

Experimental measurements of Standard Model Properties

HCP Summer School 2024

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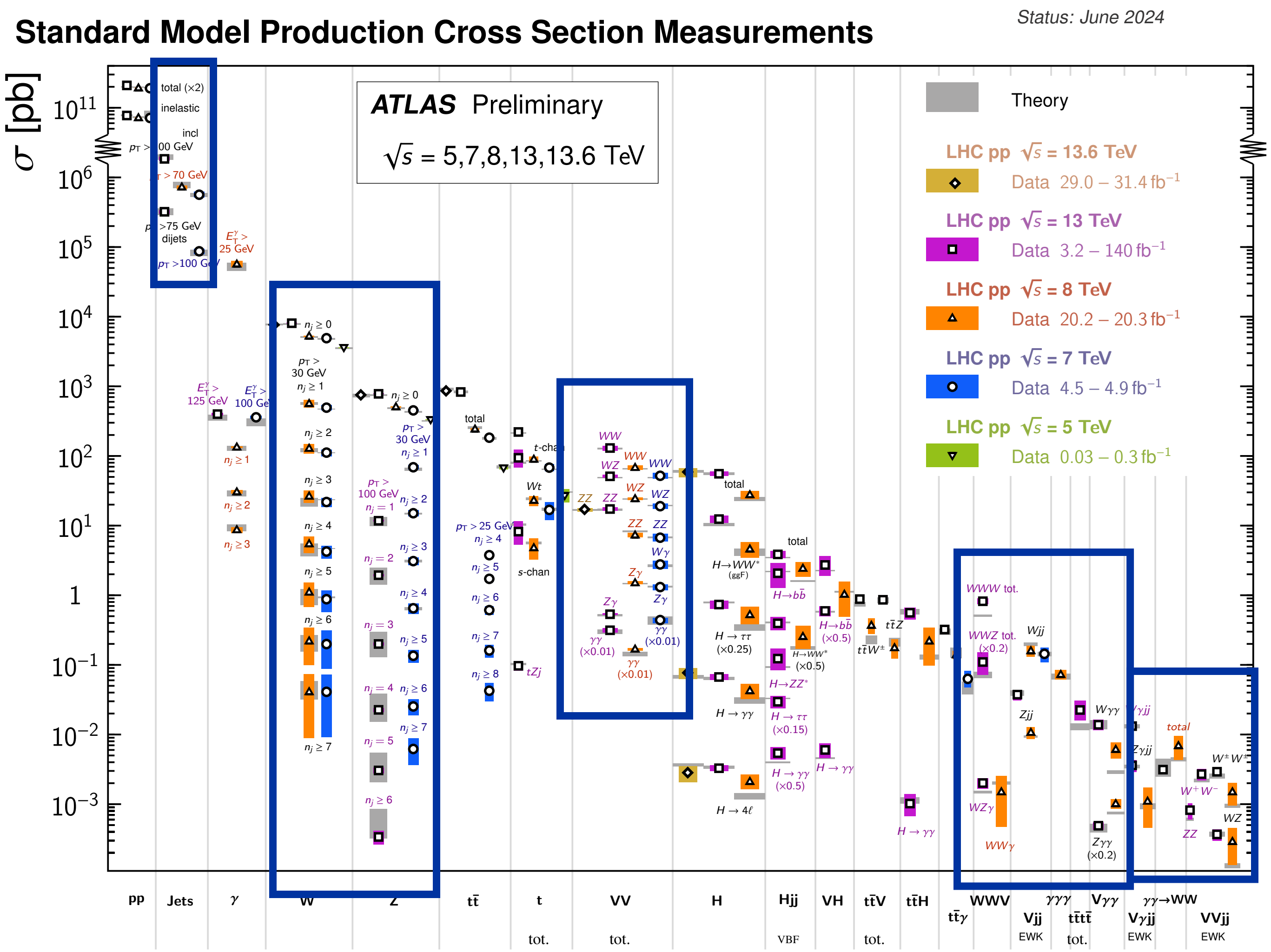
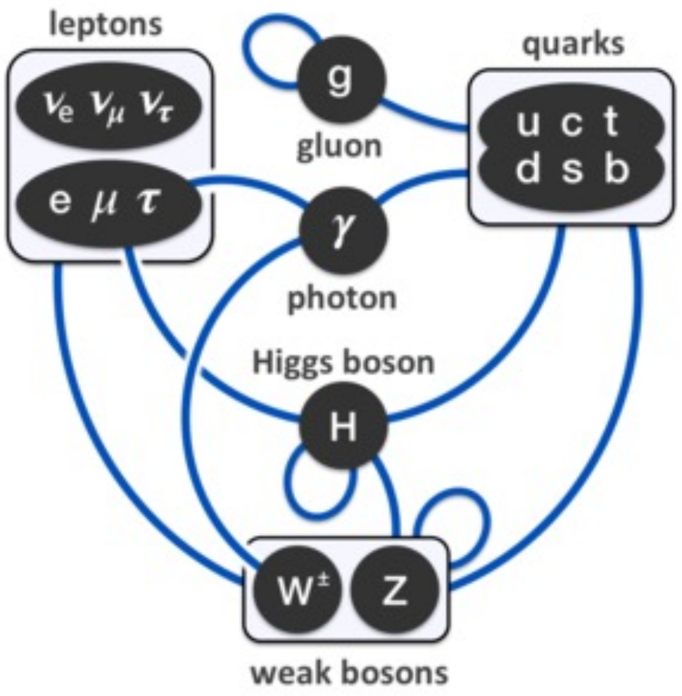
2024-07-29,30

In this talk, QCD+EW

- **Measurement of SM Properties**
  - Introduction to the SM
  - Predictions using the SM
  - Experimental measurements
- **QCD measurements**
  - Jets, PDFs, α_s
- **more QCD**
  - W and Z + jets
- **High Precision EW measurement**
  - W and Z cross sections
  - Parameters: $\sin^2\theta^l_{eff}$, m_W
- **Multiboson physics**
  - di-boson, tri-boson, VBS, polarization, TGC, QGC
- **Summary**





Nearly every diagram you find like this is wrong!

In this case the ZγWW vertex not represented

Measurement of SM Properties

and other introductory material

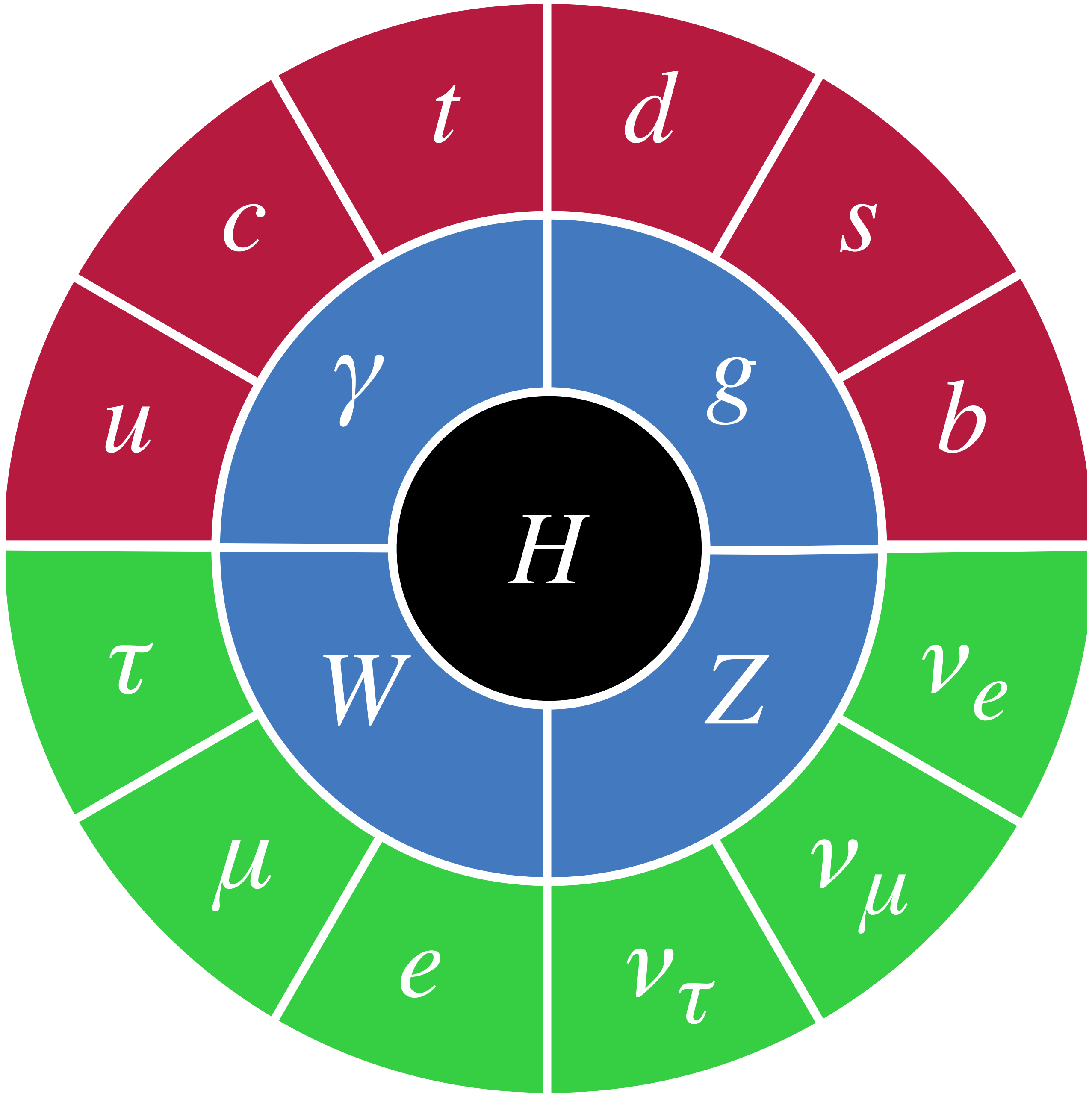
The Standard Model of Particle Physics

Exploring the fundamental theory that explains 3 (of 4) of the forces of nature.

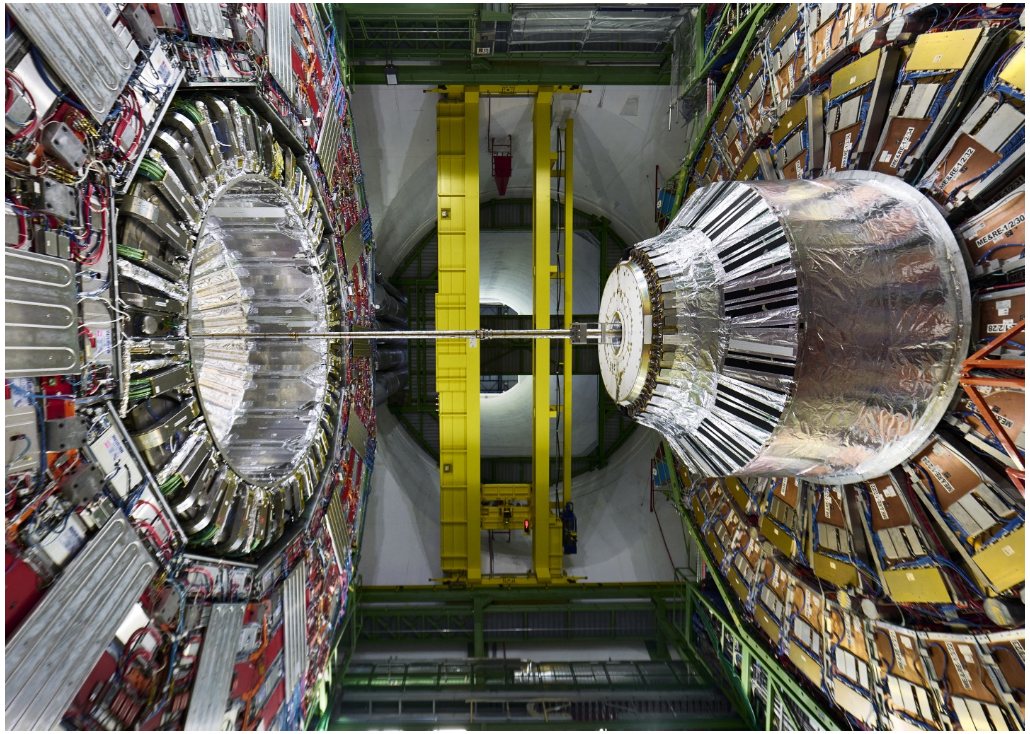
This talk will focus on selected measurements QCD and EW physics performed using high transverse momentum (p_T) and/or massive SM particles.

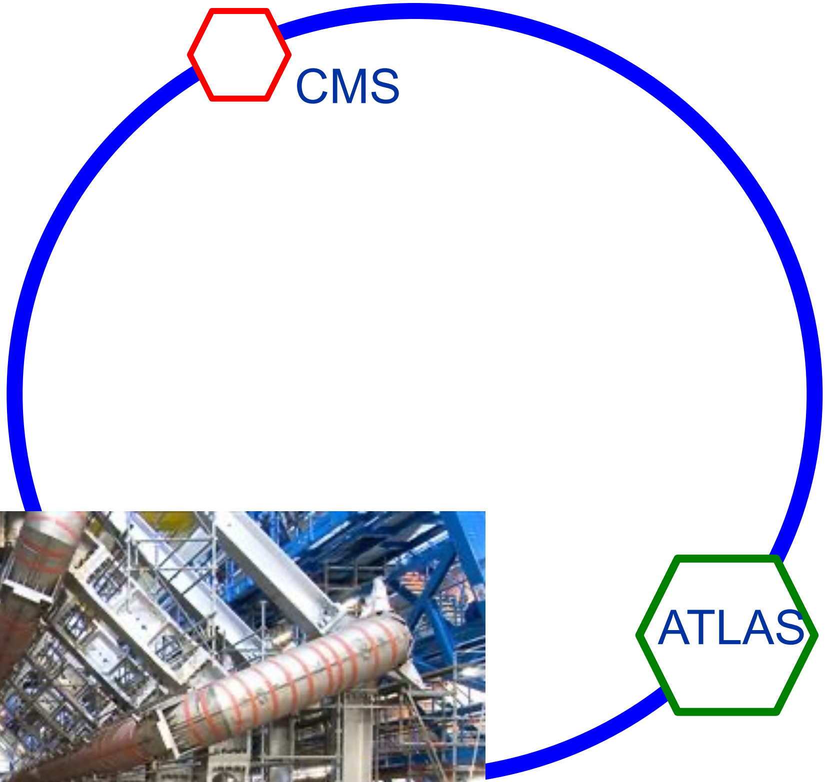
Only covers a tiny fraction of the SM measurements made at the LHC (and elsewhere)

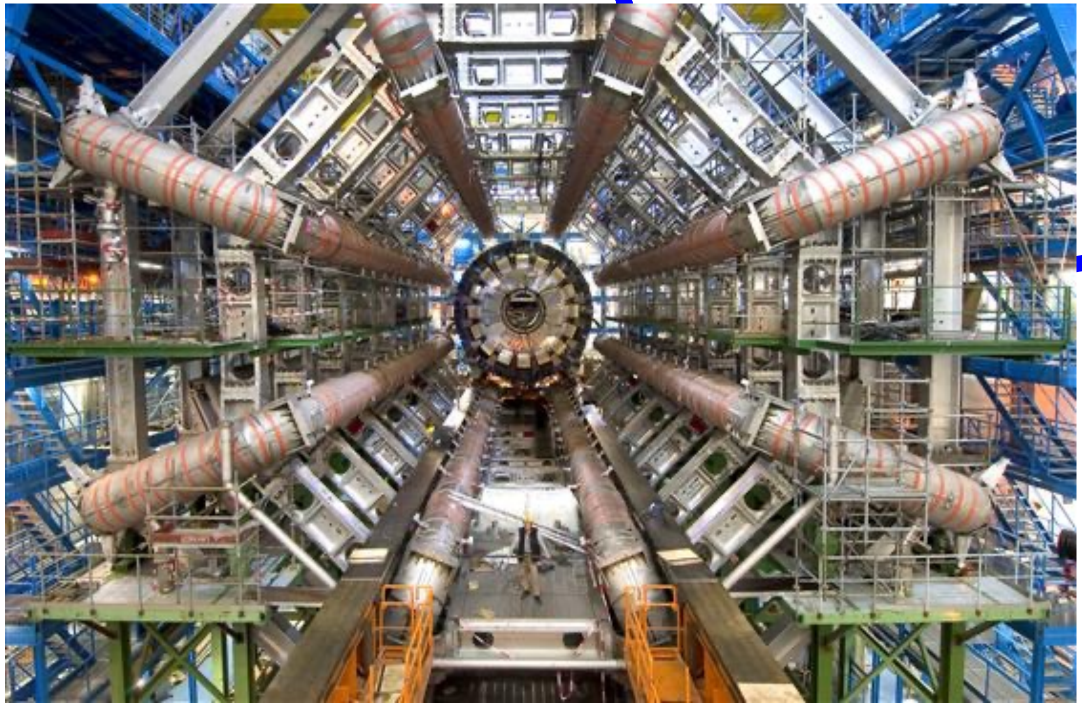
See recent reviews from: ATLAS, CMS



As measured by the ATLAS and CMS Experiments (+1 from LHCb)

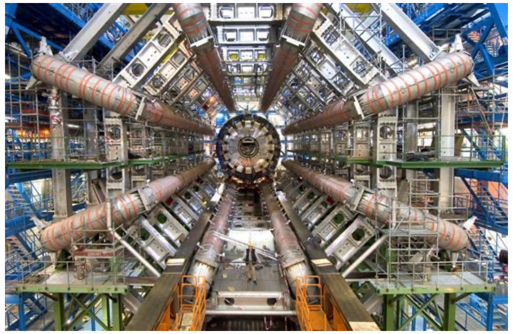


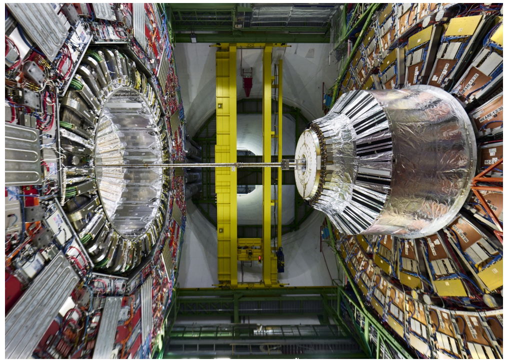




Choice of images is biased – I work on muon systems ☺.

Some qualitative remarks on the performance of these detectors





The efficiency, angular coverage, granularity, resolution and identification capabilities of the detectors are good enough that most activity from a collision can often be attributed to individual: electrons, muon, taus, photons, charged hadrons or neutral hadrons.

Electrons and muons

- Identified with low background and near 100% efficiency over large ranges of pseudo-rapidity and momentum
- Often as much as twice the pseudo-rapidity compared to previous collider detectors.
- Enables the precision measurements in single and multi-boson physics and searches for rare processes

Photons

- Identified efficiently with low background
- Enables the precise cross section measurements in modes with photons and searches for rare processes

Jets

- Particle flow jets measure and identify most of the jet constituents
- Near hadron level jets
- Excellent jet energy scale and resolution calibrations
- Corrections between reconstructed and hadron level jets fairly diagonal
- Enables an extensive program of comparison with theory, PDF and α_S determinations, and tuning of MC performance

Missing energy resolution is decent with reduced tails

All this in turn enables many precision measurements: m_W, $\sin^2\theta^l_{eff}$ …

The performance of the previous generations of detectors were nothing like this!

and the accelerator and theory communities have accomplished equivalent improvements!

CMS xs review

Predictions - Measurements

Scientific exploration

- build an experiment → take data → formulate a theory
- theory → make predictions
- build a new experiment → test the predictions

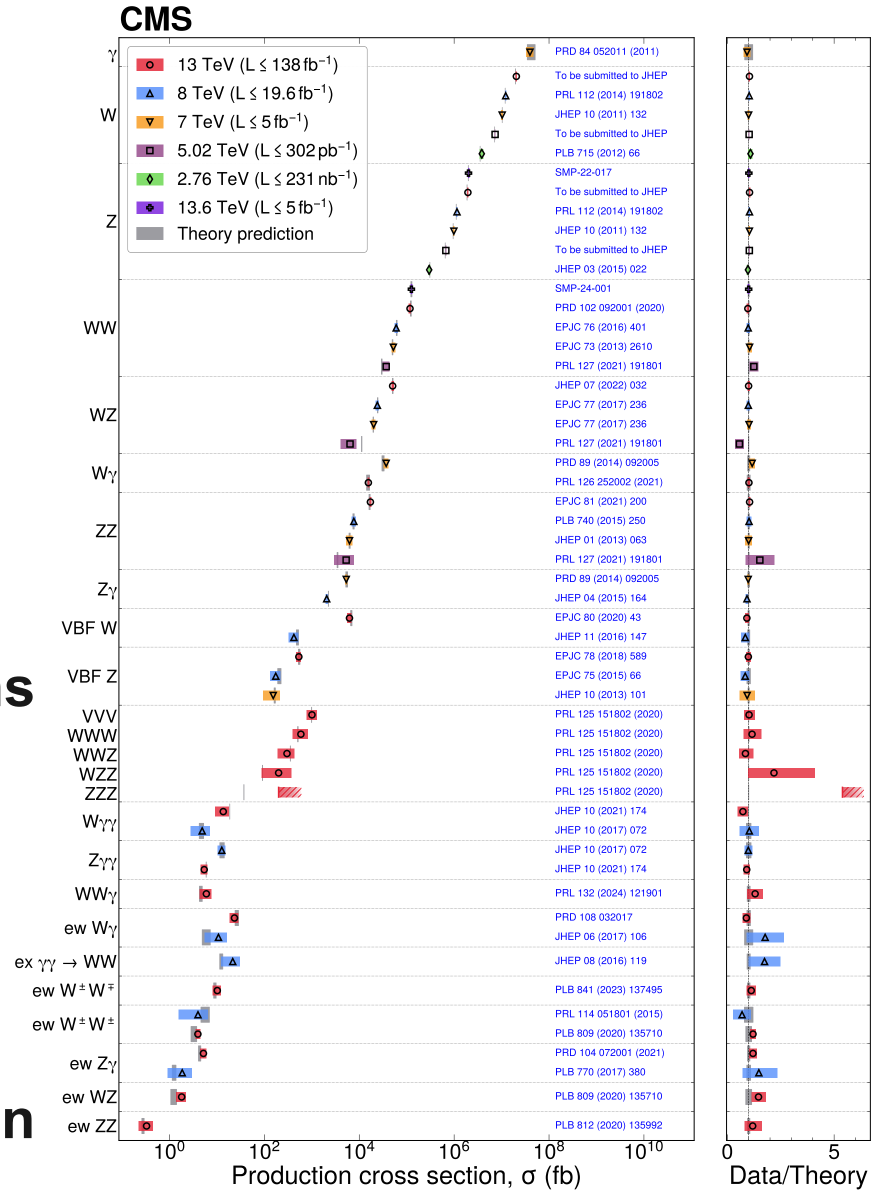
The theory is not really that useful if it's not predictive!

The Standard Model is one of the ultimate predictive theories

We need a strong understanding of the SM and calculations within the SM:

- What is interesting to measure
- How precisely can we predict measurables
- How precisely can/should we measure them
- How to build our detector

Theory/Experiment - pushing each other to higher precision



ATLAS summary plots

Elements of a SM Prediction: the cross section

The basic measurable prediction of the SM at a collider is a production cross section

Hadron collider: colliding partons: quarks and gluons

- QCD interactions are ubiquitous
- QCD factorization allows us to separate perturbative and non/semi- perturbative physics and make precisions – introduces factorization scale

Perturbative calculation hard collision

- Evaluation of Feynman diagrams - α_s, α
- LO: Almost useless: can be off by factors of 3 ($gg \rightarrow H$)
- NLO QCD: large increase in cross sections: 10-100%
  - New initial/final states (involving jets), loop diagrams
  - Renormalization necessary - renormalization scale
  - Minimum necessary for reasonable accuracy
- NNLO QCD: large increase in cross section: 5%-50%
  - Generally, achieves several percent accuracy
  - Necessary for many analyses
- NLO EW: increase (or decrease) the high energy tails of distributions: 5-30%
- Can also incorporating a logarithmic resummation calculation - helps low p_T or p_T thresholds of objects, systems,

$$\underbrace{\sigma_{pp\to \text{jet}+X}}_{\text{experimental data}} = \sum_{ij\in gq\bar{q}} \overbrace{f_i(x_i,\mu_F^2)\otimes f_j(x_j,\mu_F^2)}^{\text{PDFs}} \underbrace{\otimes\, \hat{\sigma}_{ij\to \text{jet}+X}\left(x_i, x_j, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}, \alpha_S(\mu_R^2)\right)}_{\text{SM(EFT)}}$$

SM calculation of the inclusive jet cross section

Elements of a SM Prediction: the cross section

Non/semi-perturbative physics

Colliding partons

- Proton distribution functions, PDFs, structure of the proton
- Non-perturbative at lowest energies
- Evolved up to the perturbative collision scale, factorization scale, μ_F

QCD NXLO → Jets

- Fragmentation functions and partons showers (PS)
- Hadronization
- Introduces a matching scale, jets produced in the hard collision vs PS jets

Proton remnants

- Underlying events (UE)
- Multiparton interactions (MPI)

SM calculation of the inclusive jet cross section

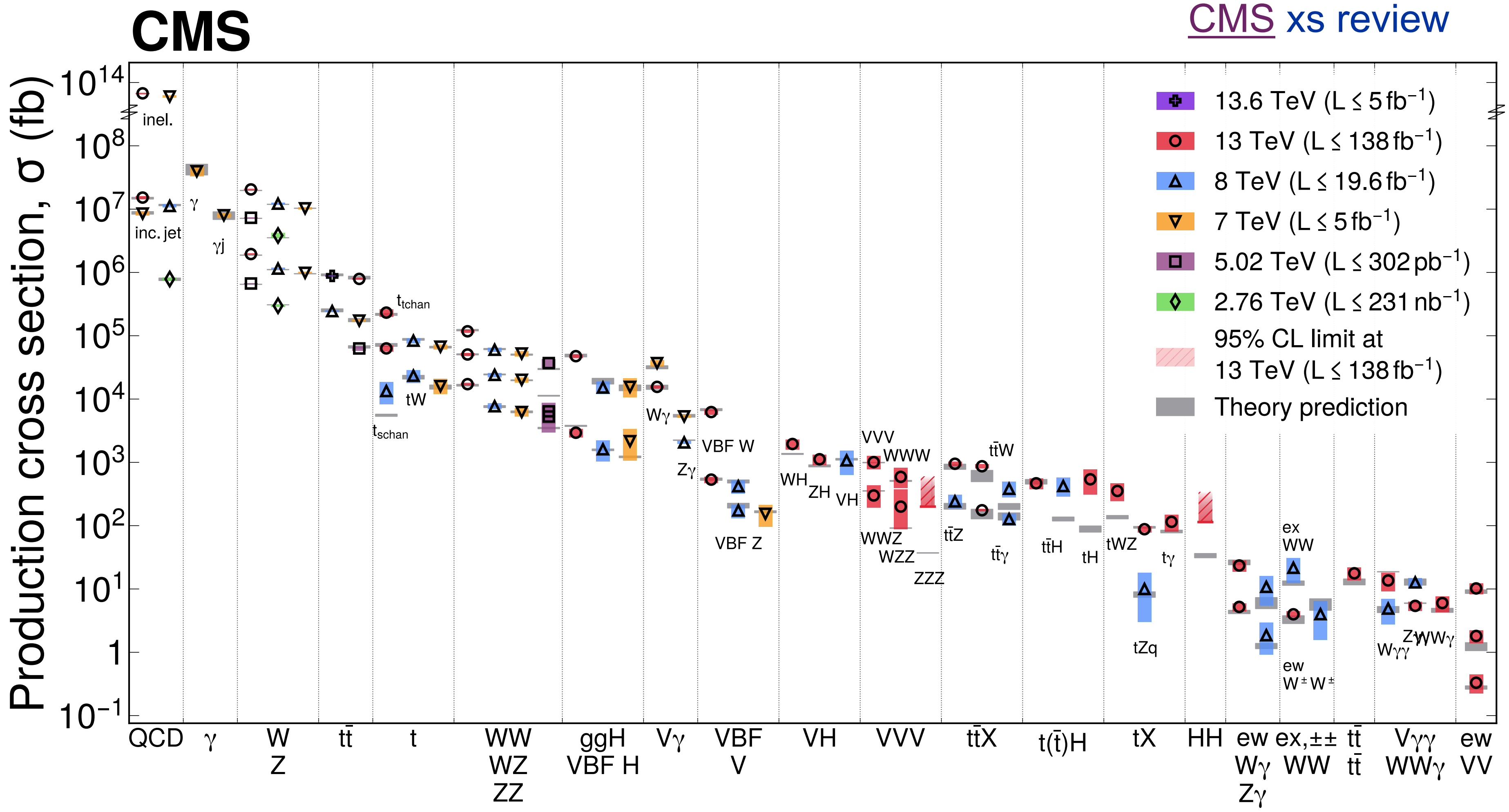
$$\underbrace{\sigma_{pp\to \text{jet}+X}}_{\text{experimental data}} = \sum_{ij\in gq\bar{q}} \overbrace{f_i(x_i,\mu_F^2)\otimes f_j(x_j,\mu_F^2)}^{\text{PDFs}} \otimes \underbrace{\hat{\sigma}_{ij\to\text{jet}+X}\left(x_i, x_j, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}, \alpha_S(\mu_R^2)\right)}_{\text{SM(EFT)}}$$

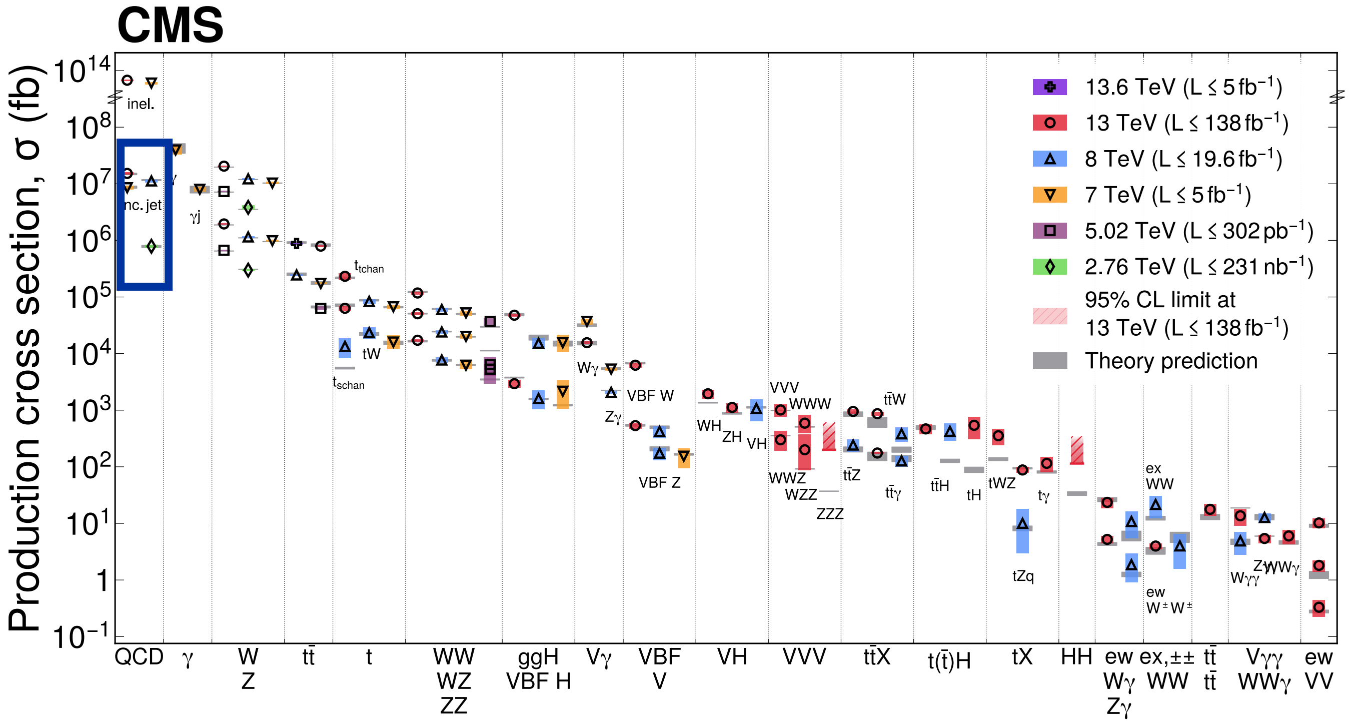
PS, UE, MPI treated with tunes and/or transverse momentum dependent TMD-PDFs

These issues must be corrected for when measuring a cross section and represent important ancillary measurements

Proceeding down the stairway to discovery!

CMS xs review





CMS xs review

QCD Measurements

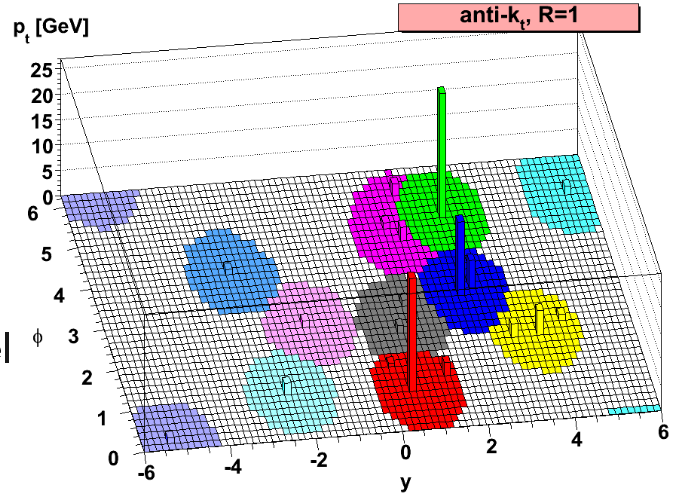
Jets, PDFs, α_s

SM measurement: inclusive jet cross section

The measurable

- Cross section to produce one jet. Multijet events → multiple contributions per pp collision
- Fiducial: p_T(jet) and y(jet) requirements. Typically differential: p_T(jet) and |yj(jet)| bins

Defining a jet



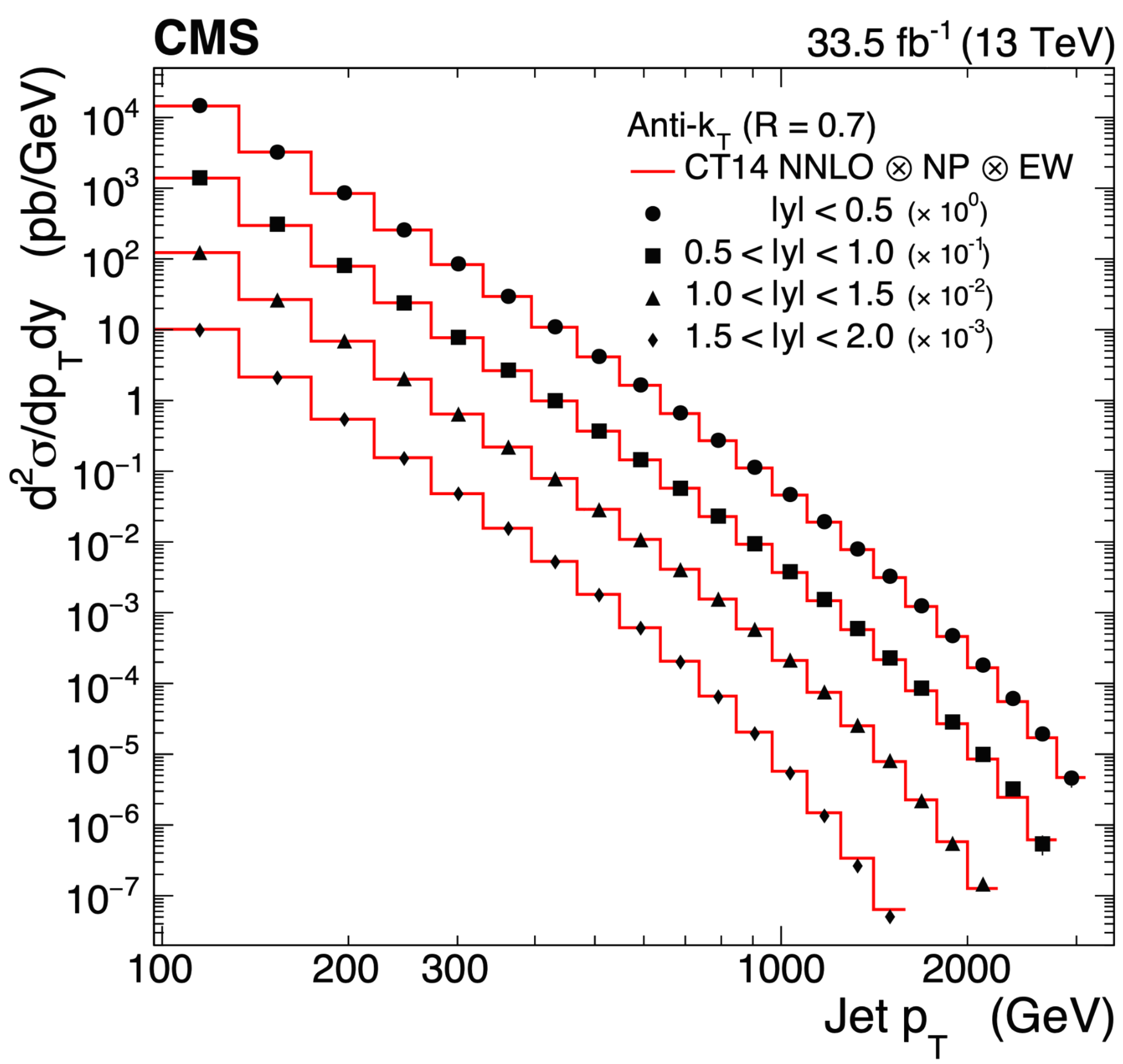
- Parton level: original quark or gluon p_T, y
  - Advantages: What was directly calculated in the cross-section calculation
  - More independent of detector or jet clustering details
  - Solid understanding of perturbative accuracy of the calculation
  - How to consider the jets formed in PS process
  - Disadvantages: Must correct for non/semi-perturbative effects to/from the parton level
- Particle level
  - Cluster jets using MC particles (mostly hadrons)
  - Use infrared/collinear safe jet clustering algorithm.
  - Advantage: closer to what is measured - detector PF objects and/or calorimeter energy clusters
  - Disadvantage: depends on clustering

Unfolding

- Account for acceptance and migrations in differential measurements – using MC
  - Finite resolutions – events outside of fiducial (or a bin) can migrate into the region and or vice versa
  - Typically iterated. Amount of migration depends on the underlying distribution. Correct the MC to the distribution observed in the data and recalculate migrations.

Inclusive Jet Cross Section - CMS

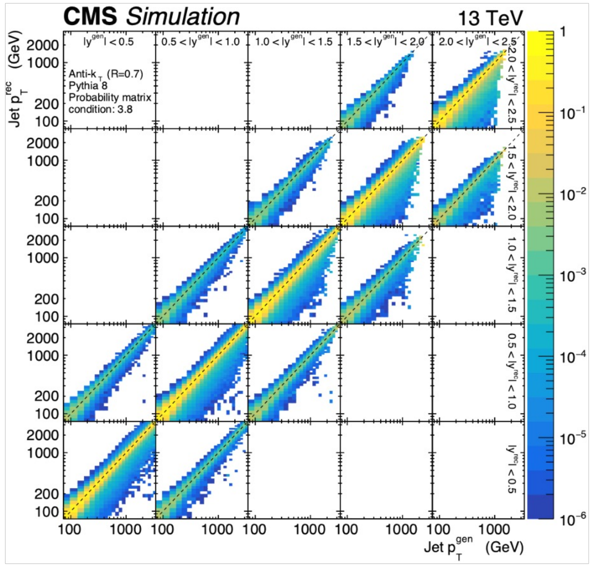
JHEP 02 142, JHEP 12 035 (2022)



Prediction: NNLO QCD with NLO EW corrections

- Corrected for NP effects to particle level jets
- NP corrections based on several MCs and tunes

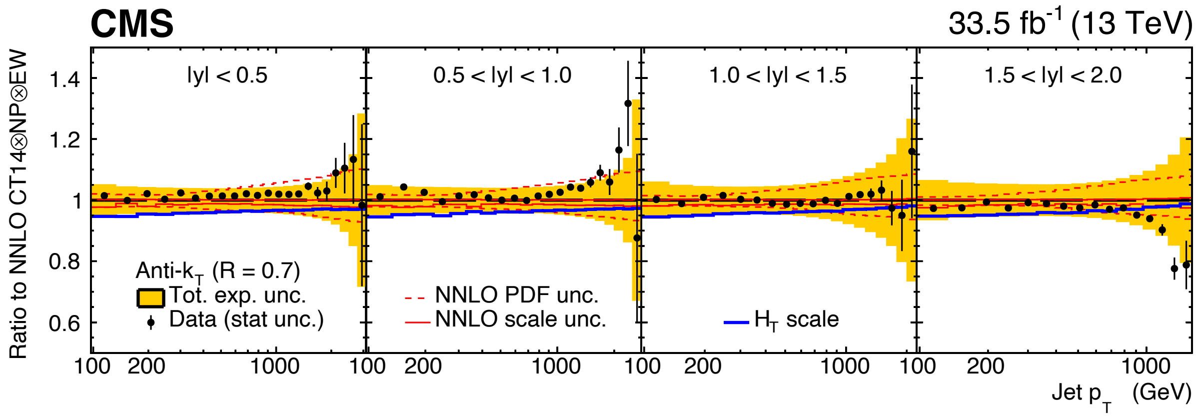
Data: Unfolded to particle level using full detector simulation

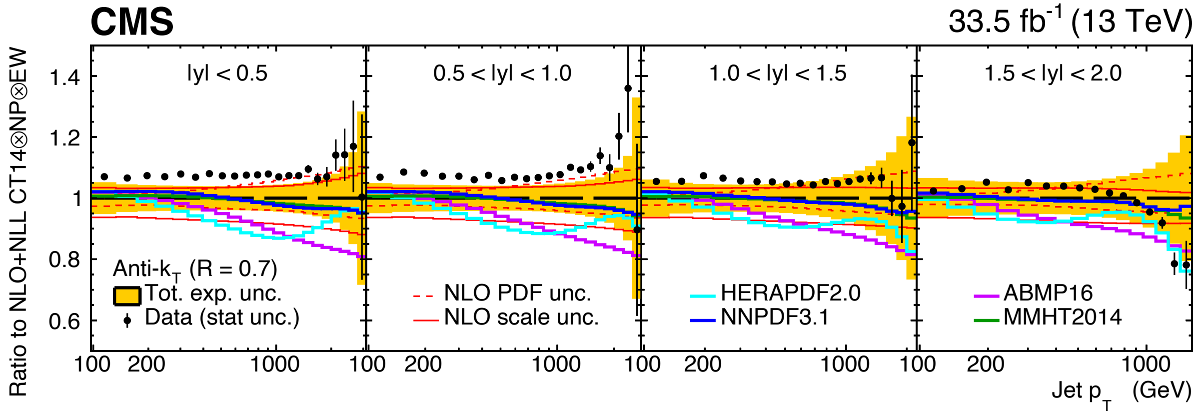


Unfolding Matrix: Reconstructed to hadron level gen jets

Excellent agreement seen with NNLO QCD + NLO EW prediction

Inclusive Jet Cross Section, NLO vs NNLO





Predictions:

NNLO QCD with NLO EW corrections

NLO+NLL QCD with NLO EW corrections

(since NLL was used corrections for PS have to account for that)

NLO, even with NLL, is not enough to achieve agreement with the data

10-20% disagreements unsurprising.

Different predictions from NLO PDFs inconsistent

NNLO calculations necessary to demonstrate consistency with SM at the precision of the LHC data for many analyses.

The "QCD Analysis"

Requirements for comparison of SM predictions to LHC data

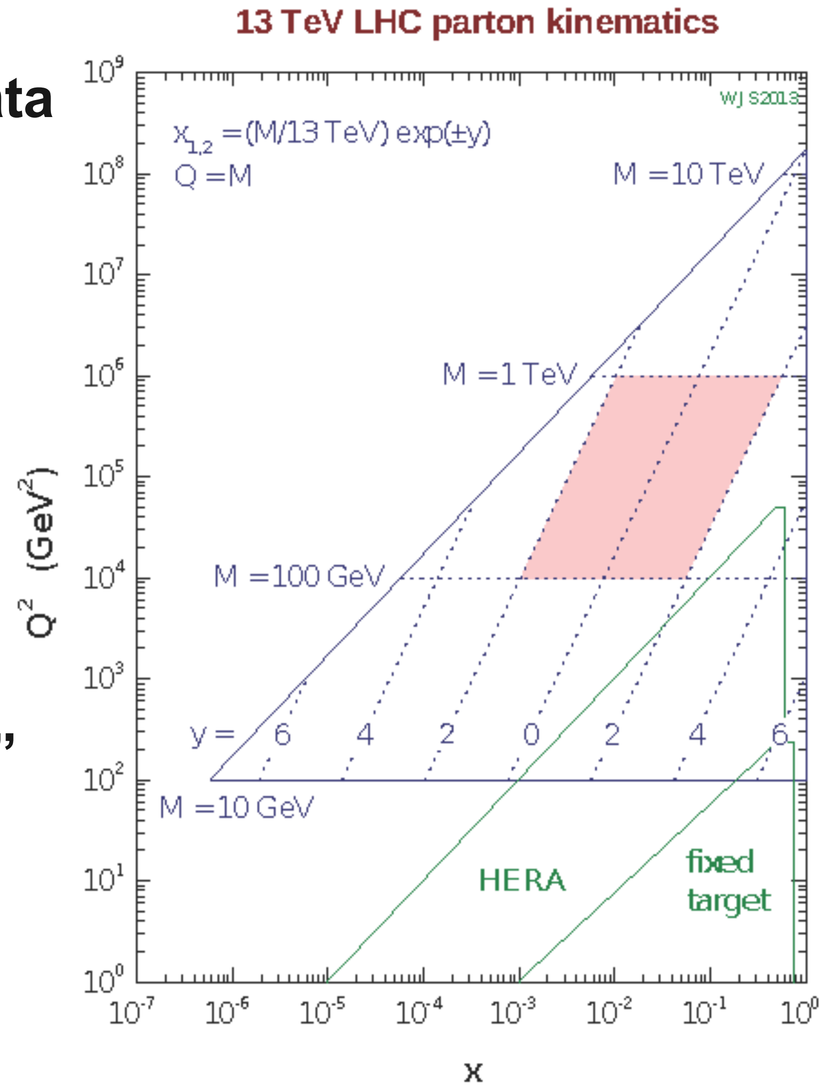
- NNLO QCD calculations
- NNLO PDF determinations
- NNLO α_S determination

PDFs

- LHC probes Q^2 and x regions of PDFs not accesses by previous accelerators
- Needs HERA data, fix lower Q^2 and x,
  where the PDF parameterization is typically defined

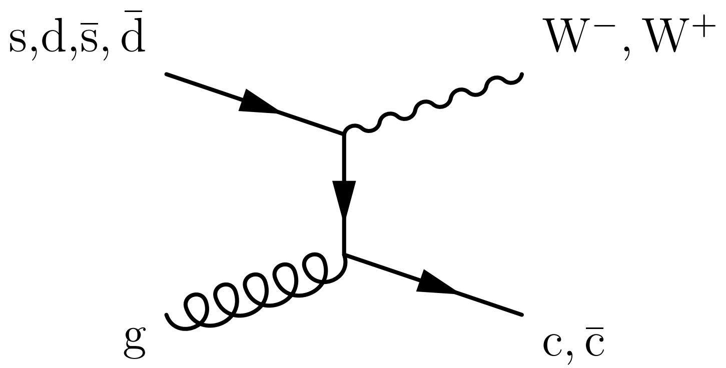
One solution, to assemble these elements: "QCD Analysis"

- Analysis of LHC QCD Jets data (and often other useful data sets)
- Determination PDFs and α_S
- Using HERA I, II datasets with LHC Jets data
- fitting framework available as open-source software - xFitter



Plot courtesy of W.J. Sterling

QCD Analysis, PDFs - ATLAS



Combined PDF fit of ATLAS data

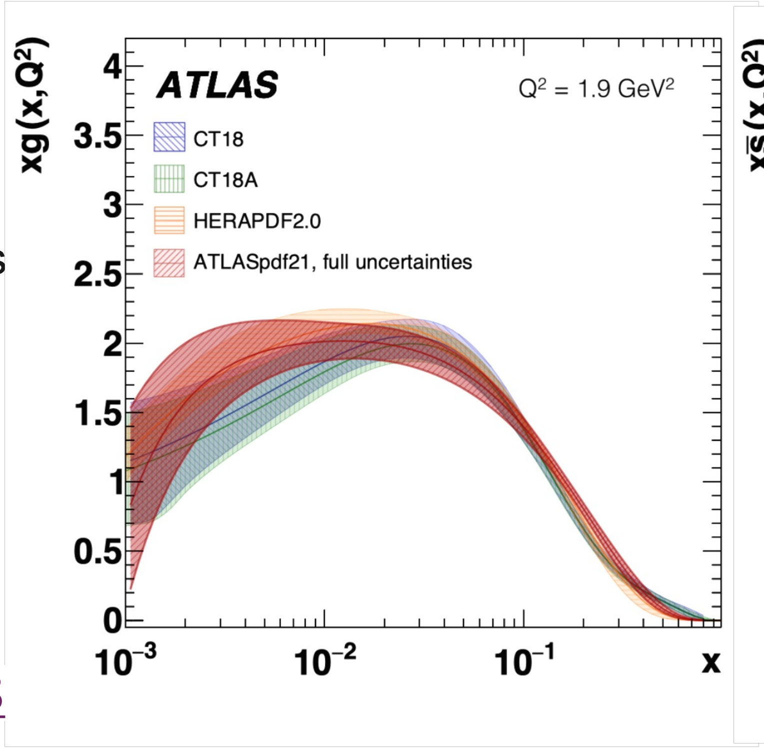
- Inclusive Jets → strongly impacts valance quark and gluon distributions
- W, Z/$\gamma*$ → strange and anti-quark, W+Jets, Z+jets → strange and anti-quark
- ttbar → high-x gluon distribution
- Inclusive isolated photon – well fit by data (has often not been the case)

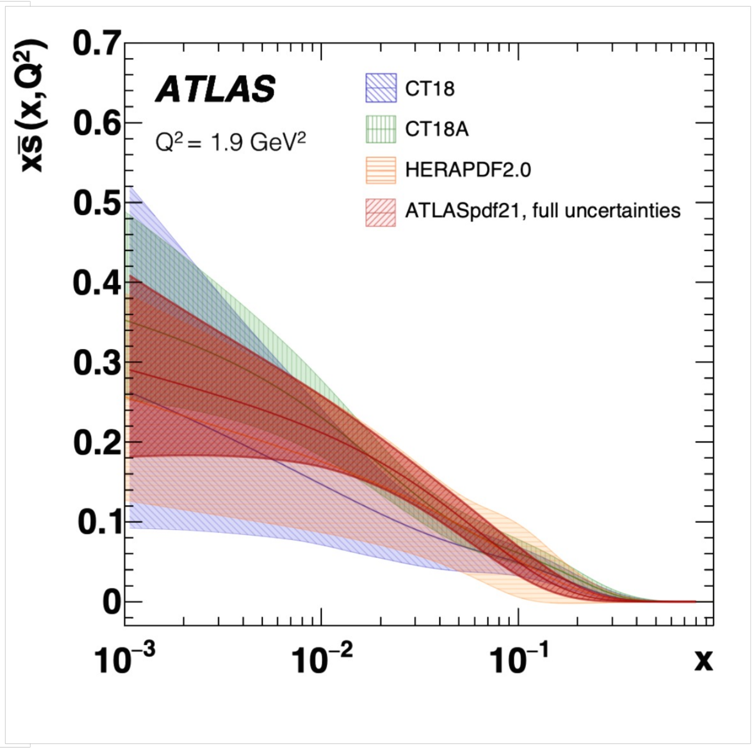
xFitter framework: ATLASpdf21

- NNLO QCD + NLO EW
- Parameterization at initial Q^2 evolved up to relevant scale using DGLAP equations
- Correlations carefully treated
  - Luminosity, jet related uncertainties

Significant improvement over HERAPDF (where expected). Equivalent performance to Global PDF fits

Eur. Phys. J. C 82 (2022) 438





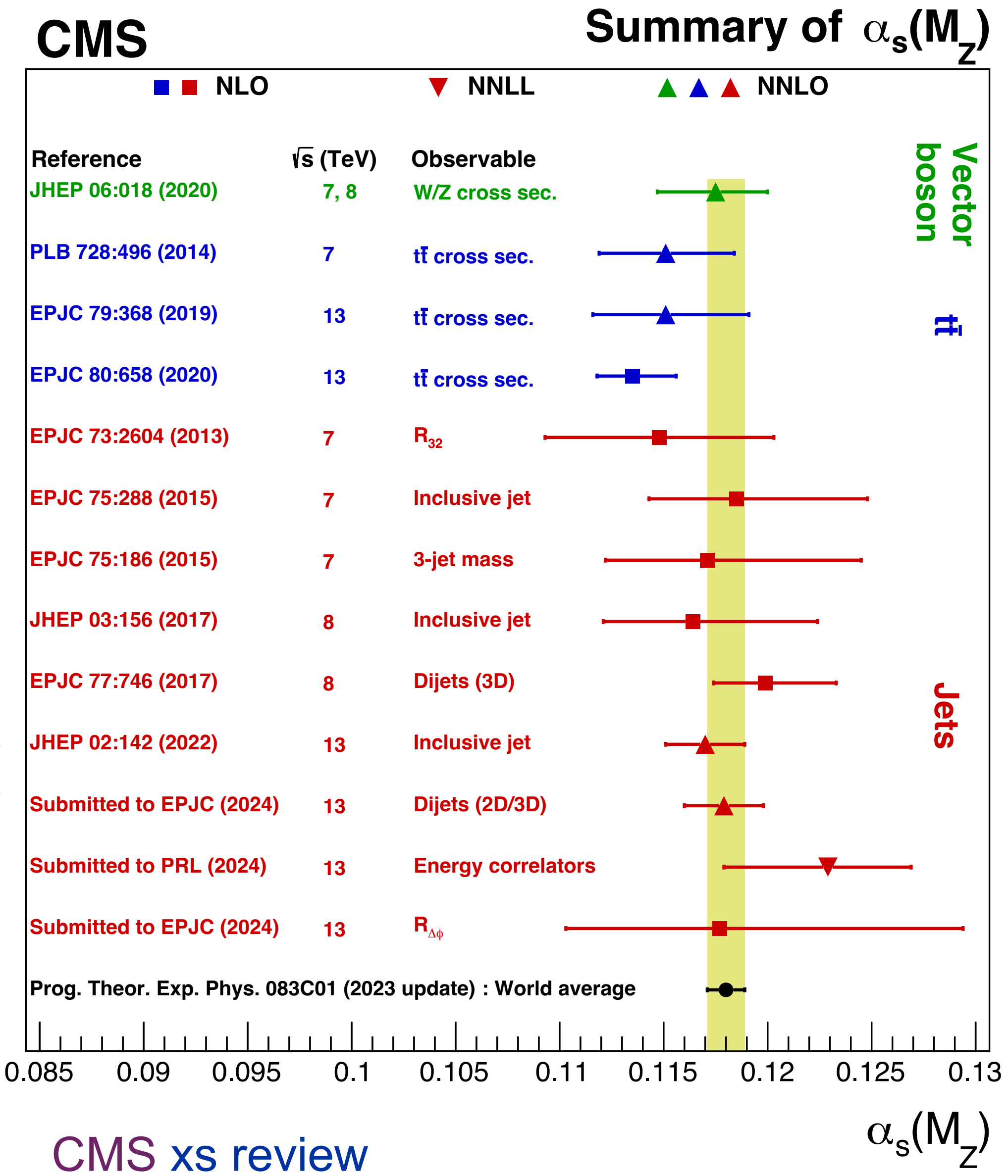
QCD Analysis, PDFs and α_S - CMS

Combined PDF and α_S fits

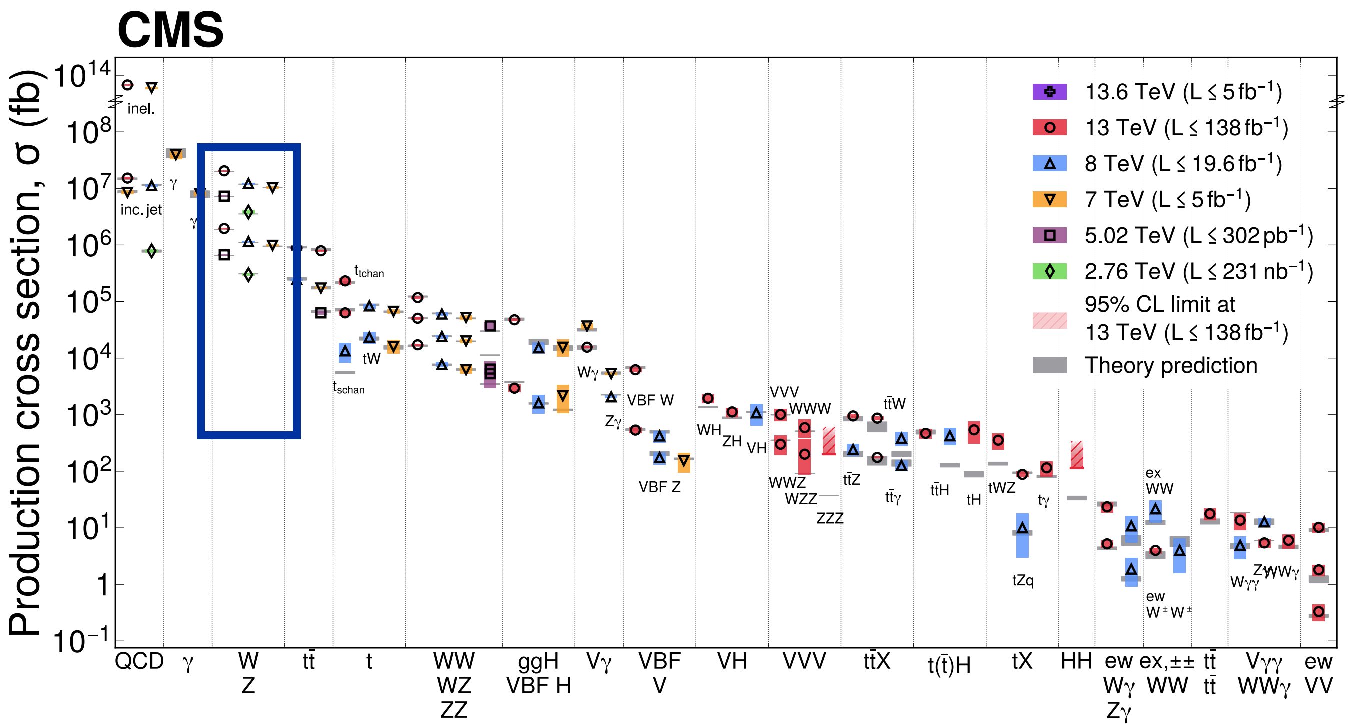
- Separate analysis with sensitivity to specific PDFs and/or α_S

Most precise α_S results from NNLO QCD Analysis of 13 TeV inclusive jet and differential di-Jet data

In general, the ultimate measurements of SM parameters that depend on PDFs will benefit from simultaneous QCD Analysis of the PDFs using appropriately chosen datasets for the parameter(s) of interest – m_W, $\sin\theta_{Weff}$ …



CMS xs review



More QCD Measurements

W+jets and Z+jets

CMS xs review

W+jets, Z+jets

LO QDC

Interference between loop and LO diagram is NLO

Excellent data-sets for QCD studies

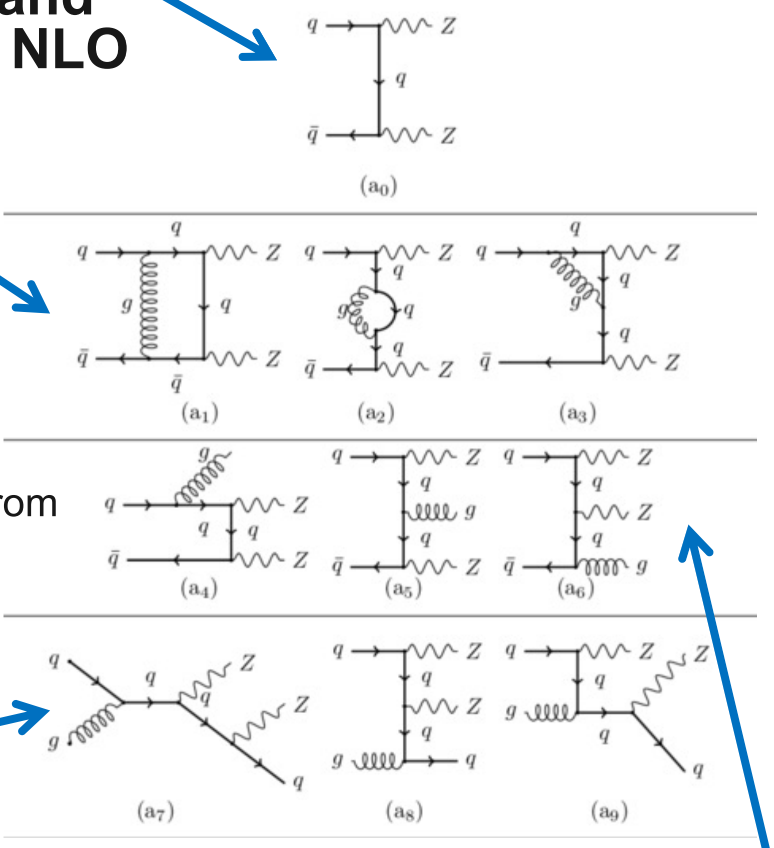
- Easily triggered pure data samples ($W \rightarrow l\nu$, $Z \rightarrow l^+l^-$)
- Interesting array of final states
  - Large numbers of jets
  - Heavy flavor jets
  - Topologies important in ttbar, Higgs, NP searches
- Study of the recoiling jets system via well measured vector boson (Z) properties - tunes

SM predictions of V+jets

- Interested in exclusive final states (V +njets) or inclusive (V + ≧ n jets)
- Calculation of all diagrams with final states up to V + n jets. If using MC, additional jets from PS

What does this mean? Some examples

- NLO ZZ+"0" jets production (I work on ZZ physics, so these diagrams were available)
  - LO ZZ prediction poor, neglects large contributions from NLO gq initial states
  - Inclusive ZZ production NLO QCD accuracy
  - Z+0 at NLO QDC accuracy
  - Renormalized NLO α_S captures some higher order behavior
  - Neglects contributions from NNLO gg initial states (often add separately)
  - ZZ+1jet production LO QCD accuracy, + ≧ 2 jets depends on accuracy of PS (if used) tune
  - Portions of the phase space of a calculation (ZZ+1jet) less accurate than the full inclusive calculation
  - Typically normalize the cross section after PS back to NLO results or to NNLO or higher



New initial states

Real emission. Negative contribution from loop diagram cancels infrared divergence in this NLO diagram

W+jets, Z+jets

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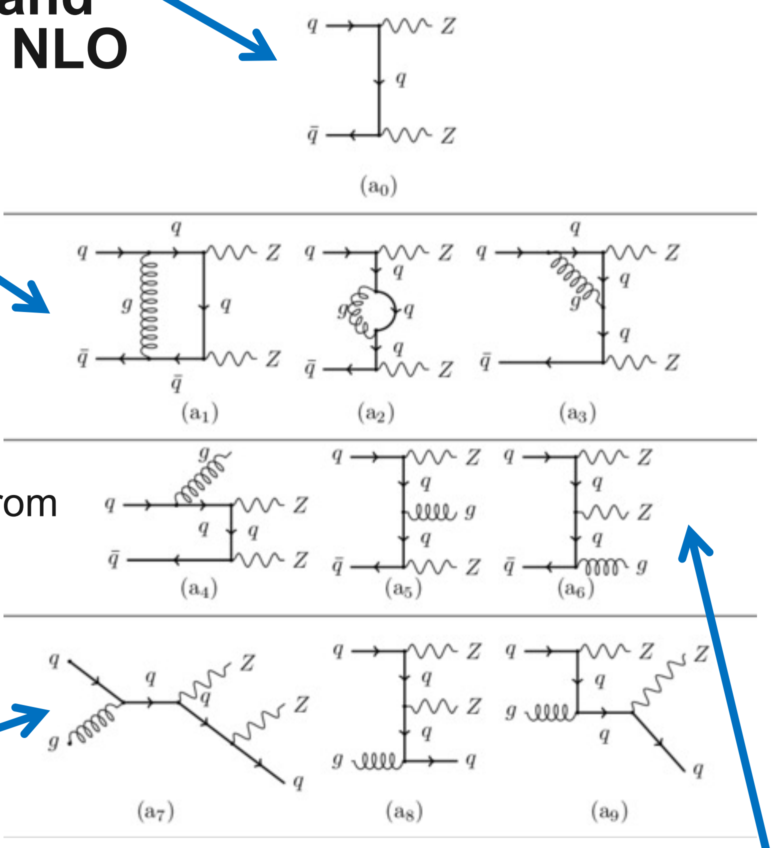
What does this mean? Some examples

- NLO Z+0,1,2 jets production (three samples generated separately and combined)
  - Inclusive Z production NLO QCD accuracy
  - Z+0,1,2 at NLO QDC accuracy
  - Renormalized NLO α_S captures some higher order behavior
  - Neglects contributions from higher order initial states
  - Z+3jet production LO QCD accuracy, + ≧ 4 jets depends on accuracy of PS (if used) tune
  - Portions of the phase space of a calculation (ZZ+3jet) less accurate than the full inclusive calculation
  - Typically normalize the cross section after PS back to NLO result or to NNLO or higher
  - This is the limit of a reasonable computing time budget

LO QDC

Interference between loop and LO diagram is NLO



New initial states

Real emission. Negative contribution from loop diagram cancels infrared divergence in this NLO diagram

W+jets, Z+jets

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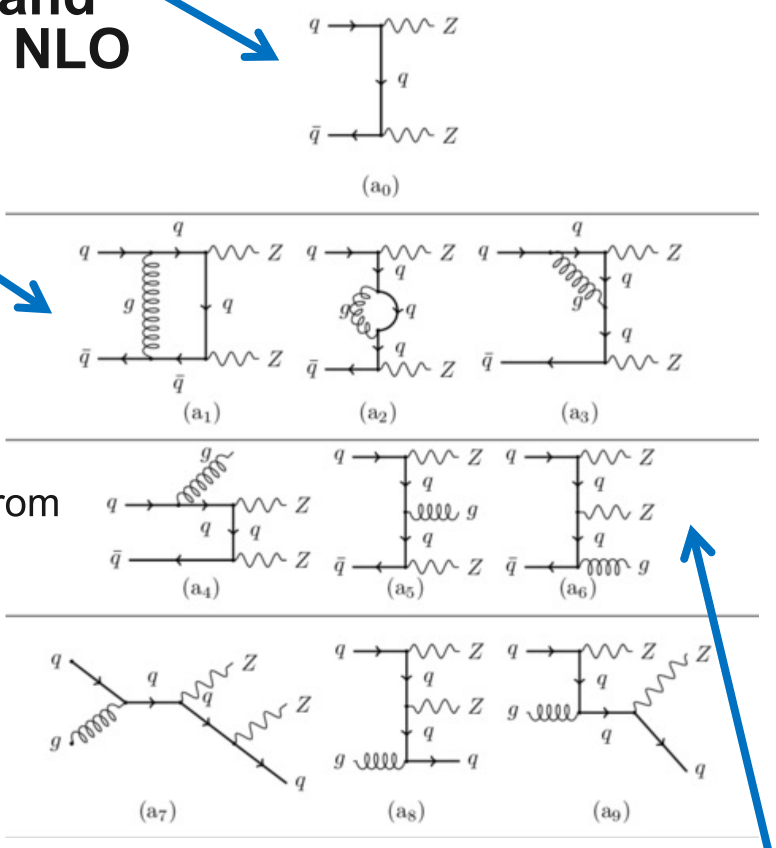
What does this mean? Some examples

- NNLO ZZ+0 Jets (three samples generated separately and combined)
  - Inclusive ZZ production NNLO QCD accuracy
  - ZZ+0 jet at NNLO, ZZ+1 at NLO, ZZ+2 at LO QCD accuracy
  - Renormalized NNLO α_S captures some higher order behavior
  - ≧ 3 jets depends on accuracy of PS (if used) tune
  - Portions of the phase space of a calculation (ZZ ≧ 1 jet) less accurate than the full inclusive calculation
  - This is the limit of a reasonable computing time budget

New initial states now include a gg diagram



Real emission. Negative contribution from loop diagram cancels infrared divergence in this NLO diagram

EPJC 78 (2018) 965

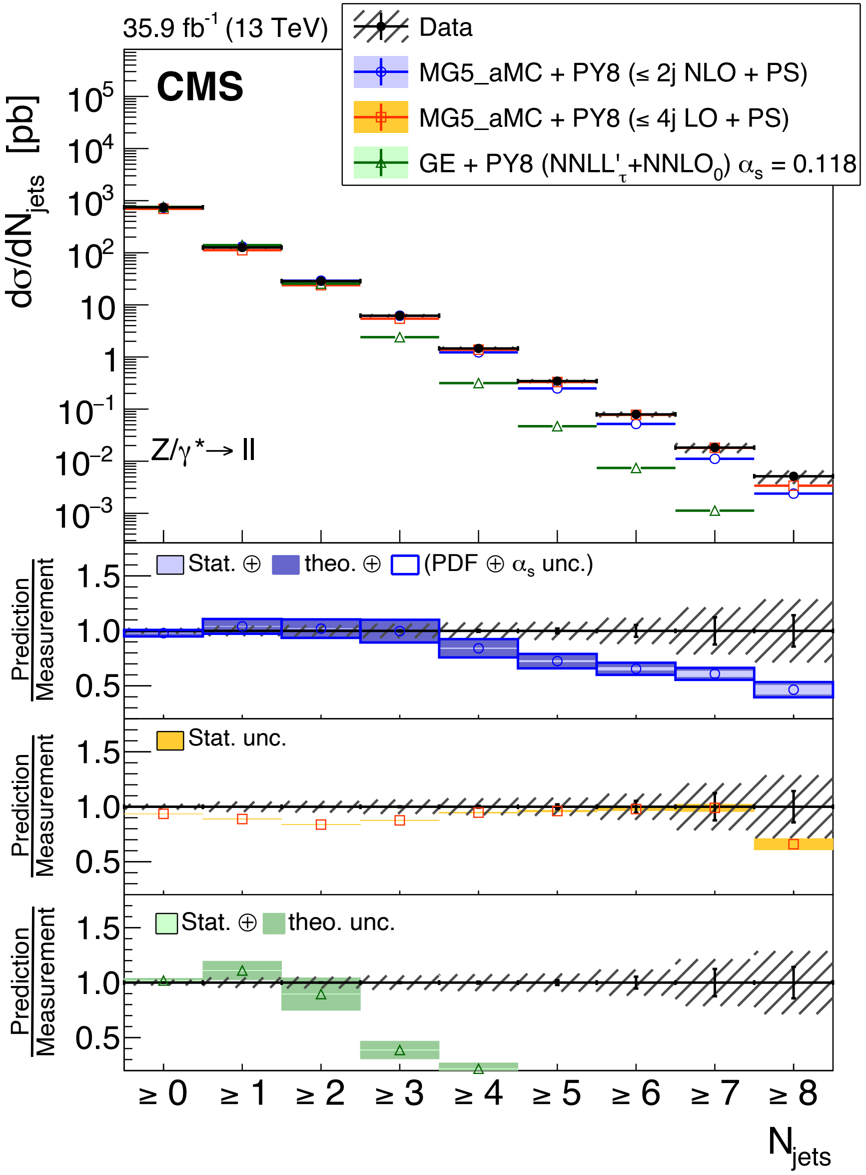
Exclusive Z+jets

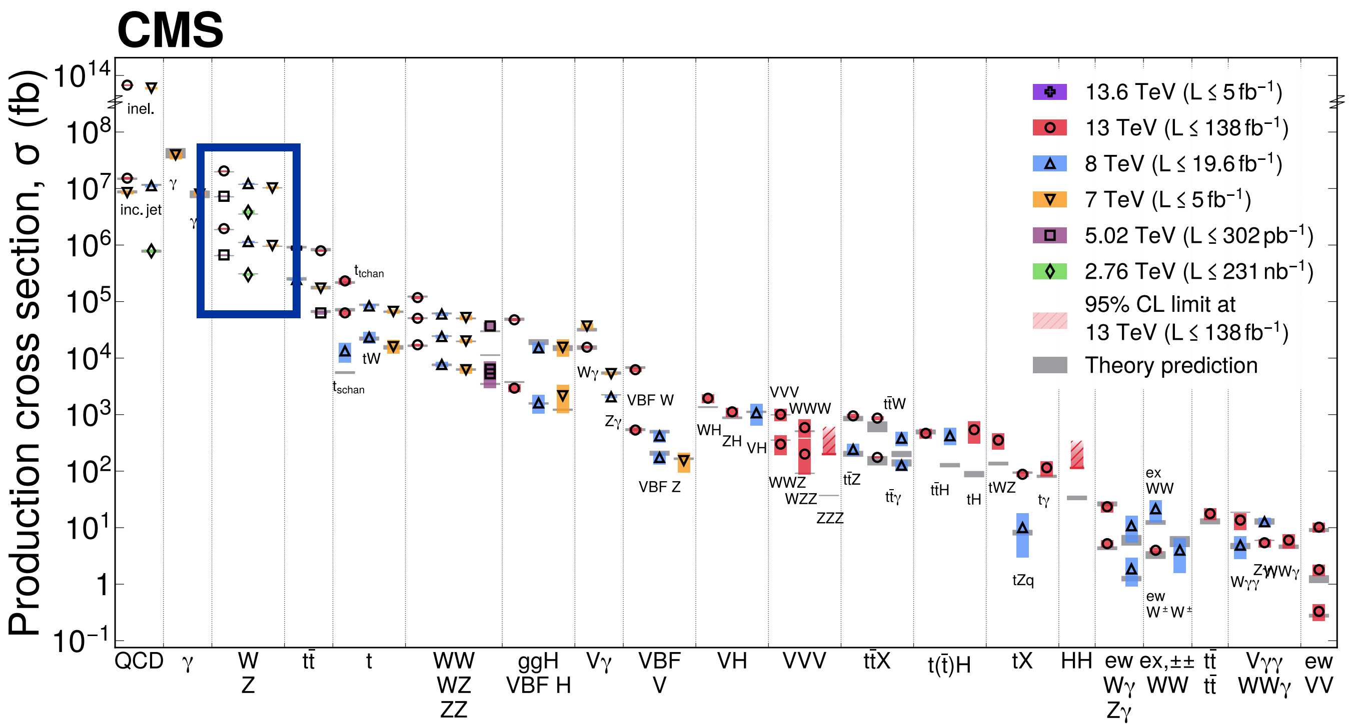
Comparison to LO, NLO and NNLO calculations/MCs

- (if there is a preference for CMS results it's only because I know where to find the plots to make my points – no reflection on the quality of the results)
- LO Magraph 0-4 jets with Pythia 8 PS
  - Why does this look so good? It's up to 4 jets. Most new initial states included.
  - Pythia tunes of the non/semi–perturbative physics heavily leverages Z data
    - UE, MPI and the PS behaviors
  - Note that only statistical uncertainties are shown
  - It's difficult to assess the uncertainty of the MC simulation or interpret the source of differences when observed. This distribution looks good, but others may/do not
- NLO Magraph 0,1,2 jets with Pythia 8 PS
  - Consistent with data and reasonable uncertainties to up to 2 jets
  - Third hard jet calculated at LO looks good
  - Does not interface well with Pythia 8 PS after that
  - Needs an NLO Tune (see ATLAS AZNLO later!)
- NNLO+NNLL Geneva "0" jets with Pythia 8 PS
  - Better uncertainty in the zero jets bin. Inclusive calculation is great!
  - Consistent with the data with reasonable uncertainties for 1 Jet (NLO) and 2 jets (LO)

To see good agreement and well understood uncertainty you need NLO up to the number of jets of interest

NNLO with jets would be better, but is often prohibitive to generate





[CMS](#) xs review

W and Z cross sections

The hadron collider precision cross section frontier

Precision pp collider cross sections

W and Z cross sections

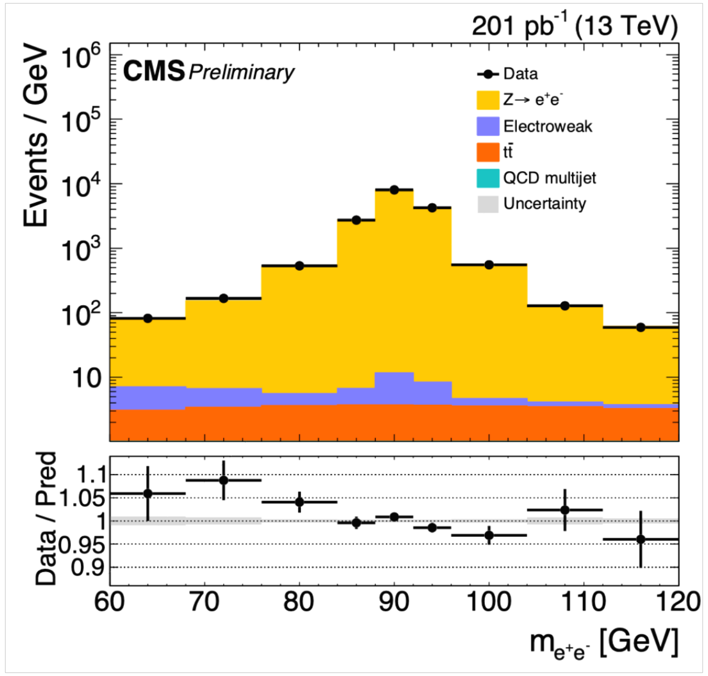
- Easily triggered pure data samples (W→lν, Z→l⁺l⁻)
- Performance of lepton triggering, reconstruction, and Id calibrated using tag and probe on large data samples.
- Can define both fiducial and total cross-section measurements.
- Dominant uncertainties
  - luminosity uncertainty
  - Extrapolation from measurement phase space to fiducial region (small) or total cross section (larger)
  - Ratios can reduce uncertainties: especially luminosity uncertainty

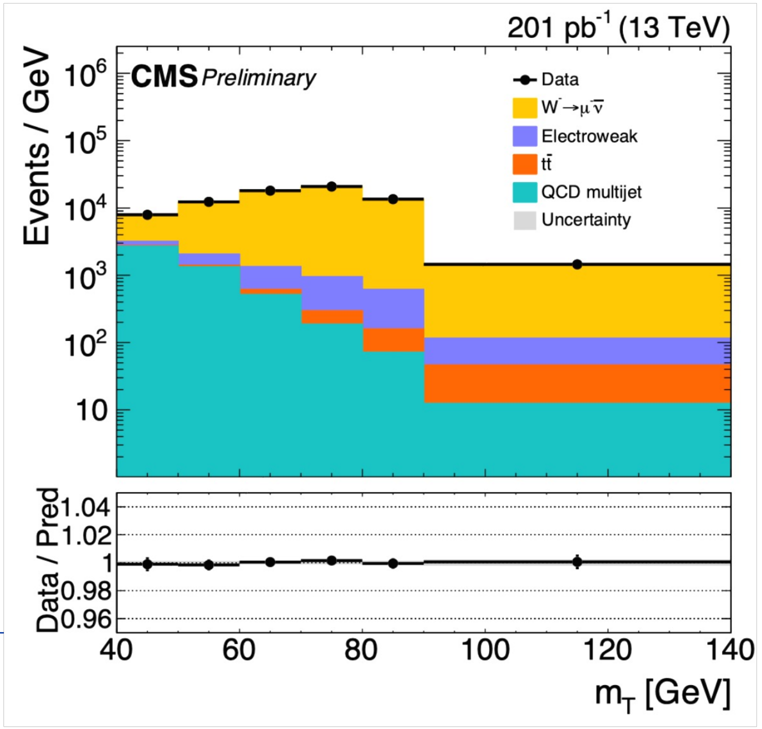
The SM calculations

- NNLO, N3L0, N3LO+N3LL, even approximate N4LO+N4LL (DYTurbo)
- Logarithmic resummation of vector boson pT
- Dominant uncertainties
  - PDF and scale uncertainty
  - Especially when phase space limited to fiducial cross-section region

The precision frontier in hadron collider cross-section measurements and predictions

Interesting dichotomy of uncertainties fiducial vs. total/ exp vs. theory cross section measurement comparisons.

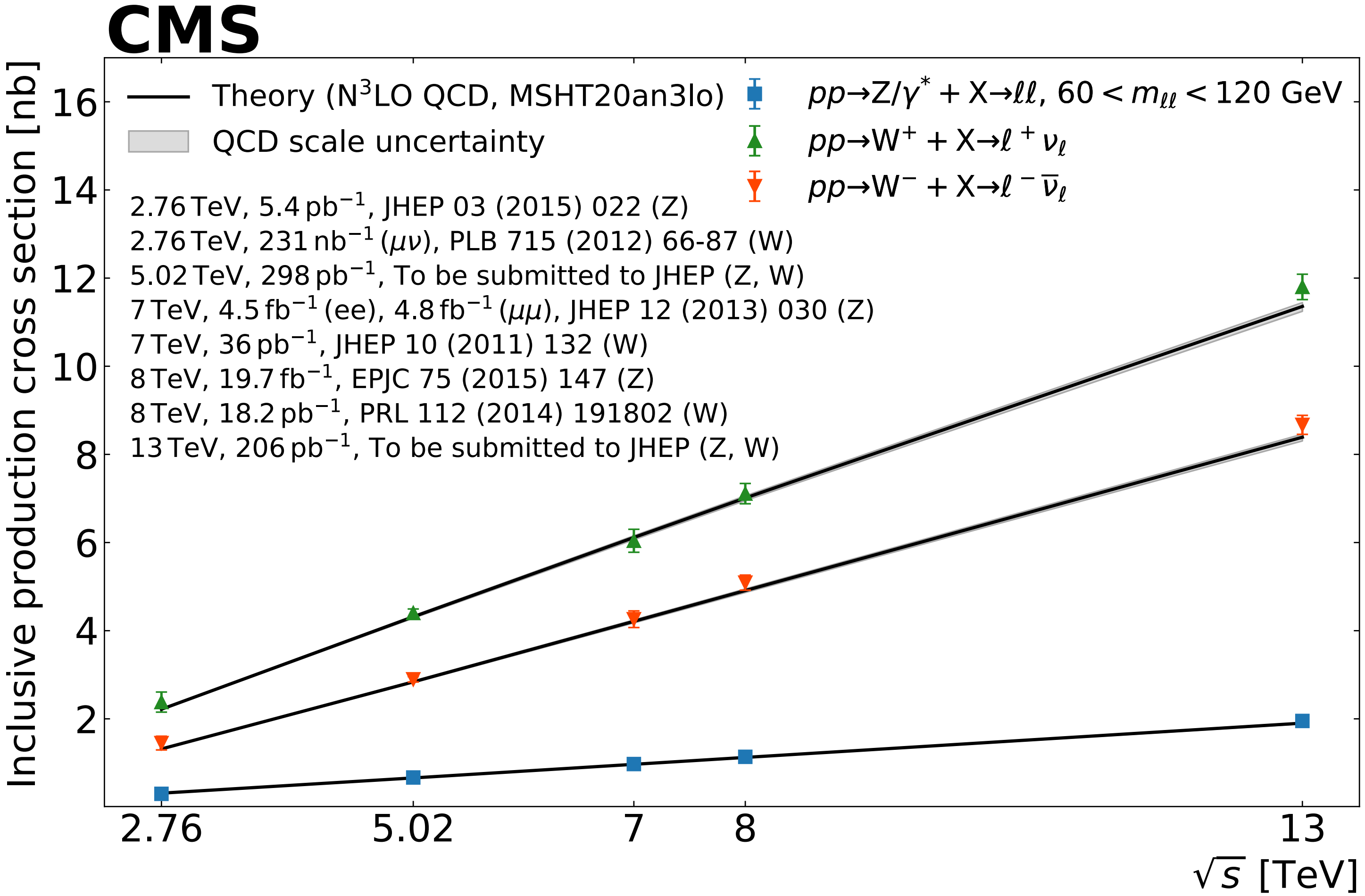




W and Z cross sections - CMS

5, 13 TeV CMS: to be submitted to JHEP

CMS xs review

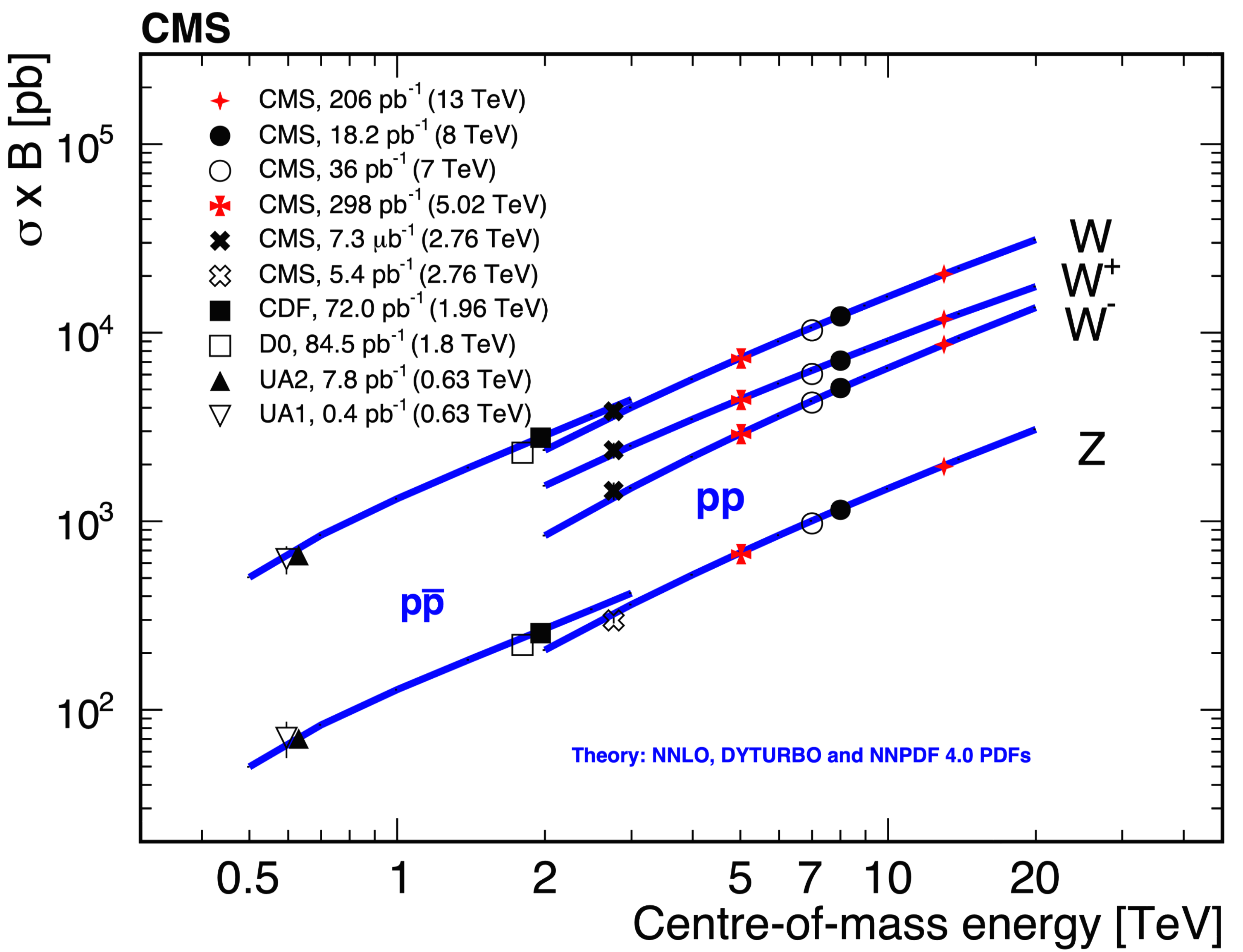


Inclusive cross section comparison to N3LO QCD with approximate N3L0 PDFs

5 energies shown. 13.6 W,Z PLB 854 (2024) 138725 (ATLAS) and 13.6 Z (CMS) results newly available.

W and Z cross sections historical Context

Takes a few minutes to collect a UA1 sized dataset at the LHC



W and Z cross sections - CMS

Inclusive cross sections, N3LO calculation

$\sqrt{s}$ (TeV)	$\sigma(Z)$ (pb)	Tot. exp. unc.	$\sigma^{SM}(Z)$ (pb)
2.76 [218]	298 ± 10 (stat) (syst) ± 11 (lumi)	5.0%	313^{+1}_{-2}
5.02 [219]	669 ± 2 (stat) ± 6 (syst) ± 13 (lumi)	2.2%	$674.7^{+7.1}_{-7.4}$
7 [221]	986 ± 22 (syst) ± 22 (lumi)	3.1%	968^{+6}_{-7}
8 [223]	1138 ± 26 (syst) ± 30 (lumi)	3.5%	1124^{+7}_{-2}
13 [219]	1952 ± 4 (stat) ± 18 (syst) ± 45 (lumi)	2.5%	1940^{+15}_{-21}

Fiducial cross sections, NNLO calculations

$\sqrt{s}$ (TeV)	$\sigma_{fid.}(Z)$ (pb)	Tot. exp. unc.	$\sigma^{SM}_{fid.}(Z)$ (pb)
5.02[219]	319.8 ± 0.9 (stat) ± 1.2 (syst) ± 6.2 (lumi)	2.0%	319.5 ± 3.7
7 [221]	524.7 ± 0.4 (stat) ± 5.2 (syst) ± 11.5 (lumi)	2.4%	525 ± 6
8 [222]	410.0 ± 10.0 (stat) ± 10.0 (syst) ± 10.0 (lumi)	4.2%	400 ± 10
13[219]	754 ± 2 (stat) ± 3 (syst) ± 17 (lumi)	2.3%	743 ± 18

CMS xs review

Experimental results

Additional theory uncertainty to extrapolate to total cross-section substantial

2% fiducial Z result at 5TeV

Special short run with reduced instantaneous luminosity

still dominated by luminosity uncertainty

Theory Calculations

Calculations in a limited phase space less accurate

Exp.-theory pattern of uncertainties best seen in measurements with the same data set

New ATLAS Run 2 luminosity measurement achieves 0.83% uncertainty. Sub 1% cross section measurements possible!

W and Z cross section ratios - CMS

CMS xs review

Inclusive cross section ratios, NNLO calculation

$\sqrt{s}$ (TeV)	Ratio	R_{exp}	Tot. exp. unc.	R_{SM}
5.02 [219]	R_{W^+/W^-}	1.519 ± 0.002 (stat) ± 0.010 (syst)	0.67%	$1.5240^{+0.33\%}_{-0.31\%}$
7 [220]	R_{W^+/W^-}	1.421 ± 0.006 (stat) ± 0.032 (syst)	1.8%	1.43 ± 0.7%
8 [222]	R_{W^+/W^-}	1.39 ± 0.01 (stat) ± 0.02 (syst)	1.6%	1.41 ± 0.7%
13 [219]	R_{W^+/W^-}	1.3615 ± 0.0018 (stat) ± 0.0094 (syst)	0.70%	$1.3536^{+0.37\%}_{-0.33\%}$
5.02 [219]	$R_{W/Z}$	10.905 ± 0.032 (stat) ± 0.054 (syst)	0.58%	$10.777^{+0.33\%}_{-0.34\%}$
7 [220]	$R_{W/Z}$	10.54 ± 0.07 (stat) ± 0.18 (syst)	2.3%	10.74 ± 0.4%
8 [222]	$R_{W/Z}$	10.63 ± 0.11 (stat) ± 0.25 (syst)	2.6%	10.74 ± 0.4%
13 [219]	$R_{W/Z}$	10.491 ± 0.024 (stat) ± 0.083 (syst)	0.82%	$10.341^{+0.41\%}_{-0.38\%}$

Fiducial cross sections ratios, NNLO calculations

$\sqrt{s}$ (TeV)	Ratio	R_{exp}	Tot. exp. unc.	R_{SM}
5.02 [219]	R_{W^+/W^-}	1.6232 ± 0.0026 (stat) ± 0.0065 (syst)	0.43%	1.631 ± 0.98%
8 [222]	R_{W^+/W^-}	1.40 ± 0.01 (stat) ± 0.02 (syst)	1.6%	1.42 ± 1.4%
13 [219]	R_{W^+/W^-}	1.3159±0.0017 (stat) ± 0.0053 (syst)	0.43%	1.307 ± 1.3%
5.02 [219]	$R_{W/Z}$	12.505 ± 0.037 (stat) ± 0.032 (syst)	0.39%	12.51 ± 0.96%
8 [222]	$R_{W/Z}$	13.26 ± 0.15 (stat) ± 0.21 (syst)	1.9%	13.49 ± 2.1%
13 [219]	$R_{W/Z}$	12.078±0.028 (stat) ± 0.032 (syst)	0.35%	12.02 ± 2.3%

Experimental measurements

Luminosity uncertainty cancels out. Other uncertainties reduced.

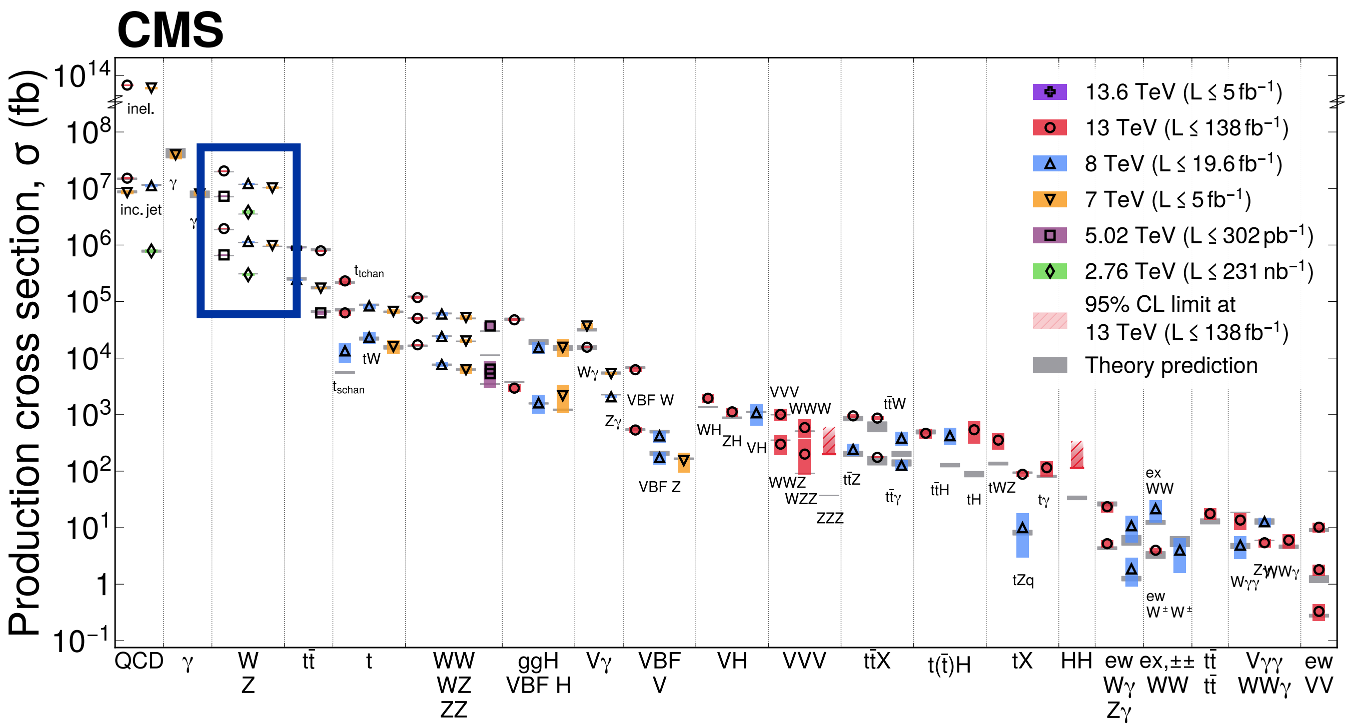
Theory calculation

Scale uncertainties reduced

Both achieve sub 0.5% uncertainty in best cases!

Not the same best cases.

Fid exp best - Total theory best



CMS xs review

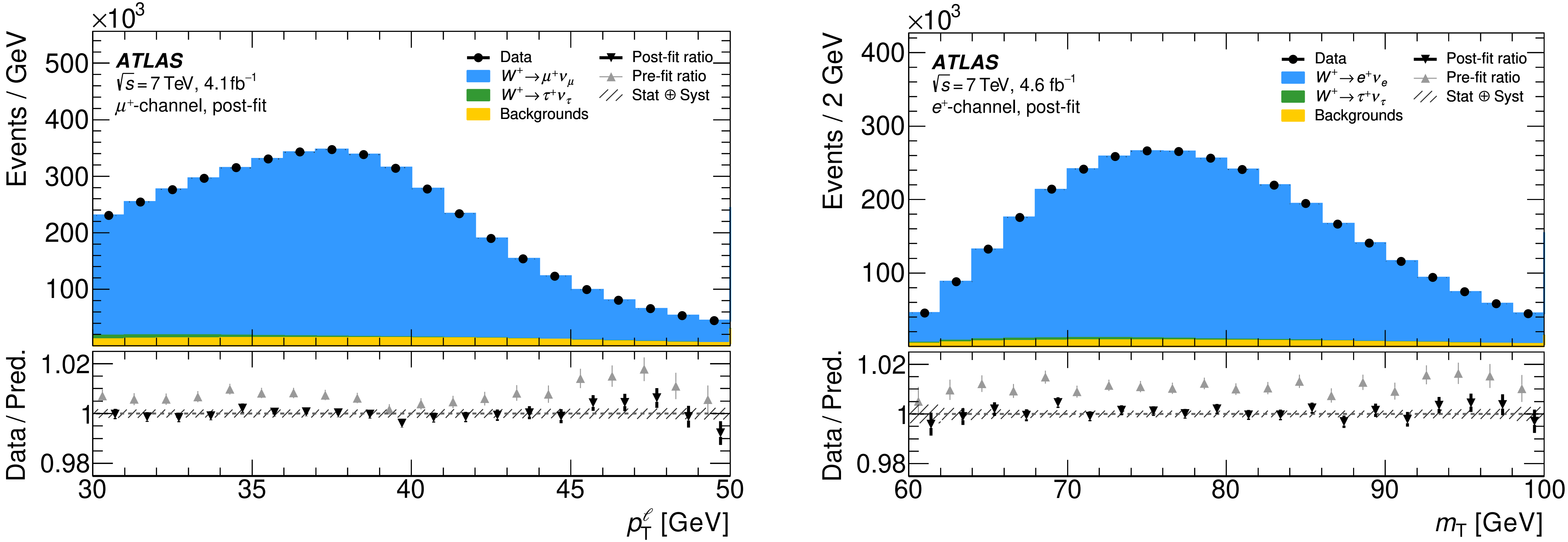
Measurements of EW Parameters

m_W, $\sin^2\theta^l_{eff}$

W mass – ATLAS Improved measurement of m_W and also Γ_W

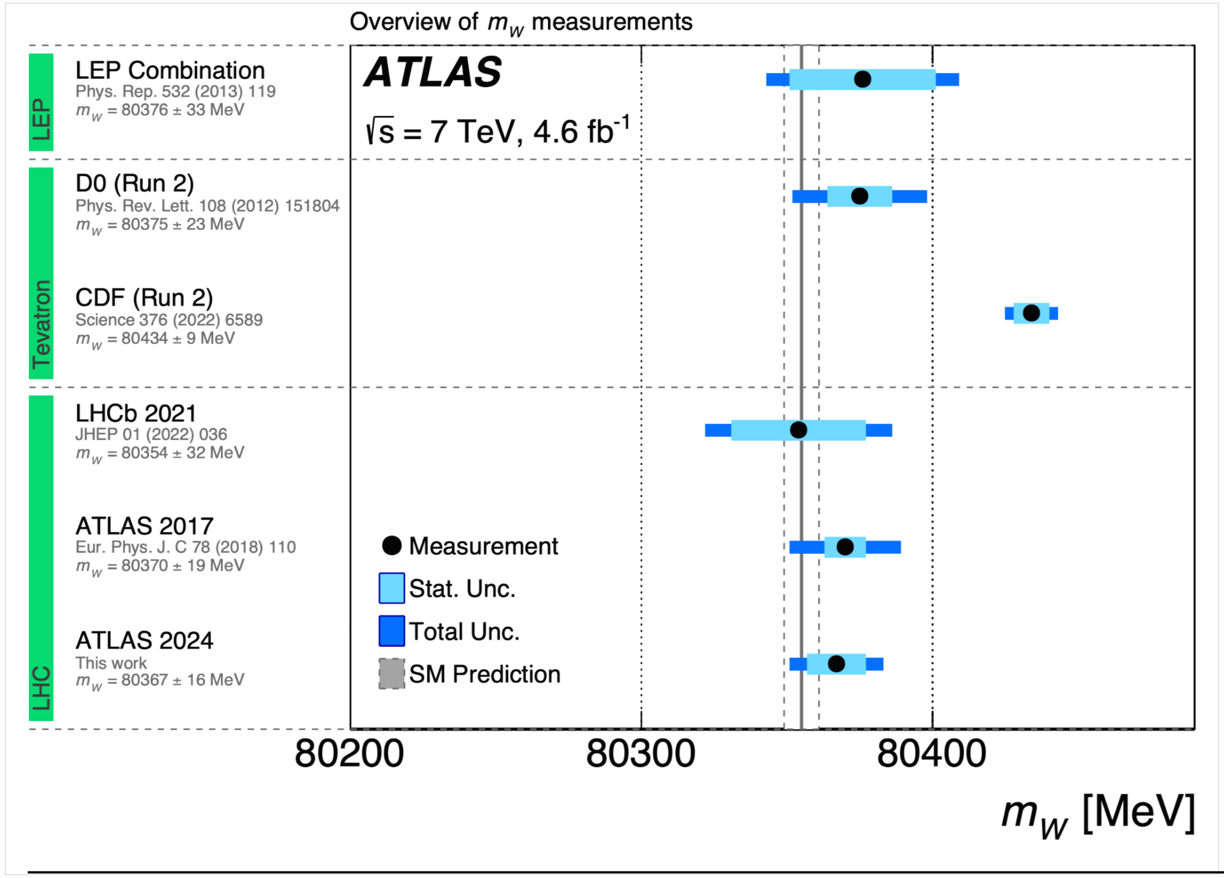
- Profile likelihood fit of $p_T(l)$ and $m_T(W)$
- Best modeling of W production kinematics and hadronic recoil
  - NLO Powheg reweighed with NNLO calculations, NNLO PDFs, Pythia 8 with AZNLO tune based on Z data
  - Predicts W pT distribution well at 5.02 and 13 TeV, Critical element for extracting m_W from $p_T(l)$ and $m_T(W)$

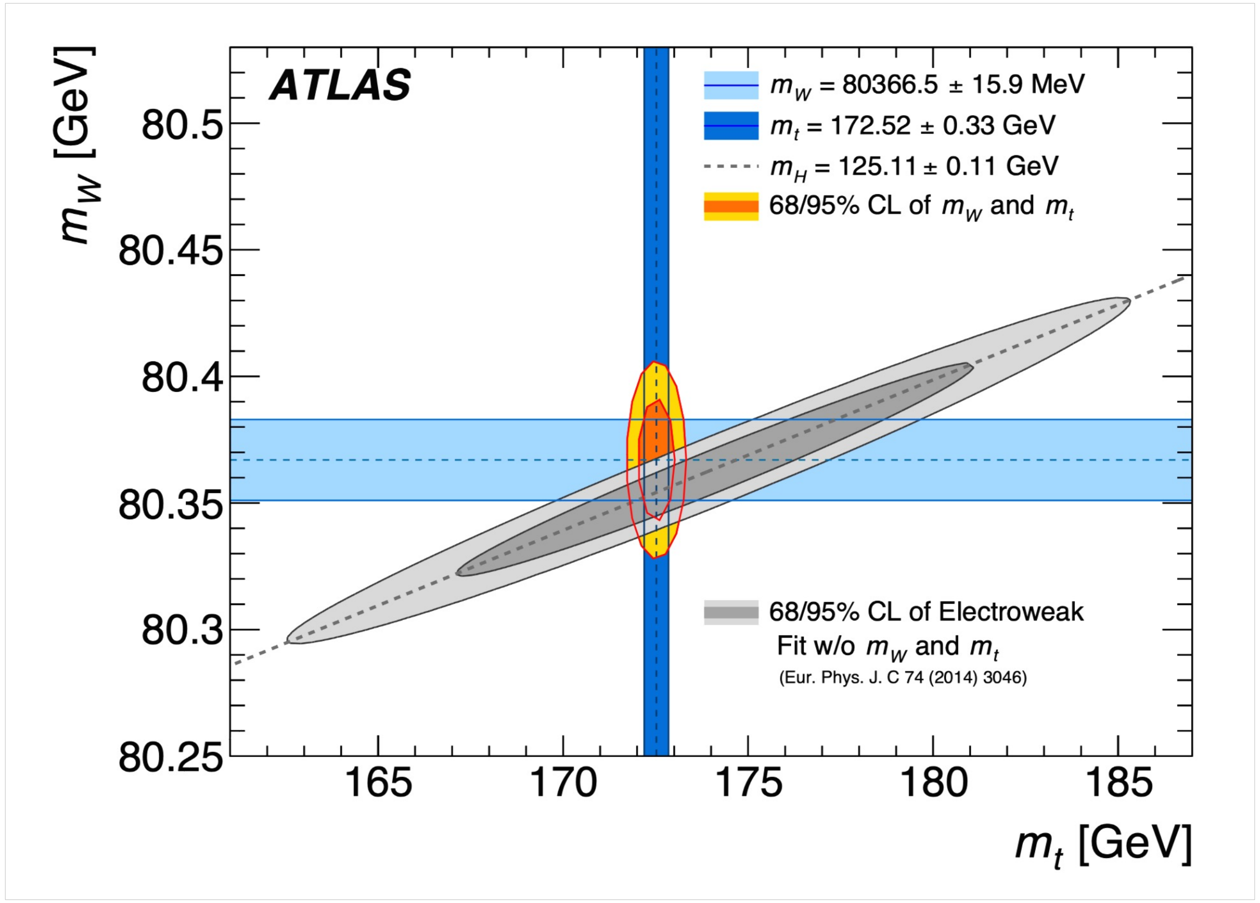
It would be interesting to see if AZNLO does well with nJet. Focused on pT(Z)



W mass - ATLAS

submitted to EPJC

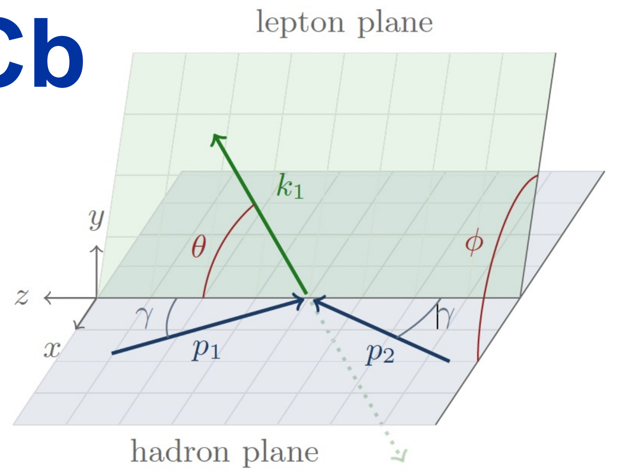




Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

Uncertainties – p_T(l) measurement dominates
Statistical component substantial
Systematic distributed over several components
Probably difficult, but possible, to match CDF uncertainty

Effective weak mixing angle – CMS, LHCb



Drell Yan, pp→l⁺l⁻ forward backward asymmetry

- A_{FB} used to determine $\sin^2\theta^l_{eff}$

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta + \frac{1}{2}A_0\left(1 - 3\cos^2\theta\right) + A_4\cos\theta$$

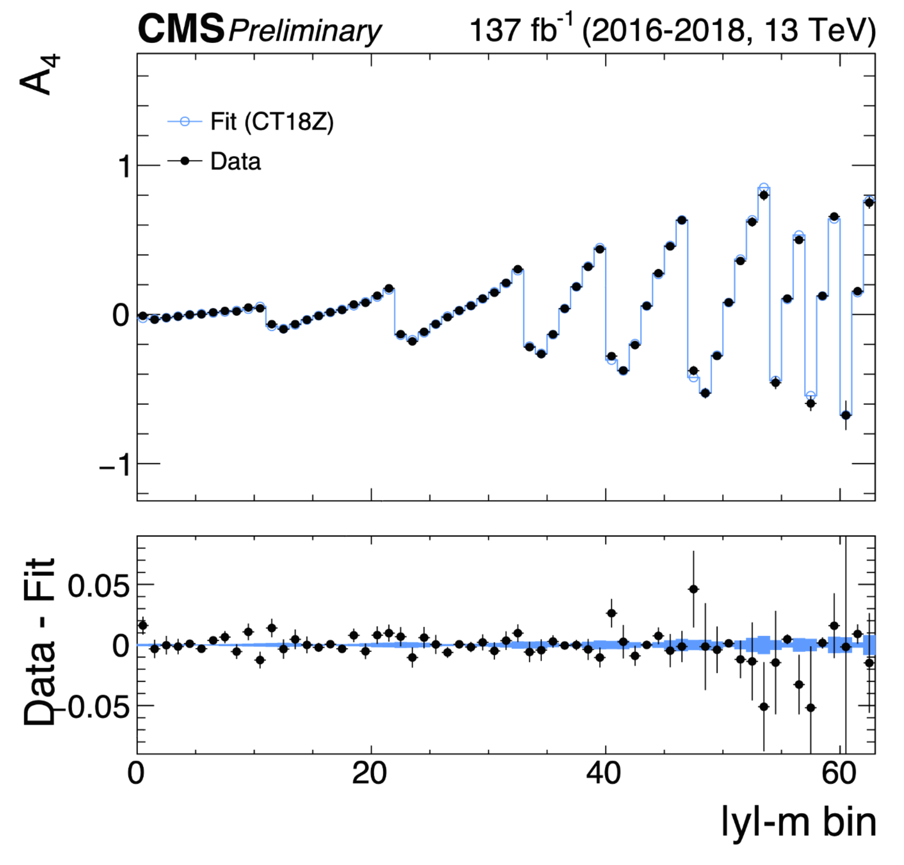
- A_{FB} due to A_4 term which depends on $\sin^2\theta^l_{eff}$
- Quark direction in the hadron plane inferred from the DY pair rapidity
- Events with forward rapidity leptons more useful for determining $\sin^2\theta^l_{eff}$

CMS includes forward HF electrons 3.14 < |η| < 4.36

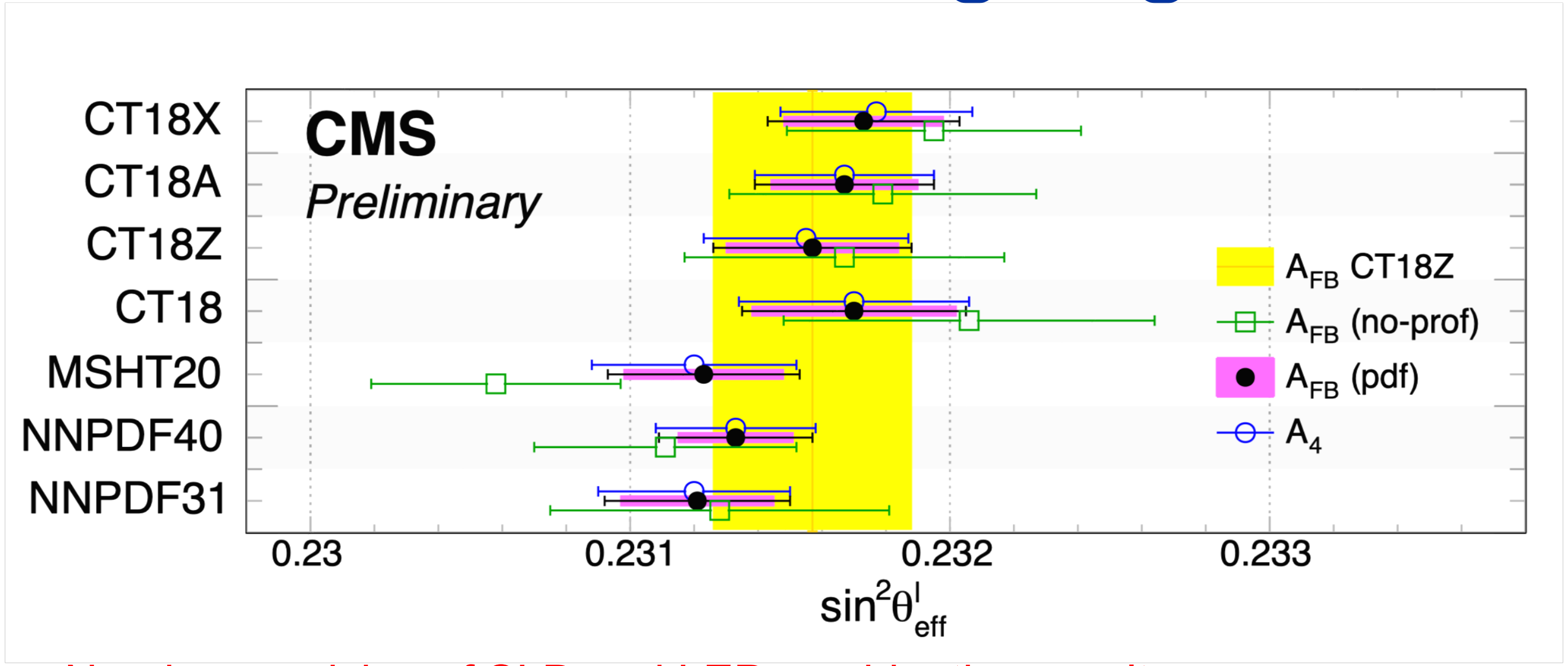
LHCb muon reconstruction 2.0 < |η| < 4.5

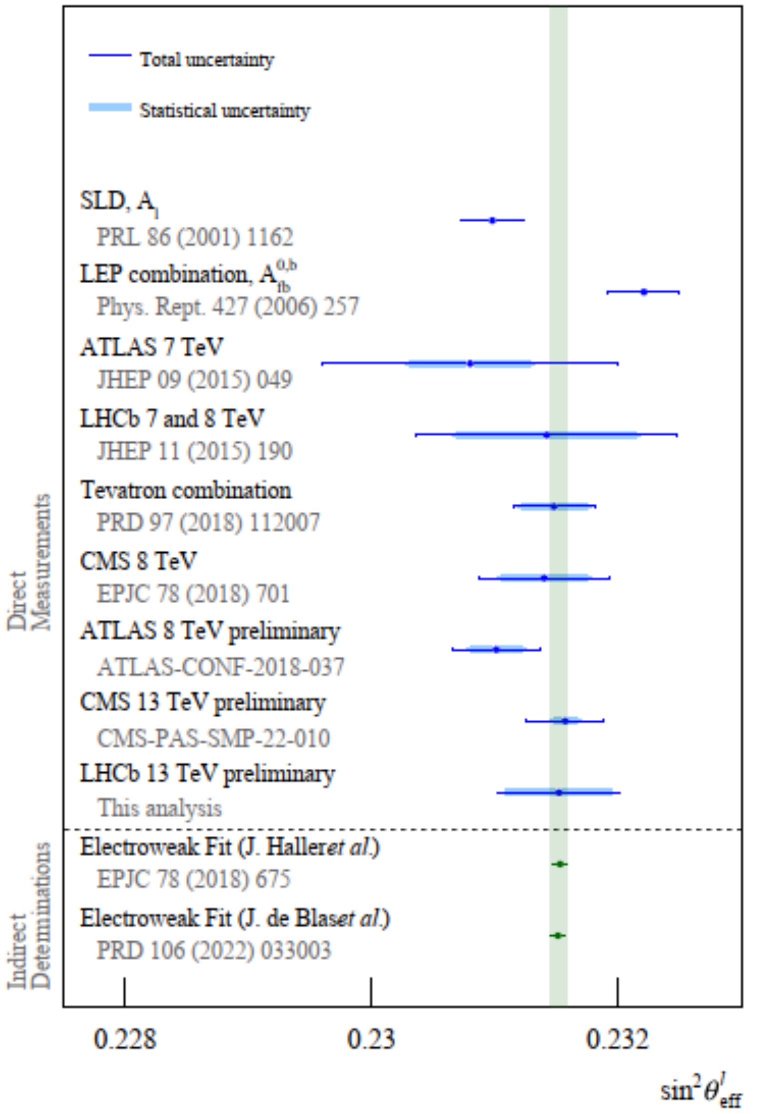
CMS Preliminary PAS-SMP-22-010

LHCb preliminary - paper in preparation



Effective weak mixing angle – CMS, LHCb



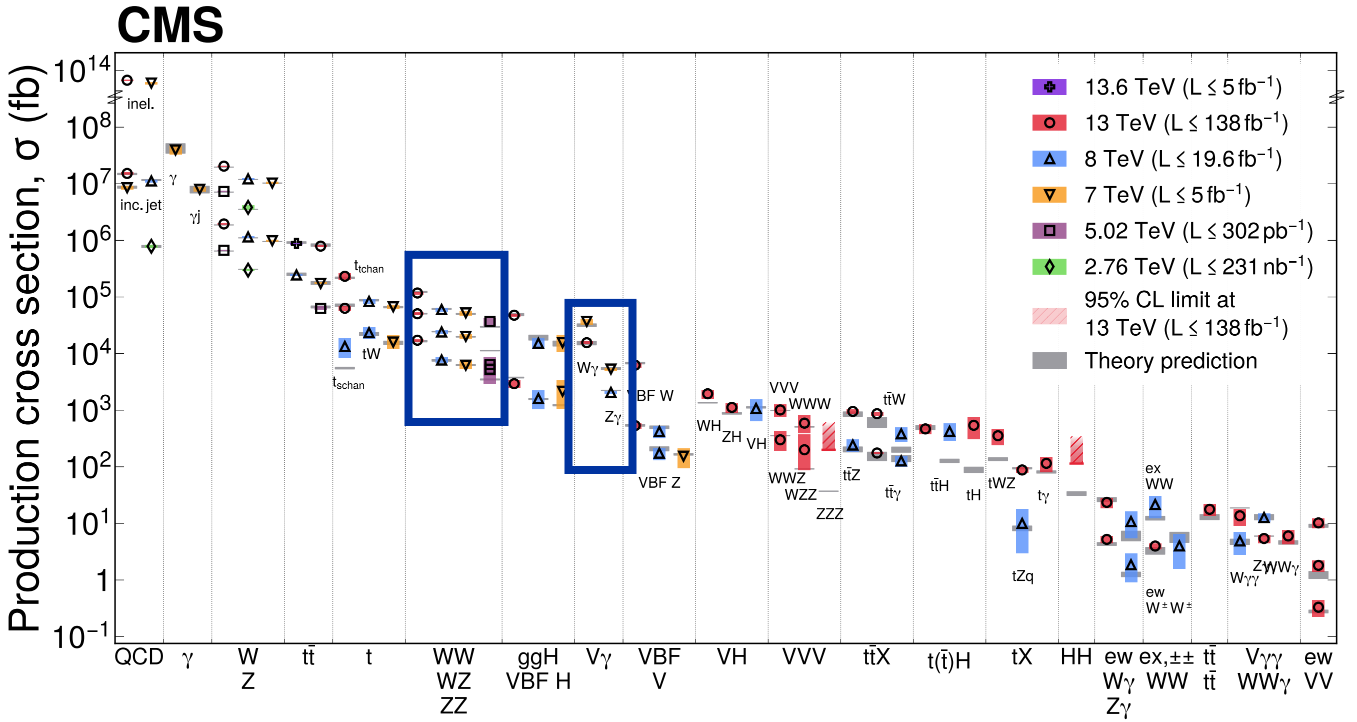


Nearing precision of SLD and LEP combination results

Hadron collider results midway between e^+e^- collider results ☺

Difference in results from various global PDF sets

PDF were profiled but a more global simultaneous QCD
Analysis of PDFs likely beneficial



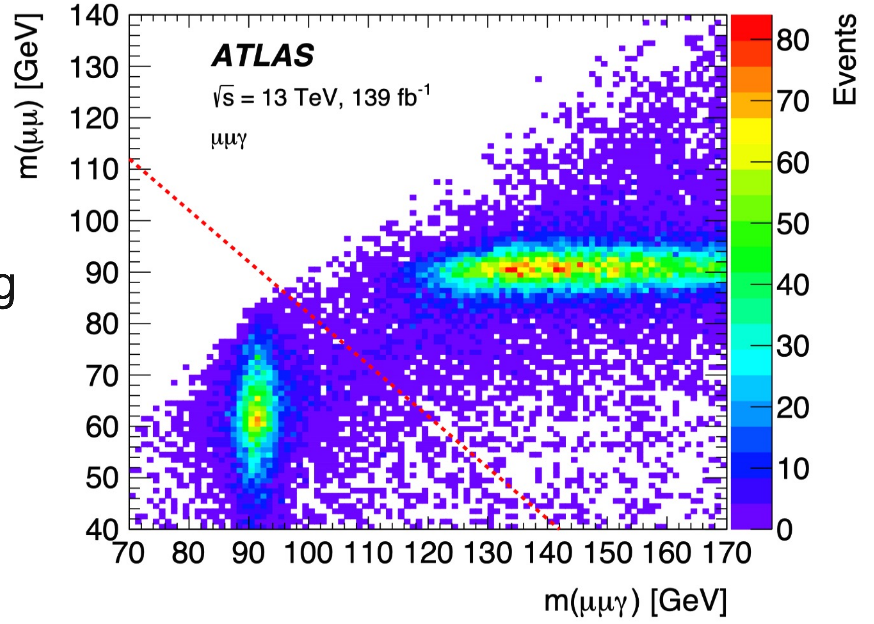
CMS xs review

Multi-boson Physics

Di-boson

Weak boson polarization, TGCs

Di-boson production cross sections



Di-boson cross sections also near the pp precision frontier

- Same advantages as W and Z physics
- Easily triggered pure data samples (typically at least one $Z \rightarrow l^+l^-$)
- Performance of lepton triggering, reconstruction, and Id calibrated using large tag and probe on large data samples.
- Good statistics due to large integrated luminosities
- Dominant uncertainties
  - luminosity uncertainty
  - Extrapolation from measurement phase space to fiducial region (small) or total cross section (larger)

The SM calculations

- NNLO QCD + NLO EW
- Dominant uncertainties
  - PDF and scale uncertainty
  - Especially when extrapolating to fiducial cross-section

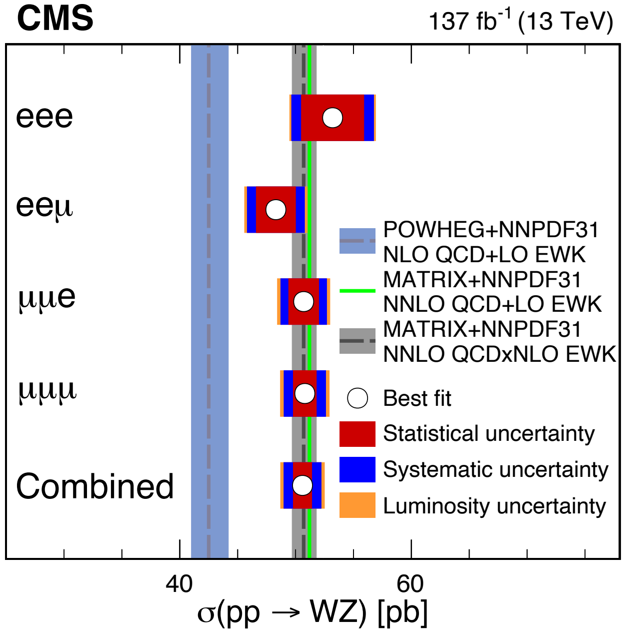
ZZ, Zγ and WZ measurement achieving precision near that of W and Z cross sections

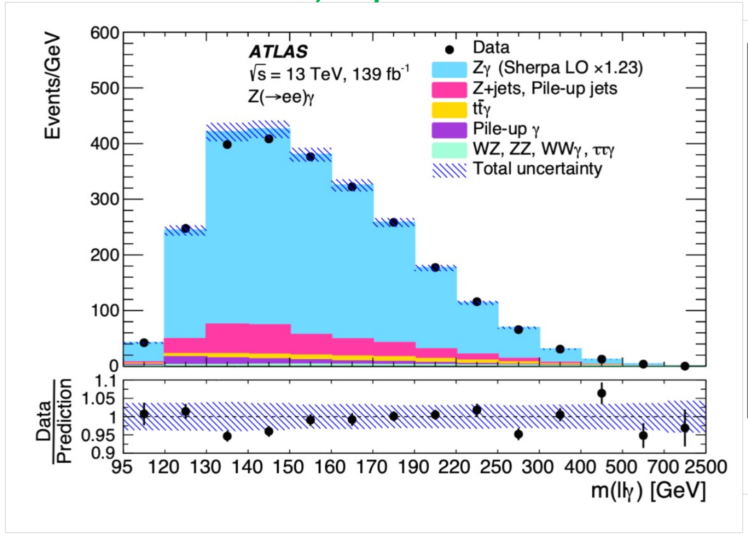
Di-boson production cross sections

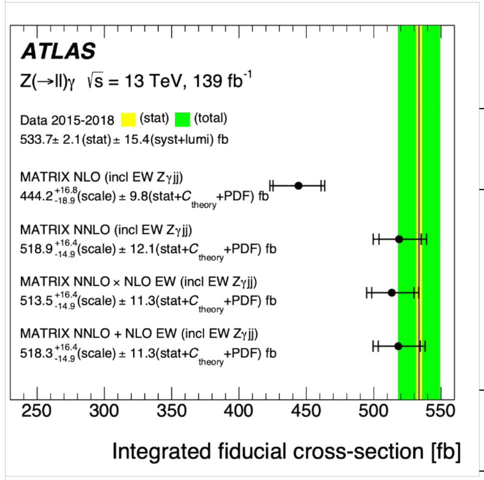
Leading precision from ATLAS Zγ, ZZ and CMS WZ measurements

JHEP 03 (2020) 054 JHEP 07 (2021) 005 JHEP 07 (2022) 032

- ZZ: 2.6% precision: 49.3 ± 0.8(stat) ± 0.8(stat) ± 0.8(lumi) (1.3 total) fb
- Zγ: 2.9% precision: 533.7 ± 2.1(stat) ± 12.4(stat) ± 9.1(lumi) fb
- WZ: 3.6% precision: 298.9 ± 4.8 (stat) ± 7.7 (syst) ± 5.4 (lumi) ± 2.7 (theo) fb
- Luminosity precision the second dominant uncertainty,
  ZZ: 2.2, Zγ: 2.5% achievable with new ATLAS luminosity. (my calculation)





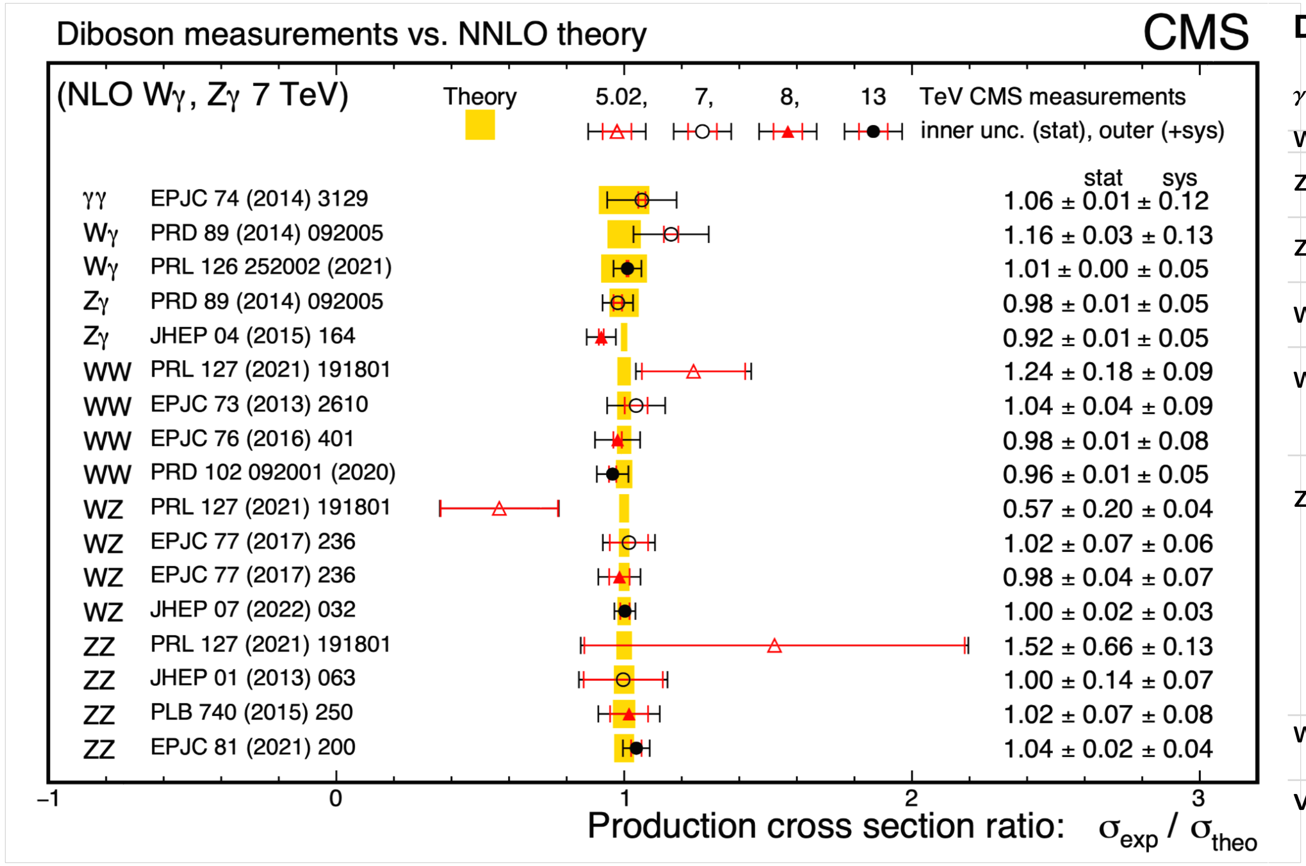


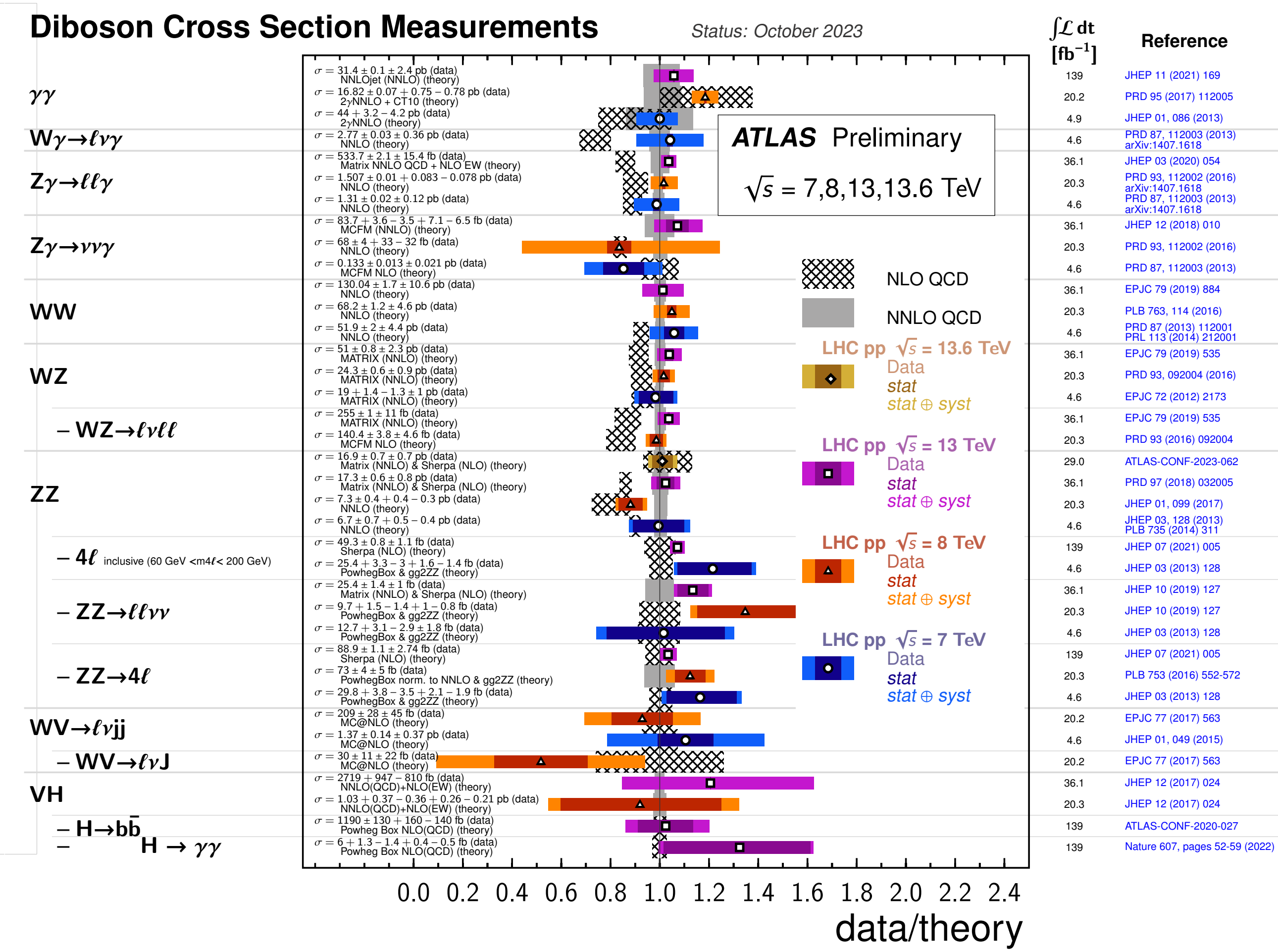
	Region				
	Full	$Z\to 4\ell$	$H\to 4\ell$	Off-shell ZZ	On-shell ZZ
Measured fiducial cross-section [fb]	88.9 ±1.1 (stat.) ±2.3 (syst.) ±1.5 (lumi.) ±3.0 (total)	22.1 ±0.7 (stat.) ±1.1 (syst.) ±0.4 (lumi.) ±1.3 (total)	4.76 ±0.29 (stat.) ±0.18 (syst.) ±0.08 (lumi.) ±0.35 (total)	12.4 ±0.5 (stat.) ±0.6 (syst.) ±0.2 (lumi.) ±0.8 (total)	49.3 ±0.8 (stat.) ±0.8 (syst.) ±0.8 (lumi.) ±1.3 (total)
Sherpa	86±5	23.6±1.5	4.57±0.21	11.5±0.7	46.0±2.9
Powheg + Pythia8	83±5	21.2±1.3	4.38±0.20	10.7±0.7	46.4±3.0

ATLAS should recalculate their Run 2 cross sections with updated luminosities! ☺

Di-boson production cross sections

Good precision achieved over a wide array of di-boson final states





Also now 13.6 TeV WZ and WW results

Di-boson differential production cross sections

Example CMS: ZZ

Submitted to JHEP

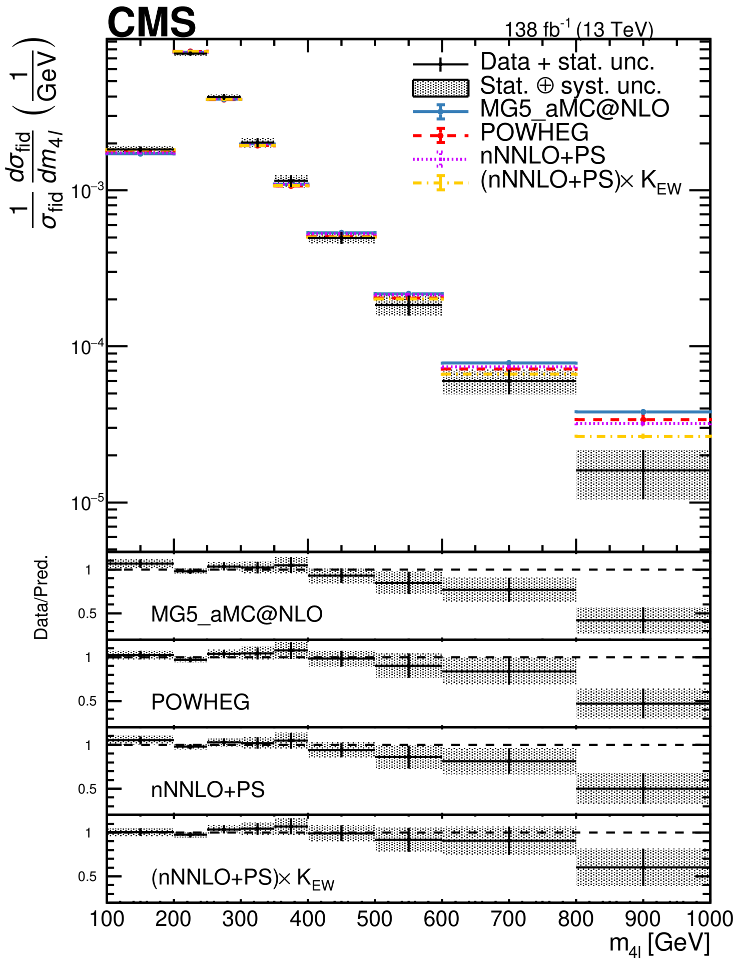
Disagreement in high mass tail m4l distribution

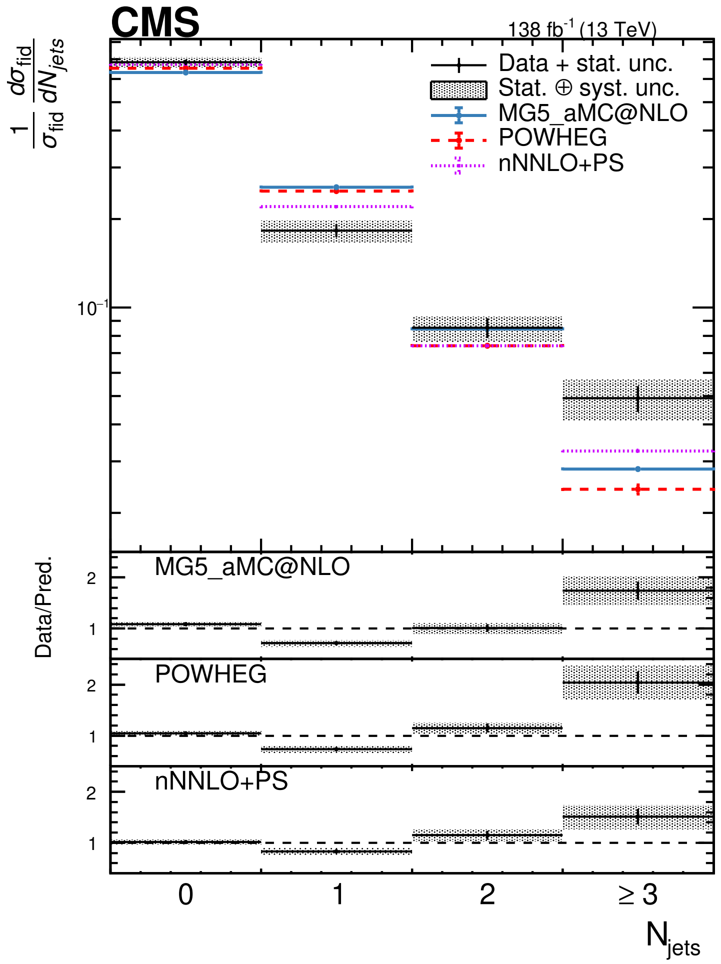
Improved by EW corrections

Disagreement in Njet distribution

Improved by nNNLO+PS MC. NNLO MC combined with PS using the MiNNLO method

QCD now extensively investigated in di-boson physics also





These disagreements were observed in previous analysis and were improved by advances in theory techniques

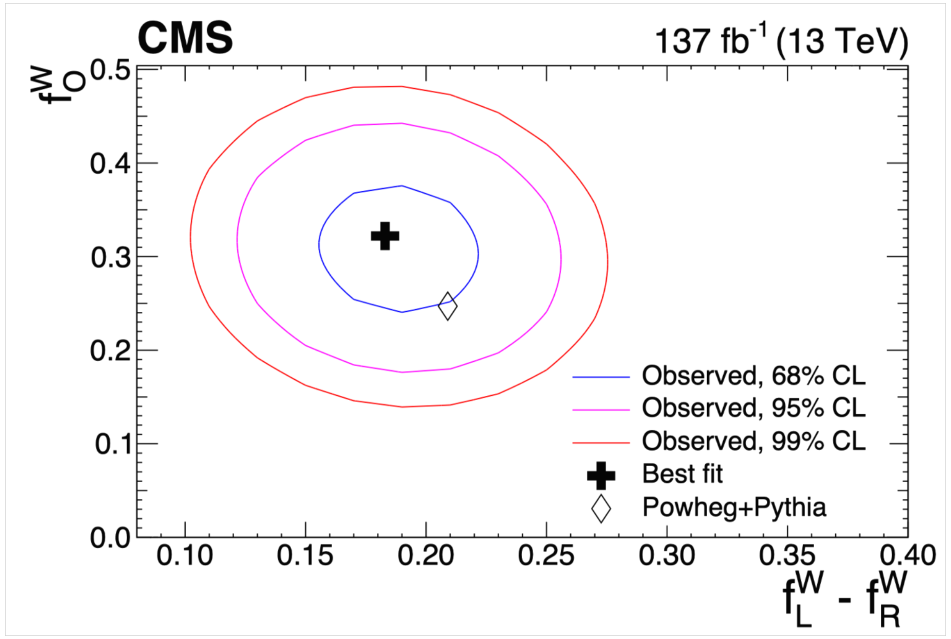
Di-boson production, weak boson polarization

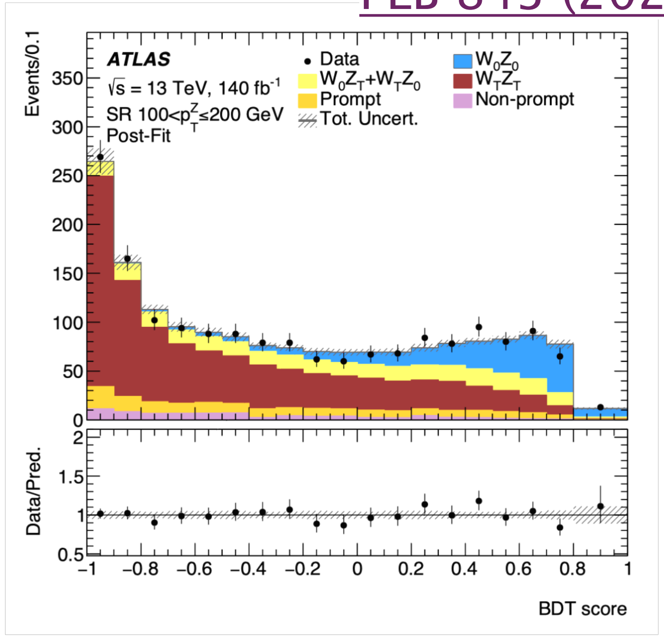
Vector boson polarization in di-boson production

- An important step toward using polarization to establish longitudinal vector boson scattering
- Longitudinal polarization state is a basic property of the weak bosons from EW symmetry breaking
- Correlations in polarization can test quantum entanglement
- CMS: Observation of individually longitudinally polarized W and Z bosons in WZ production
- ATLAS: Observation longitudinally polarized boson pairs in WZ and evidence in ZZ production (4.3σ)

JHEP 07 (2022) 032

PLB 843 (2023) 137895 JHEP 12 (2023) 107





Single boson polarization extracted from cos(θ)

θ of the lepton relative to boson flight direction in the boson CM frame

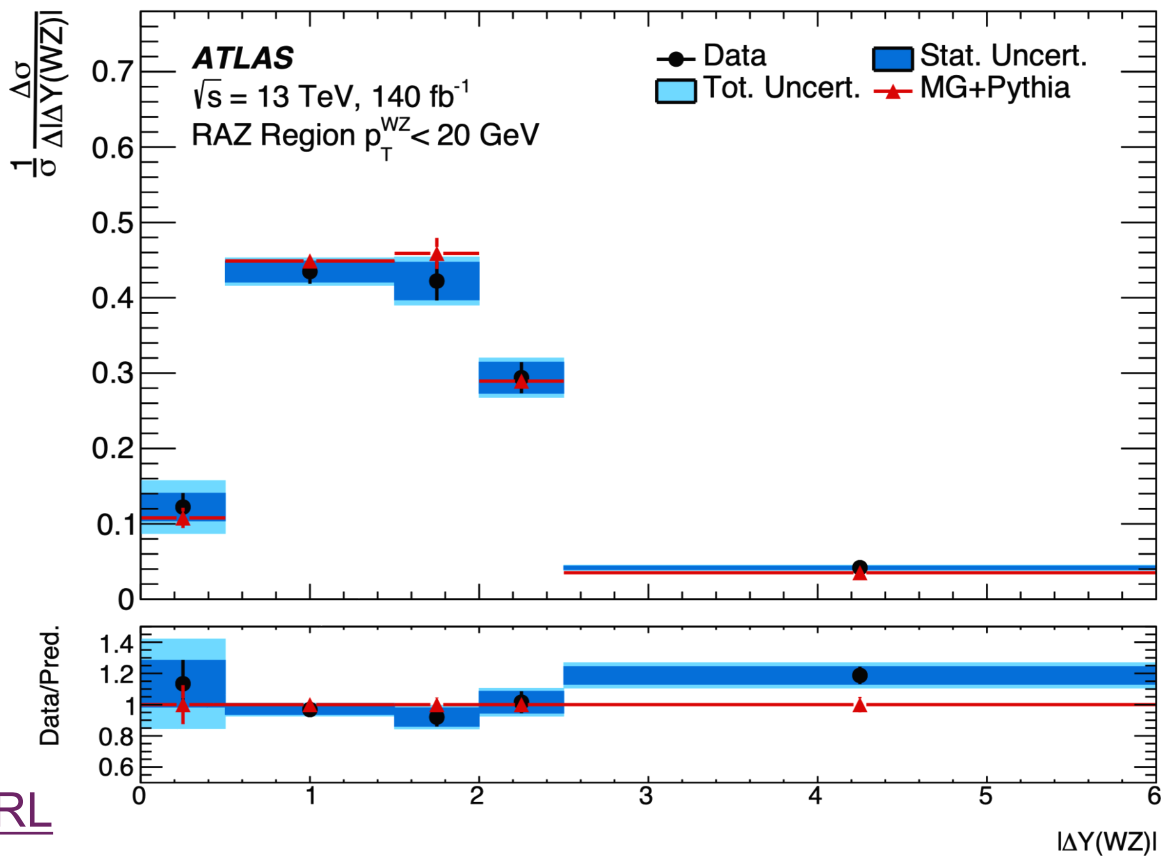
Joint polarization required a multivariate discriminant

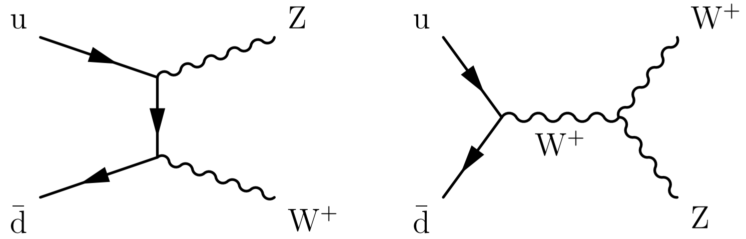
Di-boson production, WZ, polarization, RAZ, TGCs

WZ Radiation Amplitude Zero (RAZ)

- LO WZ production occurs via interfering t channel and triple gauge coupling (TGC) vertex s channel diagrams
- In the transverse-transverse polarization state there is an exact RAZ when W boson is scattered at 90° with respect to the incoming antiquark direction in the WZ rest frame
- This occurs because of an exact cancelation due to interference with the TGC diagram.
- The RAZ is inexact at NLO
- Most easily observed as a dip near zero in ΔY(WZ)
- This represents one of the few ways in di-boson production to directly observe a TGC and thus a predicted effect of the gauge structure of the SM

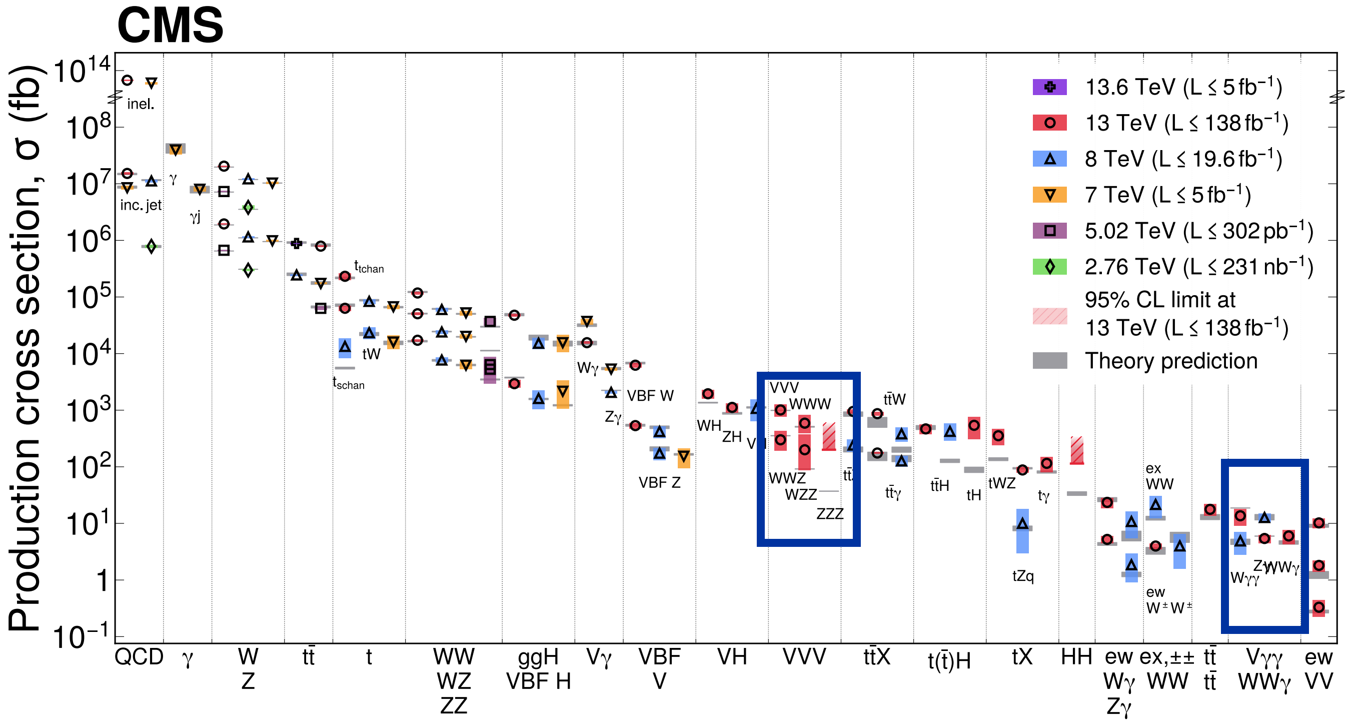
Accepted by PRL





TT signal only – TL, LT, LL subtracted as a background, pT(WZ) < 20 GeV (more LO like)

Approximate RAZ clearly observed!



CMS xs review

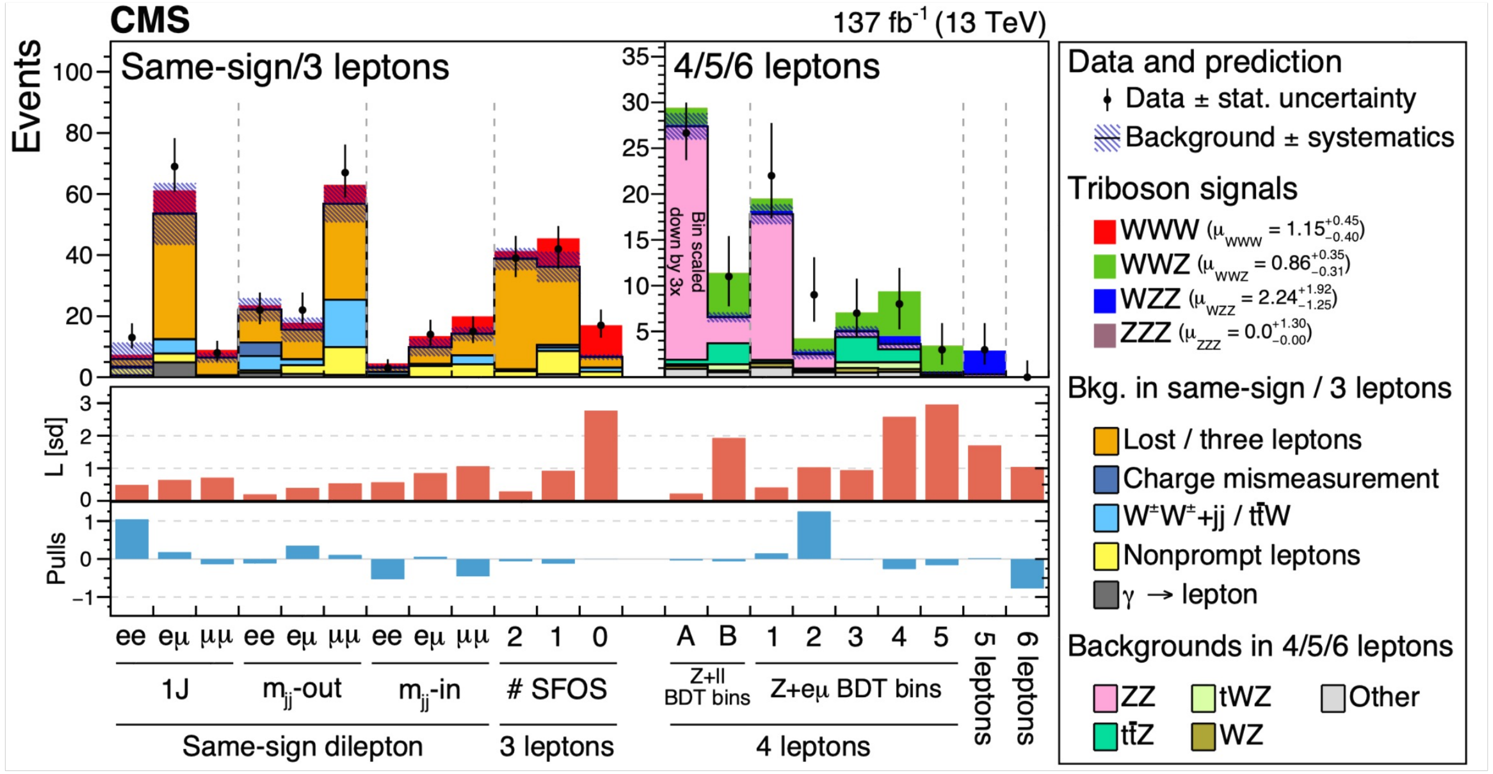
Multi-boson Physics

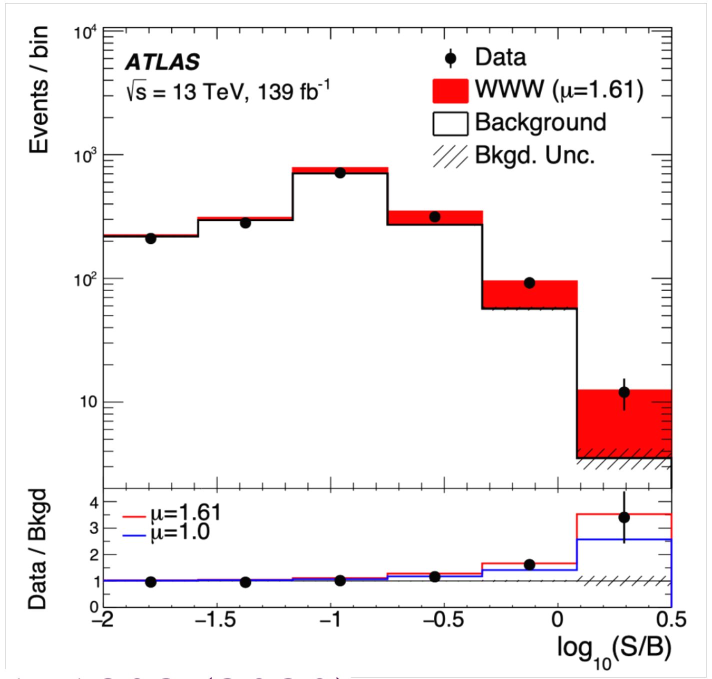
Tri-boson

Tri-boson production

Tri-boson production many states only accessible at LHC

- Most interesting states, the most difficult to observe, are VVVs. Three weak bosons
- Collectively observed by the CMS experiment. WWW observed at ATLAS. WWW, WWZ evidence CMS.
- Extensive analyses pursing all accessible leptonic and hadronic decay modes





PRL 125, 151802 (2020)

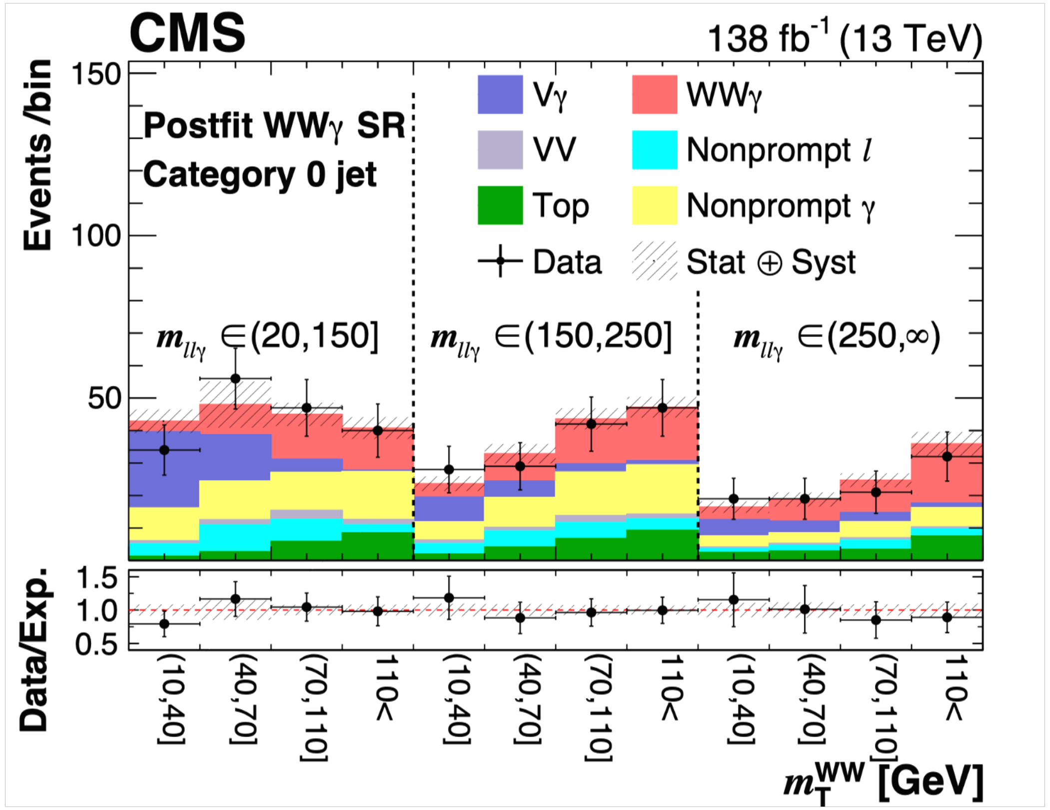
VVV production collectively observed CMS
WWW observed ATLAS.

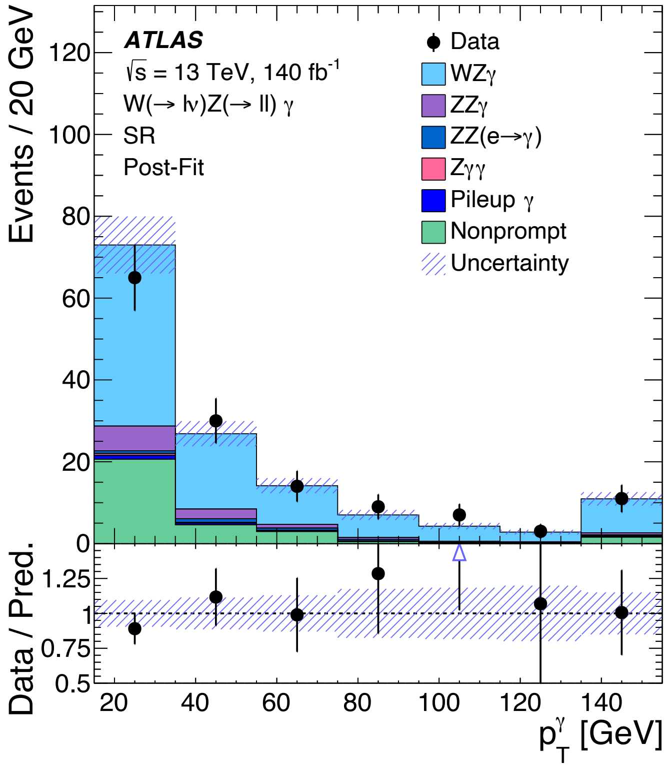
PRL 129 (2022) 061803

Tri-boson production

Several states with two weak bosons and all but one state with three yet to be observed.

- CMS WWγ: 6.0 ± 0.8 (stat) ± 0.7 (syst) ± 0.6 (modeling) fb, 5.6σ
- ATLAS WZγ: 2.01 ± 0.30(stat) ± 0.16(stat) fb, 6.3σ



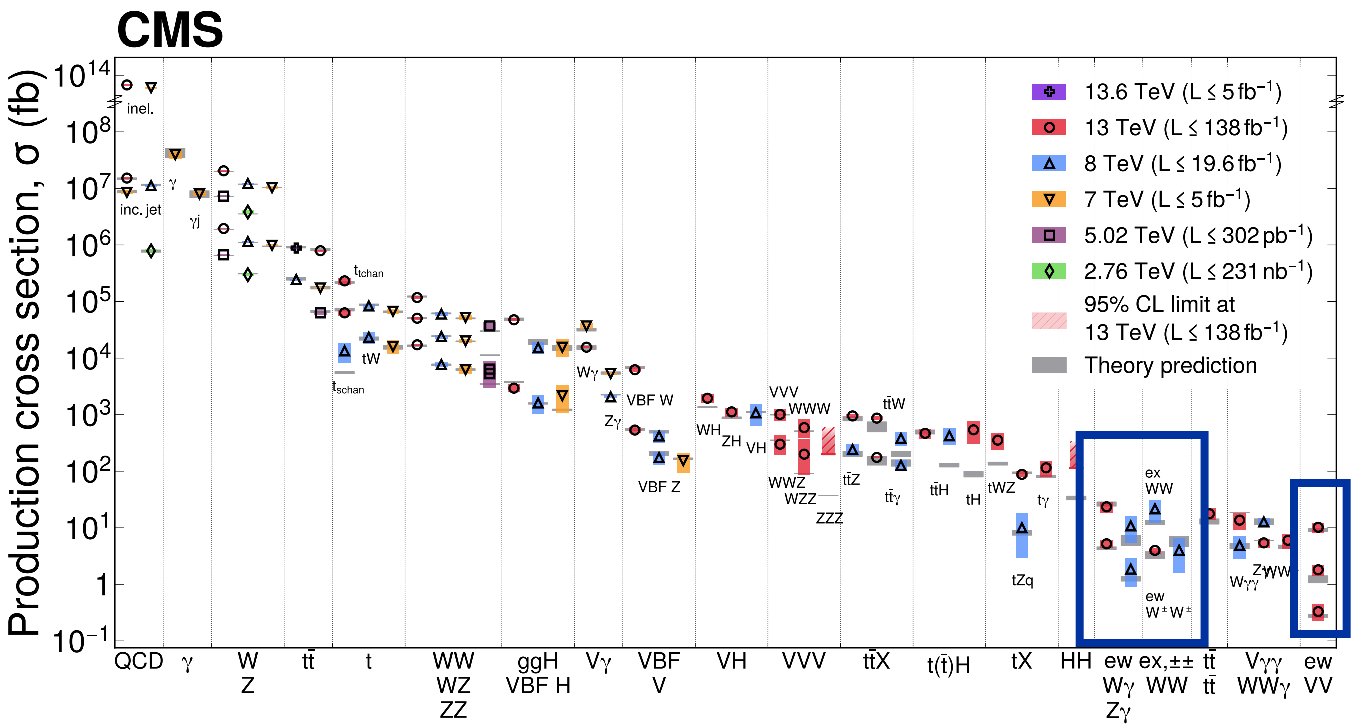


PRL 132 (2024) 121901

CMS : WWγ observed!

ATLAS: WZγ observed!

PRL 132 (2024) 021802



Multi-boson Physics

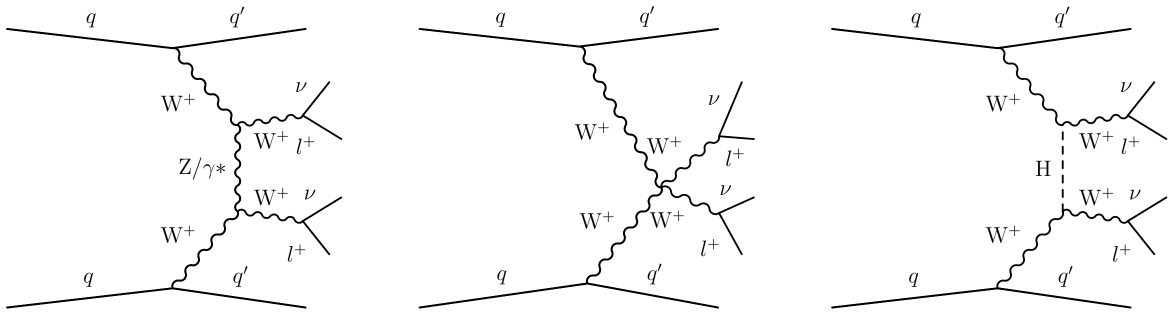
Vector boson Scattering

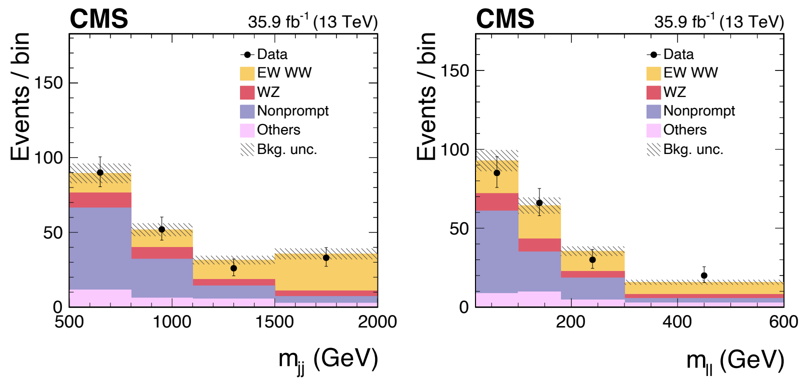
Weak boson polarization, QGCs

Vector boson scattering

Vector boson scattering (VBS) physics currently unique to the LHC

- Cross sections as small as fb or a fraction of a fb require LHC luminosities to produce observable signals
- VBS diagrams - purely EW interactions.
- Possible to isolate areas of phase space where interference with ”QCD” diagrams is minimal
- Production Diagrams include
  - Double TGC in t (and s) channel
  - Quartic gauge coupling (QGC) diagrams: possible to directly measure quartic couplings
  - Higgs scattering: scattering via the Higgs necessary to unitarize the cross section of longitudinal VBS
  - Interfering QCD diagrams
- Final state: forward scattered jets with a large rapidity difference and centrally produces boson pair



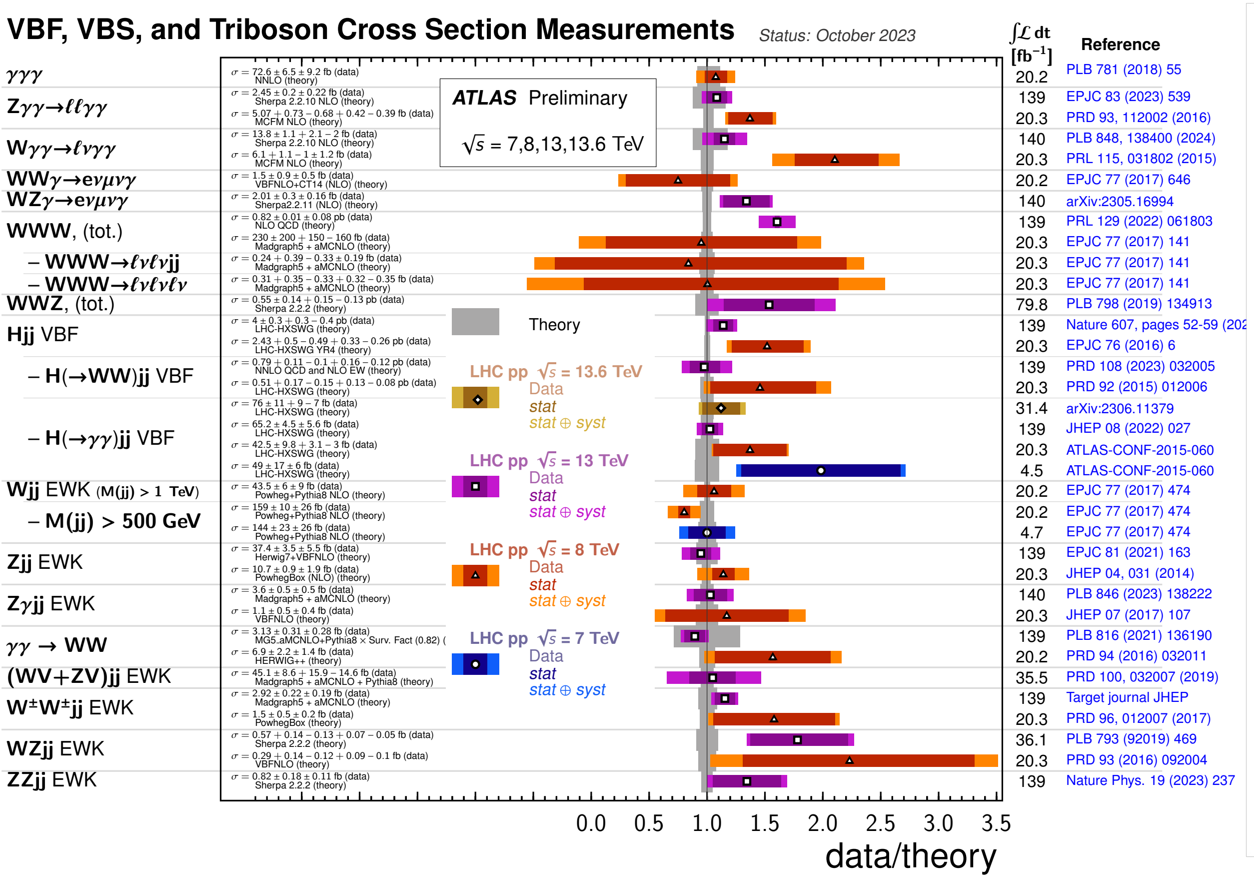


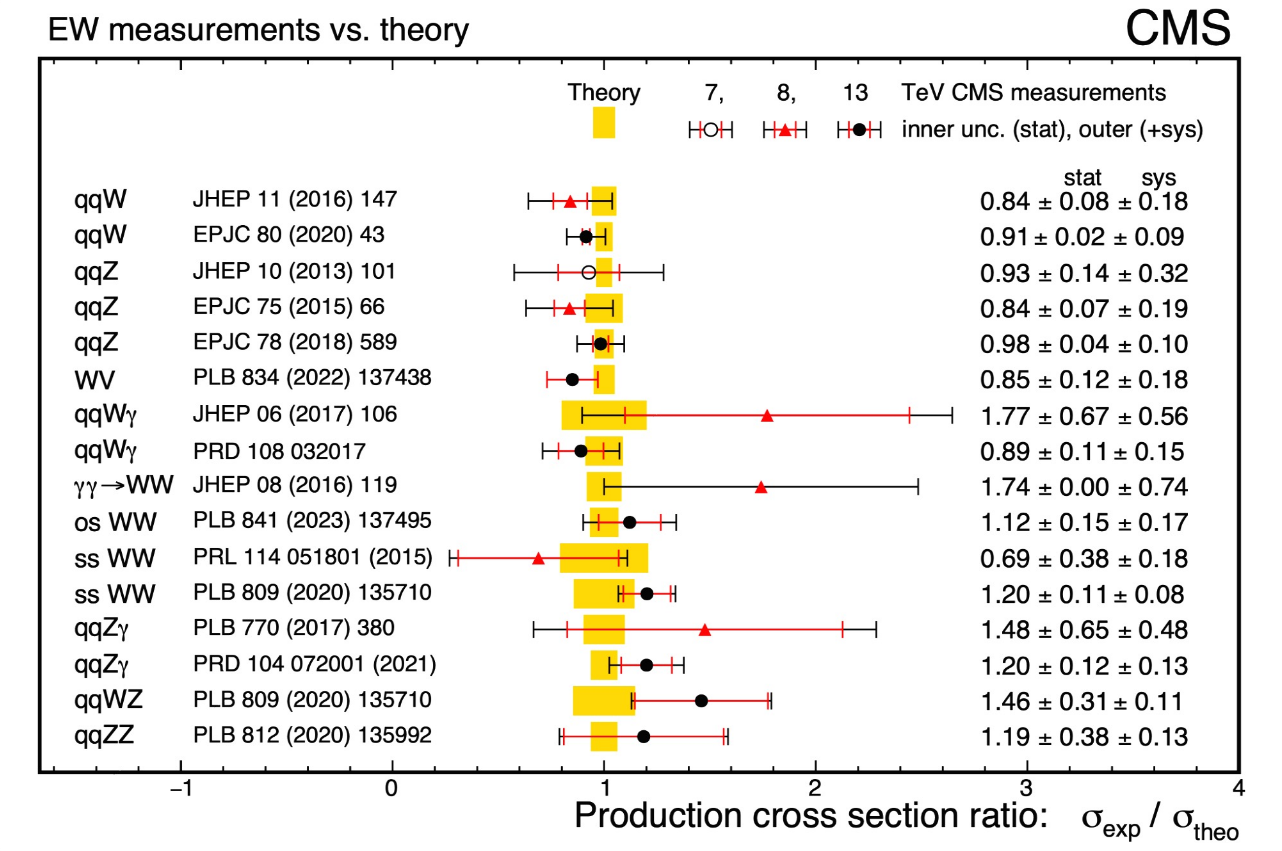
First observed CMS W±W± 5.5σ

PRL 120, 081801 (2018)

Vector boson scattering

With the full Run 2 data set all VBS final states observed





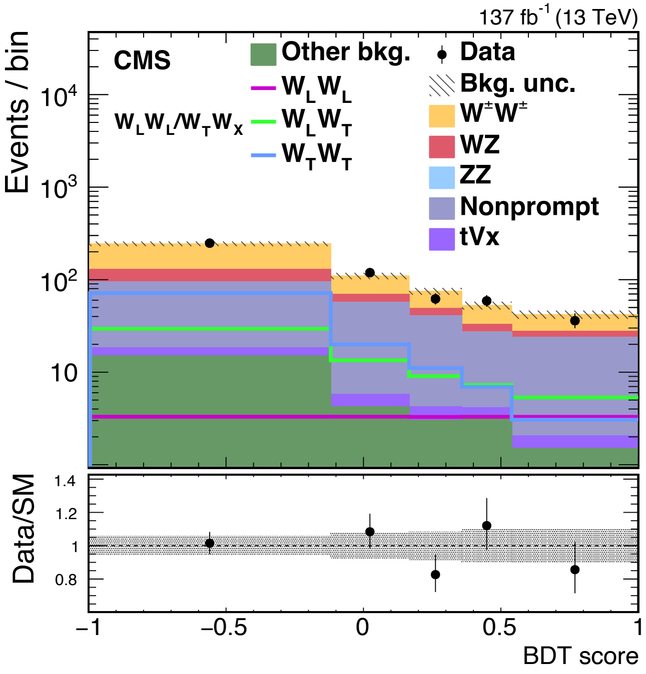
Onward to polarized VBS

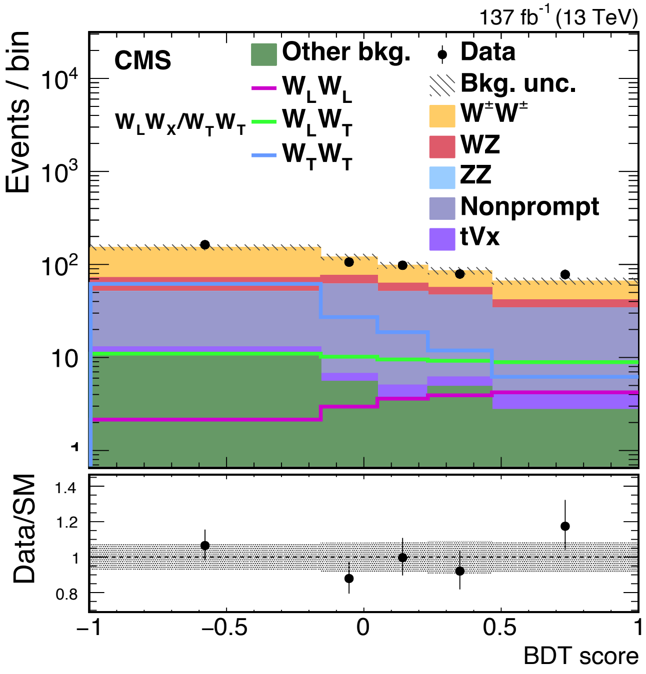
Search for polarized VBS in W±W± - CMS

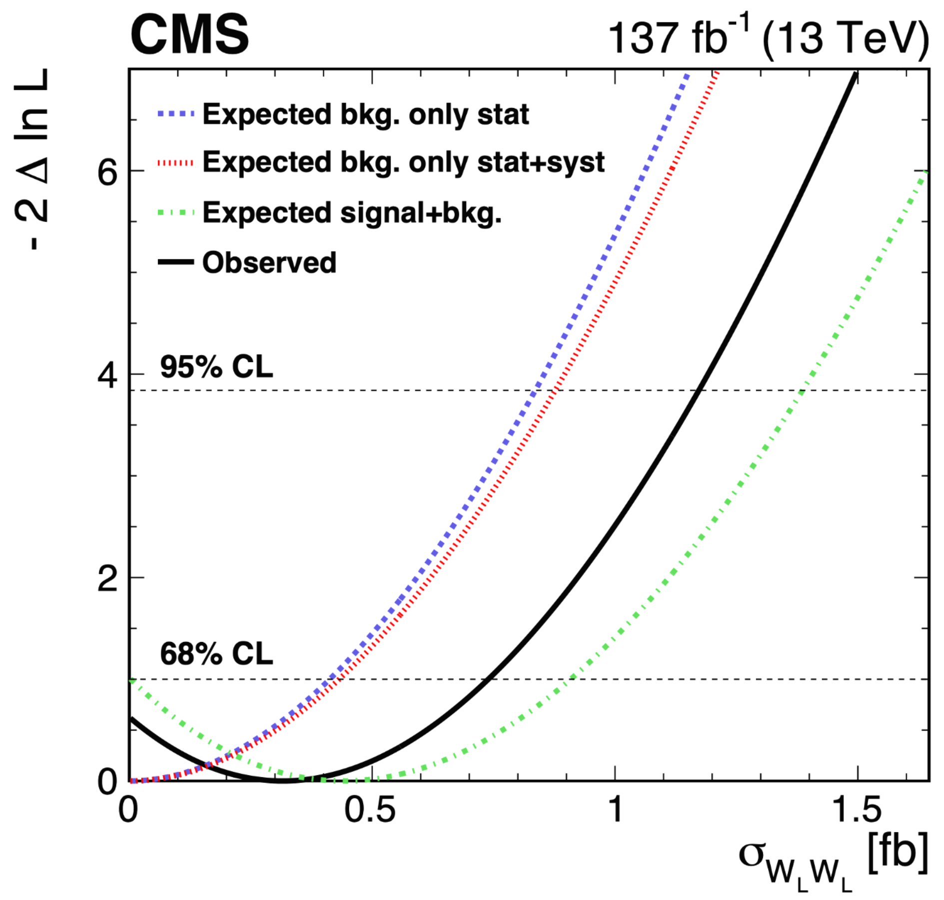
PLB 812 (2020) 136018

Searches now starting for longitudinal VBS

- Use W±W±, final state used for first observation
- Distinctive same charge final state
- Smaller background of QCD induced W±W±
- Multivariate discriminant needed to maximize sensitivity







Expected (observed) significance for one longitudinal boson 3.1(2.3)σ

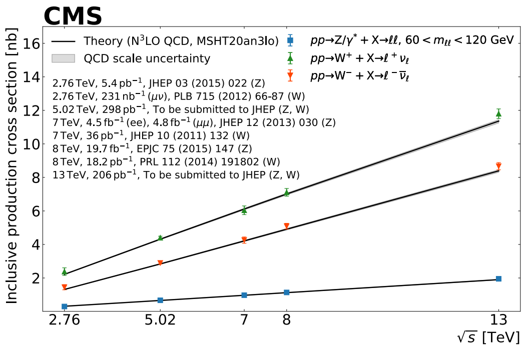
Expected σ_{LLSM} = 0.44 fb

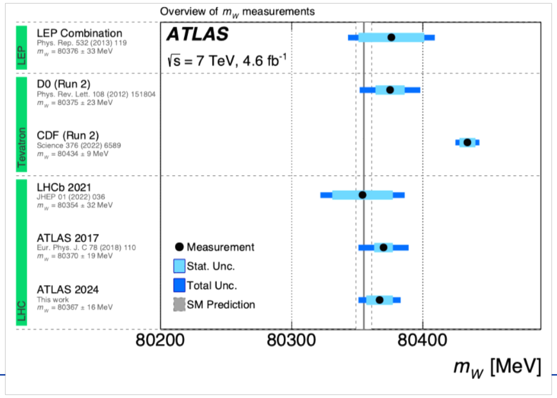
Limit 95% C.L. σ_{LL} < 1.06 fb,

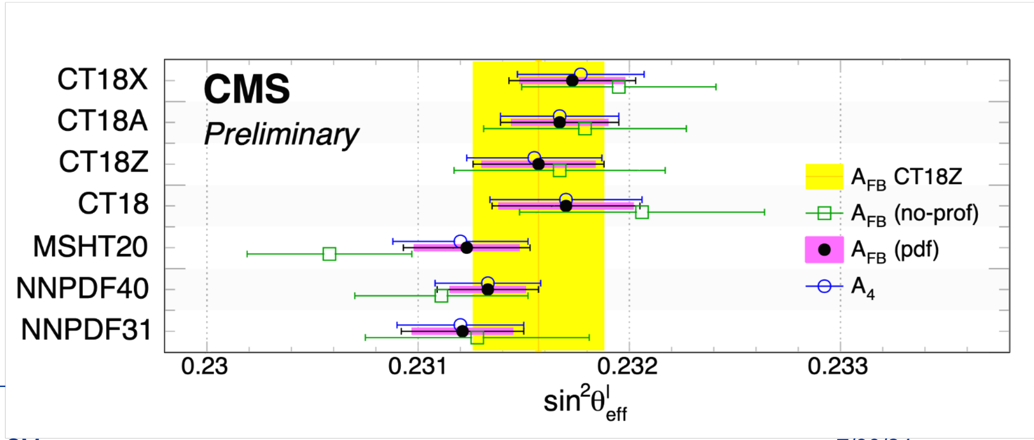
Summary

CMS and ATLAS have measured a wide array of SM cross sections and parameters

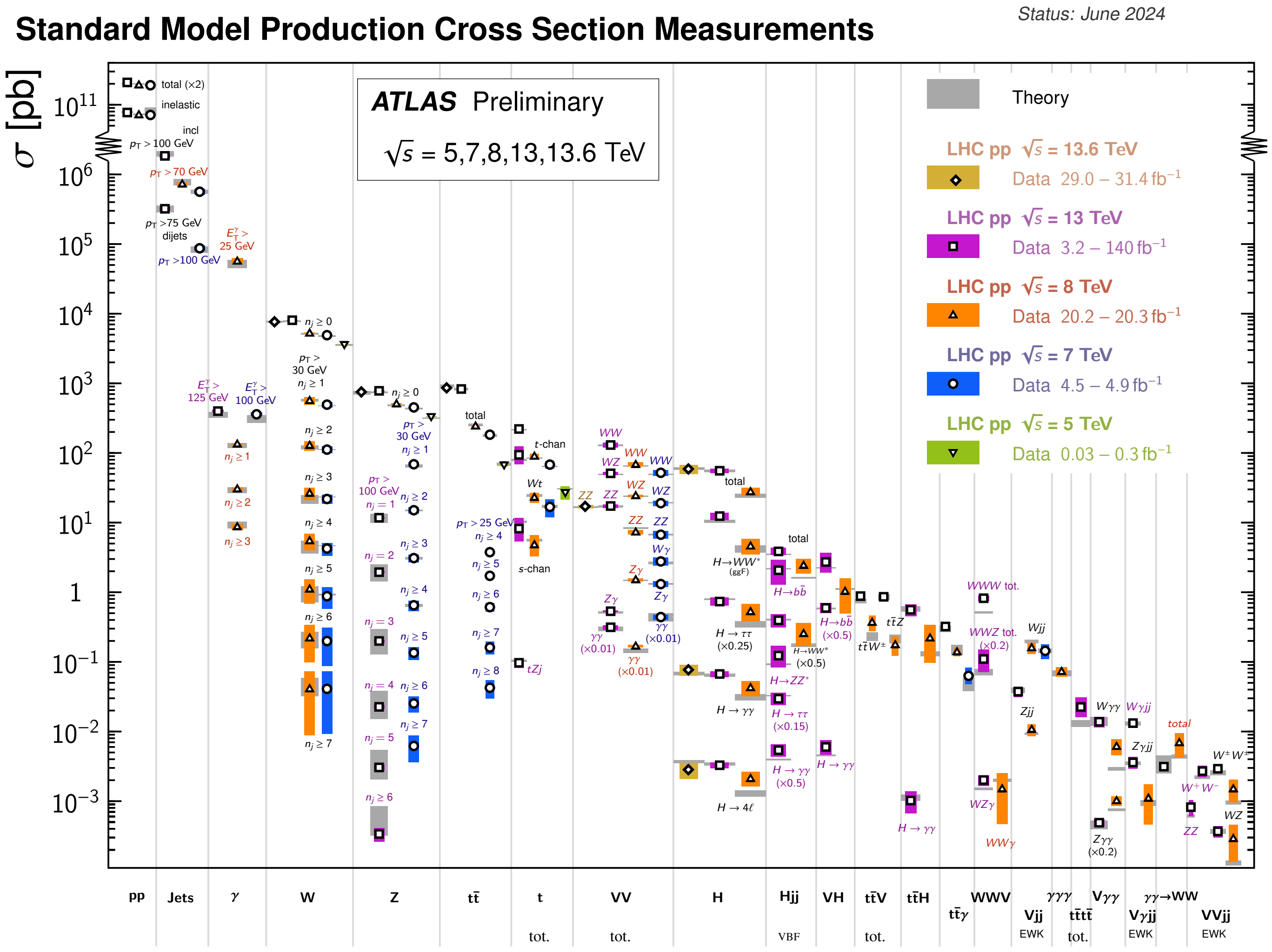
- Almost every basic QCD+EW final state you expect to produce at the LHC
- The highest precision cross section measurement have reached 2% uncertainty and 1% is likely achievable
- Measurements of fundamental SM parameters are becoming competitive and will soon surpass those of previous experiments
- The complex gauge structure of the SM is being explored with many new measurements
- There are no substantive deviations from the SM in the current set of SM measurements
    - Deviations are often seen in complex final states involving one or many vector bosons and multiple jets
    - These are areas we expect our current calculations to be inadequate
    - However, these calculations and techniques are advancing and resolving observed discrepancies
    - When we fine a statistically significant deviation from the SM that we can't otherwise explain we should be able to state with confidence whether it is new physics



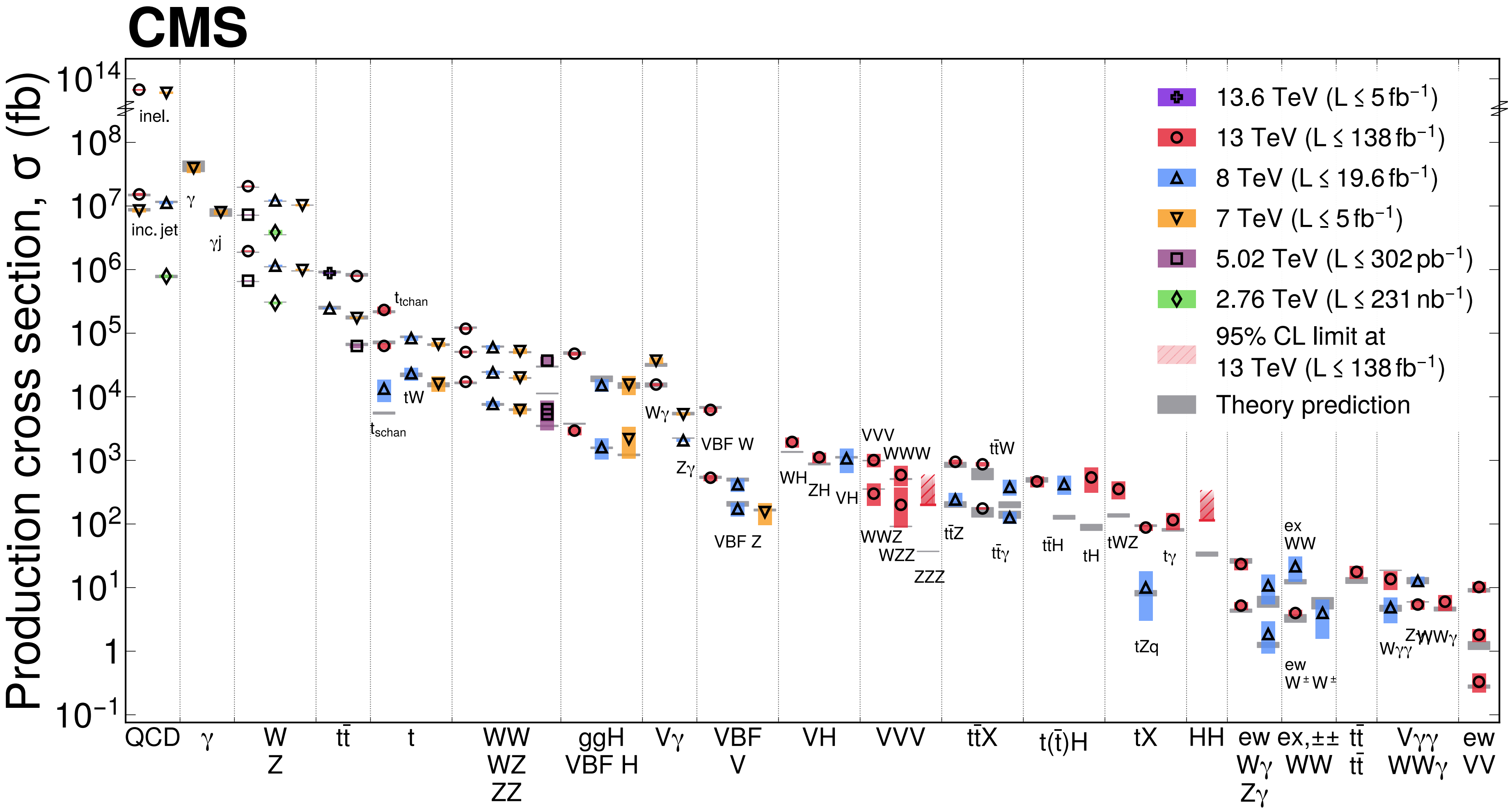




ATLAS SM Summary



CMS SM Summary



CMS SM Summary (QCD+EW)