

# Studying the standard model of particle physics

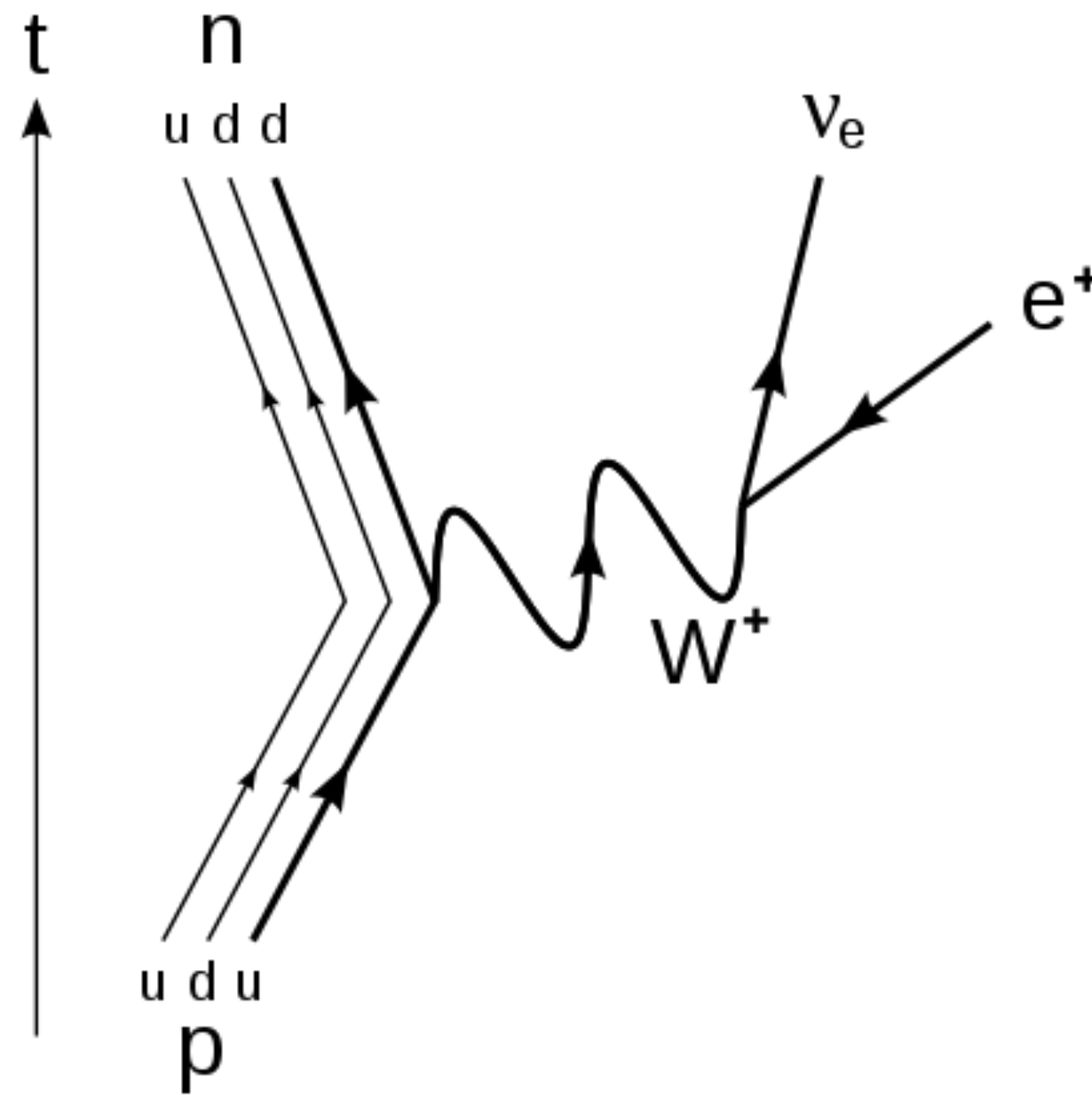
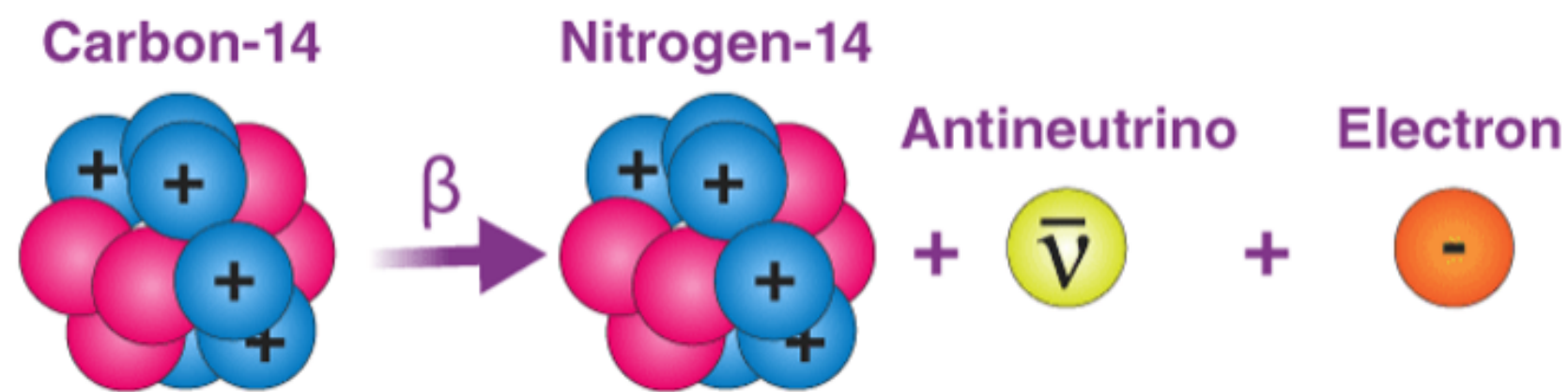
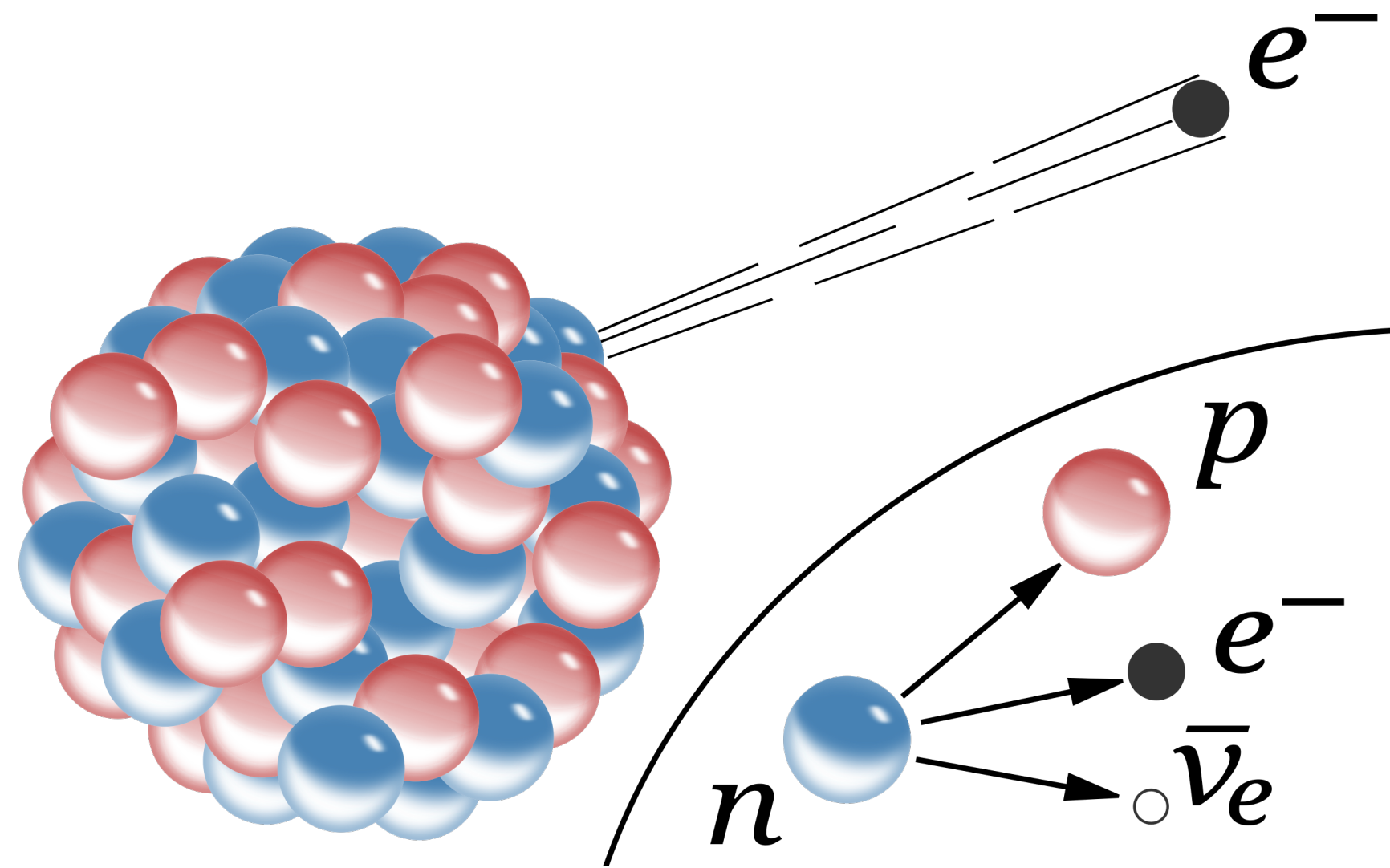
*with single and multi-boson production at the LHC*

*Rencontres de Noirmoutier*

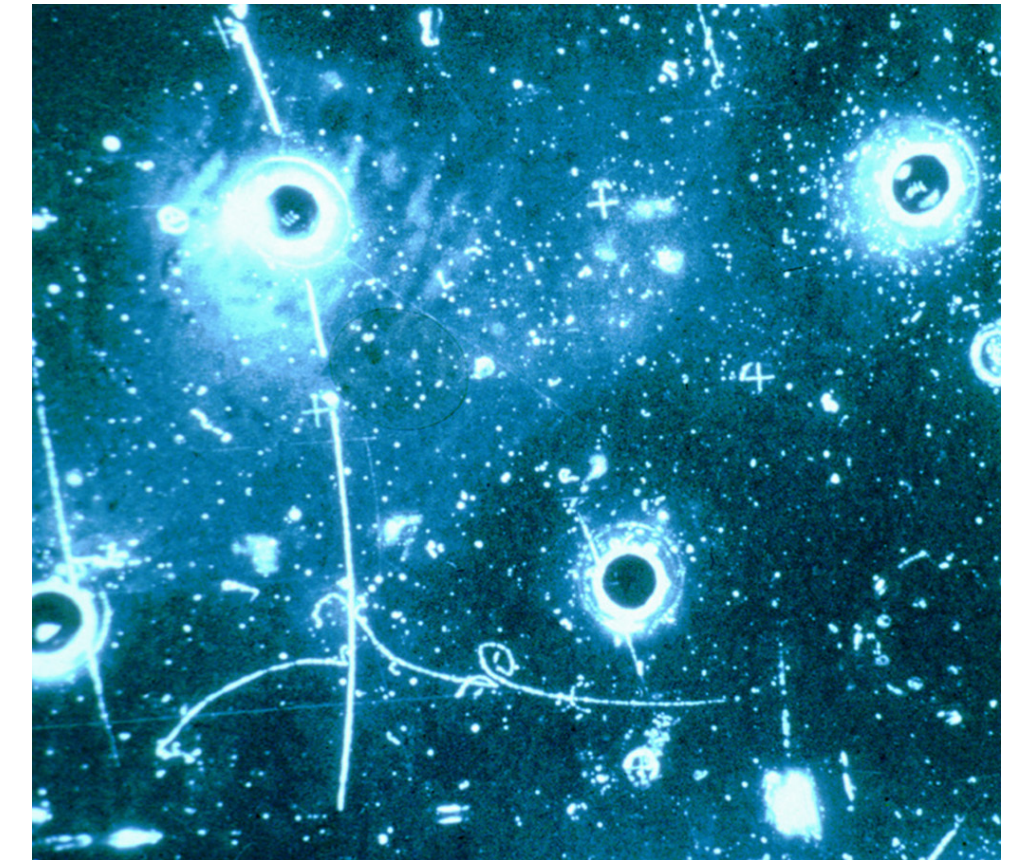
Kenneth Long  
CNRS, IP2I, Lyon

# The W and Z bosons: carriers of the weak force

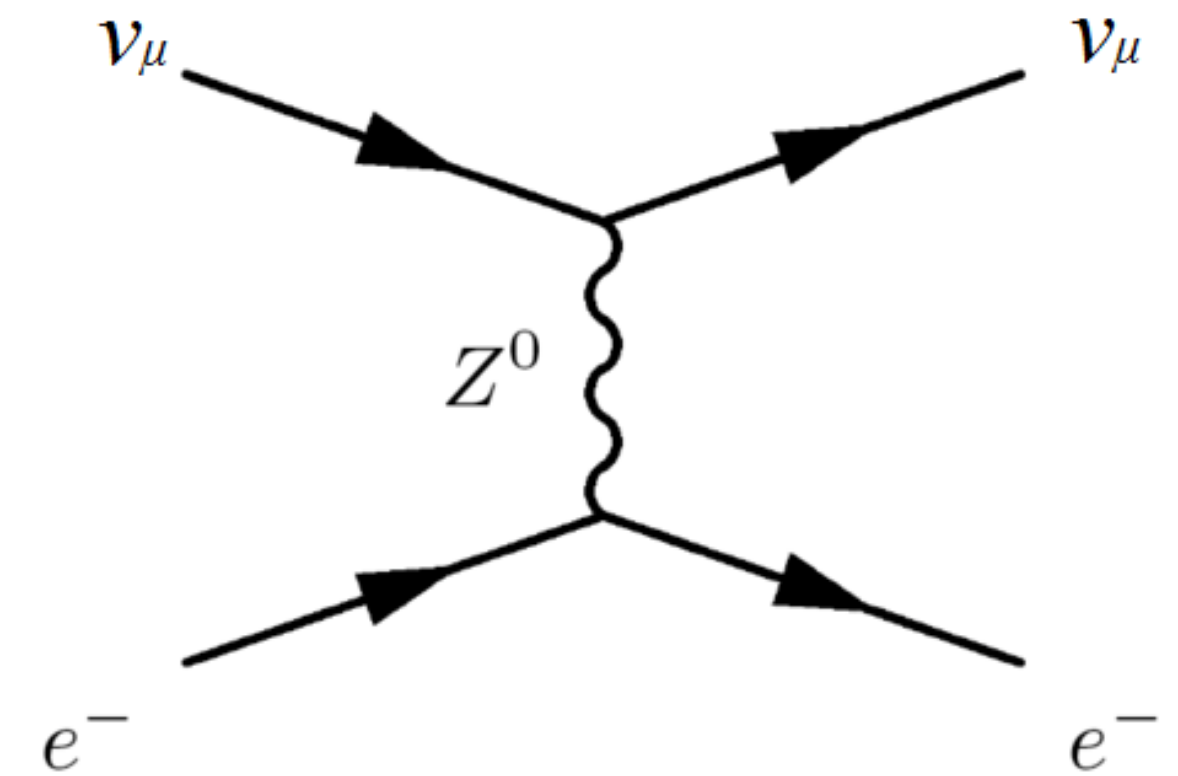
1933: Fermi 4-point interaction describing  $\beta$  decay



1960s: QFT with massive force carriers, the W and Z bosons



Gargamelle, 1973



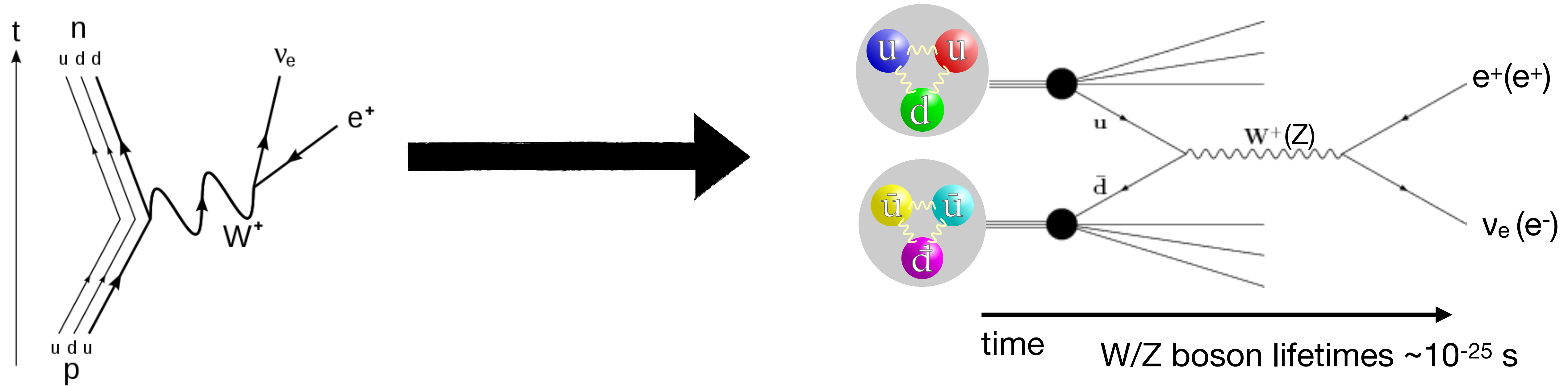
Fermi theory is an excellent low-energy approximation

$$G_F = \frac{\pi\alpha}{\sqrt{2}m_W^2 \sin^2 \theta_W} = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2}$$

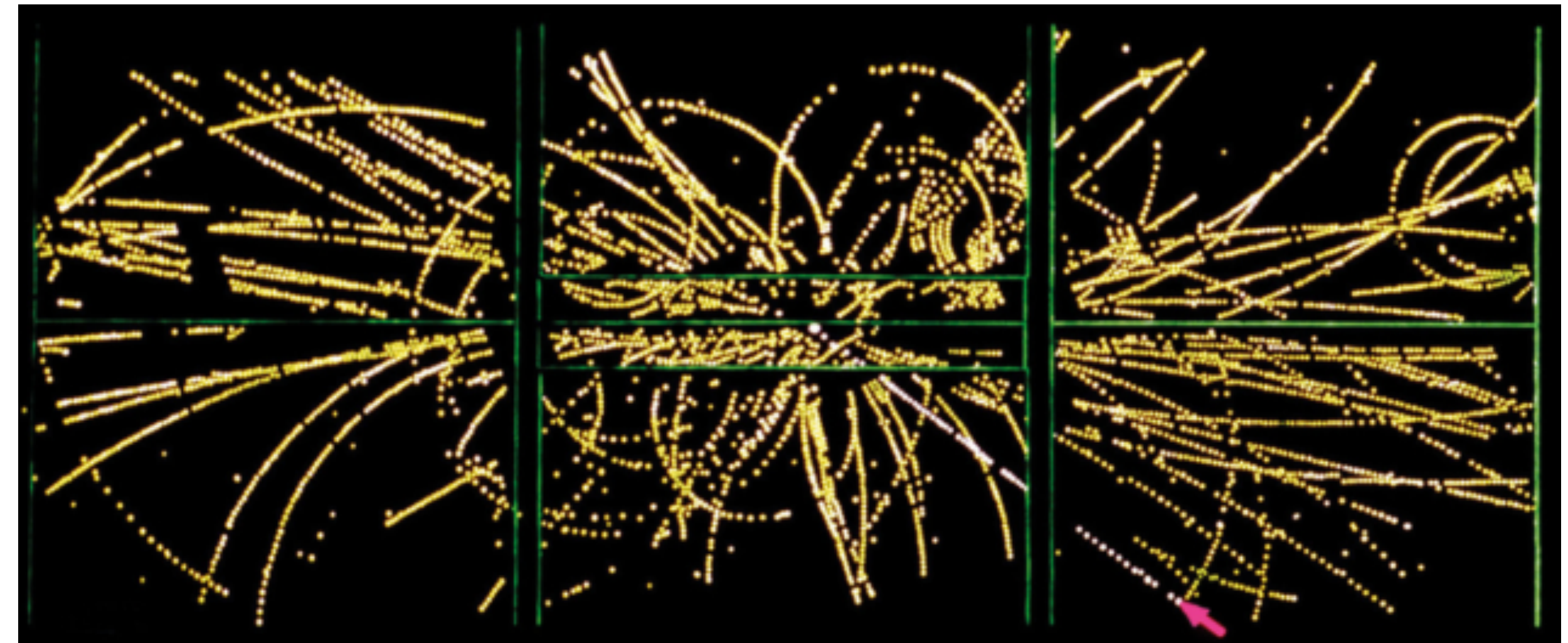
➡ Nuclear decay and charged/neutral current rates give an estimate of the W and Z masses



# Studying the W and Z bosons at colliders



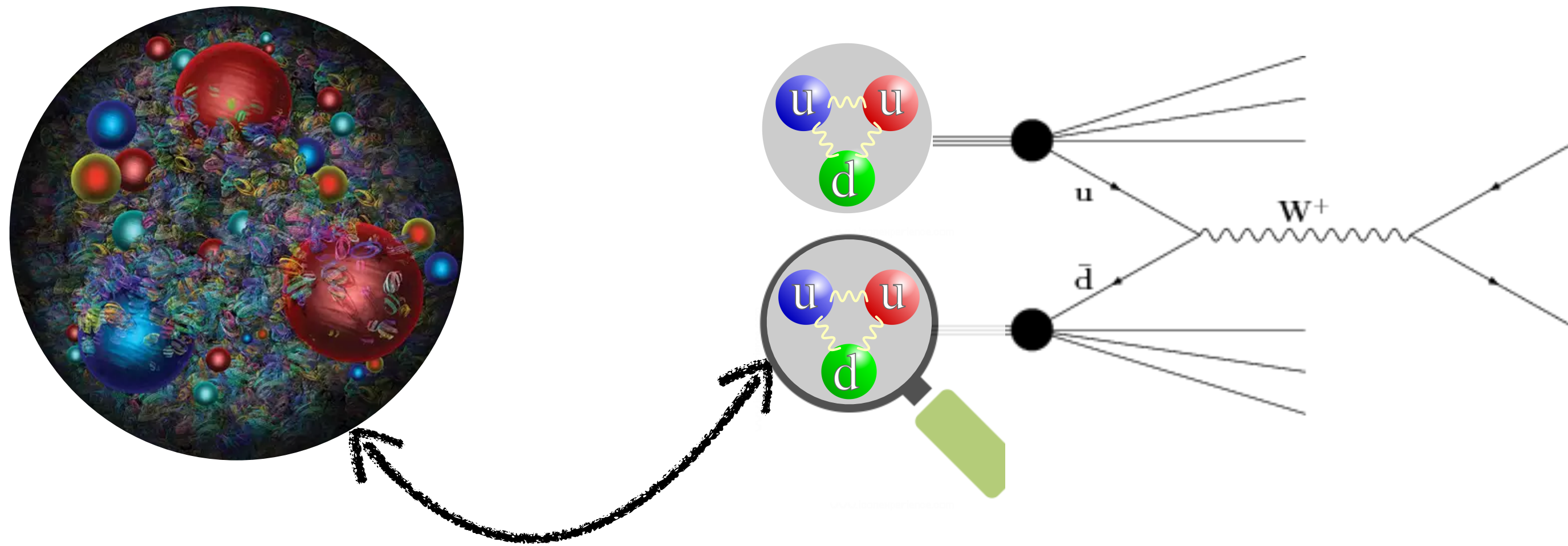
- Colliders allow us to initiate the interaction and directly produce the W and Z bosons
  - Need a quark-antiquark pair
  - Nobel Prize winning suggestion: produce and accelerate anti-protons
- ➔ W and Z bosons observed directly in 1982-83 by UA1 and UA2 at the CERN Sp $\bar{p}$ S





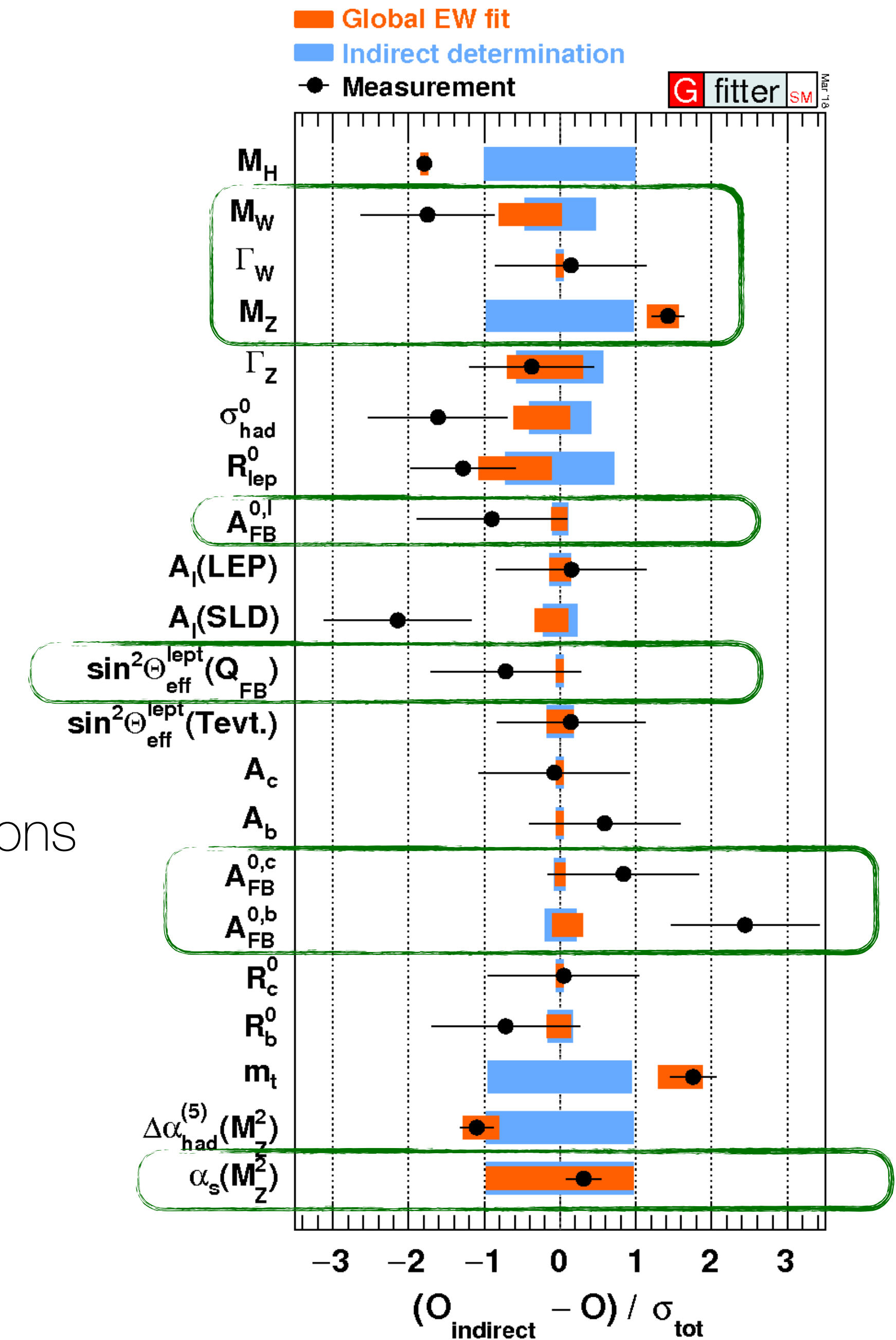
# Measuring parameters of the SM with the W and Z bosons

- A high energy proton is a rich source of antiquarks



- The LHC is a W and Z boson factory
  - Excellent detectors! Percent-level reconstruction of charged leptons
  - Production rates measured at the percent level
  - Probe fundamental params. of the SM

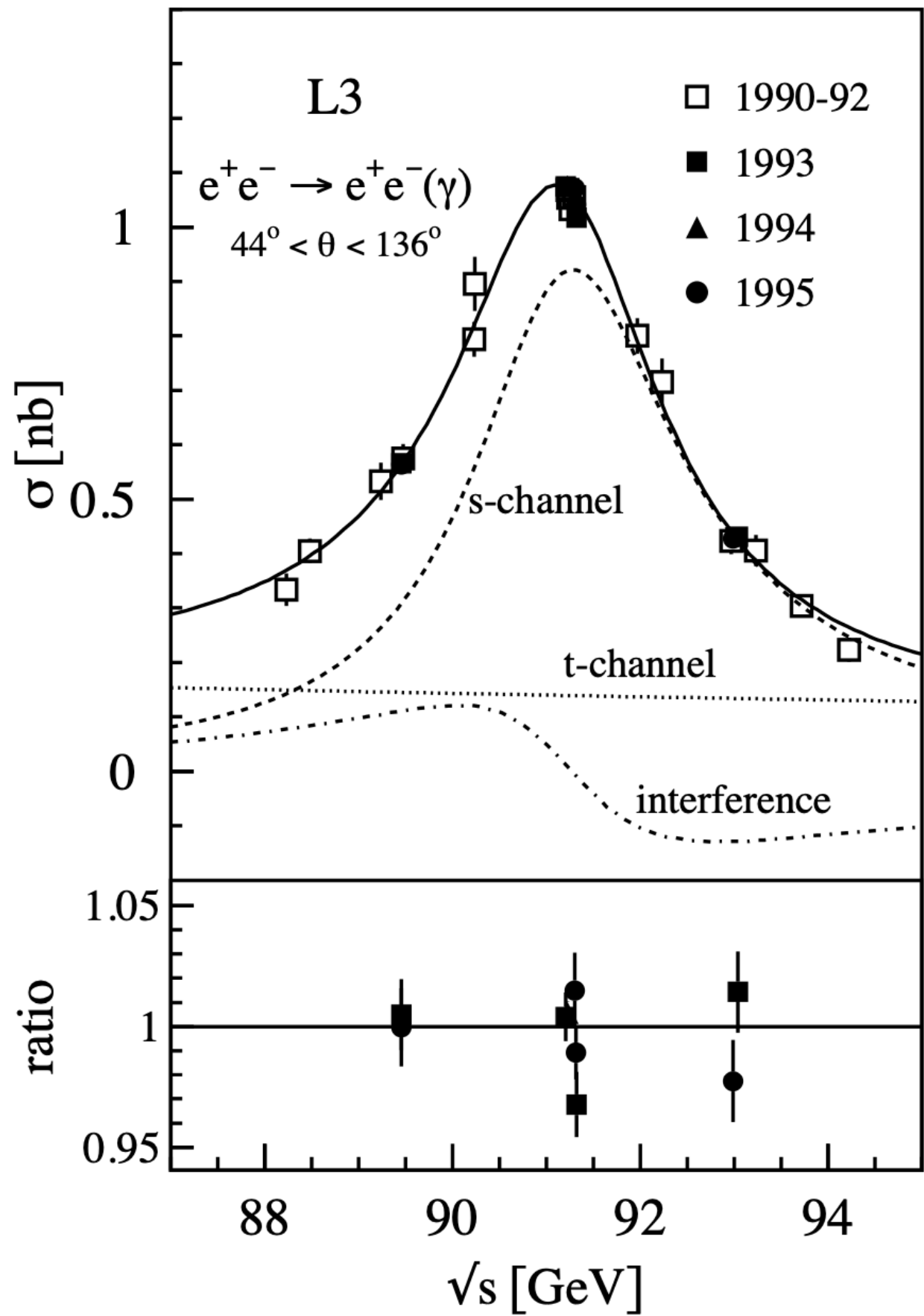
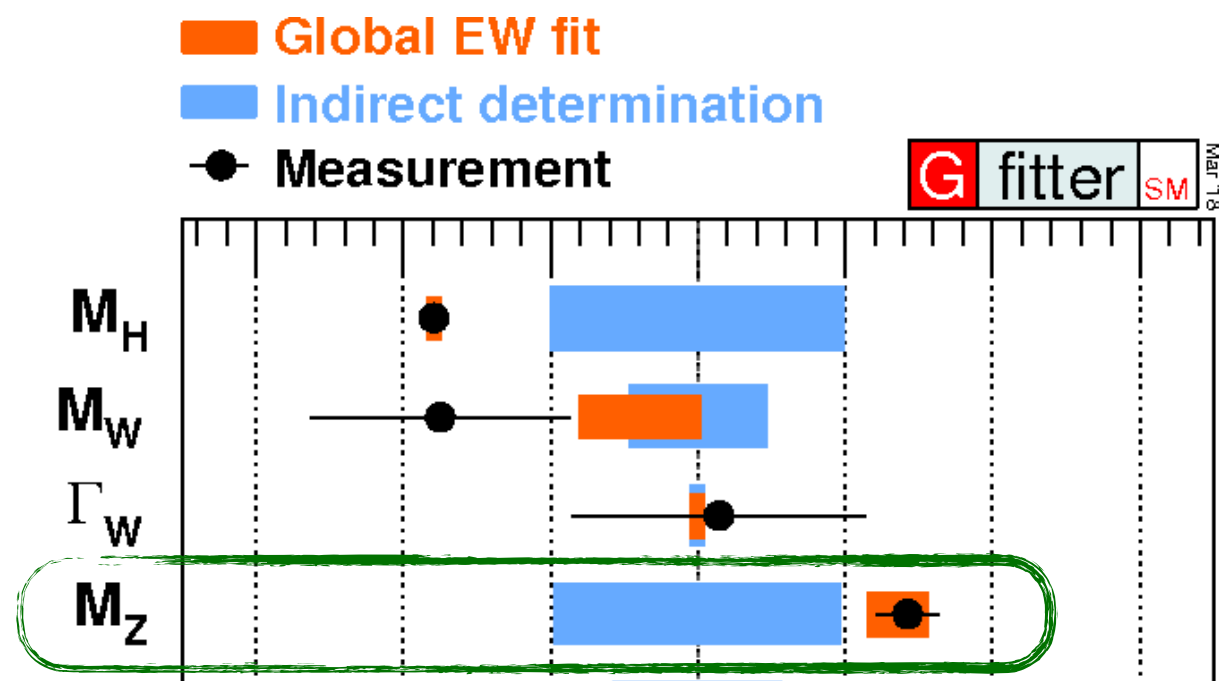
$$\sin^2\theta_W \quad m_W^2 \left( 1 - \frac{m_W^2}{m_Z^2} \right) = \frac{\pi\alpha}{\sqrt{2}G_\mu} (1 + \Delta r)$$





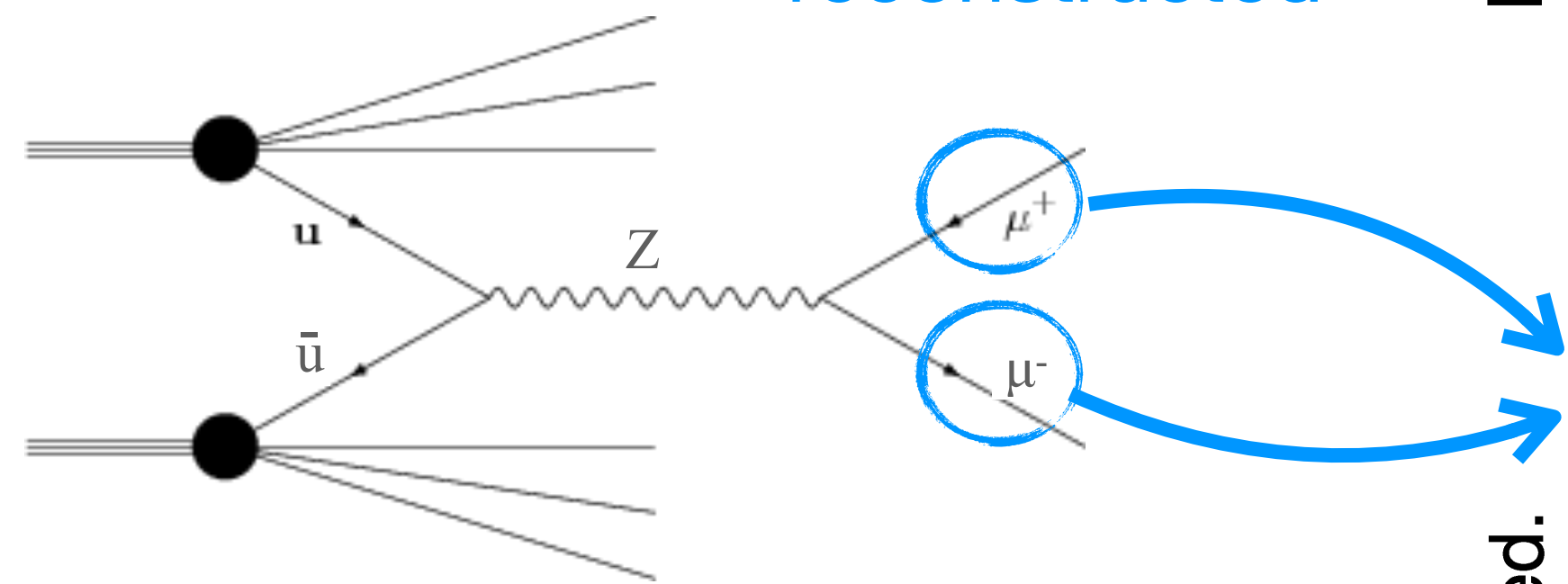
# Measuring the mass of the Z boson at the LHC

- Z boson decays to two muons (or two electrons) which can be accurately reconstructed
- $m_{\ell\ell}$  is Lorentz invariant: theoretically straightforward
- But huge experimental challenge to reach LEP precision

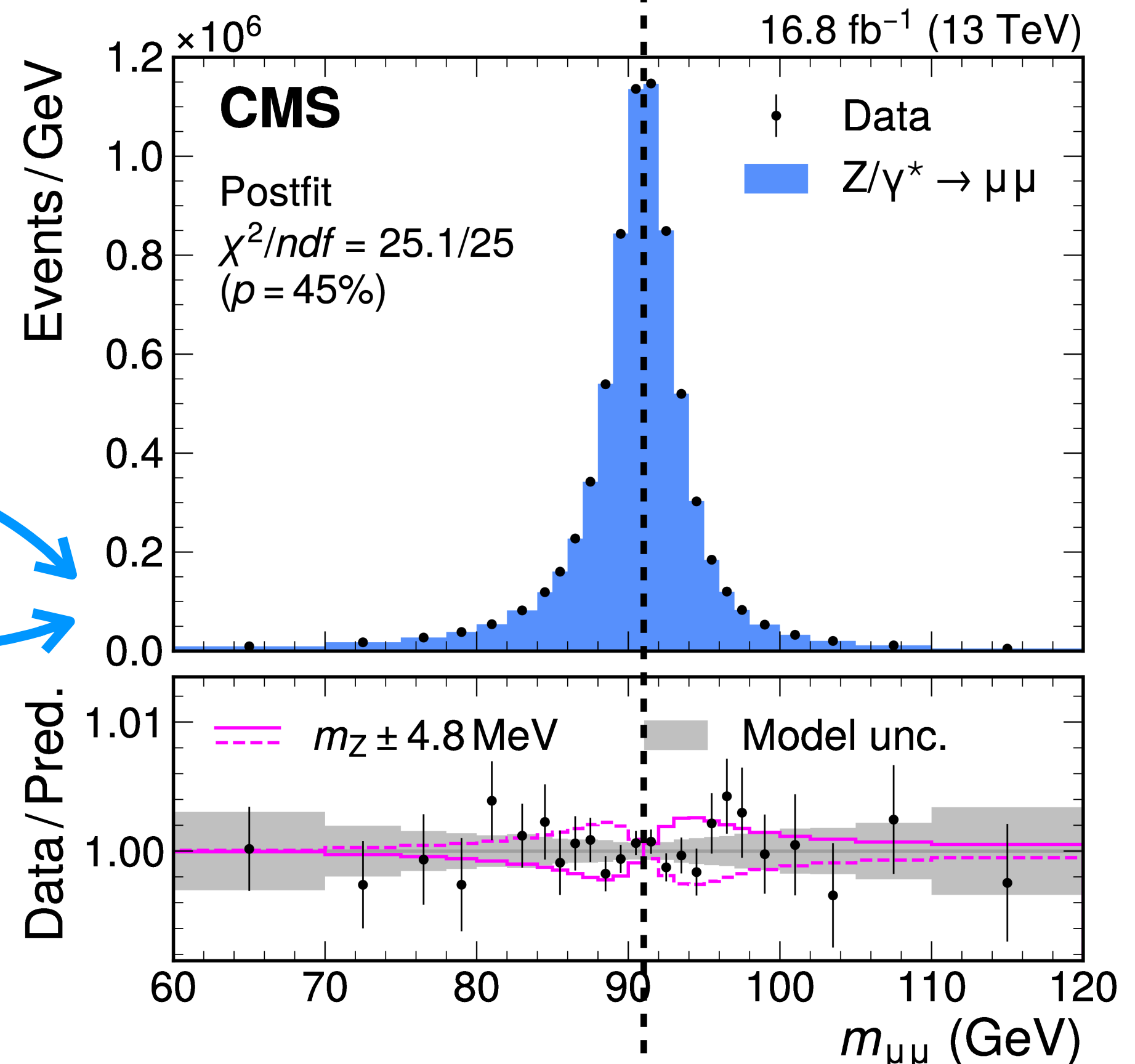


$$d_S^{rBW}(E) = \frac{2E}{\pi} \frac{M\Gamma}{(E^2 - M^2)^2 + (M\Gamma)^2} \theta(E)$$

Both muons are well reconstructed



LEP measurement based on beam energy scan



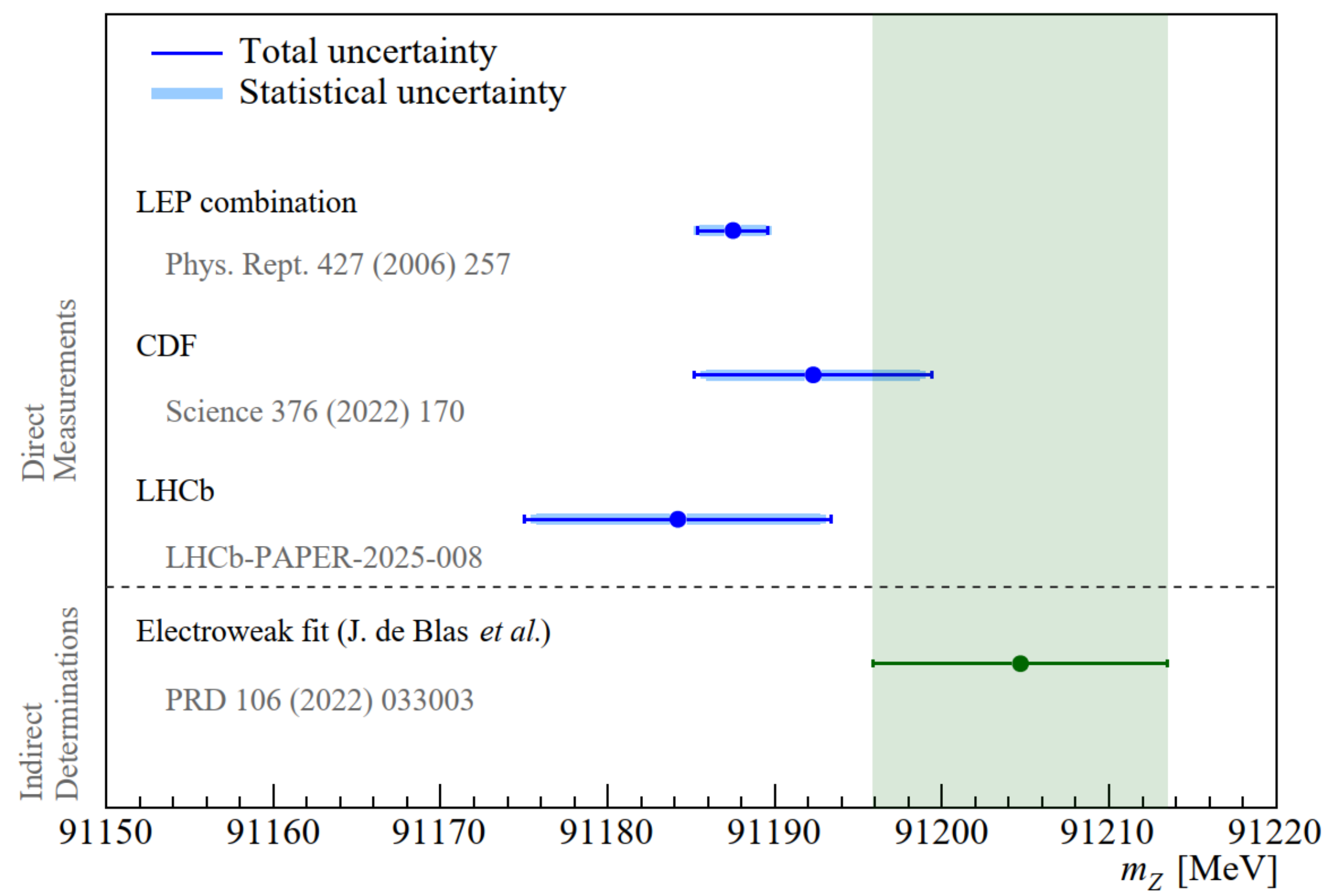
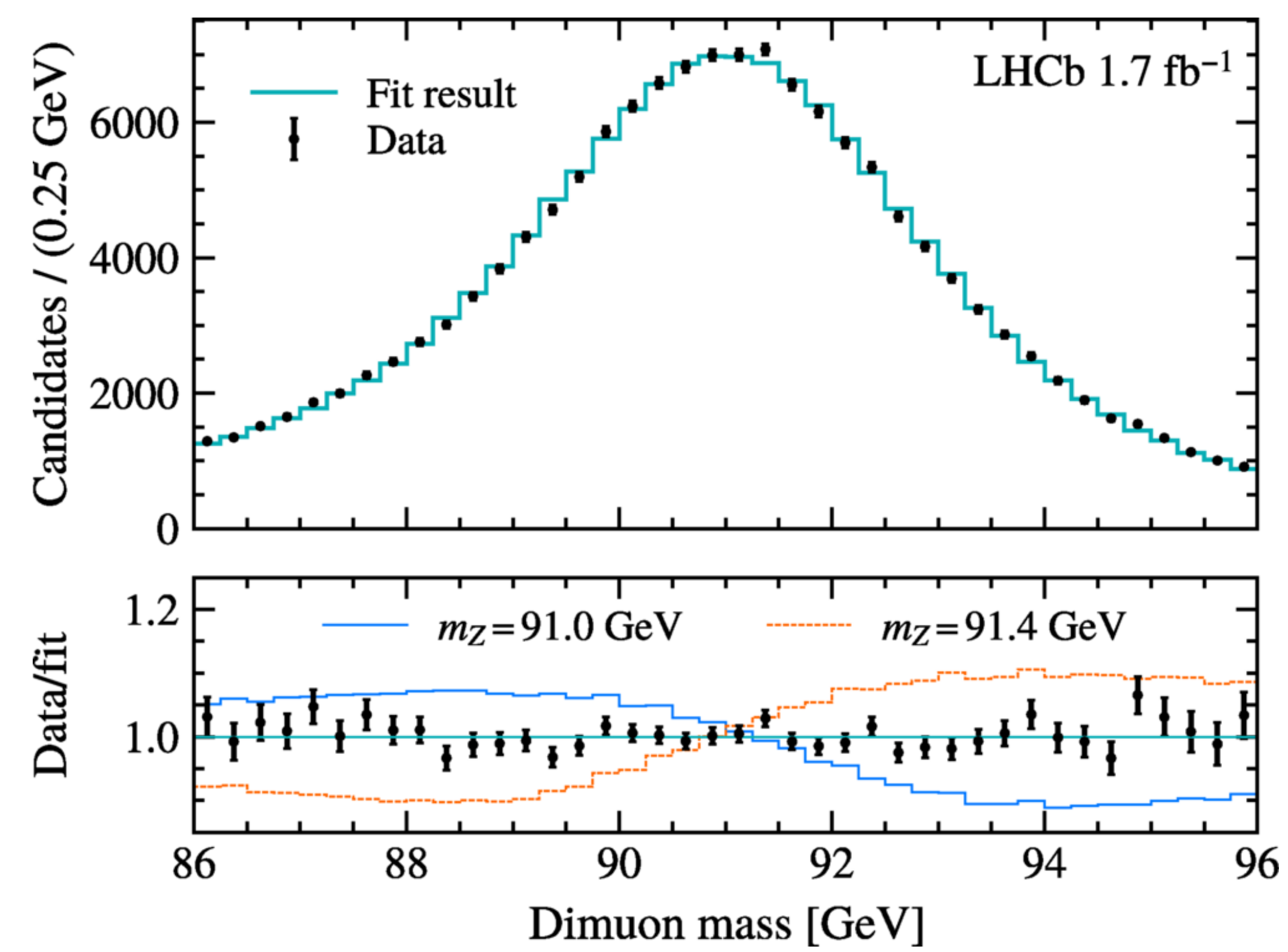
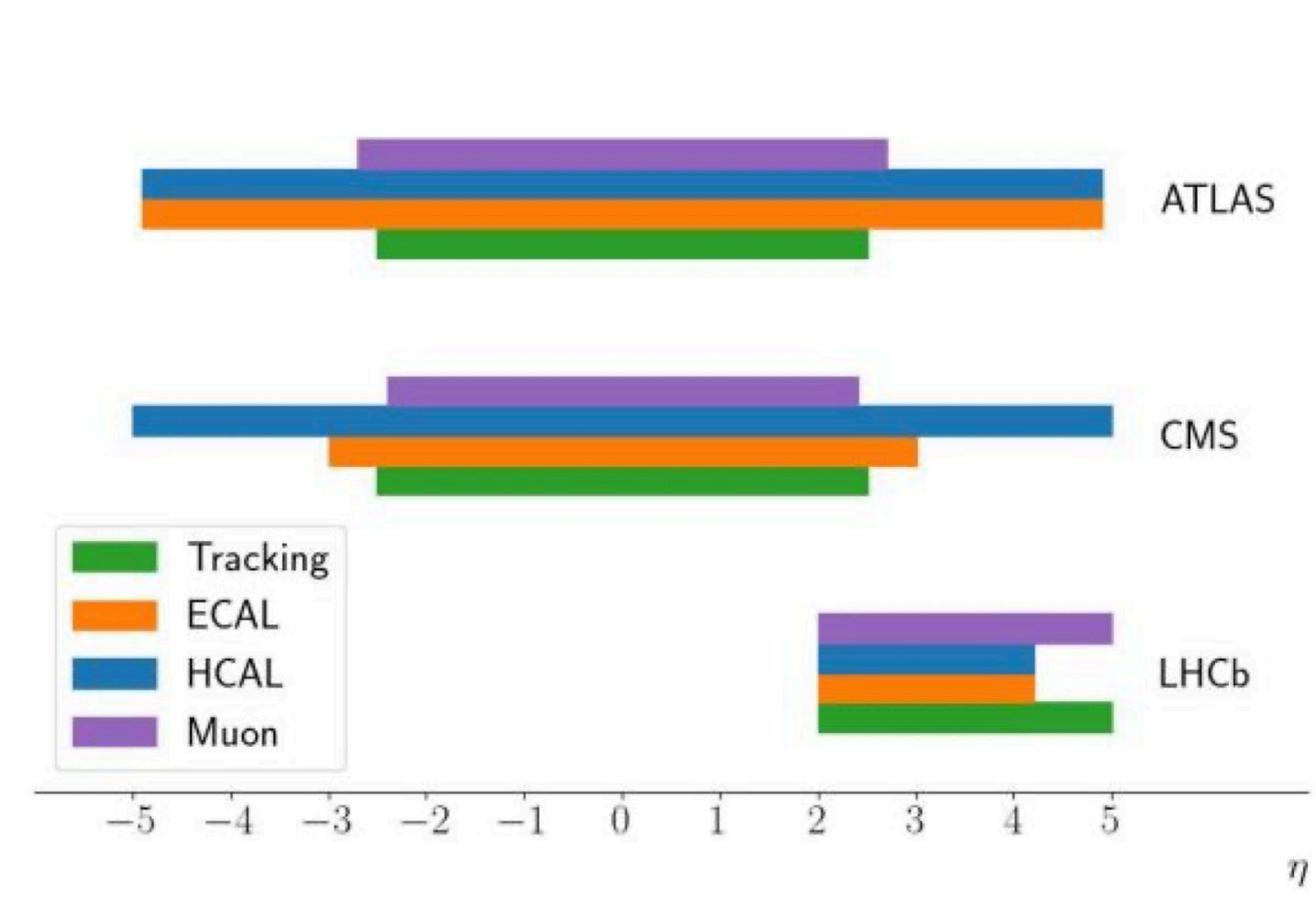
First measurement from LHCb: ~10 MeV unc.

peaks at  $m_Z$



# m<sub>Z</sub> measurement at LHCb

- First LHC m<sub>Z</sub> measurement
- Not directly competitive with LEP but
  - Major experimental accomplishment
  - Statistical uncertainty dominant



LHCb:  $m_Z = 91185.7 \pm 8.3 \pm 3.9 \text{ MeV}$

CMS (cross-check)

$m_Z - m_Z^{\text{PDG}} = -2.2 \pm 4.8 \text{ MeV} = -2.2 \pm 1.0 \text{ (stat)} \pm 4.7 \text{ (syst)} \text{ MeV}$





# Measuring the W boson at the LHC

Pileup  $\propto$  Number of vertices = 22

Very precise  $\mu$  reconstruction

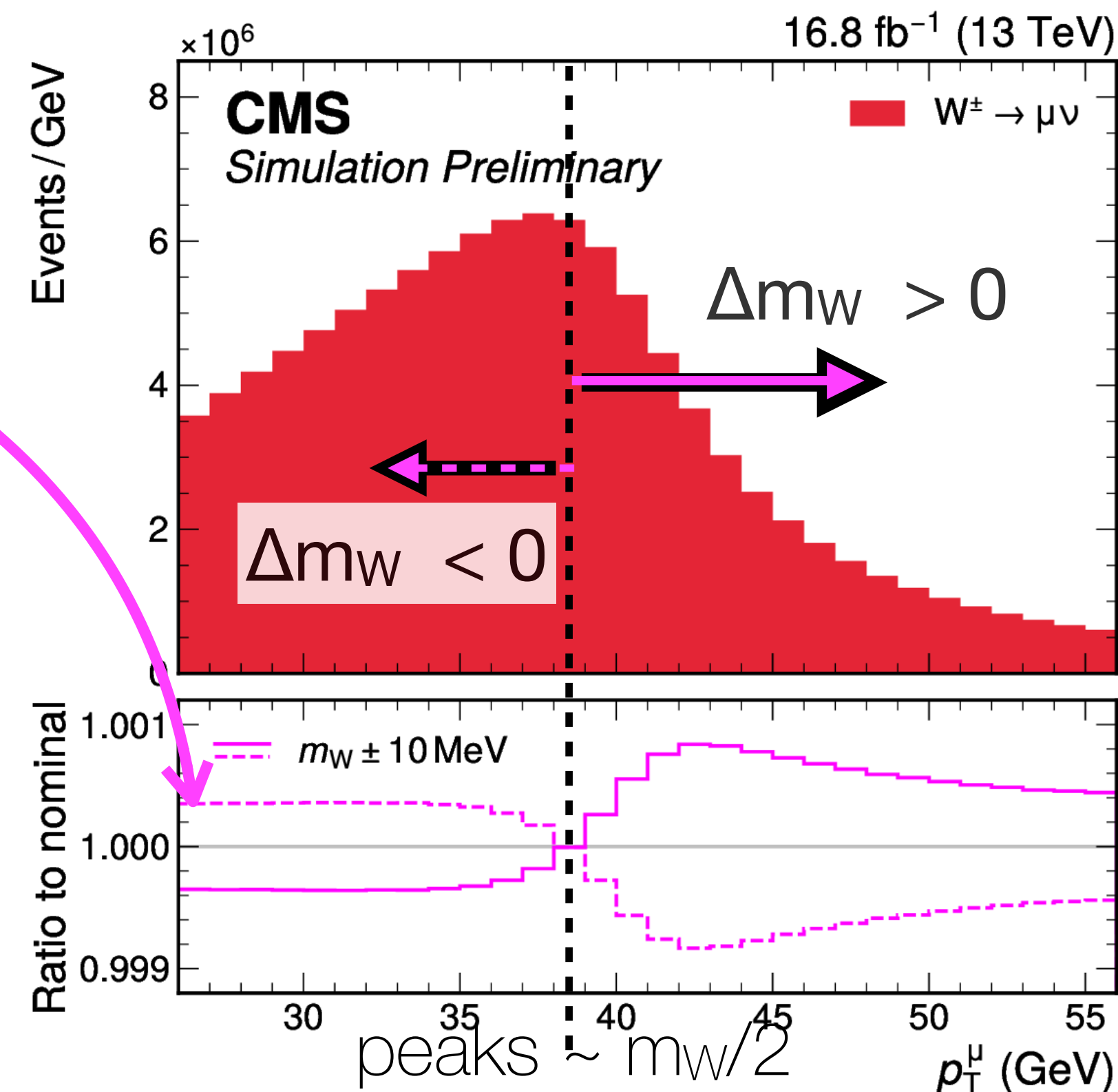
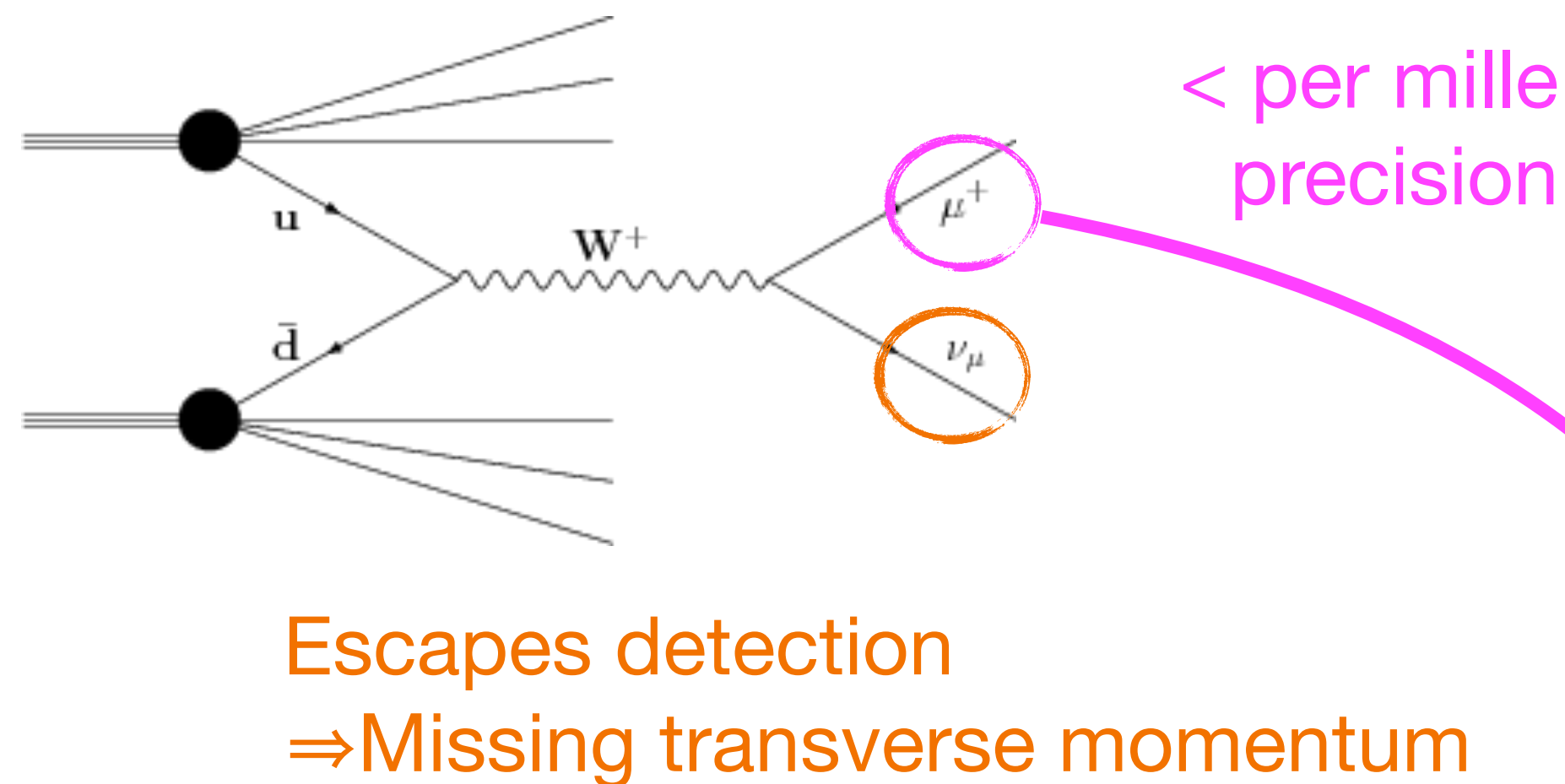
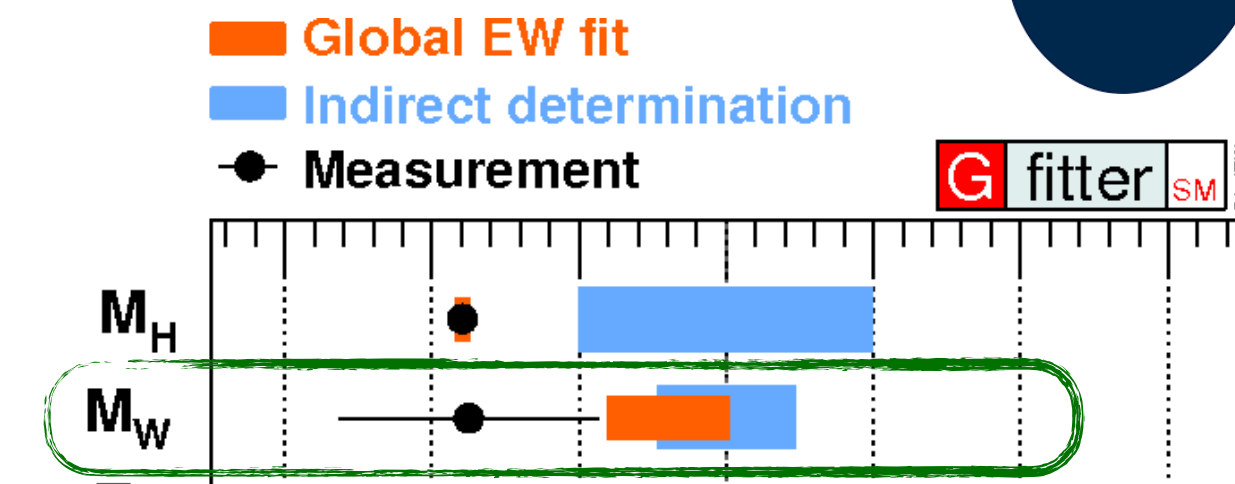
$\nu$  not directly reconstructed

<https://cds.cern.ch/record/2909335>

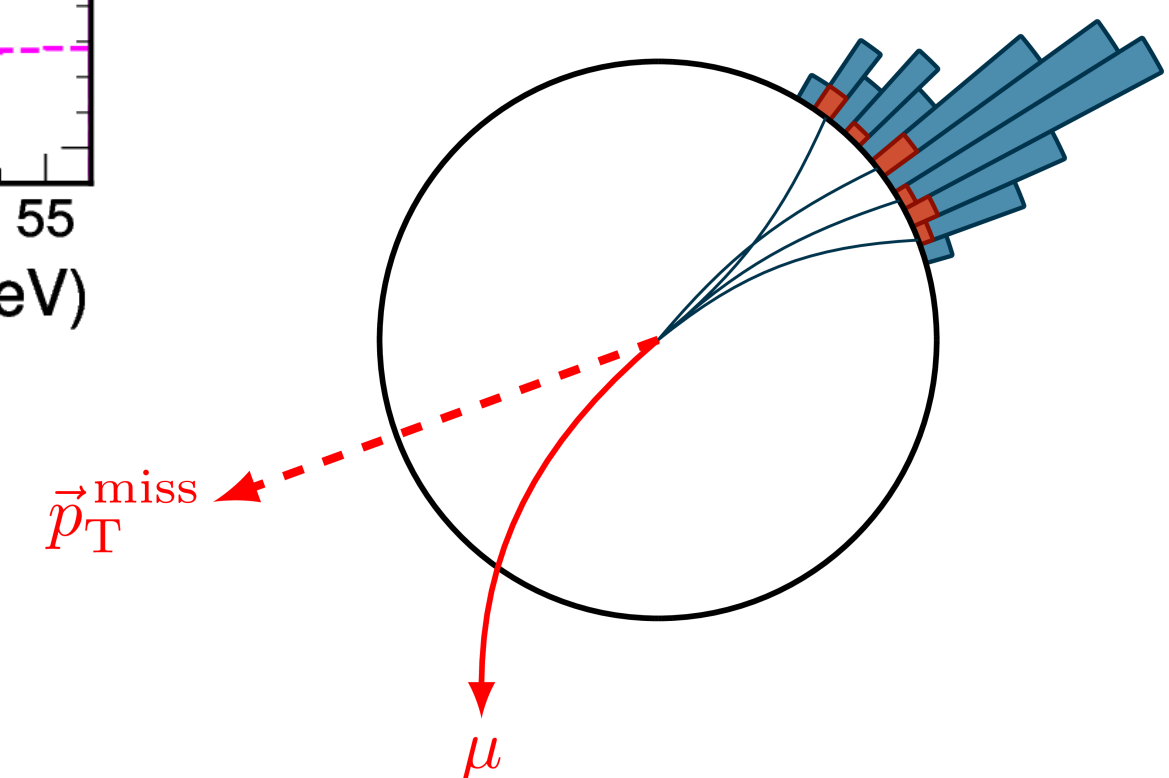


# The W boson mass measurement

- Rely on observable(s) sensitive to  $m_W$  built from well-measured objects



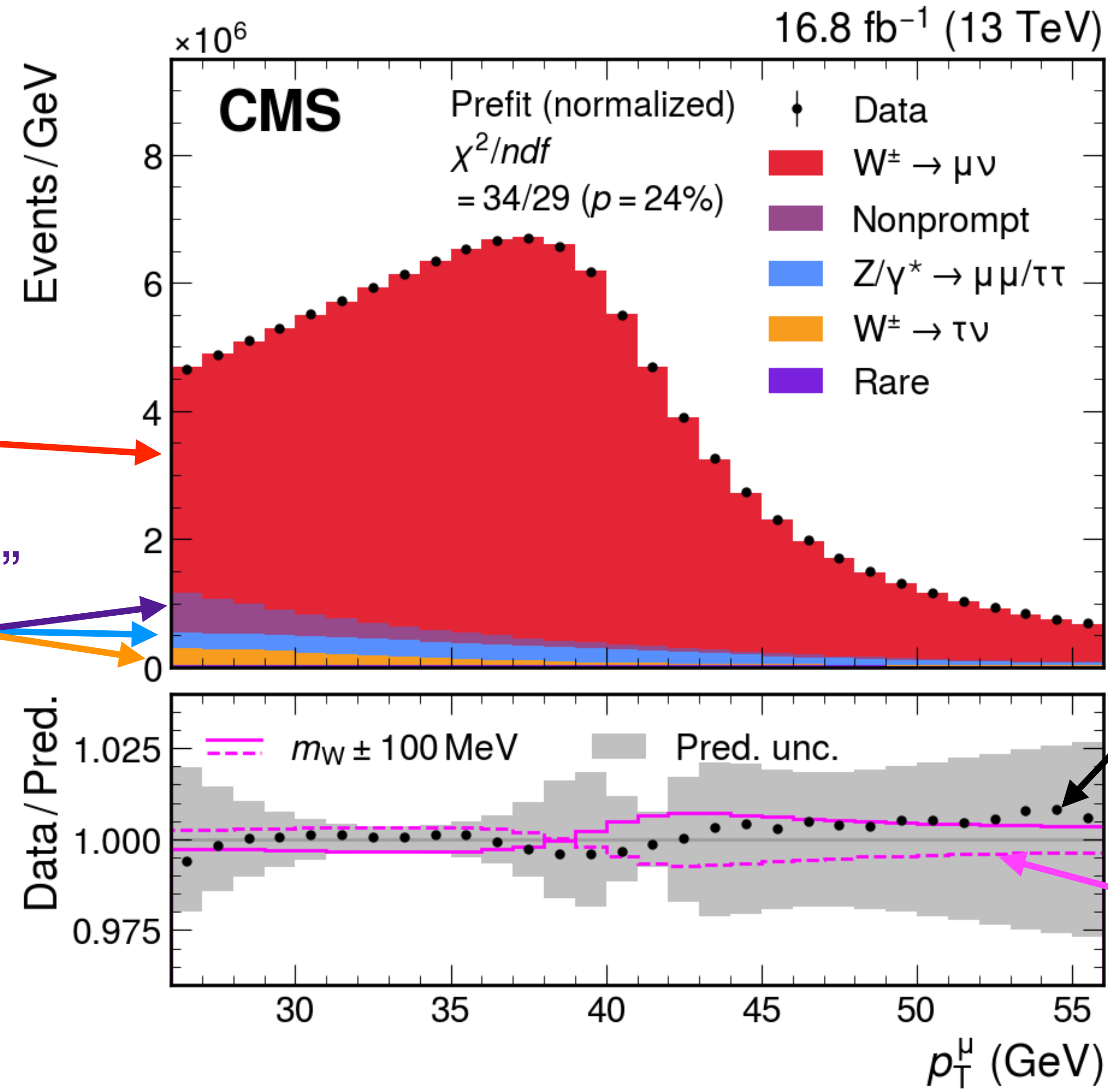
- Mass is equally divided between  $\mu$  and  $\nu$ 
  - In rest frame,  $p^{\nu} \sim p^{\ell} \sim m_W/2$
  - In lab frame, smeared by  $p^W$
- ➡ Knowledge of W momentum required



Focus on direction transverse to proton beams  
 initial momentum in the transverse direction is  $\sim 0$



# $m_W$ measurement at a glance



Predicted W boson contribution

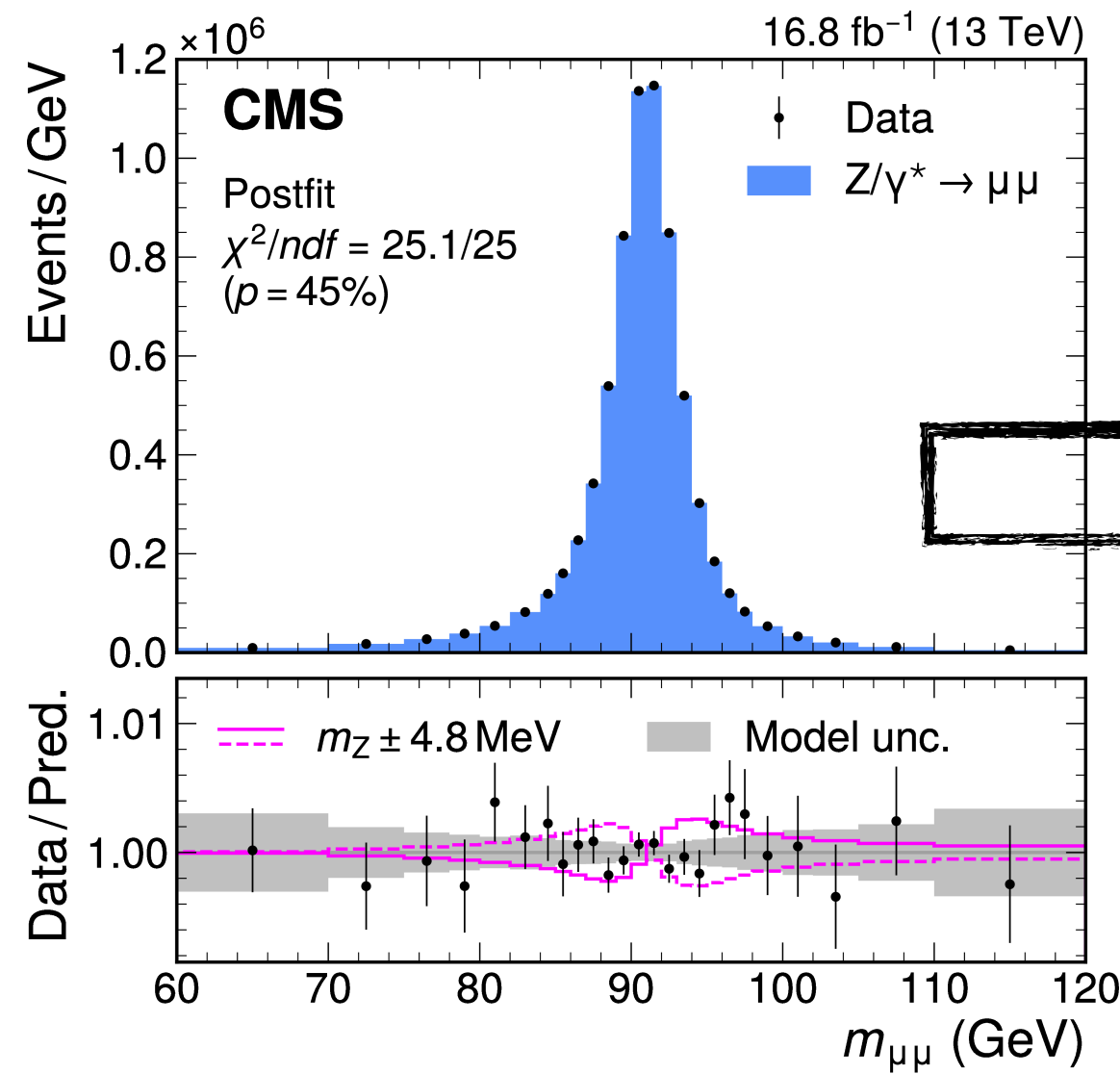
Predicted “backgrounds” from other processes

- Binned maximum likelihood fit: test consistency of data with different  $m_W$  hypotheses
- Measurement performed *blinded*

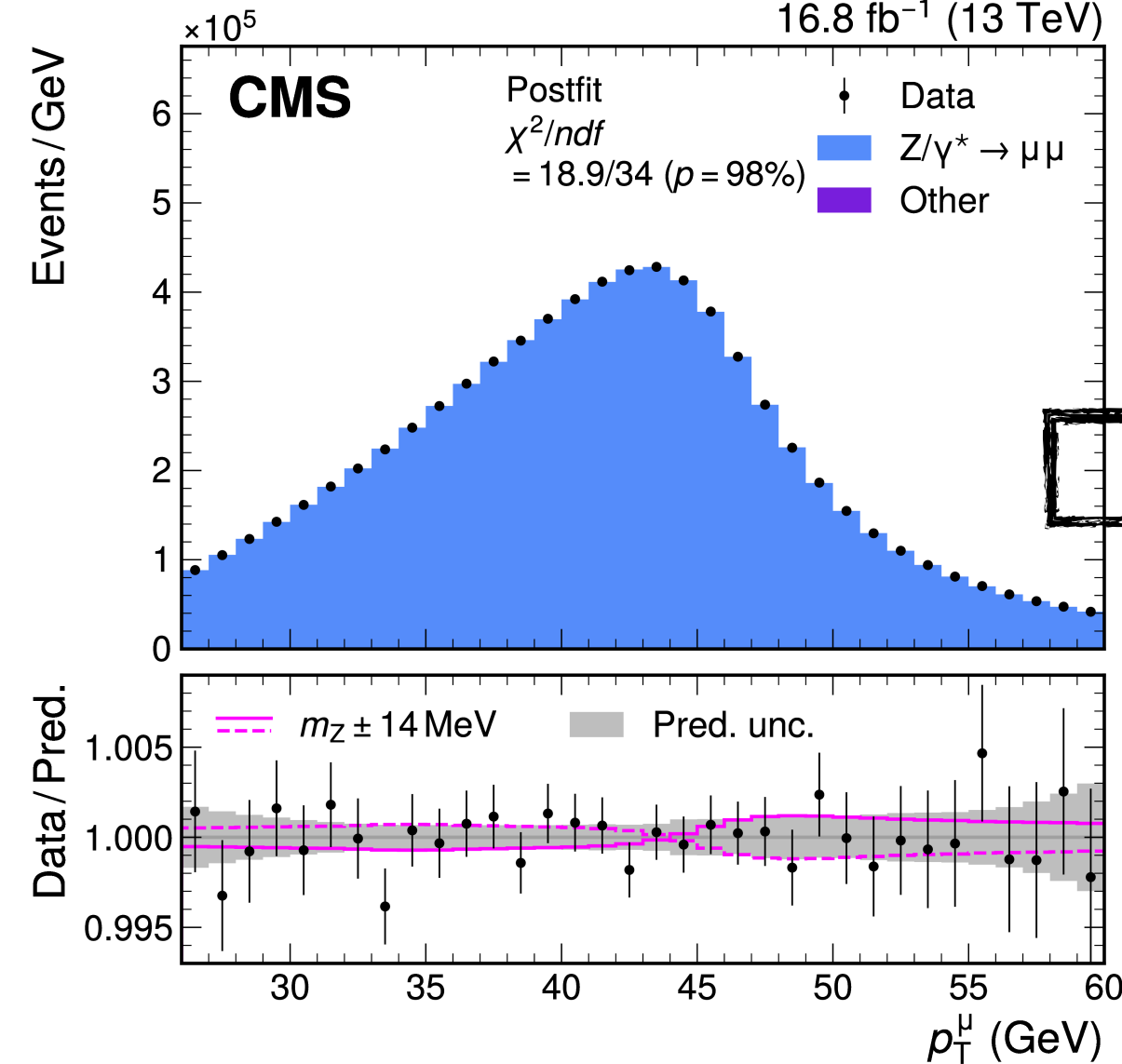


# $m_W$ measurements: last step of extensive precision physics programs

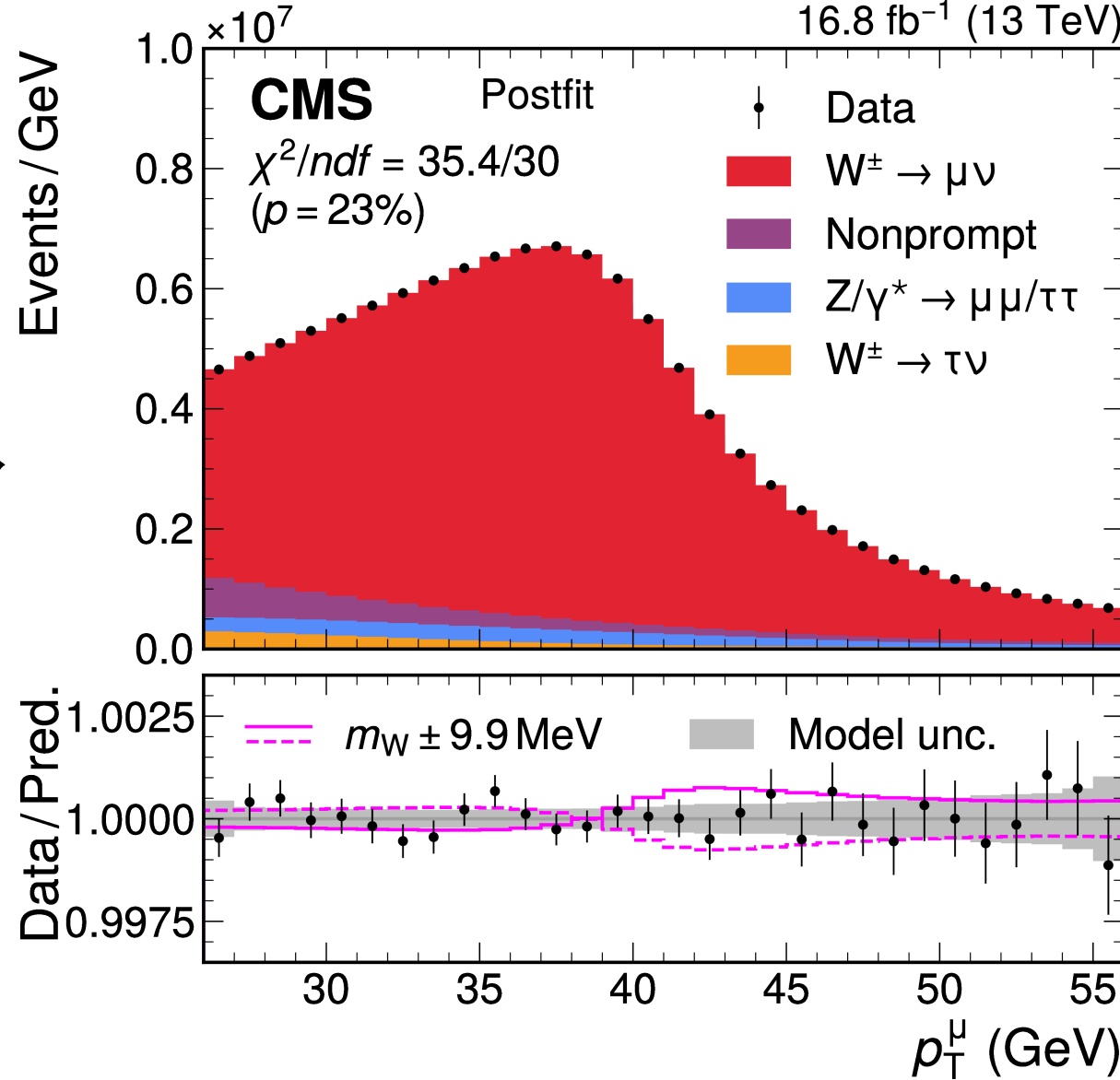
★  $m_Z$  measurement from  $m_{\mu\mu}$



★  $m_Z$  measurement from  $p_T^\mu$



★  $m_W$  measurement



Nature 652 (2026) 321



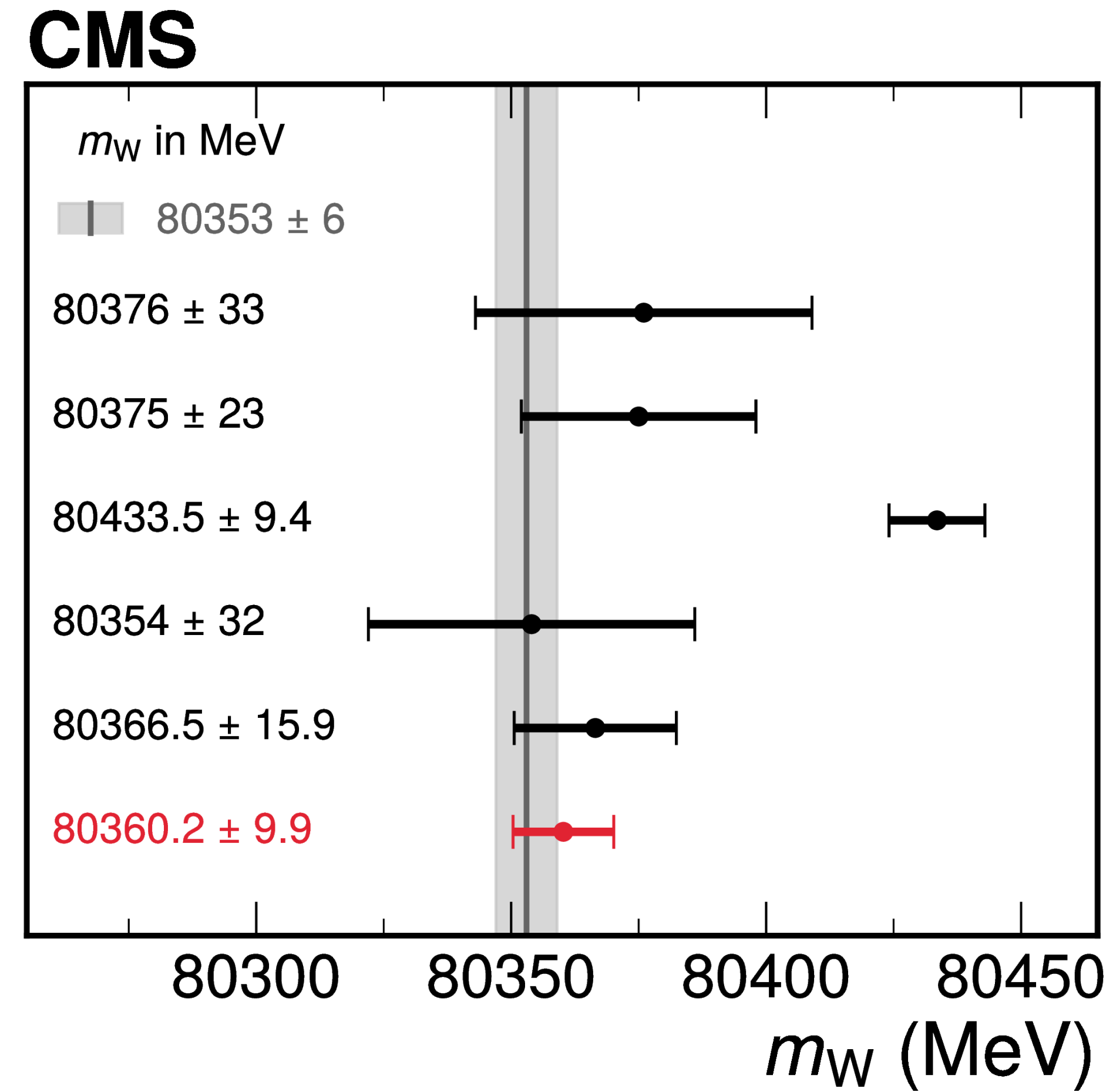
ONE DOES NOT SIMPLY MEASURE THE W MASS



# The LHC $m_W$ measurements

- **LHCb (32 MeV unc.)**
  - 13 TeV,  $p_T^\mu$  channel only; 2.4 M events
  - Forward muons
  - $p_T^\mu$  calibration with low-mass resonances ( $J/\psi$ ,  $\Upsilon$ )
- **ATLAS (15.9 MeV unc.)**
  - Published 2017, updated in 2024
  - 7 TeV,  $m_T + p_T^\ell$  ( $e + \mu$ , 3  $\eta$  bins); 14 M ev.
  - Driven by  $p_T^\ell$  channel (~90%)
  - $p_T^\ell$  calibration with Z boson
- **CMS (9.9 MeV unc.)**
  - 13 TeV,  $p_T^\mu$  (48  $\eta$  categories); 115 M ev.
  - $p_T^\mu$  calibration with low mass resonances
  - No direct tuning of theory predictions
    - Predictions at  $N^3\text{LL} + \text{NNLO}$  constrained in-situ

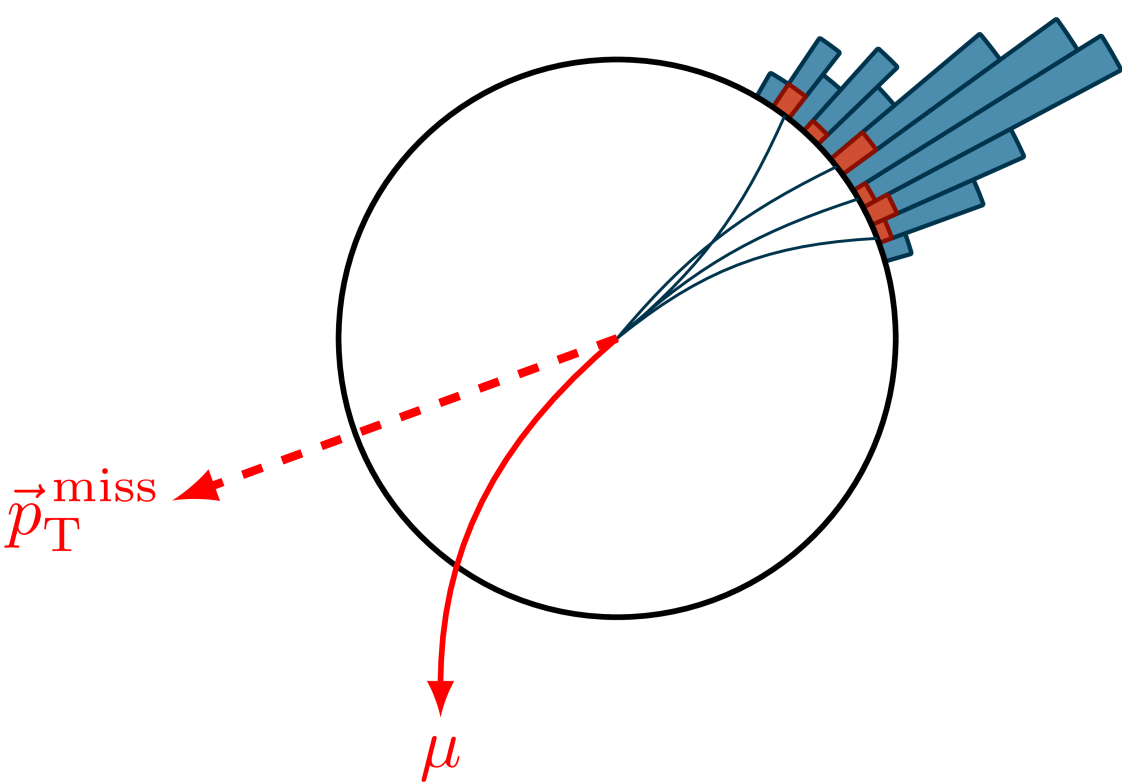
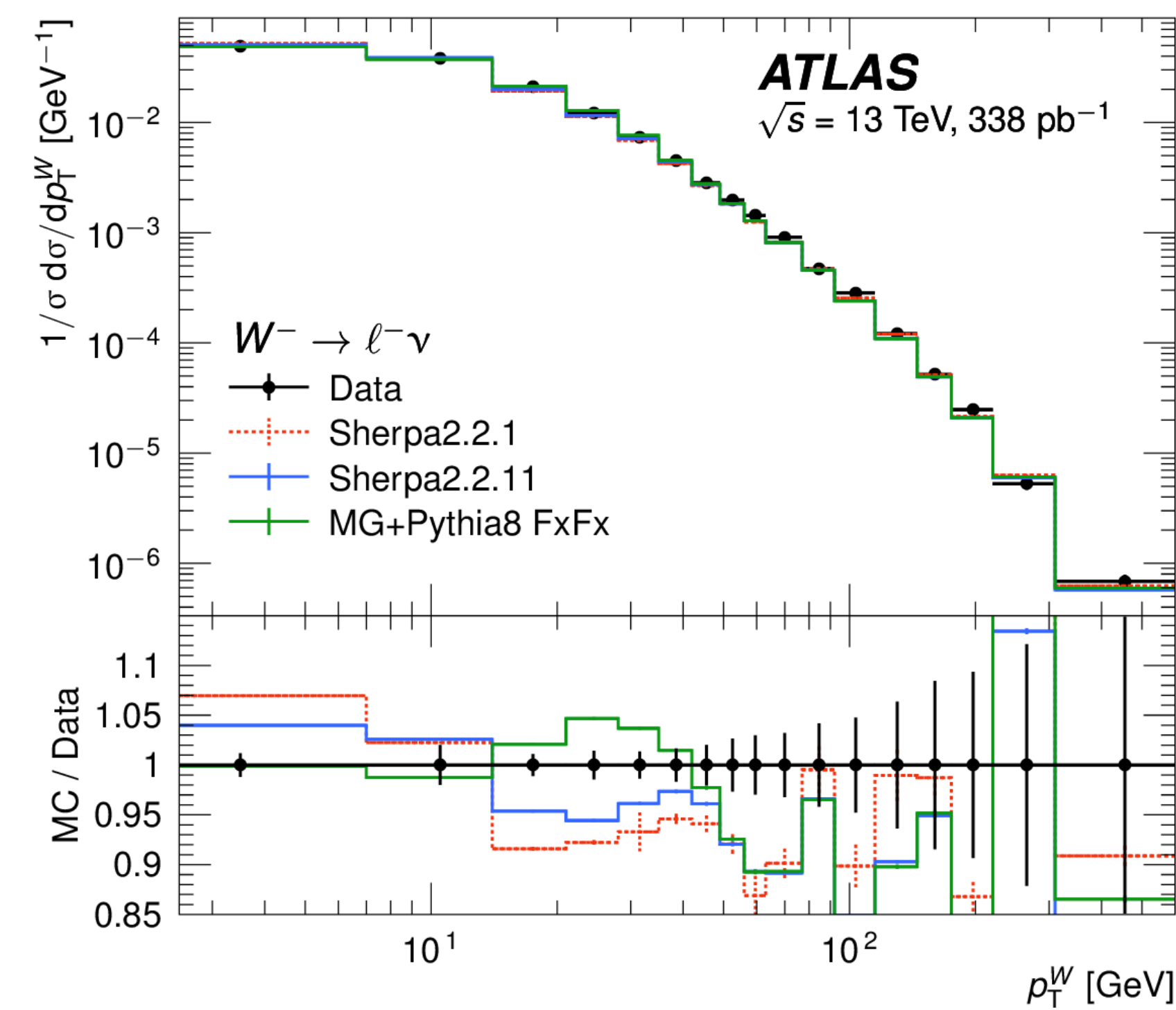
**Electroweak fit**  
 PRD 110 (2024) 030001  
**LEP combination**  
 Phys. Rep. 532 (2013) 119  
**D0**  
 PRL 108 (2012) 151804  
**CDF**  
 Science 376 (2022) 6589  
**LHCb**  
 JHEP 01 (2022) 036  
**ATLAS**  
 EPJC 84 (2024) 1309  
**CMS**  
*This work*



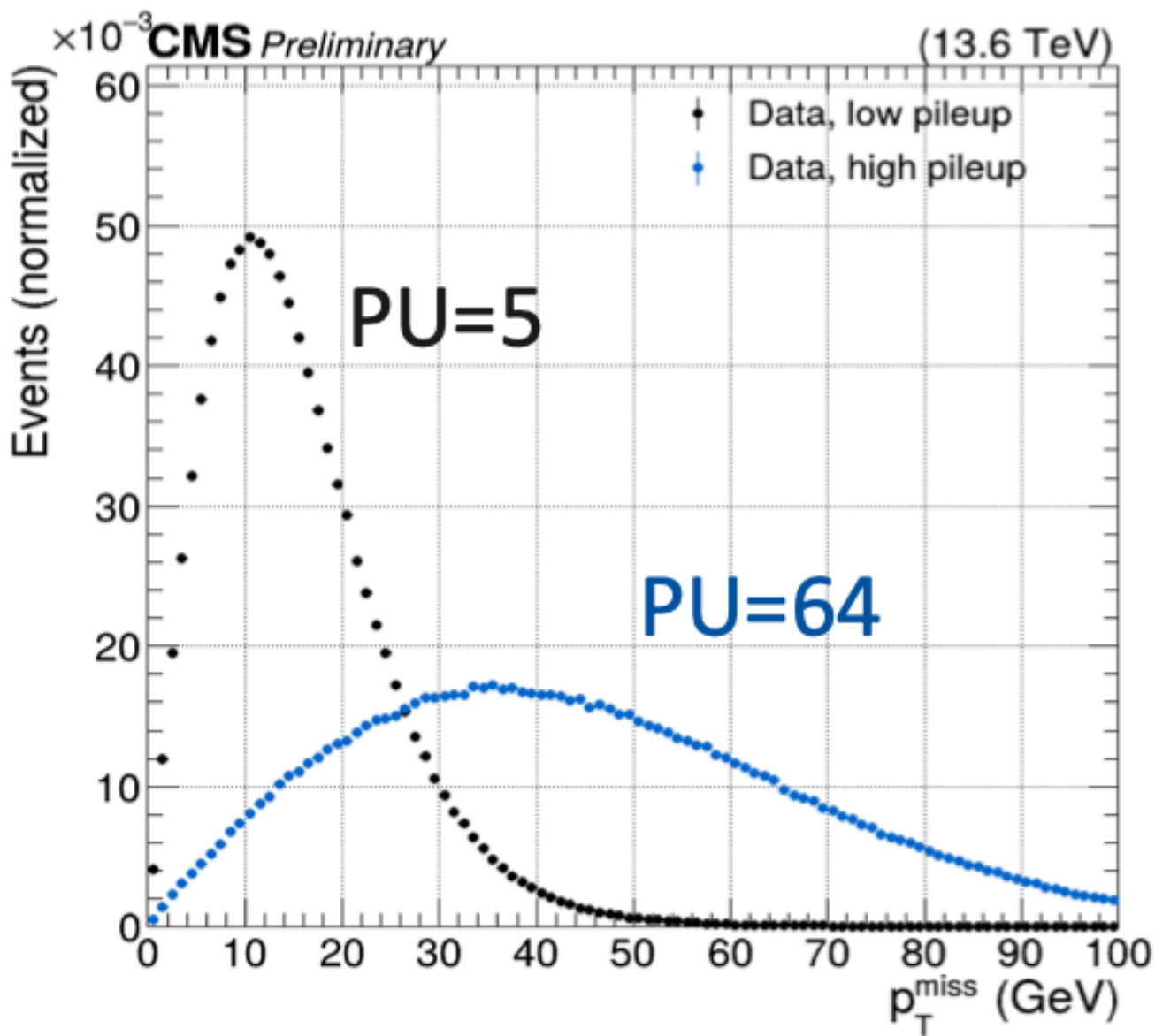
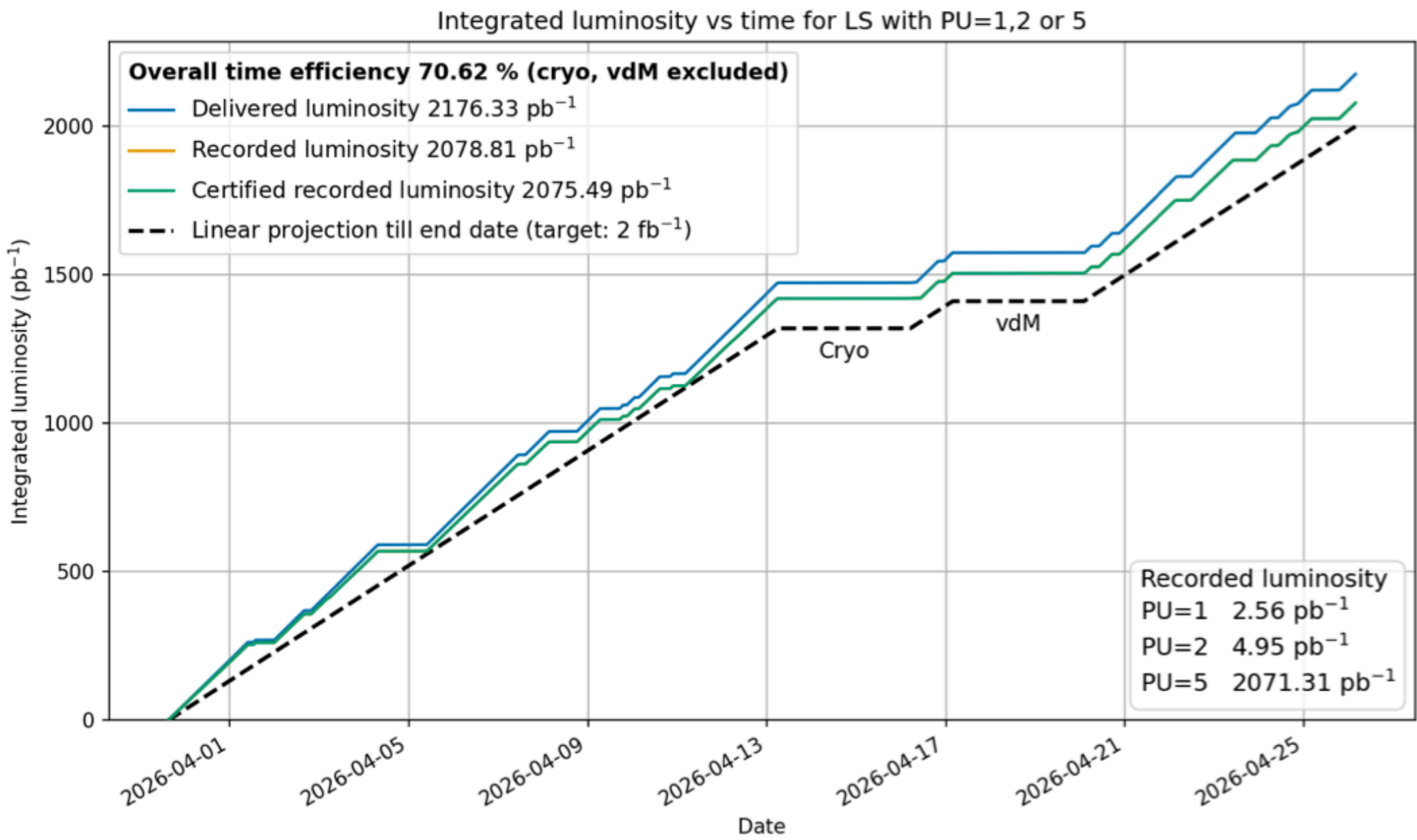


# W boson measurements with low pileup

- Large number of pp collisions per bunch crossing significantly complicate estimation of neutrino momentum
- Special “low pileup” data collection periods in 2017 and 2018
  - Best 13 TeV **measurements of W boson kinematics and production rate** in this dataset
- New, **dedicated ~1 month of data collection**
  - ➡ large, pure data set for future precision studies

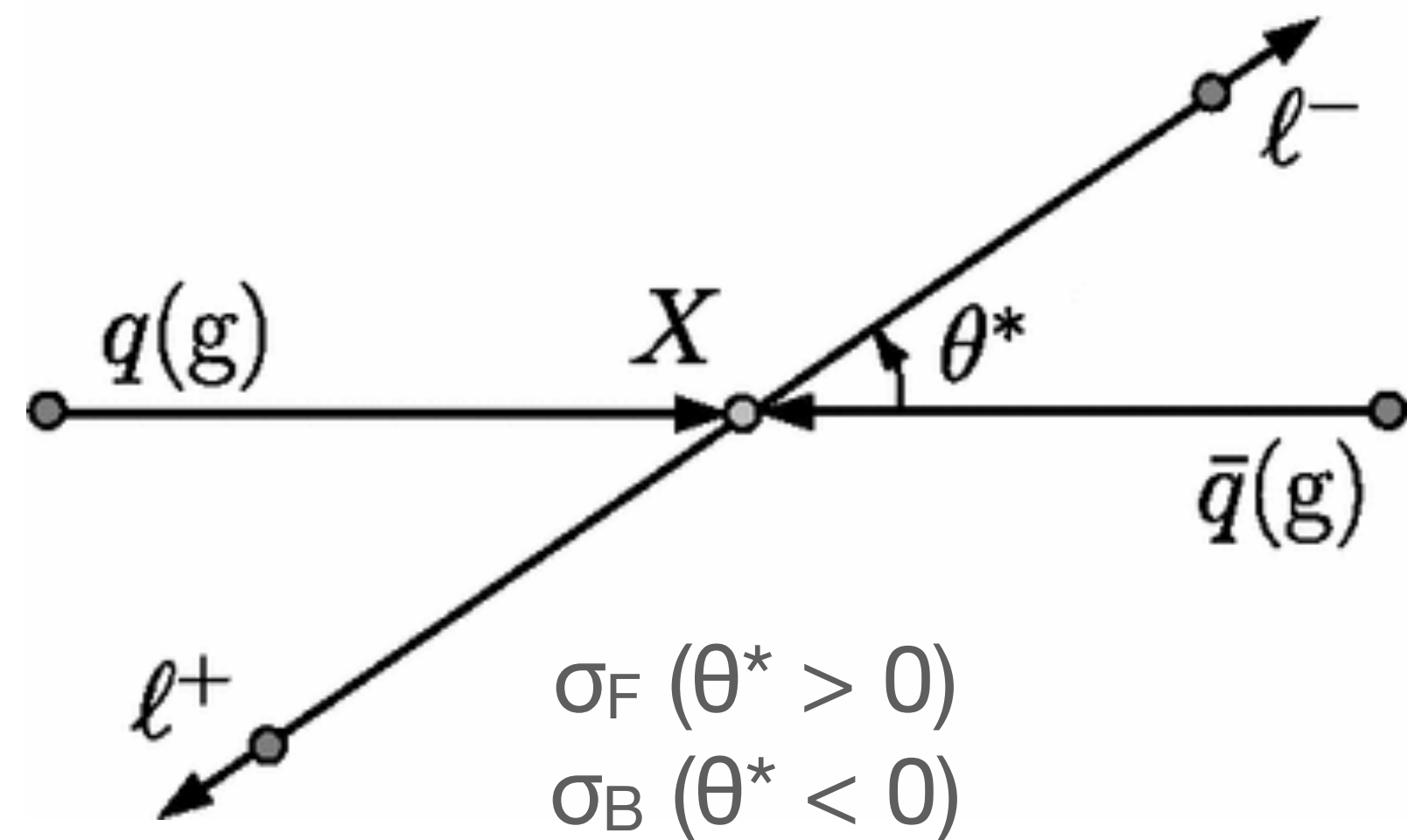


Eur. Phys. J. C 85 (2025) 729  
 JHEP 04 (2025) 162



# The forward-backward asymmetry and weak mixing angle measurement

- Drell-Yan angular properties, non-zero  $A_{\text{FB}}$  arise from **different  $Z/\gamma^*$  vector/axial couplings**, interference
  - $\sin^2\theta_{\text{eff}}^{\ell} := \kappa_F(1 - m_W^2/m_Z^2)$ 
    - Modification impacts  $A_{\text{FB}}$ , angular distributions



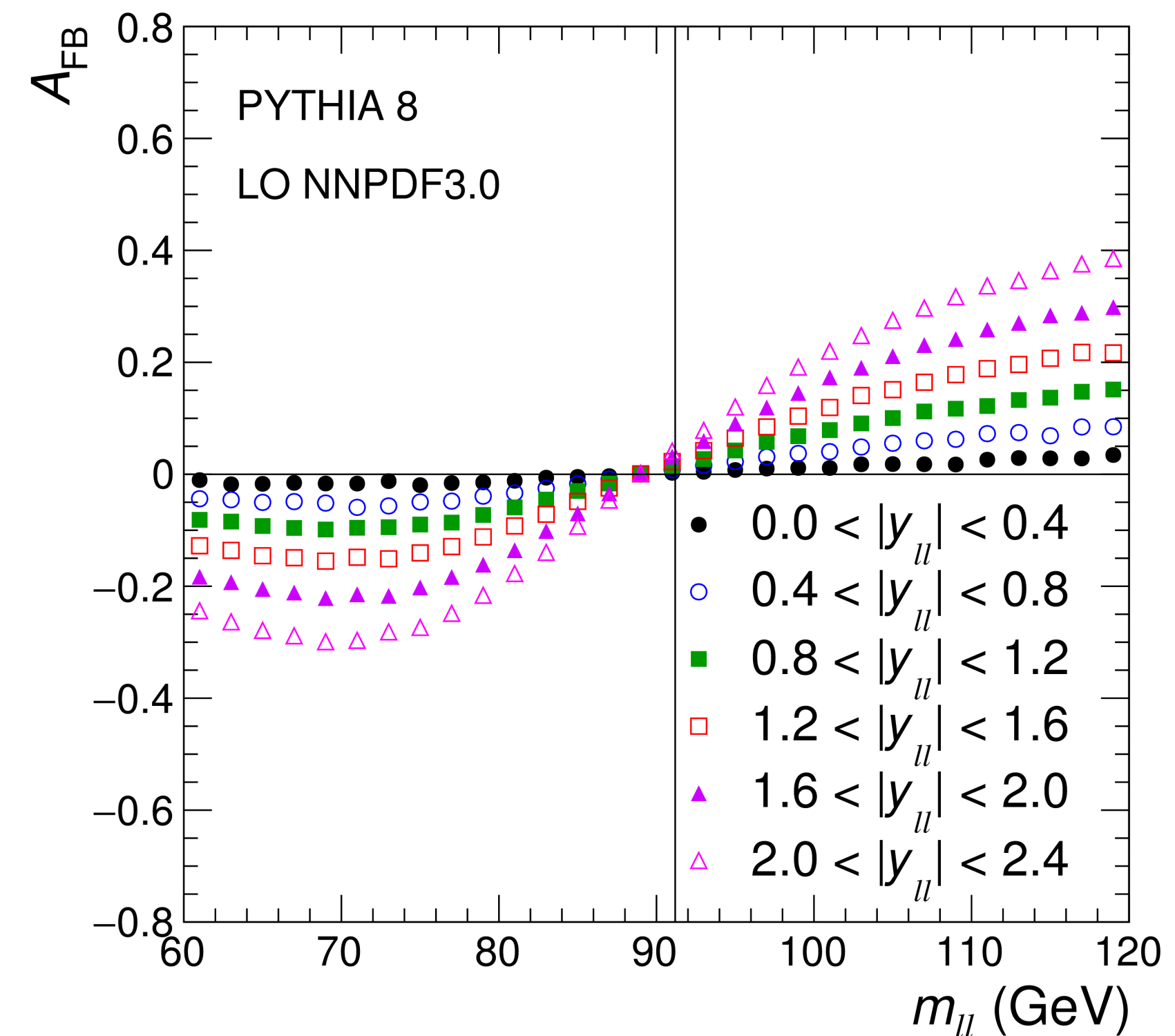
$$A_{\text{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- $\sigma_F$  and  $\sigma_B$  defined in terms of the quark direction  
 ➡ not exactly knowable in LHC collisions

$$\frac{d\sigma}{d\cos\theta^*} = C \left[ \frac{3}{8} (1 + \cos^2\theta^*) + A_{\text{FB}} \cos\theta^* \right]$$

*Z boson coupling depends on lepton helicity*

“Mixing”: relative strength of axial and vector couplings

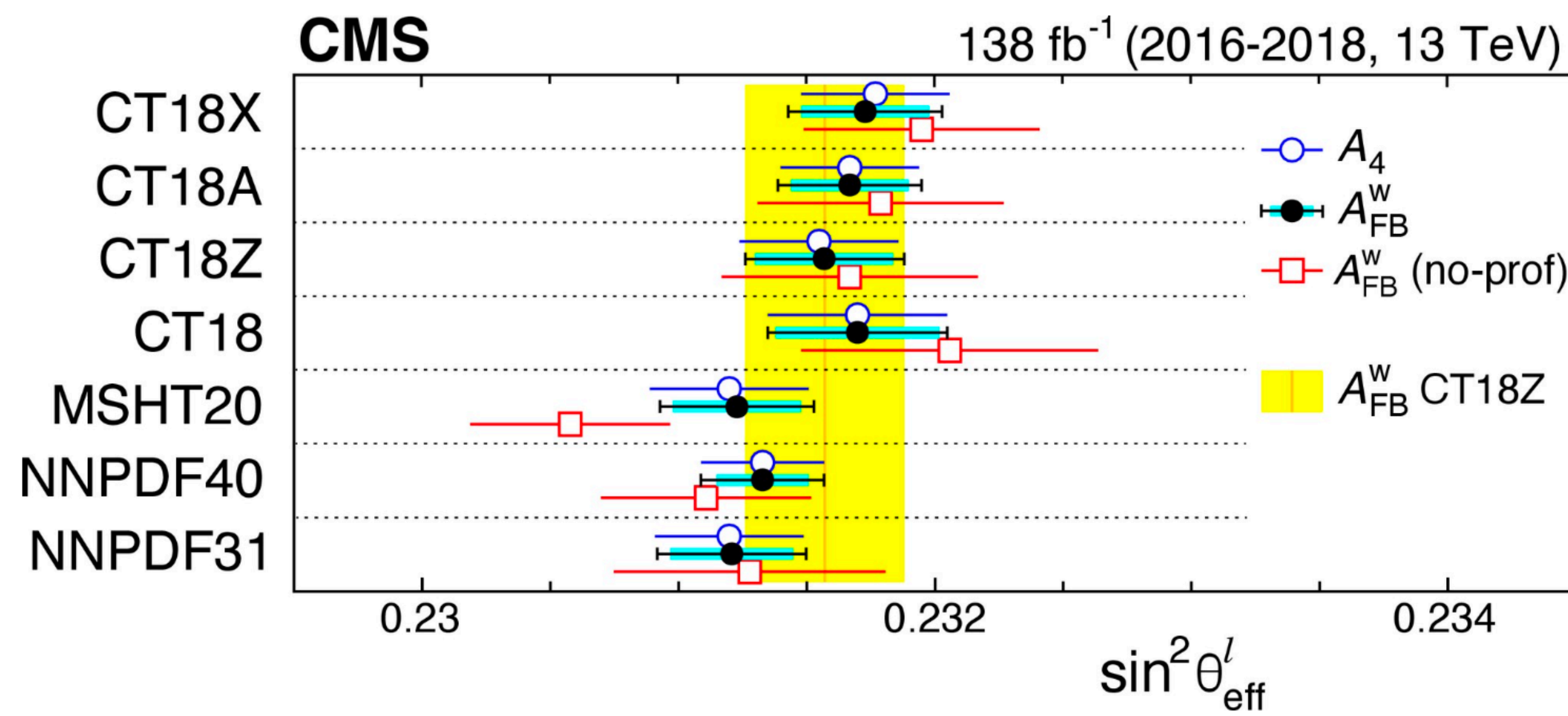


- *In general*, the valence quarks have higher momentum
- Rapidity sign is a proxy for the valence quark direction



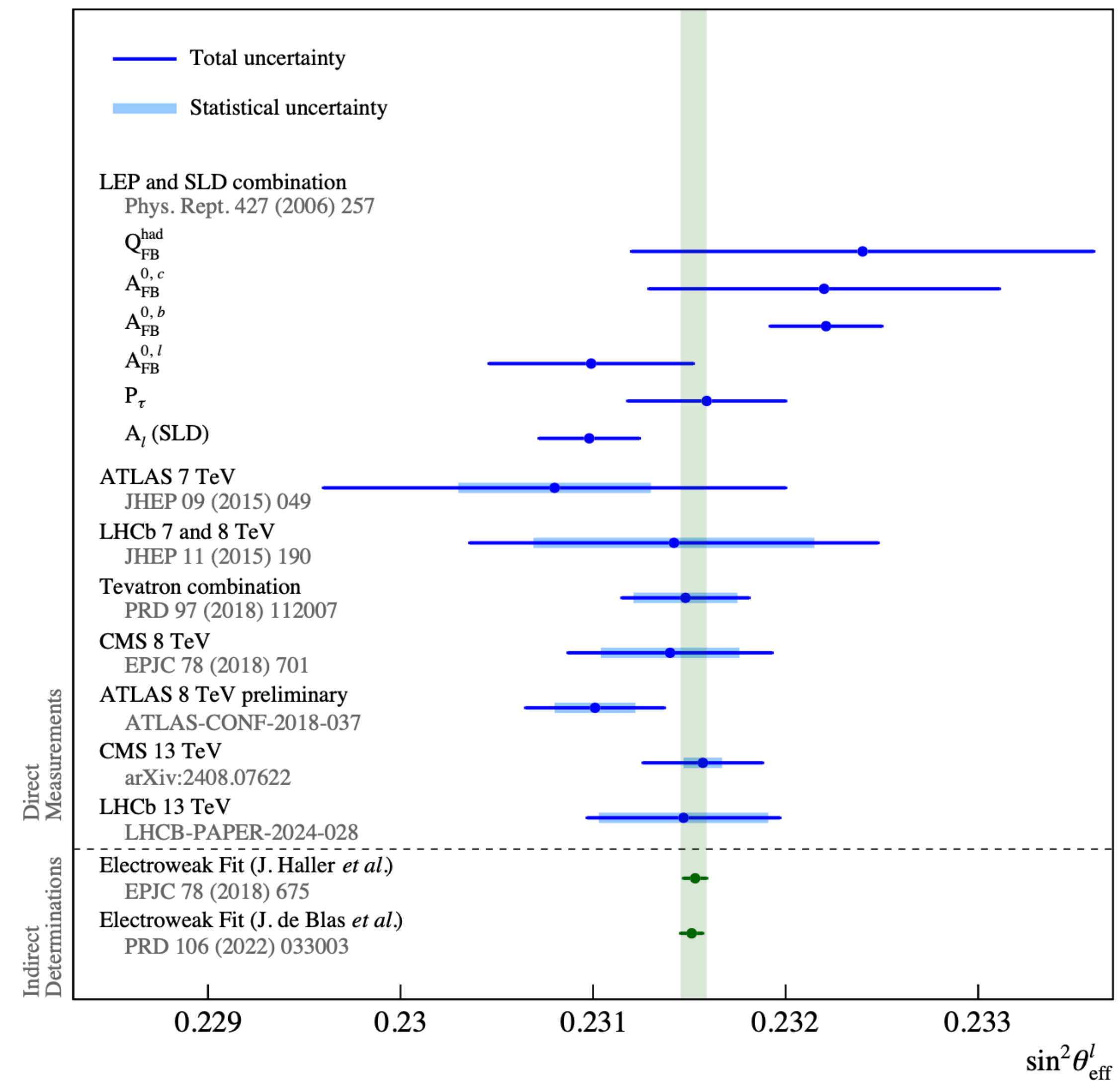
# CMS and LHCb $\sin^2\theta_{eff}^\ell$ results

- Results extracted from simulated templates with variations of  $\sin^2\theta_{eff}^\ell$  variations
  - **CMS:** both reconstructed-level and on unfolded  $A_{FB}$
- Approaching LEP and SLD sensitivity



**CMS**  $\sin^2\theta_{eff}^\ell = 0.23157 \pm 0.00031$   
 (0.00027 theory, 0.0010 stat)

**LHCb:**  $0.23147 \pm 0.00050$  (0.00023 theory, 0.0044 stat)



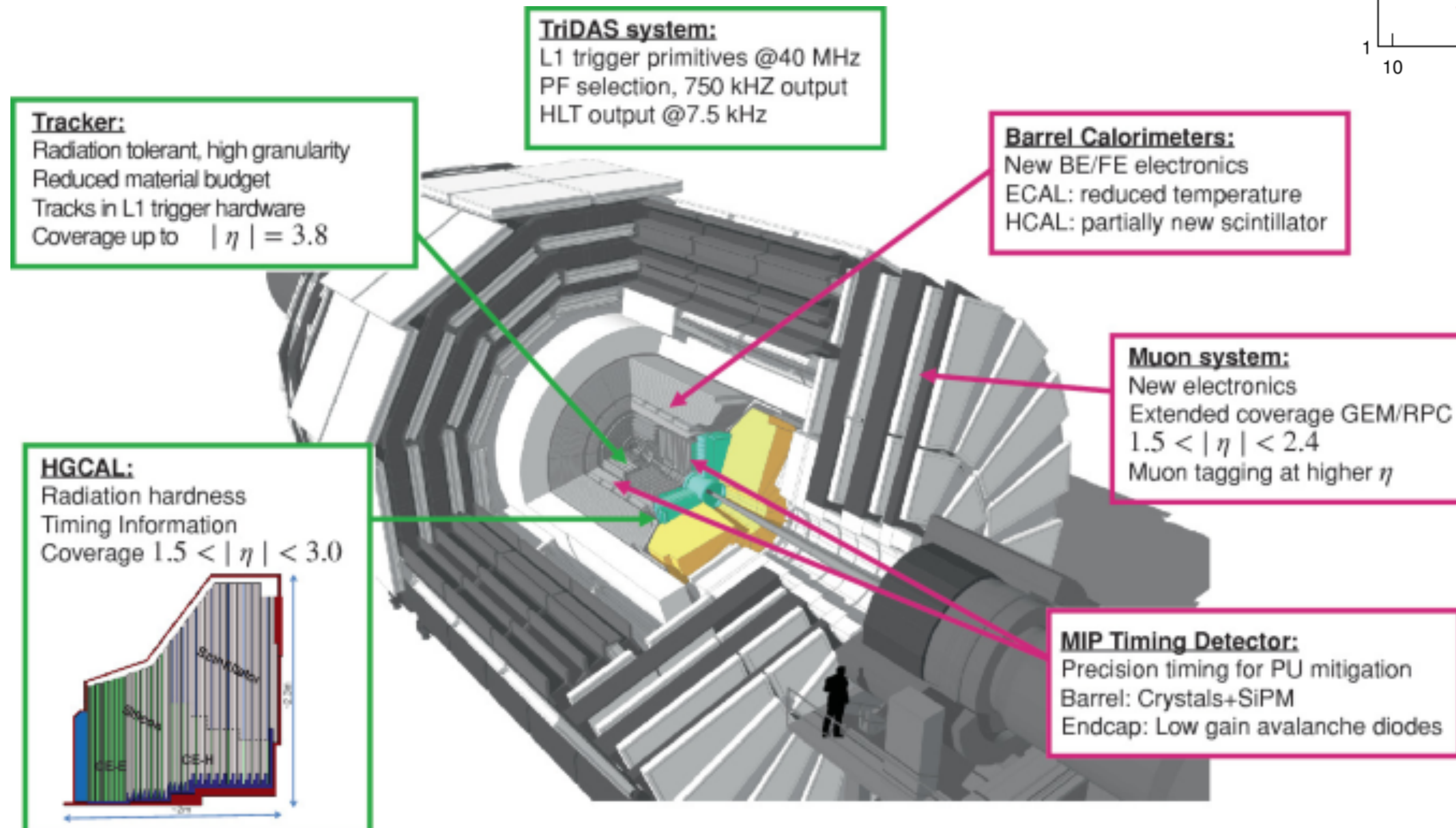
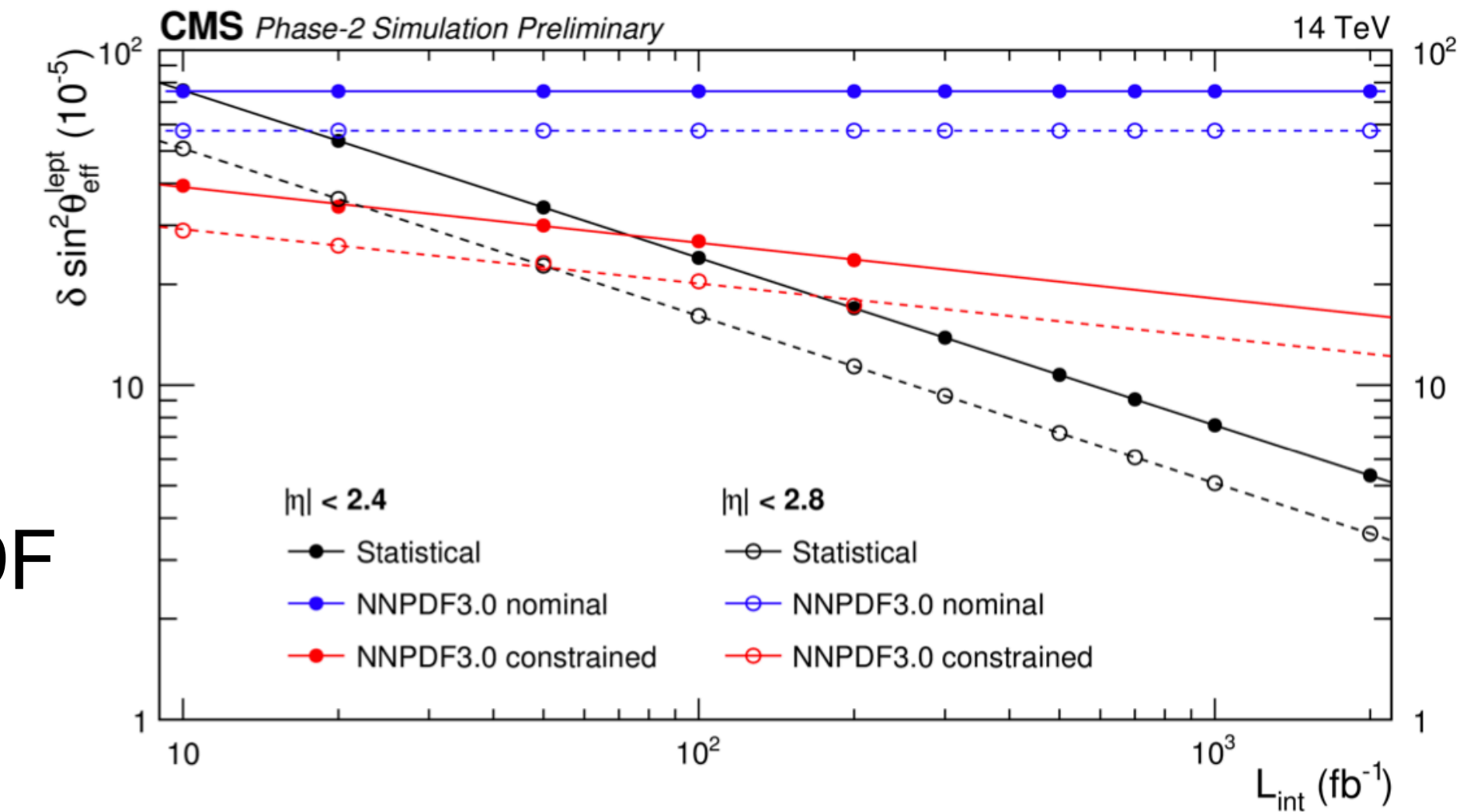
Phys. Lett. B 866 (2025) 139526

JHEP 12 (2024) 026



# Future prospects

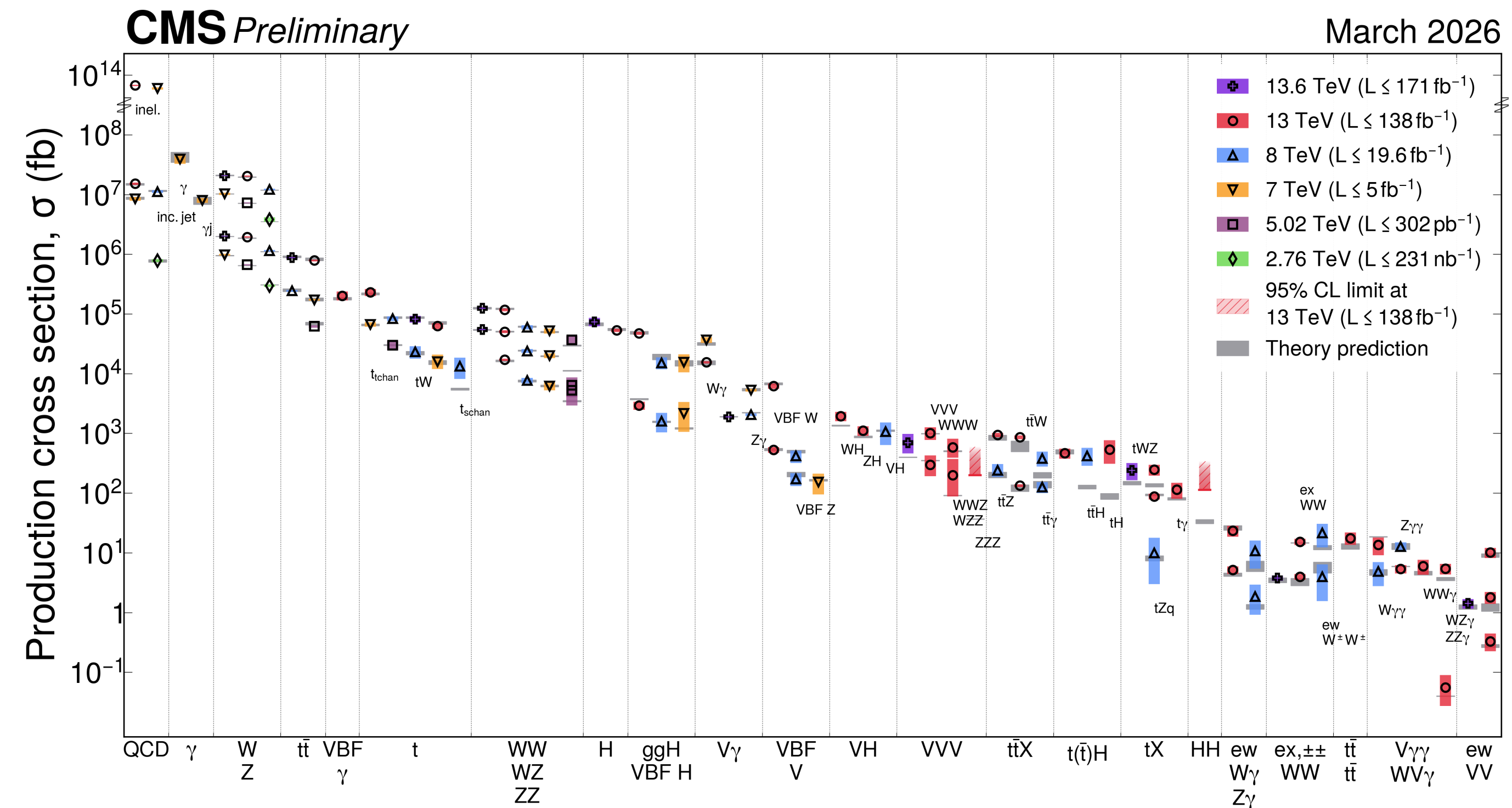
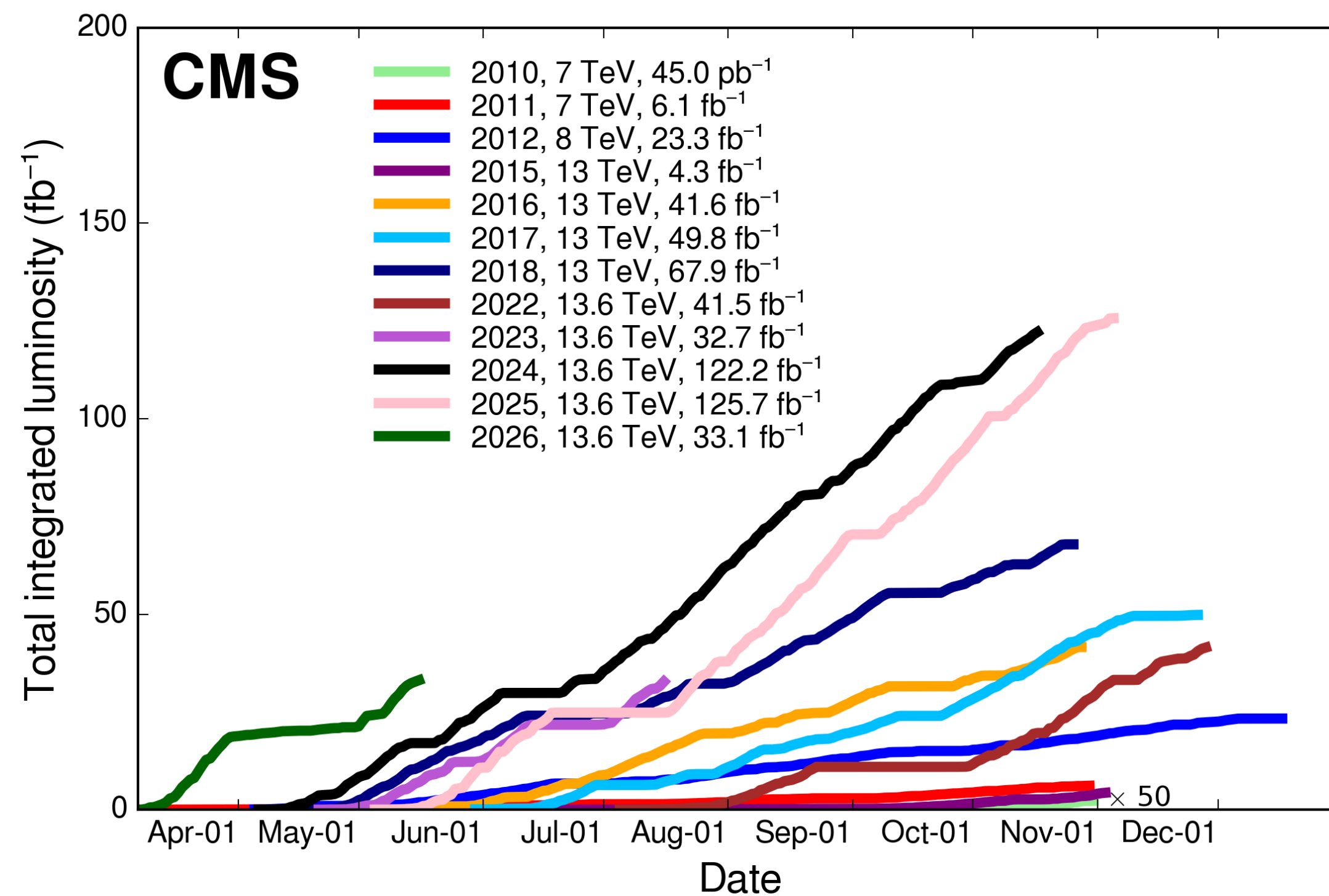
- SM precision result with **most to gain from HL-LHC upgrade**
  - Still statistically limited
  - CMS and ATLAS extend forward coverage
  - LHCb able to cope with more data
- Benefits from **simultaneous extraction of results/constraints on PDF**





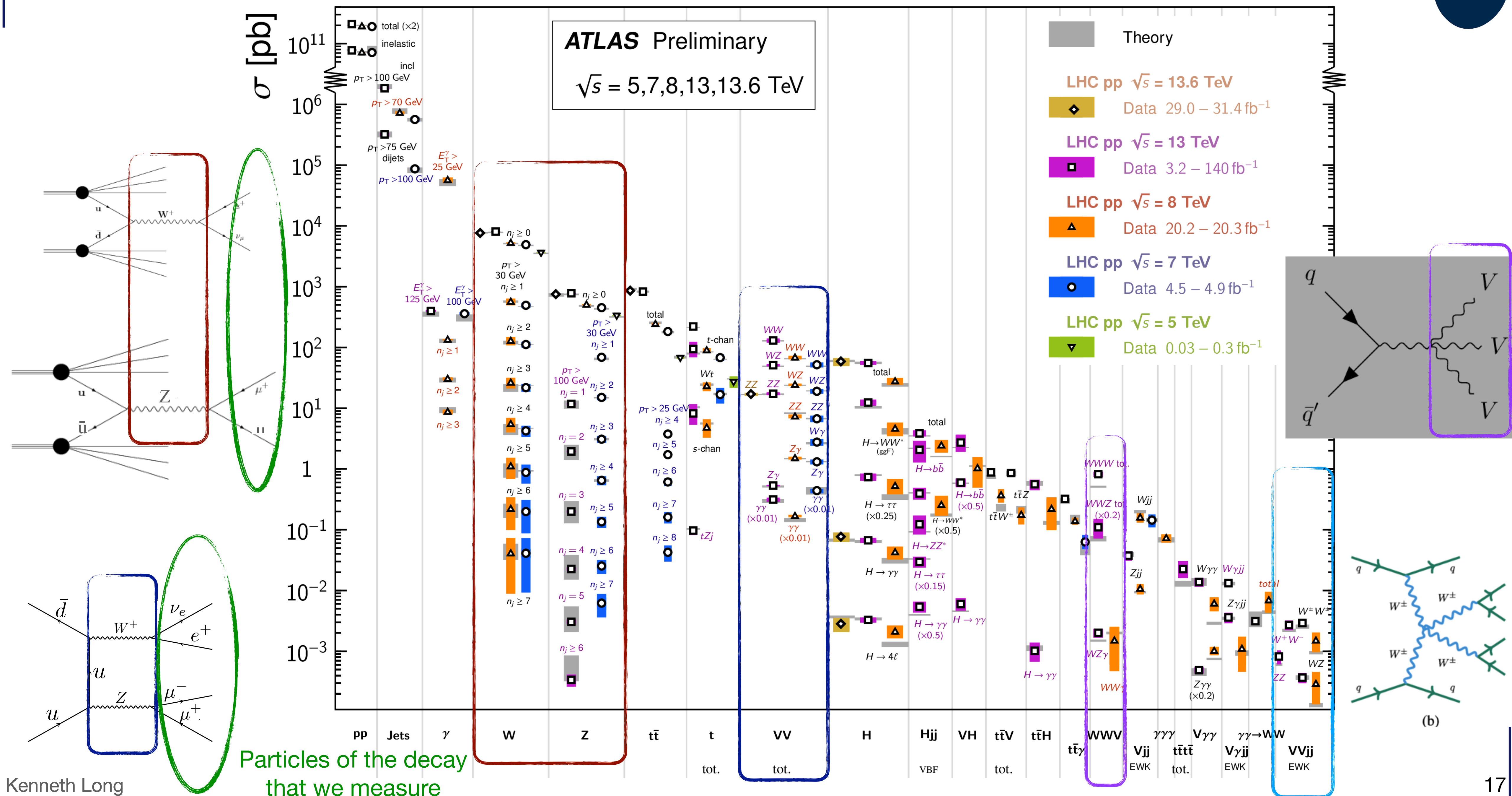
# Cataloguing the standard model with the LHC

- What particles are produced in pp collisions, how often, and with what properties?
- **Huge LHC data sets** (e.g., years of proton collisions)
  - A good “problem” to have!
  - How differential can you go?
  - How many bosons/jets/top quarks/Higgs...?



Standard Model Production Cross Section Measurements

Status: June 2024

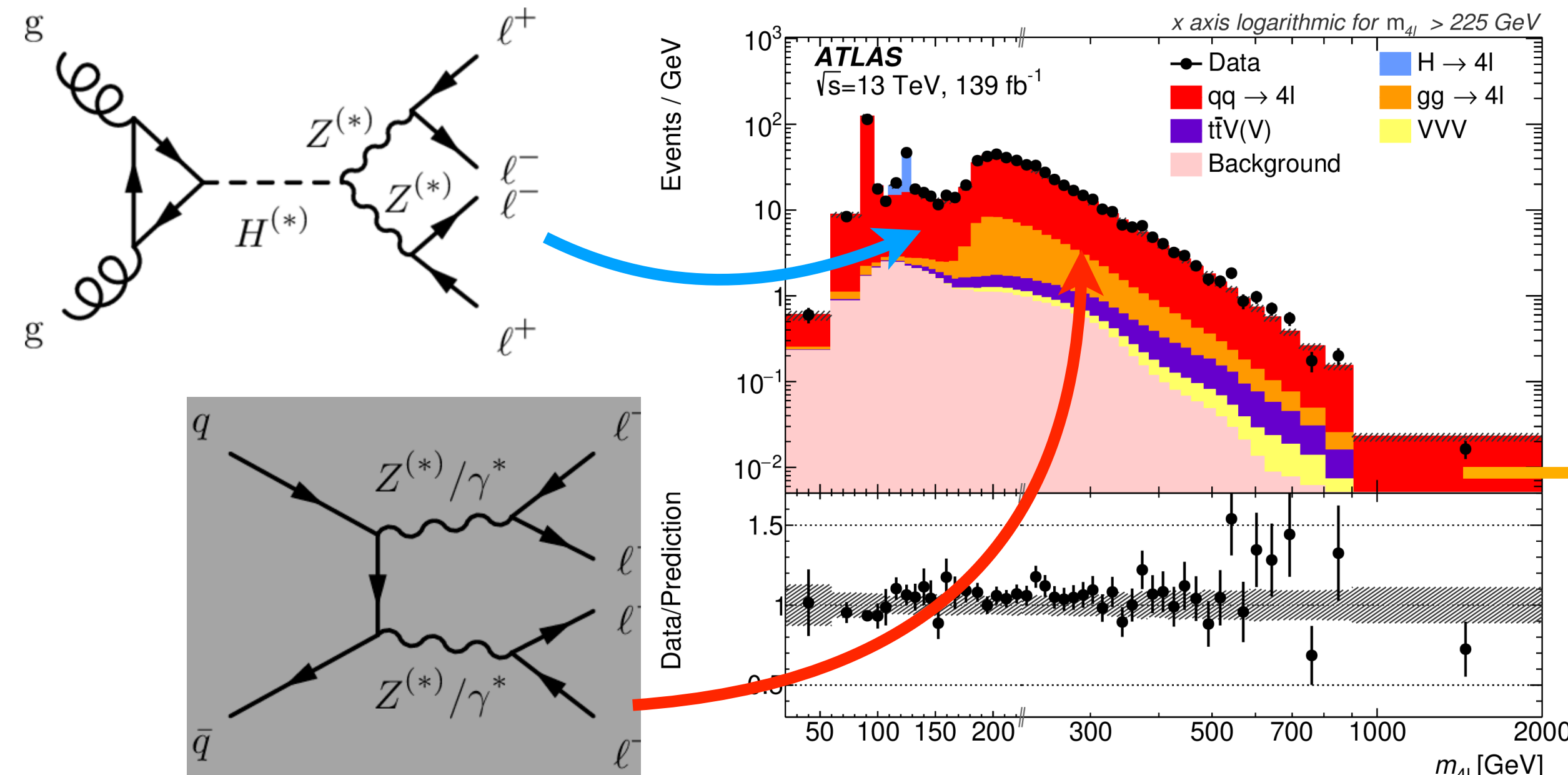
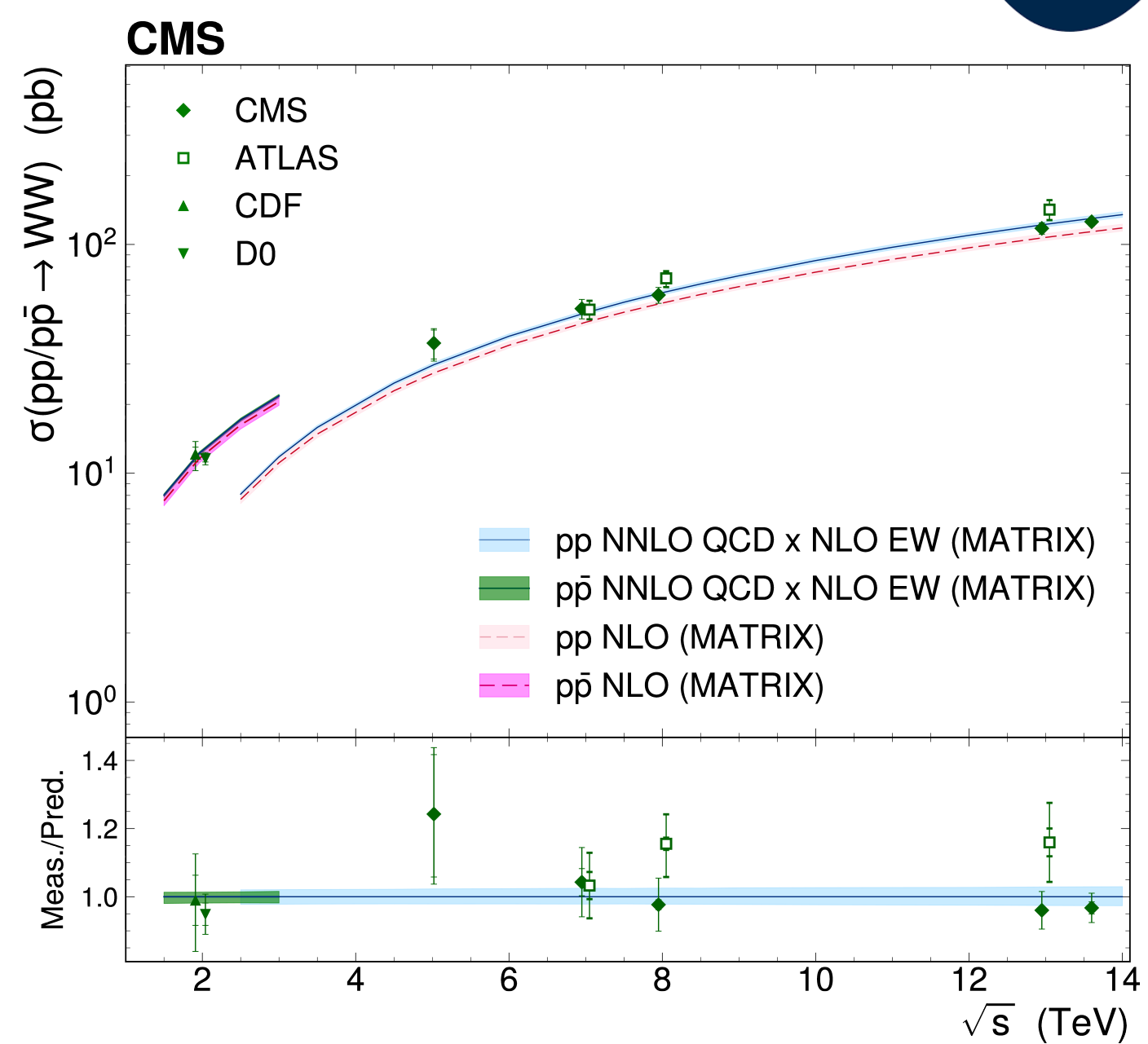
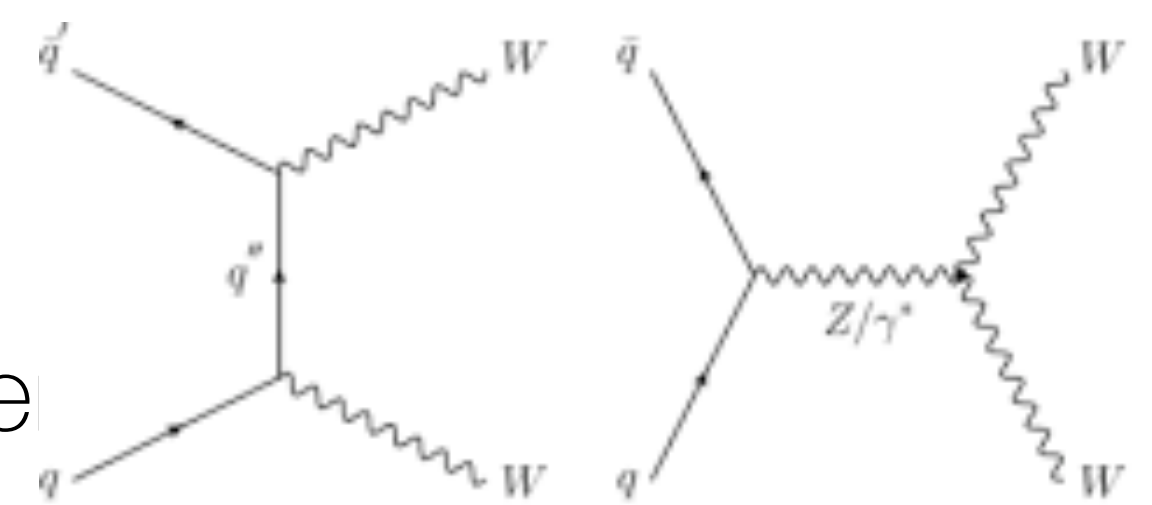


Particles of the decay that we measure



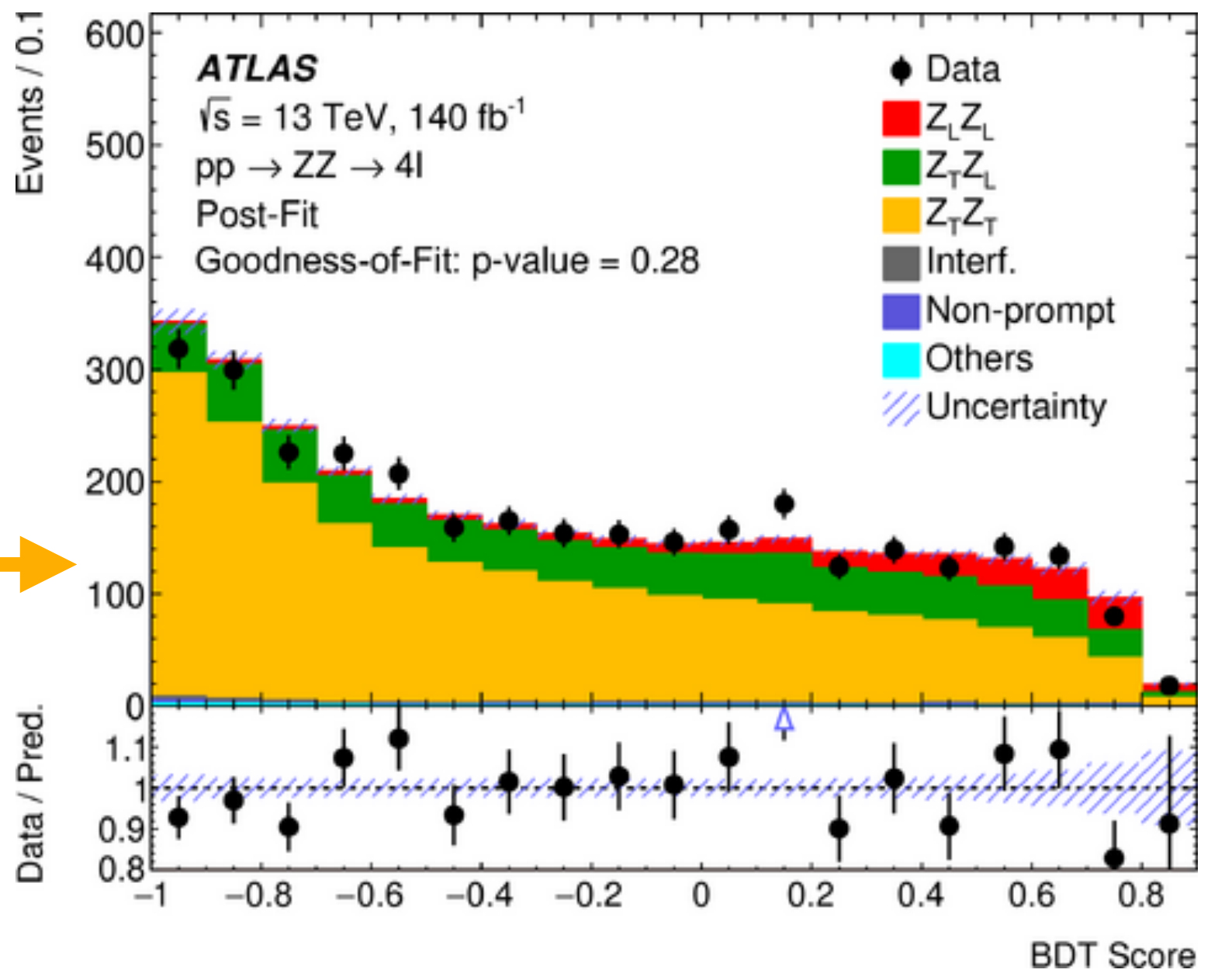
# Exploring the EW sector of the SM with diboson production

- Massive vector bosons have **quartic and triple self-couplings** due to non-Abelian electroweak theory
  - Multiboson production probes these couplings
- Higgs boson decay to boson pairs is a critical search and measurement channel
  - A **“standard candle”** analysis
- Sensitive to effects higher-order calculations
  - WW showed **need for improved calculations** after the LHC start



spin 1 V: polarisation  
(spin vs. momentum)  
important in  
production and  
decay

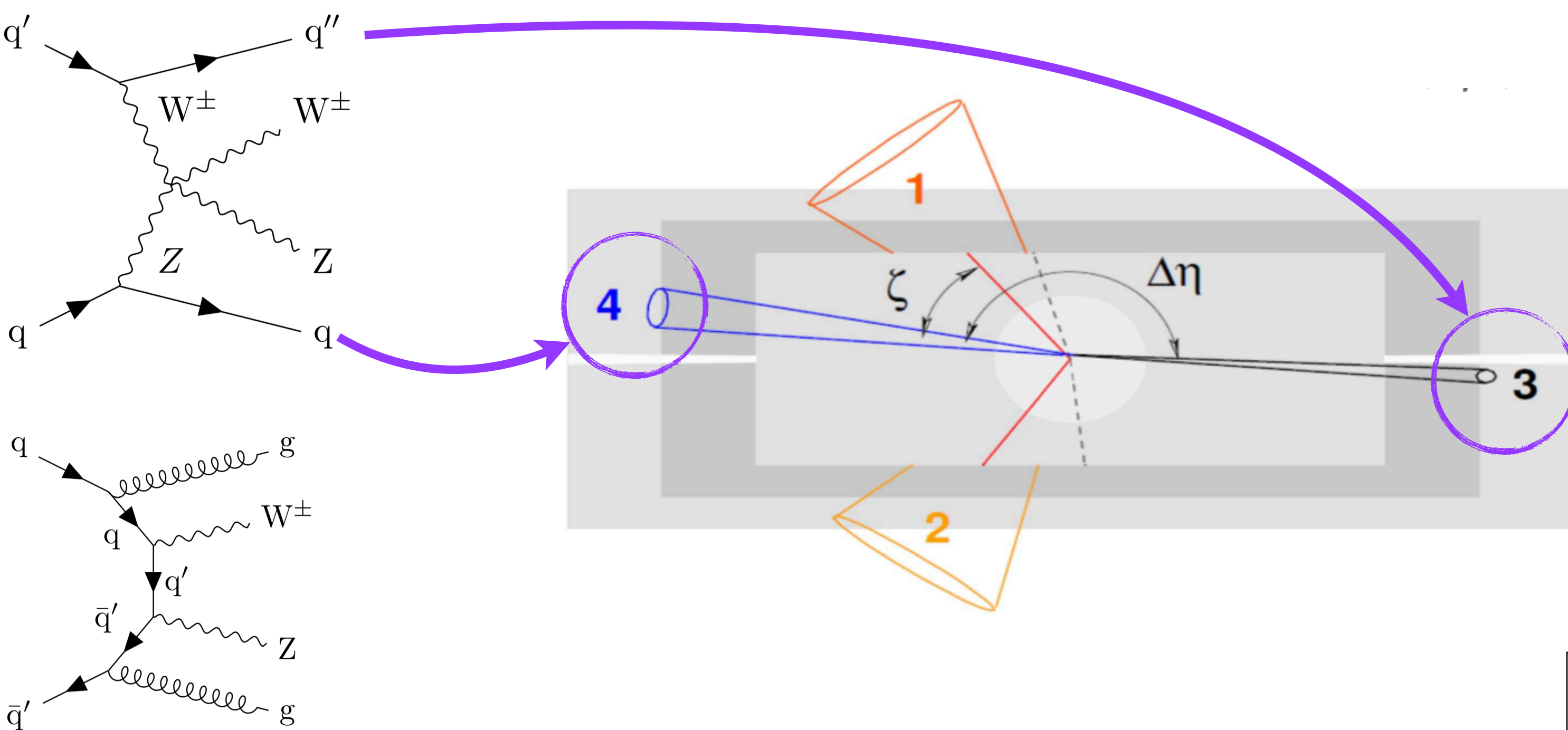
JHEP 07 (2021) 005



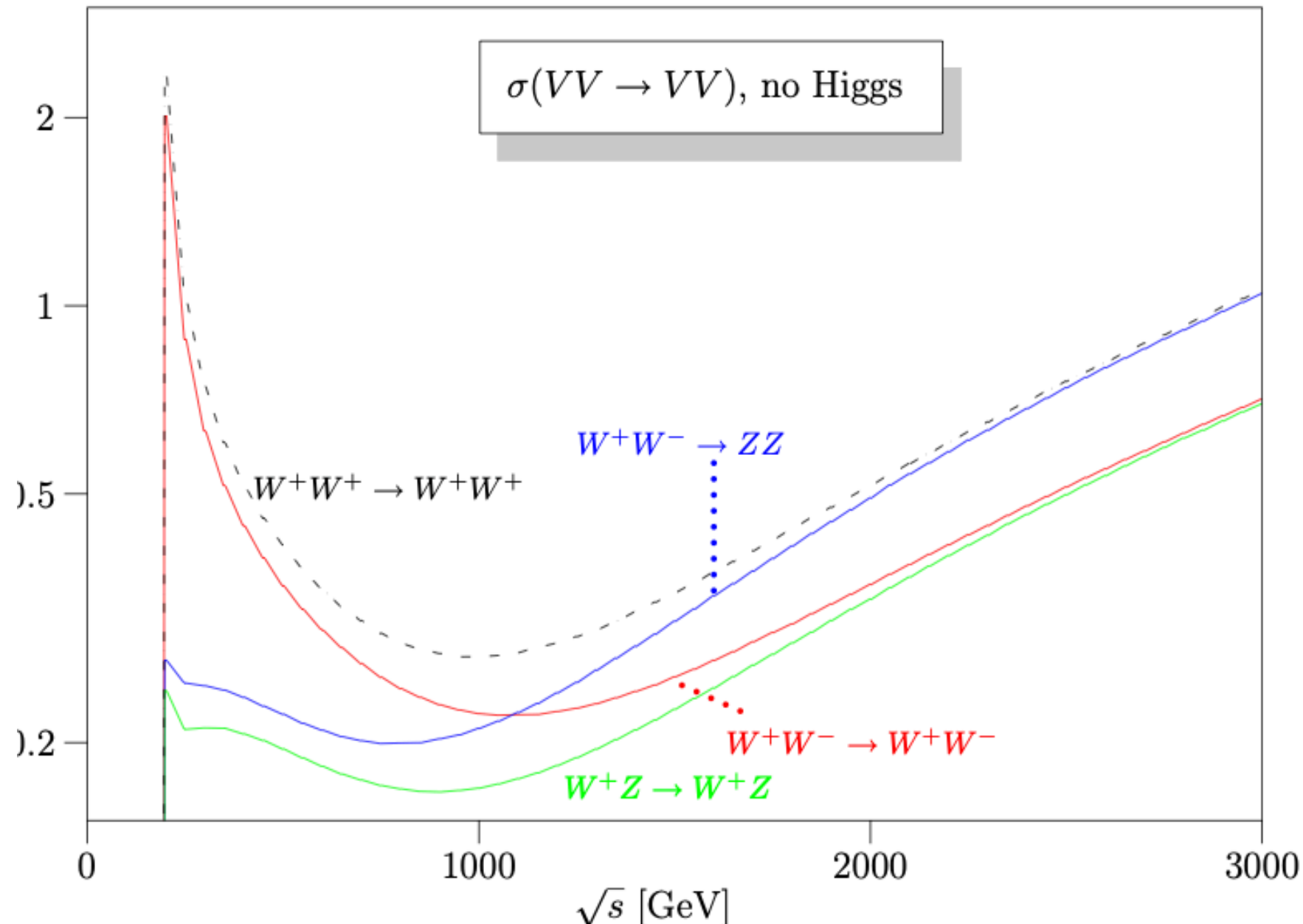
# Probing EW symmetry breaking with vector boson scattering

- Without the Higgs boson, **VV scattering rate is proportional to scattering energy** in perturbation theory (e.g., not weak!)
  - With a light Higgs boson, expected scaling restored
  - Major argument in favour of finding “something” at the LHC
- The Higgs exists, but **VBS remains a probe of EWSB**
  - Is the SM Higgs boson solely responsible for unitarization?

$$\mathcal{A}(W_L W_L \rightarrow W_L W_L) \propto (-s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2})$$



**Non-VBS background**



$$M_H^2 \leq \frac{8\pi\sqrt{2}}{3G_F} \equiv M_c^2 \simeq (1 \text{ TeV}/c^2)^2$$

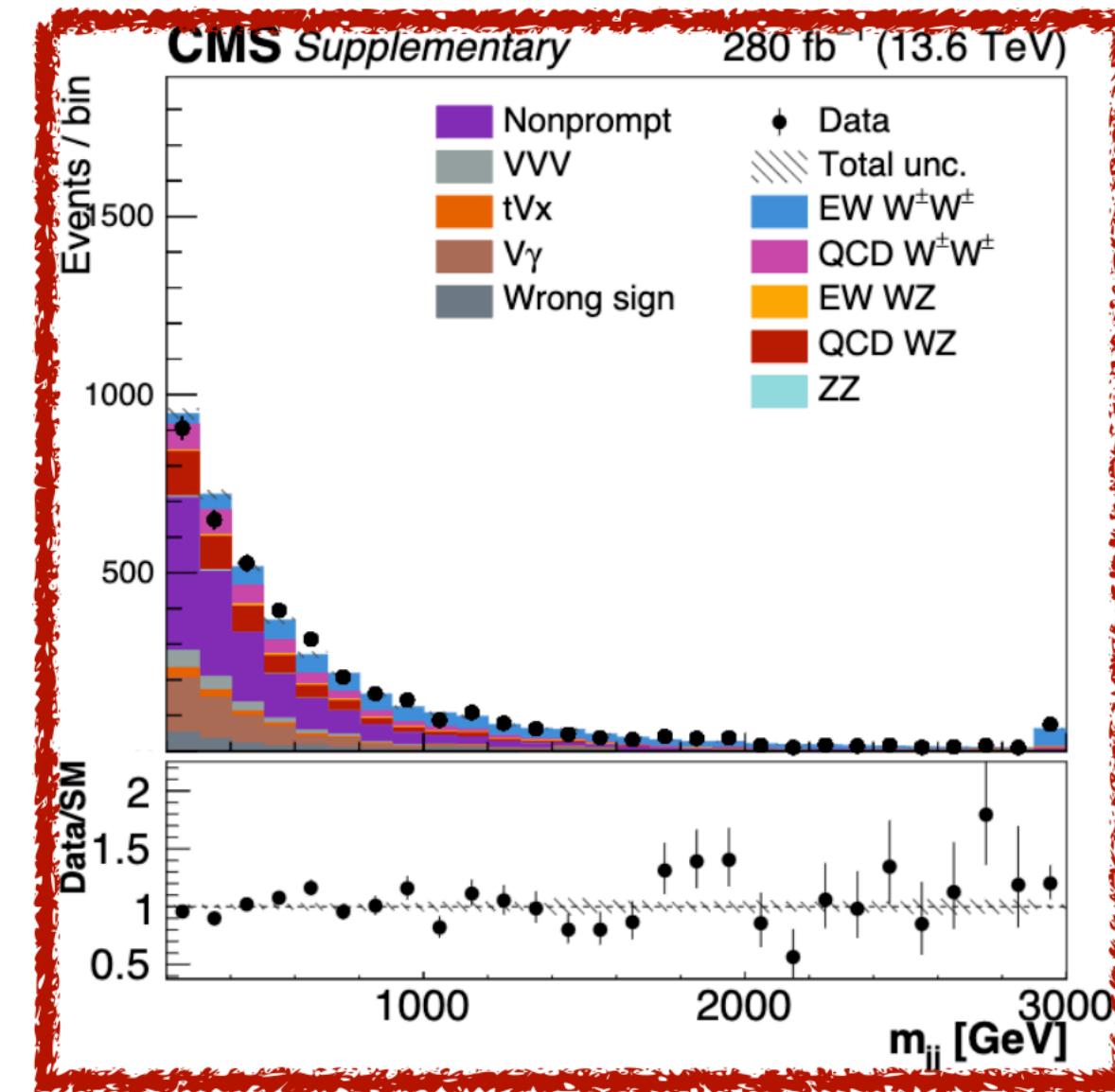
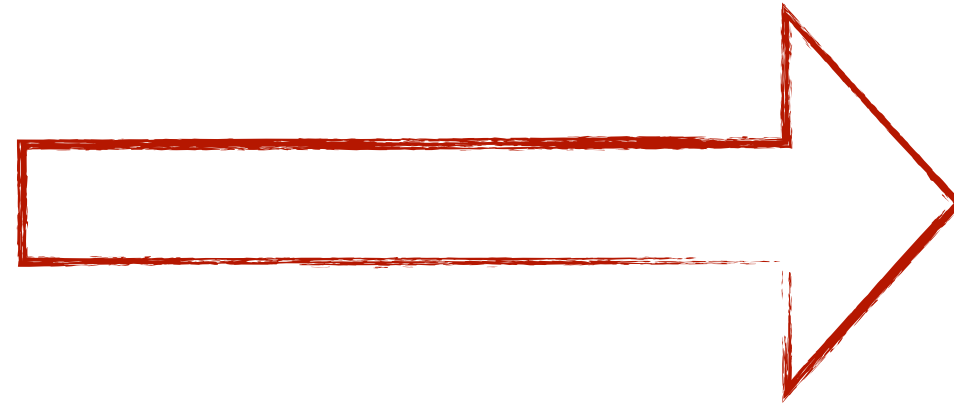
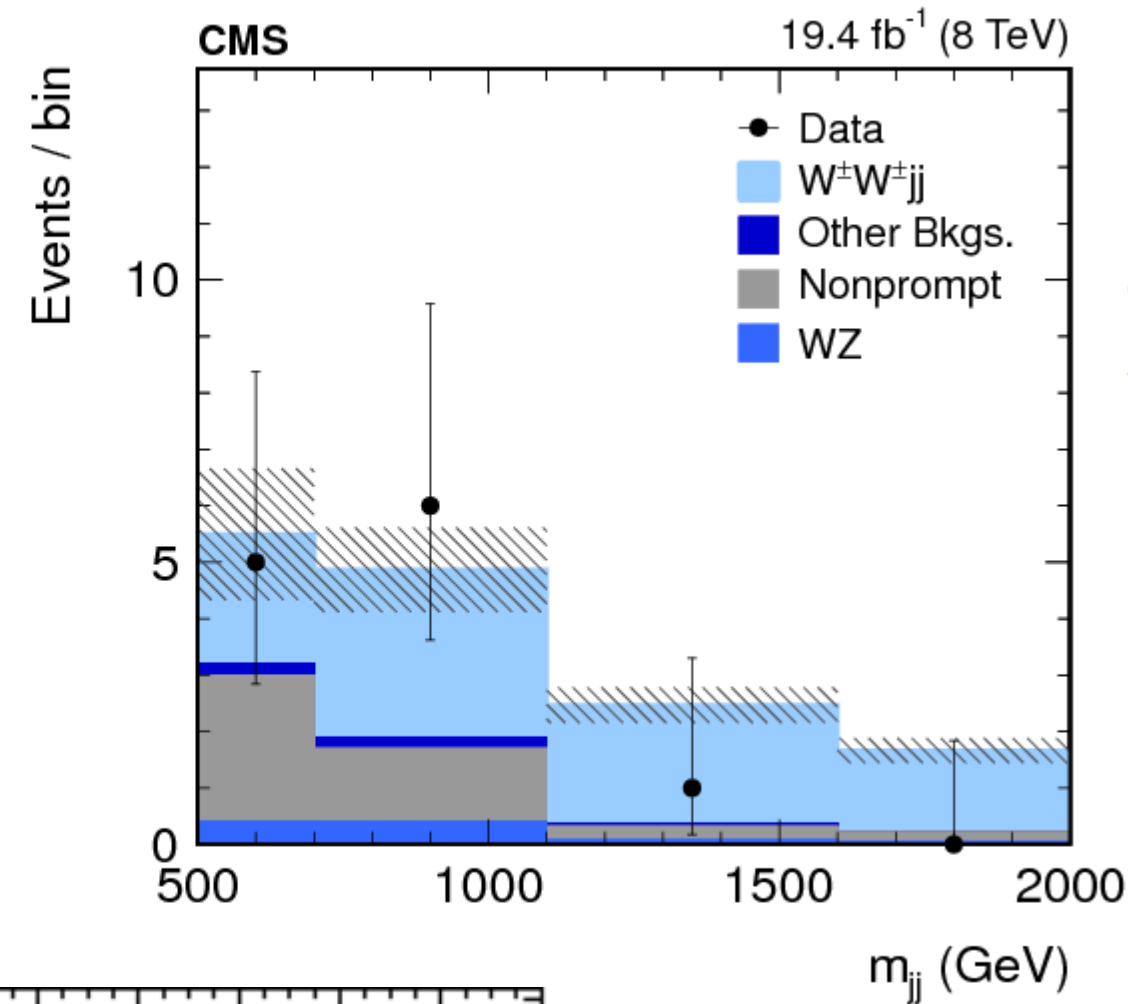
**Weak interactions at very high energies: The role of the Higgs-boson mass**

Benjamin W. Lee,\* C. Quigg,† and H. B. Thacker  
 Fermi National Accelerator Laboratory, ‡ Batavia, Illinois 60510  
 (Received 20 April 1977)



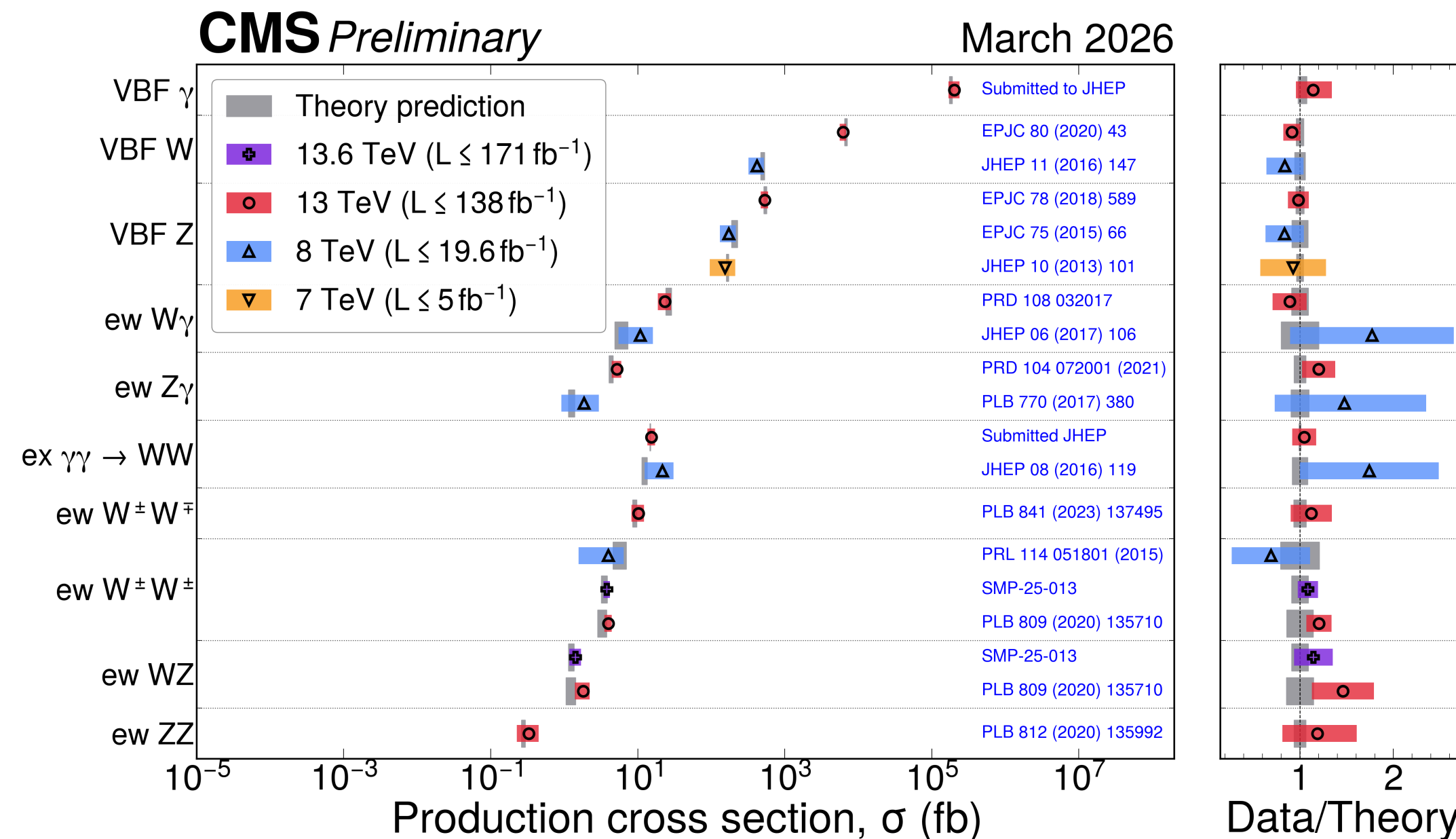
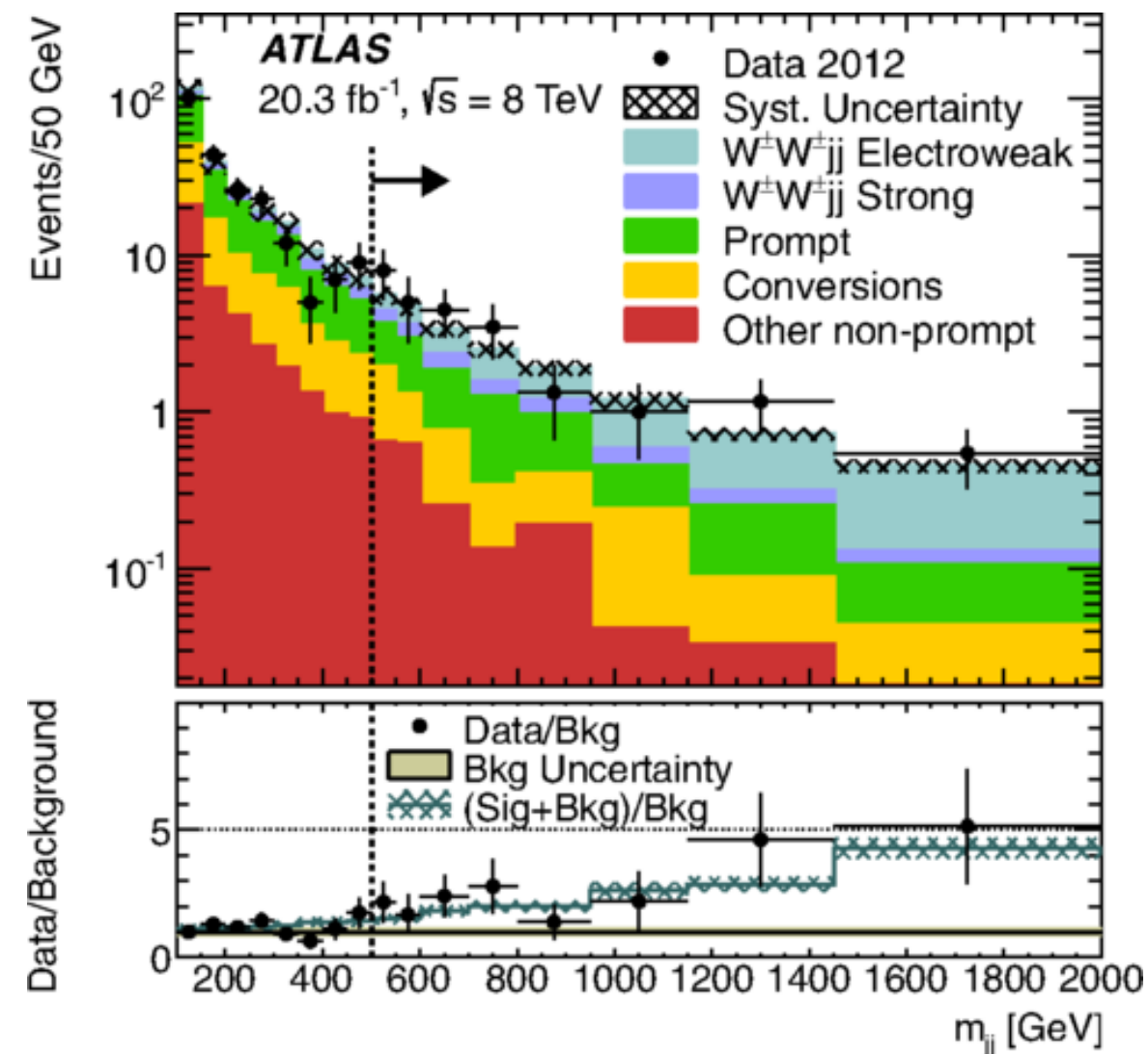
# Evolution of VBS measurements

- Production rate  $\sim 7$  orders of below  $W$  boson production
  - First observation in Run 1, now studied differentially



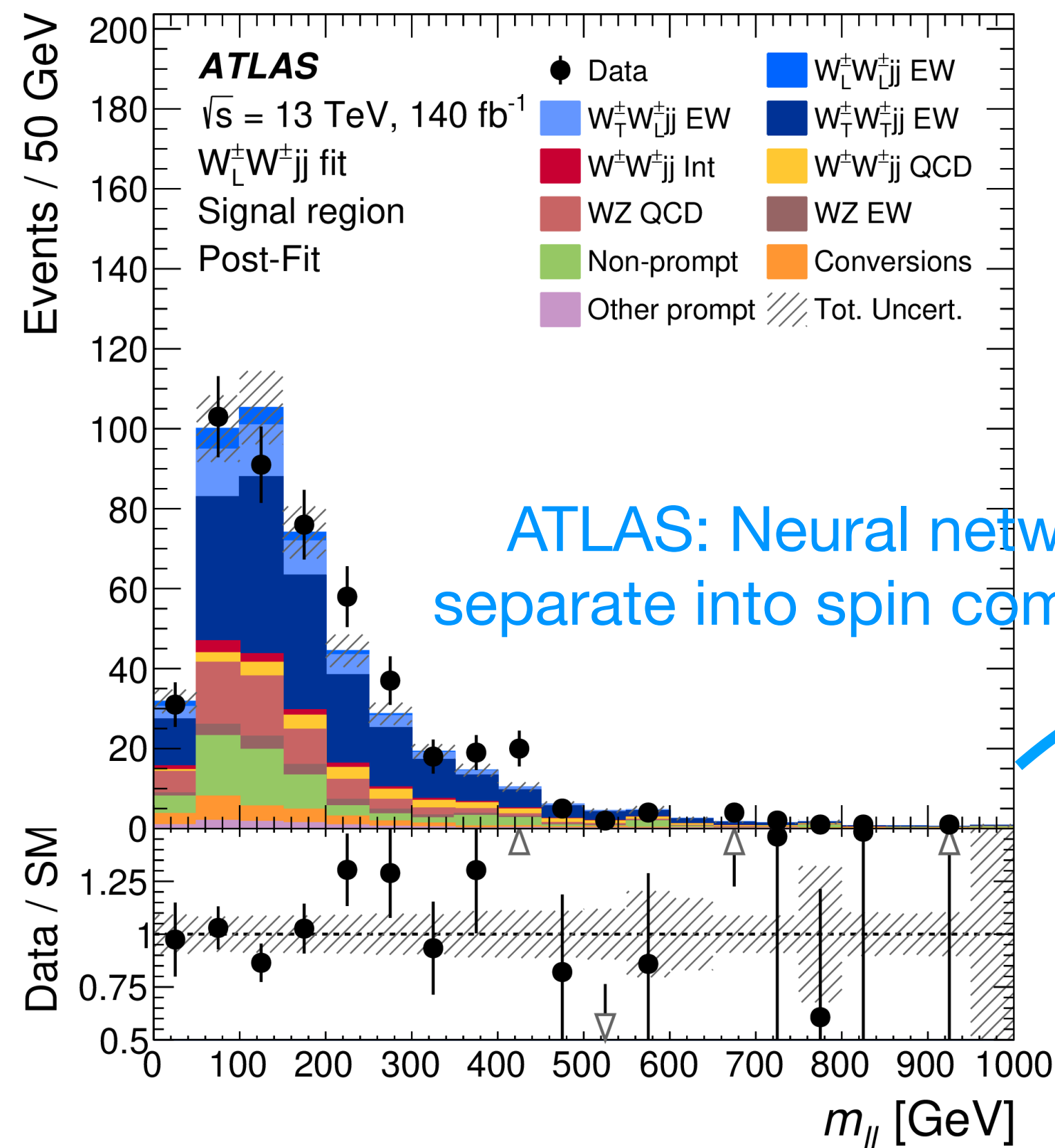
**CMS: first 13.6 TeV VBS measurement**

PRL 113 (2014) 141803  
 PRL 114 (2015) 051801  
 PRL 135 (2025) 111802  
[arXiv:2605.15396](https://arxiv.org/abs/2605.15396)



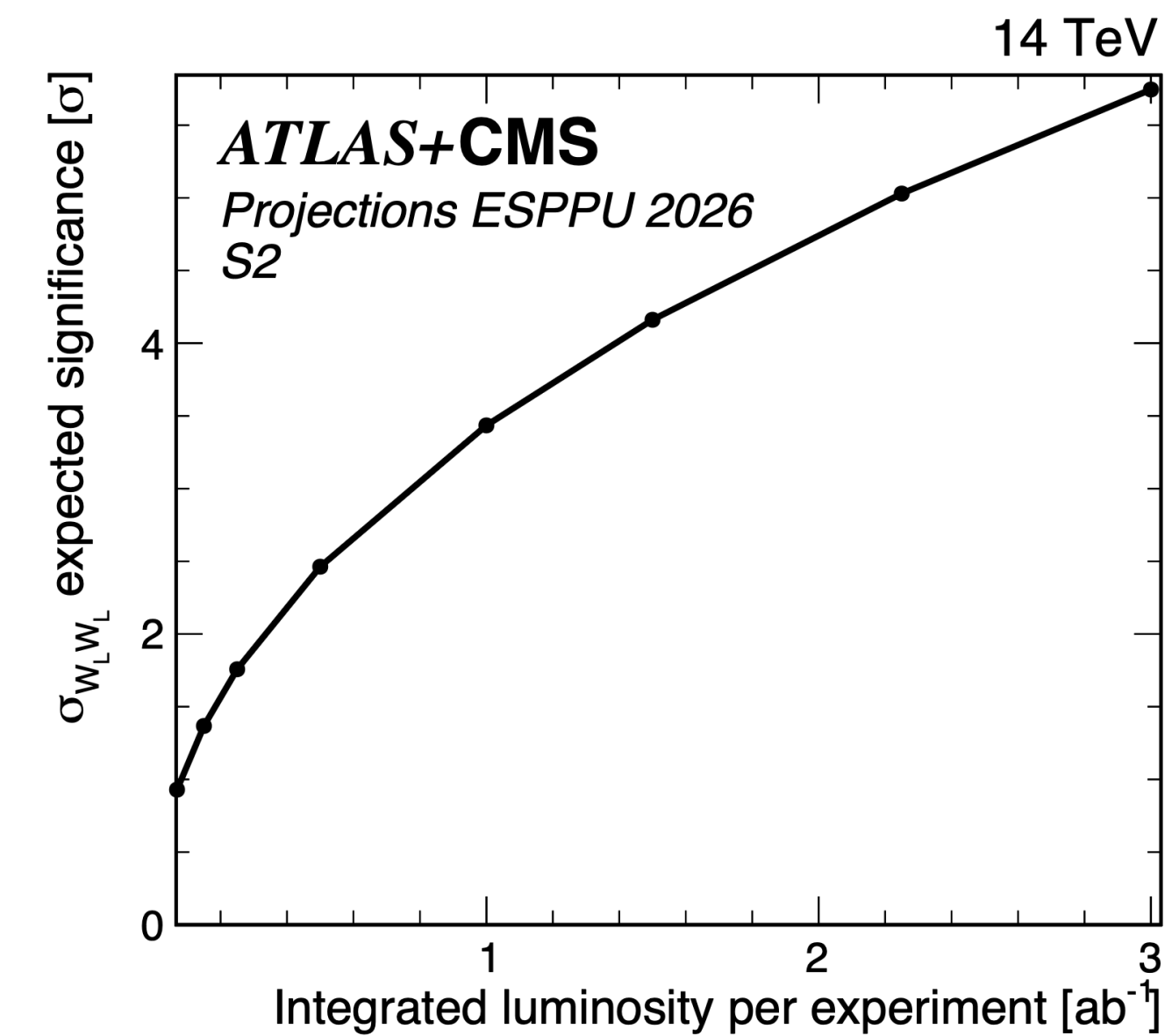
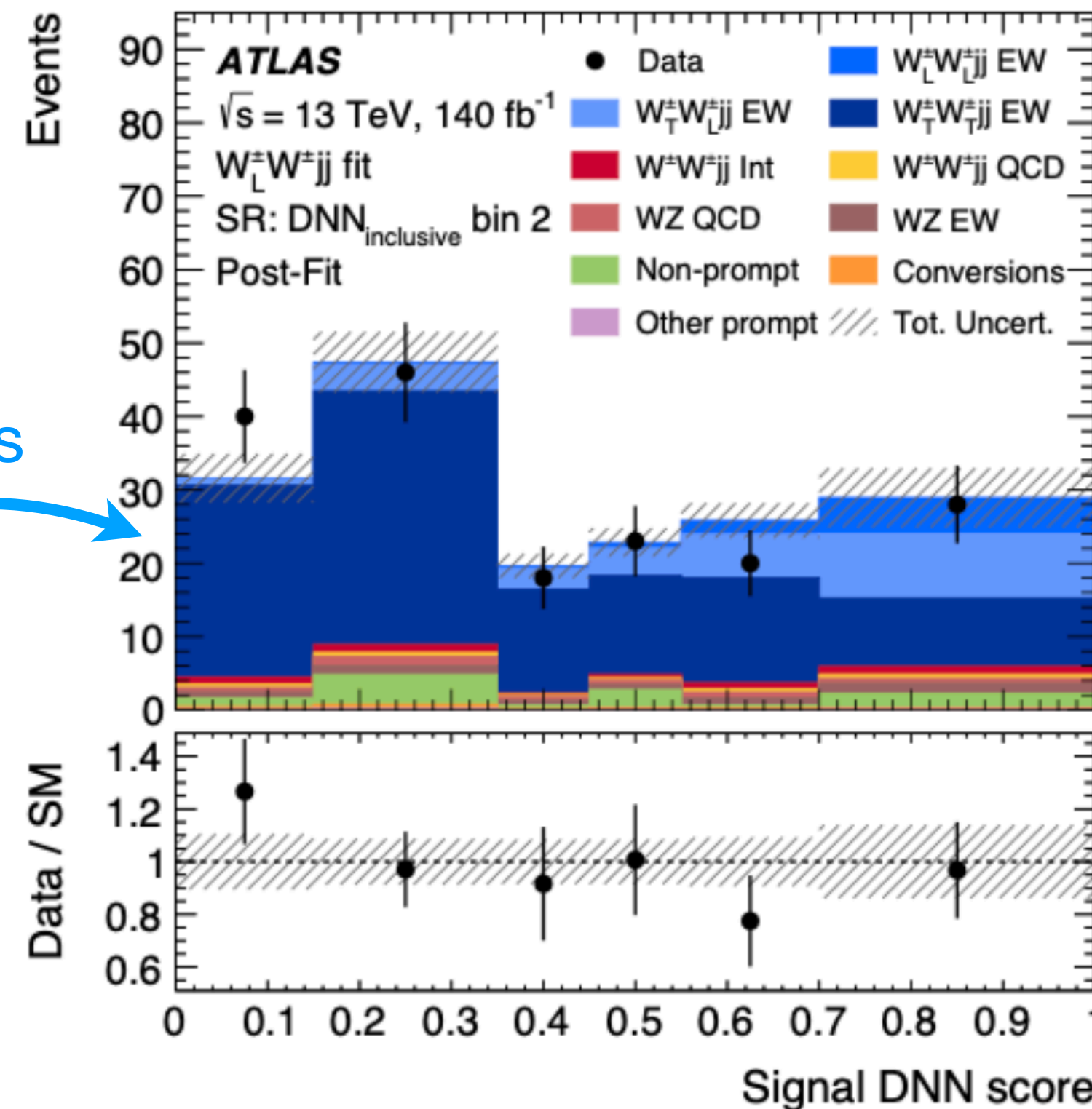
# Polarised vector boson scattering results and future prospects

- Longitudinal polarised proportion is only 10% of total VBS production
  - **First analyses with sensitivity** recently published
  - Major target for the HL-LHC



**CMS: first 13.6 TeV VBS measurement**

95% CL limit on production rate of  $W_L W_L$  set at 0.45 fb (0.70 fb exp.)



3.3 $\sigma$  (4.0 $\sigma$  exp)  
 significance ( $p \sim 5 \times 10^{-4}$ )  
 for  $W_L W_X$  scattering

PRL 135 (2025) 111802

PLB 812 (2020) 136018



# Summary and outlook

- The LHC was designed as a discovery machine

- No major discovery since the Higgs boson...

  - but huge progress in experimental techniques

  - **Better measurements than thought possible**

  - And still plenty of room to improve

- In the near (and not so near) future, LHC **has a major role to play in precise studies of the standard model**

- Enormous data set will come with increased experimental challenges:

  - high-pileup, detector aging

  - Offset by detector upgrades, reconstruction advancements

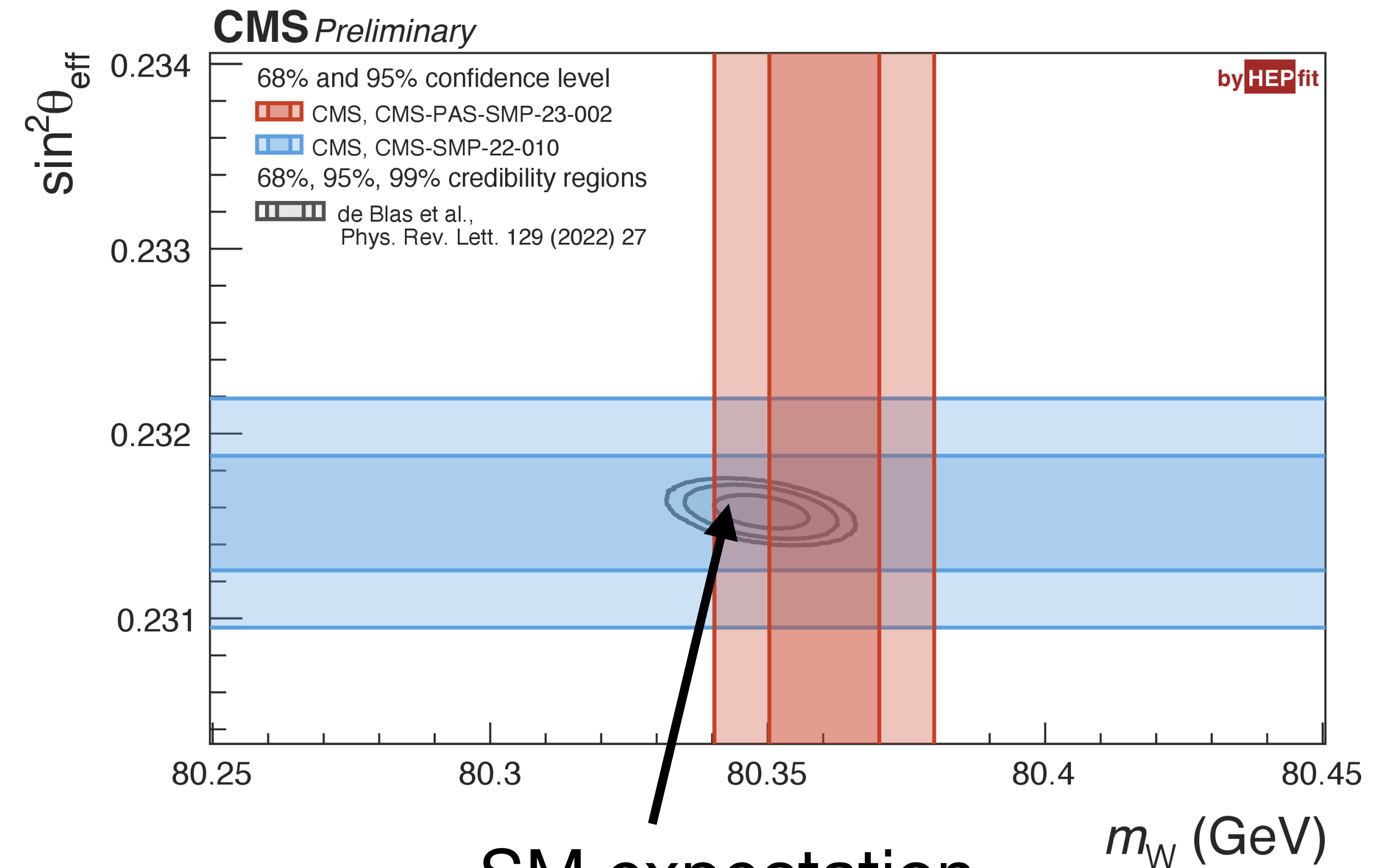
**nature**

By [Elizabeth Gibney](#)



**'The standard model is not dead':  
ultra-precise particle measurement  
thrills physicists**

**yet**



FCC-ee vs. LHC:  $\delta\sin^2\theta_{\text{eff}}: 310 \rightarrow 3 \times 10^{-6}$   
 $\delta m_W: 9.9 \rightarrow 0.25 \text{ MeV}$

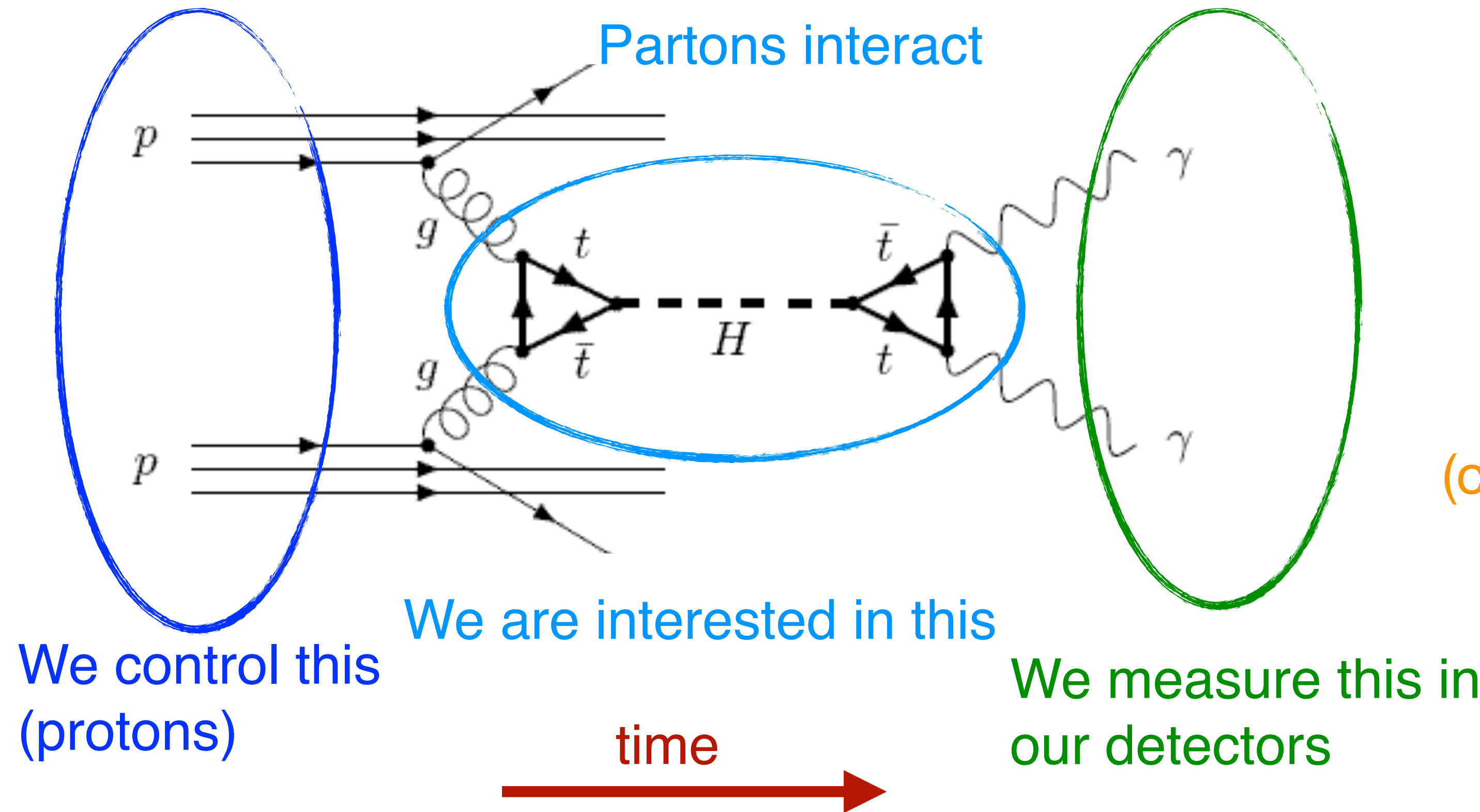
# Backup



# What do we do at the LHC?

Particles are brought to collision

Particles are produced



Events from other processes  
Events detected

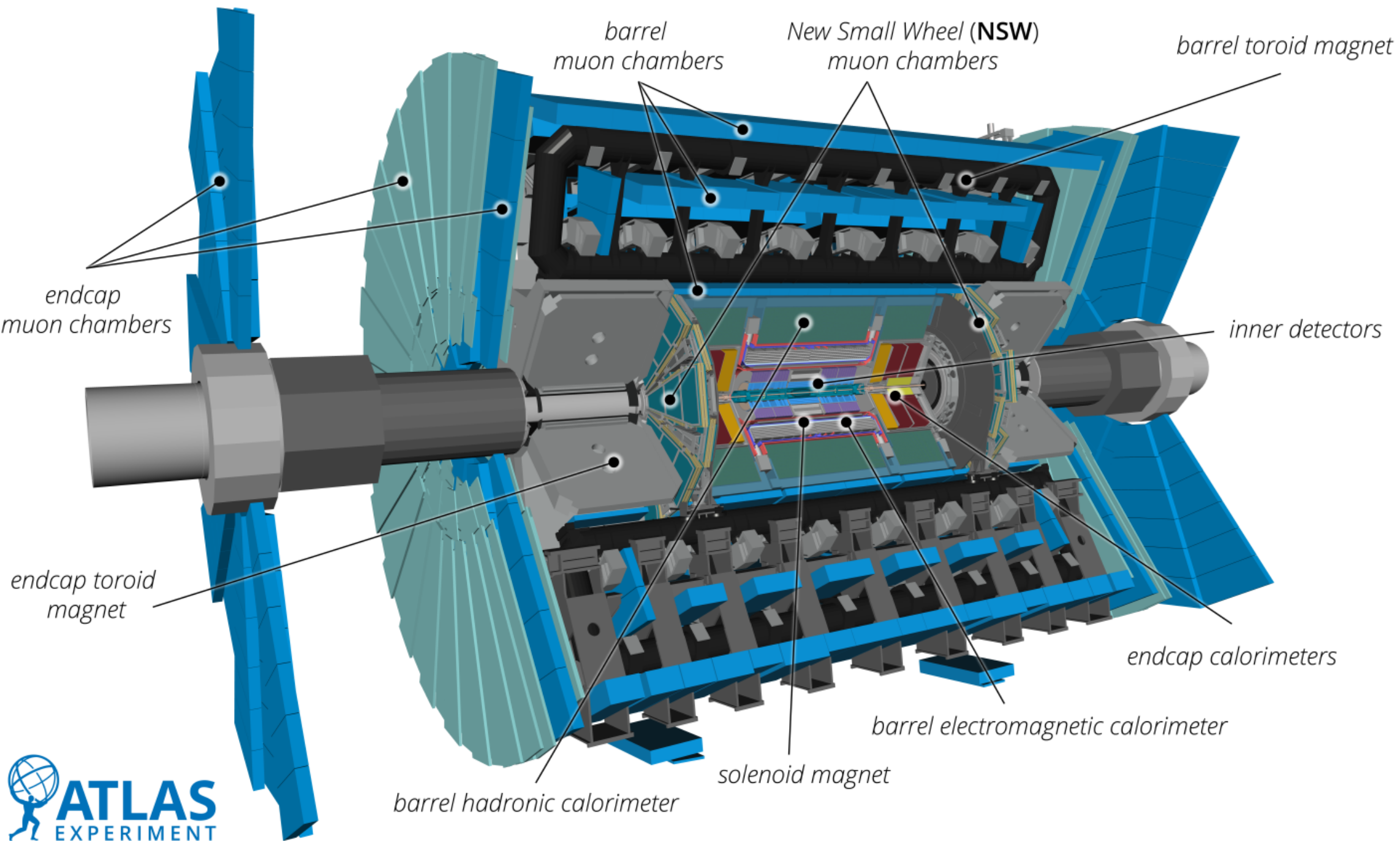
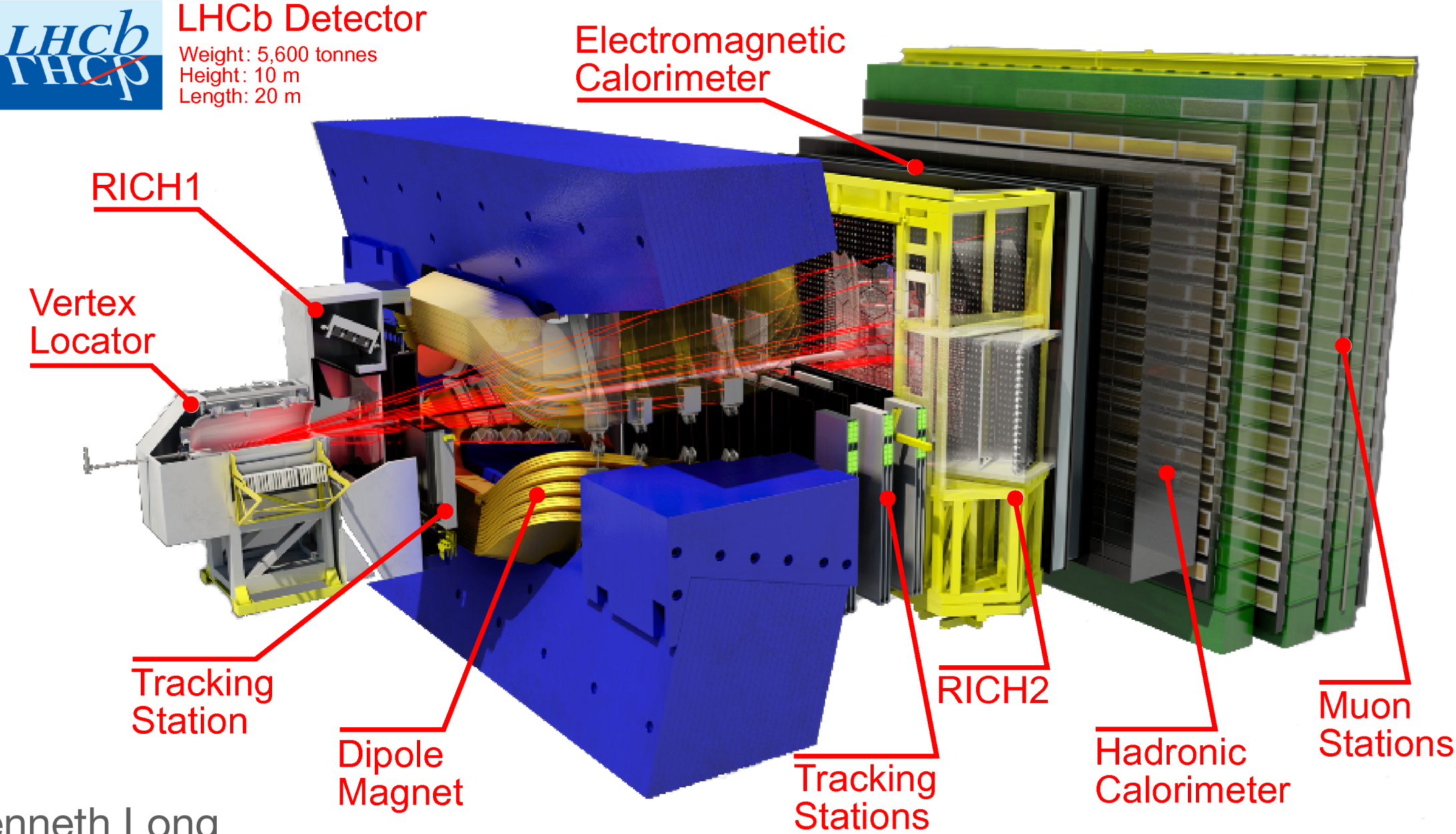
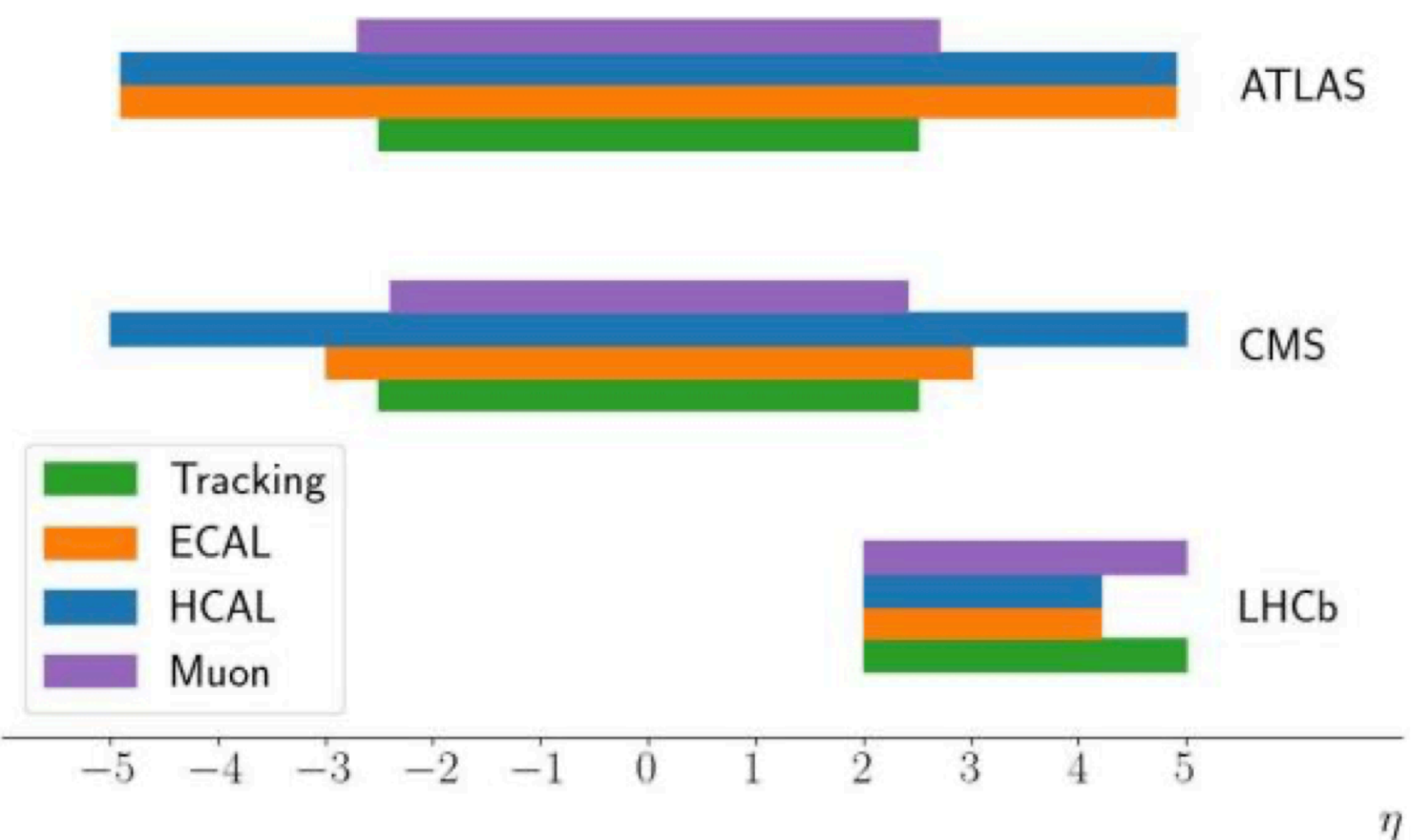
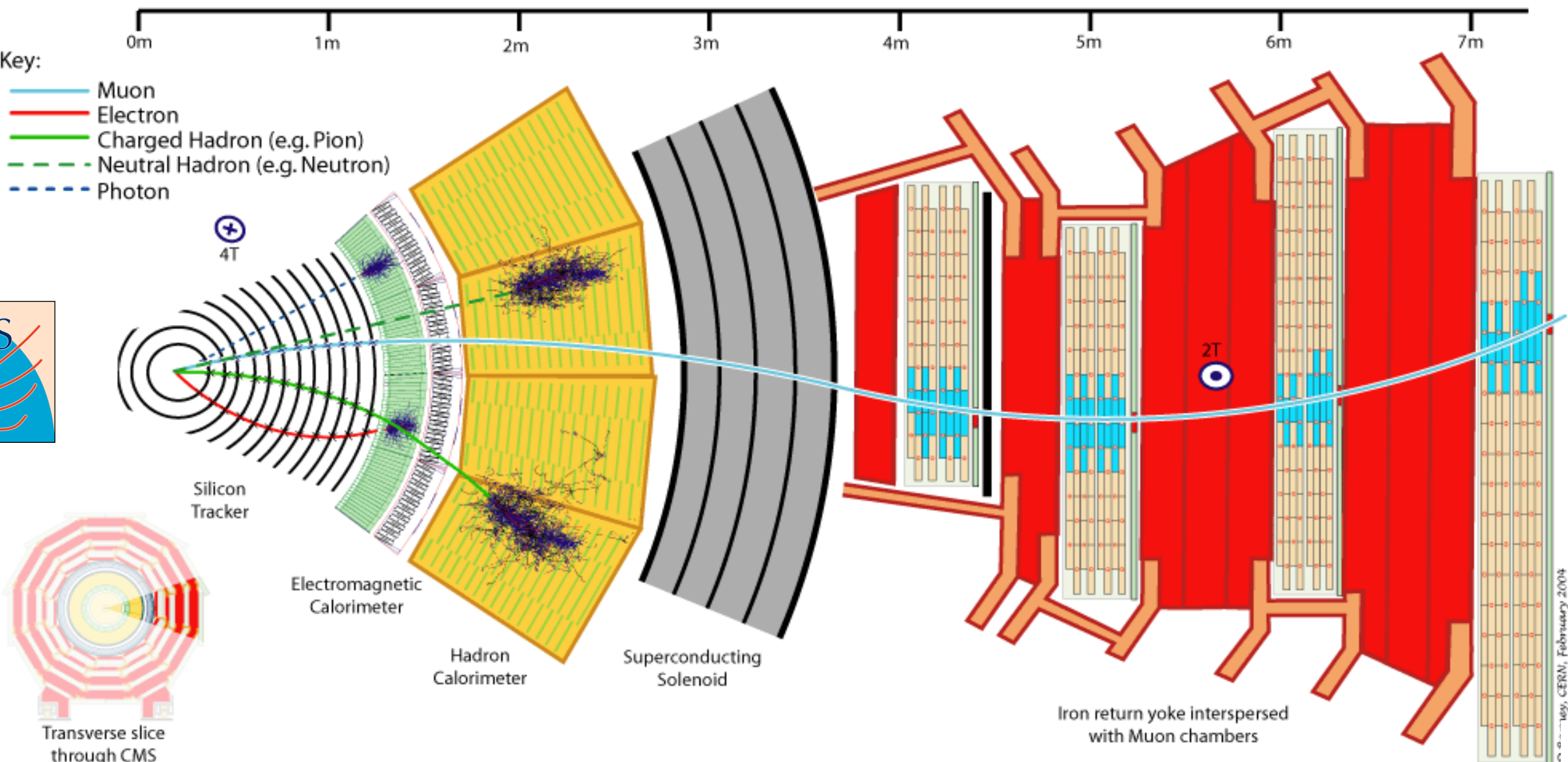
$$\sigma = \frac{N - N_{\text{bkg}}}{\int \mathcal{L} dt \cdot A \cdot \epsilon}$$

Luminosity  
(controlled by LHC)
Fraction of events  
within detector  
Reconstruction  
efficiency

- Interactions driven by quantum mechanics
  - Many, many things can happen when protons interact
  - Impossible to predict which one, exactly, will happen in one collision
  - Measure rate of occurrence over many collisions
- The LHC collides protons again and again and again
  - Look for more or more rare process, or make better measurements of more common process



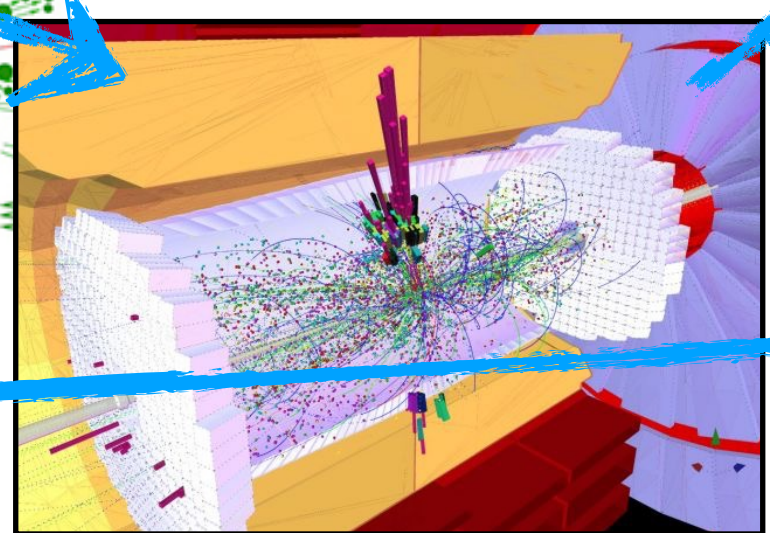
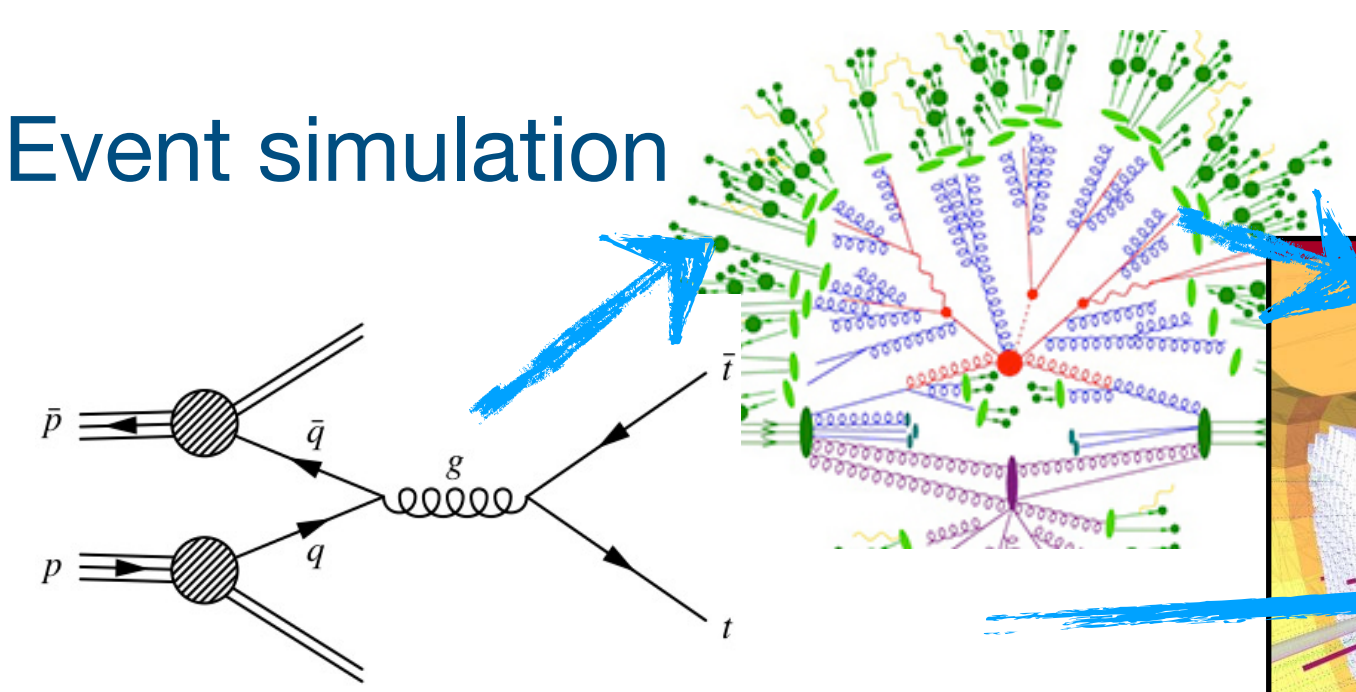
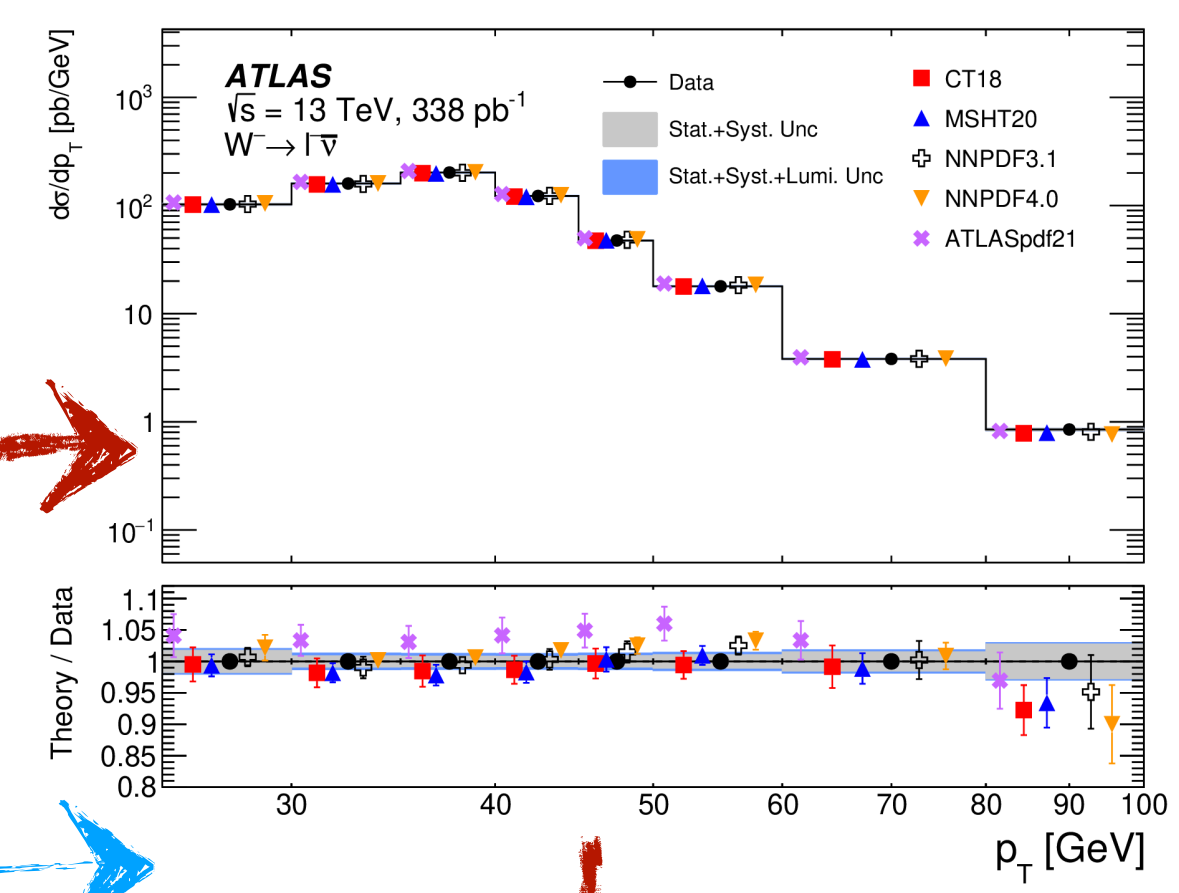
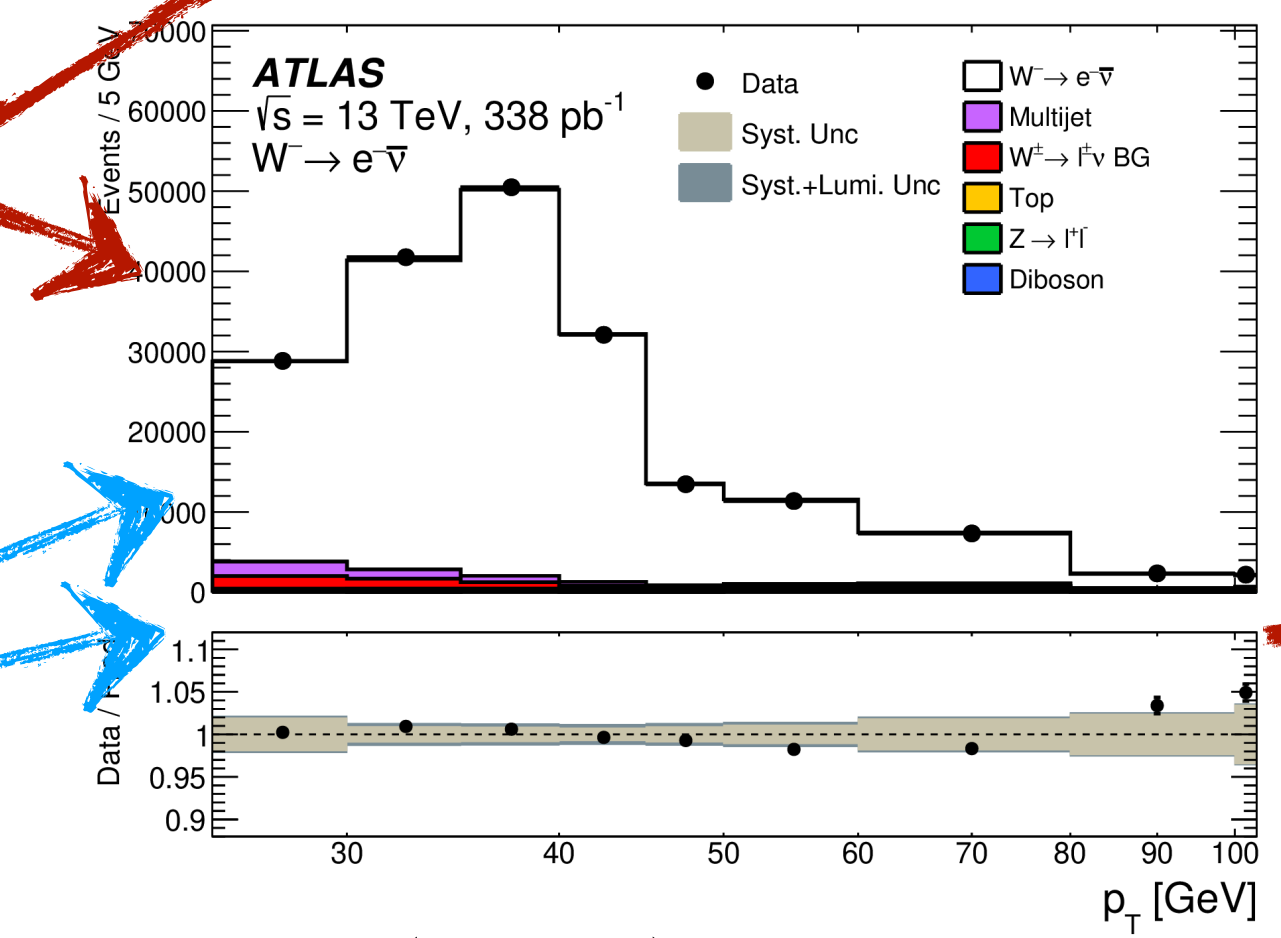
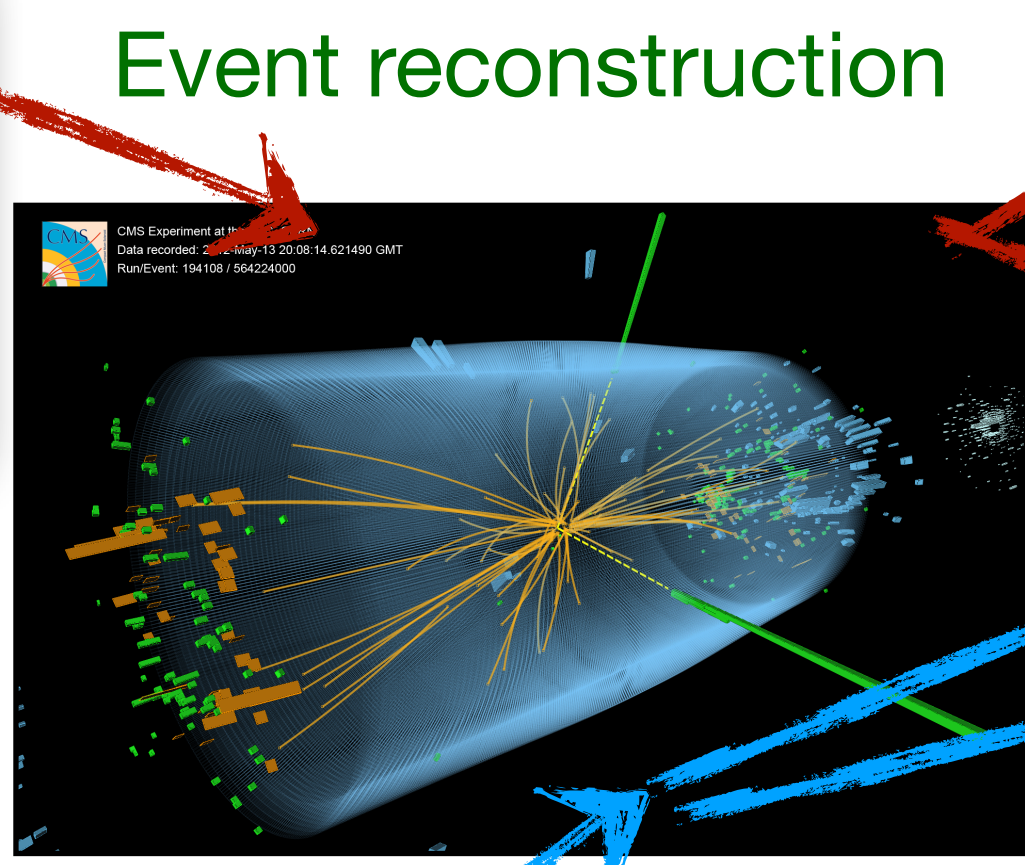
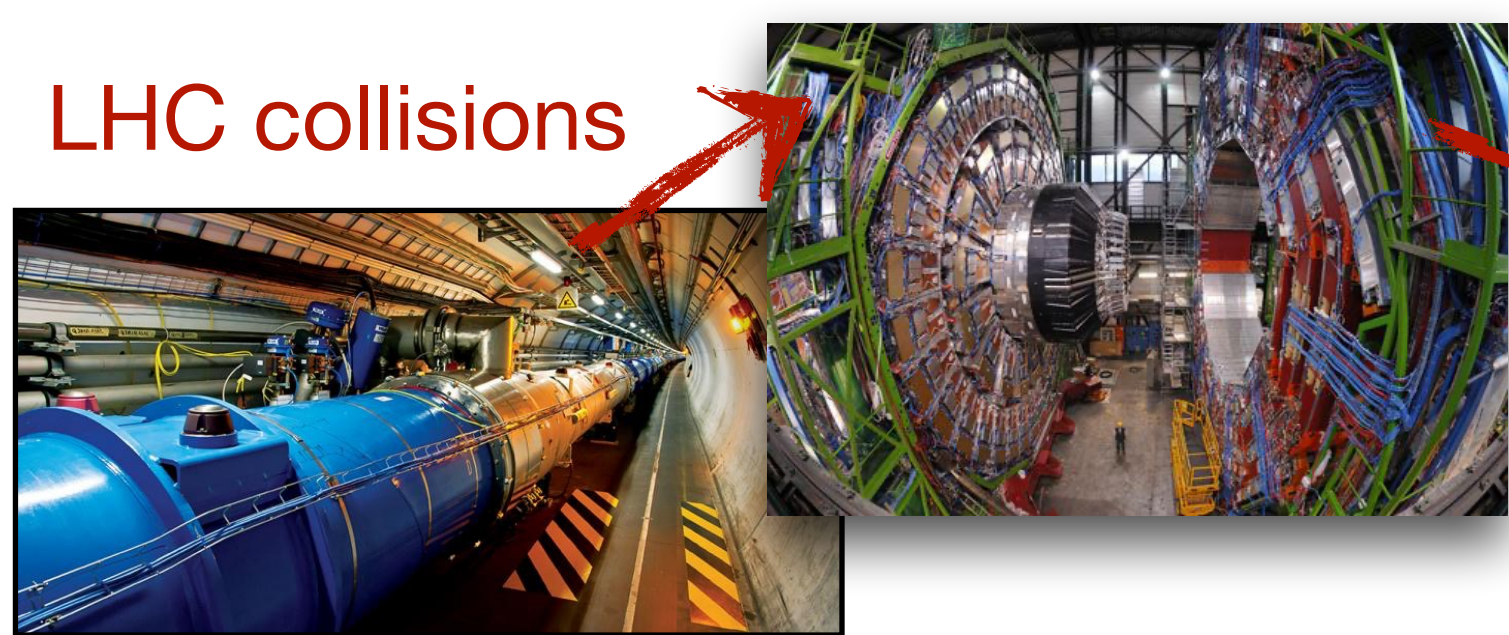
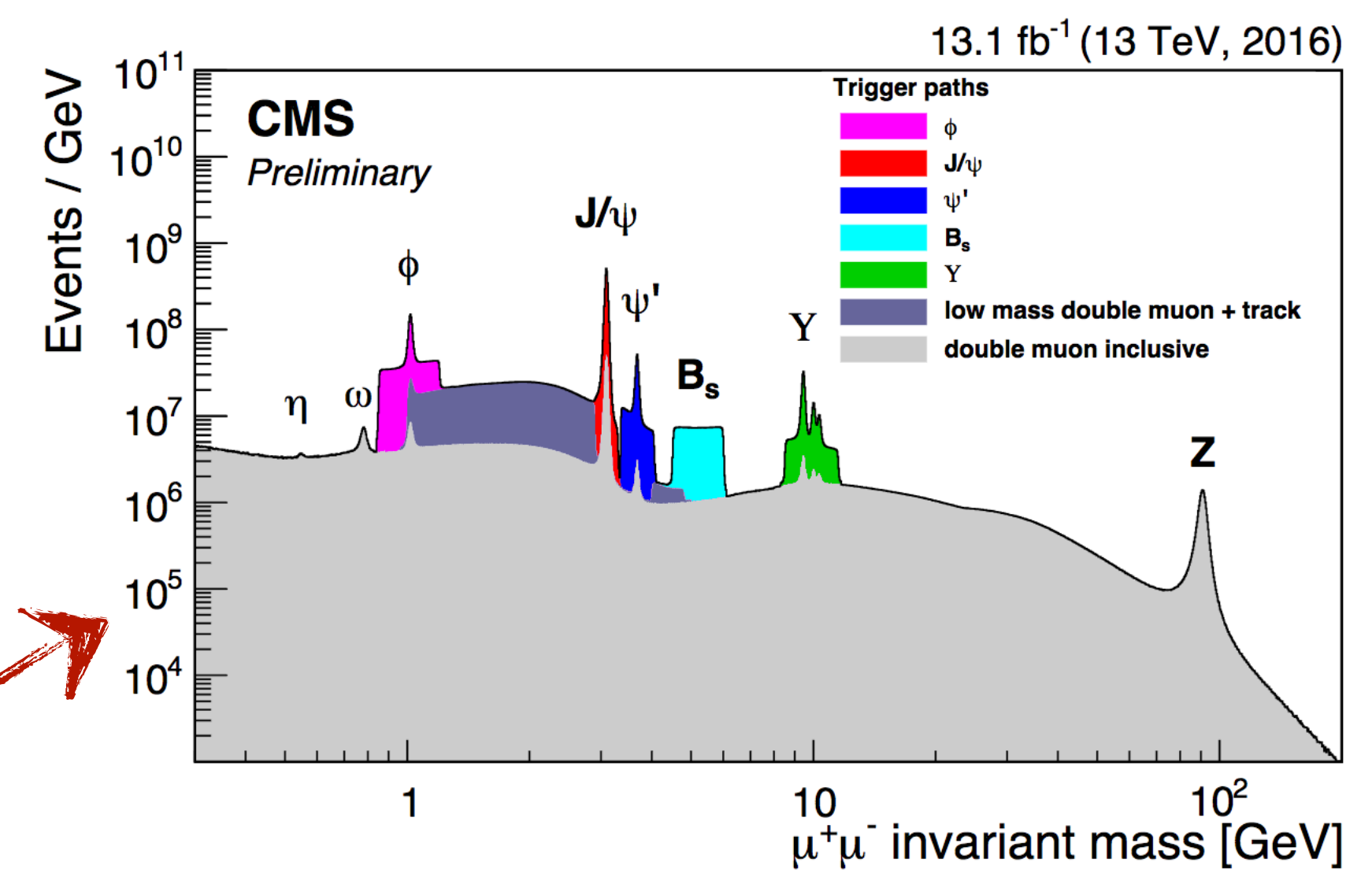
# LHC experiments for electroweak measurements





# Every LHC measurement is a test of the standard model

- Relationship between experimental and theoretical collider physics is multifaceted
  - Completely **theory independent** measurements
    - Theory guides interpretation
  - Minimally **theory dependent**: e.g., estimation of backgrounds
  - Theory-dependent conversion/extrapolation of from direct observation to indirect observable



Eur. Phys. J. C 85 (2025) 729

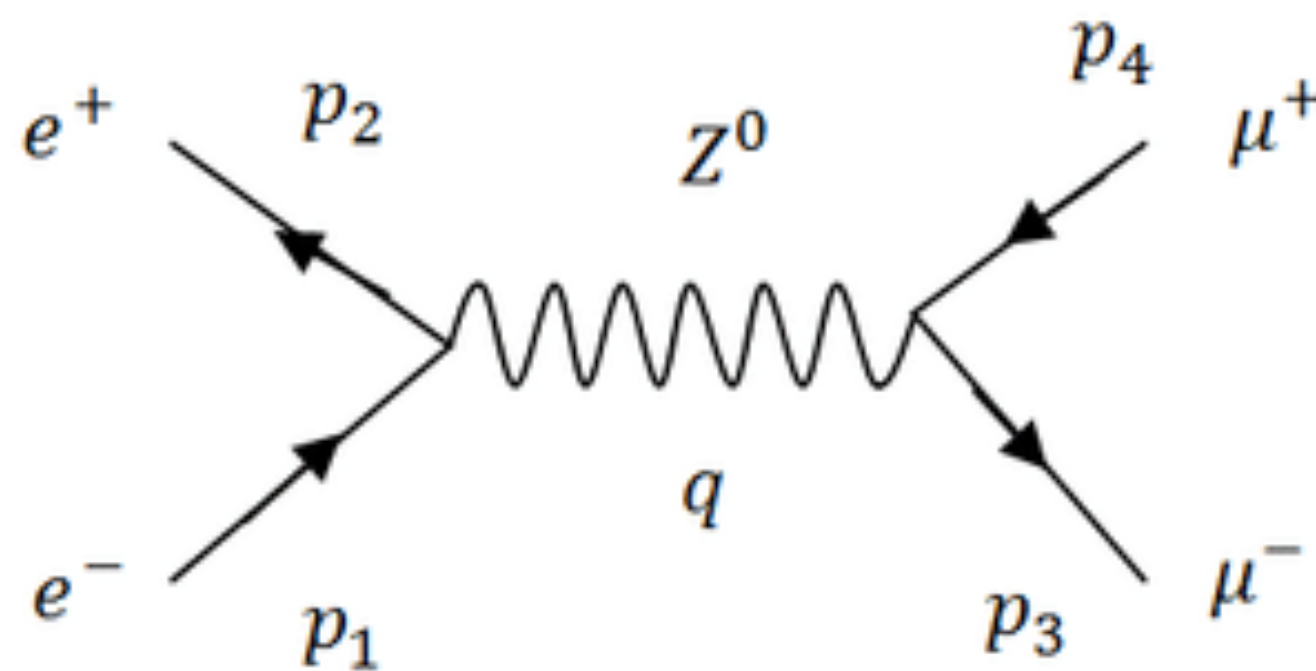
Property measurements, e.g.,  $m_W$



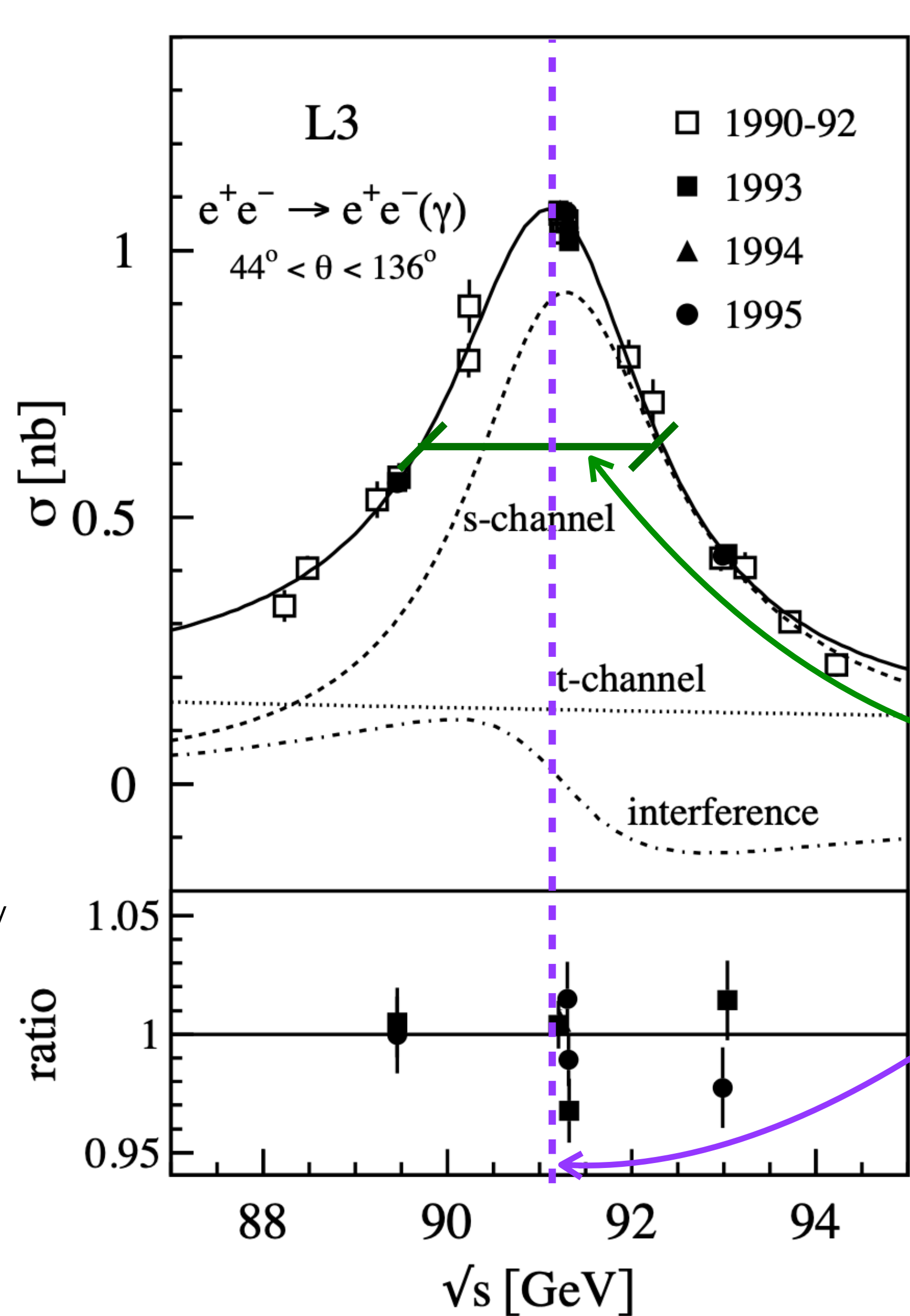
# Measuring properties of a heavy unstable particles

- Heavy particles like the W and Z boson are very short lived

Half-life ( $\tau$ ) =  $1/\Gamma \sim 10^{-25}$  s



- Measuring their properties (e.g., mass) means measuring their decay products
  - **Electrons and muons** most easily detected/measured
- Look for a “resonance” vs. energy



Energy of collision  
or total energy of  
decay products

$$\sigma_S^{\text{rBW}}(E) = \frac{2E}{\pi} \frac{M\Gamma}{(E^2 - M^2)^2 + (M\Gamma)^2} \theta(E)$$

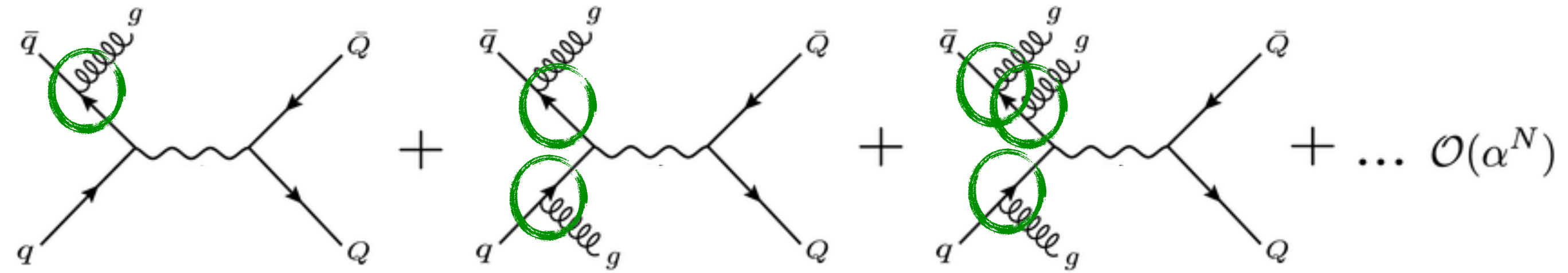
“Width” of resonance  
 $\Gamma_Z = 2.496$  MeV

Mass of the resonance  
 $m_Z = 91\,188$  MeV

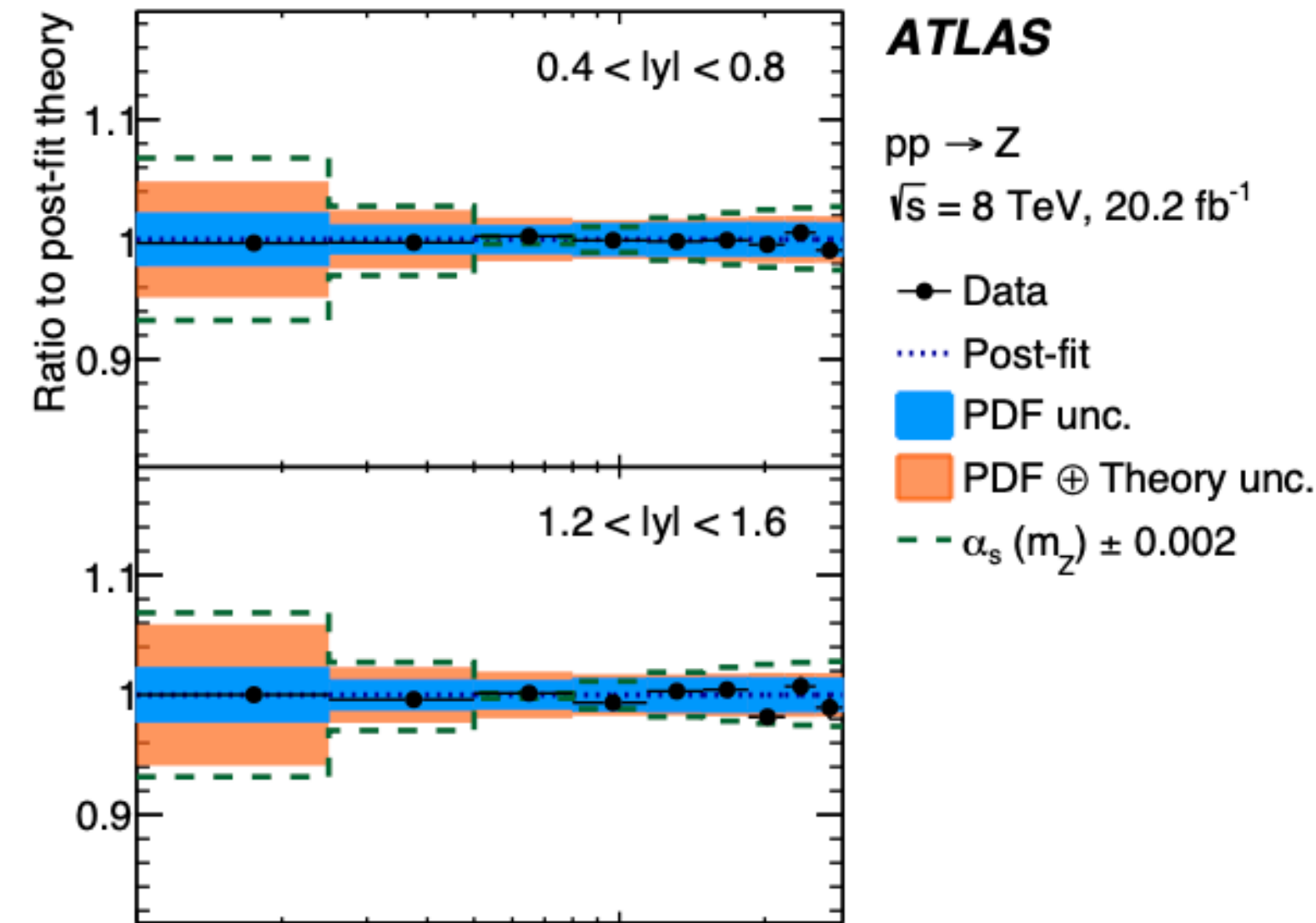
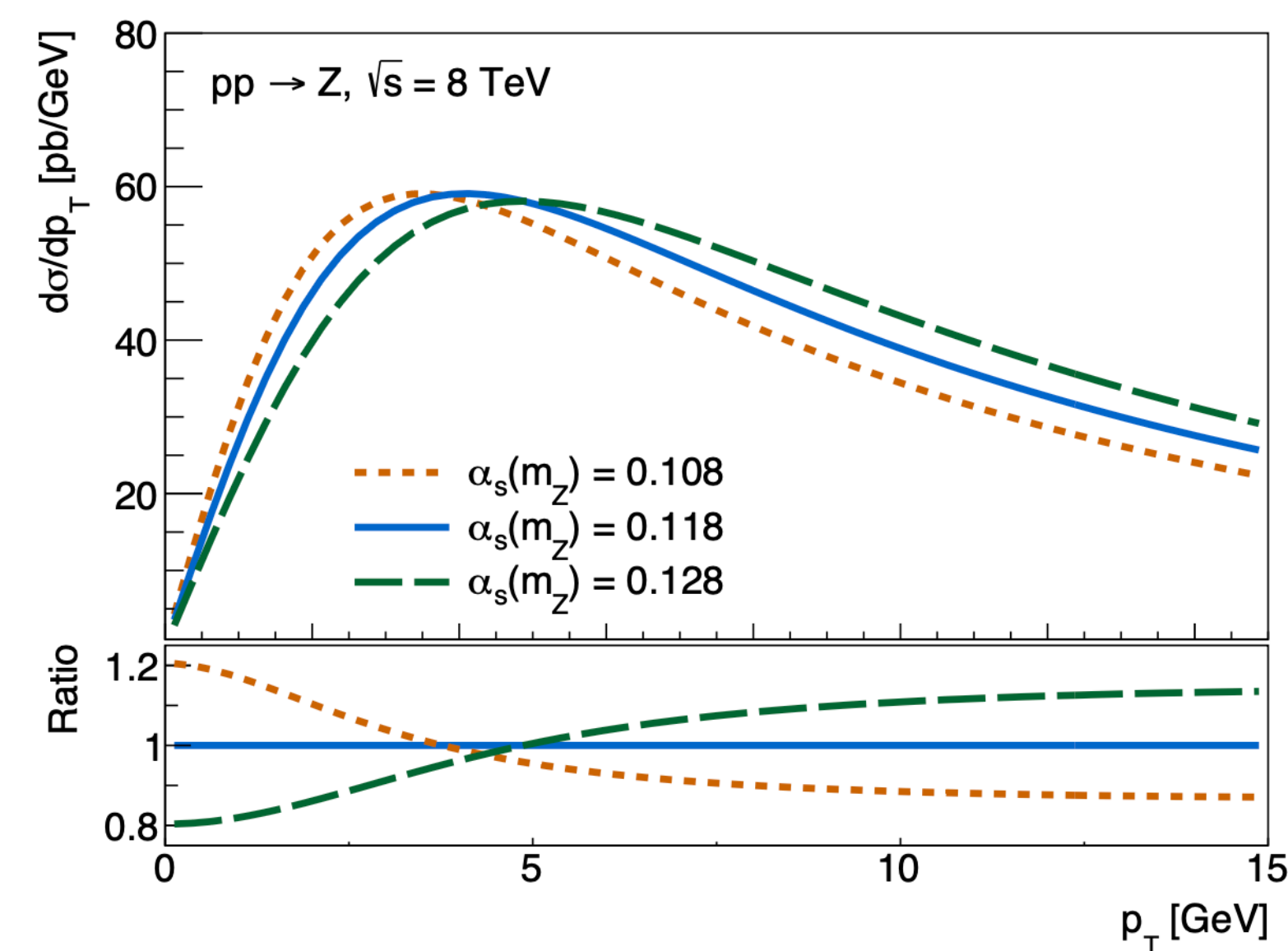


# Measurement of the strong coupling constant with Z bosons

- $p_T^Z$  naturally sensitive to  $\alpha_s$ 
    - Very well measured!
    - ... but theoretically challenging
  - ATLAS measurement has world-best precision
    - Theoretical unc. has been hotly debated
- ➡ At the state-of-the-art of theory and experiment

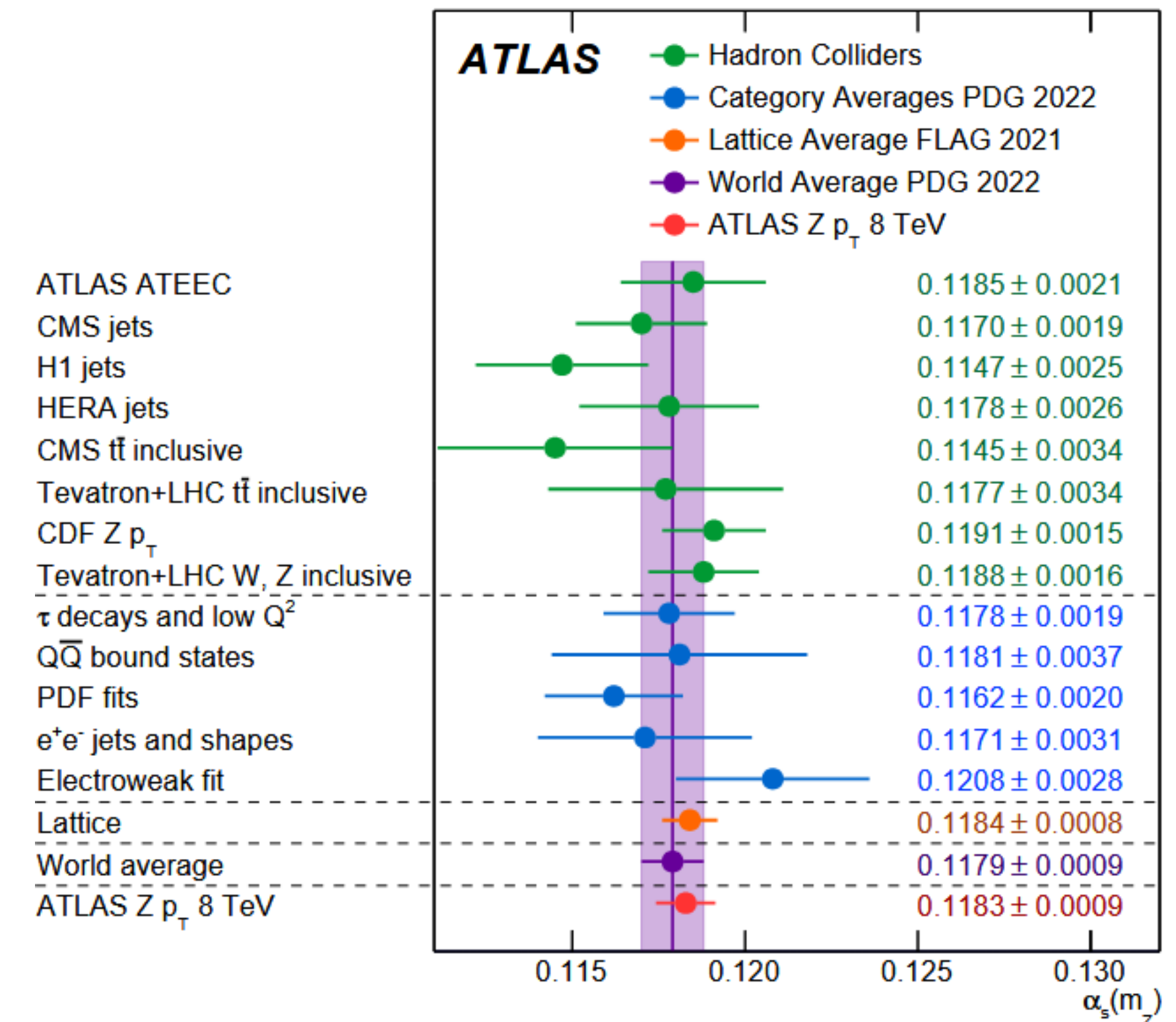


Additional  $\alpha_s$  from  
higher-order vertices



[arxiv:2309.12986](https://arxiv.org/abs/2309.12986)

Submitted to *Nature Physics*



# Muon momentum calibration: CMS and ATLAS procedure

★ Calibrate in data using a known reference: J/ψ

- Mass known precisely

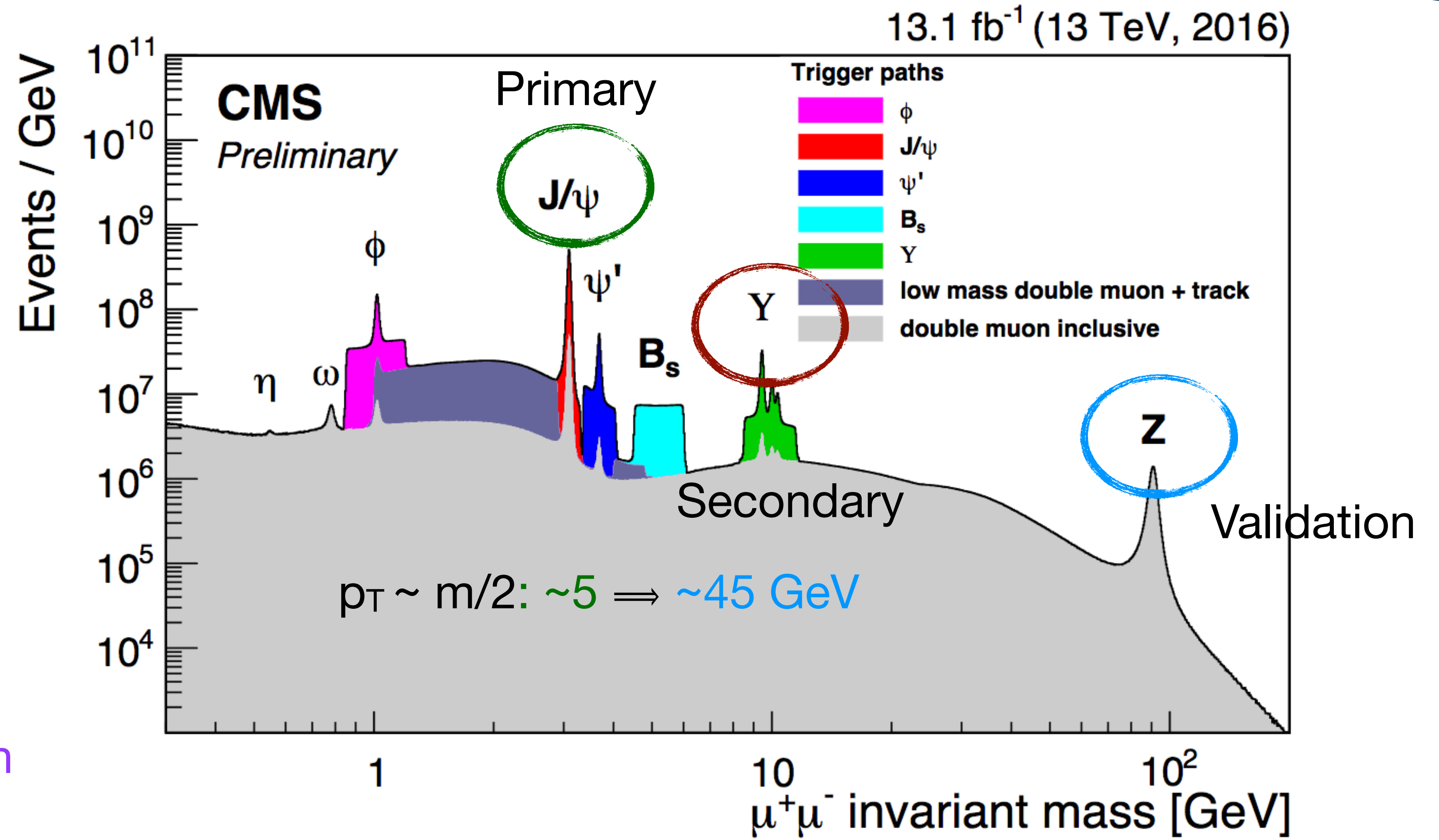
➔ Requires robust extrapolation across momentum scales

$$k_{corr} = Ak + qM + \frac{k}{1 + ek}$$

$$\delta k/k \approx \underline{A} + q\underline{M}/k - \underline{ek}$$

Parameterize by small differences in

- B-field
- Alignment
- Energy loss (material)



ATLAS: corrections derived from the Z boson



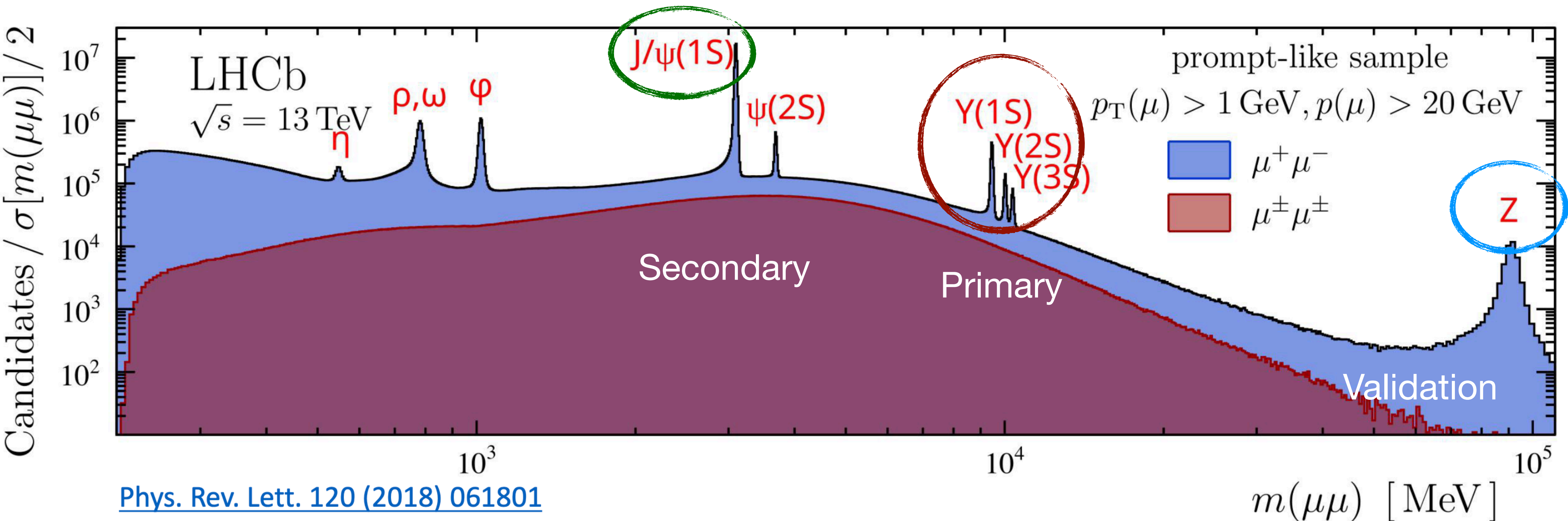
# Muon momentum calibration: LHCb procedure

- ★ Calibrate in data using a known reference: J/ψ
  - Mass known precisely
- ➔ Requires robust extrapolation across momentum scales

Scale terms

Resolution terms

$$p^\pm \rightarrow \left( 1 + \underbrace{\alpha}_{\sim A} + \underbrace{\frac{\beta}{p^\pm}}_{\sim M} \mp \underbrace{\delta p^\pm}_{\sim e} \right) (1 + a \mathcal{R}_1 \sigma_1) (1 + b \mathcal{R}_2 \sigma_2 p^\pm) p^\pm$$



[Phys. Rev. Lett. 120 \(2018\) 061801](#)



# Calibration parameters

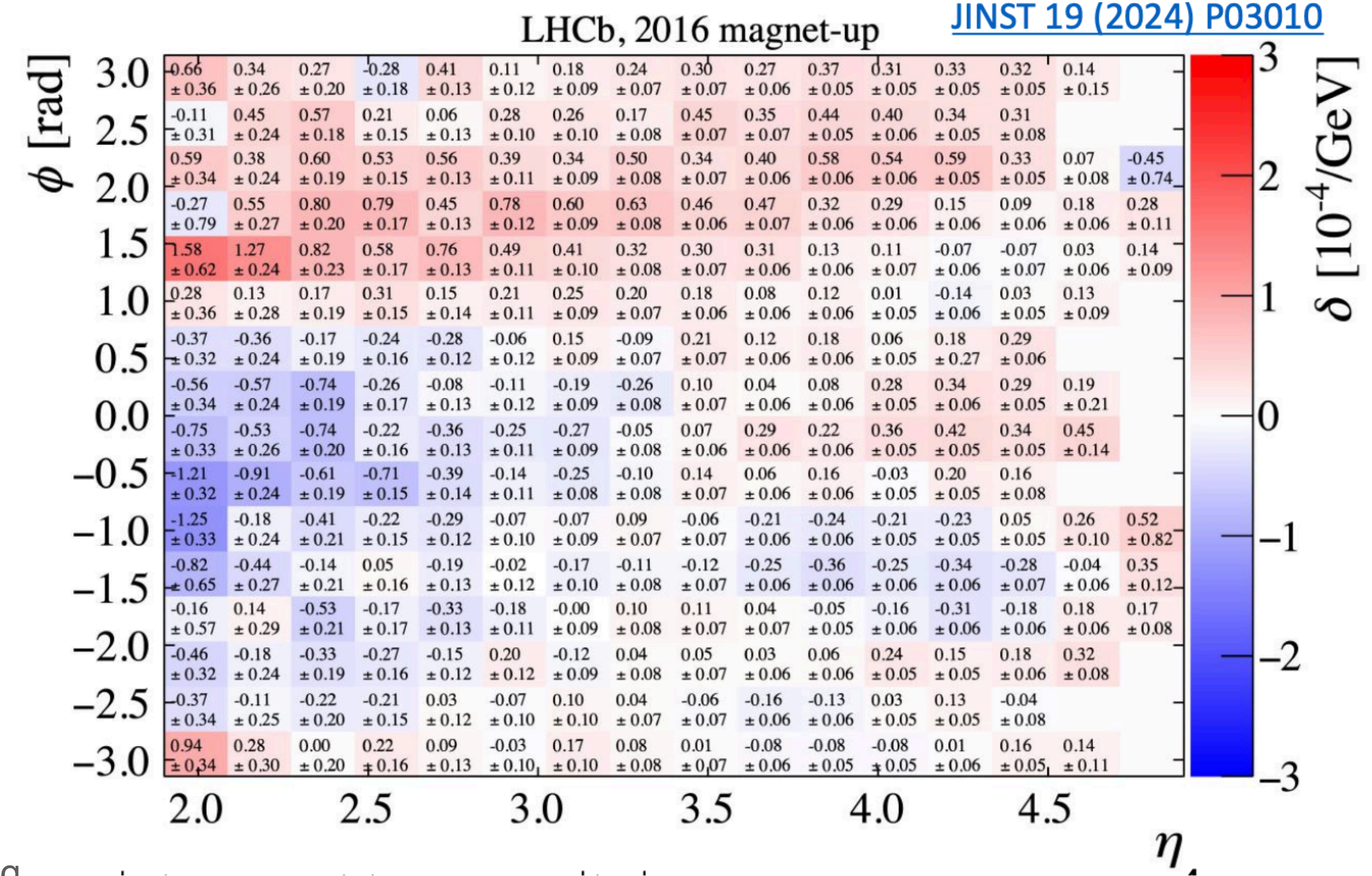
Parameterized corrections derived from known resonances

- **CMS:**  $\chi^2$  minimization to extract  $\eta$ -binned per-muon parameters
- **LHCb:** 2D binned corrections to alignment with “pseudomass”

$$M^\pm = \sqrt{2p^\pm p_T^\pm \frac{p^\mp}{p_T^\mp} (1 - \cos \theta)}$$

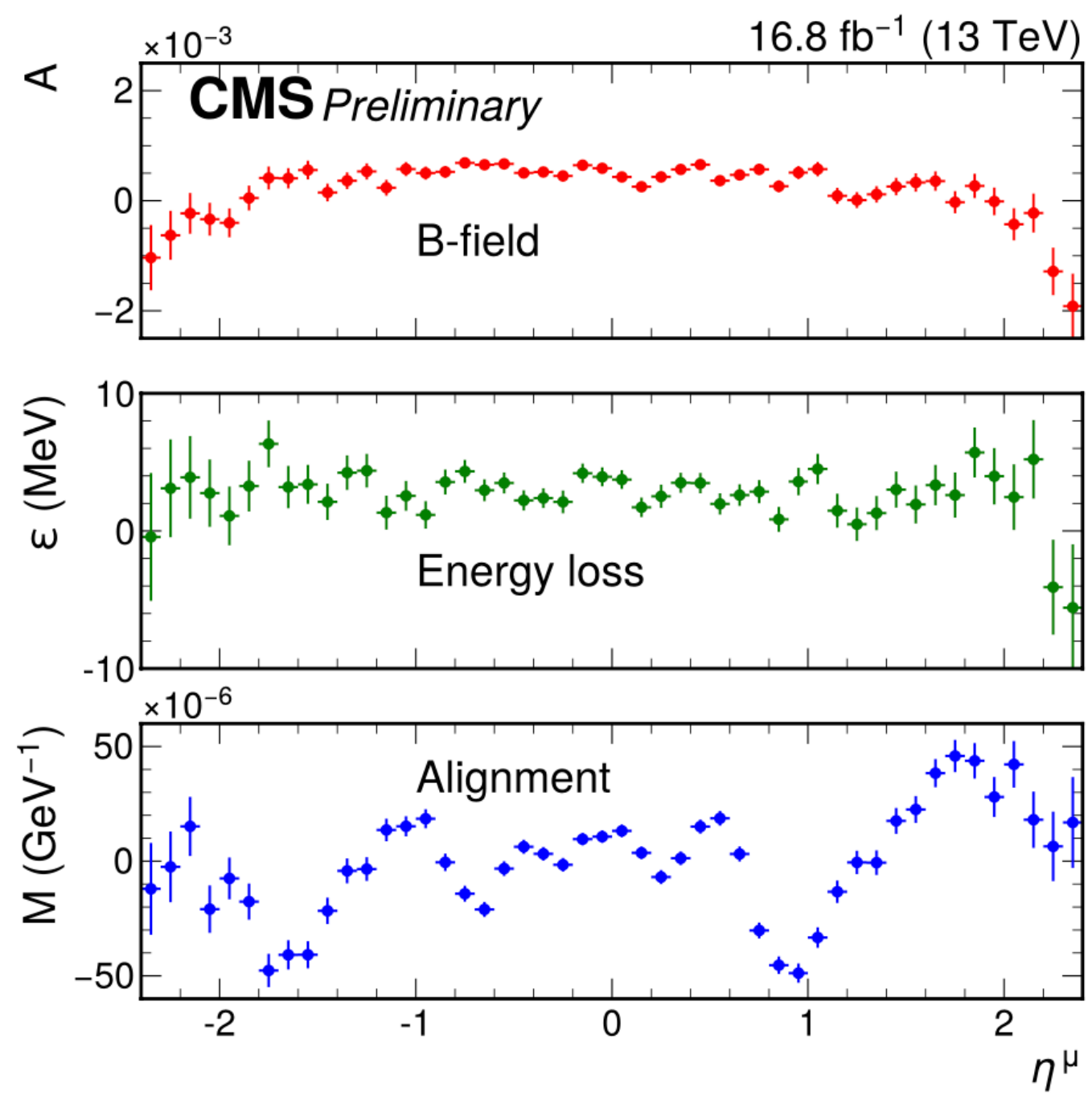
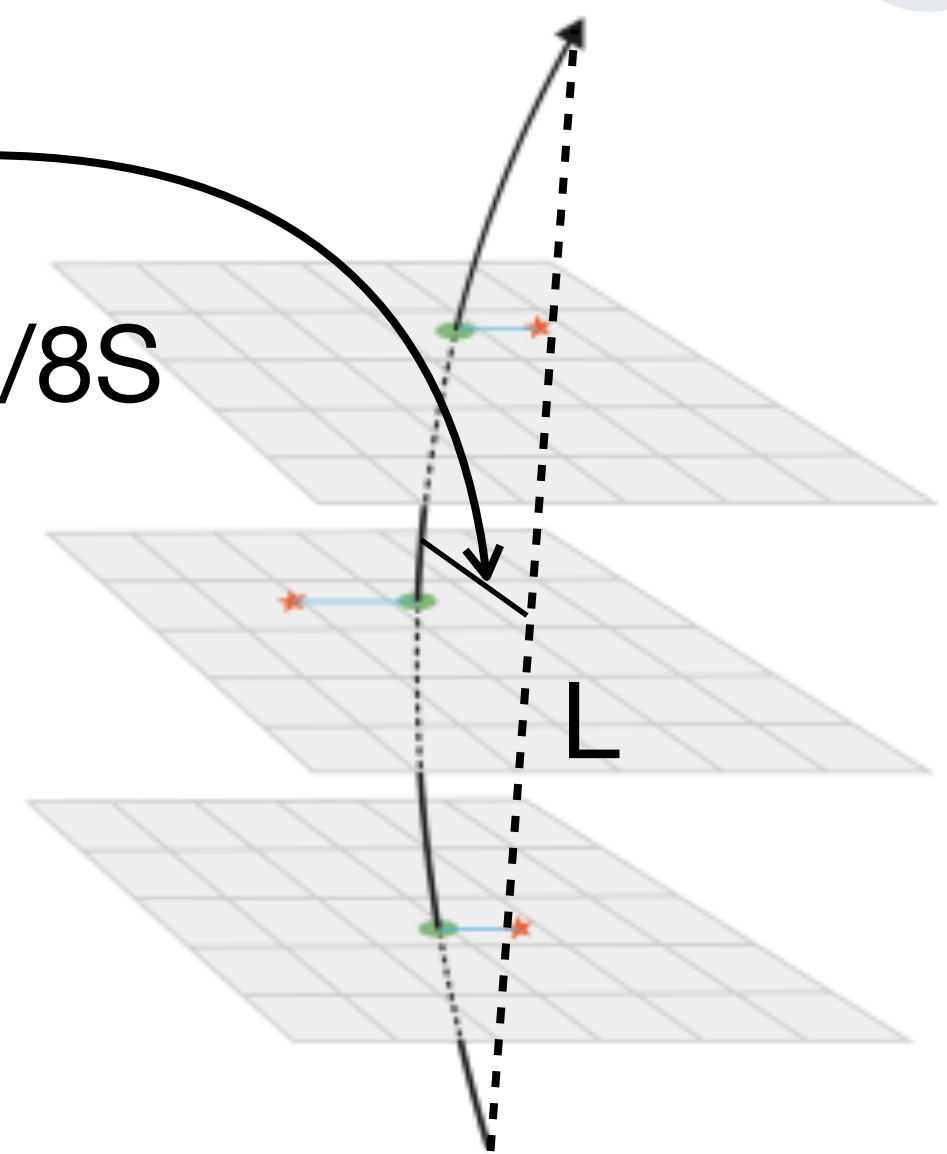
[PRD 91 \(2015\) 072002](#)

[JINST 19 \(2024\) P03010](#)



Sagitta (S)  $\leftarrow$

$p_T = qBR = qBL^2/8S$



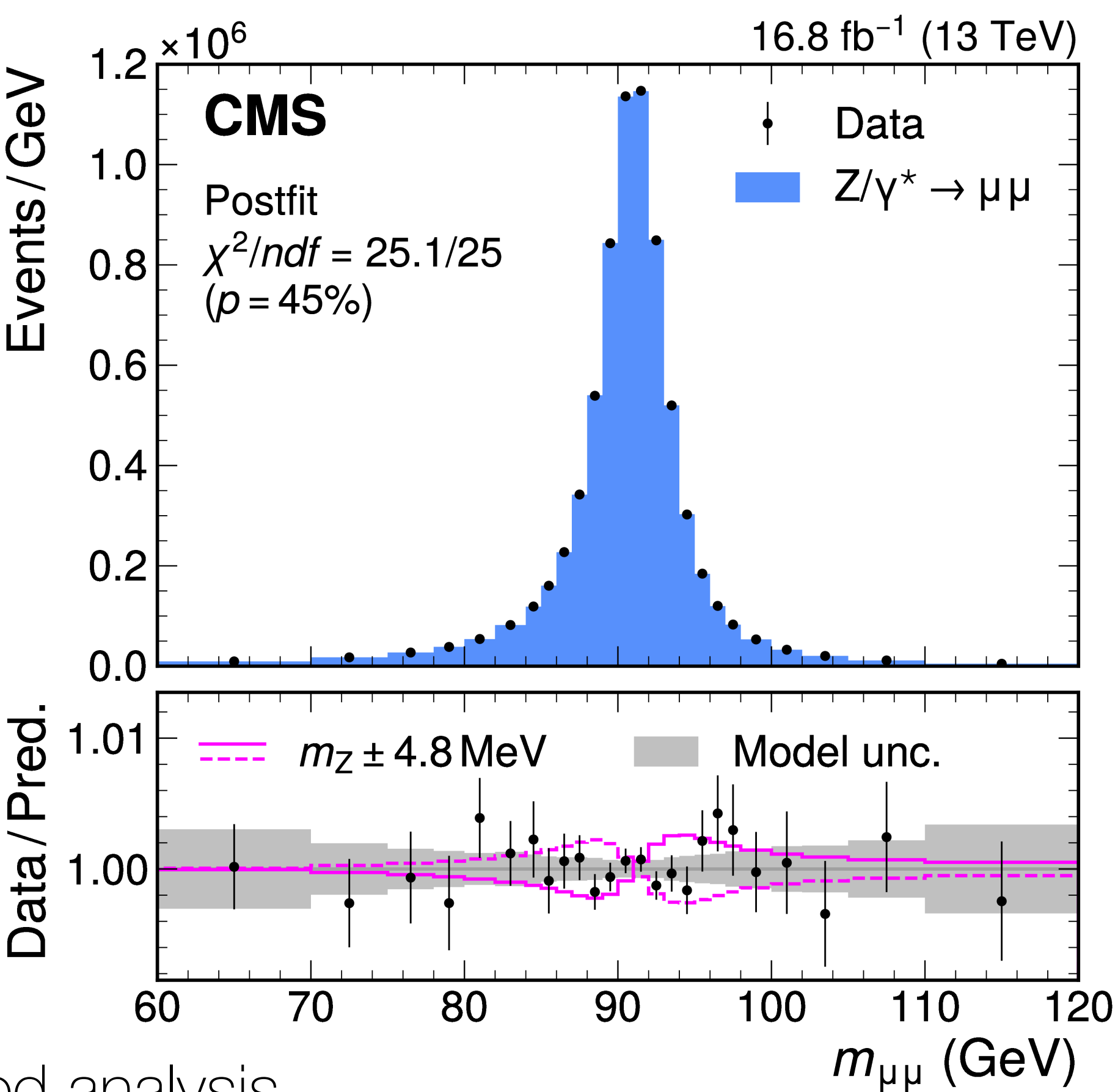
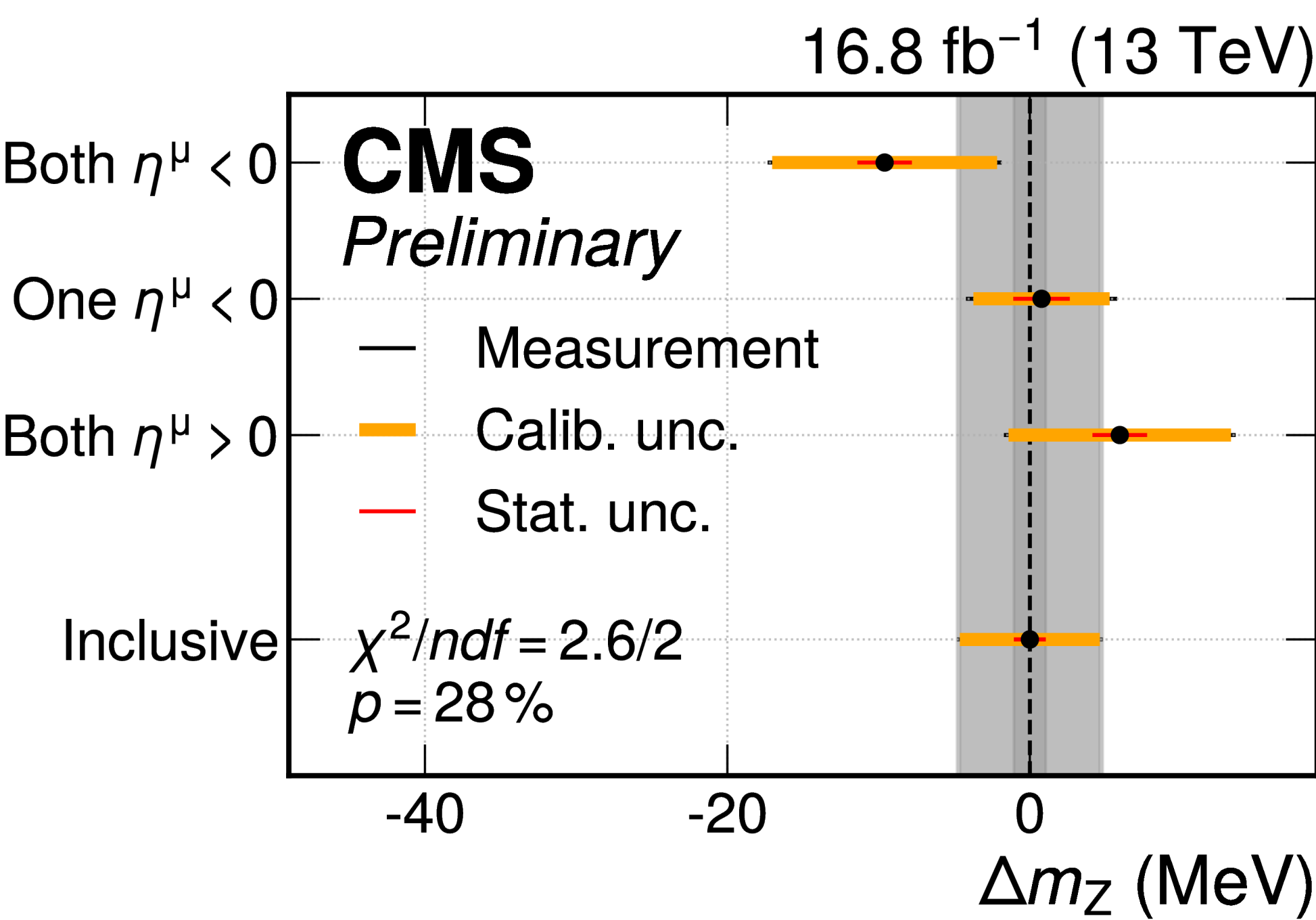


# CMS “results” and prospects

- Extract  $m_Z$  from binned likelihood fit to  $m_{\mu\mu}$  in bins of signed  $\eta^\mu$  of most forward muon
  - Intended to validate experimental input to  $m_W$

$$m_Z - m_Z^{\text{PDG}} = -2.2 \pm 4.8 \text{ MeV} = -2.2 \pm 1.0 \text{ (stat)} \pm 4.7 \text{ (syst) MeV}$$

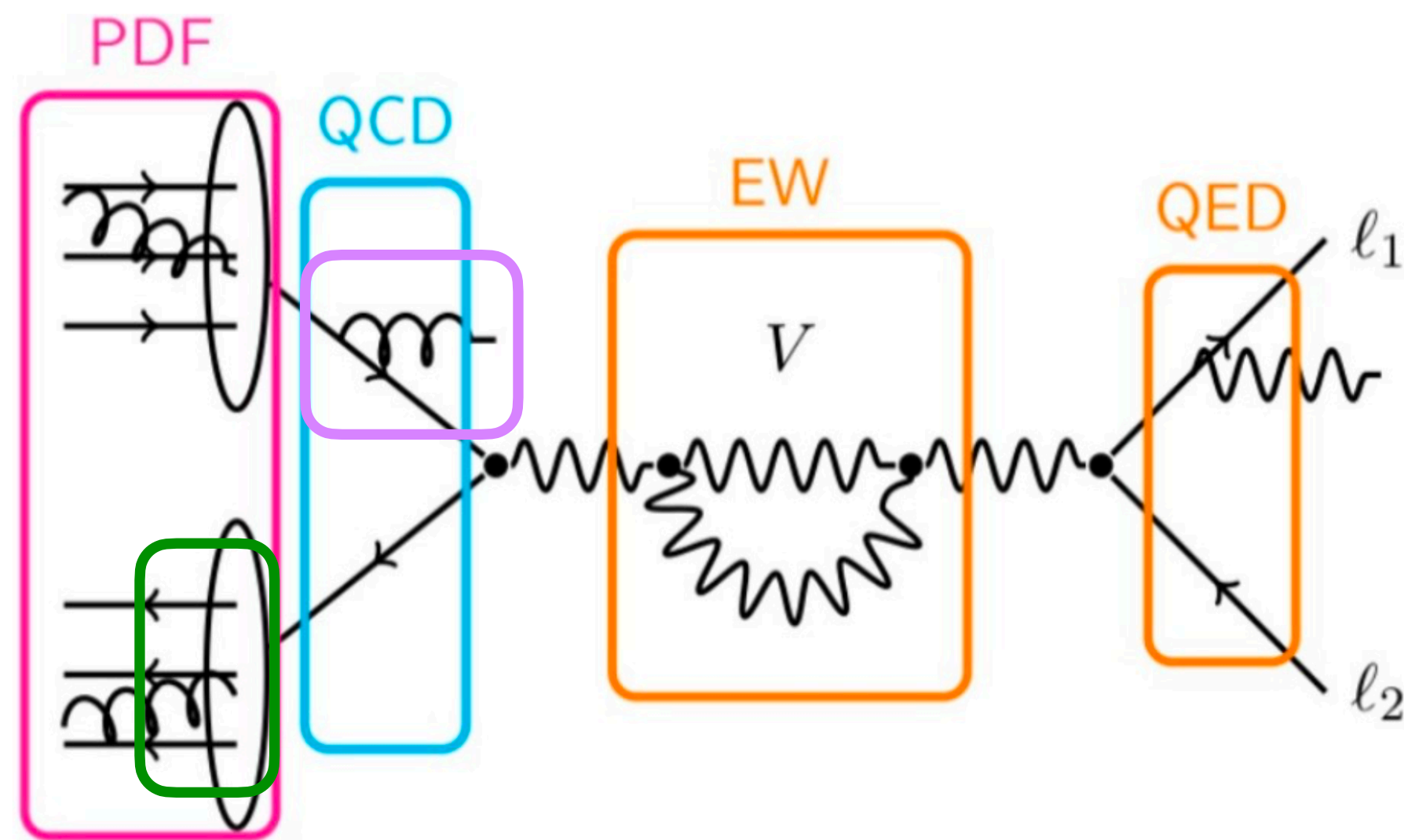
- Not (yet) an independent measurement of  $m_Z$
- Stability of result (calibration) validated across  $\eta^\mu$



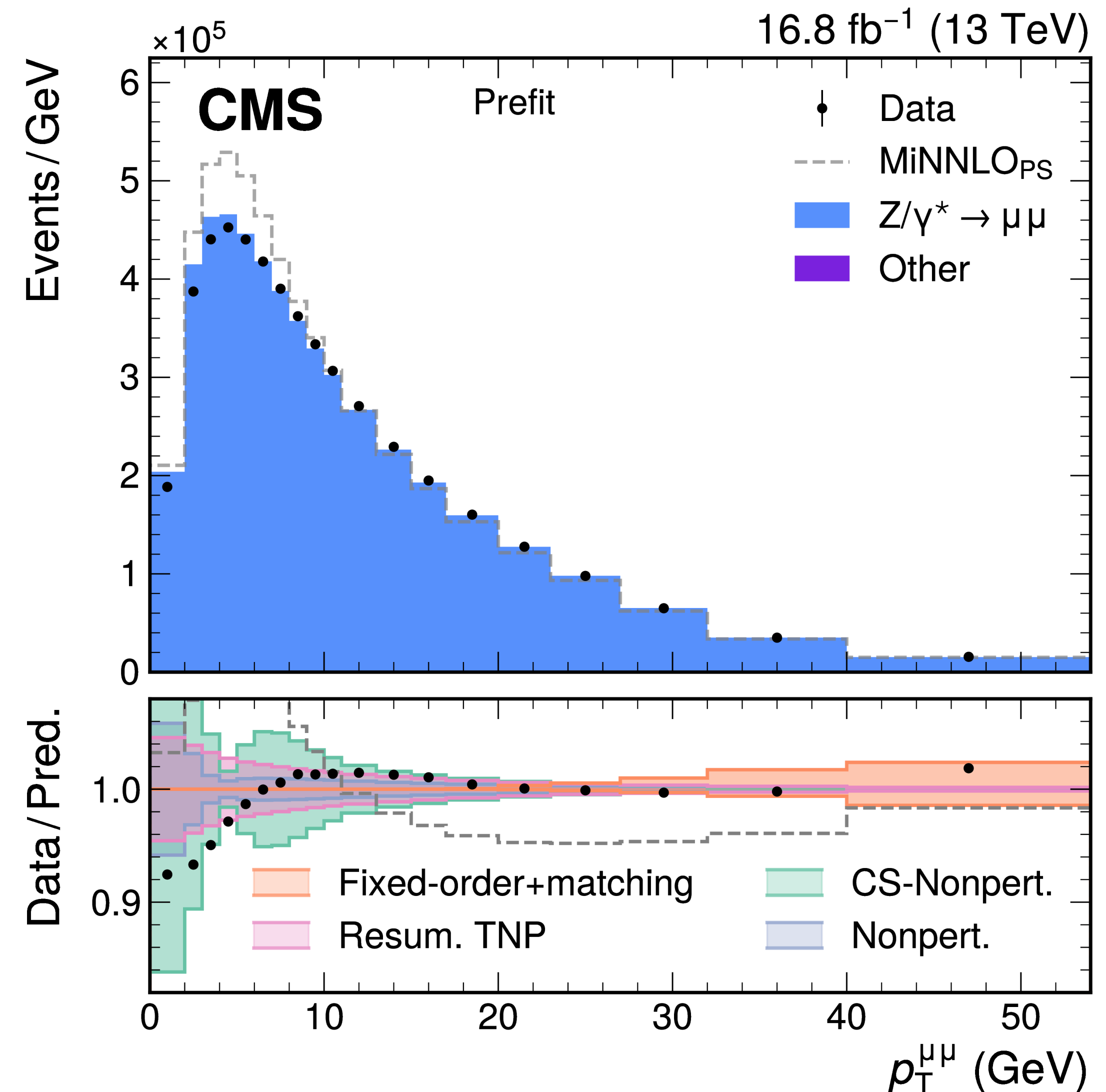
- Improve resolution calibration,  $\Upsilon$ -based calibration, perform blinded analysis

# Theoretical description of W and Z boson production at the LHC

- Measurement requires percent-level control of predictions
- Predictions for W and Z production combine complex calculations with many sources of uncertainty



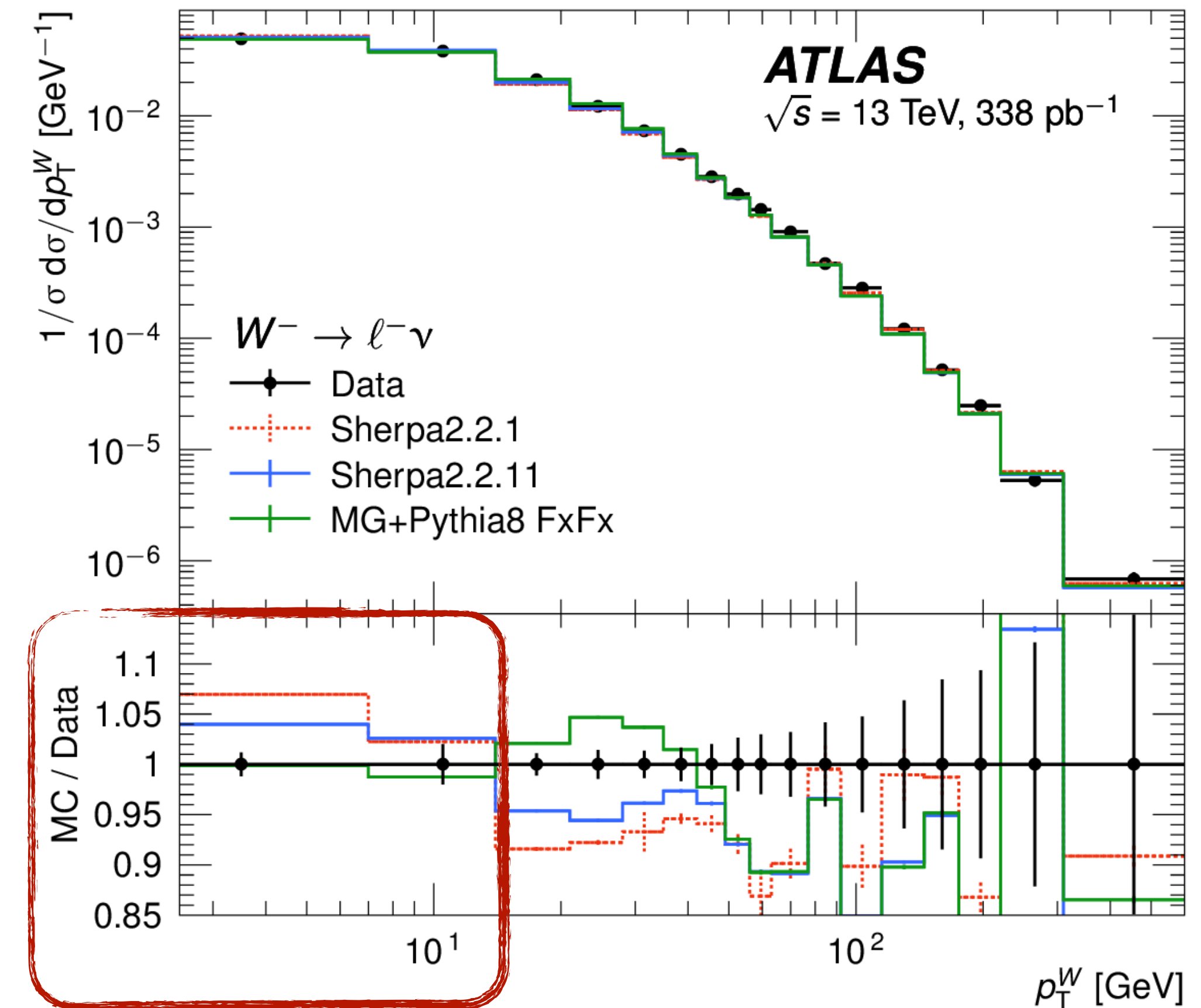
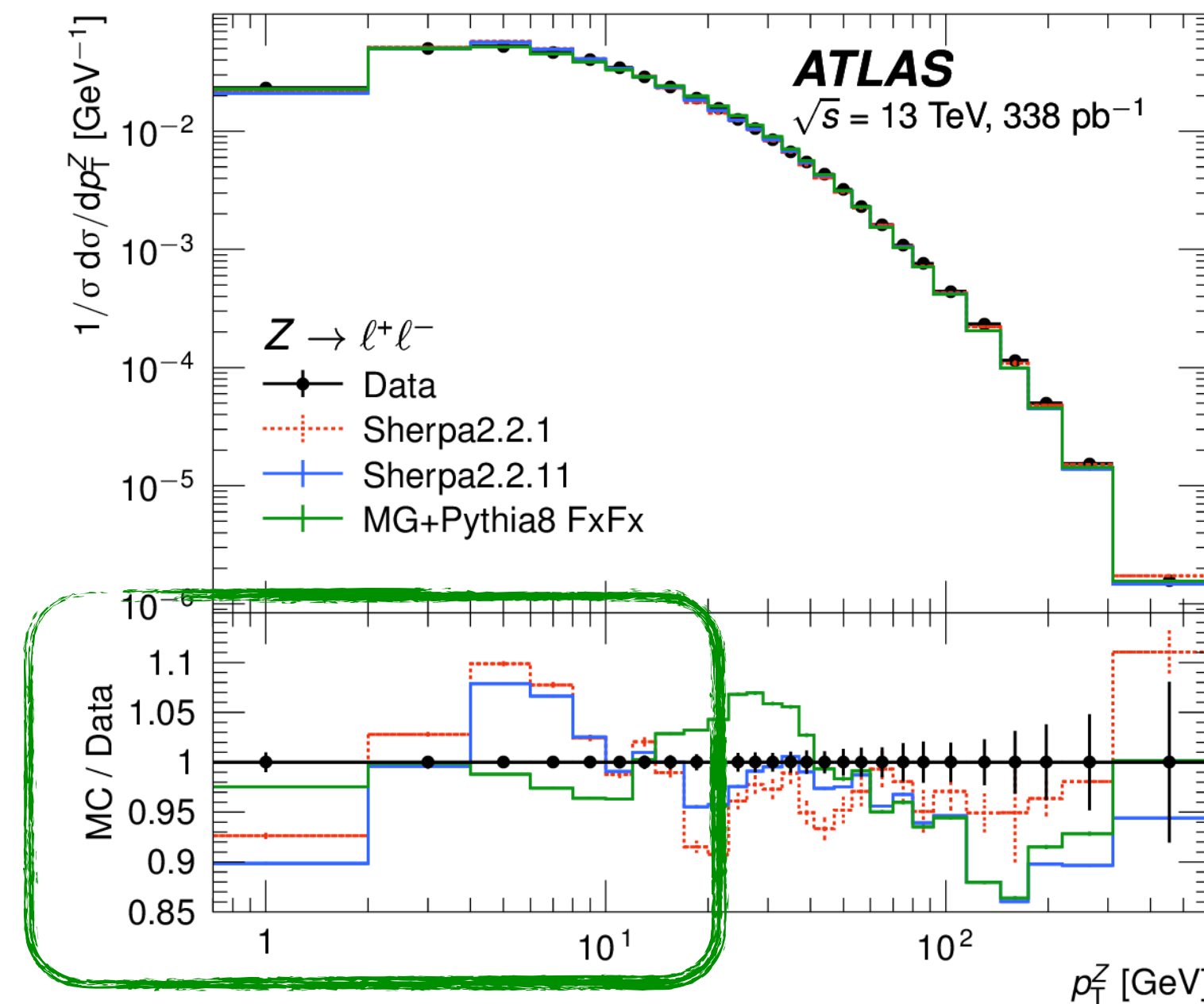
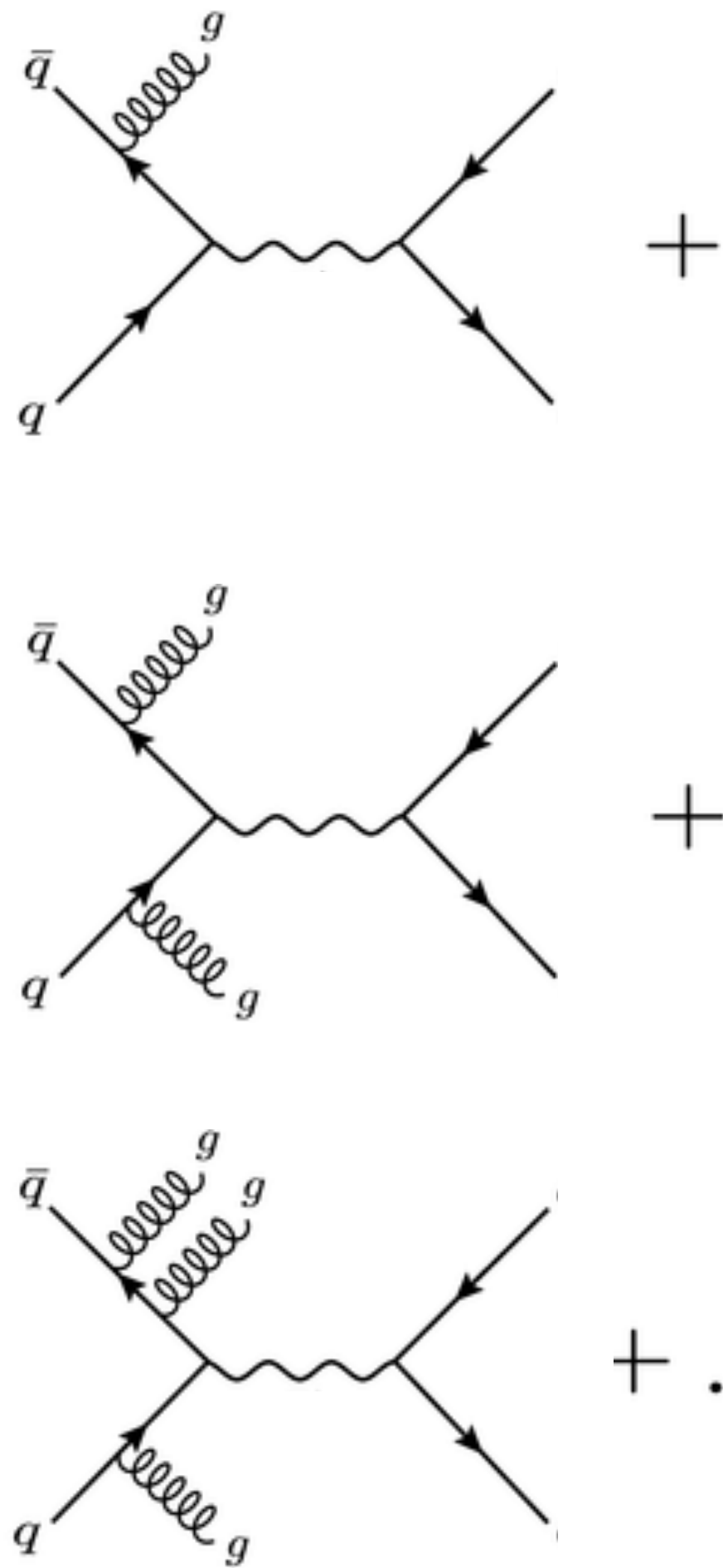
- PDF determines quark flavour and momentum
  - Non-perturbative motion of quarks important at low  $p_T^V$
- Resum soft gluons for low/intermediate region
- pQCD accurate at high  $p_T^V$
- Electroweak corrections small, but relevant





# W and Z boson production at the LHC

- $p_T^\ell$  is not Lorentz invariant  $\Rightarrow$  sensitive to W production
  - W typically produced with some momentum transverse to the beam direction ( $p_T^W$ )
  - $p_T^W$  not directly measurable w/high precision at LHC
    - $p_T^V$  due to radiation of gluons from colliding quarks
- Many similarities (but some important differences) between W and Z production

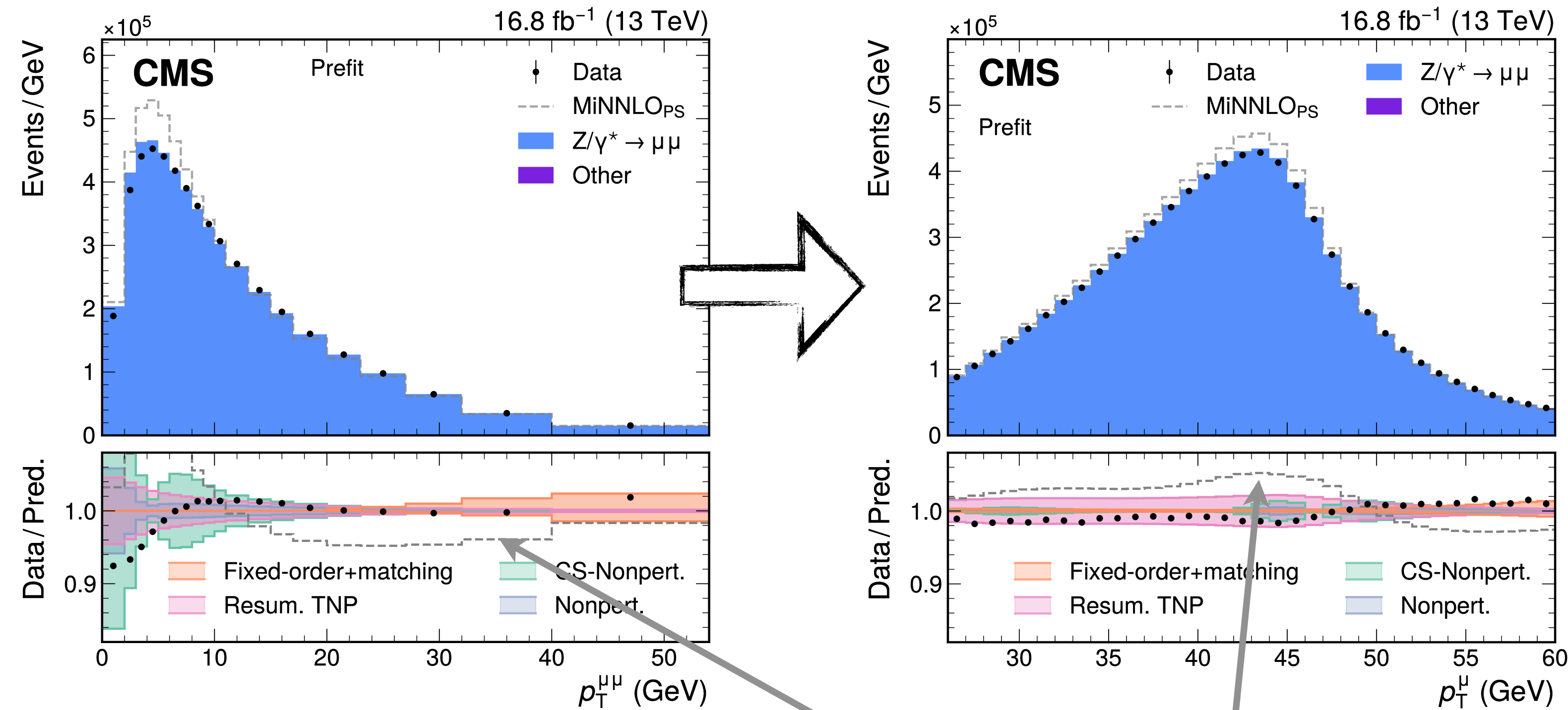


Precision, resolution of  $p_T^W$  not sufficient for  $m_W$  measurement

# W and Z boson production at the LHC

- $p_T^\ell$  is not Lorentz invariant  $\Rightarrow$  sensitive to W production
  - Motion transverse to the beam direction ( $p_T^W$ )
  - $p_T^W$  not directly measurable w/high precision at LHC
- ➔ Rely on theoretical predictions to describe  $p_T^W$ 
  - Validate with measurements of Z boson production

## Z production



Uncertainties, corrections can be much larger than  $m_W$  variation!

## W production

