Probing the Standard Model at the LHC

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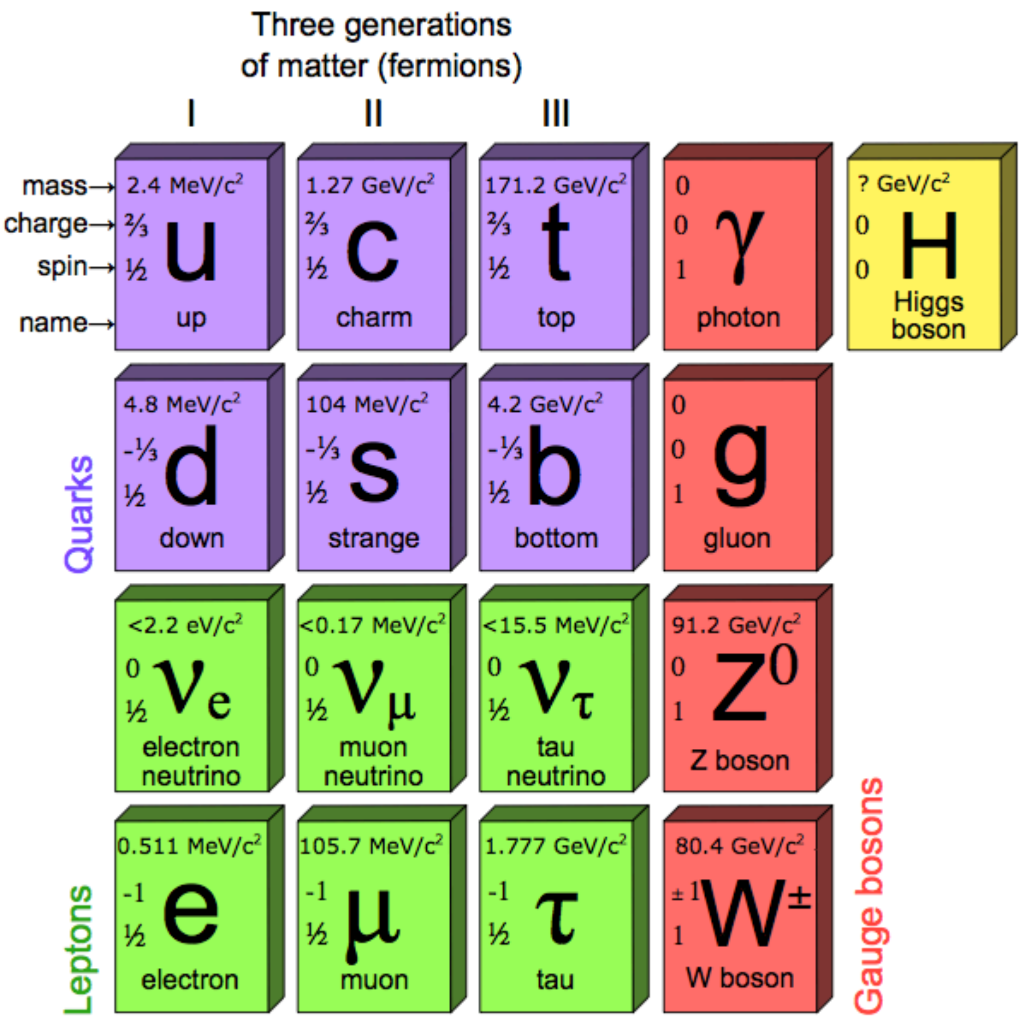
LIP Lisbon

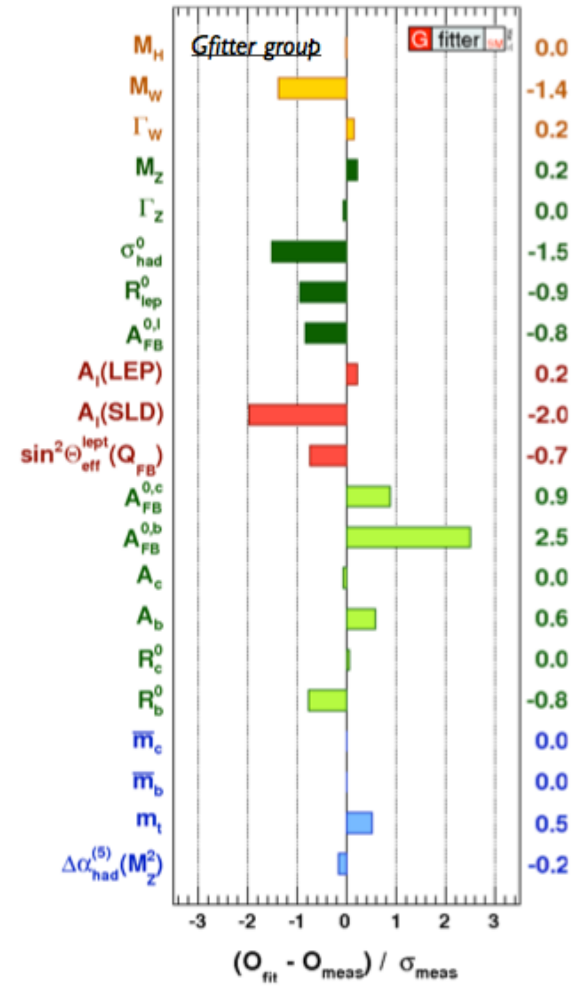
July 16, 2019

- ✓ Hadron interactions
- ✓ Minimum bias events
- ✓ Jet production
- ✓ W and Z bosons, top quark

The Standard Model

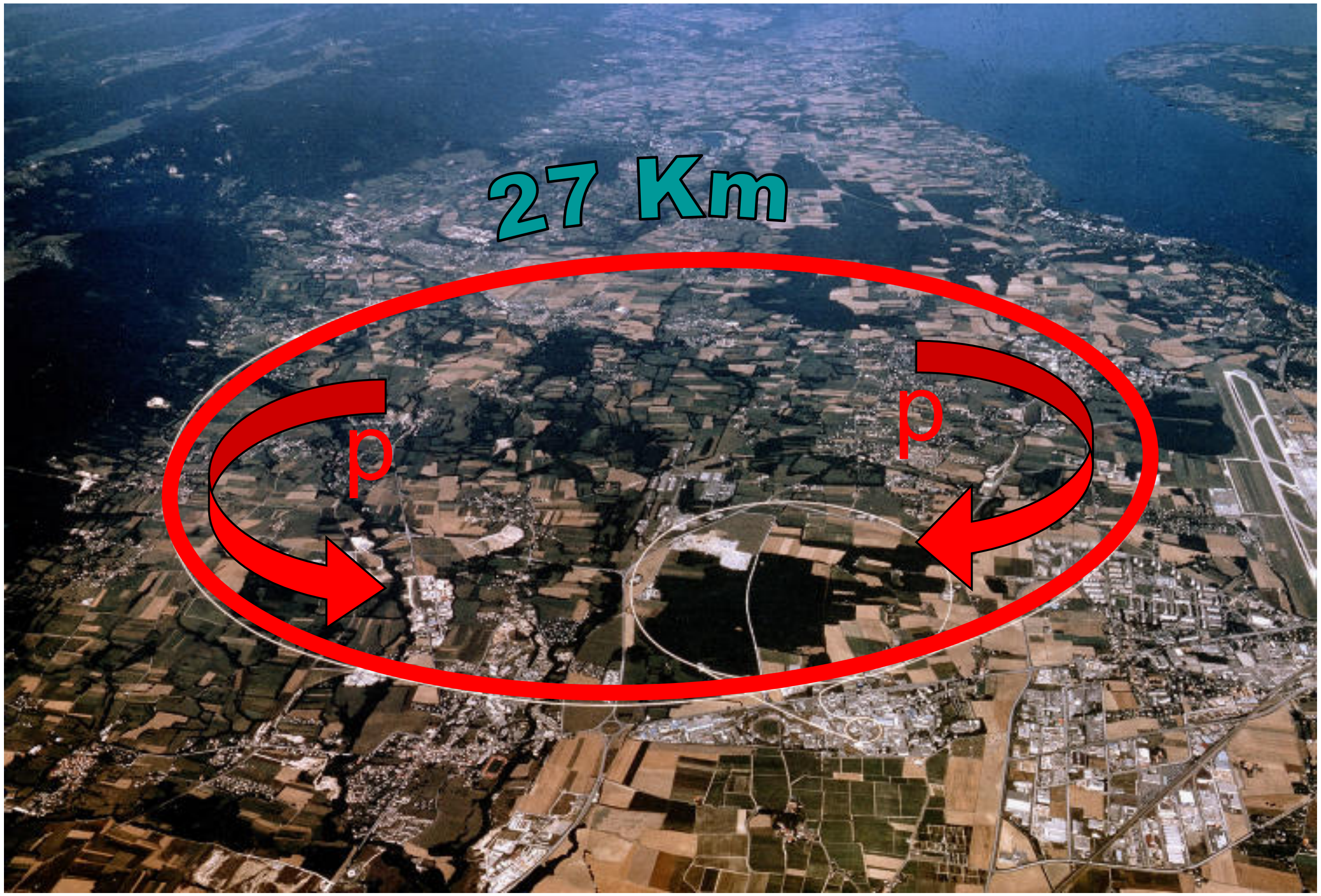


Standard model of elementary particles



Excellent agreement with all experimental results

The LHC

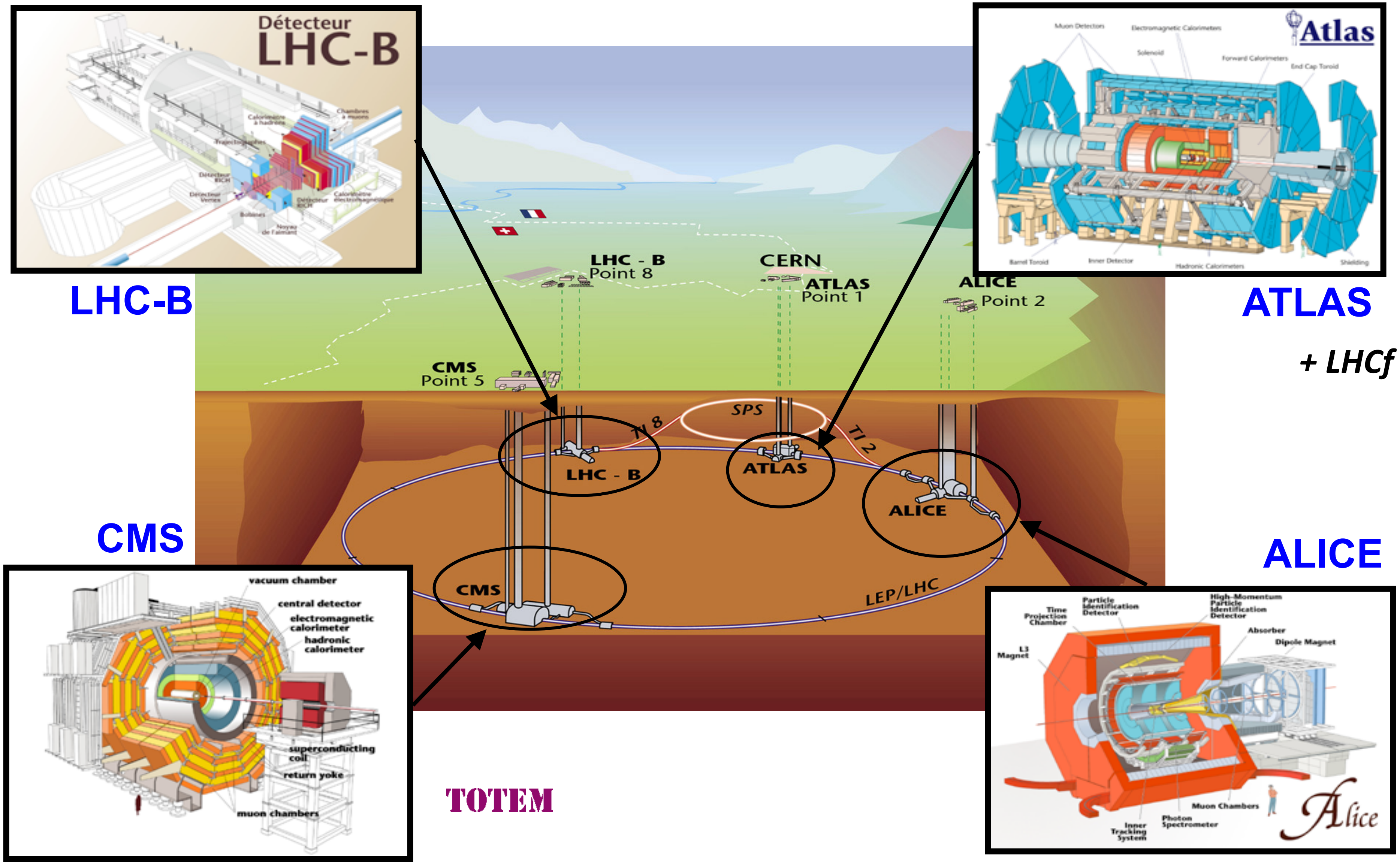


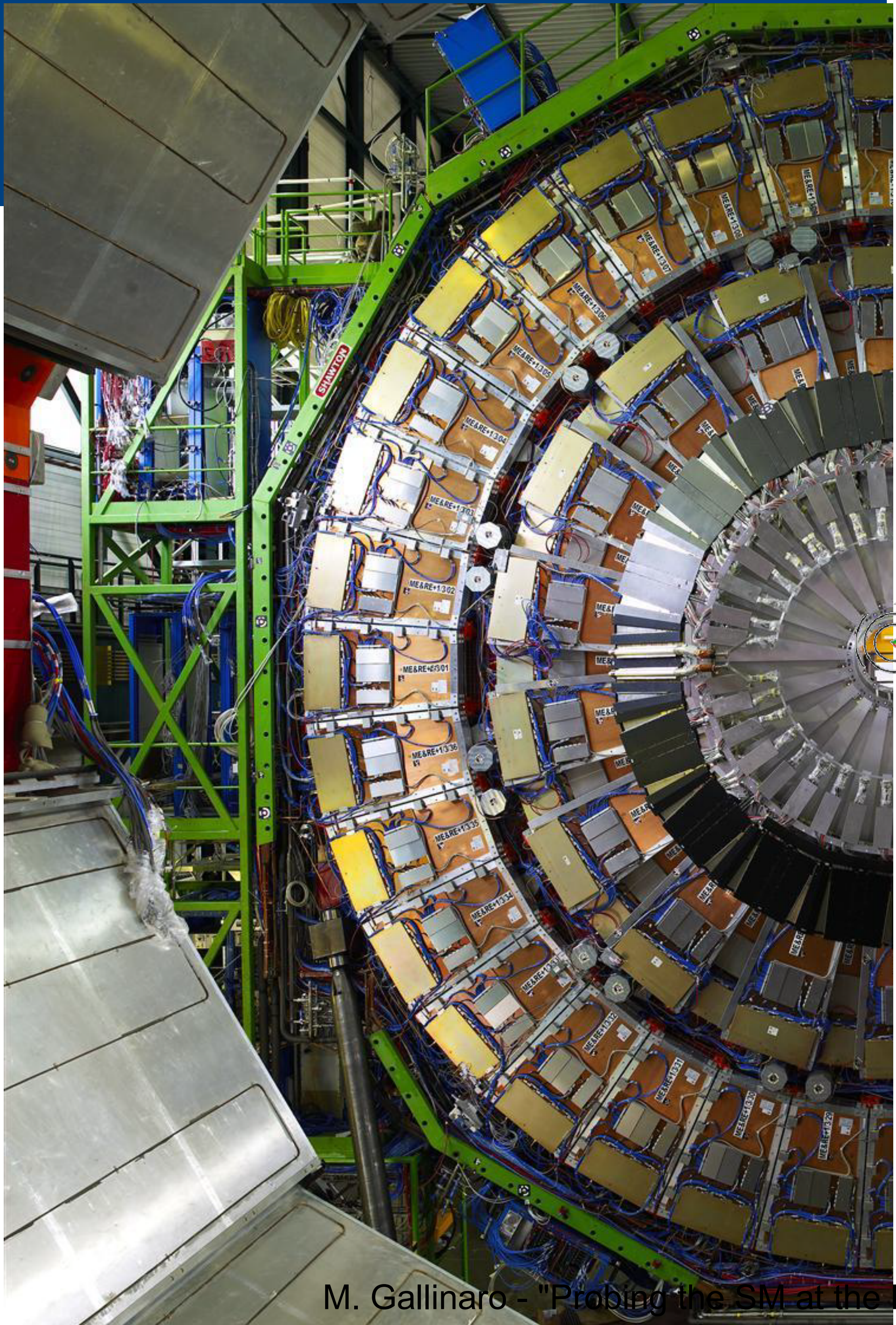
- Installation in existing LEP tunnel (27 Km)
- 1232 dipoles B=8.3T
- pp $\sqrt{s}$ = 14 TeV
  $L_{design} = 10^{34}$ cm^{-2} s^{-1}
- Heavy ions
  (e.g. Pb-Pb at 5TeV, p-Pb at 8TeV, Xe)

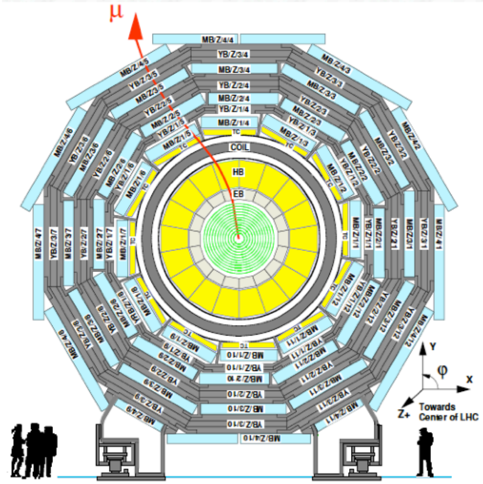
- First beam: Sept.2008
- 2012: 2 x 4 TeV
- 2015/18: 2 x 6.5 TeV
- 2021/23: 2 x 7 TeV

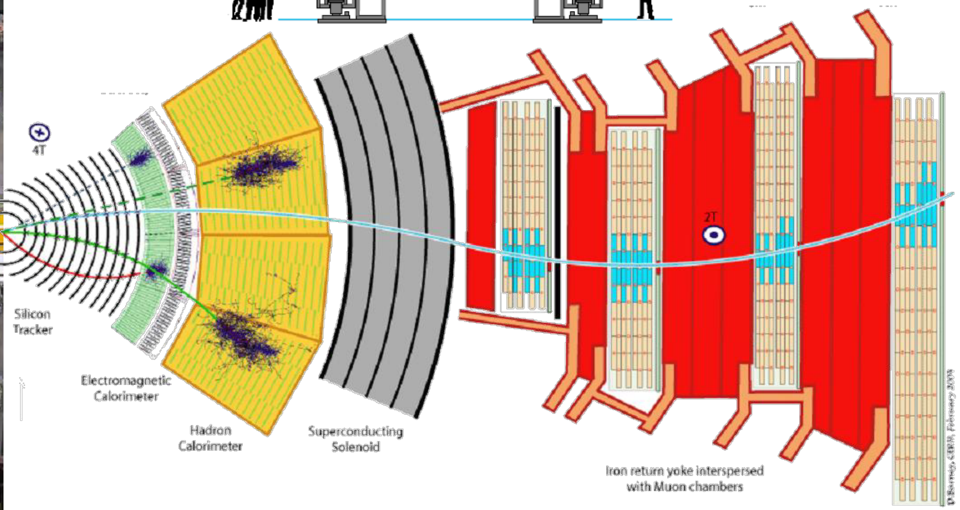
LHC experiments located at 4 interaction points

The LHC experiments



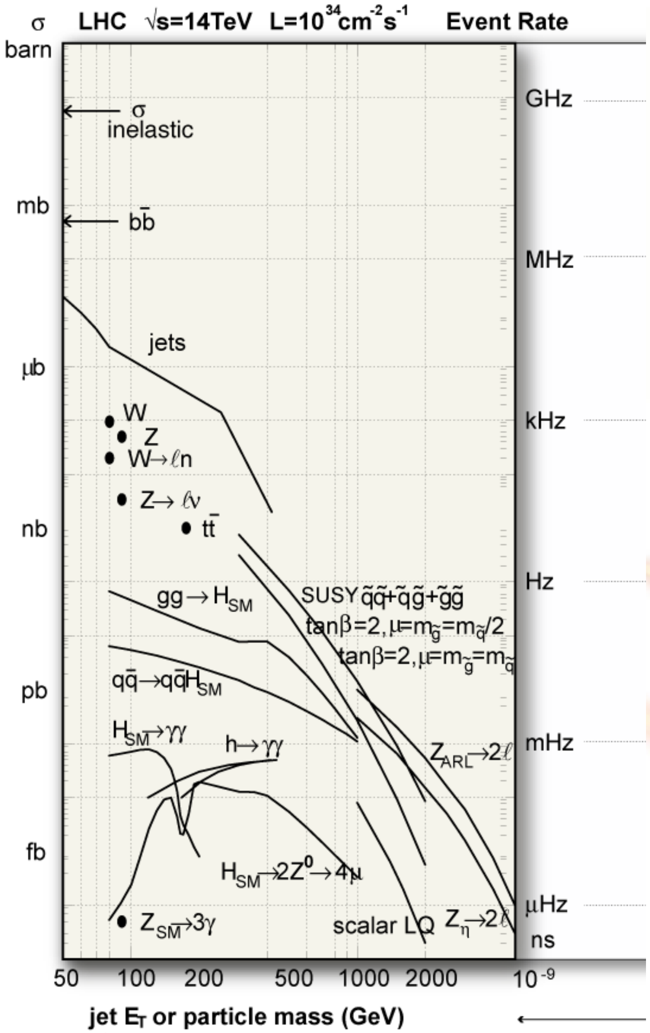


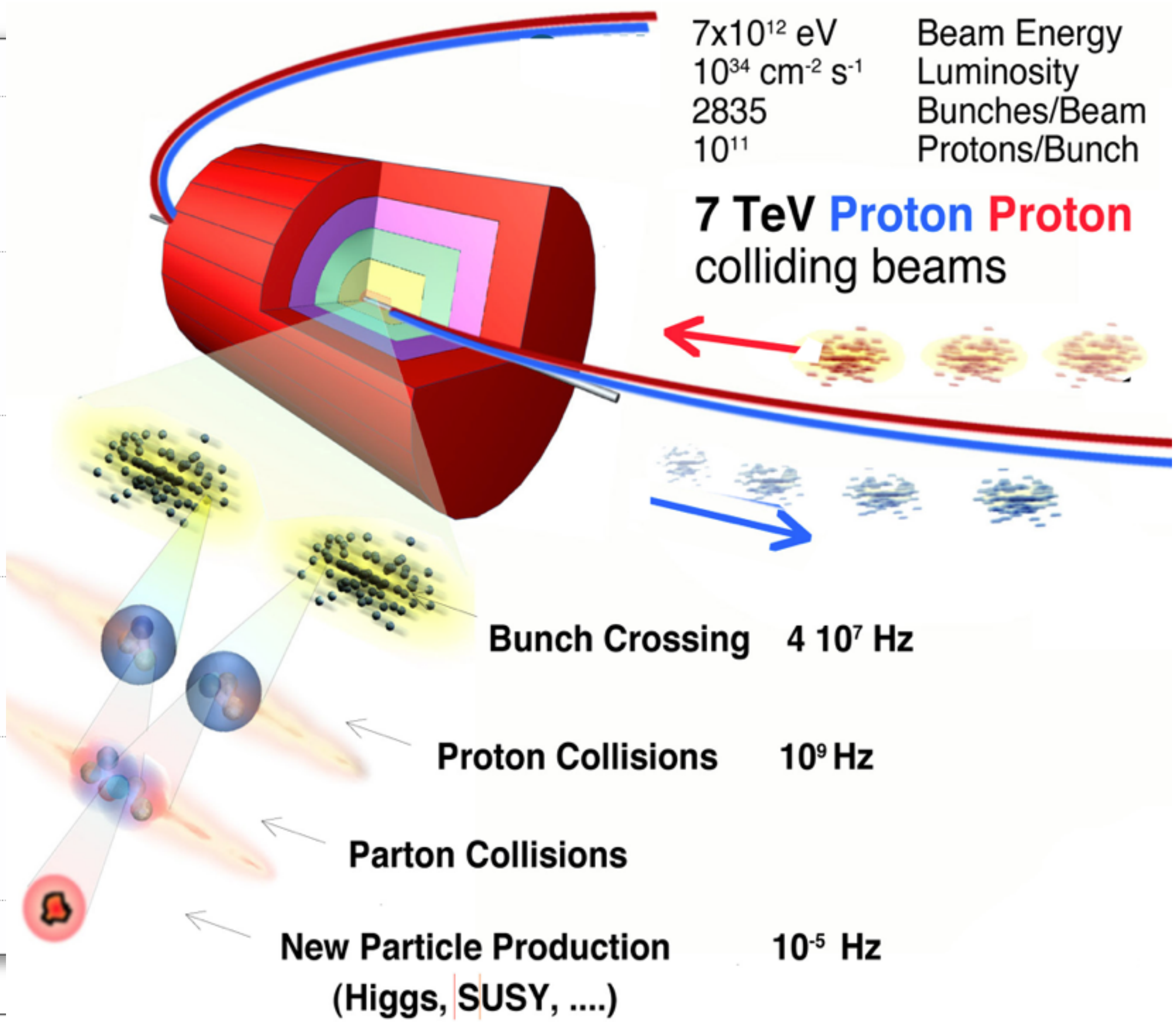

μ
COIL
HB
EB
Y
φ
x
Z+
Towards Center of LHC


4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers

Proton collisions at the LHC

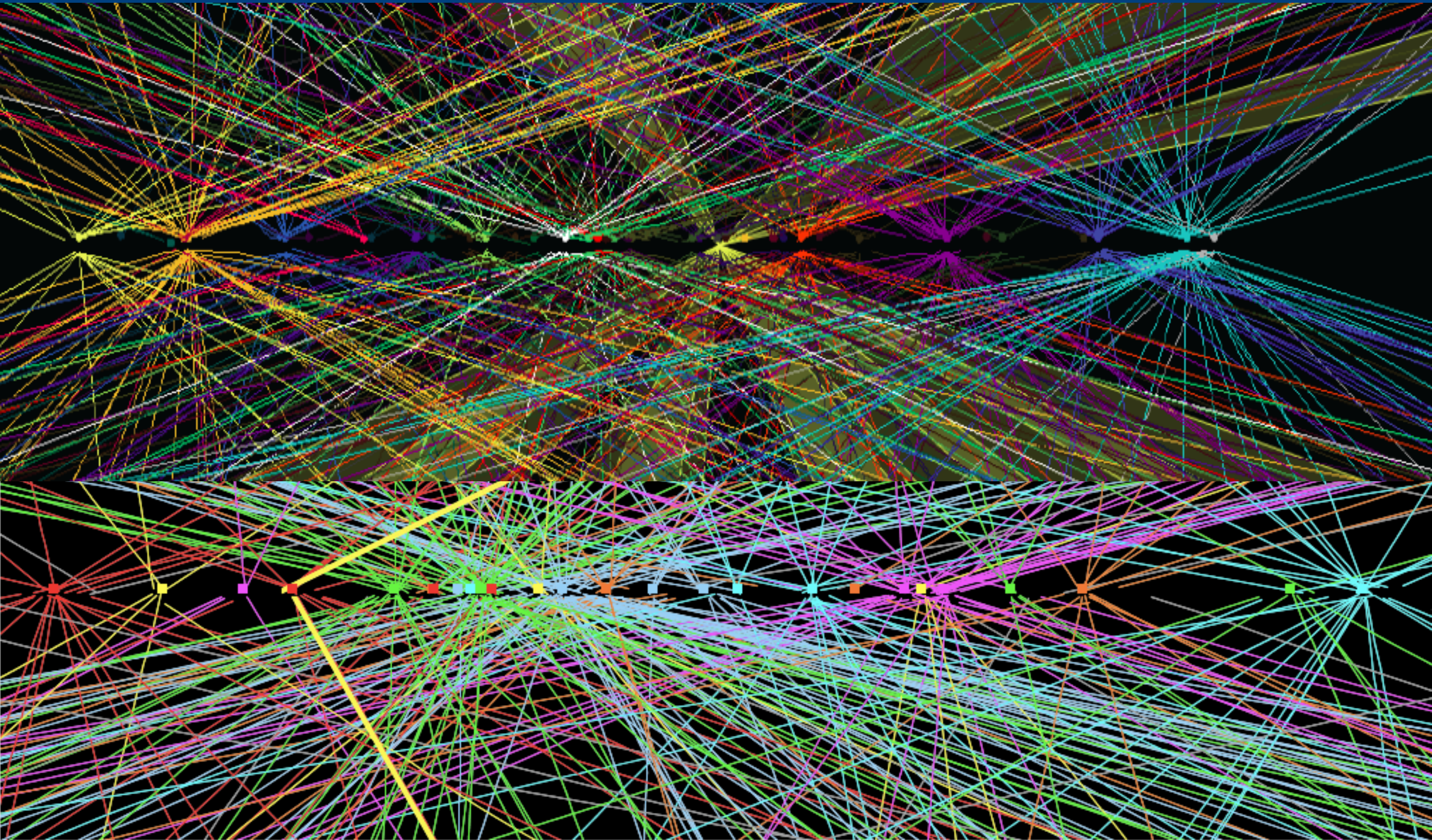
Collisions: 7-8 TeV (2011-12), 13TeV (2015-18)

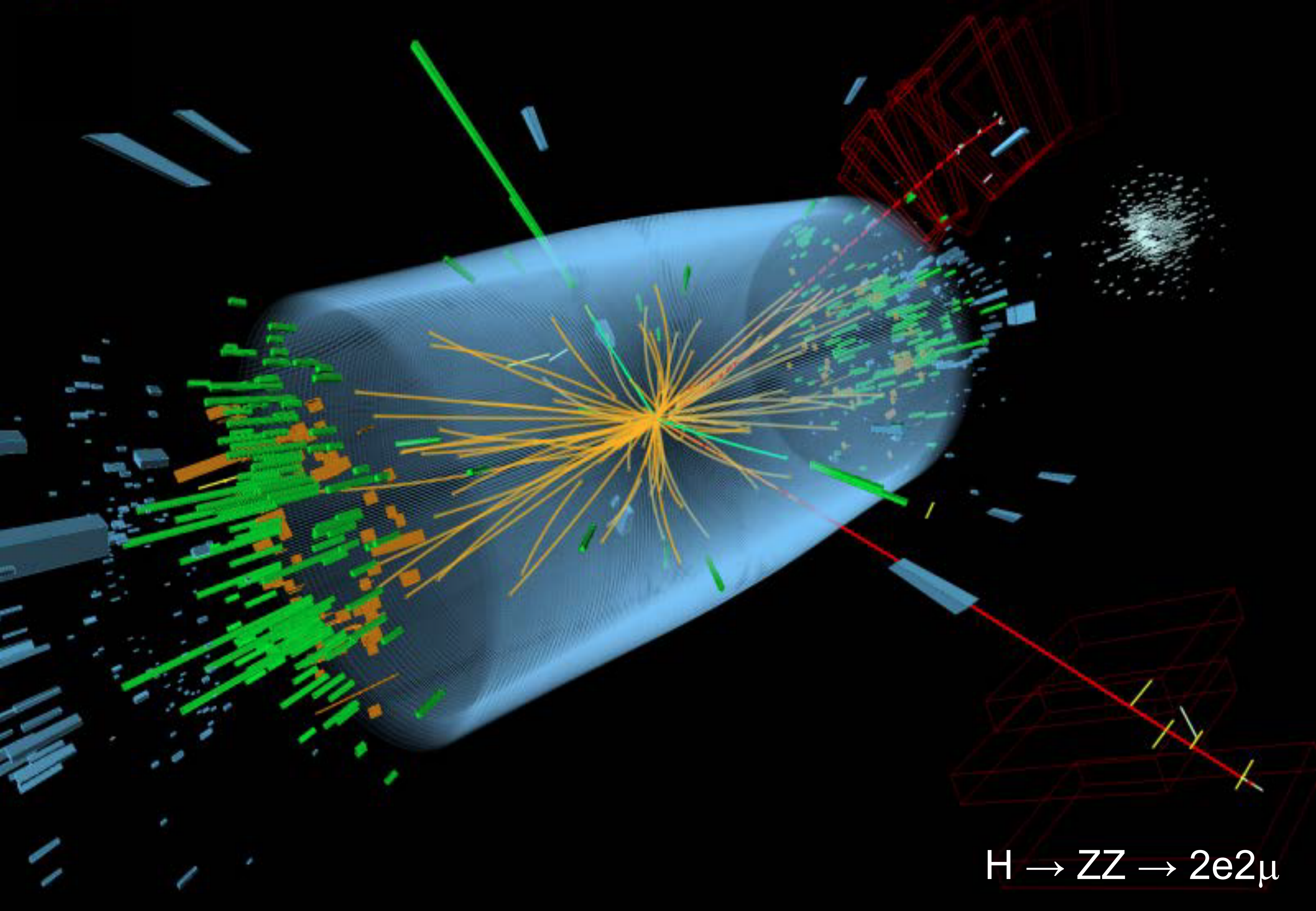




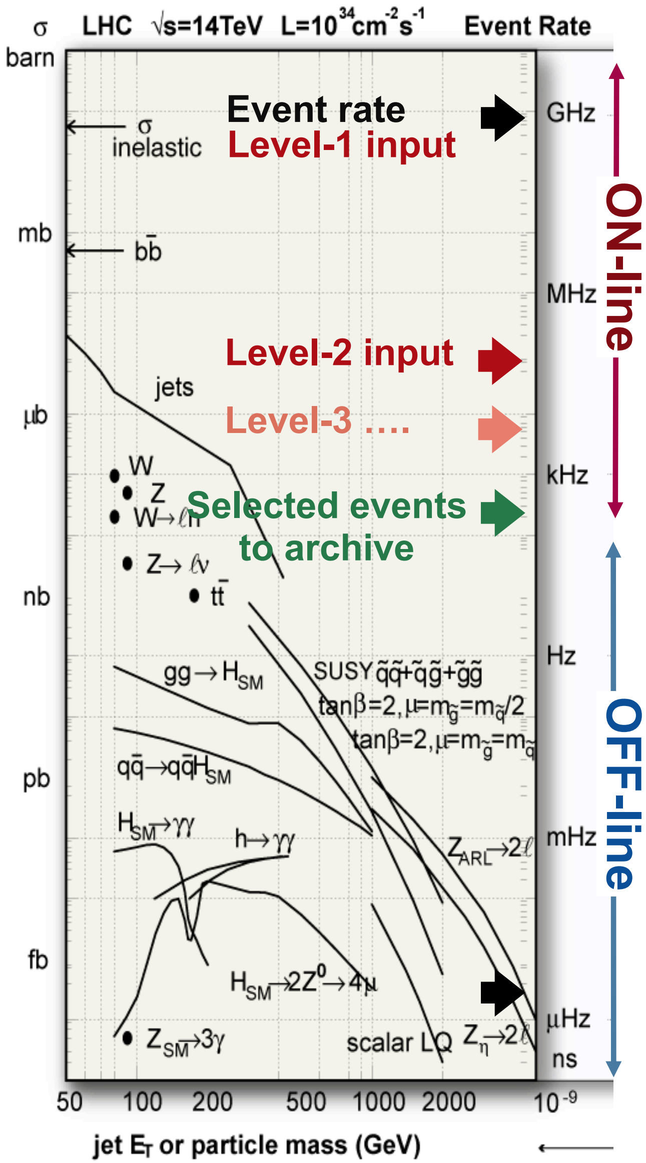
Select 1 event in 10,000,000,000,000

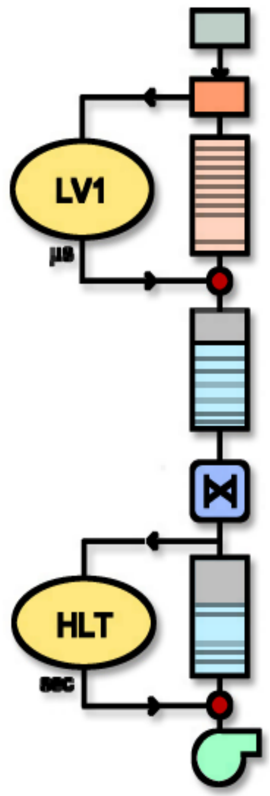
…under difficult conditions




$H \to ZZ \to 2e2\mu$

Trigger



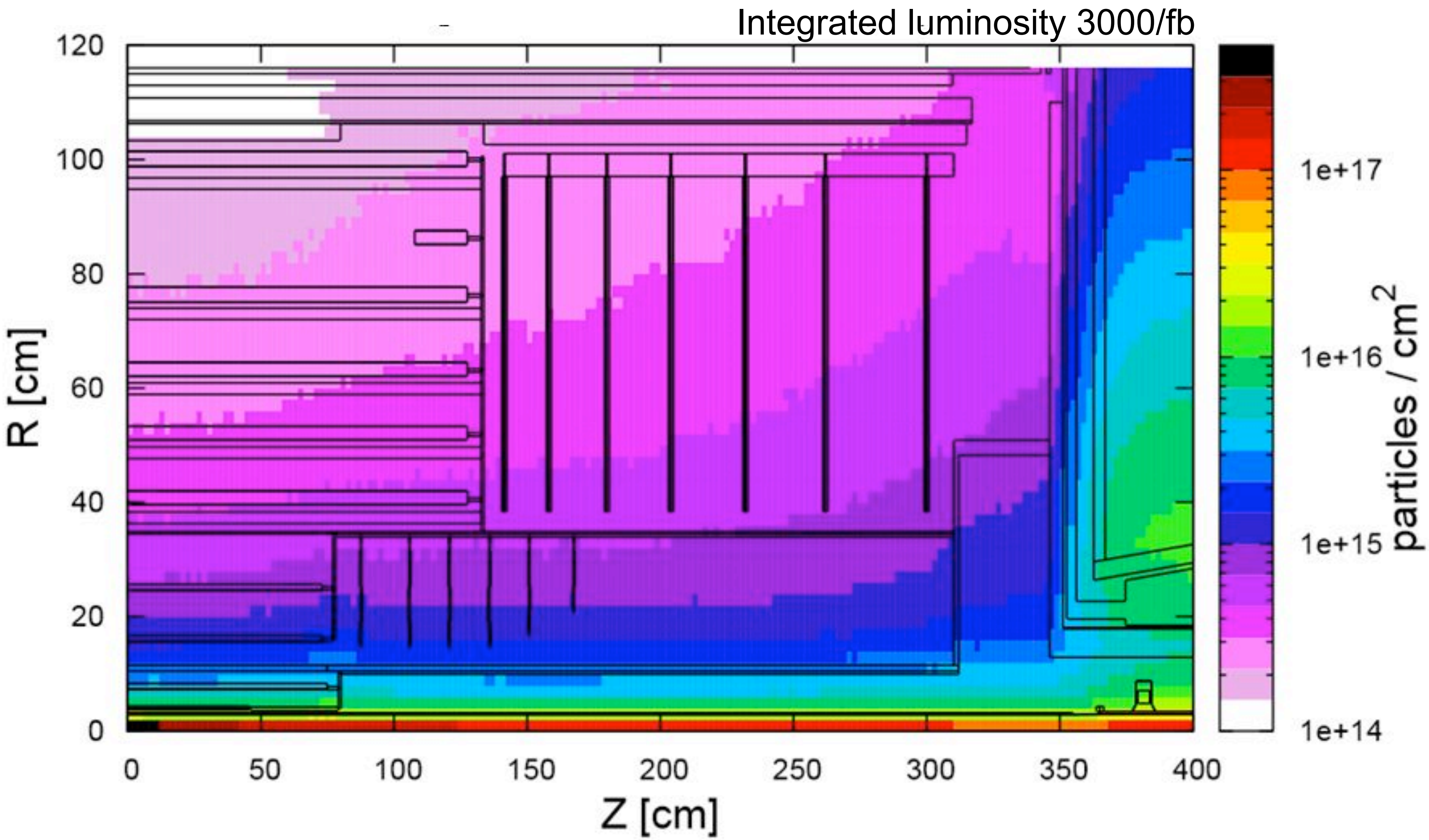


Trigger system decide if the event is interesting to be recorded

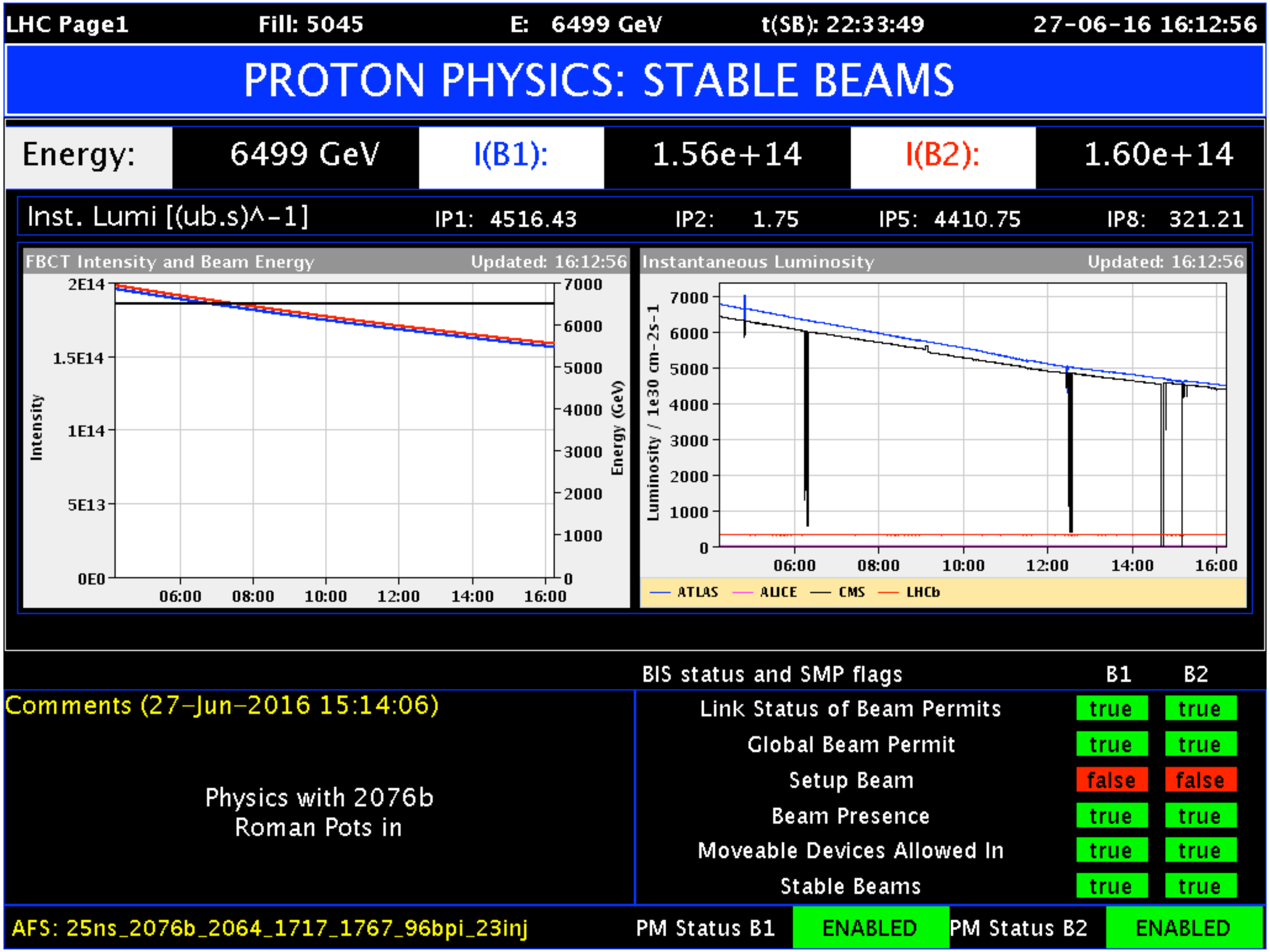
Two-step process:
- Level 1: dedicated hardware processors

- High level: computer farm

High radiation levels



LHC Page 1: stable beams

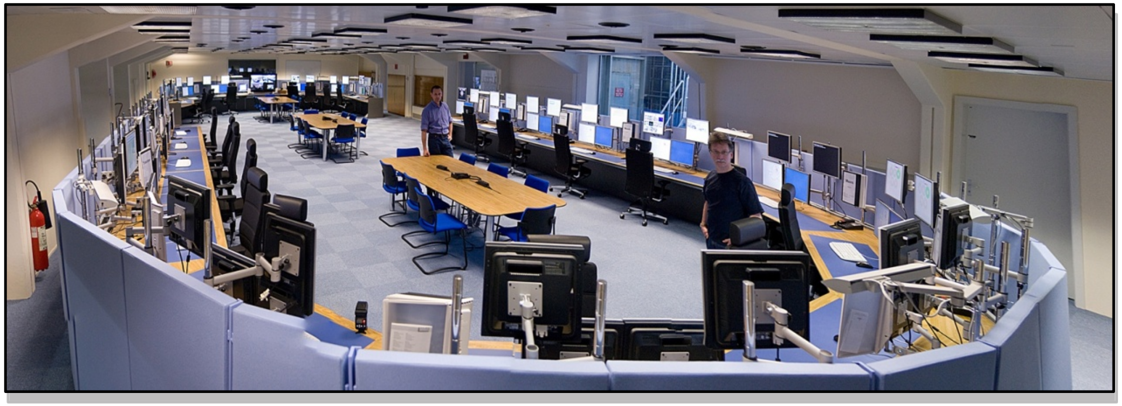


Experiments control rooms

Cessy: Master Control Room

Fermilab: Remote Operations Center

Meyrin: CMS Data Quality Monitoring Center



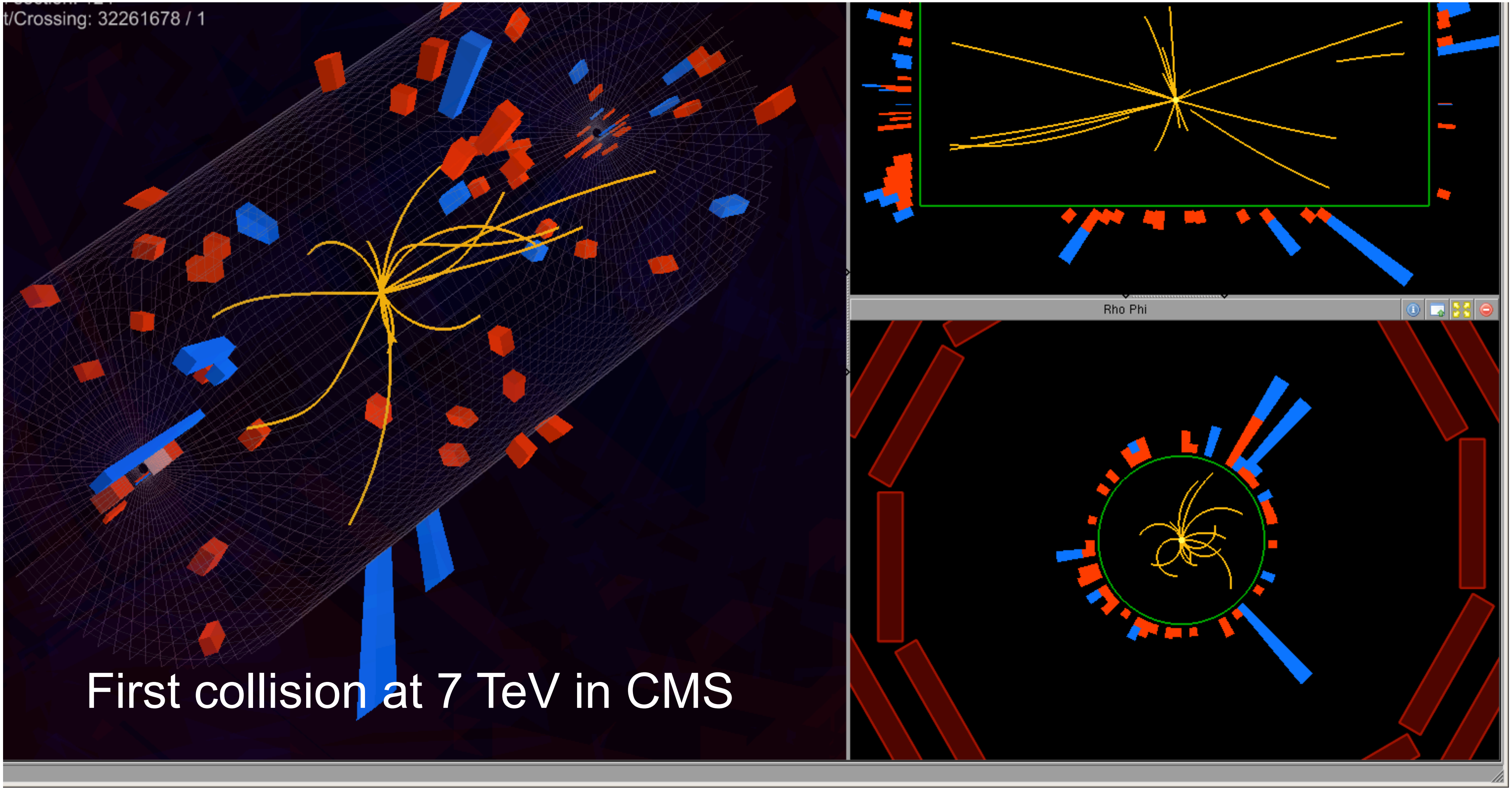
Any Internet access

2009: first collisions at LHC

November 23, 2009
First collisions at 900 GeV

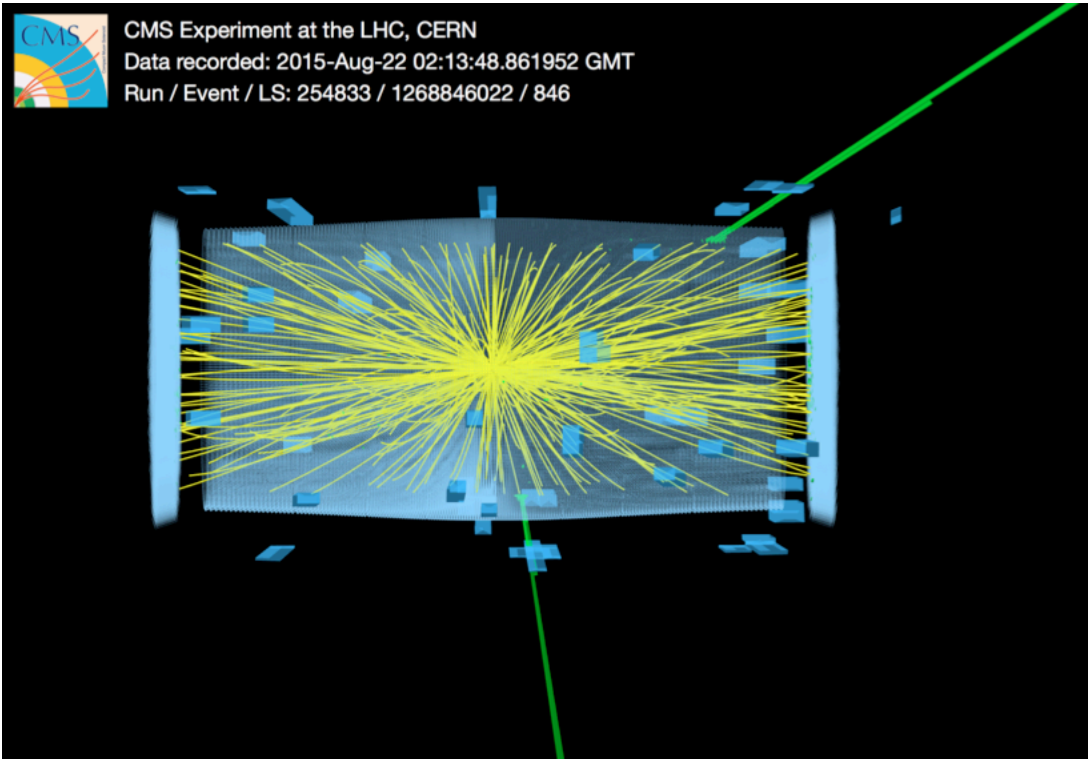
December 14, 2009
First collisions at 2.36 TeV

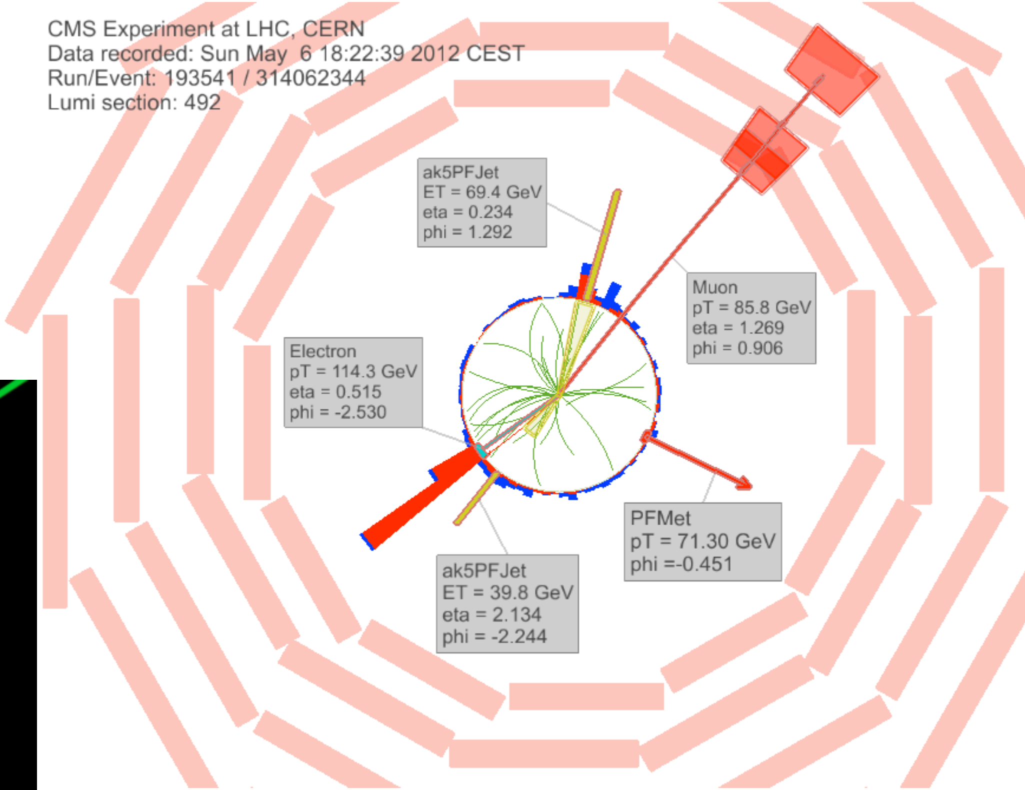
March 30, 2010
First collisions at 7 TeV



Event reconstruction

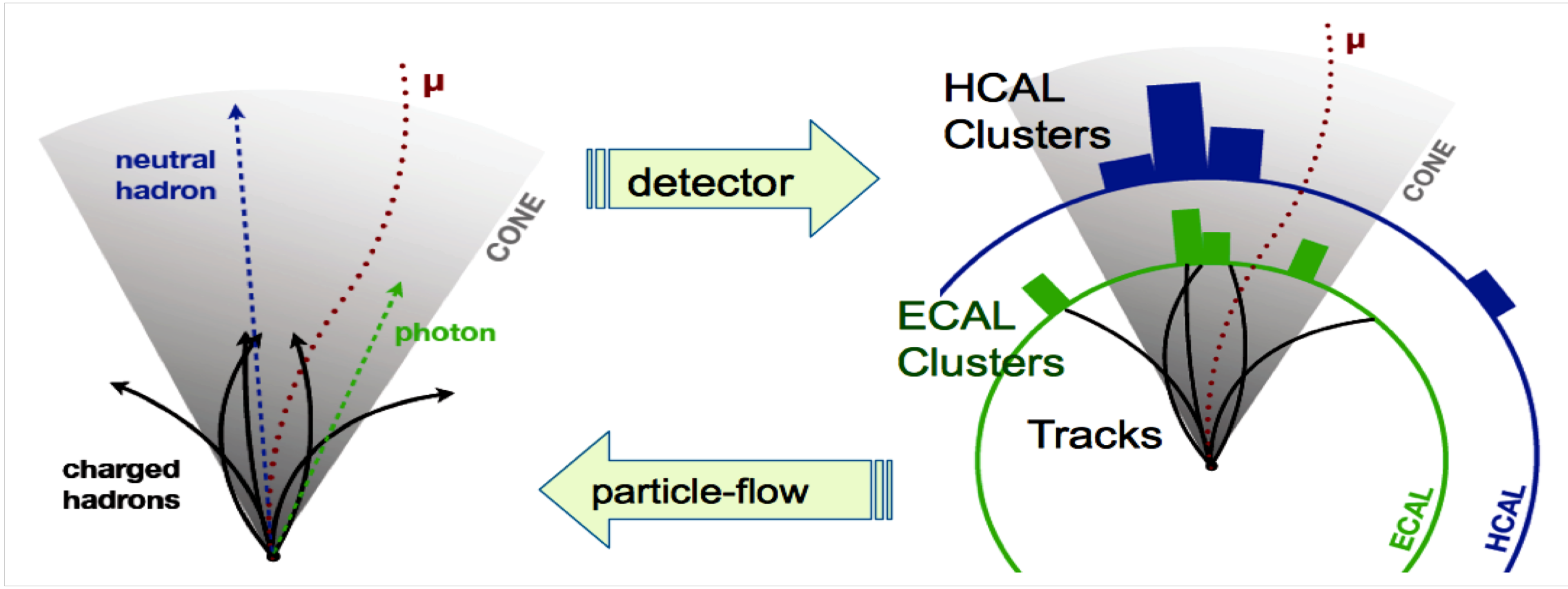
- Reconstruct event and all constituents:
  - leptons (e, μ, τ), photons
  - tracks
  - jets (b-jets)
  - missing transverse energy
  - etc.



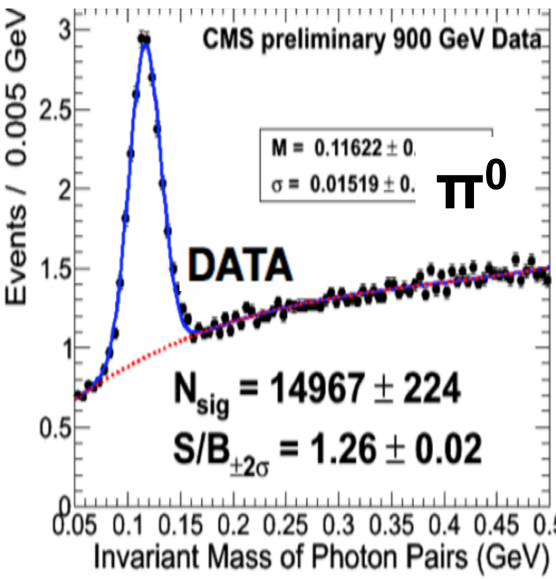


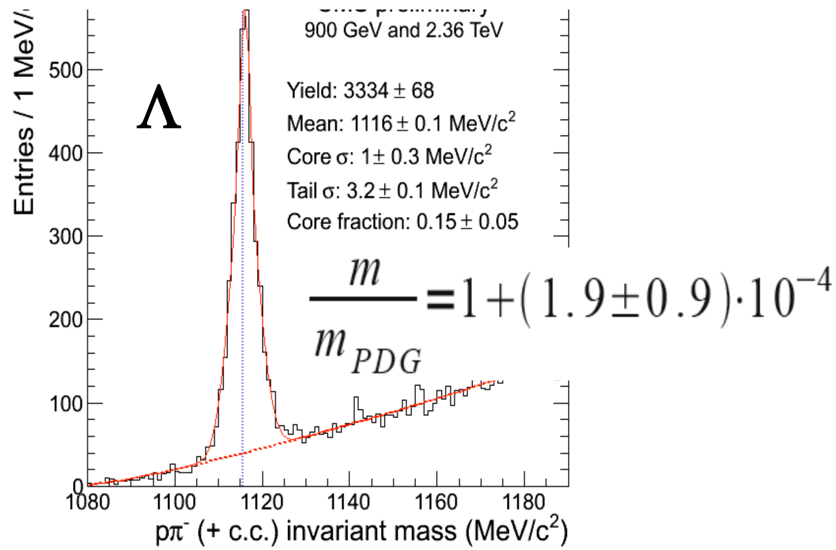
Particle Flow event reconstruction

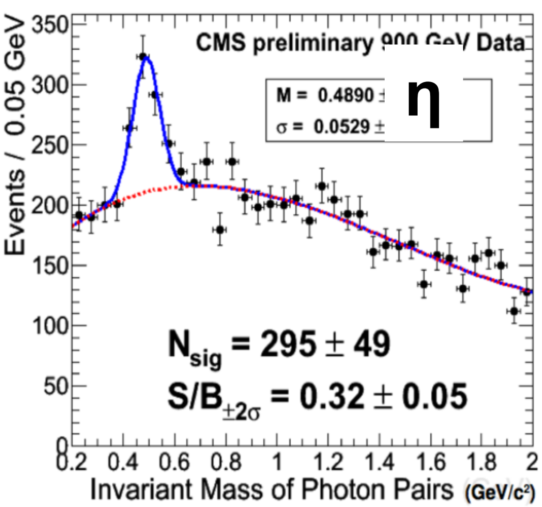
- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision
  - charged hadrons, neutral hadrons, photons, muons, electrons
  - use complementary info. from separate detectors to improve performance
  - tracks to improve calorimeter measurements
- From list of particles, can construct higher-level objects
  - Jets, b-jets, taus, isolated leptons and photons, MET, etc.

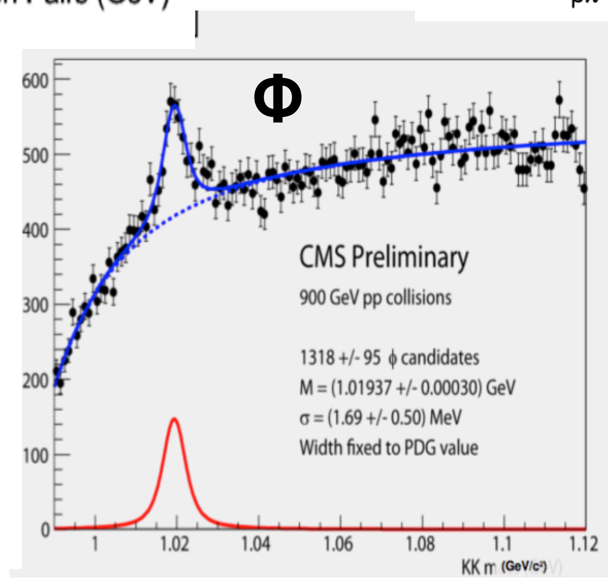


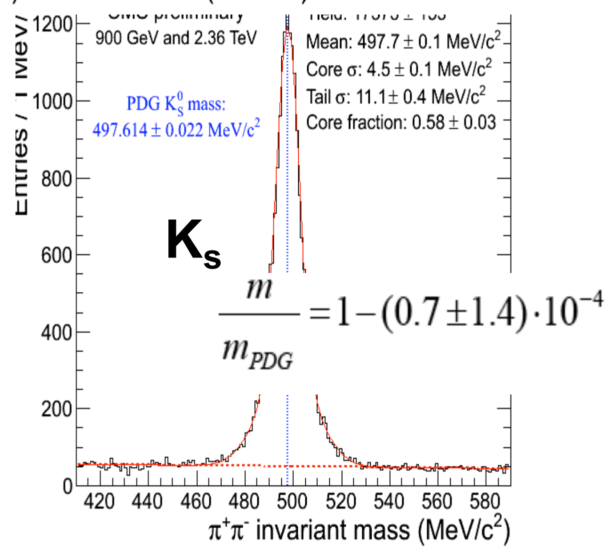
Rediscovery of resonances



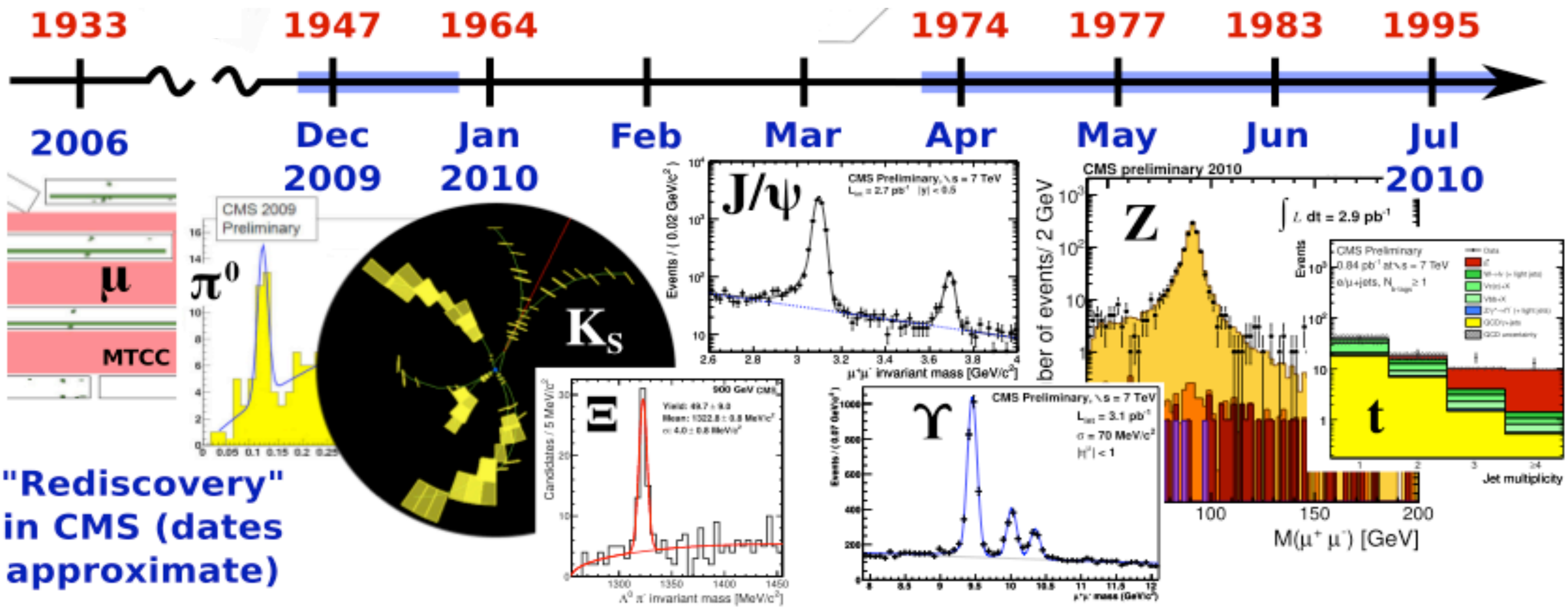




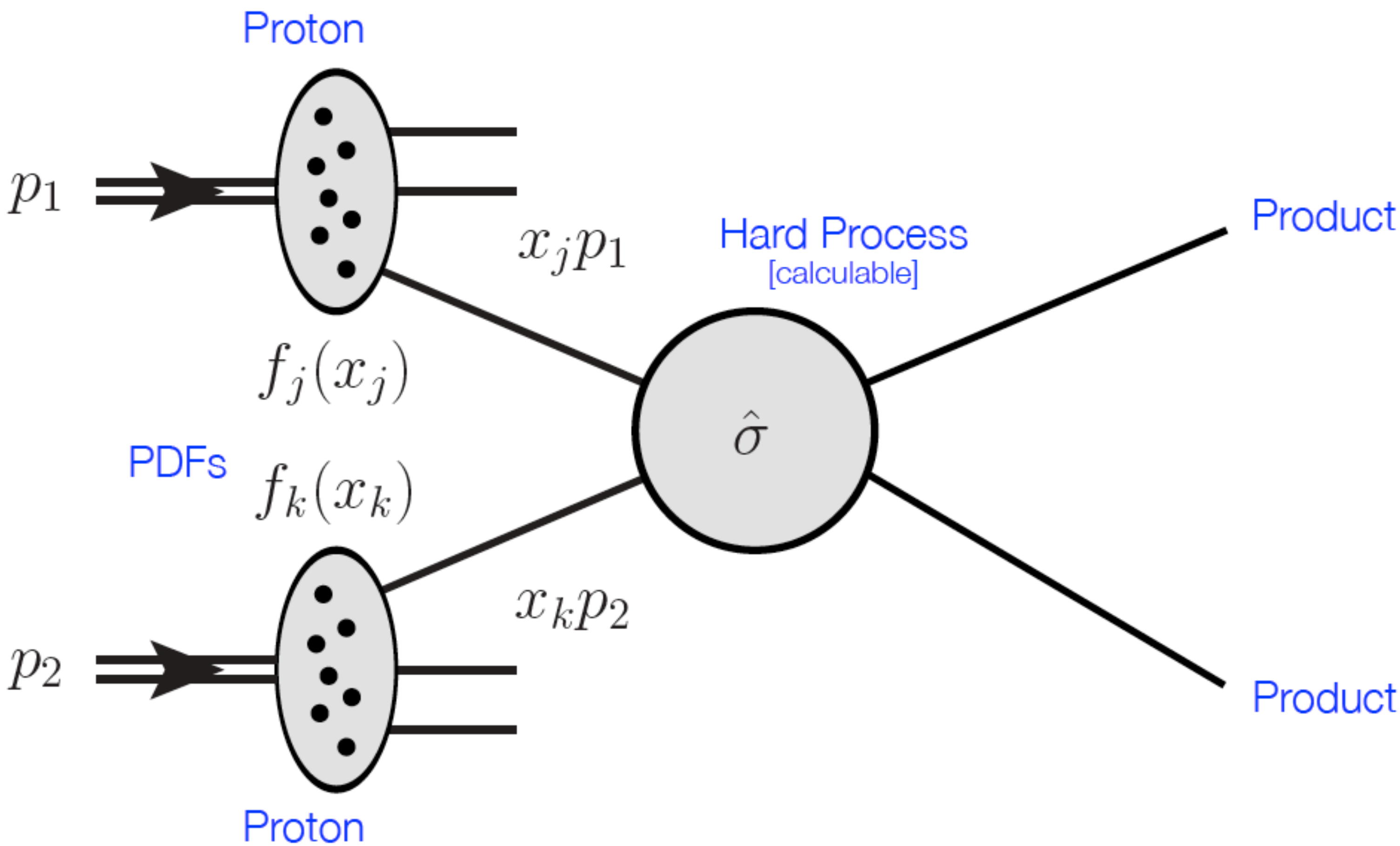




Re-discovery of the SM at LHC

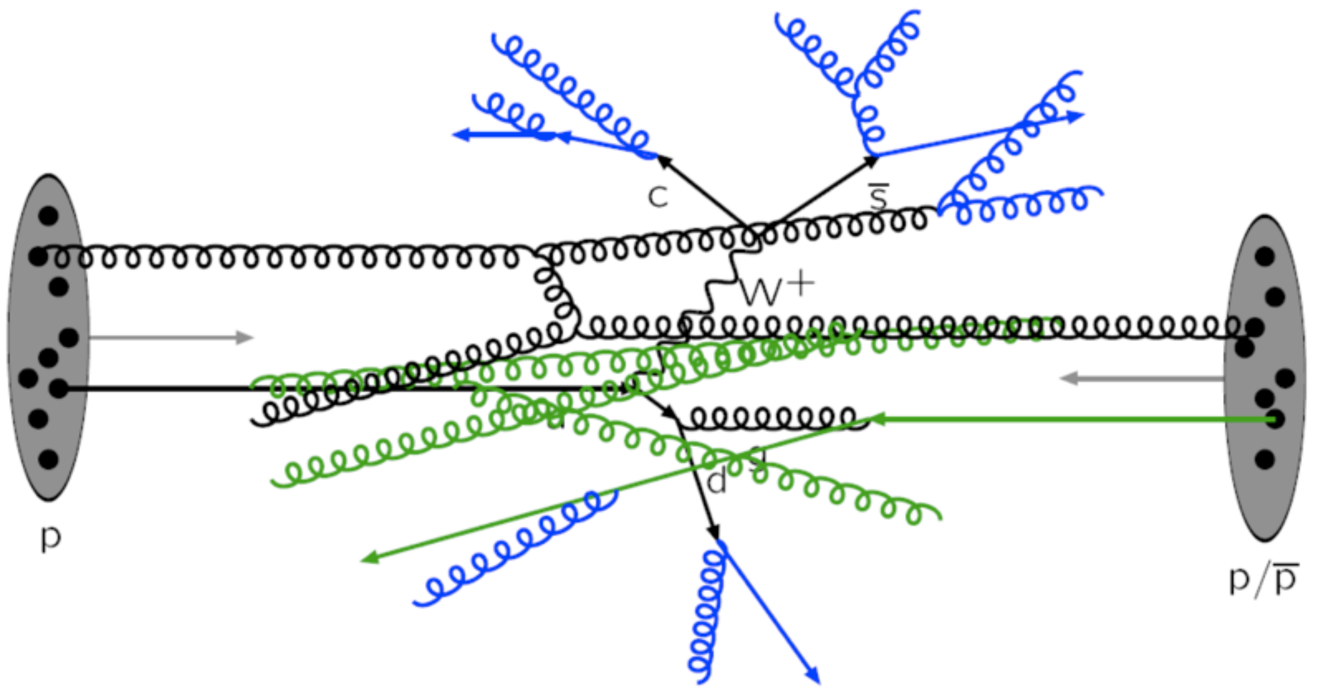


Hadron interactions: pp scattering



Proton-proton scattering at LHC

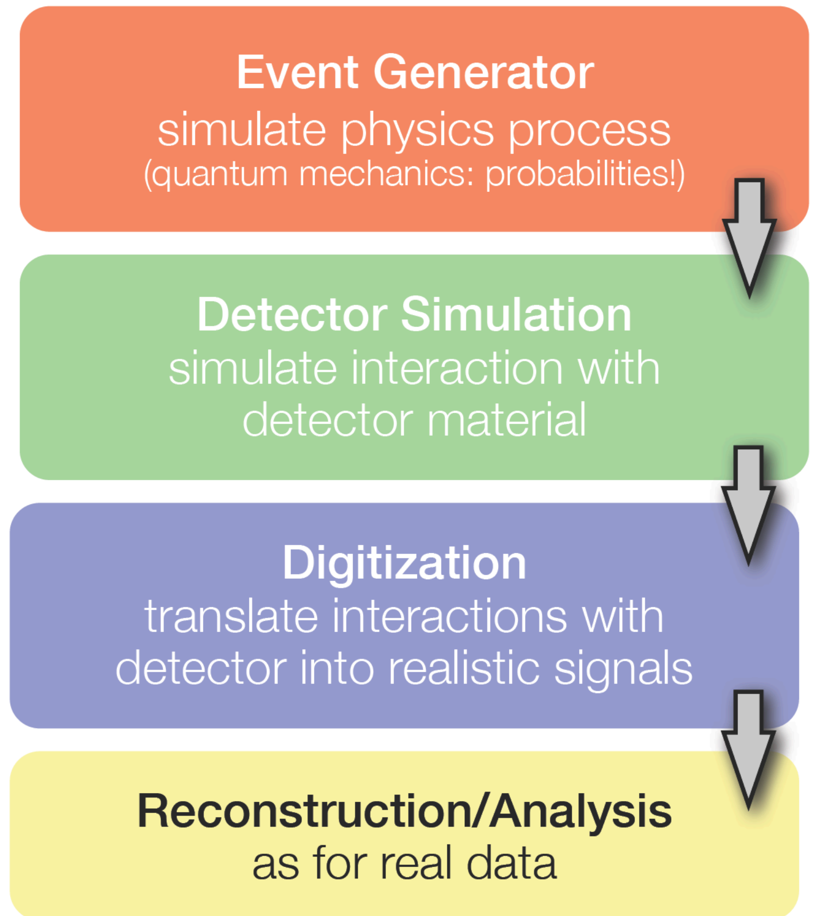
- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction [“underlying event”]



Monte Carlo simulation

Simulation

- Numerical process generation based on random numbers
- Very powerful in particle physics
- Event generation
  - Pythia, Herwig, Isajet, Sherpa …
  - Hard partonic subprocess + fragmentation, hadronization, decay
- Detector simulation
  - GEANT …
  - Interaction, response of all particles produced …



Cross section measurement

Number of
observed events

Number of
background events
*(from data, calculated
from theory)*

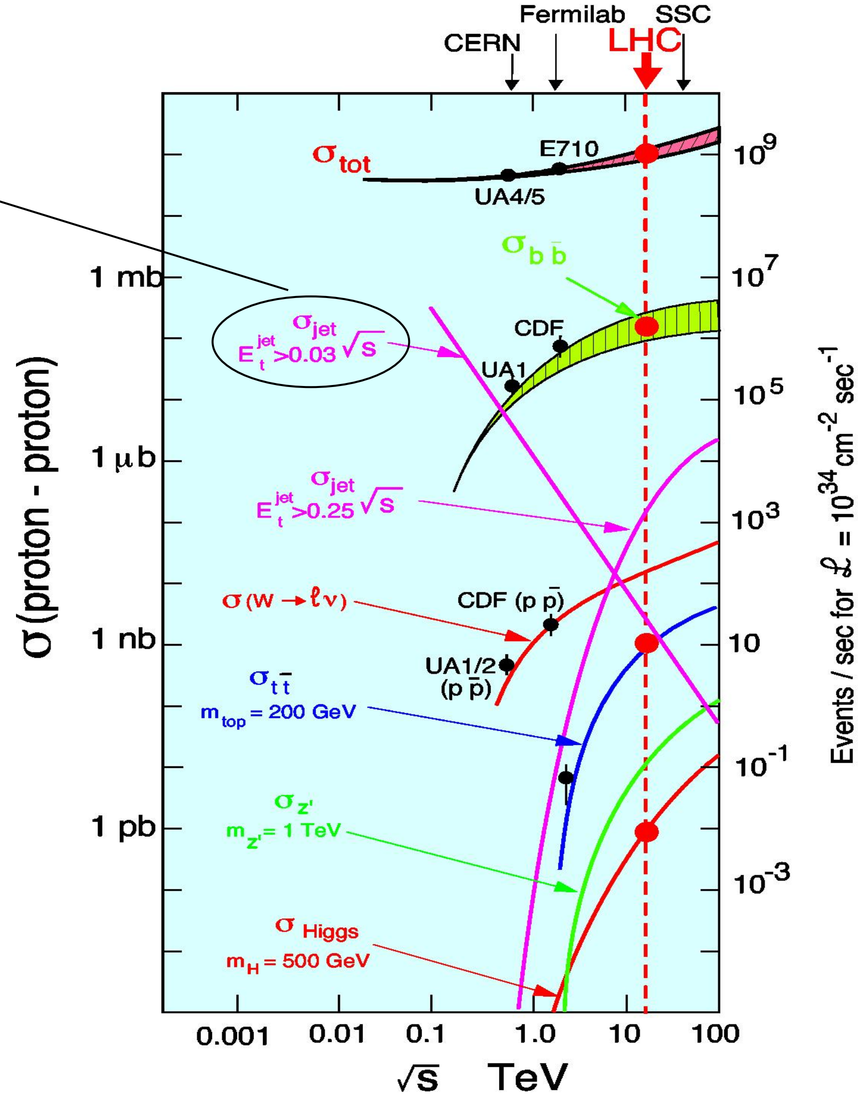
$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

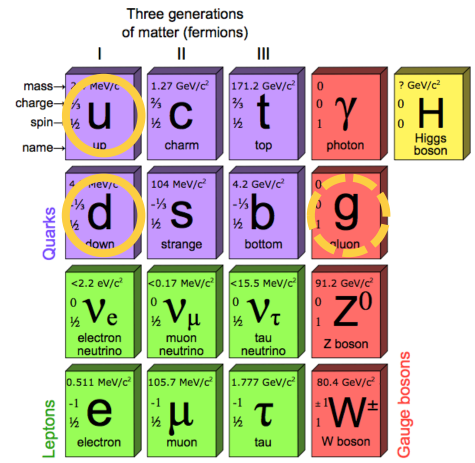
Acceptance
(experimental: detector, efficiencies)

Luminosity
*(determined by amount of data,
accelerator, triggers, etc)*

Minimum Bias

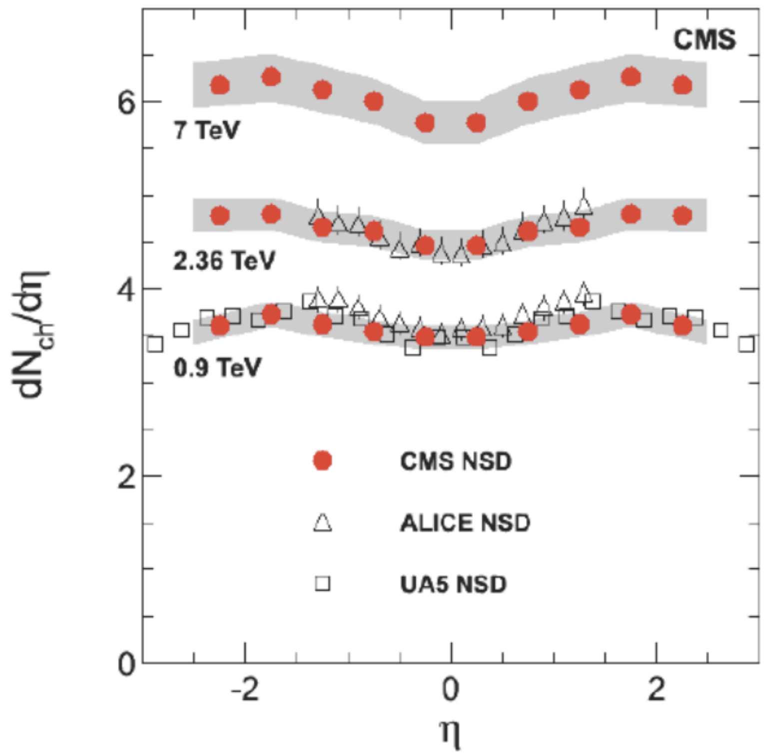
low p_T particle production

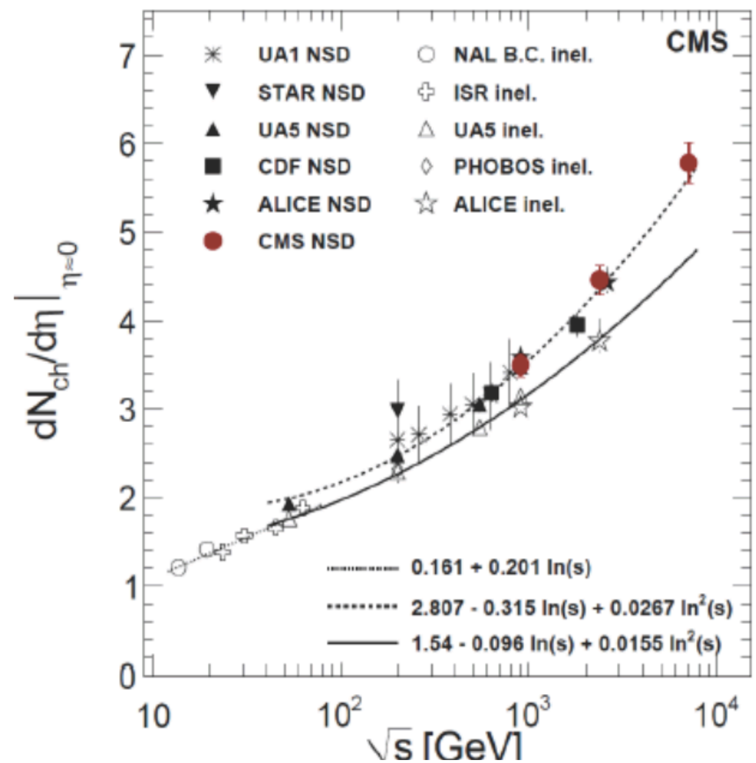




Minimum bias events

- Particle density in minimum bias events
- Soft QCD (p_T threshold on tracks: 50 MeV)

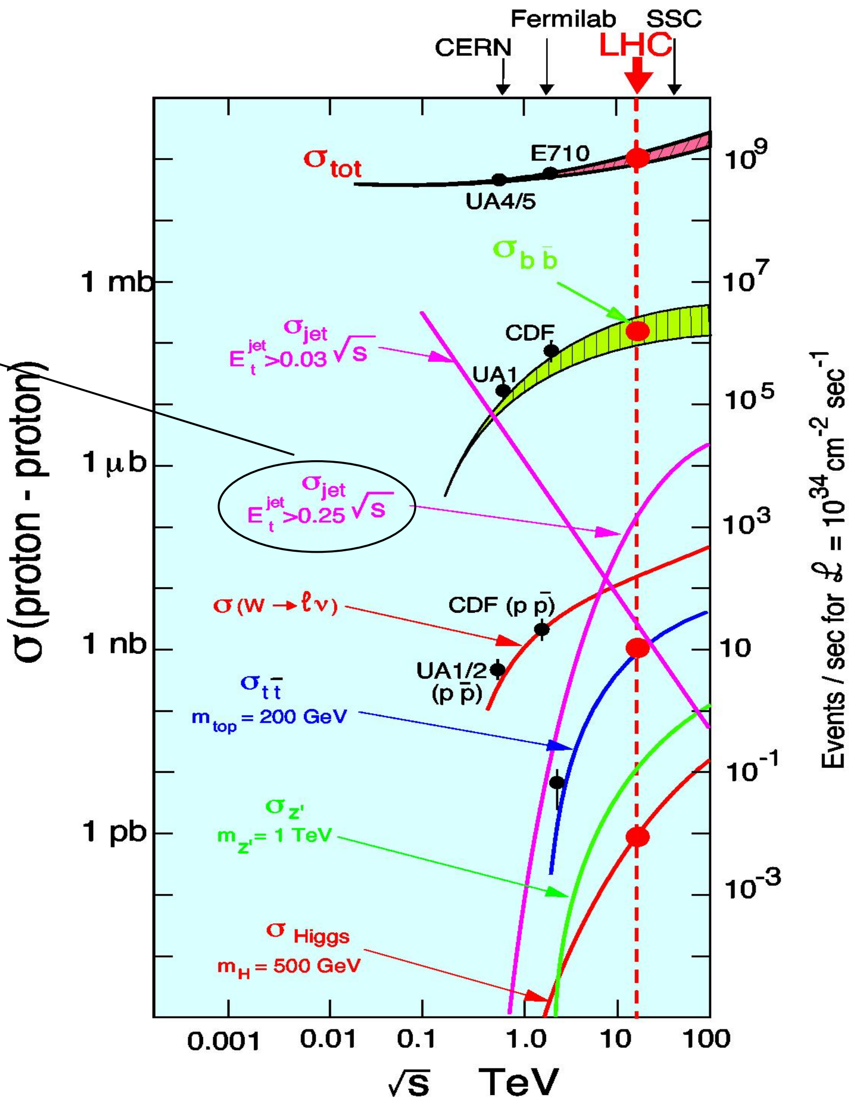


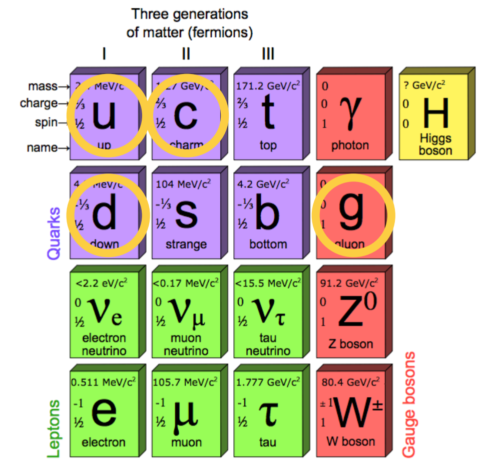


Tuning of MC generators needed

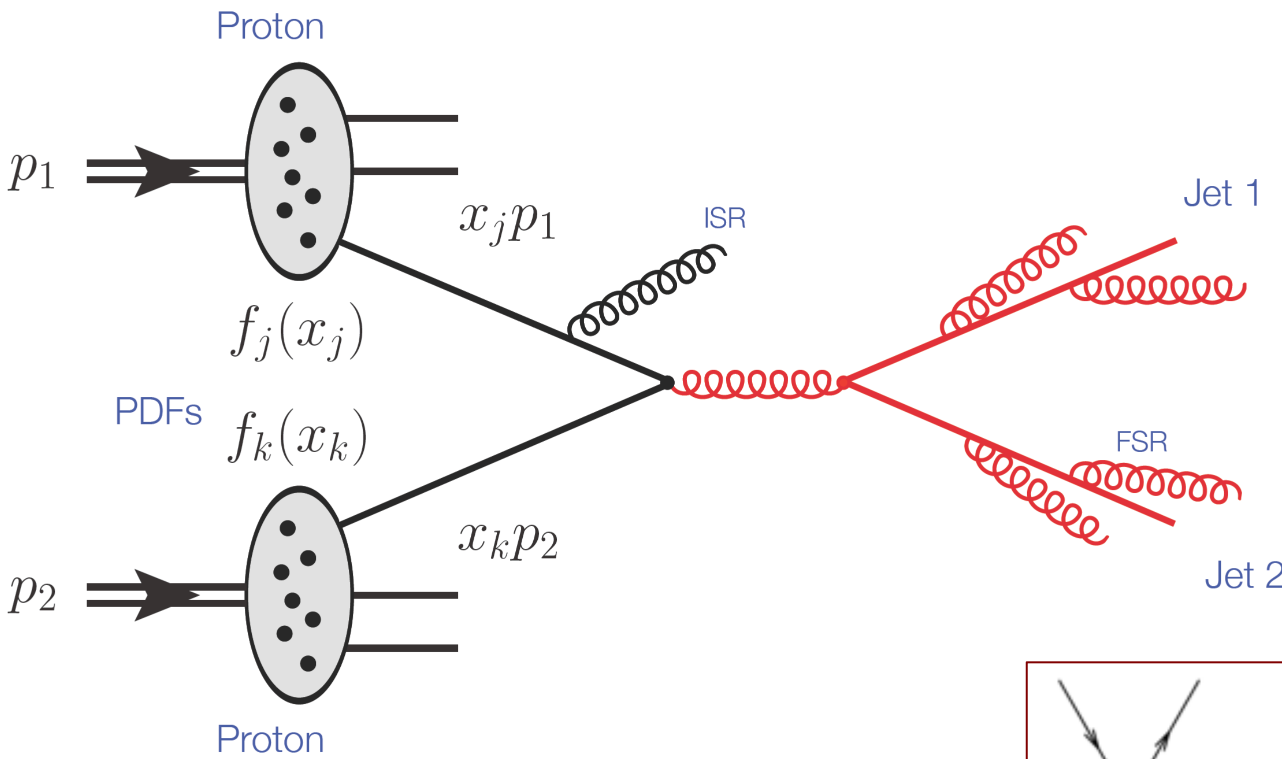
Jet production

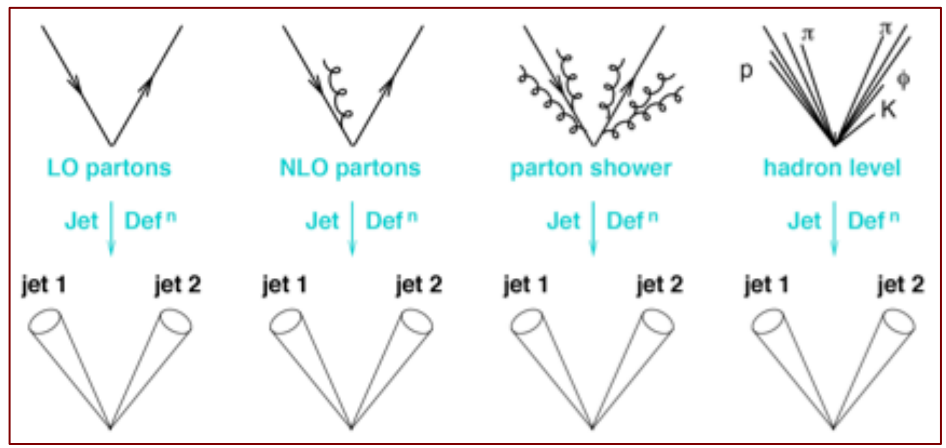
jets





Jet production at LHC

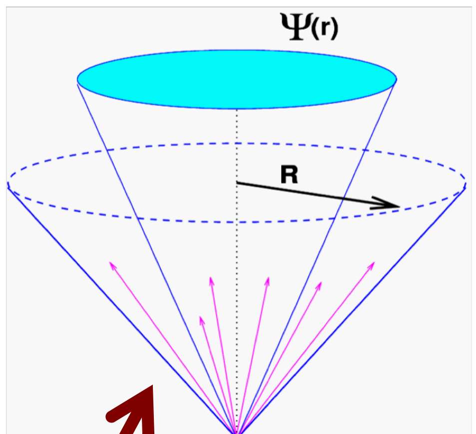




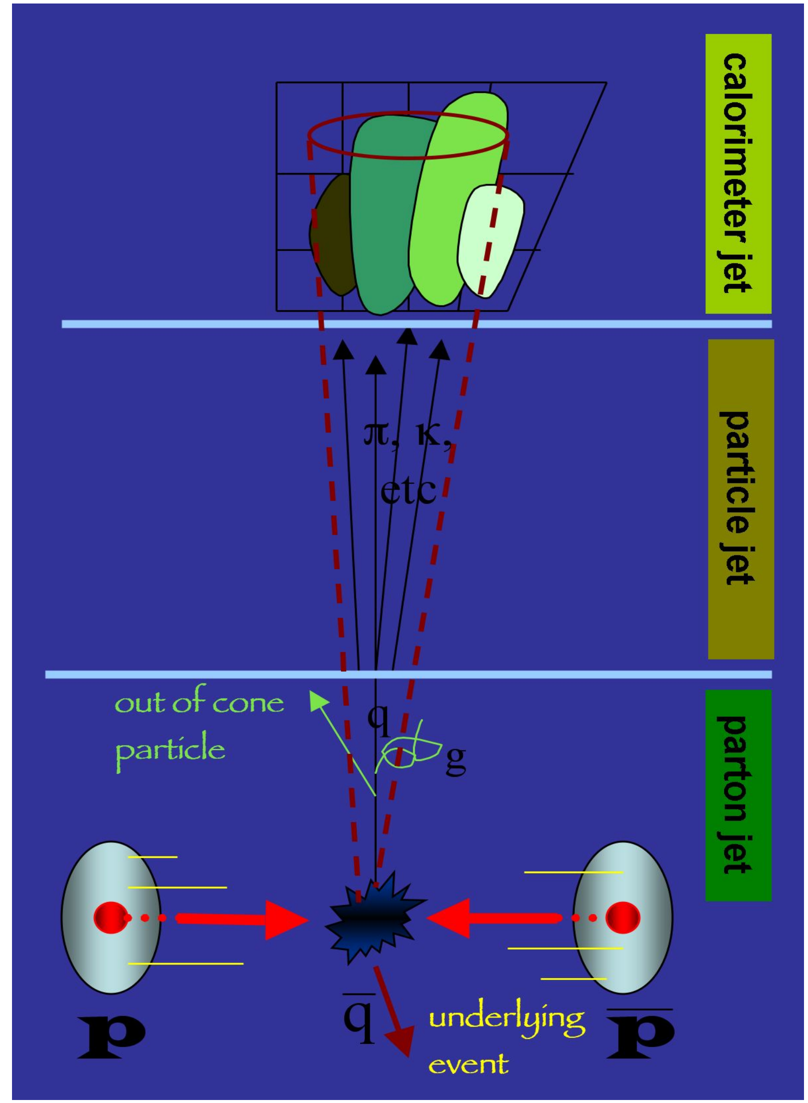
Available up to NLO, first NNLO calculations becoming available

Jet production at LHC (cont.)

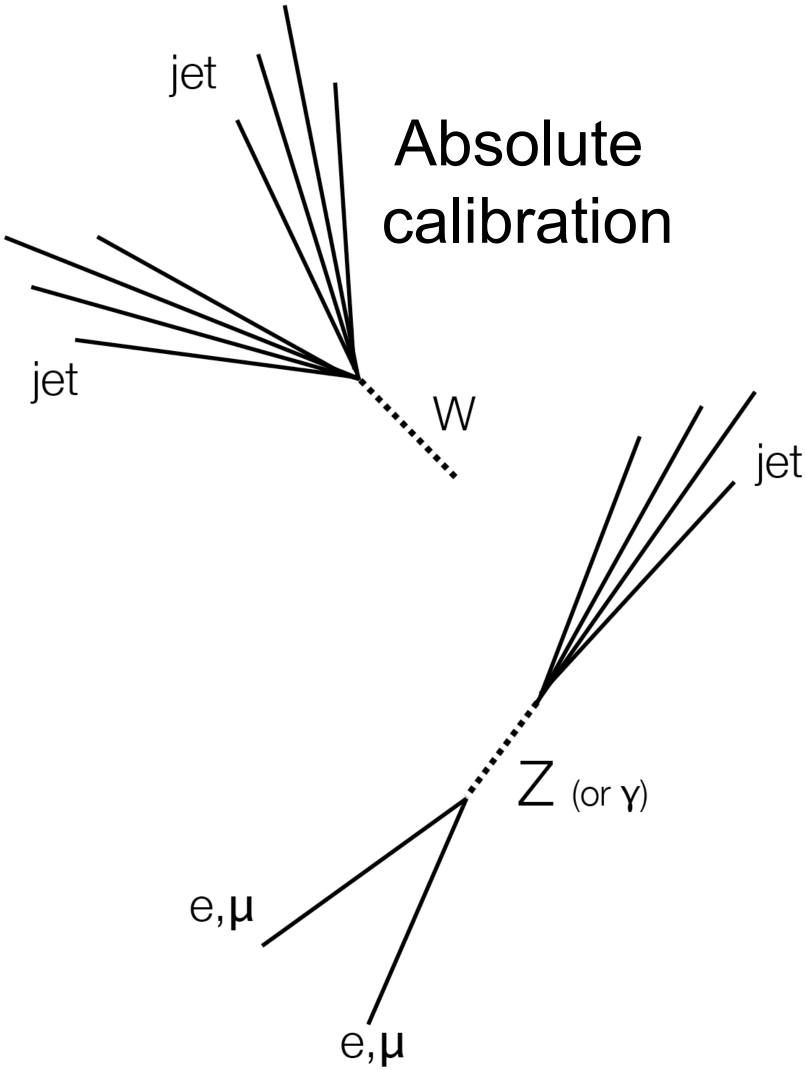
- Processes creating jets are complicated
  - Parton fragmentation, with electromagnetic or hadronic showering in the detector
- Jet reconstruction is difficult
- Jet energy scale and reconstruction is large source of uncertainty

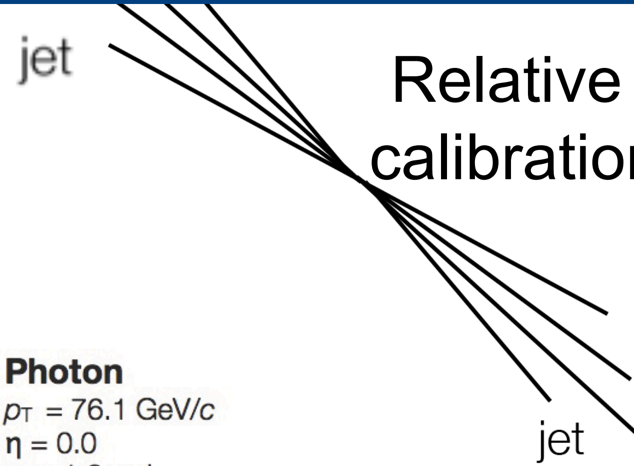


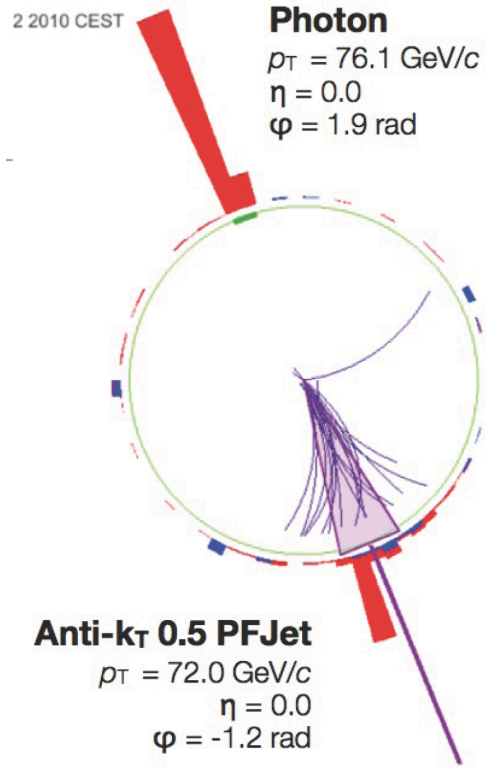
- Measure energy in a "cone"



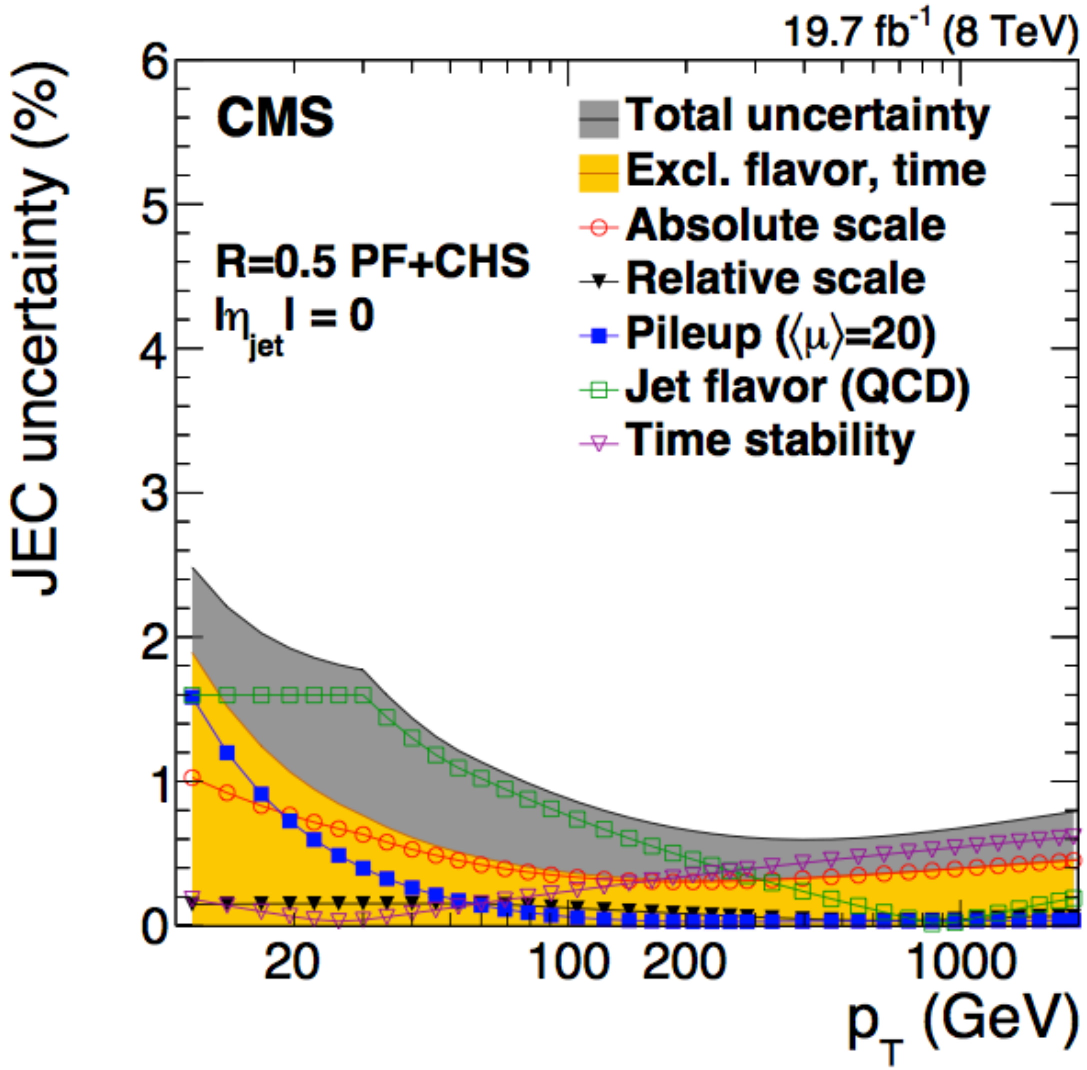
Jet energy calibration







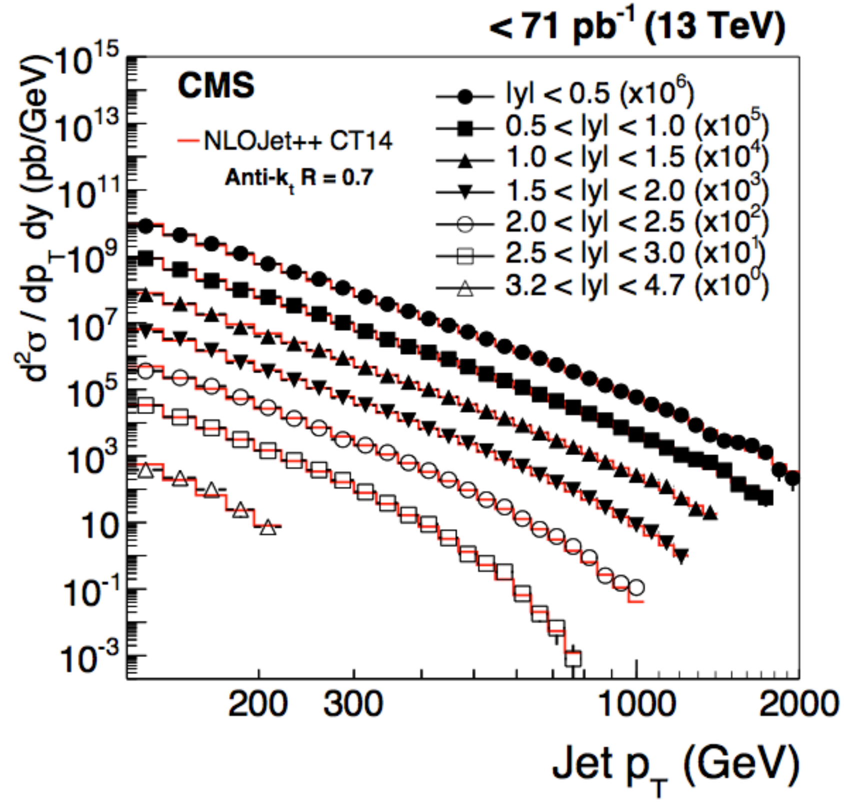
E_T can be measured precisely

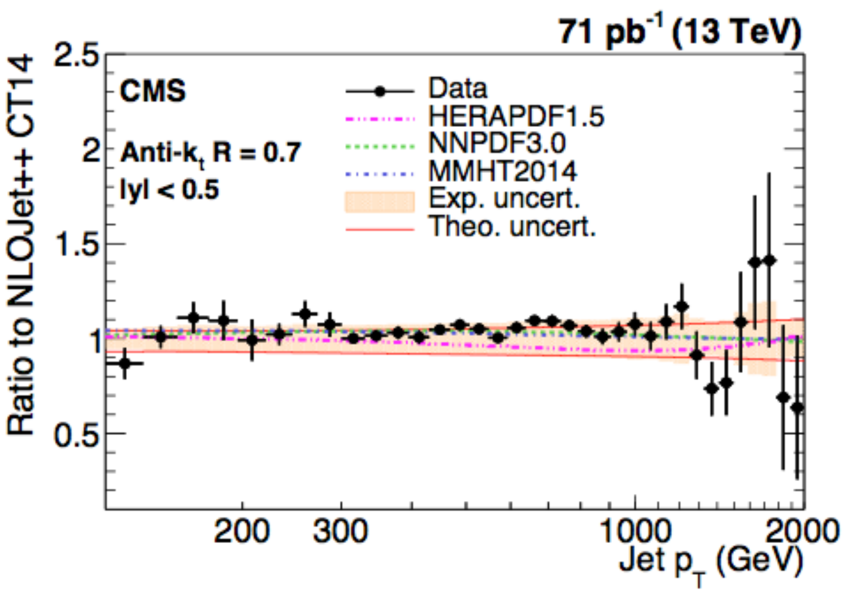


Inclusive jet distribution

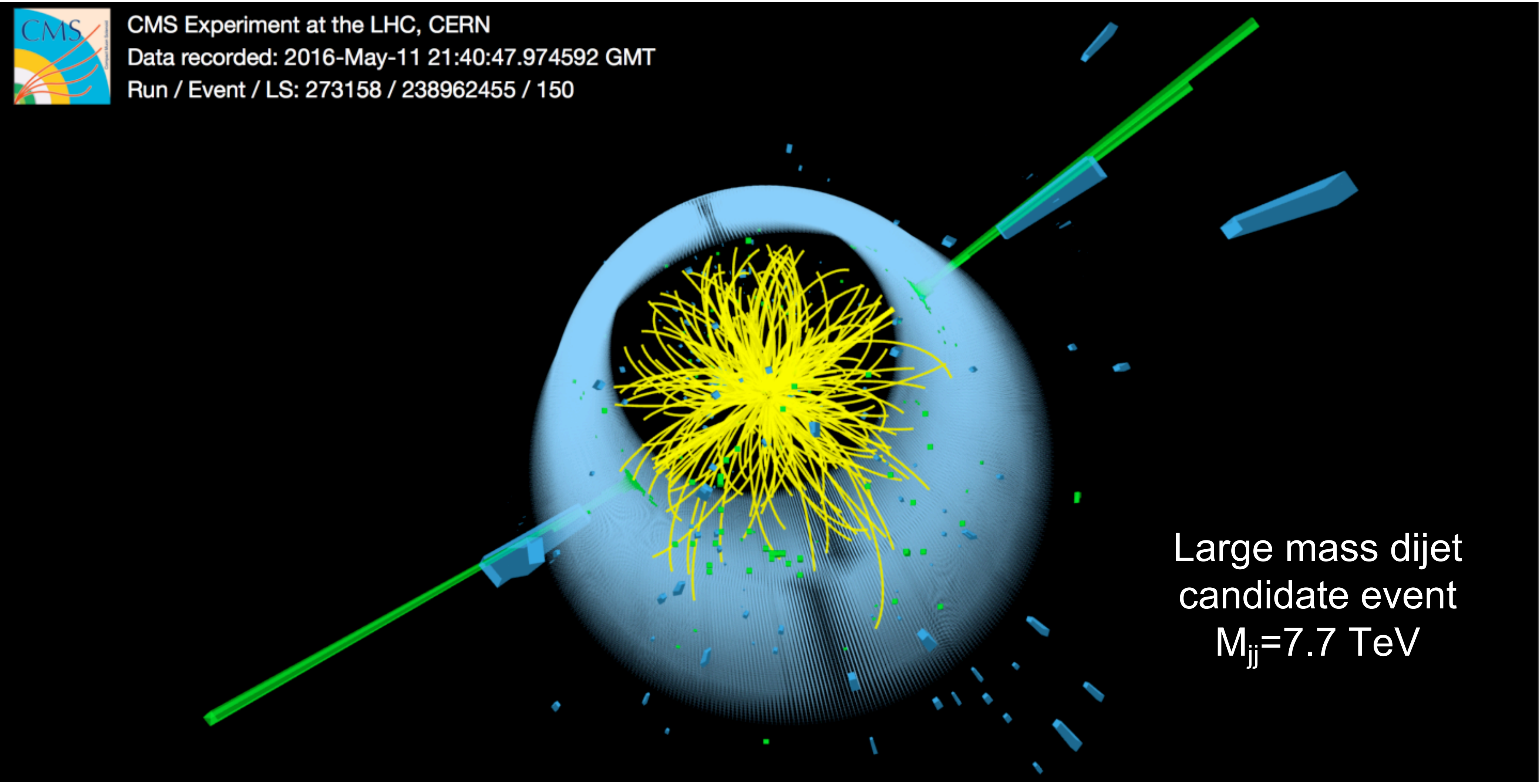
arXiv:1605.04436

- Produced abundantly at the LHC
- Very good agreement with NLO QCD over nine orders of magnitude
  - P_T extending from 20 to 2000 GeV





Dijet event at 13 TeV

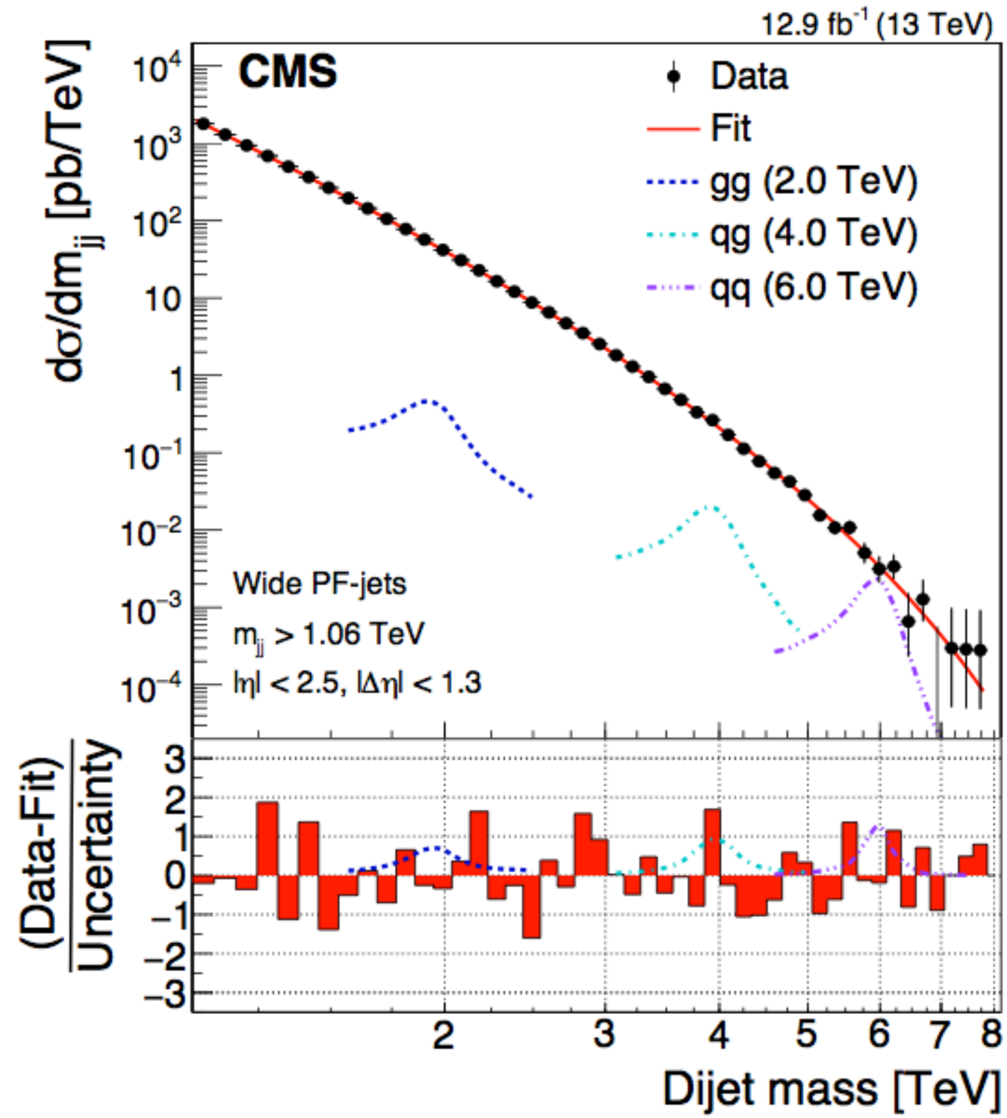


Dijet mass

arXiv:1611.03568

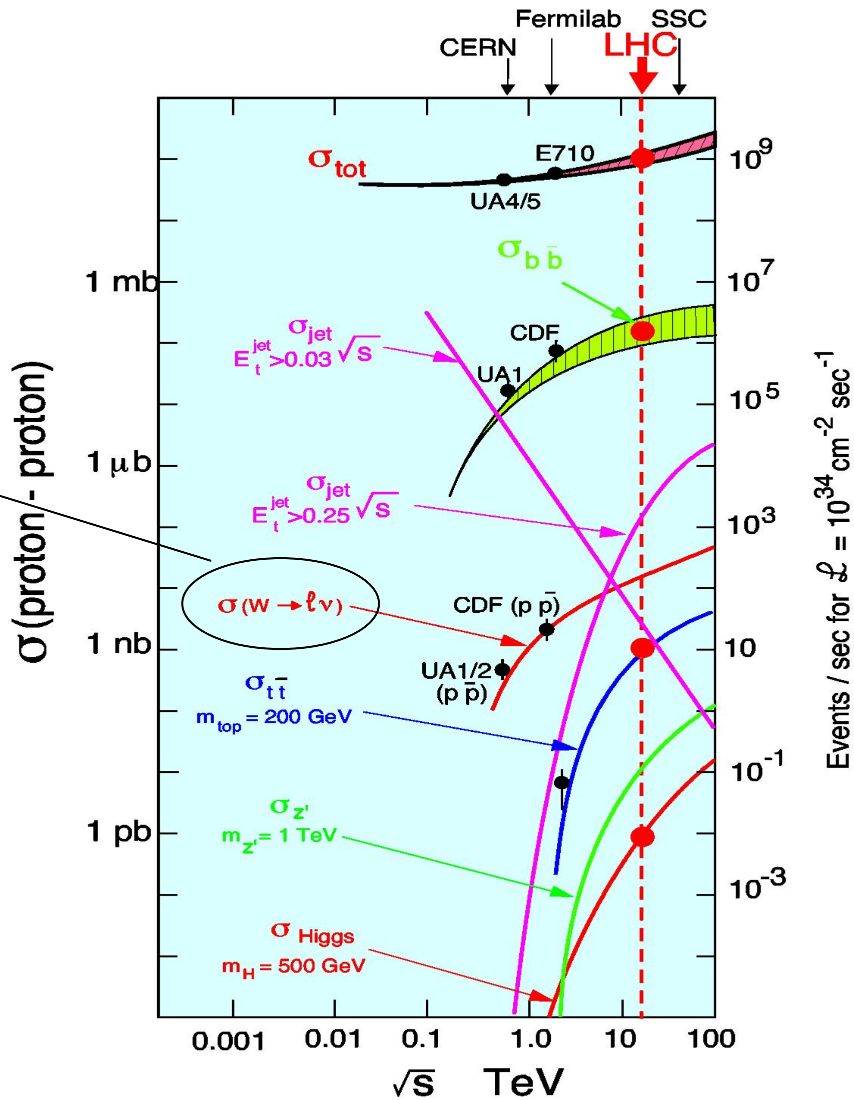
Search for numerous BSM resonances:

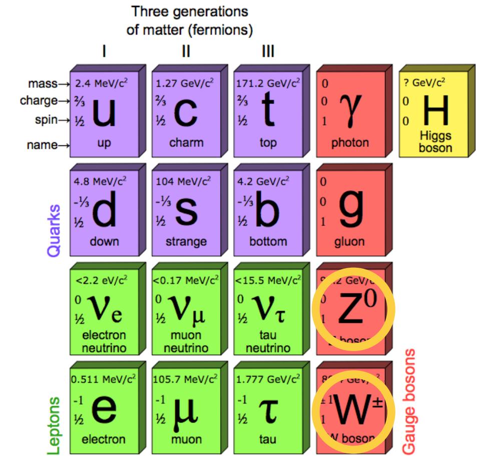
- string resonance, excited quarks, axi-gluons, colorons, E6 diquarks, W' and Z', RS gravitons



W and Z bosons

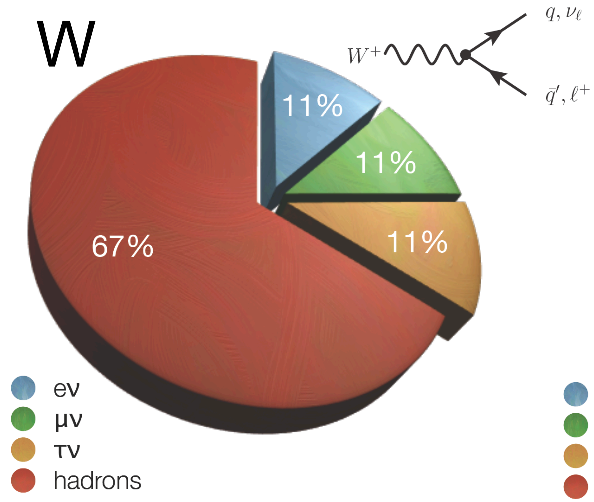
W bosons

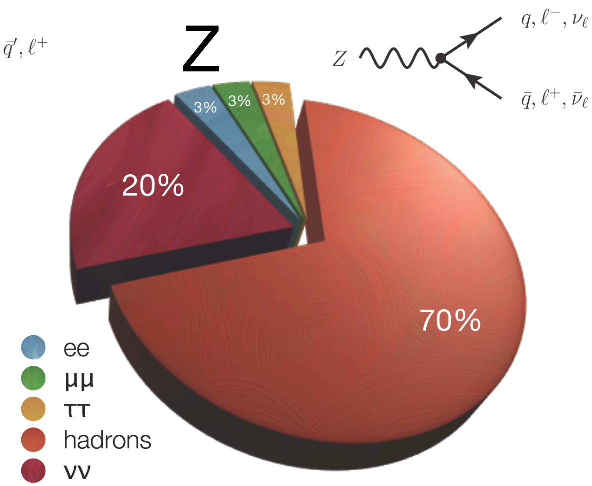


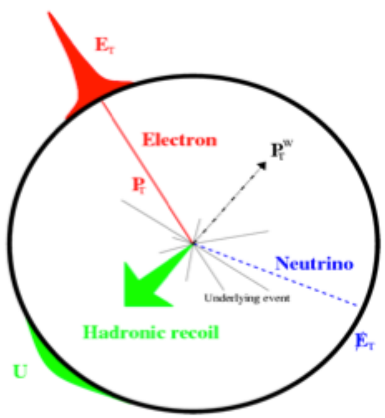


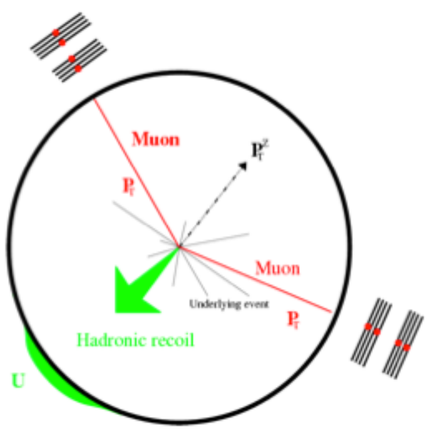
W and Z bosons

- Leptonic decays (e/μ): very clean, small branching fractions
- Hadronic decays: two-jet final state, large QCD background



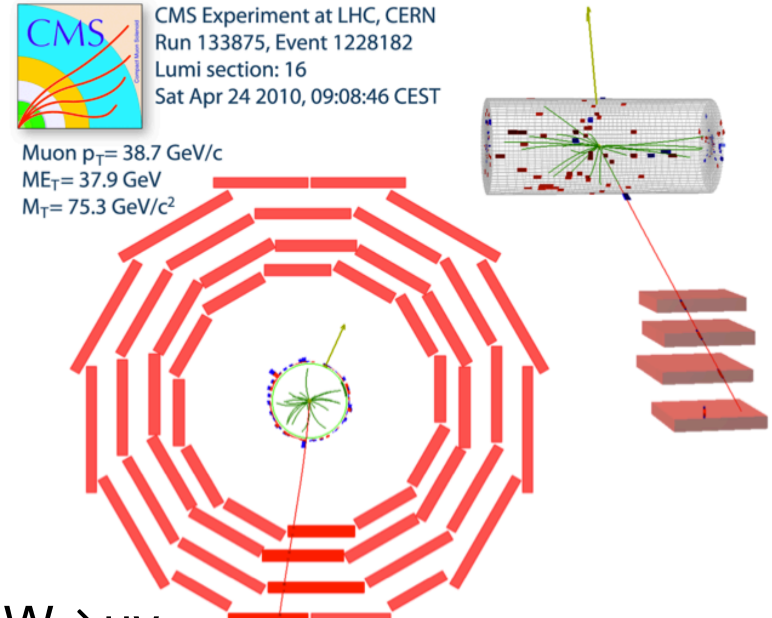




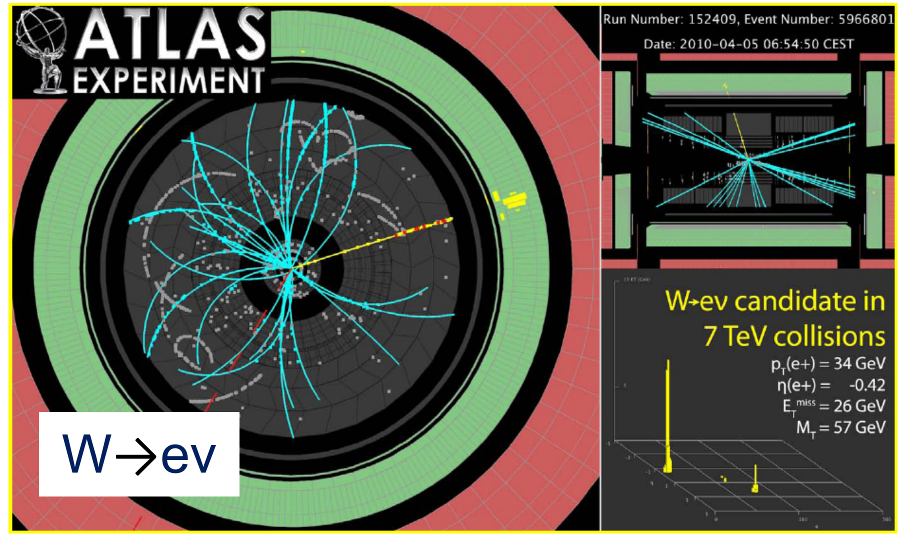


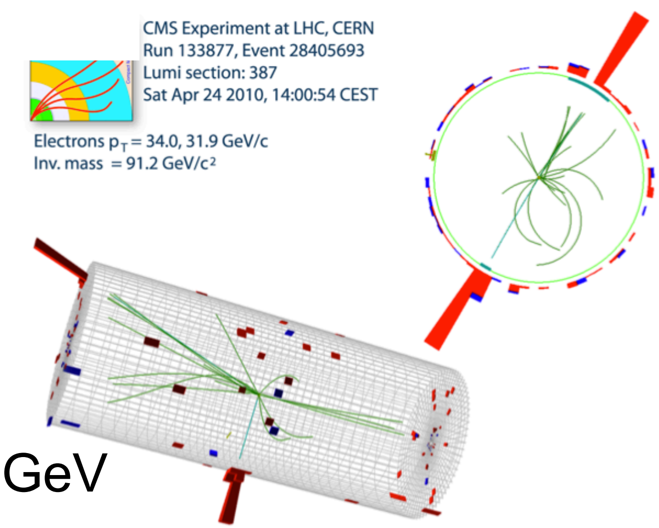
- Isolated high-p_T leptons: starting point of many analyses
  - Good rejection of QCD backgrounds
  - "Tracking" vs "calorimeter" isolation
- Excellent calibration signal
  - Electron energy scale, ID/trigger eff., etc.

W and Z bosons (cont.)



W→μν





Z→ee:

Mass= 91.2 GeV

W and Z reconstruction

- Select isolated leptons (electrons and muons)

Z mass reconstruction

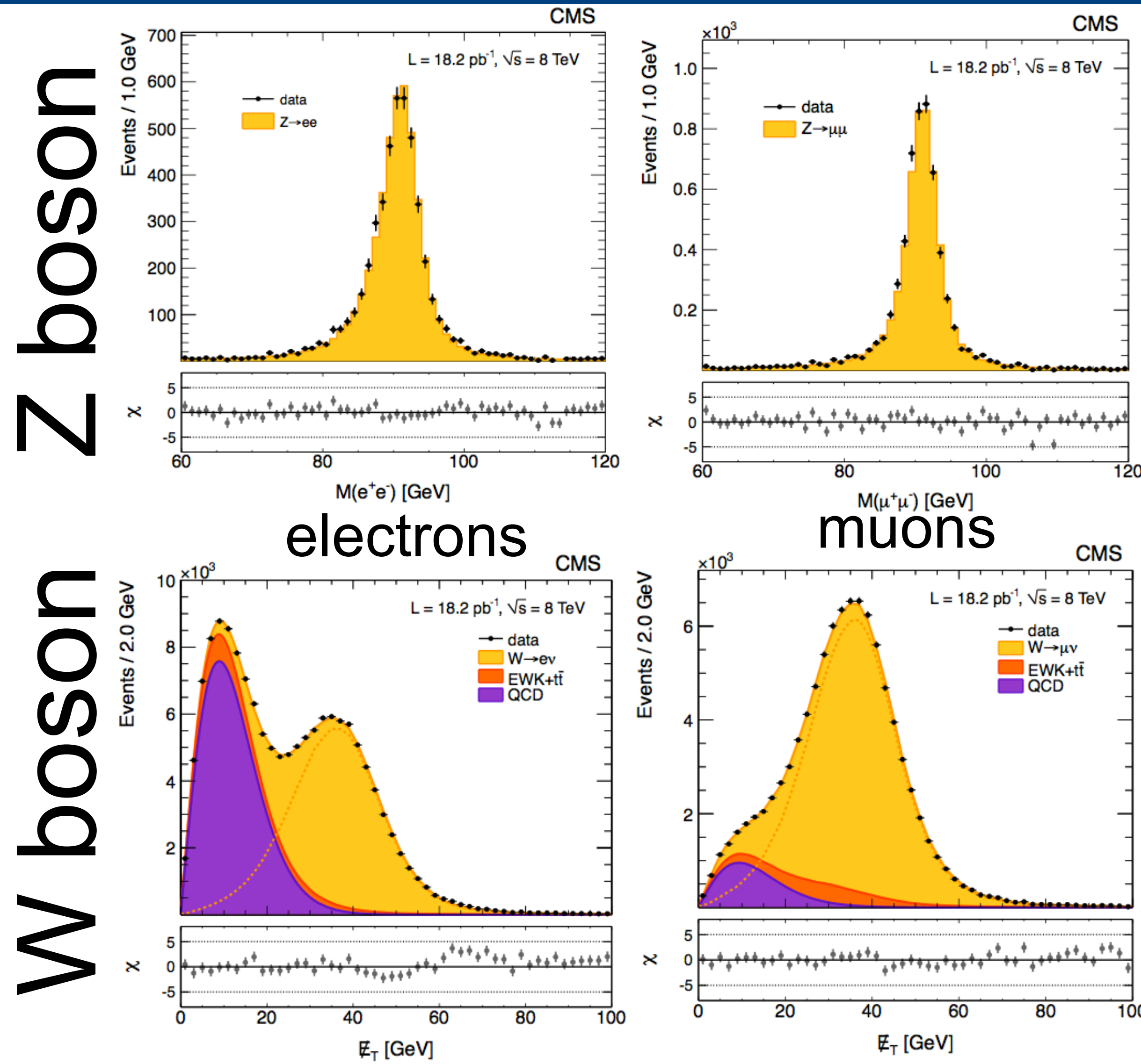
- Invariant mass of two leptons

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

W mass reconstruction

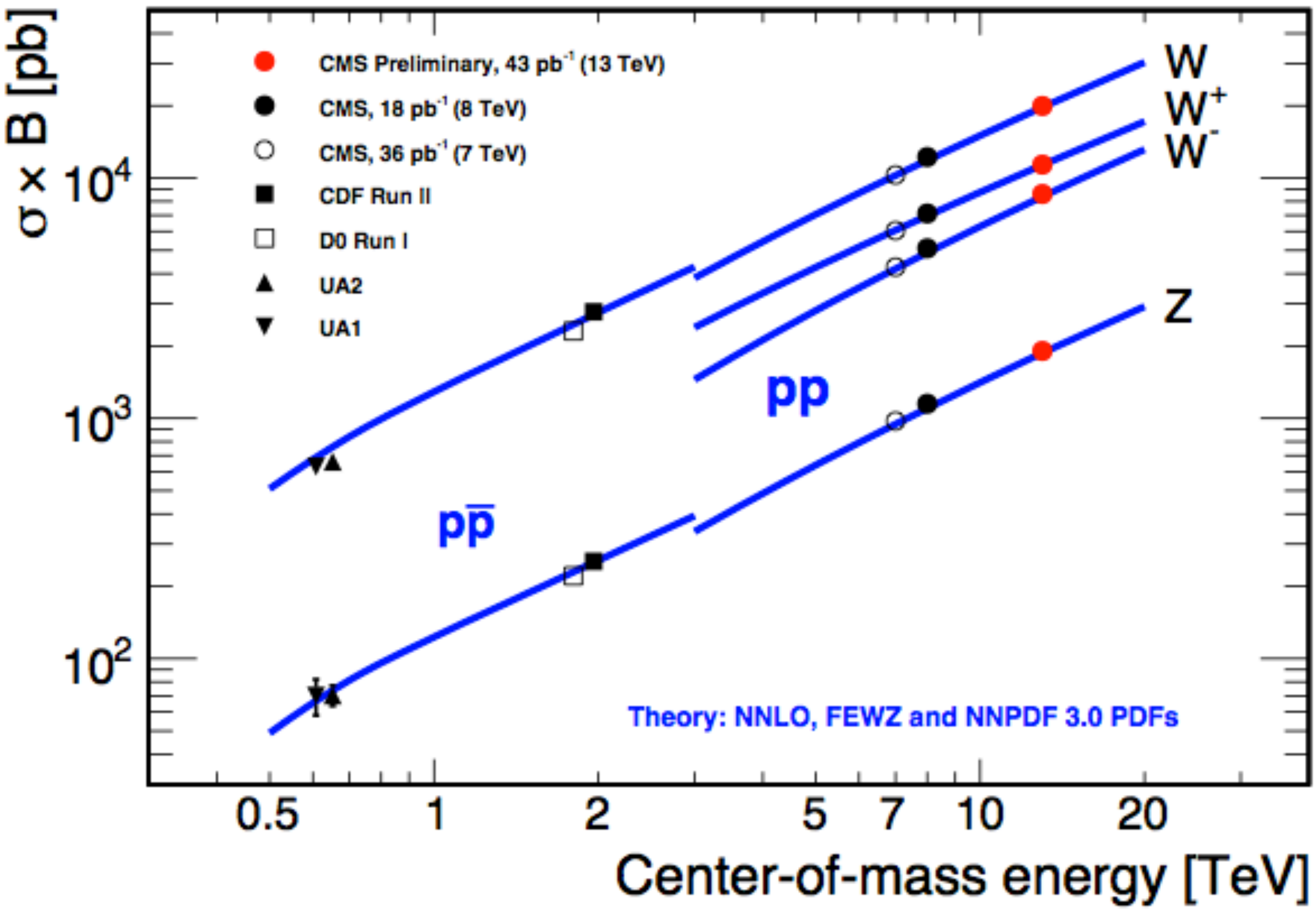
- Do not know neutrino p_Z
- No full mass reconstruction
- Transverse mass

$$m_T = \sqrt{|p_T^\ell|^2 + |p_T^\nu|^2 - (\vec{p}_T^{\,\ell} + \vec{p}_T^{\,\nu})^2}$$



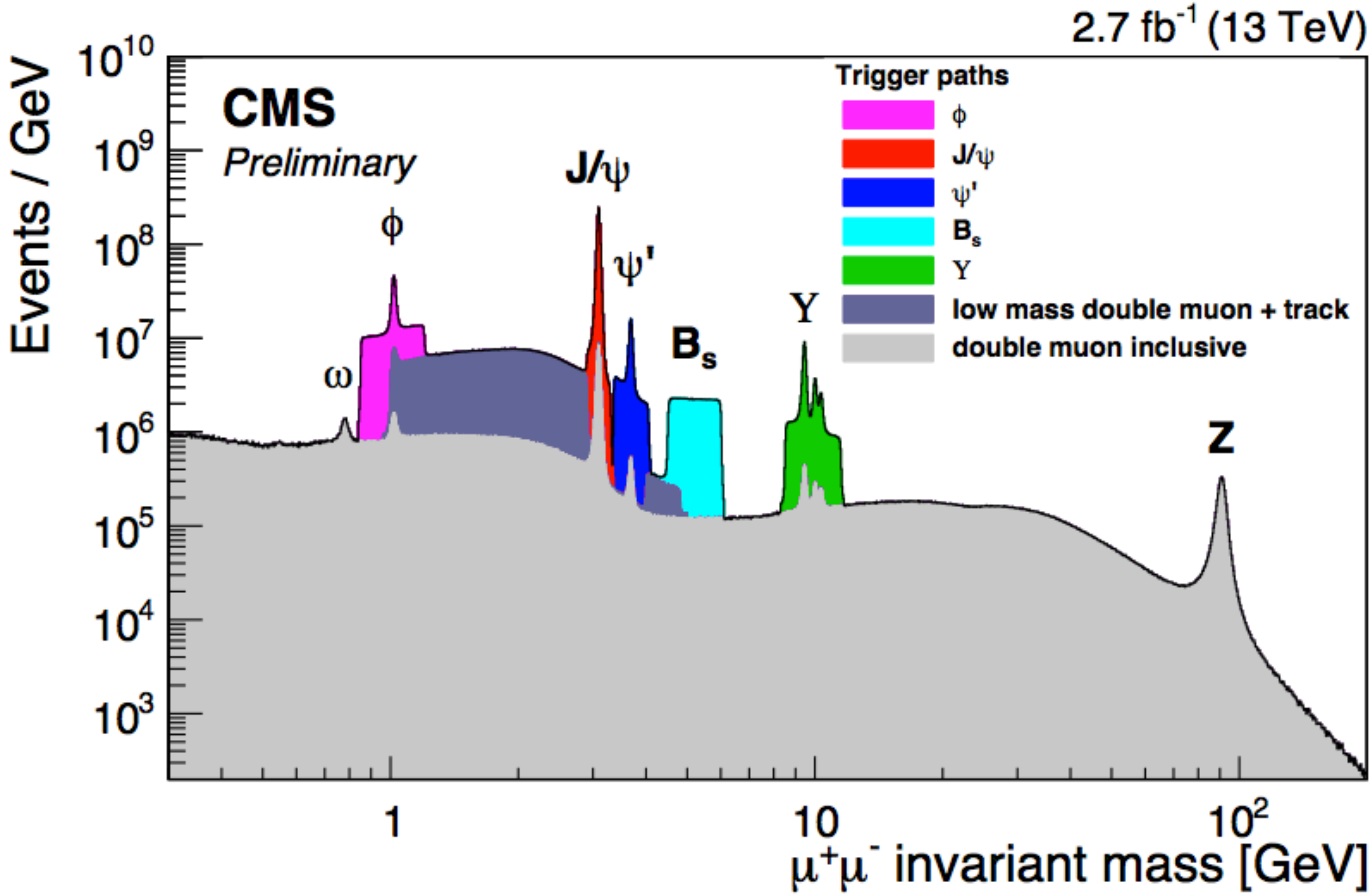
W/Z cross section vs √s

arXiv:1012.2466, CMS-SMP-15-004



Di-muon mass spectrum

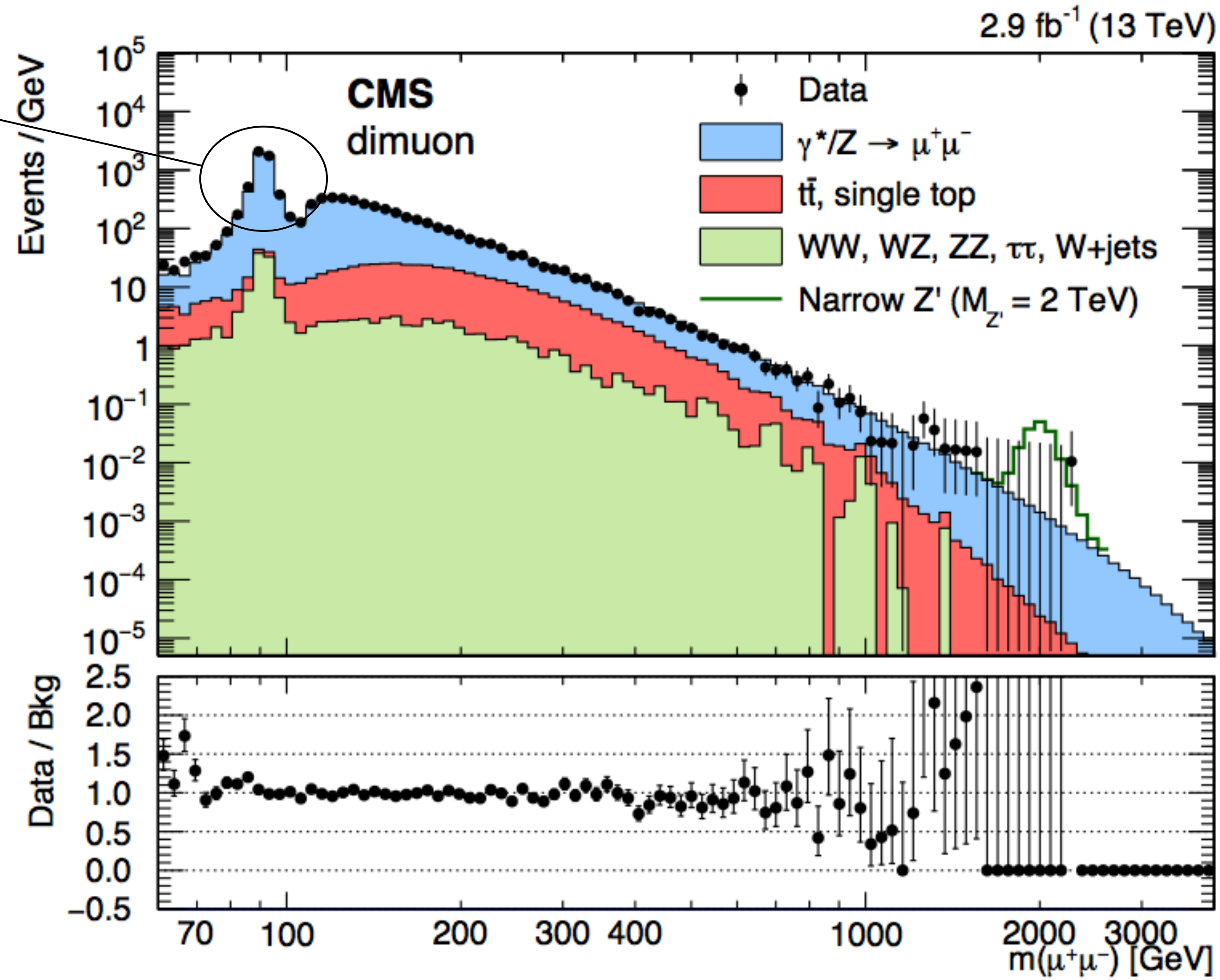
CMS-DP-2015-055



Di-lepton events

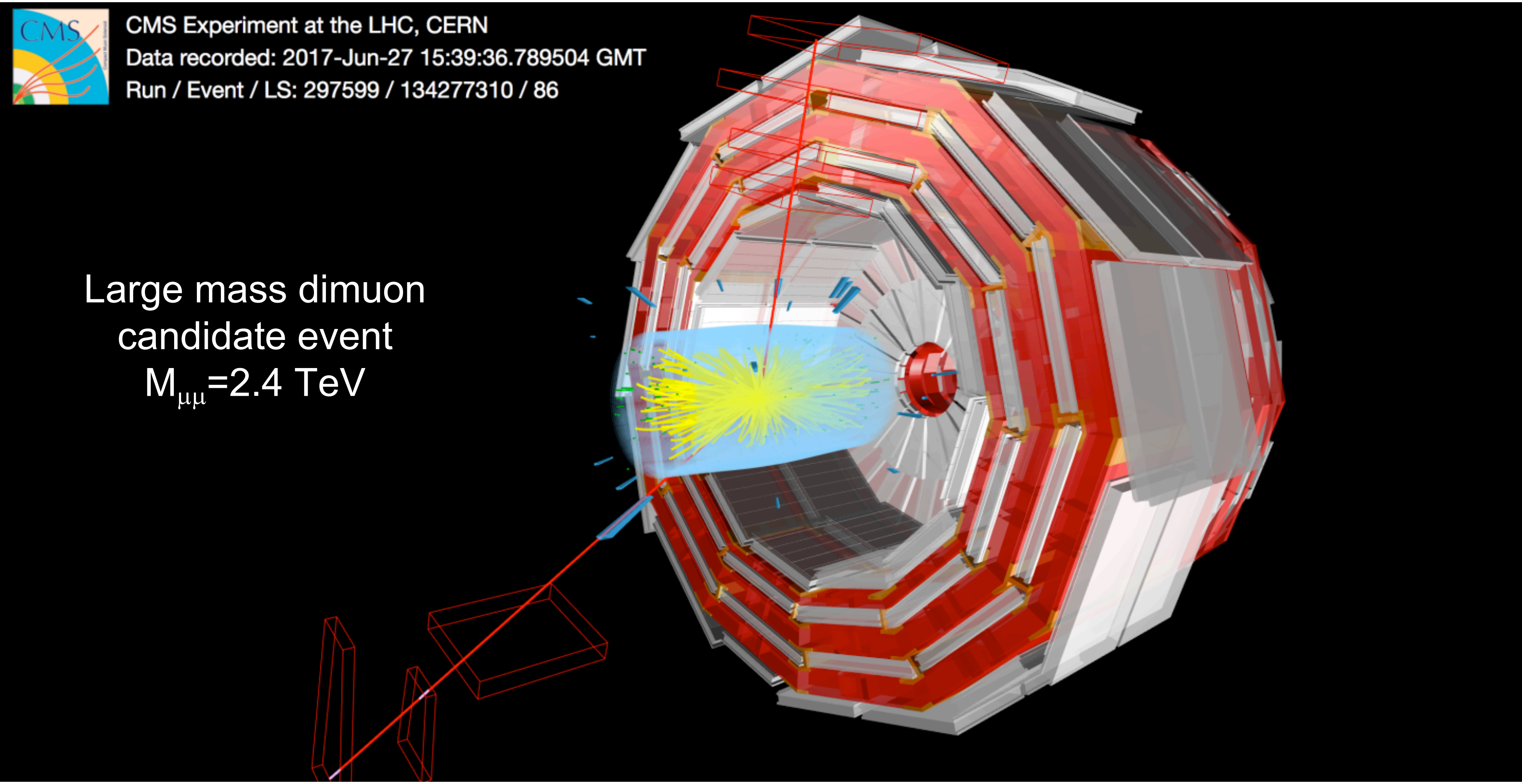
arXiv:1609.05391

Z boson resonance



- Select di-lepton candidate events
- Search for other resonances

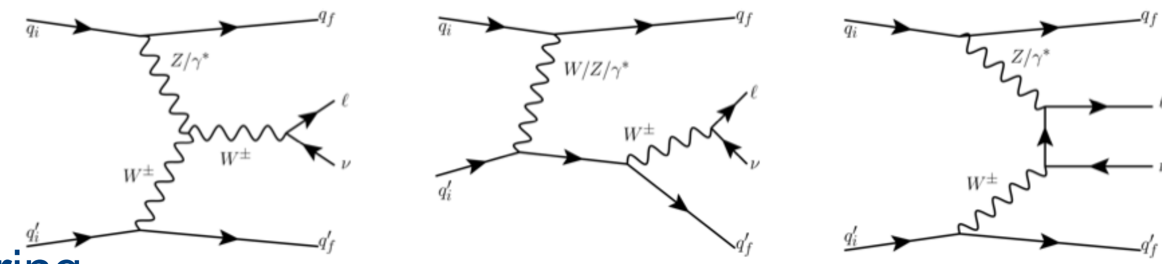
2017: Di-muon candidate event



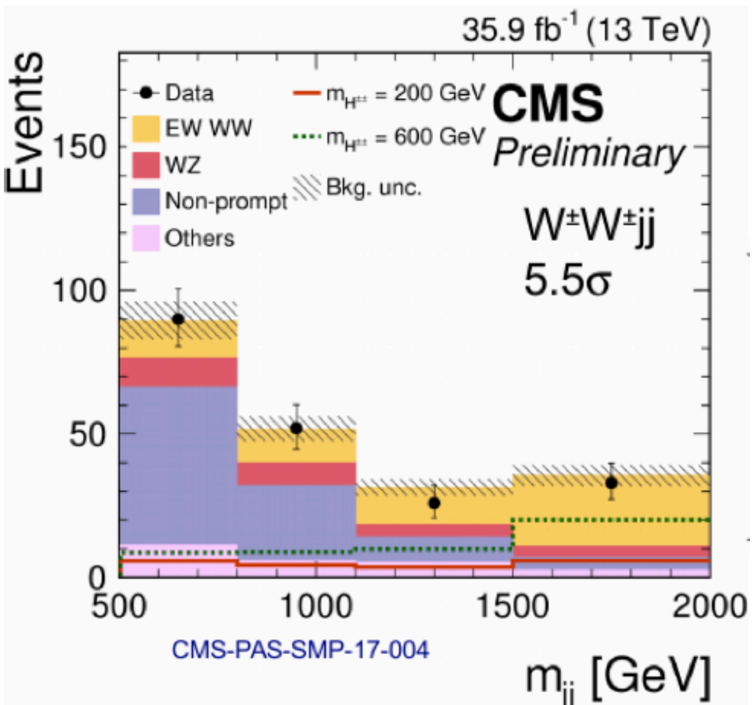
Large mass dimuon candidate event
$M_{\mu\mu}$=2.4 TeV

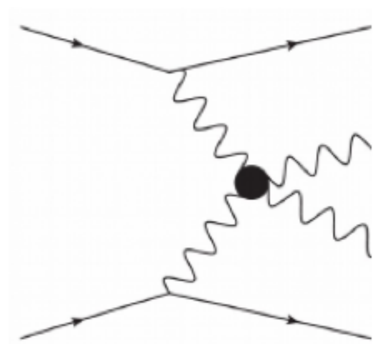
Single and diboson production

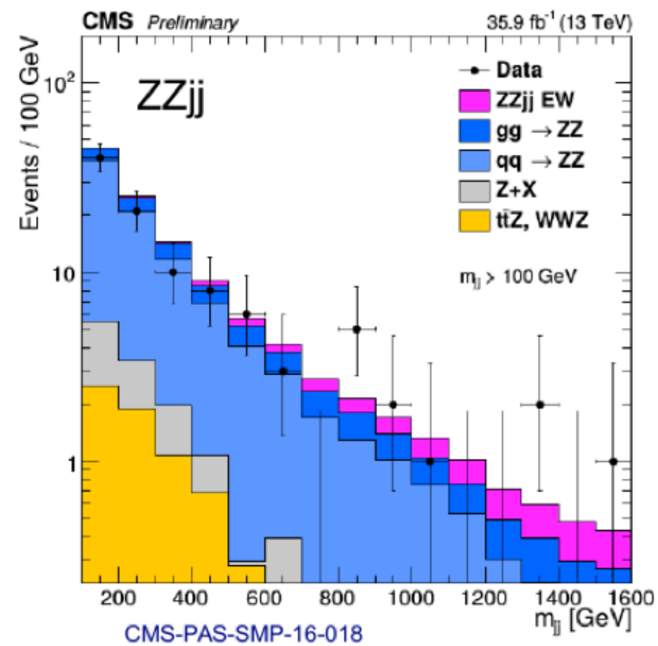
SMP-17—004, SMP-16-018



- LHC as boson-boson collider
- Single (or double) W/Z production
  - Sensitive to NP
- Observation of vector boson scattering
  - Same-sign WW
- Rich program of precision measurements

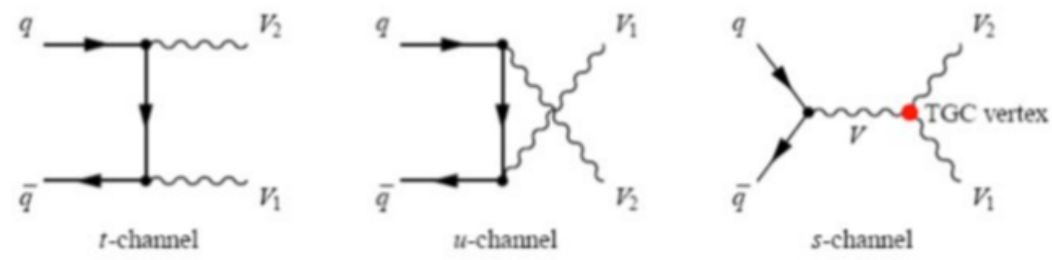


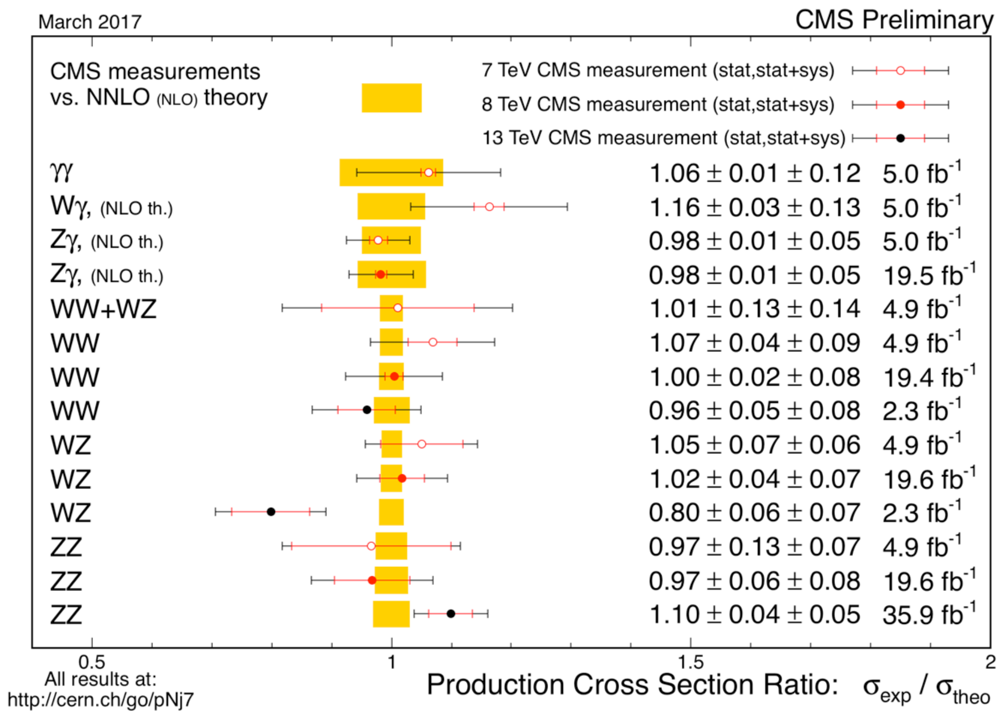


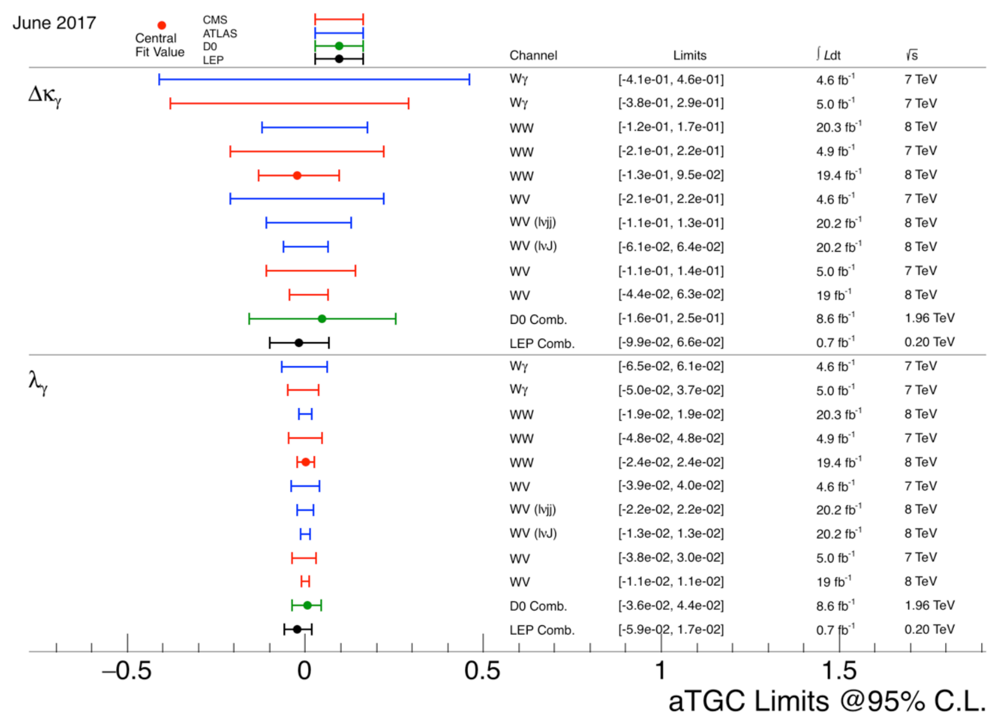


Diboson production

- Test of EW corrections
- Sensitive to New Physics from triple gauge couplings
- Increased luminosity will further improve sensitivity

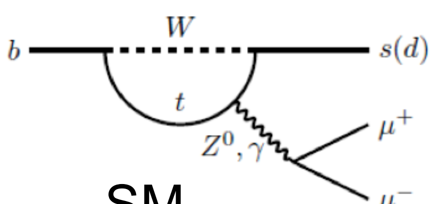




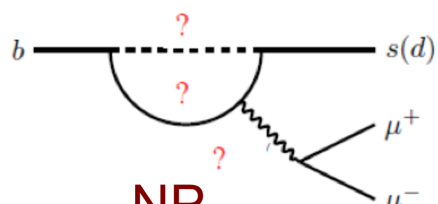


B-physics and Rare decays

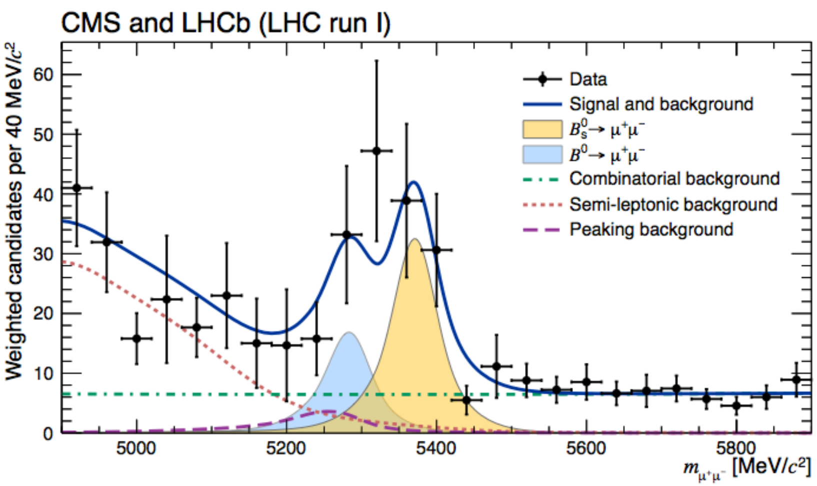
- Study rare processes to look for NP
- Indirect searches: $B_{s/d} \rightarrow \mu\mu$
- Flavour changing neutral current (FCNC) forbidden at tree level in SM
- Can only go through loop diagrams

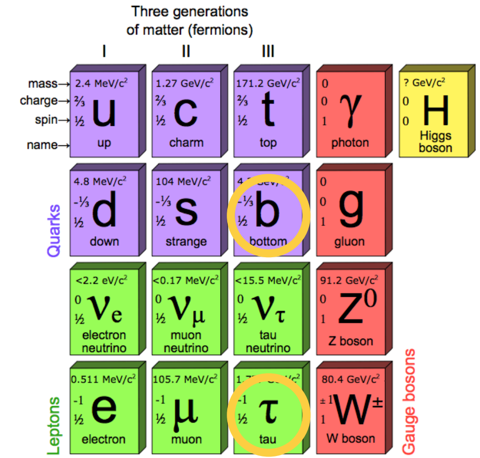


SM

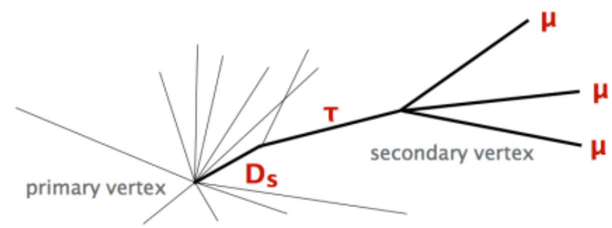


NP



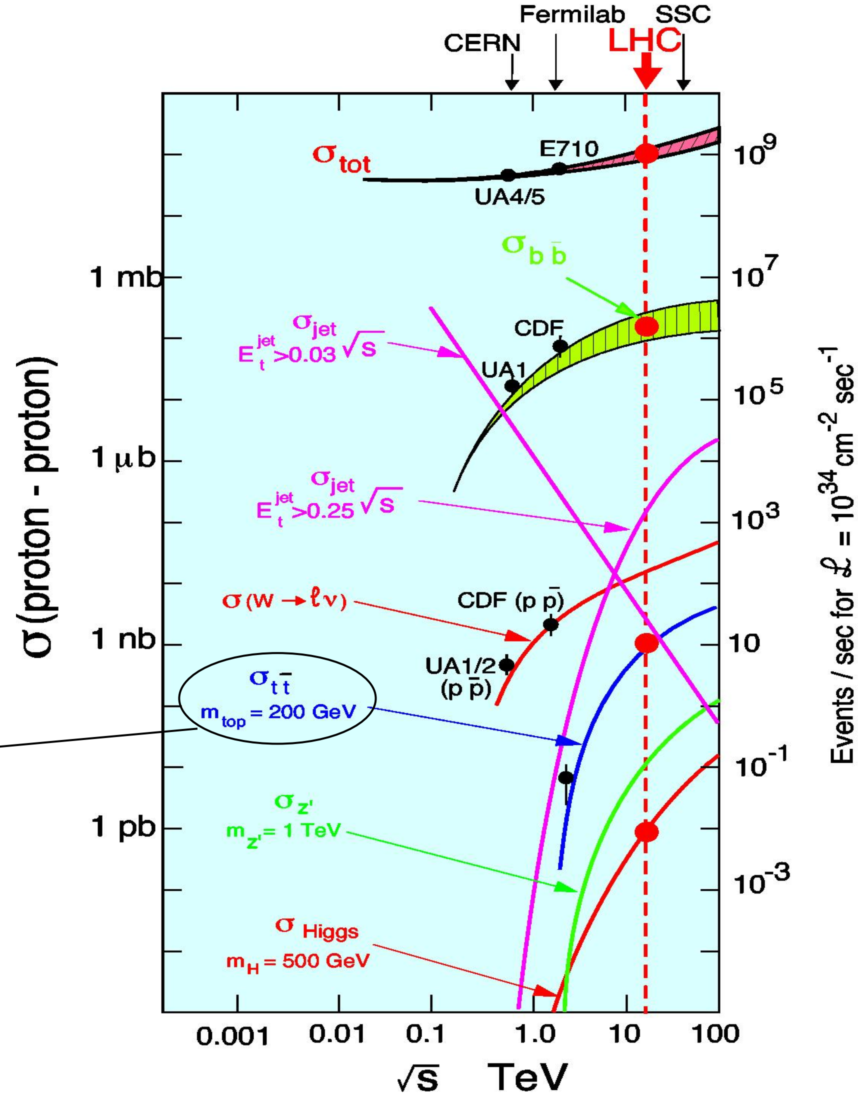


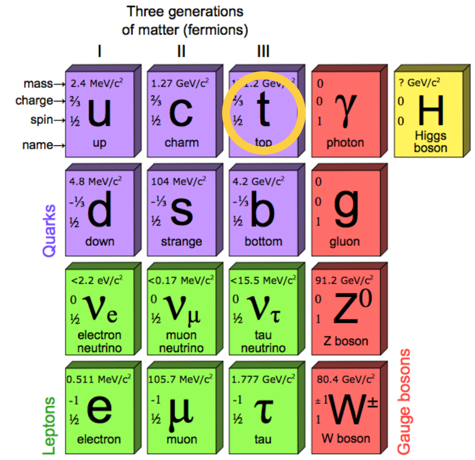
- Lepton Flavor Violation (LFV)
- Search for tau→ 3 muon decays
- Very rare process: BR~10^{-40}!
- Study in Ds and W decays



Top quark production

top quark





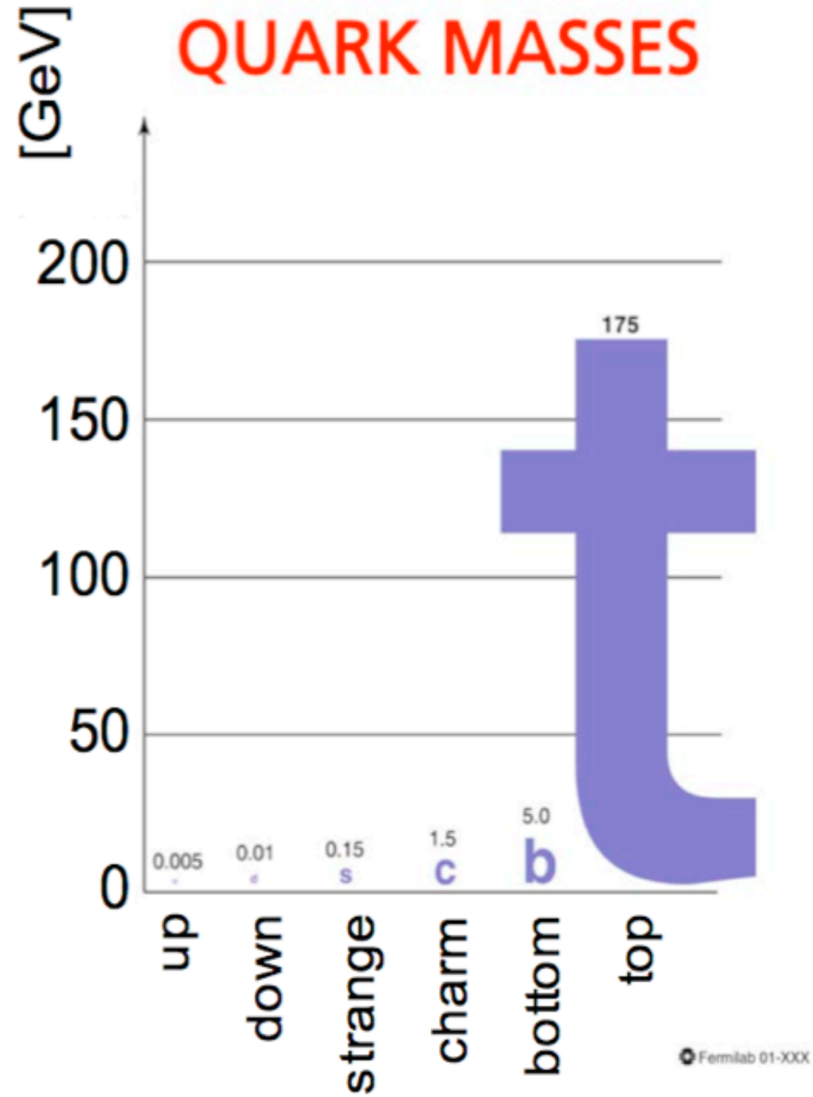
The top quark

- The heaviest known elementary particle
- Large coupling to the Higgs: ~1
- Short lifetime

τ=0.4x10^{-24} sec

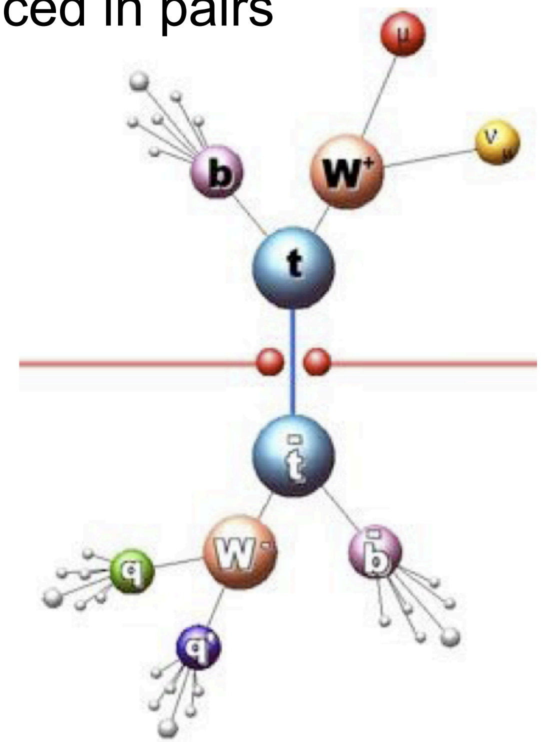
  – very short lifetime ⇒ bound states are not formed
    ⇒ opportunity to study a free quark

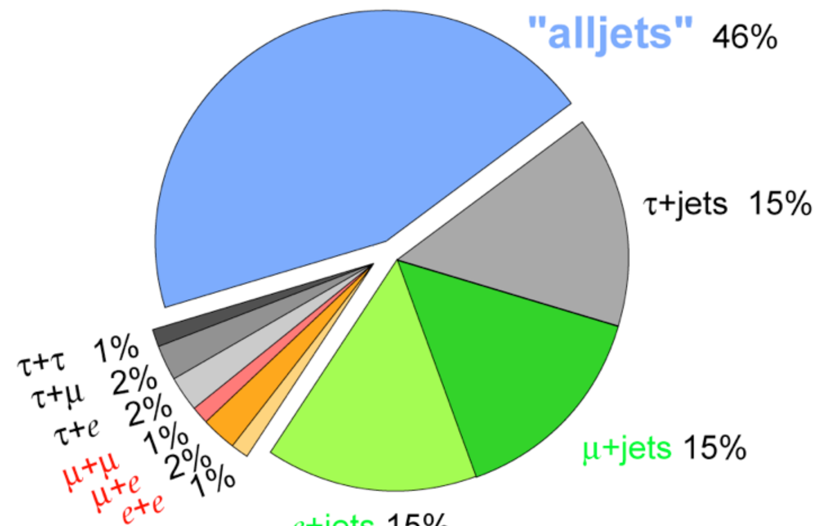
- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Measurements may provide insight into physics beyond SM



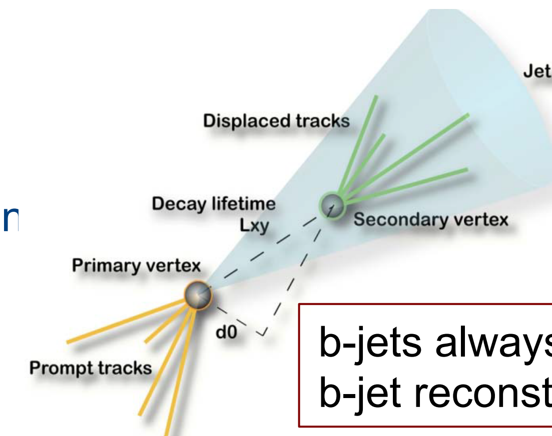
Top quark decays

Top quarks (mostly) produced in pairs





- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinos
- Lepton (e or μ) + jets
  - BR~30%, one lepton+4jets (2 from b)+1 n
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinos

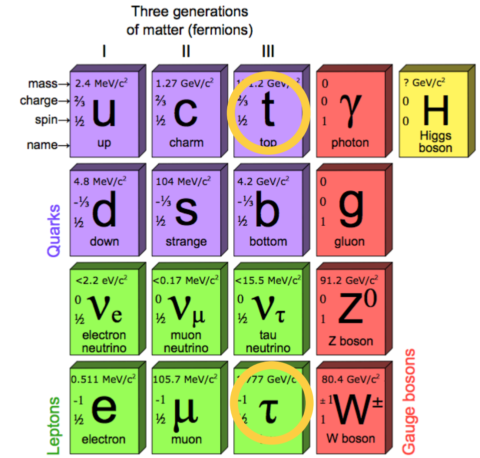


b-jets always present
b-jet reconstruction plays important role

Top quark and tau lepton

PRD 85 (2012) 112007, PLB 739 (2014) 23

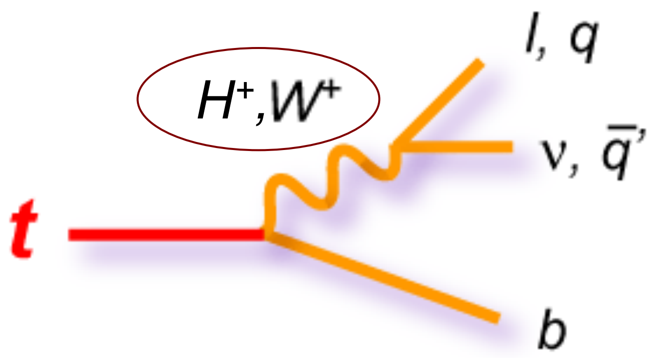
- cross section measurement including taus
- Includes only 3rd generation quarks/leptons

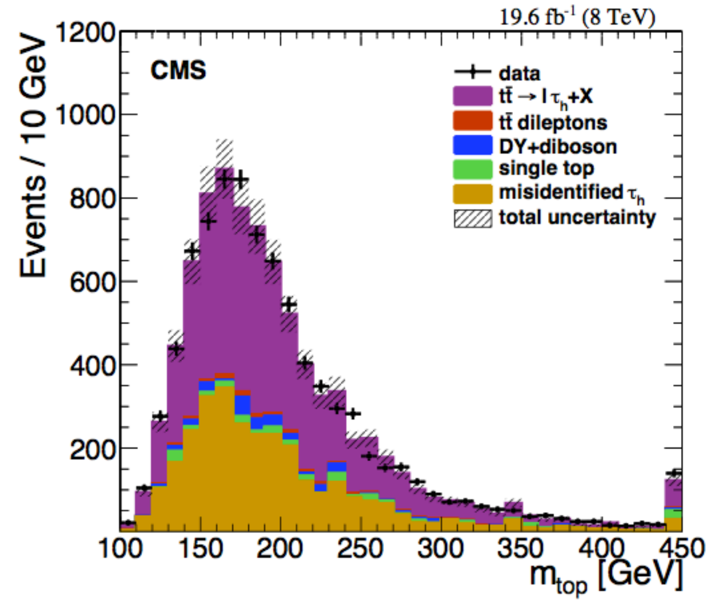


Channel	Signature	BR
Dilepton(e/μ)	*ee*,μμ,*e*μ + 2*b*-jets	4/81
Single lepton	*e*,μ + jets + 2*b*-jets	24/81
All-hadronic	jets + 2*b*-jets	36/81
Tau dilepton	*e*τ, μτ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81

→ BR~5%

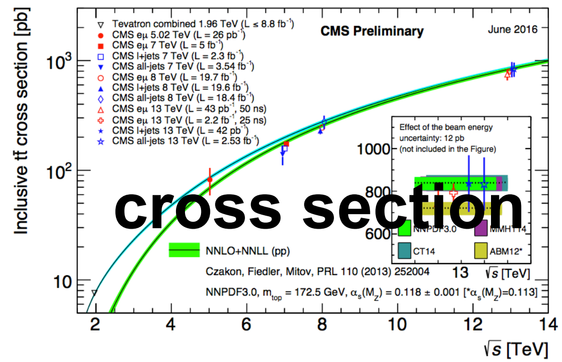
- Charged Higgs may alter coupling to W
  - Search for final states with taus

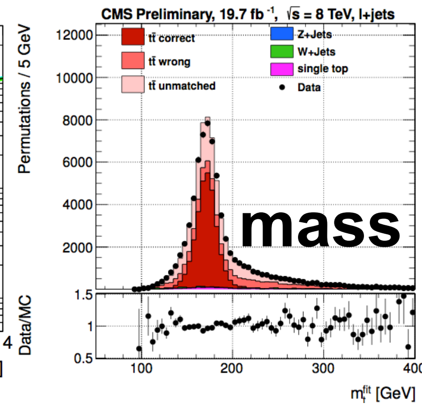


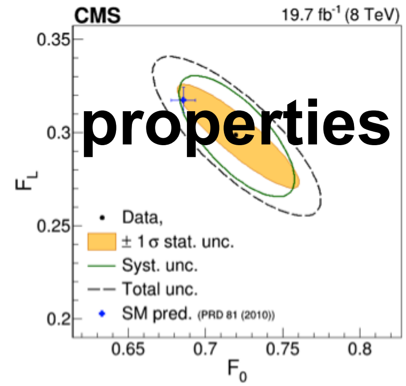


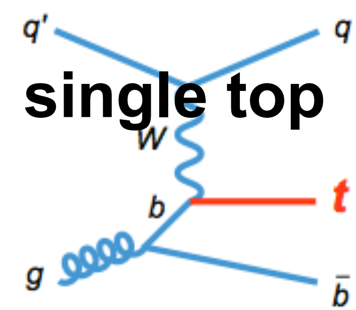
Top quarks and BSM

- Monitoring of production mechanism
- Interpretation of m_{top}: top, W, Higgs masses
- Are properties consistent with our understanding of EWSB?
- Is there any sign of NP in top production/decay?



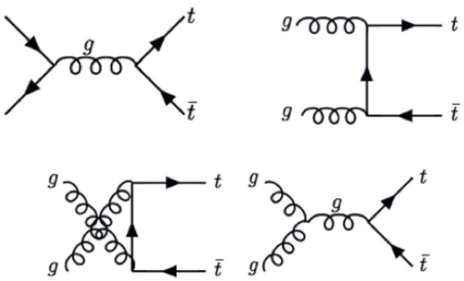






Cross sections vs √s

arXiv:1112.5675

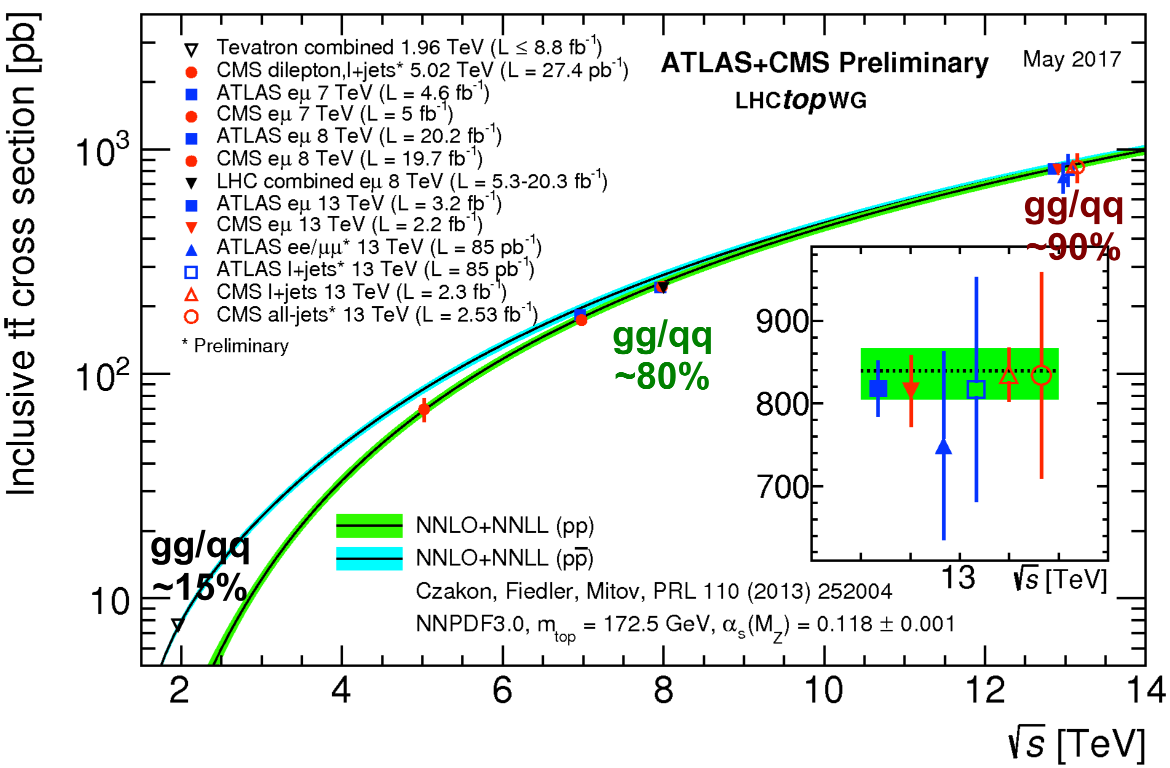


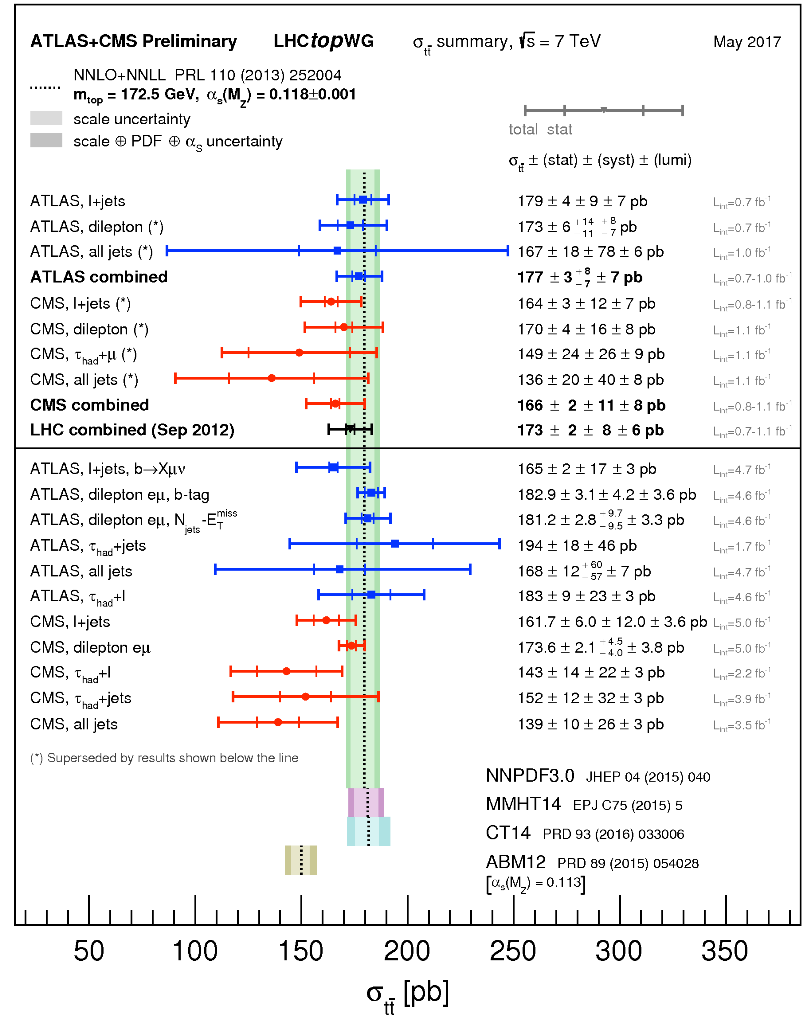
$$\sigma(7\ \mathrm{TeV}) = 177\ \mathrm{pb} \pm 7\%$$

$$\sigma(8\ \mathrm{TeV}) = 253\ \mathrm{pb} \pm 6\%$$

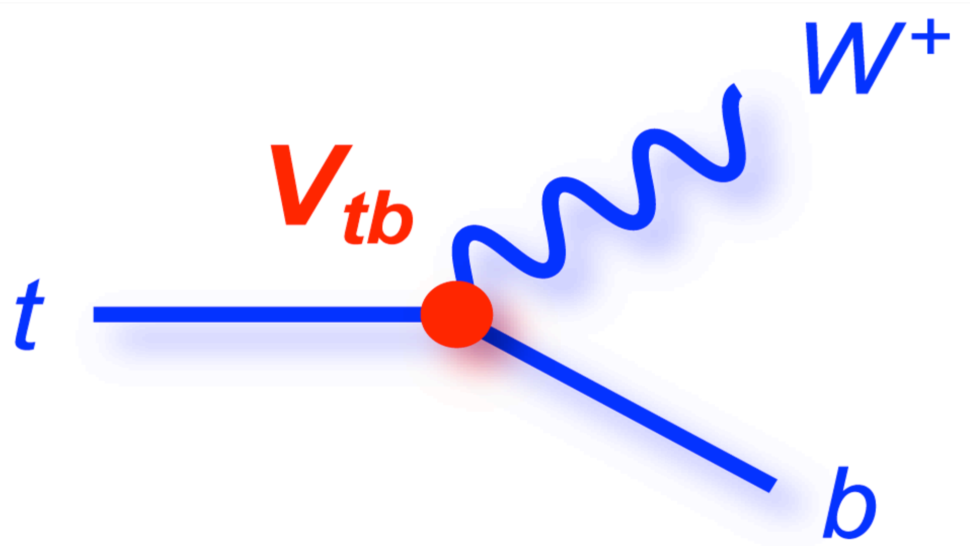
$$\sigma(13\ \mathrm{TeV}) = 832\ \mathrm{pb} \pm 5\%$$

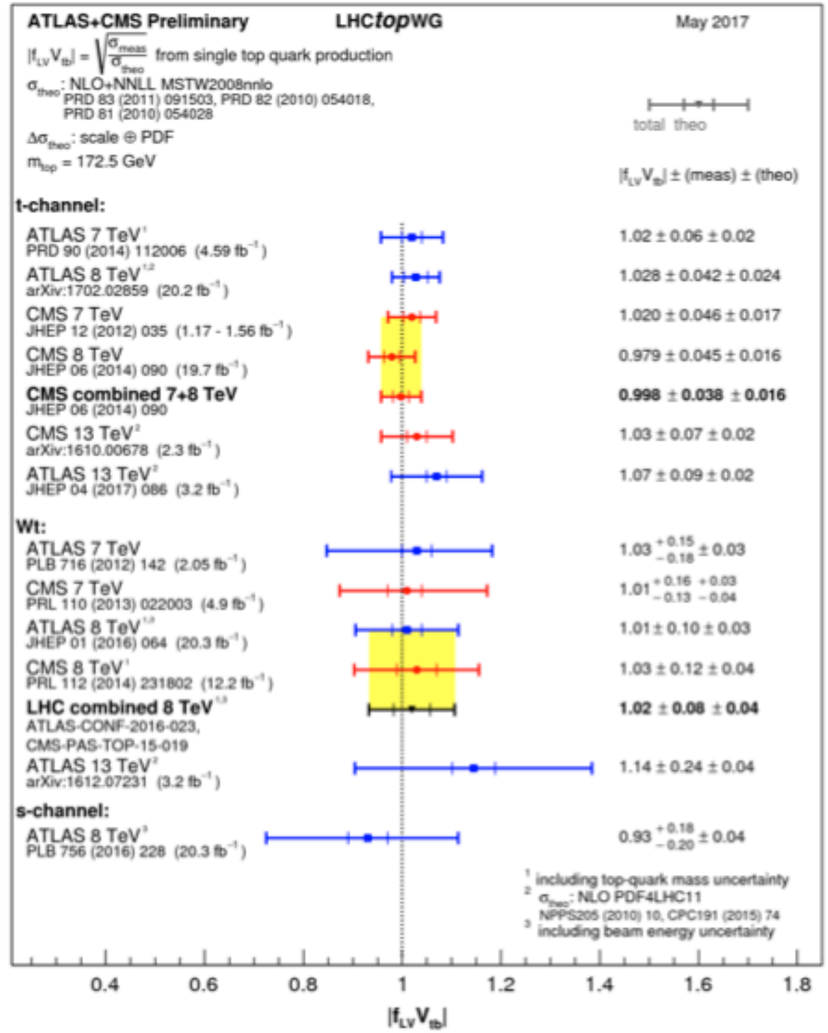
$$R_{13/8} = 3.28$$





How does a top quark decay?





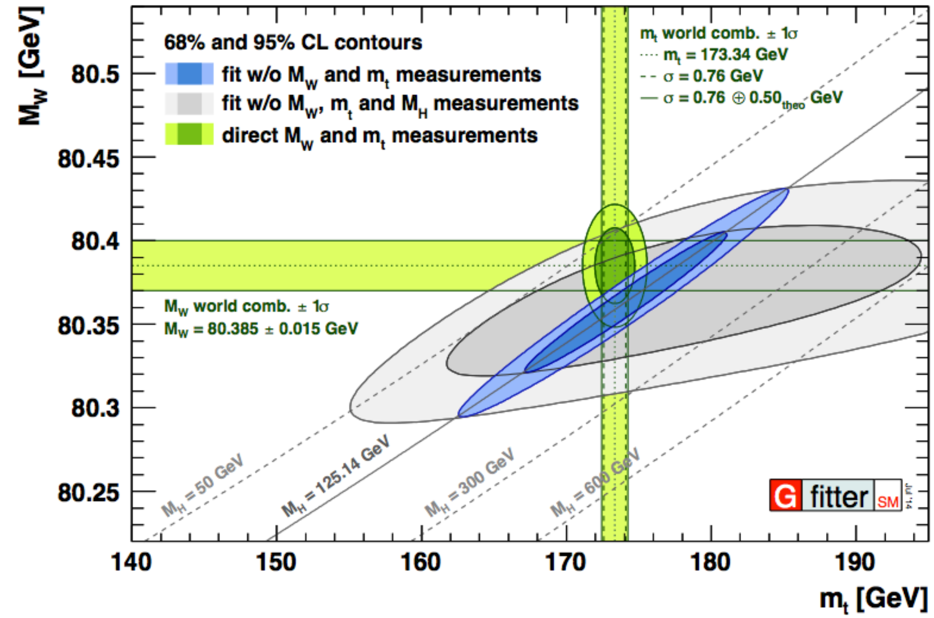
- almost always t→Wb (i.e. V_{tb}~1)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - decays W→lν (l=e,μ,τ), BR~1/9 per lepton
  - can decay W→qq, BR~2/3

Top quark mass

- Top quark mass is a fundamental parameter of the SM

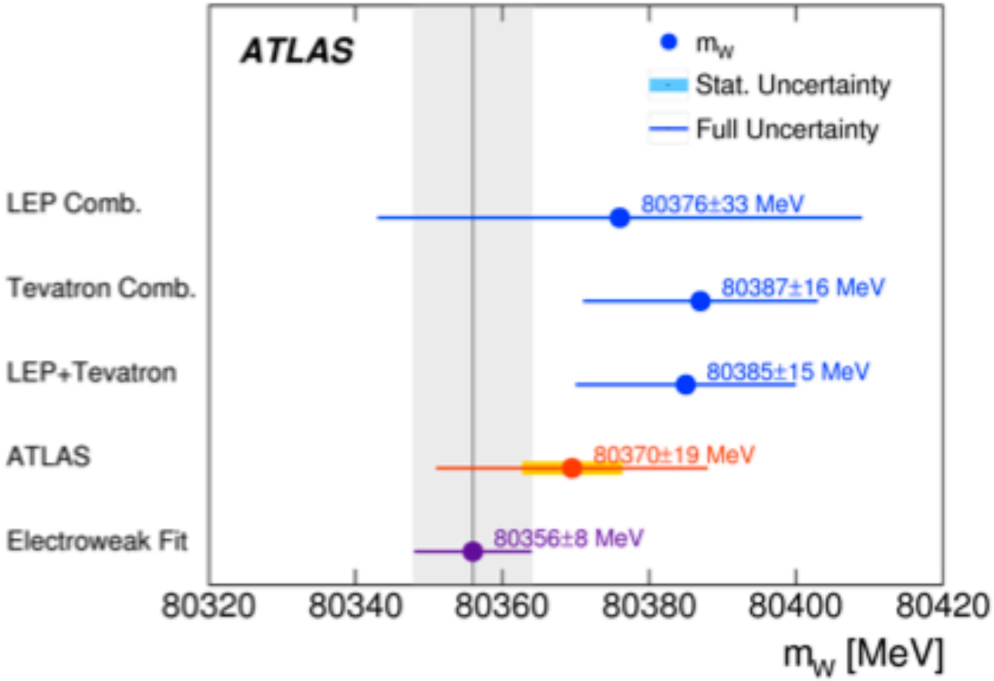
$\delta m_W \propto m_t^2$ $\delta m_W \propto \log m_h$

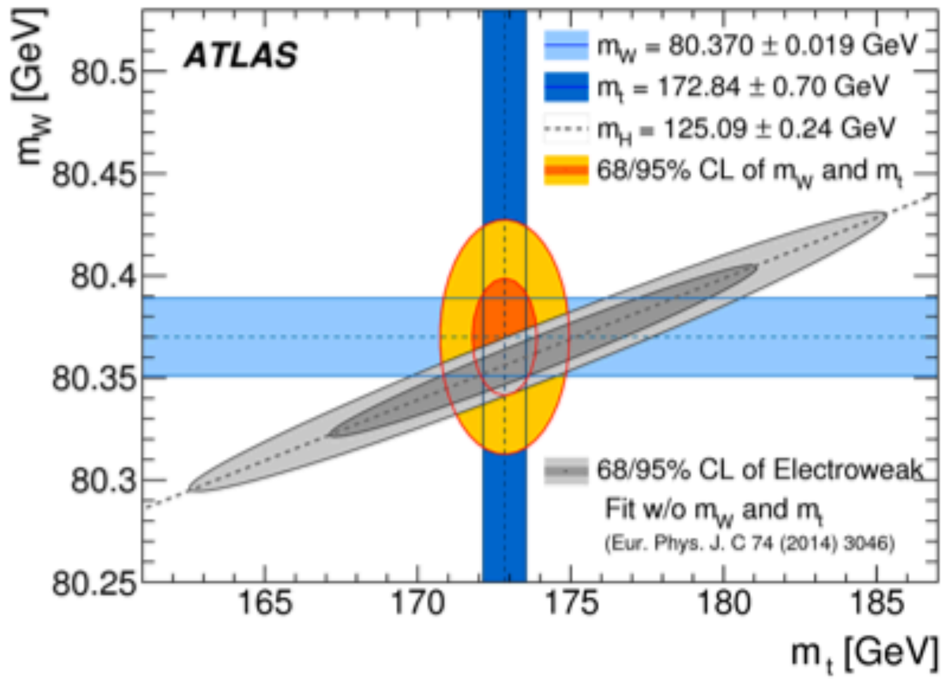
- Precise measurement needed for checking consistency of the SM



- Top is the only fermion with the mass of the order of EWSB scale
- Discovered Higgs boson fits well with precise determinations of m_W and m_{top}
- Precise measurements of m_t and m_W sensitive to presence of new particles in loop

Top quark mass



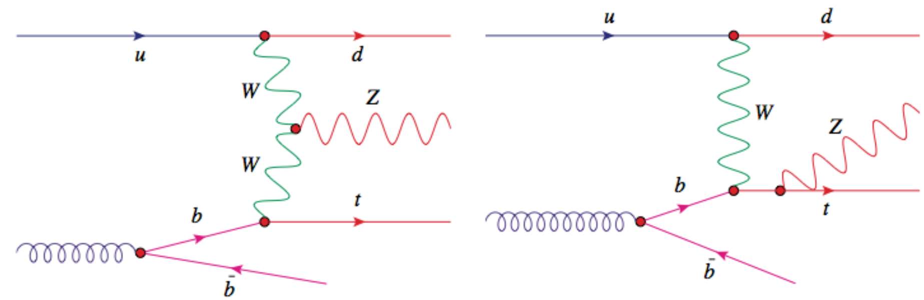


- First W mass measurement at the LHC
- Use low pileup data at 7 TeV
- Control of systematic uncertainties
- Uncertainties comparable to Tevatron results
- Expect future improvements

Rare decays: ttV (V=γ,Z,W)

arXiv:1711.02547, PLB779(2018)358, EPJC78(2018)140, CMS-TOP-17-016

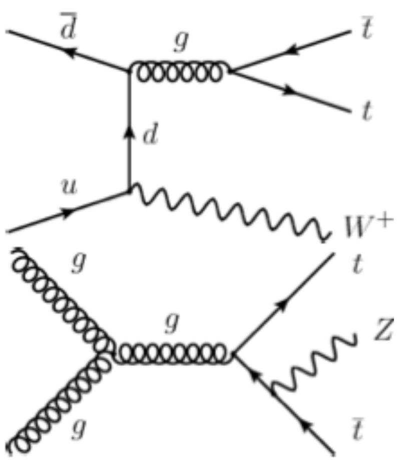
- Measurements will give access to EW couplings of the top

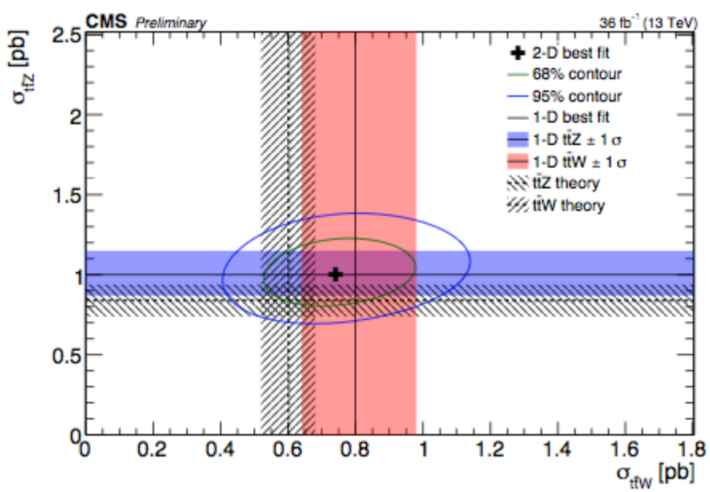


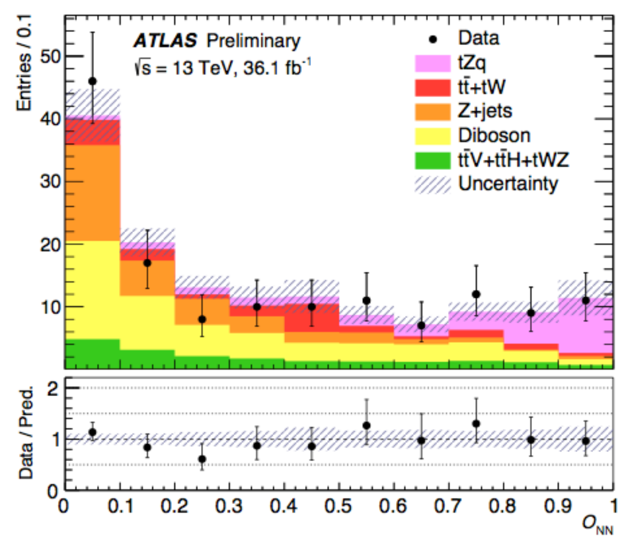
- Top+vector boson production
- tt+Z: measure ttZ coupling
- tt+W/Z: sensitive to BSM

⇒in agreement with SM

- tZq sensitive to WWZ triple gauge coupling and tZ coupling
- Multivariate technique used

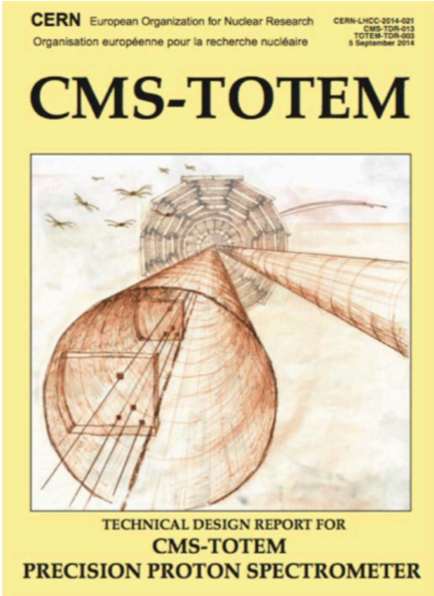




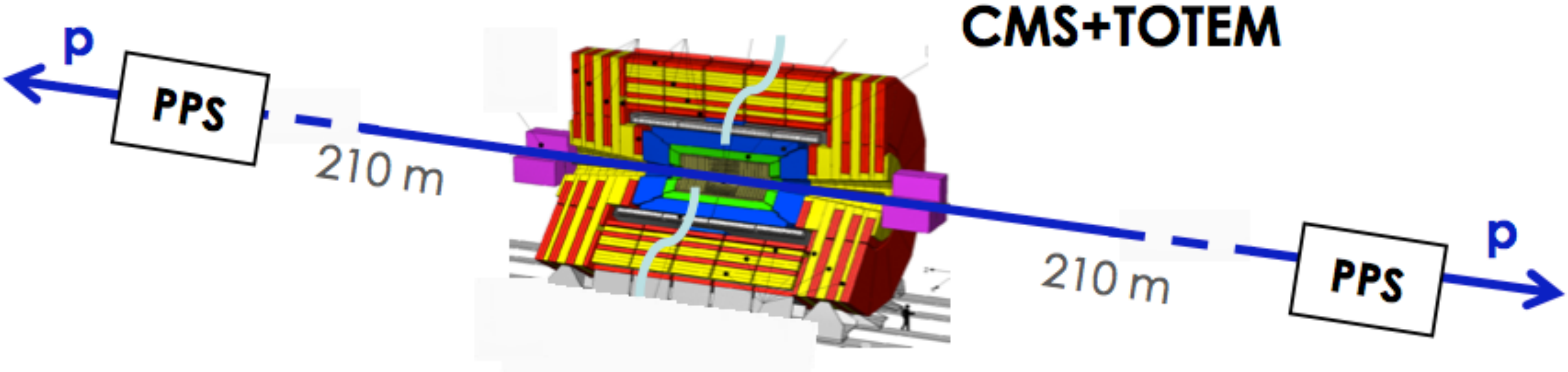


Precision Proton Spectrometer

- It is a joint CMS and TOTEM project that aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
- Tracking and timing detectors inside the beam pipe at ~210m from IP5
- Ability to operate the detectors close to beam (15-20σ, i.e. ~1-3 mm), sustain high radiation levels

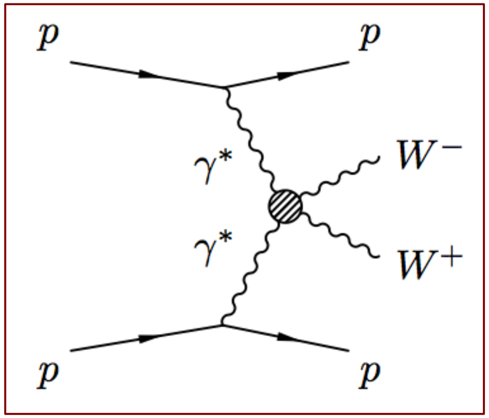


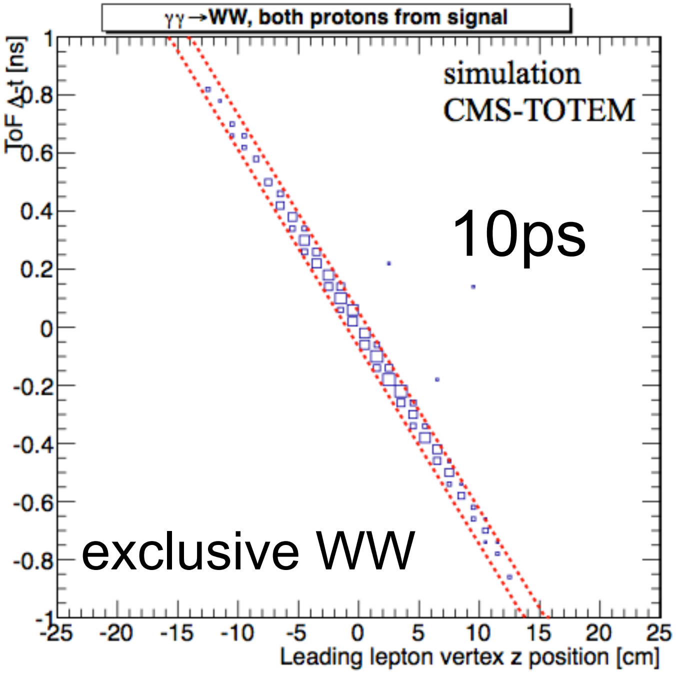
CERN-LHC-2014-021

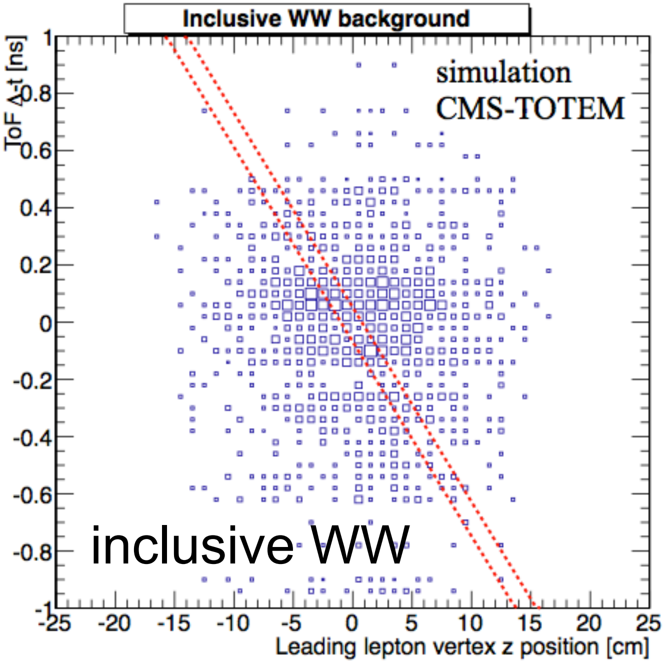


Anomalous couplings

- Study quartic gauge couplings
- Allowed in SM via charged triple+quartic gauge couplings
- Sensitive to BSM contributions in high-mass tails
- Deviations from SM can be large

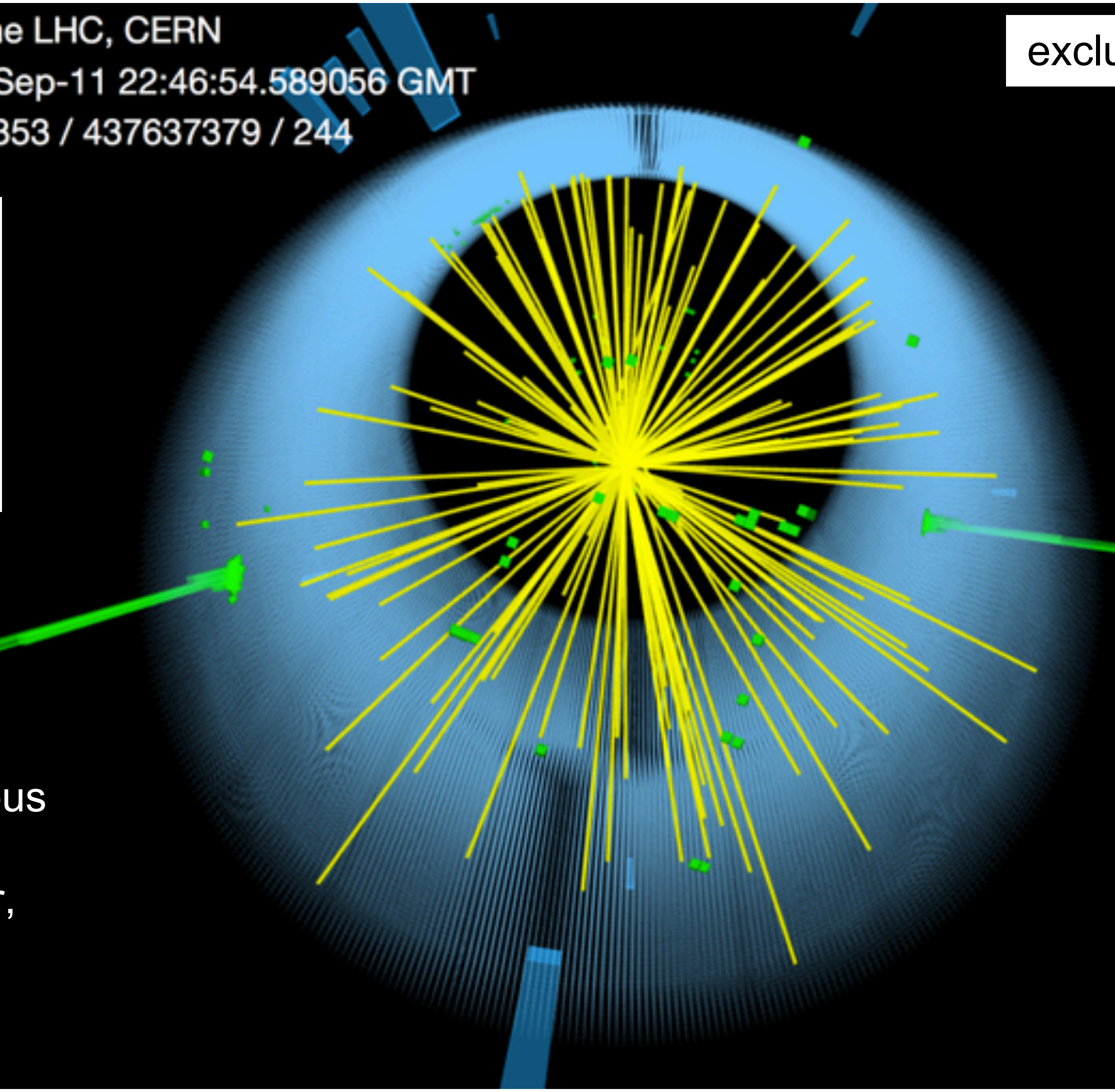




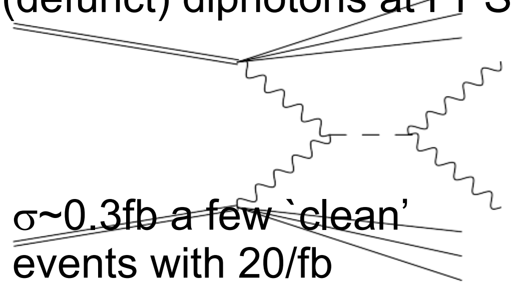


- Leptonic channels cleanest, but neutrinos prevent clear mass/rapidity matching
- time difference of two protons correlated with vertex position

BSM searches: resonances, etc.

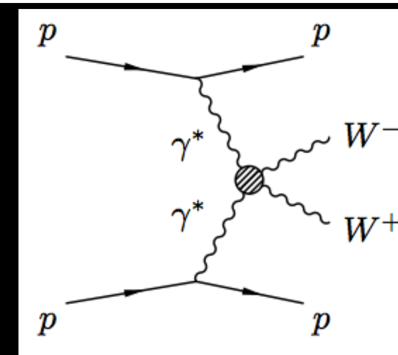


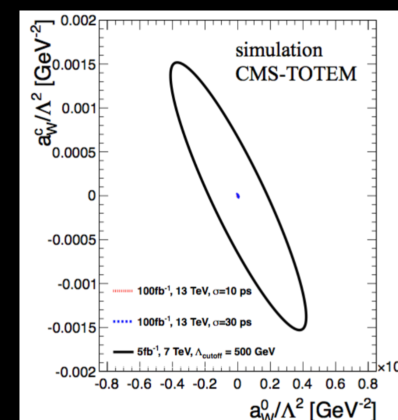
(defunct) diphotons at PPS



σ~0.3fb a few `clean' events with 20/fb

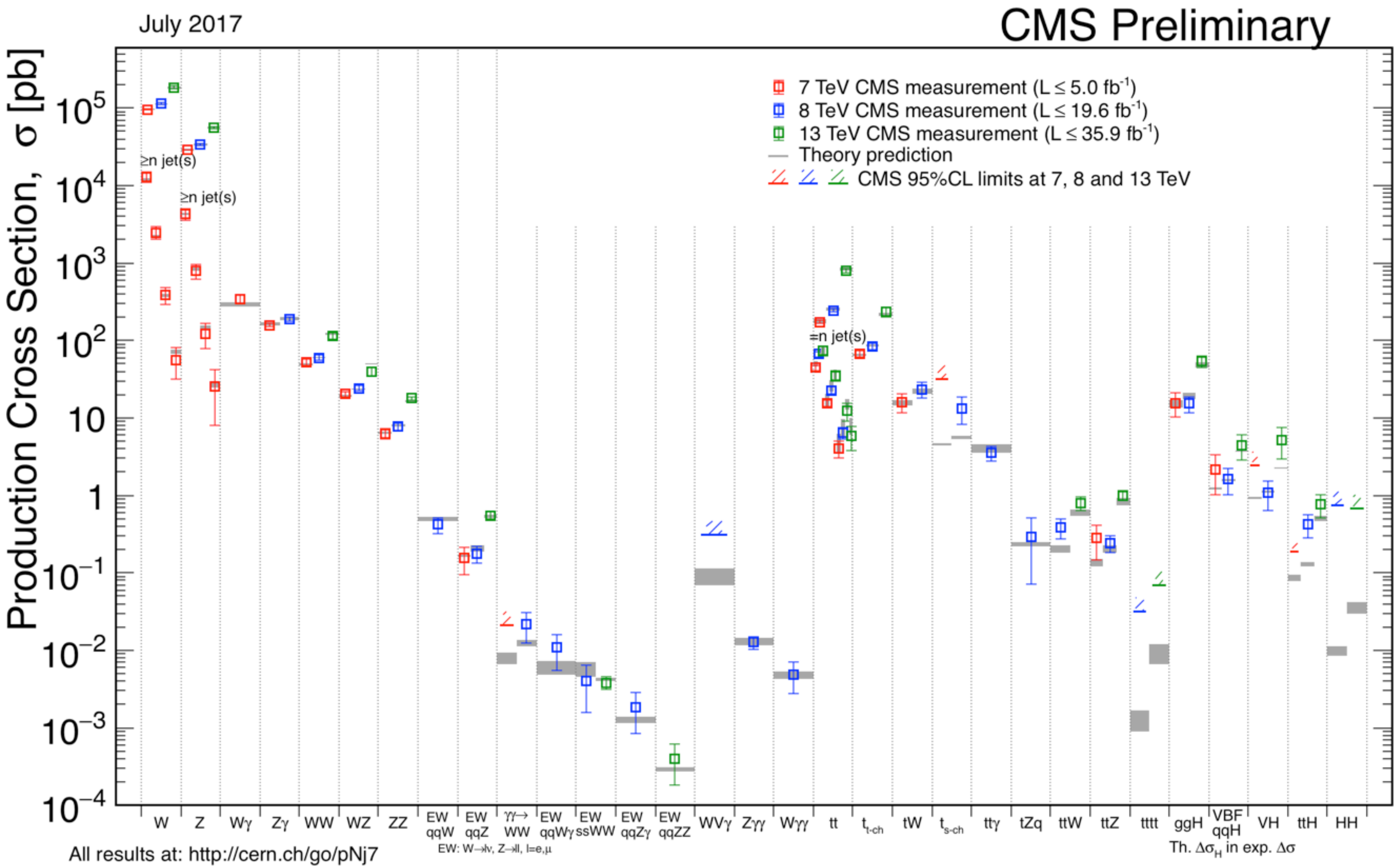
exclusive WW production





Composite Higgs, anomalous gauge-Higgs couplings, excited leptons, technicolor, extra dimensions, axions, heavy exotic states, dark matter candidates, …?

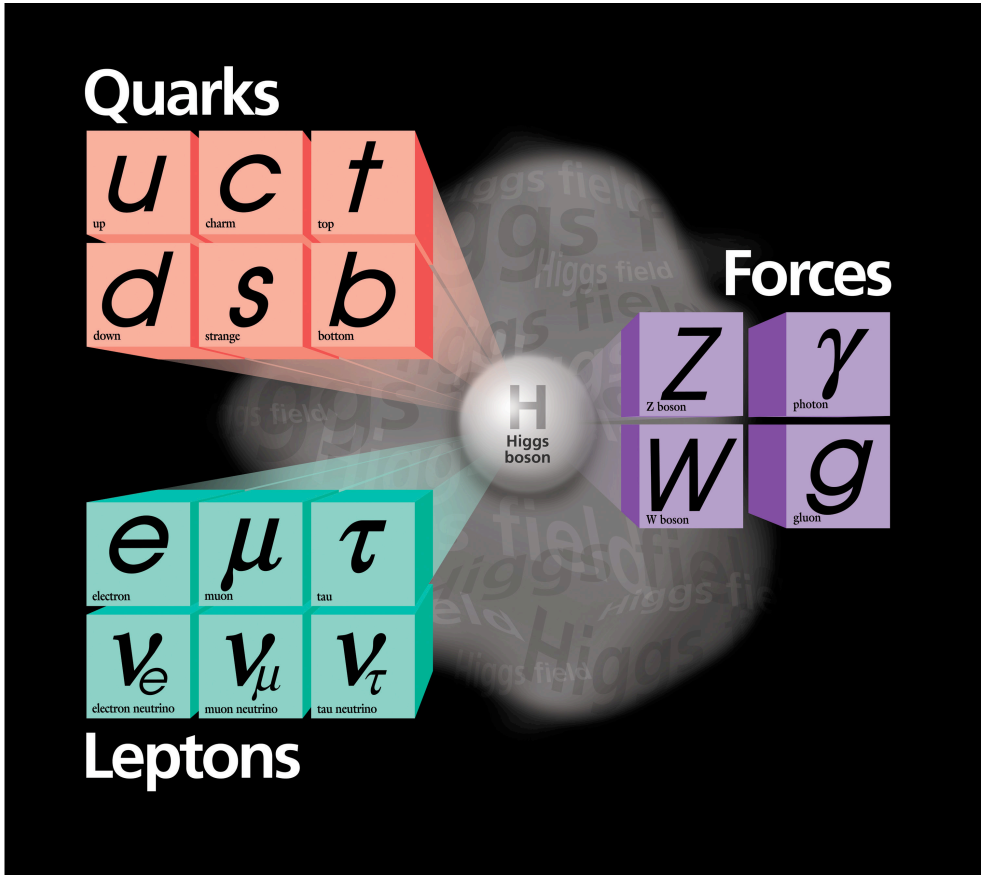
SM measurements



…each one of these measurements (or searches) is a thesis topic!

Standard Model theory of everything?

- Discovery of the Higgs boson marks the triumph of the SM
- However, even with the inclusion of the Higgs boson, SM is an incomplete theory



Beyond the Standard Model

The SM answers many of the questions about the structure of matter. But SM is not complete; still many unanswered questions:

a) Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

b) What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

c) Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

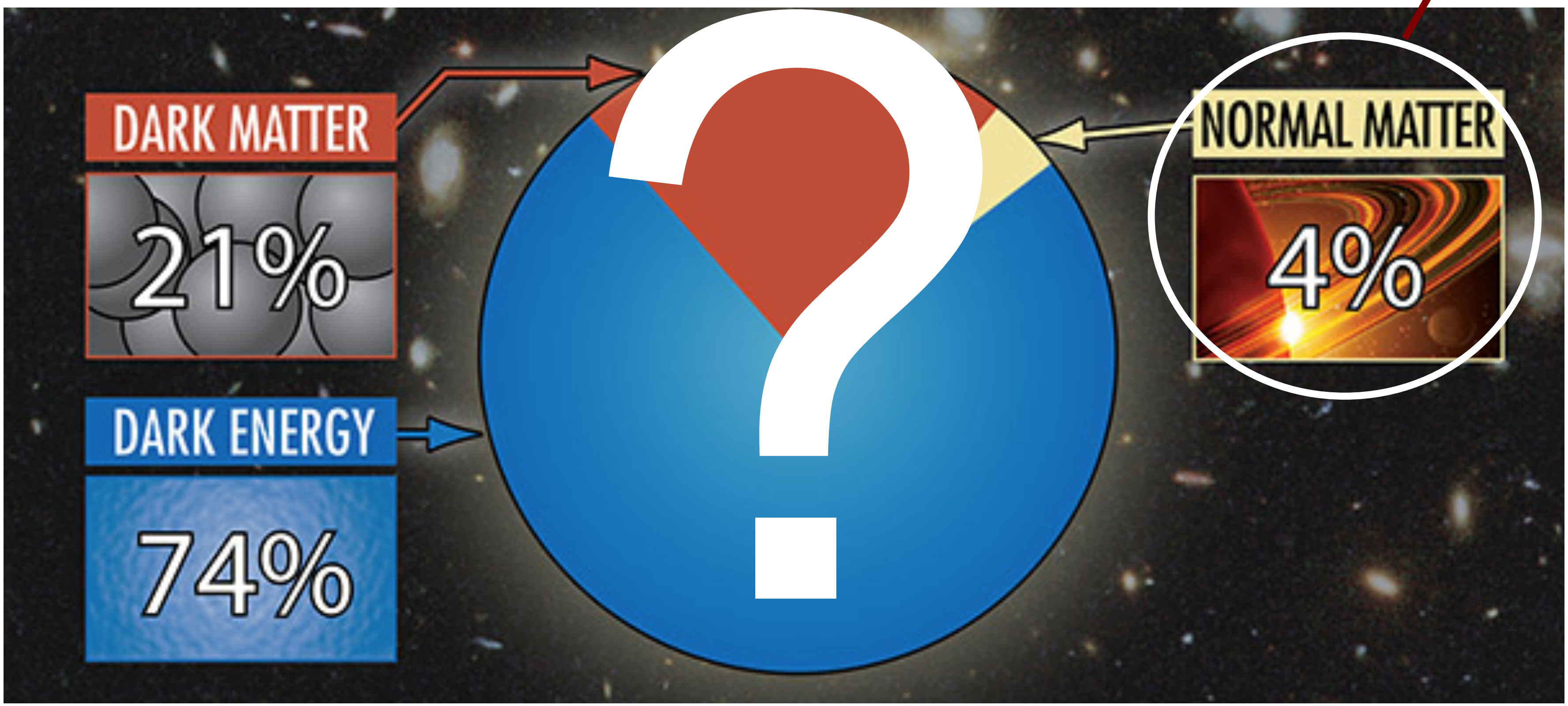
d) Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

e) How does gravity fit into all of this?

Not only SM: we need ideas!

- What is that accounts for 96% of the Universe?
  It is one of the greatest mysteries of Science

~SM



Summary

- LHC at the energy/intensity frontier
- Probing the SM with a full spectrum of measurements
- Many studies performed with data collected so far
- Excellent consistency but SM is incomplete

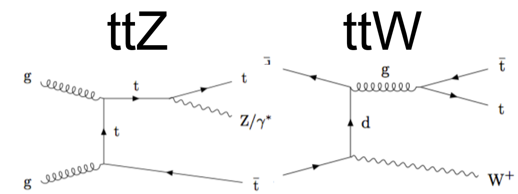
- A surprise can appear at any time

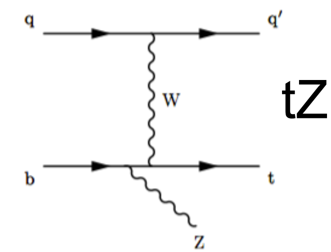
backup

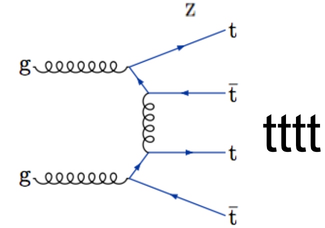
Top quarks and rare decays

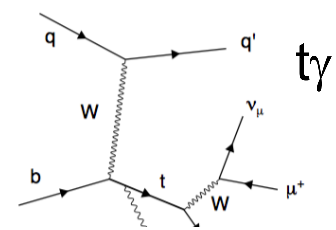
arXiv:1711.02547, PLB779(2018)358, EPJC78(2018)140, CMS-TOP-17-016

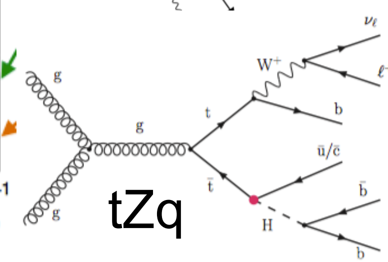
- Heaviest fundamental particle
- Study naked quark, decays before hadronization
- Strongly interacting with EWK sector and Higgs
- Anomalous couplings: Wtb vertex may include BSM terms

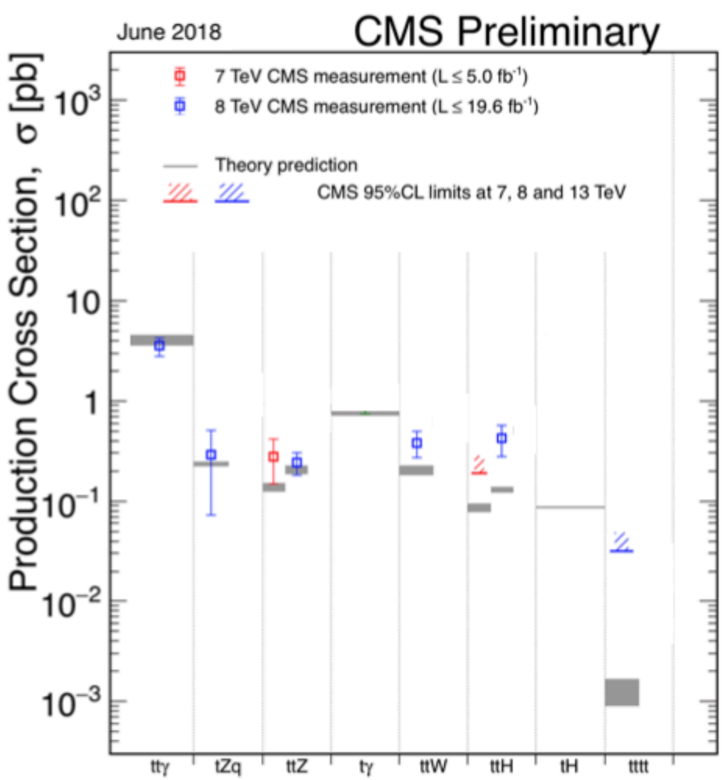


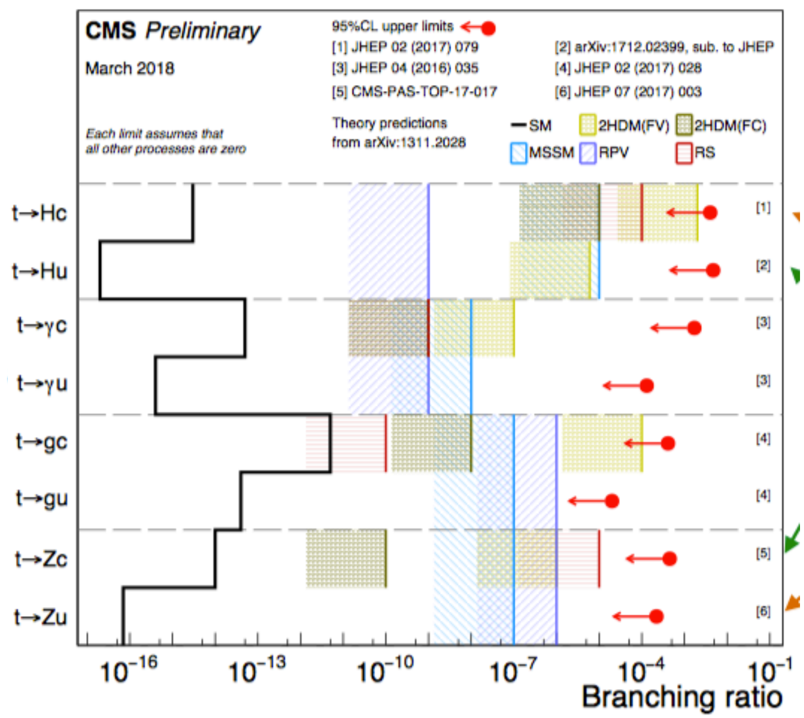




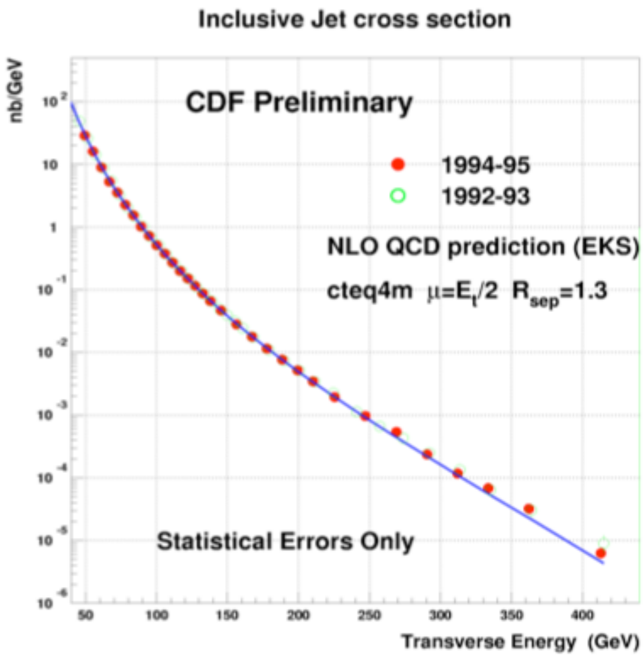




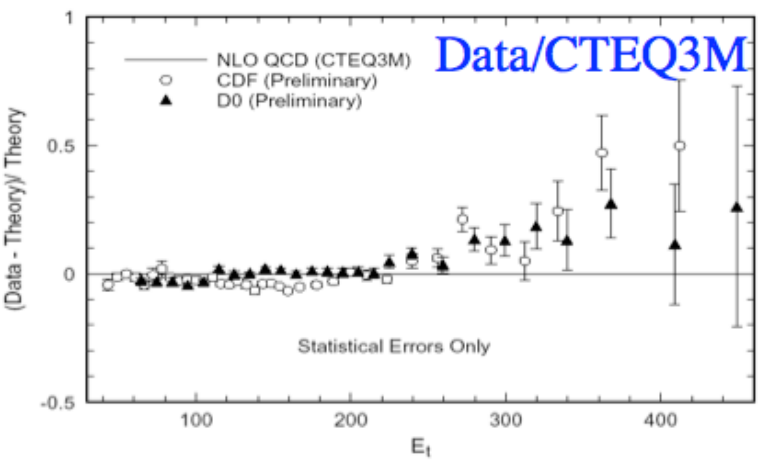


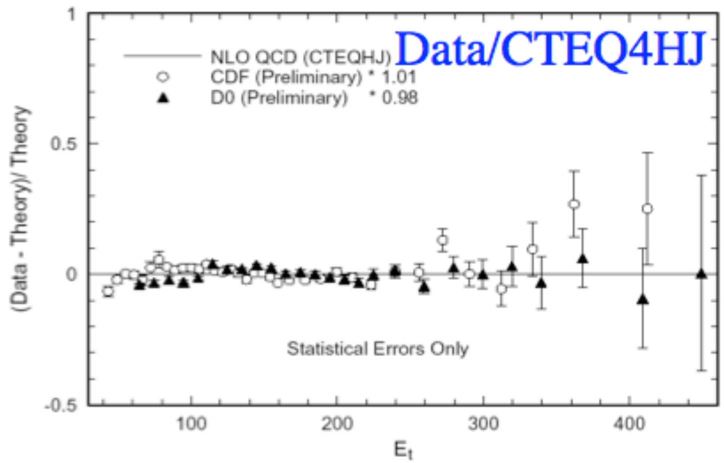


Jet cross section & PDFs: an example



- At Tevatron Run1
  - Jet cross section excess at high jet pT due to Parton Density Function…
  - Gluon density is uncertain at high x
  - Data agree well after including new PDFs



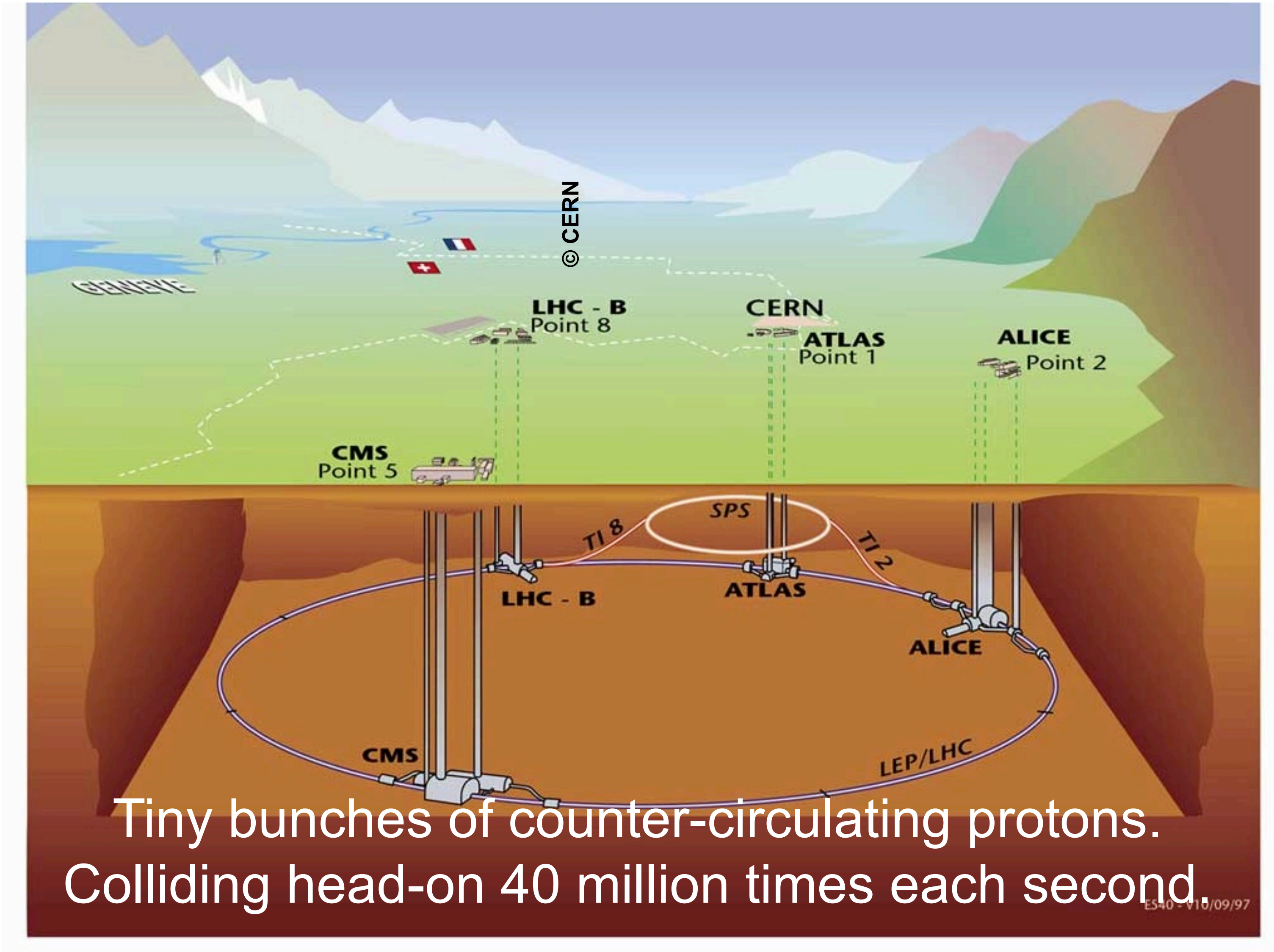


The standard model at the LHC

- Hadron interactions
- Monte Carlo generators
- Luminosity and cross section measurements
- Minimum bias events
- Jet physics
- W and Z physics

CERN and the LHC

Accelerator and experiment layout



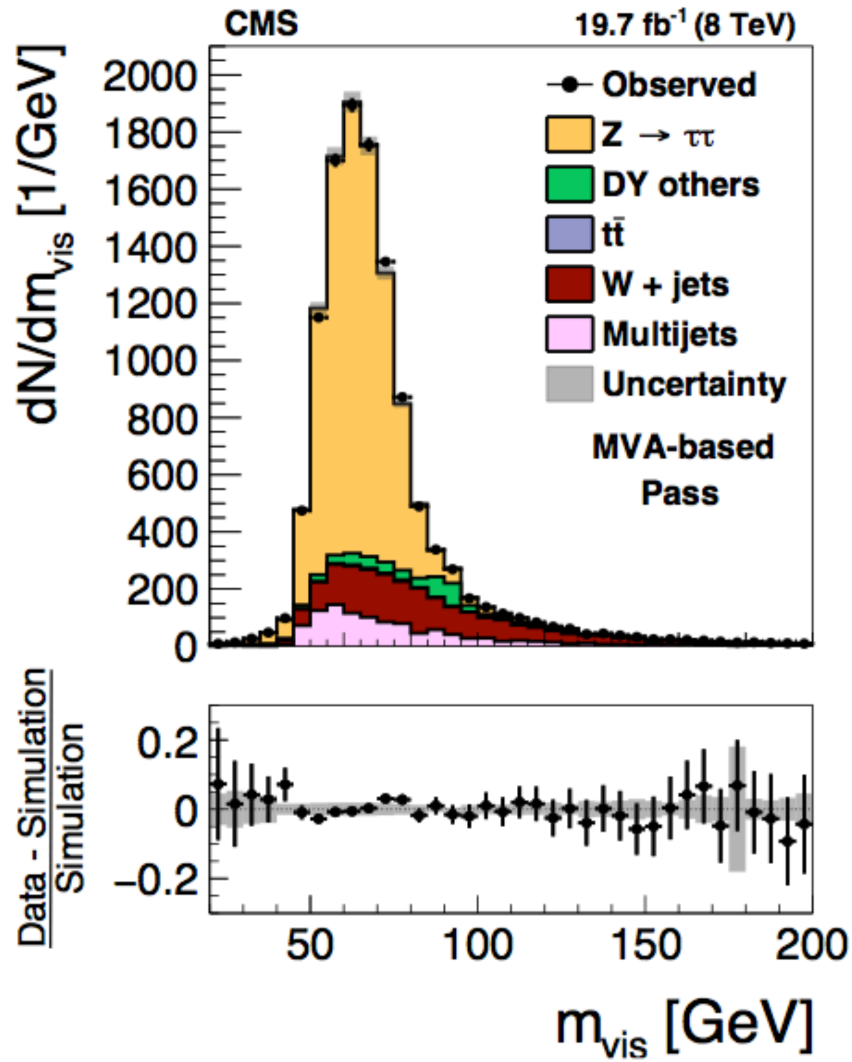
Tiny bunches of counter-circulating protons.
Colliding head-on 40 million times each second.

Trigger computer farm

W/Z production (cont.)

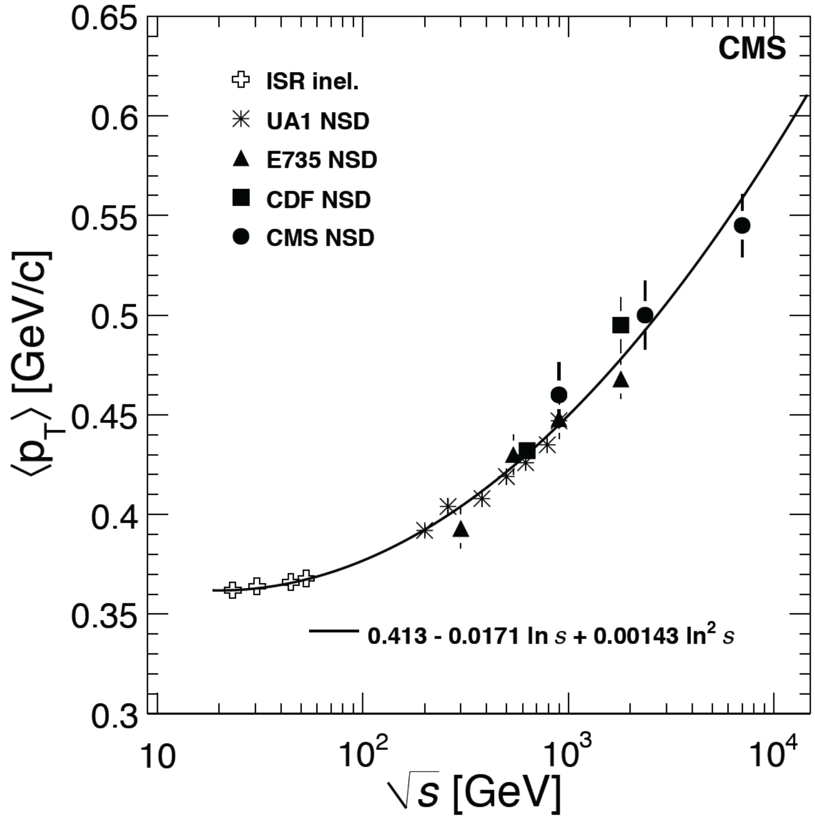
arXiv:1402.0923, arXiv:1510.07488

- Select isolated electrons and muons, and taus
- W: investigate transverse mass m_T
- Z: dilepton invariant mass

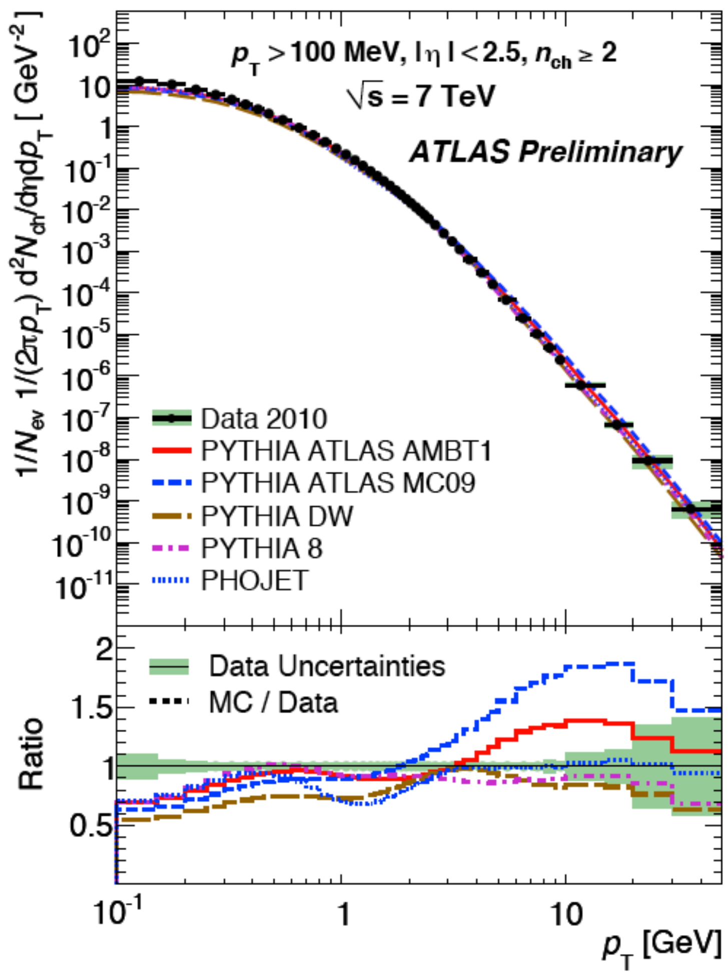


Charged particle p_T spectrum

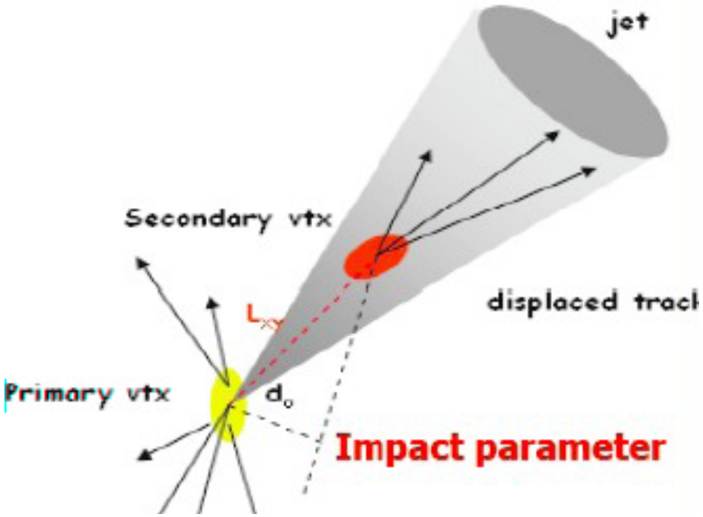
$<p_T>=0.545\pm0.005(\text{stat.})\pm 0.015$ (syst.) GeV



dN_{ch}/dp_T

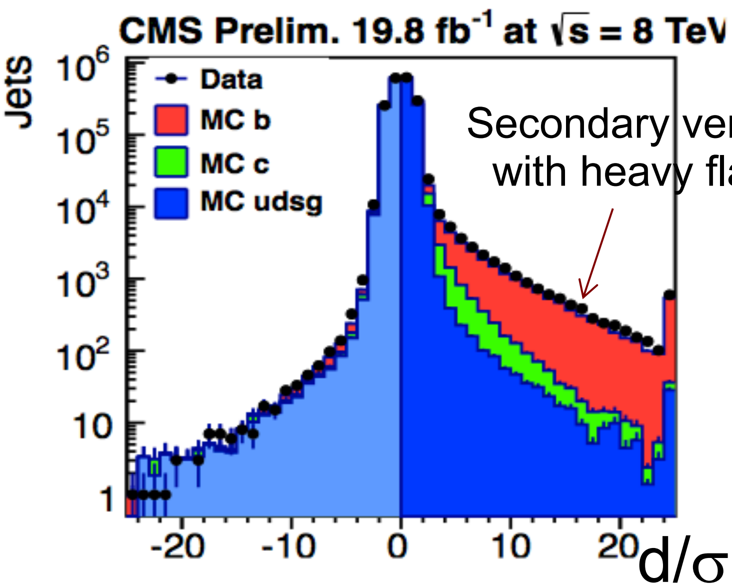


Tracking



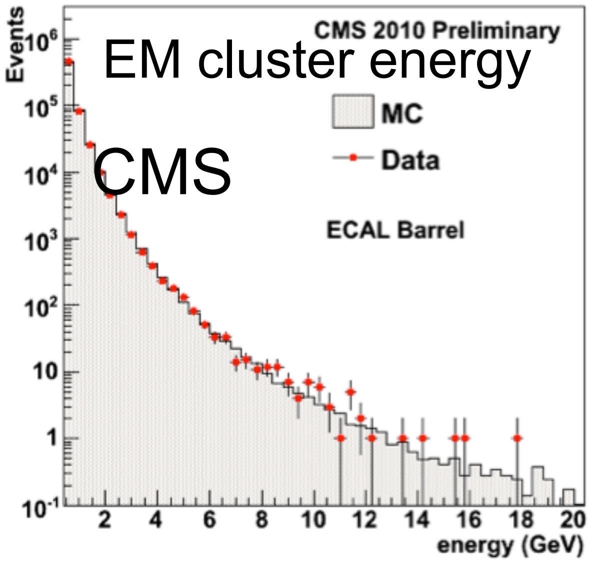
- Variables relevant for b-tagging
- Lifetime: τ_b~1-2 psec
- Reduction of backgrounds
- Secondary vertex tagging

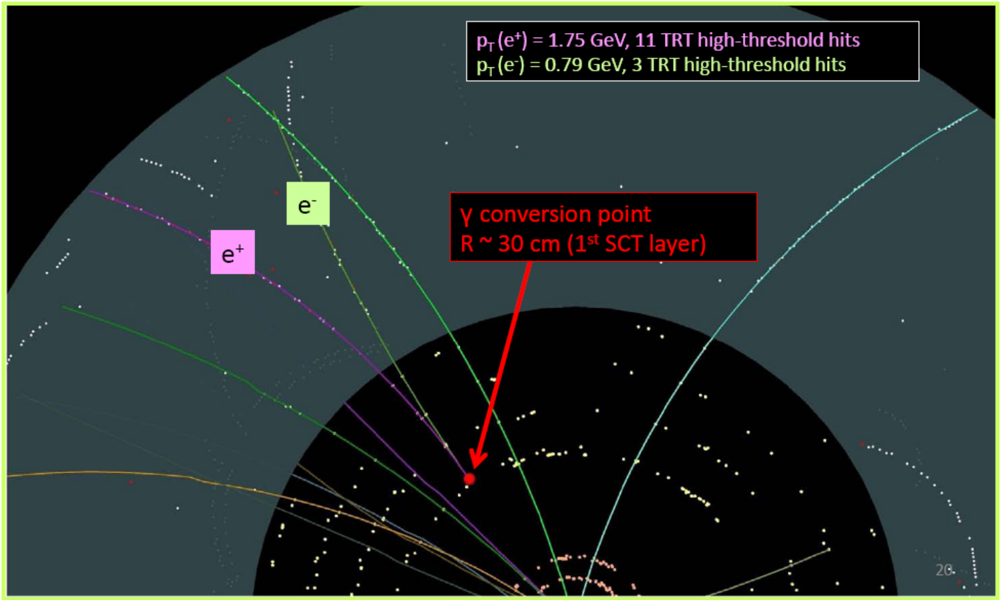
$$(b \rightarrow l\, \nu_l\, X)$$

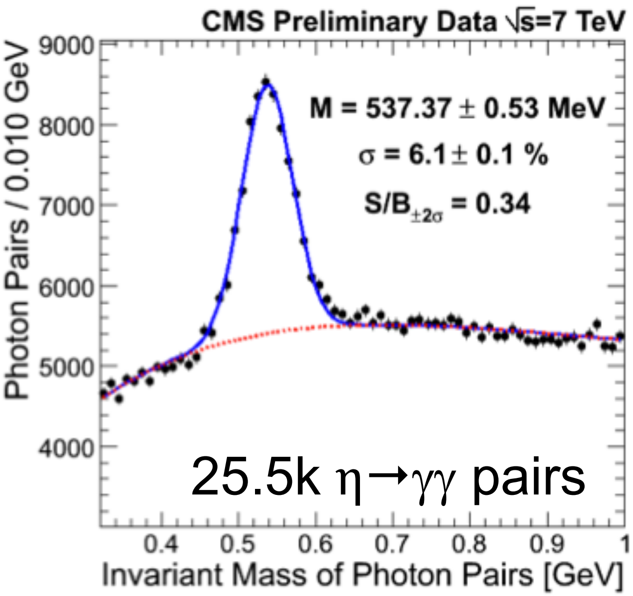


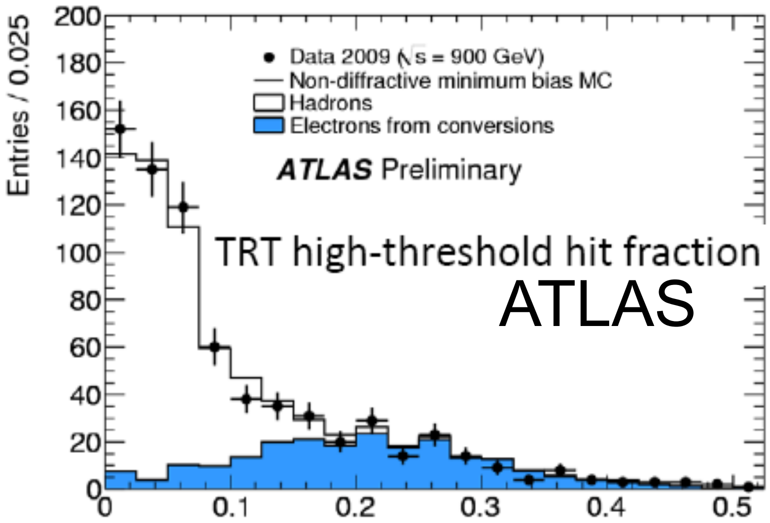
Secondary vertices compatible with heavy flavor production

Photons and electrons

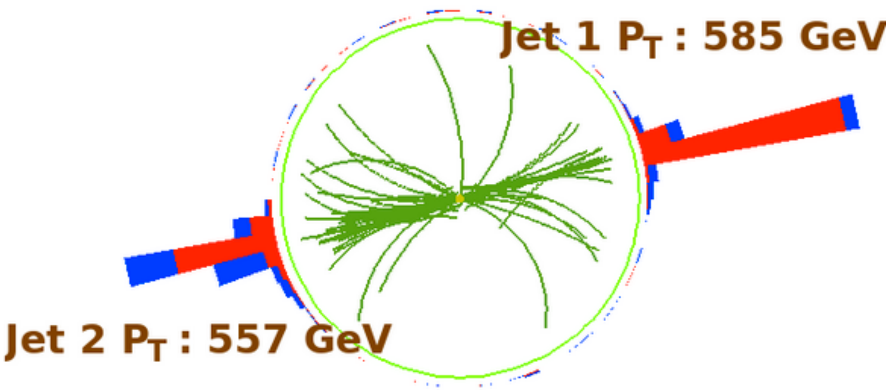


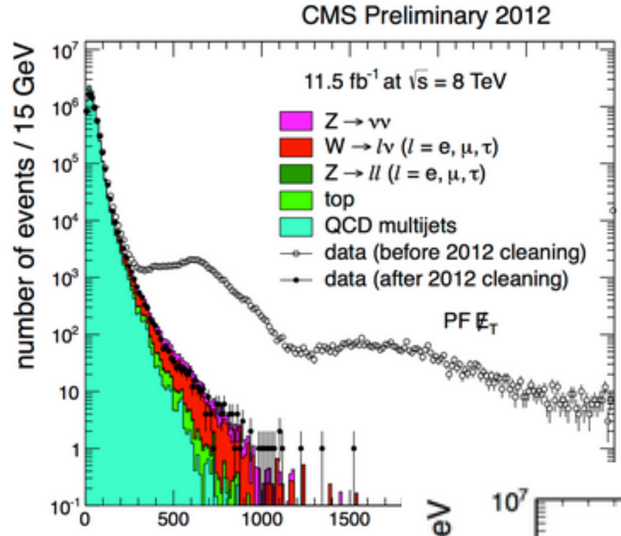


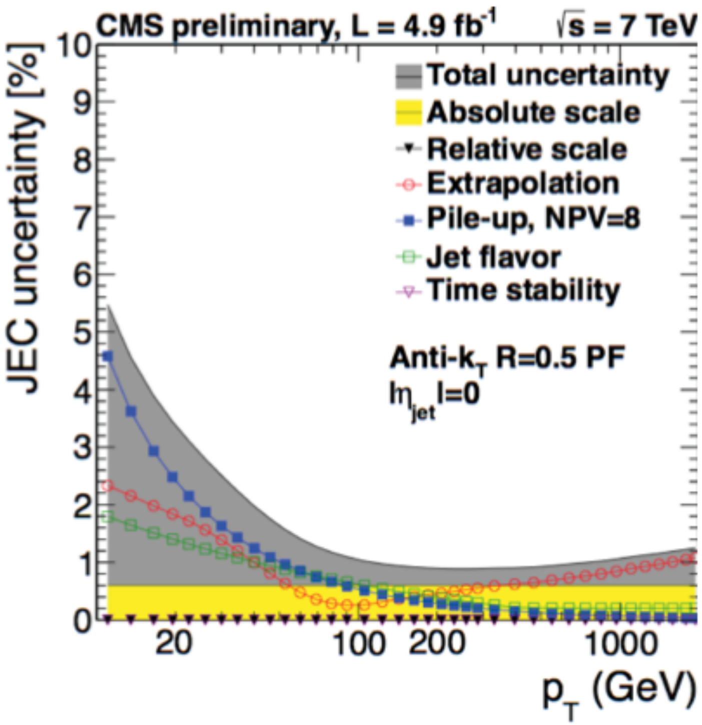


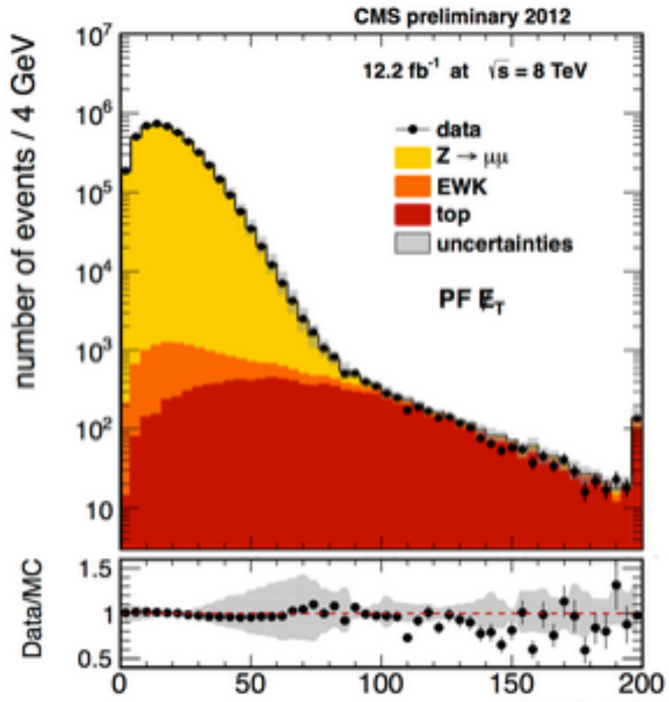


Jets and missing transverse energy



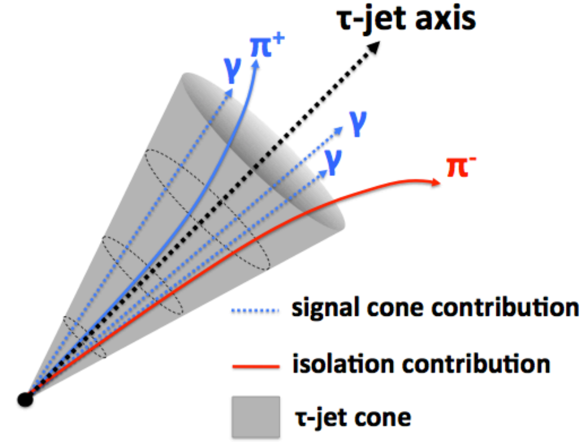


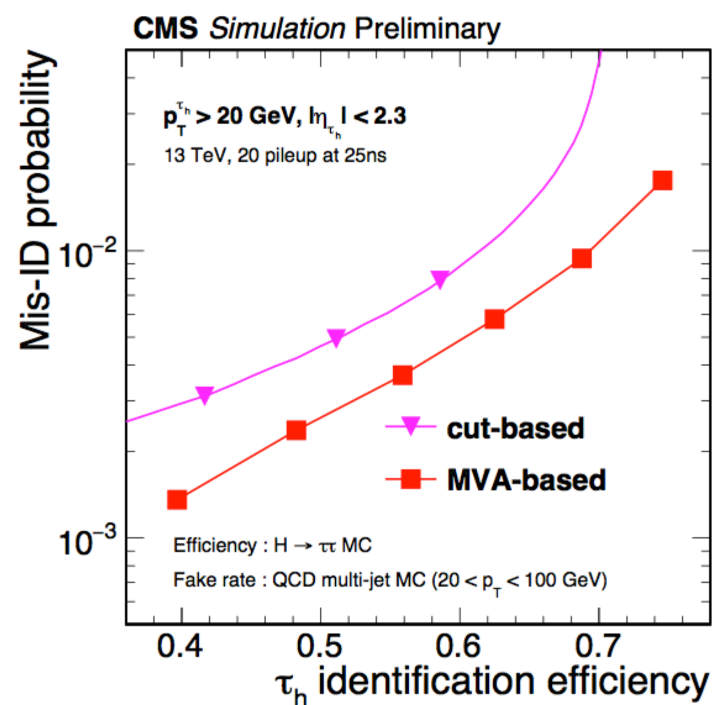




Tau jet identification

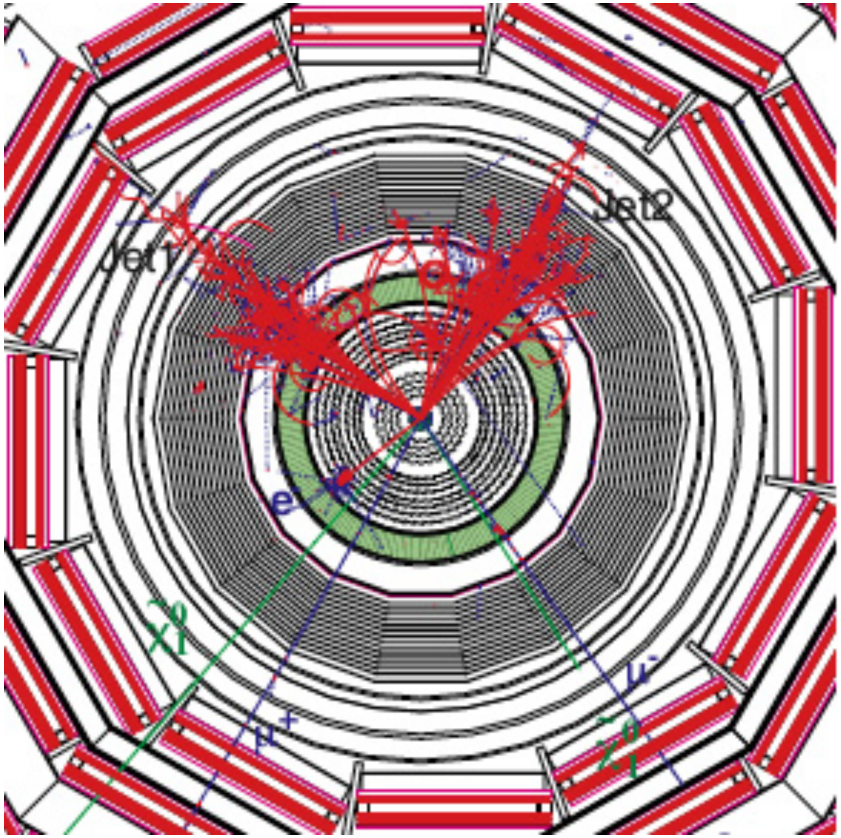
- Taus decay 65% to hadrons (i.e. jets) and 35% to leptons
  - narrow jet with few tracks
  - leptonic tau decays are similar to prompt leptons (lepton p_T is softer, 3-body decay)
- Hadronic tau decays
  - Main background from jets/electrons
  - Identified based on decay modes, charged hadrons, and ECAL deposits
- CMS: ``Hadron Plus Strips'' (HPS) algorithm
  - hadronic tau decays are reconstructed with Particle Flow (PF)
  - Uses photon conversion in tracker ($\gamma \to e^+e^-$)
  - Combines PF EM particles (γ,$e^{\pm}$) in "strips"
  - "strips" are combined with PF charged hadrons
  - Individual decay modes are reconstructed
- Fake Rate ~1% for 70% efficiency

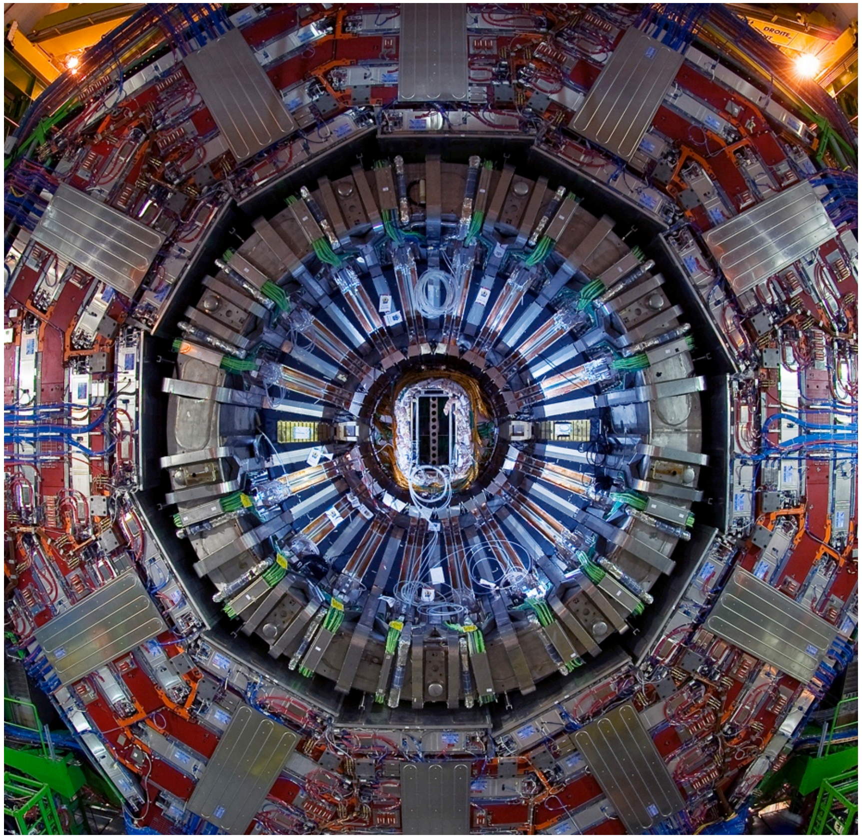


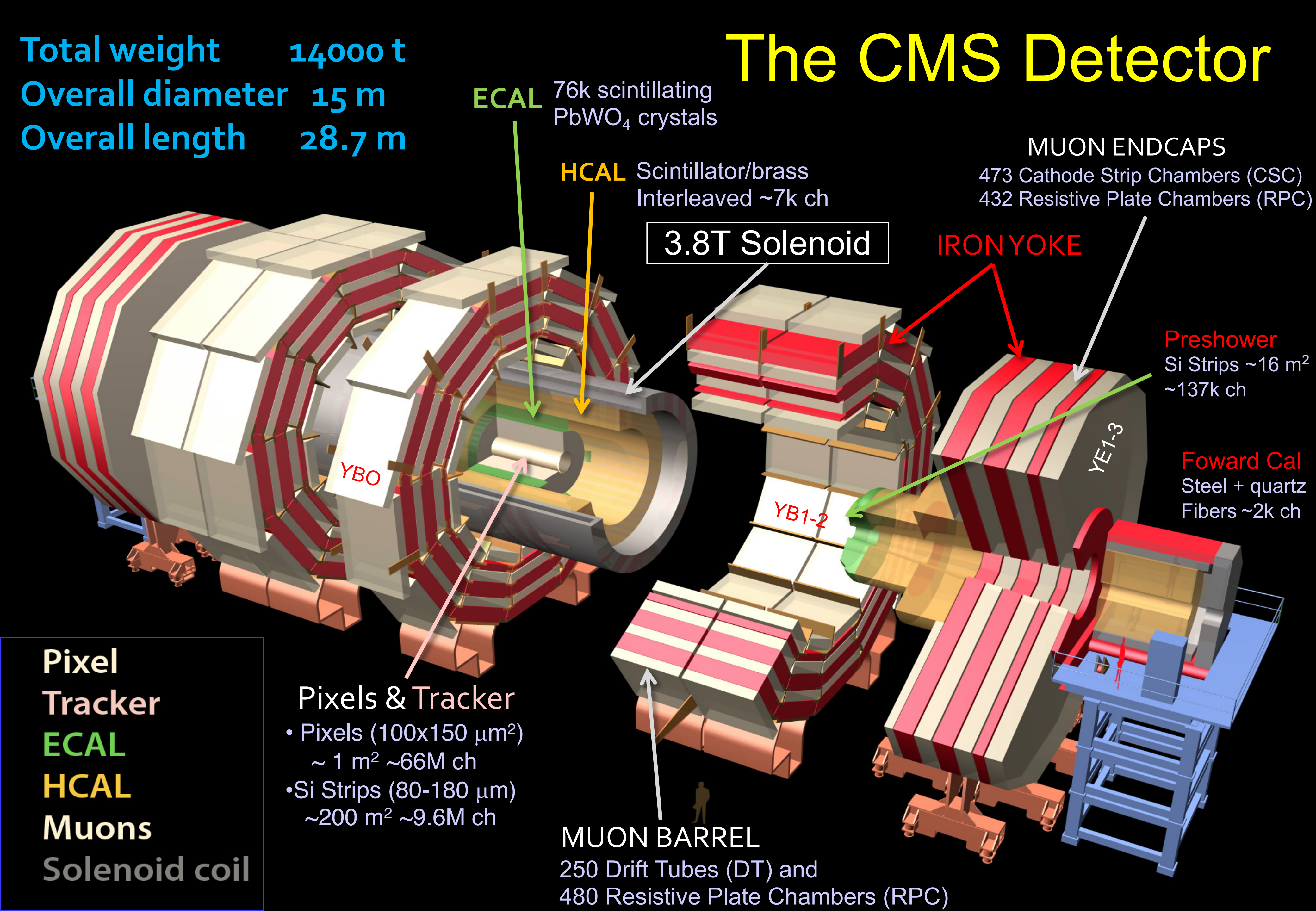


How do we prepare for discoveries?

Simulation of proton-proton collision
making two dark matter particles






The CMS Detector
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
ECAL
76k scintillating
$PbWO_4$ crystals
HCAL
Scintillator/brass
Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m^2
~137k ch
Foward Cal
Steel + quartz
Fibers ~2k ch
YBO
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

Probing the Standard Model at LHC

Michele Gallinaro

LIP Lisbon

July 18, 2017

- ✓ Accelerator, experiments, commissioning
- ✓ Hadron interactions
- ✓ Minimum bias events
- ✓ Jet production
- ✓ W and Z bosons, top quark

Probing the Standard Model at the LHC

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July 18, 2

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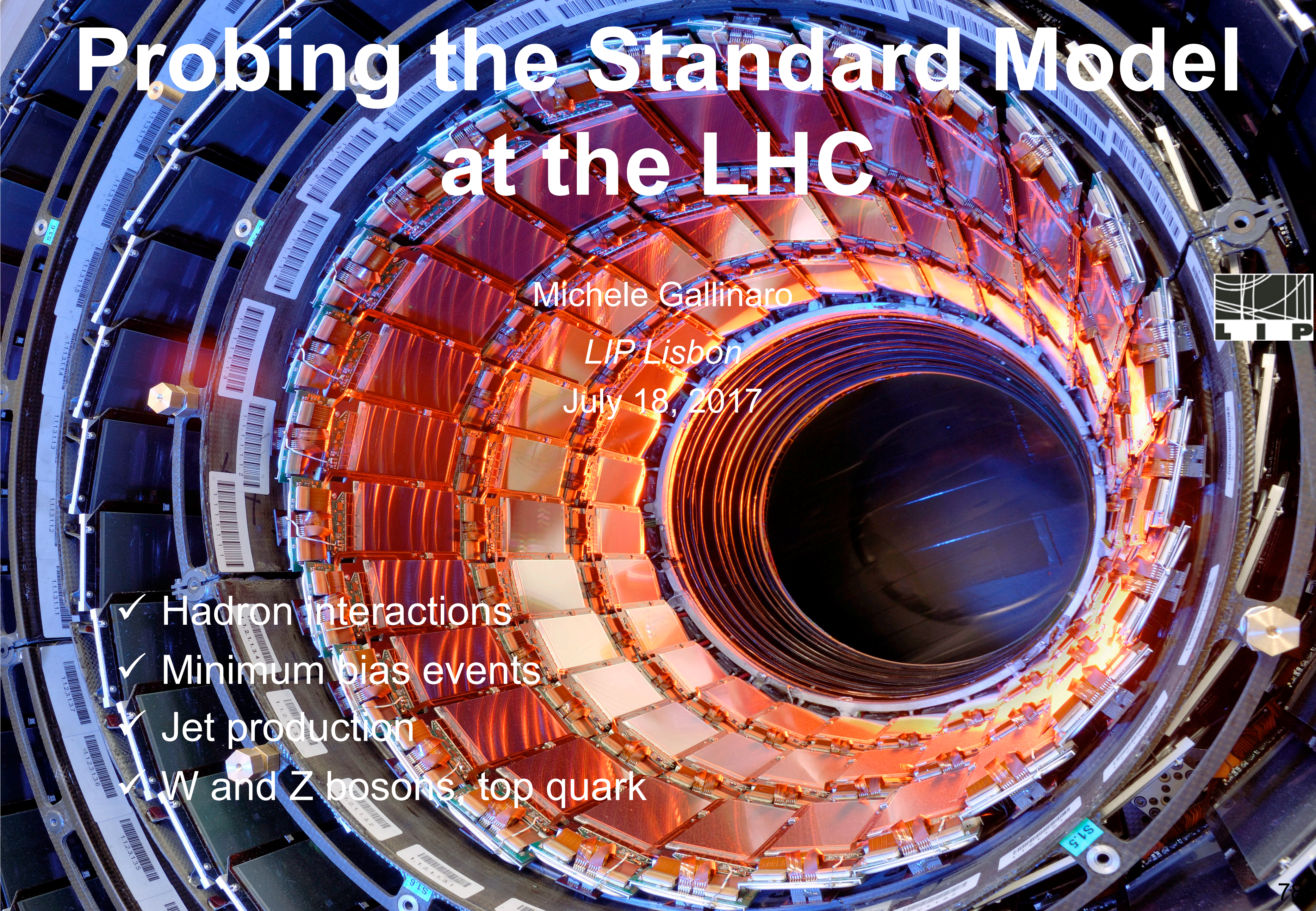

Probing the Standard Model at the LHC

Michele Gallinaro

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July 18, 2017

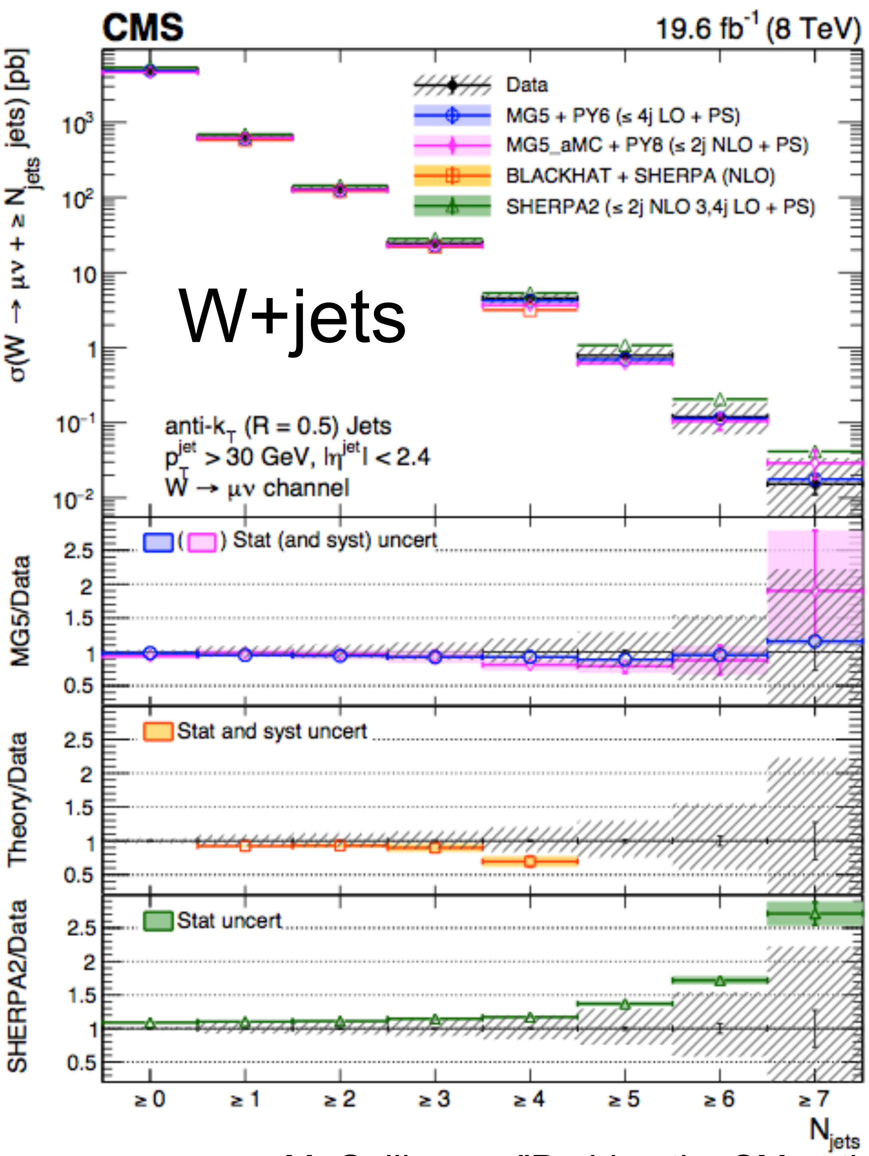
- ✓ Hadron interactions
- ✓ Minimum bias events
- ✓ Jet production
- ✓ W and Z bosons, top quark

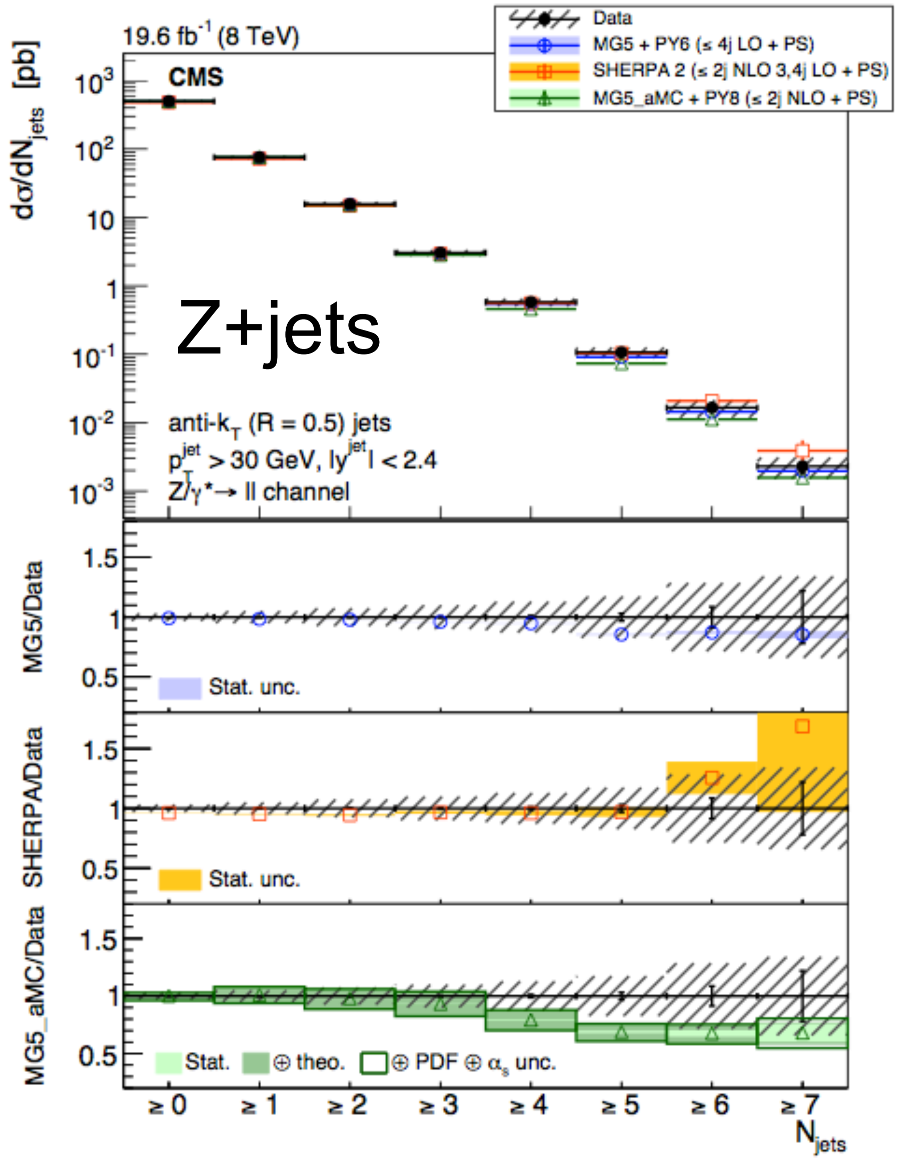
Summary

- Rediscover the SM to gain control of the measurements
- Probe the SM to test hints of New Physics
- So far, no hints for New Physics in the data…
- 13 TeV data will tell more

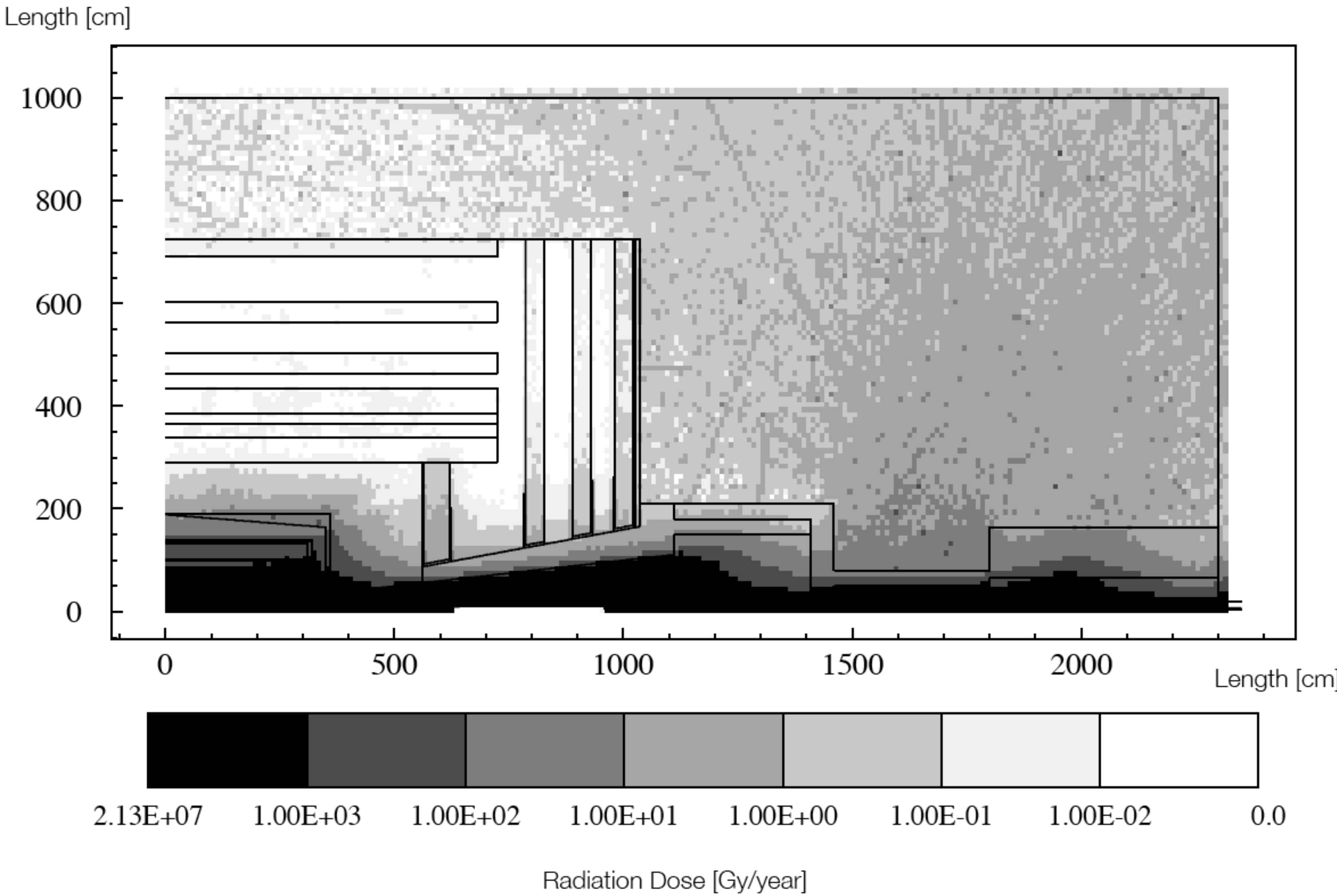
W/Z+jets

arXiv:1610.04222, arXiv:1611.03844

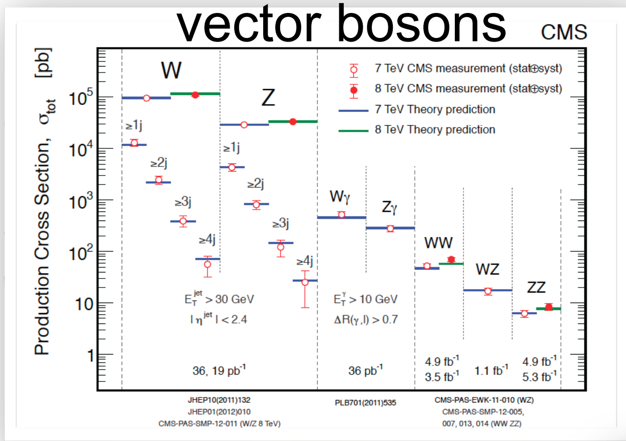


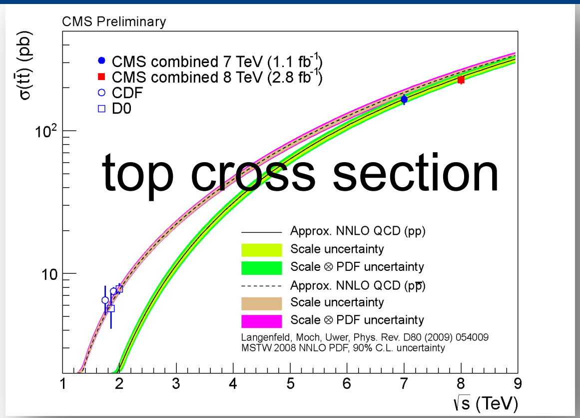


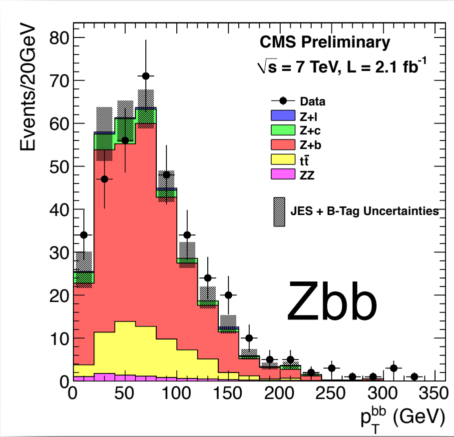
High radiation levels

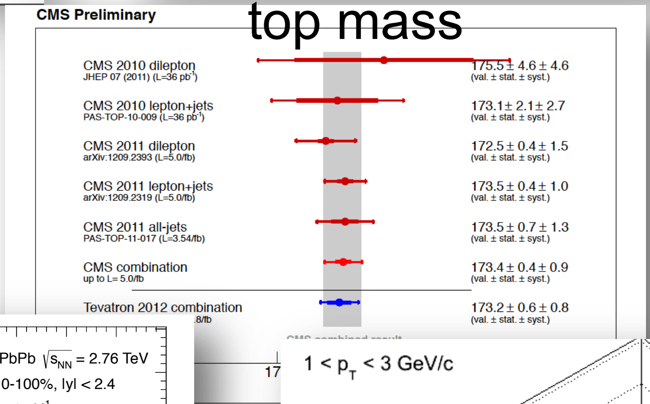


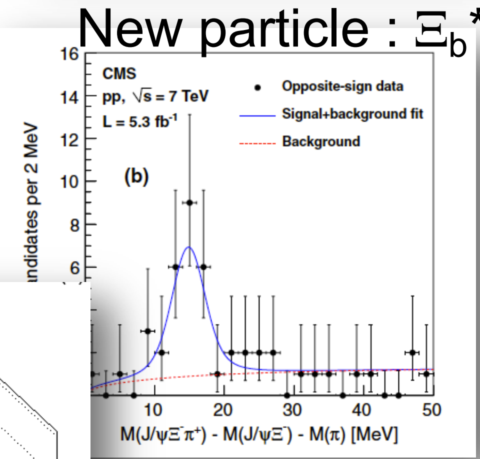
...and more physics results

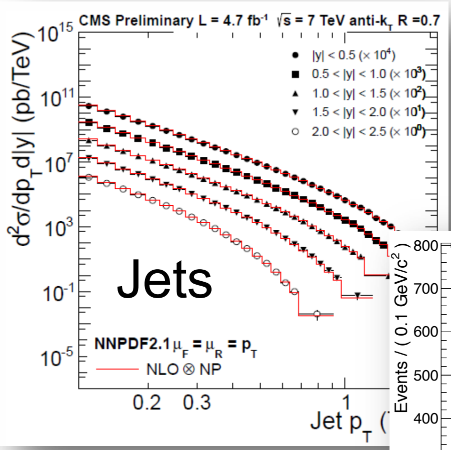


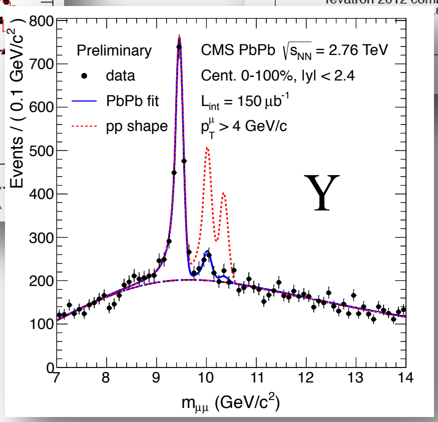


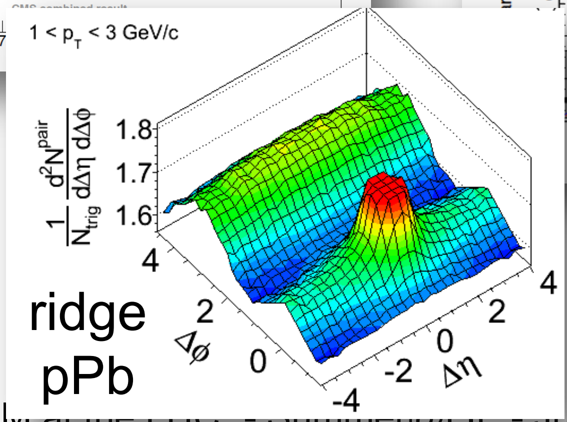












More than 1000 papers from LHC

Luminosity determination

Absolute:

accuracy: ~10%

- From LHC parameters: van-der-Meer scans, standard candles:
  - $pp \to Z/W \to ll/l\nu$ (needs cross section)

    accuracy: ~5-10%
  - $pp \to \gamma\gamma \to \mu\mu/ee$

    accuracy: ~1%?
  - Optical theorem: σ_{tot} (needs fwd det.)

    accuracy: ~2-3%
  - Elastic scattering

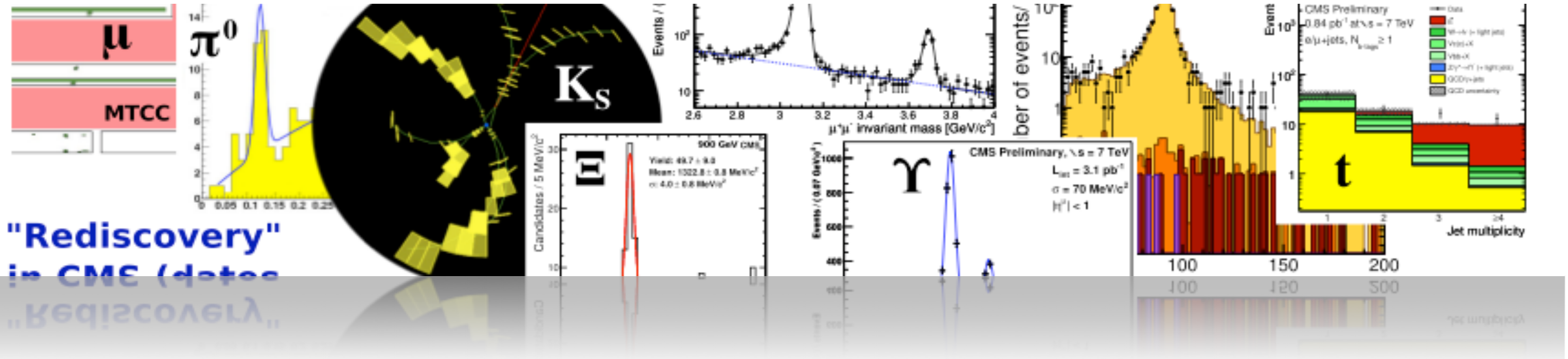
    accuracy: ~2-3%

Relative:

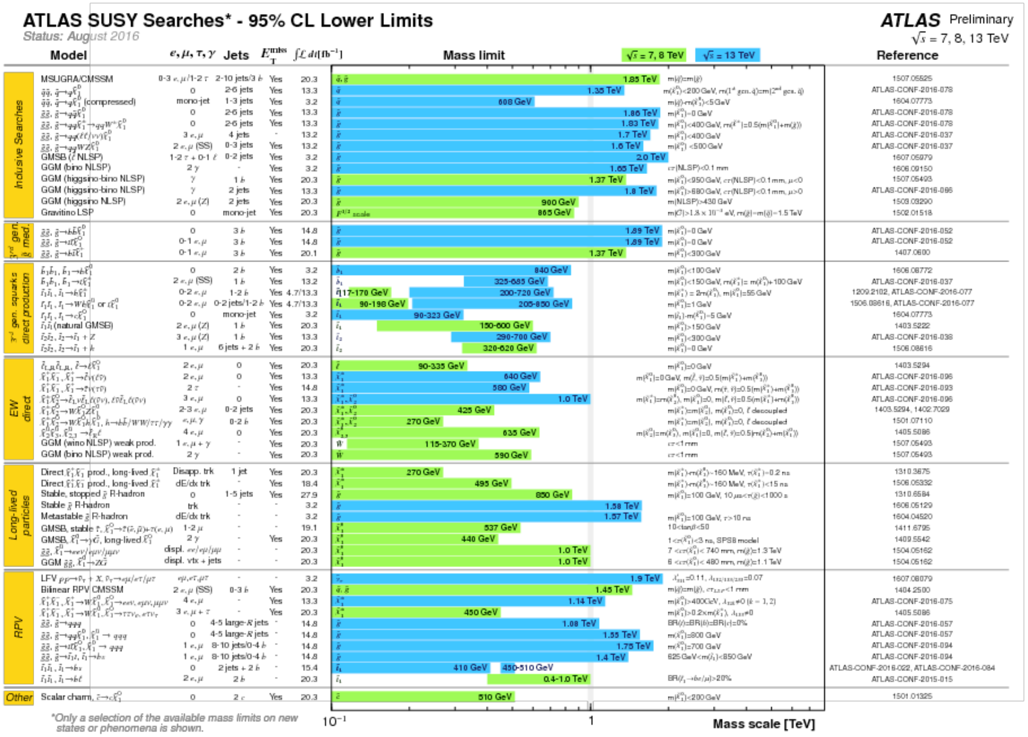
- Particle counting (i.e. Cherenkov counters): needs calibration to absolute luminosity

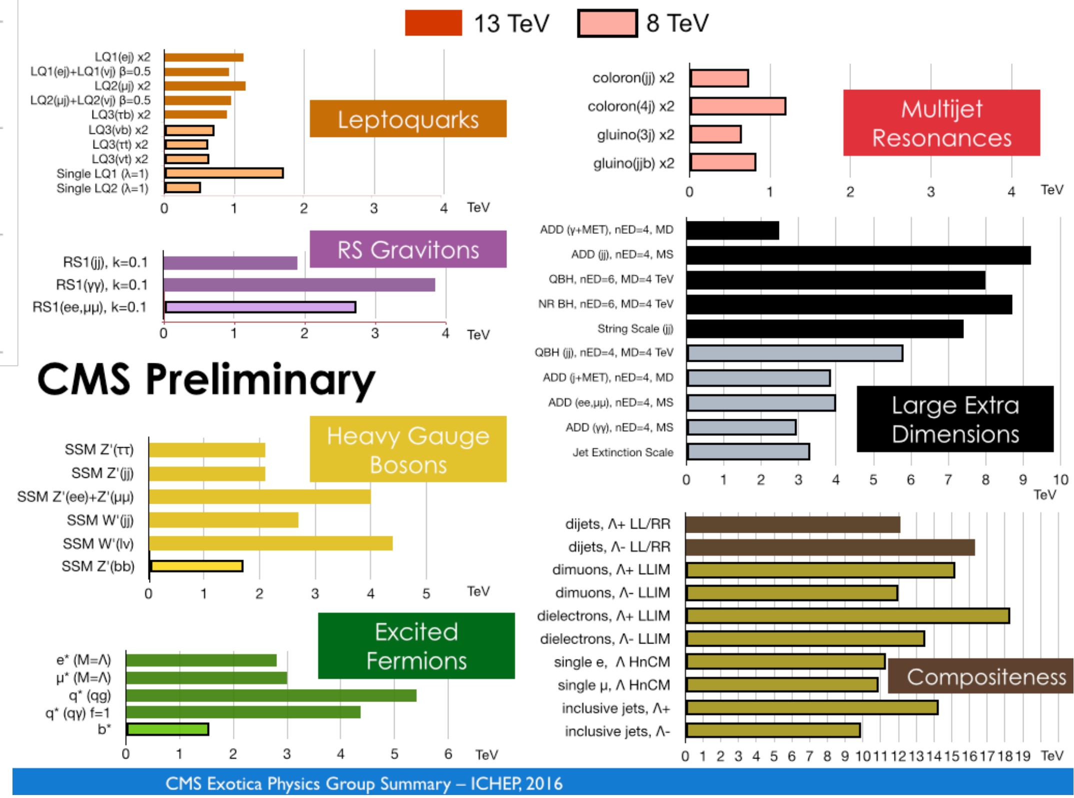
Goal: accuracy of 2-3%

Detector commissioning



Probing the SM in many ways

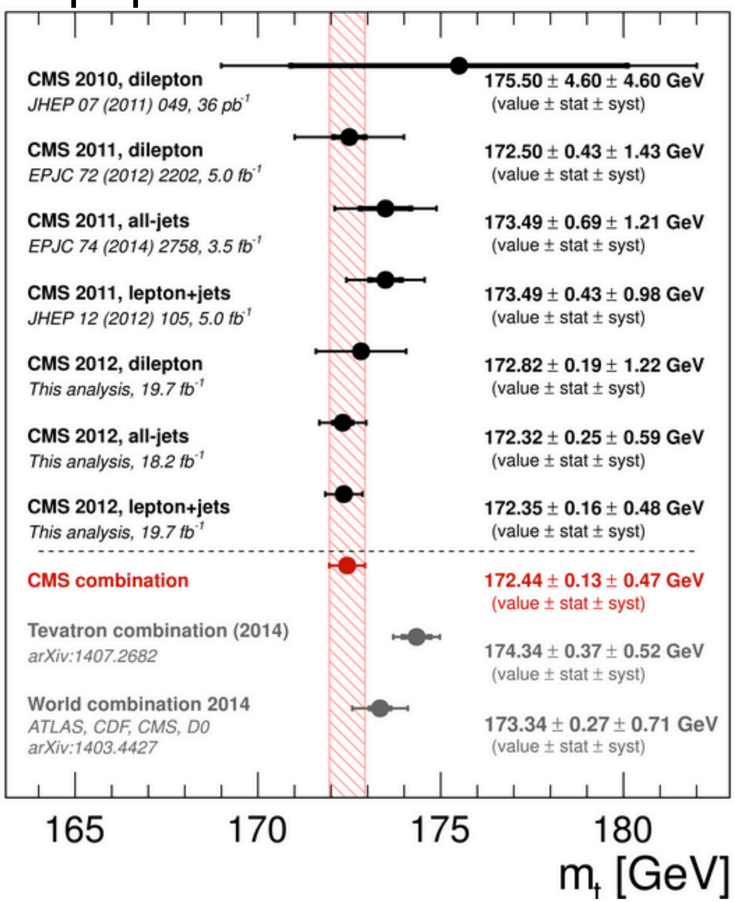




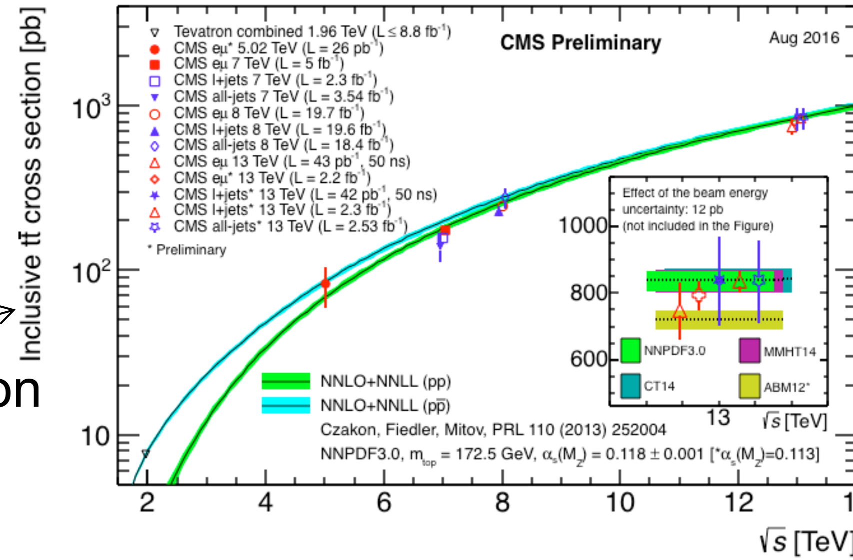
No new physics yet

Top quark physics

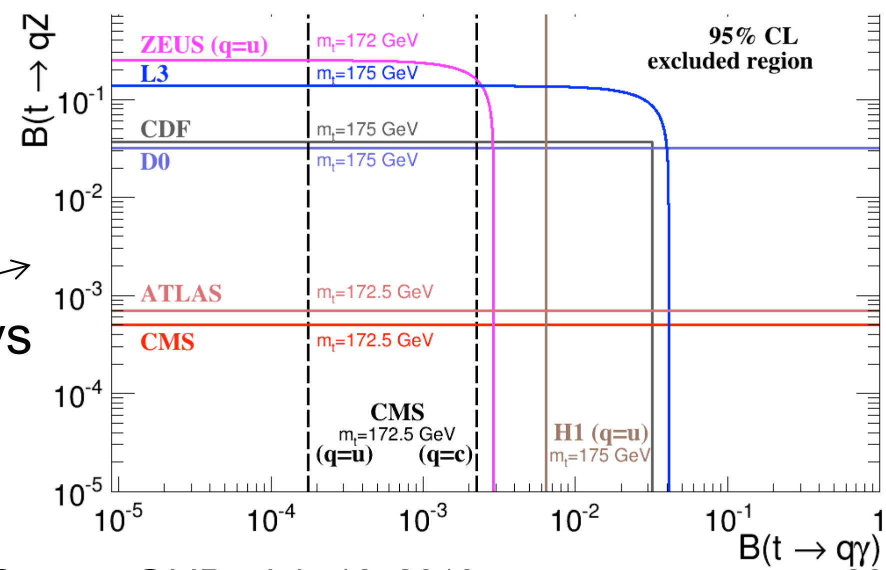
Top quark mass



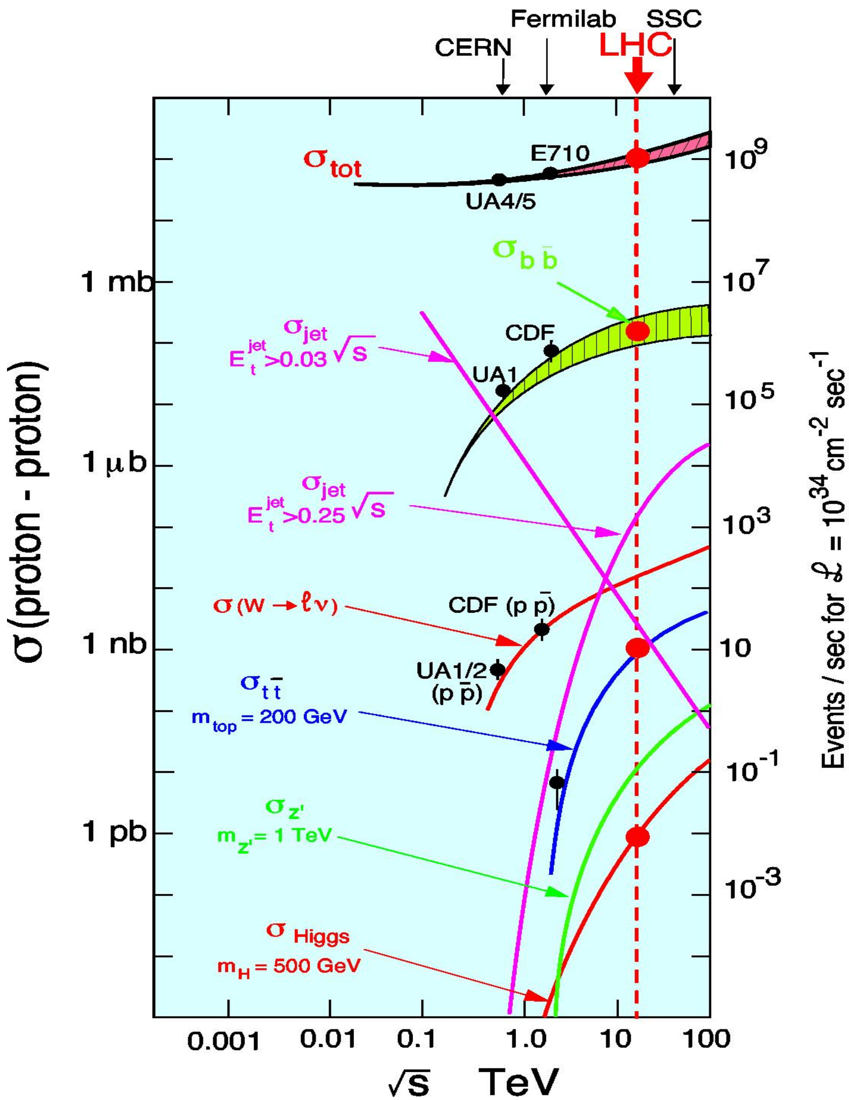
Cross section

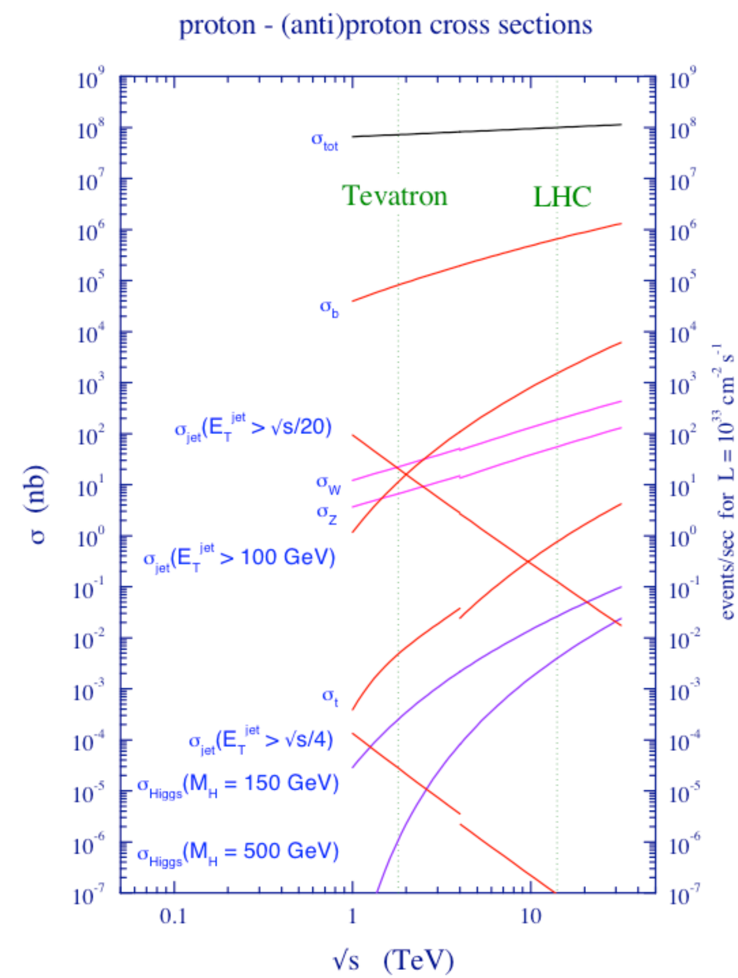


Rare decays



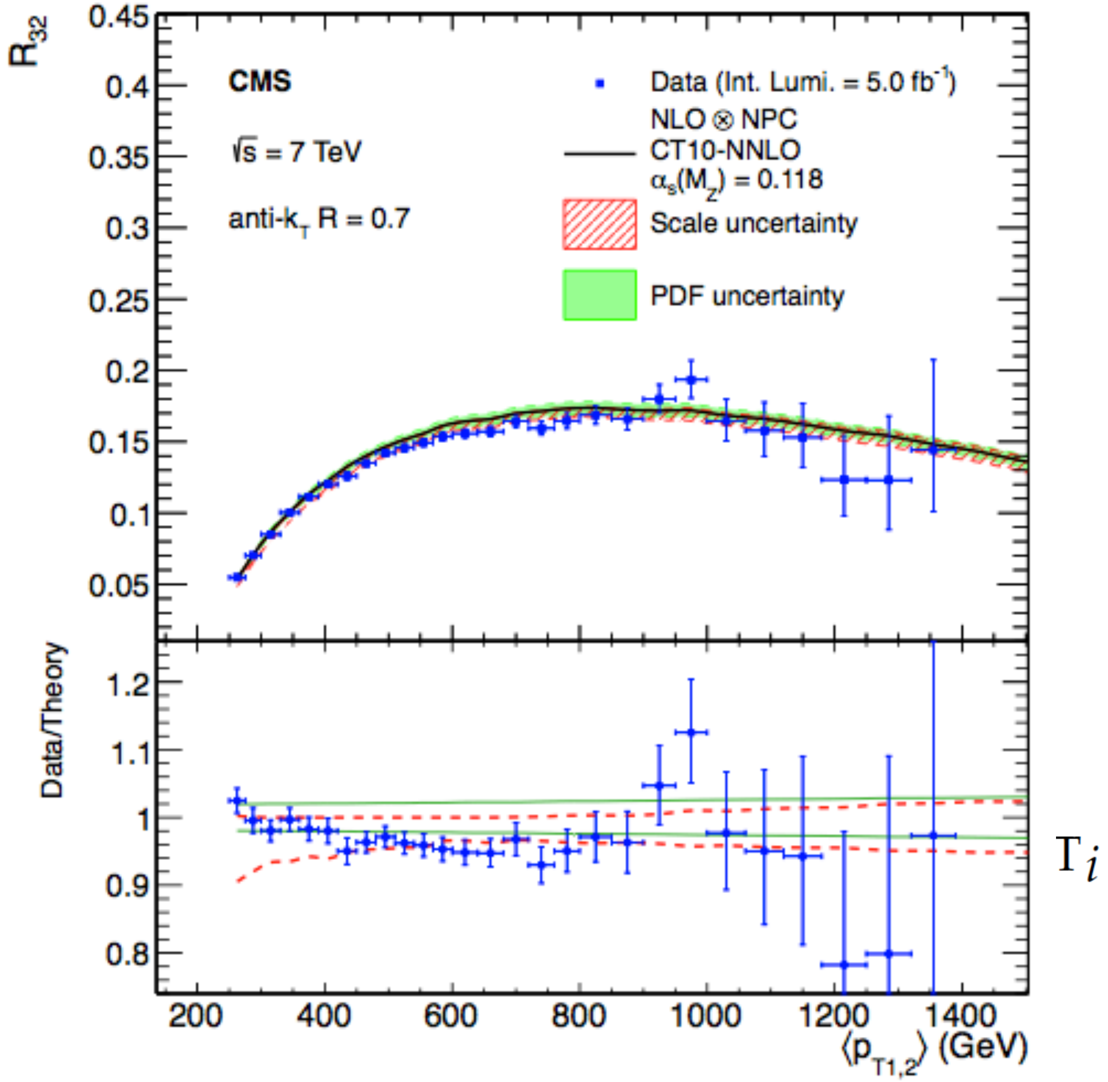
Physics processes

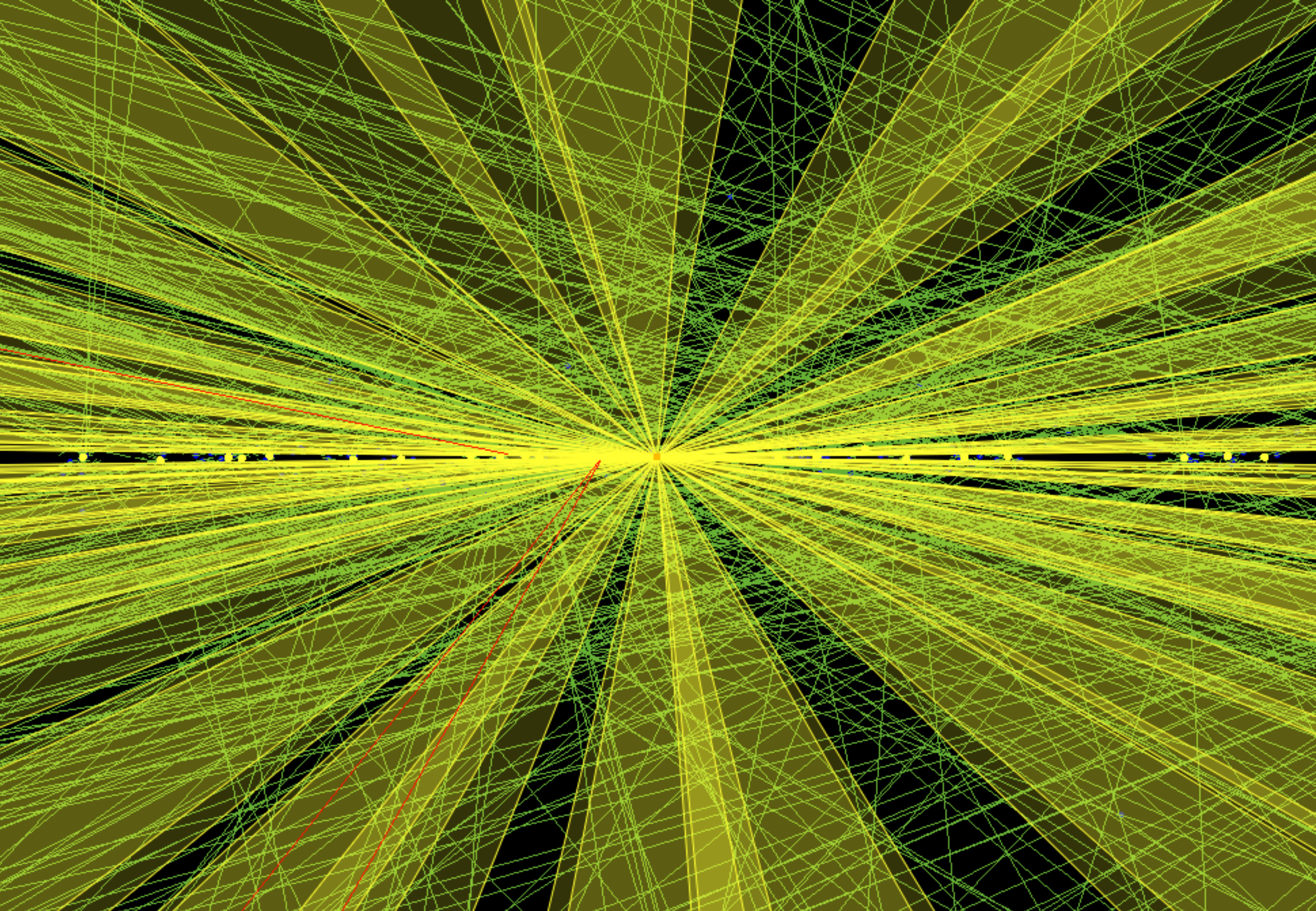


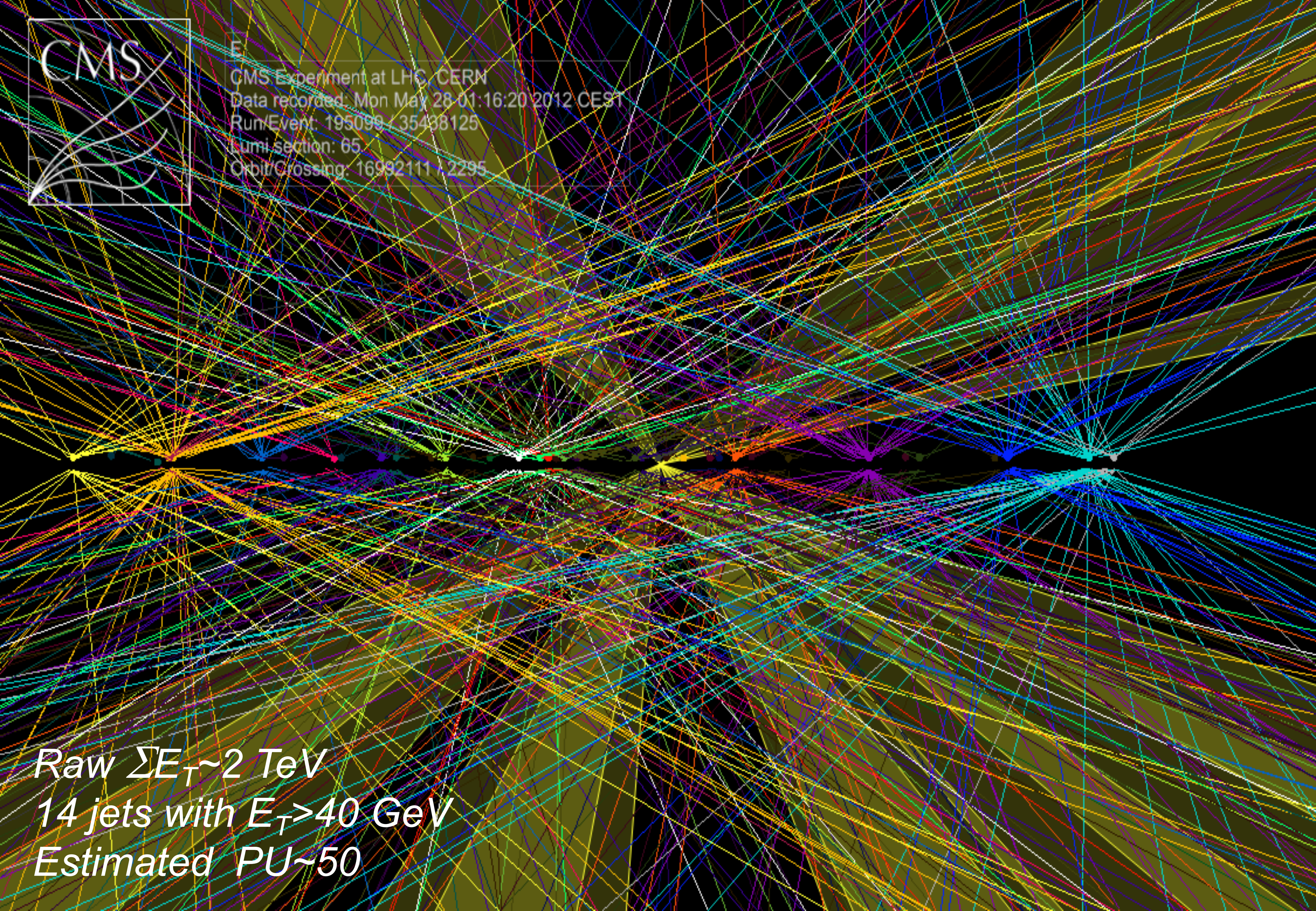


Inclusive cross section: 3-to-2 jet ratio

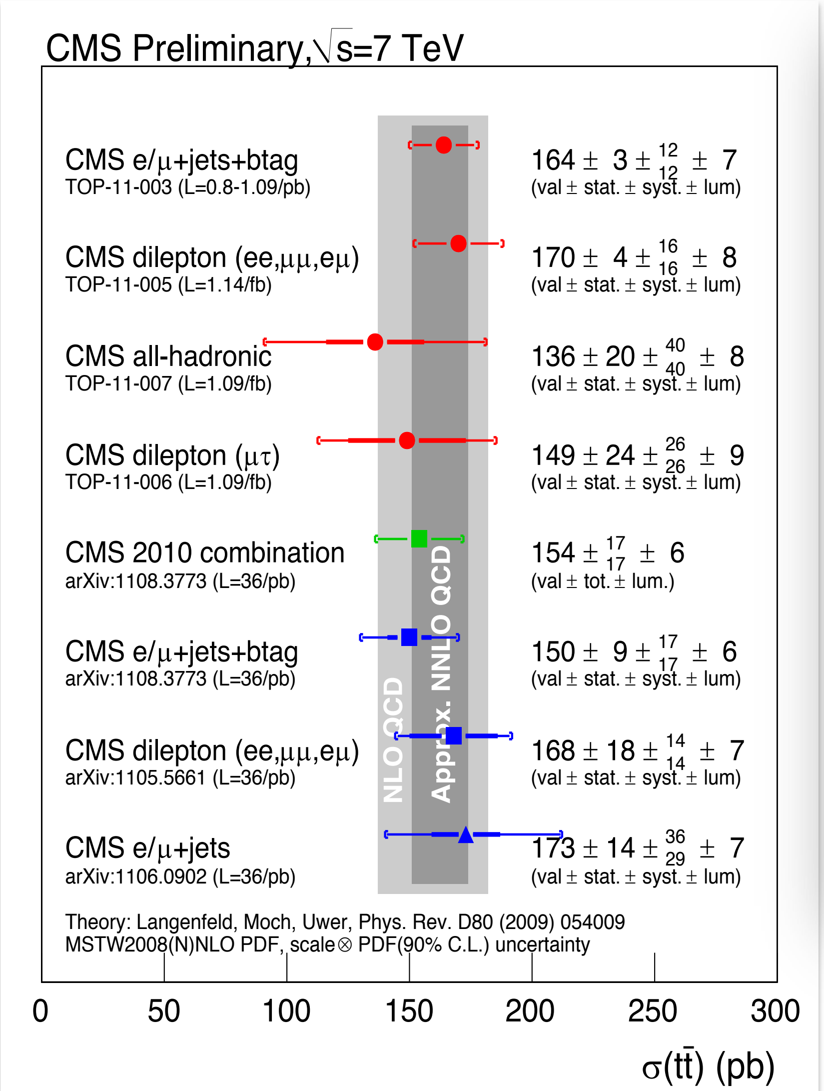
arXiv:1304.7498

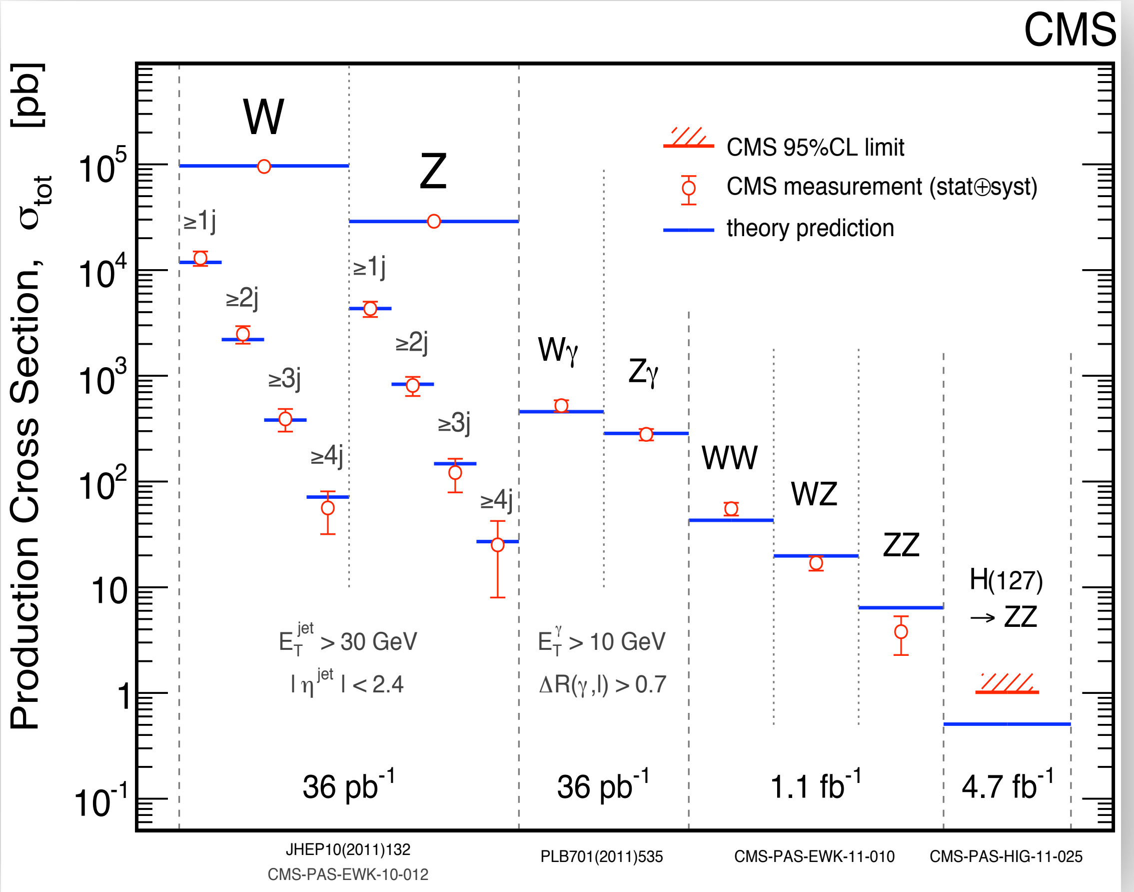




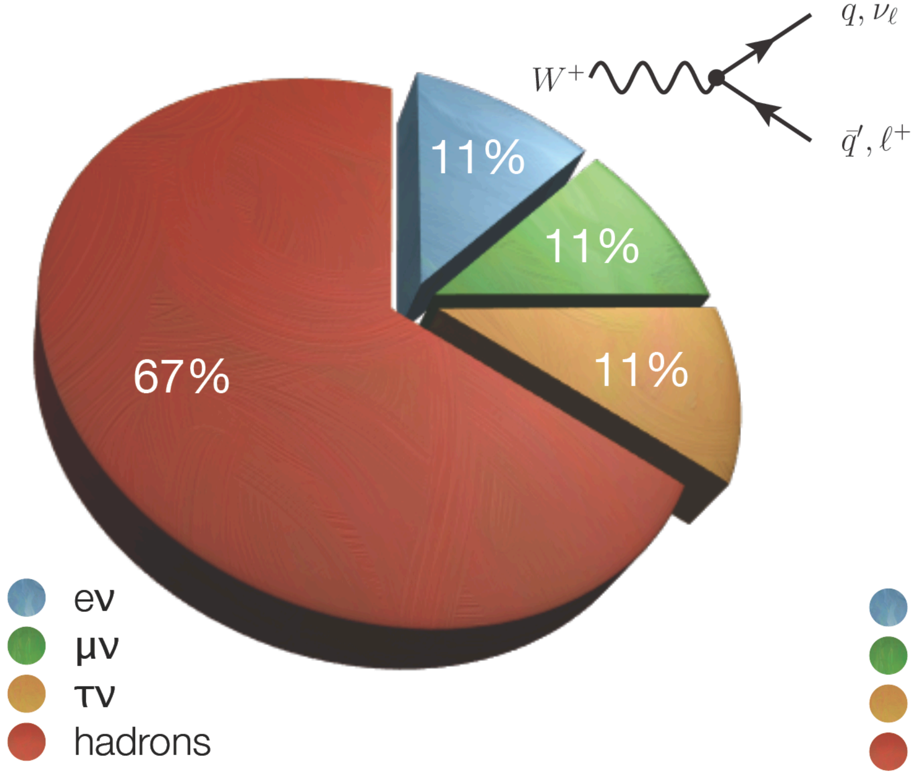

CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
Raw ΣE_T~2 TeV
14 jets with E_T>40 GeV
Estimated PU~50

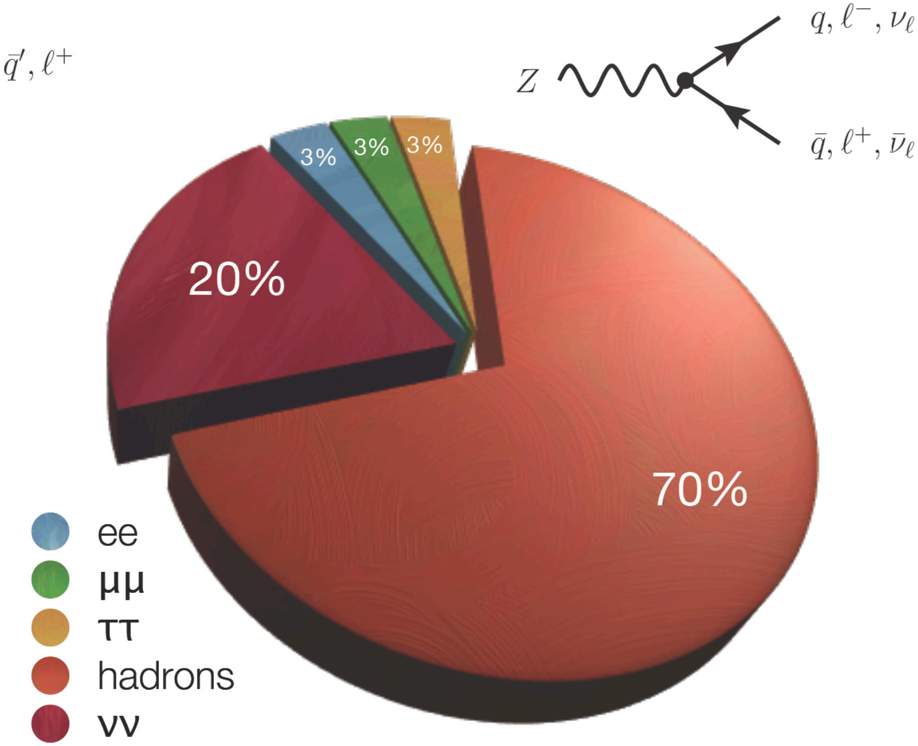
SM at 7 TeV (2010-2011)





W and Z bosons





Leptonic decays (e/μ): very clean, but small(ish) branching fractions

Hadronic decays: two-jet final states; large QCD dijet background

Tau decays: somewhere in between…

Isolated high-p_T lepton

Starting point for many hadron collider analyses:
isolated high-p_T leptons ➛ discriminate against QCD jets ...

QCD jets can be mis-reconstructed
as leptons ("fake leptons")

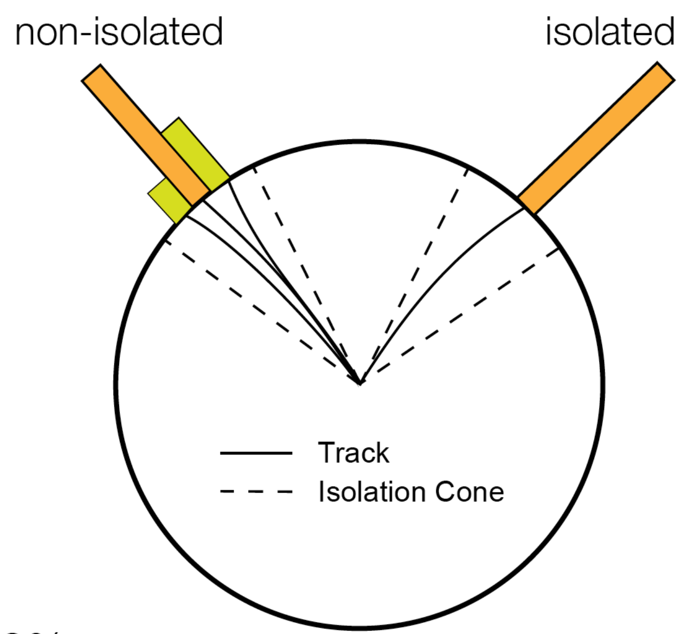
QCD jets may contain real leptons
e.g. from semileptonic B decays [$B \to l\nu X$]

➛ soft and surrounded by other particles

"Tight" lepton selection ...

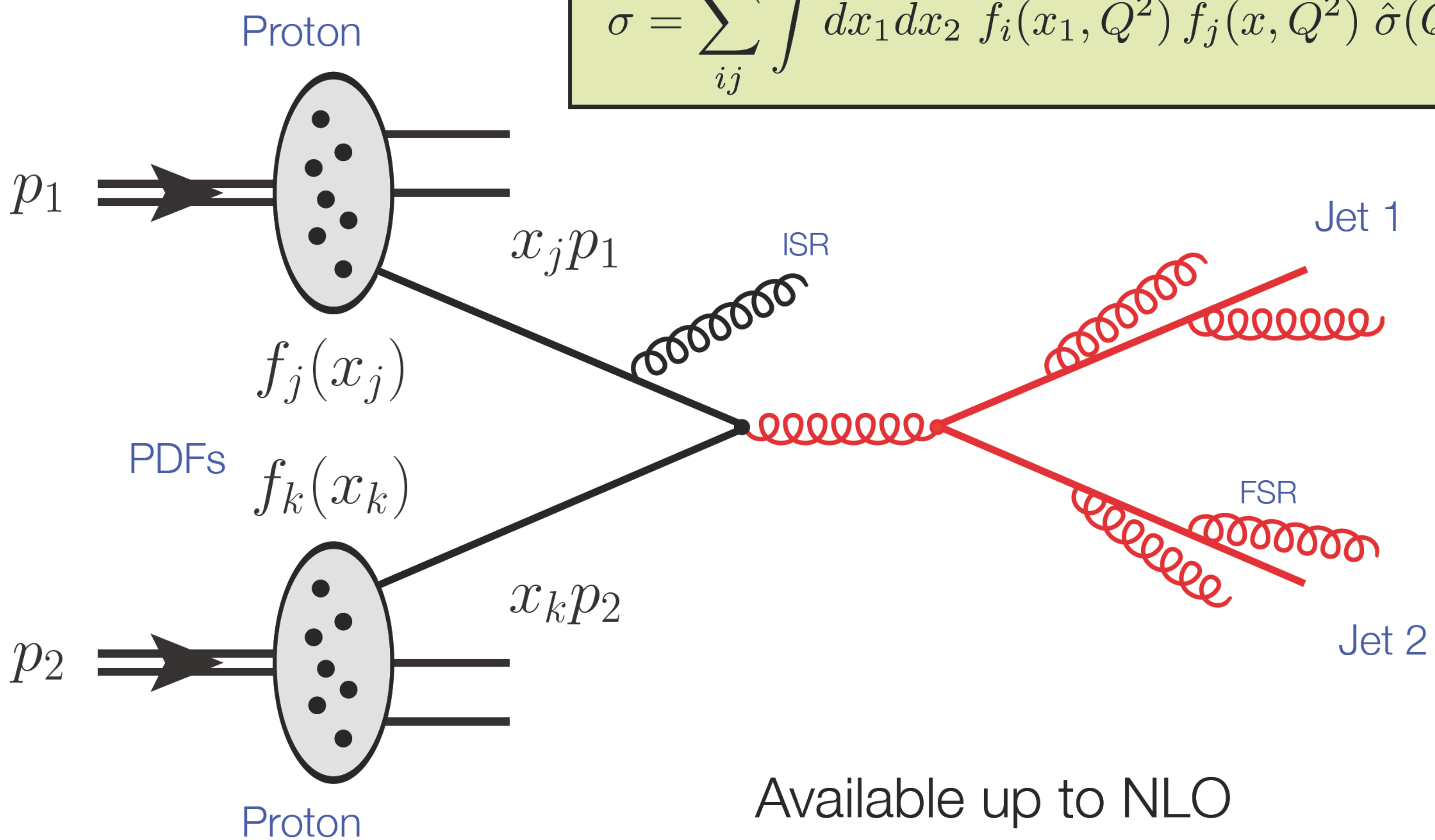
Require e/μ with $p_T >$ (at least) 20 GeV
Track isolation, e.g. $\sum p_T$ of other tracks
in cone of ΔR=0.1 less than 10% of lepton p_T

Calorimeter isolation, e.g. energy deposition
from other particles in cone of ΔR=0.2 less than 10%



Jet production at LHC

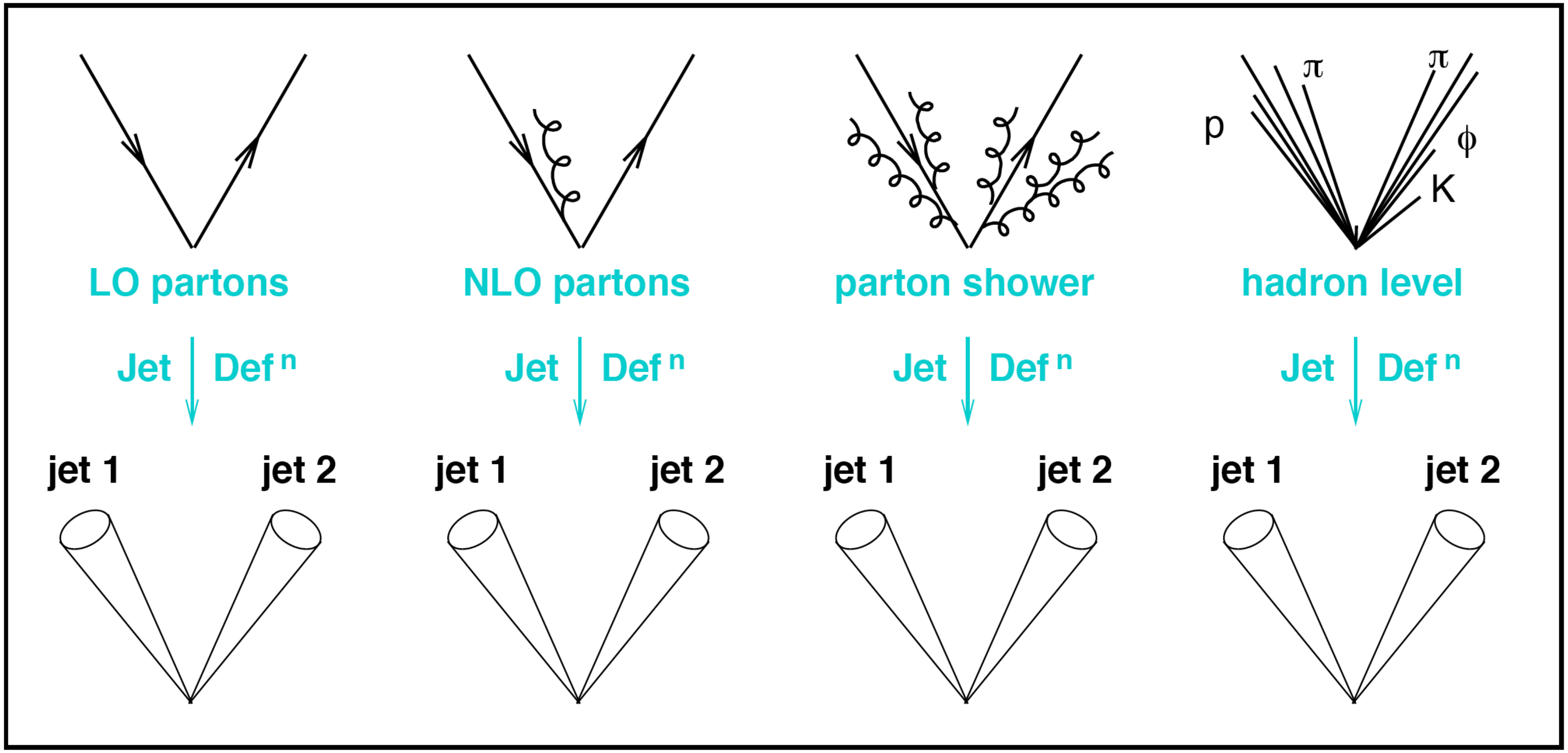
$$\sigma = \sum_{ij} \int dx_1 dx_2\ f_i(x_1, Q^2)\ f_j(x, Q^2)\ \hat{\sigma}(Q^2)$$



Available up to NLO

First NNLO calculations becoming available ...

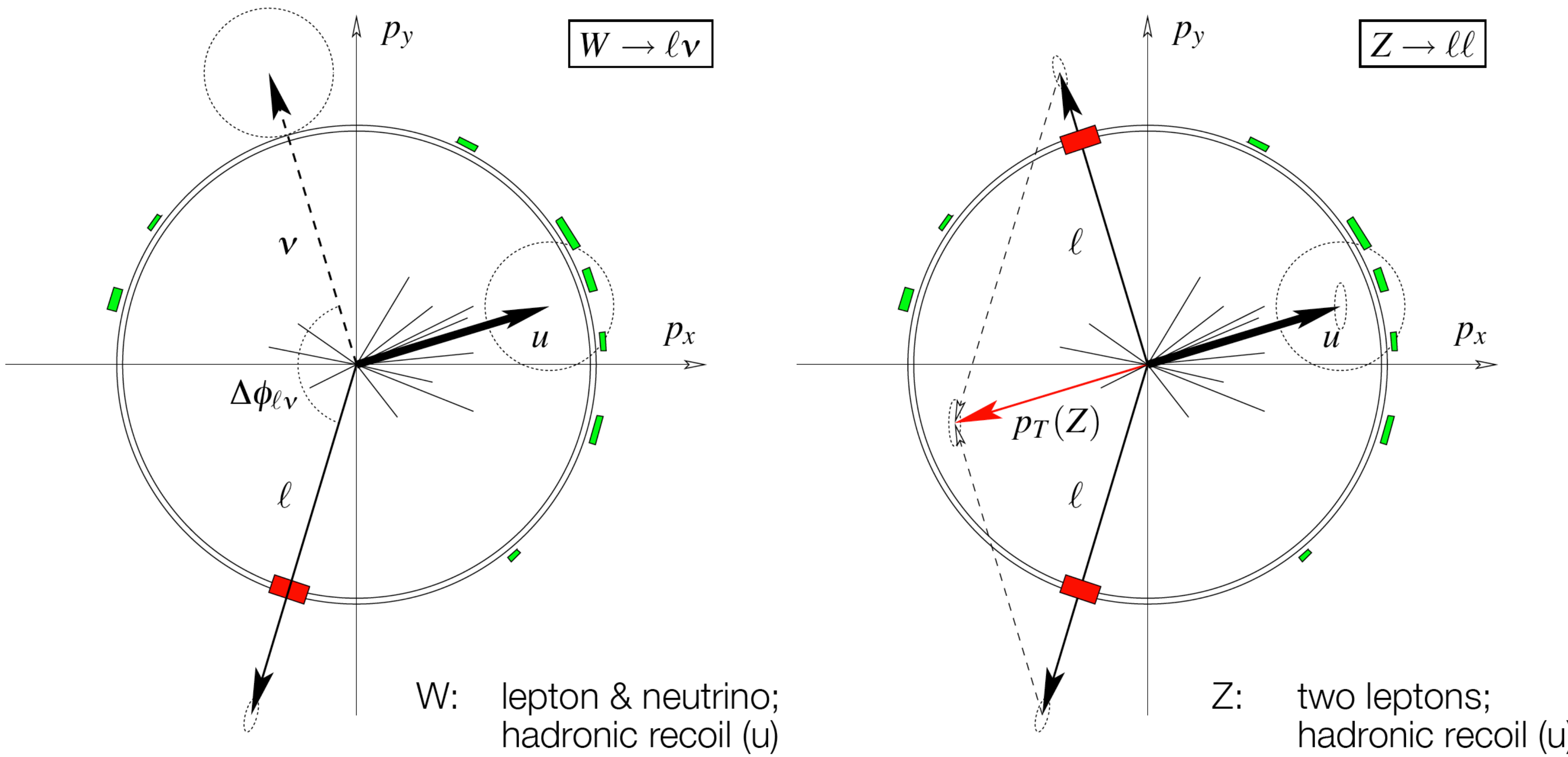
Jets (cont.)



Jets may look different at different levels

Robust jet definition ➛ stable on all jet levels

W and Z boson signatures



Additional hadronic activity ➛ recoil, not as clean as e^+e^-
Precision measurements: only leptonic decays

Monte Carlo generators

Monte Carlo simulation ...

Numerical process generation based on random numbers

Method very powerful in particle physics

Event generation programs:

Pythia, Herwig, Isajet Sherpa ...

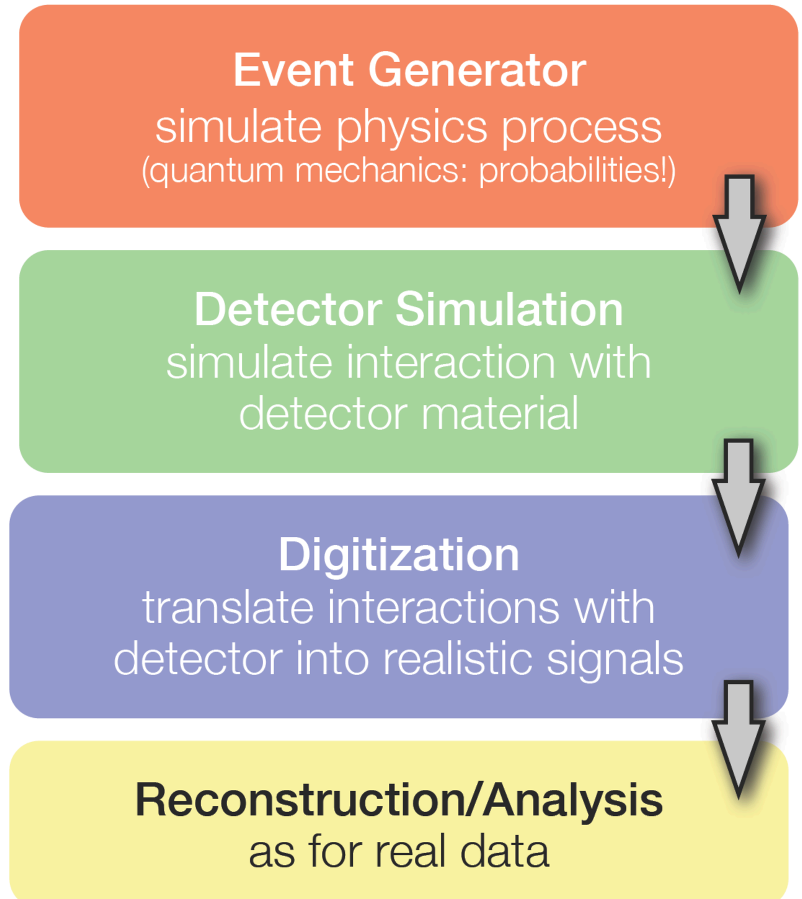
Hard partonic subprocess + fragmentation & hadronization ...

Detector simulation:

Geant ...

interaction & response of all produced particles ...

MC simulations in particle physics



From partons to jets

From partons to
color neutral hadrons:

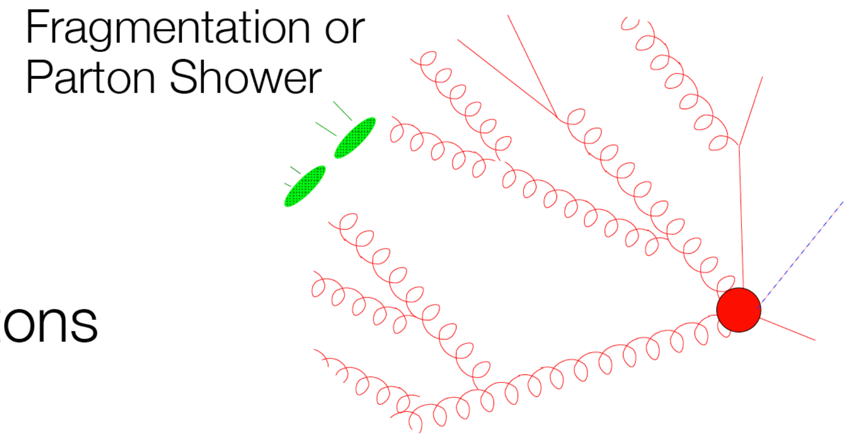
Fragmentation:

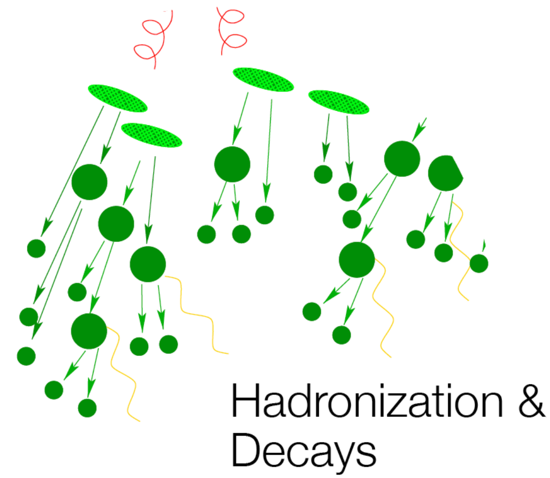
Parton splitting into other partons
[QCD: re-summation of leading-logs]
[“Parton shower”]

Hadronization:

Parton shower forms hadrons
[non-perturbative, only models]

Decay of unstable hadrons
[perturbative QCD, electroweak theory]





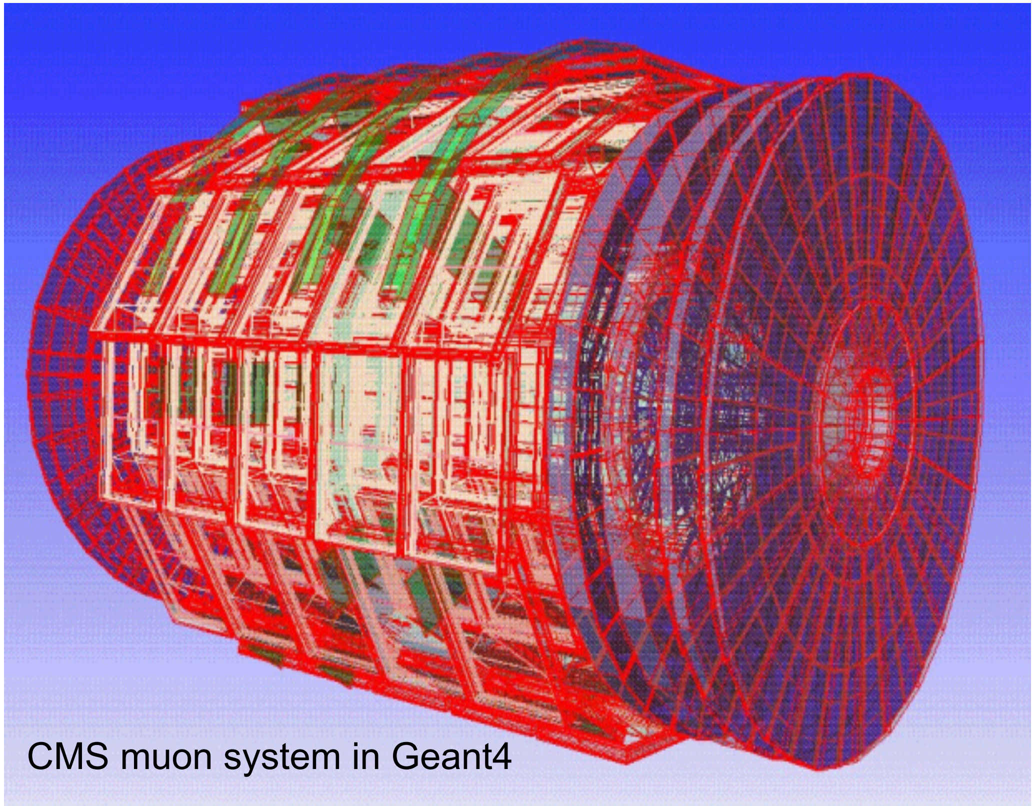
Detector simulation

GEANT
Geometry And Tracking

Detailed description of detector geometry
[sensitive & insensitive volumes]

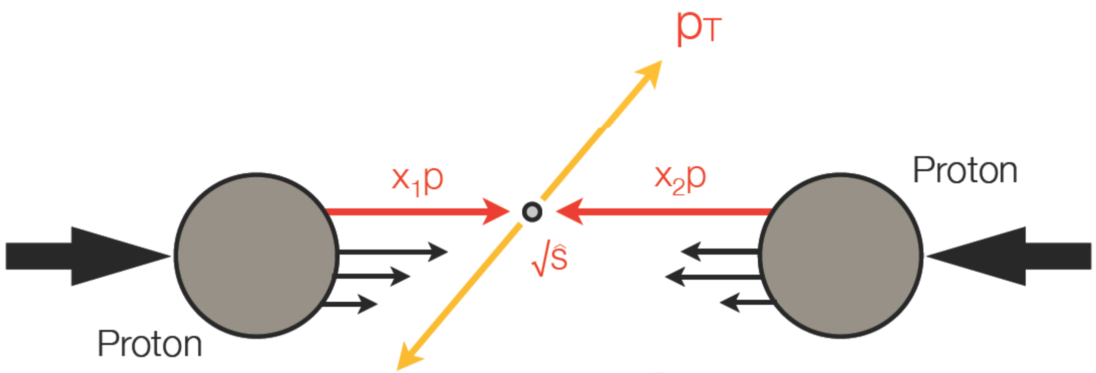
Tracking of all particles through detector material ...

➛ Detector response


CMS muon system in Geant4

Developed at CERN since 1974 (FORTRAN)
[Today: Geant4; programmed in C^{++}]

Kinematical variables

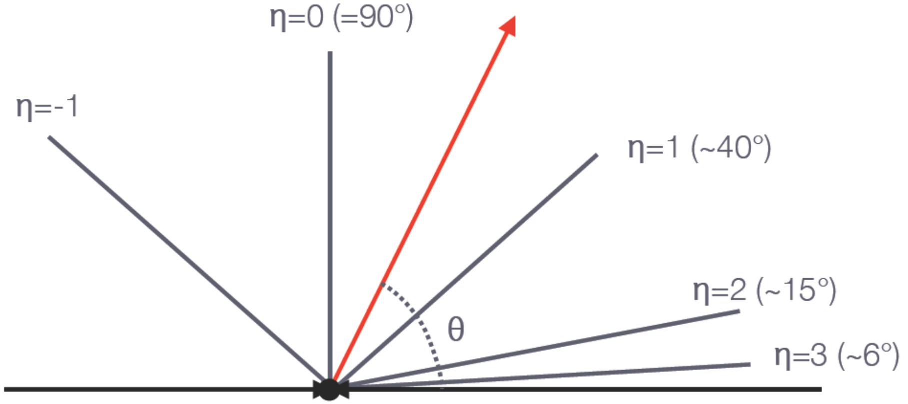


Schematic
proton-proton scattering

Relevant kinematic variables:

- Transverse momentum: p_T
- Rapidity: $y = ½ \cdot \ln (E-p_z)/(E+p_z)$
- Pseudorapidity: $\eta = -\ln \tan ½\theta$
- Azimuthal angle: φ

Pseudorapidity

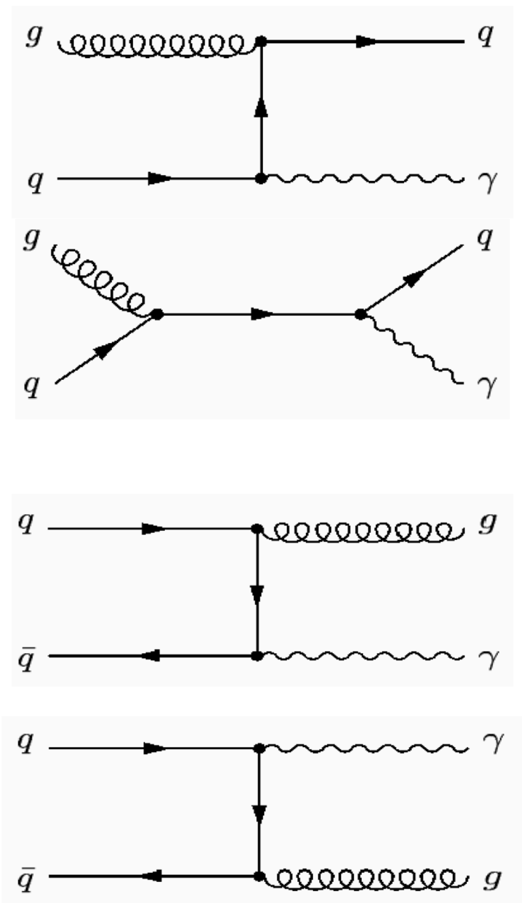


The people

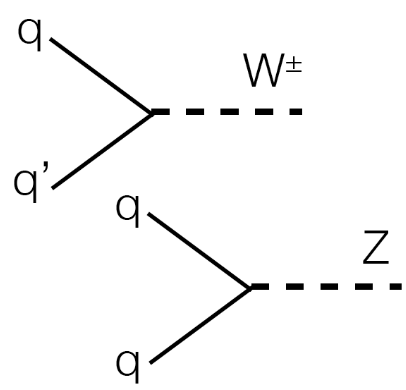
The CMS collaboration

Vector Boson Production

Direct γ-production:



Singel W/Z production:



W production: (main contributions) $\begin{cases} u\bar{d} \rightarrow W^+ \\ d\bar{u} \rightarrow W^- \end{cases}$

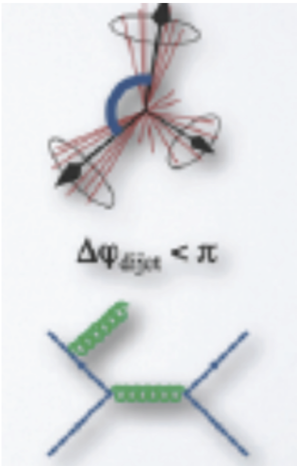
Z production: (main contributions) $\begin{cases} u\bar{u} \rightarrow Z \\ d\bar{d} \rightarrow Z \end{cases}$

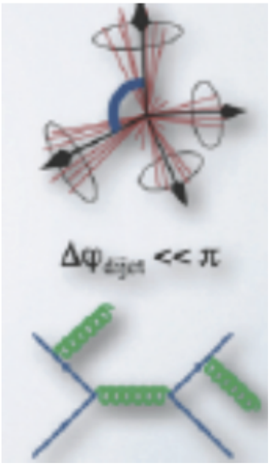
- At LHC energies these processes take place at low values of Bjorken-x
- Only sea quarks and gluons are involved
- At EW scales sea is driven by the gluon, i.e. x-sections dominated by gluon uncertainty

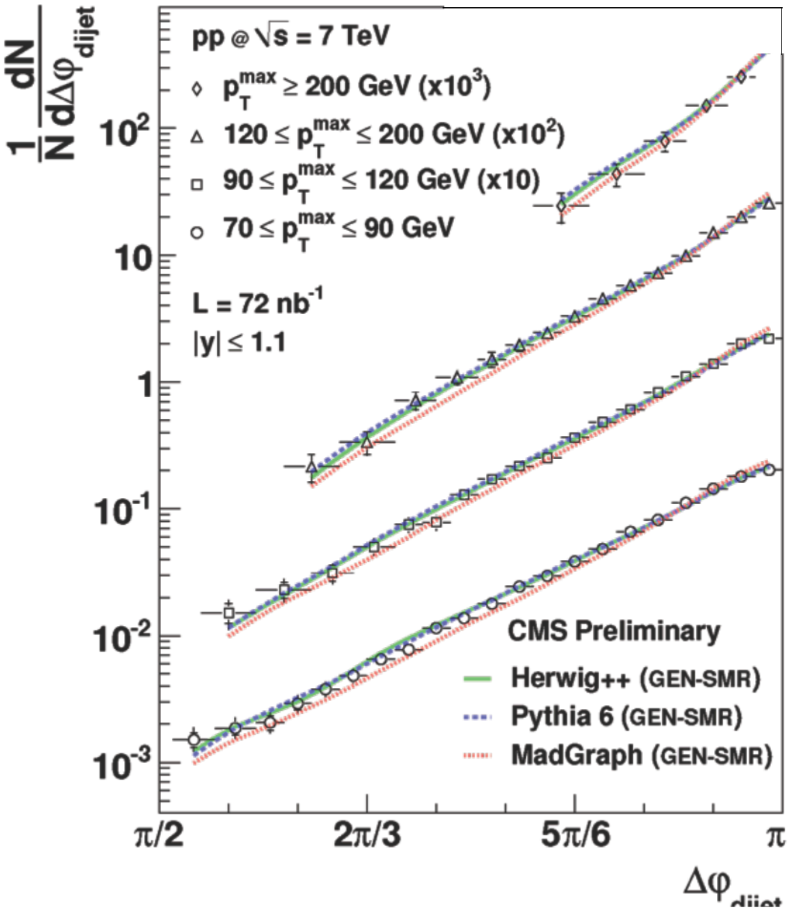
➡ Constraints on sea and gluon distributions

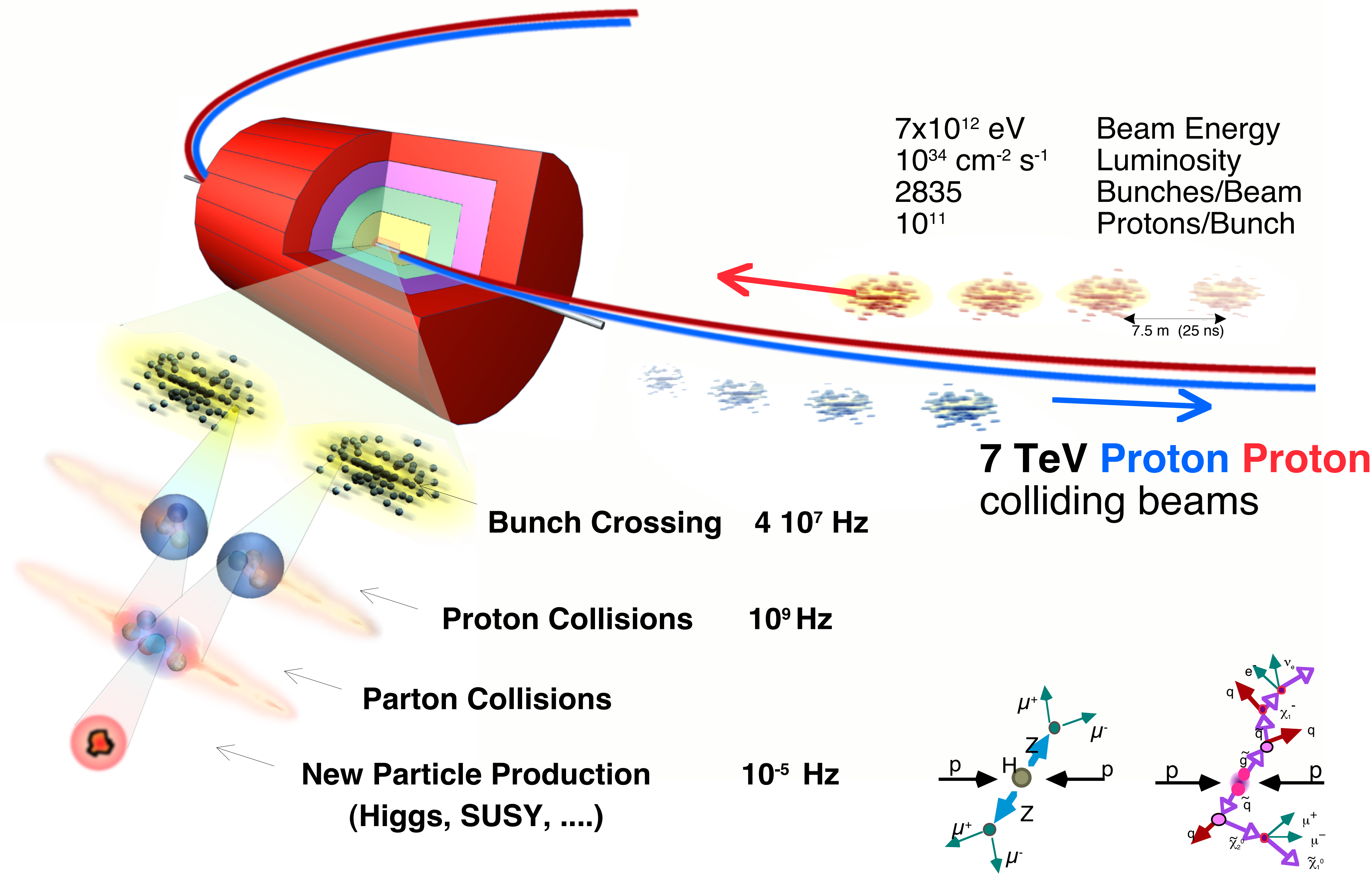
Jets: angular correlations

Difference in azimuth of the two leading jets
Probe of QCD high-order processes
Very slight dependence on JES
No dependence on luminosity





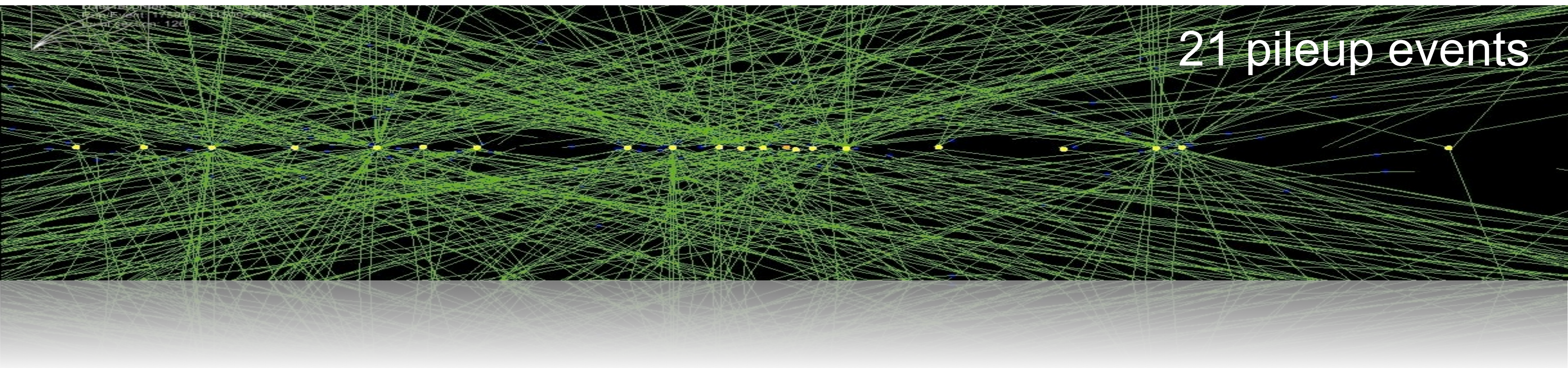




Selection of 1 event in 10,000,000,000,000

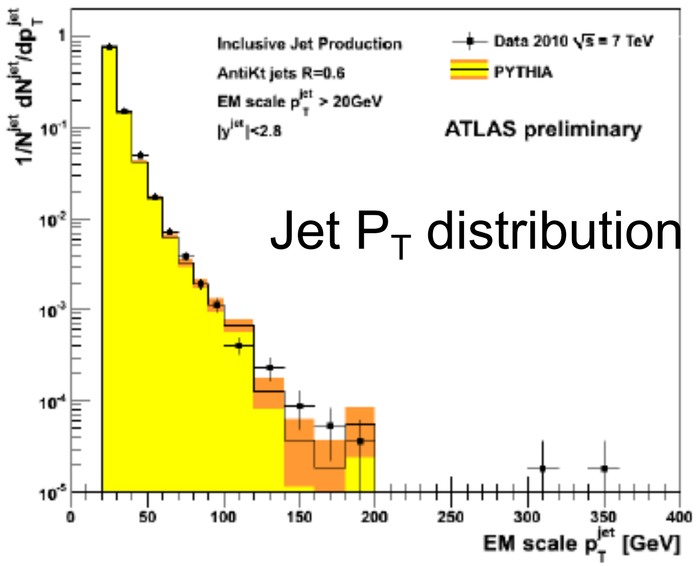
Experimental challenges

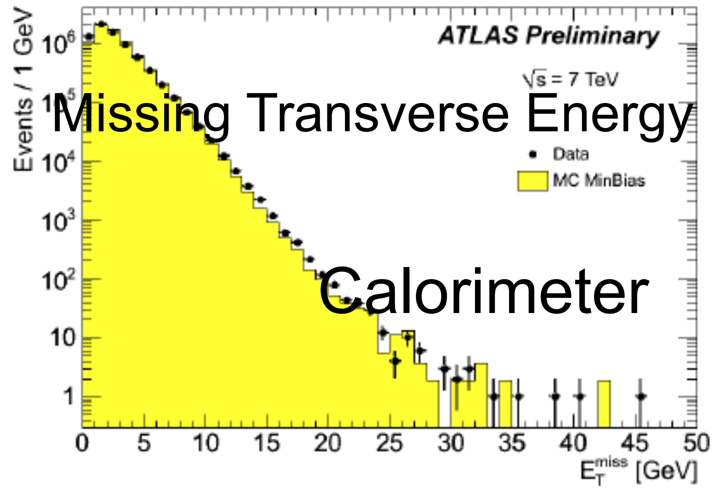
- LHC has 3564 bunches (2835 filled with protons)
- Crossing rate is 40 MHz
- Distance between bunches: 27km / 3600 = 7.5m
- Distance between bunches in time: 7.5m / c = 25ns
- Proton-proton collision per bunch crossing: ~ 25



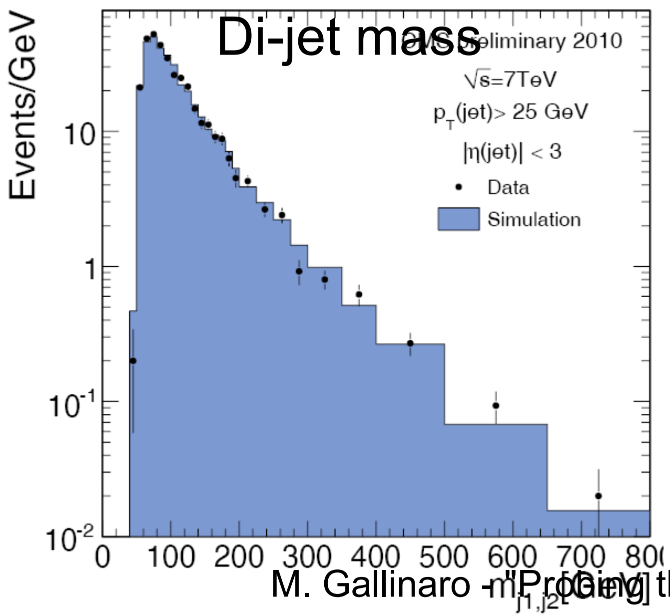
Jets and missing energy

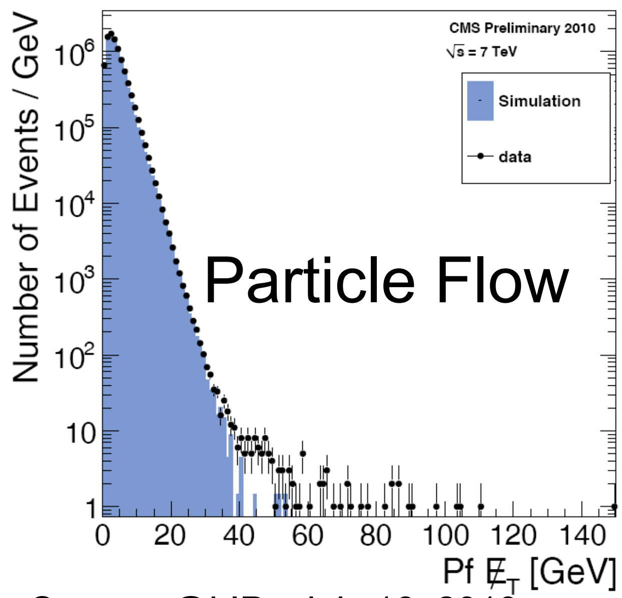
ATLAS





CMS





Luminosity and cross section

Number of observed events

just count …

Background

measured from data or calculated from theory

$$\sigma = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\int \mathcal{L}\, dt \cdot \varepsilon}$$

Luminosity

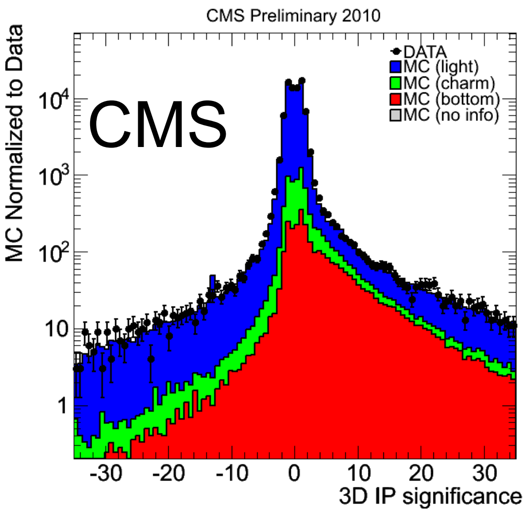
determined by accelerator, triggers, …

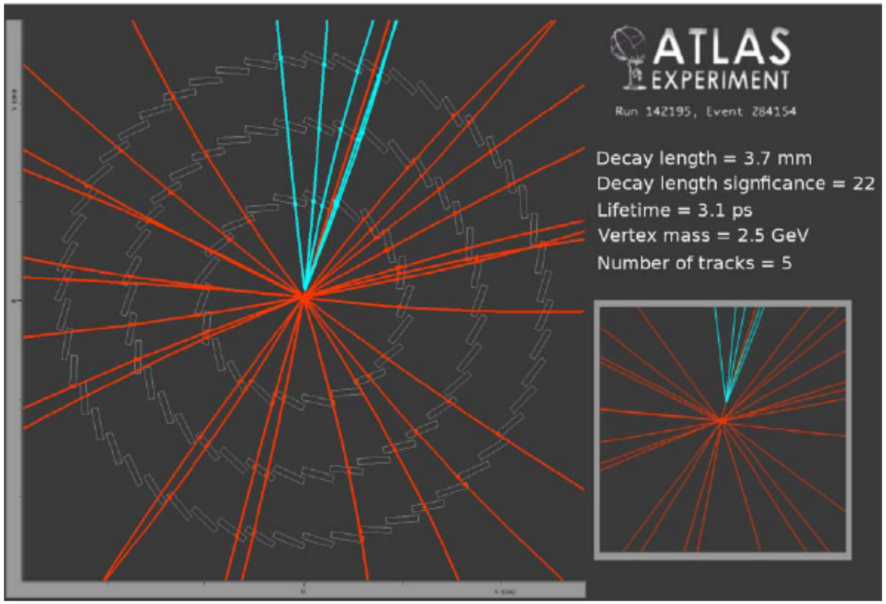
Efficiency

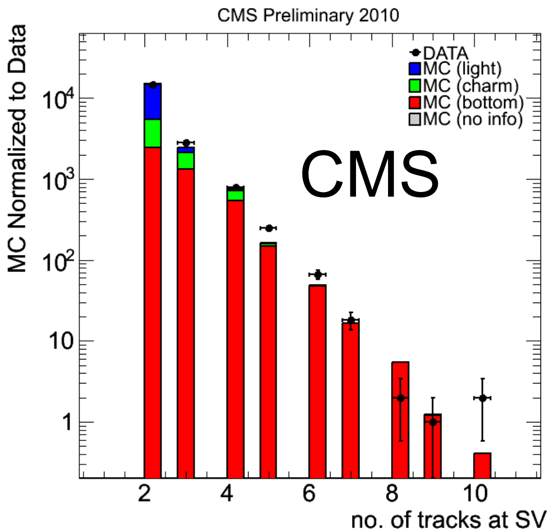
many factors, optimized by experimentalist

Tracking

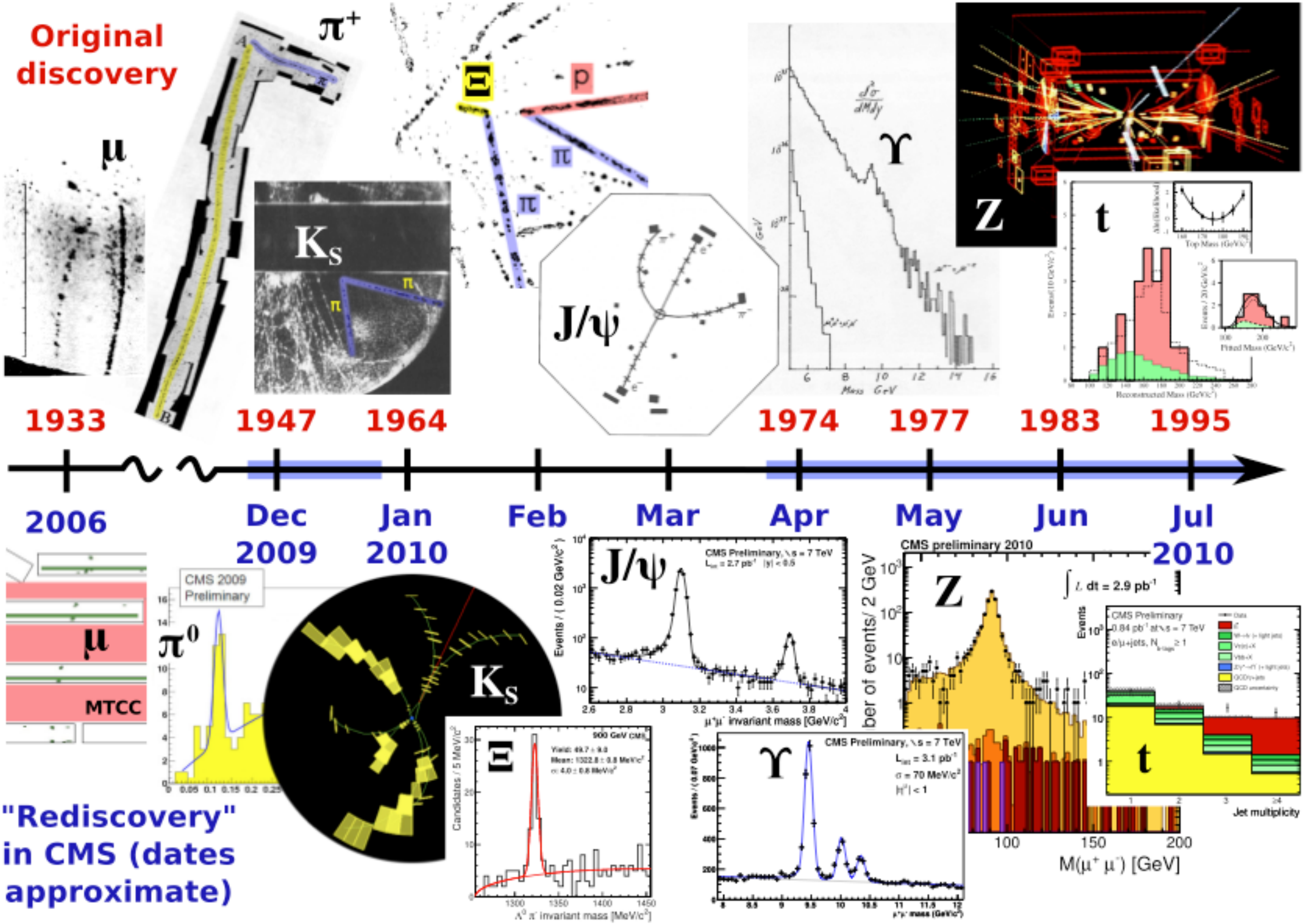
Basic variables relevant for B-tagging are well described by the simulation







Secondary vertices compatible with heavy flavor production


Original discovery
μ
π+
K_S
π
π
Ξ
p
π
π
J/ψ
ϒ
Z
t
1933
1947
1964
1974
1977
1983
1995
2006
Dec 2009
Jan 2010
Feb
Mar
Apr
May
Jun
Jul 2010
μ
MTCC
CMS 2009 Preliminary
π0
K_S
Ξ
J/ψ
CMS Preliminary, √s = 7 TeV
μ+μ- invariant mass [GeV/c²]
ϒ
CMS Preliminary, √s = 7 TeV
Z
CMS preliminary 2010
M(μ+ μ-) [GeV]
t
CMS Preliminary
Jet multiplicity
"Rediscovery" in CMS (dates approximate)