LHC Physics – Electroweak and Top

DESY Summer Student Lectures, 10.08-11.08.2023

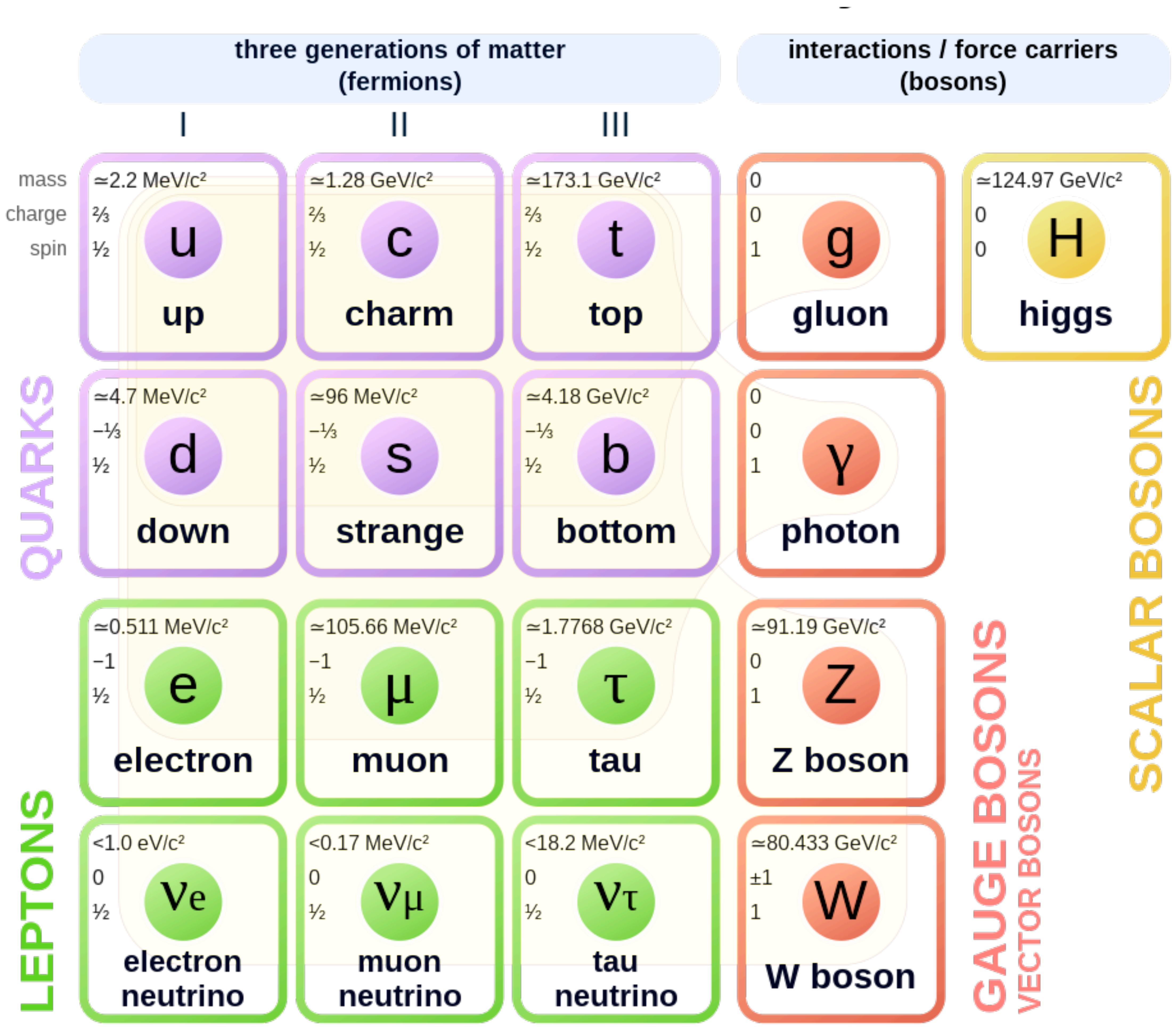
Claudia Seitz

LHC Physics goals

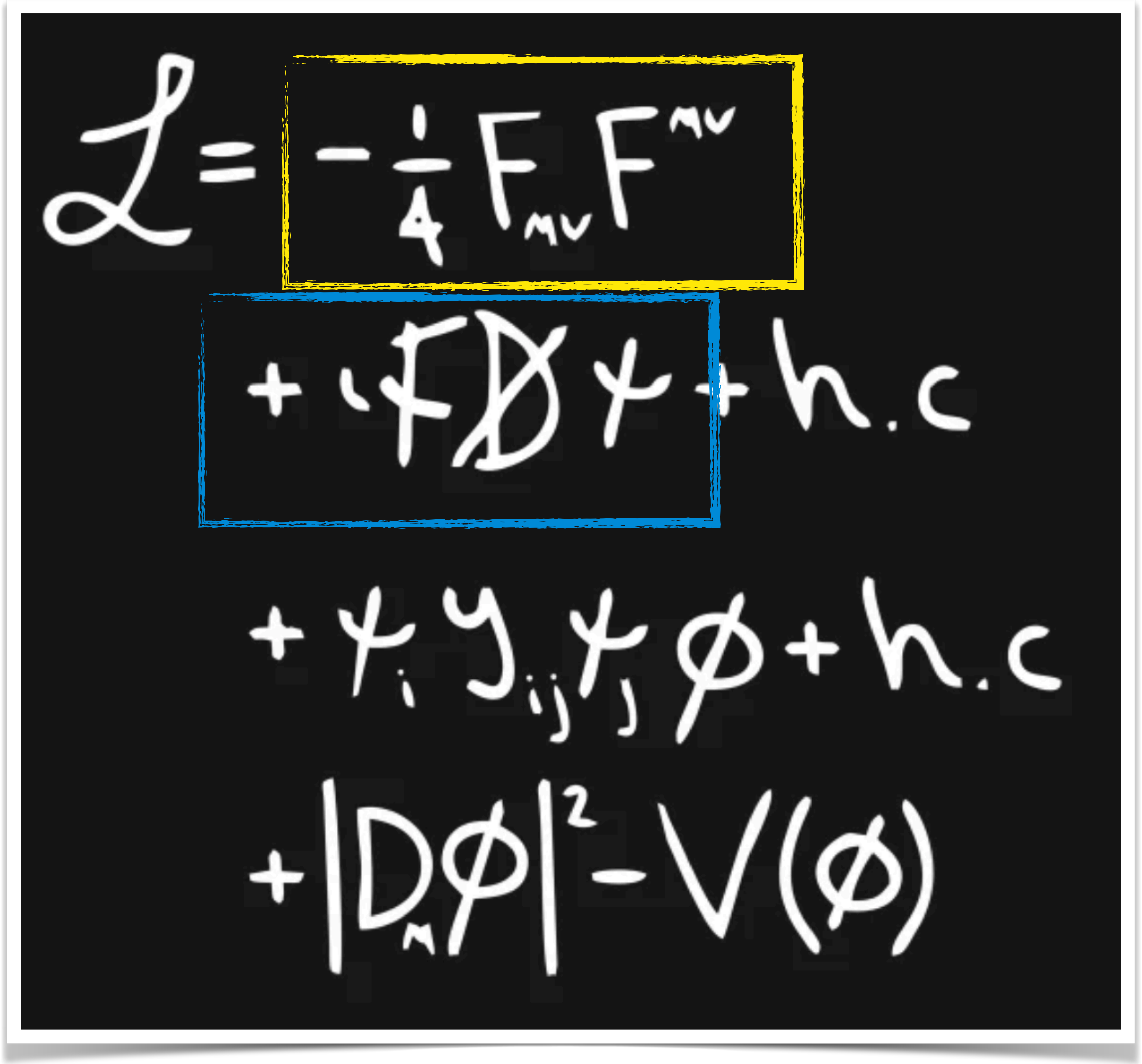
Measure ***Standard Model*** *parameters with high precision*	Search for the ***Higgs boson*** *and measure it's properties*	Search for ***New Physics*** *Beyond the Standard Model*	Study ***Quark-Gluon Plasma***

Large Hadron Collider

They Standard model and the Feynman picture

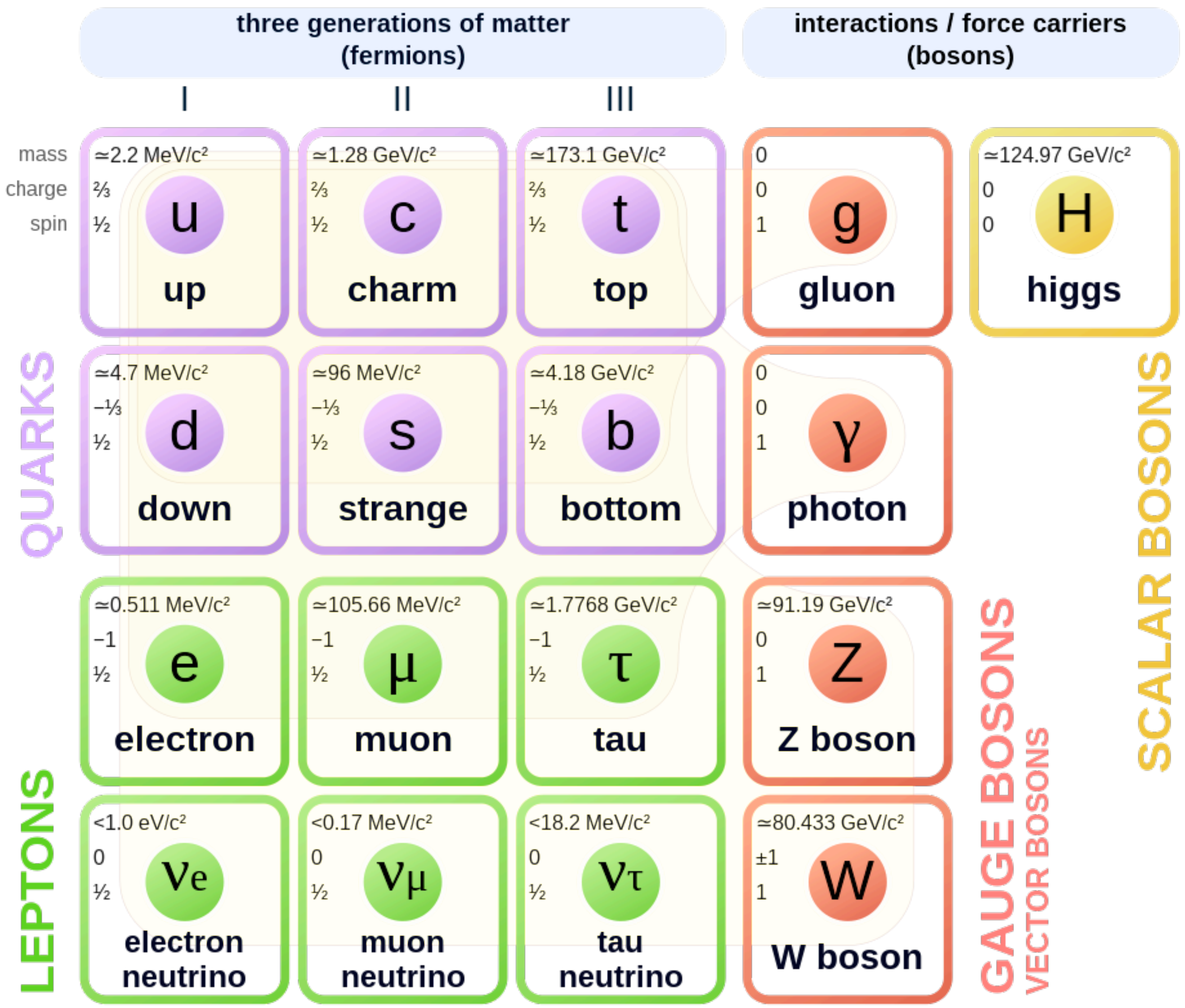


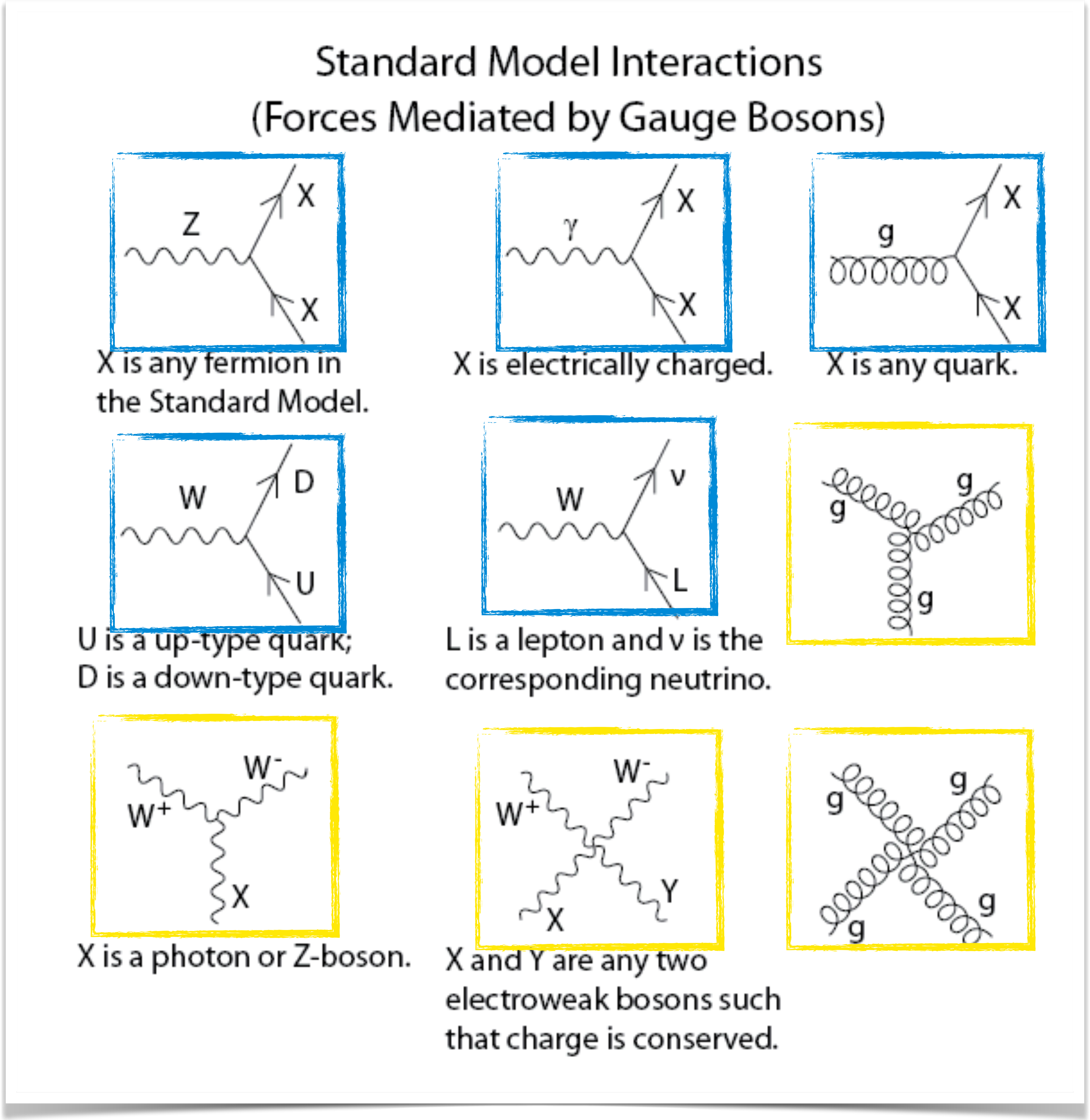
Gauge boson self-interaction



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

Connections between the parameters
m_W the weak mixing angle $\sin^2\theta_W$

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

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

Goals:

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

The SM free parameters

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$1/\alpha = 137.035999084\ (21)$
determined from the quantum Hall effect or the anomalous magnetic moment of the electron

$G_F = 1.166\ 3787 \times 10^{-5}\ \mathrm{GeV}^{-2}$
measured from the muon lifetime

CODATA

$m_Z = 91.1876 \pm 0.0021$ GeV
measured at LEP

PDG

Goals:

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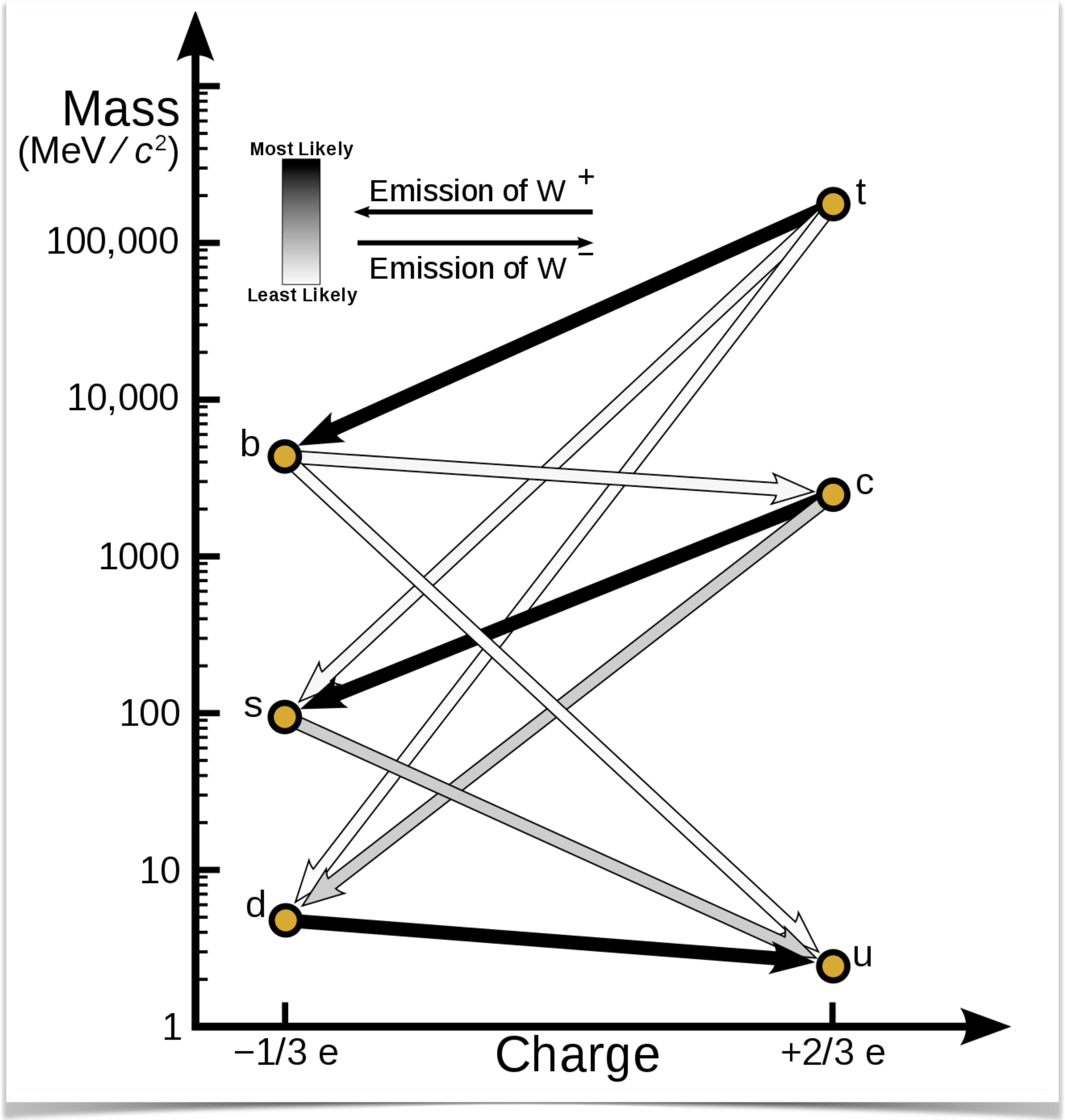
The Cabibbo–Kobayashi–Maskawa CKM matrix



Wikipedia

CKM matrix as of 2020 (from PDG)

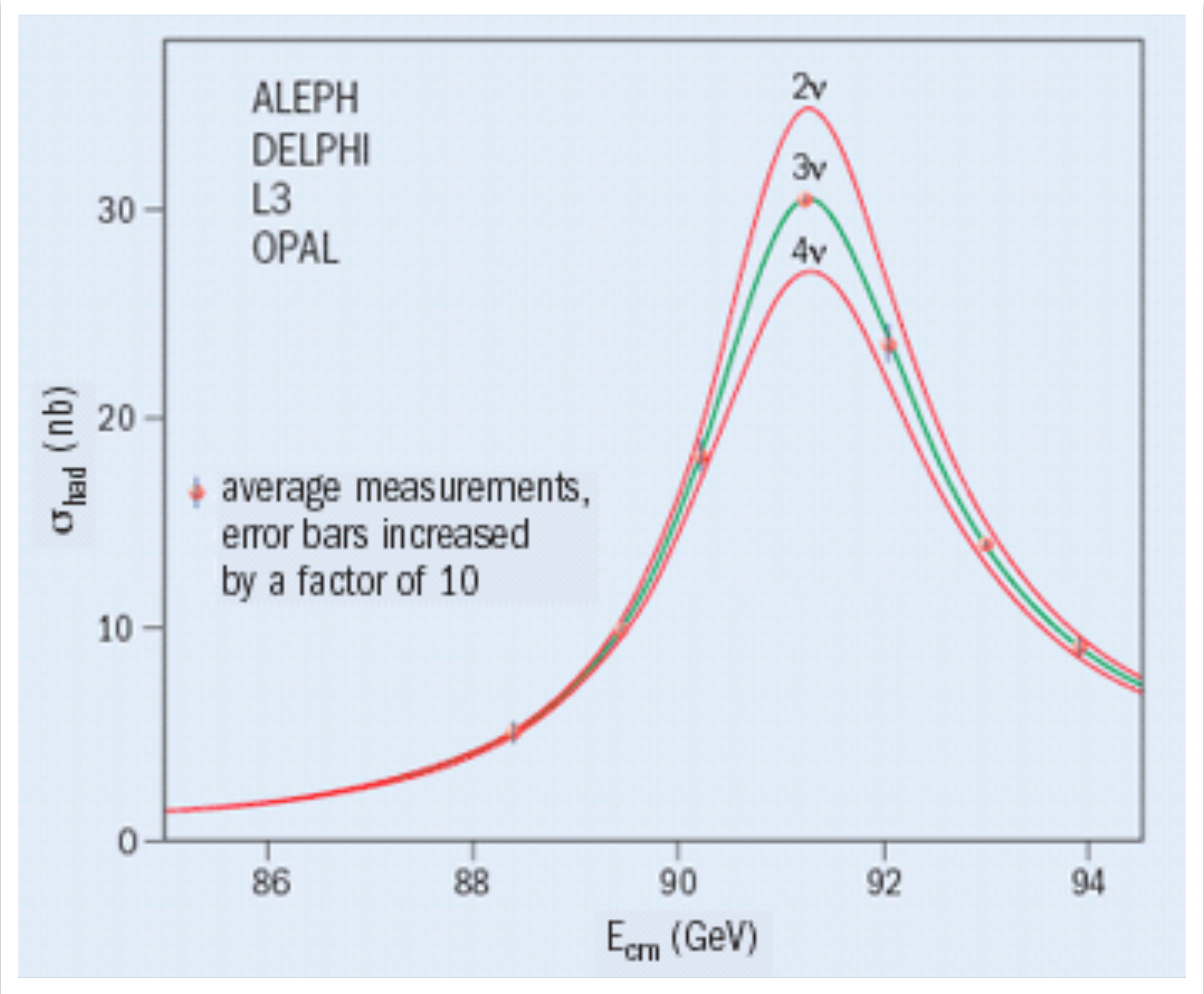
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$

$$\begin{pmatrix} 0.97401 \pm 0.00011 & 0.22650 \pm 0.00048 & 0.00361^{+0.00011}_{-0.00009} \\ 0.22636 \pm 0.00048 & 0.97320 \pm 0.00011 & 0.04053^{+0.00083}_{-0.00061} \\ 0.00854^{+0.00023}_{-0.00016} & 0.03978^{+0.00082}_{-0.00060} & 0.999172^{+0.000024}_{-0.000035} \end{pmatrix}$$

Contains information about flavor-changing weak interactions

Z-boson at LEP

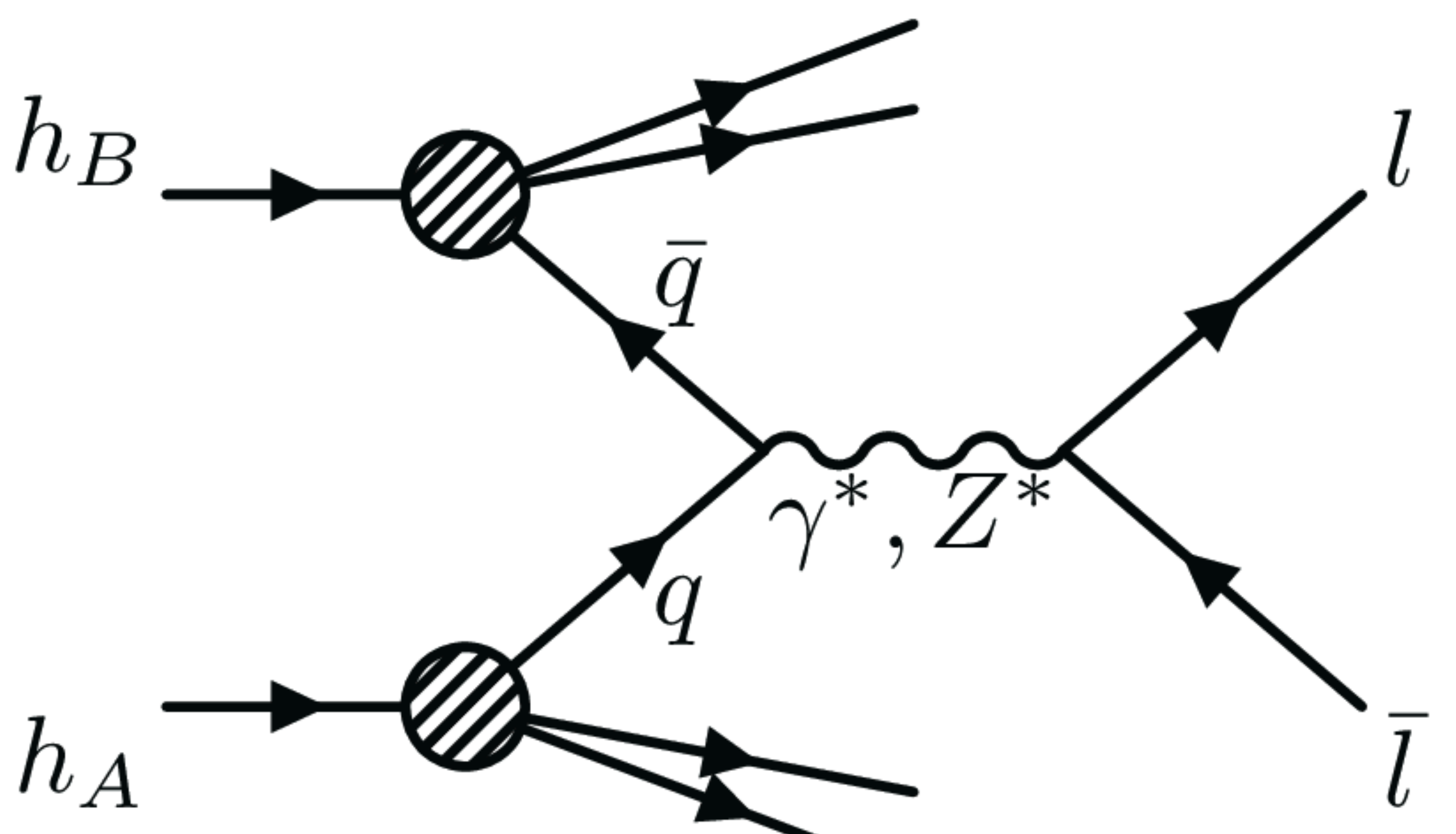
- Large Electron-Positron Collider
  - in operation at CERN 1989-2000
- Z bosons are represented by a clean peak in the invariant mass spectrum of the two leptons
  - Precise measurements of the properties from LEP
  - Mass: 91.1876± 0.0021 GeV

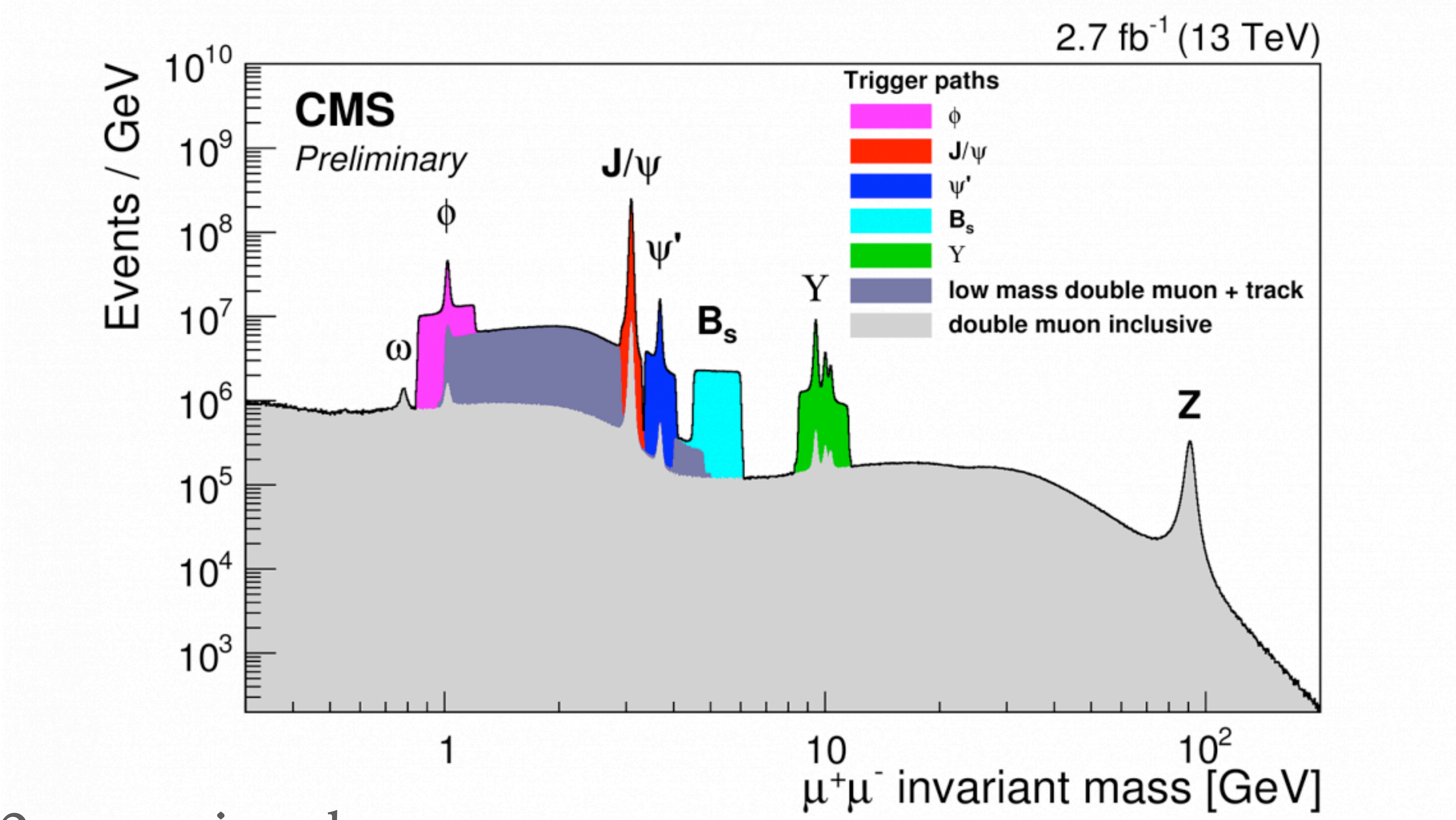


Particles		Branching ratio	
Name	Symbols	Predicted for x = 0.23	Experimental measurements[20]
Neutrinos (all)	ν_e, ν_μ, ν_τ	20.5%	20.00 ±0.06%
Charged leptons (all)	e^-, μ^-, τ^-	10.2%	10.097 ±0.003%
Electron	e^-	3.4%	3.363 ±0.004%
Muon	μ^-	3.4%	3.366 ±0.007%
Tau	τ^-	3.4%	3.367 ±0.008%
Hadrons (except * 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

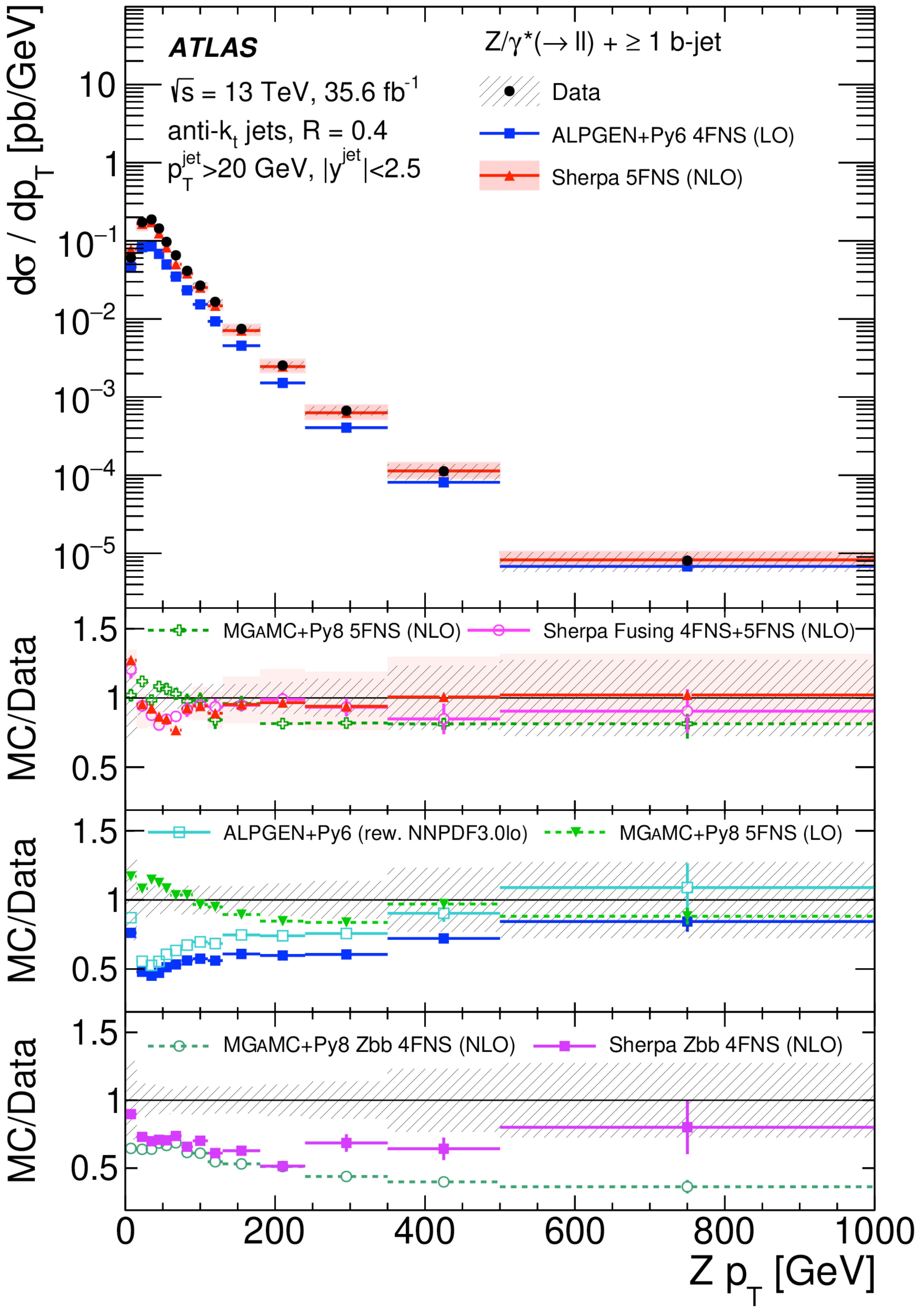




- Characteristic clean signature: 2 opposite charge, same flavor leptons
- Z bosons are used as “standard candles” at the LHC

Z+jets measurements

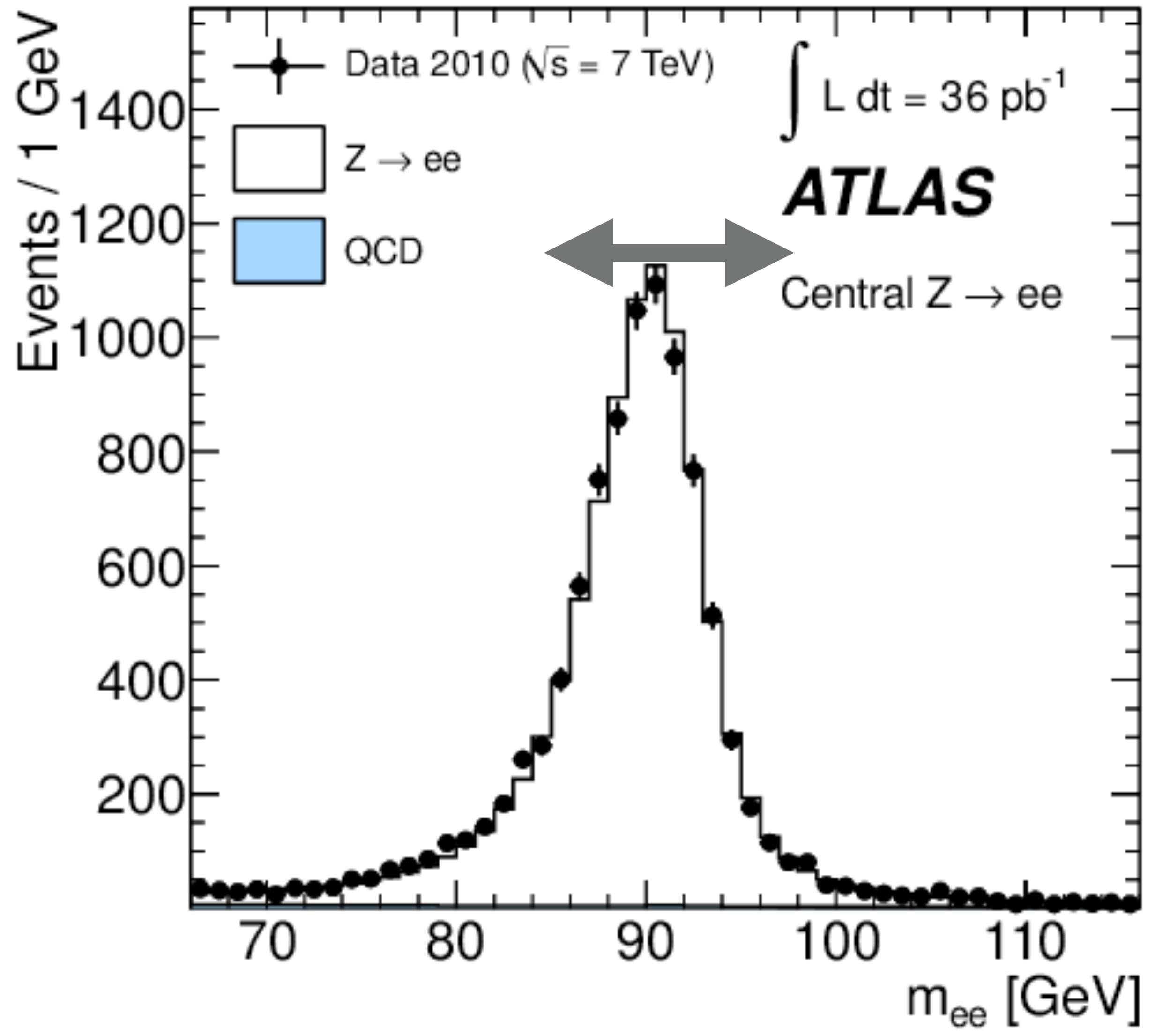
- Z produced in association with extra (b)-jets is an important process and background for many searches for new physics
- Understanding of the Z boson pT spectrum is important
  - Unfolding technique often used to turn "measured" data spectrum into particle level spectrum
  - Unfolded spectrum can then be easily compared with various simulated samples



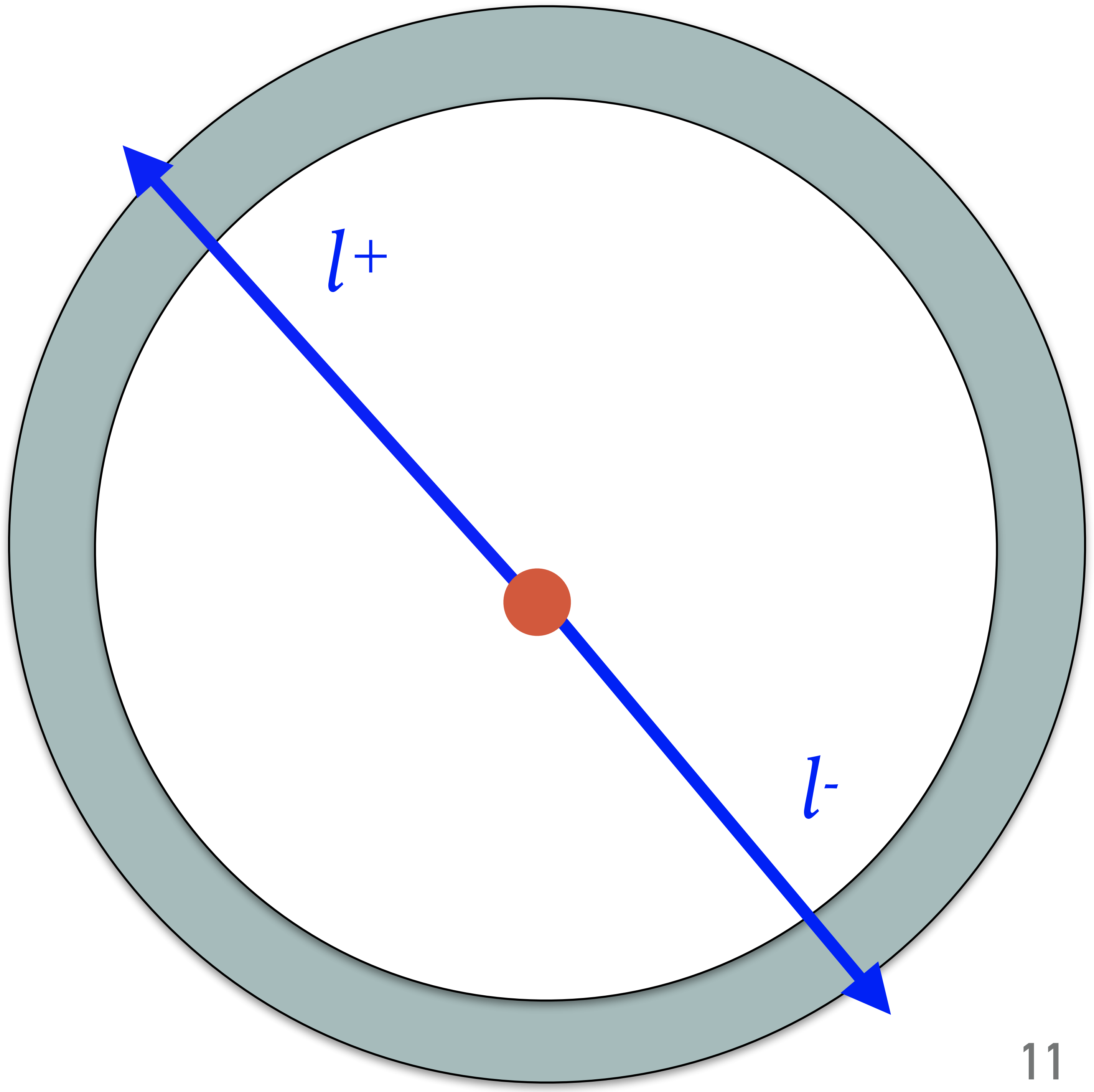
[JHEP 07 (2020) 44]

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

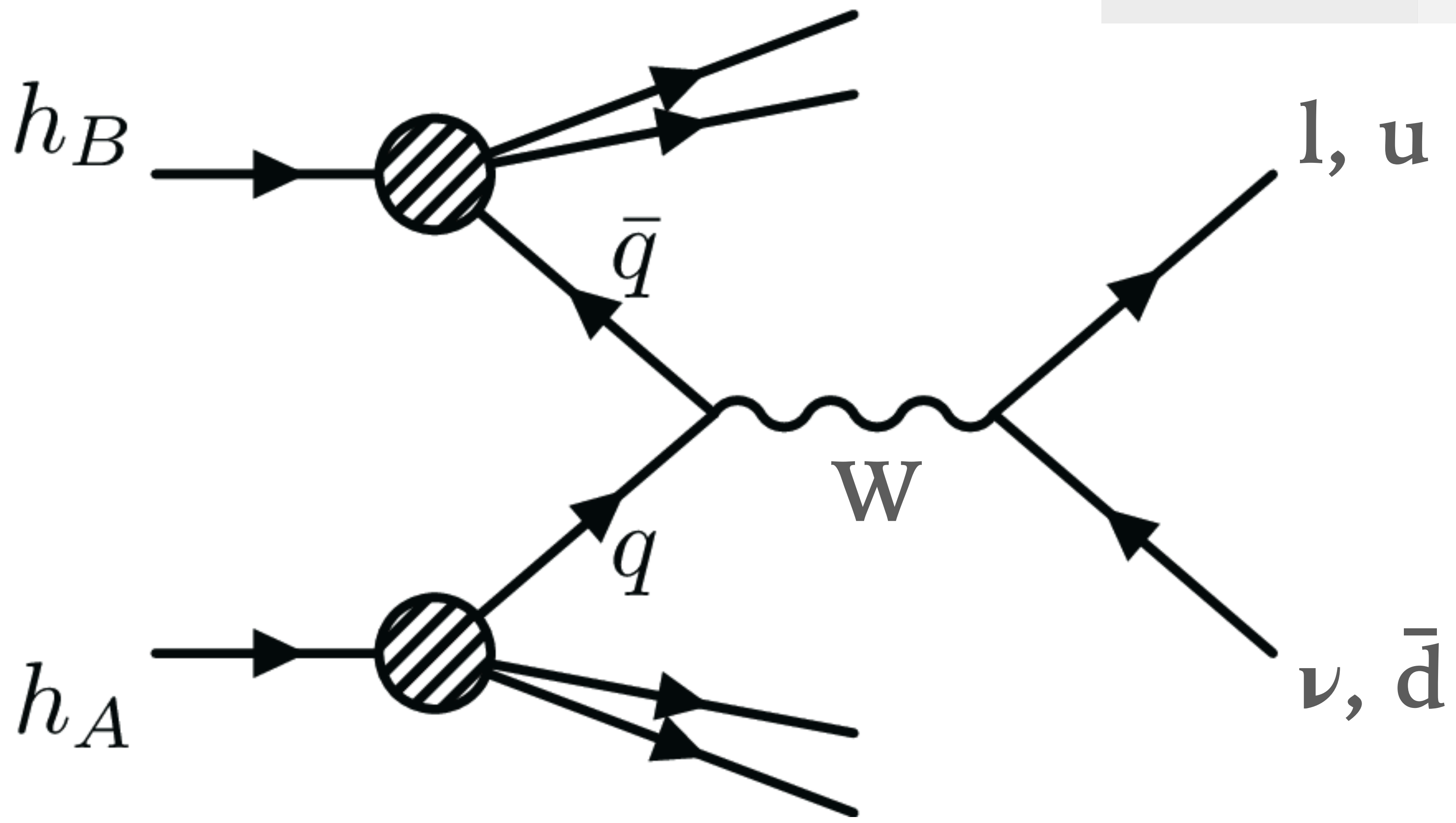


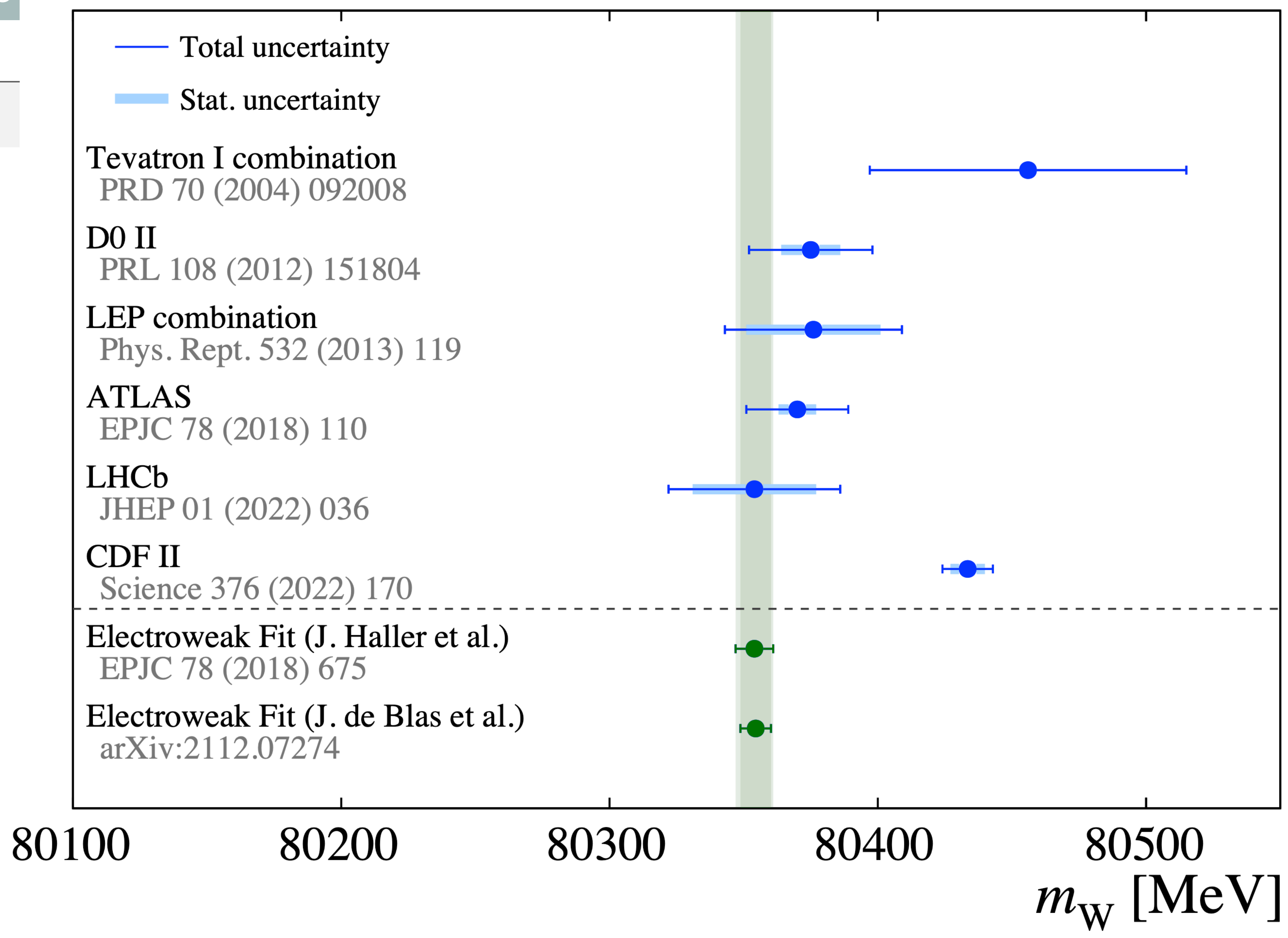
- **Lepton efficiency measurements**
- need clean sample of leptons to measure reconstruction/identification/isolation efficies
  - "Tag and Probe" method
    - select two lepton candidates with tight (Tag) and looser (Probe) selection criteria
    - Require the di-lepton mass to be around the Z peak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



W bosons

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



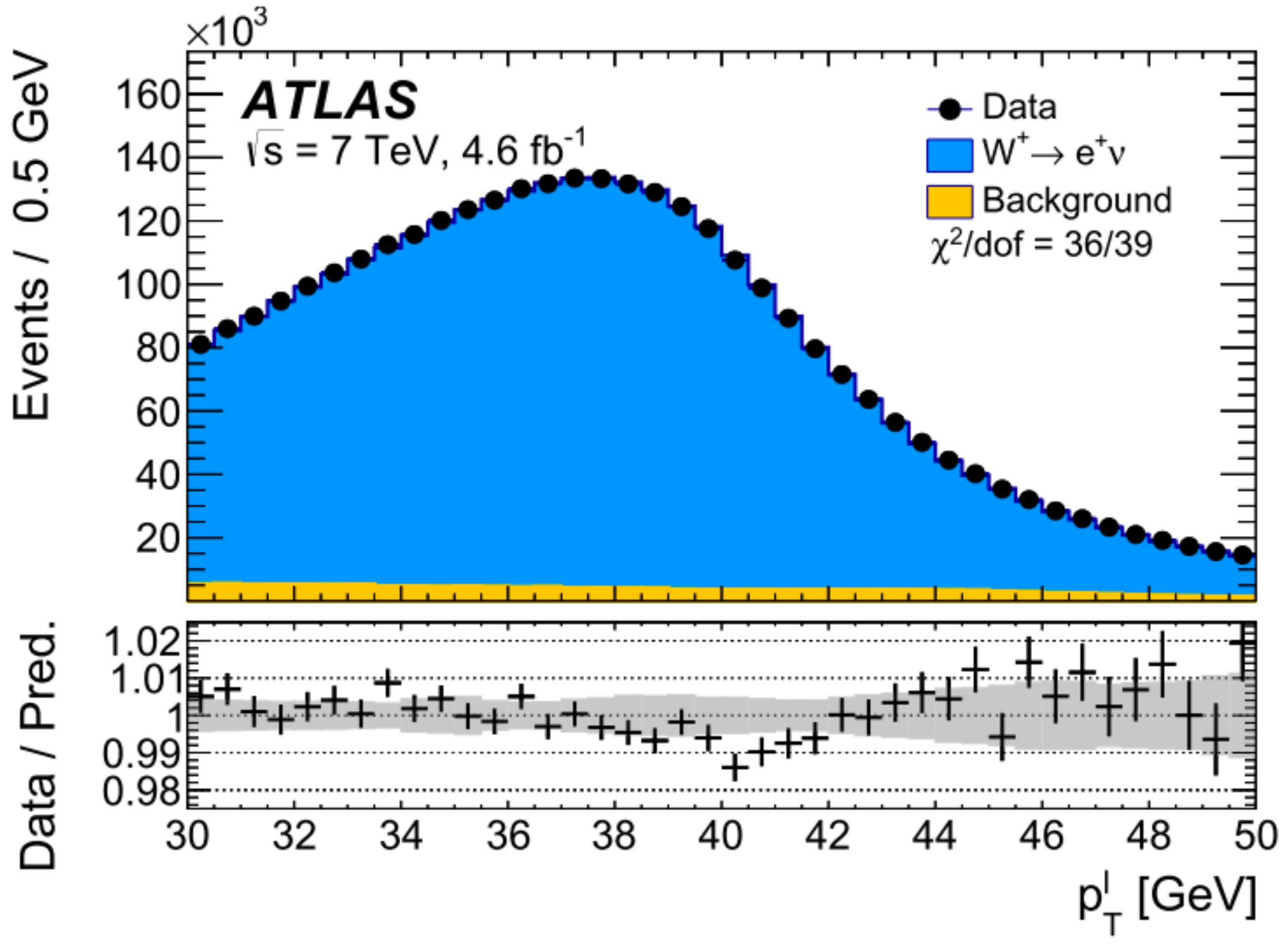


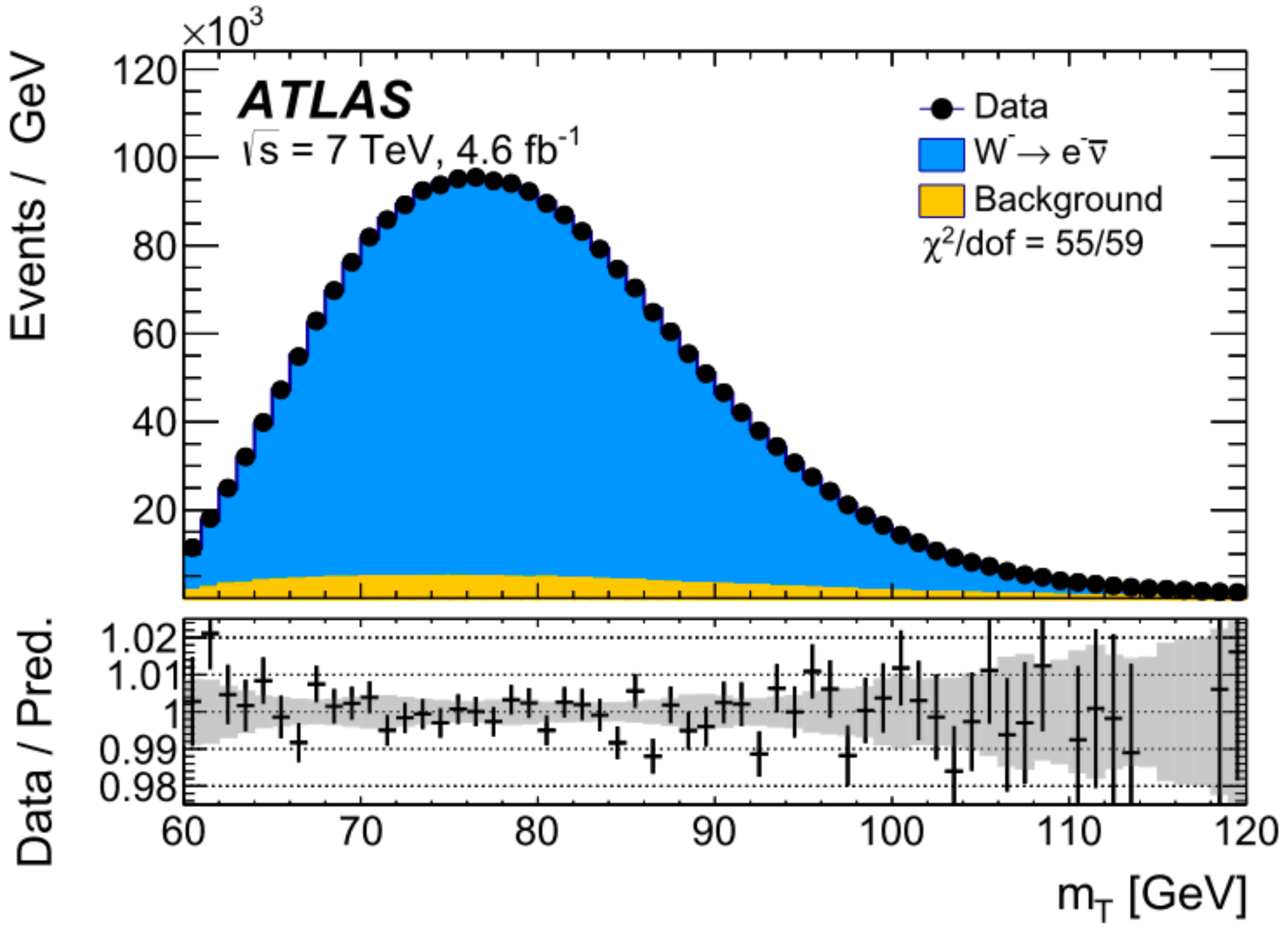
- At the LHC:
  - Special dataset collected with low pile-up
  - 4.6fb^{-1} at 7 TeV ⇒ about 15.5 M W^+ and 10.4 W^- events collected (e + μ)

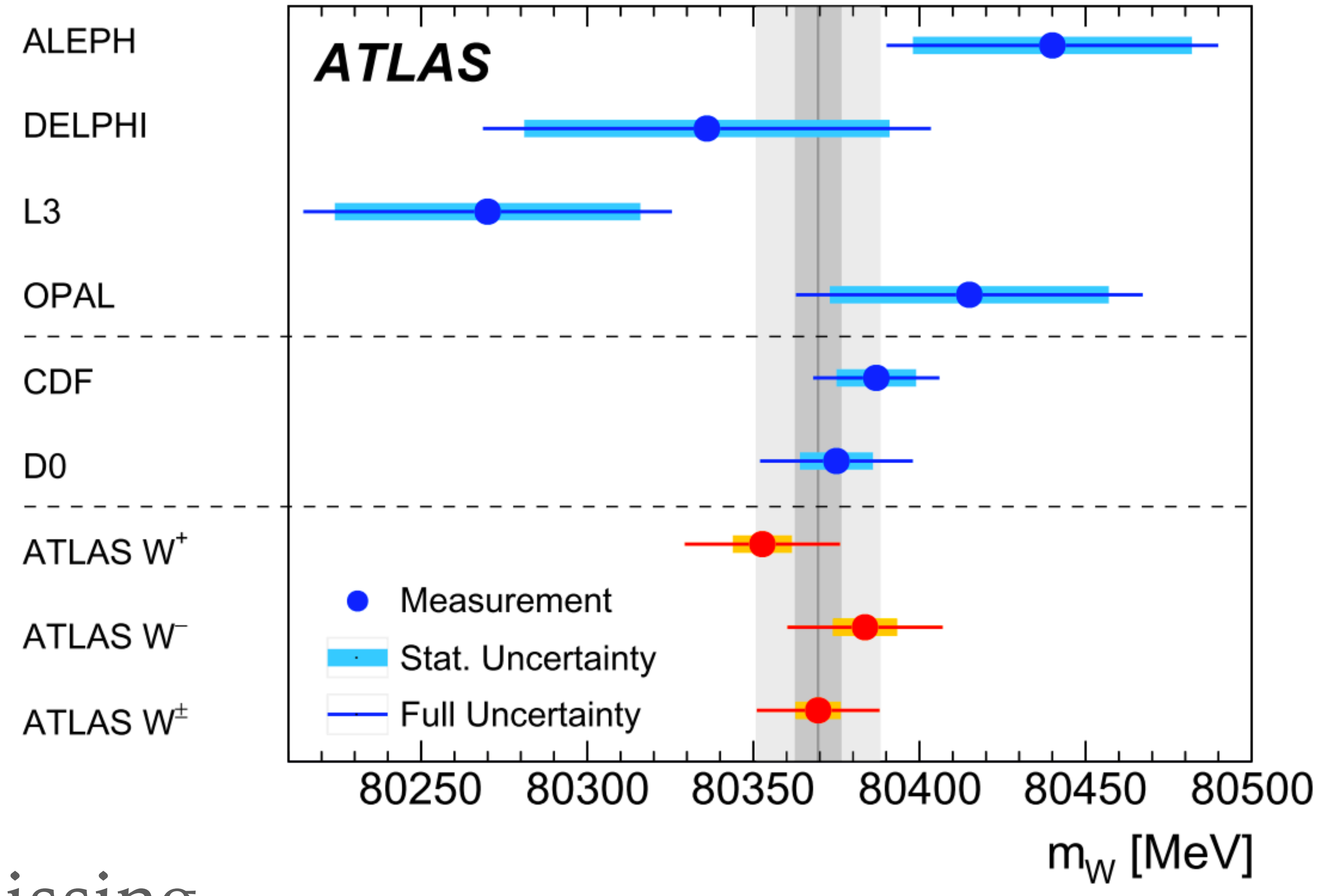
Recent CDF result of W-mass measurement updated 80433 ± 9 MeV

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

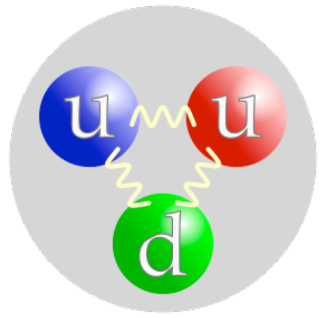
➤ m^l_T: Less sensitive to modeling but needs good understanding of missing transverse energy

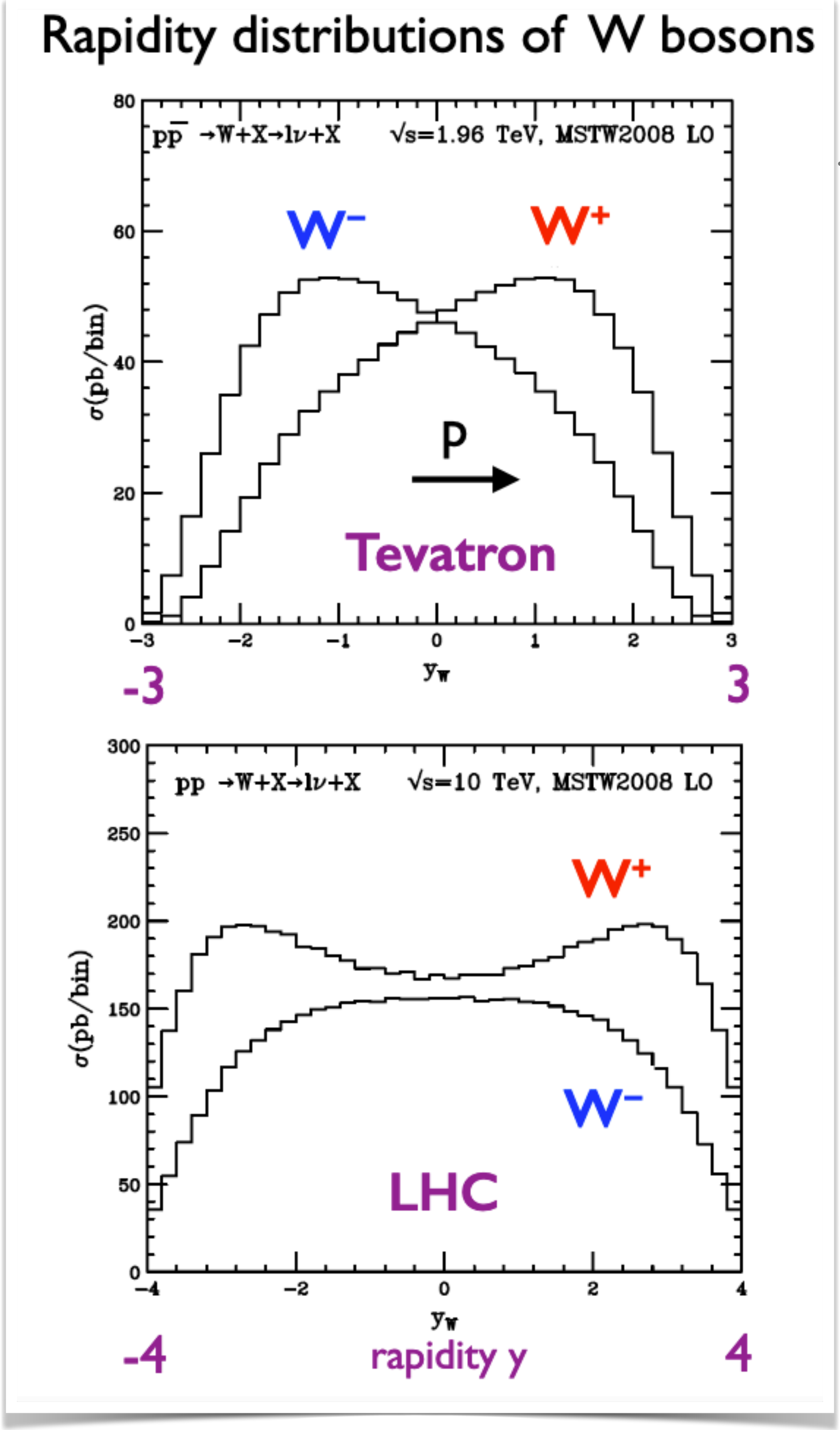
$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$

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

W+ vs W- Asymmetry

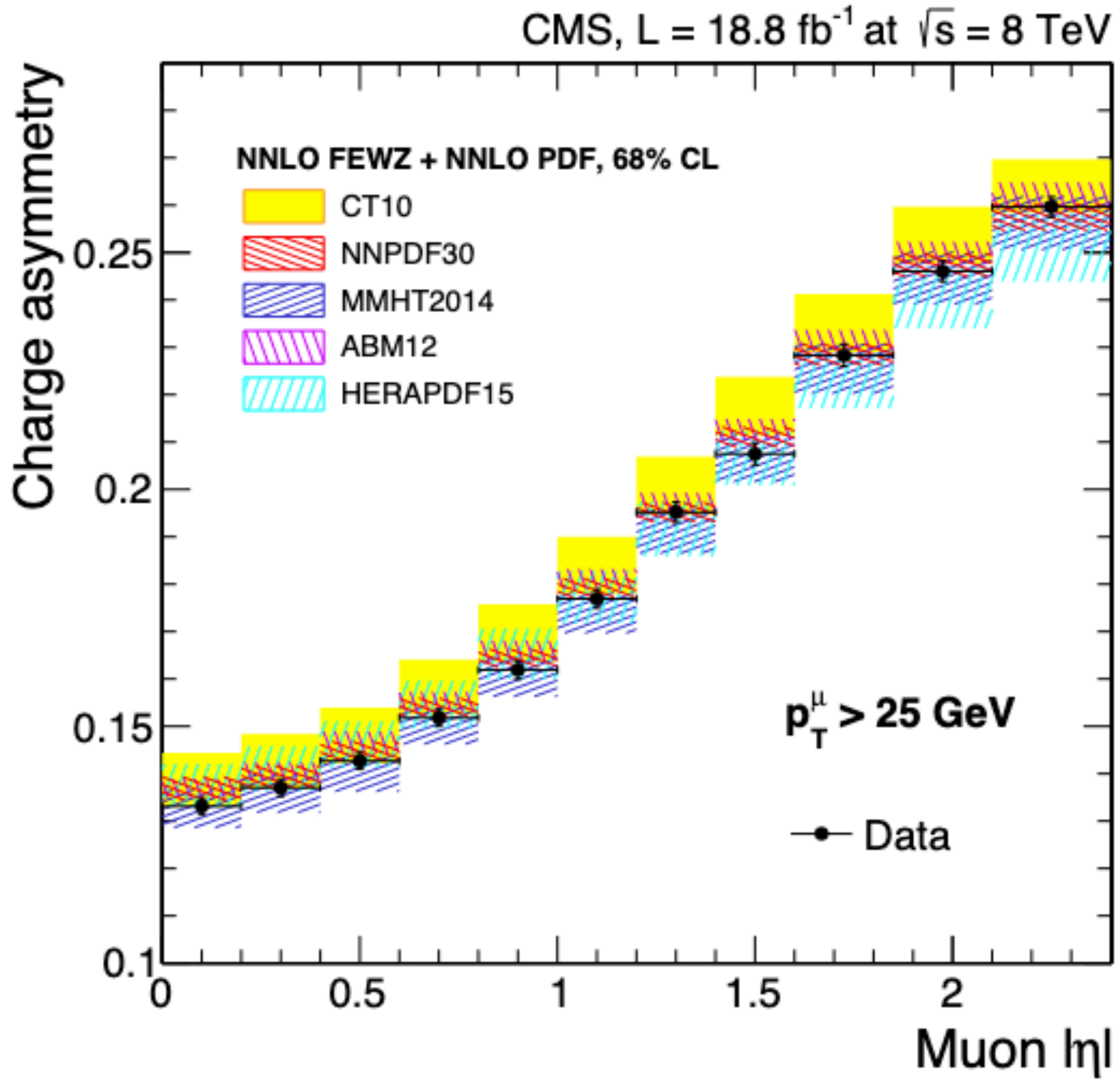
- At the **Tevatron** W^+ (W^-) bosons are produced mainly in proton (antiproton) directions
- At the **LHC** W^+ bosons are produced at higher rate than W^- bosons
  - W^- bosons are produced centrally
  - W^+ bosons are produced at larger rapidities
- Main cause of these asymmetries:
  - on average: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



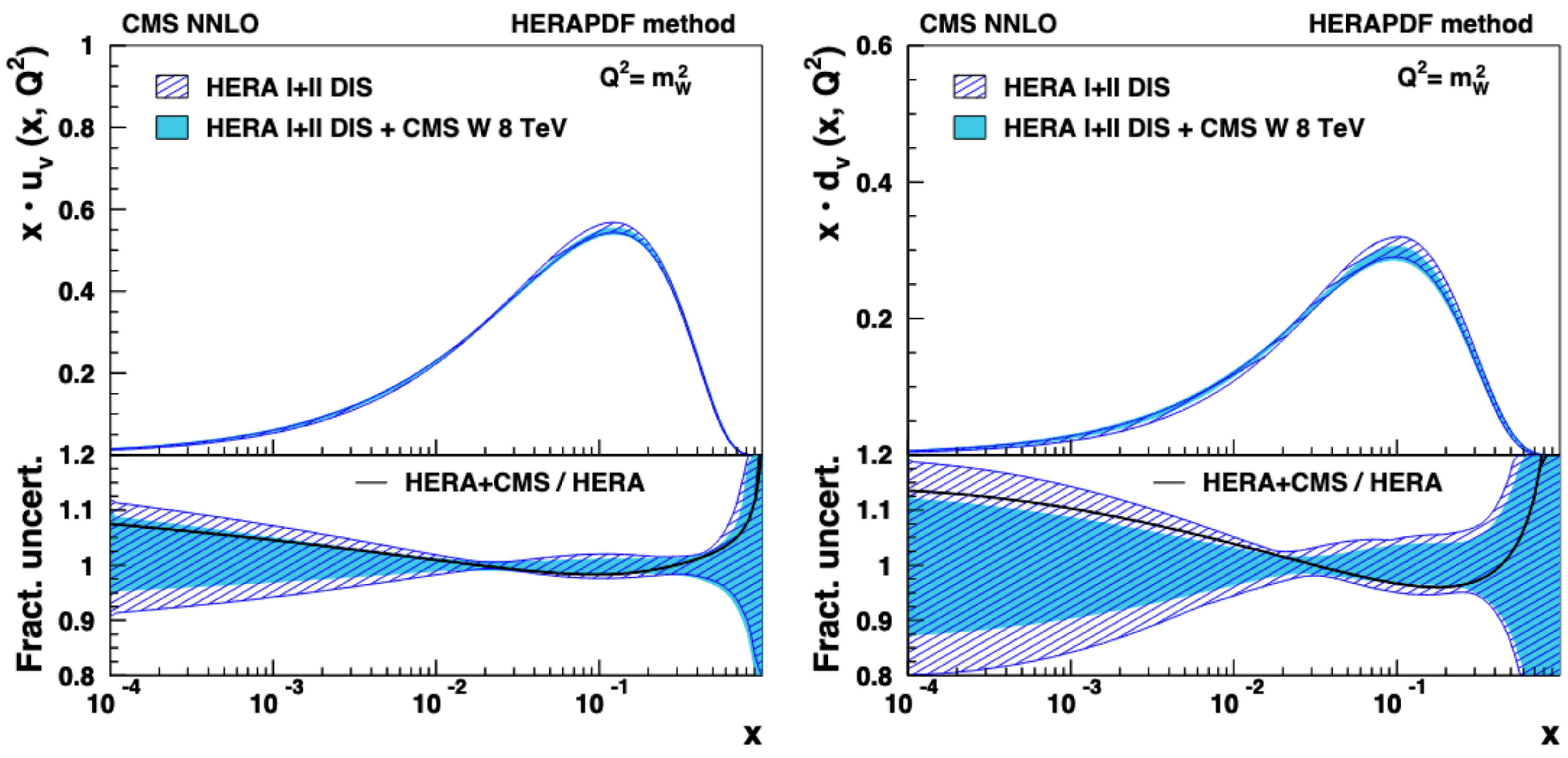


In practice: Measure lepton charge asymmetry

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



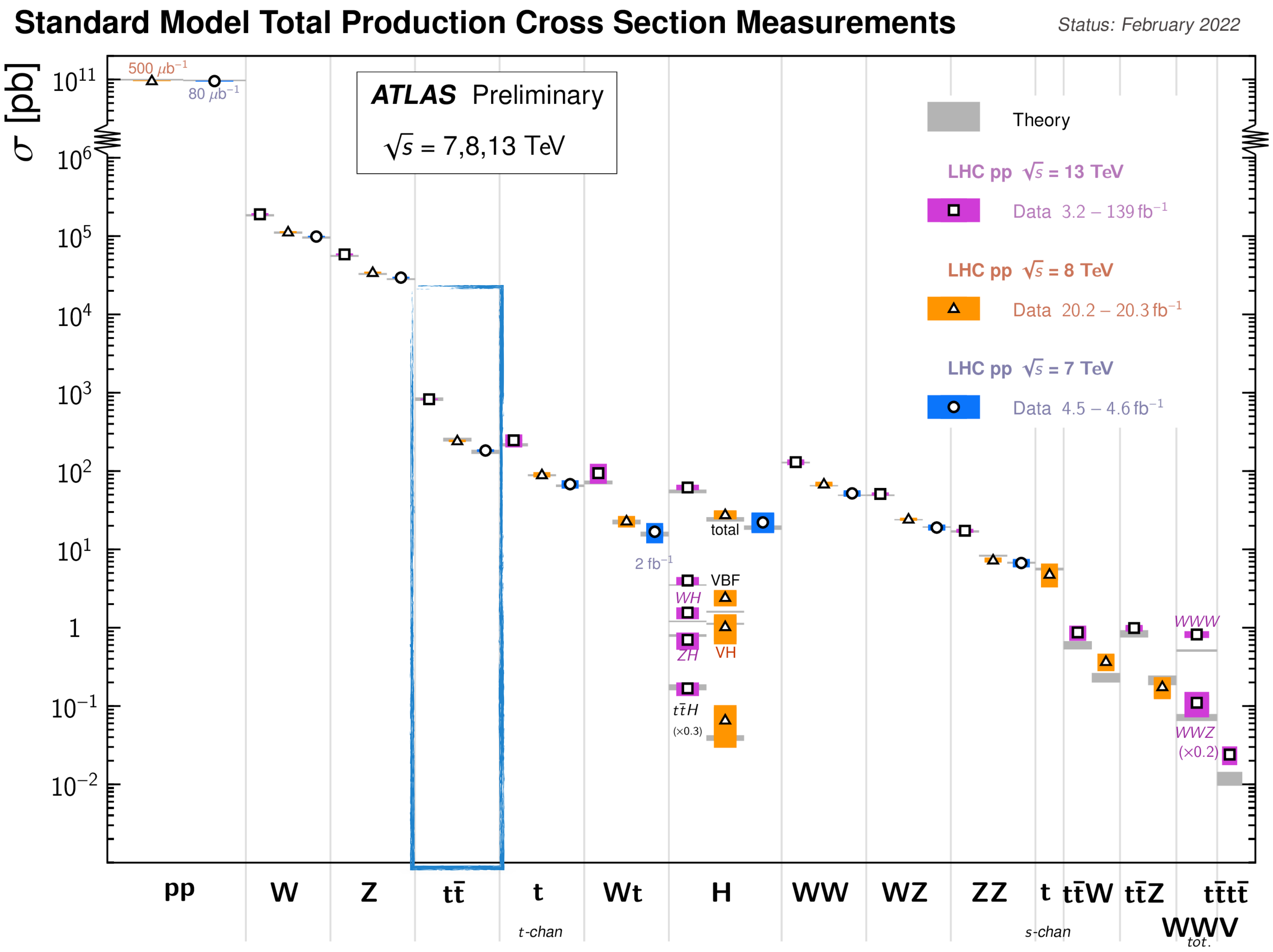
- Measurements can help to constrain u and d PDFs



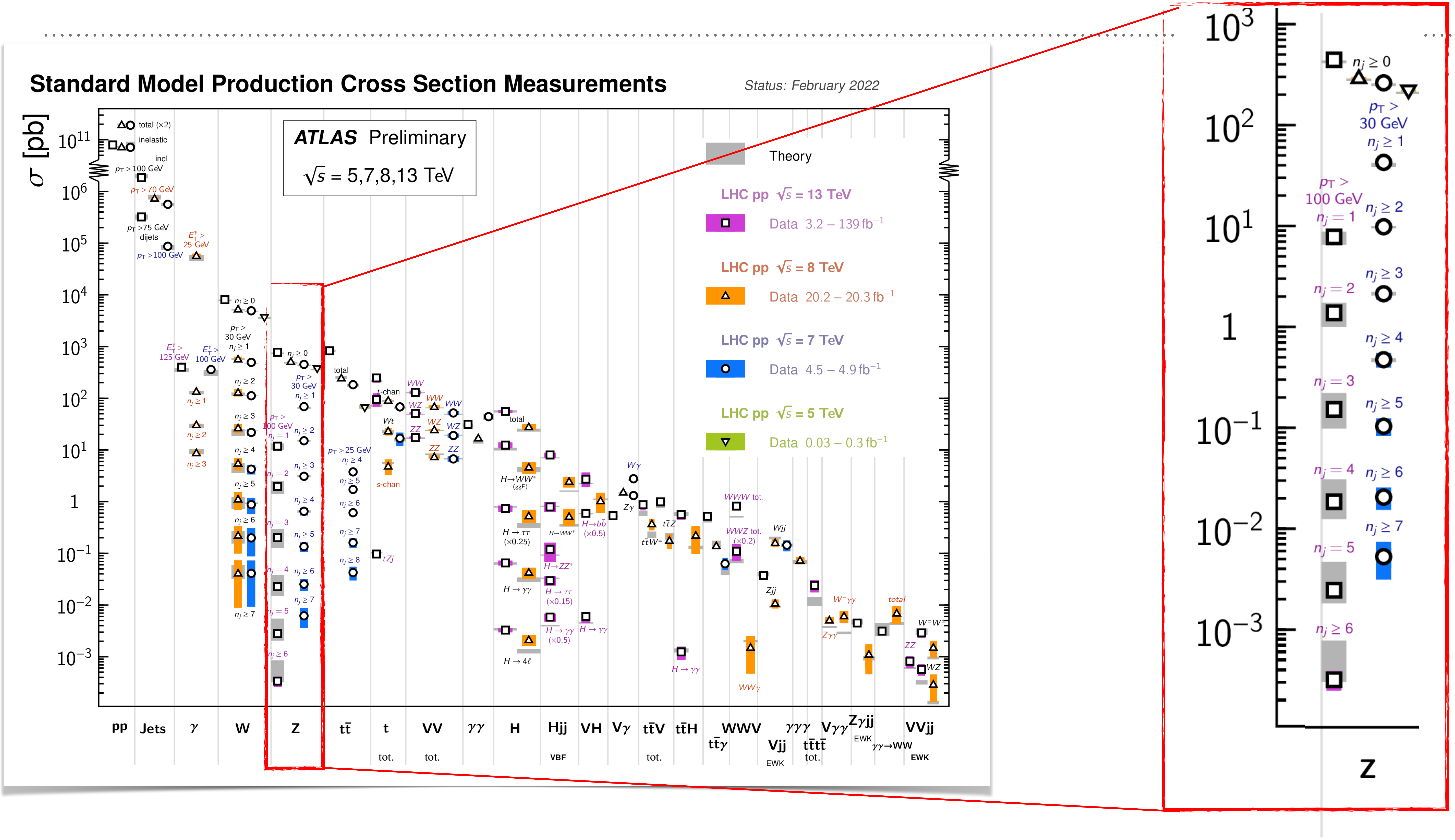
Going to rarer and rarer SM processes

Top quark pair production

→ the LHC is a top factory

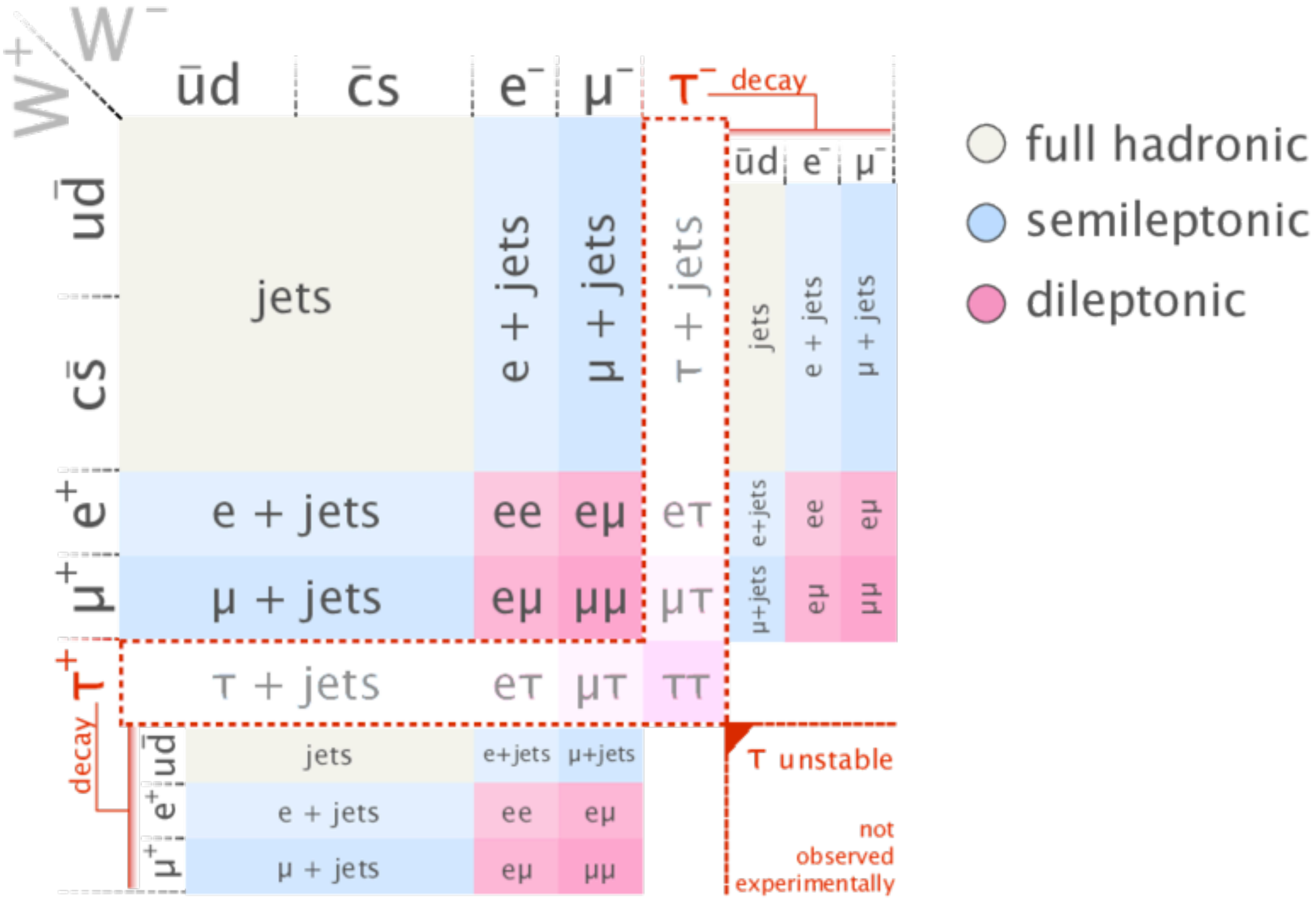


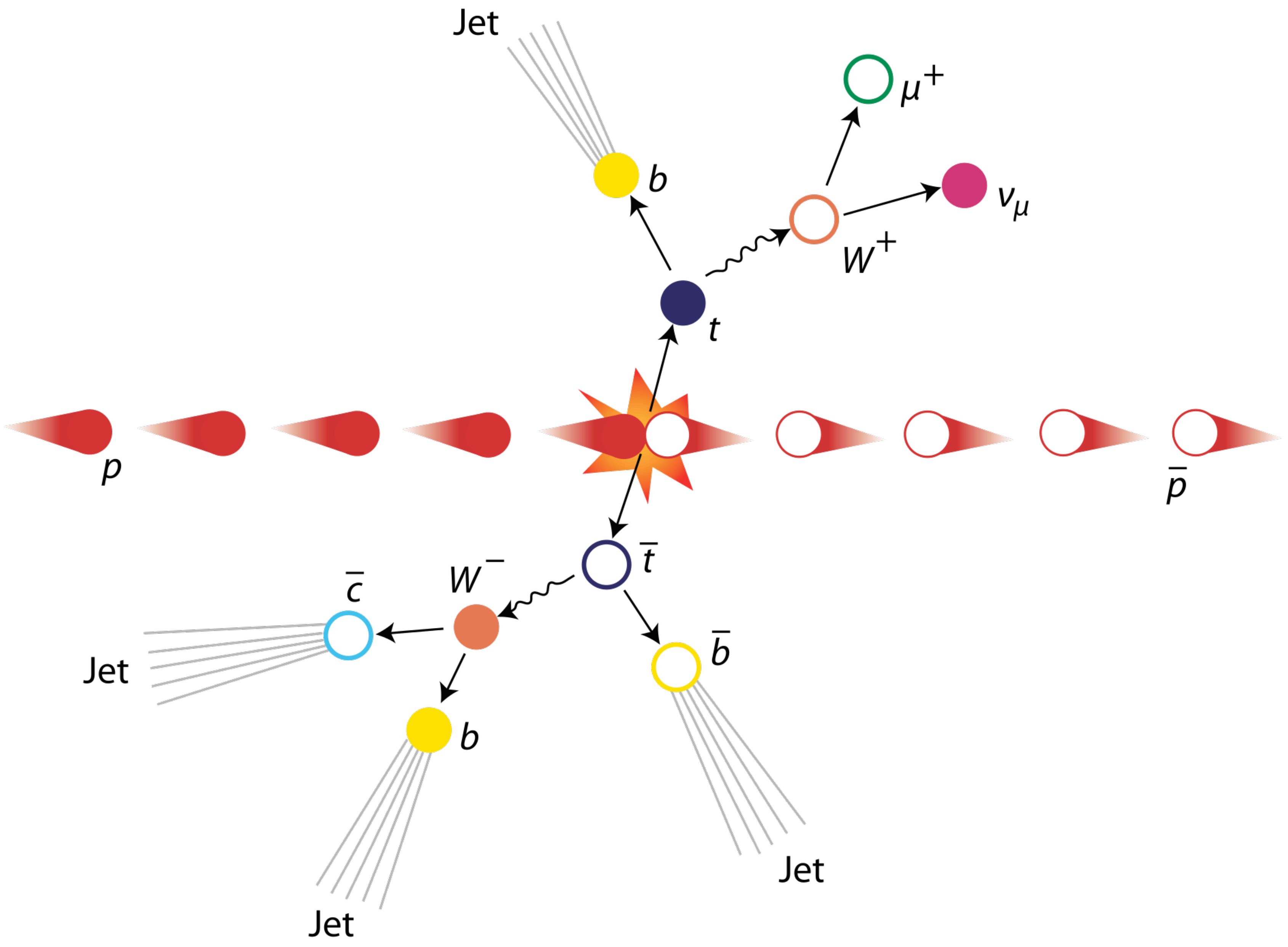
Interlude: fiducial cross sections



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

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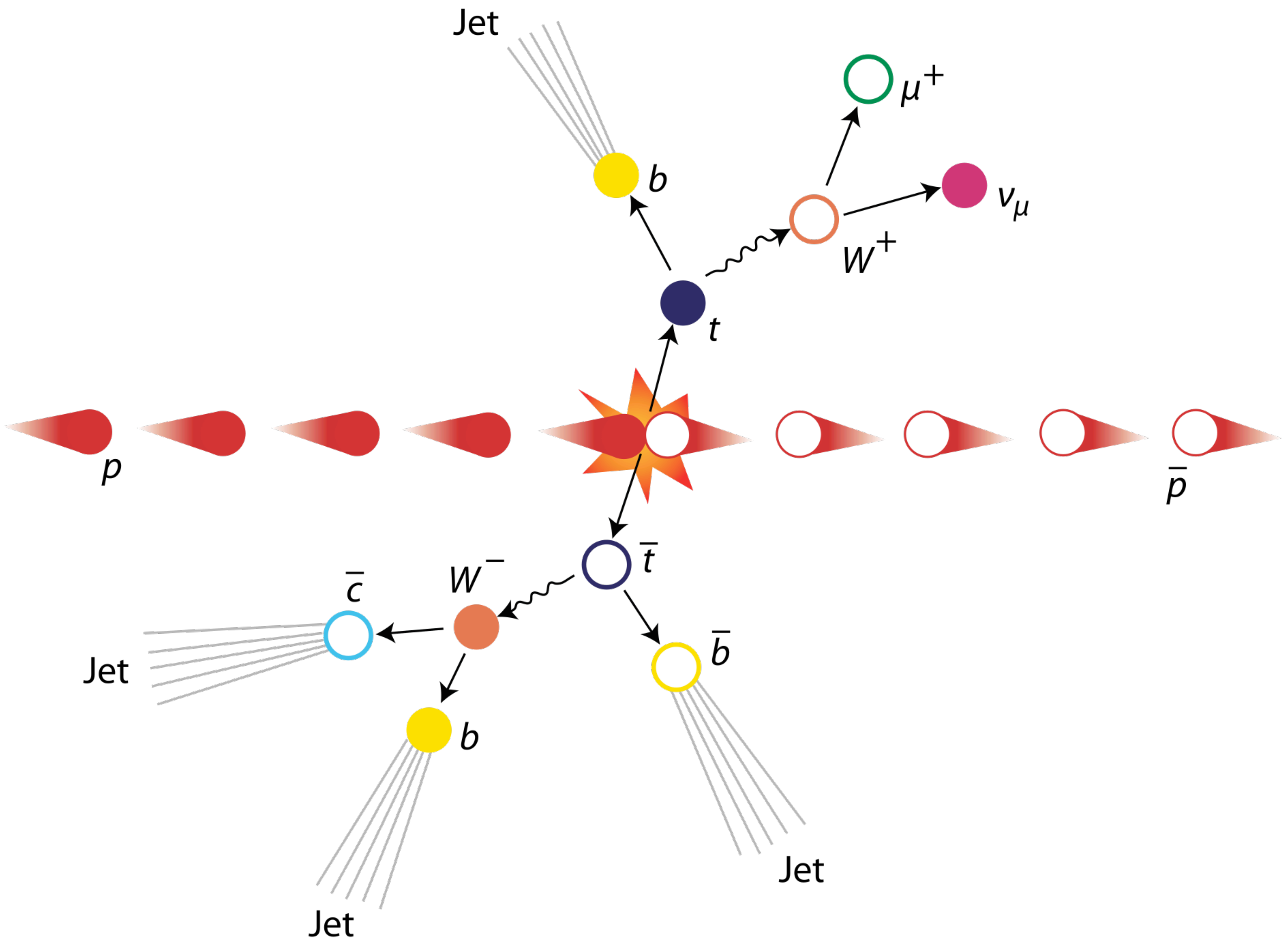

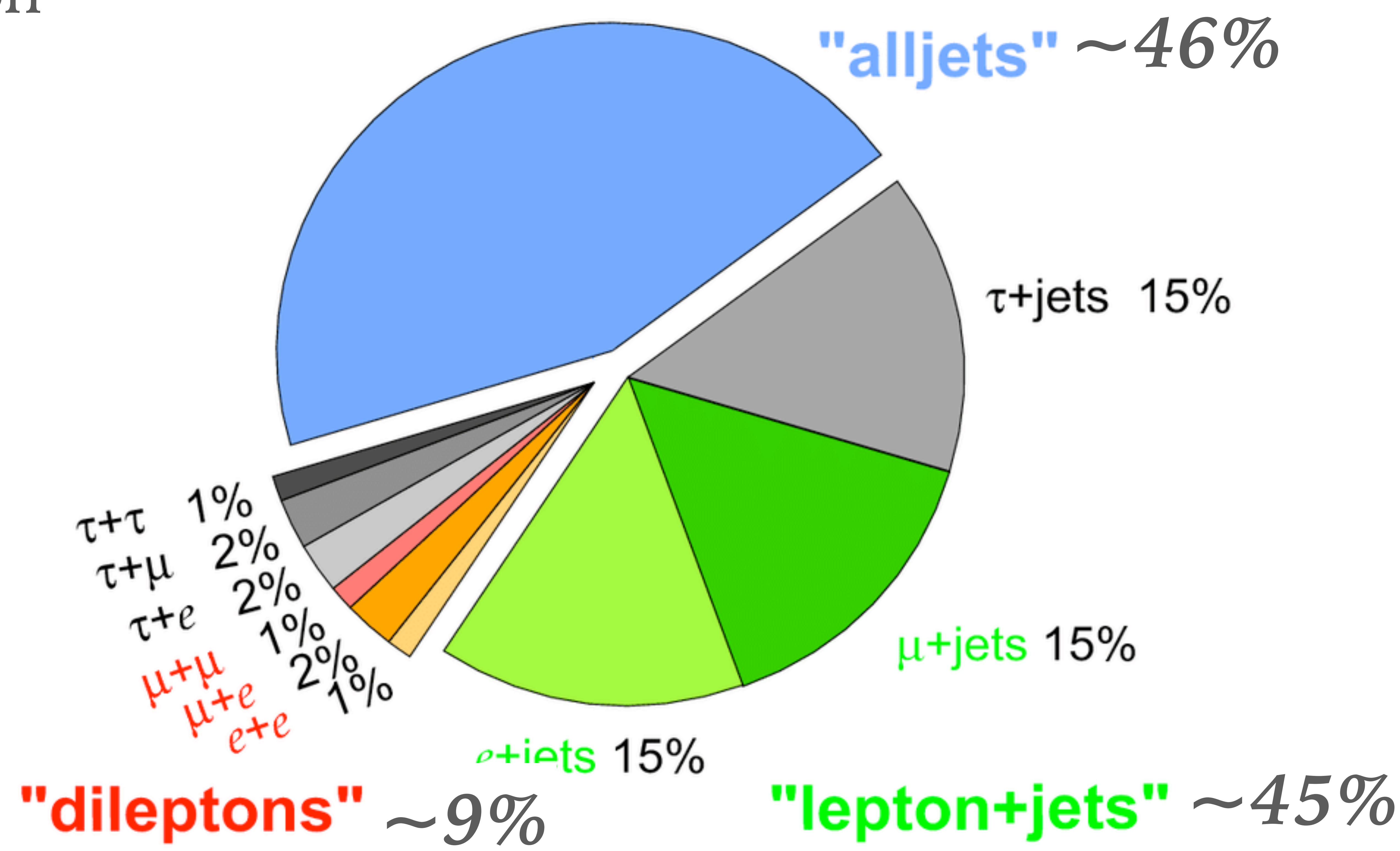

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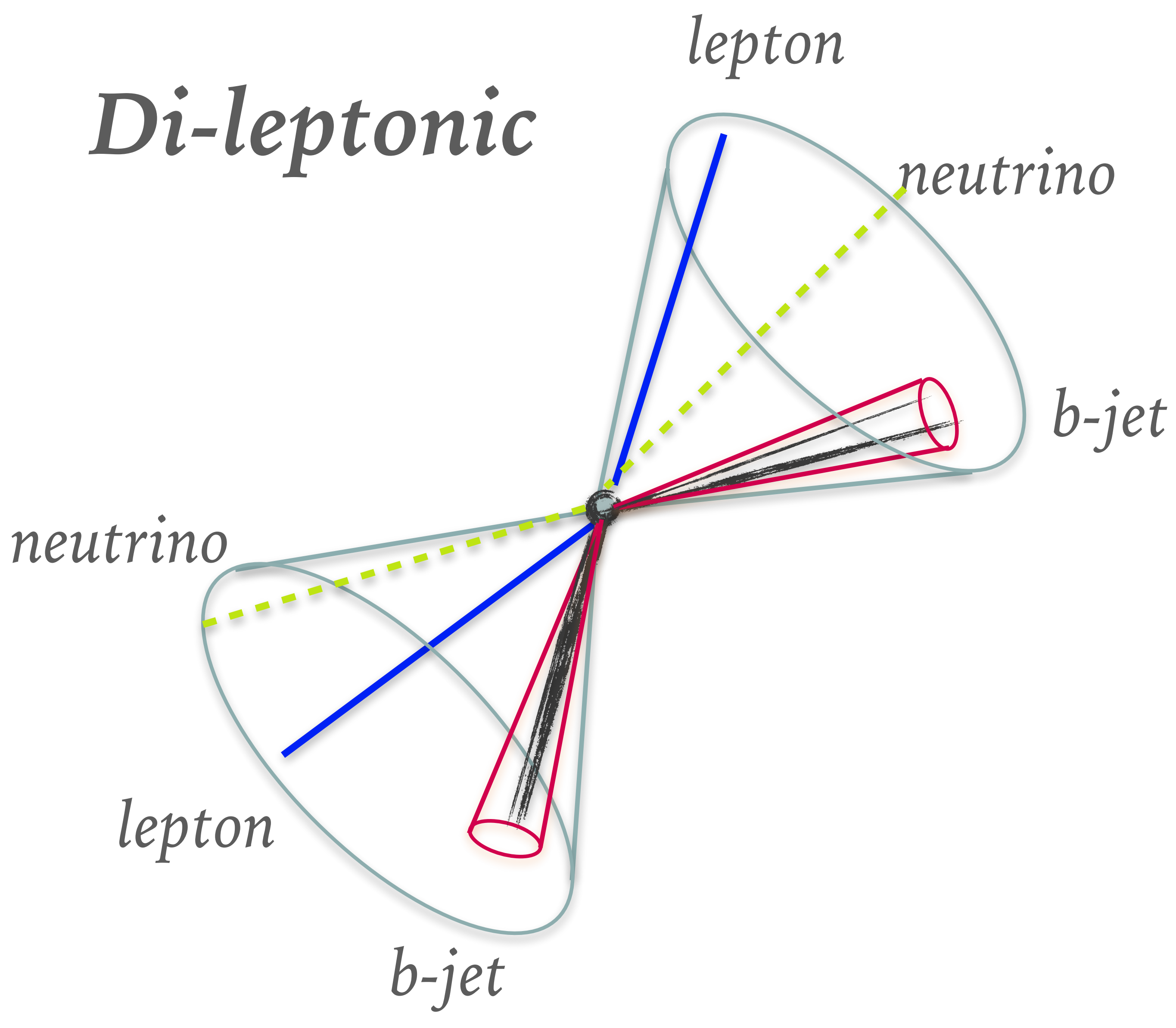
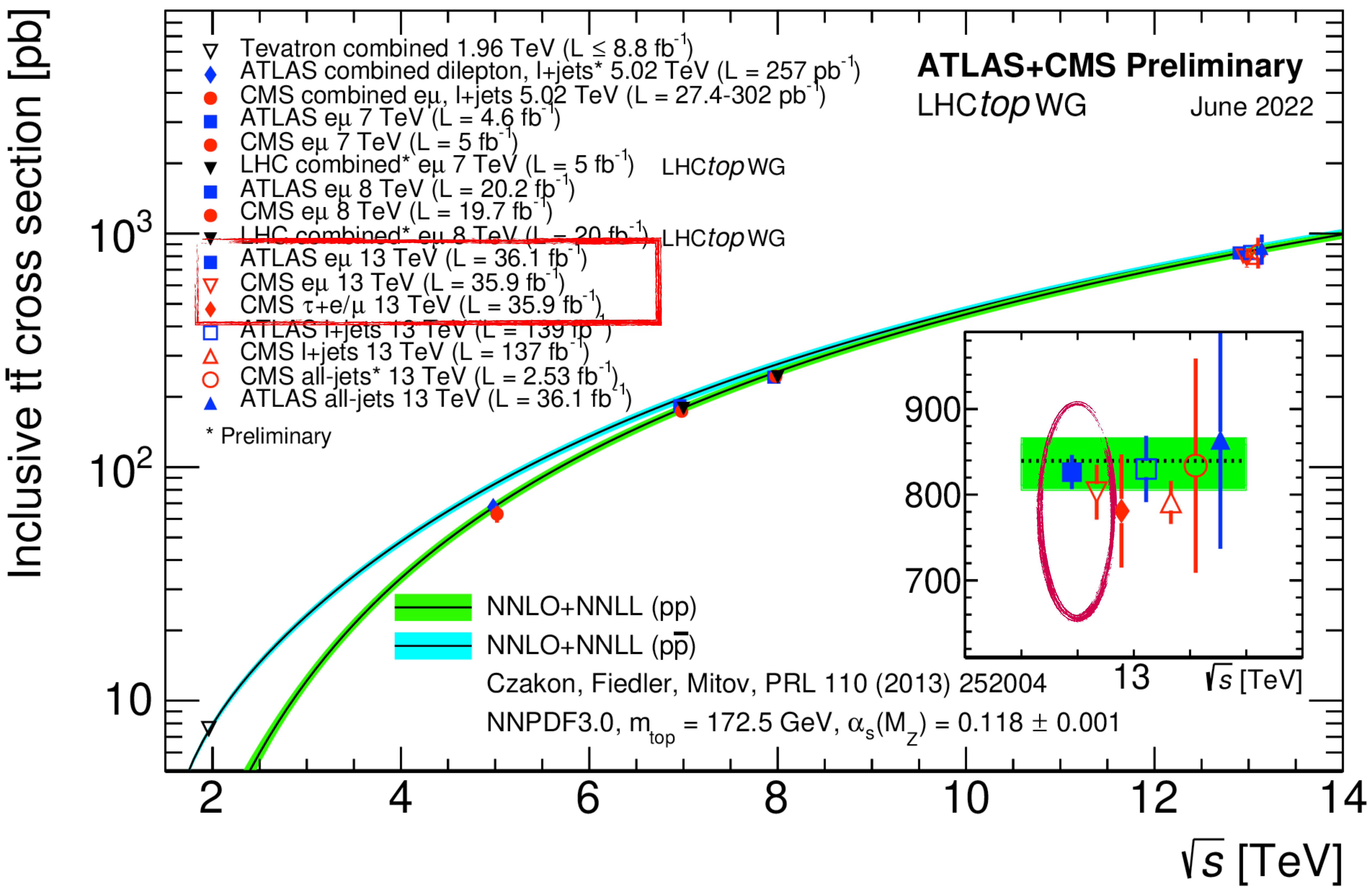
Top pair production cross section

Di-leptonic



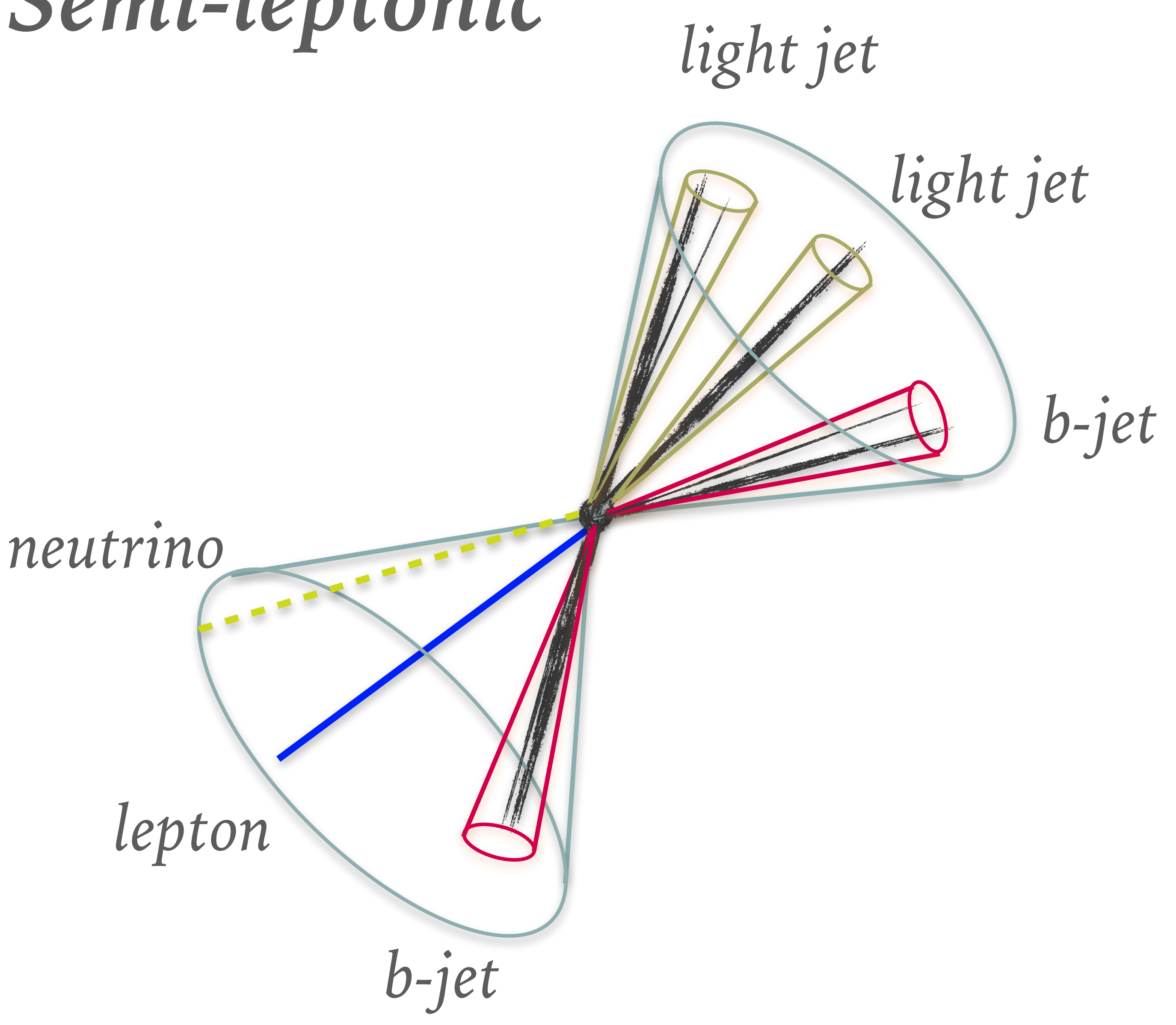
- *precise determination of cross section*
- *eμ channel very clean*
- *excellent signal to background ratio*
- *lower stats (4%)*



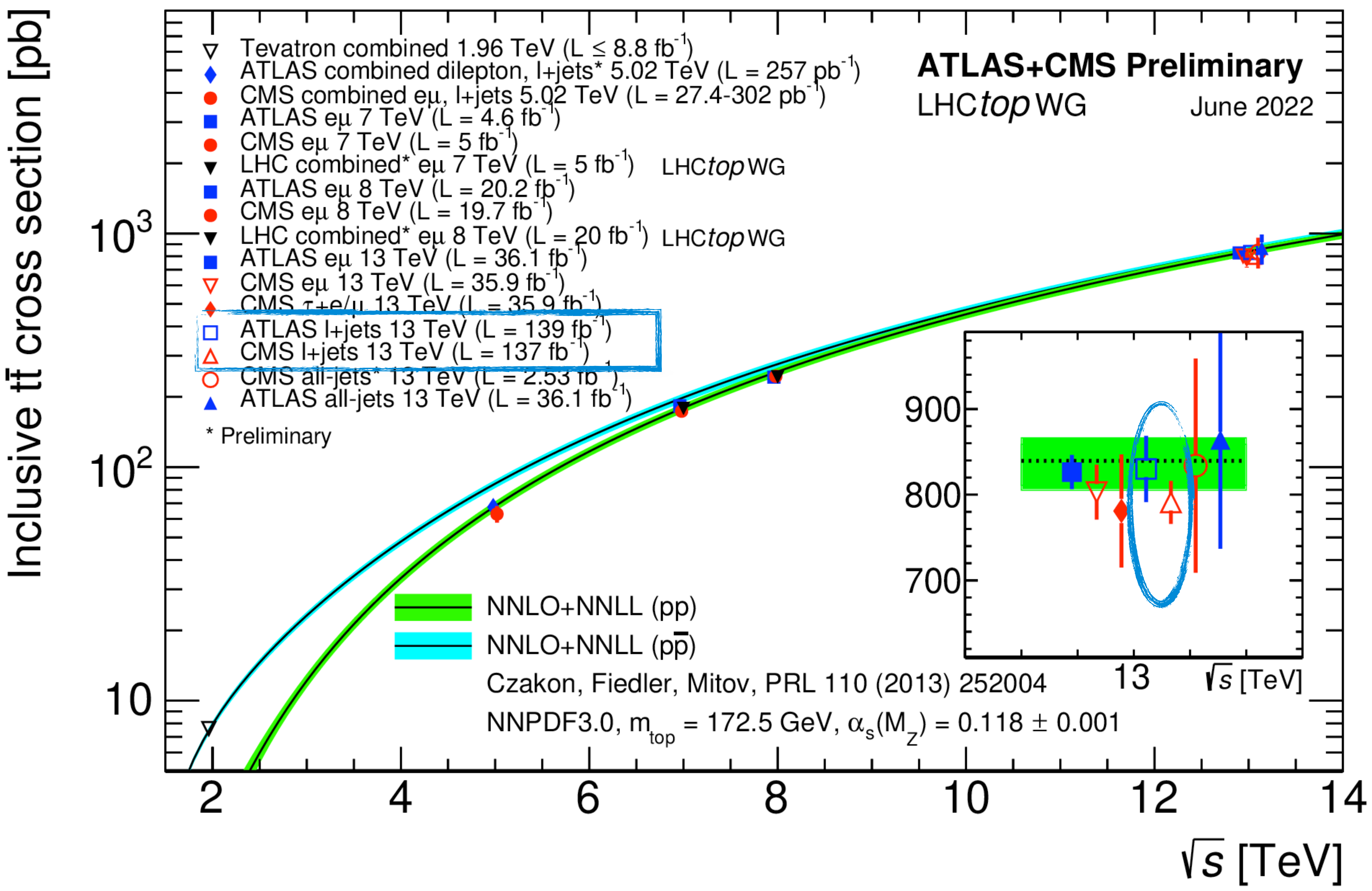
➤ Excellent agreement between measurement and NNLO+NNLL prediction

Top pair production cross section

Semi-leptonic



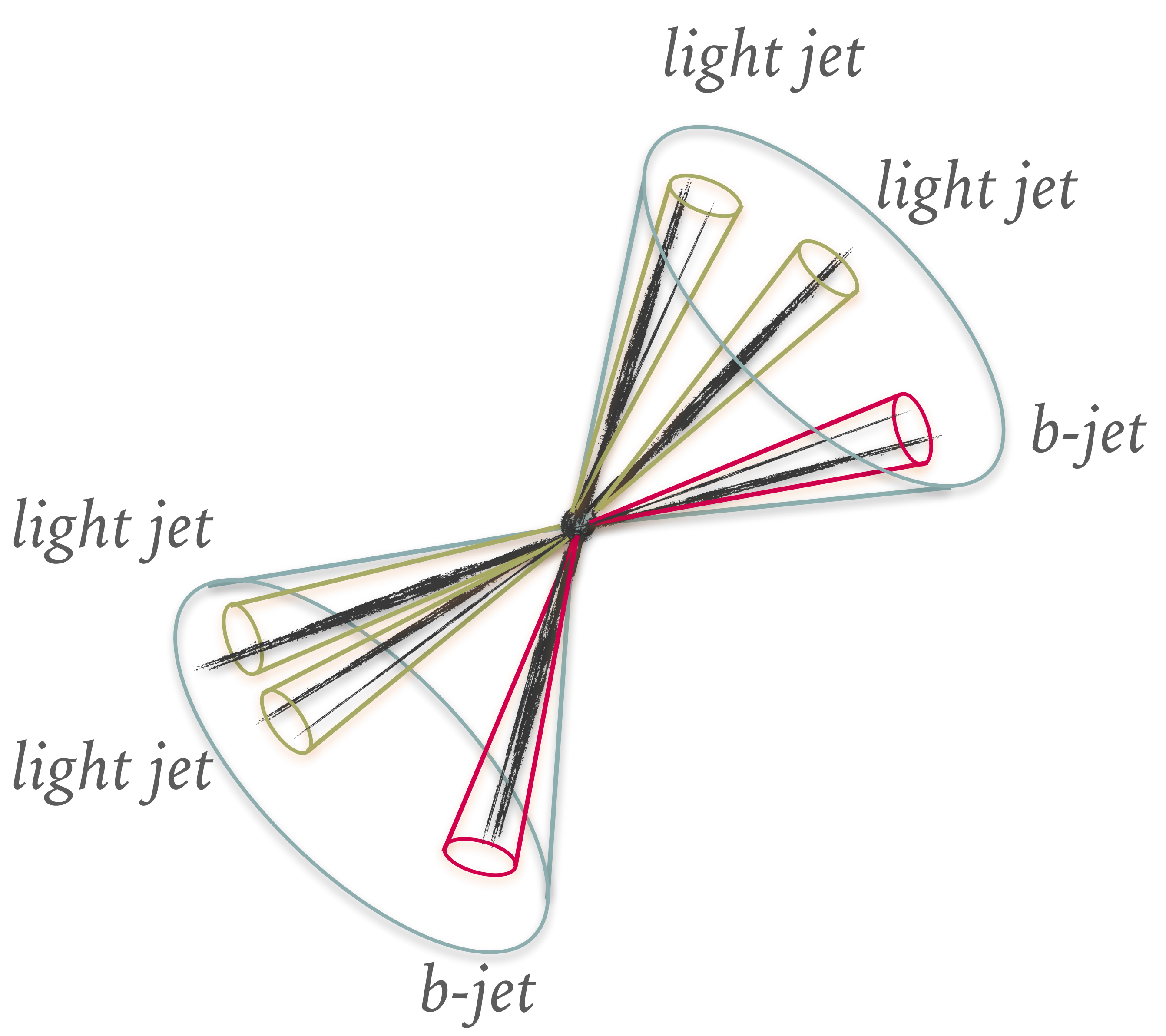
- best compromise between statistics (30%) and signal to background ratio



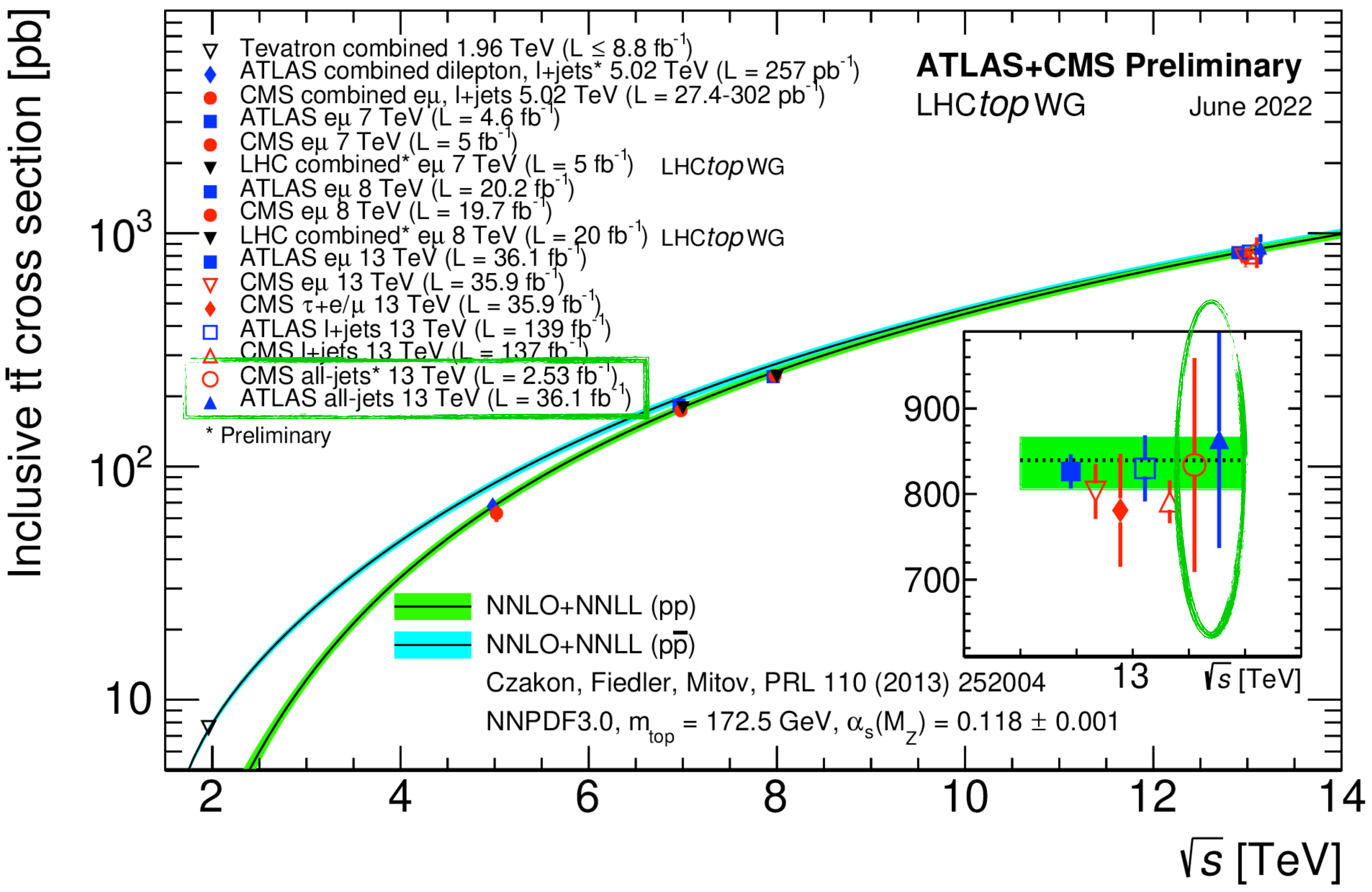
➤ Excellent agreement between measurement and NNLO+NNLL prediction

Top pair production cross section

Fully hadronic



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



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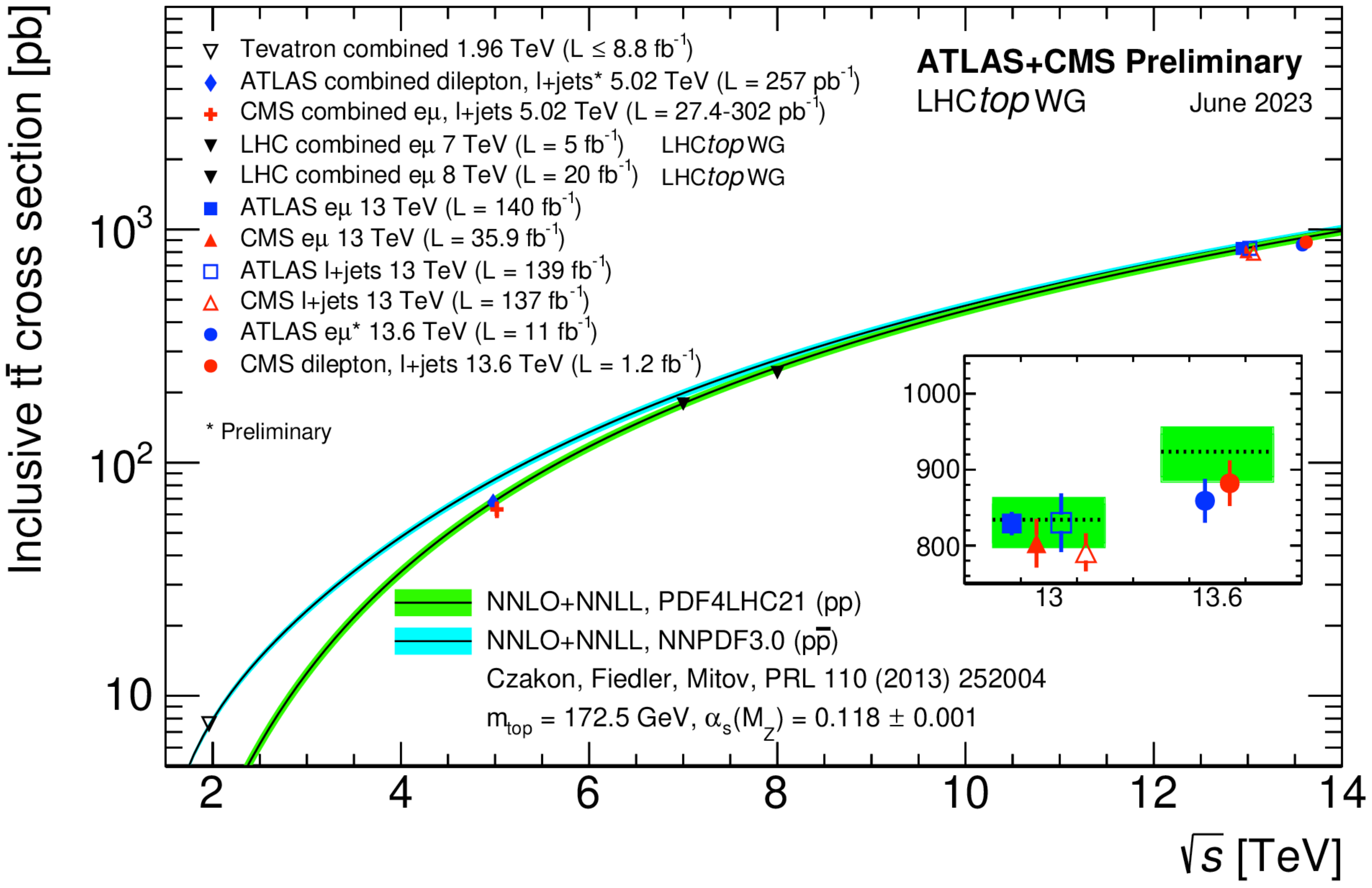
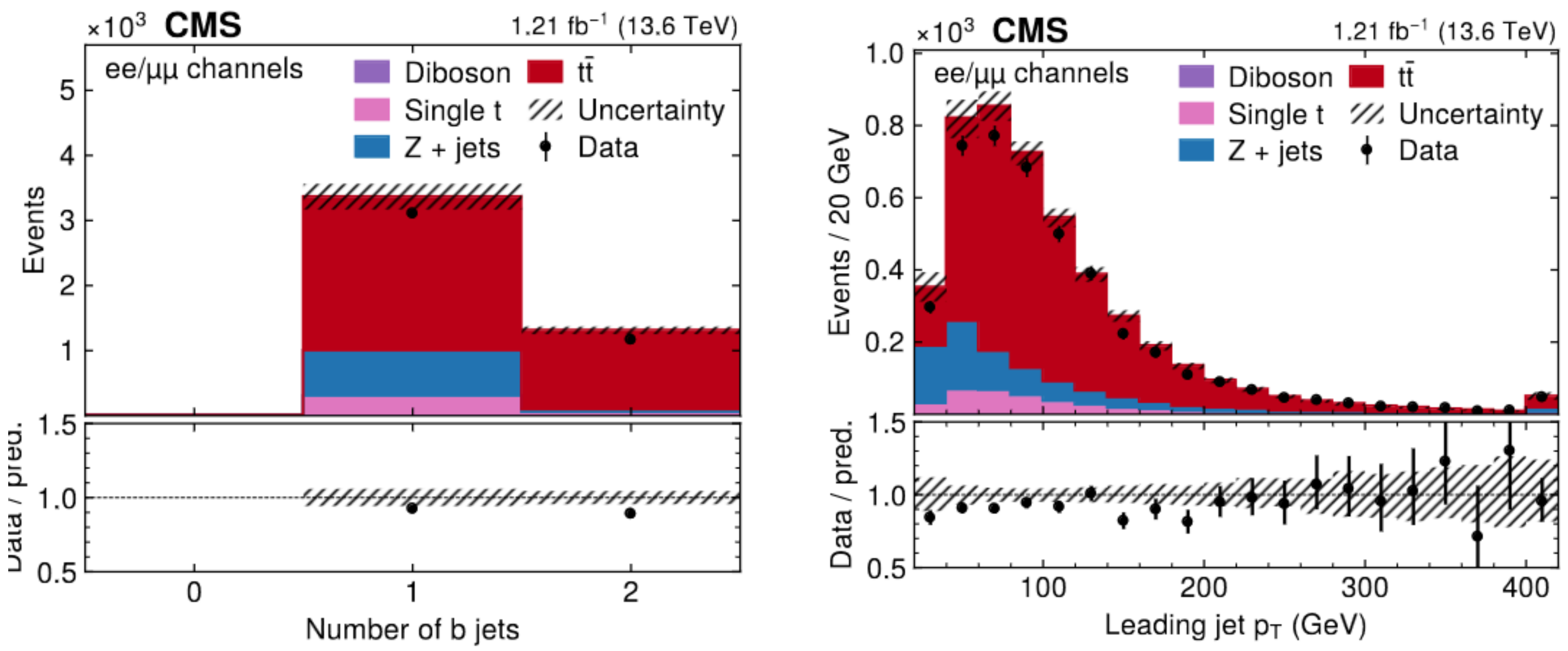
Hot of the press: First Run3 results

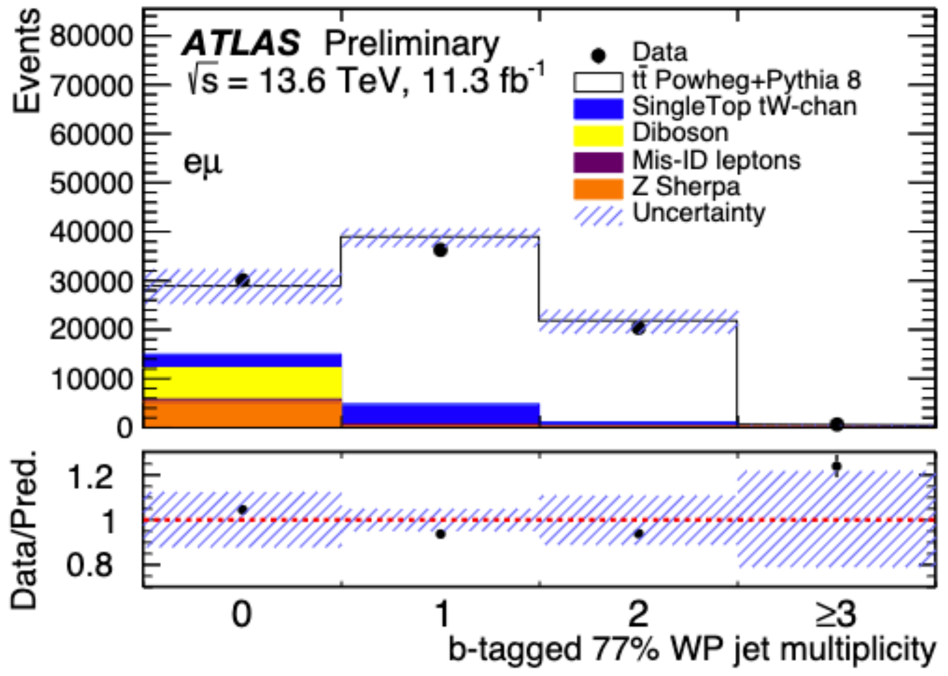
- ➤ CMS and ATLAS released first results of ttbar cross sections measurements with first Run3 data (1.2 to 11 fb^{-1}) in the di-lepton channel



CMS $882 \pm 23\,(\text{stat+syst}) \pm 20\,(\text{lumi})$ pb



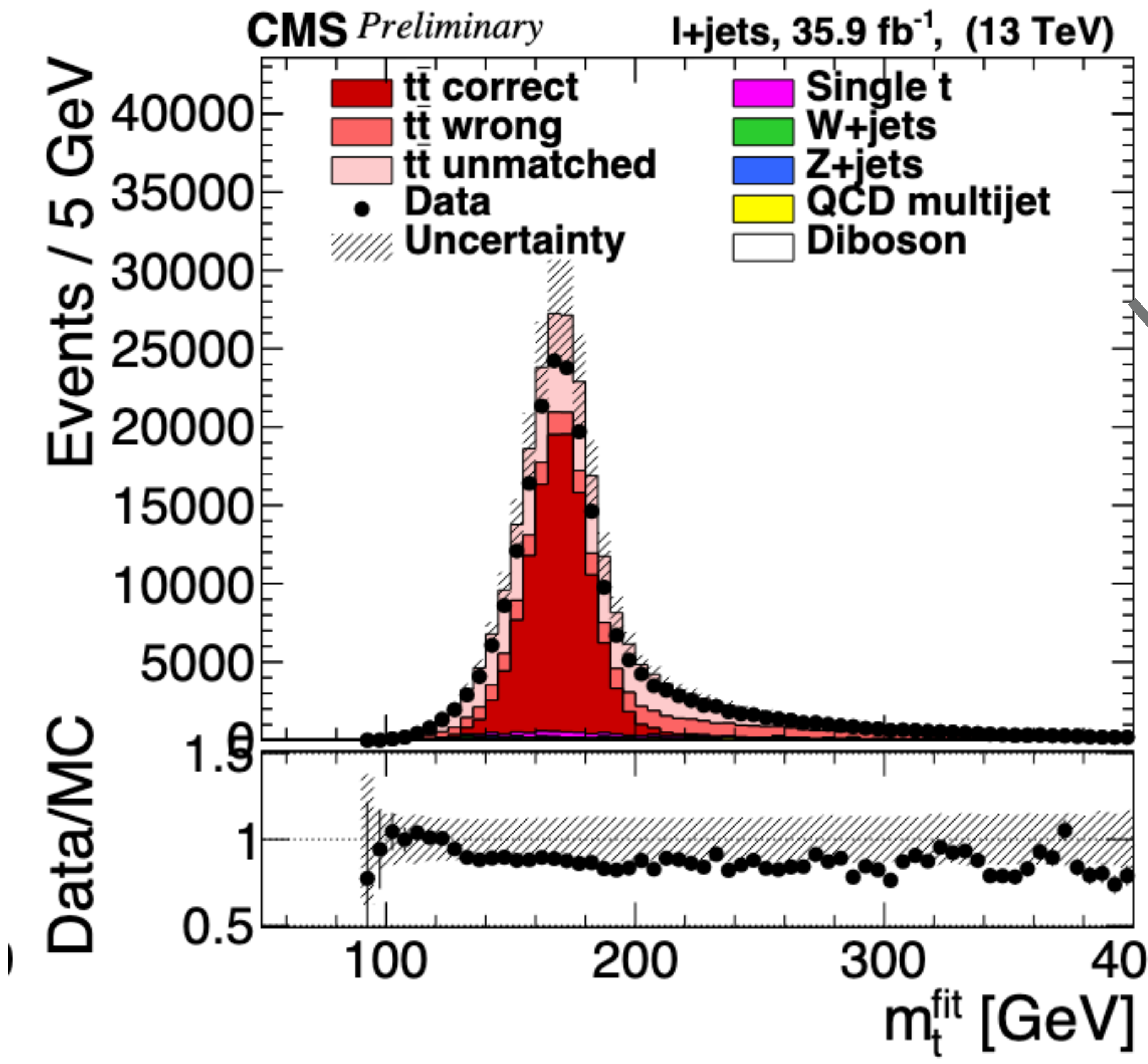
ATLAS $859 \pm 4(\text{stat.}) \pm 22(\text{syst.}) \pm 19(\text{lumi.})$ pb

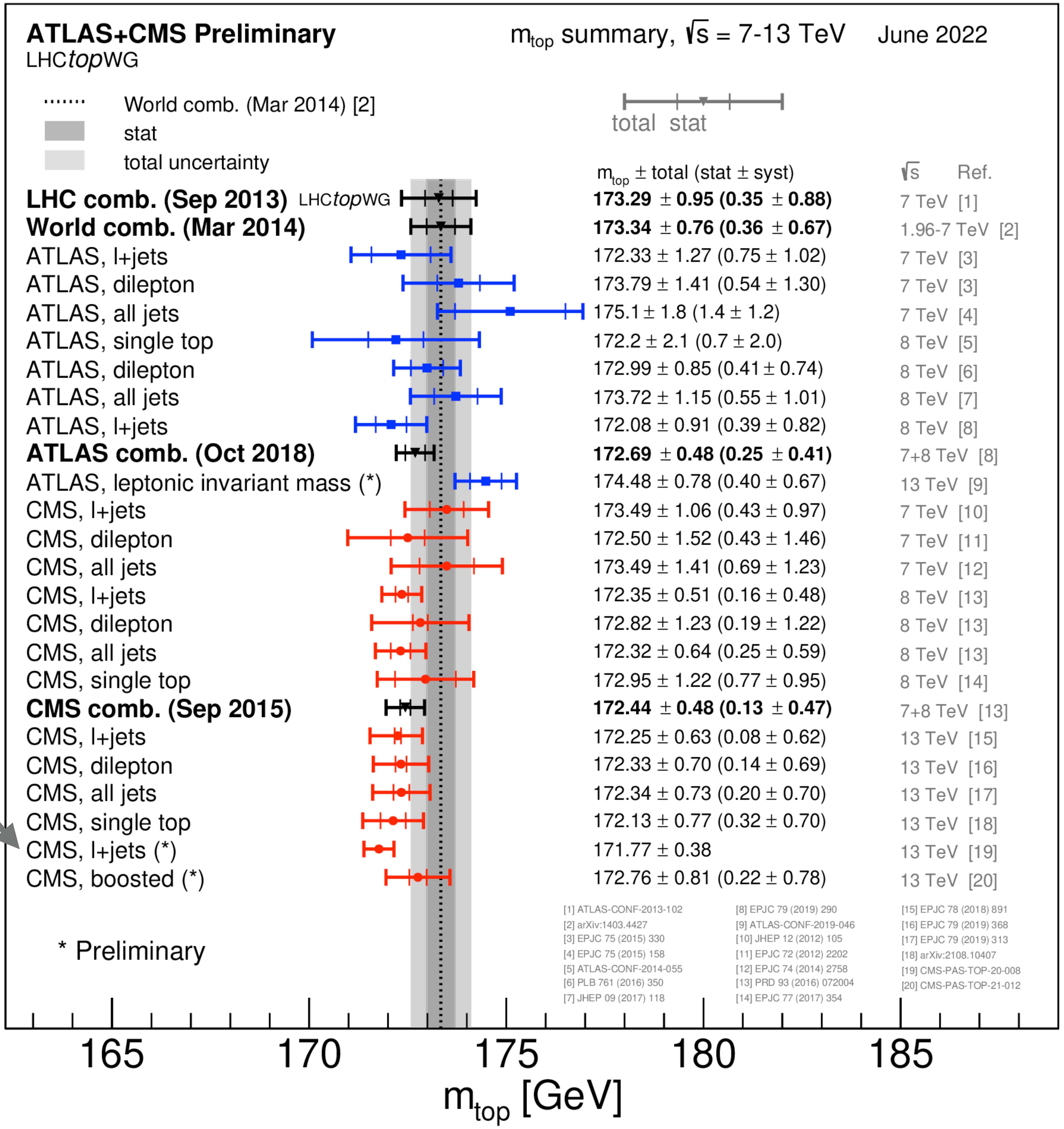


Measuring the top quark mass

- ➤ 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

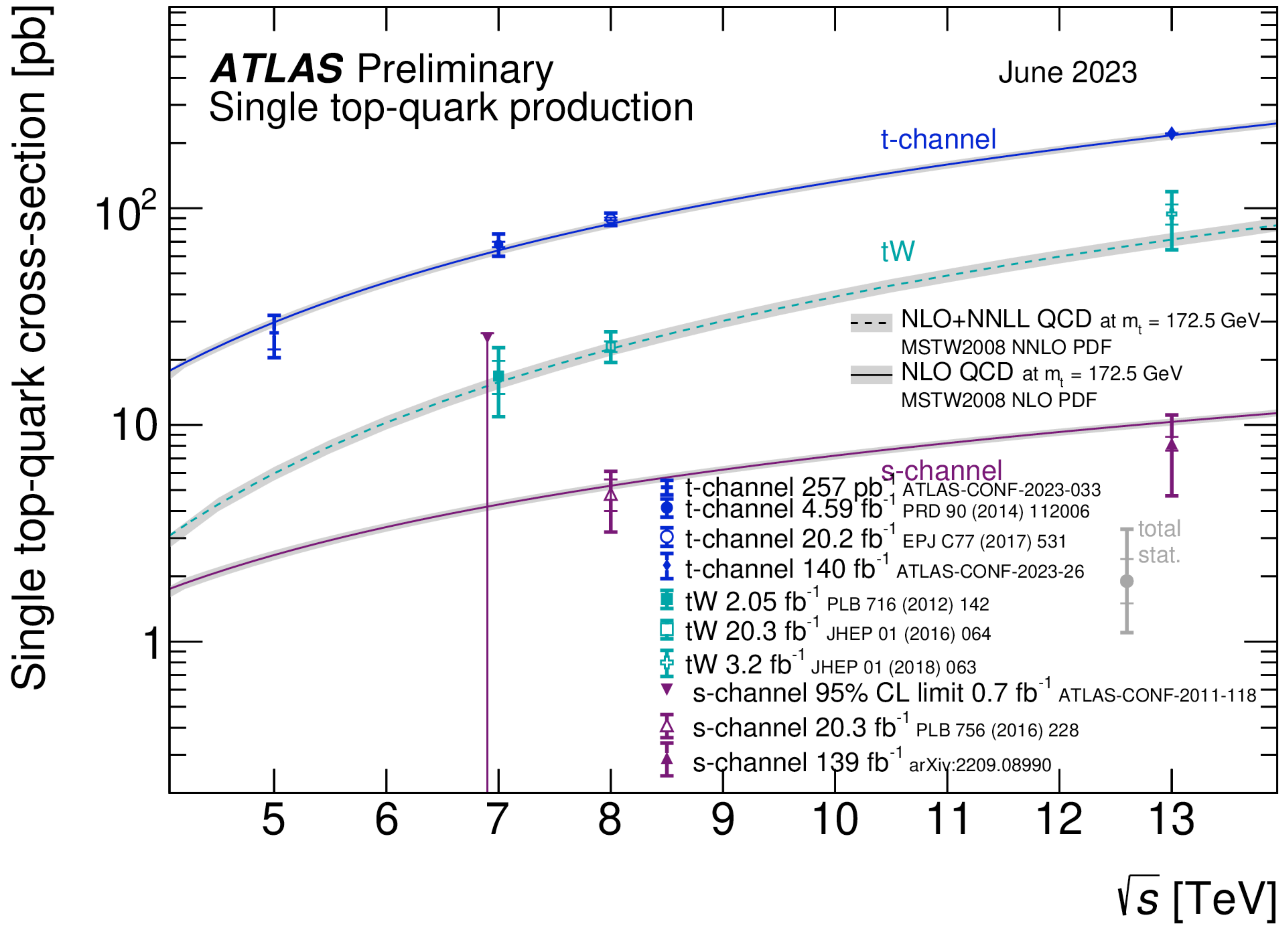


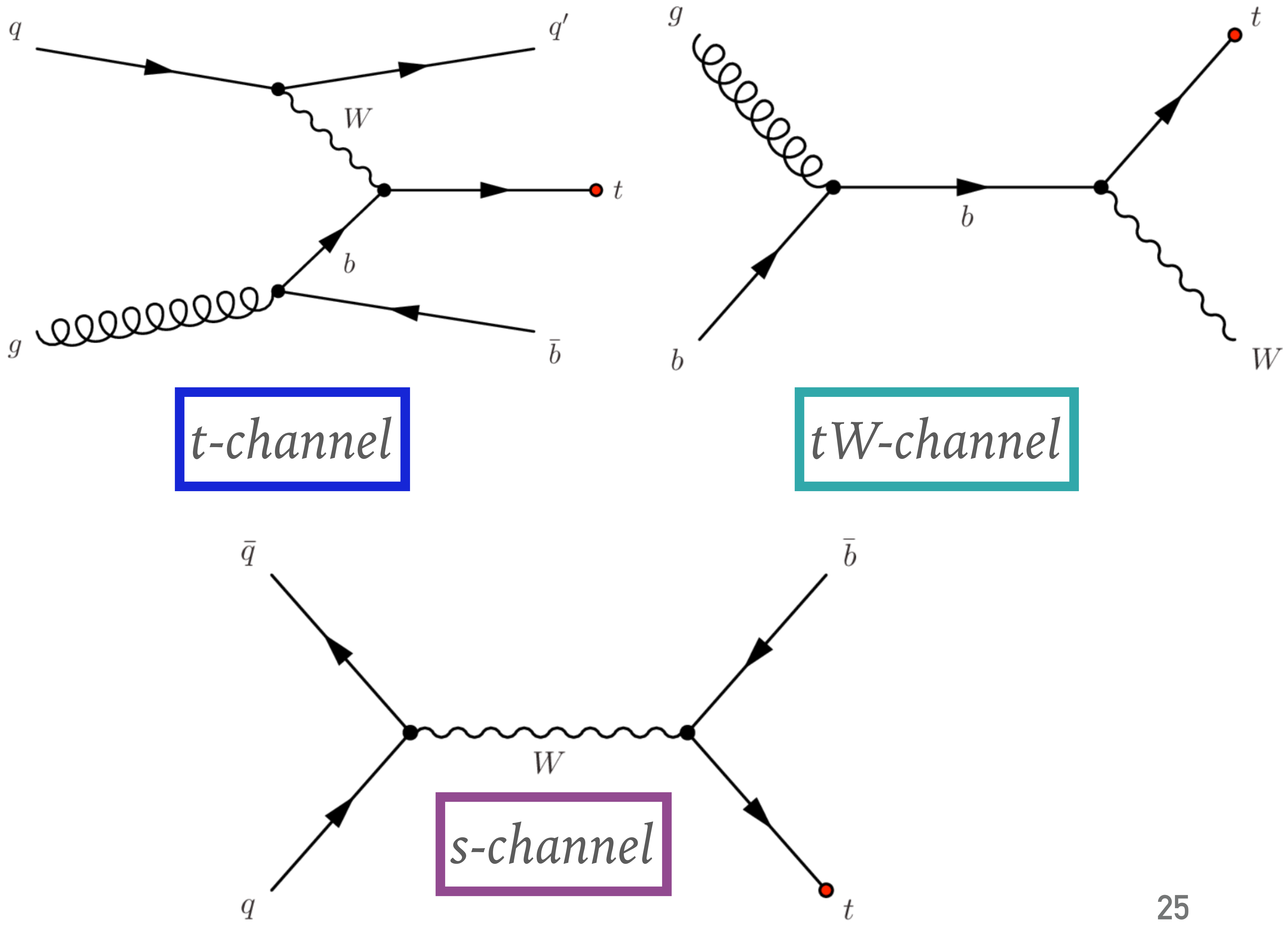


Most precise measurement: 171.77 ± 0.38 GeV (including 0.04 GeV statistical uncertainty)

Single top quark production

- ➤ Much rarer process compared to pair production (~ factor 3 lower at 13TeV)
  - ➤ Three main production modes

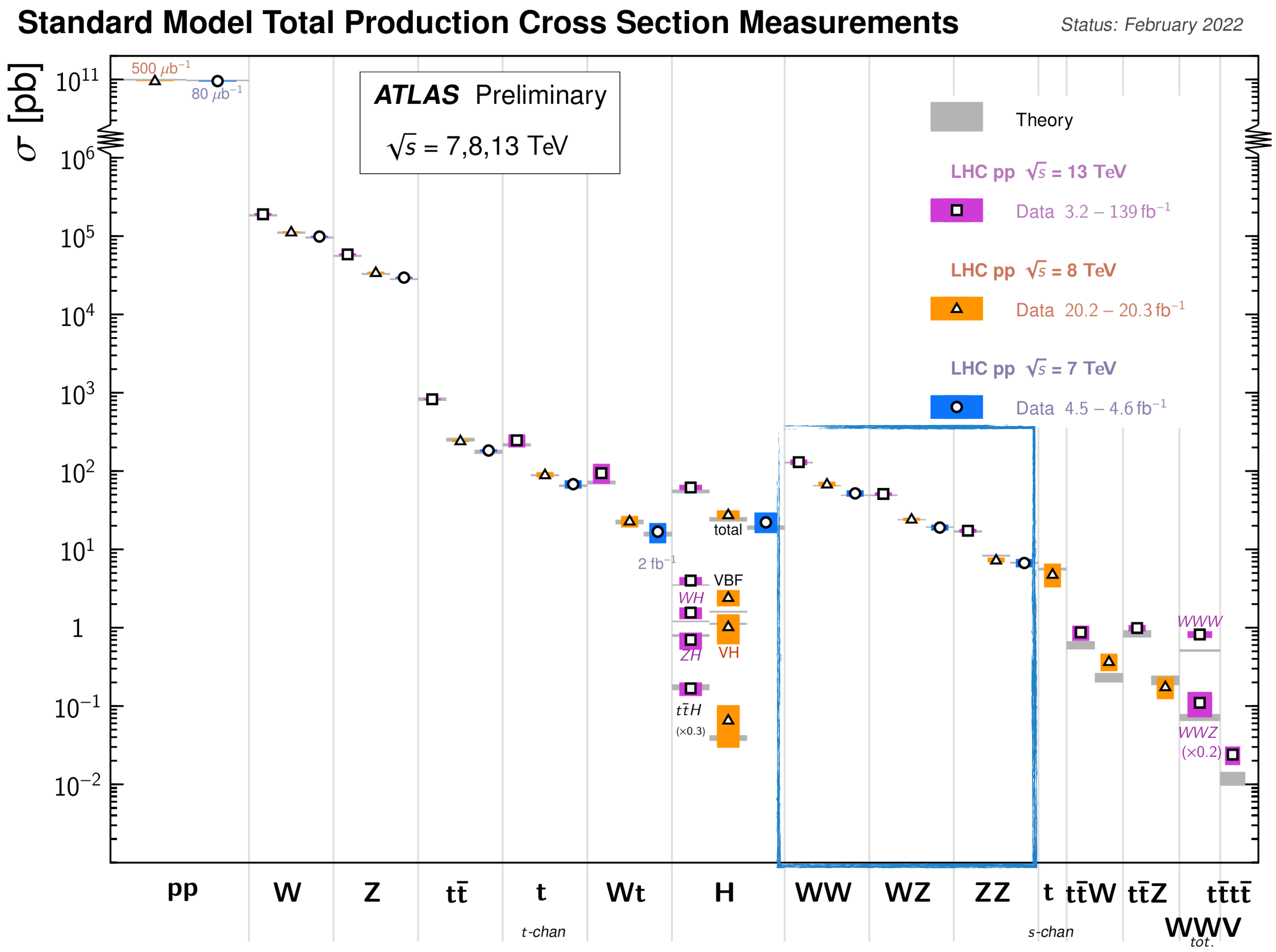




[Summary plot]

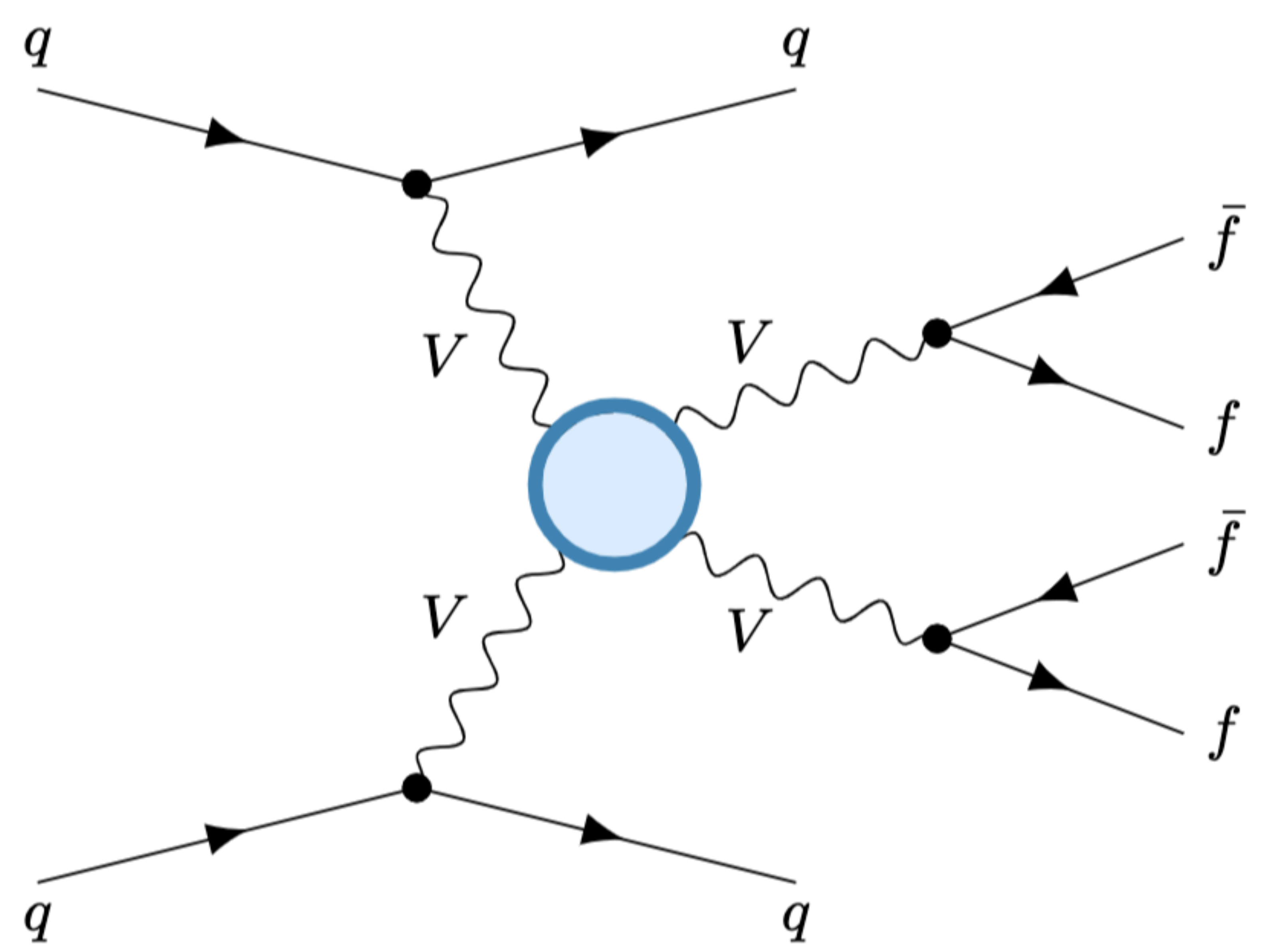
Going to rarer and rarer SM processes

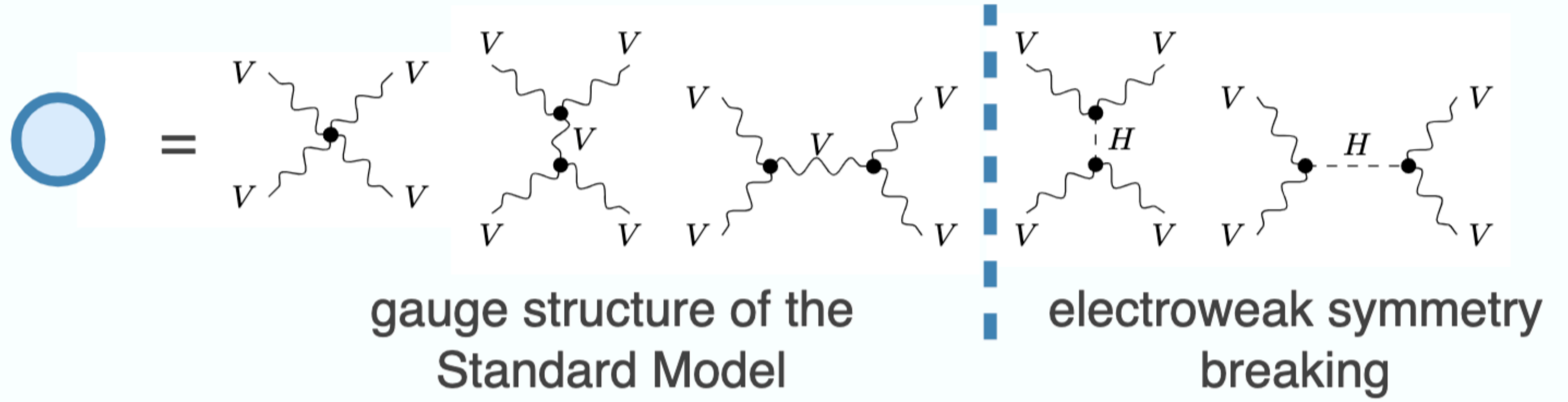
Di-boson production



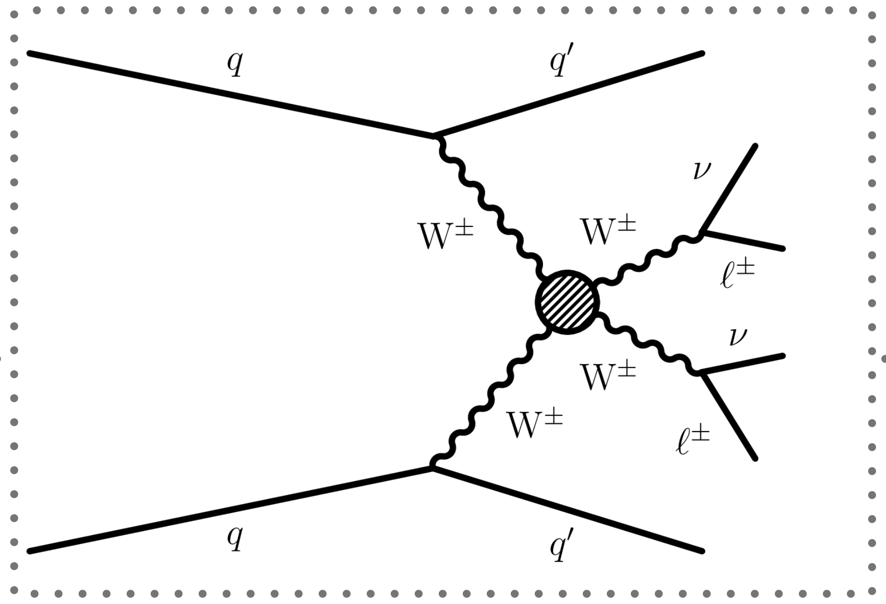
Multi-boson production

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





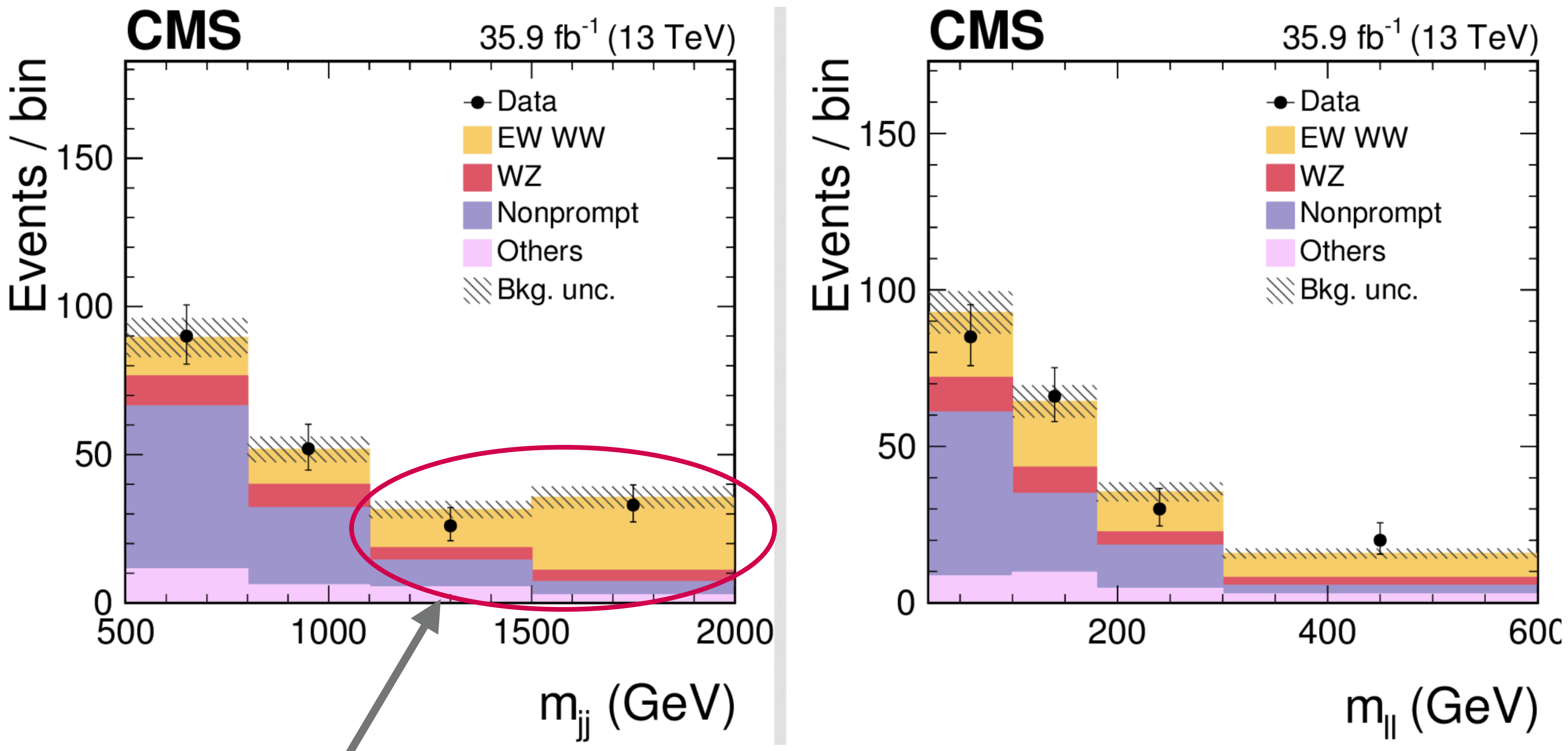
Same-sign WW



[Phys. Lett. B 809 (2020) 135710]

- **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**

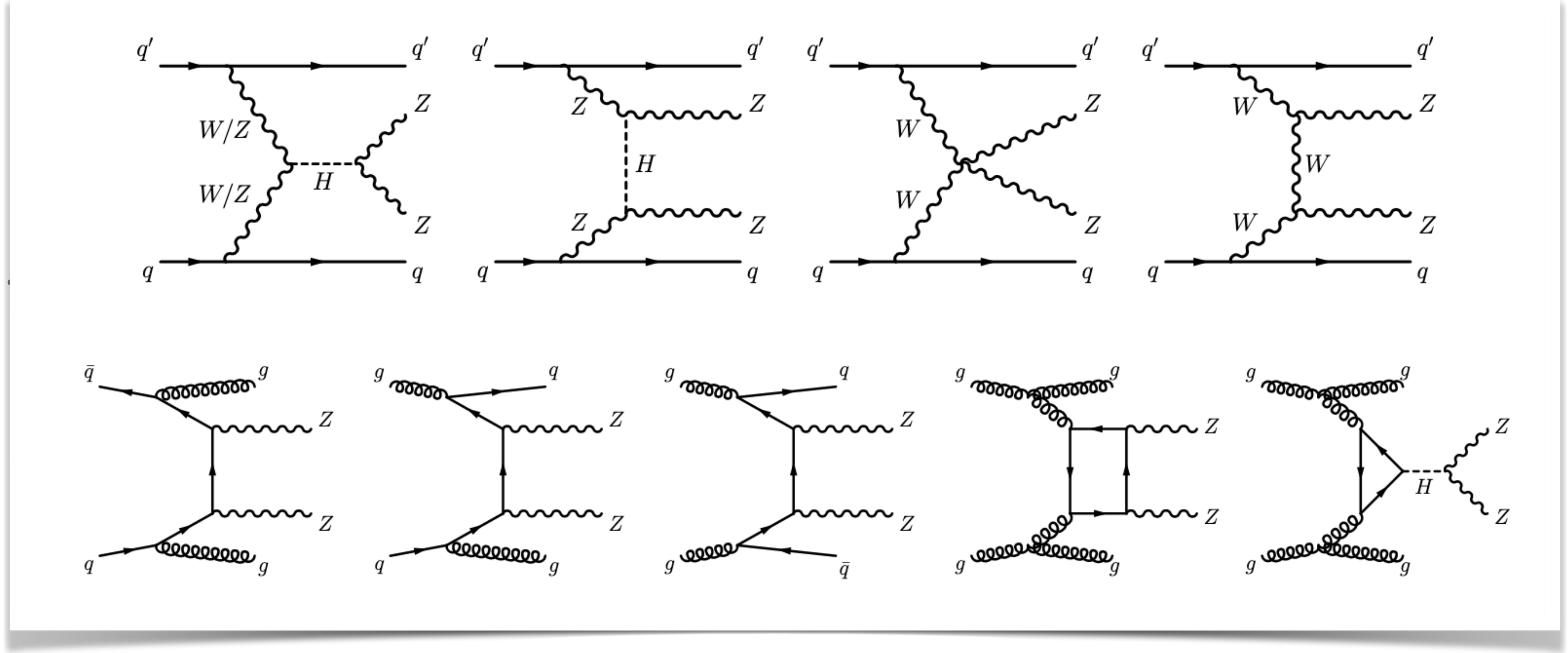


Signal populates high m_{jj} region

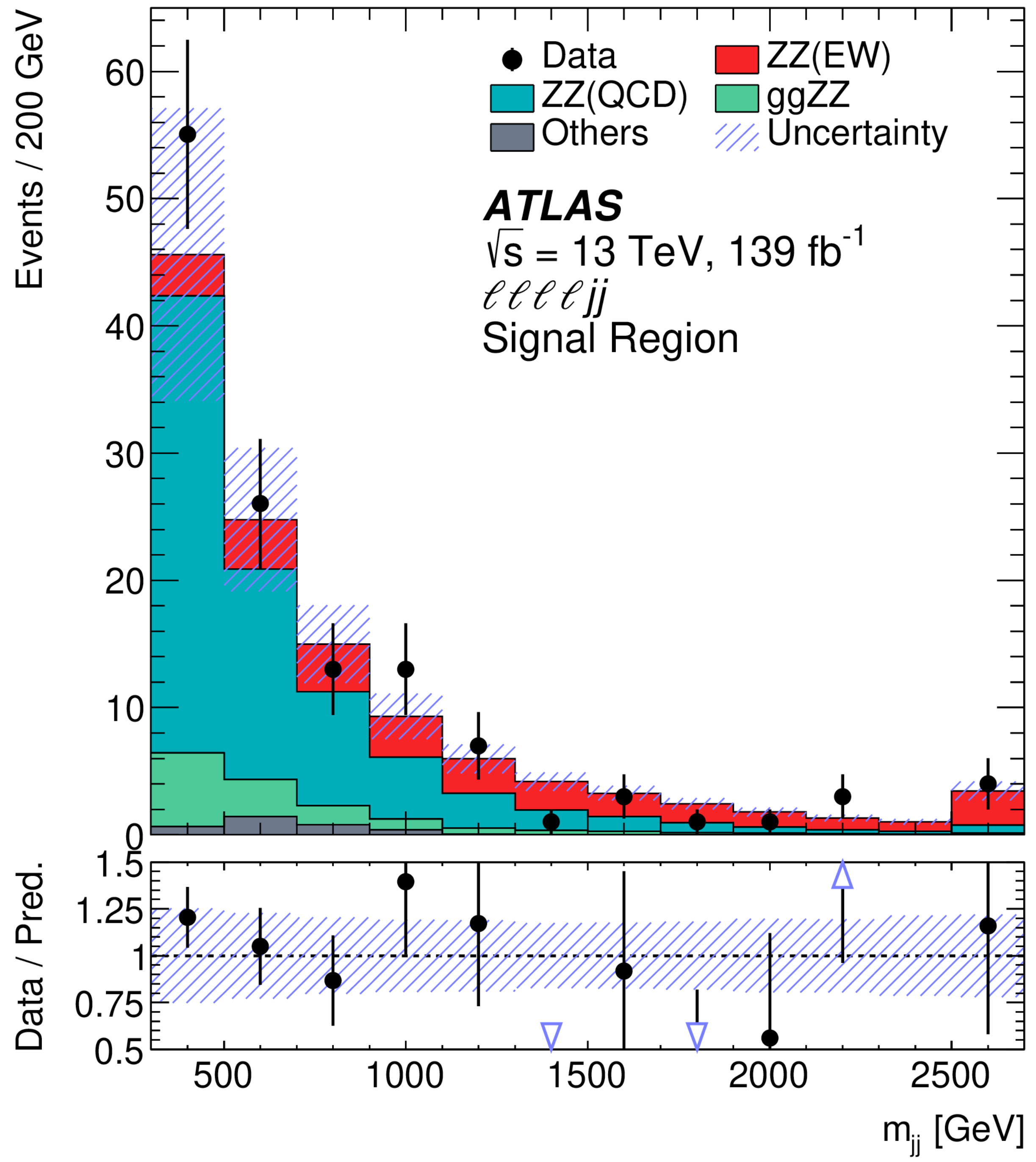
ZZ production

EWK

QCD



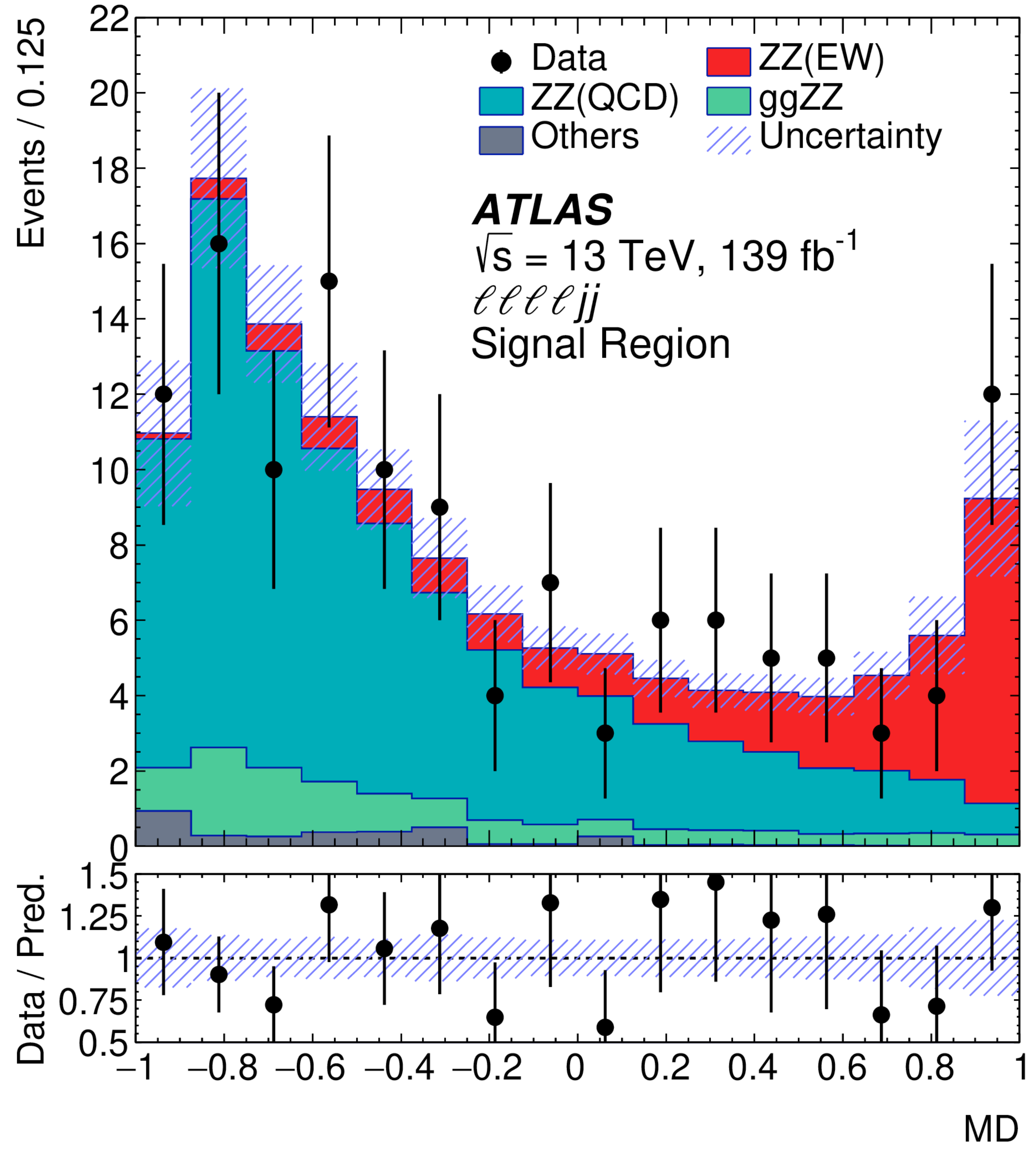
- **Signal selection**
  - 2 jets with large separation large invariant mass
    - 4 leptons same-sign opposite flavor
    - or 2 leptons + MET



From kinematic variables to improved discriminators

Inputs to BDT:

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

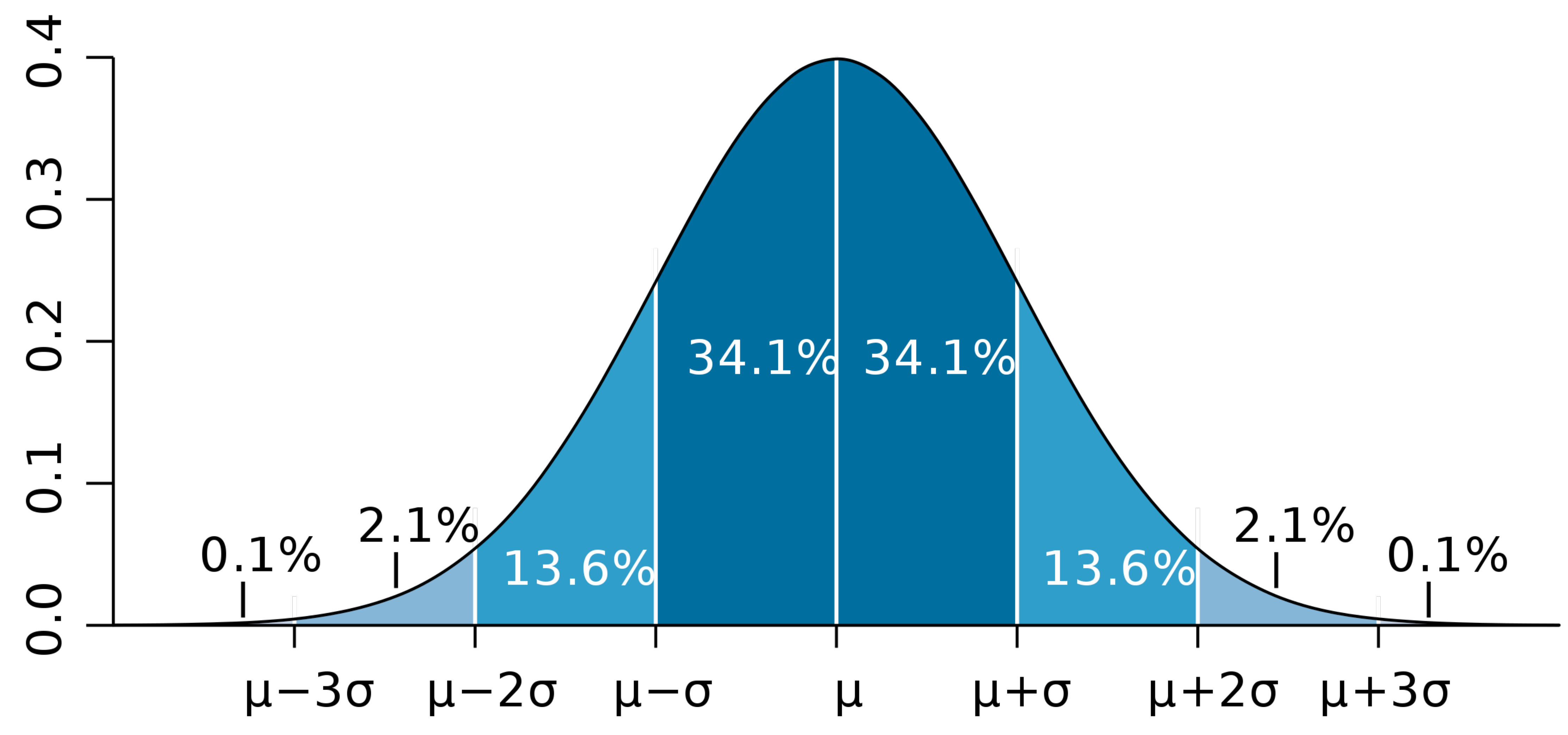


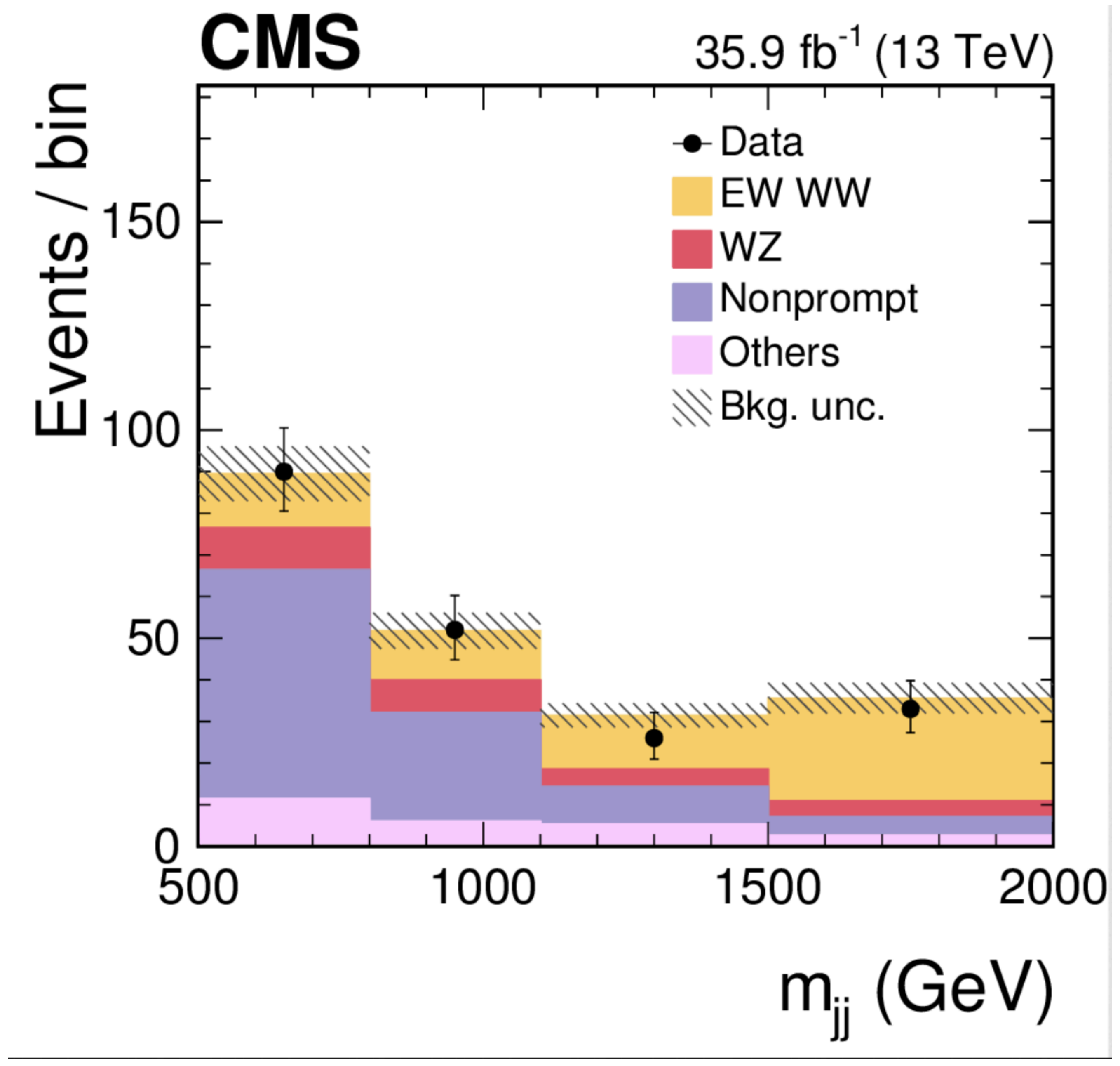
Observed significance of **5.5 sigma**

[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:
  - $1/\alpha = 137.035999084\ (21)$

determined from the quantum Hall effect
or the anomalous magnetic moment of the electron

- The Fermi constant:
  - $G_F = 1.166\ 3787 \times 10^{-5}\ \text{GeV}^{-2}$

measured from the muon lifetime

- The Z boson mass
  - $m_Z = 91.1876 \pm 0.0021$ GeV

measured at LEP

From these can calculate m_W

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

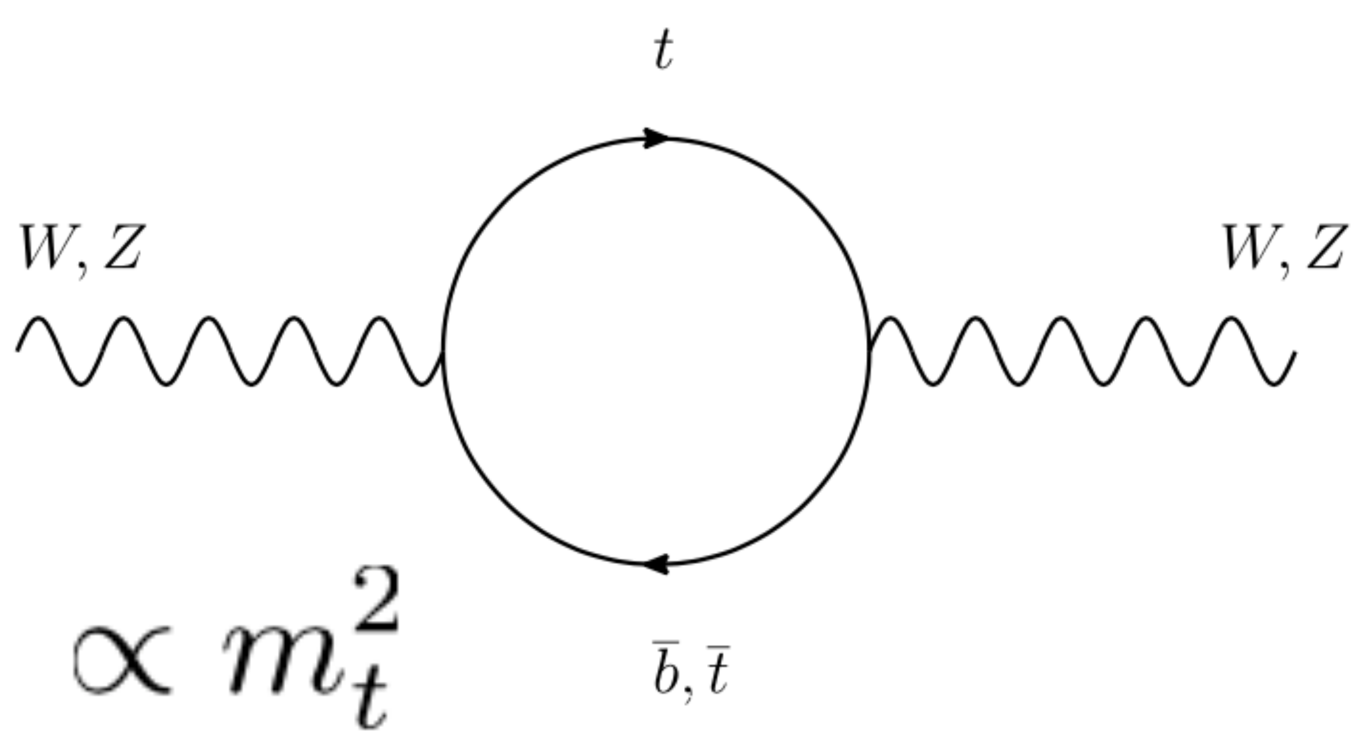
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

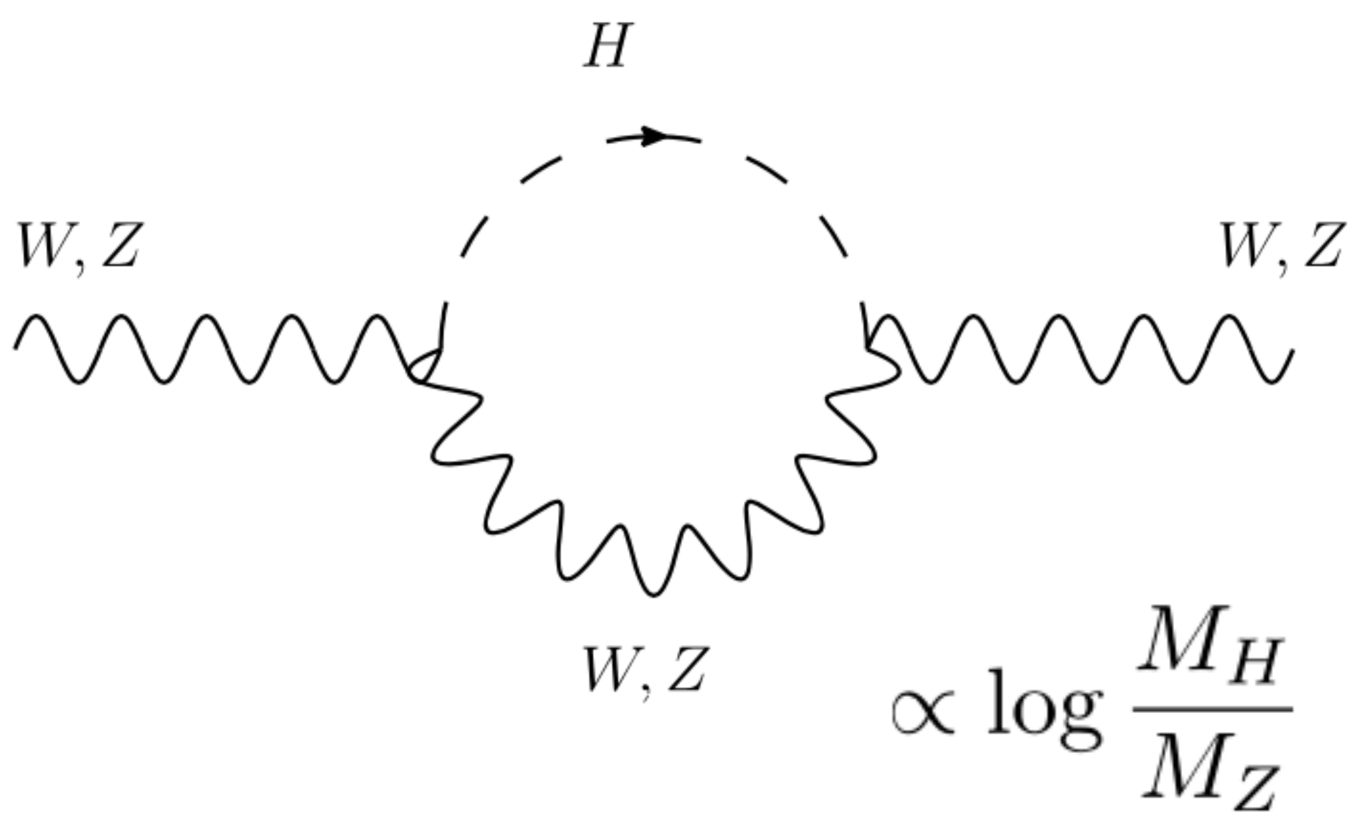
$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}$$

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

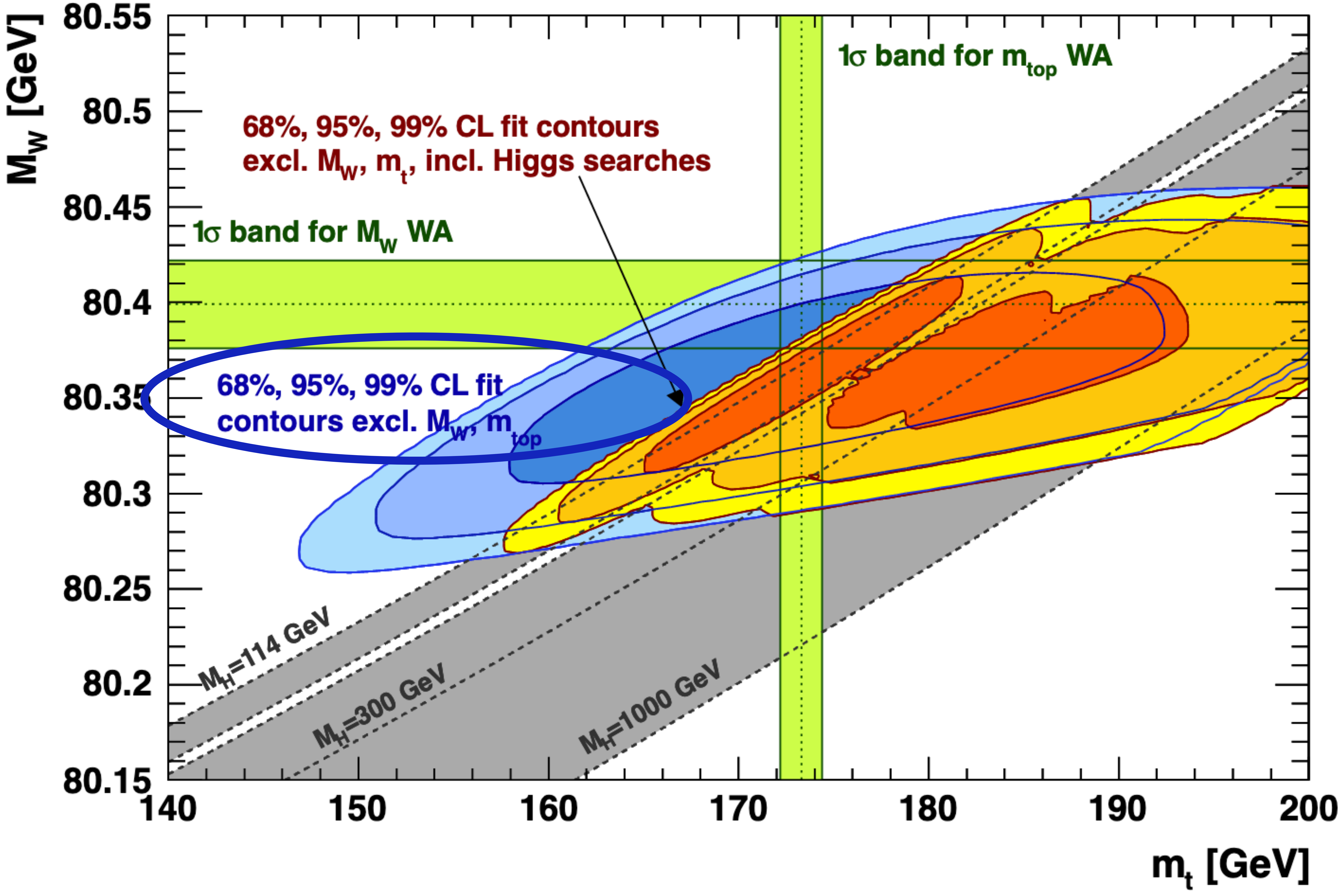




- Idea of electroweak fits:
  - measure many different observables
  - calculate the relations between all observables
  - measure redundant observables => probe consistency of Standard Model
  - predict observables => Higgs mass before the discovery!

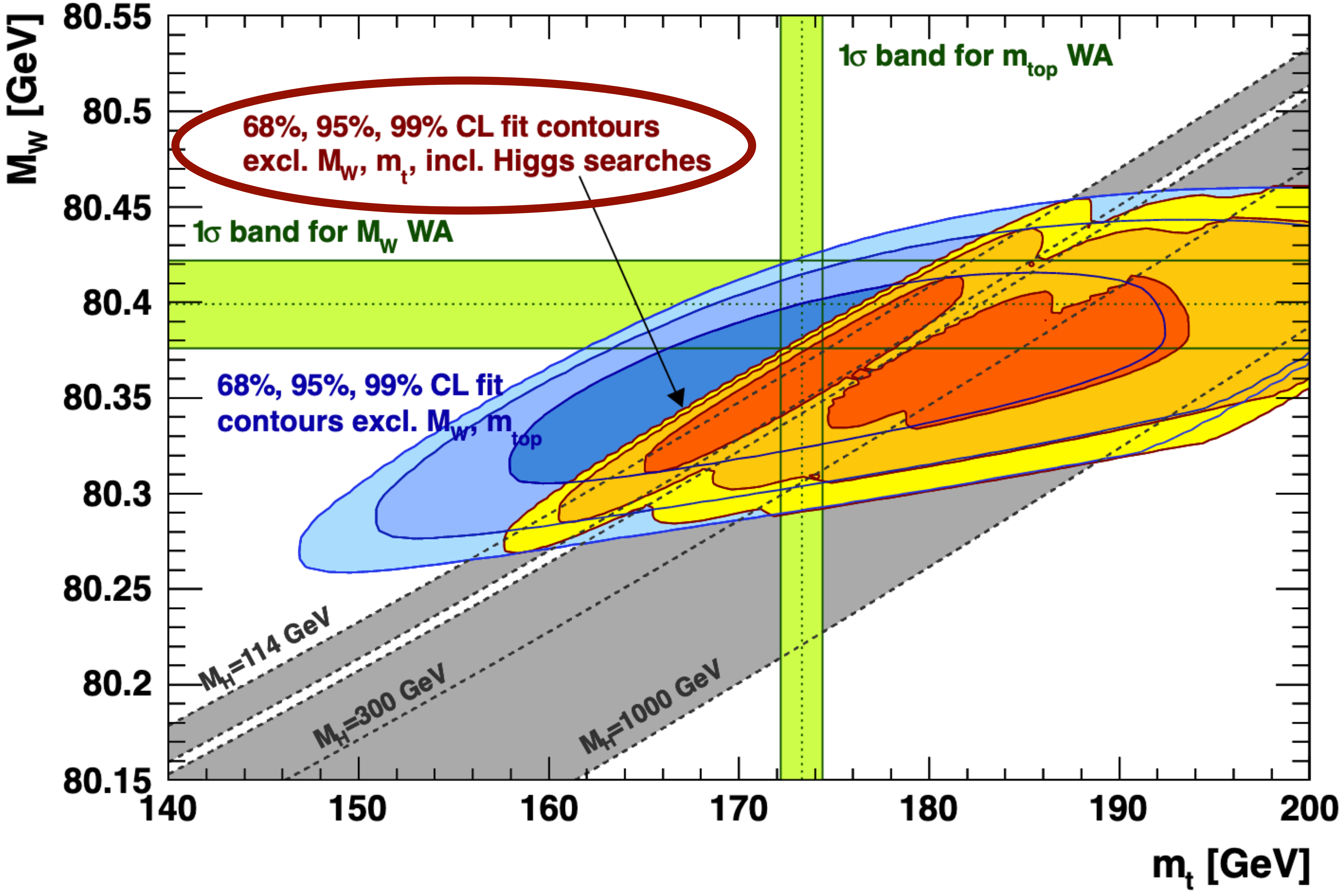
https://arxiv.org/pdf/1107.0975.pdf

Standard Model fits before the Higgs discovery: 2012



Predicting the top and W mass from SM parameter measurements

Standard Model fits before the Higgs discovery: 2012

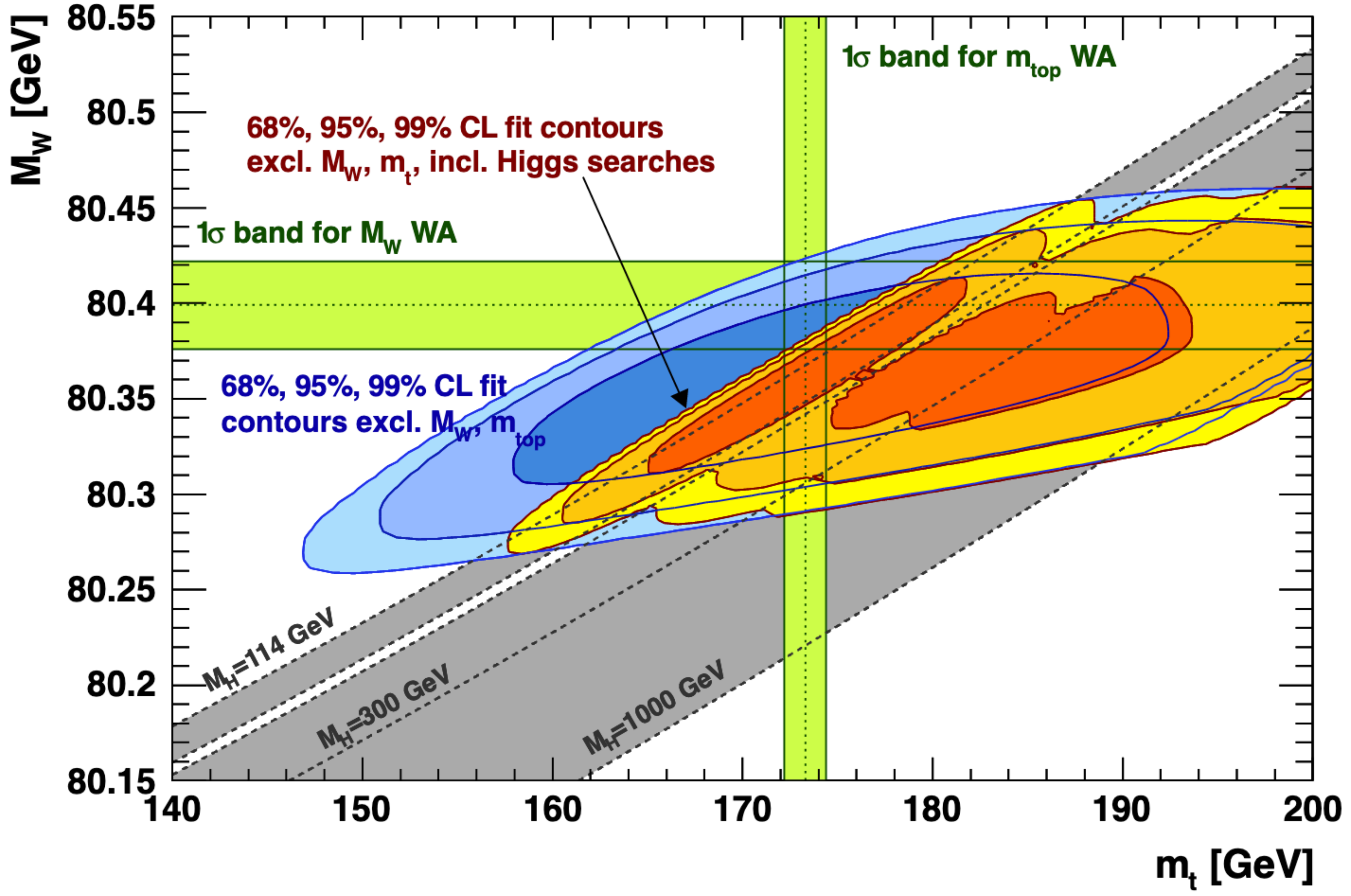


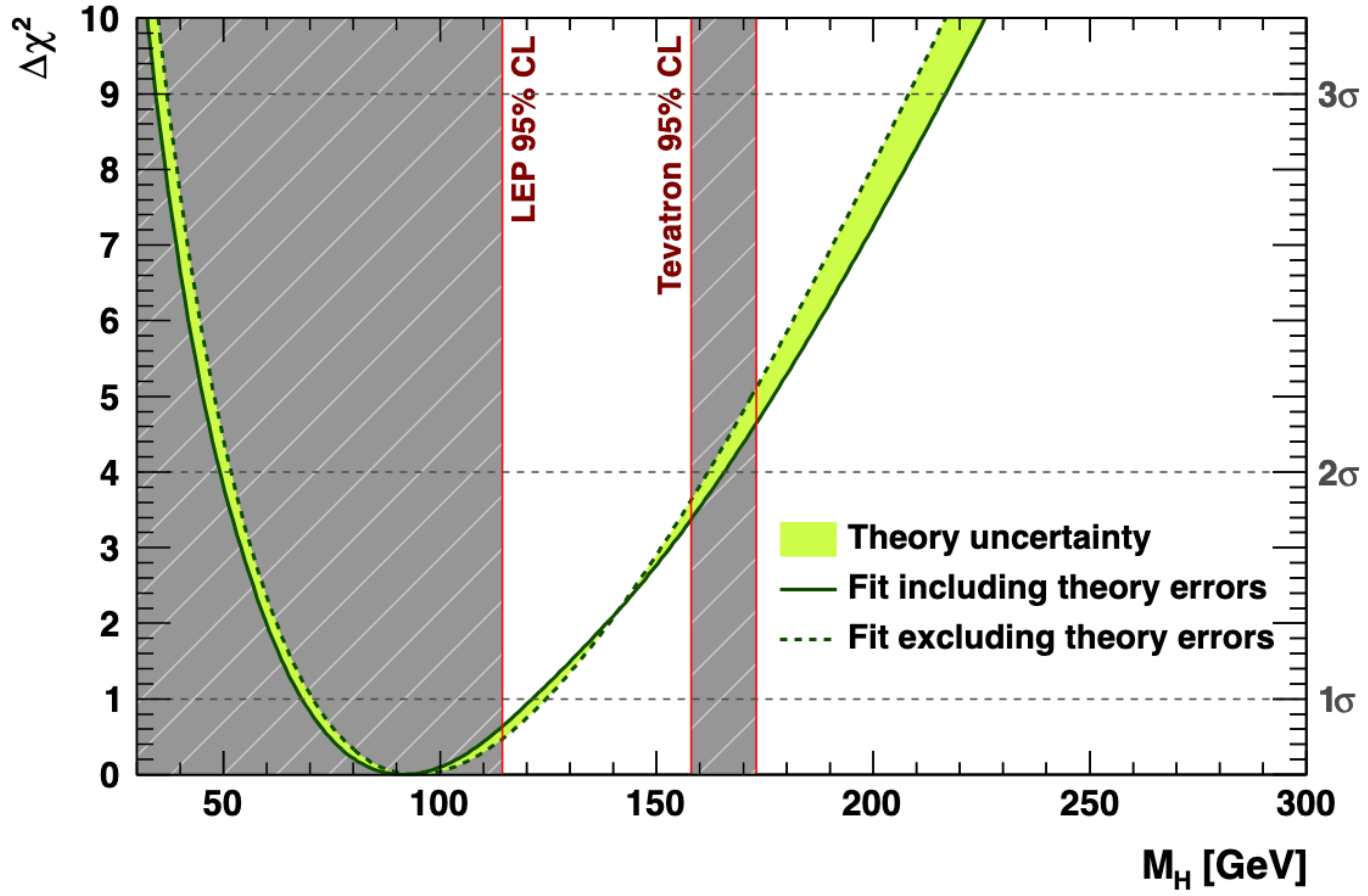
Predicting the top and W mass from SM parameter measurements

including Higgs search results

Gfitter 2012: https://arxiv.org/pdf/1107.0975.pdf

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