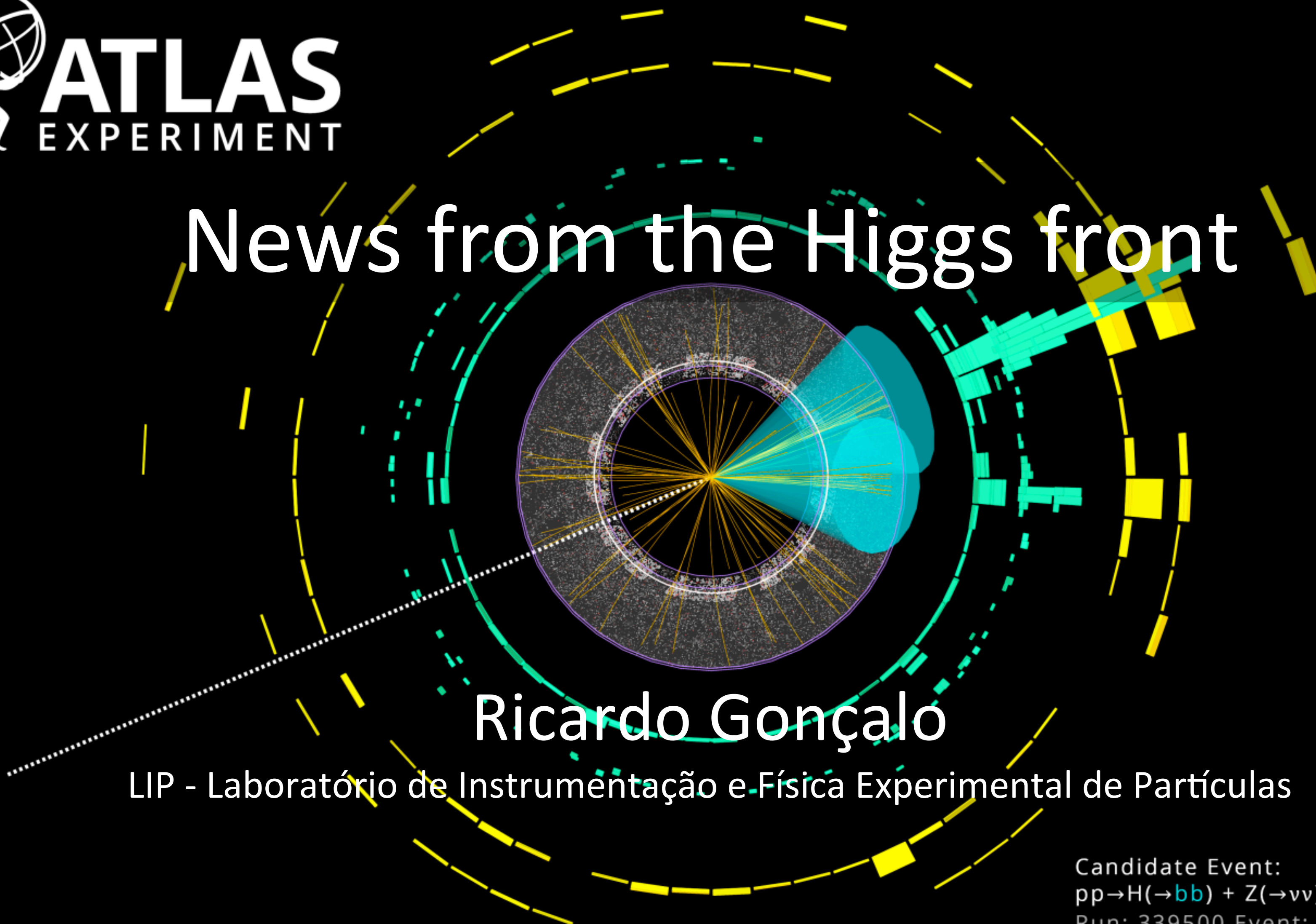
ATLAS EXPERIMENT

News from the Higgs front



Ricardo Gonçalo

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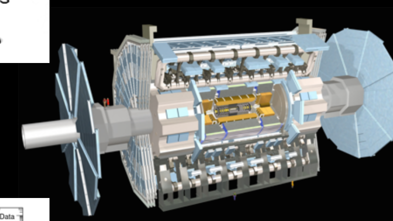
LIP · Ciências ULisboa · FCT Fundação para a Ciência e a Tecnologia

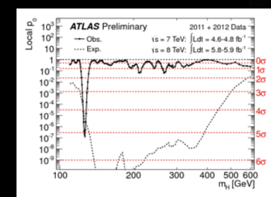
Cofinanciado por: COMPETE 2020 · PORTUGAL 2020 · UNIÃO EUROPEIA Fundos Europeus Estruturais e de Investimento · ATLAS EXPERIMENT

Motivation: why the Higgs?

The LHC and experiments

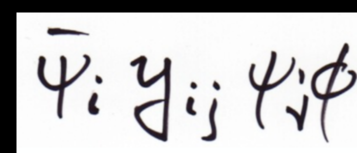


The Run 1 legacy

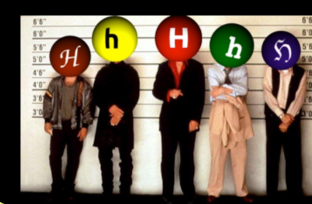


Probing the 125 GeV Higgs

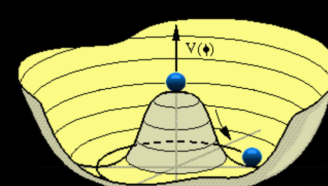
Probing the Yukawa sector



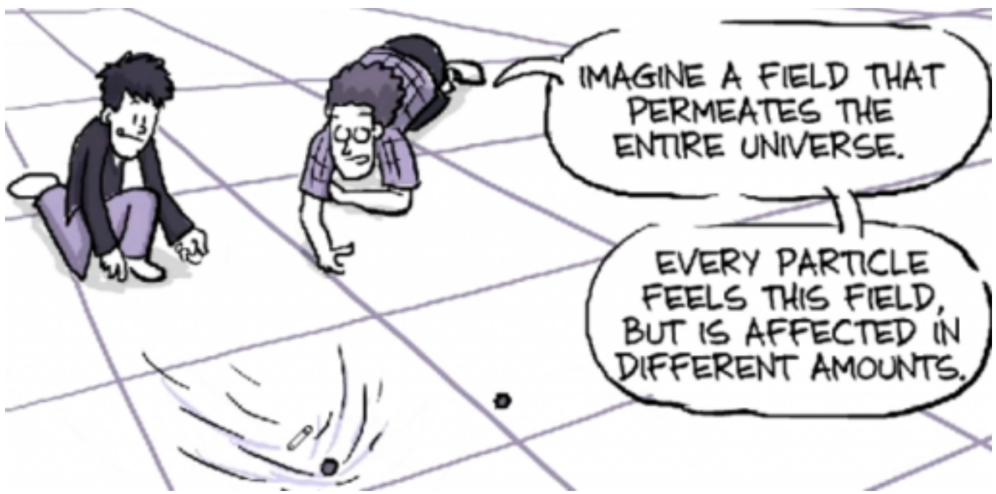
Searching wider



The long run: di-Higgs



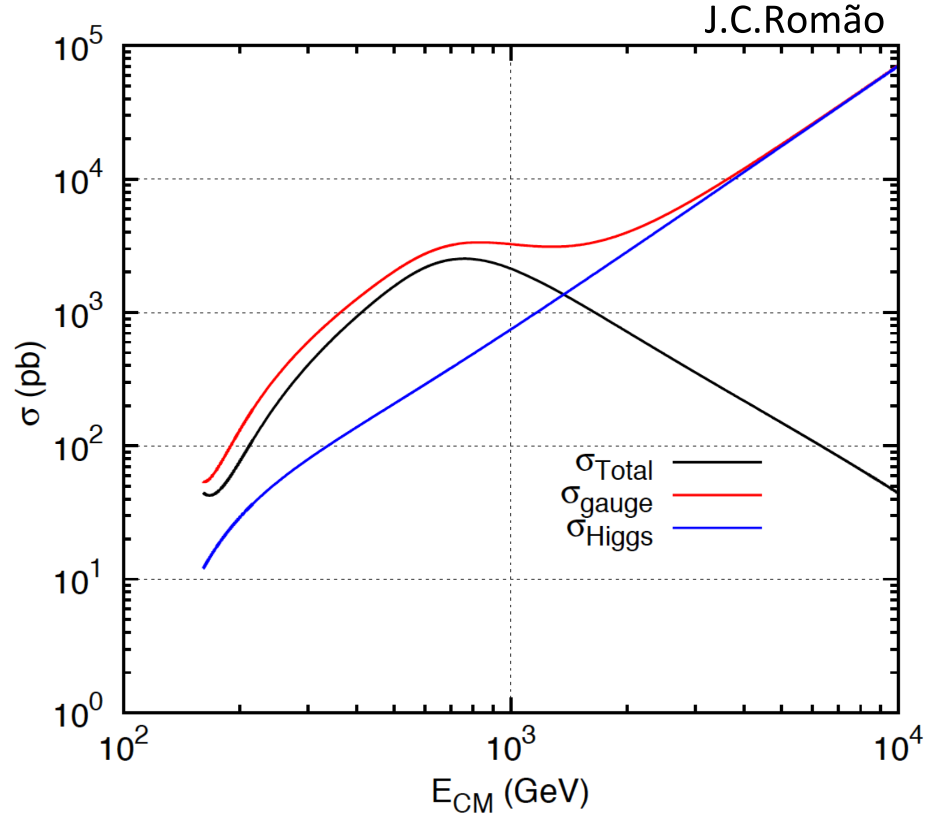
Why the Higgs?

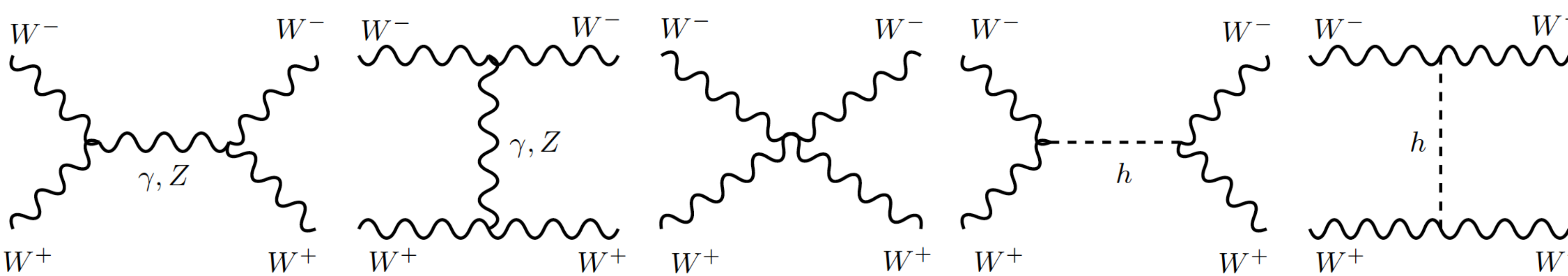


1: Longitudinal gauge-boson scattering

In the absence of the Higgs, some processes have cross sections that grow with the centre of mass energy of the collision… i.e. breaks unitarity!

The Higgs regulates the cross section through negative interference





Feynman diagrams contributing to longitudinal WW scattering

2: Mass of elementary particles and gauge bosons

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu \partial_\mu - m_e)\psi - e\bar{\psi}\gamma^\mu \psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\gamma A_\mu A^\mu$$

To keep the Lagrangian gauge invariant against a U(1) **local** phase transformation:

$$\psi(x) \rightarrow \psi'(x) = e^{iq\chi}\psi(x)$$

with $\boldsymbol{\chi} = \boldsymbol{\chi}(x)$. The photon field transforms as:

$$A_\mu \rightarrow A'_\mu = A_\mu - \partial_\mu \chi$$

But the $\boldsymbol{A^\mu}$ mass term breaks the invariance of the Lagrangian:

$$\frac{1}{2}m_\gamma A_\mu A^\mu \rightarrow \frac{1}{2}m_\gamma (A_\mu - \partial_\mu)(A^\mu - \partial^\mu \chi) \neq \frac{1}{2}m_\gamma A_\mu A^\mu$$

For the $SU(2)_L$ gauge symmetry transformations of the **weak interaction** the fermion mass term $\boldsymbol{m_e\bar{\psi}\psi}$ also breaks invariance!

Bottom line: **the SM (without the Higgs mechanism) results in wrong calculations and breaks down for massive particles**

The Higgs Mechanism

Robert Brout (1928 – 2011)

Peter Higgs (b. 1929)

François Englert (b. 1932)

- Introduce a SU(2) doublet of spin-0 complex fields

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi 4 \end{pmatrix}$$

- The Lagrangian is

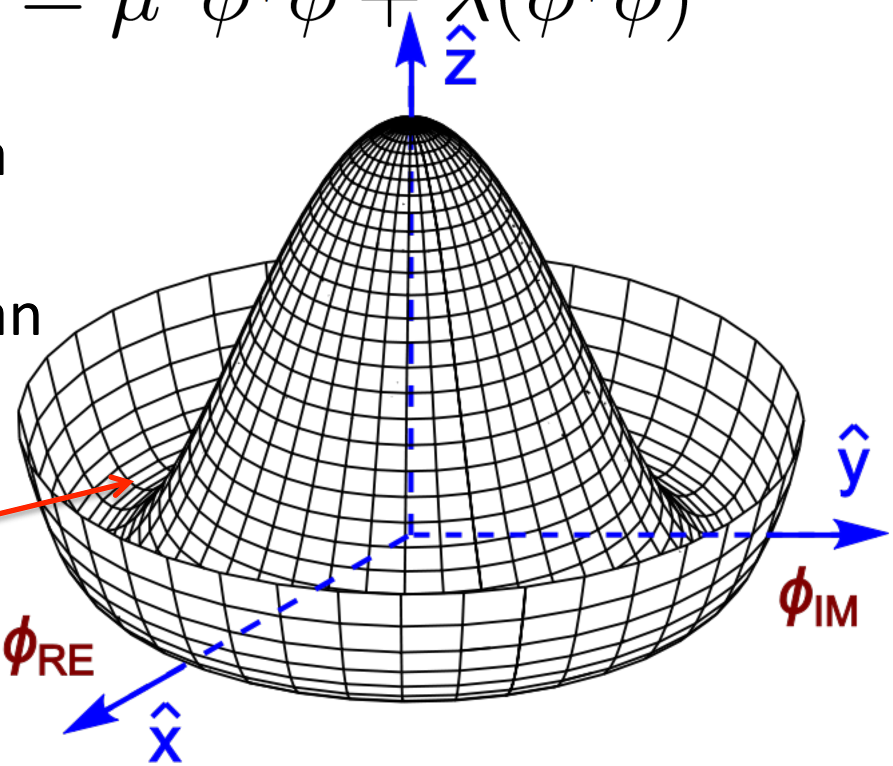
$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

- With a potential

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

- For $\lambda>0$, $\mu^2>0$ the potential has a minimum at the origin
- For $\lambda>0$, $\mu^2<0$ the potential has an infinite number of minima at:

$$|\phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$$



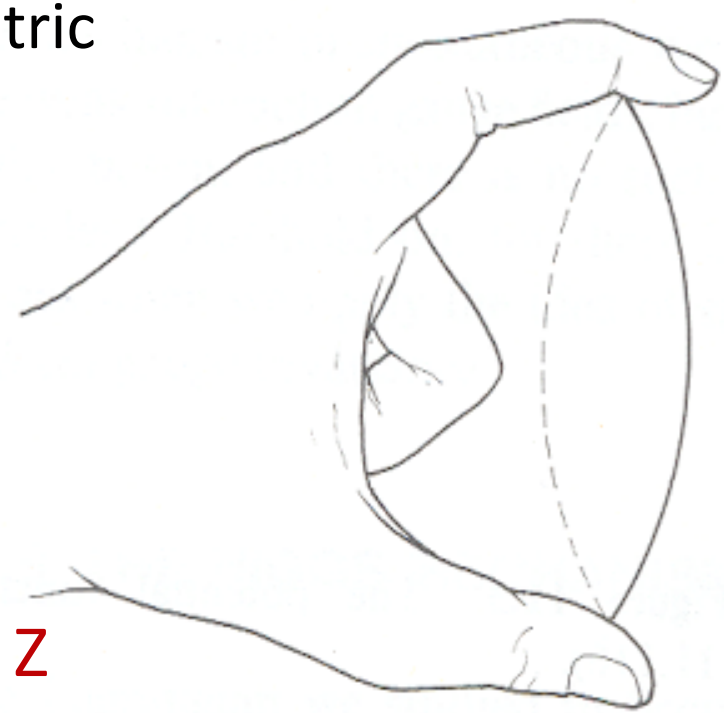
The choice of vacuum (lowest energy state of the field) breaks the symmetry of the Lagrangian

Electroweak symmetry breaking

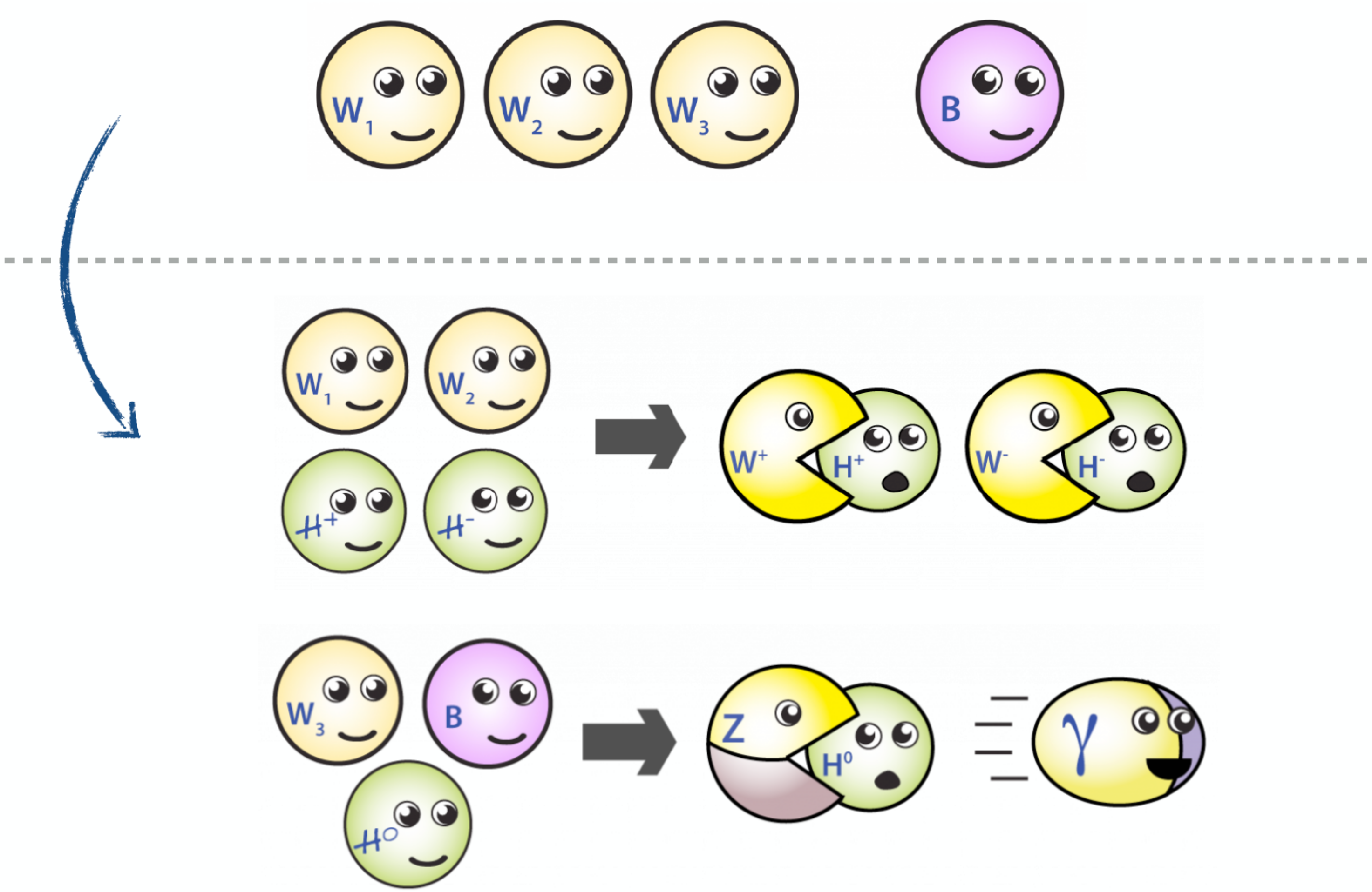
- In the Standard Model with no Higgs mechanism, interactions are symmetric and particles do not have mass

- Electroweak symmetry is broken:
  - Photon does not have mass
  - W, Z have a large mass

- Higgs mechanism: mass of W and Z results from the Higgs mechanism
- Masses of fermions come from a direct interaction with the Higgs field



EWK Symmetry Breaking in Pictures

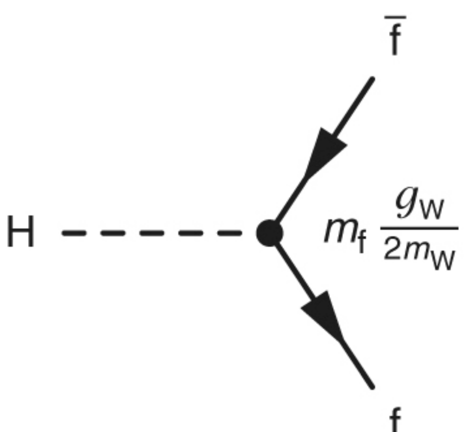


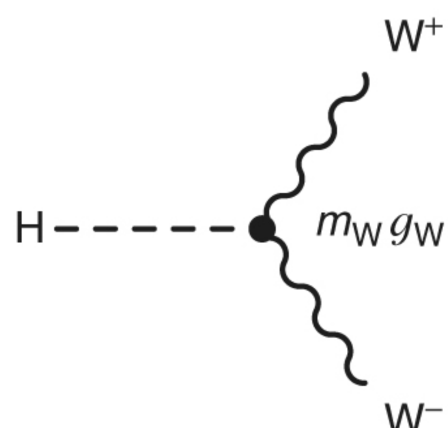
What (we think) we know:

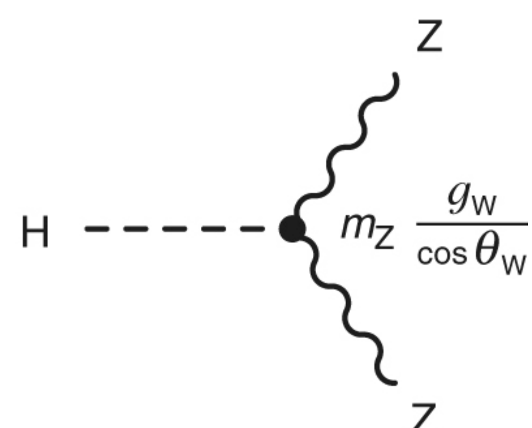
- Higgs mass was(!) the only unknown parameter of the SM

$$m_h = \sqrt{2\lambda}v$$

- We can give mass to $W^{\pm}$ and Z while keeping the photon massless
- Higgs couples to W and Z proportionally to their masses
- Higgs couples to fermions proportionally to their mass

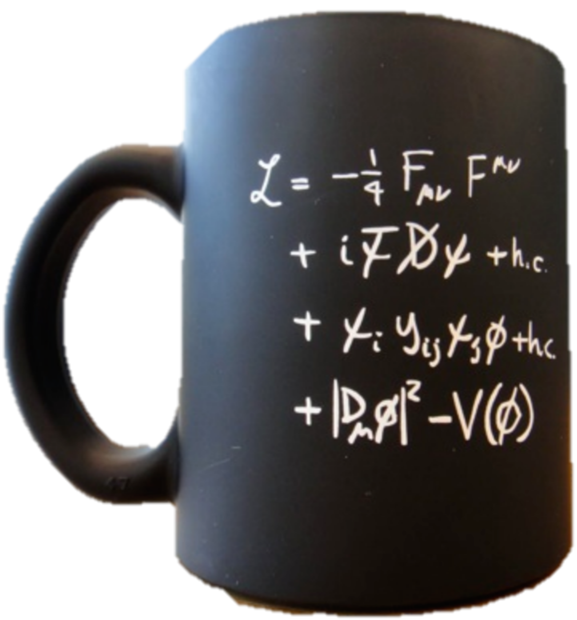




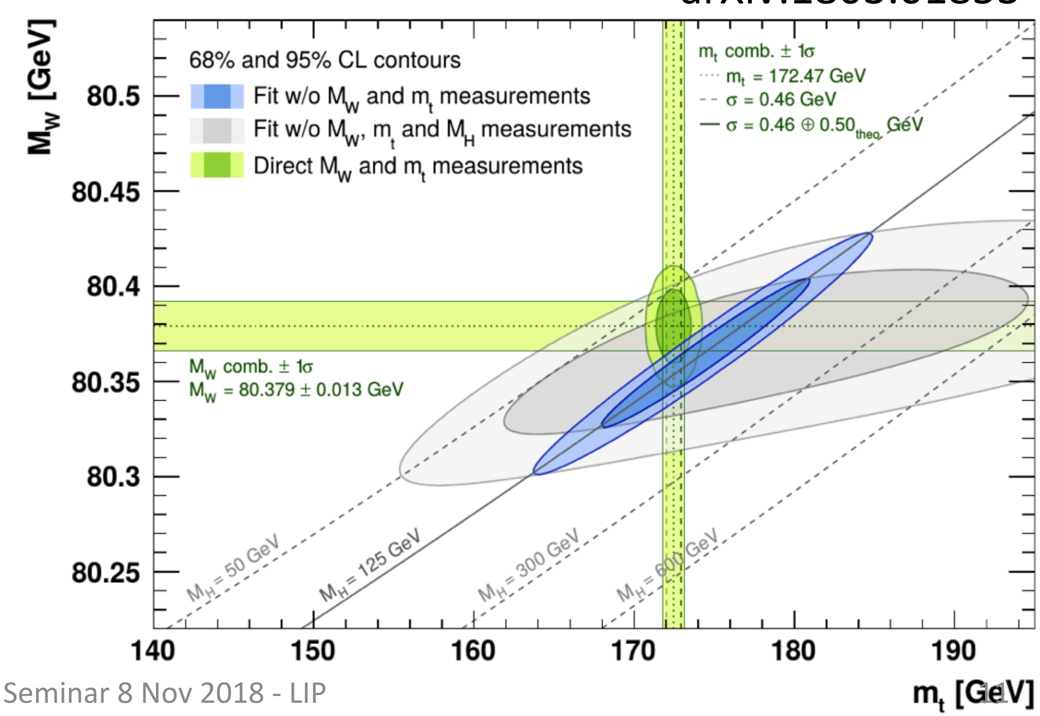


Exploring the electroweak scale

- Precision measurements of m_W, m_t, m_H are stringent tests of the SM at the EW scale
  - E.g. excluding measured m_H, global EW fit gives m_H = 90 ± 21 GeV (1.7 σ tension)

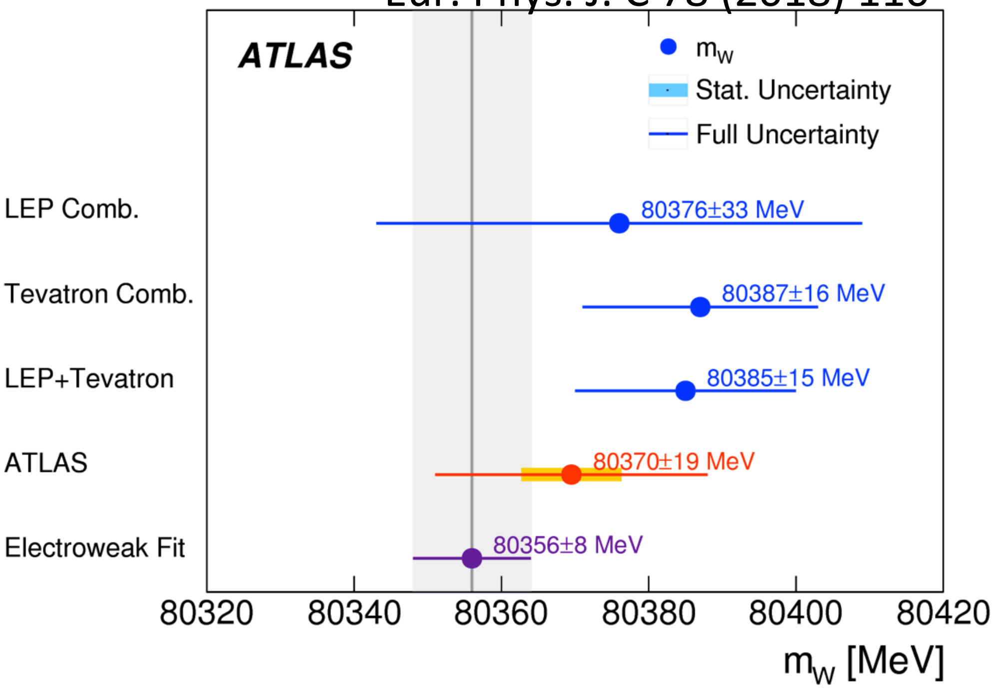


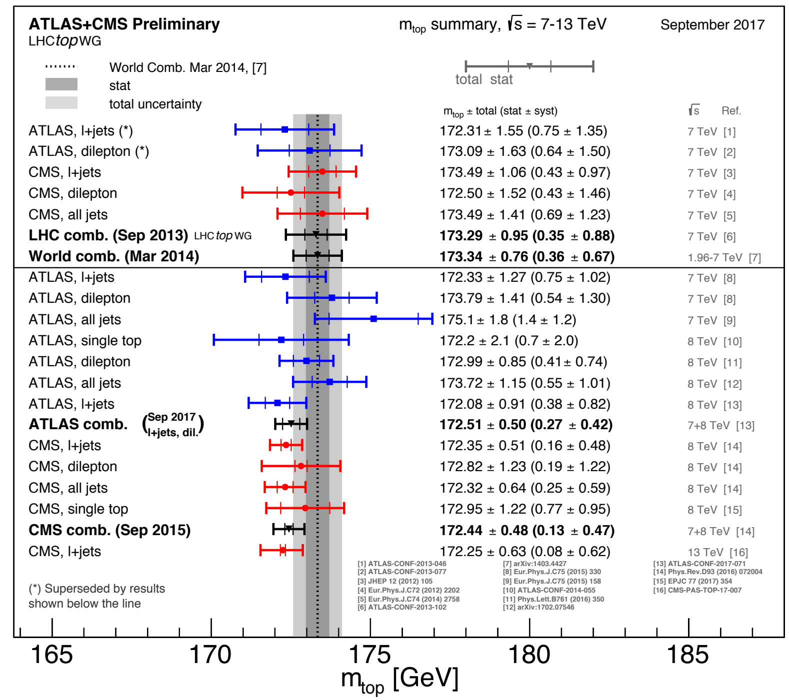
arXiv:1803.01853



M_W AND M_T: THE STORY SO FAR...

Eur. Phys. J. C 78 (2018) 110





https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

Per mille precision!

Tools of the Trade

The LHC and its experiments

Design (p-p run):

$\sqrt{s}$ = 14 TeV (design)

$N_p = 1.2 \times 10^{11}$ p/bunch

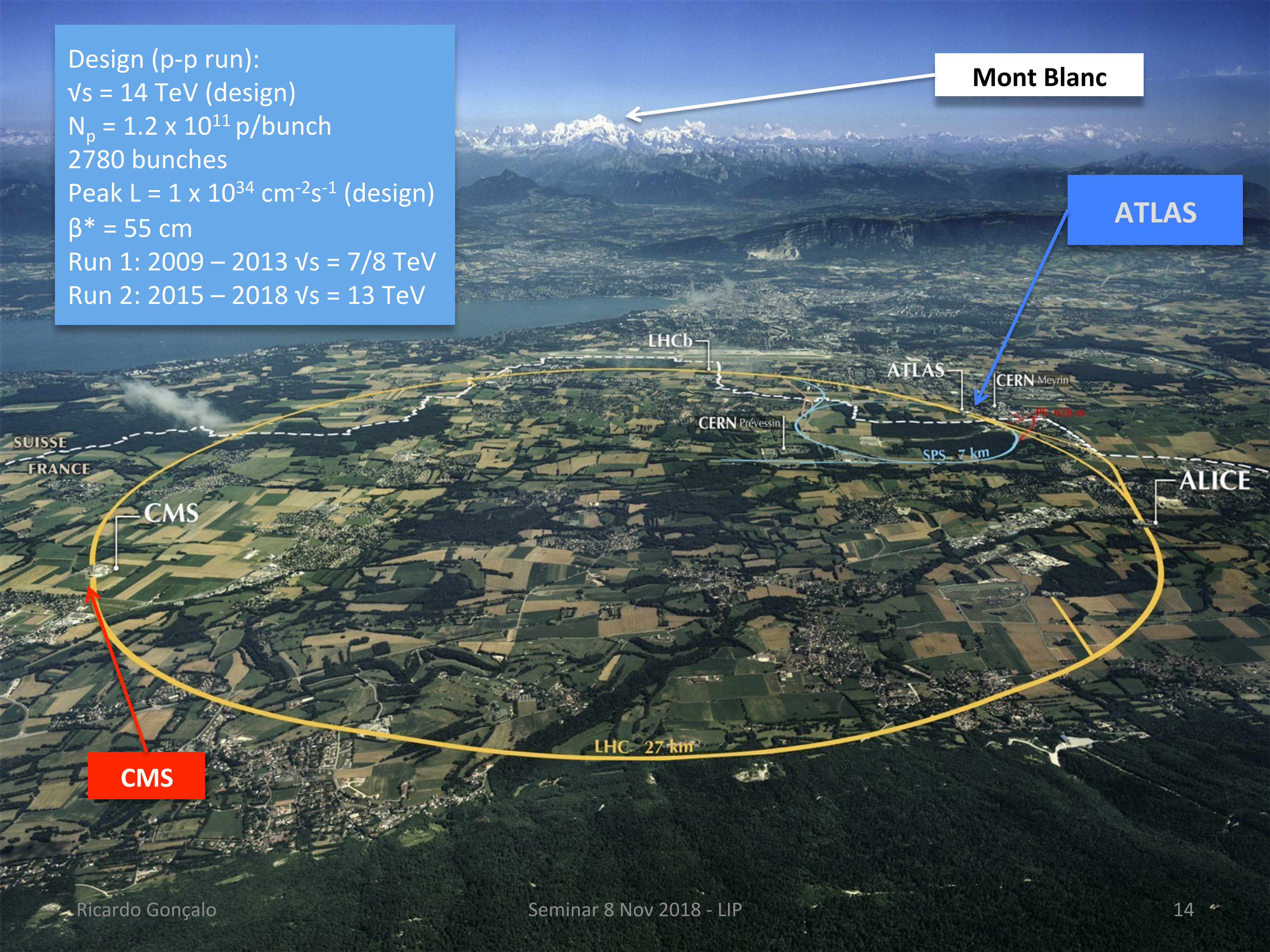
2780 bunches

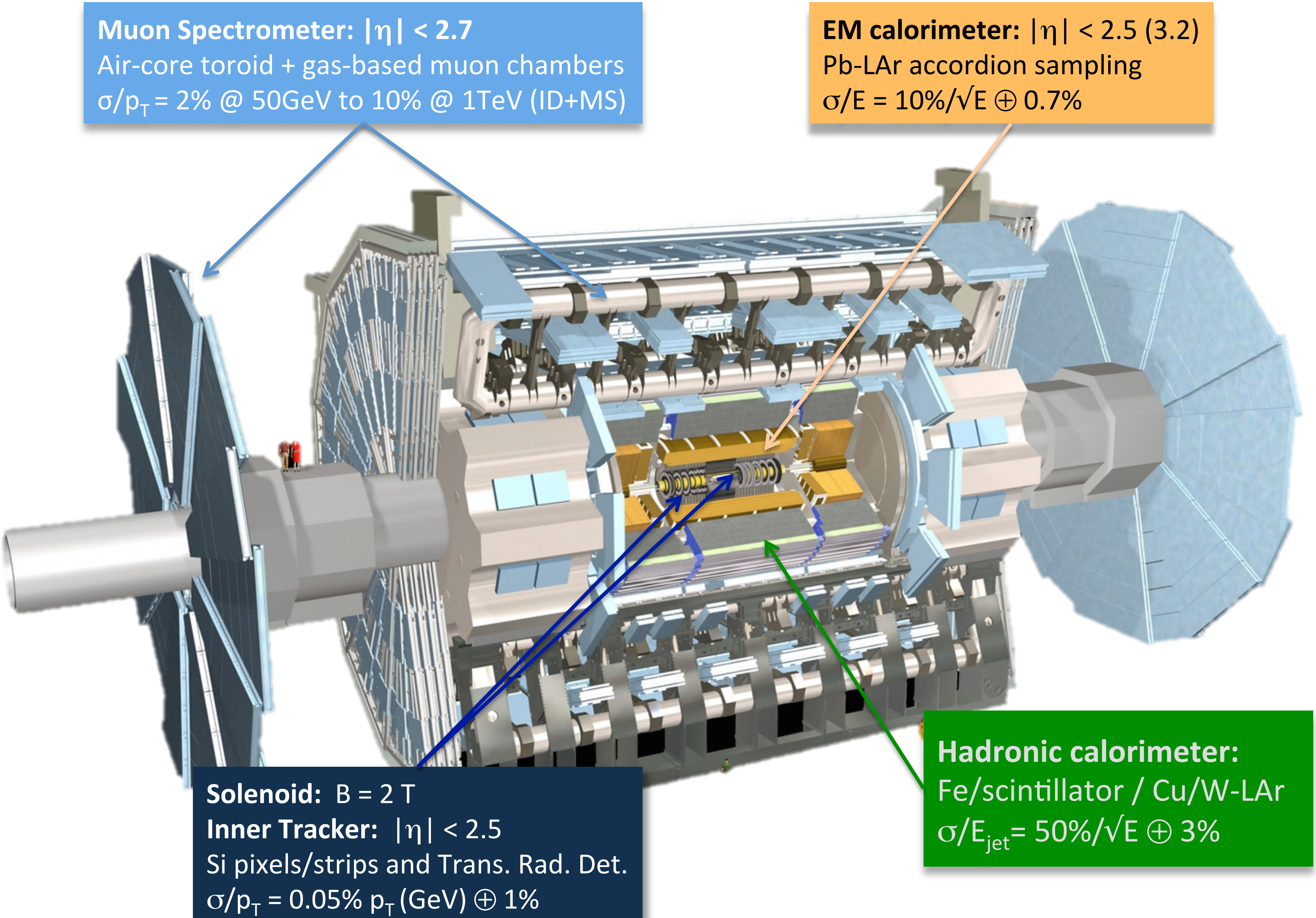
Peak $L = 1 \times 10^{34}\ cm^{-2}s^{-1}$ (design)

β^* = 55 cm

Run 1: 2009 – 2013 $\sqrt{s}$ = 7/8 TeV

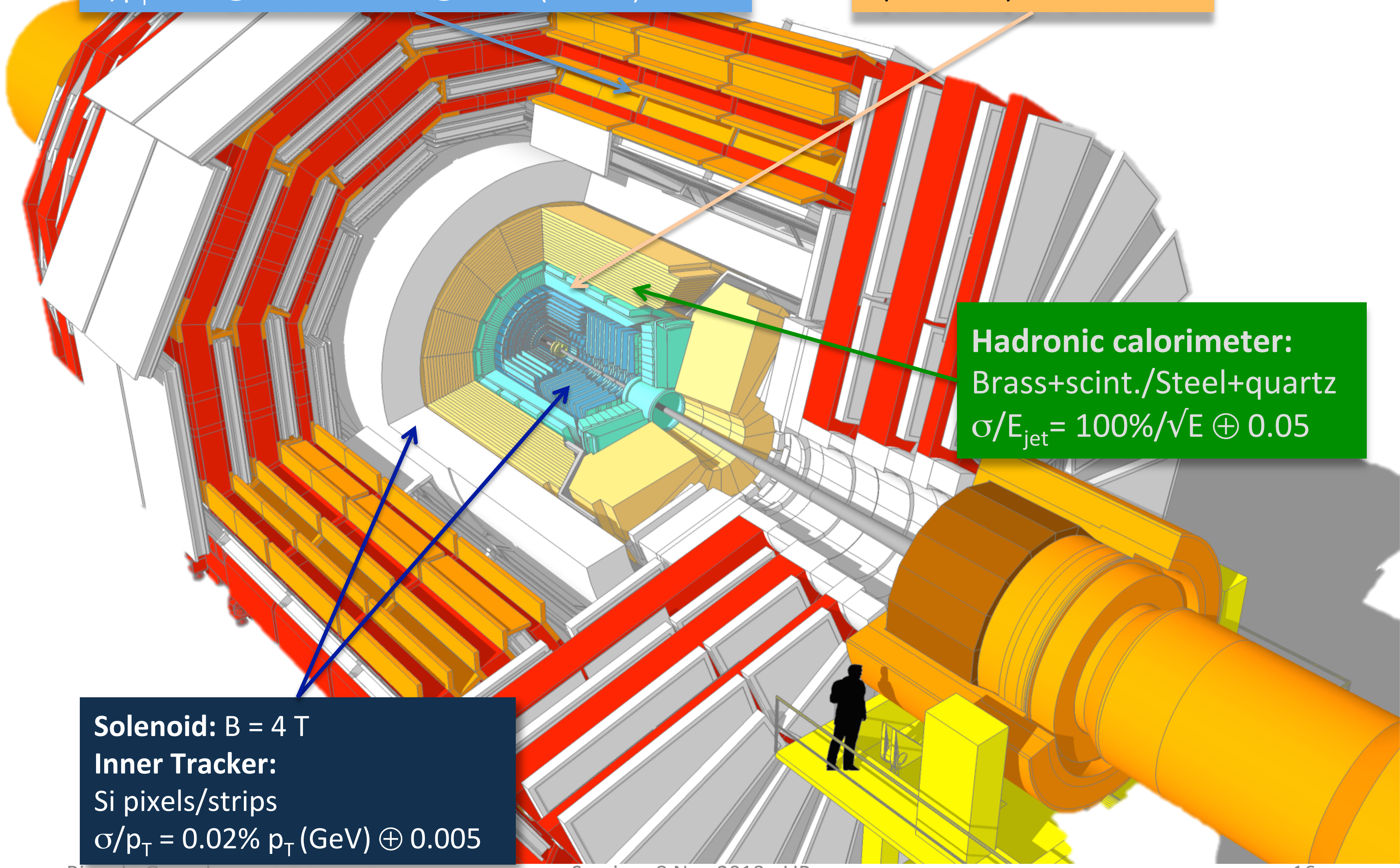
Run 2: 2015 – 2018 $\sqrt{s}$ = 13 TeV




Muon Spectrometer: $|\eta| < 2.7$
Air-core toroid + gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)
EM calorimeter: $|\eta| < 2.5$ (3.2)
Pb-LAr accordion sampling
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$
Hadronic calorimeter:
Fe/scintillator / Cu/W-LAr
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$
Solenoid: B = 2 T
Inner Tracker: $|\eta| < 2.5$
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\text{GeV}) \oplus 1\%$

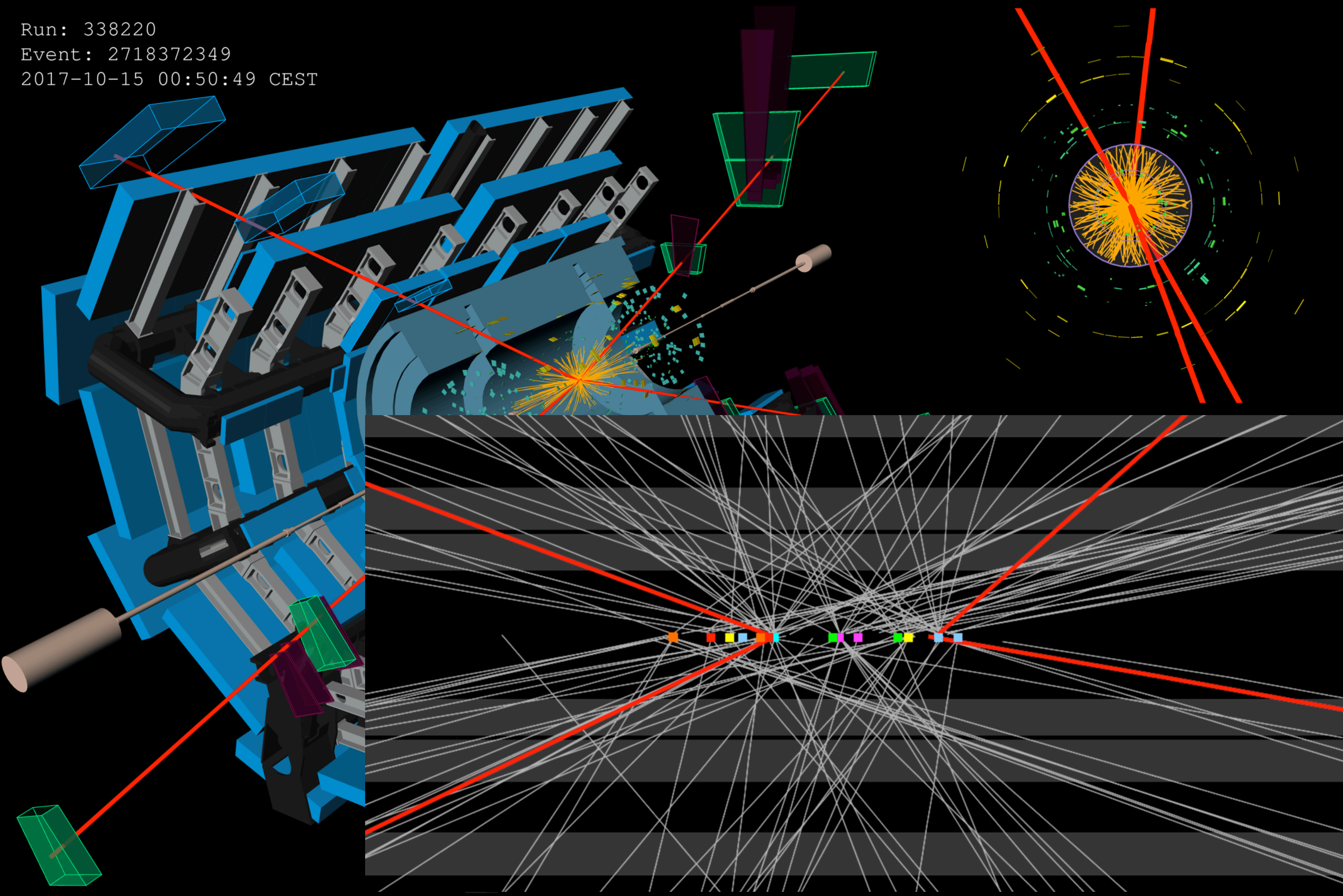
Muon Spectrometer:
Steel return yoke and gas-based muon chambers
σ/p_T = 1% @ 50GeV to 5% @ 1TeV (ID+MS)

EM calorimeter:
$PbWO_4$ crystals homogen.
$\sigma/E = 2\text{-}5\%/\sqrt{E} \oplus 0.005$



Hadronic calorimeter:
Brass+scint./Steel+quartz
$\sigma/E_{jet} = 100\%/\sqrt{E} \oplus 0.05$

Solenoid: B = 4 T
Inner Tracker:
Si pixels/strips
$\sigma/p_T = 0.02\%\ p_T\,(\text{GeV}) \oplus 0.005$


Run: 338220
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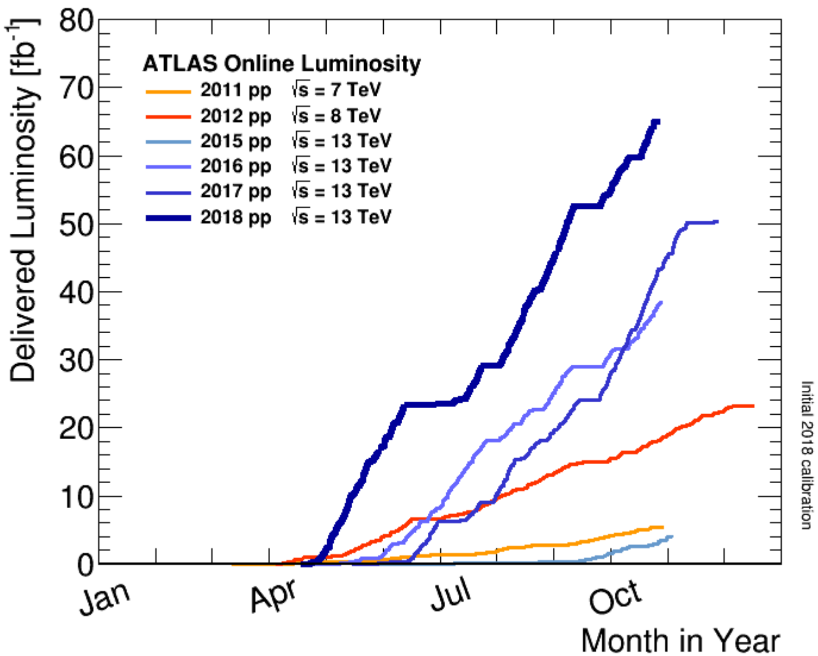
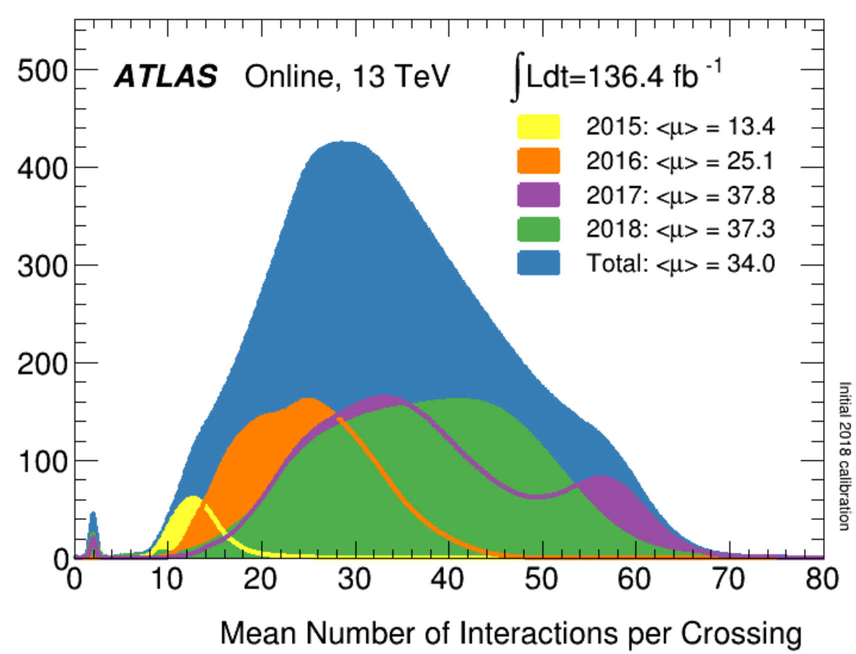
ATLAS, CMS and the LHC

- Run 1: 2009 – 2013; ≈ 5 fb^{-1} at √s = 7 and ≈ 20 fb^{-1} at 8 TeV per experiment
- Run 2: 2013 – 2018; 149 fb^{-1} recorded at √s = 13 TeV by the end of pp run
- Instantaneous luminosity of **2 x 10^{34} $cm^{-2}s^{-1}$** in 2017 (2x design!)
- Downside is pileup => experimental challenge!
  - Multiple vertices, large occupancy, degraded reconstruction resolution, etc
  - LHC breaking new ground to go around this: leveling!

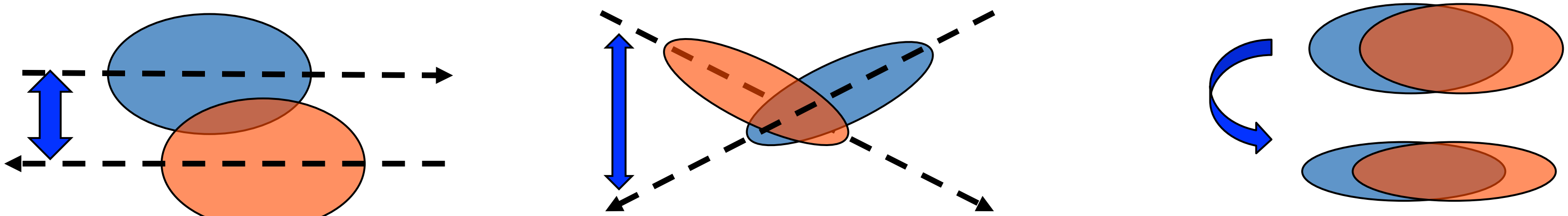


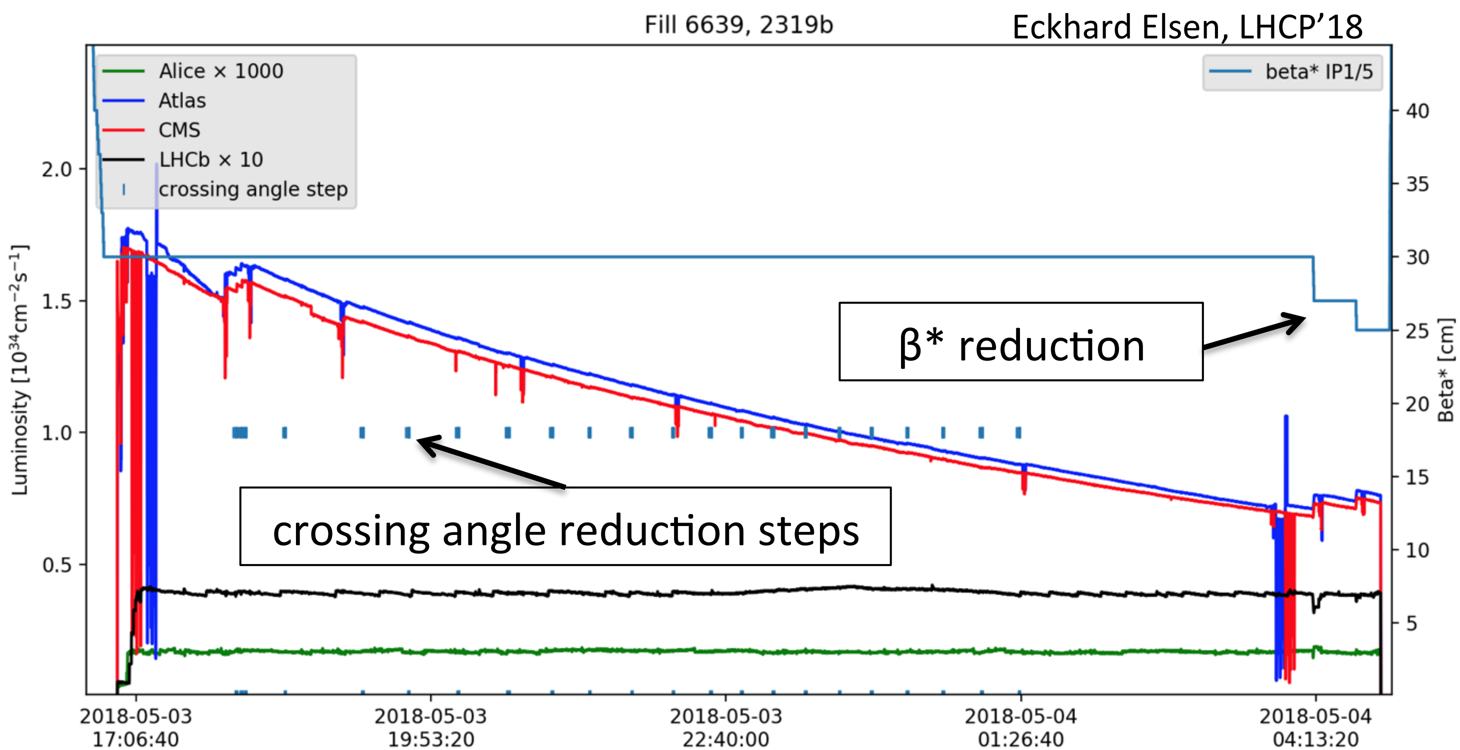


Leveling by beam offset

Anti-leveling: crossing angle

Anti-leveling: β* reduction

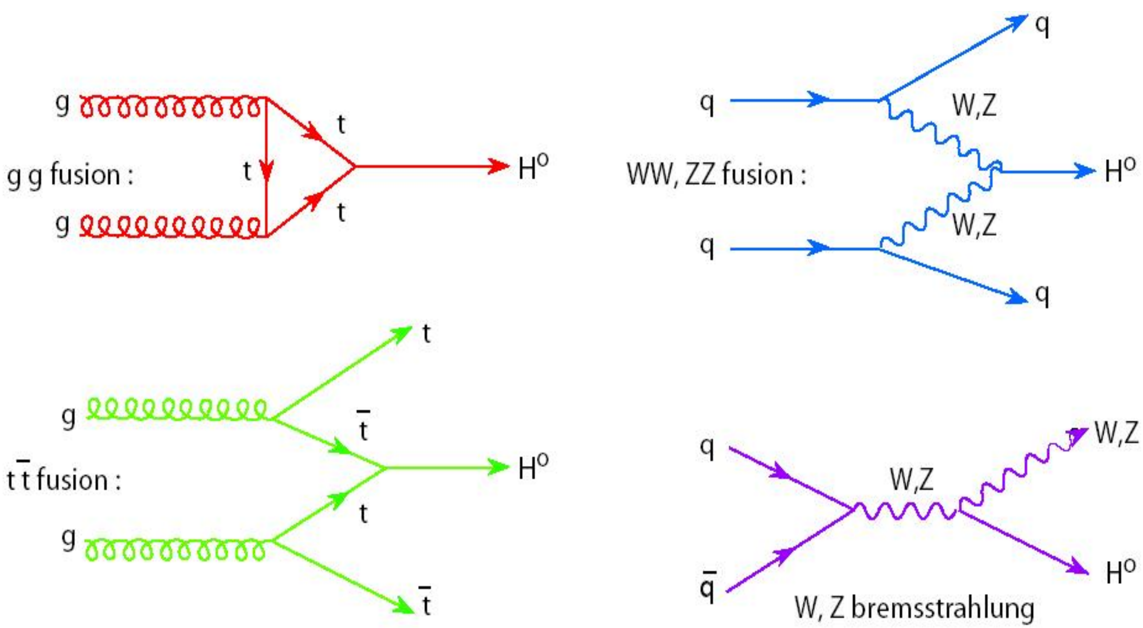


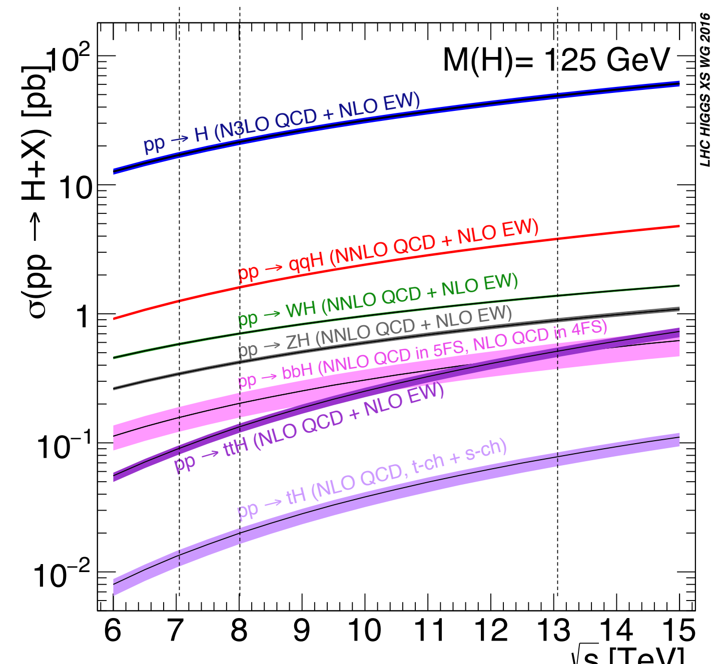


Higgs at the LHC

Higgs @ the LHC

- Many different production and decay mechanisms
  - Span 3 orders of magnitude in cross section and branching ratio
  - Some very clean decays with low BR (γγ, 4l)
  - Other very difficult with higher rates (bb, WW, ττ,...)
- Access Higgs properties through combination of different channels
- Enormous amount of progress since discovery 6 years ago!





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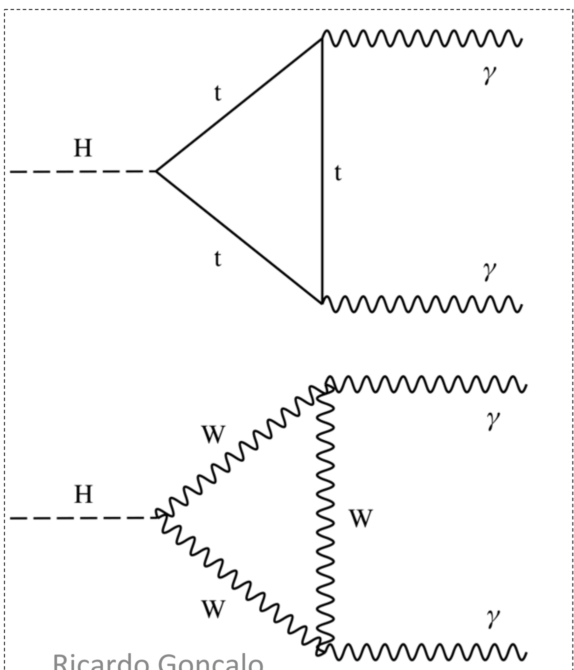
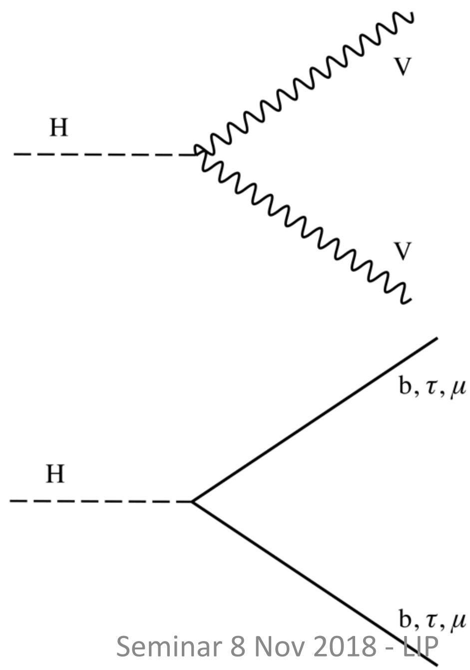
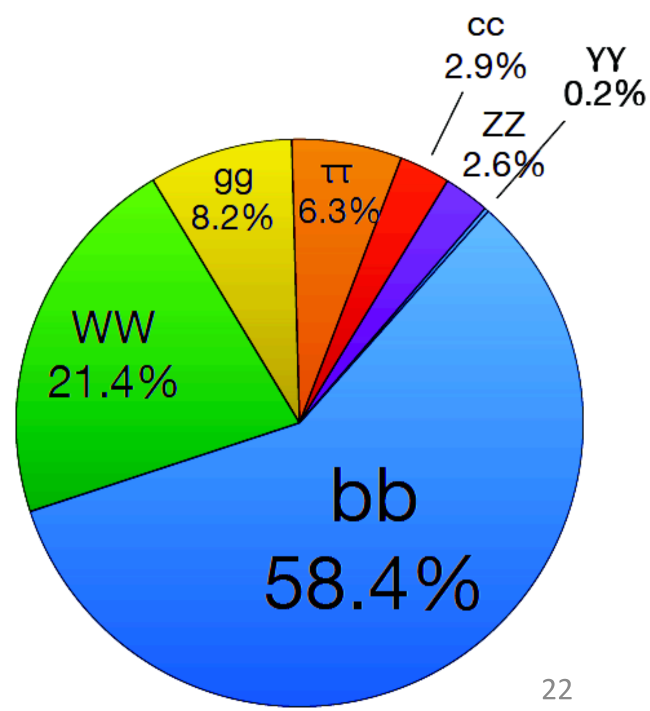
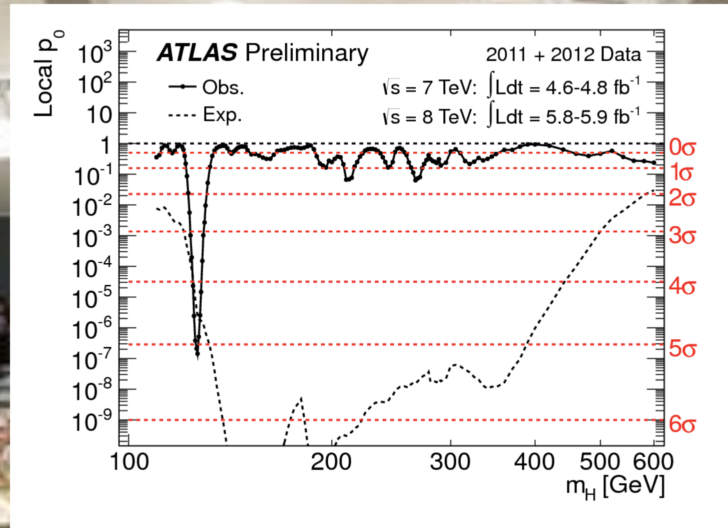




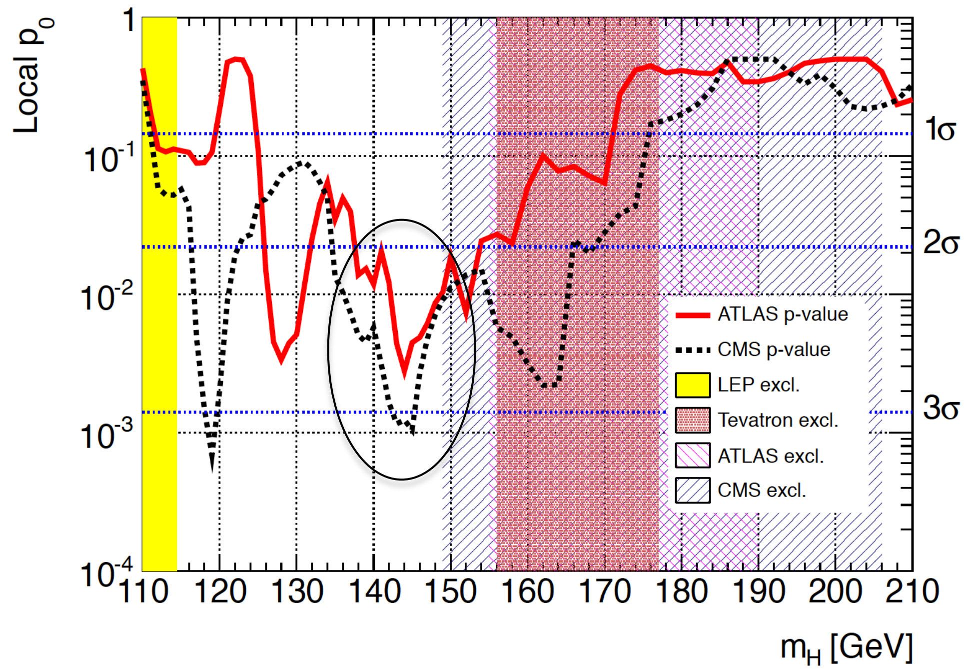




The Run 1 legacy

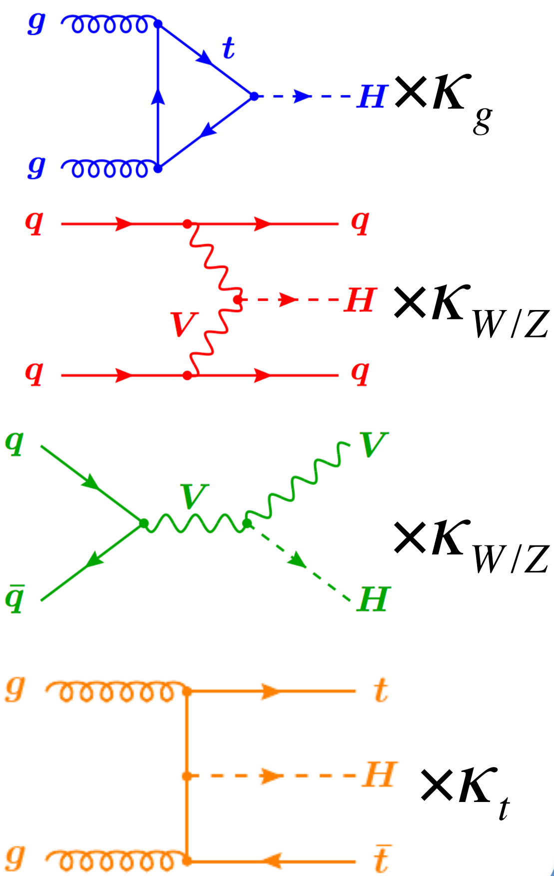
It takes time to get it right

EPS-HEP 2011 conference



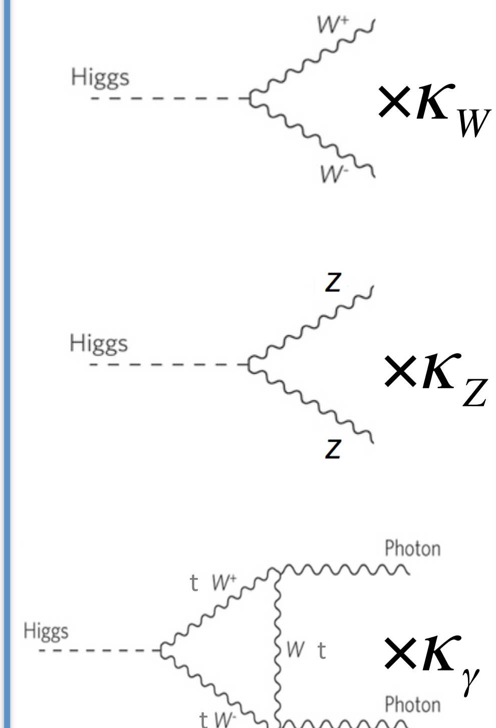
$$\kappa_i^2 = \sigma_i / \sigma_i^{SM} \qquad \kappa_f^2 = \Gamma_f / \Gamma_f^{SM} \qquad \mu = \frac{(\sigma \cdot BR)^{Obs.}}{(\sigma \cdot BR)^{SM}} = \kappa_i^2 \cdot \kappa_f^2$$

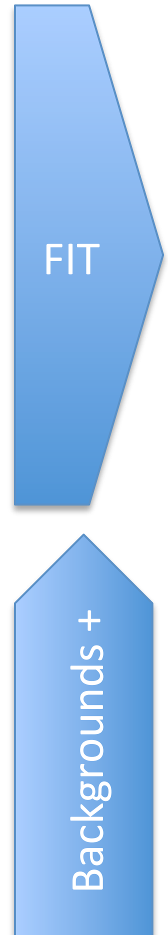
Production

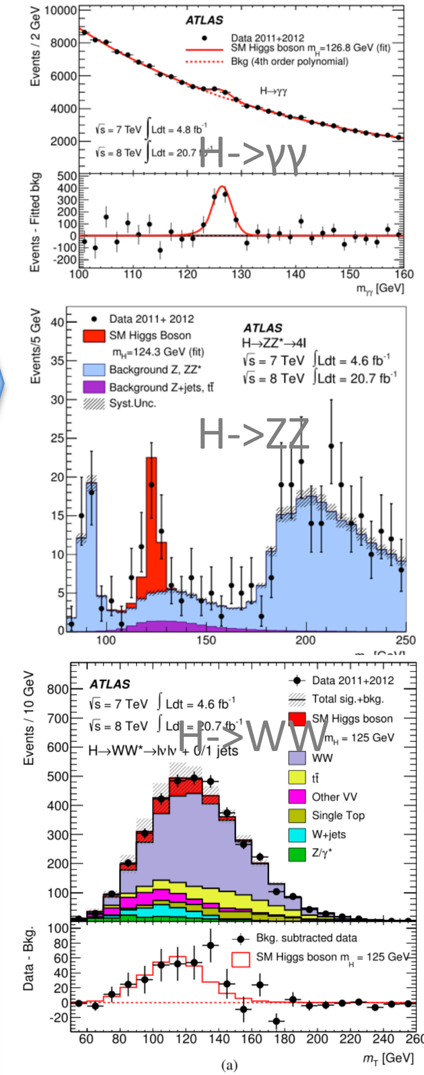


$\times$

Decay



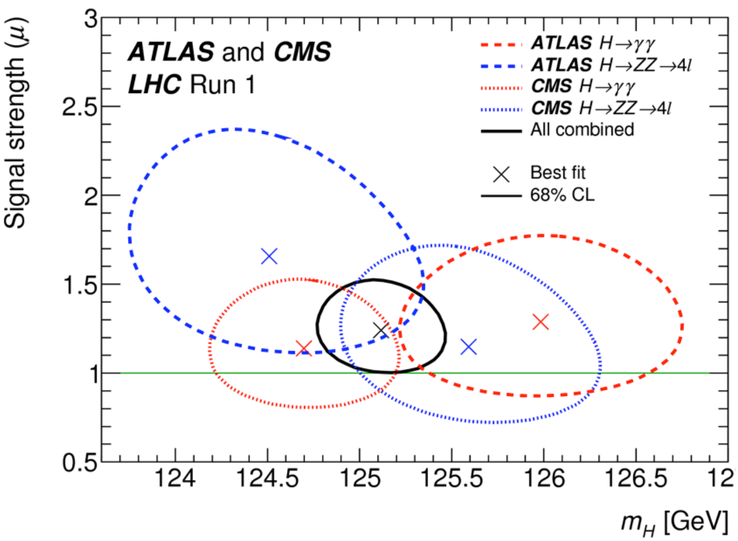


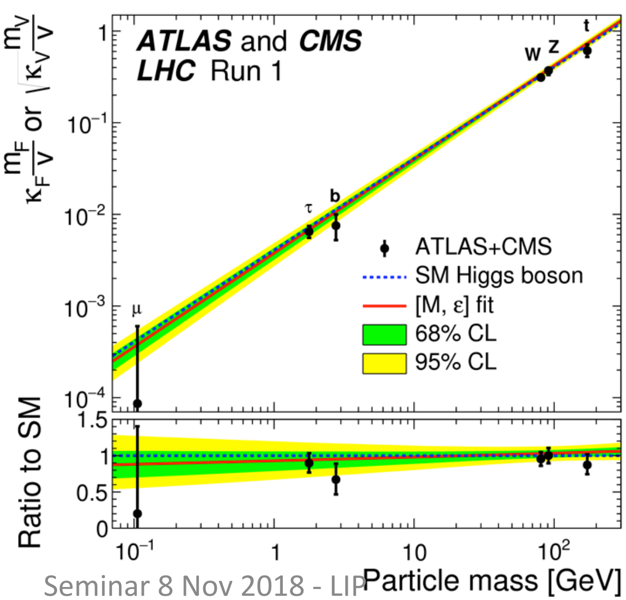


The Run 1 legacy

- Mass – Higgs mass measured with 0.2% accuracy:
  - **m_H = 125.09 ± 0.21 (stat.) ± 0.11 (scale) ± 0.02 (other) ± 0.01 (theory) GeV**
- Couplings:
  - ggF with H → ZZ,γγ,WW **observed** by individual experiments
  - VBF and H → ττ observed with **>5σ** significance by ATLAS+CMS combination
  - ttH, VH production and H → bb **not observed** during Run1
- Couplings **compatible with SM**:
  - Signal strength: $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.06^{+0.35}_{-0.27}$
  - Coupling modifiers broadly consistent with SM but large uncertainty

$\mu = (\sigma \times BR)_{Obs} / (\sigma \times BR)_{SM}$





Significance (σ)		
Prod.	Obs.	Expect.
VBF	5.4	4.7
VH	3.5	4.2
ttH	4.4	2.0
Decay	Obs.	Expect.
H→ττ	5.5	5.0
H→bb	2.6	3.7

Phys. Rev. Lett. 114 (2015) 191803
JHEP 08 (2016) 045

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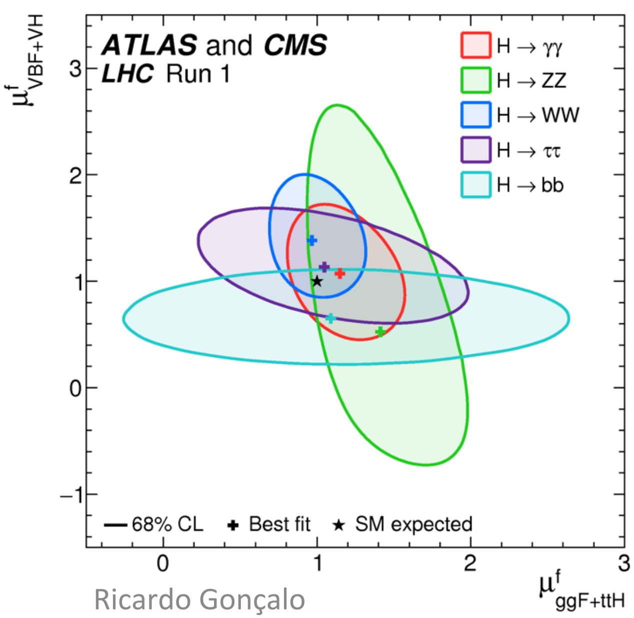

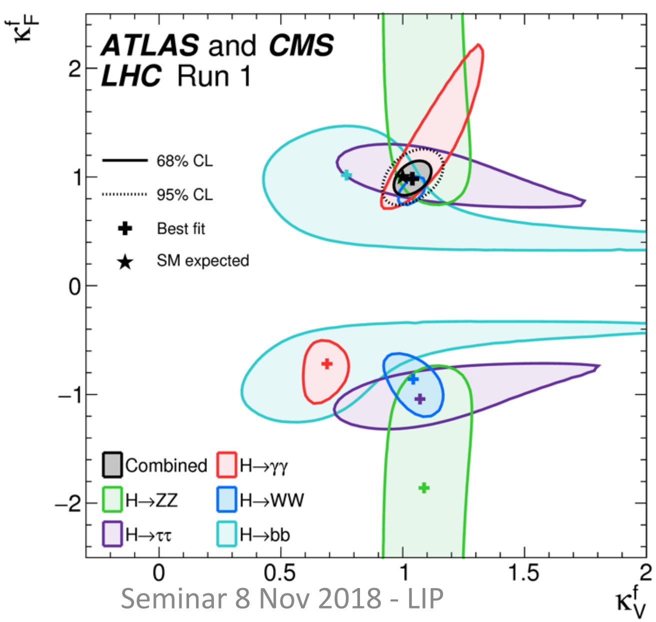

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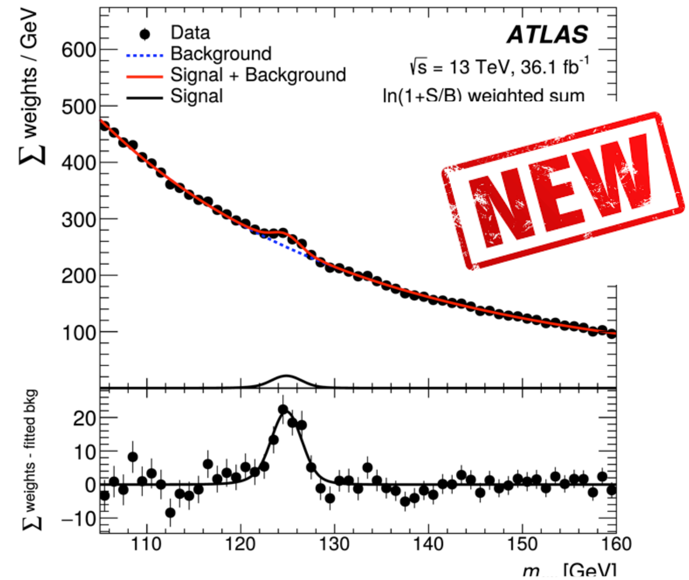
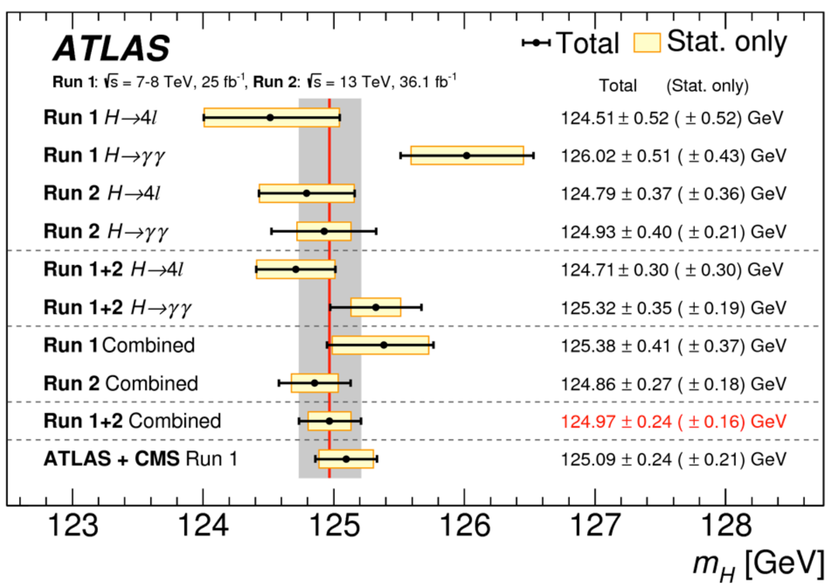
Probing the 125 GeV Higgs in Run 2

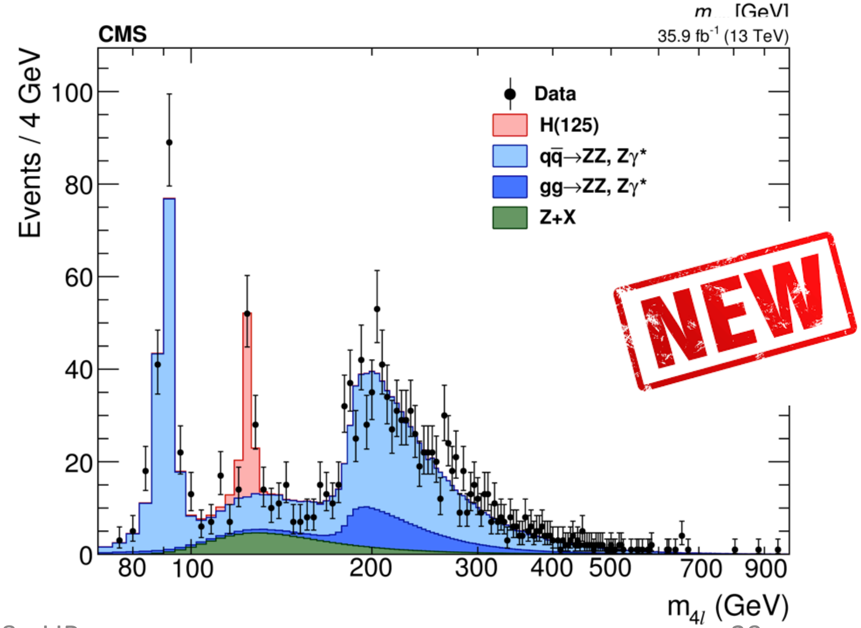
arXiv:1804.02716 [hep-ex]; arXiv:1706.09936 [hep-ex]; arXiv:1806.00242 [hep-ex]

Higgs boson mass

- Mass measurement from CMS $H \rightarrow ZZ^* \rightarrow 4l$:
  $m_H^{ZZ*} = 125.26 \pm 0.20\ (stat) \pm 0.08\ (syst)$ GeV
- New Measurements from ATLAS
  $H \rightarrow \gamma\gamma$: $m_H^{\gamma\gamma} = 124.93 \pm 0.40$ GeV
  $H \rightarrow ZZ^* \rightarrow 4l$: $m_H^{ZZ*} = 124.79 \pm 0.37$ GeV
- Run 1+2 combination from ATLAS:
  $m_H = 124.97 \pm 0.19\ (stat) \pm 0.13\ (syst.)$ GeV





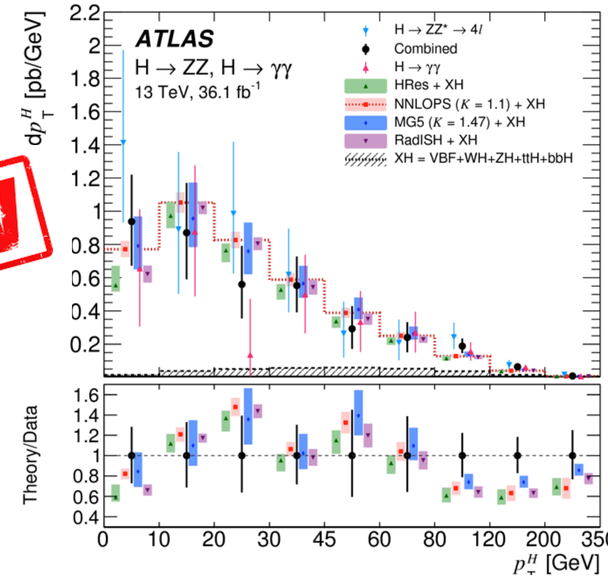


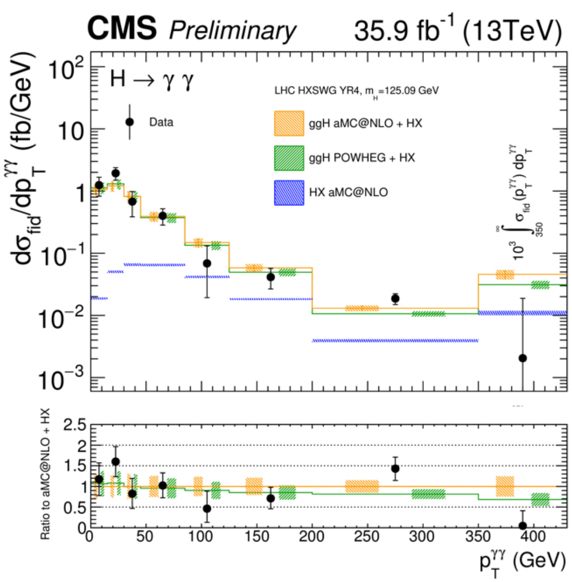
JHEP 11 (2017) 047; CMS-HIG-17-015; ATLAS-CONF-2018-002; ATLAS-CONF-2018-018

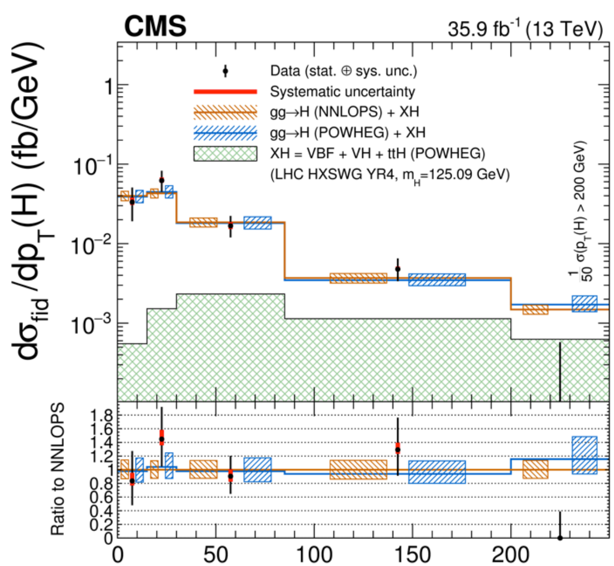
Differential Higgs boson cross sections

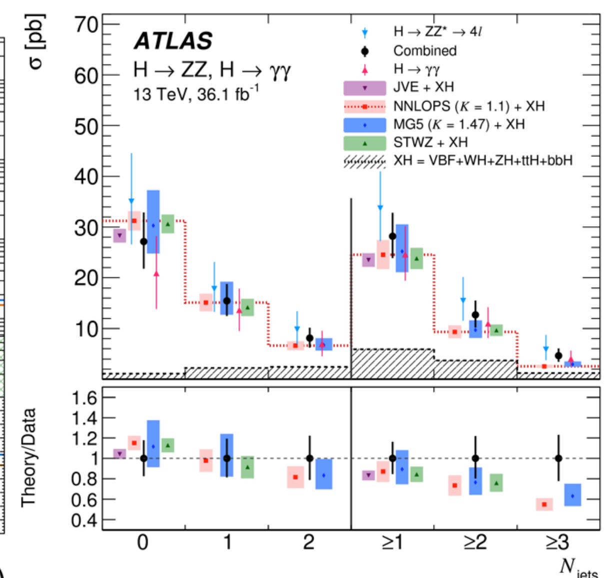
- Reached a new phase in the exploration of the Higgs sector!
- Differential cross sections:
  - Higgs p_T sensitive to new physics in gluon-fusion loop
  - Number of jets sensitive to modeling of radiation and different production modes

NEW





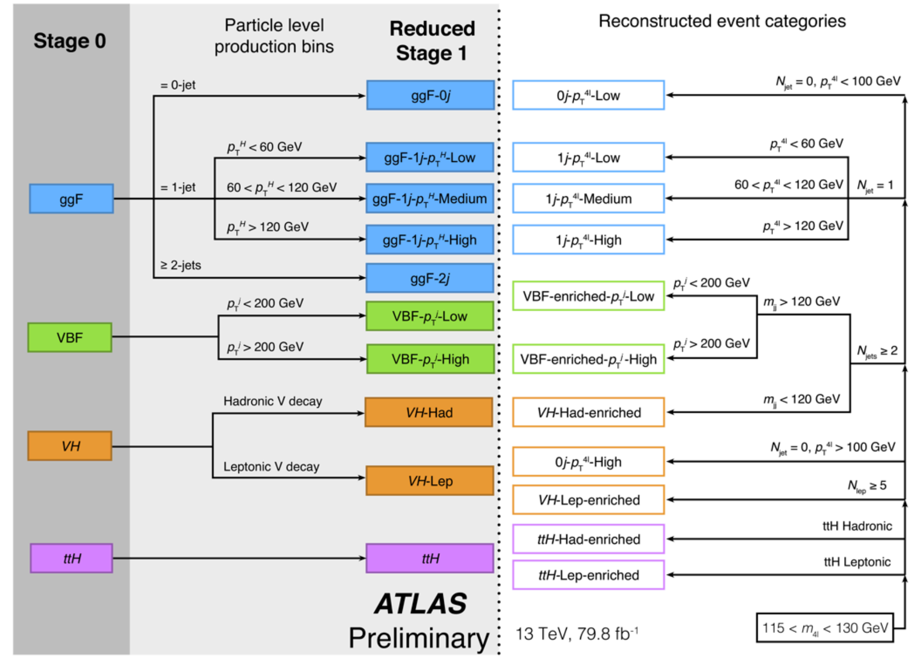


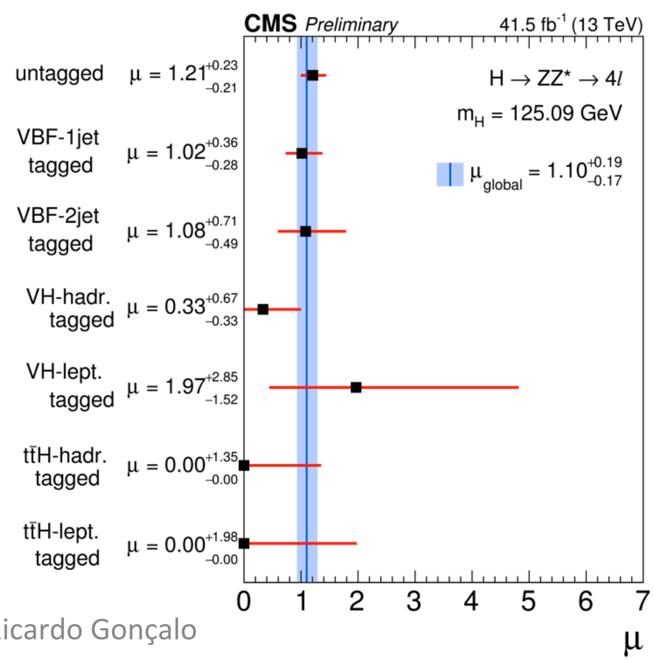


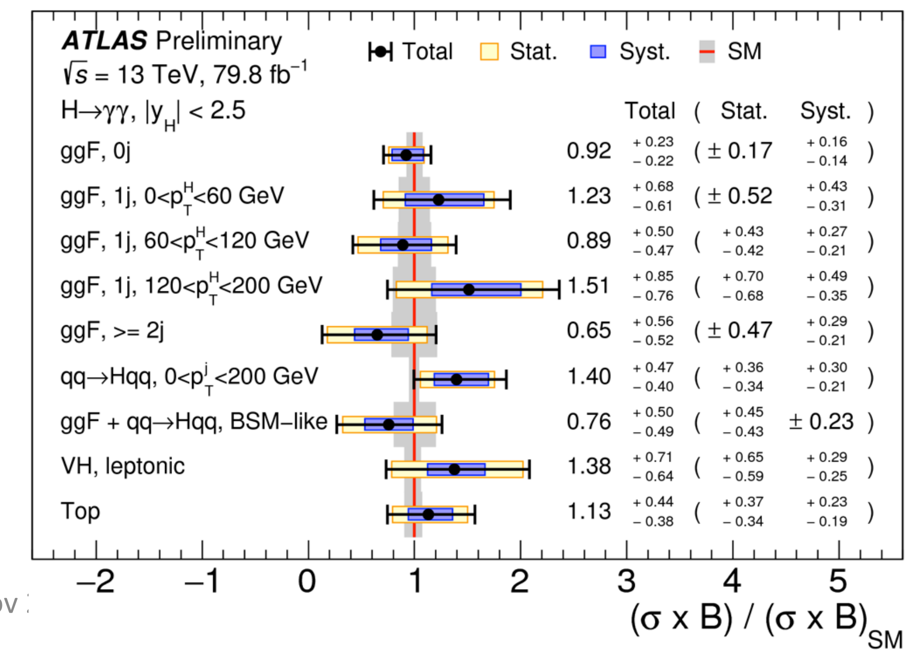
NEW
5 July 2018

ATLAS-CONF-2017-047; ATLAS-CONF-2018-028

- Simplified template cross sections (STXS):
  - Independent, simple fiducial region definition for each production mode
  - Common for ATLAS, CMS and theory
  - Good balance between experimental precision and theory uncertainty







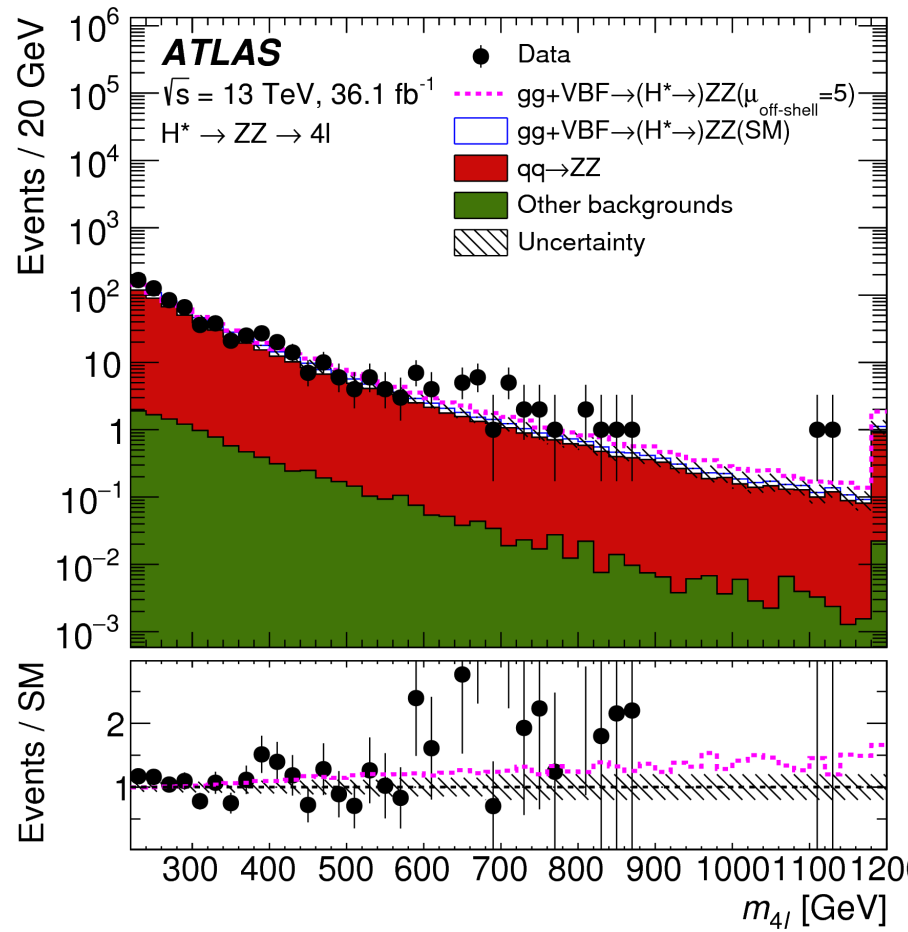
NEW
2 Aug 2018

Higgs boson width

- SM Higgs width Γ_H~4.1 MeV
  - Too small to be measured directly
  - Best direct limit from CMS:
    - Γ_H < 1.1GeV @ 95% CL
- Off-shell Higgs production sensitive(*) to Γ_H

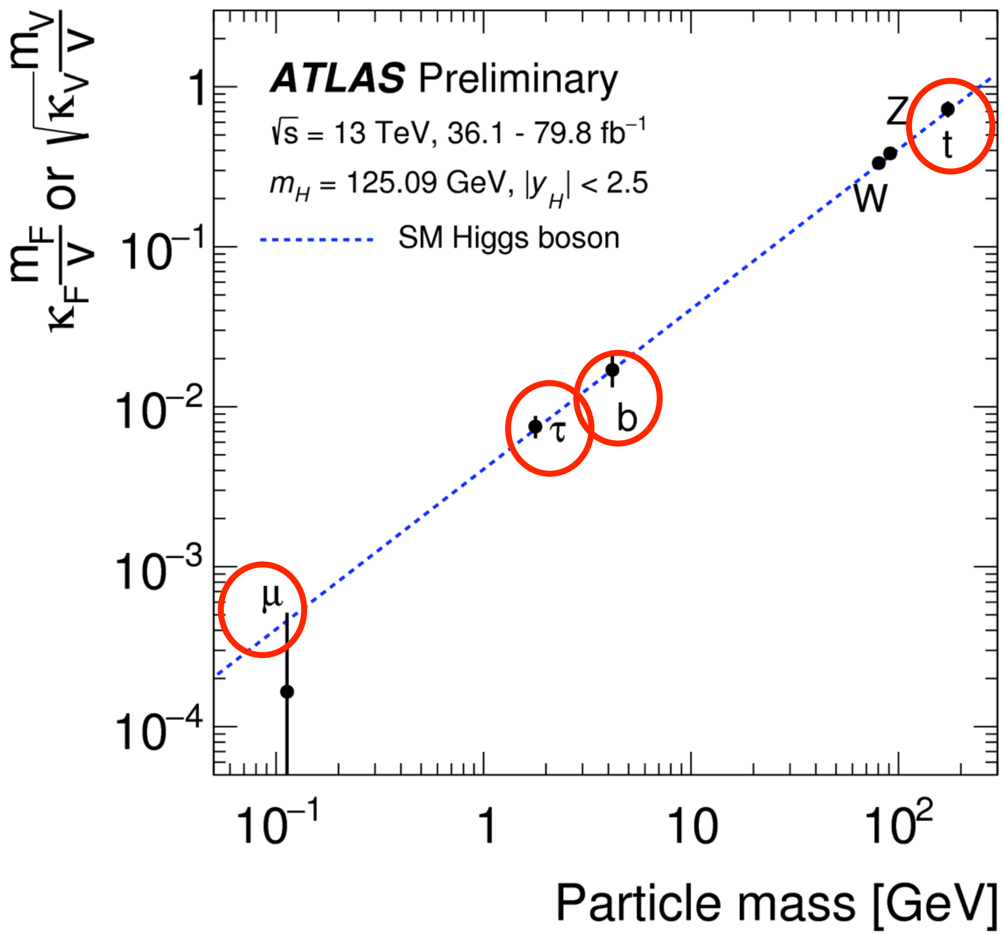
$$\frac{\mu_{\mathrm{off-shell}}}{\mu_{\mathrm{on-shell}}} = \frac{\kappa^2_{\mathrm{g,off-shell}} \cdot \kappa^2_{\mathrm{Z,off-shell}}}{\kappa^2_{\mathrm{g,on-shell}} \cdot \kappa^2_{\mathrm{Z,on-shell}}} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

- ATLAS measurement:
  - **pp→H→ZZ→4l** and ZZ→2l2ν
  - **m(H) > 2 m(Z)**
  - 36.1 fb^{-1} of 13 TeV data
  - Observed (expected) limit:
    - Γ_H < 14.4 (15.2) MeV



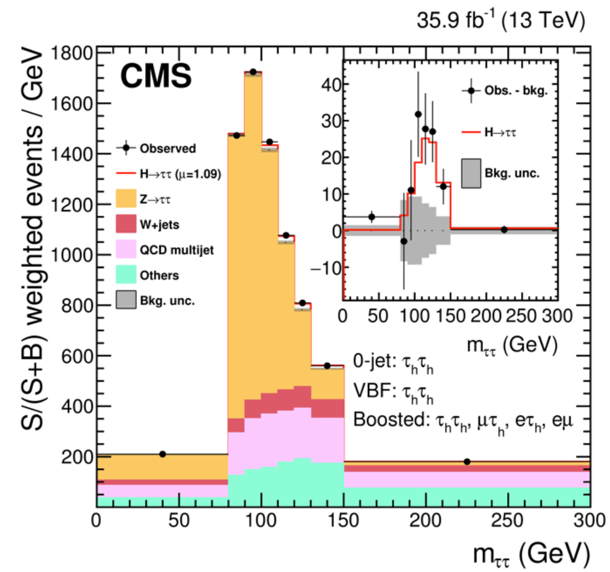
(*) Assume interference term with $gg \to ZZ$ proportional to $\kappa_{g,\text{off-shell}} \cdot \kappa_{Z,\text{off-shell}}$

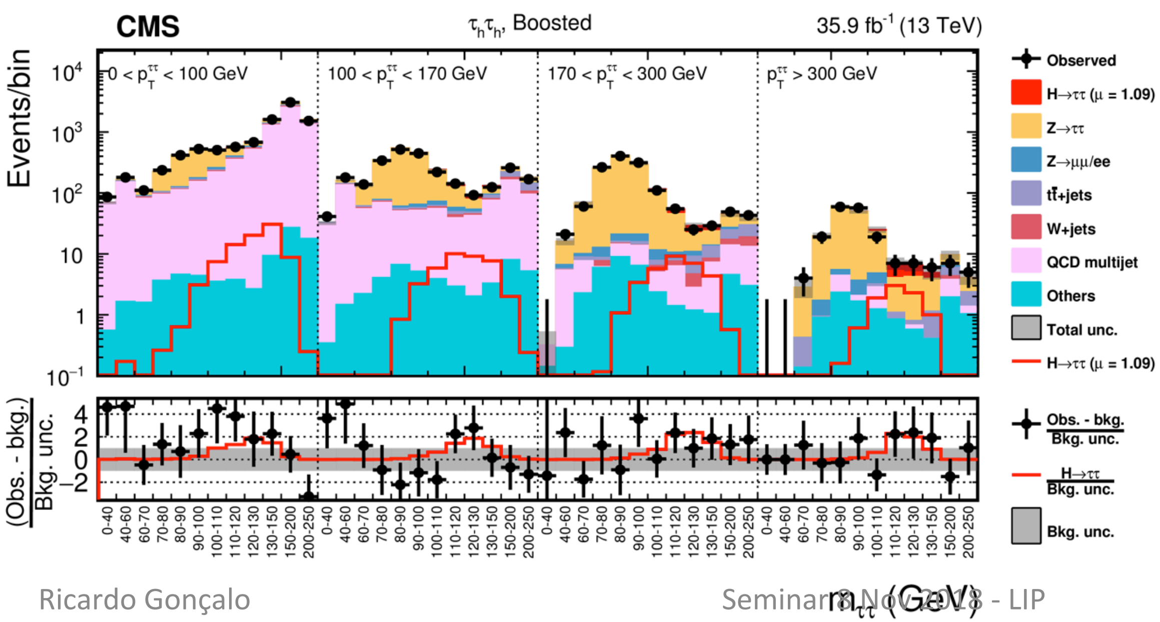
Exploring the Yukawa sector

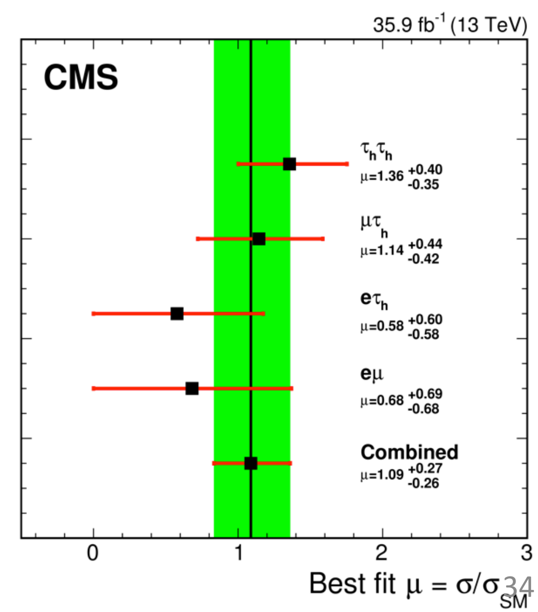


Observation of H→ττ

- Combine all final: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_{lep}\tau_{lep}$
- 3 categories: 0-jet, VBF and boosted (mostly ggF)
- 35.9 fb-1 of 13 TeV data
- 2D likelihood fit using $m_{\tau\tau}$, m_{jj} or $p_T^{\tau\tau}$
- Observed (expected) significance of 4.9σ (4.7σ)
- Combining with Run 1:
  - 36 fb-1 of 13 TeV data: 4.9 σ observed; 4.7 σ expected
  - Combining with Run 1: 5.9 σ observed; 5.9 σ expected
  - μ = 0.98 ± 0.18



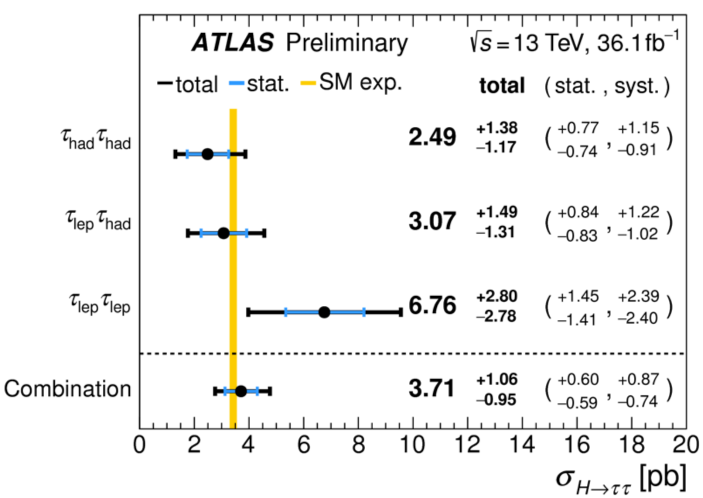


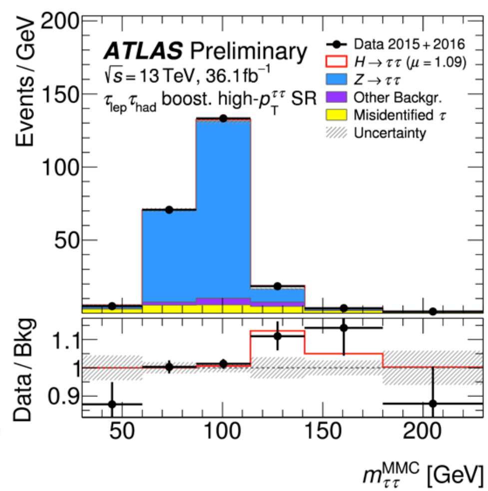


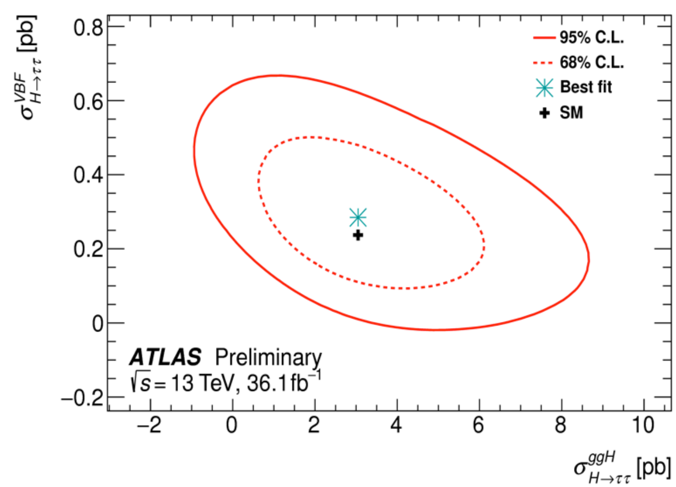
Observation of H→ττ

NEW
3 June 2018

- Combine all final: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_{lep}\tau_{lep}$
- Categories targeting boosted Higgs (mostly ggF) and VBF (additional jets)
- Dominant backgrounds from $Z\rightarrow\tau\tau$ and jets faking taus
- Cut-based analysis using fit to $m_{\tau\tau}$ distribution in 13 signal regions
- Largest uncertainties: data and MC statistics, signal modelling and jets
- Cross section measurement (13 TeV):
- $\sigma^{ggF} = 3.0 \pm 1.0\ (\text{stat.})\ ^{+1.6}_{-1.2}\ (\text{syst.})$ pb; $\sigma^{VBF} = 0.28 \pm 0.09\ (\text{stat.}) \pm 0.10\ (\text{syst.})$ pb
- Significance:
  - 36 fb^{-1} of 13 TeV data: 4.4 σ observed; 4.1 σ expected
  - Combining with 7 and 8 TeV data: 6.4 σ observed; 5.4 σ expected





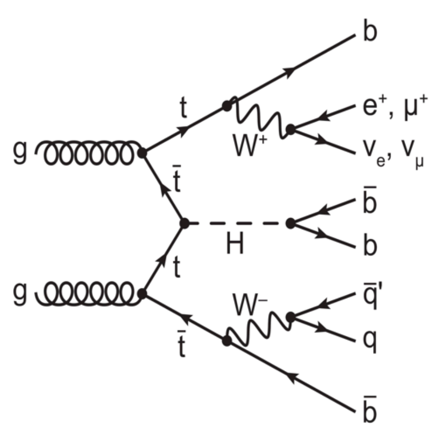


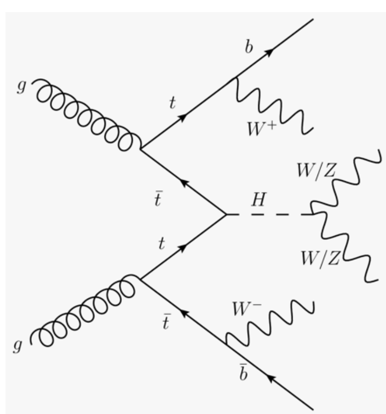
arXiv:1804.02610 [hep-ex]; arXiv:1806.00425 [hep-ex];

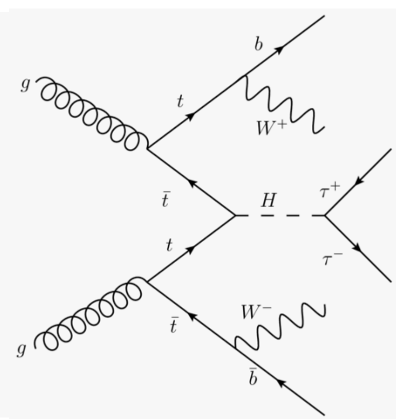
Observation of ttH production

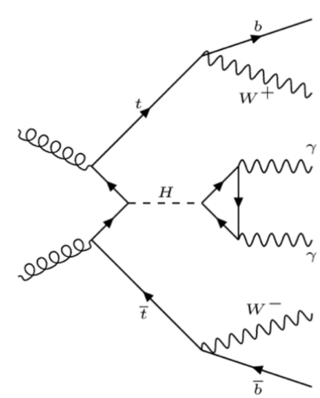
- **Direct** access to top Yukawa coupling
- Experimental tour-de-force!
  - Complex final states
  - Large irreducible backgrounds
  - Small cross sections: O(0.5)pb @ 13 TeV

- Use all available final states:
  - **H→bb**: high stats but low purity BR≈58%, S/B≈1-6%
  - **Multileptons:** H→$\tau\tau$, H→WW*, H→ZZ* BR = 30%, S/B=4-34%
  - **H→$\gamma\gamma$**: clean but low stats BR = 0.23%, S/B=5-200%
  - **H→ZZ*→4lep**: clean but very low stats BR = 0.01%, S/B=50-500%







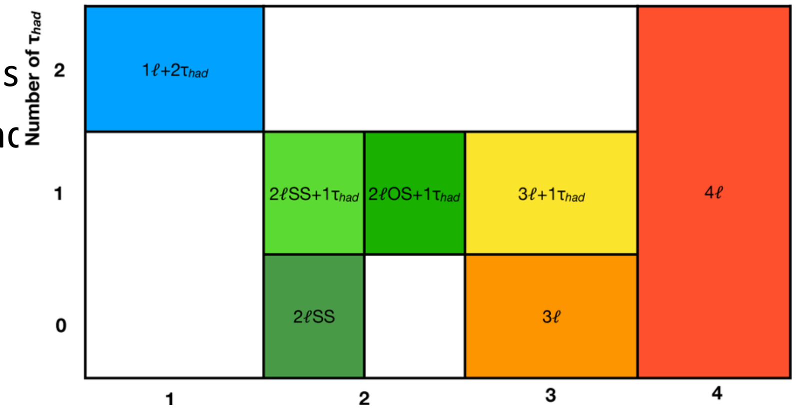


ttH(ML) Phys. Rev. D 97 (2018) 072003; arXiv:1803.05485 [hep-ex]
ttH(bb) Phys. Rev. D 97 (2018) 072016; JHEP 01 (2018) 054

ttH observation: bb and Multileptons

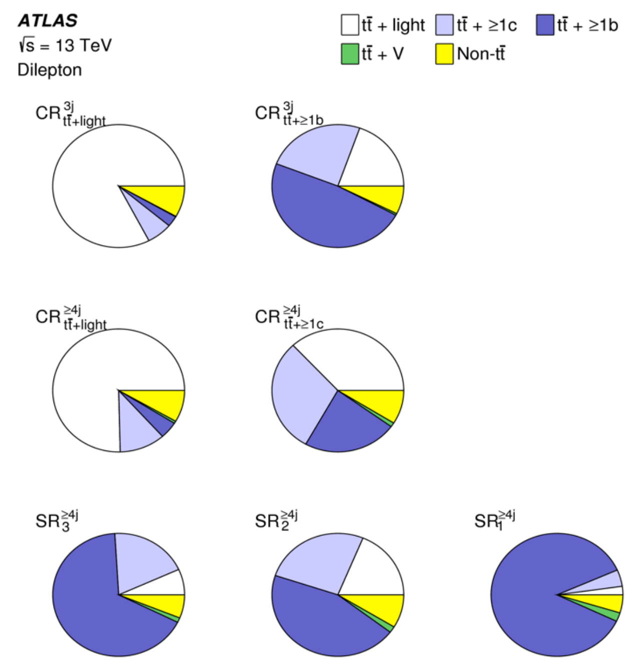
ttH(H→leptons)

- Sensitive to: H→$\tau\tau$, H→WW* and H→ZZ*
- Backgrounds: ttW/ttZ, non-prompt leptons and fake taus
- Main uncertainties: signal modelling, jet energy scale and non-prompt lepton estimate
- ATLAS: 4.1σ observed; 2.8σ expected
- CMS: 3.2σ observed; 2.8σ expected



ttH(H→bb):

- Profit from large H→bb branching ratio (58.4%)
- But challenging final state: large ttbb irreducible background, theory uncertainties, combinatorics...
- Main uncertainties: tt+heavy flavours, b tagging, jet calib.
- ATLAS: 1.2σ observed; 1.6σ expected
- CMS: 1.6σ observed; 2.2σ expected



For **both** channels:

- Intensive use of dedicated machine learning (NN, BDT) and matrix element methods: suppress fake leptons, reconstruct events, flavour tagging, and enhance S/B

ttH observation

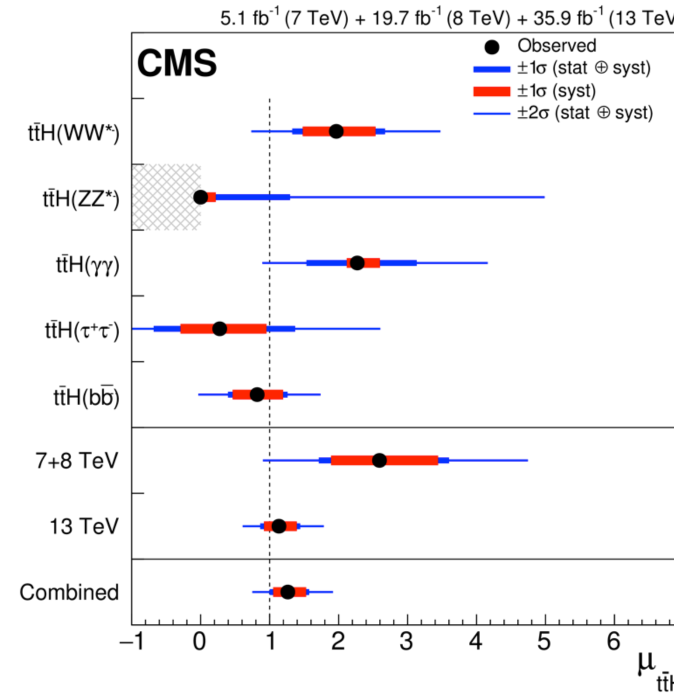
CMS:

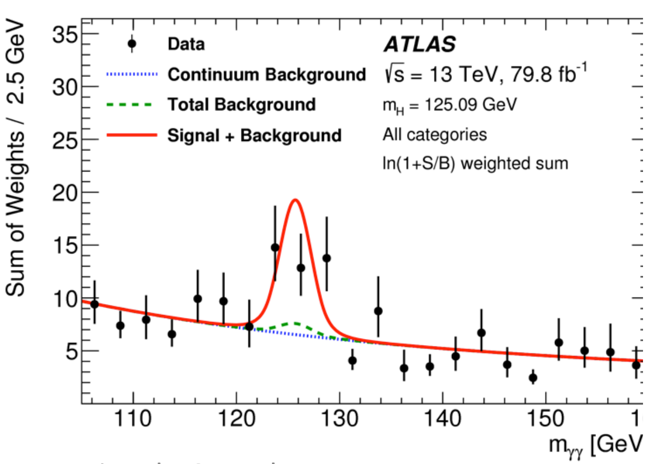
- Combined Run 1 + 36.1 fb^{-1} Run 2:
- 5.2 σ observed, 4.2 σ expected

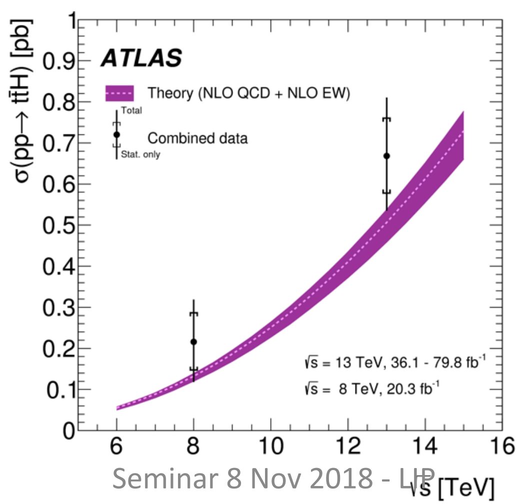
ATLAS:

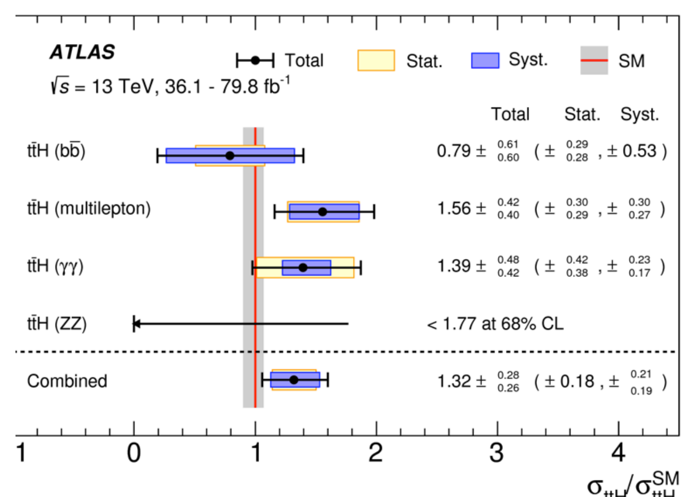
- ttH(H→$\gamma\gamma$):
  - New signal categories from BDT discriminant
  - **Sensitivity increased by 50%**
- Run 2 data from 2015+2016+2017 ($\gamma\gamma$/ZZ): **79.8 fb^{-1}**
  - 5.2 σ observed, 4.9 σ expected
- Adding Run 1: 6.3 σ observed, 5.1 σ expected
- Measured production cross section at 13 TeV:

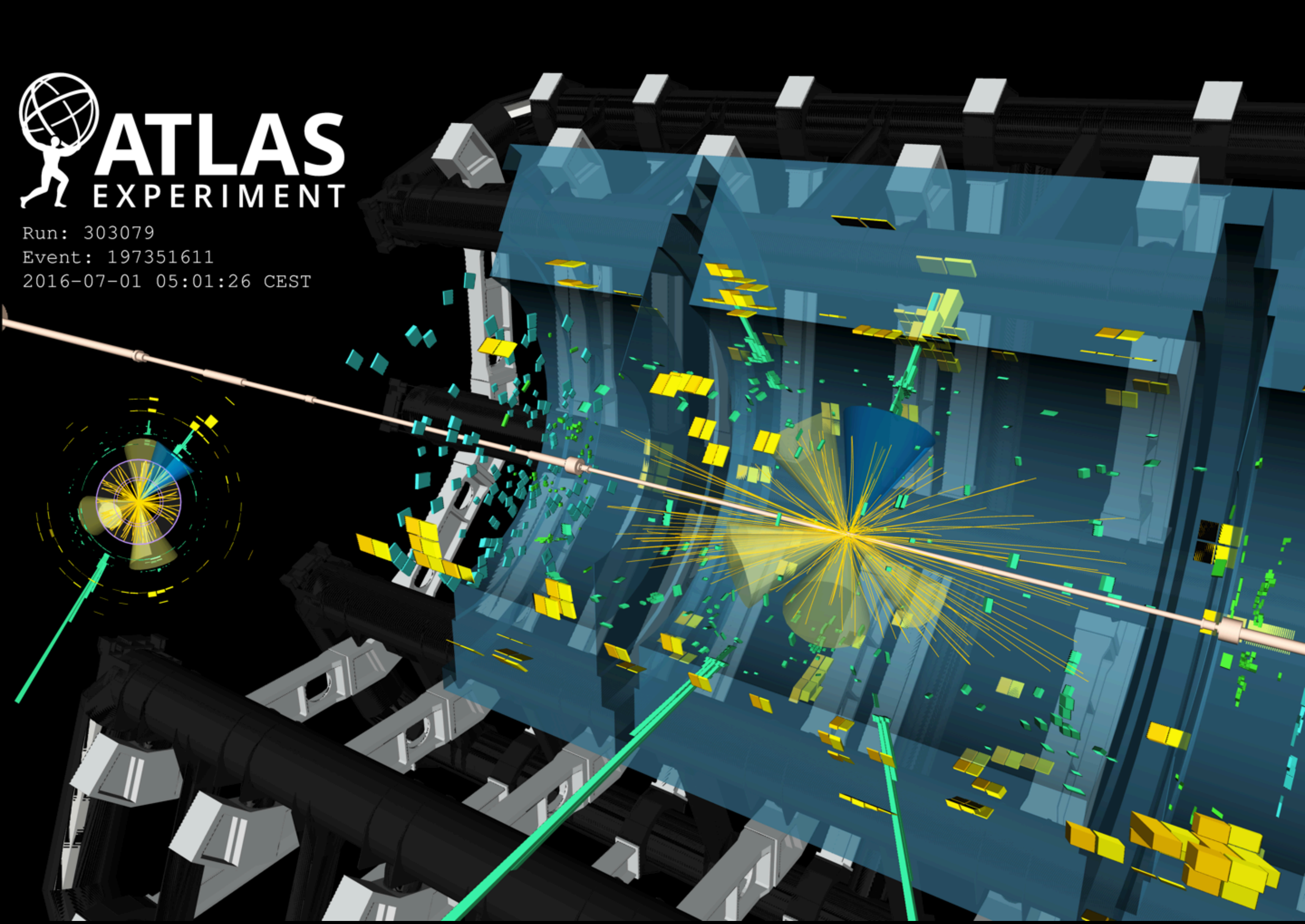
670 ± 90 (stat.) +110−100 (syst.) fb










ATLAS
EXPERIMENT
Run: 303079
Event: 197351611
2016-07-01 05:01:26 CEST

Next steps in ttH(→bb) @ LIP

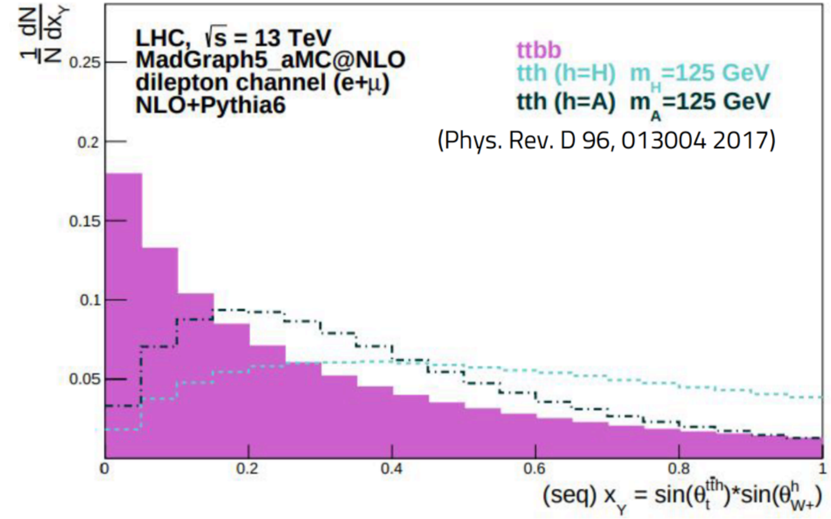
- In BSM scenarios could have mixed-CP structure of top Yukawa coupling

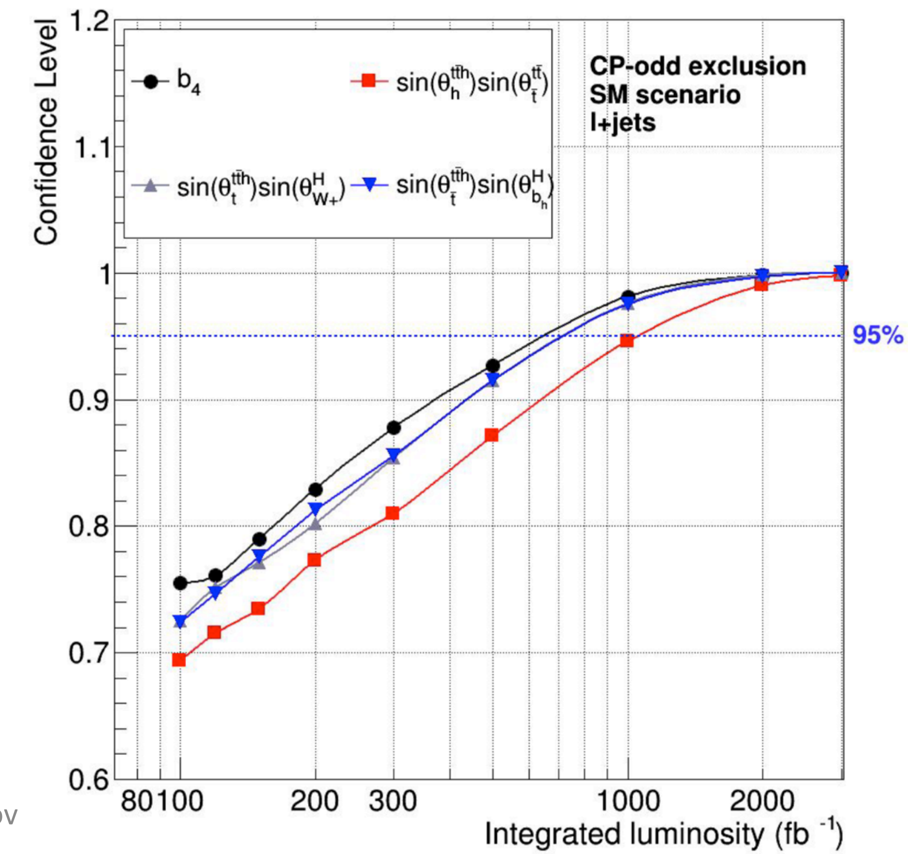
$$\mathcal{L} = \kappa\, y_t\, \bar{t}\,(\cos\alpha + i\gamma_5 \sin\alpha)\, t\, h$$

  - e.g. 2HDM
  - α = 0 recovers SM
- Study done with fast simulation so far
- See e.g.:

  Phys. Rev. D 96, 013004 2017

  Phys. Rev. D 98, 033004 2018





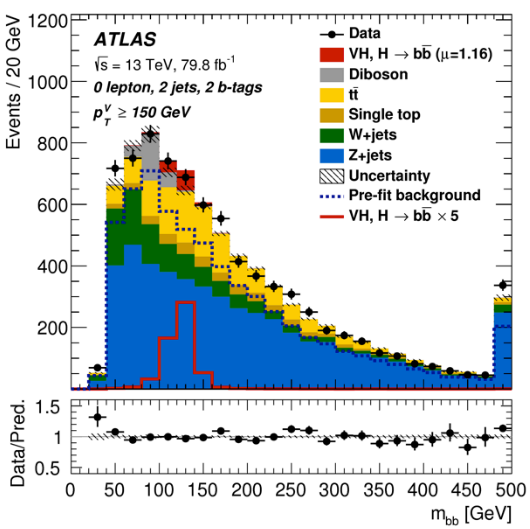
arXiv:1808.08238; arXiv:1808.08242 [hep-ex]

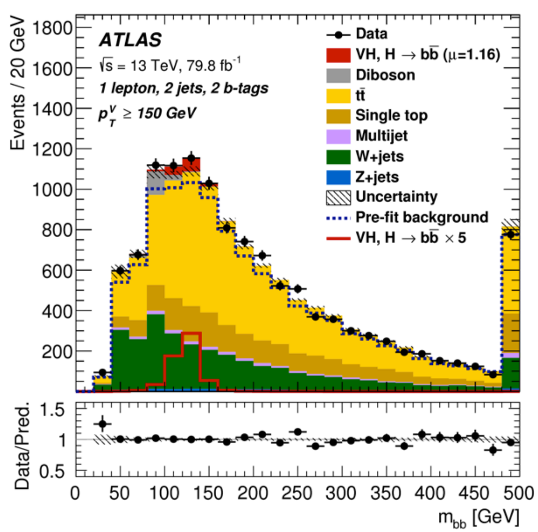
Observation of H→bb

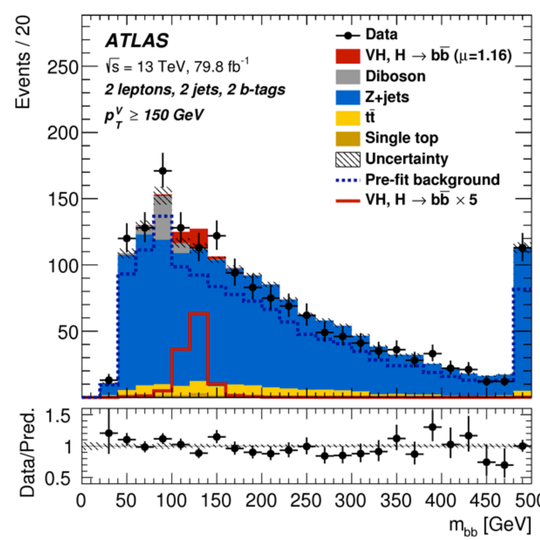
- See **CERN seminar: observation in ATLAS and CMS**
  - https://indico.cern.ch/event/750541/
- Largest branching fraction (58.4%) but huge background from heavy flavour production
- Must use associated production: WH/ZH
  - Require 2 b jets + 0 (Z→$\nu\nu$), 1 (W→$\ell\nu$) or 2 (Z→$\ell\ell$) leptons
- Largest backgrounds:
  - Z+heavy flavour (0- and 2-lepton) and tt (1-lepton)
  - Irreducible background from VZ with Z→bb

NEW

9 July 2018

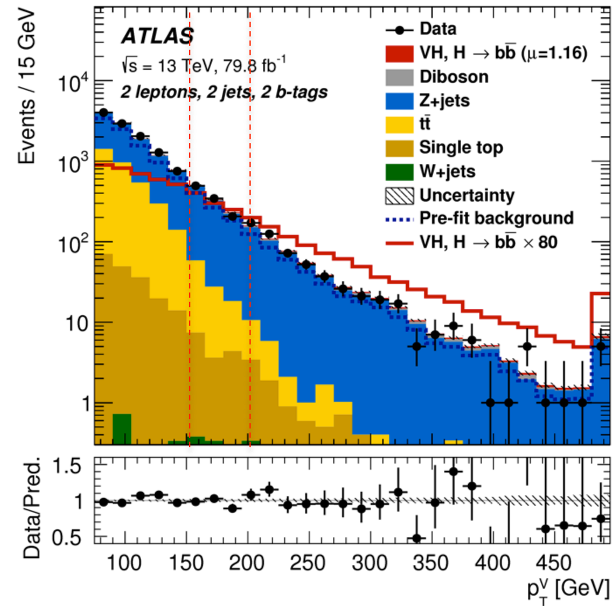




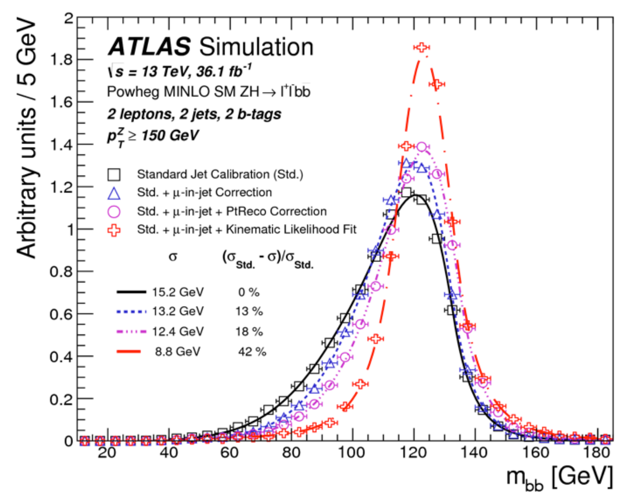


Observation of H→bb

- Harder p_T spectrum for signal than backgrounds
  - Go to high p_T to improve S/B
- Use for event categories:
  - $75 < p_T^V < 150$ GeV (2ℓ only)
  - $150 < p_T^V < 200$ GeV
  - $p_T^V > 200$ GeV



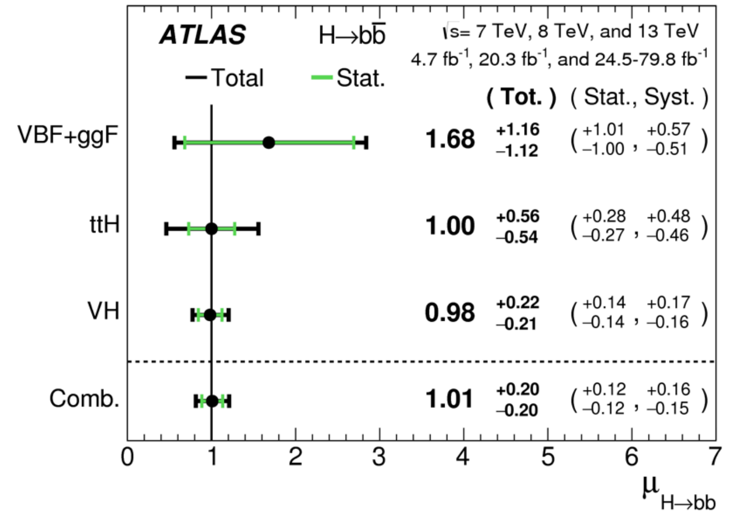
- Main discriminant variables m_{bb}, p_T^V and ΔR_{bb}
  - m_{bb} resolution extremely important!

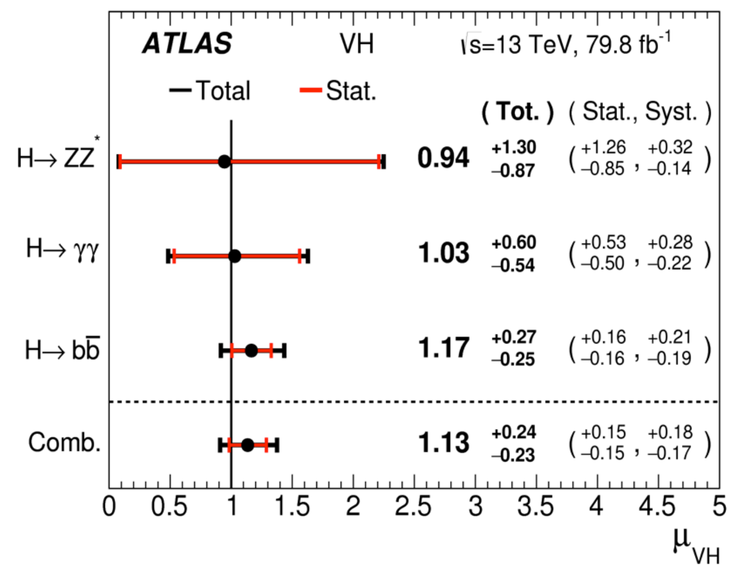


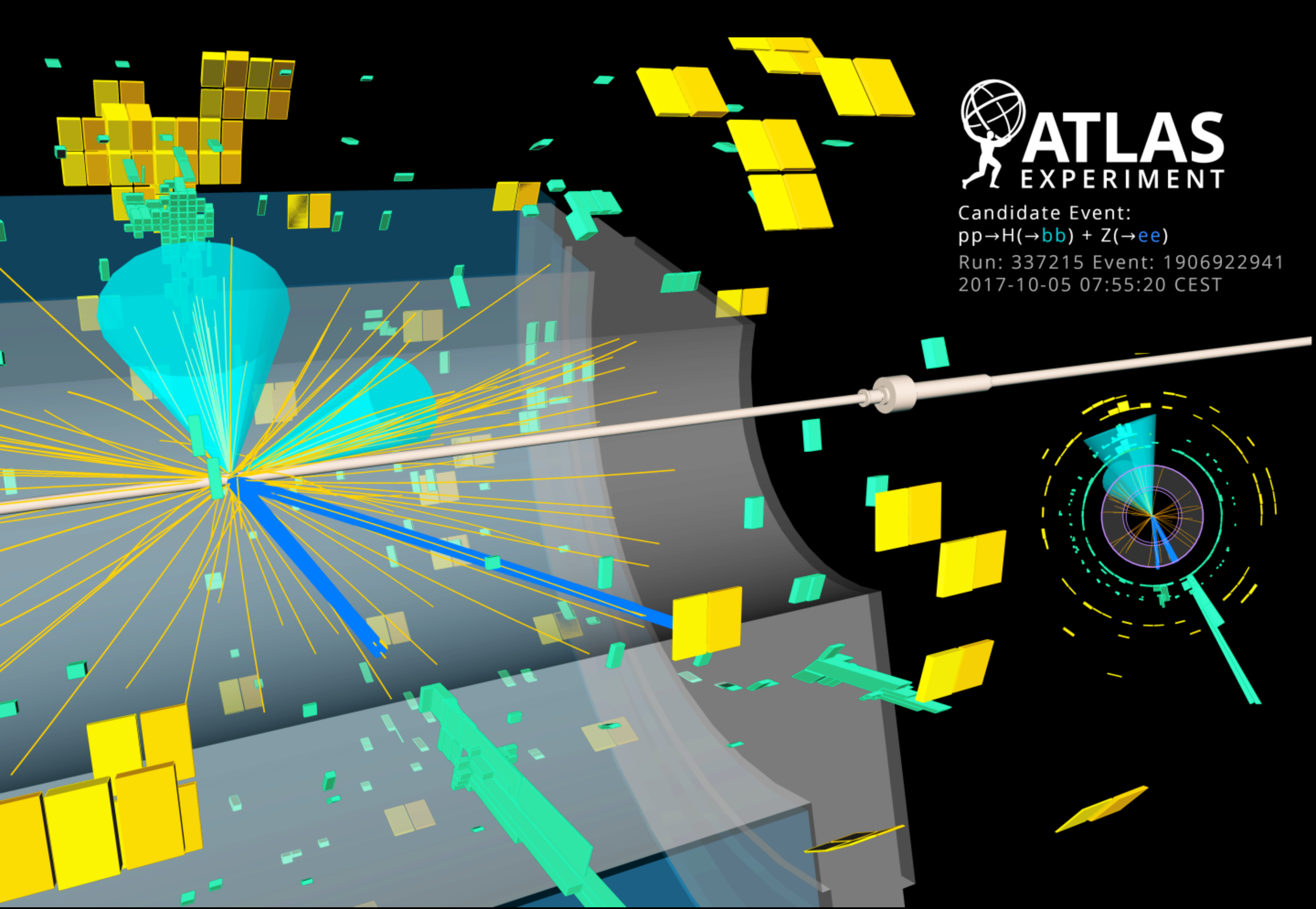
arXiv:1808.08238

Observation of H→bb

- Run 2:
  - Observed (expected) of 4.9σ (4.3σ)
- Adding Run 1:
  - Observed (expected) of 4.9σ (5.1σ)
- Adding ttH and VBF:
  - Observed (expected) of 5.4σ (5.5σ)
  - **Observation of H→bb decays**
- Adding H→ZZ and H→γγ:
  - Observed (expected) of 5.3σ (4.8σ)
  - **Observation of VH production**

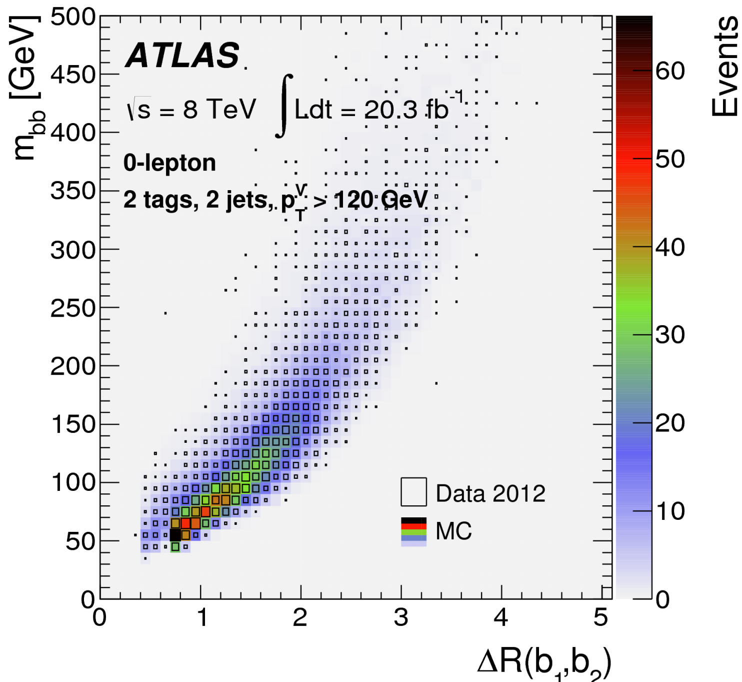





ATLAS
EXPERIMENT
Candidate Event:
pp→H(→bb) + Z(→ee)
Run: 337215 Event: 1906922941
2017-10-05 07:55:20 CEST

H→bb @ LIP

- Boosted decision tree (BDT)
- Combine many different variables
- Trained in 8 categories: 3 lepton, 2/3 jets, low/high p_T^V bin (2 lepton channel)
- Most discrimination from m_{bb} and DR(b_1,b_2)



Variable	0-lepton	1-lepton	2-lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
m_{ll}			×
m_{Top}		×	
$\lvert\Delta Y(V, H)\rvert$		×	
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

New in run 2:

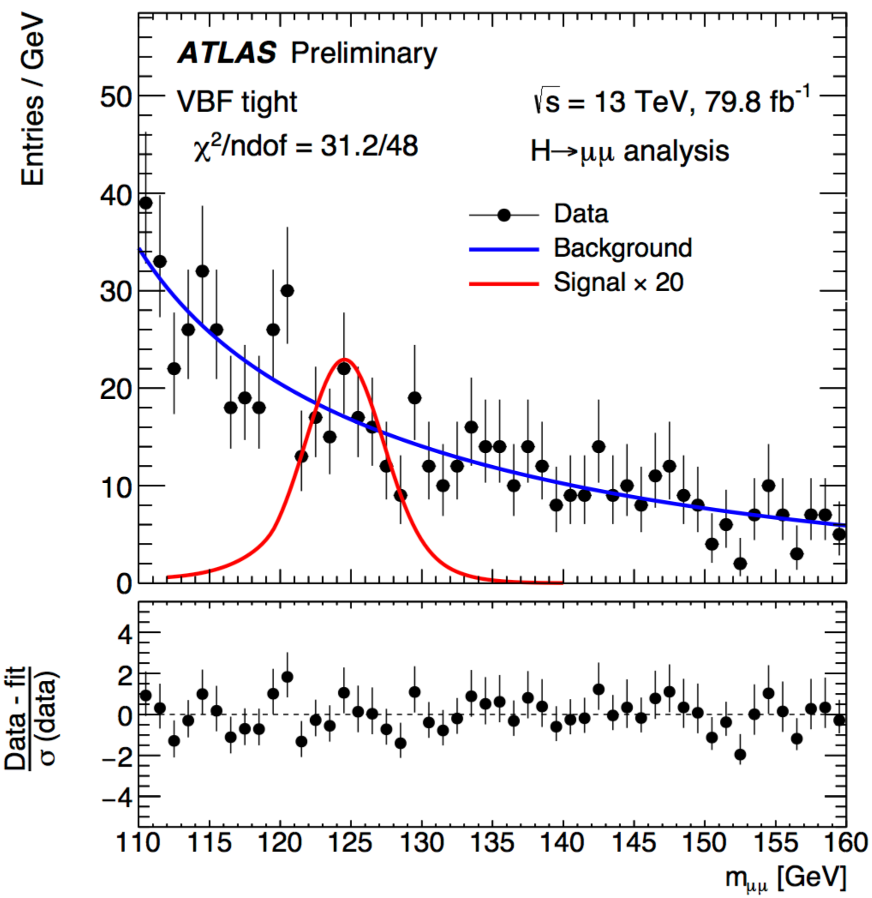
m_{Top}, |DY(V,H)| → +7% in sensitivity

2^{nd} generation Yukawa: H→μμ

NEW

2 July 2018

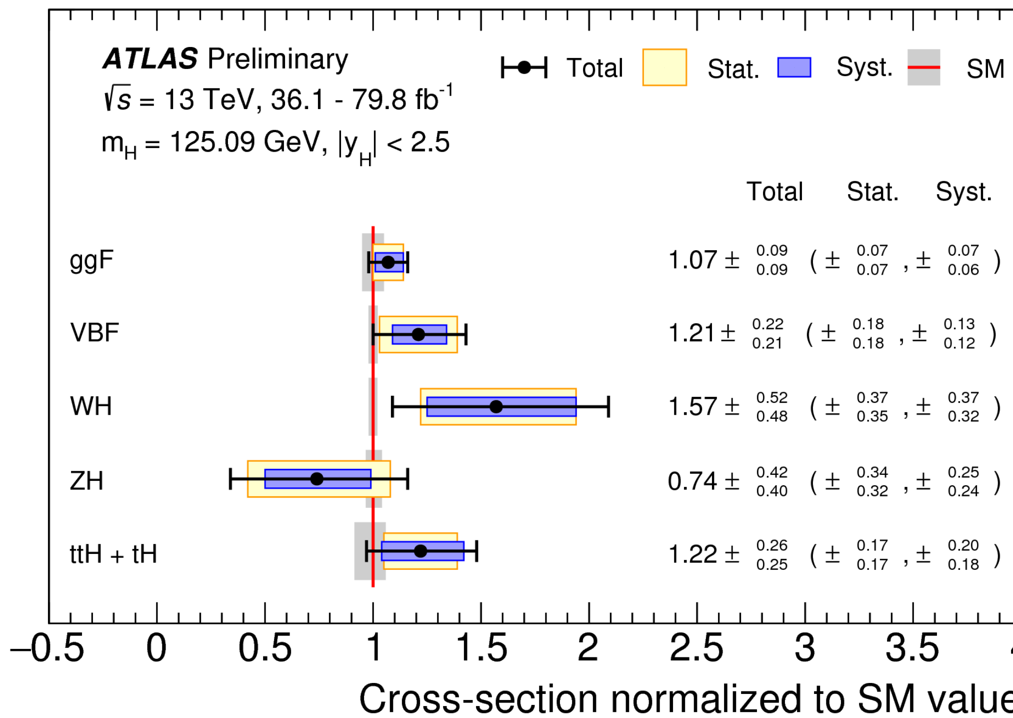
- Easy to trigger on, but very rare
- Used 80 fb^{-1} of 13 TeV data
- Event categories based on muon η, $p_T^{\mu\mu}$, and VBF (BDT)
- Search peak in $m_{\mu\mu}$
- Background from sidebands à la H→γγ analysis
- 95% CL limits:
  2.1 (obs), 2.0 (exp)
- **Getting close to SM sensitivity!**



Combination

- Combined γγ, ZZ, WW,ττ, μμ and bb (incl. ttH+tH modes)
  - Up to 79.8 fb^{-1} of $\sqrt{s}$ = 13 TeV data
- Combination yields VBF significance 6.5σ (5.3σ expected) **from ATLAS alone**
- Main production modes (ggF, VBF, VH, ttH) have all been observed!!
- Good agreement with SM predictions
- Overall signal strength:

  $\mu = 1.13^{+0.09}_{-0.08}$
- Quantified space for undetectable decays or modified BR (e.g. BSM H→cc)
  - B_{BSM} < 0.13 at 95% CL.(*)



(*) In determination of κ_g and κ_γ - assumption dependent

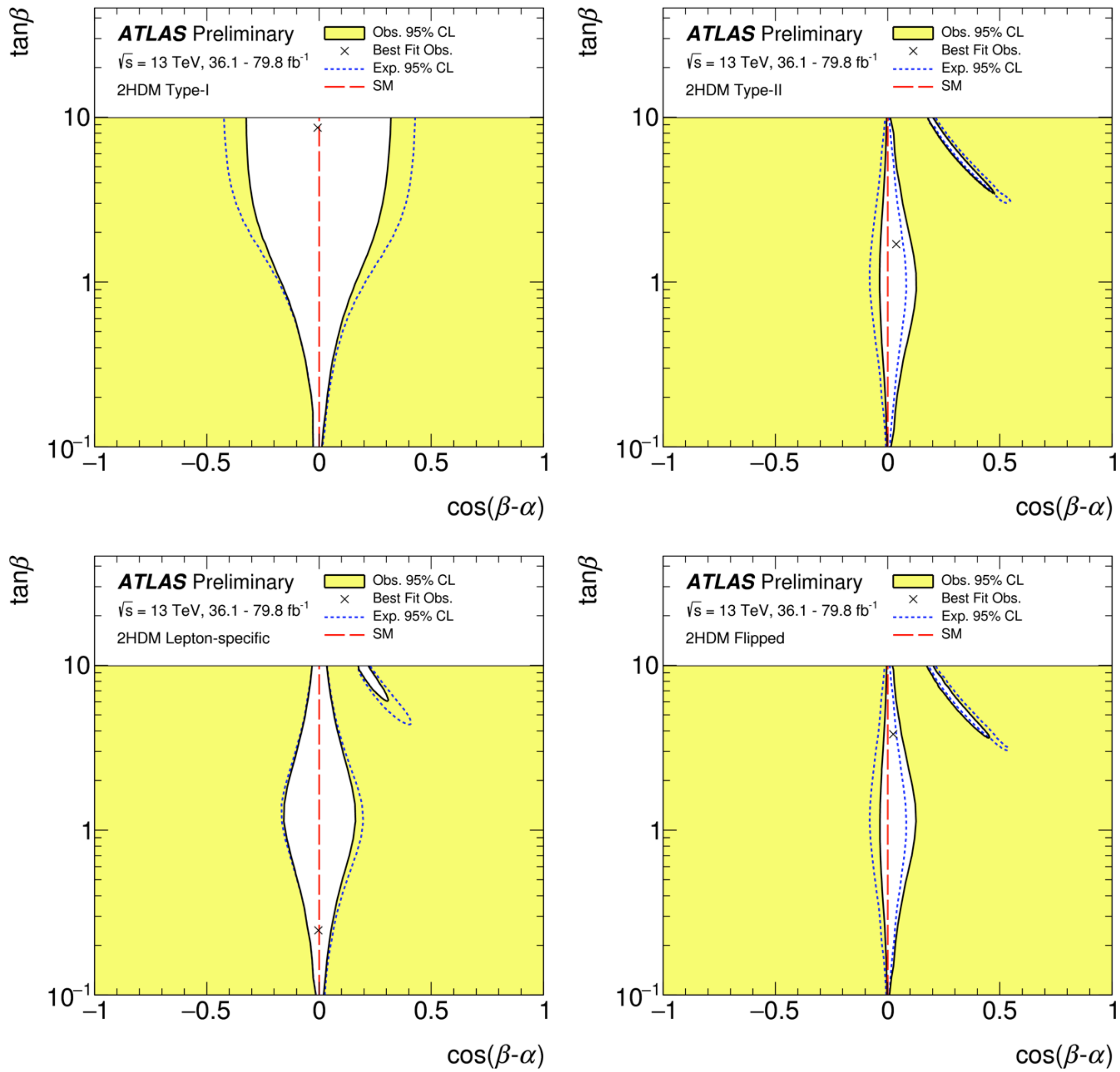
Two Higgs Doublet Model (2HDM)

- Two Higgs doublets: Φ_1 and Φ_2 → 5 Higgs bosons incl. 2 charged
- Free parameters:
  - 4 masses (Do we know one? Assume it's m_h)
  - $\tan\beta = v_1/v_2$ ratio of v.e.v.'s of Φ_1 and Φ_2
  - Mixing angle of h and H: α
- 4 possible Yukawa coupling arrangements ("types") with no FCNC
- Most common SUSY benchmark (MSSM) is based on Type II
- If $\cos(\beta-\alpha) = 0$, h = Standard Model H^0

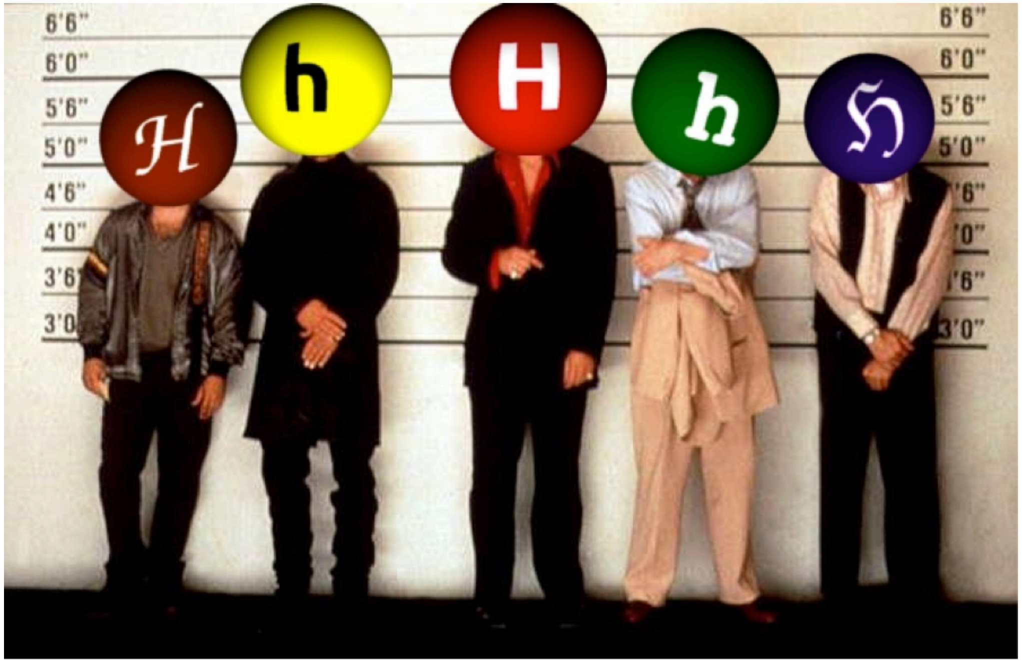
	Type I	Type II	Lepton Specific	Flipped
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Implications for 2HDM

- H(125) assumed to be light CP-even neutral scalar *h* in 2HDM
- *h* production and decay same as for SM Higgs boson



Casting a wider net

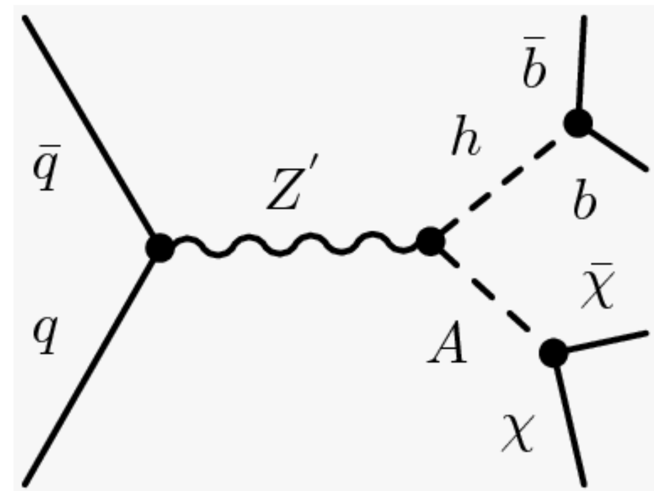


ATLAS-CONF-2018-039

NEW
25 July 2018

Higgs + Dark Matter

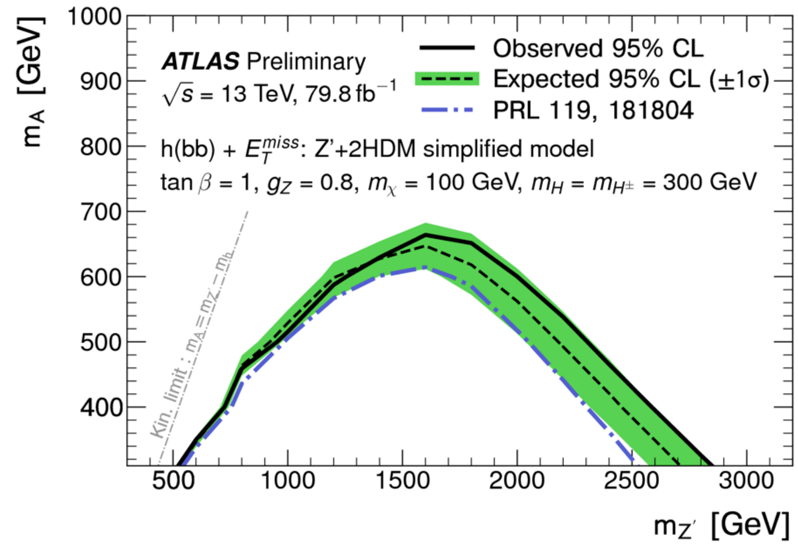
- Used 79.8 fb^{-1} of 13 TeV data
  - High E_T^{miss} (>150GeV) and b-tagging to suppress backgrounds
  - Reconstruct b-jets as 2 small jets or merged variable-radius (VR) track jets



- Signal benchmark: Type-II 2HDM + $U(1)_{Z'}$ symmetry (Z'-2HDM)

- Main backgrounds: tt, W/Z+jets

- Excluded region in $m_A - m_{Z'}$ plane



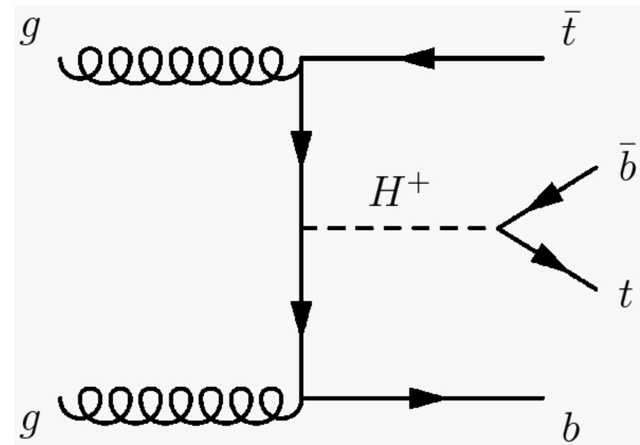
Charged Higgs: $H^+ \rightarrow tb$

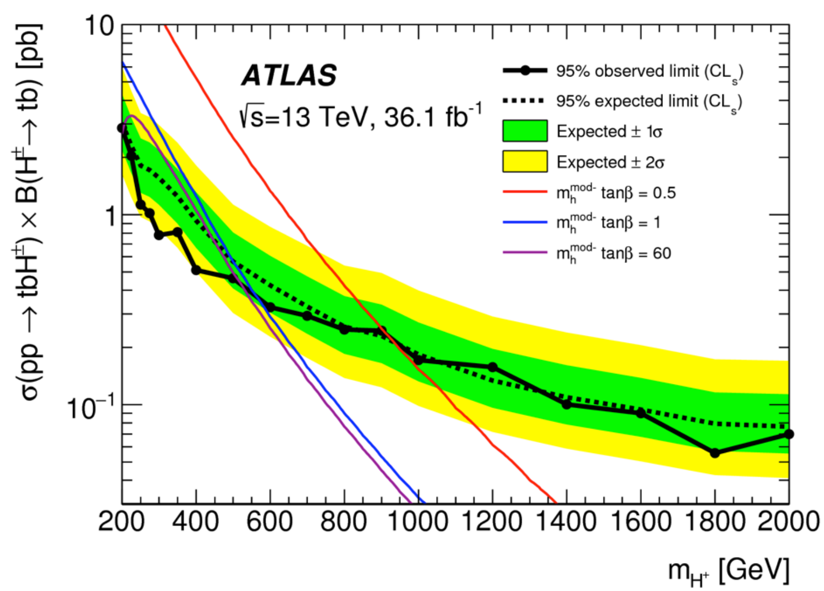
- Explored single-lepton and dilepton tt final states
  - In range m_{H+}: 200 – 2000 GeV
- 36.1 fb^{-1} of 13 TeV data

- Events categories: N_{jets} and $N_{b\text{-}tags}$
  - Allow to constrain backgrounds in simultaneous fit

- BDTs trained in signal regions
  - Separate signal and background for 18 mass points
  - Matrix method used in single-lepton channel

- Extracted limits on σ x BR and on m_{H+} - tan β plane for two MSSM scenarios





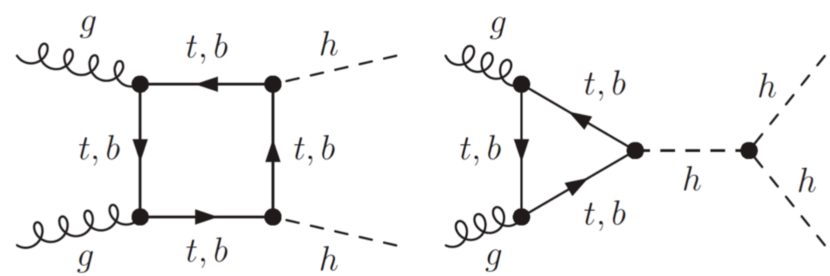
NEW
7 July 2018
4 Sep 2018

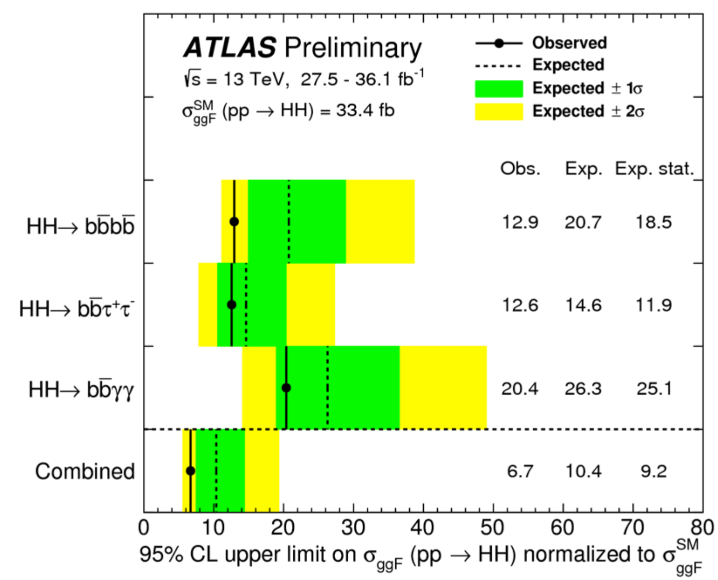
Triple Higgs coupling

- The triple Higgs coupling λ_{HHH} can be probed through di-Higgs production
- Very suppressed in SM!
  - Negative interference between LO diagrams
  - Cross section 1500x less than ggF
- Wide range of decay BR and channel purity
- bbττ analysis:
  - Used 36 fb^{-1} of 13 TeV data
  - Final state BR(bbττ)=7%
  - Non-Resonant 95% CL limit:

    μ < 12.7 observed (14.8 expexcted)
- Combination: at ≈10 x SM sensitivity – with 3% of the HL-LHC luminosity analyzed

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

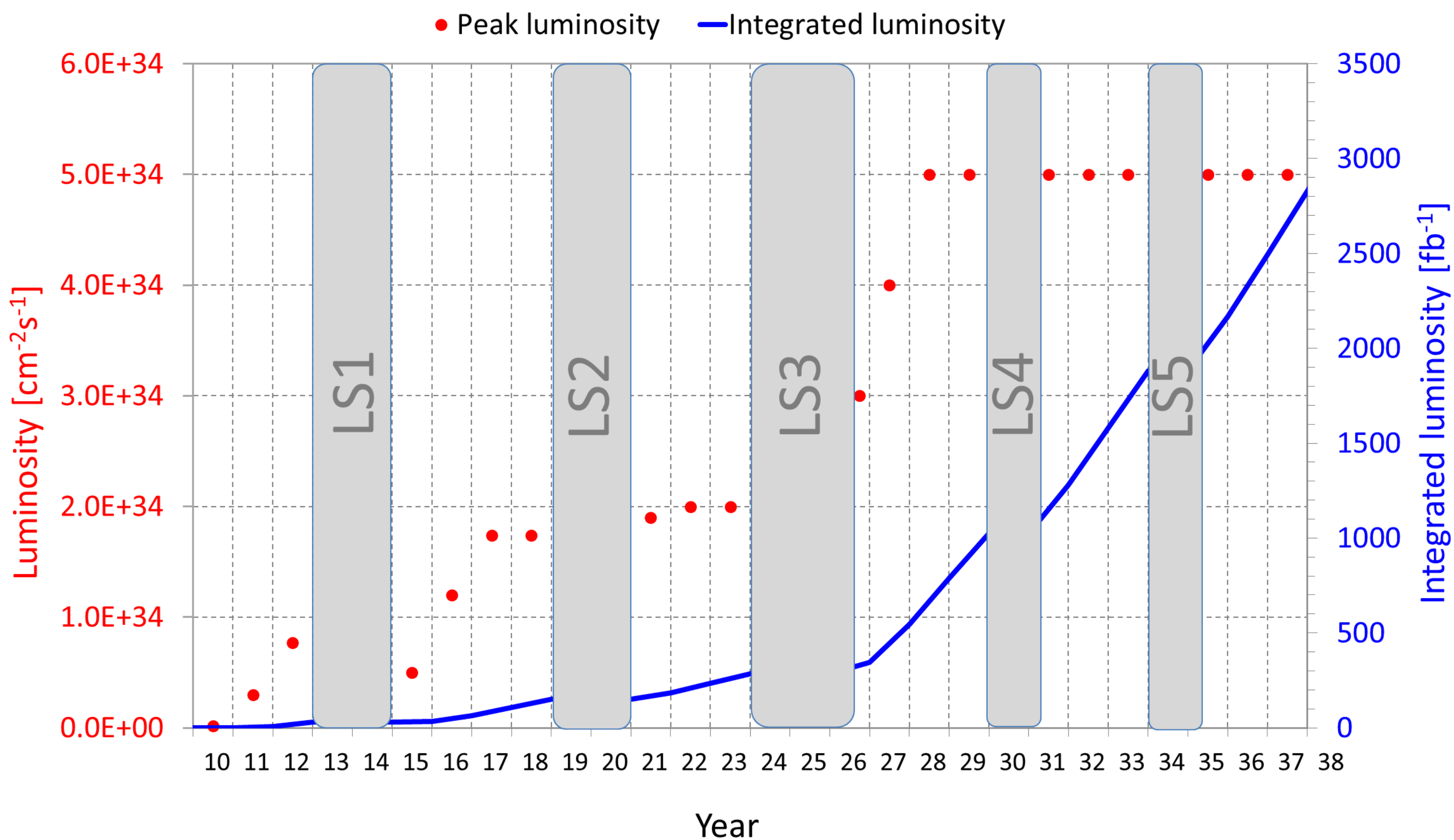




Di-Higgs combination plot here

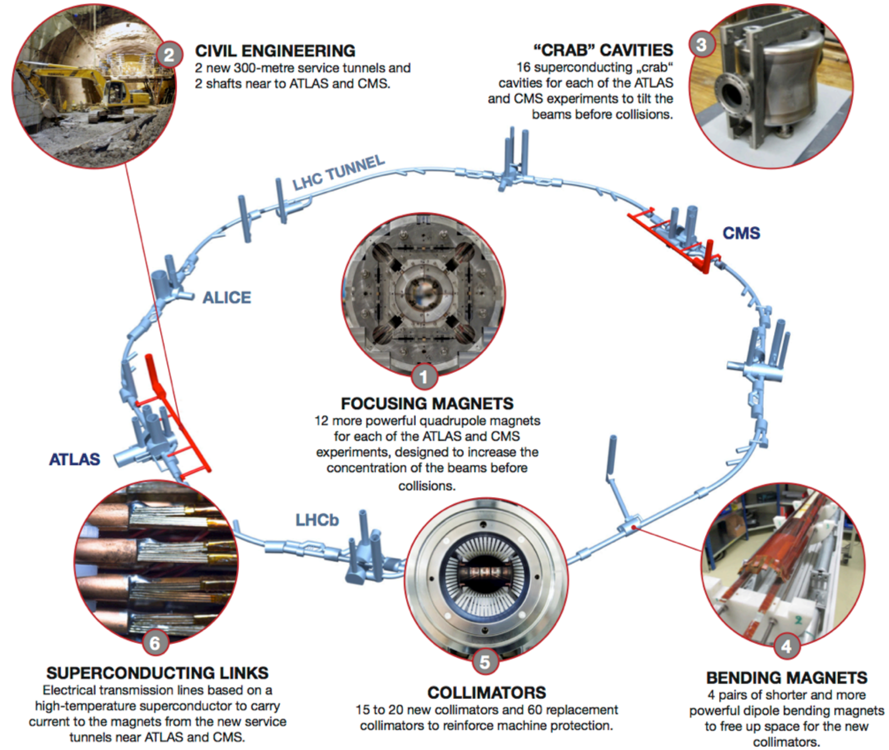
The future

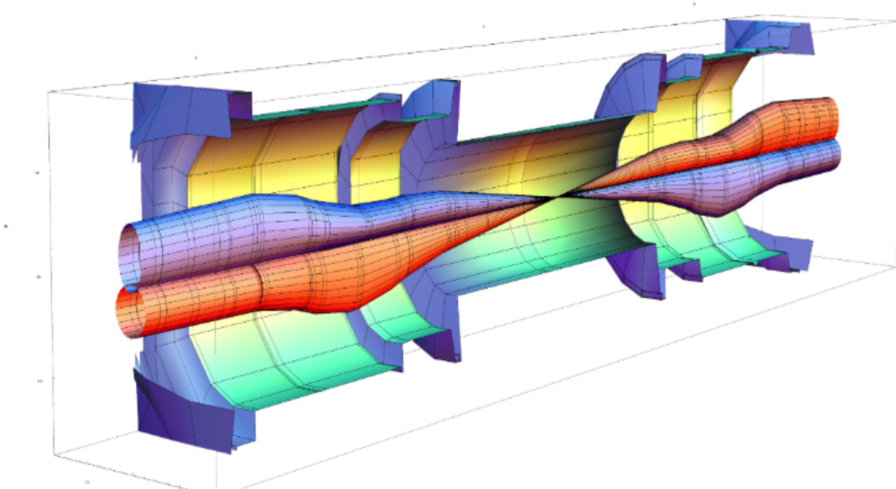
LHC and HL-LHC timeline

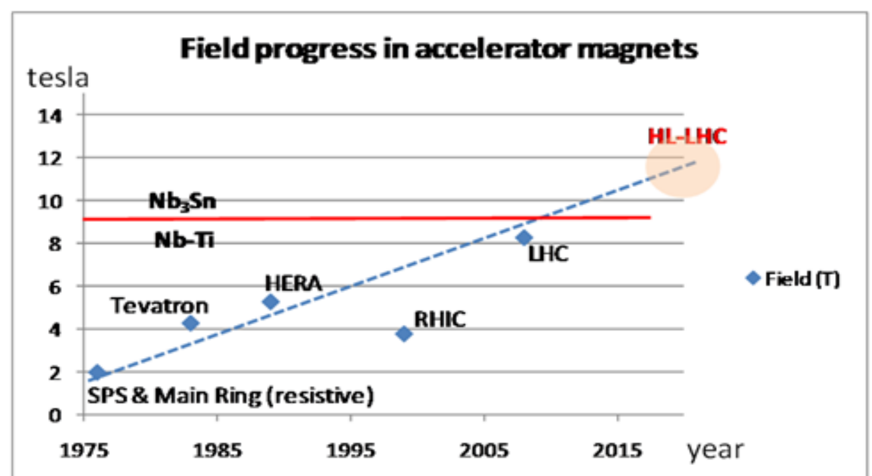


LHC Upgrades

- Development of a new generation of superconducting magnets with higher critical field (Nb_3Sn):
  - 13.5 T instead of 8 T (LHC, NbTi)
- Development of “crab cavities” to increase bunch overlap
- Colimators, connectors, civil eng., etc







R. Gonçalo - LIP
Ciência 2018
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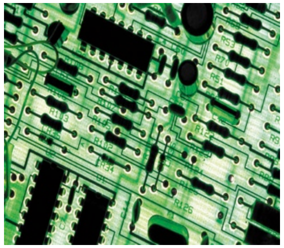
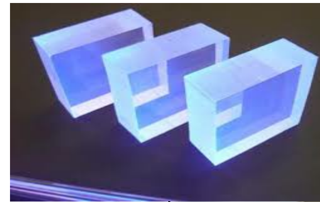
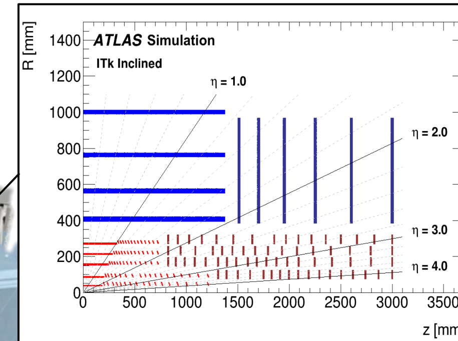


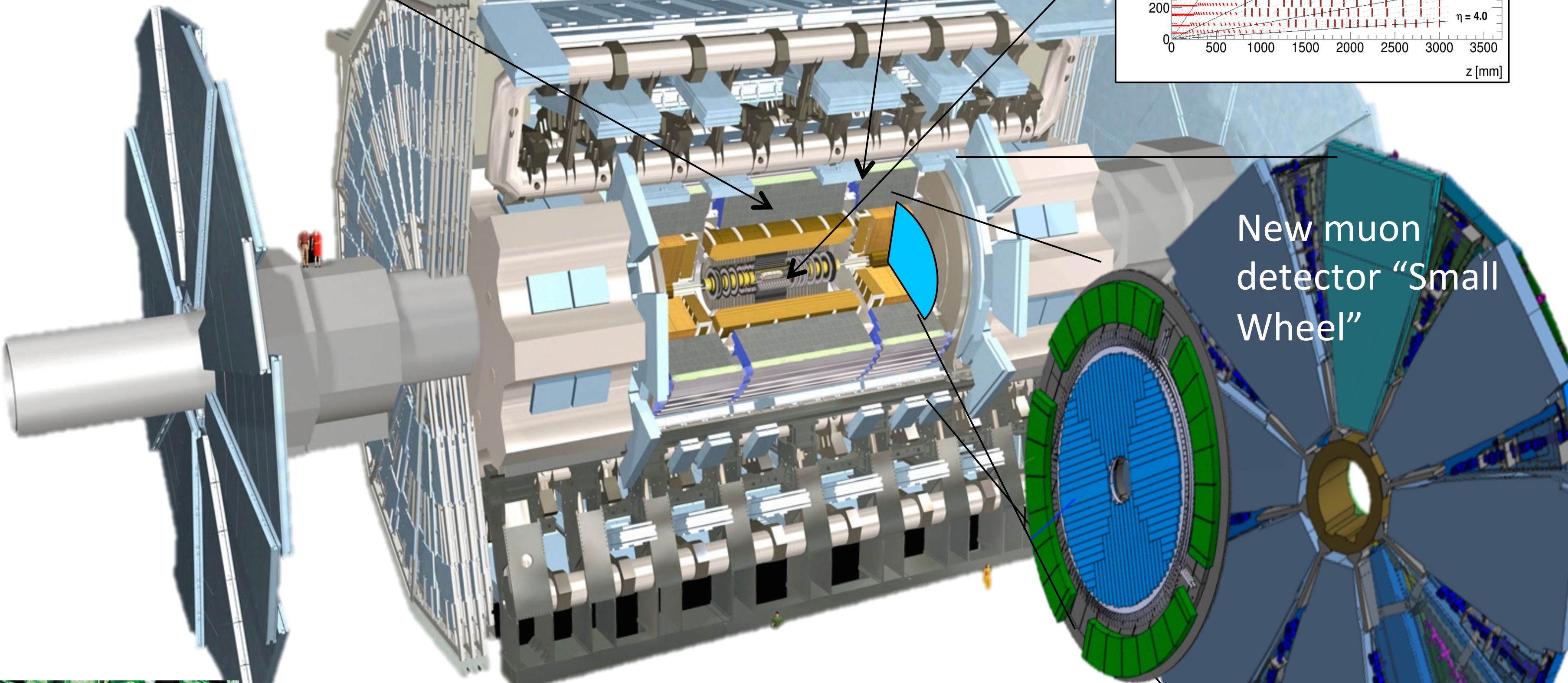
Calorimeter: new DAQ electronics, HV sources and gap scintillators

Gap scintillators

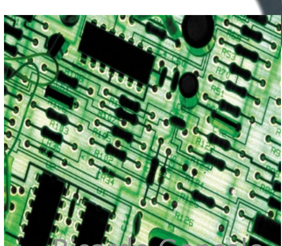


New tracking detector





New muon detector “Small Wheel”

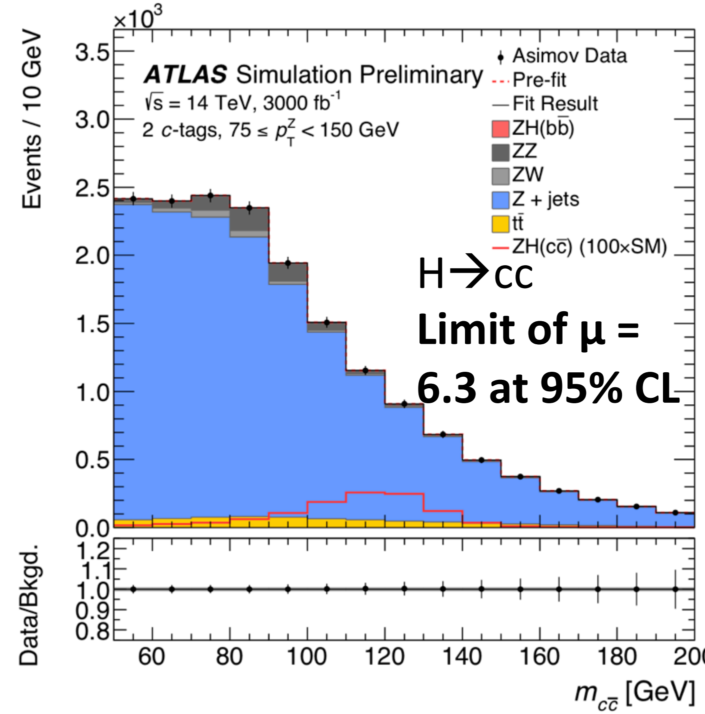


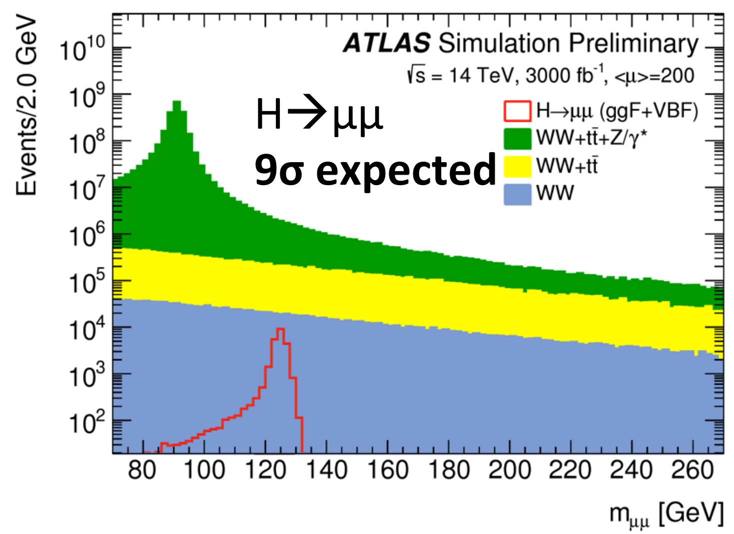
New dedicated hardware tracking processor for trigger

High Granualrity Timing Detector (30ps/track)

Future of Higgs: HL-LHC

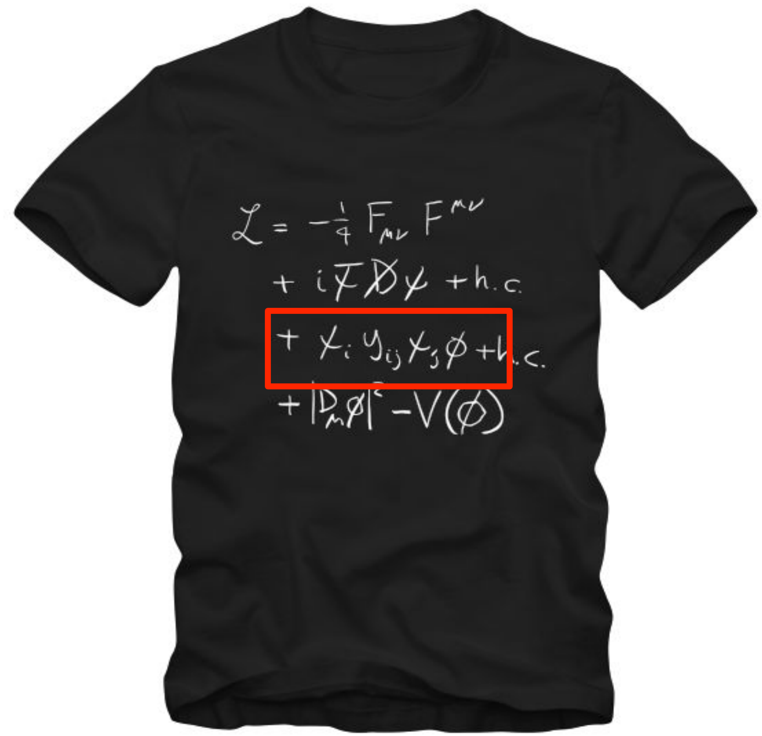
- A lot can be done with 3000fb^{-1} !!!





Summary

- Important milestones were crossed this year by ATLAS and CMS with the ttH and H→bb observations
- Main production modes (ggF, VBF, VH, ttH) have all been observed!!
- The Higgs sector continues to look SM-like
- **But!**
- We know there is new physics out there!
- We have only collected ≈150 fb^{-1} of 3000 fb^{-1} of 13 TeV data expected at the HL-LHC
- We have a strong programme of precision measurements and searches for new Higgs states and decays



Overall highlight from the past year (very personal bias!):
"The >5σ observations of ttH and H → ττ, independently by ATLAS and CMS, firmly establish the existence of a new kind of fundamental interaction, Yukawa interactions."
Gavin Salam (LHCP'18)

See here for more: ATLAS Public results page