Probing the Standard Model at the LHC

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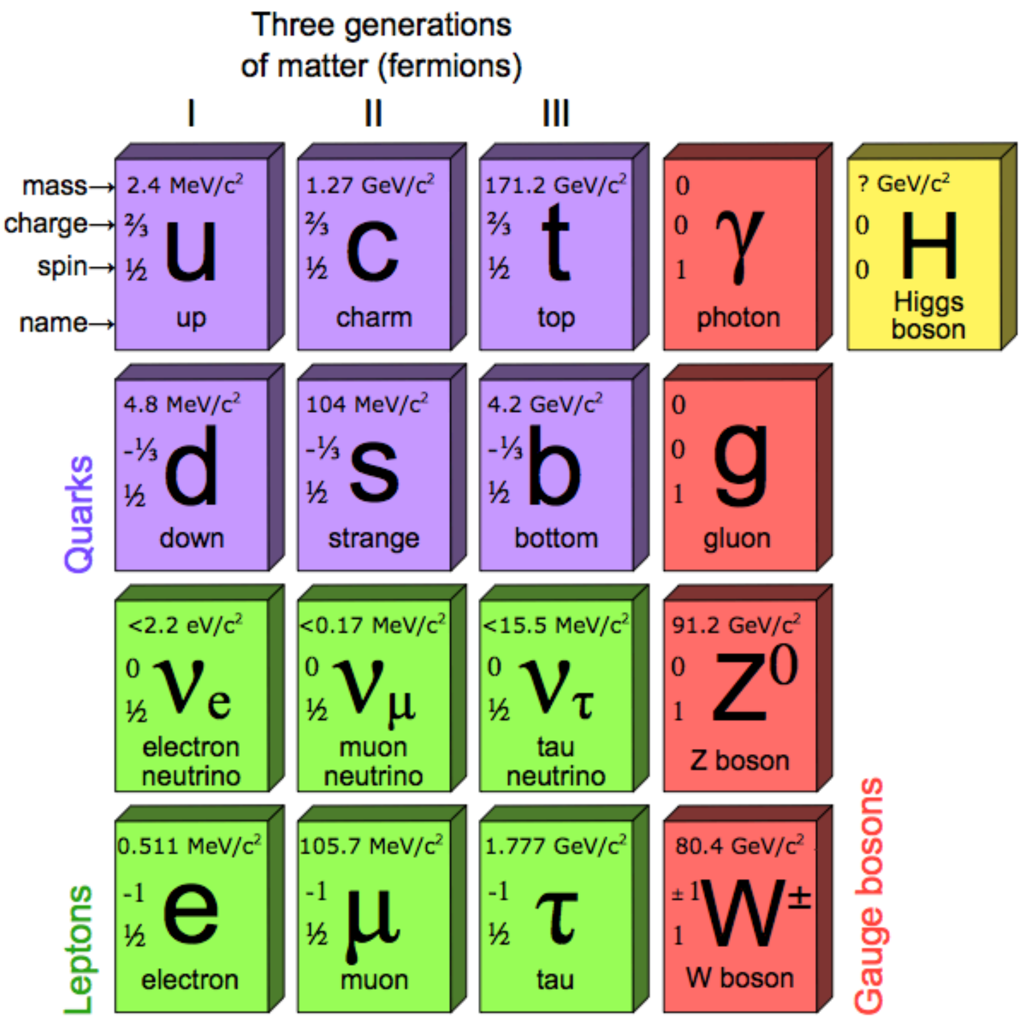
LIP Lisbon

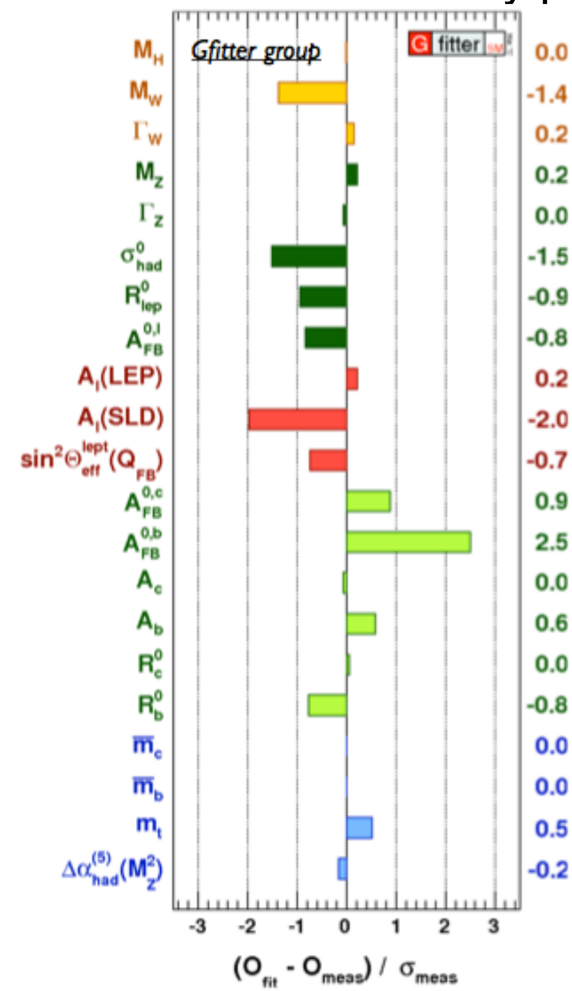
July 18, 2017

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

The Standard Model



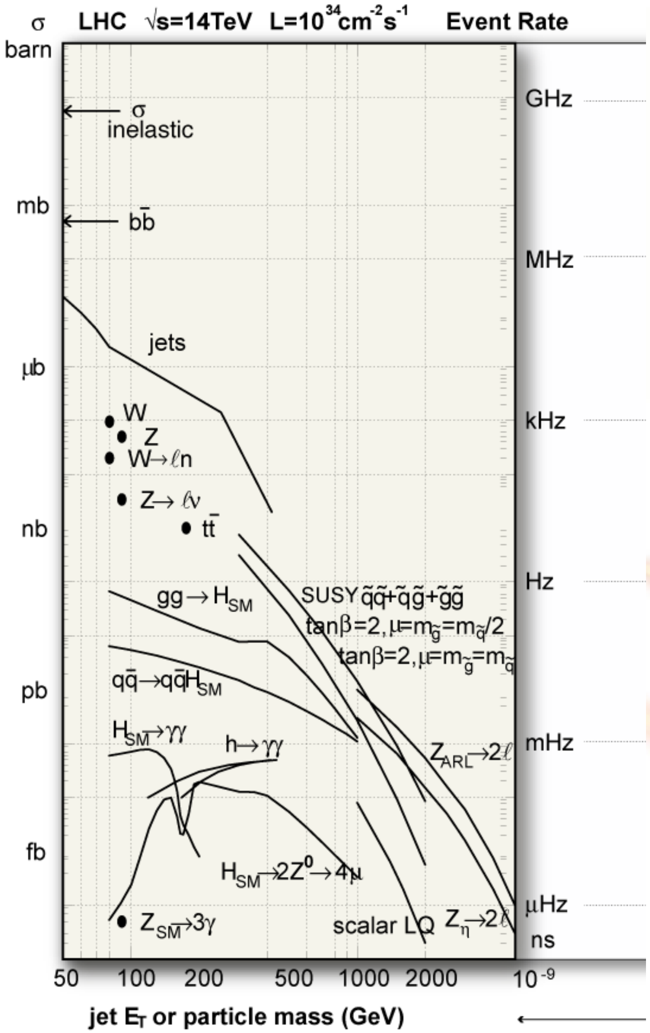
Standard model of elementary particles

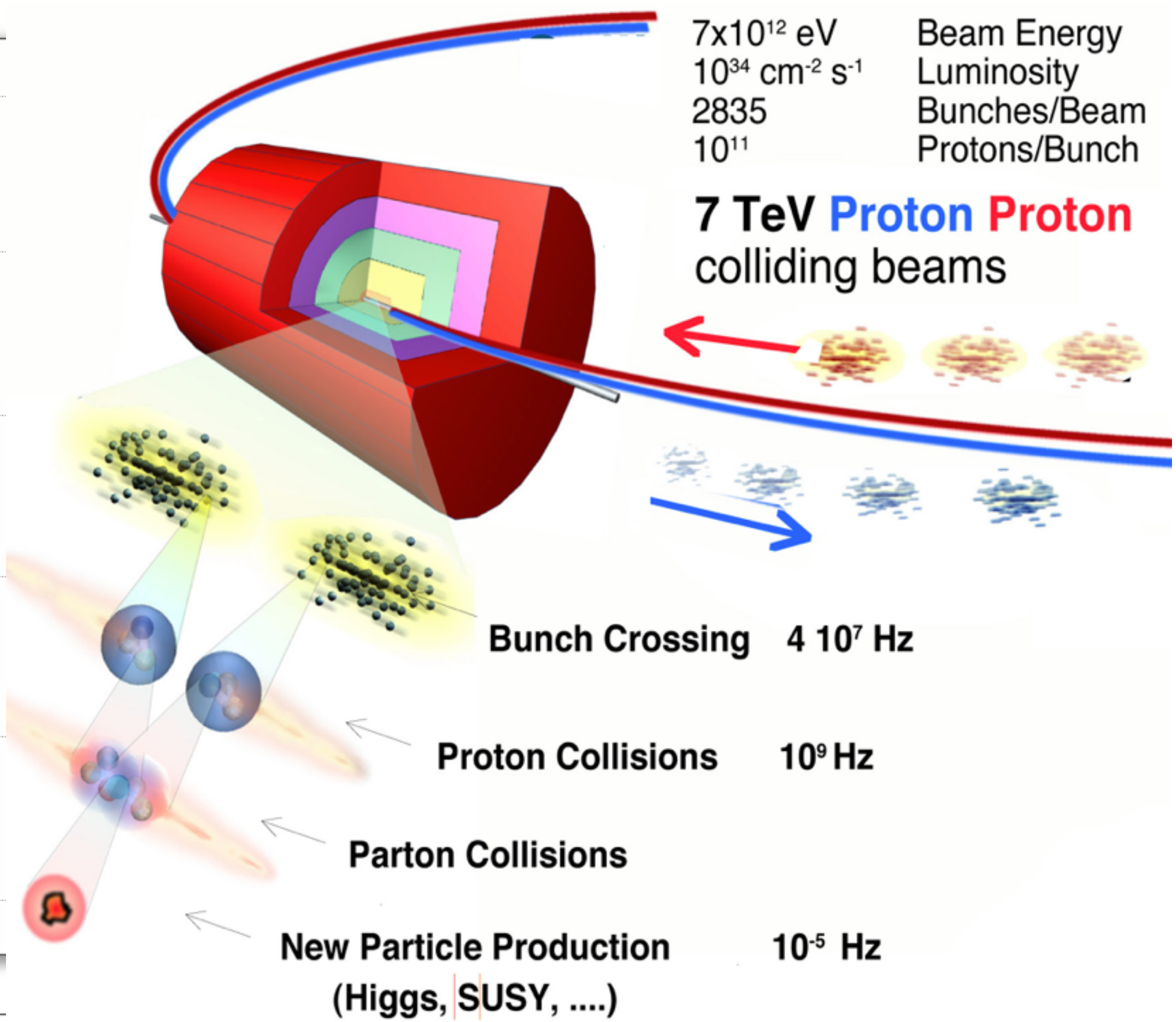


Excellent agreement with all experimental results

Proton collisions at the LHC

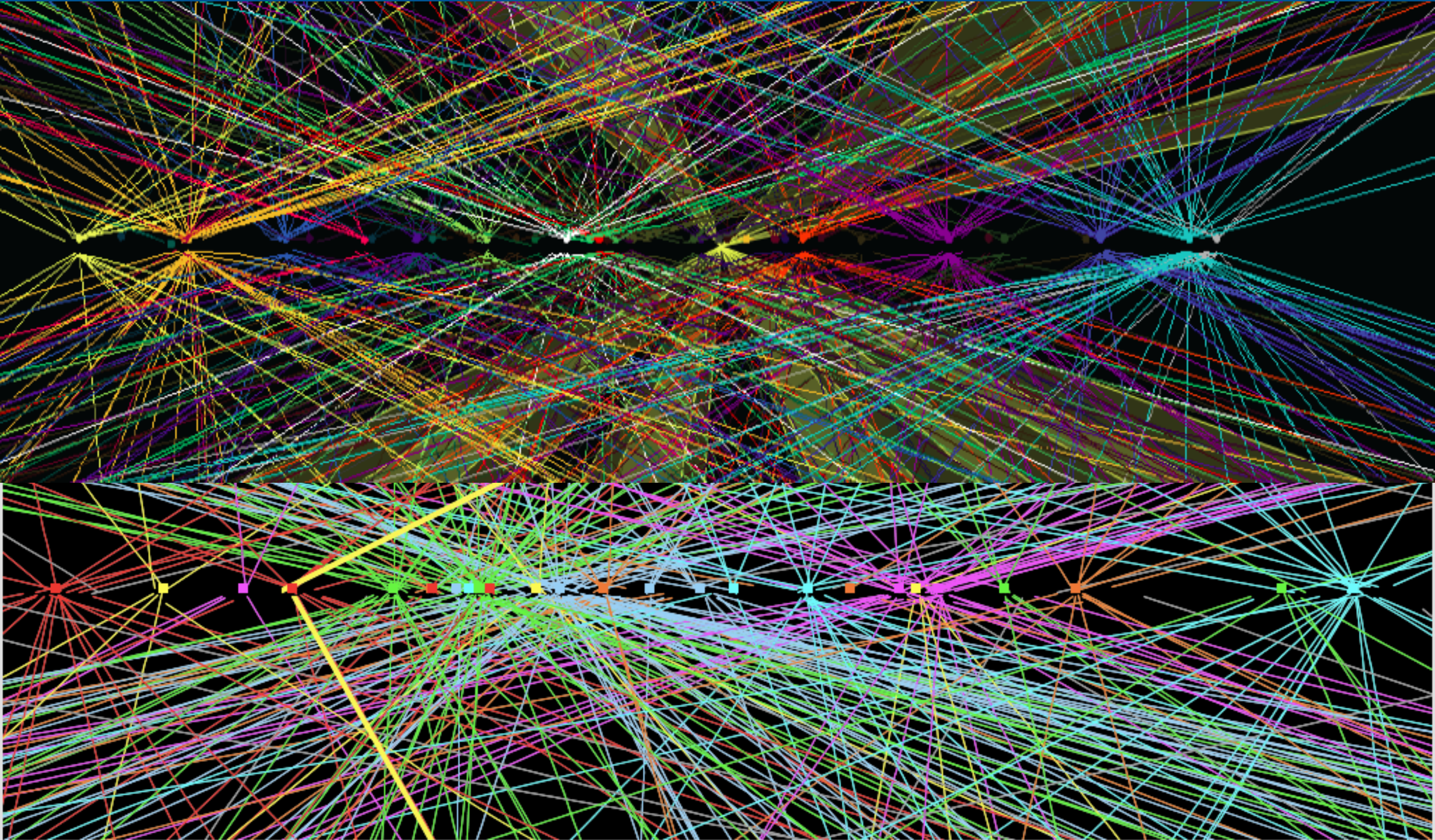
Collisions: 7-8 TeV (2011-12), 13TeV (2015-17)

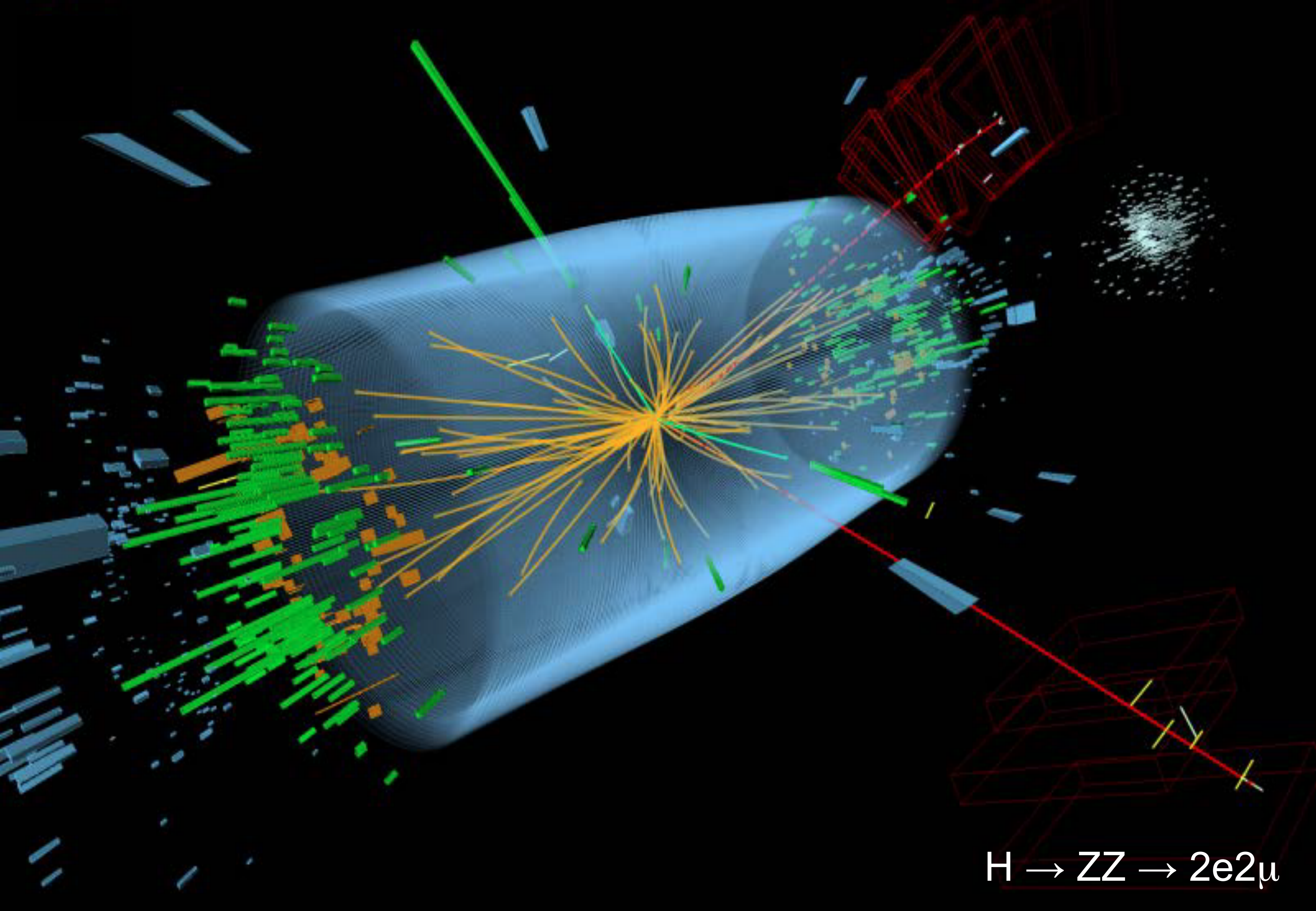




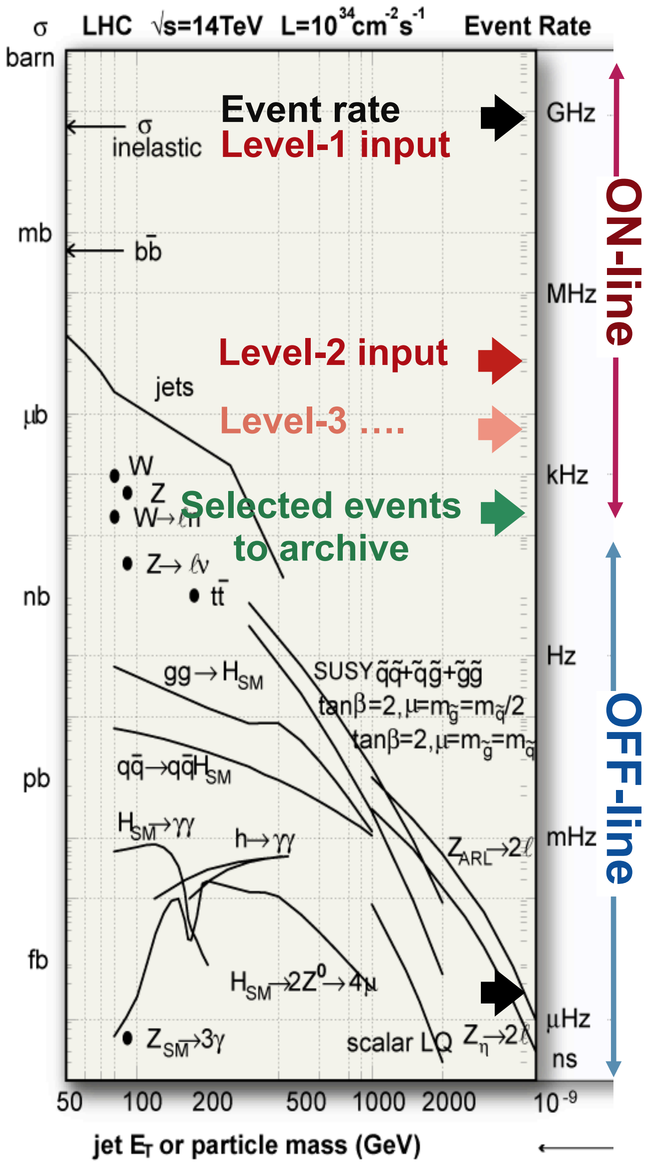
Select 1 event in 10,000,000,000,000

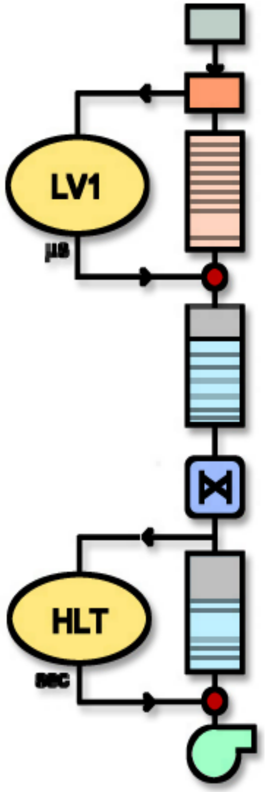
…under difficult conditions




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

Trigger



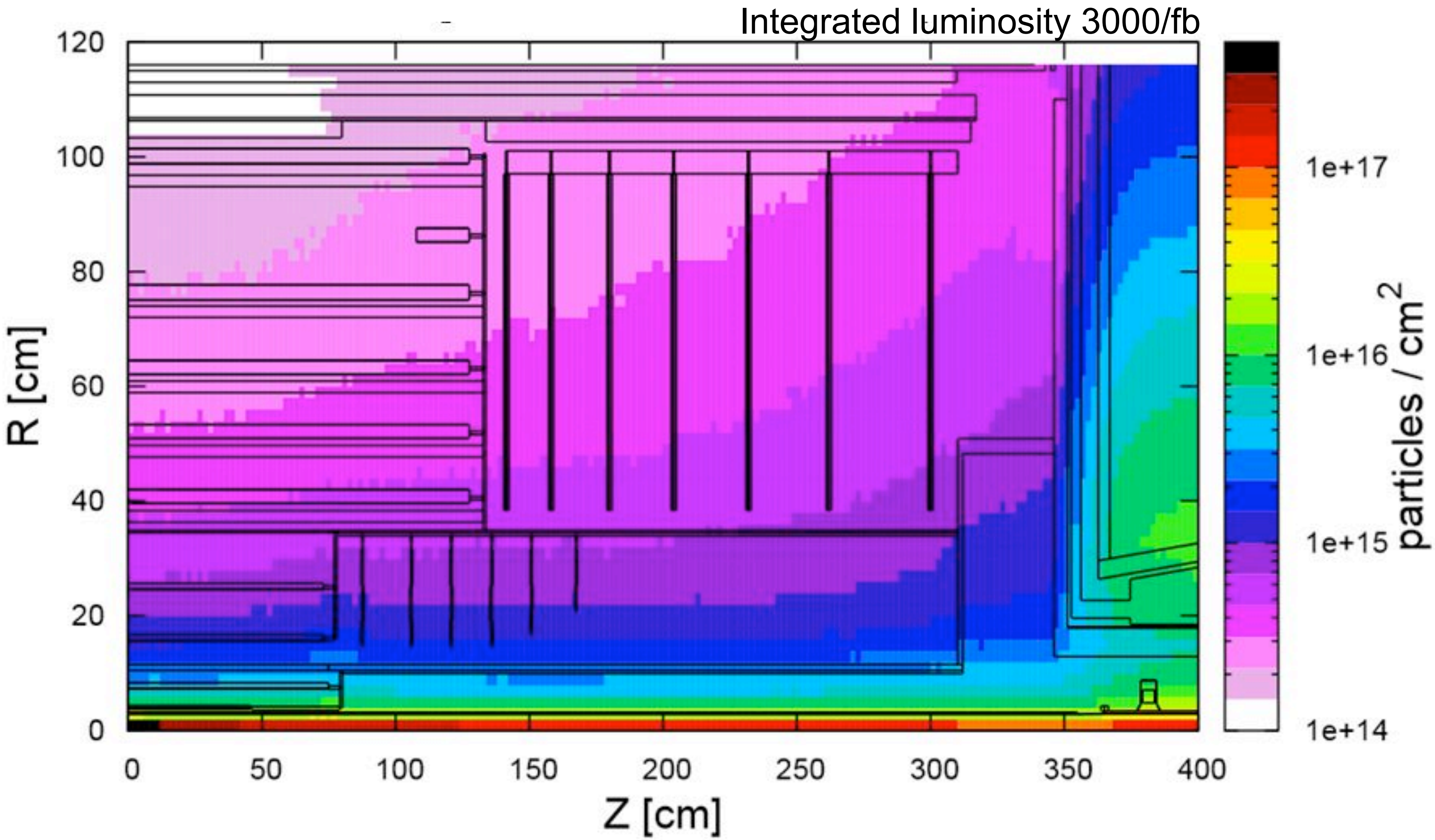


Trigger system decide if the event is interesting to be recorded

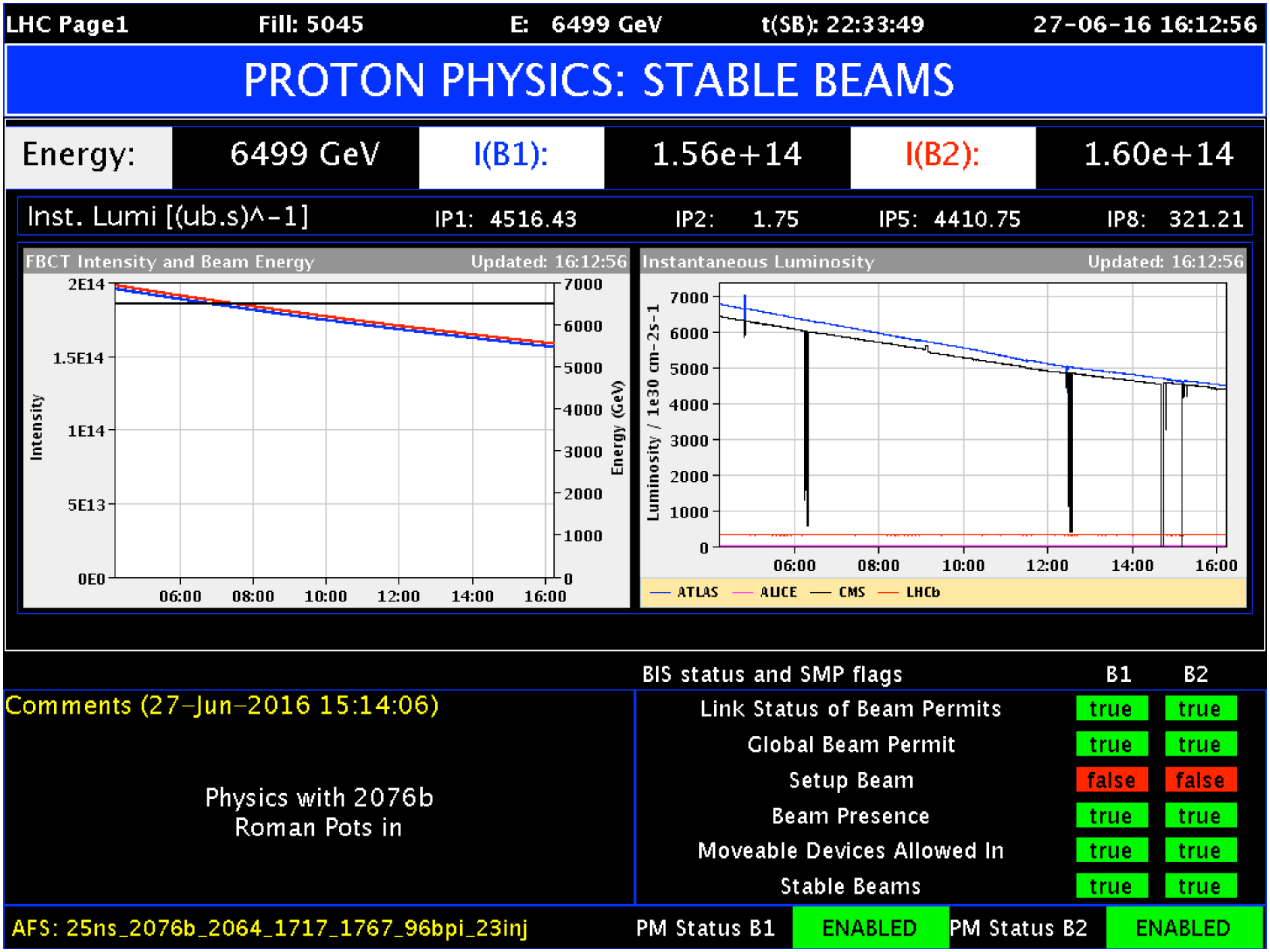
Two-step process:

- 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

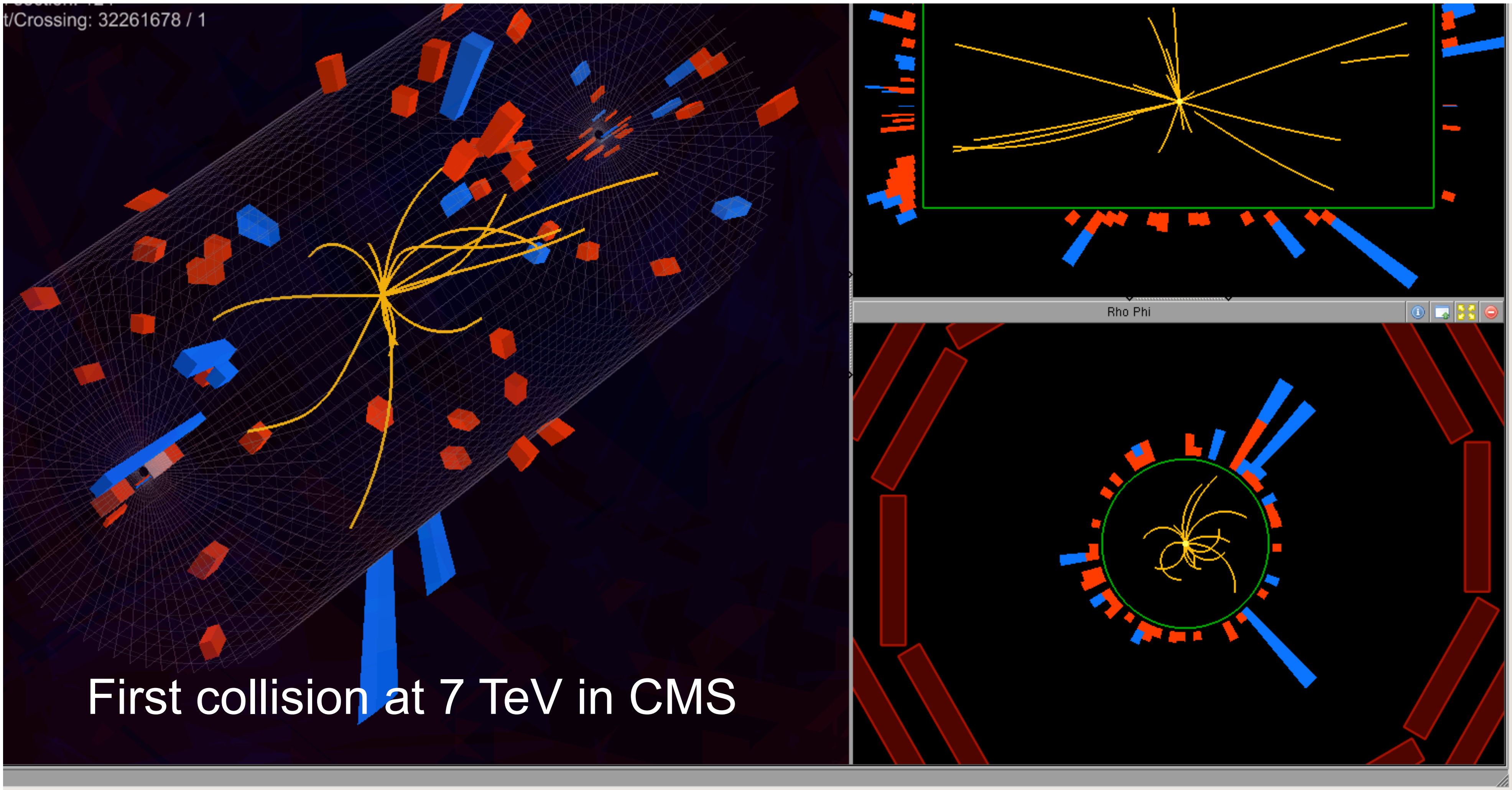
Any Internet access

2009: first collisions at LHC

November 23, 2009
First collisions at 900 GeV

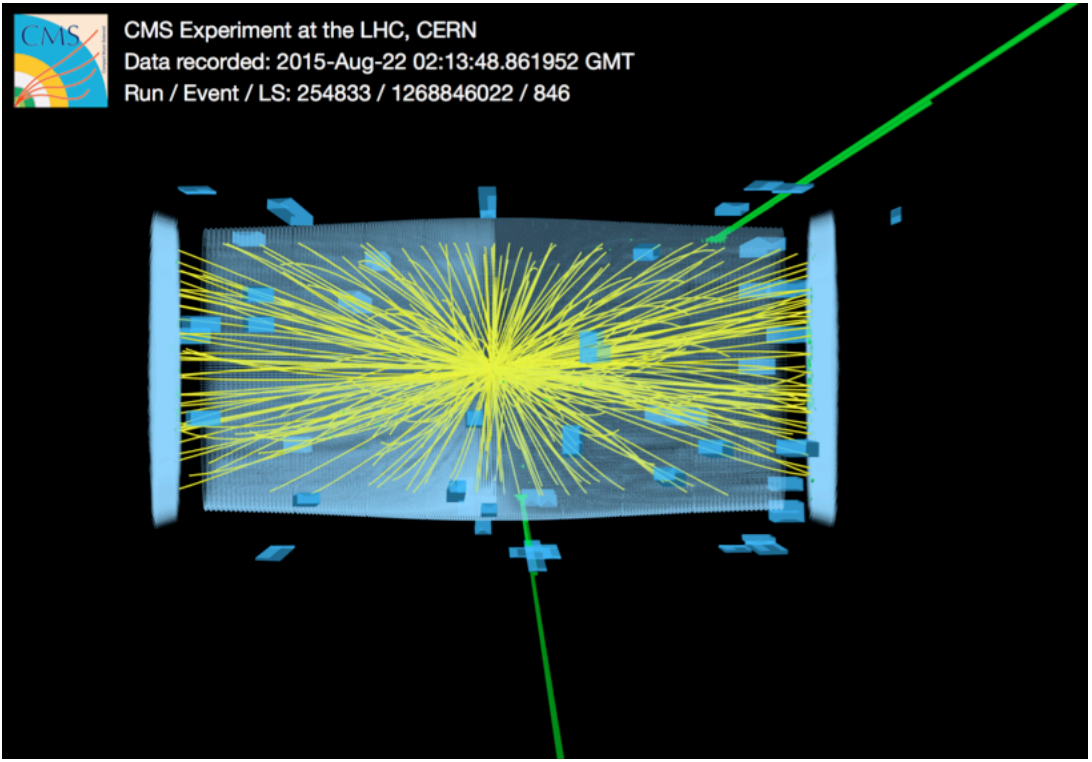
December 14, 2009
First collisions at 2.36 TeV

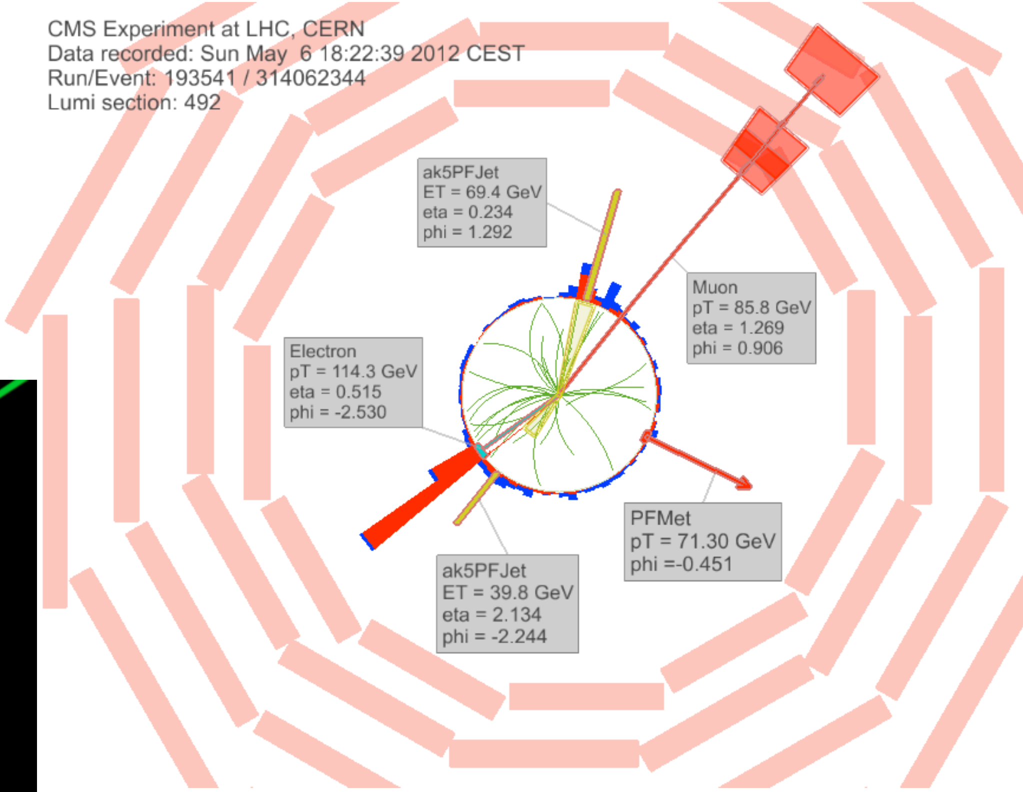
March 30, 2010
First collisions at 7 TeV



Event reconstruction

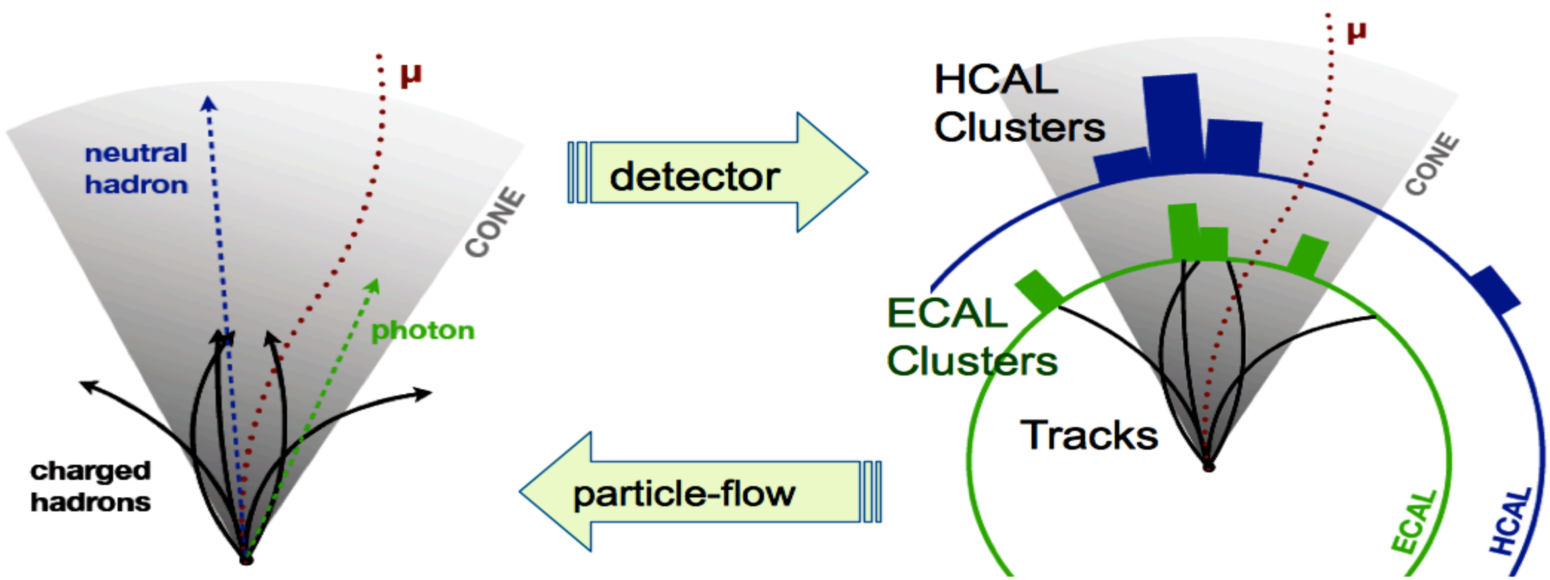
- Reconstruct event and all constituents:
  - leptons (e, μ, τ), photons
  - tracks
  - jets (b-jets)
  - missing transverse energy
  - etc.



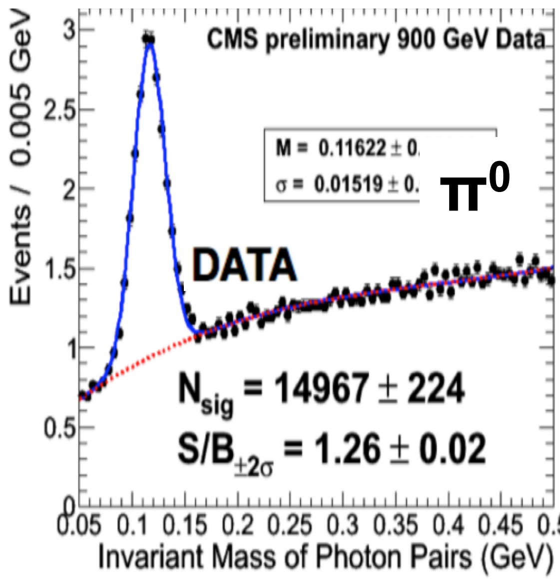


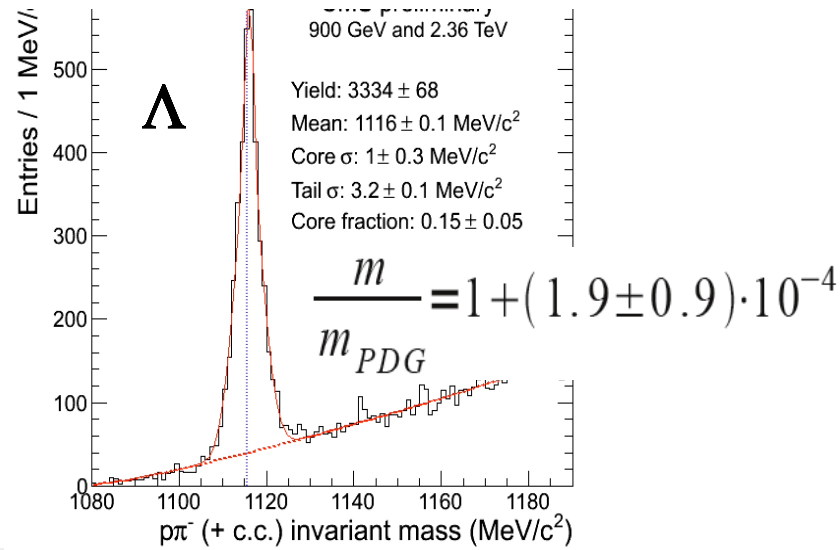
Particle Flow event reconstruction

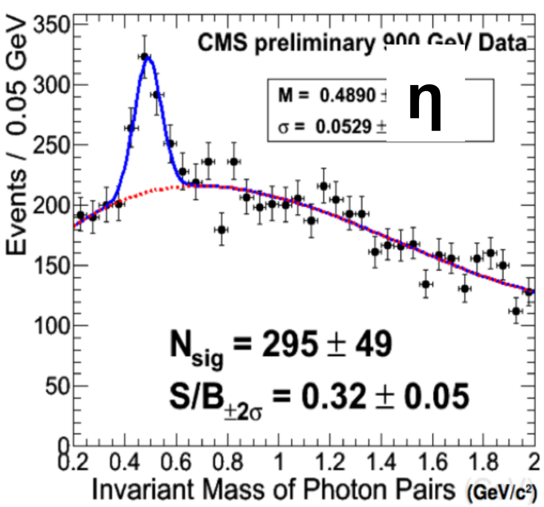
- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision
  - charged hadrons, neutral hadrons, photons, muons, electrons
  - use complementary info. from separate detectors to improve performance
  - tracks to improve calorimeter measurements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

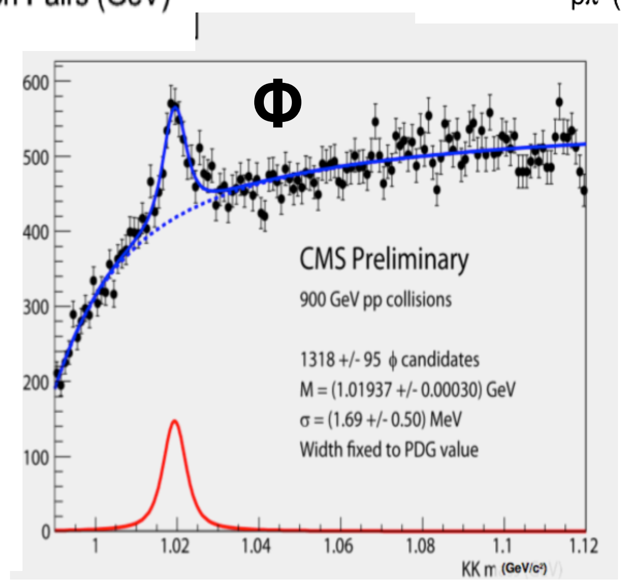


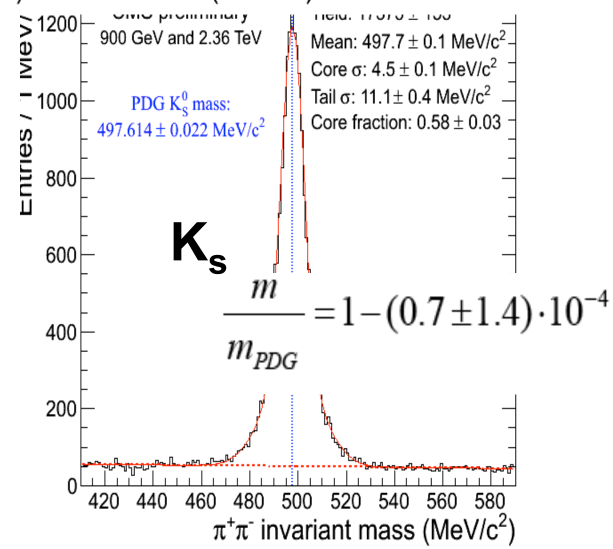
Rediscovery of resonances



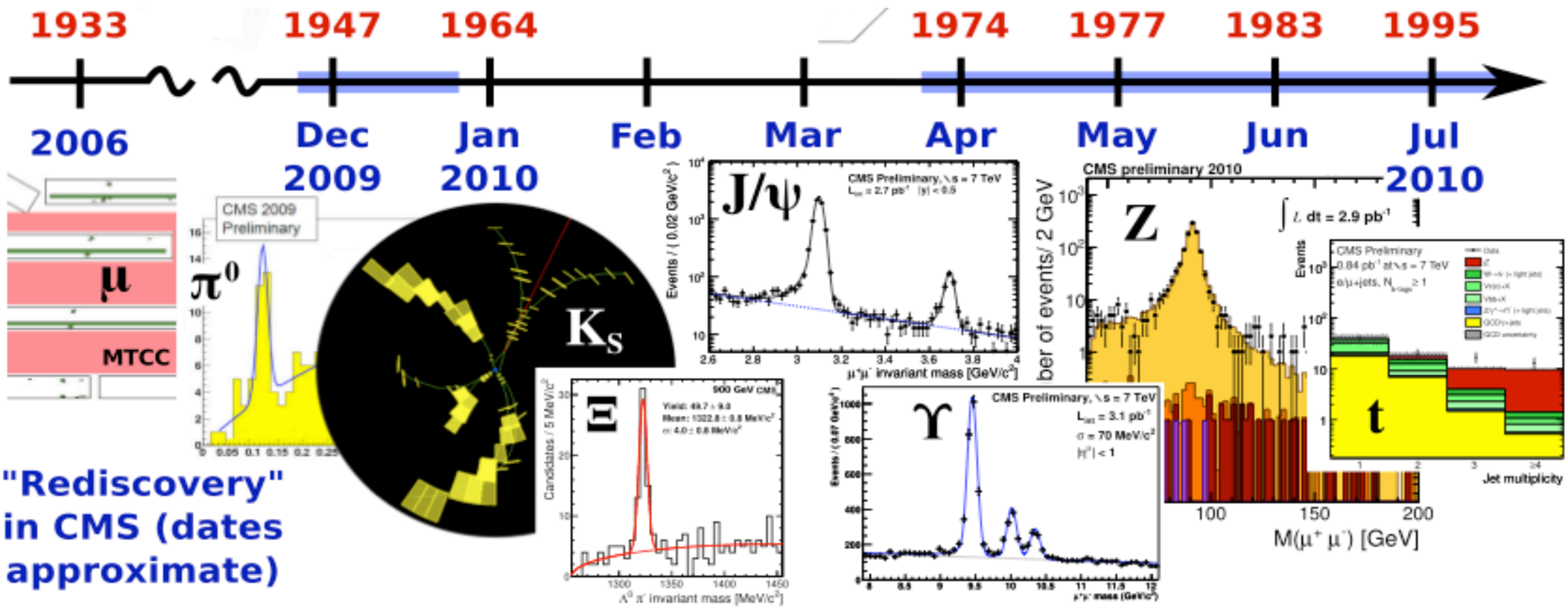






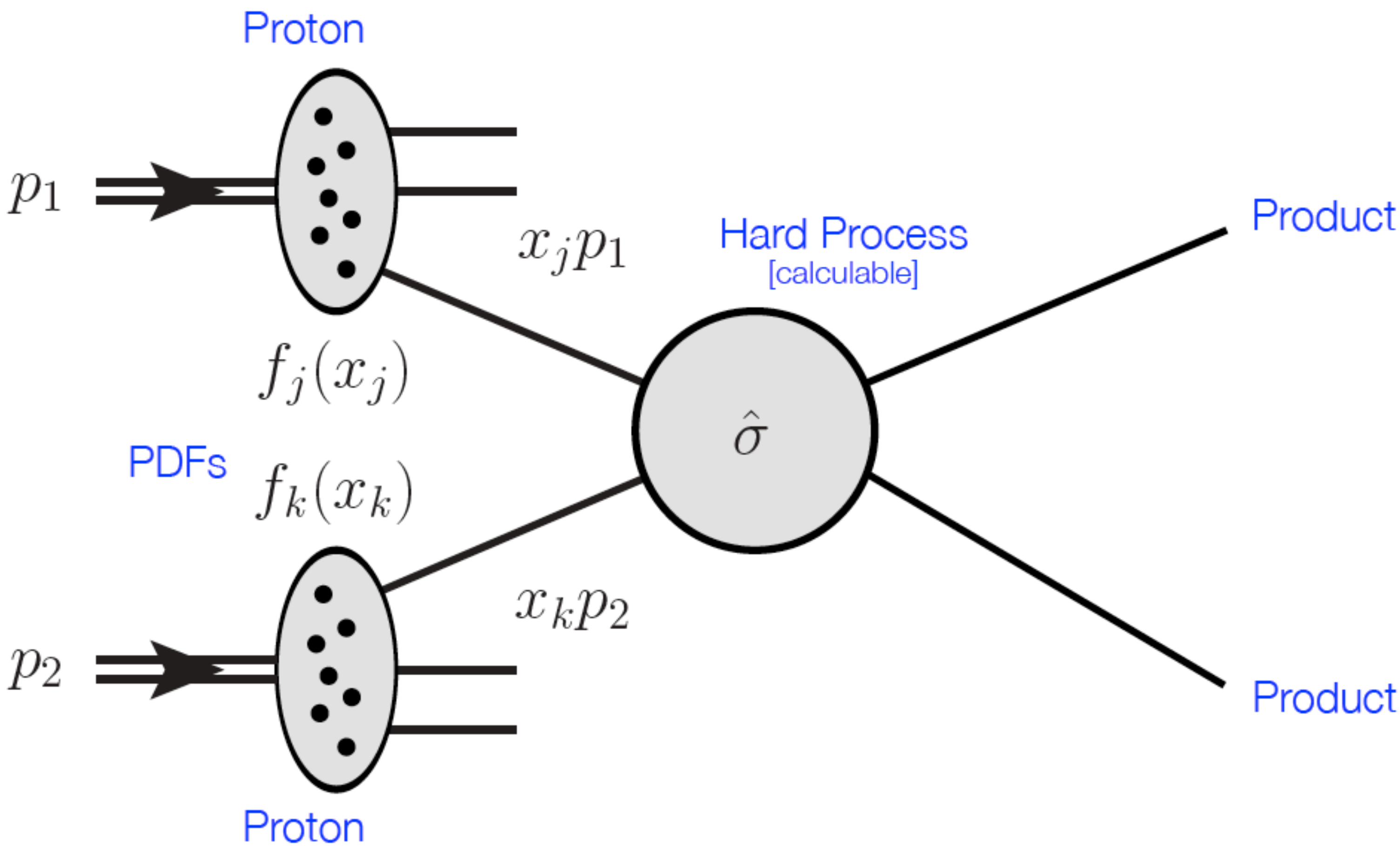


Re-discovery of the SM at LHC



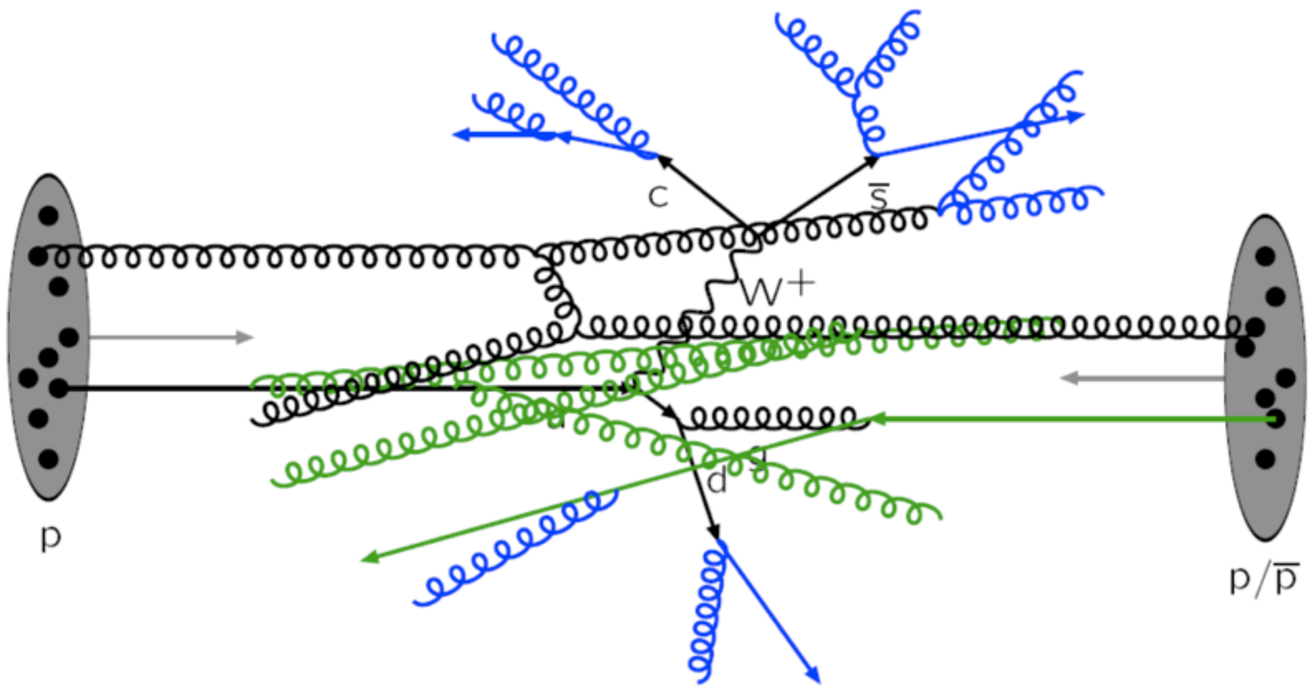
"Rediscovery" in CMS (dates approximate)

Hadron interactions: pp scattering



Proton-proton scattering at LHC

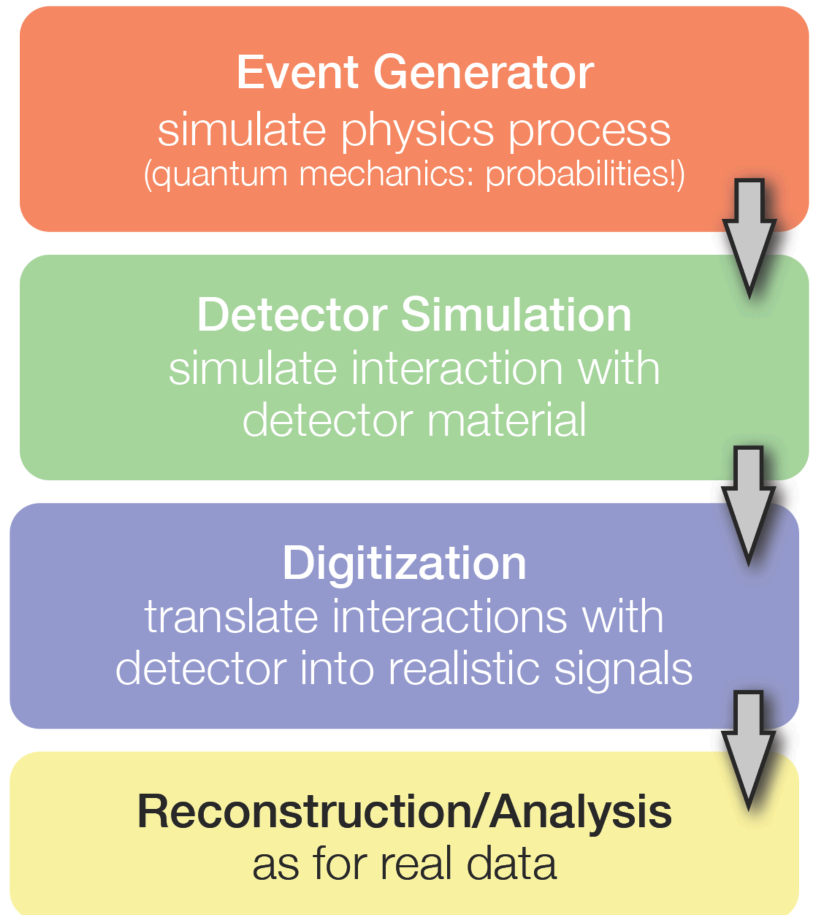
- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction [“underlying event”]



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)*

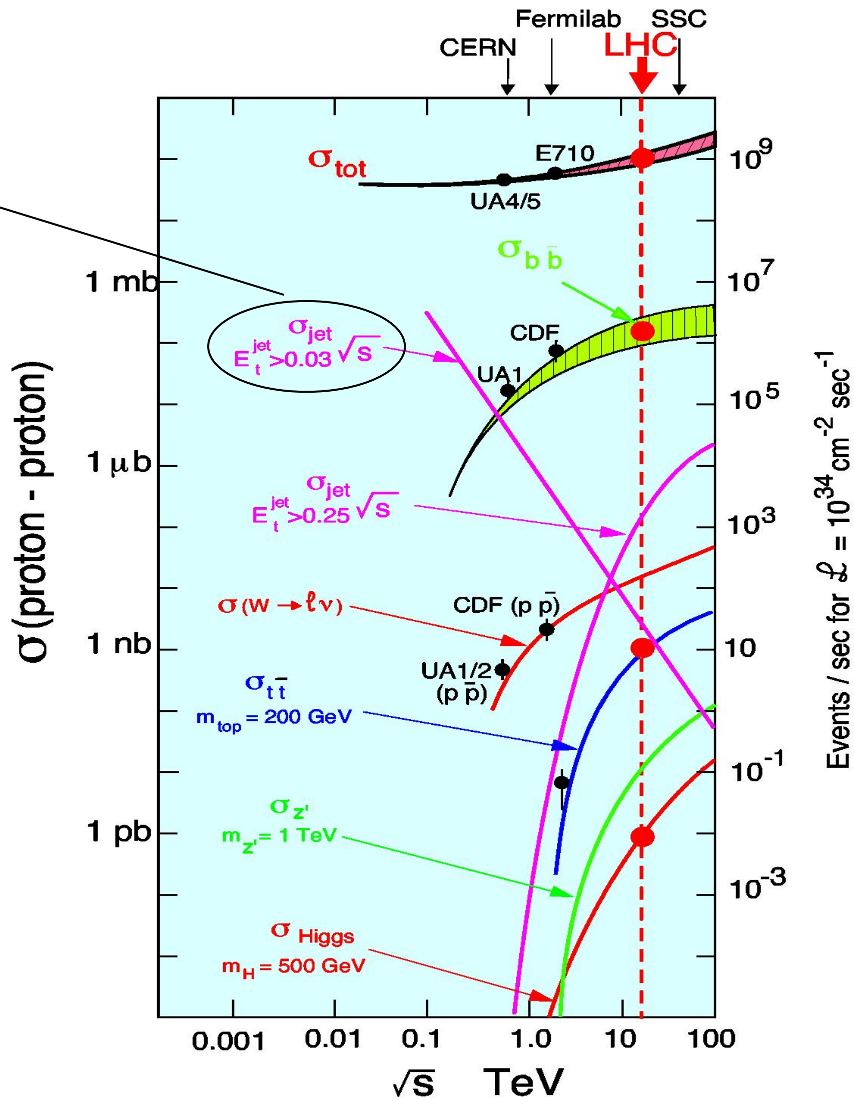
$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

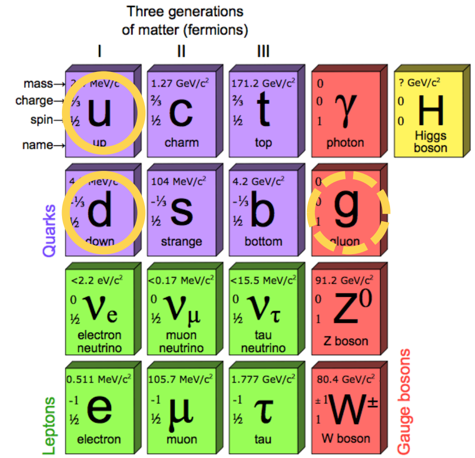
Acceptance *(experimental: detector, efficiencies)*

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

Minimum Bias

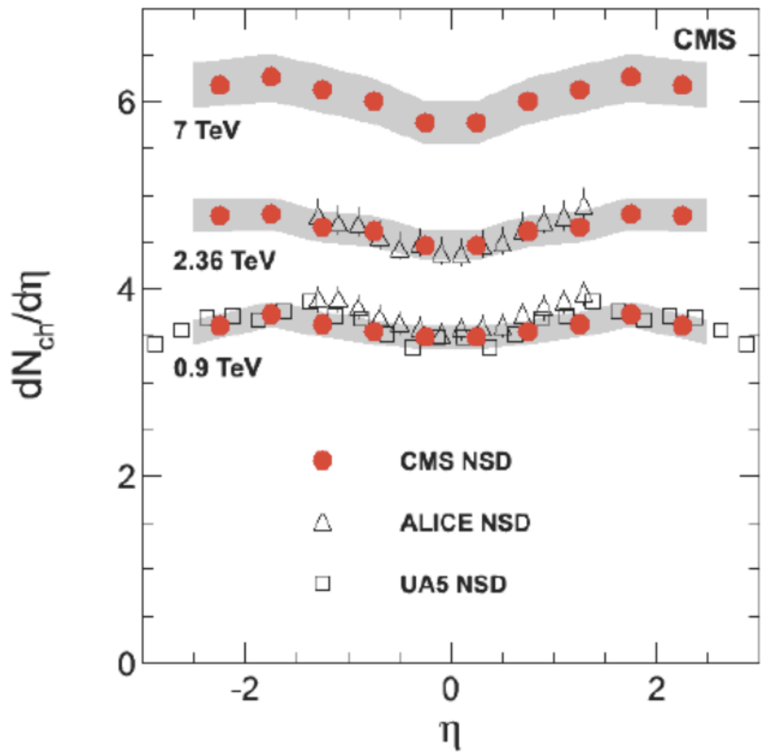
low p_T particle production

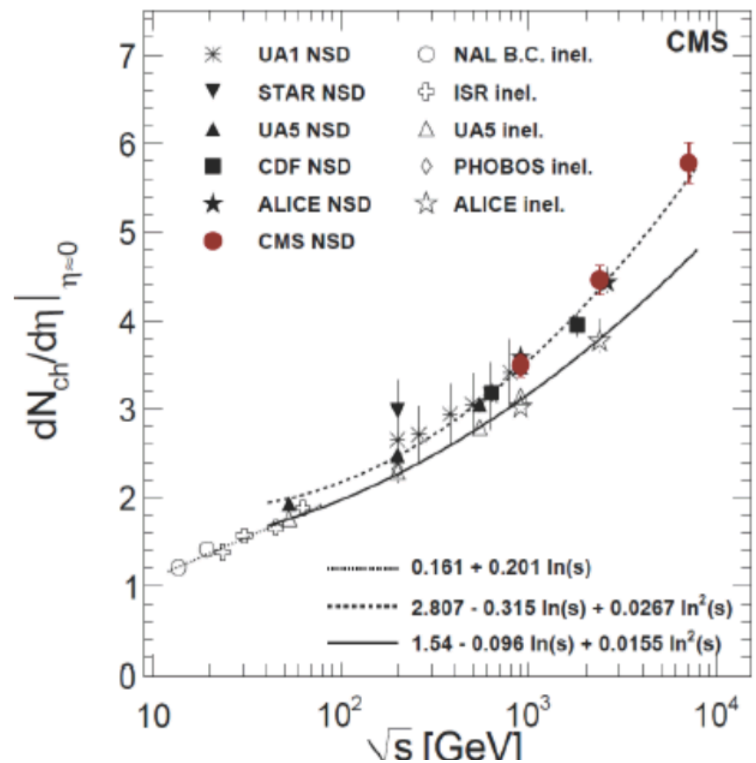




Minimum bias events

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

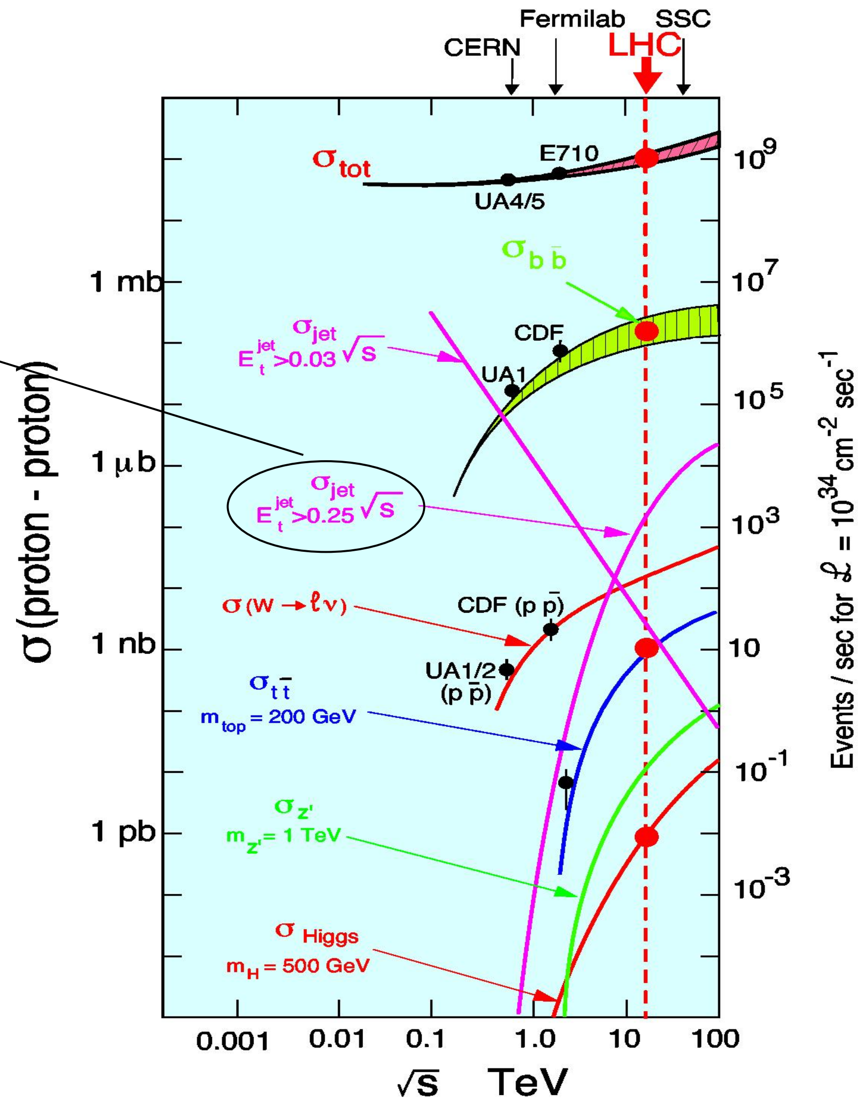


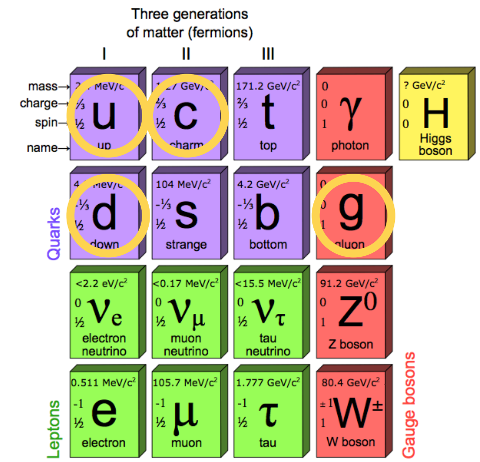


Tuning of MC generators needed

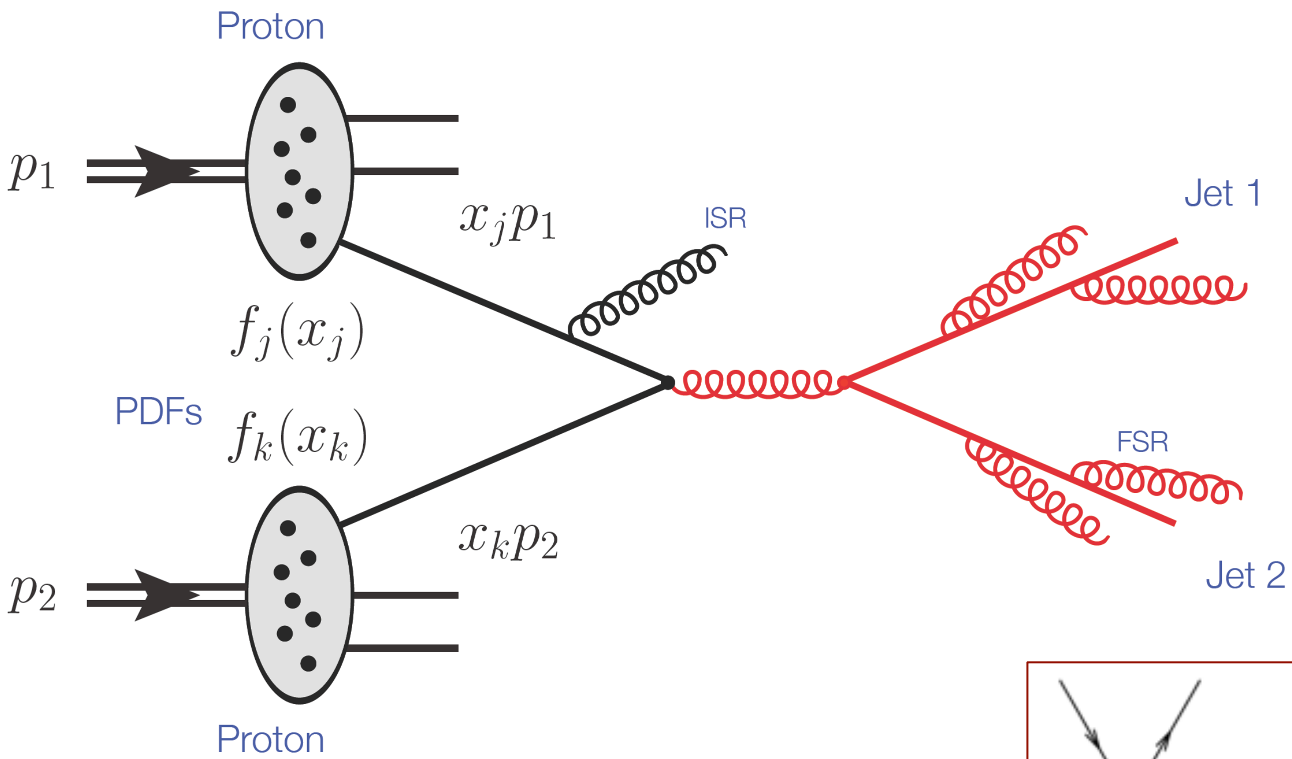
Jet production

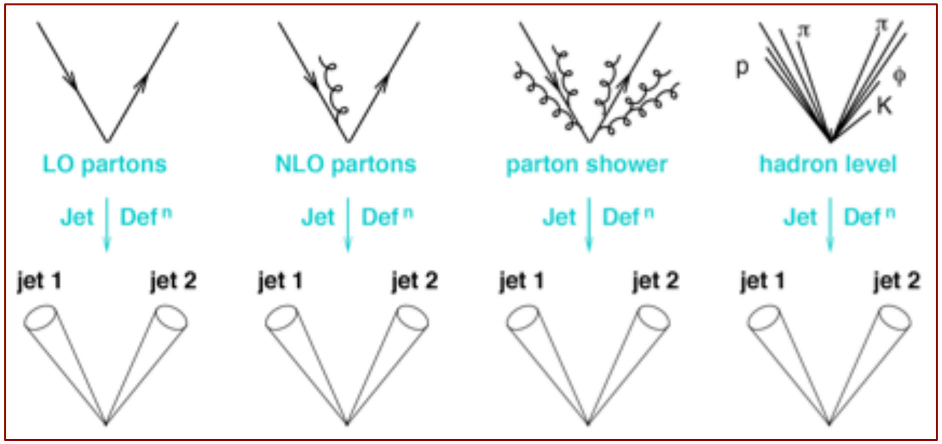
jets





Jet production at LHC

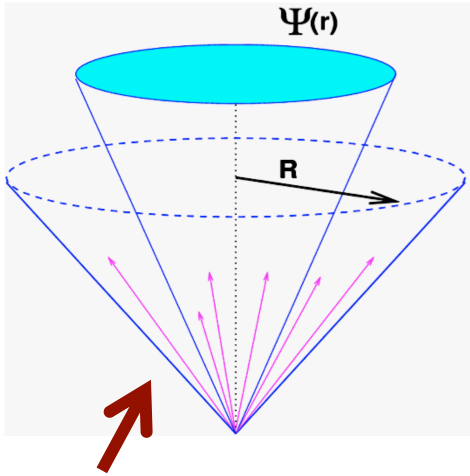


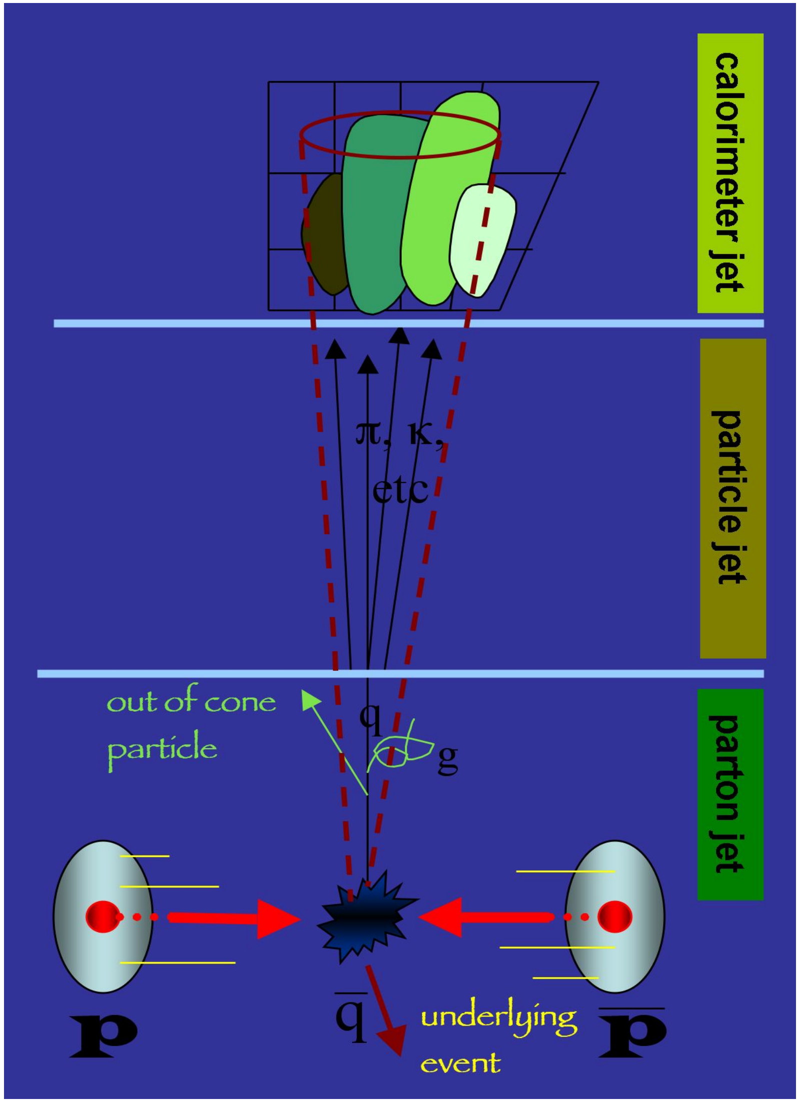


Available up to NLO, first NNLO calculations becoming available

Jet production at LHC (cont.)

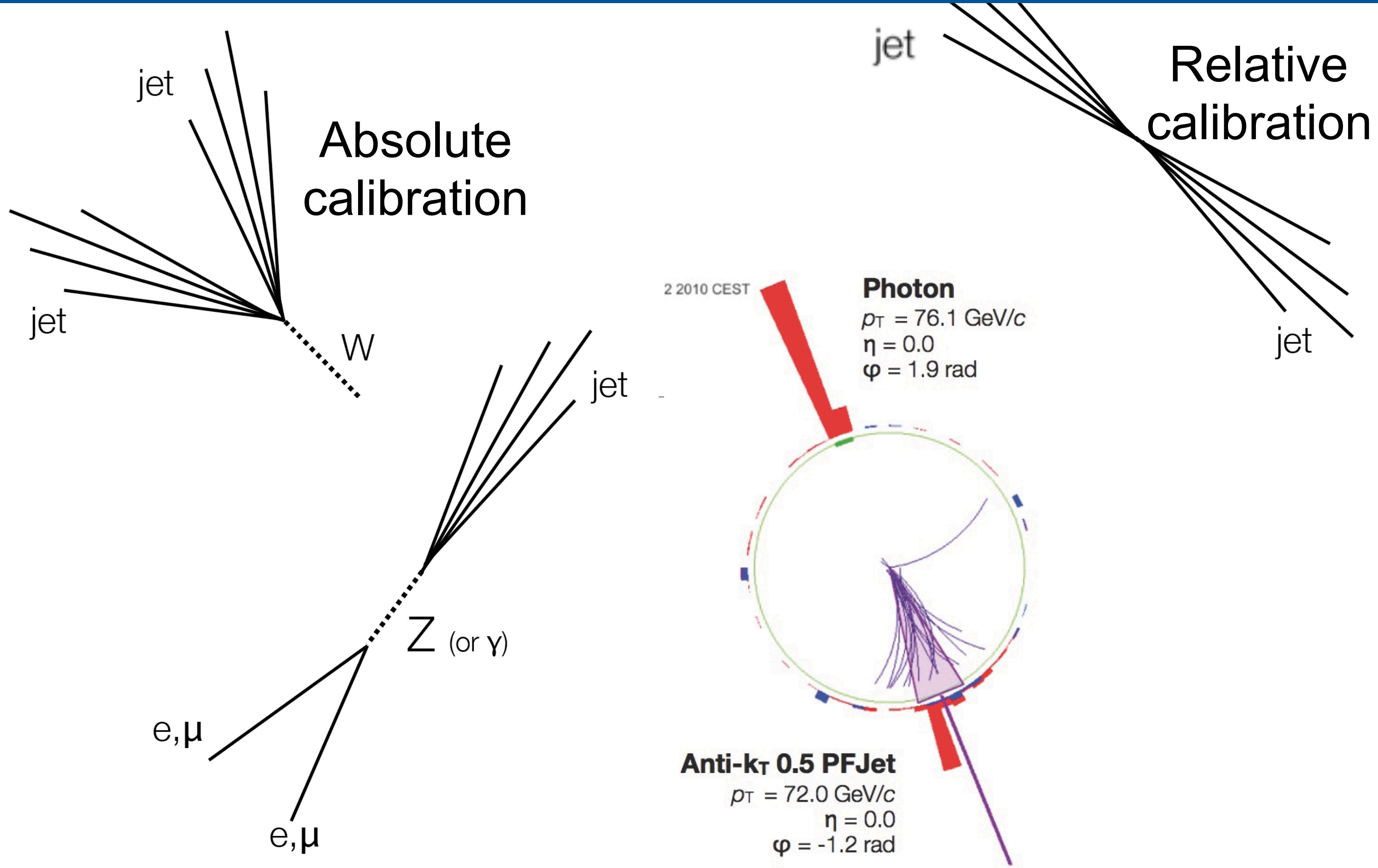
- Processes creating jets are complicated
  - Parton fragmentation, with electromagnetic or hadronic showering in the detector
- Jet reconstruction is difficult
- Jet energy scale and reconstruction is large source of uncertainty



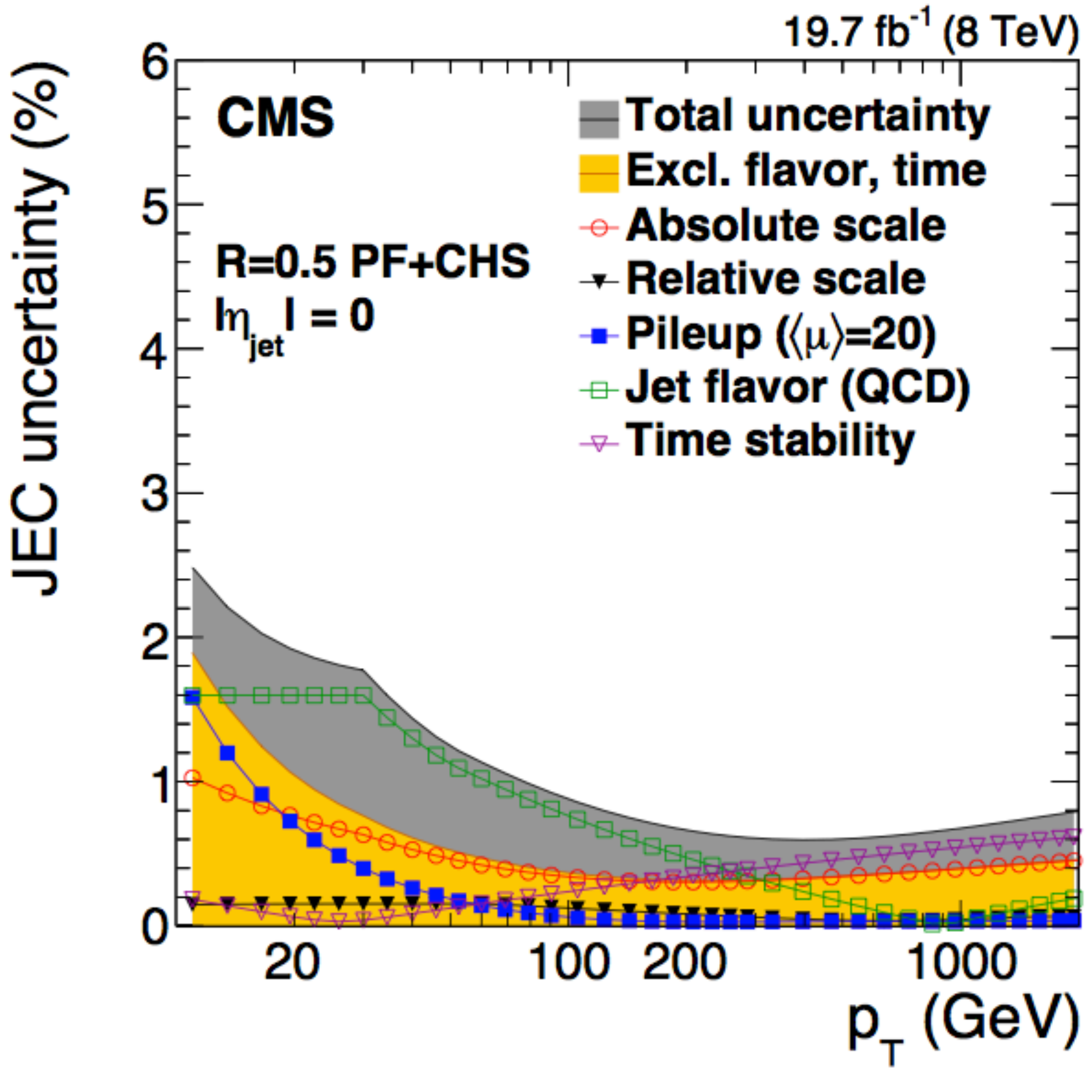


- Measure energy in a “cone”

Jet energy calibration



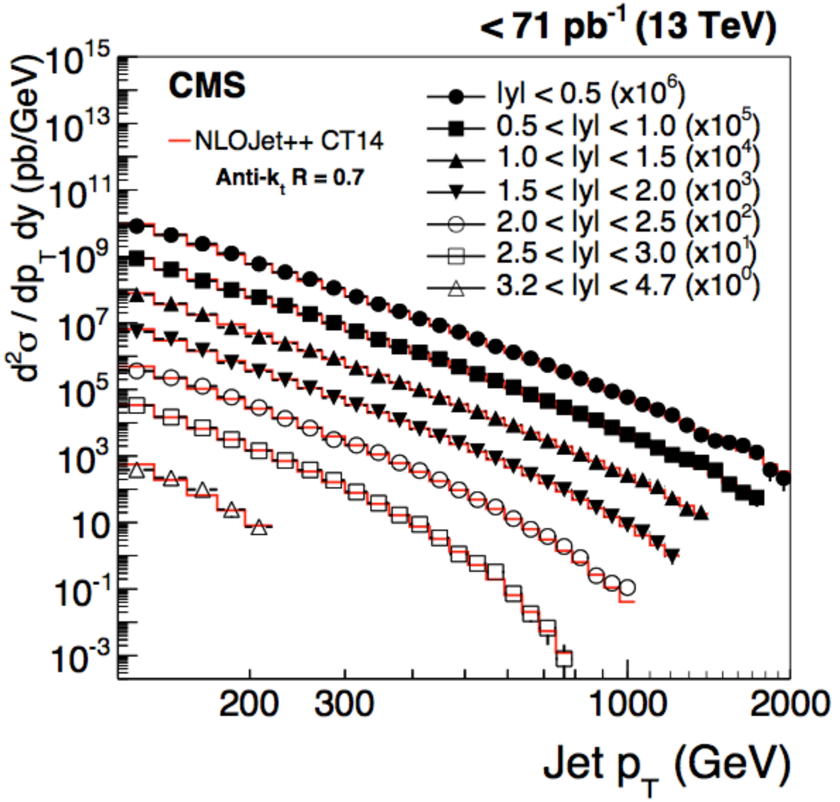
E_T can be measured precisely

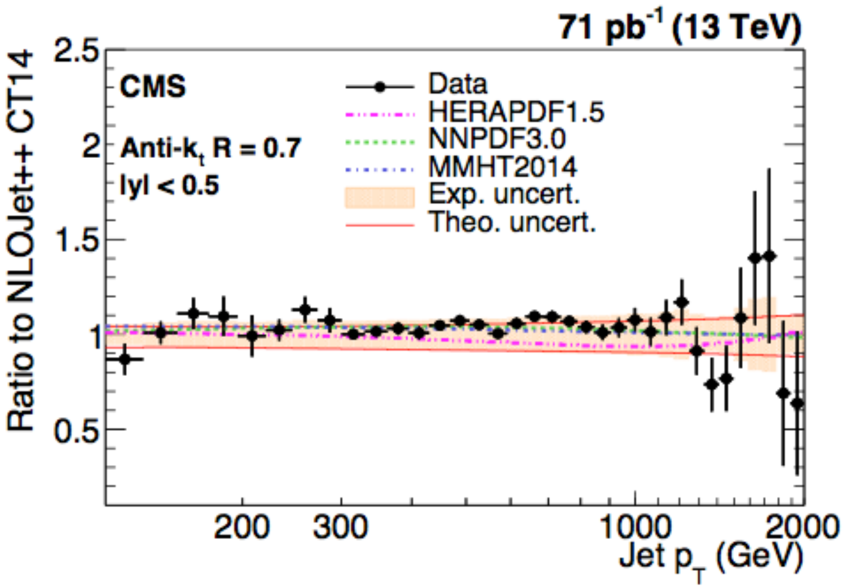


Inclusive jet distribution

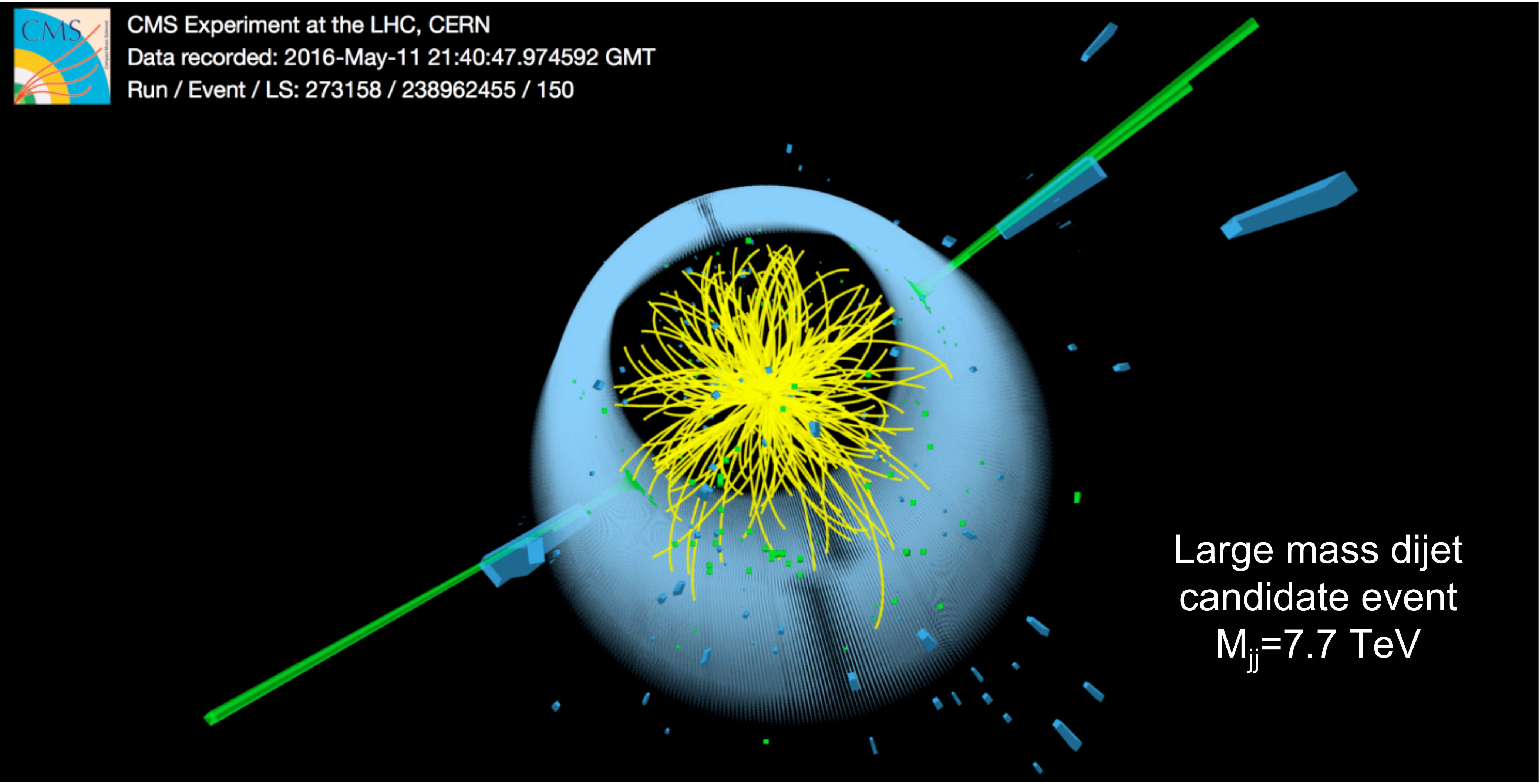
arXiv:1605.04436

- 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

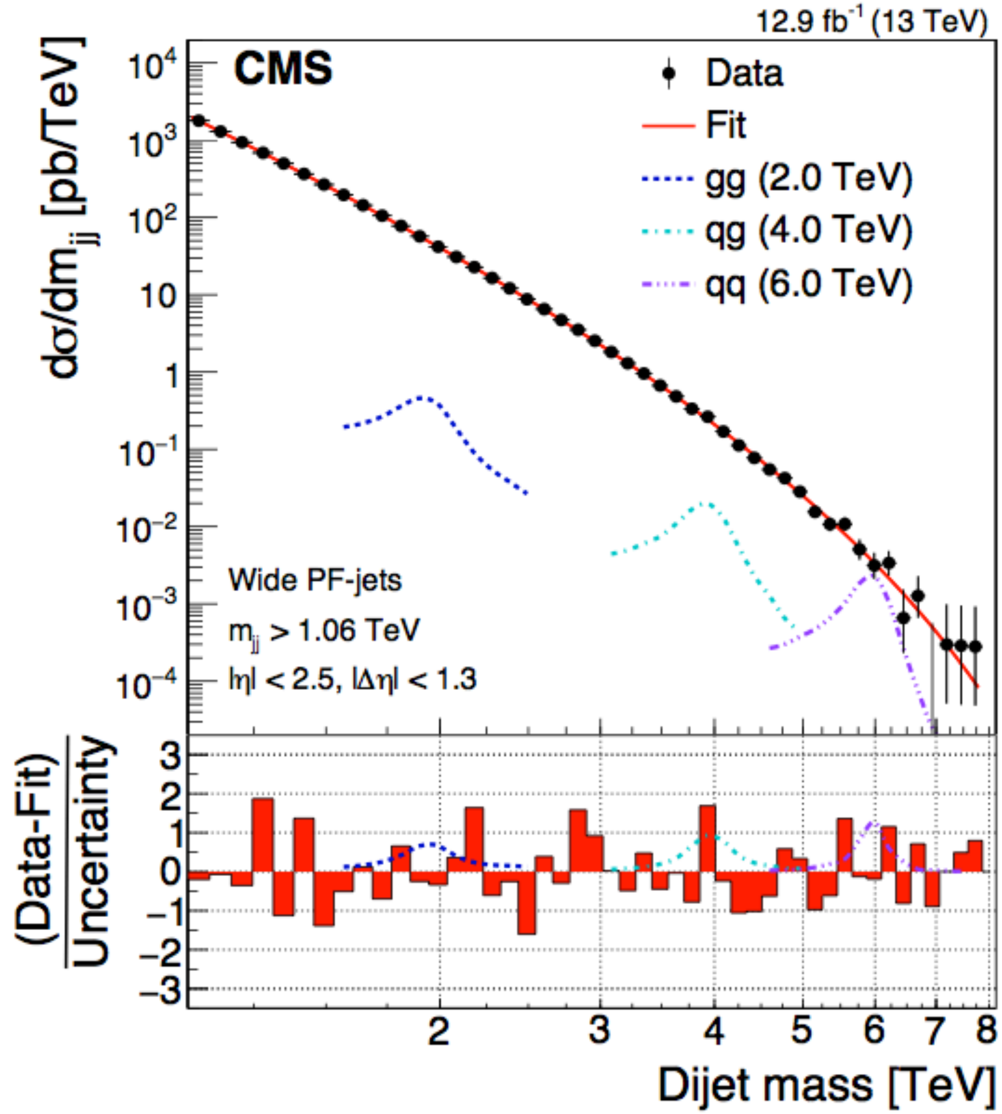


Dijet mass

arXiv:1611.03568

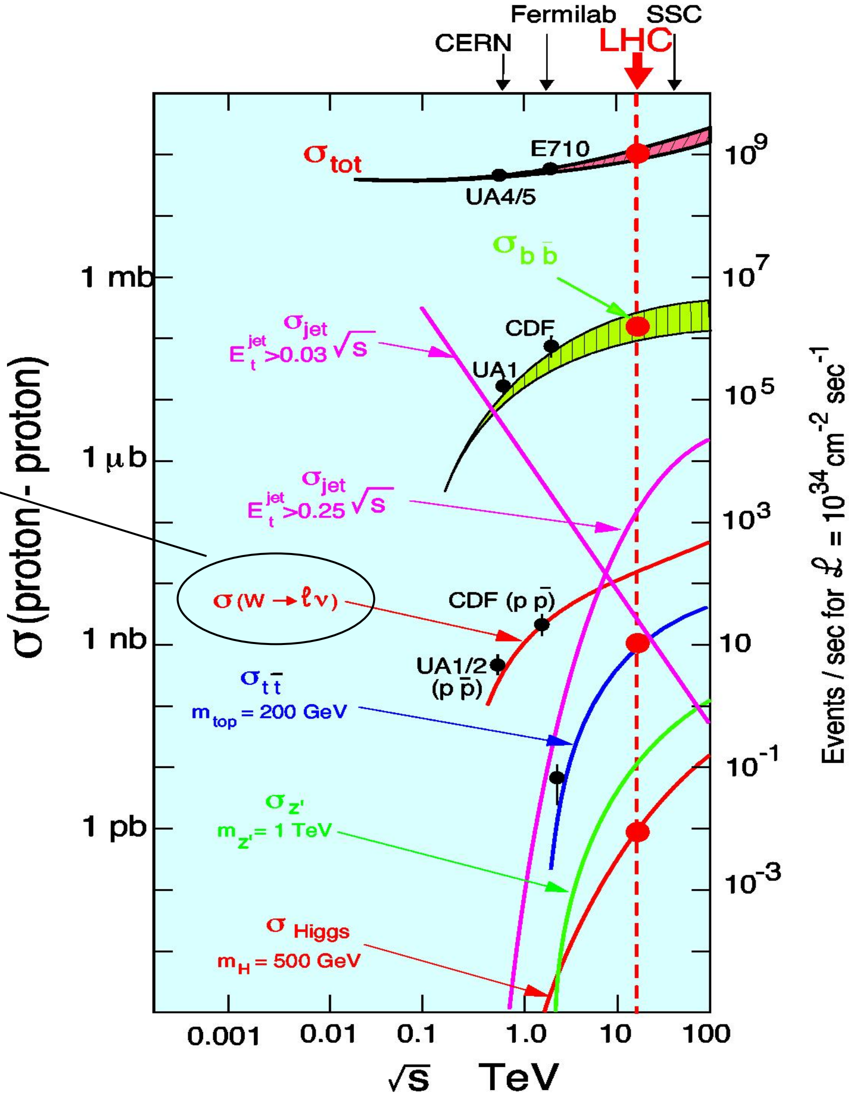
Search for numerous BSM resonances:

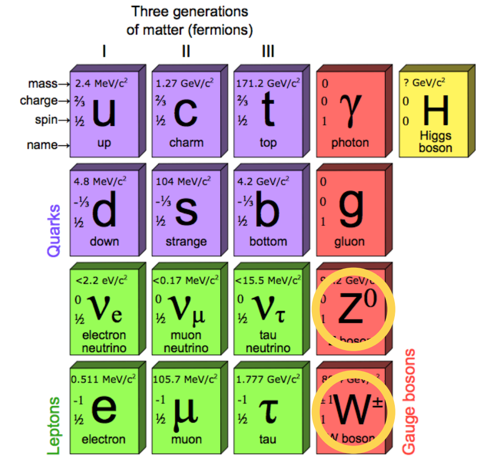
- string resonance, excited quarks, axi-gluons, colorons, E6 diquarks, W' and Z', RS gravitons



W and Z bosons

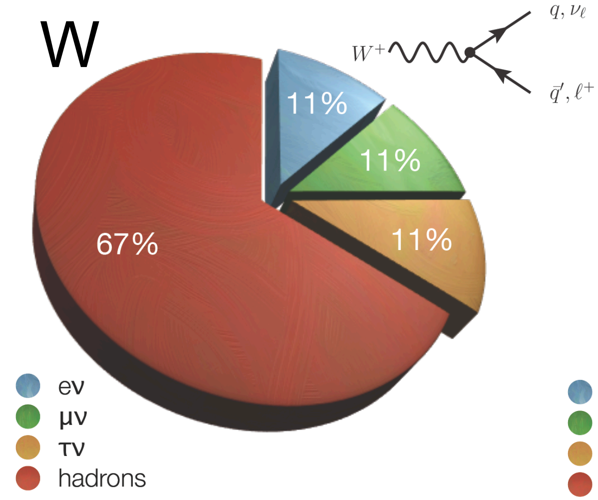
W bosons

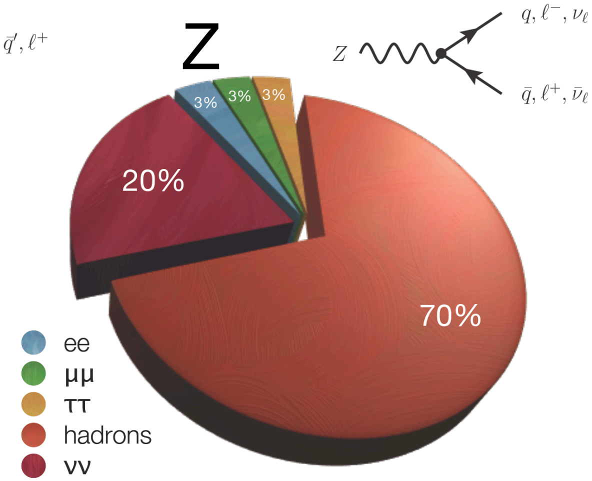


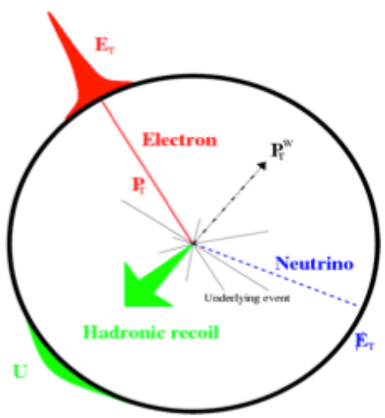


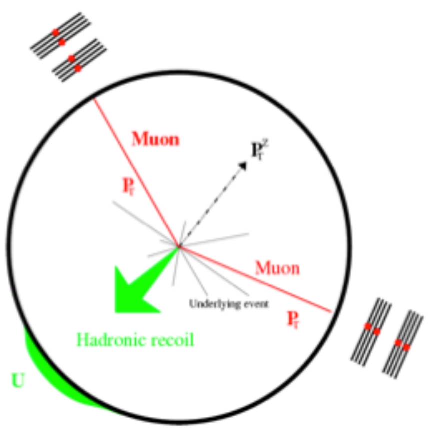
W and Z bosons

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



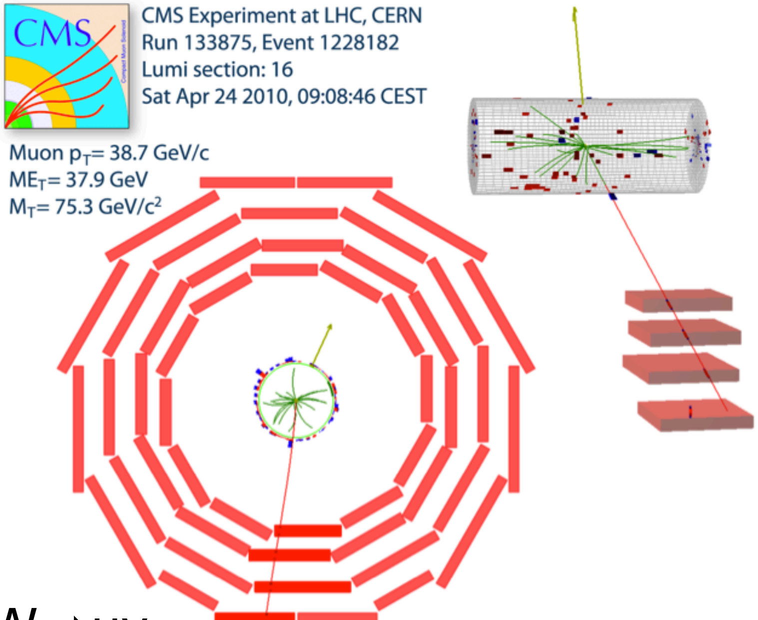




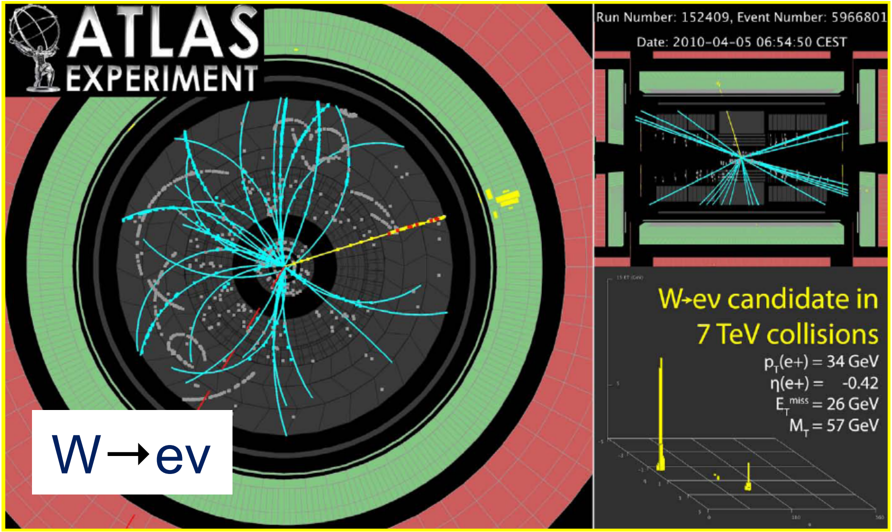


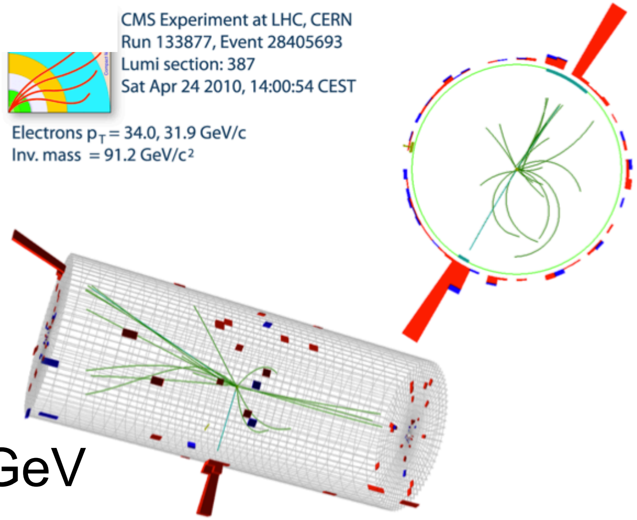
- Isolated high-p_T leptons: starting point of many analyses
  - Good rejection of QCD backgrounds
  - “Tracking” vs “calorimeter” isolation
- Excellent calibration signal
  - Electron energy scale, ID/trigger eff., etc.

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

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

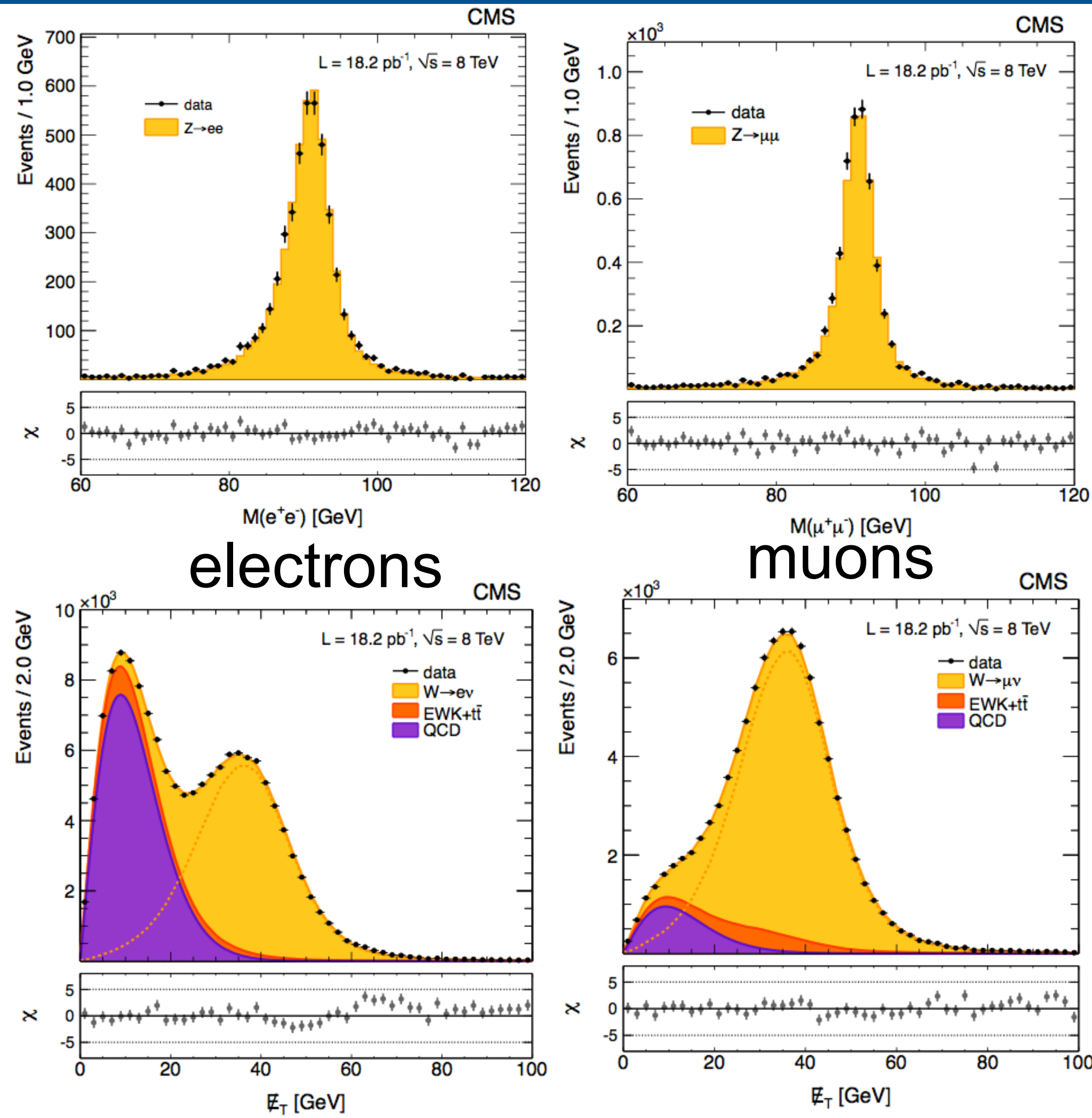
W mass reconstruction

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

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

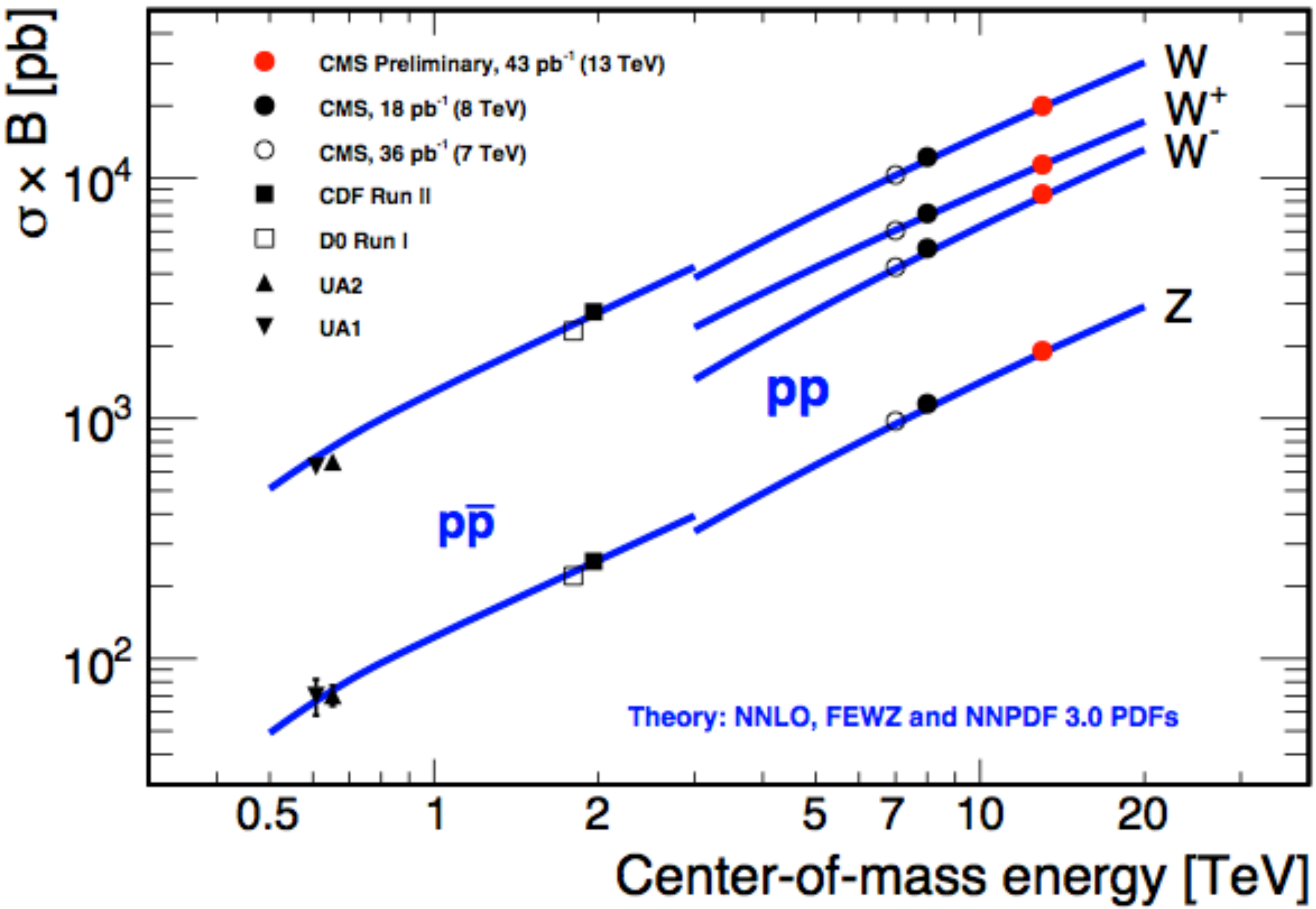
Z boson

W boson



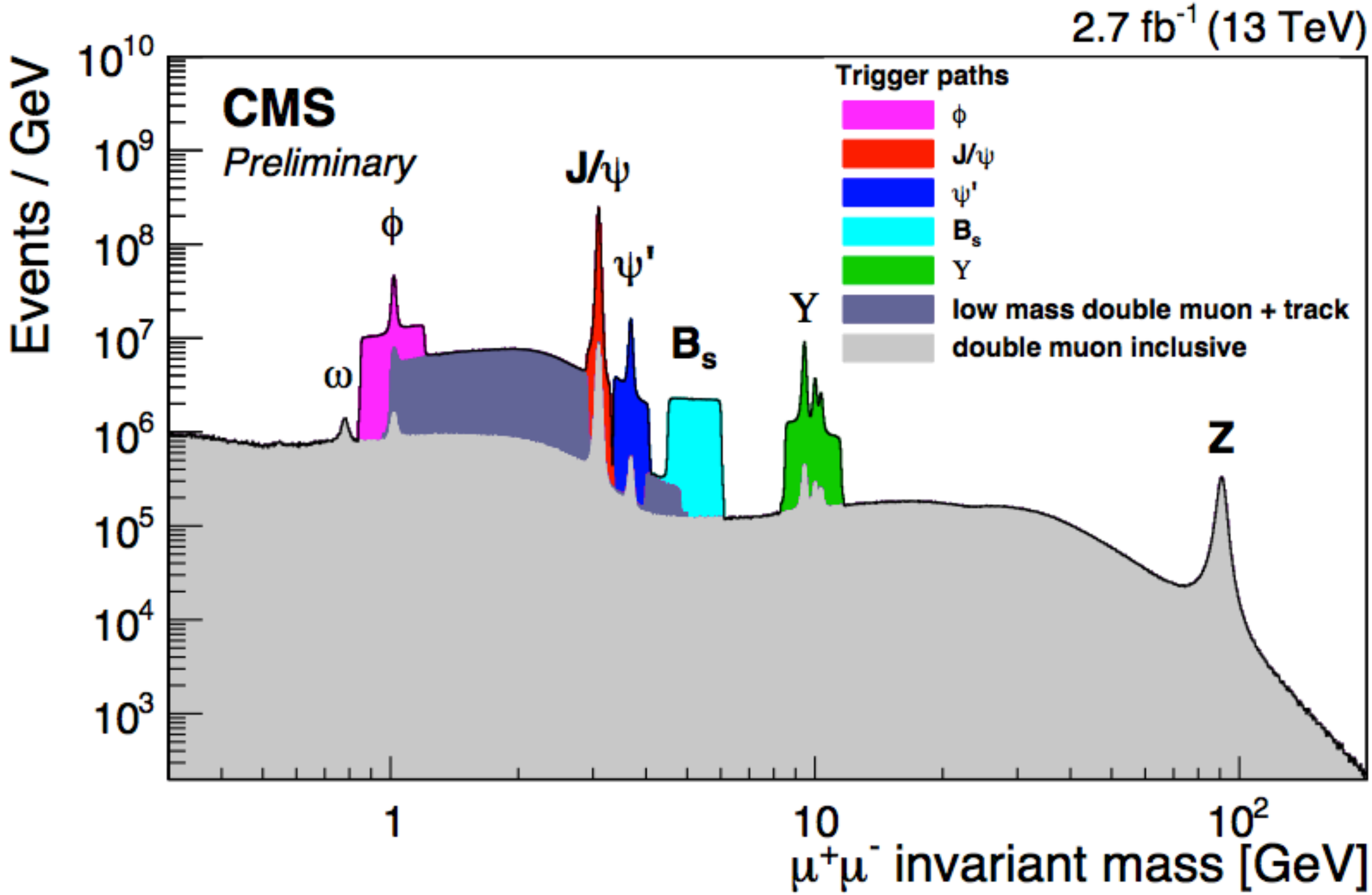
W/Z cross section vs √s

arXiv:1012.2466, CMS-SMP-15-004



Di-muon mass spectrum

CMS-DP-2015-055

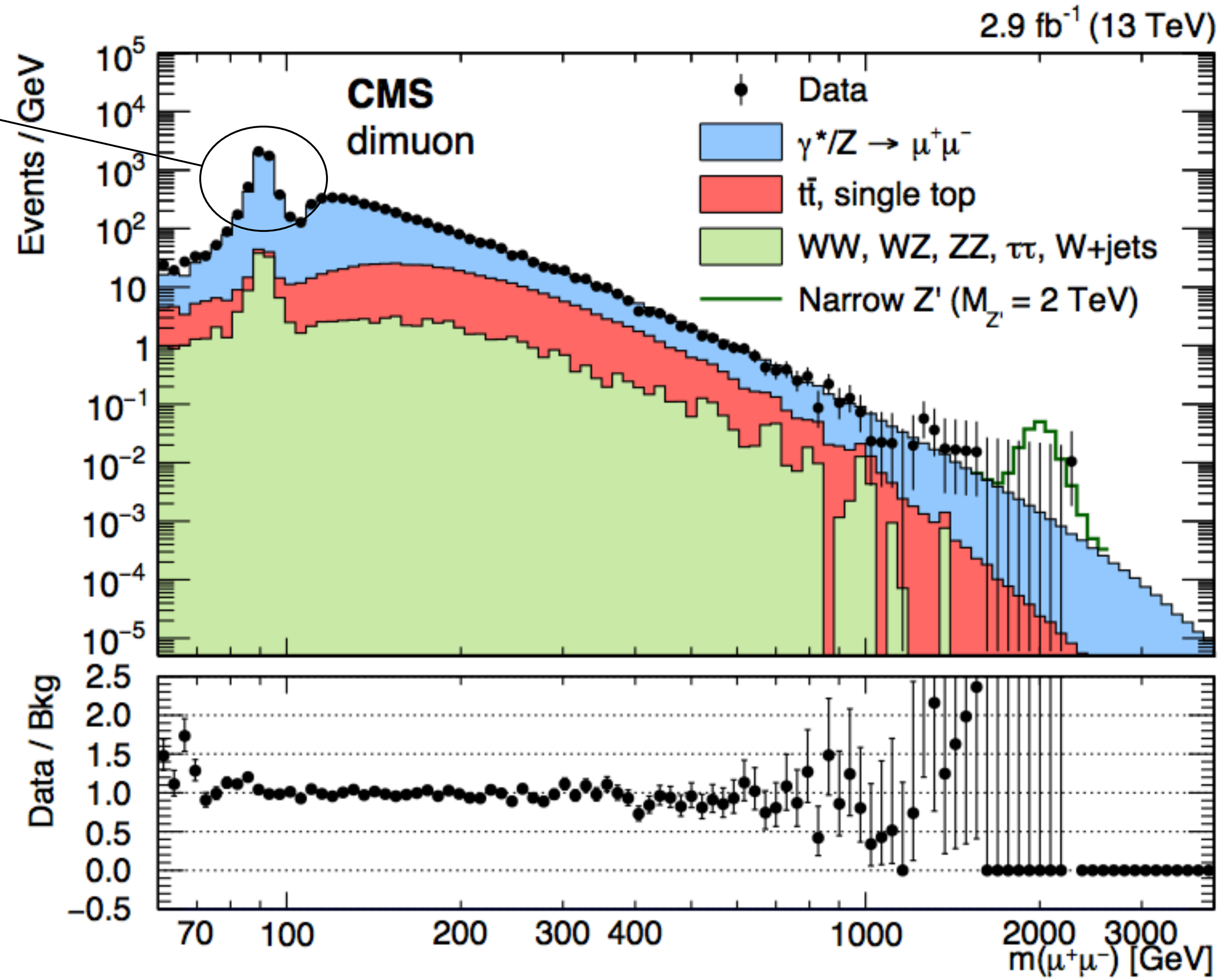


Di-lepton events

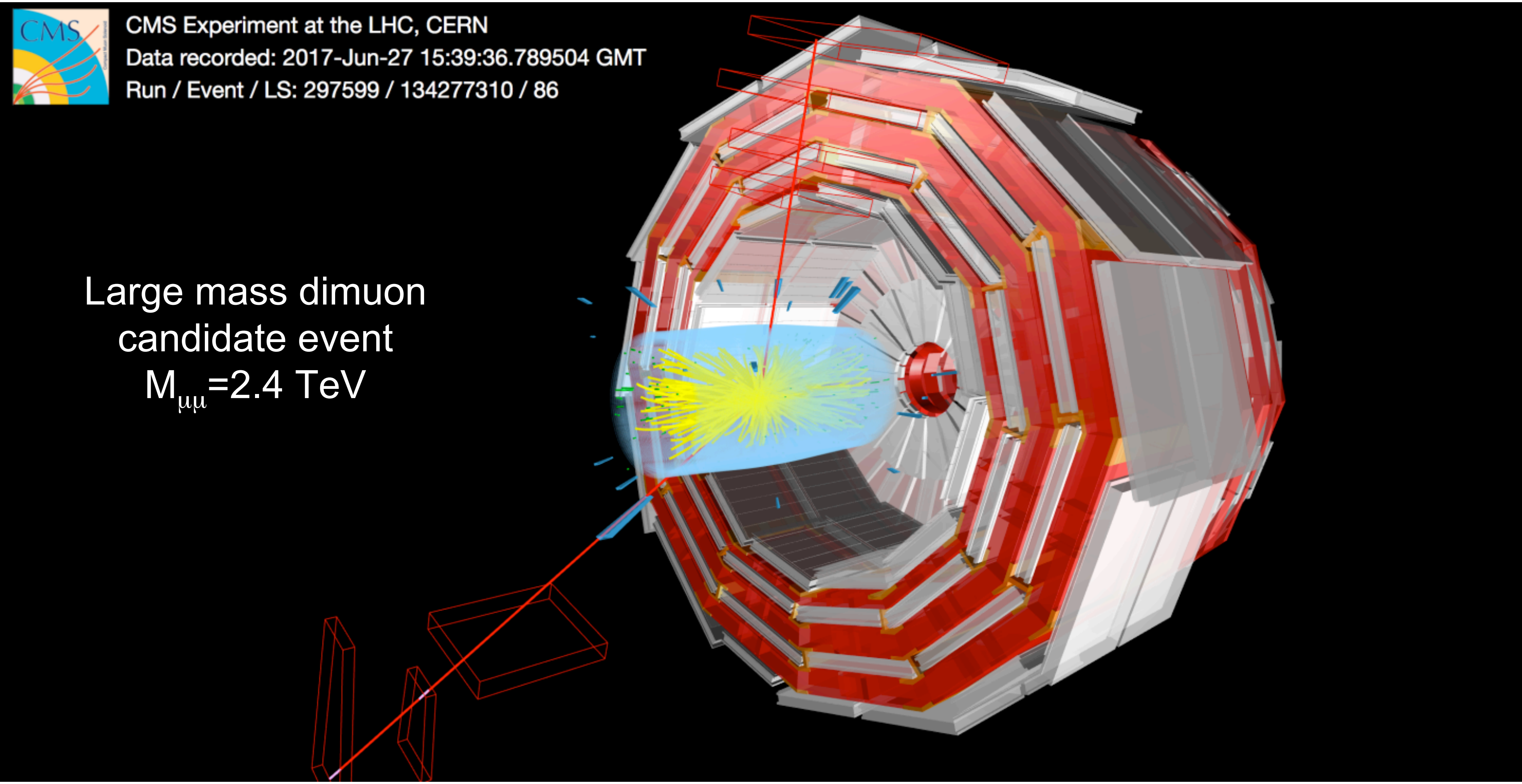
arXiv:1609.05391

Z boson resonance

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



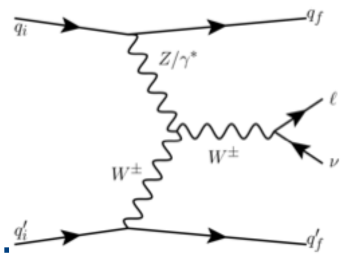
2017: Di-muon candidate event

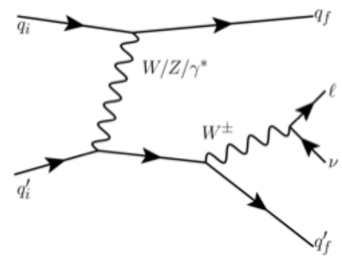


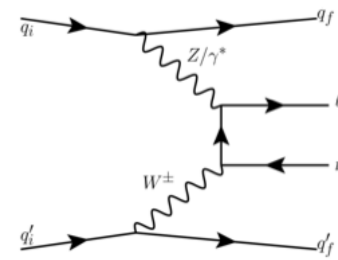
Single and diboson production

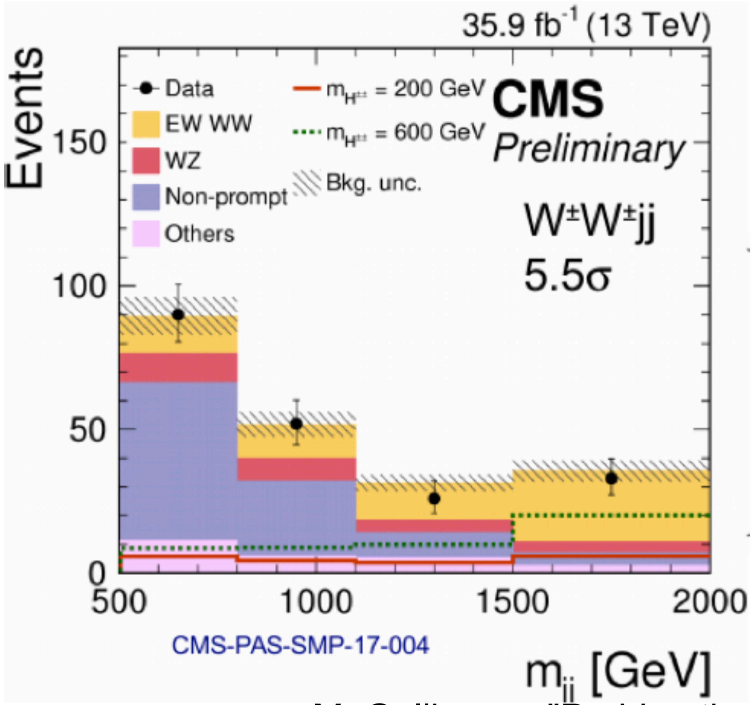
SMP-17—004, SMP-16-018

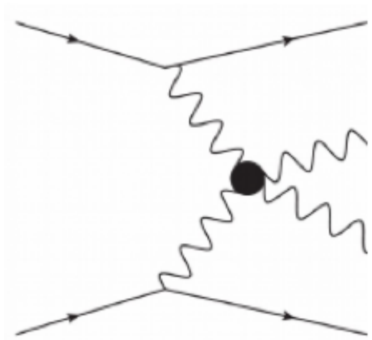
- LHC as boson-boson collider
- Single (or double) W/Z production
  - Sensitive to NP
- Observation of vector boson scattering
  - Same-sign WW
- Rich program of precision measurements

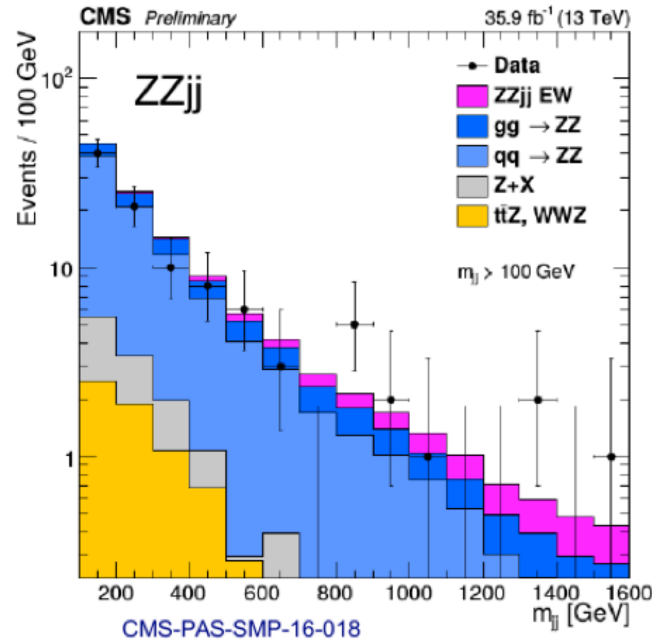






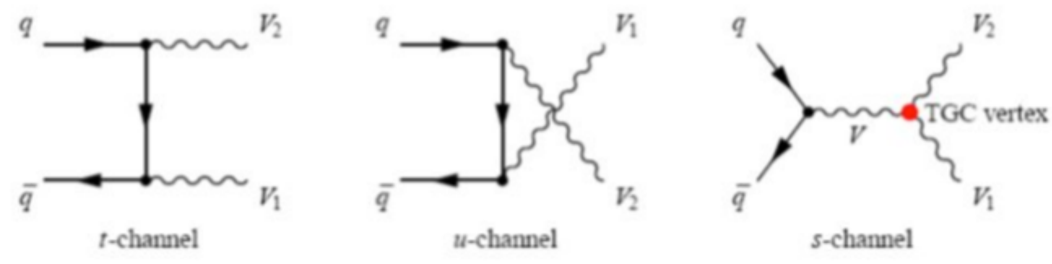


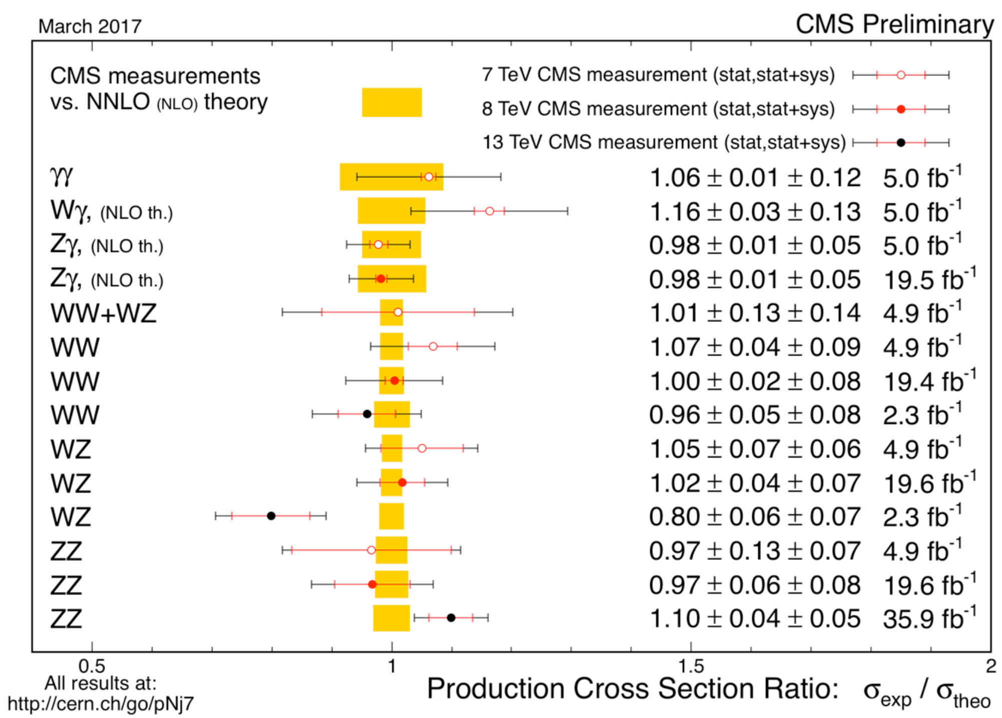


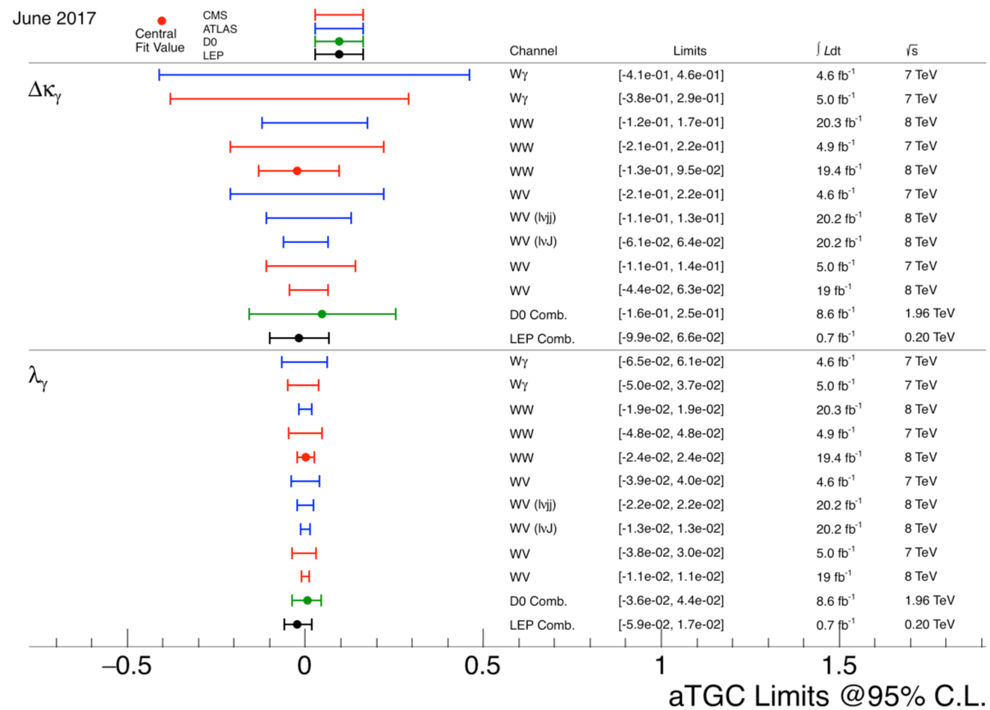


Diboson production

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

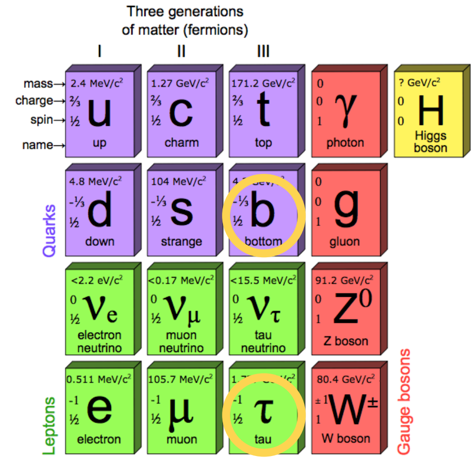


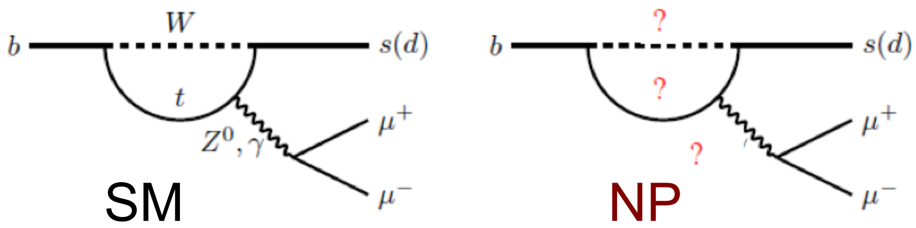


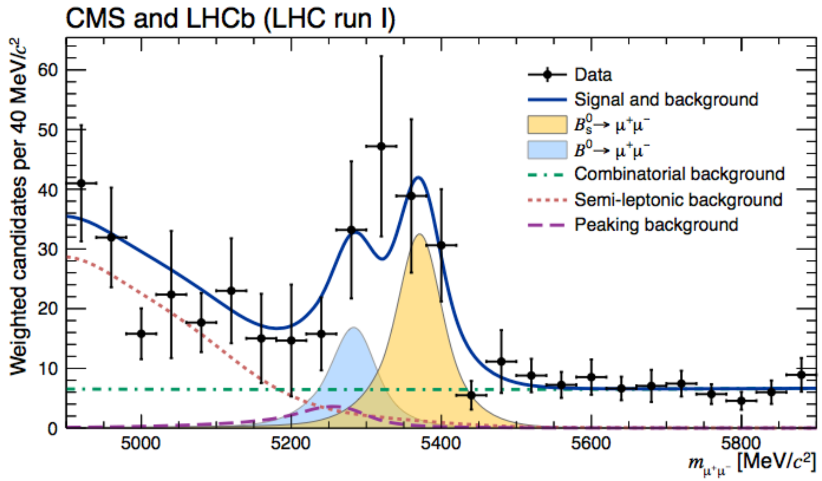


B-physics and Rare decays

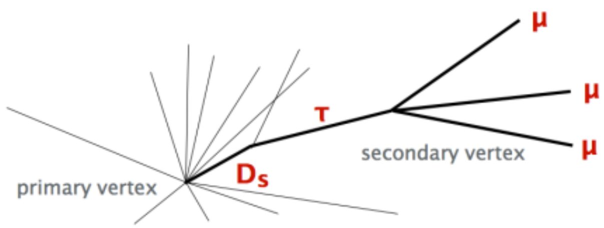
- Study rare processes to look for NP
- Indirect searches: $B_{s/d} \rightarrow \mu\mu$
- Flavour changing neutral current (FCNC) forbidden at tree level in SM
- Can only go through loop diagrams





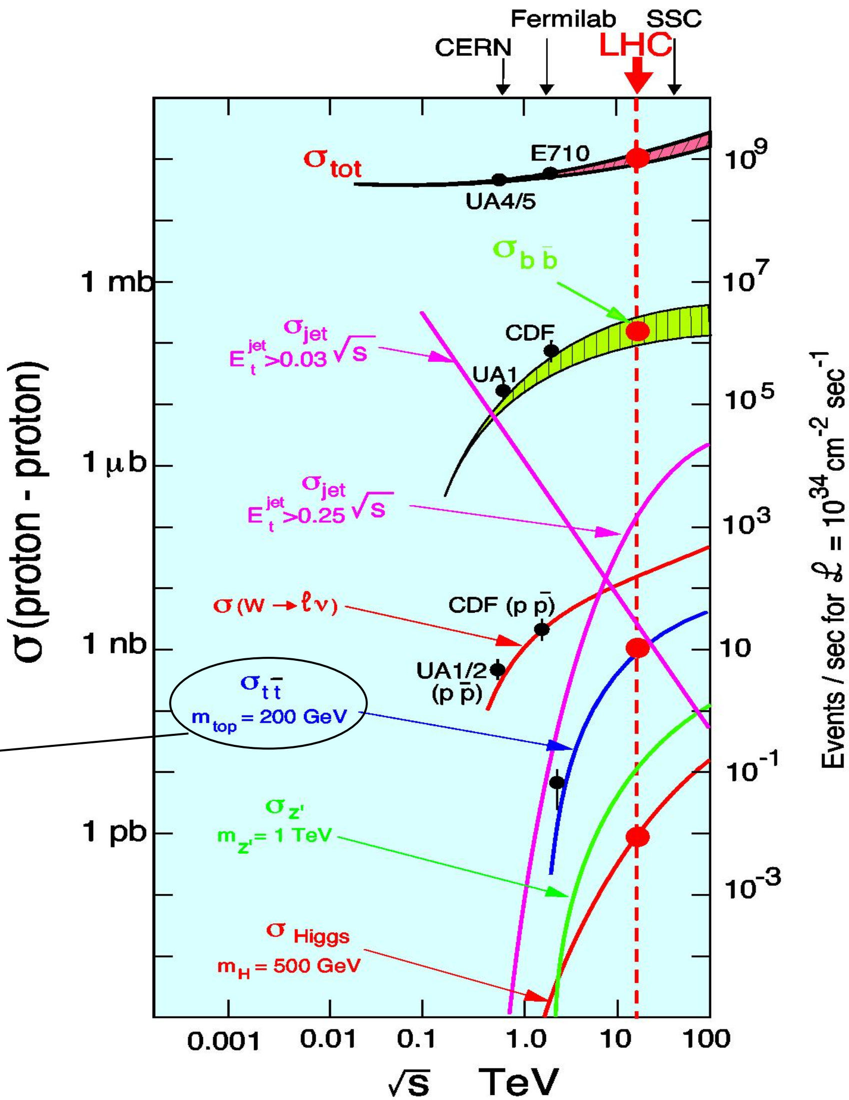


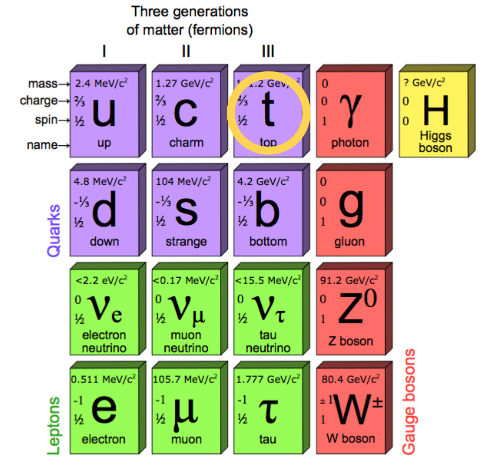
- Lepton Flavor Violation (LFV)
- Search for tau→ 3 muon decays
- Very rare process: BR~10^{-40}!
- Study in Ds and W decays



Top quark production

top quark





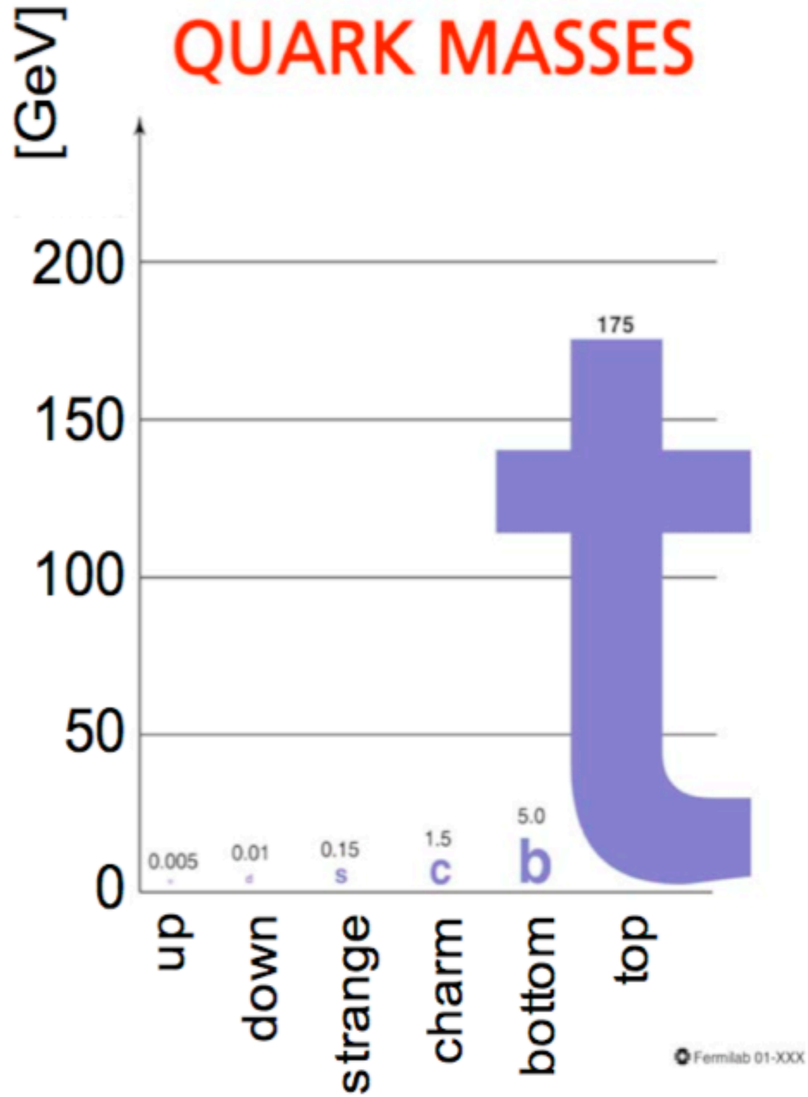
The top quark

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

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

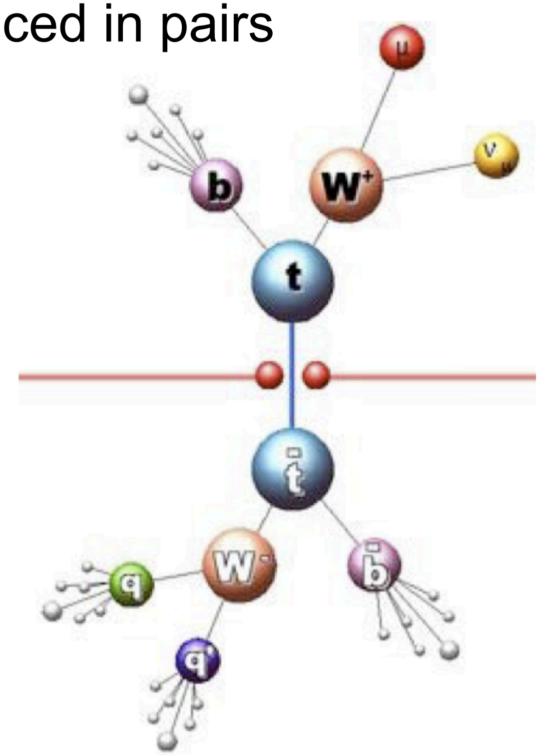
  - very short lifetime ⇒ bound states are not formed ⇒ opportunity to study a free quark

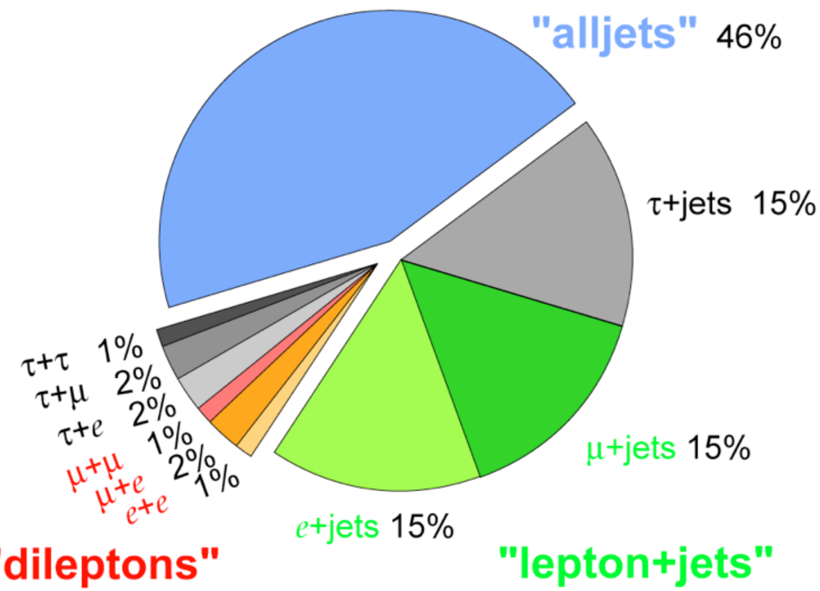
- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Measurements may provide insight into physics beyond SM



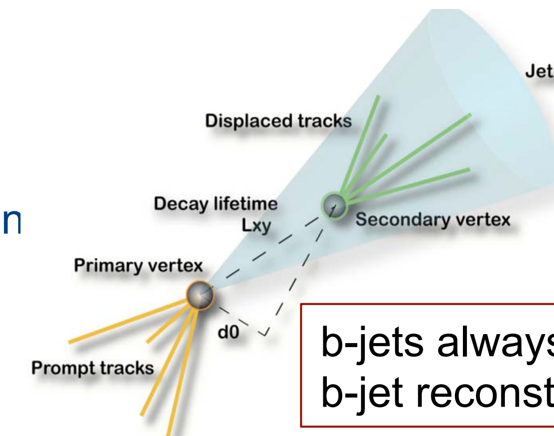
Top quark decays

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

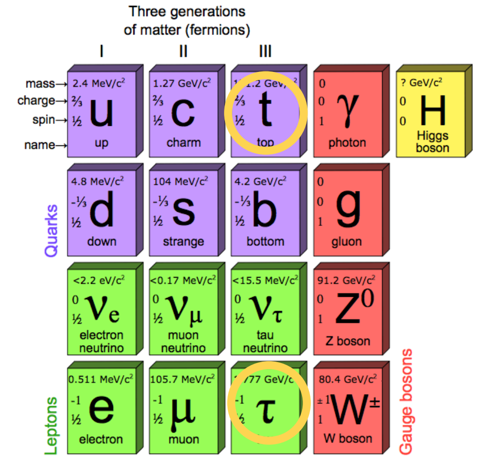


b-jets always present
b-jet reconstruction plays important role

Top quark and tau lepton

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

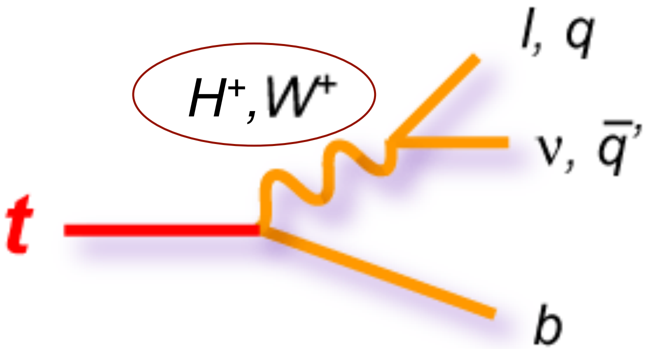
- cross section measurement including taus
- Includes only 3rd generation quarks/leptons

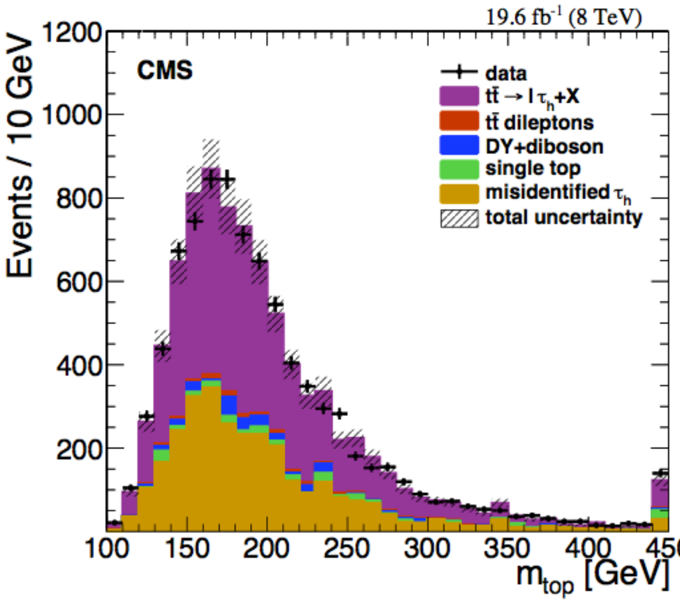


Channel	Signature	BR
Dilepton(e/μ)	*ee*,μμ,*e*μ + 2*b*-jets	4/81
Single lepton	*e*,μ + jets + 2*b*-jets	24/81
All-hadronic	jets + 2*b*-jets	36/81
Tau dilepton	*e*τ, μτ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81

→ BR~5%

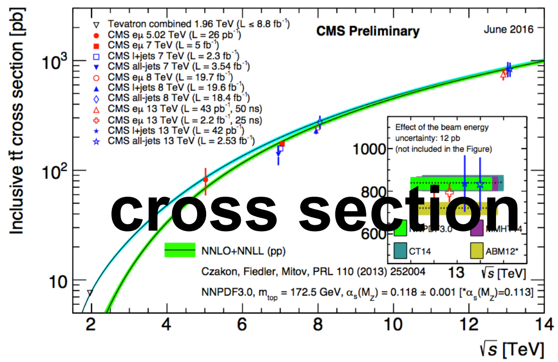
- Charged Higgs may alter coupling to W
  - Search for final states with taus

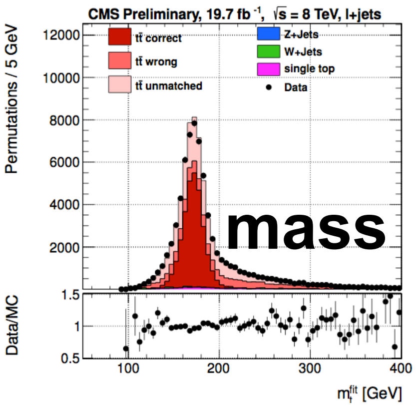


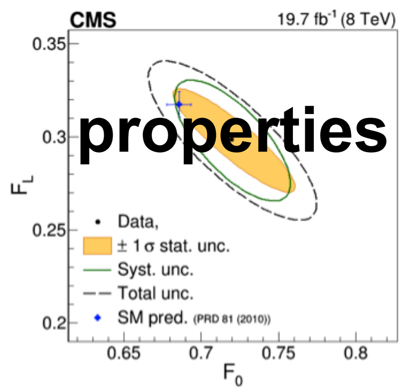


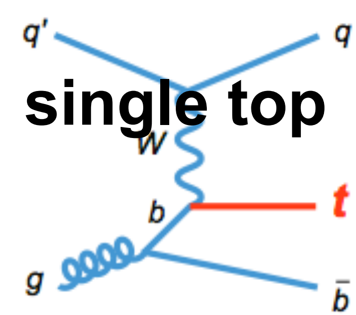
Top quarks and BSM

- 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?



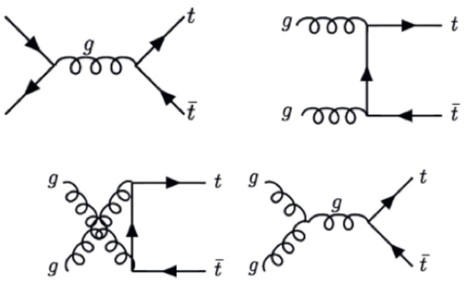






Cross sections vs √s

arXiv:1112.5675

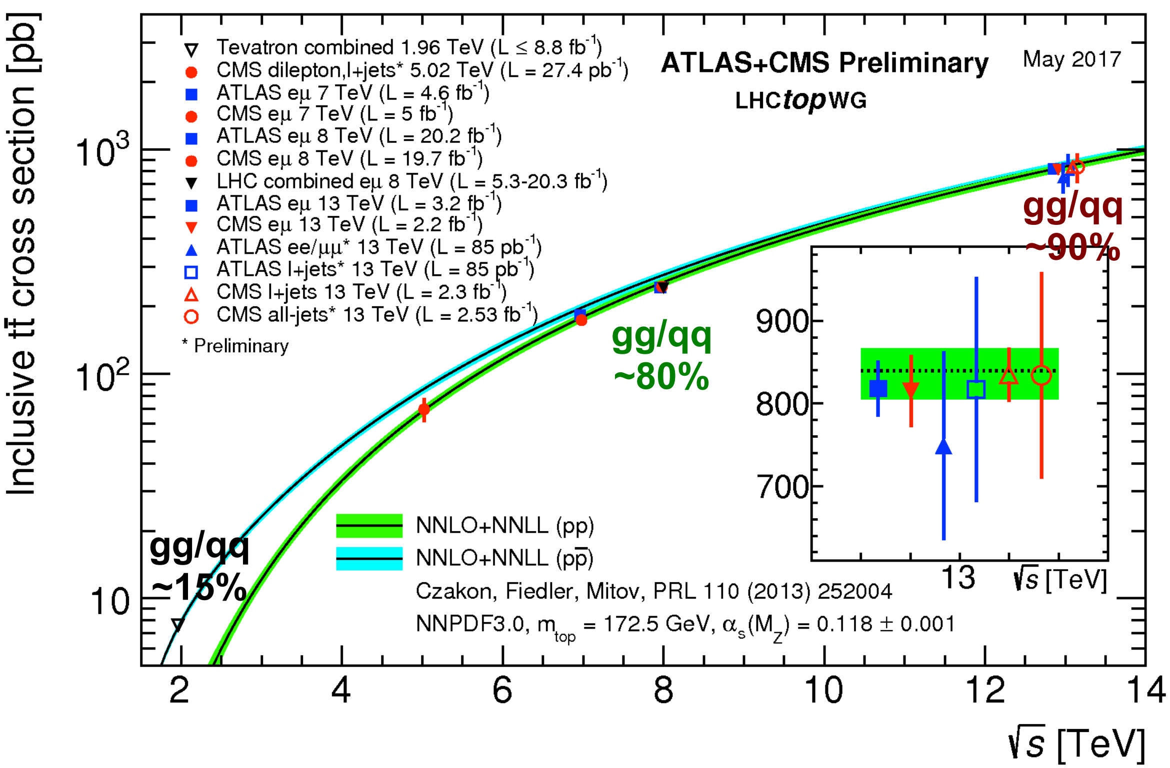


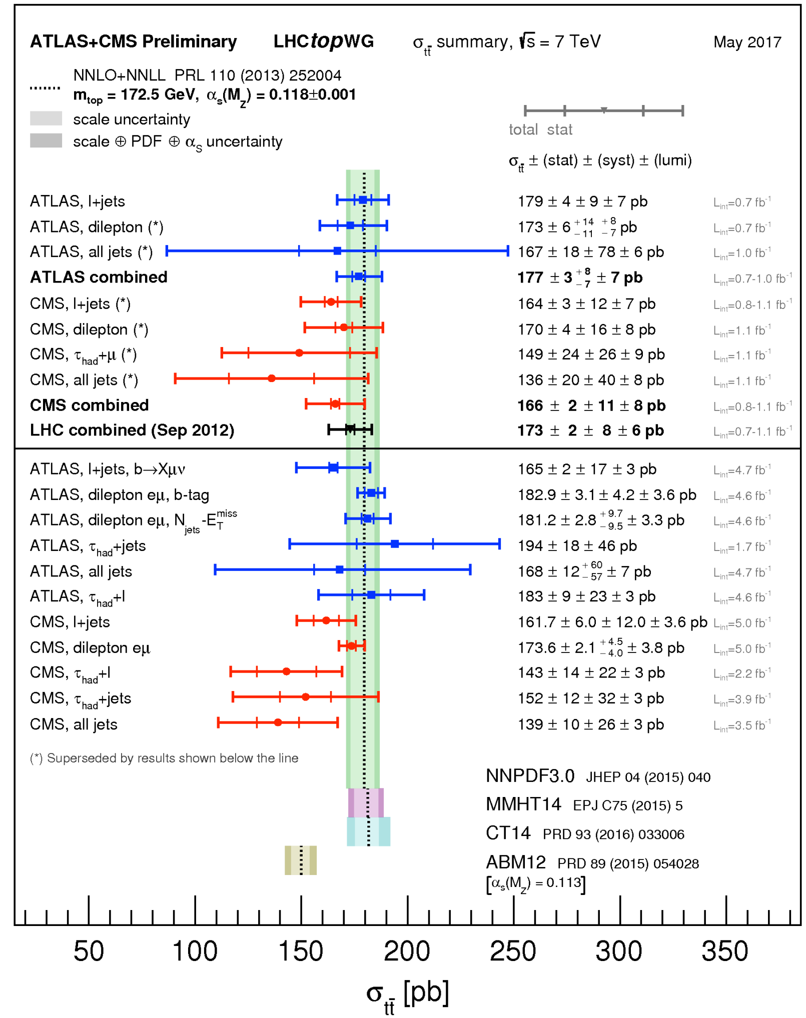
$$\sigma(7\ \mathrm{TeV}) = 177\ \mathrm{pb} \pm 7\%$$

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

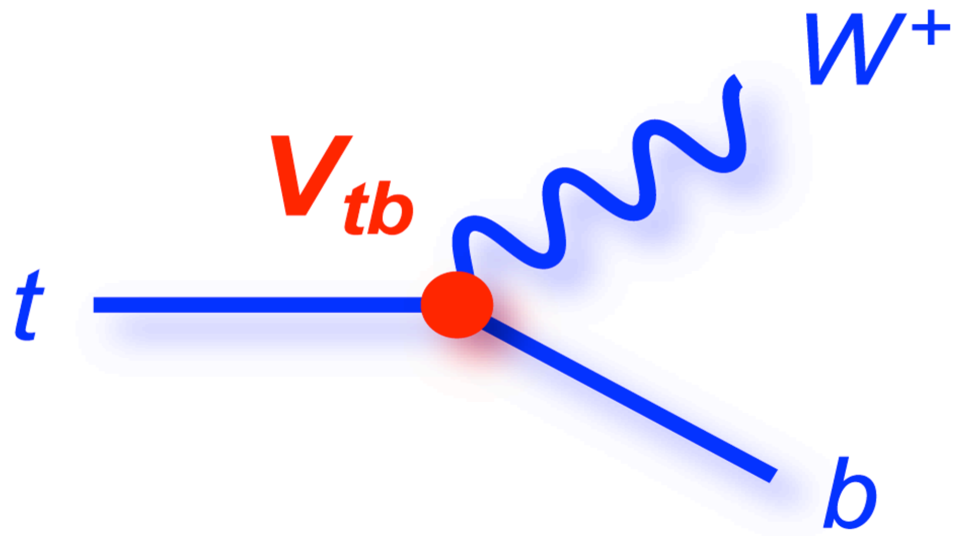
$$\sigma(13\ \mathrm{TeV}) = 832\ \mathrm{pb} \pm 5\%$$

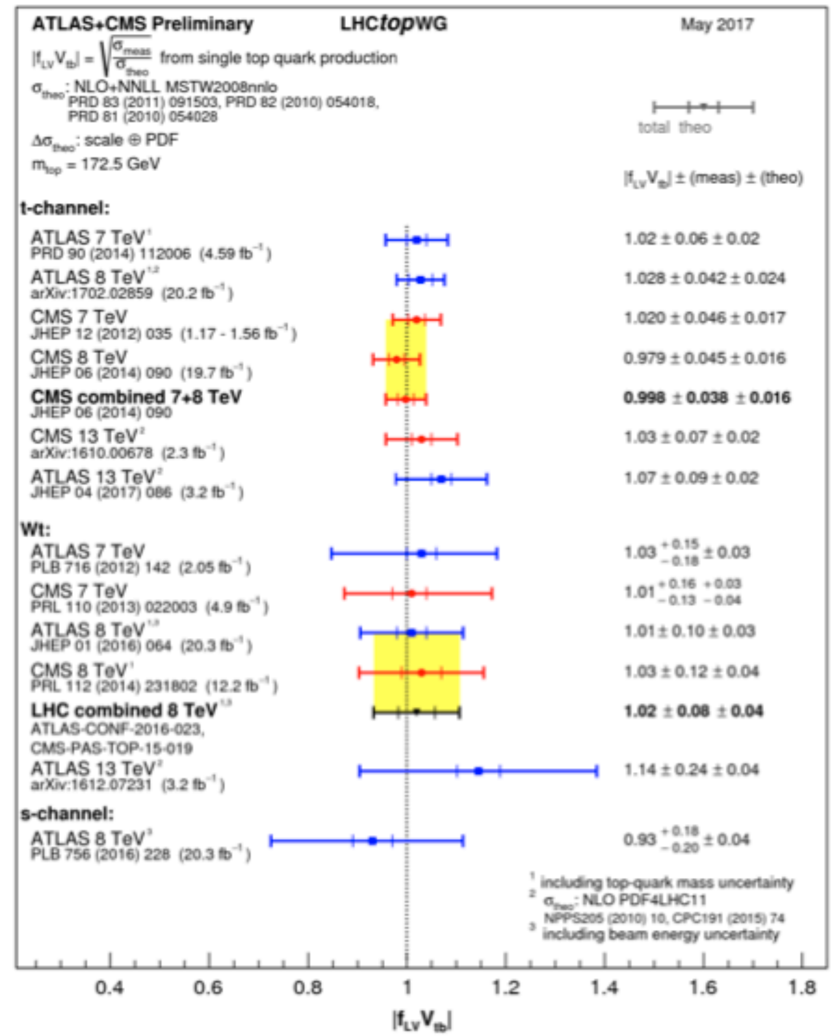
$$R_{13/8} = 3.28$$





How does a top quark decay?





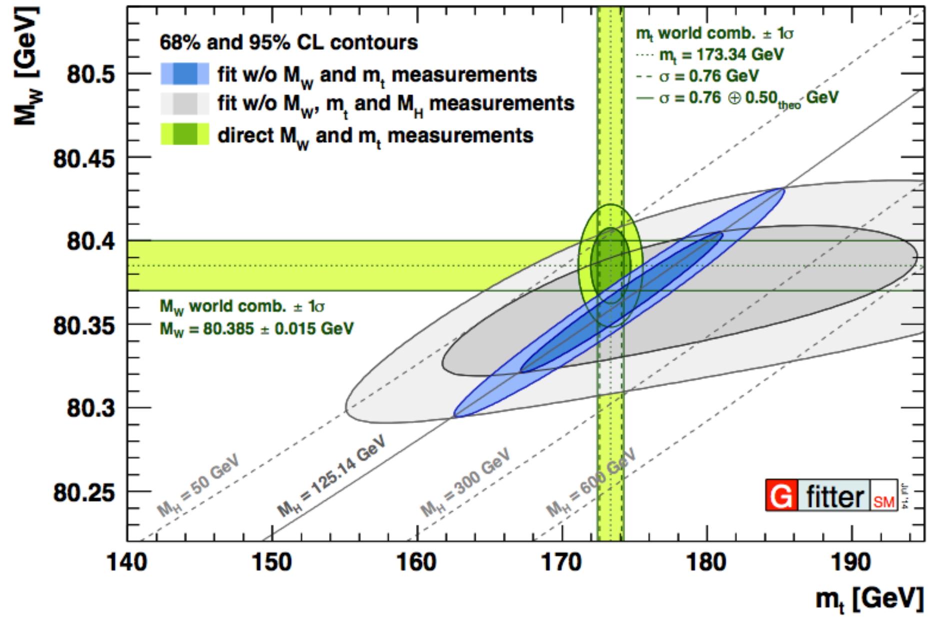
- almost always $t \to Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - decays $W \to l\nu$ ($l = e, \mu, \tau$), BR~1/9 per lepton
  - can decay $W \to qq$, BR~2/3

Top quark mass

- Top quark mass is a fundamental parameter of the SM

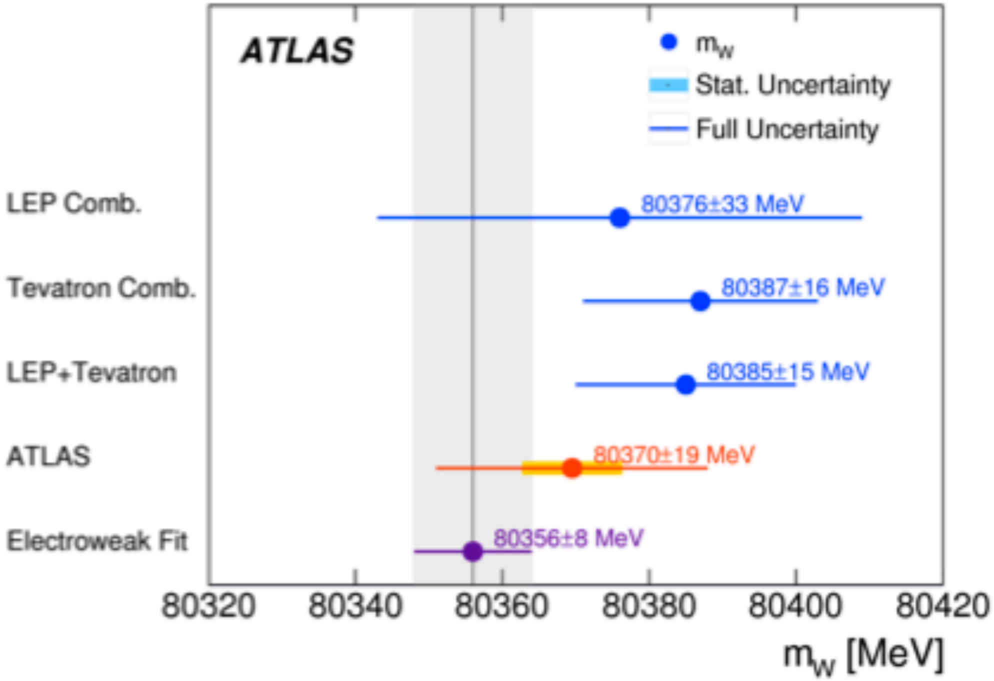
$\delta m_W \propto m_t^2$ $\delta m_W \propto \log m_h$

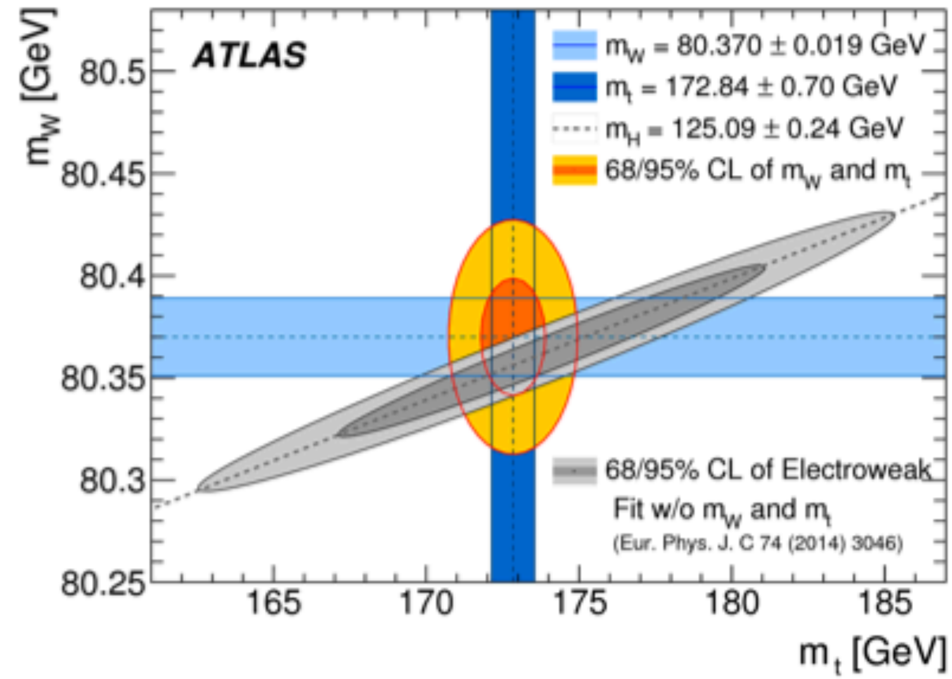
- Precise measurement needed for checking consistency of the SM



- 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



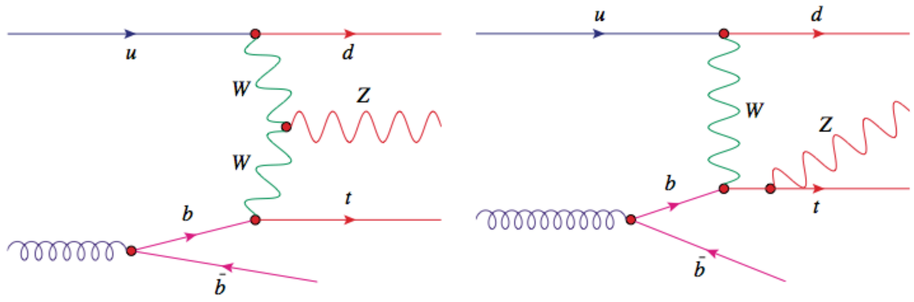


- First W mass measurement at the LHC
- Use low pileup data at 7 TeV
- Control of systematic uncertainties
- Uncertainties comparable to Tevatron results
- Expect future improvements

ttV (V=γ,Z,W)

CMS-TOP-17-005, ATLAS-2017-052

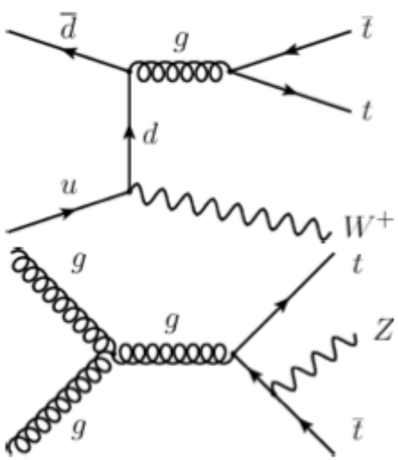
- Measurements will give access to EW couplings of the top

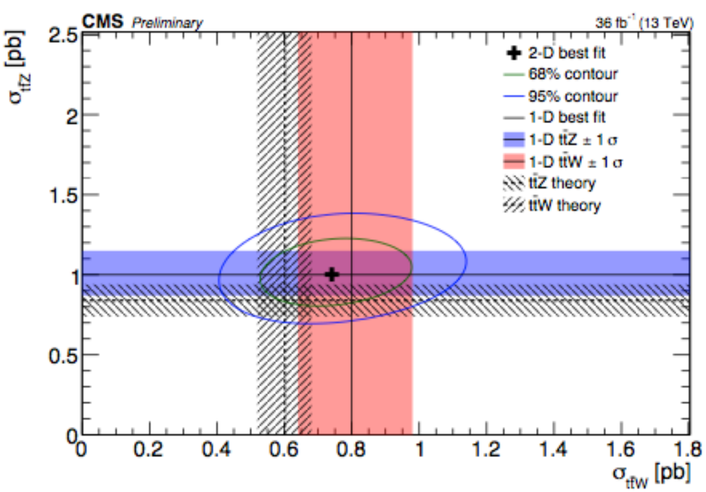


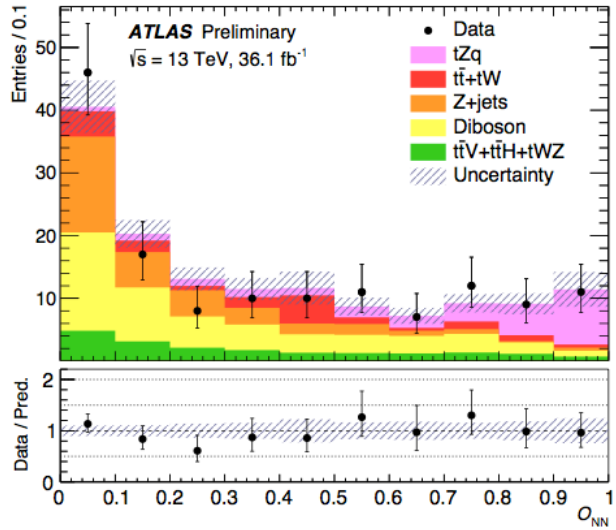
- Top+vector boson production
- tt+Z: measure ttZ coupling
- tt+W/Z: sensitive to BSM

⇒in agreement with SM

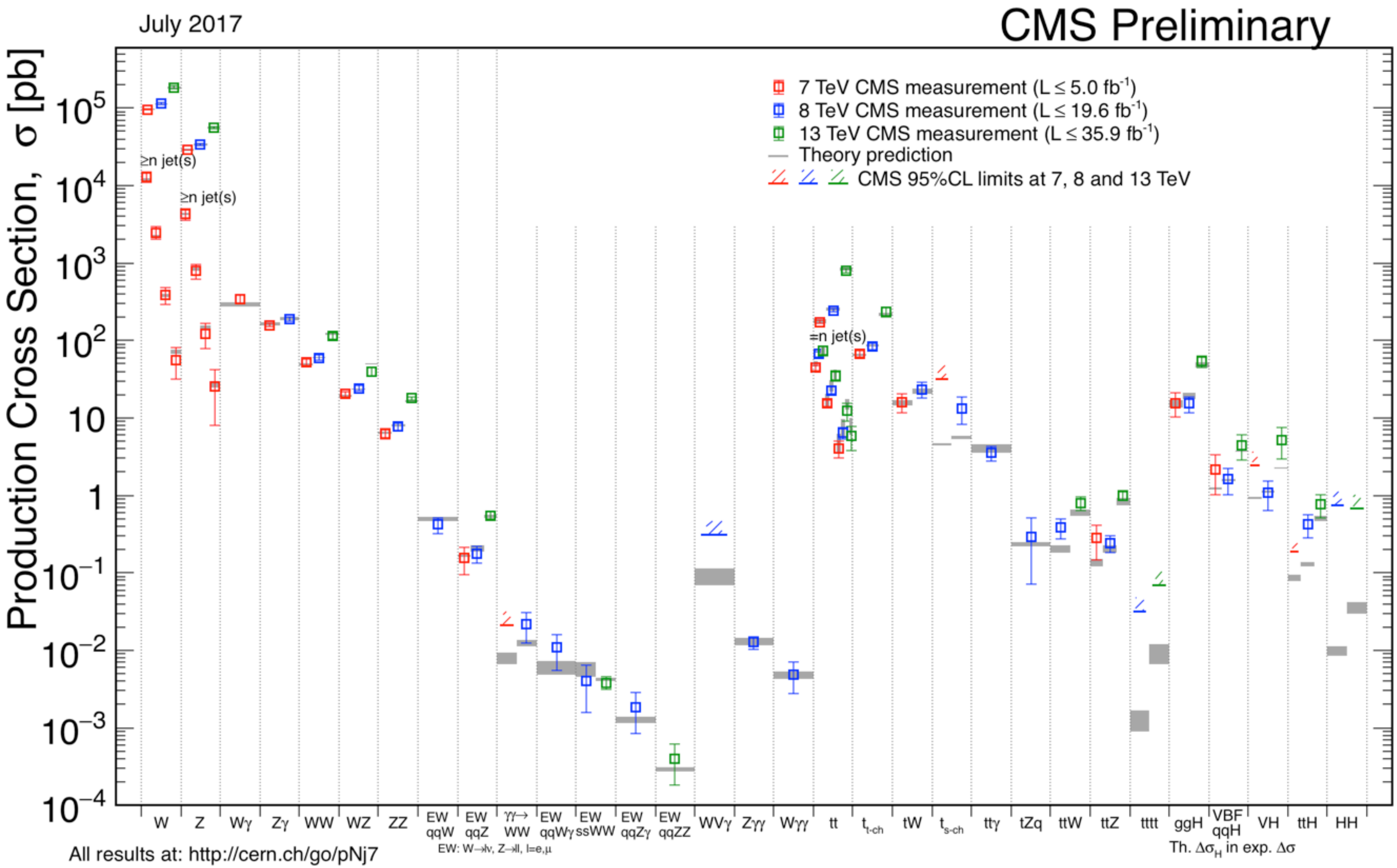
- tZq sensitive to WWZ triple gauge coupling and tZ coupling
- Multivariate technique used







SM measurements

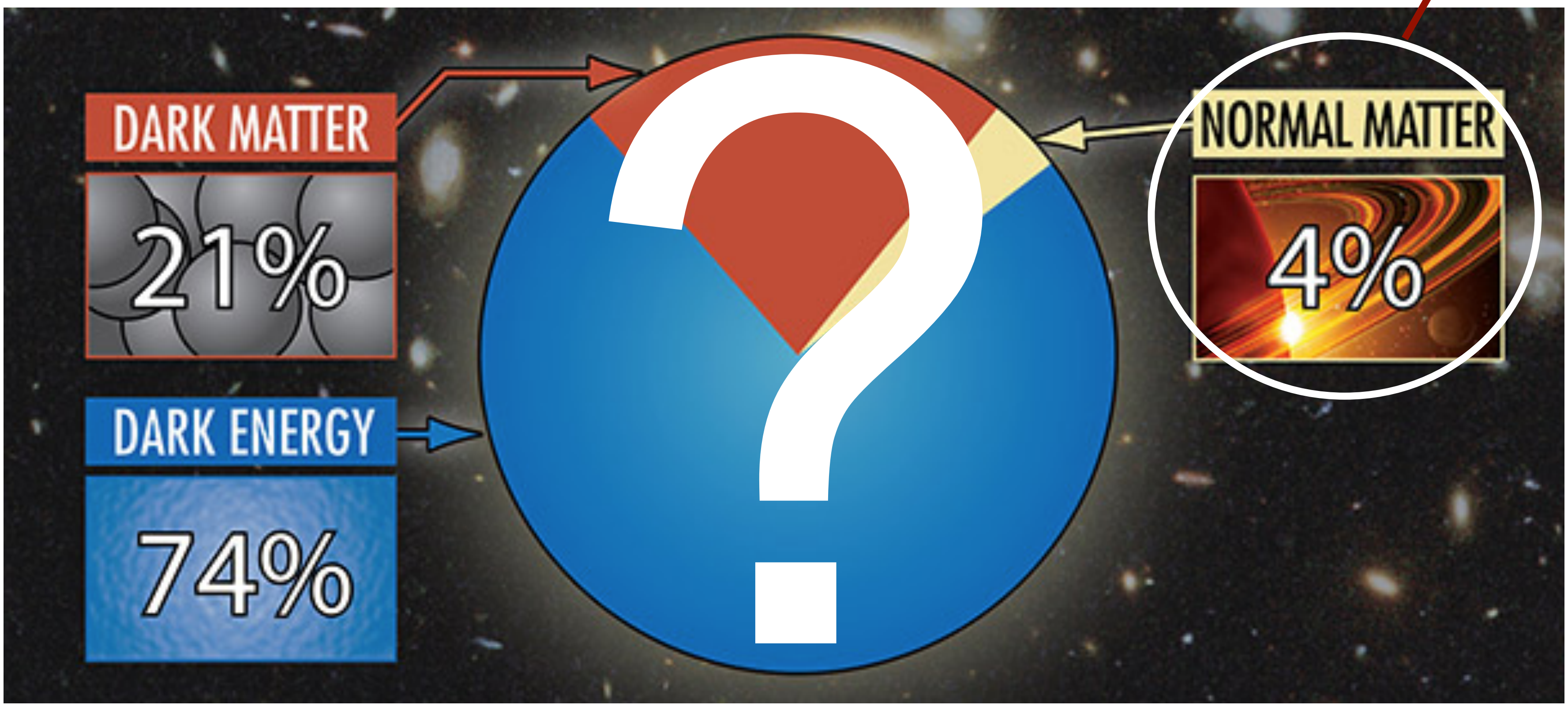


…each one of these measurements (or searches) is a thesis topic!

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