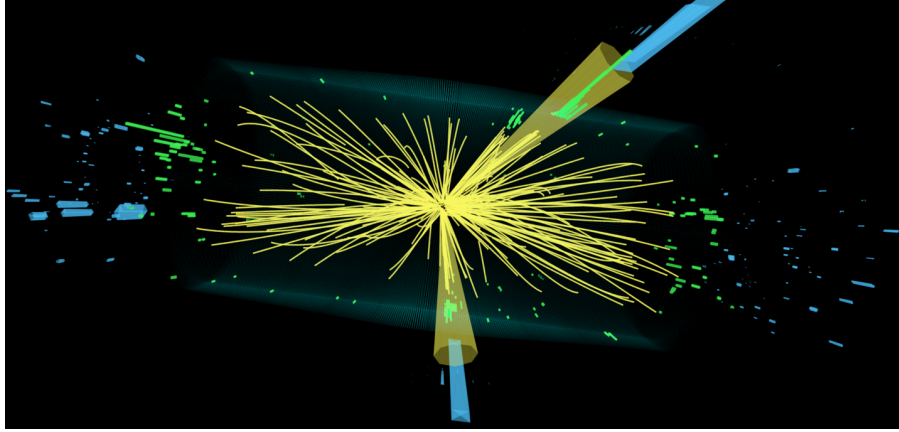


Higgs/EW physics: Experiment Part 2

17th Hadron Collider Physics Summer School

August 17-18, 2022

Aram Apyan, Brandeis University

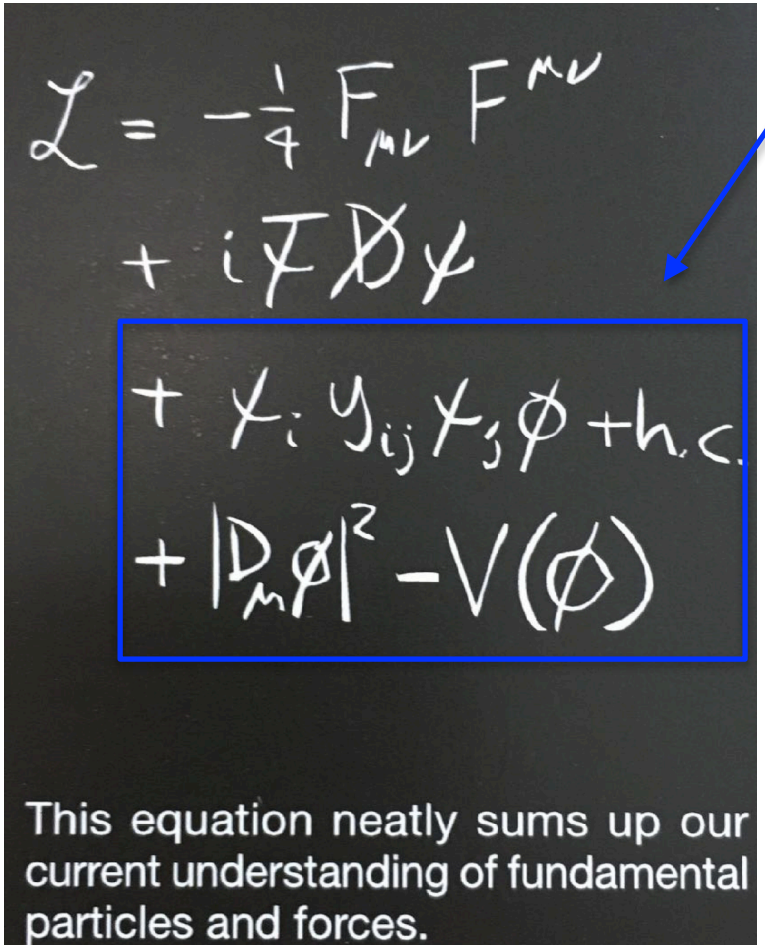
Overview

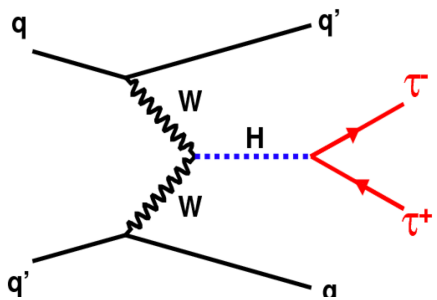
- Day-1: Higgs boson
  - What did we know before LHC?
  - How do we discover/study the Higgs boson?
  - Gauge and Yukawa couplings
  - From discovery to precision tests -> The portrait of the Higgs boson after 10 years
  - New couplings: Higgs boson self interactions

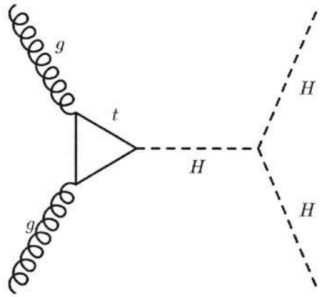
- Day-2: Electroweak physics
  - Quartic and triple gauge couplings
  - Higgs boson and Vector boson scattering
  - Precision electroweak observables
  - How do we measure the W mass?
  - How do we measure the Weinberg angle?

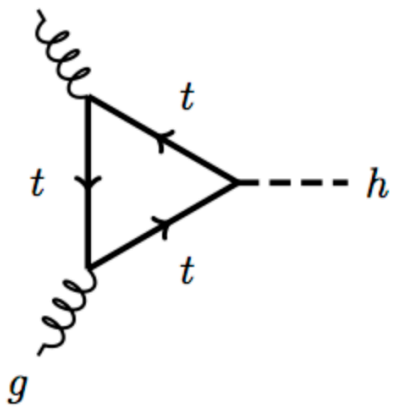
Day 1 Langrangian

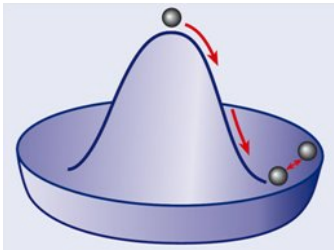
- Yesterday we mainly concentrated on these terms in the Langrangian





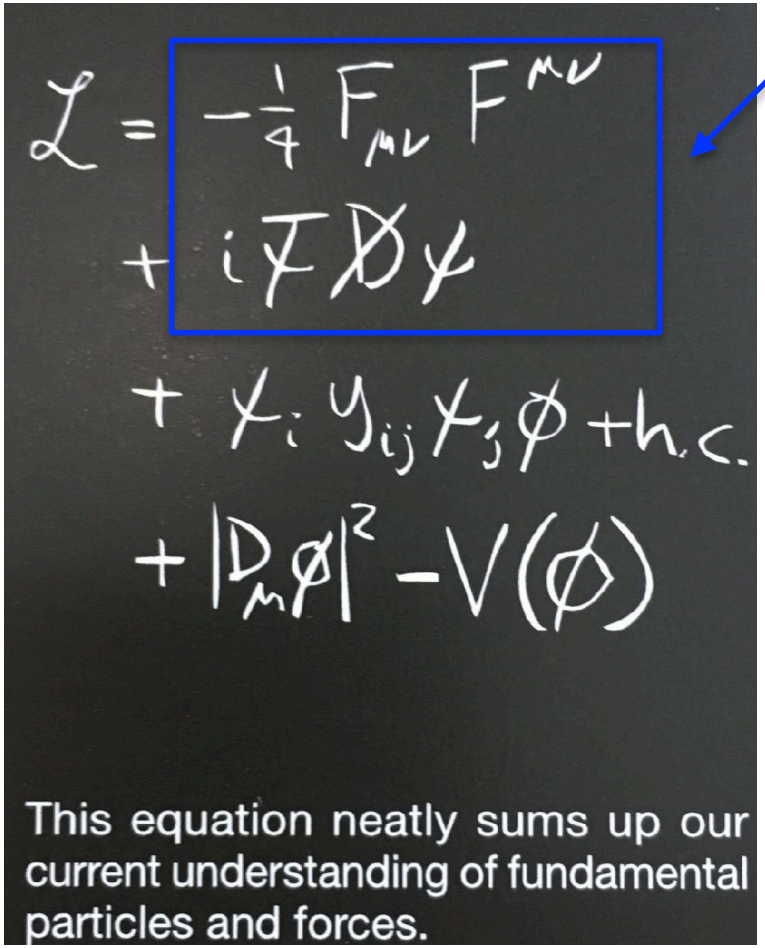


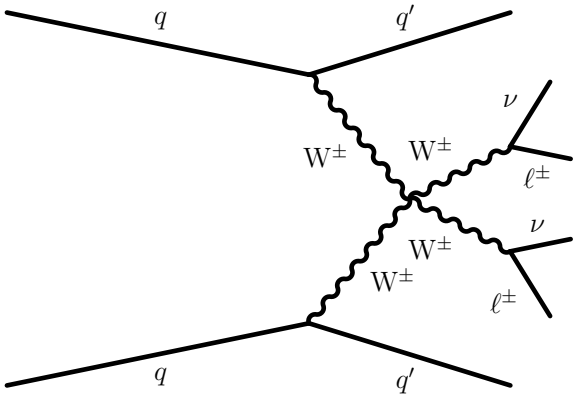


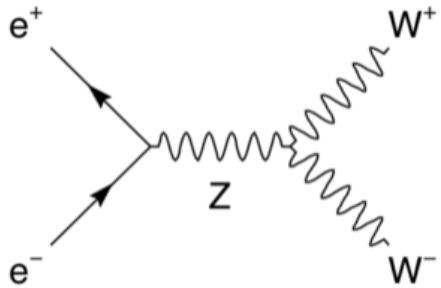


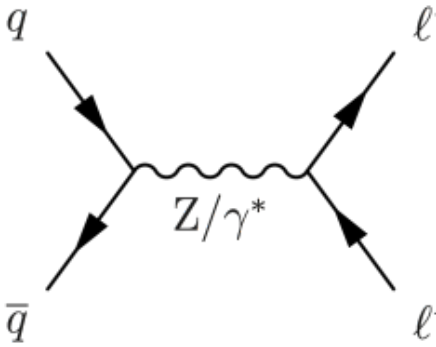
Day 2 Langrangian

- Today we mainly concentrate on the first two terms





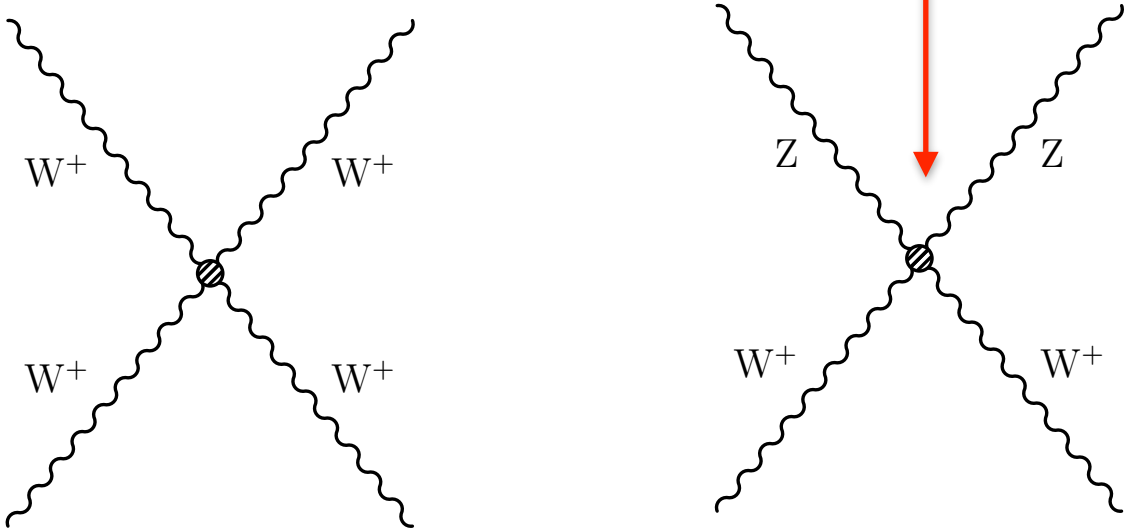




Boson self-couplings

- W/Z boson self couplings predicted in non-abelian U(1)xSU(2) symmetry
- Quartic boson couplings (QGC)
  - WWZZ,WWWW,WWZγ,WWγγ
- Triple boson couplings (TGC)
  - WWZ,WWγ
- However, neutral couplings absent in SM
  - ZZZZ, ZZγγ, ZZZ, ZZγ,…

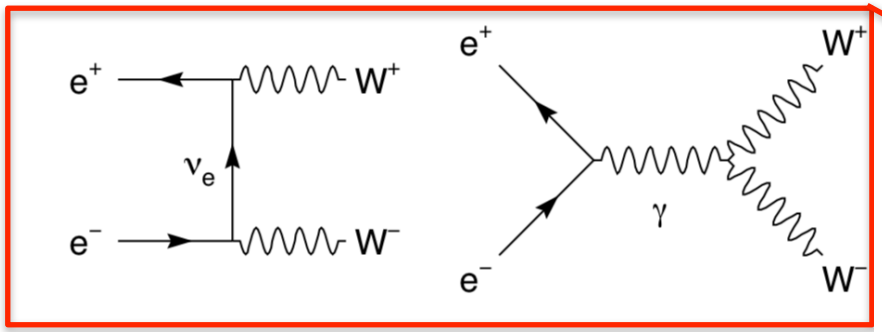
New Physics?

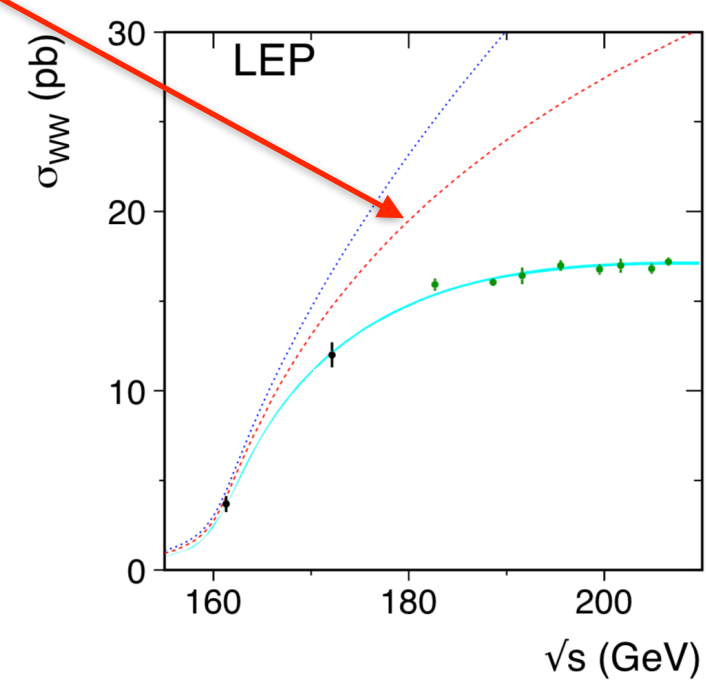


But how can we collide W and Z bosons?

Example: High energy behavior and unitarity

- W bosons can be produced in e+e- colliders

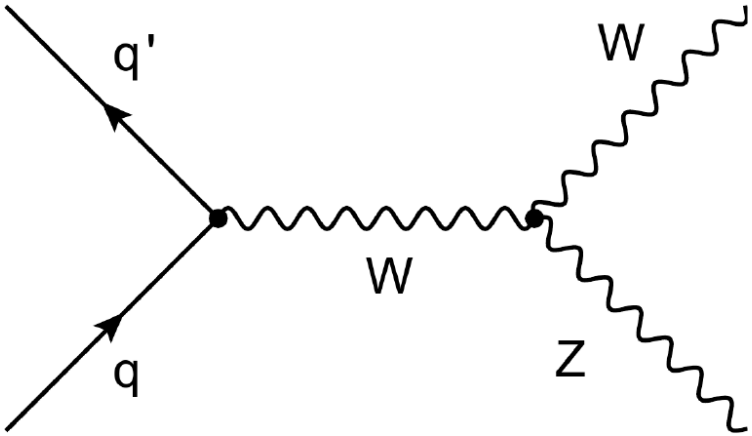


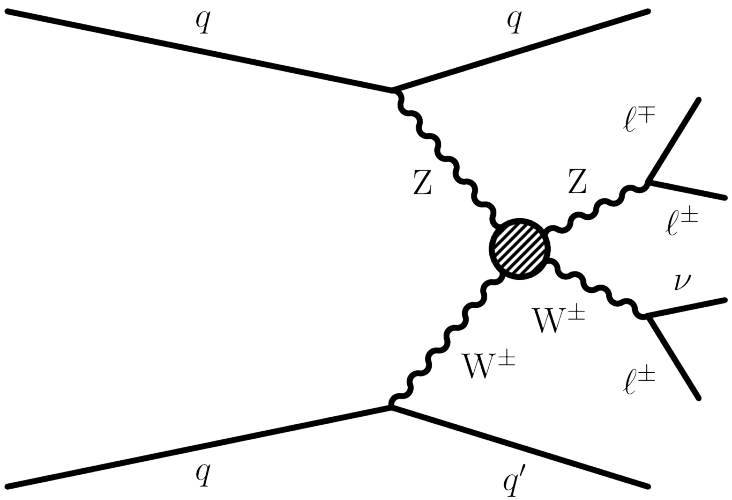


- There is a problem at high energies!
  - Cross section grows with energy
  - QM unitarity is violated
    - Probability not conserved

Boson self-couplings

- Multiboson production at the LHC can test the triple and quartic gauge couplings
  - Search for anomalous gauge couplings
    - Results typically quoted using effective field theory (EFT)



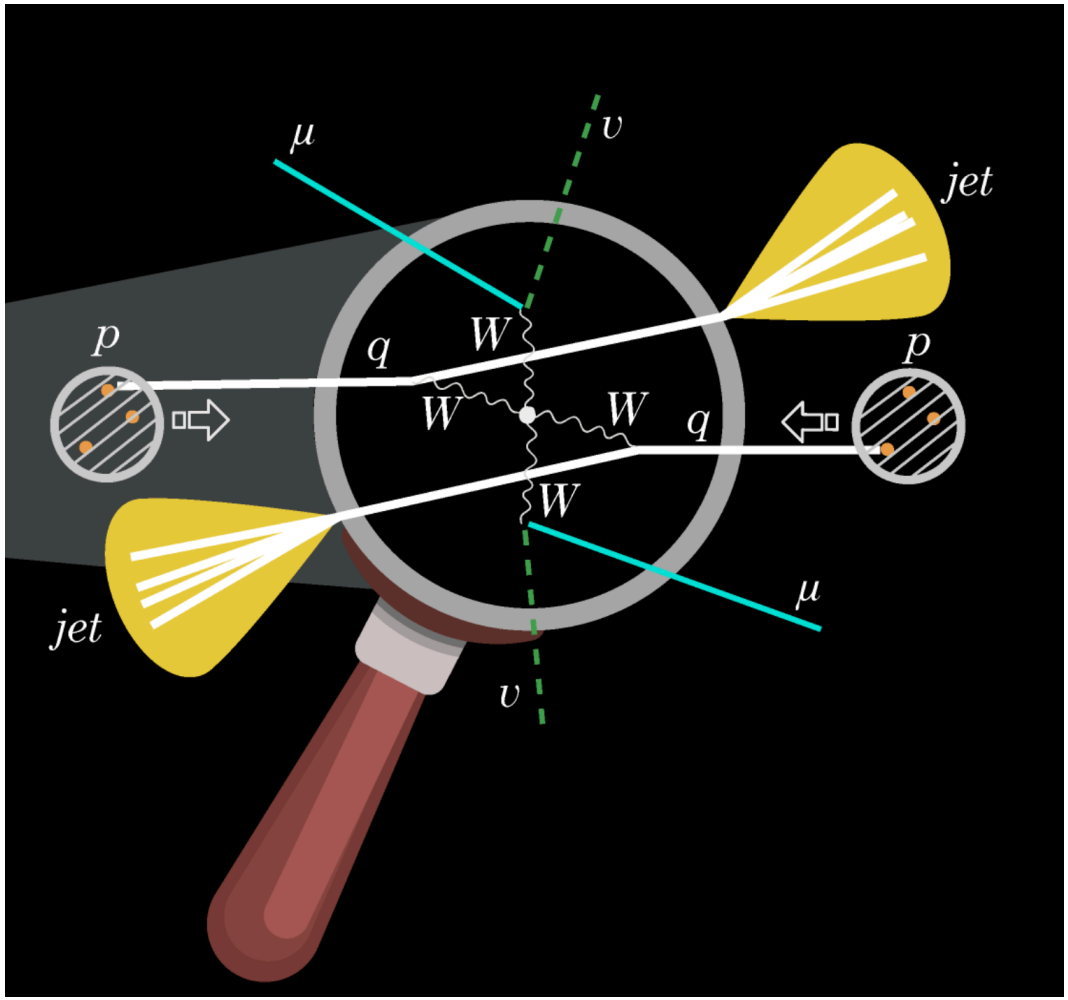


Inclusive production

Vector boson scattering

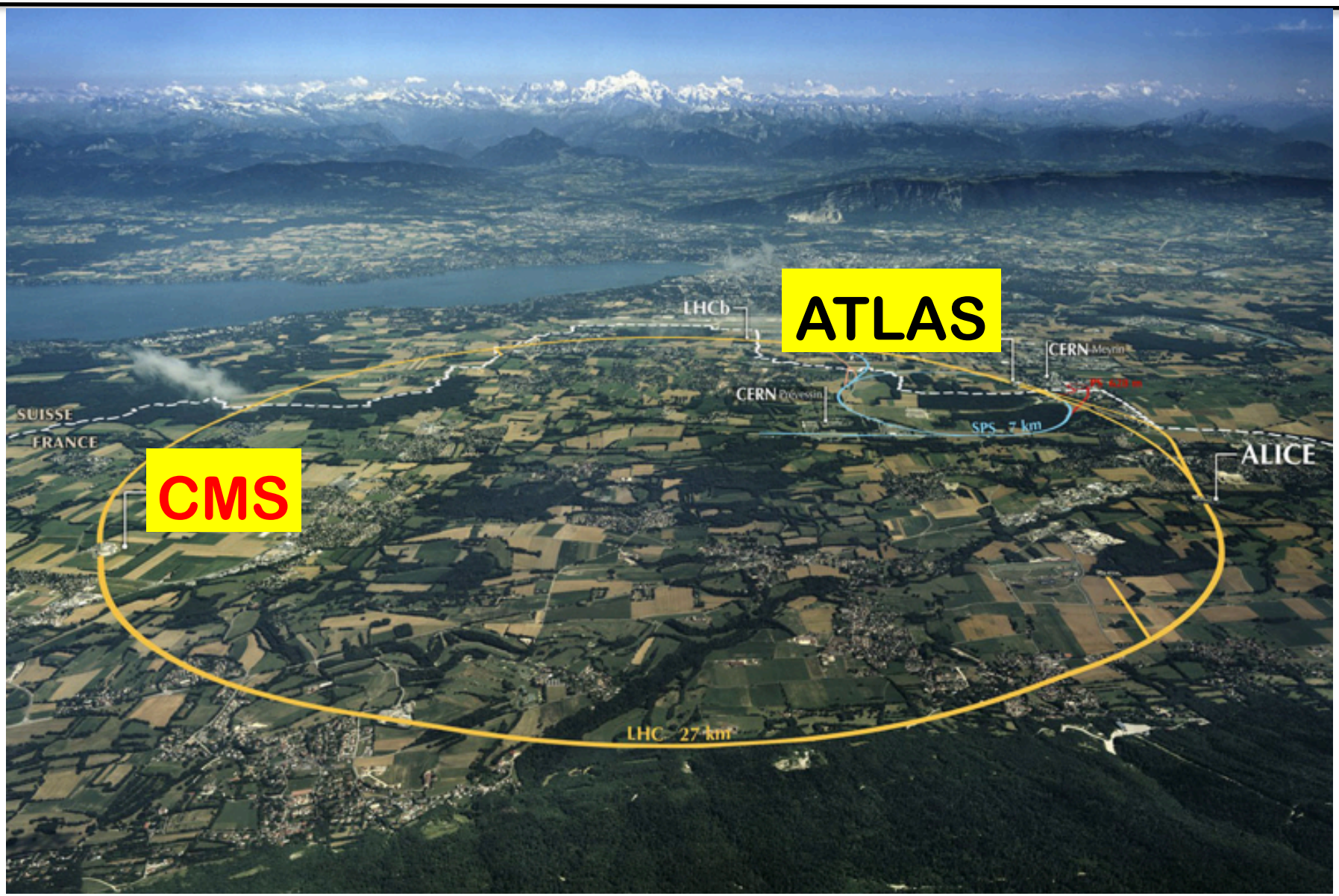
Boson collider

- Start with a hadron collider and look for vector boson scattering (VBS)



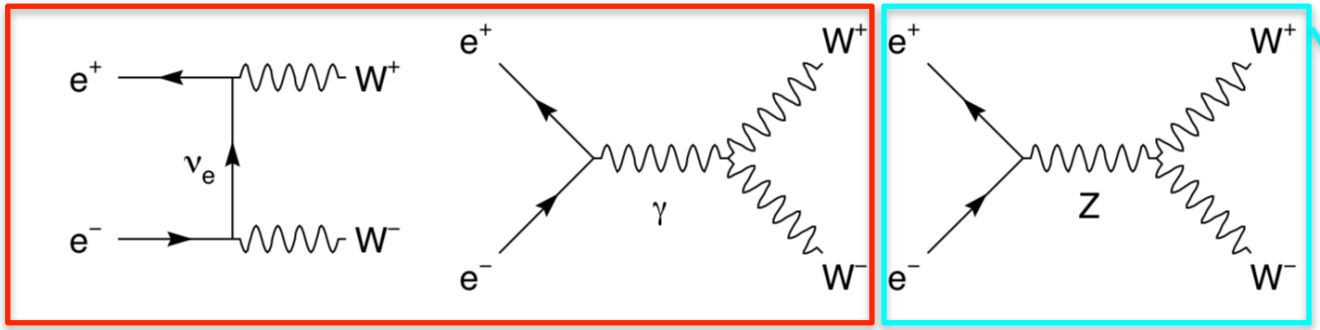
- Similar to VBF, the two forward VBS jets provide additional handles to isolate the candidate events of interest
- High energy behavior of the VBS processes deserves a special attention

Large ~~Hadron~~ Boson Collider



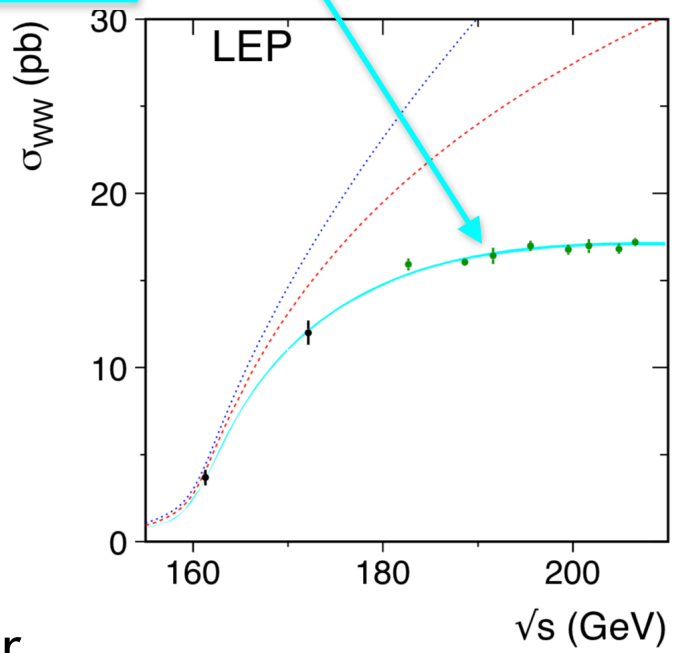
High energy behavior and unitarity

- W bosons can be produced in e+e- colliders



- Bad behavior 'fixed' by the Z boson

- Takeaways:
  - High energy behavior –> new particles
  - W and Z boson self interactions

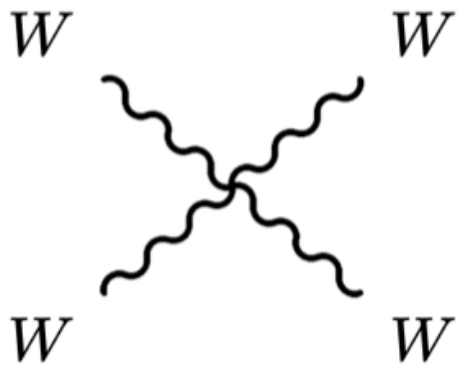


Large Electron-Positron Collider 1989-2000

High energy behavior (again)

- Spin-1 massive bosons (W, Z) exist in three polarization states (left/right transverse and longitudinal)
  - Reminder from Day 1: Heavy vector bosons W and Z acquire their mass and longitudinal polarization state through Higgs mechanism

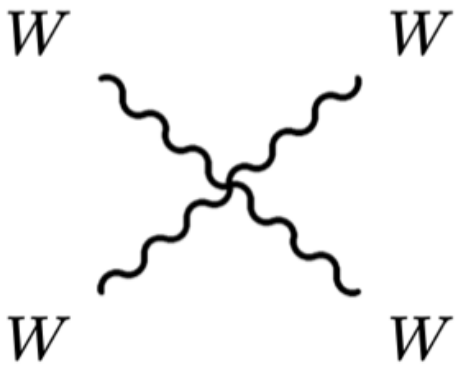
- Consider the cross section of the longitudinal scattering $W_L W_L \to W_L W_L$



Big problem at high energies!
Amplitude ~ $(\text{Energy})^4$
Unitarity is violated

High energy behavior (again)

- Consider the cross section of the longitudinal scattering $W_L W_L \to W_L W_L$



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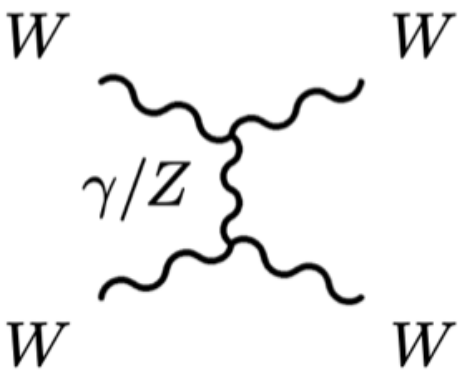


A1 ~ $(\text{Energy})^4$

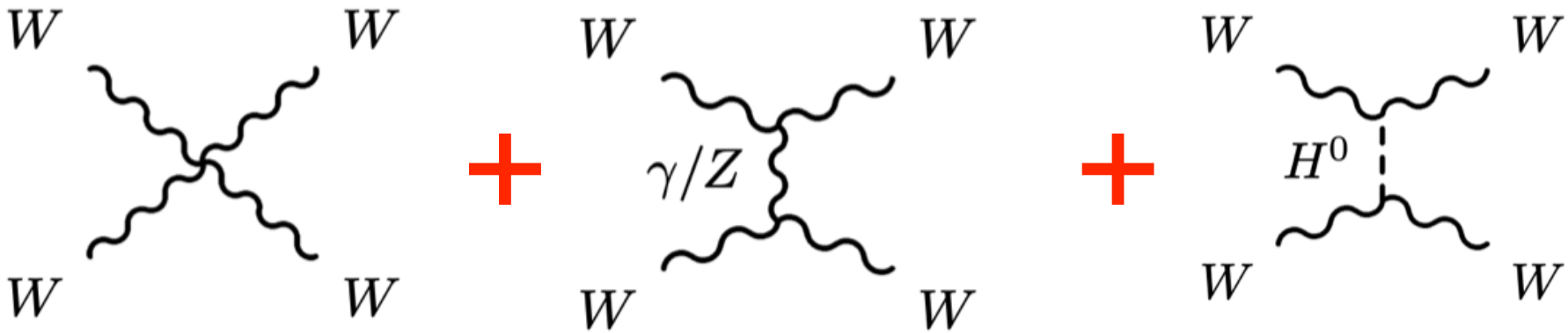
A2 ~ $(\text{Energy})^4$

A1+A2 ~ $(\text{W mass})^2(\text{Energy})^2$

- $(\text{Energy})^4$ behavior is cured by the 2nd diagram but there is still a problem: $(\text{Energy})^2$
- A spinless particle with couplings proportional to W boson mass would solve the problem!

High energy behavior (again)

- Consider the cross section of the longitudinal scattering $W_L W_L \to W_L W_L$



A1 ~ (Energy)^4 A2 ~ (Energy)^4 A3 ~ (W mass)^2(Energy)^2

- A1+A2+A3 is well behaved at high energies!
- Higgs boson 'fixes' the high energy unitarity problem

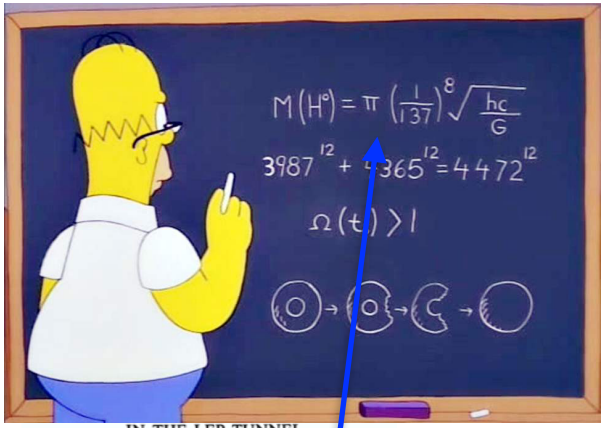
Before Higgs discovery

PHYSICAL REVIEW D VOLUME 16, NUMBER 5 1 SEPTEMBER 1977

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

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

We give an S-matrix-theoretic demonstration that if the Higgs-boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$, parital-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation of this bound to the structure of the Higgs-Goldstone Lagrangian, and speculate on the consequences of strongly coupled Higgs-Goldstone systems. Prospects for the observation of massive Higgs scalars are noted.



IN THE LEP TUNNEL
Vol. I

Also mH < 1TeV

11. SUMMARY AND CONCLUSIONS

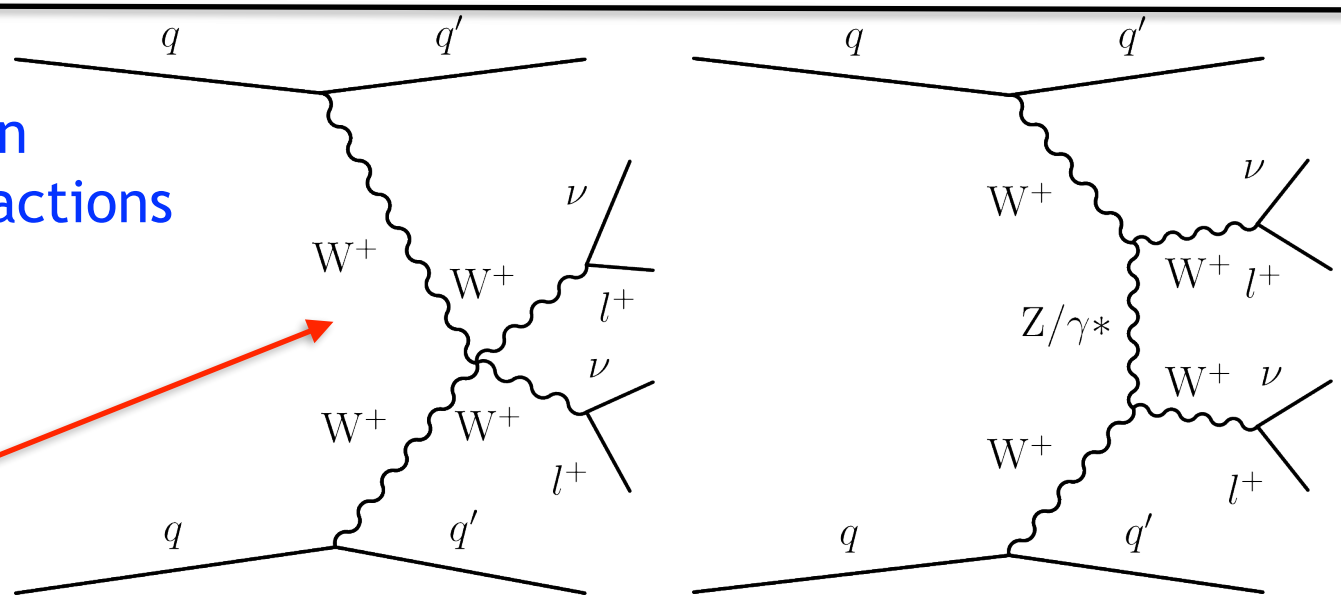
A theoretical consensus is emerging that new phenomena will be discovered at or below 1 TeV. There is no consensus about the nature of these phenomena but it is interesting that many of the ideas which have been suggested can be tested in experiments at an LHC. Although many, if not all, of these ideas will doubtless have been discarded, disproved or established by the time an LHC is built, this demonstrates the potential virtues of such a machine.

- The amplitude may still violate unitarity for large Higgs mass
- Lee-Quigg-Thacker bound:

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

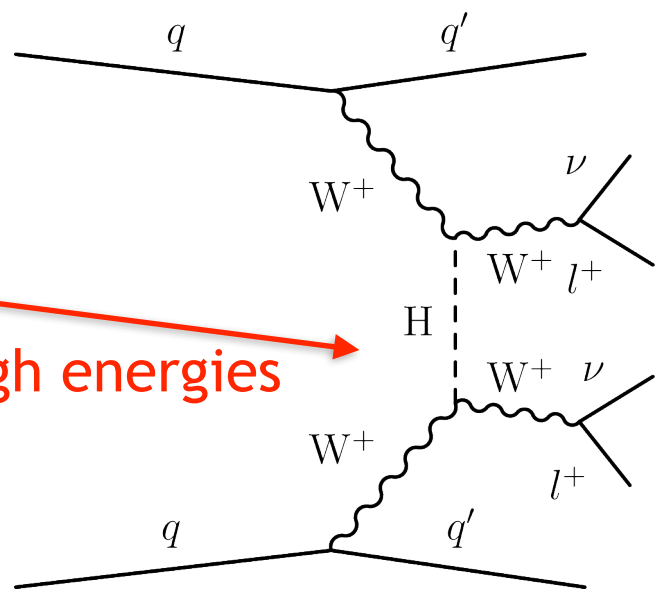
Vector boson scattering

W, Z boson
self-interactions



New physics: anomalous
quartic couplings?

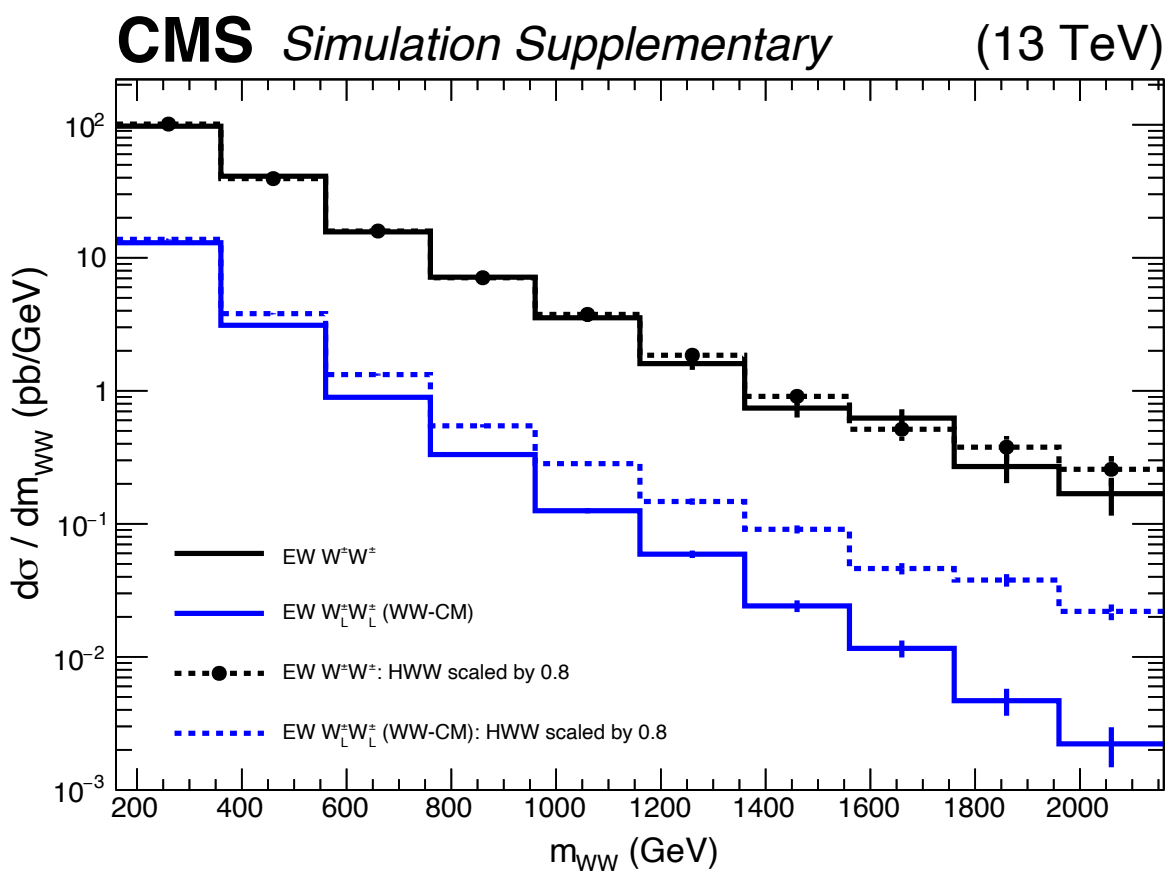
New physics
in Higgs sector?
Probe Higgs couplings at high energies



Higgs

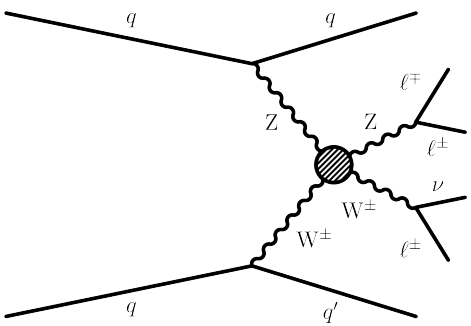
Longitudinal scattering and Higgs

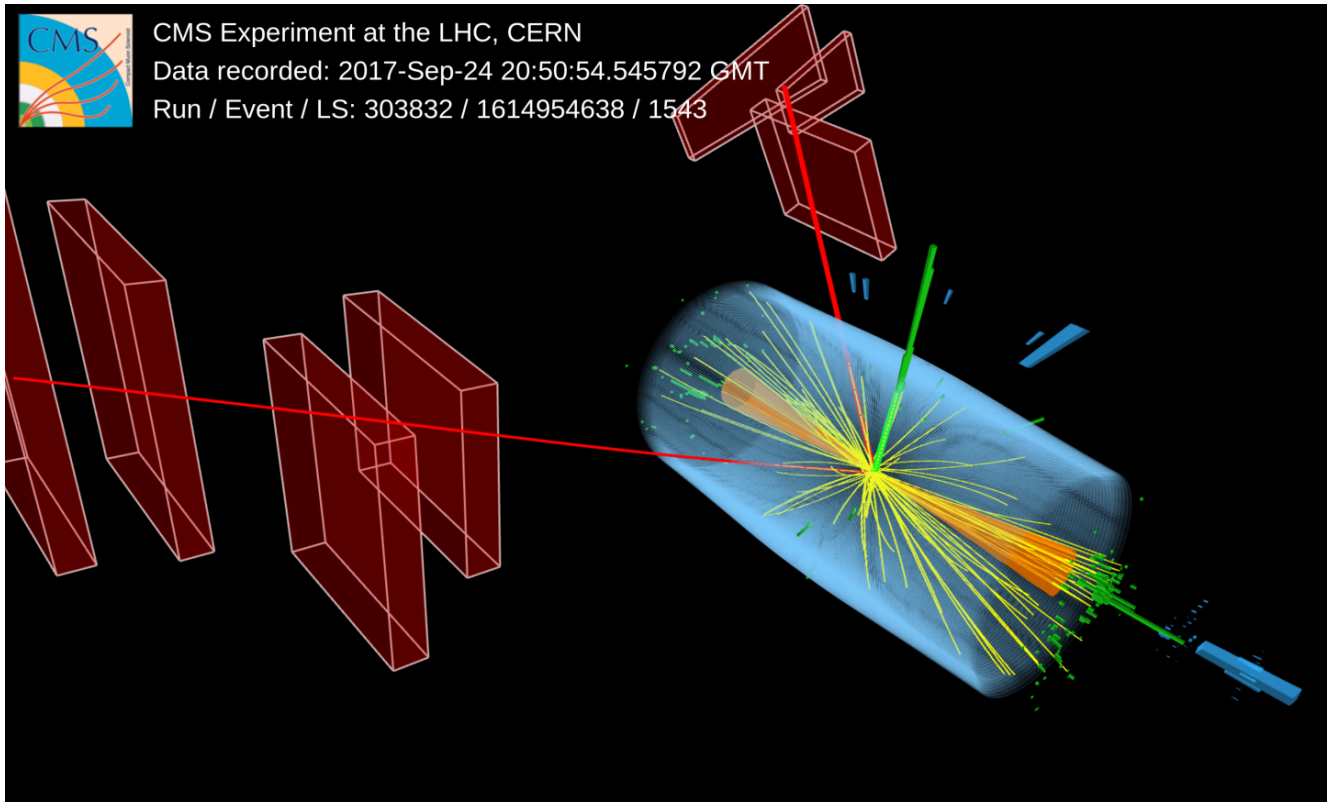
- Can we measure polarized VBS processes
  - Extremely challenging as the $W_L W_L \to W_L W_L$ is ~10% of the total WW scattering cross section



Vector boson scattering

- Vector boson scattering (VBS) at the LHC->colliding bosons
  - Extremely rare processes

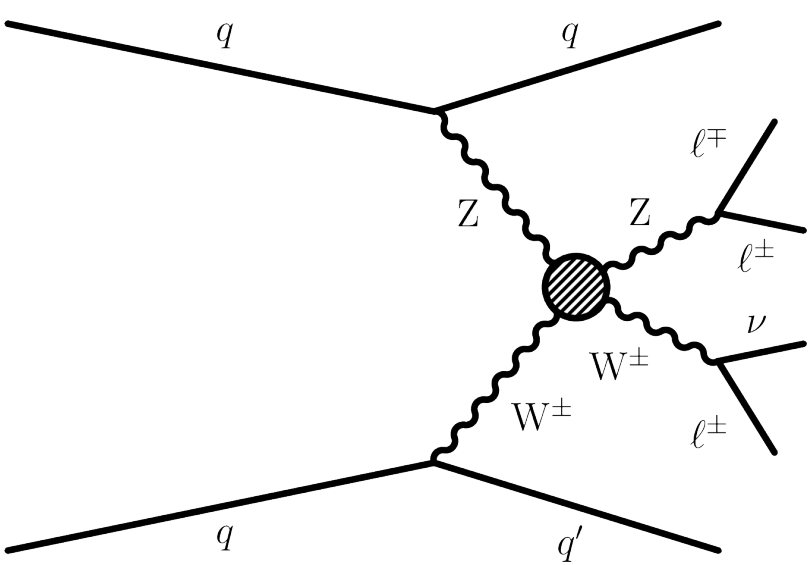




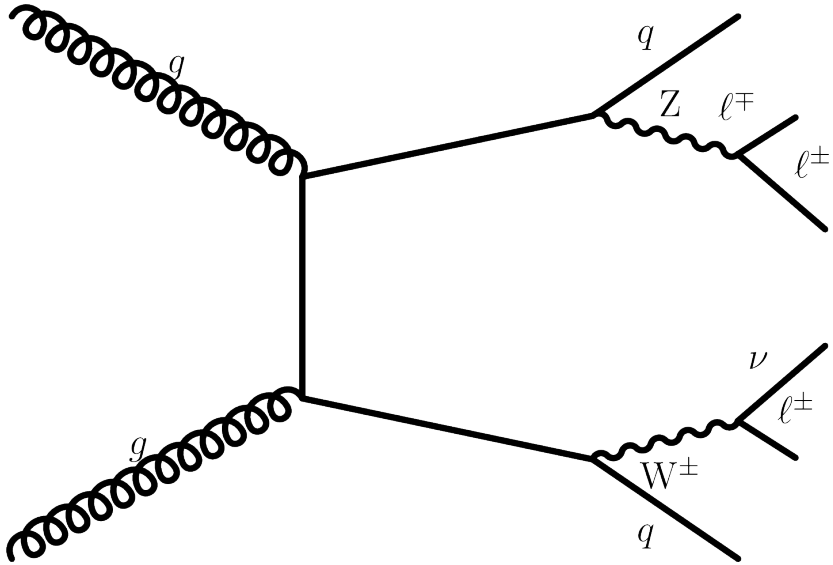
- Signature of VBS events: Forward jets in opposite hemispheres of the detector

Multiple ways to produce WZjj

EW WZ



QCD WZ



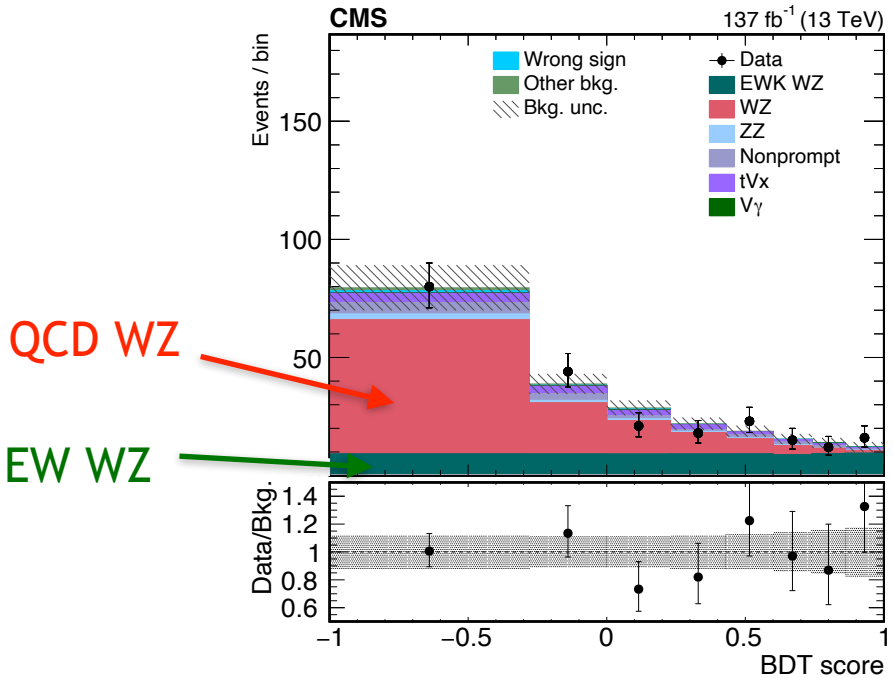
- Electroweak WZjj production
- Includes Vector boson self-coupling and Higgs contributions

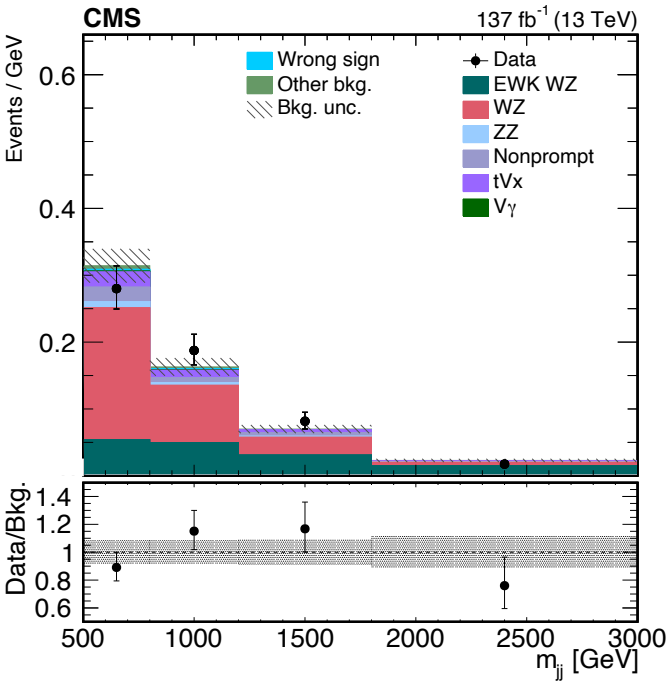
- Strong force induced WZjj (quantum chromodynamics)

Observation of EW WZ scattering!

ArXiv:2005.01171

- Measurement performed in three lepton final states
  - QCD WZ is also simultaneously measured
  - Use Machine Learning to separate the small EW WZ contribution
- Observation of the EW WZ in CMS with signal significance larger than 5 standard deviations

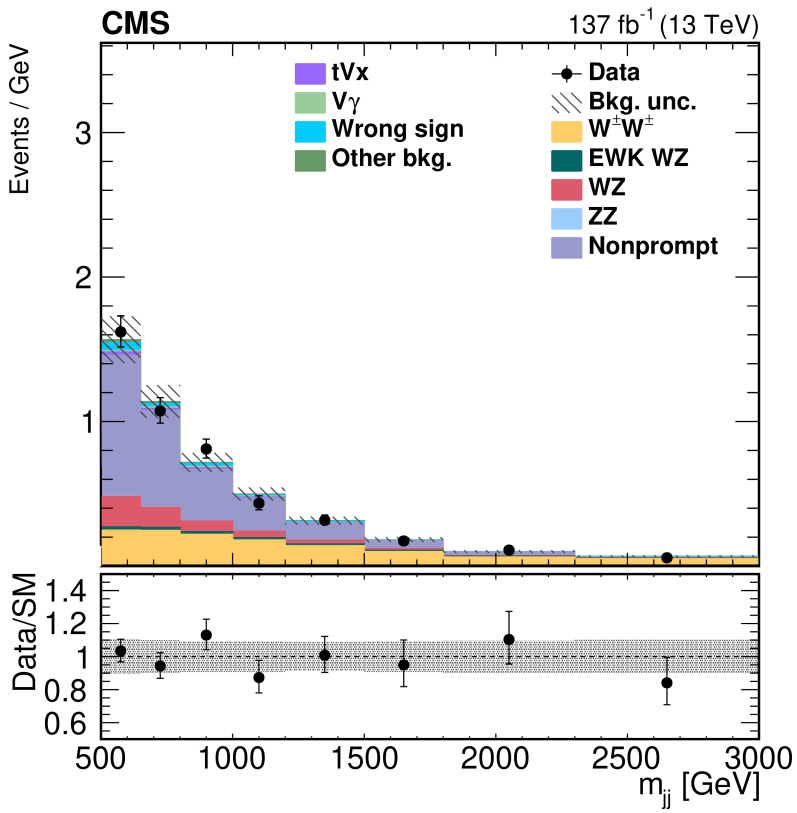


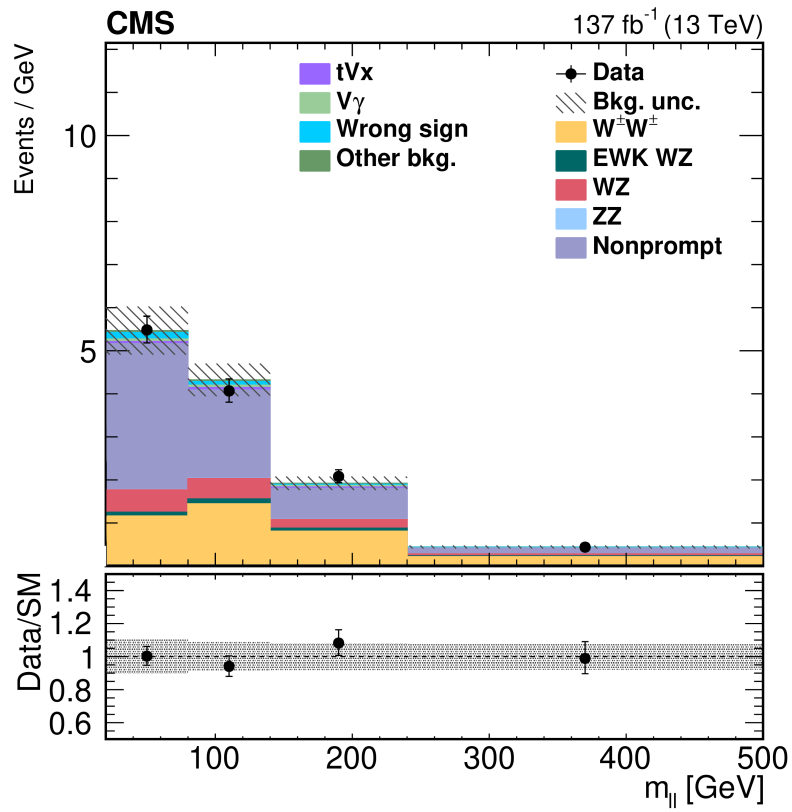


Same-sign WW

ArXiv:2005.01171

- Observed number of events consistent with SM predictions
  - Dijet mass (left) and dilepton mass (right) distributions used in the fit
  - Much lower QCD induced production due to same-sign structure





Inclusive fiducial cross sections

- First simultaneous W±W±jj and WZjj production cross section measurements
- Measurements compatible with predictions within uncertainties

$W^{\pm}W^{\pm}$ fiducial region:

- two same-sign leptons with $p_T > 20\text{GeV}$, $|\eta| < 2.5$, and $m_{\ell\ell} > 20\text{GeV}$
- two jets with $m_{jj} > 500\text{GeV}$ and $|\Delta\eta_{jj}| > 2.5$

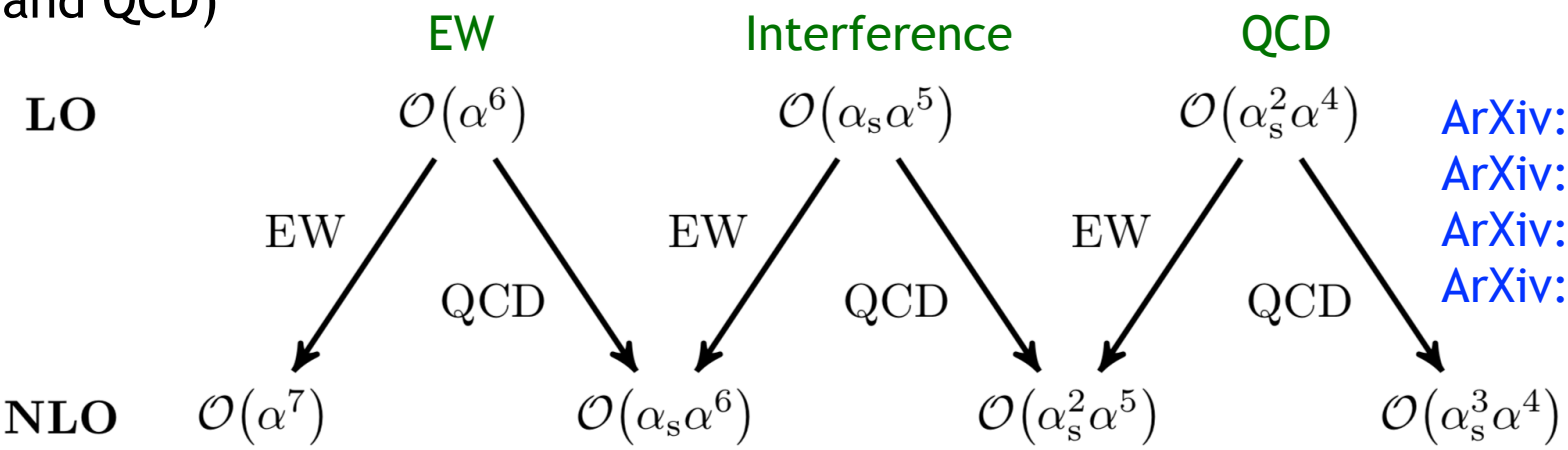
WZ fiducial region:

- three leptons with $p_T > 20\text{GeV}$, $|\eta| < 2.5$, and a pair of opposite charge same-flavor lepton pair $|m_{\ell\ell} - m_Z| < 15\text{GeV}$
- two jets with $m_{jj} > 500\text{GeV}$ and $|\Delta\eta_{jj}| > 2.5$

Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 $0.39\,(\text{stat}) \pm 0.14\,(\text{syst})$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 $0.40\,(\text{stat}) \pm 0.23\,(\text{syst})$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 $0.45\,(\text{stat}) \pm 0.18\,(\text{syst})$	3.12 ± 0.70	3.12 ± 0.70

Higher order corrections

- Same sign WW is the only diboson process with full NLO computation (EW and QCD)



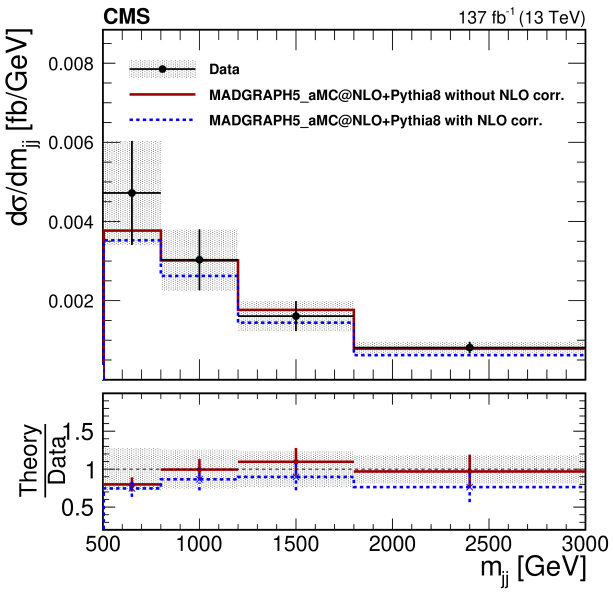
ArXiv:1611.02951
ArXiv:1708.00268
ArXiv:1904.00882
ArXiv:2009.00411

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\mathrm{NLO}}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

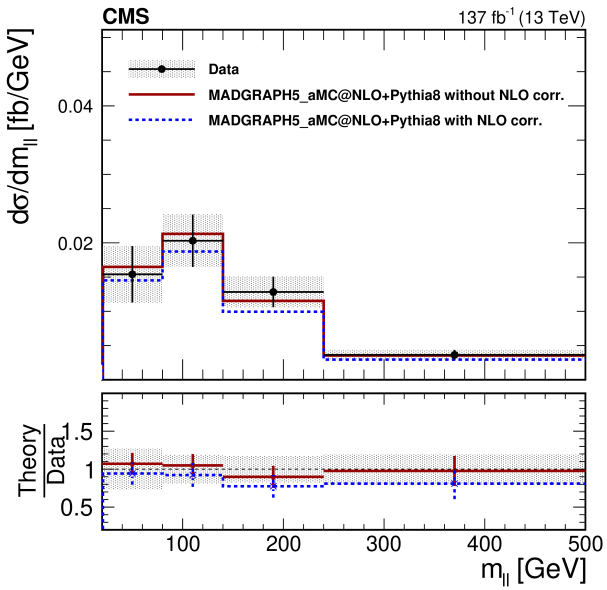
- EW corrections are large and negative (~-15%) in the fiducial region
  - Similar large EW corrections for the WZ and ZZ(new) processes
  - Corrections increase in magnitude with increasing dilepton/dijet masses
- Blurred distinction between EW signal and QCD background at NLO

Differential measurements

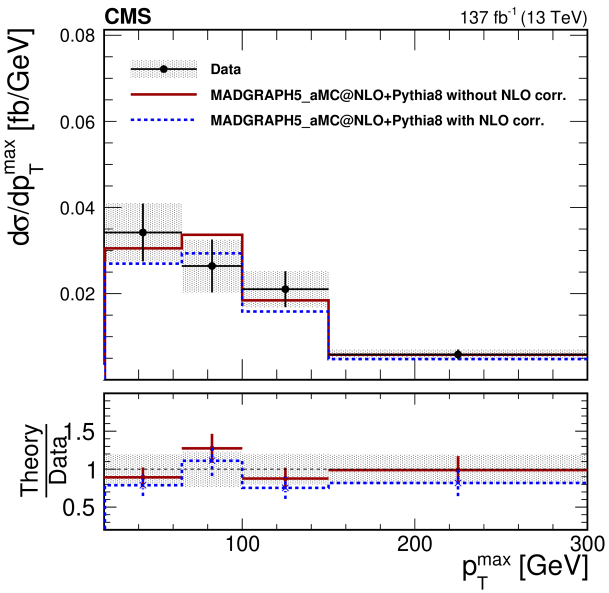
- Detailed characterization of the WW production
  - Consistent picture with the SM!
  - Absolute and normalized cross section measurements
  - Measurements compared to LO Madgraph predictions (blue) and predictions with NLO corrections (red)



Dijet mass



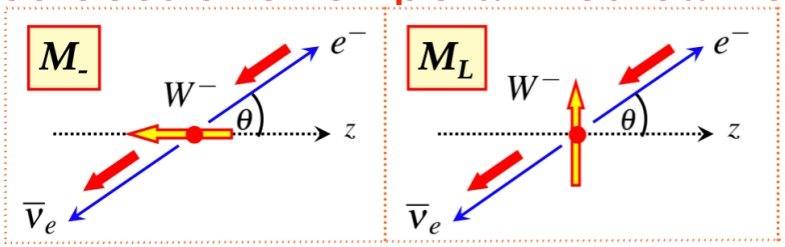
Dilepton mass

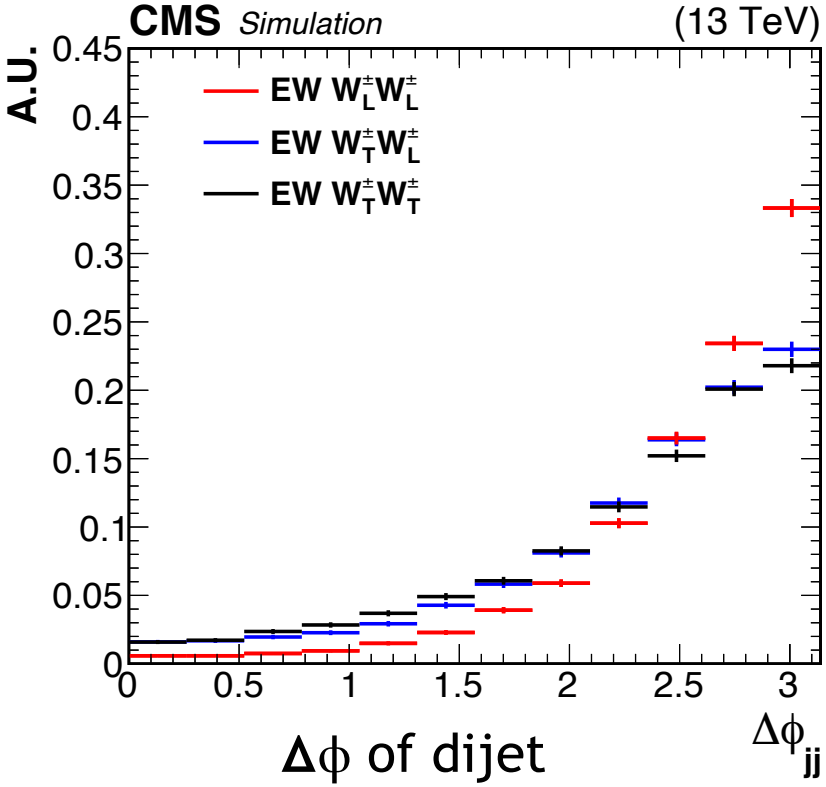


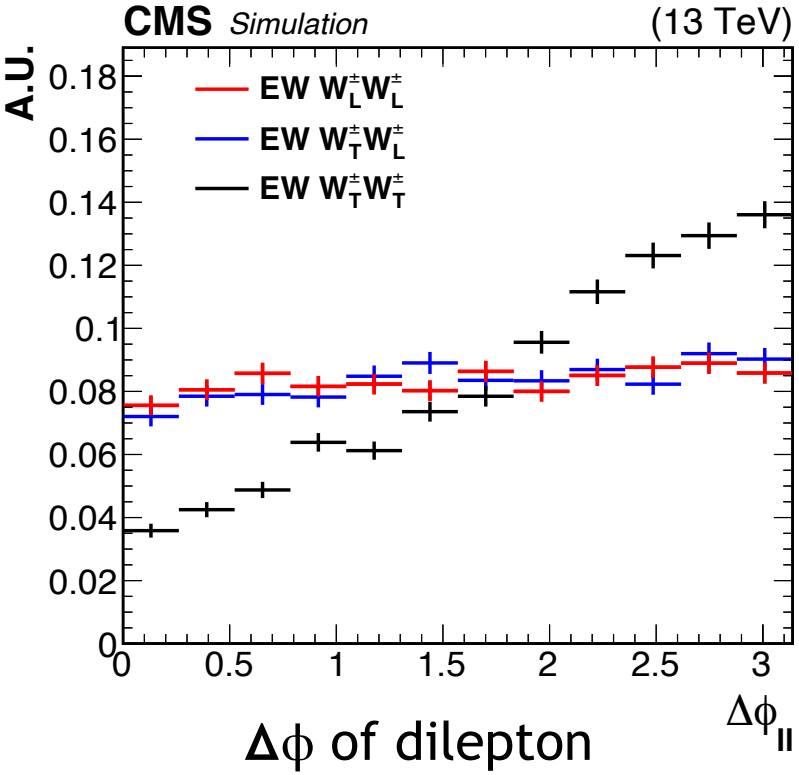
Leading lepton p_T

Polarized same-sign WW scattering

- First measurement of production cross sections for polarized same-sign WW scattering!
- Three distinct contributions:
  - $W_L W_L$, $W_L W_T$, $W_T W_T$



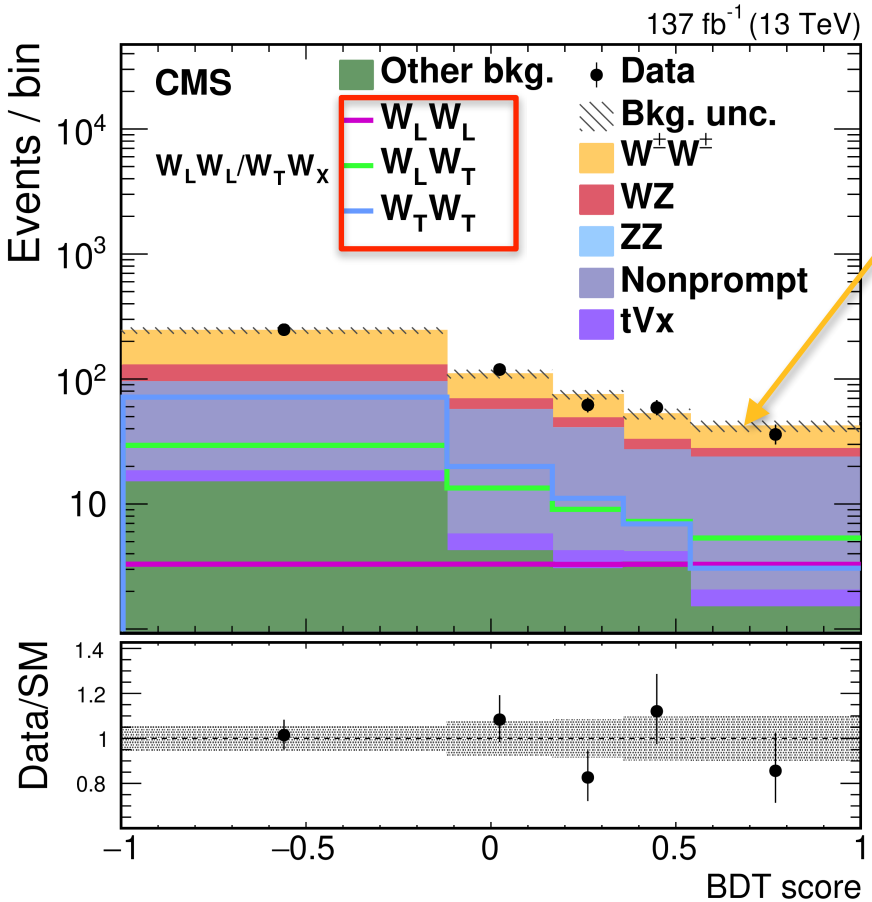




Polarized scattering

ArXiv:2009.09429

- Exploit kinematic differences with machine learning to separate the different polarized scattering processes

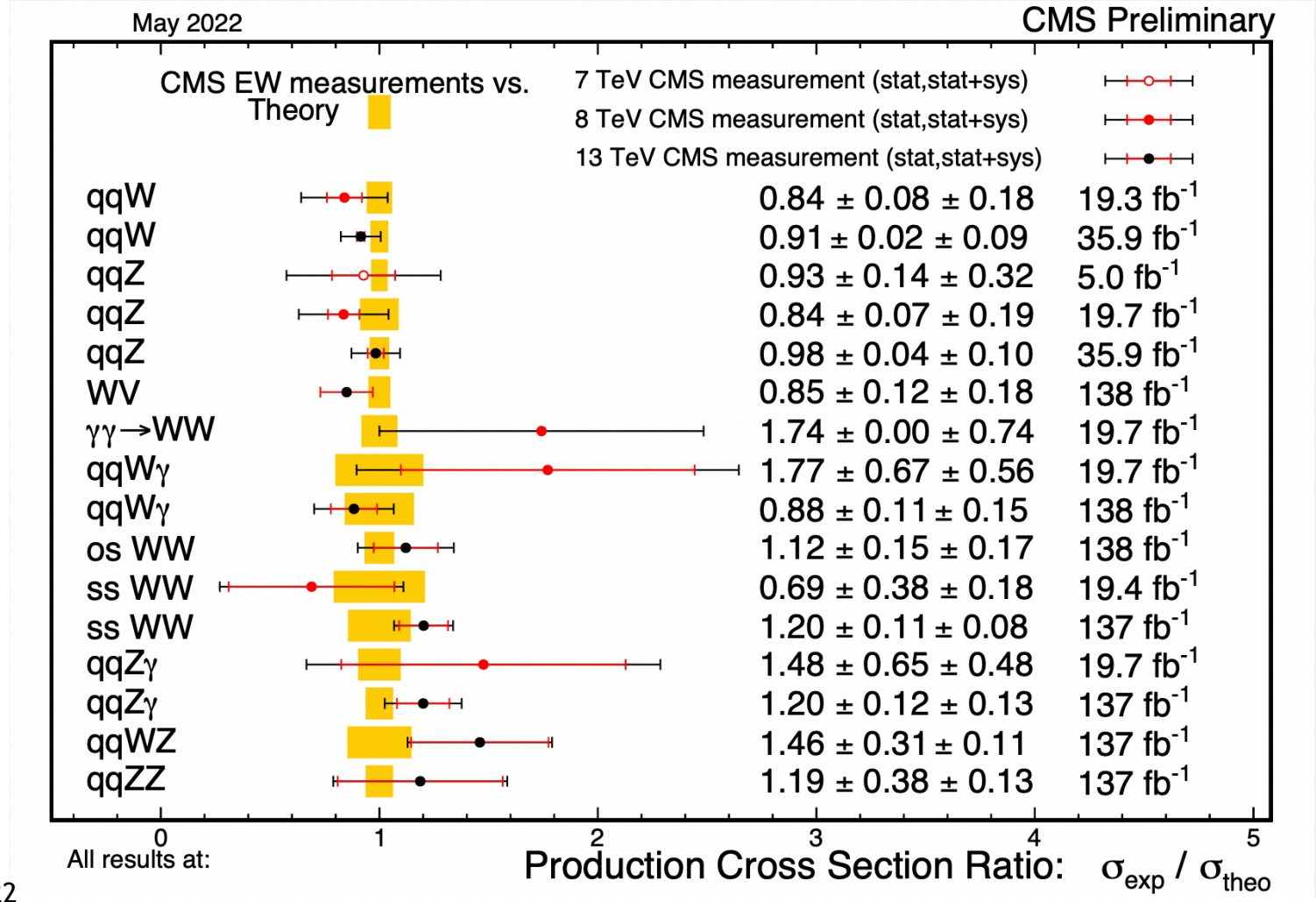


Same-sign WW

Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^\pm W_L^\pm$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^\pm W_T^\pm$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^\pm W_X^\pm$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^\pm W_T^\pm$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

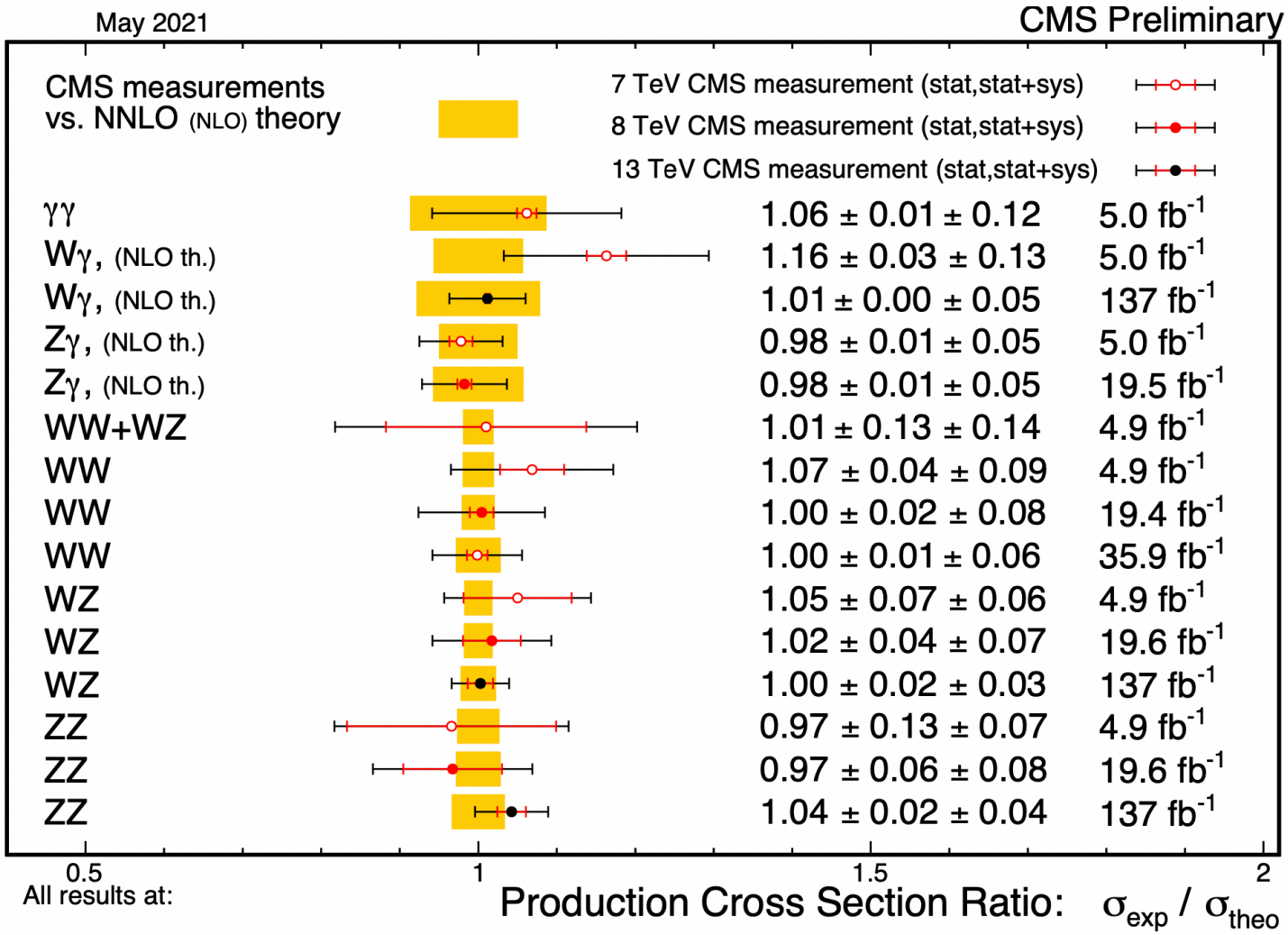
VBS measurements at LHC

- Broad and spectacular confirmation of the SM



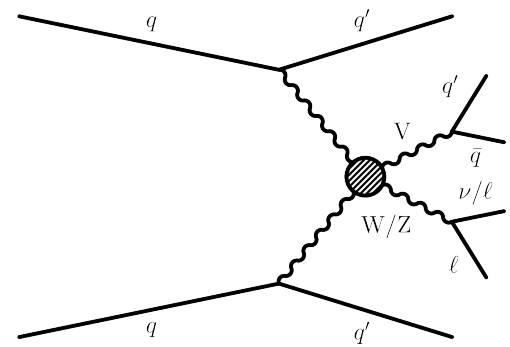
Multiboson measurements

- Broad and spectacular confirmation of the SM

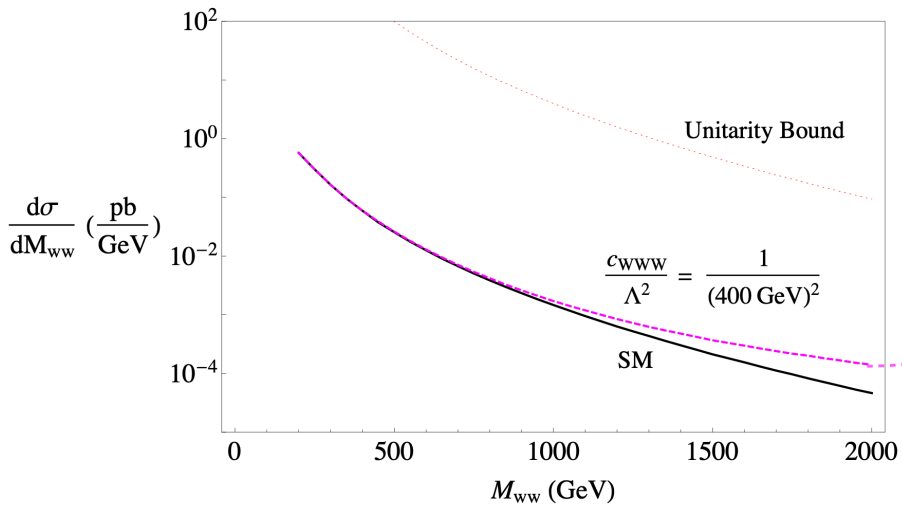


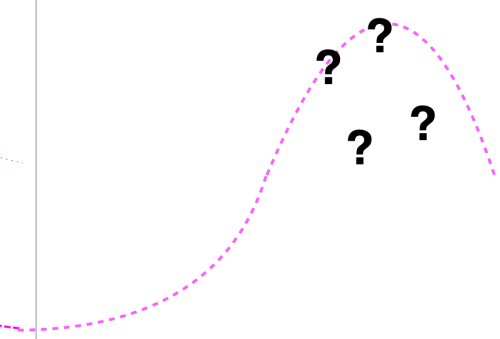
Going beyond SM

- Hints of new physics using effective field theory approach to probe for anomalous TGC and QGC



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}^i_{\rm dim-6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}^j_{\rm dim-8} + \dots$$

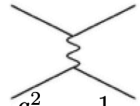




C. Degrande et al arxiv:1205.4231

Historic example: 4-fermion vertex (dim-6), Weak Interactions

$\Lambda = M_W$



$\propto \frac{g^2}{8}\frac{1}{q^2 - M_W^2}$

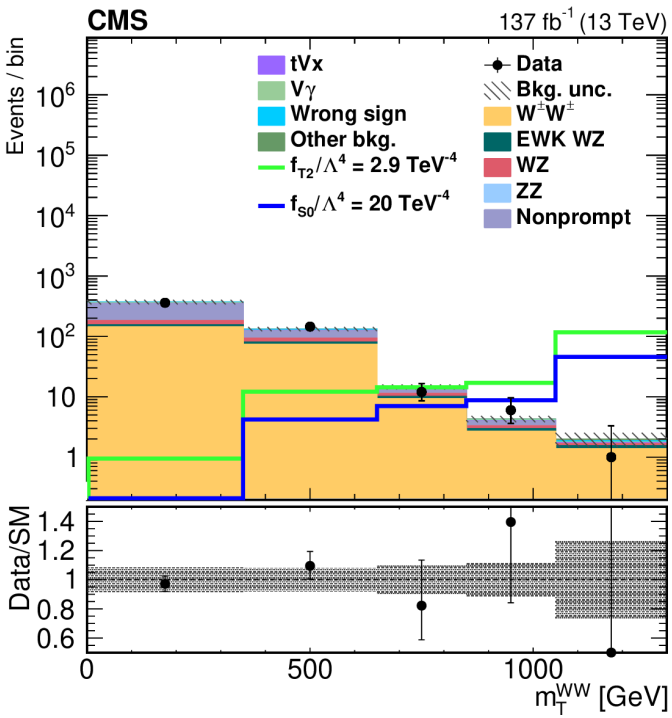
$\xrightarrow{q^2 << M_W^2}$

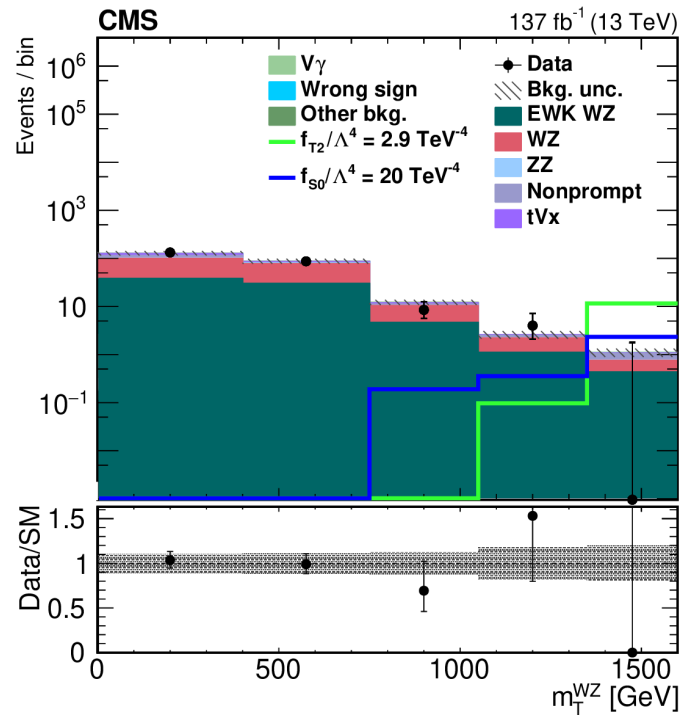
$\propto \frac{g^2}{8}\frac{1}{M_W^2} = \frac{G_F}{\sqrt{2}}$

Anomalous Gauge Couplings

- Use the tails of the distributions to set limits on EFT operators
  - Dim-6 and Dim-8 operators
  - EFT validity and unitarity issues should be
  - adressed

$$\mathcal{O}_{S_0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S_1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S_2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$





Electroweak precision observables

- Electroweak (EW) precision observables
  - $\alpha_{\mathrm{em}}, \mathrm{G_F}, m_{\mathrm{W}}, m_{\mathrm{Z}}, \sin^2\theta_{\mathrm{W}}, m_h$
- Constrained by three precisely measured parameters

α = 1 / 1370359999679...

G_μ = 1.16637 (1) $\times$ 10^{-5} GeV^{-2}

m_Z = 91.1876 (21) GeV

- Not independent but related through Standard Model (SM)

$$m_{\mathrm{W}}^2 \sin^2\theta_{\mathrm{W}} = \frac{\pi\alpha}{\sqrt{2}\mathrm{G_F}} \qquad \sin^2\theta_{\mathrm{W}} = 1 - \frac{m_{\mathrm{W}}^2}{m_{\mathrm{Z}}^2}$$

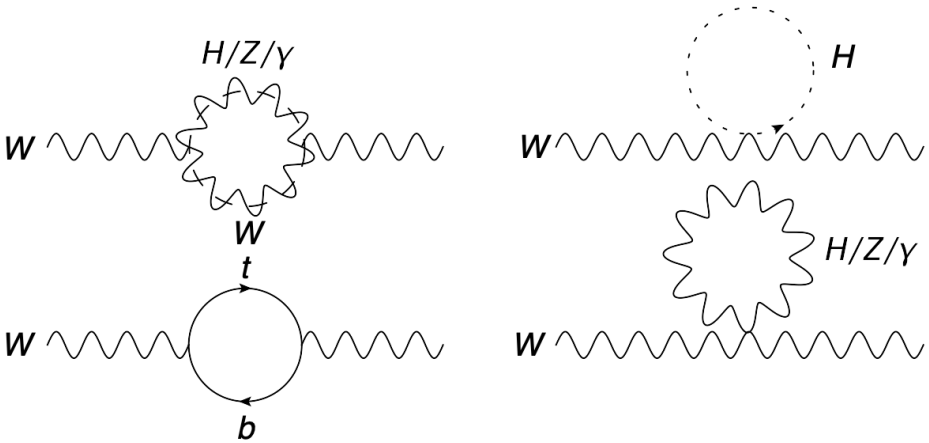
(Tree level)

- Precision EW measurements
  - Testing the consistency of the SM and looking for hints for new physics

Higher order corrections

- Higher order electroweak corrections are dominated by top quark and Higgs loops
  - Tree level couplings are replaced by effective couplings

$$
\begin{aligned}
M_W^2 &= \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right), \\
\sin^2\theta_{\rm eff}^f &= \kappa_Z^f \sin^2\theta_W \ , \\
g_V^f &= \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \sin^2\theta_{\rm eff}^f\right), \\
g_A^f &= \sqrt{\rho_Z^f} I_3^f \ ,
\end{aligned}
$$



Super precision front!

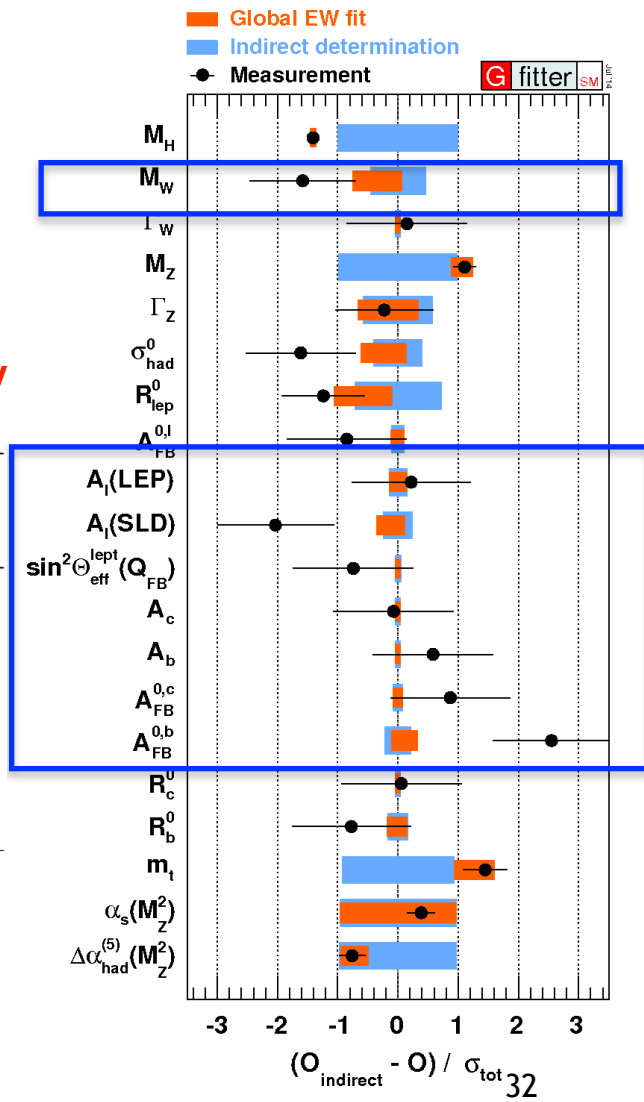
Global EW fits

- Relation between m_t, m_h, m_W provides stringent test of SM

- Indirect determination of m_W more precise than direct measurement after Higgs discovery

parameter	measurement	EWK fit excl. input in line	
		without m_H	with m_H
M_H [GeV]	125.09 ± 0.15	91 ± 19	91 ± 19
M_W [GeV]	80.380 ± 0.013	80.364 ± 0.017	80.356 ± 0.006
Γ_W [GeV]	2.085 ± 0.042	2.092 ± 0.001	2.091 ± 0.001
m_t [GeV]	172.9 ± 0.5	177.6 ± 8	176.5 ± 2.1
$\sin^2 \theta^l_{\text{eff}}$	0.2314 ± 0.00023	0.2314 ± 0.0001	0.23152 ± 0.00006

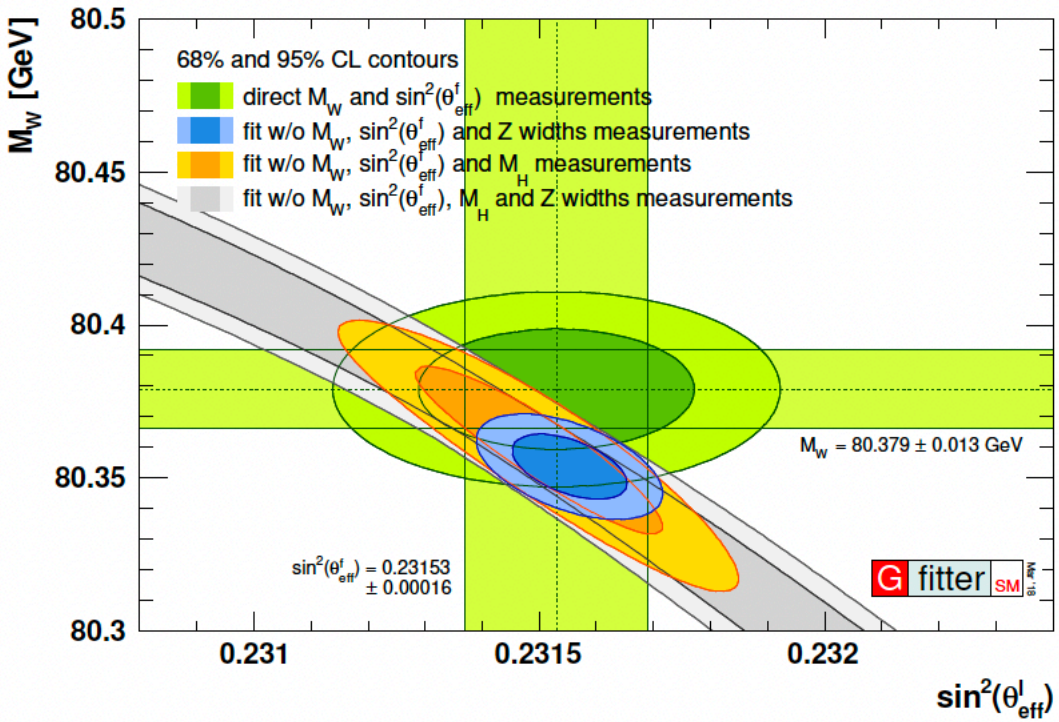
Arxiv:1902.05142



Eur. Phys. J. C 74, 3046 (2014)

Beyond SM physics

- Quantum fluctuations are sensitive to new physics
- Leading new operators for EW precision observables in effective field theory framework enter at dim-6
- New physics scale constrained to be larger than O(TeV) [PDG]

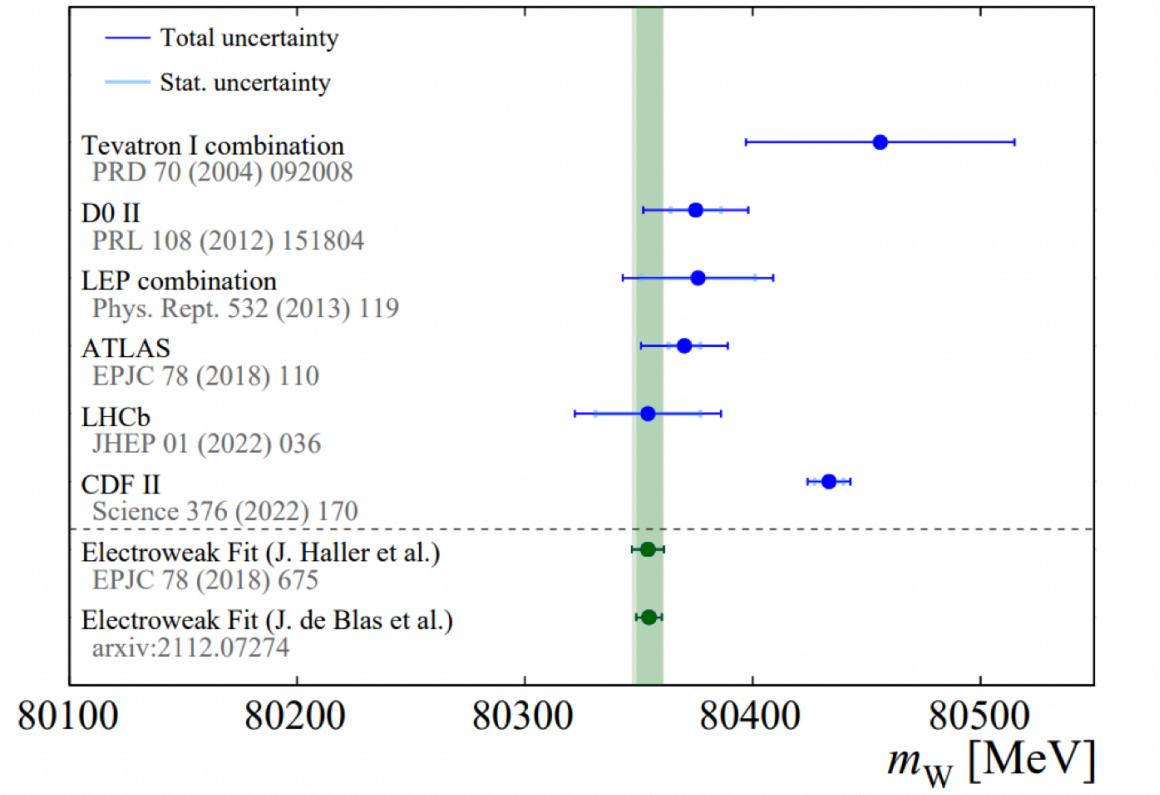


$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{d>4} \sum_i \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i \ ,$$

Precise consistency tests of the SM by measuring the W mass and $\sin^2\theta_W$

W mass excitement!

- Impressive precision achieved by CDF (Science 376 (2022) 170)
  - The result is in tension with the SM and other experiments

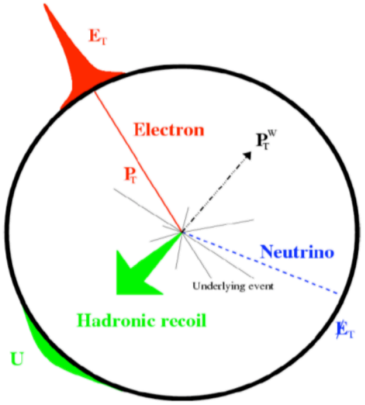


  - Complex measurements requiring O(5-10) years

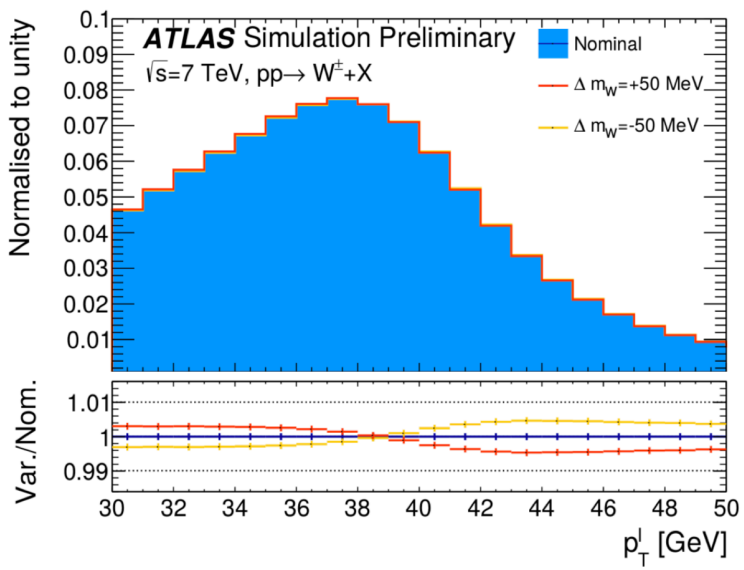
How do we measure W mass?

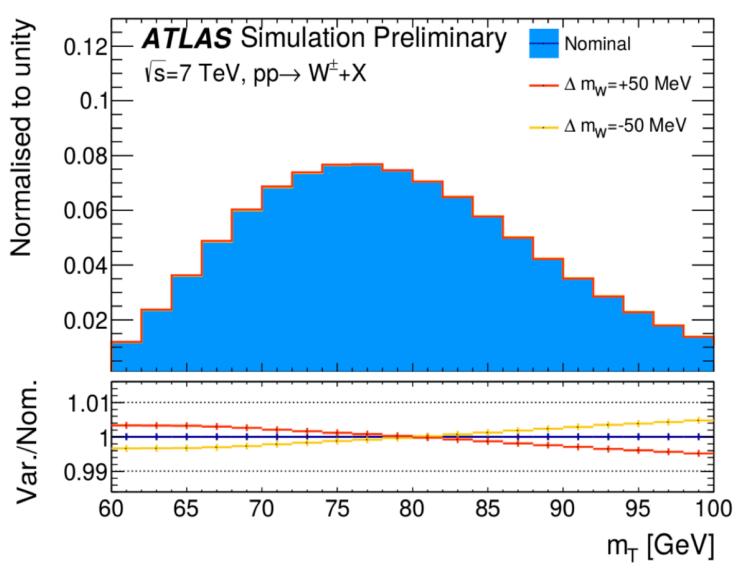
- Main signature is a final state lepton (electron or muon)
- Neutrino escapes detection-> missing energy

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right) \qquad m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$



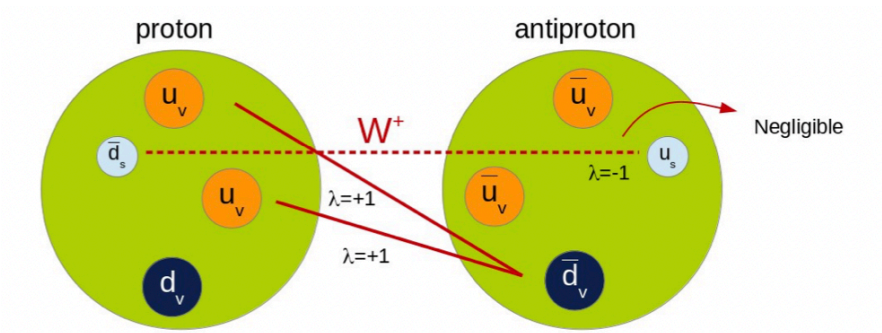
- Lepton p_T has a Jacobian edge at $m_W/2$
- m_T has a Jacobian edge at m_W
- Fit the distributions of p_T and m_T (also p_T^{miss}) to determine W mass

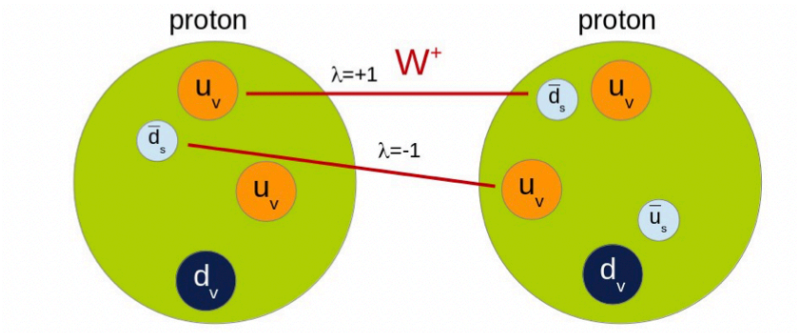




W mass at hadron colliders

- Extremely challenging environment and prone to biases due to QCD effects
  - Proton-proton collider is more challenging compared to proton-antiproton

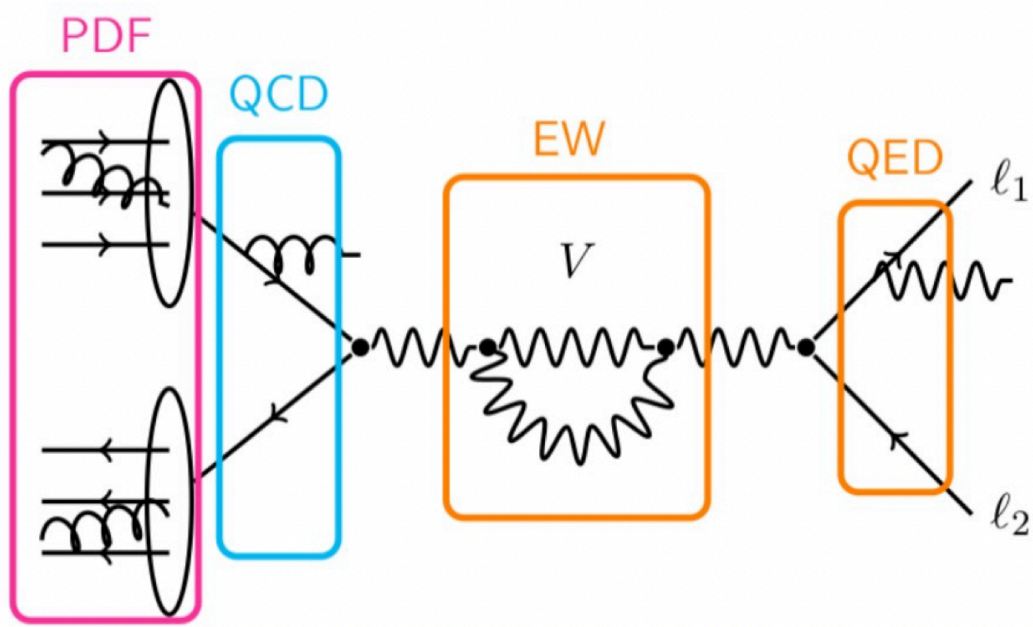




- QCD complications at LHC:
  - Larger role for heavy flavor induced processes
  - W polarization uncertainty affecting the lepton pT
  - Larger gluon induced W production,
  - W+,W-, and Z produced by different light flavor fractions,
  - …

W mass measurement ingredients

- Precise momentum calibrations
  - Requires huge amount of work
- Physics modeling (experimental and theoretical challenges)
  - Parton distribution functions (PDFs)
  - Measurements of pT W, pT W/Z
  - Electroweak corrections
  - Measurements and predictions of angular coefficients



Systematic uncertainties

- Focus on 3 recent measurements: CDF2, ATLAS, and LHCb

Source	Final CDF Run 2 (MeV)	ATLAS (MeV)
Lepton uncertainties	3.5	9.2
Recoil energy scale & resolution	2.2	2.9
Backgrounds	3.3	4.5
Model theorical uncertainties	3.5	9.9
PDFs	3.9	9.2
Statistical	6.4	6.8
Total	9.4	18.5

CDF:
Science 376 (2022) 170
$\sqrt{s}$=1.96 TeV, 8.8 fb^{-1}

ATLAS:
arXiv:1701.07240
$\sqrt{s}$=7 TeV, 4.6 fb^{-1}

Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

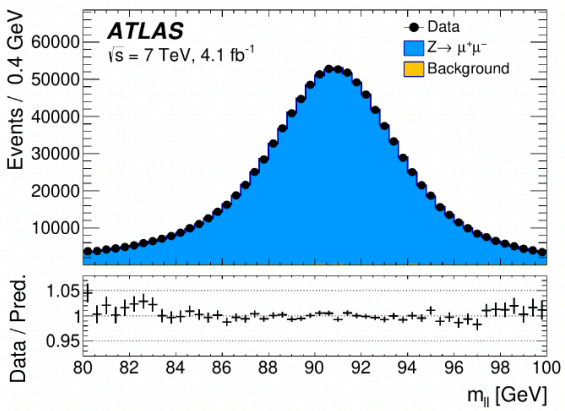
LHCb:
arXiv:2109.01113
$\sqrt{s}$=13 TeV, 1.7 fb^{-1}

- Similar statistical precision between ATLAS and CDF
- Larger theoretical uncertainties in ATLAS and LHCb results

- Larger datasets at the LHC yet to be explored
  - Larger Z samples for detector calibration
  - Possible in-situ theory constrains
  - Larger detector coverage

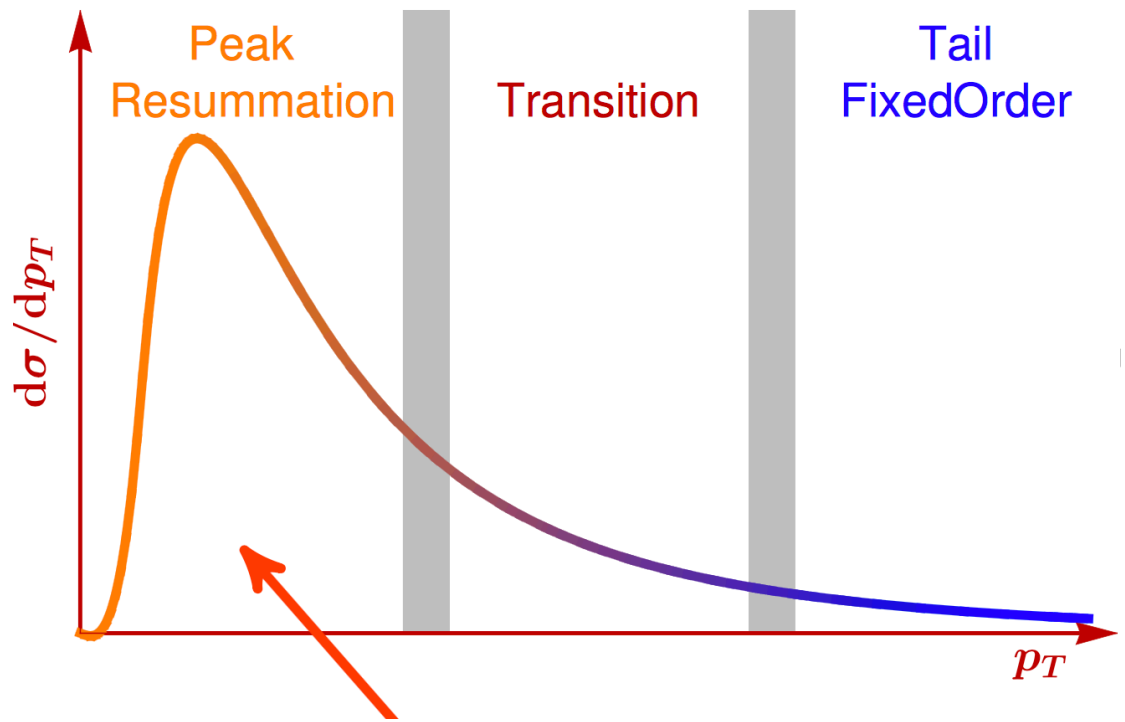
Muon momentum scale and resolution

- $Z \to \mu\mu$ can also be used as a standard candle for the muon momentum scale and resolution, since the mass (and width) are known very precisely from the LEP beam energy scan and calibration (mass is known to 2.3×10^{-5} relative precision)
- J/ψ and Υ can also be used (Υ mass is known to similar precision, and J/ψ mass to 2×10^{-6})
- **To first order calibration is trivial:** Match the Z peak (+ width) between data and MC (in bins of η for example)
- **More complicated:** Account for possible charge/p_T dependence of any momentum scale or resolution bias



State of the art W and Z pT predictions

- Fixed order perturbative calculation works for pT~m_V (NNLO $O(\alpha_s^3)$)
- Large logarithmic terms appear and needs to be resummed to all orders for pT<<m_V (resummation of soft gluon radiation)



$$L = Q^2/q_T^2$$

$$\frac{d\hat{\sigma}}{dq_T} = \frac{d\hat{\sigma}^{(\mathrm{res})}}{dq_T} + \frac{d\hat{\sigma}^{(\mathrm{fin})}}{dq_T}$$

Very difficult observable to predict!

W mass and W pT

- W pT distribution must be known to very good precision for the W mass measurement, especially when fitting the lepton pT distribution
  - Roughly: O(%) uncertainty in W pT translates to O(10) MeV uncertainty
- Approach is based on very precise measurement of Z pT and accurate predictions of W/Z pT ratio

$$\frac{\mathrm{d}\sigma(W)}{\mathrm{d}p_T} = \left[\frac{\mathrm{d}\sigma(W)/\mathrm{d}p_T}{\mathrm{d}\sigma(Z)/\mathrm{d}p_T}\right]_{\mathrm{theory}} \times \left[\frac{\mathrm{d}\sigma(Z)}{\mathrm{d}p_T}\right]_{\mathrm{measured}}$$

- Require great understanding of:
  - Non-perturbative QCD effects
  - qT Resummation
  - Heavy flavor initiated production

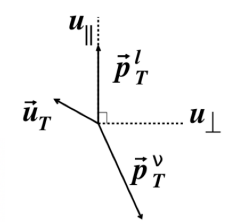
- Different approaches for the measurements:
  - ATLAS uses Pythia8 predictions tuned on Z pT
  - LHCb uses Powheg+Pythia8 predictions tuned on Z pT
  - CDF uses Resbos (NNLL + NLO)

CDF W pT

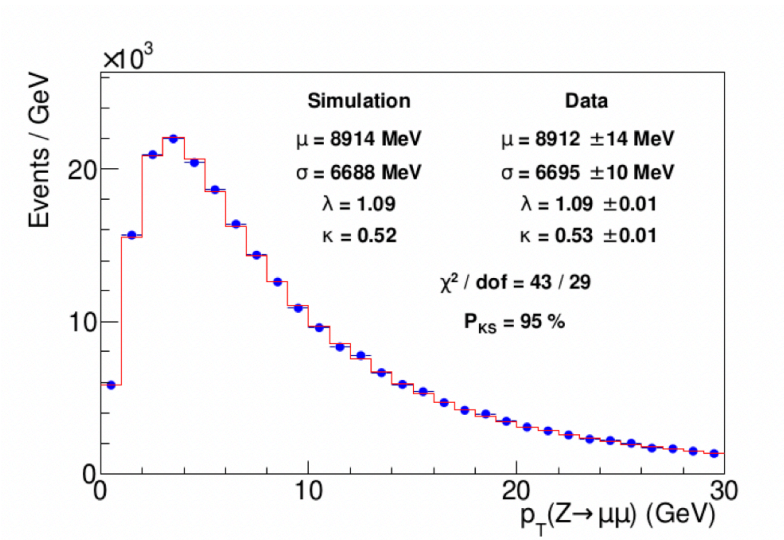
- Fitting the non-perturbative g_2 parameter in Resbos using the dilepton pT
- α_s is also tuned using dilepton pT
  - 1.8 MeV uncertainty from pT Z

$$S = \left[g_1 - g_2 \log \left(\frac{\sqrt{\hat{s}}}{2Q_0} \right) - g_1 g_3 \log \left(\frac{100\hat{s}}{s} \right) \right] b^2,$$

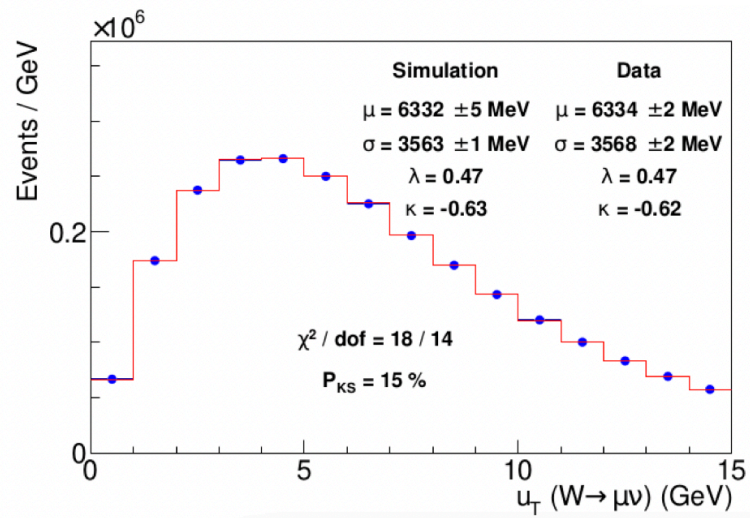
- New feature in the analysis: Use the recoil pT distribution to constrain the scale uncertainties in the pTW/pTZ ratio (evaluated with DYQT)
  - Impressive recoil resolution (low √s) and agreement with data
  - 1.3 MeV uncertainty from pTW/pTZ



$$|\vec{u}| = |\sum_i E_i sin\theta_i|$$



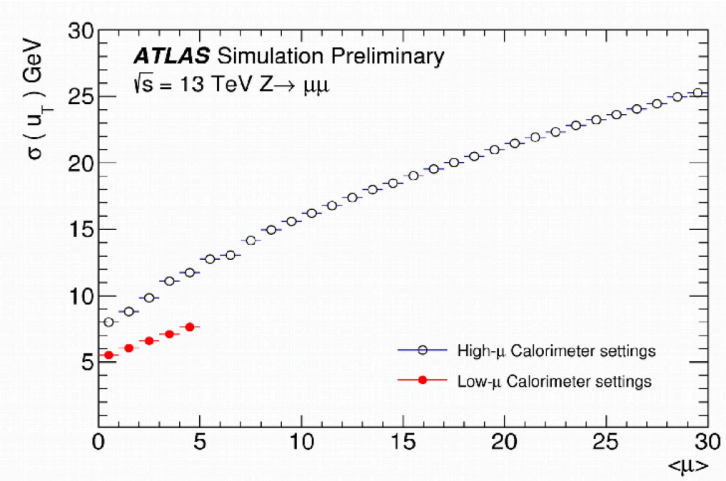
Z pT

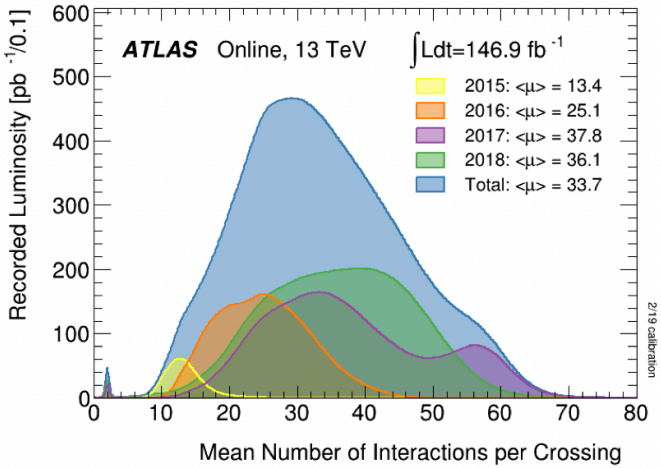


Recoil u_T

LHC W mass measurements

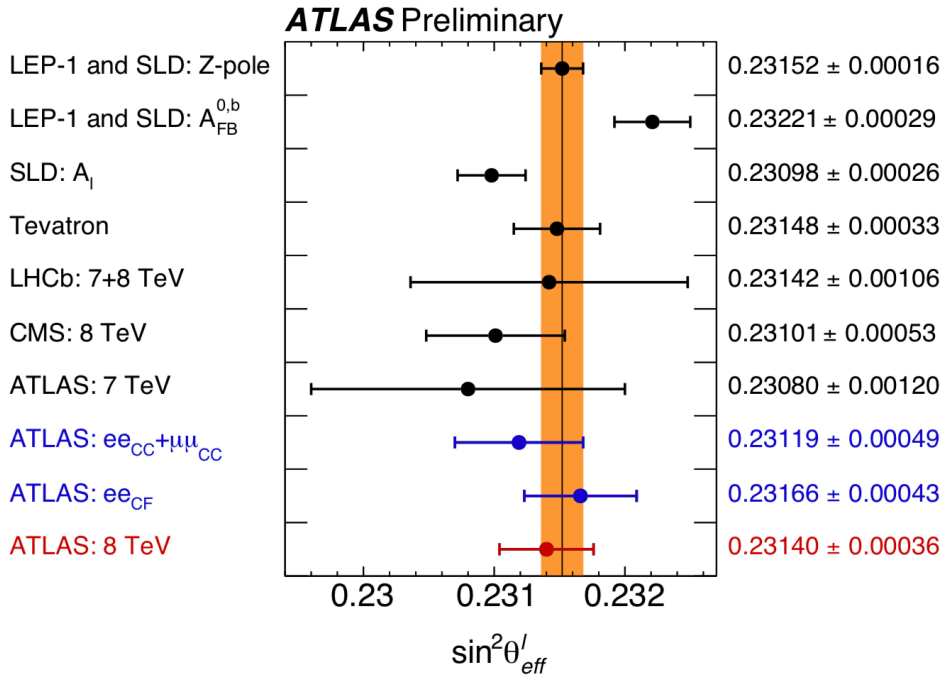
- Much harder data taking conditions at LHC due to ~10 times more pileup events
  - Degradation of the recoil resolution with pileup (lepton pT becomes dominant compared to mT)
- For the same integrated luminosity the number of W bosons events at the LHC is about 10 times larger than Tevatron
  - Factor of ~5 larger cross section,Factor of ~2 larger detector coverage
- Dedicated low pileup runs at the LHC are important for mT based W mass measurements as well as for W pT measurements to constrain theory modeling and uncertainties for lepton pT based W mass measurements
  - Orthogonal approaches with high and low pileup measurements





Weak mixing angle measurements

- Recent LHC measurements of $\sin^2\theta^{\ell}_{\rm eff}$
  - Comparable to precision at the Tevatron!
  - Uncertainties in knowledge of the PDFs dominate
  - Statistical uncertainties are large



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

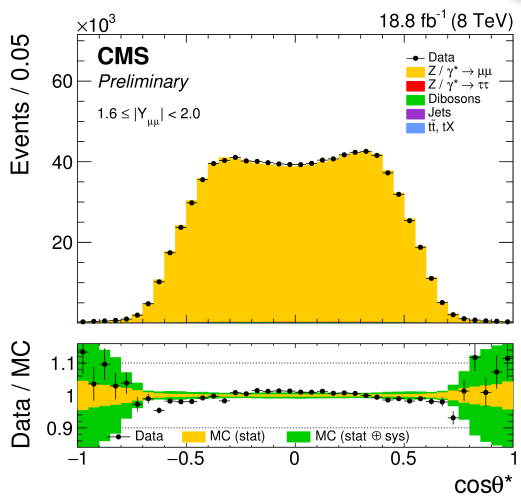
Dilepton production at the LHC

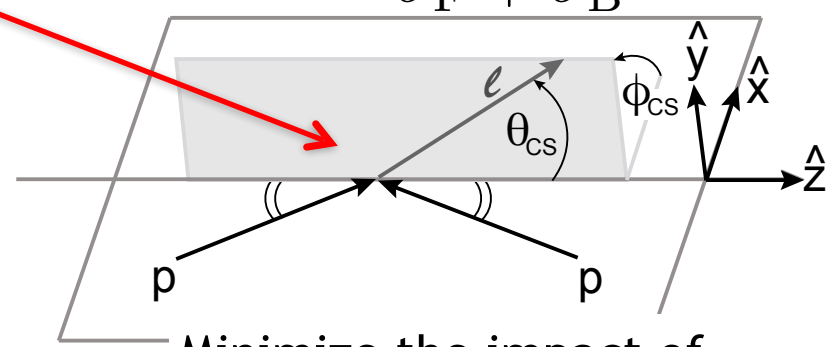
- Measure weak mixing angle using $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$
- Z boson couplings are different for left and right-handed fermions
- Forward-backward asymmetry (A_{FB}) in the polar angle distribution of negatively charged lepton in the rest frame of di-lepton system
  - Defined with respect to the incoming quark

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta} = \frac{3}{8}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}\left\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + \boxed{A_4\cos\theta}\right\}$$

- A_{FB} defined in Collin-Soper (CS) frame $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$

F: cosθ>0
B: cosθ<0

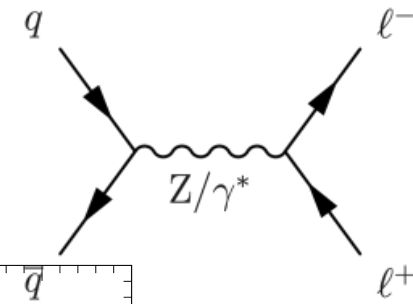


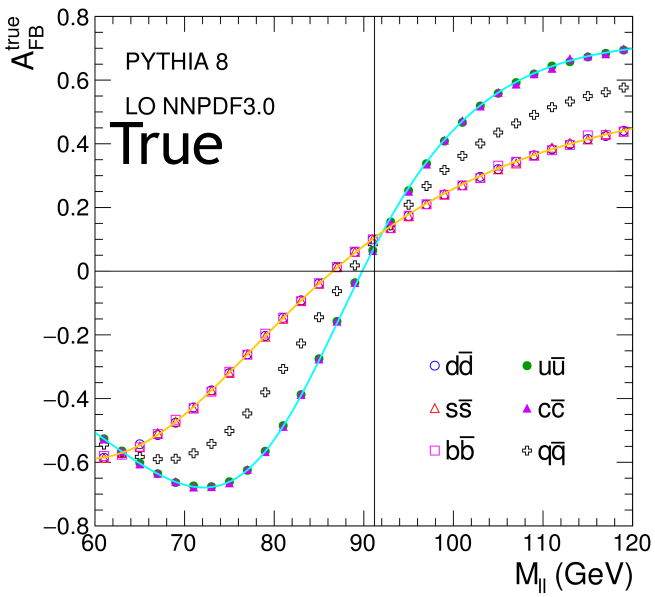


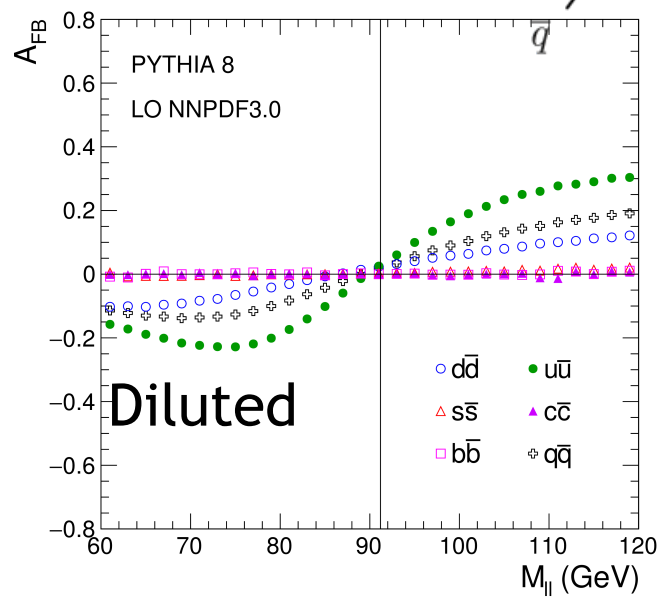
Minimize the impact of incoming quark transverse momentum

Forward-backward Asymmetry

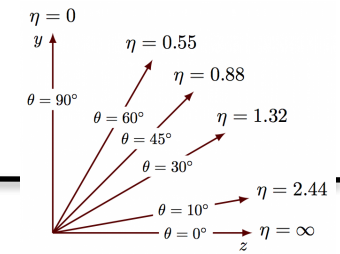
- But what is the quark direction?
  - Direction of longitudinal boost?
- A_{FB} measured as function of di-lepton mass in muon and electron final states (mass dependence from the Z/gamma* interference)
  - Quark direction is not always along the positive axis
    - Dependence on PDF from large-x antiquarks



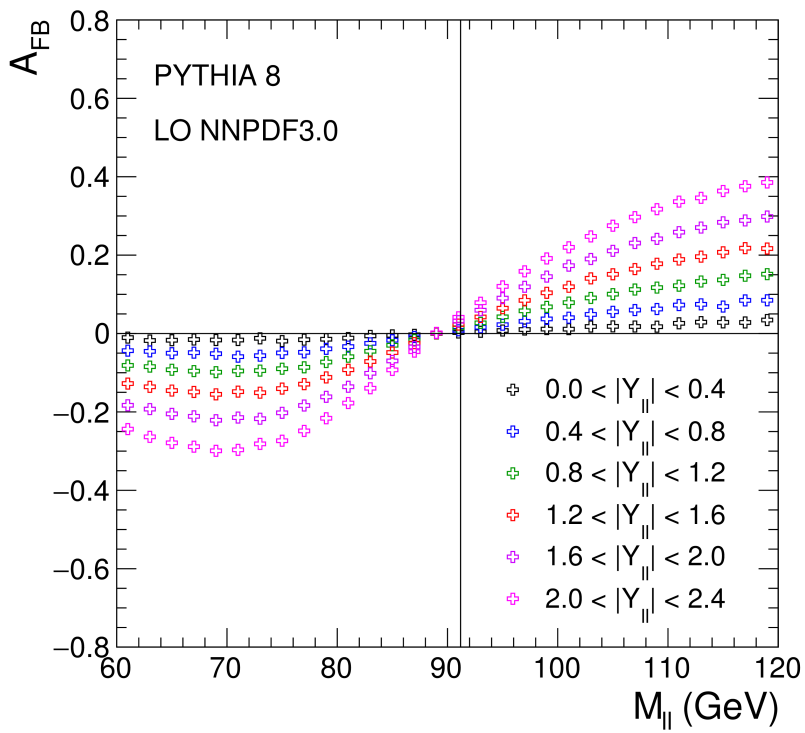


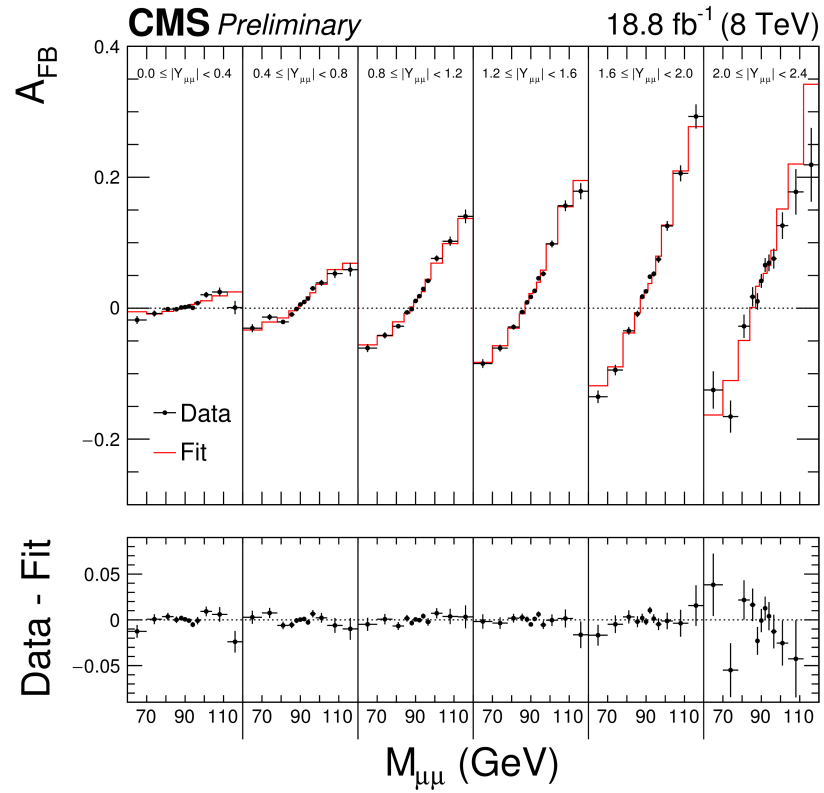


A_{FB} and $\sin^2\theta^{\ell}_{\mathrm{eff}}$



- Dilution strongly depends on rapidity->maximal at Y=0->A_{FB}=0
- ATLAS significantly improves sensitivity by including forward electrons
  - Beyond tracking acceptance
- Extract $\sin^2\theta^{\ell}_{\mathrm{eff}}$ by fitting the measured A_{FB} with different templates

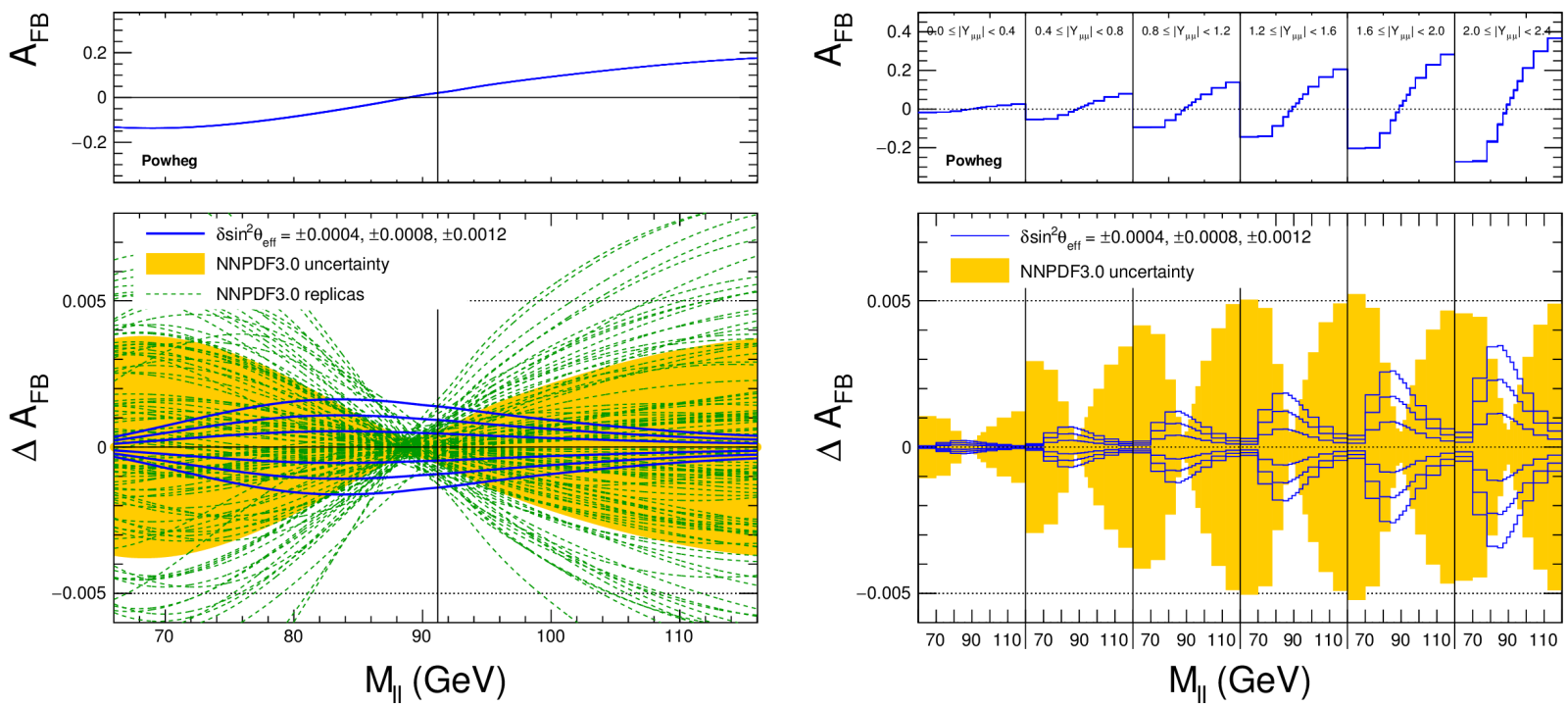




Measurement details

Eur. Phys. J. C78, 9 (2018)

- Measured A_{FB} is sensitive to the PDFs
  - Different couplings of u and d-type quarks to Z boson
  - Size of the dilution effect (large-x antiquarks)
- PDF dependence is large at small and large masses, small near the peak



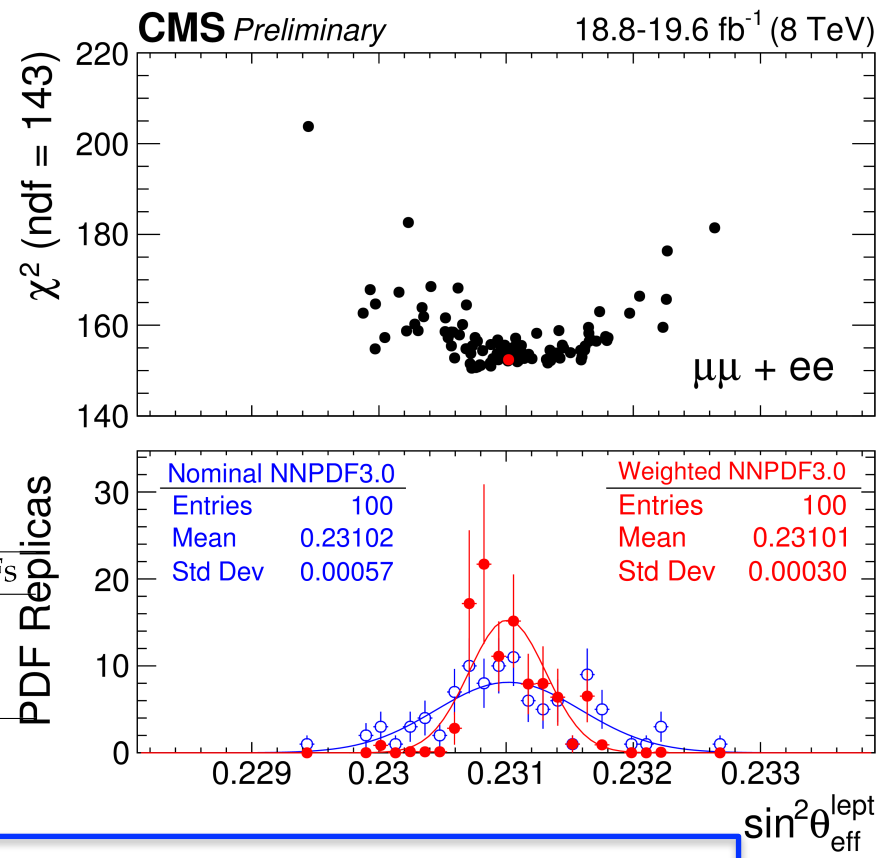
PDF uncertainties

- Bayesian χ^2 reweighing method used to constrain the PDFs in-sity
- Perform the $\sin^2\theta^{\ell}_{\text{eff}}$ fit for each NNPDF3.0 replica
- Weight each replica by:

$$w_i = \frac{e^{-\frac{\chi^2_{\text{min}}}{2}}}{\frac{1}{N}\sum_{i=1}^{N} e^{-\frac{\chi^2_{\text{min}}}{2}}},$$

- Consistent between electron/muon
- PDF uncertainties reduced by x2

Channel	without constraining PDFs	with constraining PDFs
Muon	0.23125 ± 0.00054	0.23125 ± 0.00032
Electron	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030



- Similar picture with Hessian PDF sets

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

Conclusions (Day 2)

- Exciting developments with impressive precision by CDF on W boson mass
  - Sizable tension with the SM EW fit predictions and other experiments
- Could LHC W mass measurements reach 10 MeV precision?
  - Perhaps but it will require patience
  - Future measurements will likely follow two orthogonal paths:
    - Low pileup measurements dominated by mT
    - High pileup measurements dominated by lepton pT
- Weak mixing angle measurement prospects at the LHC
  - Existing measurements already reduce PDF uncertainties with in-situ constraints
  - LHC measurements already comparable to precision at the Tevatron!
  - Measurements with full HL-LHC data can reach and perhaps surpass LEP+SLD precision!

Conclusions (Day 2)

- Multiboson measurements probe the structure of the SM
  - Key measurements to fully explore EW symmetry breaking
  - Run 2 established the production of rare EW processes and strong constraints on New Physics
- (HL-) LHC datasets are growing
  - ~1% analyzed so far
  - ~4% recorded and partly analyzed

4 LHC Pause

- Extensive work, challenges and opportunities ahead to collect quality data and produce quality physics