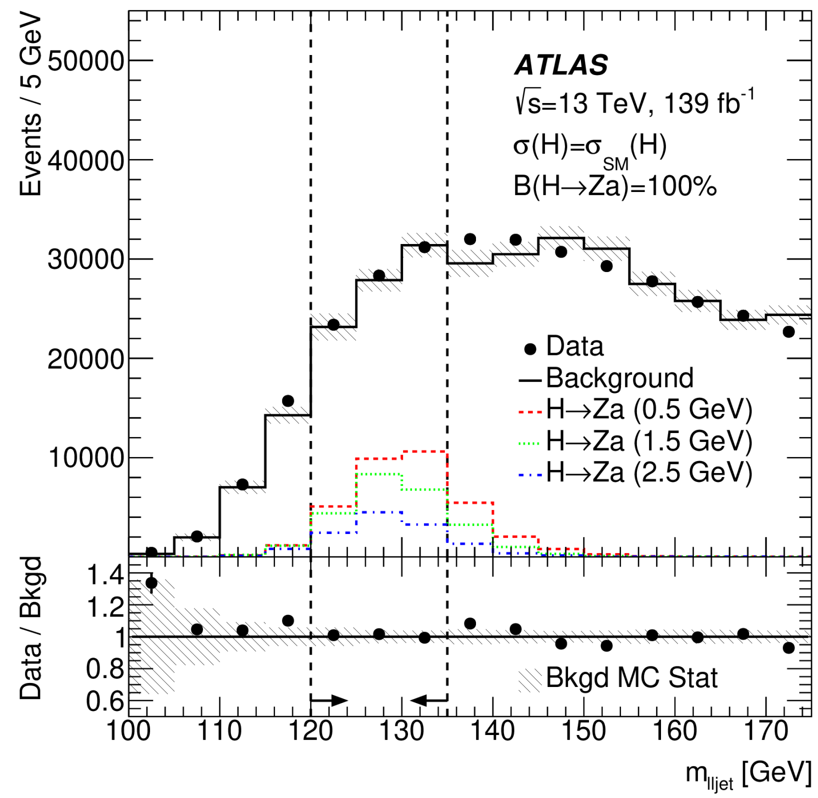

ATLAS
√s=13 TeV, 139 fb-1
σ(H)=σSM(H)×100
B(H→Za)=100%
Data
Background
H→Za (0.5 GeV)
H→Za (1.5 GeV)
H→Za (2.5 GeV)
Events / 0.1
×10³
Data / Bkgd
Bkgd MC Stat
MLP Mass Estimator


ATLAS
√s=13 TeV, 139 fb-1
σ(H)=σSM(H)
B(H→Za)=100%
Data
Background
H→Za (0.5 GeV)
H→Za (1.5 GeV)
H→Za (2.5 GeV)
Events / 0.01
Data / Bkgd
Bkgd MC Stat
MLP Discriminant


ATLAS Simulation
√s=13 TeV, 139 fb-1
H→Za (0.5 GeV)
H→Za (0.75 GeV)
H→Za (1 GeV)
H→Za (1.5 GeV)
H→Za (2 GeV)
H→Za (2.5 GeV)
H→Za (3 GeV)
H→Za (3.5 GeV)
H→Za (4 GeV)
Background
Signal Efficiencies
Background Efficiency

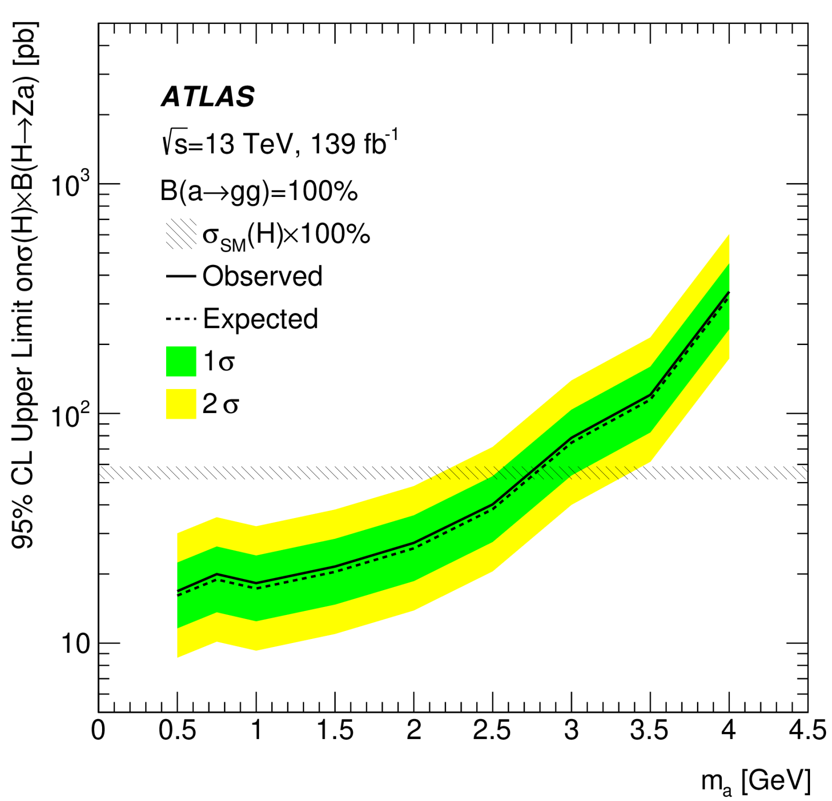

Data
Background
ATLAS
√s=13 TeV, 139 fb-1
Events
×10³
(Data - Bkgd) / σTot
MLP>0.052
0.034<MLP<0.052
0.026<MLP<0.034
100 GeV<mlljet<110 GeV
110 GeV<mlljet<120 GeV
120 GeV<mlljet<135 GeV
135 GeV<mlljet<150 GeV
150 GeV<mlljet<155 GeV

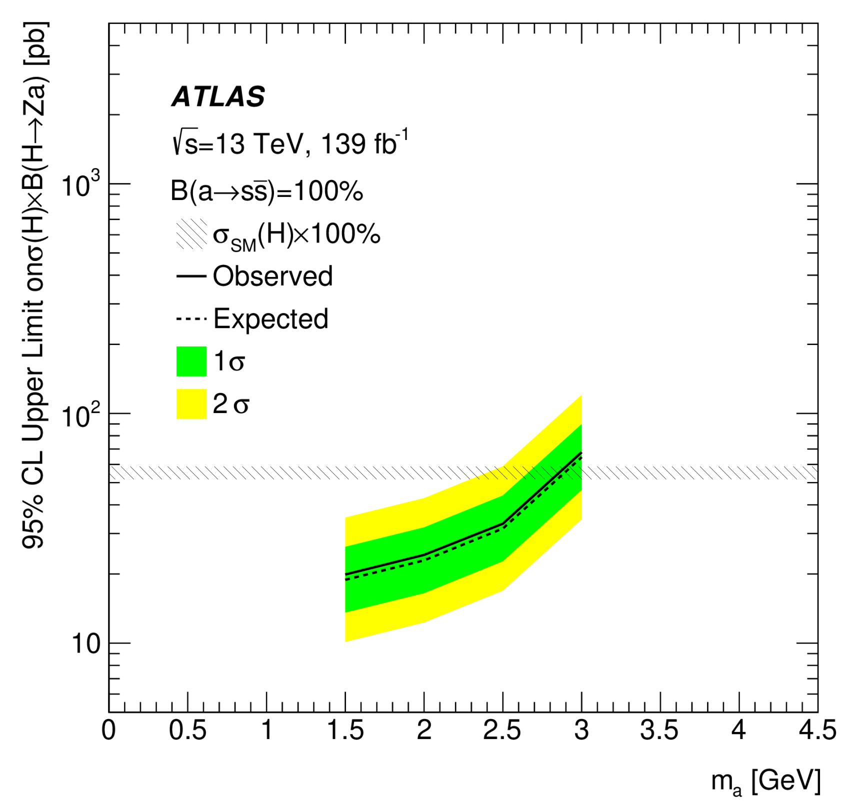
h→Za→ll+jet



Expected Bkg: 82400±3700

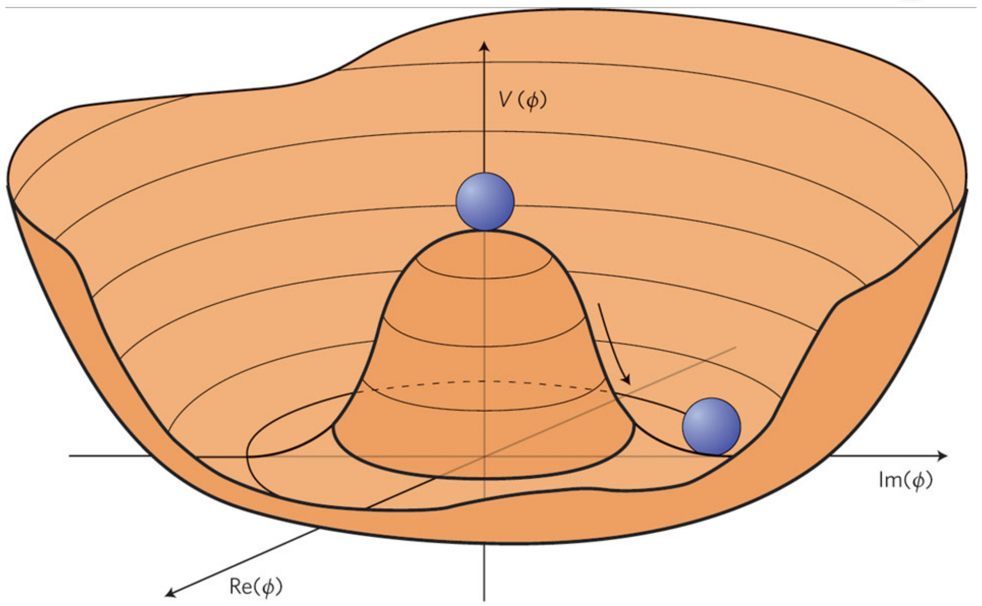
Observed: 82908





The Shape of the Higgs Potential

$$L_\Phi = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \boxed{\lambda^4} (\Phi^\dagger \Phi)$$



$$L = \frac{1}{2}\left(\partial_\mu h\right)^2 - \frac{1}{2}\left(2\lambda u^2\right) h^2 - \boxed{\lambda u h^3} - \boxed{\frac{\lambda}{4} h^4}$$

$$+ M_W^2 W_\mu^+ W^{\mu -}\left(1 + \frac{h}{u}\right)^2 + \frac{1}{2} M_Z^2 Z \mu Z^\mu \left(1 + \frac{h}{u}\right)^2$$

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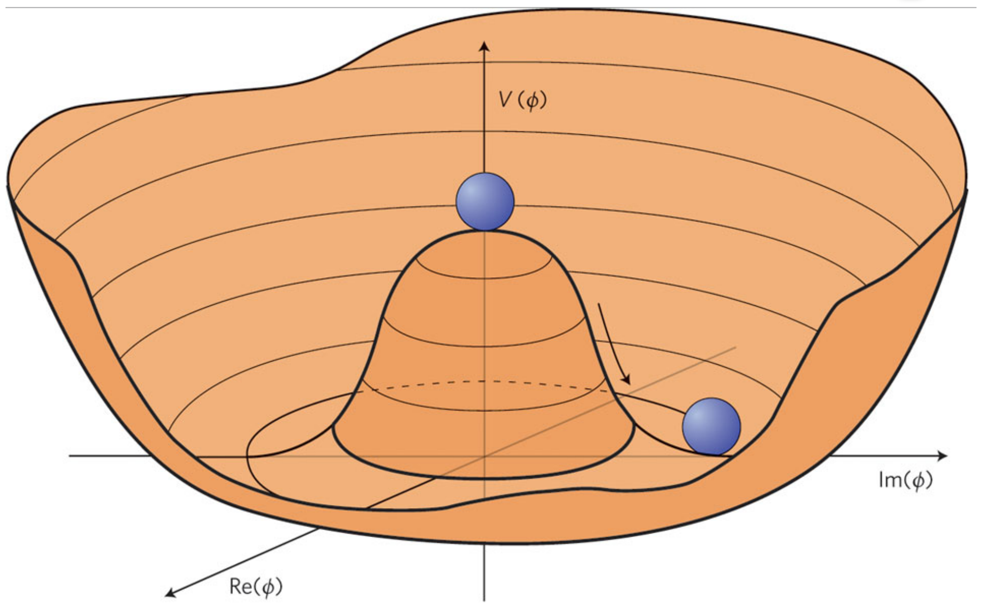

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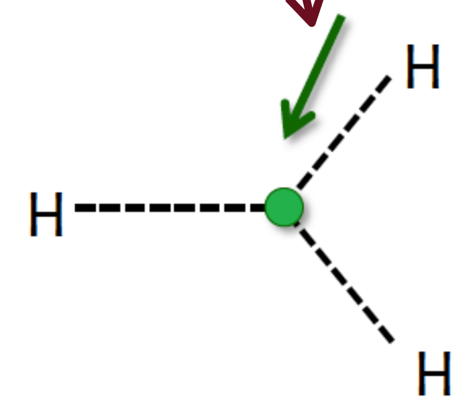

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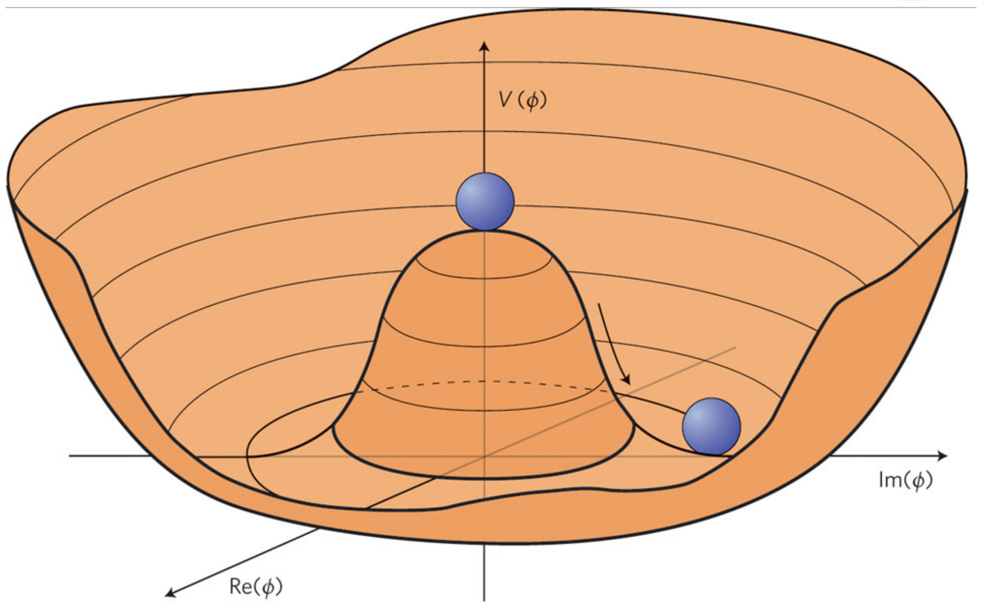

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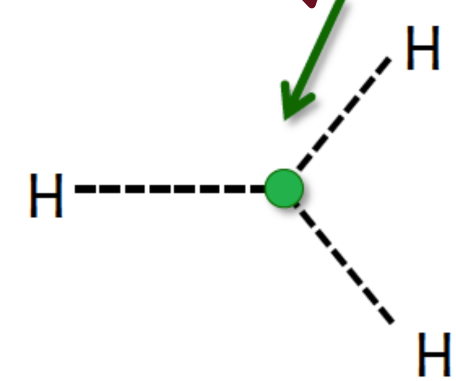

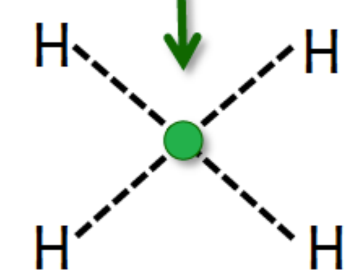

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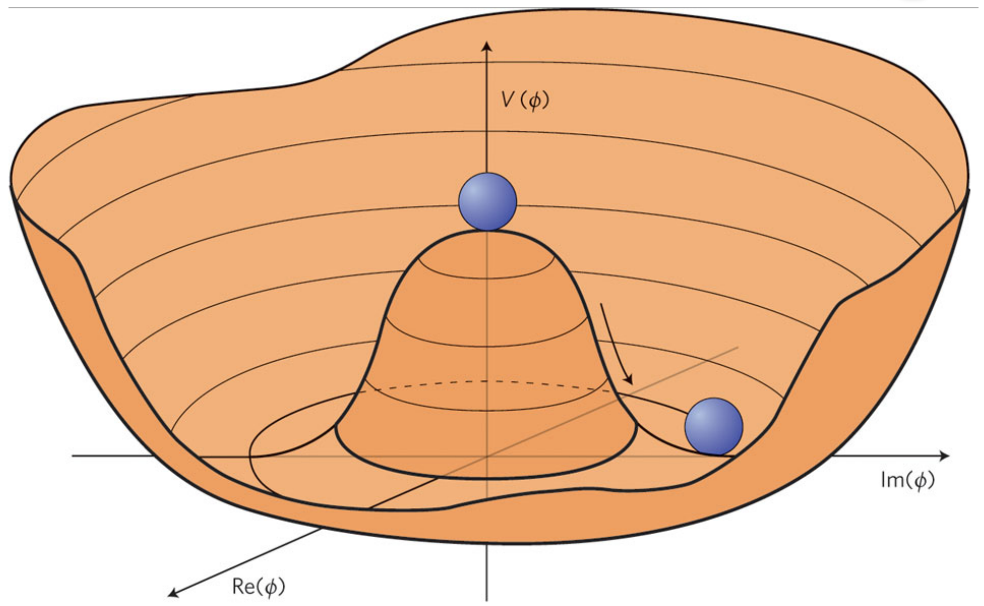

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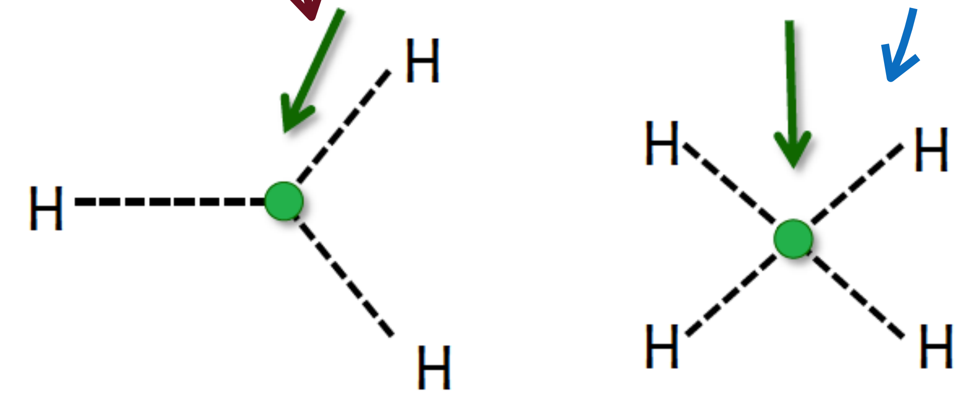
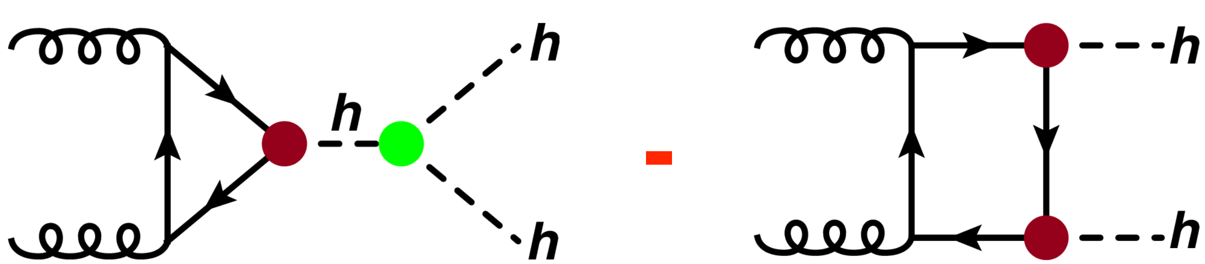
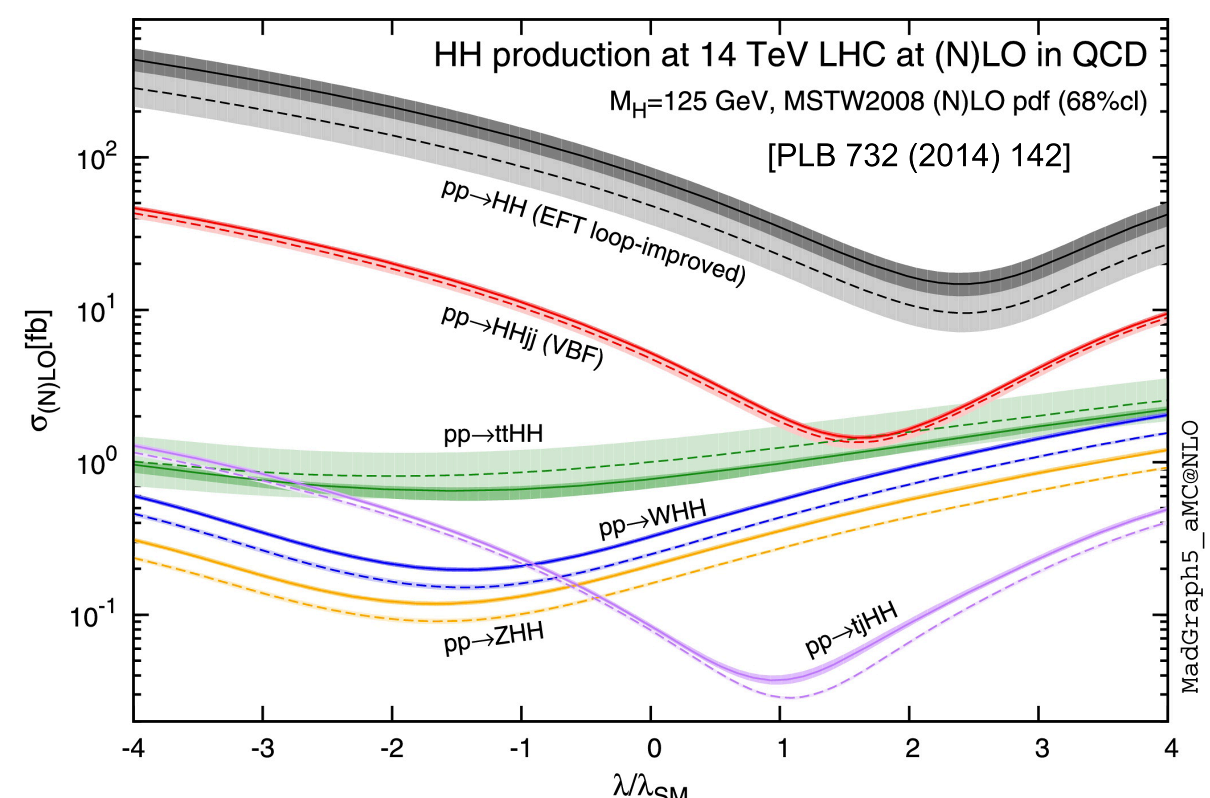




- Destructive interference!
  - More hh events expected for λ=0!
- Another possibility:
  - Self-couplings from single-Higgs production
    - NLO correction of O(1%)
    - Enhanced in specific kinematic phase-space



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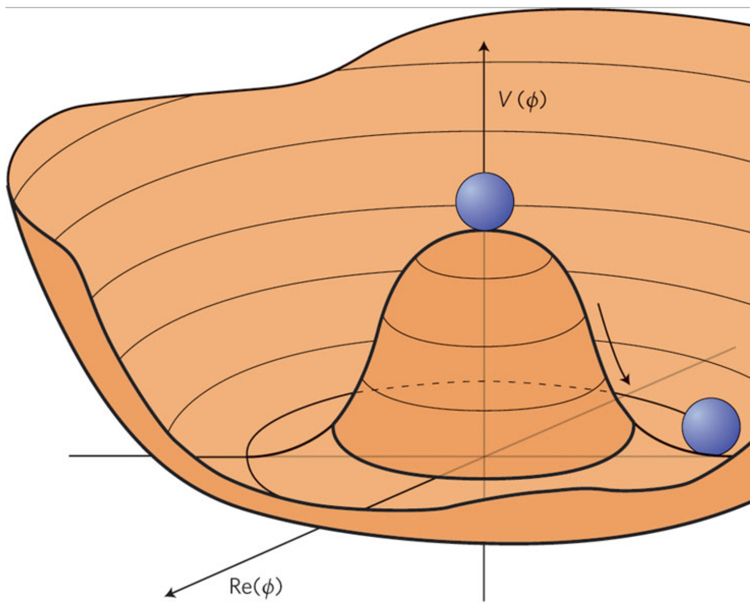
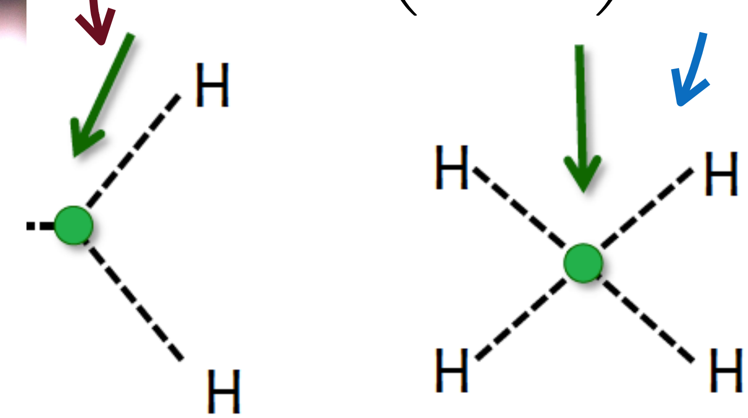
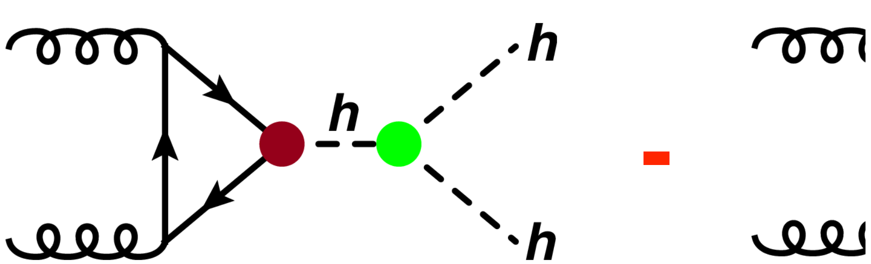
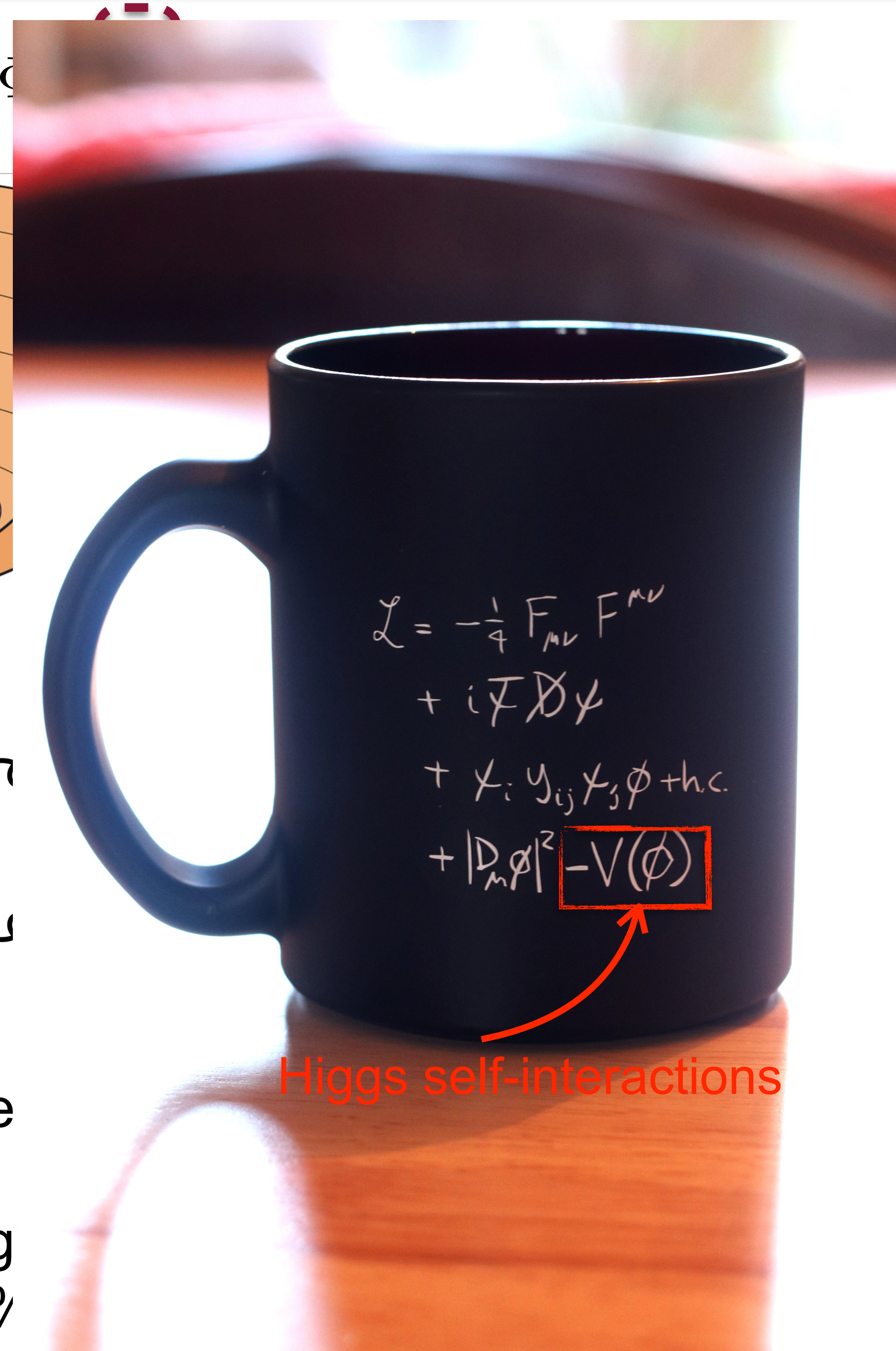


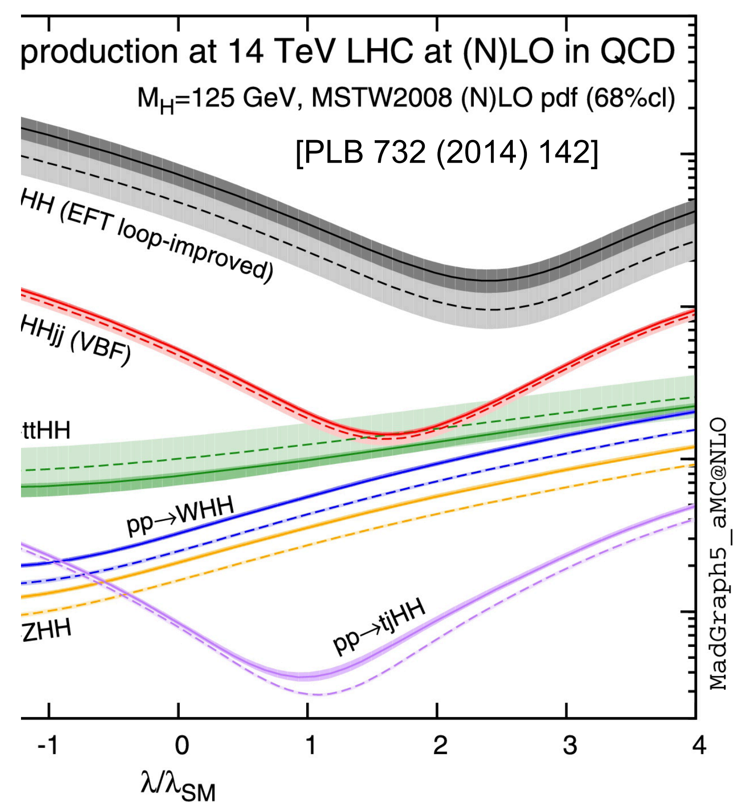
$$\lambda u^2)\, h^2 - \boxed{\lambda u h^3} - \boxed{\frac{\lambda}{4} h^4}$$

$$\frac{1}{2} M_Z^2 Z\mu Z^\mu \left(1 + \frac{h}{u}\right)^2$$









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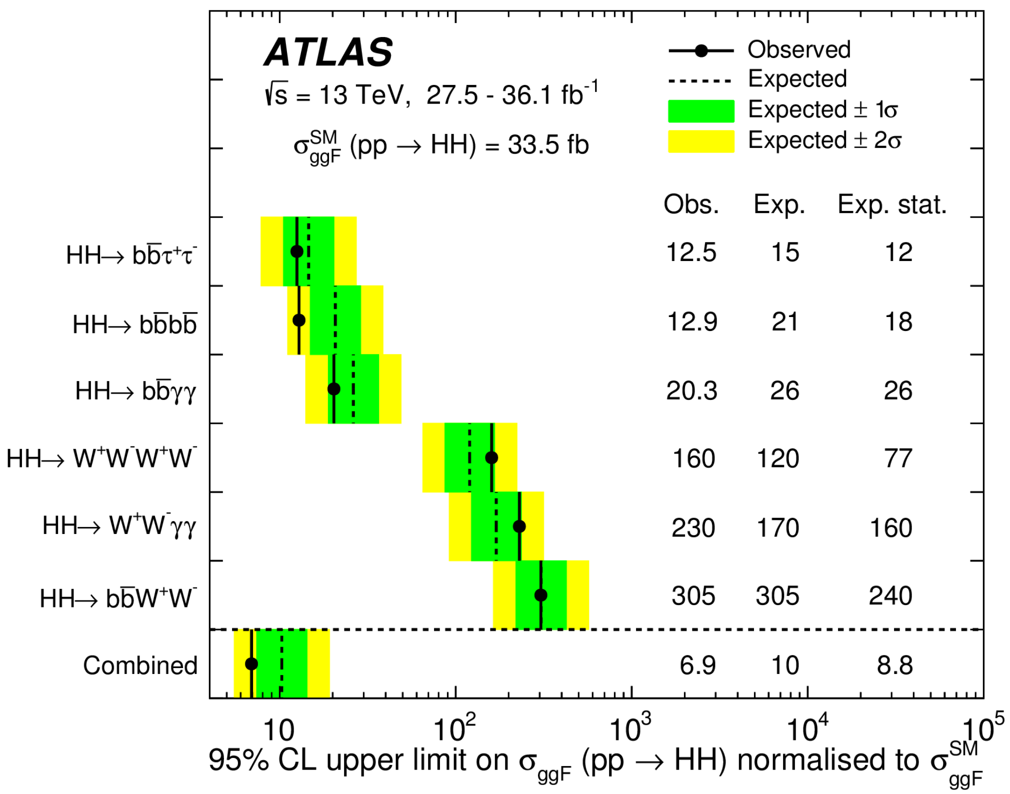
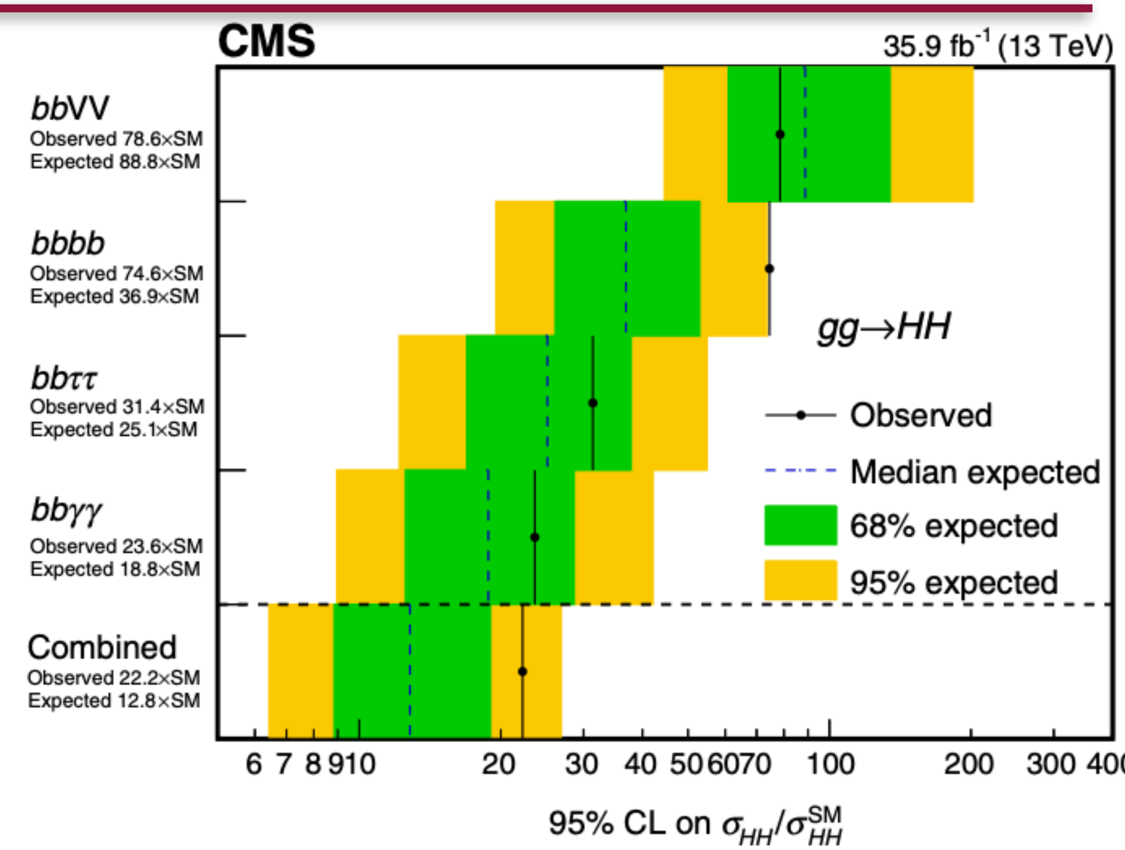
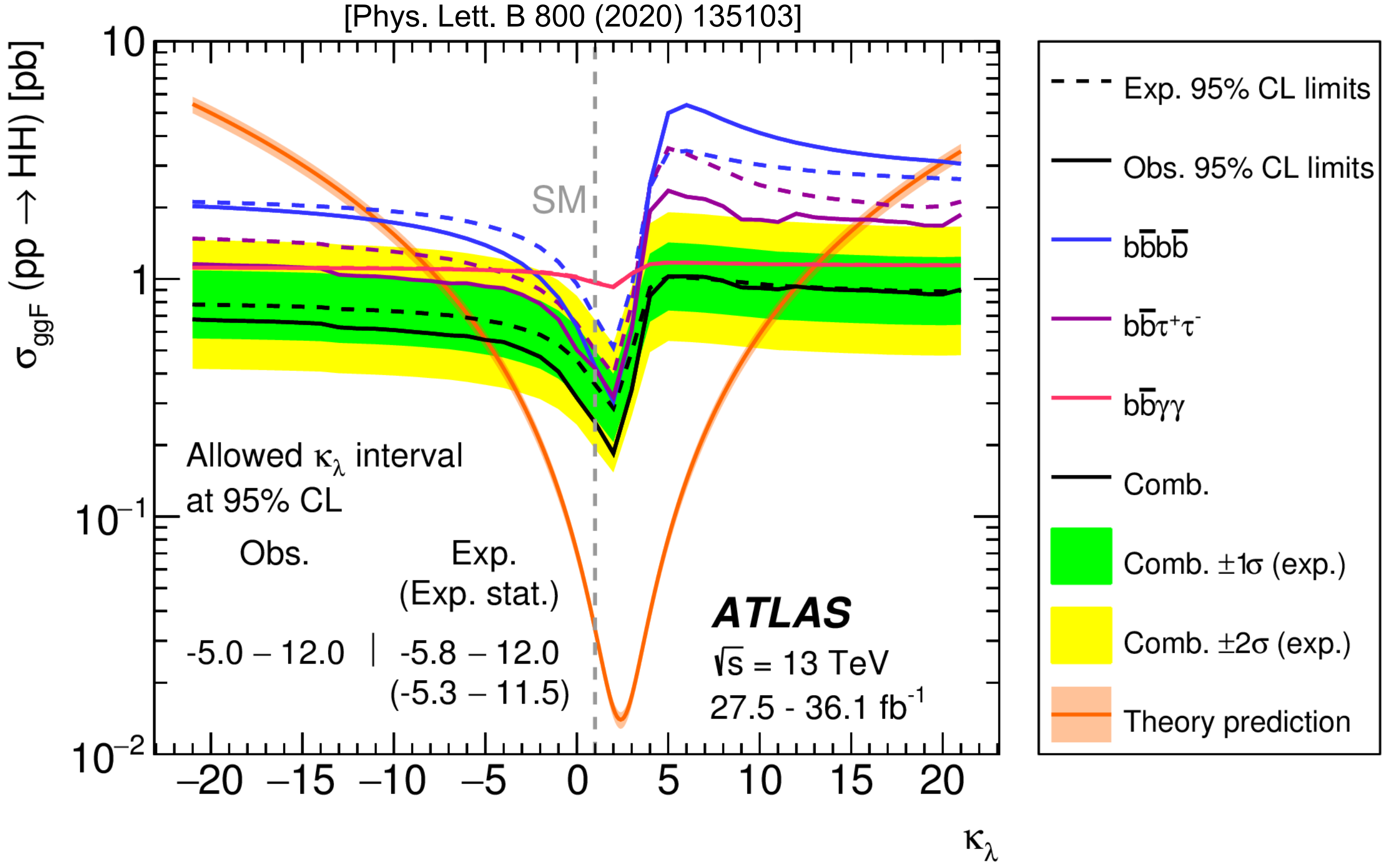
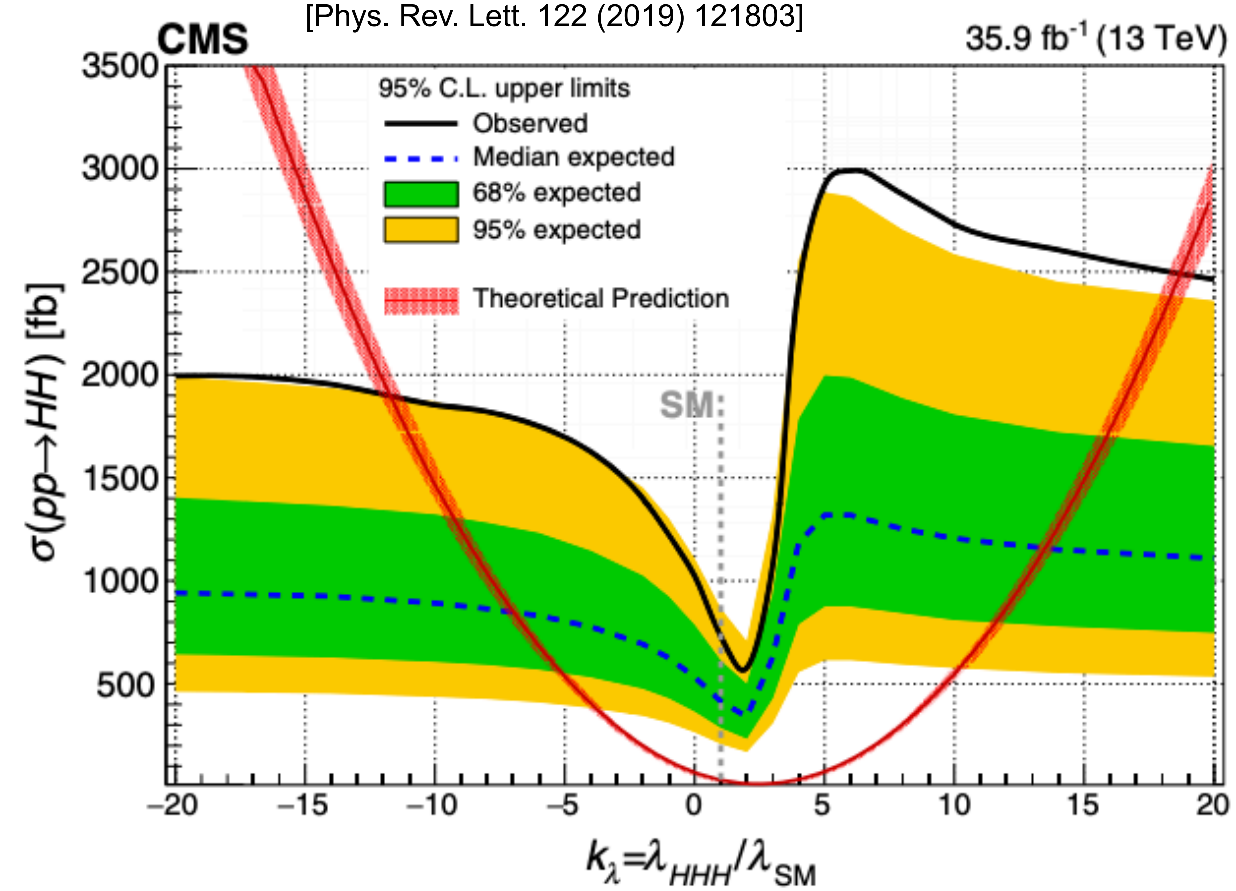




[Phys. Lett. B 800 (2020) 135103]



[Phys. Rev. Lett. 122 (2019) 121803]



European Strategy for Particle Physics

1

Major developments from the 2013 Strategy

A. Since the recommendation in the 2013 Strategy to proceed with the prog of upgrading the luminosity of the LHC, the HL-LHC project, was approved by the CERN Council in June 2016 and is proceeding according to plan. In parallel, the I has reached a centre-of-mass energy of 13 TeV, exceeded the design luminosity, produced a wealth of remarkable physics results. Based on this performance, cou with the innovative experimental techniques developed at the LHC experiments a their planned detector upgrades, a significantly enhanced physics potential is exp with the HL-LHC. The required high-field superconducting Nb_3Sn magnets have been developed. ***The successful completion of the high-luminosity upgrade the machine and detectors should remain the focal point of European partic physics, together with continued innovation in experimental techniques. Th full physics potential of the LHC and the HL-LHC, including the study of flav physics and the quark-gluon plasma, should be exploited.***

B. The existence of non-zero neutrino masses is a compelling sign of new physics. The worldwide neutrino physics programme explores the full scope of th neutrino sector and commands strong support in Europe. Within that programme, Neutrino Platform was established by CERN in response to the recommendation 2013 Strategy and has successfully acted as a hub for European neutrino resear accelerator-based projects outside Europe. ***Europe, and CERN through the Ne Platform, should continue to support long baseline experiments in Japan a United States. In particular, they should continue to collaborate with the Un States and other international partners towards the successful implementa the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neu Experiment (DUNE).***
Experiment (DUNE).

3

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

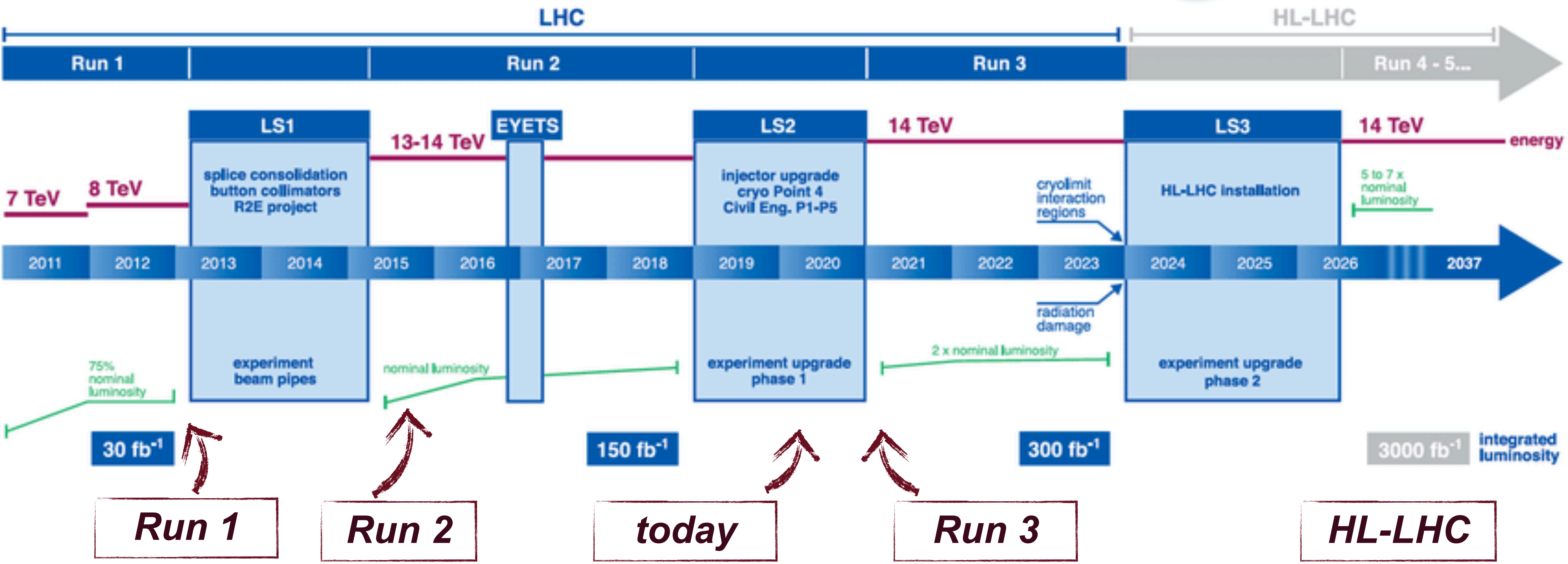
- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

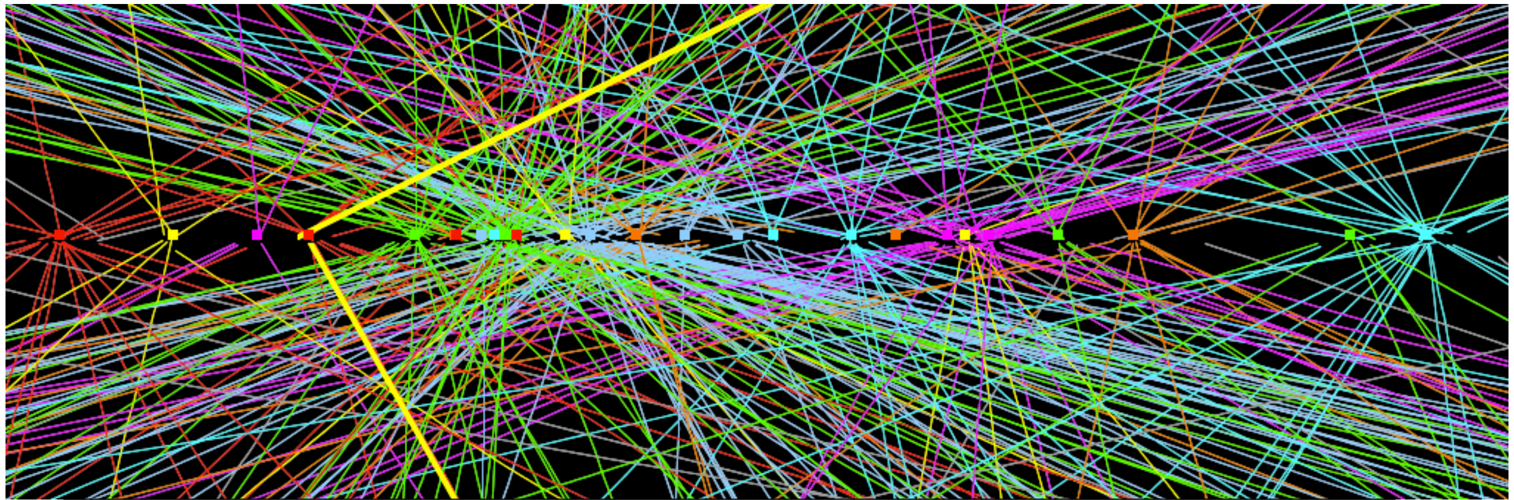
- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

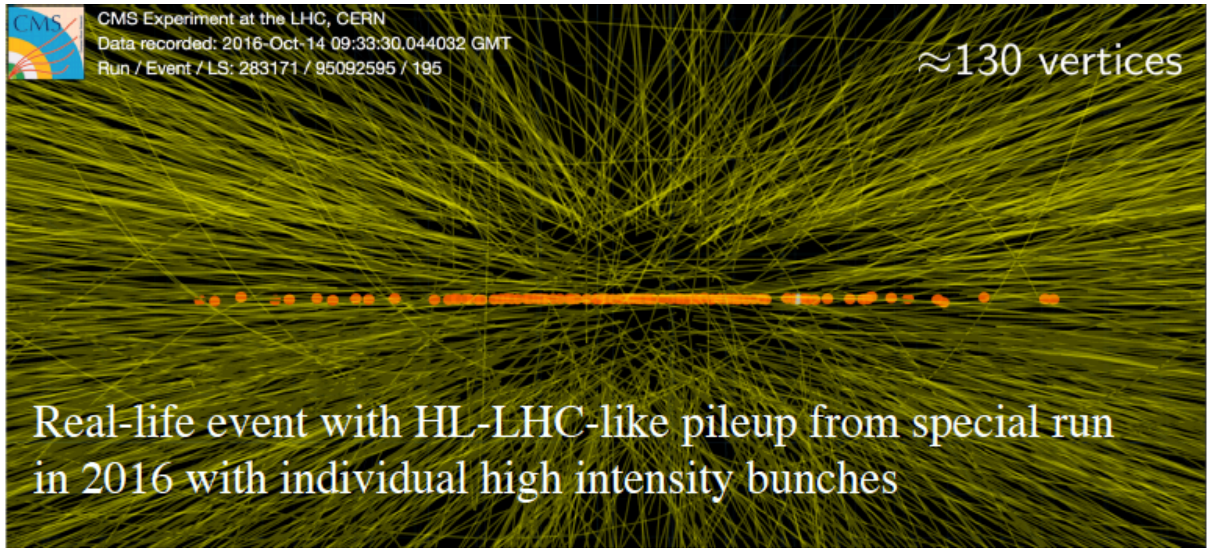
B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

LHC / HL-LHC Plan

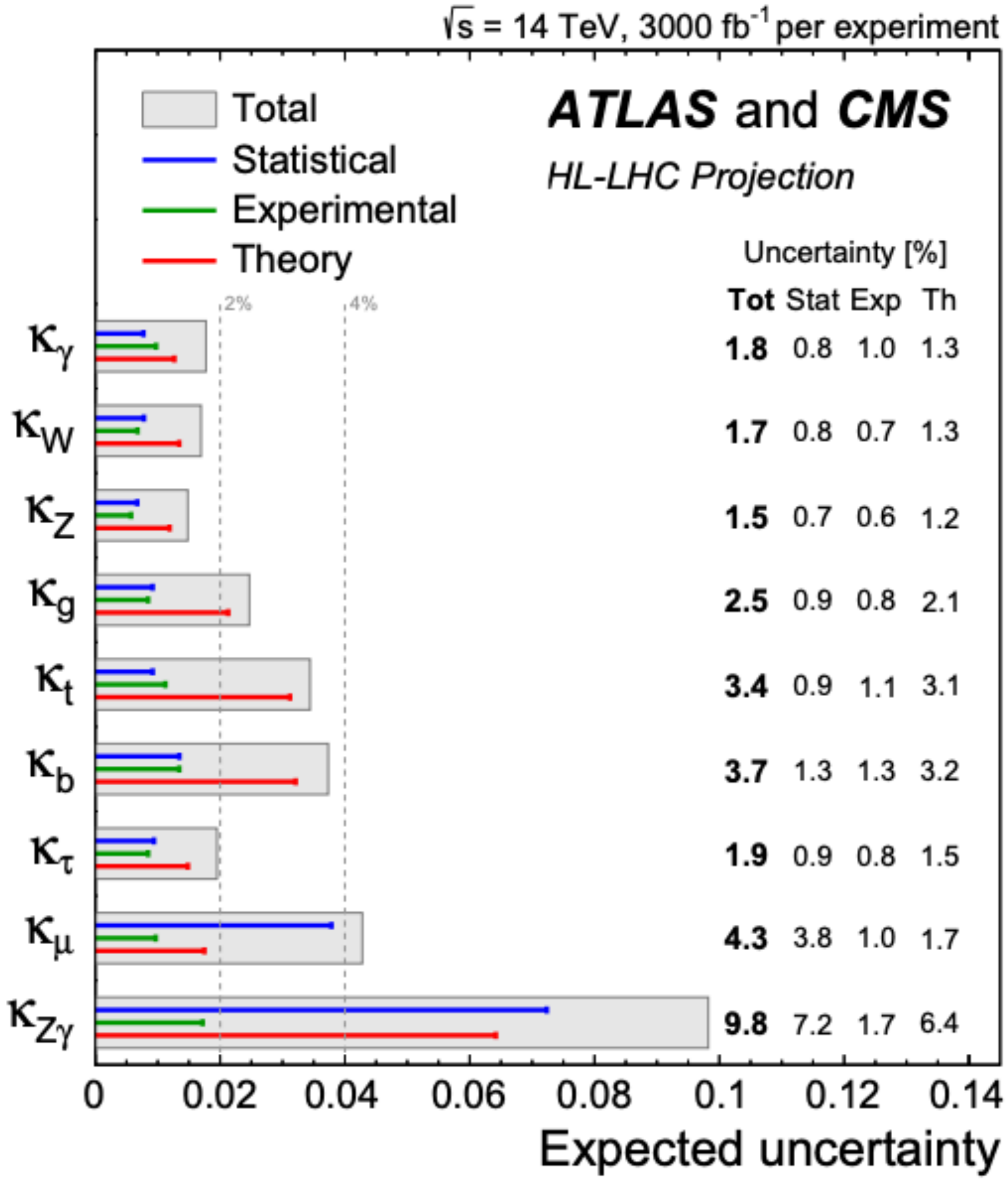




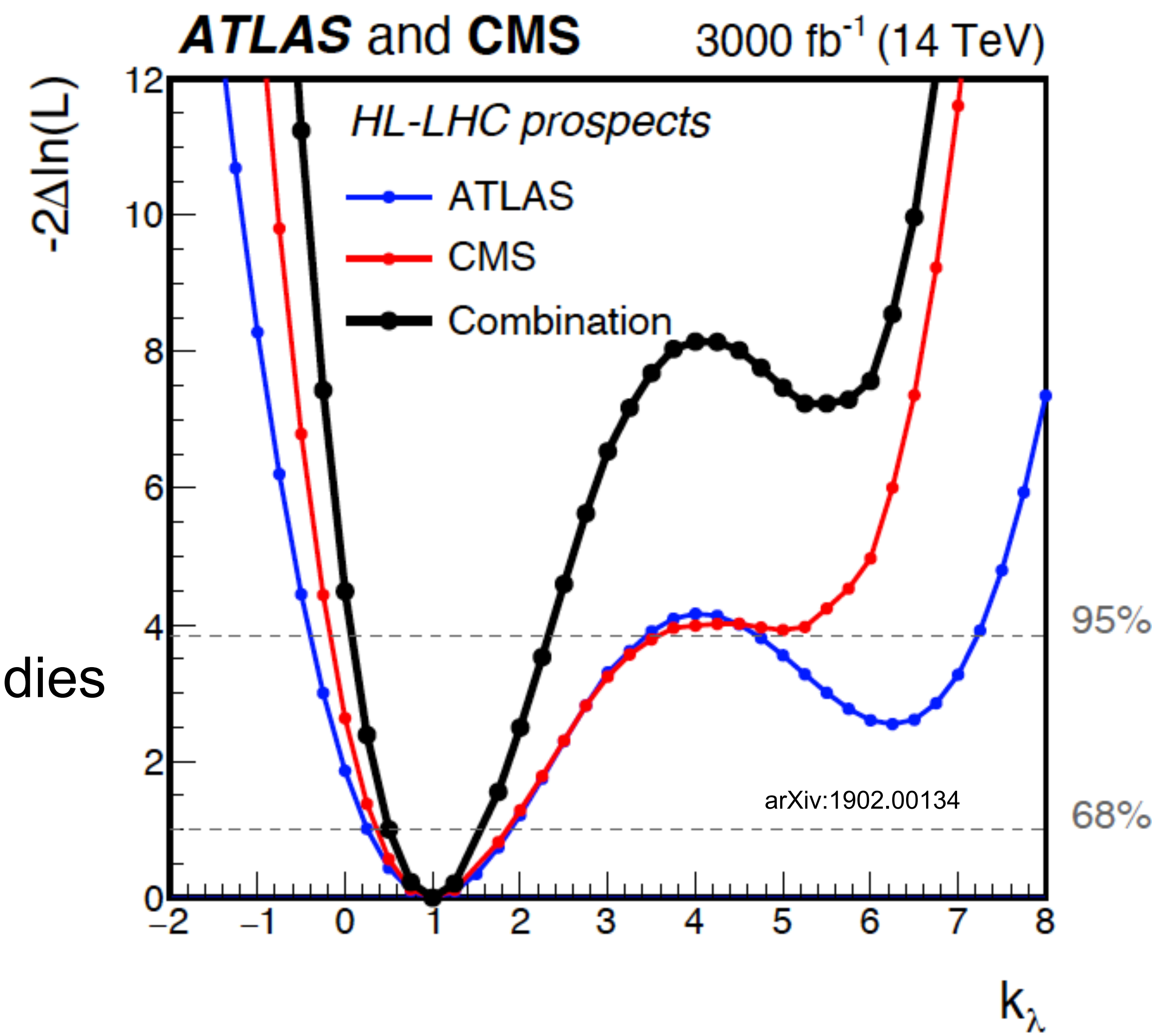
Z→μμ candidate with 25 reconstructed vertices from the 2012 run.
Only good quality tracks with pT>0.4GeV are shown



HL-LHC expected: 250 vertices!



	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

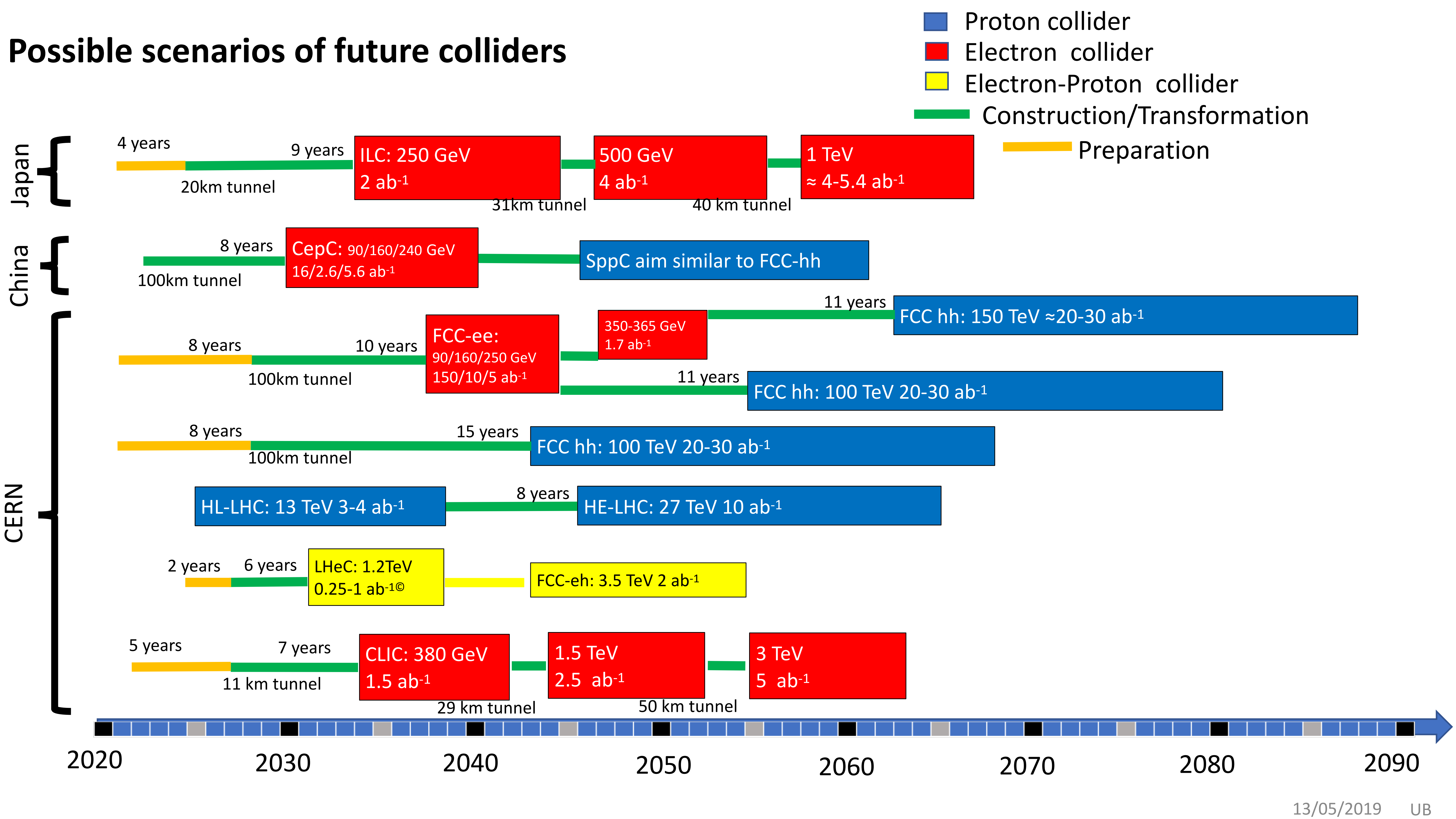


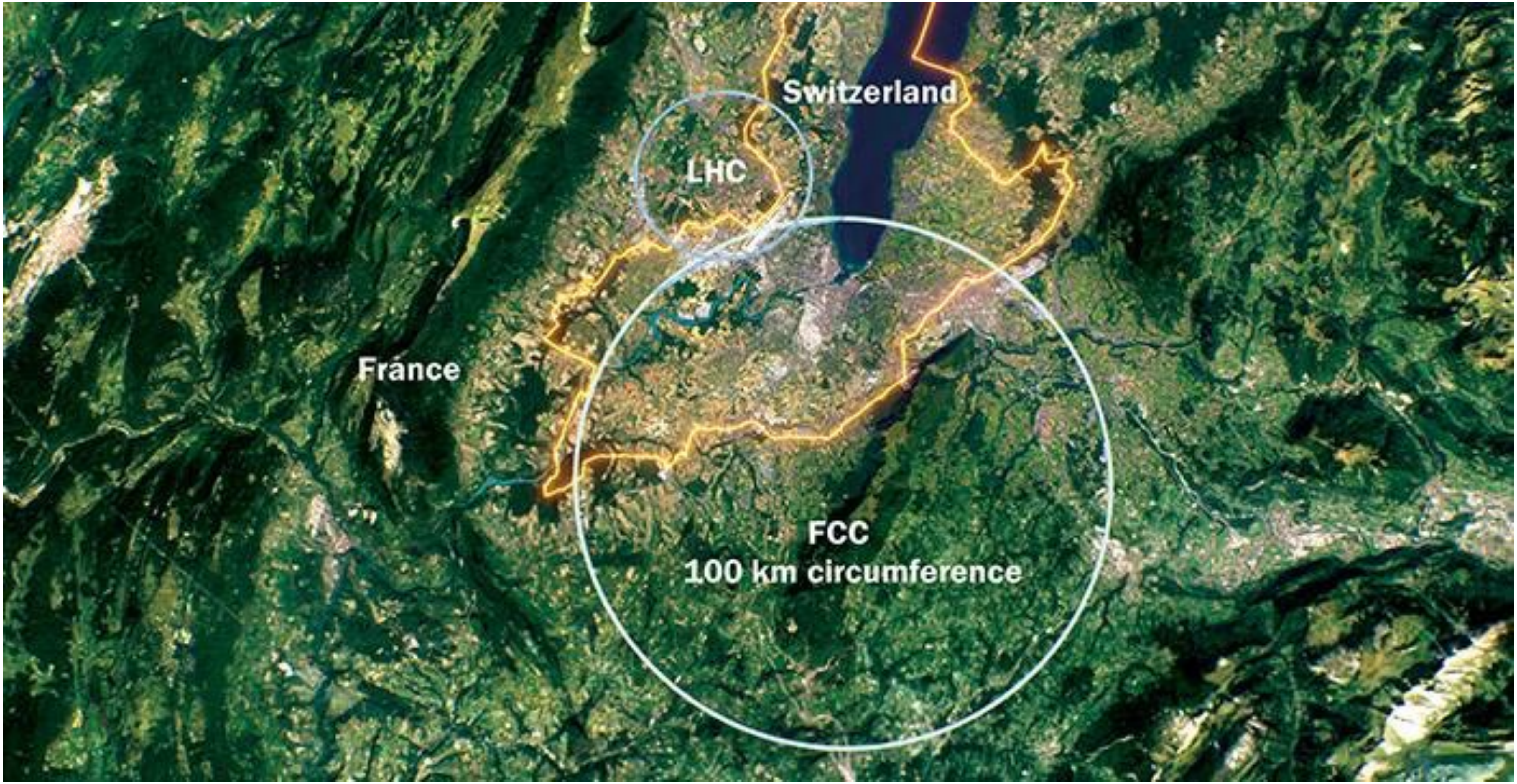
- Significant improvement in couplings studies
  - Also detailed differential cross-section measurements
- Higgs self-coupling
  - 4σ significance against λ=0!
  - $0.1 \le \kappa_\lambda \le 2.3$ at 95%CL

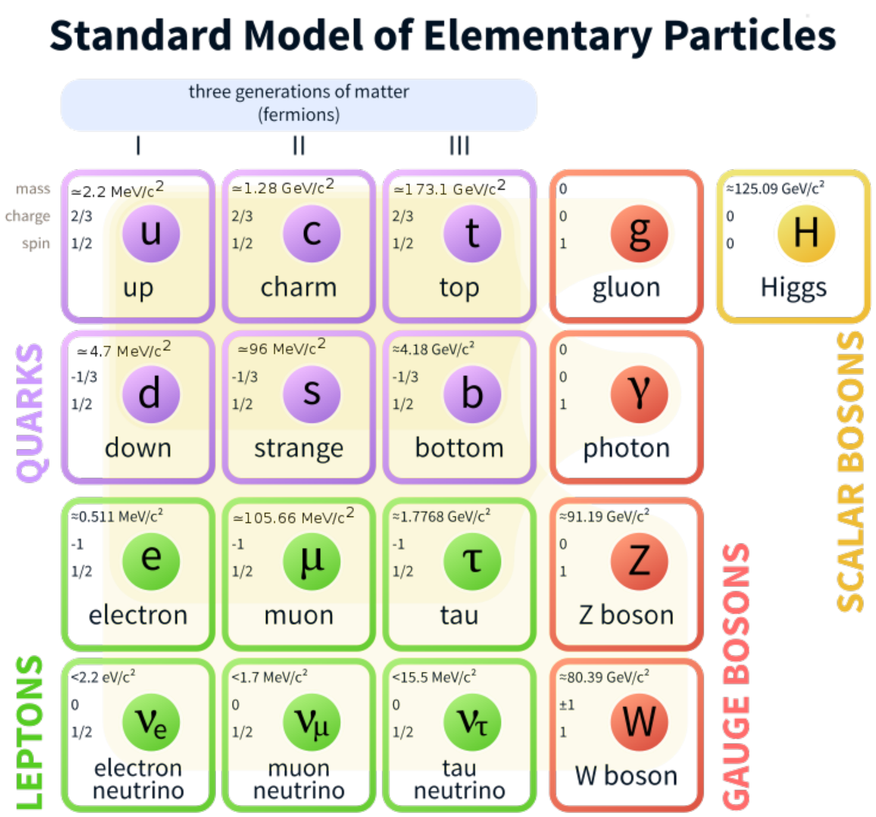

@herrherrmann

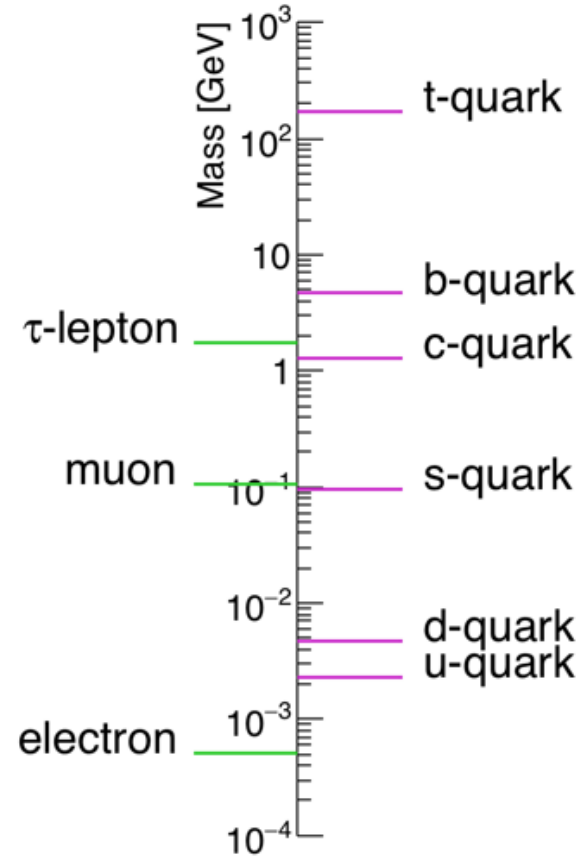
Project	Type	CM Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6	2+1	149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	0.060 e / 7 p	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

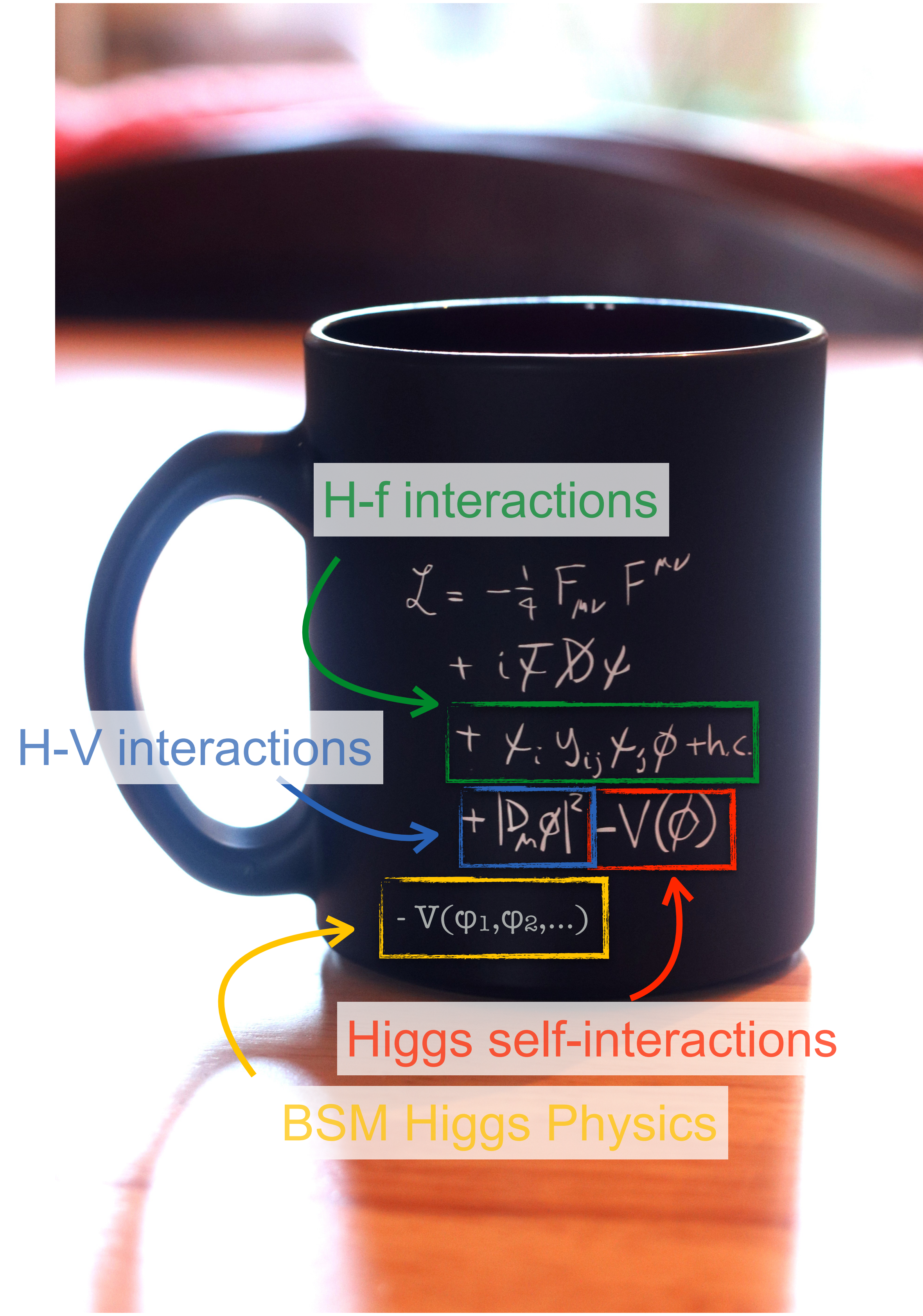
Possible scenarios of future colliders

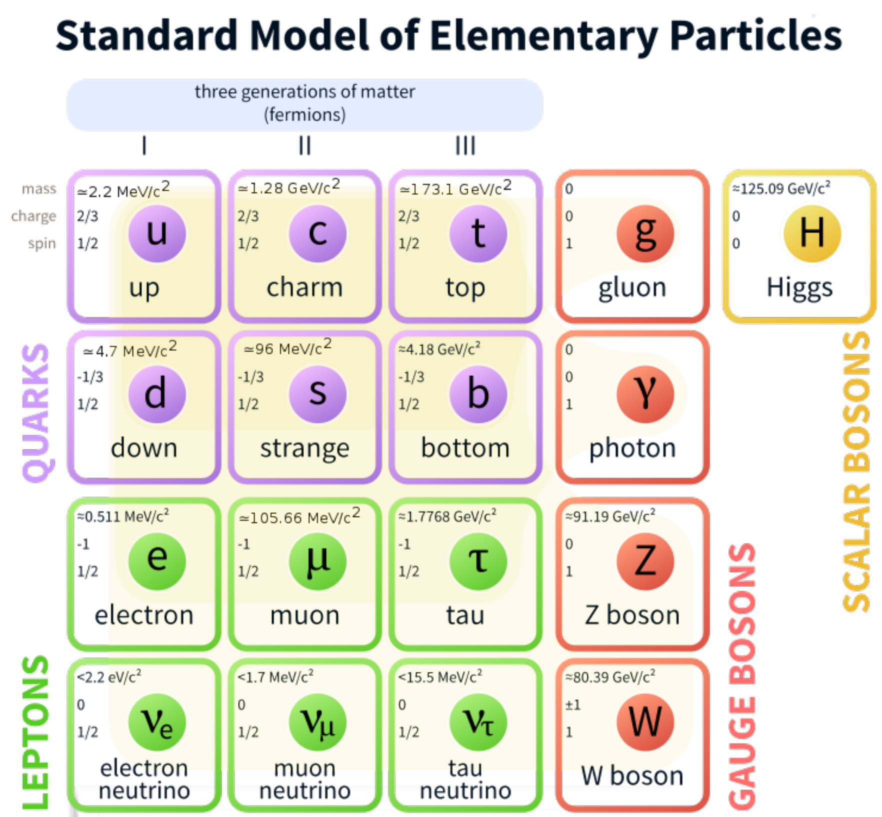



Switzerland
LHC
France
FCC
100 km circumference


Standard Model of Elementary Particles
three generations of matter (fermions)
I
II
III
mass
charge
spin
≃2.2 MeV/c²
2/3
1/2
u
up
≃1.28 GeV/c²
2/3
1/2
c
charm
≃173.1 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≃125.09 GeV/c²
0
0
H
Higgs
≃4.7 MeV/c²
-1/3
1/2
d
down
≃96 MeV/c²
-1/3
1/2
s
strange
≃4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
≃0.511 MeV/c²
-1
1/2
e
electron
≃105.66 MeV/c²
-1
1/2
μ
muon
≃1.7768 GeV/c²
-1
1/2
τ
tau
≃91.19 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<1.7 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
≃80.39 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
SCALAR BOSONS


Mass [GeV]
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
t-quark
b-quark
c-quark
s-quark
d-quark
u-quark
τ-lepton
muon
electron


H-f interactions
H-V interactions
Higgs self-interactions
BSM Higgs Physics
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
$- V(\varphi_1, \varphi_2, \ldots)$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top
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≃96 MeV/c²
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≃4.18 GeV/c²
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-1
1/2
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tau
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Z
Z boson
<2.2 eV/c²
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1/2
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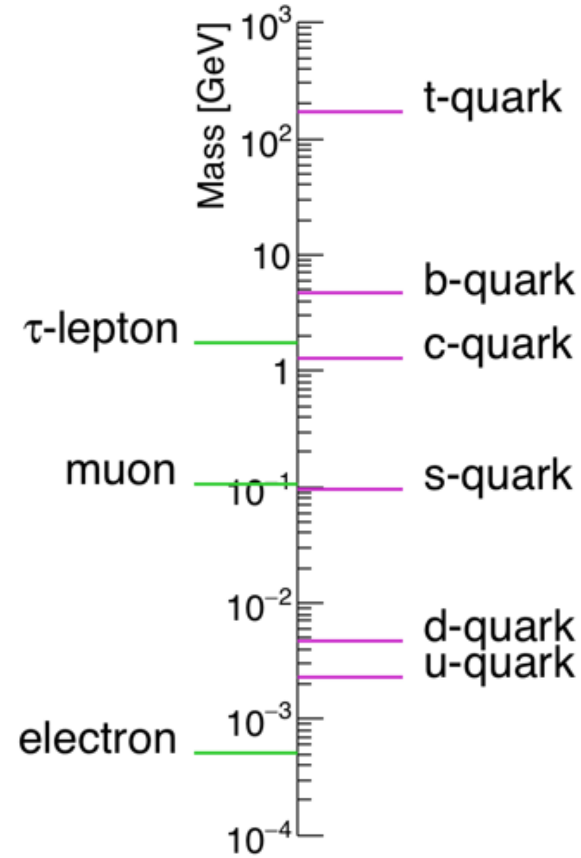
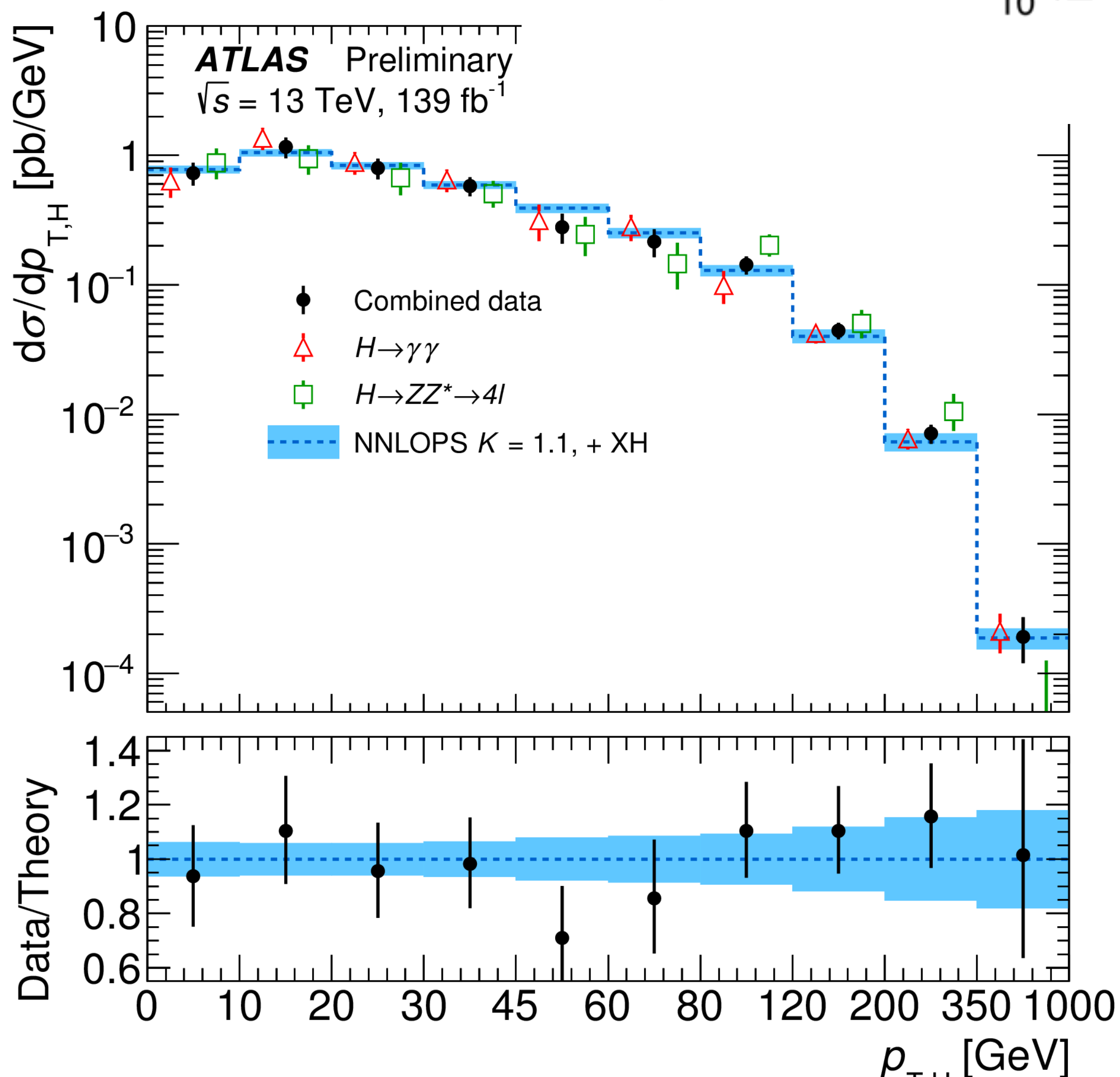
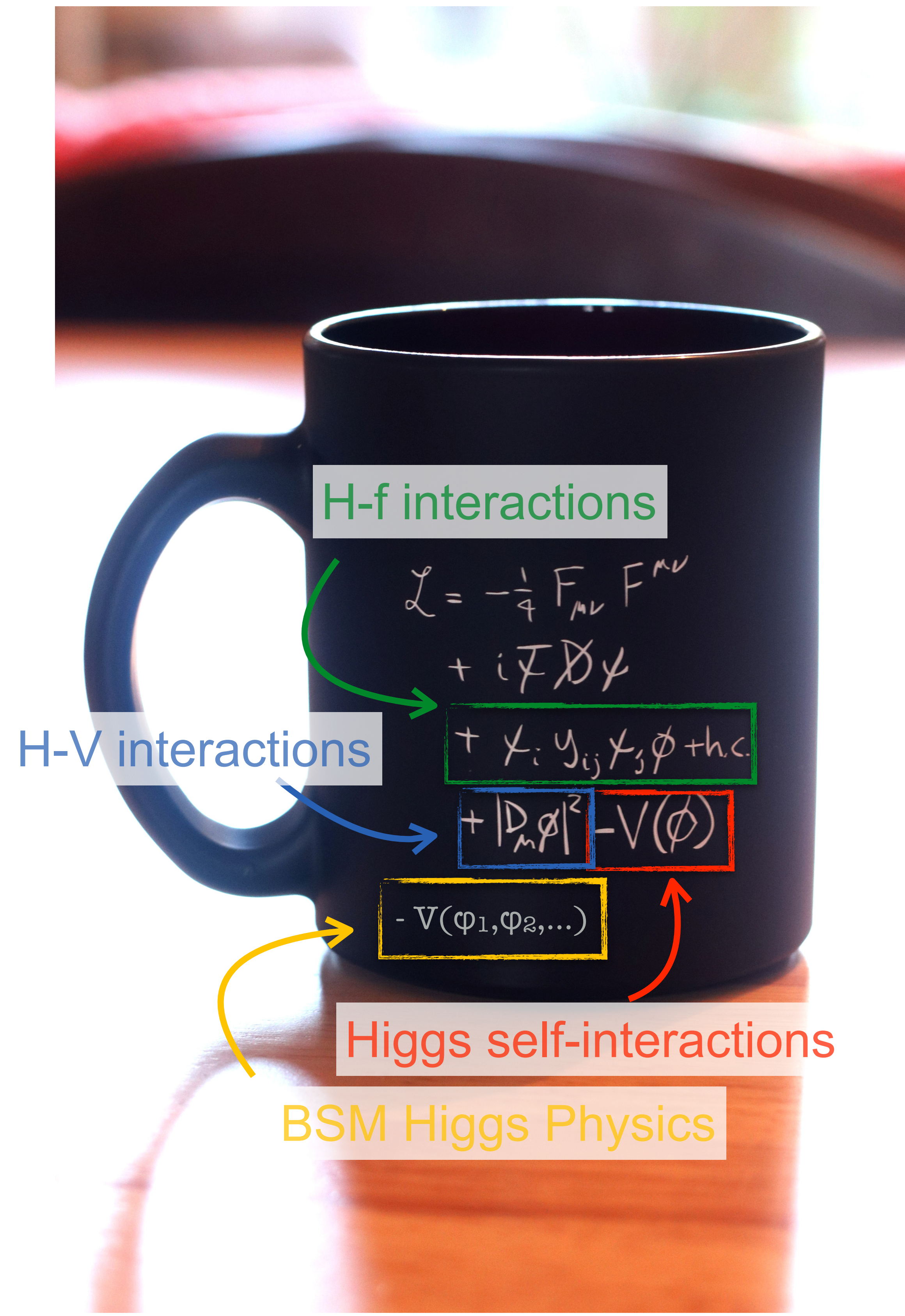
W boson
QUARKS
LEPTONS
GAUGE BOSONS
SCALAR BOSONS


Mass [GeV]
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
t-quark
b-quark
c-quark
s-quark
d-quark
u-quark
τ-lepton
muon
electron


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
$d\sigma/dp_{T,H}$ [pb/GeV]
Combined data
$H\to\gamma\gamma$
$H\to ZZ^*\to 4l$
NNLOPS K = 1.1, + XH
Data/Theory
0 10 20 30 45 60 80 120 200 350 1000
$p_{T,H}$ [GeV]


H-f interactions
H-V interactions
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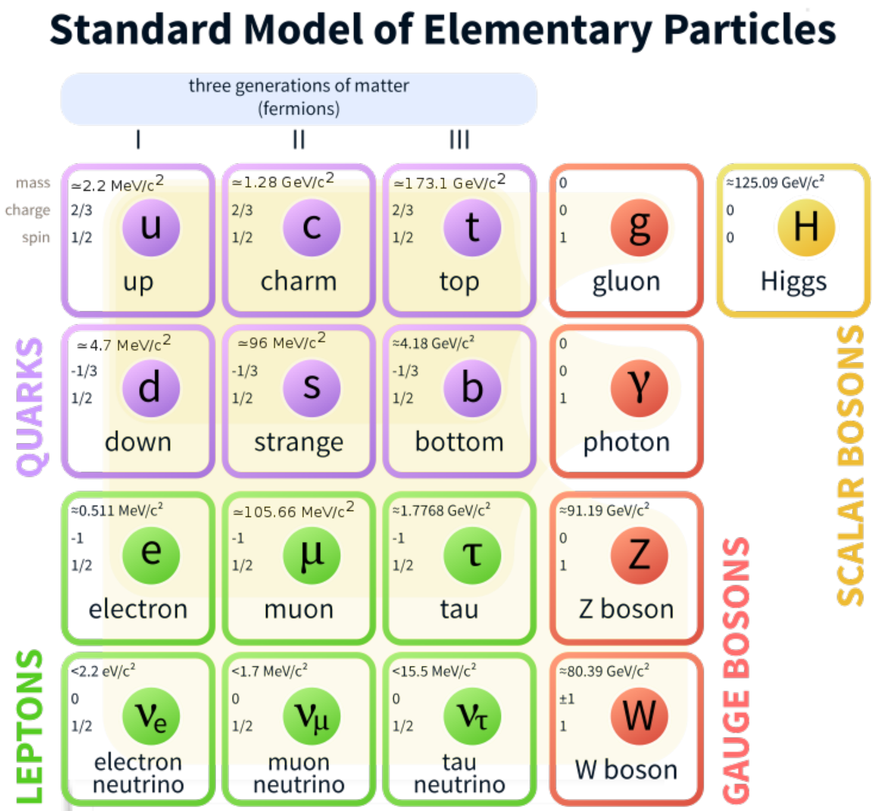
$+ i\bar{\psi} \not{D} \psi$
$+ \chi_i y_{ij} \chi_j \phi + h.c.$
$+ |D_\mu \phi|^2$
$- V(\phi)$
$- V(\varphi_1, \varphi_2, \ldots)$
Higgs self-interactions
BSM Higgs Physics



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t
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Z boson
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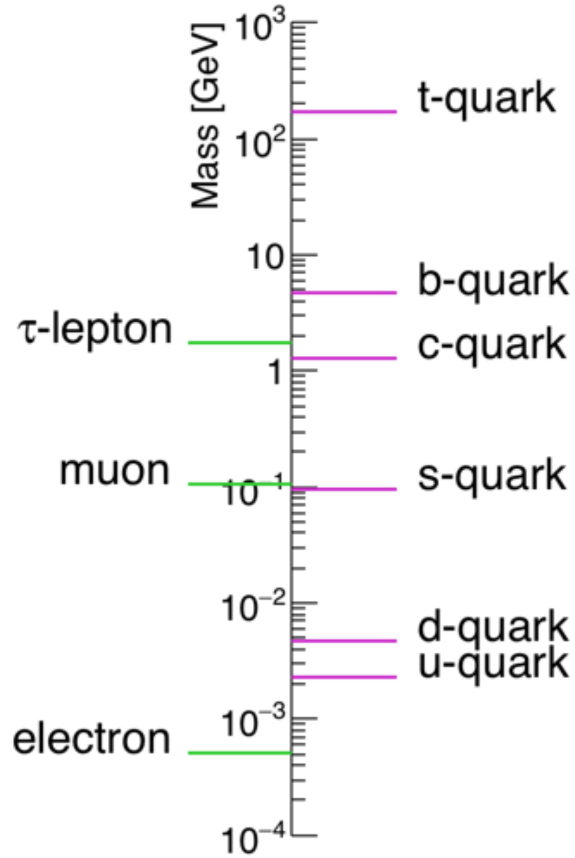
QUARKS
LEPTONS
GAUGE BOSONS
SCALAR BOSONS



Mass [GeV]
10³
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10
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10⁻¹
10⁻²
10⁻³
10⁻⁴
t-quark
b-quark
c-quark
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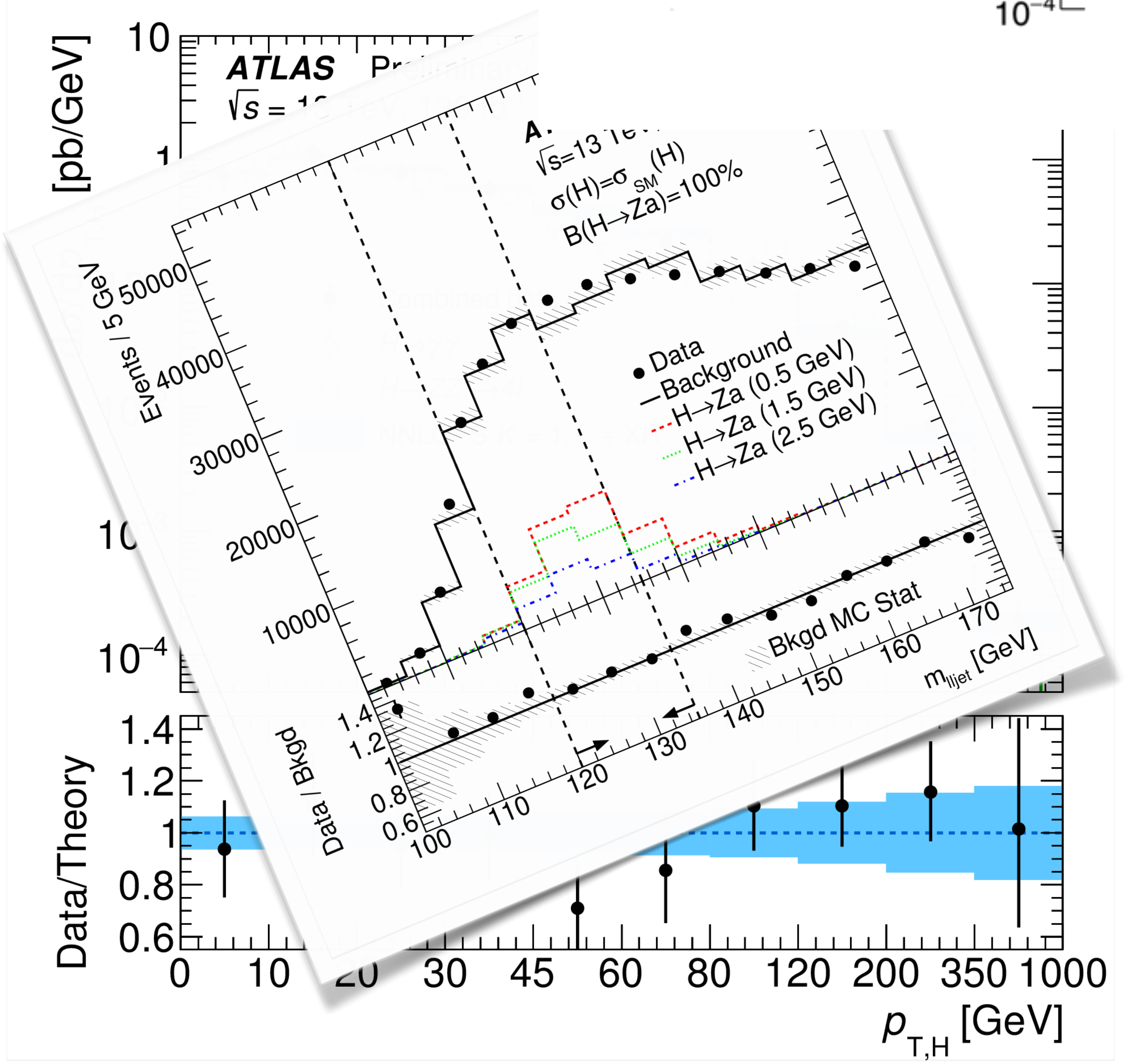
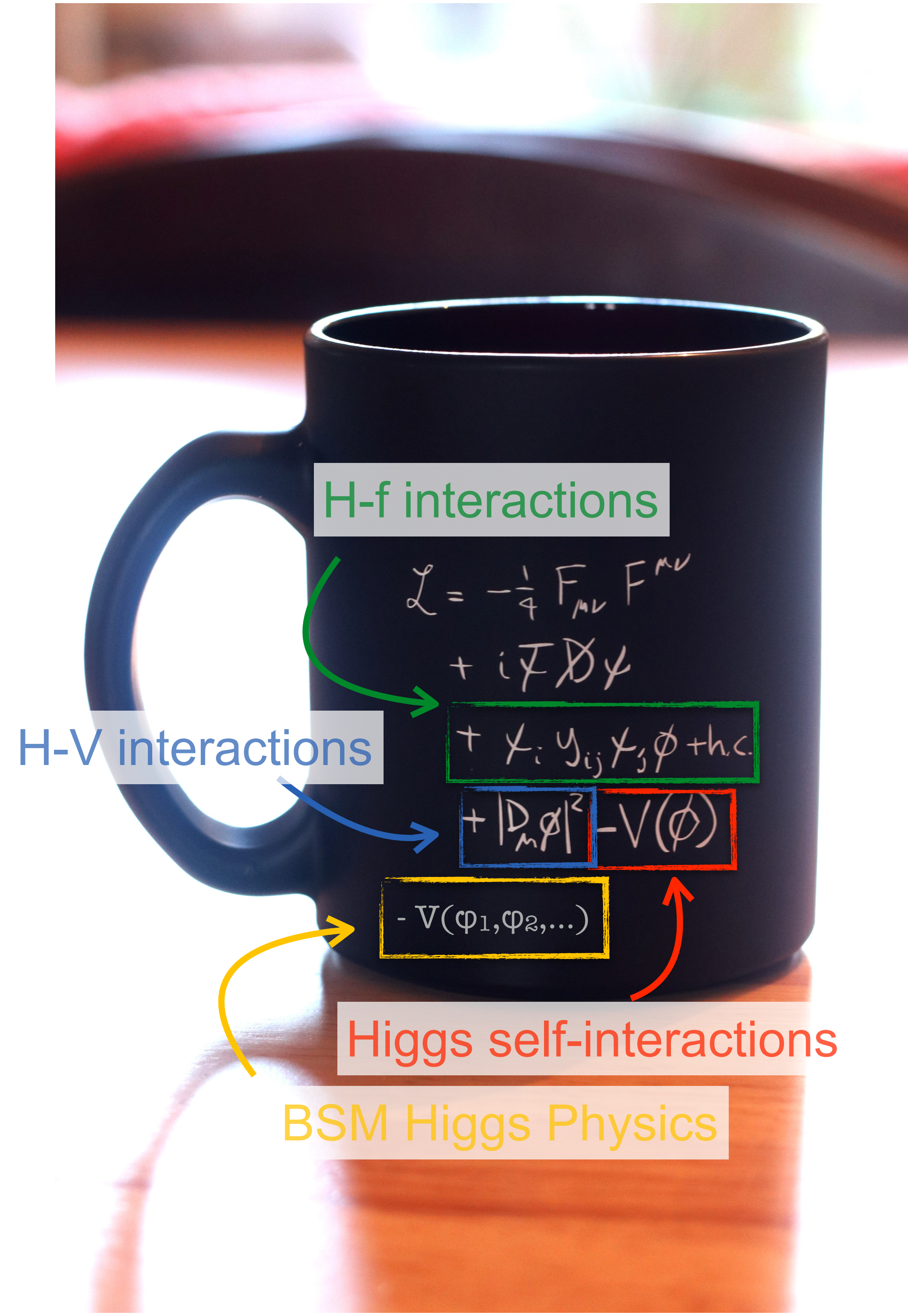
τ-lepton
muon
electron



[pb/GeV]
ATLAS
√s = 13 TeV
σ(H)=σ_SM(H)
B(H→Za)=100%
Events / 5 GeV
Data
Background
H→Za (0.5 GeV)
H→Za (1.5 GeV)
H→Za (2.5 GeV)
Bkgd MC Stat
Data / Bkgd
m_llljet [GeV]
Data/Theory
p_T,H [GeV]



H-f interactions
H-V interactions
Higgs self-interactions
BSM Higgs Physics
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
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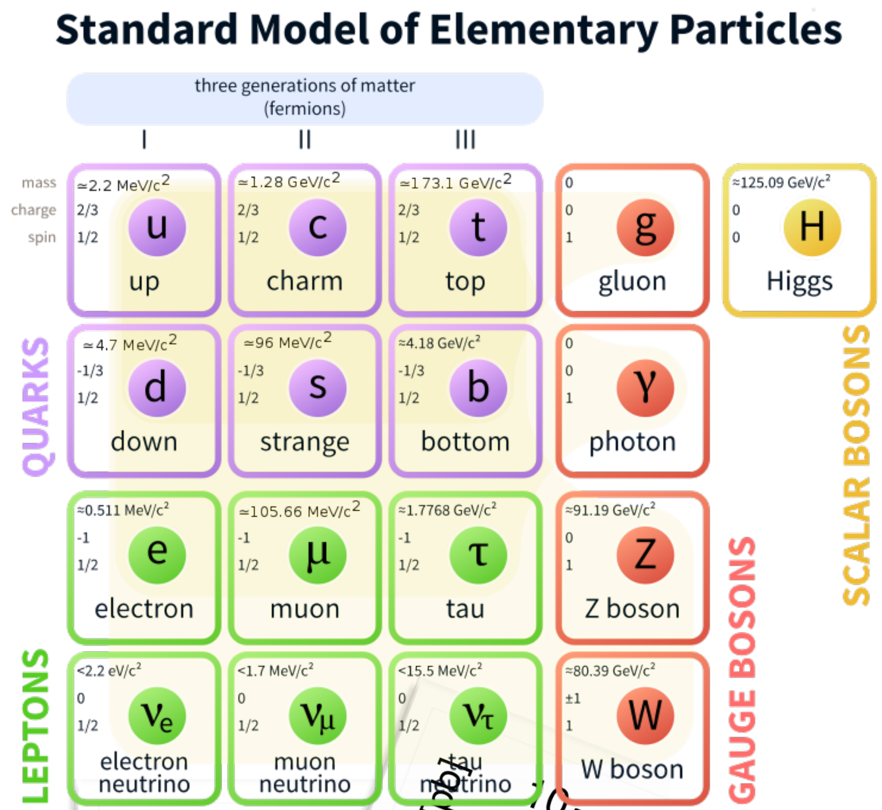
$+ |D_\mu \phi|^2 - V(\phi)$
$- V(\varphi_1, \varphi_2, \ldots)$


Standard Model of Elementary Particles
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c
charm
≈173.1 GeV/c²
t
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g
gluon
≈125.09 GeV/c²
H
Higgs
≈4.7 MeV/c²
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d
down
≈96 MeV/c²
s
strange
≈4.18 GeV/c²
b
bottom
γ
photon
≈0.511 MeV/c²
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≈105.66 MeV/c²
μ
muon
≈1.7768 GeV/c²
τ
tau
≈91.19 GeV/c²
Z
Z boson
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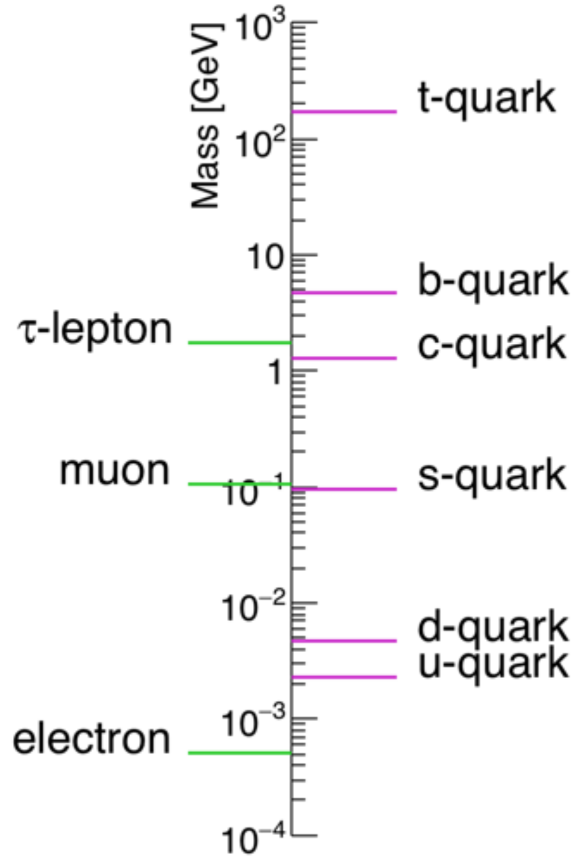
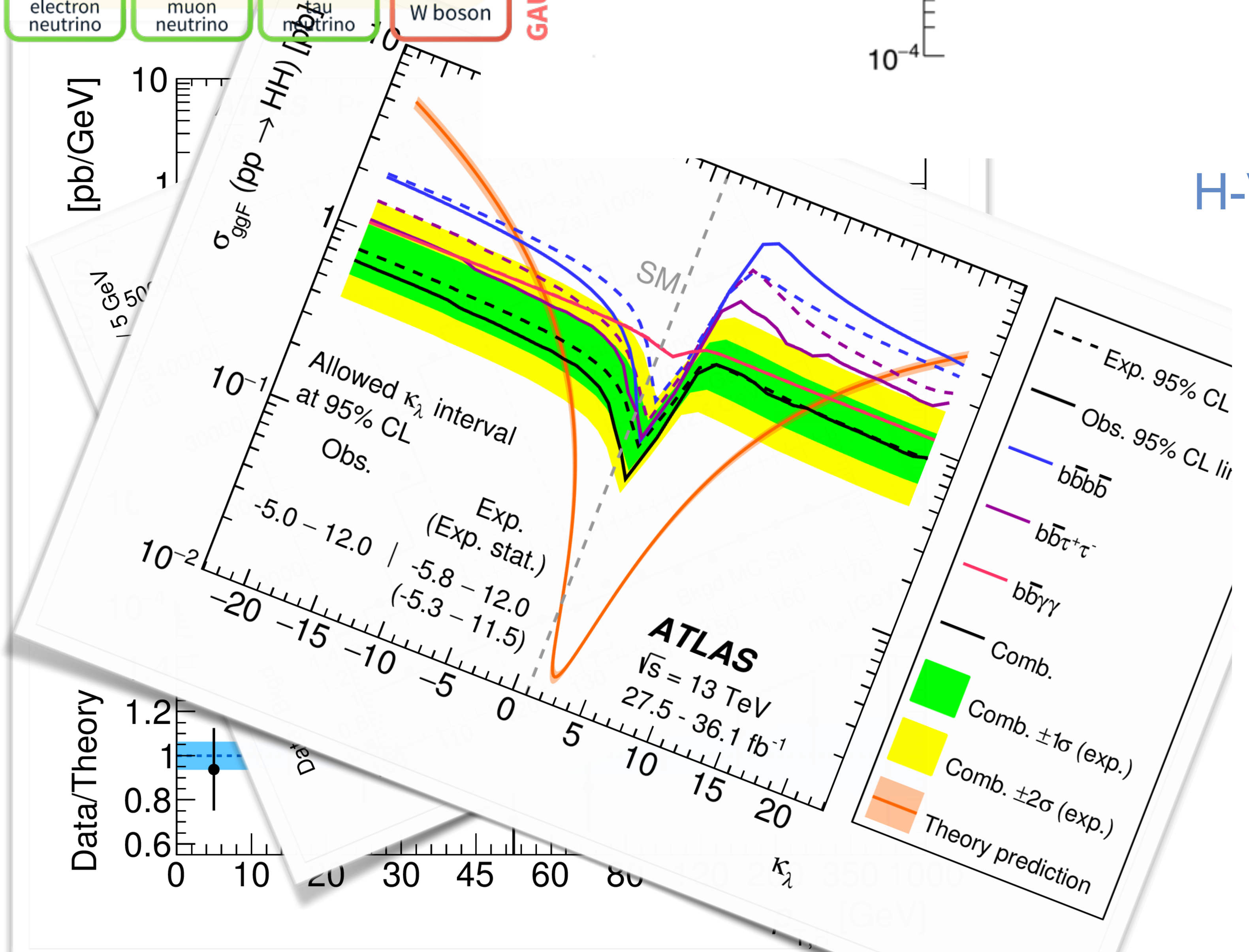
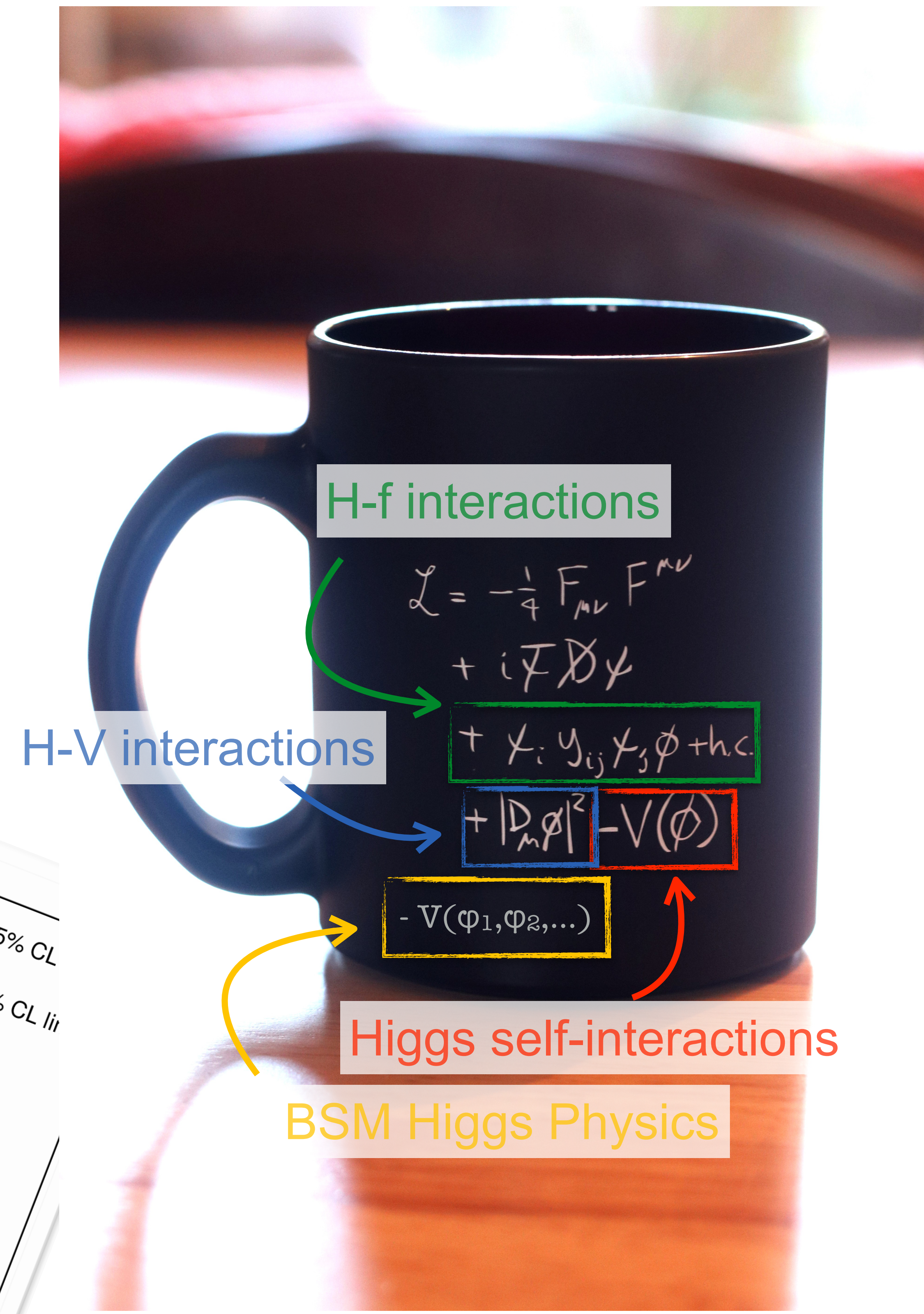
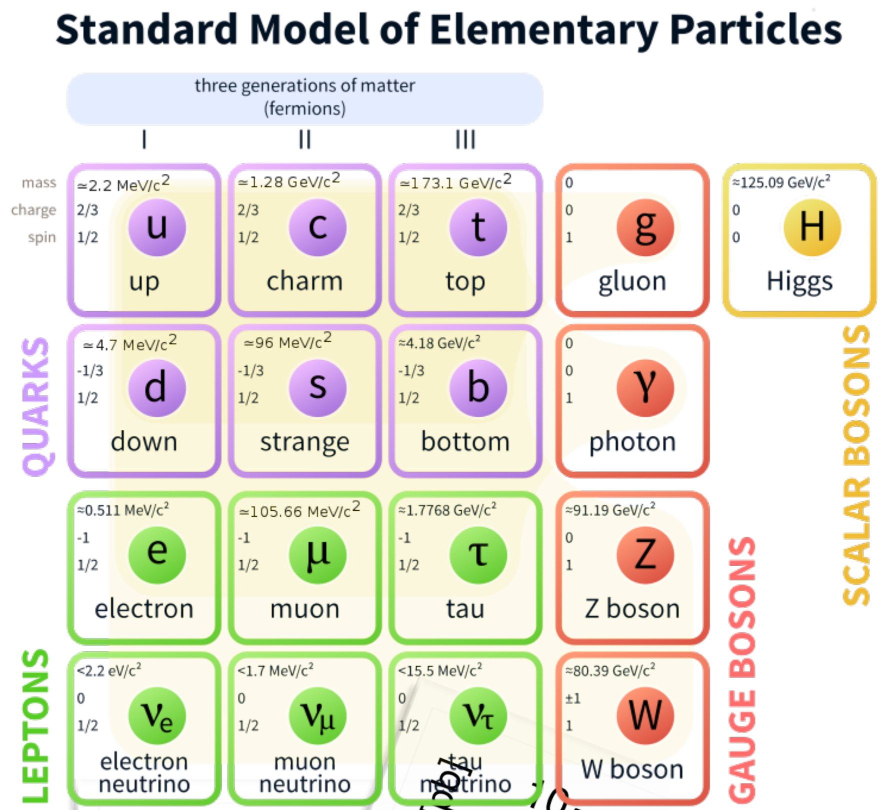
νμ
muon neutrino
<15.5 MeV/c²
ντ
tau neutrino
≈80.39 GeV/c²
±1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
SCALAR BOSONS


Mass [GeV]
t-quark
b-quark
c-quark
τ-lepton
muon
s-quark
d-quark
u-quark
electron


σggF (pp → HH) [pb]
SM
Allowed κλ interval at 95% CL
Obs.
Exp.
(Exp. stat.)
-5.0 – 12.0
-5.8 – 12.0
(-5.3 – 11.5)
ATLAS
√s = 13 TeV
27.5 - 36.1 fb⁻¹
κλ
Exp. 95% CL
Obs. 95% CL
bb̄bb̄
bb̄τ⁺τ⁻
bb̄γγ
Comb.
Comb. ±1σ (exp.)
Comb. ±2σ (exp.)
Theory prediction
[pb/GeV]
Data/Theory


H-f interactions
H-V interactions
Higgs self-interactions
BSM Higgs Physics
- V(φ1,φ2,...)


Standard Model of Elementary Particles
three generations of matter (fermions)
I II III
mass
charge
spin
≈2.2 MeV/c² 2/3 1/2 u up
≈1.28 GeV/c² 2/3 1/2 c charm
≈173.1 GeV/c² 2/3 1/2 t top
0 0 1 g gluon
≈125.09 GeV/c² 0 0 H Higgs
≈4.7 MeV/c² -1/3 1/2 d down
≈96 MeV/c² -1/3 1/2 s strange
≈4.18 GeV/c² -1/3 1/2 b bottom
0 0 1 γ photon
≈0.511 MeV/c² -1 1/2 e electron
≈105.66 MeV/c² -1 1/2 μ muon
≈1.7768 GeV/c² -1 1/2 τ tau
≈91.19 GeV/c² 0 1 Z Z boson
<2.2 eV/c² 0 1/2 νe electron neutrino
<1.7 MeV/c² 0 1/2 νμ muon neutrino
<15.5 MeV/c² 0 1/2 ντ tau neutrino
≈80.39 GeV/c² ±1 1 W W boson
QUARKS
LEPTONS
GAUGE BOSONS
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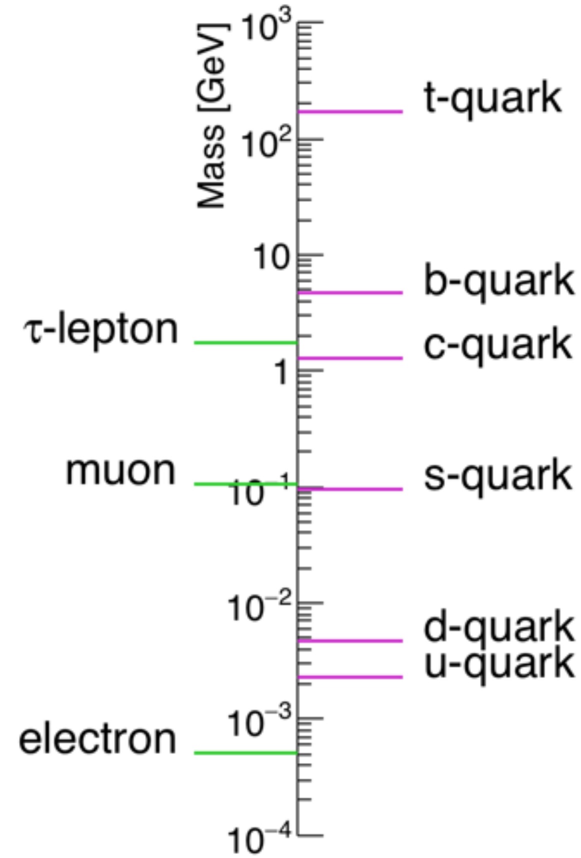
Mass [GeV]
10³
10²
10
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10⁻¹
10⁻²
10⁻³
10⁻⁴
t-quark
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muon
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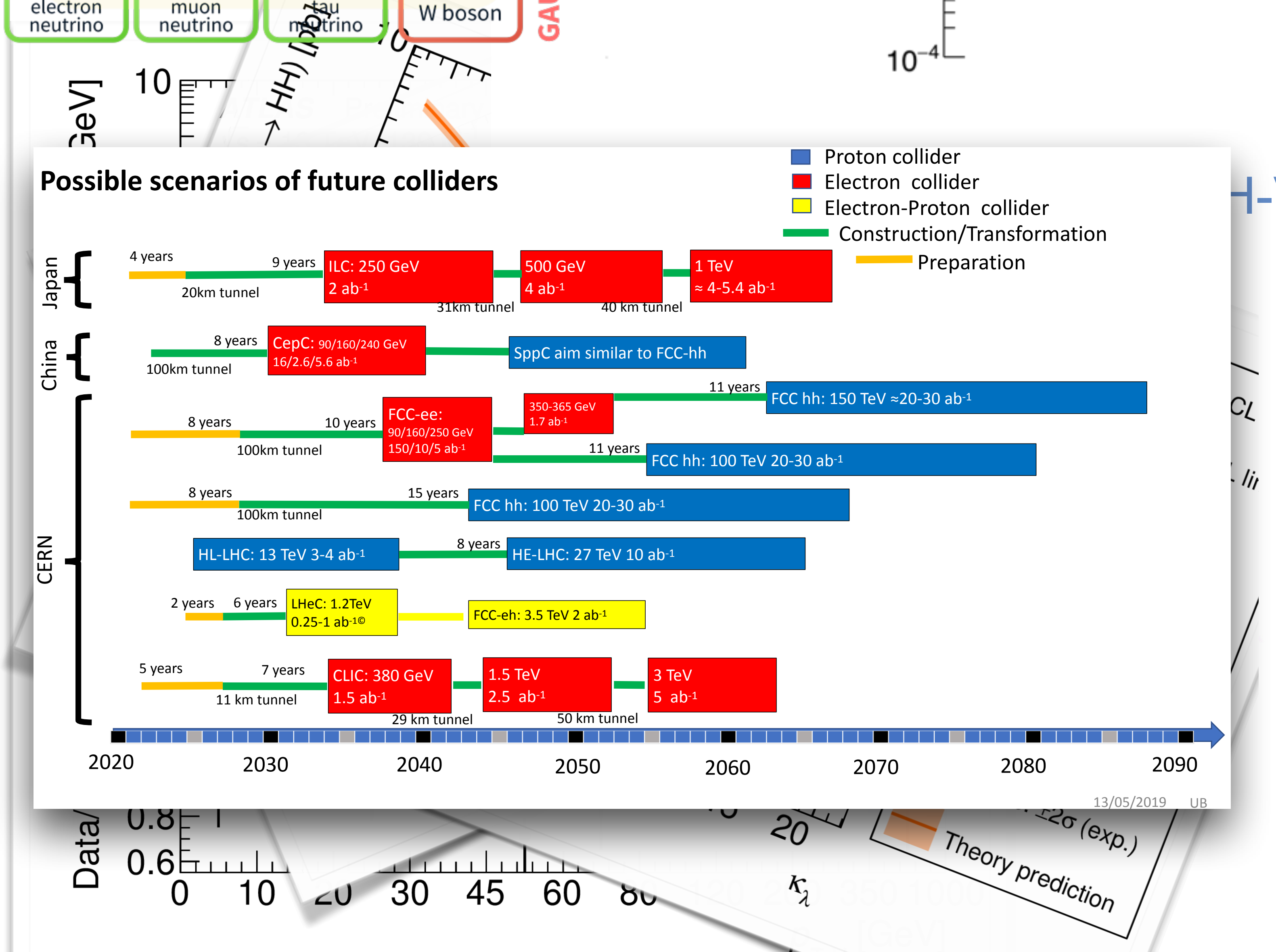
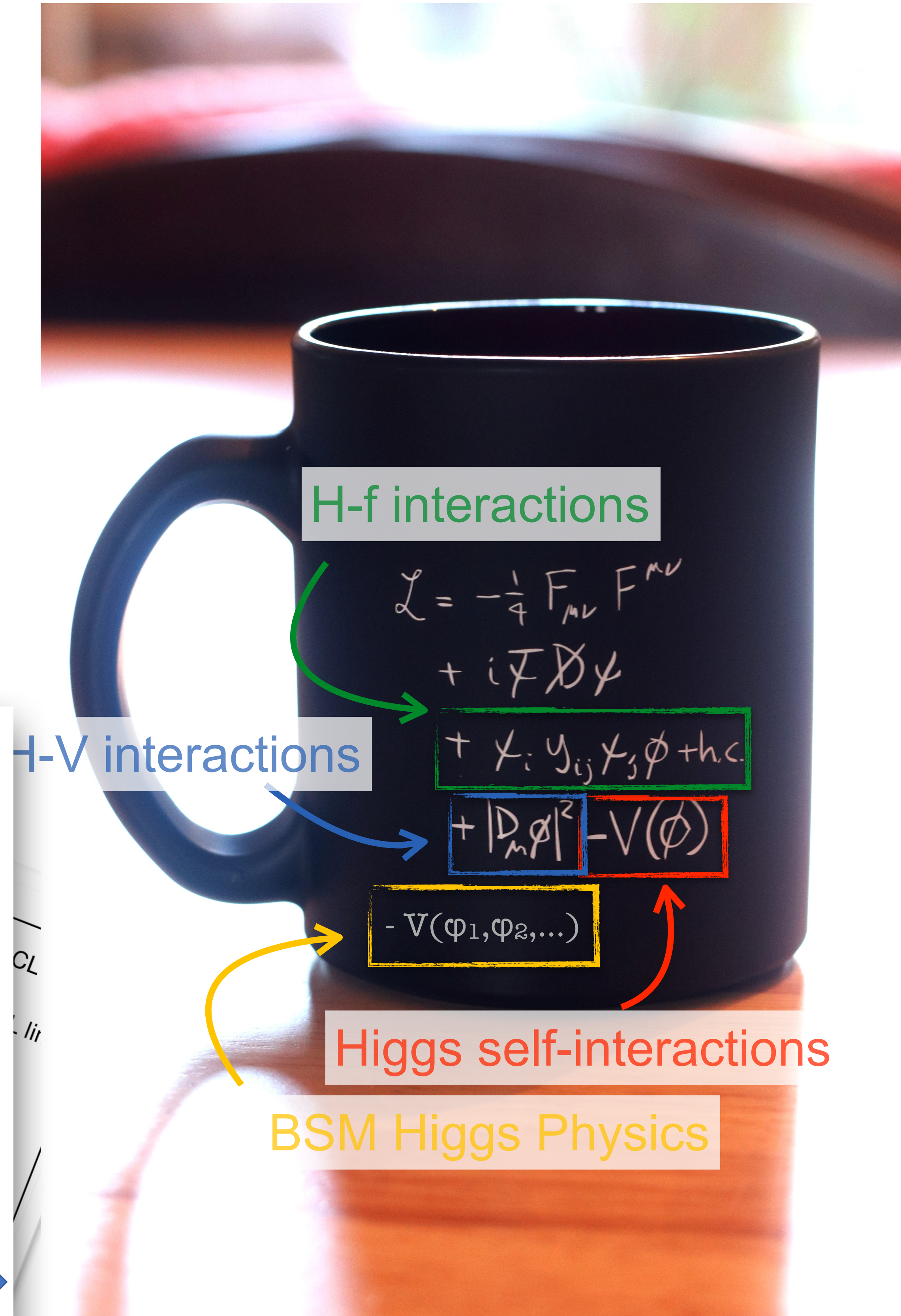

Possible scenarios of future colliders
Proton collider
Electron collider
Electron-Proton collider
Construction/Transformation
Preparation
Japan
China
CERN
4 years
9 years
20km tunnel
ILC: 250 GeV 2 ab⁻¹
31km tunnel
500 GeV 4 ab⁻¹
40 km tunnel
1 TeV ≈ 4-5.4 ab⁻¹
8 years
100km tunnel
CepC: 90/160/240 GeV 16/2.6/5.6 ab⁻¹
SppC aim similar to FCC-hh
8 years
10 years
100km tunnel
FCC-ee: 90/160/250 GeV 150/10/5 ab⁻¹
350-365 GeV 1.7 ab⁻¹
11 years
FCC hh: 150 TeV ≈20-30 ab⁻¹
11 years
FCC hh: 100 TeV 20-30 ab⁻¹
8 years
15 years
100km tunnel
FCC hh: 100 TeV 20-30 ab⁻¹
HL-LHC: 13 TeV 3-4 ab⁻¹
8 years
HE-LHC: 27 TeV 10 ab⁻¹
2 years
6 years
LHeC: 1.2TeV 0.25-1 ab⁻¹
FCC-eh: 3.5 TeV 2 ab⁻¹
5 years
7 years
11 km tunnel
CLIC: 380 GeV 1.5 ab⁻¹
29 km tunnel
1.5 TeV 2.5 ab⁻¹
50 km tunnel
3 TeV 5 ab⁻¹
2020
2030
2040
2050
2060
2070
2080
2090
13/05/2019
UB
Data/
0.8
0.6
0
10
30
45
60
20
Theory prediction
±2σ (exp.)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$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
$- V(\varphi_1, \varphi_2, \ldots)$

Additional Slides

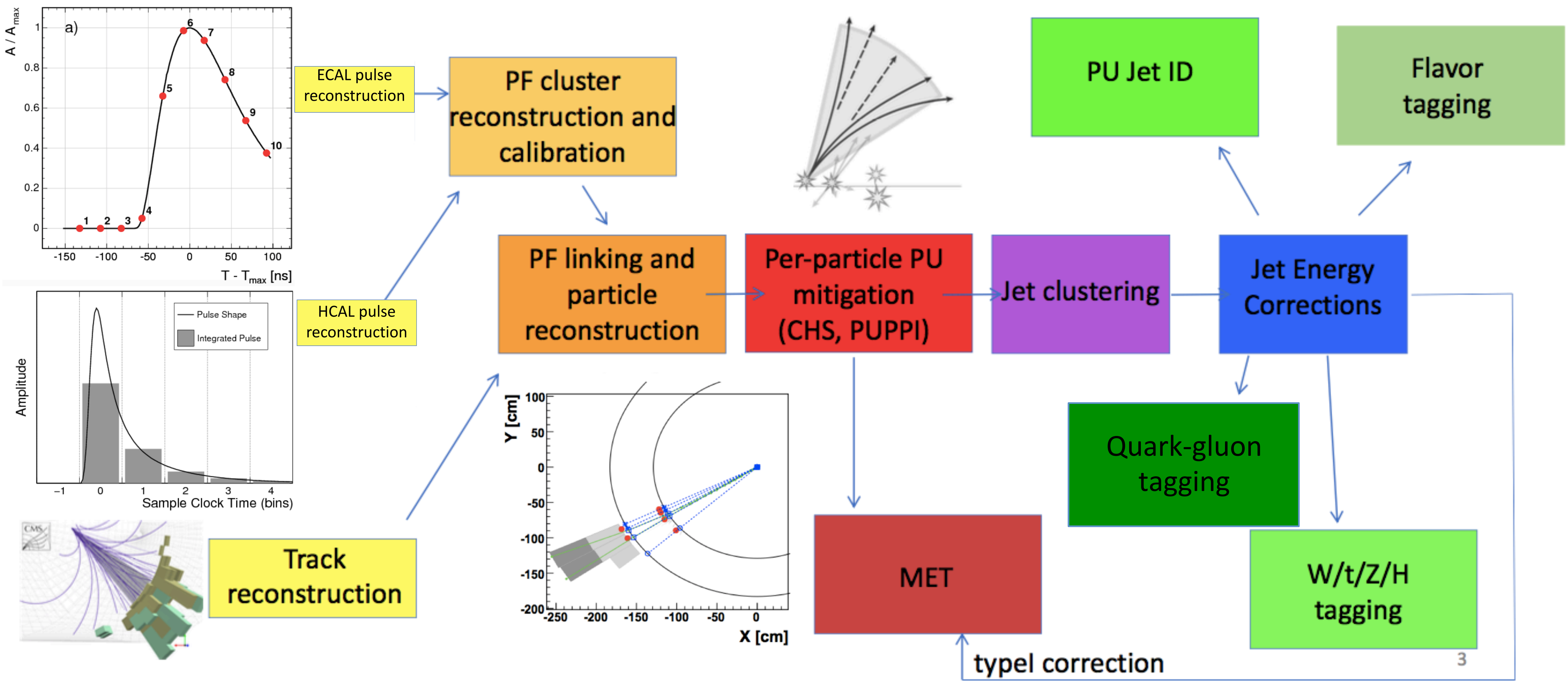
Project	Type	CM Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6	2+1	149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	0.060 e / 7 p	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

D. Schulte Future colliders, LHCP, May 2020 3

	HL-LHC	HE-LHC	FCC-hh	SppC
Cms energy [TeV]	14	27	100	75
Int. L., 2 det. [ab^{-1}]	6	15	30	
Operation [years]	12	20	25	
L [$10^{34}cm^{-2}s^{-1}$]	5	16	20-30	10
Circumference	26.7	26.7	97.75	100
Arc dipole field [T]	8	16	16	12
Bunch dist. [ns]	25	25	25	25
Backgr. events/bx	135	440	<1020	
Bunch length [cm]	7.5	7.5	8	7.55

HE-LHC is not cheap and has similar challenges than FCC-hh
Physics case appears less interesting
Note: "low"-field NbTi magnets in FCC tunnel were looked at, but cost saving is limited, and energy compromised significantly (< 40 TeV)

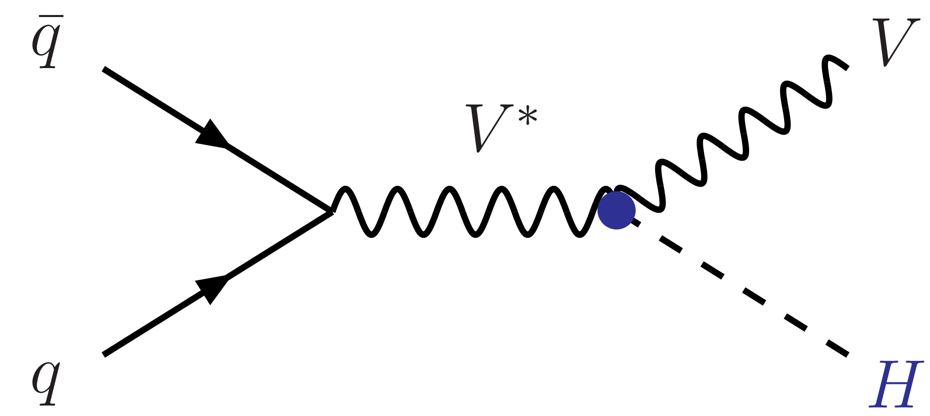
MET reconstruction in CMS



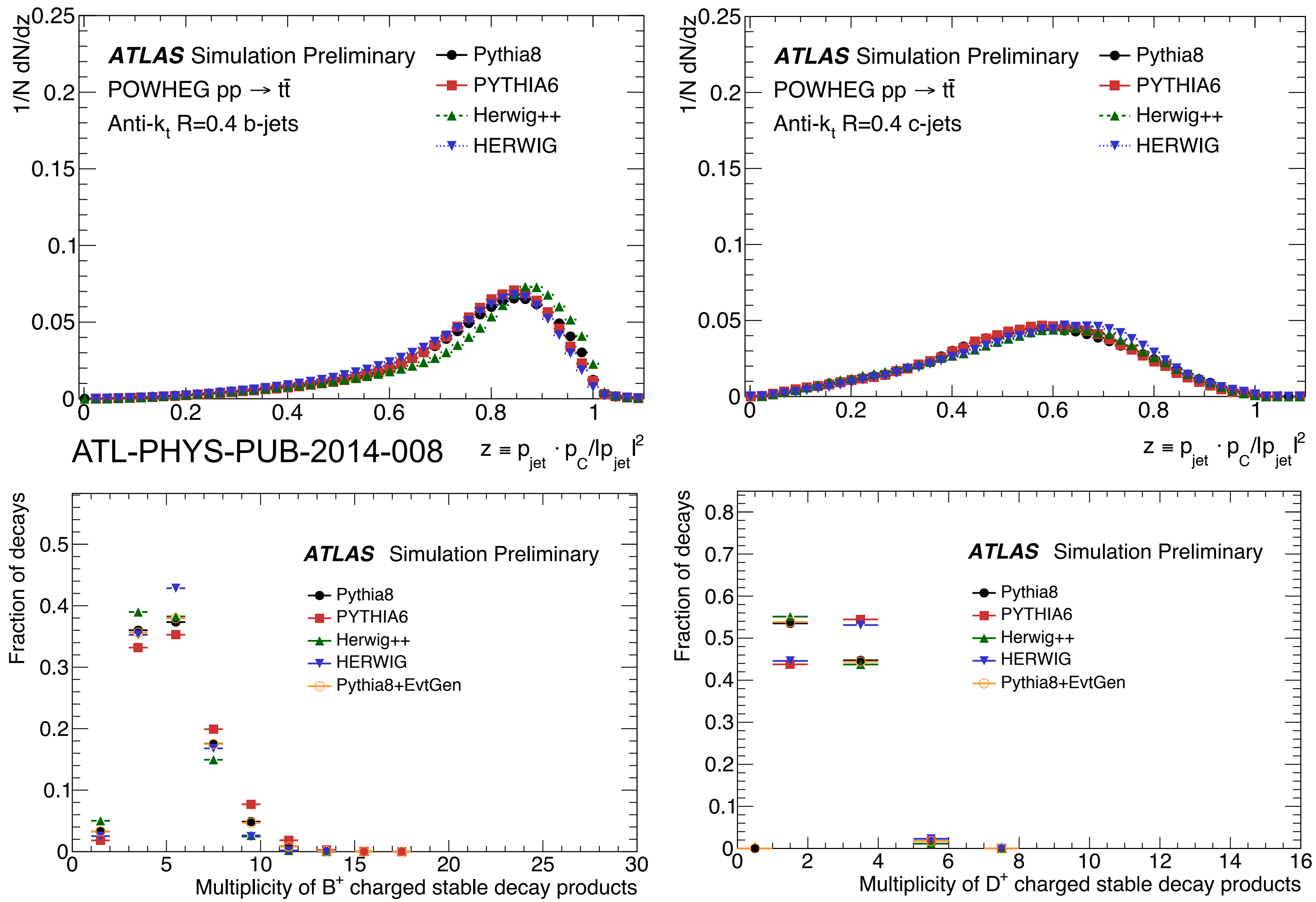
M. Dordevic, Univ. of Belgrade, LHCP2020

Higgs boson-charm quark coupling

- Search for **inclusive** h→cc decays, similar to h→bb
  - SM BR(h→ccbar)/BR(h→bbbar) ~ 5.1%
- **First search** for exclusive Zh→llcc decays, l=e, μ
- Need a **c-tagging** algorithm
  - c-jets less distinct than b-jets; e.g. ×3.5 less displacement
  - First used **Run 1** for search for s-charm



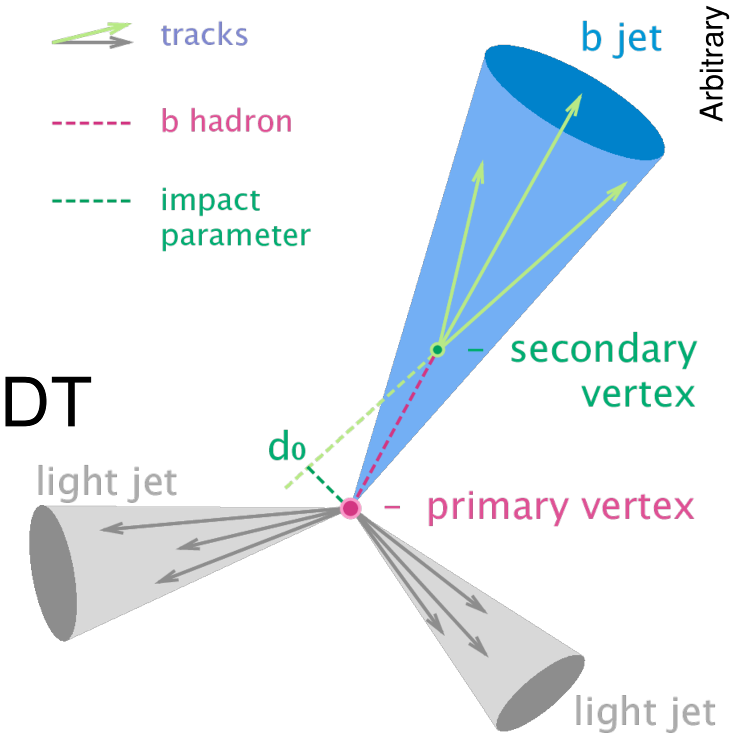
[Phys.Rev.Lett. 114 (2015) 161801]

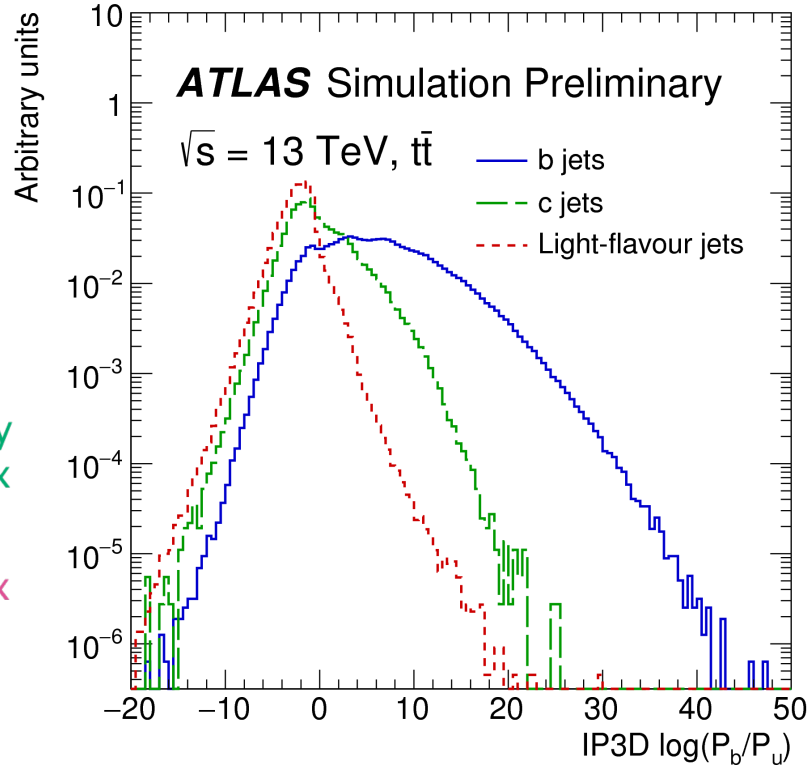


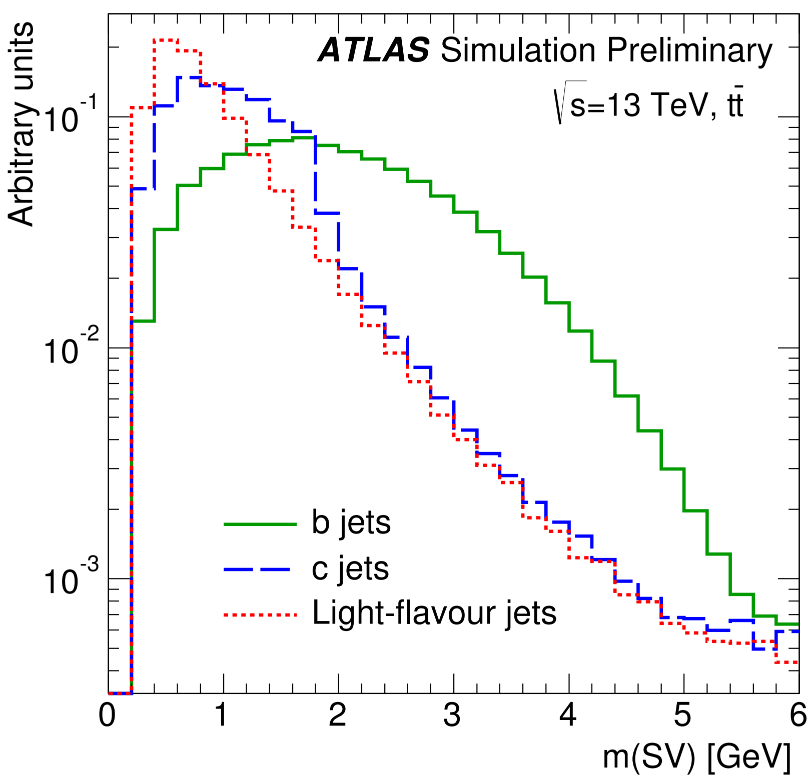
ATL-PHYS-PUB-2014-008

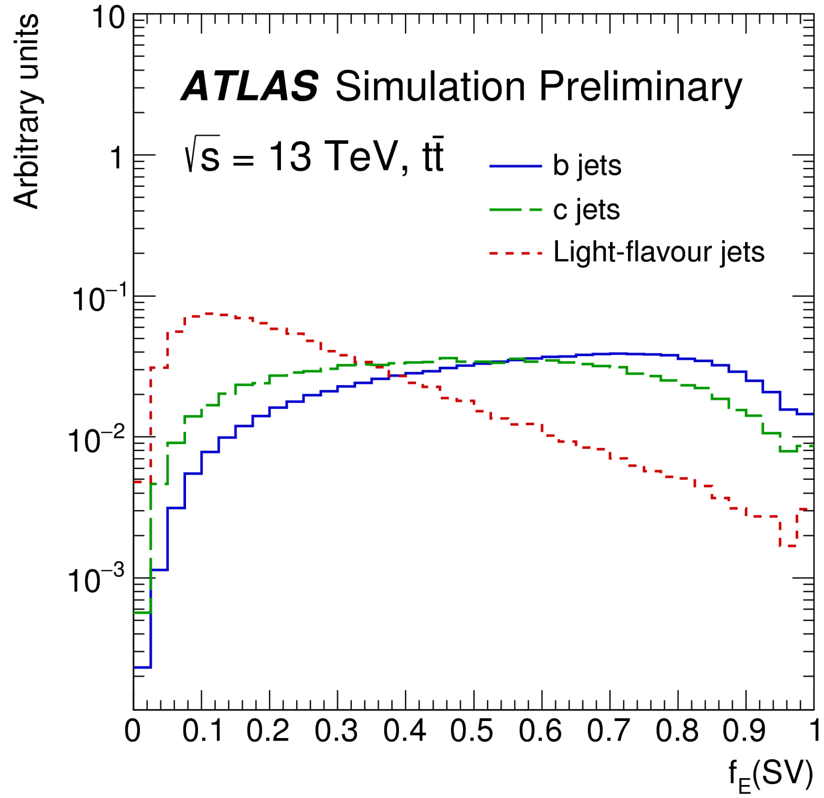
Higgs boson-charm quark coupling

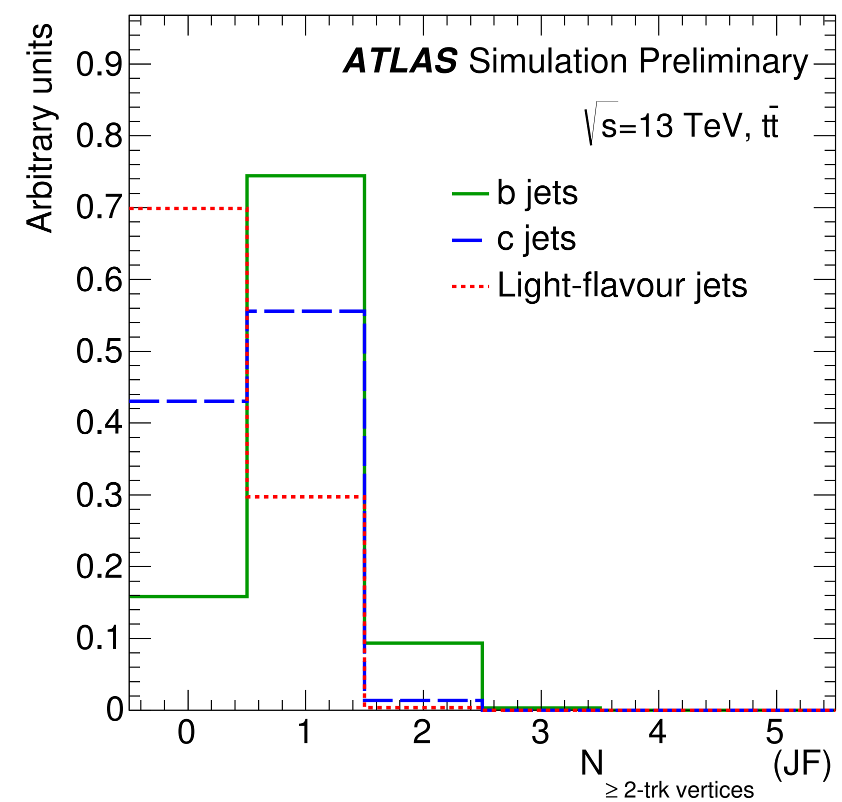
- **Run 2** new "inclusive" c-tagging
  - "Low level" taggers:
    - Track Impact Parameter
    - Secondary Vertices
    - JetFitter: b/c-et decay chain fit
  - "High level" tagger obtained with BDT











Higgs boson-charm quark coupling

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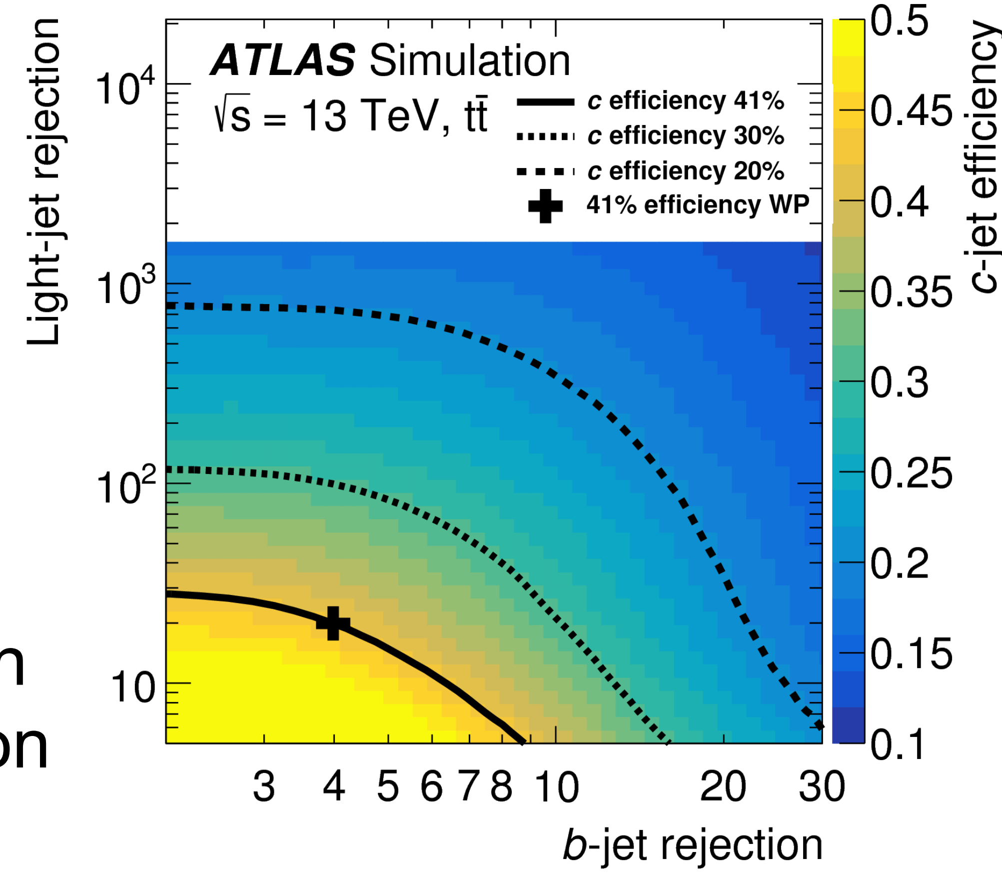
  - “Low level” taggers:
    - Track Impact Parameter
    - Secondary Vertices
    - JetFitter: b/c-et decay chain fit
  - “High level” tagger obtained with BDT

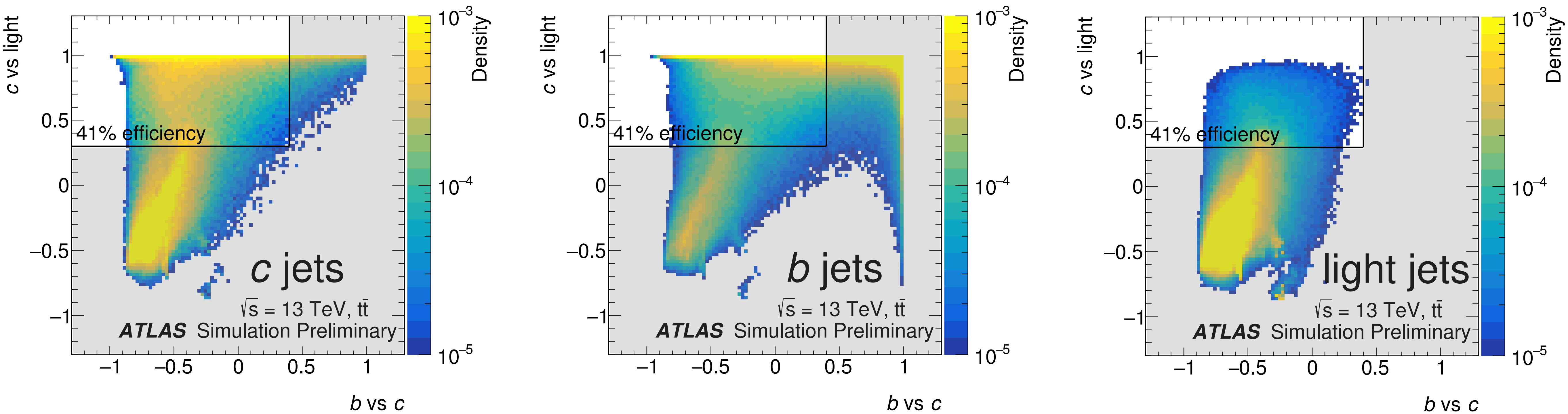
- c-tagging: 41% c-jet eff; 4×b-jet & 20×light jet rejection
- b-tagging: 77% b-jet eff; 6×c-jet &134×light jet rejection



c-jets

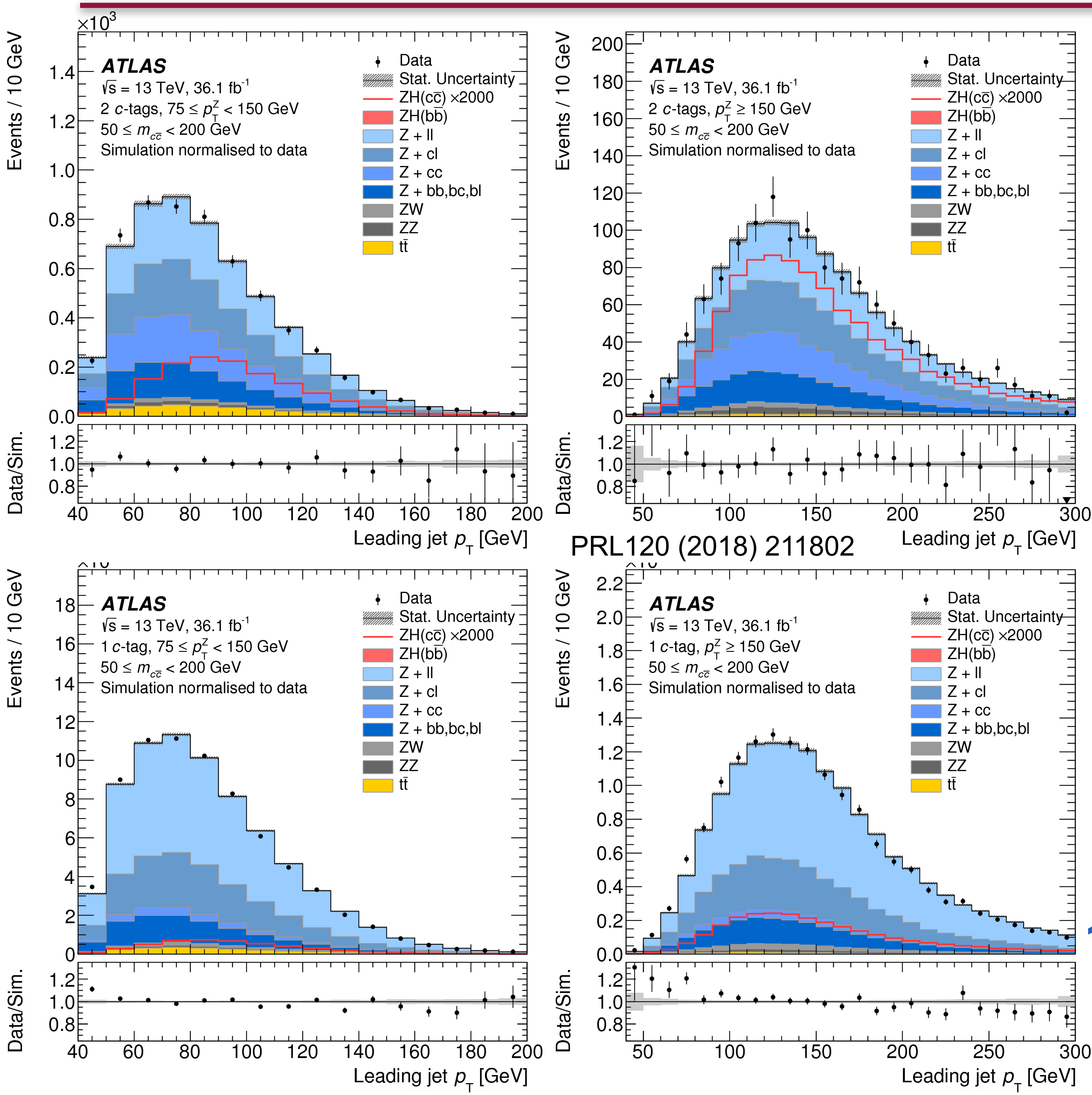
b-jets

light flavour (*u*, *d*, *s*, *g*) jets



ATLAS-CONF-2017-078

Zh(→cc):Background Composition



PRL120 (2018) 211802

2 c-tags

1 c-tag

75< $p_T Z$ < 150 GeV **$p_T Z$ > 150 GeV**

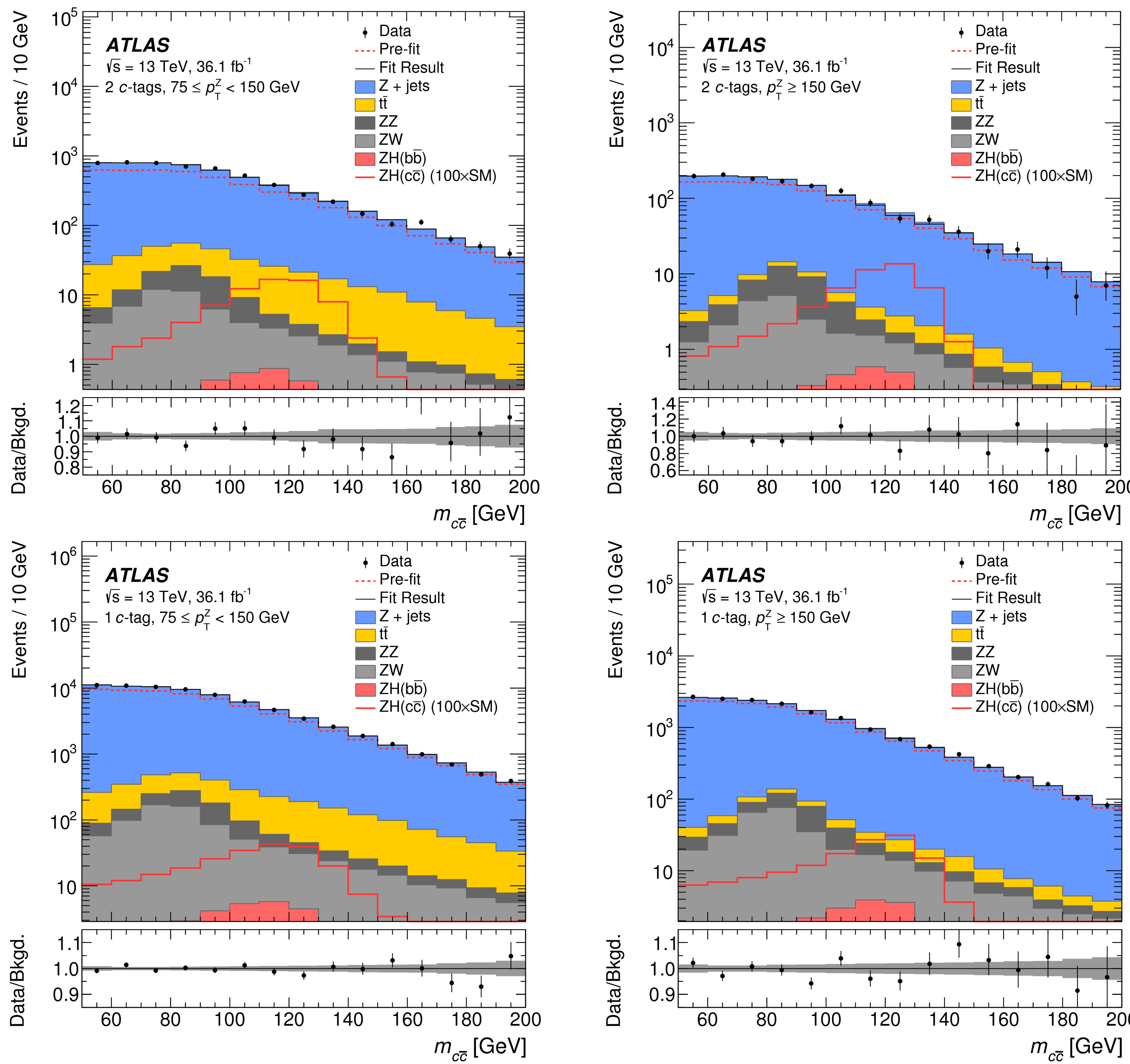
- Background modelling & uncertainties validated with Z(Z/W) measurement
  - Observed (expected) ZV production at 1.4σ (2.2σ)
  - Measured ZV signal strength=$0.6^{+0.5}_{-0.4}$

Zh(→cc):Fit Results

PRL120 (2018) 211802

2 c-tags

1 c-tag



75< p_TZ < 150 GeV

p_TZ > 150 GeV

Zh(→cc):Results

- **No evidence** for Zh(→cc) production with current dataset PRL120 (2018) 211802

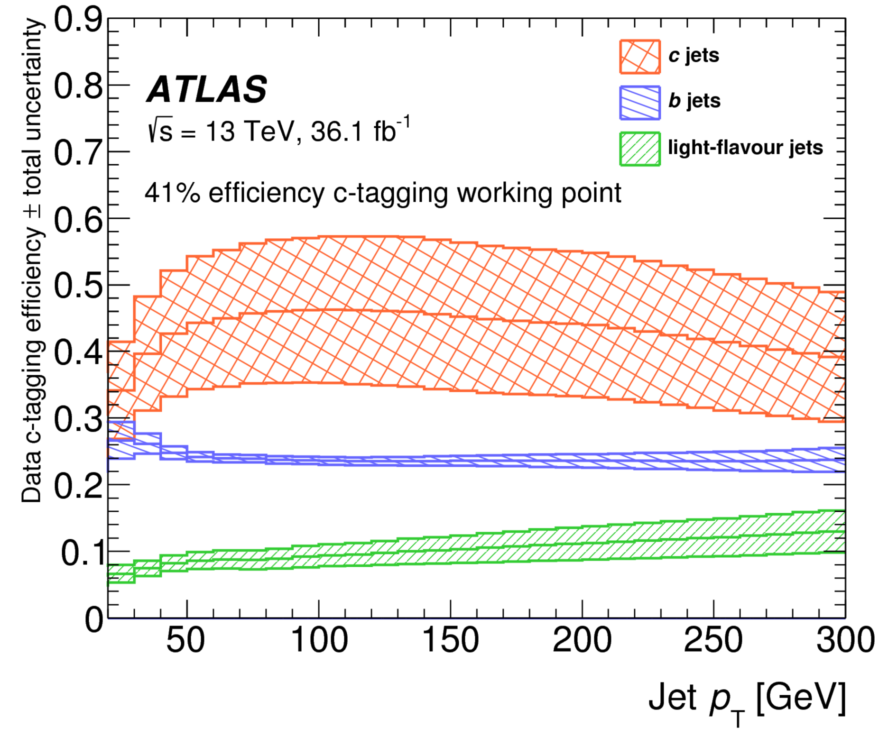
- SM: 2.55×10^{-2} pb
  - 110×SM (150^{+80}_{-40})

Limits on ZH(→ $c\bar{c}$) production

95% CL_s upper limit on $\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})$ [pb]			
Observed	Expected	Expected $+1\sigma$	Expected -1σ
2.7	3.9	6.0	2.8

Source	σ/σ_{tot}
Statistical	**49%**
Floating Z + jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

The sum in quadrature of the individual components differs from the total uncertainty due to correlations between the components.

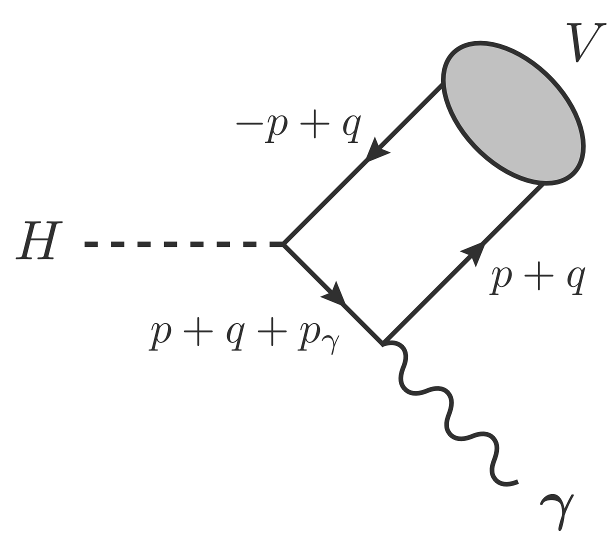


- Single tagging working point constrains linear combination of h→cc/h→bb
  - Analysis in conjunction with h→bb; account for cross-contamination
- For future key is controlling of systematic uncertainties
  - Phenomenological analysis indicates $|\kappa_c|\lesssim2.5$-5.5 at 95%CL
  - 2×3000 fb^{-1} depending on the c-tagging scenario [Phys.Rev. D93 (2016) 013001]
  - ATLAS HL-LHC projection for Z(ll)H(cc) alone μ<6.3 [ATL-PHYS-PUB-2018-016]

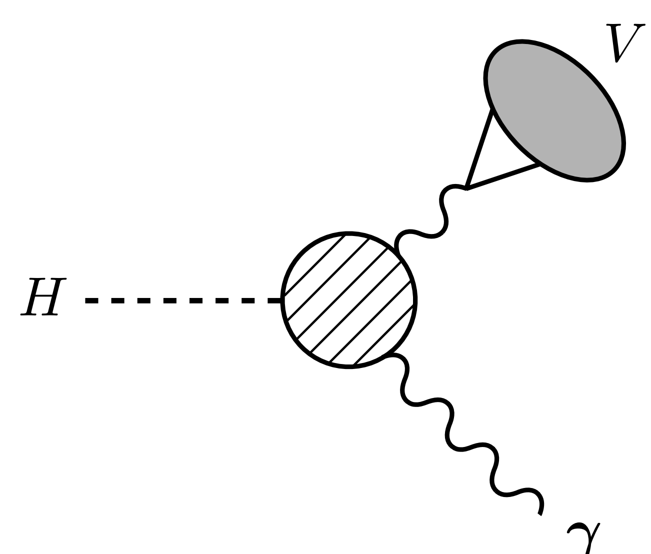
Exclusive Decays h→Qγ

- **h→Qγ decays: clean probe** for Higgs-quark couplings for 1st/2nd generation quarks
  - Q is a vector meson or quarkonium state
- **Two contributions:**
  - **Direct amplitude:** sensitive to Higgs boson-quark couplings
  - **Indirect amplitude:** insensitive to Higgs boson-quark couplings; larger than direct
  - **Destructive interference**

"Direct"



"Indirect"



$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

Phys.Rev. D90 (2014) 11, 113010

- **Similar decays of W± and Z bosons: also rich physics programme**
  - **Novel** precision studies of quantum chromo-dynamics
  - **W±/Z boson interactions with light quarks** not well covered at earlier facilities
  - **Discovery potential** for new physics processes

Exclusive Decays $h \to Q\gamma$

- Substantial interest from theory community on branching ratio estimates and feasibility

Mode	Branching Fraction $[10^{-6}]$		
Method	NRQCD [1487]	LCDA LO [1486]	LCDA NLO [1489]
$\mathrm{Br}(h \to \rho\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(h \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(h \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$

PRD90 (2014) 113010 PRL 114 (2015) 101802 JHEP 1508 (2015) 012

Not exhaustive; accurate at the time of YR4.

e.g. Phys.Rev. D95 (2017) 054018
Phys.Rev. D96 (2017) 116014
Phys.Rev. D97 (2018) 016009

Decay mode	Branching ratio
$Z^0 \to \pi^0\gamma$	$(9.80\,^{+0.09}_{-0.14}\,{}_{\mu} \pm 0.03_f \pm 0.61_{a_2} \pm 0.82_{a_4}) \cdot 10^{-12}$
$Z^0 \to \rho^0\gamma$	$(4.19\,^{+0.04}_{-0.06}\,{}_{\mu} \pm 0.16_f \pm 0.24_{a_2} \pm 0.37_{a_4}) \cdot 10^{-9}$
$Z^0 \to \omega\gamma$	$(2.89\,^{+0.03}_{-0.05}\,{}_{\mu} \pm 0.15_f \pm 0.29_{a_2} \pm 0.25_{a_4}) \cdot 10^{-8}$
$Z^0 \to \phi\gamma$	$(8.63\,^{+0.08}_{-0.13}\,{}_{\mu} \pm 0.41_f \pm 0.55_{a_2} \pm 0.74_{a_4}) \cdot 10^{-9}$
$Z^0 \to J/\psi\,\gamma$	$(8.02\,^{+0.14}_{-0.15}\,{}_{\mu} \pm 0.20_f\,^{+0.39}_{-0.36}\,{}_{\sigma}) \cdot 10^{-8}$
$Z^0 \to \Upsilon(1S)\,\gamma$	$(5.39\,^{+0.10}_{-0.10}\,{}_{\mu} \pm 0.08_f\,^{+0.11}_{-0.08}\,{}_{\sigma}) \cdot 10^{-8}$
$Z^0 \to \Upsilon(4S)\,\gamma$	$(1.22\,^{+0.02}_{-0.02}\,{}_{\mu} \pm 0.13_f\,^{+0.02}_{-0.02}\,{}_{\sigma}) \cdot 10^{-8}$
$Z^0 \to \Upsilon(nS)\,\gamma$	$(9.96\,^{+0.18}_{-0.19}\,{}_{\mu} \pm 0.09_f\,^{+0.20}_{-0.15}\,{}_{\sigma}) \cdot 10^{-8}$

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h/Z→ψ(mS)γ (m=1,2) and h/Z→Υ(nS)γ (n=1,2,3)

- **Run 1: Non-universal quark-Higgs boson coupling**
- **New results** with Run 2 data, including also ψ'

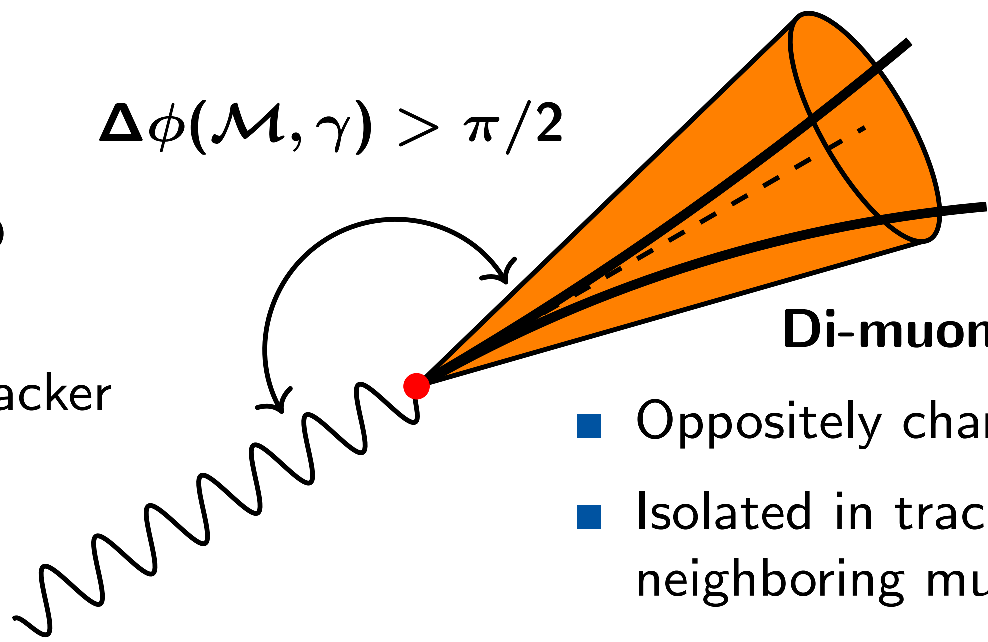
[Phys.Rev.Lett. 114 (2015) 12, 121801, Phys.Lett. B753 (2016) 341, Phys.Rev. D92 (2015) 033016, JHEP 1508 (2015) 012]

Photon Selection

- "Tight" photon ID requirements
- Isolated in both tracker and calorimeter

$p_T^{\gamma} > 35$ GeV

$\Delta\phi(\mathcal{M},\gamma) > \pi/2$



$p_T^{\mu\ \mathrm{lead}} > 18$ GeV

$p_T^{\mu\ \mathrm{sub\text{-}lead}} > 3$ GeV

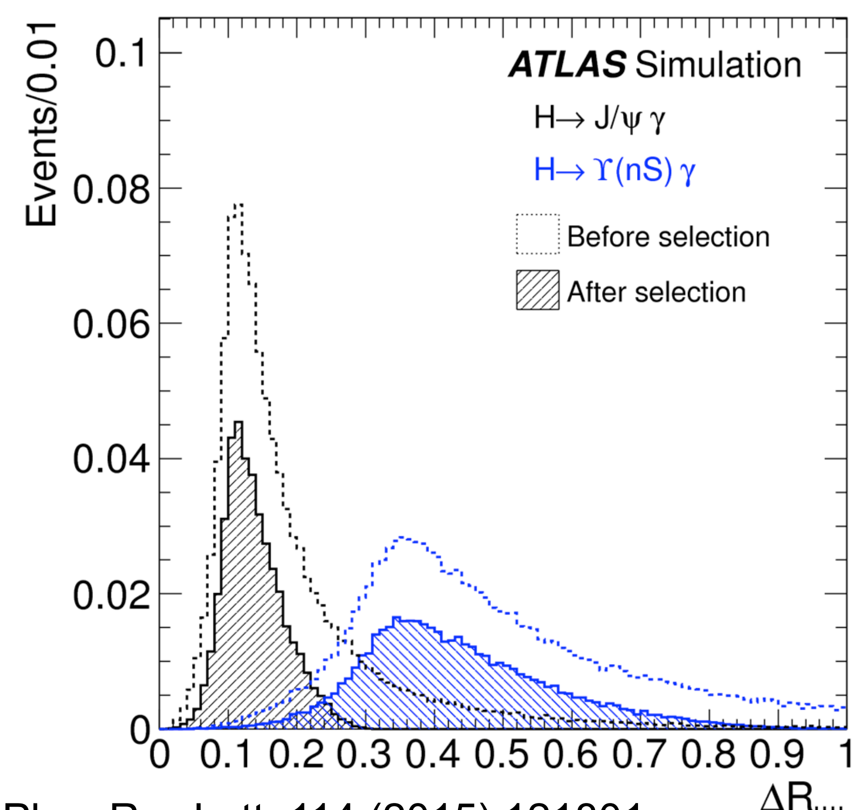
$p_{T\mu\mu}$ >34-54.4 GeV [function of $m_{\mu\mu\gamma}$]

Di-muon Selection

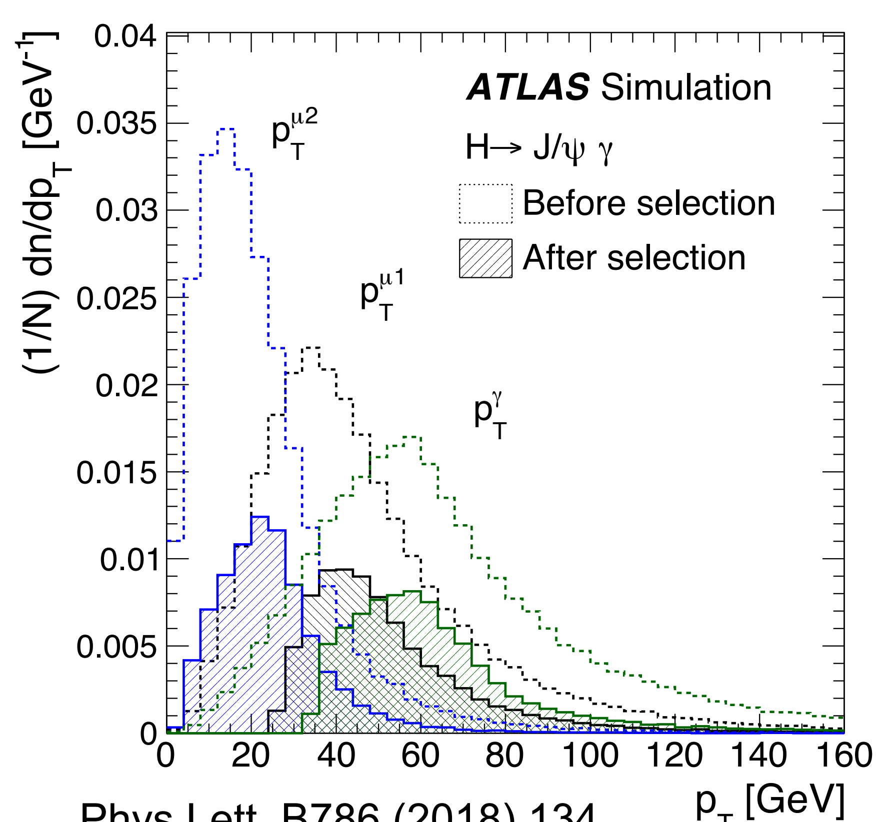
- Oppositely charged pair of muons
- Isolated in tracker (accounting for neighboring muon track)
- $L_{xy}/\sigma_{L_{xy}} < 3$ to reject $b \to \psi(nS)$

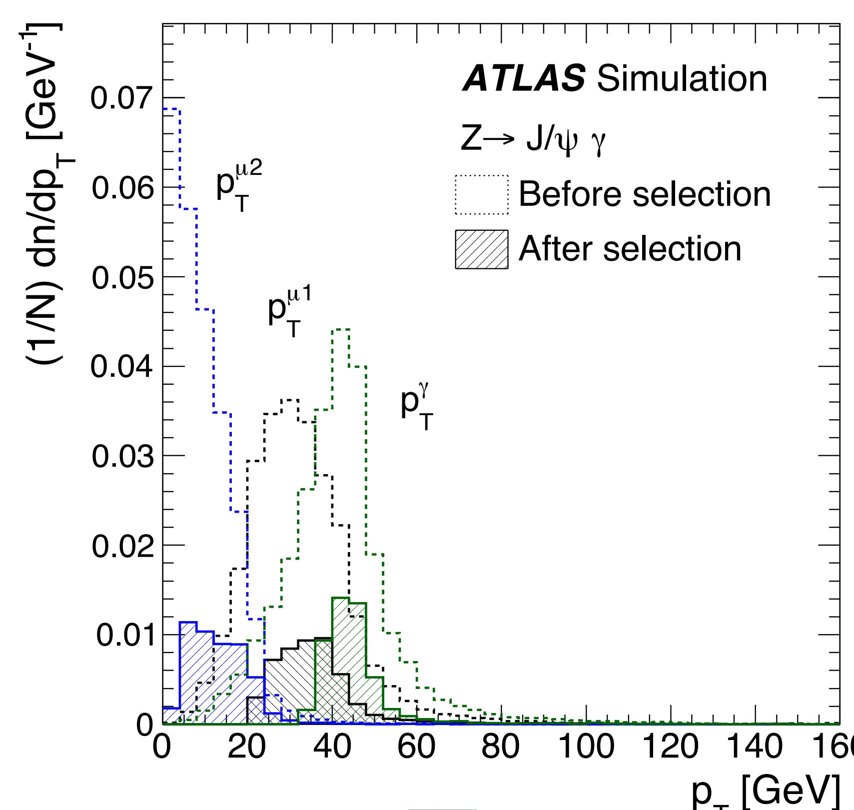
Signal $\mathcal{A}\times\epsilon$

- h/Z→J/ψ(→μμ)γ ~19% (11%)
- h/Z→Υ(→μμ)γ ~ 23% (16%)



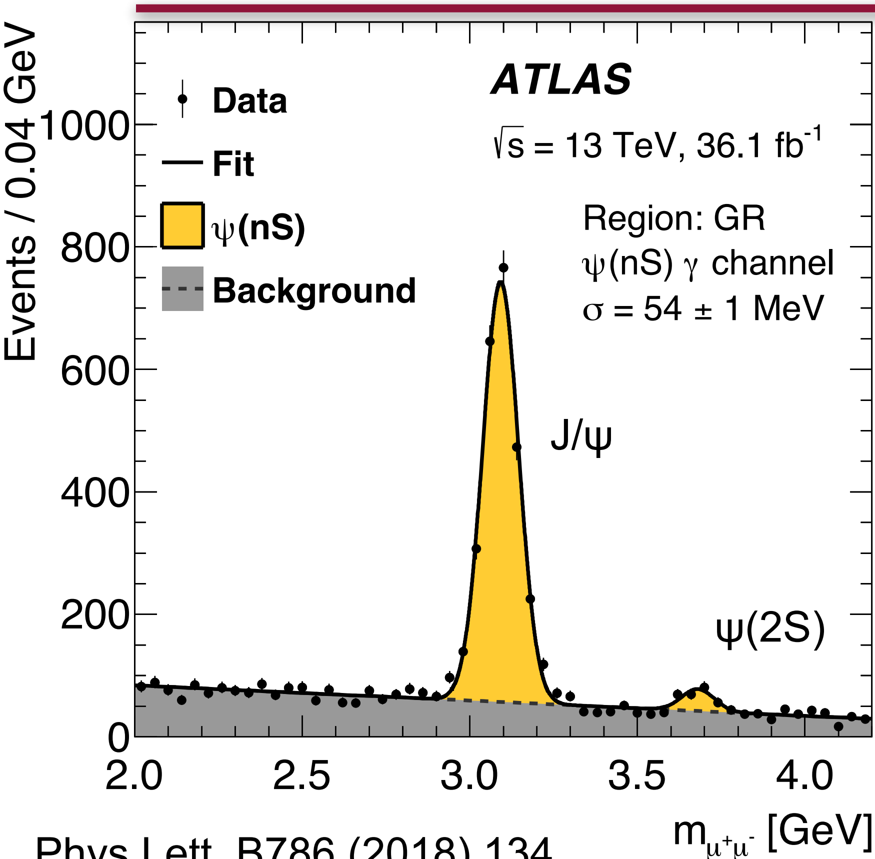
Phys.Rev.Lett. 114 (2015) 121801

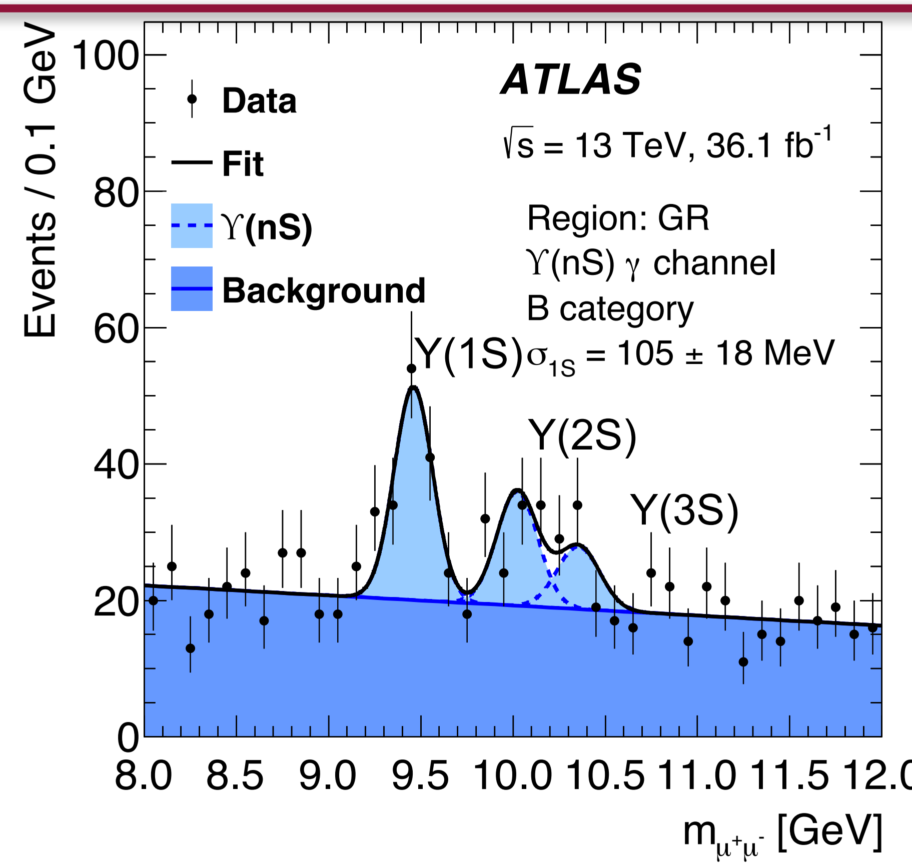


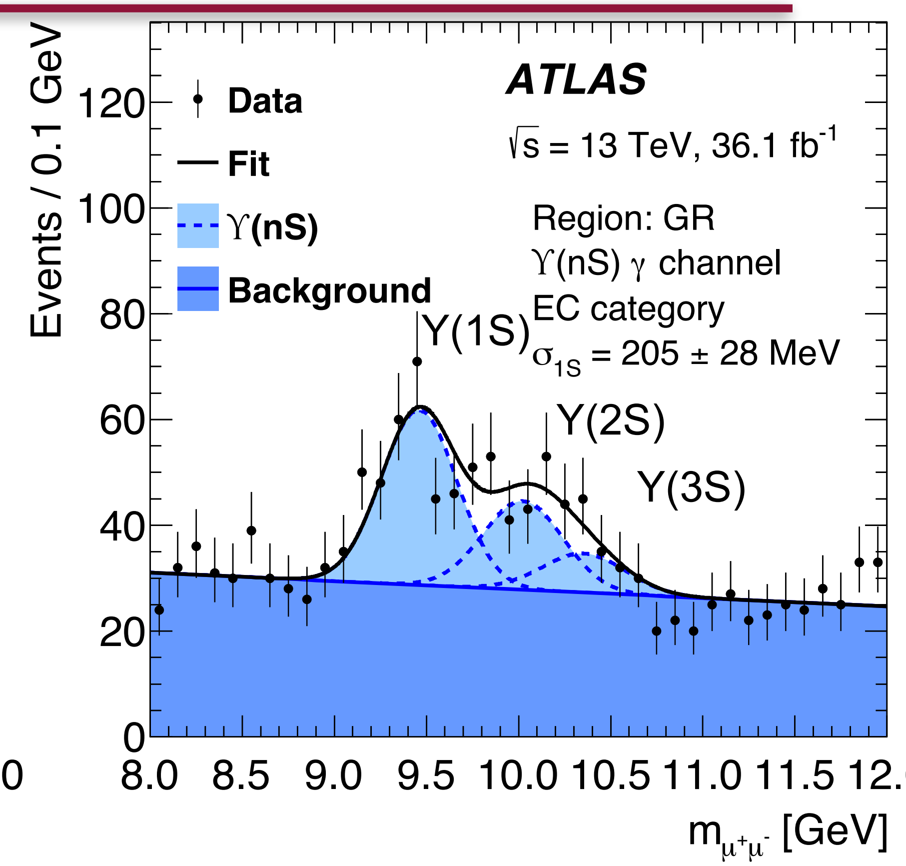


Phys.Lett. B786 (2018) 134

h/Z→ψ(mS)γ (m=1,2) and h/Z→Υ(nS)γ (n=1,2,3)

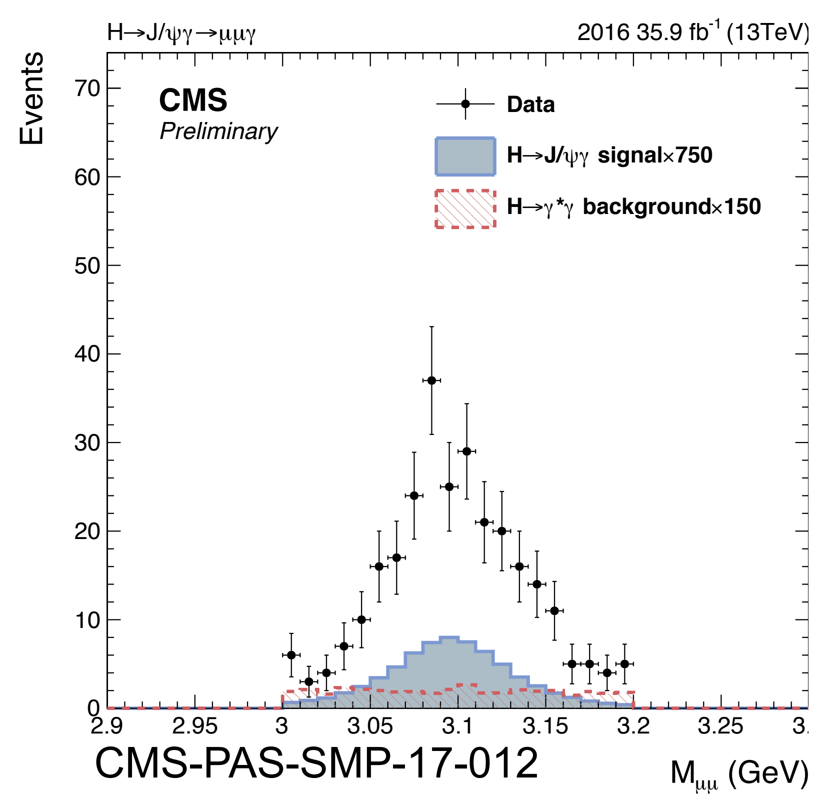




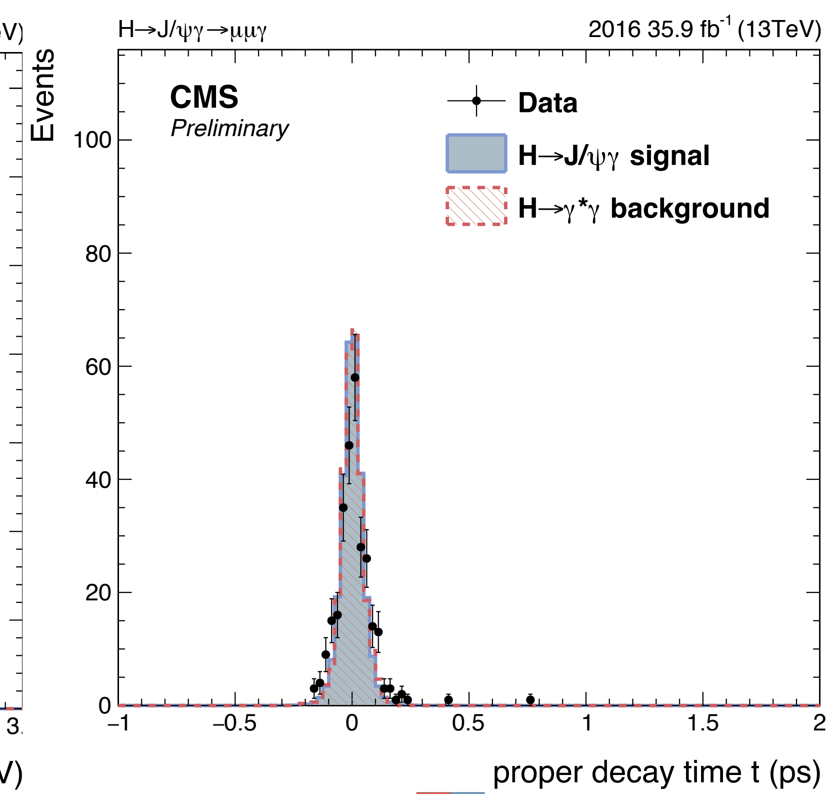


Phys.Lett. B786 (2018) 134

- Mostly no categorisation
  - ATLAS Υ(nS): 2 μ categories
  - CMS ZJ/ψ: 3 γ categories
- Mass resolution ~1.6-1.8%

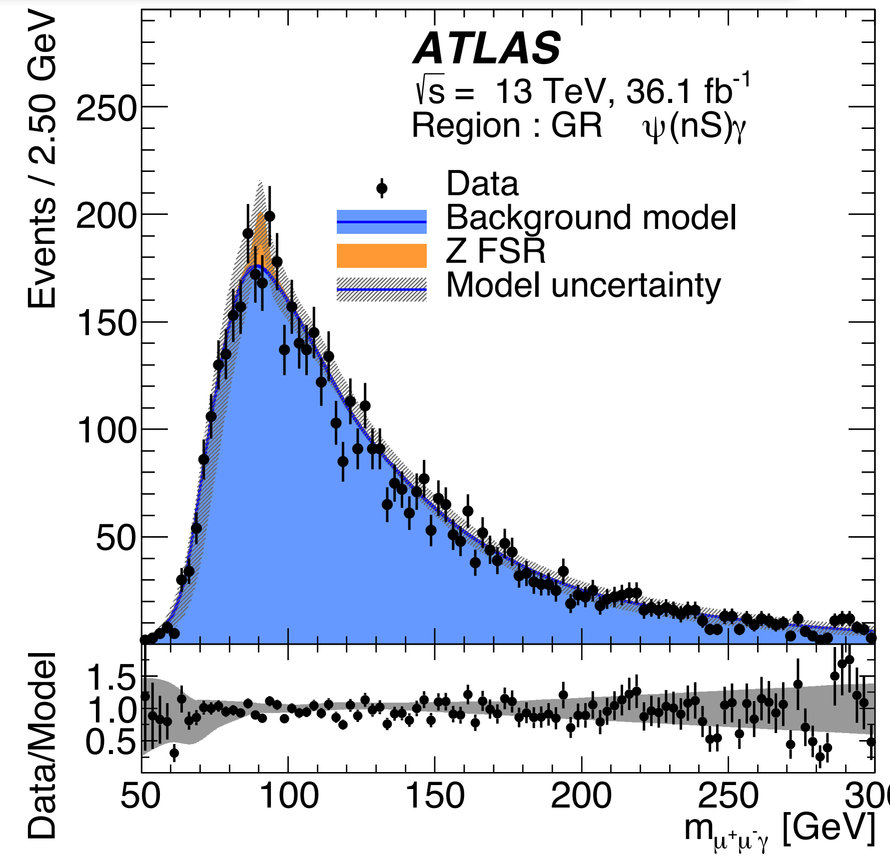


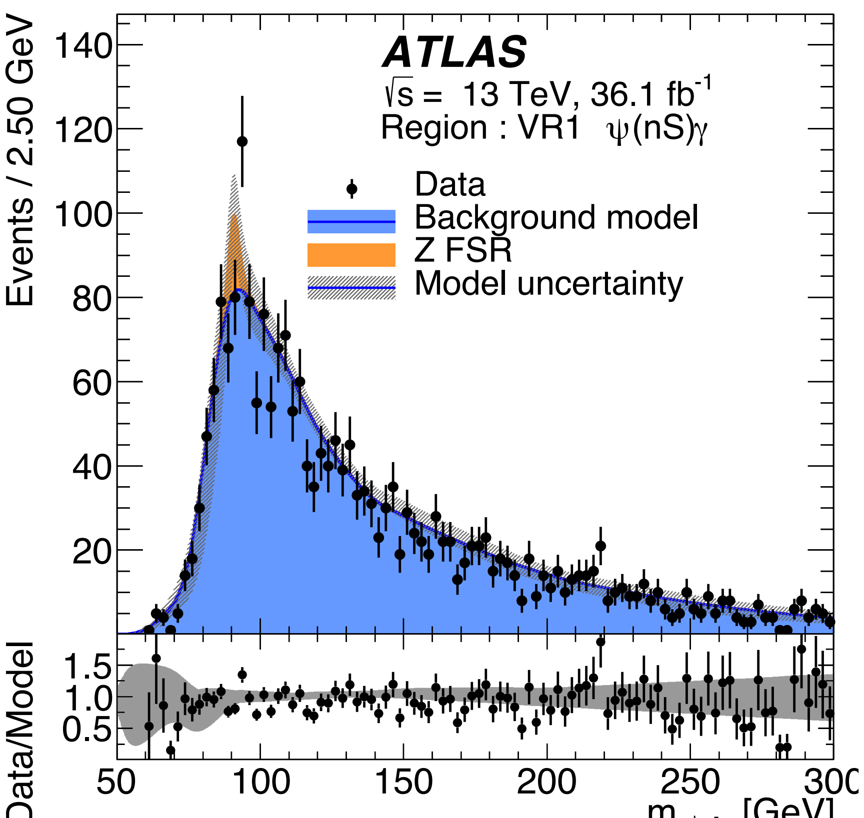
CMS-PAS-SMP-17-012

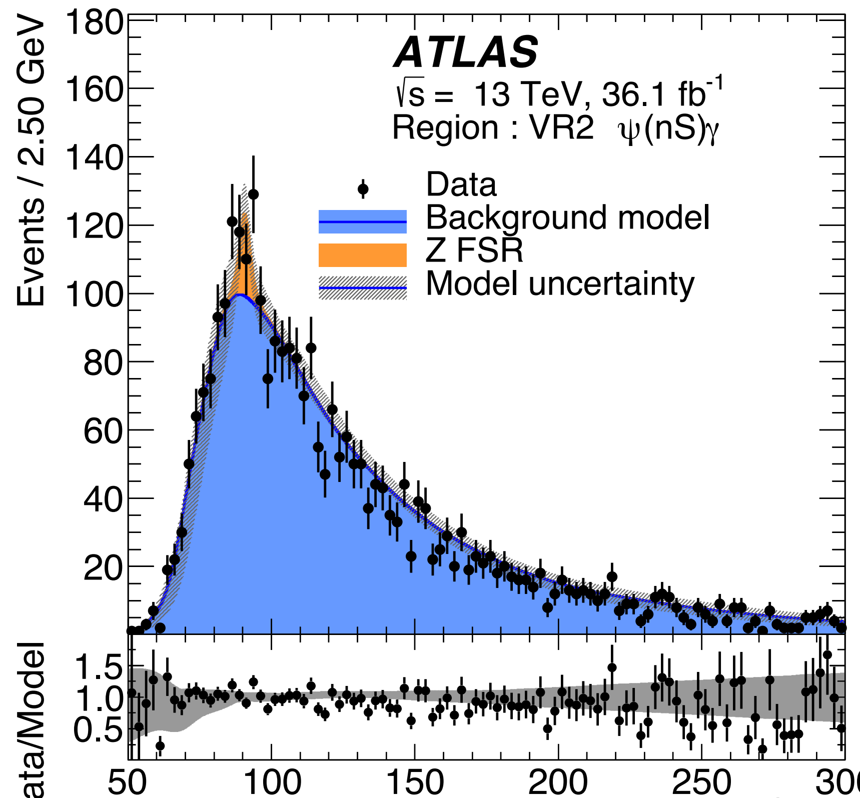


h/Z→Qγ: Background

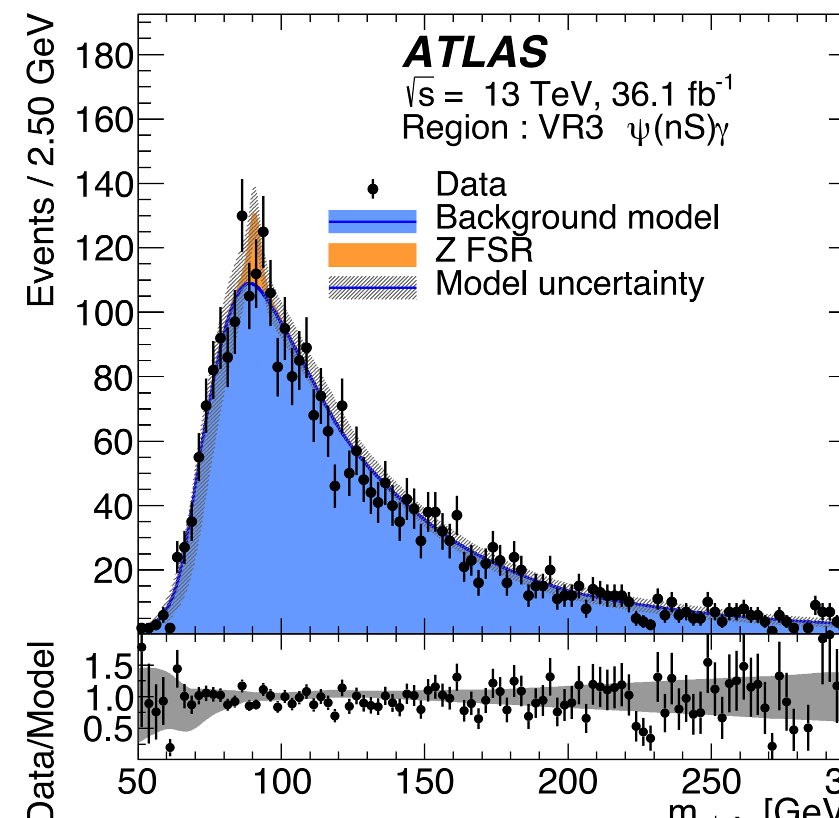
- **Inclusive quarkonium** with jet “seen” as γ
  - combinatoric background: small contribution
  - contribution from Q+γ production
- **Non-parametric data-driven** background model
  - Obtain loose sample of candidates
  - Model kinematic and isolation distributions
  - Generate “pseudo”-background events
  - Apply selection to “pseudo”-candidates
- **CMS:** polynomials for background model
- **Peaking backgrounds**
  - $Z\to\mu\mu\gamma_{FSR}$ from side-band fit
  - $H\to\mu\mu\gamma_{FSR}$ (small contribution wrt other backgrounds)



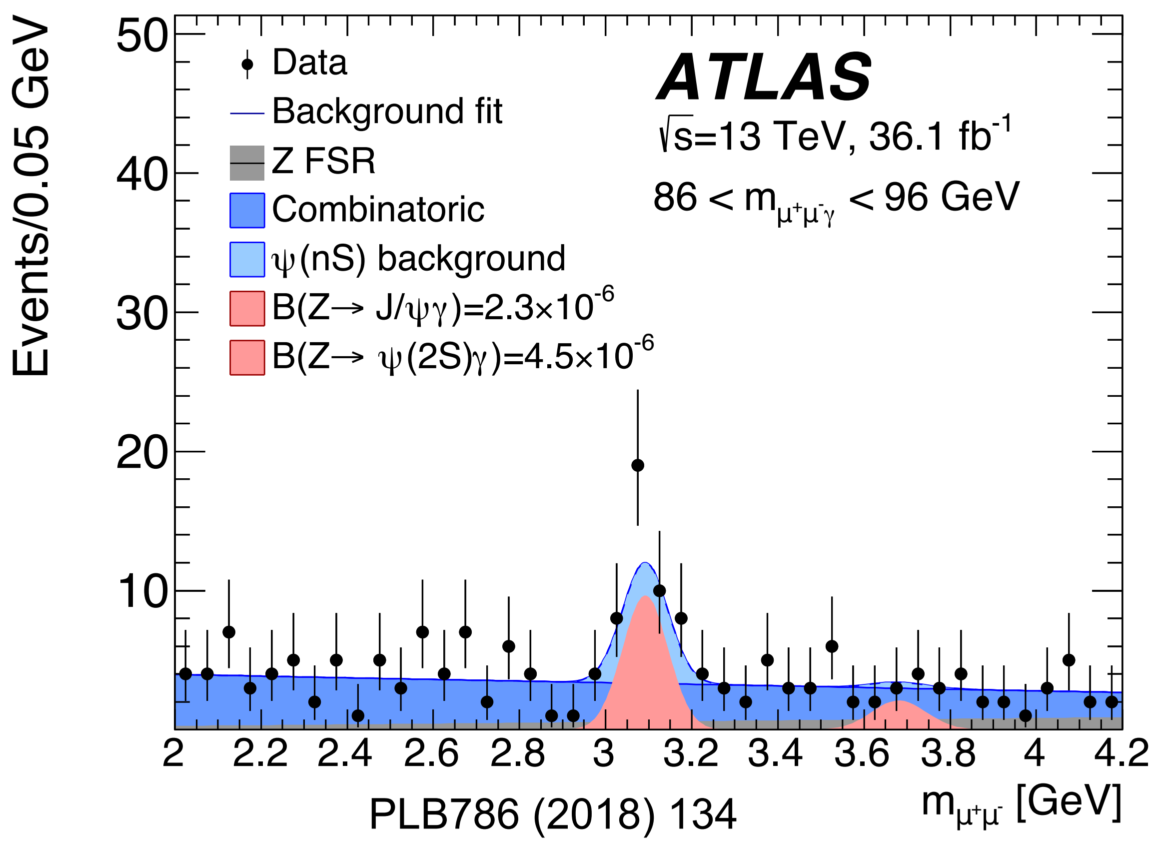


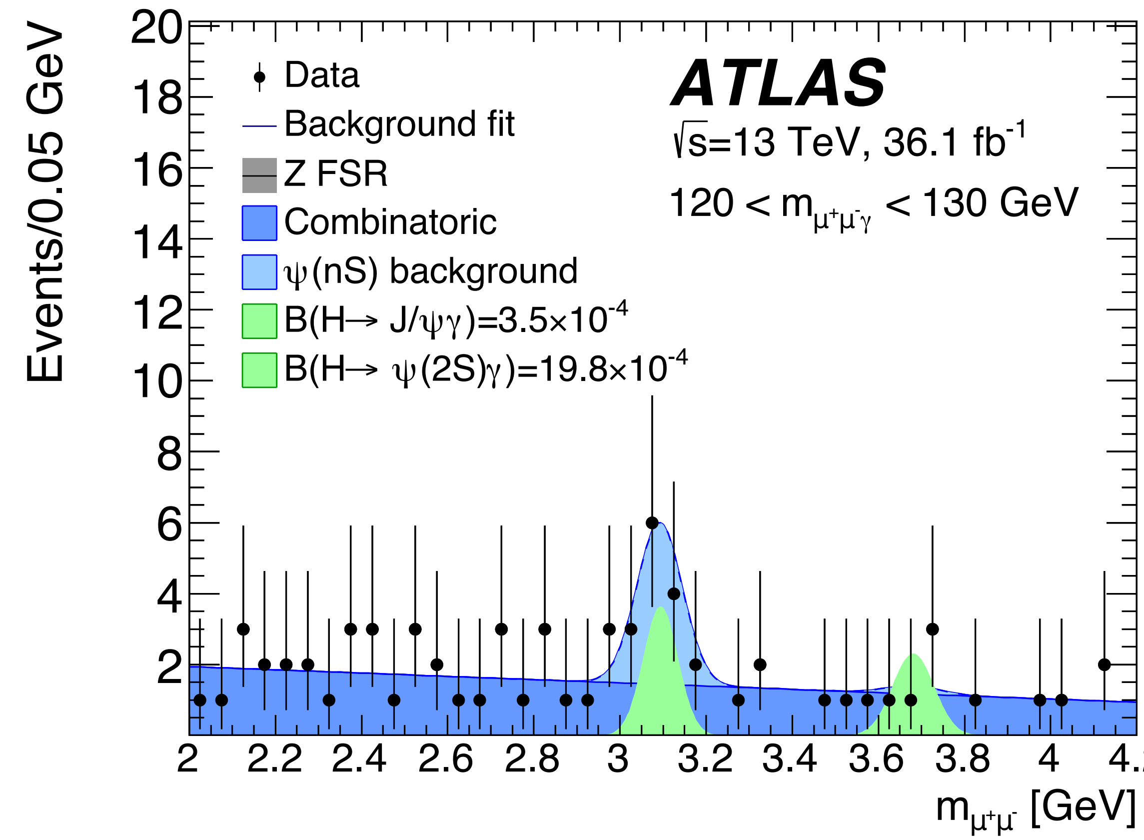


PLB786 (2018) 134

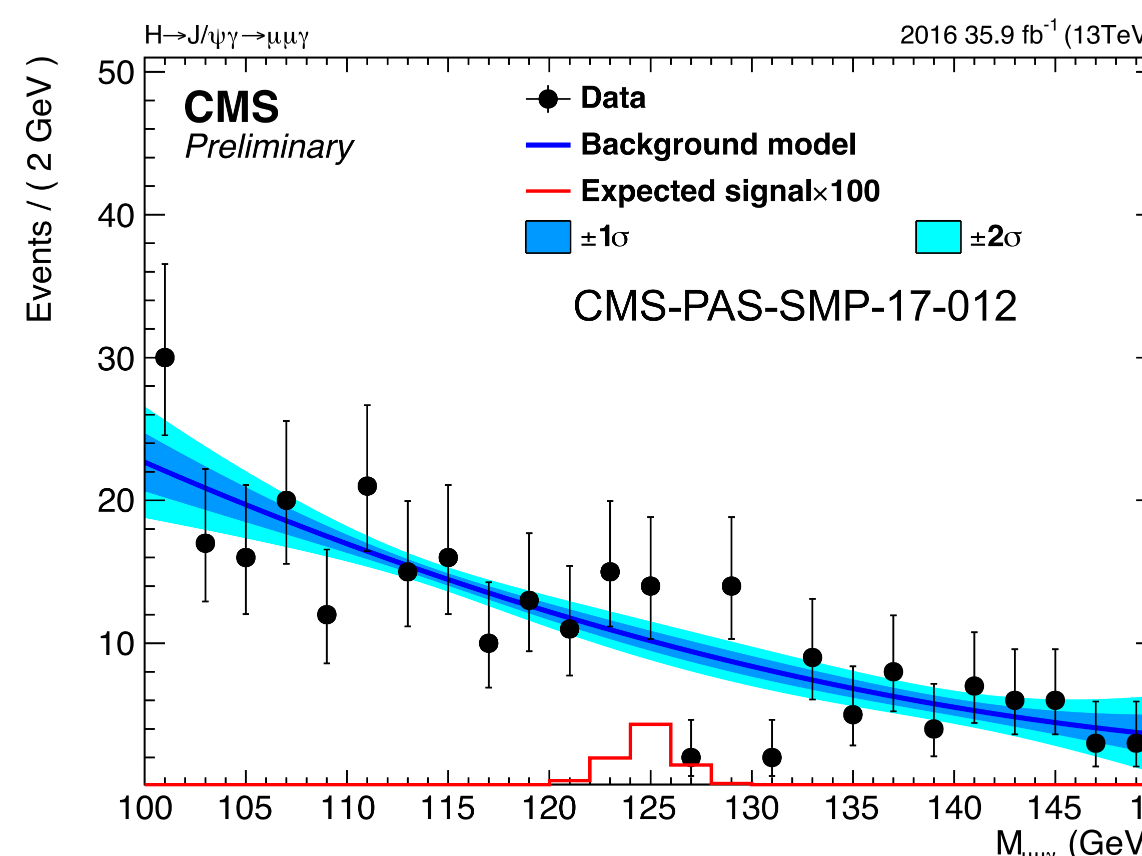


h/Z→Qγ: Results

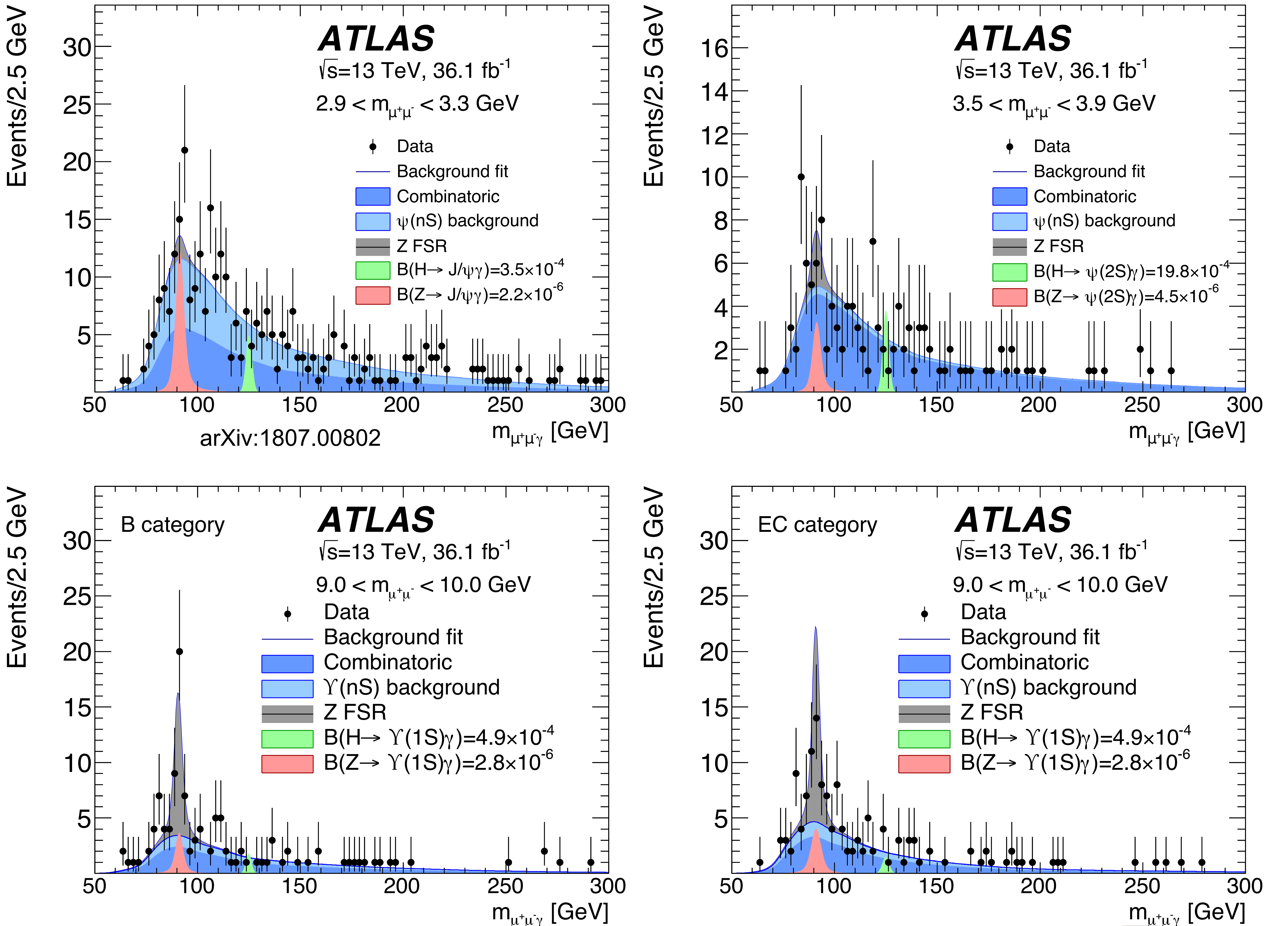




- **Maximum Likelihood fit**
  - **ATLAS:** $m_{\mu\mu\gamma}$, $m_{\mu\mu}$
  - **CMS:** $m_{\mu\mu\gamma}$,
- **No significant excess** above background observed for J/ψ, ψ(2S) and Υ(ns) final states



h/Z→Qγ: Results



h/Z→Qγ: Results

	ATLAS		CMS	
Branching fraction limit (95% CL)	Observed	Expected	Observed	Expected
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$	3.5	$3.0^{+1.4}_{-0.8}$	7.6	$5.2^{+2.4}_{-1.6}$
$\mathcal{B}(H \to \psi(2S)\,\gamma)\,[\,10^{-4}\,]$	19.8	$15.6^{+7.7}_{-4.4}$	-	-
$\mathcal{B}(Z \to J/\psi\,\gamma)\,[\,10^{-6}\,]$	2.3	$1.1^{+0.5}_{-0.3}$	1.4	$1.6^{+0.7}_{-0.5}$
$\mathcal{B}(Z \to \psi(2S)\,\gamma)\,[\,10^{-6}\,]$	4.5	$6.0^{+2.7}_{-1.7}$	-	-

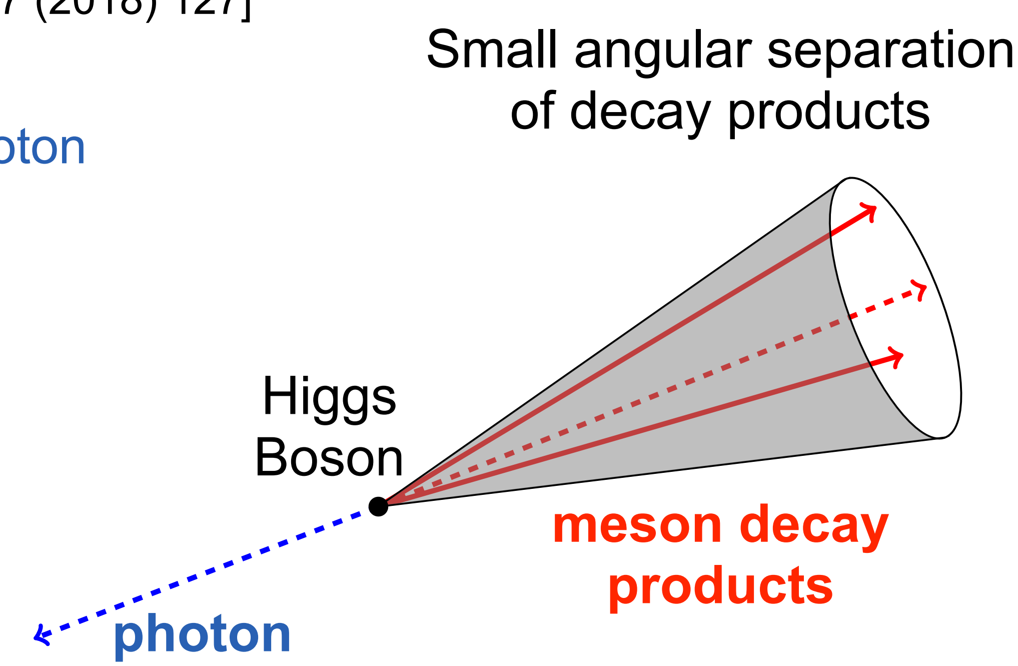
Branching fraction limit (95% CL)	Observed	Expected
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	4.9	$5.0^{+2.4}_{-1.4}$
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	5.9	$6.2^{+3.0}_{-1.7}$
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	5.7	$5.0^{+2.5}_{-1.4}$
$\mathcal{B}(Z \to \Upsilon(1S)\,\gamma)\,[\,10^{-6}\,]$	2.8	$2.8^{+1.2}_{-0.8}$
$\mathcal{B}(Z \to \Upsilon(2S)\,\gamma)\,[\,10^{-6}\,]$	1.7	$3.8^{+1.6}_{-1.1}$
$\mathcal{B}(Z \to \Upsilon(3S)\,\gamma)\,[\,10^{-6}\,]$	4.8	$3.0^{+1.3}_{-0.8}$

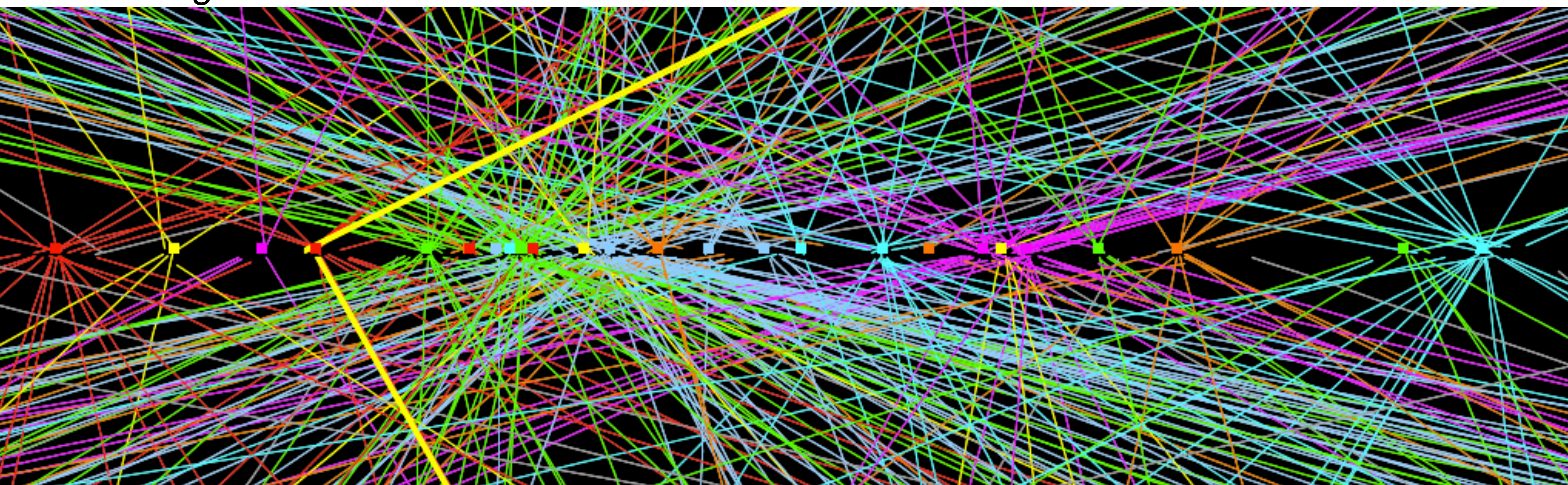
- Substantial improvement with respect to Run 1
  - Expected limit improved by factor 3-4 for Higgs and by 60-80% for Z
- Current limits imply: $-165<\kappa_c<200$
  - Predictions on the direct amplitude have been revised downwards as a function of time

c.f Phys.Rev. D96 (2017) 116014 → PRD90 (2014) 113010

h/Z→φγ/ργ: Analysis Strategy

- **First search** for h/Z→φγ with 2.7 fb^{-1}@13 TeV from 2015 [Phys. Rev. Lett. 117, 111802]
- **New results** with up to 35.6/fb, added h/Z→ργ [JHEP 1807 (2018) 127]
- **Distinct experimental signature**
  - Collimated high-pT isolated track pair recoils vs high-pT isolated photon
- **Meson decays:**
  - **$\phi \to K^+K^-$**, BR=49%
  - **$\rho \to \pi^+\pi^-$**, BR~100%
- **Small opening angles between decay products**
  - Particularly for $\phi \to K^+K^-$
  - Tracking in dense environments





Z→μμ candidate with 25 reconstructed vertices from the 2012 run. Only good quality tracks with pT>0.4GeV are shown

h/Z→φγ/ργ: Analysis Strategy

- **First search** for h/Z→φγ with 2.7 fb^{-1}@13 TeV from 2015
- **New results** with up to 35.6/fb, added h/Z→ργ
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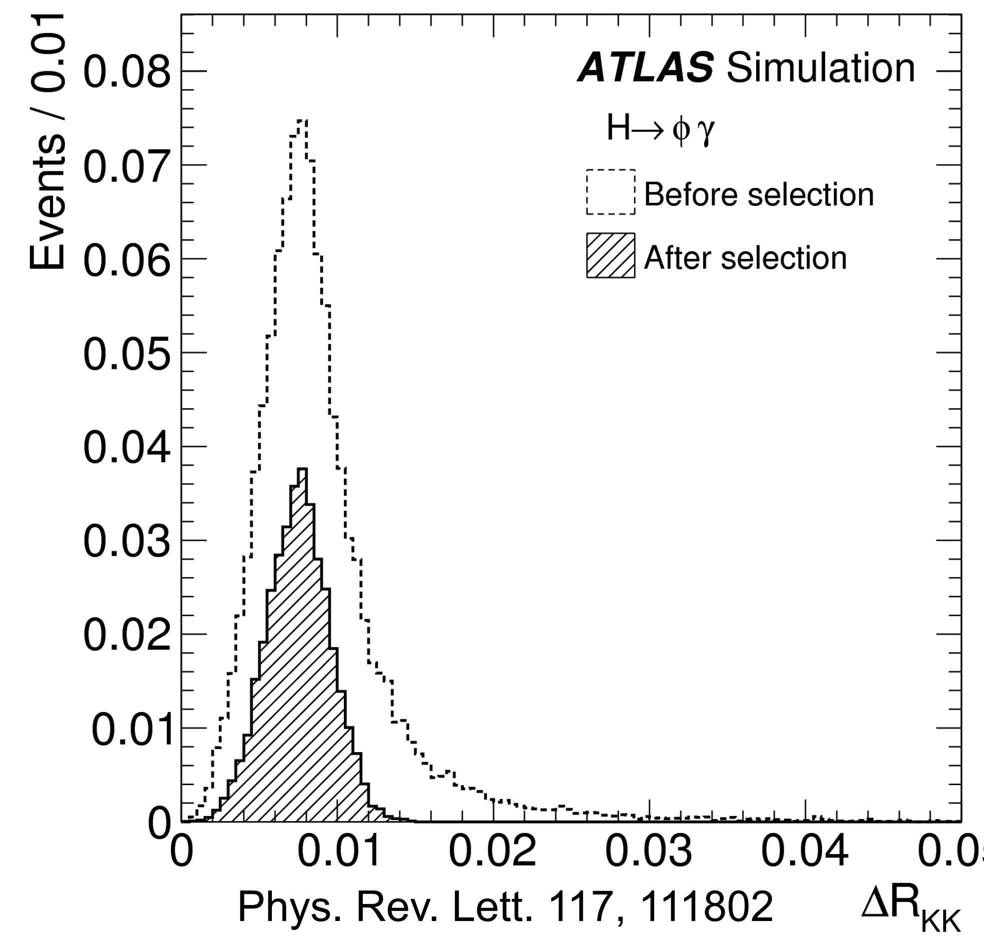
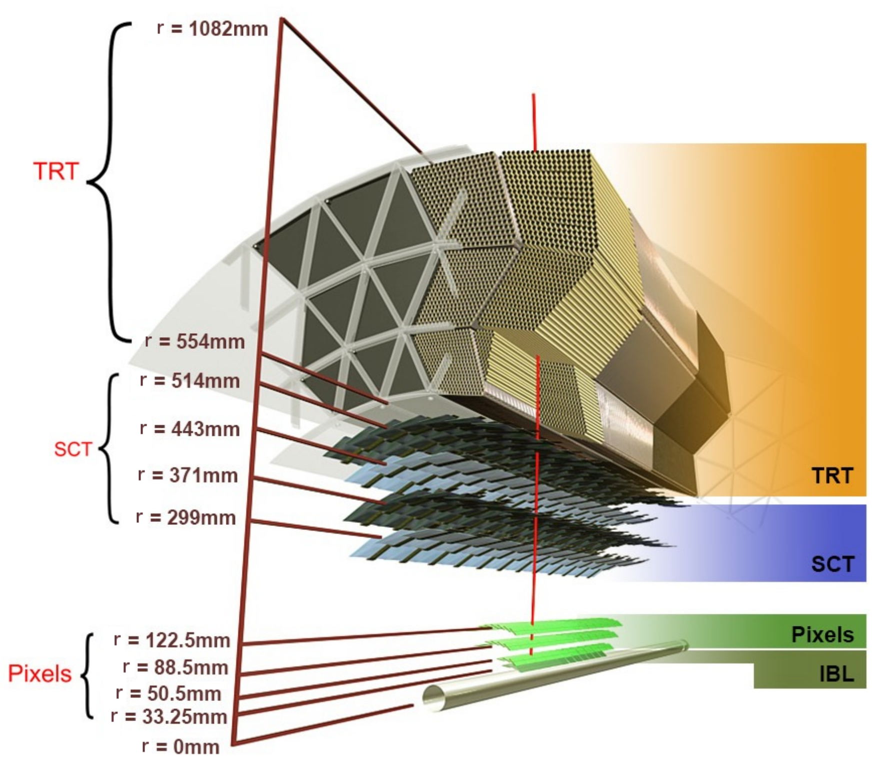
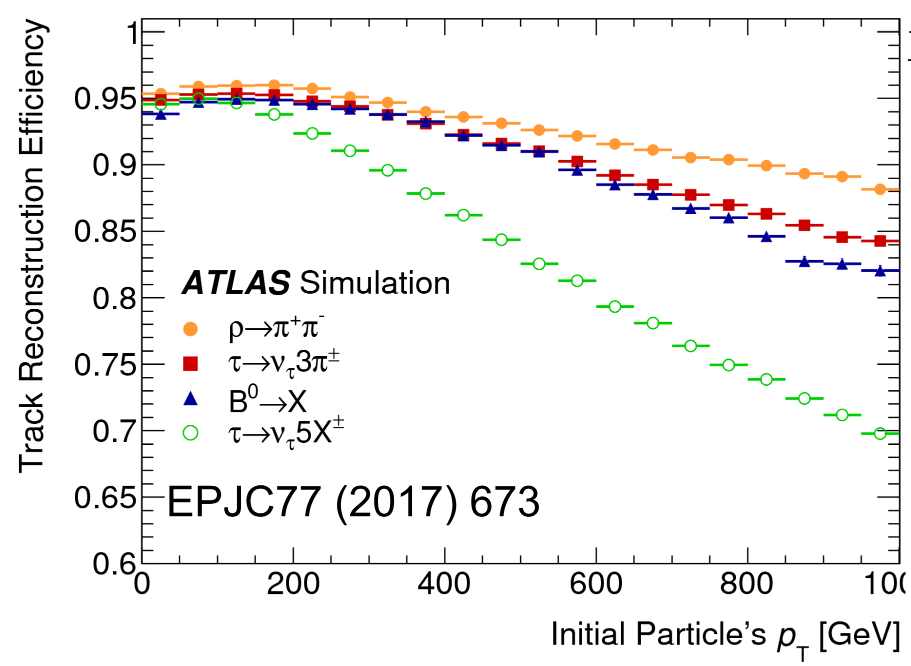
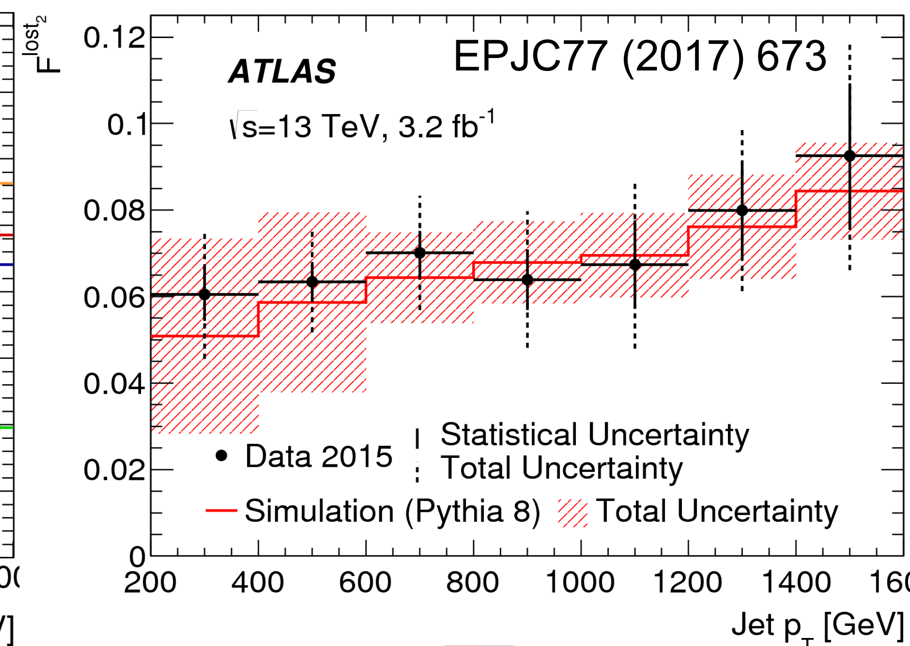


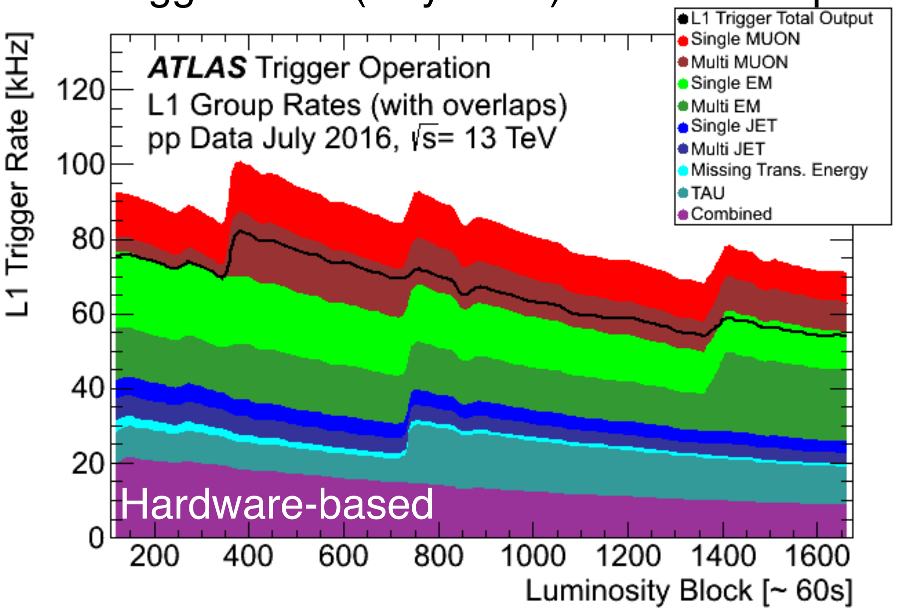


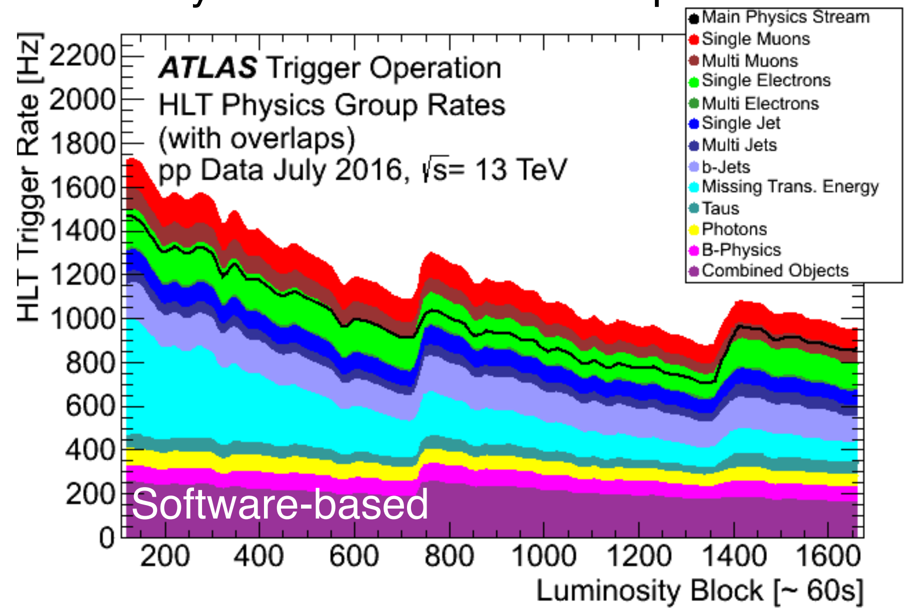




h/Z→φγ/ργ: Trigger Strategy

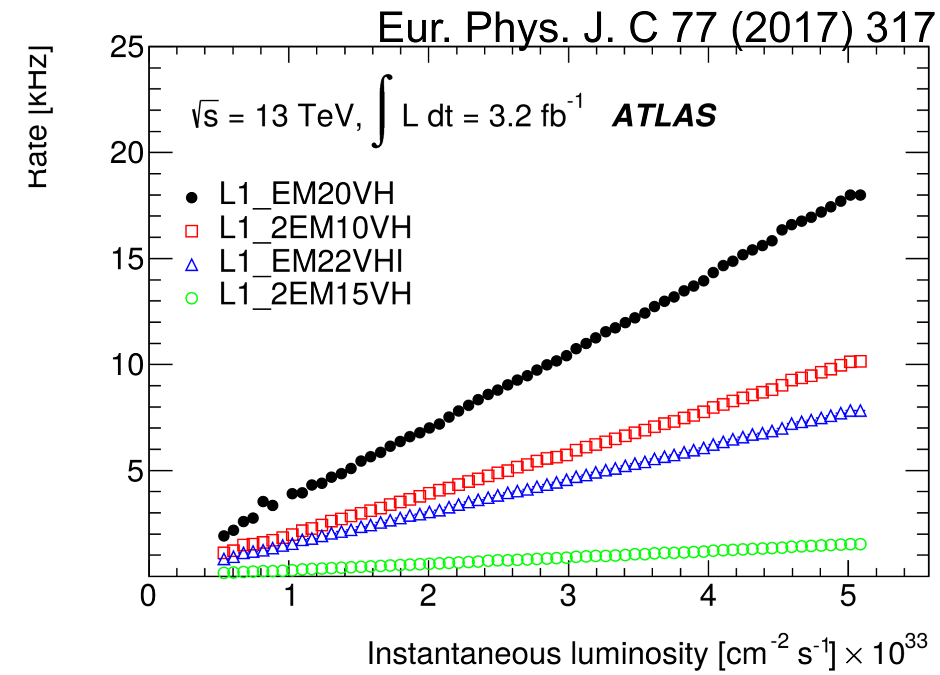
Trigger rates (July 2016) LHC fill with peak luminosity $1.02 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ and $\langle\mu\rangle = 24.2$





Two-level trigger system

- Level-1: Hardware-based
- HLT: Software-based



☑ Enabled by dedicated trigger items

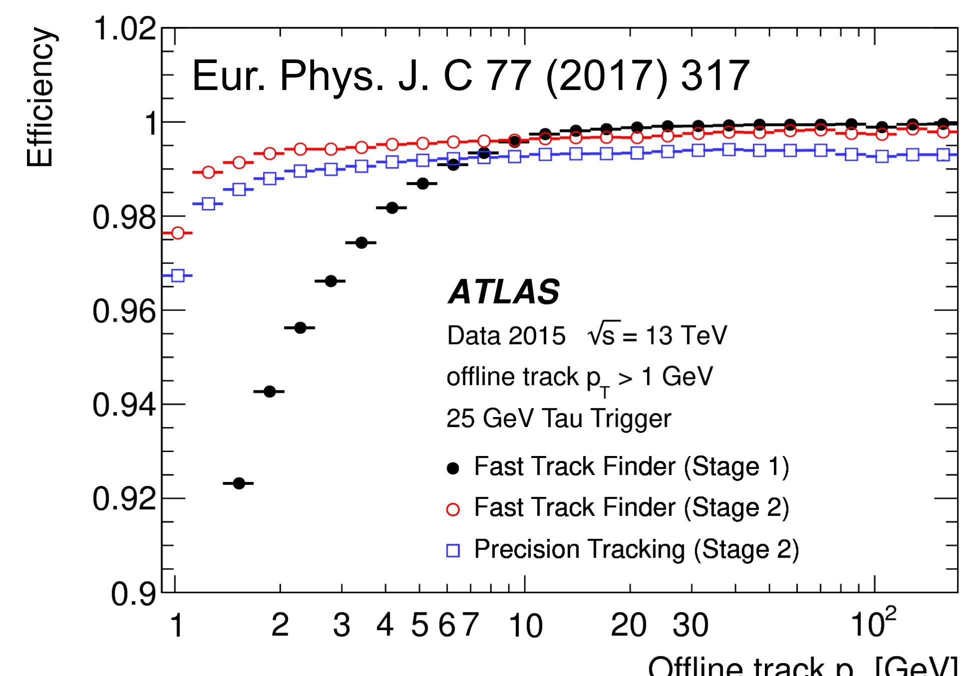
- Modified τ-lepton algorithms
- Activated: 9/2015 (φγ) and 5/2016 (ργ)
- Efficiency ~80% w.r.t offline selection

☑ Level-1: Isolated EM object

- Lowest pT unprescaled EM object

☑ HLT: Collimated/isolated high-pT track pair recoiling against high-pT photon

- Isolated di-track (leading $p_T > 15$ GeV) consistent with m_{Meson}
- Photon ($p_{T\gamma} > 35$ GeV)

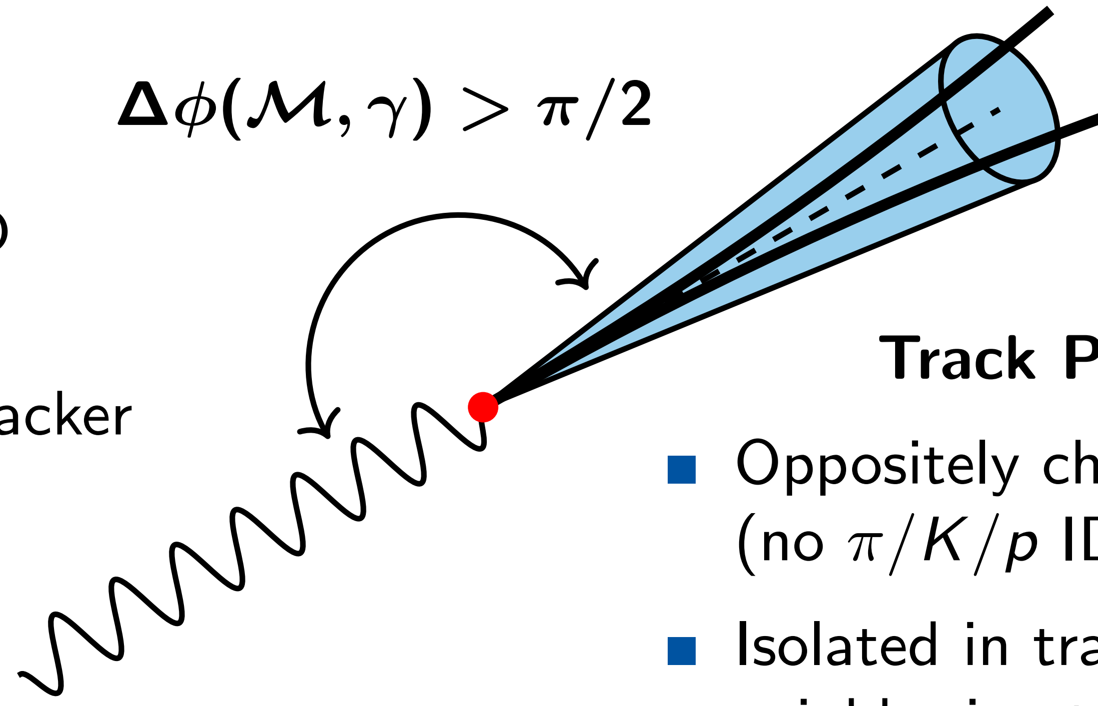


Event Selection

$p_{\mathrm{T}}^{\text{lead trk.}} > 20$ GeV

$p_{\mathrm{T}}^{\text{sub-lead trk.}} > 15$ GeV

$\Delta\phi(\mathcal{M},\gamma) > \pi/2$



Photon Selection

- "Tight" photon ID requirements
- Isolated in both tracker and calorimeter

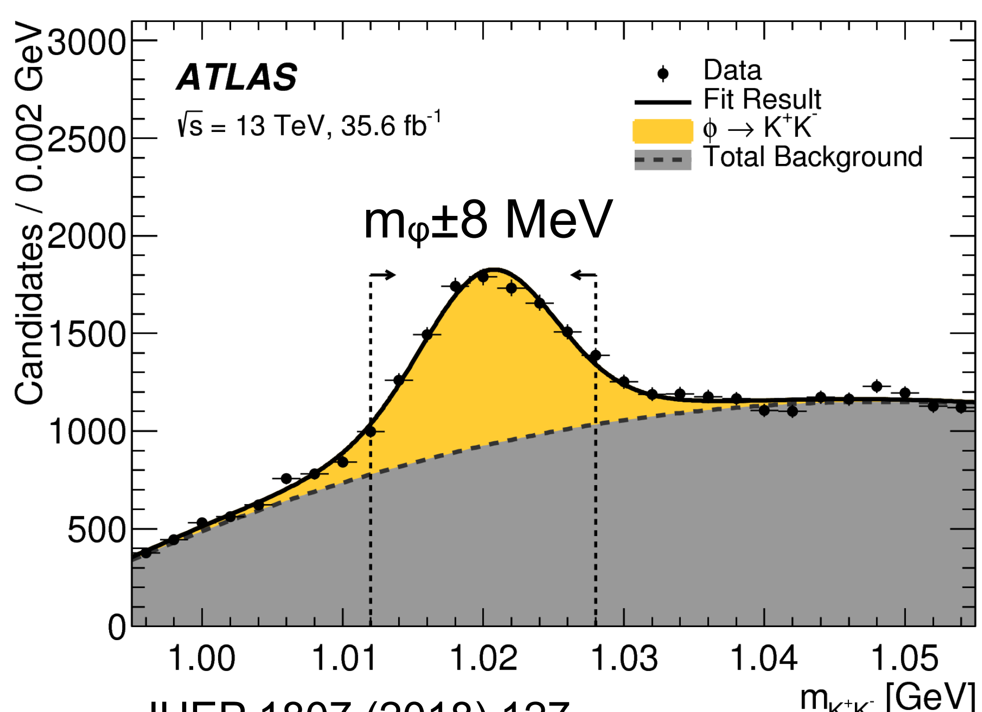
$p_{\mathrm{T}}^{\gamma} > 35$ GeV

Track Pair Selection

- Oppositely charged pair of tracks (no $\pi/K/p$ ID applied)
- Isolated in tracker (accounting for neighboring track)

$$p_{\mathrm{T}}^{M} > \begin{cases} 40\ \text{GeV}, & \text{for } m_{M\gamma} \leq 91\ \text{GeV} \\ 40 + 5/34 \times (m_{M\gamma} - 91)\ \text{GeV}, & \text{for } 91\ \text{GeV} < m_{M\gamma} < 140\ \text{GeV} \\ 47.2\ \text{GeV}, & \text{for } m_{M\gamma} \geq 140\ \text{GeV} \end{cases}$$

Signal $\mathscr{A}\times\epsilon$
- h(Z)→φ(→K⁺K⁻)γ ~17% (8%)
- h(Z)→ρ(→π⁺π⁻)γ ~10% (0.4%)



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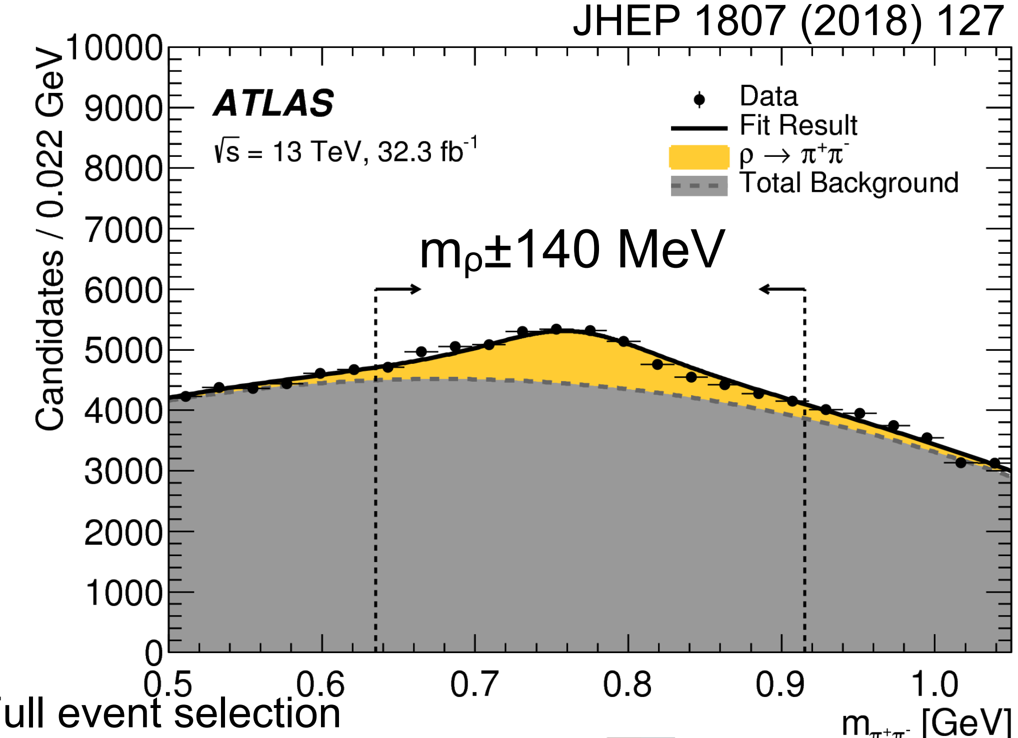
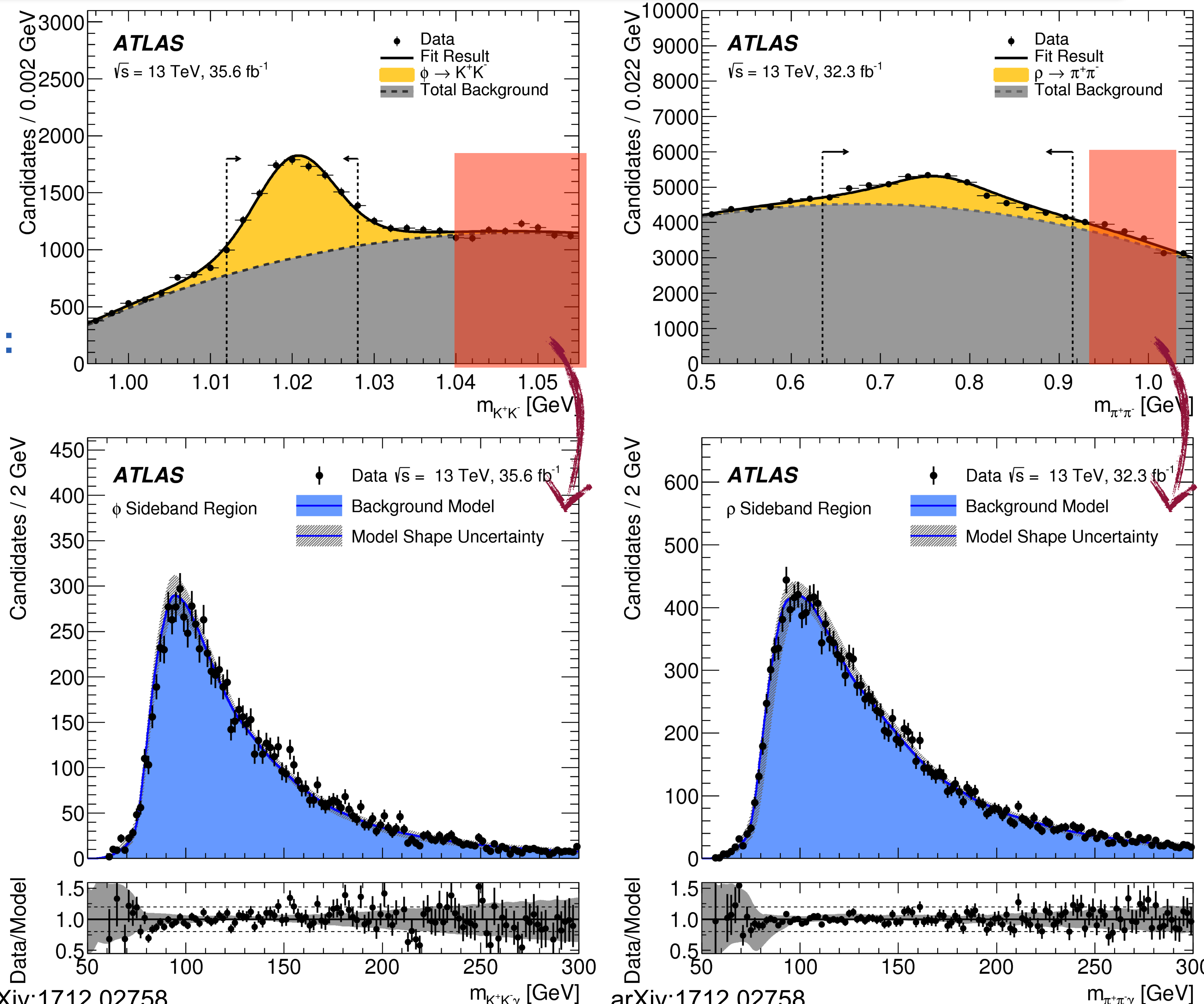


Full event selection w/o $m_{KK/\pi\pi}$ requirement

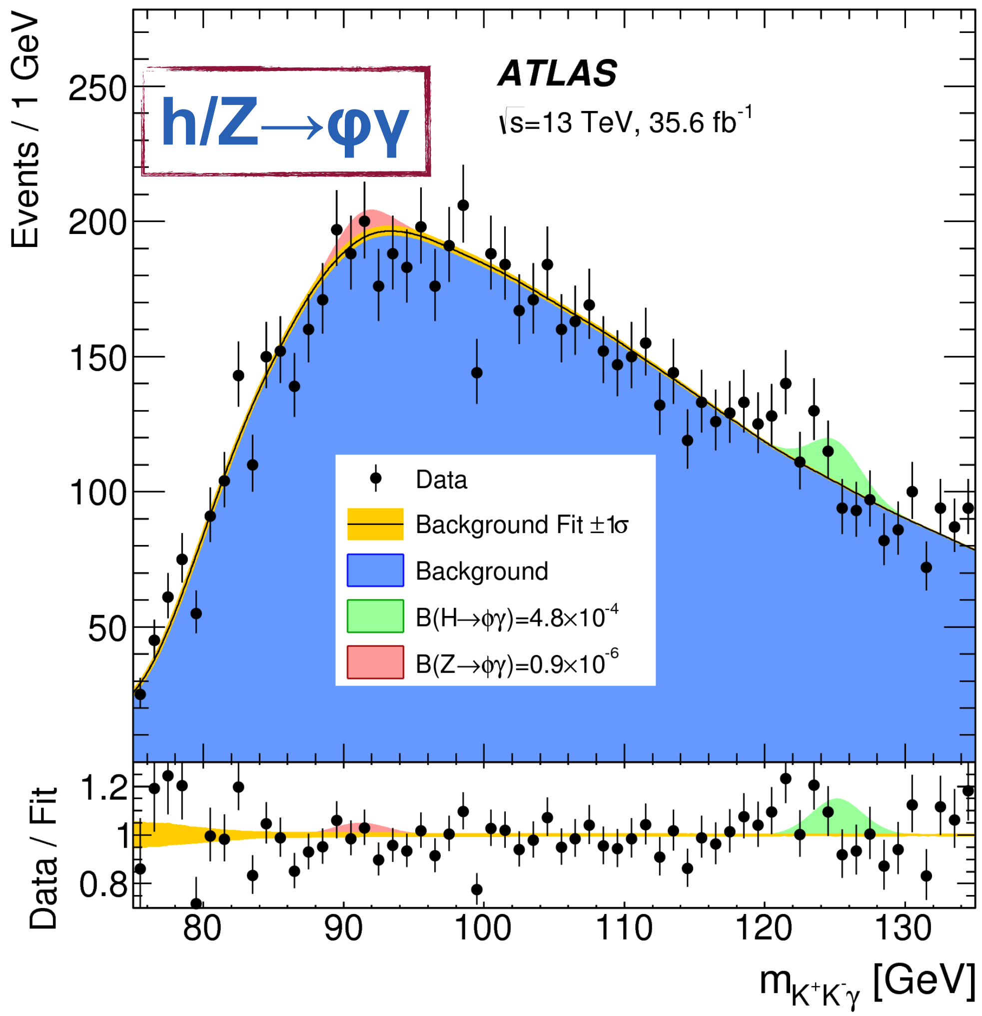
Background model/validation

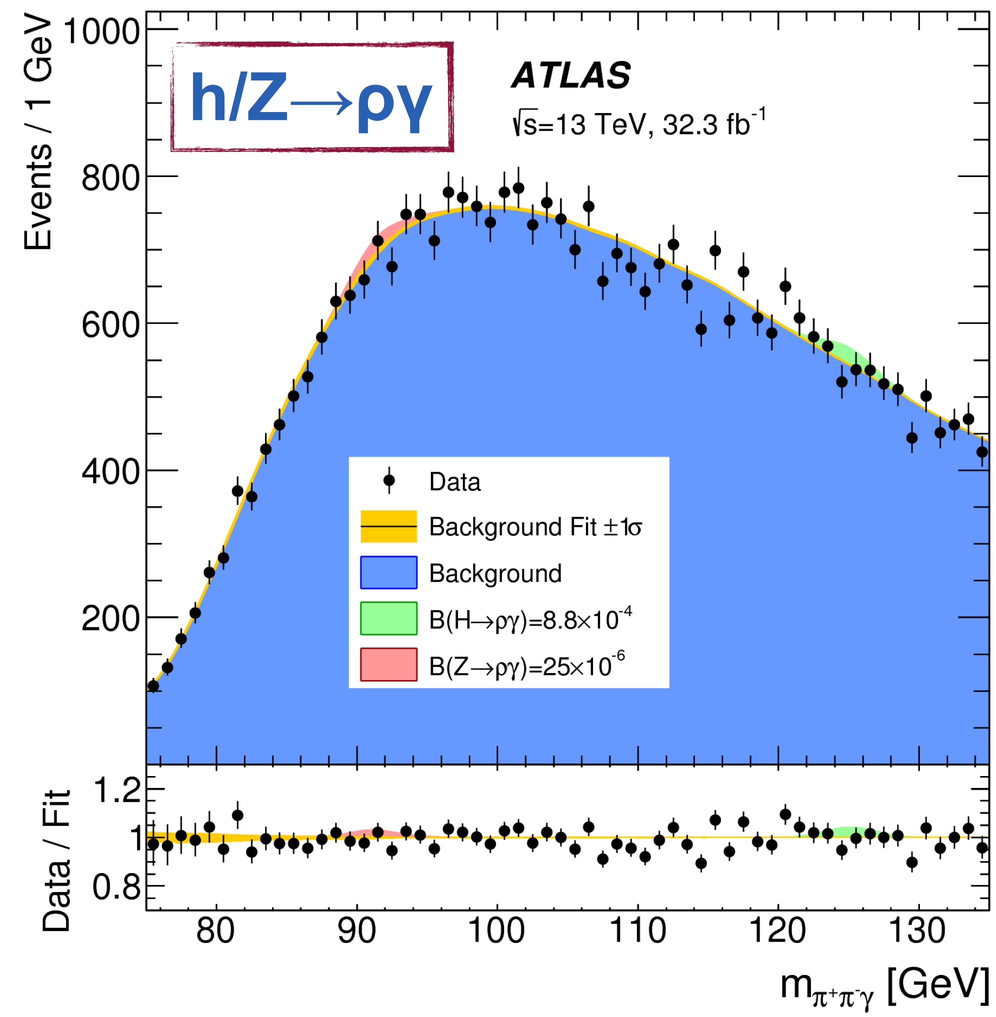
- **Background model:** same approach as in $h/Z \to \psi(mS)\gamma$ and $h/Z \to \Upsilon(nS)\gamma$
- Validation: also side-bands in ϕ/ρ mass



arXiv:1712.02758 arXiv:1712.02758

Results





- **Final discriminant** is $m_{KK\gamma}$ and $m_{\pi\pi\gamma}$
- **No significant signal observed**
- 95% confidence level **upper limit**
  - CLs with profile likelihood test statistic
  - Limit on production cross-section times branching ratio
    - $h\to\varphi\gamma$ < 25.3 fb
    - $h\to\rho\gamma$ < 45.5 fb

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H\to\phi\gamma)\ [10^{-4}]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z\to\phi\gamma)\ [10^{-6}]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H\to\rho\gamma)\ [10^{-4}]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z\to\rho\gamma)\ [10^{-6}]$	33^{+13}_{-9}	25

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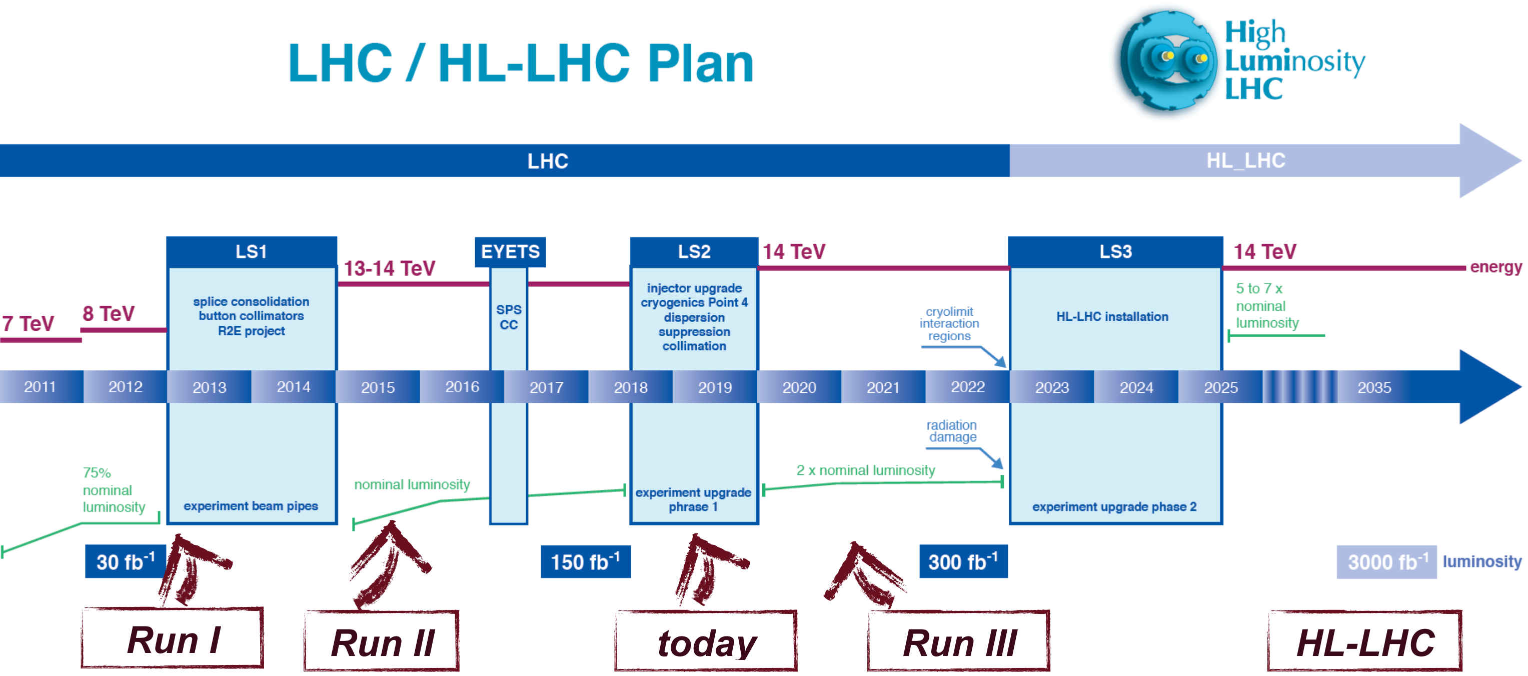
x3 improvement in expected limits with respect to 2.7/fb result [PRL 117, 111802]

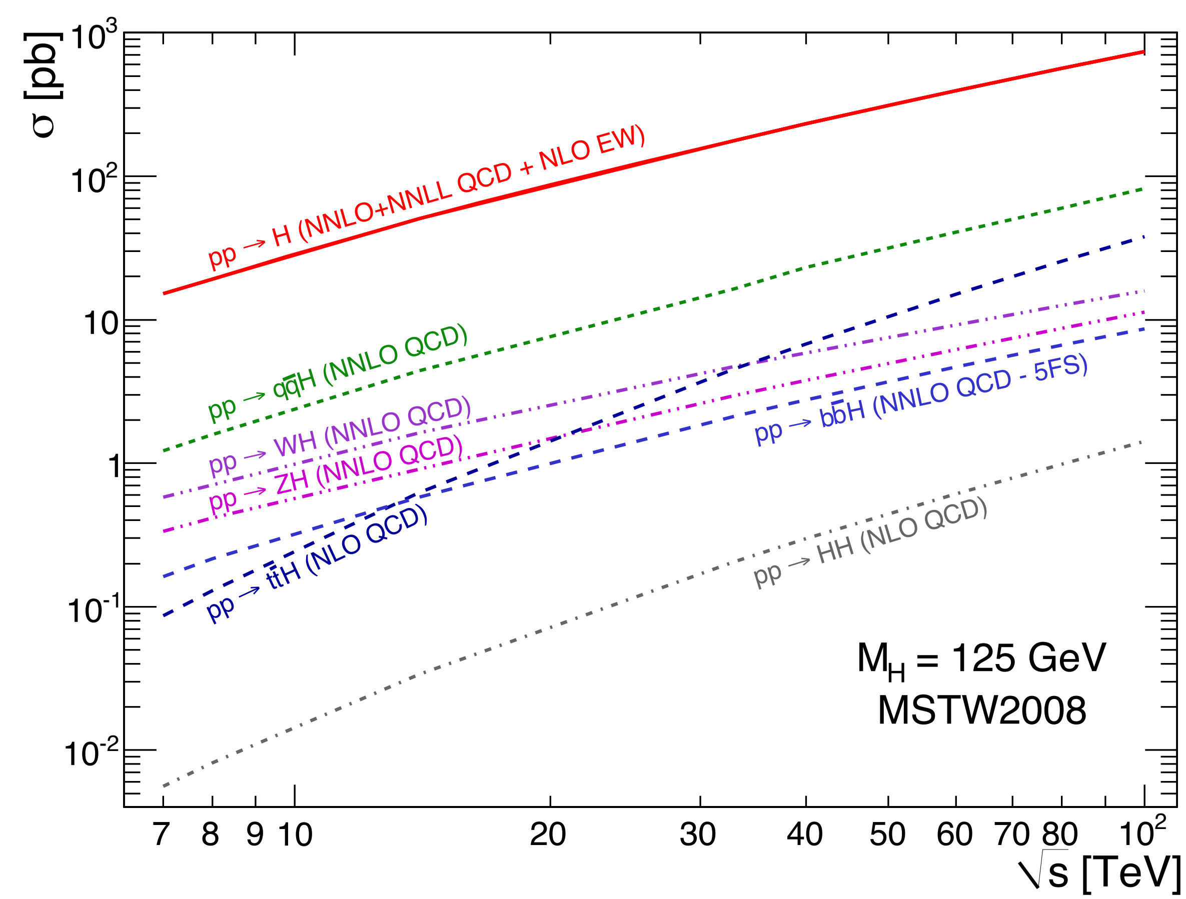
HL-LHC and beyond



ATLAS-PHYS-PUB-2015-043

	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)\ [10^{-6}]$		$\mathcal{B}(Z \to J/\psi\gamma)\ [10^{-7}]$
	Cut Based	Multivariate Analysis	Cut Based
$300\ \text{fb}^{-1}$	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
$3000\ \text{fb}^{-1}$	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$
	Standard Model expectation		
	$\mathcal{B}(H \to J/\psi\gamma)\ [10^{-6}]$		$\mathcal{B}(Z \to J/\psi\gamma)\ [10^{-7}]$
	2.9 ± 0.2		0.80 ± 0.05

- HL-LHC is a Higgs boson factory
  - $\mathcal{O}$(200M) Higgs bosons produced
- HL-LHC projections for h/Z→J/ψγ
  - Simple and, relatively, clean final state
  - Small branching ratio, few events expected
  - At SM sensitivity h→μμγ_{FSR} contribution ~3×h→J/ψγ and (Z→μμγ_{FSR} for Z)
  - Sensitive to "anomalous" h→γγ; use ratio
- Future colliders: leap in Higgs production rate
  - FCC-hh 100 TeV 20/ab: $\mathcal{O}$(15G) Higgs bosons



Associated production

- For HL-LHC **pp→hc** could be used
  - with high purity Higgs boson decays
  - SM cross section $\sigma(pp\to hc)\sim 166$ fb
- Main backgrounds are
  - $pp\to hg$ ($\sigma\sim 12$pb), $pp\to hcc$ (~ 55fb),
  - $pp\to hb$ ($\sigma\sim 200$fb)
- Phenomenological study suggests:
  - 2×3000 fb^{-1} $|\kappa_c|\lesssim 2$ at 95%CL

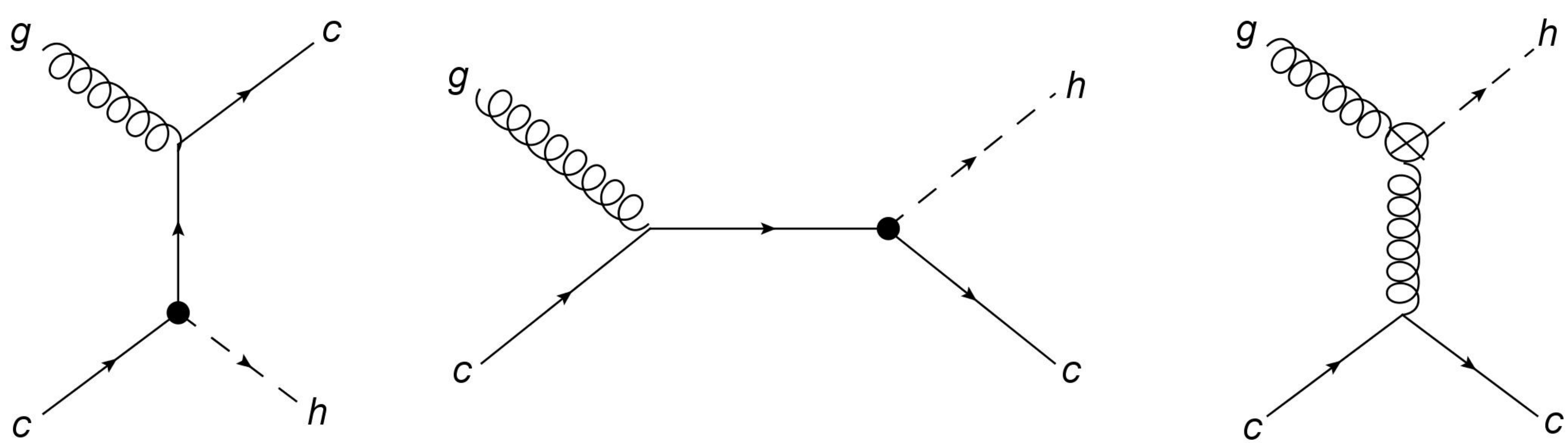
Phys.Rev.Lett. 115 (2015) 211801

$pp\to ch(\to\gamma\gamma)$ 3000 fb^{-1}

κ_c	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2
S	874	877	885	899	917	941	973	1008	1052

κ_c	2.25	2.5	2.75	3	3.25	3.5	3.75	4	4.25	4.5
S	1097	1148	1206	1276	1350	1424	1504	1590	1683	1786

[p_{Tj}>20 GeV, $|\eta_j|$<5, DR(j_1,j_2)>0.4, ε_c=0.4, $\varepsilon_{g\to c}$=1%, $\varepsilon_{b\to c}$=30%]



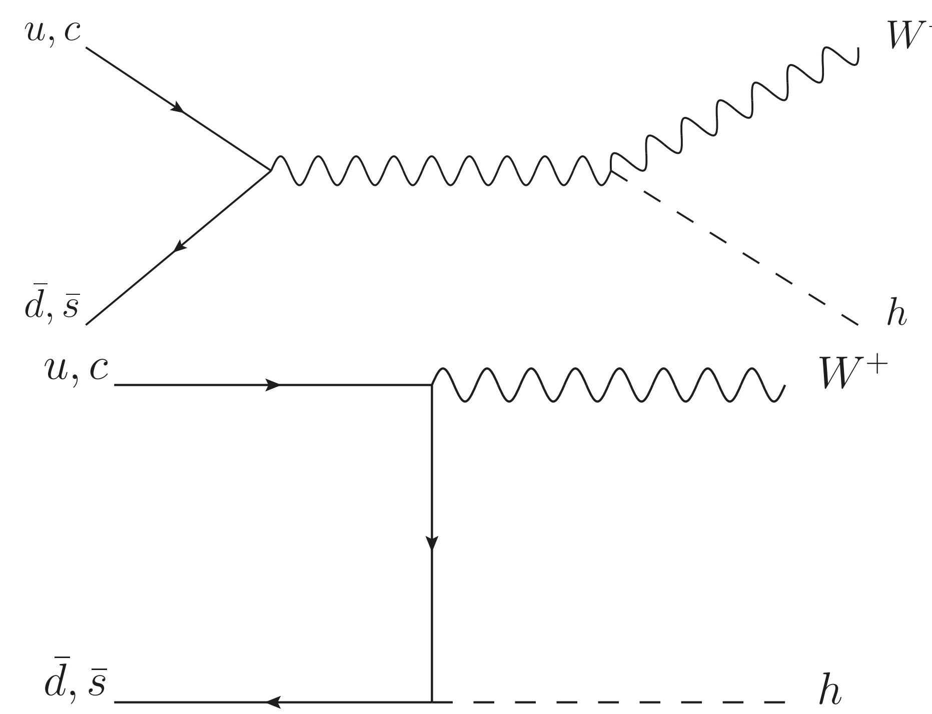
Wh production asymmetries

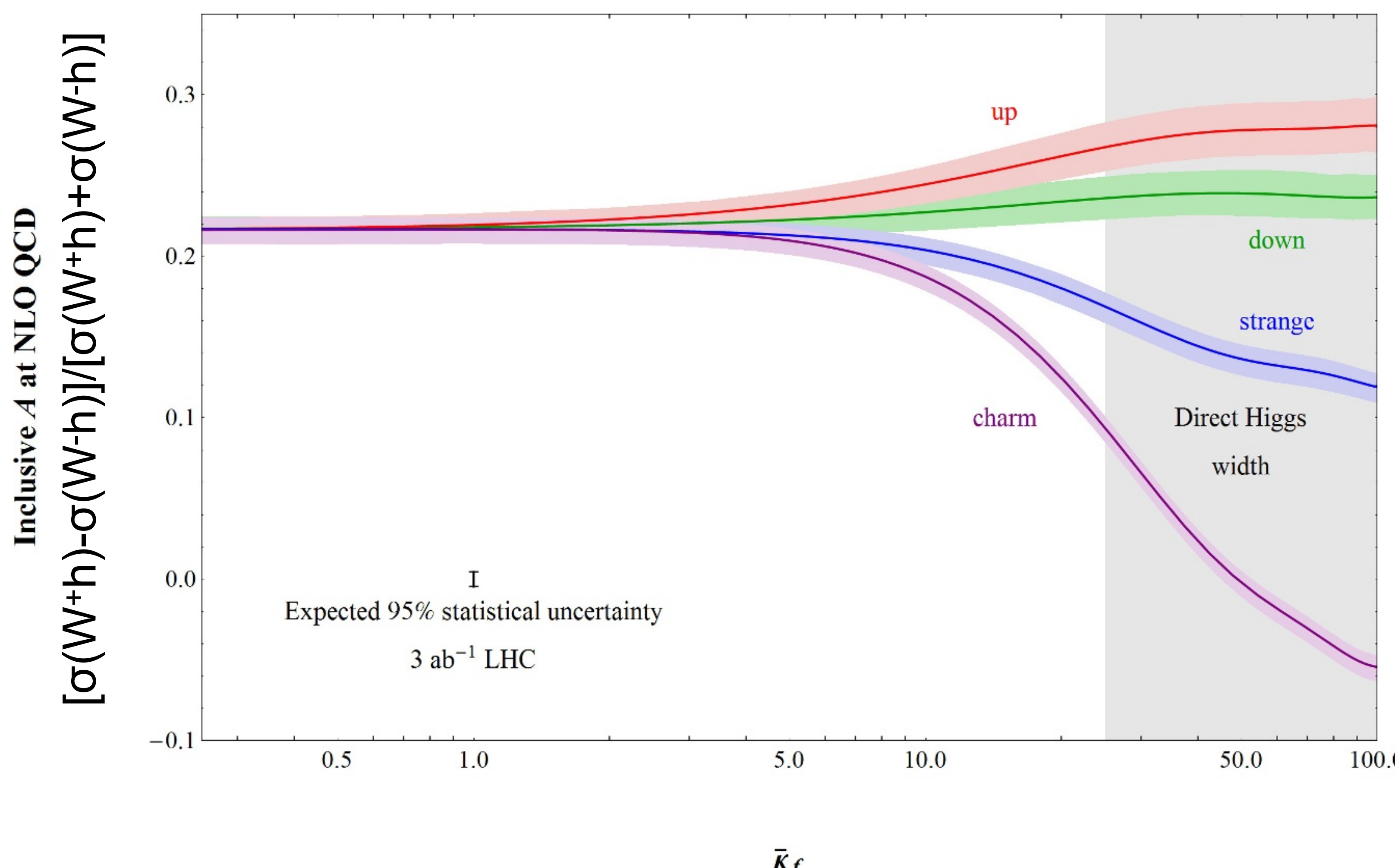
- Derive constraints on Higgs boson-quark couplings through asymmetry in **Wh production**
  - SM σ(W⁺h)/σ(W⁻h) = 1.56
- Phenomenological study of Wh→WWW→l±νl±νjj for HL-LHC suggests the following constraints:

$$\kappa_d < 1270, \quad \kappa_u < 2860, \quad \kappa_s < 53, \quad \kappa_c < 5$$

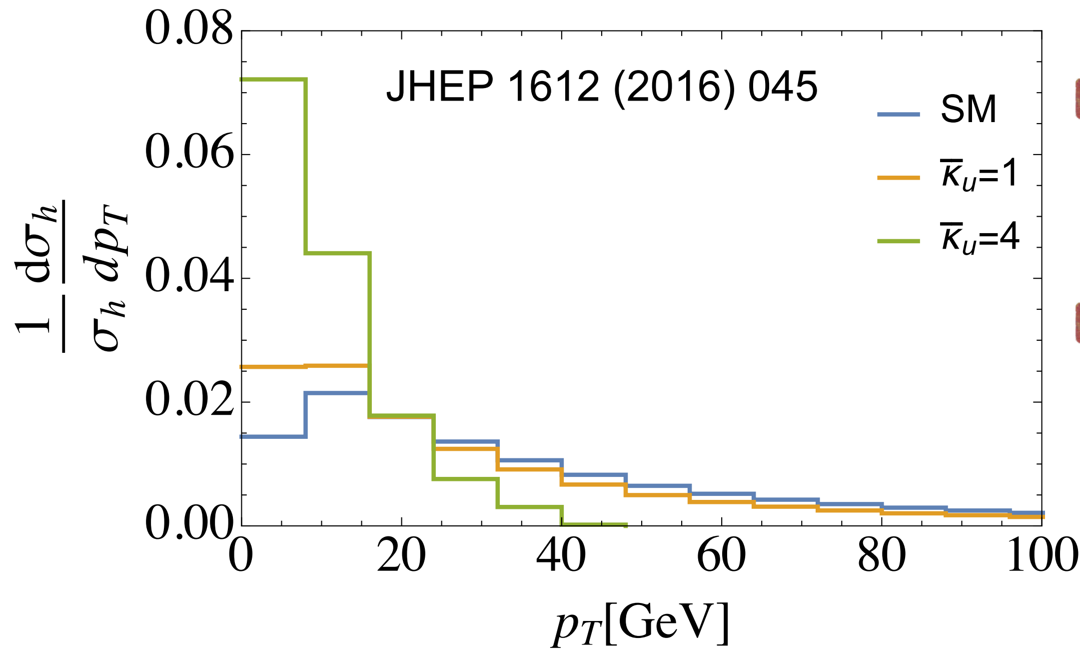
$$\bar{\kappa}_d < 1.24, \quad \bar{\kappa}_u < 1.34, \quad \bar{\kappa}_s < 1.03, \quad \bar{\kappa}_c < 1.14\,,$$

JHEP 02 (2017) 083



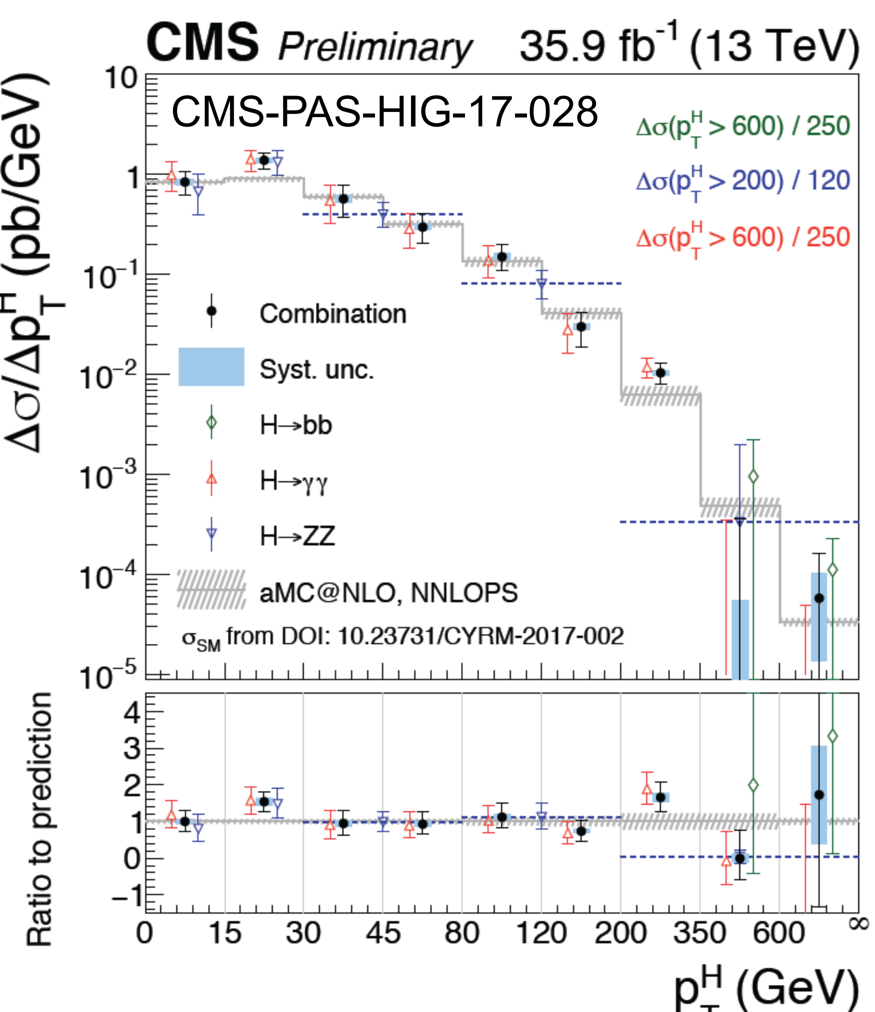


Kinematic distributions

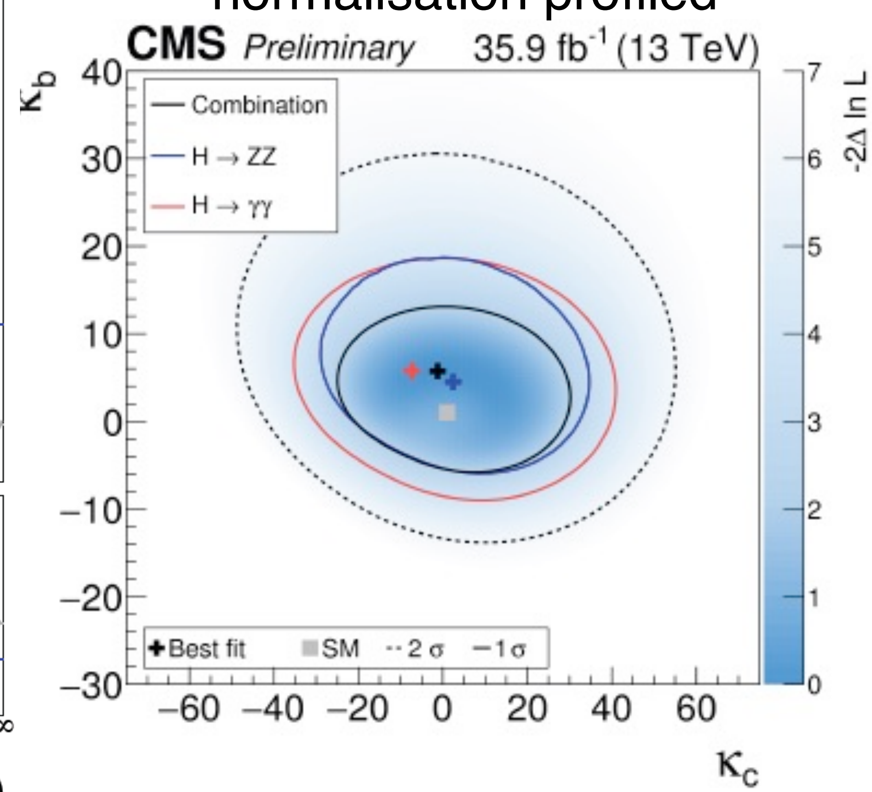


- Derive constraints on Higgs boson-quark couplings through the **Higgs boson kinematic distributions**
  - For example pT_h or y_h
- Phenomenological study suggests that couplings to up- and down-quarks could be constrained to <0.4 of the b-quark Yukawa at HL-LHC.

PRL 118 (2017) 121801, JHEP 1612 (2016) 045, arXiv:1608.04376



BR freely floating
Constraints only from shape
normalisation profiled

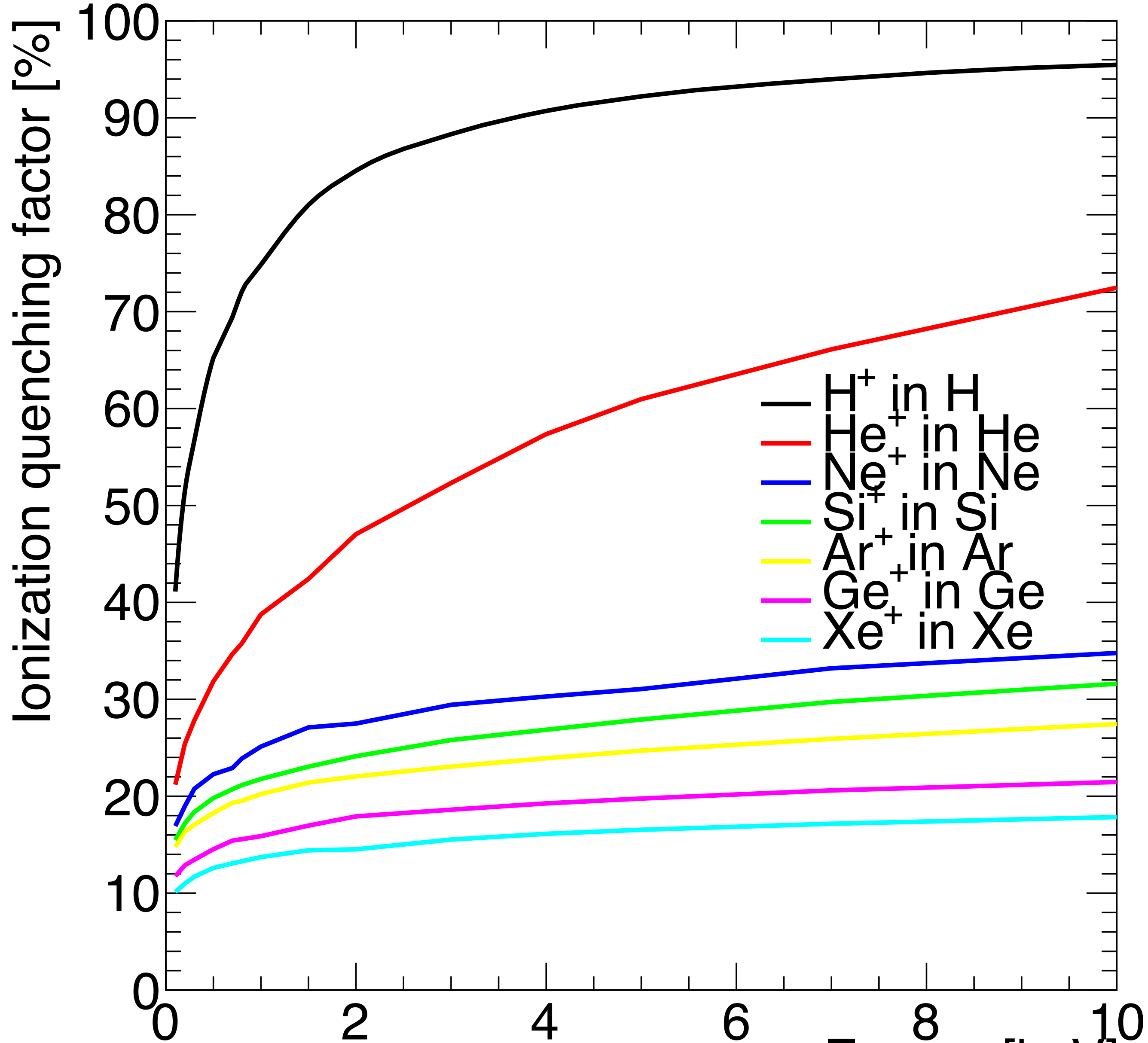


- Inputs: h→γγ, h→ZZ→4l
  - 13 TeV and 35.9 fb^{-1}
  - boosted h→bb sensitivity pTH>350 GeV not used
- MADGRAPH5 aMC@NLO
  - ggF reweighted to NNLOPS
- PT spectra w/ light quark effects from PRL 118 (2017) 121801

- Limits on κ_c at 68% CL:
  - Observed: (-18.0,22.9)
  - Expected: (- 15.7,19.3)

Searching for light DM: Quenching Factor

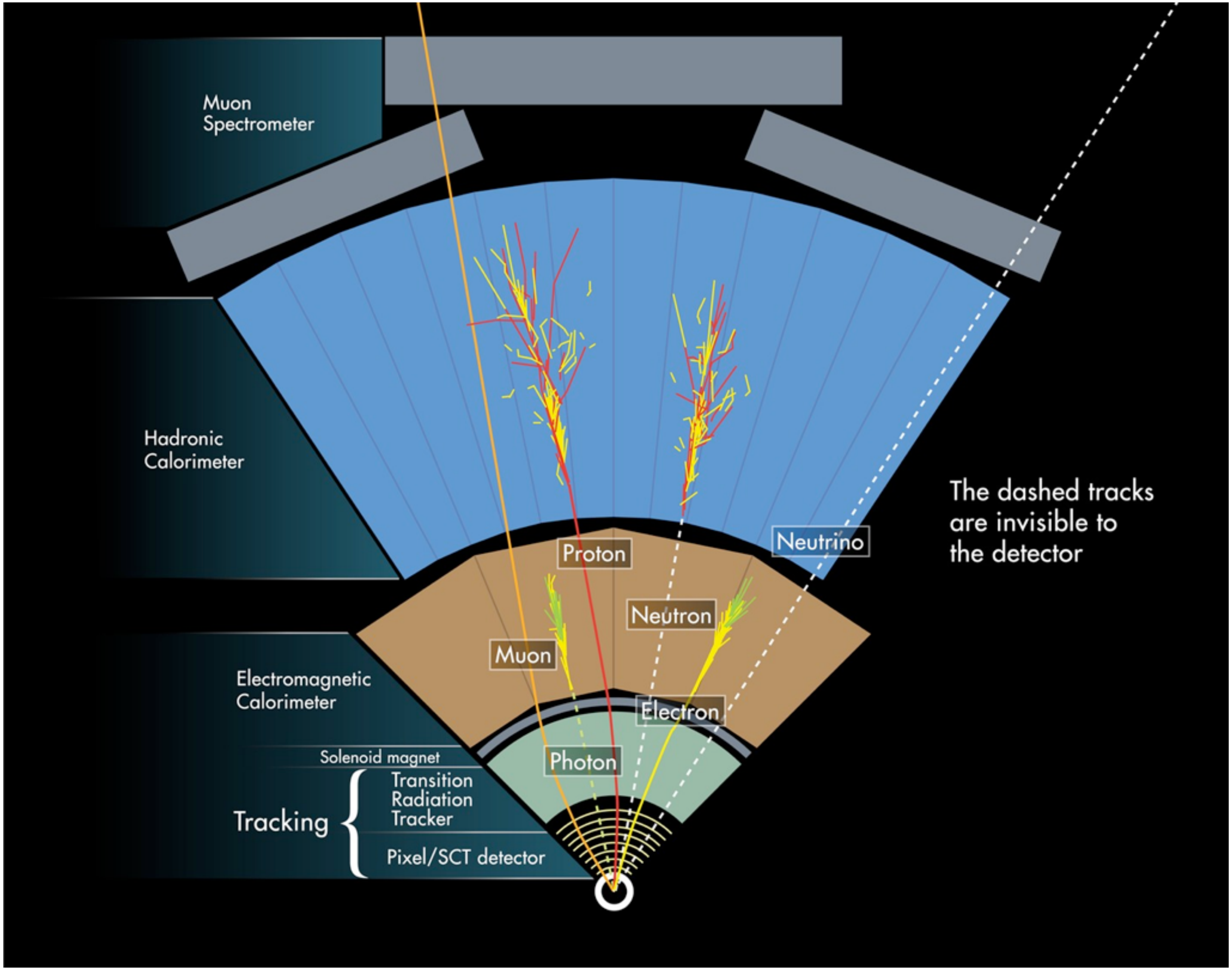
- Quenching factor: fraction of ion kinetic energy dissipated in a medium in the form of ionization electrons and excitation of the atomic and quasi-molecular states.



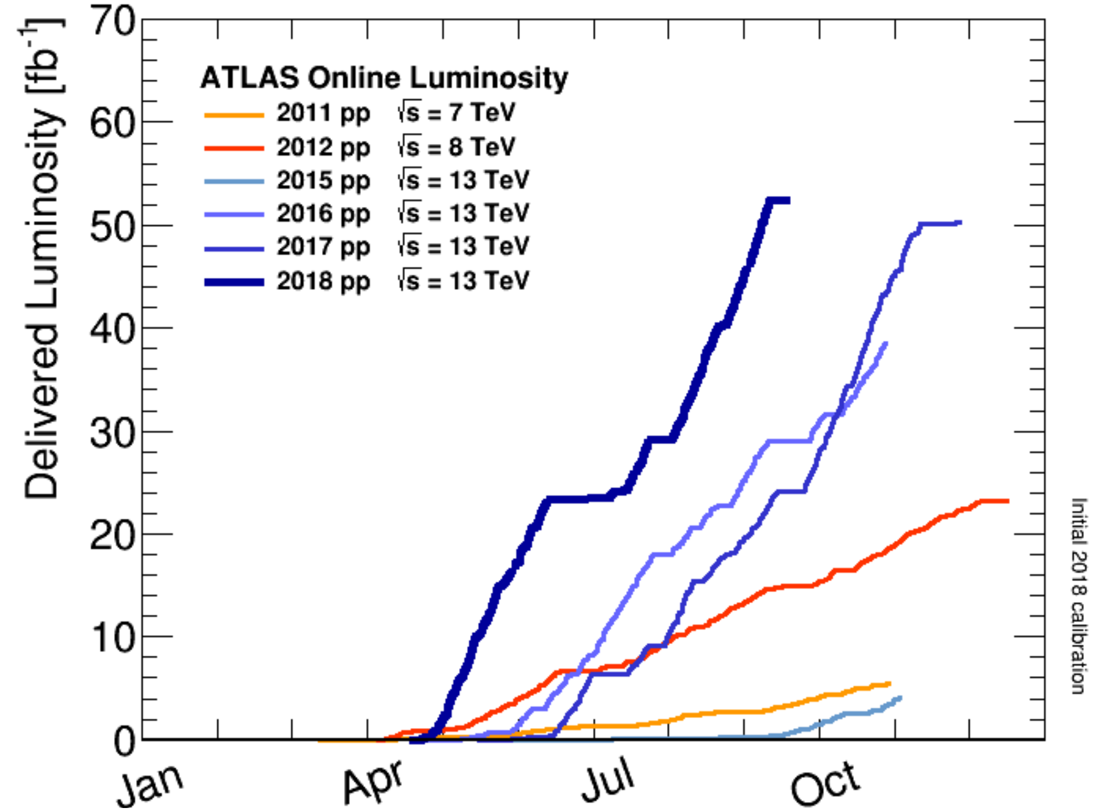
Plot by I. Katsioulas

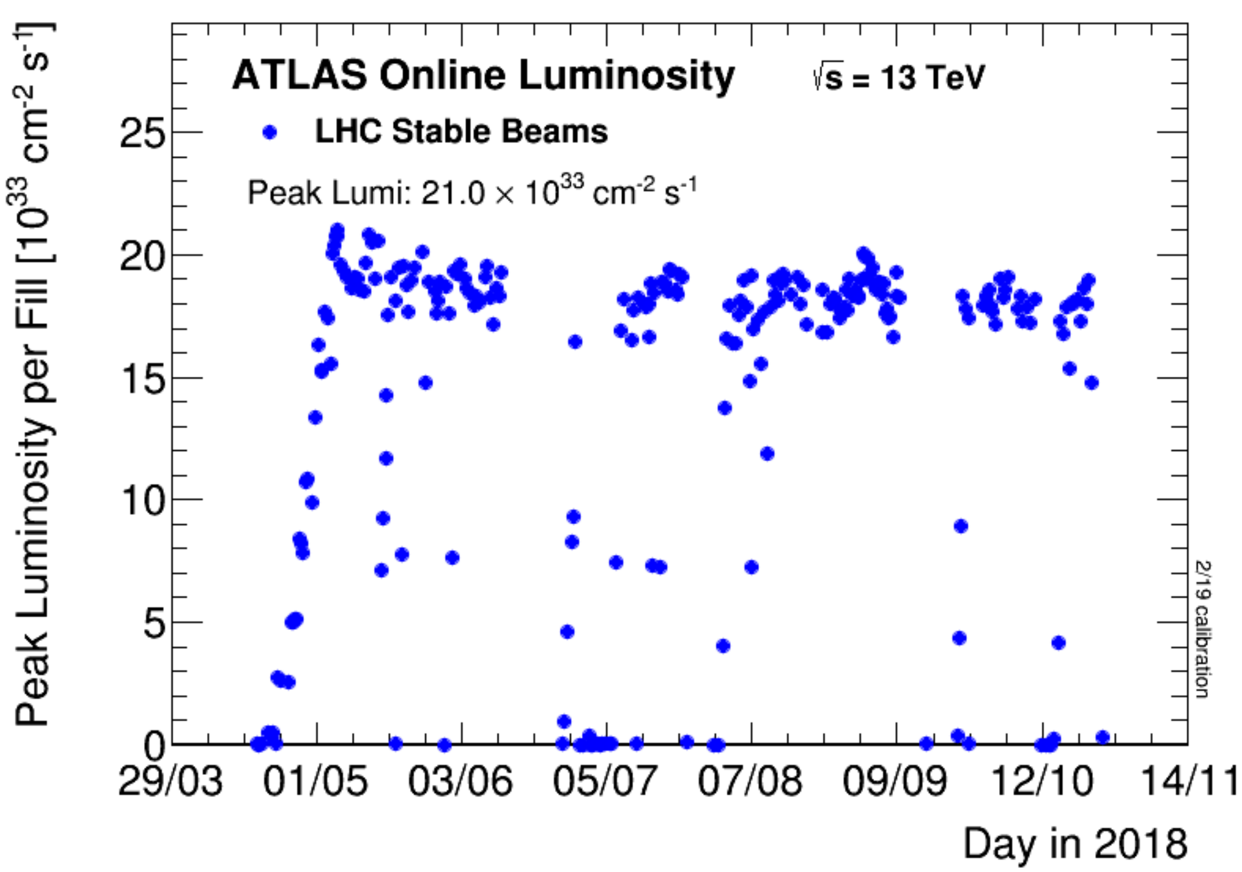
- Direct detection experiment using light gases as target (H, He, Ne)
  - Better projectile-target kinematic match
  - Favourable quenching factor

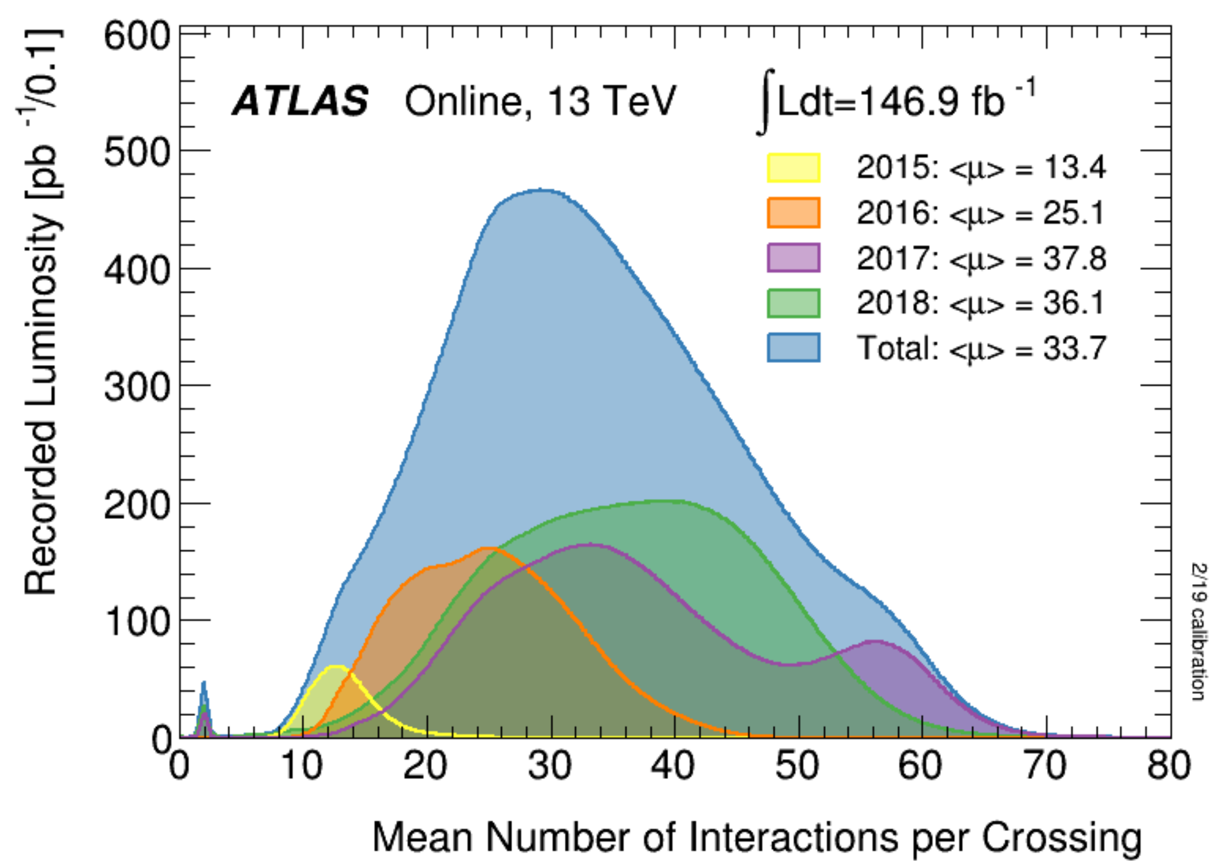
The ATLAS detector



The Large Hadron Collider

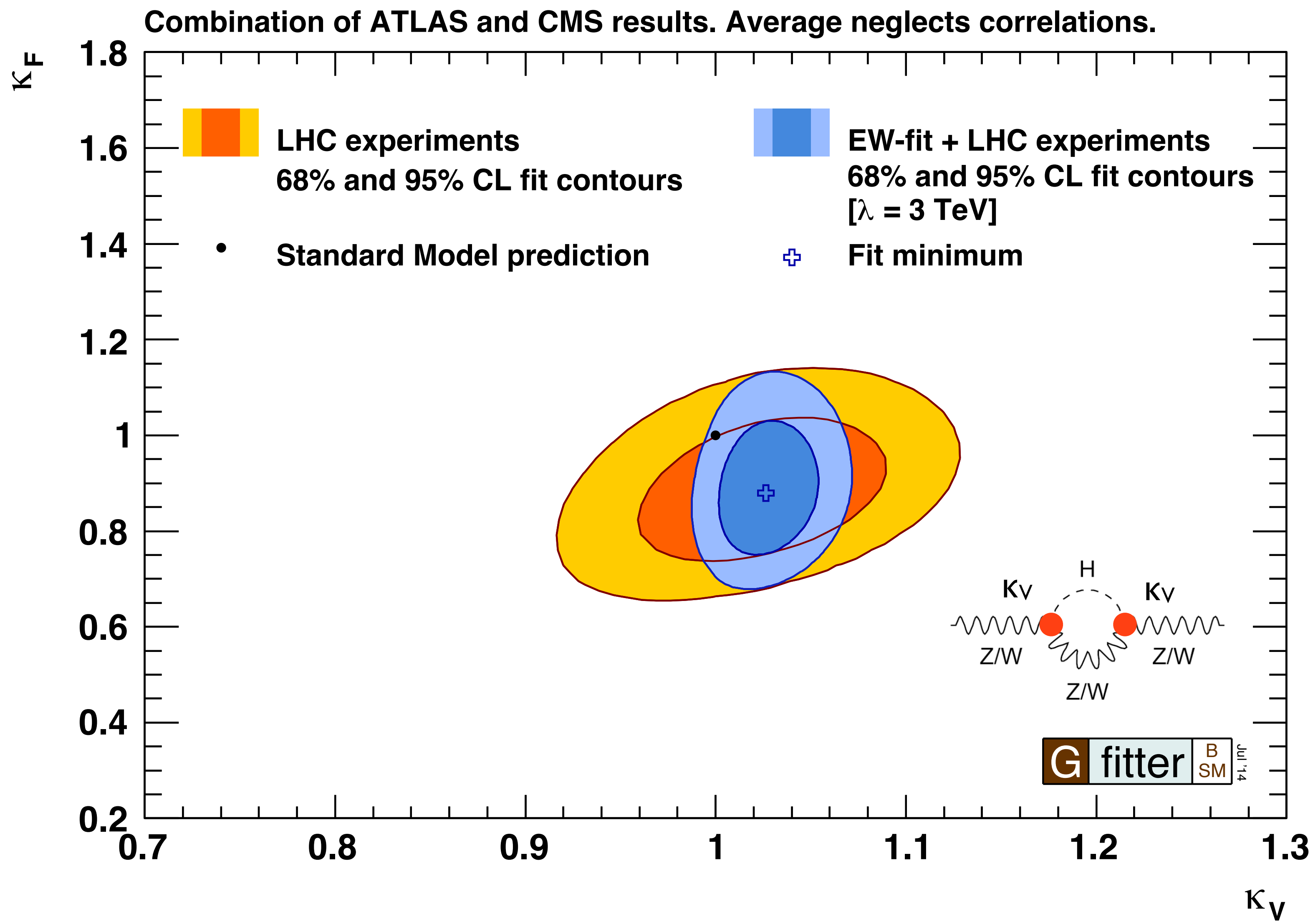






Higgs boson and electroweak fit

Common coupling scaling for all Fermions (κ_F) and for all Bosons (k_V); no BSM contributions



Global EW fit still more precise for κ_V than Higgs boson measurements
κ_V>1 preferred (many BSM scenarios require κ_V<1)
Global EW fit has ~ no effect on determination of κ_F

Experimental information on Yukawa couplings essential to fully characterize the observed Higgs boson!

Zh(→cc):Event Selection

- **First search** for exclusive Zh→llcc decays, l=e, μ
  - Main backgrounds: Z+jets, Z(W/Z), ttbar

$Z \to \ell^+\ell^-$ Selection

- Trigger with lowest available p_{T} single electron or muon triggers
- Exactly two same flavour reconstructed leptons (e or μ)
- Both leptons $p_{\mathrm{T}} > 7$ GeV and at least one with $p_{\mathrm{T}} > 27$ GeV
- Require opposite charges (dimuons only)
- $81 < m_{\ell\ell} < 101$ GeV
- $p_{\mathrm{T}}^{Z} > 75$ GeV

$H \to c\bar{c}$ Selection

- Consider anti-k_{T} $R = 0.4$ calorimeter jets with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 20$ GeV
- At least two jets with leading jet $p_{\mathrm{T}} > 45$ GeV
- Form $H \to c\bar{c}$ candidate from the two highest p_{T} jets in an event
- At least one c-tagged jet from $H \to c\bar{c}$ candidate
- Dijet angular separation ΔR_{jj} requirement which varies with p_{T}^{Z}

- Split events into 4 categories
  - h→cc candidates with 1 or 2 c-tags
  - p_{TZ} above/below 150 GeV

Exclusive Decays $h \to Q\gamma$

- Substantial interest from theory community on branching ratio estimates and feasibility

Mode	Branching Fraction [10^{-6}]		
Method	NRQCD [1487]	LCDA LO [1486]	LCDA NLO [1489]
$\mathrm{Br}(h \to \rho\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(h \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(h \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$

PRD90 (2014) 113010 PRL 114 (2015) 101802 JHEP 1508 (2015) 012

Not exhaustive; accurate at the time of YR4.

e.g. Phys.Rev. D95 (2017) 054018
Phys.Rev. D96 (2017) 116014
Phys.Rev. D97 (2018) 016009

Decay mode	Branching ratio
$Z^0 \to \pi^0\gamma$	$(9.80\,^{+0.09}_{-0.14}\,{}_{\mu} \pm 0.03_f \pm 0.61_{a_2} \pm 0.82_{a_4}) \cdot 10^{-12}$
$Z^0 \to \rho^0\gamma$	$(4.19\,^{+0.04}_{-0.06}\,{}_{\mu} \pm 0.16_f \pm 0.24_{a_2} \pm 0.37_{a_4}) \cdot 10^{-9}$
$Z^0 \to \omega\gamma$	$(2.89\,^{+0.03}_{-0.05}\,{}_{\mu} \pm 0.15_f \pm 0.29_{a_2} \pm 0.25_{a_4}) \cdot 10^{-8}$
$Z^0 \to \phi\gamma$	$(8.63\,^{+0.08}_{-0.13}\,{}_{\mu} \pm 0.41_f \pm 0.55_{a_2} \pm 0.74_{a_4}) \cdot 10^{-9}$
$Z^0 \to J/\psi\,\gamma$	$(8.02\,^{+0.14}_{-0.15}\,{}_{\mu} \pm 0.20_f\,^{+0.39}_{-0.36}\,{}_{\sigma}) \cdot 10^{-8}$
$Z^0 \to \Upsilon(1S)\,\gamma$	$(5.39\,^{+0.10}_{-0.10}\,{}_{\mu} \pm 0.08_f\,^{+0.11}_{-0.08}\,{}_{\sigma}) \cdot 10^{-8}$
$Z^0 \to \Upsilon(4S)\,\gamma$	$(1.22\,^{+0.02}_{-0.02}\,{}_{\mu} \pm 0.13_f\,^{+0.02}_{-0.02}\,{}_{\sigma}) \cdot 10^{-8}$
$Z^0 \to \Upsilon(nS)\,\gamma$	$(9.96\,^{+0.18}_{-0.19}\,{}_{\mu} \pm 0.09_f\,^{+0.20}_{-0.15}\,{}_{\sigma}) \cdot 10^{-8}$

JHEP 1504 (2015) 101

Kinematic Distributions

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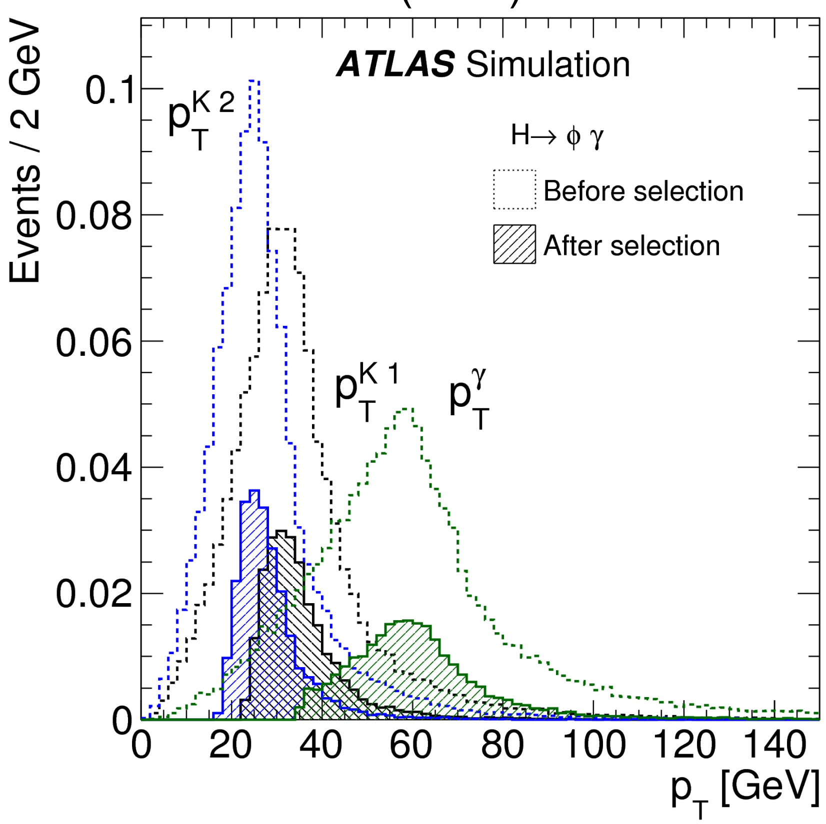

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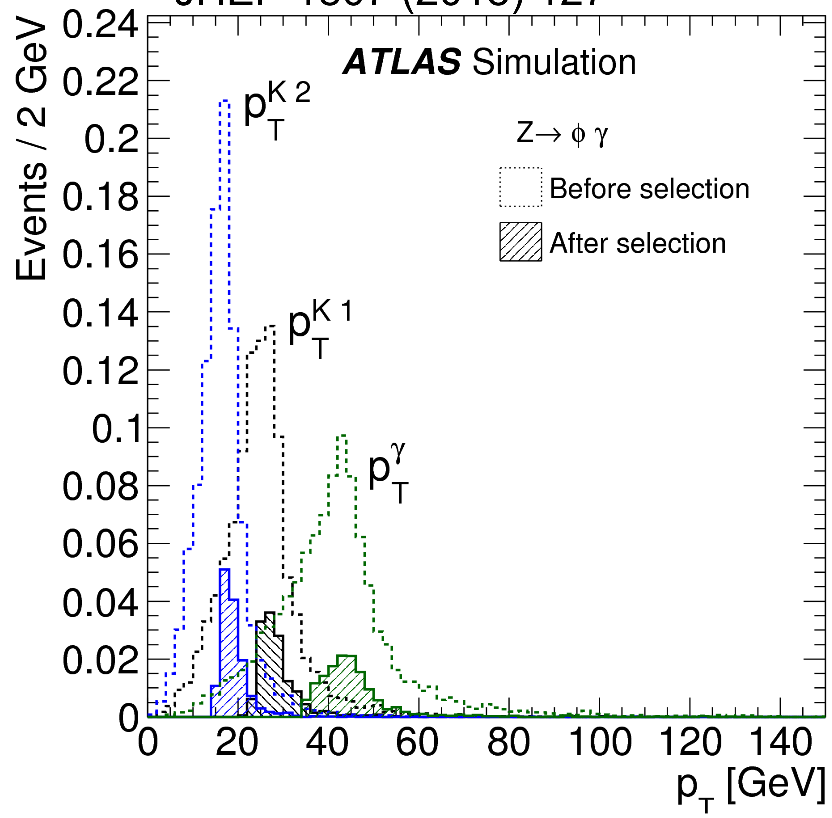

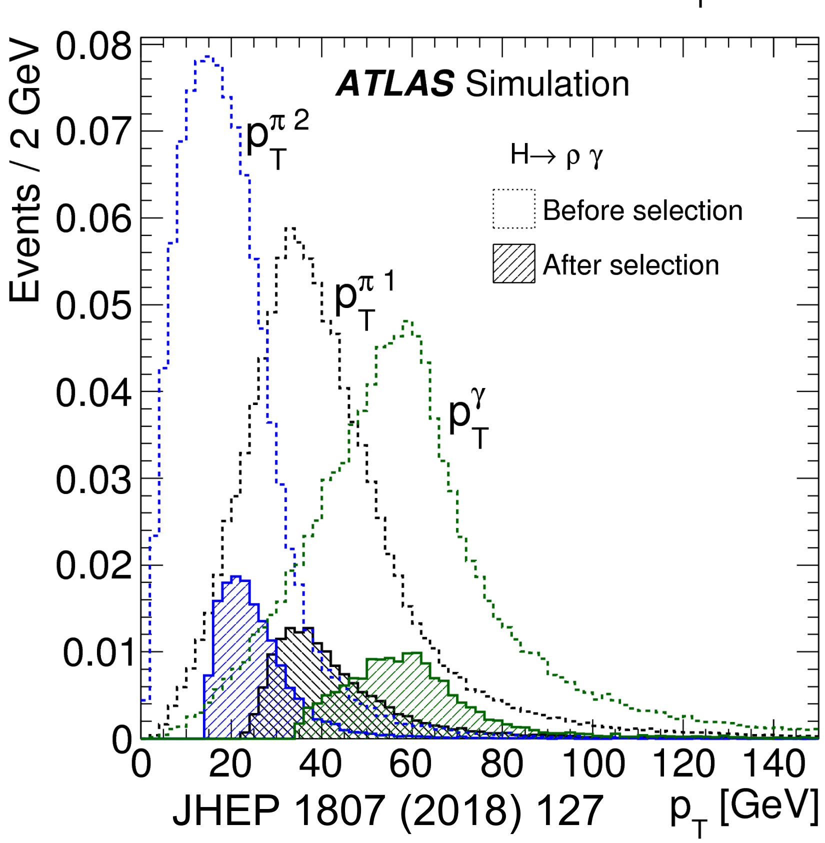

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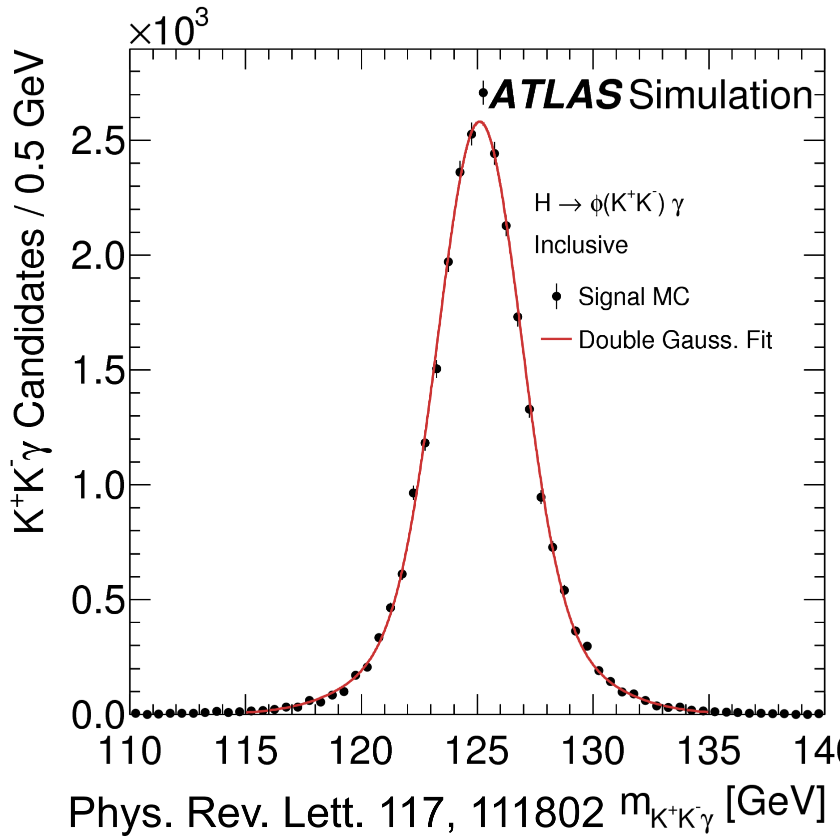


Phys. Rev. Lett. 117, 111802

- **No categorisation**
- **Mass resolution ~1.8%**
- **Signal Model**
  - Higgs: double Gauss
  - Z: double Voigt with eff. corr.
- **Signal Systematic Uncertainty**

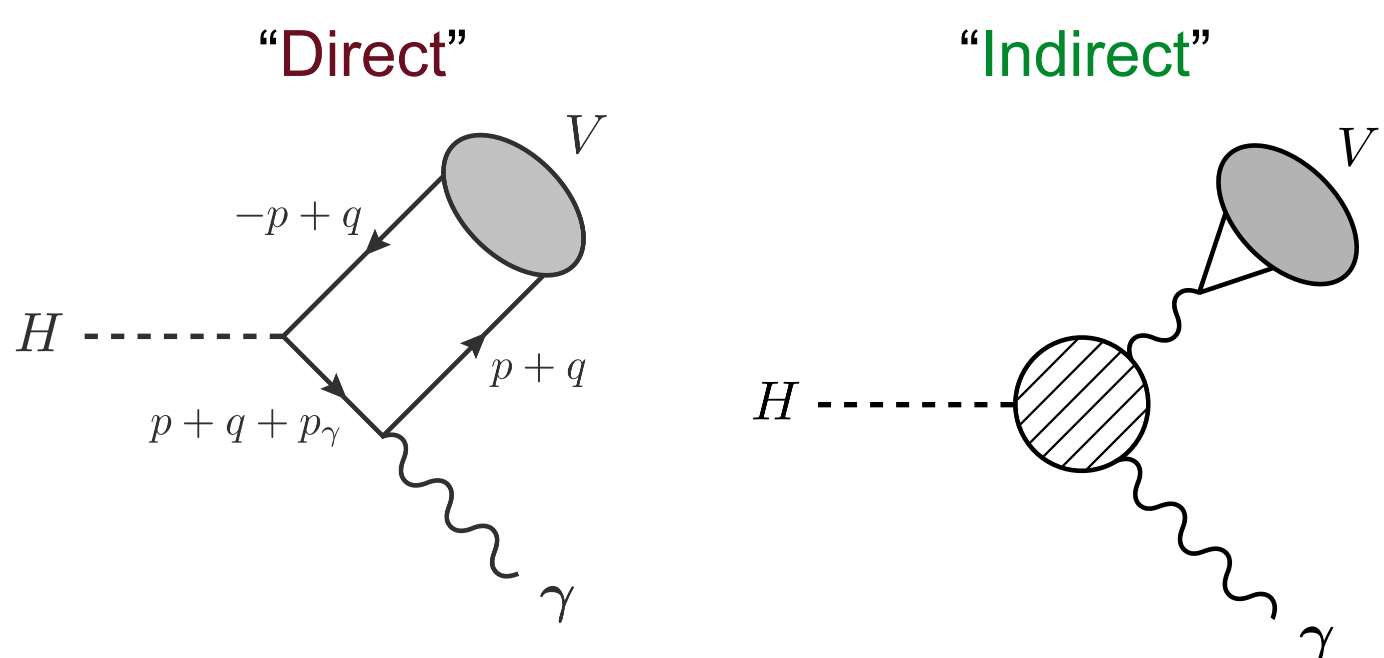
Source of systematic uncertainty	Yield uncertainty
Total H cross section	6.3%
Total Z cross section	2.9%
Integrated luminosity	3.4%
Photon ID efficiency	2.5%
Trigger efficiency	2%
Tracking efficiency	6%

Exclusive Decays: Signal uncertainties

Source of Uncertainty	Signal Yield Uncertainty [%]	
	ϕ/ρ	ψ/Υ
H Signal Modelling	6.3	7.2
Z Signal Modelling	2.9	5.7
Integrated Luminosity	3.4	2.1
Photon ID Efficiency	2.5	1.4
Trigger Efficiency	2.0	2.0
Tracking Efficiency	6.0	–
Muon ID Efficiency	–	2.8

Exclusive Decays h→Qγ

- **h→Qγ decays: clean probe** for Higgs-quark couplings for 1st/2nd generation quarks
  - Q is a vector meson or quarkonium state
- **Two contributions:**
  - **Direct amplitude:** sensitive to Higgs boson-quark couplings
  - **Indirect amplitude:** insensitive to Higgs boson-quark couplings; larger than direct
  - **Destructive interference**



BR(h→J/ψγ)~2.9 10^{-6}

$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

Phys.Rev. D90 (2014) 11, 113010

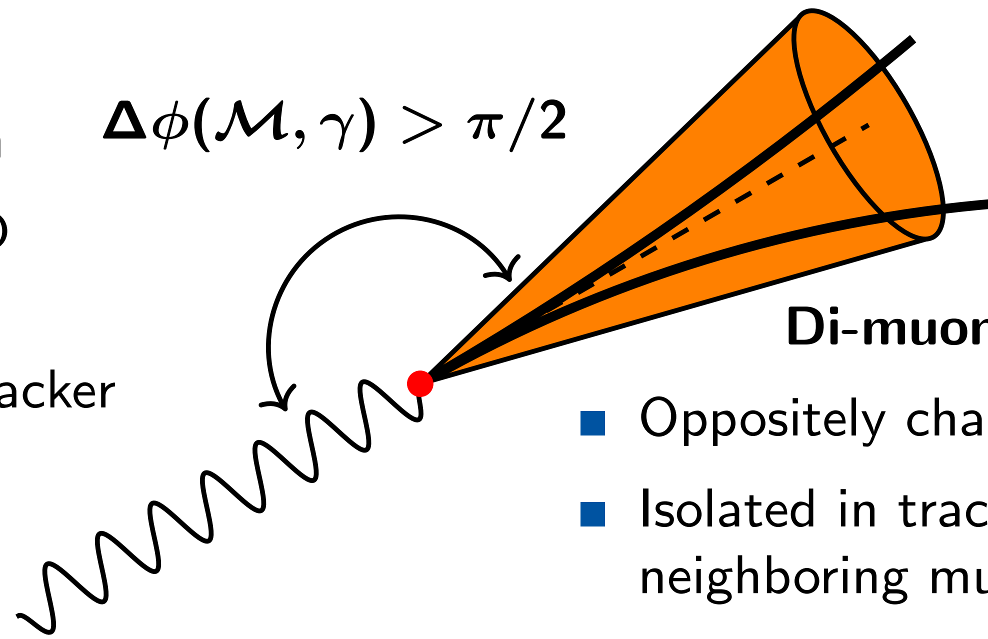
- **Similar decays of W± and Z bosons: also rich physics programme**
  - **Novel** precision studies of quantum chromo-dynamics
  - **W±/Z boson interactions with light quarks** not well covered at earlier facilities
  - **Discovery potential** for new physics processes

h/Z→ψ(mS)γ (m=1,2) and h/Z→Υ(nS)γ (n=1,2,3)

Photon Selection

- "Tight" photon ID requirements
- Isolated in both tracker and calorimeter

$\Delta\phi(\mathcal{M},\gamma) > \pi/2$



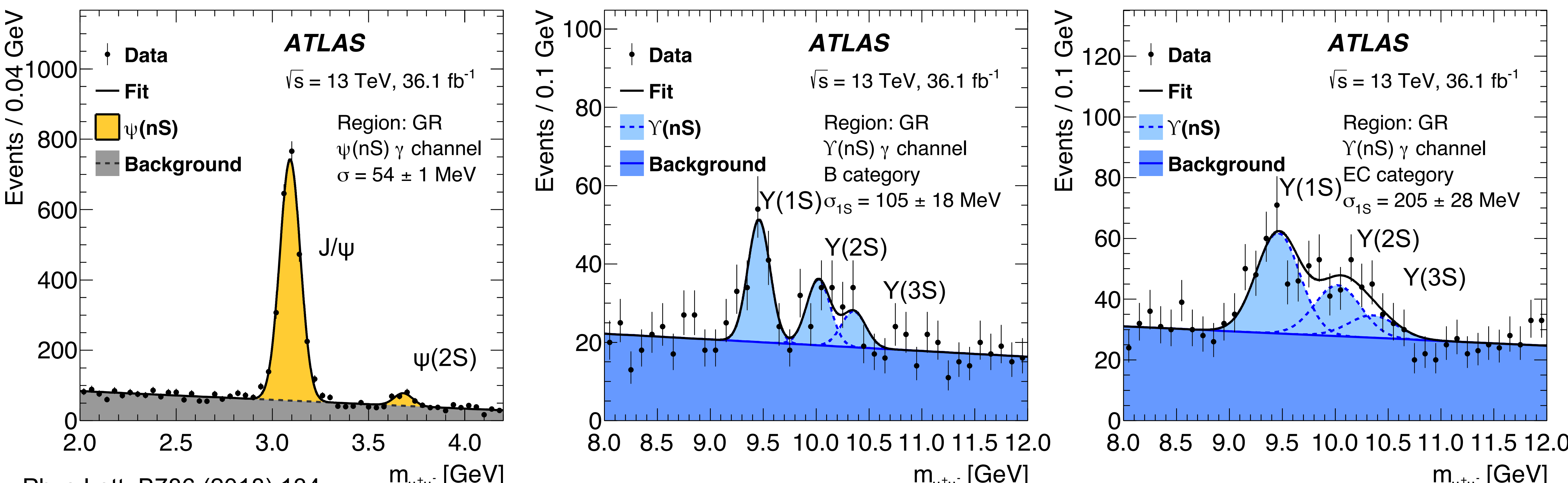
$p_{\mathrm{T}}^{\gamma} > 35$ GeV

$p_{\mathrm{T}}^{\mu\ \mathrm{lead}} > 18$ GeV

$p_{\mathrm{T}}^{\mu\ \mathrm{sub\text{-}lead}} > 3$ GeV

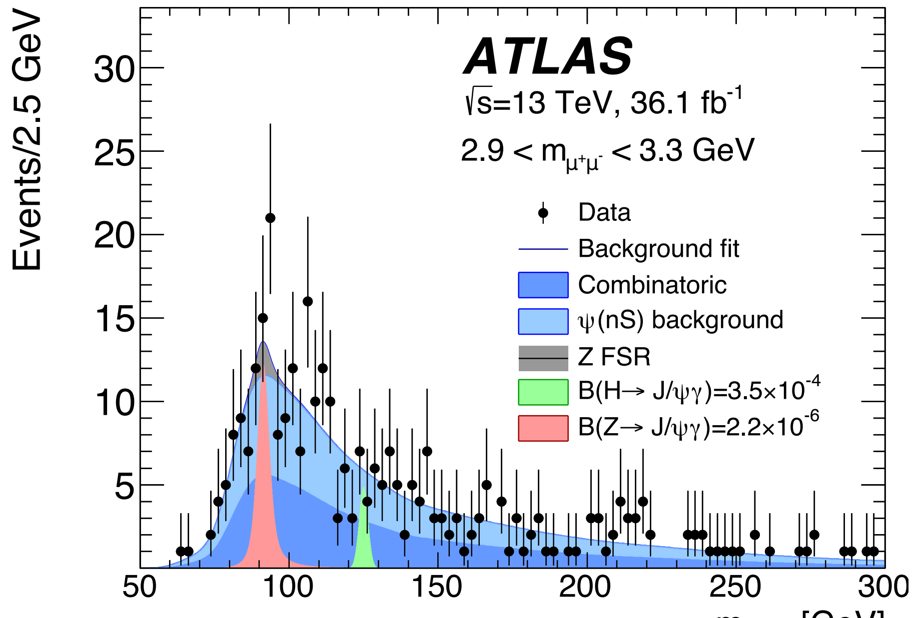
Di-muon Selection

- Oppositely charged pair of muons
- Isolated in tracker (accounting for neighboring muon track)
- $L_{xy}/\sigma_{L_{xy}} < 3$ to reject $b \to \psi(nS)$

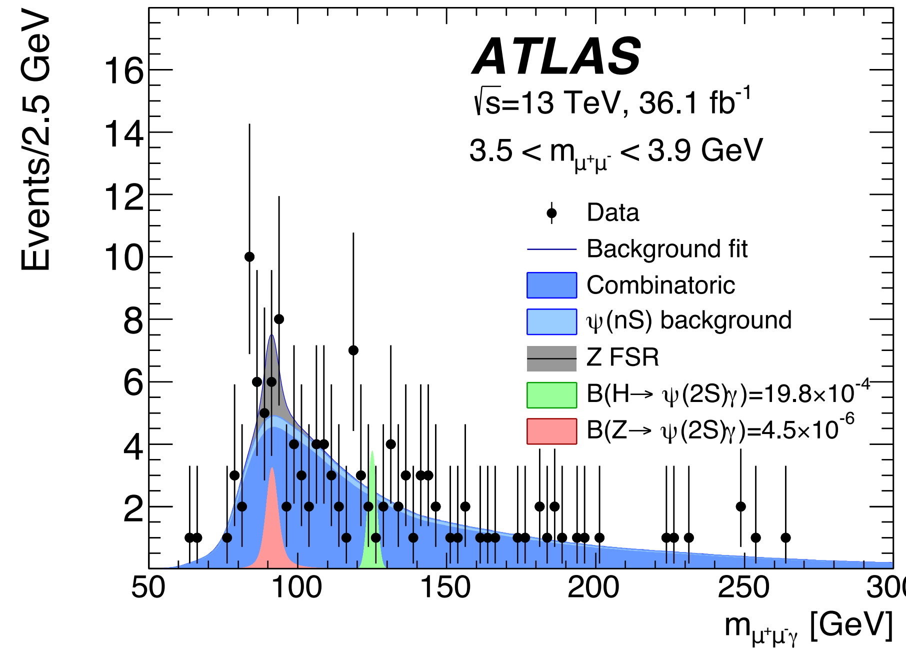


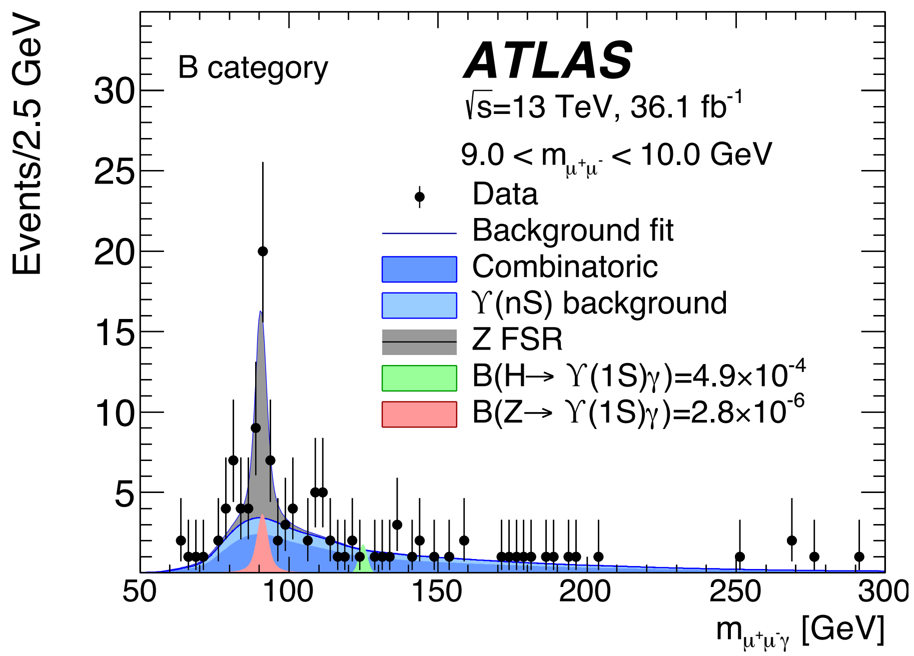
Phys.Lett. B786 (2018) 134

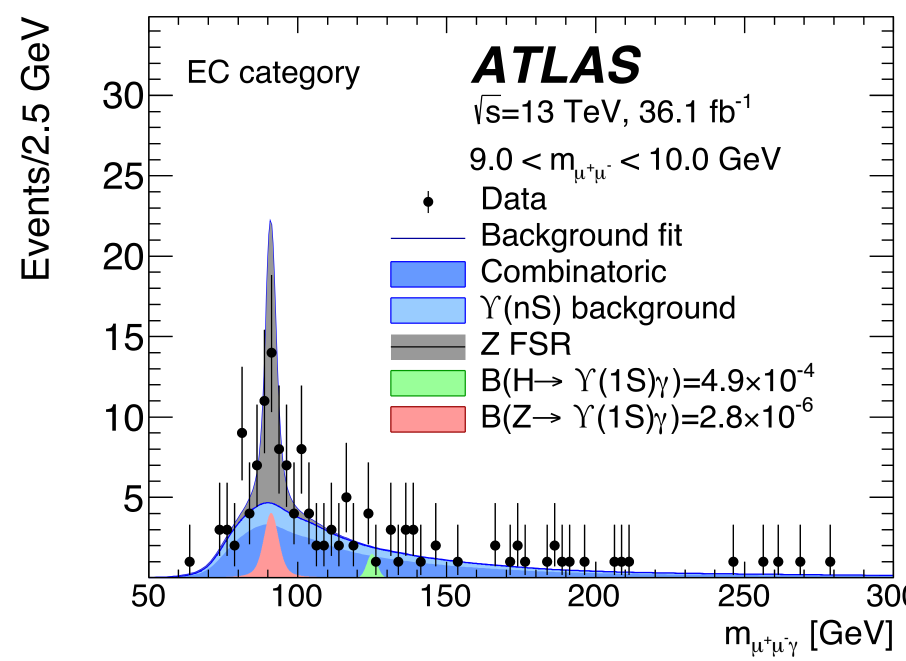
h/Z→Qγ: Results



arXiv:1807.00802





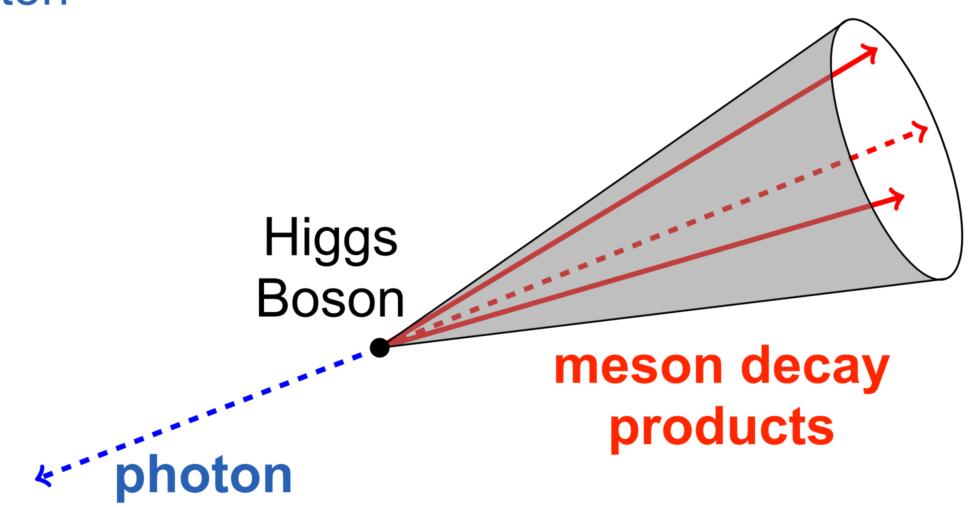


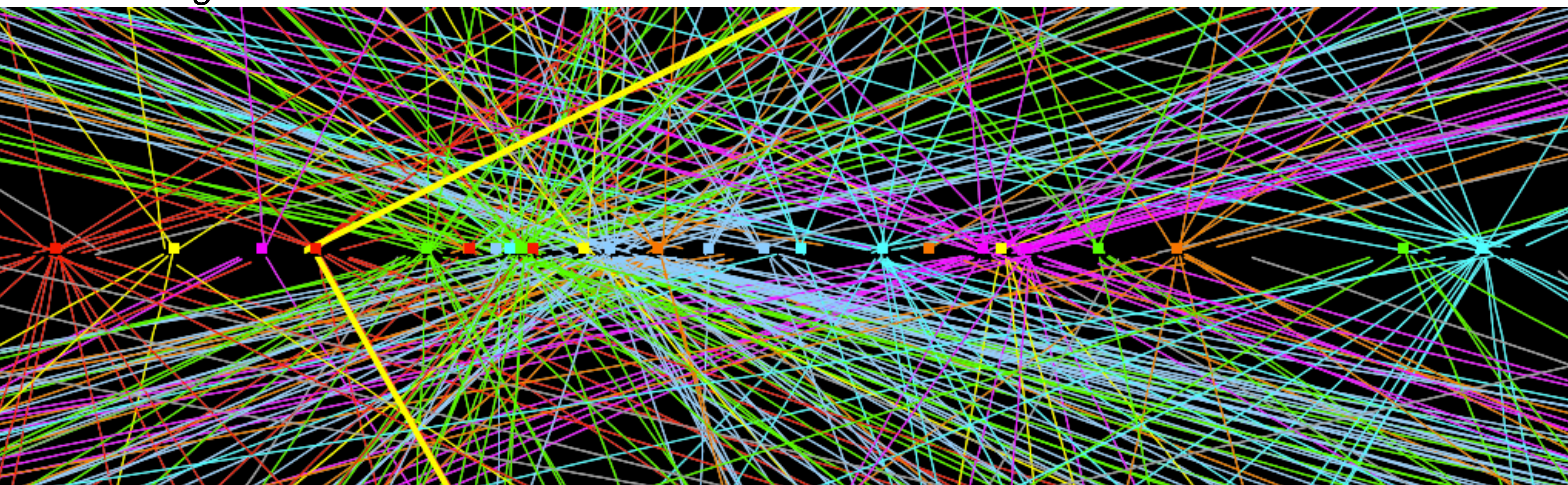
	ATLAS		CMS	
Branching fraction limit (95% CL)	Observed	Expected	Observed	Expected
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$	3.5	$3.0^{+1.4}_{-0.8}$	7.6	$5.2^{+2.4}_{-1.6}$
$\mathcal{B}(H \to \psi(2S)\,\gamma)\,[\,10^{-4}\,]$	19.8	$15.6^{+7.7}_{-4.4}$	-	-
$\mathcal{B}(Z \to J/\psi\,\gamma)\,[\,10^{-6}\,]$	2.3	$1.1^{+0.5}_{-0.3}$	1.4	$1.6^{+0.7}_{-0.5}$
$\mathcal{B}(Z \to \psi(2S)\,\gamma)\,[\,10^{-6}\,]$	4.5	$6.0^{+2.7}_{-1.7}$	-	-

Branching fraction limit (95% CL)	Observed	Expected
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	4.9	$5.0^{+2.4}_{-1.4}$
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	5.9	$6.2^{+3.0}_{-1.7}$
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	5.7	$5.0^{+2.5}_{-1.4}$
$\mathcal{B}(Z \to \Upsilon(1S)\,\gamma)\,[\,10^{-6}\,]$	2.8	$2.8^{+1.2}_{-0.8}$
$\mathcal{B}(Z \to \Upsilon(2S)\,\gamma)\,[\,10^{-6}\,]$	1.7	$3.8^{+1.6}_{-1.1}$
$\mathcal{B}(Z \to \Upsilon(3S)\,\gamma)\,[\,10^{-6}\,]$	4.8	$3.0^{+1.3}_{-0.8}$

h/Z→φγ/ργ

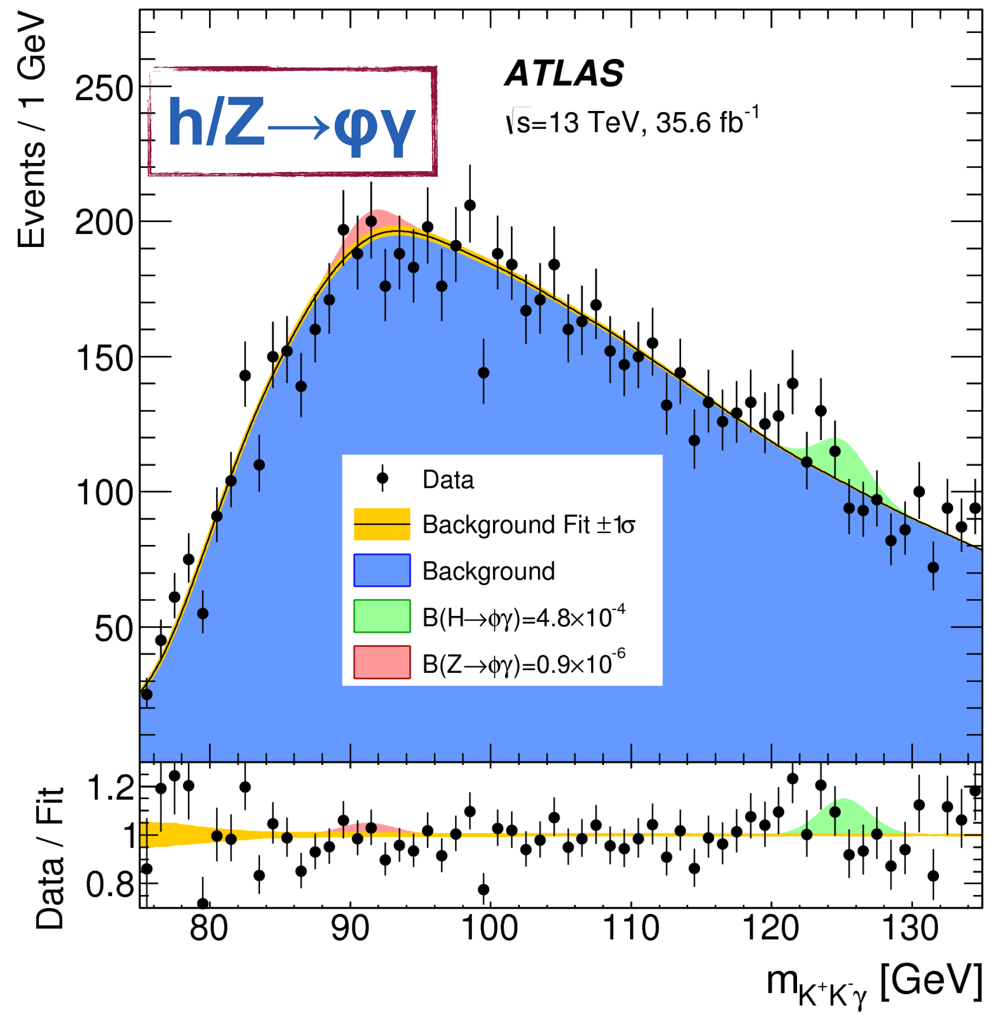
- **First search** for h/Z→φγ with 2.7 fb^{-1}@13 TeV from 2015 [Phys. Rev. Lett. 117, 111802]
- **New results** with up to 35.6/fb, added h/Z→ργ [JHEP 1807 (2018) 127]
- **Distinct experimental signature**
  - Collimated high-p_T isolated track pair recoils vs high-p_T isolated photon
- **Meson decays:**
  - **$\phi \to K^+K^-$**, BR=49%
  - **$\rho \to \pi^+\pi^-$**, BR~100%
- **Small opening angles between decay products**
  - Particularly for $\phi \to K^+K^-$
  - Tracking in dense environments

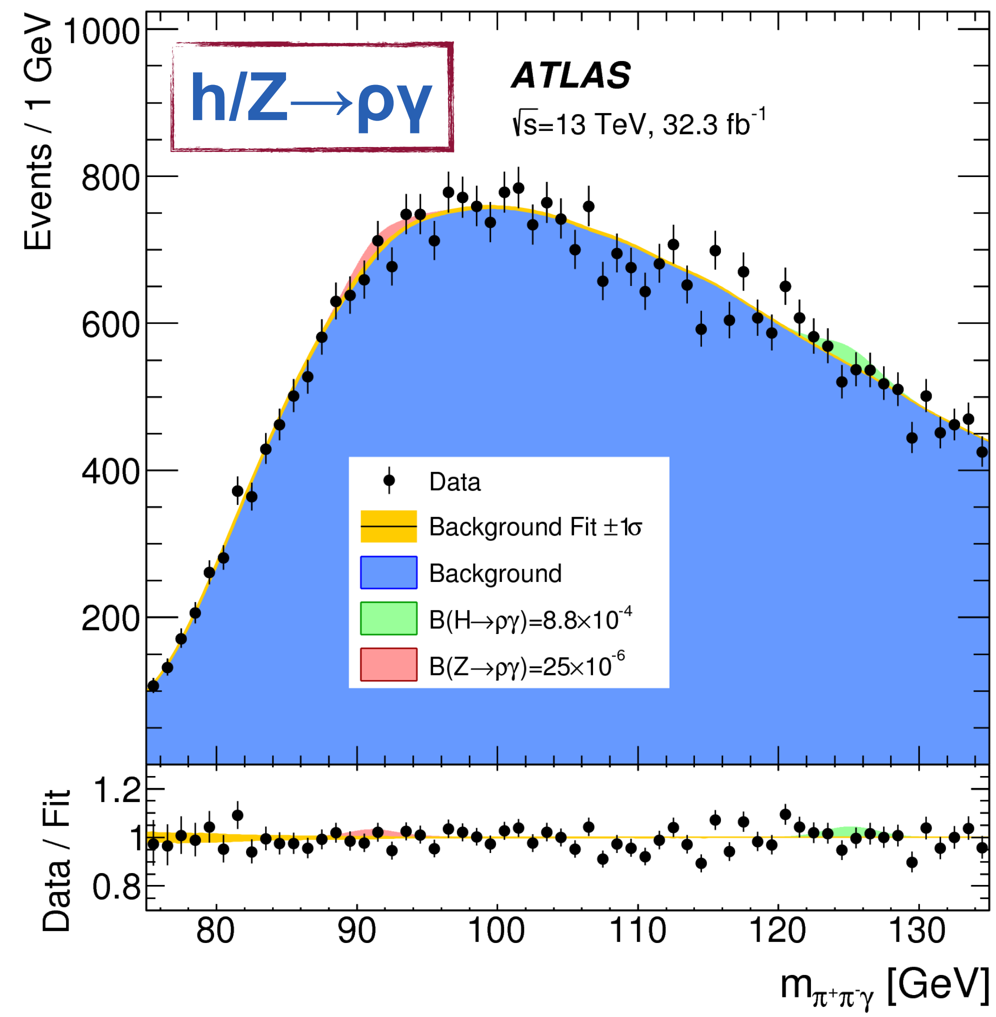




Z→μμ candidate with 25 reconstructed vertices from the 2012 run. Only good quality tracks with pT>0.4GeV are shown

h/Z→φγ/ργ: Results





- **Final discriminant** is $m_{KK\gamma}$ and $m_{\pi\pi\gamma}$
- **No significant signal observed**

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\ [\ 10^{-4}\ ]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)\ [\ 10^{-6}\ ]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)\ [\ 10^{-4}\ ]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)\ [\ 10^{-6}\ ]$	33^{+13}_{-9}	25

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