Summary of ATLAS Standard Model Results

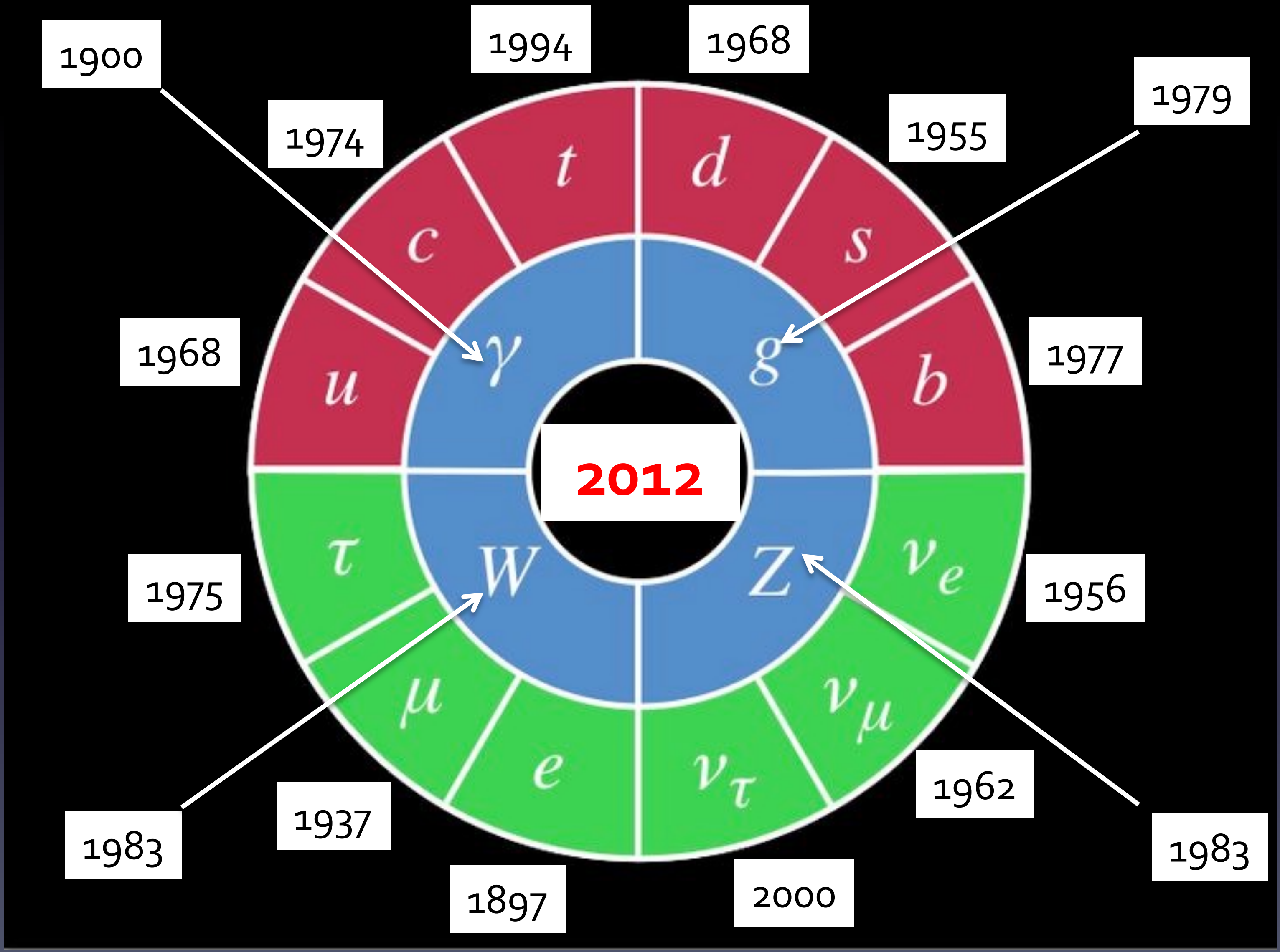
Hugo Beauchemin

Tufts University

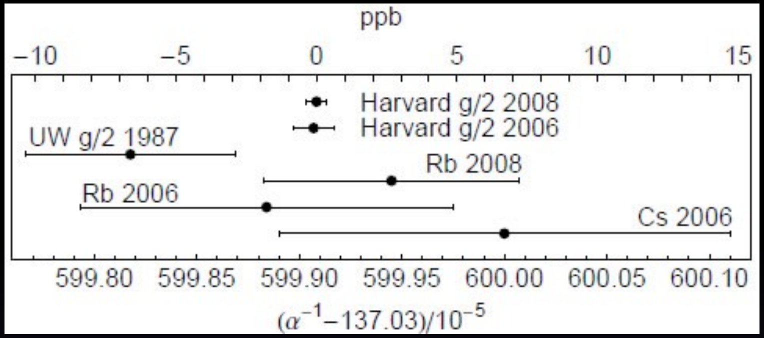
On behalf of the ATLAS Collaborations

BSM23, Hurghada (Egypt), November 9, 2023

The particle content of the Standard Model has fully been directly and unambiguously observed!

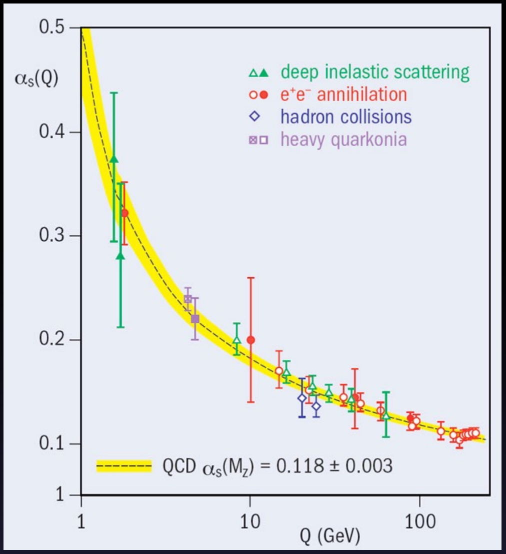


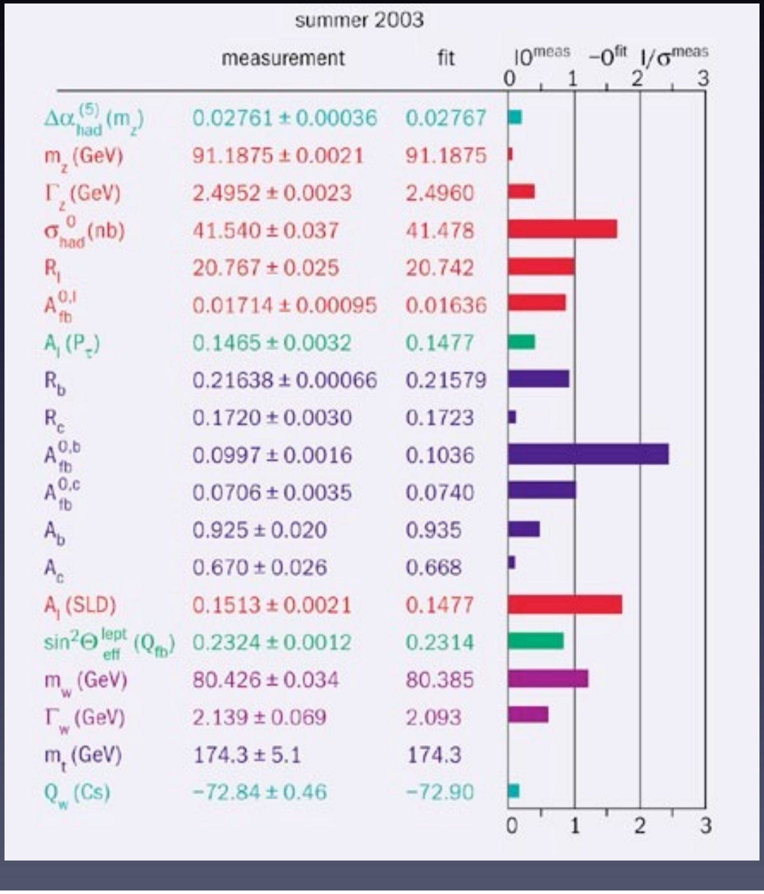
The description of the 3 fundamental interactions of the SM has long been confirmed to a high level of precision



Fine structure constant

Strong coupling constant



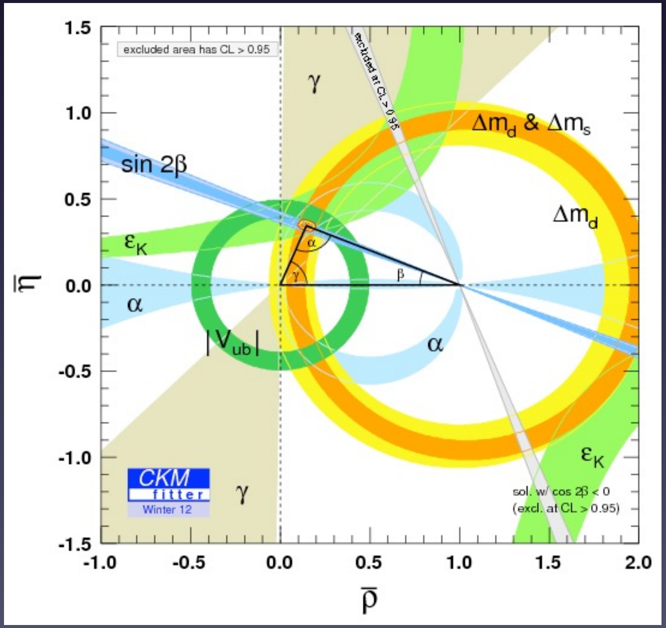


summer 2003

	measurement	fit	$\lvert O^{meas} - O^{fit} \rvert / \sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02767	
m_Z (GeV)	91.1875 ± 0.0021	91.1875	
Γ_Z (GeV)	2.4952 ± 0.0023	2.4960	
σ^0_{had} (nb)	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01636	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477	
R_b	0.21638 ± 0.00066	0.21579	
R_c	0.1720 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1036	
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0740	
A_b	0.925 ± 0.020	0.935	
A_c	0.670 ± 0.026	0.668	
A_l (SLD)	0.1513 ± 0.0021	0.1477	
$\sin^2\Theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W (GeV)	80.426 ± 0.034	80.385	
Γ_W (GeV)	2.139 ± 0.069	2.093	
m_t (GeV)	174.3 ± 5.1	174.3	
Q_W (Cs)	−72.84 ± 0.46	−72.90	

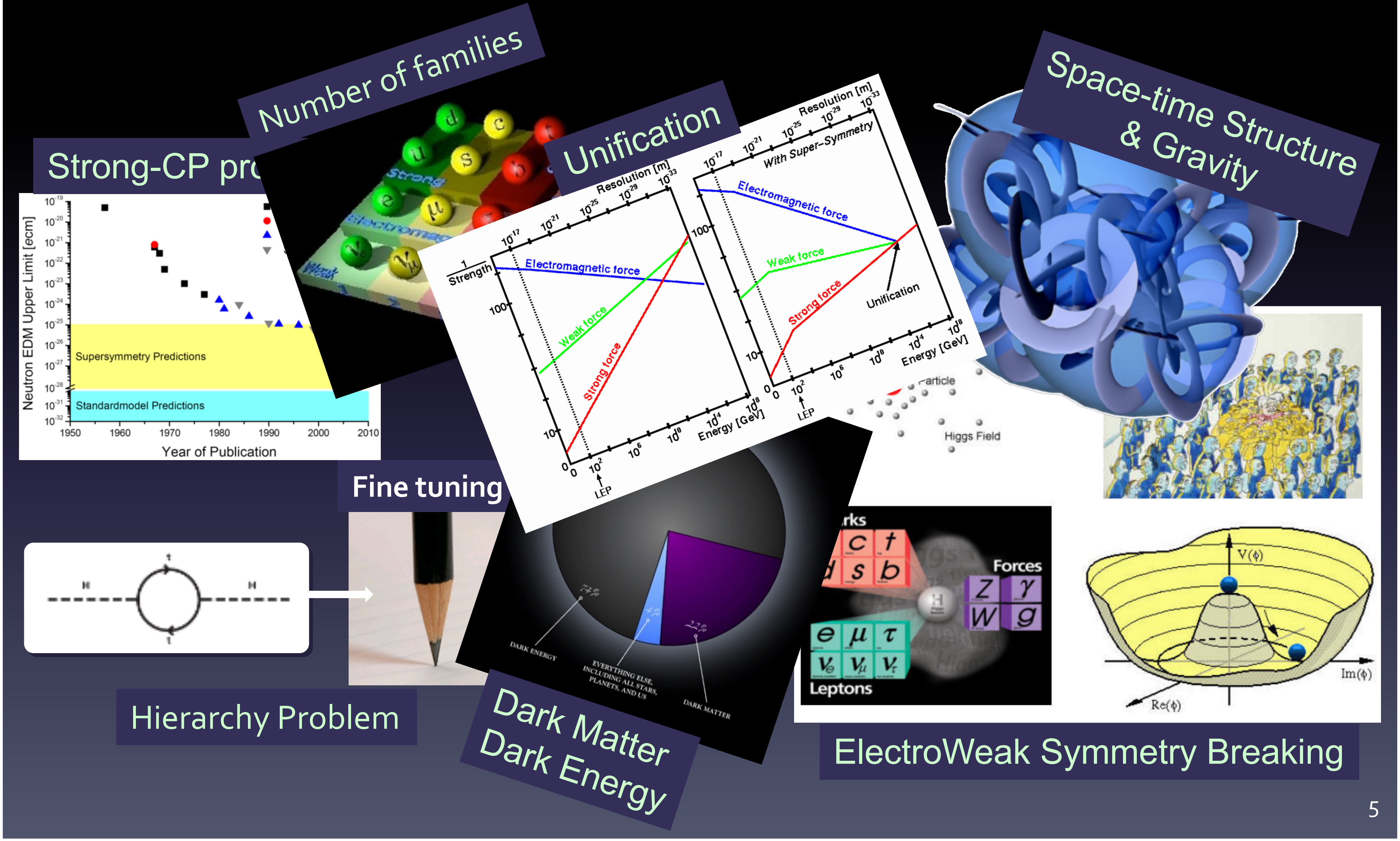
Weak interaction Parameters (LEP combination)

Unitarity triangle



But why I am here at BSM23???

What is relevant for this conference is theory beyond the SM story…



Number of families

Strong-CP pro

Unification

Space-time Structure & Gravity

Fine tuning

Hierarchy Problem

Dark Matter
Dark Energy

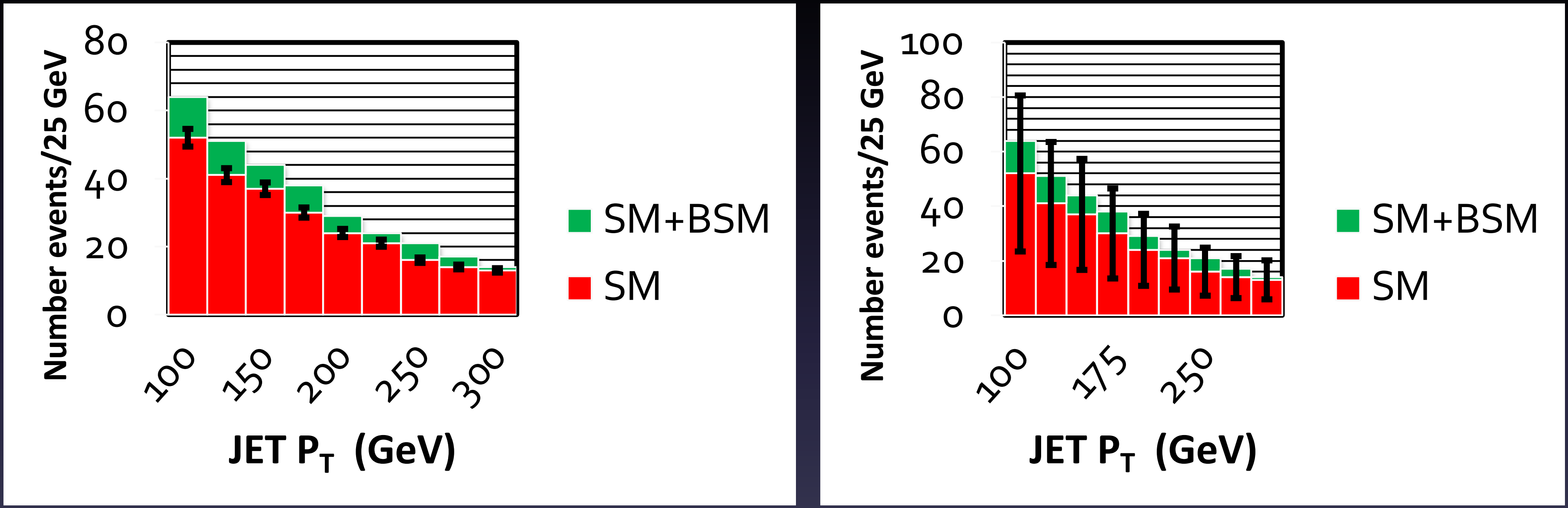
ElectroWeak Symmetry Breaking

…and why dedicating so much effort in performing evermore precise and sophisticated measurements of Standard Model physics, known and well-established for decades???

Answer part A:

Better Understanding of the SM Directly Impacts Sensitivity to BSM Physics

The key to make a discovery is to control systematic uncertainties and errors, maximizing the sensitivity to the physics of interest and get convinced of the validity of a discovery.



Theoretical uncertainties affect both the predictions and experimental results.

Feedback loop between precision measurement and better theory predictions

So we need more precision on SM measurements to improve theory predictions because:

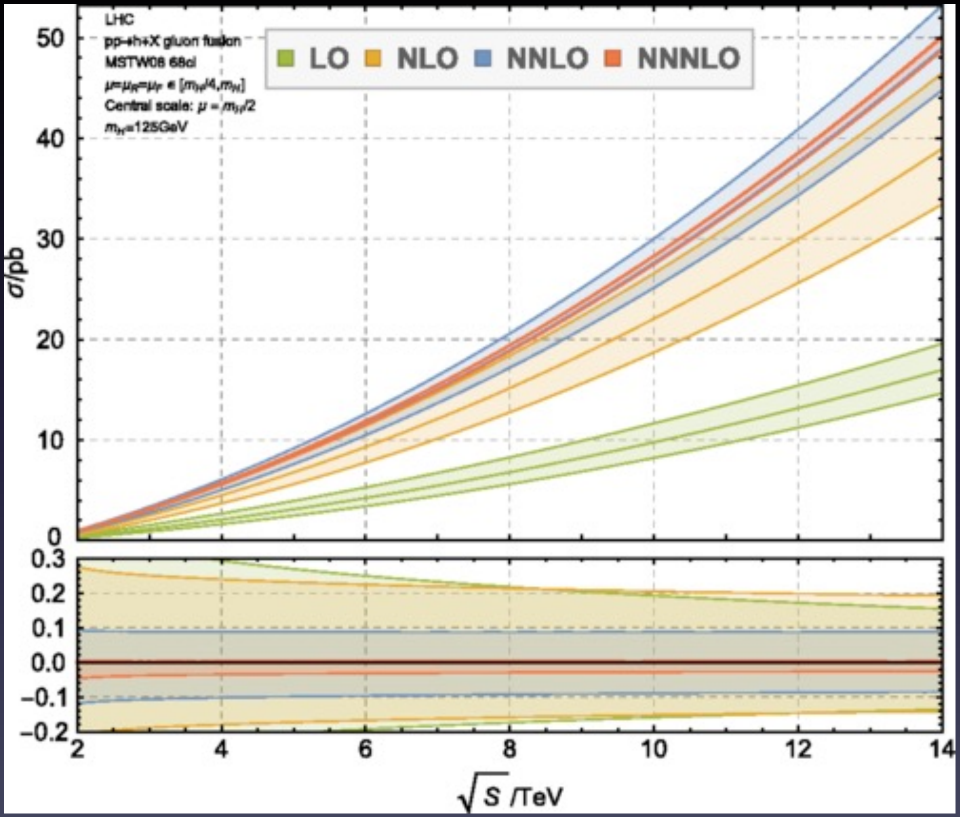
- Errors in the SM predictions can mask new physics signals or lead to false discovery

- Large uncertainties on SM predictions result in a suppression of the sensitivity of the experiments to new physics

For some processes, higher-order QCD corrections can be a game changer!

Example:

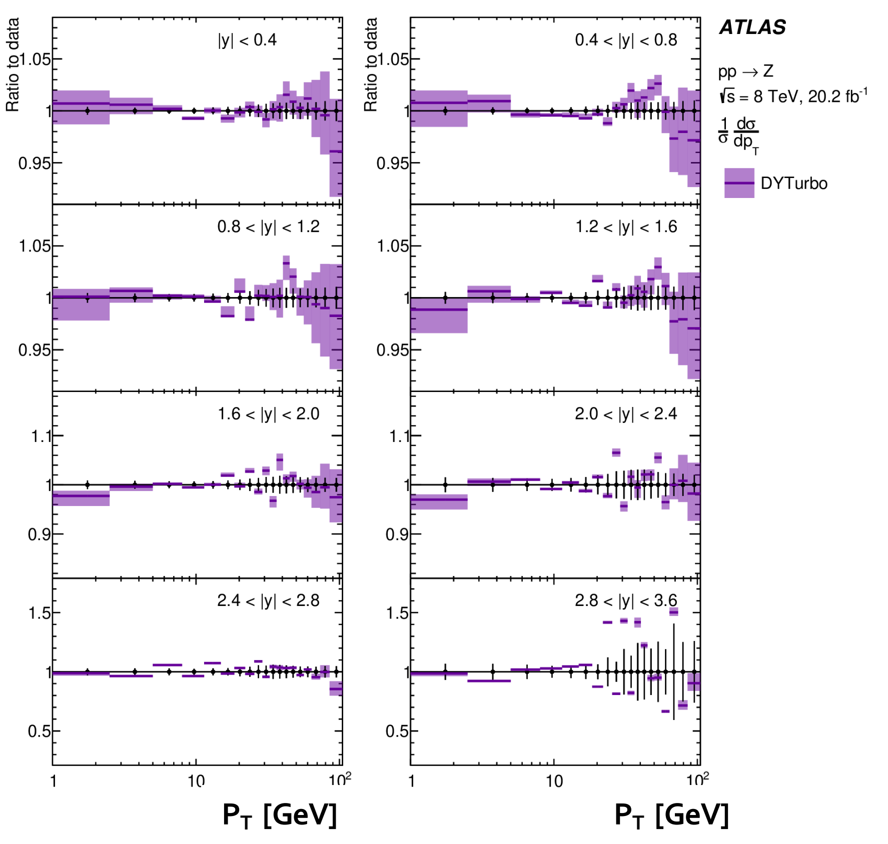
- Higgs production (gluon fusion) vs √s including scale uncertainty
  - NLO / LO correction = 70%
  - NNLO / NLO = 30%
  - $N^3LO/NNLO \sim 1.$
  - ΔNNLO: ~10% vs ΔN3LO: ~1%

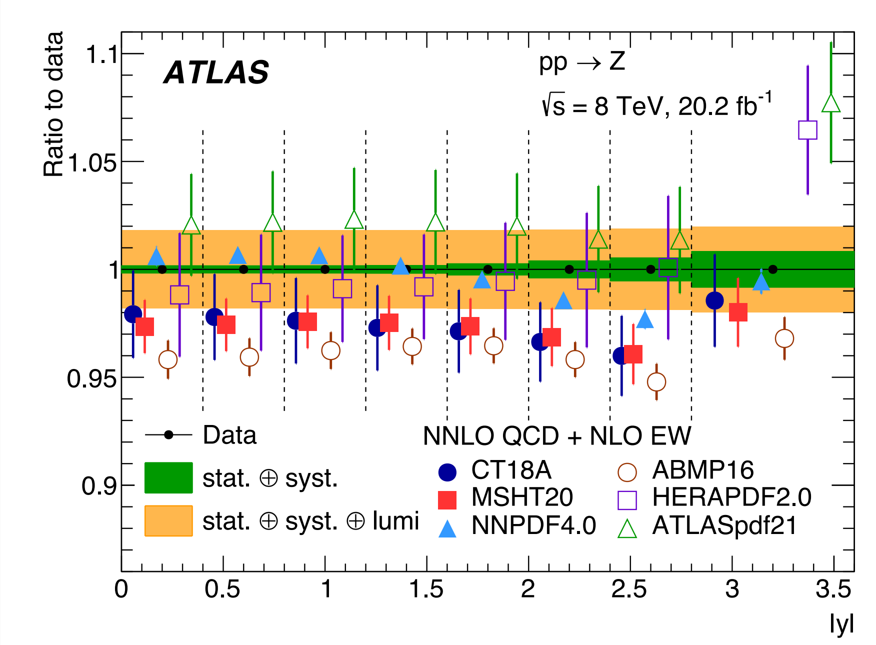


An Example: $\frac{d\sigma(Z/\gamma^*)}{dp_T dy}$

- A recent measurement of Z-boson kinematics in the full phase space reached the experimental precision (Δ<1%) required to test approximate N4LL+ N3LO+ calculations

arXiv:2309.09318 [hep-ex]





high sensitivity to Parton Distribution Functions arXiv:2309.12986 [hep-ex]

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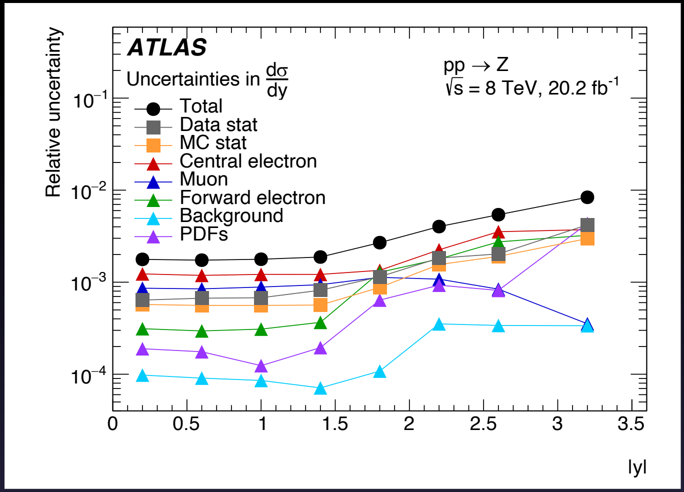
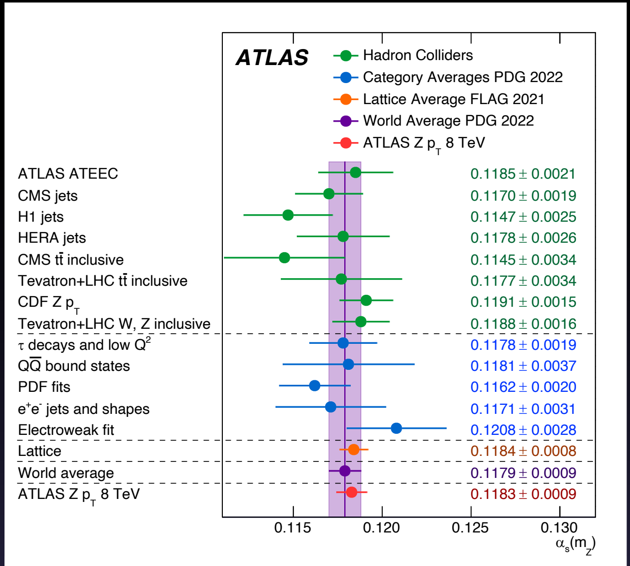
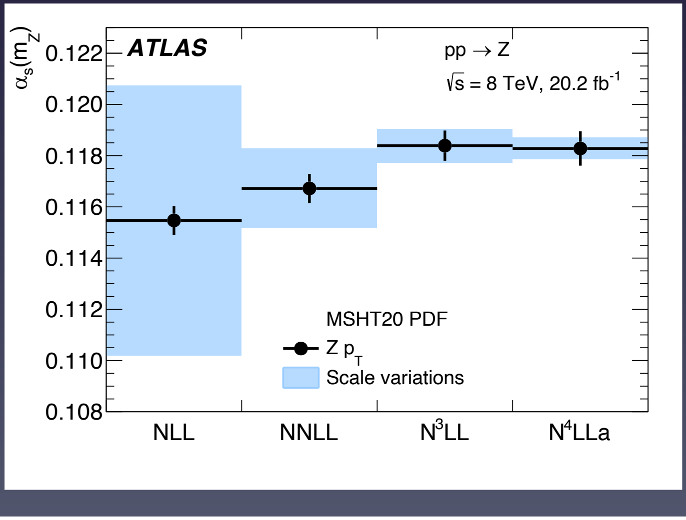
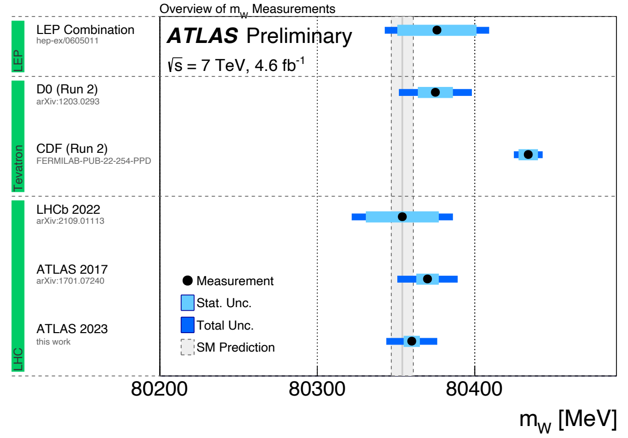
- Experimental and theoretical precision allowed getting the highest precision and accuracy on SM parameters





$\alpha_s(M_Z)$ = 0.1183 ± 0.0009

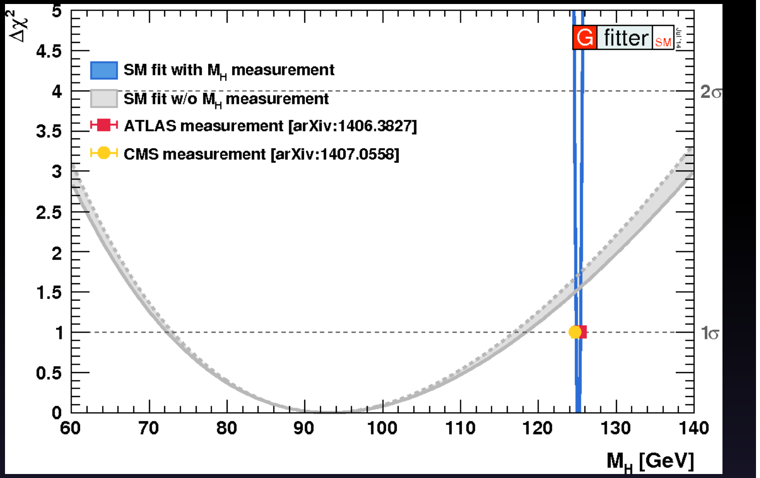


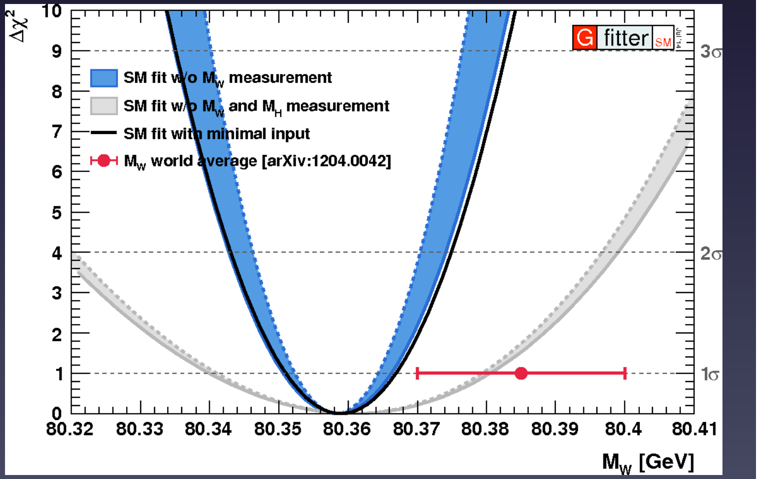


M_W = 80360 ± 5 (stat) ± 15 (syst) MeV

Consistency tests

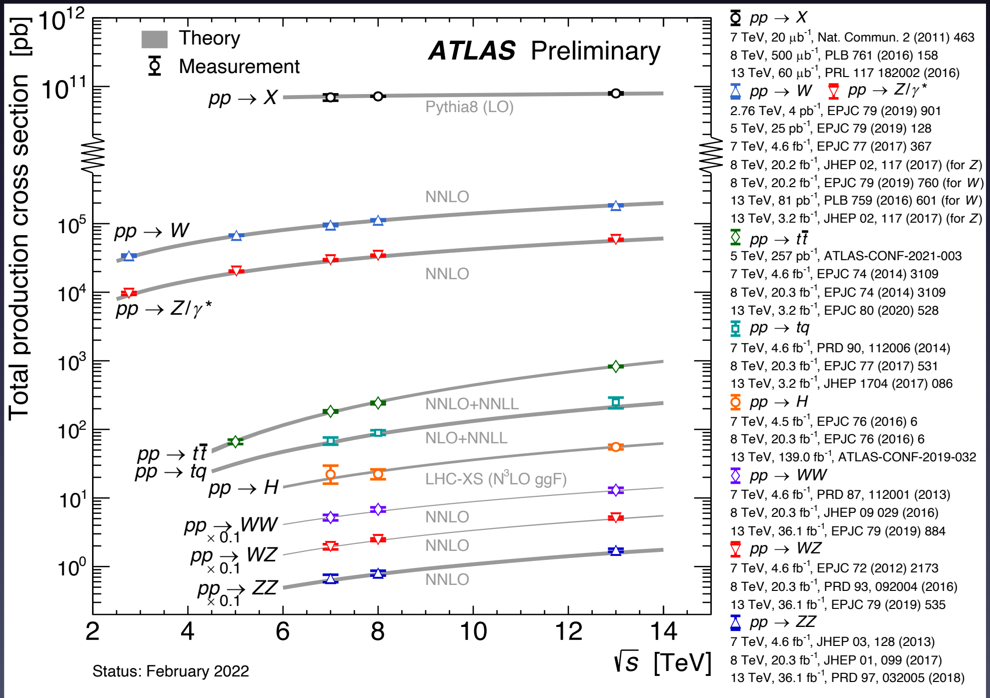
- The SM contains 26 free parameters:
  - 12 fermions masses
  - 3 coupling constants
  - 9 matrix elements and phases
  - Higgs mass and vacuum expect. value
- Only 17 need to be measured: relations between EWK parameters in the SM
- Global fit tests can reveal inconsistencies between parameter measured values:
  - Issues with some of the measurements
  - Hints of new physics
- New precise measurements of SM parameters give more stringent consistency tests or could resolve tensions

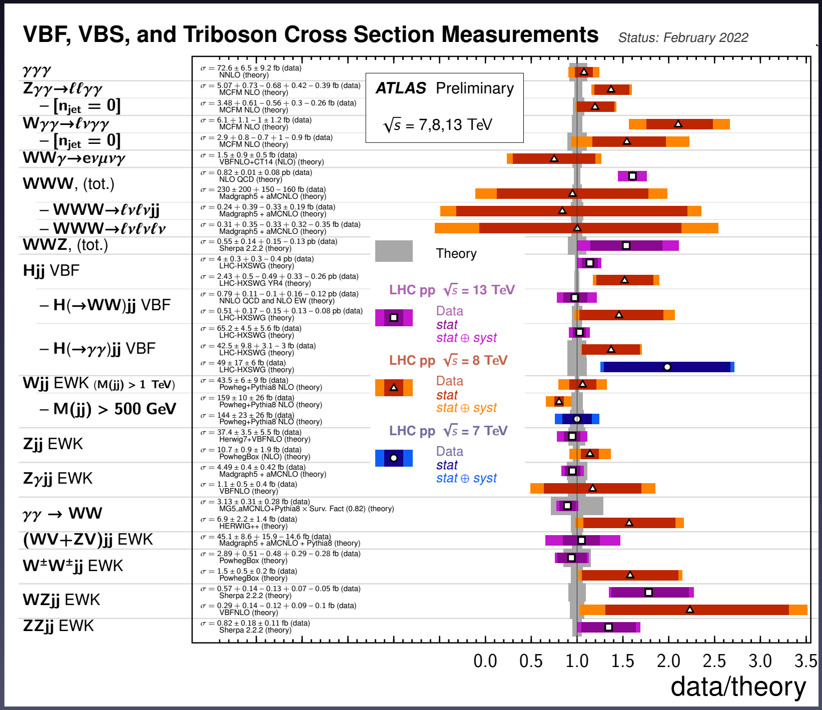




Rare Processes

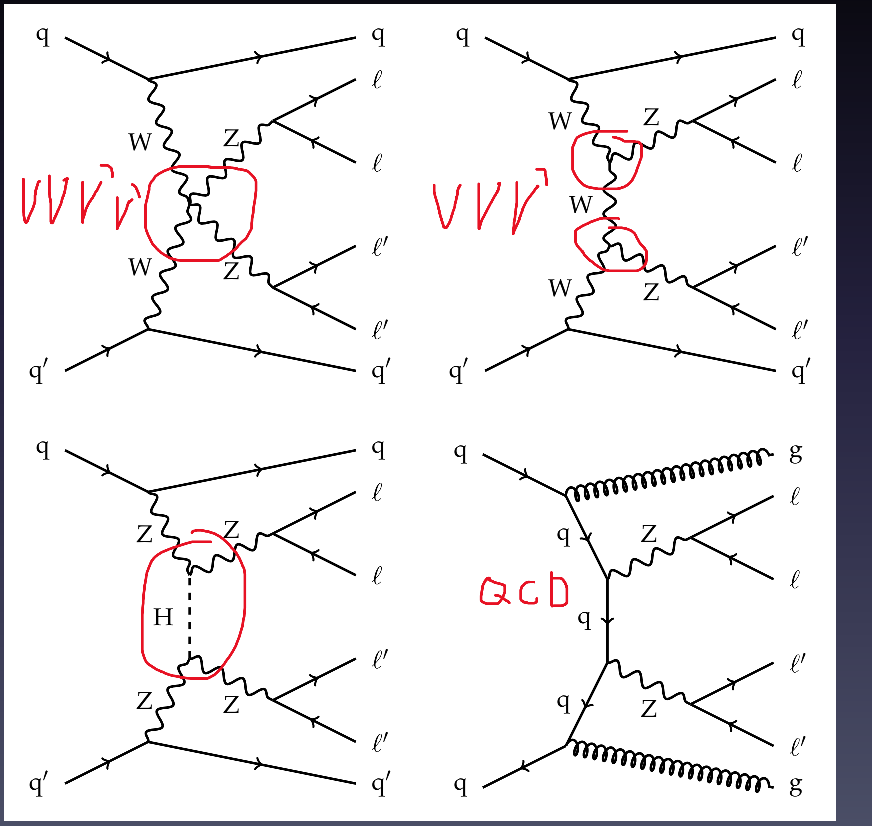
- This level of precision is not achievable for rare processes that often constitute the main irreducible background to BSM signals
  - Electroweak processes with σ~O(fb)
  - Measuring these (differential) cross sections demonstrates the possibility to discover a large variety of BSM





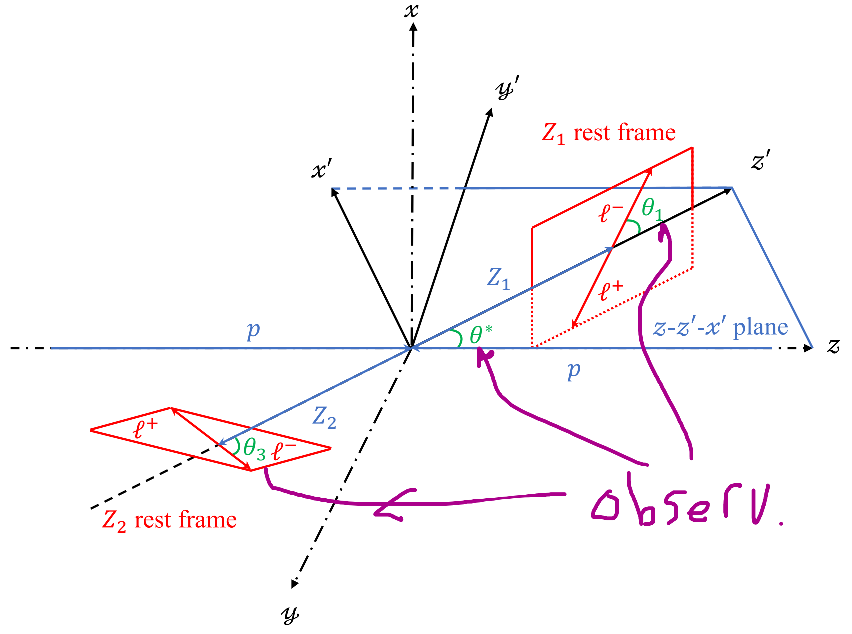
Vector Boson Scattering

- VBS are rare processes particularly interesting to study:
  - Directly probe the electroweak symmetry breaking sector of the SM; the Higgs prevents the divergence of longitudinally polarized vector bosons scattering amplitudes at high energy
  - It provides a unitarity test of the EWK sector
  - Sensitive to the non-abelian structure of the EWK interaction (gauge-boson self-interactions)
  - Also tests of pQCD because to separate such EWK contribution from the large QCD induced processes of same final state required to accurately model pQCD



Polarization and CP-Sensitive Angle Measurements

- Measurements of vector boson polarization states in diboson VBS processes provides another direct probe of the Electroweak Symmetry Breaking mechanism, through which the W and Z bosons obtain their longitudinally polarized states



- The Z boson can be either transversely or longitudinally polarized, and the fractions of states depend on the transverse momentum of the Z boson

General Measurement Strategy

- For such data to prediction comparison to be meaningful:
  - Background must be subtracted
  - Detector effects must be unfolded from data
    - Iterative Bayesian unfolding
    - Profile Likelihood fit approach

$$\frac{d\sigma}{dO} = \frac{N_{data} - N_{bkg}}{L} U(O)$$

- The objective of such SM measurements is precision:
  - Dependence of measurement results on theory input is minimal
    - Fiducial cross section measurements
  - Well-defined quantities and final states
- All systematic uncertainties with correlations must be assigned properly and taken into account in fits or in data-to-MC comparisons

Answer part B:

Offer a Direct, Model Independent, Probe to Physics Beyond the SM

A Gateway to New Physics

- Deviations can be due to New Physics; SM measurements are not optimizing to BSM ➡ Model-independance

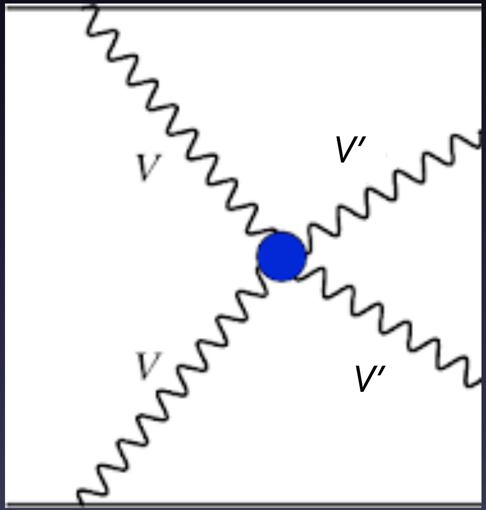
- New physics can add a contribution to Triple or Quartic Gauge Couplings (anomalous couplings)

- Use Effective Field Theory to parametrize new physics by adding higher dimension operators to L_{SM} without relying on explicit models

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j^{(8)} + \ldots$$

- The measurement of CP-sensitive observables in diboson production can explore new source of CP-violation in the gauge-boson sector.

An example of QGC



Dim-8 Operators in EFT

- Quartic Gauge Coupling (QGC) vertices appear in the lowest order as Dim-8 operator in EFT
  - Many different possible operators corresponding to different Lorentz structures
    - E.g. Scalar, tensor, mixed scalar-tensor operators, …
- VBS is ideal for probing these Dim-8 operators
  - These operators only induce anomalous quartic weak-boson self-interactions
  - Assumed Dim-6 operators are zero, i.e. they are already constrained by measurements diboson of VBF
- In the EFT framework, non-zero aQGCs will violate tree-level unitarity at large energy.
  - Important to test how limits are affected by this: remove the BSM EFT contribution above a certain scale, keeping only the SM above such scales.

General Constraint Strategy

- Start from unfolded measurement results for invariant mass distributions (or the sensitive observable of interest)

- Parametrize the cross section in each bin *i* of the sensitive observable in terms of the Wilson coefficient c_i to constraint

$$\sigma^i = \sigma^i_{\mathrm{SM}} + c \cdot \sigma^i_{\mathrm{interference}} + c^2 \cdot \sigma^i_{\mathrm{quadratic}},$$

  - Distribution templates with c_i=1 are generated from simulation for SM, interference and quadratic contributions
  - Each sample is scaled by its relevant floating parameter

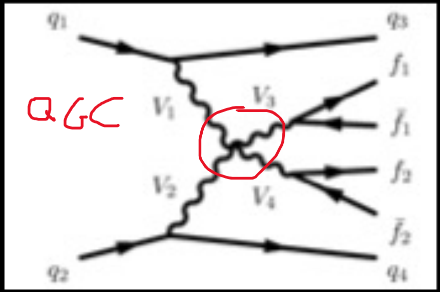
- A profile likelihood ratio test statistics is performed to estimate a confidence interval for each Wilson coefficient
  - Coefficient ci are usually set to non-zera value one at the time

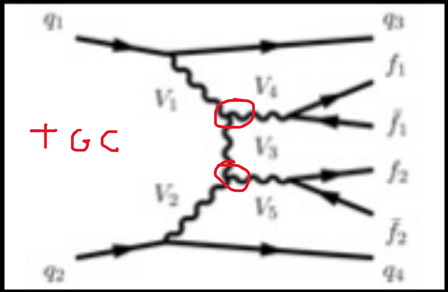
Some Recent Interesting Measurement Results

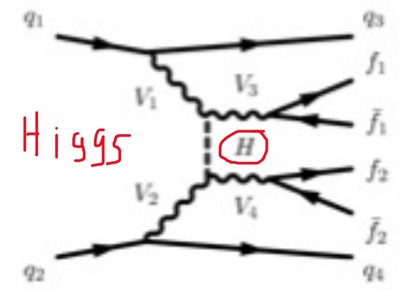
Same-Sign W Pair plus 2 Jets ($W^{\pm}W^{\pm}jj$)

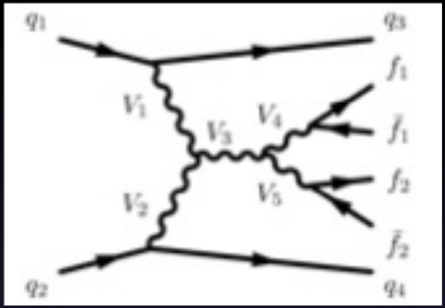
ATLAS-CONF-2023-023

- The $W^{\pm}W^{\pm}jj$ final state is ideal for measuring VBS
    - It has the largest ratio of EWK to QCD production cross section compared to other VBS diboson processes, while suffering from little SM bkg
        - Same sign lepton selections suppress more non-VBS than VBS contributions
        - Measure both component, and the independently the total.
- Large sensitivity to Dim-8 effective operators
    - 9 independent charge-conjugate and parity conserving operators affecting the quartic gauge coupling
- Can also be used to search for H++ signal
    - Constraint contribution from isotriplet scalar fields to W/Z mass

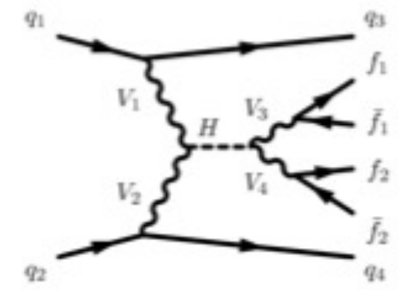




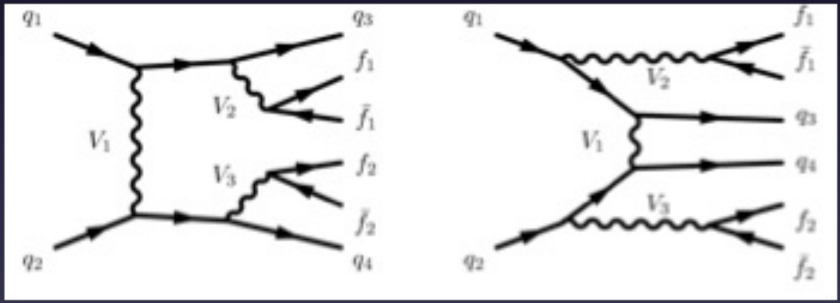




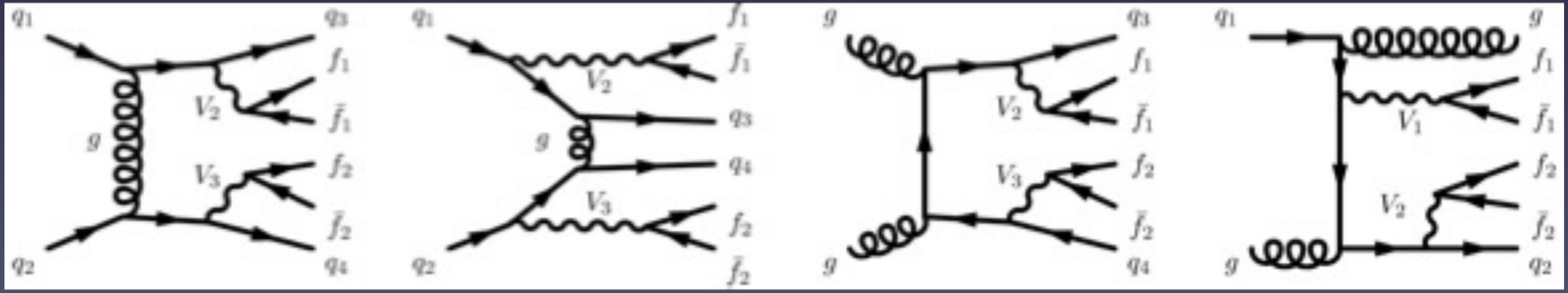
Forbidden for $W^{\pm}W^{\pm}jj$ in SM



Allowed for $W^{\pm}W^{\pm}jj$ BSM
(e.g. H++)



Other EWK contributions with no VBS but which cannot be separated from VBS in a gauge invariant way



Forbidden for $W^{\pm}W^{\pm}jj$

Predictions

- Obtained with MadGraph5+Herwig7 at LO accuracy
    - QCD: $\alpha_{ewk}^{4}\alpha_{s}^{2}$; Int:$\alpha_{ewk}^{5}\alpha_{s}$; EWK: α_{ewk}^{6}
    - Partial NLO pQCD corrections applied

Analysis Specifics

- VBS signature: M_{jj}>500, |Δy(jj)|>2
    - In SR: Ewk signal =52%, int=1.7%, QCD=5.4%
    - bkg: WZ (22%), non-prompt lepton (12%)

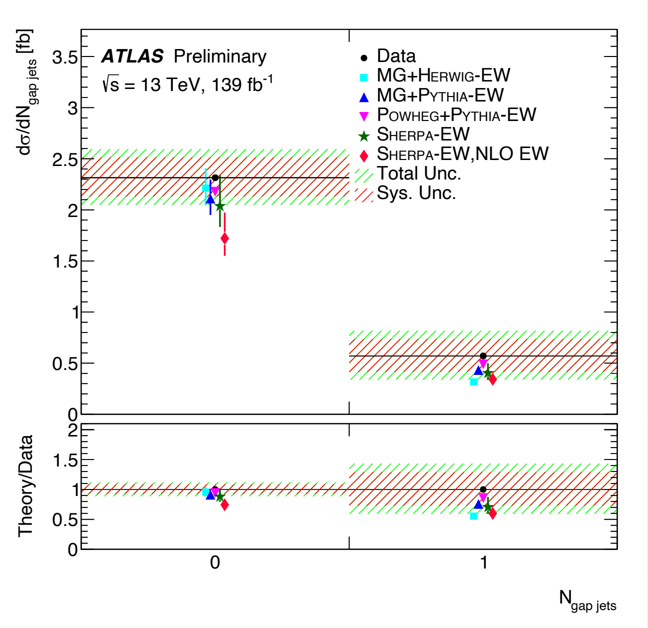
- Meas: $\sigma_{ewk} = 2.88 \pm 0.21 \pm 0.19\ fb$

$$\sigma_{tot} = 3.35 \pm 0.22 \pm 0.20\ fb$$

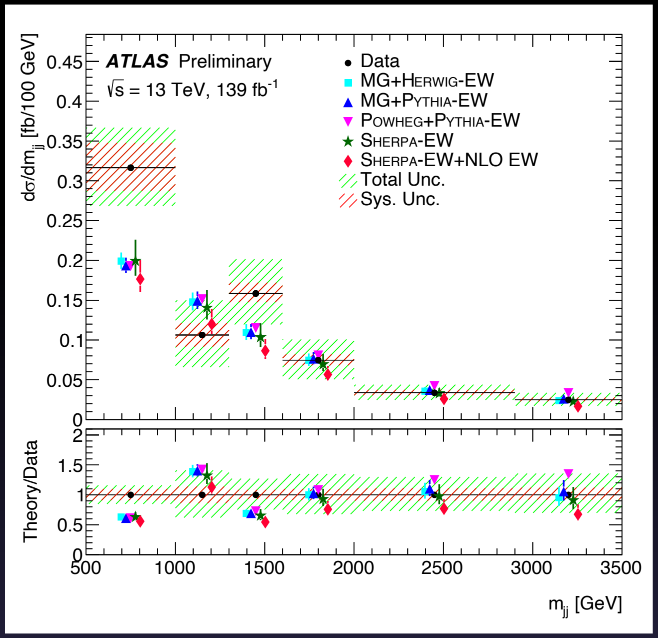
- Pred: $\sigma_{ewk} = 2.04 \pm 0.04\ (PDF) \pm \begin{matrix}0.22\\0.19\end{matrix}(scale)\ fb$

$$\sigma_{tot} = 2.39 \pm 0.05\ (PDF) \pm \begin{matrix}0.34\\0.27\end{matrix}(scale)\ fb$$

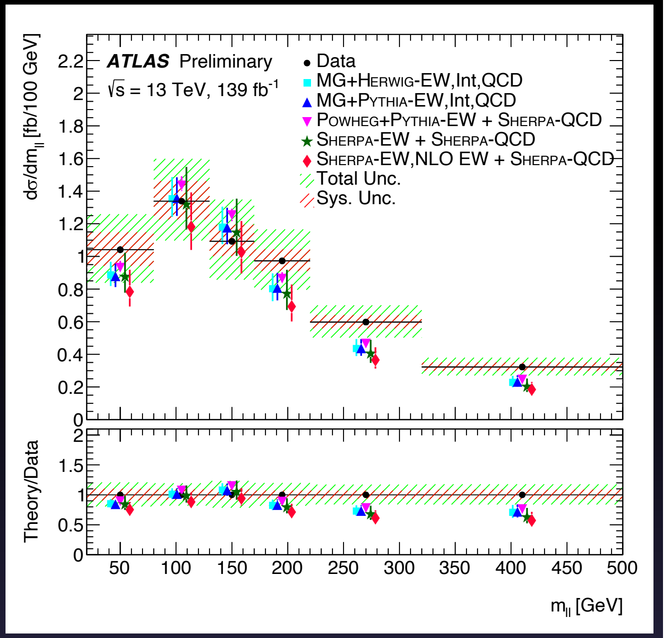
Some differential cross section results:



EWK: N_{gap} - good



EWK: M_{jj} - bad



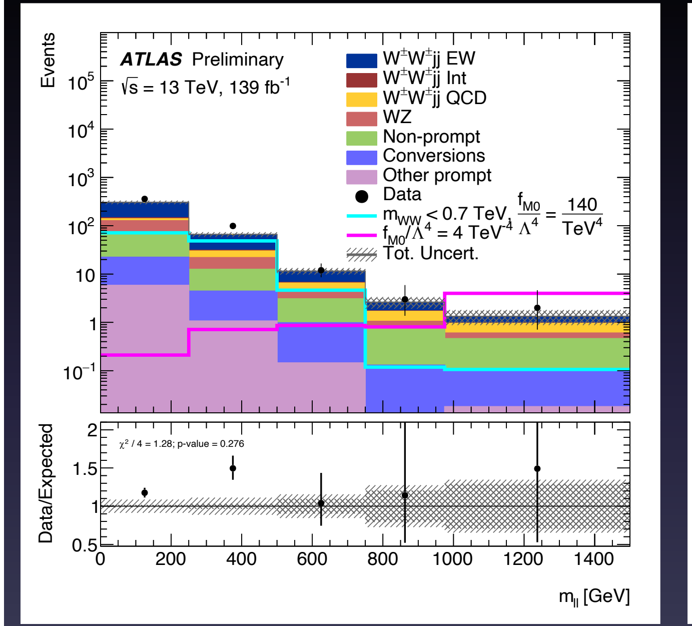
Full: M_{ll} - good

- All predictions tend to slightly underestimate the data
  - Agreement worse for M_T.

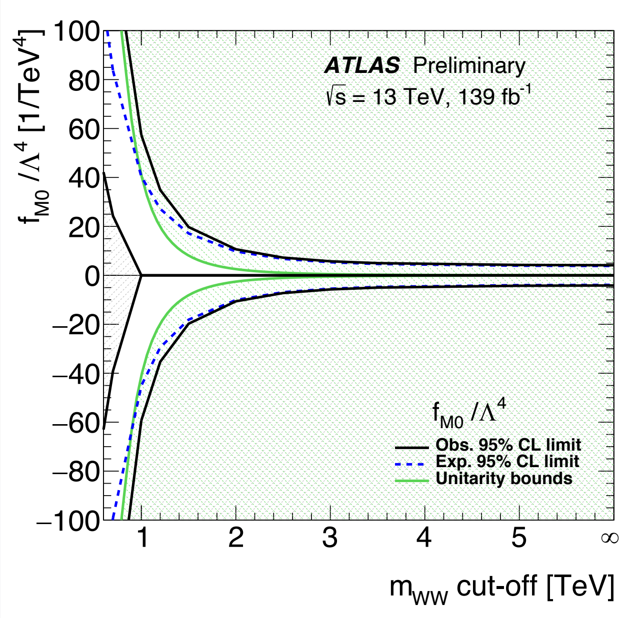
Limits on some EFT Dim-8 Wilson Coefficients:

(Only 1 non-zero coefficient at the time)

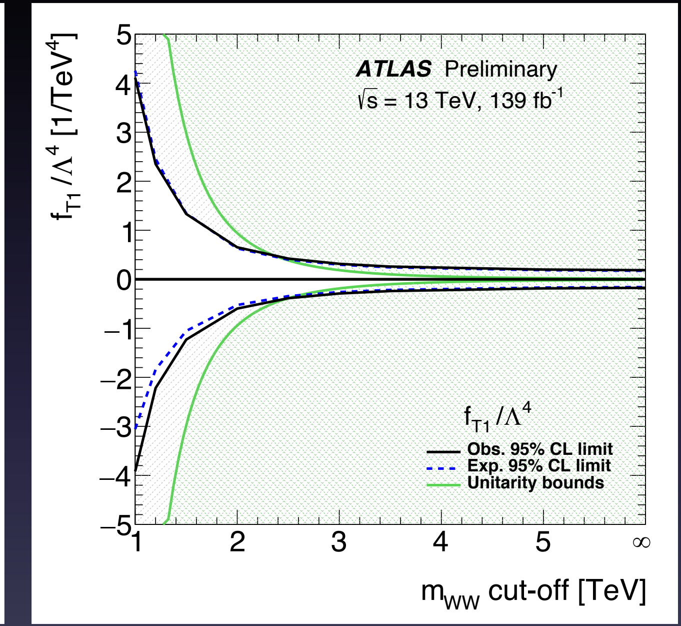
- Limits vary with an upper cut on the scale removing of non-unitary contribution
  - Large cut-off value corresponds to stronger constraints from unitary than from data
  - For low cutoff (< 1TeV), a few coefficient cannot be zero.



Impact of BSM signal; the peak at M_{ll}=400 is responsible for c=0 exclusion at low cut



Tighter constraint from unitarity; also exclusion of f_{MO}=0 at low cut

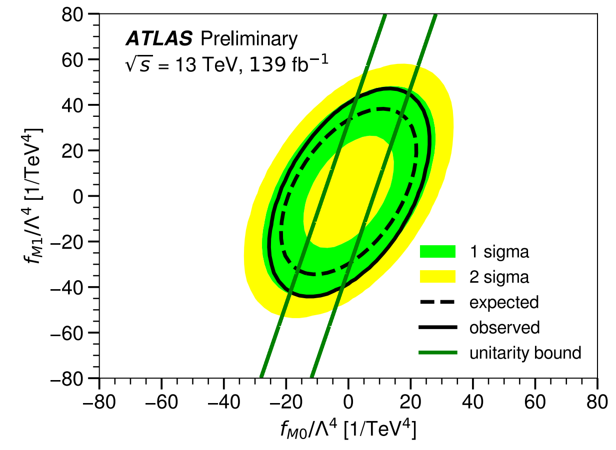


Tighter constraint from data for M_{cutoff} < 2 TeV

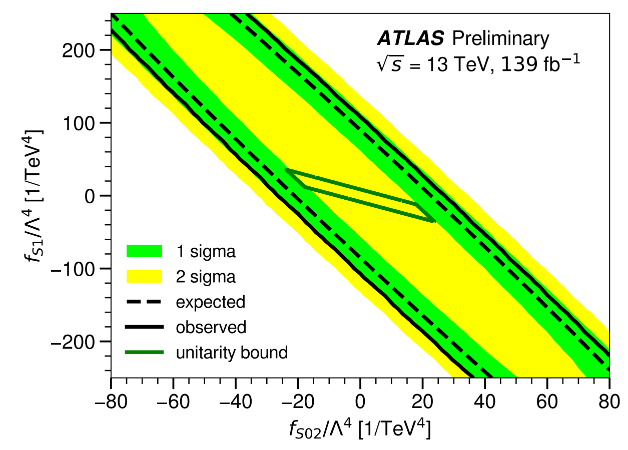
Limits on some EFT Dim-8 Wilson Coefficients:

(2 non-zero coefficient at the time)

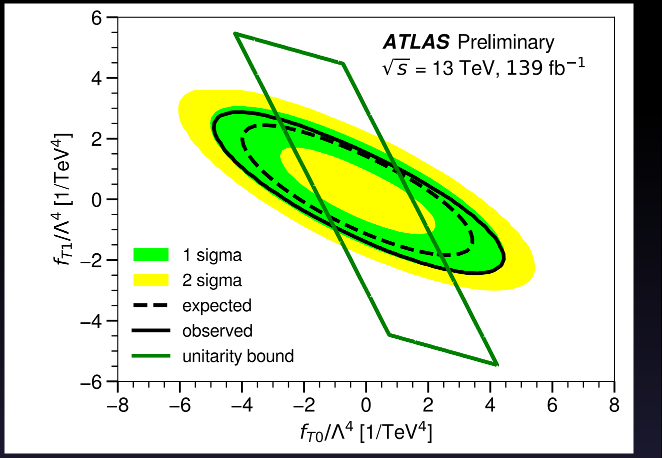
Cutoff mass = 1.5 TeV



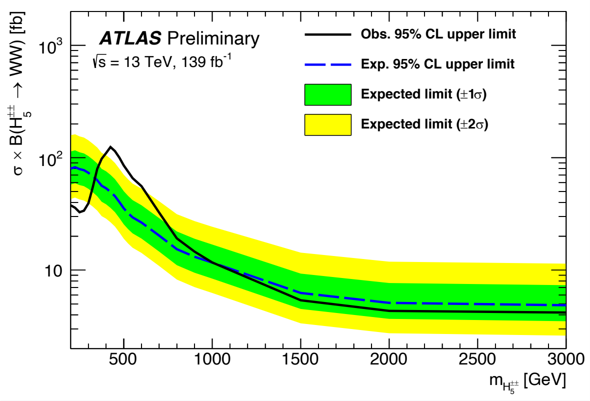
Constraints on mix operators (significant further constraints from data)



Constraints on scalar operators
(Data don't add over unitary)



Constraints on tensor operators
(Interesting complementarity between data and unitarity)

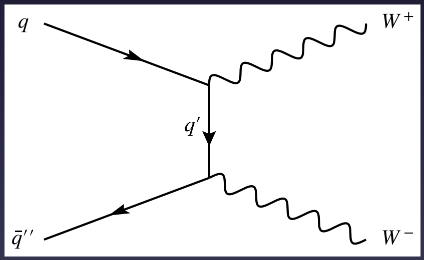


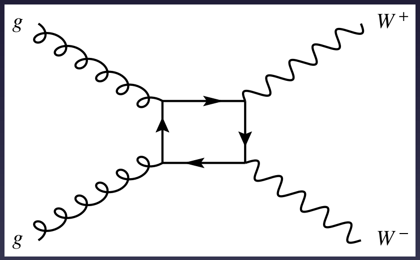
Limits on H^{++}
has a function of M_{H++} .

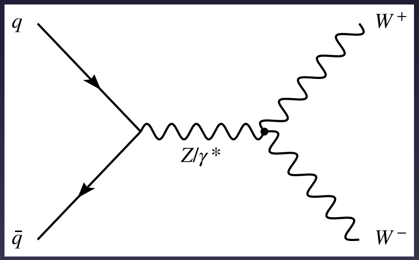
Inclusive Jet WW Diboson Production

ATLAS-CONF-2023-012

- Previous WW measurements applied a jet veto to control top background. To better control QCD, this measurement does not apply any jet veto
  - No large log due to jet veto
  - Smaller theory uncertainty
  - More precise estimate of top bkg rather than cutting hard on it







$\sigma \sim 0.05\,\sigma_{LO}$

Predictions

- $q\bar{q} \rightarrow WW$: NNLO with Powheg MiNNLO+Pythia8
- $gg \rightarrow WW$: Sherpa 2.2.2 (MEPS@NLO)
- EWK VVjj: Sherpa 2.2.2 (MEPS@LO)
  - Include off-shell contribution and Higgs
  - Partial NLO pQCD corrections applied
  - EWK NLO corr (multi. scheme)

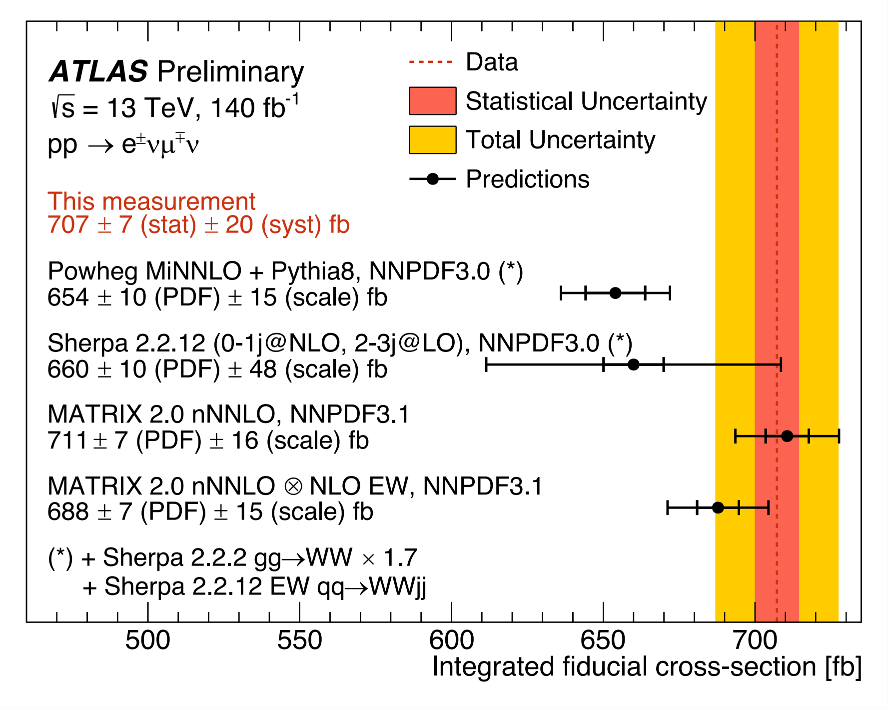
Analysis Specifics

- Opposite charge and flavor channels
- Signal strength obtained from fit to S_T
  - One template for each signal type

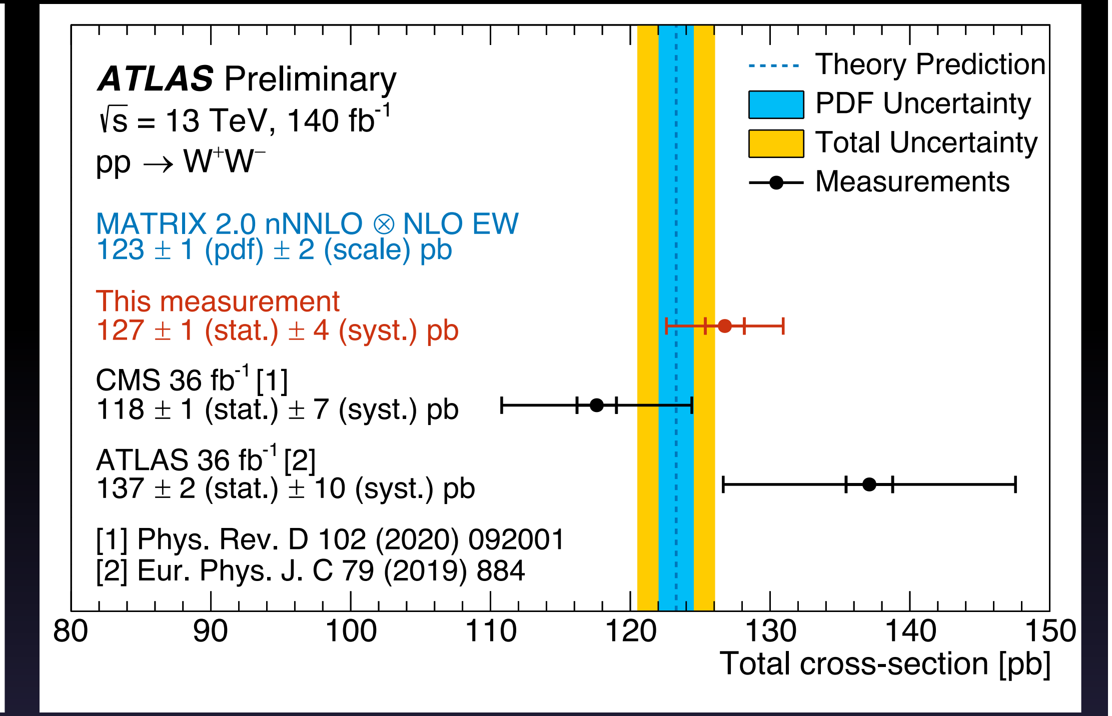
- Meas: $\sigma_{fid} = 707 \pm 17 \pm 20\ fb$ ⟶ Total Uncertainty = 3.1%

$$\sigma_{full-WW} = 127 \pm 1 \pm 4\ pb$$

Fiducial cross section



Total cross section

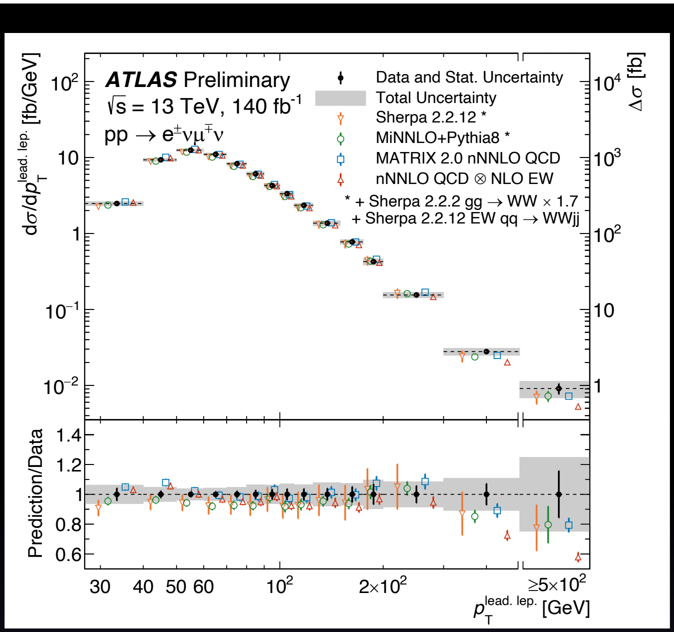


2σ tension with MiNNLO, but good agreement with nNNLO MATRIX 2.0.1

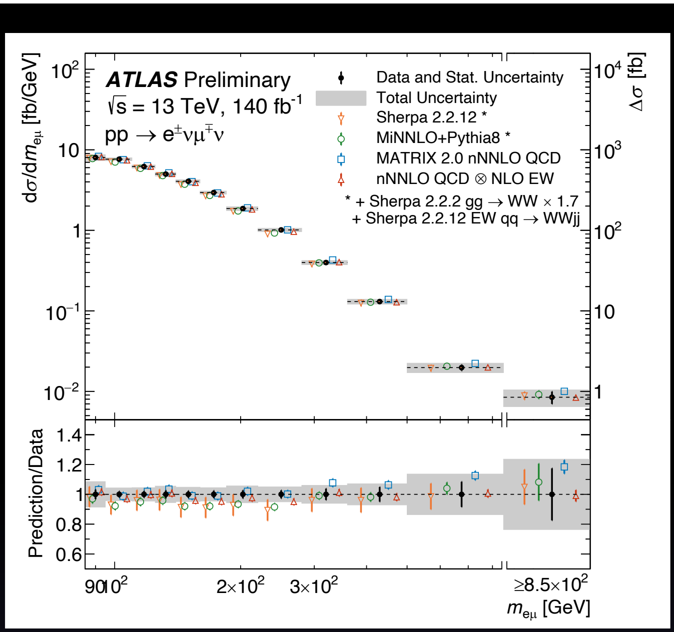
- mostly due to PDF and photon induced processes

Precision improved due to inclusive jet (less theory), and data driven bkg

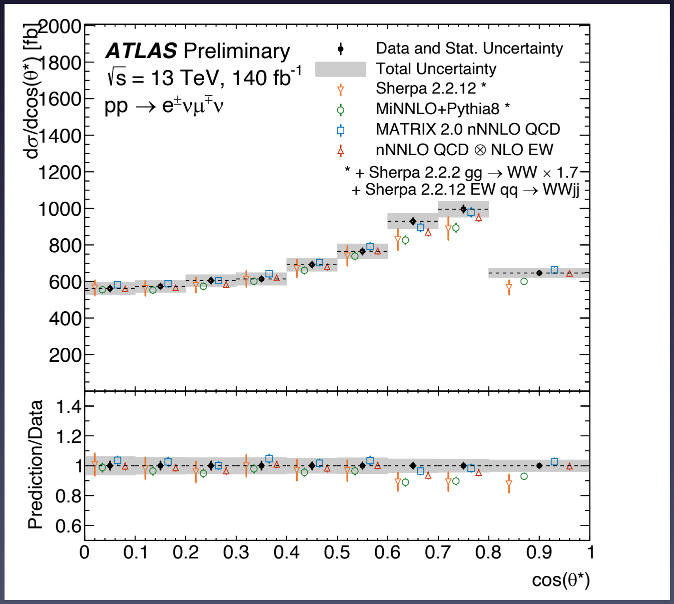
MATRIX: *A fixed-order prediction at nNNLO QCD using NNPDF3.1nnlo luxQED*



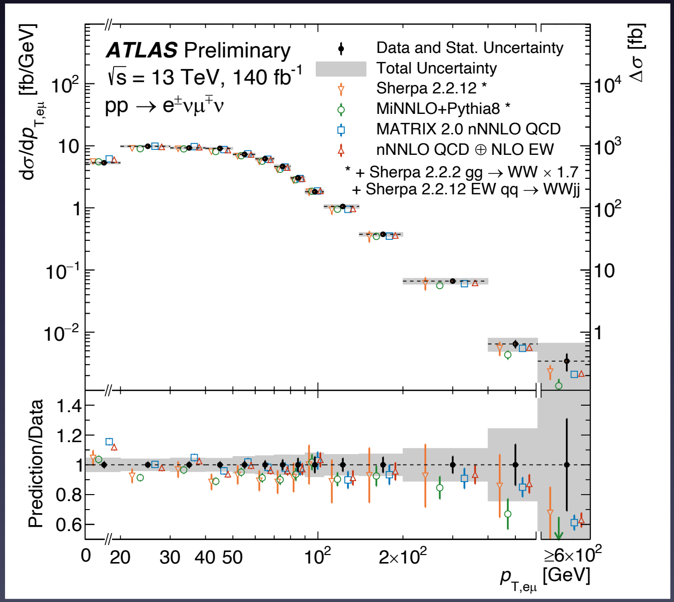
Excellent description except when EWK corrections are added at high-pt (expected)



But EWK improves description at high $m_{e\mu}$



Sensitive to the spin structure of W pair



PS improves description at low WW p_T or higher jet final states

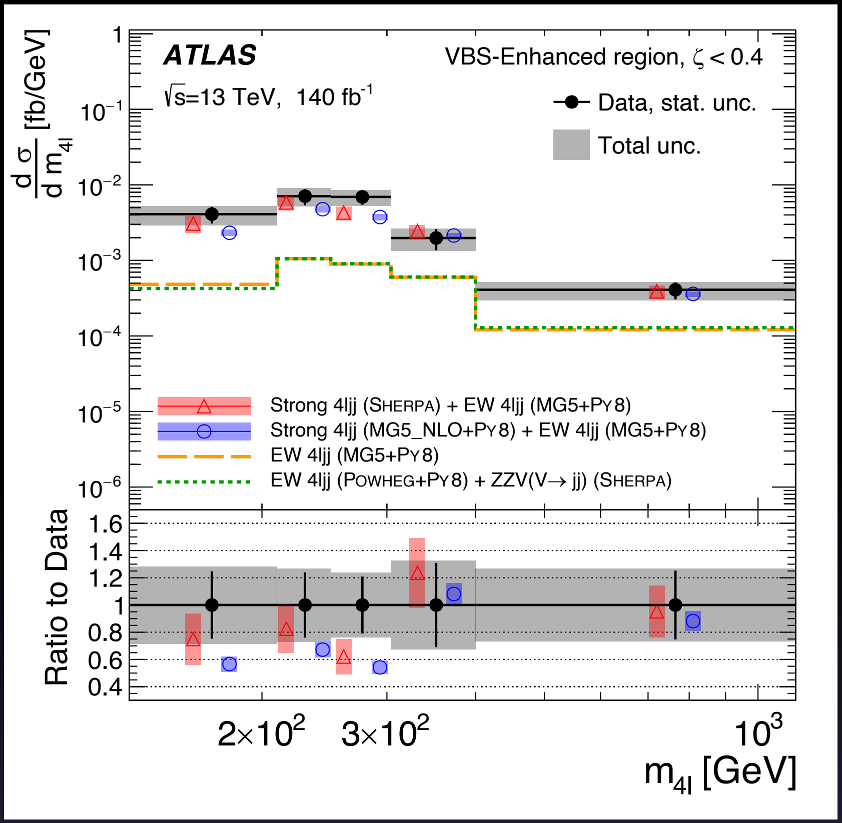
$Z(\to \ell\ell)Z\,(\to \ell'\ell')$ jj

arXiv:2308.12324 [hep-ex]

- Measure a variety of observables:
  - Sensitive to VBS and to WWZ and WWZZ couplings
  - Allow constraining anomalous quartic couplings
  - Probe the Z polarization, charge conjugation, parity
  - Test of higher-order quark and gluon emission in pQCD

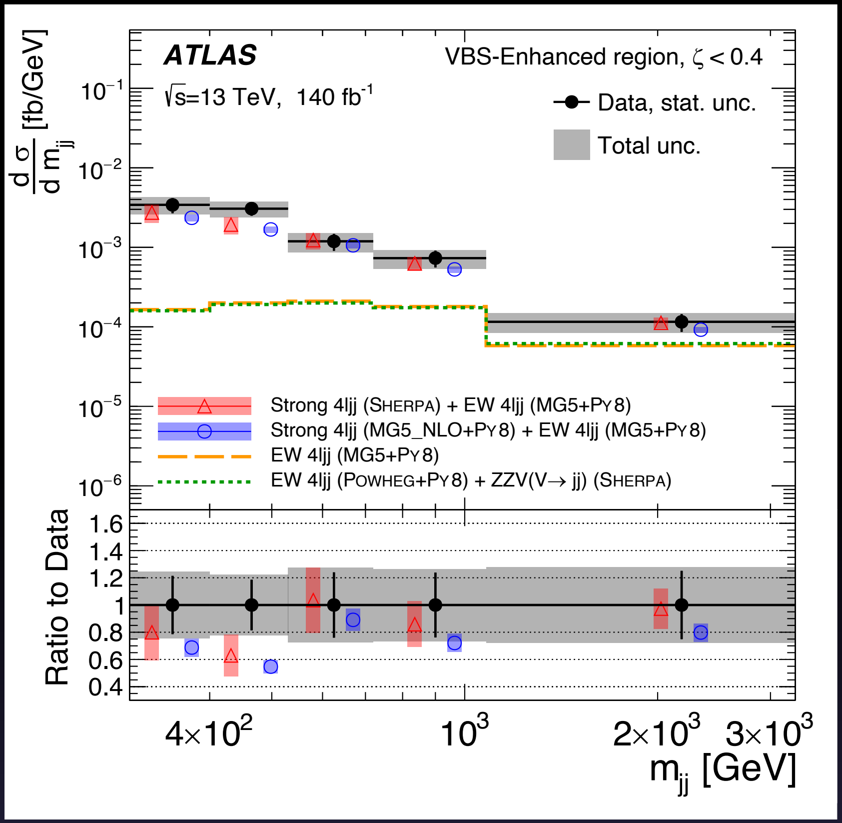
Predictions

- QCD $4\ell jj$: Sherpa 2.2.2 (NLO 1st parton, LO extra 3 partons matched with MEPS@NLO)
- EWK $4\ell jj$: MadGraph5+Pythia8 at LO accuracy



Observable sensitive to VBS

- EWK contribution: ~20%

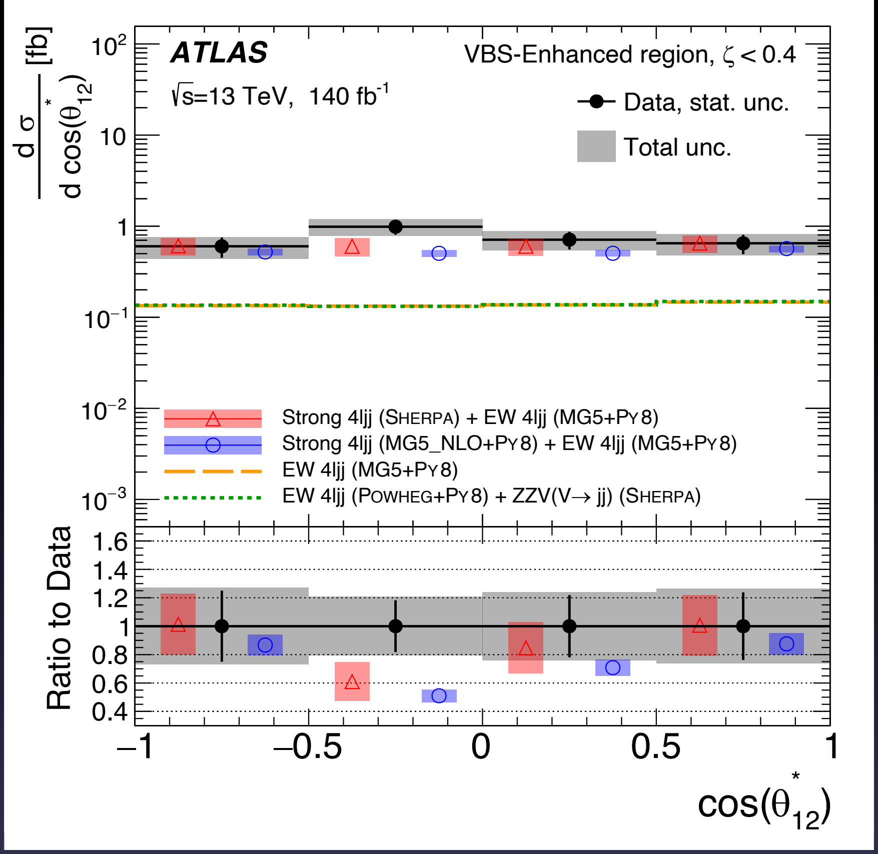


Observable sensitive to EWK contributions

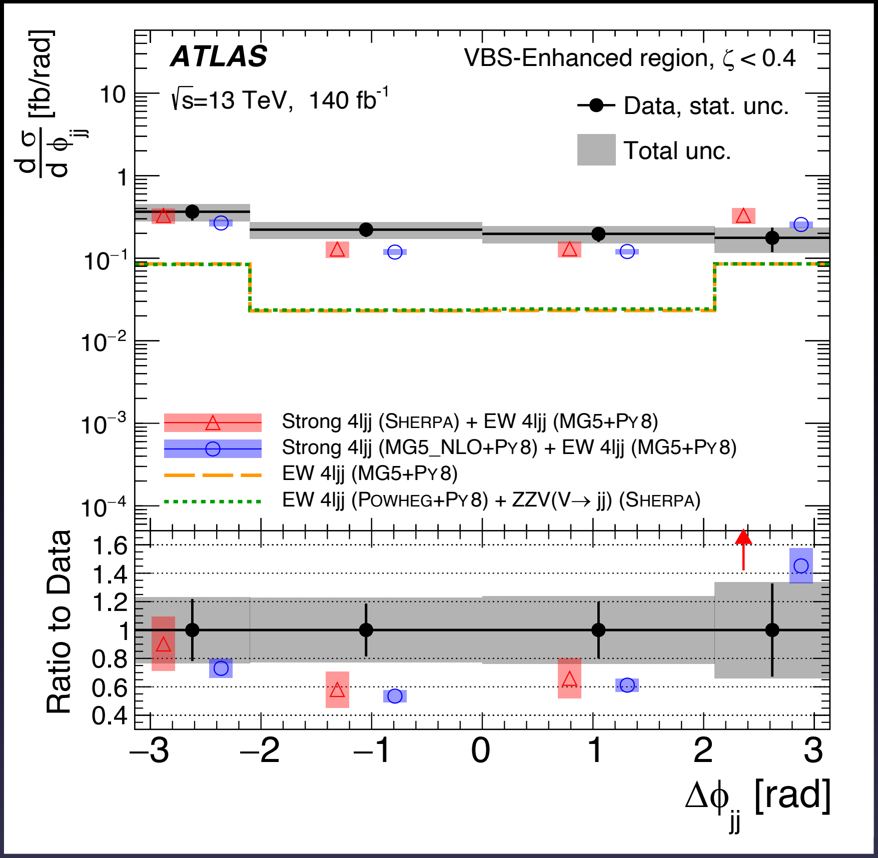
- Low M_{jj}: ~5%
- High M_{jj}: ~50%

- Sherpa predictions for QCD 4ℓjj agree with data for all measured distributions in the VBS-enhanced region.
- MG5+Py predictions for QCD 4ℓjj underestimate the cross-section in all distributions, with disagreement especially noticeable at low m_{jj} , low $\mathrm{m}_{4\ell}$ and low |$\Delta\phi_{jj}$|.

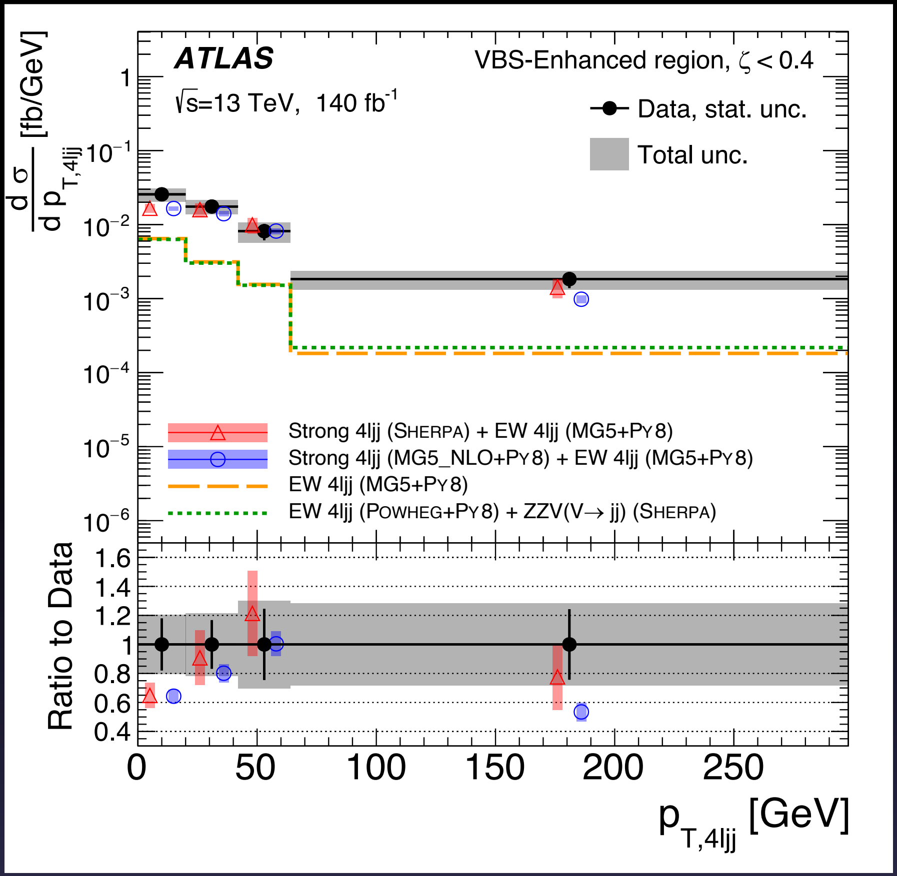
Sensitive to leading Z polarization



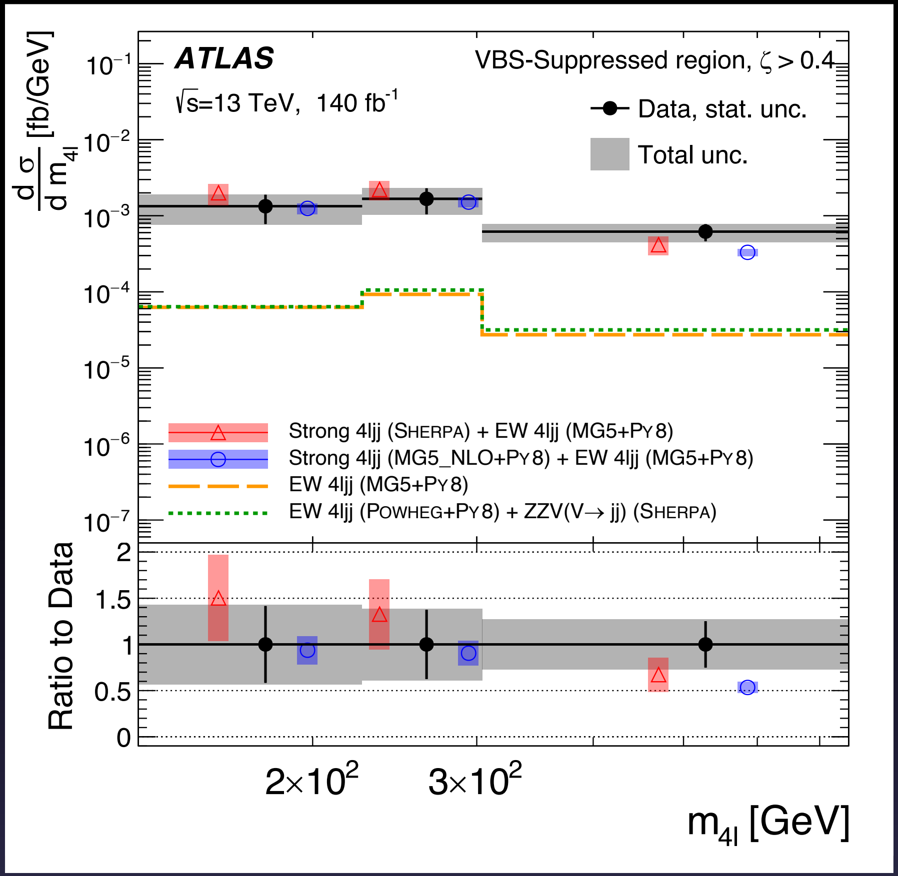
Sensitive to charge-conjugation and parity structure of WWZ and WWZZ interactions



The Powheg+Pythia8 and the MG5+Py8 EW $4\ell jj$ prediction are in very good agreement for all measured distributions, demonstrating that the choice of EW model has very little impact on $4\ell jj$ predictions.



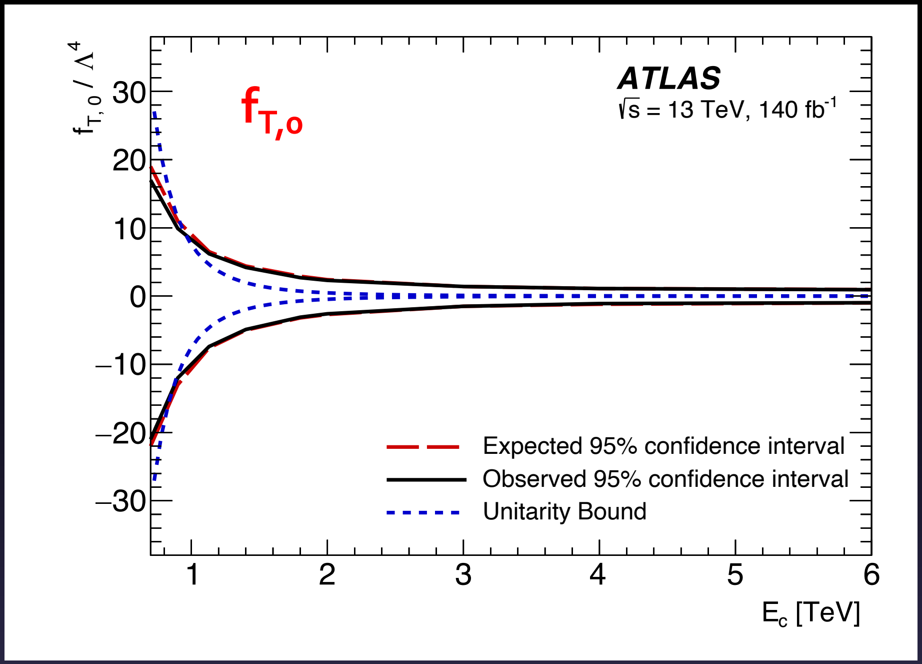
Sensitive to higher-order real emission of quarks and gluons

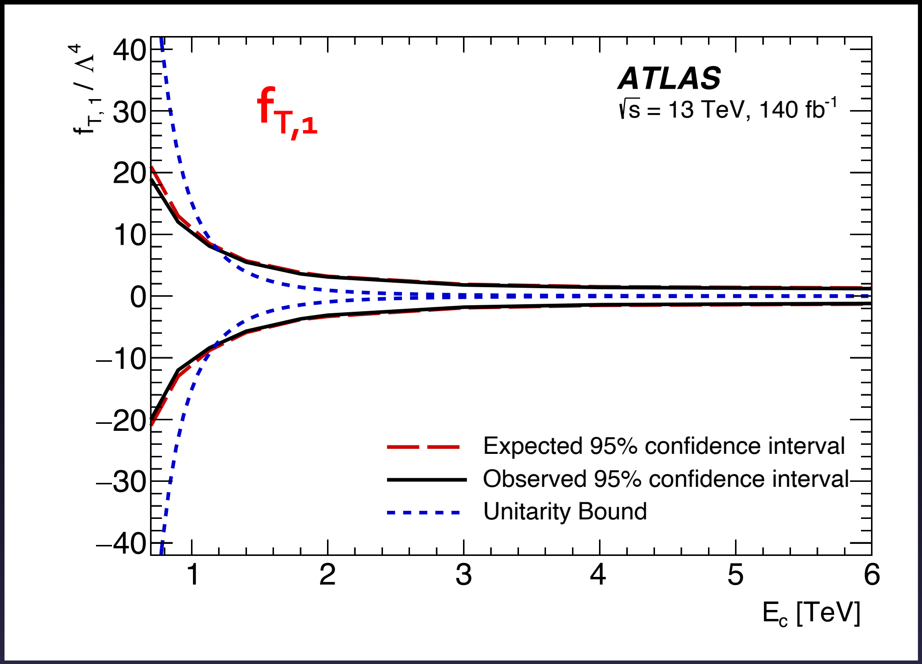


VBS-suppressed region

Limits on some EFT Dim-8 Wilson Coefficients:

(Only 1 non-zero coefficient at the time)



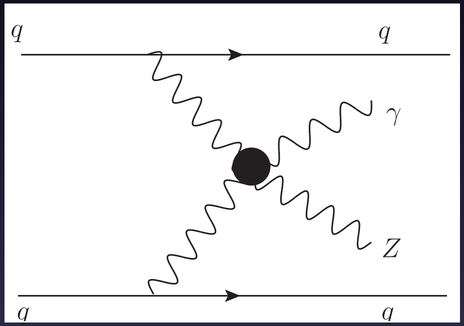


- In all cases, the Wilson coefficients are consistent with zero.
  - The limits are only valid if higher-order terms in the EFT expansion do not contribute significantly.

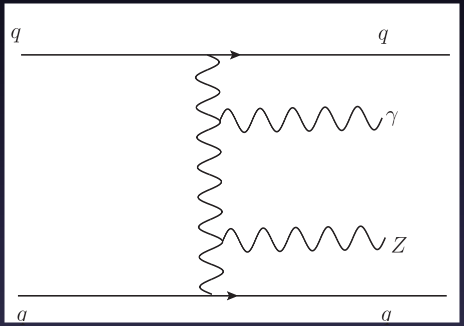
Zγ+jets

Phys. Lett. B 846 (2023) 138222

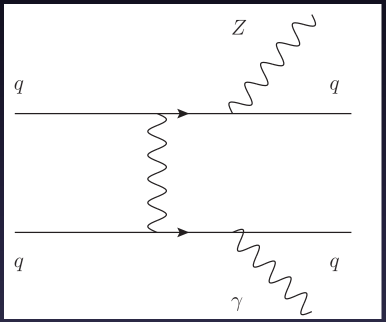
- Zγ+jets allows probing the same neutral quartic gauge couplings as ZZ, but with a larger cross section
    - Forbidden in the SM at tree-level
    - Sensitive to VBS process



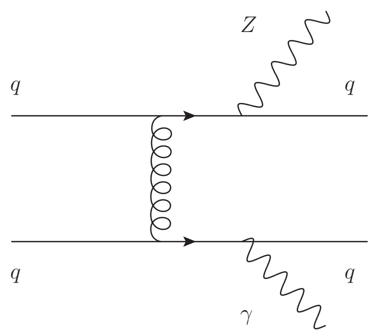
Sensitive to quartic coupling



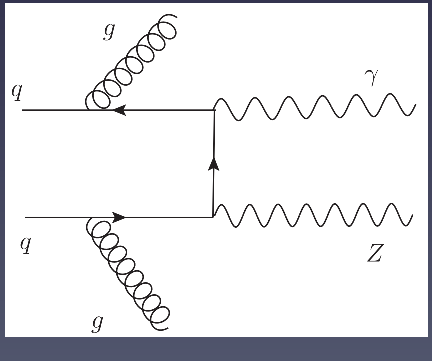
Sensitive to triplet gauge coupling



Pure EWK contribution



← QCD contributions →



Predictions

- EWK: LO accuracy at α_{ewk}^4 with MadGraph+Pythia8

Analysis Specifics

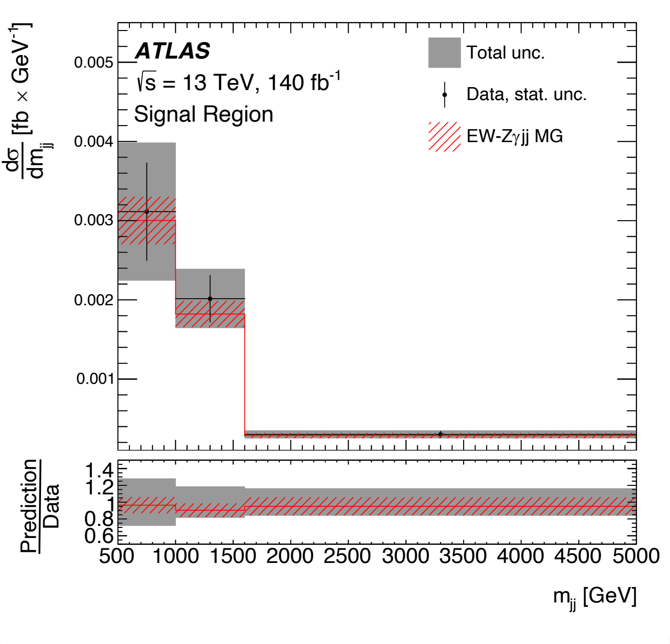
- Signal enriched by large M$_{jj}$ and jet-jet rapidity gap (separate QCD from EWK)
    - Signal region: M$_{jj}$ > 500 geV
    - Extended region: M$_{jj}$ > 150 GeV
- Obtain both EWK and total cross sections
- Signal strength obtained from fit to signal and control regions

- Meas: $\sigma_{ewk} = 3.6 \pm 0.5\ fb$

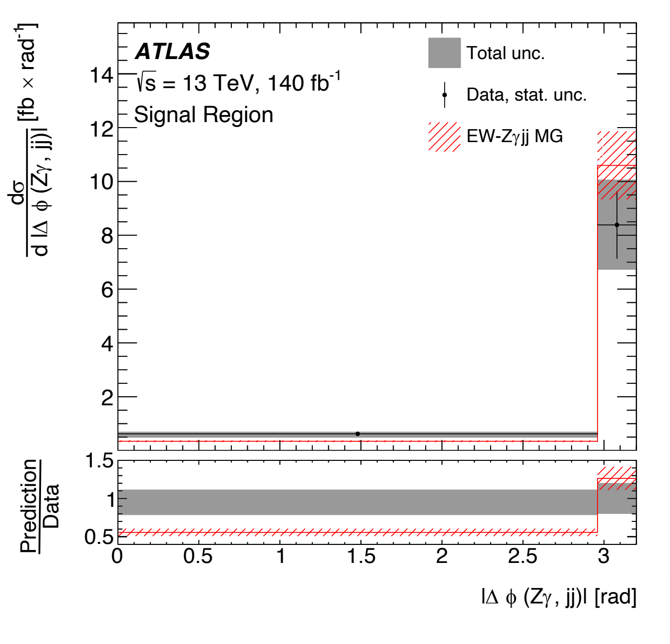
  $$\sigma_{tot} = 16.8 \pm \frac{2.0}{1.8}\ fb$$

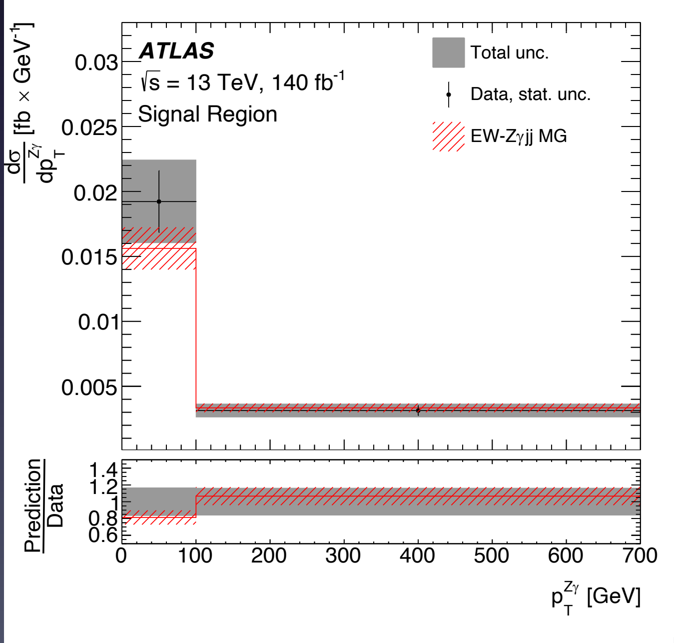
- Pred: $\sigma_{ewk} = 3.5 \pm 0.02\ fb$

  $$\sigma_{tot} = 15.7 \pm \frac{5.0}{2.6}\ fb$$

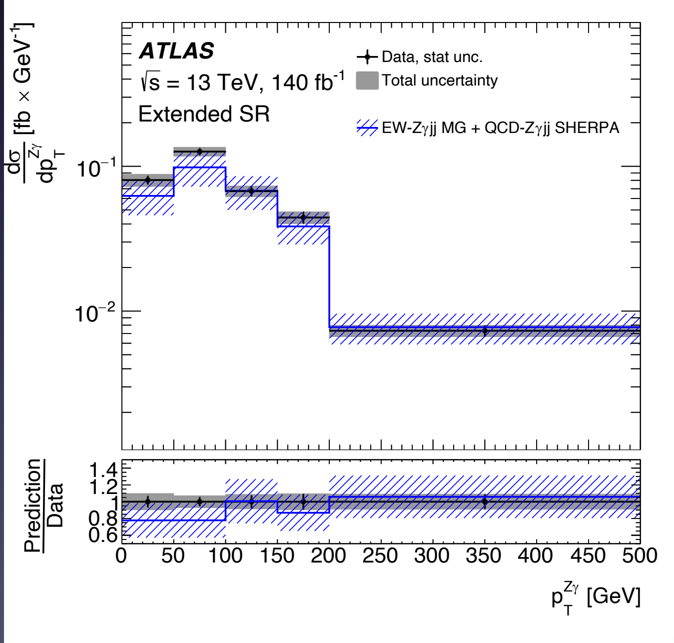


Predictions agree well with data, except for $|\Delta\phi(Z\gamma, jj)|$ where a ~2σ discrepancy in the lowest bin is observed





Better precision, but also larger QCD contribution for the observables in the extended signal region



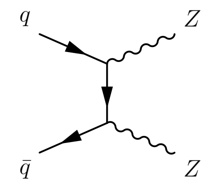
Polarization and CP-properties in Z($\rightarrow \ell\ell$)Z ($\rightarrow \ell'\ell'$)

arXiv:2310.04350 [hep-ex]

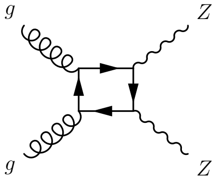
- Focus on the measurement of longitudinally polarized Z-boson pair ($Z_L Z_L$) decaying in 4-lepton final states
  - Develop a new CP-odd angular observable referred to as the Optimal Observable (OO)
  - Provide unfolded differential cross section for this quantity
- This observable can be used to explore new sources of CP-violation in the gauge-boson sector
  - Constrains two anomalous neutral triple gauge couplings (aNTGC) that violate CP symmetries

Predictions

- qq → 4ℓ: Sherpa 2.2.2 (NLO 1st parton, LO extra 3 partons matched with MEPS@NLO)
  - NLO EWK corrections are included



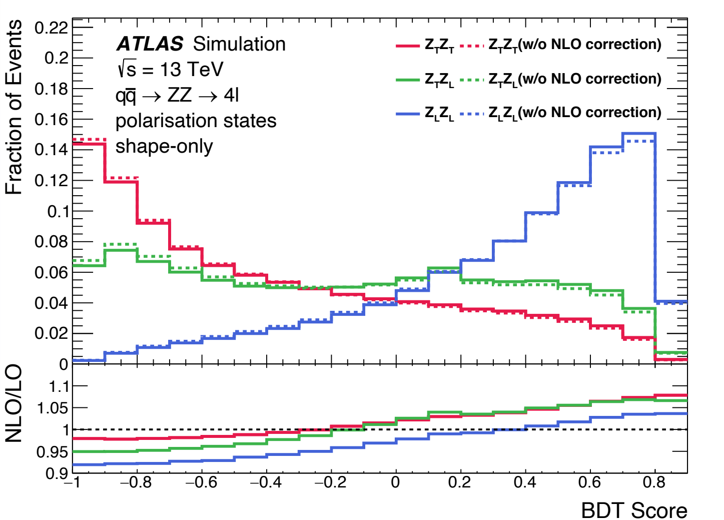
- gg → 4ℓ: Sherpa 2.2.2 (LO 1st parton, matched with MEPS@LO)



- qq → $ZZjj$: MadGraph+Pythia8 at LO accuracy

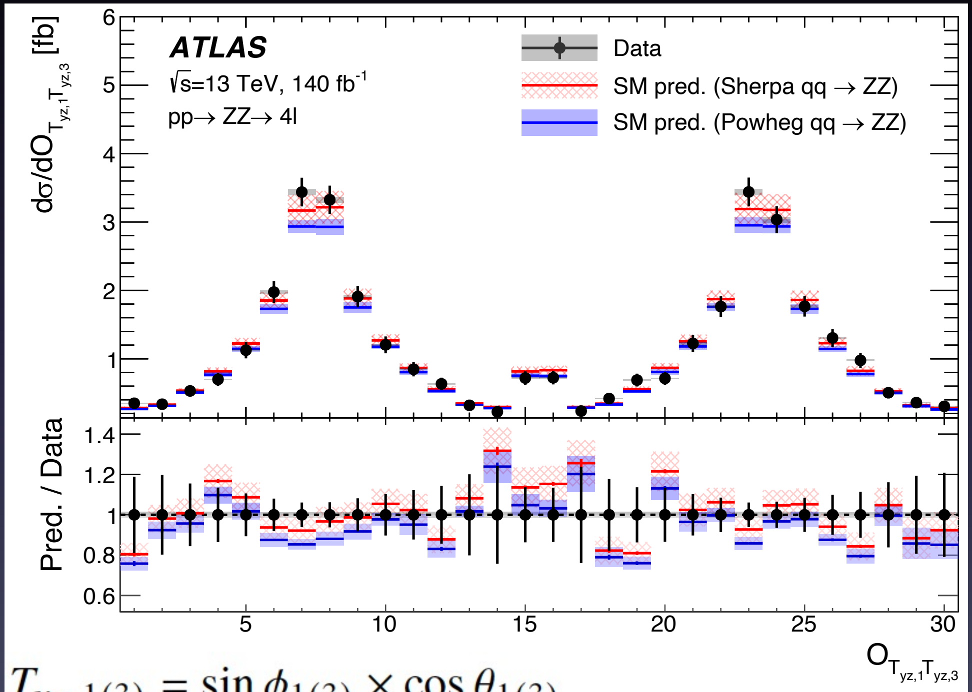
Analysis Specifics

- A BDT is used to enhance the separation between Z_LZ_L and the other two states, based on angular variables
- Z_LZ_L fraction obtained from binned maximum likelihood fit to the BDT distribution using different templates for the 3 polarization states, and bkg.



- Meas: $\sigma_{Z_L Z_L} = 2.45 \pm 0.56 \pm 0.21\ fb$

- Pred: $\sigma_{Z_L Z_L} = 2.10 \pm 0.09\ fb$



$T_{yz,1(3)} = \sin\phi_{1(3)} \times \cos\theta_{1(3)}$

Differential cross section as a function of the Optimal Observable after unfolding

No significant deviation is observed

aNTGC parameter	Interference only		Full	
	Expected	Observed	Expected	Observed
f_Z^4	$[-0.16, 0.16]$	$[-0.12, 0.20]$	$[-0.013, 0.012]$	$[-0.012, 0.012]$
f_γ^4	$[-0.30, 0.30]$	$[-0.34, 0.28]$	$[-0.015, 0.015]$	$[-0.015, 0.015]$

Constraints on aNTGC:

Since the OO is not sensitive to the high-p_{T} regime, these limits are not tighter than those obtained with high-pT kinematic observables

Conclusion

Conclusions

QCD and EWK are pervasive elements of particle physics:

- ○ Subject of a variety of challenging experimental measurements… only a small subset has been shown
- ○ Each measurement usually delivers an important message to the experimental and theoretical communities
- ○ Comparison against state-of-the-art theory predictions
  - Tensions with predictions indicate where theoretical improvements are needed
  - Limits on anomalous gauge couplings
- ○ These measurements help reducing uncertainties, which improves search sensitivity to new physics

Mastering QCD and EWK is both essential for the future of the LHC program and for the advancement of our knowledge