Probing the Standard Model at the LHC

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LIP Lisbon

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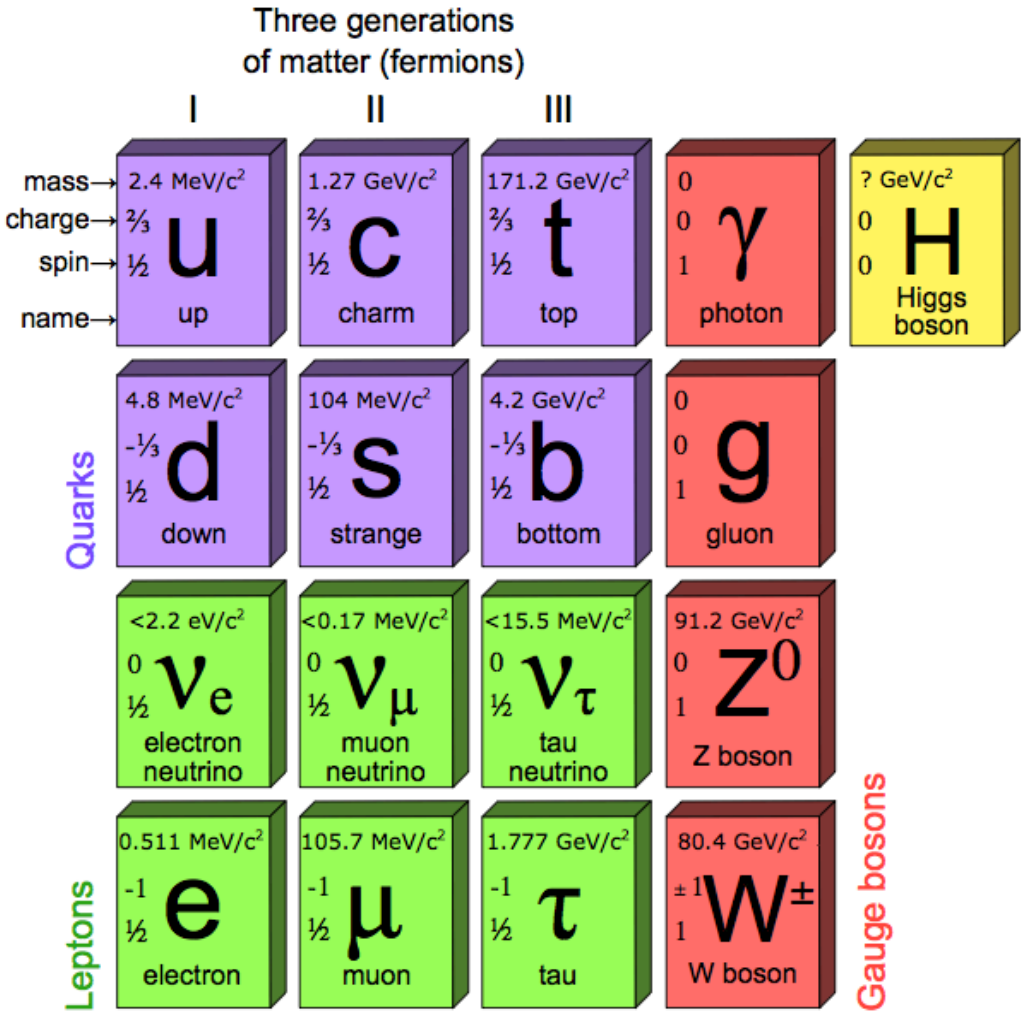
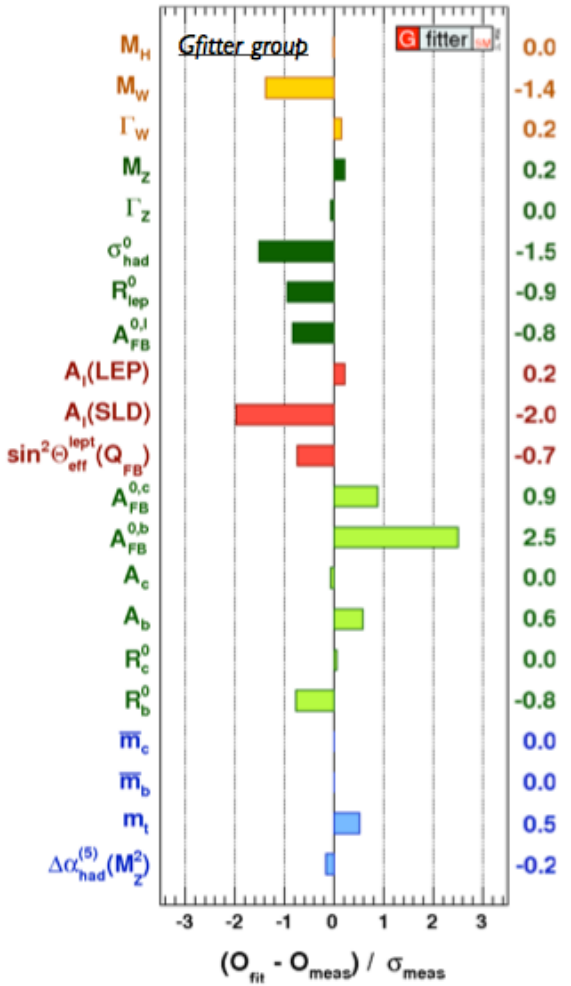
- ✓ Hadron interactions
- ✓ Minimum bias events
- ✓ Jet production
- ✓ W and Z bosons, top quark

The Standard Model

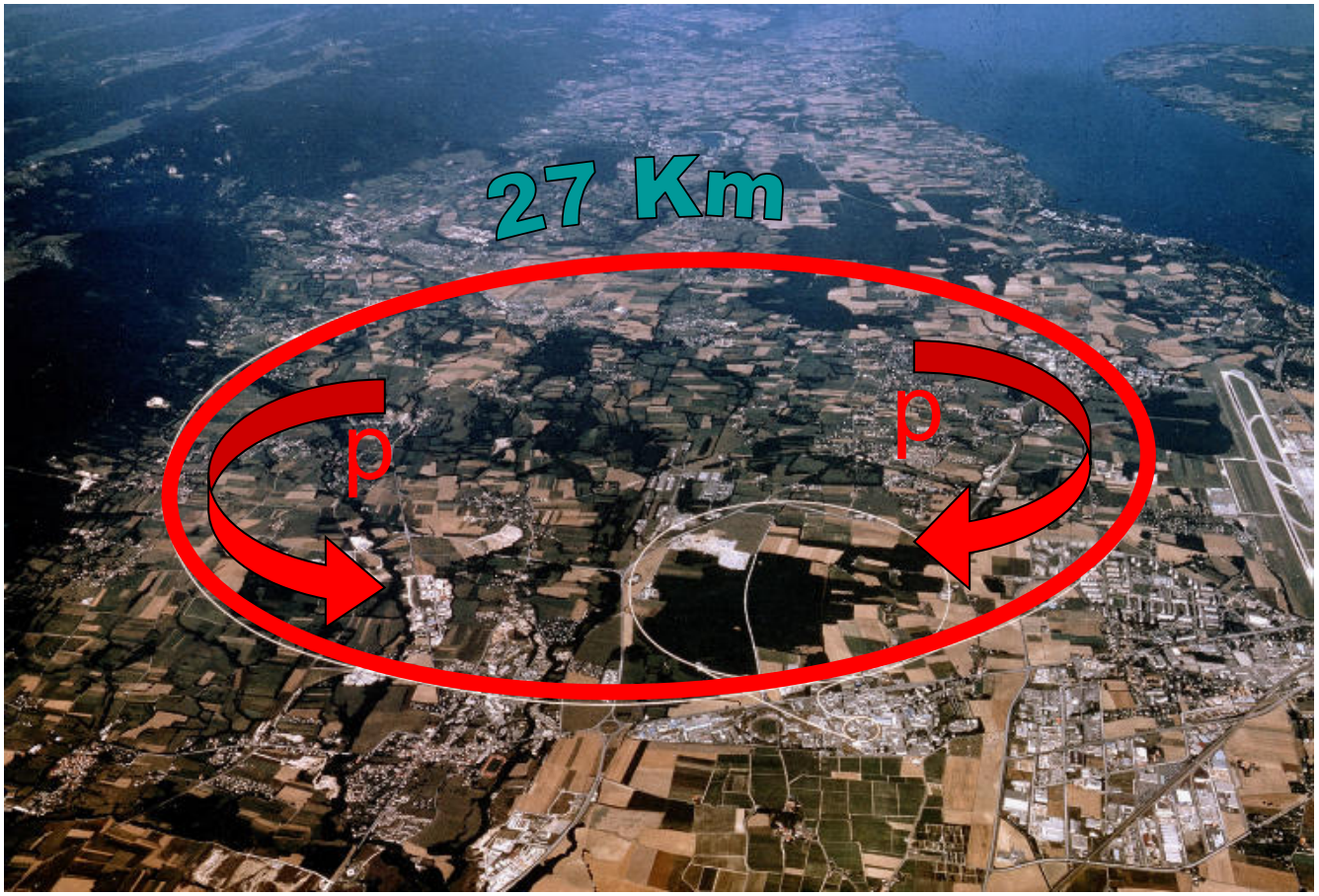


Standard model of elementary particles



Excellent agreement with all experimental results

The LHC

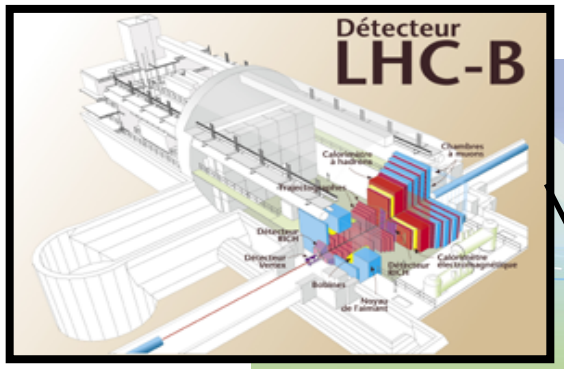


- Installation in existing LEP tunnel (27 Km)
- 1232 dipoles B=8.3T
- pp $\sqrt{s}$ = 14 TeV
  $L_{design} = 10^{34}$ cm^{-2} s^{-1}
- Heavy ions
  (e.g. Pb-Pb at 5TeV, p-Pb at 8TeV, Xe)

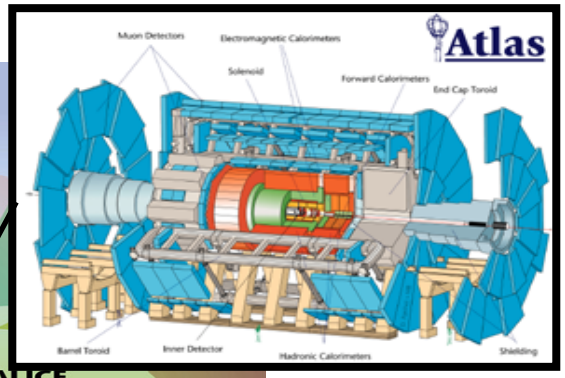
- First beam: Sept.2008
- 2012: 2 x 4 TeV
- 2015/18: 2 x 6.5 TeV
- 2021/23: 2 x 7 TeV

LHC experiments located at 4 interaction points

The LHC experiments

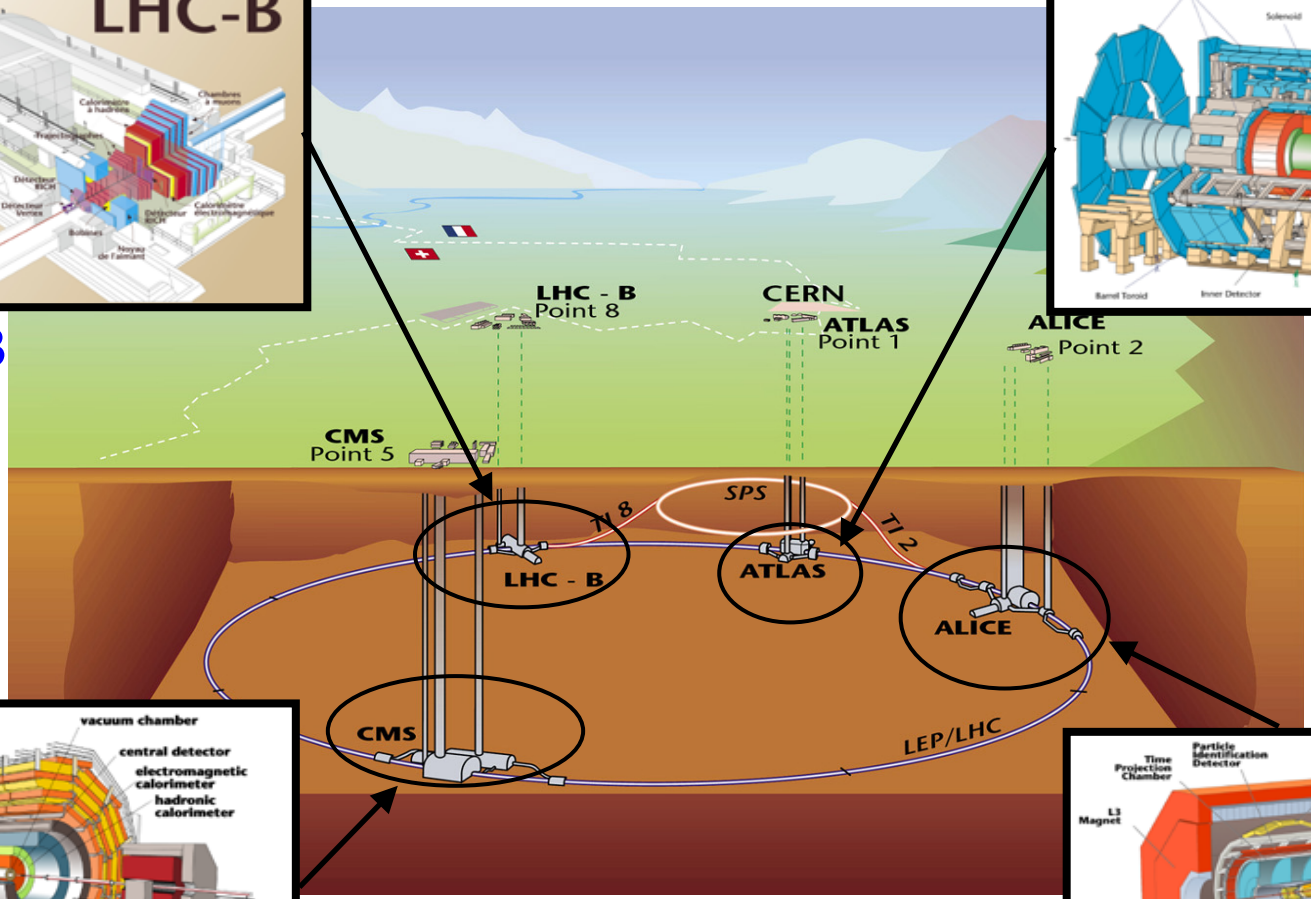


LHC-B

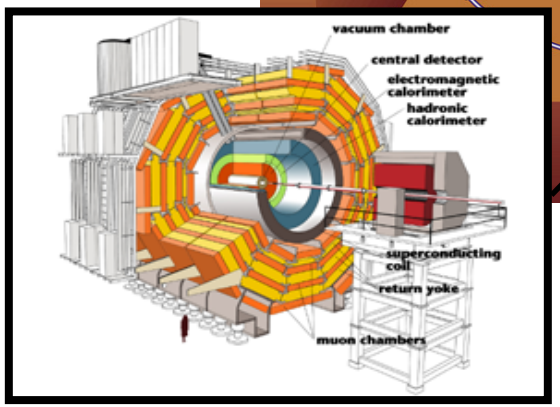


ATLAS

+ *LHCf*

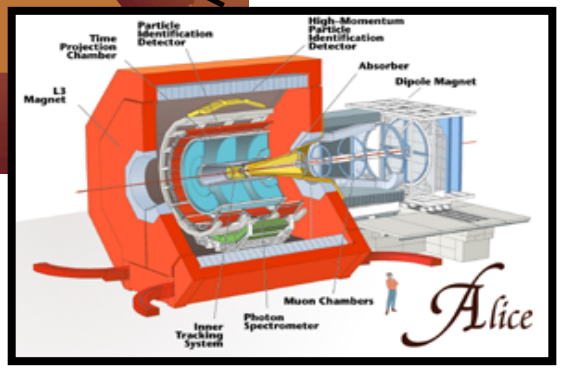


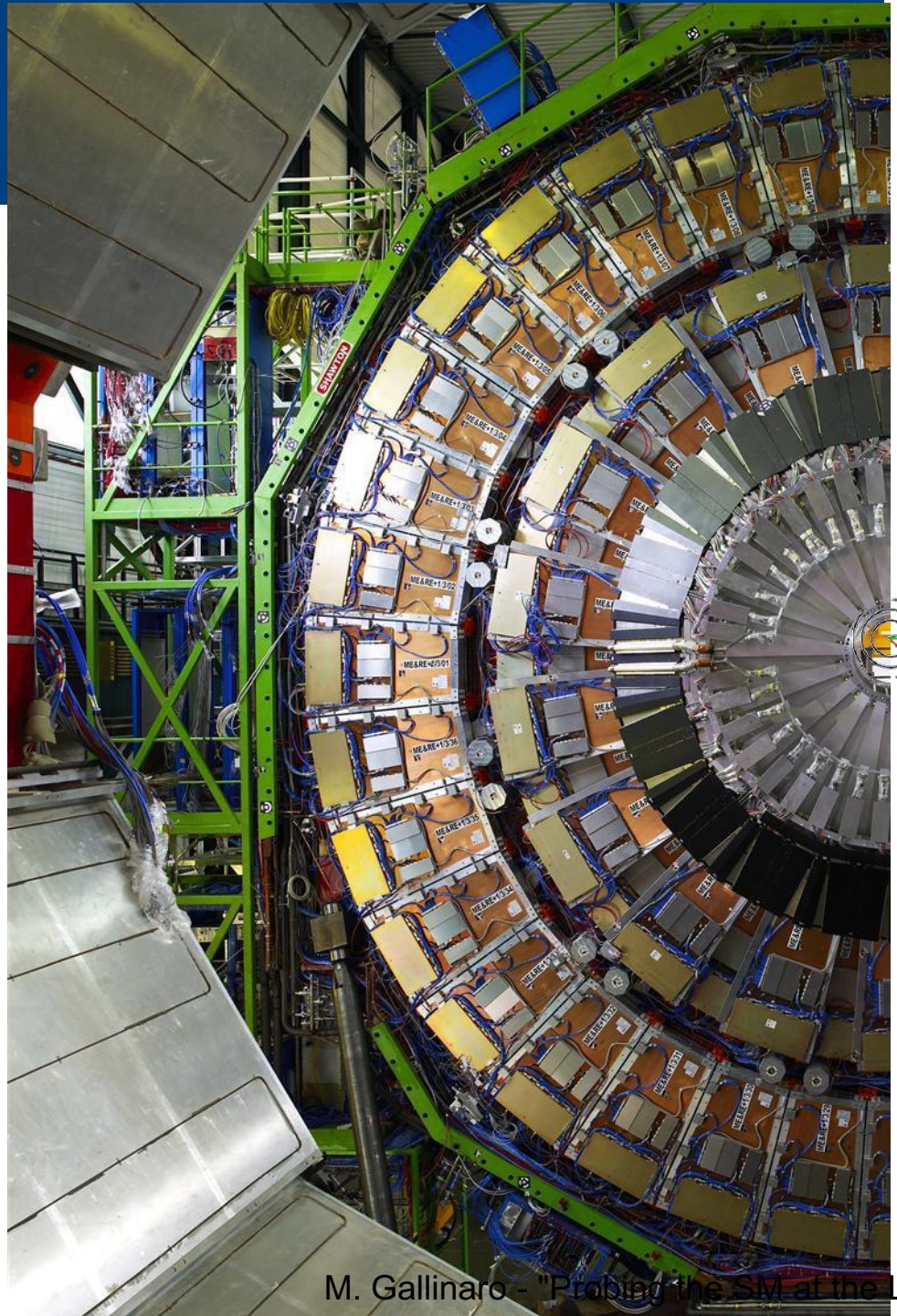
CMS

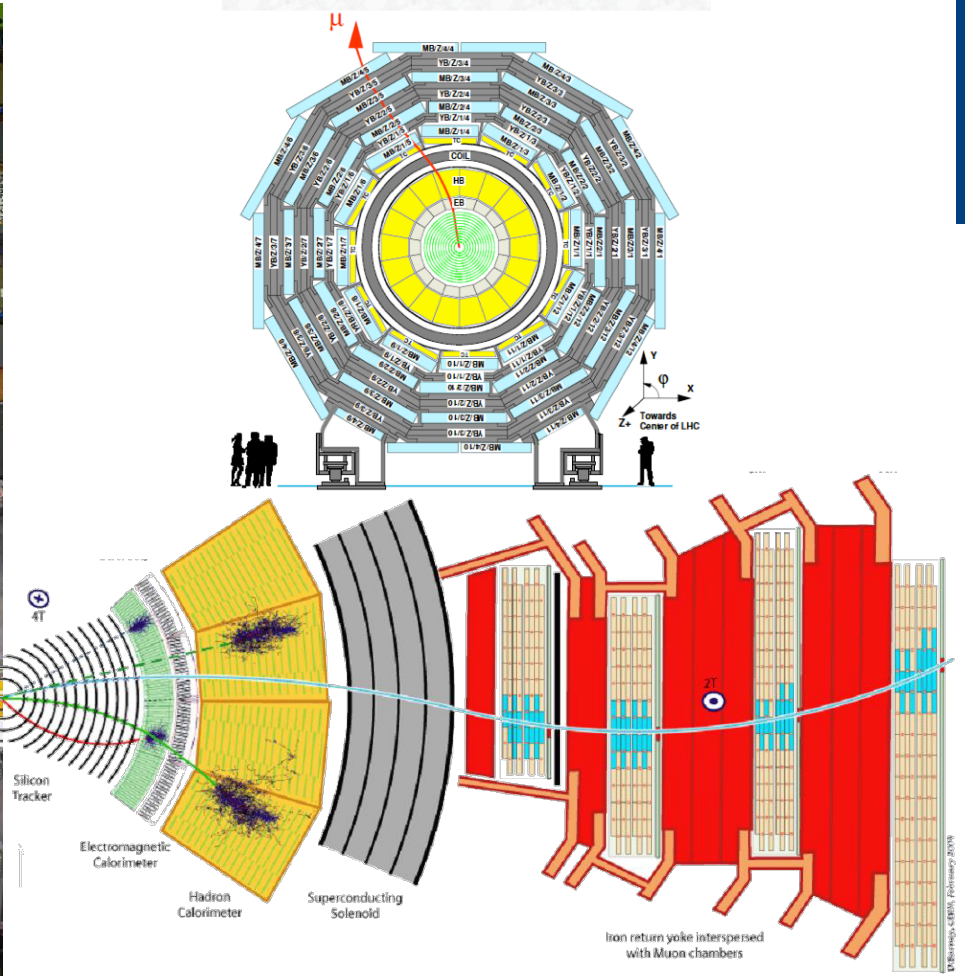


TOTEM

ALICE

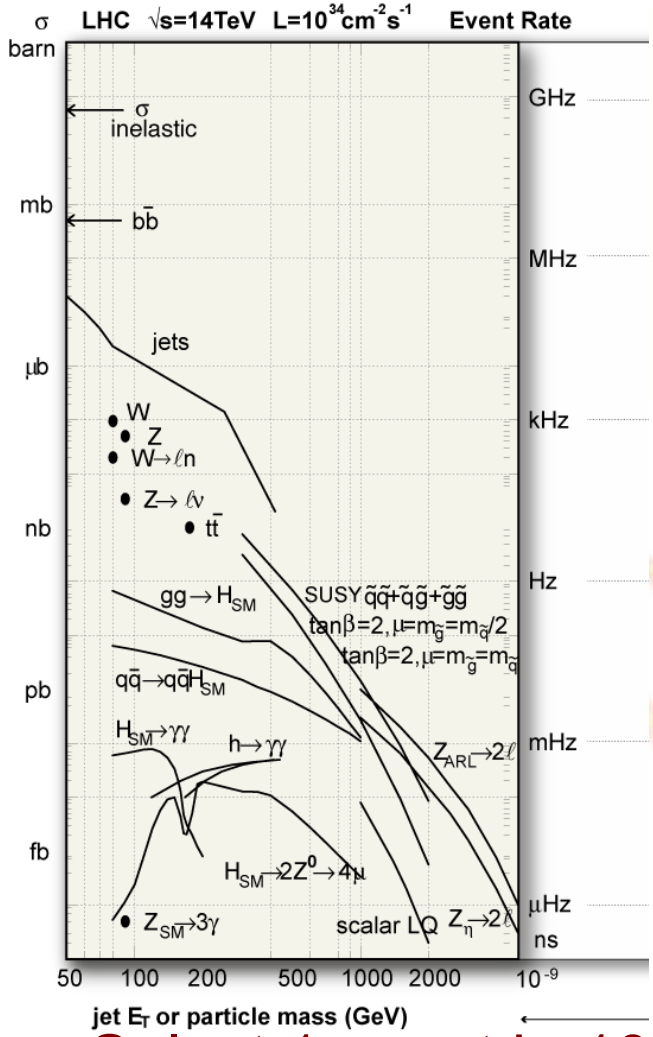


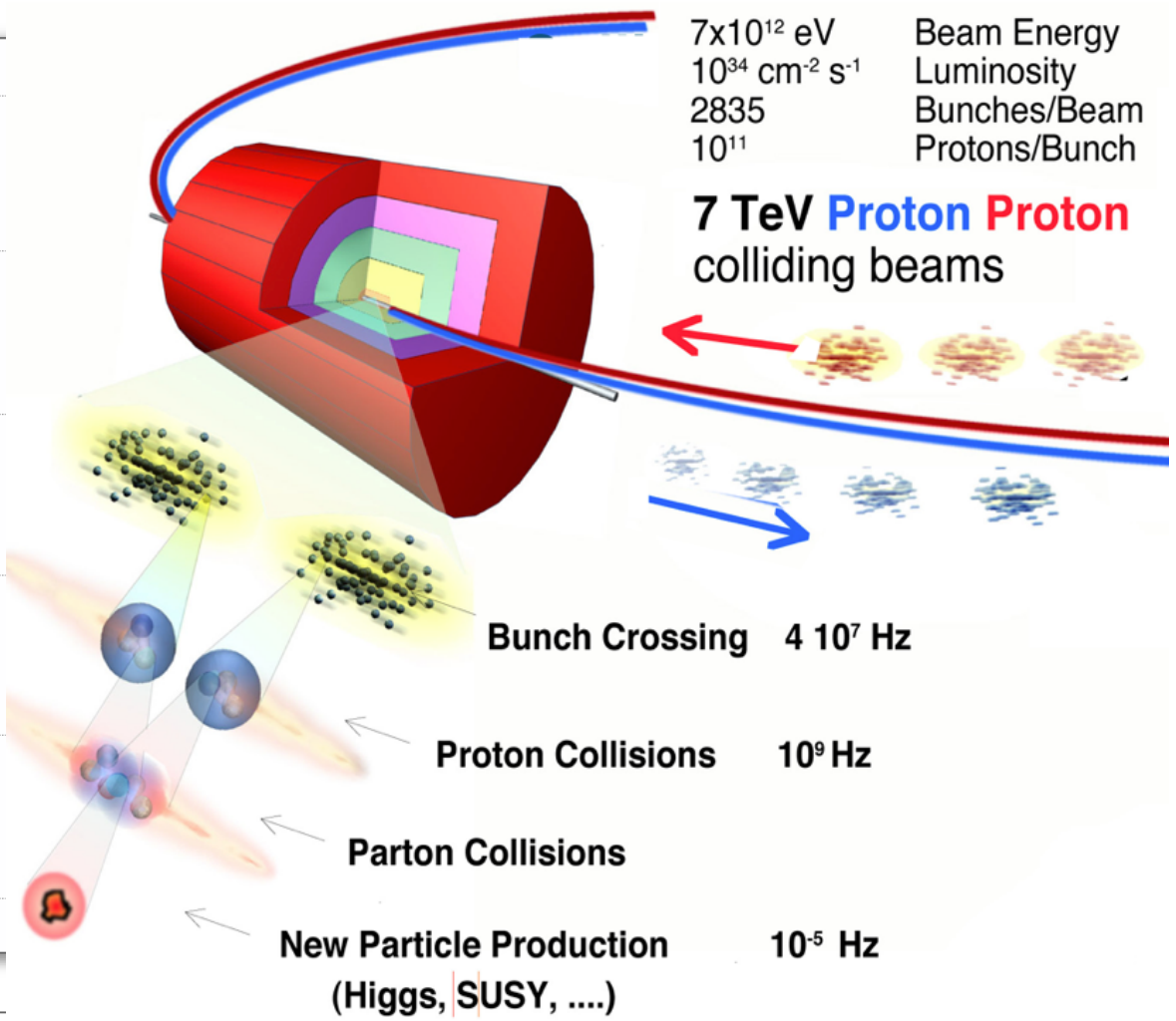



μ
COIL
HB
EB
Towards Center of LHC
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers

Proton collisions at the LHC

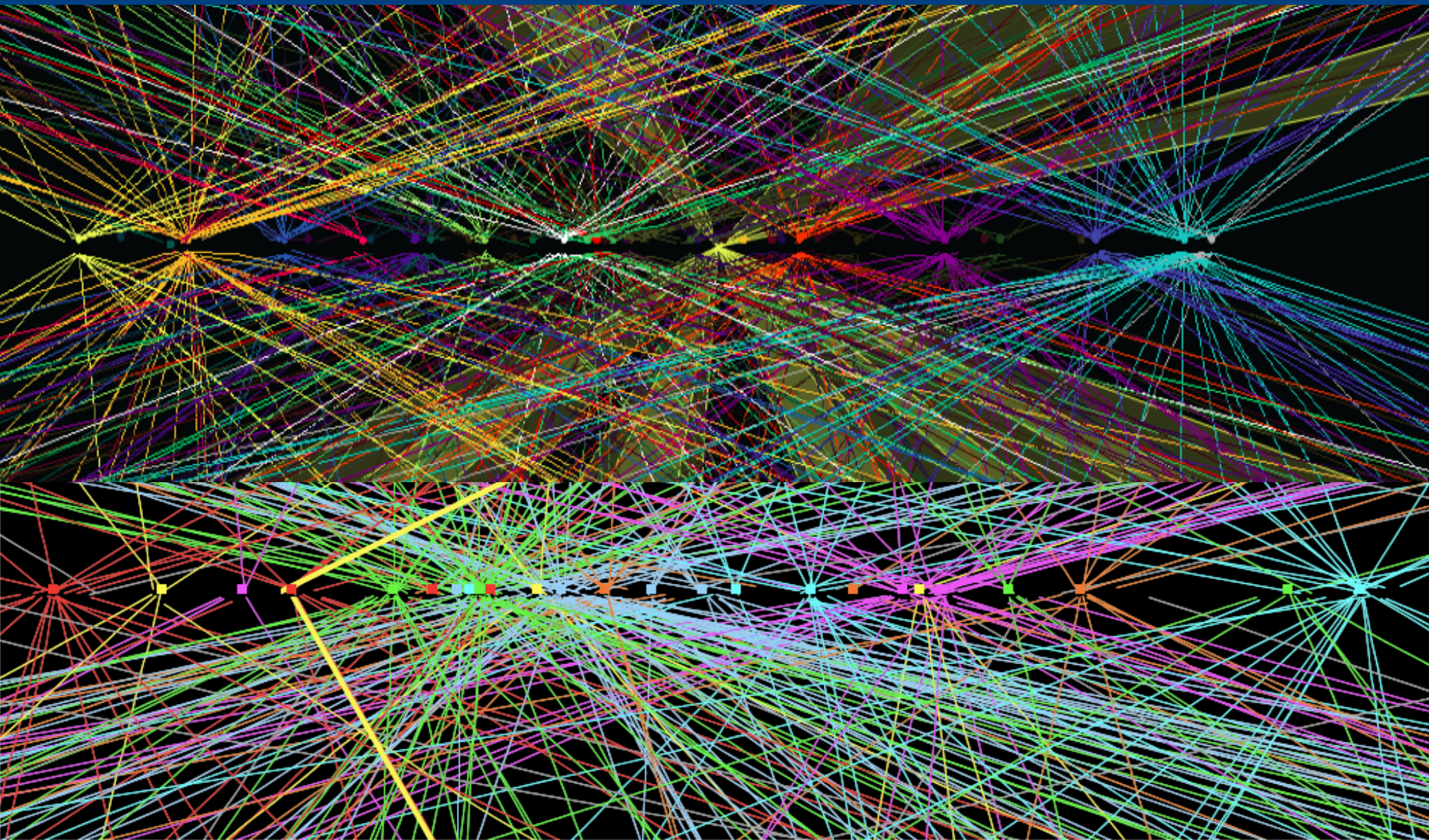
Collisions: 7-8 TeV (2011-12), 13TeV (2015-18)

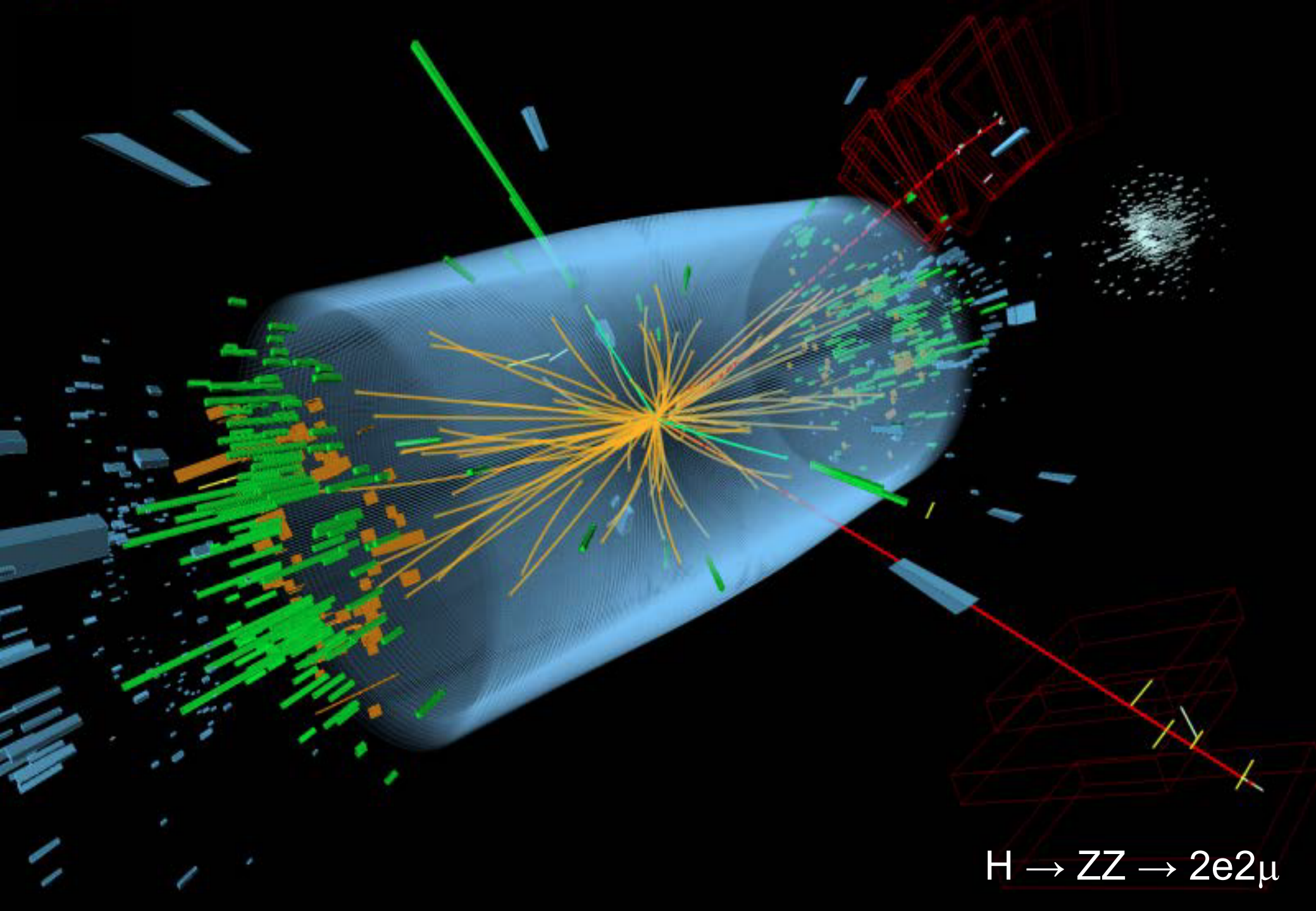




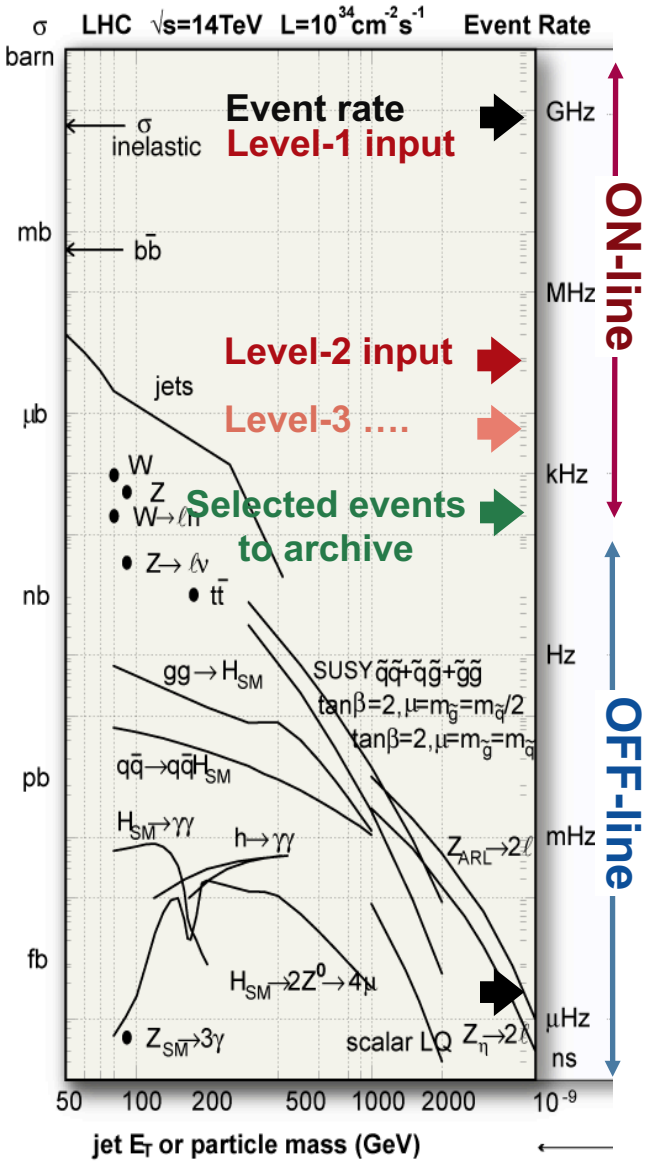
Select 1 event in 10,000,000,000,000

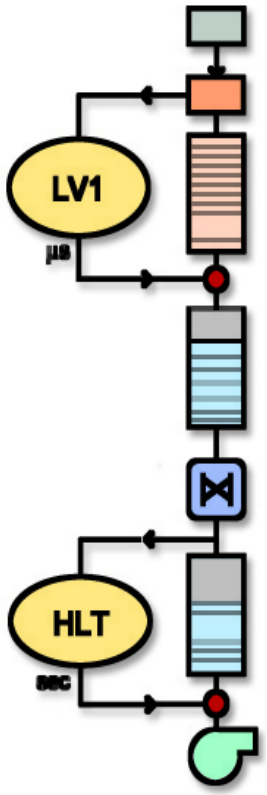
…under difficult conditions




$H \rightarrow ZZ \rightarrow 2e2\mu$

Trigger



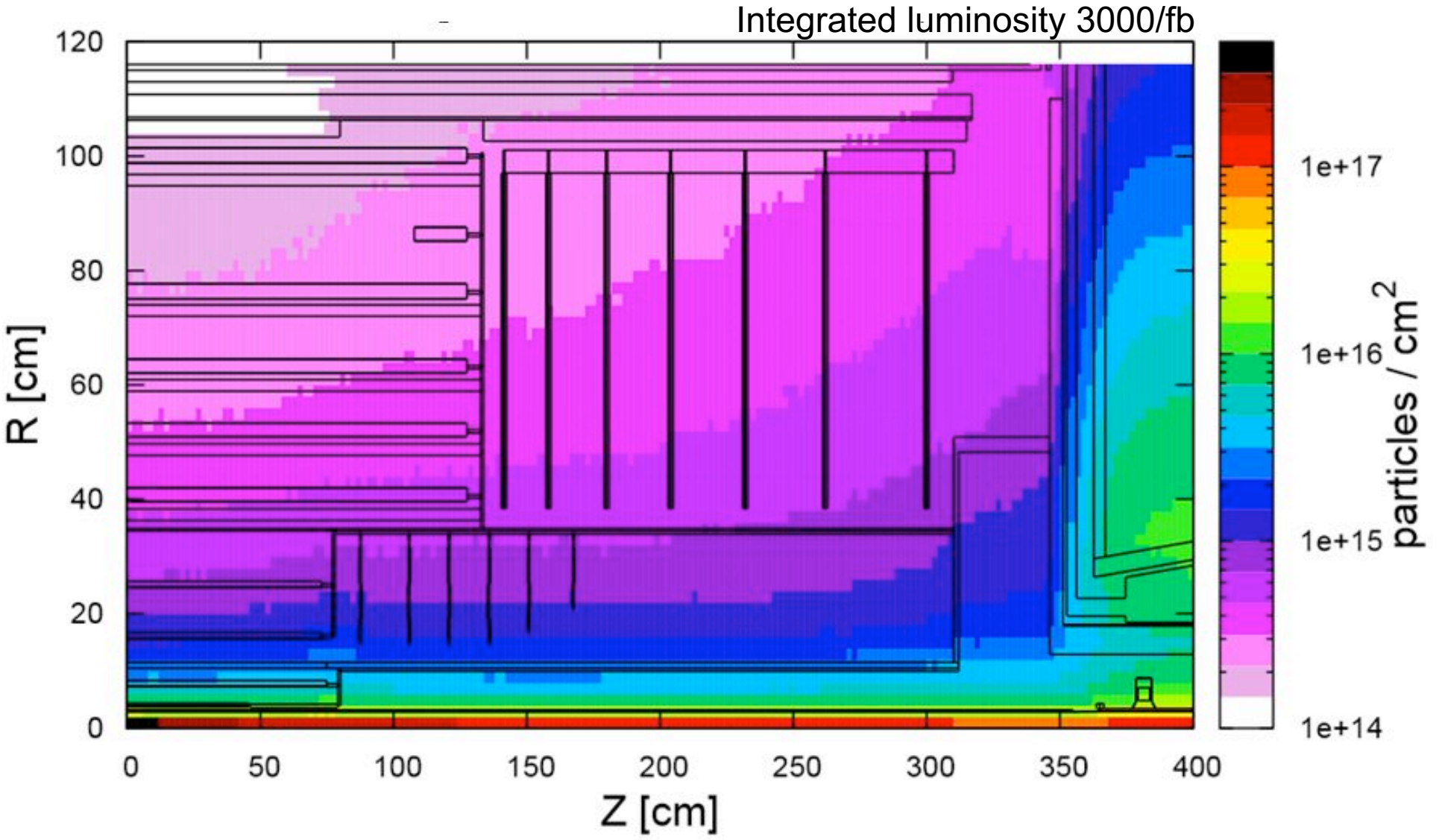


Trigger system decide if the event is interesting to be recorded

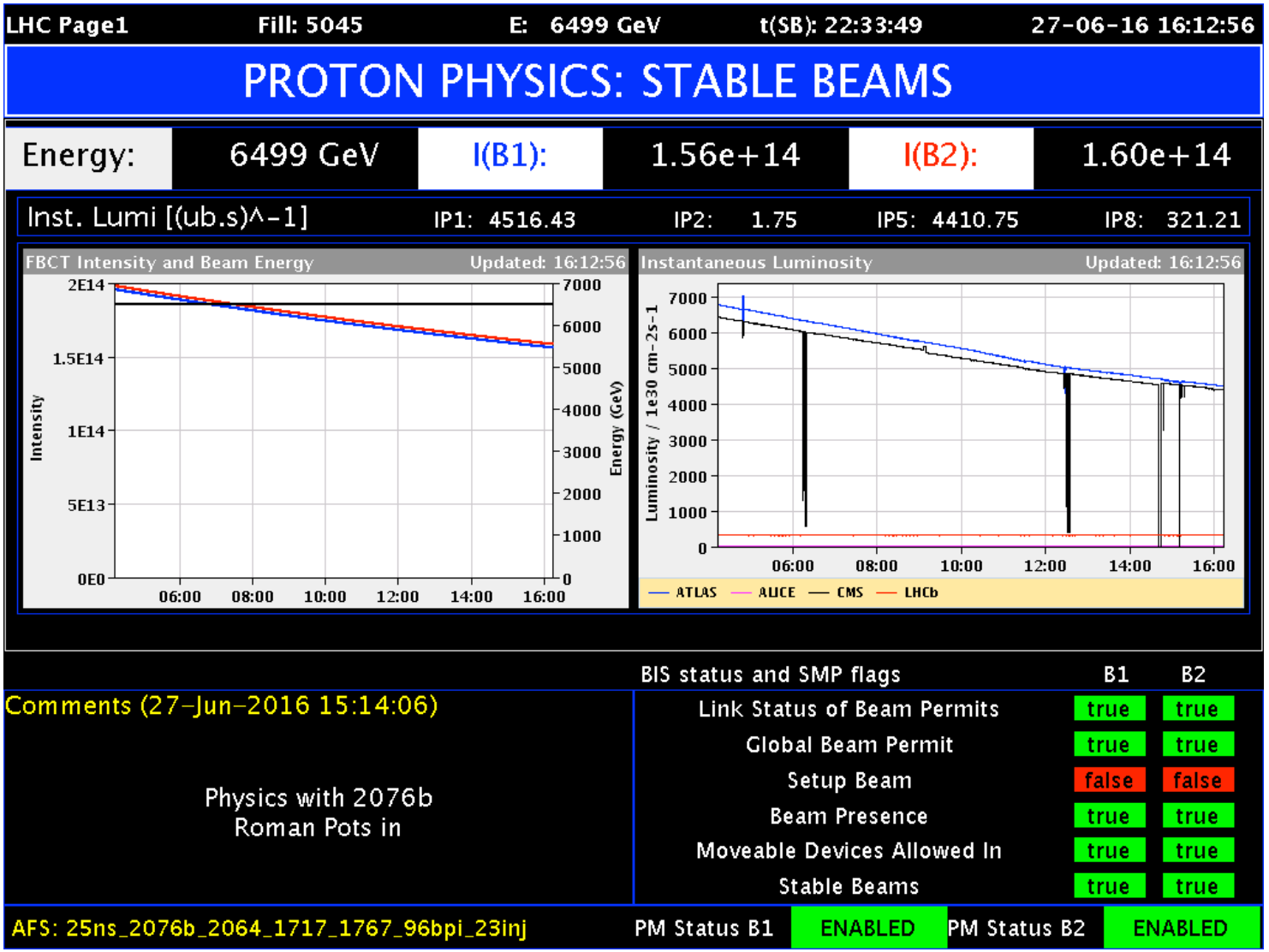
Two-step process:
- Level 1: dedicated hardware processors

- High level: computer farm

High radiation levels



LHC Page 1: stable beams

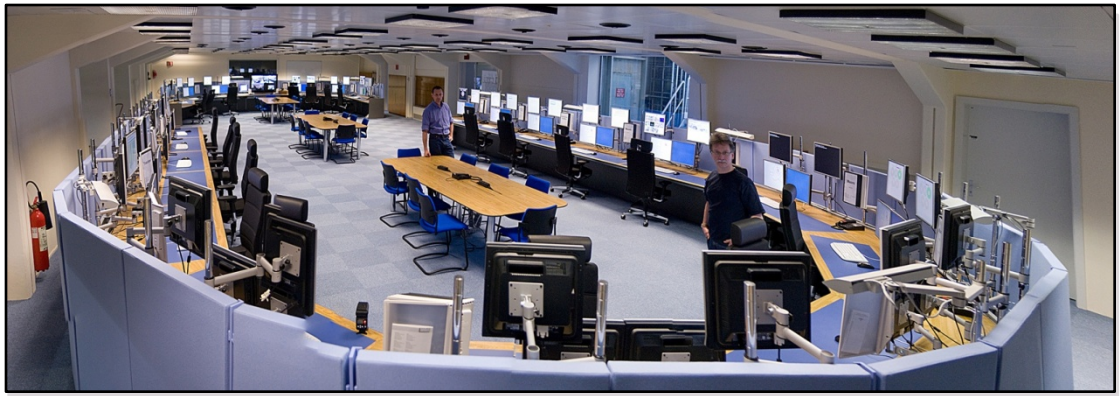


Experiments control rooms

Cessy: Master Control Room

Fermilab: Remote Operations Center

Meyrin: CMS Data Quality Monitoring Center



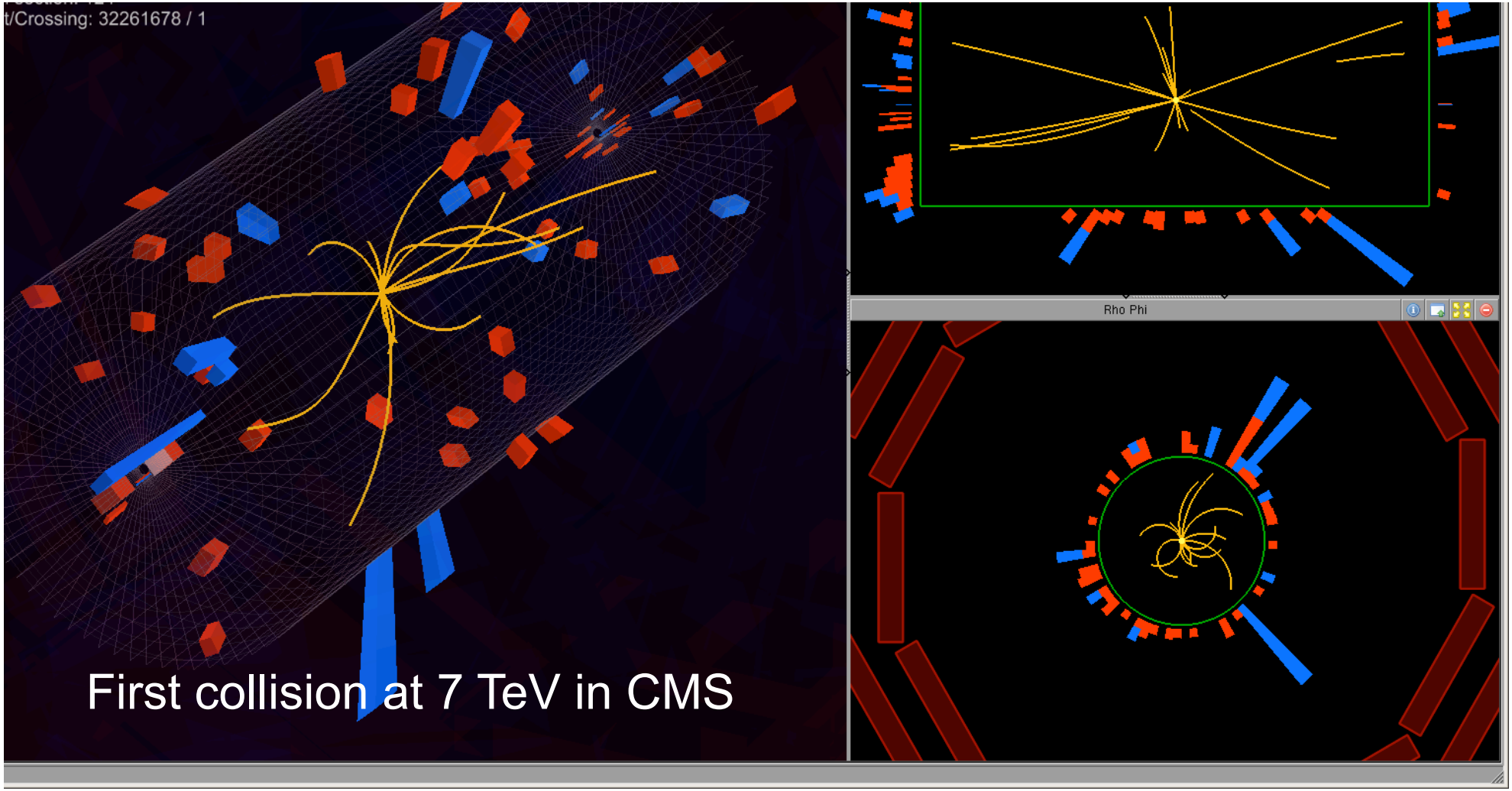
Any Internet access

2009: first collisions at LHC

November 23, 2009
First collisions at 900 GeV

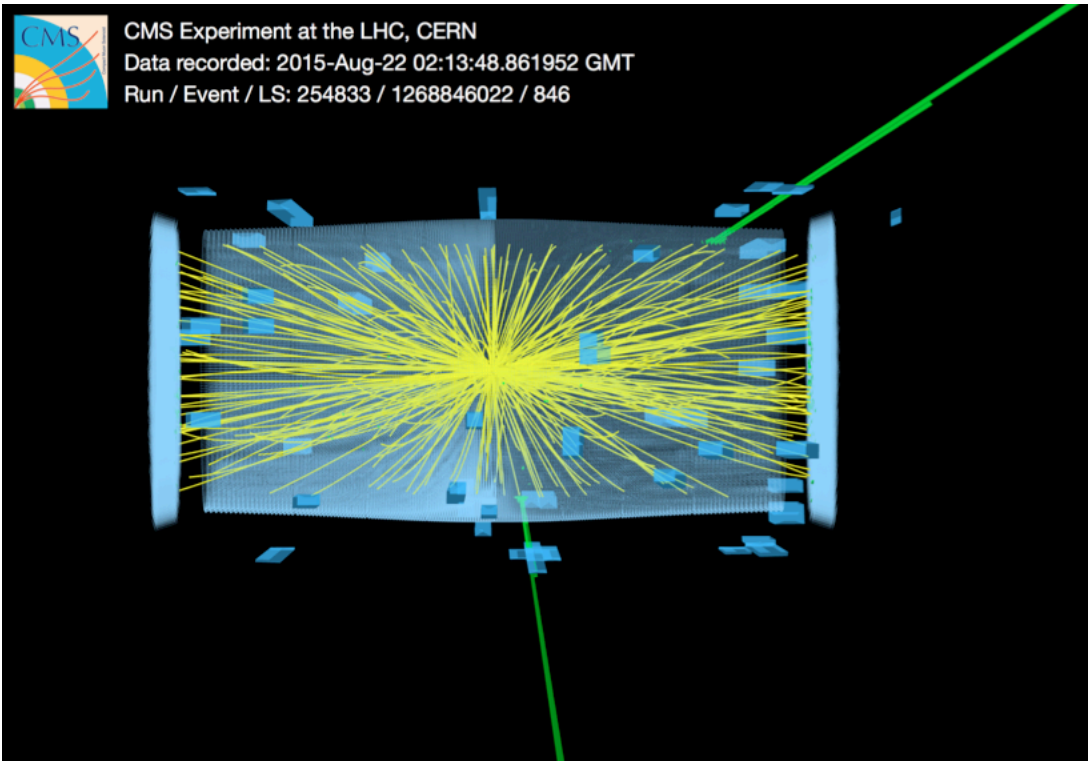
December 14, 2009
First collisions at 2.36 TeV

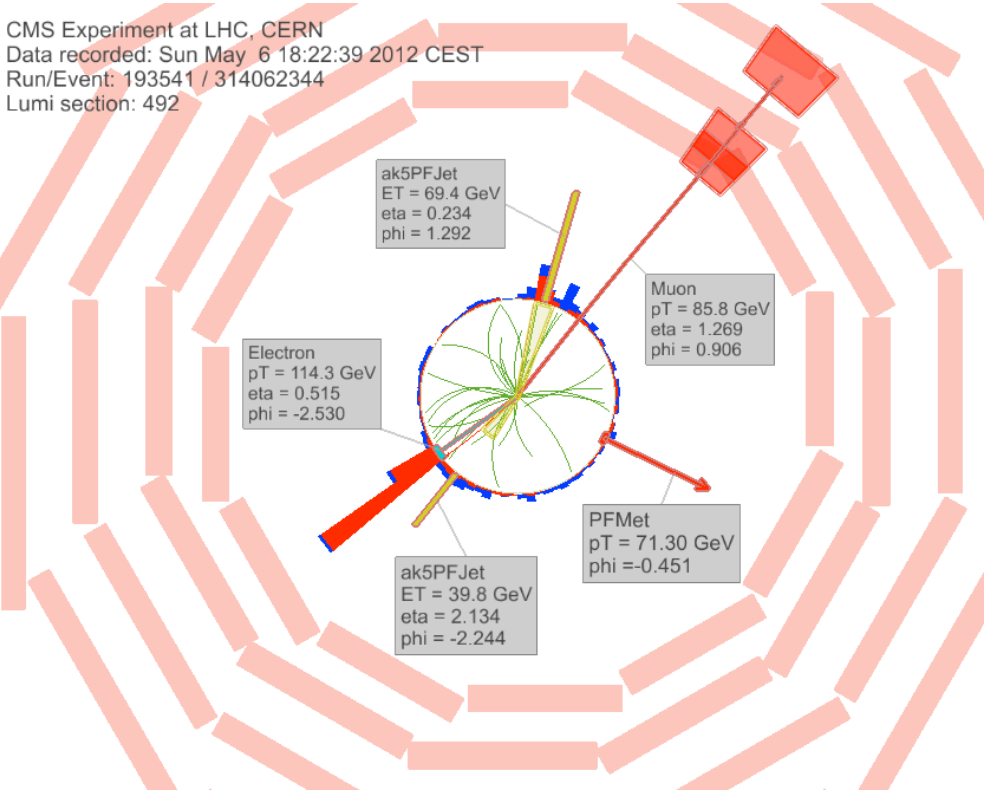
March 30, 2010
First collisions at 7 TeV



Event reconstruction

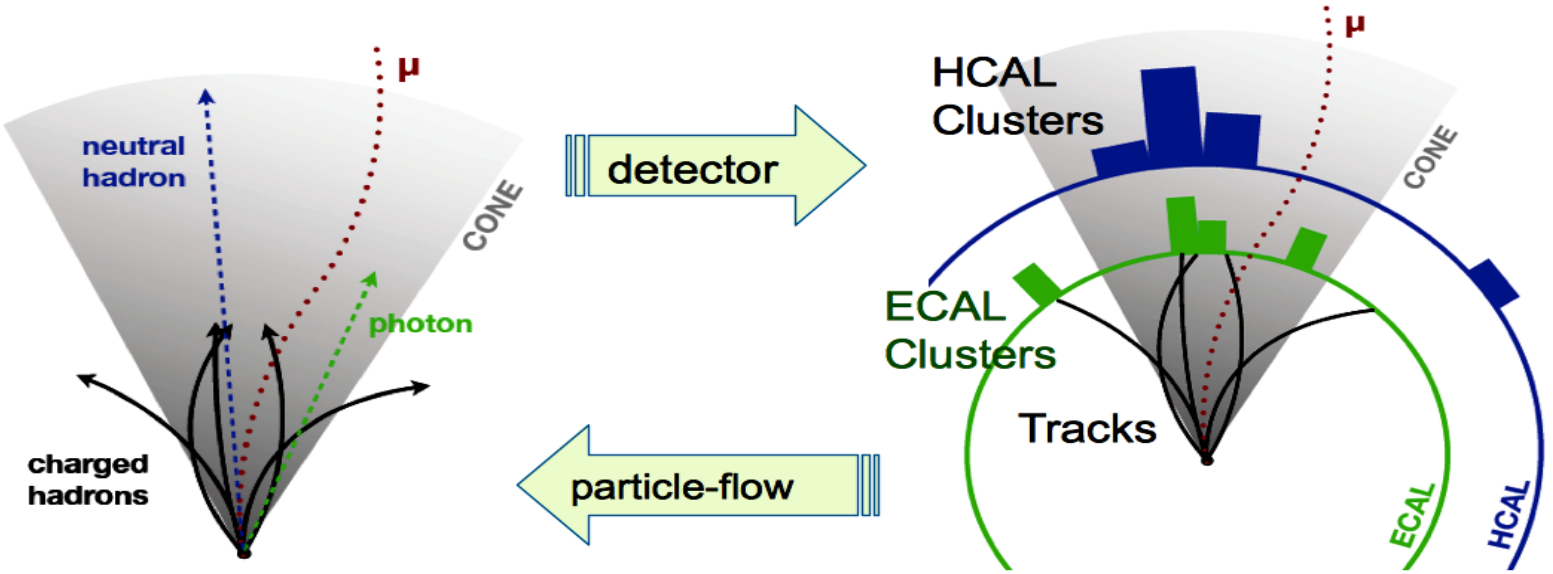
- Reconstruct event and all constituents:
  - leptons (e, μ, τ), photons
  - tracks
  - jets (b-jets)
  - missing transverse energy
  - etc.



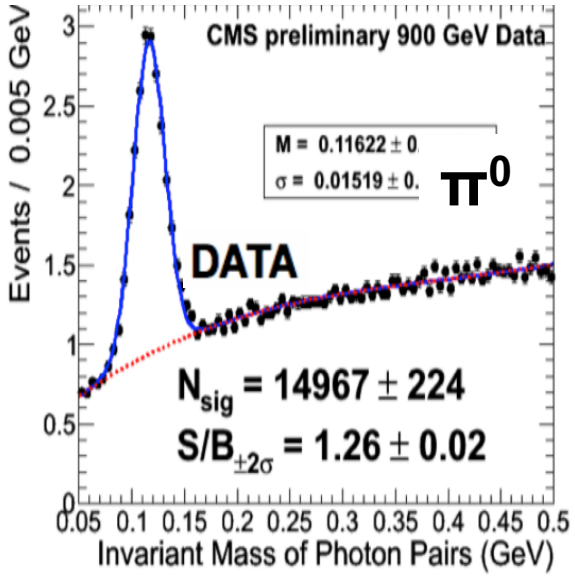


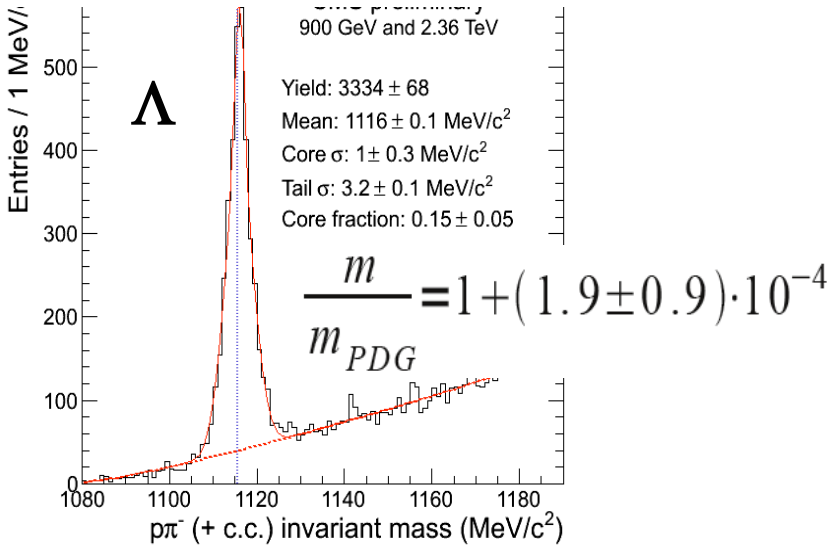
Particle Flow event reconstruction

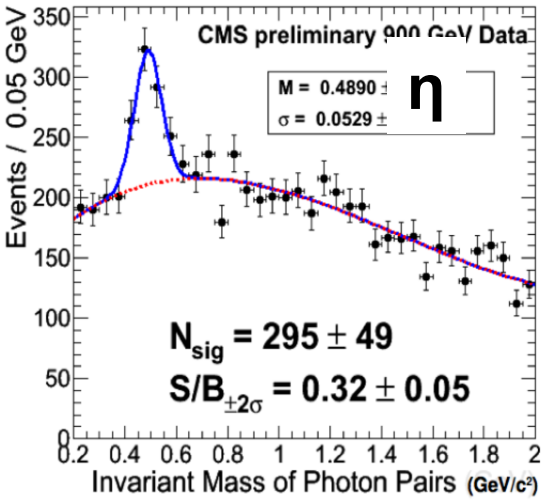
- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision
  - charged hadrons, neutral hadrons, photons, muons, electrons
  - use complementary info. from separate detectors to improve performance
  - tracks to improve calorimeter measurements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

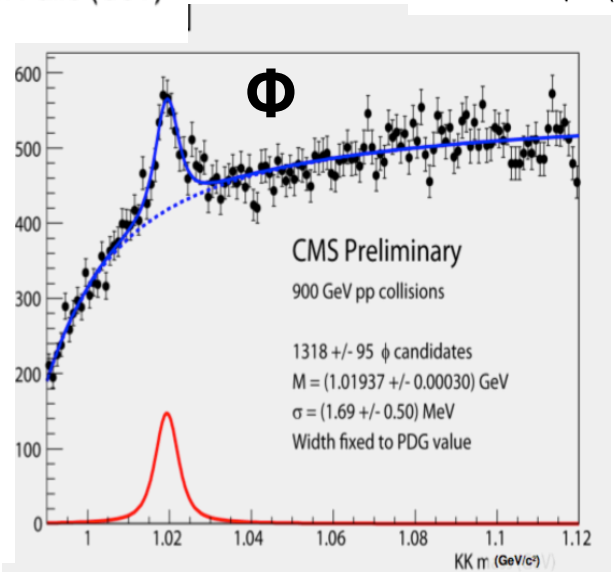


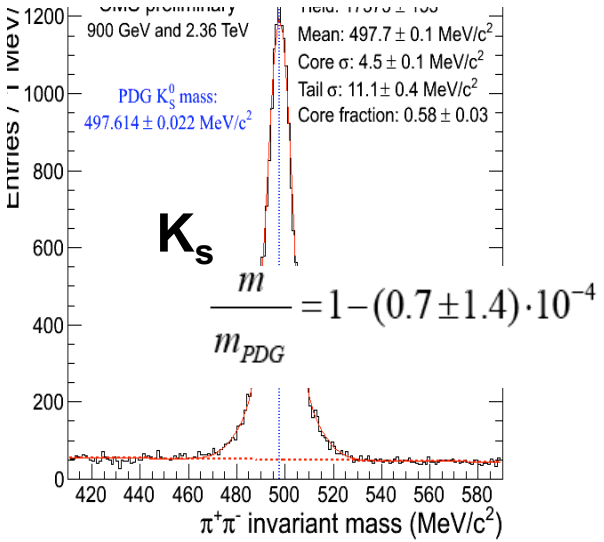
Rediscovery of resonances



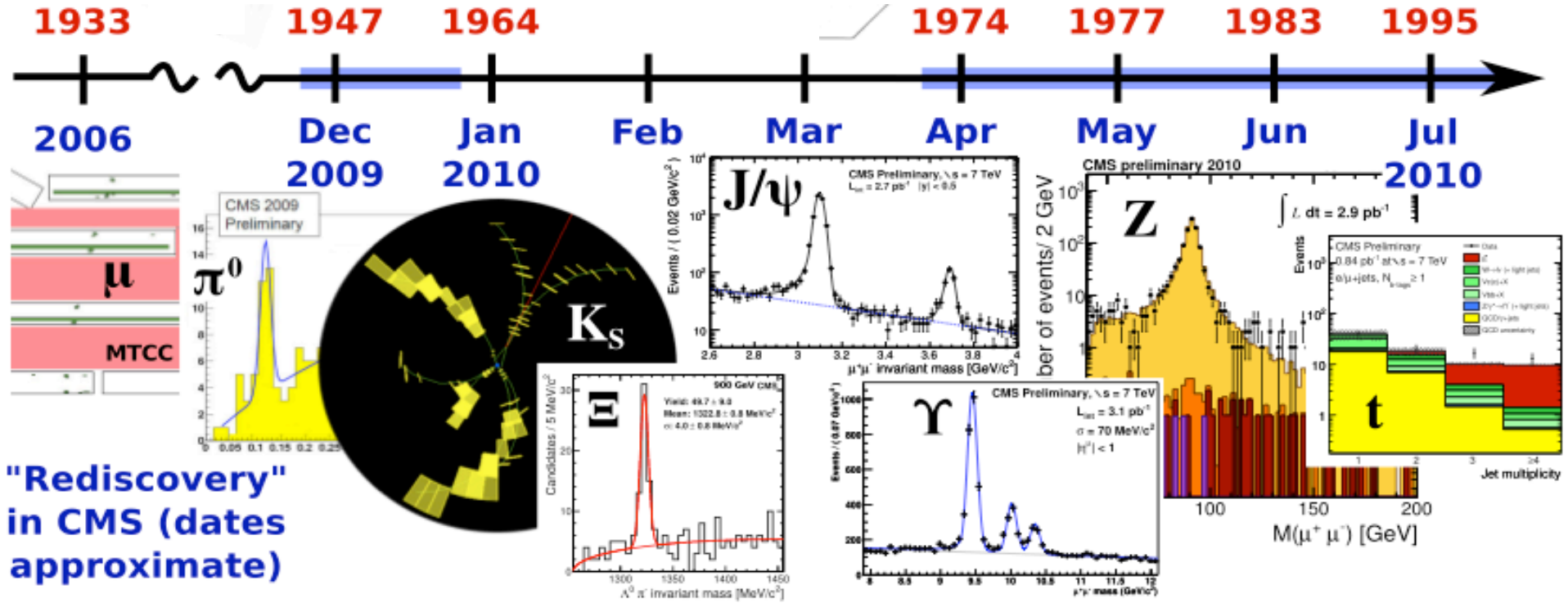




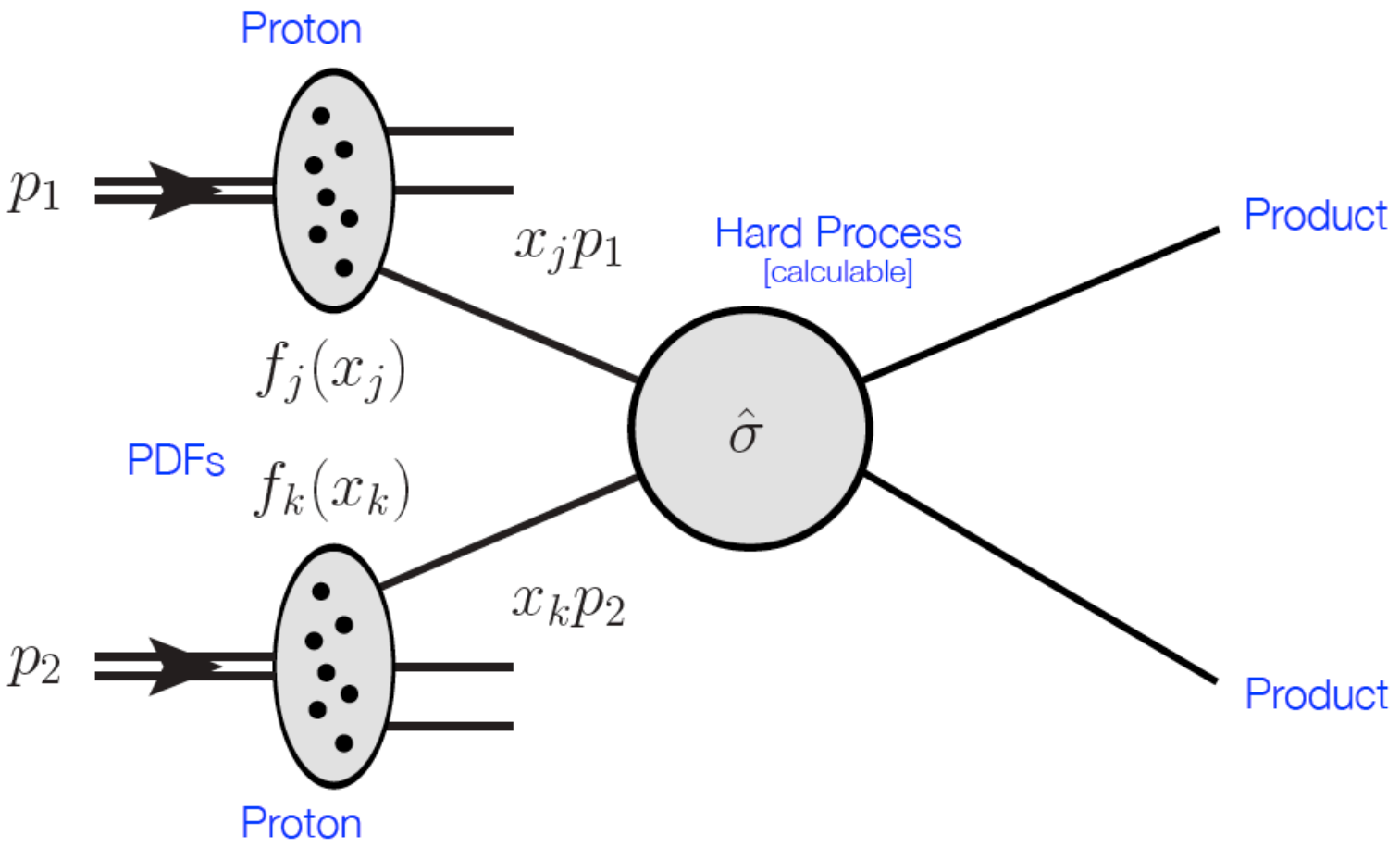




Re-discovery of the SM at LHC

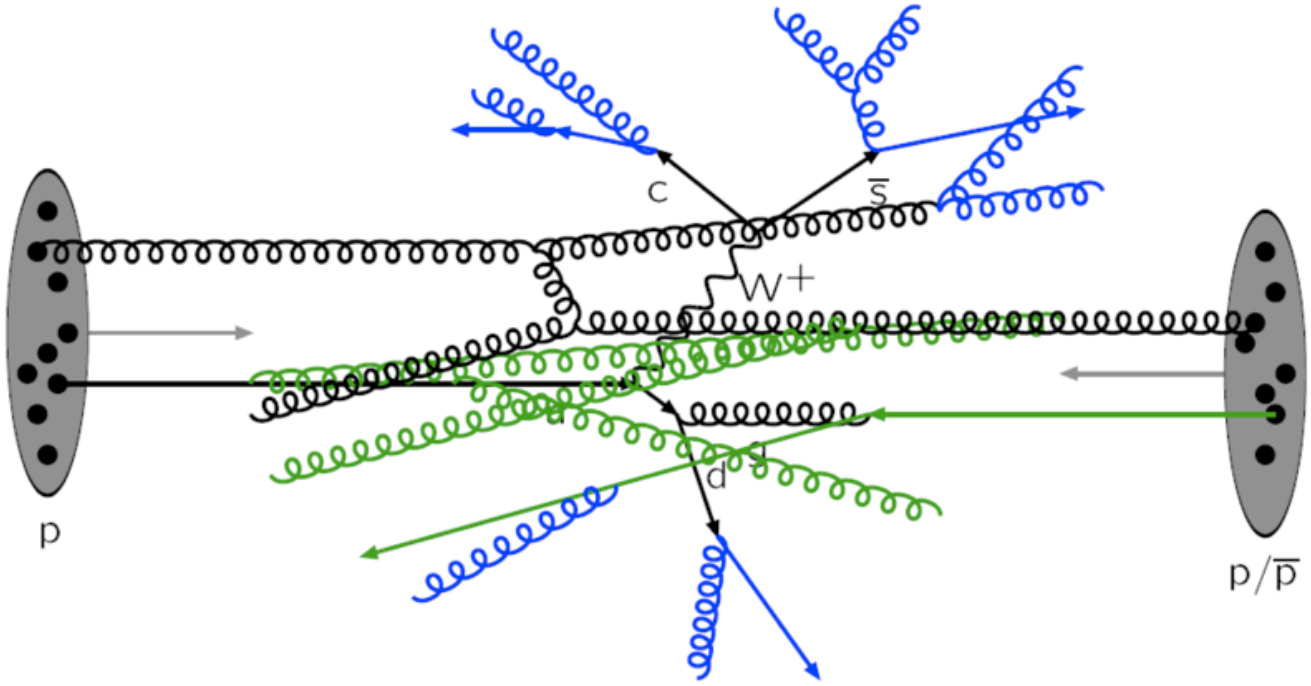


Hadron interactions: pp scattering



Proton-proton scattering at LHC

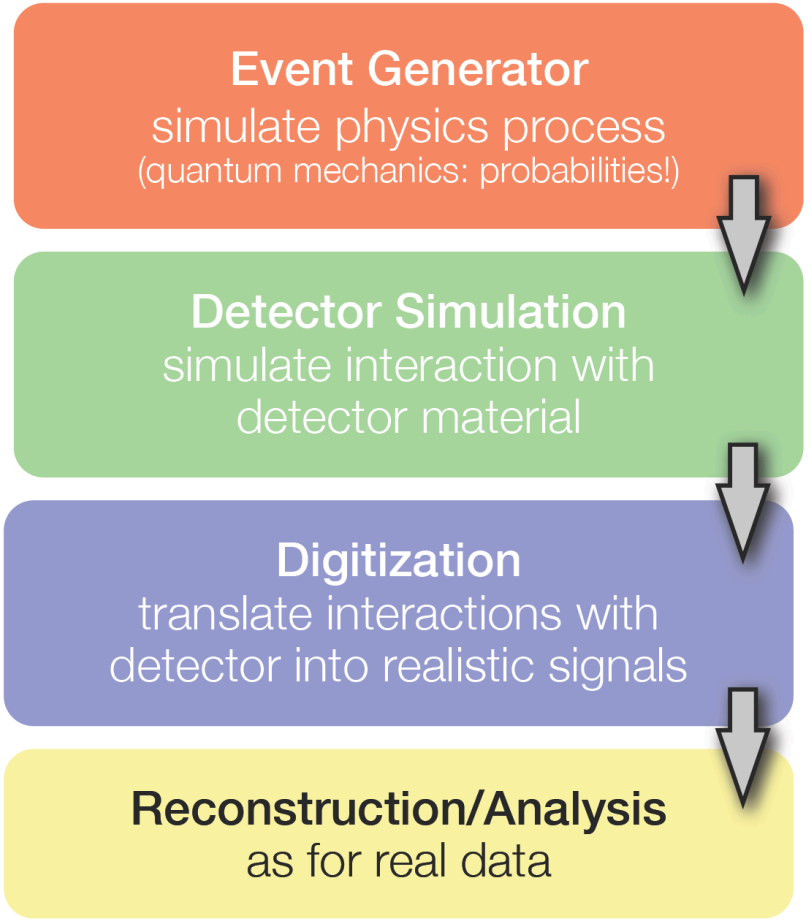
- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction [“underlying event”]



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)*

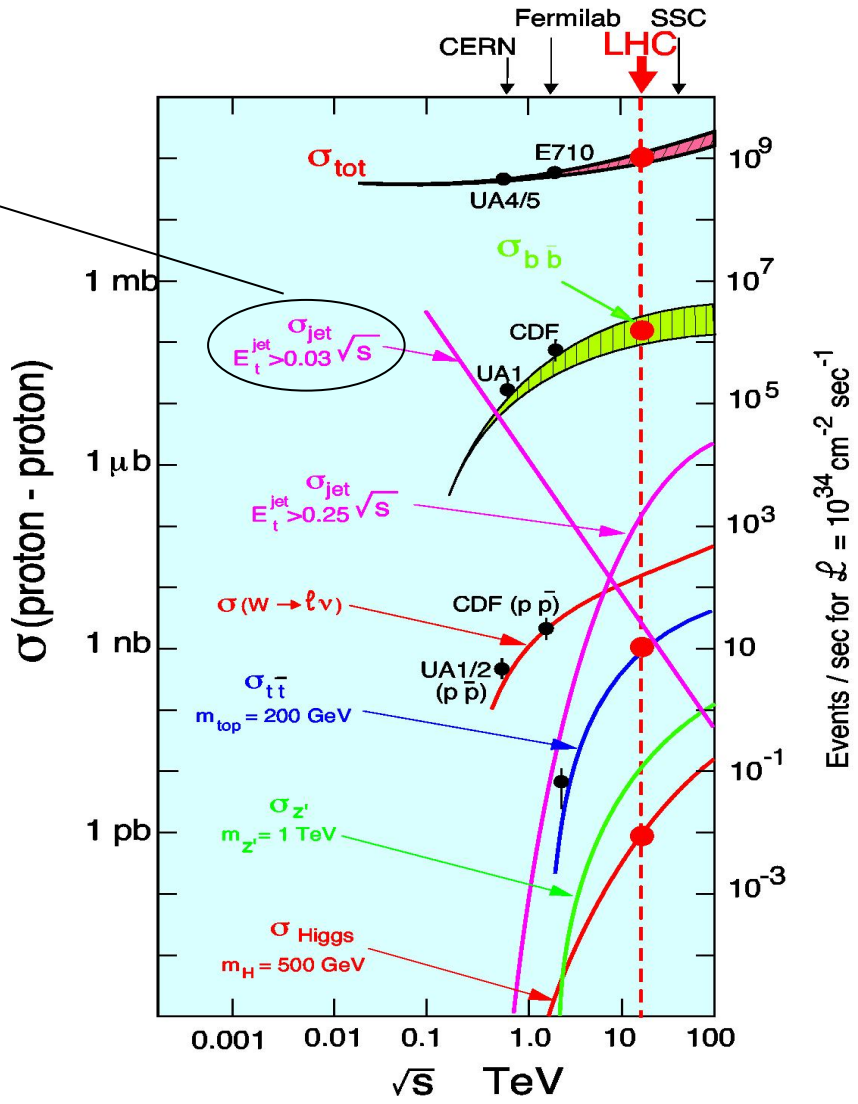
$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int Ldt}$$

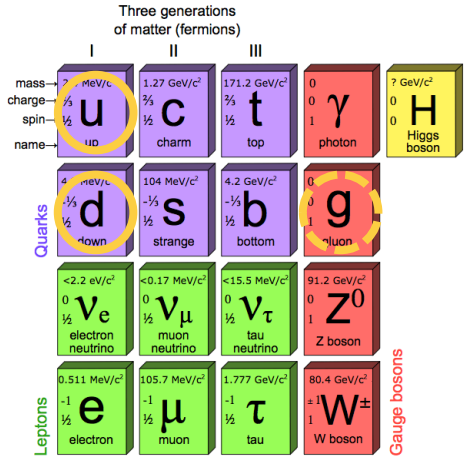
Acceptance *(experimental: detector, efficiencies)*

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

Minimum Bias

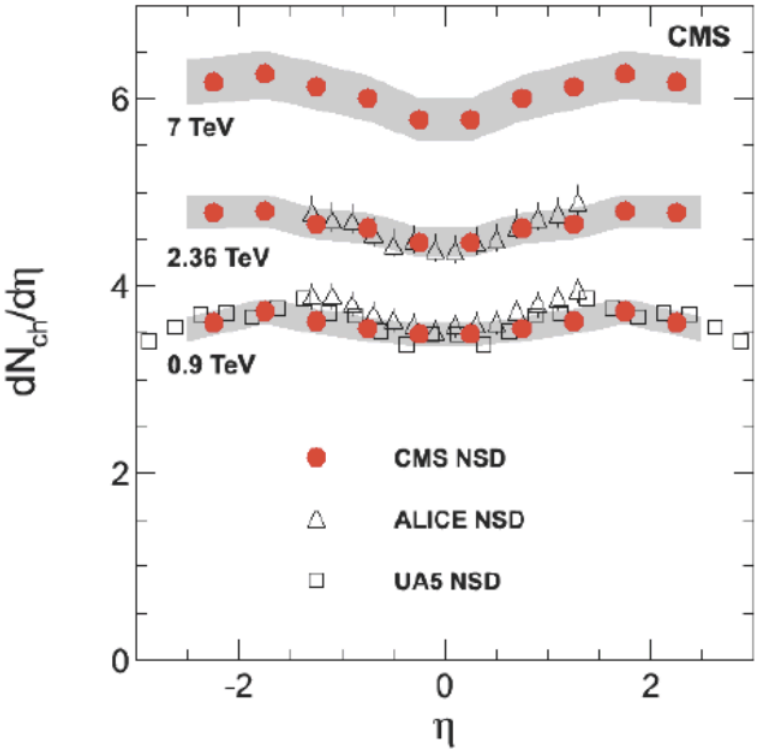
low p_T particle production

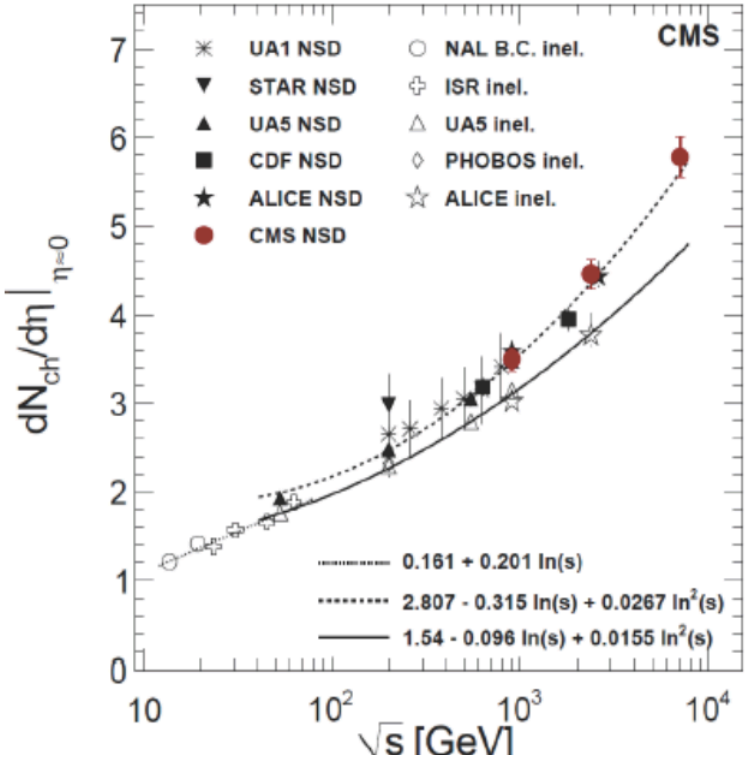




Minimum bias events

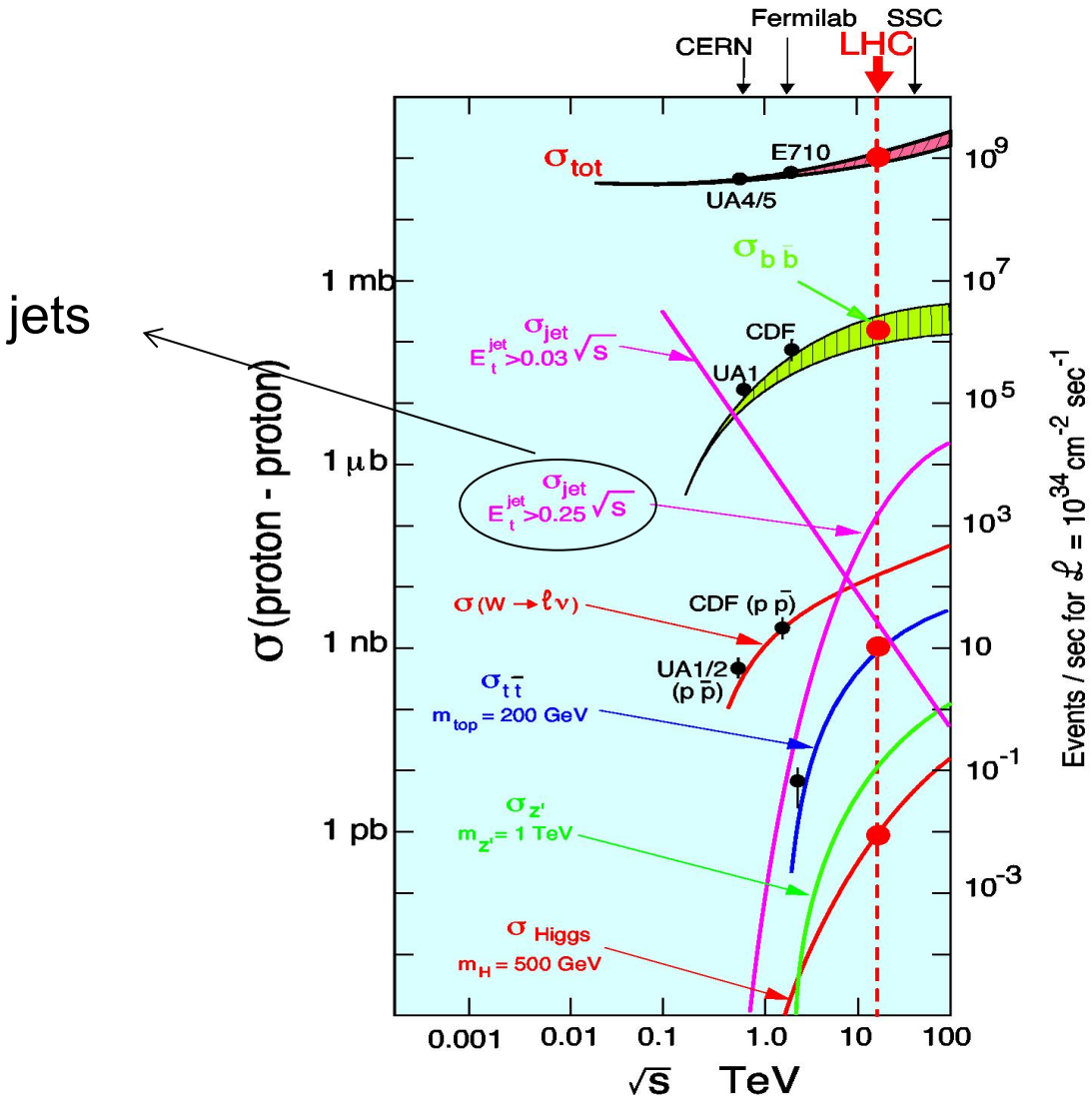
- Particle density in minimum bias events
- Soft QCD (p_T threshold on tracks: 50 MeV)

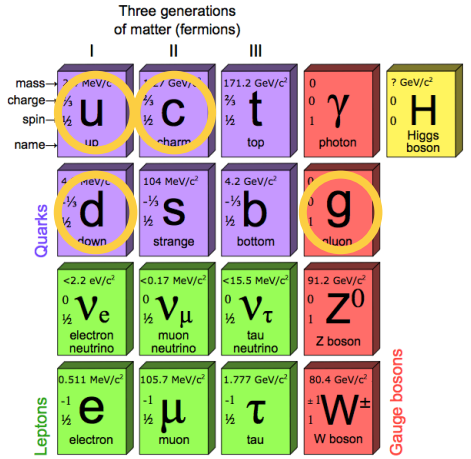




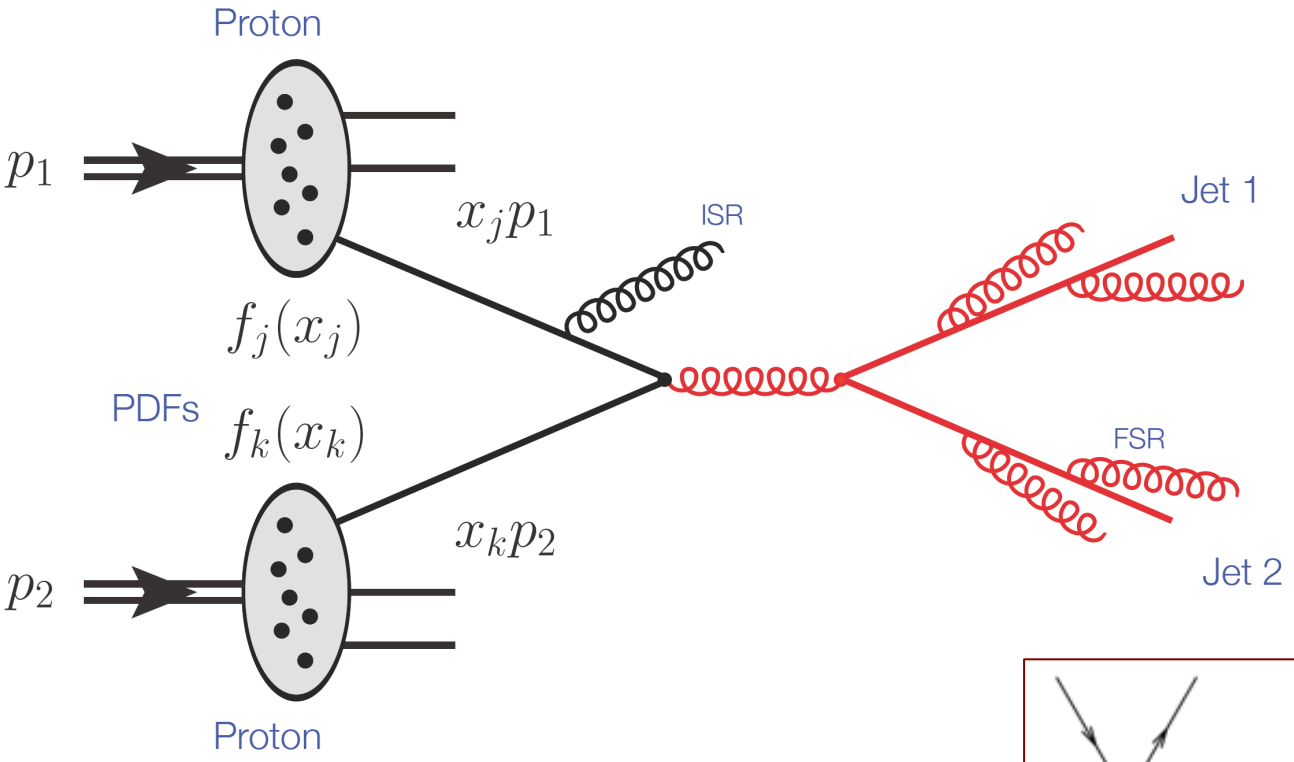
Tuning of MC generators needed

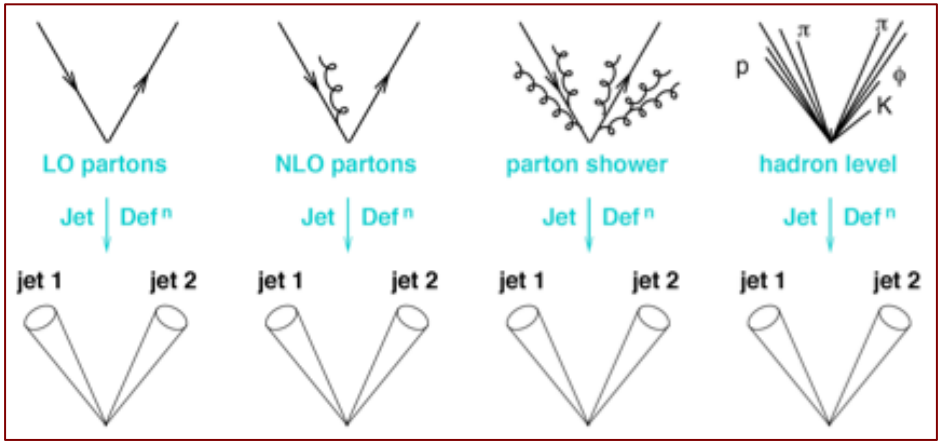
Jet production





Jet production at LHC

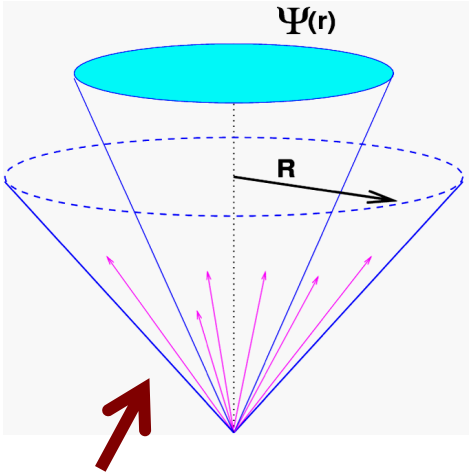




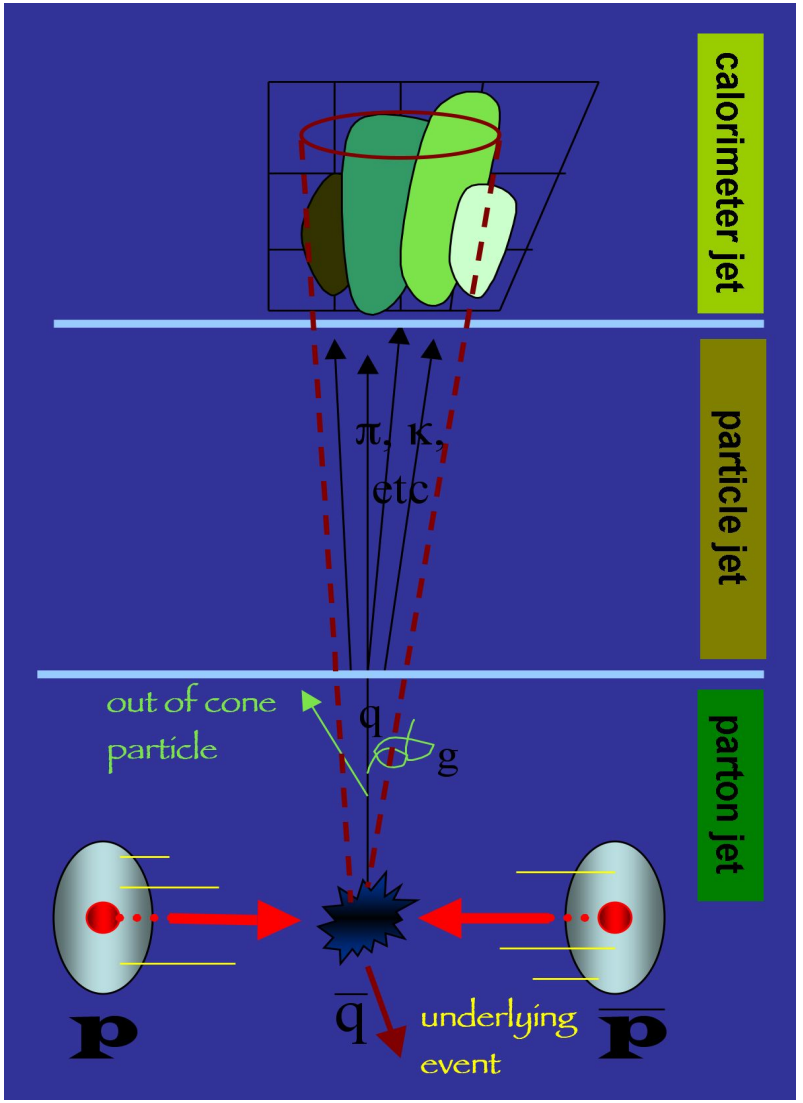
Available up to NLO, first NNLO calculations becoming available

Jet production at LHC (cont.)

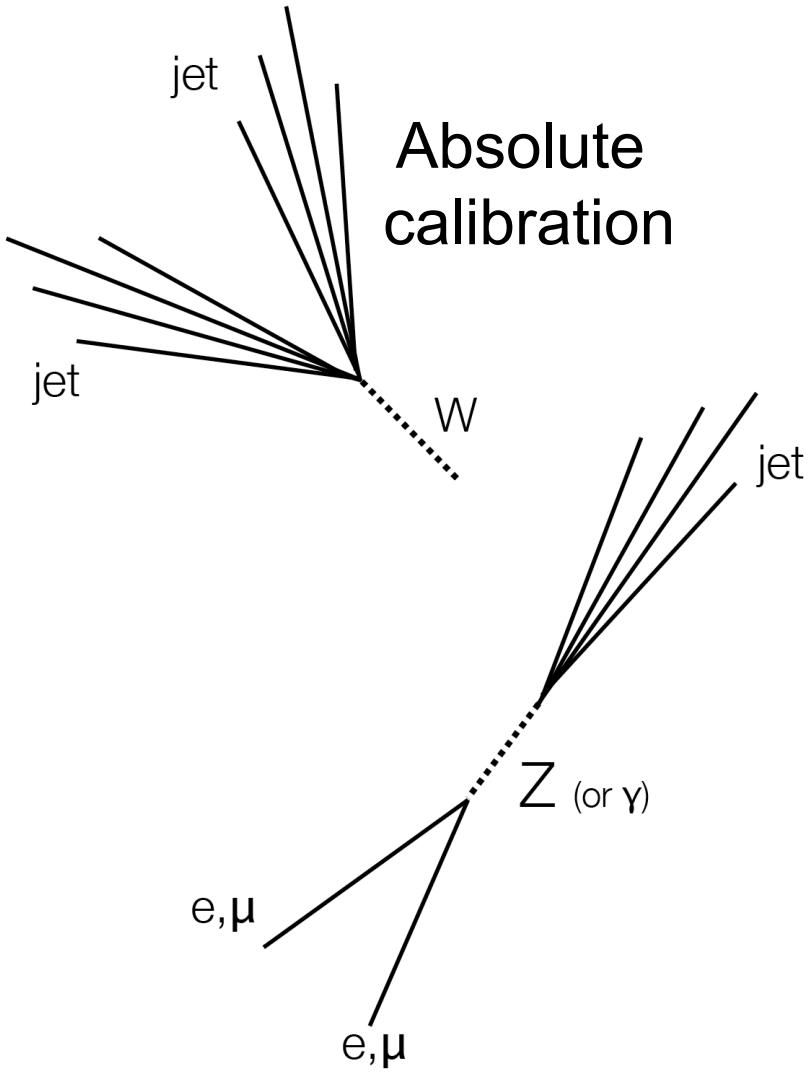
- Processes creating jets are complicated
  - Parton fragmentation, with electromagnetic or hadronic showering in the detector
- Jet reconstruction is difficult
- Jet energy scale and reconstruction is large source of uncertainty

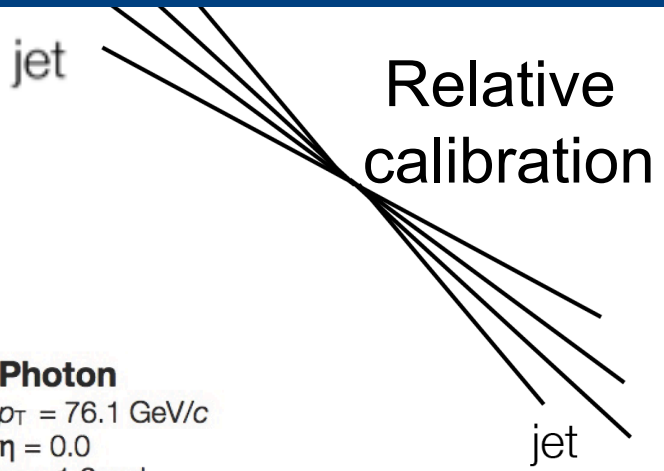


- Measure energy in a “cone”

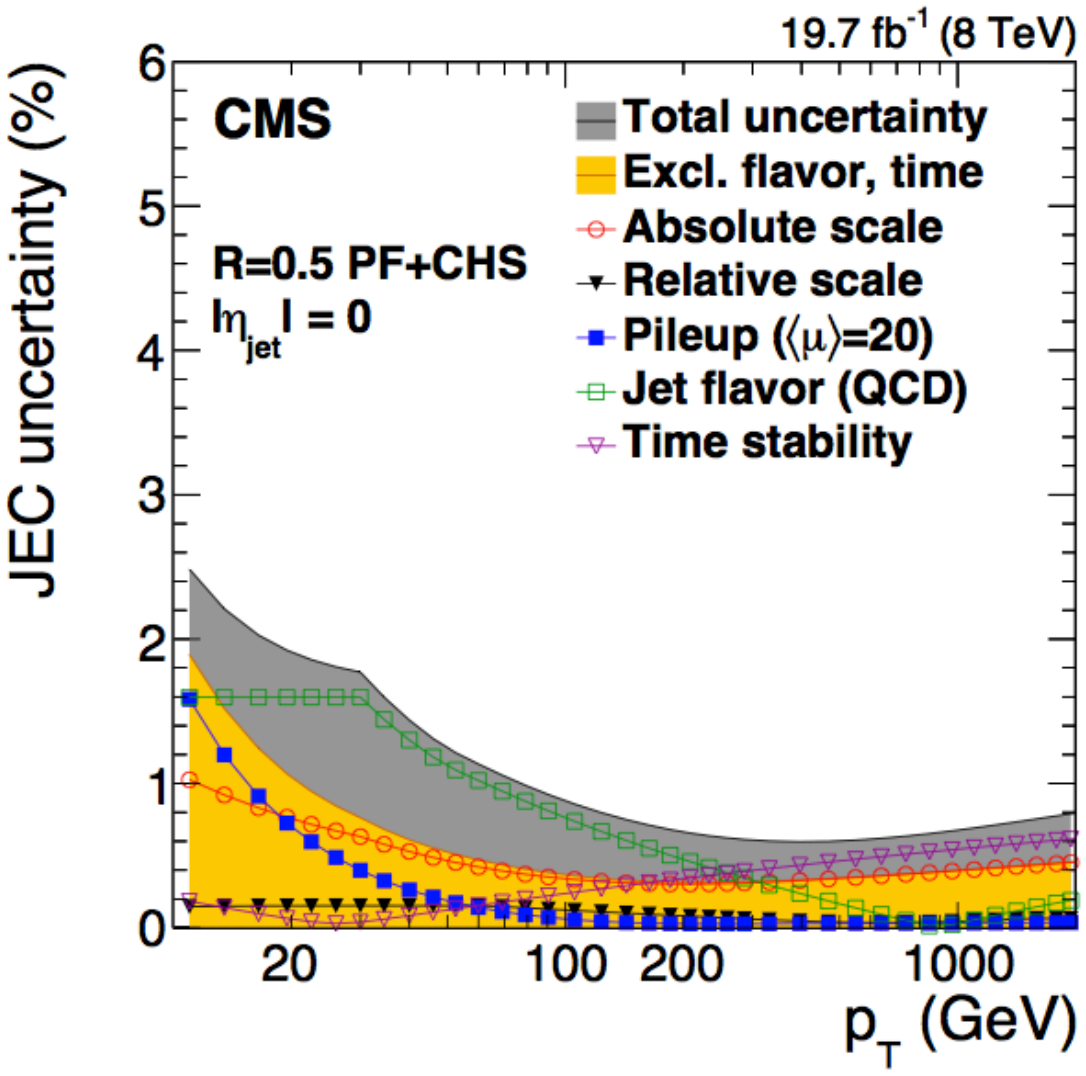


Jet energy calibration





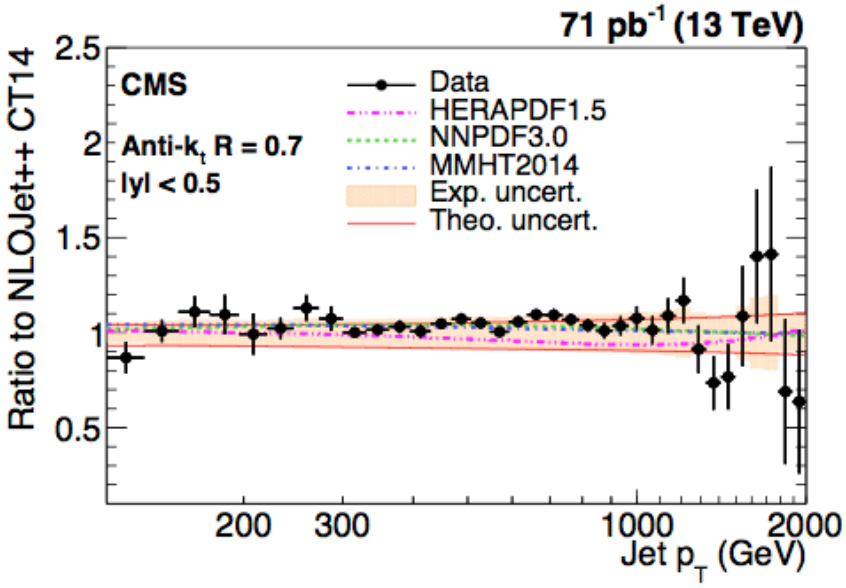
E_T can be measured precisely

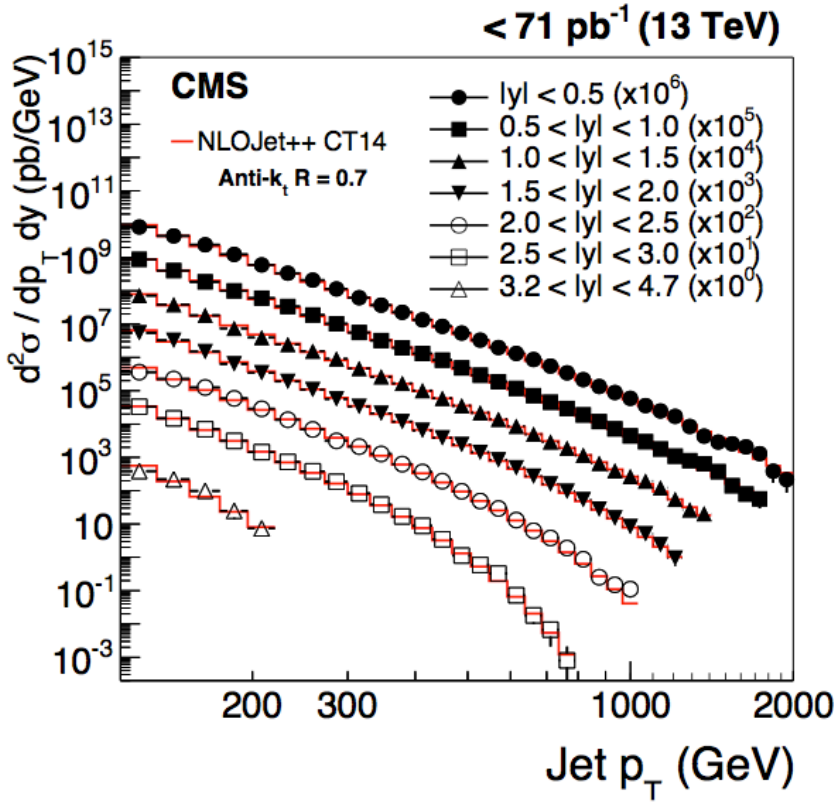


Inclusive jet distribution

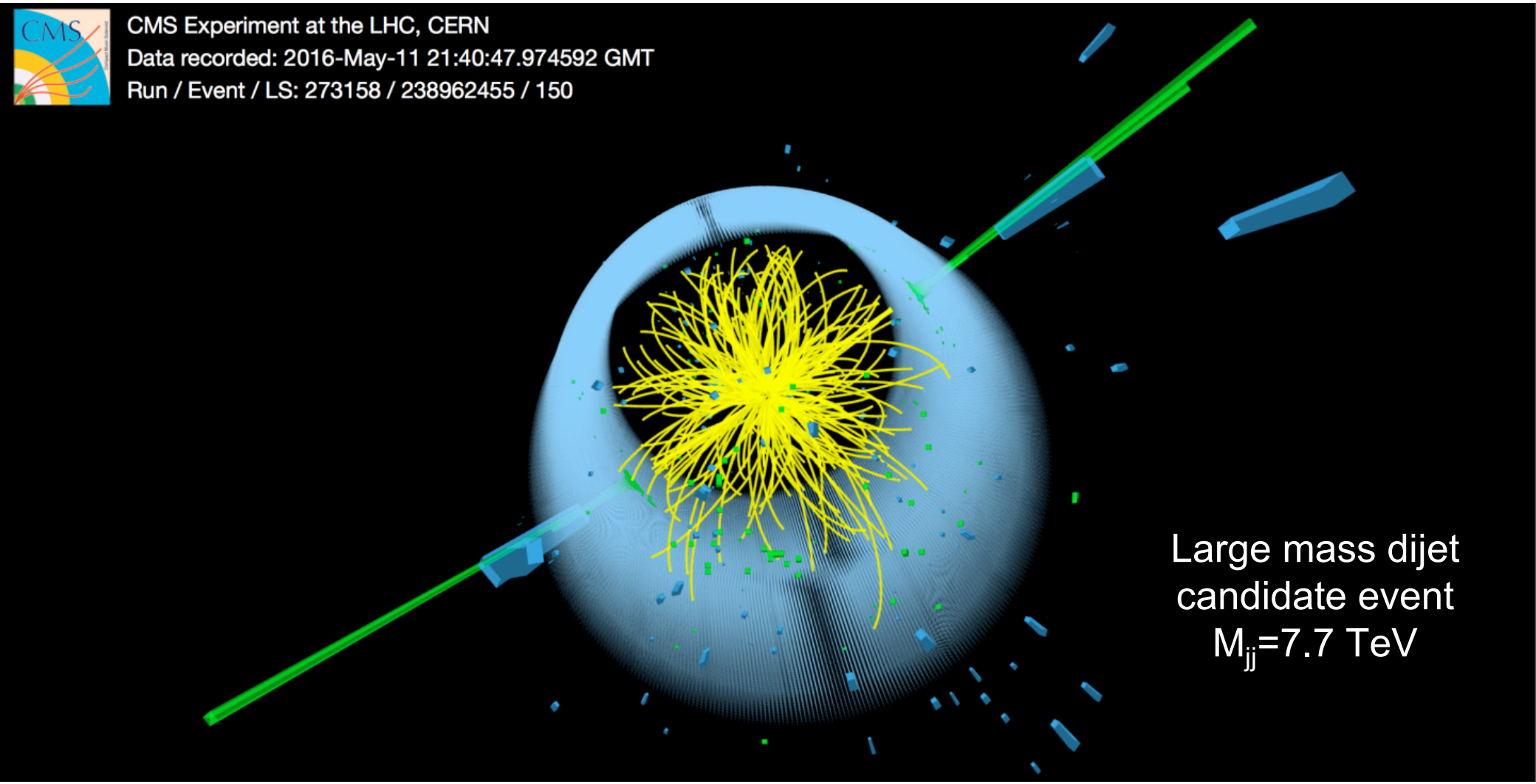
arXiv:1605.04436

- 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

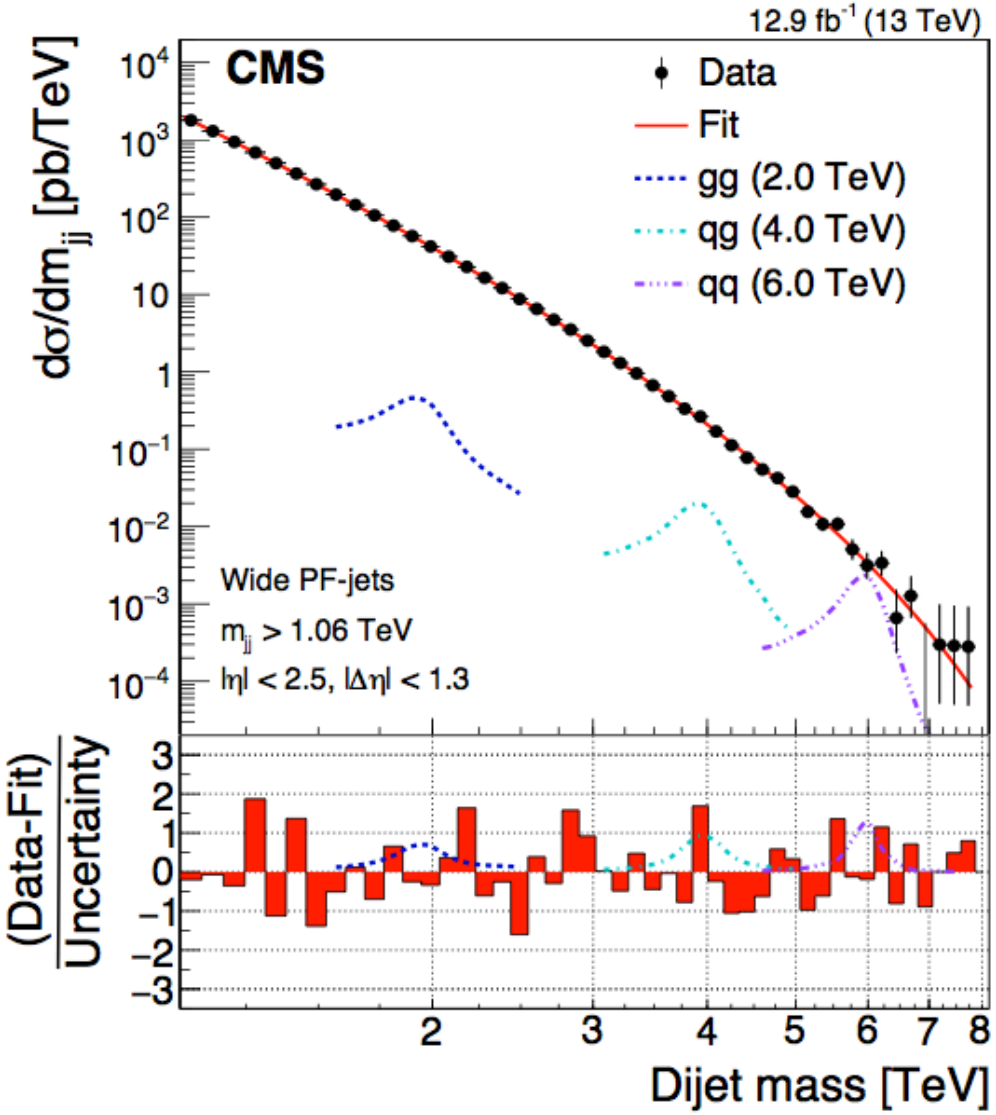


Dijet mass

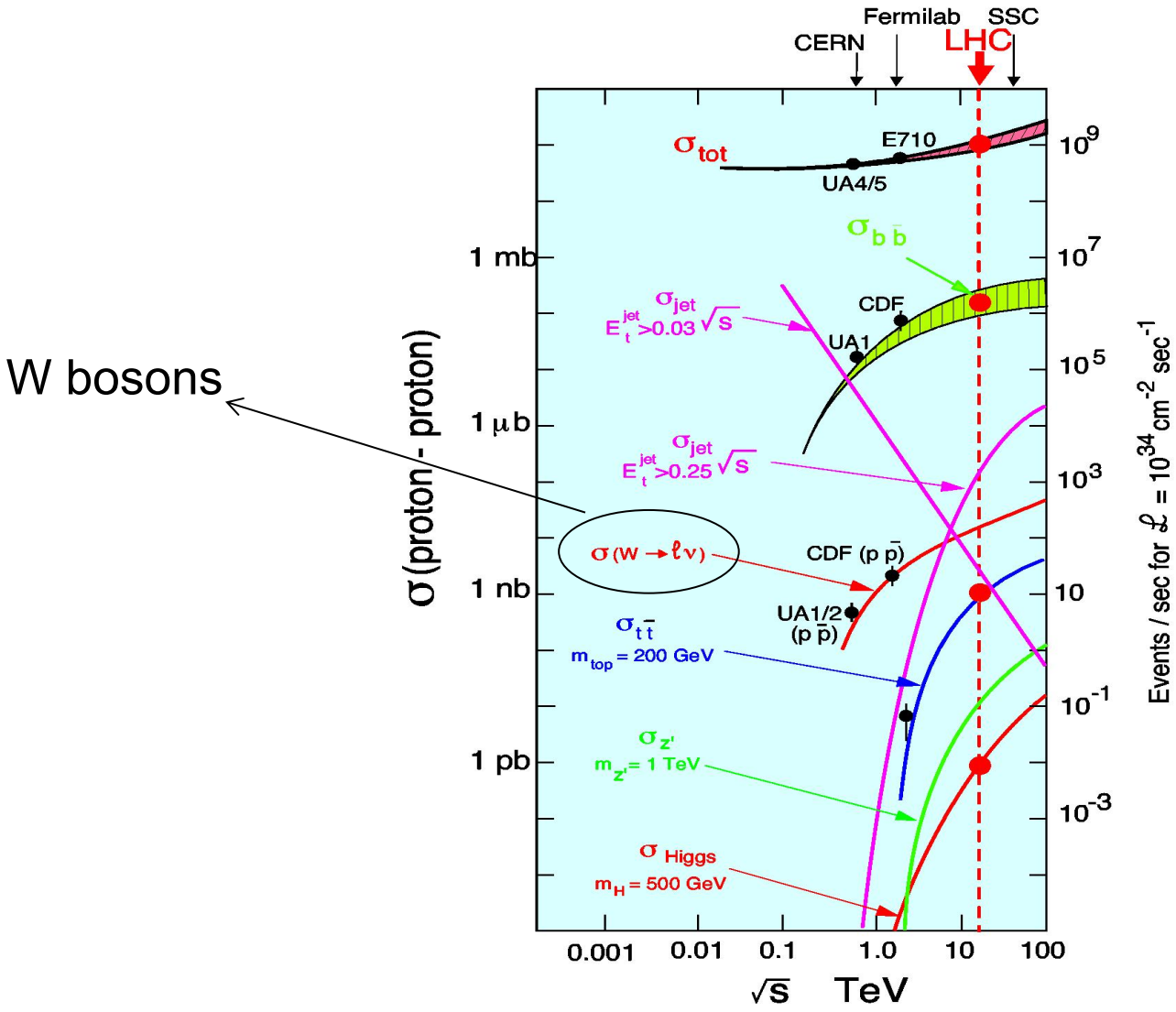
arXiv:1611.03568

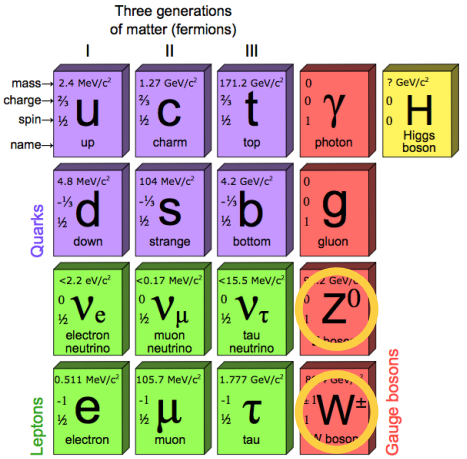
Search for numerous BSM resonances:

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



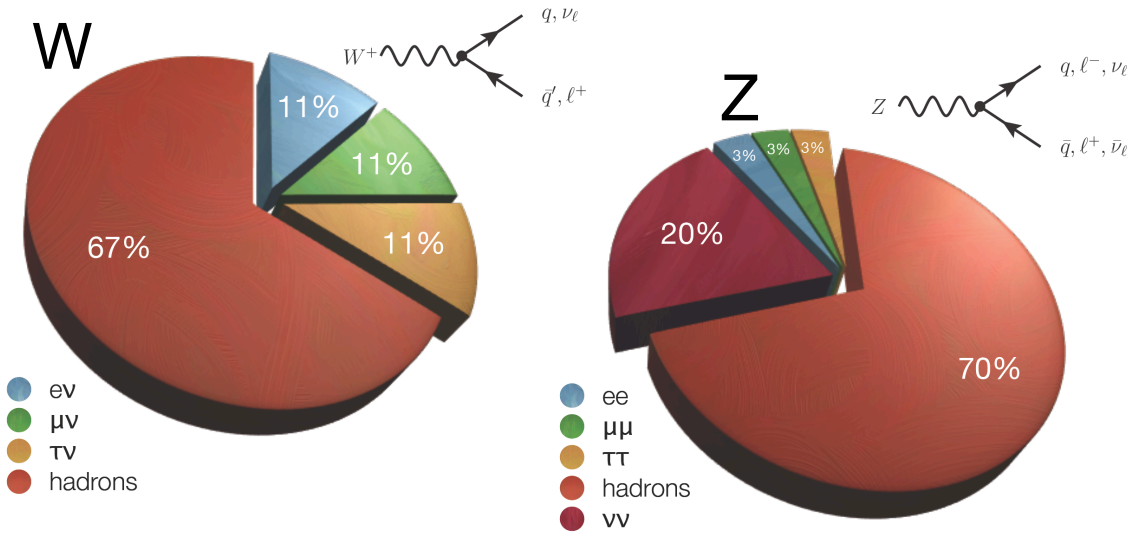
W and Z bosons

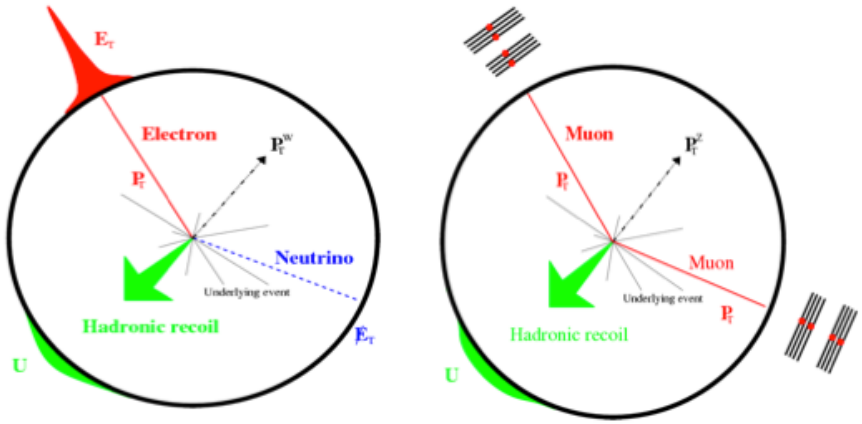




W and Z bosons

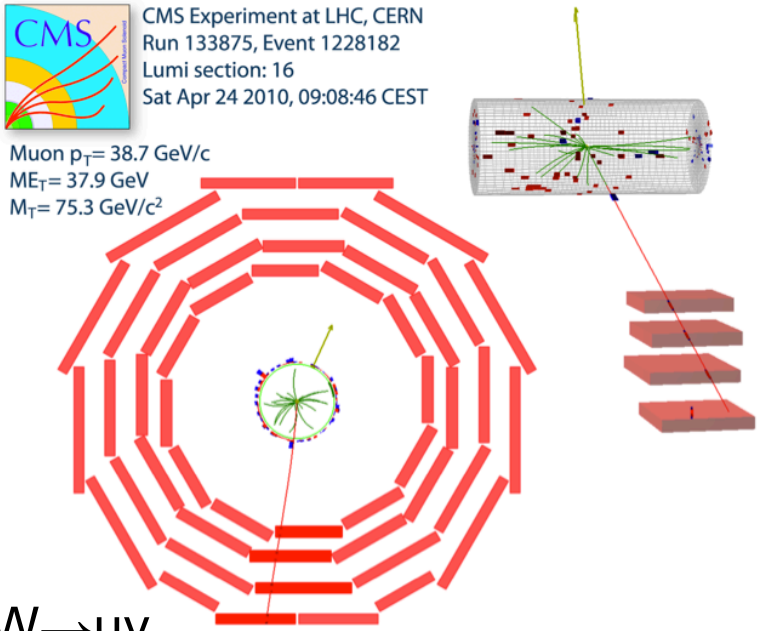
- Leptonic decays (e/μ): very clean, small branching fractions
- Hadronic decays: two-jet final state, large QCD background



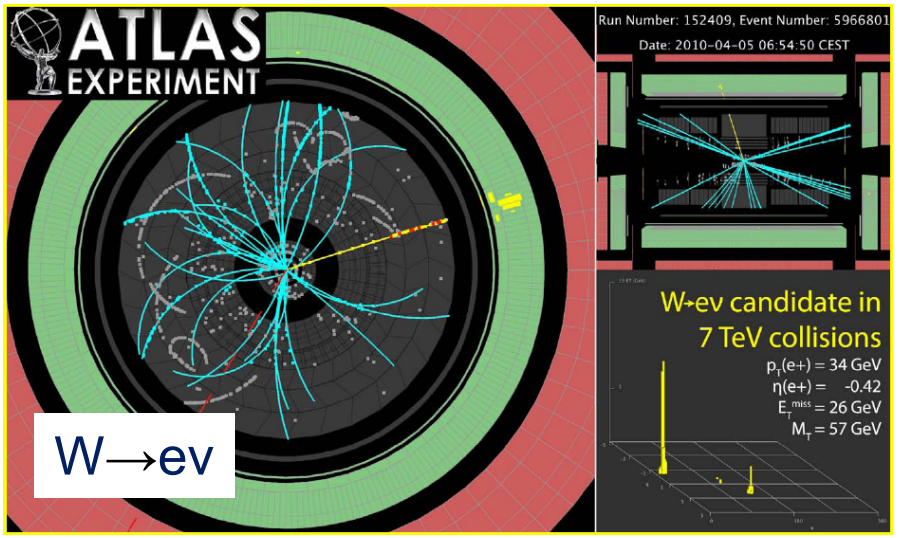


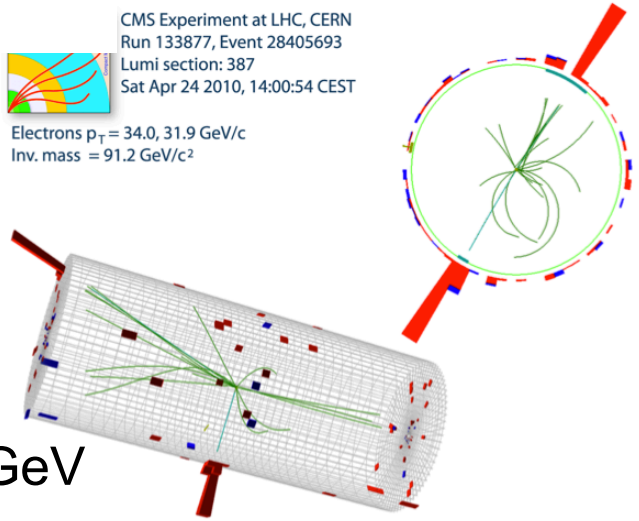
- Isolated high-p_T leptons: starting point of many analyses
  - Good rejection of QCD backgrounds
  - "Tracking" vs "calorimeter" isolation
- Excellent calibration signal
  - Electron energy scale, ID/trigger eff., etc.

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

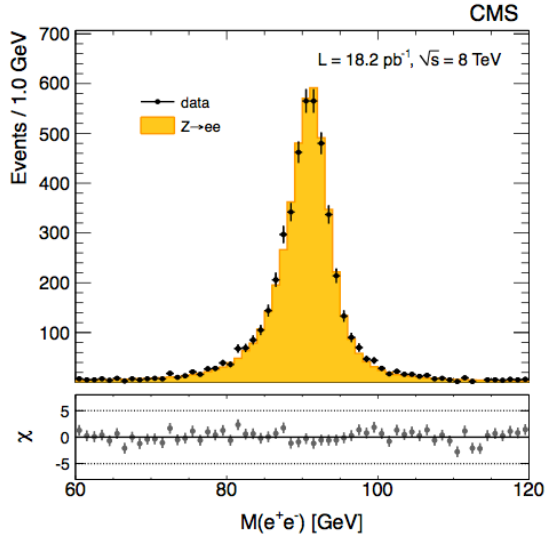
$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

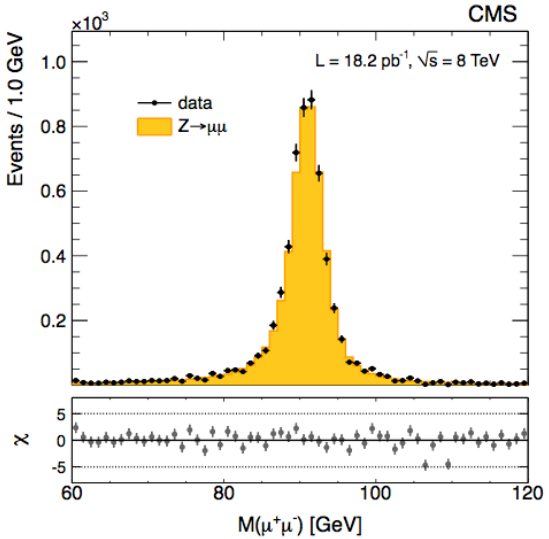
W mass reconstruction

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

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

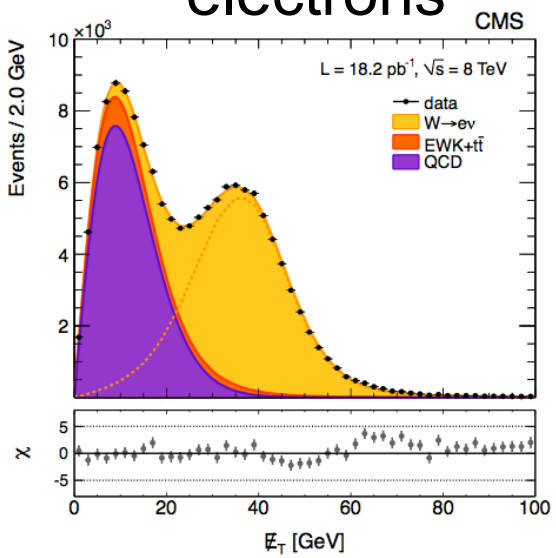
Z boson



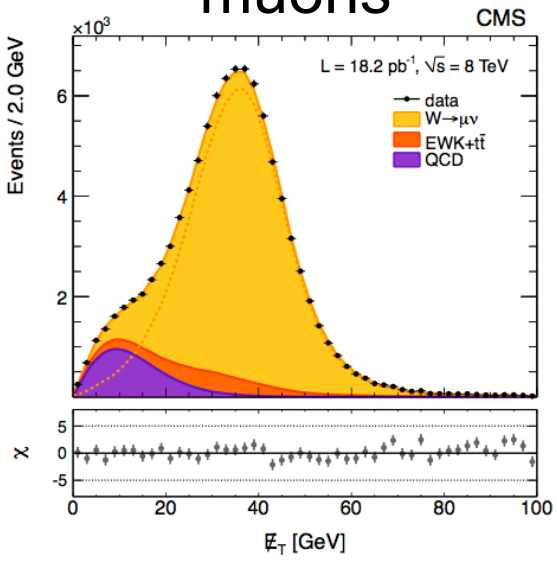


W boson

electrons

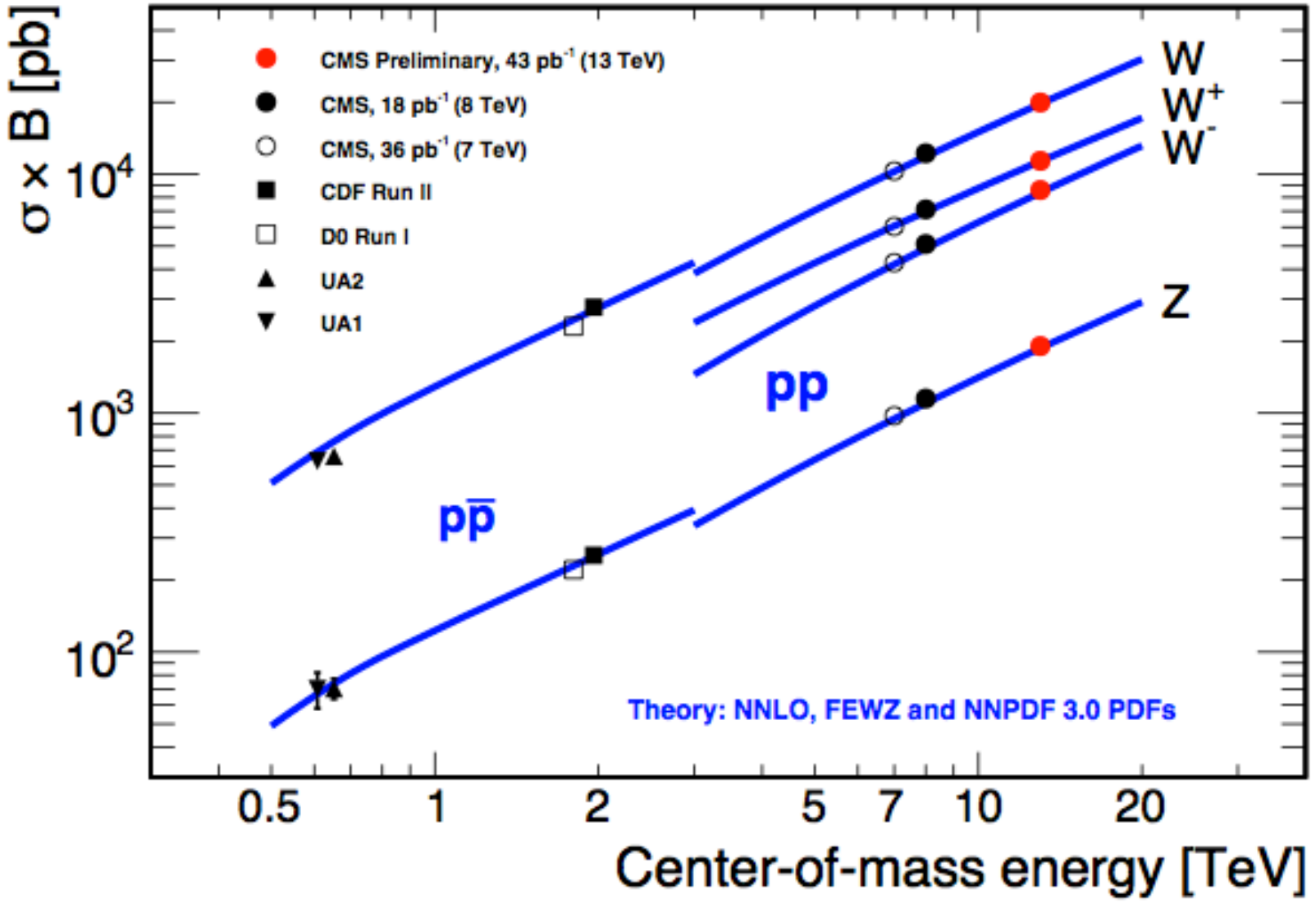


muons



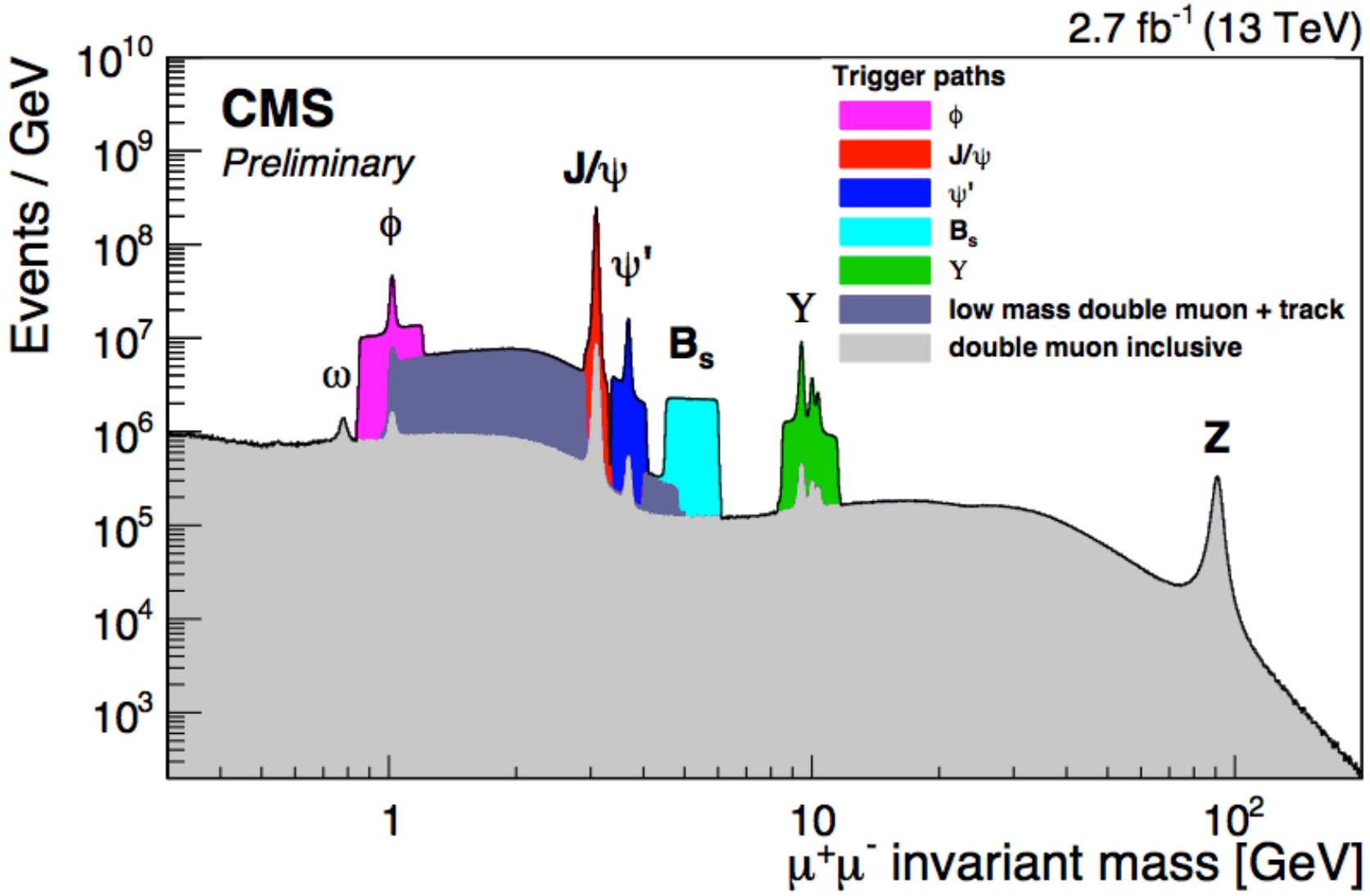
W/Z cross section vs √s

arXiv:1012.2466, CMS-SMP-15-004



Di-muon mass spectrum

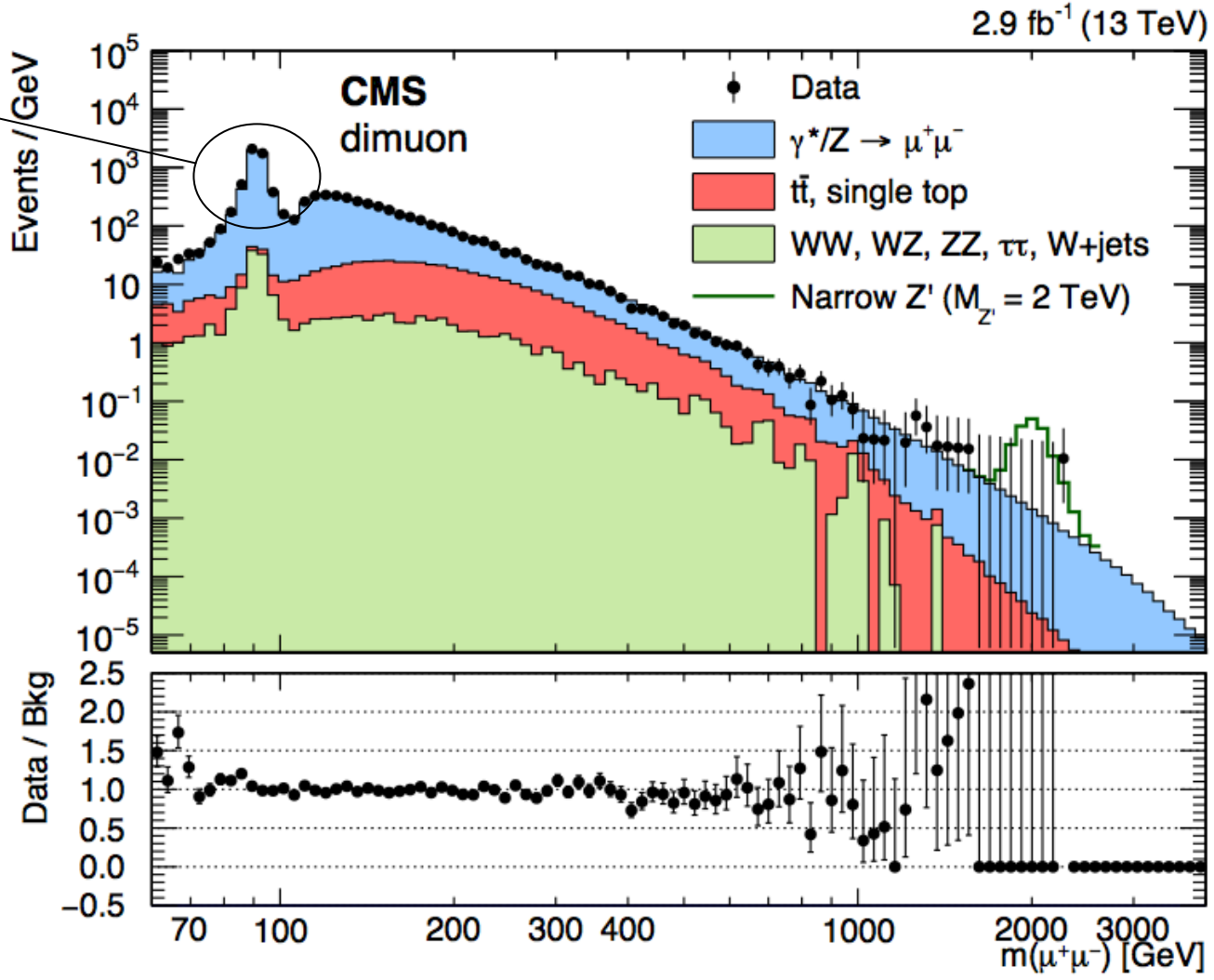
CMS-DP-2015-055



Di-lepton events

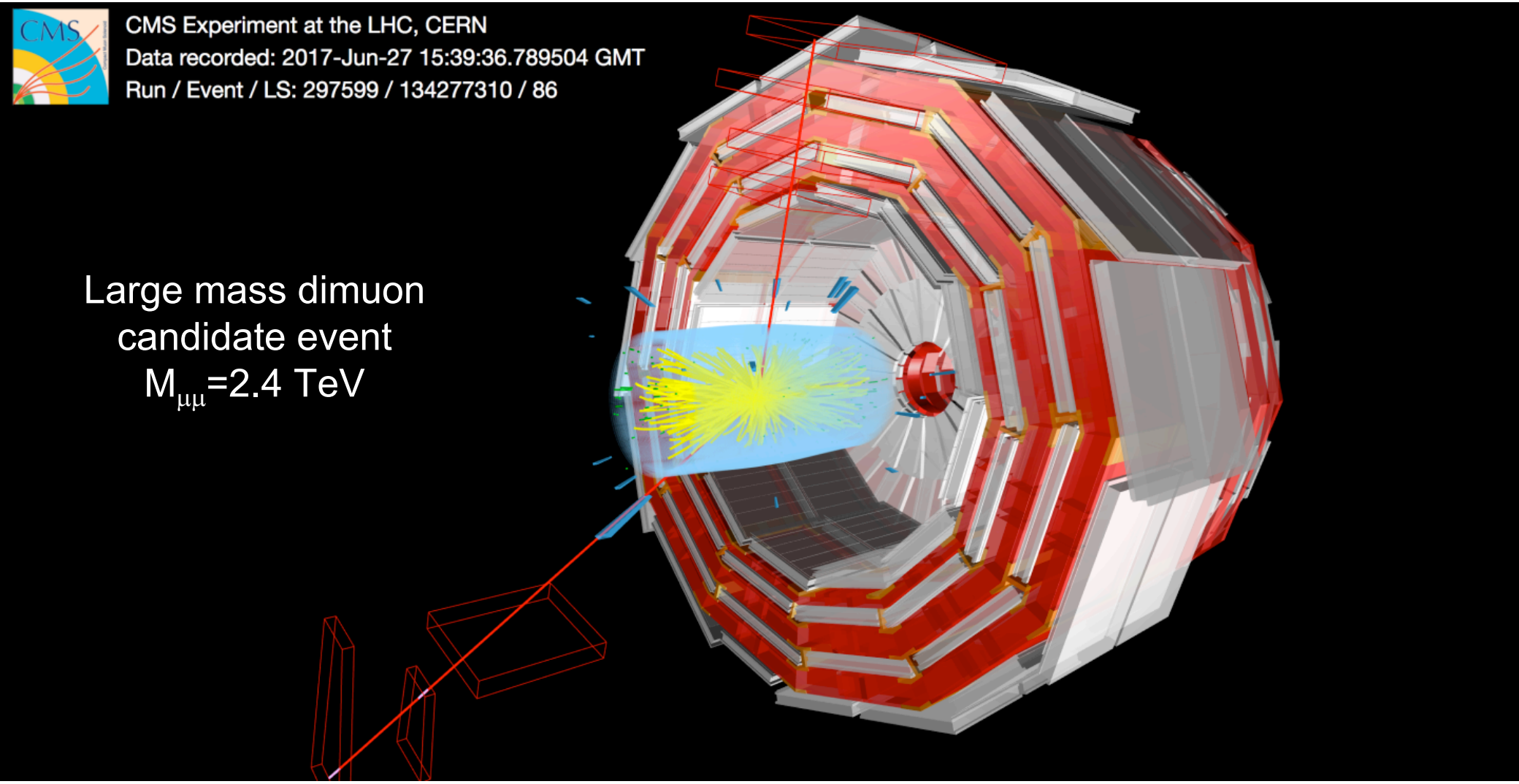
arXiv:1609.05391

Z boson resonance



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

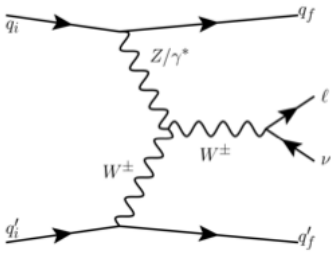
2017: Di-muon candidate event

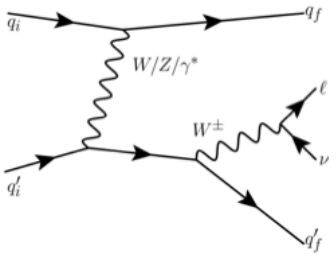


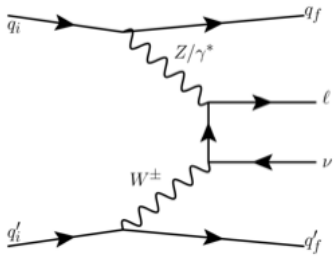
Single and diboson production

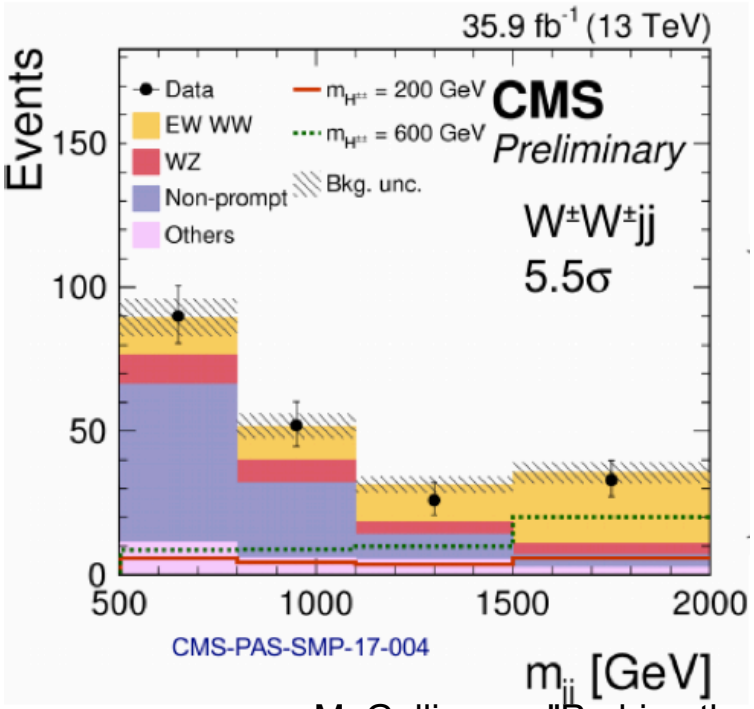
SMP-17—004, SMP-16-018

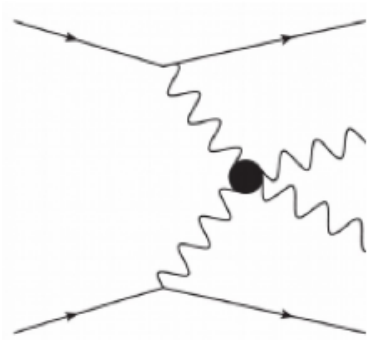
- LHC as boson-boson collider
- Single (or double) W/Z production
  - Sensitive to NP
- Observation of vector boson scattering
  - Same-sign WW
- Rich program of precision measurements

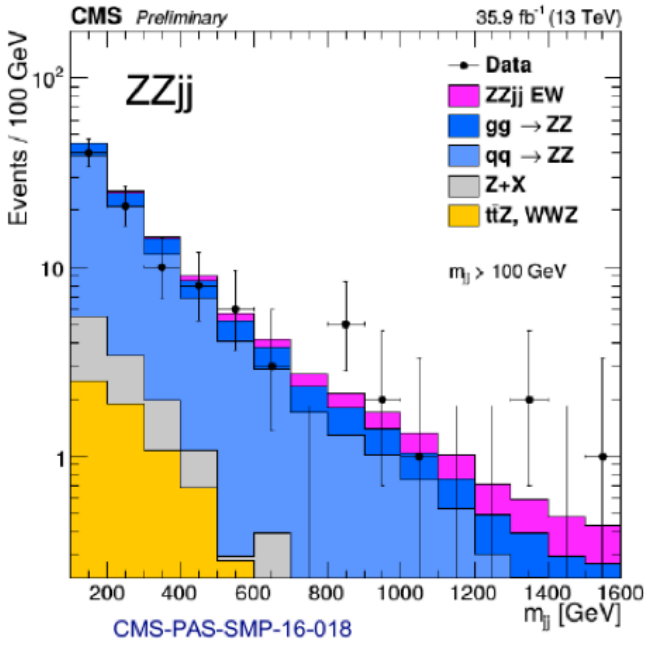






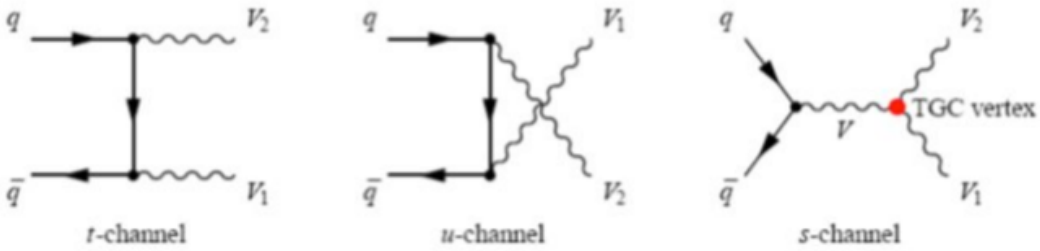


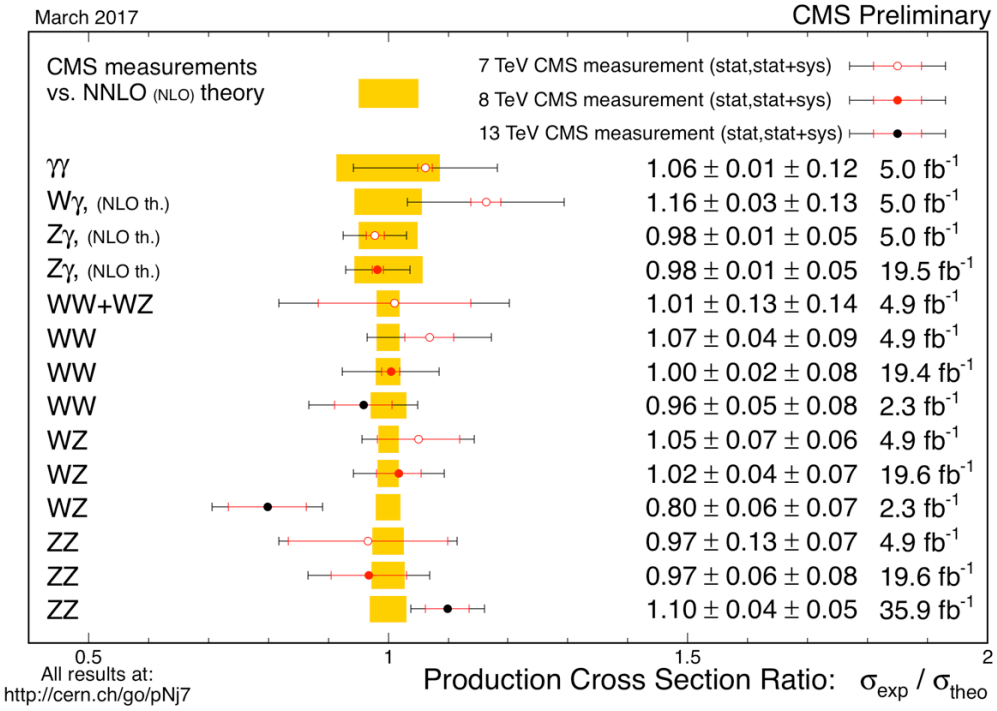


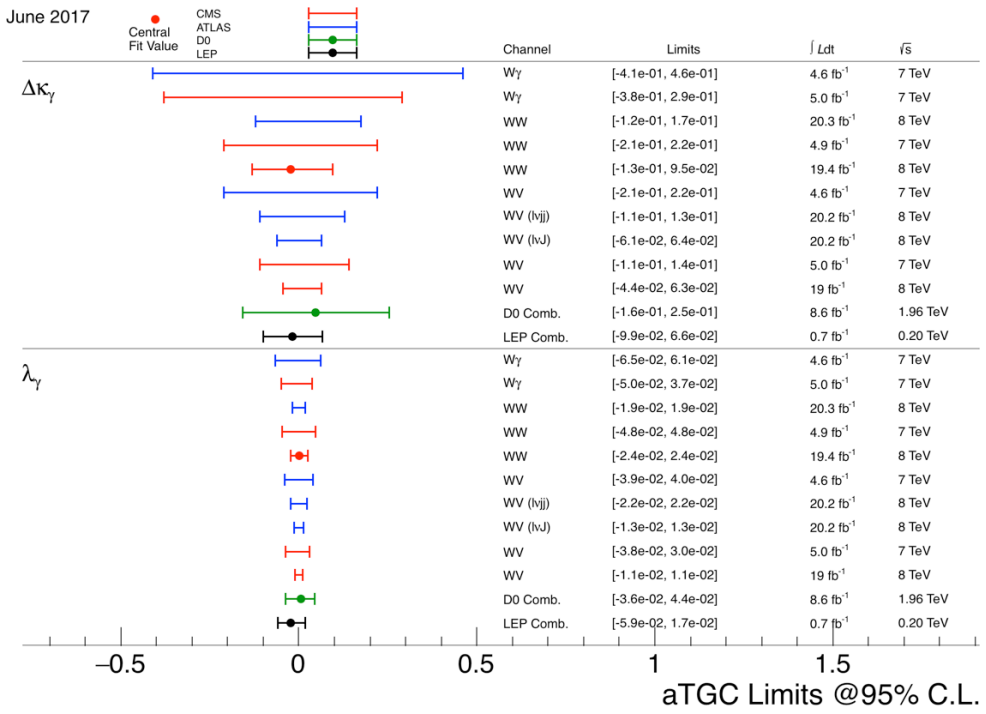


Diboson production

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

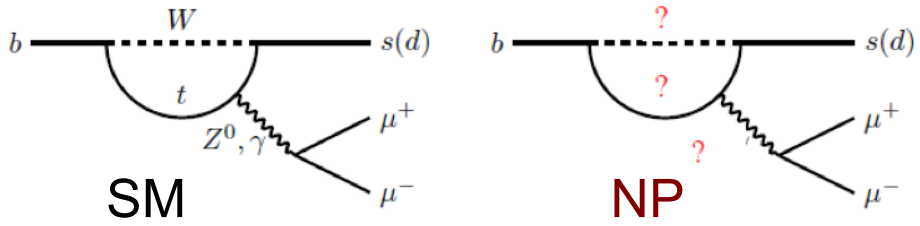


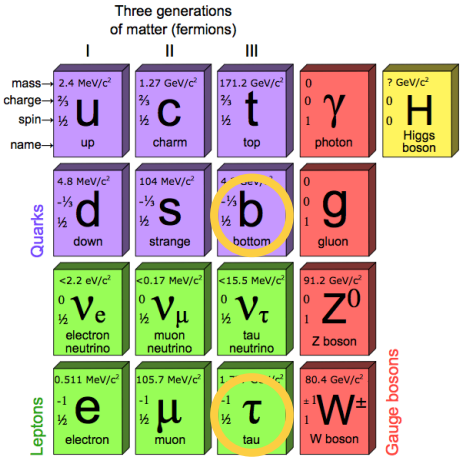


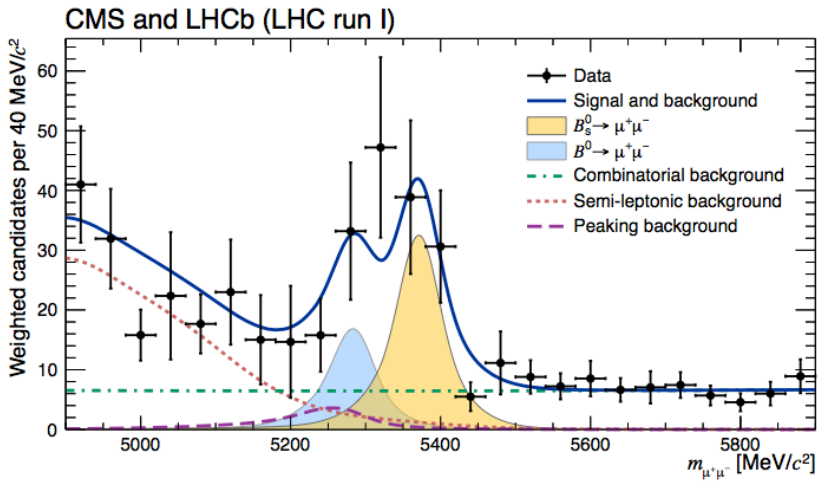


B-physics and Rare decays

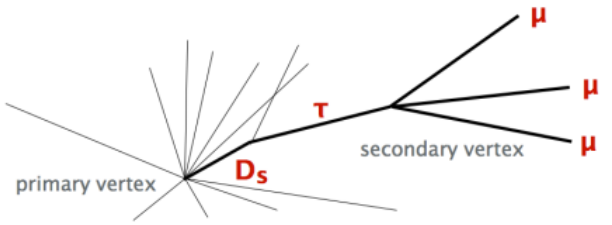
- Study rare processes to look for NP
- Indirect searches: $B_{s/d} \rightarrow \mu\mu$
- Flavour changing neutral current (FCNC) forbidden at tree level in SM
- Can only go through loop diagrams



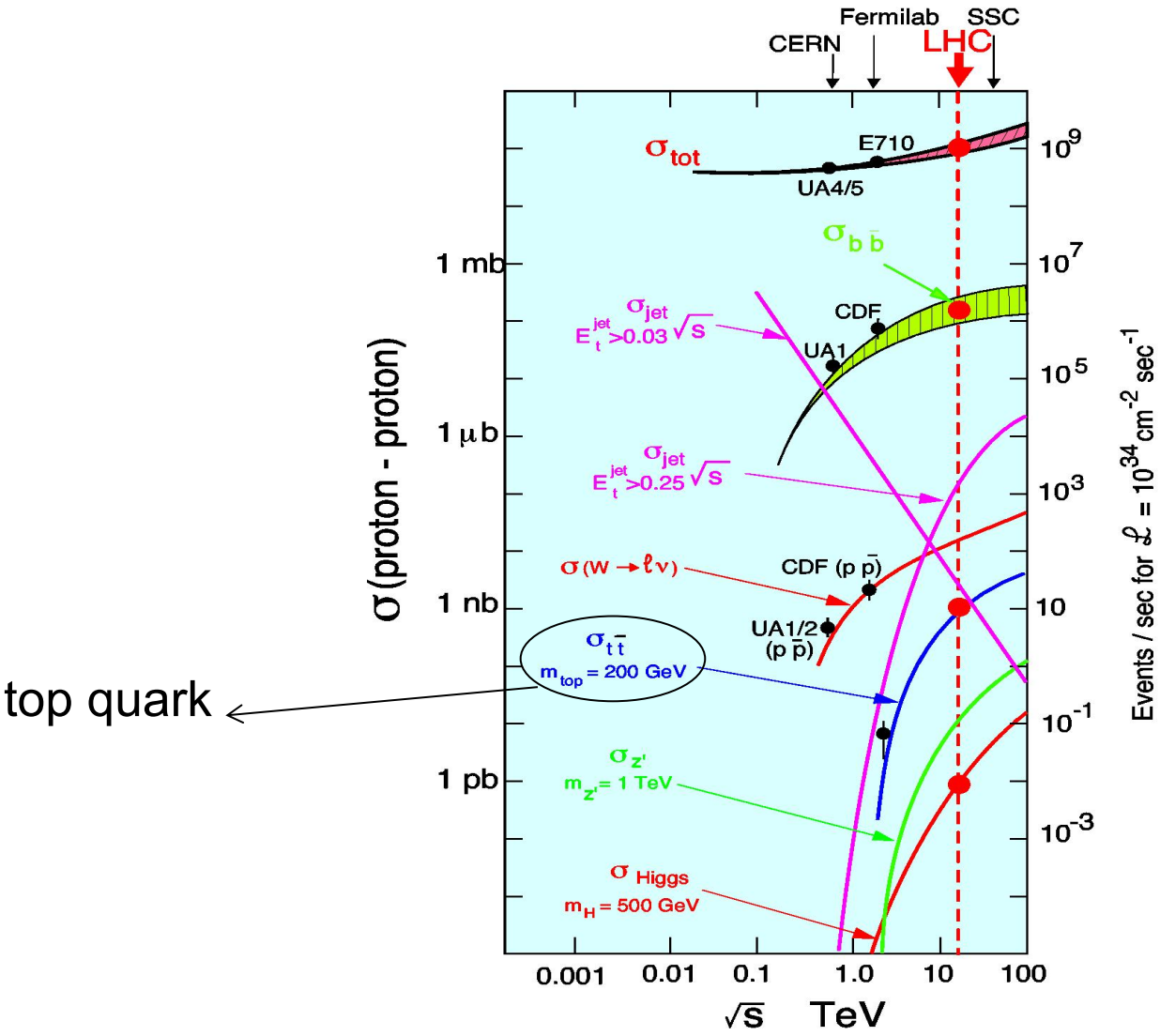




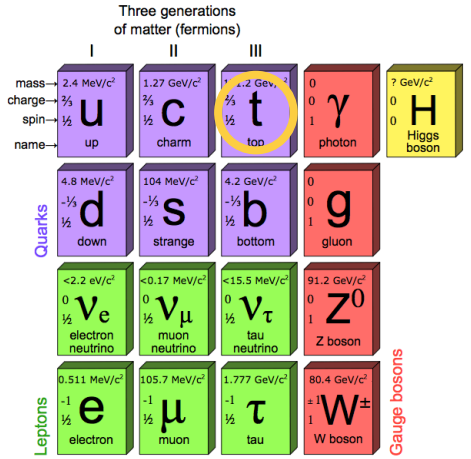
- Lepton Flavor Violation (LFV)
- Search for tau→ 3 muon decays
- Very rare process: BR~10^{-40}!
- Study in Ds and W decays



Top quark production



top quark



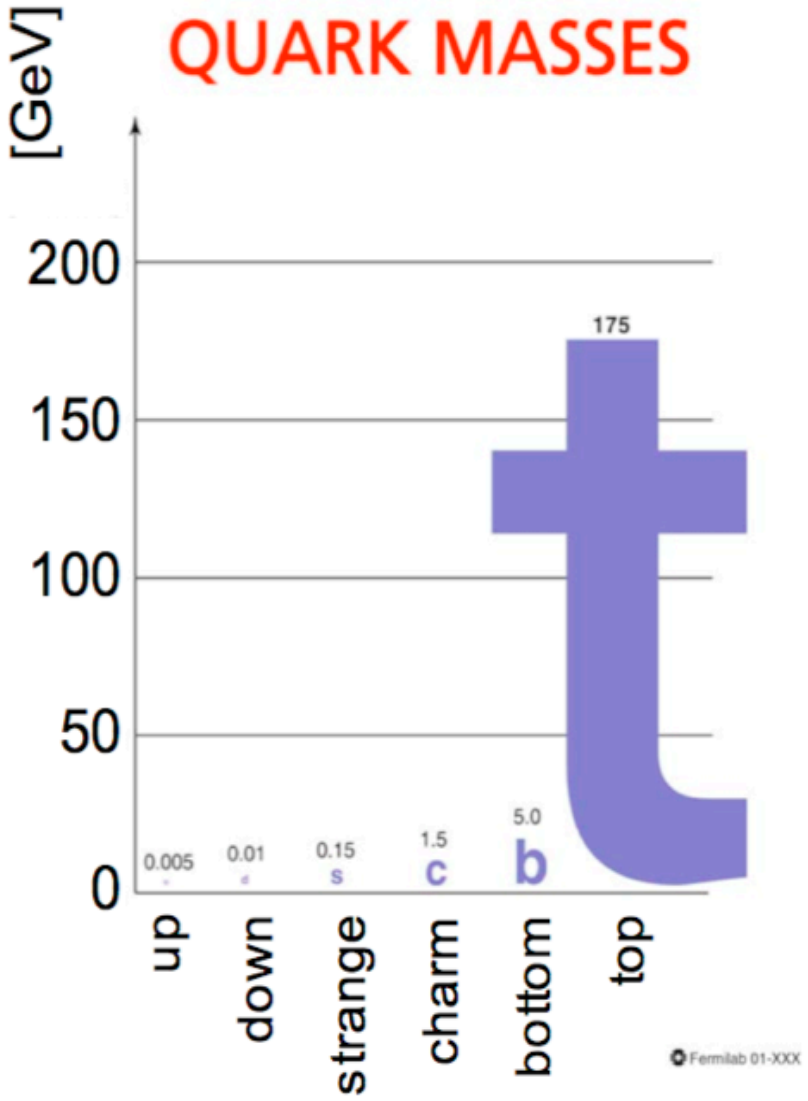
The top quark

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

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

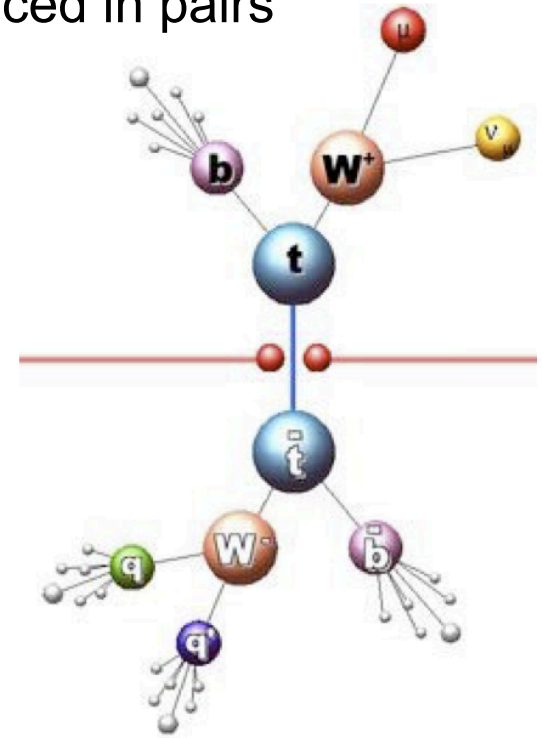
  – very short lifetime ⇒ bound states are not formed
  ⇒ opportunity to study a free quark

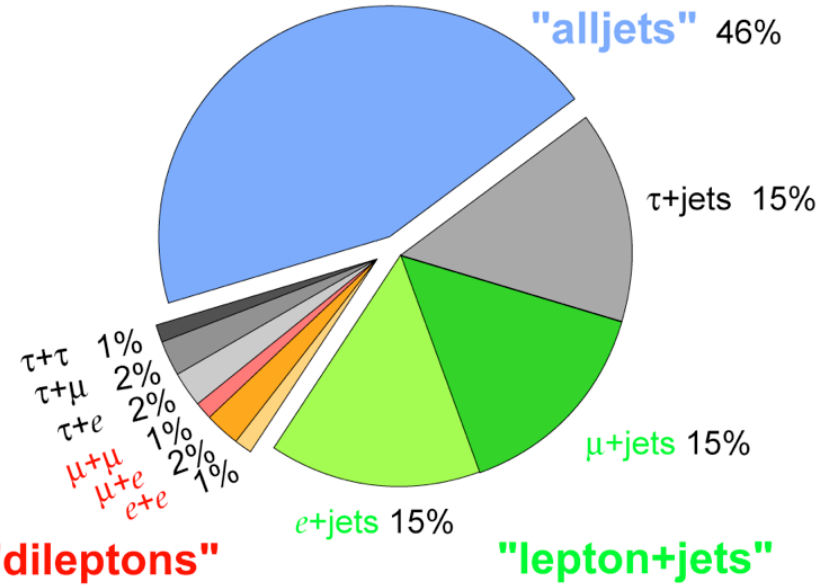
- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Measurements may provide insight into physics beyond SM



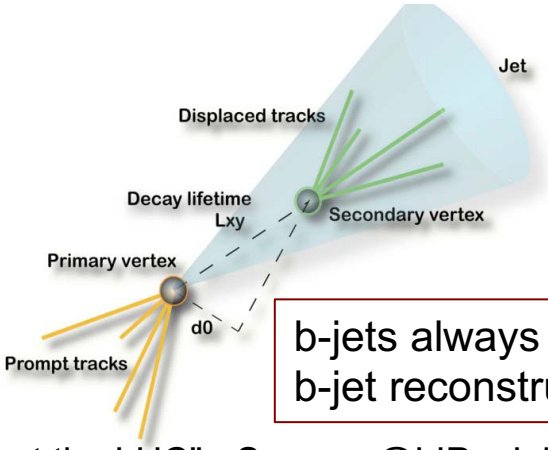
Top quark decays

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 r
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinos



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

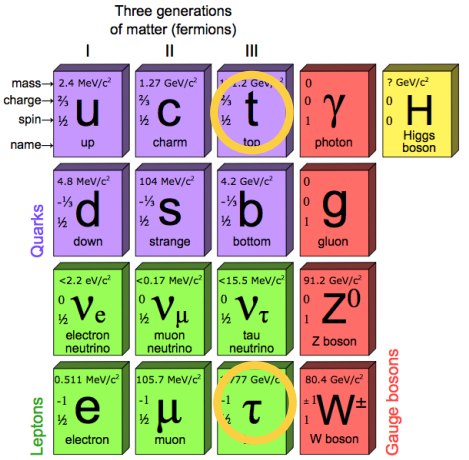
Top quark and tau lepton

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

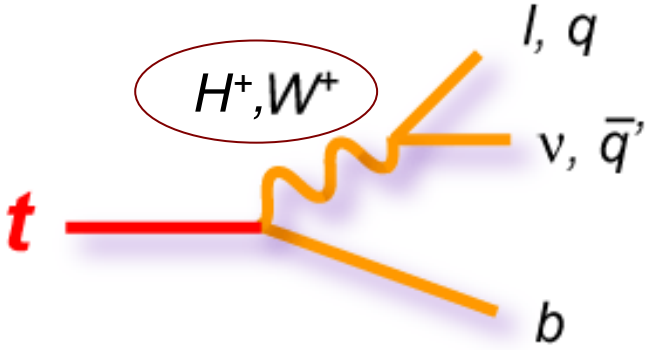
- cross section measurement including taus
- Includes only 3rd generation quarks/leptons

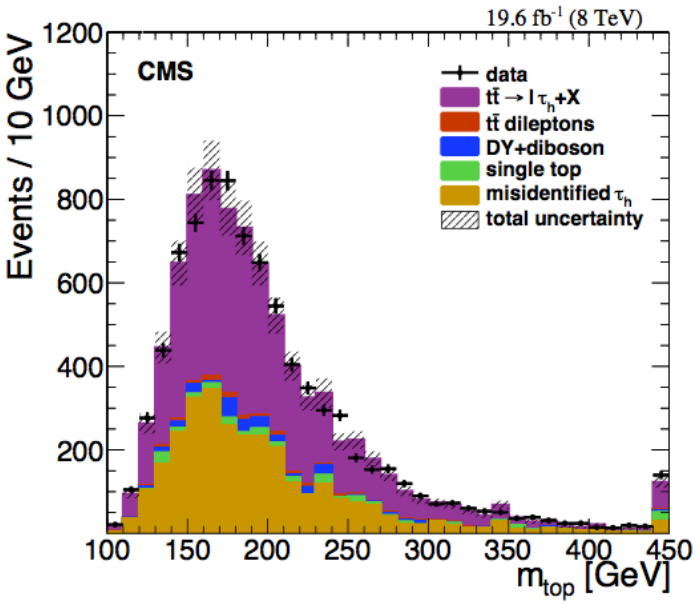
Channel	Signature	BR
Dilepton(e/μ)	*ee*,μμ,eμ + 2*b*-jets	4/81
Single lepton	*e*,μ + jets + 2*b*-jets	24/81
All-hadronic	jets + 2*b*-jets	36/81
Tau dilepton	eτ, μτ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81

→ BR~5%



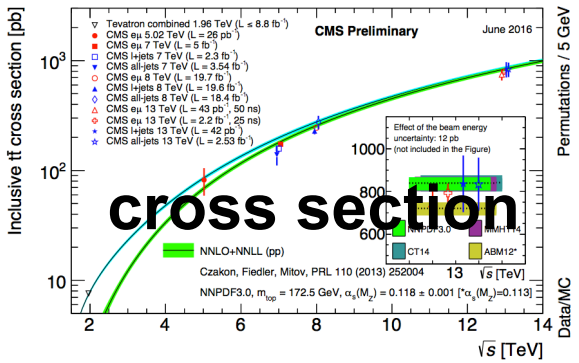
- Charged Higgs may alter coupling to W
  - Search for final states with taus

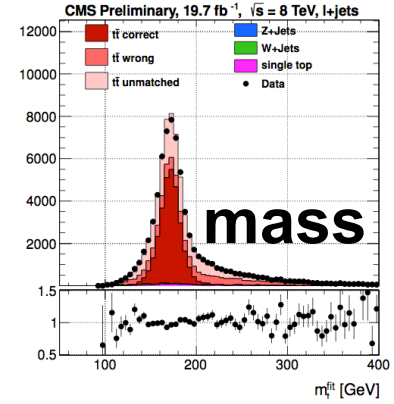


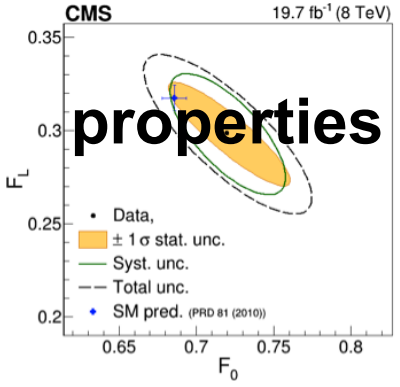


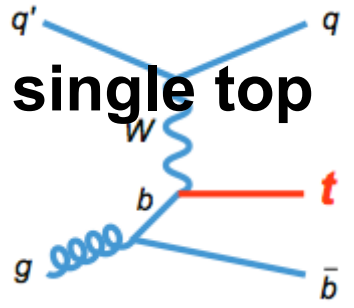
Top quarks and BSM

- 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?



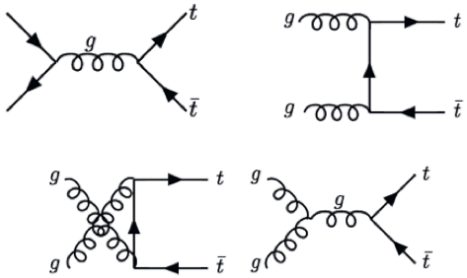






Cross sections vs √s

arXiv:1112.5675

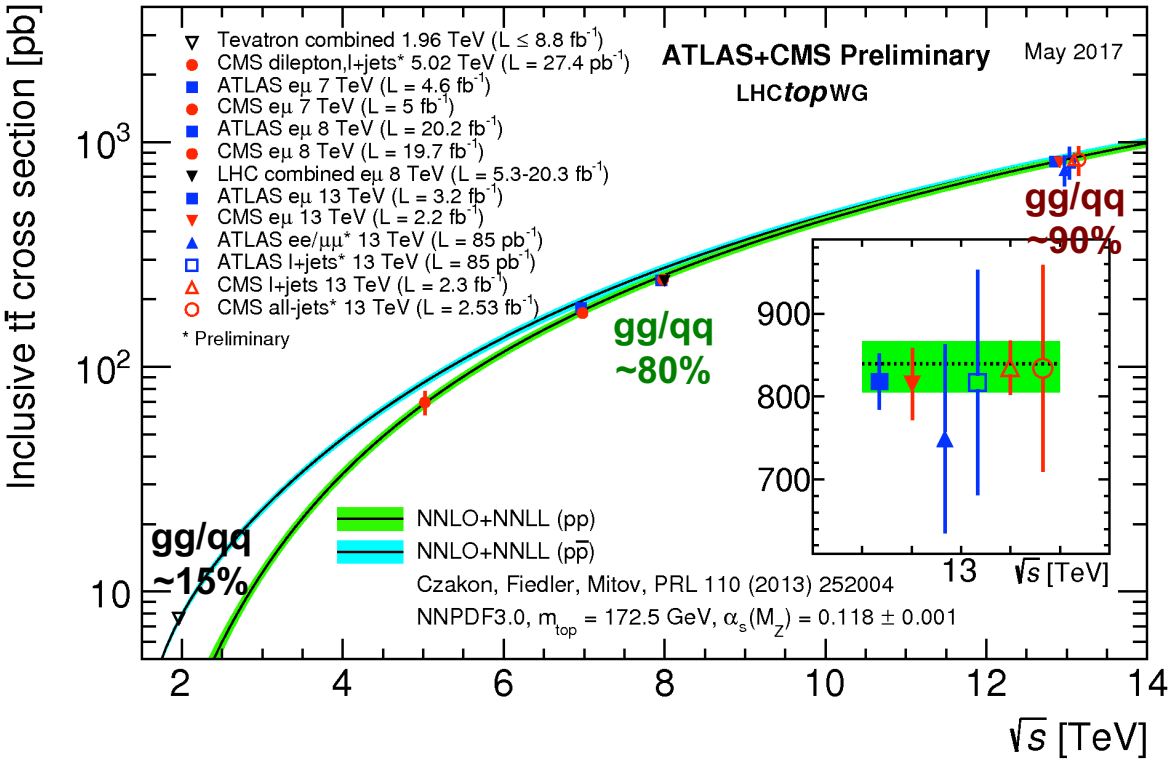


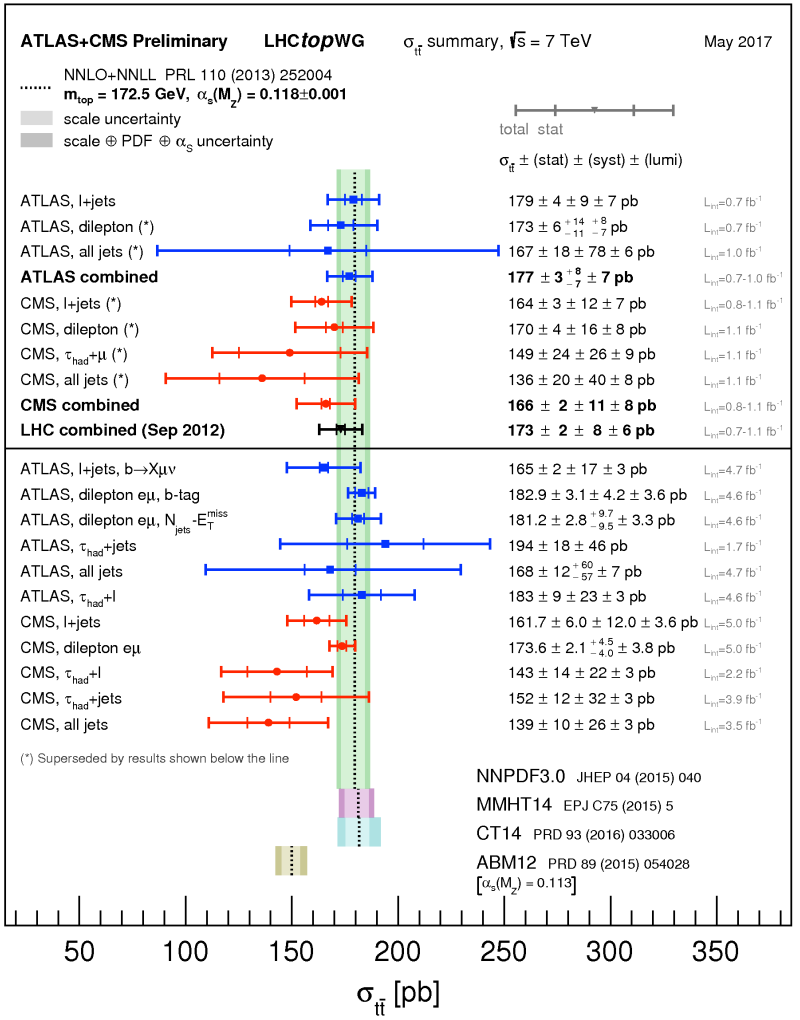
$$\sigma(7\ \text{TeV}) = 177\ \text{pb} \pm 7\%$$

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

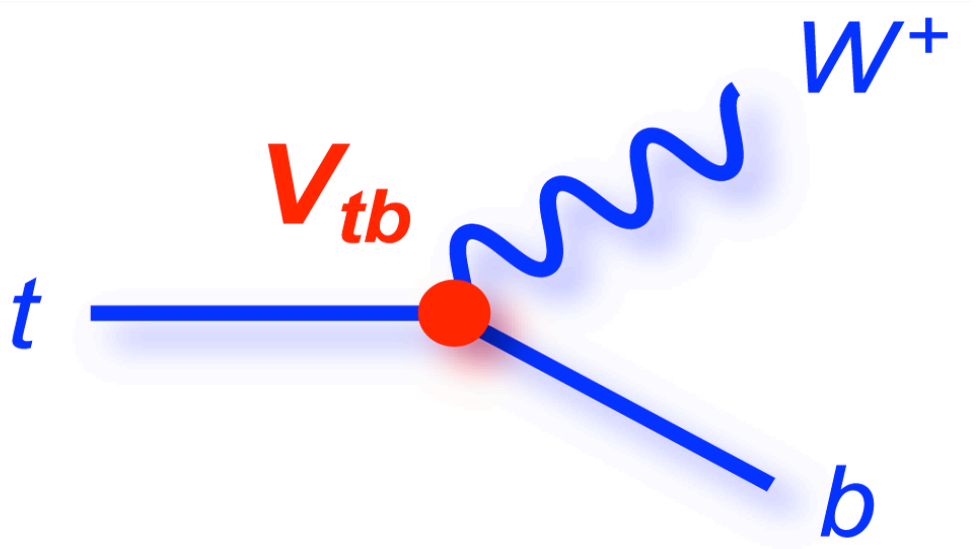
$$\sigma(13\ \text{TeV}) = 832\ \text{pb} \pm 5\%$$

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

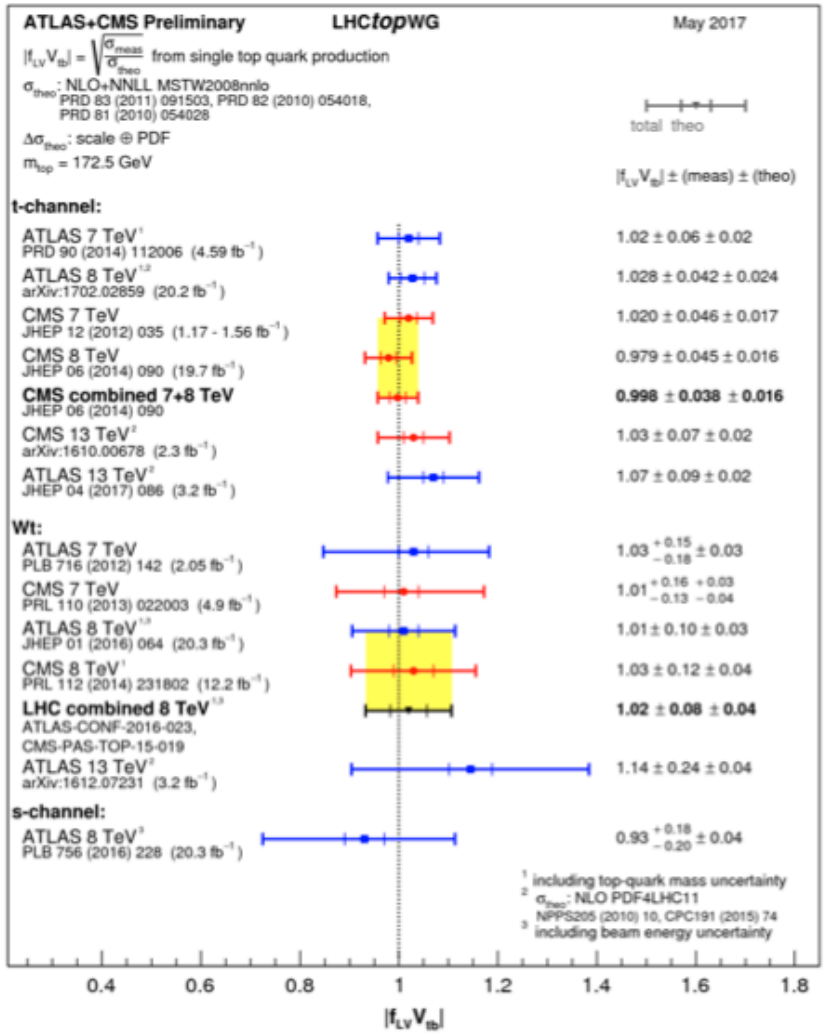




How does a top quark decay?

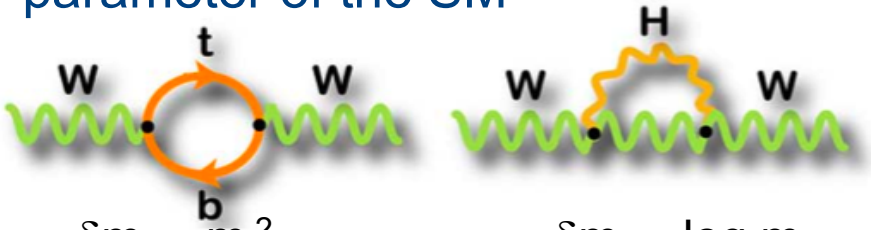


- almost always t→Wb (i.e. V_{tb}~1)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - decays W→lν (l=e,μ,τ), BR~1/9 per lepton
  - can decay W→qq, BR~2/3



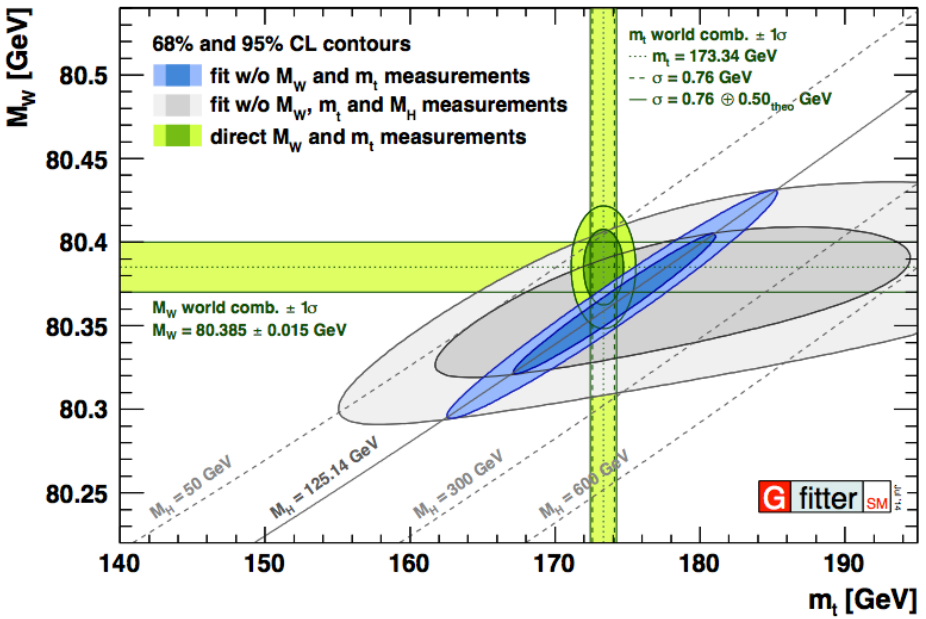
Top quark mass

- Top quark mass is a fundamental parameter of the SM



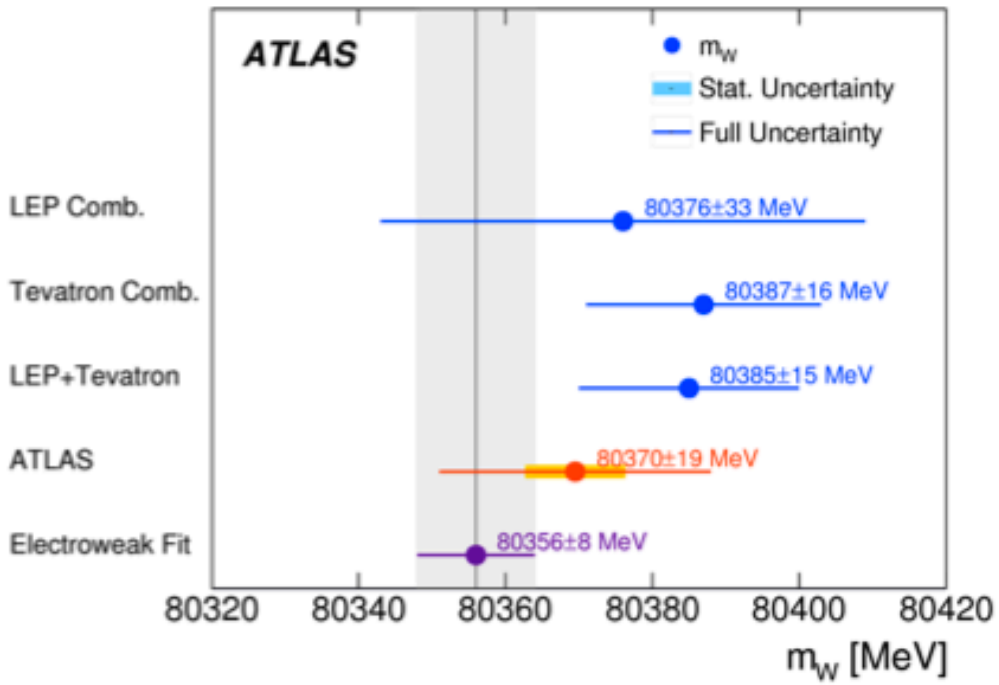
$\delta m_W \propto m_t^2$ $\delta m_W \propto \log m_h$

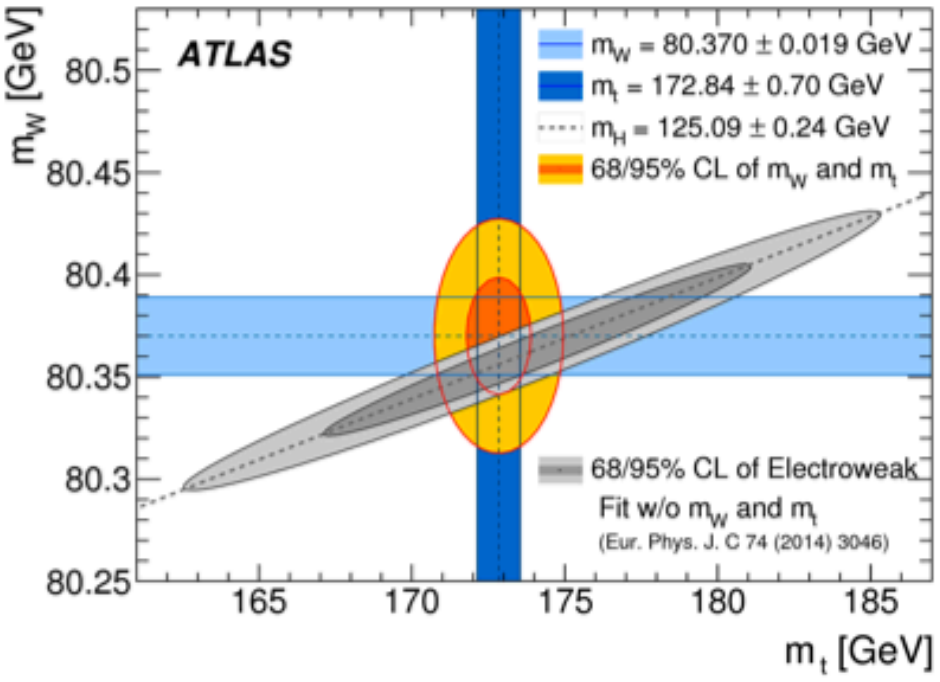
- Precise measurement needed for checking consistency of the SM



- 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



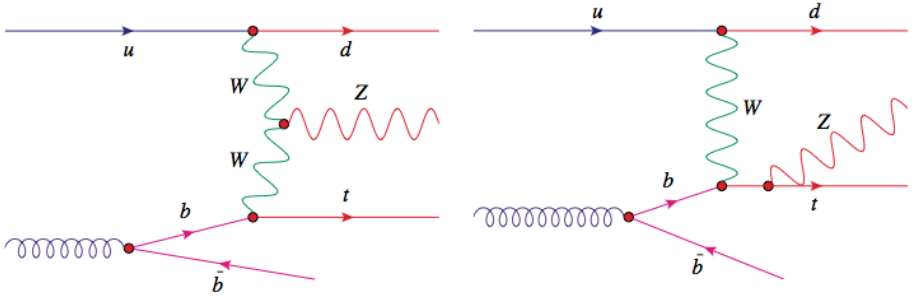


- First W mass measurement at the LHC
- Use low pileup data at 7 TeV
- Control of systematic uncertainties
- Uncertainties comparable to Tevatron results
- Expect future improvements

Rare decays: ttV (V=γ,Z,W)

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

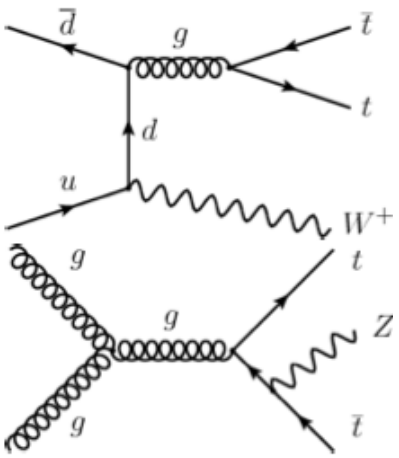
- Measurements will give access to EW couplings of the top

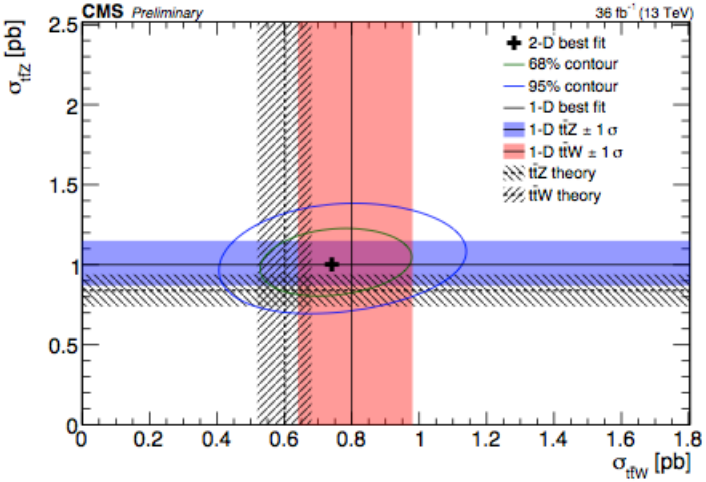


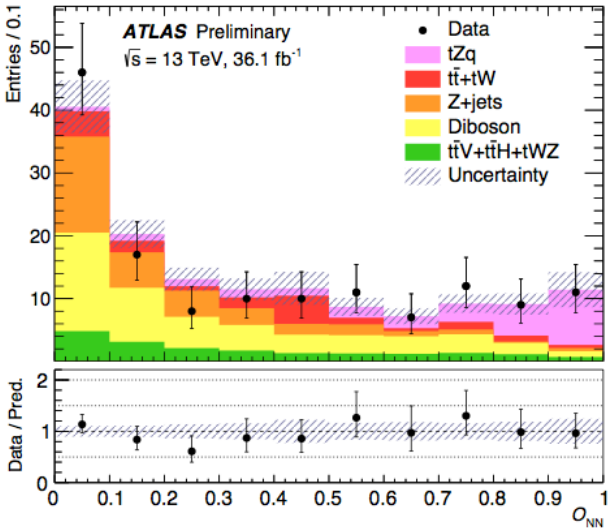
- Top+vector boson production
- tt+Z: measure ttZ coupling
- tt+W/Z: sensitive to BSM

⇒in agreement with SM

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

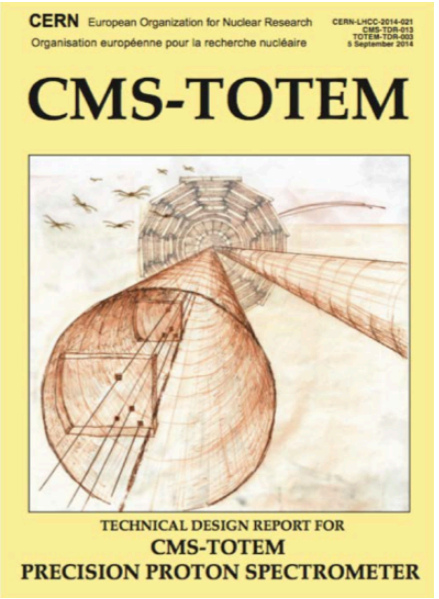




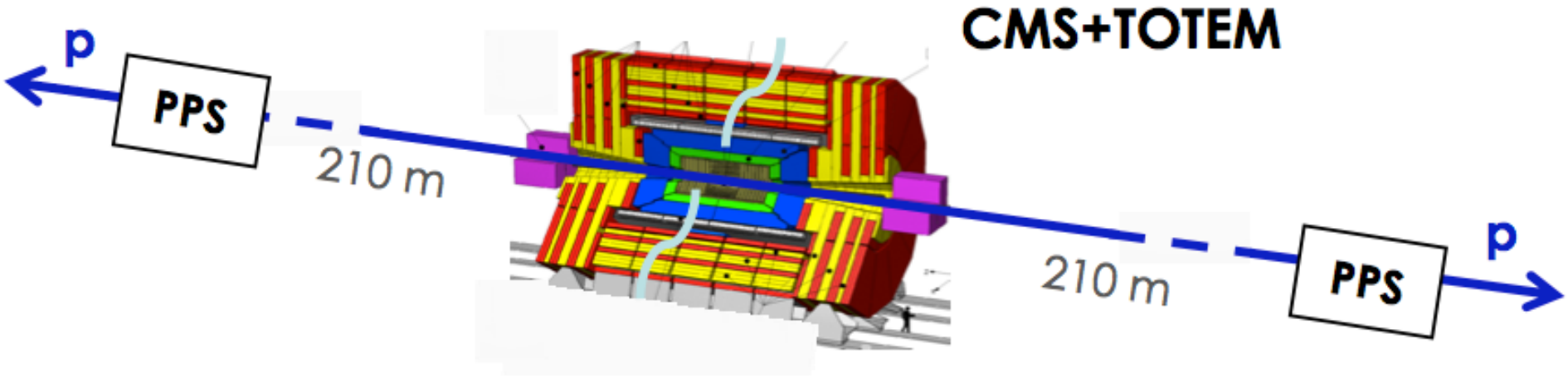


Precision Proton Spectrometer

- 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

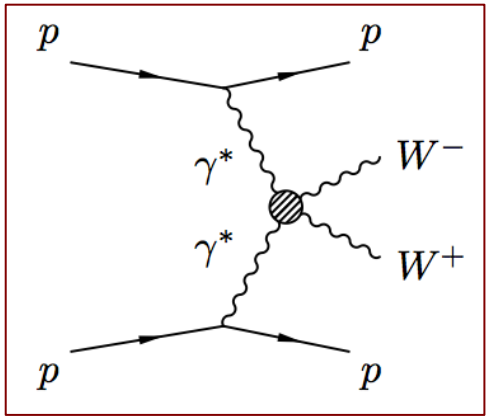


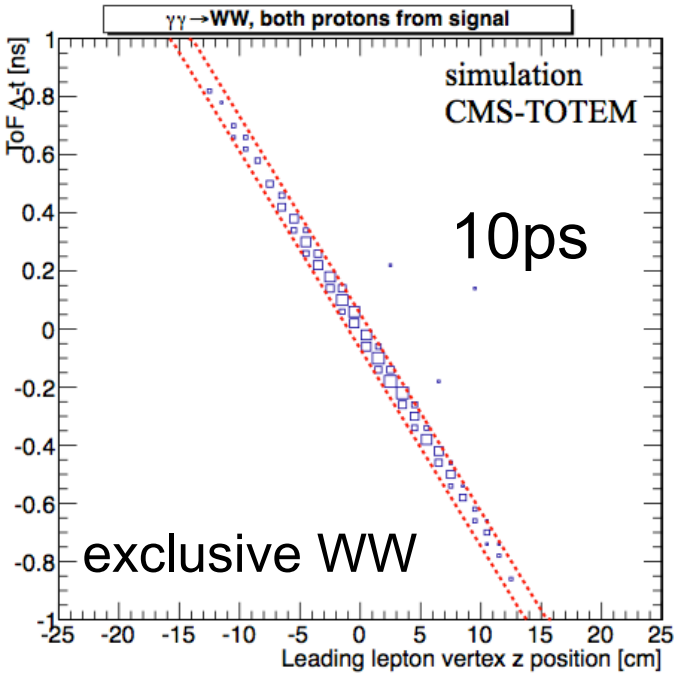
CERN-LHC-2014-021

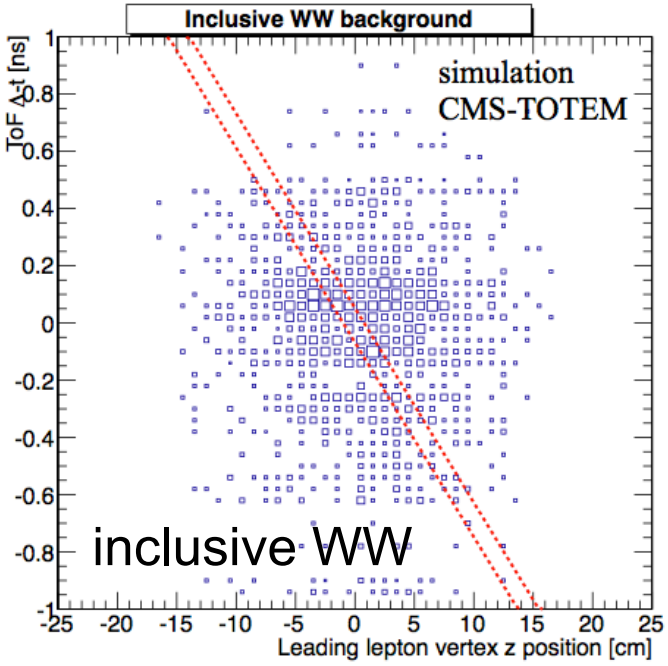


Anomalous couplings

- 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





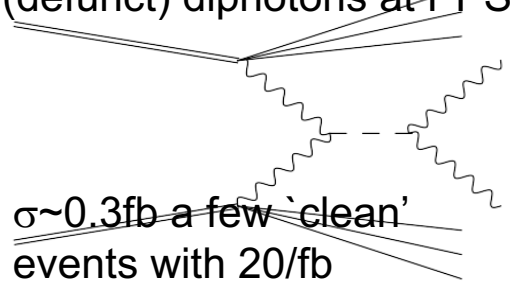


- Leptonic channels cleanest, but neutrinos prevent clear mass/rapidity matching
- time difference of two protons correlated with vertex position

BSM searches: resonances, etc.

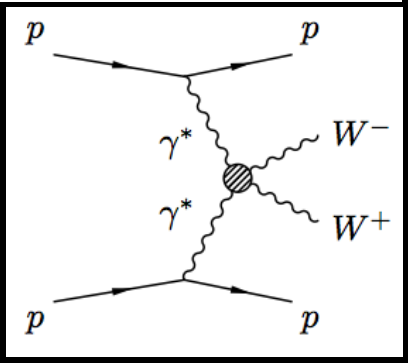
CMS Experiment at the LHC, CERN
Data recorded: 2015-Sep-11 22:46:54.589056 GMT
Run / Event / LS: 256353 / 437637379 / 244

(defunct) diphotons at PPS

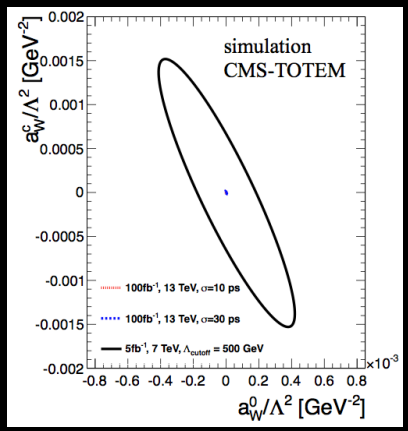


~~σ~0.3fb a few `clean'~~
events with 20/fb

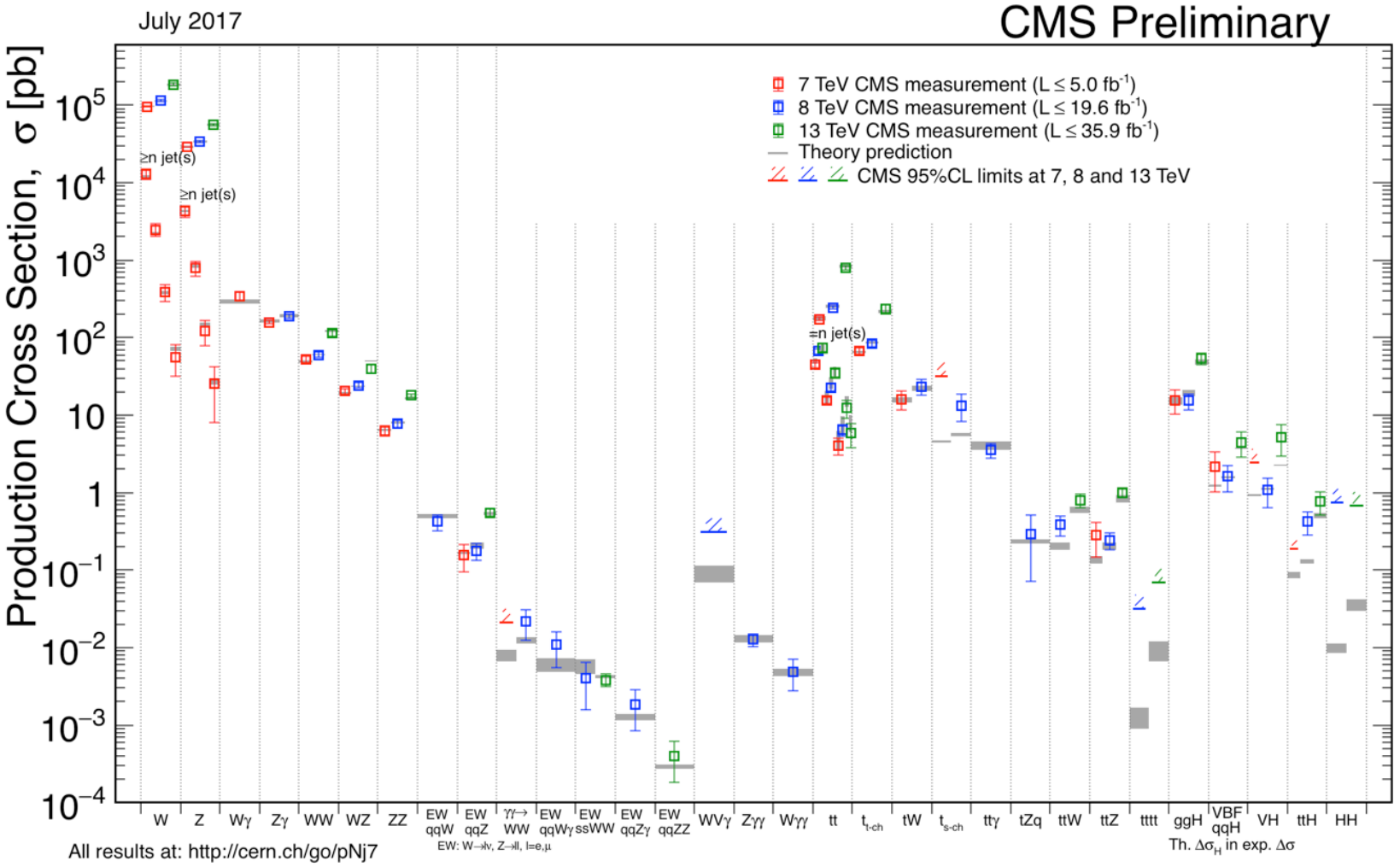
exclusive WW production



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



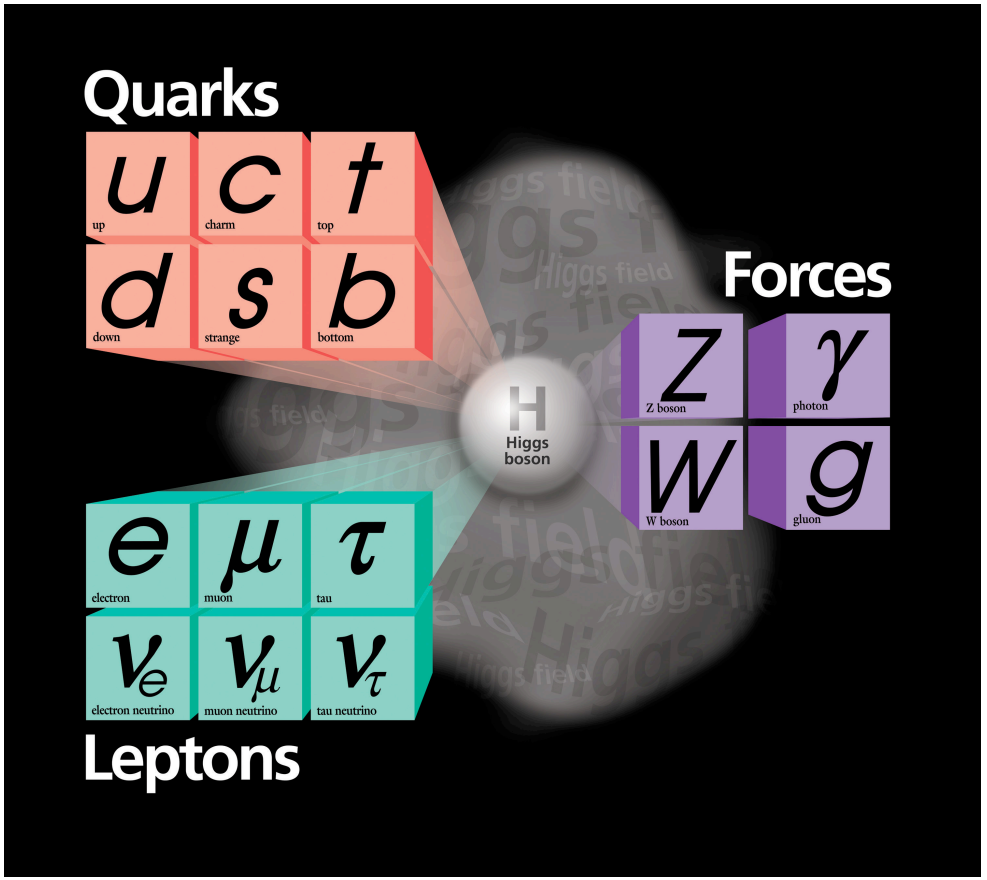
SM measurements



…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?

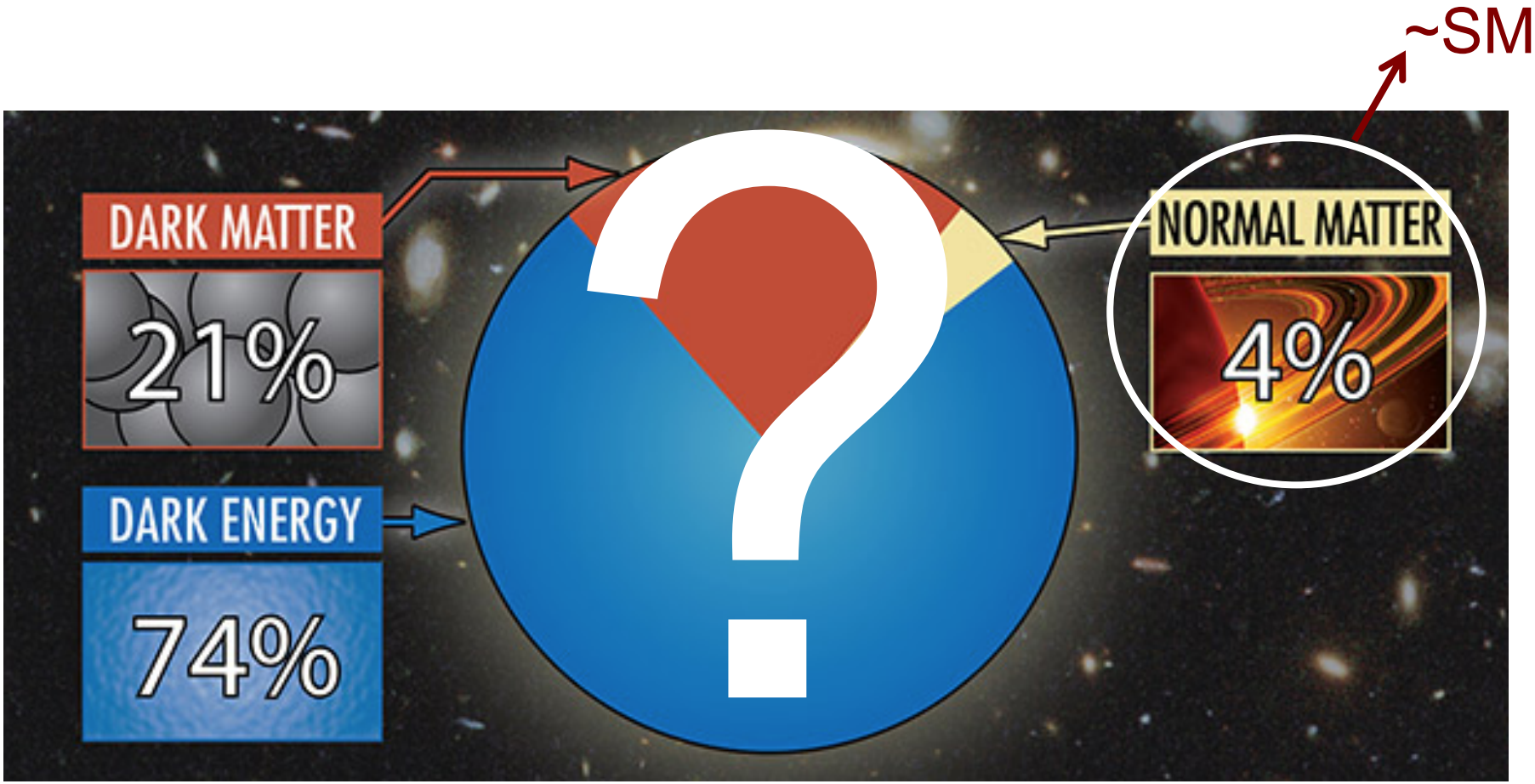
c) Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

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



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