Experimental perspective of the future SM LHC program

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Weak mixing angle @ CMS & ATLAS

$$A_{FB} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)} = \frac{3}{8}\frac{B}{A},$$

$$A = Q_l^2 Q_q^2 - 2Q_l g_V^q g_V^l \chi_1 + (g_A^{q\,2} + g_V^{q\,2})(g_A^{l\,2} + g_V^{l\,2})\chi_2 ,$$

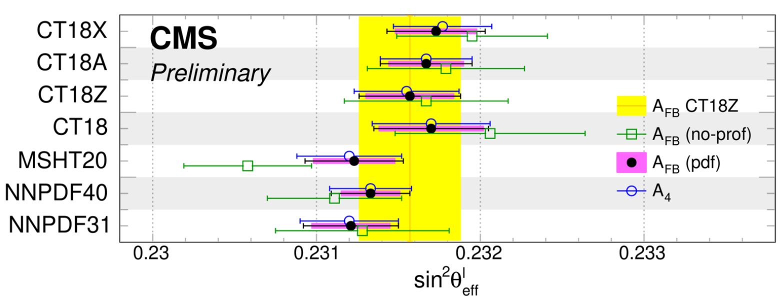
$$B = -4Q_l g_A^q g_A^l \chi_1 + 8 g_A^q g_V^q g_A^l g_V^l \chi_2 ,$$

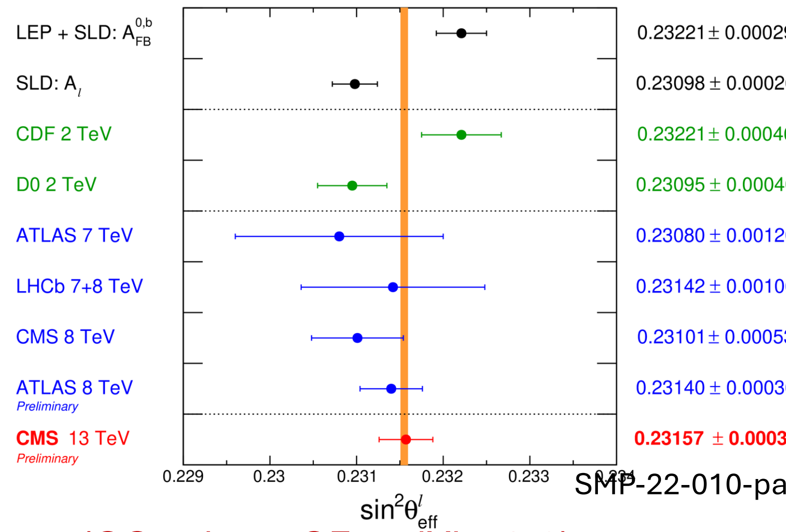
$$g_V^f = t_3^f - (2Q_f \times \sin^2\theta_W)$$

- Challenge@pp: Dilution, PDF
- New **CMS** measurement based on 13TeV data (CCee/μμ)
  - reduced stat unc: 0.00036 → 0.00010
  - reduce total uncertainty: 0.00053 → 0.00031
  - → **Now systematically dominated**

See: Rhys Taus: Weak mixing angle measurement at CMS, Thu, 09:55

$$\sin^2\theta^\ell_{\text{eff}} = 0.23157 \pm 0.00010\,(\text{stat}) \pm 0.00015\,(\text{syst}) \pm 0.00009\,(\text{theo}) \pm 0.00027(\text{PDF}).$$





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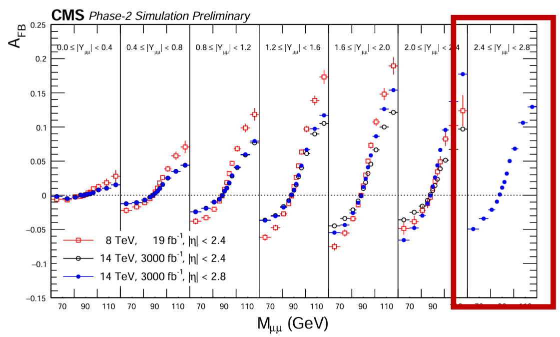
- **ATLAS** plans:
  - ATLAS final measurement on 8TeV data set (CCee/μμ + CFee: |Y| < 3.6)
    - Preliminary: ATLAS-CONF-2018-037: stat: 0.00021, total: 0.00036
  - Future ATLAS measurement on 13TeV data set (CC + CF): expect reduced stat unc. etc

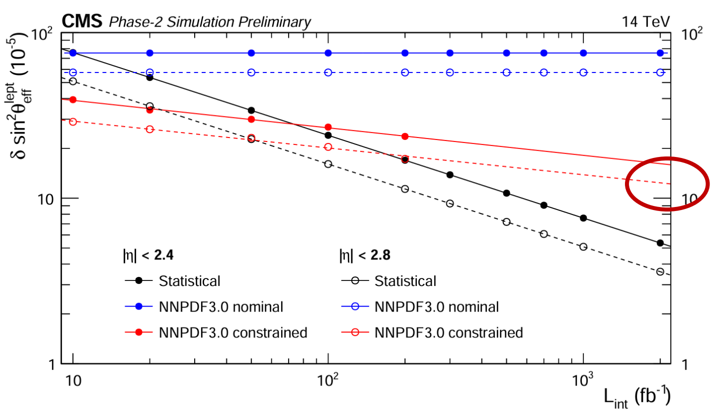
Weak mixing angle @ HL LHC

- Stat unc and (constrained) PDF unc decrease with high luminosity
- Extended forward tracking capability → reduce dilution

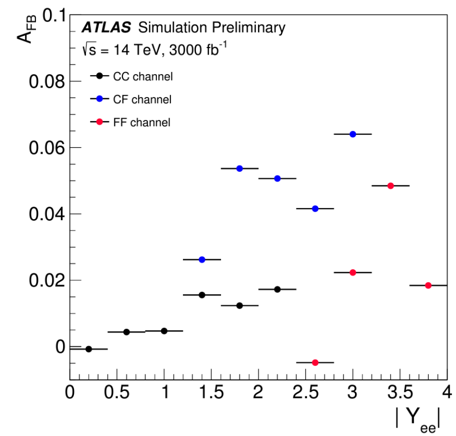
} expect unc of ~0.00015

- CMS (CMS-PAS-FTR-17-001):
  - μμ: acceptance → |η| < 2.8
    → stat. unc. - 30% and PDF unc. -20%
  - Stat unc negligible for lumi > 1000/fb





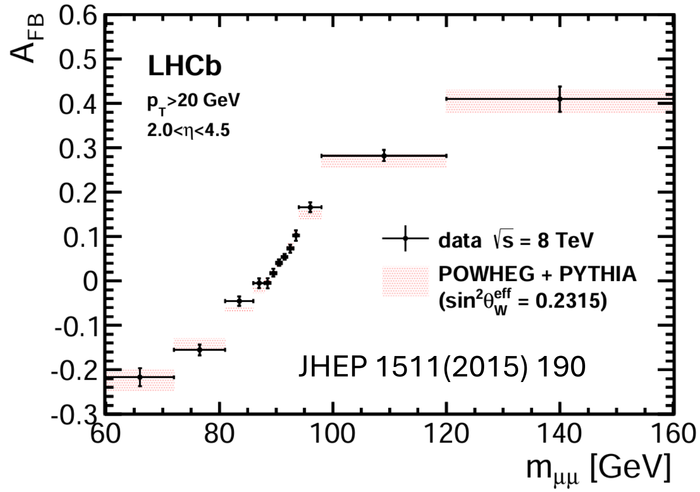
- ATLAS (ATL-PHYS-PUB-2018-037):
  - ee: → CC + CF + FF → |Y| < 4.0



	ATLAS $\sqrt{s}$ = 14 TeV	ATLAS $\sqrt{s}$ = 14 TeV
$\mathcal{L}$ [fb^{-1}]	3000	3000
PDF set	CT14 [13]	PDF4LHC15$_{\text{HL-LHC}}$ [19]
$\sin^2\theta_{eff}$ [$\times 10^{-5}$]	23153	23153
Stat.	± 4	± 4
PDFs	± 16	± 13
Experimental Syst.	± 8	± 6
Other Syst.	-	-
Total	± 18	± 15

Weak mixing angle @ LHCb

- + lower dilution in forward region, - less statistics, - larger PDF uncertainty
- Published results on combination of 7TeV and 8TeV data set for $2.0 < \eta(\mu) < 4.5$



stats *exp* *theory*

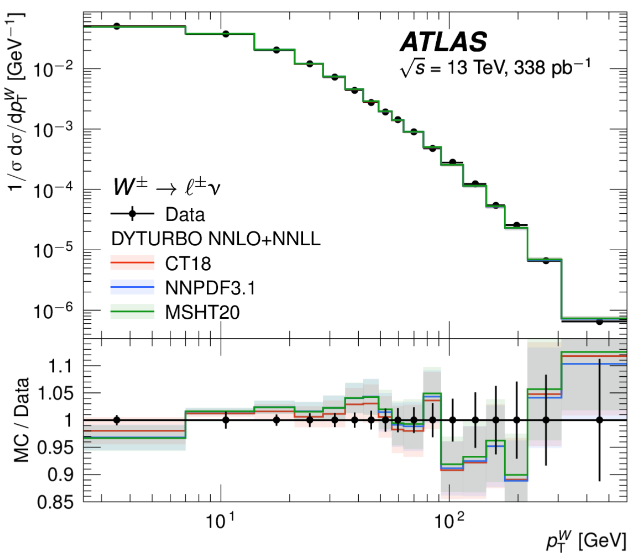
$$\sin^2\theta_W^{\text{eff}} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056,$$

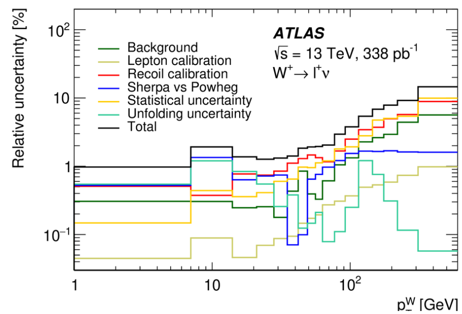
- Working on including the full Run2 data set → reduce the statistical uncertainty
- Use more modern PDF with constraints in the forward region from recent LHC data

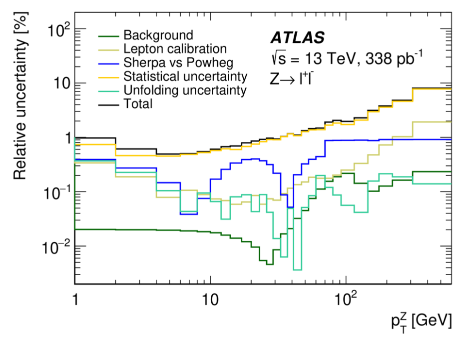
ATLAS low-μ $p_T W$ and $p_T Z$

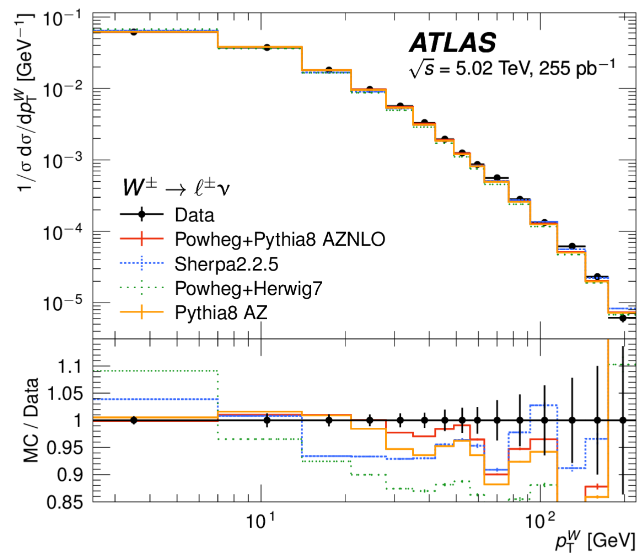
- Special data sets with μ~2: 5TeV, 250/pb, 13TeV, 338/pb, lumi precision @ATLAS ~ 1%
- Inclusive and normalized differential cross sections and their ratios
  - ~1% precision up to $p_T V$ ~ 40 GeV , $p_T Z$ is stats limited
  - Discriminating up to pTV ~ 100 (22) GeV for 5(13) TeV
  - DYturbo resumed prediction describe data best
  - Powheg+Py8 & Pythia8 tuned to 7-TeV ATLAS data describe $p_T V$ < 40GeV range

See: Fabrice Balli/Jan Eysermans: Low-mu run (ATLAS/CMS): today, 16:30/16:45







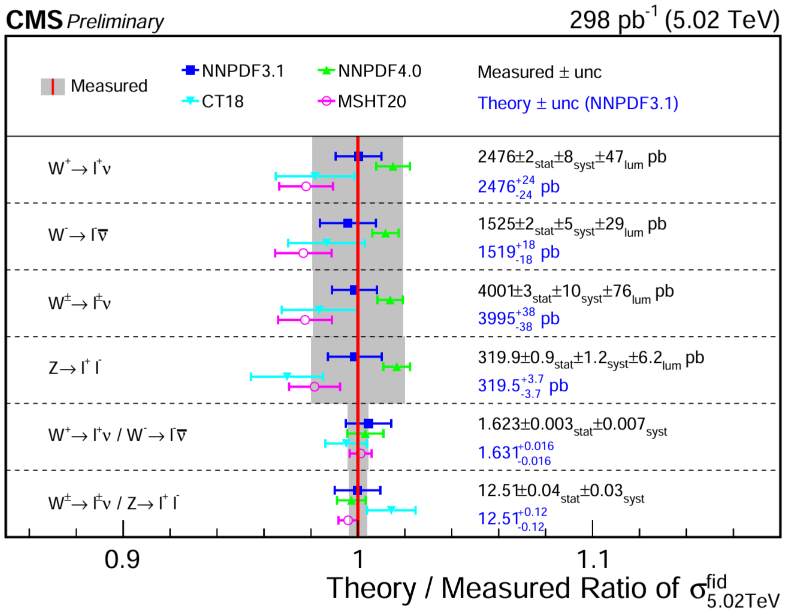


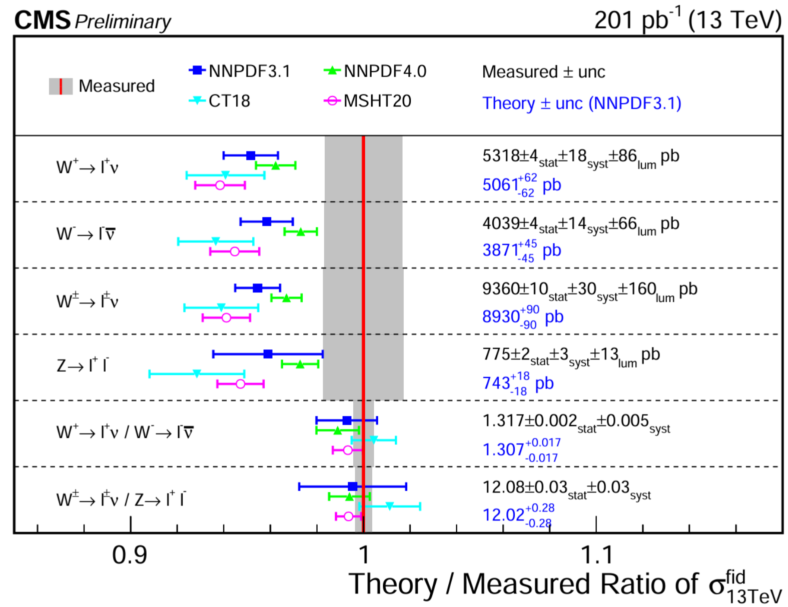
Systematic precision < %
1% level precision for inclusive cross sections due to precise lumi:

Process	$\sigma_{\text{fid}}(\sqrt{s} = 5.02\text{ TeV})$ [pb]	$\sigma_{\text{fid}}(\sqrt{s} = 13\text{ TeV})$ [pb]
$W^- \to \ell^-\nu$	1384 ± 2 (stat.) ± 5 (syst.) ± 15 (lumi.)	3486 ± 3 (stat.) ± 18 (syst.) ± 34 (lumi.)
$W^+ \to \ell^+\nu$	2228 ± 3 (stat.) ± 8 (syst.) ± 23 (lumi.)	4571 ± 3 (stat.) ± 21 (syst.) ± 44 (lumi.)
$Z \to \ell\ell$	333.0 ± 1.2 (stat.) ± 2.2 (syst.) ± 3.3 (lumi.)	780.3 ± 2.6 (stat.) ± 7.1 (syst.) ± 7.1 (lumi.)

CMS low-μ W and Z cross sections

- Special data sets with μ~2: 5TeV, 289/pb, 13TeV, 201/pb, lumi precision @CMS ~ 1.9% / 1.6%
- Inclusive W and Z (fiducial and total) cross sections and their ratios
- Systematic precision < 0.5%

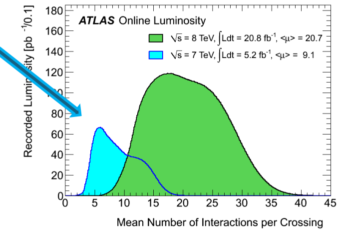




See: Fabrice Balli/Jan Eysermans: Low-mu run (ATLAS/CMS): today, 16:30/16:45

ATLAS W mass

@ μ~9

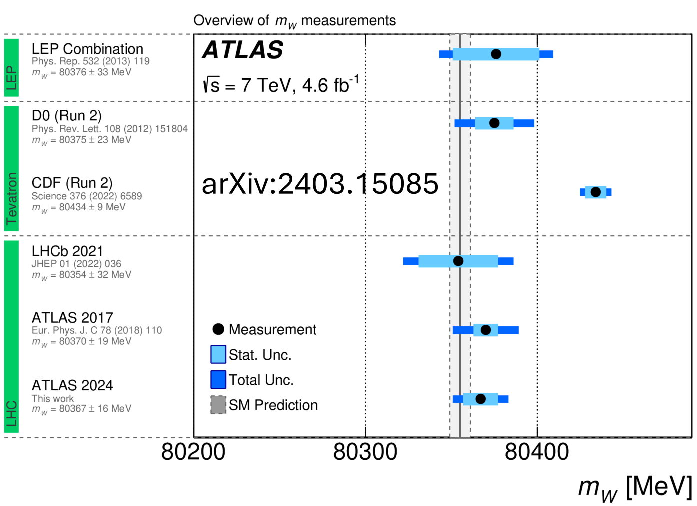


- New: ATLAS measurement:
  - 7TeV data set as in EPJC 78 (2018)110
  - PLH fit instead of χ^2 based offset method
  - Modern PDF

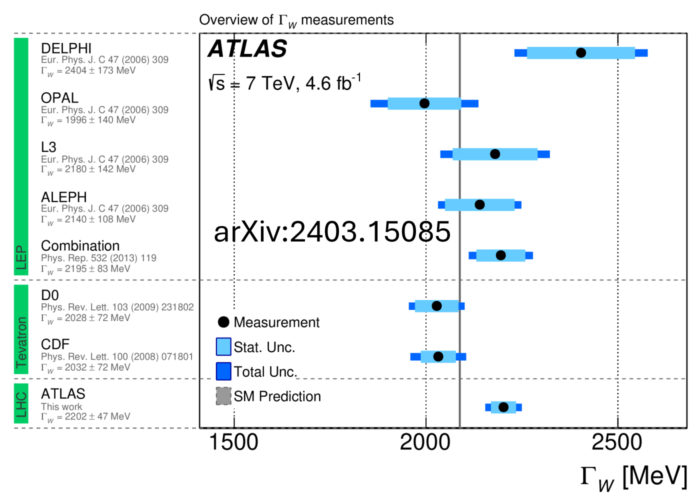
See: "W mass and width measurement"
Maarten Boonekamp, Thu, 11.7, 9:25

→ consistent with EPJC 78 (2018)110, improved precision 18.5 MeV → 16.9 MeV

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



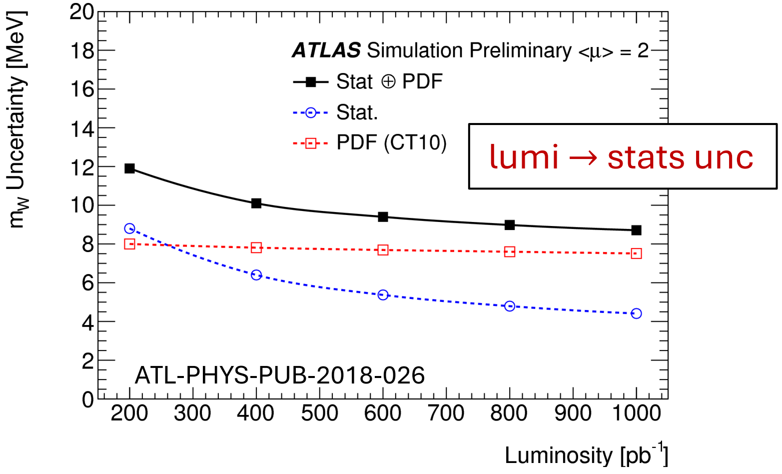
- Additional W width measurement

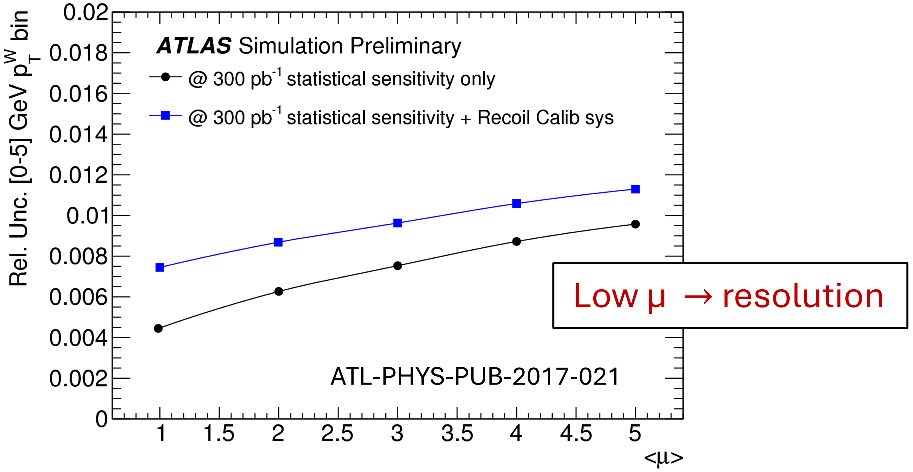


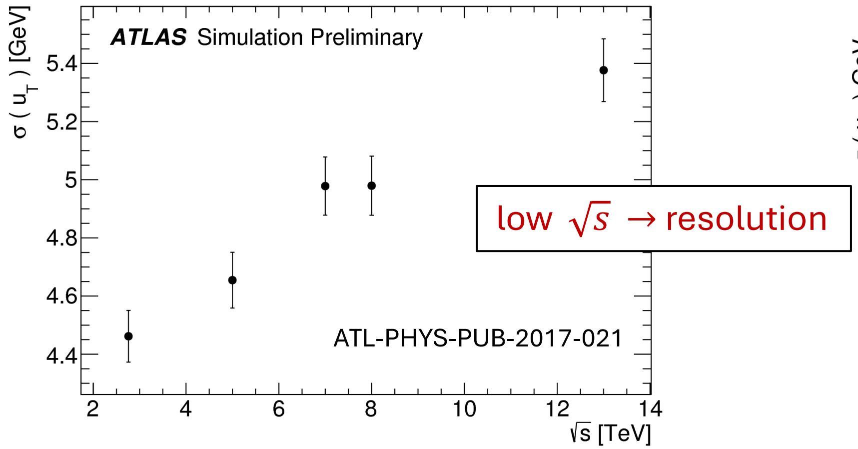
→ Looking forward to CMS results

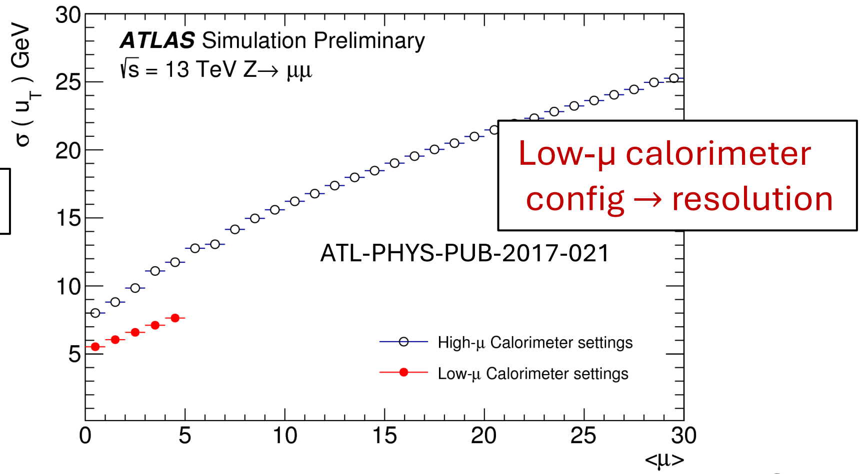
W mass @ low-μ

- mW measurement relies on precise modelling of soft $p_T W$ spectrum (via u_T)
  - Low-μ → improve recoil resolution, need sufficient lumi (stats unc, calibration)
  - Lowering $\sqrt{s}$ improves resolution
  - ATLAS: low-μ calorimeter settings further improves resolution (but much more work)



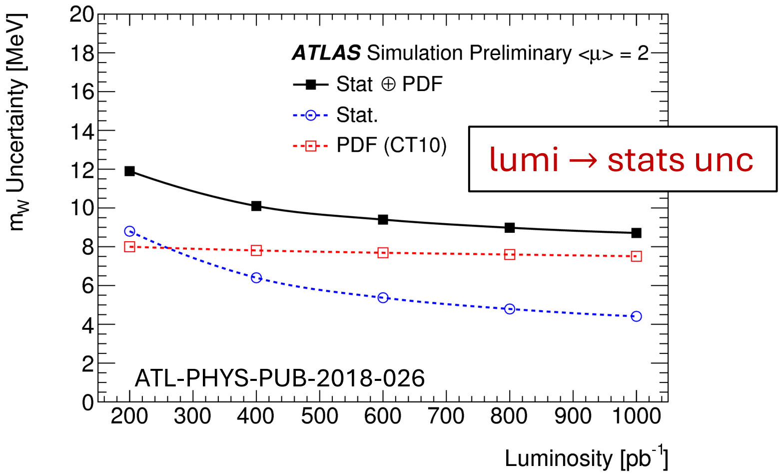


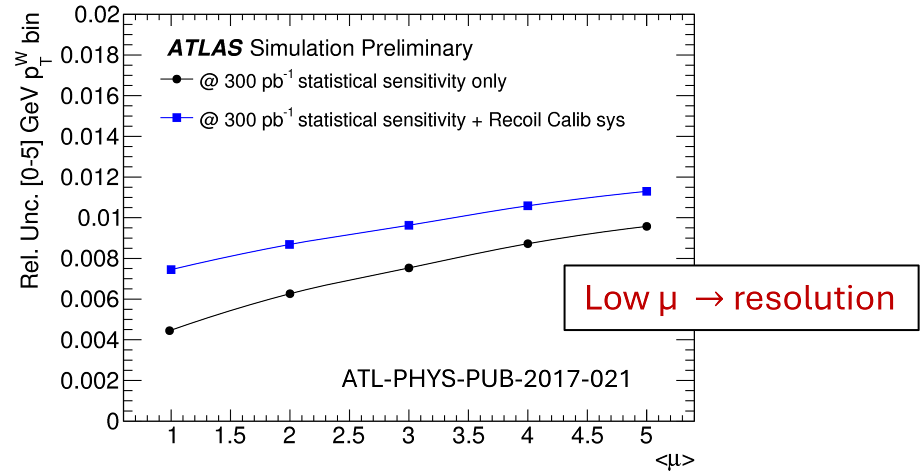




W mass @ low-μ

- Current data set: 13TeV, μ~2, 338/pb, (ATLAS high-μ calo setting)
  5TeV, μ~2, 250/pb, (ATLAS high-μ calo setting)
- 2024 reference run for HI: 5TeV, μ~4, X00/pb, (ATLAS low-μ calo setting → new calibration!)
- 2025/26 ? 13TeV, μ~2, 1/fb ? → start campaigning! → need studies!



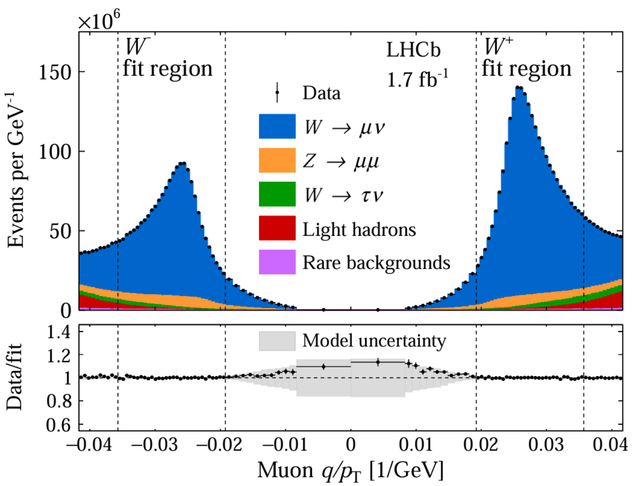


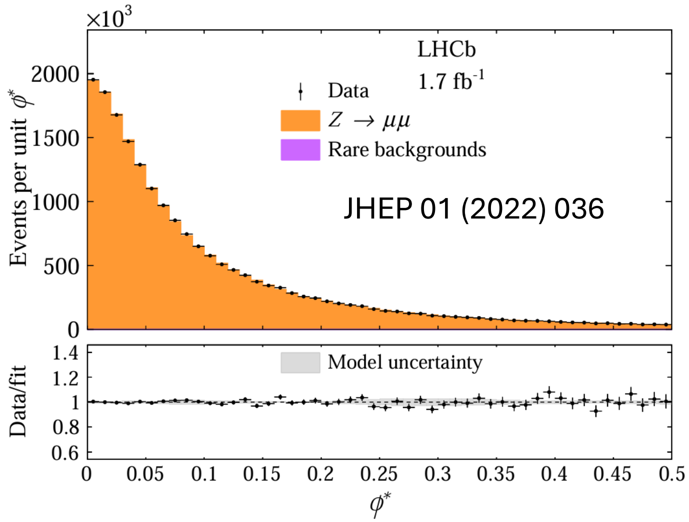
- HL LHC 14 TeV, μ~2, 200+/pb? Improvements by including forward leptons

$\sqrt{s}$ [TeV]	Lepton acceptance	Uncertainty in m_W [MeV]		
		p_T^ℓ fits	m_T fits	p_T^ℓ, m_T fits
14	$\lvert\eta_\ell\rvert < 2.4$	20.6 (14.8 ⊕ 14.4)	18.0 (13.8 ⊕ 11.5)	16.0 (10.6 ⊕ 12.0)
14	$\lvert\eta_\ell\rvert < 4$	15.6 (12.6 ⊕ 9.2)	14.2 (12.0 ⊕ 7.6)	11.9 (8.8 ⊕ 8.0)

W mass @ LHCb

- Combined fit of W q/pTl and Z $\phi*$ in partial Run2 data set in muon channel
- Uncertainty: 32 MeV





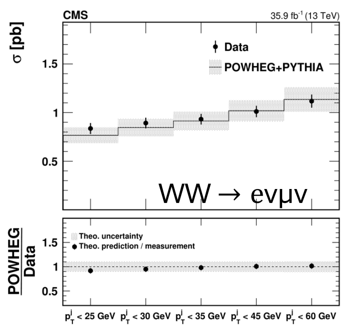
$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}.$$

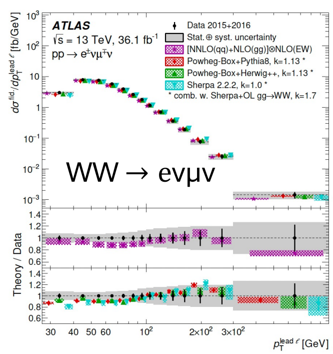
- Future steps:
  - Update to full Run2 data set: stat unc: 23MeV → 14 MeV
  - Improvements in systematics
  - → total uncertainty: 32 MeV → 20 MeV

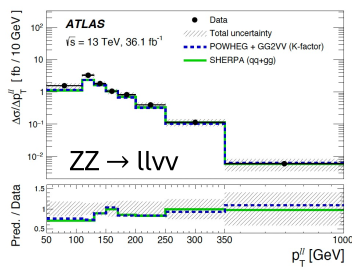
Strong di-boson production

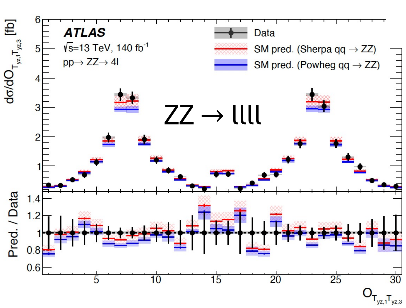
- Sensitive to ZWW, gWW TGC, high-energy tails sensitive to BSM → EFT fits
- Not statistically limited @ Run2, except for extreme phase spaces
- Differential cross sections, and VV+jets (Background to Higgs->VV and VH)
- Polarisation measurements: individual W/Z polarisation → joint polarization
- Started Run3 measurements: ATLAS ZZ, CMS: W^+W^-

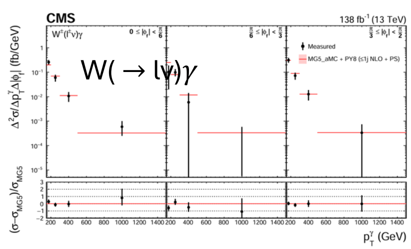
Run2

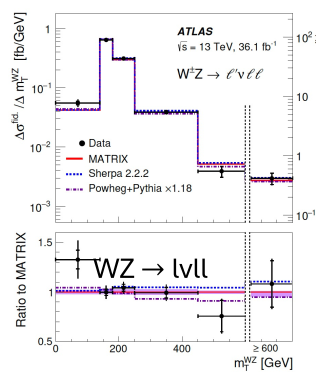




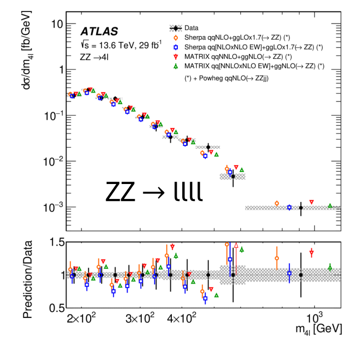


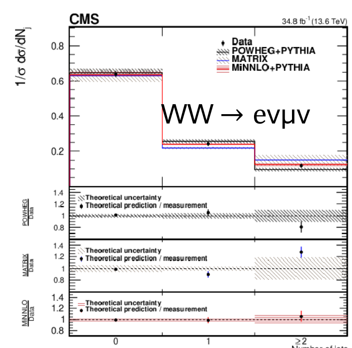






Run3: 13.6 TeV

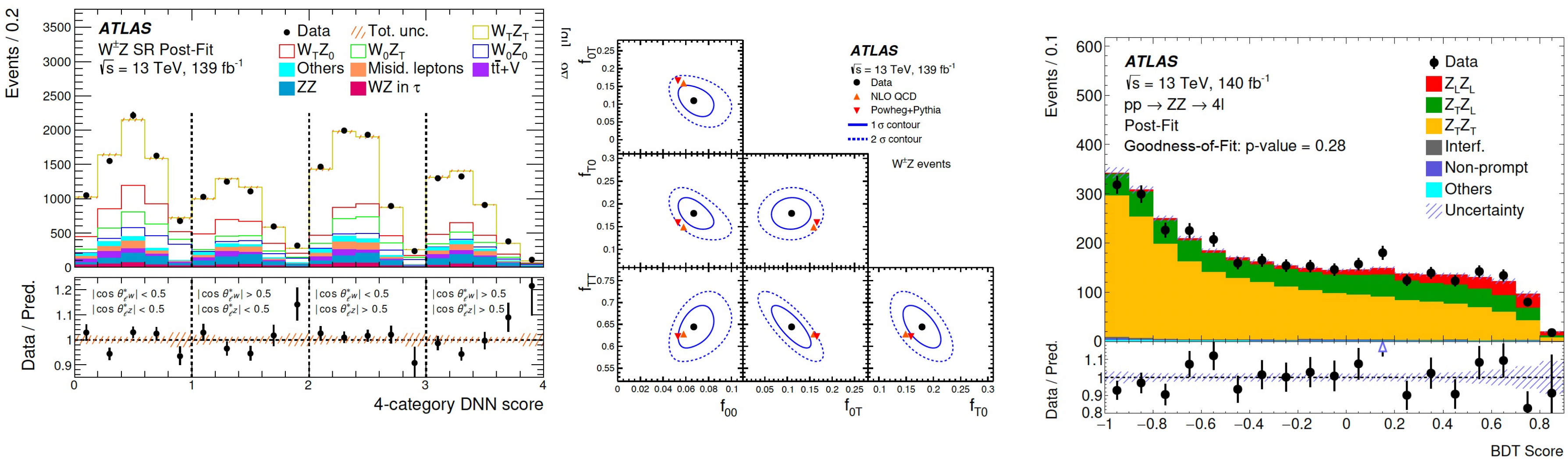




See: Multiboson and VBS measurements Mattia Lizzo, 11.7.24, 11:00

Di-bosons and polarisation

- **ATLAS WZ**: Jointly longitudinally polarized $W^{\pm}Z$ observed with 7.1 (6.3) σ , agrees SM.
  - $pz(\nu)$ via NN regression. DNN to separate the four joint helicity states.
- **ATLAS ZZ**: 4.3 (3.8) σ evidence for jointly longitudinally polarised ZZ
  - pLLH fit to the output of a boosted decision tree (BDT) on angular variables.
- **CMS $W_L^{\pm}W_L^{\pm}$ jj**: upper limits (~2-3SM) on $W_L^{\pm}W_L^{\pm}$ jj and $W_L^{\pm}W_X^{\pm}$ jj cross section at 2.3 (3.1) σ

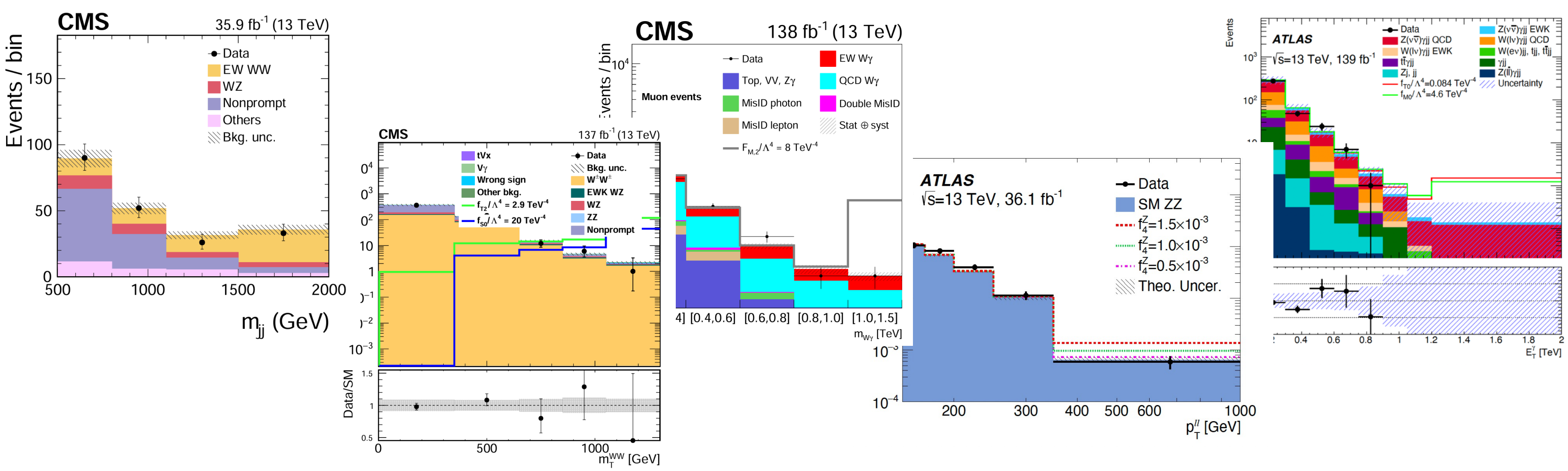


See: Polarisation measurement
Erik Bachmann, 11.7.24, 11:40

VBS measurements

EW VVjj with VBS component and s/t channels V/H exchange, which regularizes amplitude

- Run~2: Golden Era: observed $W^{\pm}W^{\pm}jj$, $W^{+}W^{-}jj$, ZZjj, 4ljj, WZjj, $W\gamma jj$, $Z\gamma jj$
  - Final states with charged leptons, neutrinos and photons (CMS evidence for VV → lvjj)
- Advanced machine-learning and fitting techniques, strong VVjj background constrained in CR
- Started to go differential → EFT fits in tails of mass/energy distributions (→ dim-8 operators)
- Still large statistical unc. component in many measurements → profit from more data

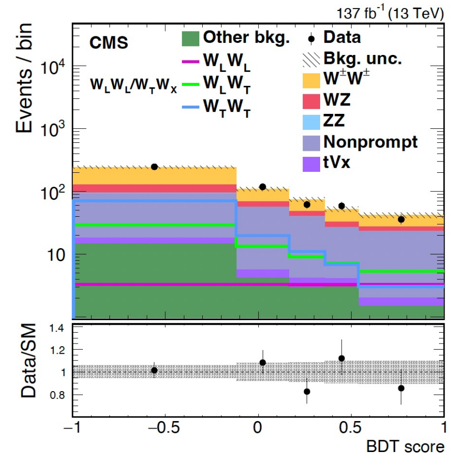


- Future developments:
  - More stats -> increase general precision and reach in EFT-sensitive mass/energy ranges
  - Extract joint polarization components

See: Multiboson and VBS measurements
Mattia Lizzo, 11.7.24, 11:00

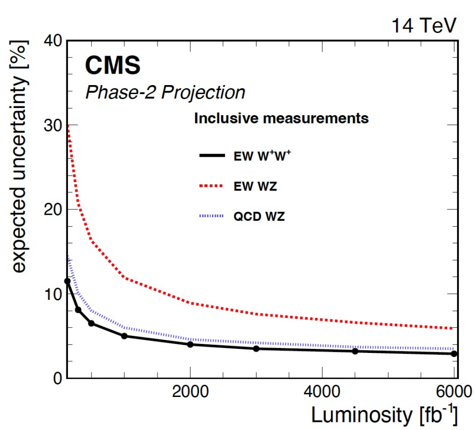
Prospects for VBS Joint VV polarisation

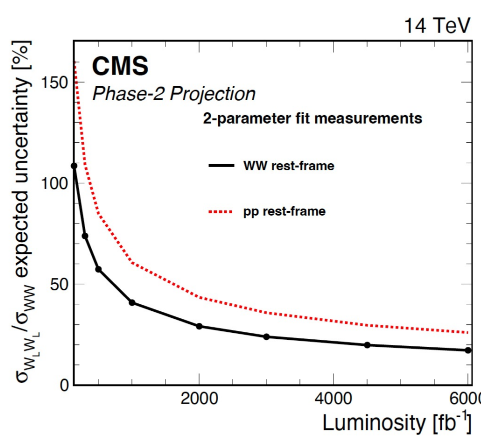
Test of EW structure, sensitive to BSM (e.g. modification of H-VV coupling, new resonances)
Complementary to direct Higgs coupling measurements.
Can be defined in WW cms system and in the parton cms system
Fraction of $W_L^{\pm}W_L^{\pm}$ jj is 11% (7%) in WW (parton) cms system

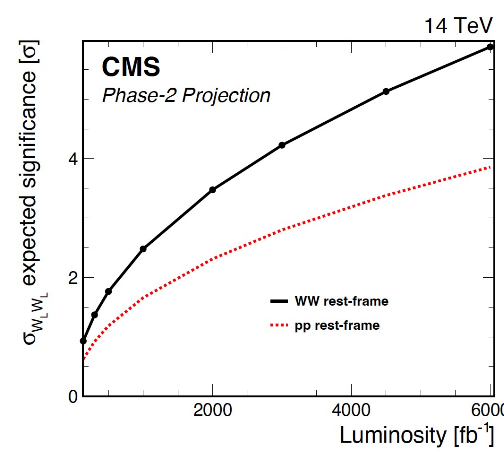


PL B 812 (2020) 136018

- **CMS Run2** $W_L^{\pm}W_L^{\pm}$ jj (PL B 812 (2020) 136018)
  - Fits to $W_L^{\pm}W_L^{\pm}$ jj and $W_T^{\pm}W_T^{\pm}$ jj BDTs
  - Upper limit on $W_L^{\pm}W_L^{\pm}$ jj at 2.7 (2.0) SM (WW cms)
  - $W_L^{\pm}W_X^{\pm}$ jj cross section at 2.3 (3.1) σ (WW cms)
- **CMS HLLHC:** $W_L^{\pm}W_L^{\pm}$ jj (FTR-21-001-PAS)
  - @3000/fb expected 2% stat unc, 3% sys unc on $W^{\pm}$ $W^{\pm}$jj
  - 4 σ significance of $W_L^{\pm}W_L^{\pm}$ jj @3000/fb



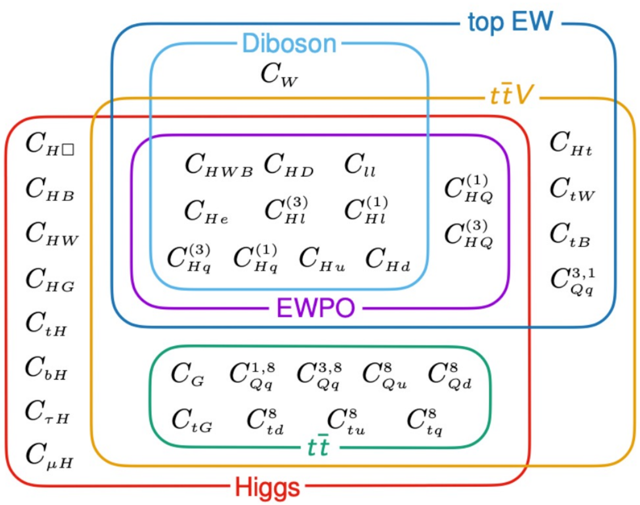




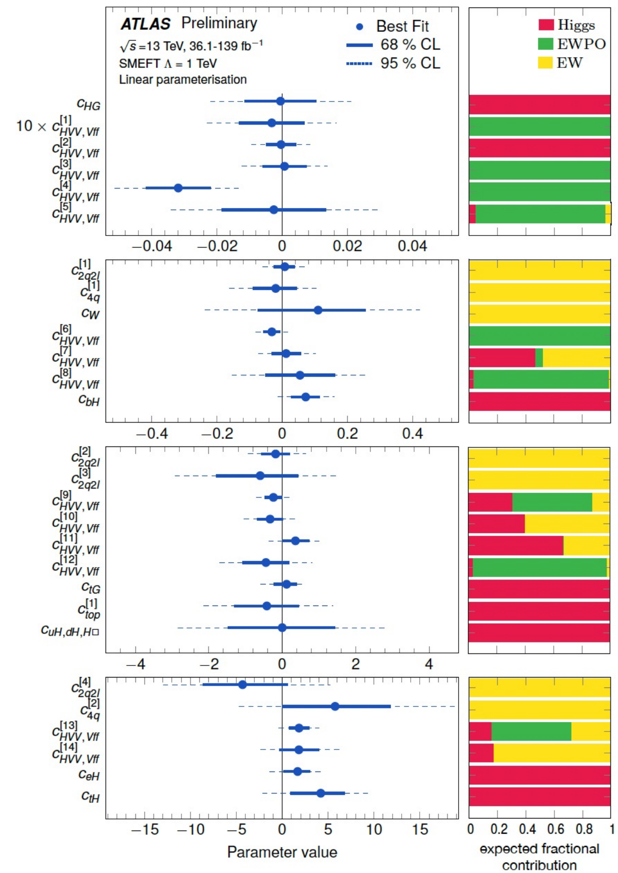
SMEFT fits with EWK data

- **ATLAS SM only fit:** $W^+W^-, W^\pm Z, \; Z \to llll$ and EW Zjj : fit to 15 EFT parameters leading dimension 6 and dimension 8 terms, LLH fits with PCA
- **ATLAS global EFT fit:** Higgs data, diboson & VBF Z, EW precision data (LEP, SLC) (ATL-PHYS-PUB-2022-037)

- Perspectives: Several global SMEFT fitting packages
  Regular global fit updates, similar to EWK fits?



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots .$$



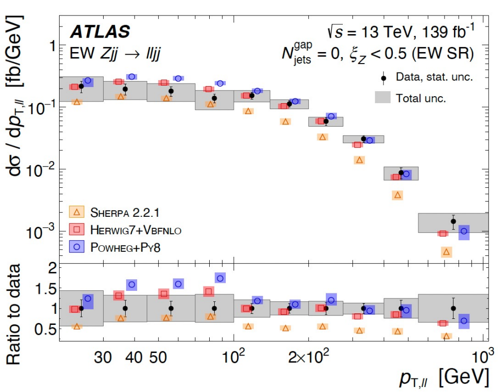
V+light jets

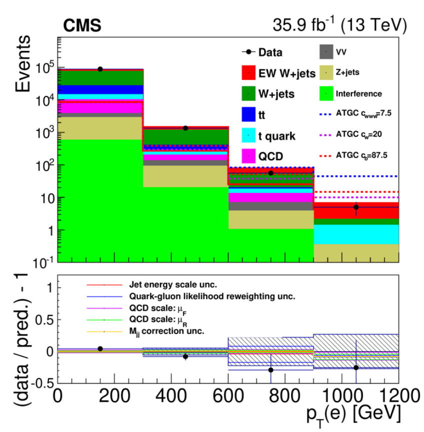
- Important probe of QCD & bkg to Higgs/BSM
- Larger data set → extreme space regions:
  - Large pTZ: EWK corrections
  - Large pT(jet), Collinear Z emission
- High precision tests of MEPS at NLO and NNLO V+jets
- EW Vjj:
  - Sensitive to VBF (TGC)
  - differential measurements → EFT
- Perspectives:
  - Update to full Run2 (especially W+jets) → Run3
  - Test NNLO+PS, N^3LO V+jet
  - Test QCD-EW corrections at high pTV
  - Improve EFT constraints through EW Vjj

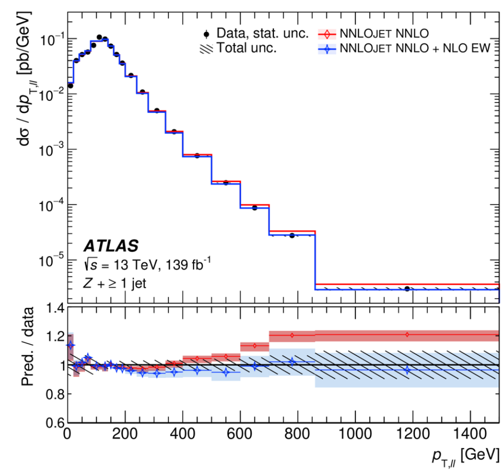
	CMS	ATLAS
W + Jets	arxiv: 1707.05979	arXiv: 1711.03296 (only 8 TeV)
EW W + Jets	arxiv: 1903.04040	arxiv: 1703.04362 (only 8 TeV)
Z + Jets	arxiv: 2210.16139 and arxiv: 1804.05252	arxiv: 2405.20041 and arXiv: 2205.02597
EW Z + Jets	arxiv: 1712.09814	arxiv: 2006.15458
γ + Jets	arxiv: 1807.00782	arxiv: 1912.09866
EW γ + Jets	-	-

See: V+light jets (ATLAS+CMS) Giorgio Pizzati, Tosay 15:40

See: V+light jets (LHCb and ALICE), Nathan Grieser, 15:55

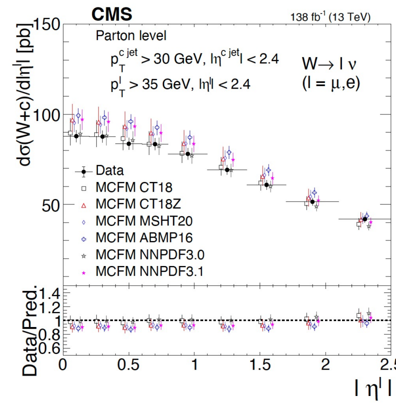


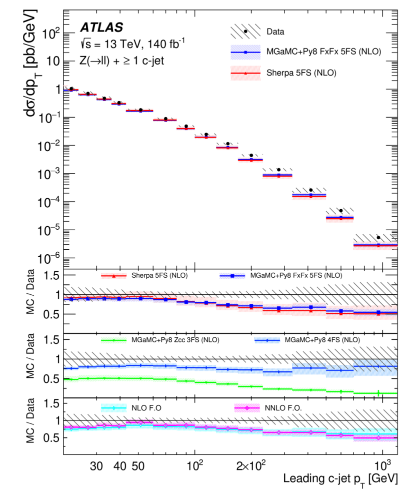


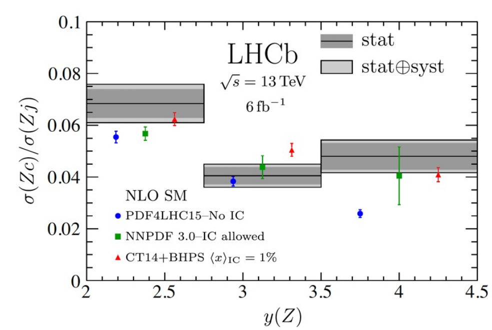


V+HF

- **W+charm**
  - Sensitive to PDF (s), D or c-jet, now systematics limited
  - Agrees with SM but trends → impact on PDF from eta and Rc
  - Perspectives:
    - More differential, e.g. in $R_c = \sigma W^{+}c / \sigma W^{-}c$.
    - Improved charm tagging.
- **Z+b(b)**
  - More differential with Run2 data, More stats helps with Z+bb
  - Modelling ok in general but identified some generator issues
  - First comparisons with IRC predictions at NNLO V+HF
  - Perspectives:
    - Boosted Z+bb: profit from larger data set
    - Unfold to IRC safe b-jet algorithms
- **Z+c(c)**
  - ATLAS & CMS: Z+c inclusive and differential
  - Identified some modelling issues
  - LHCb: Forward Z+c: discrepancy with SM → Intrinsic Charm?
  - Perspectives:
    - Improve c tagging
    - Z+c with forward Z (LHCb, ATLAS: CF, HLLHC: FF)
    - More stats, better c-tagging: Z+cc





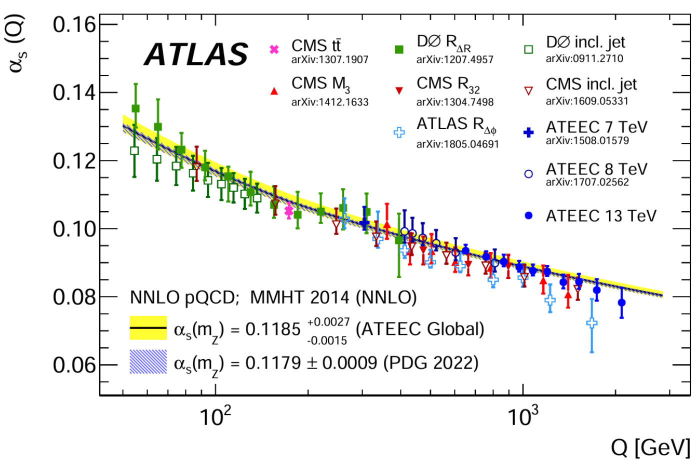


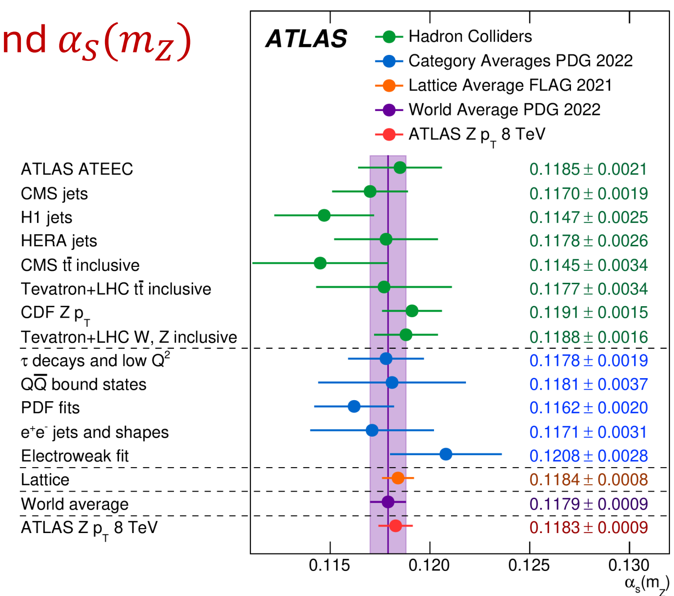
See: Experimental aspects of flavour definition, Federico Sforza. Today, 18:10

See: V+light jets (LHCb and ALICE), Nathan Grieser, 15:55

Strong coupling constant

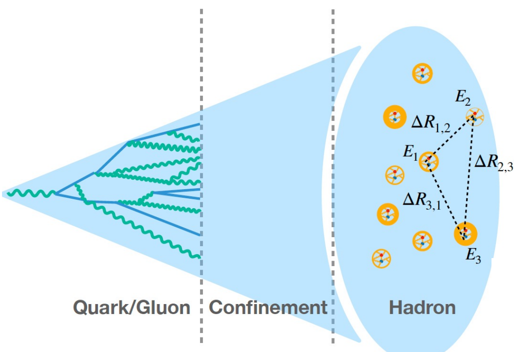
- **Inclusive jets, Jet multiplicities**
  - CMS Run2 azimuthal correlations: $\alpha_S(m_Z) = 0.1177^{+0.0117}_{-0.0074}$ (Theory: NLO)
  - CMS Run2 2D inclusive jets, HERA+CMS QCD fit: : $\alpha_S(m_Z) = 0.1166 \pm 0.0017$
    ATLAS Run2 TEEC* asymmetry: $\alpha_S(m_Z) = 0.1185^{+0.0027}_{-0.0015}$ (NNLO)
  - CMS Run2 EEC jet substructure: $\alpha_S(m_Z) = 0.1229^{+0.0040}_{-0.0050}$ (NLO+NNLL$_{\text{approx}}$)
- **Drell-Yan precision measurements**
  - CMS Run1 Drell-Yan combination: $\alpha_S(m_Z) = 0.1175^{+0.0025}_{-0.0028}$. (NNLO)
  - ATLAS 8TeV, ZpT: $\alpha_S(m_Z) = 0.1183 \pm 0.0009$ (N4LLa+N3LO)
- Perspectives:
  - Most promising: precision Drell-Yan, inclusive jets, TEEC
  - Improvements expected with upgraded theory predictions
  - PDF become important → joint extraction of PDF and $\alpha_S(m_Z)$

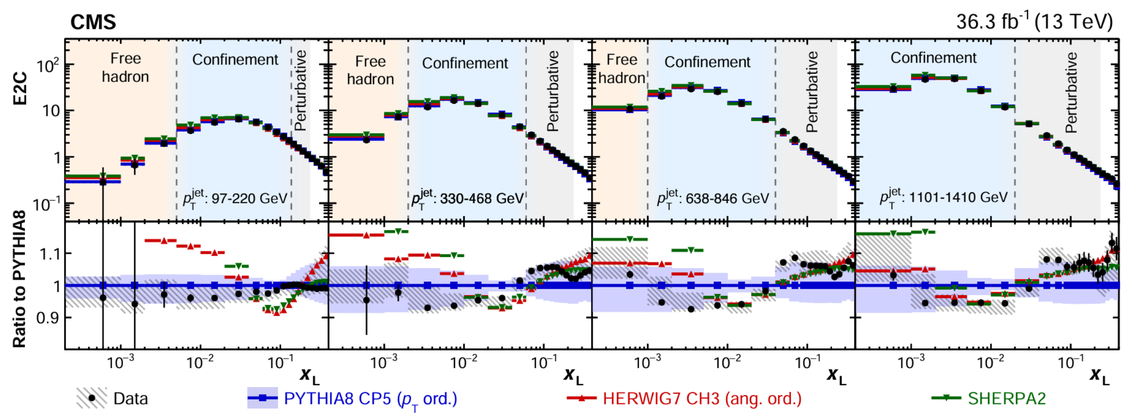




Jet substructure perspectives

- **EEC inside jets** (arXiv:2004.11381):
  - Angular correlation between particles in a jet, E~ order 10GeV
  - Collinear dominant, NLO+NNLLapprox
  - **CMS:** arXiv:2402.13864: 2particle and 3 particle correlators E2C and E3C
    - Not impacted by soft emissions → no grooming techniques needed
    - Also extracted $\alpha_S(m_Z)$ from E3C/E2C ratio

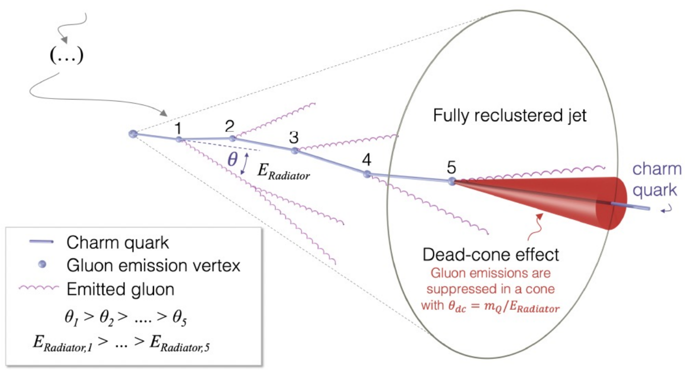


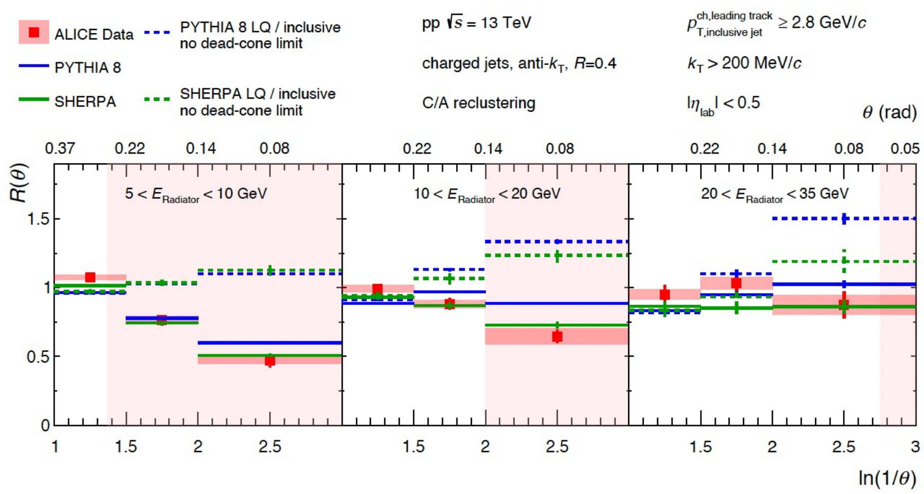


See: Energy-energy correlation measurements (CMS+ATLAS), Meng Xiao, today, 16:10

Jet substructure perspectives

- **Dead cone:**
  - Suppression of the gluon spectrum emitted by a heavy quark of mass mQ and energy E, within a cone of angular size mQ/E around the emitter
  - **Observed by ALICE**, Nature 605 (2022) 440-446, in Jets with D mesons
  - Observable: Ratio R(θ) of splitting angle distributions
  - Dead cone effect observed with 7.7σ (3.5 σ) for the 5<Erad <10GeV (10< Erad.< 20GeV)

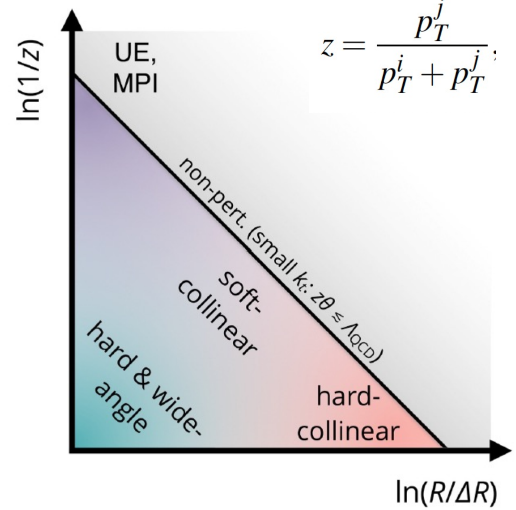




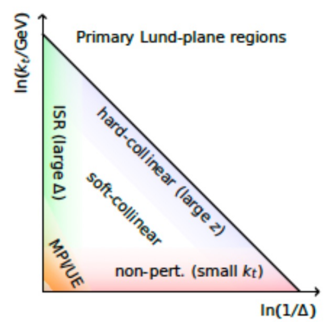
$$R(\theta)_{\text{no dead-cone limit}} = \frac{1}{N^{\text{LQ jets}}} \frac{\mathrm{d}n^{\text{LQ jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}} \frac{\mathrm{d}n^{\text{inclusive jets}}}{\mathrm{d}\ln(1/\theta)} \Big|_{k_T, E_{\text{Radiator}}}$$

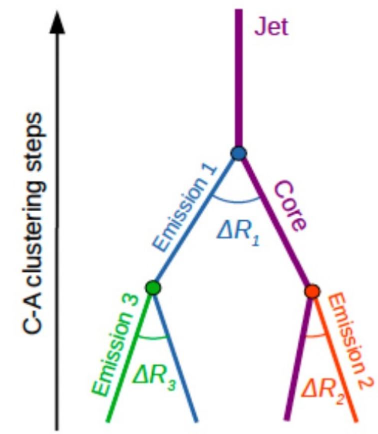
Jet substructure perspectives

- **Lund jet plane:**
  - Recluster anti-kt jets with size R using C/A algorithm
  - Primary Lund plane from core emission
  - Secondary Lund plan from secondary emission etc.
  - → new identification and calibration algorithms for booste resonances
- Example Publications:
  - ATLAS (Phys. Rev. Lett. 124, 222002 (2020)): Lund jet plane in dijets, based on track jets
  - ALICE (ALICE-PUBLIC-2021-002) Primary lund jet plane
  - CMS (JHEP 05 (2024) 116): Primary Lund jet plane density
  - ATLAS (ATL-PHYS-PUB-2023-017) Tagging boosted Wbosons applying ML to the Lund Jet Plane



- **Lund subjet multiplicity (Lund multiplicity):**
  - ATLAS: arXiv:2402.13052
  - JSS observable used to test for the inclusion of   double-soft splittings
  - Built from kT vs R/ ΔR





Summary

- Exciting new perspectives for Run3/HLLHC
- Precision Drell-Yan and W mass: more low-μ data
- Weak mixing angle: Larger data sets and higher Z rapidities at HLLHC
- Di-Bosons: differential cross sections, EFT-sensitive variables, joint polarization, inclusion into global EFT fits
- EW VVjj: Larger stat sets reduce stats limitation, joint polarisation at HL LHC
- V+light jets: test more precise predictions, test EWK corrections, EFT sensitivity through EW Vjj → global EFT fits
- V+HF: IRC safe b/c jet algorithms, Z+c with forward Z, improve c-tagging
- Strong coupling constant: Drell-Tan precision, inclusive jets (global fit), TEEC
- Jet substructure: Many new ideas: Lund jet plane, EEC inside jets, Dead Cone,..