Standard Model Processes

Course on Physics at the LHC

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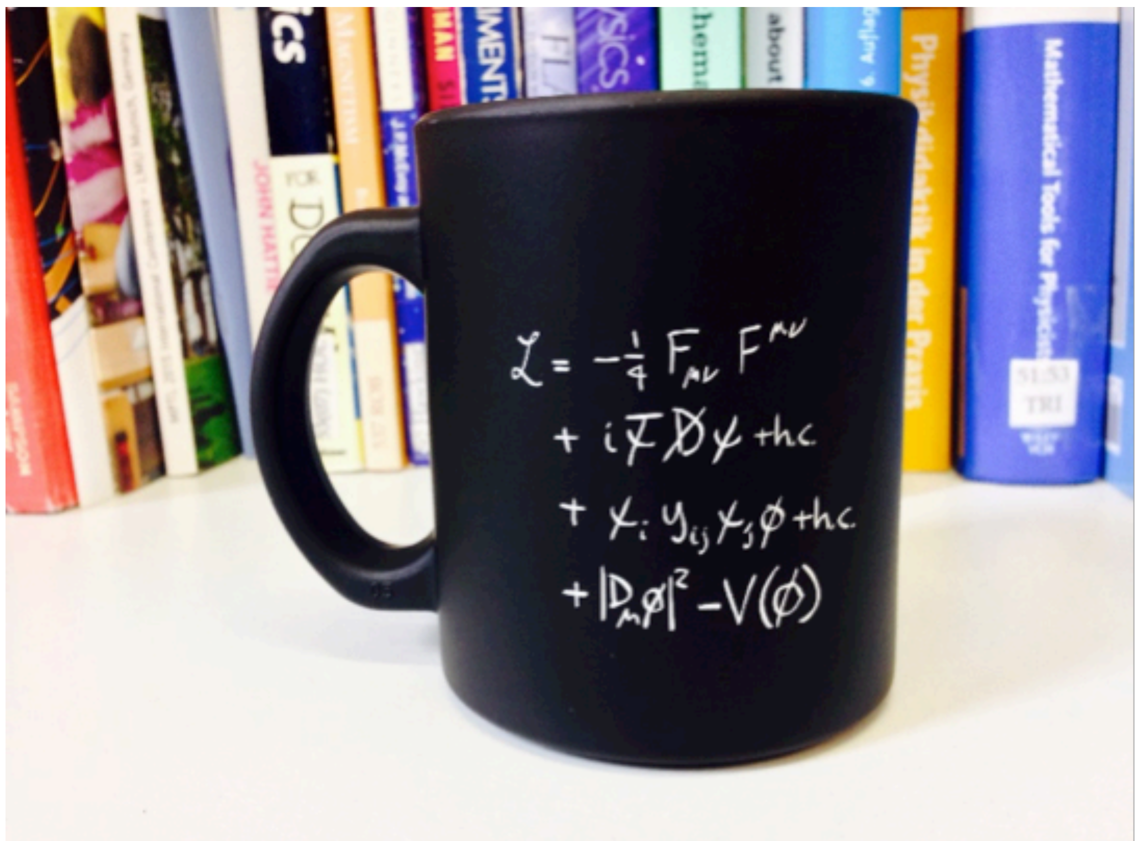
March 14, 2022

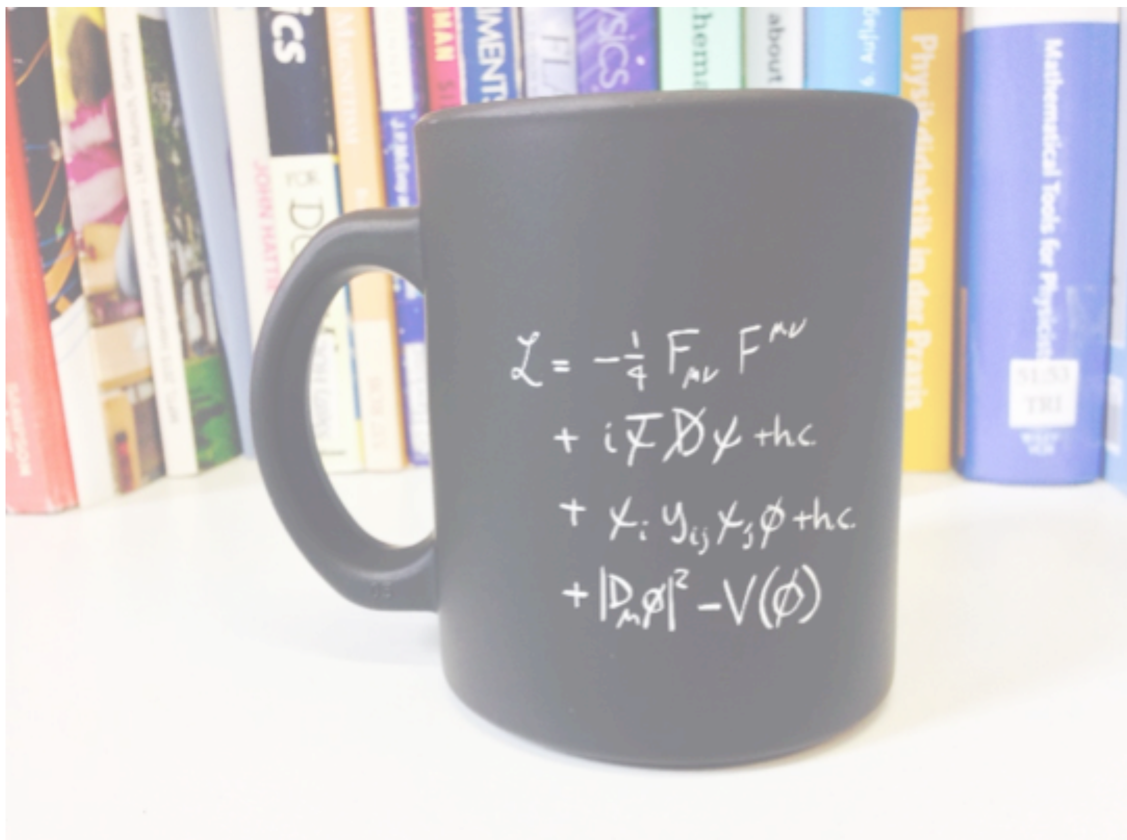
LIP

The Standard Model is…

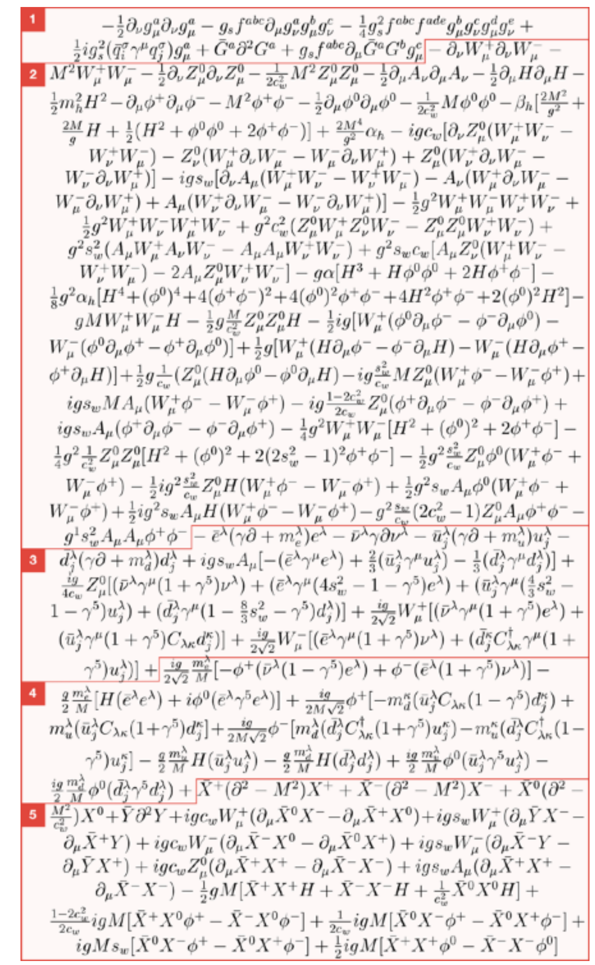


One of the most predictive, precisely tested theories of nature in human history

The Standard Model is…

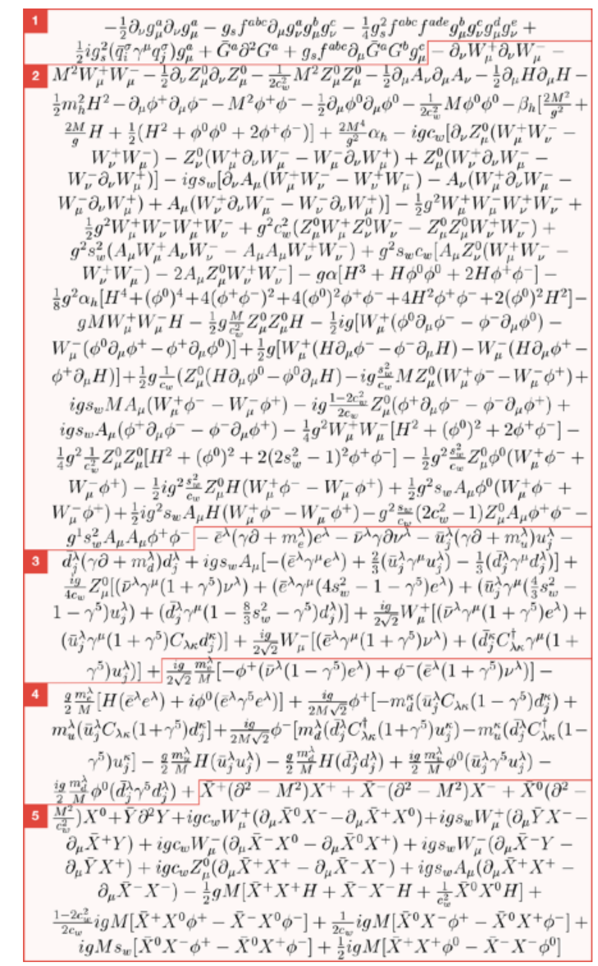


One of the most predictive, precisely tested theories of nature in human history



Kind of a bricolage, with good reasons to believe it’s incomplete

If there is physics beyond the SM, how can we find it at the LHC?



1. Directly search for new particles (see lectures April 18-May 4)
2. **Measure properties and interactions of known particles, to find where the Standard Model falls apart**

"Standard Model" encompasses many areas…

Electroweak sector (this lecture)

Properties and interactions of *W, Z, γ*

- Is the SM self-consistent? (**Precision measurements of particle properties + SM parameters**)
- Do EWK particles interact at the expected rates? (**Cross sections & anomalous couplings**)

QCD

Interactions of gluons and quarks - see lecture on March 3

If time today - W/Z as tools to study QCD

Flavor and top physics

Properties and interactions of top, bottom, and other heavy quarks or leptons

See lectures March 21- 28 and May 9

Higgs physics

Properties and interactions of the Higgs boson

See lectures April 4-13

…though EWK gauge bosons connect to many of them

Electroweak sector (this lecture)

Properties and interactions of *W, Z, γ*

- Is the SM self-consistent? (**Precision measurements of particle properties + SM parameters**)
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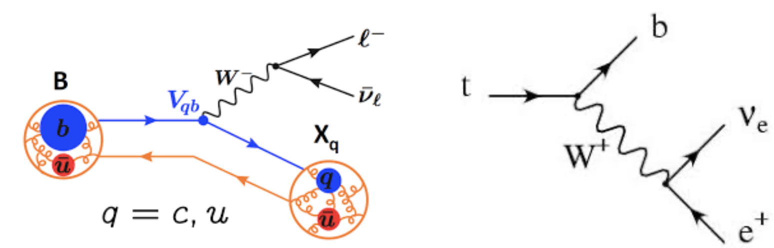
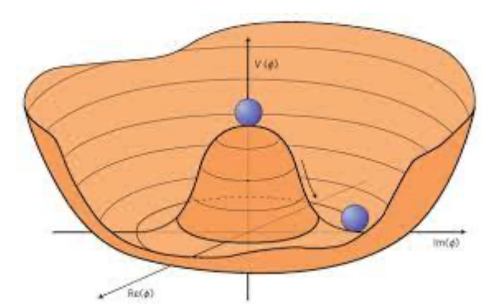
Flavor and top physics



W/Z/γ **mediate** weak interactions of quarks & leptons

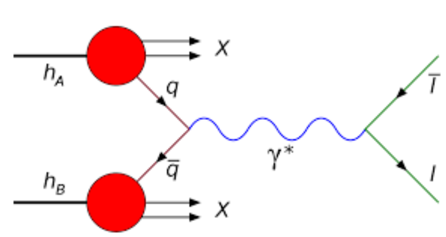
Higgs physics



W/Z are **given mass by** the Higgs mechanism

QCD

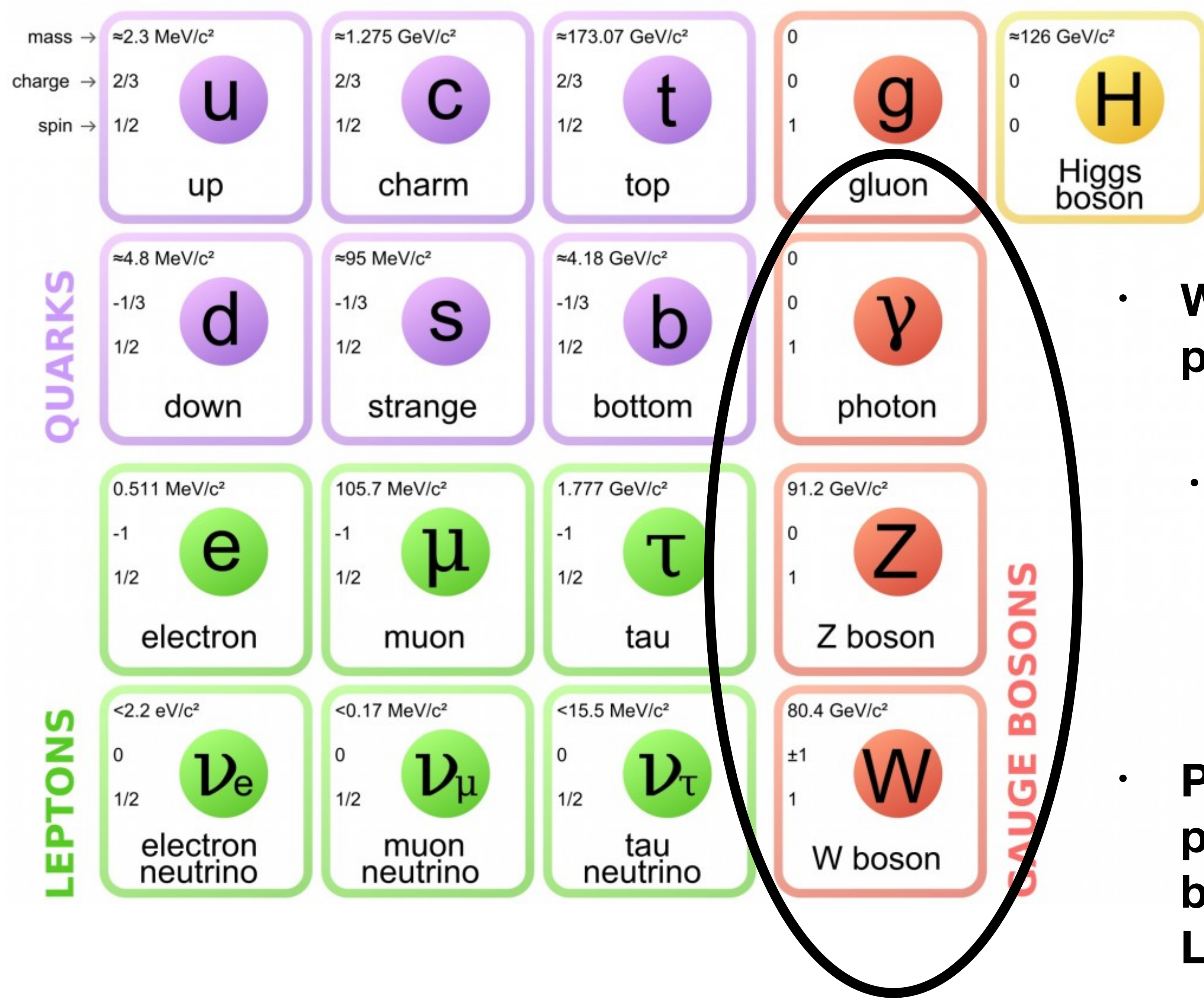
W/Z/γ can be **produced by** quark or quark+gluon interactions



The tools: Large Hadron Collider at CERN

- proton-proton collisions at 7/8 TeV (Run 1), 13 TeV (Run2)
- SM-Electroweak mainly studied at the large general-purpose detectors CMS and ATLAS
  - Also at LHCb in the forward direction

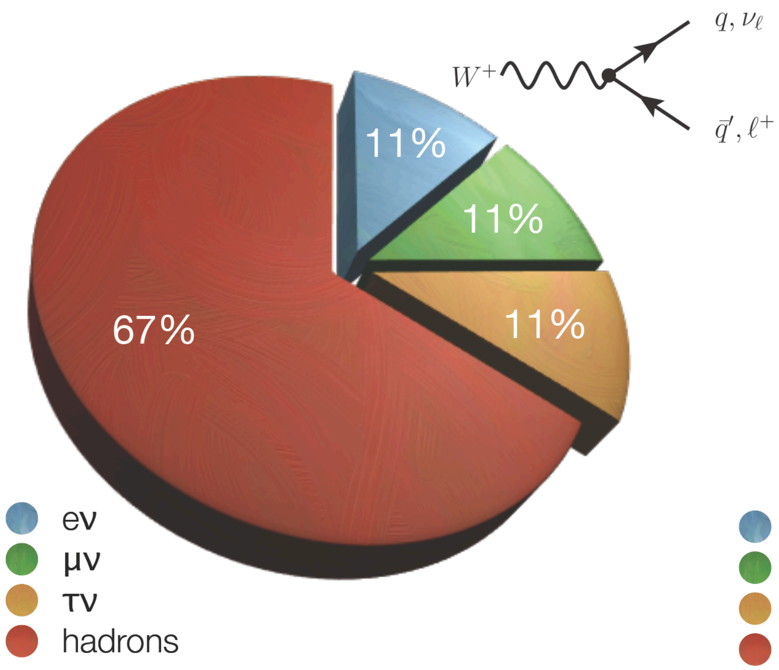
The players: *W, Z, γ*

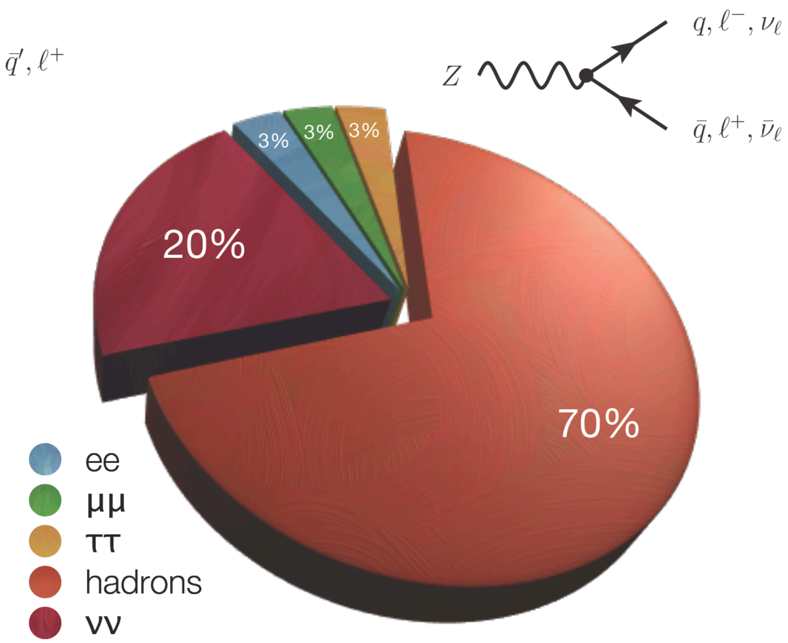


- **W and Z: heavy unstable particles**
  - quickly decay into quarks or leptons that are measured in the LHC detectors
- **Photons: massless particles, directly detected by energy deposits in the LHC calorimeters**

W and Z decays, by the numbers

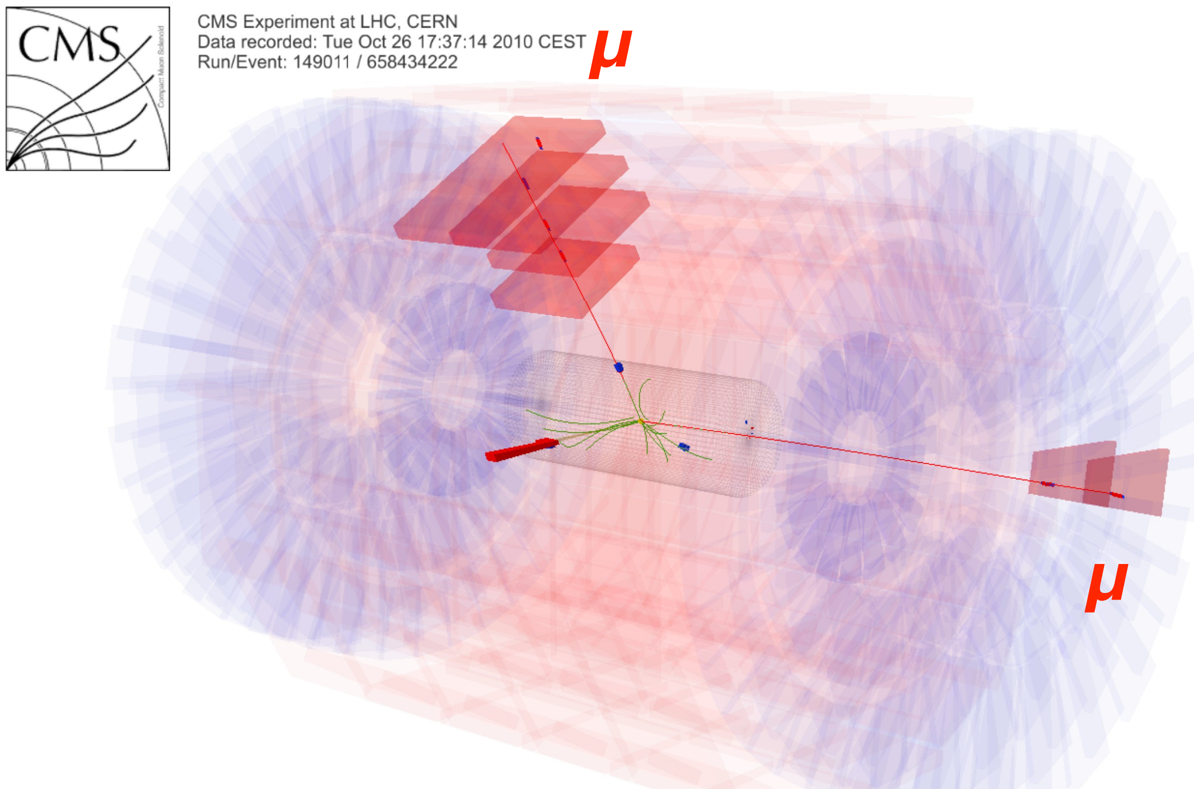
- **Most of the time (~67-70%), W and Z bosons decay into quarks/hadrons**
    - Followed by decays to neutrinos for the Z
    - High rate, but also low experimental resolution, high background

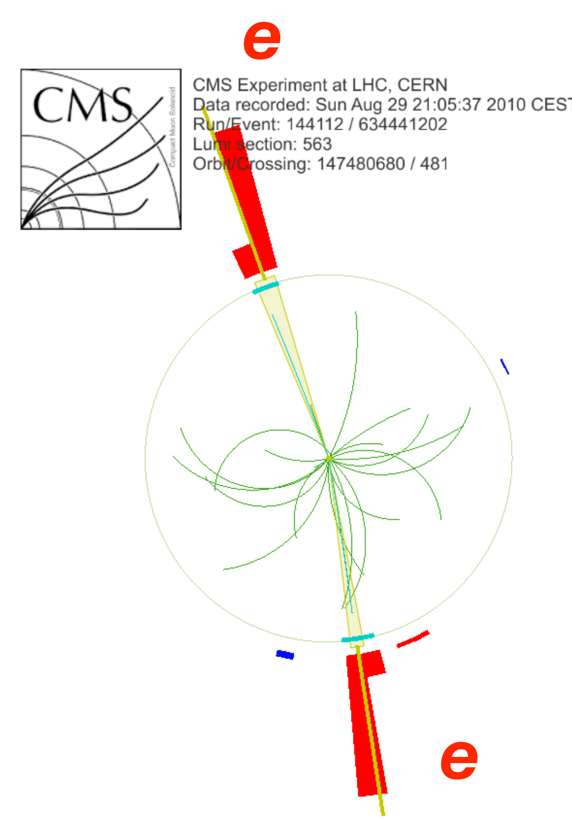




- **Decays with muons and electrons**
    - **Low rate, but lowest background/cleanest signals**
- **Taus: Can be reconstructed via either decays to e/μ, or to hadrons**

Leptonic Z reconstruction

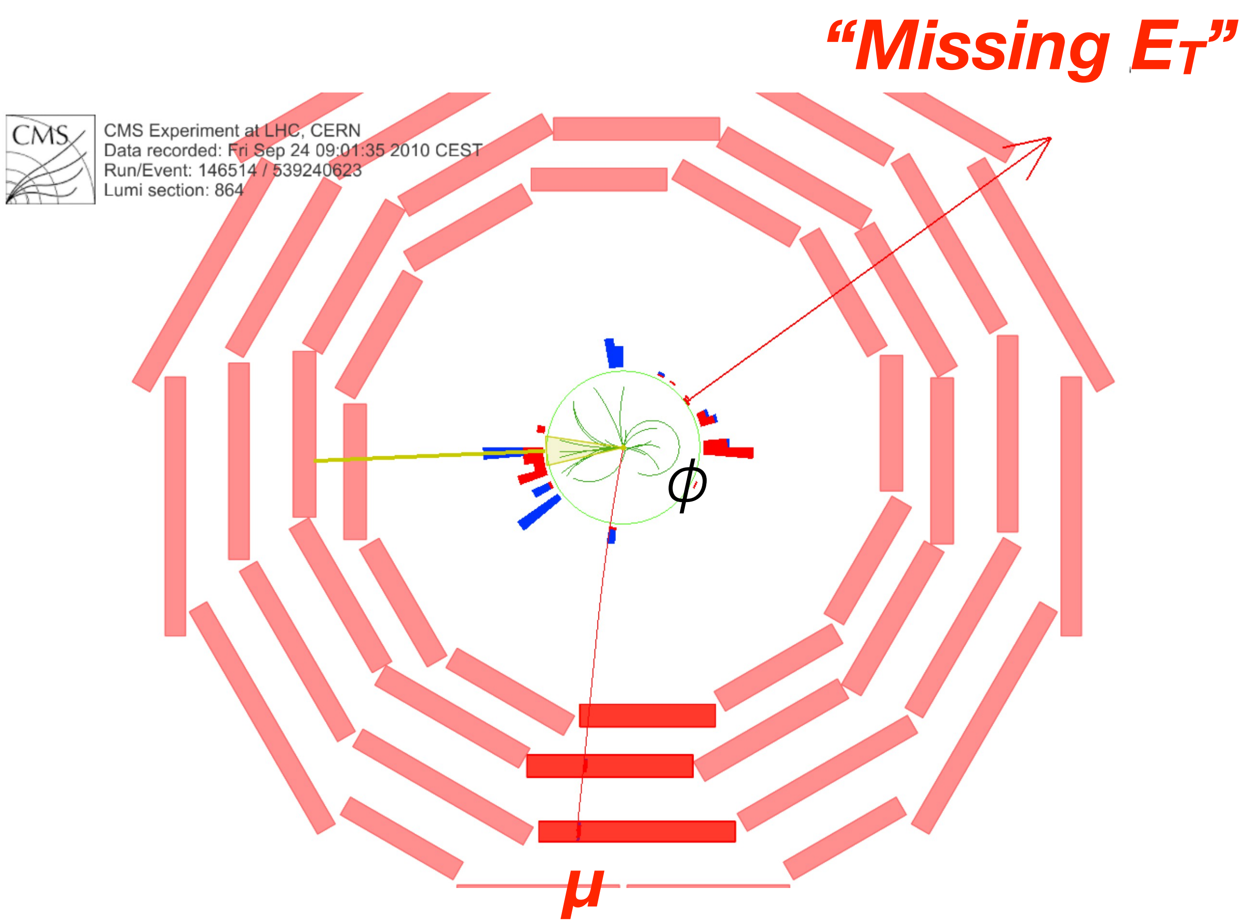




- ***Z→ll*: One of the cleanest signatures at a hadron collider**
  - **Opposite charge high-p_T muons or electrons, with invariant mass near the Z mass (~91 GeV)**
  - Lepton isolation (require leptons separated from other tracks/calorimeter deposits):
    - Suppress “fake” backgrounds from QCD/misidentified hadrons, light meson decays-in-filght
    - Suppress “non-prompt” leptons from decays of heavy flavor bottom/charm quarks

Leptonic *W* reconstruction

- **W→*lν*: high-p_T isolated muon or electron, with “missing transverse energy” inferred from sum of all particles from the collision vertex**

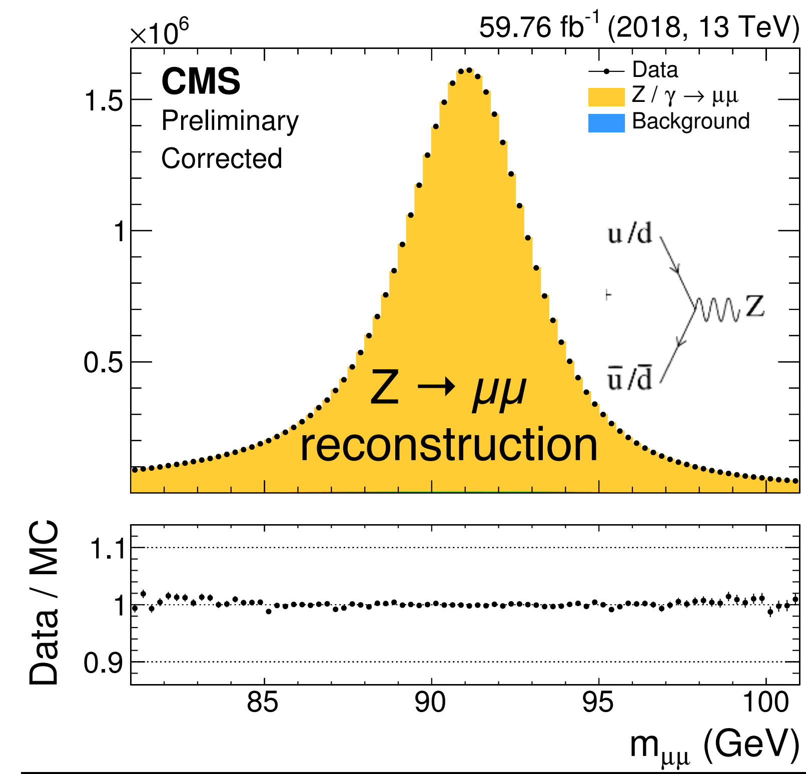


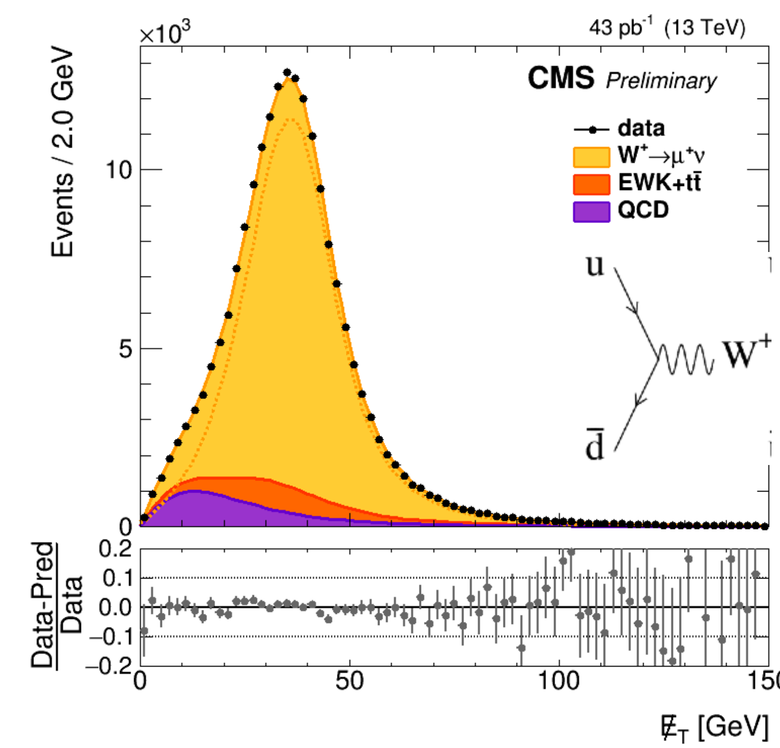
- **Presence of undetected neutrino => no clear invariant mass peak, so rely on other variables**
    - Lepton p_T
    - Missing E_T or p_T
    - “Transverse mass”, using angle between lepton and missing energy/momentum

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{miss} cos\Delta\phi}$$

Leptonic *W* and *Z* signals

- **Huge samples of W's and Z's produced via q/qbar interactions**
  - Even in the low branching-fraction leptonic decays
- In 150fb-1 at 13 TeV, expect:
  - ~3B $W \rightarrow l\nu$ events produced
  - ~300M $Z \rightarrow ll$ events produced
- **Very high signal/background, especially in** $\boldsymbol{Z \rightarrow ll}$



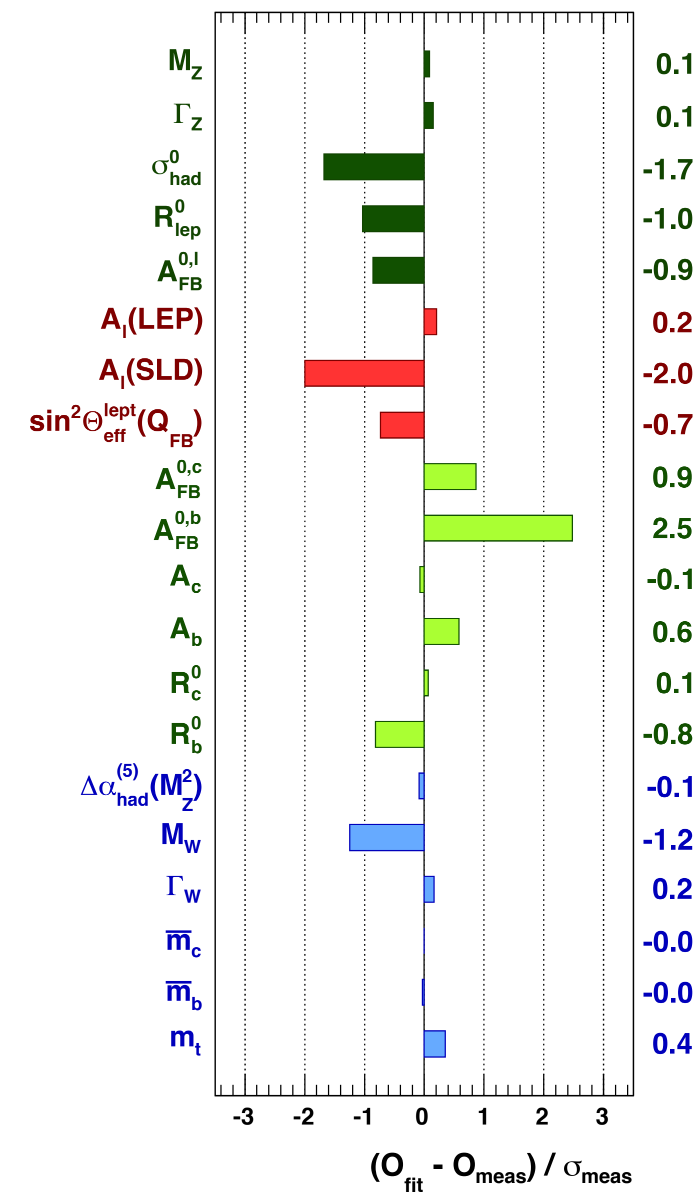


Electroweak physics:
Precision measurements of SM parameters

Precision SM measurements

- Is the Standard Model self-consistent?
  - Measure many observables closely related to SM parameters, then check if SM can fit all the data
- Electroweak sector traditionally the domain of e^+e^- colliders: LEP@CERN, SLC@SLAC
  - Hadron colliders unique for top, Higgs inputs (see upcoming lectures)
- **But LHC also produces enormous numbers of W,Z bosons => in some cases, can also do precision EWK measurements**

Disagreement (# of standard deviations) from the SM



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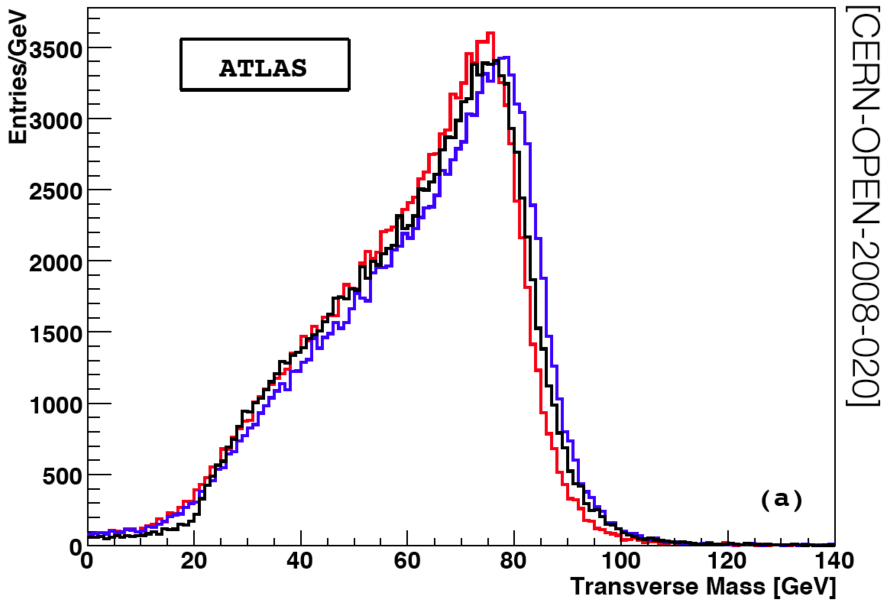
Precision SM measurements: W mass

- Basic approach: Generate many Monte Carlo “templates” simulated with different W-mass values
  - Fit to the data, to determine which mass best describes reality
- **Requires extremely precise control of systematics**
  - Experimental aspects
    - Precision of lepton momentum/energy measurement
    - Control of missing E_T reconstruction
  - Theory/model aspects
    - Uncertainties due to PDFs
    - Uncertainties due to “underlying event” activity produced together with the *W*
  - Use comparisons to well-reconstructed *Z* samples to control (some of) these



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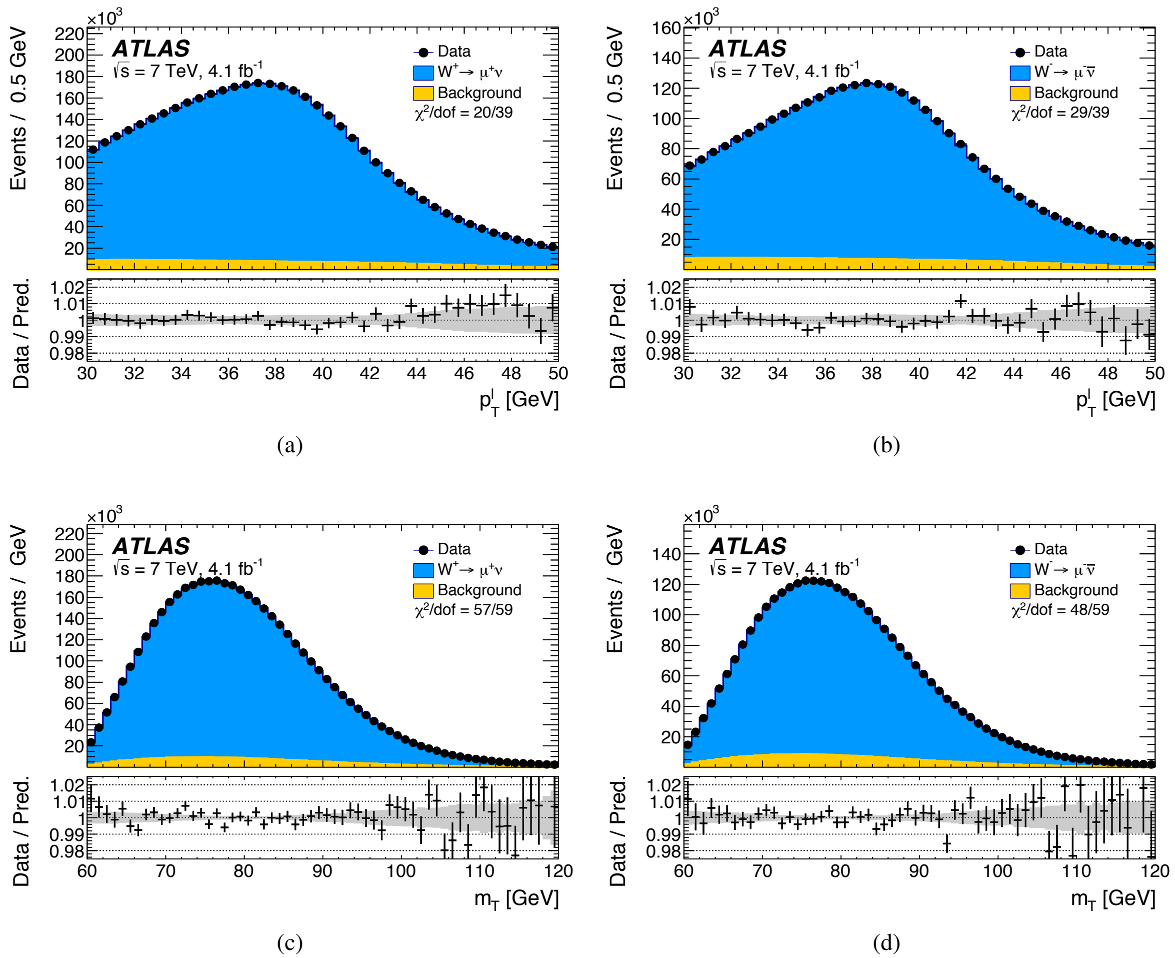
Precision SM measurements: W mass



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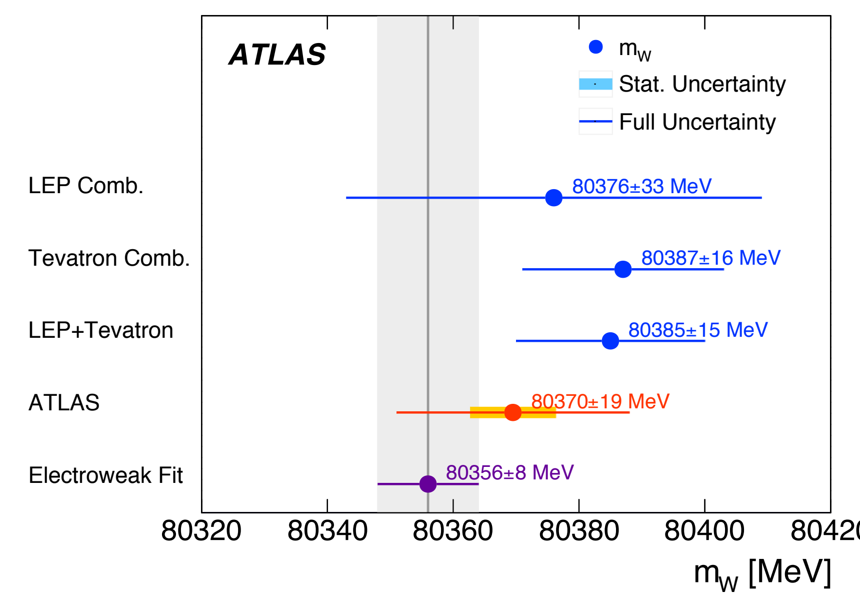


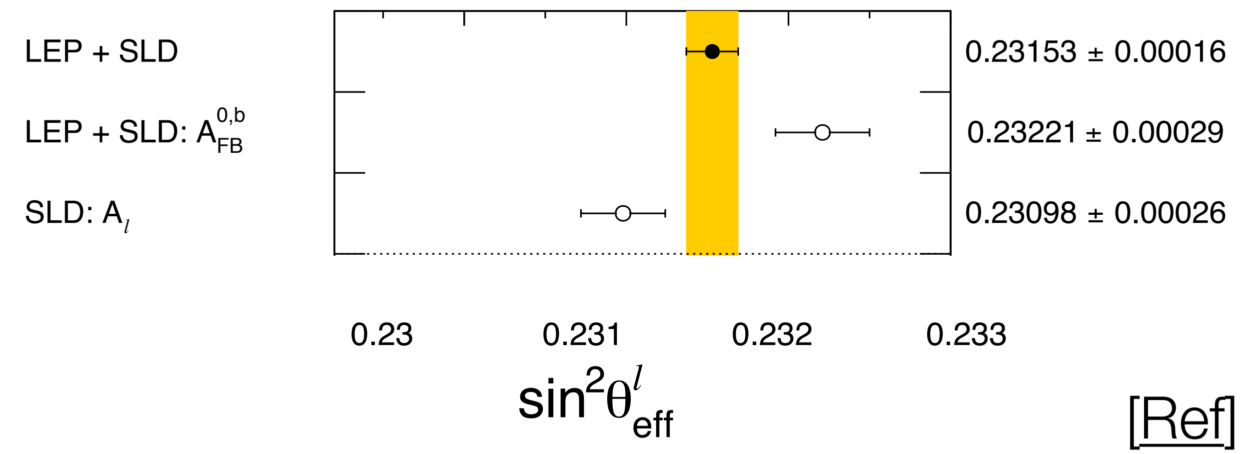
- First LHC measurement at 7 TeV, using lepton p_T and M_T distributions
  - Split in many bins of charge, η
- Consistent with, and approaching precision of, best previous measurements

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

- **Ultimate LHC goal: uncertainties <10 MeV**

Precision SM measurements: weak mixing angle

- Weak mixing angle $sin^2\theta_{eff}$
  - Enters in $f\bar{f} \rightarrow Z \rightarrow l^+l^-$ production via vector-axial interference
  - The two most precise measurements at e^+e^- colliders are marginally consistent



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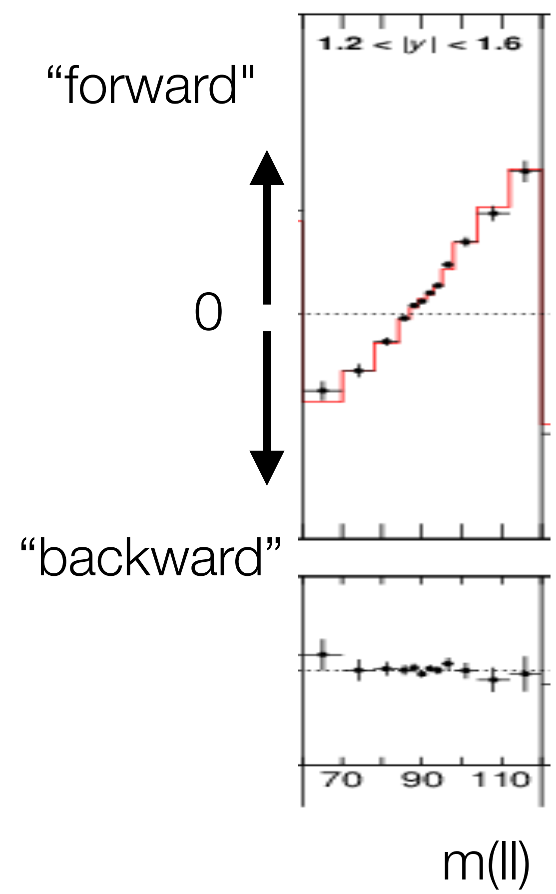
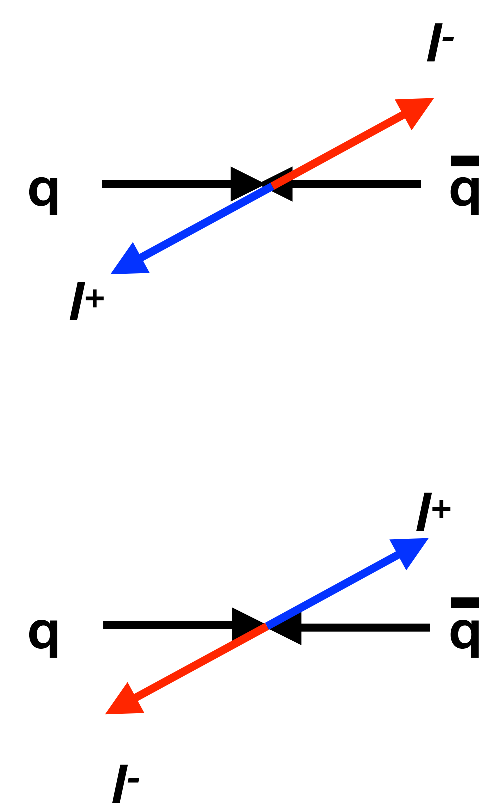
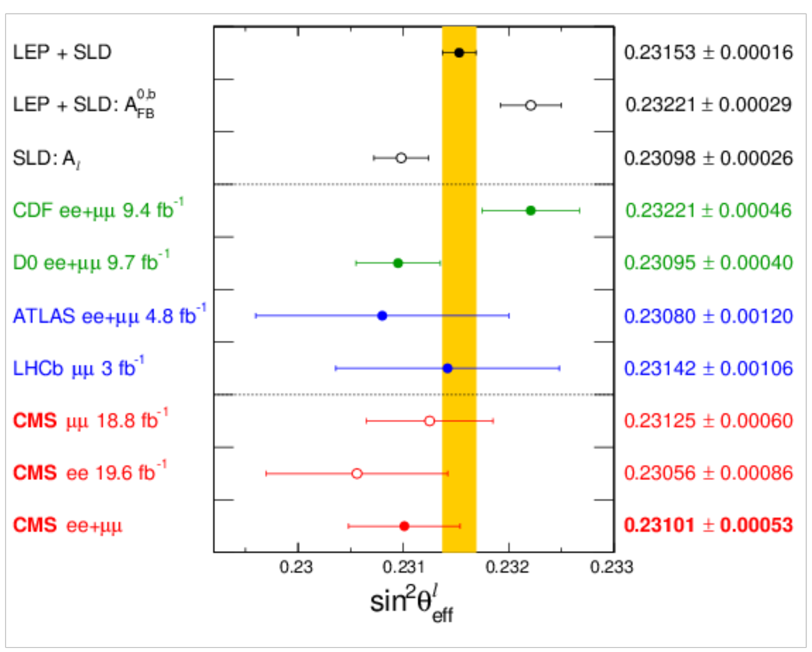
- **Can be measured from "forward-backward" asymmetry of leptons**
  - Count number of positively charged leptons along the inferred quark vs. the anti-quark direction

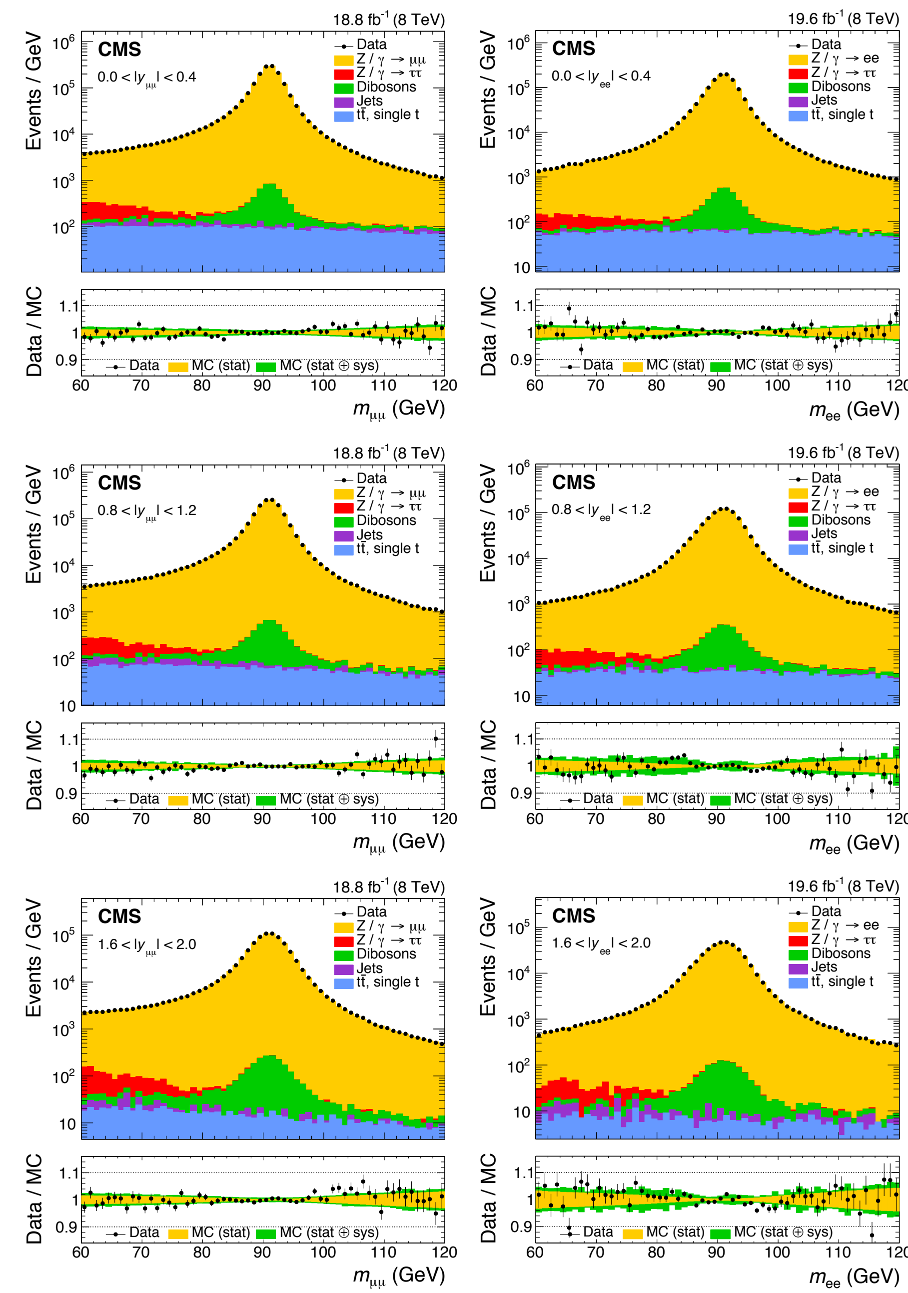




Precision SM measurements: weak mixing angle

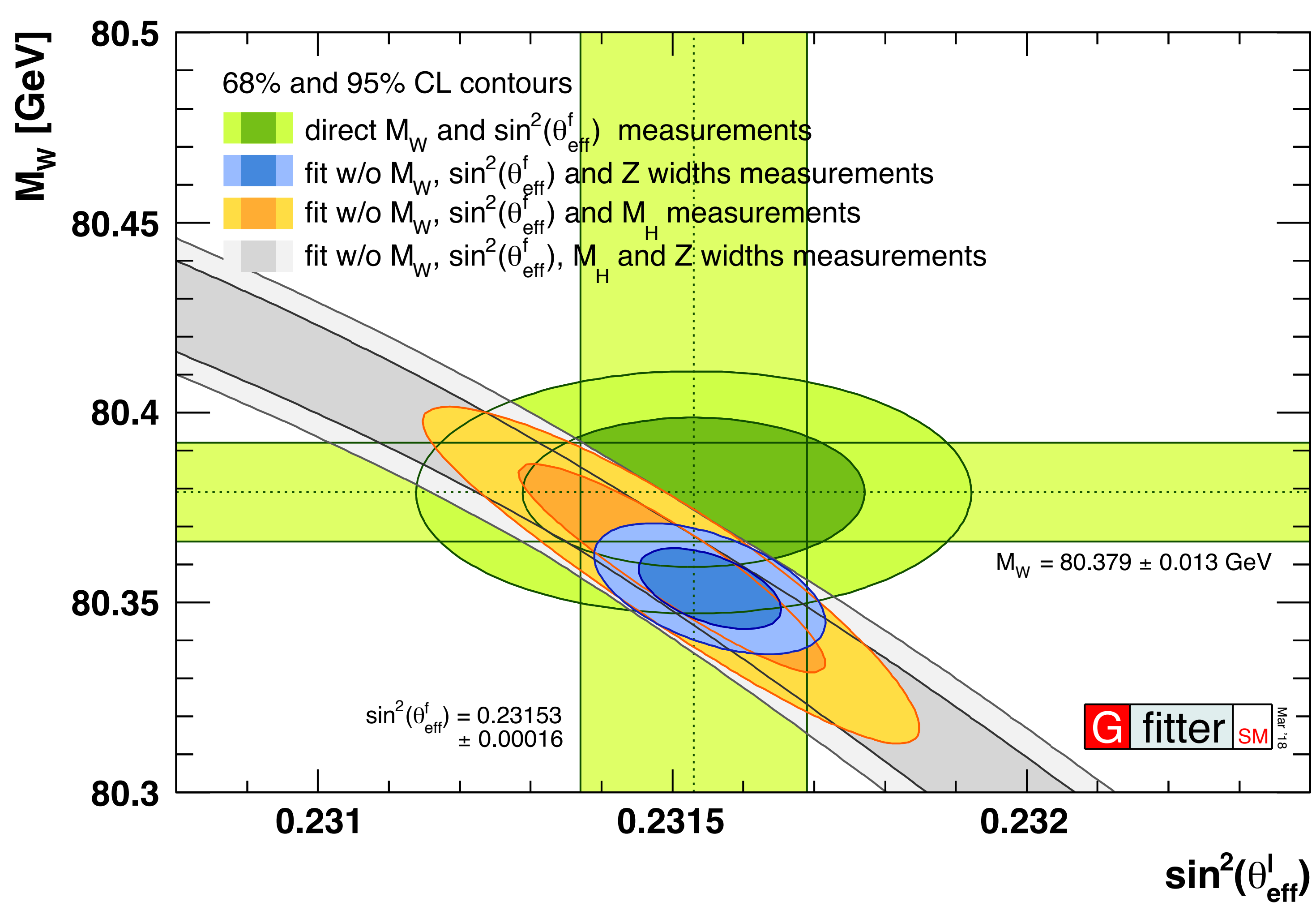
- Afb measured in many bins of invariant mass and rapidity
  - Fit for best value of $sin^2\theta_{eff}$
- **LHC measurements not yet the most precise, but becoming competitive**





$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00016\,(\text{theo}) \pm 0.00031\,(\text{PDF})$$

Global SM fits: impact of precision measurements



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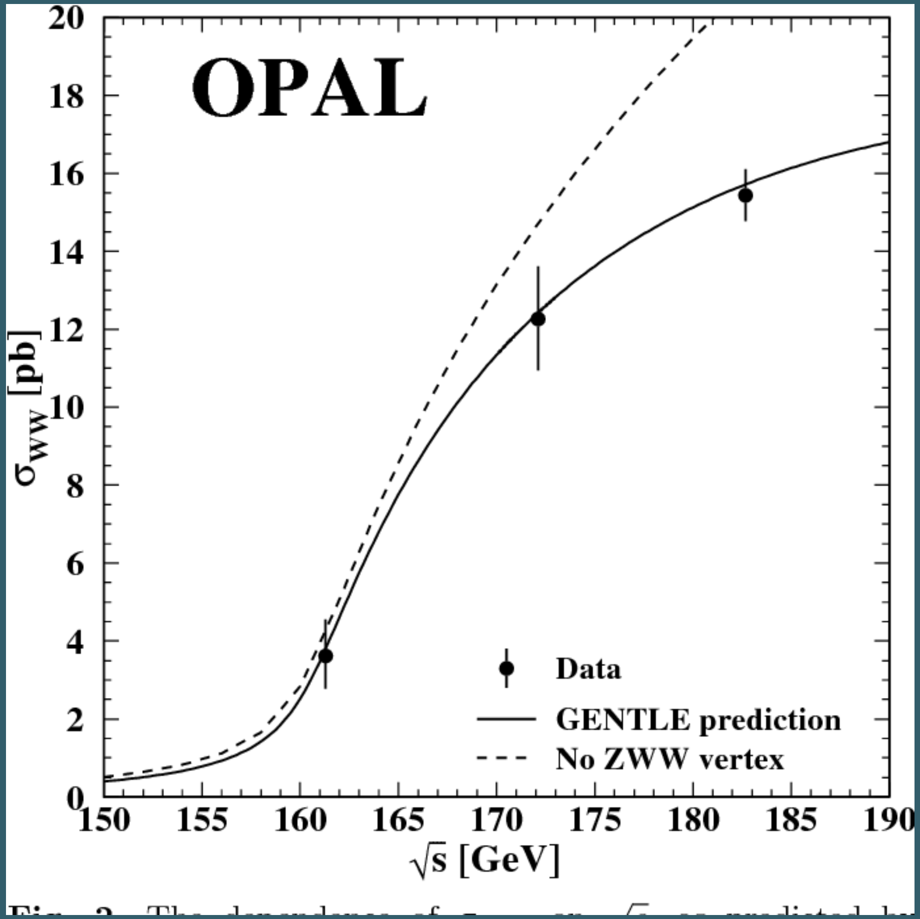
- In green: the direct measurements of **only *sin²θ$_{eff}$* and M$_W$**
- In blue: SM fit prediction, with **all other data except *sin²θ$_{eff}$* or M$_W$ (or Γ$_Z$) measurements**
- **Will green/blue eventually overlap (=SM is consistent), or diverge (=breakdown of SM)?**
  - TBD with more data/higher precision measurements

Electroweak physics:
cross sections and gauge boson couplings

Rates of Standard Model processes and electroweak couplings

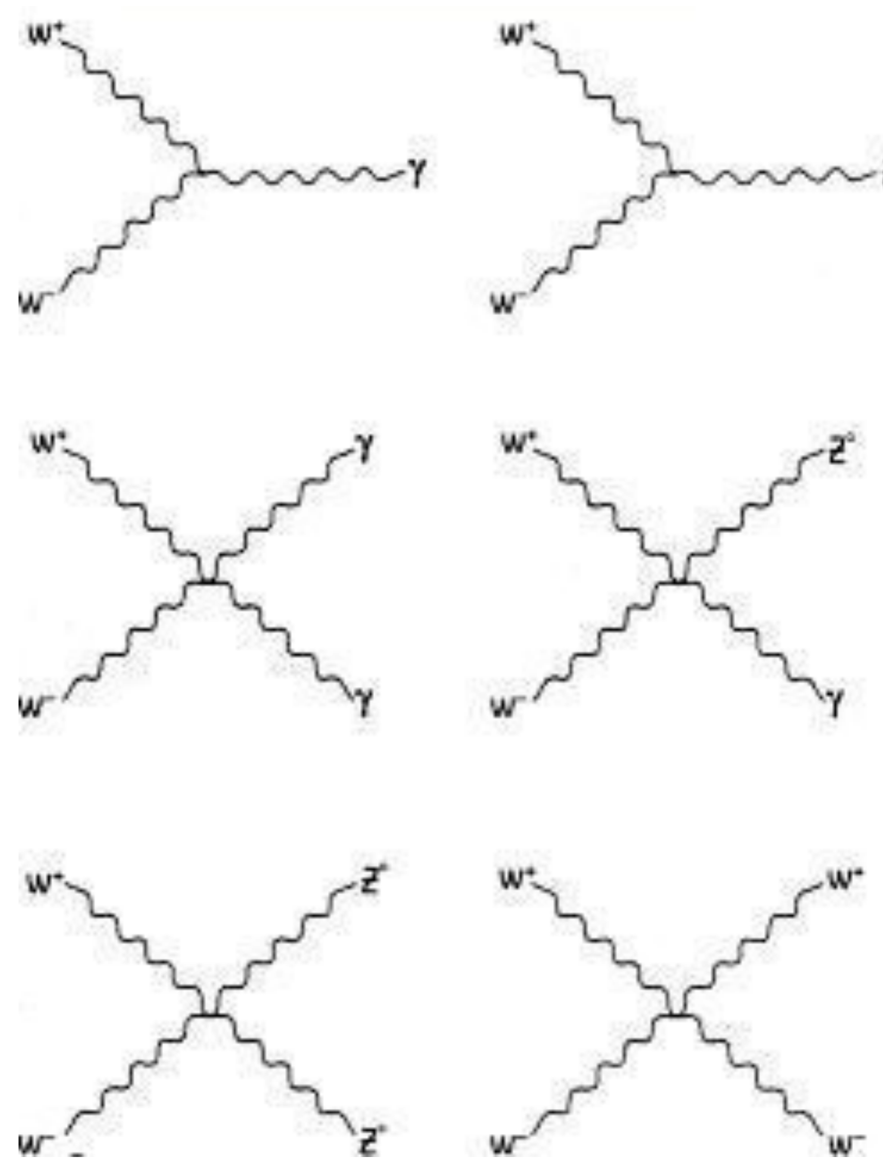
- Another way to test the Standard Model:
  - Do W/Z/γ's interact with each other as predicted by the Standard Model?
  - **In other words - does LHC measure cross sections involving gauge boson interactions at the rates expected from the SM?**
- Especially interesting to look in the high-energy tails of distributions



- **Legacy of the LEP e^+e^- collider: existence of charged triple gauge (WWZ/WWγ) couplings established**
- **LHC: increase in energy from ~0.2 TeV to ~13/14 TeV!**

Gauge boson self-interactions

- **Reminder: The SM precisely predicts the strength of EWK gauge boson interactions**
  - **True triple and quartic couplings involving W-pairs are predicted to occur**
  - **True neutral triple and quartic couplings (with all Z's or all γ's) are forbidden**
    - Processes can occur through higher-order (loop/box) diagrams at very low rates



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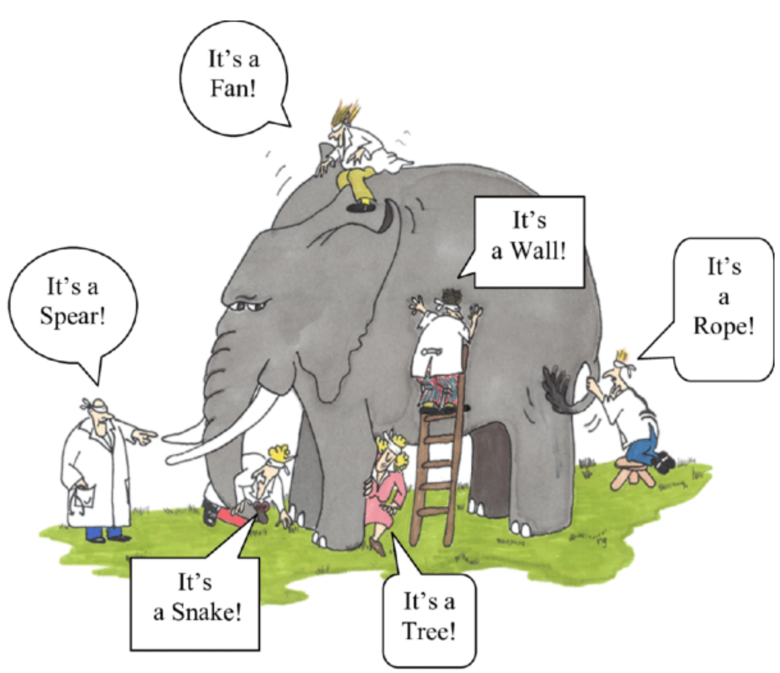
Triple gauge couplings: different views

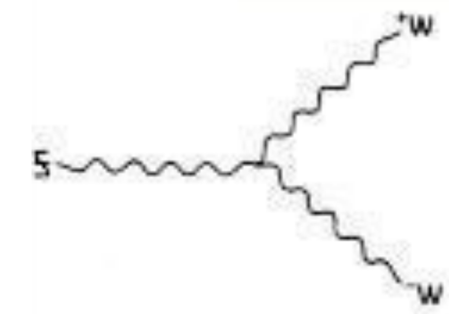
- Usually more than 1 way to probe each coupling
  - Different experimental systematics, backgrounds, etc.
  - **Study all of them to get a complete picture**



Processes sensitive to WWZ couplings

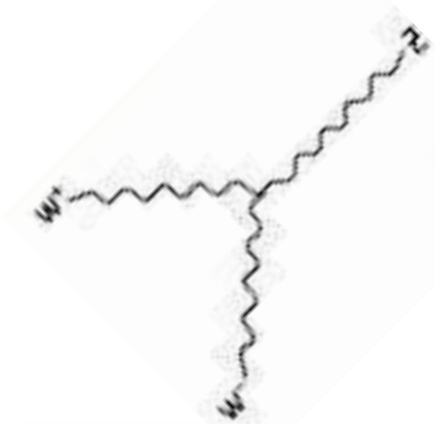
Z→WW

(diboson production)



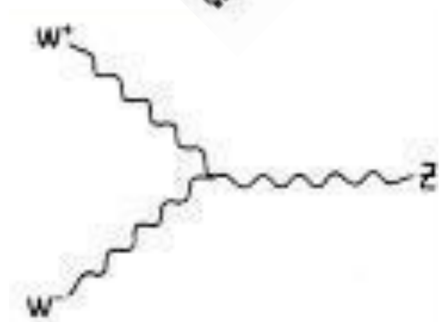
W→WZ

(diboson production)



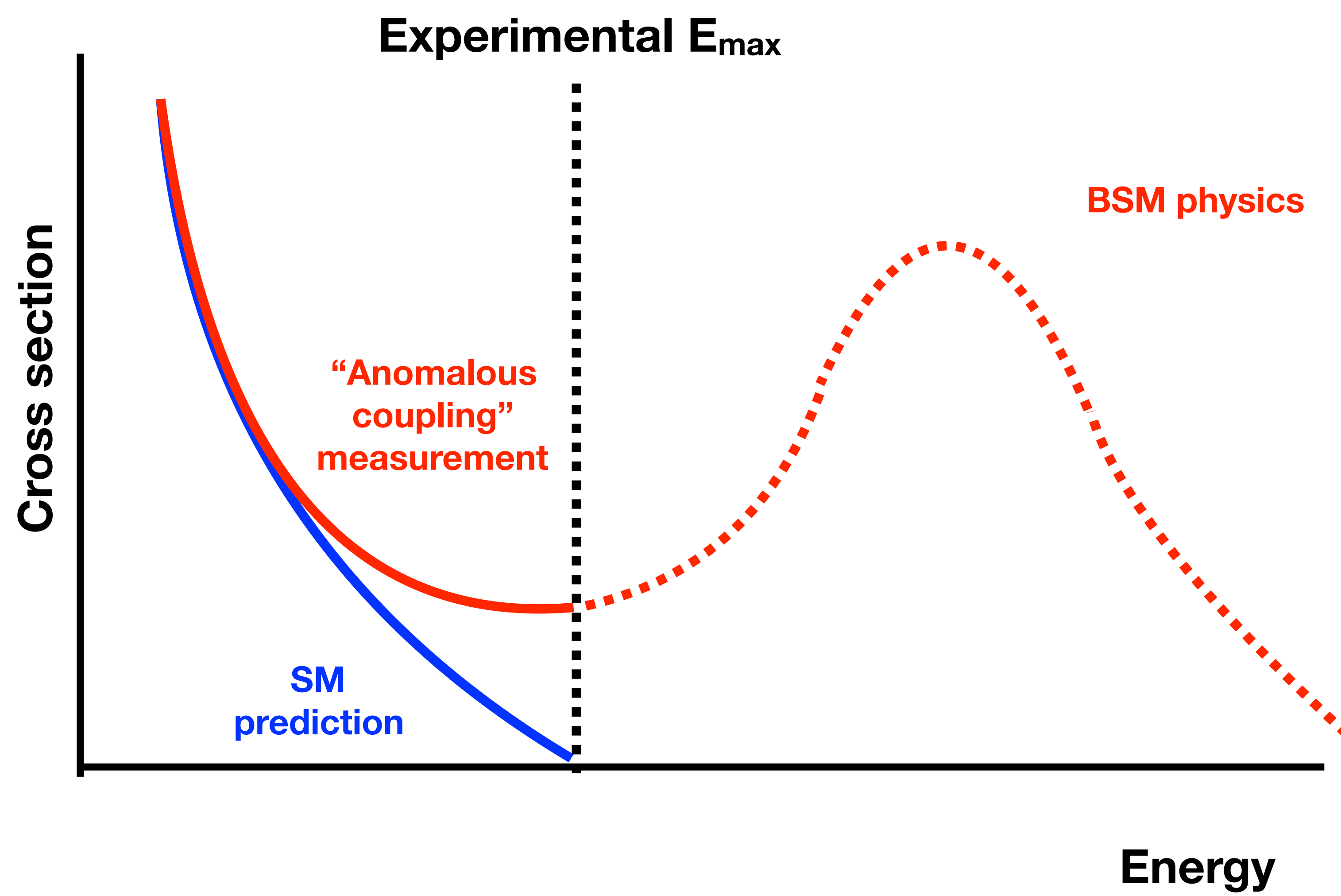
WW→Z

(vector-boson fusion)



“Anomalous” gauge couplings

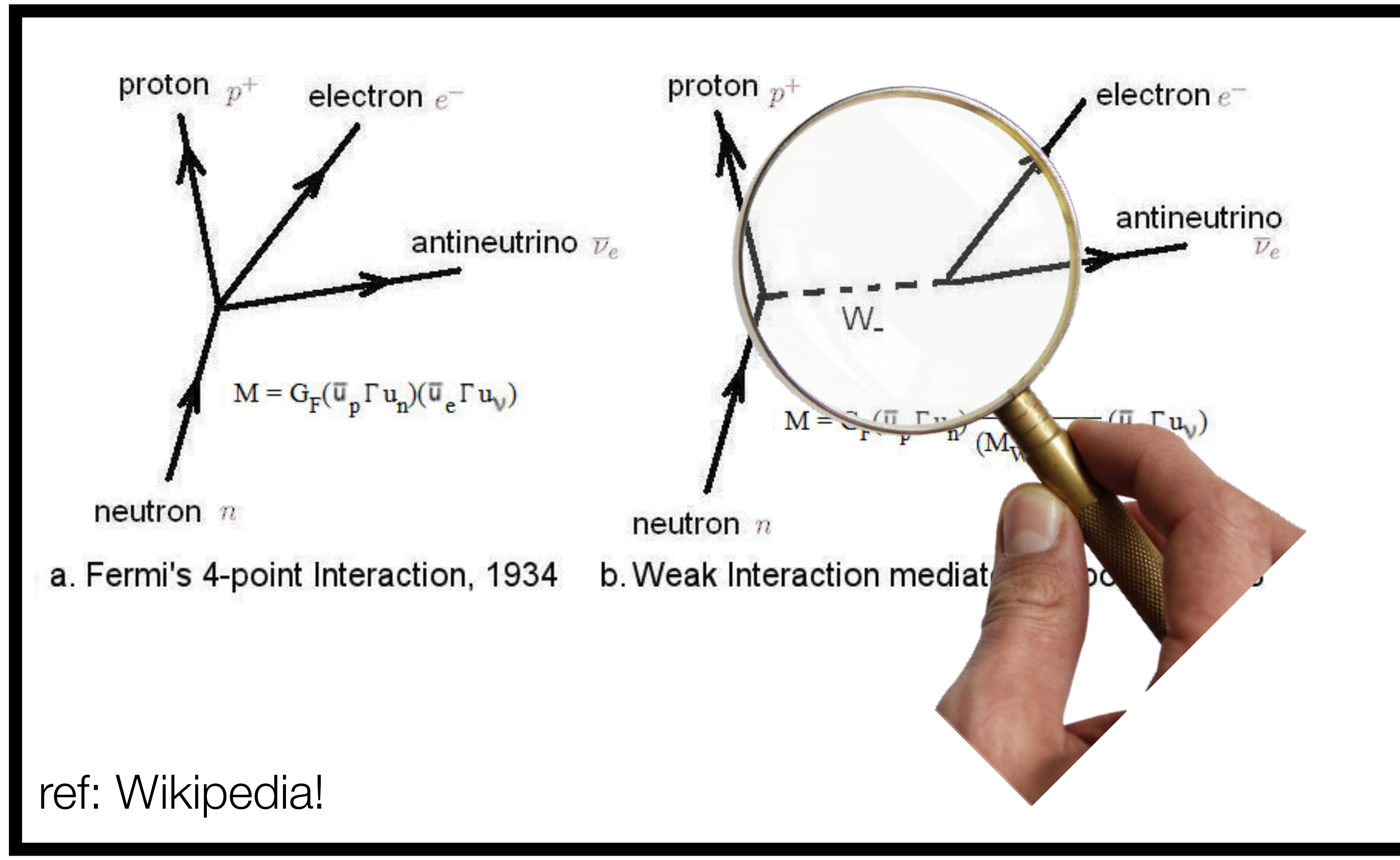
- Differences (or not) from the SM can be quantified with “anomalous gauge couplings”
  - Mostly model-independent/agnostic about details of new physics
- Modern interpretation
  - Assume new physics occurs at energies too high to directly produce new particles at the LHC



- **Anomalous couplings are “fingerprints” of beyond-SM physics at lower energies from off-shell or loop-level effects**

Anomalous couplings and indirect searches

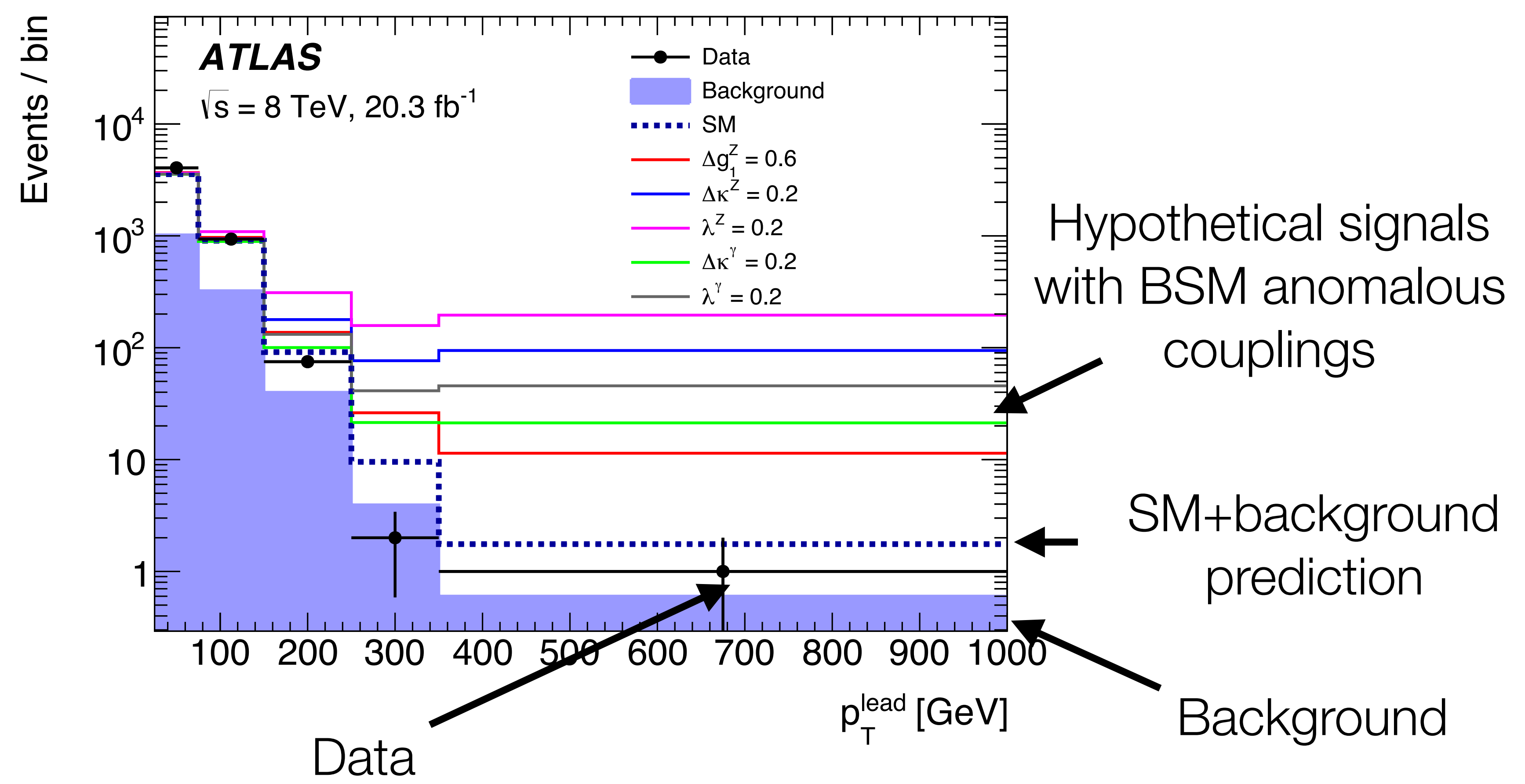
- **Classic example: beta decay of neutrons**
  - Discovered in **1899**
  - **Apparent "Anomalous quartic coupling" of *npev* in original Fermi theory**



- Higher energies (better microscope) were needed to allow direct observation of the "mediator" particle responsible
  - *W*-boson finally directly detected at CERN in **1983**
- **Indirect searches/anomalous couplings sometimes point to new physics long before direct detection of new particles**

Triple gauge couplings: anatomy of a LHC analysis

- Measure cross section or # of events,
  - Ideally in several bins (of pT, mass, energy… depending on the final state)

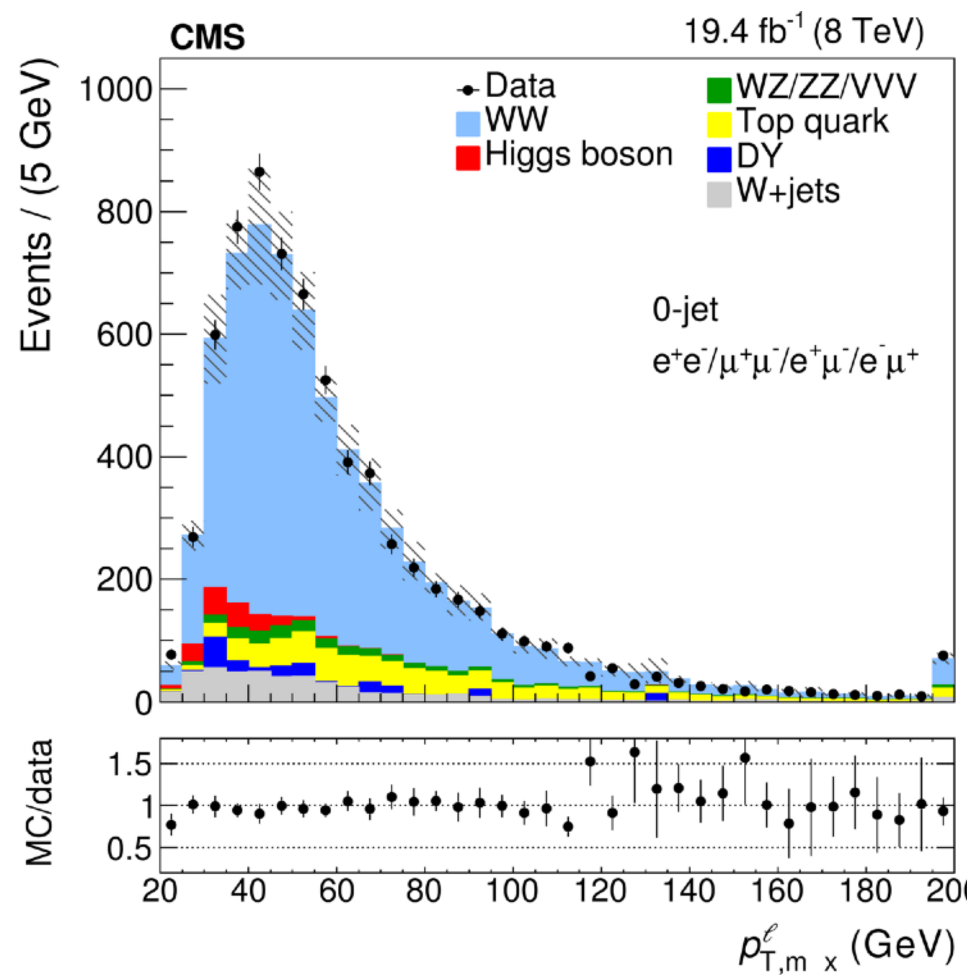


- Compare bulk of distribution to SM prediction+backgrounds
  - Quantify any deviations in the high energy tails

[Ref]

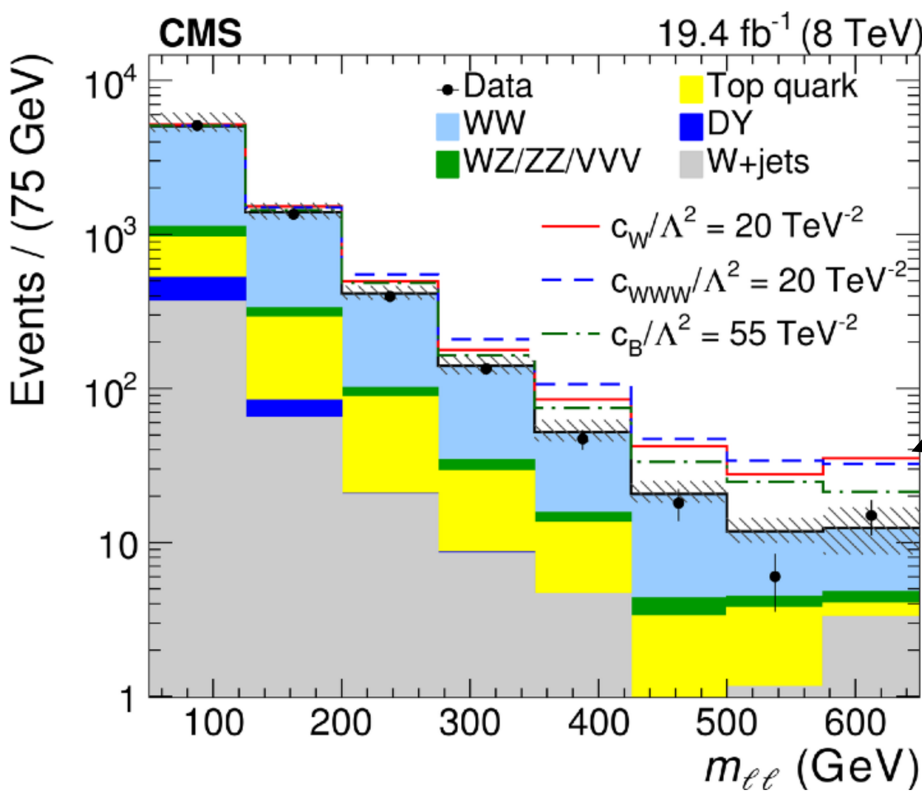
Triple gauge couplings with *WW* production

- Measure cross sections for events with 2 leptons + missing E_T
  - High statistics
  - Fairly low backgrounds from top quark production, QCD fakes - estimated from data control samples and simulation
    - (Even the Higgs could be considered a background here!)

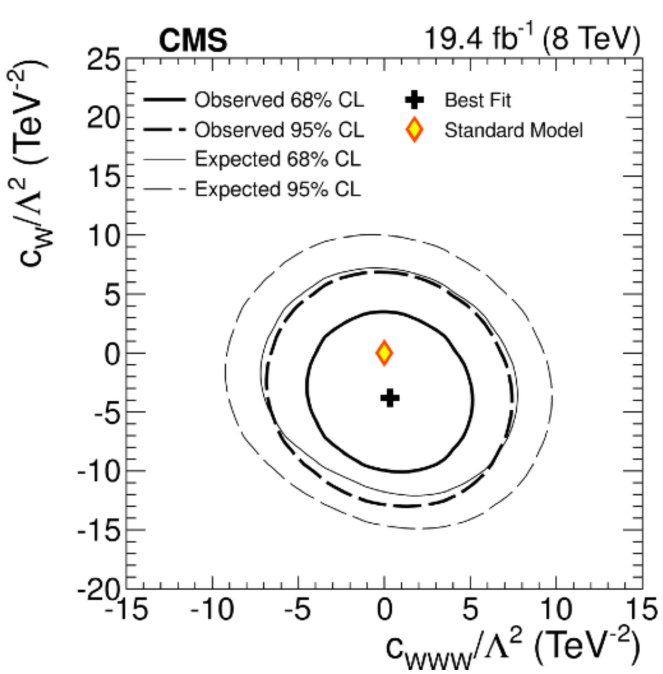


- Overall, cross sections as a function of p_T agree with the Standard Model (Run 1 data shown)
  - **Reminder: WWγ and WWZ couplings are allowed in the SM, and are included the cross section prediction**

Triple gauge couplings with *WW* production (II)

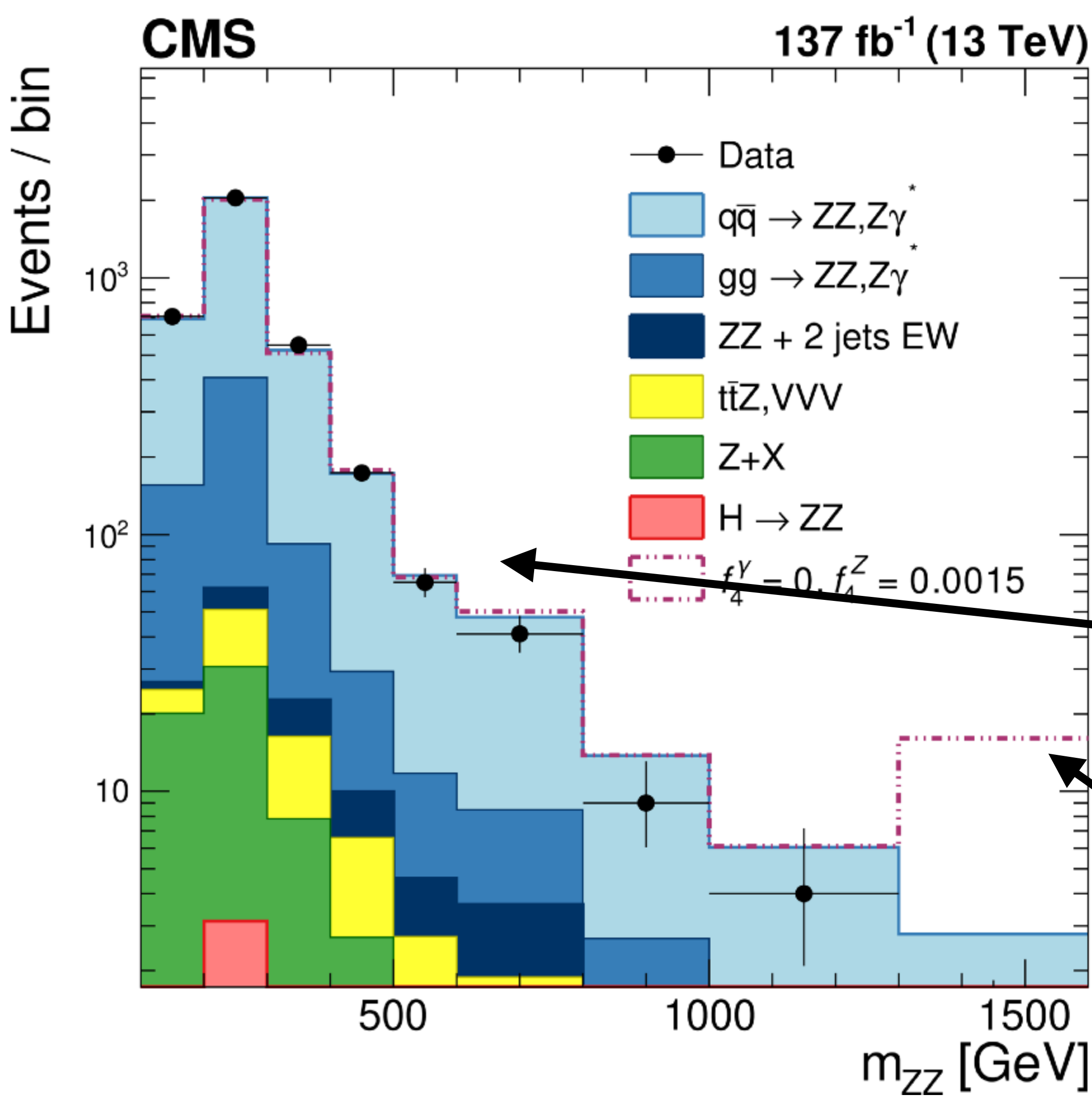


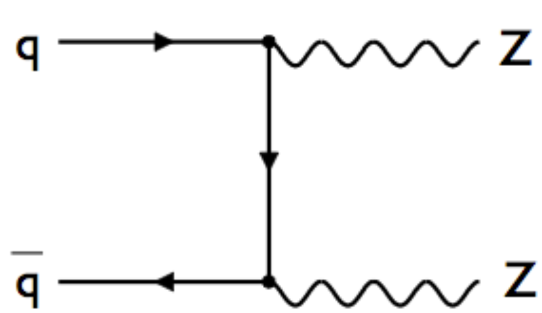
- Anomalous couplings?
- Plot m_{ll} and zoom on the high-mass tails
  - No sign of excess, data agrees with the SM



- Convert into upper limits on anomalous coupling parameters
  - One-by-one, or for several couplings in a 2-d space

ZZ and triple gauge couplings production

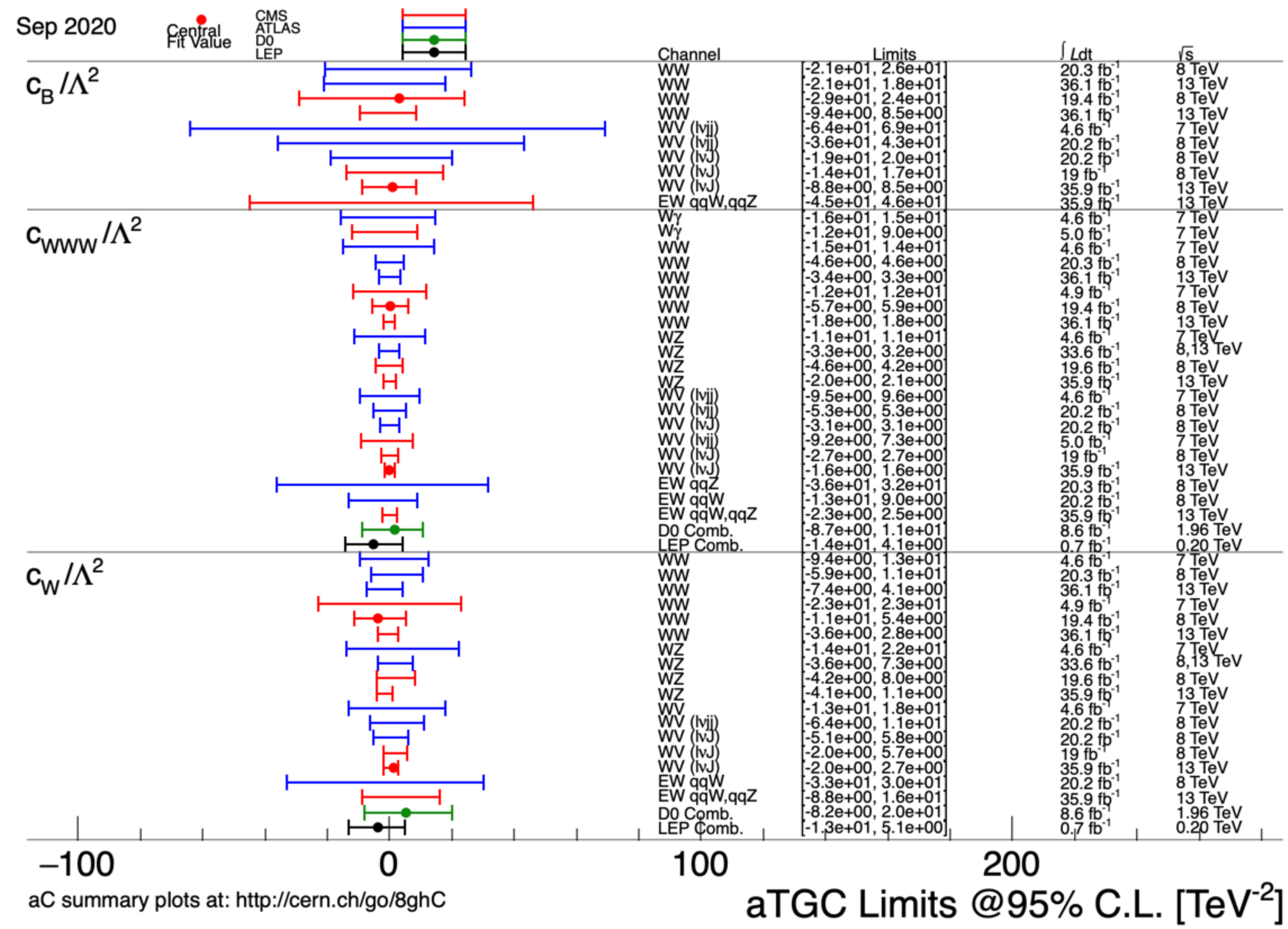




- Golden signature: 4 leptons, with 2 pairs compatible with a $Z^{(*)}$ (either e^+e^-, $\mu^+\mu^-$)
    - Very little background, especially at high mass
- Cross sections compatible with SM at lower m_{ZZ}
- No sign of BSM couplings at large m_{ZZ}
- Reminder: no direct ZZZ or γZZ couplings in the SM, prediction comes from q-qbar interactions

Summary of TGCs

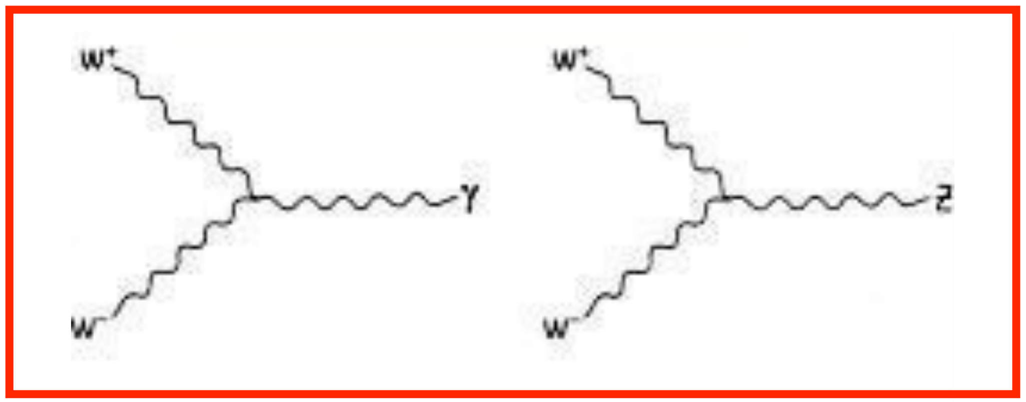
- LHC has studied many more processes sensitive to TGCs
  - Charged TGCs are consistent with SM predictions
  - Neutral TGCs are consistent with 0 (=SM prediction) - not shown

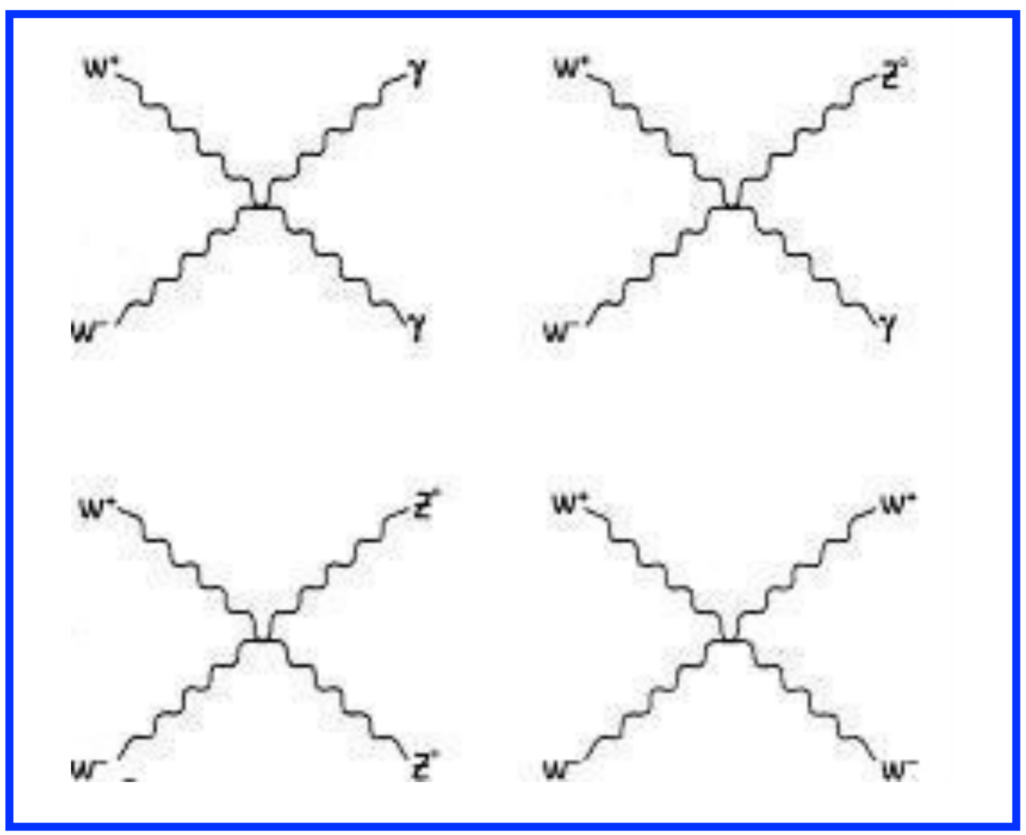


Charged aTGCs (measured - SM)

- **LHC limits on new physics in TGCs now the world's best**

From TGCs to QGCs

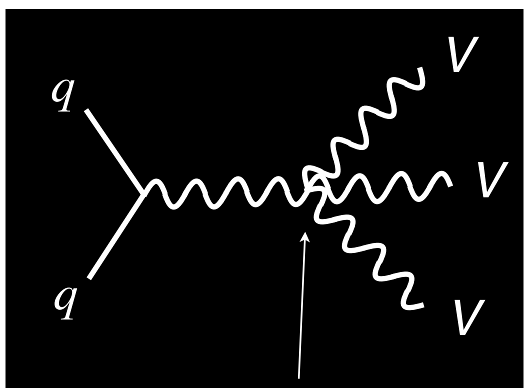




- **Triple Gauge Couplings seem to agree with the SM, within the current experimental precision**
  - WWZ and WWγ measured at expected rates
  - No sign of unexpected all-neutral couplings
- **What about the Quartic Gauge Couplings?**
  - Much smaller cross sections
  - Much less explored before the LHC

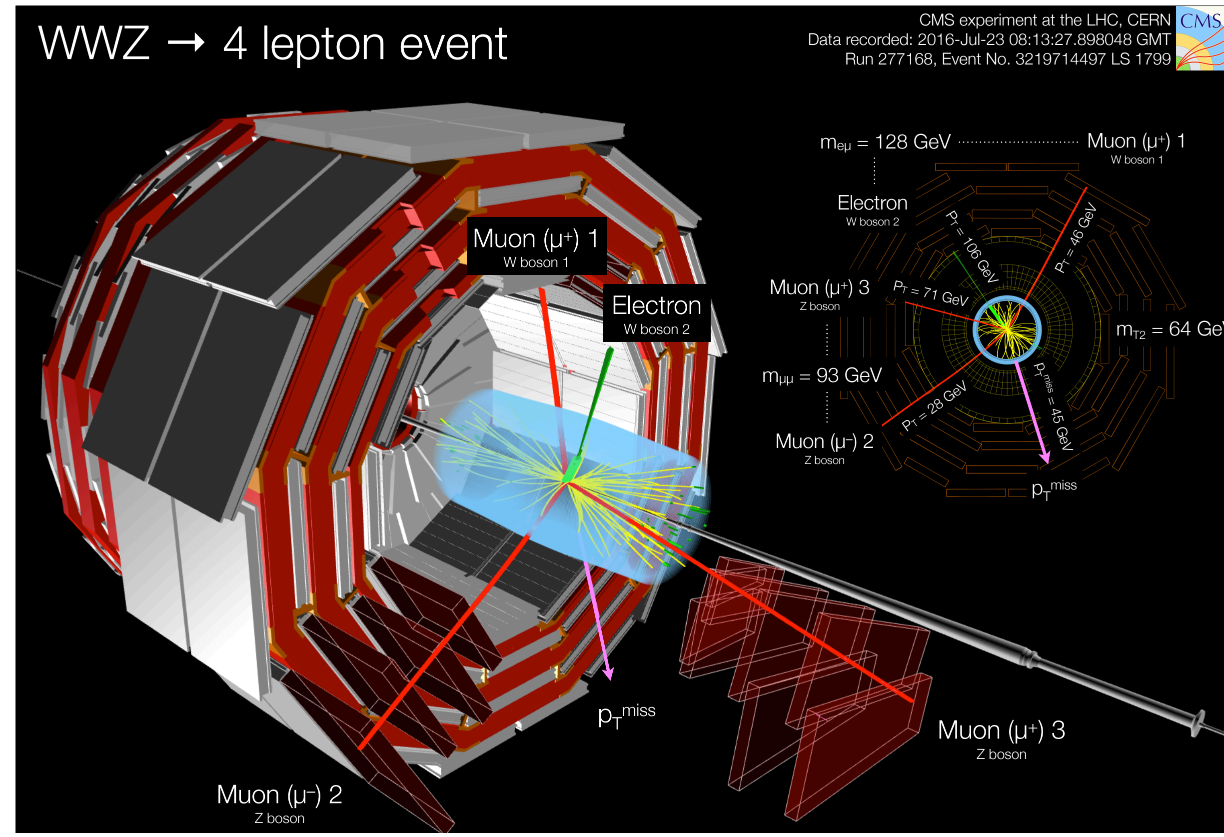
Quartic gauge interactions: triple-boson production

- One way to probe quartic couplings: look for events with 3 final-state gauge bosons



- **With leptonic W or Z decays: 4, 5, or 6 leptons**

- Very low cross sections - a few events expected with all the currently available LHC data



Candidate for *WWZ* production

4 leptons + missing E_T

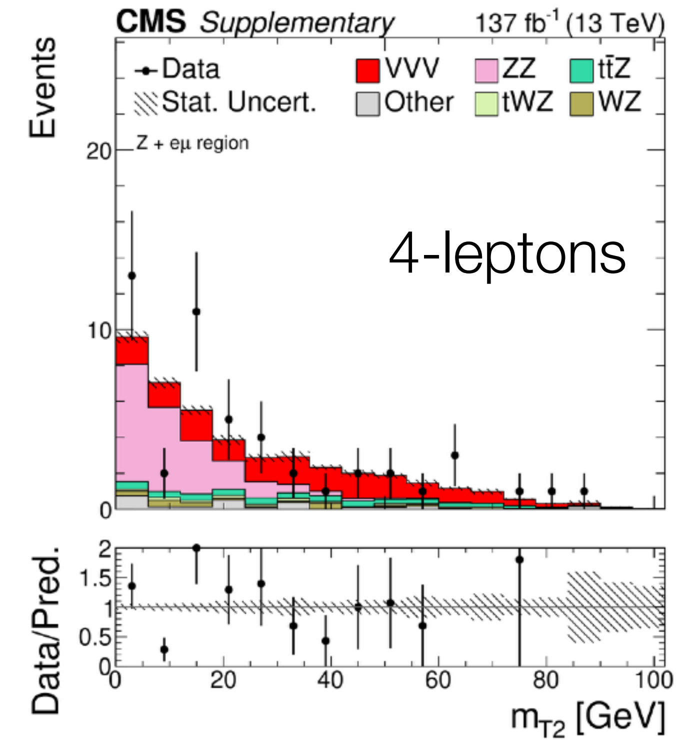
$Z \rightarrow \mu\mu$

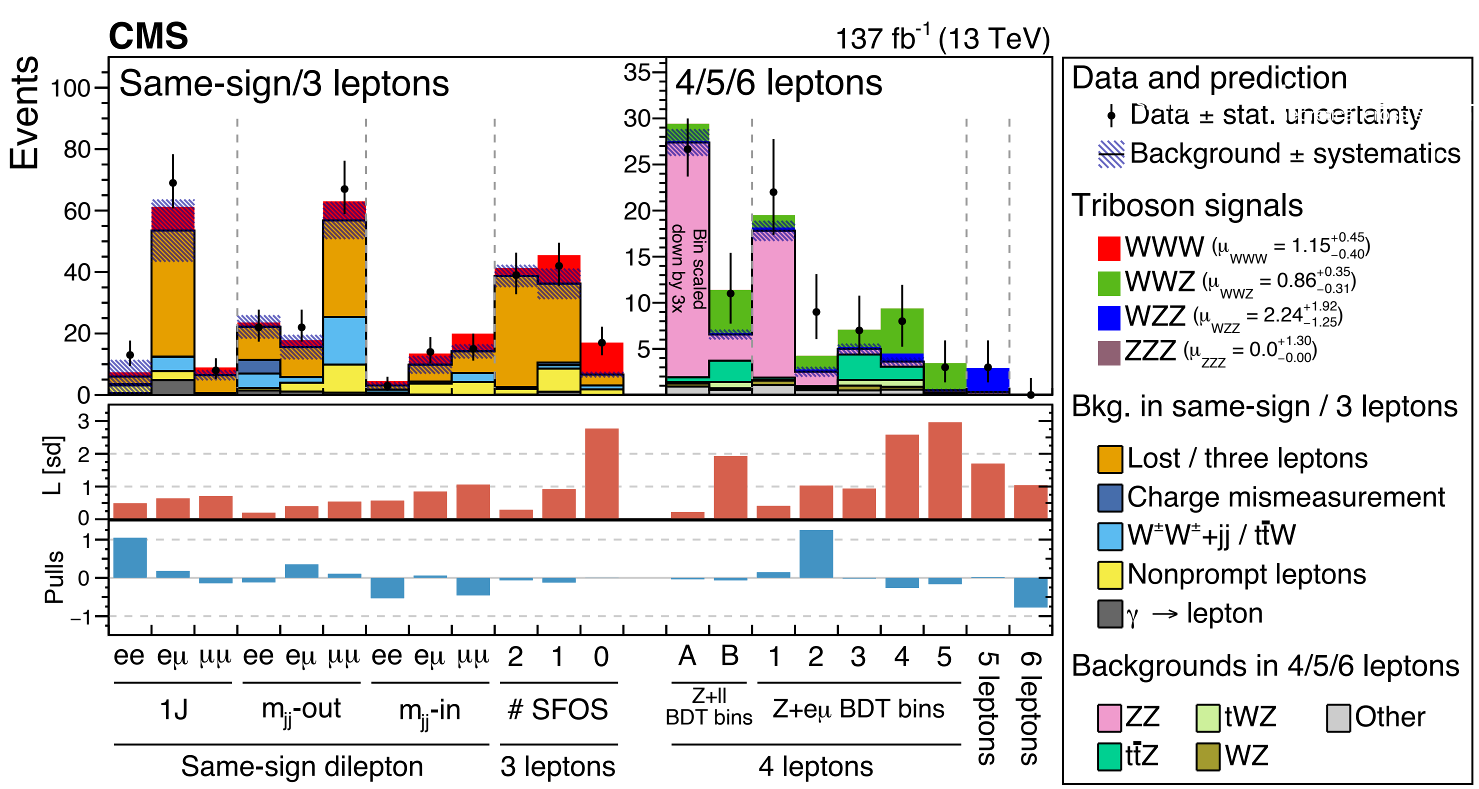
$W \rightarrow \mu\nu$

$W \rightarrow e\nu$

Quartic gauge interactions: triple-boson production

- Backgrounds from top quark production, diboson production + fake/non-prompt leptons
- Hunt for signal in tails of transverse mass (leptons+missing E_T), or using multi-variate analyses



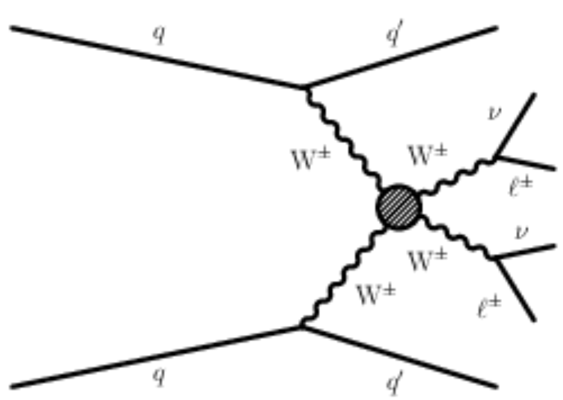


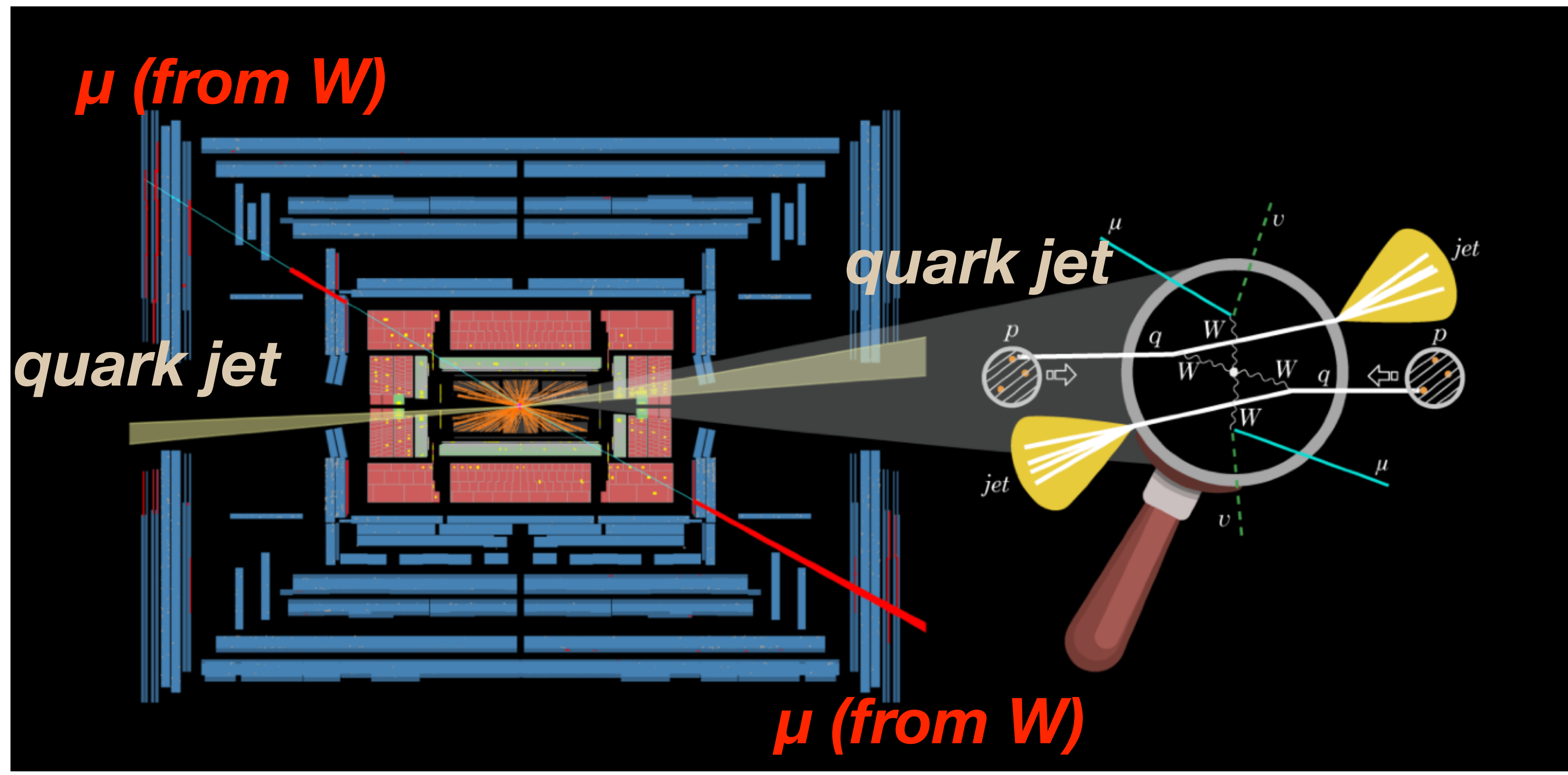
- **Small excesses over background in several channels - compatible with SM signal!**

[Ref]

Quartic gauge interactions: vector-boson scattering

- Scattering of 2 vector bosons to produce 2 vector bosons
    - *VV→VV*

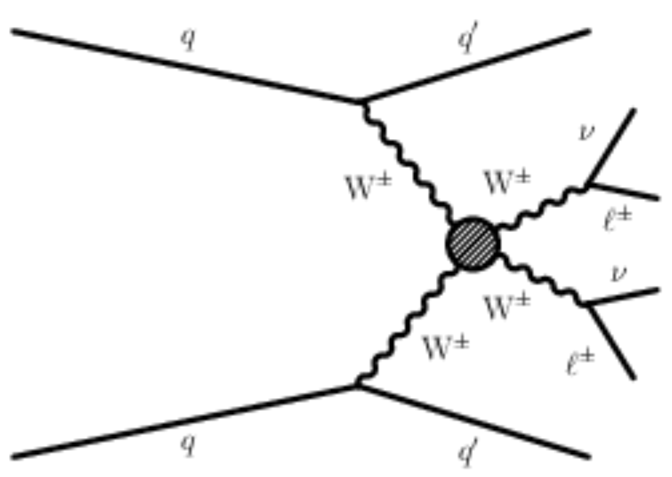




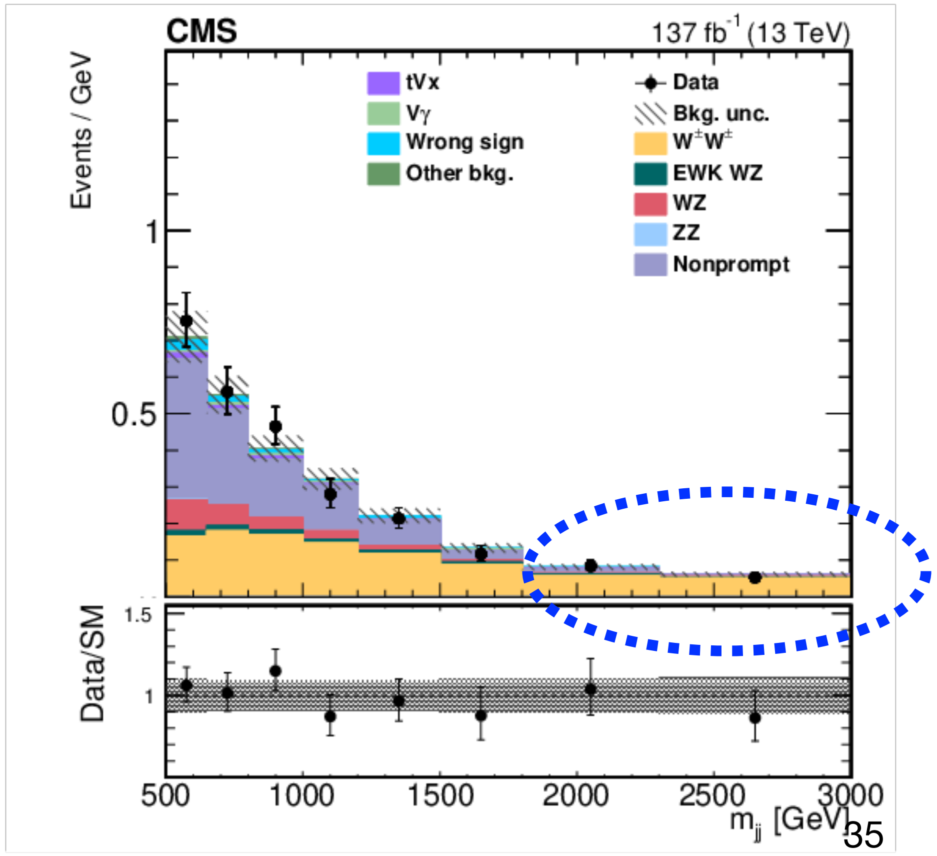
- **Spectacular signatures:**
    - **Typically 2 high energy forward-backward quark jets, in addition to 2 vector bosons**

Quartic gauge interactions: WW→WW scattering

- **Intimately connected to Higgs sector and new physics**
  - SM cross section would grow and become unitarity violating/unphysical at ~TeV scales, unless:
    - There is a Higgs boson OR other new physics



- Signal appears as excess of events with large m(jj) and m_T
  - Fit for sum of signal and backgrounds
  - **Now observed with >5σ significance at the LHC**
    - **Next frontier with more data - probe W polarization for greater sensitivity**



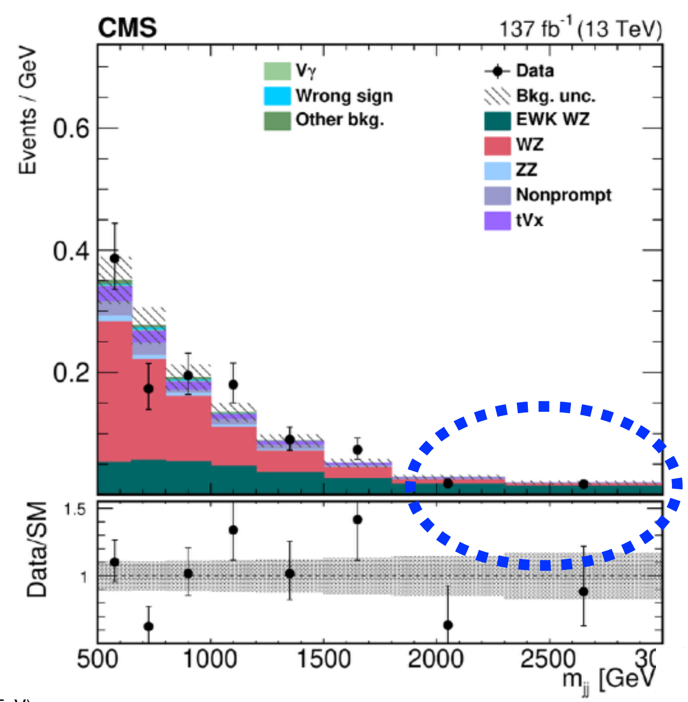
Quartic gauge interactions: other VBS processes

- **What about other vector-boson scattering processes?**

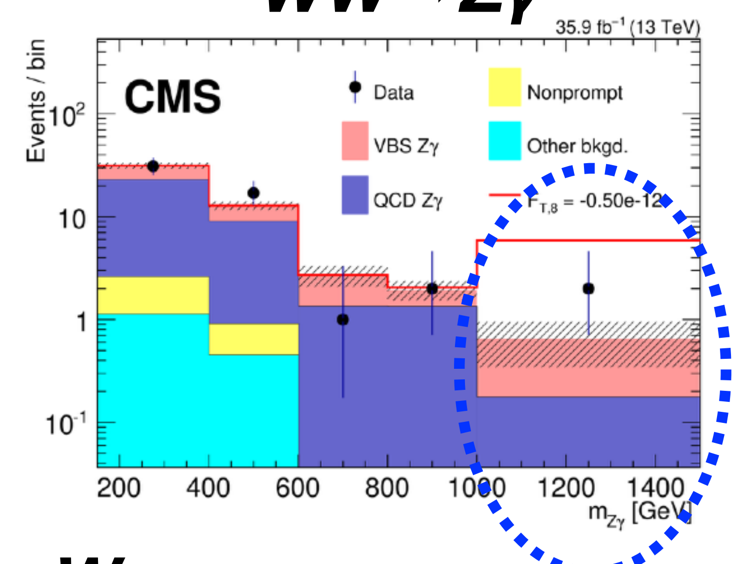
- No anomalous excesses

- Several processes observed for the first time

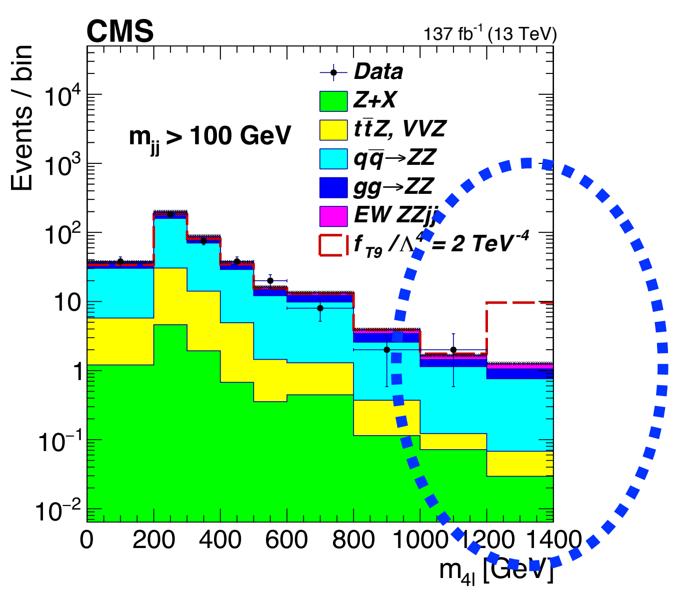
WZ→WZ



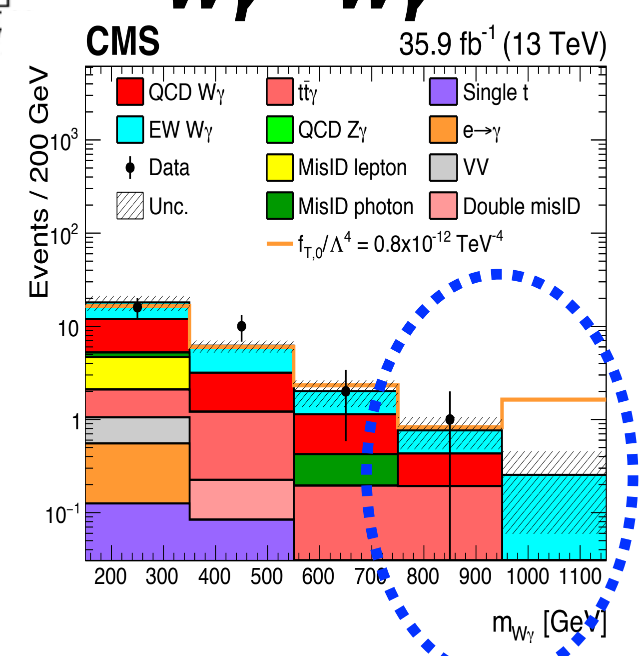
WW→Zγ



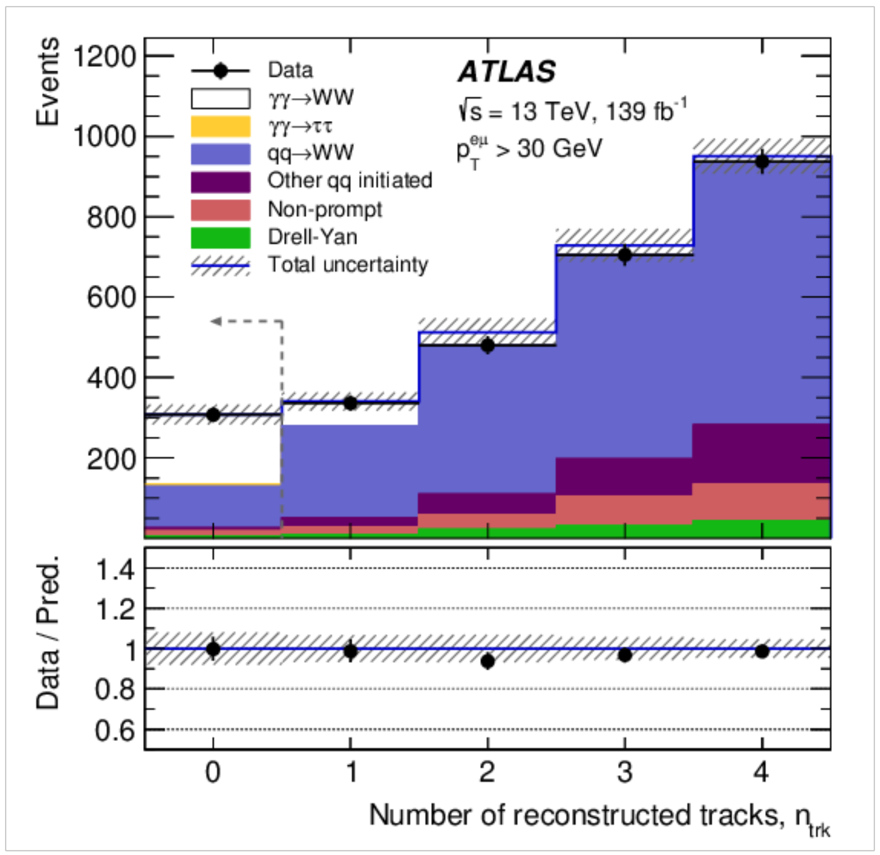
WW→ZZ

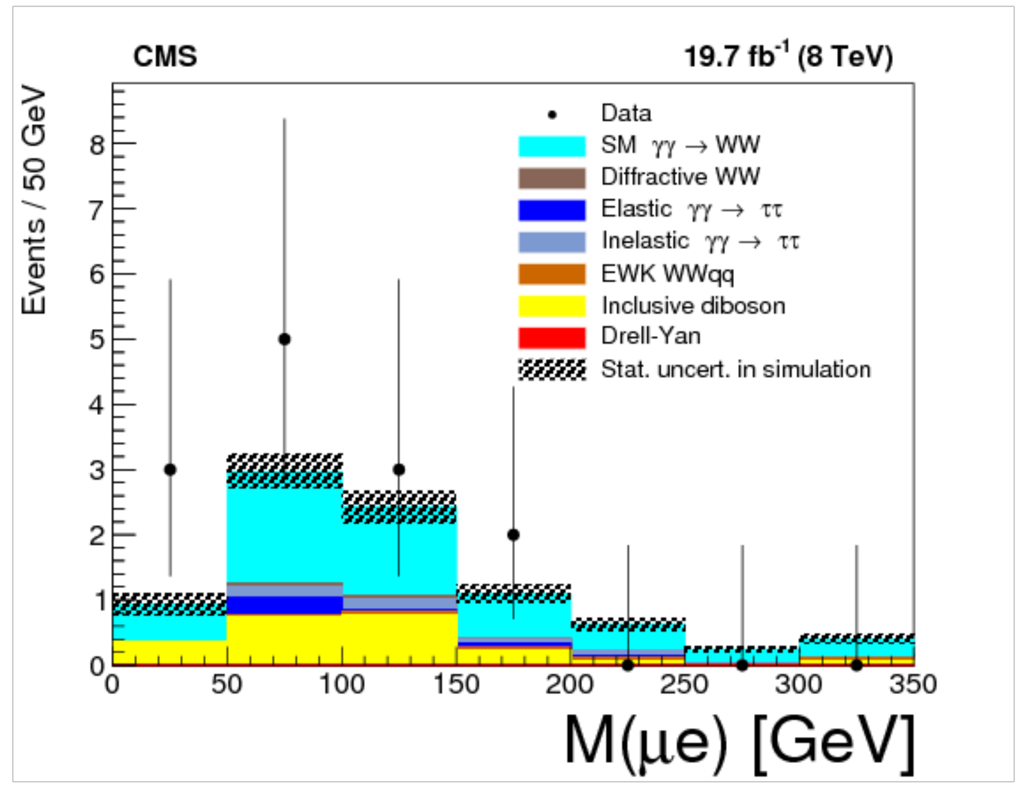


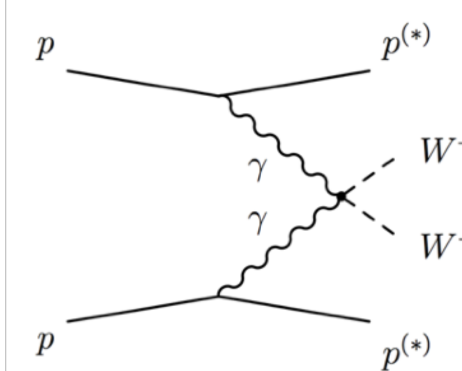
Wγ→Wγ



More quartic gauge interactions: γγ→*WW* scattering



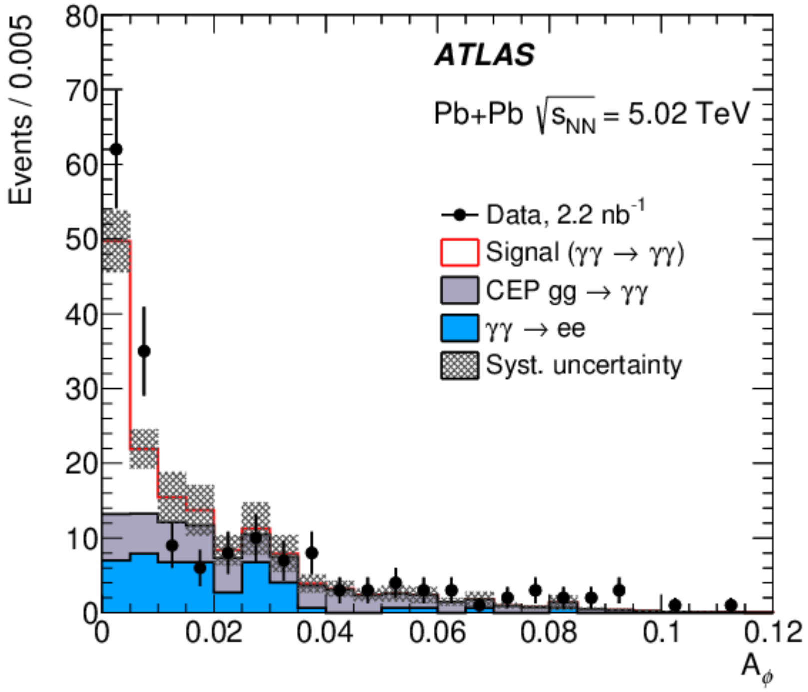


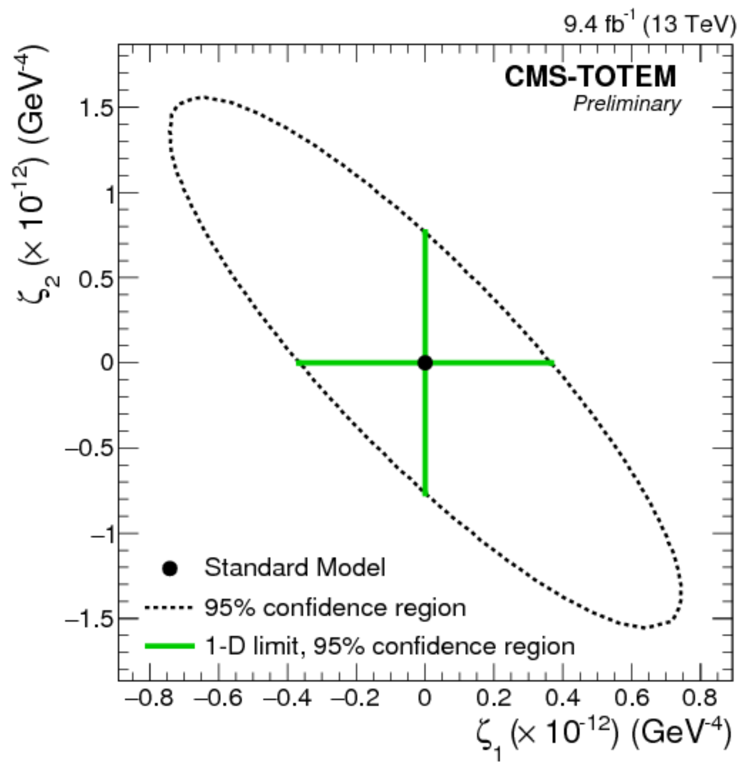


- **What about processes with *initial-state* photons radiated off of protons?**
  - Special case: usually no forward jets, infer γγ production by *lack* of other activity besides 2 W-bosons
  - γγ→WW studied by CMS and ATLAS, results consistent with the SM

Even more quartic gauge interactions: "Light-by-light" scattering

- **What about processes with *only* photons: $\gamma\gamma \to \gamma\gamma$?**
    - Very difficult in normal p-p collisions, so new techniques/detectors developed
- Heavy-ion collisions
    - Look for back-to-back photons with no other activity
    - **SM-like cross section measured, no new physics seen up to ~100 GeV**
- p-p collisions with new forward proton detectors
    - **No excesses observed from ~300 GeV to ~2 TeV -> limits on anomalous γγγγ couplings**

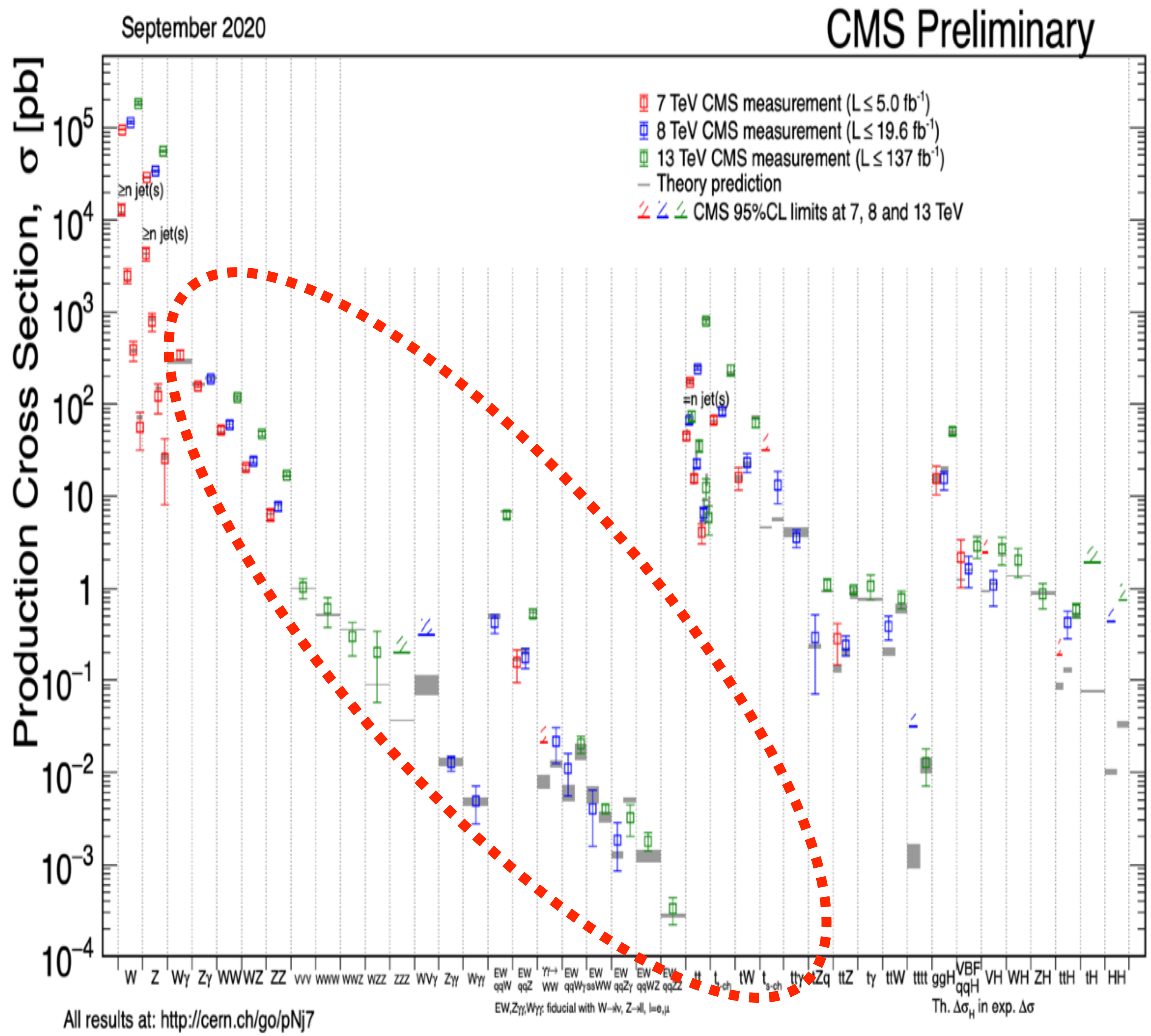




Putting it all together:
summary of cross sections and anomalous couplings

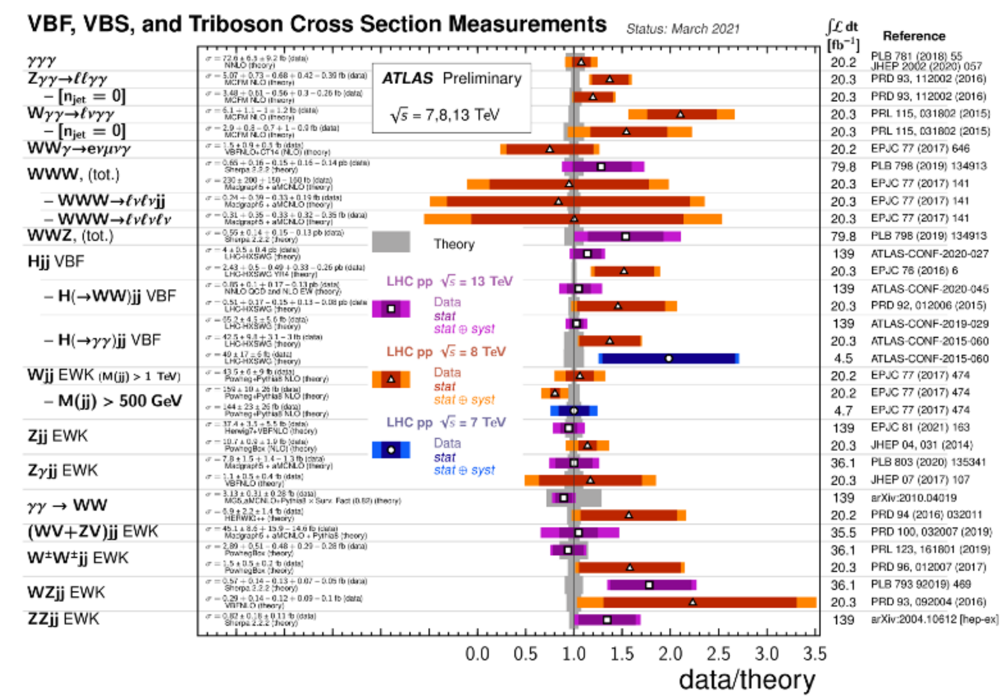
Production rates via gauge boson interactions

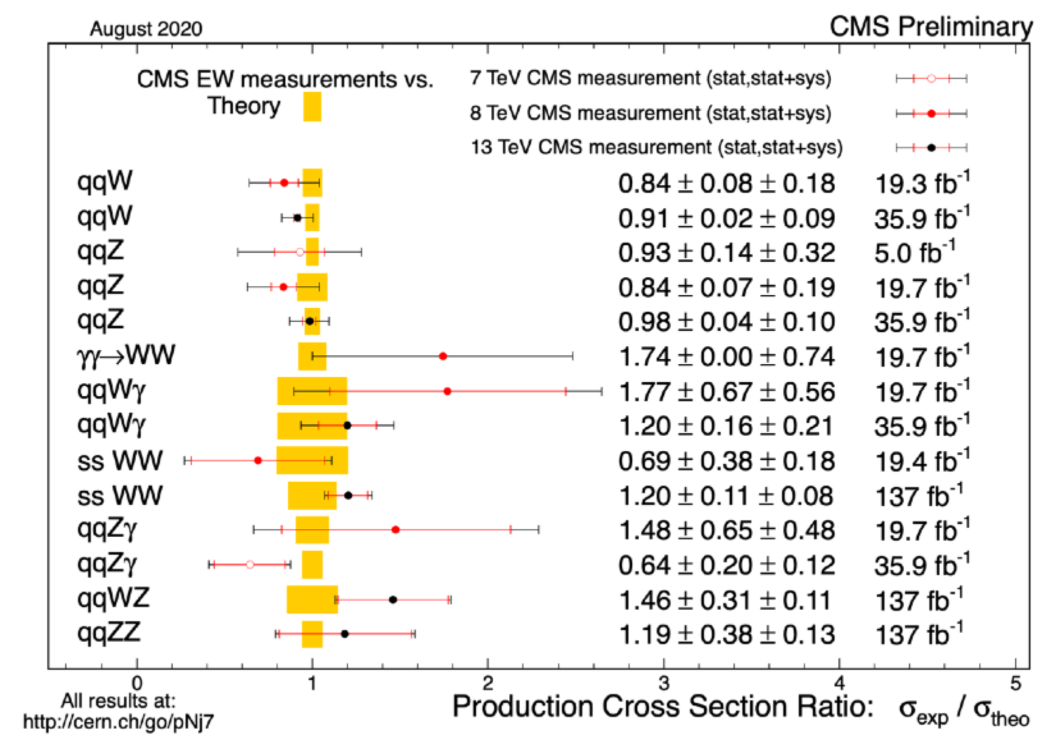
- Back to the original question:
- **Does LHC measure cross sections involving gauge boson interactions at the rates expected from the SM?**
- **So far, yes…**
  - Over almost 6 orders of magnitude!



Rates of VBS/tri-boson processes

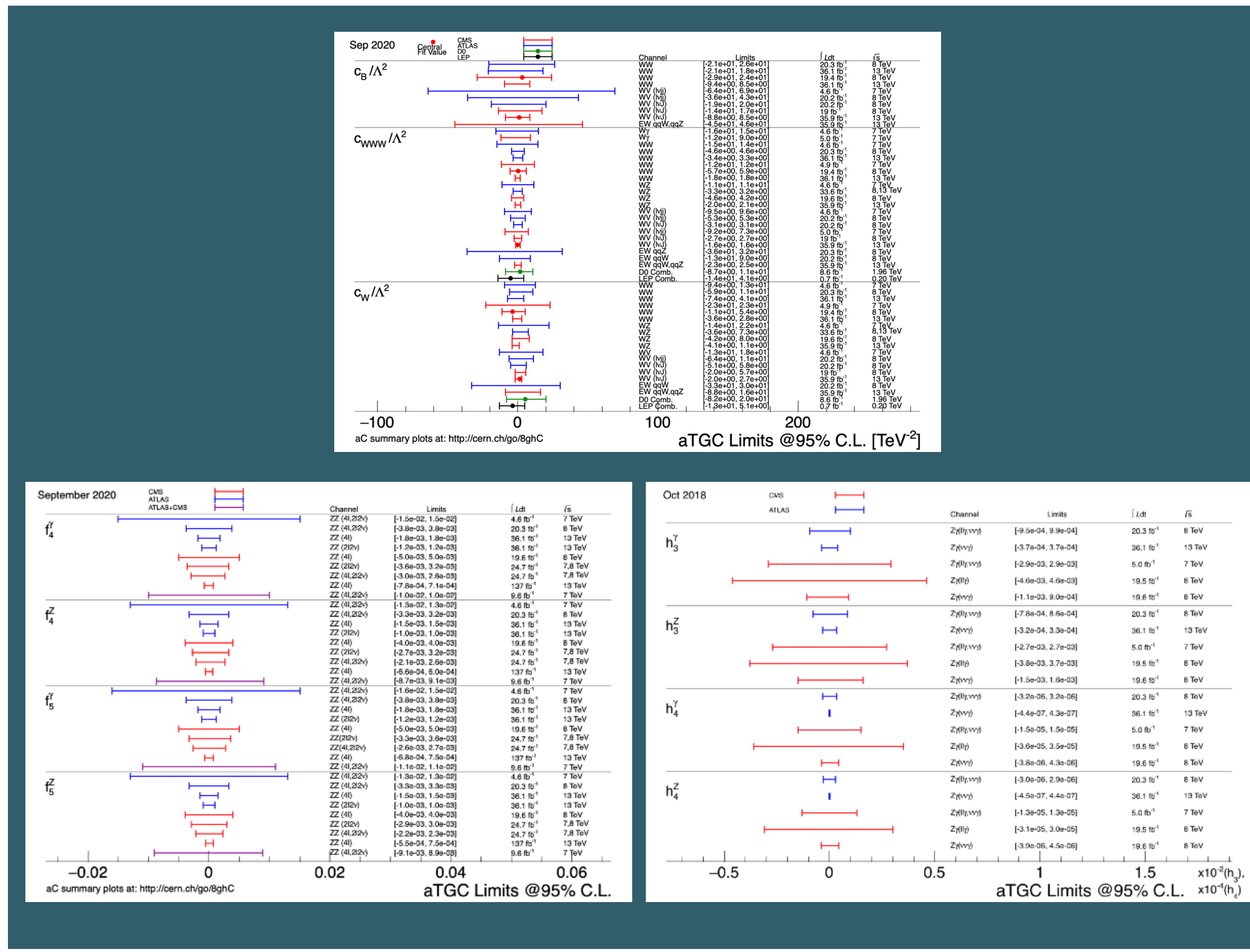
- **What about the very rare processes?**
- Zoom in on tri-boson production and vector boson scattering
    - Plot ratio of measurement/SM prediction
- **Large uncertainties, but so far so good**





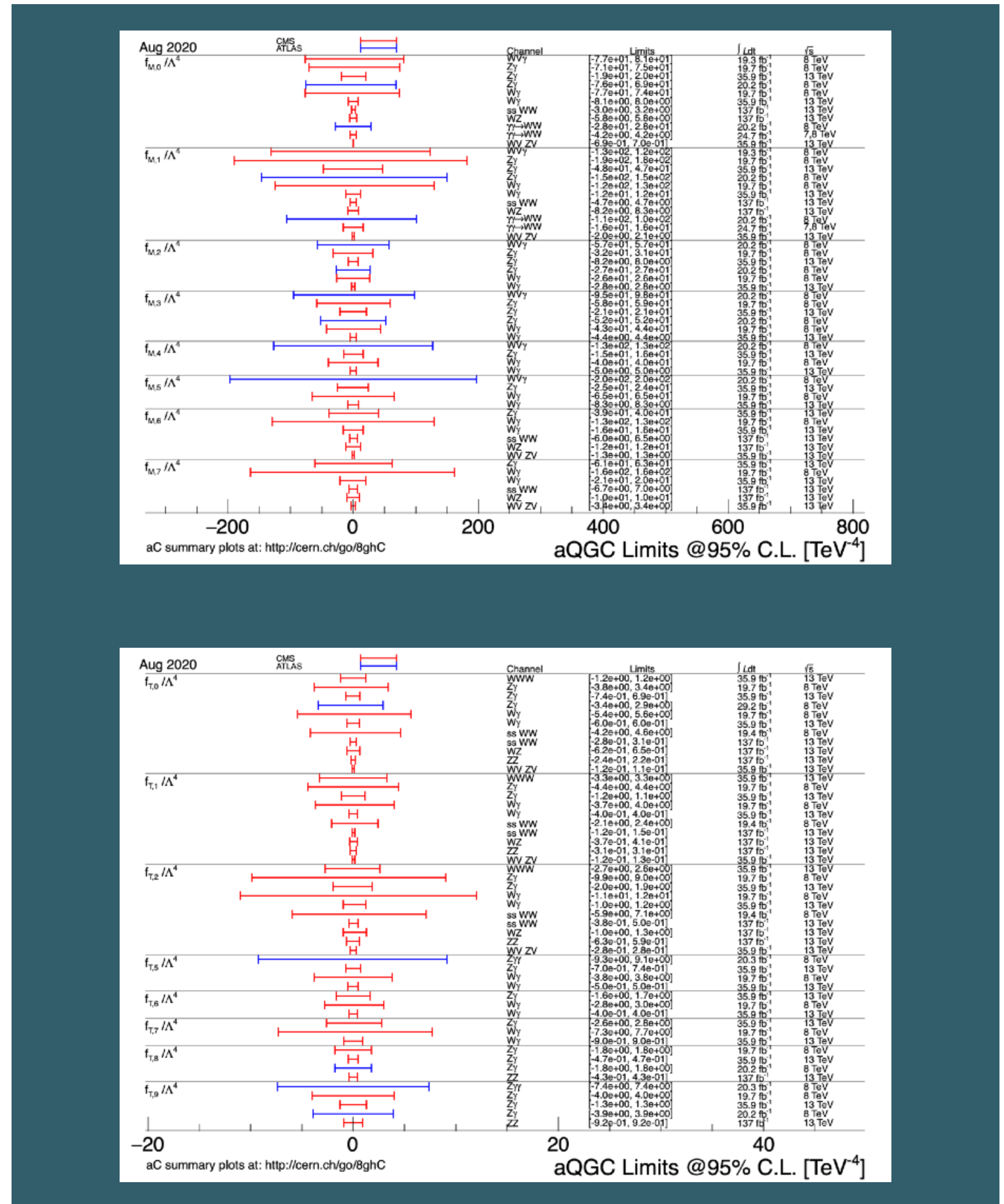
Anomalous gauge couplings scorecard (I)

- **LHC exploring all the possible EWK 3-boson couplings**
- Many upper limits placed on anomalous triple-gauge couplings
  - **So far no deviations from the SM!**



Anomalous gauge couplings scorecard (II)

- **LHC exploring all the possible EWK 4-boson couplings**
- Many upper limits placed on anomalous quartic-gauge couplings
    - Several for the first time
    - **So far no deviations from the SM!**

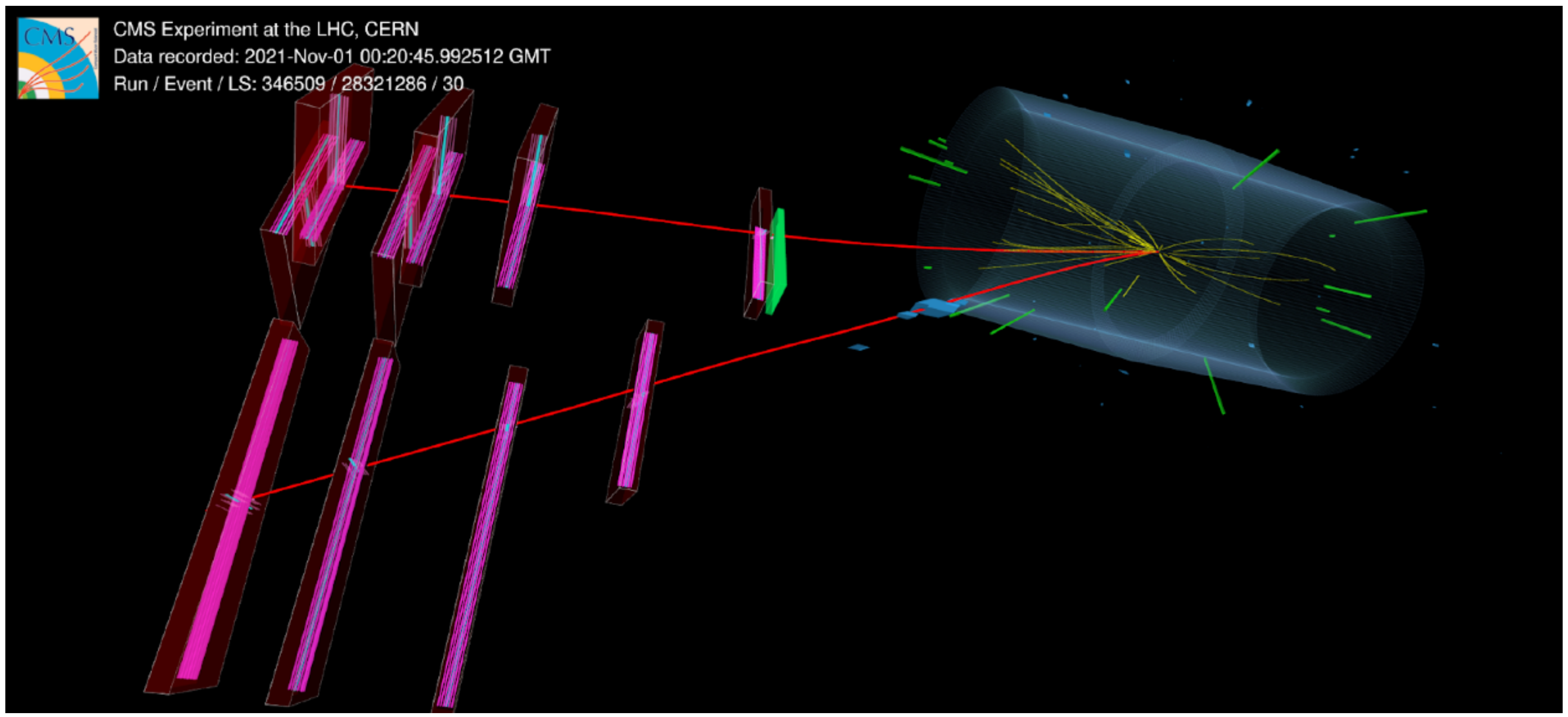


Electroweak physics - where to go from here?

Electroweak physics - where to go from here?

- **LHC precision measurements of some SM parameters start to be competitive with the best from e^+e^- colliders**
  - Important impact on global fits and combinations with Higgs, top data
  - **Systematic uncertainties** are important: important to improve analysis techniques & detectors
- **Pattern of gauge boson interactions/anomalous couplings so far agrees with the Standard Model**
  - Including several very rare processes observed for the first time at the LHC
  - In most cases, sensitivity is to ~TeV scale new physics with large couplings
  - Results are limited by **statistical uncertainties**: will improve just by collecting more data

LHC Run 3

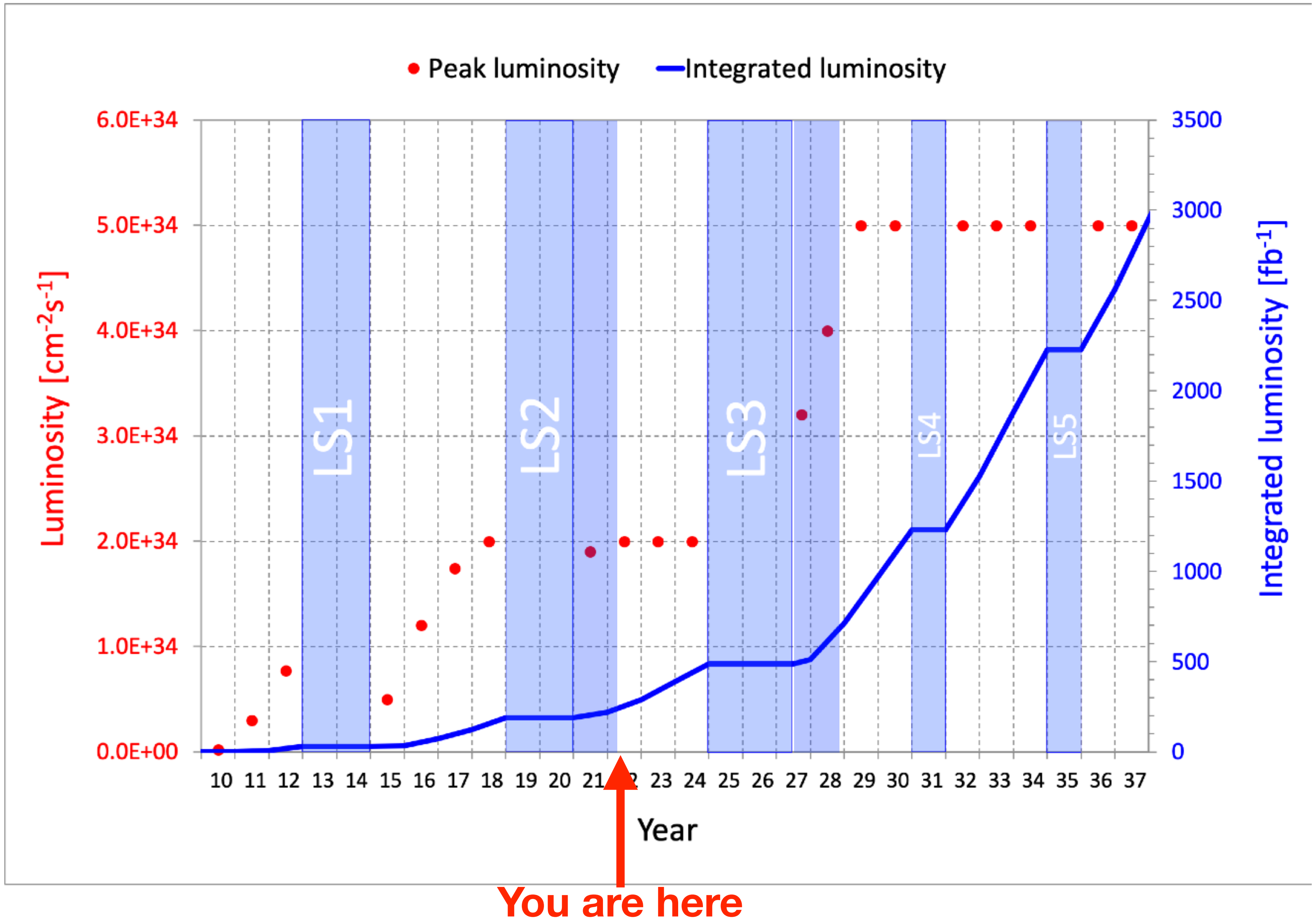


- **The LHC is now preparing to restart for Run 3, after a 3.5 year stop to refurbish and improve equipment**
  - First test collisions already in October 2021
  - Real collisions starting in Spring 2022

- Energy will be raised to 13.6 TeV
- Run 3 will last for 3-4 years
  - **More than doubling the current dataset**

Beyond Run 3: High-Luminosity LHC

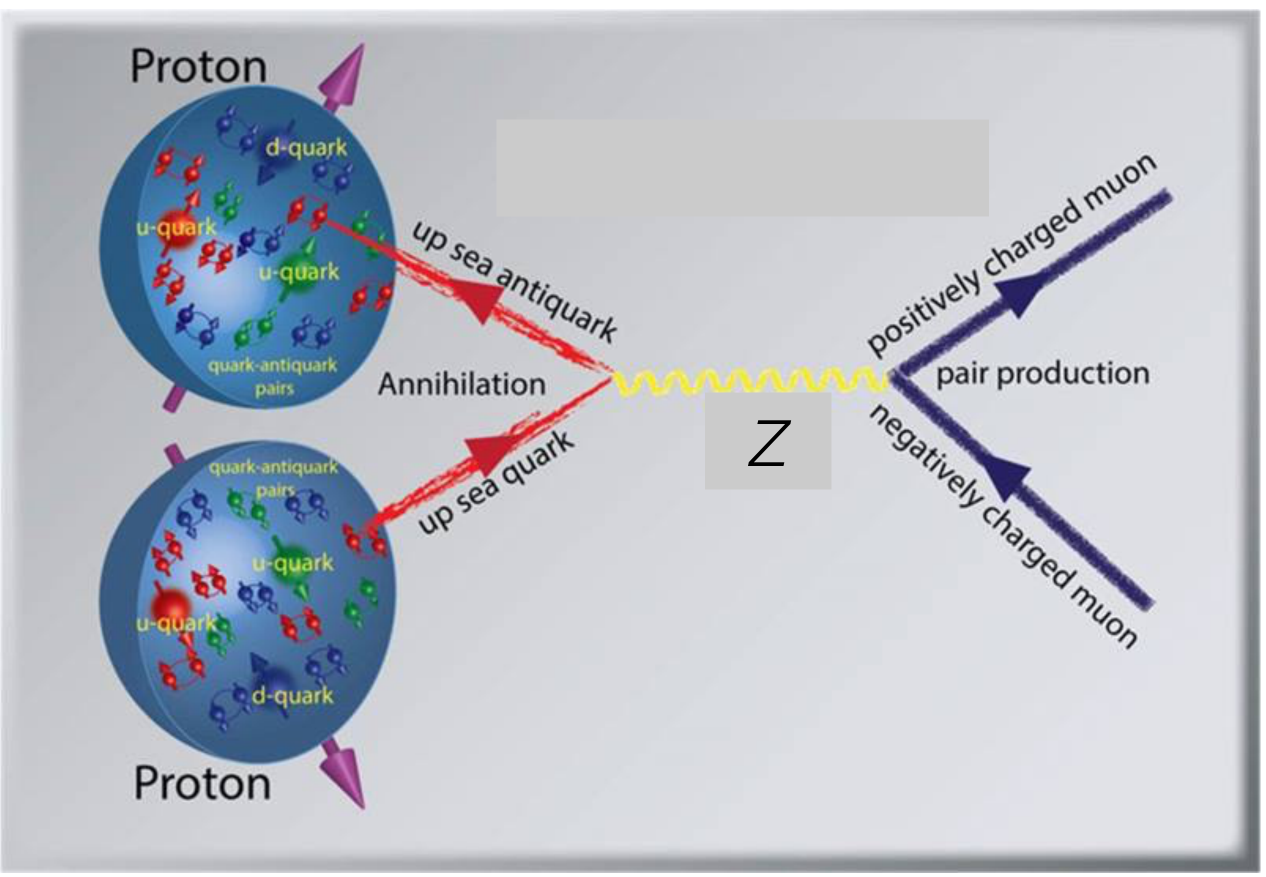
- After Run 3, LHC will be upgraded to the "High luminosity LHC"
    - **~20x more data expected by the end of the HL-LHC program - probe smaller deviations from the SM**
    - **Program of detector upgrades will enable new measurements/ analysis techniques**



W/Z/γ as tools for QCD (time permitting)

W/Z/γ as tools for QCD

- Single W/Z/γ's at the LHC are usually produced by interactions of quarks or quarks+gluons

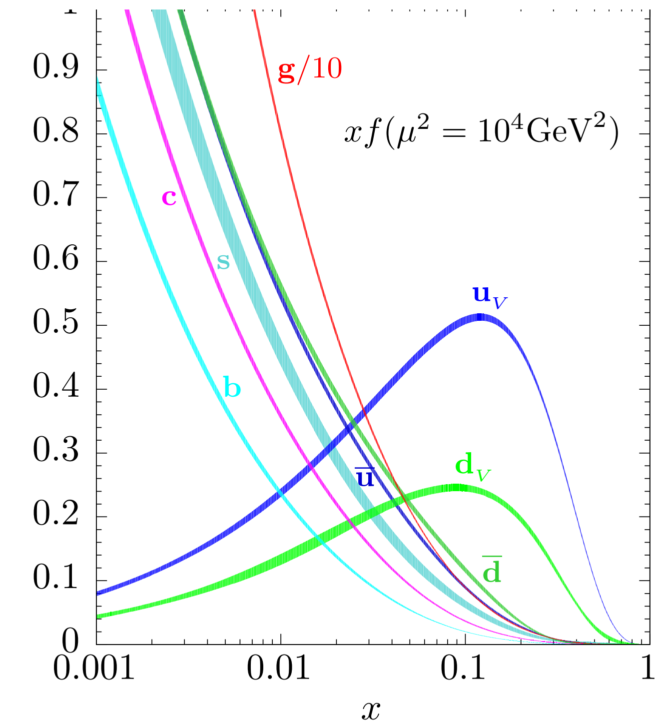


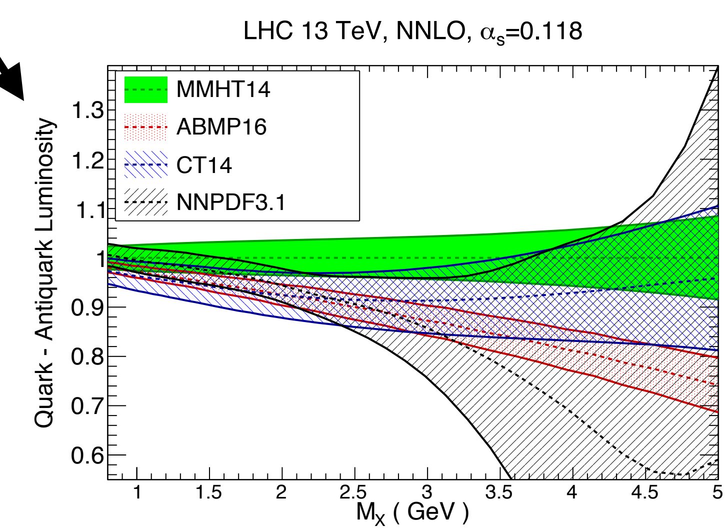
[Ref]

- **=> Apart from "purely" electroweak physics, W/Z/γ production can also be used to probe internal structure and dynamics of the proton**

W/Z as tools for QCD: PDFs

- **Major uncertainty in many LHC measurements and searches: “Parton Distribution Functions”**
    - Describe fraction of proton momentum carried by the partons (quarks or gluons)
    - Better knowledge of PDF’s means better predictions for any process involving production by quarks/gluons



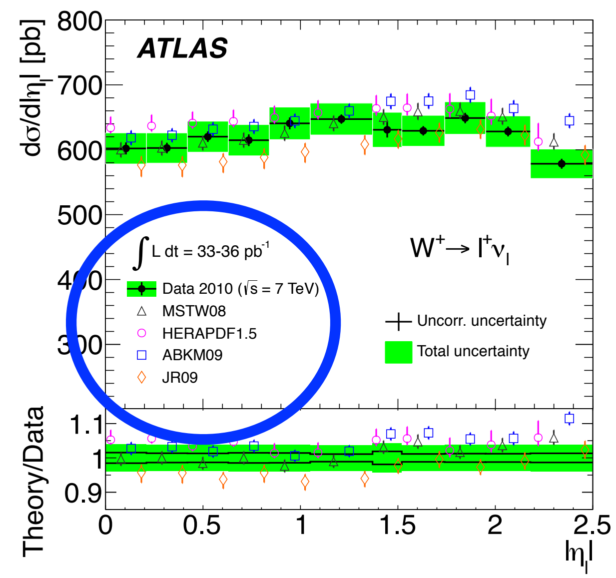


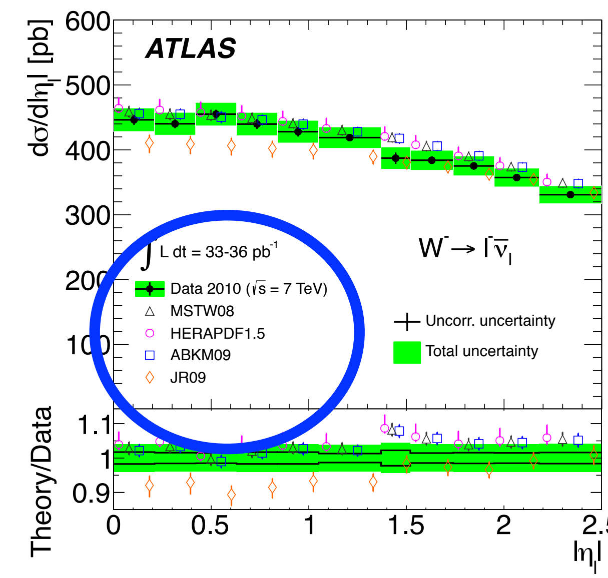
- **Jet production more sensitive to gluon PDFs, Z and W depend on quark PDFs**

[Ref]

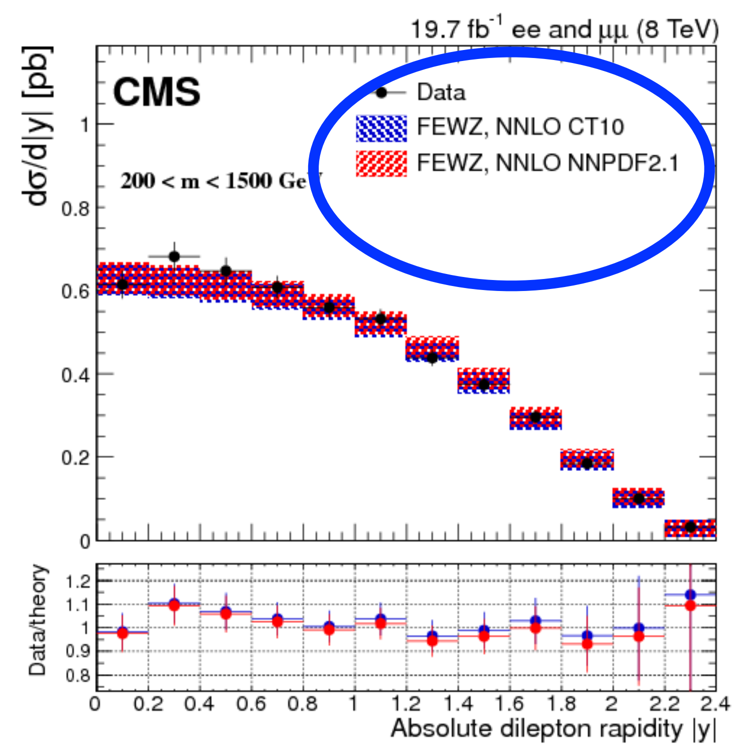
W/Z as tools for QCD: PDFs

- Measure differential cross sections
  - Separately for W^+ and W^-
    - Different sensitivity to up and down quark PDFs
  - In invariant mass+rapidity for Z (or non-resonant Drell-Yan)



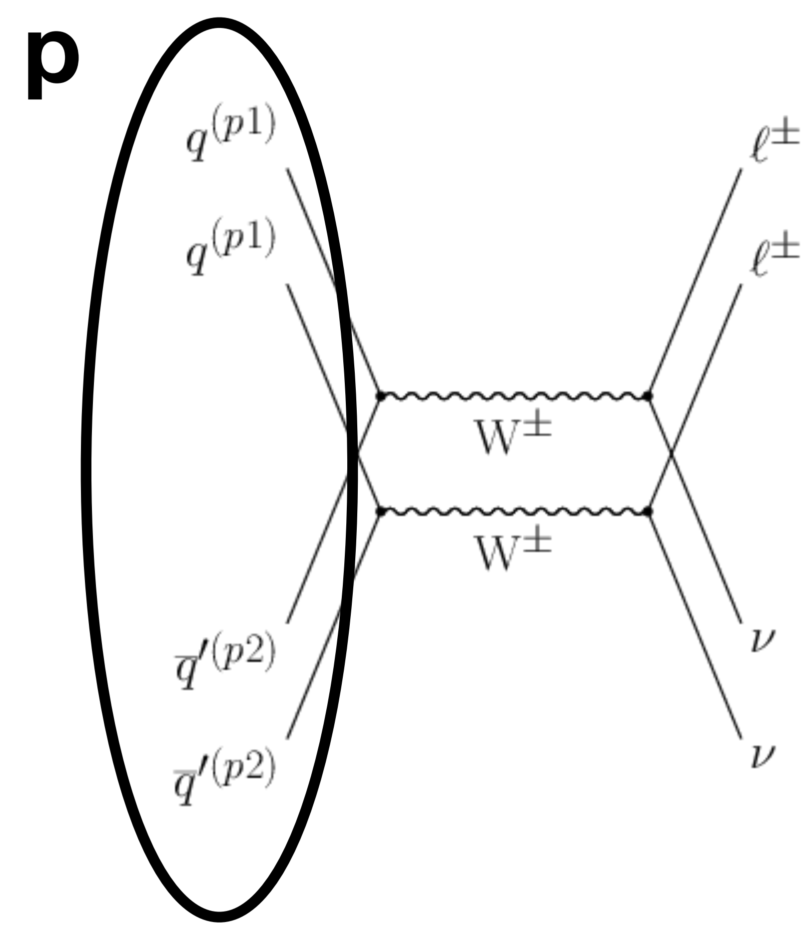


- **Differences between different PDF predictions**
  - **=> Use data as input to improve PDF fits**



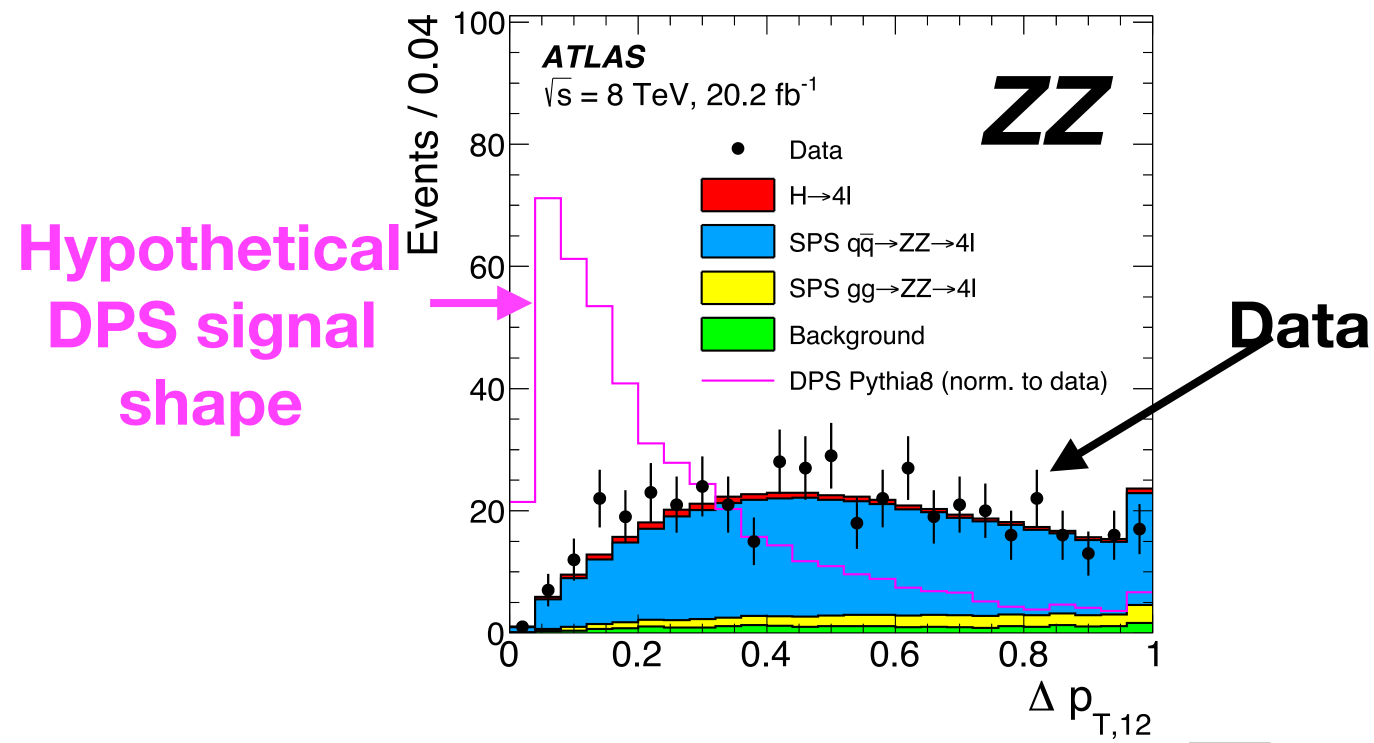
W/Z as tools for QCD: Double-parton scattering

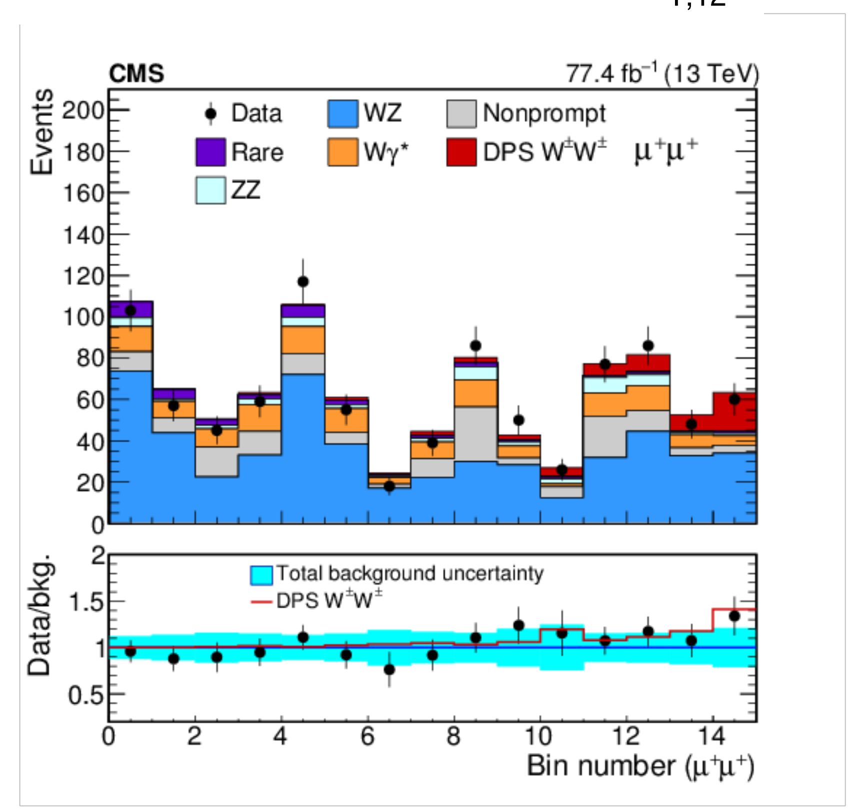
- Usually only 1 "hard" quark or gluon interaction in a single proton-proton collision
    - **In rare cases can have 2 or more => "Double parton scattering"**
- Can produce spectacular/"weird" signatures
    - **Potential background to new physics searches, and electroweak measurements**



W/Z as tools for QCD: Double-parton scattering

- Similar W/Z reconstruction as electroweak measurements
  - Look for pairs of particles from the same vertex, with non-correlated kinematics
    - Unbalanced p_T, phi, etc.
- **Several DPS processes seen for the first time at LHC (W^+W^+, W+jets, Z+jets…), for others still looking (ZZ…)**





Summary

- **The electroweak sector of the Standard Model has been so far remarkably (ridiculously) successful, even at LHC energies**
  - **But attempts to break it are ongoing from all directions**
    - Combination of precision measurements of SM parameters
    - Searches for excesses in high-energy tails of distributions/anomalous couplings
    - Close connections to Higgs, top, flavor-physics studies (see upcoming lectures)

Extra