LHC physics

DESY summer student lecture
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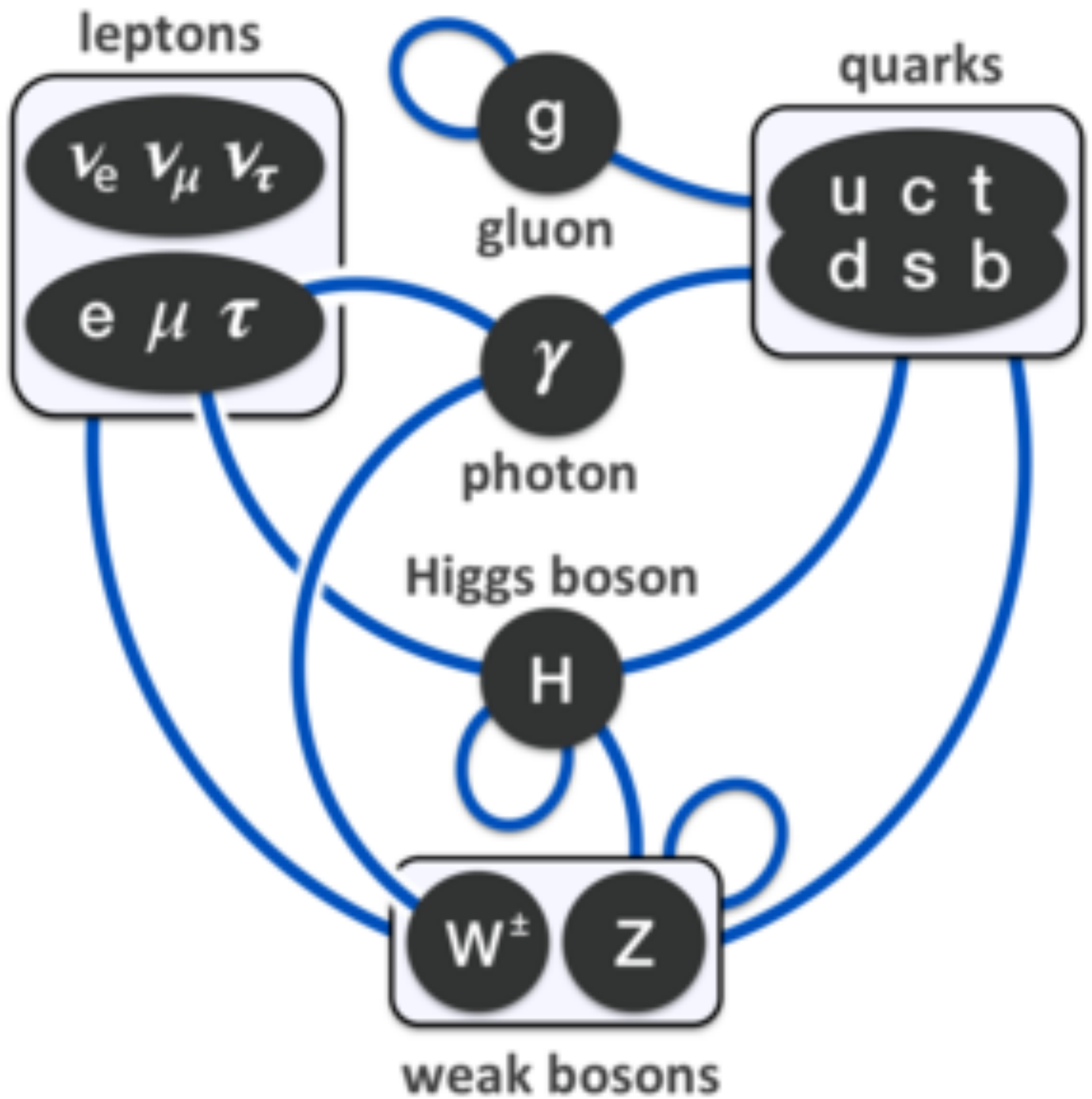
Overview of these lectures

- Intro
- Electroweak physics, top quark
- Higgs boson
- Searches for physics beyond the Standard Model

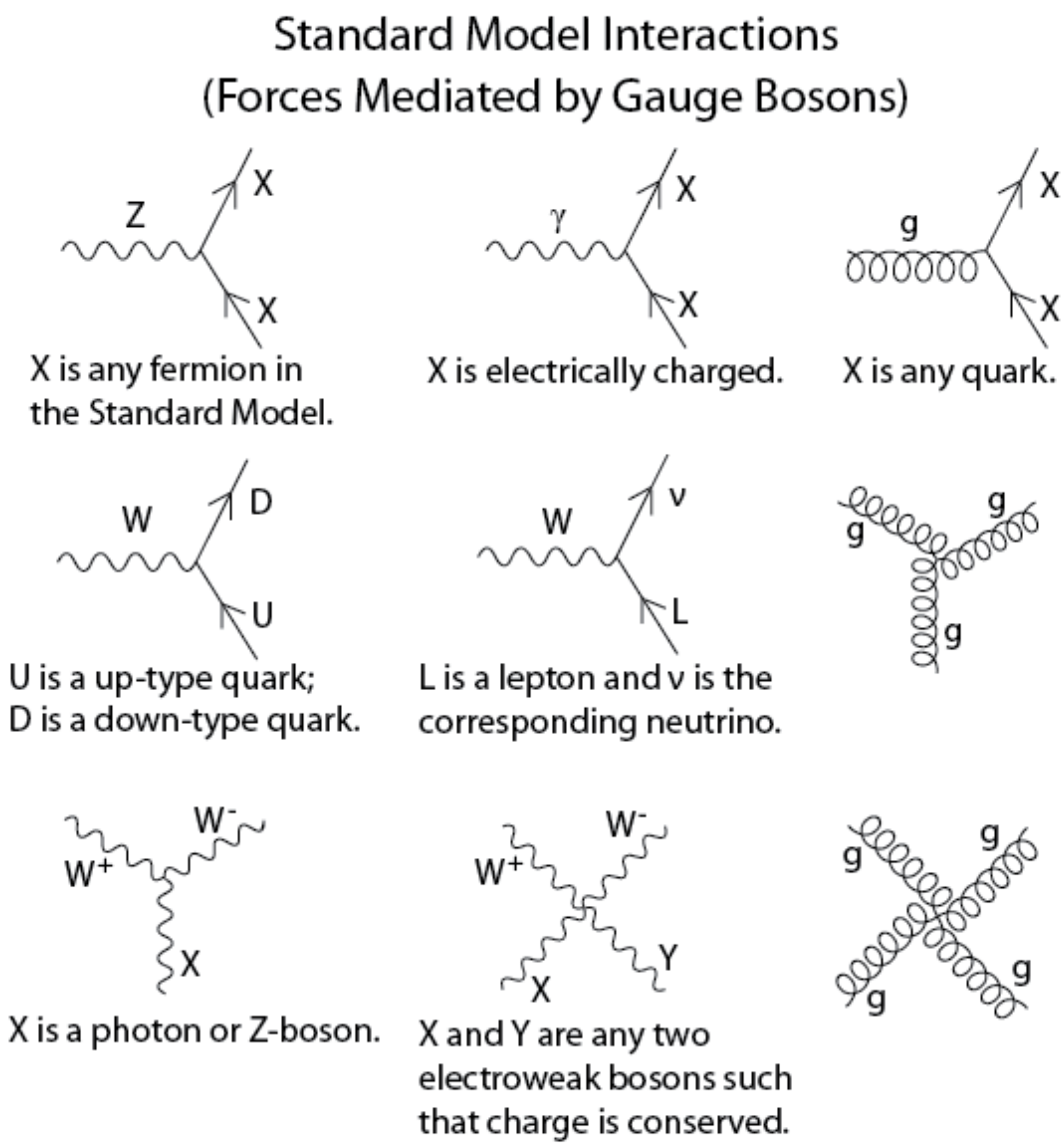
First goal of LHC: Measure and test the SM

$$\begin{aligned}\mathcal{L} = & -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\Psi + h.c. \\ & + \Psi_i y_{ij} \Psi_j \Phi + h.c. \\ & + |D_\mu \Phi|^2 - V(\Phi)\end{aligned}$$

Particles and interactions of the SM



In the Feynman picture



Goal: Measure these interactions and compare to the SM predictions!

The SM free parameters

9 fermion masses (+ 3 m_ν)

3 CKM mixing angles + 1 phase (+3+1 for m_ν != 0)

1 electromagnetic coupling constant $\boldsymbol{\alpha}$

1 strong coupling constant $\boldsymbol{\alpha}_S$

1 weak coupling constant G_F

1 Z mass

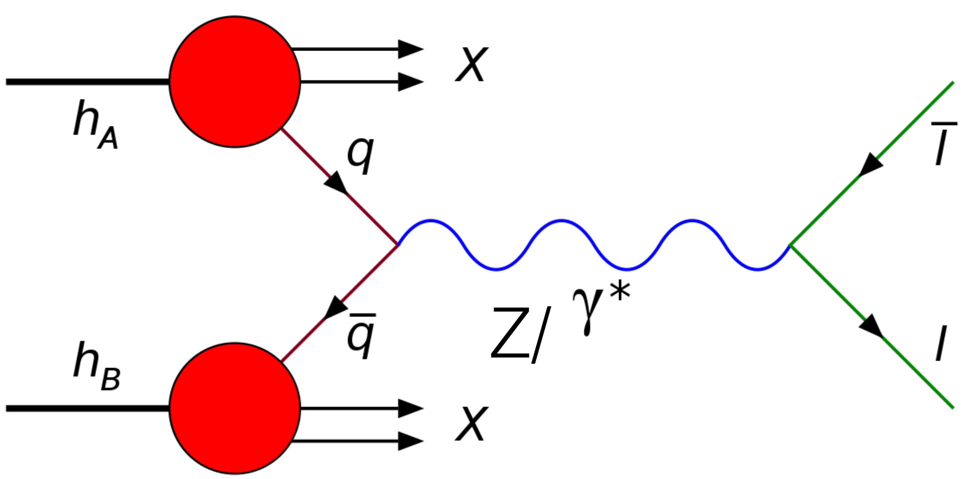
1 Higgs mass

Goal:

- **Measure them**
- **Measure redundant parameters and test the SM relations between them by doing a consistency check (see end of this lecture)**

First step at the LHC: Rediscover the W/Z bosons

- protons collide at higher energies than ever before
  - are the SM predictions valid at these high energies?



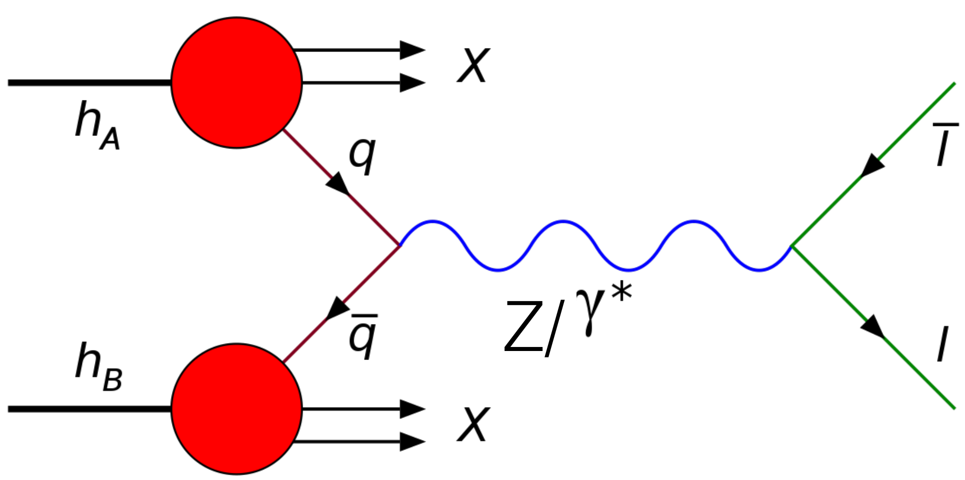
- check if the detectors are working properly

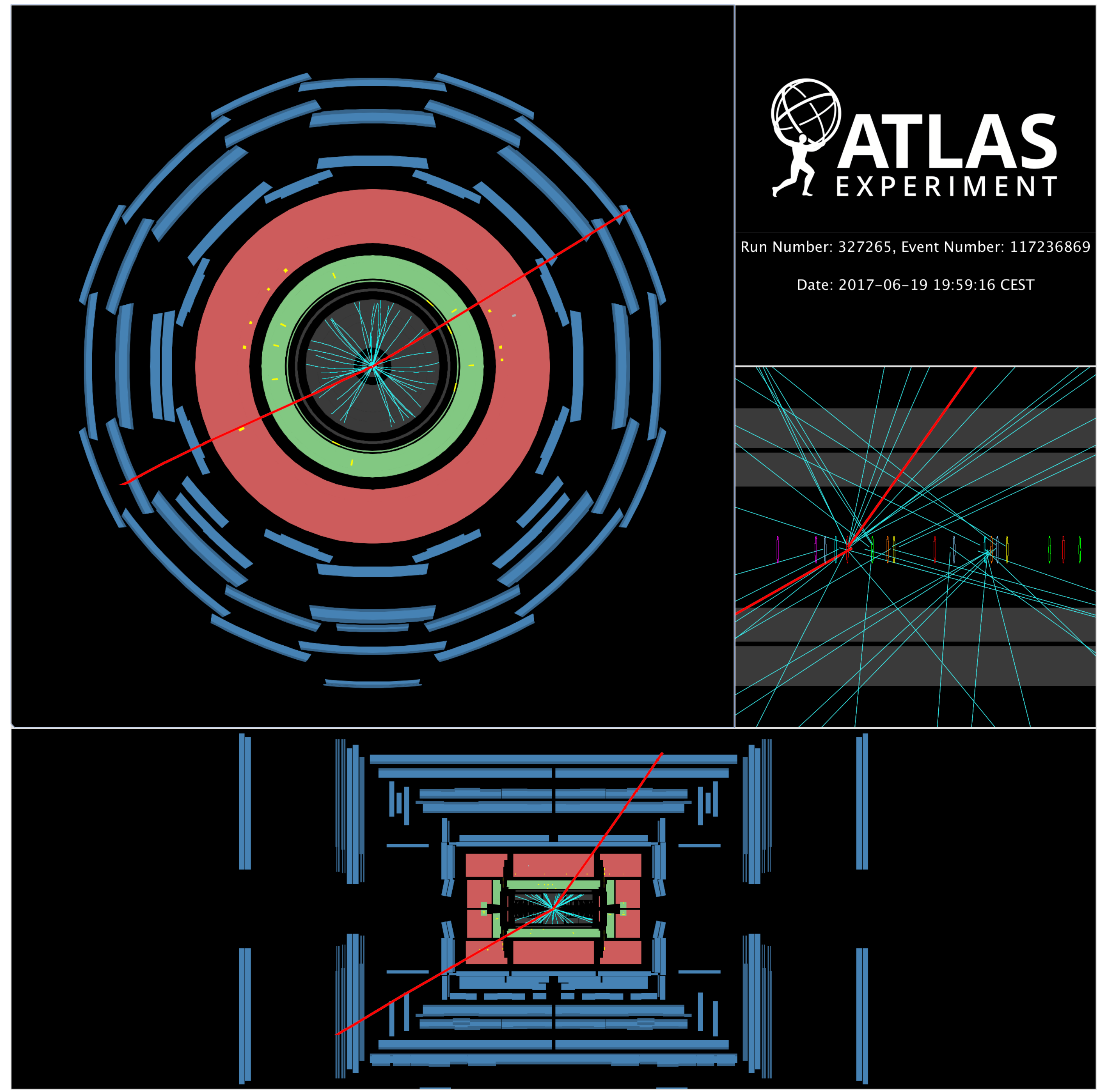
- once re-discovered, can use the known particles as standard candles, for calibrations

Afterwards go beyond previous measurements at Tevatron/LEP
- test processes with smaller and smaller XS
- in many cases: improve the precision

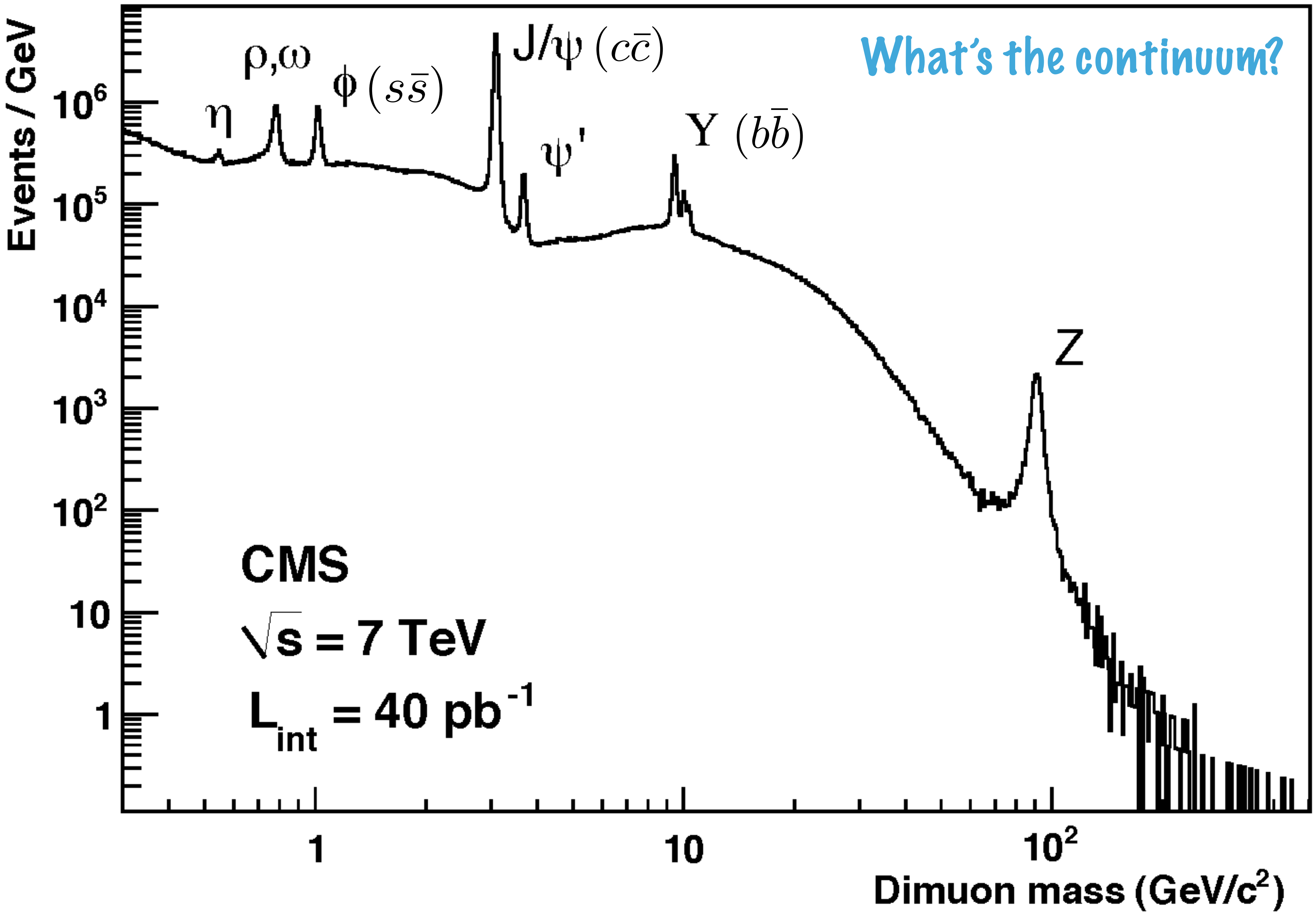
Z boson measurement

Filter collisions to find events with 2 leptons (electrons and muons easiest)



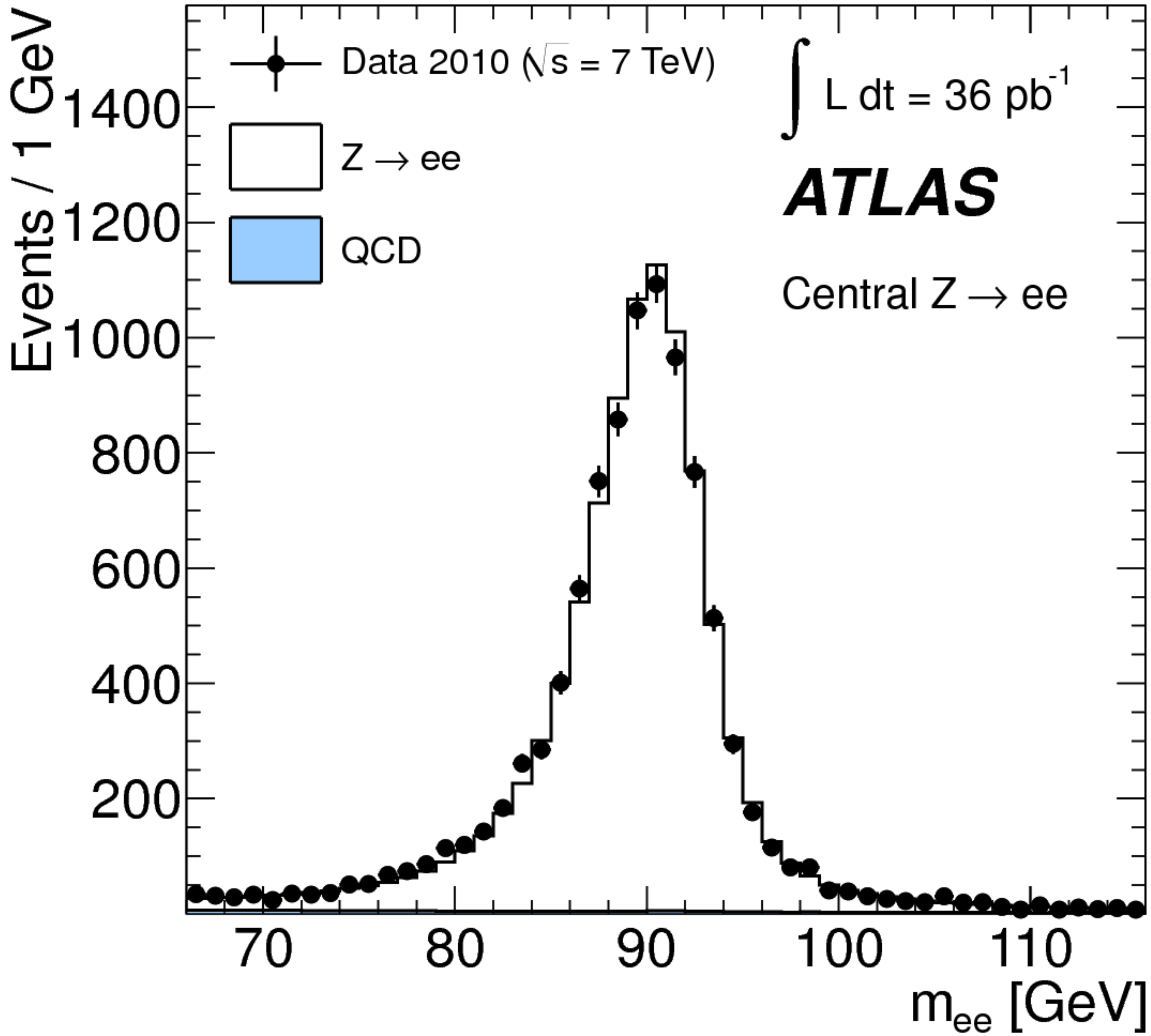


Di-muon spectrum



Z boson measurement

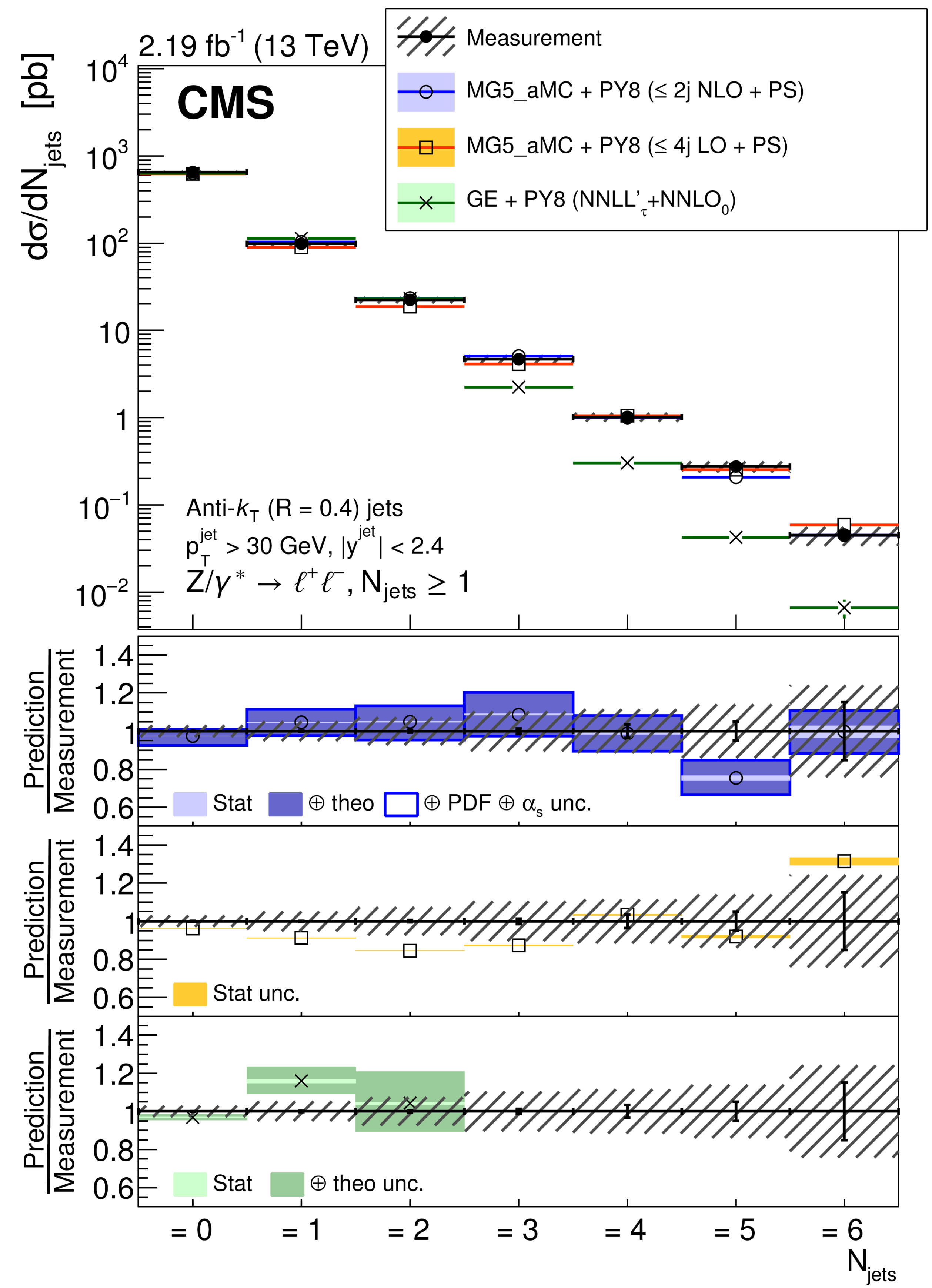
…and comparison to simulation (Pythia, normalized to NNLO)



Signal extraction: could just count events in data, or do template fit

Z boson measurement

$$\sigma = \frac{N}{L * \epsilon * A * B}$$



- Z+jets: test of QCD predictions

- Other things one can use Z cross sections for:
  - measurement of Weinberg angle through asymmetry
  - lepton universality checks
  - PDF constraints
  - important background in many searches

Z boson as standard candle

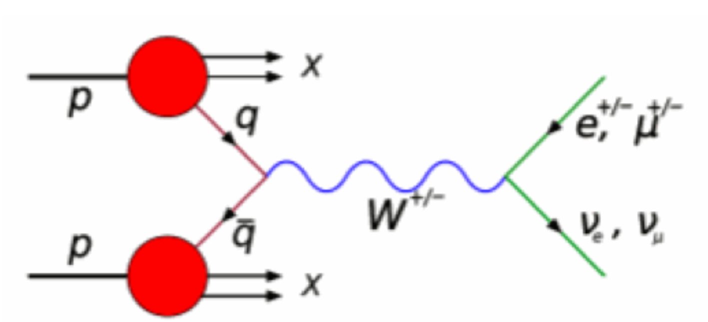
Energy/momentum calibration

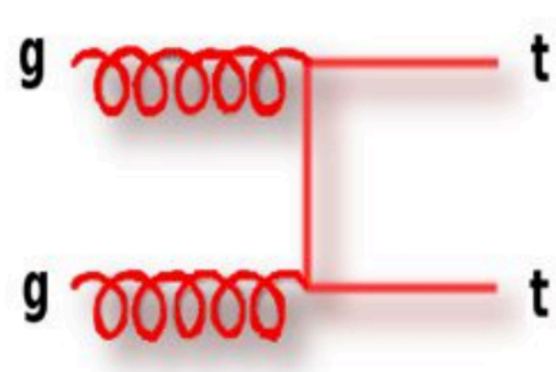
- adjust the position of the Z peak until it corresponds to the value we expect
=> done by adjusting the energy/momentum scale

Lepton efficiency measurements

- need clean sample of leptons to measure reconstruction/identification/isolation/trigger efficiencies
- "Tag and Probe"

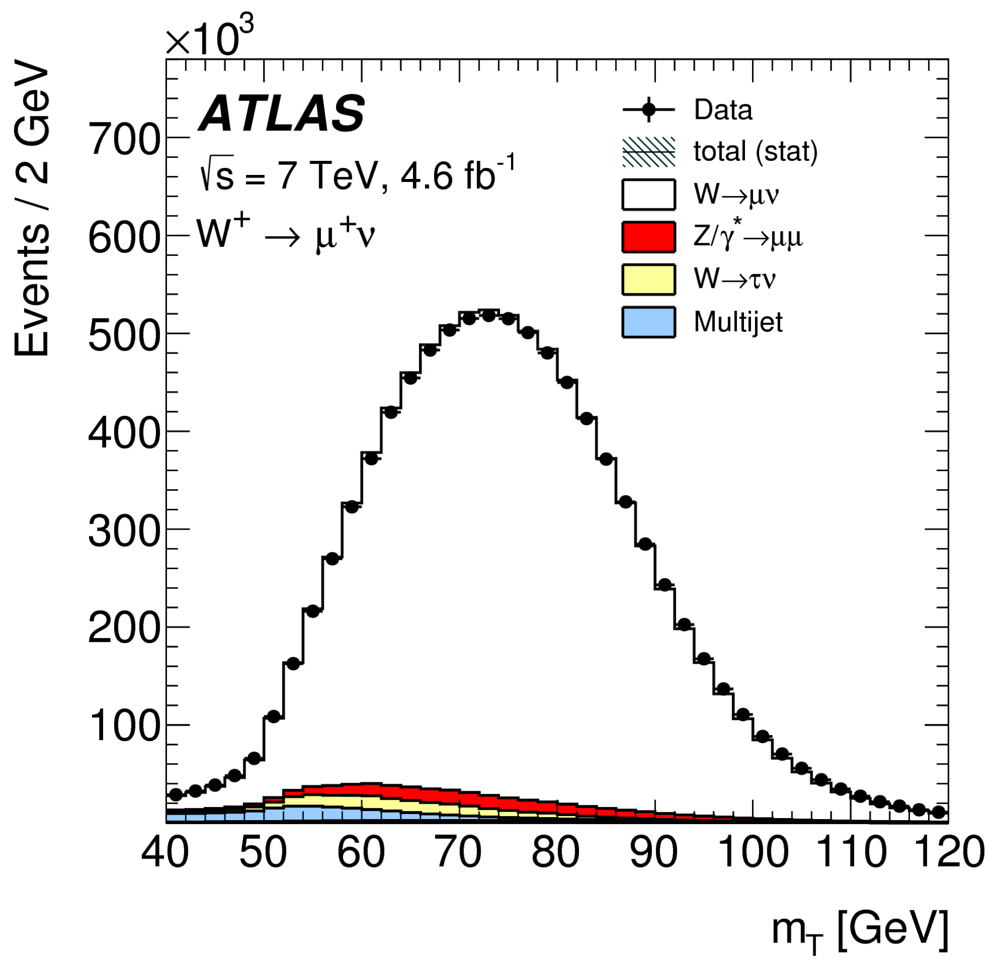
Some other standard candles are the dilepton resonances, plus:



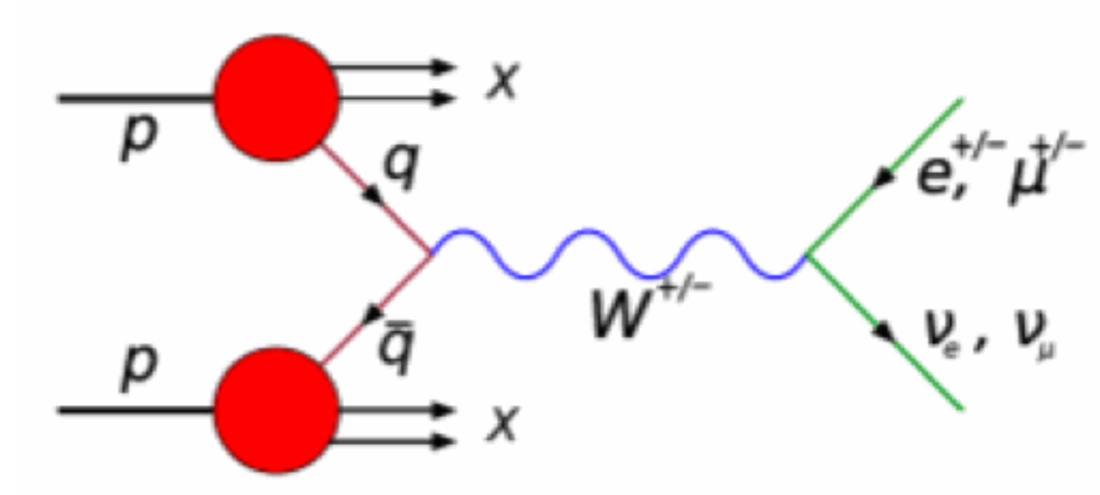


W bosons

- charged lepton and neutrino (missing transverse momentum)



$$m_T = \sqrt{2p_T^\ell p_T^{miss}(1 - \cos\Delta\phi)}$$



Backgrounds

Z->ll with one lost lepton

- from simulated samples

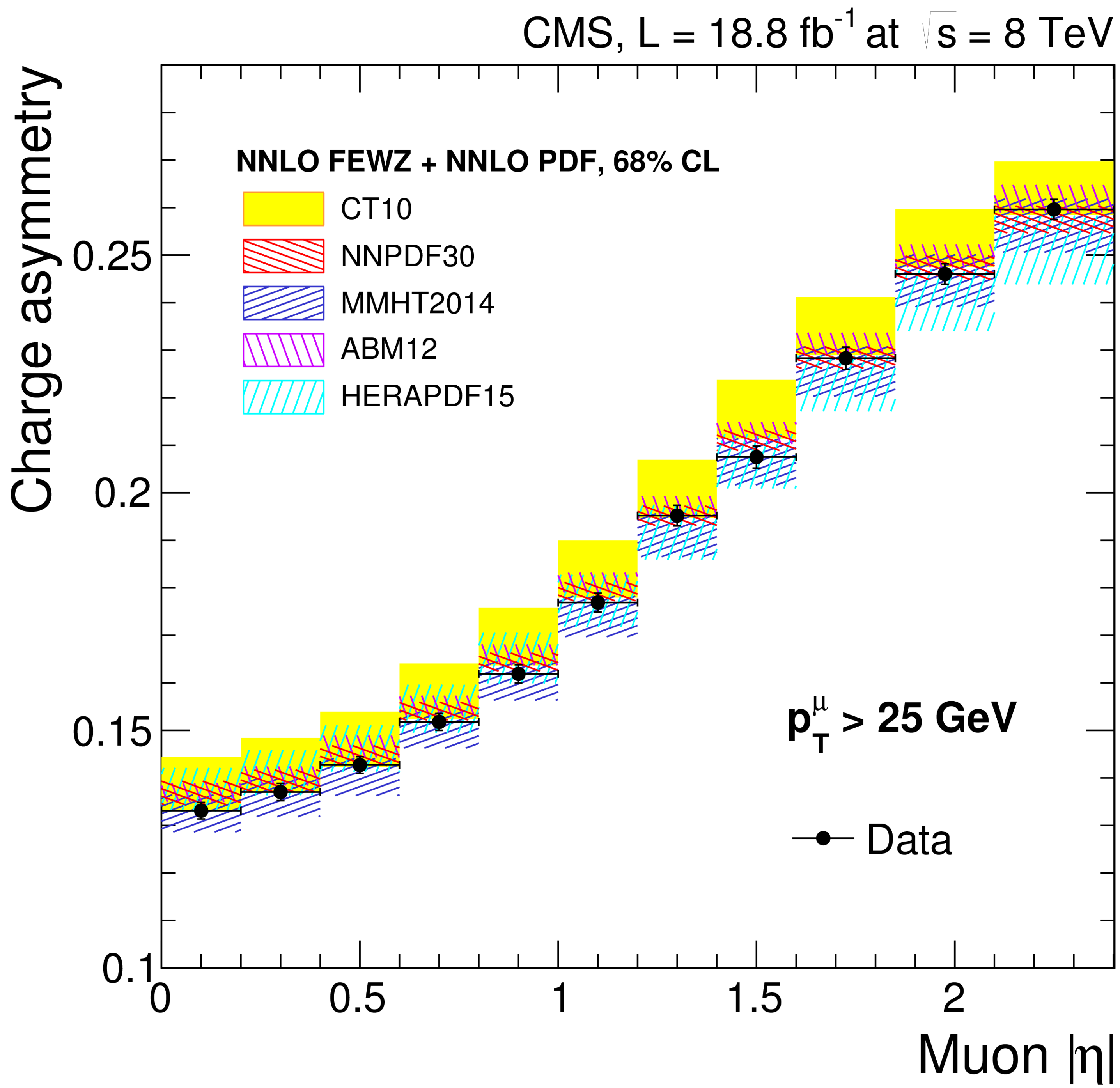
QCD: Dijets, with one jet misidentified as a lepton

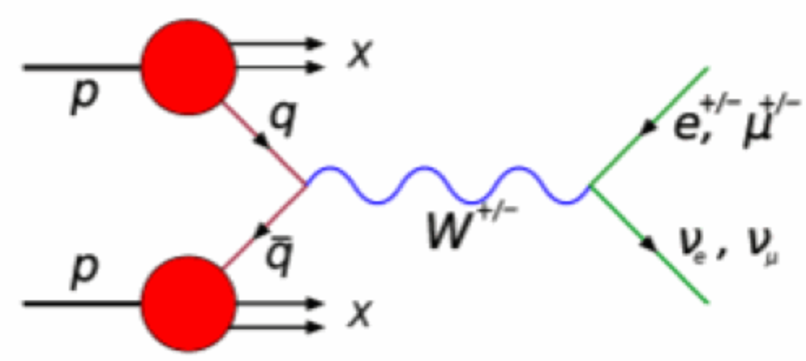
- from data control region with transfer factors

Measured XS [pb]

$10720 \pm 3\,(\mathrm{stat}) \pm 60\,(\mathrm{syst}) \pm 190\,(\mathrm{lumi}) \pm 130\,(\mathrm{acc})$

W+ vs W- charge asymmetry

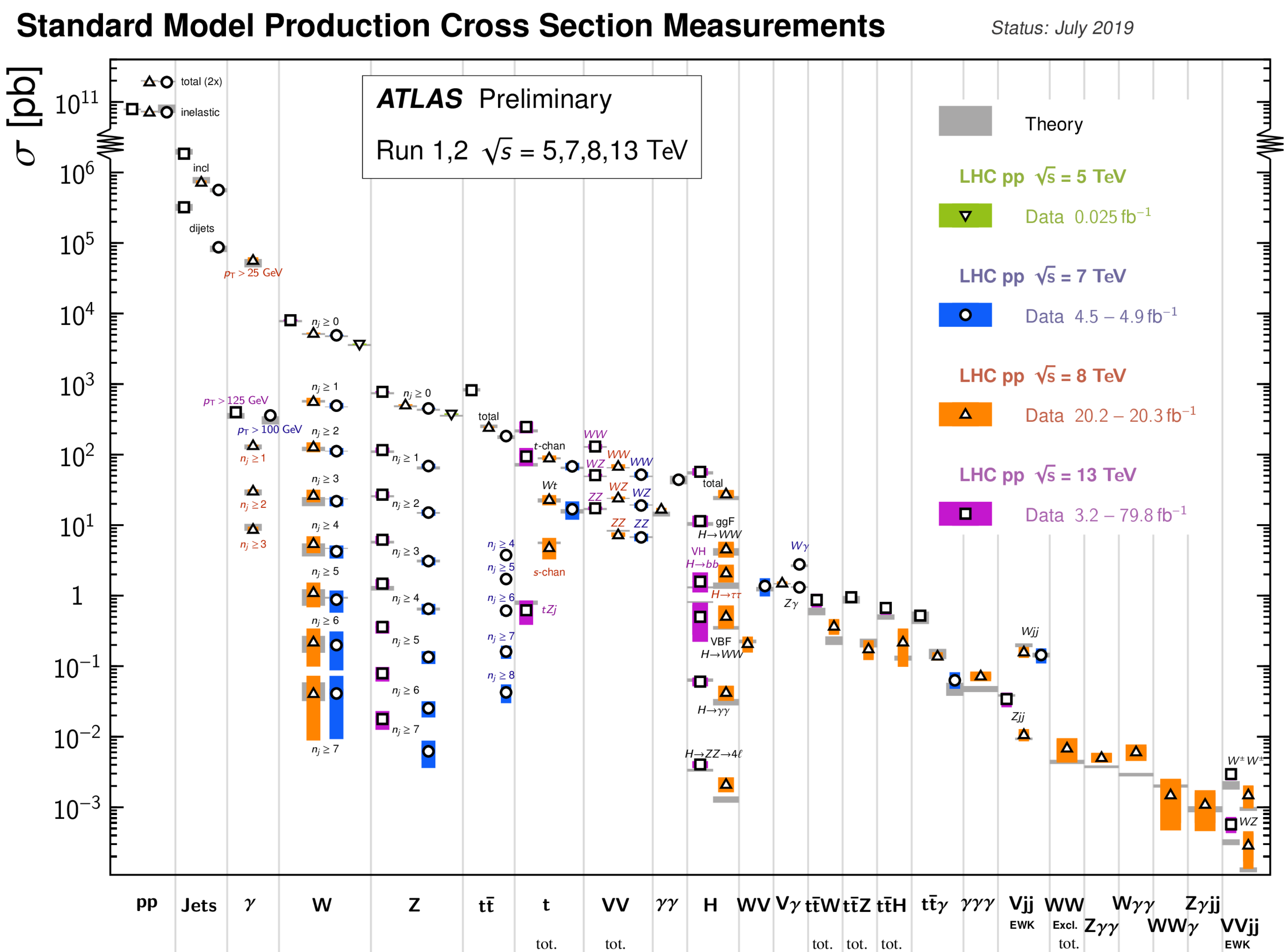




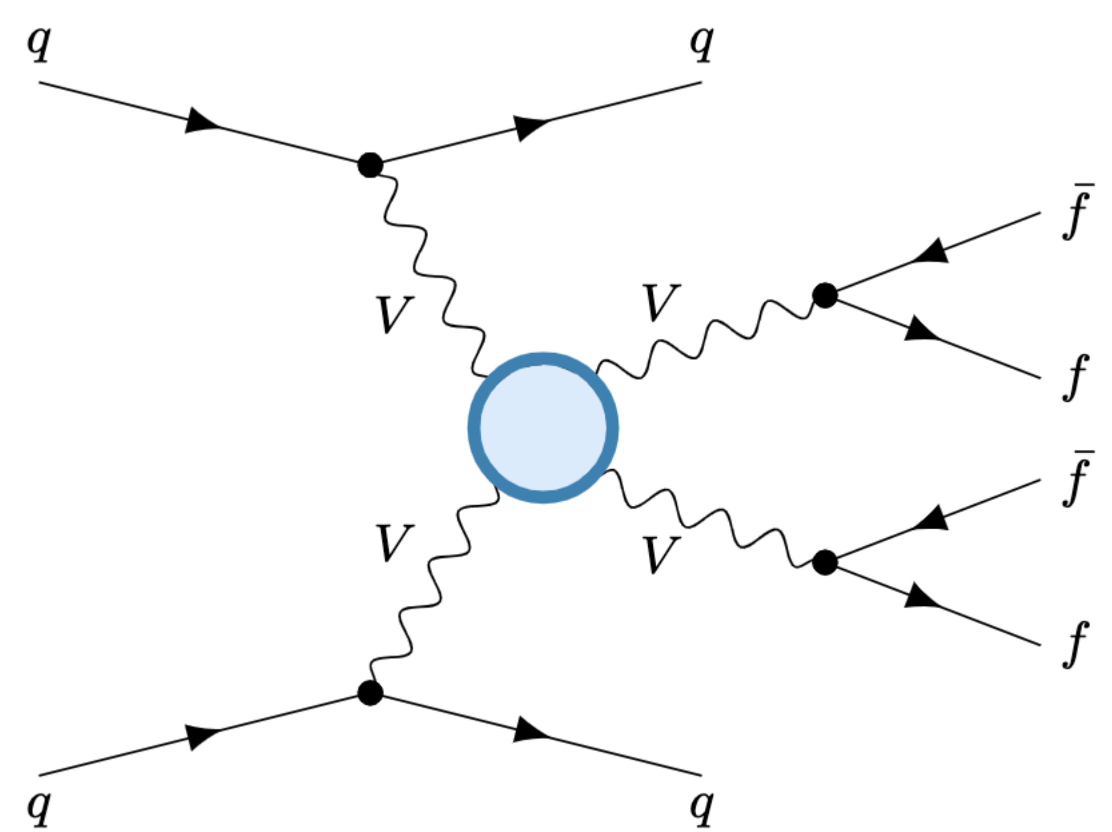
$$\mathcal{A}(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-},$$

Measurement can help to constrain PDFs!

Going to rarer and rarer processes - LHC discoveries

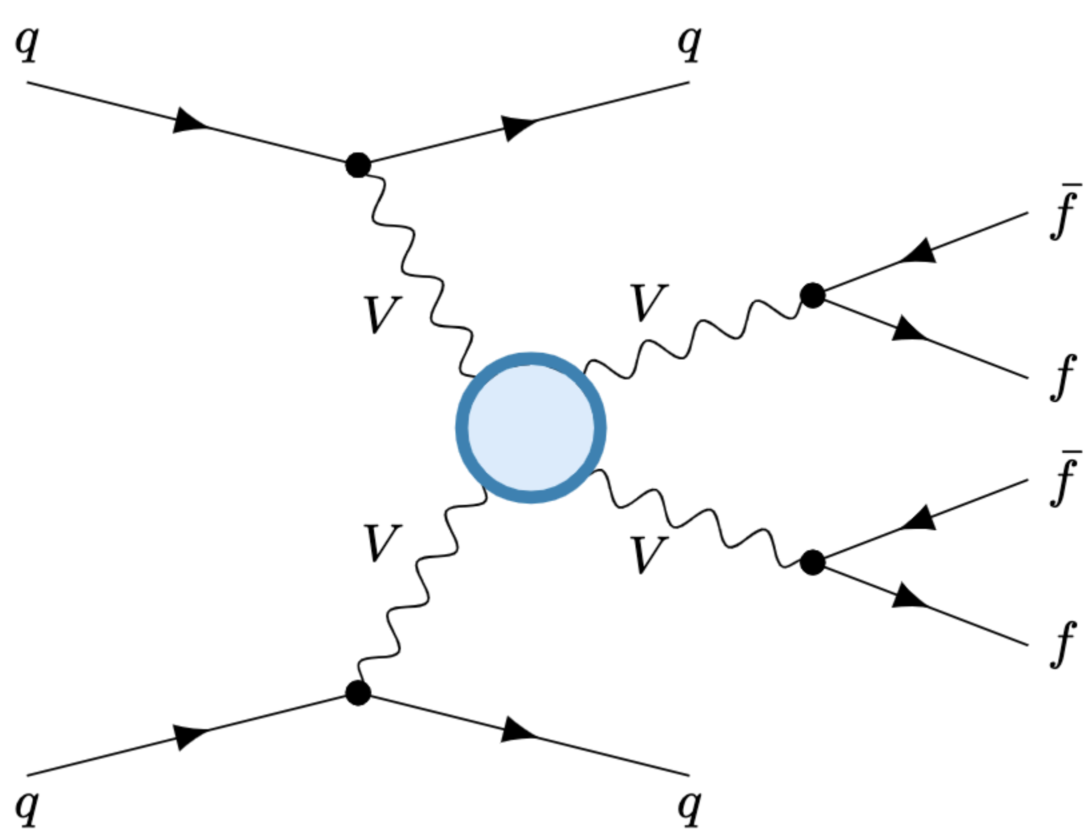


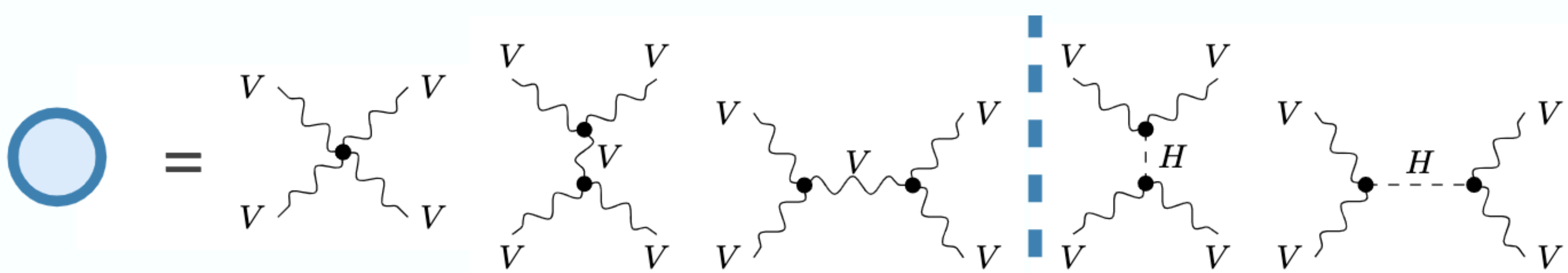
Vector boson scattering



V = W or Z bosons

Vector boson scattering

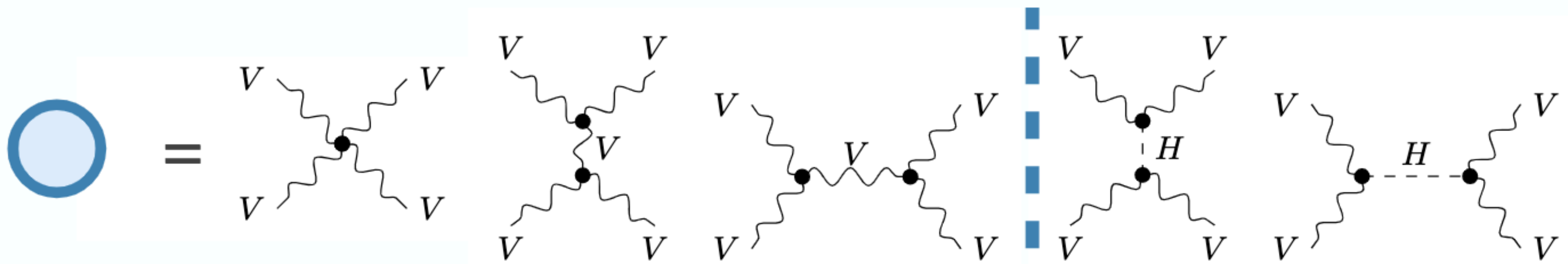




gauge structure of the Standard Model

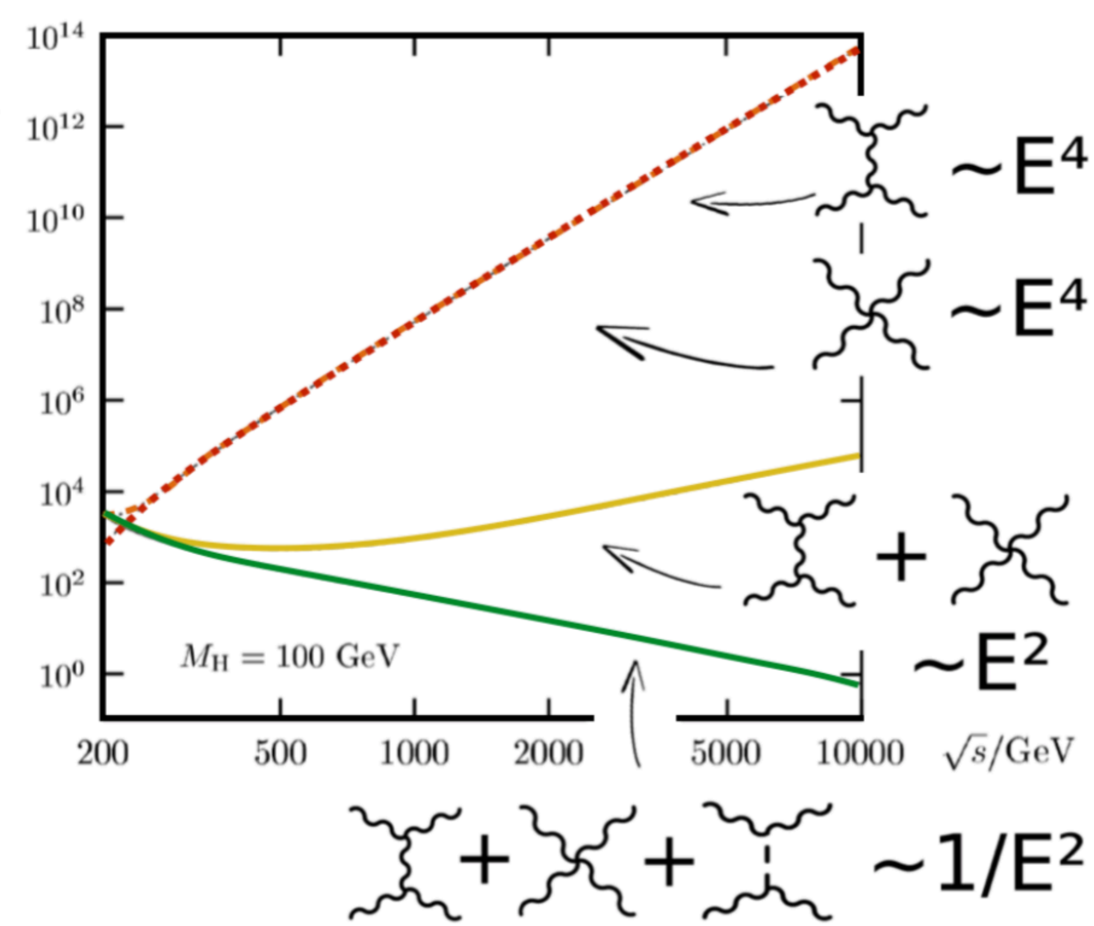
electroweak symmetry breaking

Why is vector boson scattering exciting

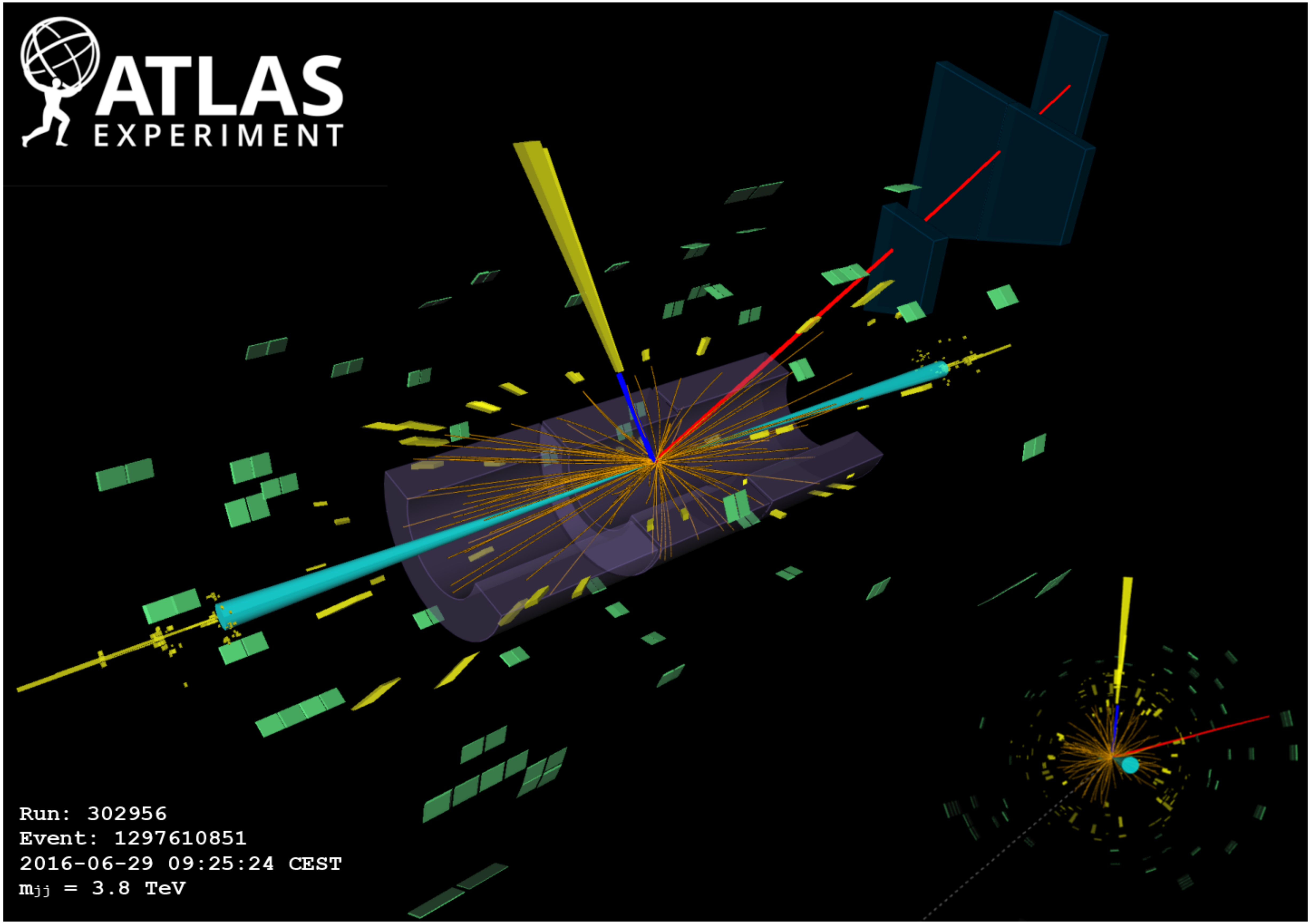


gauge structure of the Standard Model | electroweak symmetry breaking

Cross-section for longitudinal $W_L^+W_L^- \rightarrow W_L^+W_L^-$ scattering: [Denner, Hahn, 1997]



Vector boson scattering - WW event display



Electroweak production of same sign WW

Topological selection cuts (to reject backgrounds)

2 jets with large separation, large invariant mass

2 leptons, same charge

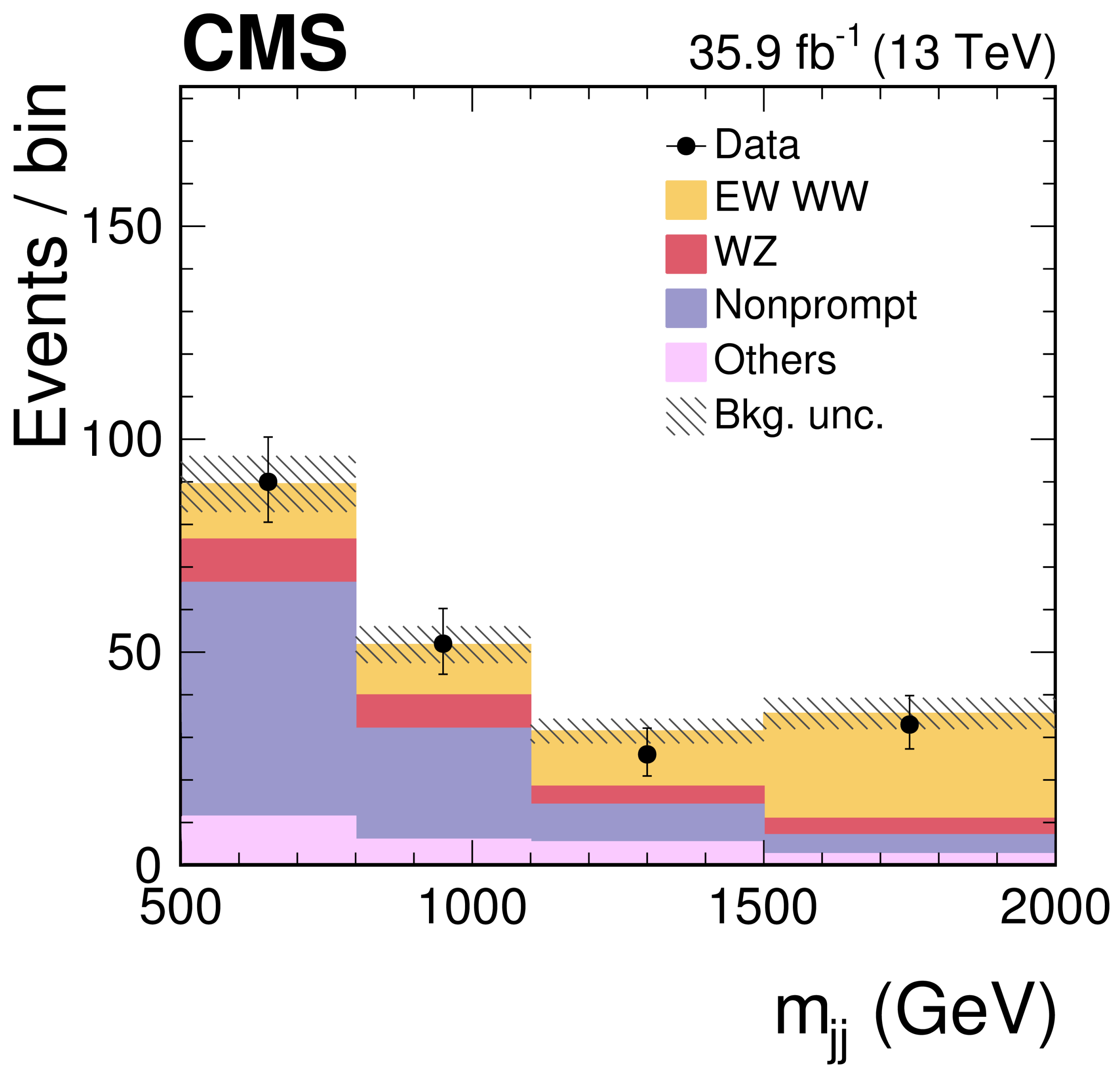
Missing ET

Same sign?

- to suppress backgrounds, like Z+jets
- charge misidentification big challenge

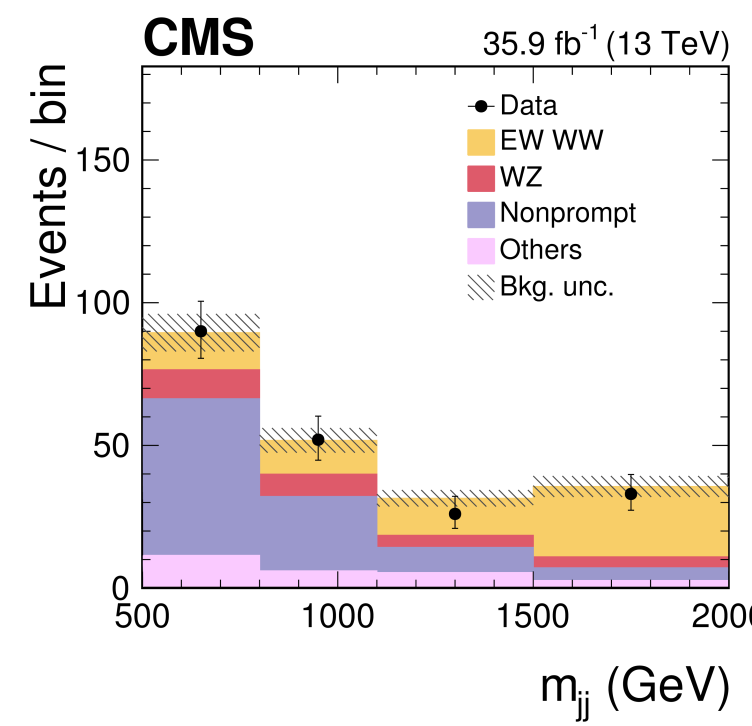
Backgrounds

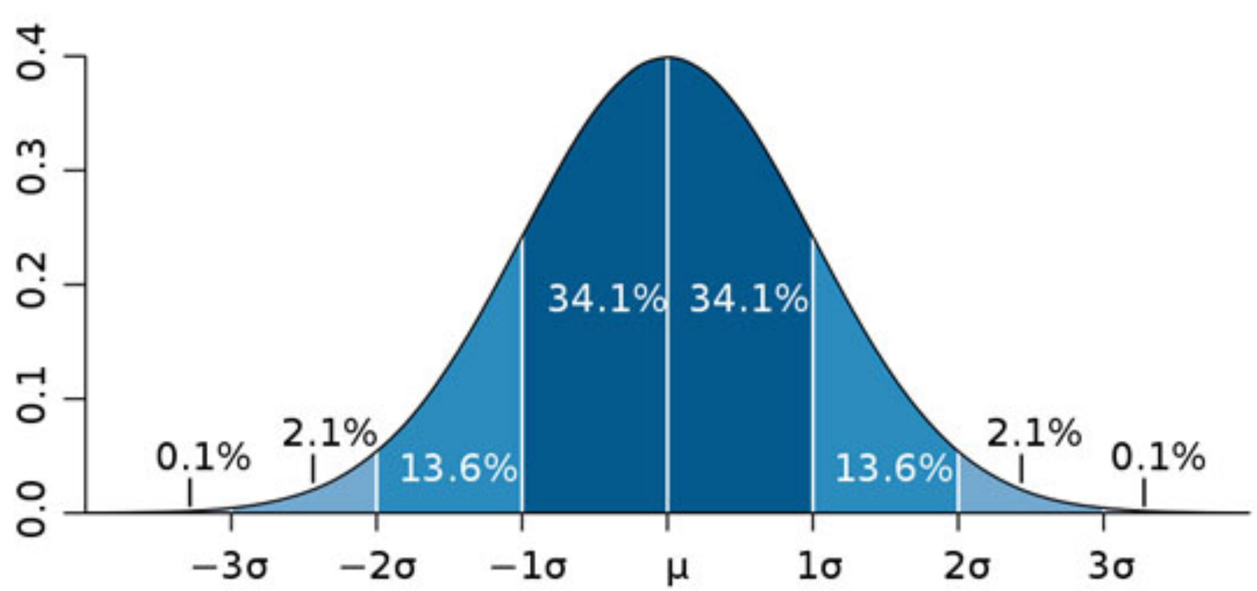
- WZ with one lepton lost
  - 3 lepton CR
- lepton fakes - from data, with transfer factors



Significances

- how likely is the excess produced by a statistical fluctuation of the background?
- different ways of estimating this, with various approximations
- translate probability into standard deviations

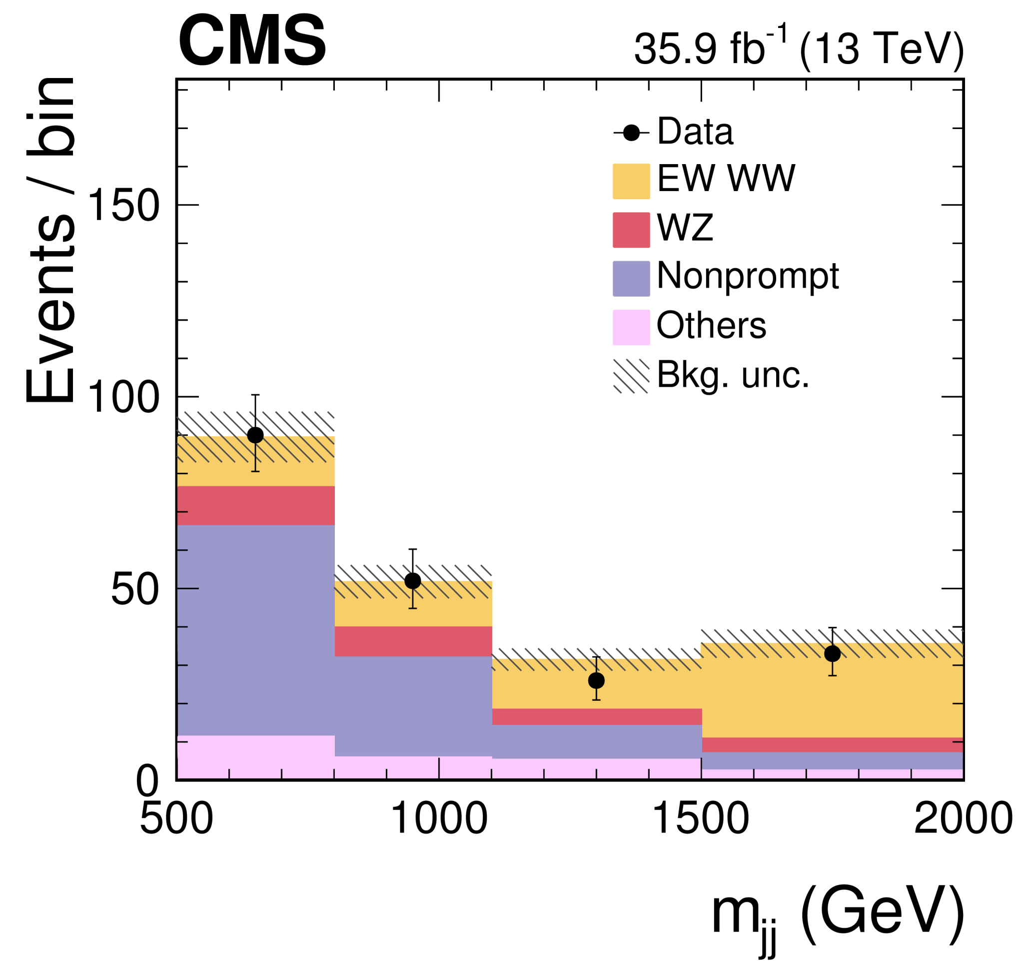




0.05 -> 2 sigma
0.003 -> 3 sigma (evidence)
0.0000003 -> 5 sigma (discovery)

Significances

- often used: S/sqrt(B)
  - sqrt(B) is the Gaussian uncertainty of the number of background events
  - you basically check how many sigma you would need to explain the signal as a background fluctuation



Total data yield: 201
Expected background: 138
=> what significance would you estimate?

Caveats

- assumes Gaussian uncertainties! Problematic in the low event yield regime
- does not take systematics into account
- there are more sophisticated formulas (see a good discussion here)
- safest way: p-values from pseudo-experiments or likelihoods => see Higgs slides

Vector boson scattering - same sign WW

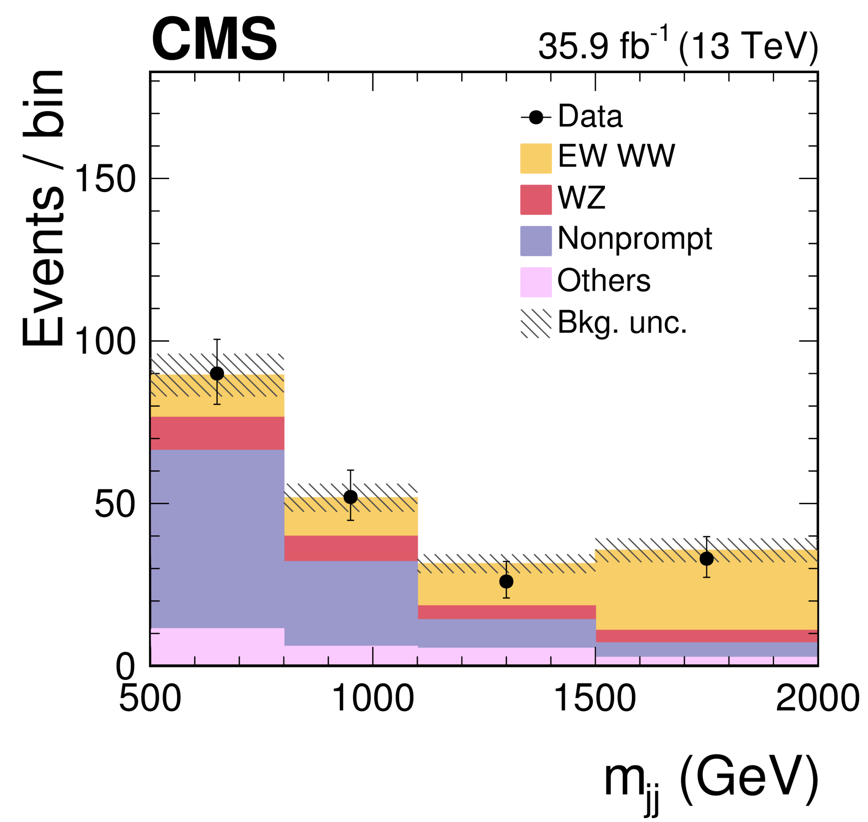
Signal extraction

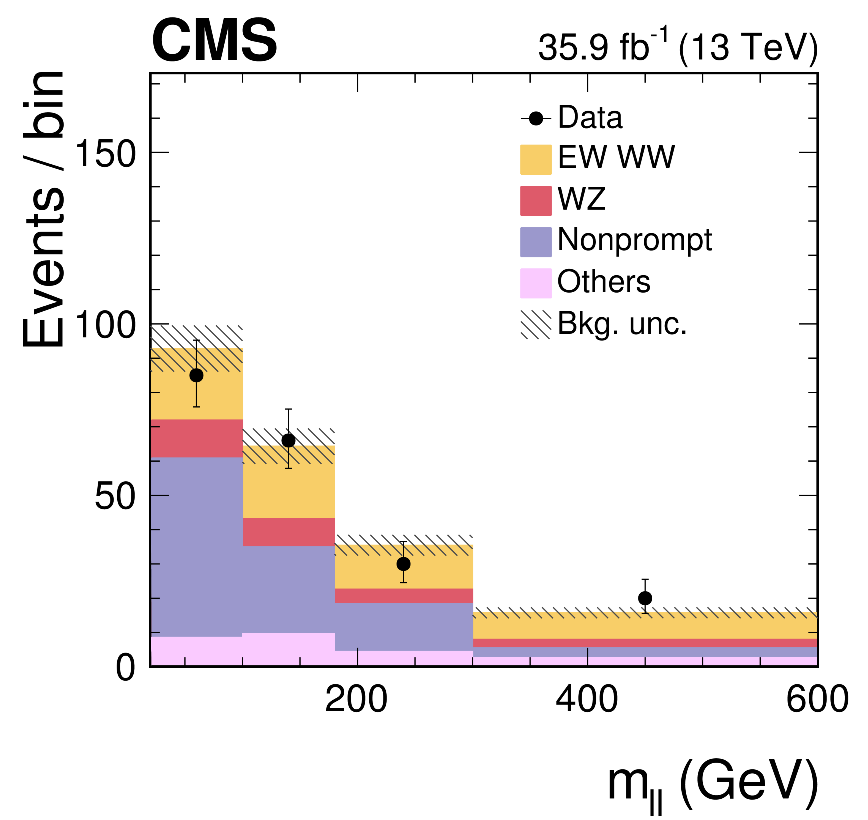
- fit in m_{jj}/m_{ll} (discriminate well)
- include fit for WZ at the same time

Measured (fid) XS

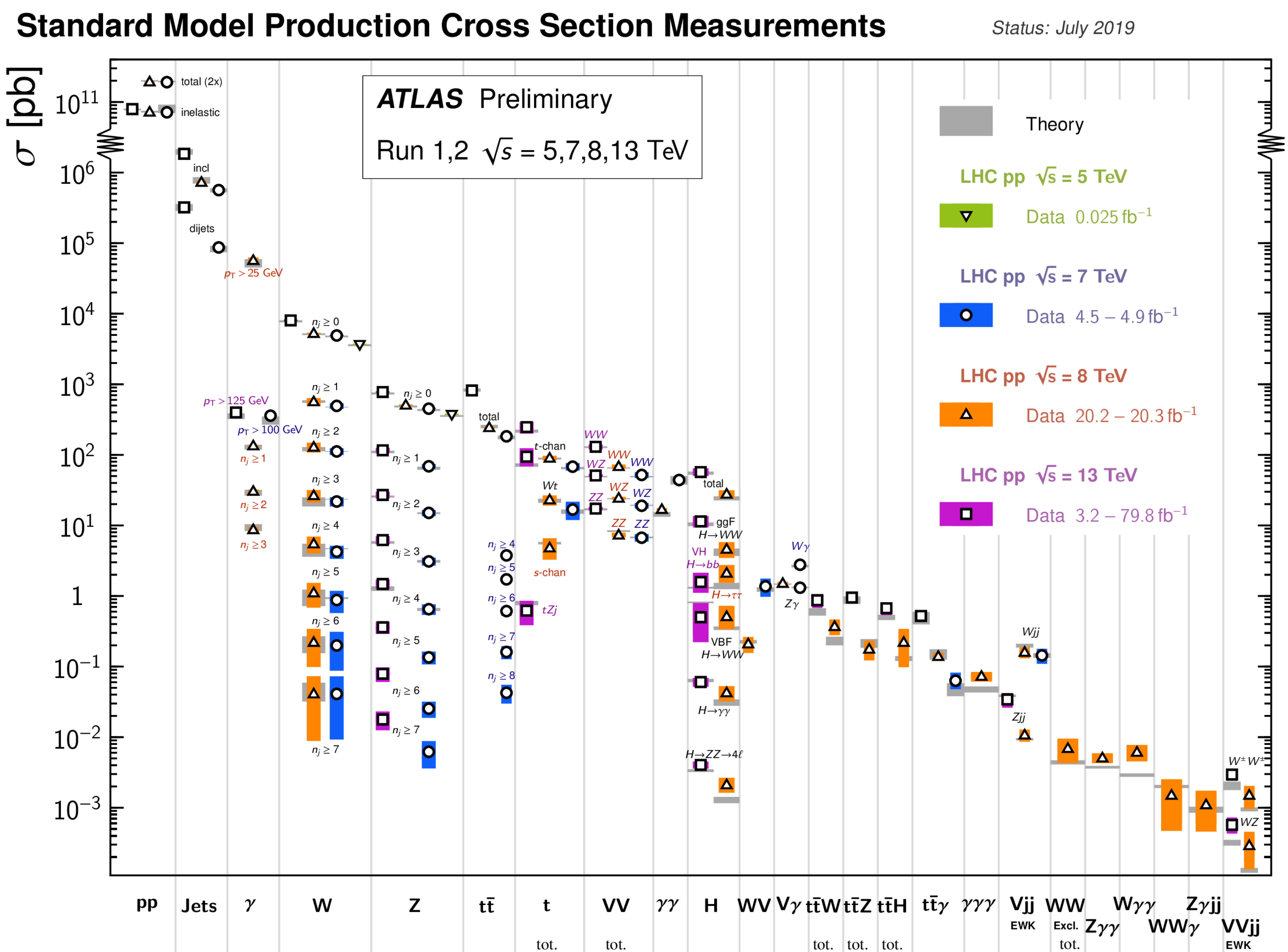
3.83 ± 0.66 (stat) ± 0.35 (syst) fb
LO prediction: 4.25 ± 0.27 fb

Observed significance: 5.5 sigma
Expected significance: 5.7 sigma





SM cross section plot



Mass measurements

Why are the masses interesting?

- fermion masses: free parameters of the SM
- boson masses: predicted
- can be used in SM consistency fits

Examples

- Z mass
  - LEP legacy
- W mass
  - Tevatron legacy, also LHC measurement
- Top mass
  - Tevatron legacy, also LHC measurements
  - not predicted, needs to be measured
  - top is heaviest particle in SM => special role?
  - W+top+Higgs masses related => consistency checks

W mass measurement

- based on 7 TeV data (less pileup)

- divide data into categories
    - lepton charge, flavor, pseudo-rapidity

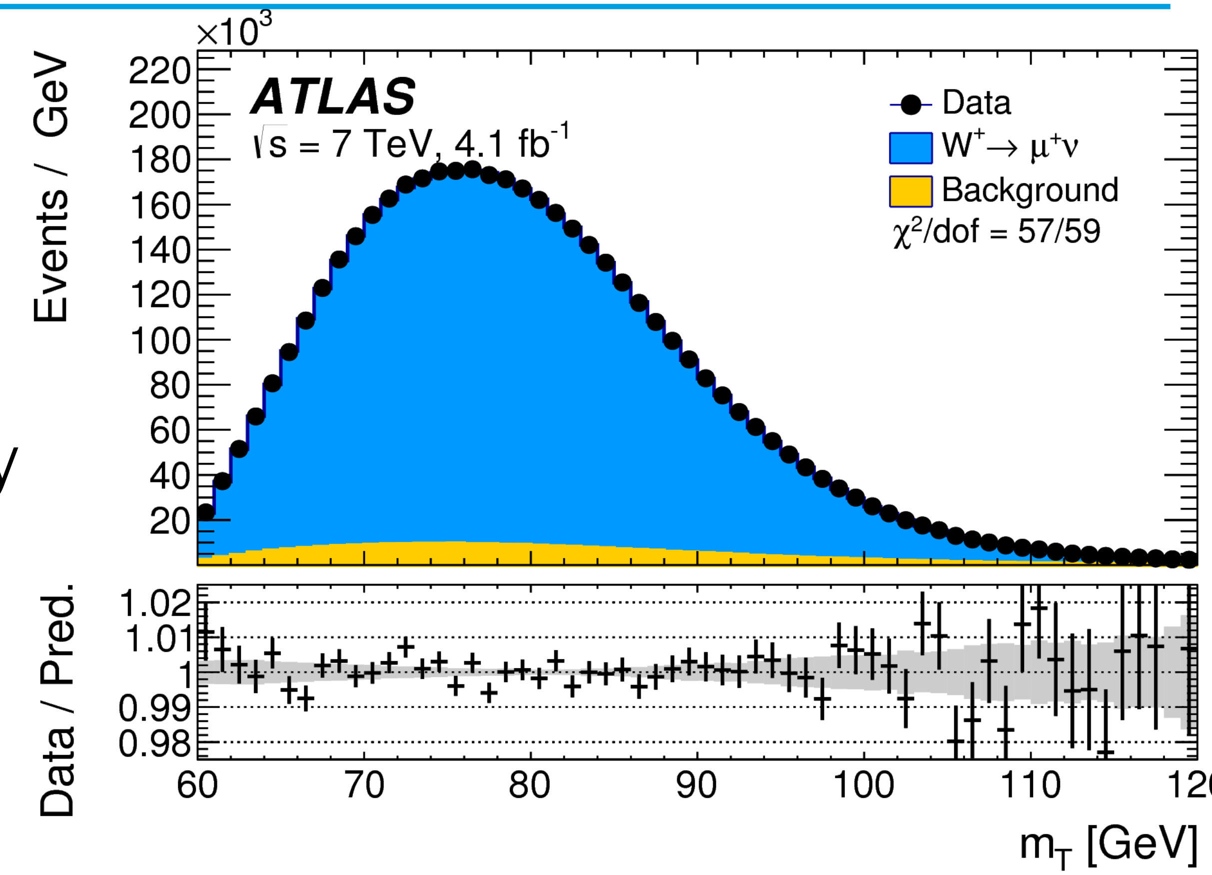
- fit transverse mass
    - includes missing energy

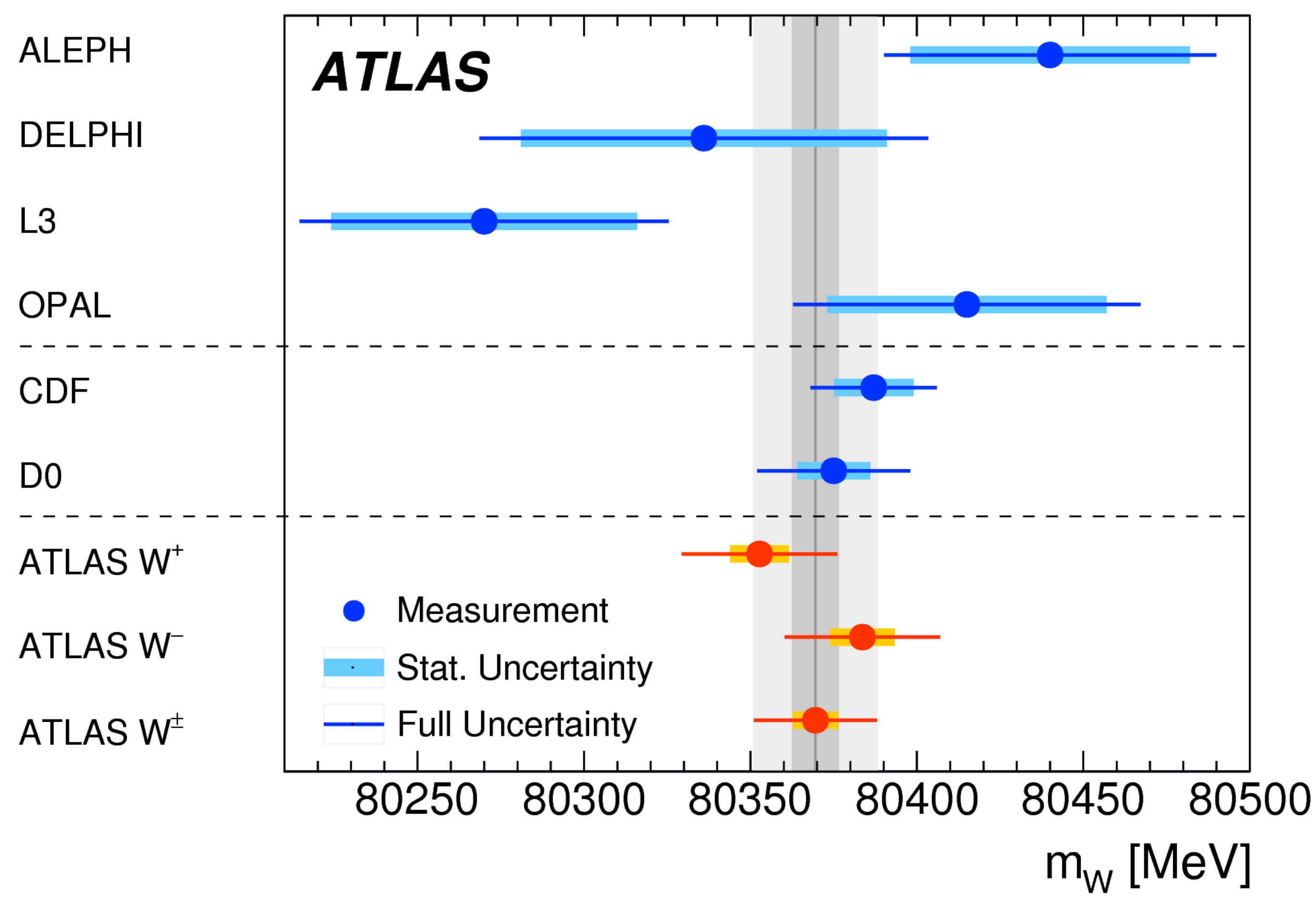
$$m_T = \sqrt{2p_T^{\ell}p_T^{miss}(1-\cos\Delta\phi)}$$

- also fit lepton pt
    - cleaner measurement
    - model dependence

- result (0.2 permille accuracy!)

$$m_W = 80369.5 \pm 18.5\ \mathrm{MeV}$$

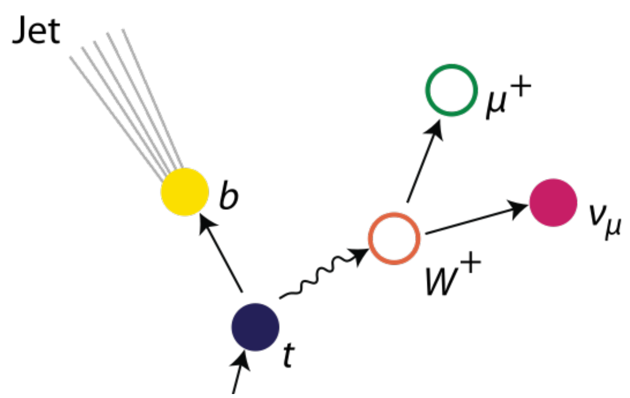


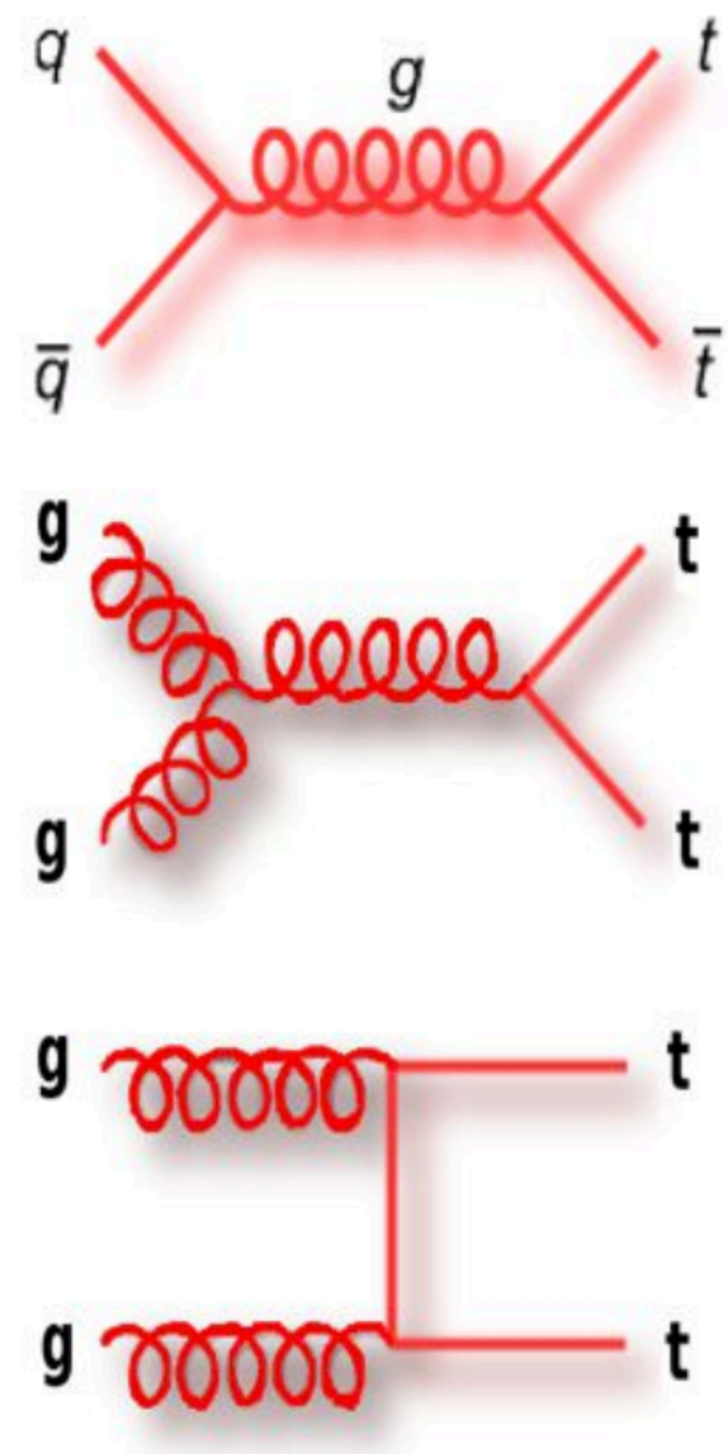


Top quarks

- top quark was discovered at the Tevatron
- LHC: top factory

- top quark decays
  - t-Wb in ~100%
  - leptonic or hadronic W decays



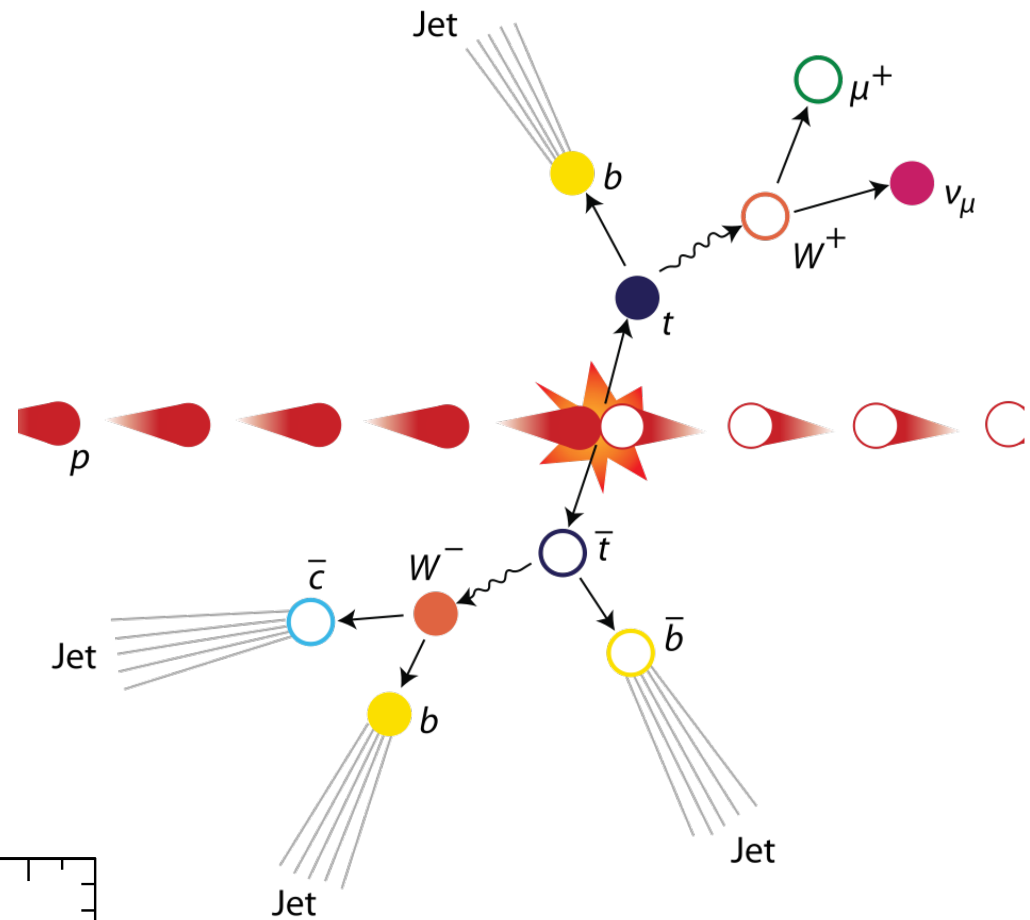


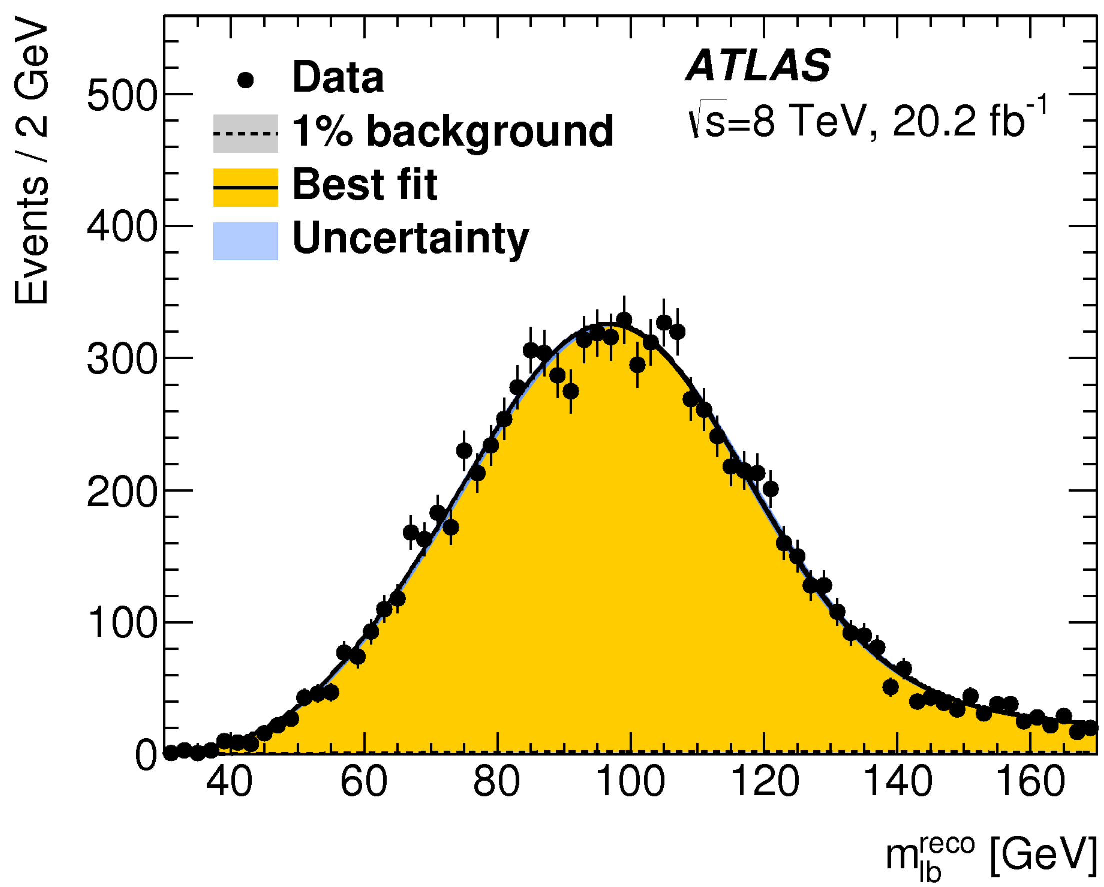
- Can do many things with top quarks
  - measure mass, charge, width
  - measure cross sections, kinematics in top pair and single top production
  - search for new particles decaying into top pairs
  - measure Vtb
  - measure spin correlations

Top pair selection

event selection
- depends on whether the W decays hadronically or leptonically
- stats vs S/B

Fully leptonic decay (very clean!)
- 2 jets, one of the b-tagged
- 2 leptons





Top quark mass measurement

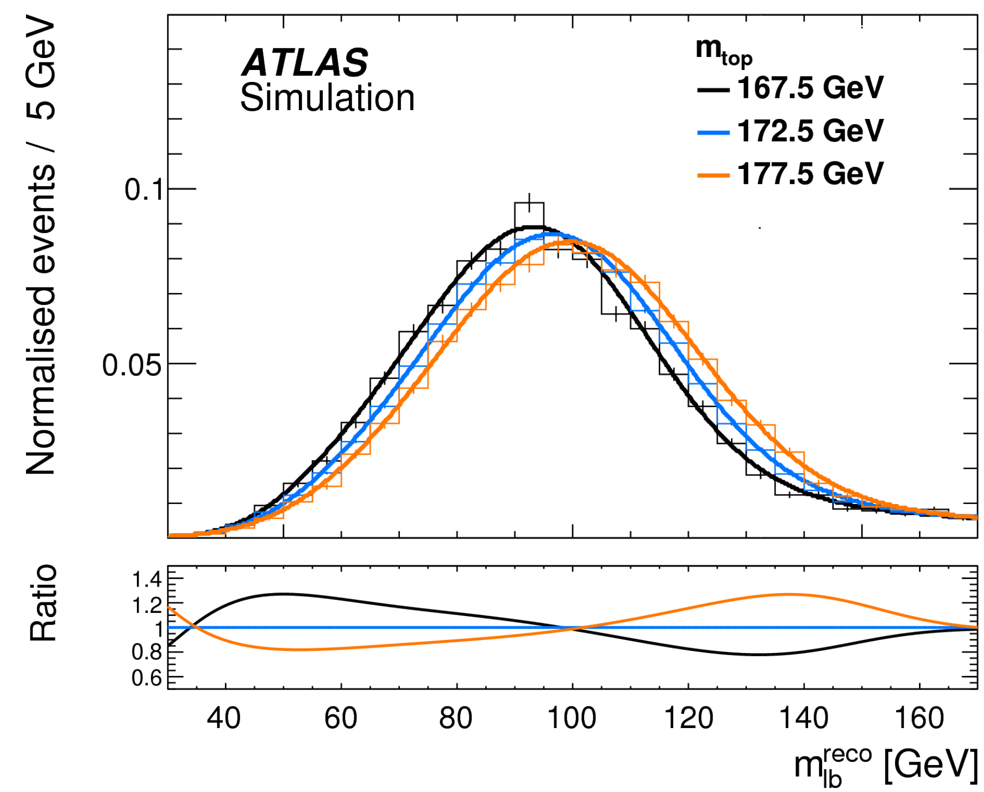
Two masses (differ by ~0.4 GeV)

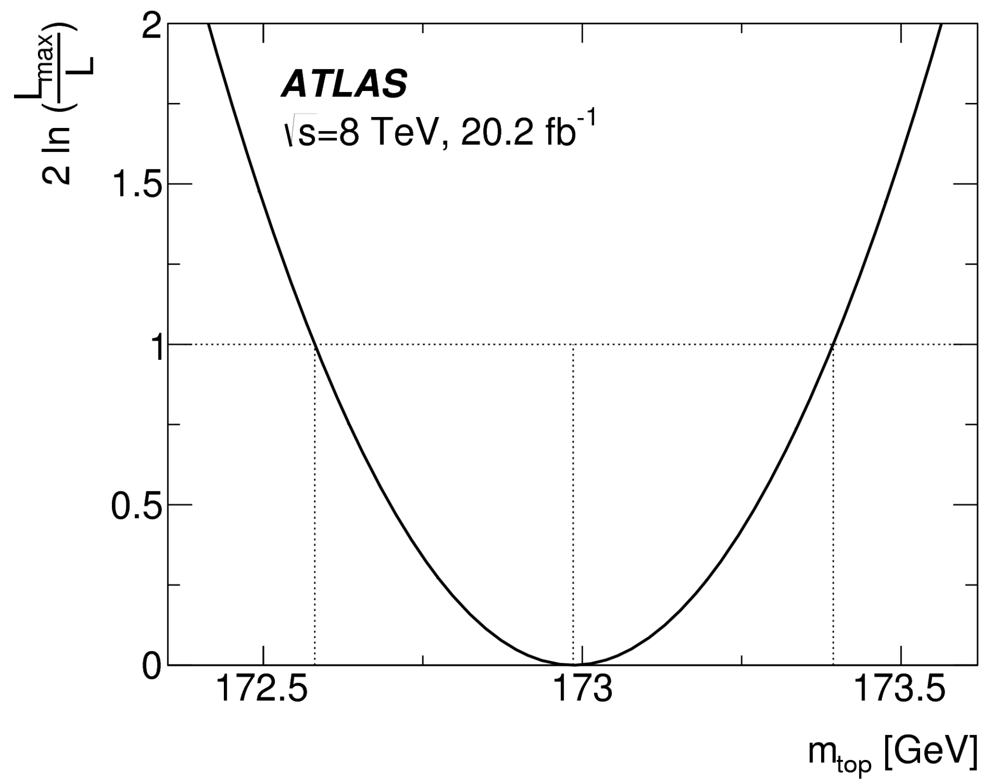
- "MC mass": mass reconstructed from the decay products (affected by strong interactions)
- Pole mass: mass of free particle ("rest mass")

How would you get the pole mass?

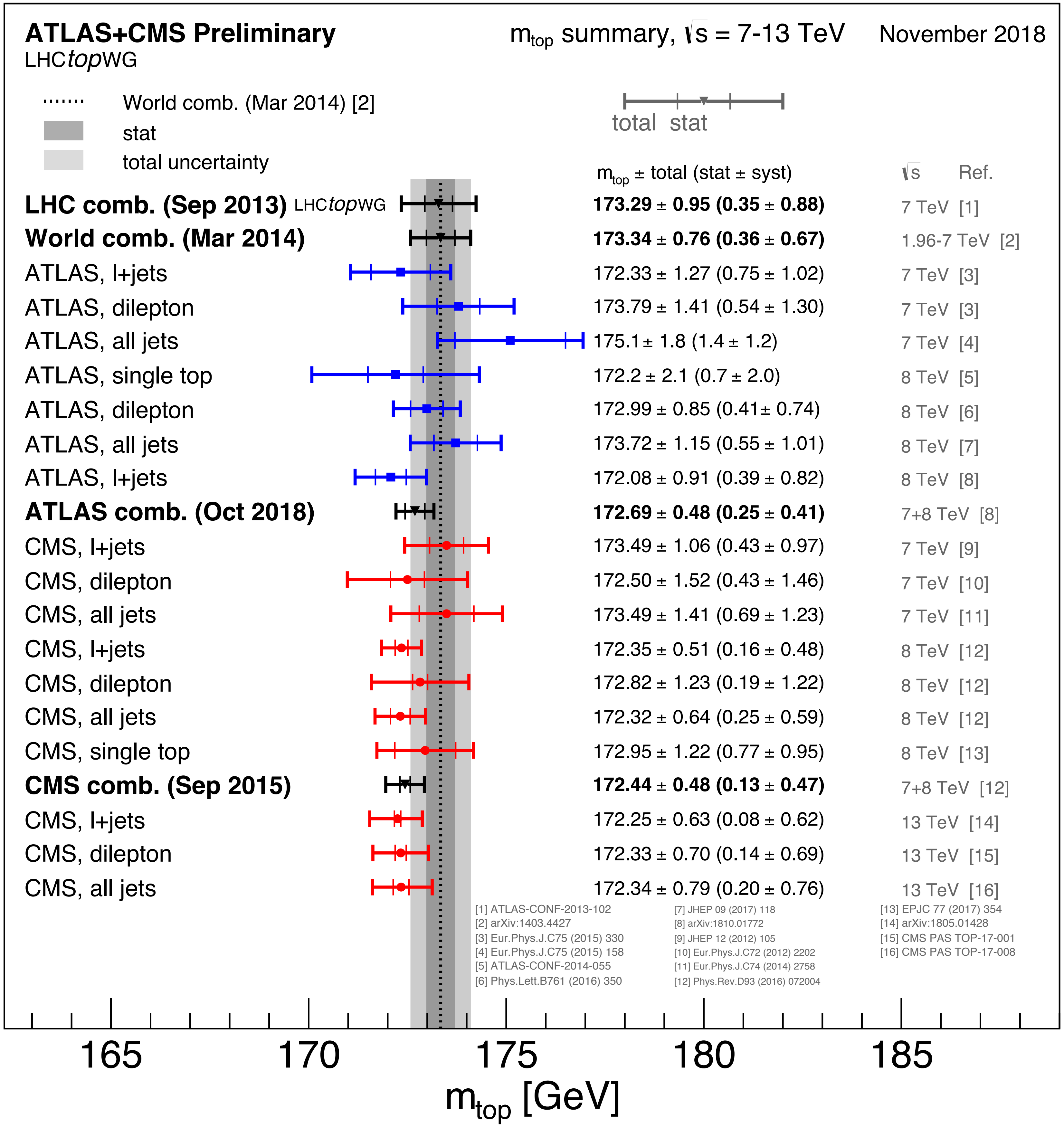
- measure cross sections that do not depend on detailed reconstruction of top final states
- cross sections depend on the mass

MC Mass





Top quark mass measurement



MC mass

3 permille!

Parameters of the electroweak sector

9 fermion masses (+ 3 mν)

3 CKM mixing angles + 1 phase (+3+1 for mν != 0)

1 electromagnetic coupling constant **α**. (10^{-9})

1 strong coupling constant α_s

1 weak coupling constant G_F (10^{-5})

1 Z mass (10^{-5})

1 Higgs mass

From these can calculate m_W, $\sin^2\theta_W$

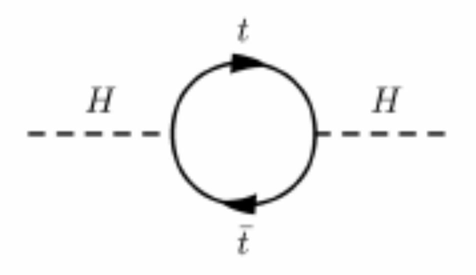
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

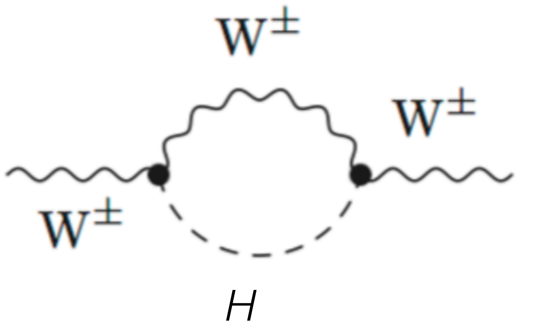
$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}$$

SM fits

Top, W, Higgs mass are related through higher order corrections

Examples:

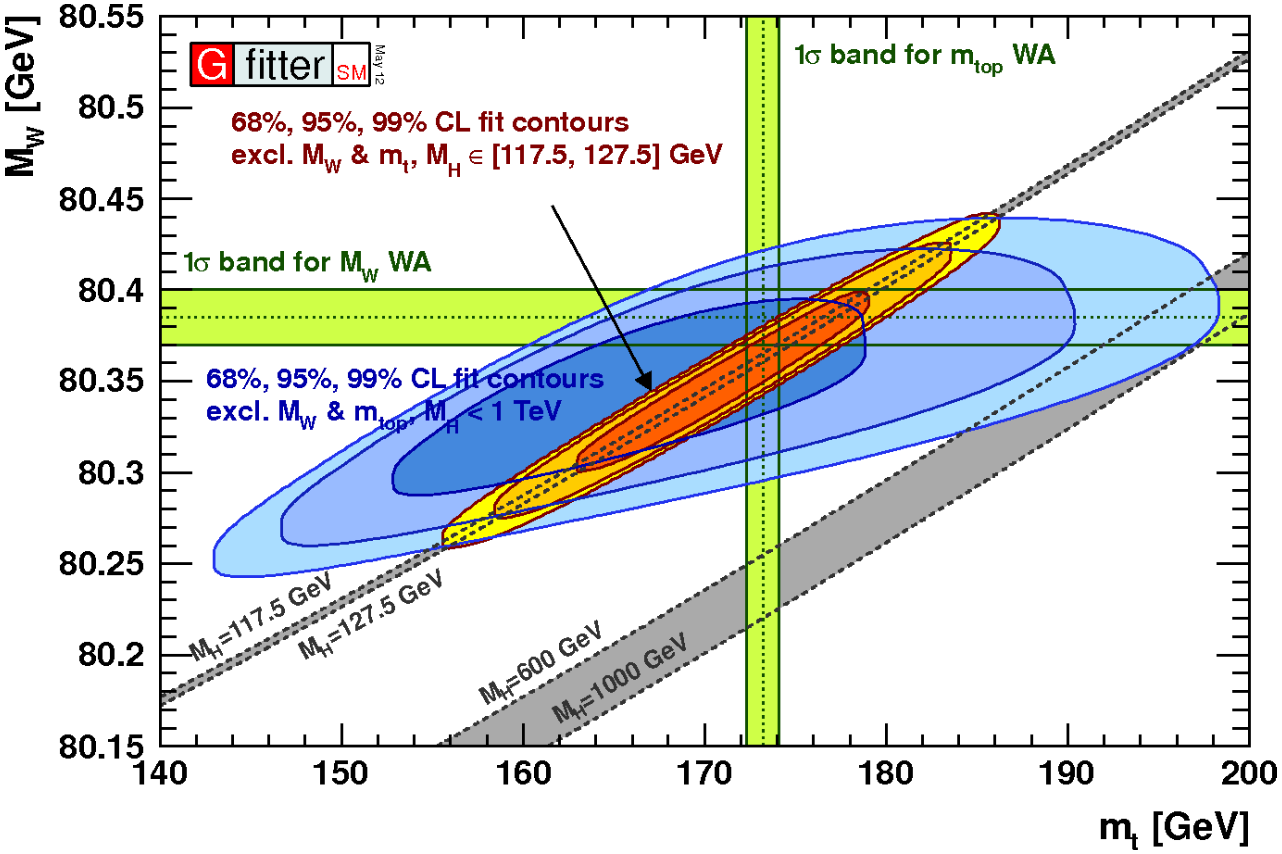


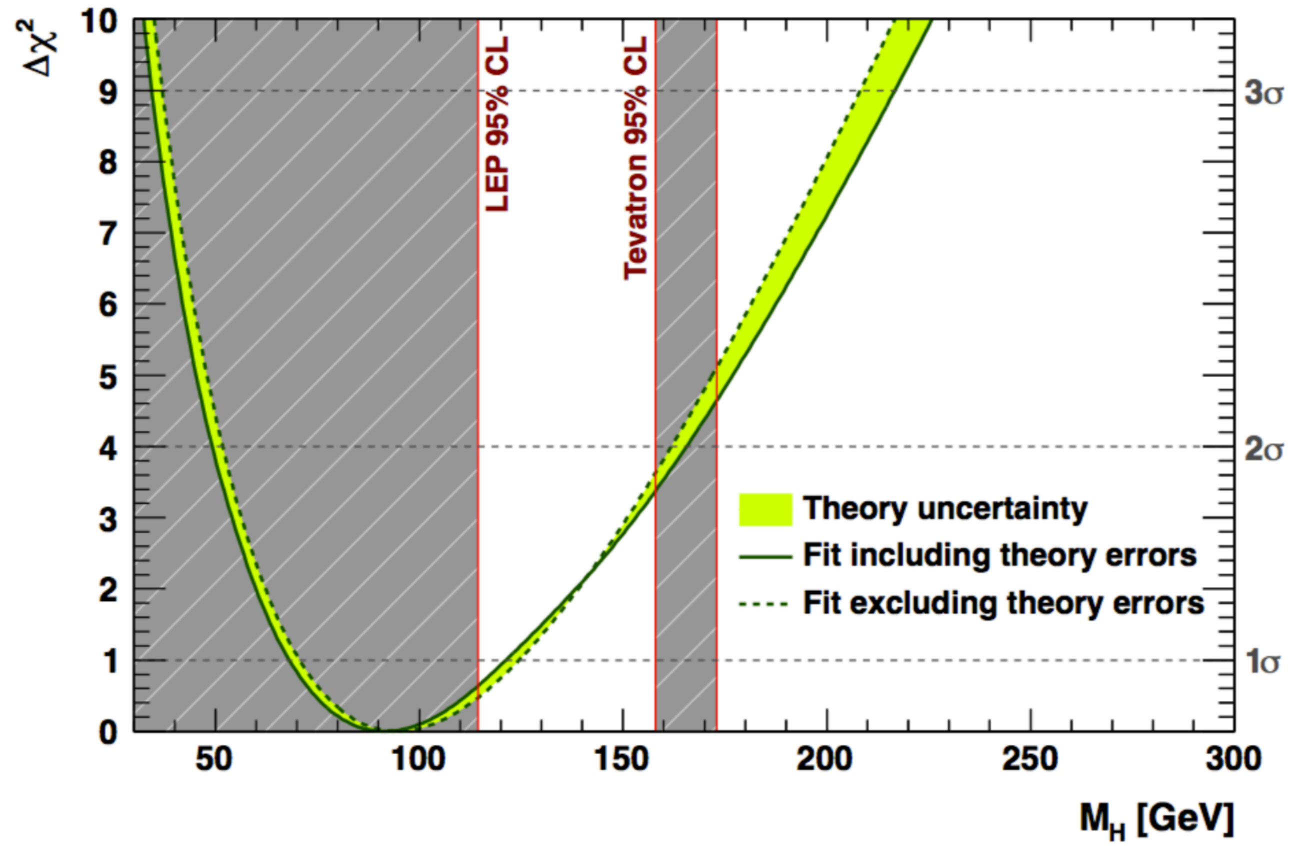


Idea of electroweak fits

- measure many different observables
- calculate the relations between all observables
- measure redundant observables => probe consistency of Standard Model
- predict observables => Higgs mass before the discovery!

SM fits - before Higgs discovery





$$m_H = 91^{+30}_{-23}\ \text{GeV}$$