SM measurements at the LHC

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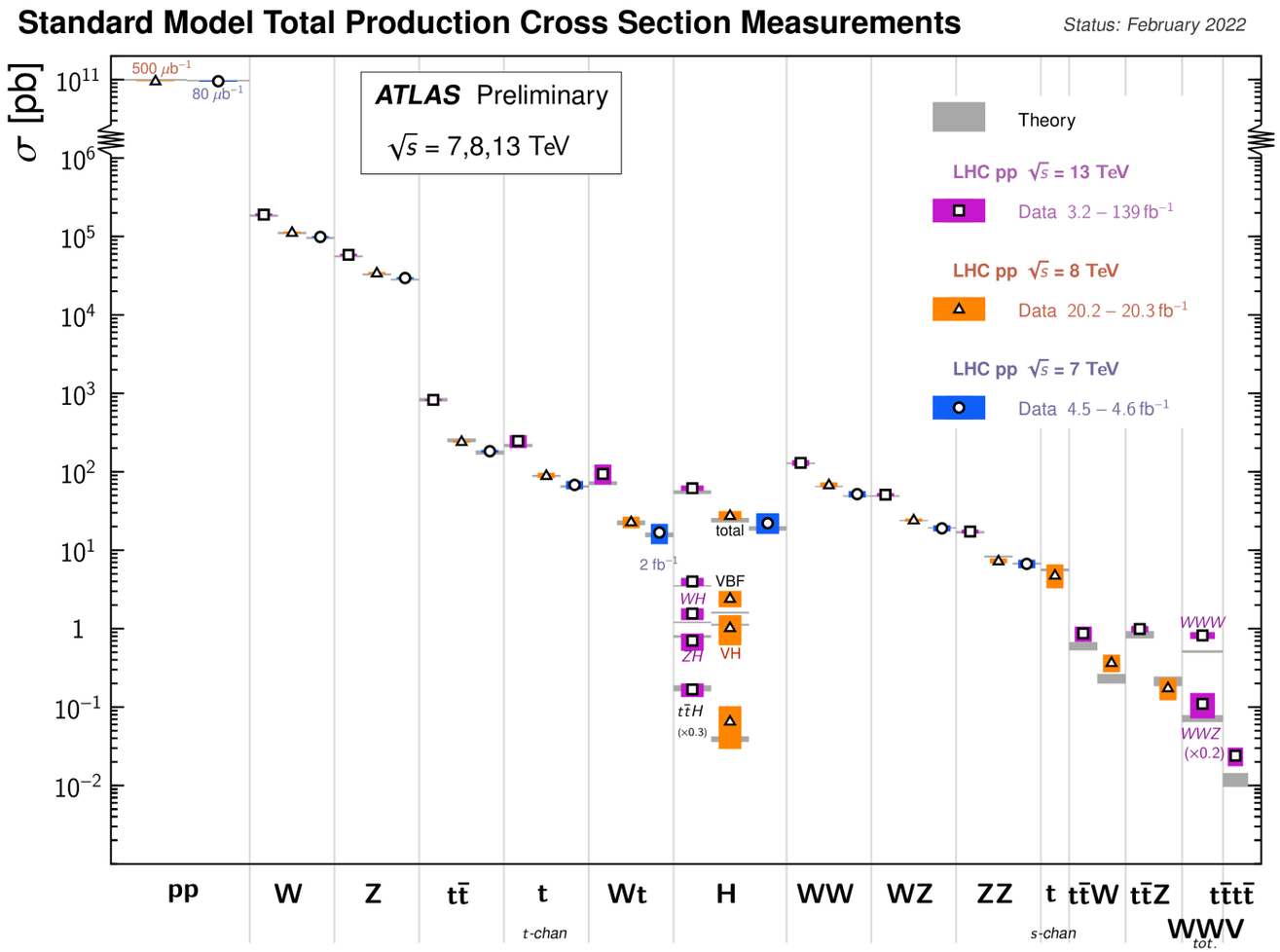
9th China LHC Physics Workshop
Shanghai, 16-20 November 2023

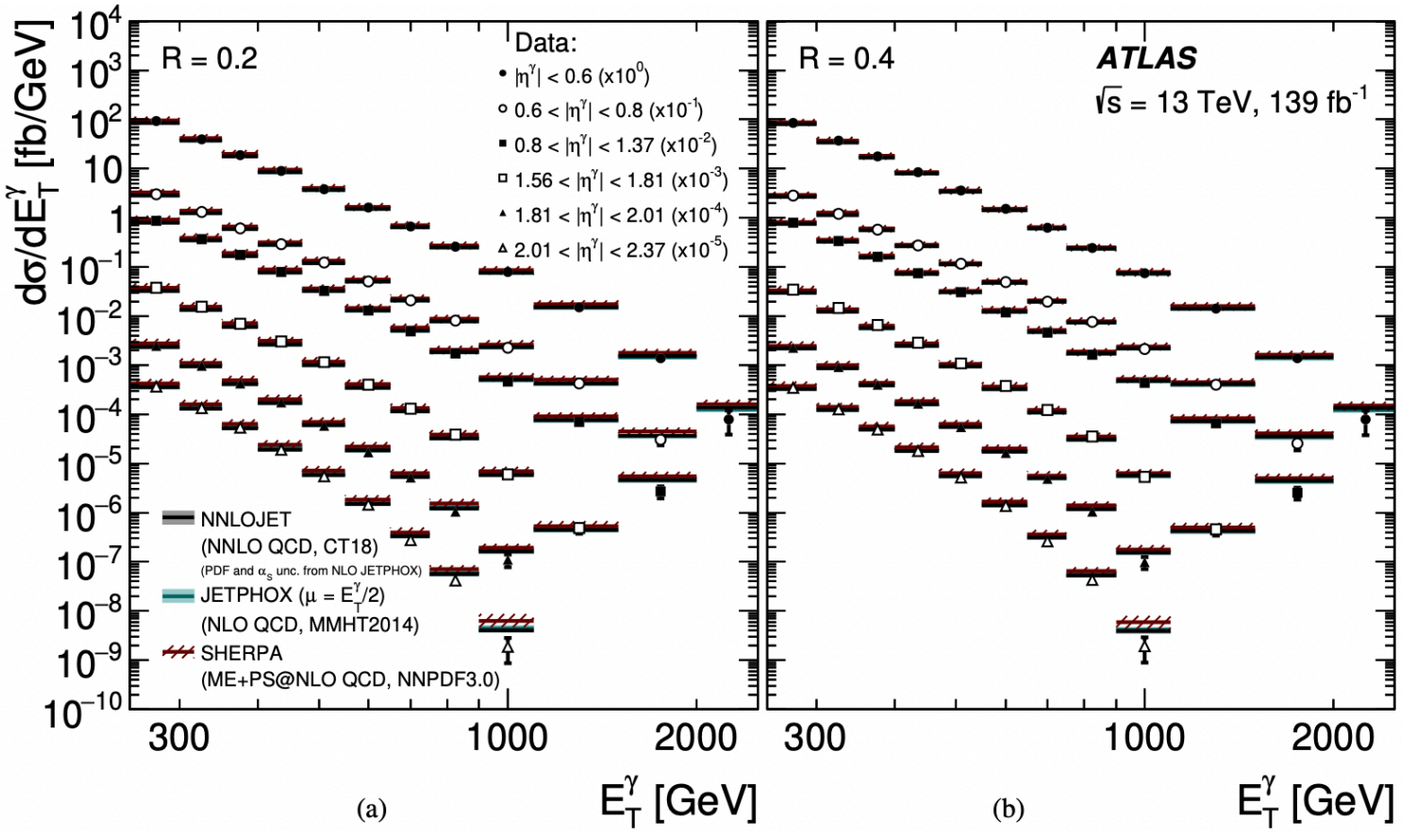
Introduction

- SM measurements at the LHC is a broad field
  - Precision measurement of “usual” processes
  - Observation of rare processes
- Also an important field
  - Deviation from the SM predictions would provide clue for new physics
  - Understanding background for direct searches for new physics



Jet and Photon Physics

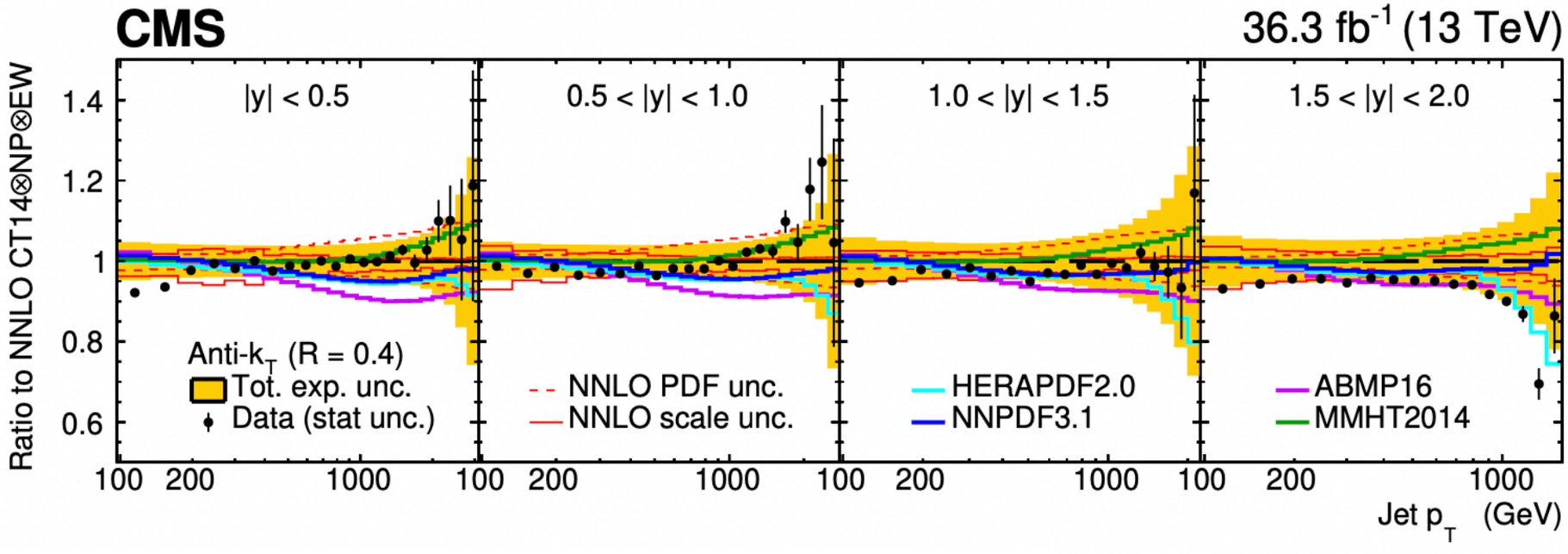
Inclusive photon measurement



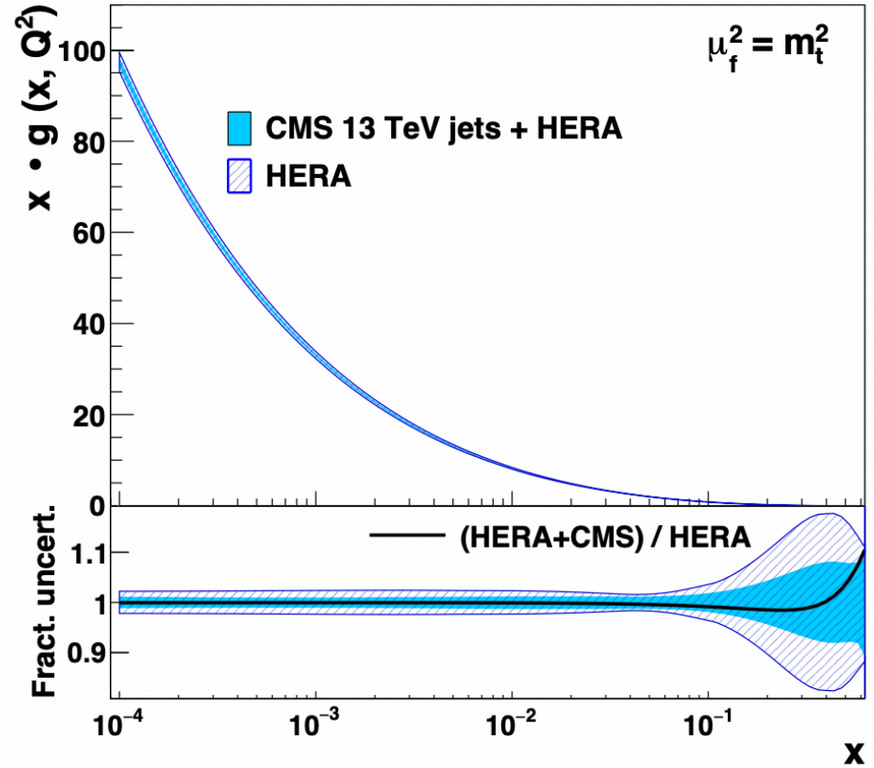
JHEP07(2023)086

- Measure differential cross sections for inclusive isolated photon production at 13 TeV
  - Provided for different isolation radii and with a more granular segmentation in photon pseudorapidity
- Important measurement for test of pQCD, can be exploited in improving determination of PDFs

Inclusive jet measurement



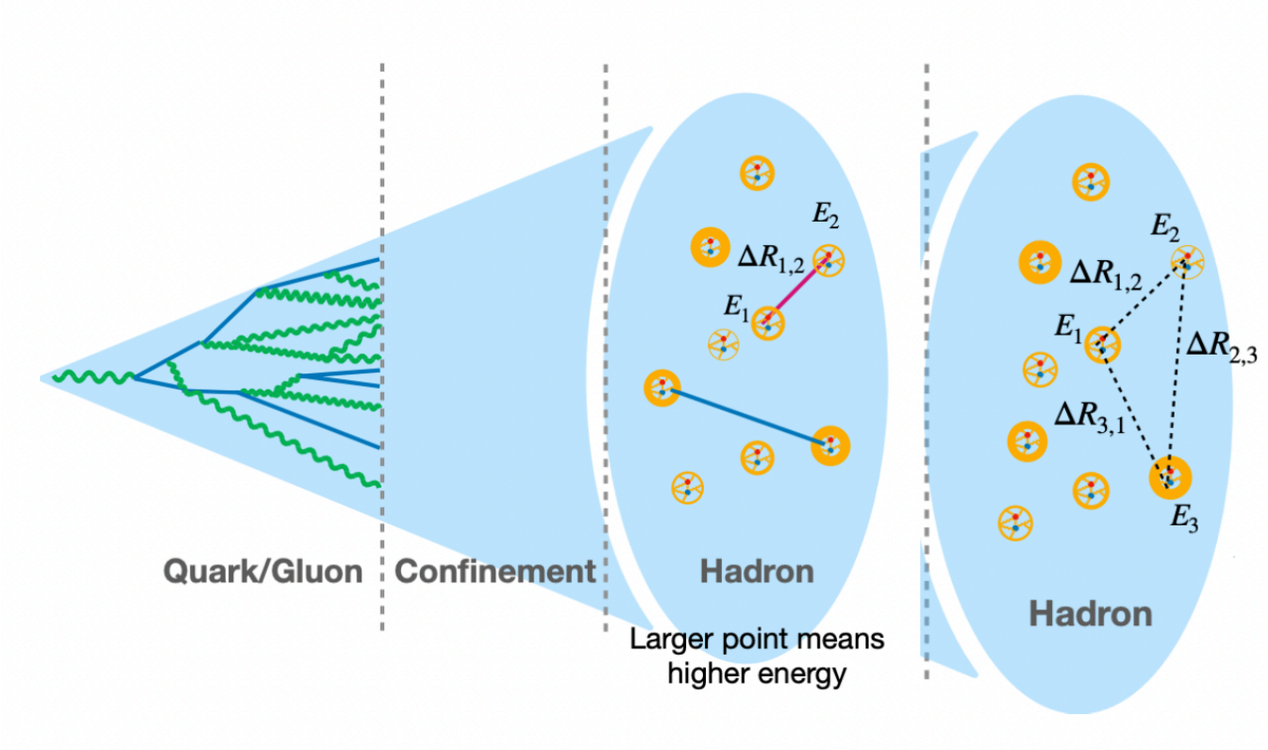
- Measure differential cross sections for inclusive jet production at 13 TeV
- Extract PDF and α_S simultaneously (NNLO)
- Perform SMEFT analysis (NLO)



$\alpha_s(m_Z) = 0.1166 \pm 0.0017$ (1.5 % rel.)

JHEP02(2022)142 JHEP12(2022)035

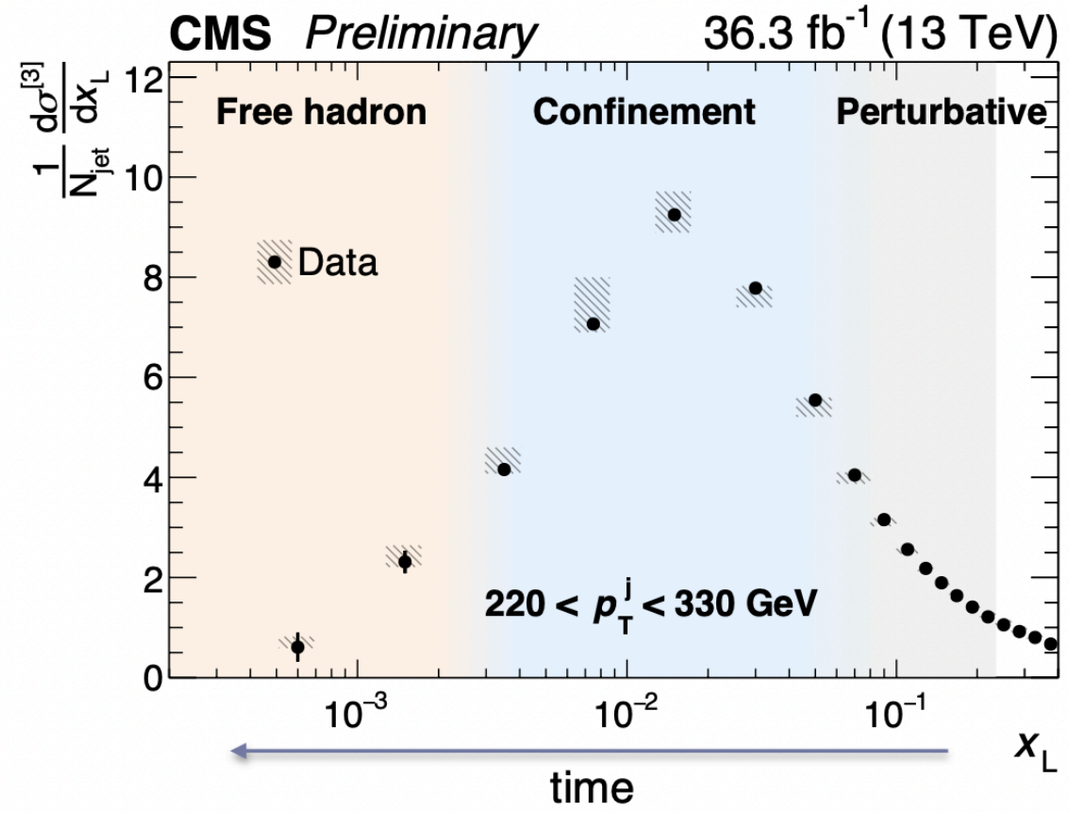
Energy correlator inside jets



$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j}),$$

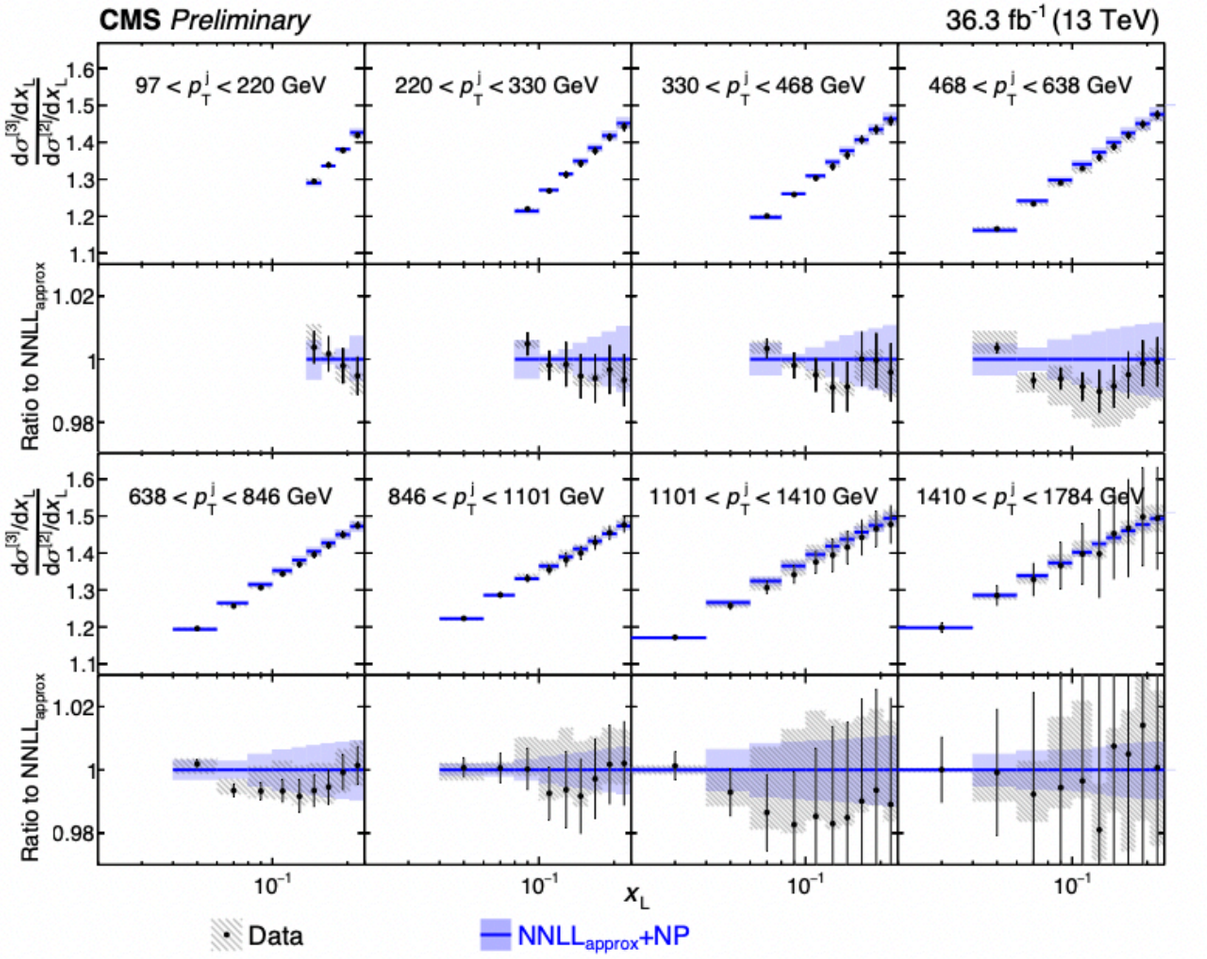
$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k})),$$

CMS-PAS-SMP-22-015

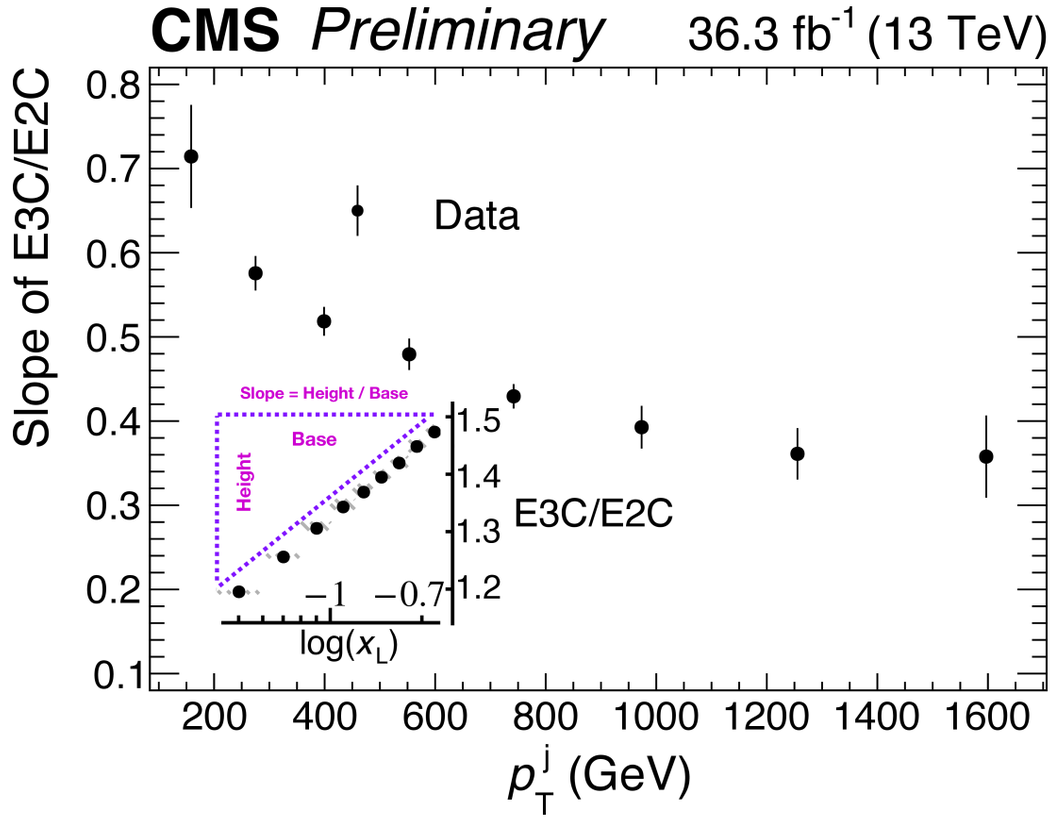


- Motivated by arxiv:2307.07510, CMS measures two-point and three-point energy correlator jet substructure observables (E2C and E3C)
  - reveal confinement and asymptotic freedom in a straightforward way
- E2C and E3C distributions show a sharp transition from quarks and gluons' quantum interactions to hadrons' classical interactions

Energy correlator inside jets



CMS-PAS-SMP-22-015



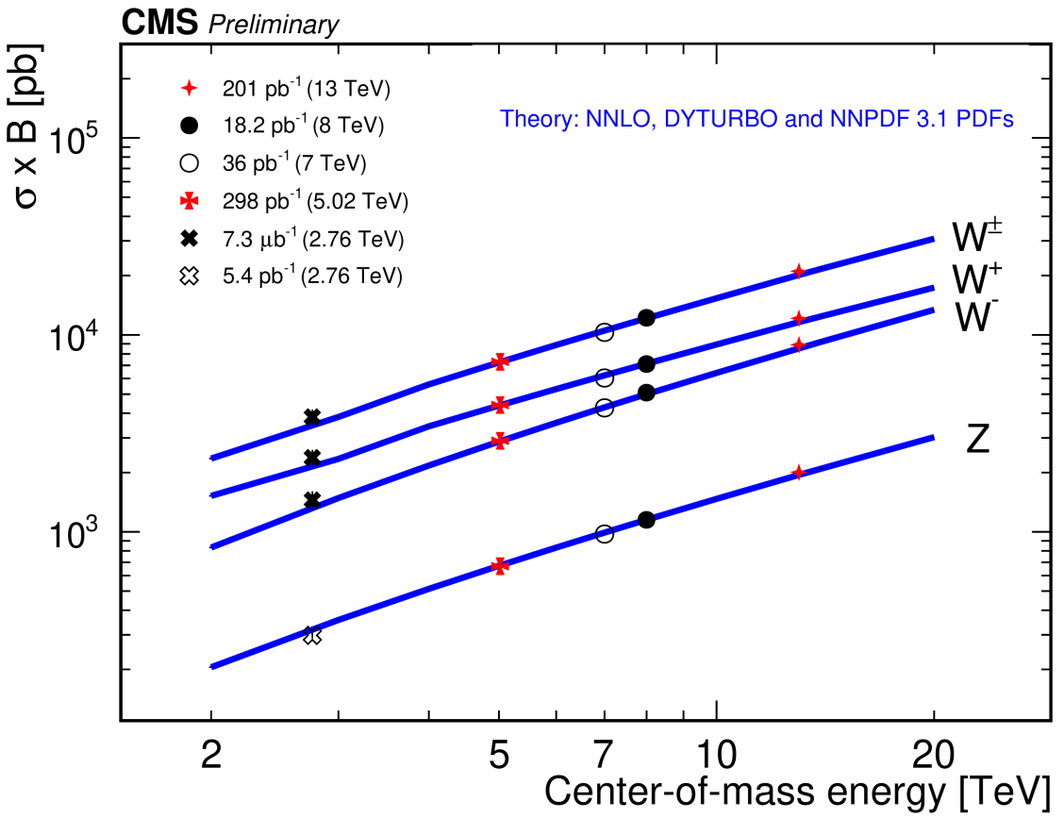
- E3C/E2C is directly proportional to the strong coupling constant α_S
  - slopes of E3C/E2C are measured in multiple jet pT regions, consistent with expected decrease of α_S with increasing energy due to asymptotic freedom
- Extraction of α_S:

$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050} \ (< 4.1\,\%\ \text{rel.})$$

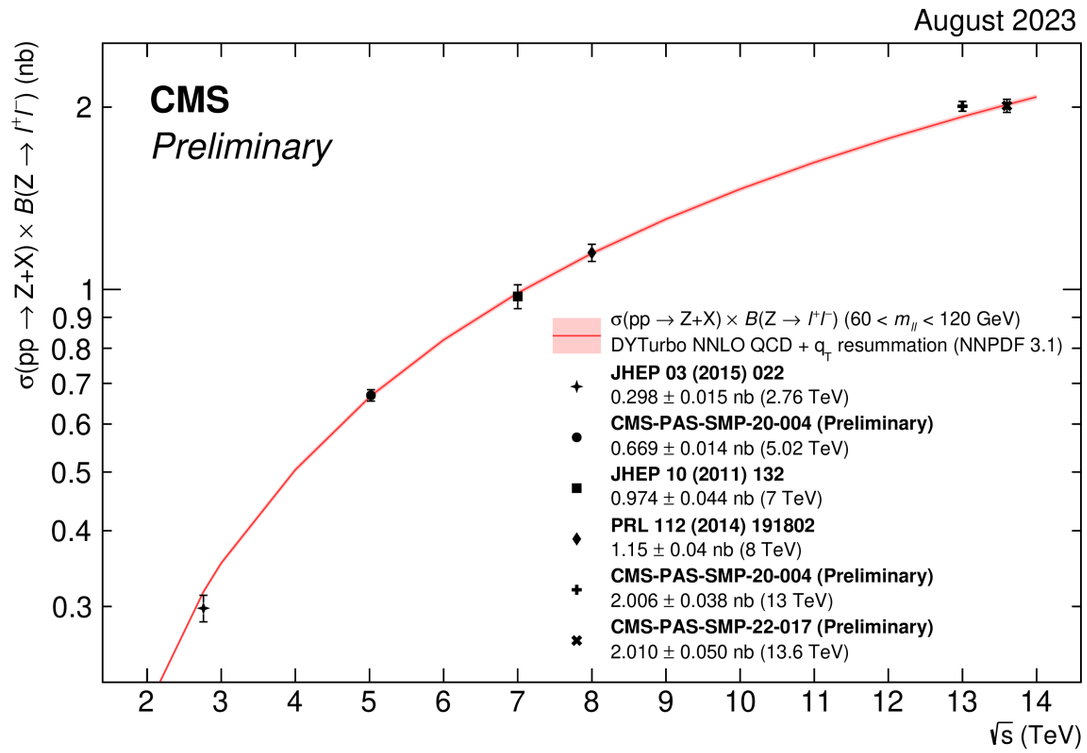
W/Z Physics

Cross section of W/Z production

CMS-PAS-SMP-20-004



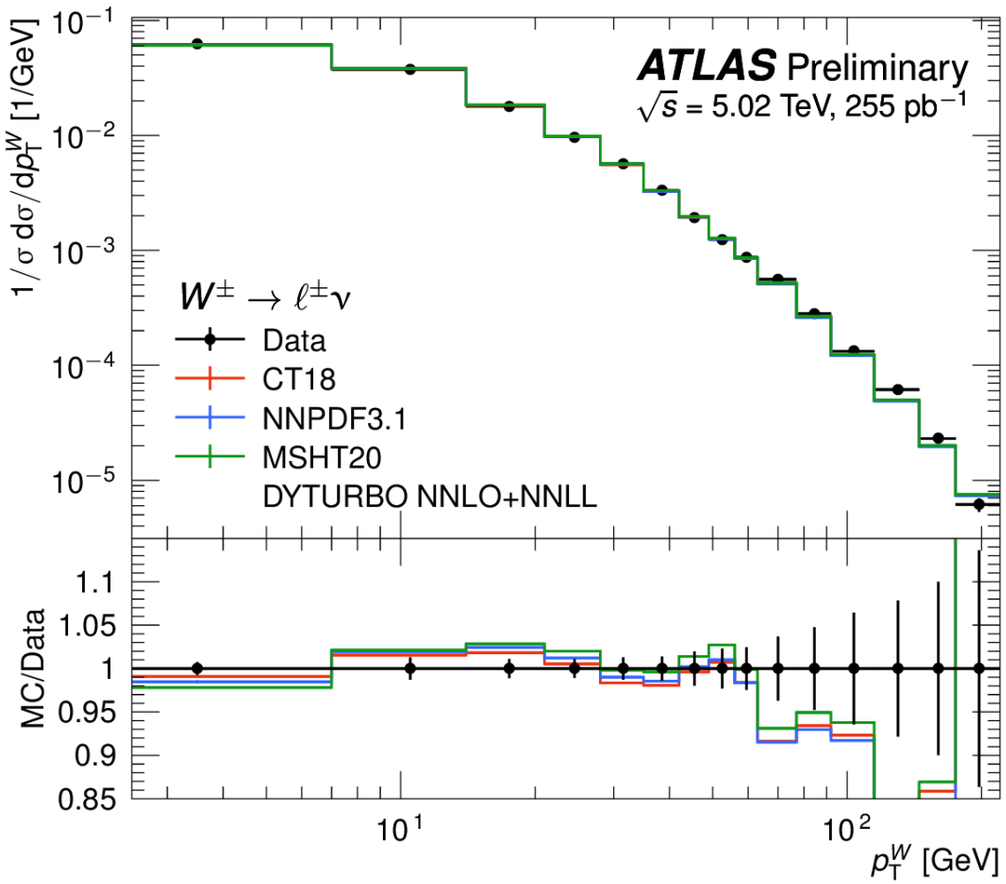
CMS-PAS-SMP-22-017

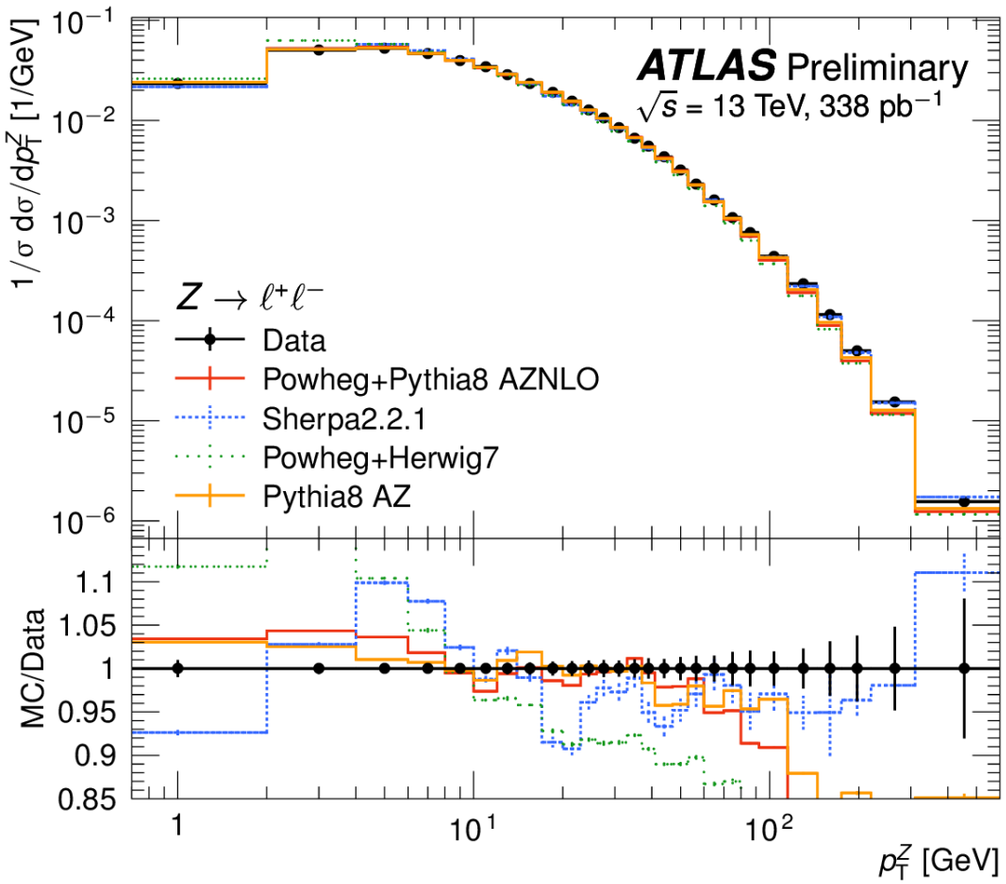


- CMS recently measured W/Z production cross sections using low pileup pp data at 5.02 TeV and 13 TeV
  - Also released Z production cross section result at 13.6 TeV
- Results (at different collision energies) are in agreement with the Standard Model predictions (NNLO QCD)

p_T spectra of W/Z production

ATLAS-CONF-2023-028

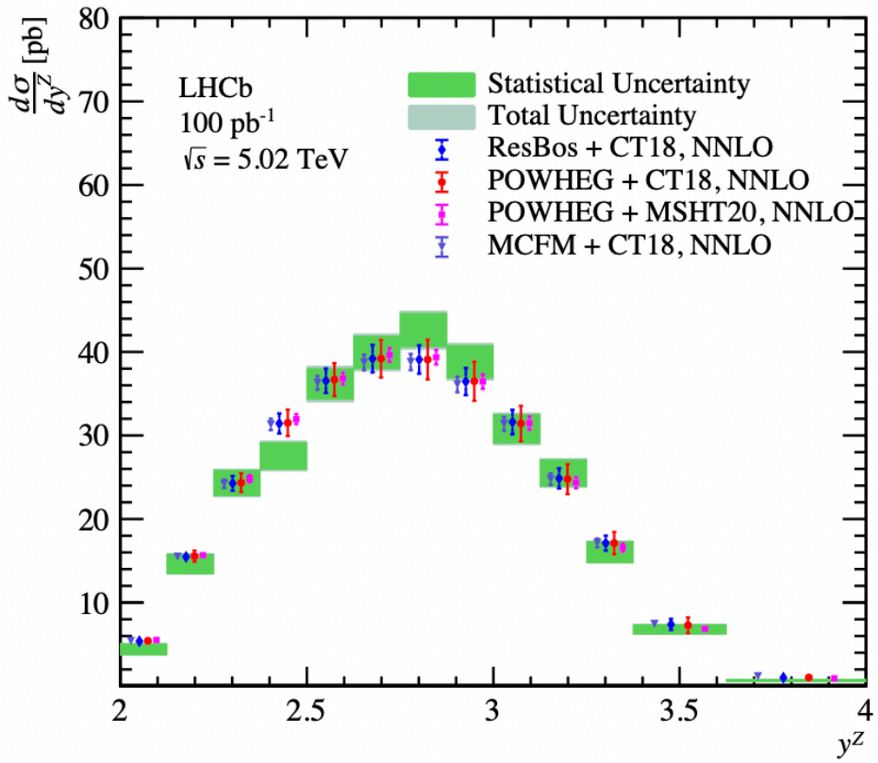


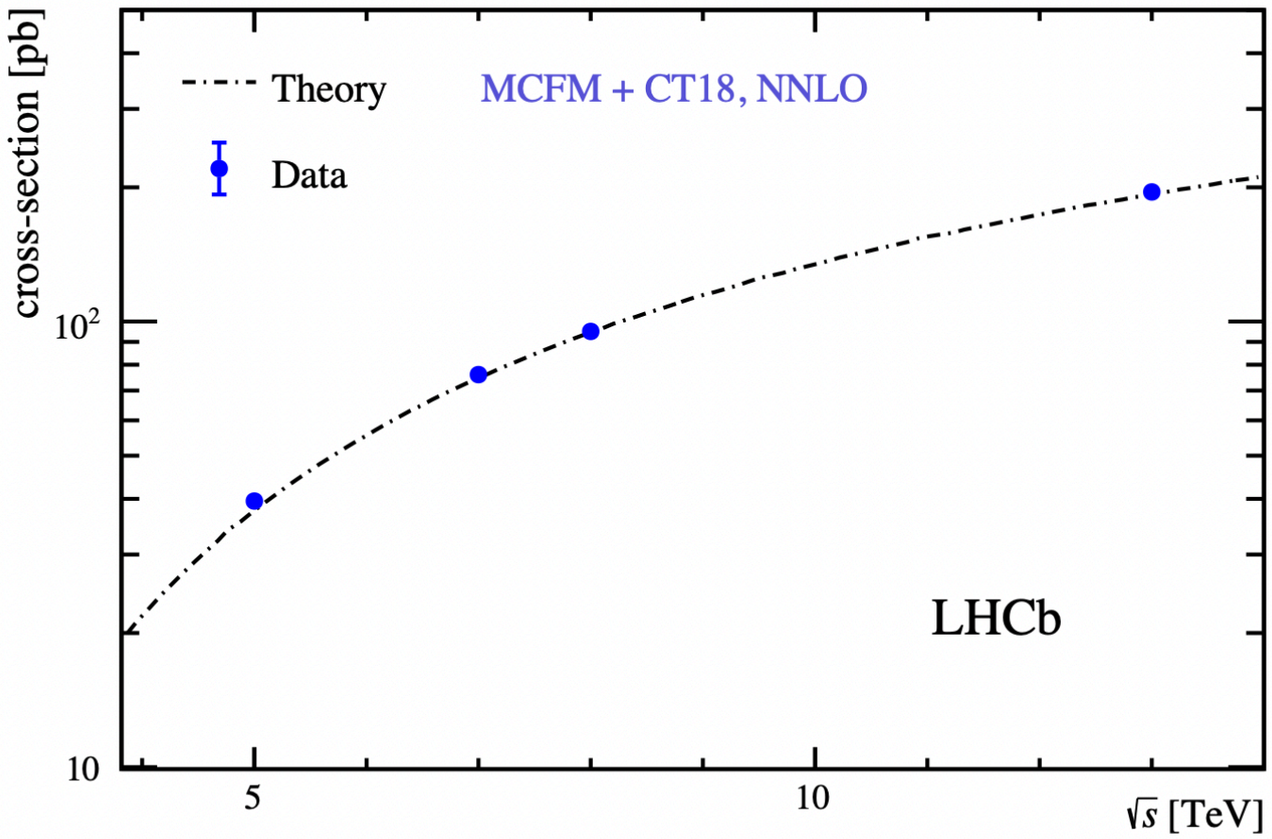


- ATLAS recently measured p_T spectra of W/Z production using low pileup pp data at 5.02 TeV and 13 TeV
  - Dedicated low pileup runs optimize reconstruction of the *W*-boson p_T
- Higher-order resummed predictions based on DYTURBO generally match the data best

Forward Z-boson

arXiv:2308.12940



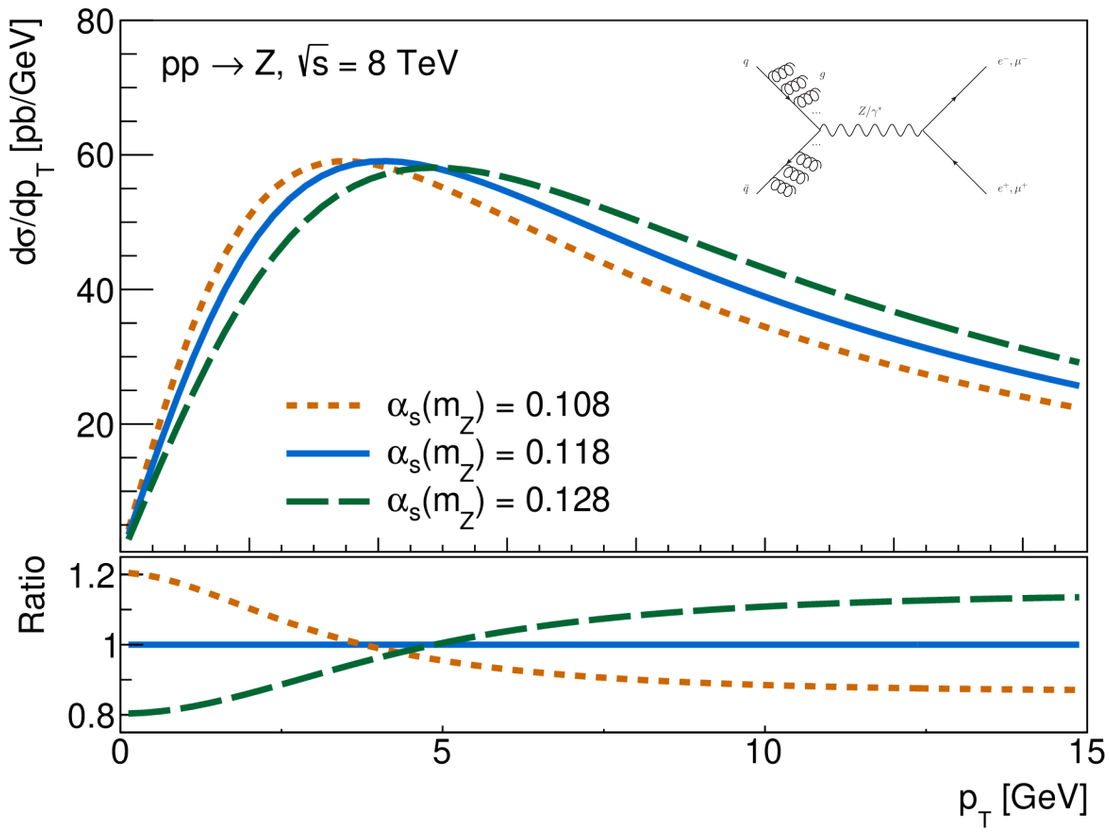


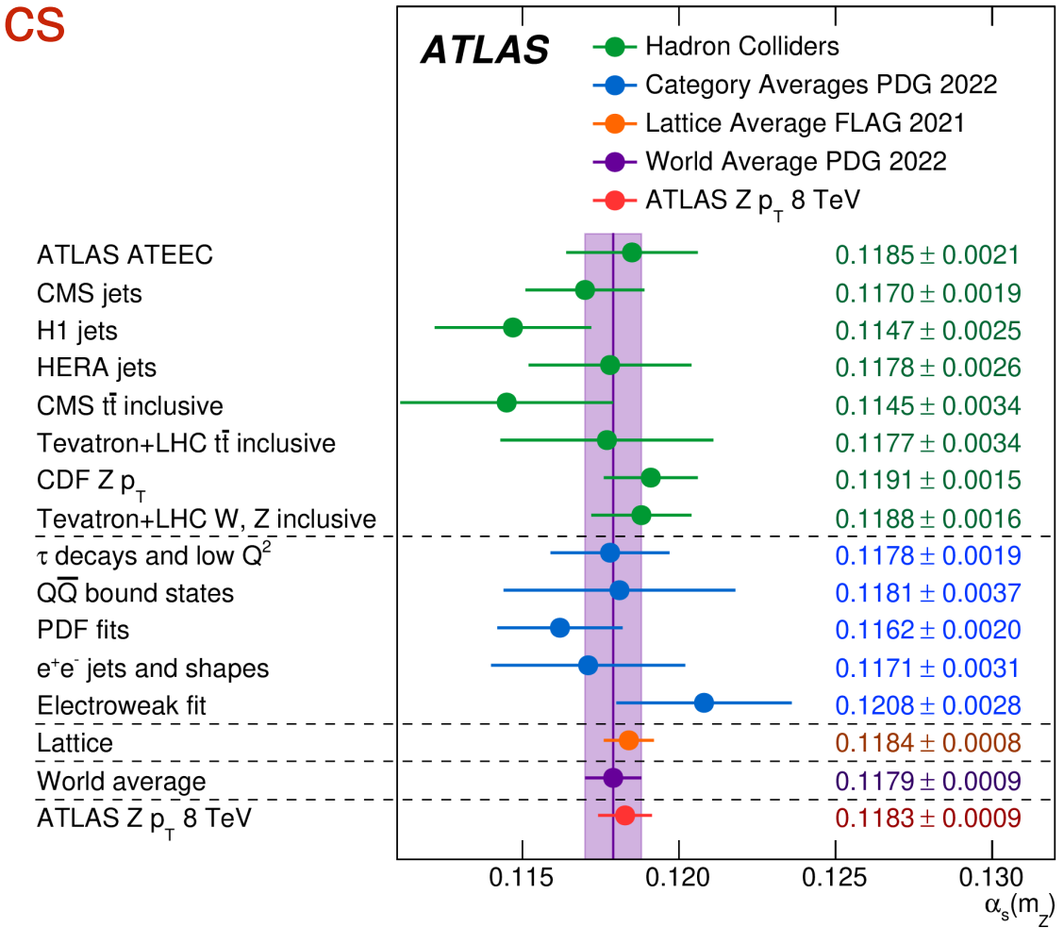
- LHCb measures inclusive and differential cross sections of Z boson production in forward region using 5.02 TeV pp collision data
  - Unique coverage, complementary to ATLAS/CMS measurement
- Combining with the Z production result using 5.02 TeV pPb collision data, nuclear modification factor is measured for the first time at this energy

$$R^{\mathrm{F}}_{pPb} = 1.2^{+0.5}_{-0.3}\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst}) \qquad R^{\mathrm{B}}_{pPb} = 3.6^{+1.6}_{-0.9}\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst})$$

Determination of α_S using Z p_T

arxiv:2309.12986 submitted to Nature Physics



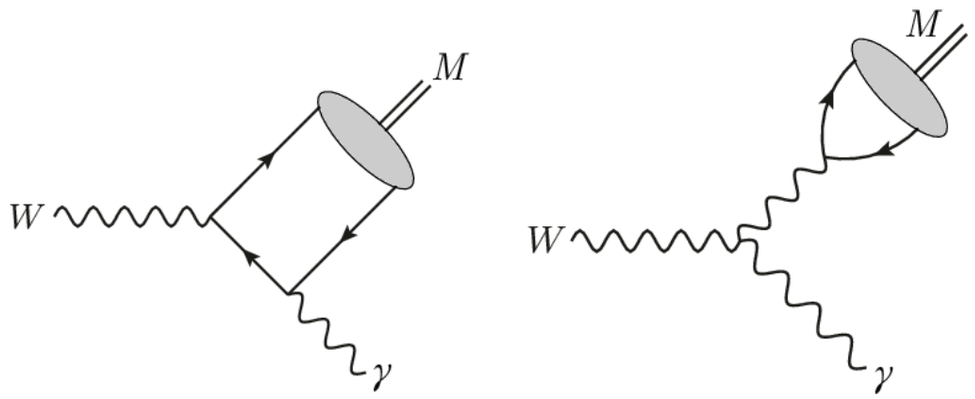


- ATLAS looks into Z pT distributions in 8 TeV data
  - Z bosons recoil against QCD ISR; Position of the Z p_T-peak (Sudakov peak) highly sensitive to α_S
- Most precise experimental measurement of $\alpha_s(m_Z)$ and first time using N3LO+N4LL $p_T(Z)$ prediction

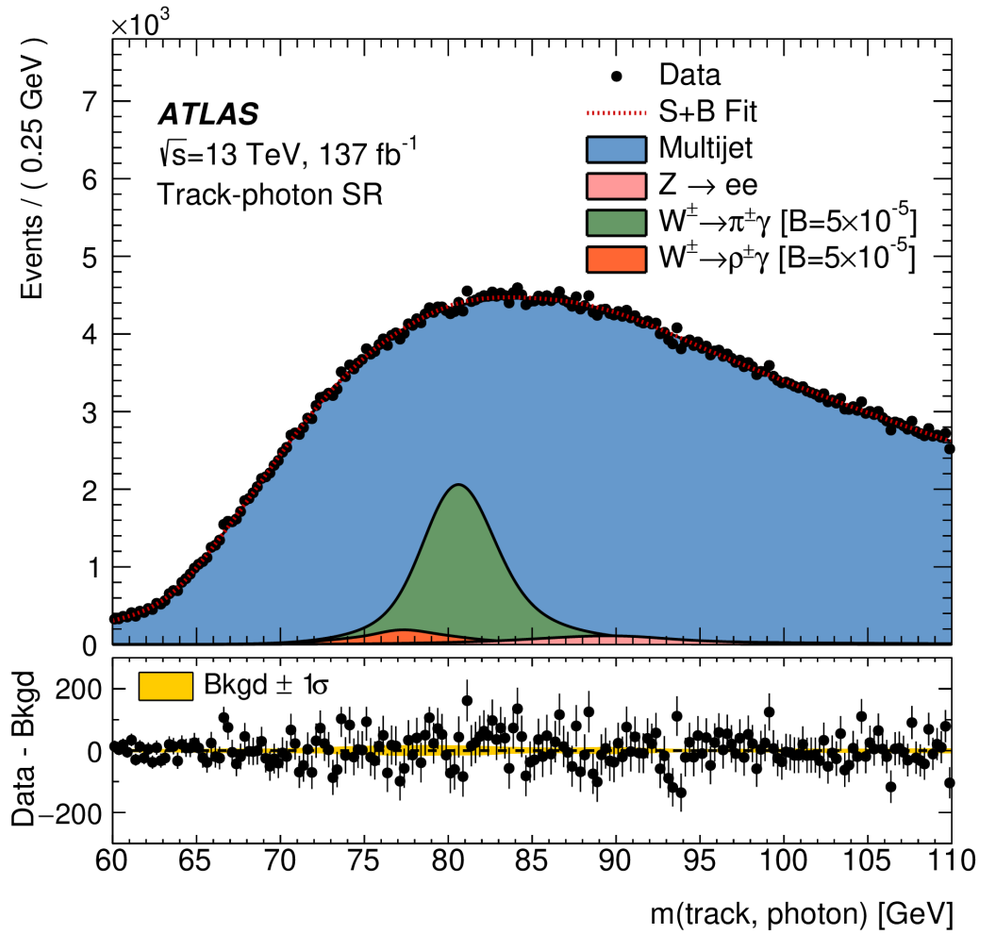
$$\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088} \ (0.7\,\%\ \text{rel.})$$

Search for exclusive W boson hadronic decays

arxiv:2309.15887 submitted to PRL



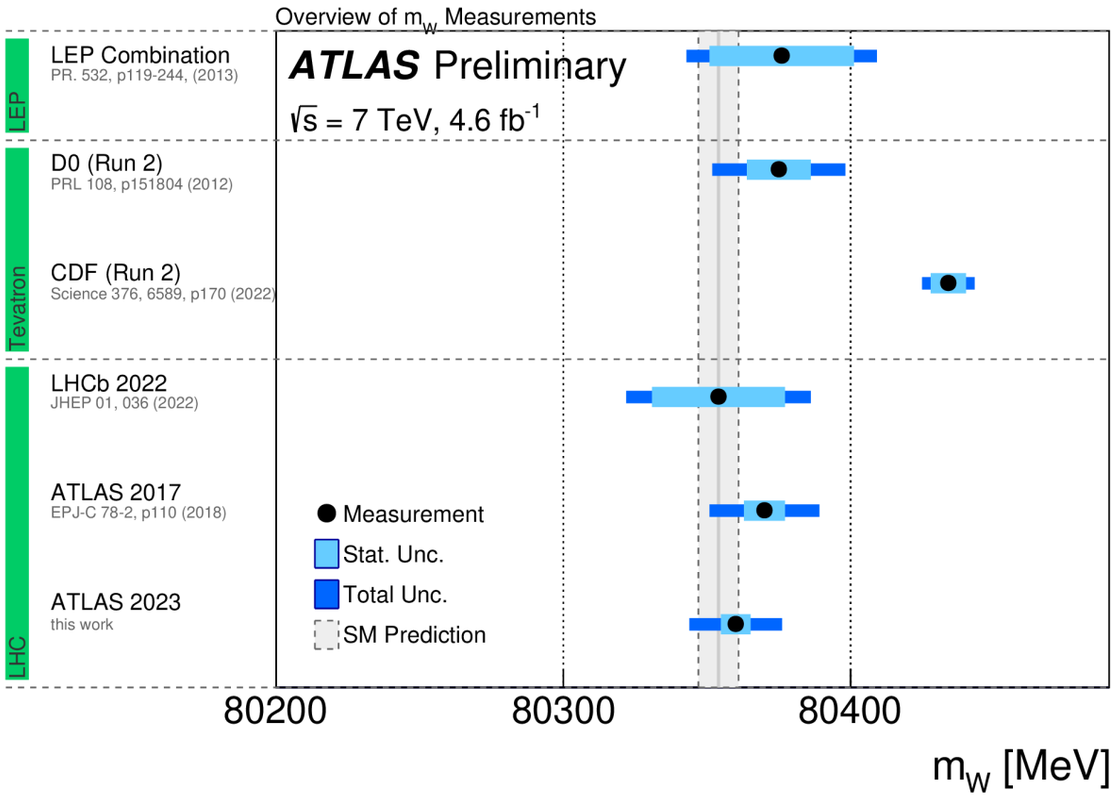
	95% CL upper limits	
Branching fraction	Expected $\times 10^{-6}$	Observed $\times 10^{-6}$
$\mathcal{B}(W^{\pm} \to \pi^{\pm}\gamma)$	$1.2^{+0.5}_{-0.3}$	1.9
$\mathcal{B}(W^{\pm} \to K^{\pm}\gamma)$	$1.1^{+0.4}_{-0.3}$	1.7
$\mathcal{B}(W^{\pm} \to \rho^{\pm}\gamma)$	$6.0^{+2.3}_{-1.7}$	5.2

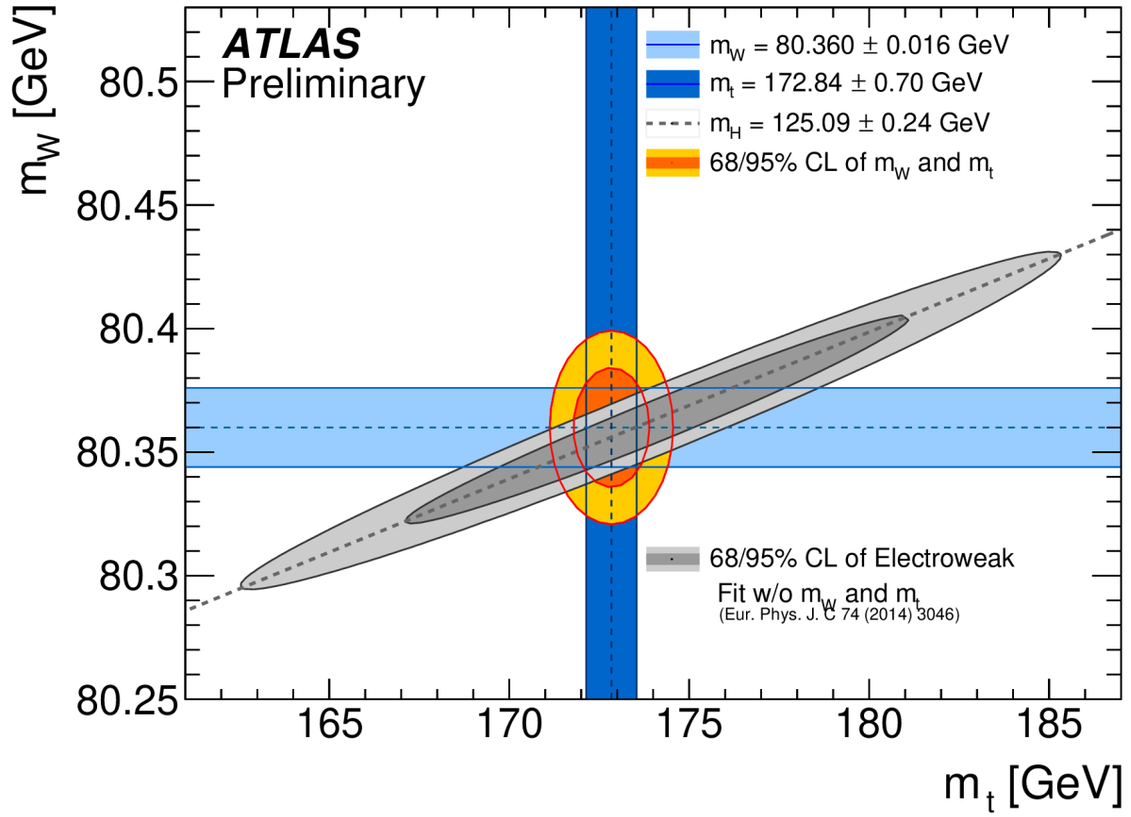


- Improve previous upper limit on B($W^{\pm} \to \pi^{\pm}\gamma$) by approximately a factor of four and provide first upper limits on B($W^{\pm} \to K^{\pm}\gamma$) and B($W^{\pm} \to \rho^{\pm}\gamma$)
- Provide a test bench for the QCD factorization formalism, as well as a probe of W boson coupling to quarks and a new way to measure W boson mass

W mass measurement

ATLAS-CONF-2023-004

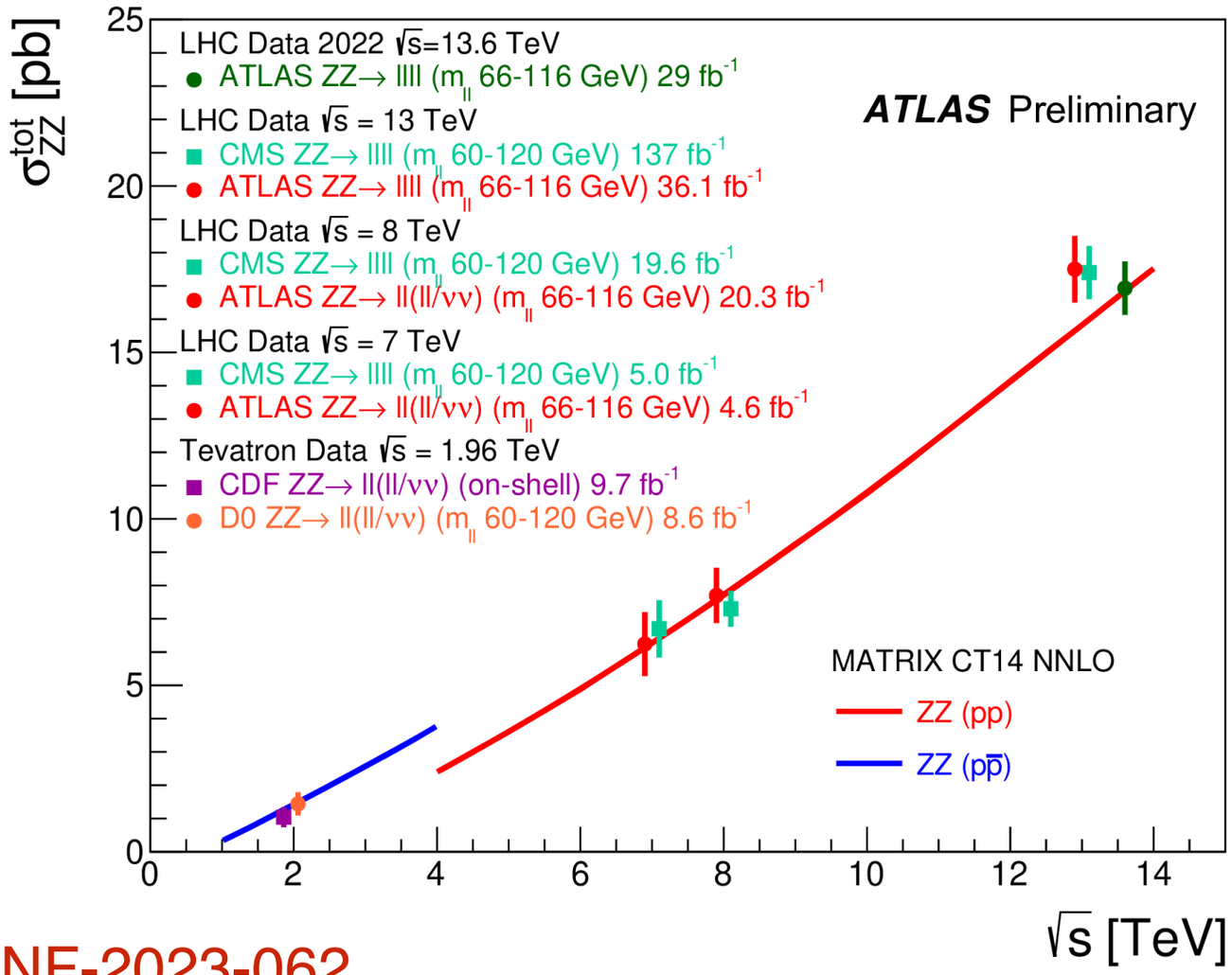




- Higher order correction introduce dependance of W mass on top/Higgs mass, etc.
- ATLAS updated W mass measurement using 7 TeV pp data
  - Rigorous checks of modelling and advances in PDFs allow to use a profile likelihood fit => Several systematic uncertainties are reduced
  - m_W=80360±5(stat.)±15(syst.)=80360±16MeV
- Tension with CDF measurement; consistent with global EW fit

Multiboson Physics

Cross section of ZZ production



ATLAS-CONF-2023-062

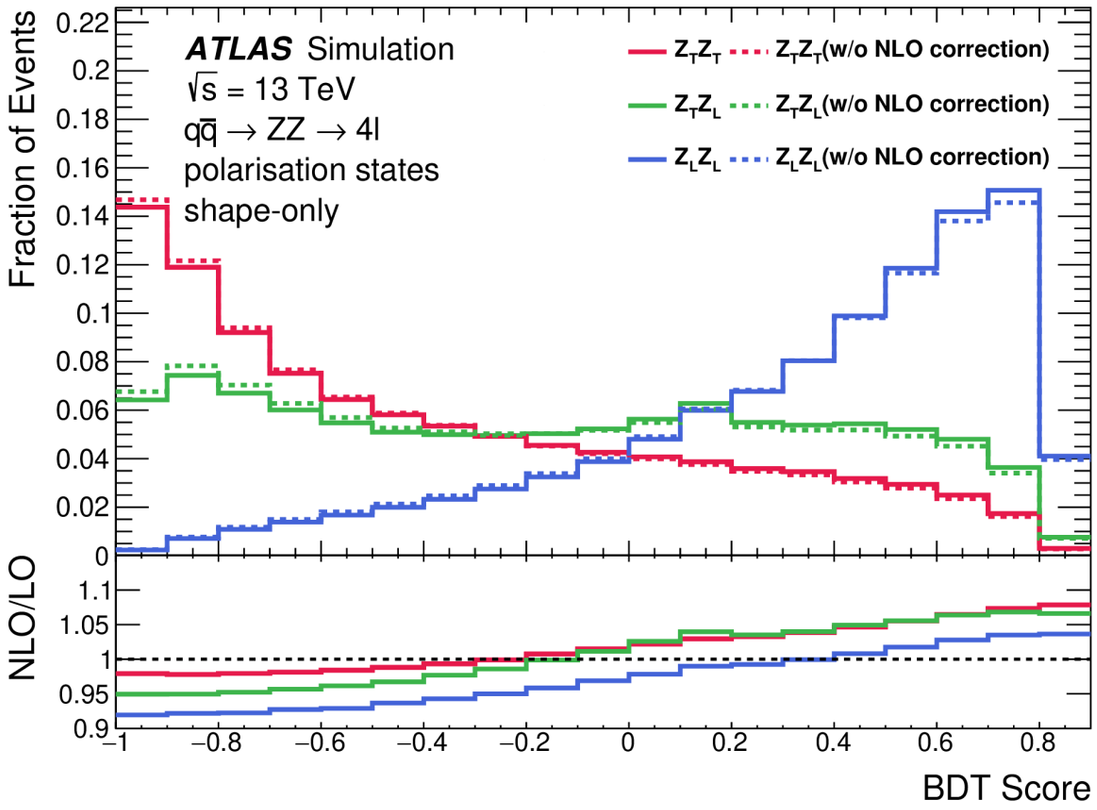
- ATLAS has just released a new measurement of ZZ production cross section using data collected during Run 3 of the LHC
  - pioneers the use of PHYSLITE – a new, reduced data format that requires significantly less storage
- Results (at different collision energies) are well described by the Standard Model predictions

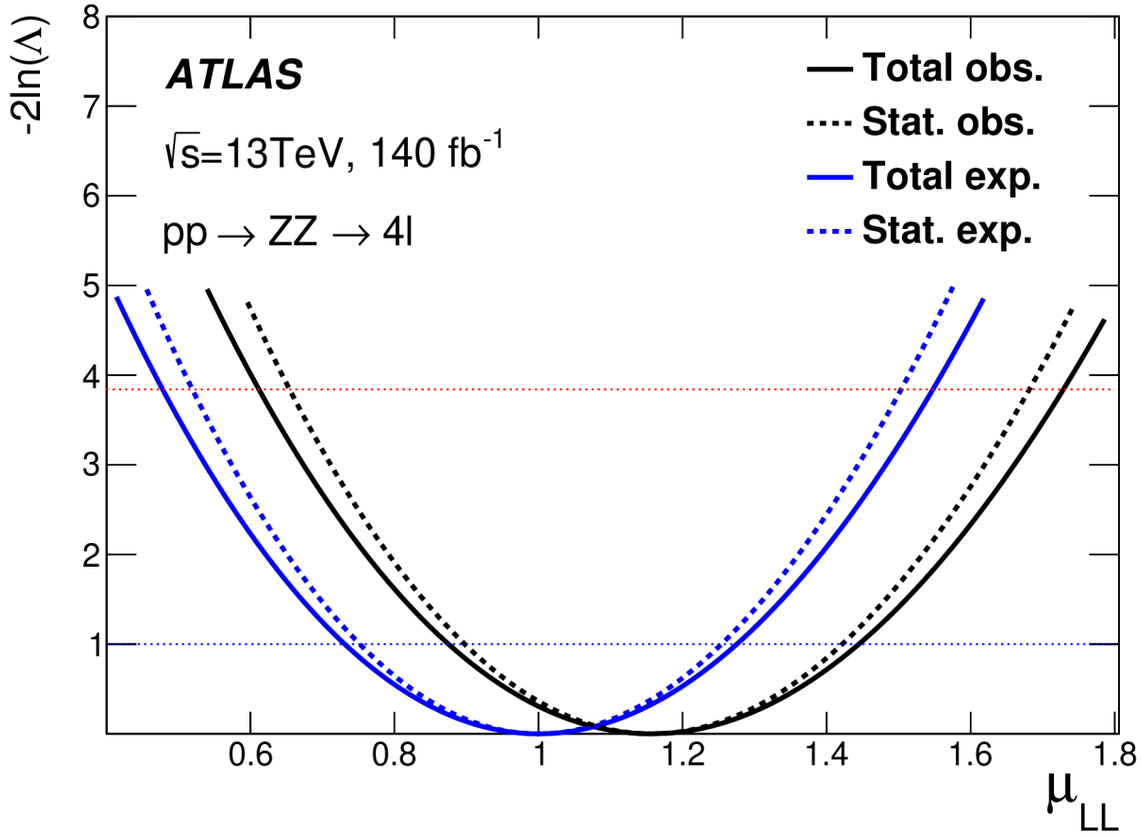
Polarization of ZZ production

arxiv:2310.04350 submitted to JHEP

$\sigma_{fid} = 2.4 \pm 0.6$ fb

(SM NLO $\sigma_{fid} = 2.1 \pm 0.1$ fb)

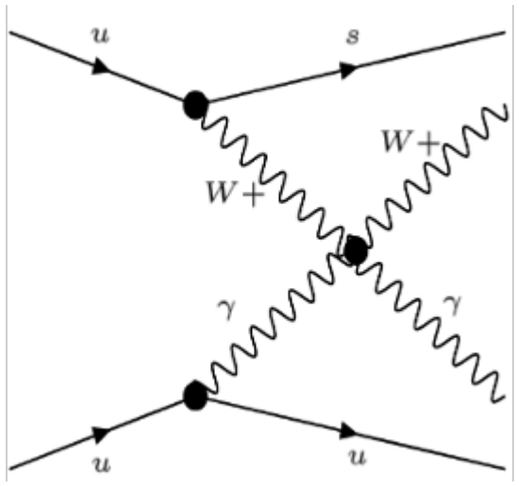


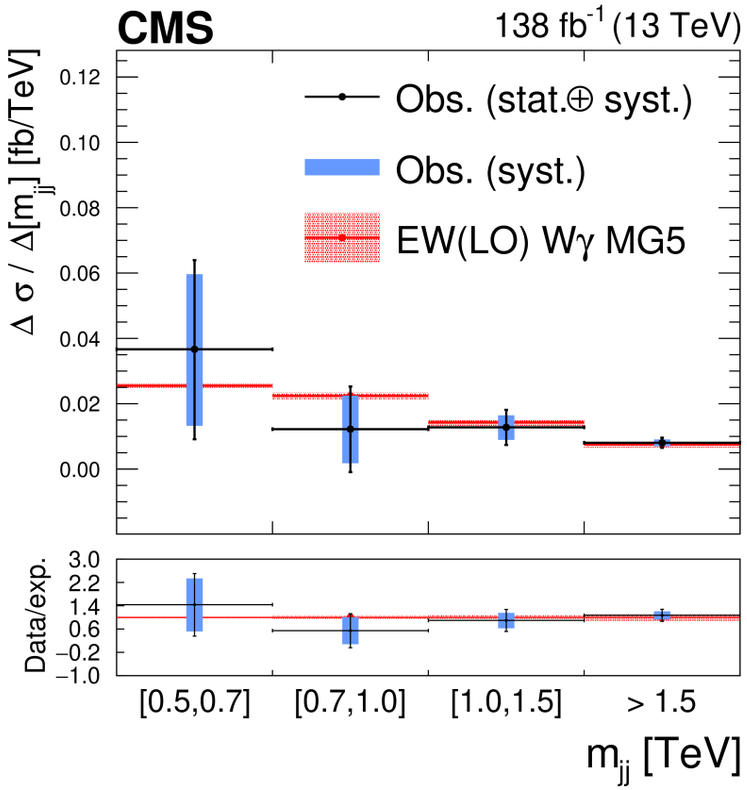


- ATLAS studies polarization of ZZ production in 4-lepton final state
  - BDT using only angular variables to distinguish TT, LT/TL, LL
- Evidence (**4.3σ**) of pair production of longitudinally polarized Z bosons

Electroweak Wγ measurement

Phys. Rev. D 108 (2023) 032017





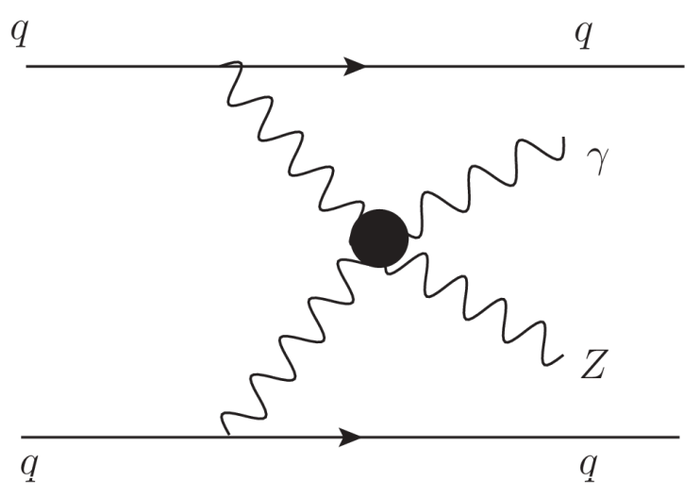
Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

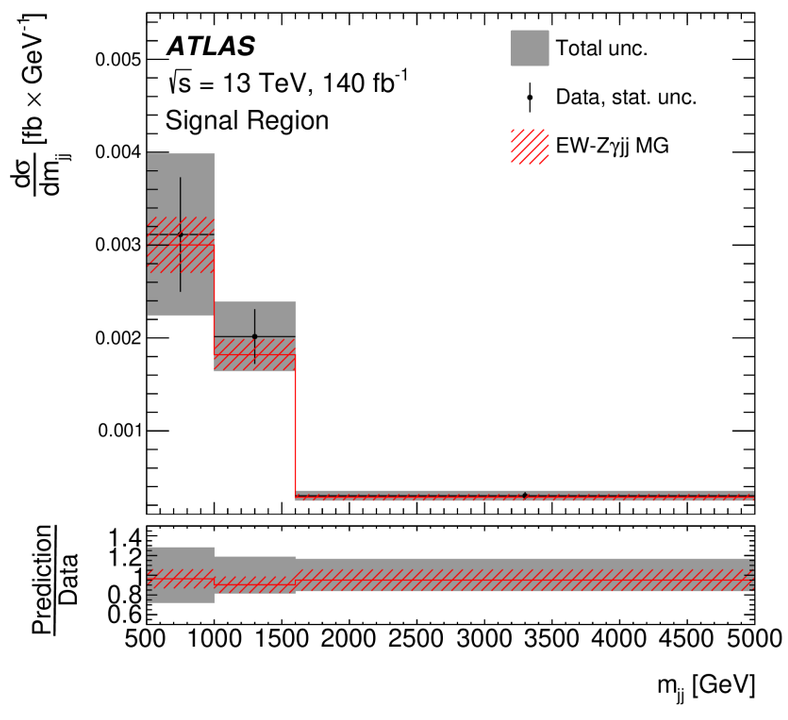
CMS performs measurement for EWK Wγ, a rare Standard Model process

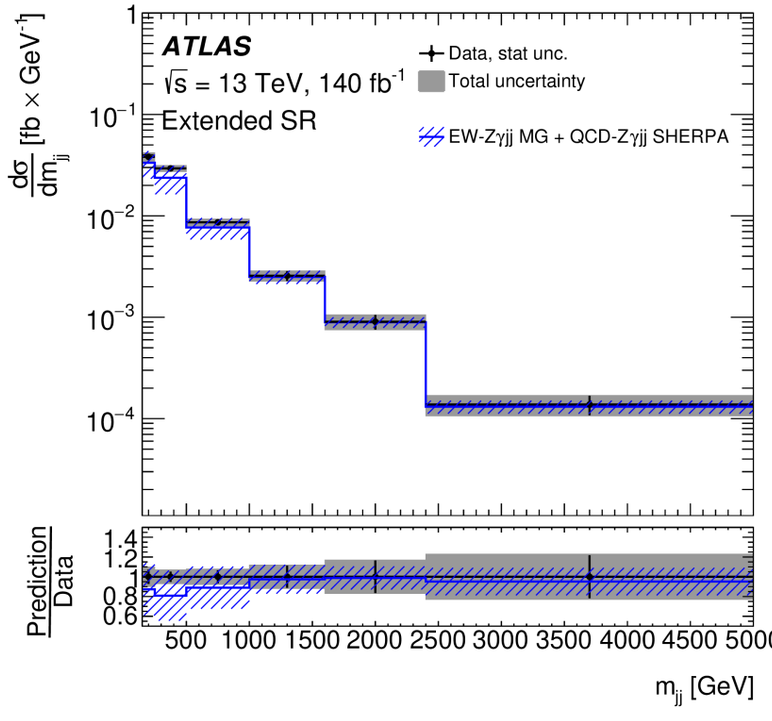
1. "Re-discover" EWK Wγ at 13 TeV
2. First differential cross section measurement for EWK Wγ
3. Most precise measurement for some anomalous quartic gauge couplings (aQGCs) (FM2-5, FT5-7)

Electroweak Zγ measurement

Phys. Lett. B 846 (2023) 138222







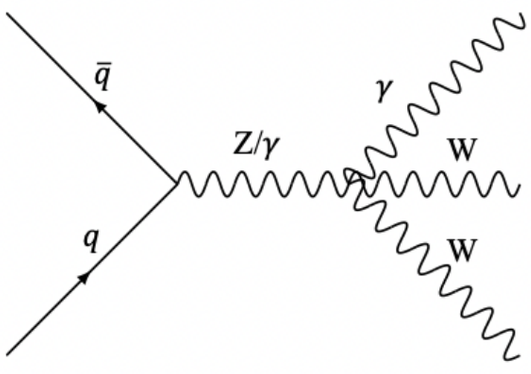
ATLAS performs measurement for EWK Zγ, a rare Standard Model process

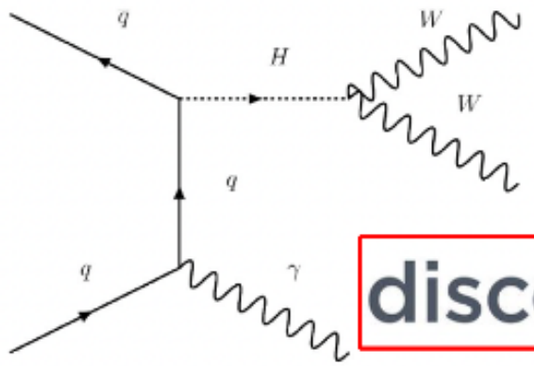
1. Observed and expected significance well above 5 standard deviations
2. Fiducial cross sections of EWK Zγ and EWK+QCD Zγ are measured and consistent with SM predictions
3. Differential cross-sections are also measured using the same events and compared with Monte Carlo simulations

First observation of WWγ production

arxiv:2310.05164 submitted to PRL

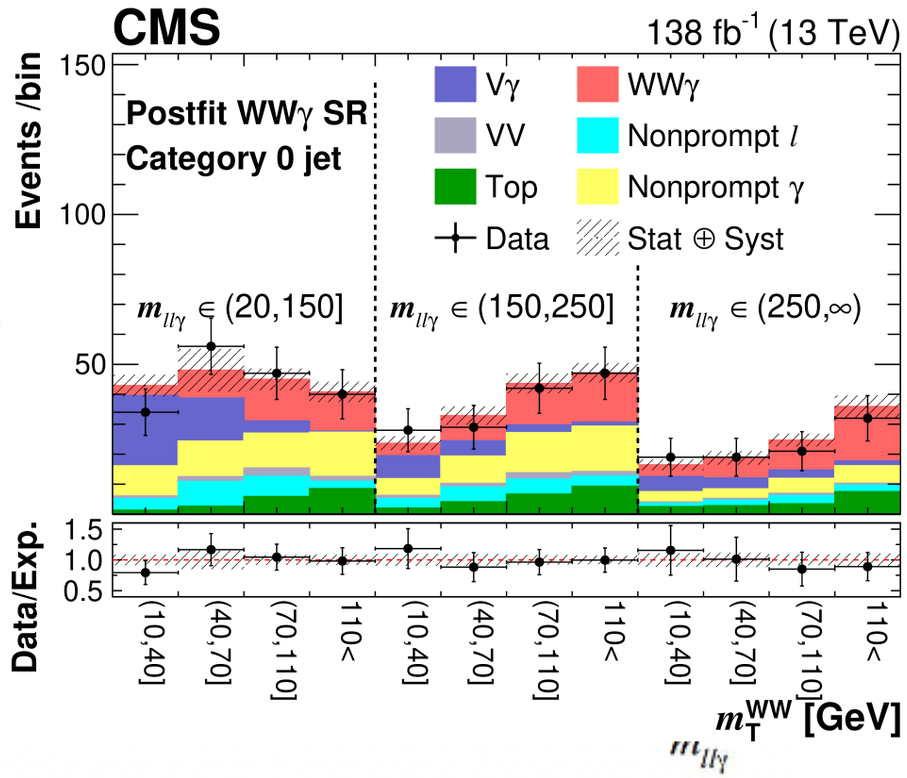
- First observation (**5.6σ**) of WWγ production
  - Provide the best sensitivity for Yukawa couplings between Higgs and light quarks





discovery+

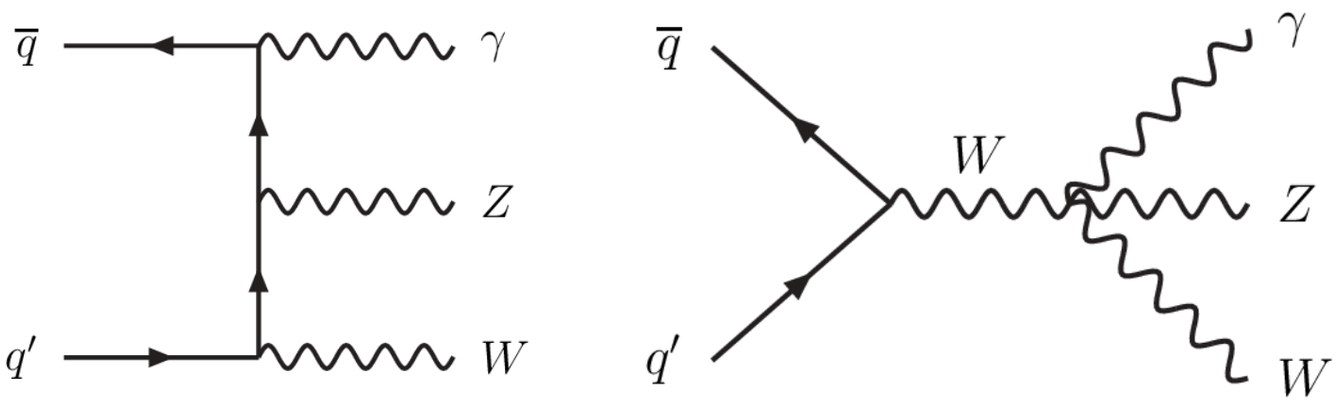
Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq$13000 (16000)
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq$14000 (17000)
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq$1300 (1700)
$c\bar{c} \to H + \gamma \to e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq$110(200)

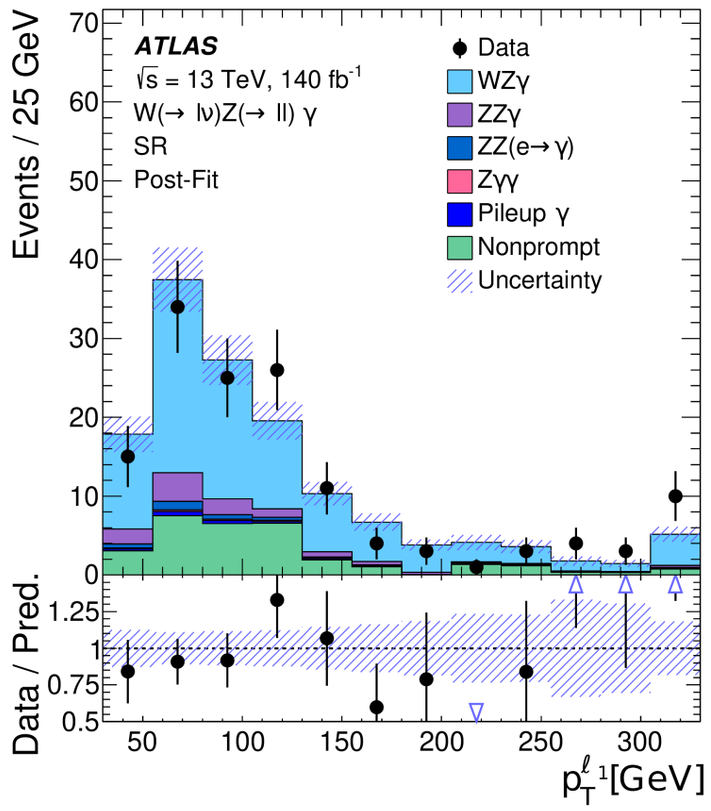


First observation of WZγ production

arxiv:2305.16994 submitted to PRL

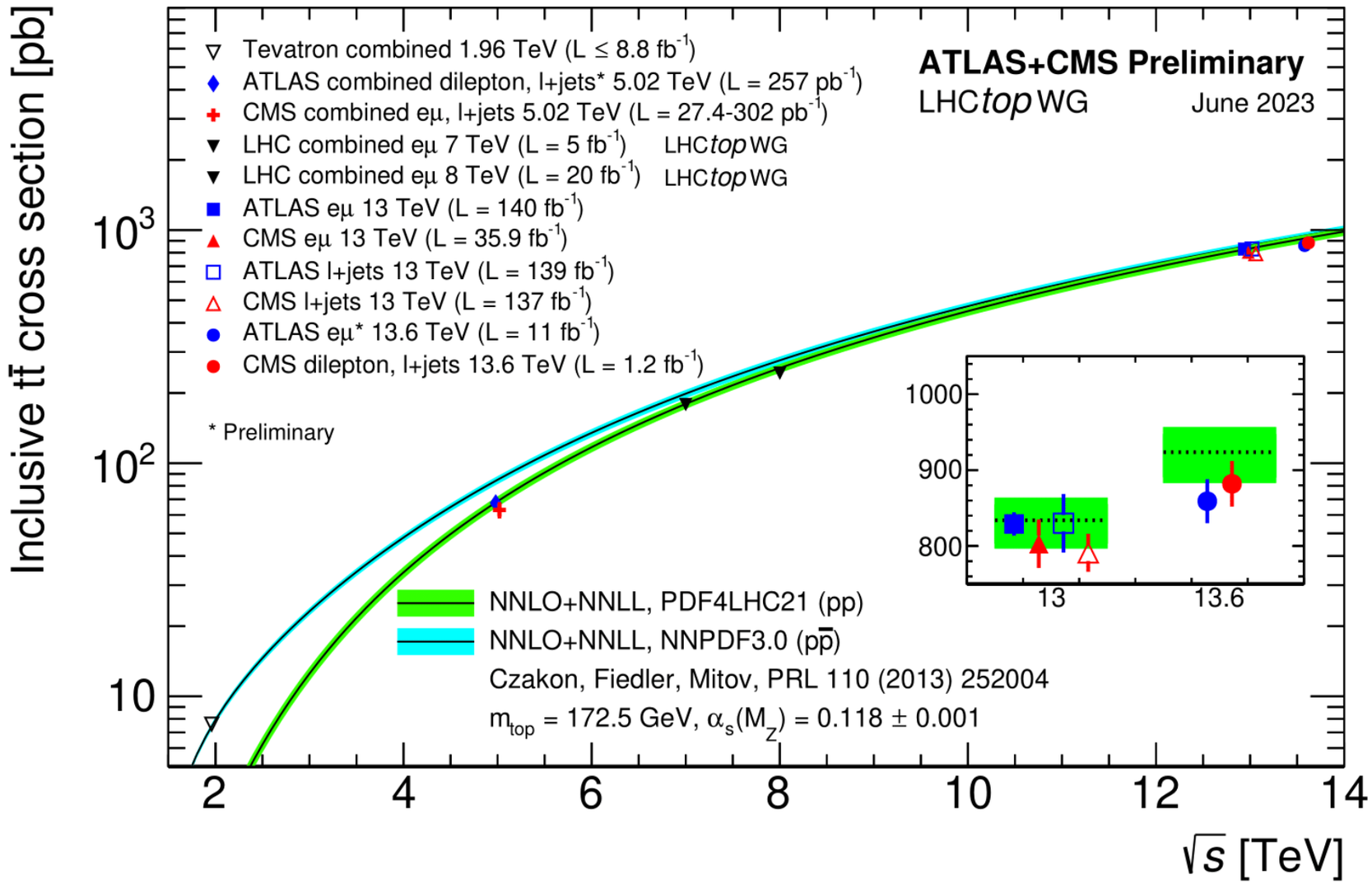
- First observation (**6.3σ**) of WZγ production
  - Provide one of the primary means to probe the quartic interactions between EW gauge bosons





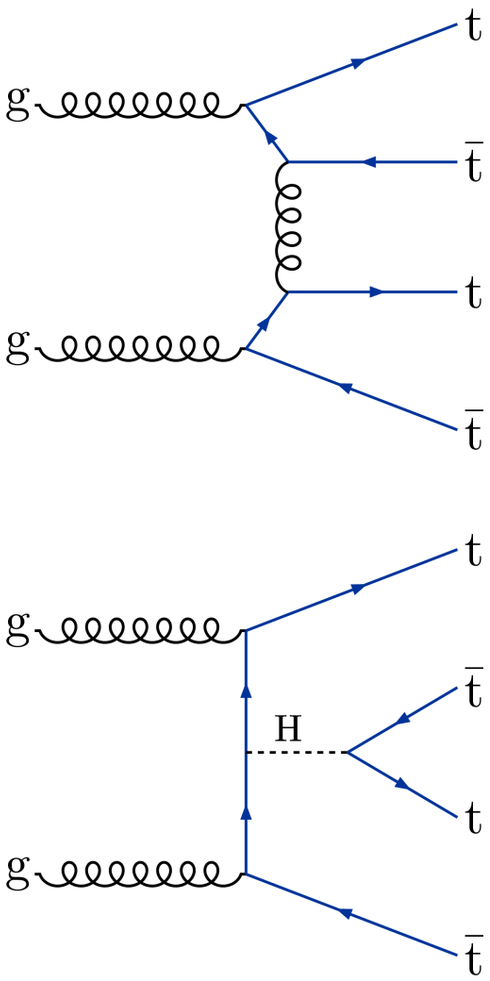
Top Physics

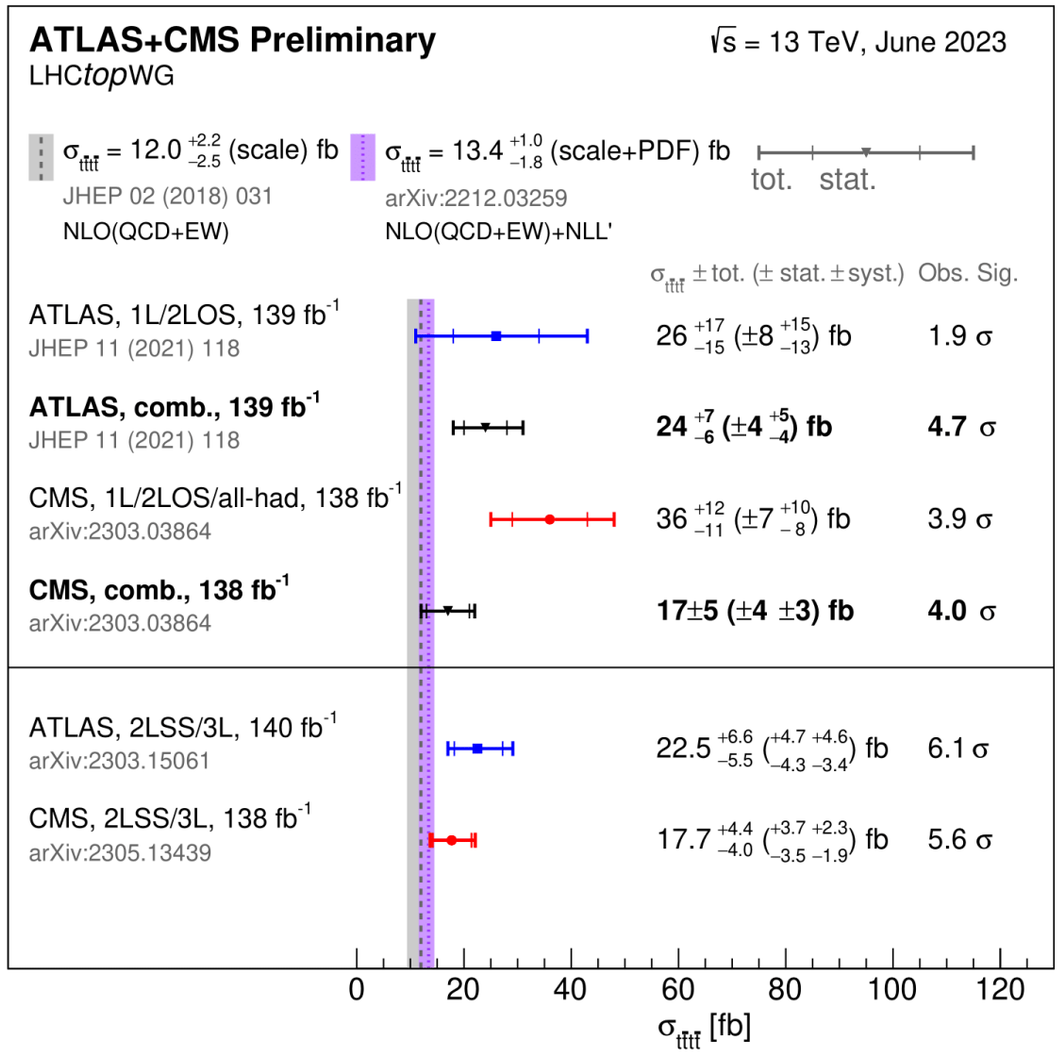
Cross section of top pair production



- Early Run-3 results from both ATLAS and CMS experiments
  - with remarkable precision (~3.5%) arxiv:2308.09529 JHEP 08 (2023) 204
- At 13 TeV ATLAS has a cross-section measurement with a relative uncertainty of only 1.8% arxiv:2303.15340
- Results are consistent with NNLO+NNLL predictions

Observation of four top production



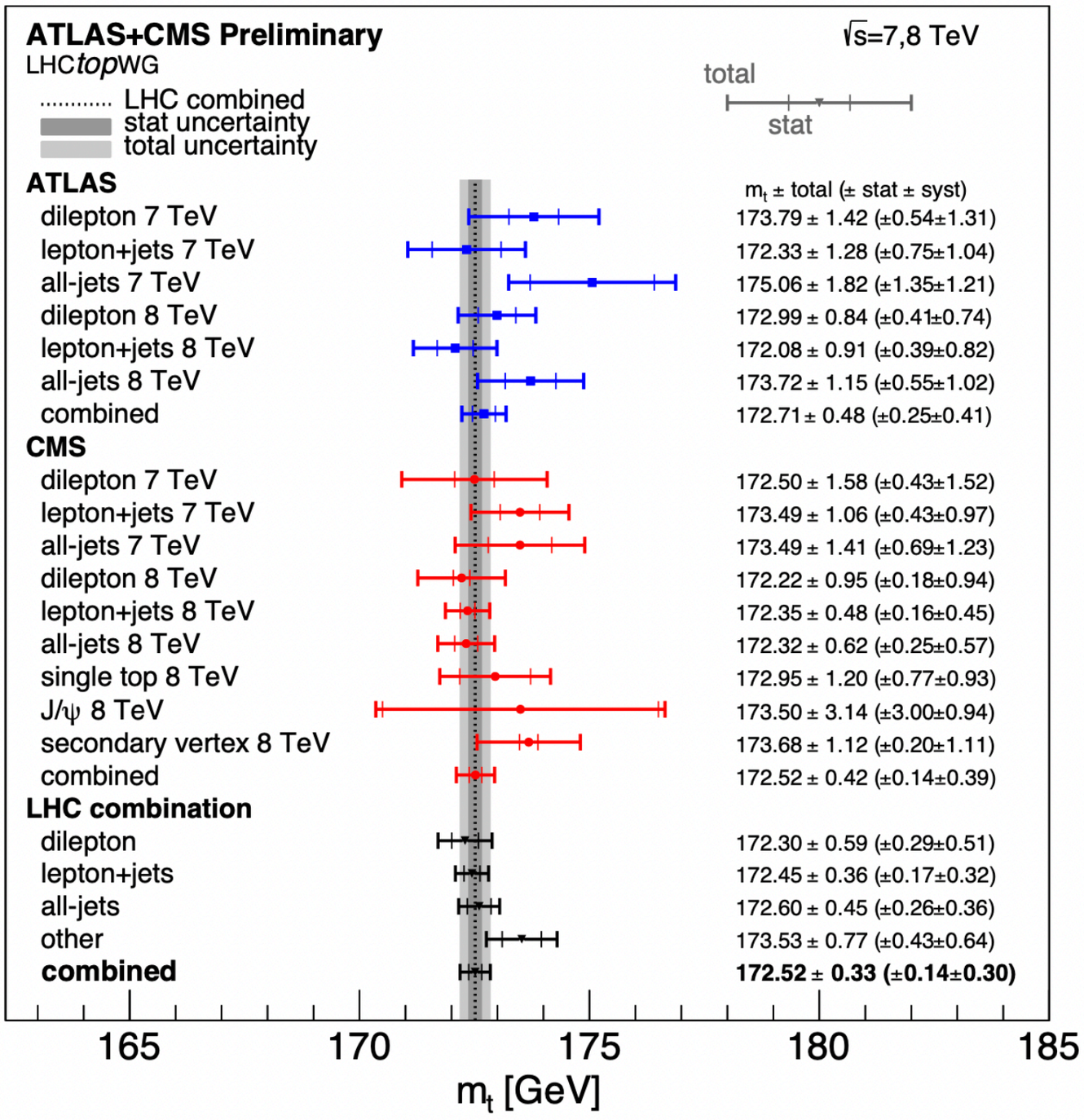


Eur. Phys. J. C 83 (2023) 496

Phys. Lett. B 847 (2023) 138290

- Observation by ATLAS and CMS experiments independently
  - this process is extremely rare compared to top-pair production, but it is already a measurement limited by systematics
- Results provides sensitivity to the Higgs-top Yukawa coupling

Top mass measurements



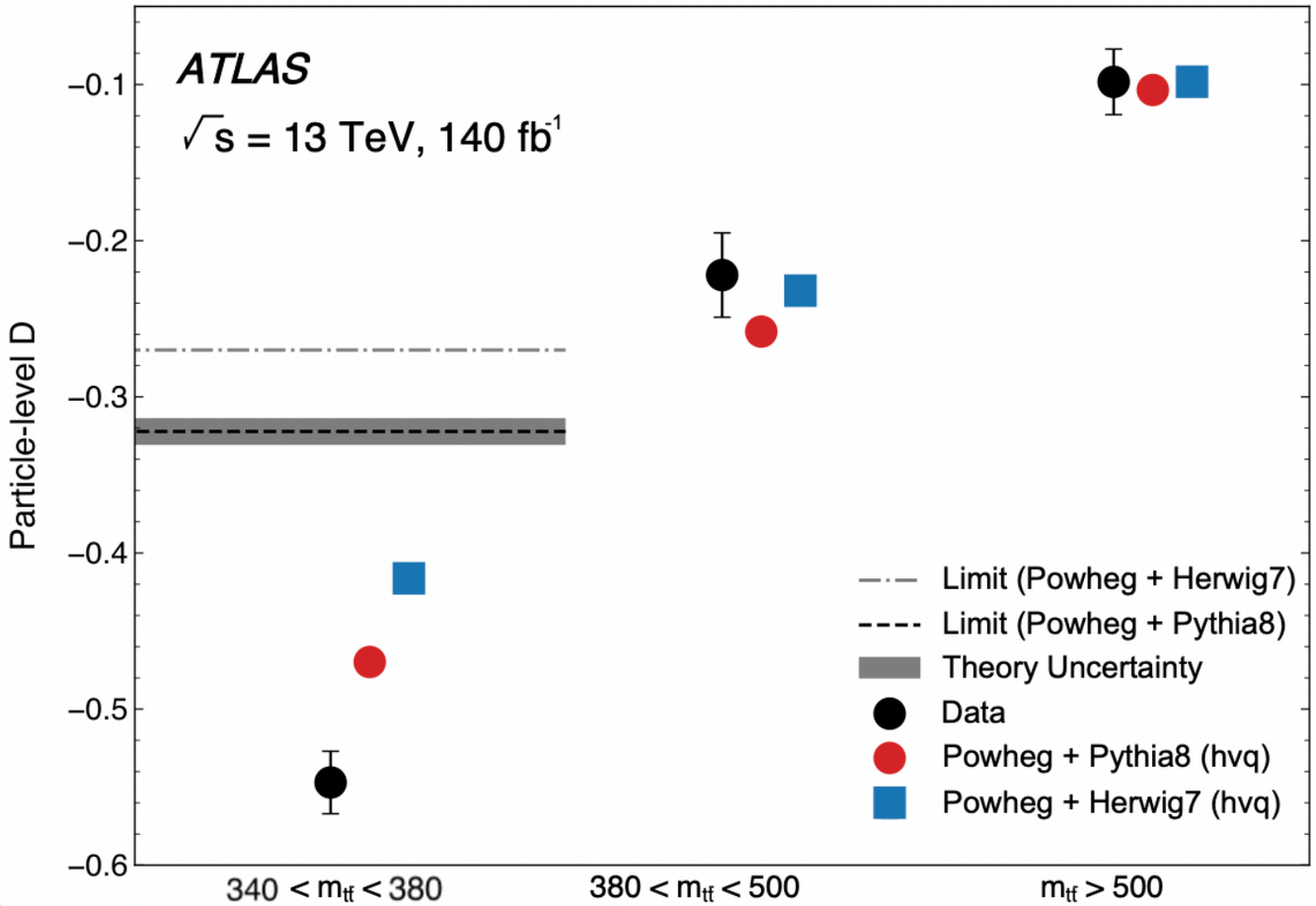
- Combination of top mass measurements performed by ATLAS and CMS experiments with Run 1 data:
  - m_t = 172.52 ± 0.33 GeV

CERN-LPCC-2023-02

- Top mass measurement by CMS experiment with Run 2 data using profile likelihood in lepton+jets channel:
  - m_t = 171.77 ± 0.37 GeV

Eur. Phys. J. C 83 (2023) 963

Quantum entanglement in top pair production



arxiv:2311.07288
Submitted to Nature

- Spin entanglement is detected from the measurement of a single observable D, inferred by angle between charged leptons in top quark rest frames
  - it is necessary to restrict the selection to events close to the production threshold
- More than 5 five standard deviations from a scenario without entanglement
  - **the first observation of entanglement in a pair of quarks and the observation of entanglement at the highest energy to date**

Summary

- LHC experiments continue to deliver many **interesting SM measurement results**
  - αs (~1% precision)
  - W (~0.02% precision) and top (~0.2% precision) masses
  - First observation WWγ, WZγ and 4-top productions
  - Quantum entanglement
  - etc.
- Many new measurements are being pursued. **Please stay tuned!**

Thank you!

Observation of $\gamma\gamma \to \tau\tau$ in PbPb collisions

Phys. Rev. Lett. 131 (2023) 151802

- Observation of $\gamma\gamma \to \tau\tau$ in ultraperipheral PbPb collisions
  - $\mu = 1.03^{+0.06}_{-0.05}$
- Constraints on the τ-lepton anomalous magnetic moment: $-0.057 < a_\tau < 0.024$
  - competitive with existing lepton-collider constraints