LHC Physics - Electroweak & Top

Lydia Beresford

DESY Summer Student Lectures

04.08.25

Physics Goals of the LHC

wikimedia

Measure the Standard Model

Standard Model particles

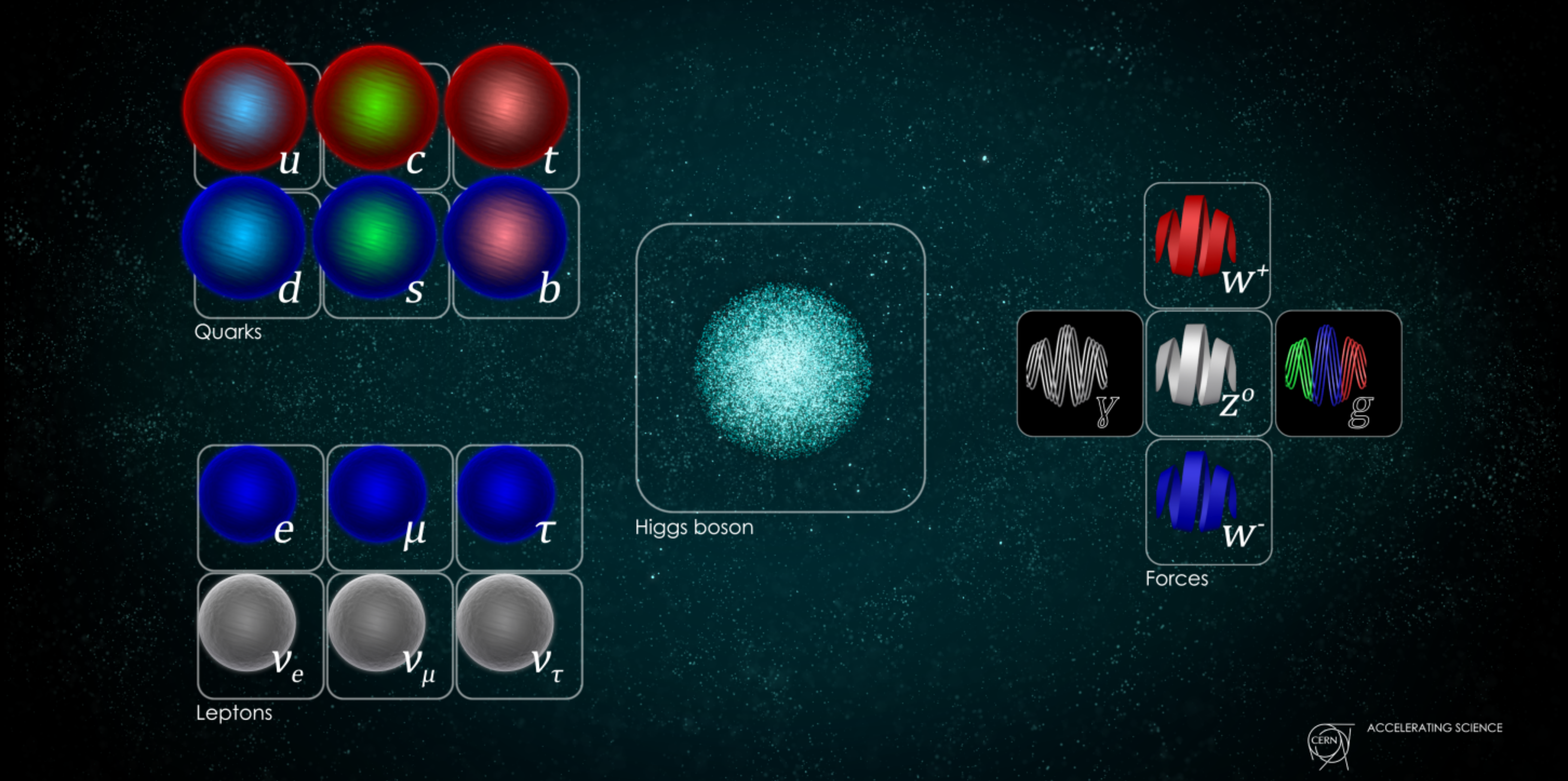
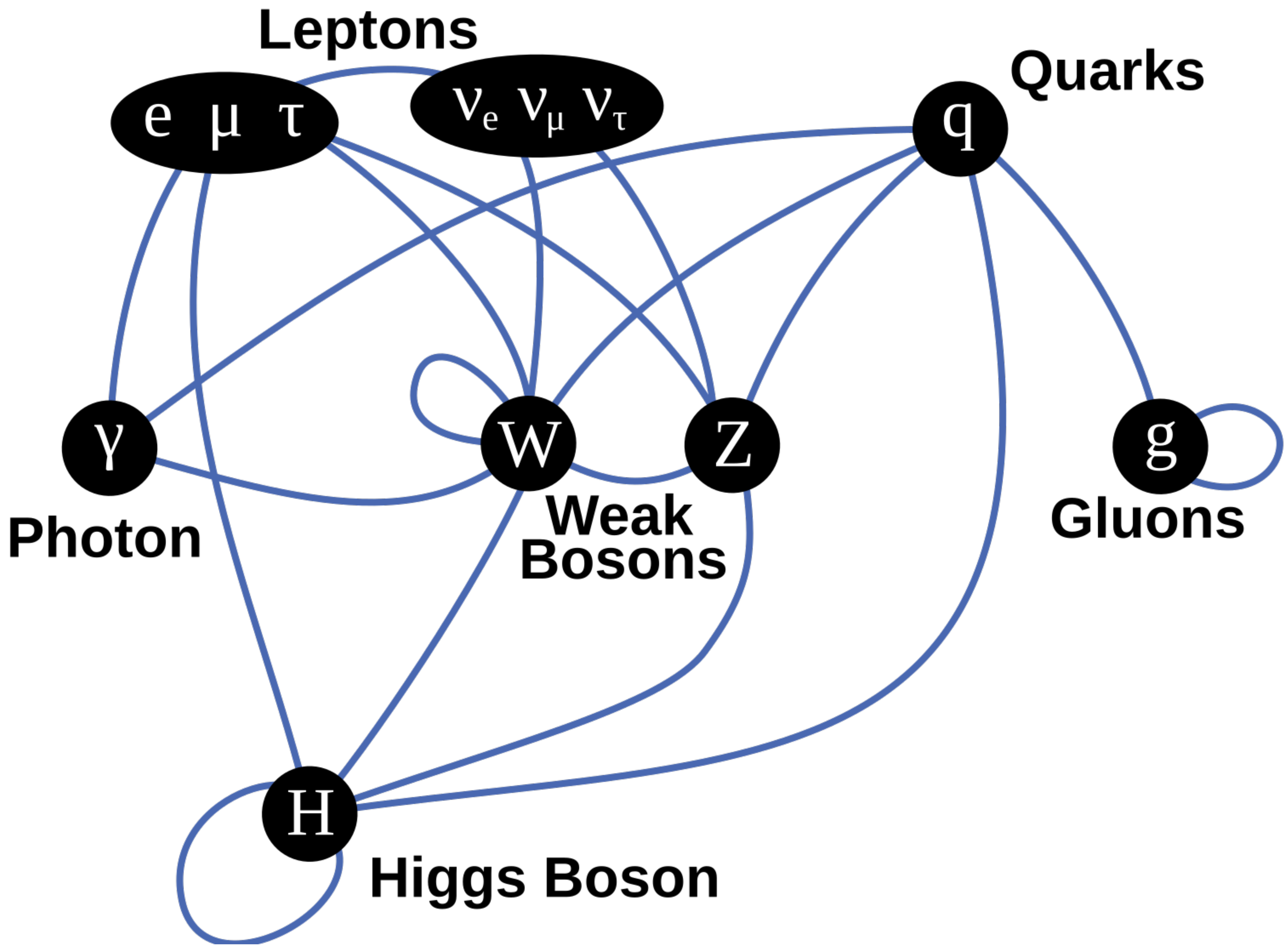


Image: Daniel Dominguez/CERN

Standard Model interactions



wikipedia

The Standard Model (SM)

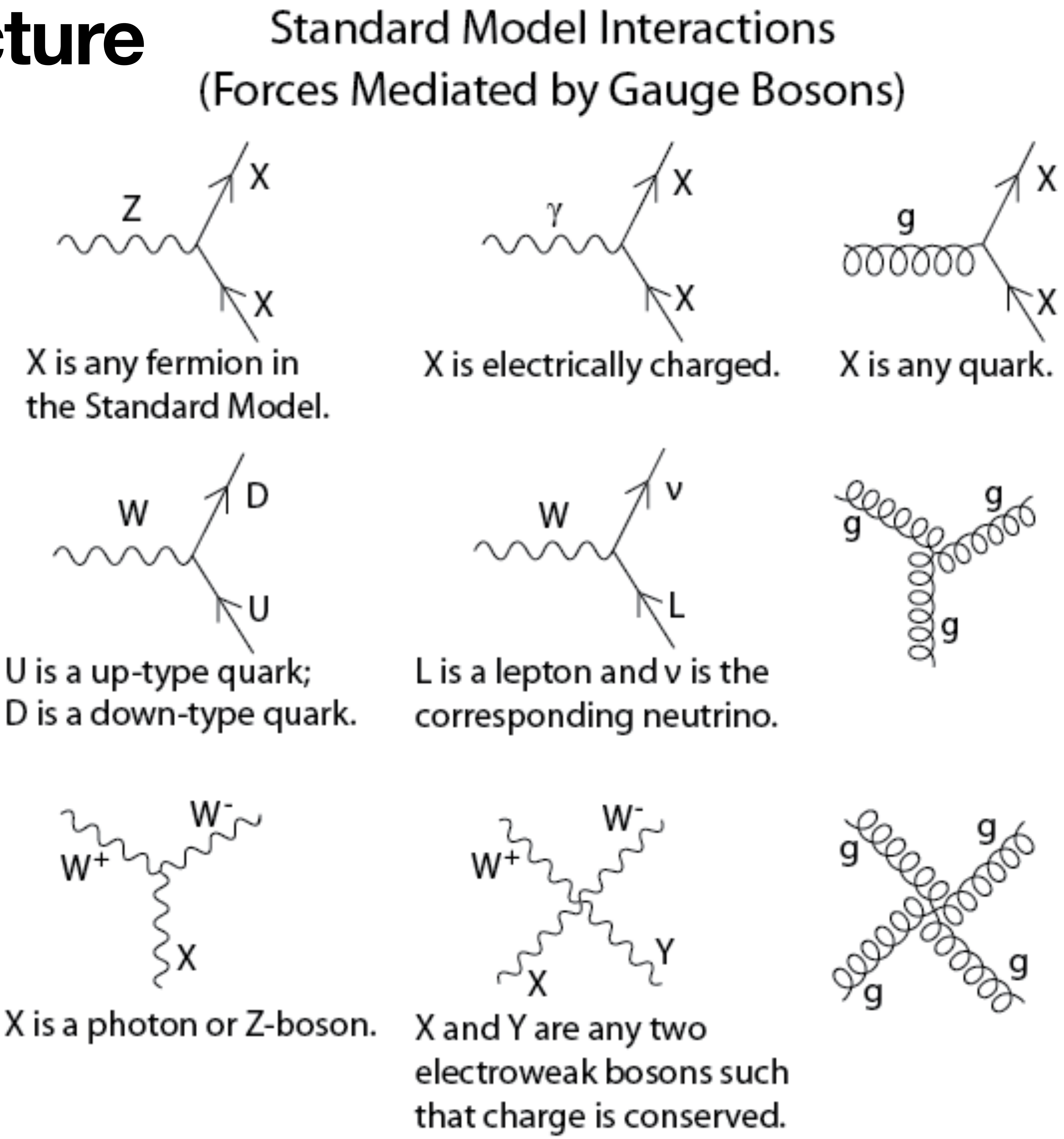
See lectures by:
Hyungjin Kim for more on HEP Theory
Markus Diehl for more on QCD

Gauge boson self-interaction

Gauge boson fermion interactions

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i\bar{\psi} \not{D} \psi + h.c.$$
$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

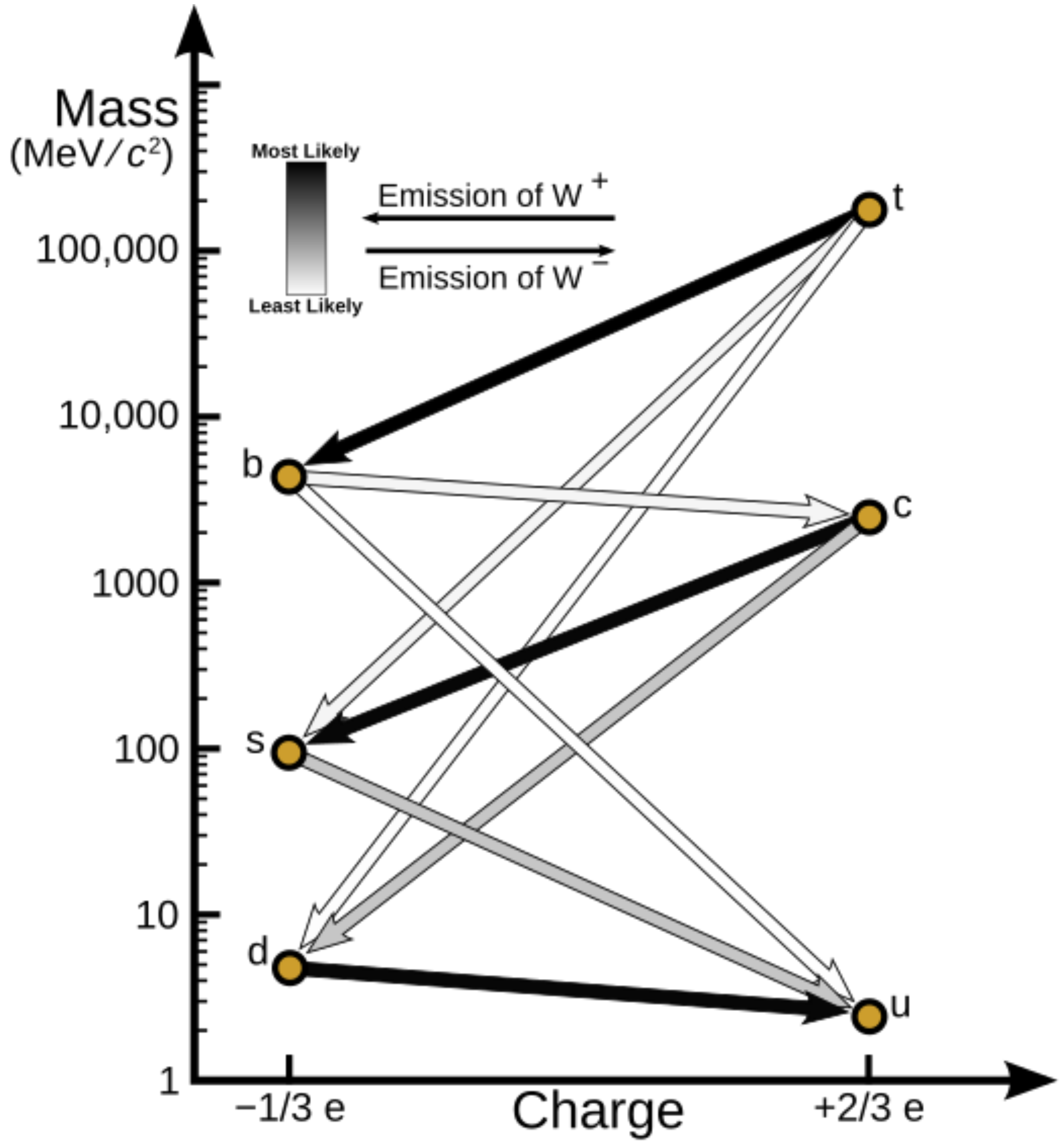
The Feynman picture



Goal: Measure such interactions & compare to SM prediction!

wikimedia

The Cabibbo-Kobayashi-Maskawa (CKM) matrix



wikipedia

CKM matrix as of 2024 (from PDG)

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

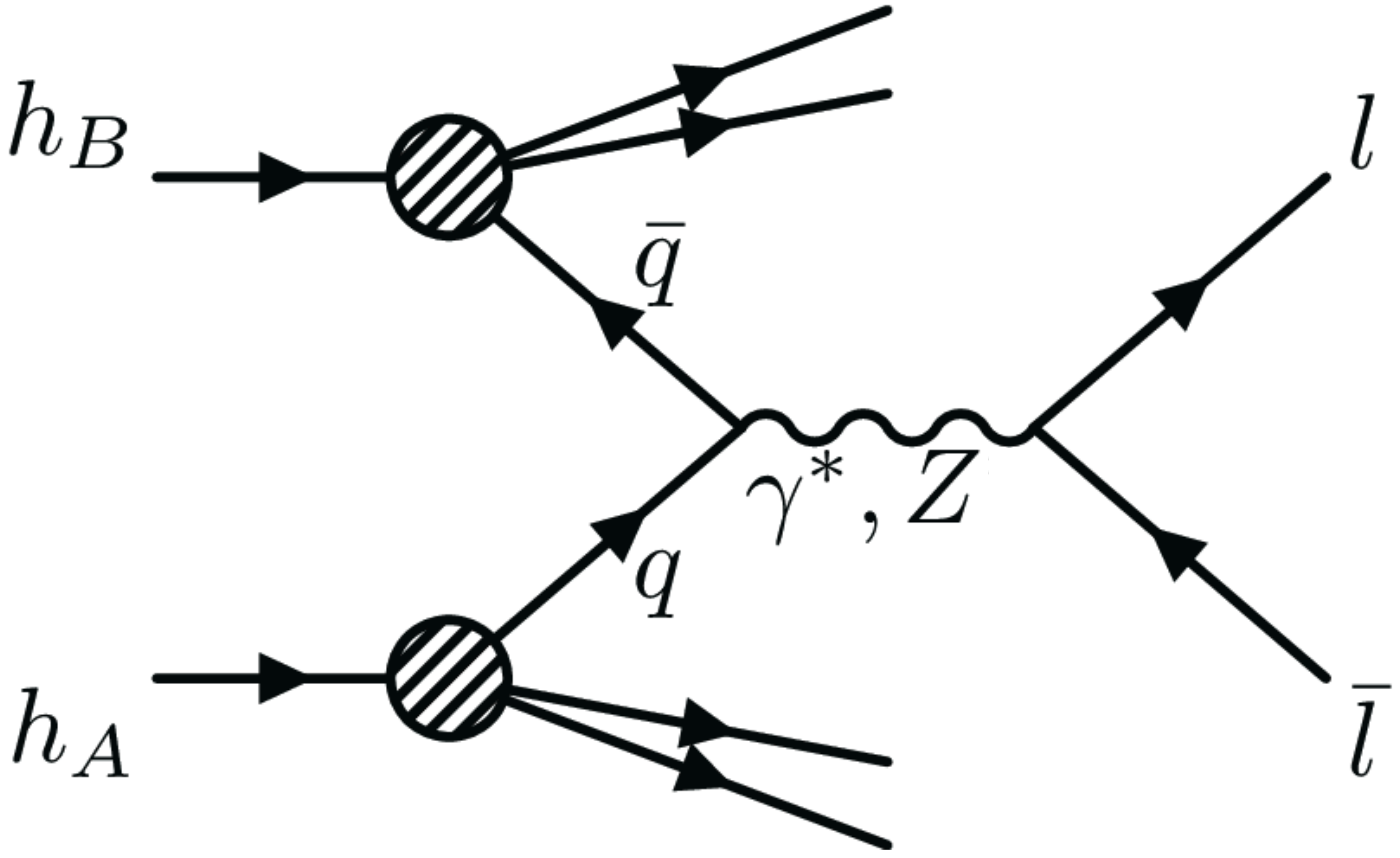
$$\begin{pmatrix} 0.97435 \pm 0.00016 & 0.22501 \pm 0.00068 & 0.003732^{+0.000090}_{-0.000085} \\ 0.22487 \pm 0.00068 & 0.97349 \pm 0.00016 & 0.04183^{+0.00079}_{-0.00069} \\ 0.00858^{+0.00019}_{-0.00017} & 0.04111^{+0.00077}_{-0.00068} & 0.999118^{+0.000029}_{-0.000034} \end{pmatrix}$$

See lectures by Thibaud Humair for more on flavour physics

Contains information about flavour-changing weak interactions

Rediscover Z boson (& W boson) at LHC

Drell-Yan:

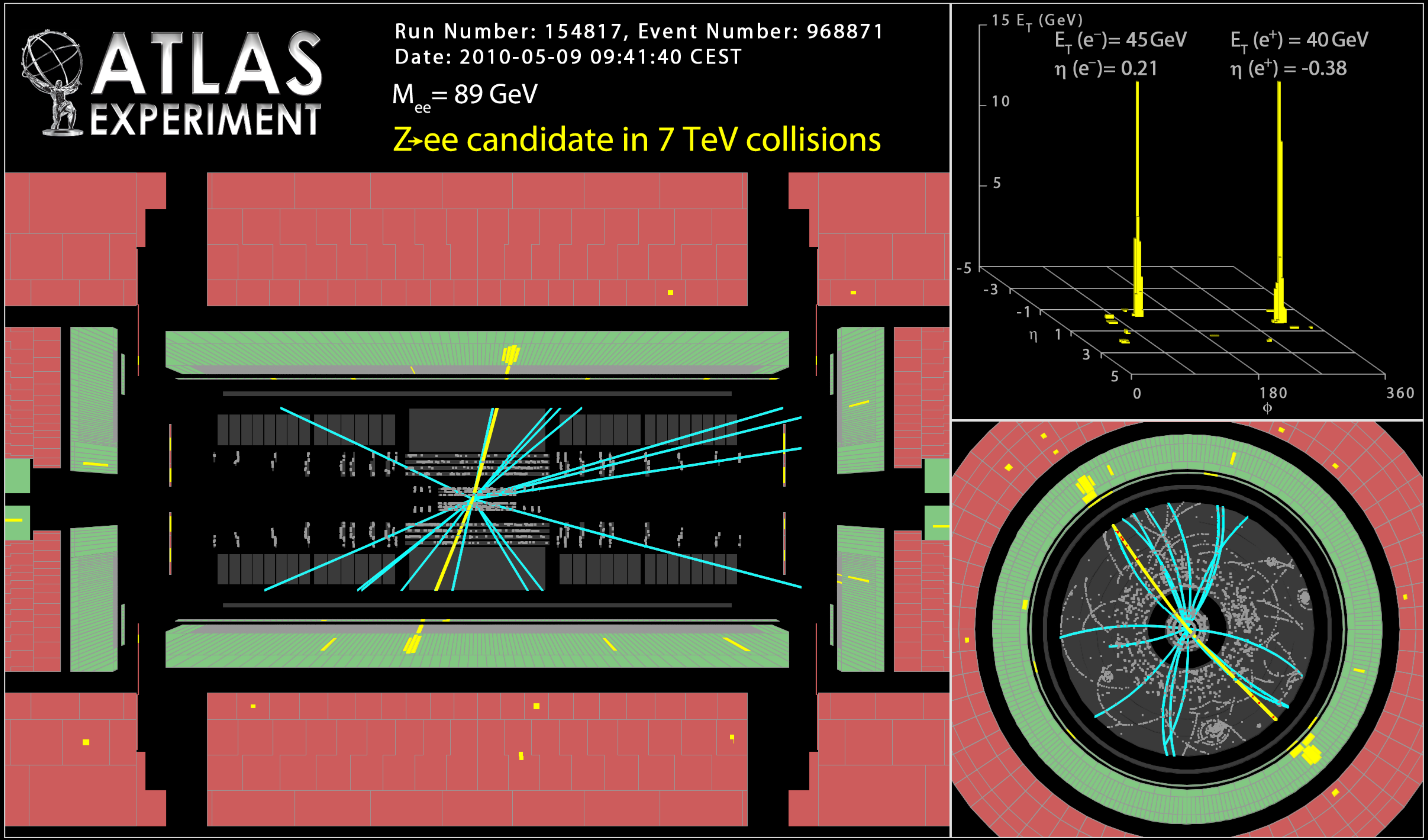


- **Characteristic clean signature:**
  2 opposite charge, same flavour leptons

Fun-fact: Z-boson decays to
- Quarks ~70%
- Neutrinos ~20%
- Charged leptons ~10%

Adapted from 254469235

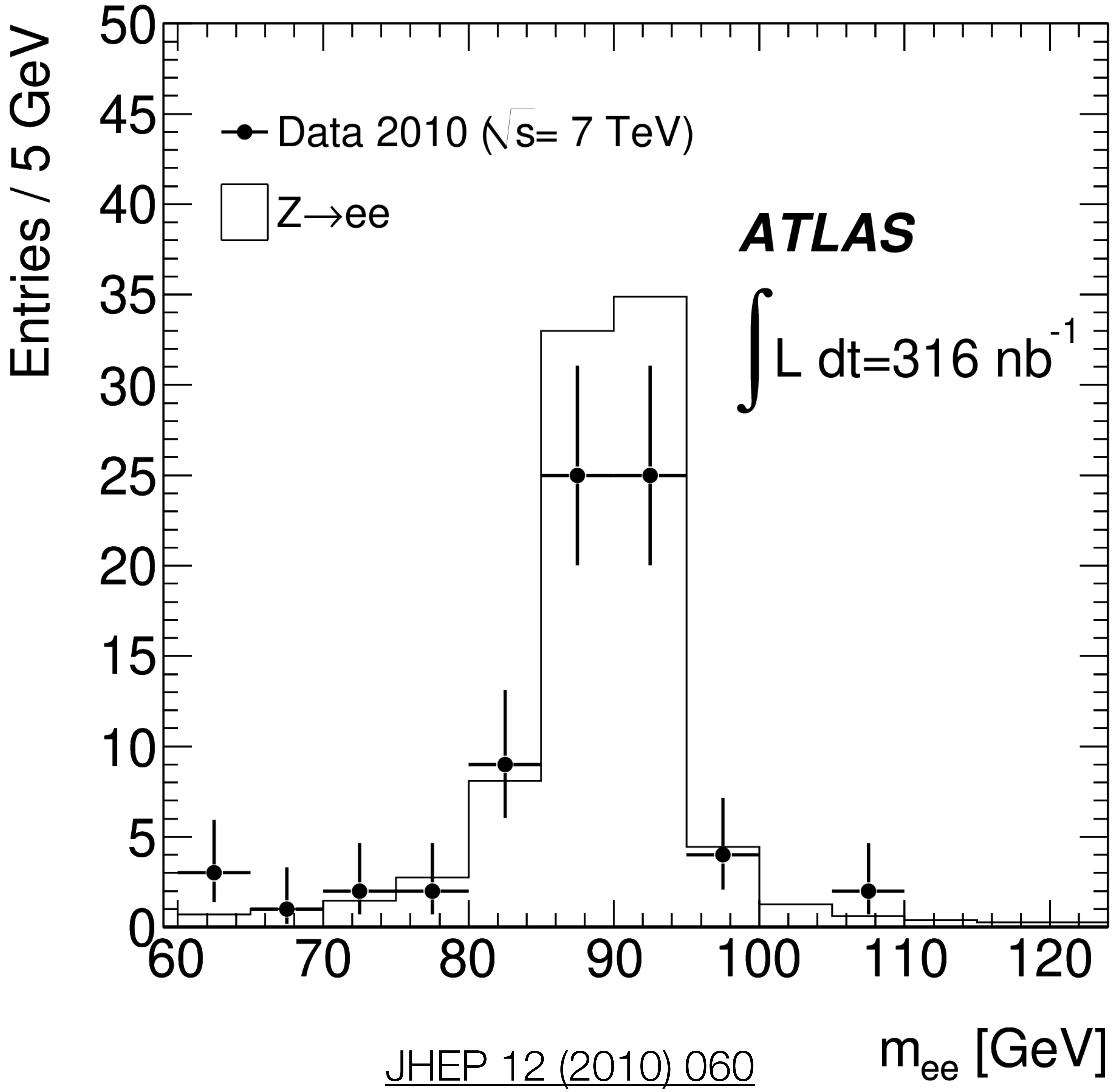
Z boson candidate event



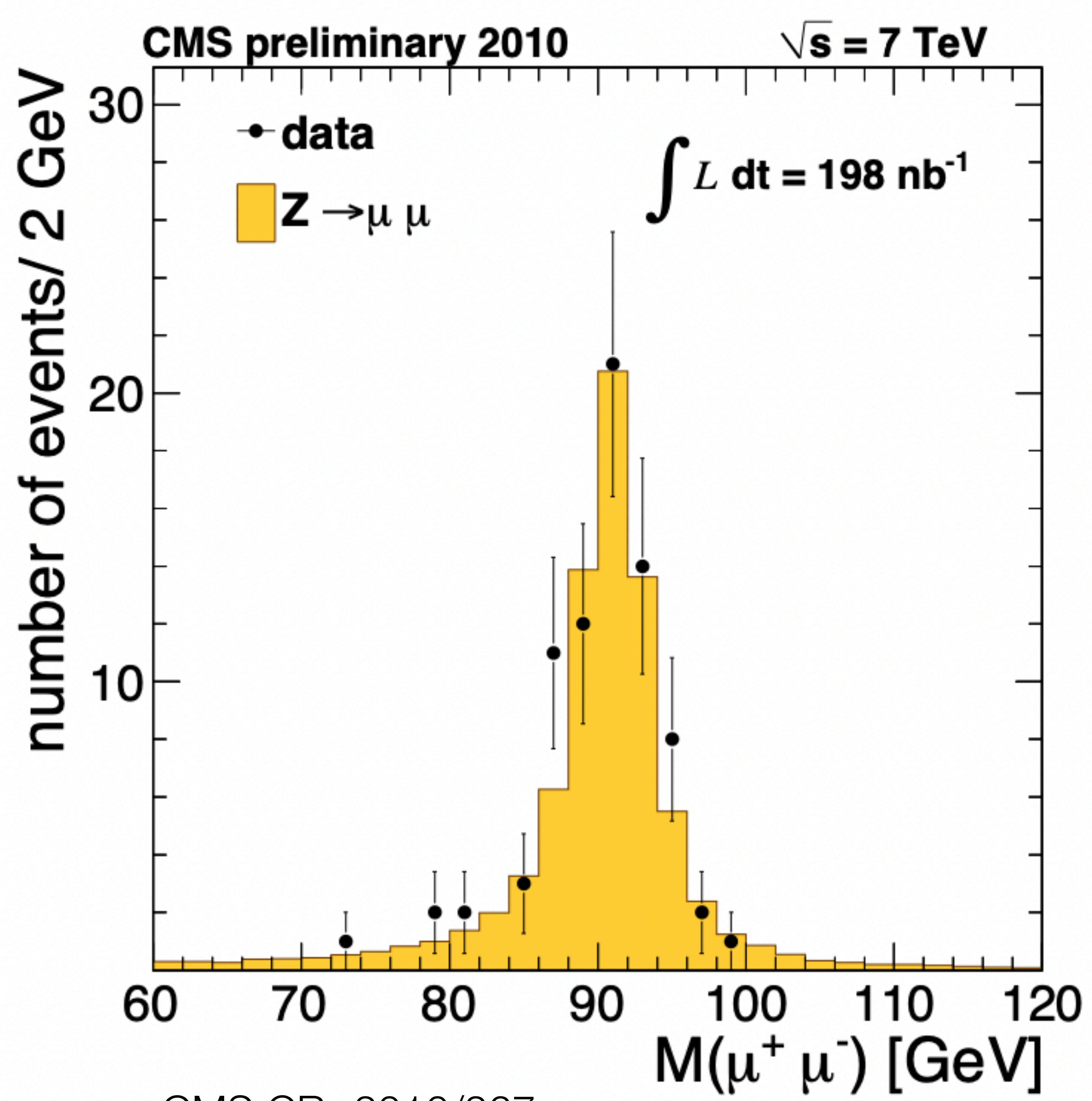
ATLAS event display

Rediscover Z boson at LHC

Early data-MC comparisons:

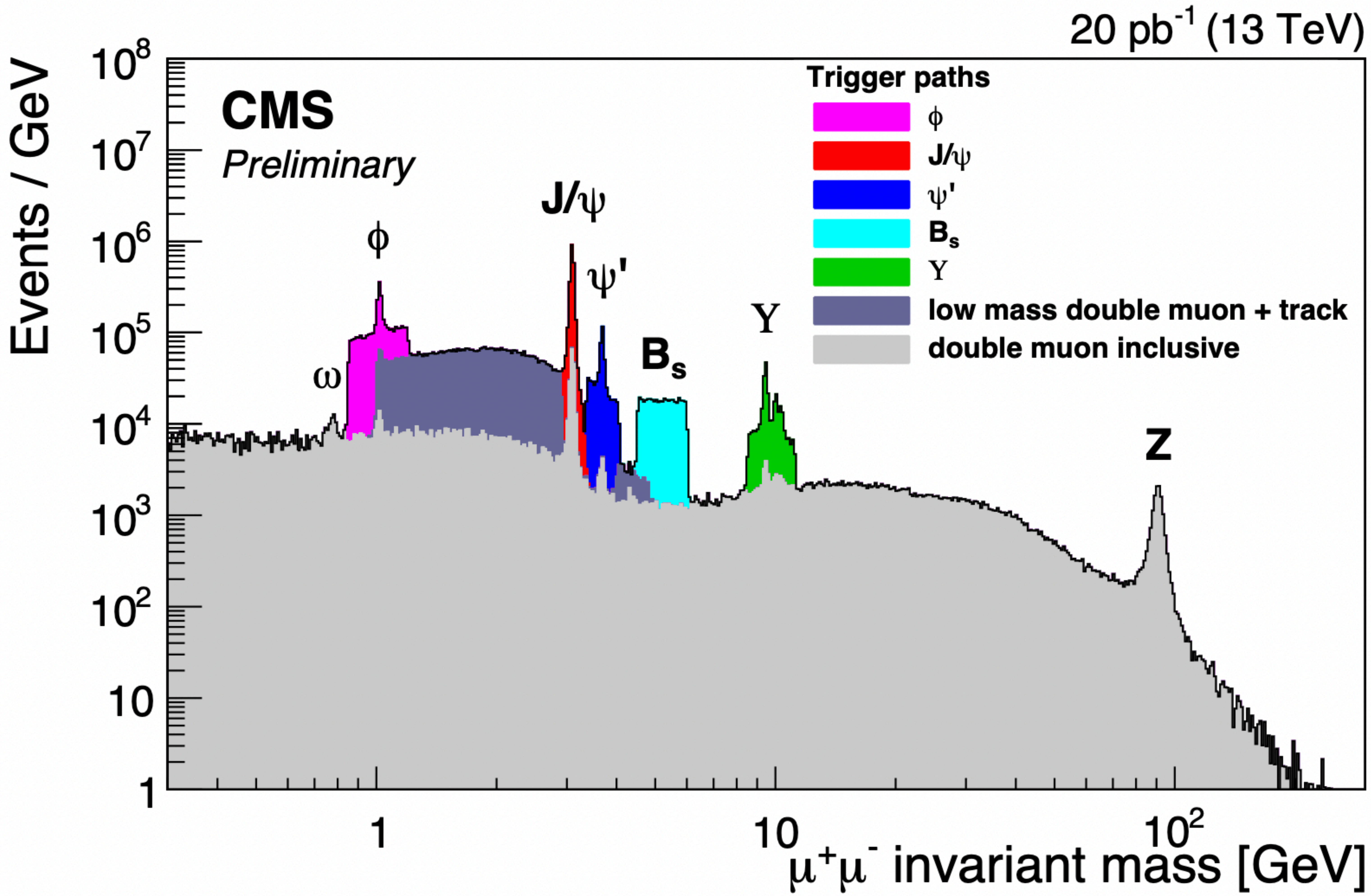


JHEP 12 (2010) 060



CMS CR -2010/267

Di-muon mass spectrum



Quiz: What is the continuum?

2037379

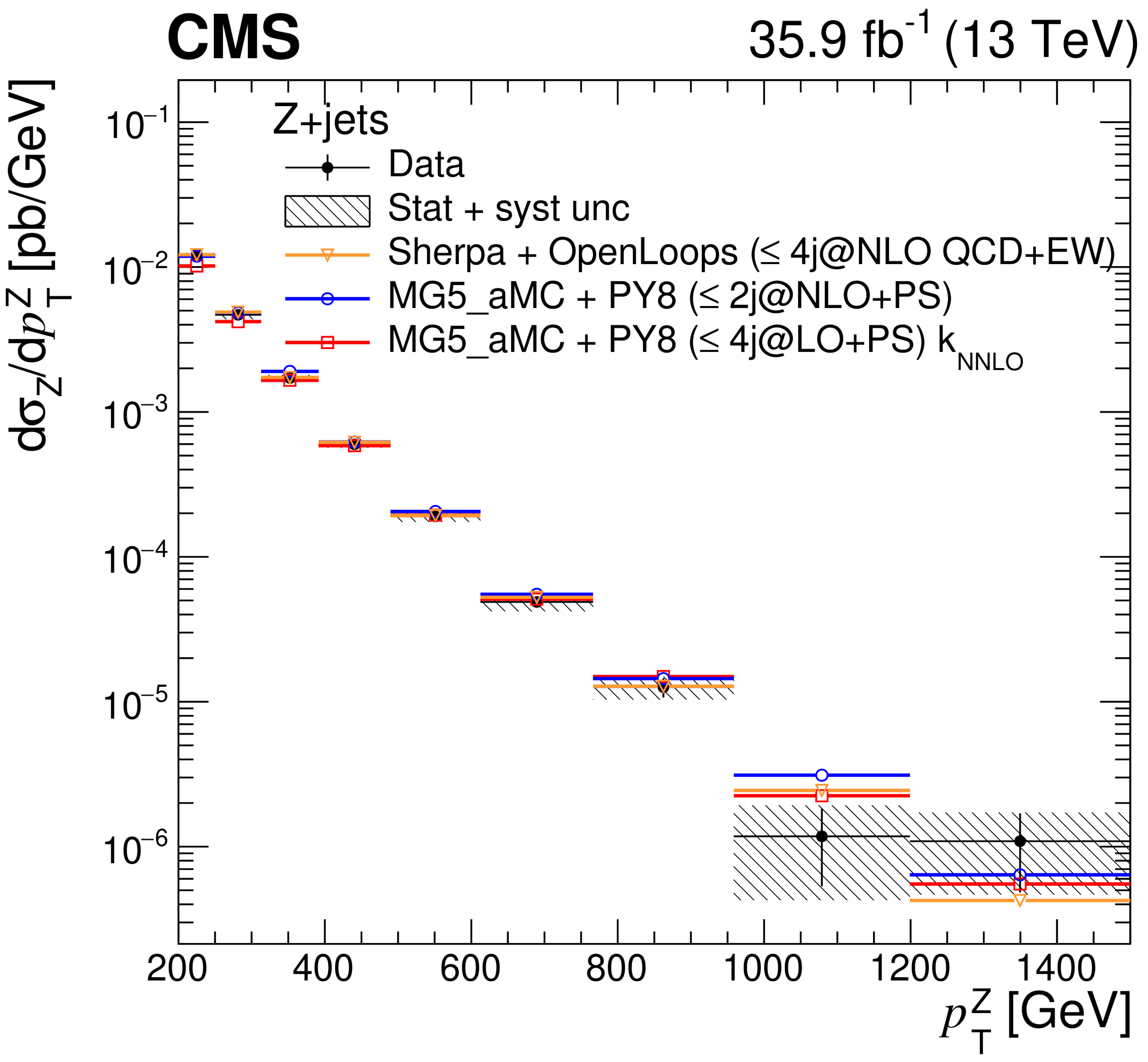
Z+jets measurements

Important process & background for many new physics searches:

Understanding Z boson p_T spectrum is important:

- Unfolding: Turn “measured” data spectrum into particle level spectrum

- Unfolded spectrum
  → Easily compared to simulated samples



JHEP 05 (2021) 285

Z+jets measurements

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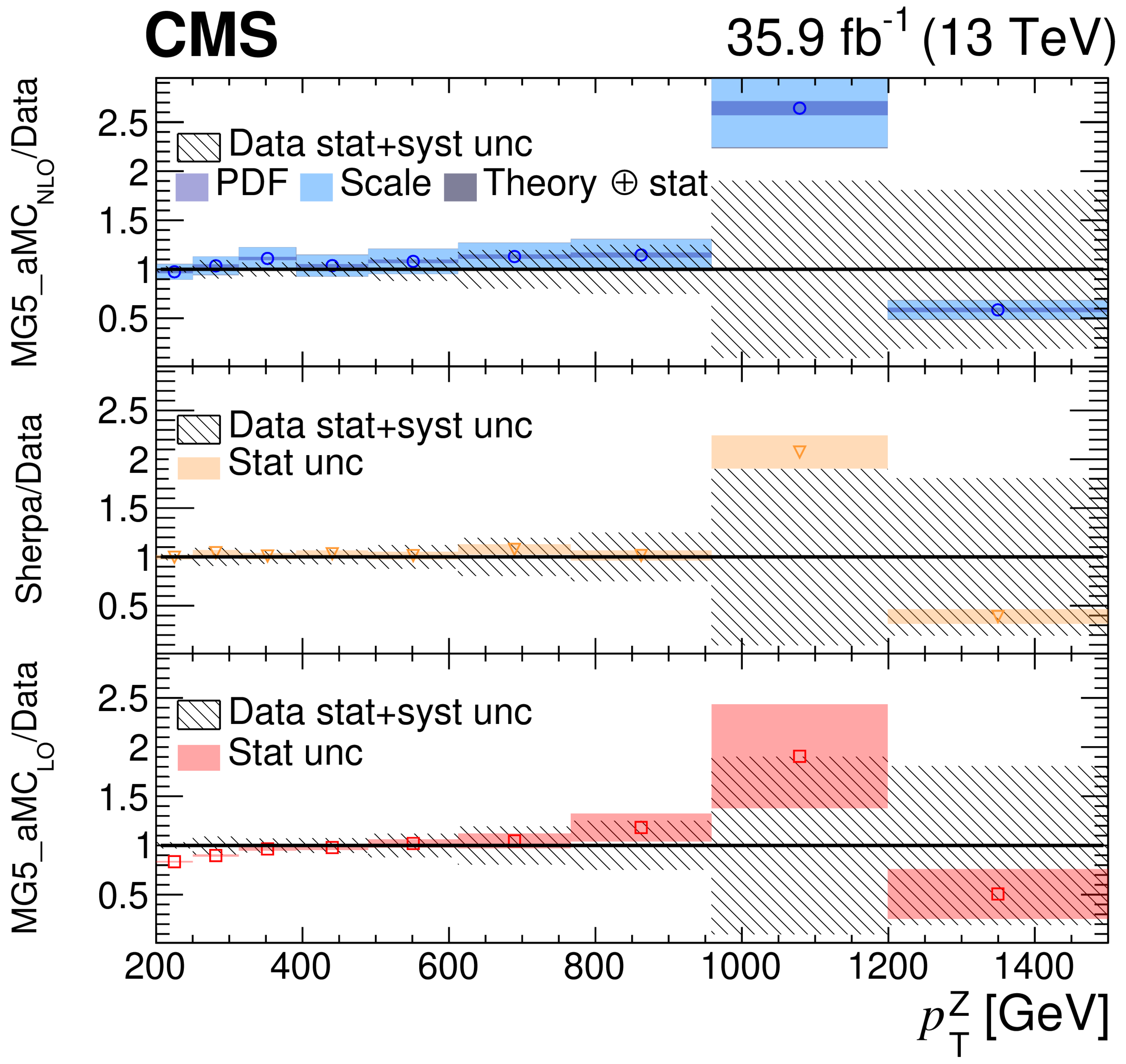

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Z bosons as standard candles

Energy/momentum calibration

- Adjust the position of the Z peak until it corresponds to the value we expect
- Done by adjusting energy/momentum scale

Lepton efficiency measurements

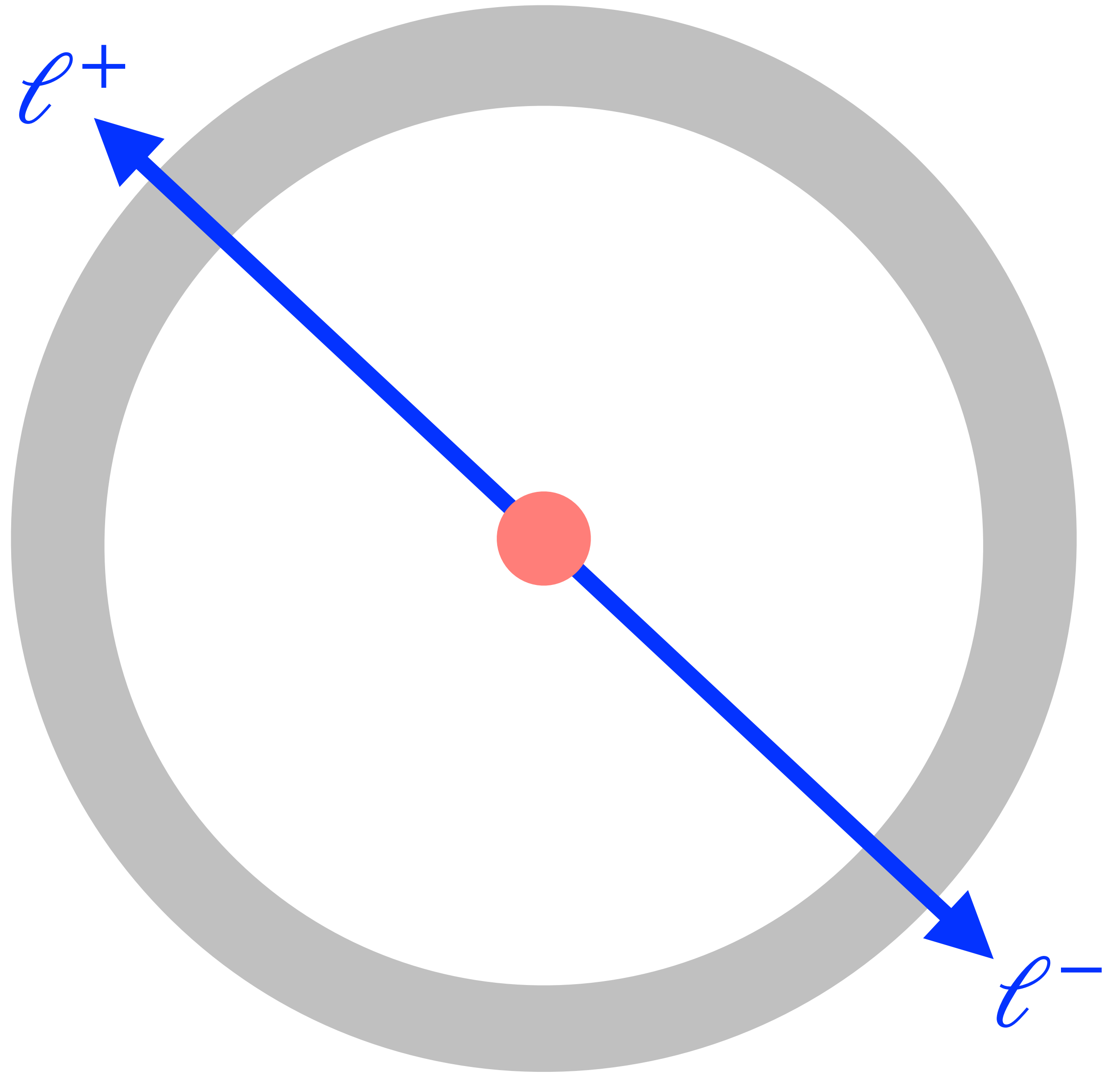
- Need clean lepton sample to measure reconstruction/identification/isolation efficiencies

<u>"Tag and Probe" method:</u>

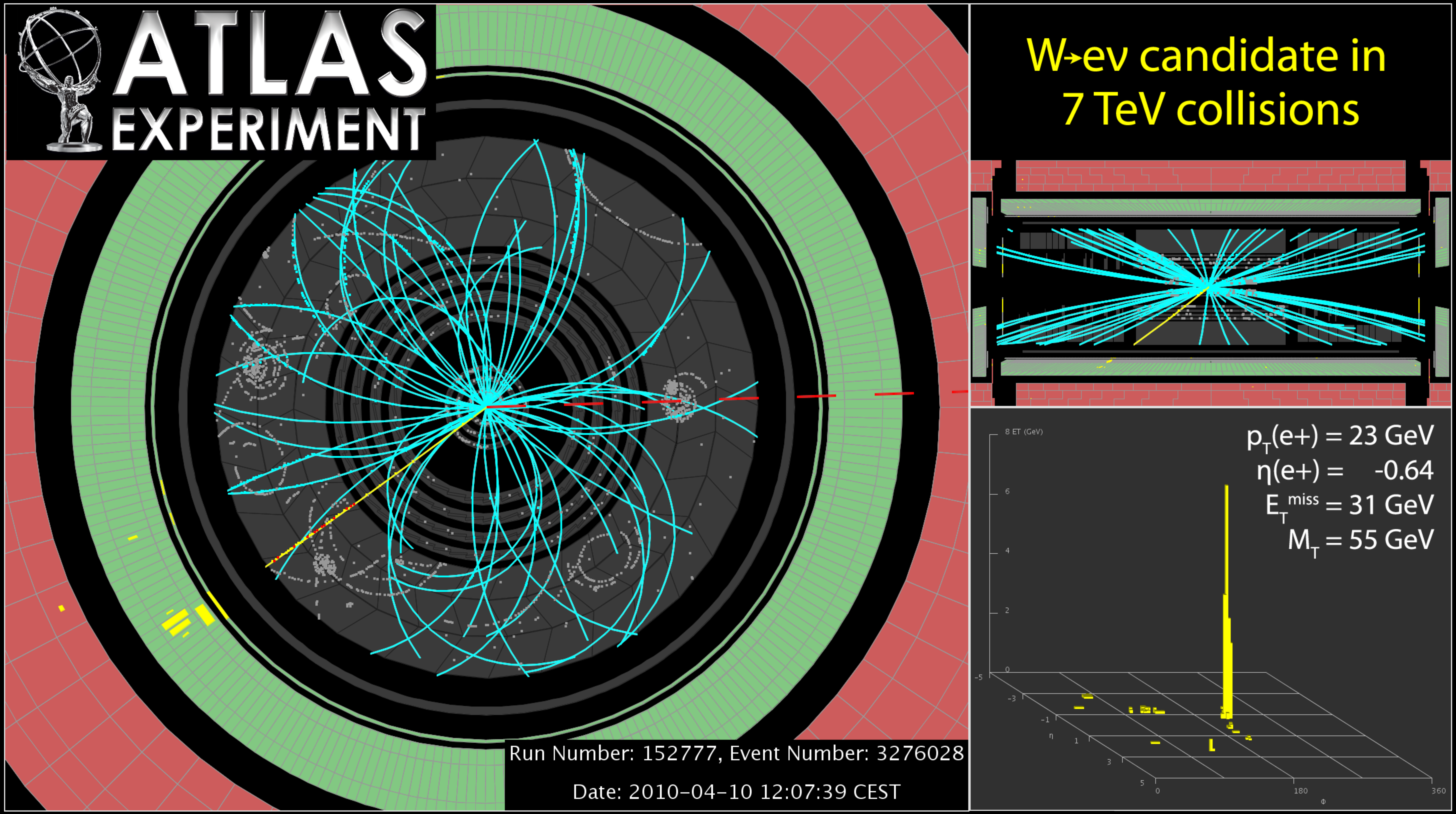
Select two lepton candidates with tight (Tag) and looser (Probe) selection criteria

Require di-lepton mass to be around Z peak

→ Likely that both leptons are "good" leptons

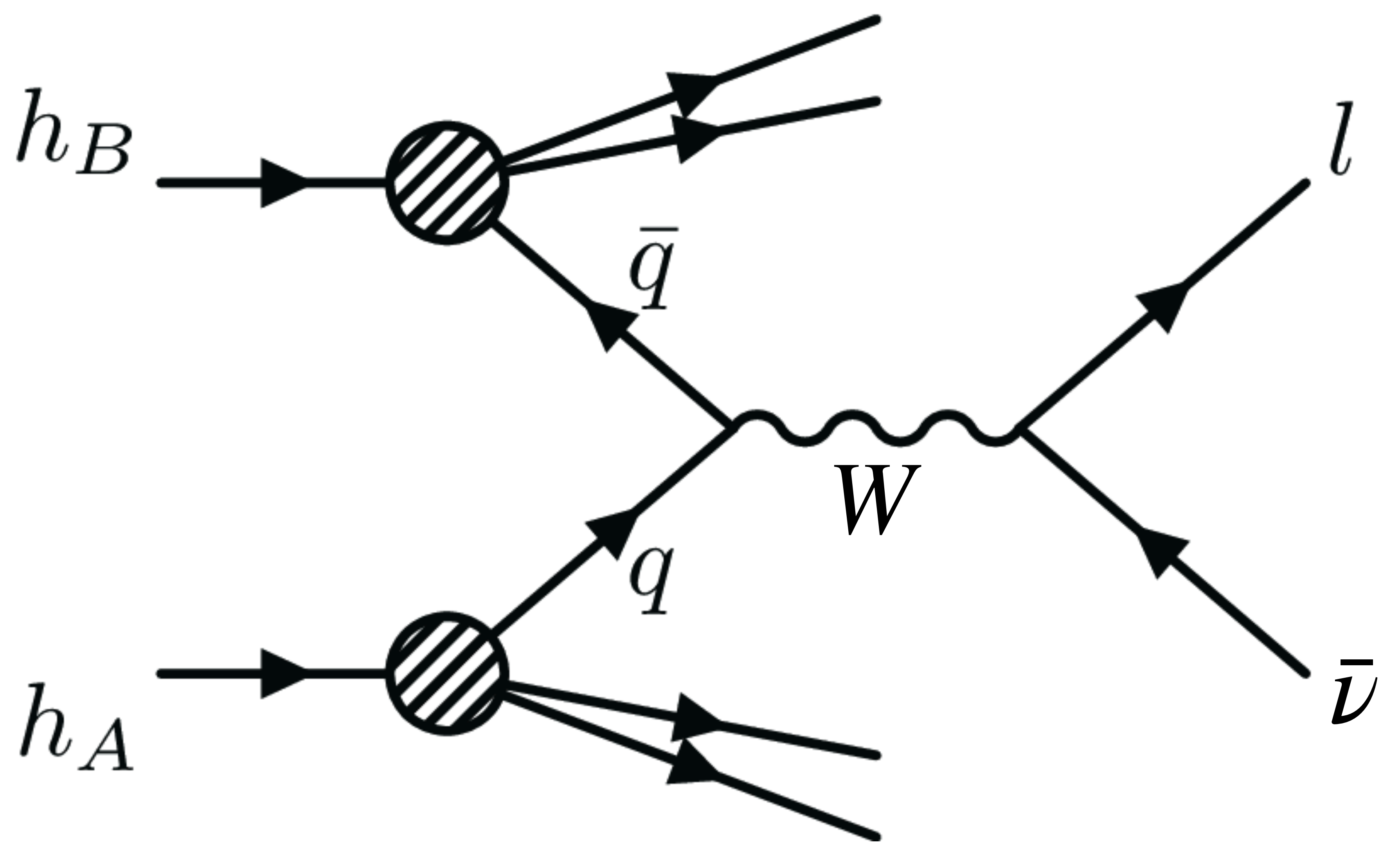


W boson candidate event



ATLAS event display

W bosons



Decay mode	branching ratio
$e\bar{\nu}_e$	~1/9
$\mu\bar{\nu}_\mu$	~1/9
$\tau\bar{\nu}_\tau$	~1/9
$u\bar{d}$	~1/3
$c\bar{s}$	~1/3

- **Characteristic signature:**
  Charged lepton and neutrino (MET)

Quiz: why is the branching ratio to $u\bar{d}$ higher than to $e\bar{\nu}_e$?

Adapted from 254469235

W^+ vs W^- asymmetry

At the LHC:

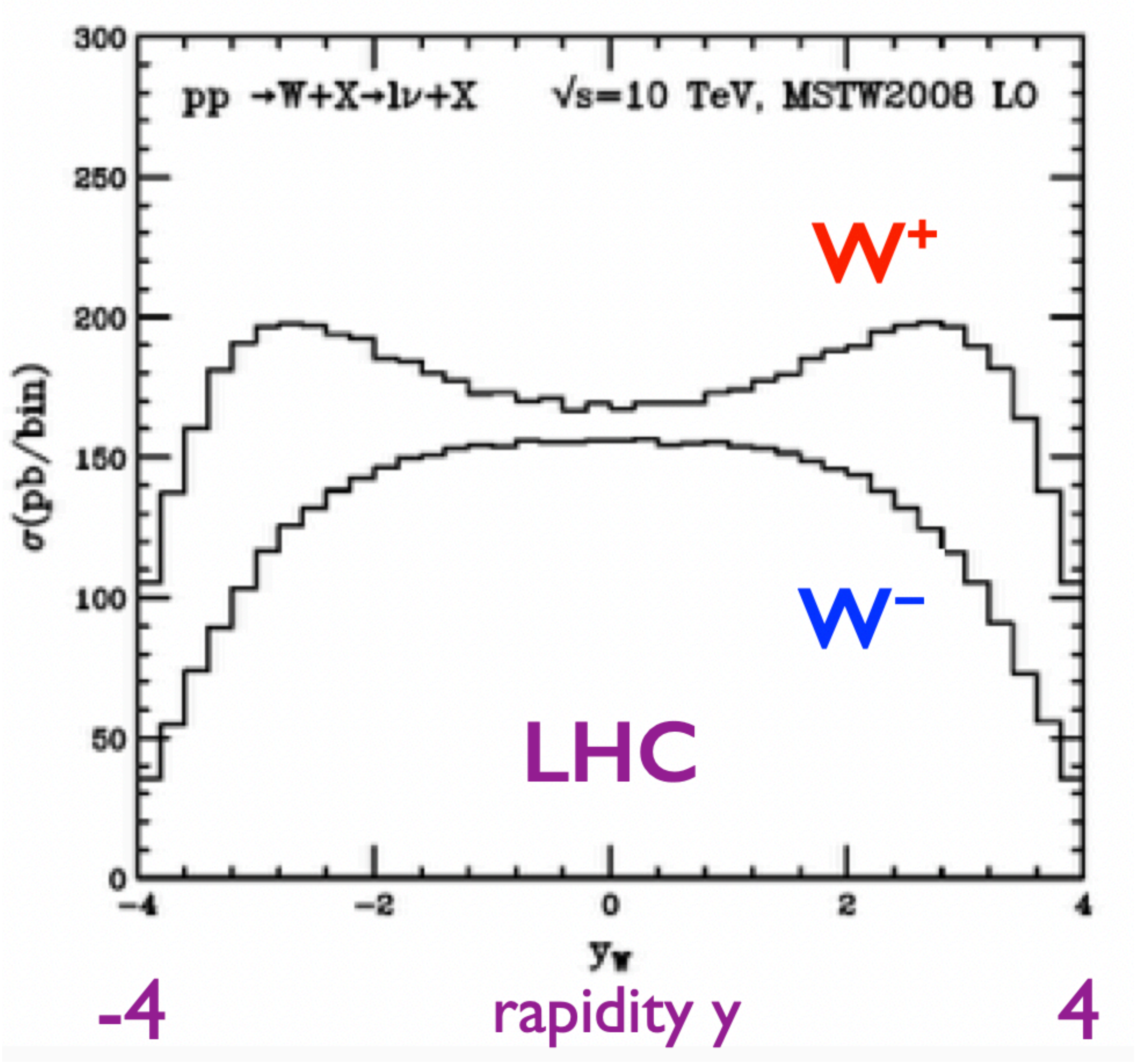
- **W^+ produced at higher rate than W^-**
- **W^+ bosons produced at higher rapidities**

Main reasons:

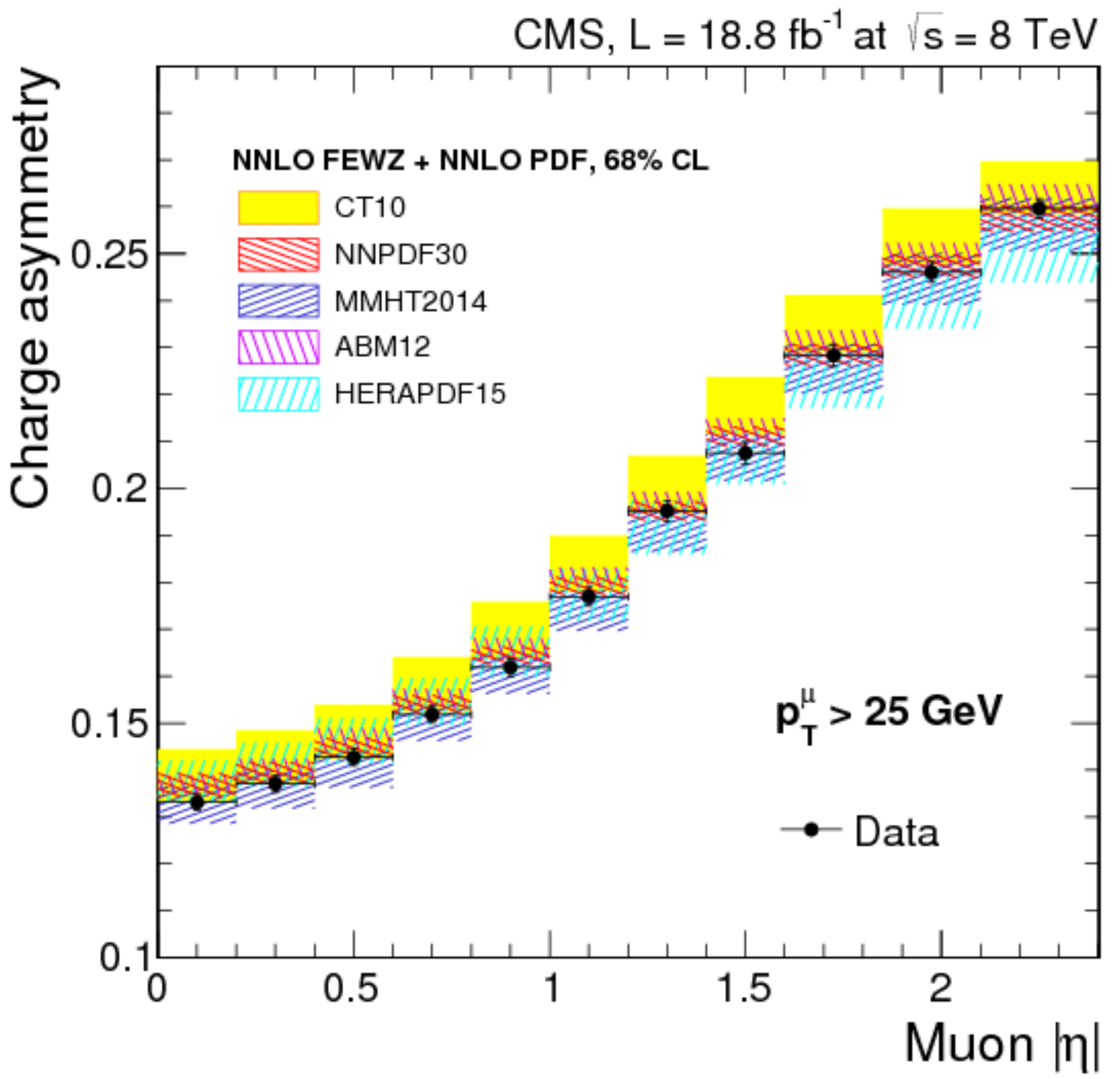
W^+ production more often involves valence quark

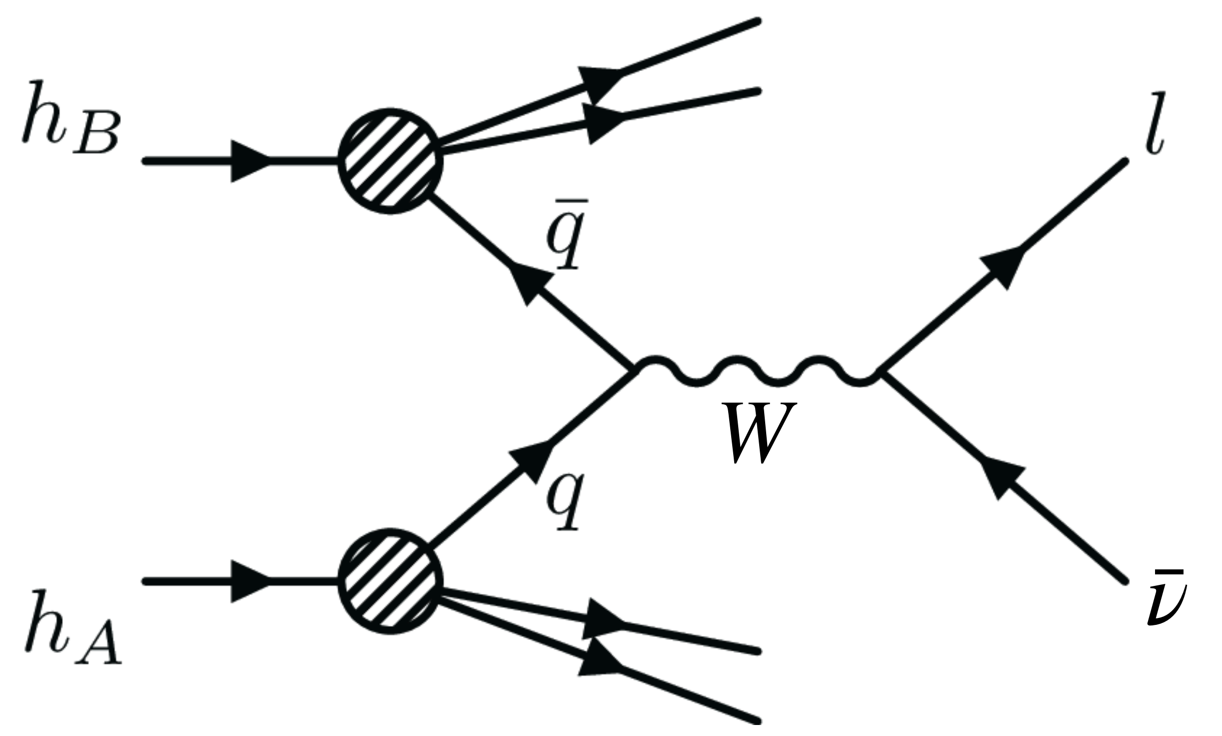
u carries more of proton momentum than d on avg

W bosons typically produced from valence-sea quark annihilation



In practice: measure lepton charge asymmetry





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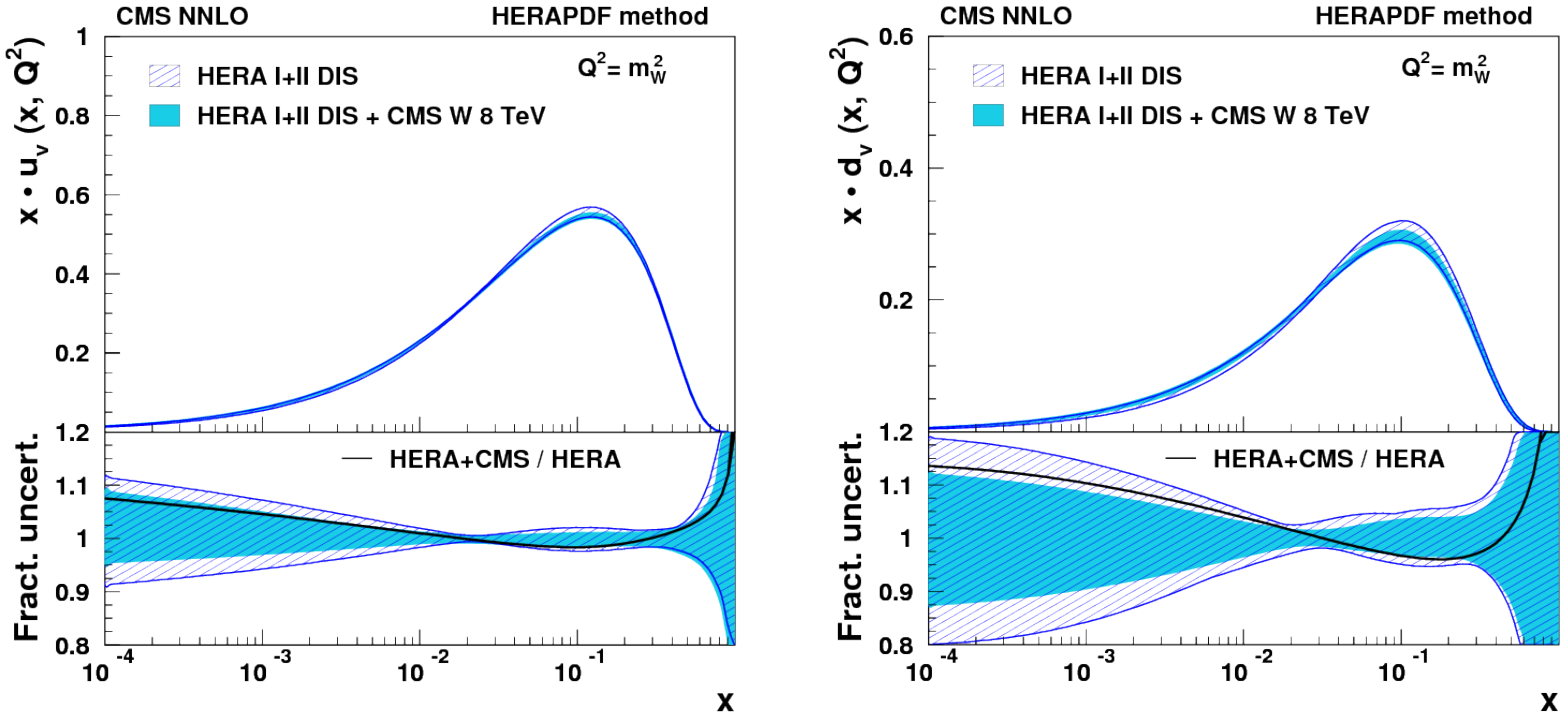
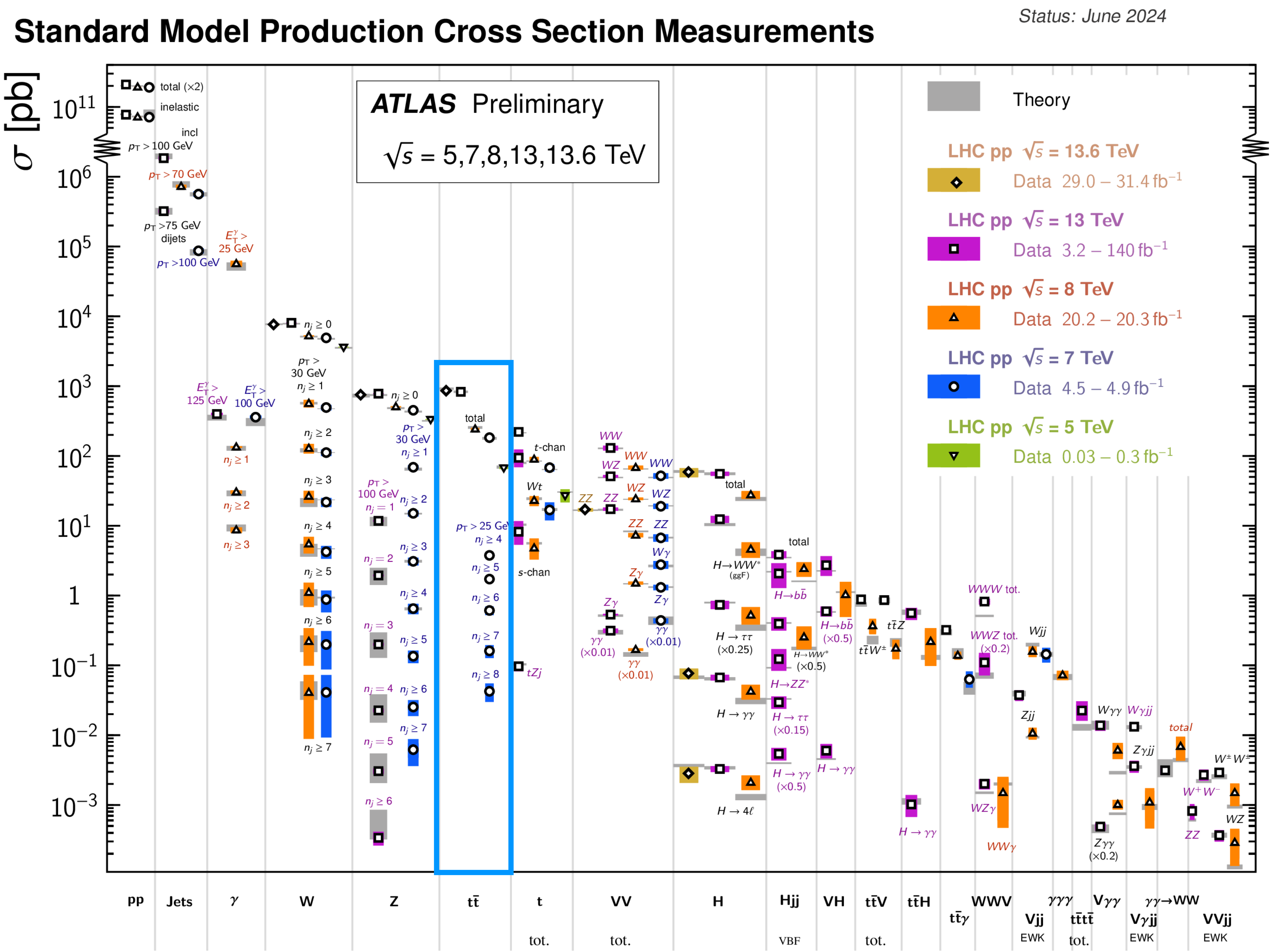


$$\mathcal{A}(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$$

Measurements can help to constrain u and d PDFs

Eur. Phys. J. C 76 (2016) 469

Going to rarer and rarer SM processes

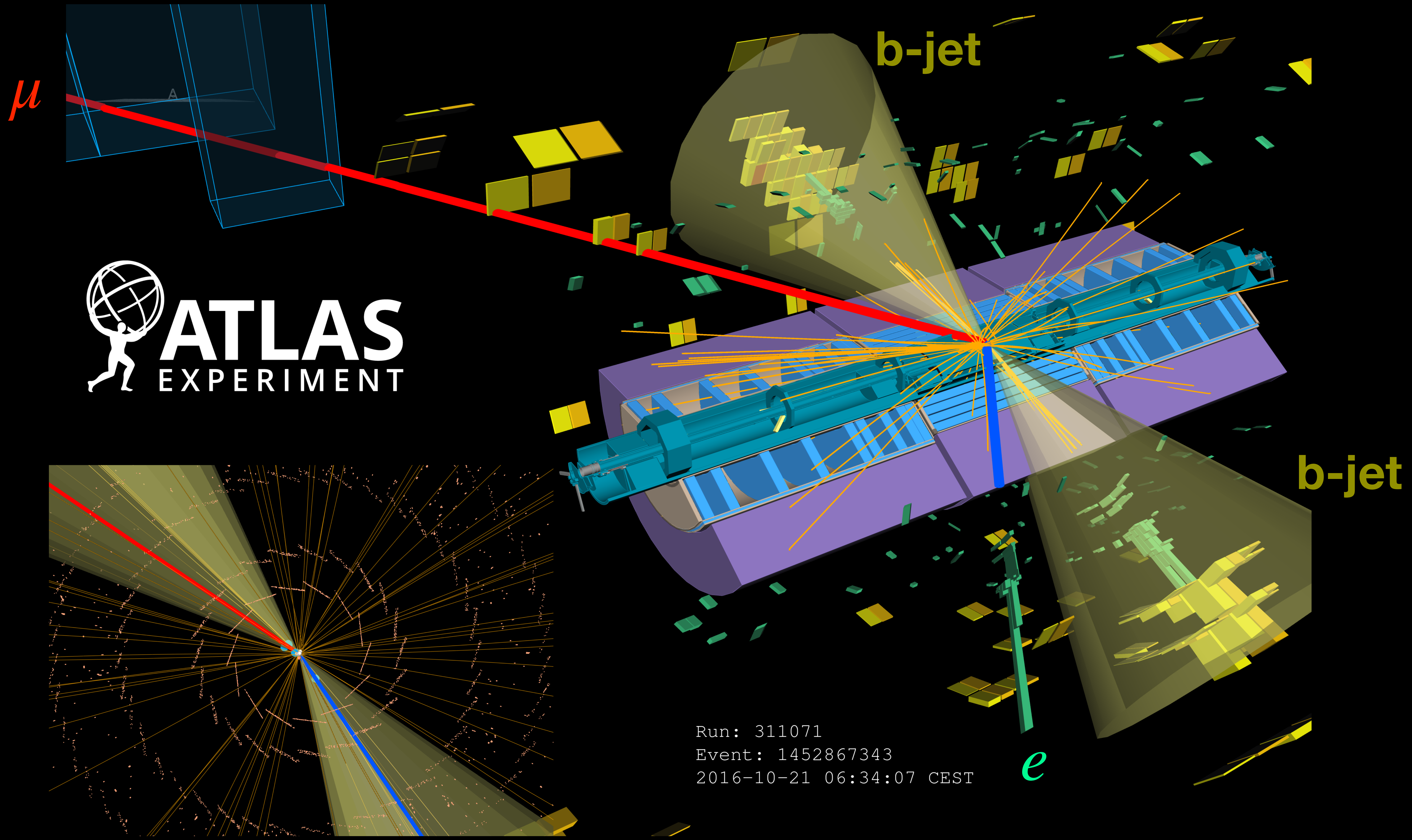


Top quark pair production

→ LHC is a top factory

ATL-PHYS-PUB-2024-011

Top quark pair candidate event



ATLAS Event Display

Going to rarer and rarer SM processes

Top quark pair production

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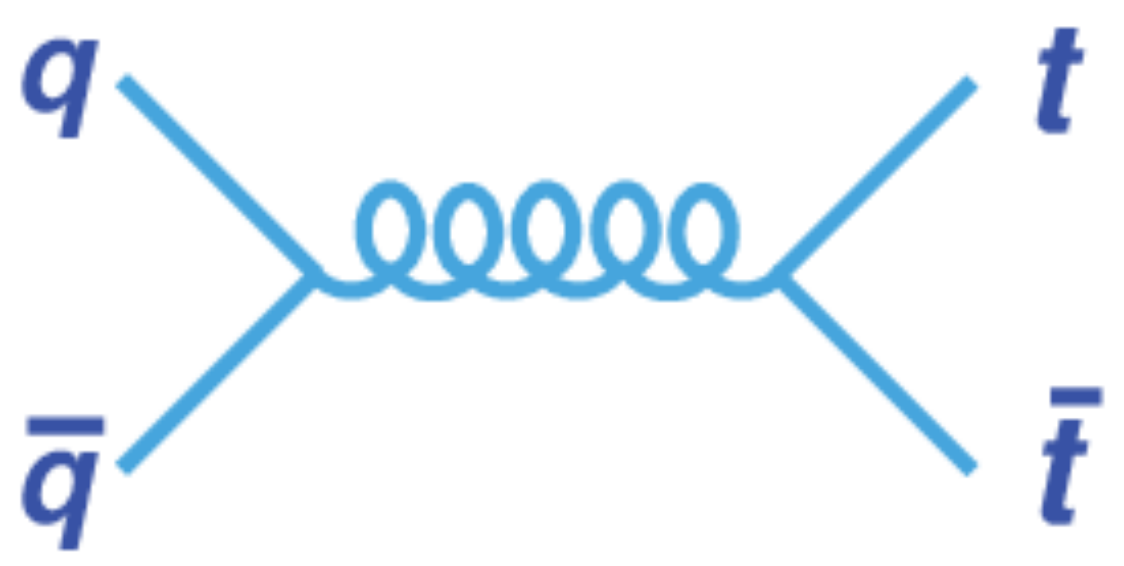
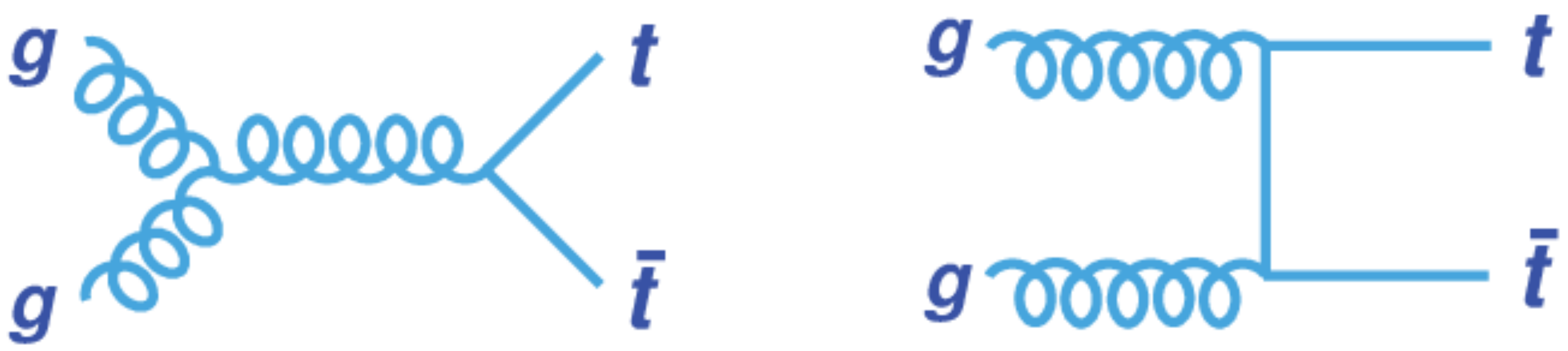


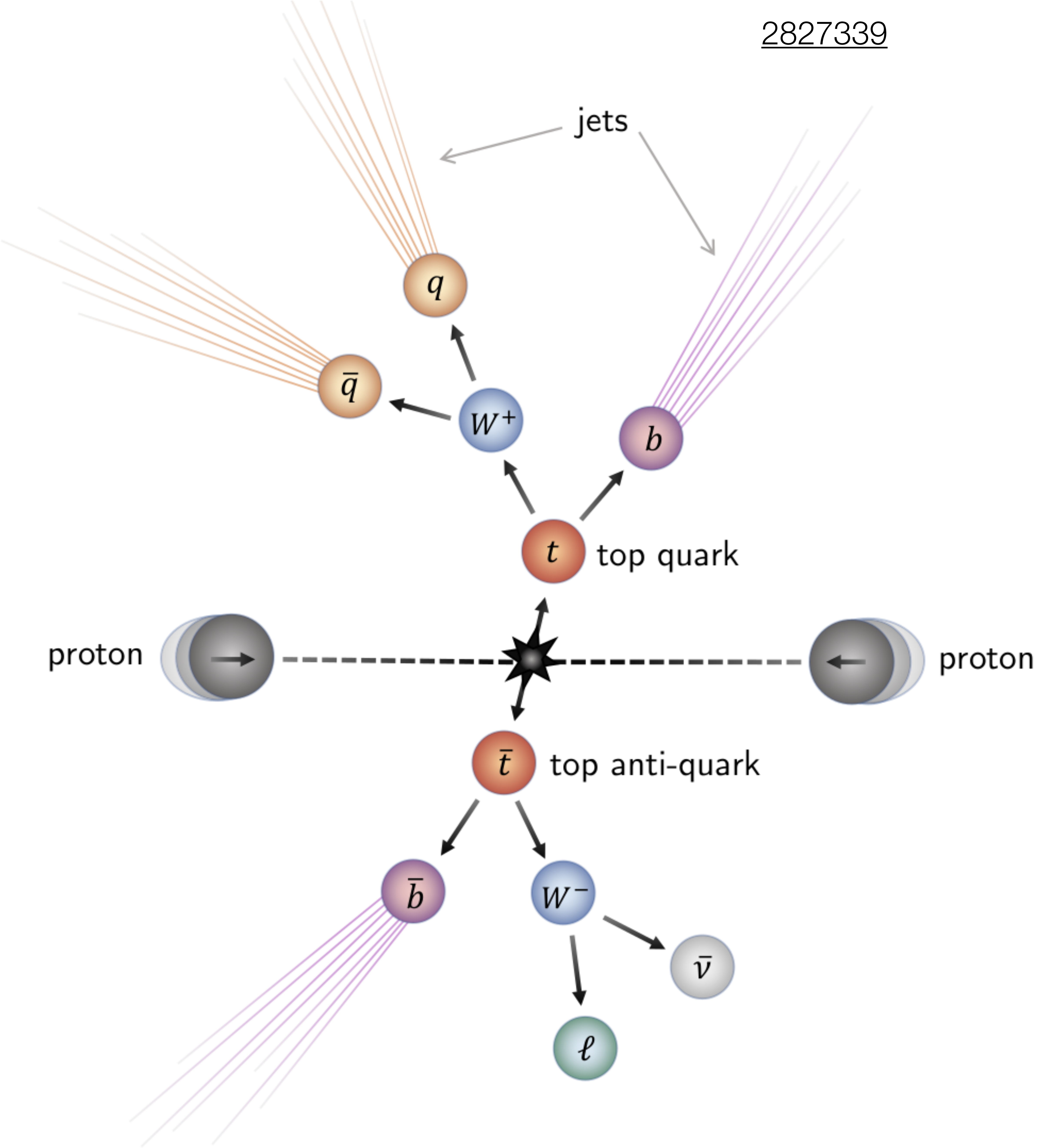


PhysRevD.86.092003

Top quark pair production

Heaviest quark in the SM

- Decays before it can hadronise
- Decays almost exclusively to Wb



Has become a "standard candle" at the LHC

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Top quark pair production

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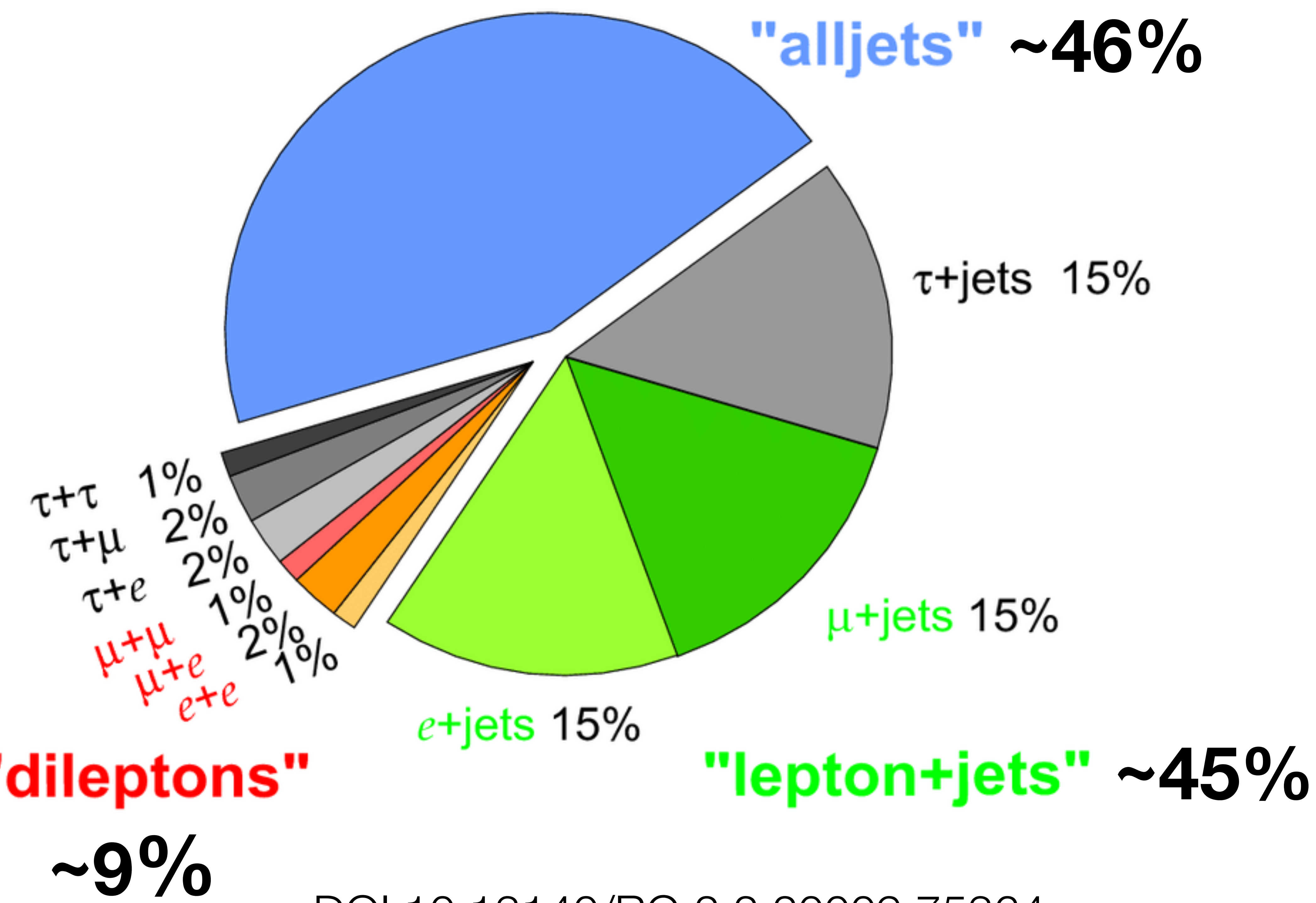
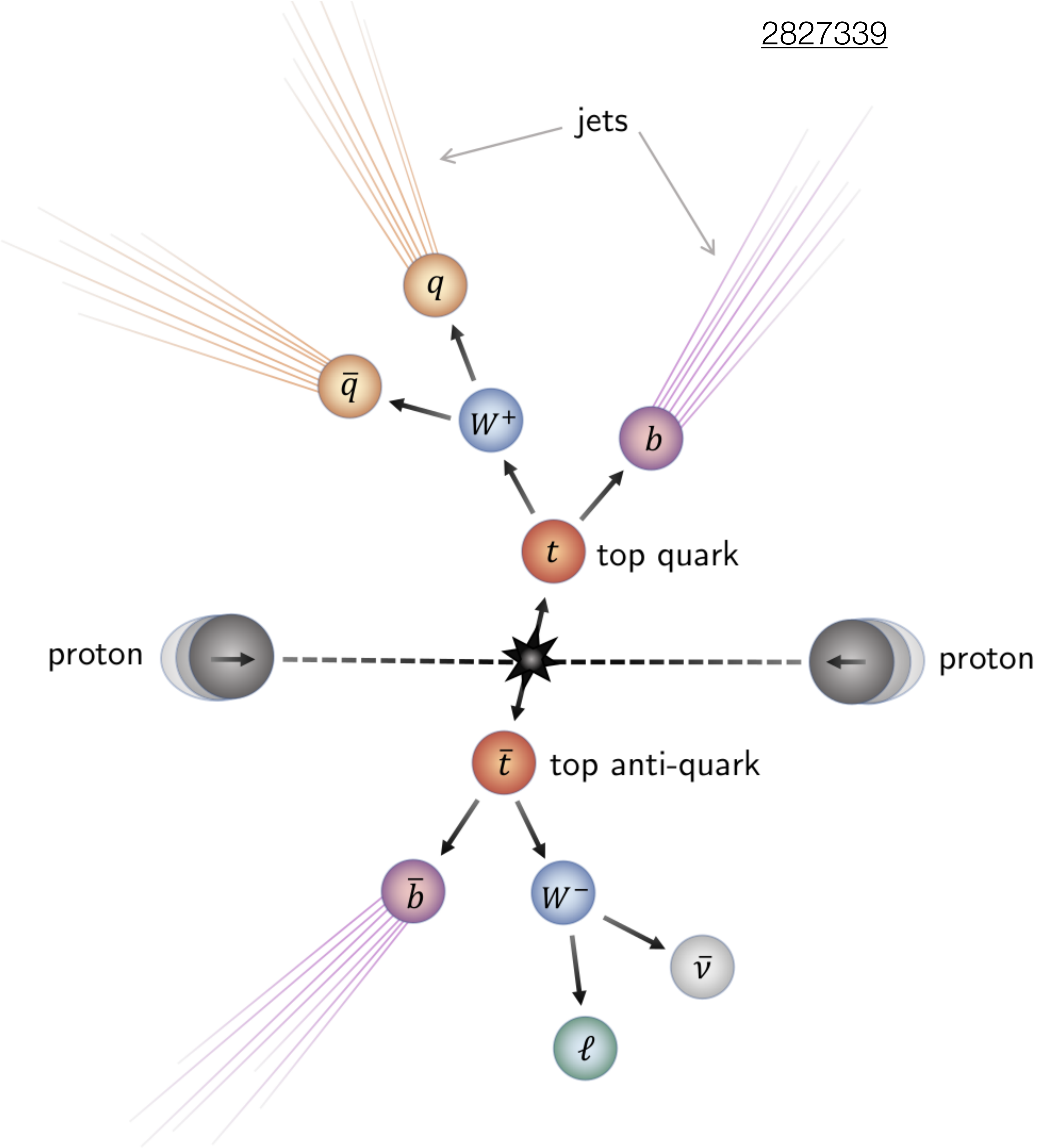


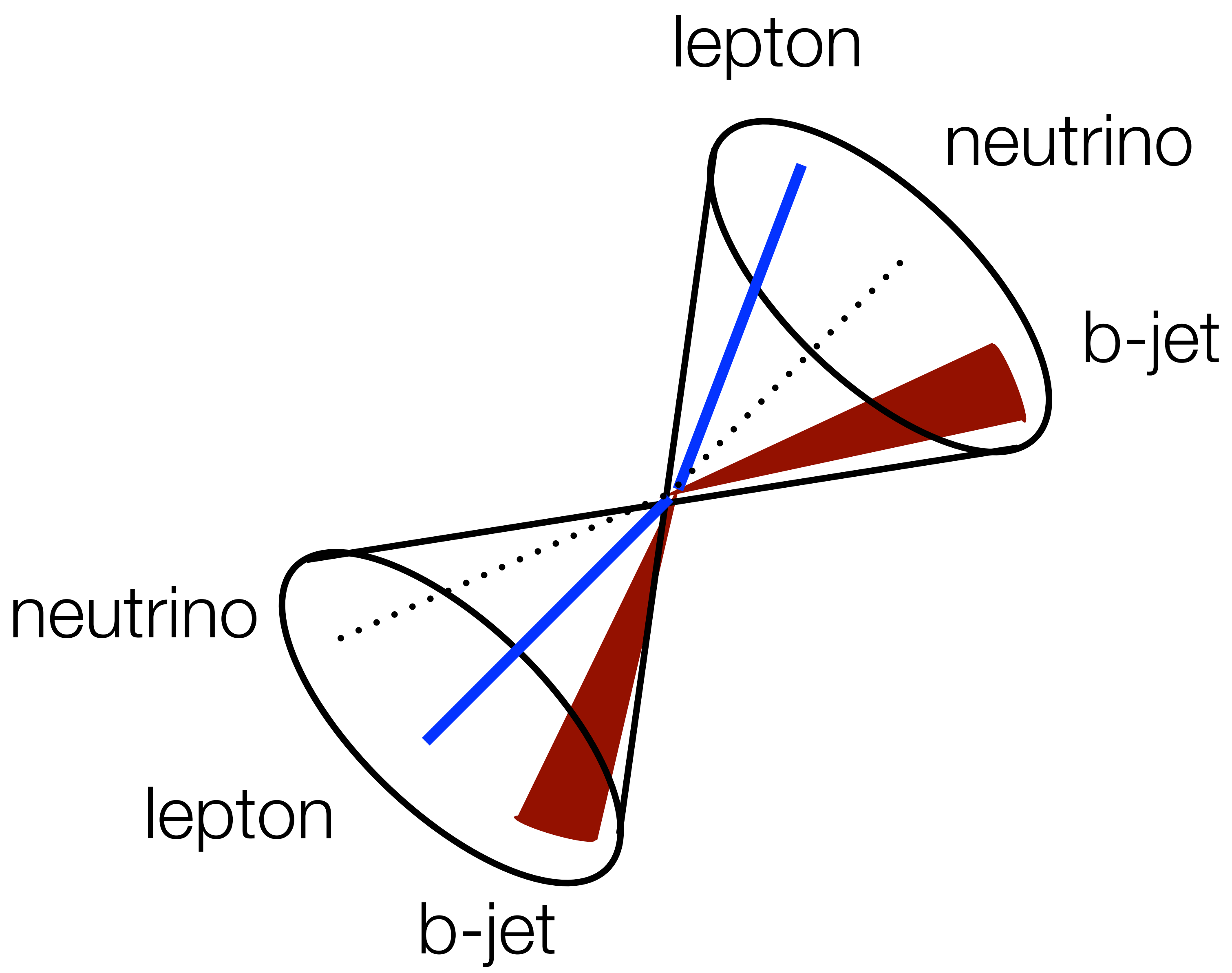
DOI:10.13140/RG.2.2.20009.75364



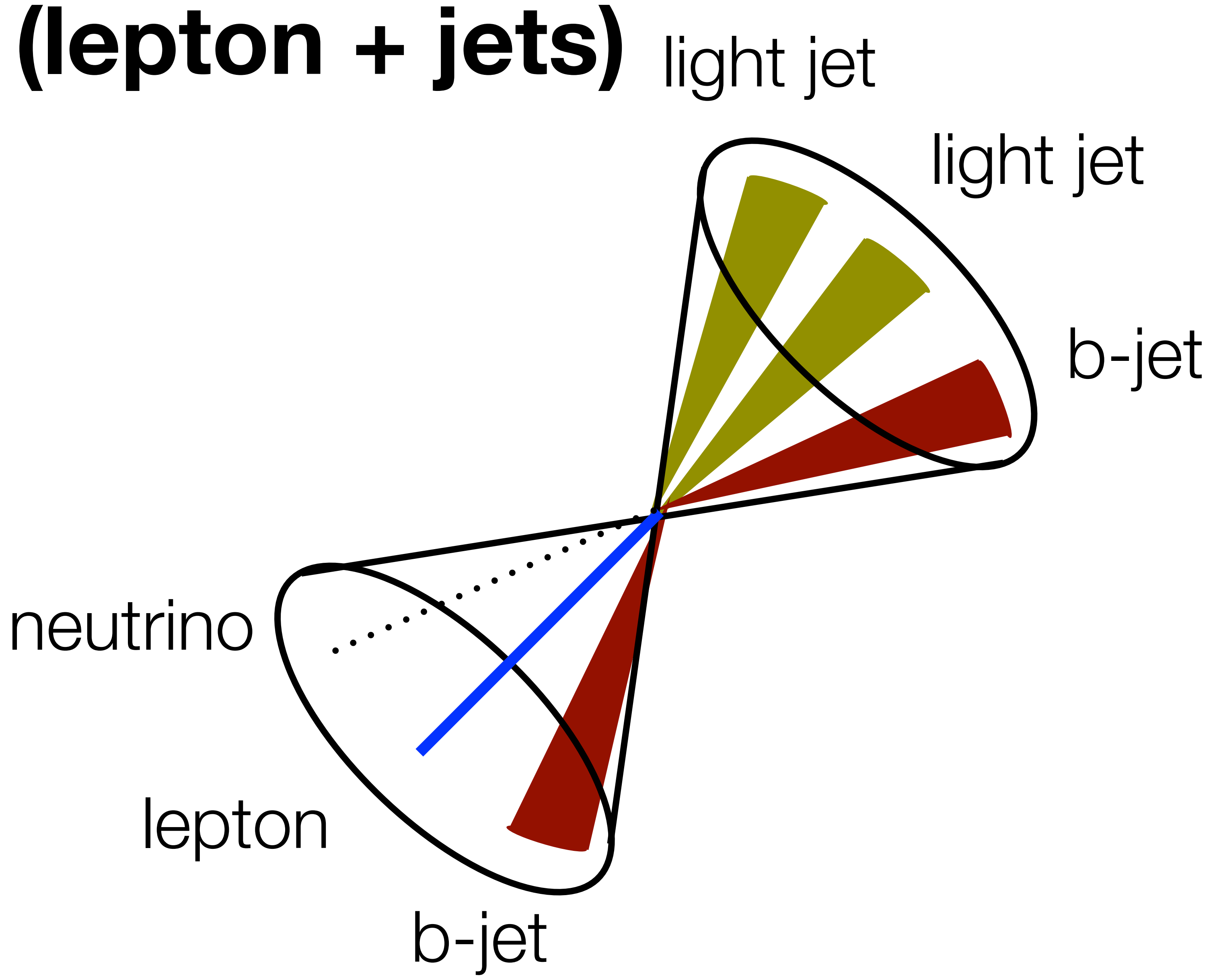
Has become a "standard candle" at the LHC

Top quark pair production

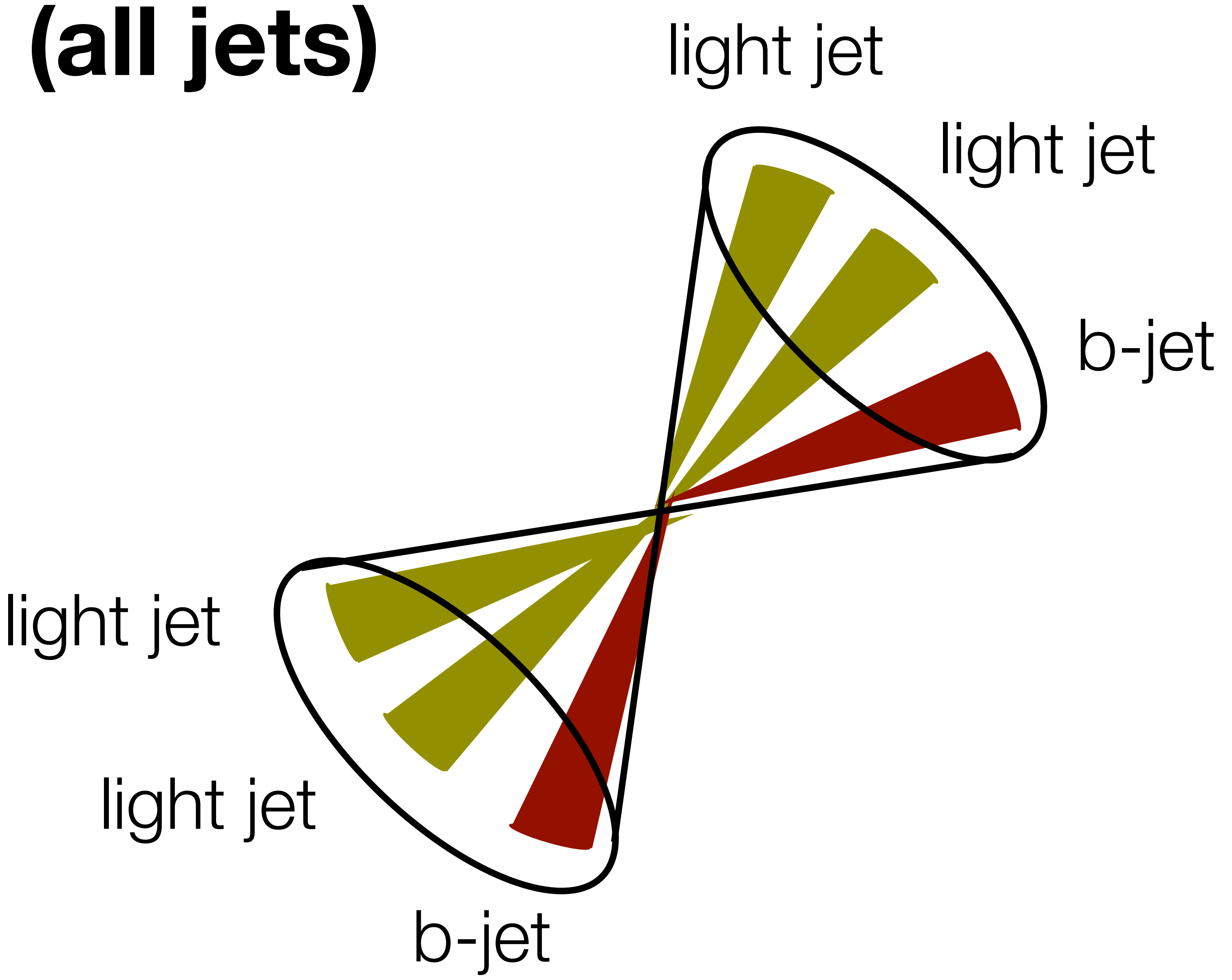
Di-leptonic



Semi-leptonic (lepton + jets)



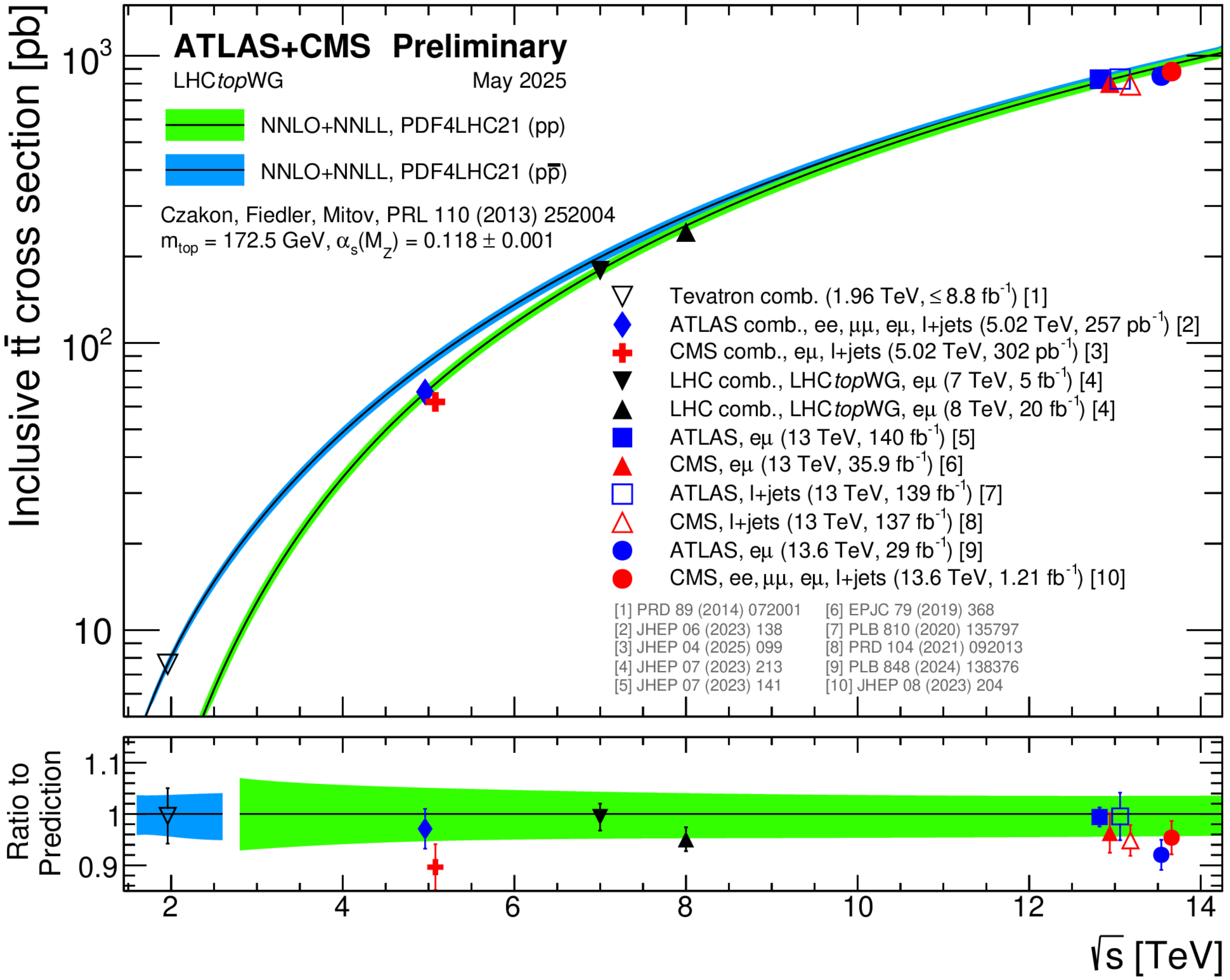
Fully hadronic (all jets)



Higher signal stats but more backgrounds

& combinatorics more challenging

Top pair production cross section



Excellent agreement between measurement and prediction

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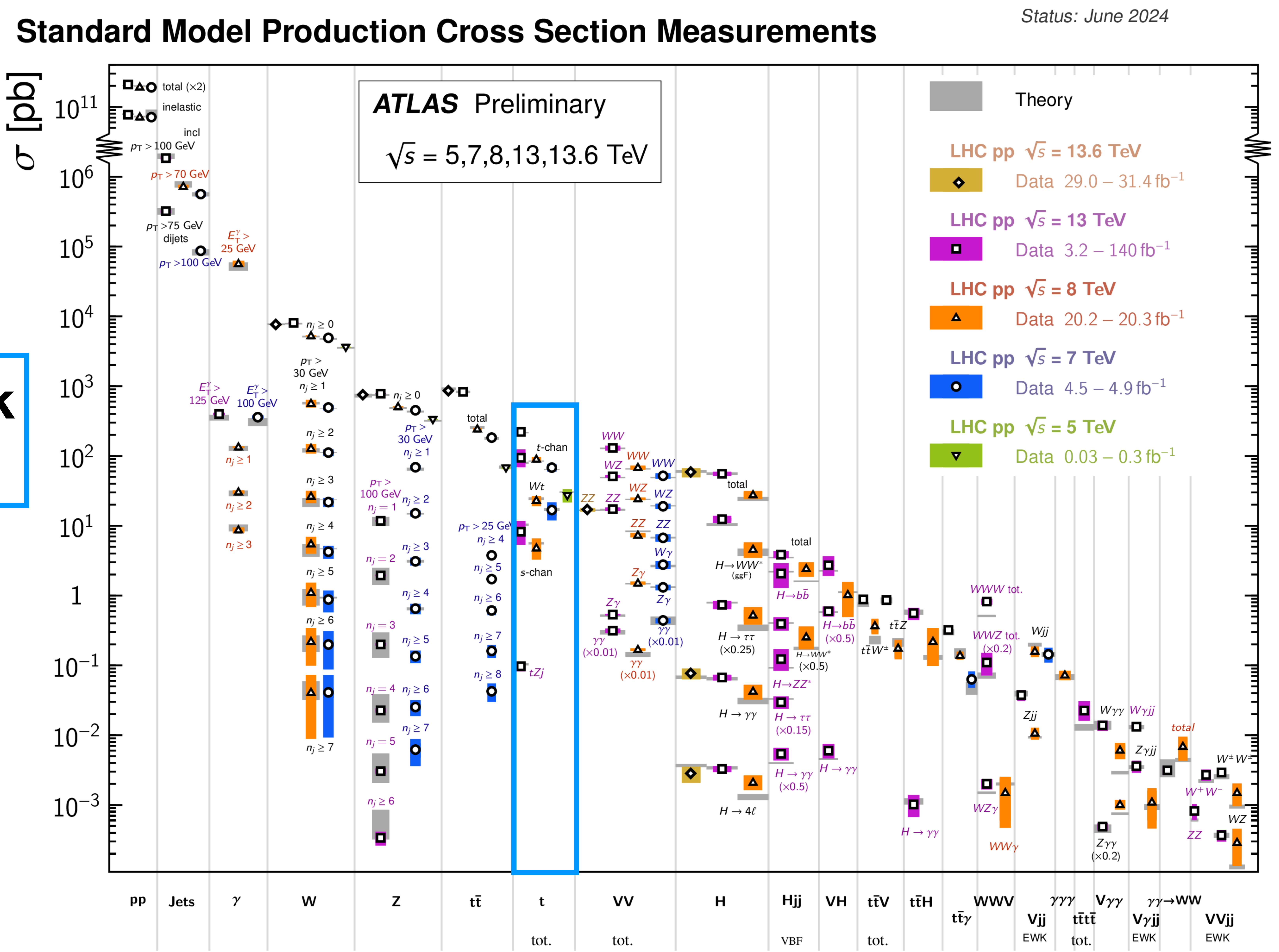
Going to rarer and rarer SM processes



Single top quark production

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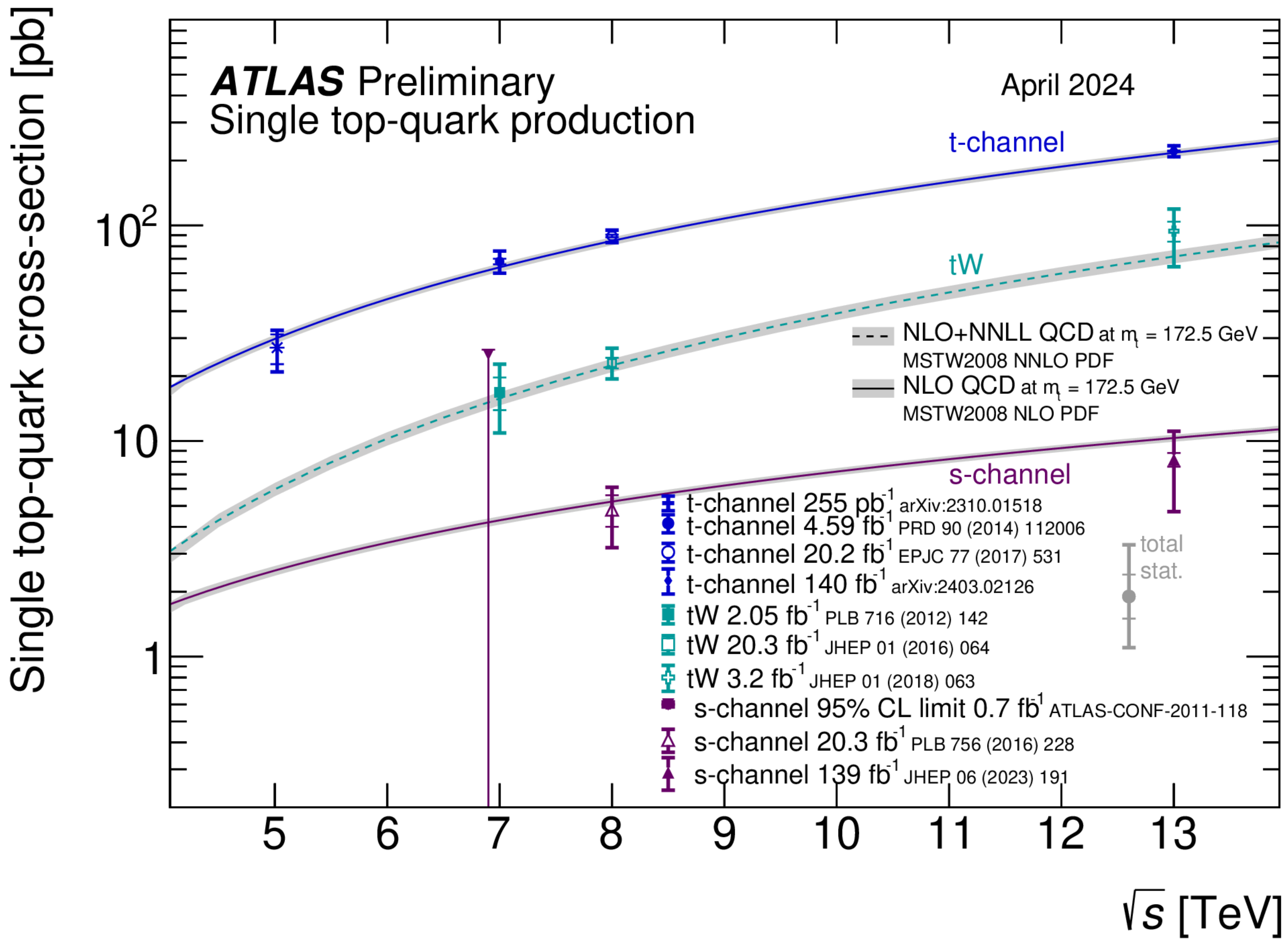
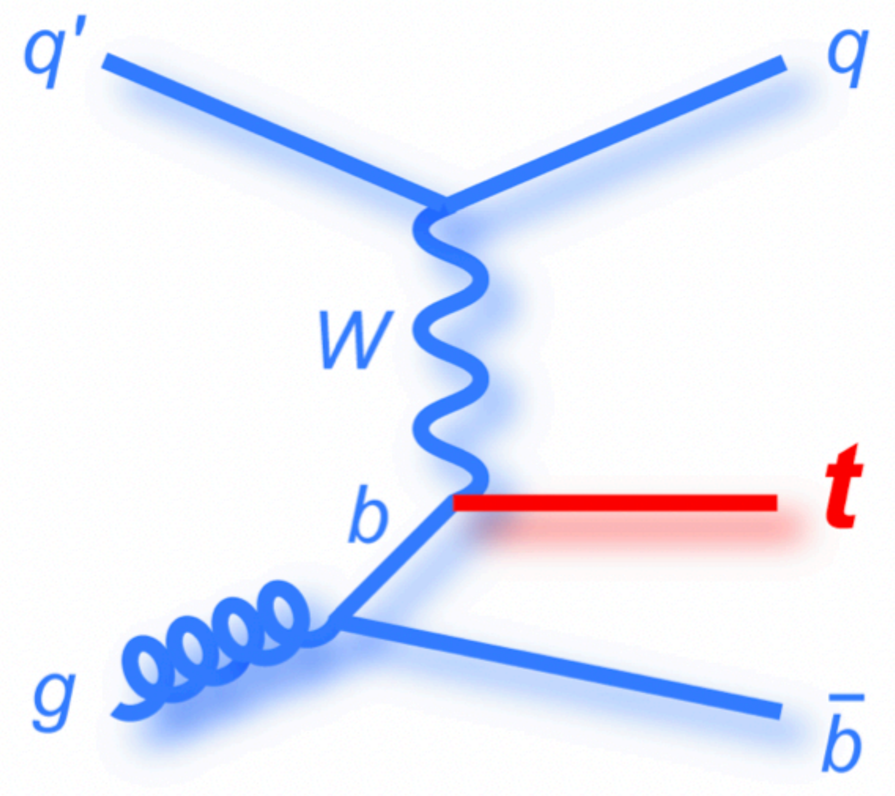
Single top quark production

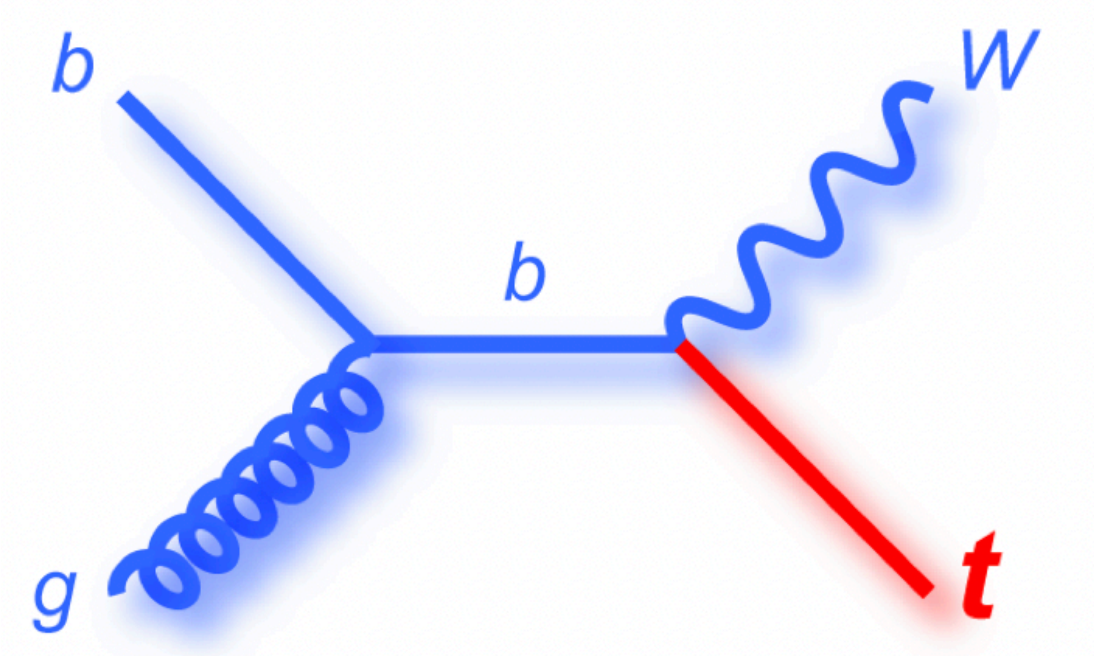
Much rarer process compared to pair production (~ factor 3 lower at 13 TeV)

Three main production modes

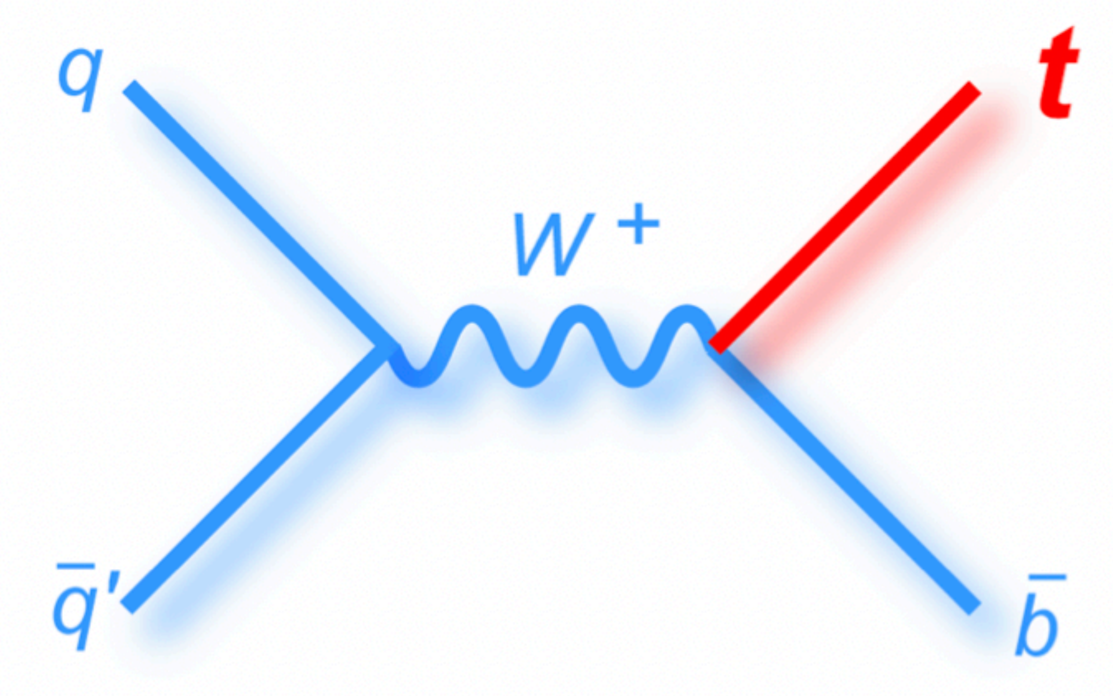




t-channel



tW-channel



s-channel

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1955004

Hot off the press: toponium?

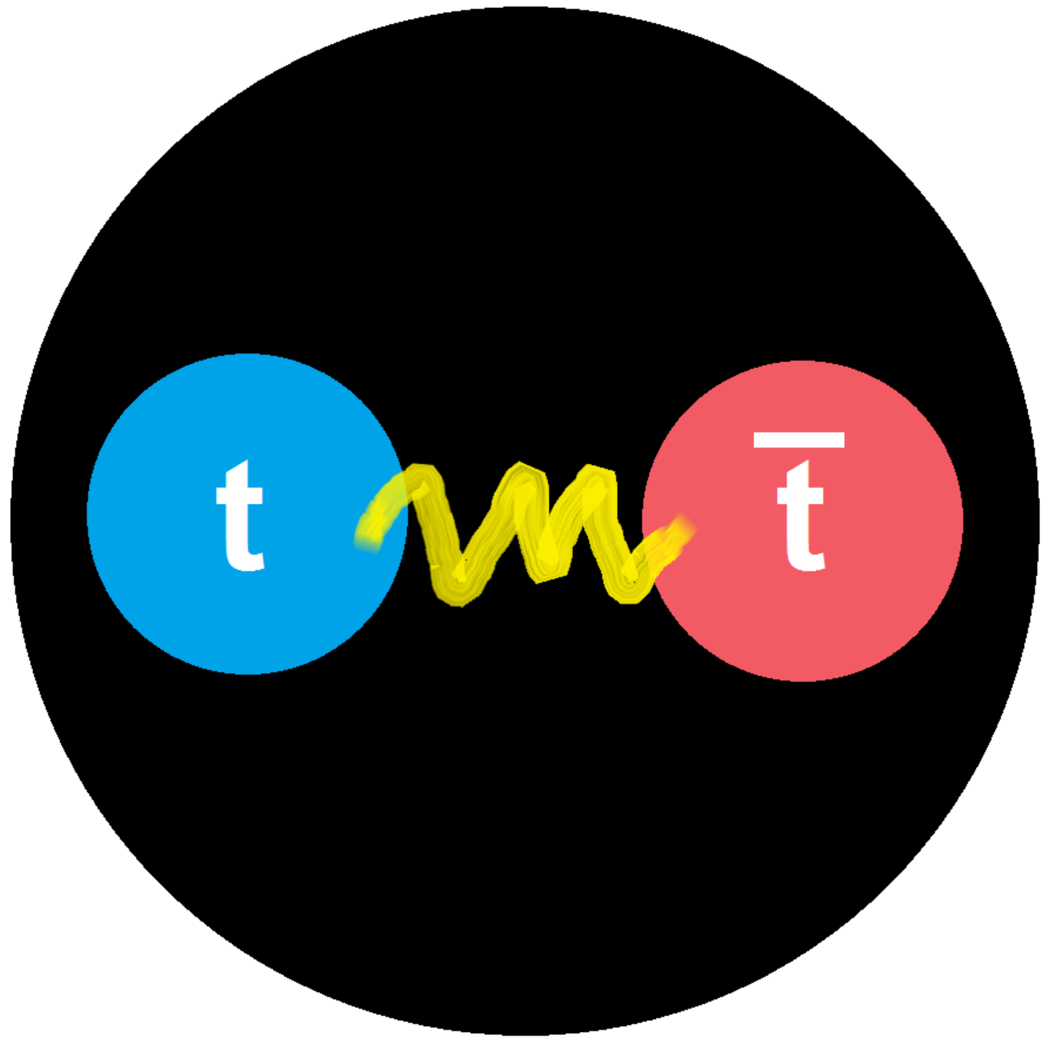
Quarks can form bound states (hadrons) e.g. J/ψ is charm anti-charm

Top quark is very short-lived → Decays before it hadronises

ATLAS & CMS recently observed data excess at top anti-top mass threshold → Could be explained by existence of toponium

Toponium: Top and anti-top momentarily pair up in a "quasi-bound-state"

Toponium



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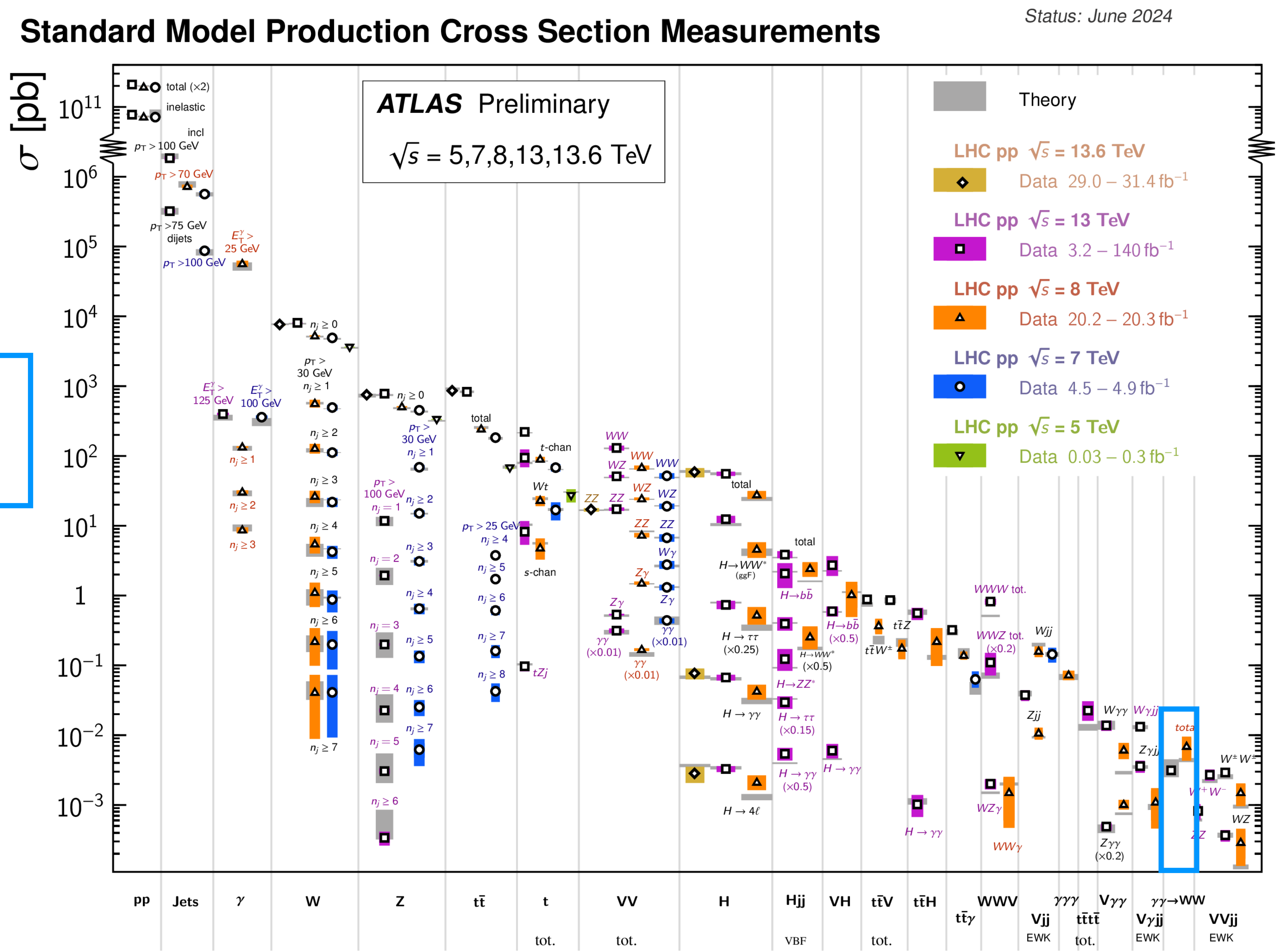
CERN press release

ATLAS-CONF-2025-008

CMS 2503.22382

Going to rarer and rarer SM processes



Photon-fusion WW

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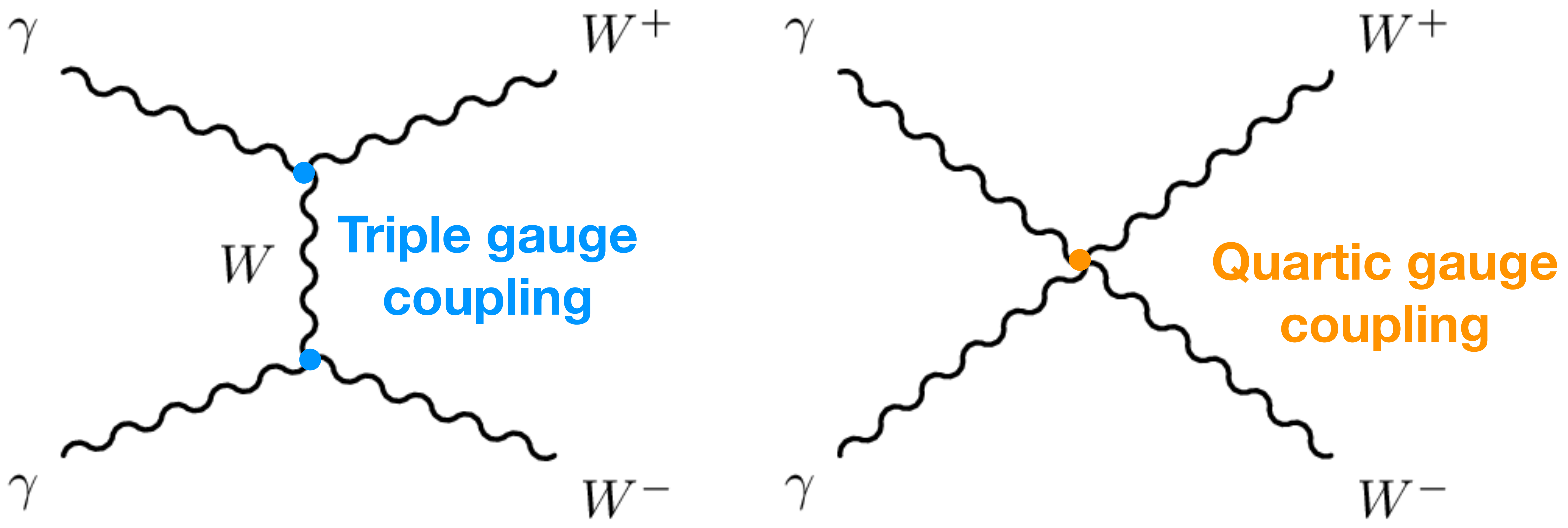
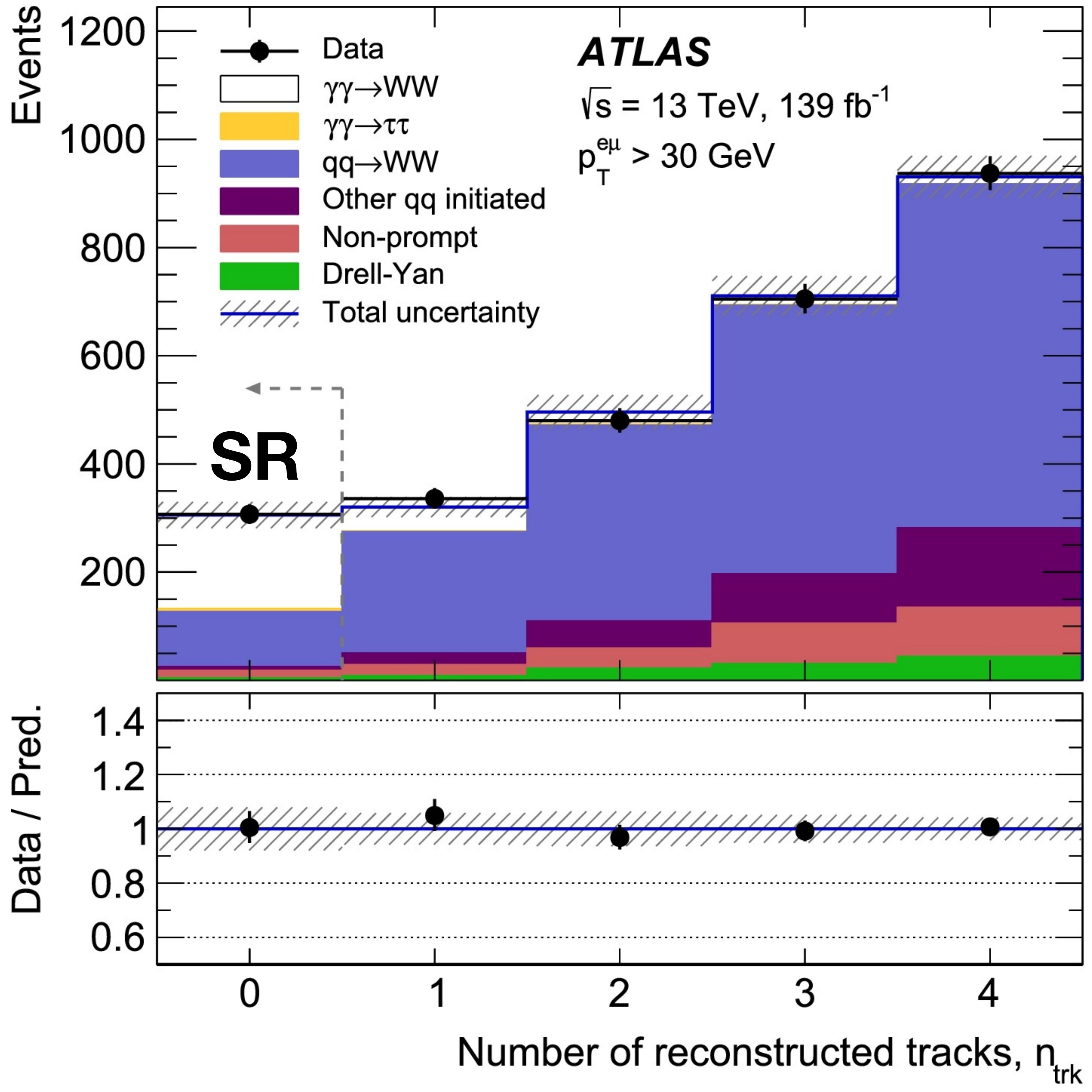
Photon-fusion WW

Use clean $e^{\pm}\mu^{\mp}(+\nu\bar{\nu})$ events

Di-lepton mass > 20 GeV, di-lepton p_T > 30 GeV, n_{trk}=0



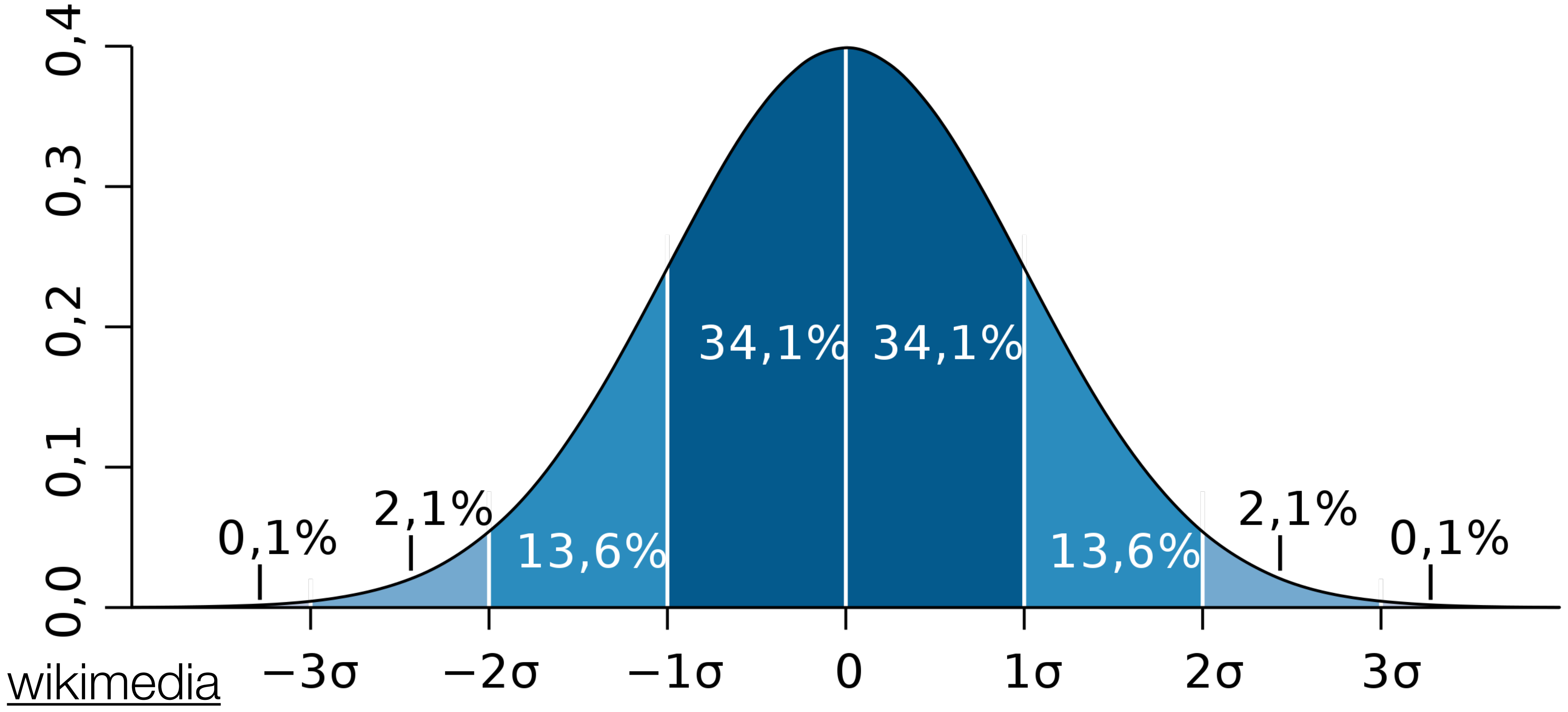


Sensitive to anomalous gauge self-interactions

PLB 816 (2021) 136190

Significances

- **How likely is the excess produced by a fluctuation of the background**
- **Different ways of estimating this, with various approximations**
- **Translate probability into standard deviations**



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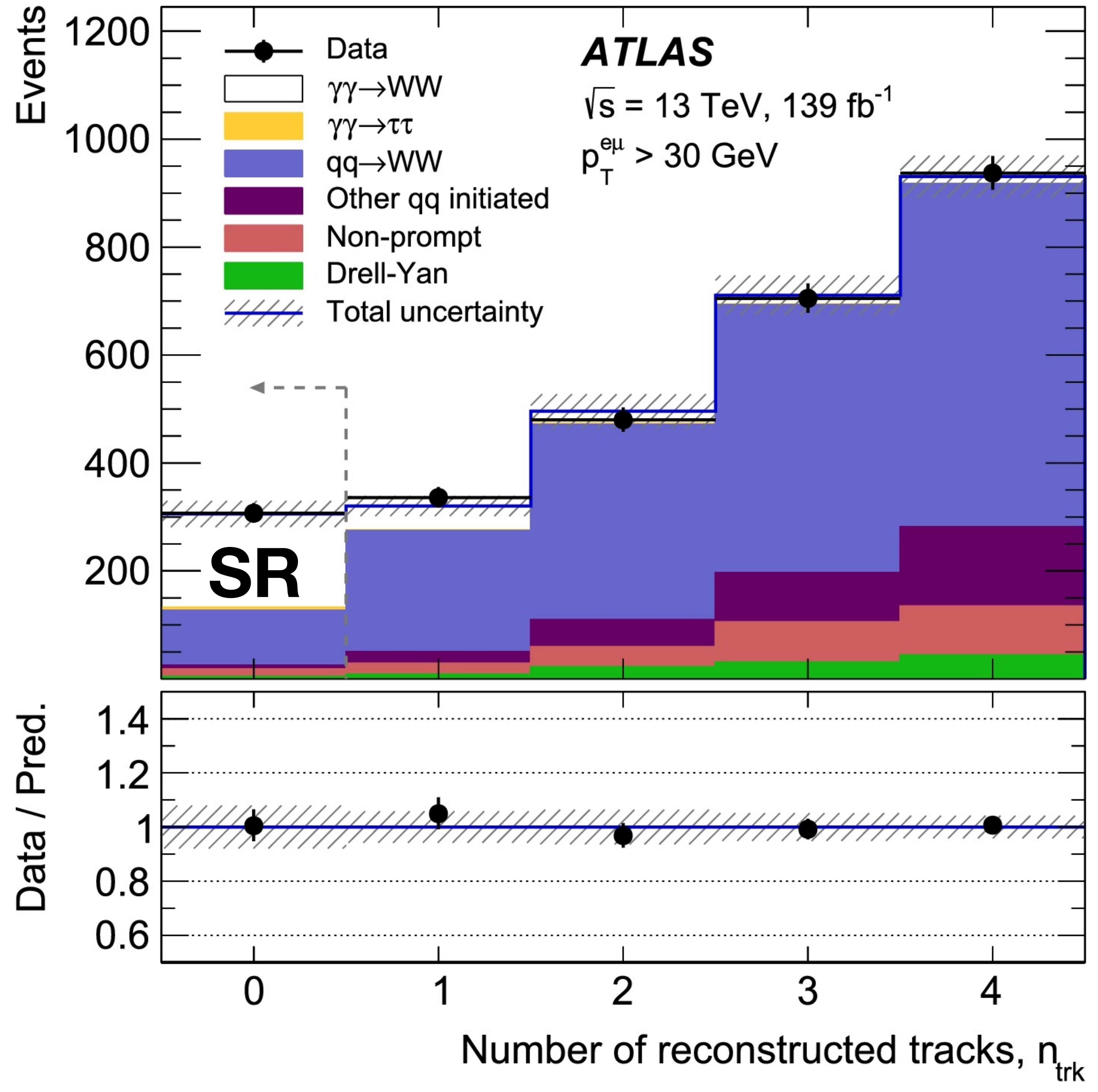
0.05 → 2 sigma

0.003 → 3 sigma (evidence)

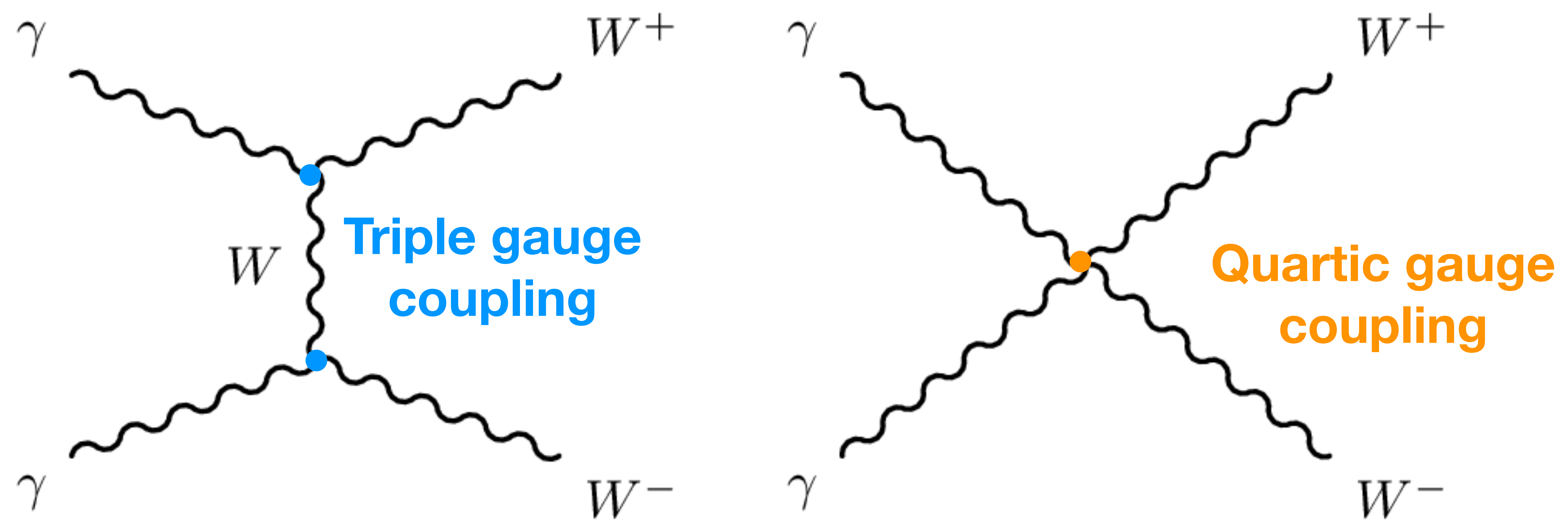
0.0000003 → 5 sigma (discovery)



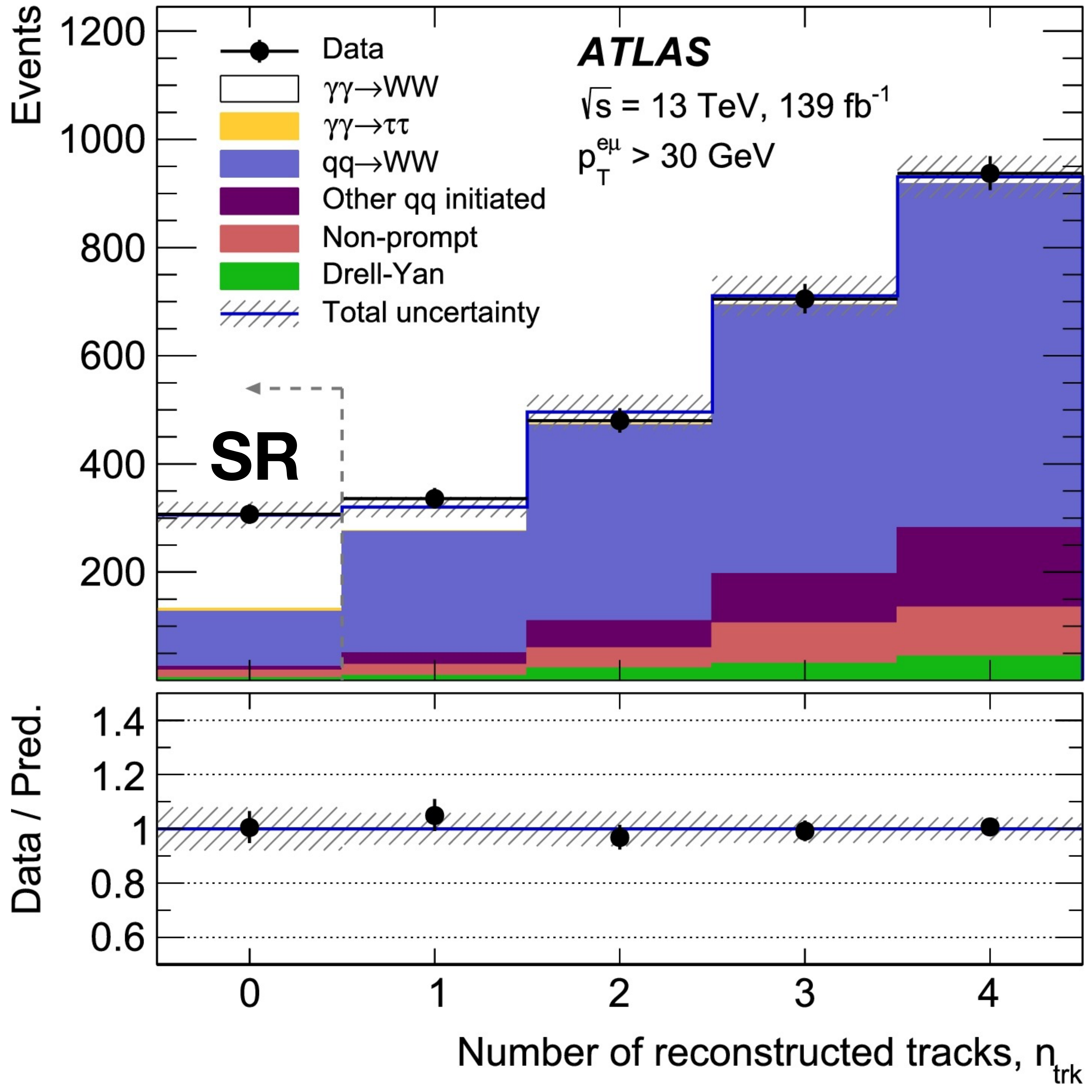
Imagine this plot without the white histogram

Photon-fusion WW

Observed significance well above 5 sigma



$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\text{ fb}$$



Sensitive to anomalous gauge self-interactions

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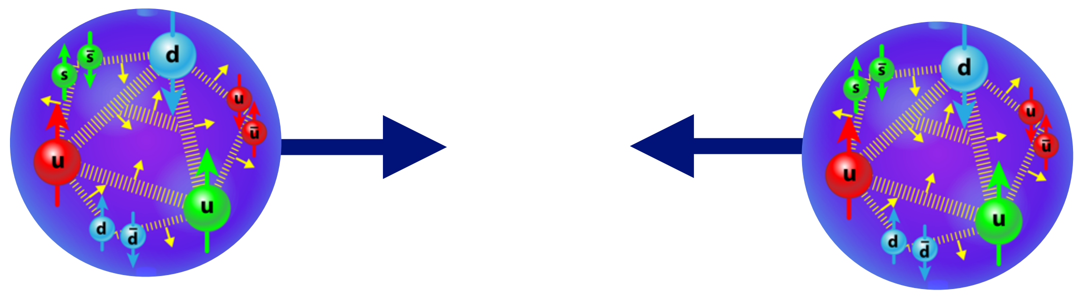
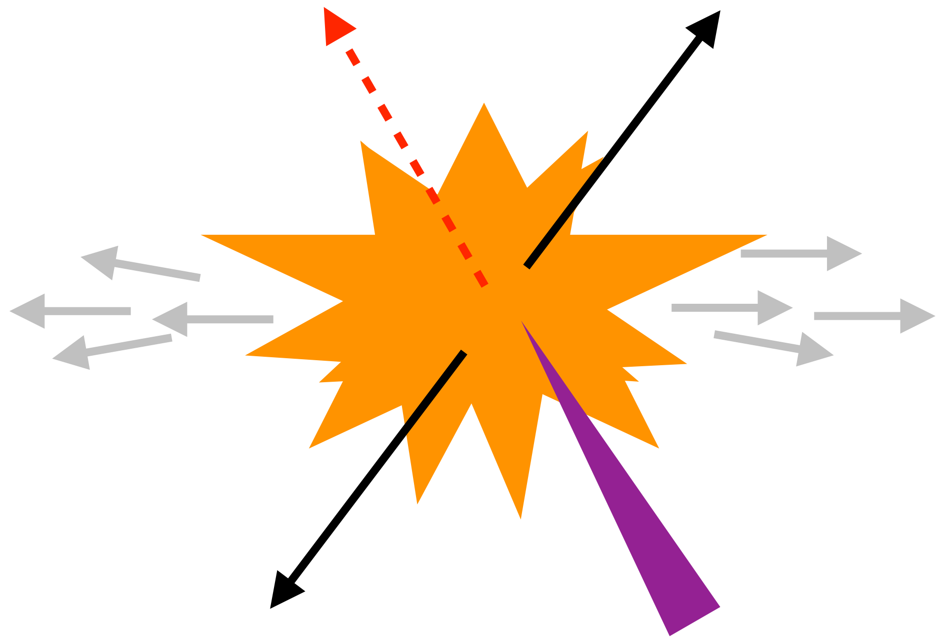
The LHC as a photon collider

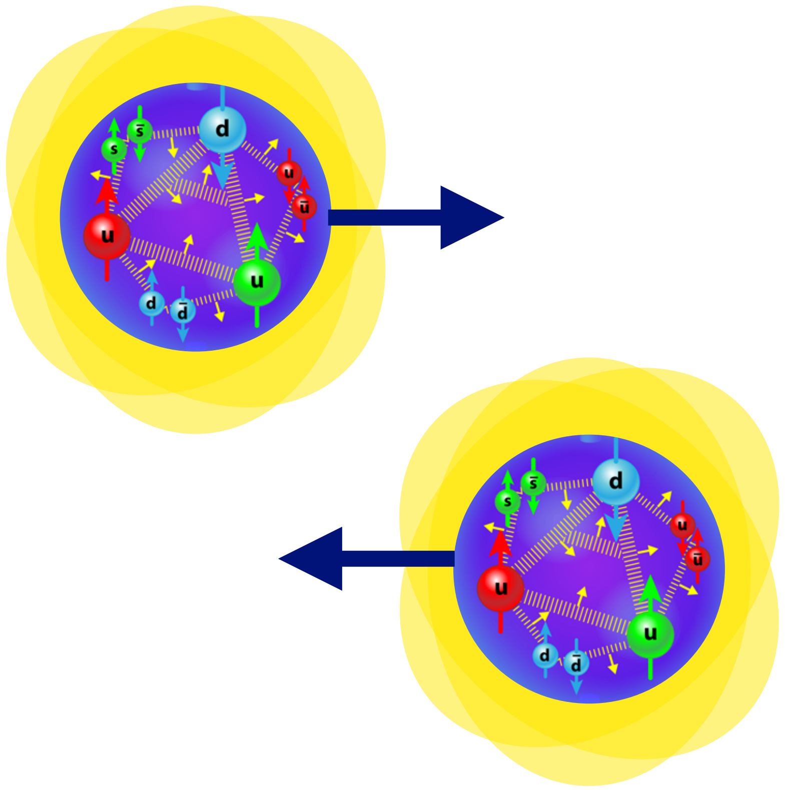
Head-on collision



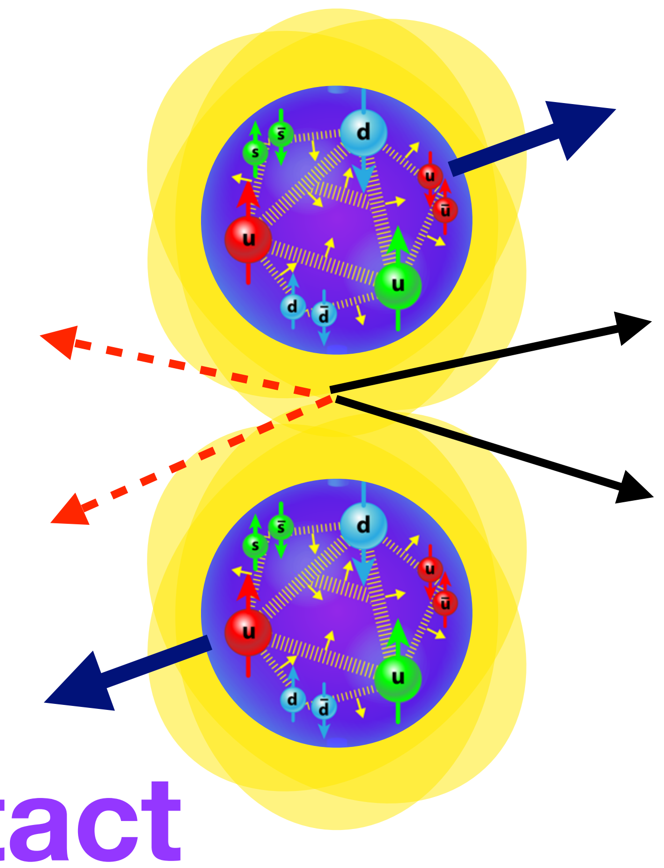
Partons collide
to produce new particles



Protons 'miss'



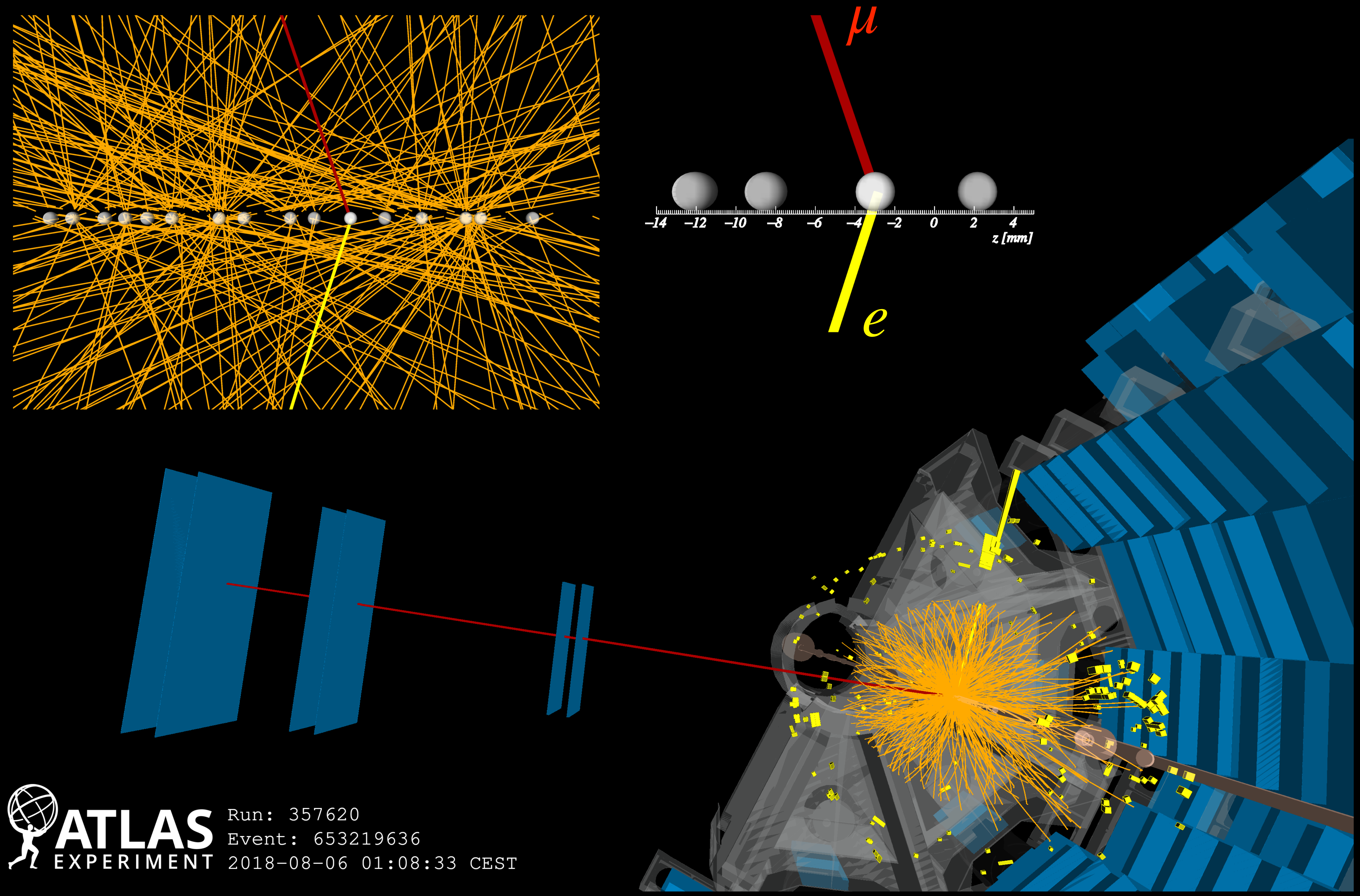
Photons collide
to produce new particles



**Protons
can remain intact**

LHC is the world's highest energy photon collider

Photon-fusion WW candidate event



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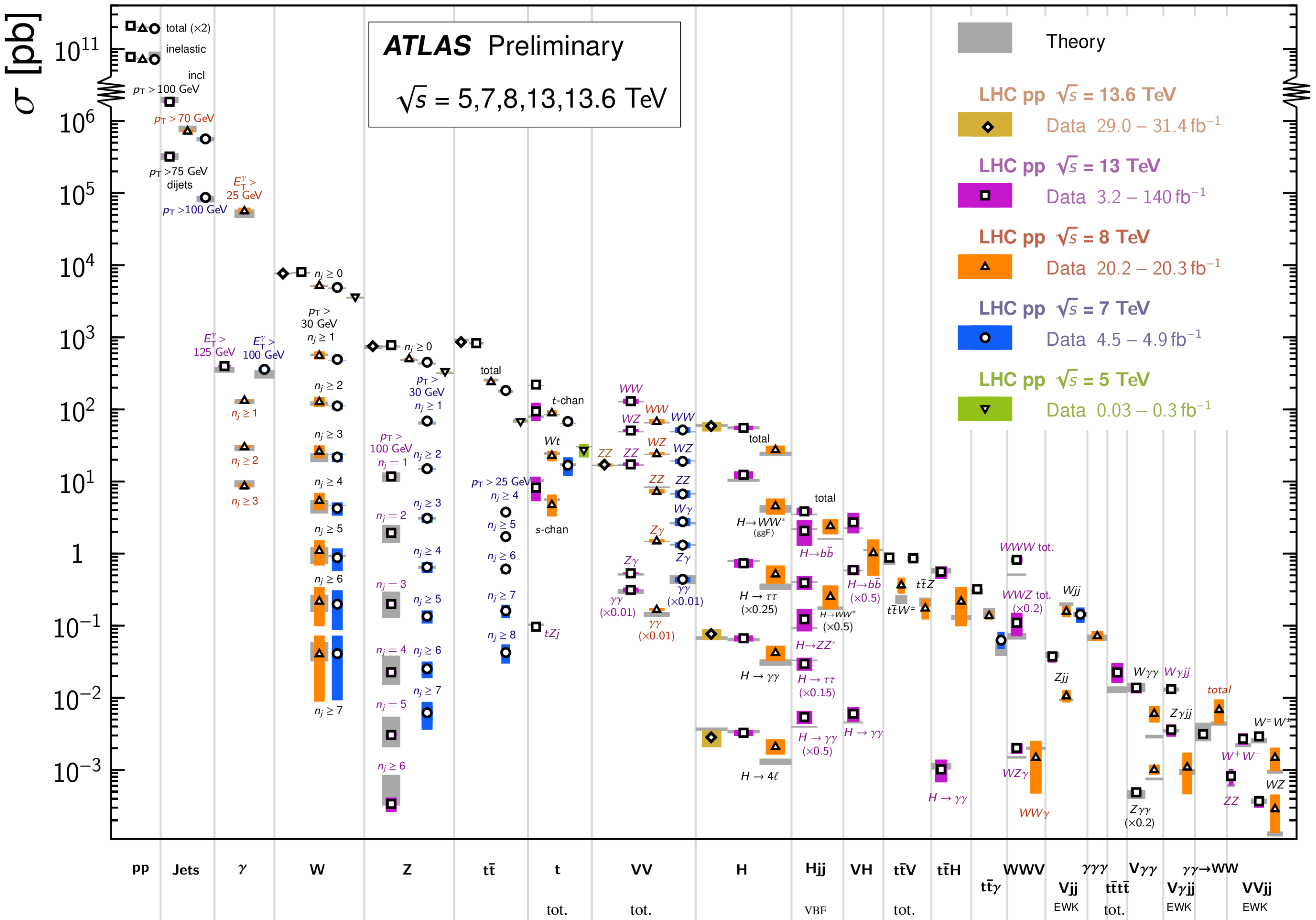
Standard Model Production Cross Section Measurements

Status: June 2024



Measuring top quark mass

Fermion masses are free parameters in SM

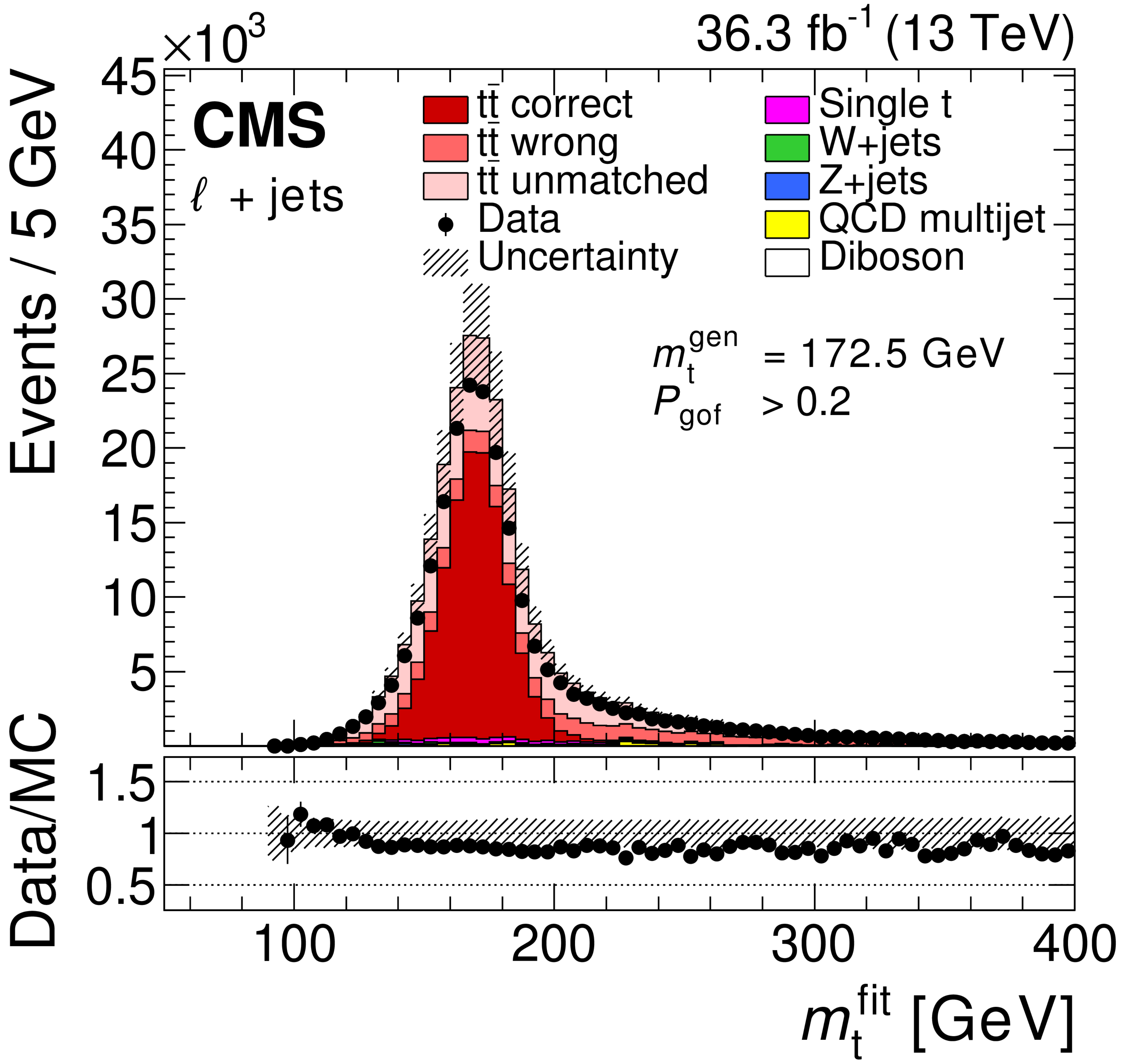
Top quark is heaviest particle in SM, does it play a special role?

W, top & Higgs masses are related

CMS most precise single measurement

171.77 ± 0.38 GeV

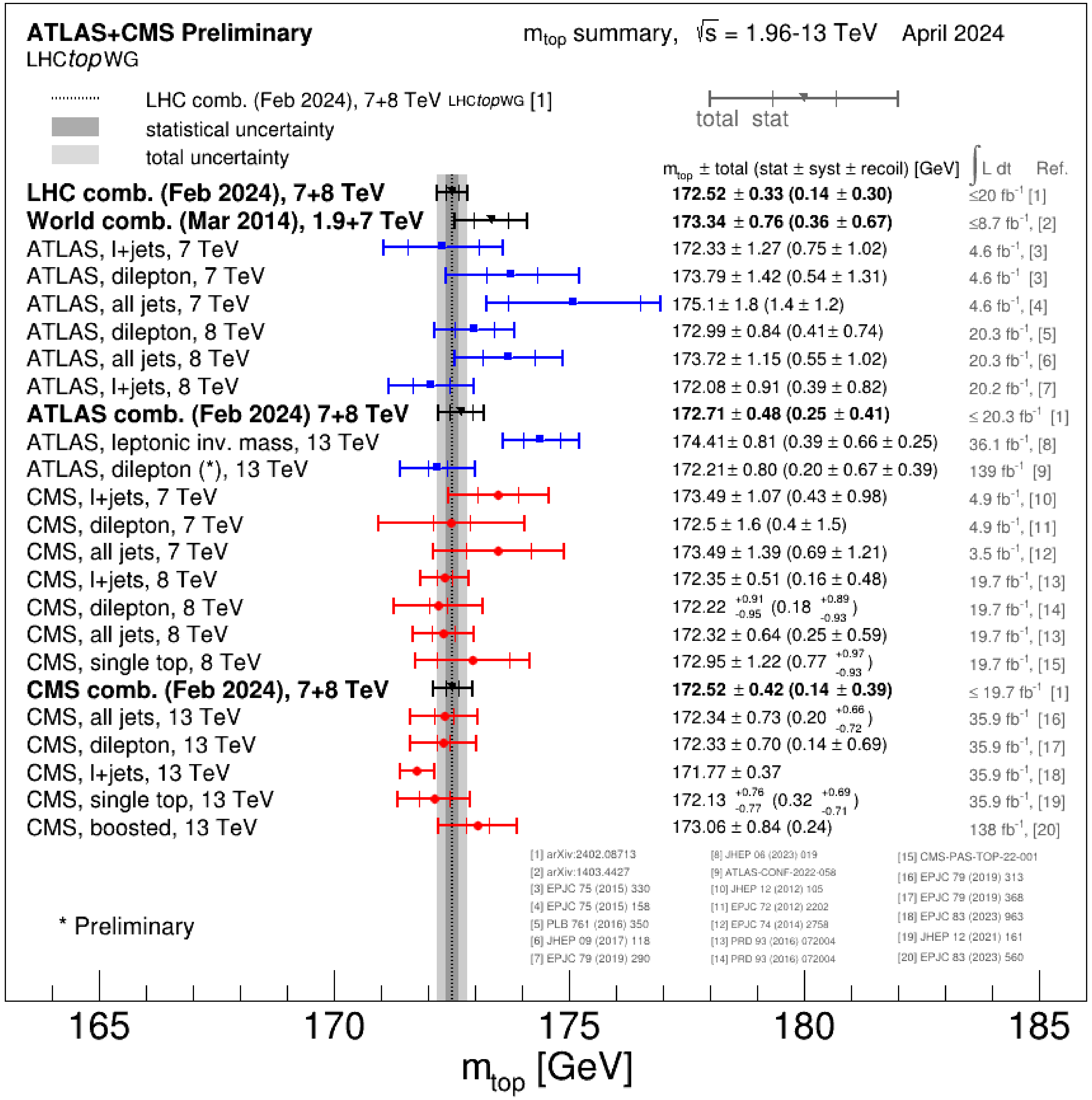
(Including 0.04 GeV statistical uncertainty)



Measuring top quark mass

All channels used to measure top quark mass

LHCTopWGSummaryPlots

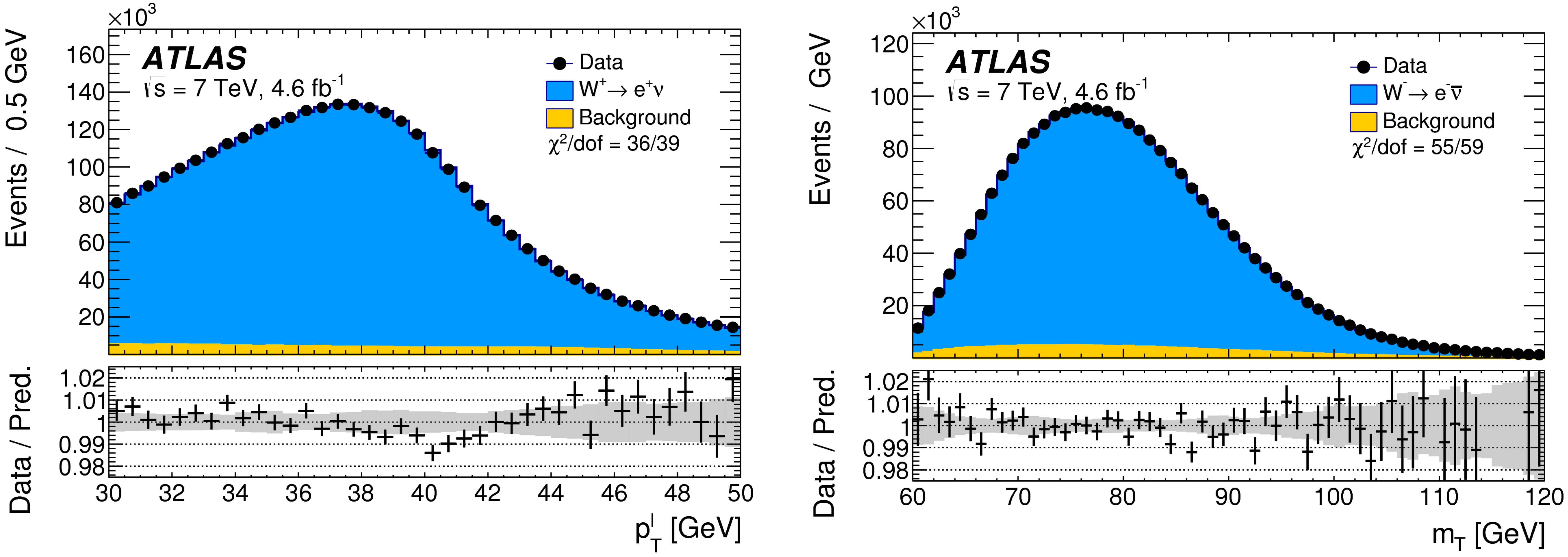


ATLAS W mass measurement

Special dataset collected with low pile-up

4.6 fb^{-1} at 7 TeV → about 15.5 M W^+ and 10.4 M W^- events collected (leptonic decays)

Analysis strategy based on two kinematic distributions fitted in several categories



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

$\Delta\phi$ Is beween charged lepton and missing transverse momentum

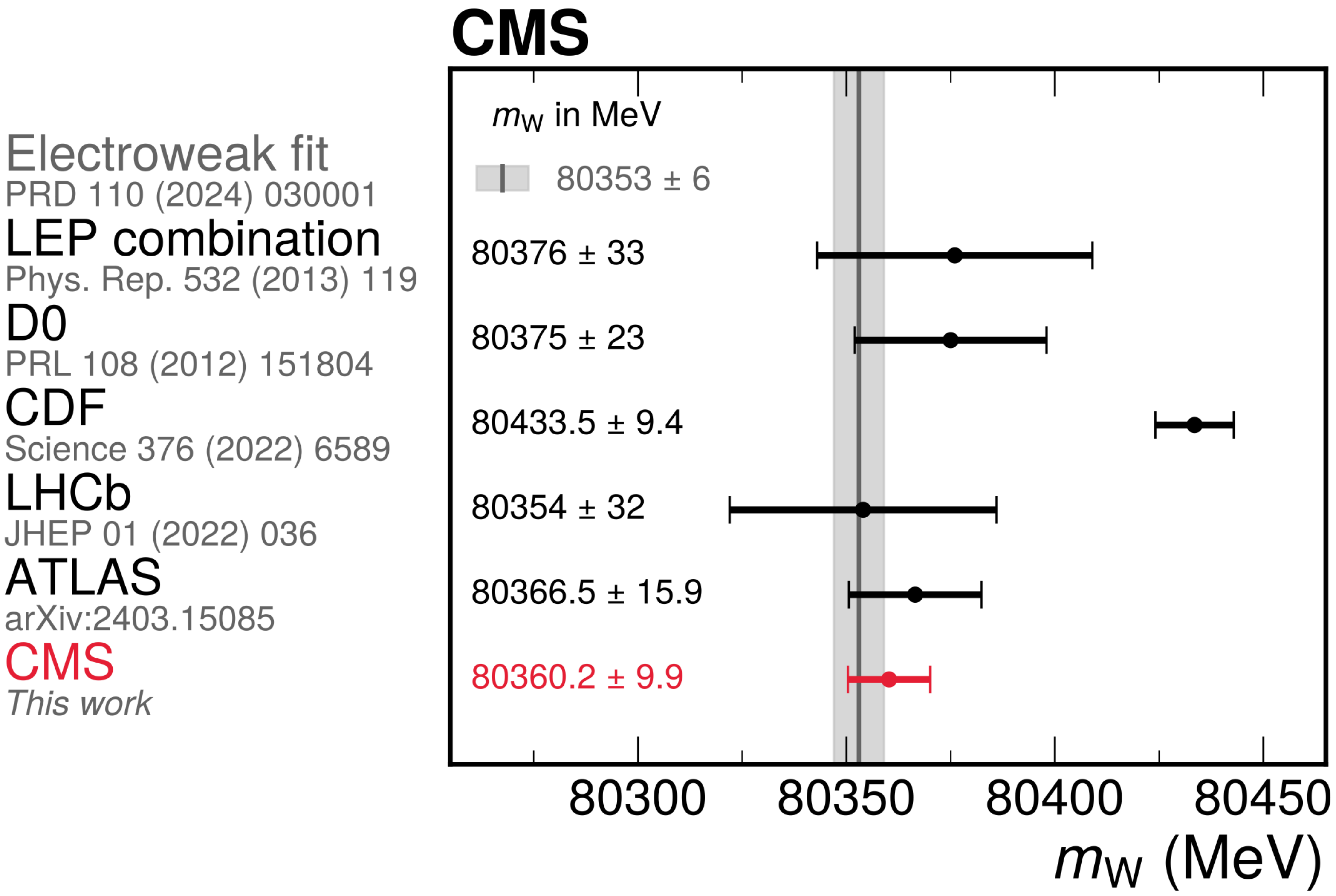
$$\begin{aligned} m_W &= 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14(\text{mod. syst.})\text{MeV} \\ &= 80370 \pm 19\text{MeV}, \end{aligned}$$

13 TeV low pile-up dataset on tape
→ Stay tuned!

Eur. Phys. J. C 78 (2018) 110

W bosons

Recent CMS measurement using high pile-up dataset: 80360.2 ± 9.9 MeV



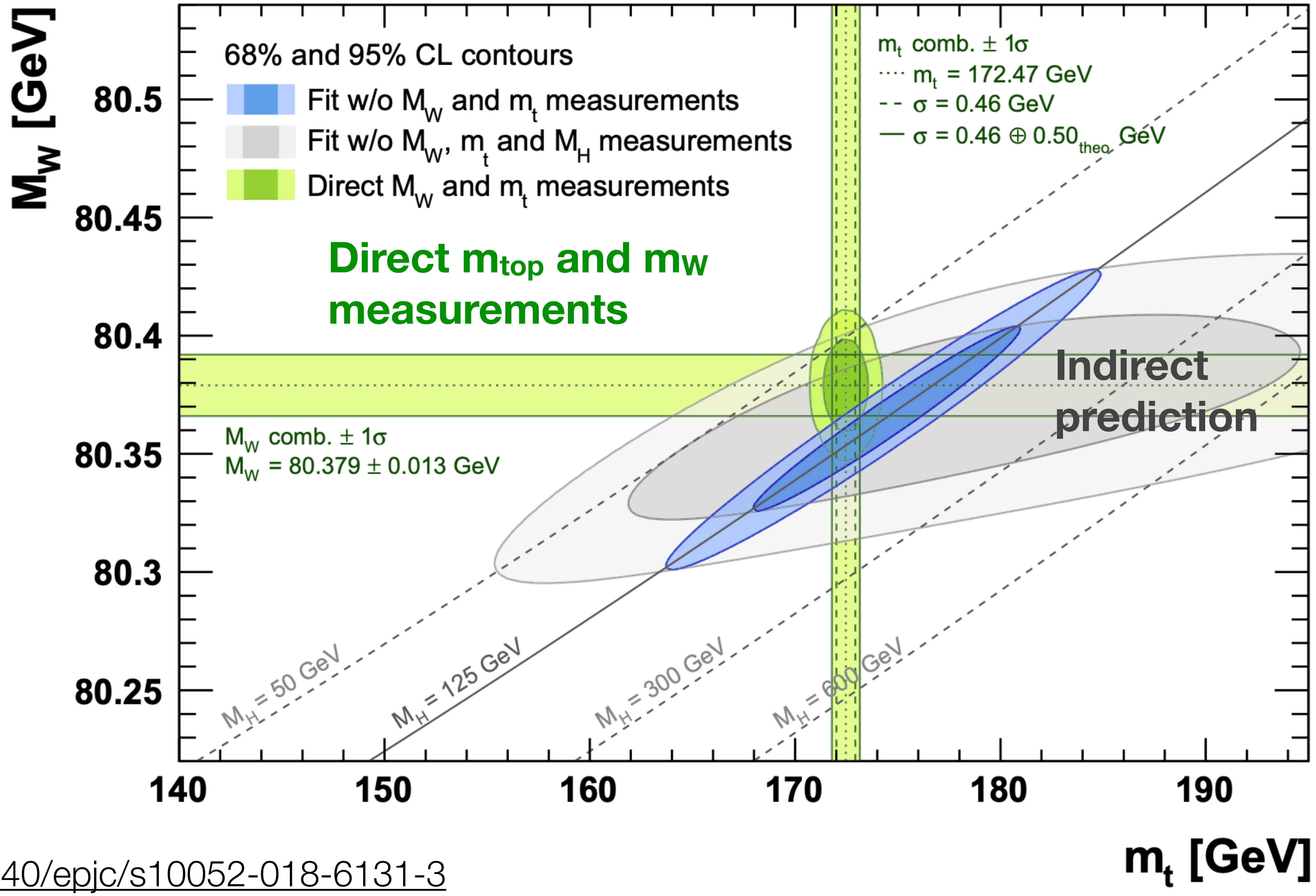
2412.13872

A word on global SM fits

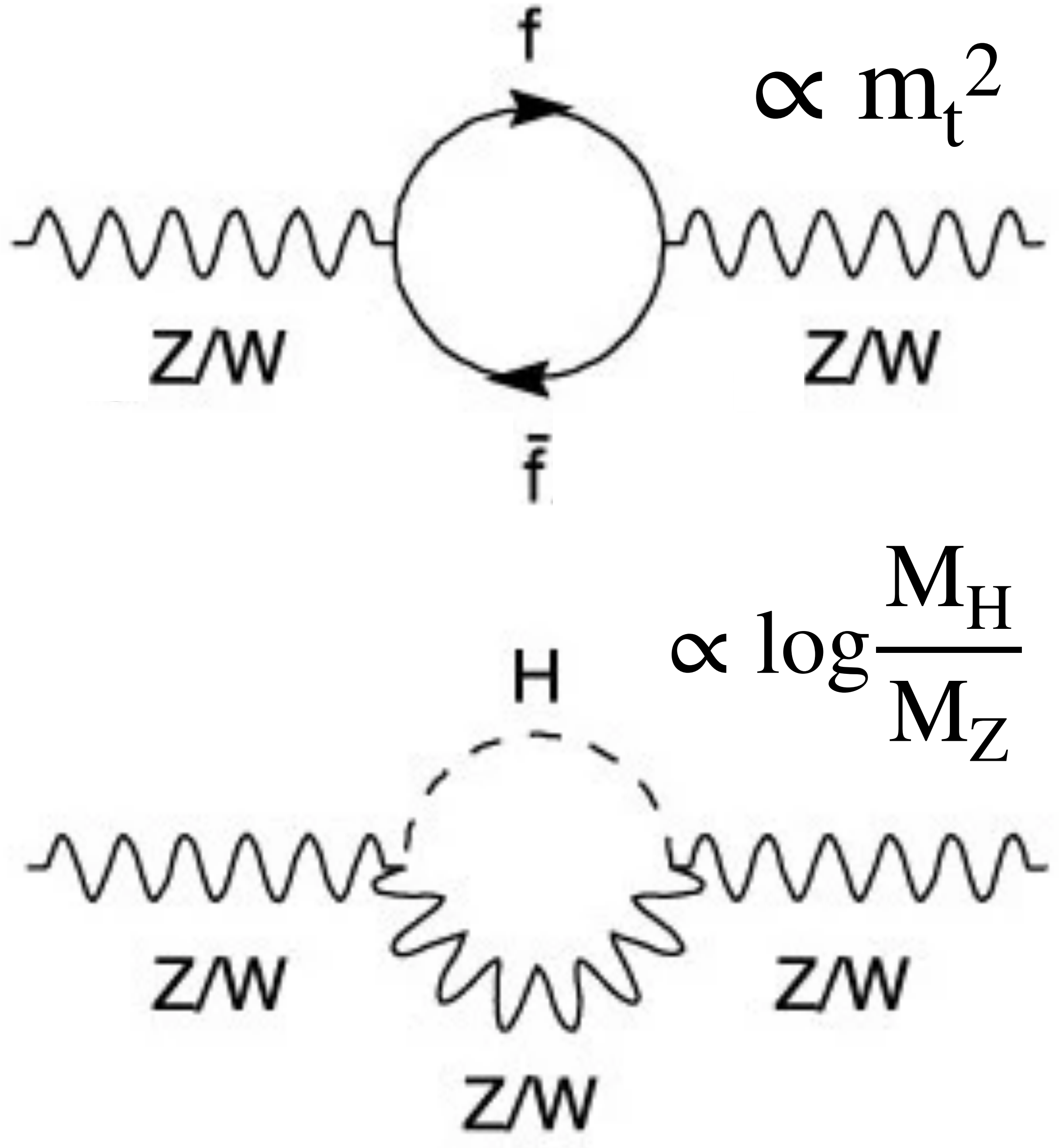
Top, W, Higgs mass are related through higher order corrections

Indirectly 'predict' top mass and Higgs mass before discoveries

New CDF & CMS measurements not included



10.1140/epjc/s10052-018-6131-3

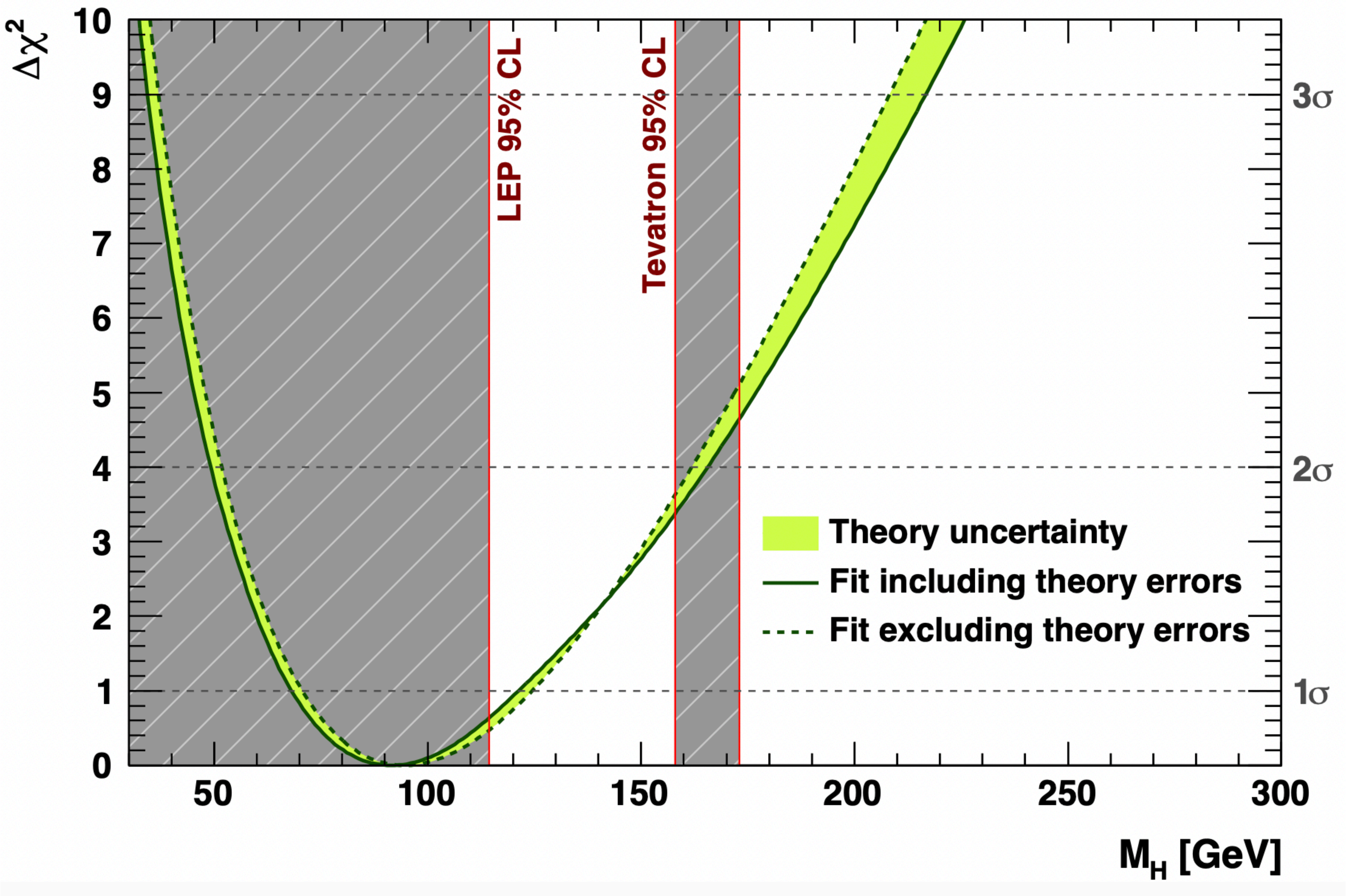


Nature 428, 141–144 (2004)

SM internally consistent

SM fits before the Higgs discovery: 2012

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



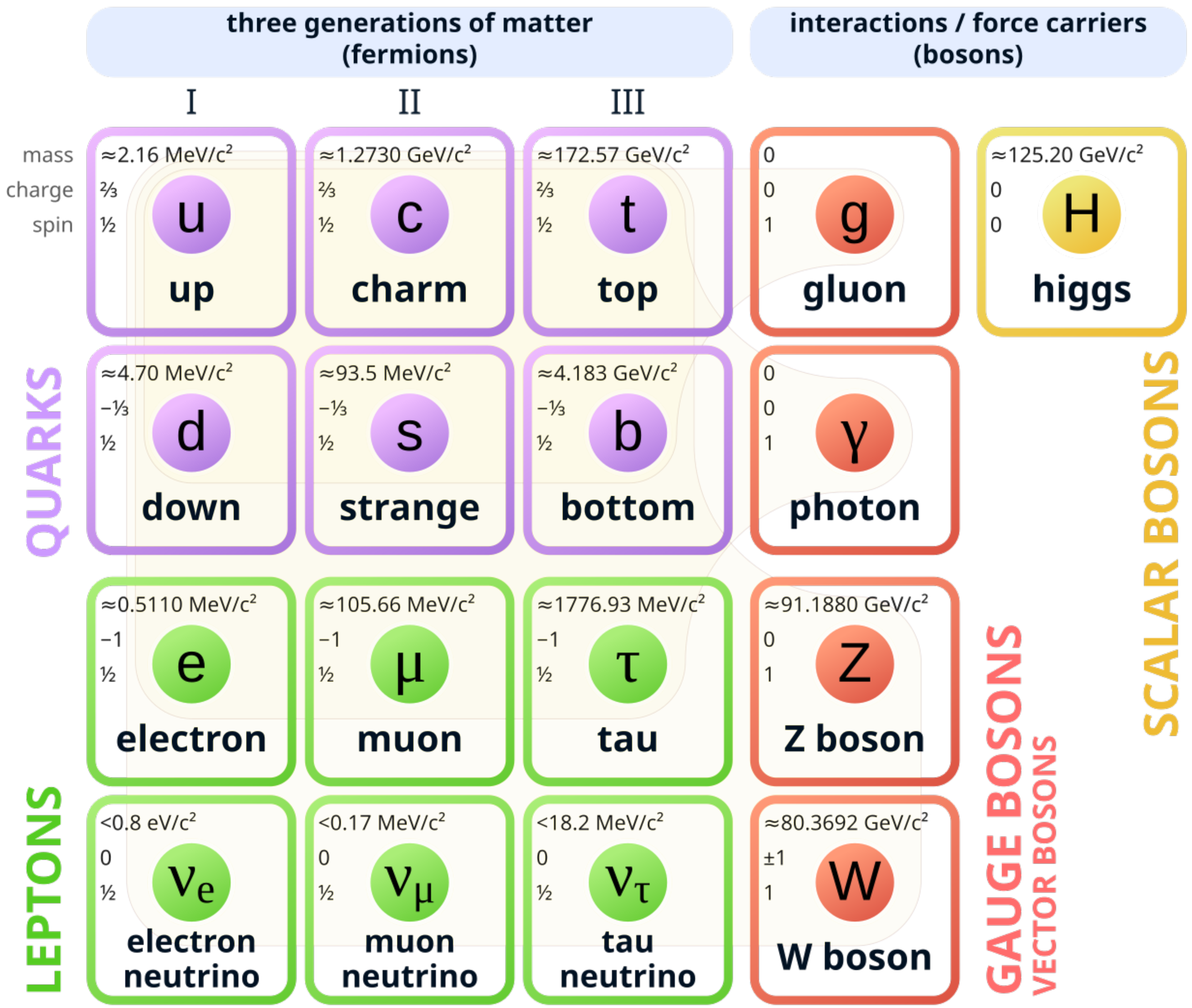
Eur. Phys. J. C72 (2012) 2003

Next lecture

wikimedia

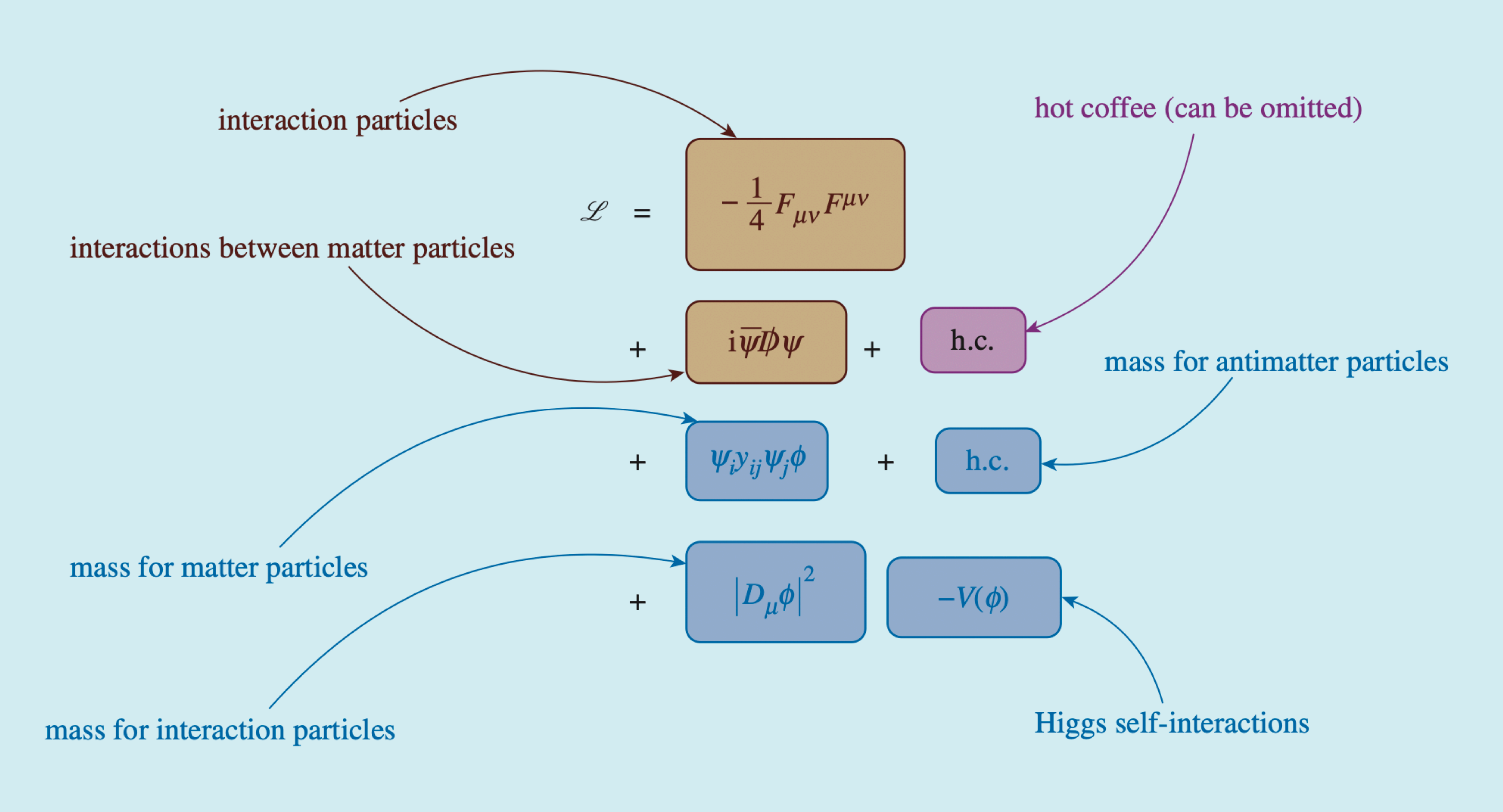
Search for the Higgs Boson

Standard Model of Elementary Particles



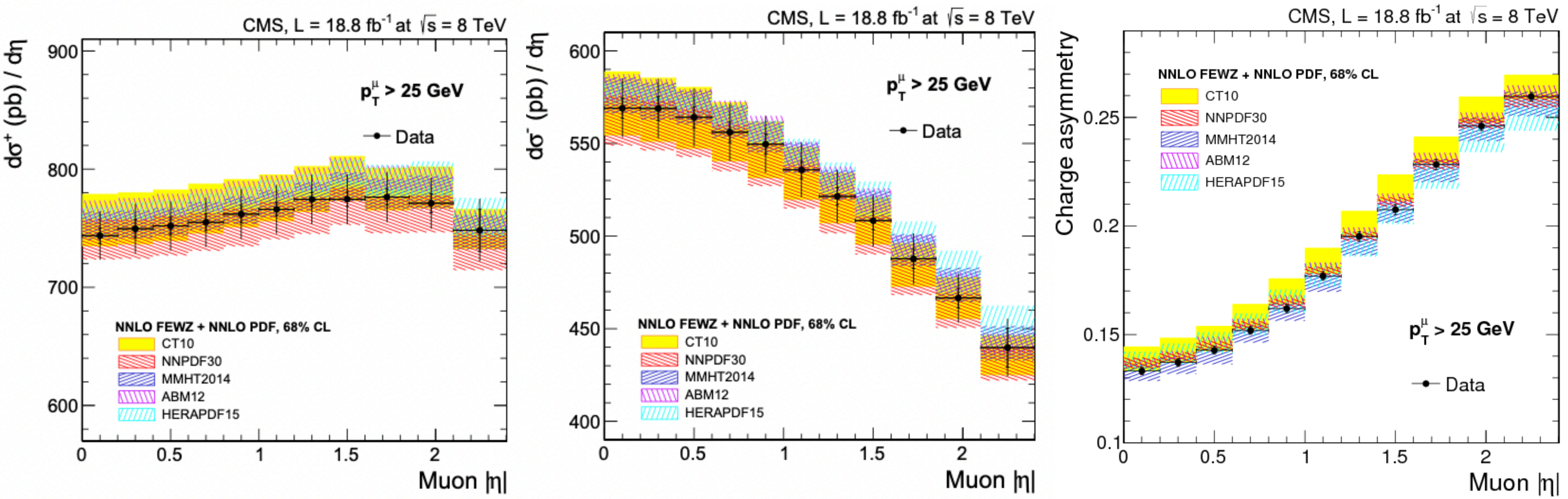
wikipedia

The Standard Model



Julia Woithe et al 2017 Phys. Educ. 52 034001

In practice: measure lepton charge asymmetry

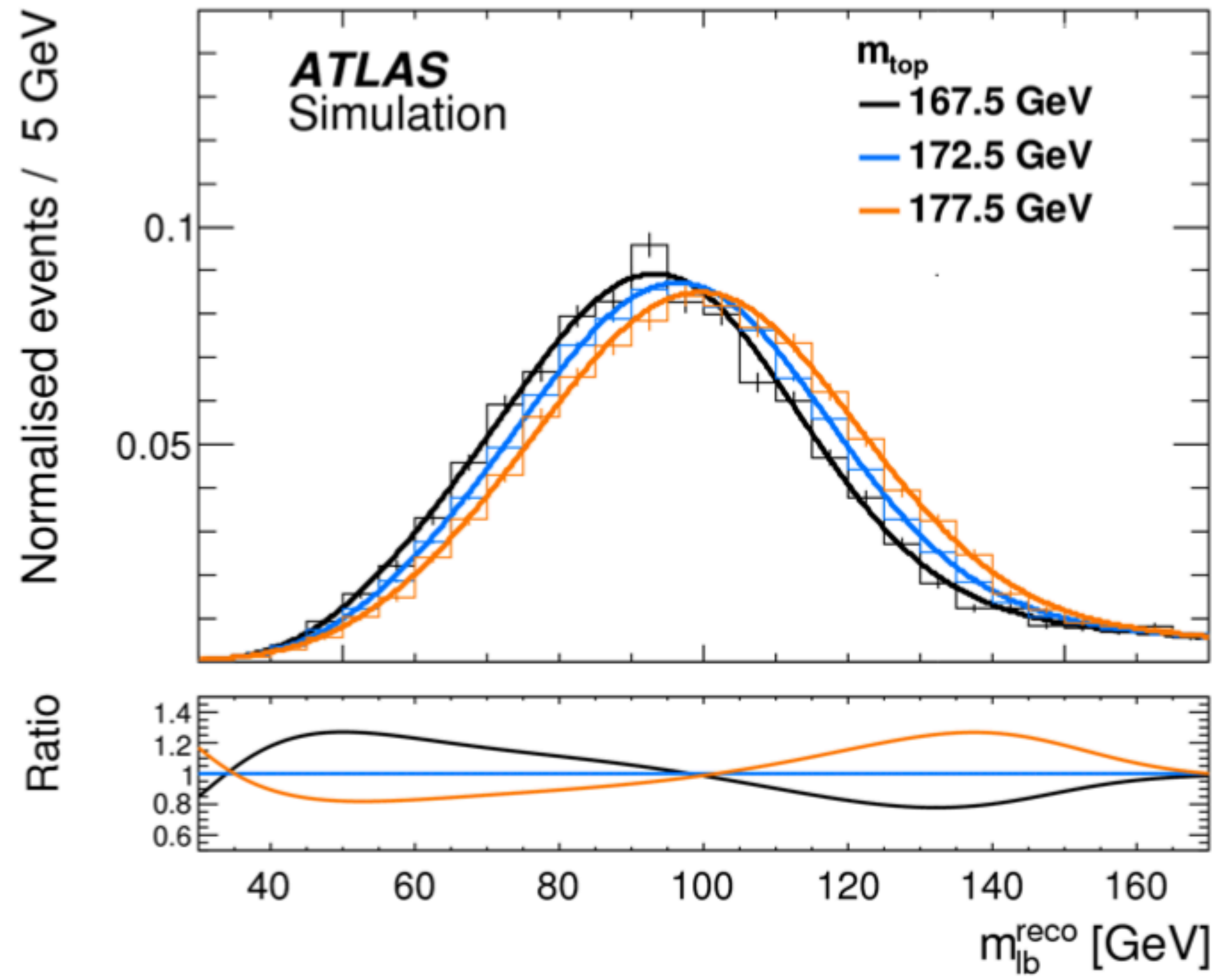


$$\mathcal{A}(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$$

Eur. Phys. J. C 76 (2016) 469

Top quark mass measurement

MC Mass



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