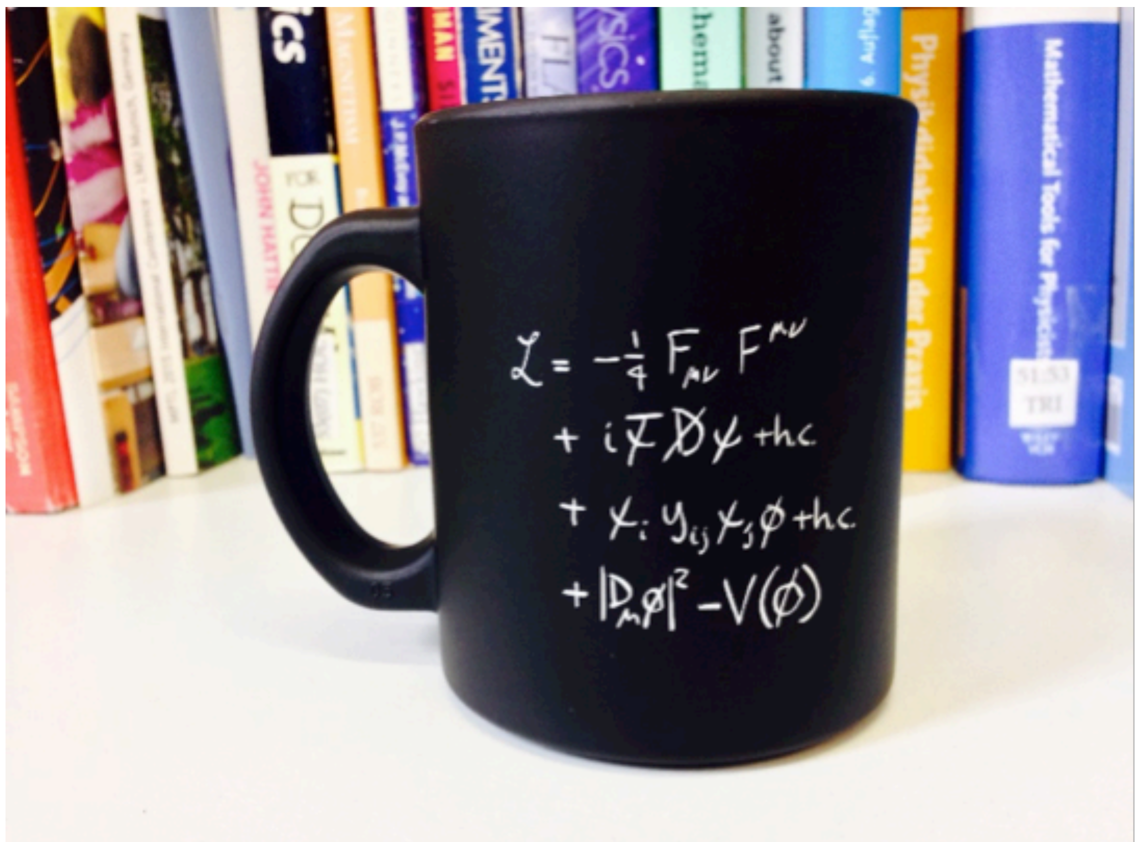
Standard Model Processes

Course on Physics at the LHC

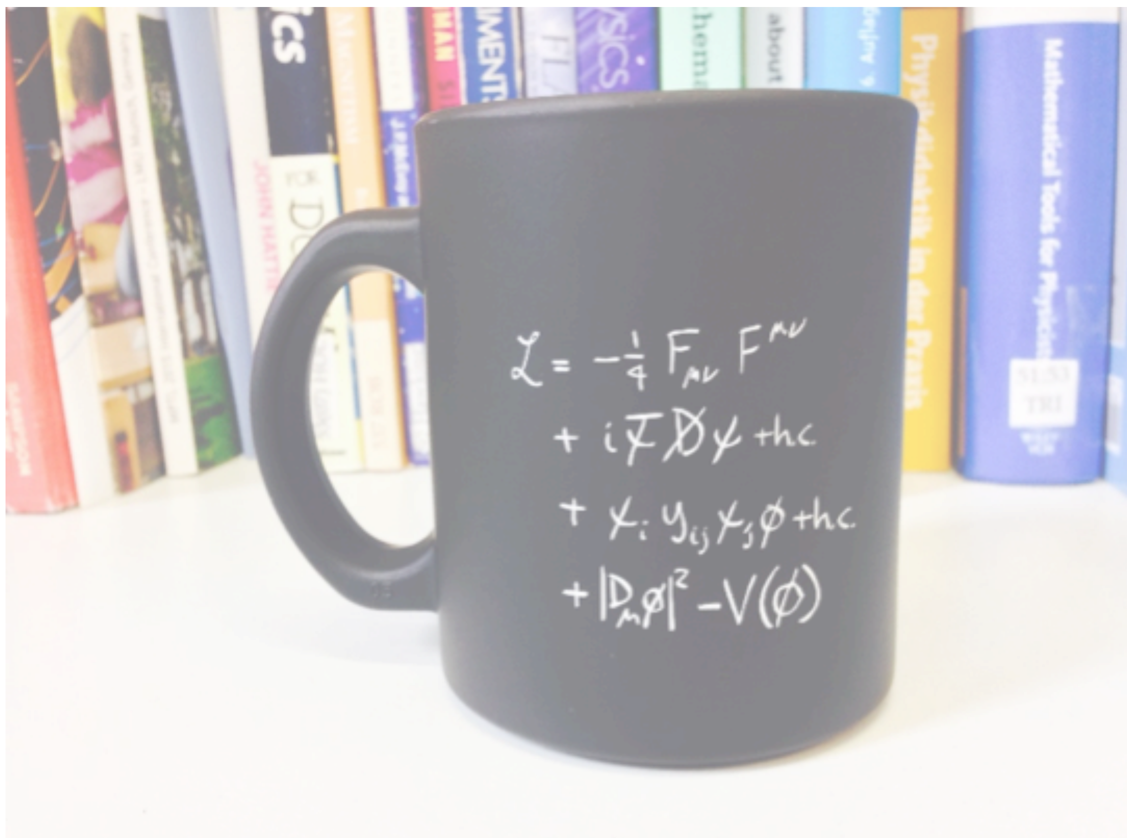
Jonathan Hollar (LIP)
March 9, 2026

The Standard Model is…

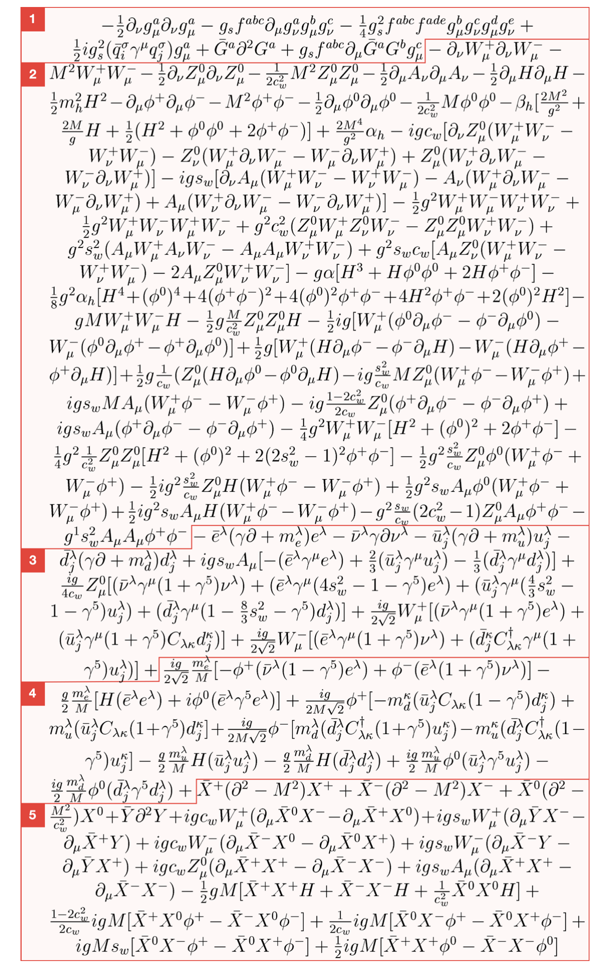


One of the most predictive, precisely tested theories of nature in human history

The Standard Model is…

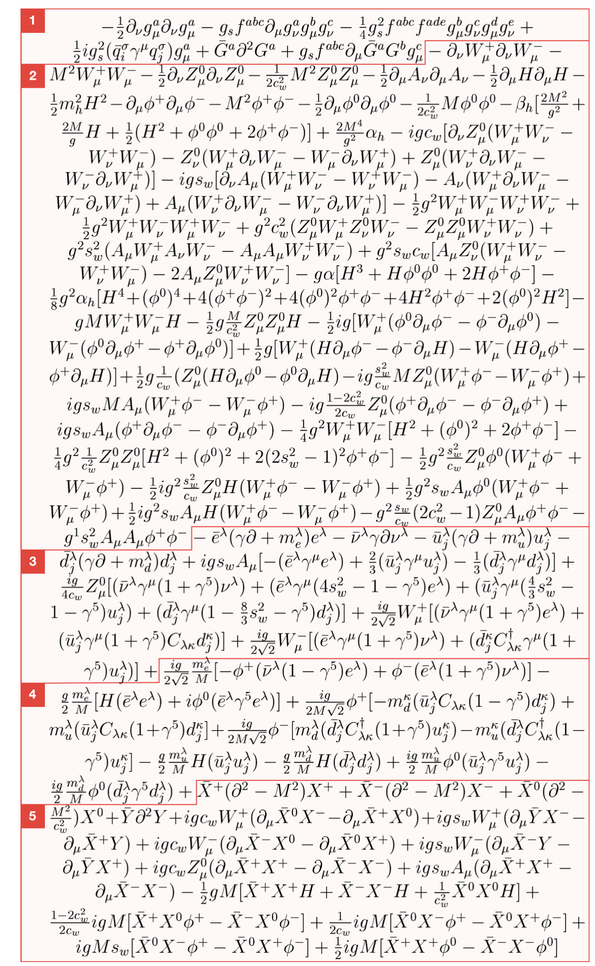


One of the most predictive, precisely tested theories of nature in human history



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 later lectures)

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*

- Are SM/EWK parameters self-consistent? (**Precision measurements of particle properties + SM parameters**)
- Are SM/EWK interactions self-consistent? (**Rates/cross sections & anomalous couplings**)

QCD

Interactions of gluons and quarks - see first lecture

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 in March-April

Higgs physics

Properties and interactions of the Higgs boson

See lectures in March-April

…though EWK gauge bosons connect to many of them

Electroweak sector (this lecture)

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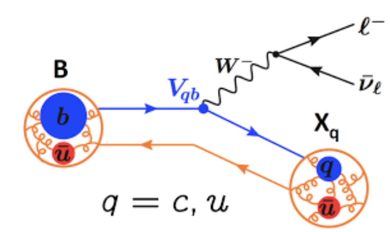
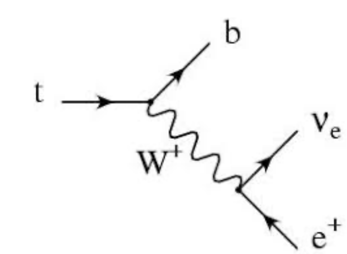
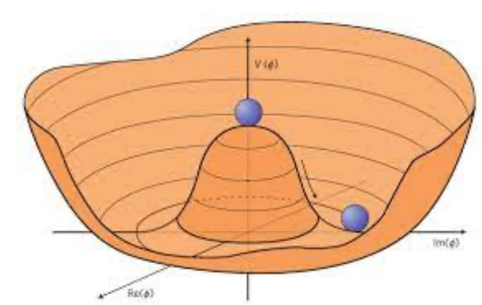
Flavor and top physics





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

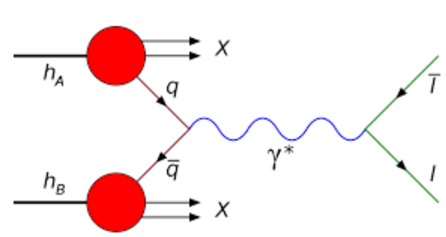
Higgs physics



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, 2010-2012)

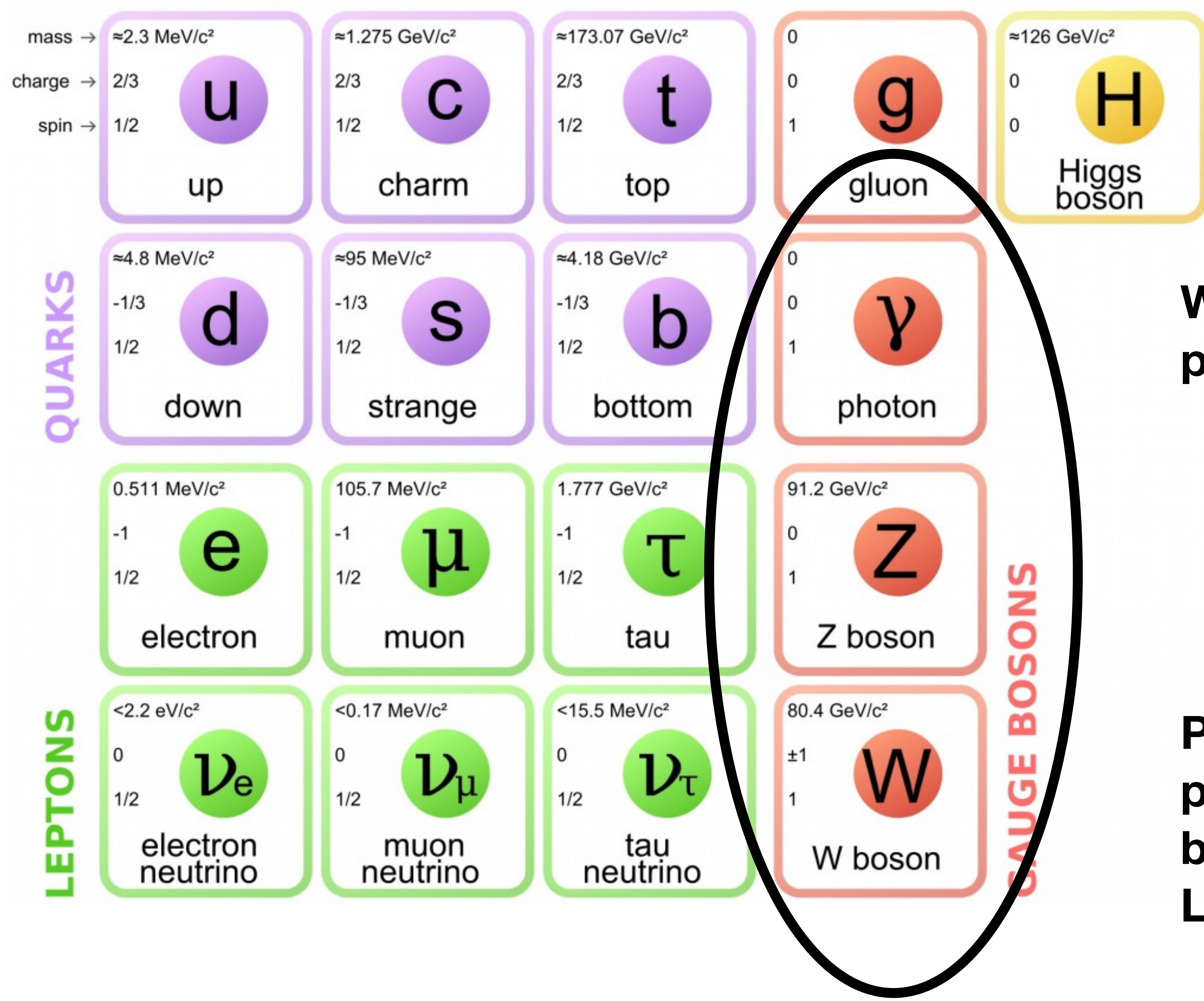
13 TeV (Run2, 2015-2018)

13.6 TeV (Run3, 2022-)

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

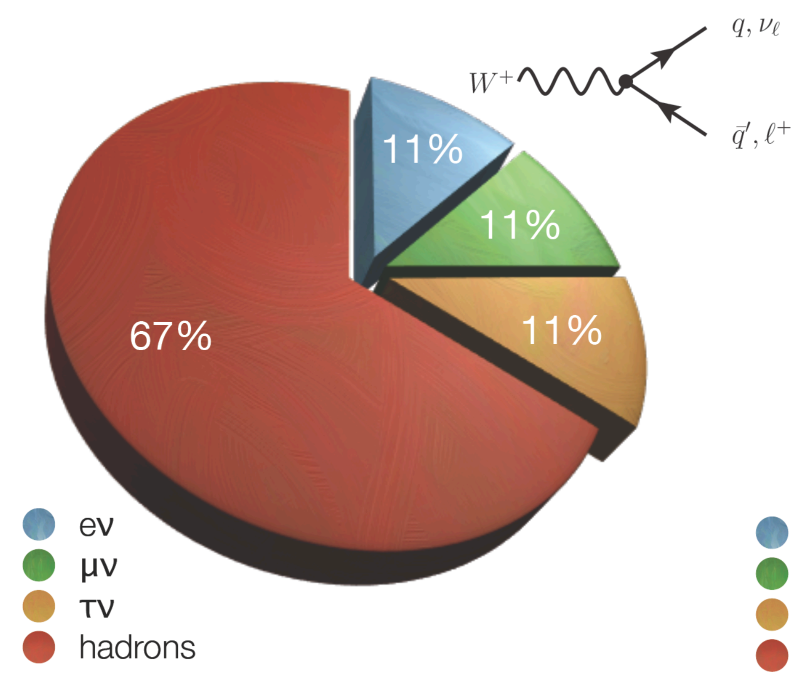
Photons: massless particles, directly detected by energy deposits in the LHC calorimeters

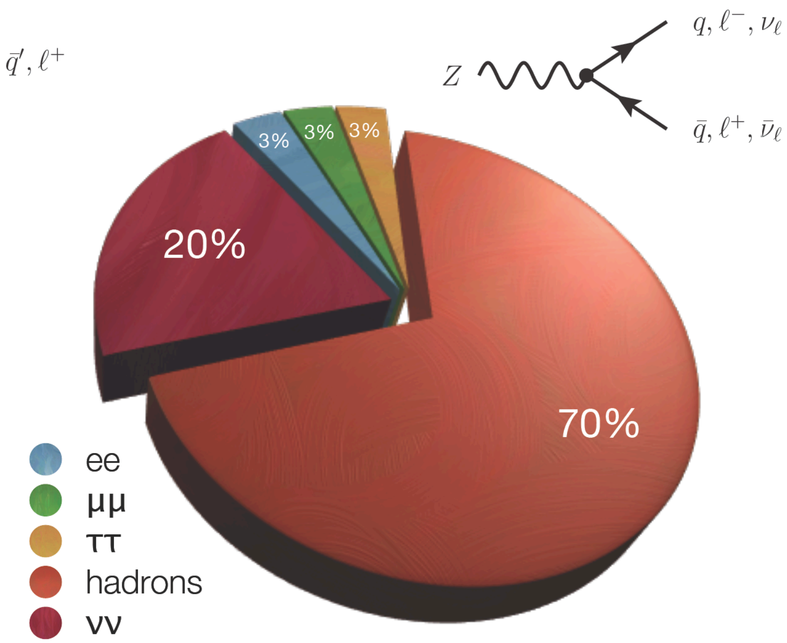
W and *Z* decays, by the numbers

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



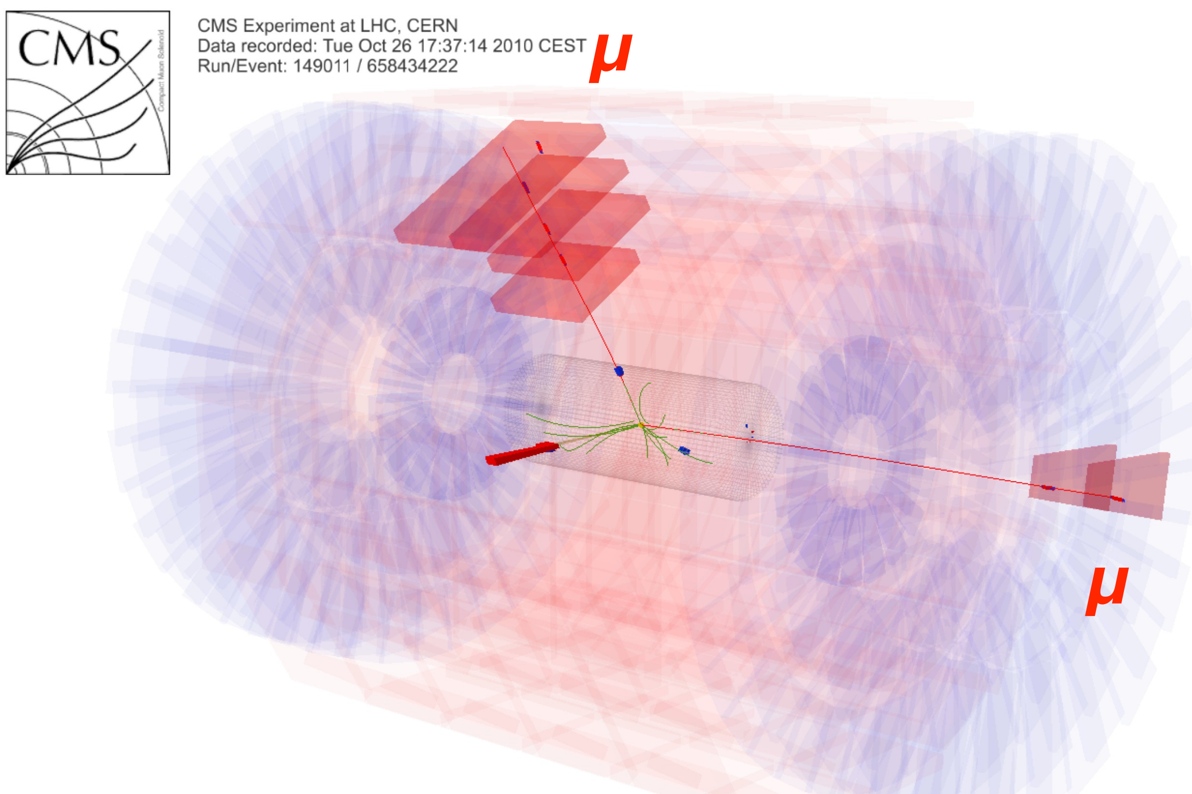


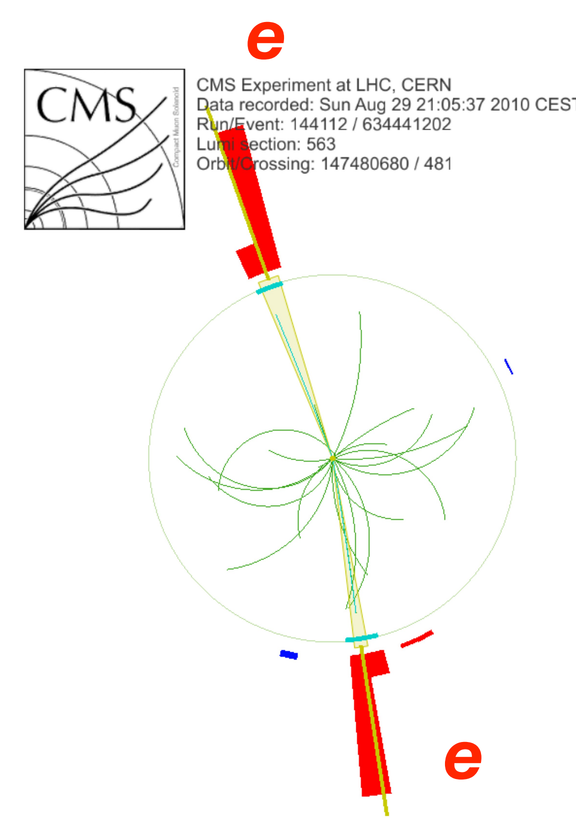
Decays with muons and electrons

Low rate, but lowest background/cleanest signals

Taus: Can be reconstructed via either decays to e/μ, or to hadrons

Leptonic Z reconstruction





$Z \to ll$: 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)

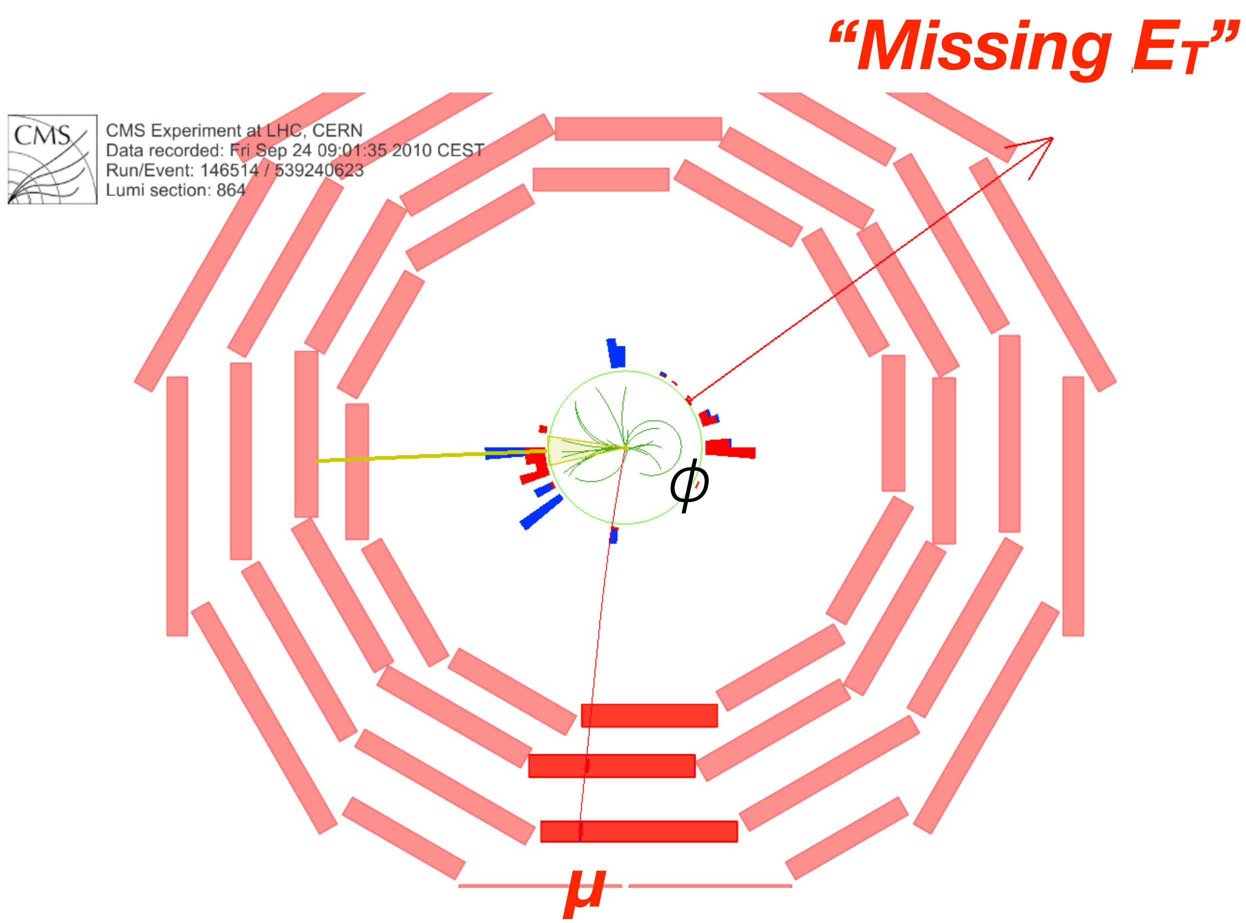
Lepton isolation (require leptons separated from other tracks/calorimeter deposits):

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

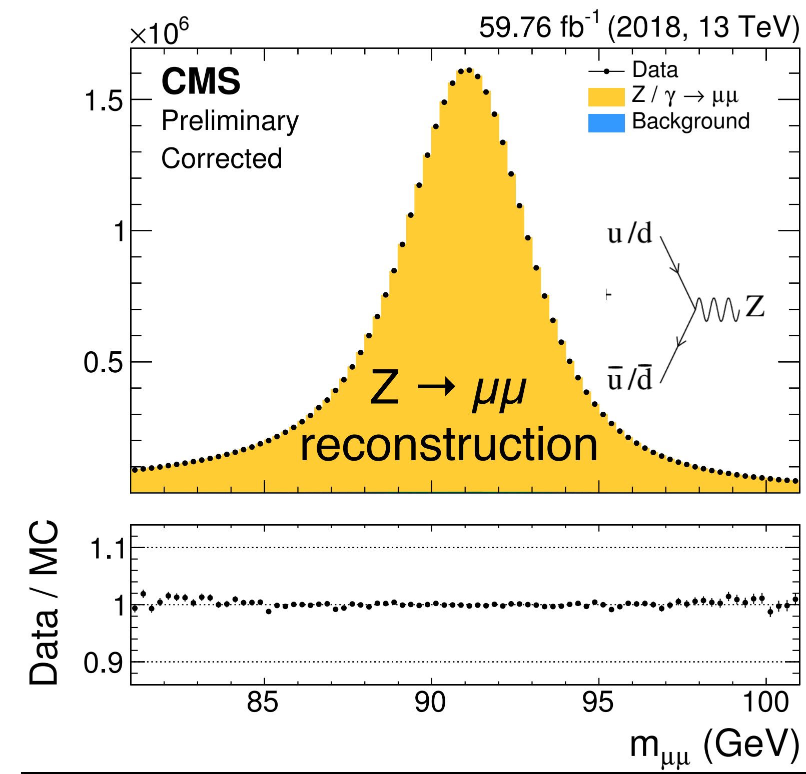
Even in the low branching-fraction leptonic decays

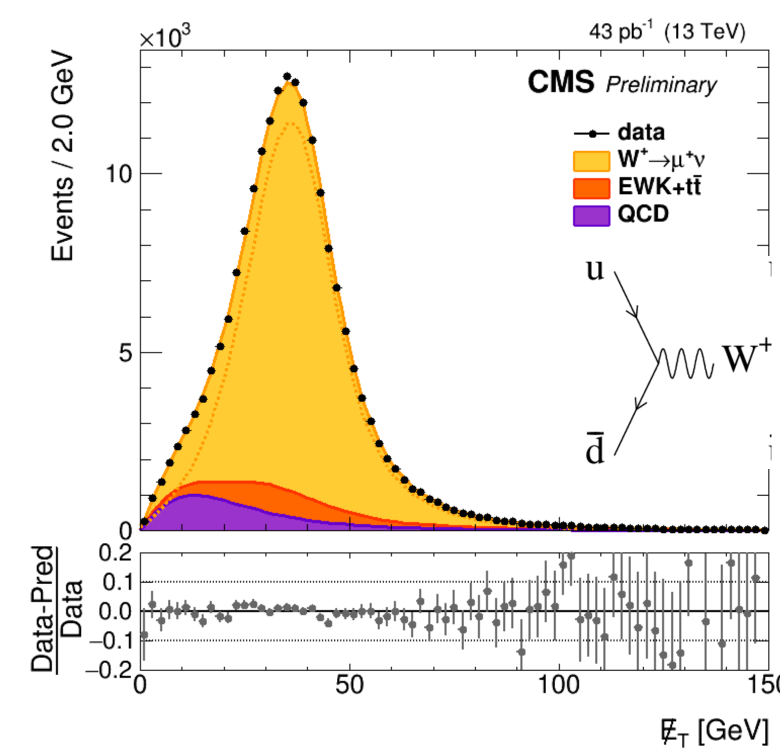
In 300fb-1 at 13 TeV, expect:

~6B *W→lν* events produced

~600M *Z→ll* events produced

Very high signal/background, especially in *Z→ll*





Electroweak physics:
Precision measurements of SM parameters

Precision SM measurements

Is the Standard Model self-consistent?

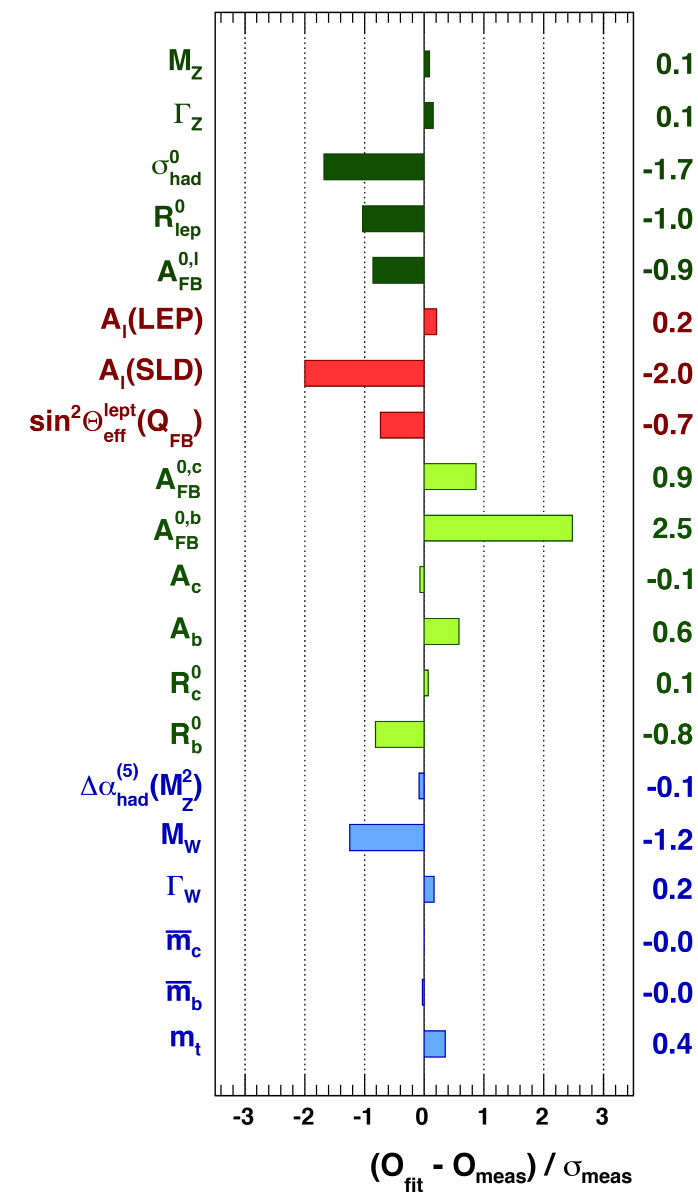
Measure many observables closely related to SM parameters, then check if SM can fit all the data

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

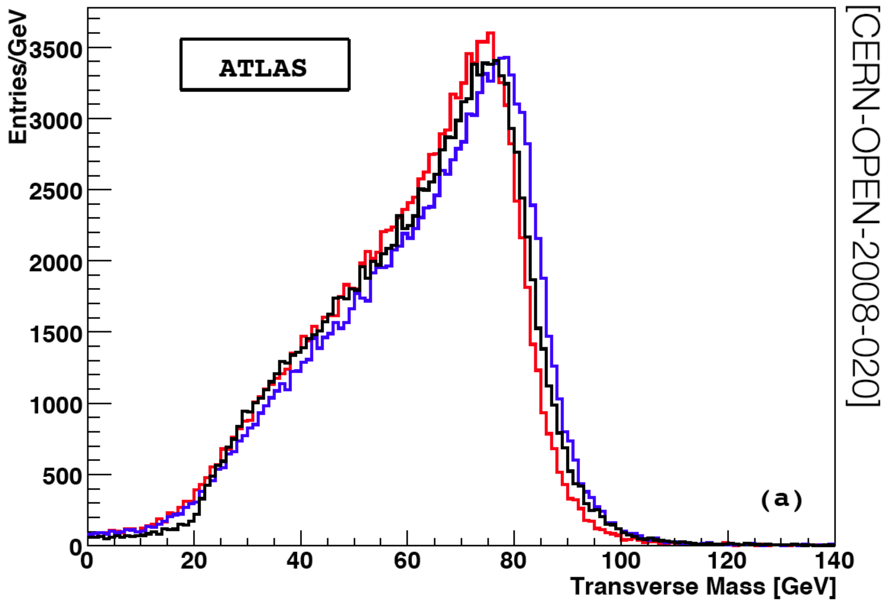
Control of missing E_T reconstruction

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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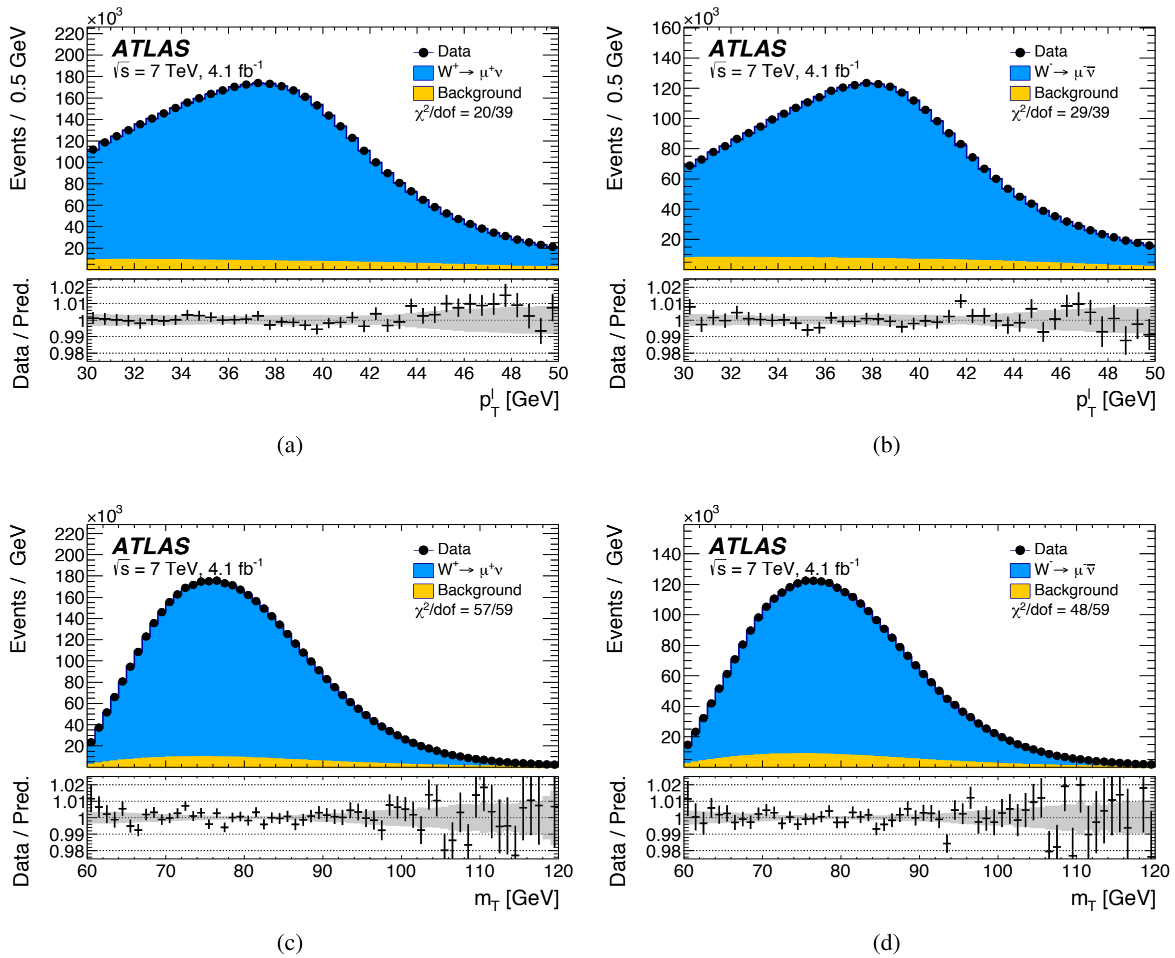
Precision SM measurements: W mass



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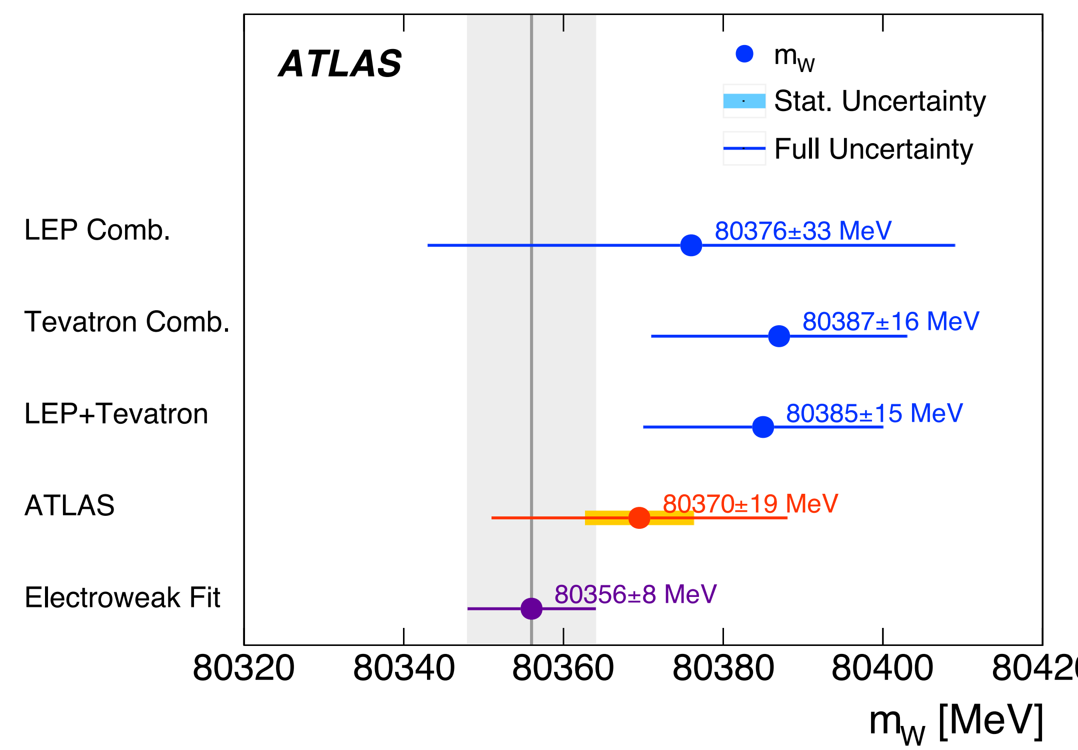
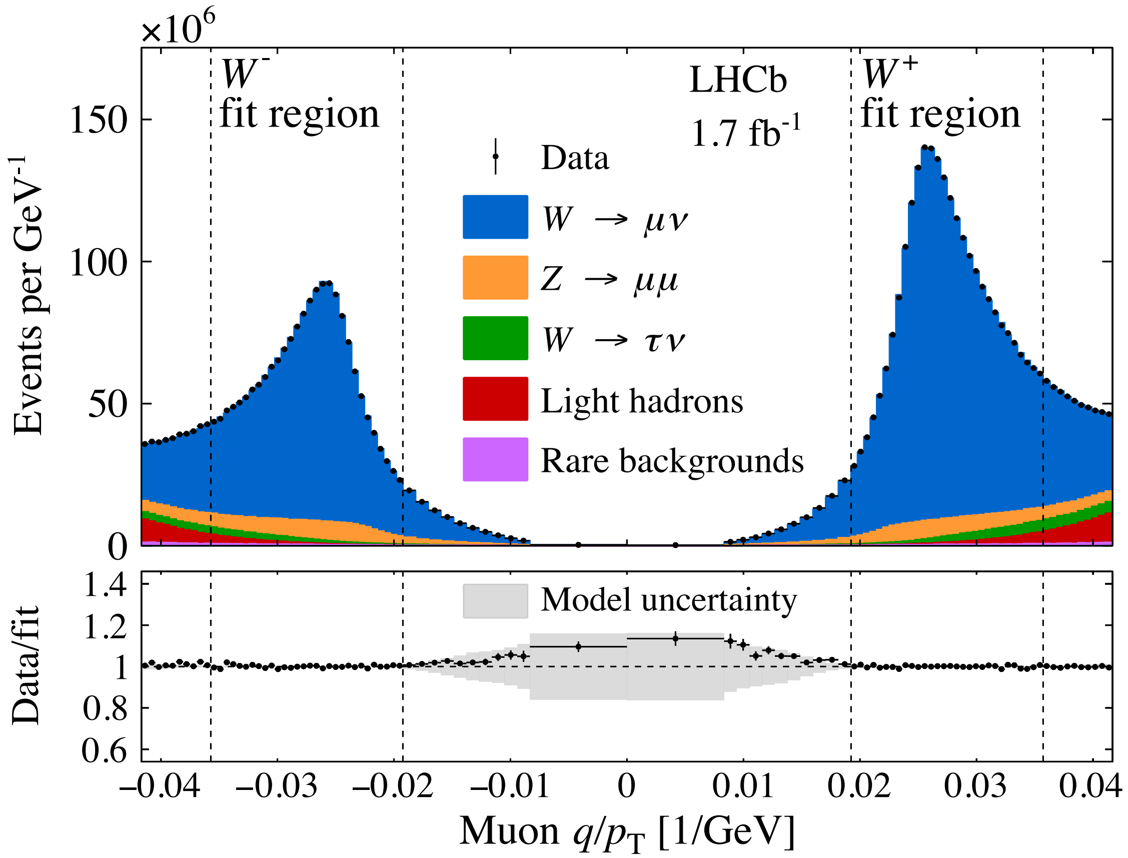


First LHC measurement at 7 TeV, using lepton p_T and M_T distributions

Split in many bins of charge, η

Precision SM measurements: more W mass



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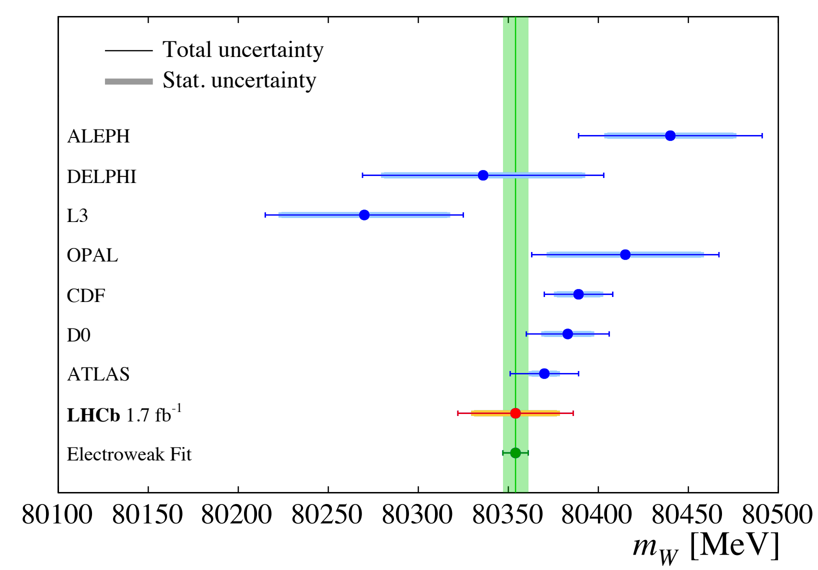
Even LHCb (dedicated experiment designed for B-physics) can measure the W mass at forward rapidities



- LHC results consistent with, and approaching precision of, best previous measurements

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

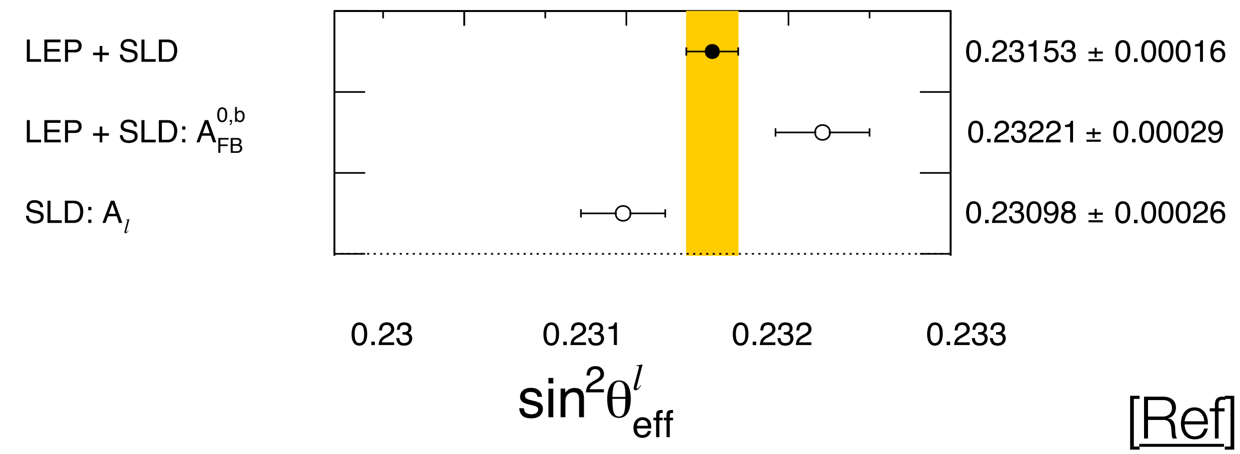
LHCb $m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$

- **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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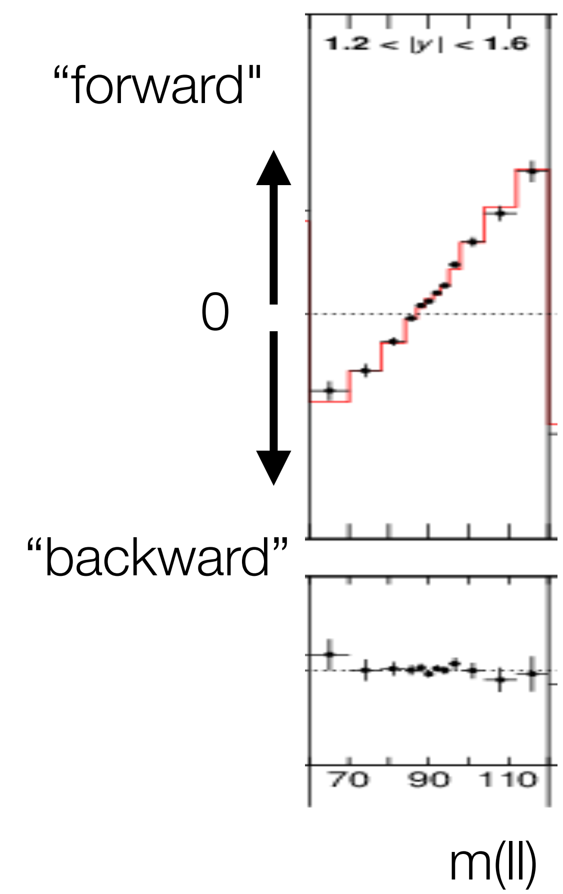
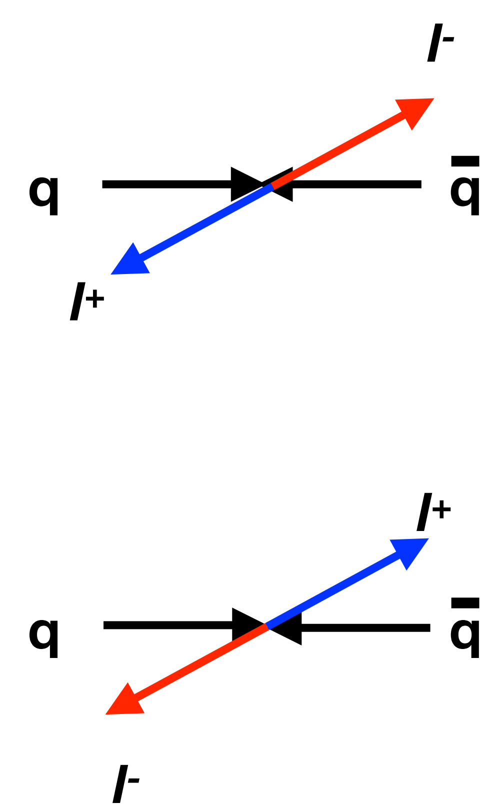
Can be measured from "forward-backward" asymmetry of leptons

- Count number of positively charged leptons along the inferred quark vs. the anti-quark direction



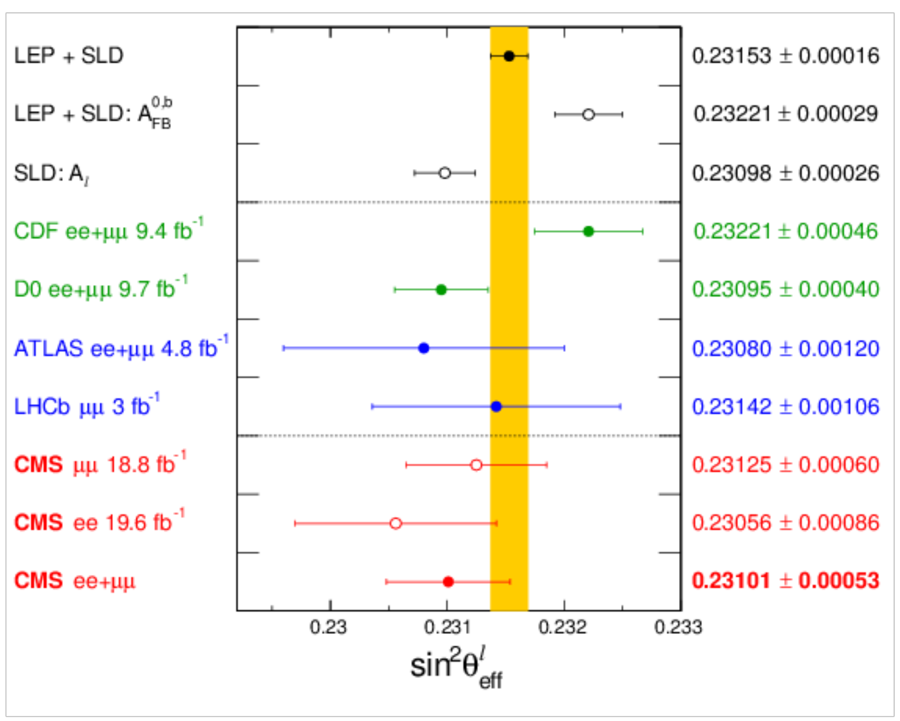


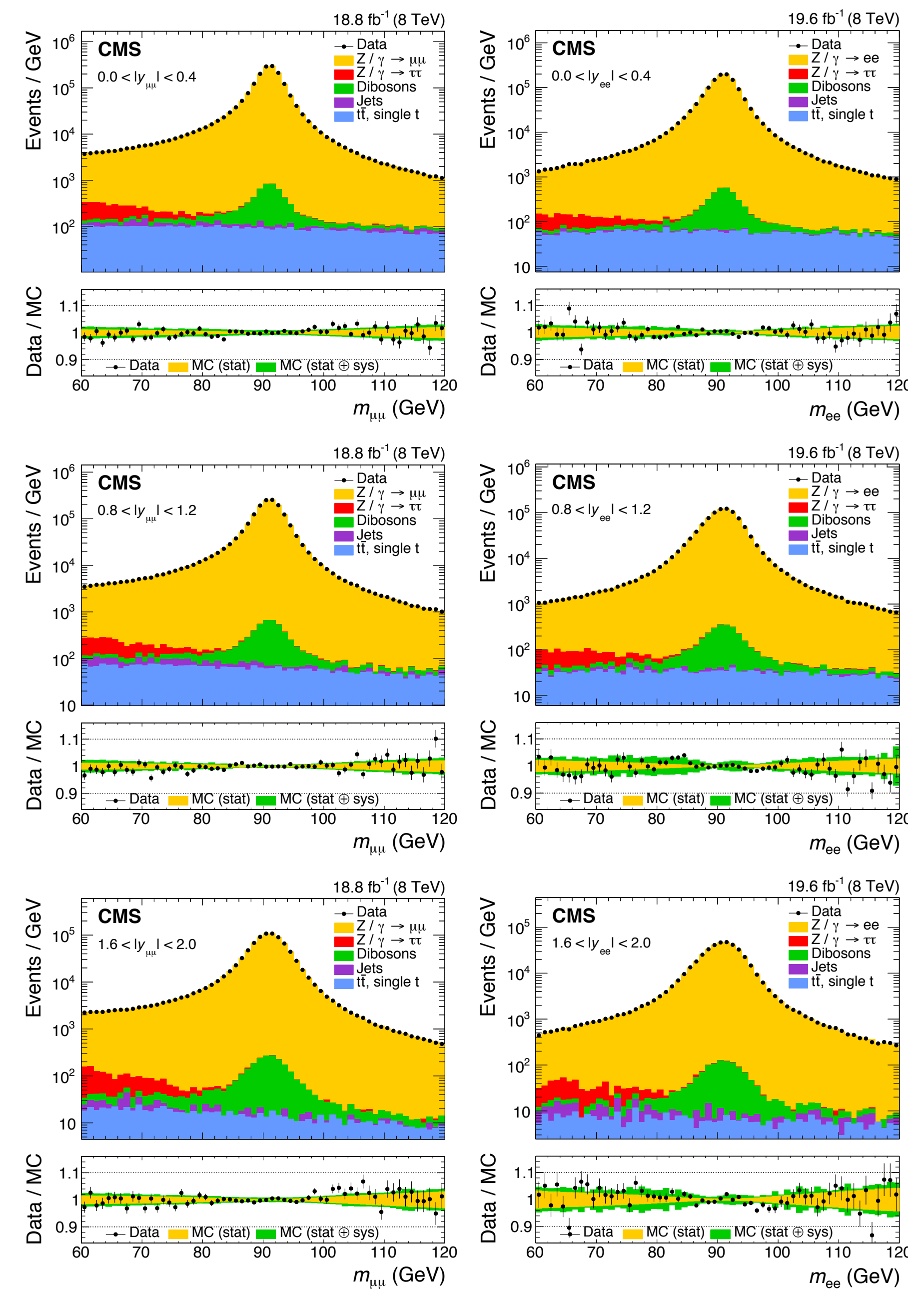
Precision SM measurements: weak mixing angle

Afb measured in many bins of invariant mass and rapidity

Fit for best value of $sin^2\theta_{eff}$

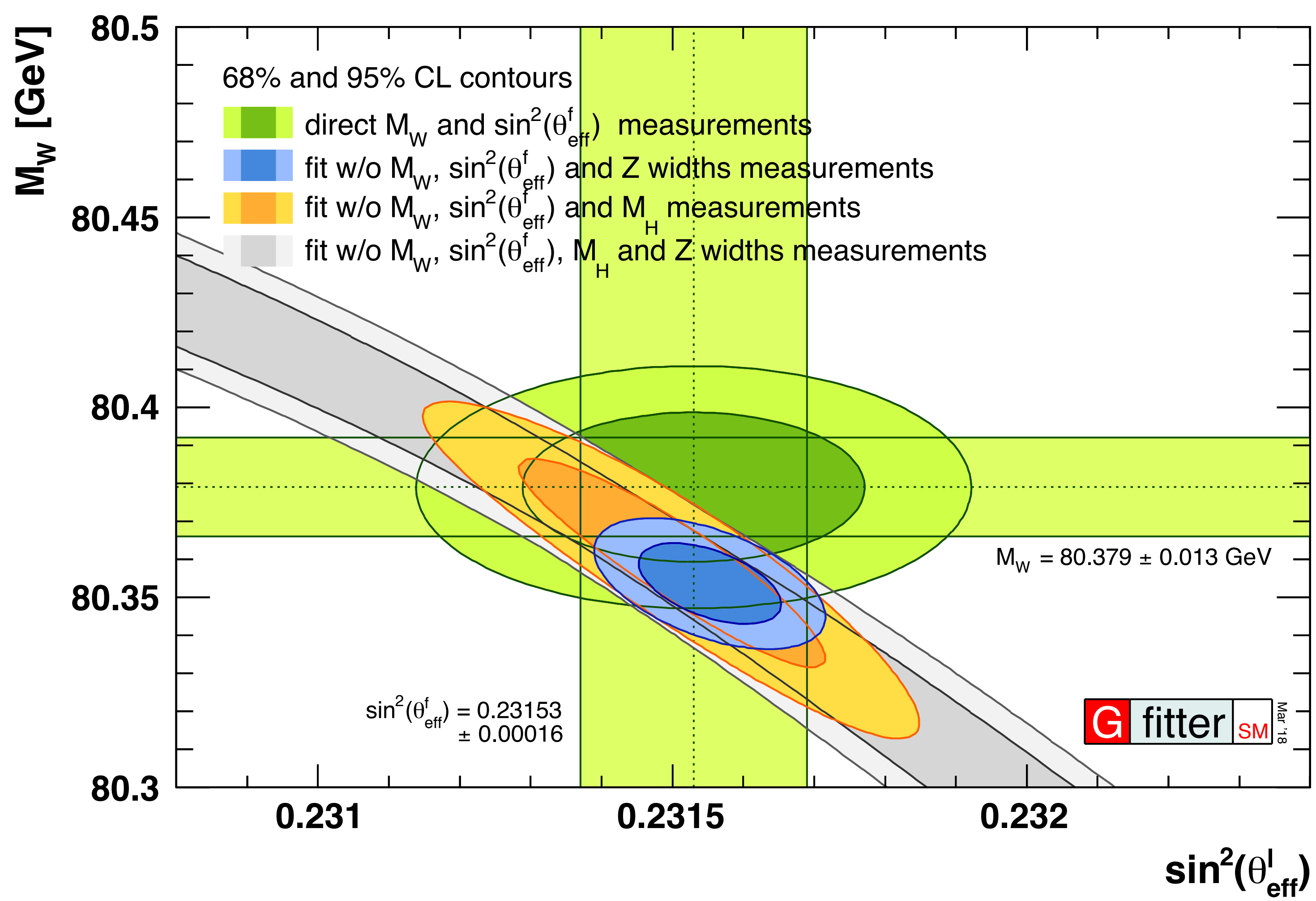
LHC Run 1 measurements not yet the most precise, but becoming competitive





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

Global SM fits: impact of precision measurements



[Ref]

In green: the direct measurements of only *$\sin^2\theta_{eff}$* and M_W

In blue: SM fit prediction, with all other data except *$\sin^2\theta_{eff}$* 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 precision measurements: Latest updates from the front lines

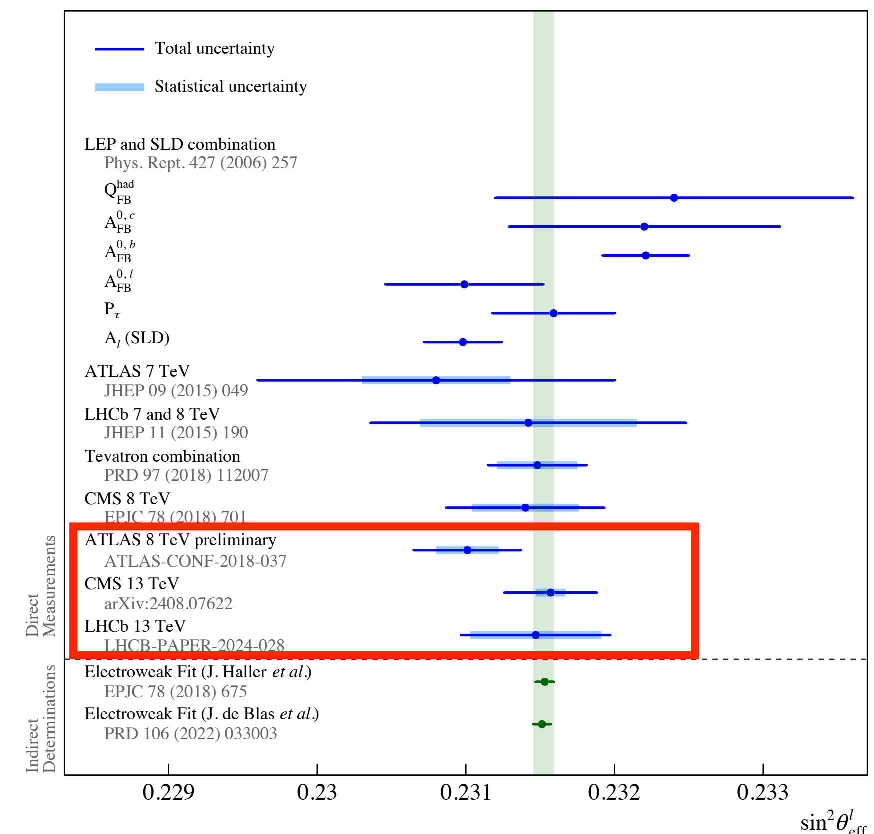
Precision SM measurements: weak mixing angle

Afb measured in many bins of invariant mass and rapidity

Fit for best value of $sin^2\theta_{eff}$

~~**LHC Run 1 measurements not yet the most precise, but becoming competitive**~~

New 13 TeV results published in 2024: LHC precision now comparable to the best e^+e^- collider results

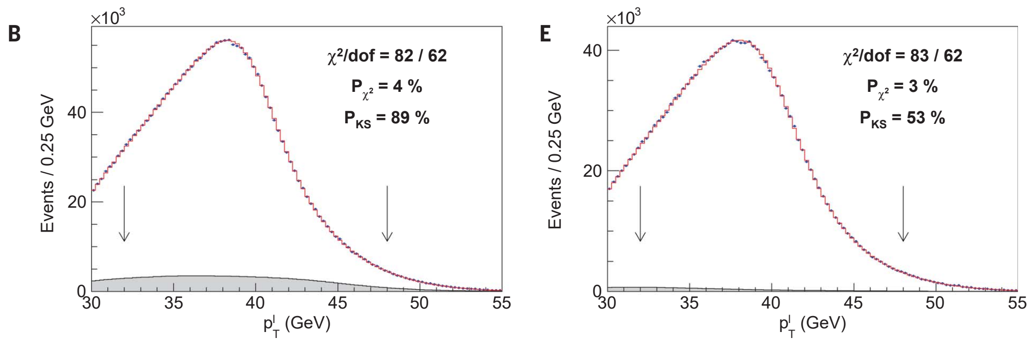


$$\sin^2 \theta^{\ell}_{\text{eff}} = 0.23157 \pm 0.00031$$

$$\sin^2 \theta^{\ell}_{\text{eff}} = 0.23147 \pm 0.00044 \pm 0.00005 \pm 0.00023,$$

$$0.23140 \pm 0.00021\,(\text{stat.}) \pm 0.00024\,(\text{PDF}) \pm 0.00016\,(\text{syst.}),$$

A surprise from across the Atlantic (& Lake Michigan): W mass from CDF



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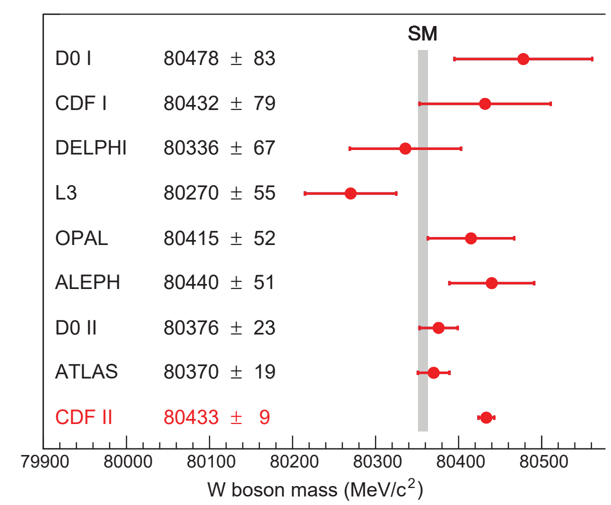
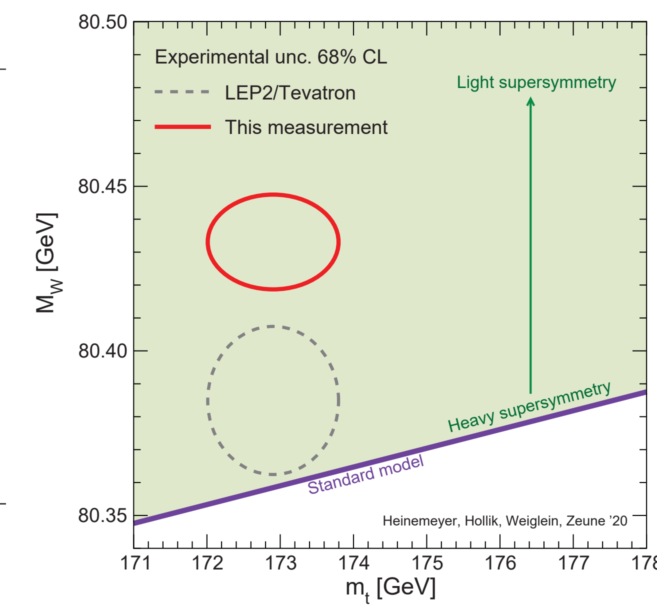
In 2022 the CDF experiment released the final W-mass measurement from $p\bar{p}$ collisions at the Fermilab Tevatron

Results are the most precise to date, far from the SM fit expectation, and far from the most precise previous experiments





$$M_W = 80{,}433.5 \pm 6.4_{\mathrm{stat}} \pm 6.9_{\mathrm{syst}} = 80{,}433.5 \pm 9.4\ \mathrm{MeV}/c^2$$

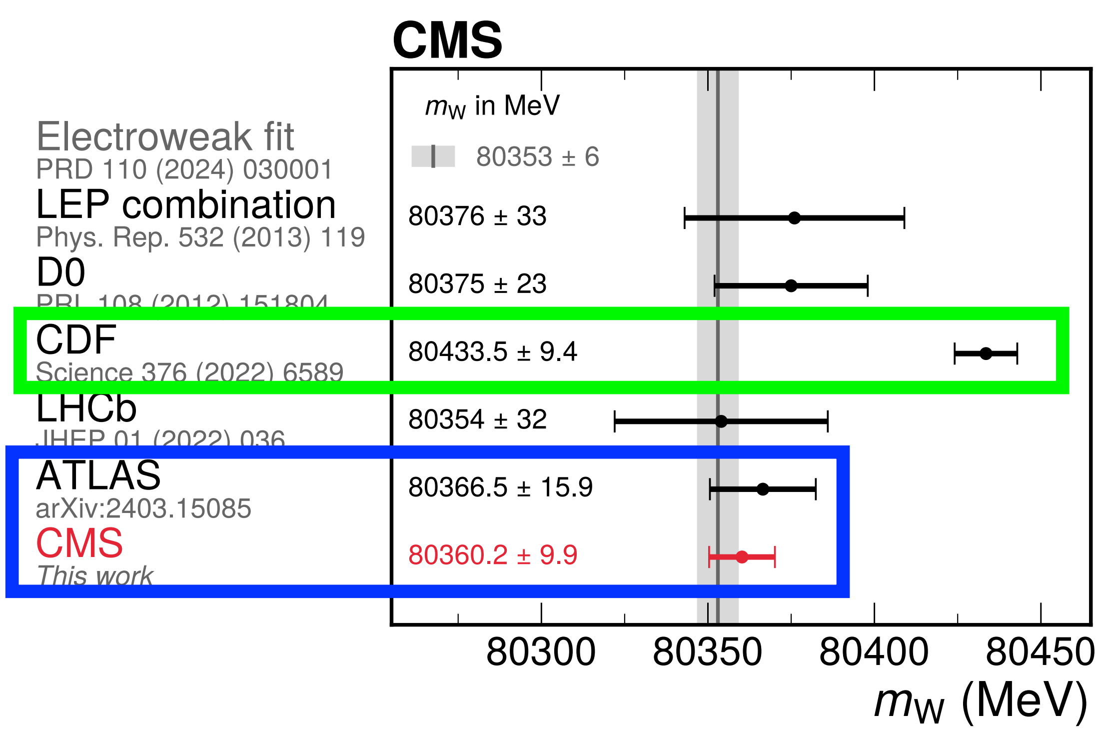
All eyes were on the LHC to confirm (or not) this unexpected result

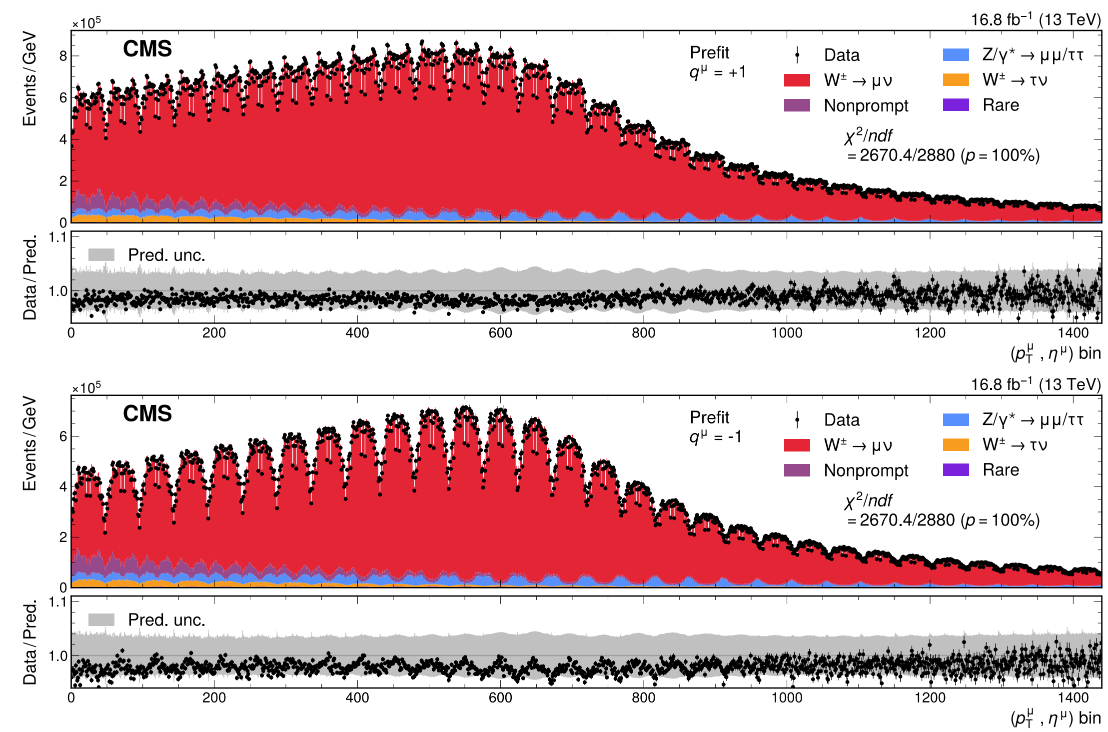
The SM strikes back: new LHC measurements

Since last year's version of this lecture, both the CMS + ATLAS collaborations have released new W-mass measurements

ATLAS uses 2011 data with a low number of overlapping interactions

CMS uses high pileup/high statistics data from 2016, fits in many bins of pT and eta





Both agree quite well with the SM/other measurements, and not with CDF

Results submitted to EPJ-C and Nature

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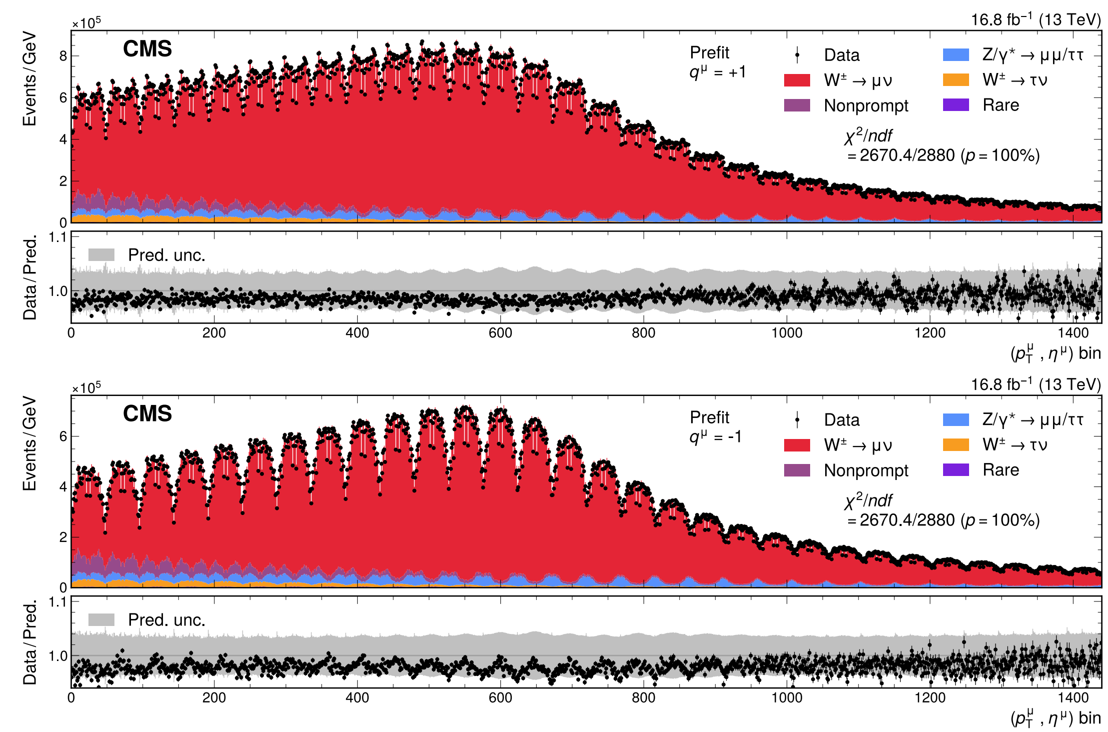


Both agree quite well with the SM/other measurements, and not with CDF

Results published in EPJ-C and Nature

At least for now, the SM wins again

Electroweak physics:
cross sections and gauge boson couplings

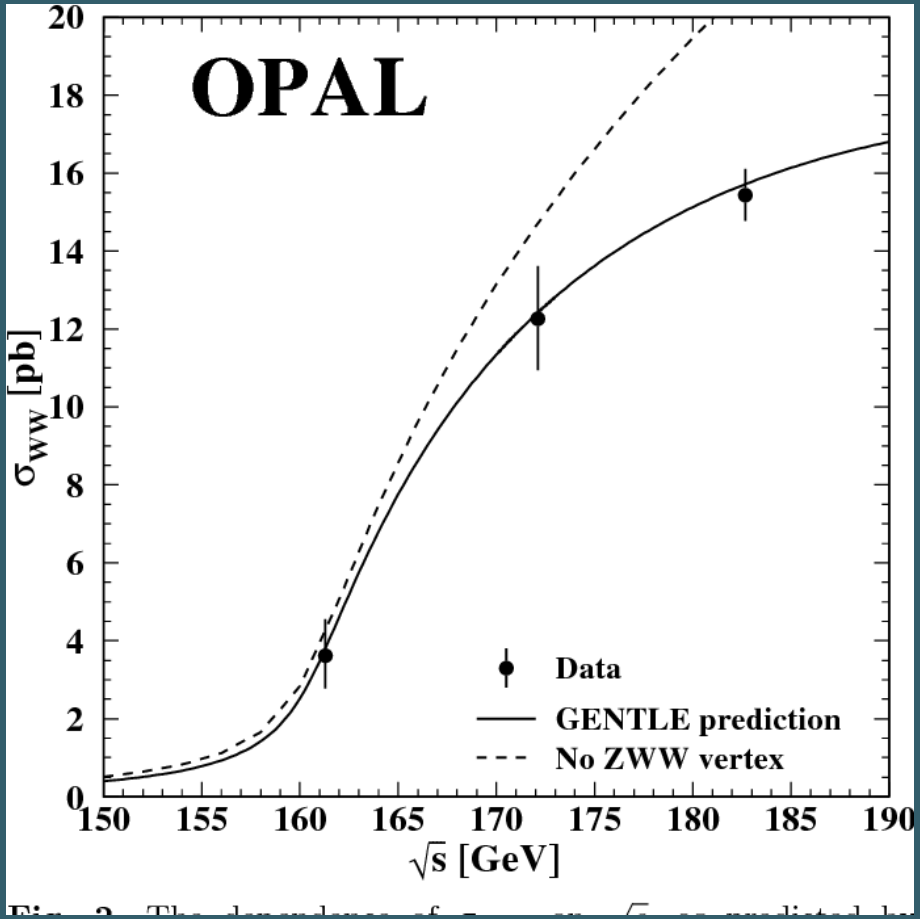
Rates of Standard Model processes and electroweak couplings

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!**

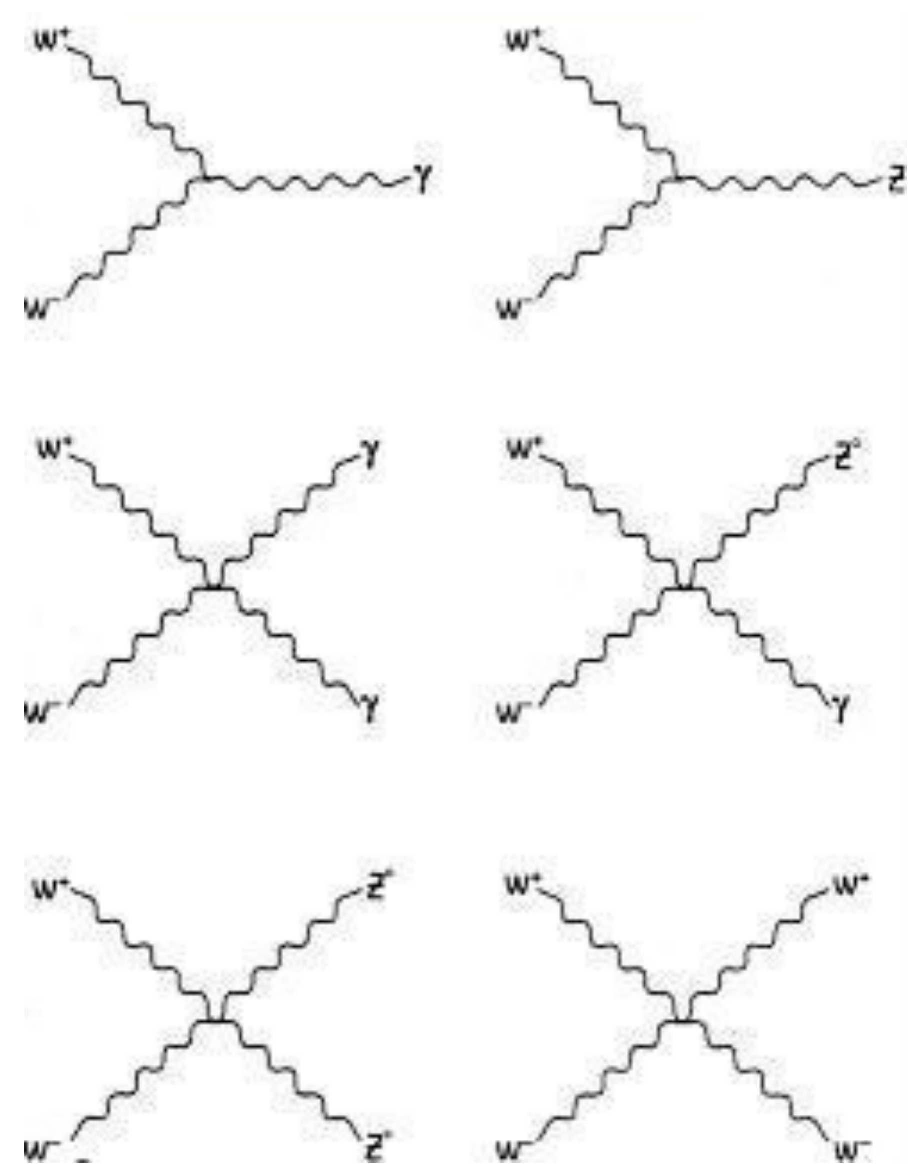
Gauge boson self-interactions

Reminder: The SM precisely predicts the strength of EWK gauge boson interactions

True triple and quartic couplings involving W-pairs are expected 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



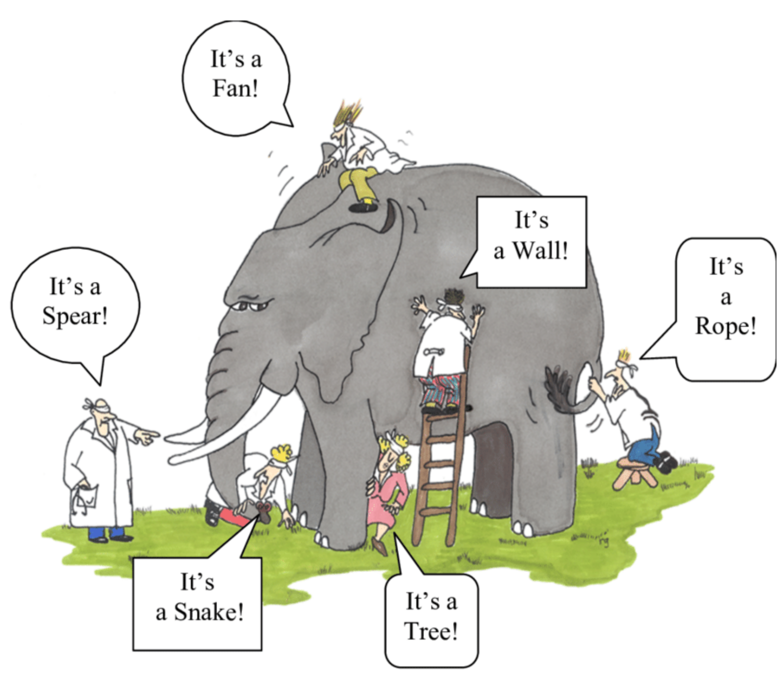
[Ref]

Triple gauge couplings: different views

Usually more than 1 way to probe each coupling

Different experimental systematics, backgrounds, etc.

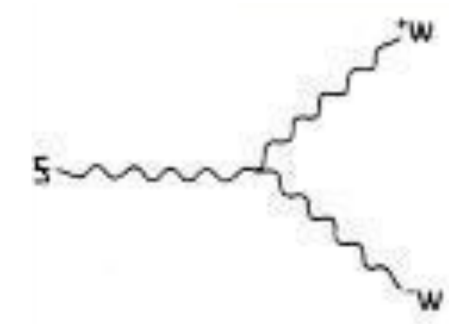
Study all of them to get a complete picture



Processes sensitive to WWZ couplings

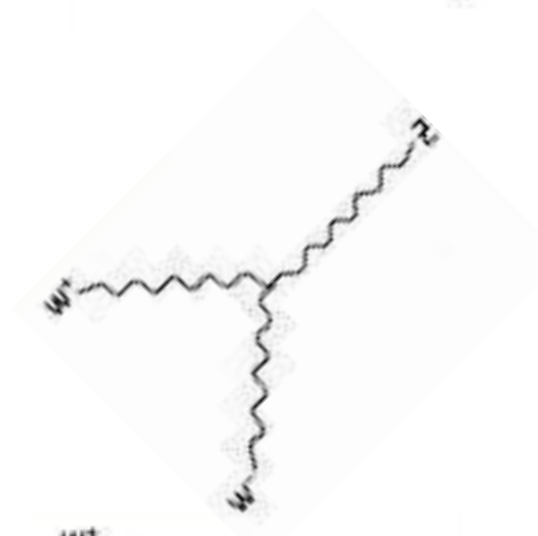
Z(*)→WW

(diboson production)



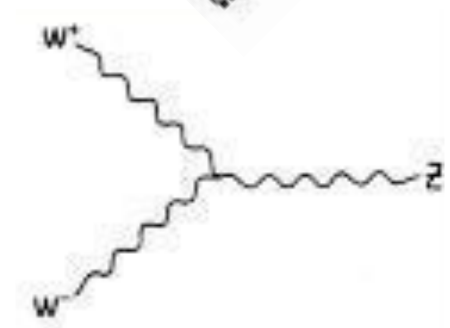
W(*)→WZ

(diboson production)



WW→Z

(vector-boson fusion)



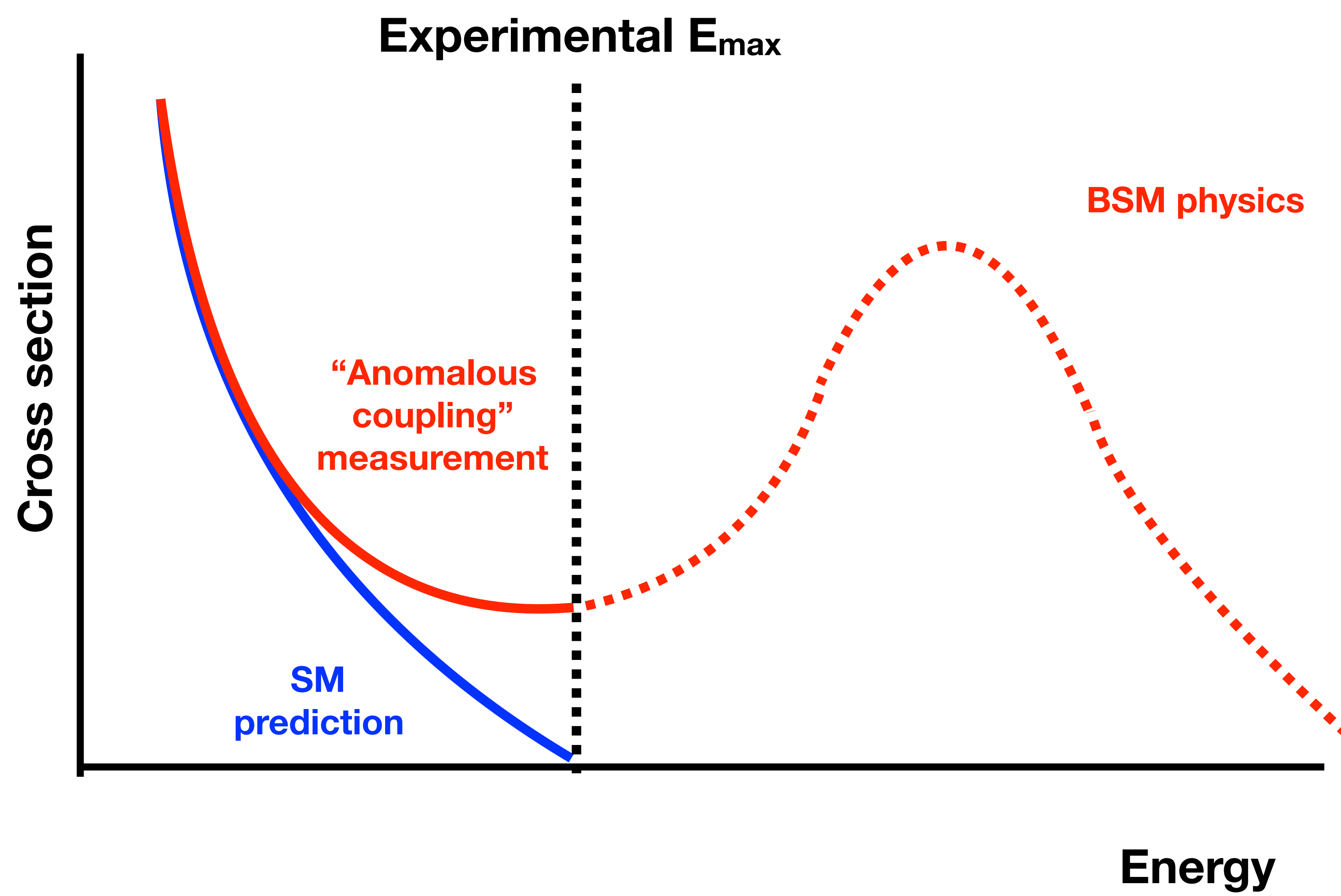
“Anomalous” gauge couplings

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



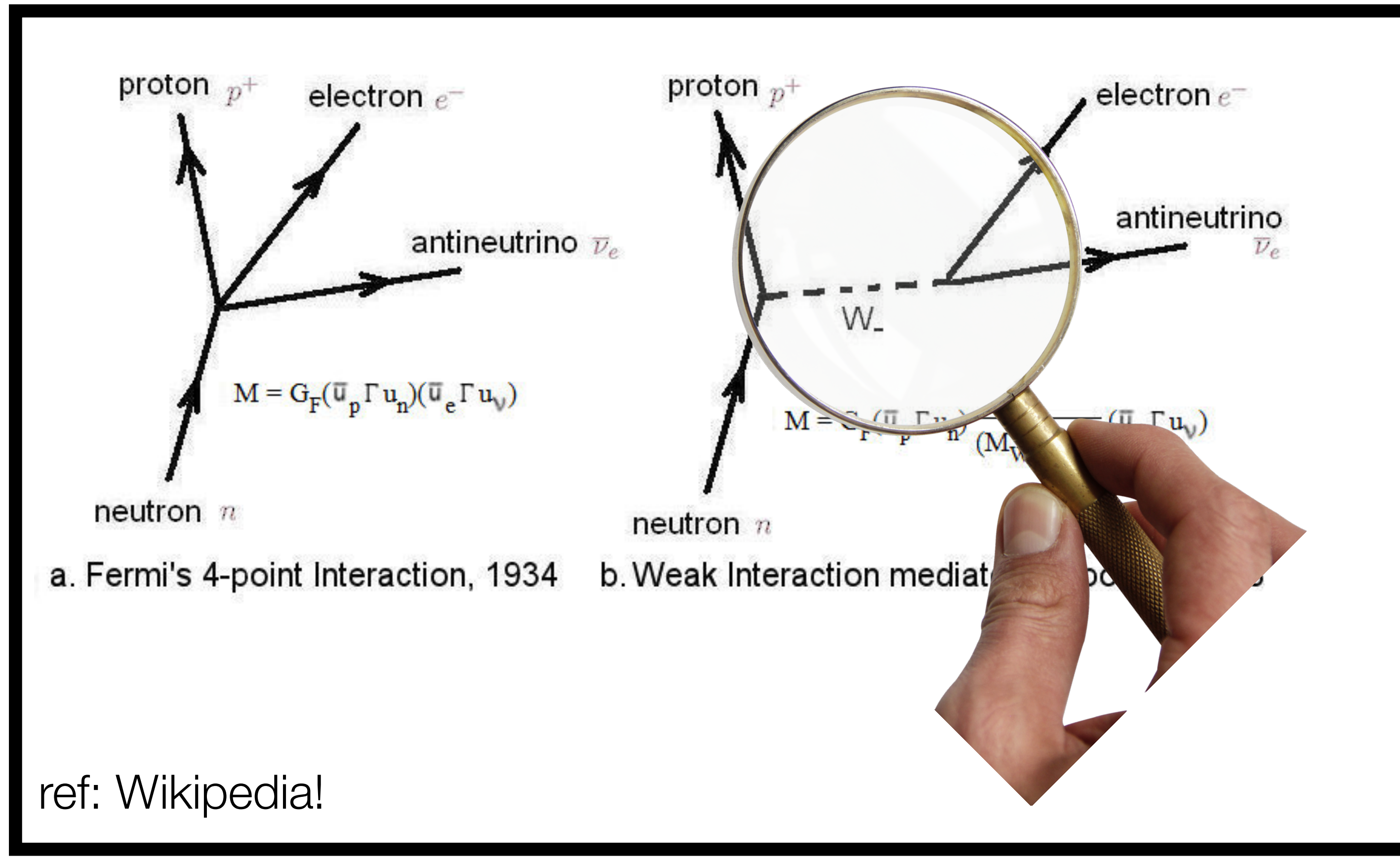
Anomalous couplings are “fingerprints” of beyond-SM physics at lower energies from off-shell or loop-level effects

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

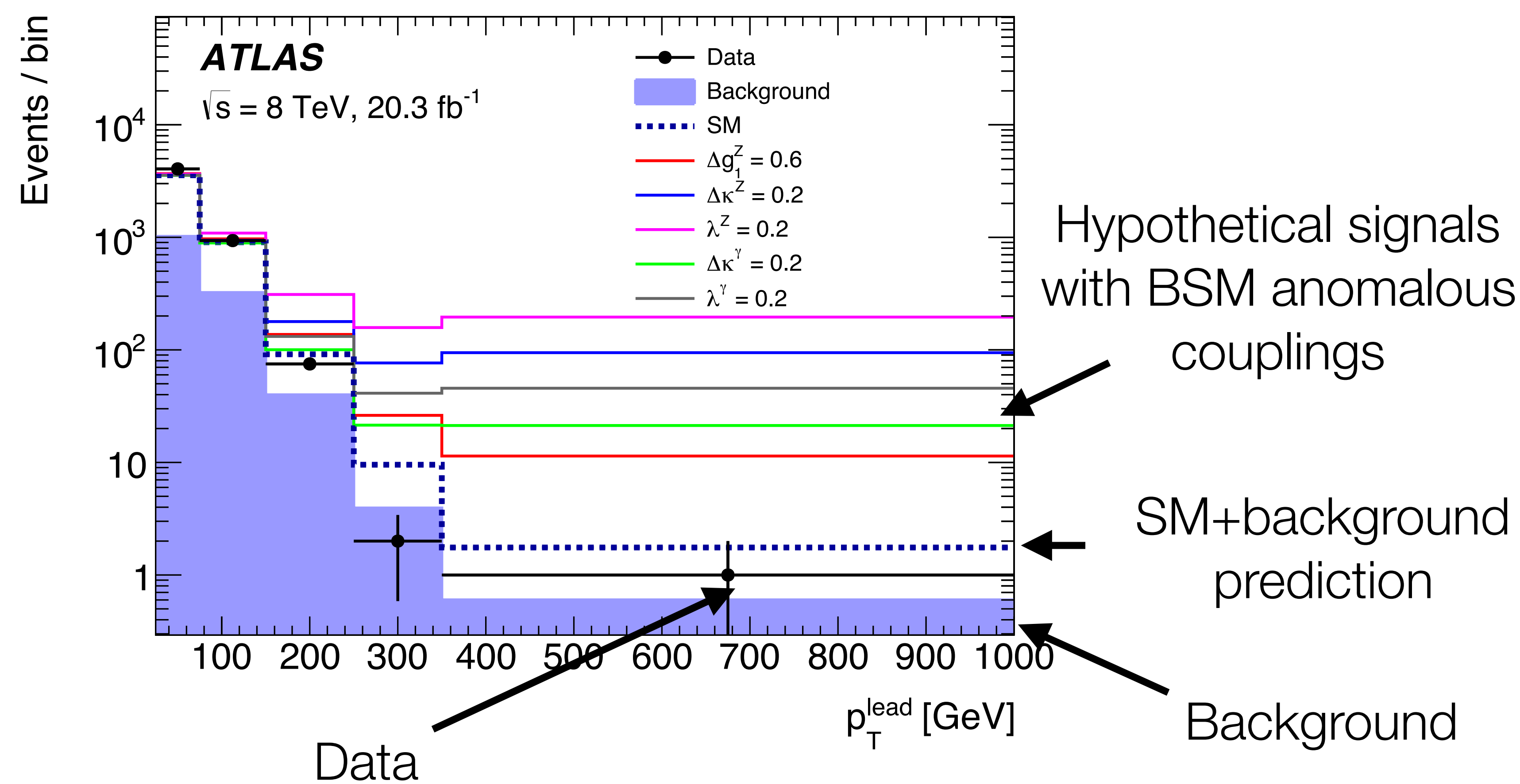
W-boson finally directly detected at CERN in **1983**

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

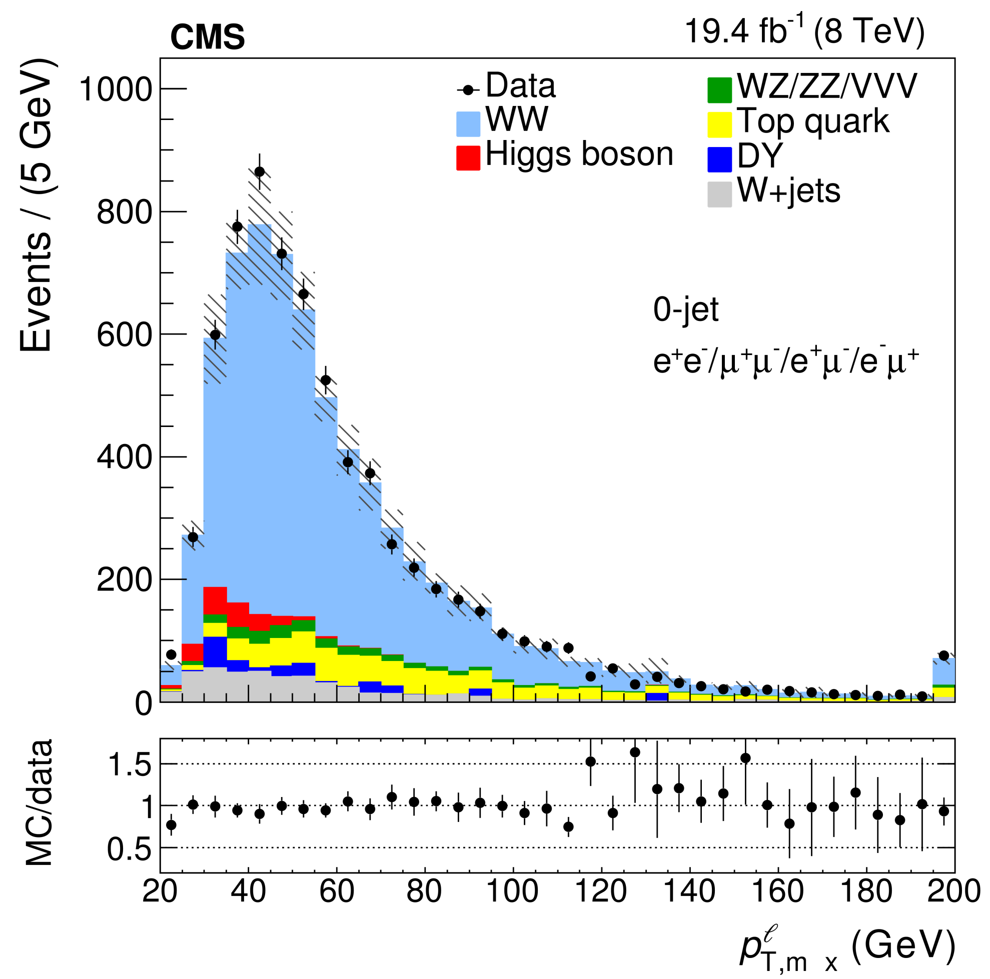
Quantify any deviations in the high energy tails

[Ref]

Triple gauge couplings with *WW* production

Measure cross sections for events with 2 leptons + missing E_T

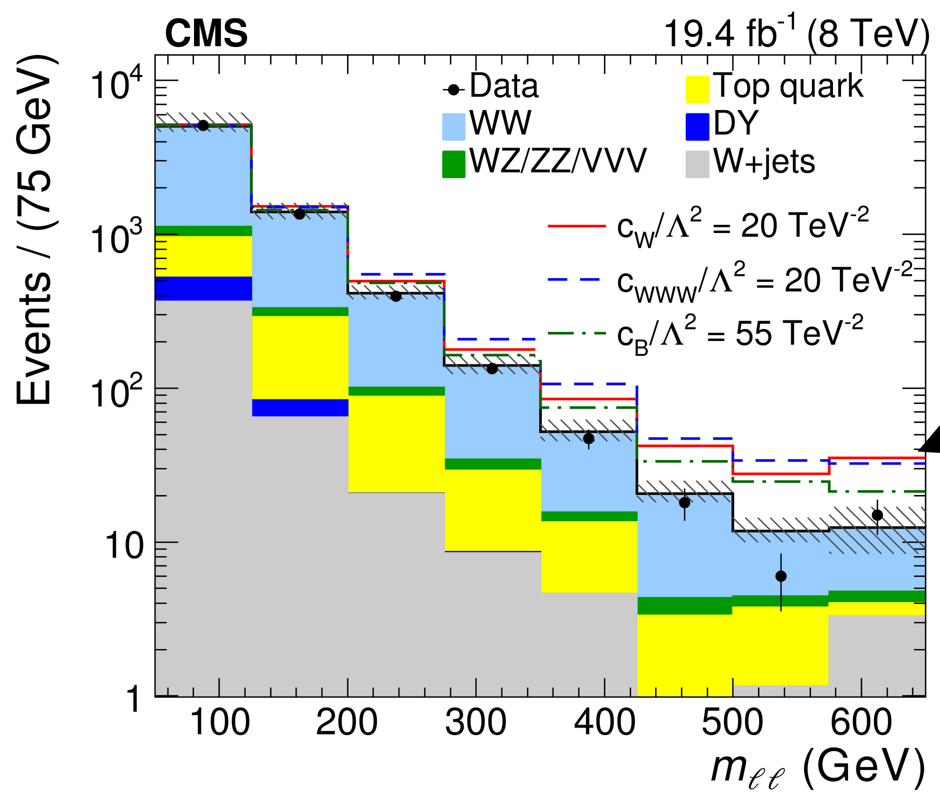
- High statistics
- Fairly low backgrounds from top quark production, QCD fakes - estimated from data control samples and simulation
  - (Even the Higgs could be considered a background here!)



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

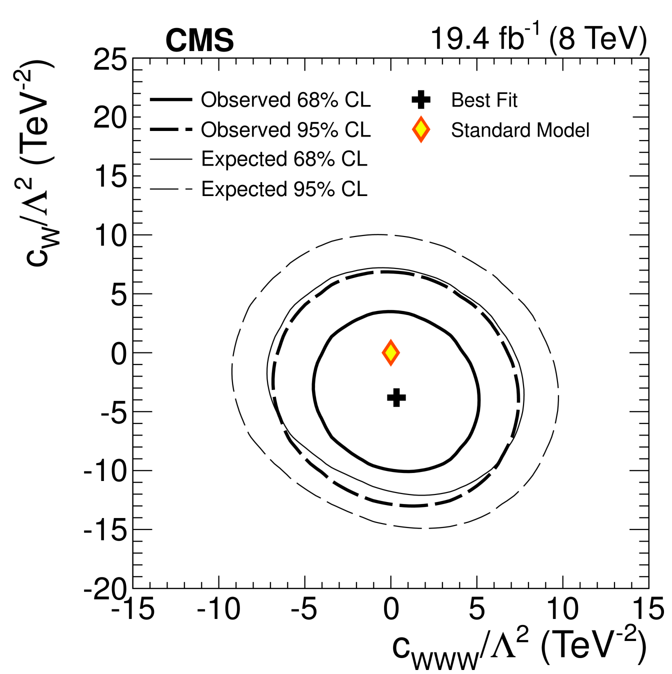
Triple gauge couplings with *WW* production (II)



Anomalous couplings?

Plot m_{ll} and zoom on the high-mass tails

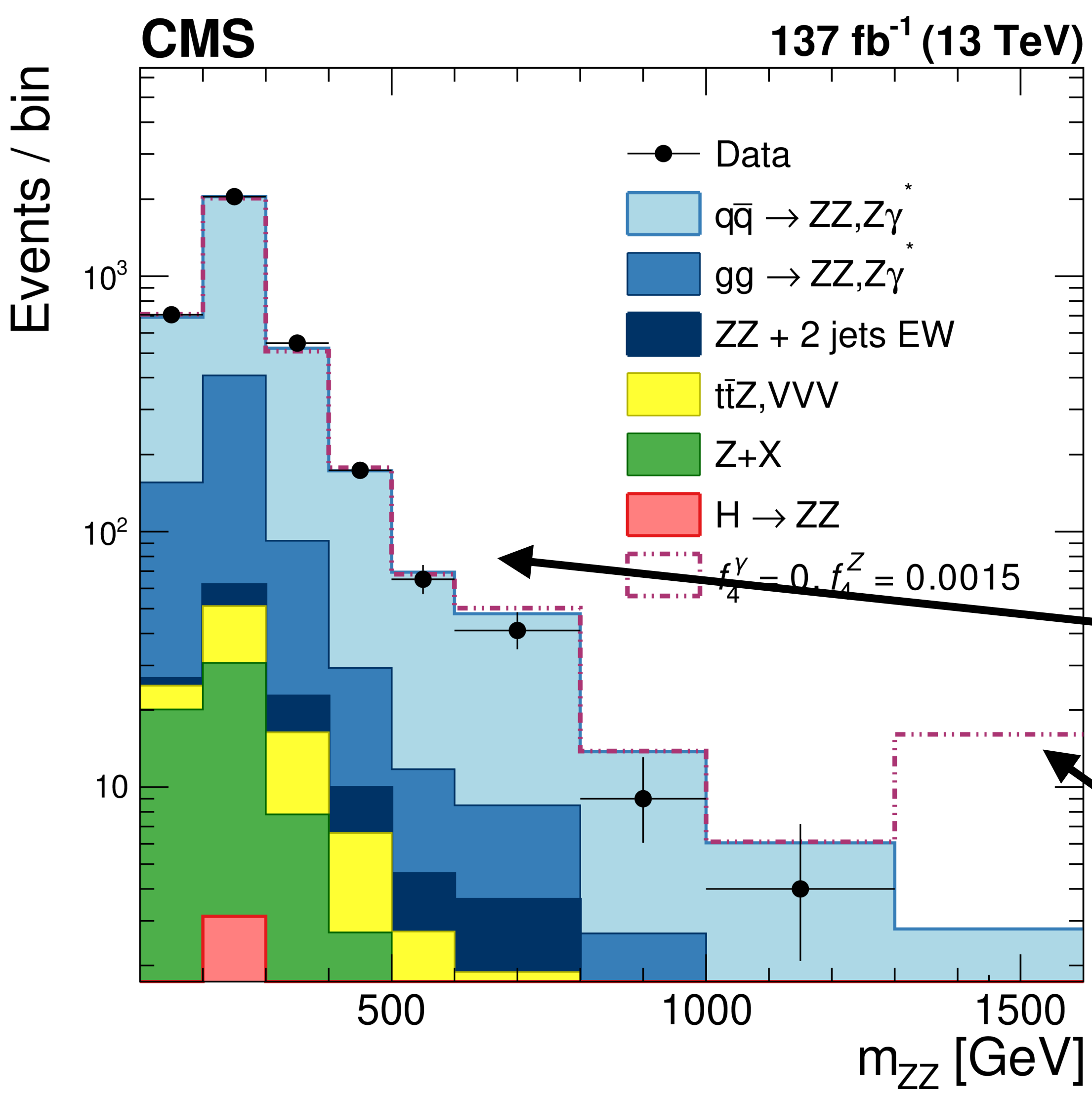
No sign of excess, data agrees with the SM



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

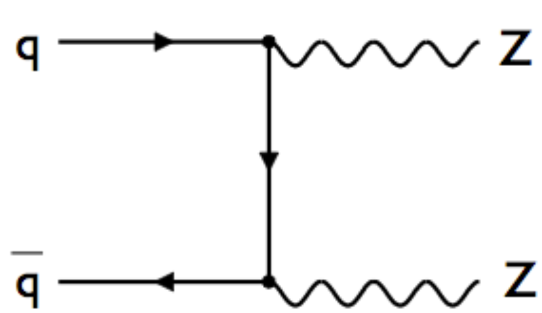


Golden signature: 4 leptons, with 2 pairs compatible with a $Z^{(*)}$ (either e^+e^-, $\mu^+\mu^-$)

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}



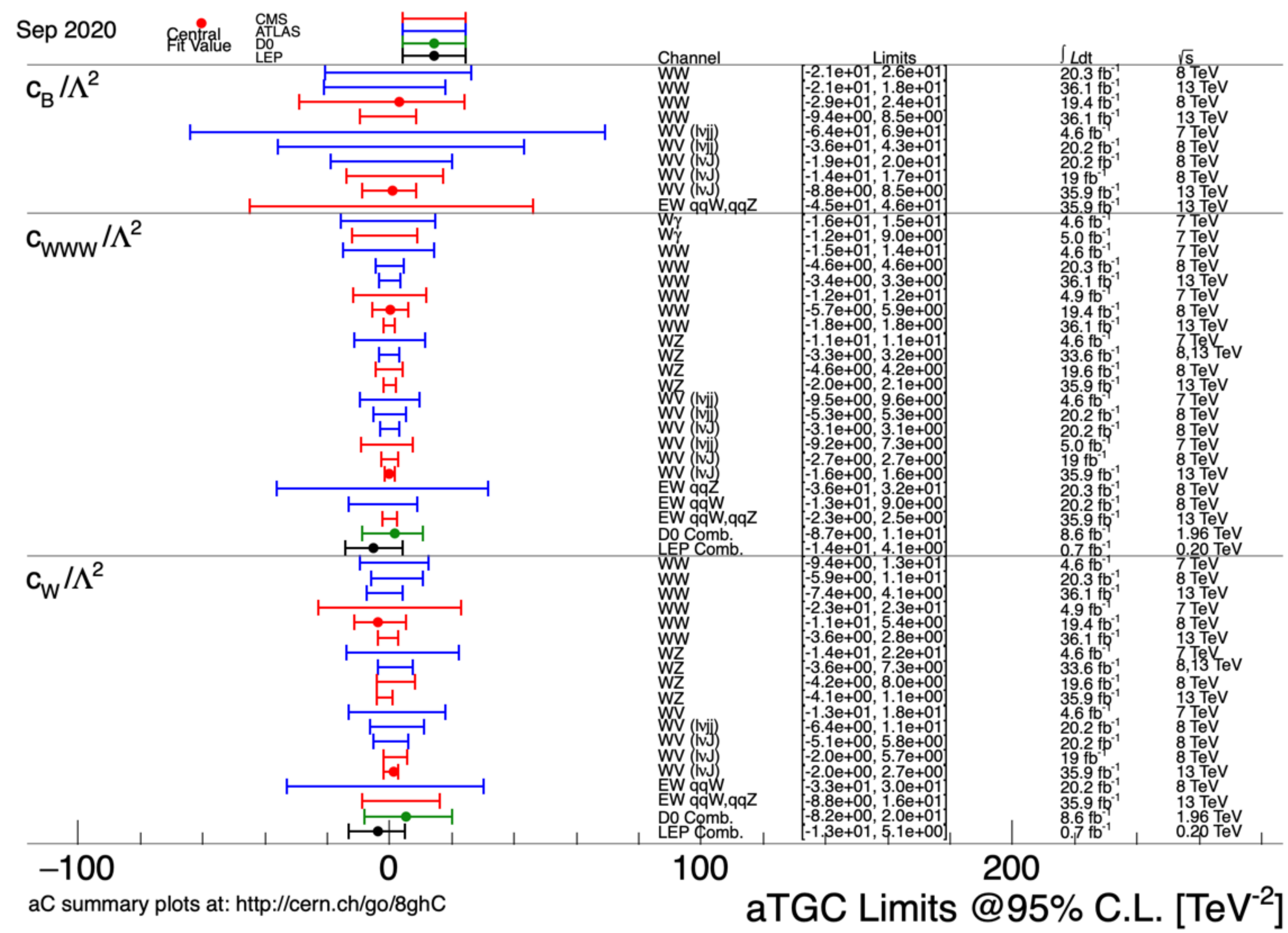
Reminder: no direct ZZZ or γZZ couplings in the SM, prediction comes from q-qbar interactions

Summary of TGCs

LHC has studied many more processes sensitive to TGCs

- Charged TGCs are consistent with SM predictions

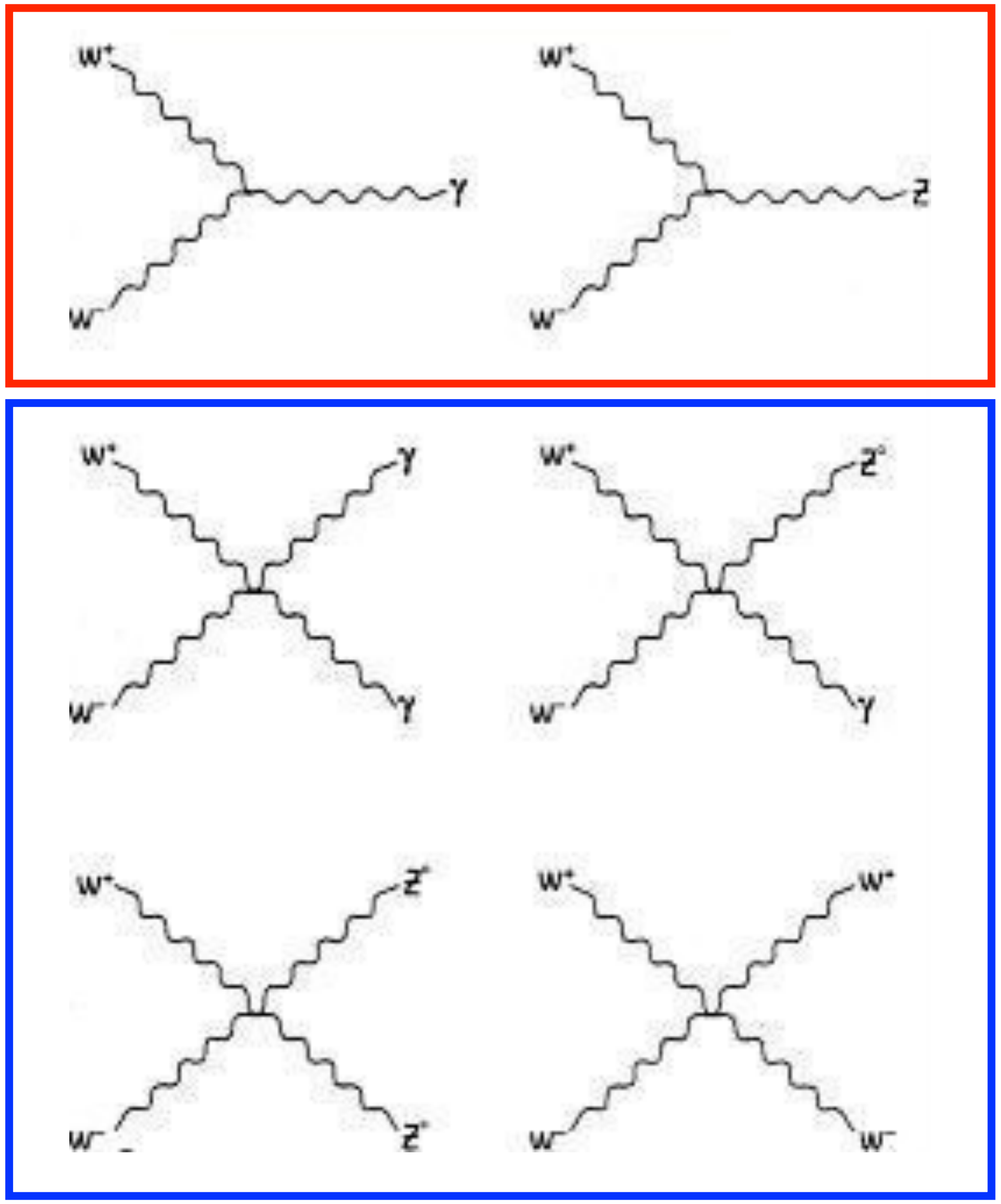
- Neutral TGCs are consistent with 0 (=SM prediction) - not shown



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

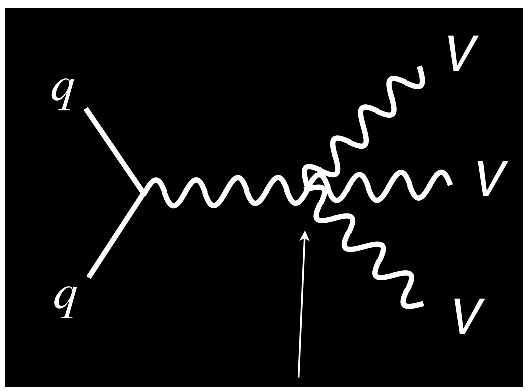
What about the Quartic Gauge Couplings?

Much smaller cross sections

Much less explored before the LHC

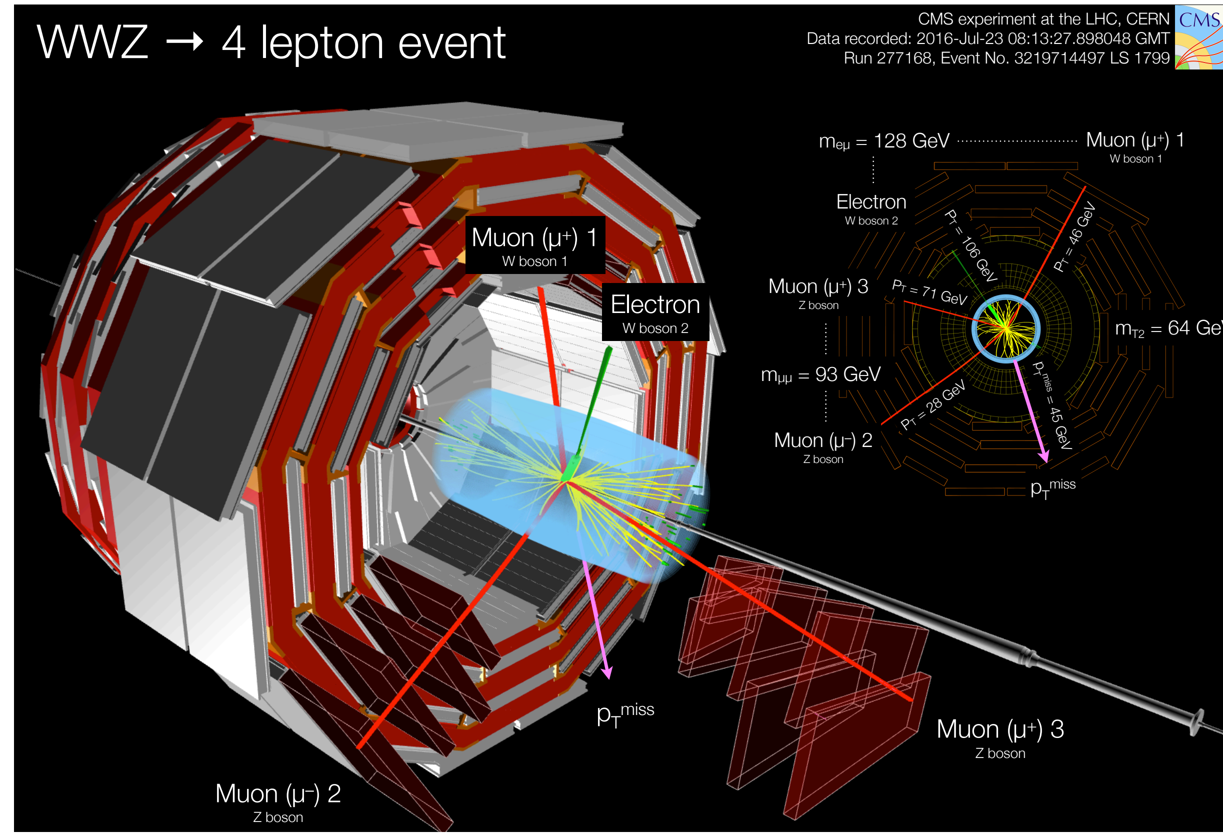
Quartic gauge interactions: triple-boson production

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

$Z \rightarrow \mu\mu$

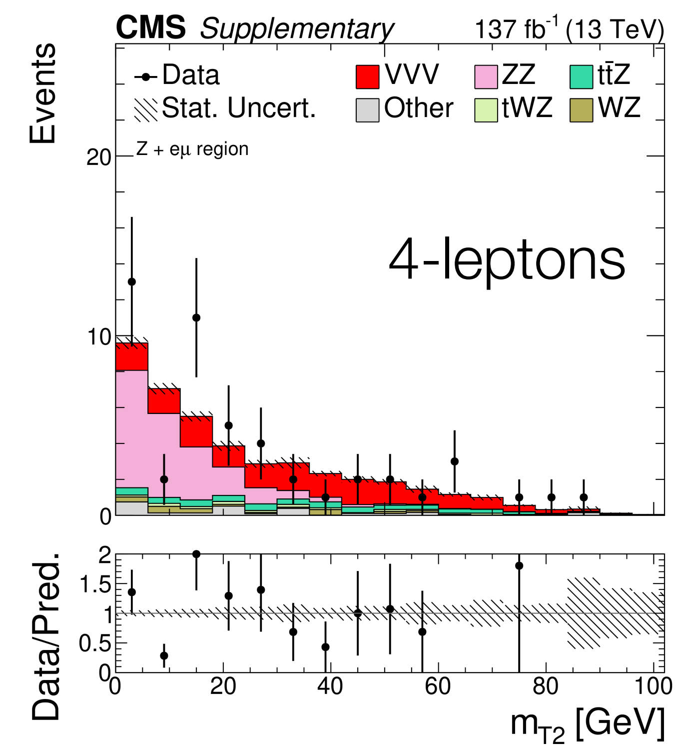
$W \rightarrow \mu\nu$

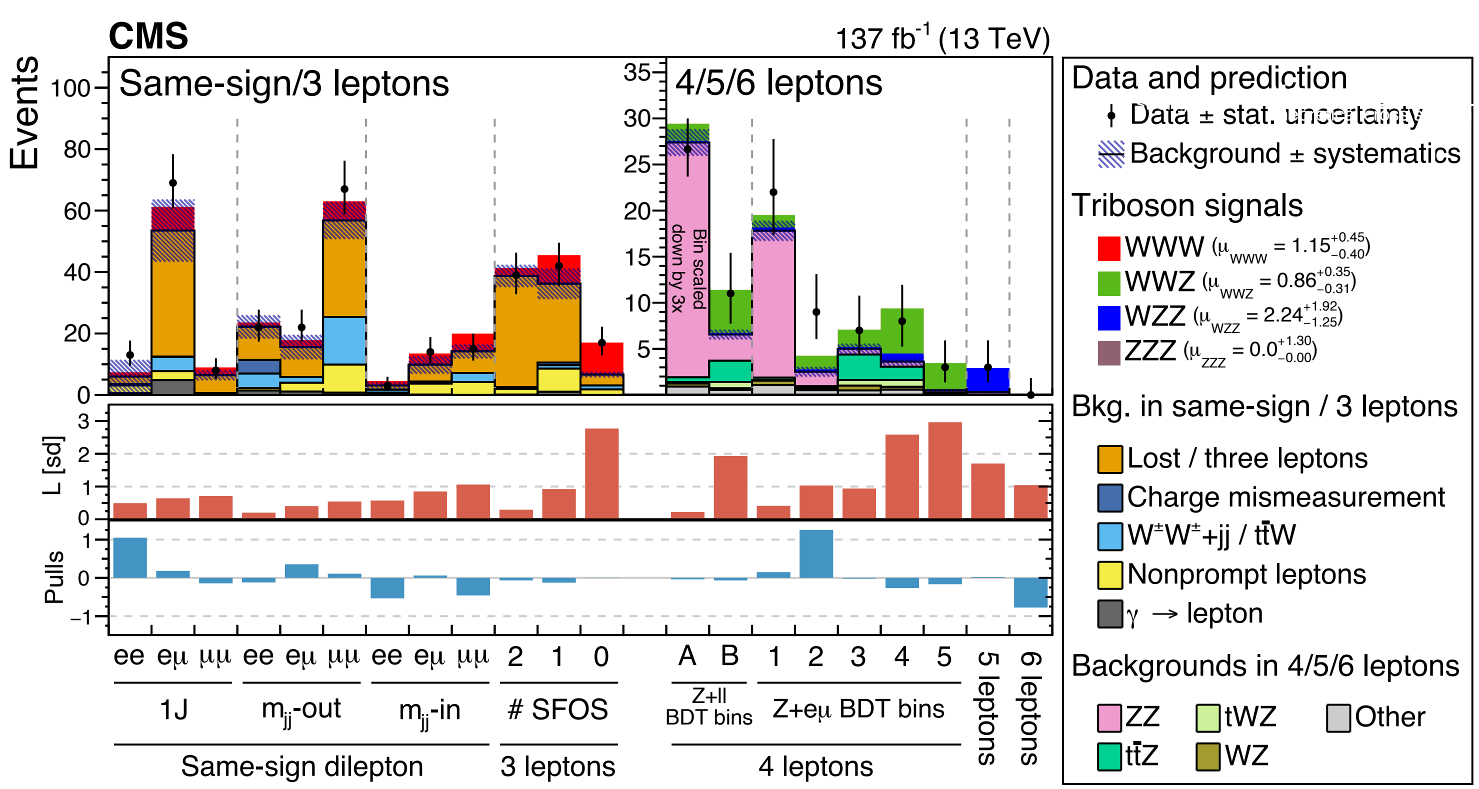
$W \rightarrow e\nu$

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





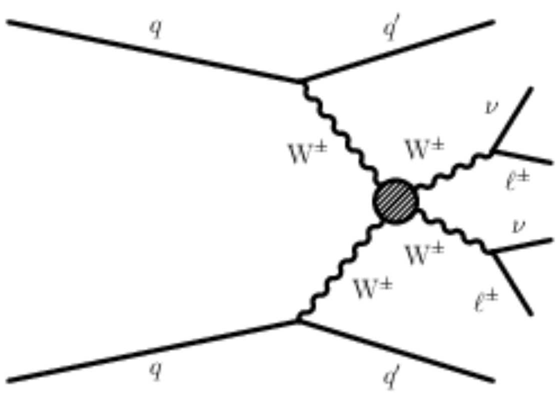
Small excesses over background in several channels - compatible with SM signal!

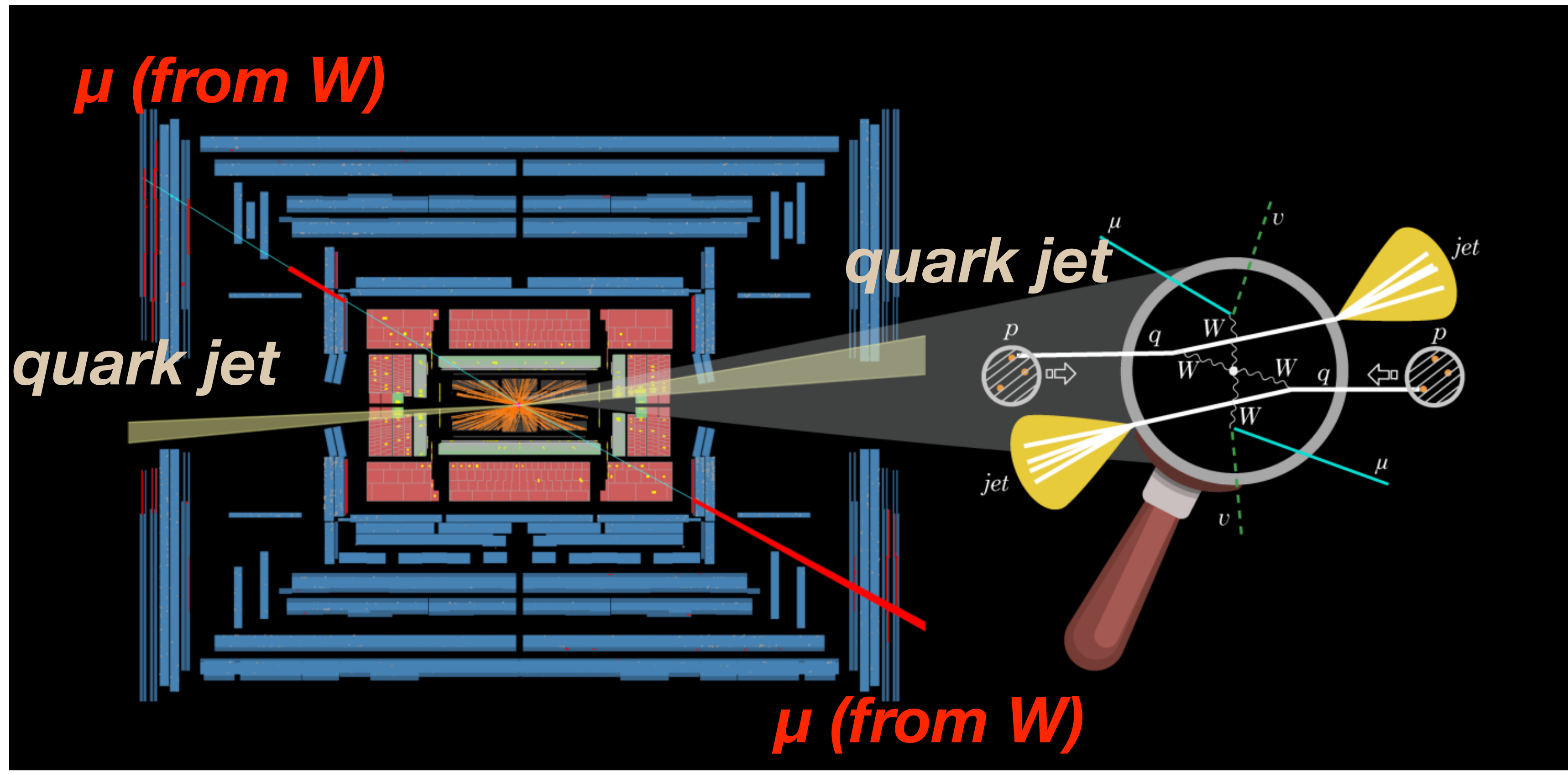
[Ref]

Quartic gauge interactions: vector-boson scattering

Scattering of 2 vector bosons to produce 2 vector bosons

$VV \rightarrow VV$

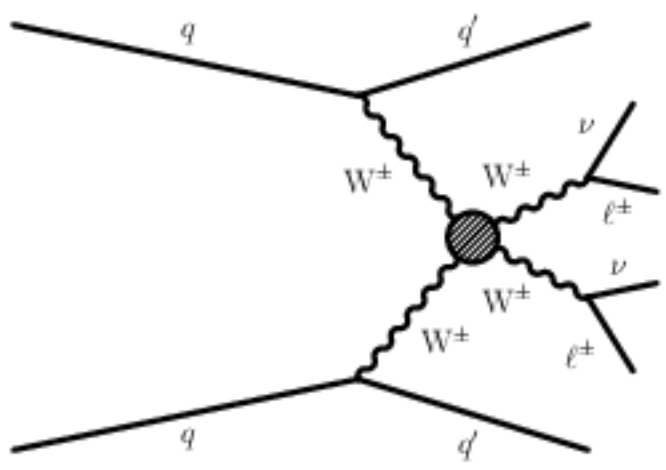




Spectacular signatures:

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:

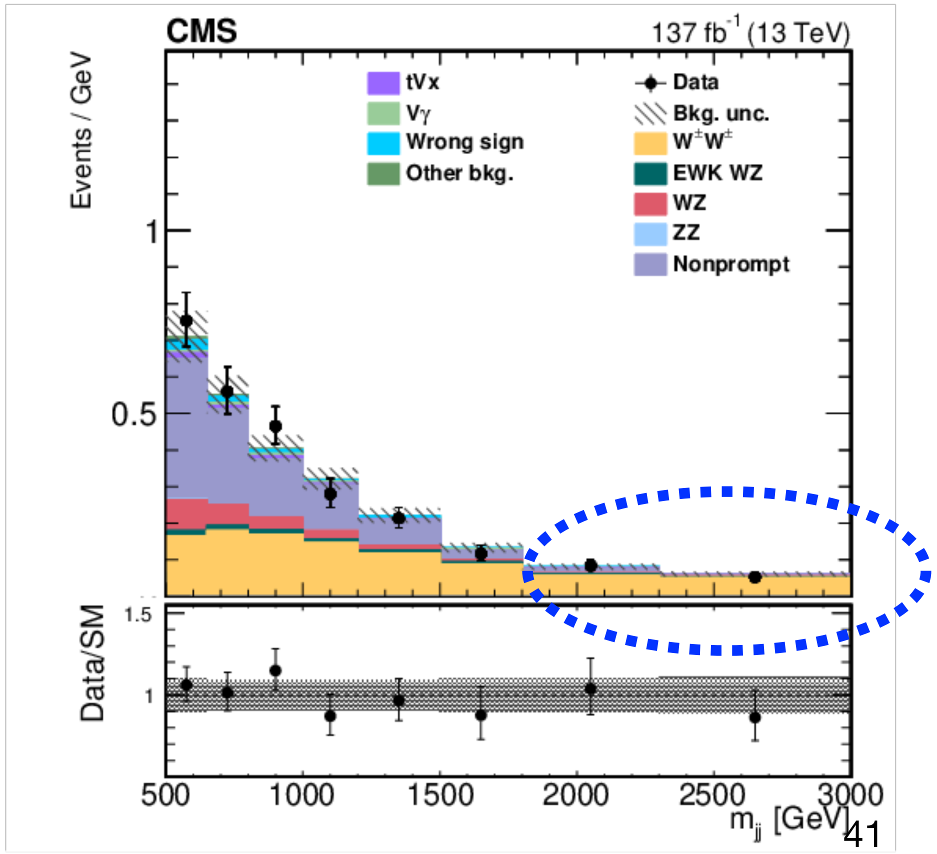
There is a Higgs boson OR other new physics

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



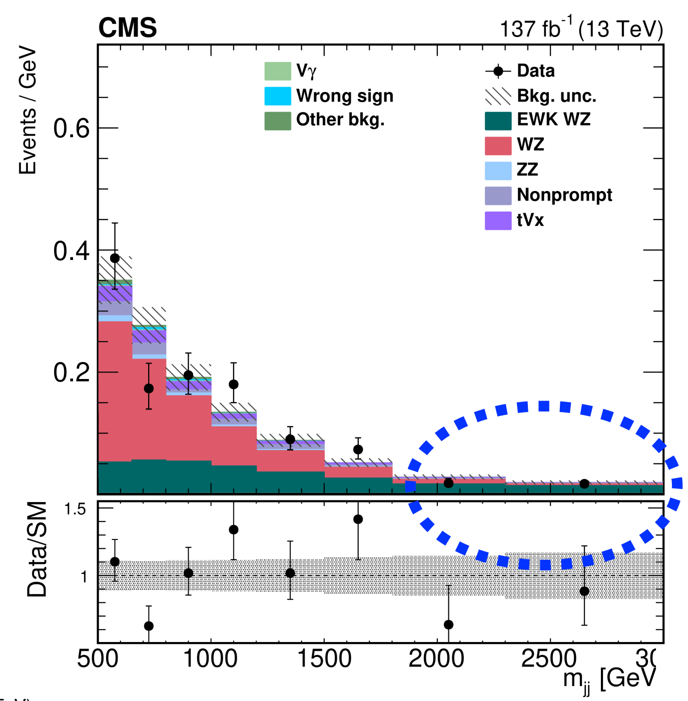
Quartic gauge interactions: other VBS processes

What about other vector-boson scattering processes?

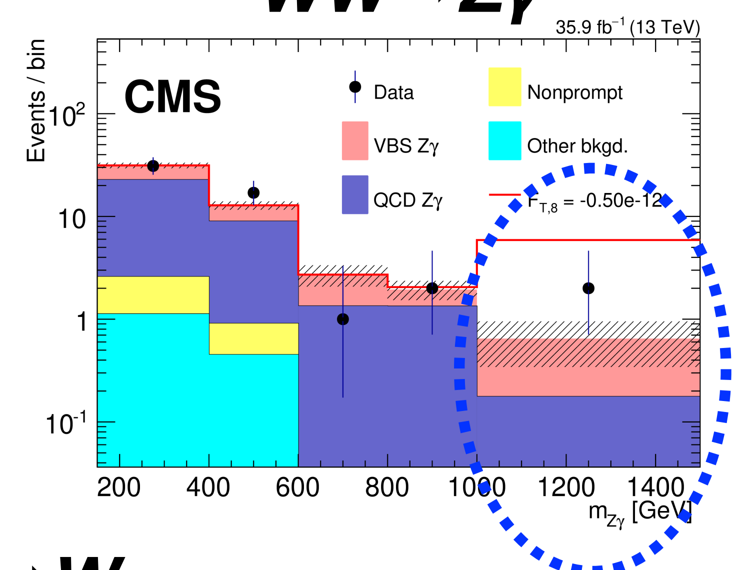
No anomalous excesses

Several processes observed for the first time

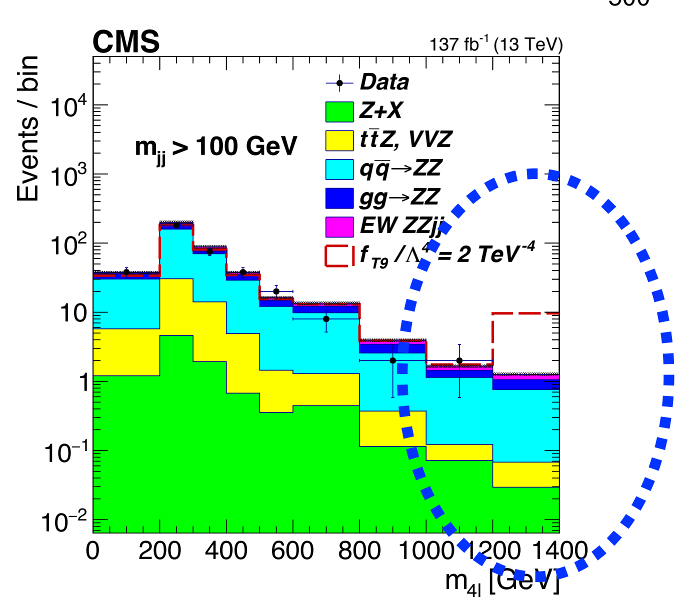
WZ→WZ



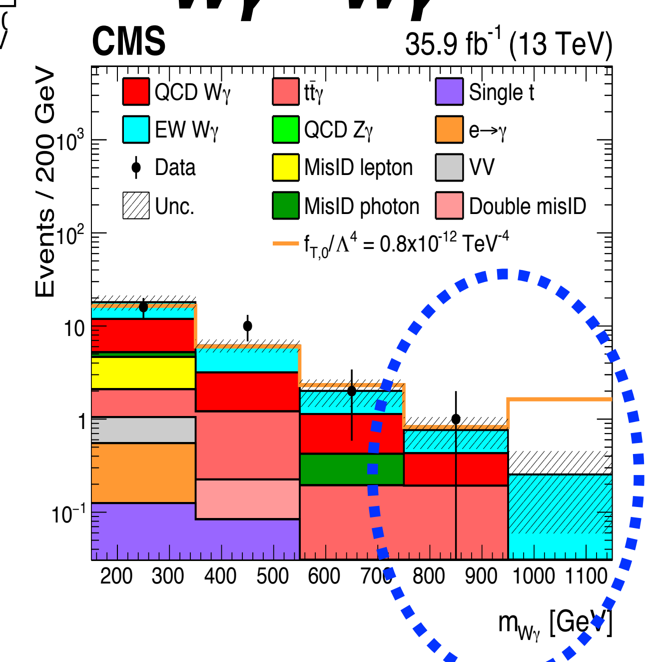
WW→Zγ



WW→ZZ



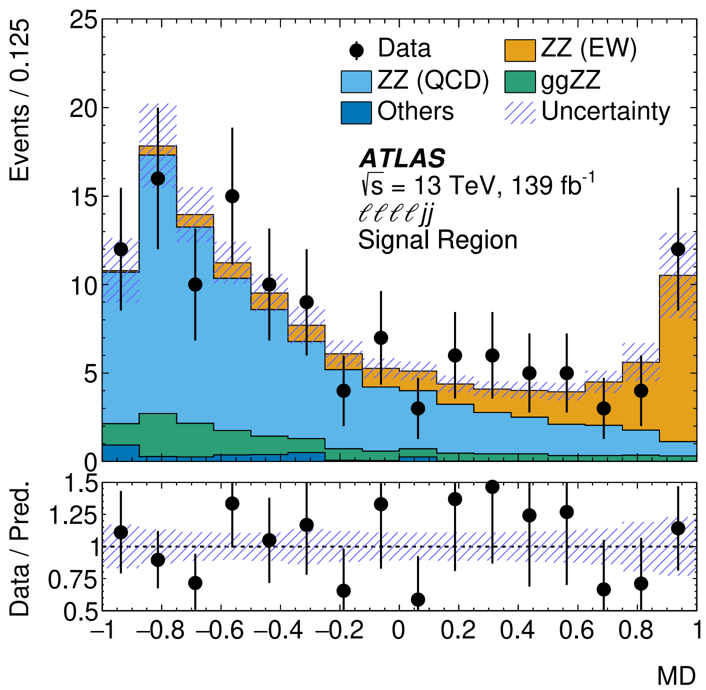
Wγ→Wγ



Standard Model Vector Boson Scattering

The rare electroweak production of $ZZjj$ events is observed using 139 fb^{-1} of $\sqrt{s}$ = 13 TeV proton–proton collision data collected with the ATLAS detector. The measurement of this rarest electroweak $VVjj$ process is an important milestone in the study of electroweak physics at the LHC. This result also marks an important step towards understanding the nature of the electroweak symmetry breaking, as it completes the observation of all major channels and confirms the consistency of the experimental results with the mechanism predicted by the Standard Model. This result marks the start of a new era in precision studies of rare processes in the electroweak sector and in searches for new phenomena that can be investigated with higher precision and in higher energy regimes with future larger datasets.

Nature Phys. 19 (2023) 2, 237-253

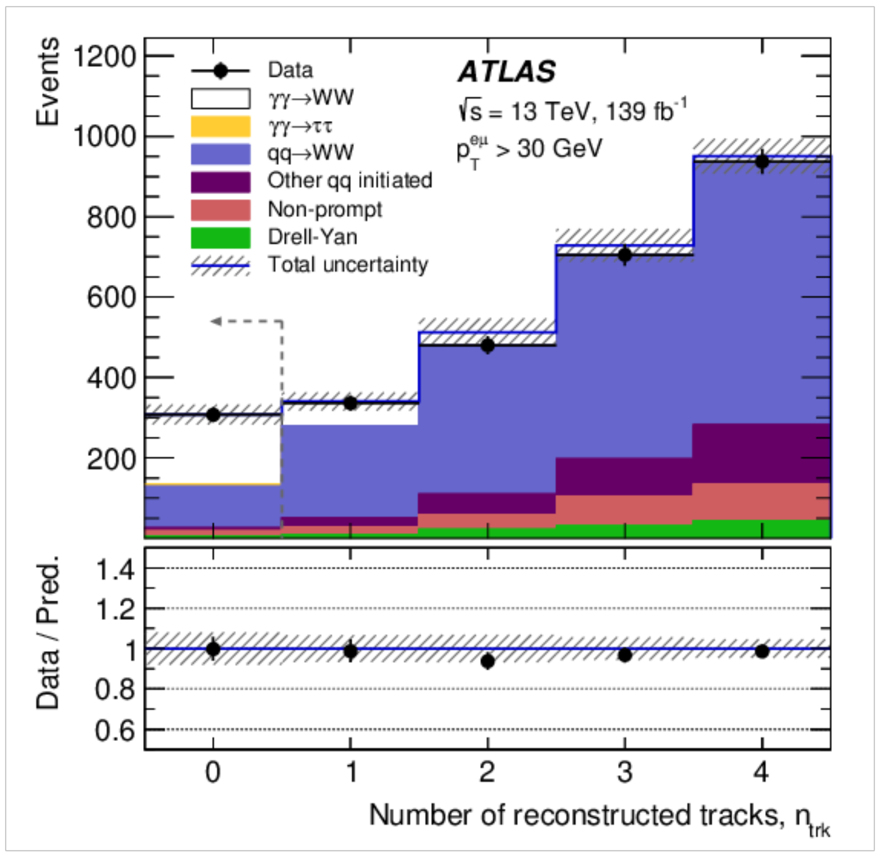


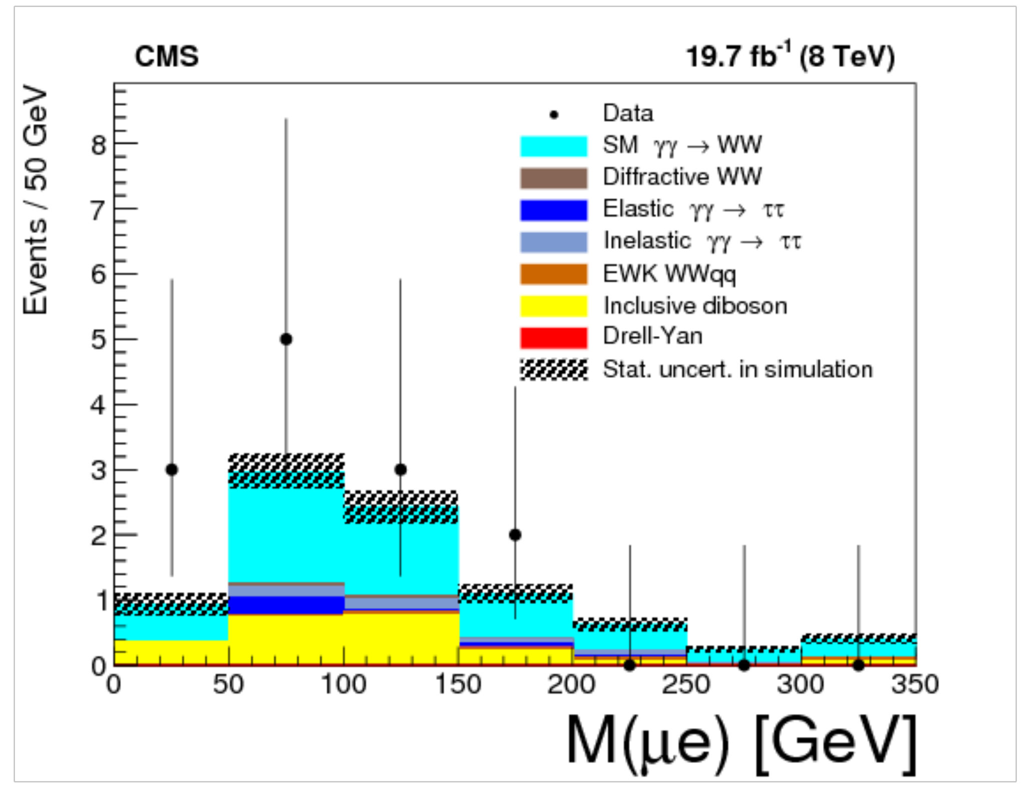
At the end of LHC Run 2/early Run 3

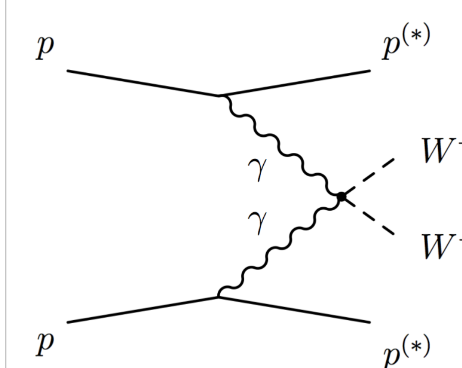
All heavy VV final states have been observed via VV→VV scattering (VV = WW or ZZ or WZ)

Moving from the era of searches to precision measurements

More quartic gauge interactions: γγ→*WW* and γγ→ZZ scattering







What about processes with *initial-state* photons radiated off of protons?

Special case: usually no forward jets, only forward protons - use special forward proton detectors, or infer γγ production by *lack* of other activity besides 2 W/2 Z-bosons

γγ→WW and γγ→ZZ studied by CMS/ATLAS with and without detecting the protons, results consistent with the SM

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

What about processes with *only* photons: γγ→γγ?

Very difficult in normal p-p collisions, so new techniques/detectors developed

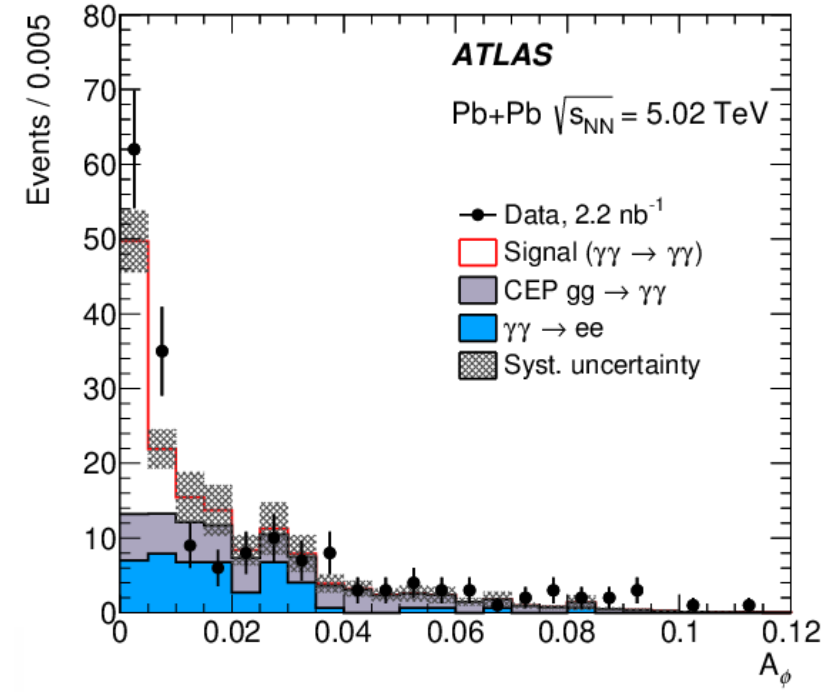
Heavy-ion collisions

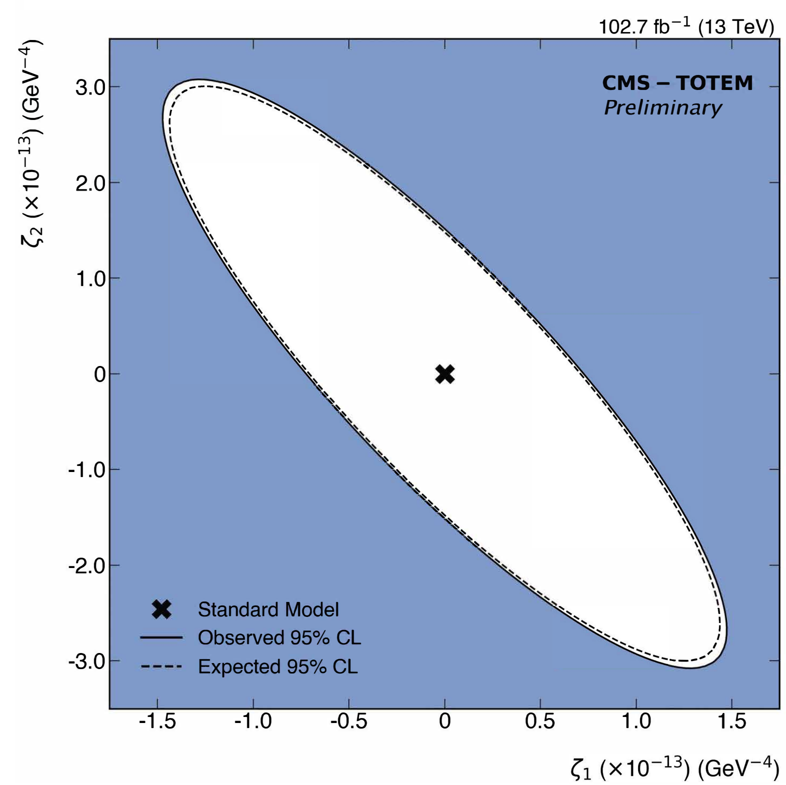
Look for back-to-back photons with no other activity

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

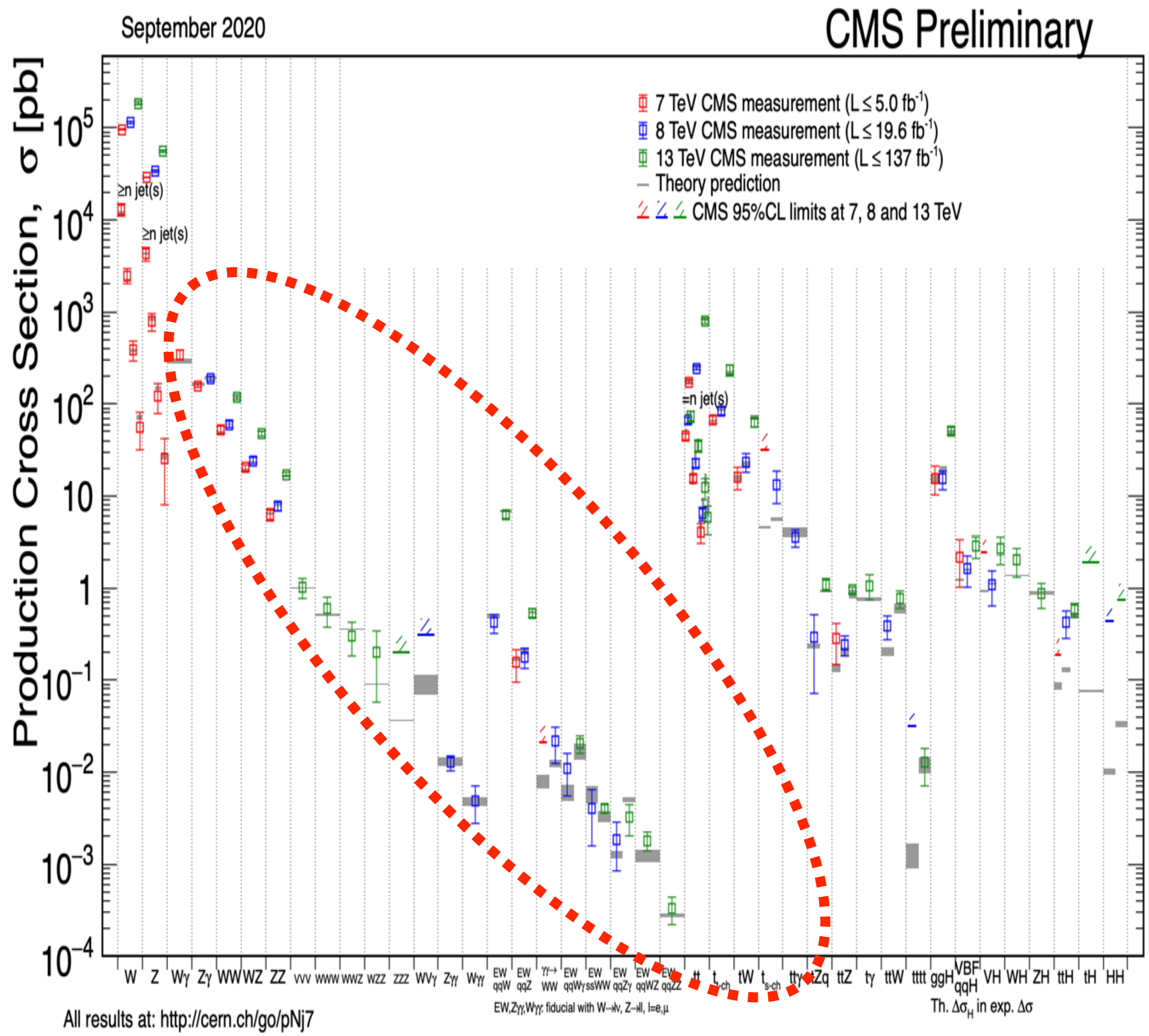
Production rates via gauge boson interactions

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!



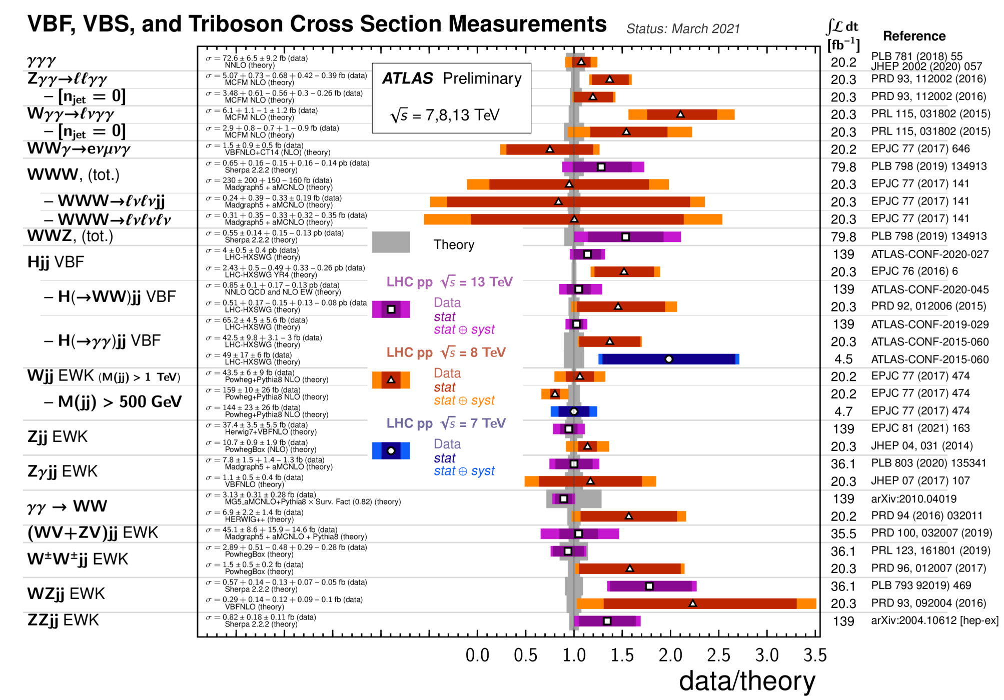
Rates of VBS/tri-boson processes

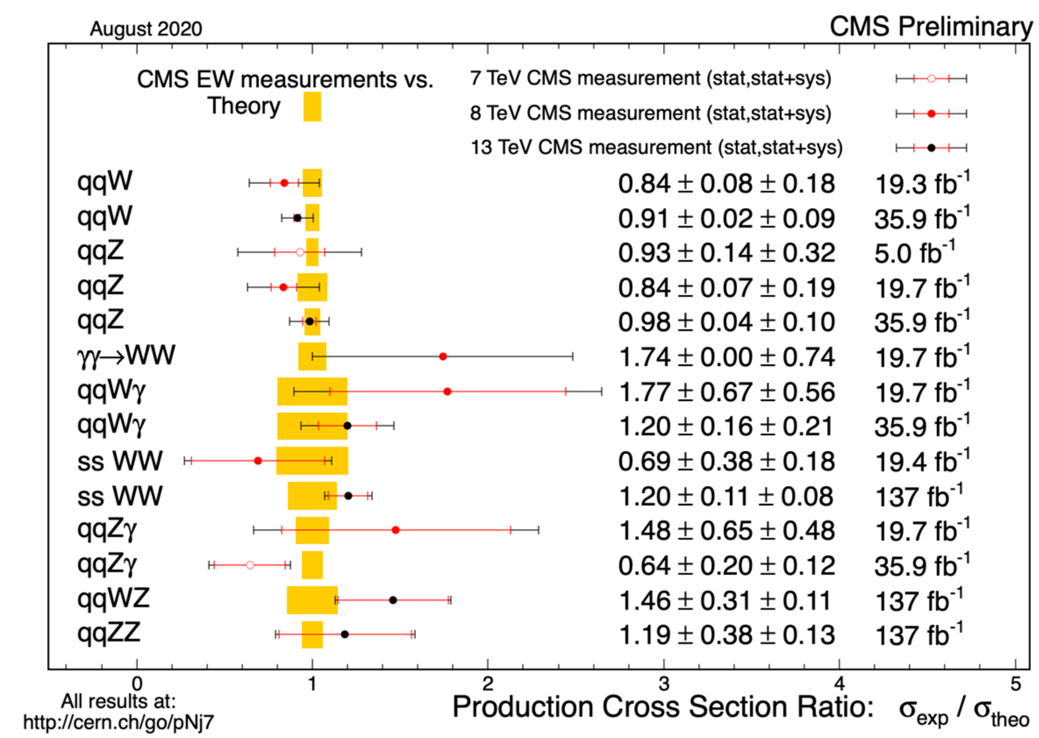
What about the very rare processes?

Zoom in on tri-boson production and vector boson scattering

Plot ratio of measurement/SM prediction

Large uncertainties, but so far so good



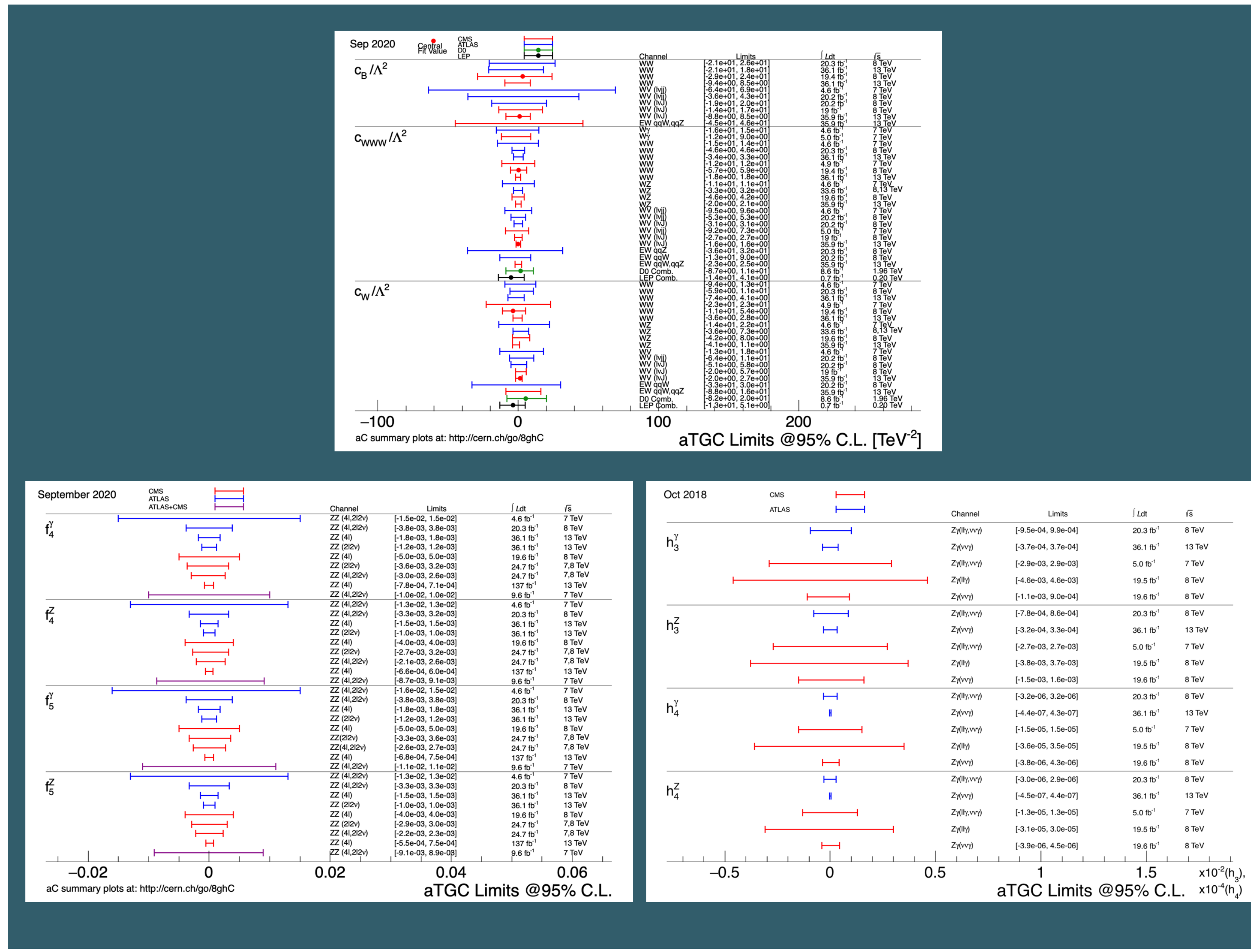


Anomalous gauge couplings scorecard (I)

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!



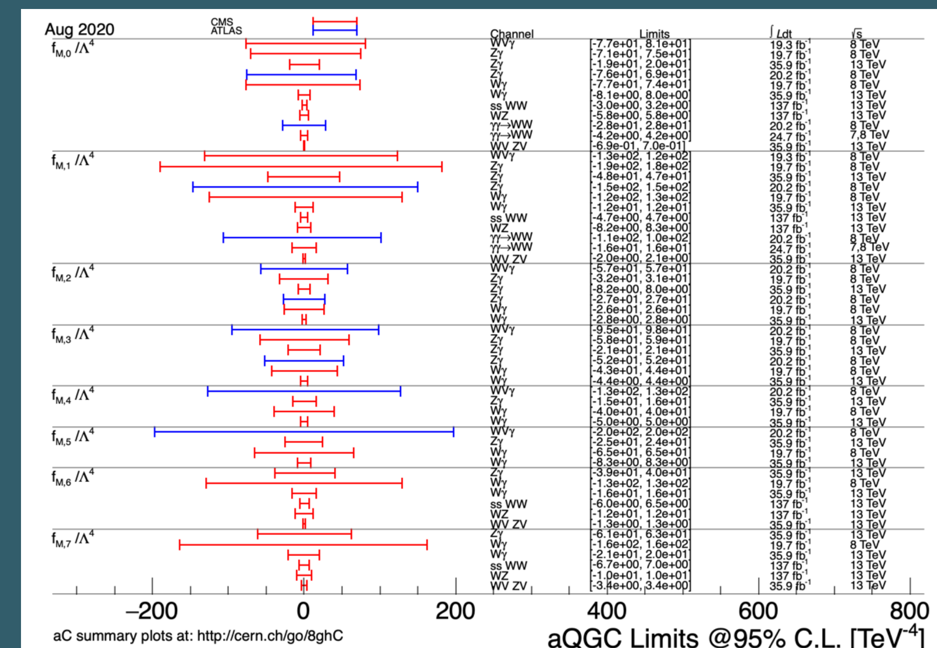
Anomalous gauge couplings scorecard (II)

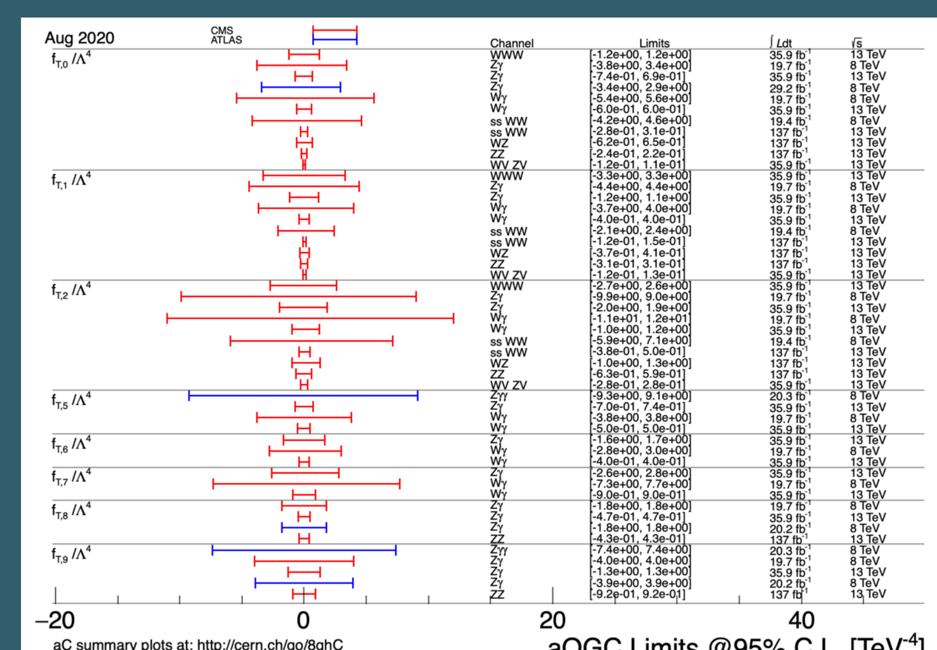
LHC exploring all the possible EWK 4-boson couplings

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?

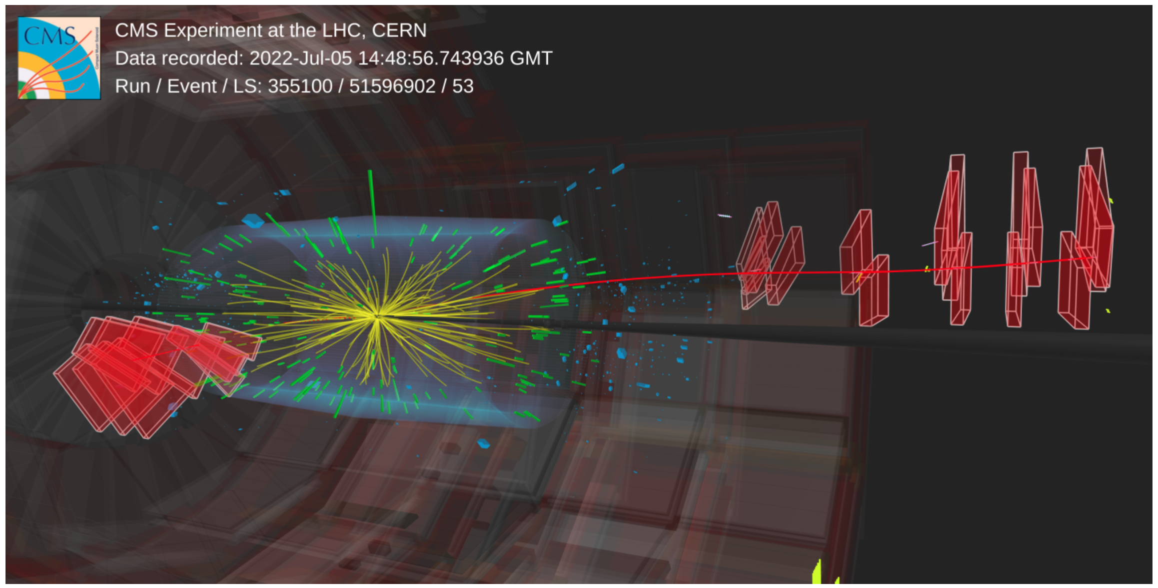
LHC precision measurements of some SM parameters start to be competitive with the best from e^+e^- colliders

- Important impact on global fits and combinations with Higgs, top quark data
- **Systematic uncertainties** are key: important to improve analysis techniques & detectors

Pattern of gauge boson interactions/anomalous couplings so far agrees with the Standard Model

- Including many 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 often limited by **statistical uncertainties**: will improve just by collecting more data => probe higher energy scales/smaller couplings

LHC Run 3



In 2022 the LHC restarted for Run 3, after a 3.5 year stop to refurbish and improve equipment

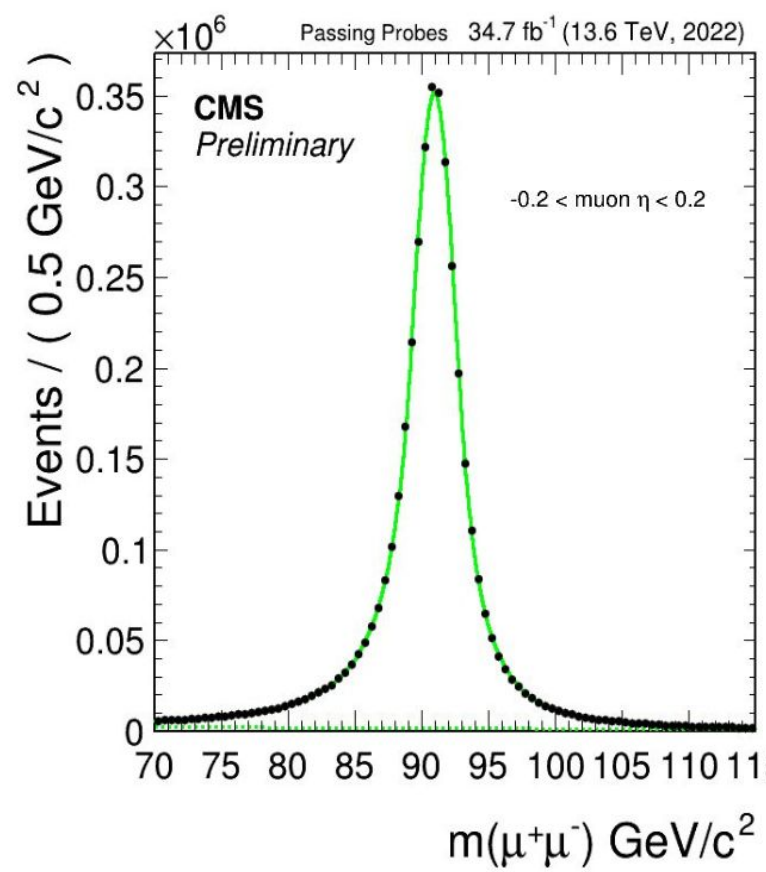
Energy increased to 13.6 TeV

Already large numbers of W and Z bosons produced in 2022-2025, and restarting for 2026 in the next weeks

Run 3 will end in mid-2026

More than doubling the Run 2 dataset

First diboson results already published

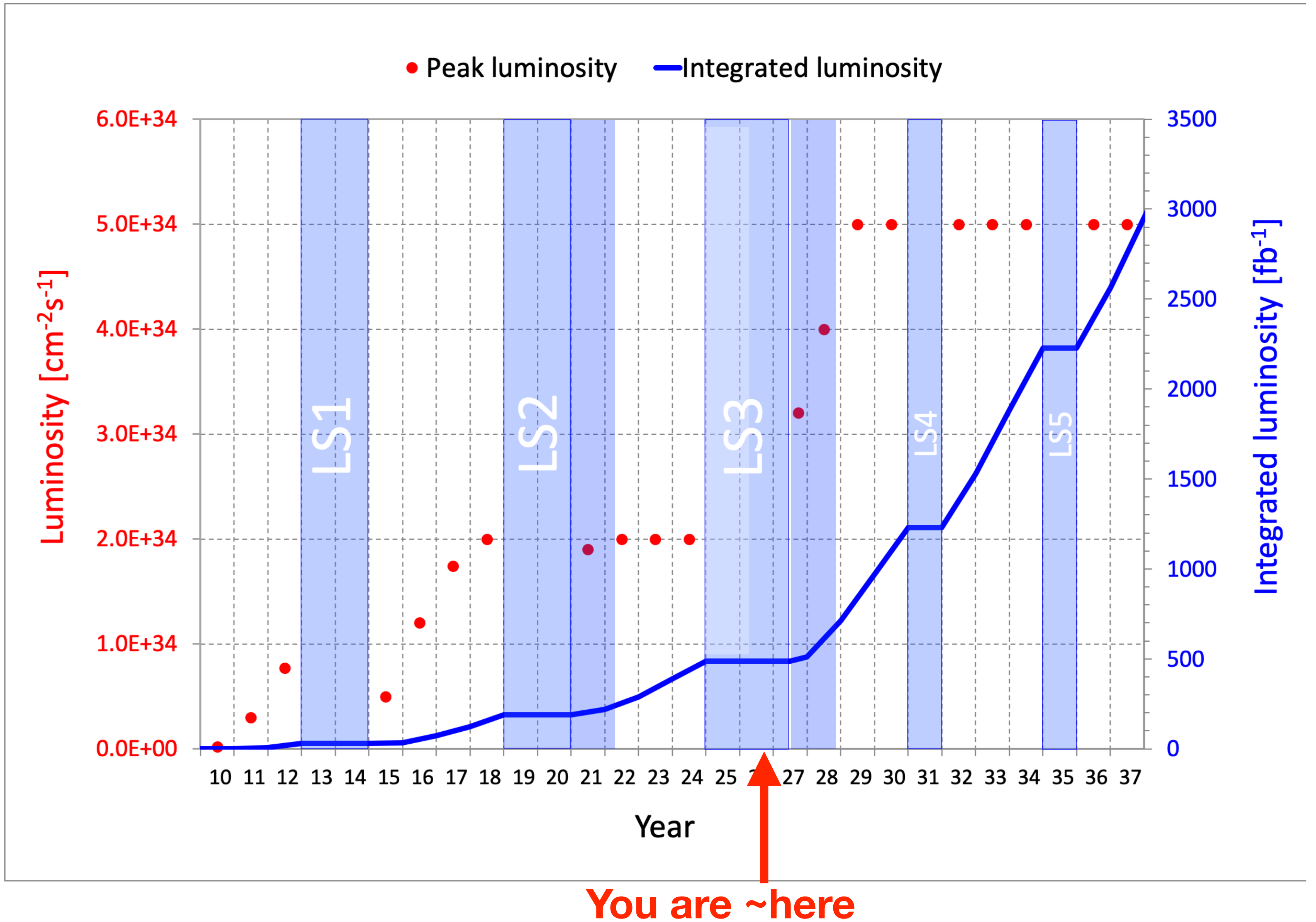


Beyond Run 3: High-Luminosity LHC

After Run 3, LHC will be upgraded to the “High luminosity LHC”

~10x 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

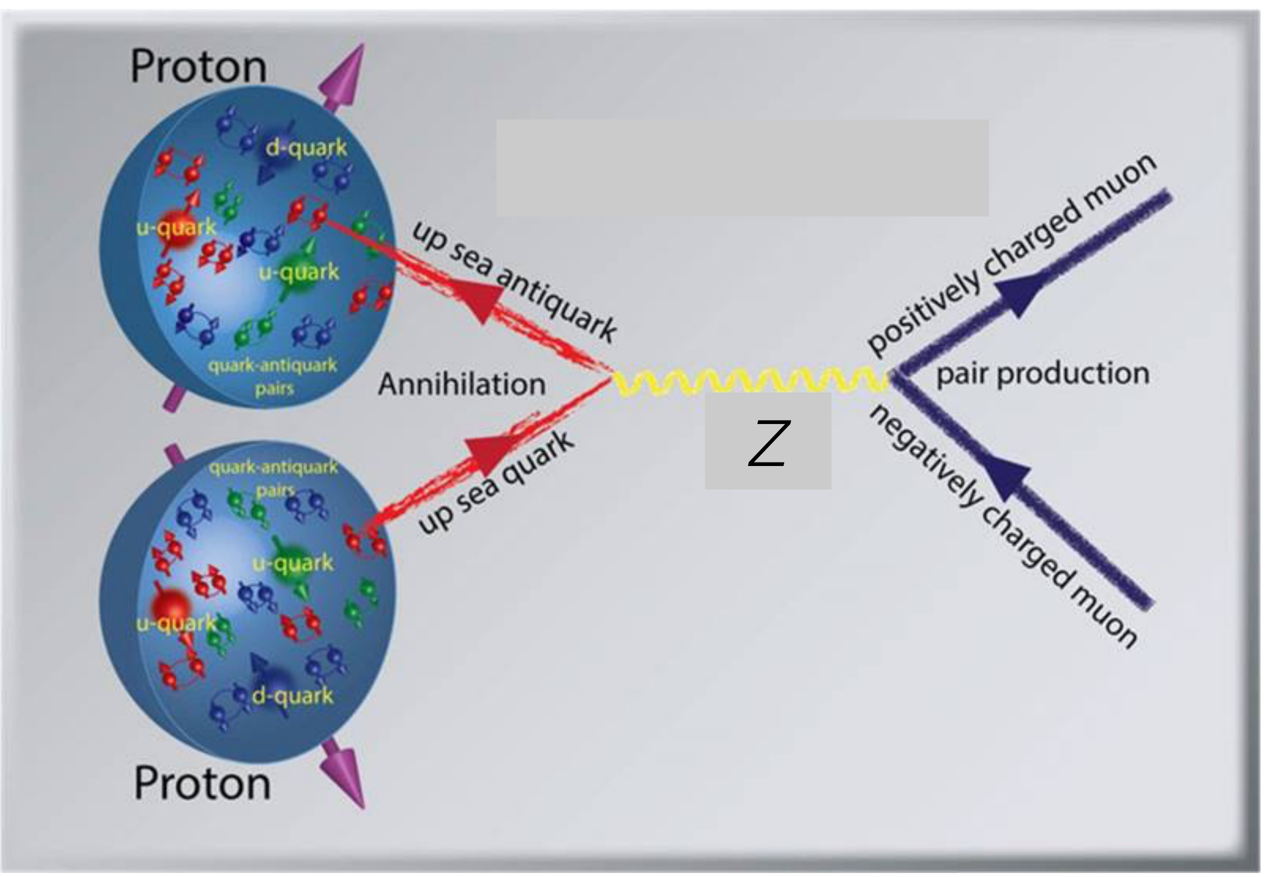


See upcoming lectures for details/updated schedule

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



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

[Ref]

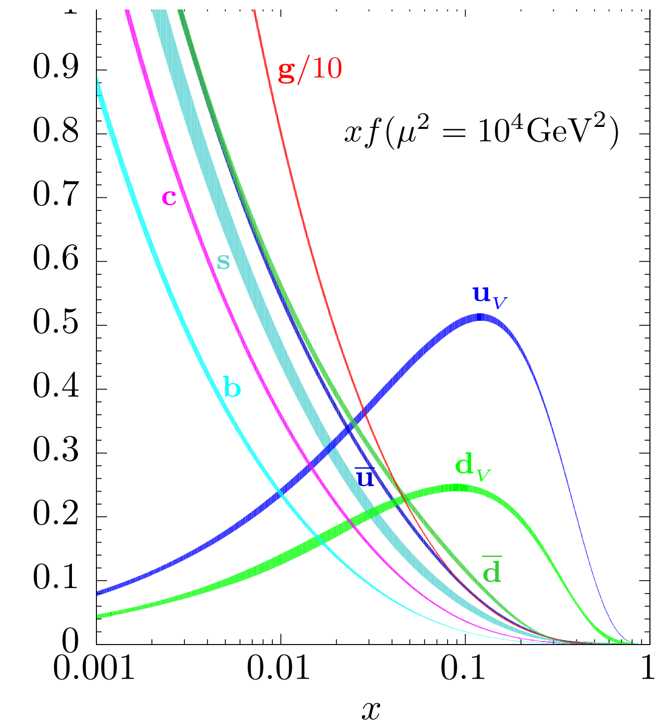
W/Z as tools for QCD: PDFs

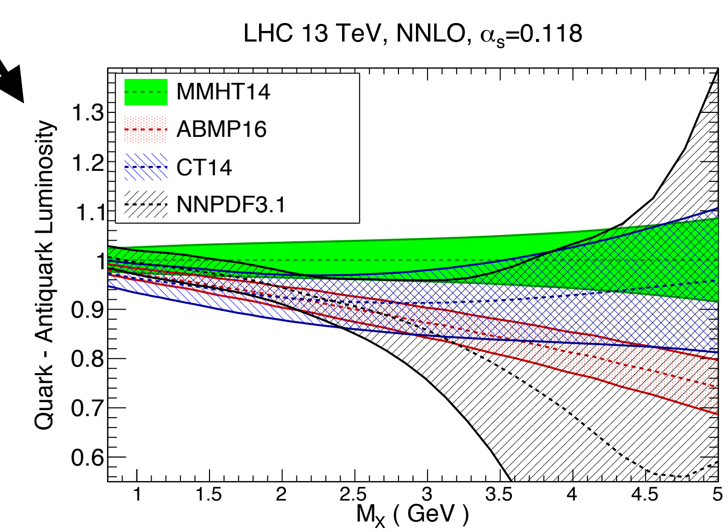
Major uncertainty in many LHC measurements and searches: “Parton Distribution Functions”

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



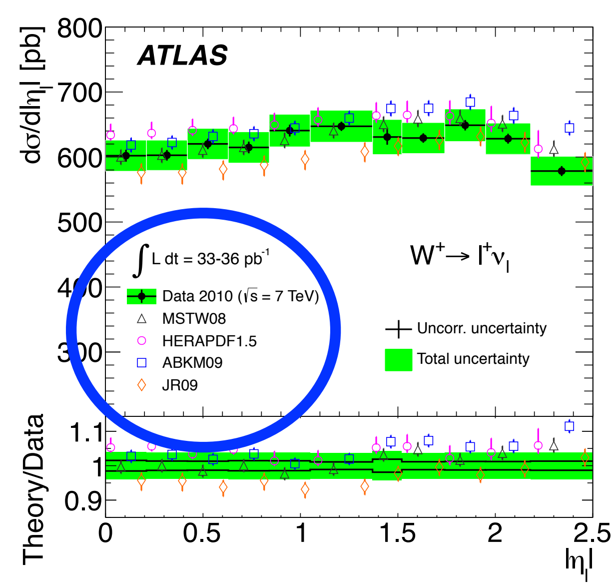


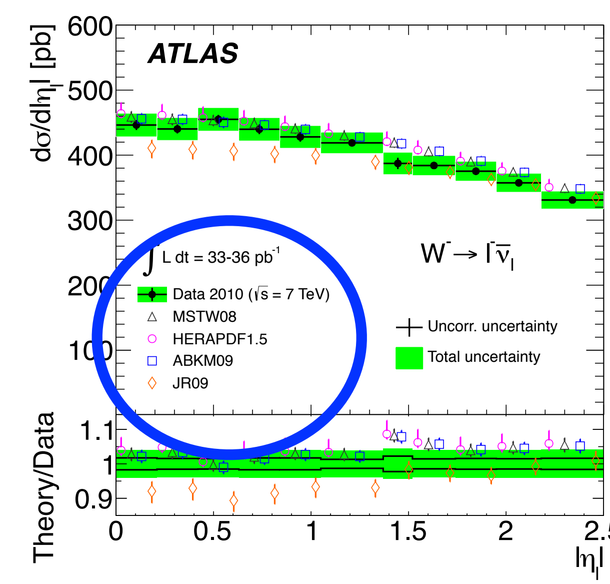
[Ref]

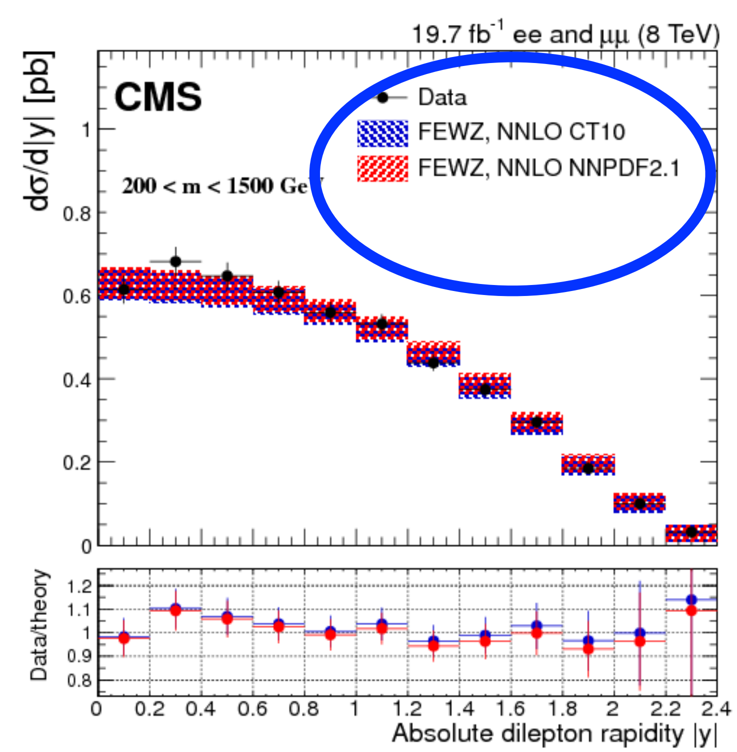
W/Z as tools for QCD: PDFs

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

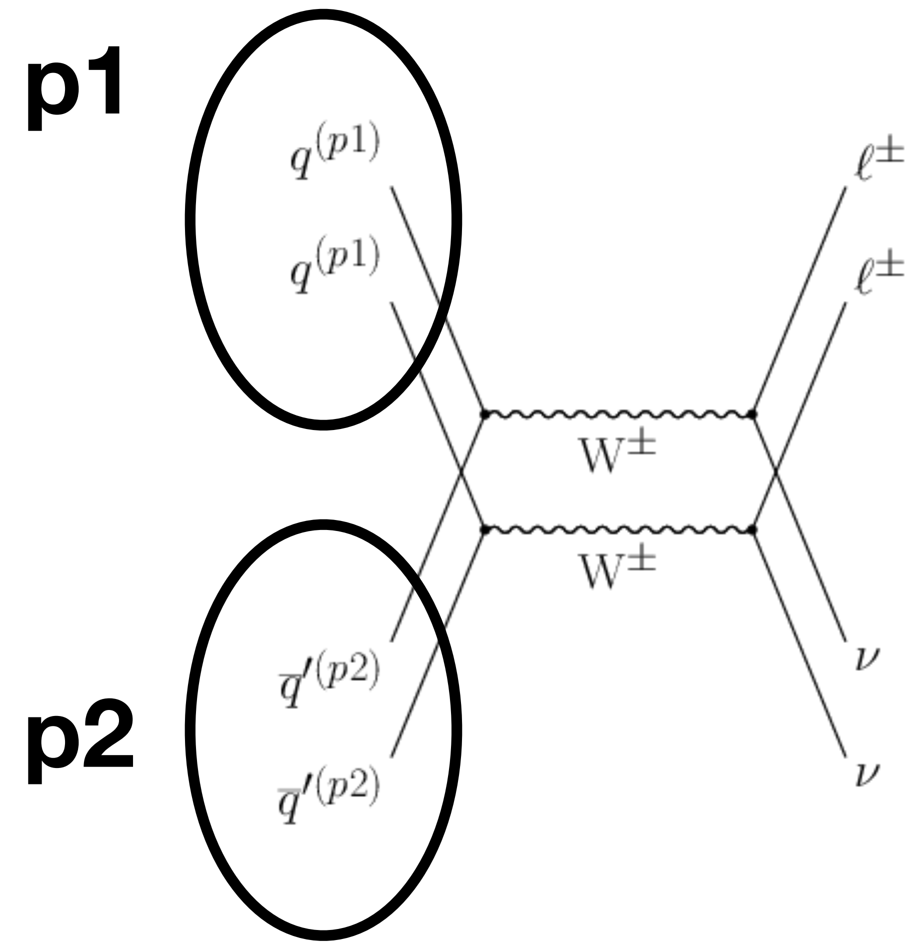
W/Z as tools for QCD: Double-parton scattering

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

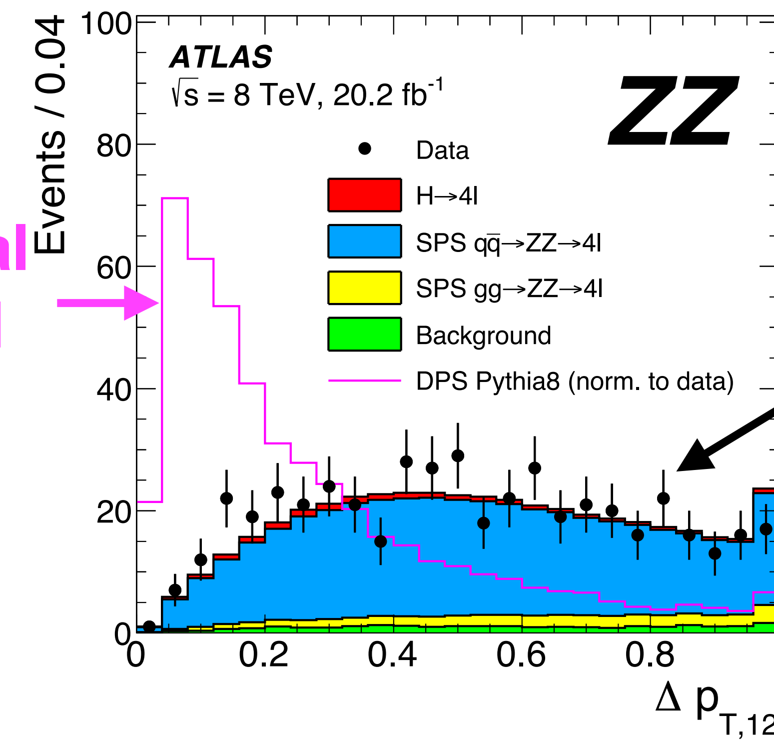
Similar W/Z reconstruction as electroweak measurements

Look for pairs of particles from the same vertex, with non-correlated kinematics

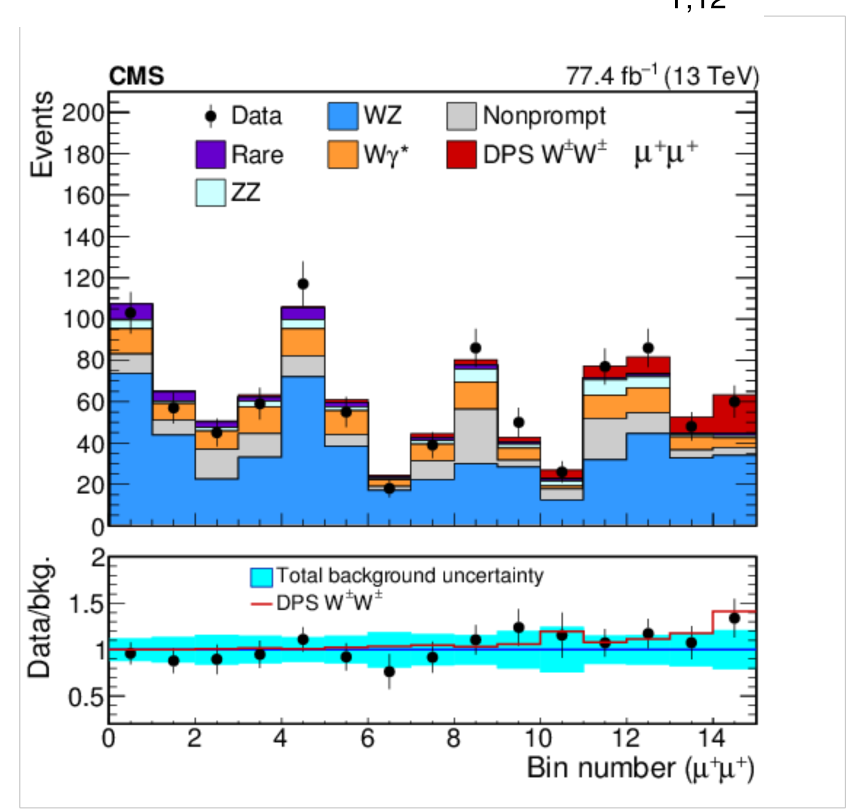
Unbalanced p_T, phi, etc.

Several DPS processes seen for the first time at LHC (W^+W^+, W+jets, Z+jets…), for others still looking (ZZ…)

Hypothetical DPS signal shape



Data



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)

Apart from the "pure" electroweak physics, W/Z/γ remain important tools to probe the internal structure of the proton

Extra