LHC Physics – Electroweak and Top

DESY Summer Student Lectures, 16.08-17.08.2022

Claudia Seitz

LHC Physics goals

Measure

Standard Model

parameters with high precision

Search for the

Higgs boson

and measure it's properties

Search for

New Physics

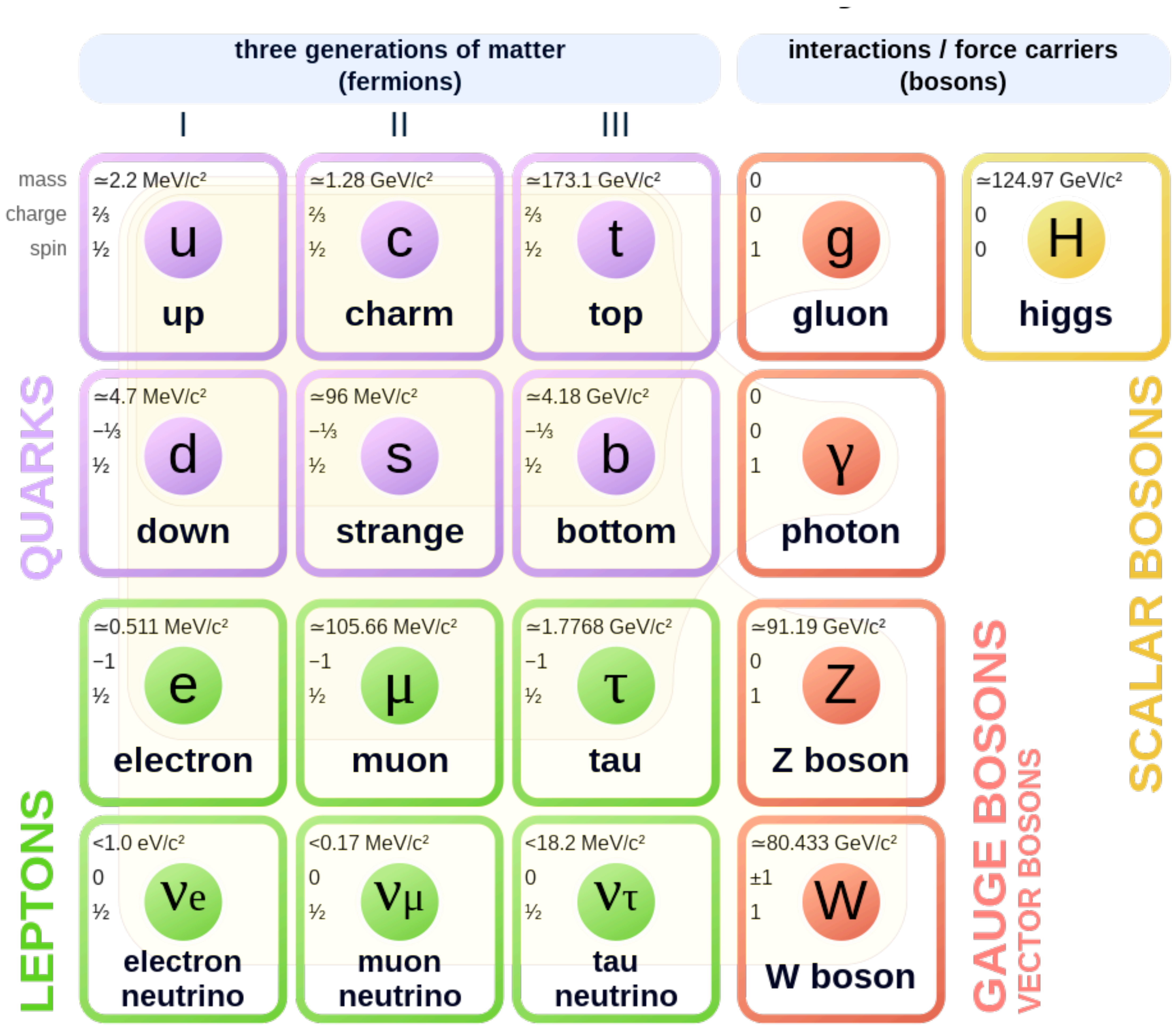
Beyond the Standard Model

Study

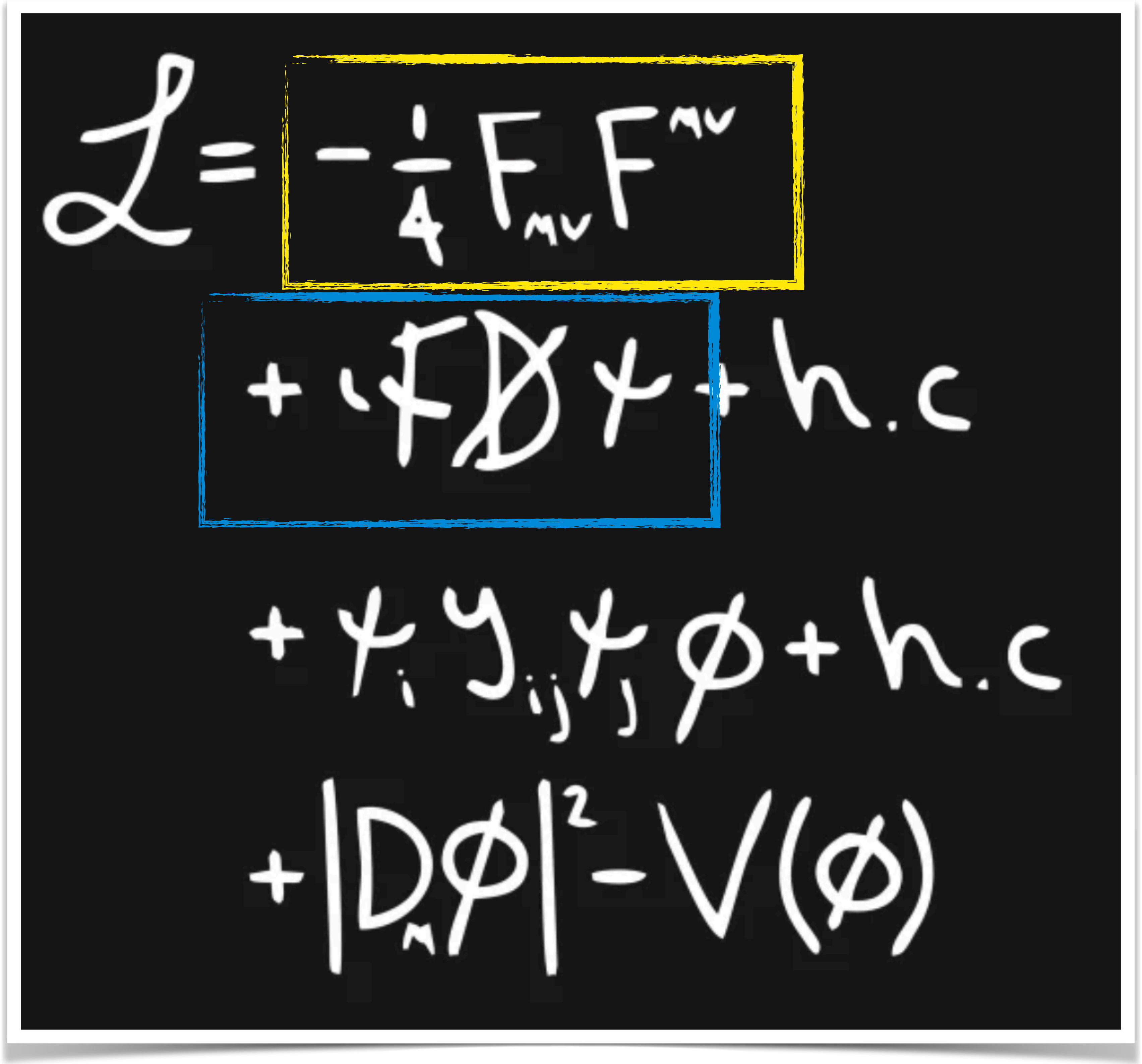
Quark-Gluon Plasma

Large Hadron Collider

They Standard model and the Feynman picture

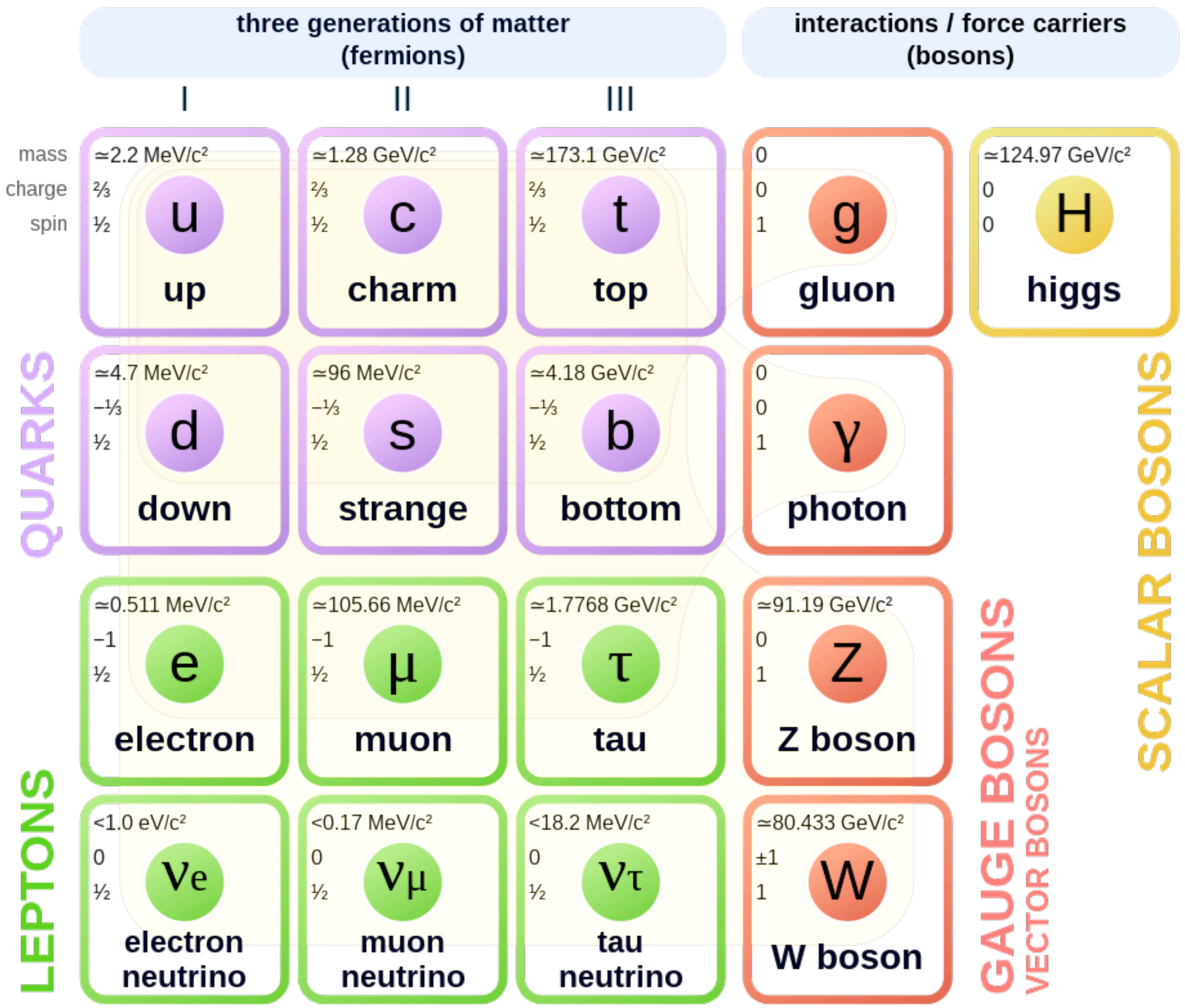


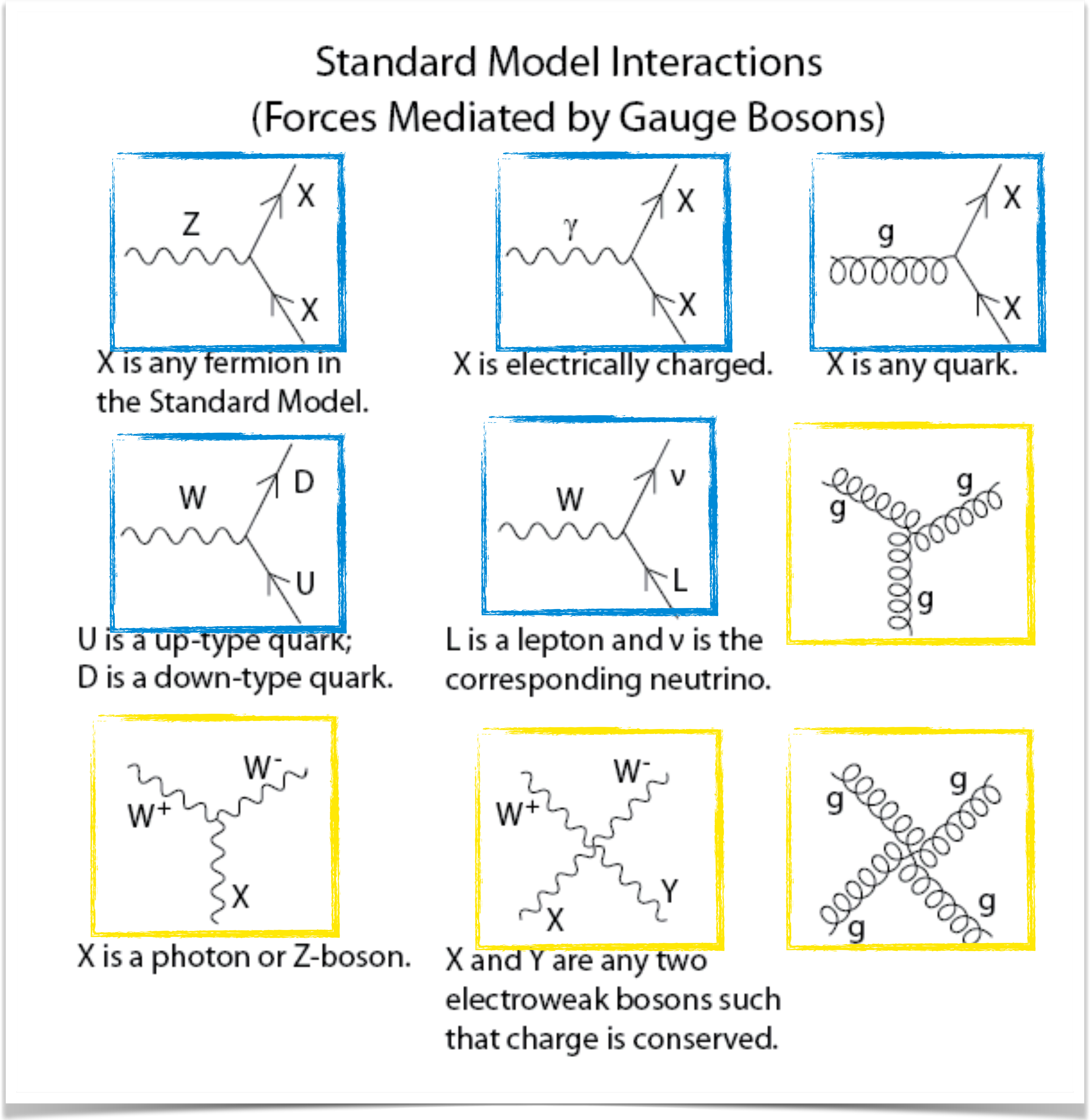
Gauge boson self-interaction



Gauge boson fermion interactions

They Standard model and the Feynman picture



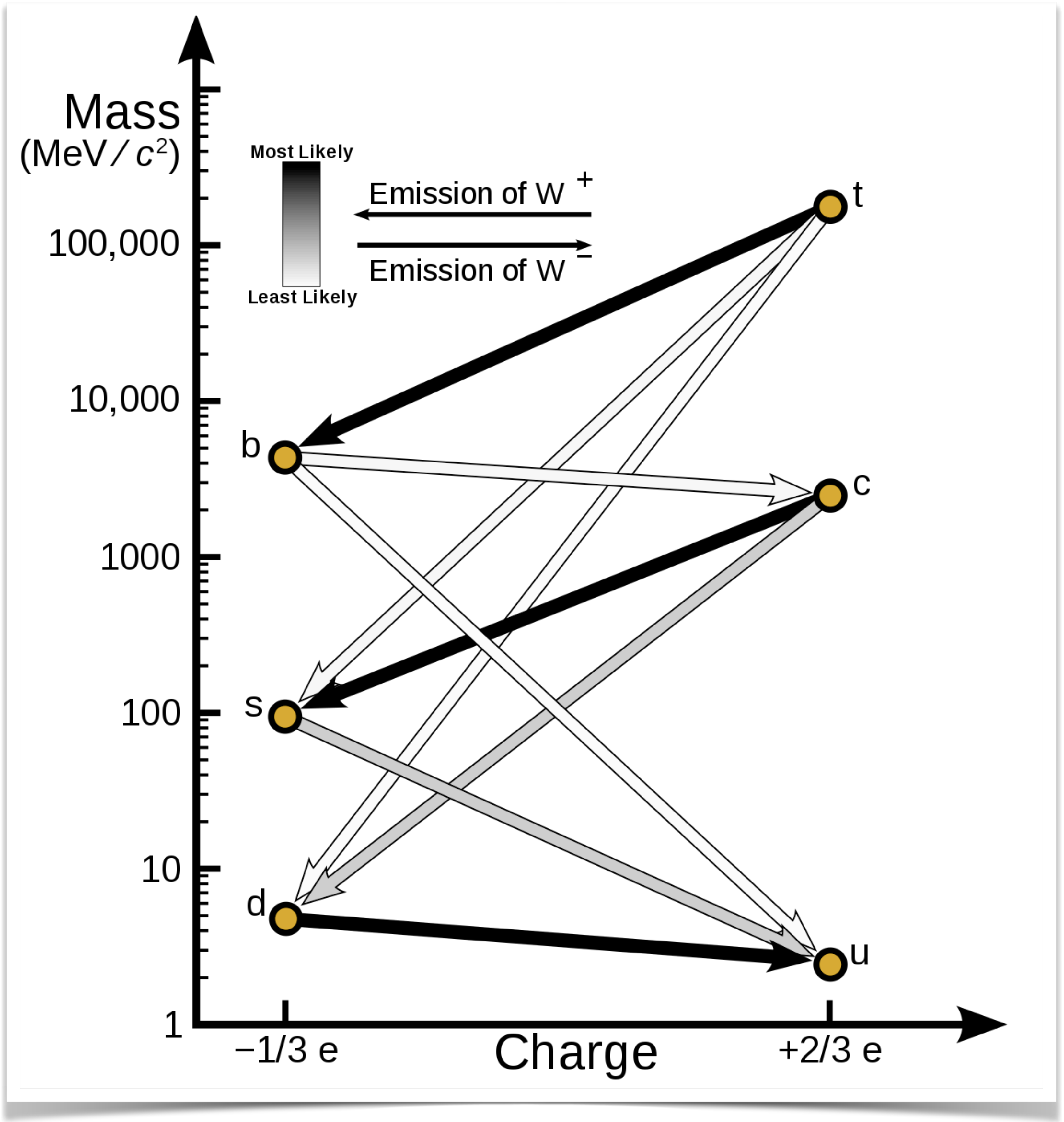


Wikipedia

The SM free parameters

- 9 fermion masses
- 3 CKM mixing angles + 1 phase
- 1 electromagnetic coupling constant (fine structure constant) α
- 1 strong coupling constant α_s
- 1 weak coupling constant (Fermi constant) G_F
- 1 Z mass
- 1 Higgs mass

Depiction of the CKM matrix



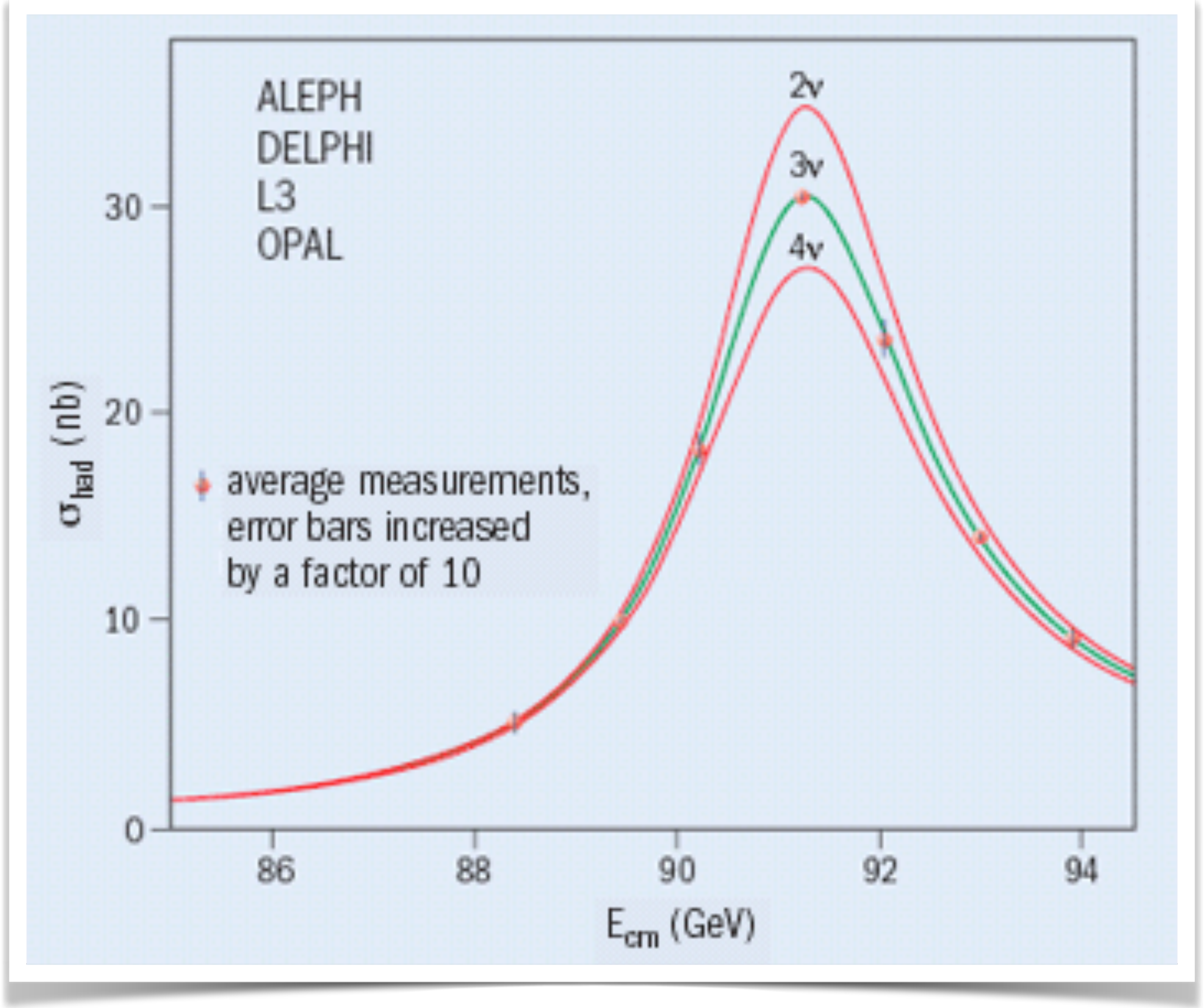
Wikipedia

Goals:

- **Measure them**
- **Measure redundant parameters and test the SM relations between them by doing a consistency check**

Z-boson at LEP

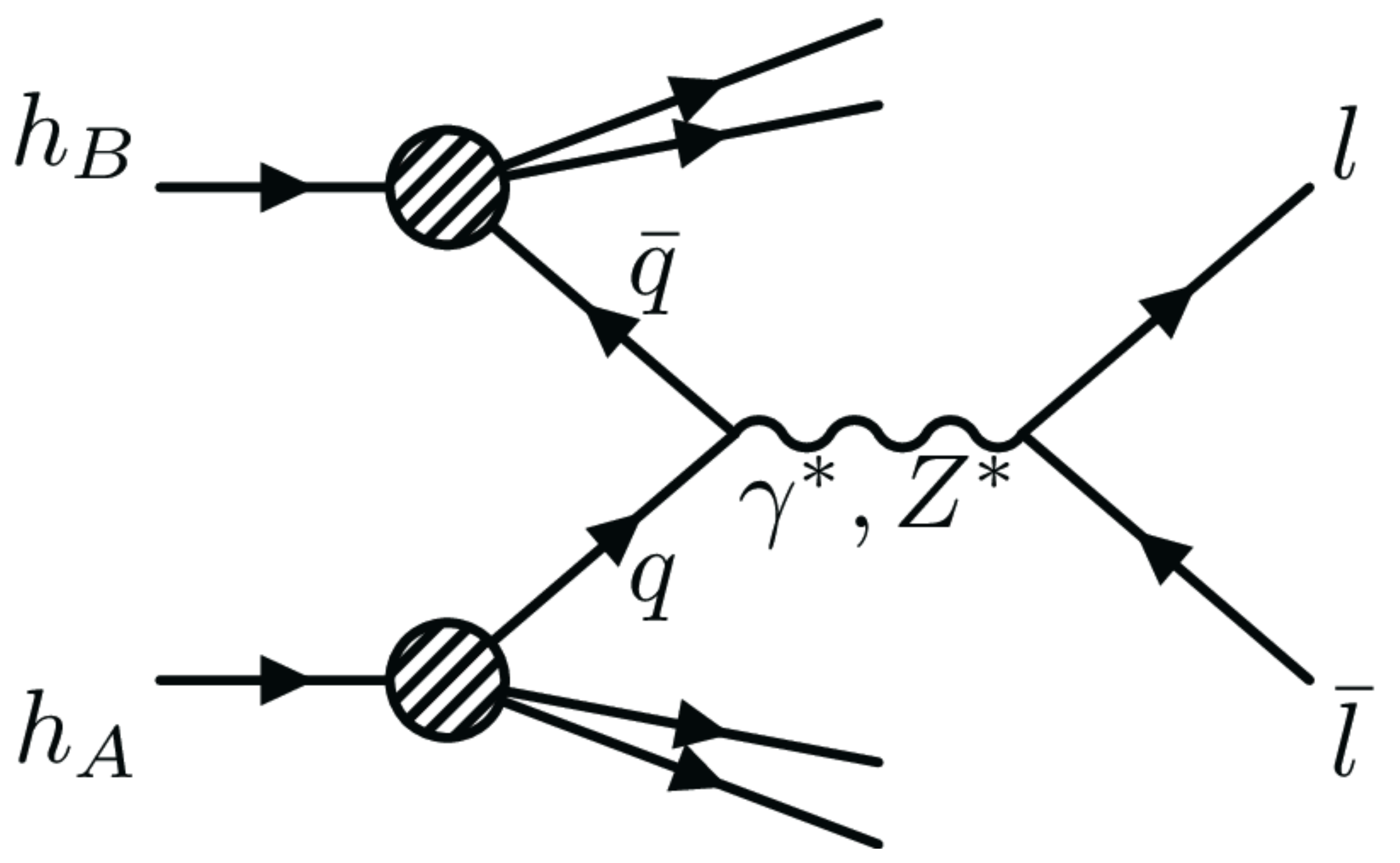
- Large Electron-Positron Collider
  - in operation at CERN 1989-2000
- Z bosons are represented by a clean peak in the invariant mass spectrum of the two leptons
    - Precise measurements of the properties from LEP
    - Mass: 91.1876± 0.0021 GeV

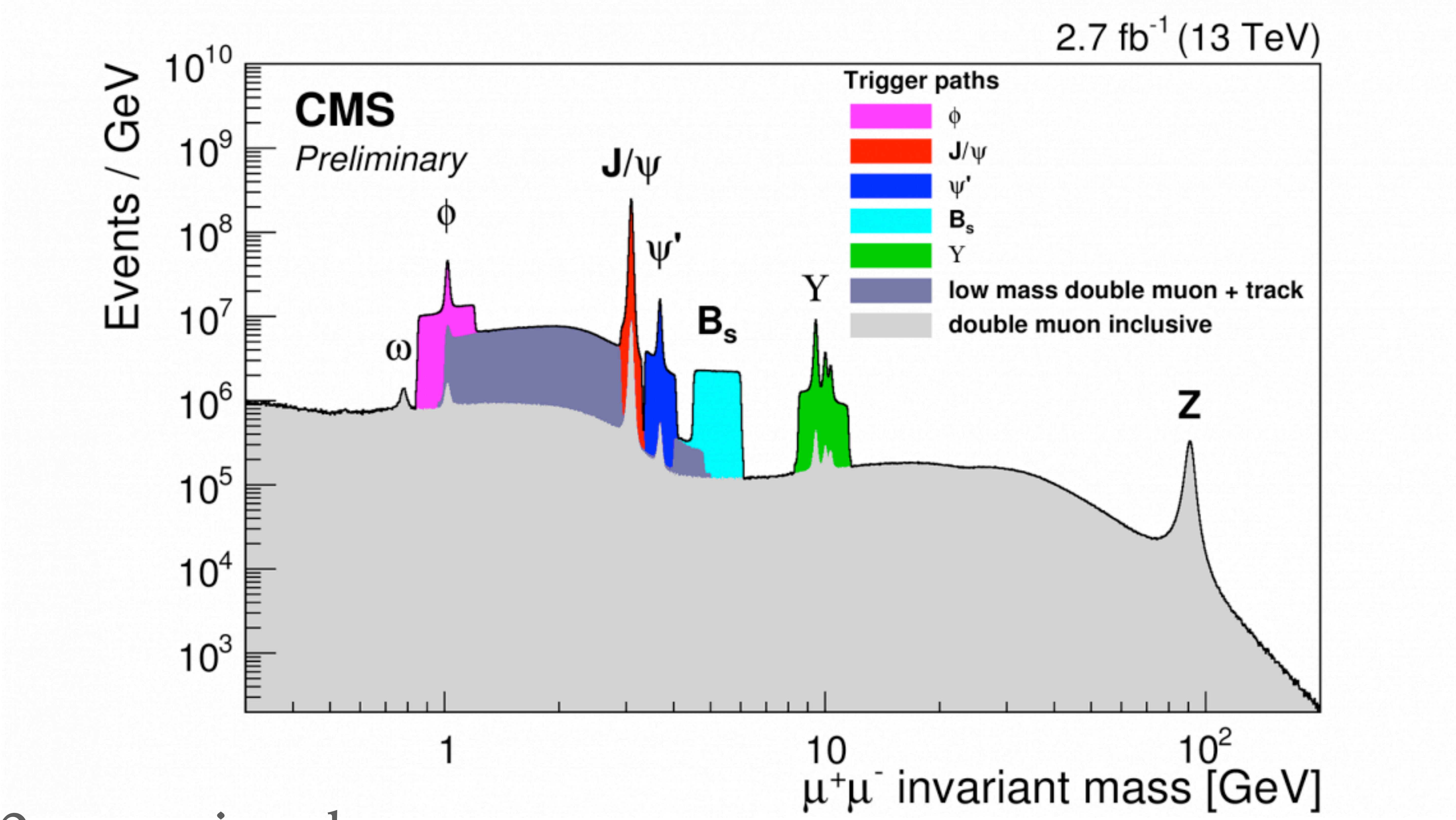


Particles		Branching ratio	
Name	Symbols	Predicted for $x = 0.23$	Experimental measurements[20]
Neutrinos (all)	ν_e, ν_μ, ν_τ	20.5%	20.00 ±0.06%
Charged leptons (all)	e^-, μ^-, τ^-	10.2%	10.097 ±0.003%
Electron	e^-	3.4%	3.363 ±0.004%
Muon	μ^-	3.4%	3.366 ±0.007%
Tau	τ^-	3.4%	3.367 ±0.008%
Hadrons (except * t)		69.2%	69.91 ±0.06%
Down-type quarks	d, s, b	15.2%	15.6 ±0.4%
Up-type quarks	u, c	11.8%	11.6 ±0.6%

Fun-fact: the main Z-boson decay mode is the decay to quarks (~70%) or neutrinos (~ 20%)

Re-discover Z boson at the LHC



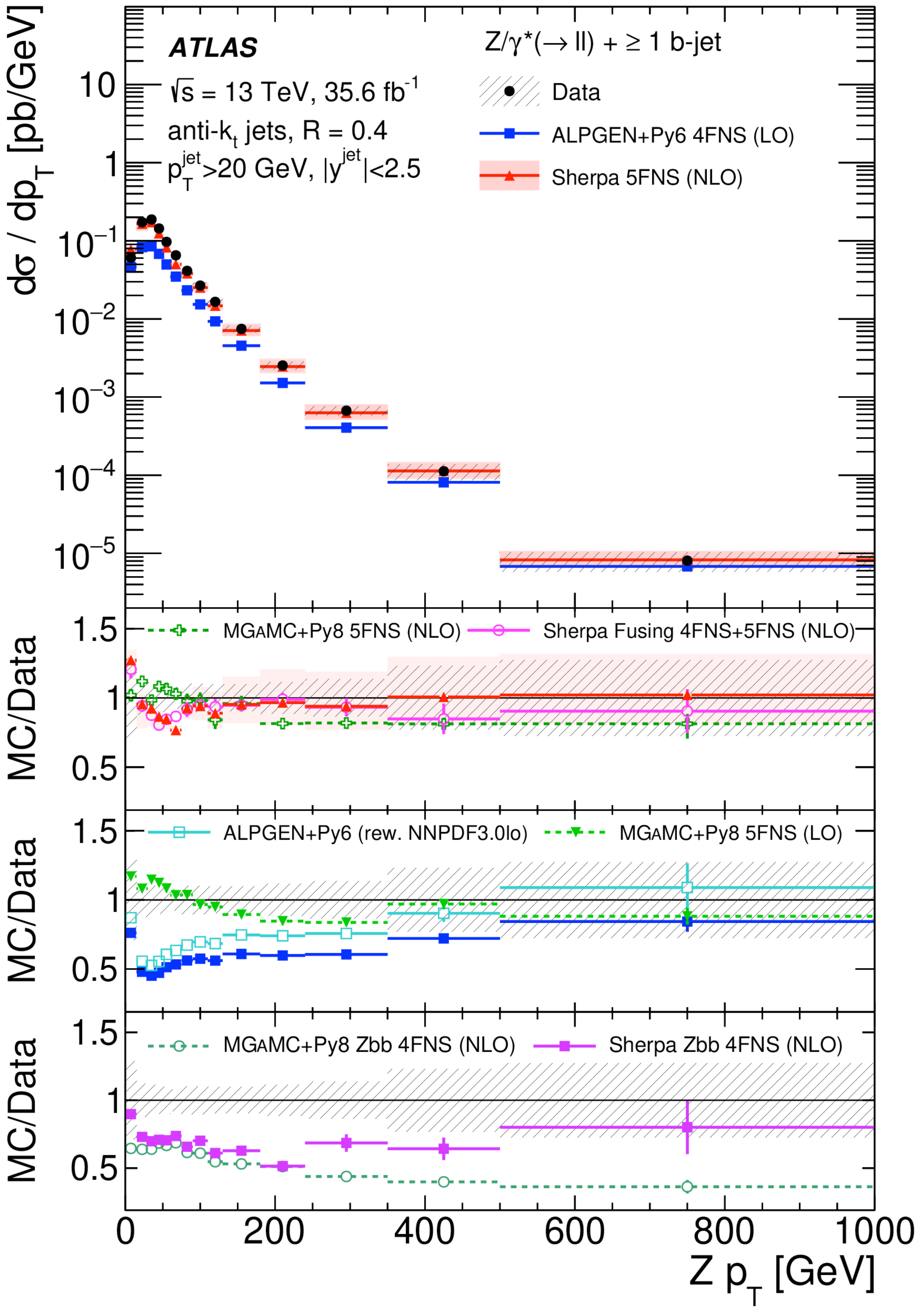


- ➤ Characteristic clean signature: 2 opposite charge, same flavor leptons
- ➤ Z bosons are used as “standard candles” at the LHC

Z+jets measurements

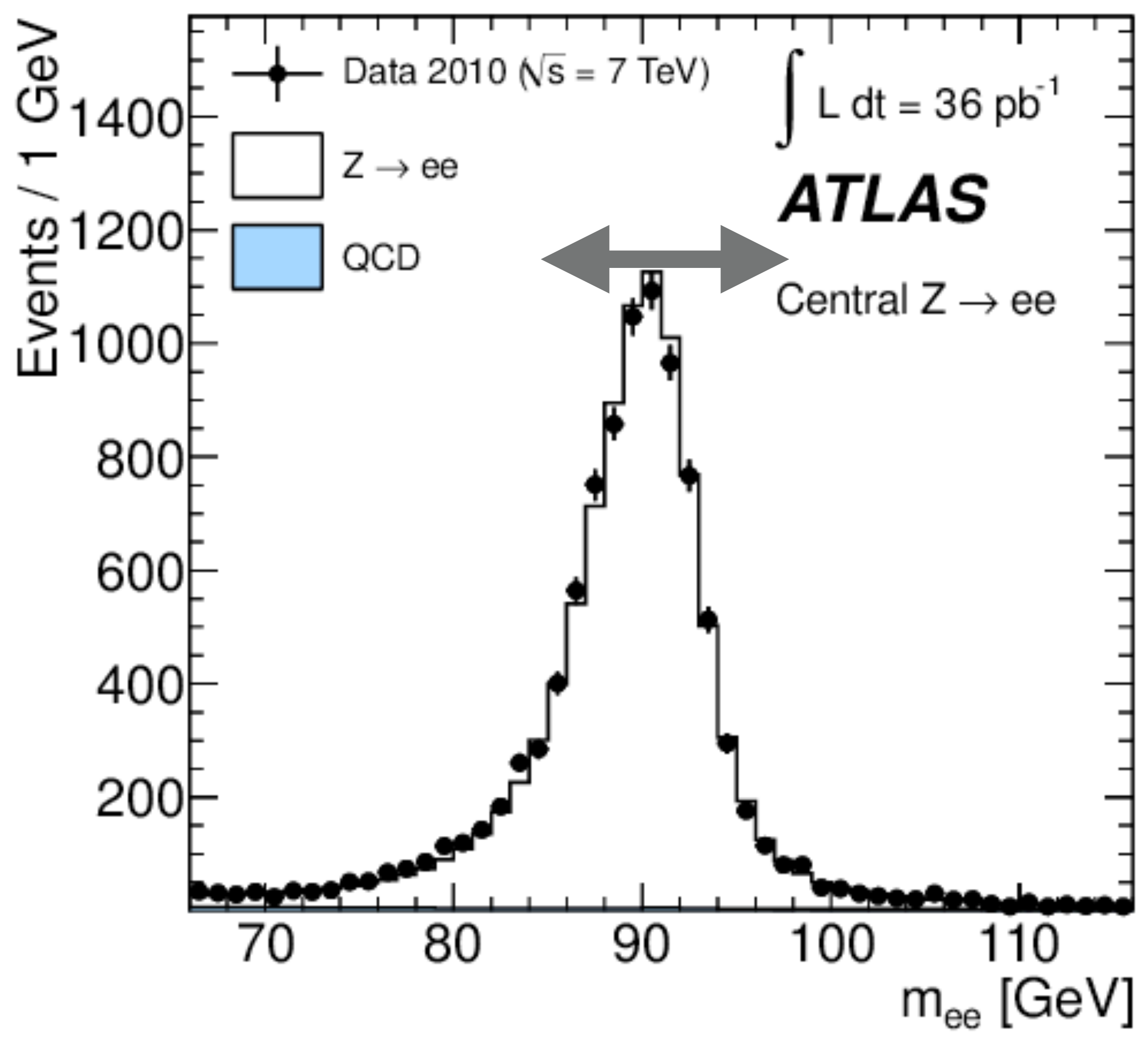
- Z produced in association with extra (b)-jets is an important process and background for many searches for new physics

- Understanding of the Z boson pT spectrum is important
  - Unfolding technique often used to turn “measured” data spectrum into particle level spectrum
  - Unfolded spectrum can then be easily compared with various simulated samples



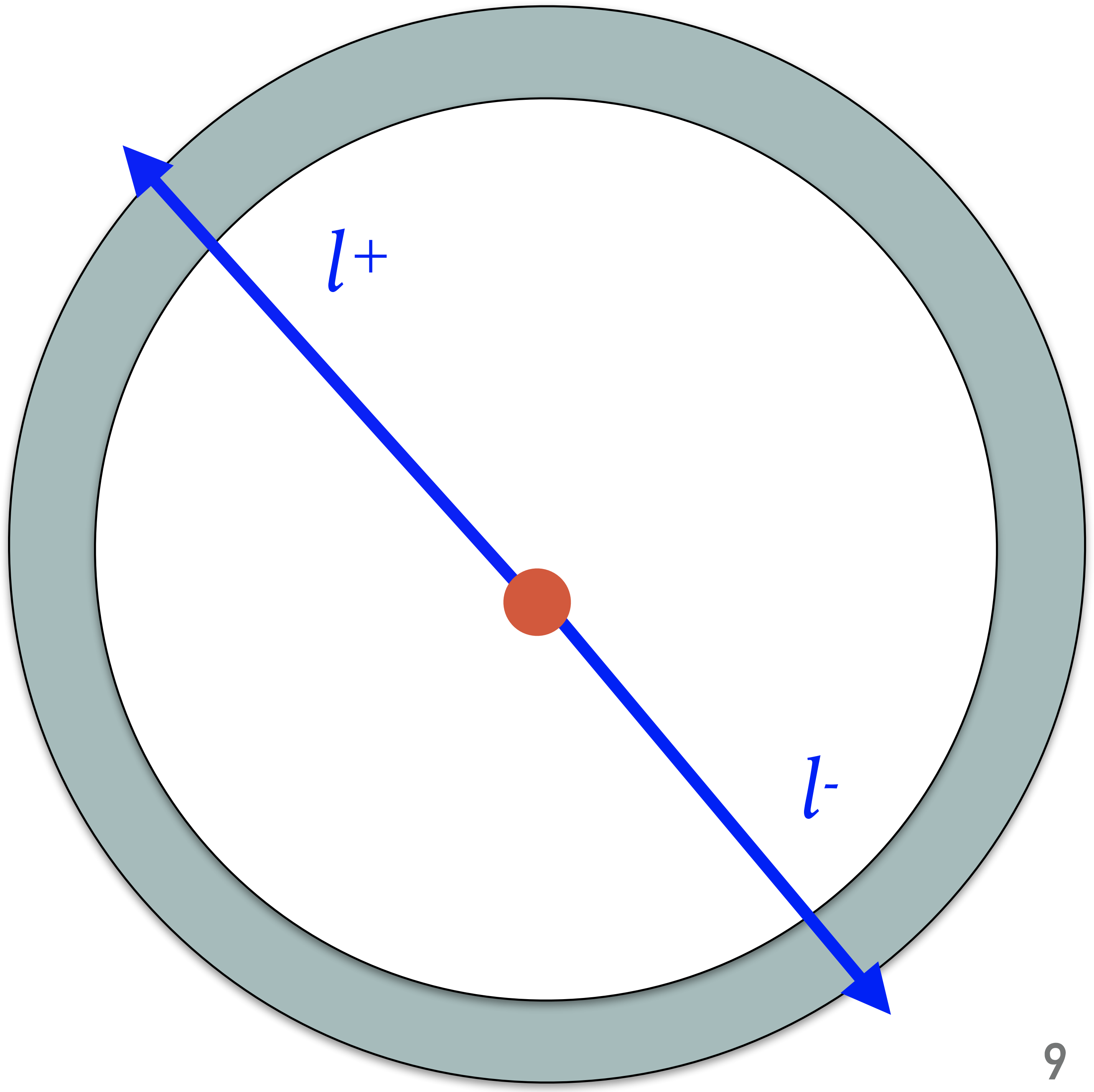
[JHEP 07 (2020) 44]

Z bosons as standard candles



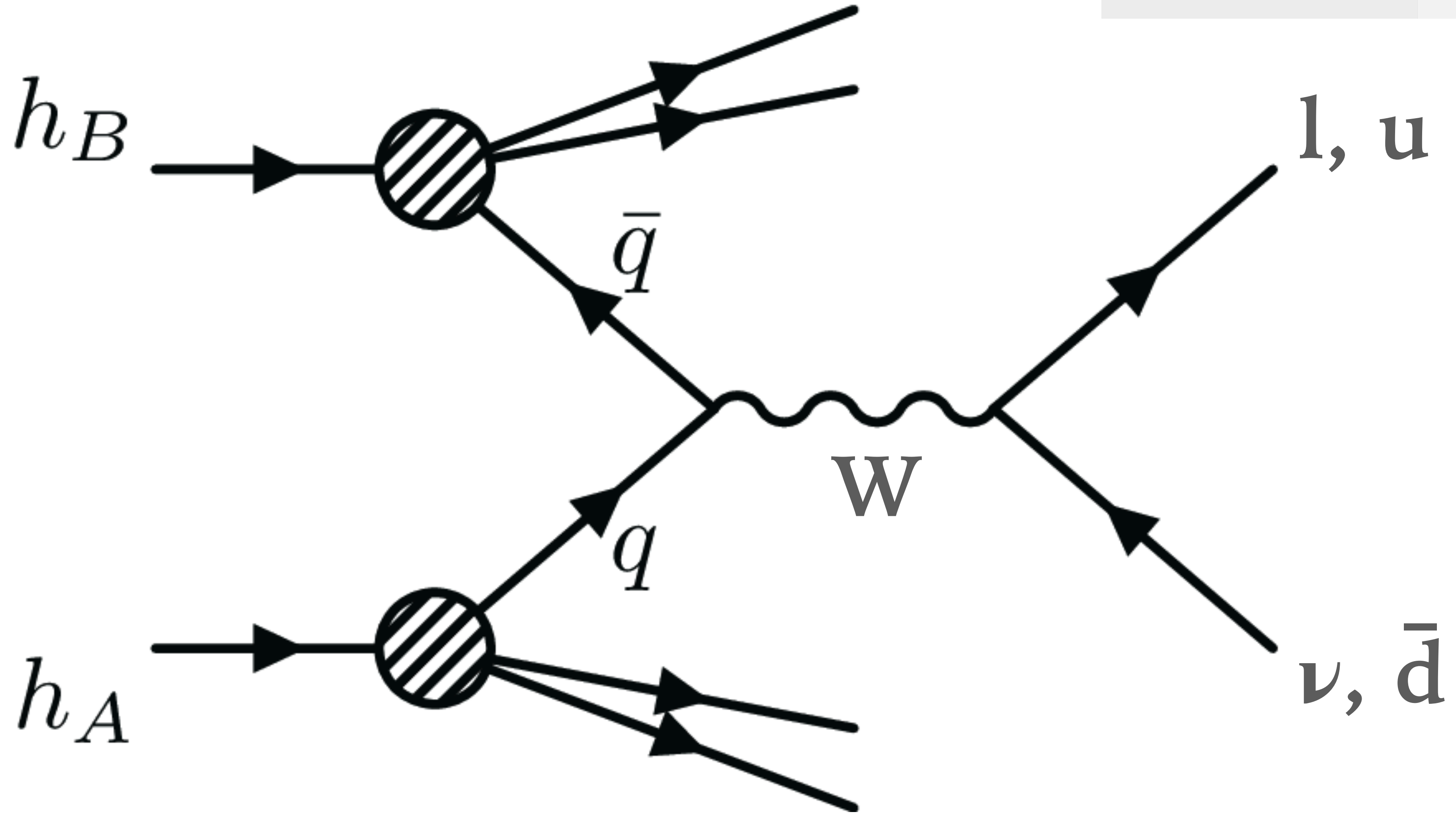
- **Energy/momentum calibration**
  - adjust the position of the Z peak until it corresponds to the value we expect
    ⇒ done by adjusting the energy/momentum scale

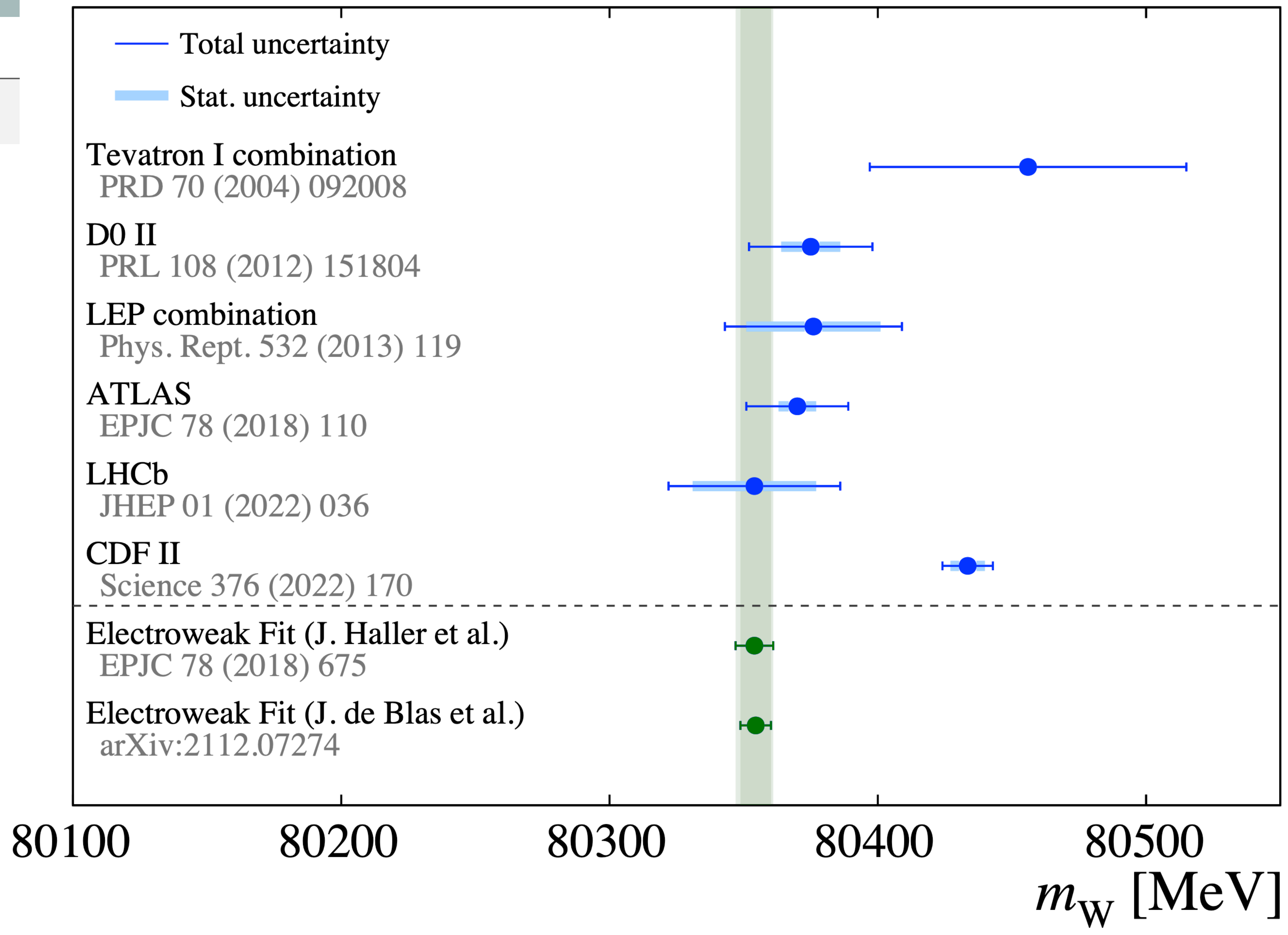
- **Lepton efficiency measurements**
- need clean sample of leptons to measure reconstruction/identification/isolation efficies
  - "Tag and Probe" method
    - select two lepton candidates with tight (Tag) and looser (Probe) selection criteria
    - Require the di-lepton mass to be around the Z peak
      ⇒ likely that both leptons are "good" leptons



W bosons

decay mode	branching ratio
$q\bar{q}$	68.5%
$l\nu$	31.5%



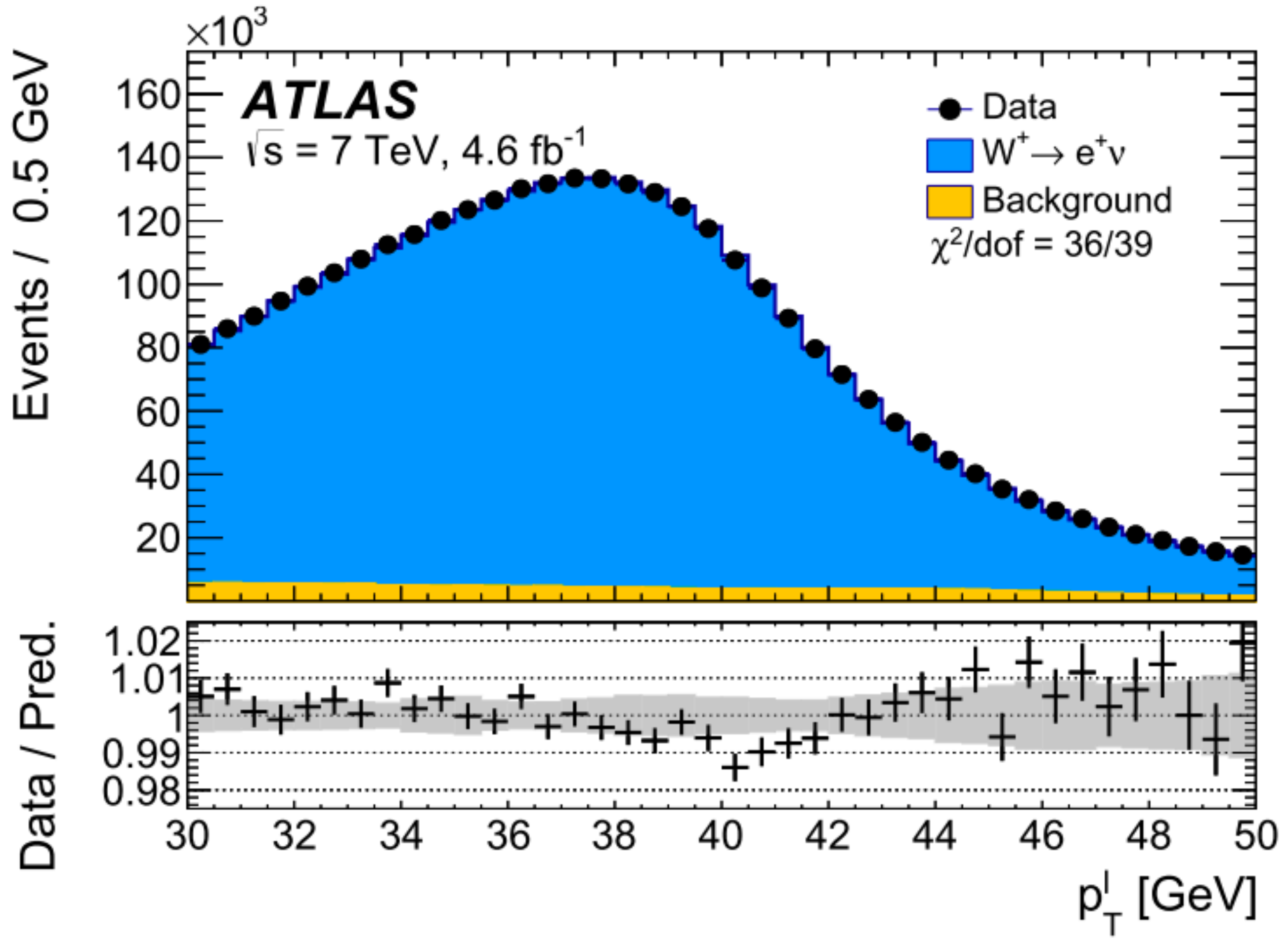


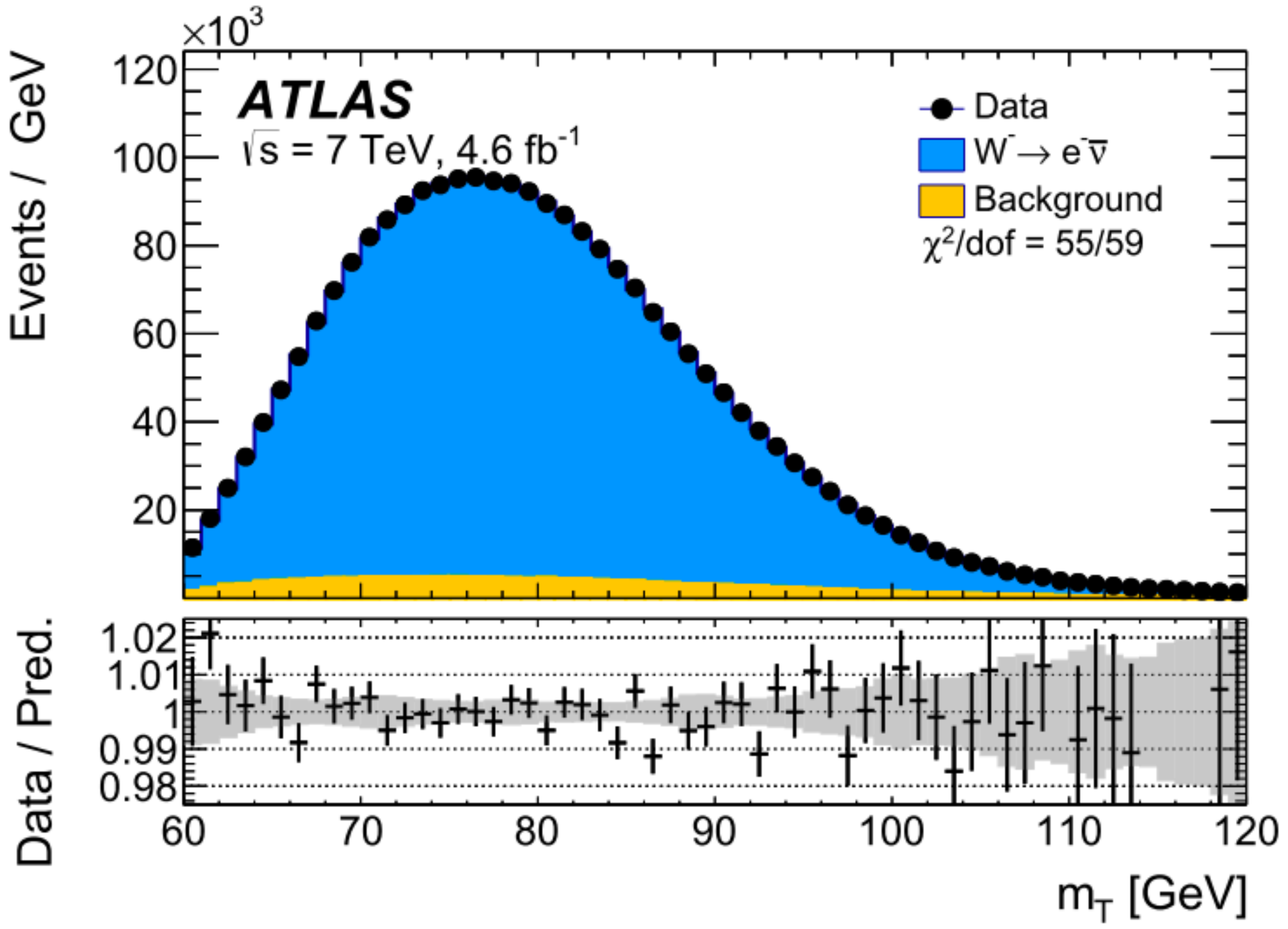
- At the LHC:
  - Special dataset collected with low pile-up
  - 4.6fb^{-1} at 7 TeV ⇒ about 15.5 M W^+ and 10.4 W^- events collected (e + μ)

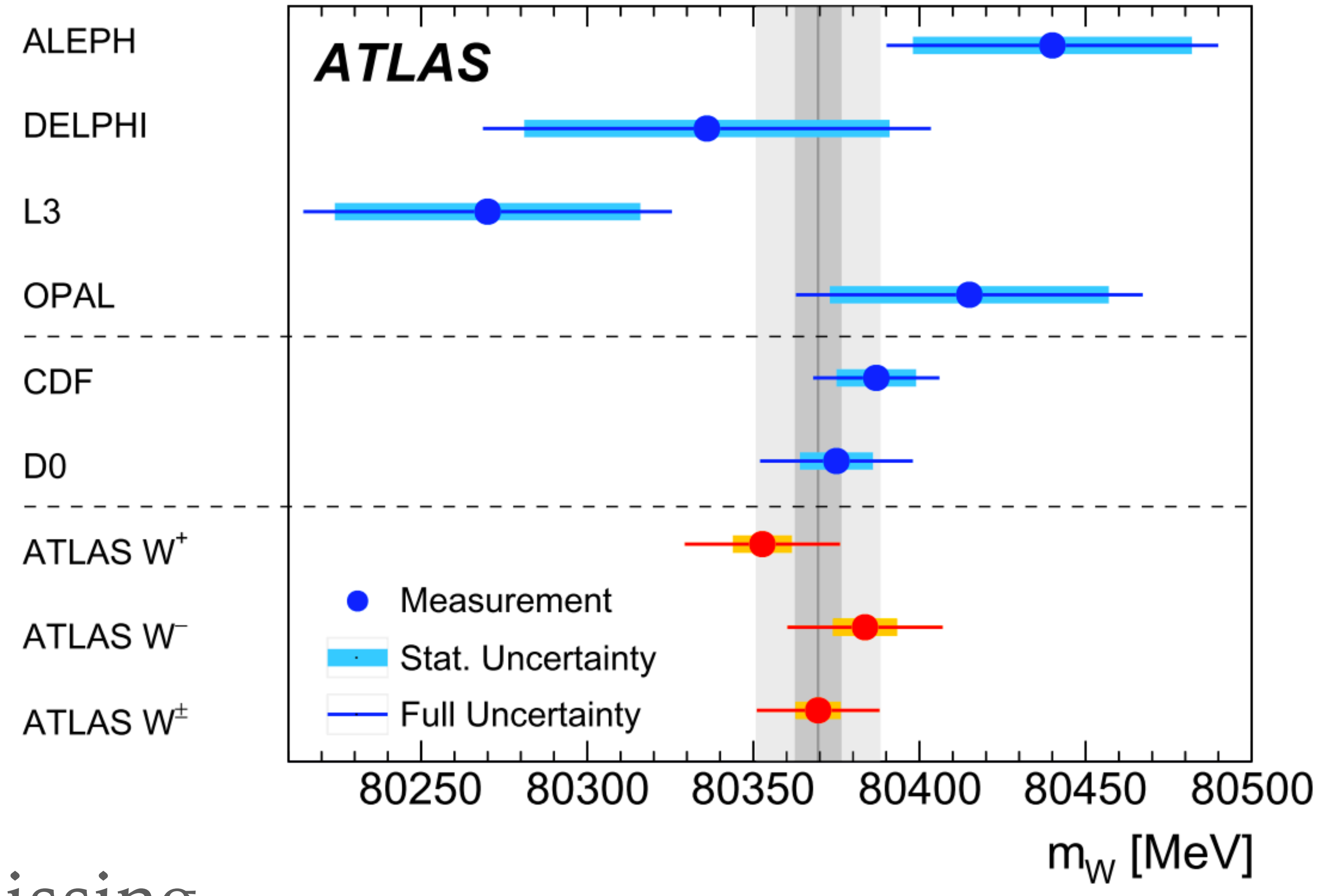
Recent CDF result of W-mass measurement updated 80433 ± 9 MeV

ATLAS W mass measurement

- Analysis strategy based on two kinematic distributions fitted in several categories







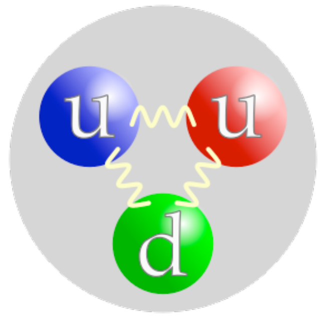
- p^l_T: sensitive to the modeling of the W transverse momentum
- m^l_T: Less sensitive to modeling but needs good understanding of missing transverse energy

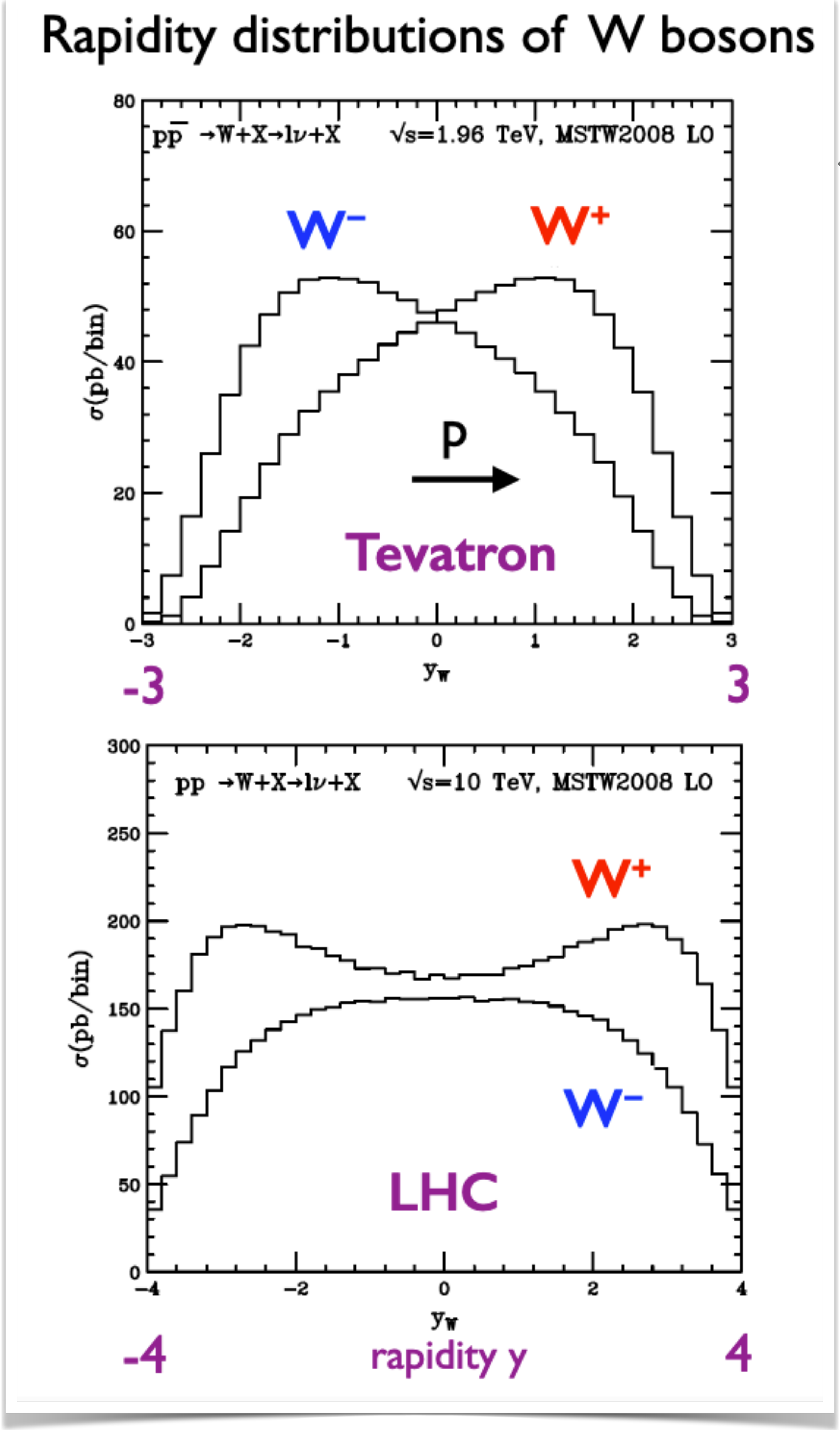
$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$

- 13 TeV low mu dataset on tape ⇒ stay tuned!

W+ vs W- Asymmetry

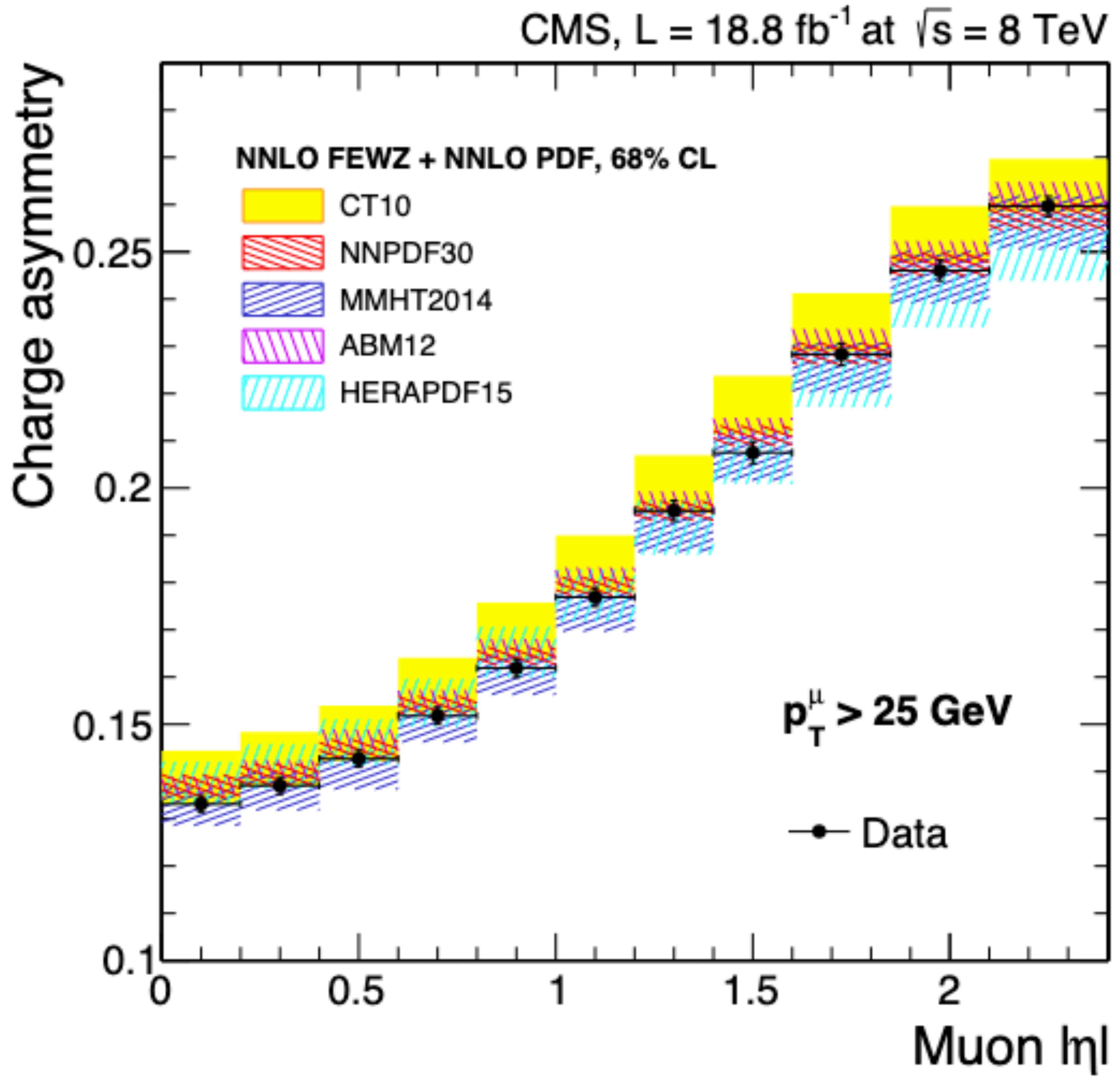
- At the **Tevatron** W^+ (W^-) bosons are produced mainly in proton (antiproton) directions
- At the **LHC** W^+ bosons are produced at higher rate than W^- bosons
  - W^- bosons are produced centrally
  - W^+ bosons are produced at larger rapidities
- Main cause of these asymmetries:
  - on average: u quark carries more proton momentum fraction than the d quark
  - more valence quark involved in W^+ bosons at the LHC



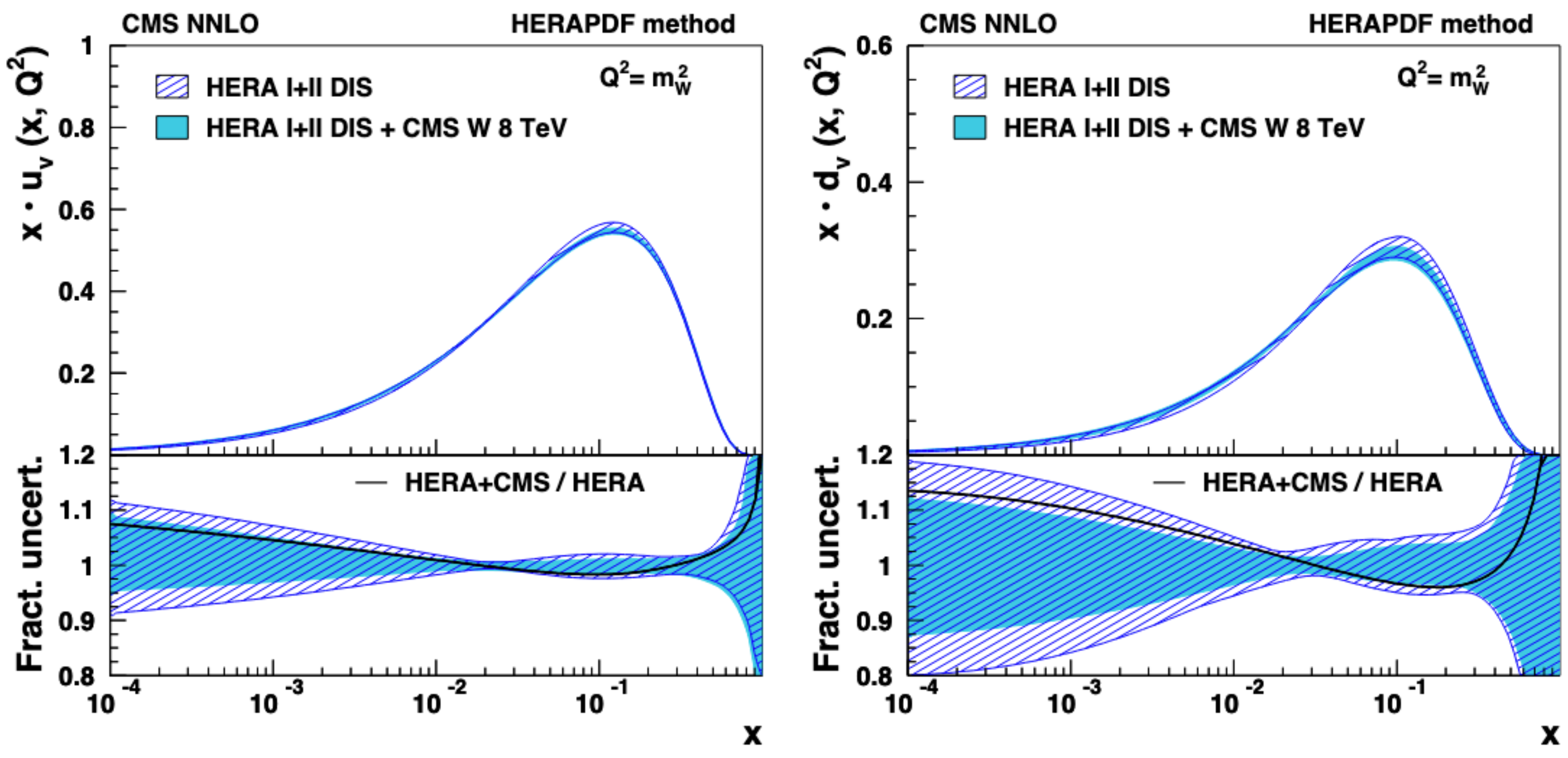


In practice: Measure lepton charge asymmetry

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



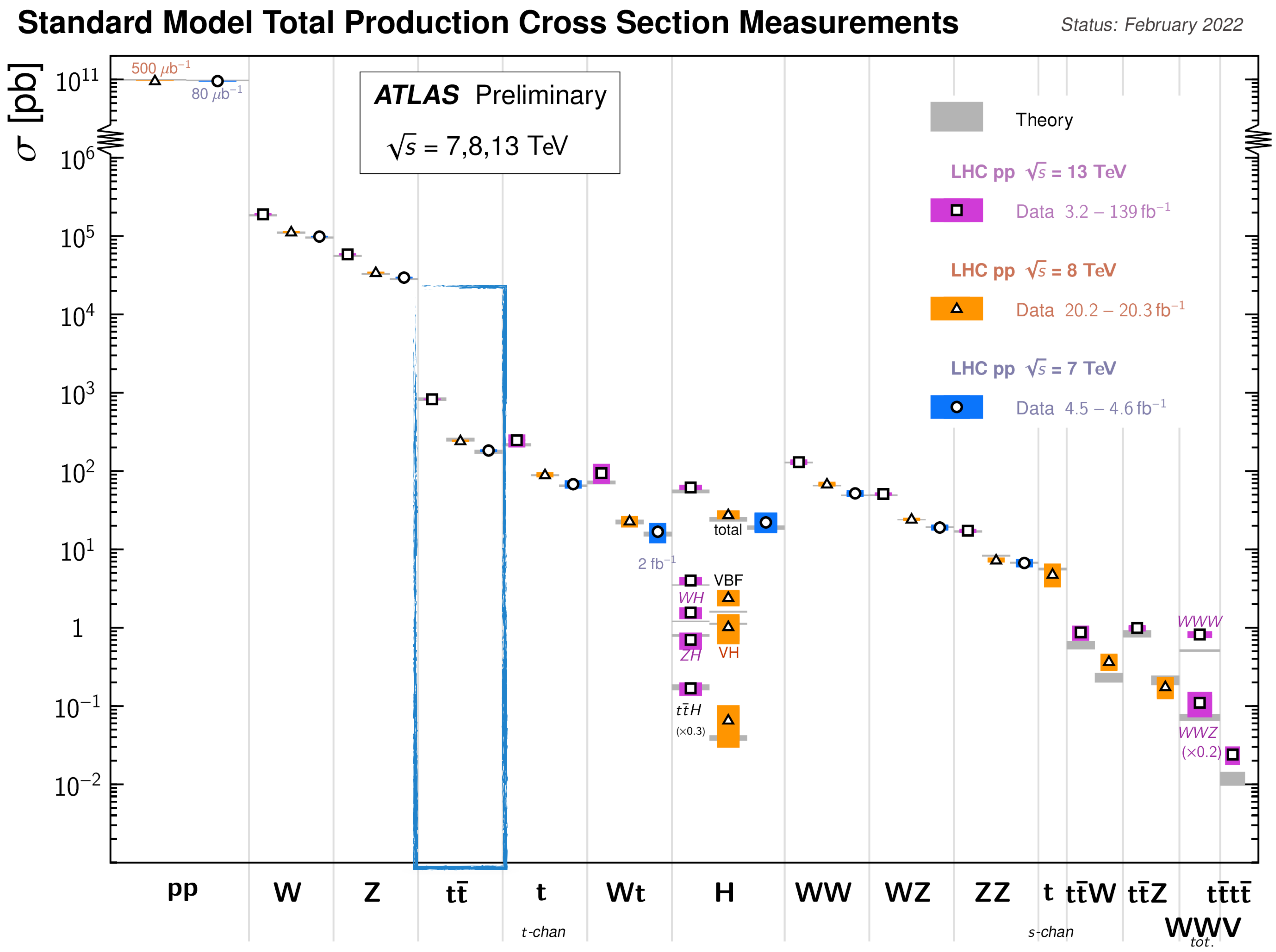
- ➤ Measurements can help to constrain u and d PDFs



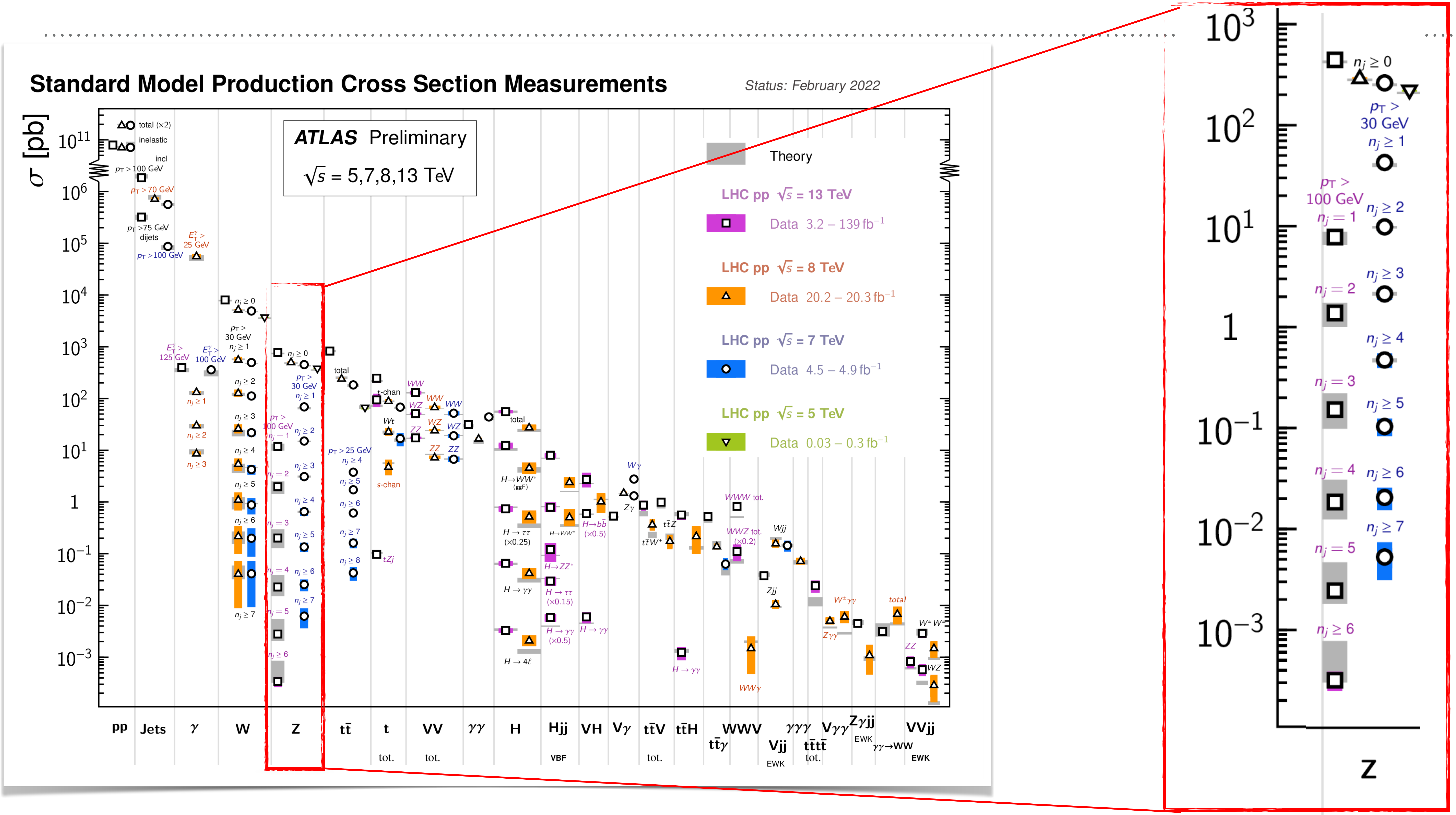
Going to rarer and rarer SM processes

Top quark pair production

→ the LHC is a top factory

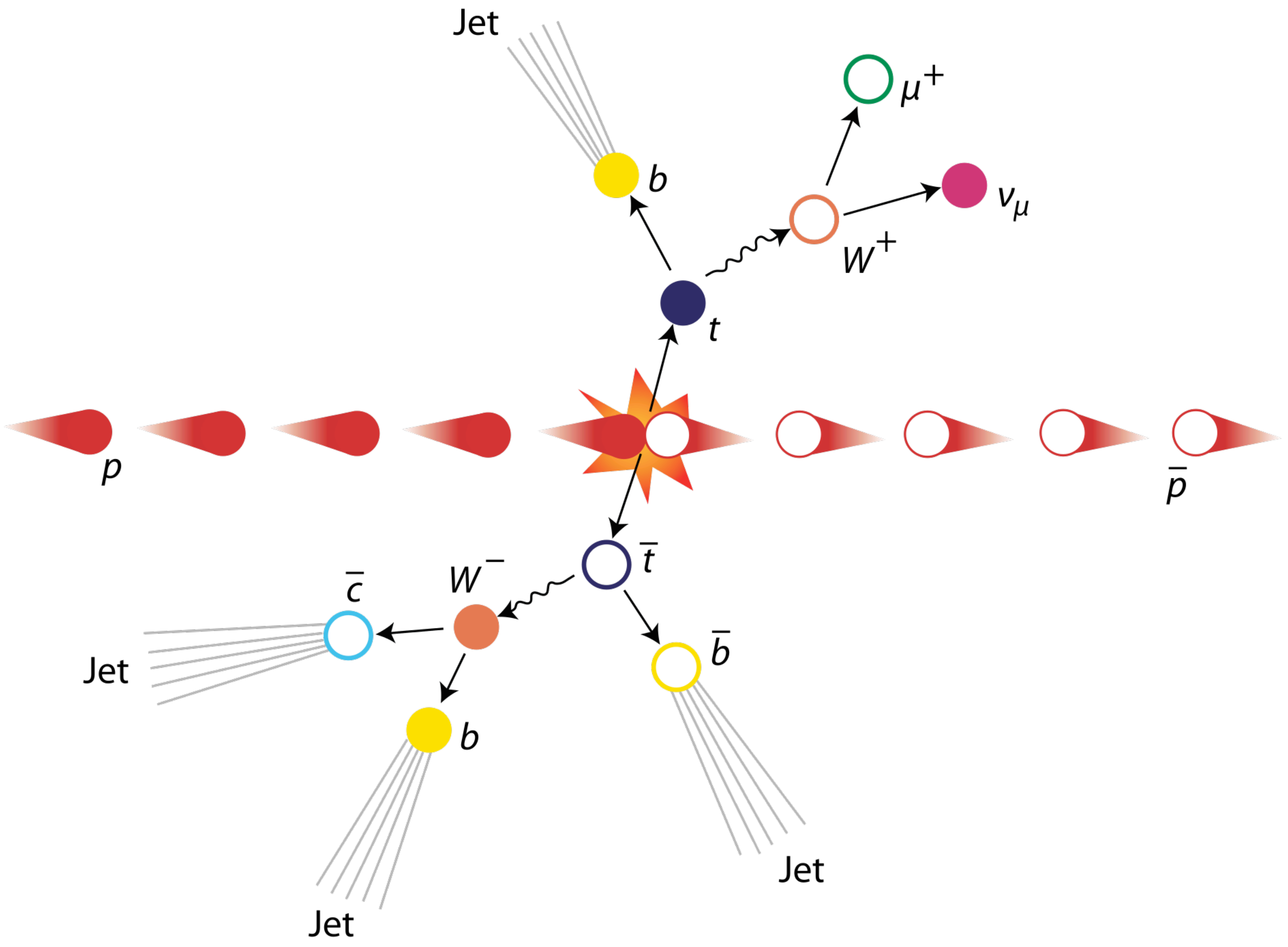


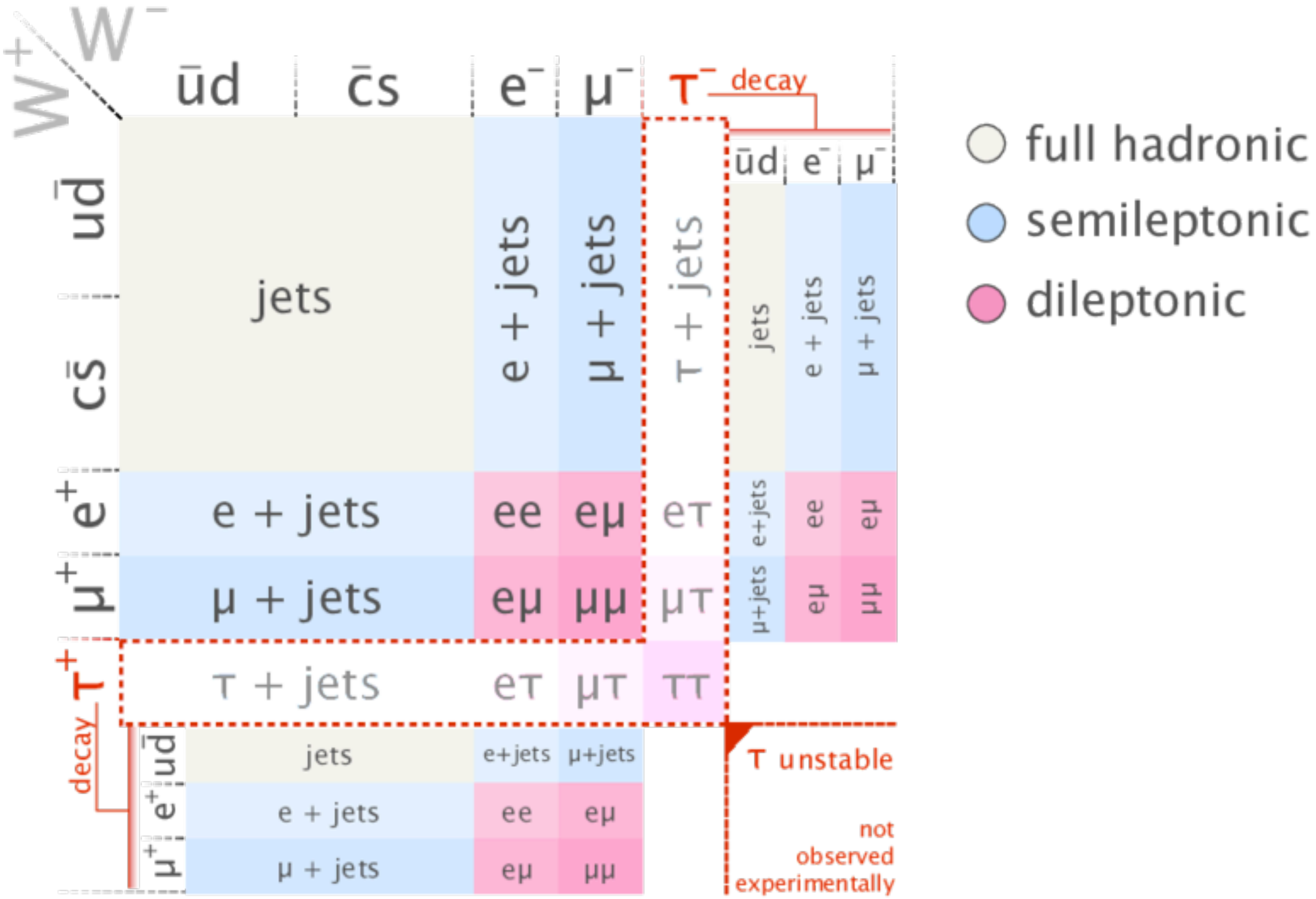
Interlude: fiducial cross sections



Top quark pair production

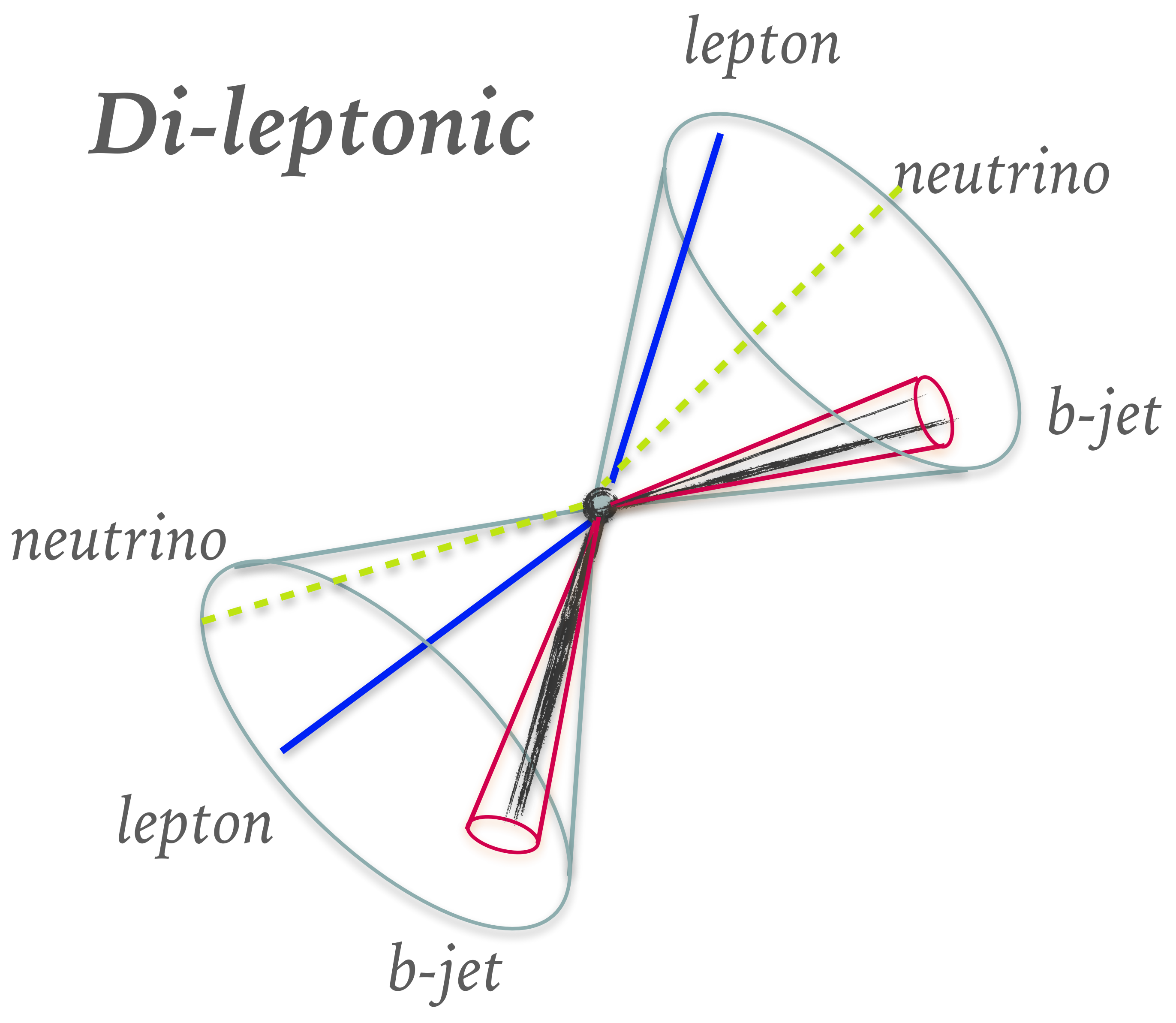
- Top quark discovered 1995 at the Tevatron
- Heaviest quark in the SM
  - decays before it can hadronize
  - almost exclusively into Wb



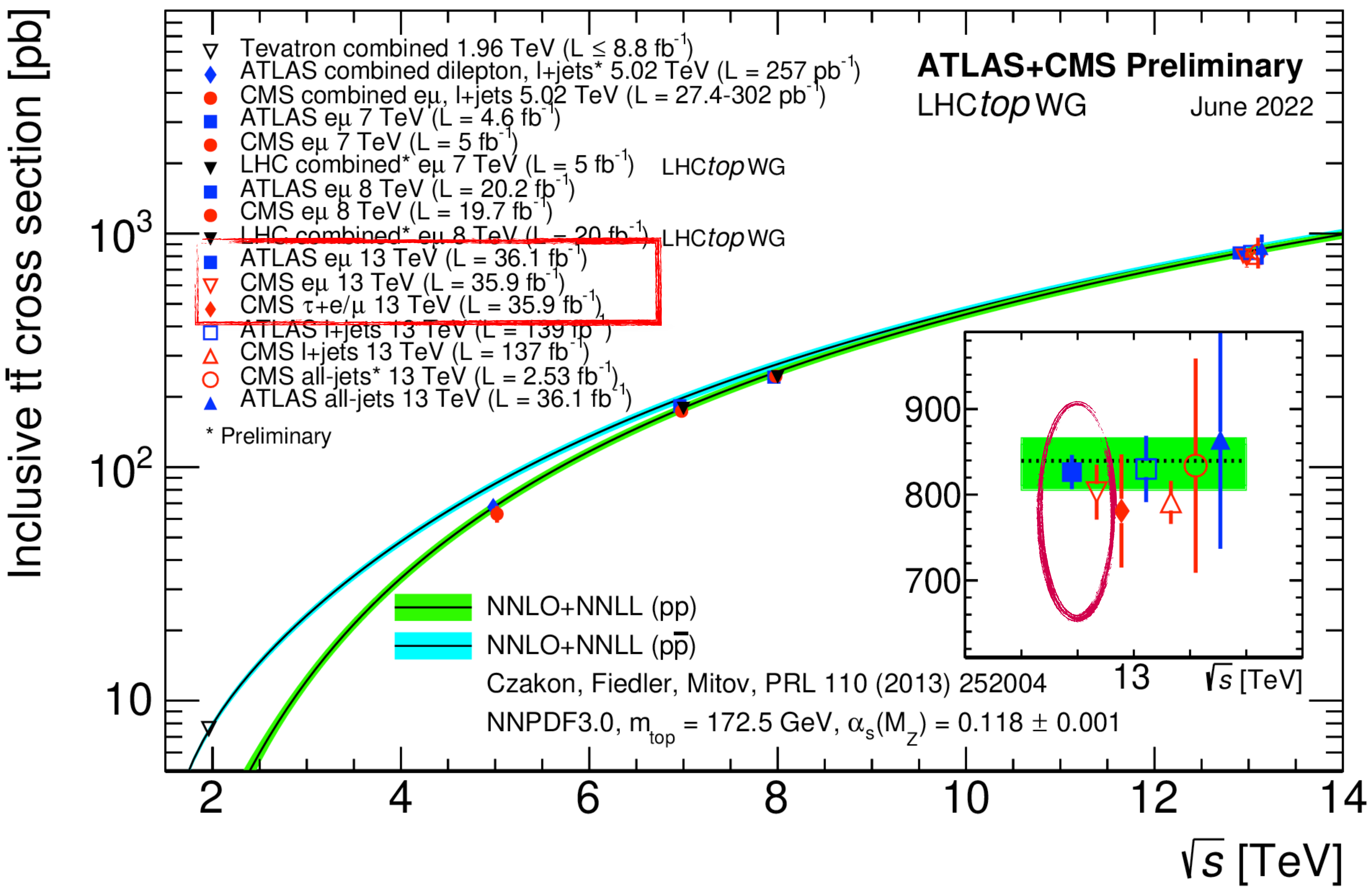


- Has become a "standard candle" at the LHC

Top pair production cross section

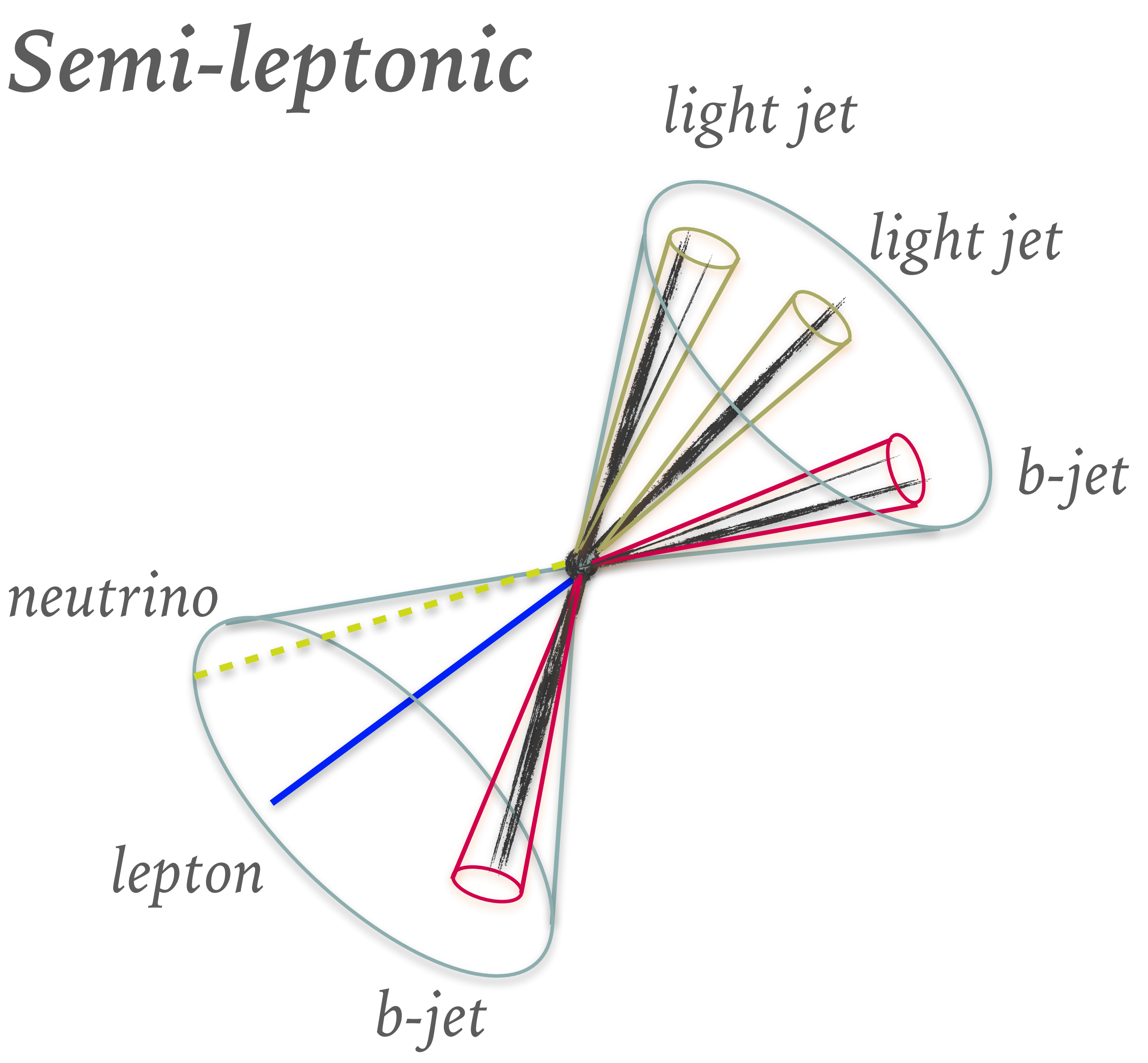


- *precise determination of cross section*
- *eμ channel very clean*
- *excellent signal to background ratio*
- *lower stats (4%)*

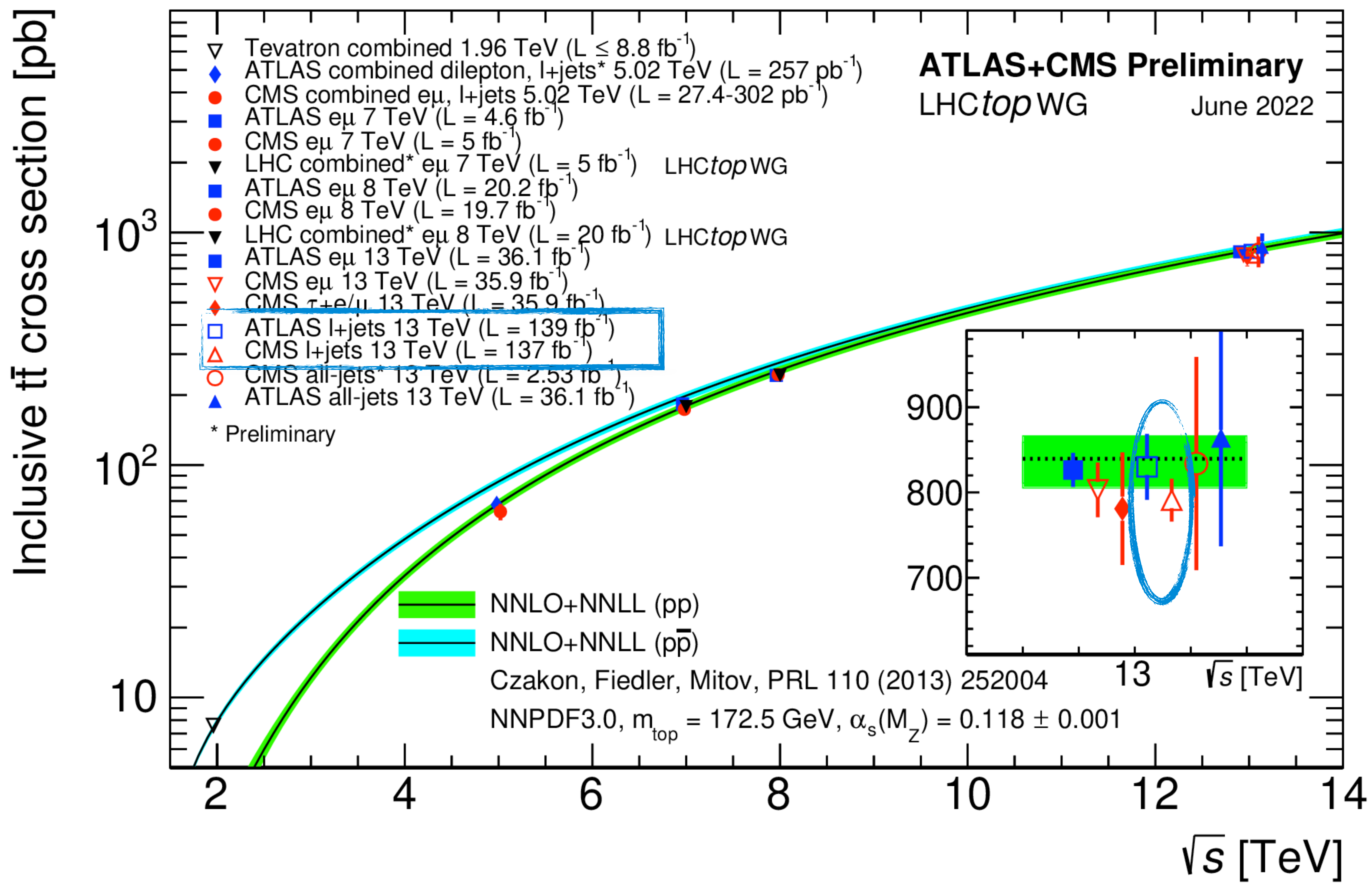


➤ Excellent agreement between measurement and NNLO+NNLL prediction

Top pair production cross section



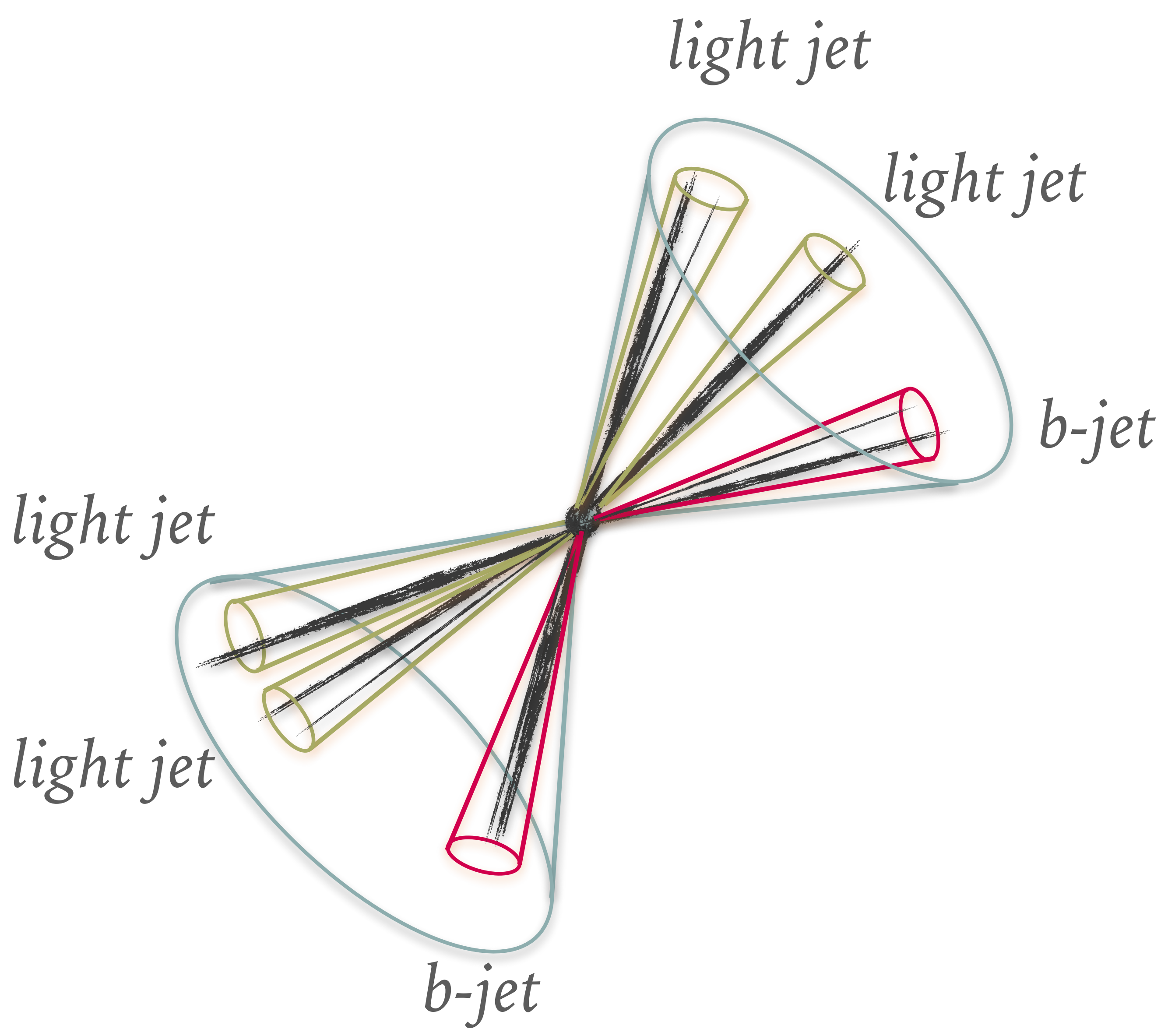
- best compromise between statistics (30%) and signal to background ratio



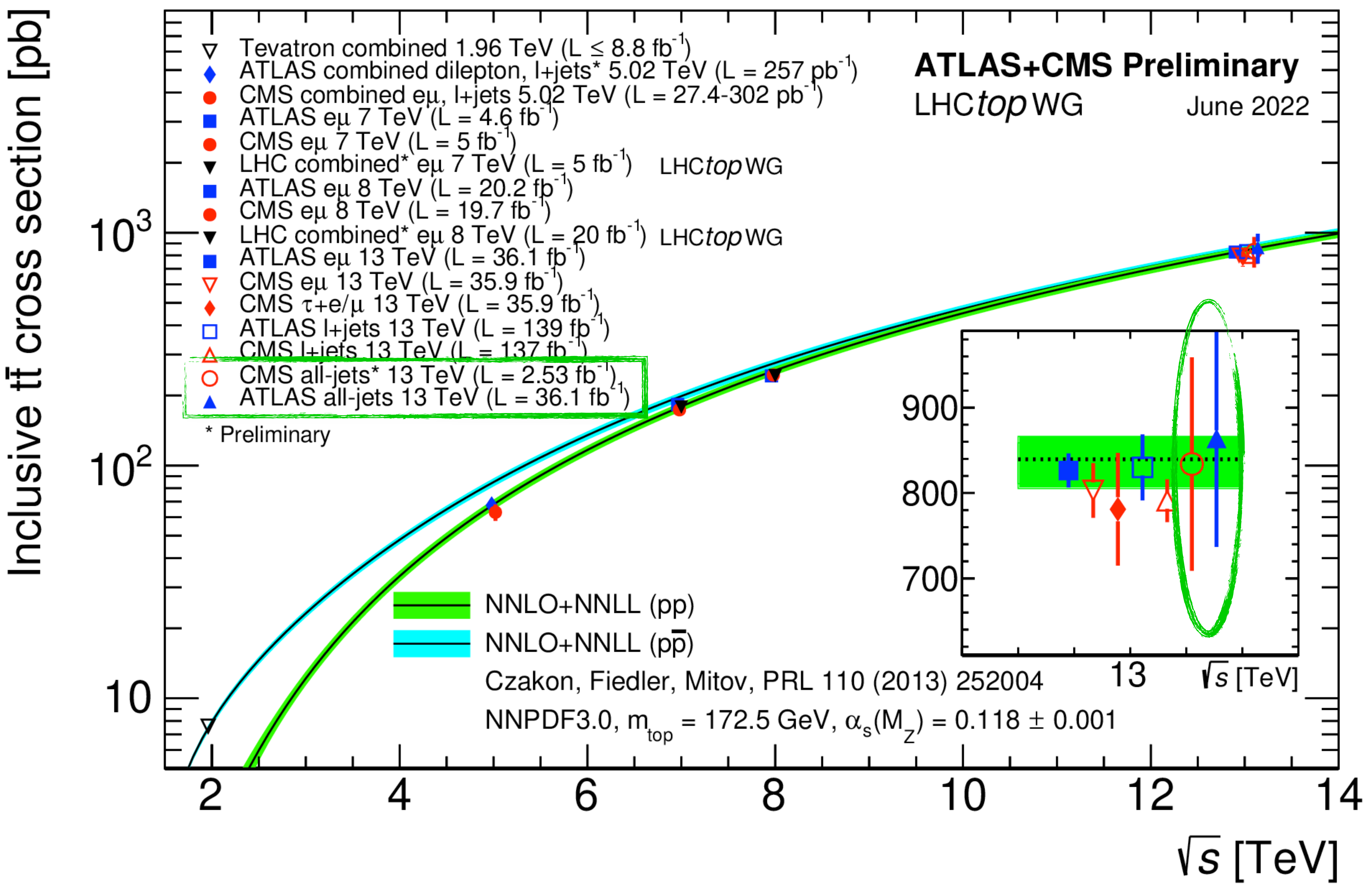
➤ Excellent agreement between measurement and NNLO+NNLL prediction

Top pair production cross section

Fully hadronic



- *largest stats (50%)*
- *but larger multi-jet background and*
- *large combinatorics*

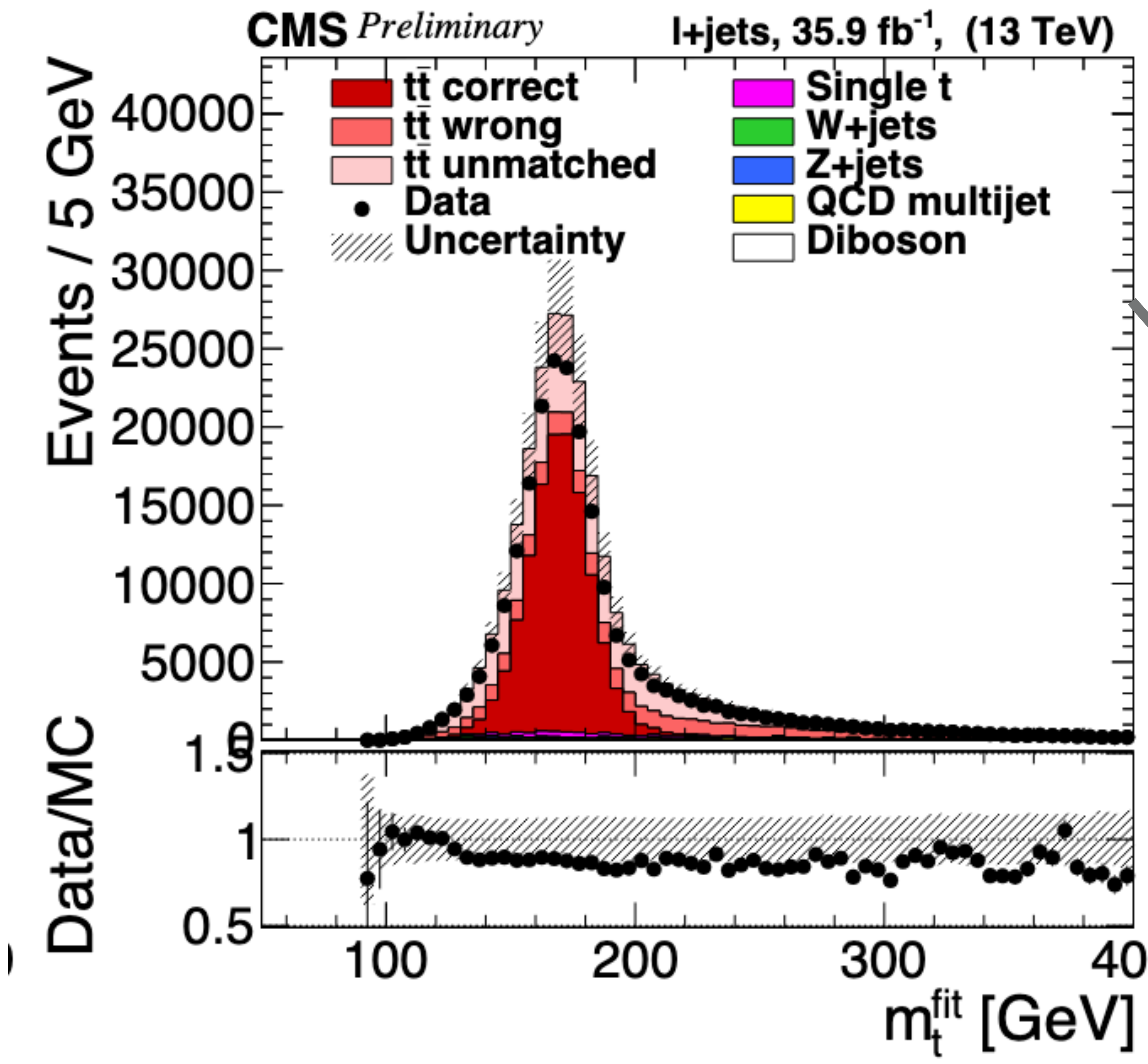


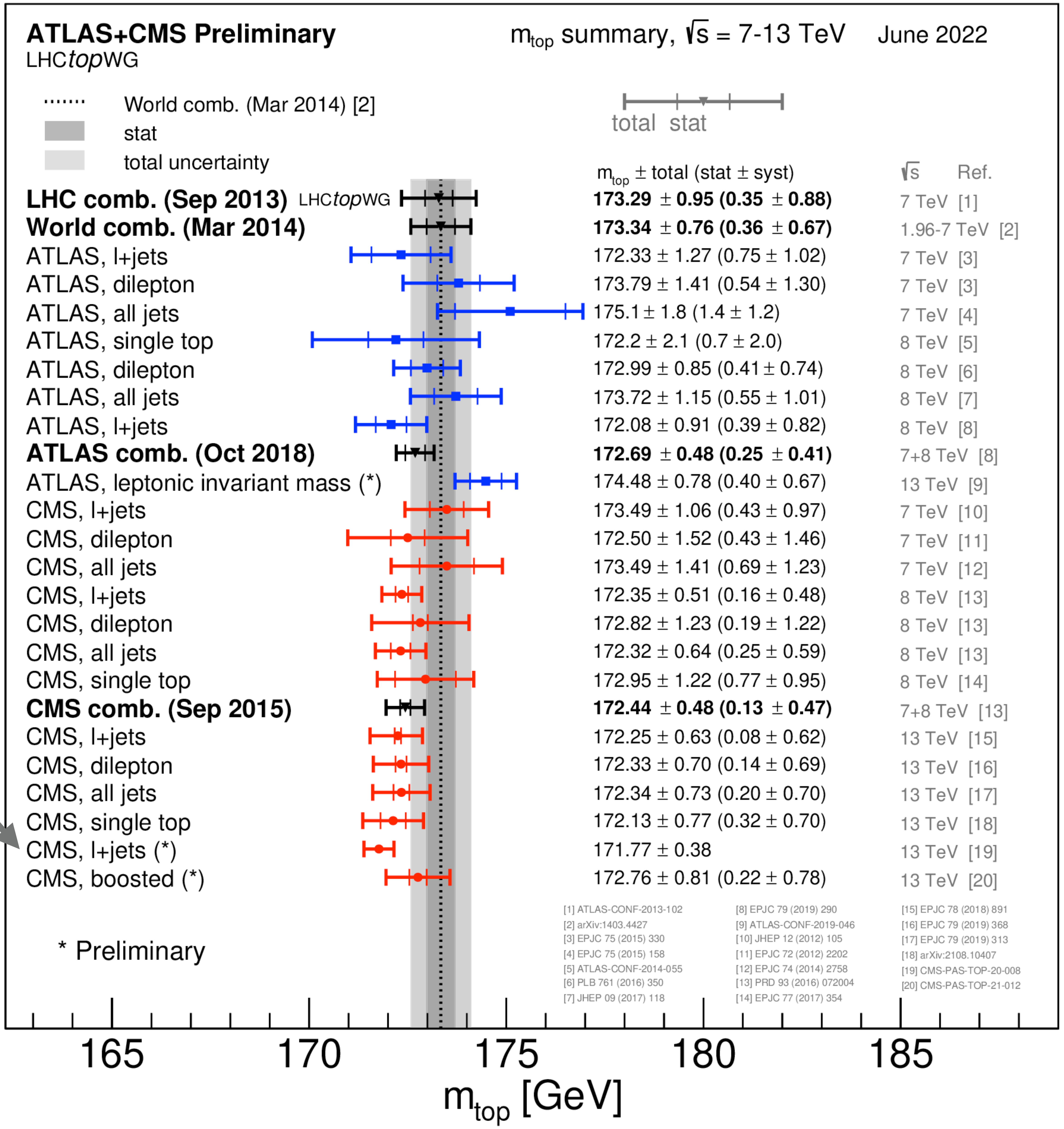
➤ Excellent agreement between measurement and NNLO+NNLL prediction

Measuring the top quark mass

- All channels have been used to measure the top quark mass
- Semi-leptonic channel often yielding best results

Maximum likelihood fit to several kinematic variables

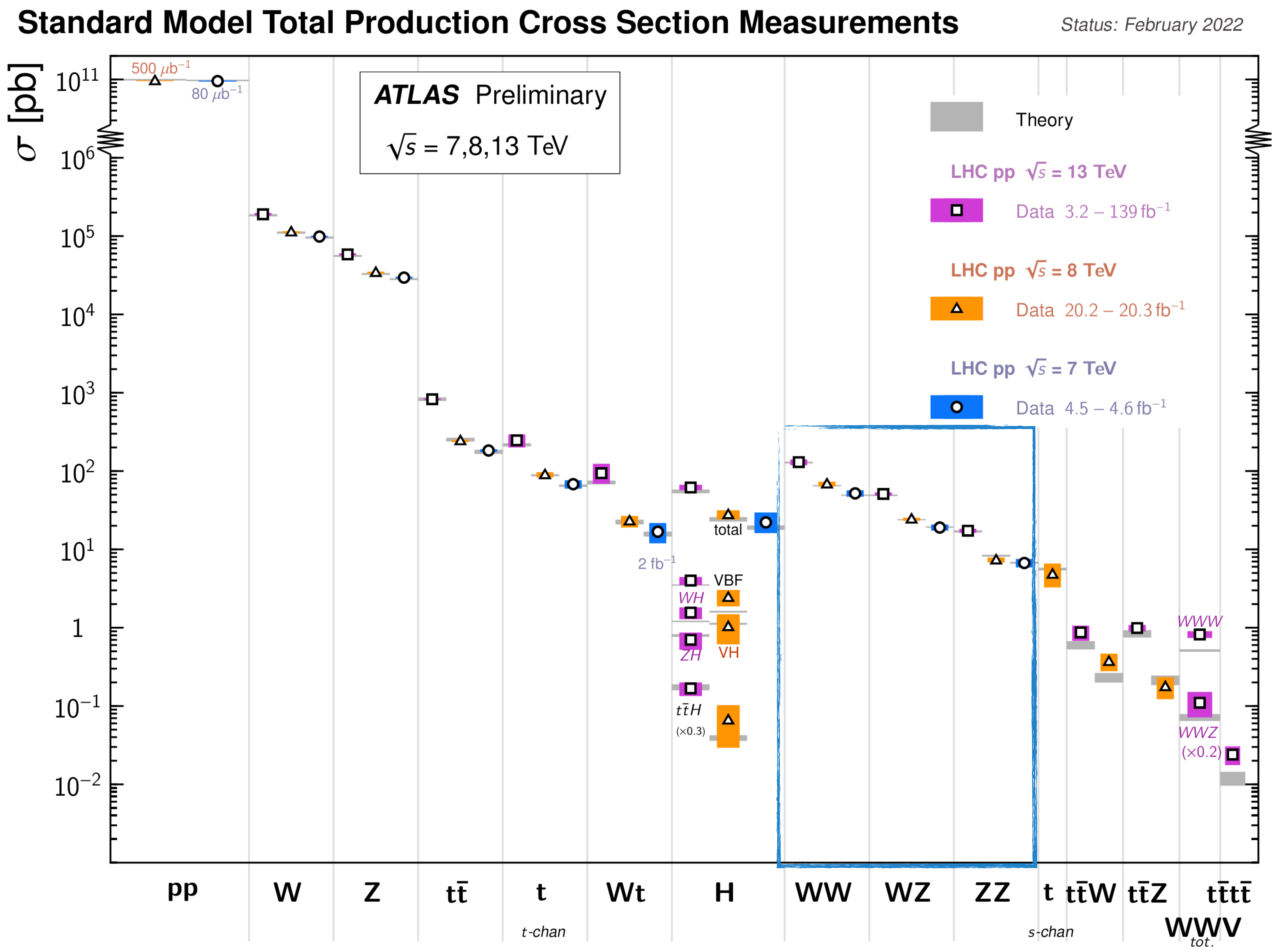




Most precise measurement: 171.77 ± 0.38 GeV (including 0.04 GeV statistical uncertainty)

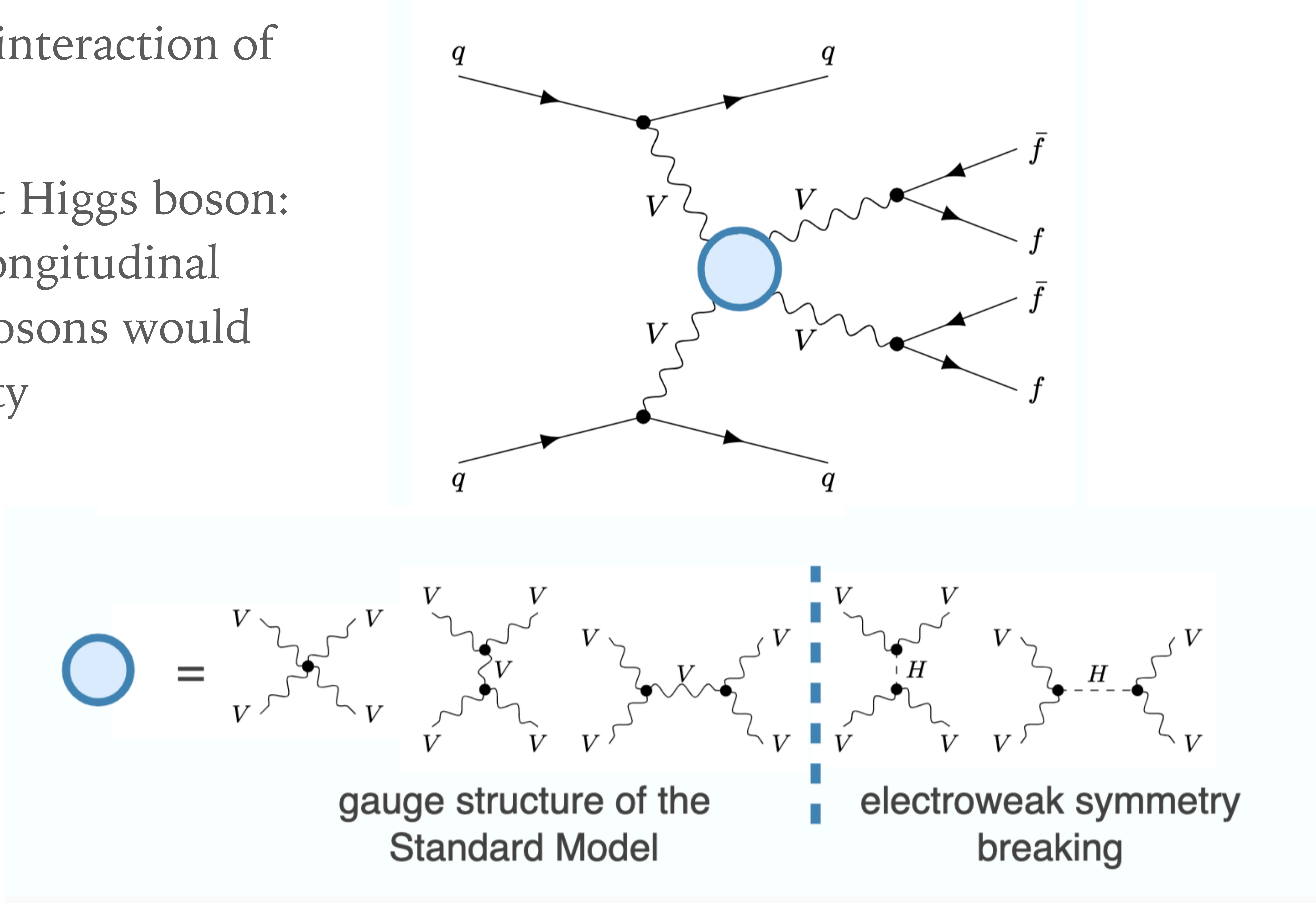
Going to rarer and rarer SM processes

Di-boson production

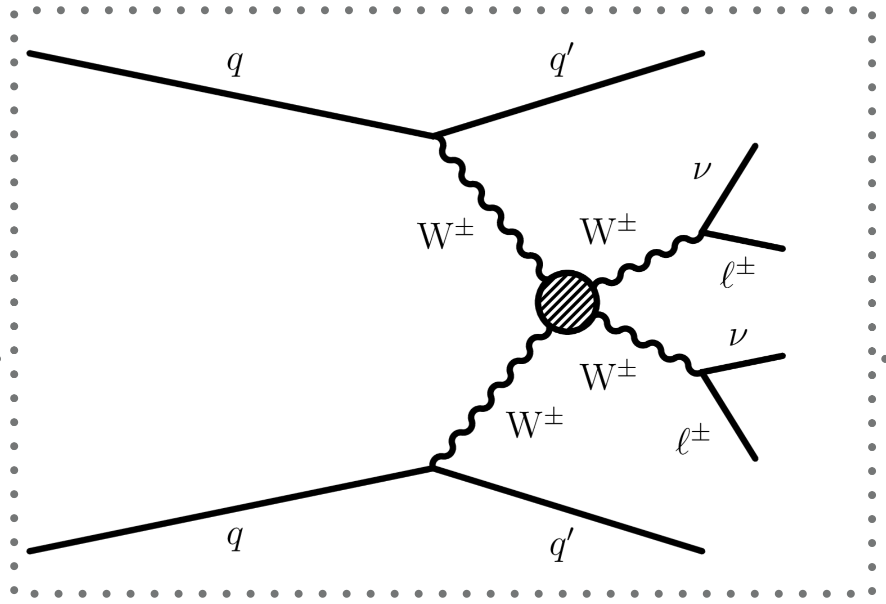


Multi-boson production

- SM predicts self-interaction of vector bosons
  - without a light Higgs boson: scattering of longitudinal polarized W bosons would violate unitarity

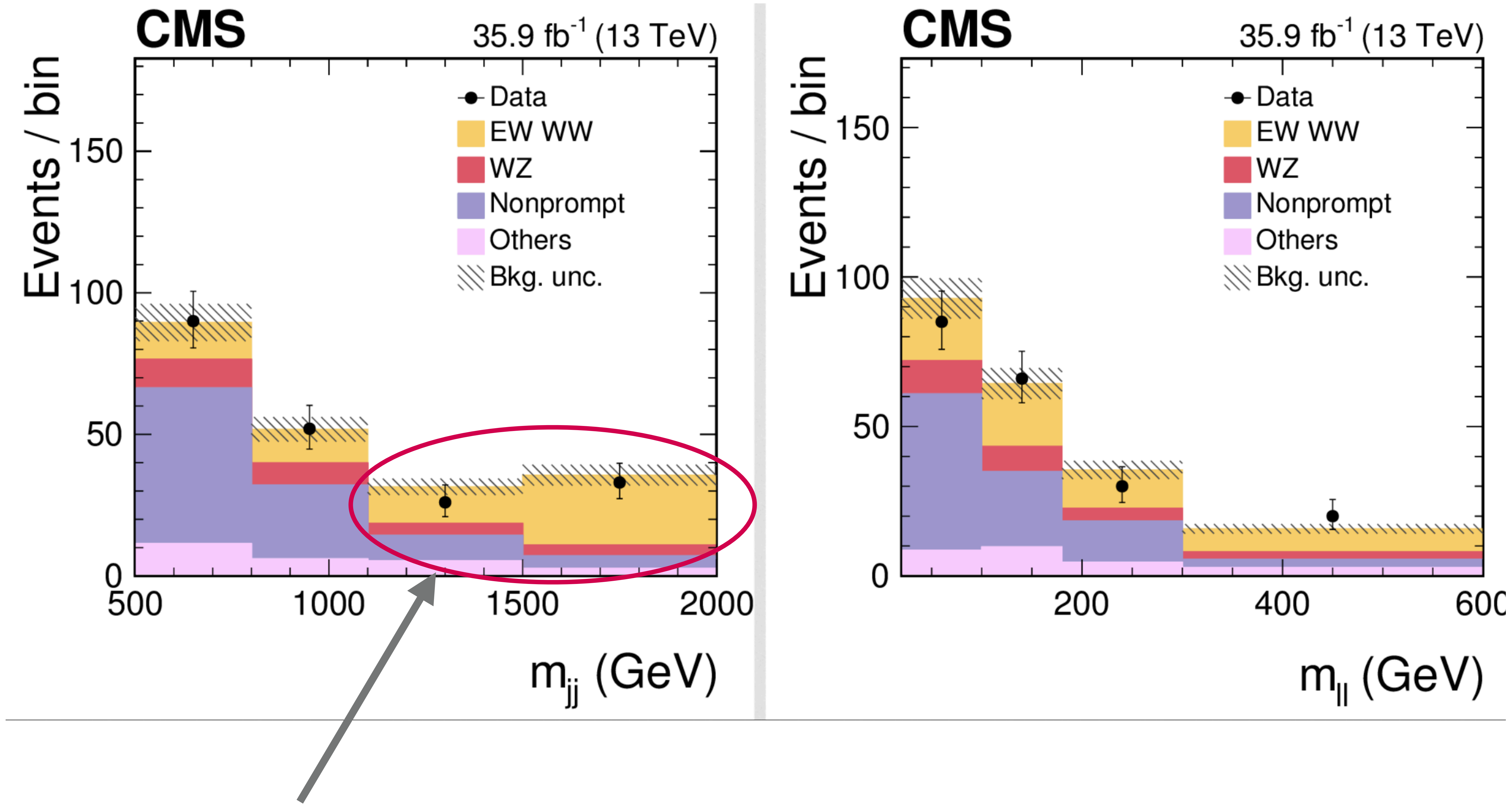


Same-sign WW



- **Signal selection**
  - 2 jets with large separation large invariant mass
  - 2 leptons, same charge
    - reduces Z+jets background
    - charge mis-ID is a challenge
  - MET
- **Backgrounds**
  - **WZ** with one lepton lost 3 lepton CR
  - lepton fakes - estimated from data

Observed (expected) significance of **5.5 (5.7) sigma**



Signal populates high m_{jj} region

ZZ production

➤ **Signal selection**

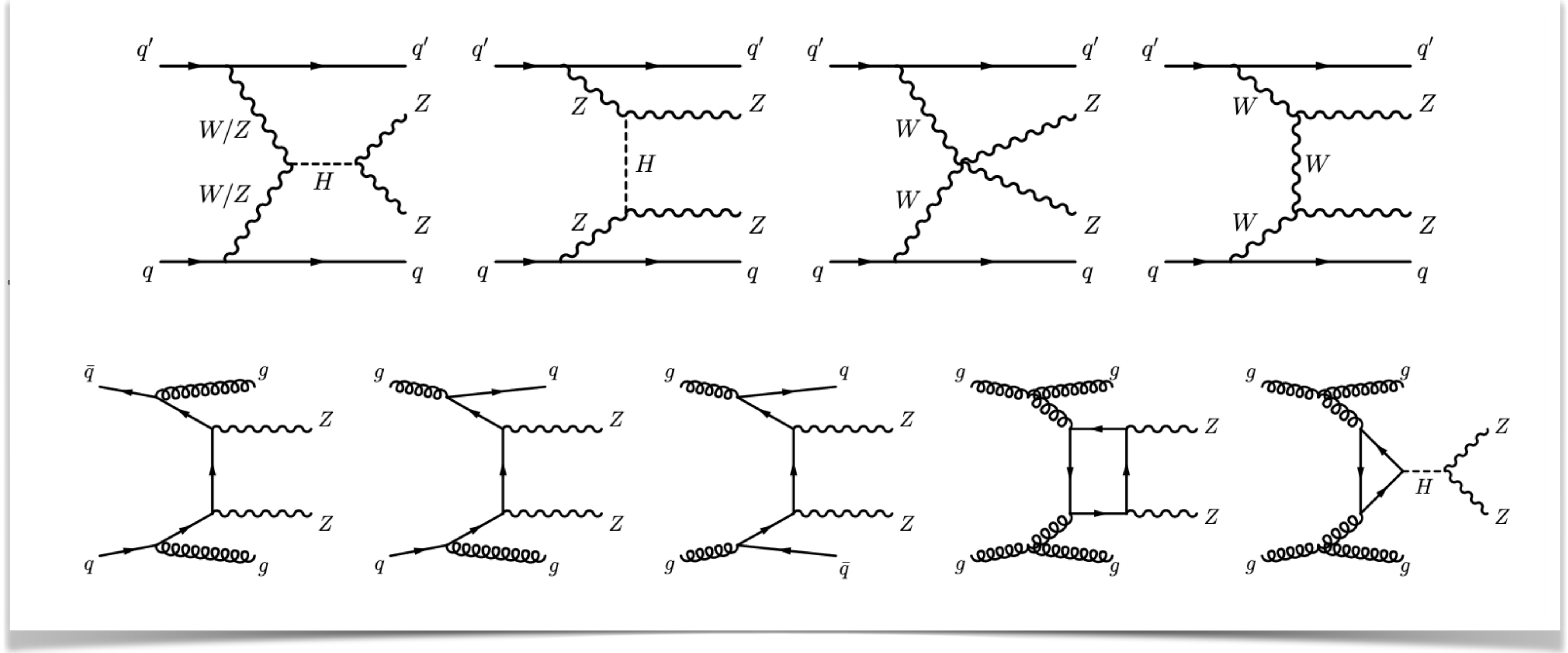
➤ 2 jets with large separation large invariant mass

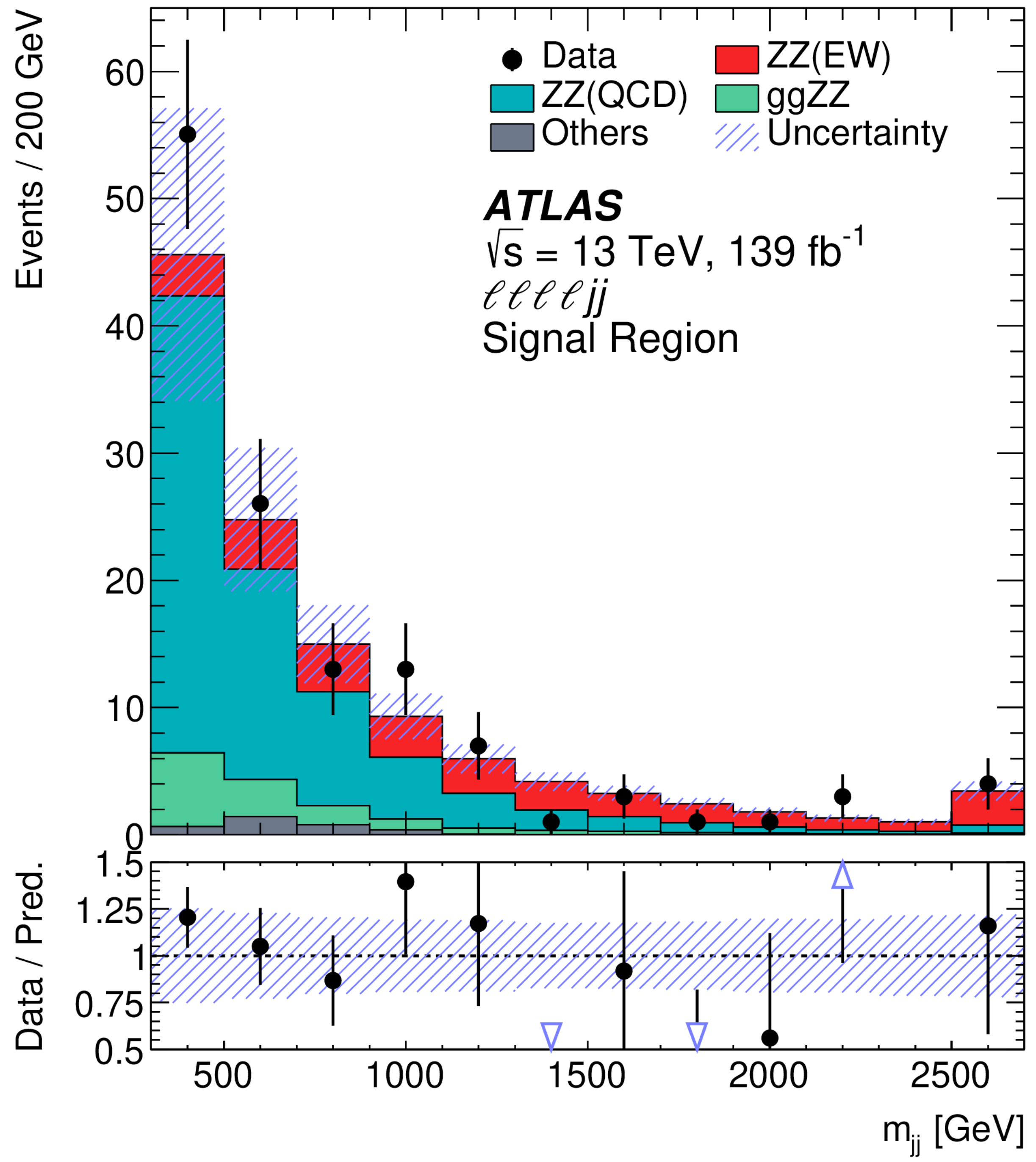
➤ 4 leptons same-sign opposite flavor

➤ or 2 leptons + MET

EWK

QCD

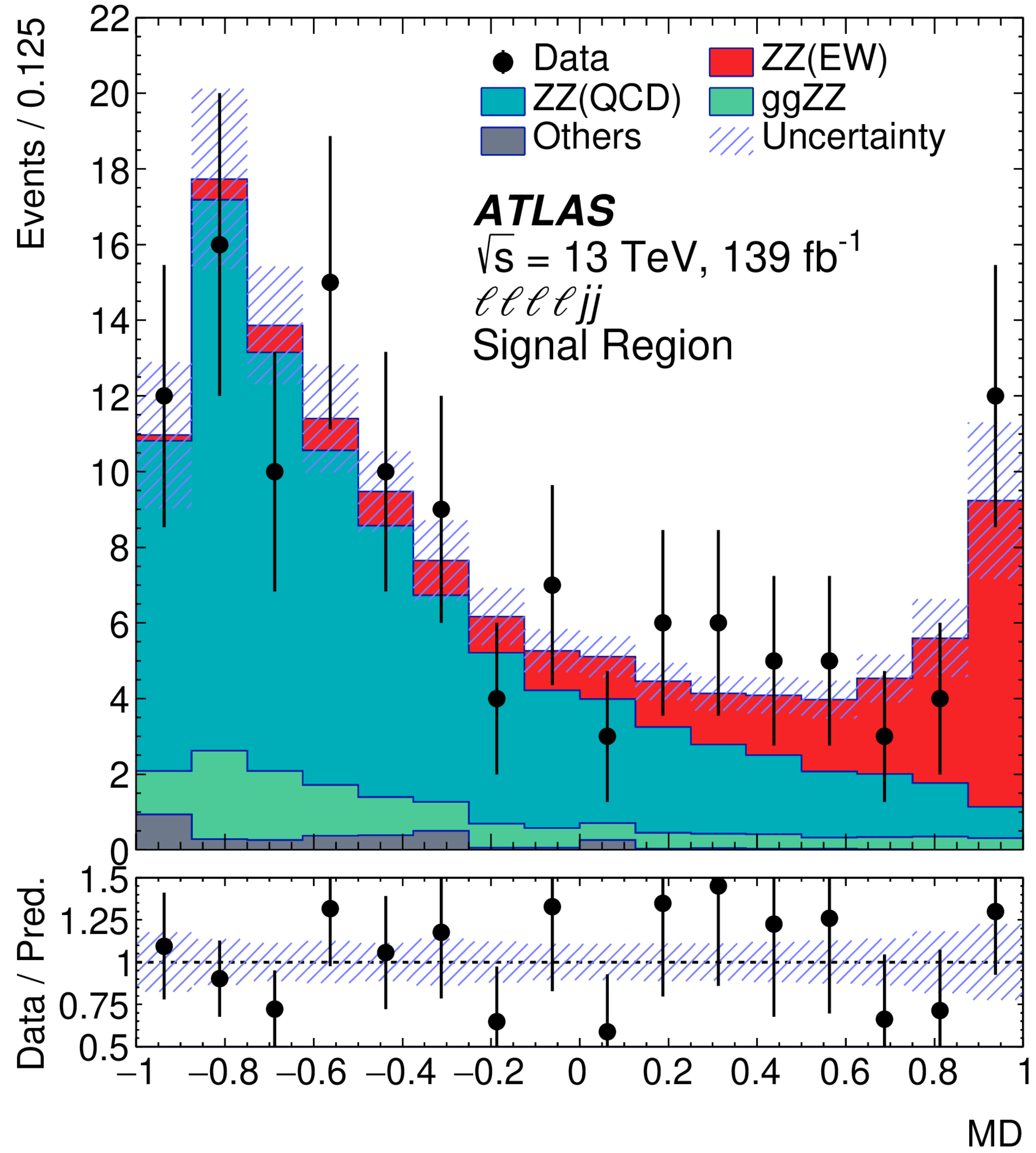




From kinematic variables to improved discriminators

Inputs to BDT:

- *mjj, Δy(j1,j2), pT(j1) pT(j2), pT(Z boson) …*

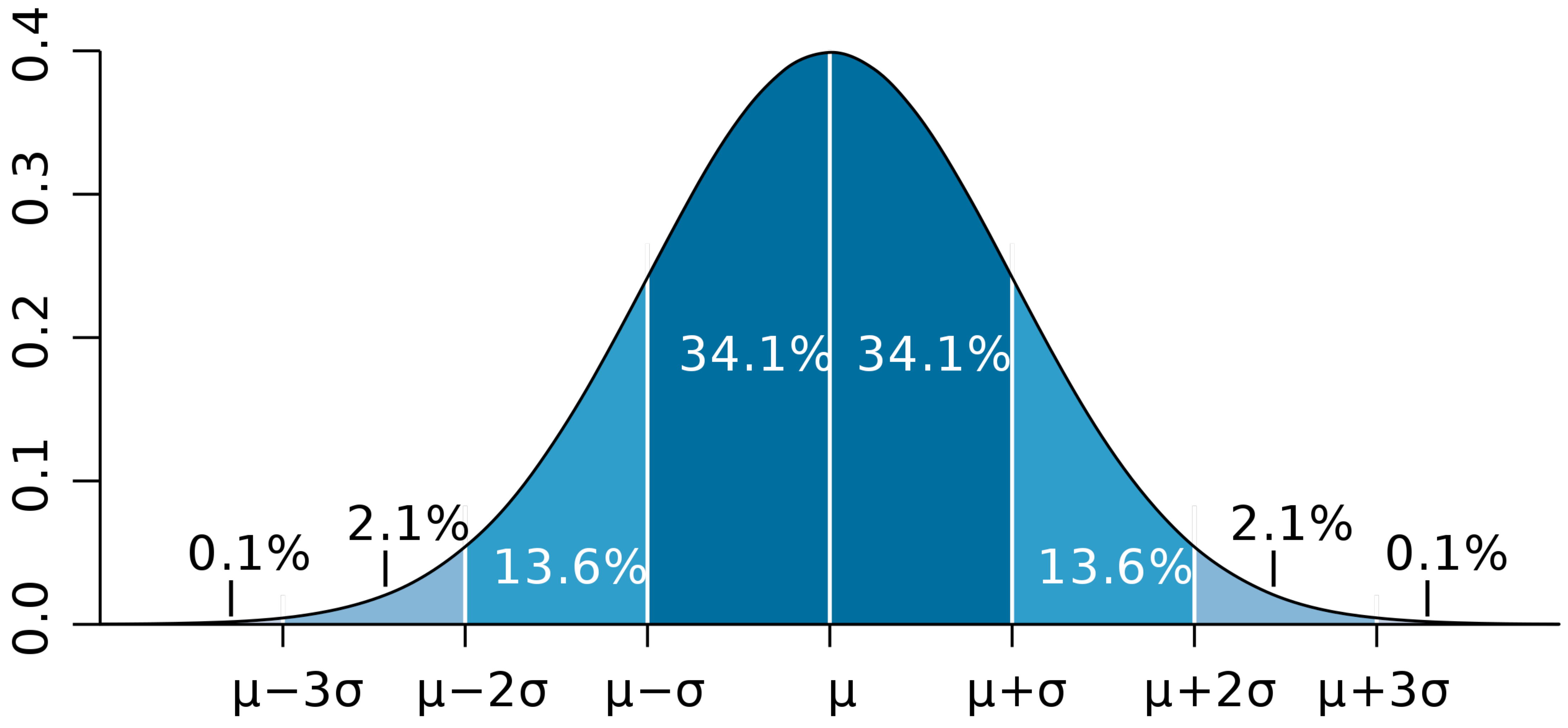


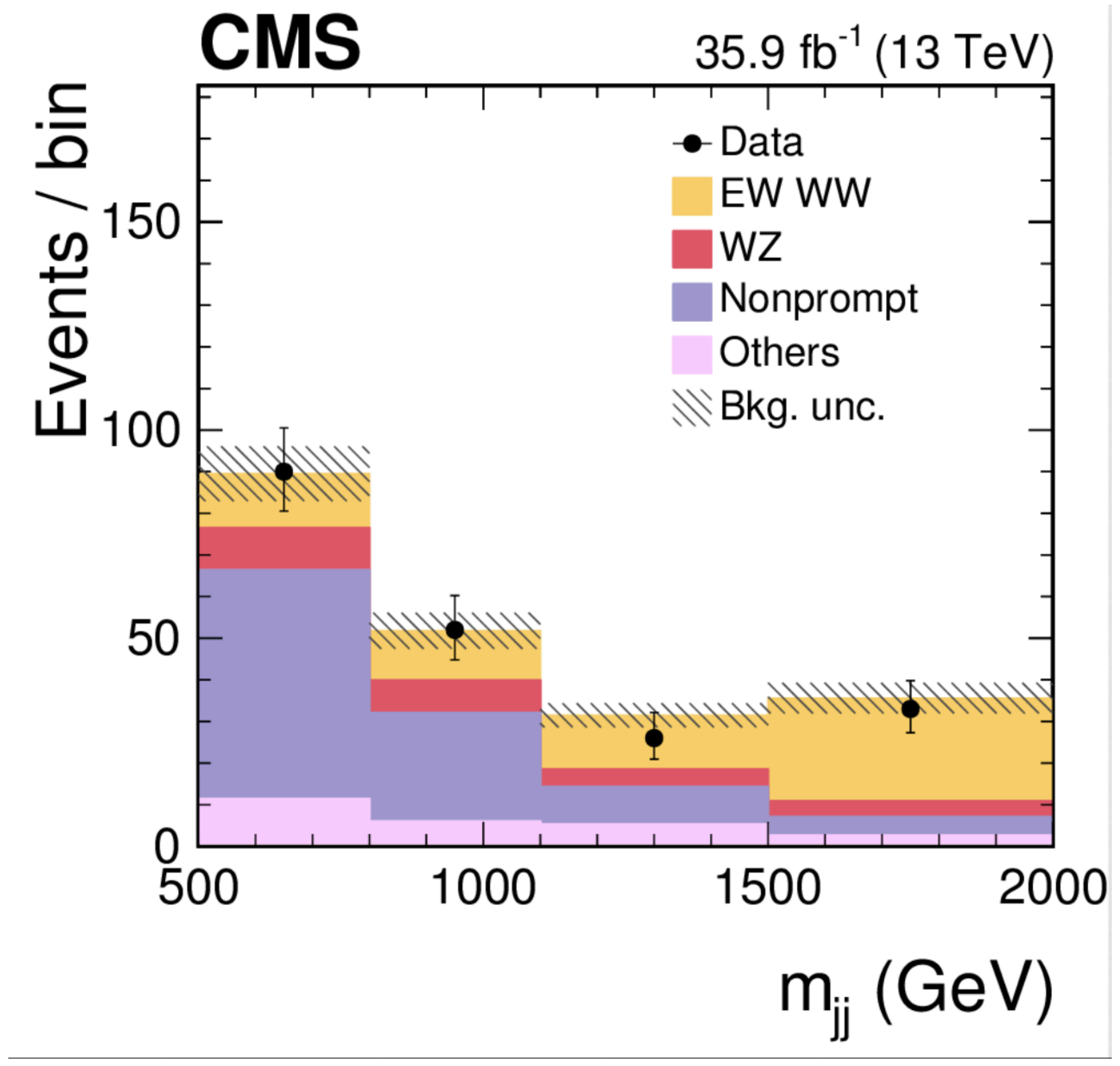
Observed significance of **5.5 sigma**

[arXiv:2004.10612]

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





imagine this plot without the yellow histogram

0.05 ⇒ 2 sigma
0.003 ⇒ 3 sigma (evidence)
0.0000003 ⇒ 5 sigma (discovery)

A word on global SM fits

- The fine structure constant:
  - $\alpha = 1/137.035999679\ (94)$

    Determined at low energy by electron anomalous magnetic moment and quantum Hall effect
- The Fermi constant:
  - $G_F = 1.166367(5) \times 10^{-5}\ \text{GeV}^{-2}$

    Determined from muon lifetime
- The Z boson mass
  - $M_Z = 91.1876(21)$ GeV

    From LEP measurement

From these can calculate m_W

the weak mixing angle $\sin^2\theta_W$

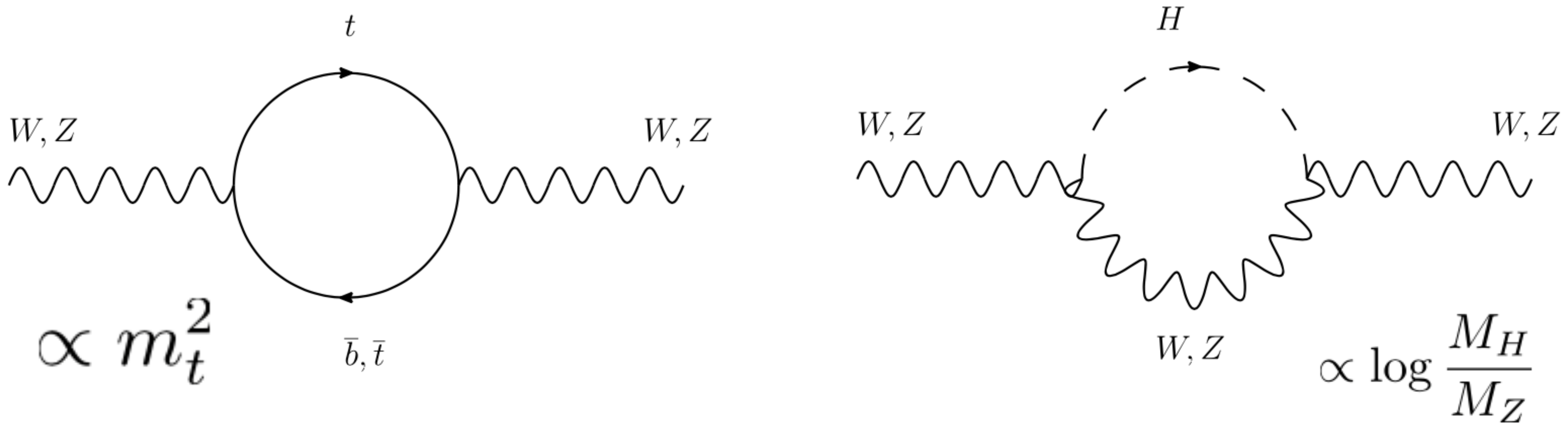
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

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

We haven't discussed the Higgs yet, but lets assume it exists!

A word on global SM fits

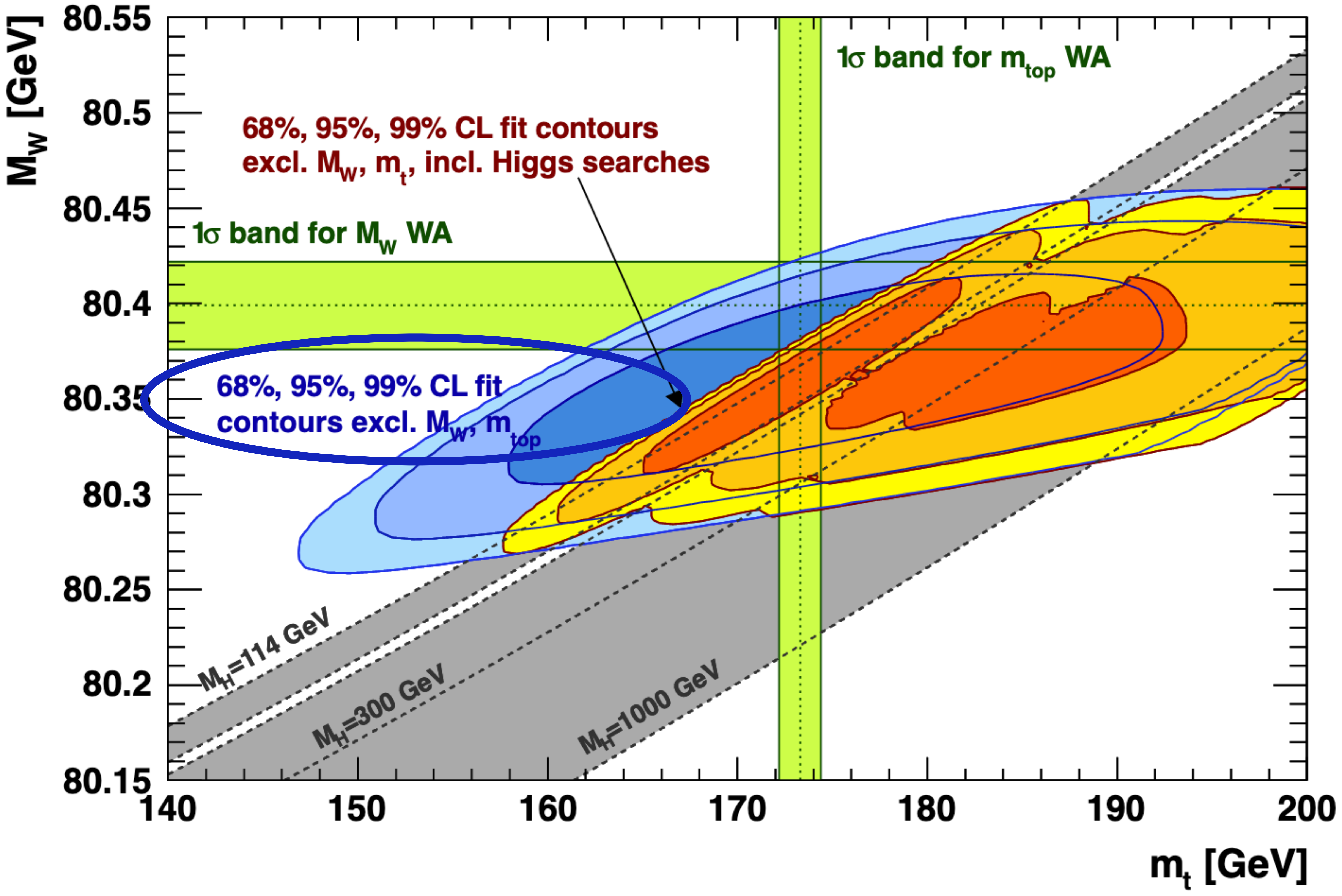
- Top, W, Higgs mass are related through higher order corrections



- 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!

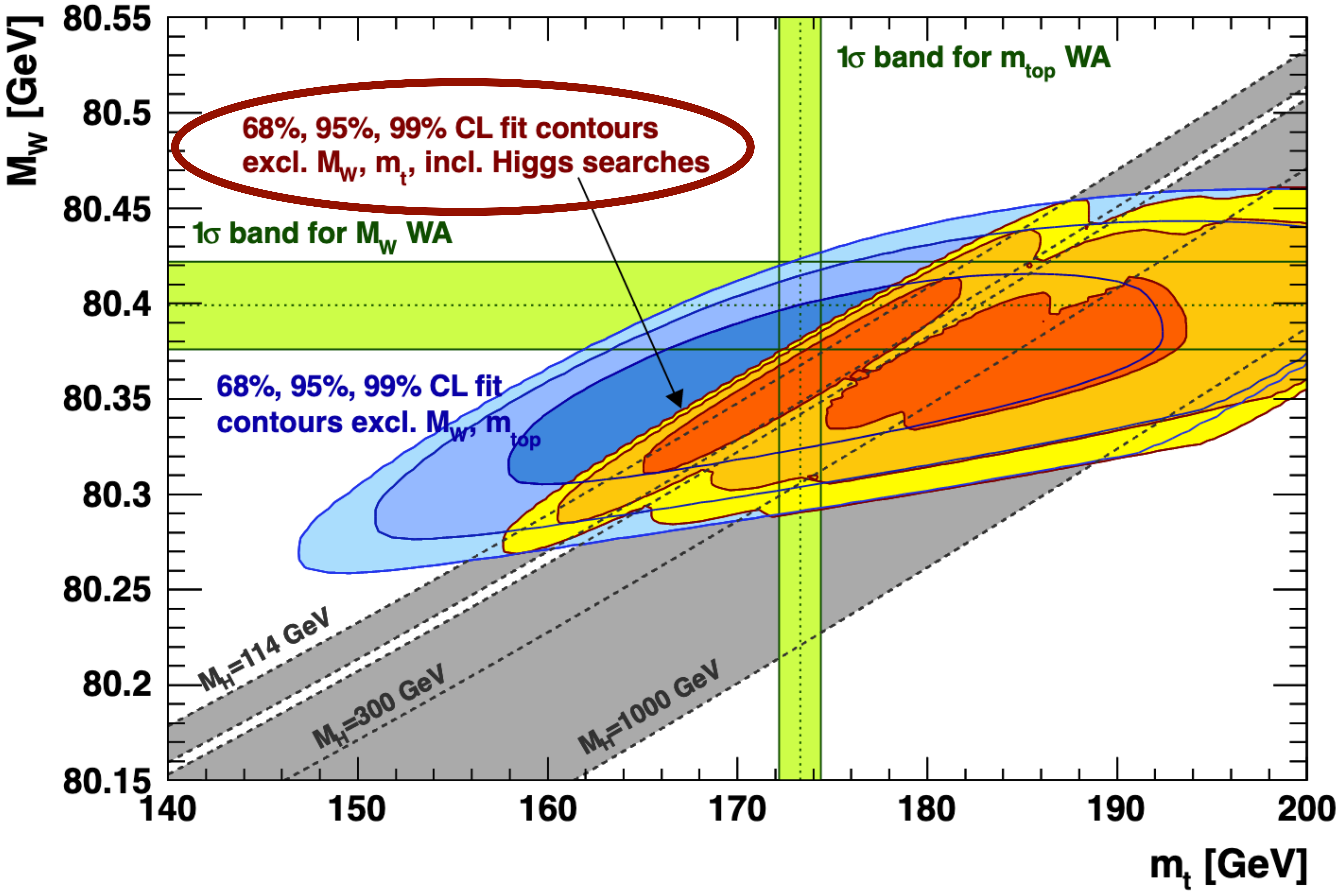
https://arxiv.org/pdf/1107.0975.pdf

Standard Model fits before the Higgs discovery: 2012



Predicting the top and W mass from SM parameter measurements https://arxiv.org/pdf/1107.0975.pdf

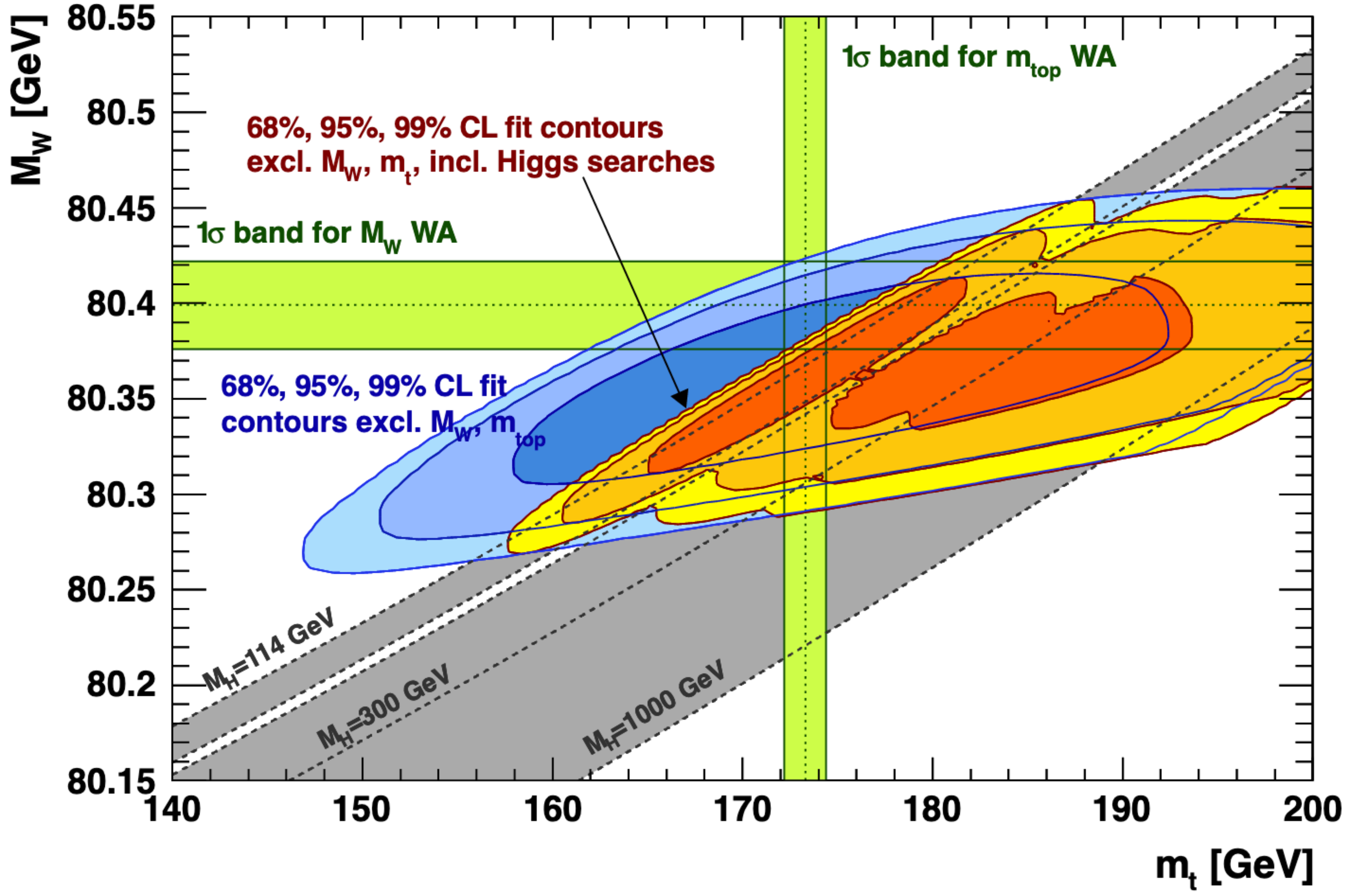
Standard Model fits before the Higgs discovery: 2012

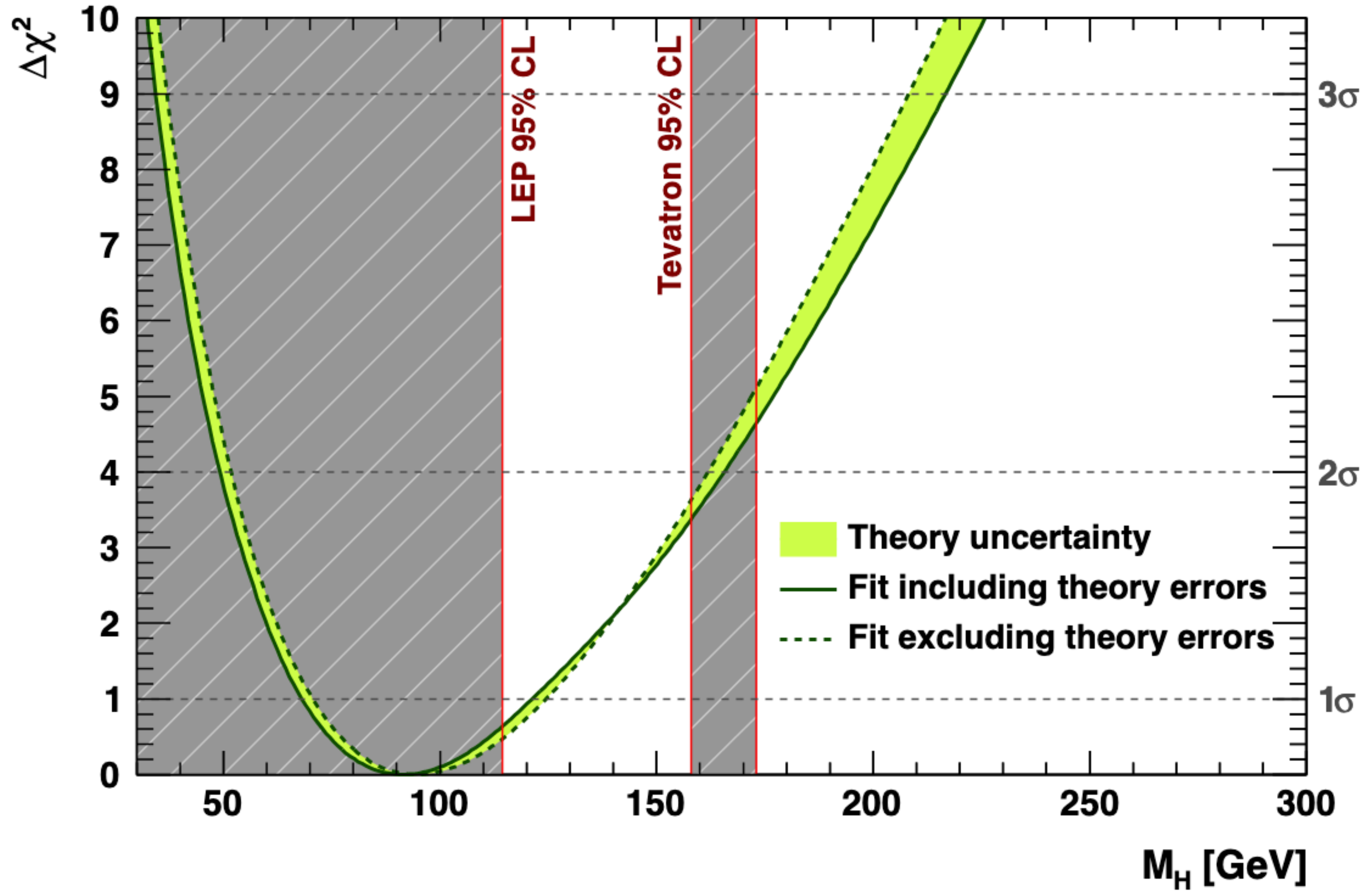


Predicting the top and W mass from SM parameter measurements

including Higgs search results

Standard Model fits before the Higgs discovery: 2012





- Predicting the Higgs mass $m_H = 95^{+30}_{-23}$ GeV including top and W mass measurements

Next Lecture

Measure	*Search for the*	*Search for*	*Study*
Standard Model	***Higgs boson***	***New Physics***	***Quark-Gluon Plasma***
parameters with high precision	*and measure it's properties*	*Beyond the Standard Model*	

Large Hadron Collider

- https://upload.wikimedia.org/wikipedia/commons/7/75/Standard_Model_Feynman_Diagram_Vertices.png