Introduction to LHC physics: Probing the Standard Model

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LIP Lisbon

July 6, 2021

- ✓ The Large Hadron Collider
- ✓ Experiments
- ✓ Experimental program
- ✓ Standard model

Experimental particle physics

Particle physics is a modern name for century-old effort to understand the basics laws of physics

Edward Witten

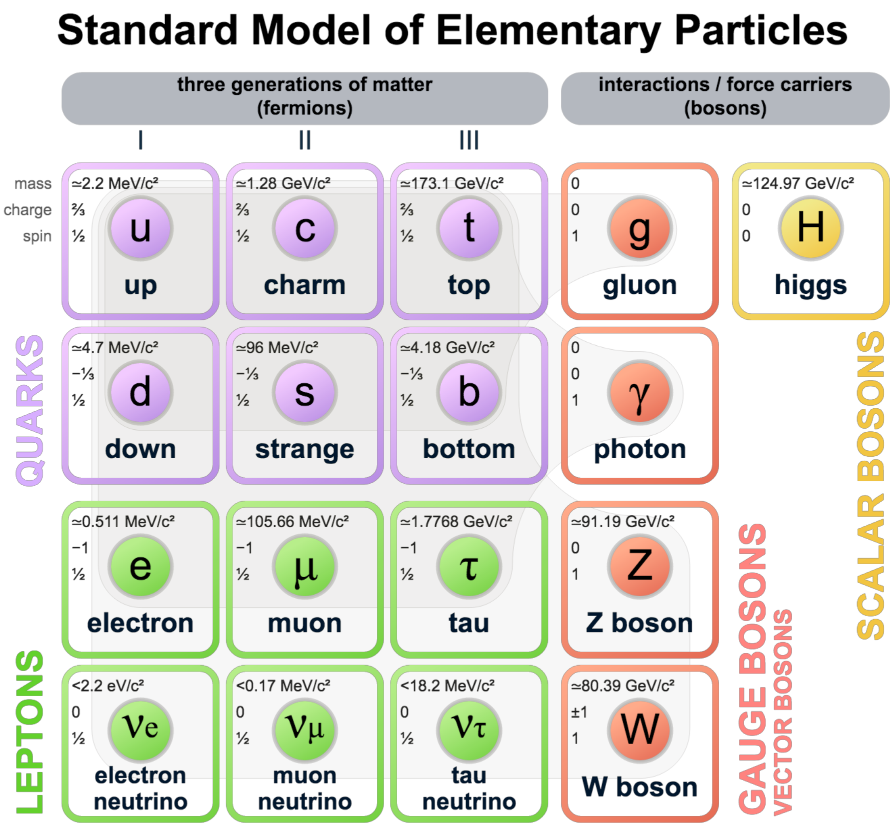
Questions:

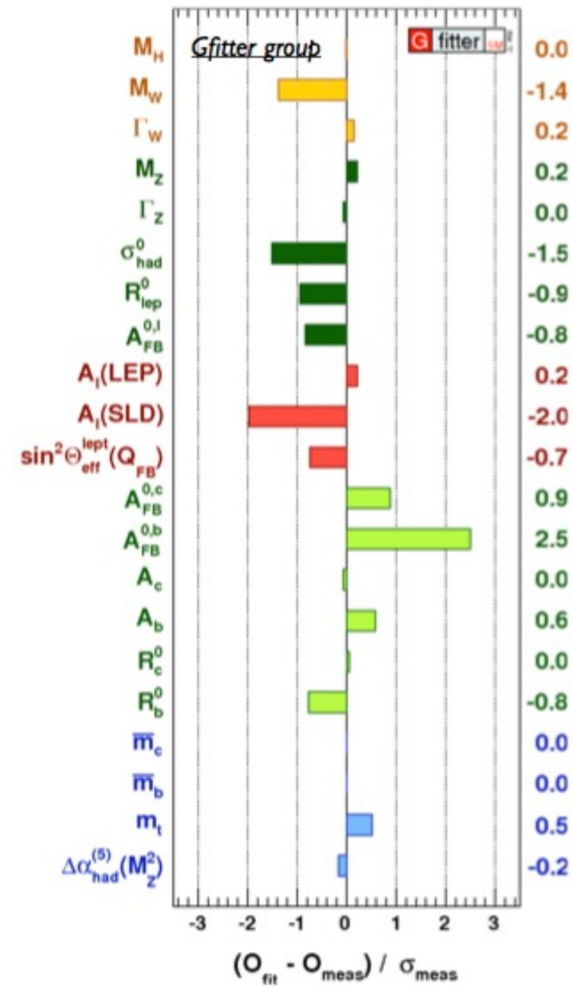
- What are the elementary constituents of matter?
- What are the forces that determine their behavior

Experimentally

- Get particles to interact and study what happens

The Standard Model

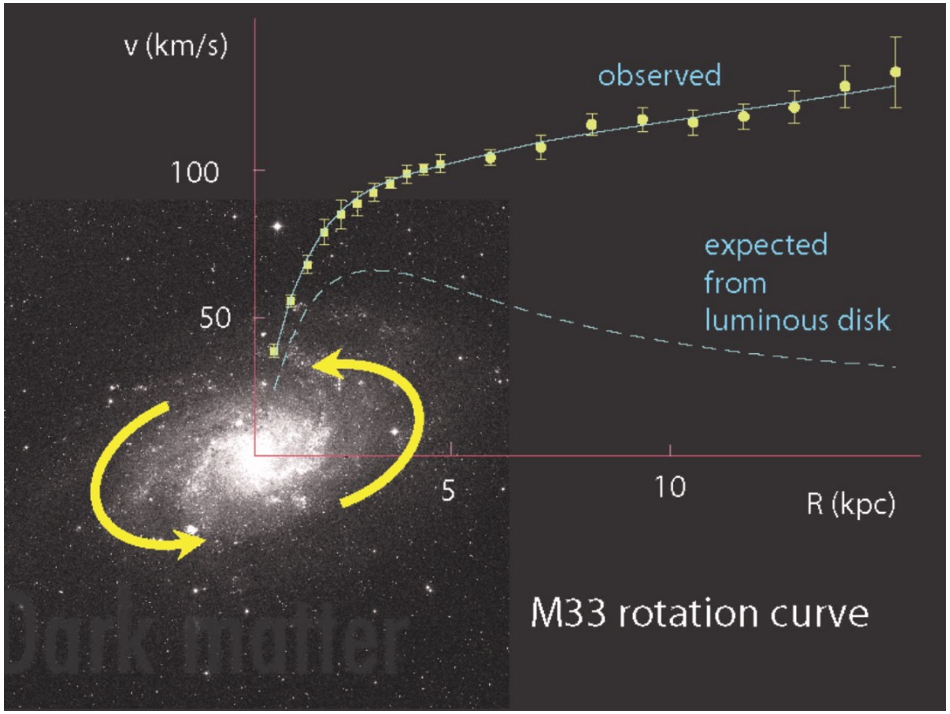




Excellent agreement with all experimental results

Dark side of the Universe

- We know that ordinary matter is only ~4% of matter-energy in the Universe
- What is the remaining 96%?



The LHC may help to solve this problem, by discovering dark matter

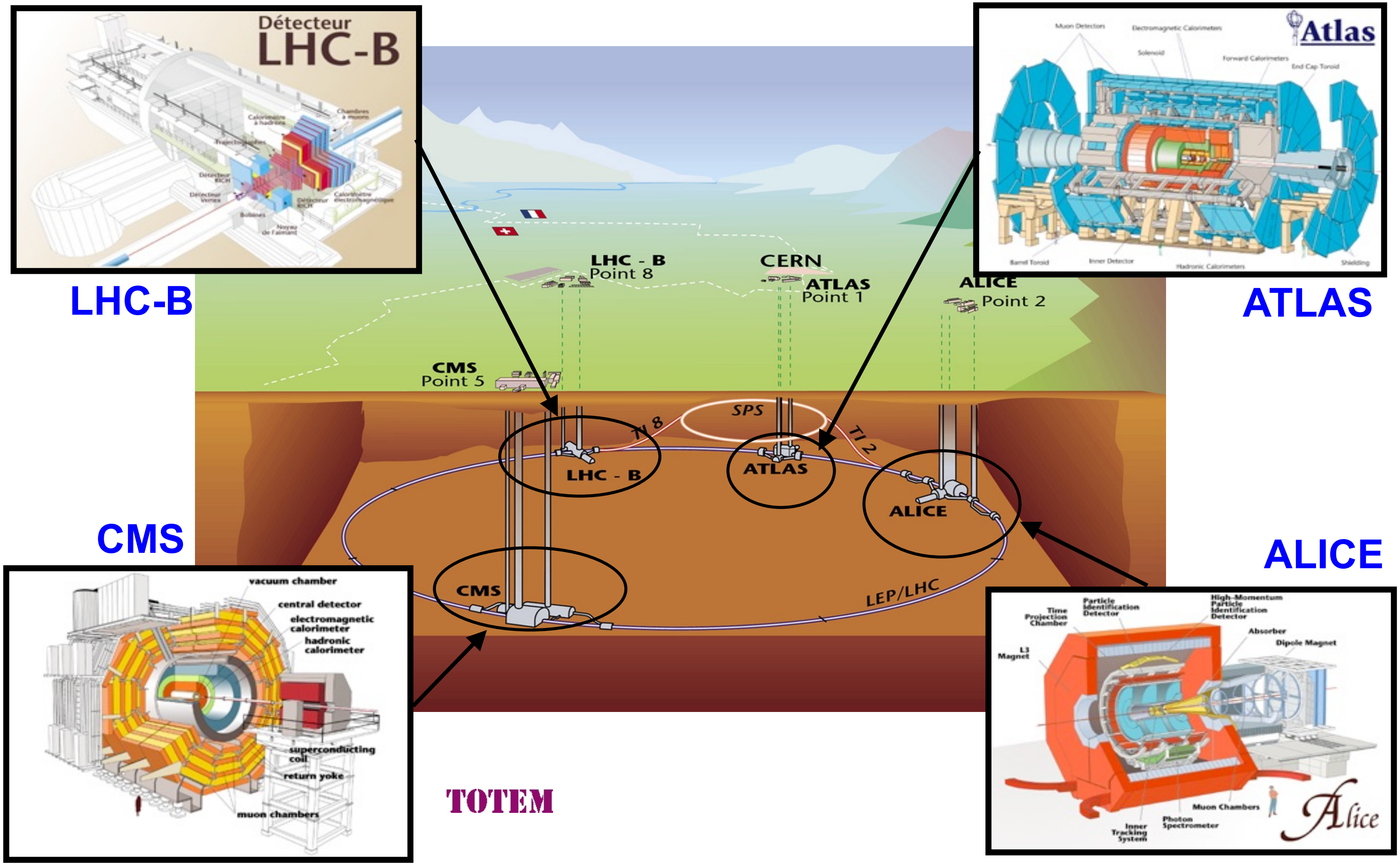
The Large Hadron Collider

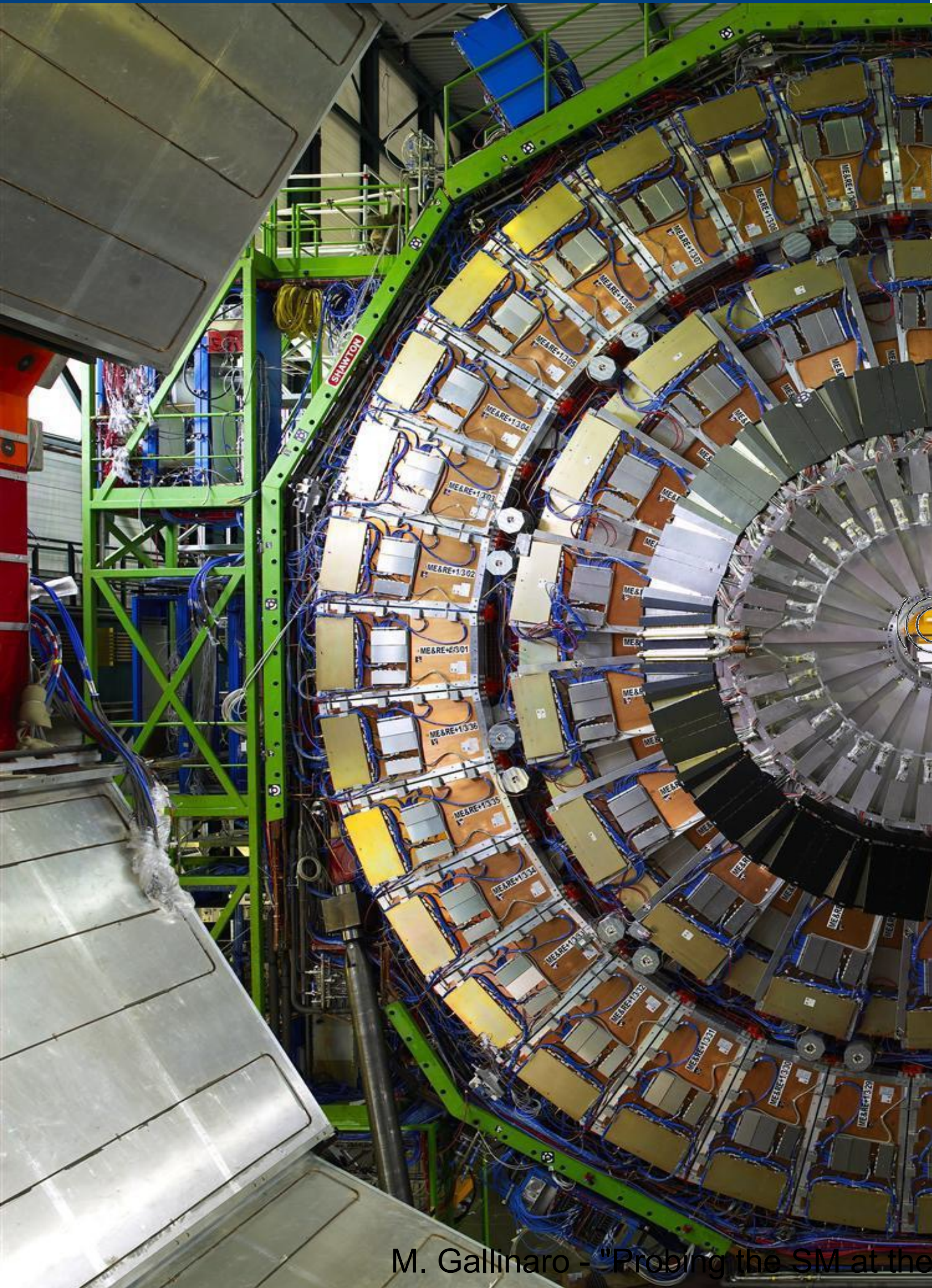
- Installation in existing LEP tunnel (27 Km)
- 1232 dipoles B=8.3T
- pp $\sqrt{s}$ = 14 TeV
  $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$
- Heavy ions
  (e.g. Pb-Pb at 5TeV, p-Pb at 8TeV, Xe)

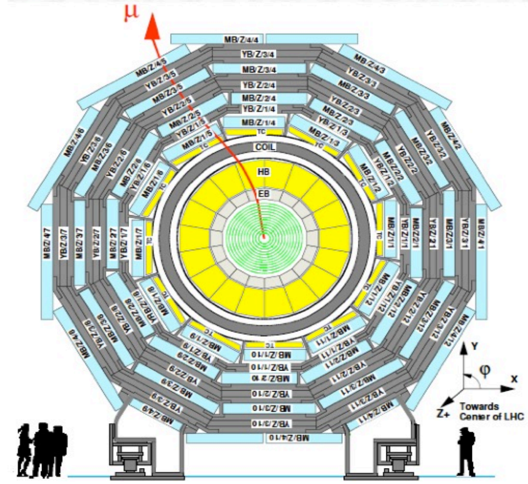
- First beam: Sept.2008
- 2012: 2 x 4 TeV
- 2015/18: 2 x 6.5 TeV
- 2021/23: 2 x 7(?) TeV

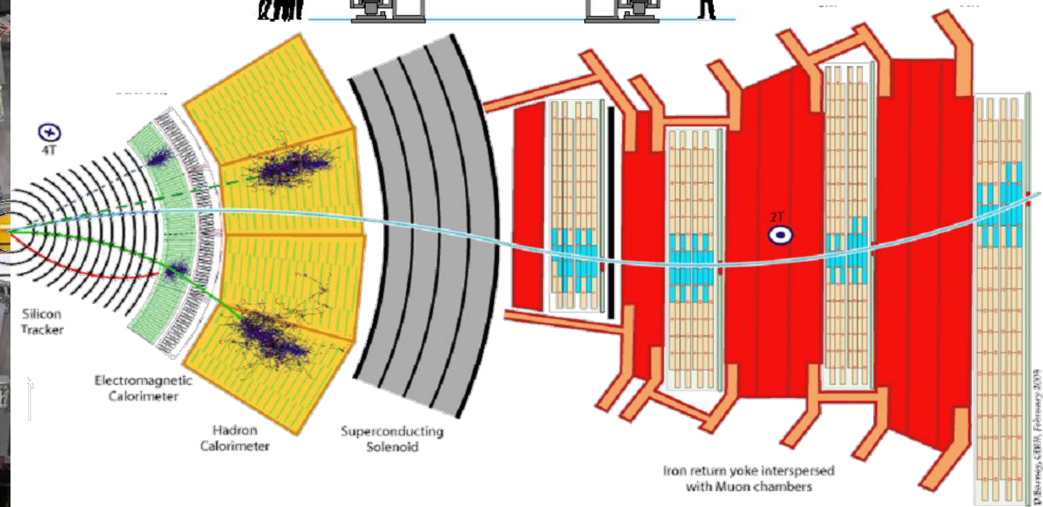
LHC experiments located at 4 interaction points

The LHC experiments








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

Proton collisions at the LHC

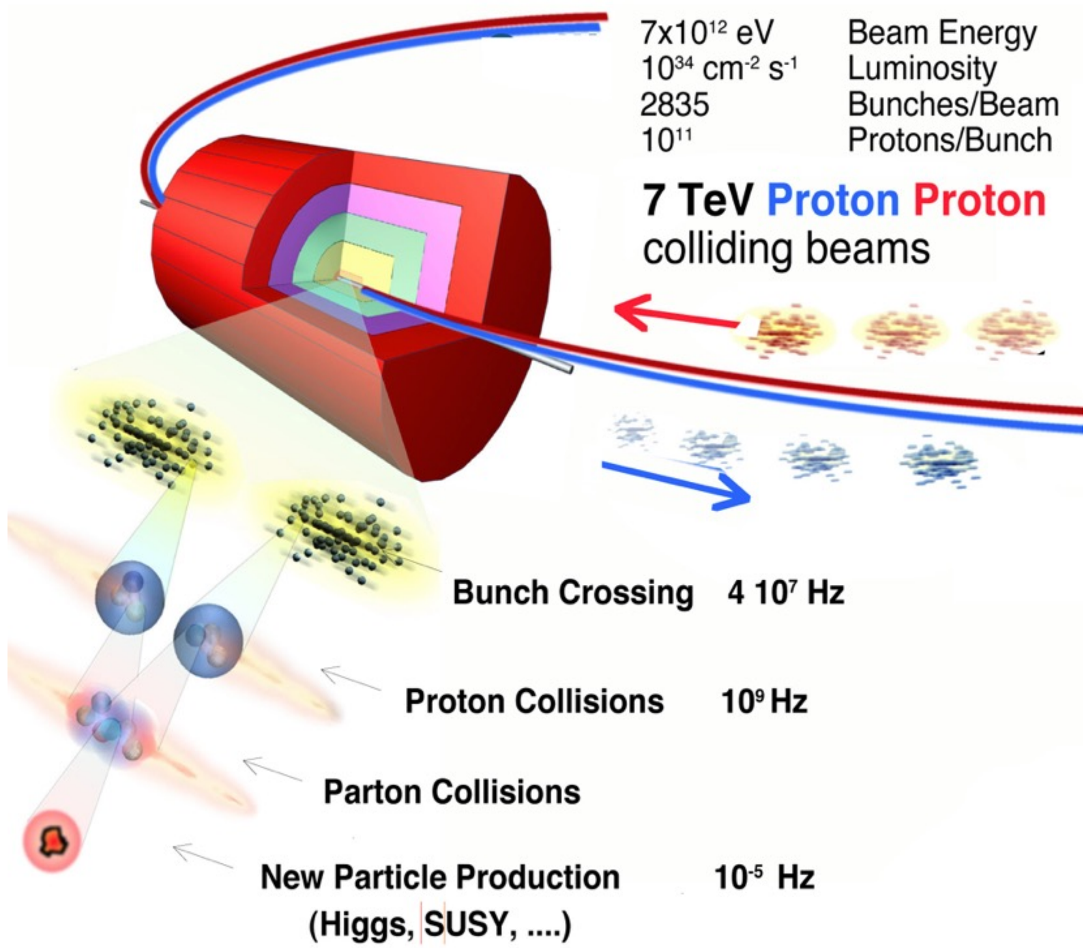
2010-2012

- Energy: 7/8 TeV
- Luminosity: 8×10^{33} $cm^{-2}s^{-1}$

2015-2018

- Energy: 13 TeV
- Luminosity: 2×10^{34} $cm^{-2}s^{-1}$

LHC collisions will restart in 2021 (14TeV?)



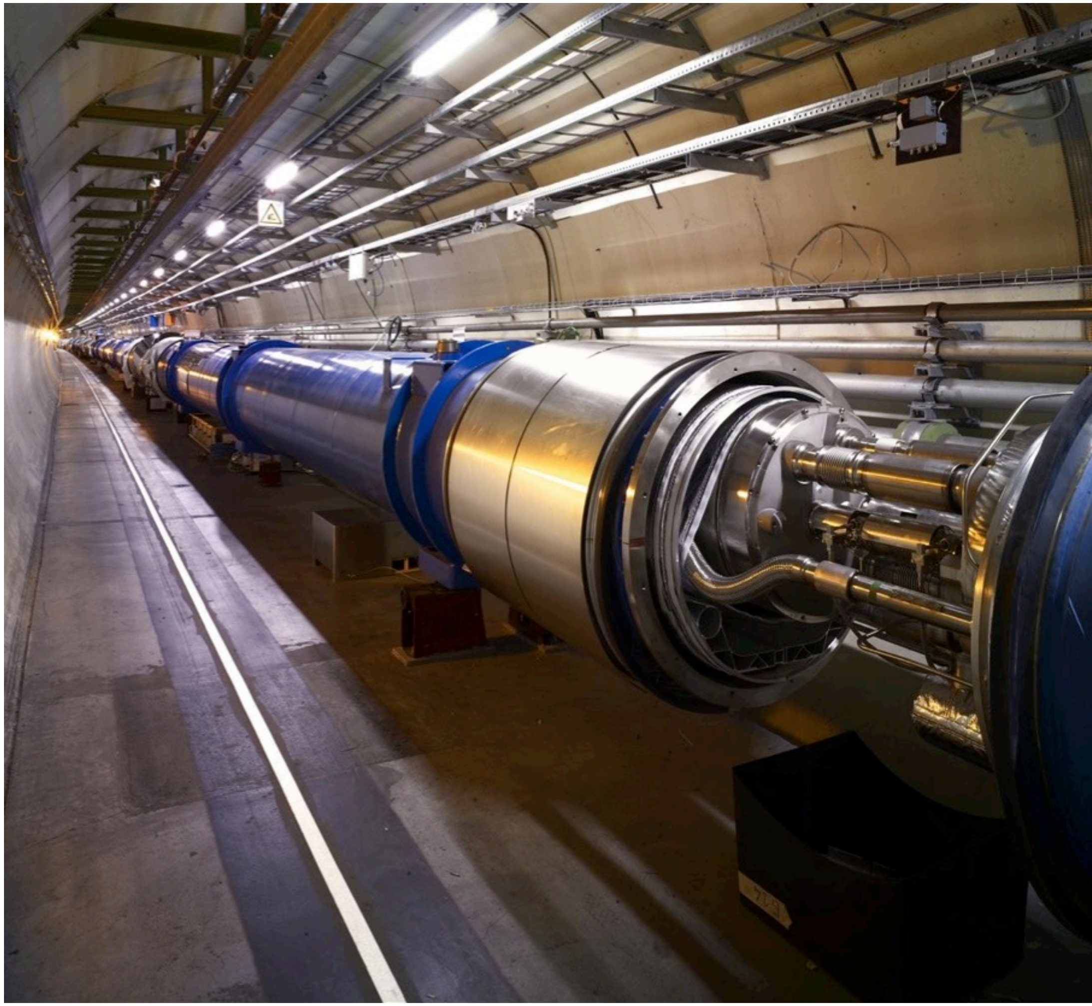
Accelerator challenges

Relative to the Tevatron (Fermilab, USA)

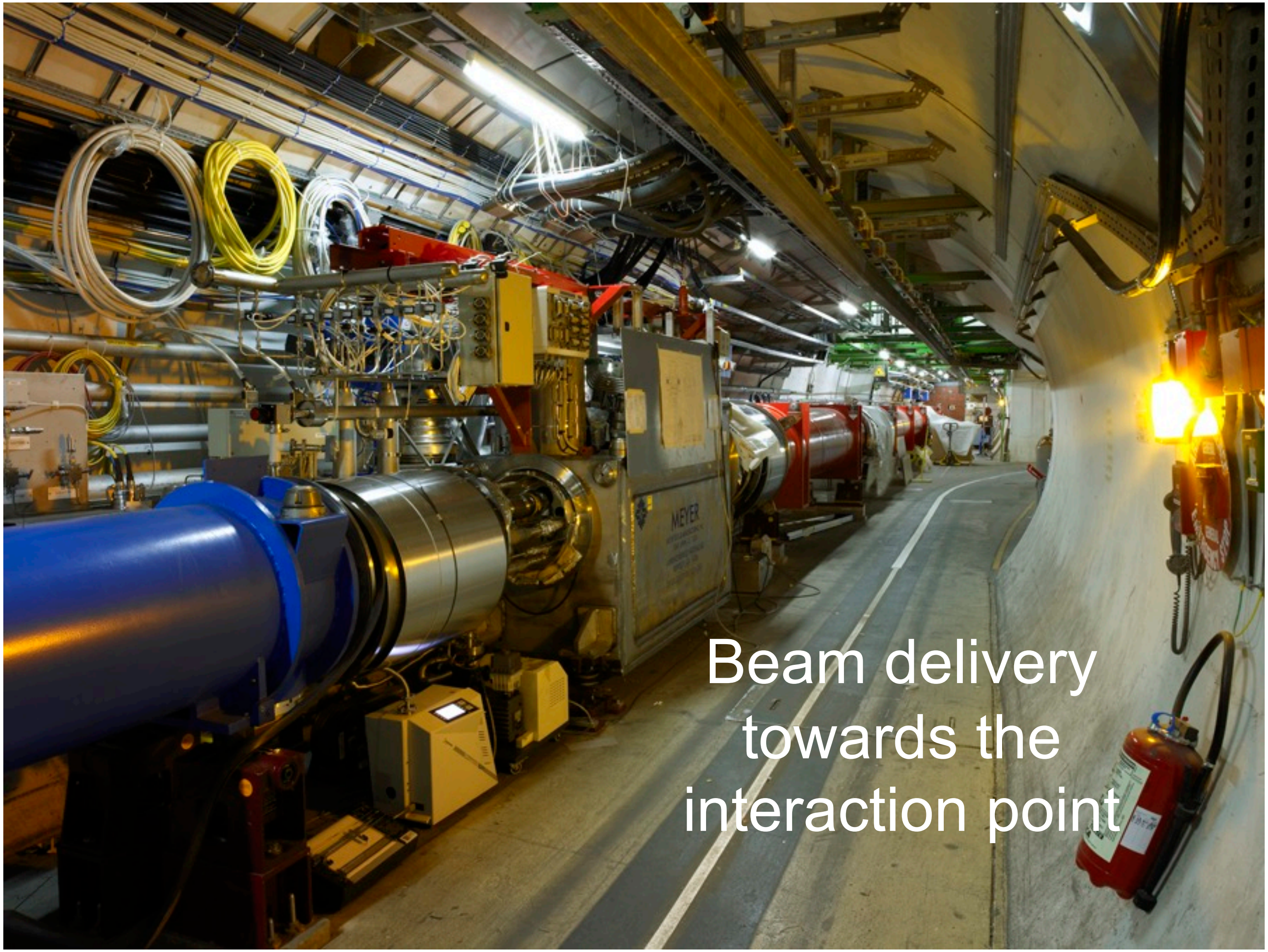
- Energy (14 TeV) x 7
- Luminosity (10^{34} $cm^{-2}s^{-1}$) x30

- Superconducting dipoles 8.3 T
- Operating temperature 1.9K (-271 C)
- More than 2000 dipoles
- 100 tons of liquid Helium

- Stored energy per beam: 350 MJoule
- Energy of a train of 400 tons at 150 Km/h
- LHC power consumption 120 MW

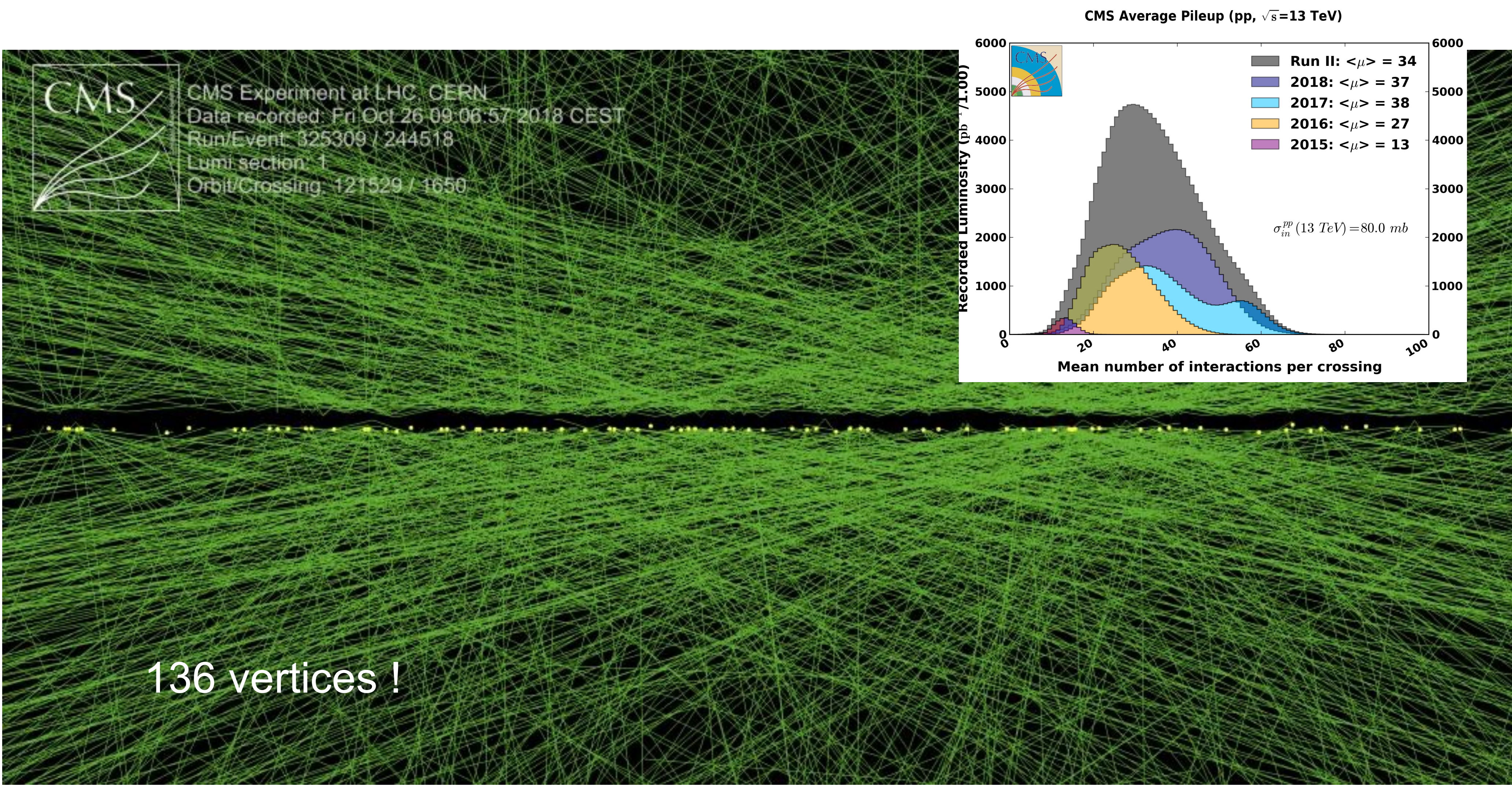


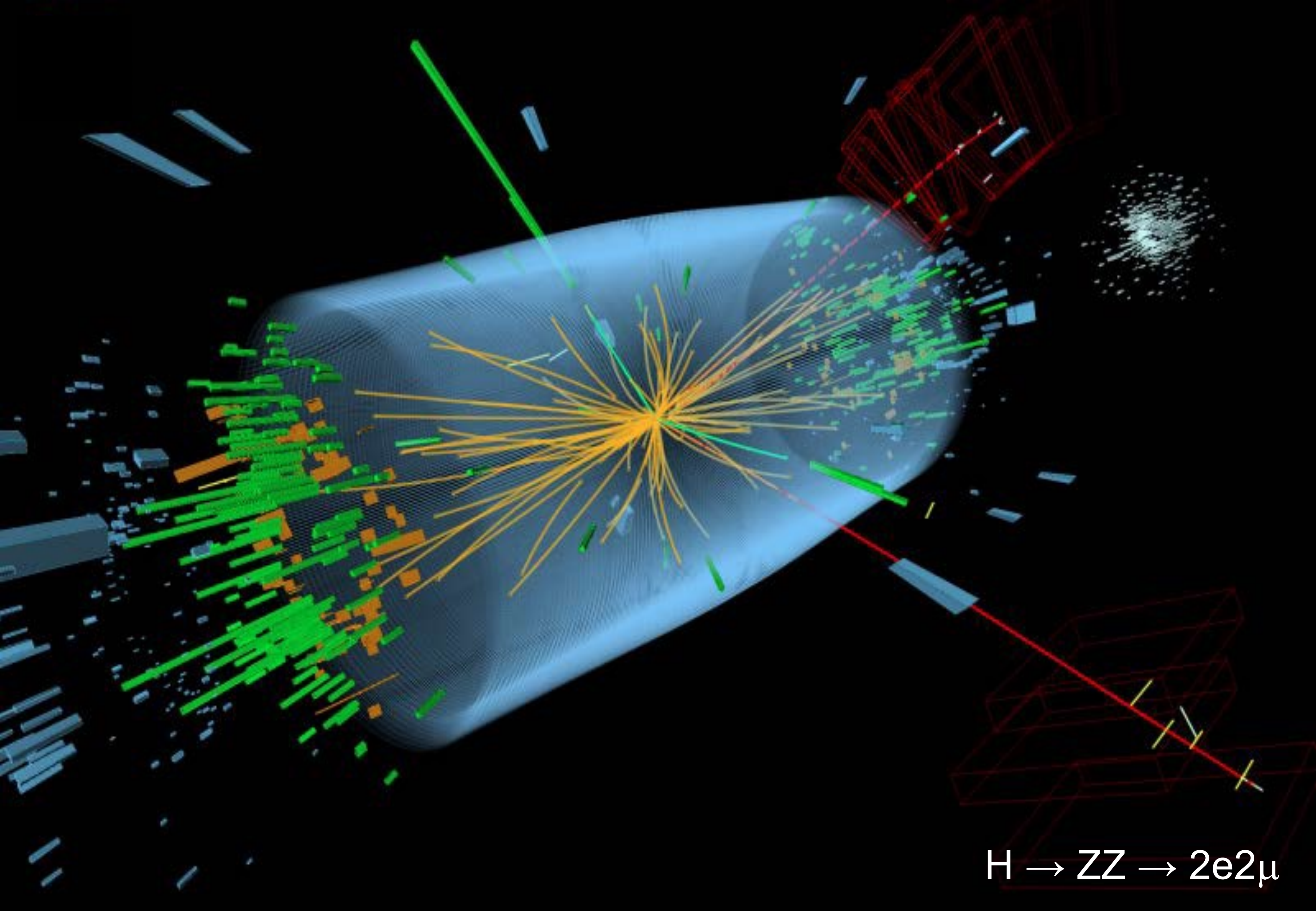
In the tunnel



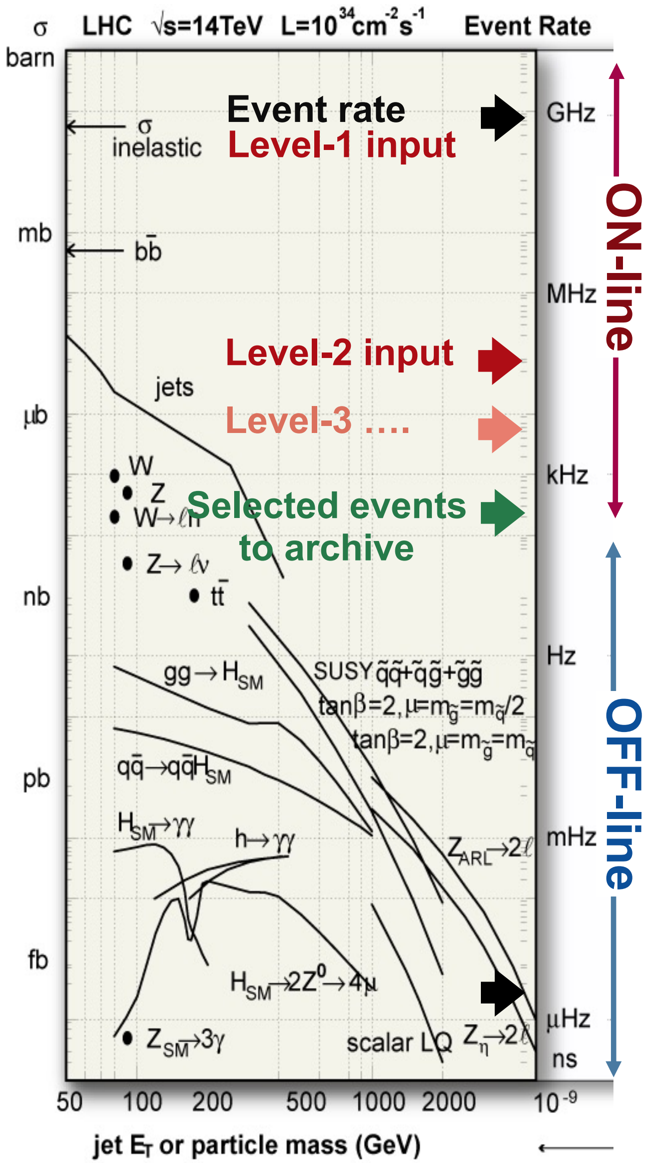

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2010-Jul-09 02:25:58.839811 GMT(04:25:58 CEST)
Run / Event: 139779 / 4994190
First collisions at 7 TeV
(c) CERN 2009. All rights reserved.

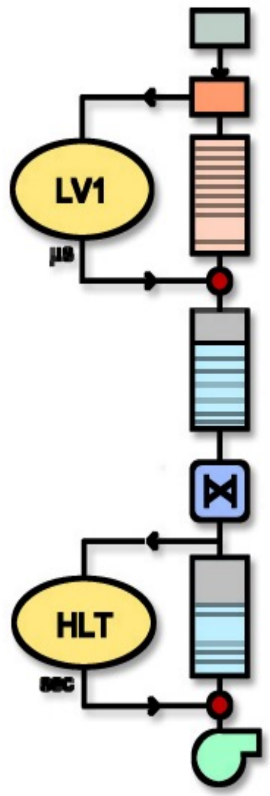
…in a challenging environment




H → ZZ → 2e2μ

Trigger



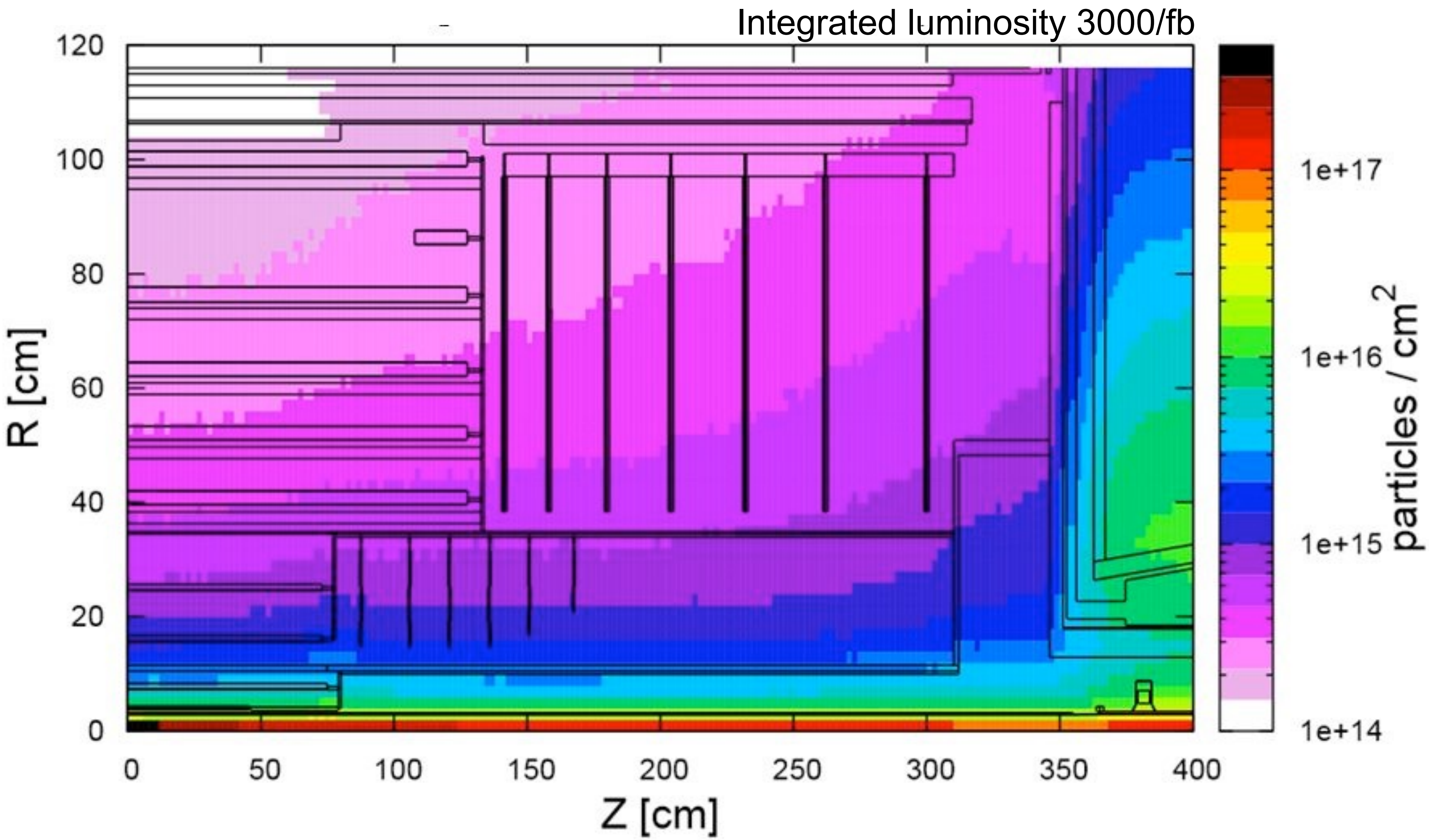


Trigger system decide if the event is interesting to be recorded

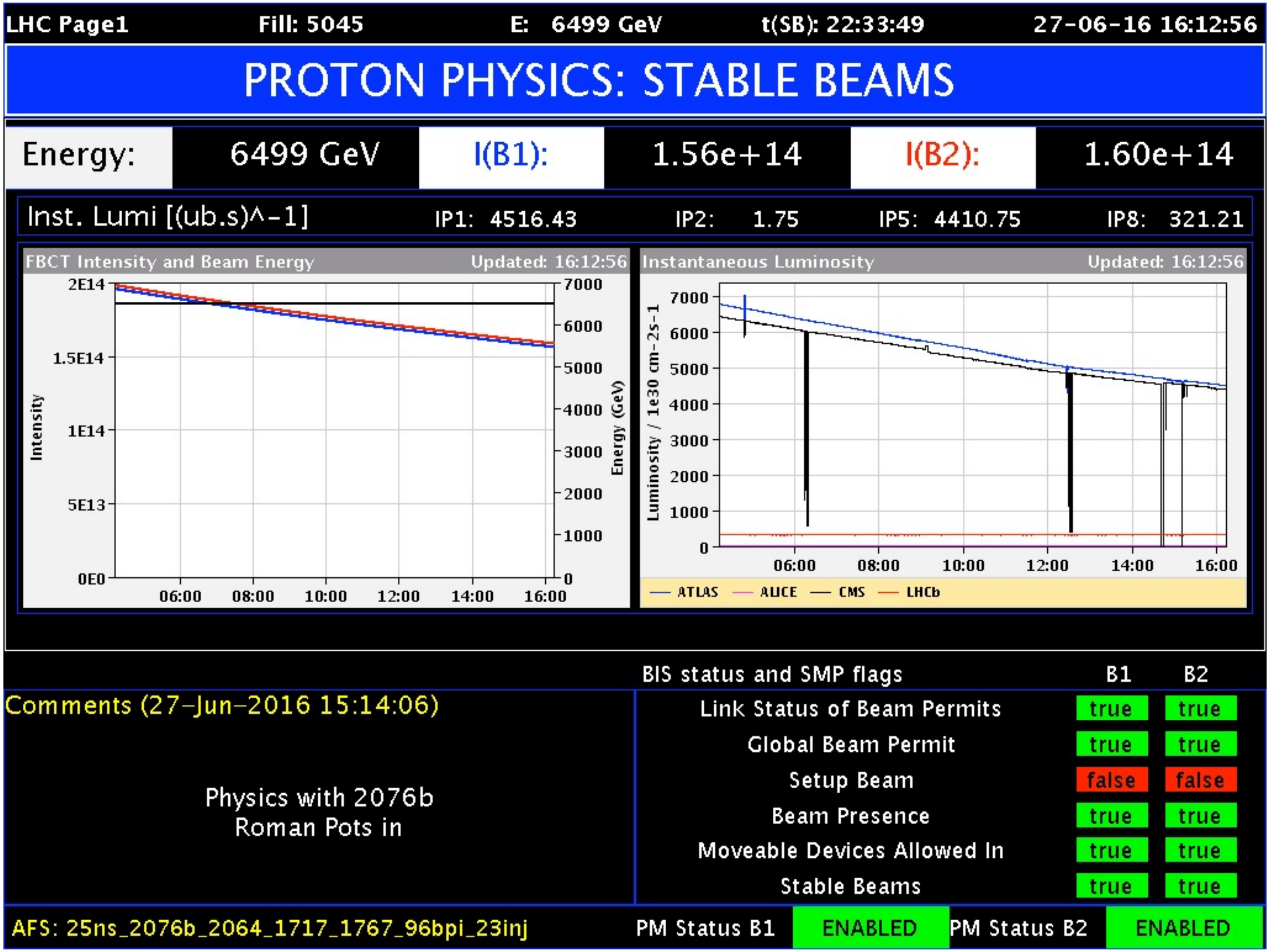
Two-step process:
- Level 1: dedicated hardware processors

- High level: computer farm

High radiation levels



LHC Page 1: stable beams



Experiment control rooms

Cessy: Master Control Room

Fermilab: Remote Operations Center

Meyrin: CMS Data Quality Monitoring Center

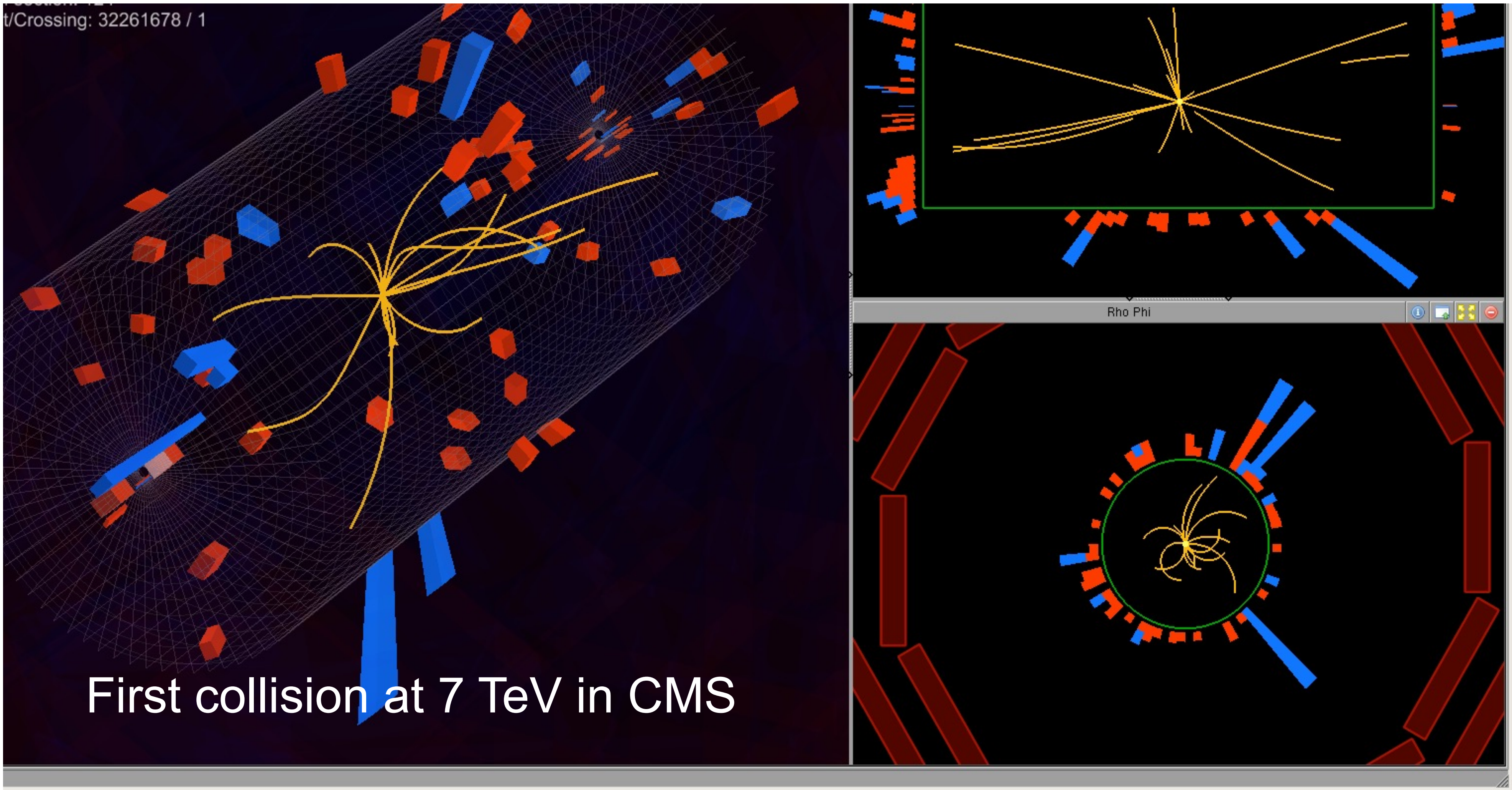
Any Internet access

2009: first collisions at LHC

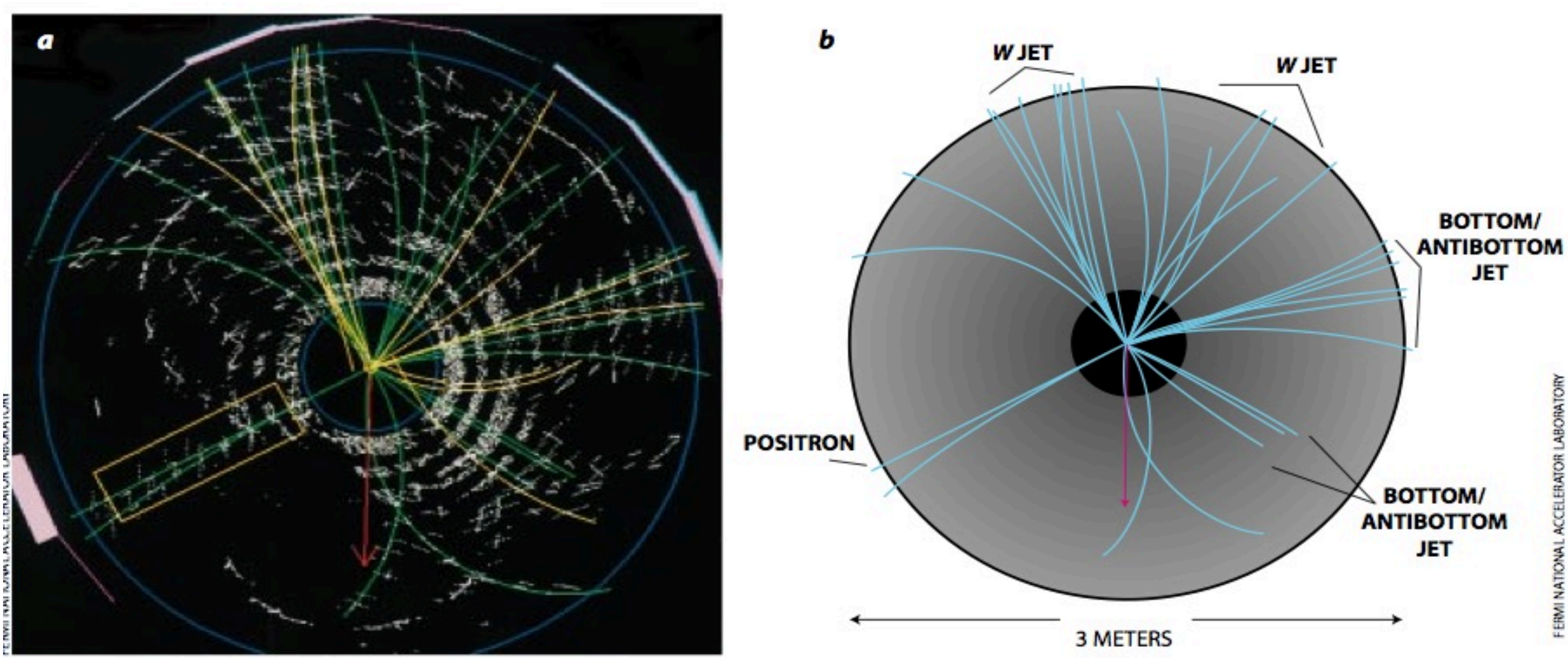
November 23, 2009
First collisions at 900 GeV

December 14, 2009
First collisions at 2.36 TeV

March 30, 2010
First collisions at 7 TeV

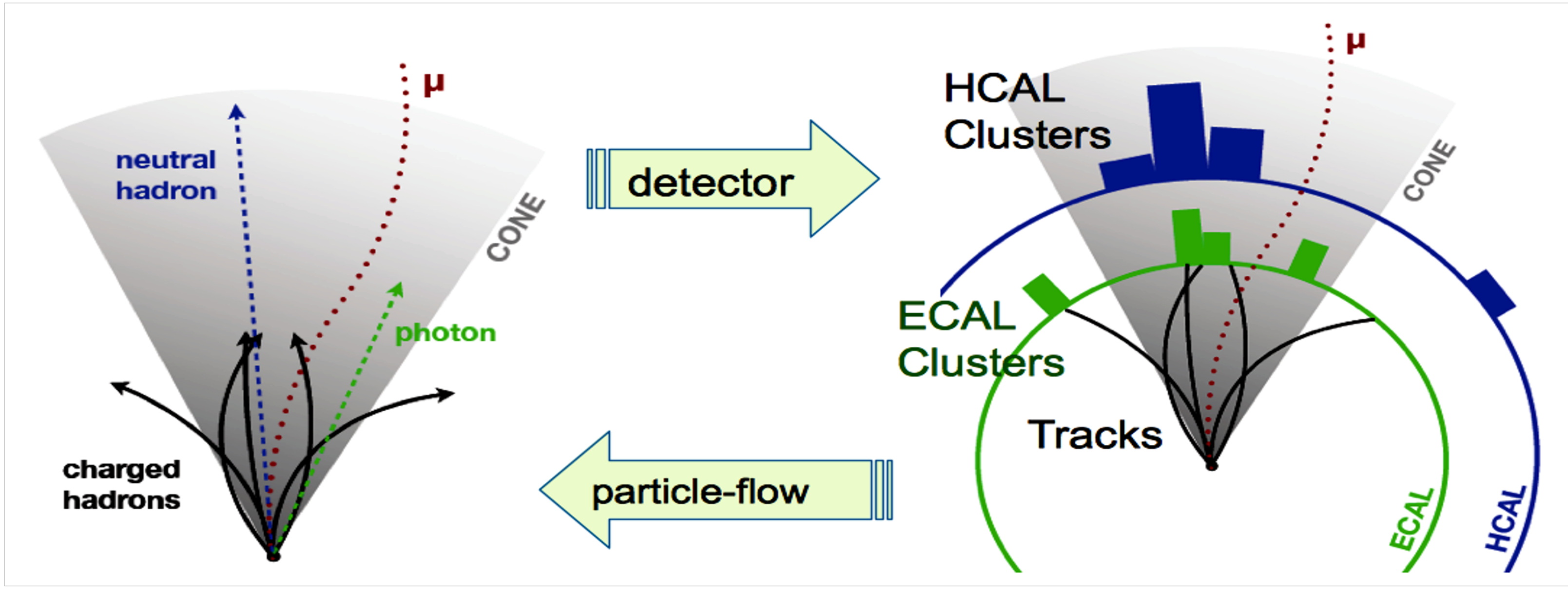


From Picture to Reconstruction

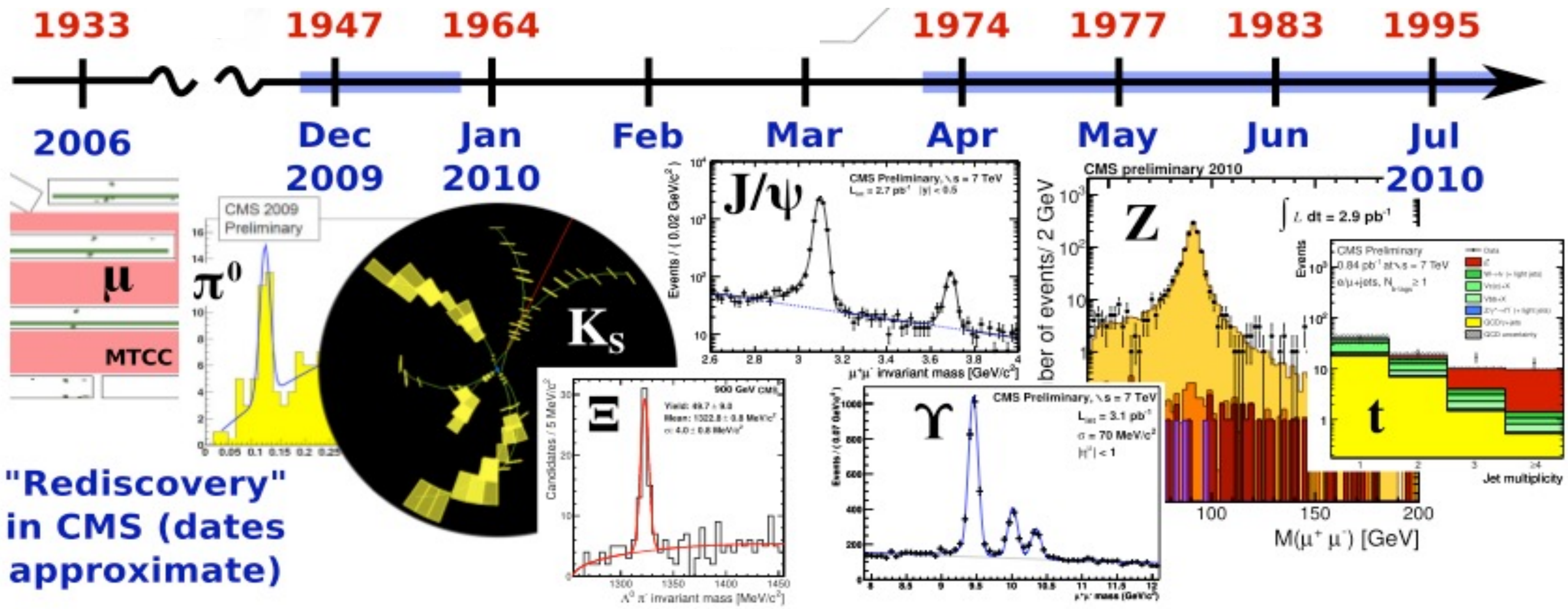


Particle Flow event reconstruction

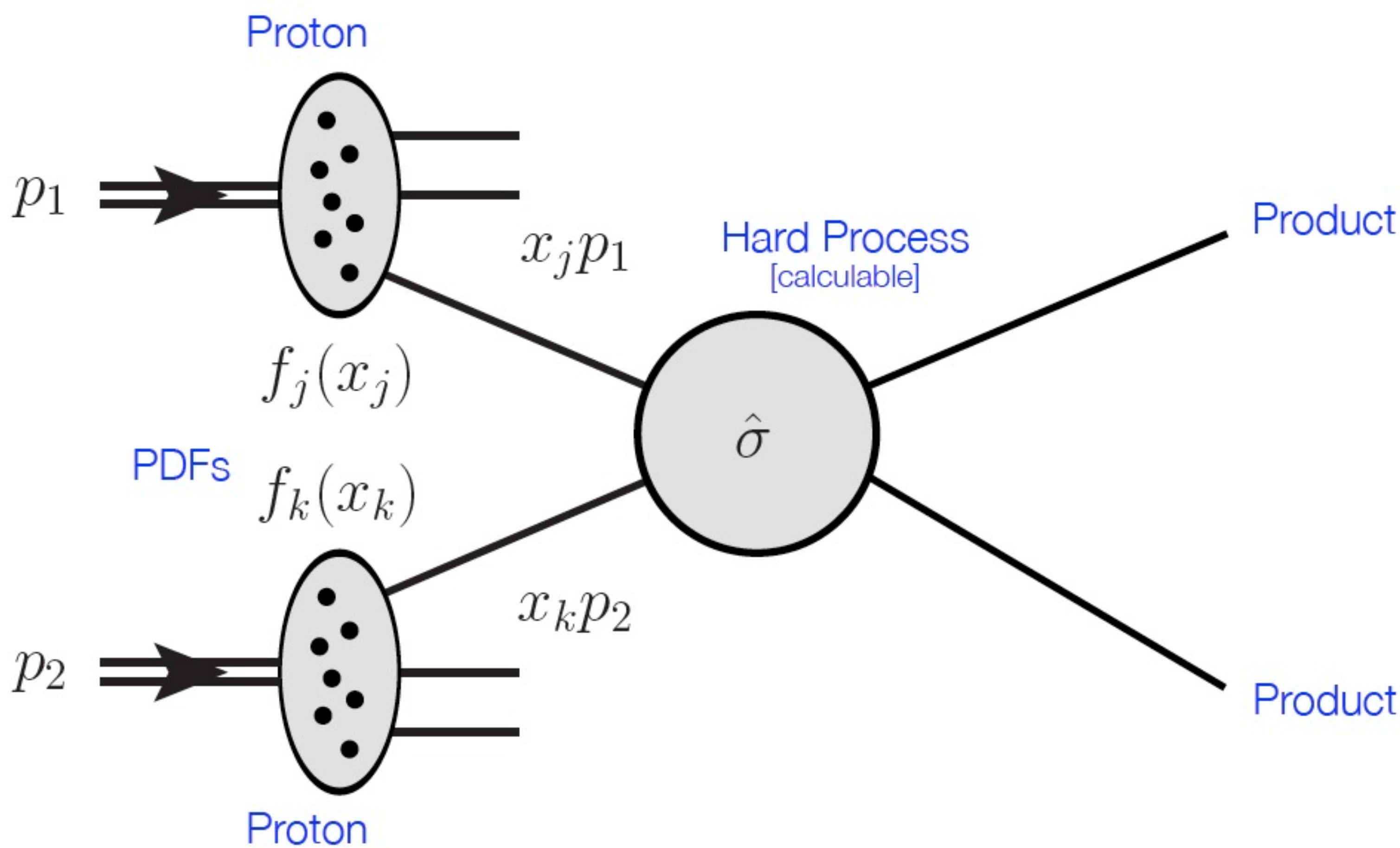
- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision
  - charged hadrons, neutral hadrons, photons, muons, electrons
  - use complementary info. from separate detectors to improve performance
  - tracks to improve calorimeter measurements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



Re-discovery of the SM at LHC

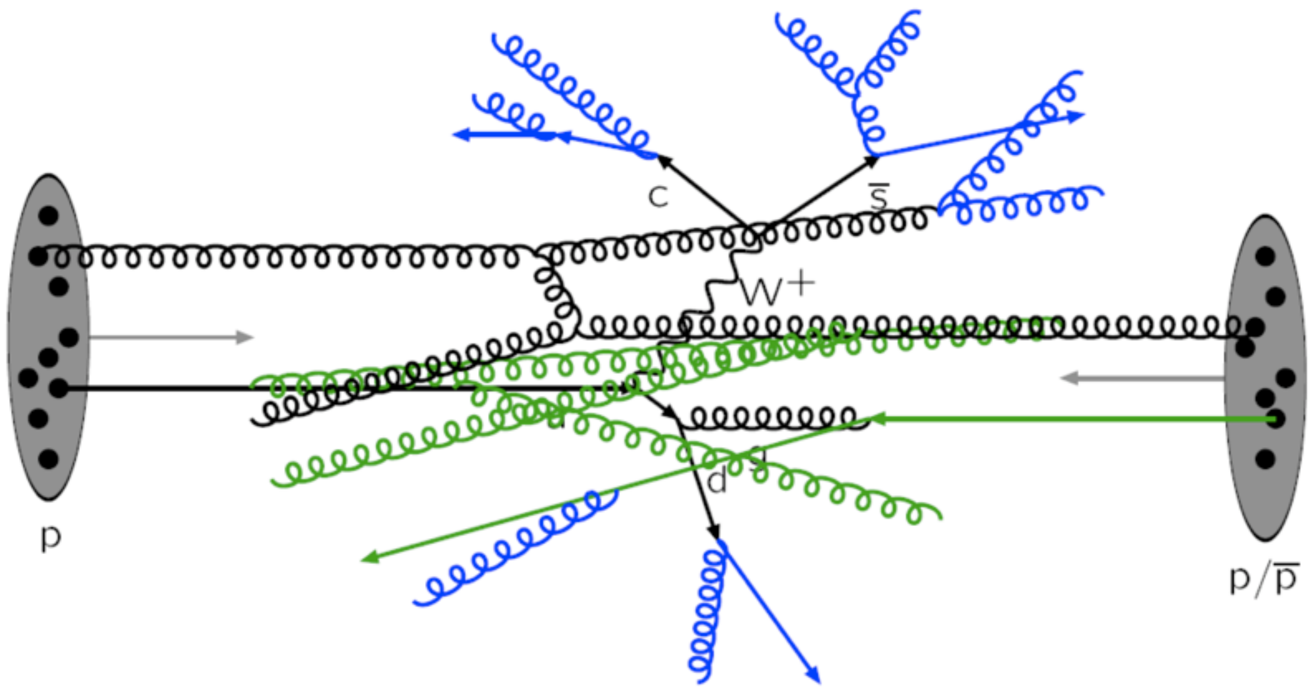


Hadron interactions: pp scattering



Proton-proton scattering at LHC

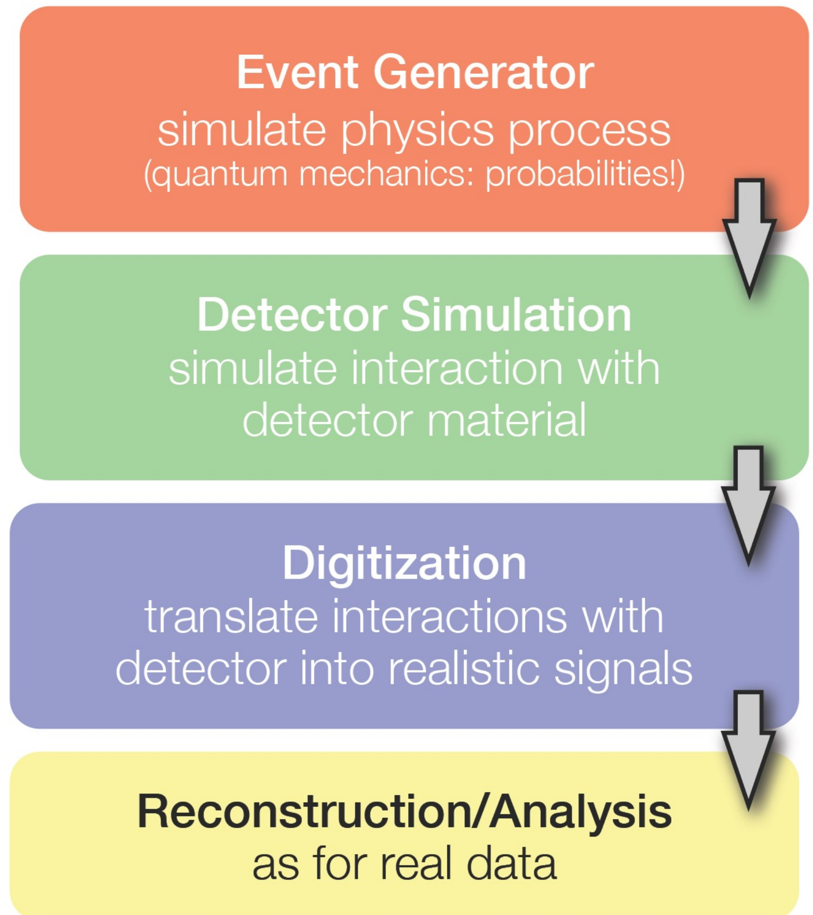
- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction [“underlying event”]



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)*

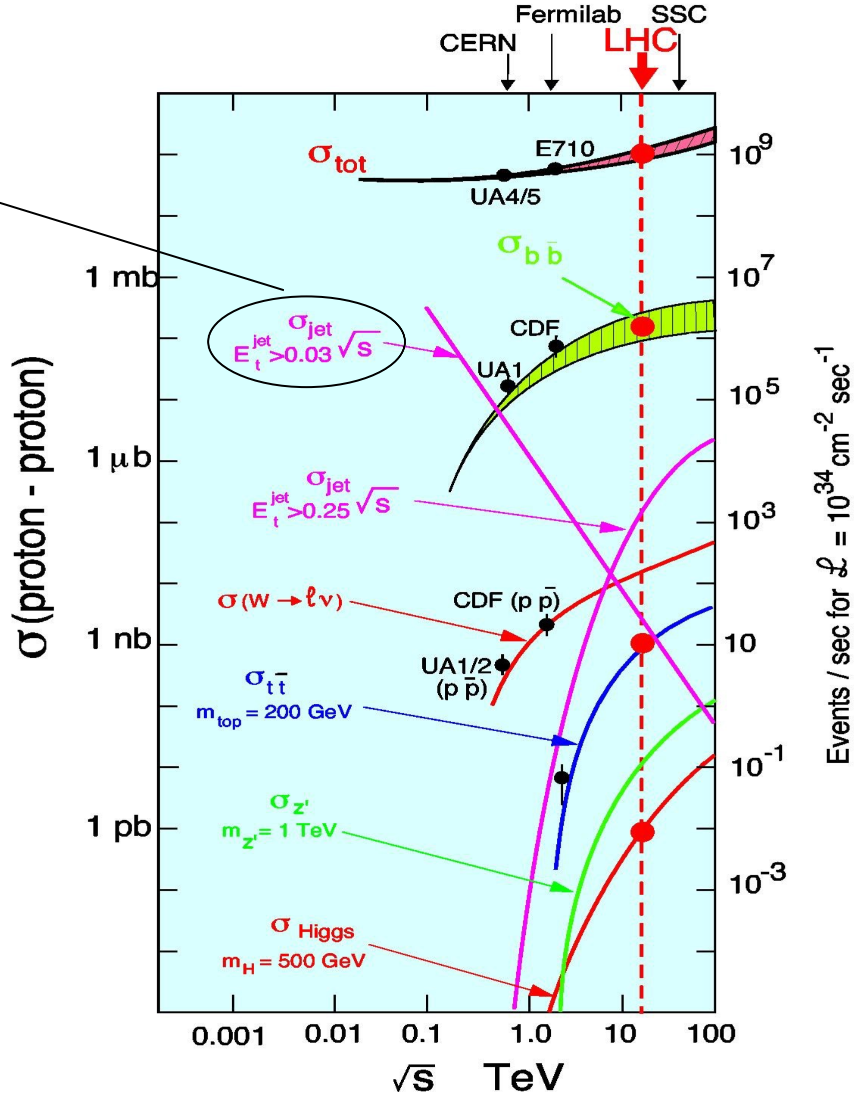
$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

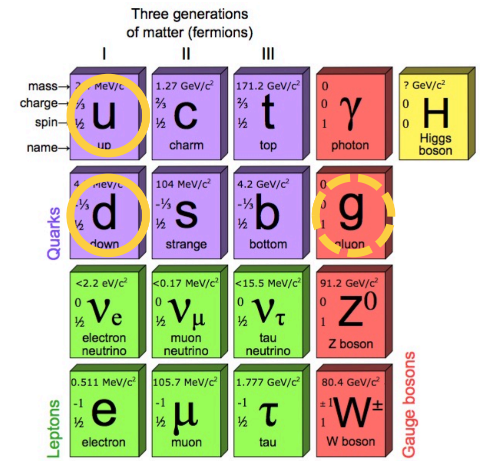
Acceptance
(experimental: detector, efficiencies)

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

Minimum Bias

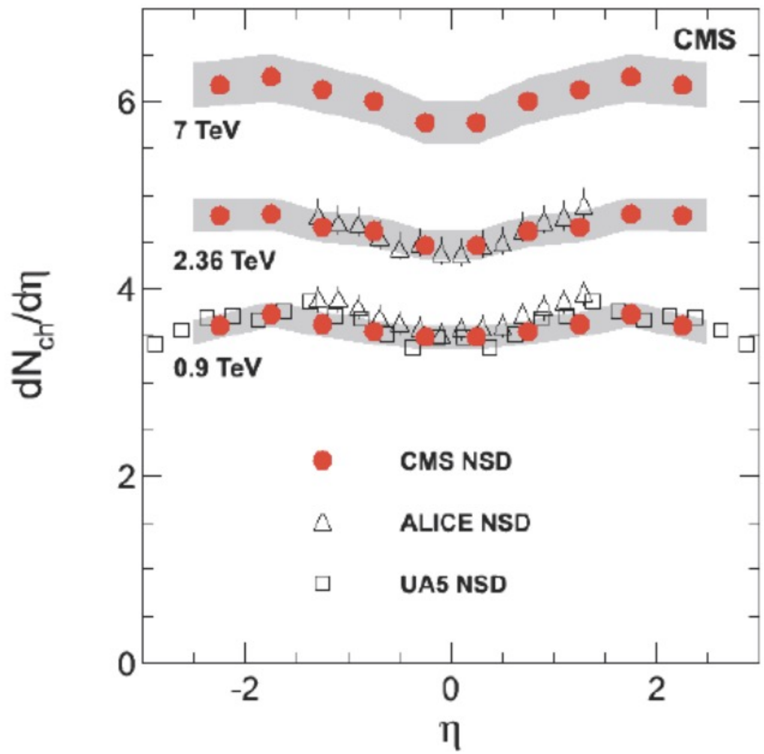
low p_T particle production

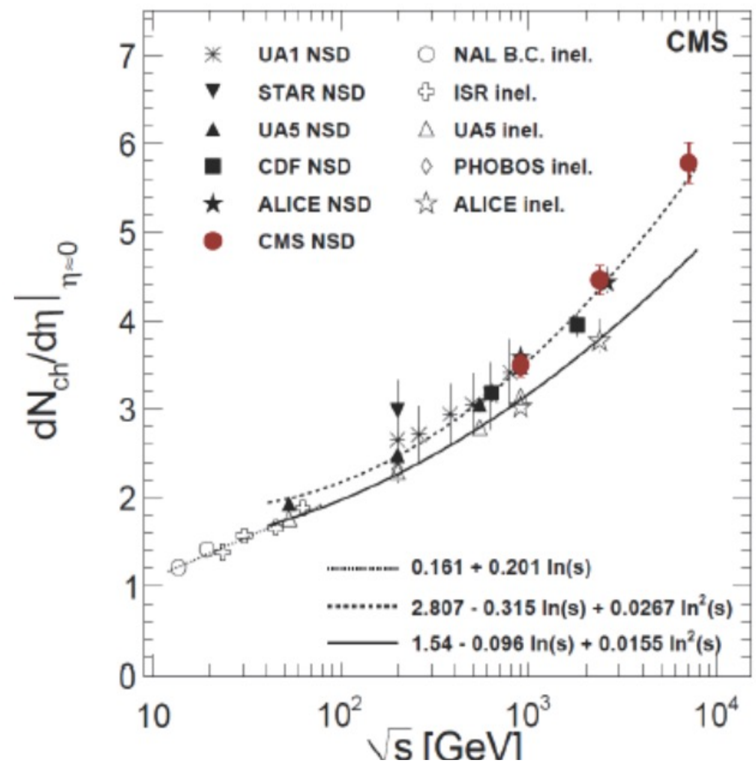




Minimum bias events

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

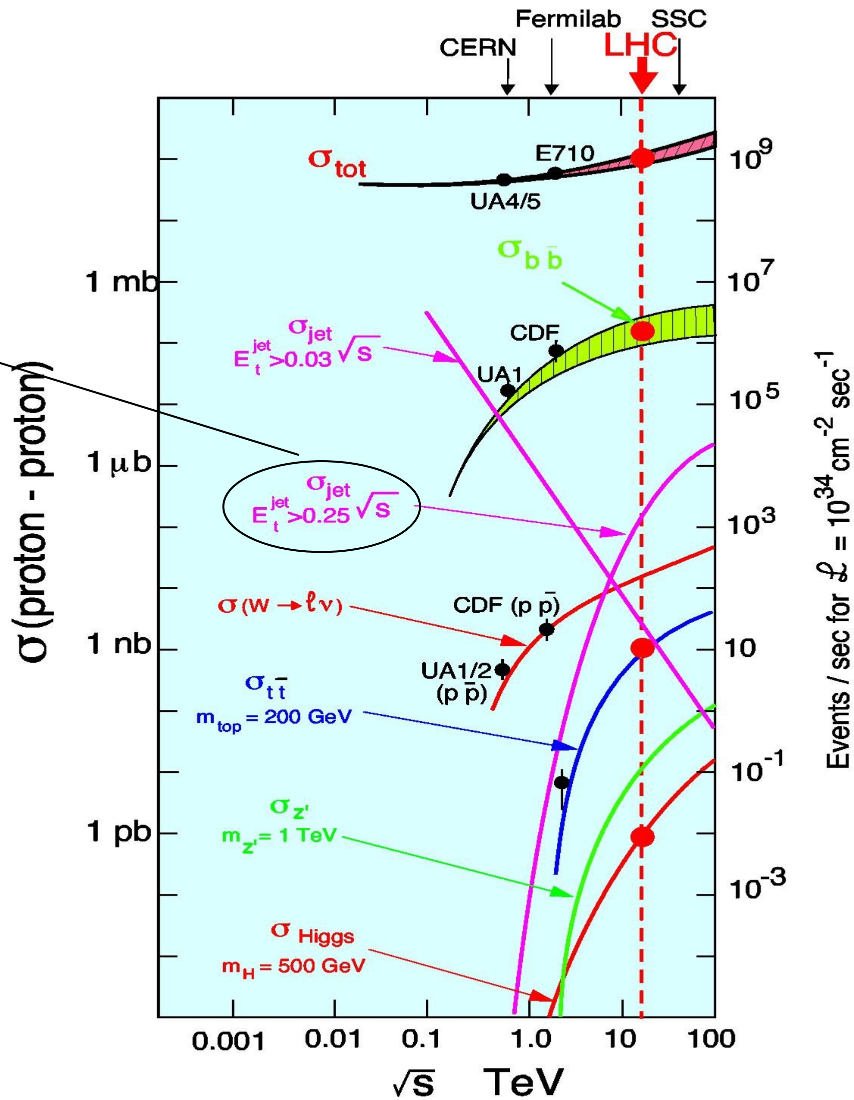


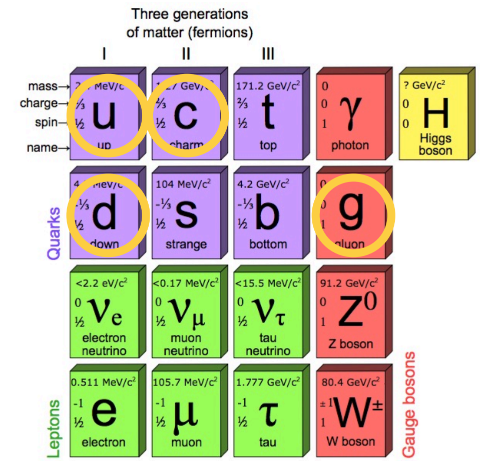


Tuning of MC generators needed

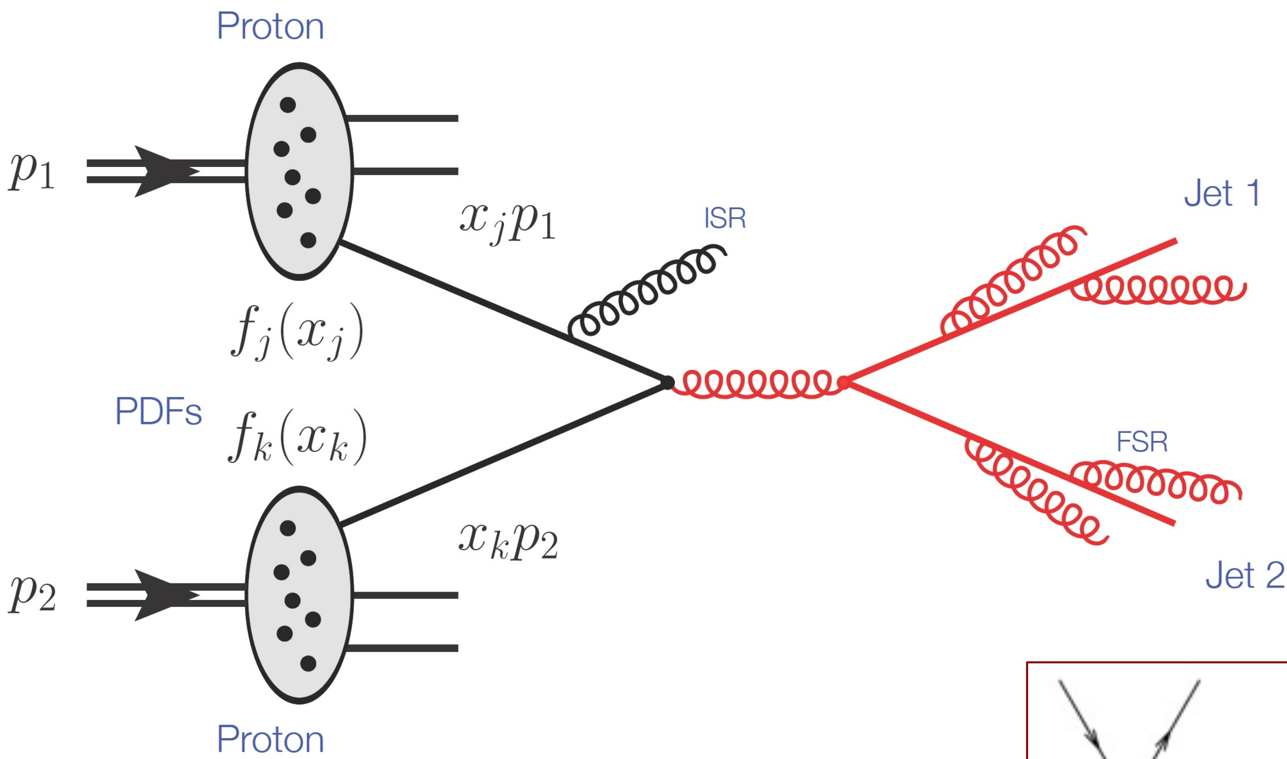
Jet production

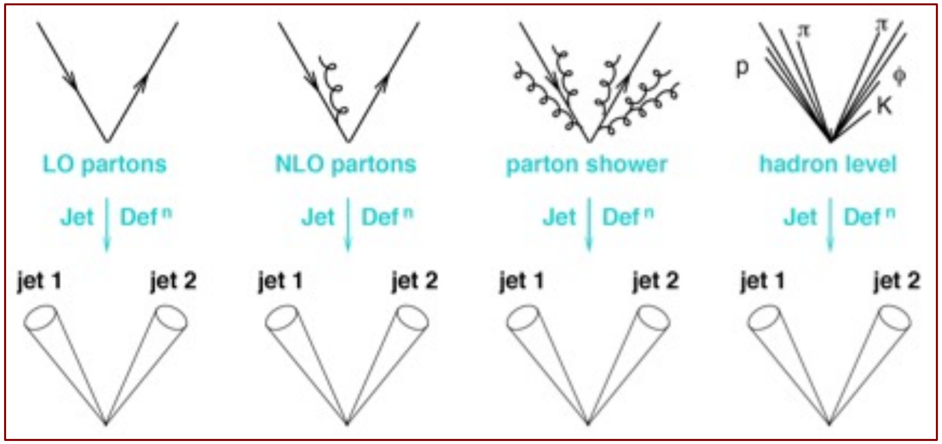
jets





Jet production at LHC

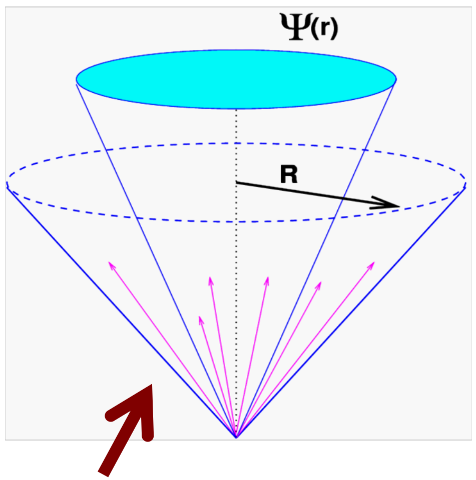


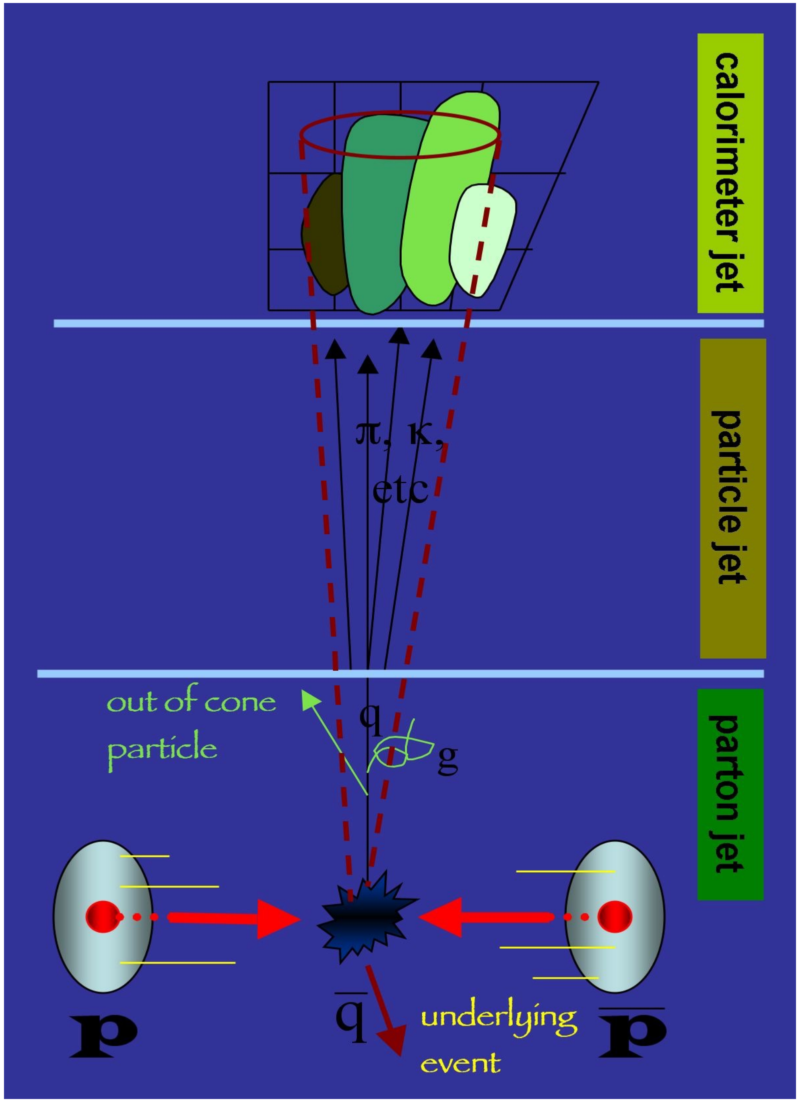


Available up to NLO, first NNLO calculations becoming available

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

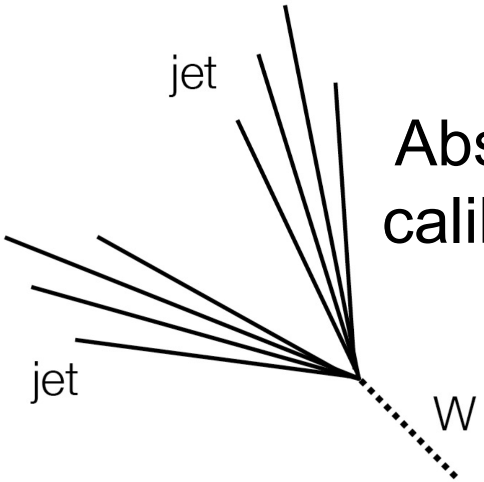


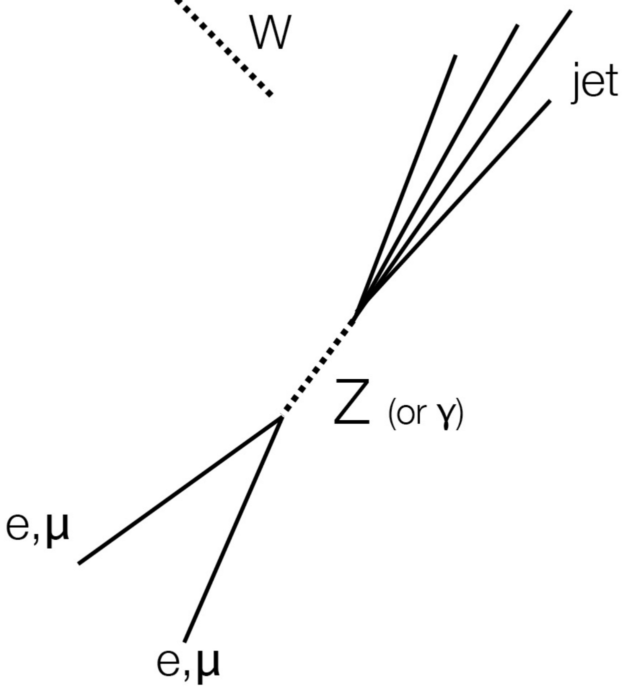


- Measure energy in a "cone"

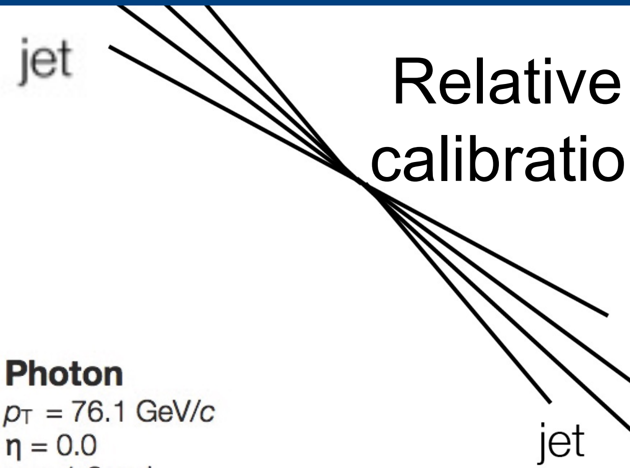
Jet energy calibration

Absolute calibration





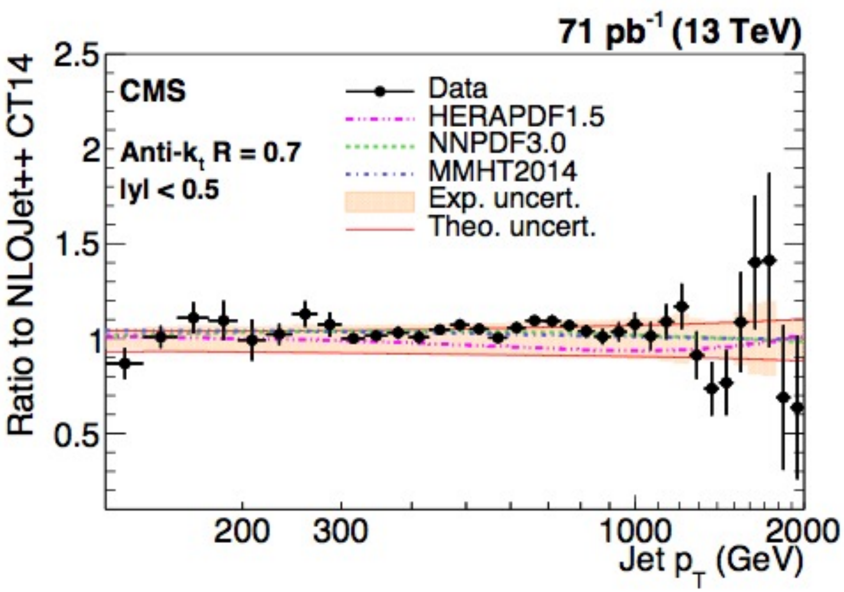
Relative calibration

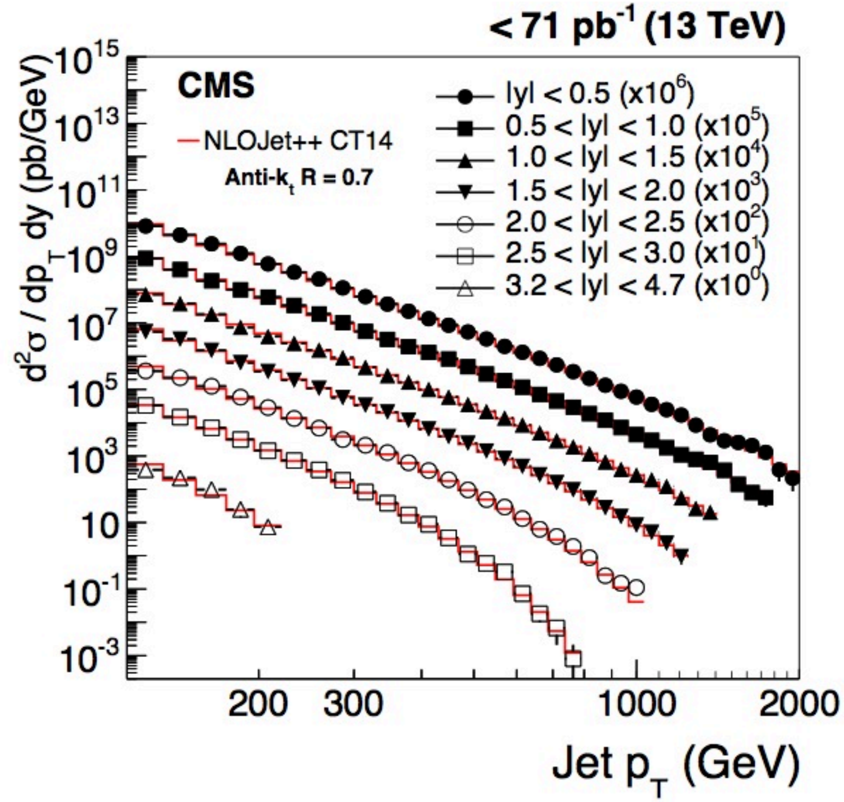


Inclusive jet distribution

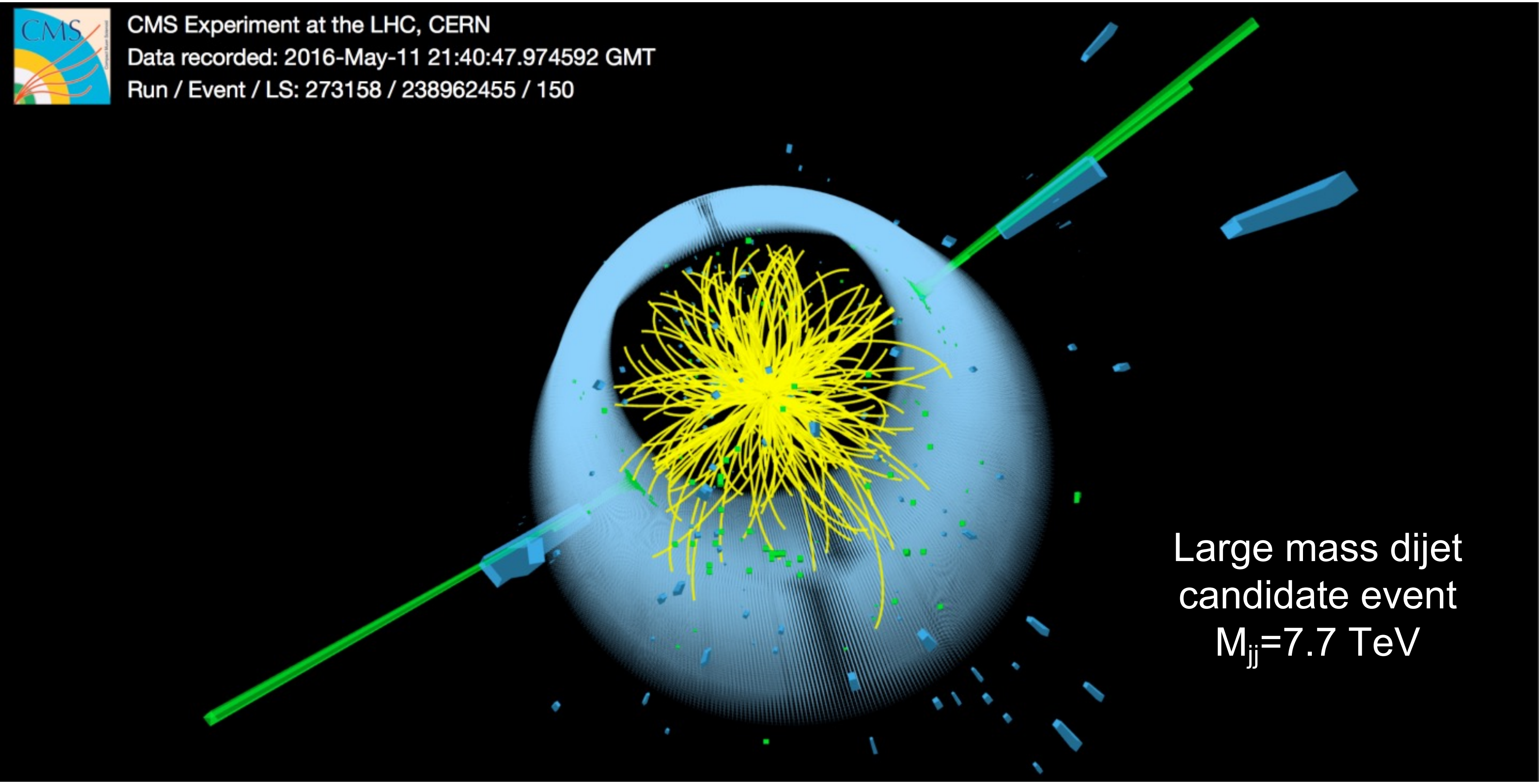
arXiv:1605.04436

- 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



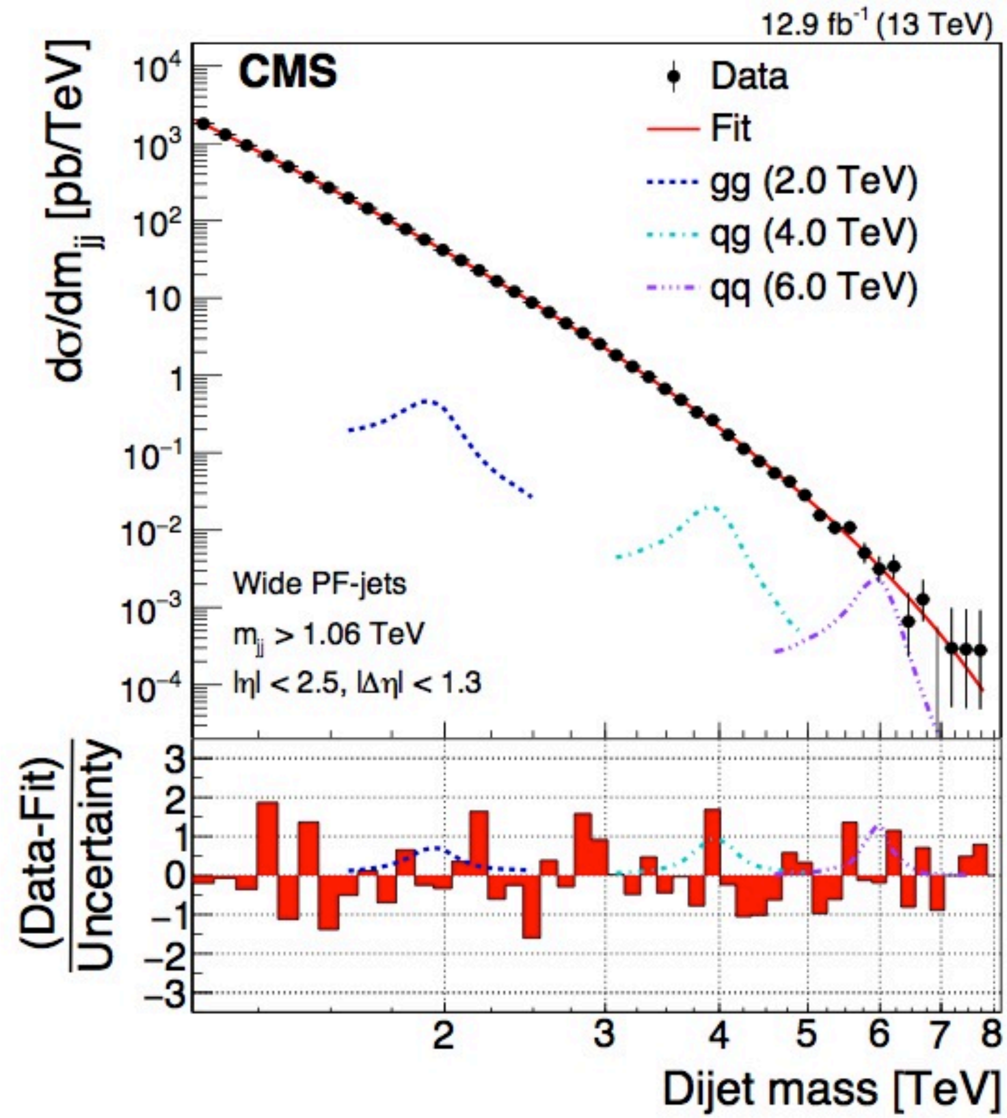
Large mass dijet candidate event
M_{jj}=7.7 TeV

Dijet mass

arXiv:1611.03568

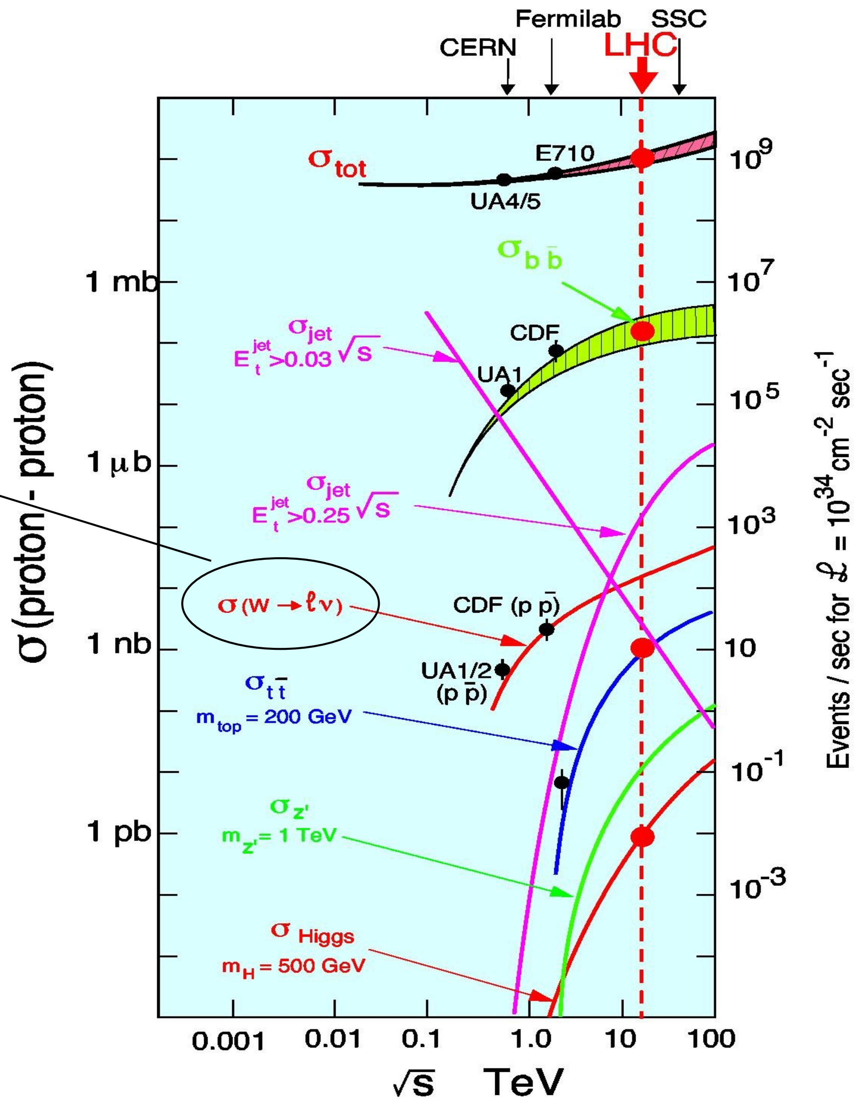
Search for numerous BSM resonances:

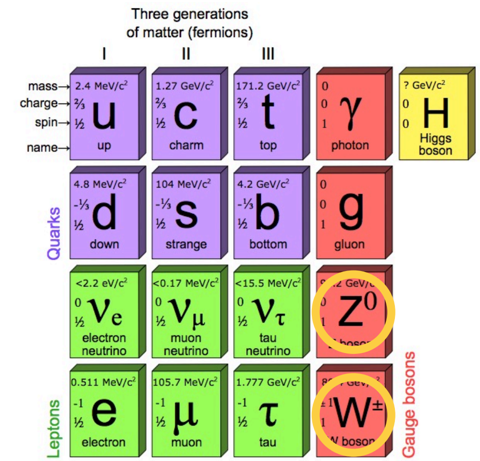
- string resonance, excited quarks, axi-gluons, colorons, E6 diquarks, W' and Z', RS gravitons



W and Z bosons

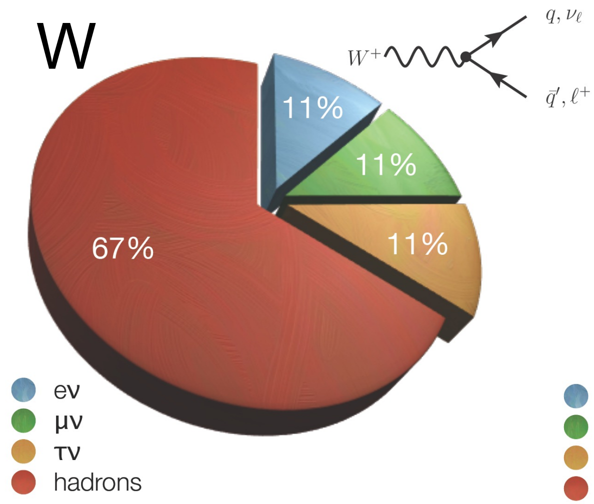
W bosons

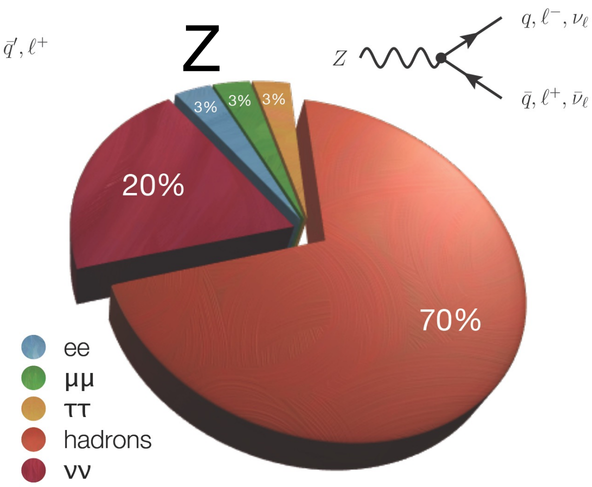


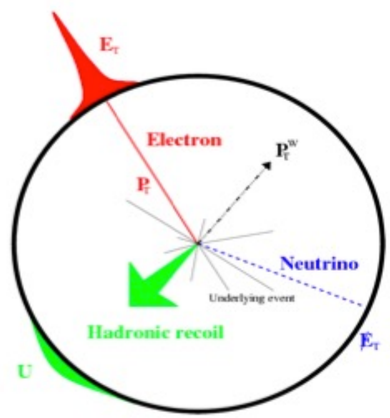


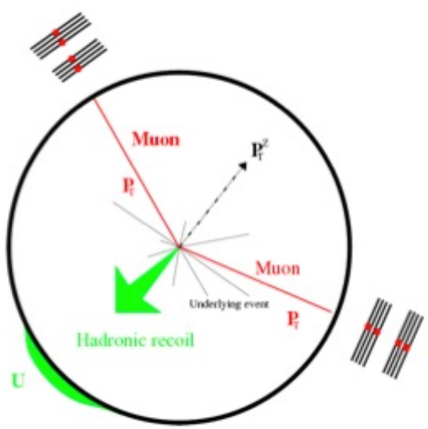
W and Z bosons

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



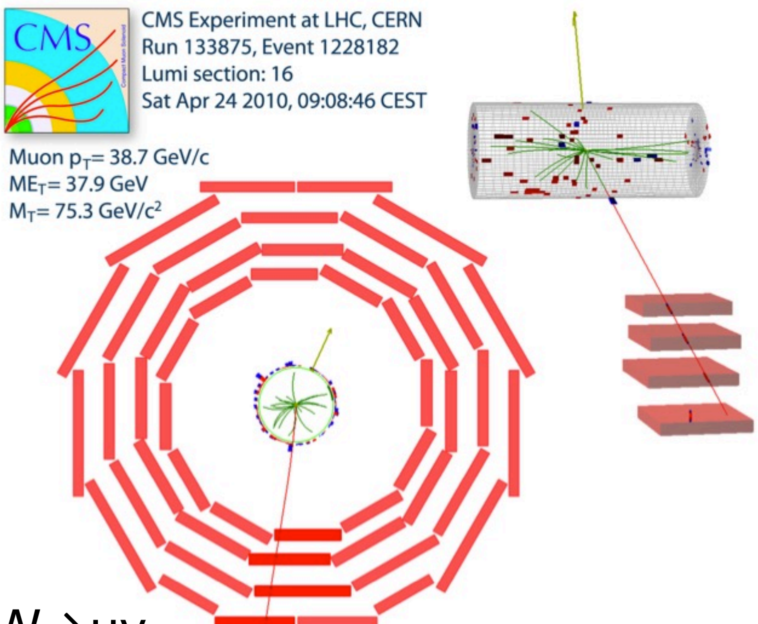




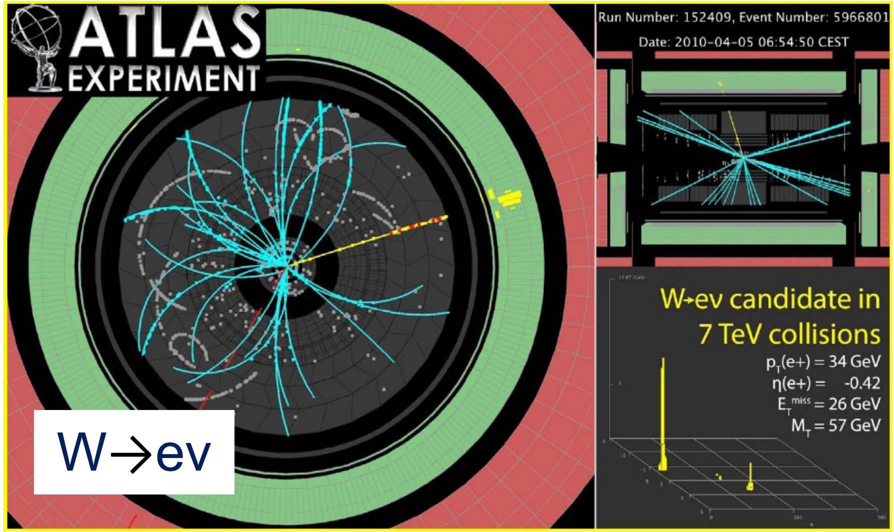


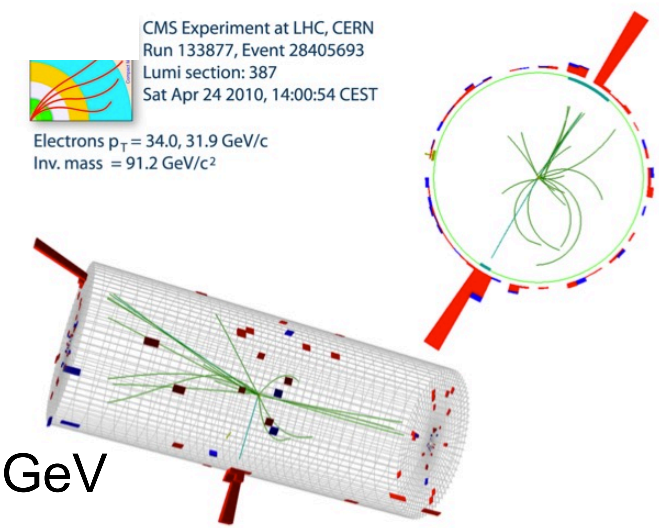
- Isolated high-p_T leptons: starting point of many analyses
  - Good rejection of QCD backgrounds
  - "Tracking" vs "calorimeter" isolation
- Excellent calibration signal
  - Electron energy scale, ID/trigger eff., etc.

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

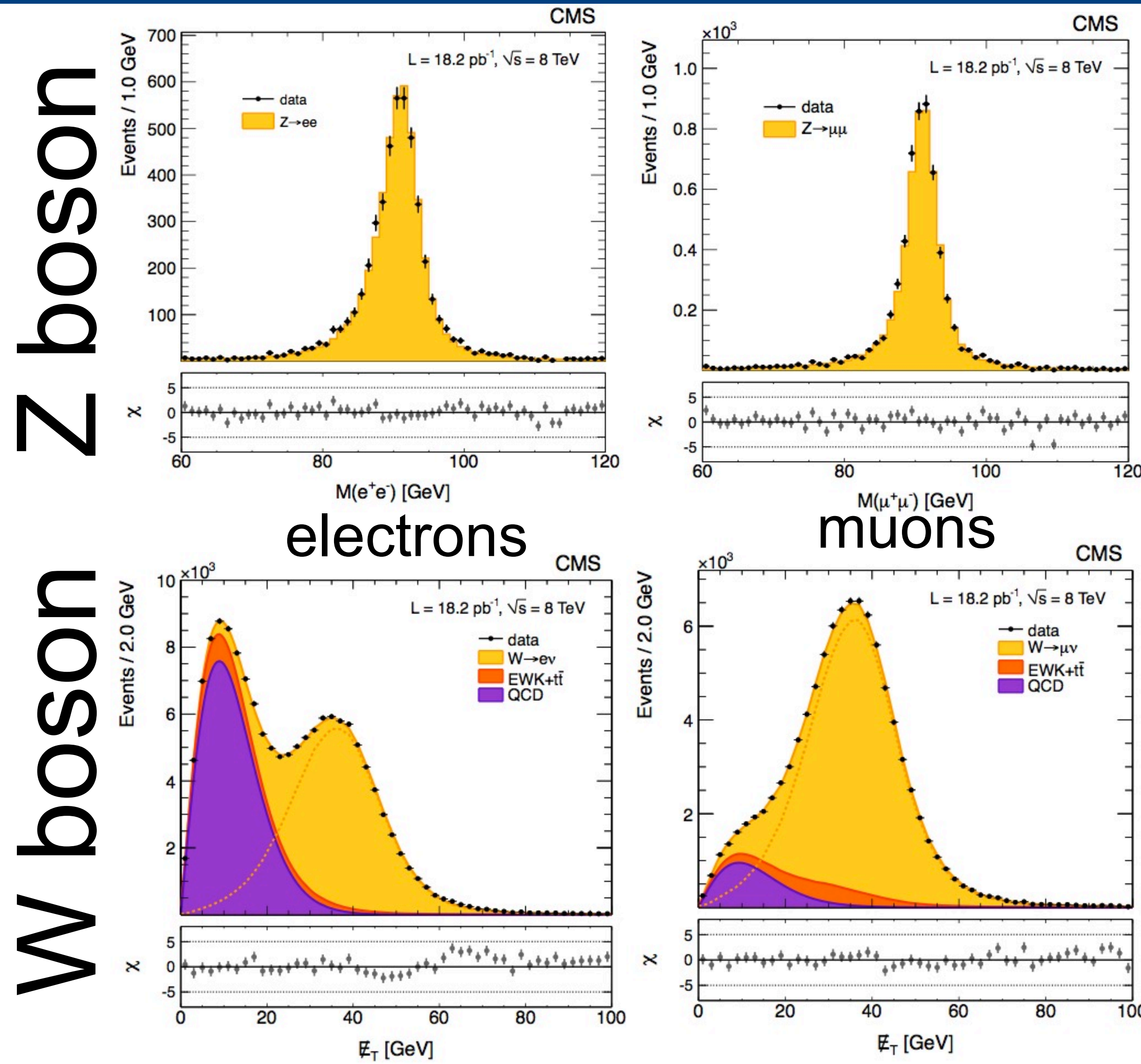
- Invariant mass of two leptons

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

W mass reconstruction

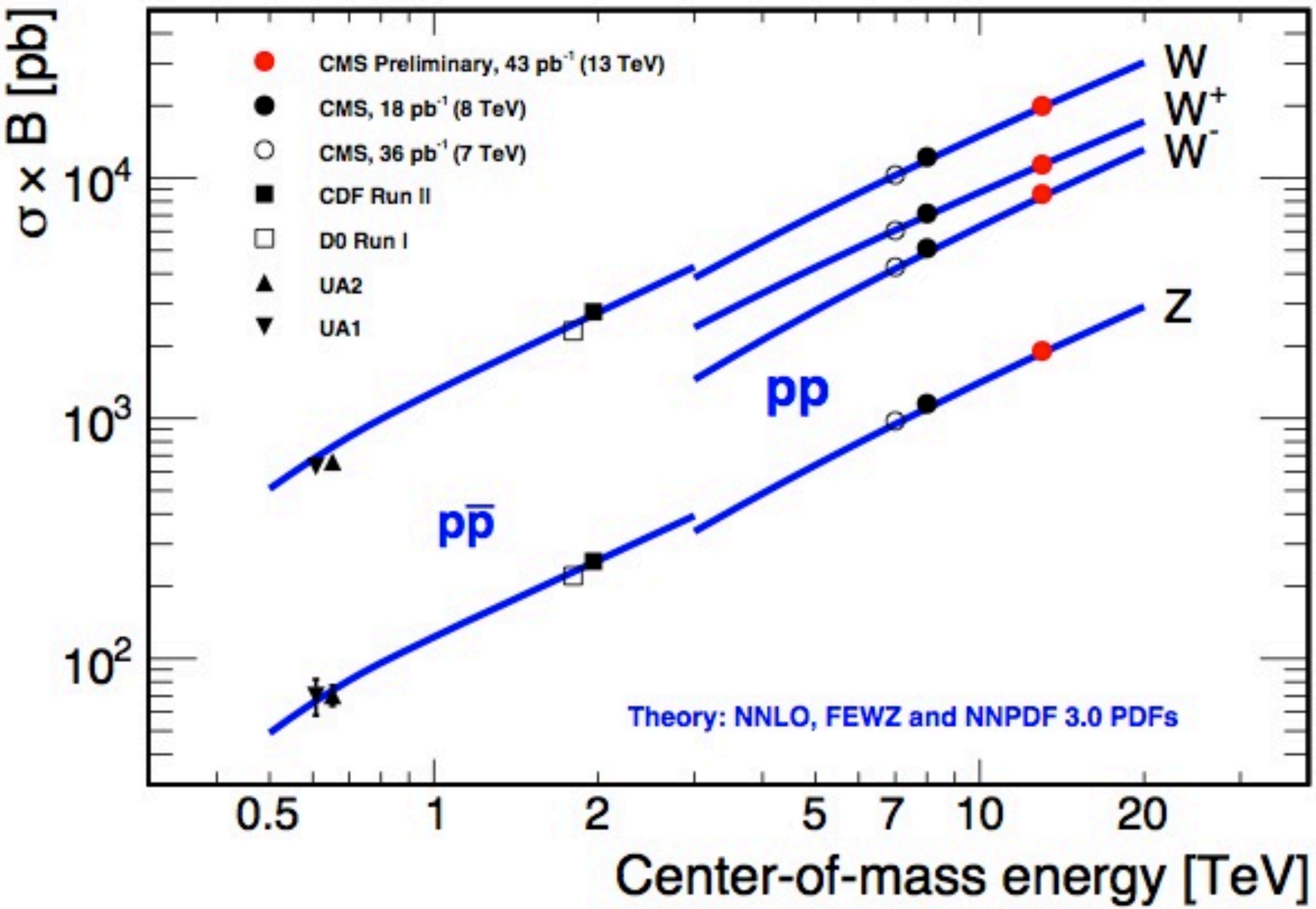
- Do not know neutrino p_Z
- No full mass reconstruction
- Transverse mass

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



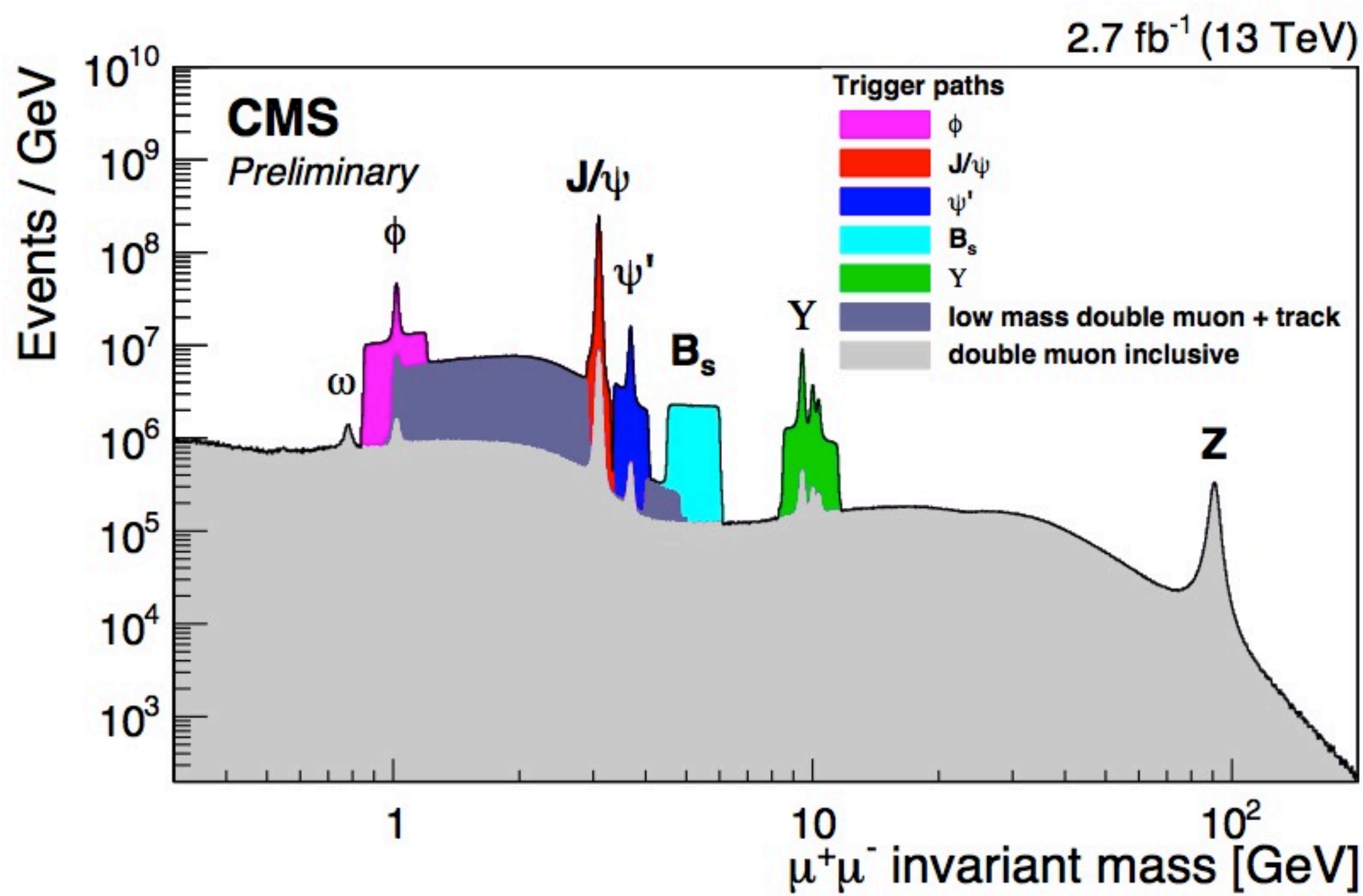
W/Z cross section vs √s

arXiv:1012.2466, CMS-SMP-15-004



Di-muon mass spectrum

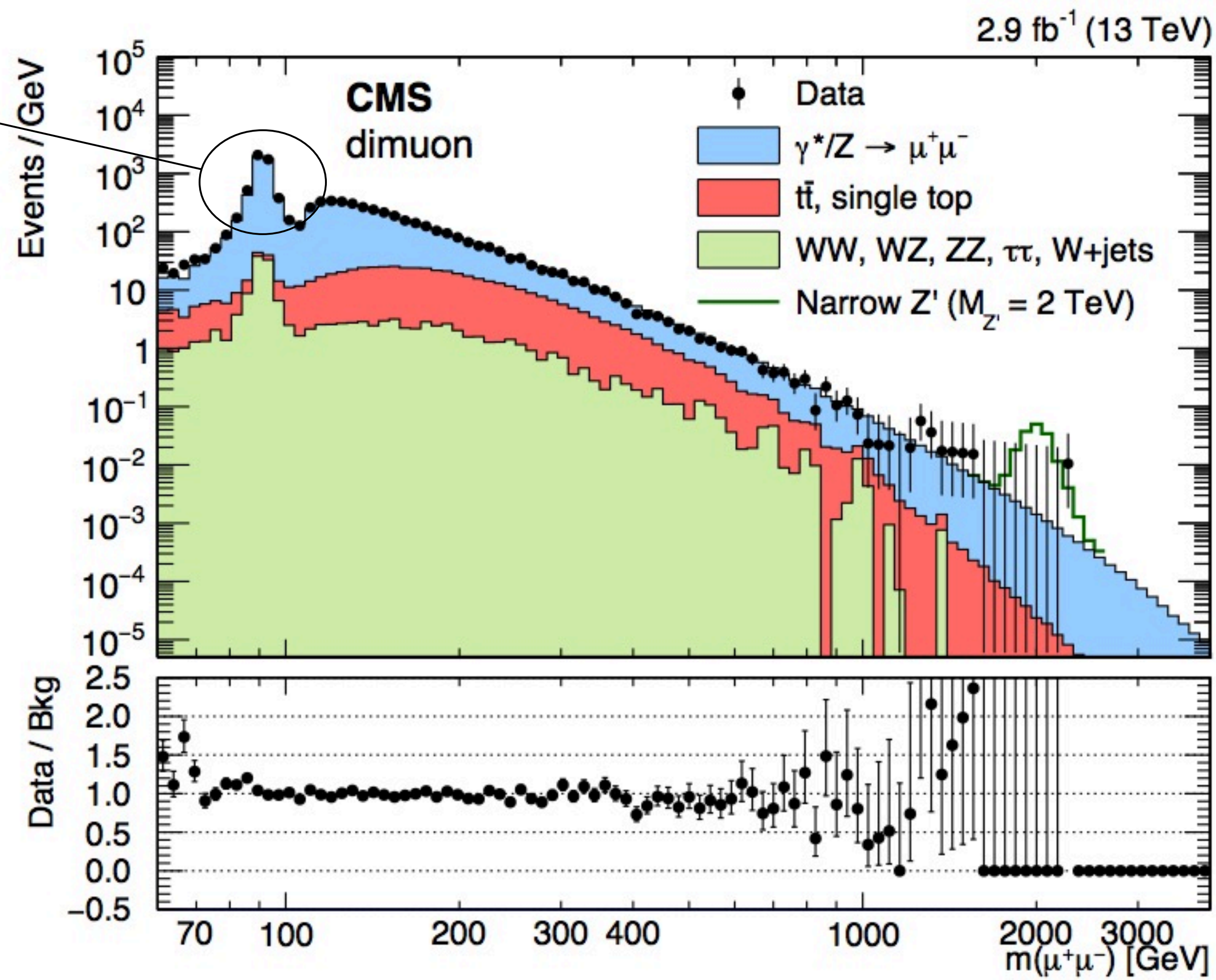
CMS-DP-2015-055



Di-lepton events

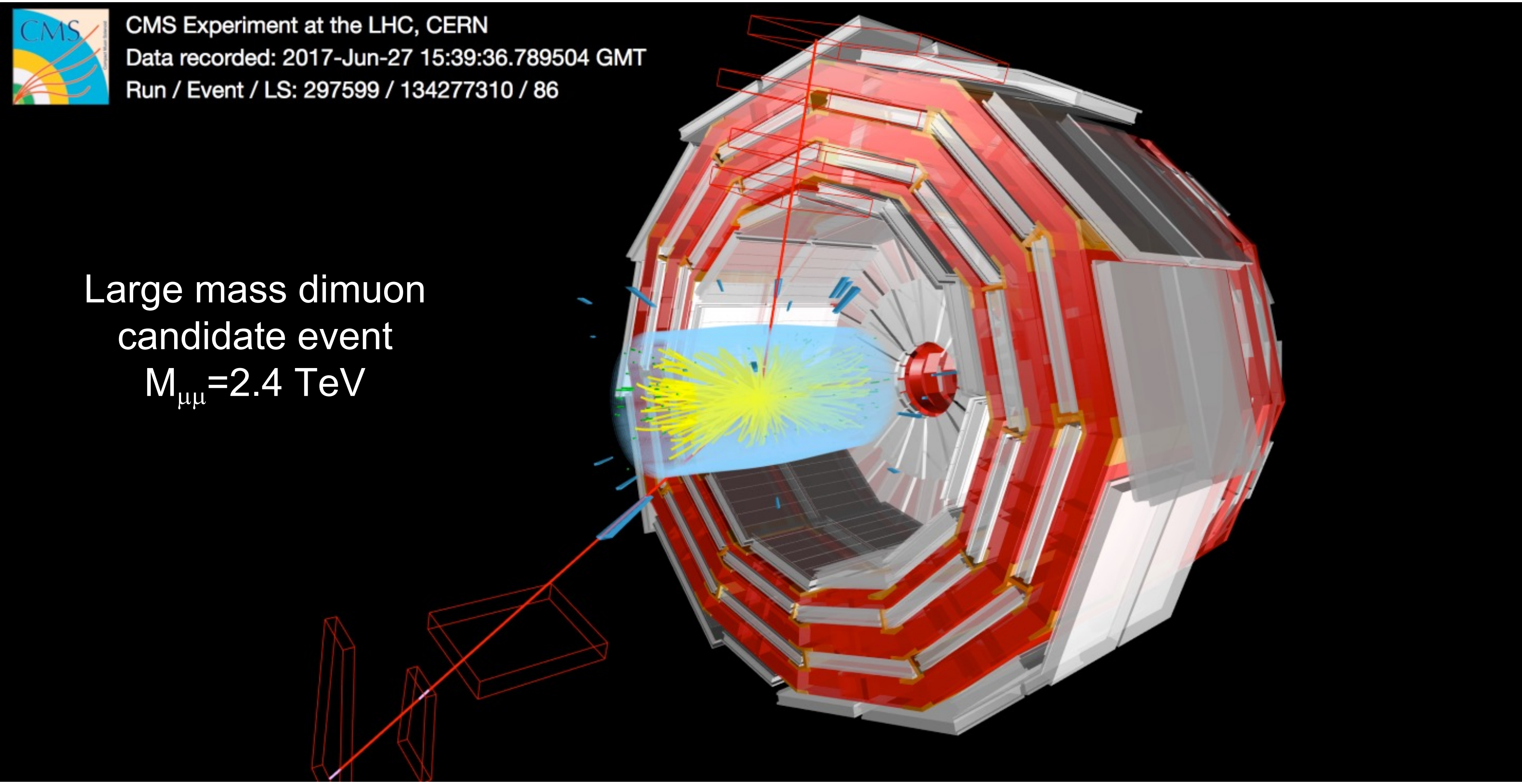
arXiv:1609.05391

Z boson resonance



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

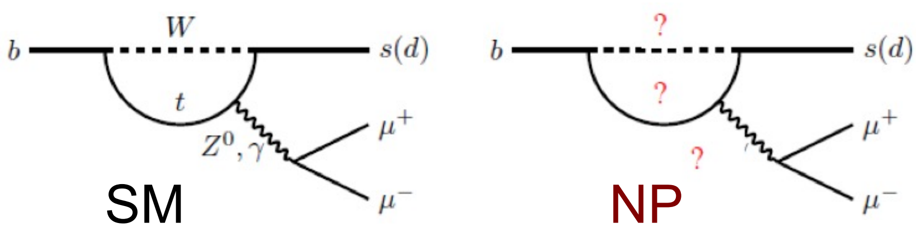
2017: Di-muon candidate event

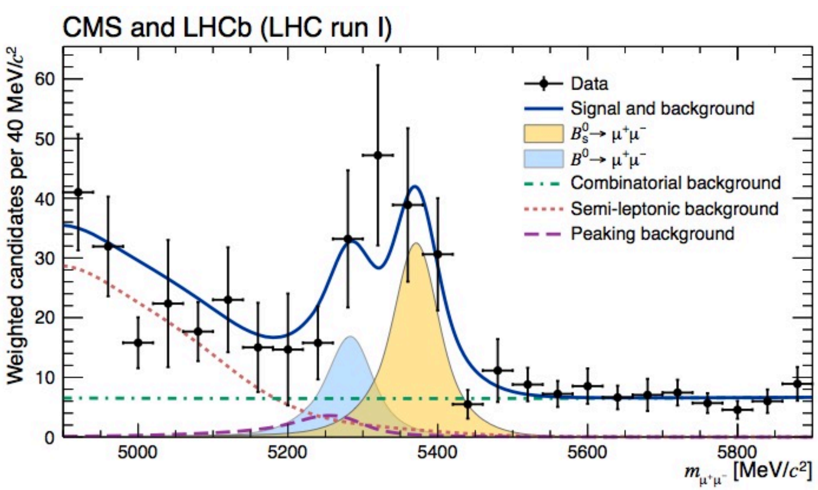


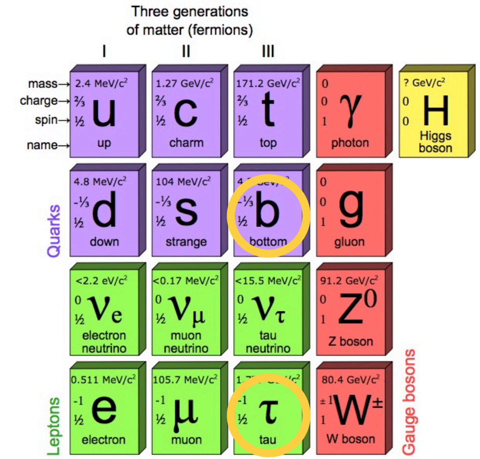
Large mass dimuon candidate event
$M_{\mu\mu}$=2.4 TeV

B-physics and Rare decays

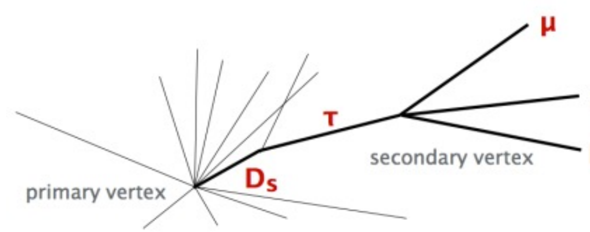
- Study rare processes to look for NP
- Indirect searches: $B_{s/d} \rightarrow \mu\mu$
- Flavour changing neutral current (FCNC) forbidden at tree level in SM
- Can only go through loop diagrams





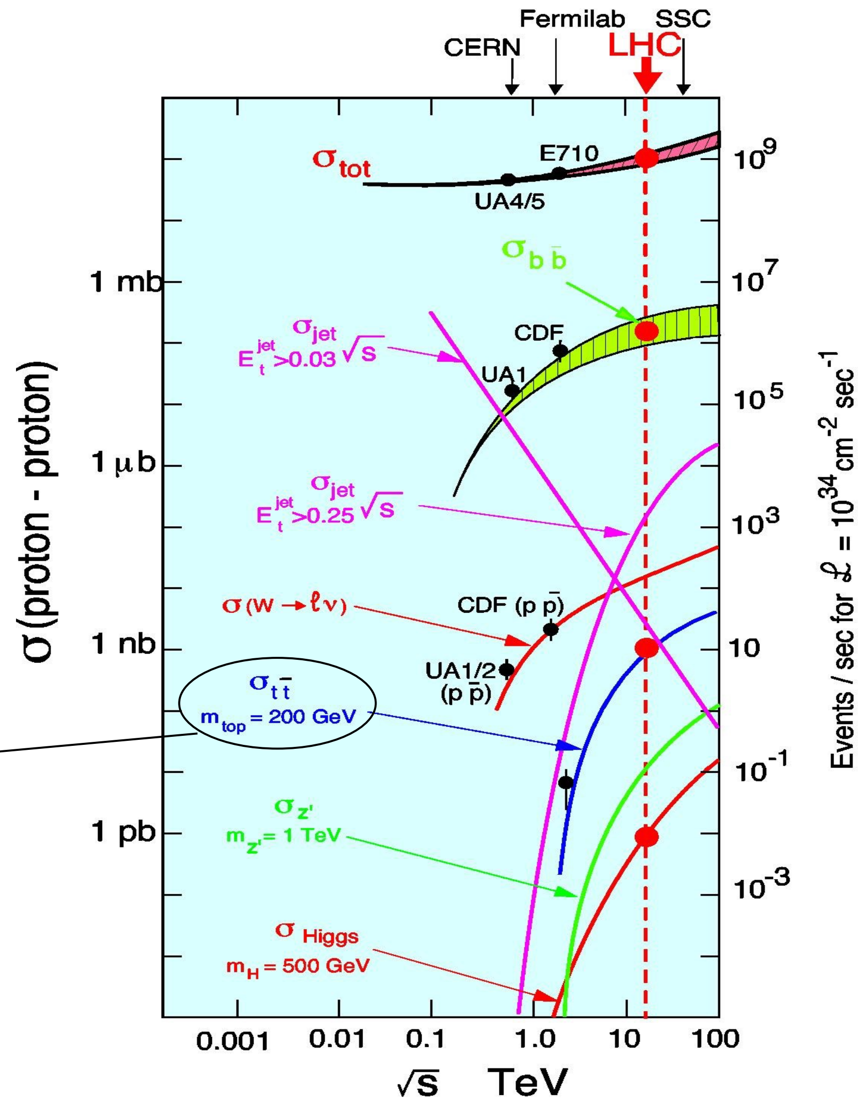


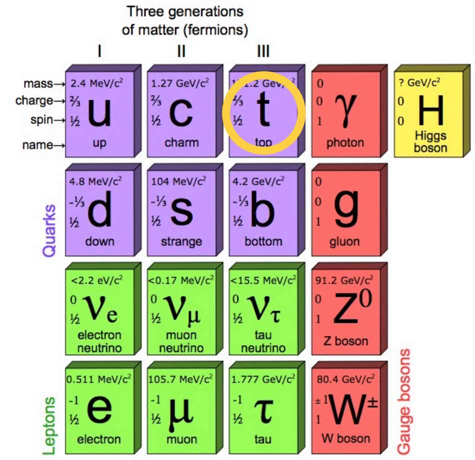
- Lepton Flavor Violation (LFV)
- Search for tau→ 3 muon decays
- Very rare process: BR~10^{-40}!
- Study in Ds and W decays



Top quark

top quark





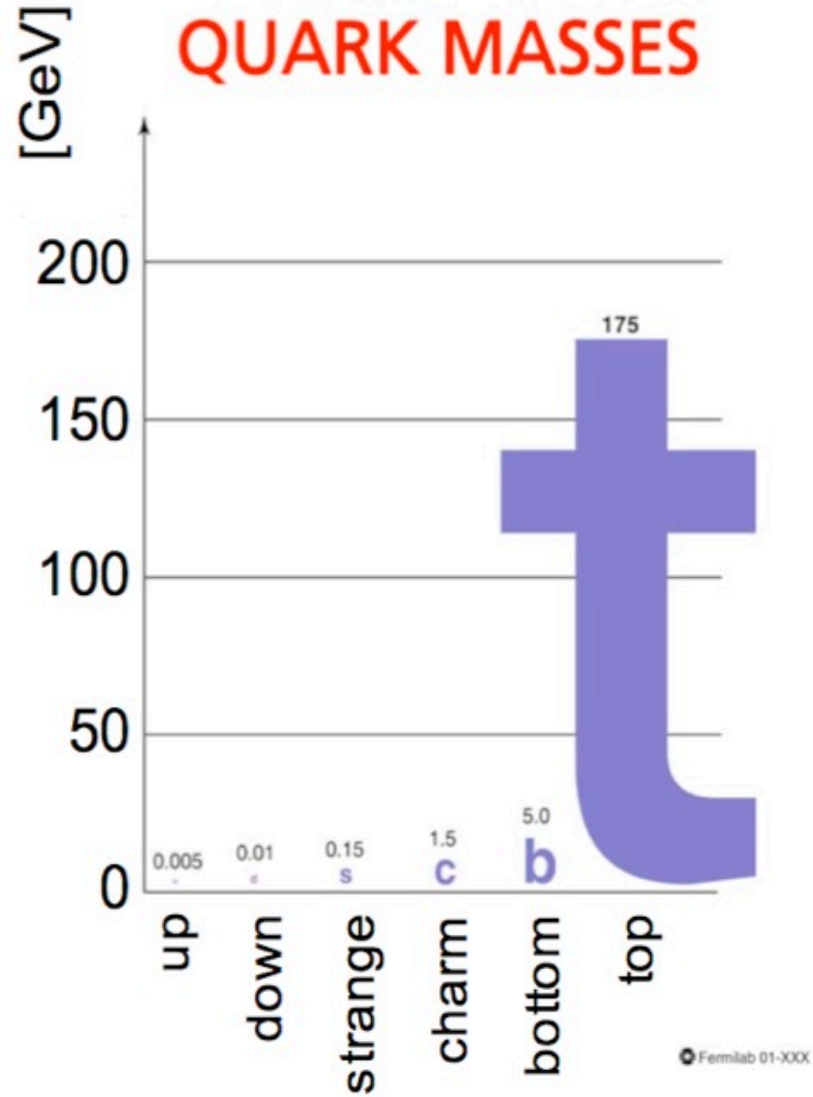
The top quark

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

$\tau = 0.4 \times 10^{-24}$ sec

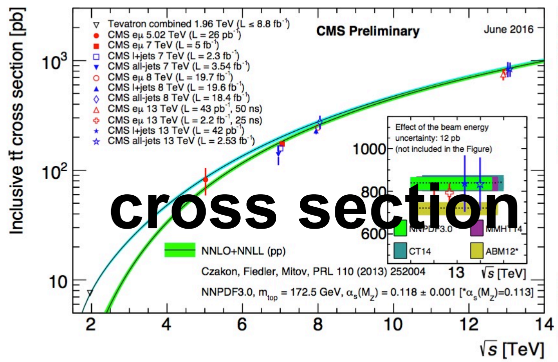
  - very short lifetime ⇒ bound states are not formed
    ⇒ opportunity to study a free quark

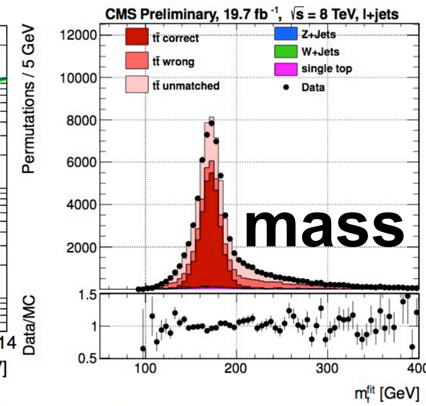
- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Measurements may provide insight into physics beyond SM

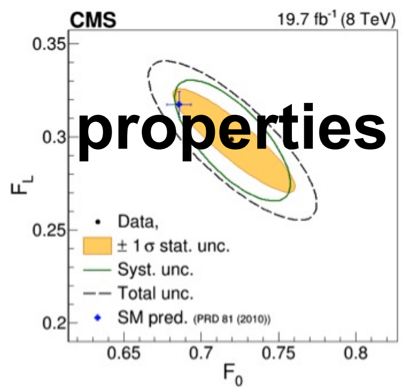


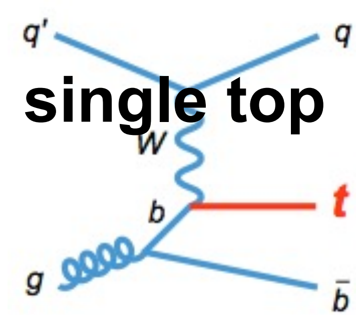
Top quarks and BSM

- 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?



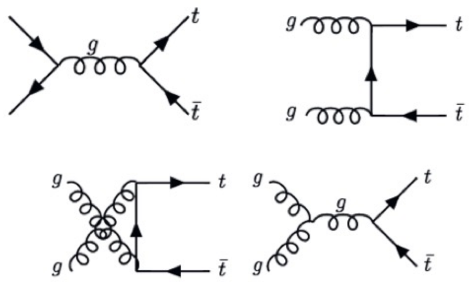






Cross sections vs √s

arXiv:1112.5675

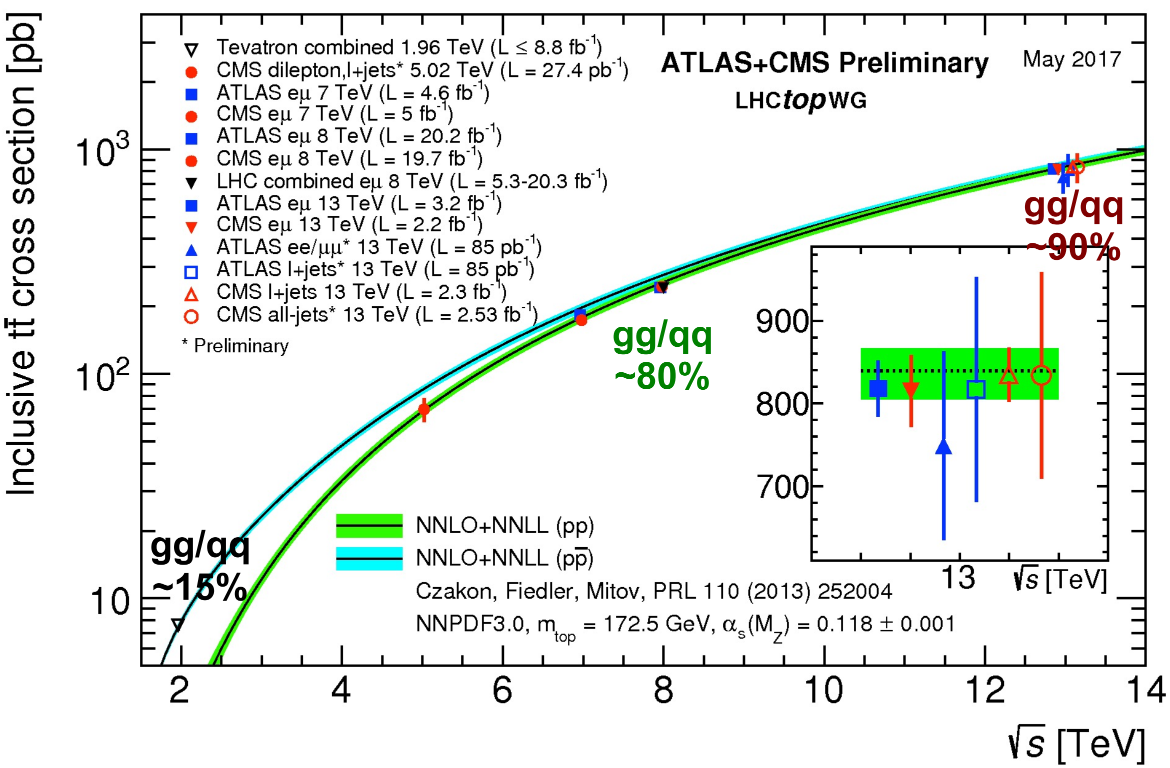


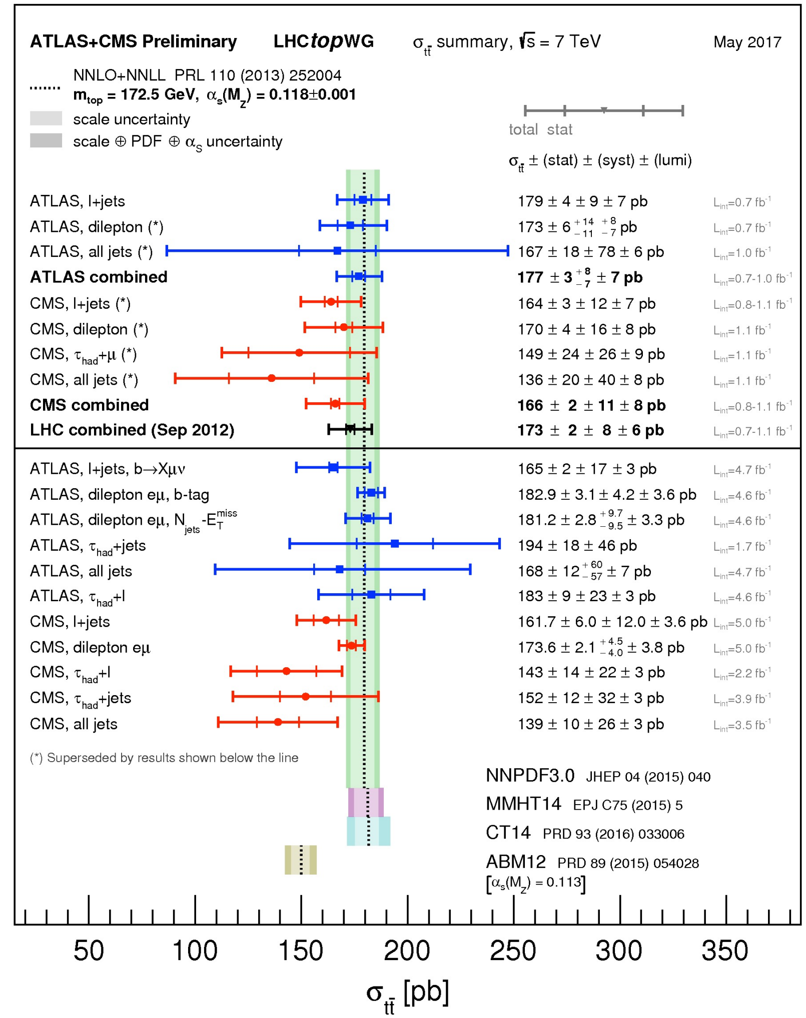
$$\sigma(7\ \mathrm{TeV}) = 177\ \mathrm{pb} \pm 7\%$$

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

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

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

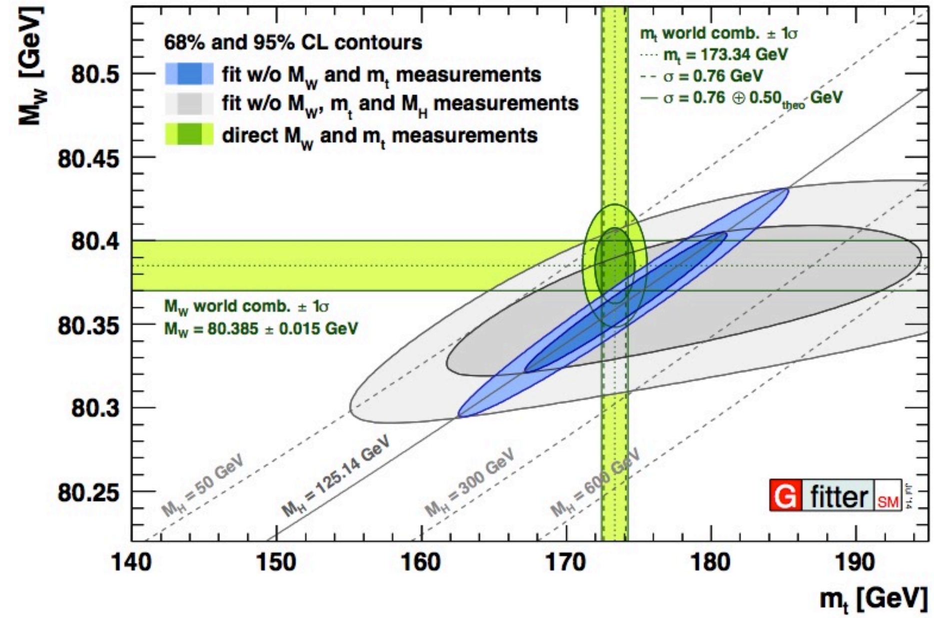




Top quark mass

- Top quark mass is a fundamental parameter of the SM

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



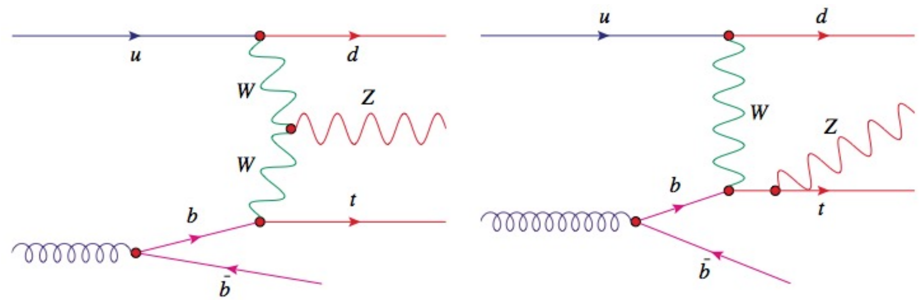
- Precise measurement needed for checking consistency of the SM

- 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

Rare decays: ttV (V=γ,Z,W)

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

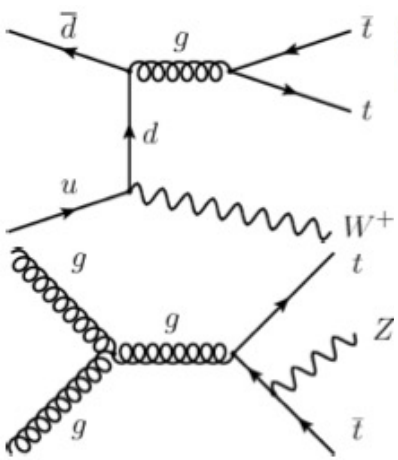
- Measurements will give access to EW couplings of the top

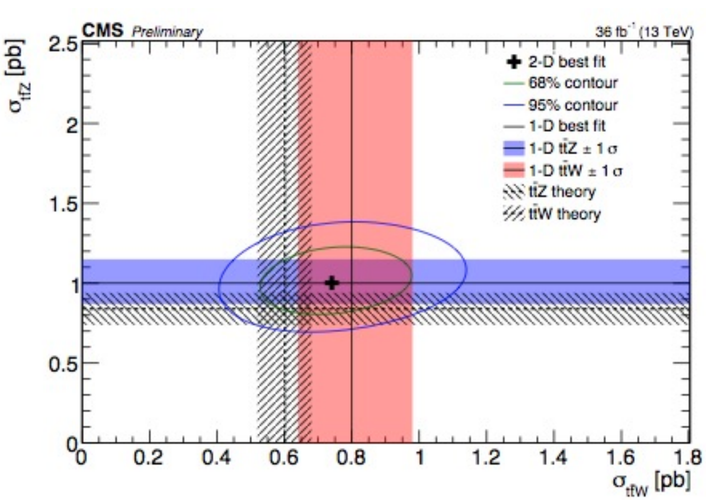


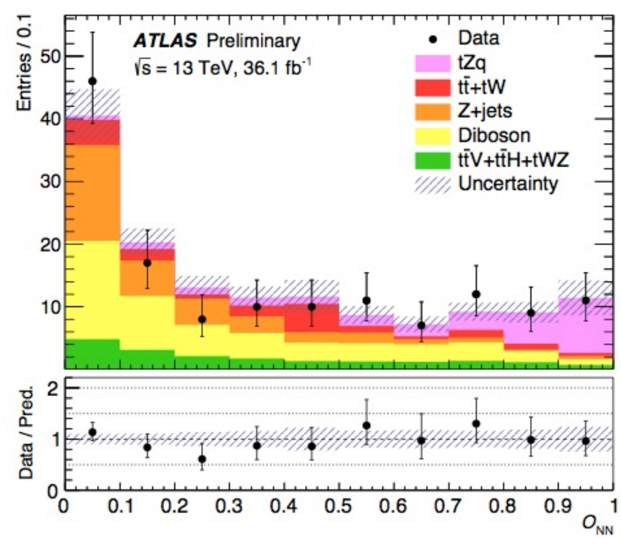
- Top+vector boson production
- tt+Z: measure ttZ coupling
- tt+W/Z: sensitive to BSM

⇒in agreement with SM

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



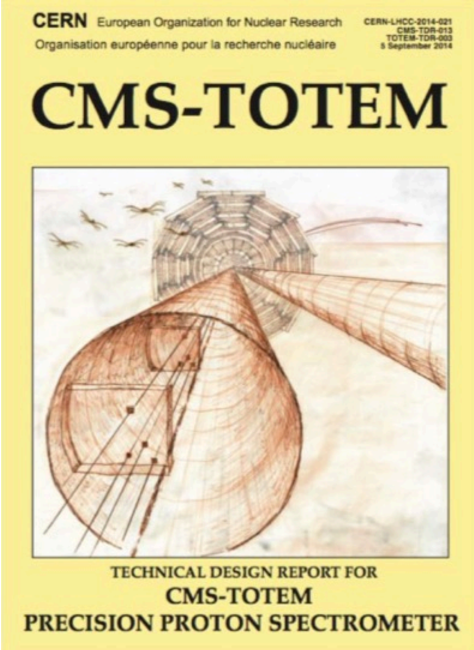


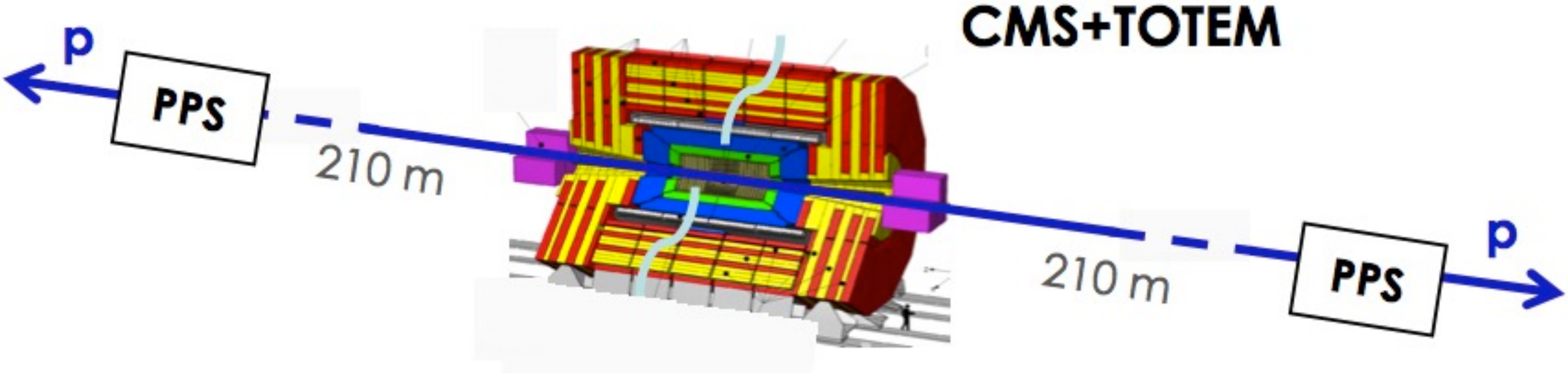


Precision Proton Spectrometer

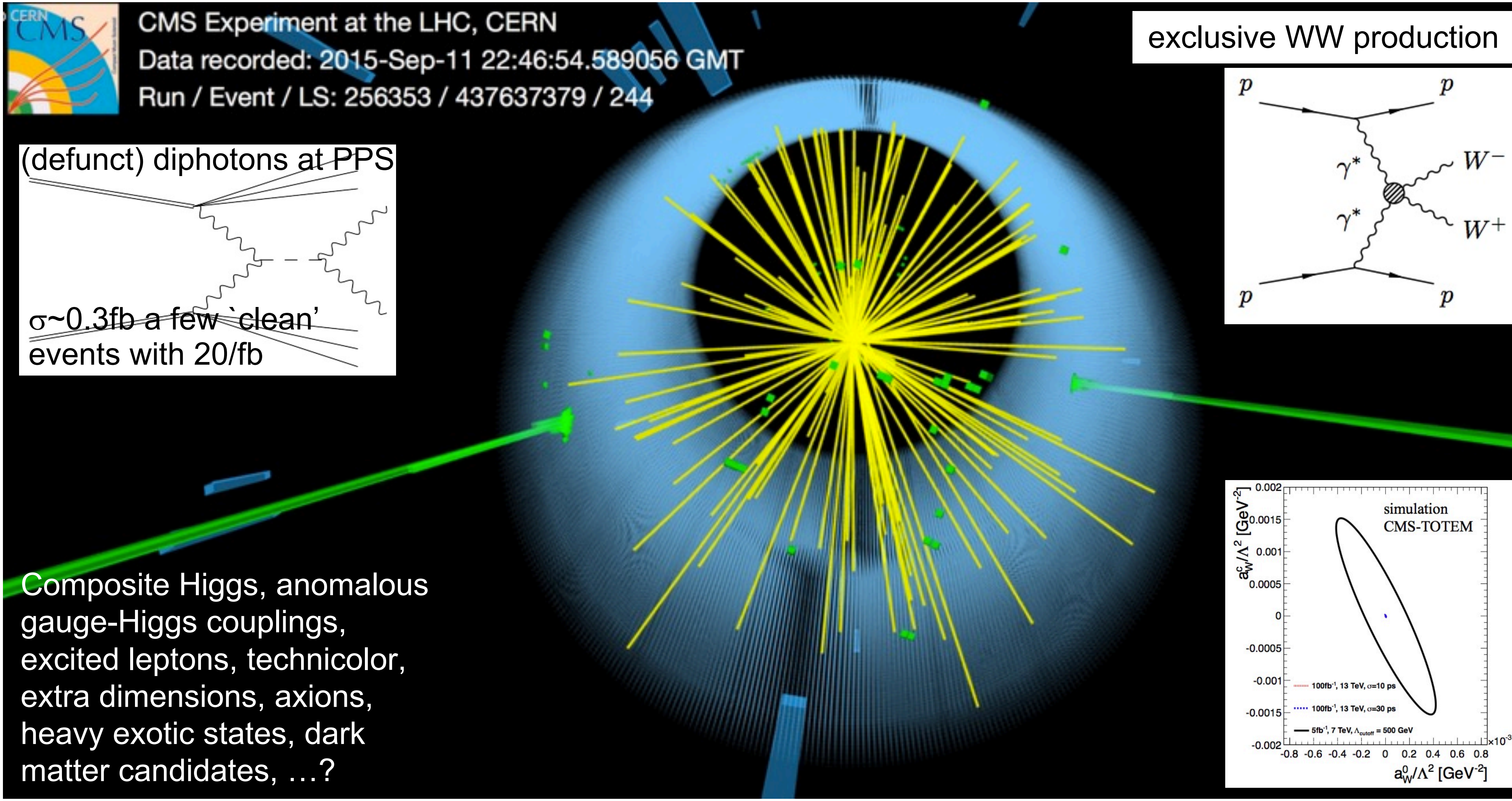
CERN-LHC-2014-021

- PPS aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
- Allows detection of very rare SM processes and is sensitive to possible BSM processes through the anomalous couplings or direct production of new particles





BSM searches: resonances, etc.



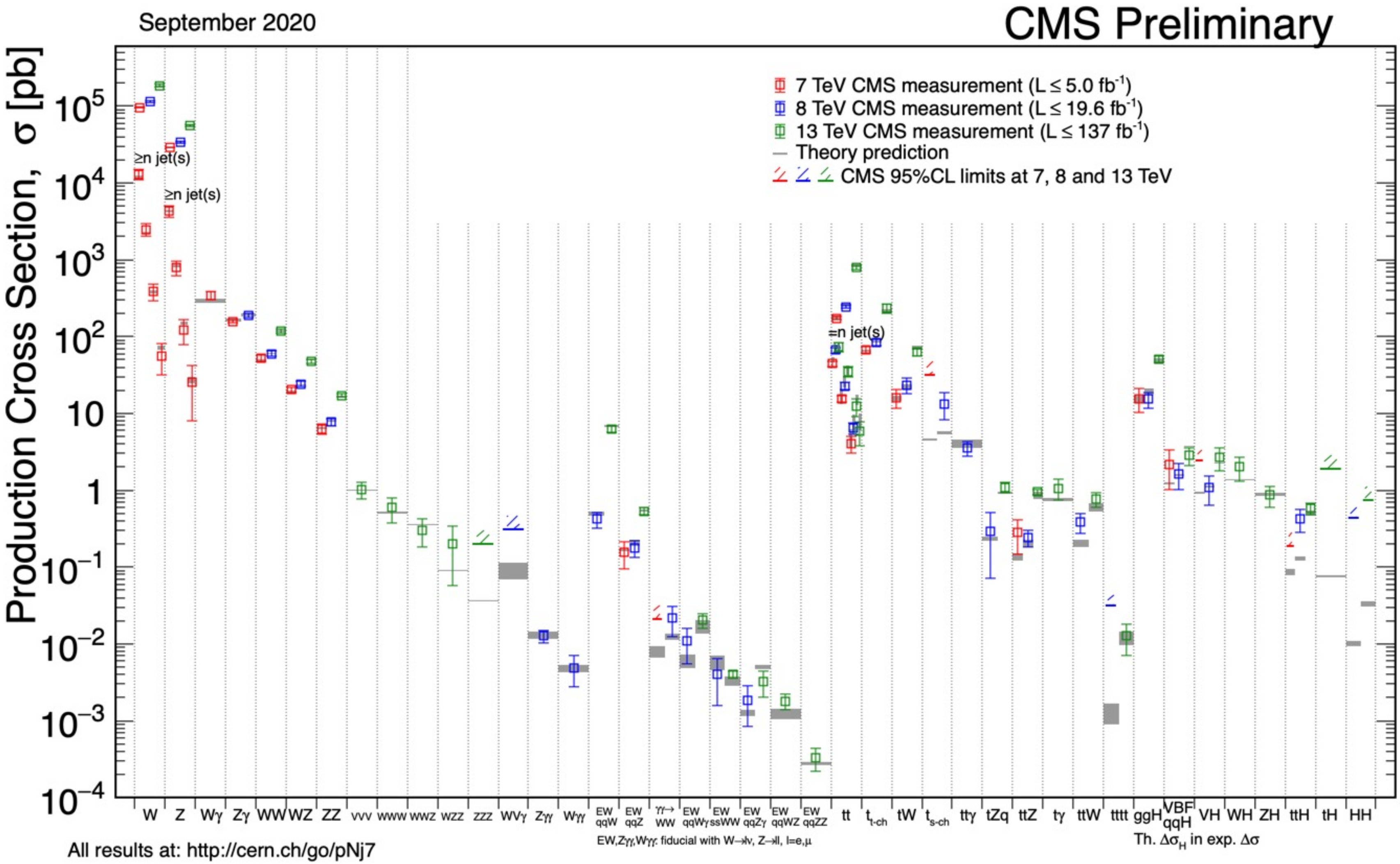
(defunct) diphotons at PPS

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, …?

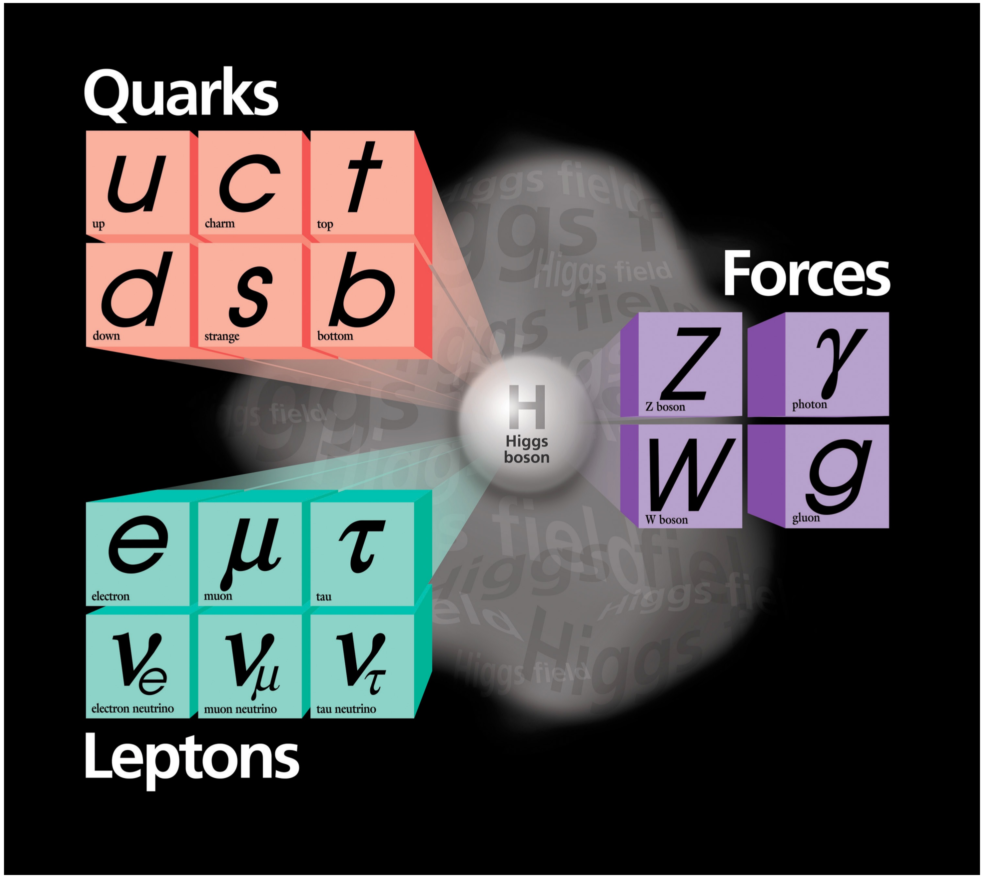
SM measurements



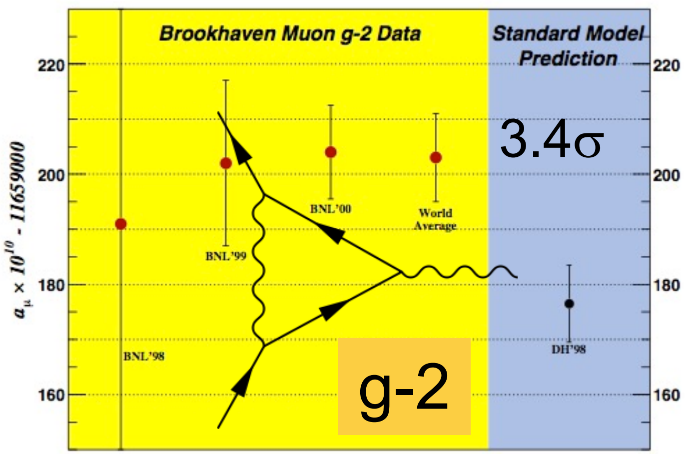
…each one of these measurements (or searches) is a thesis topic!

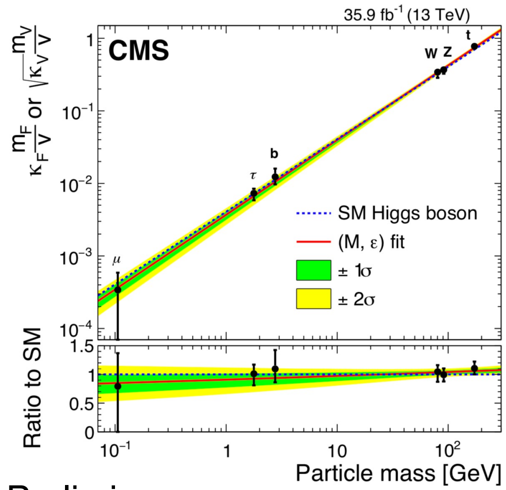
Standard Model theory of everything?

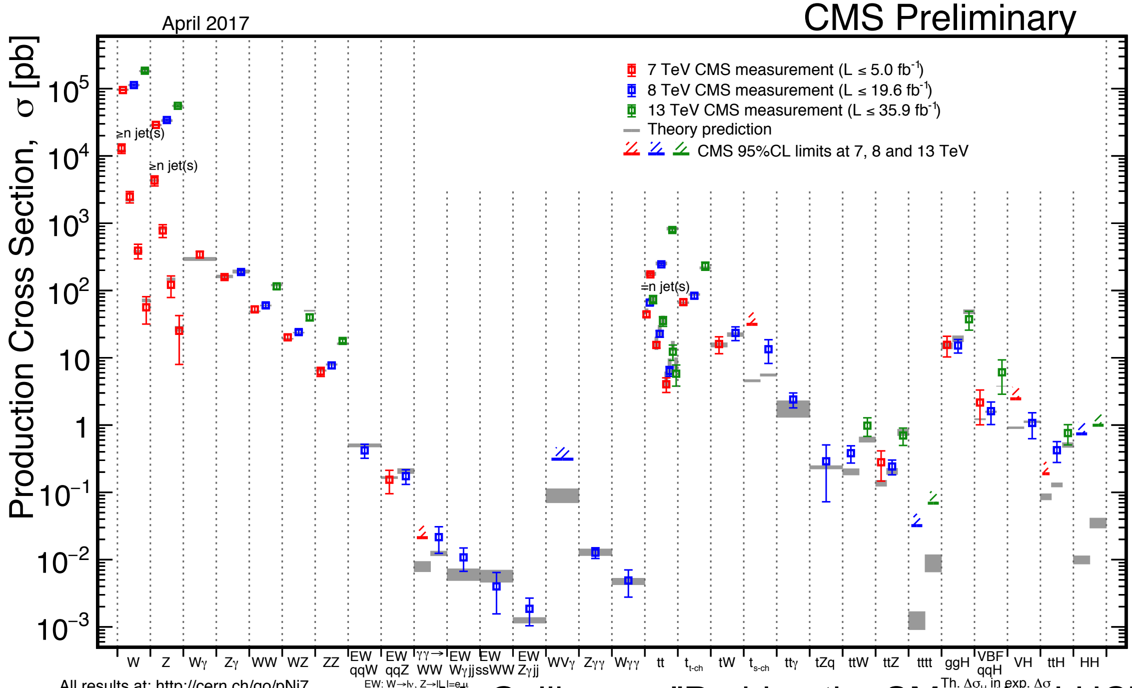
- Discovery of the Higgs boson marks the triumph of the SM
- However, even with the inclusion of the Higgs boson, SM is an incomplete theory

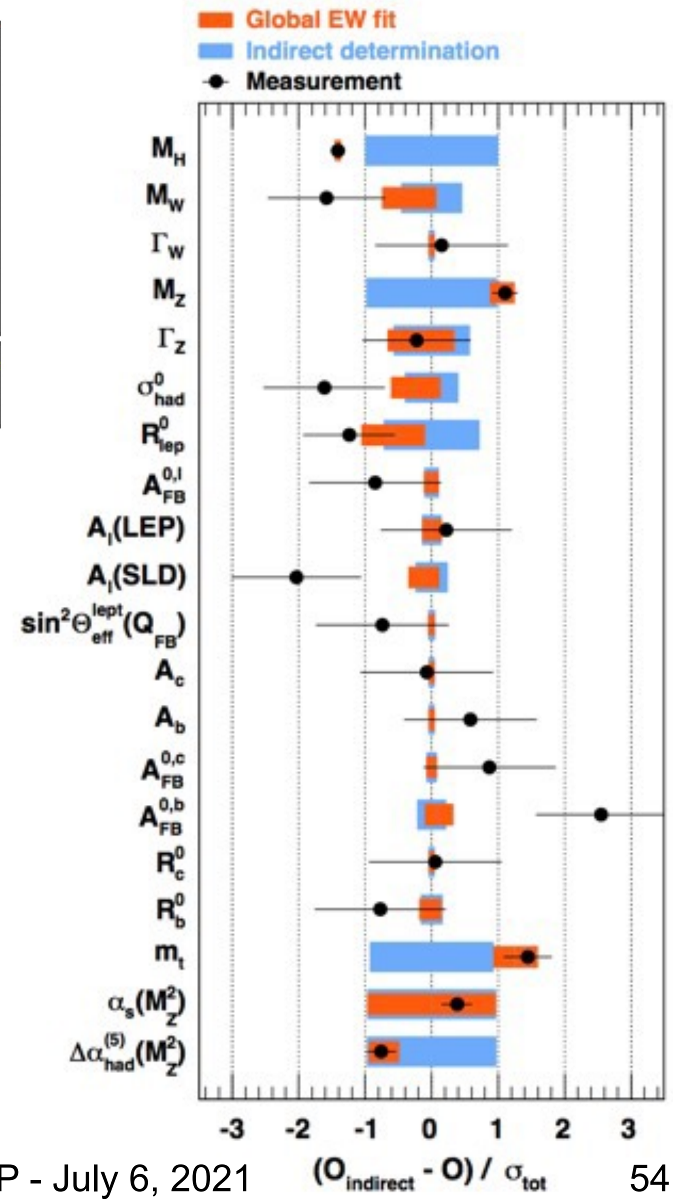


Tests of the SM









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?

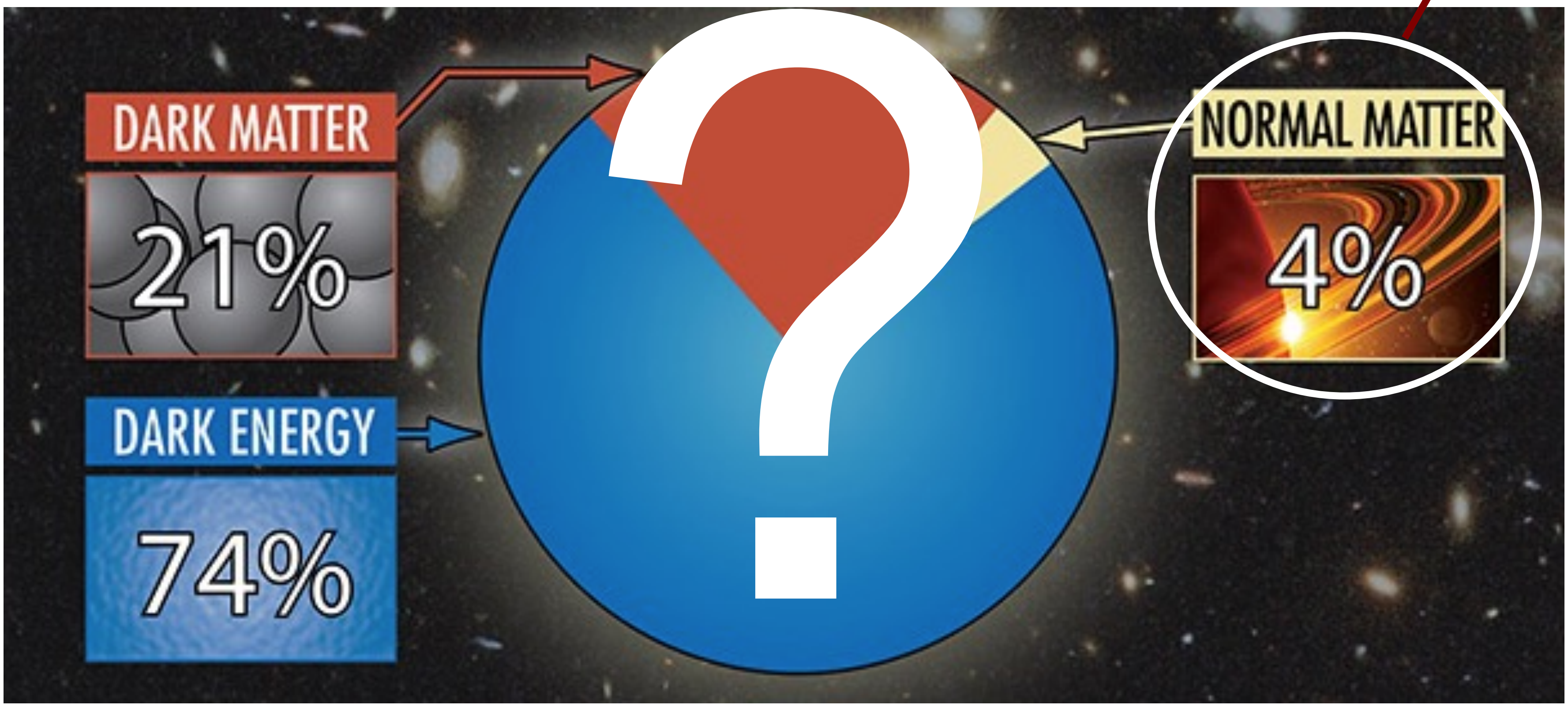
d) Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

e) How does gravity fit into all of this?

Not only SM: we need ideas!

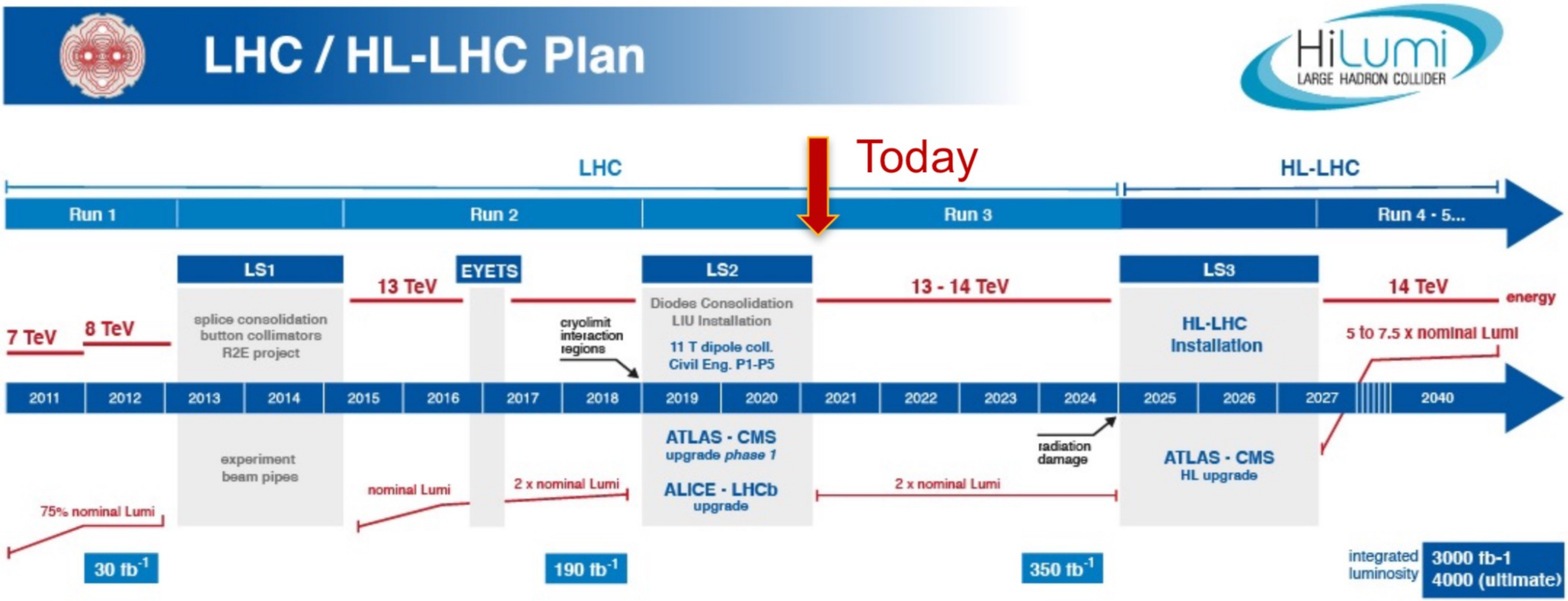
- What is that accounts for 96% of the Universe?
  It is one of the greatest mysteries of Science

~SM



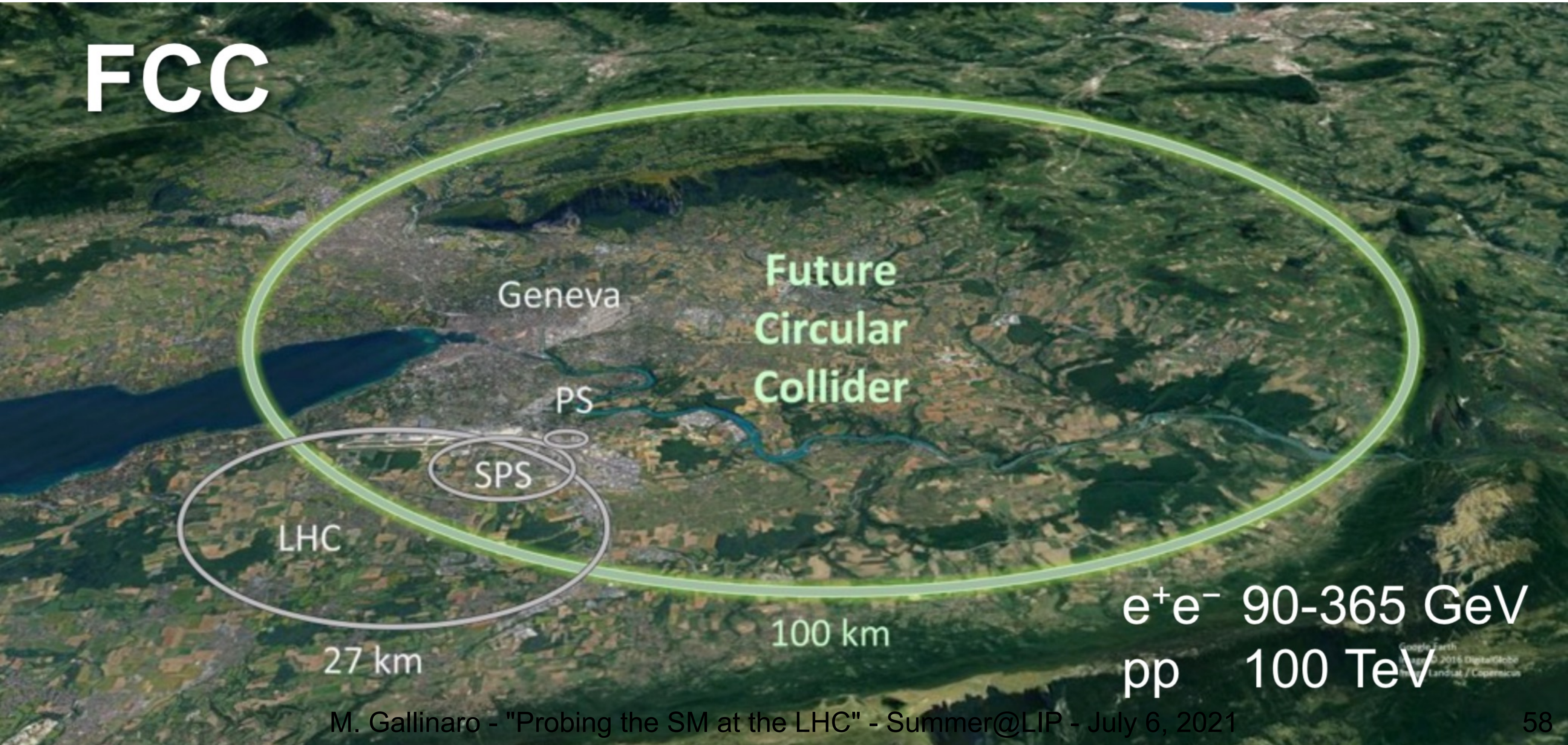
Near future: High-Luminosity LHC

The HL-LHC will provide x20 more data than available today



Future machine at CERN (?)

- Future Circular Collider with 100Km circumference
  - Phase 1 (FCC-ee): electron-positron collisions at energies 90-365 GeV
  - Phase 2 (FCC-hh): proton-proton collisions at 100 TeV



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