CORFU2023: 23RD HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY

SM (QCD+EW) in ATLAS and CMS

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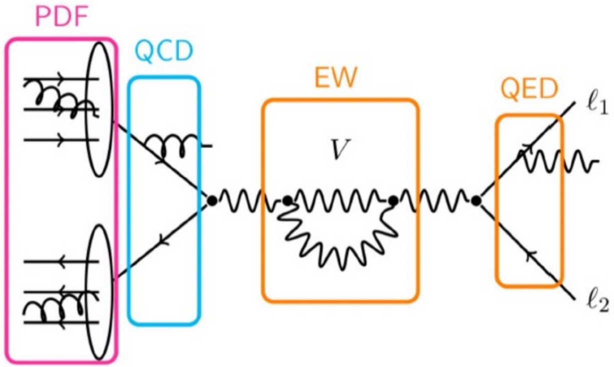
On behalf of ATLAS and CMS

Workshop on the Standard Model and Beyond
AUGUST 27 - SEPTEMBER 7, 2023

Why measuring the SM?

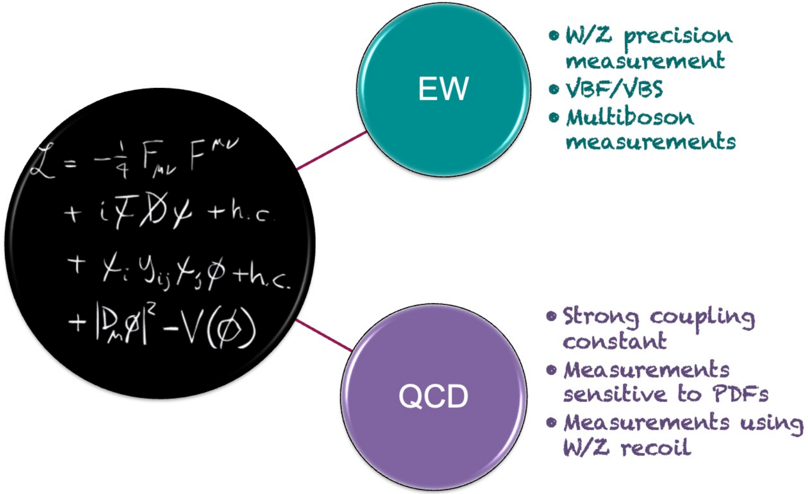


Most successful theory ever, precision physics also at LHC, search for deviations, "legacy" measurements

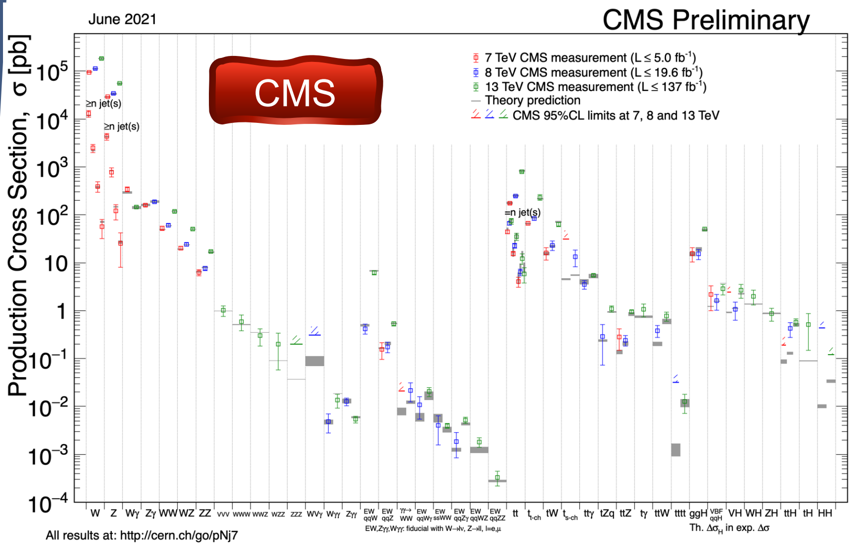
- ► Many new physics models reveal deviations from SM similar to the ones from NLO or NNLO QCD
- ► Understanding of backgrounds to new physics searches
- ► Explore the SM self consistency: Measure its parameters with high-precision

Collider endeavours on precision comparisons between observations and predictions:

- ☣ precisely test the Standard Model (cross-sections, parameters,…)
- ☣ search for new physics phenomena (resonances, deviations)
- ☣ knock on the door to potentially answer outstanding questions (dark matter, matter-anti-matter asymmetry, hierarchies, …)



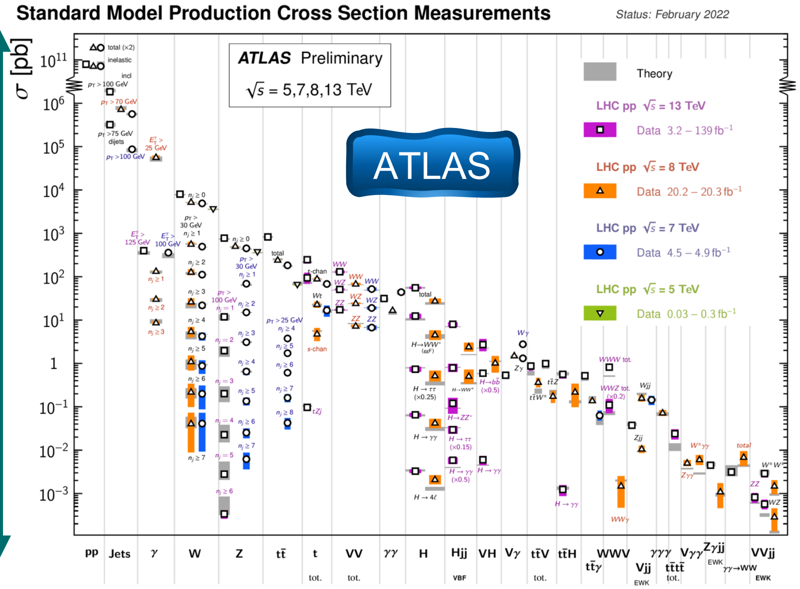
Overview of Standard Model measurements at ATLAS & CMS: Physics with electroweak bosons



- ATLAS Public Results
- CMS Public Results

Production of EW bosons tests N^nLO generators, PDFs, non-perturbative physics

15 order of magnitude!



EW boson self interactions:

- **rare processes to probe SM predictions**
- **BSM portal to be interpreted through Effective Field Theories**

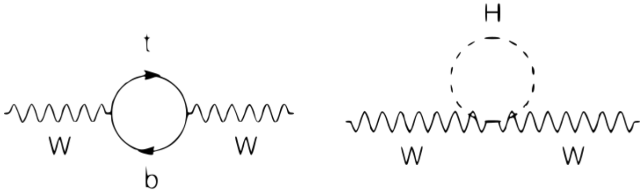
Vector boson scattering tests details of electroweak symmetry breaking

Global analyses of EW parameters probe the fundamental consistency of the SM

Three free parameters of electroweak symmetry breaking mechanism are over constrained by experimental observables

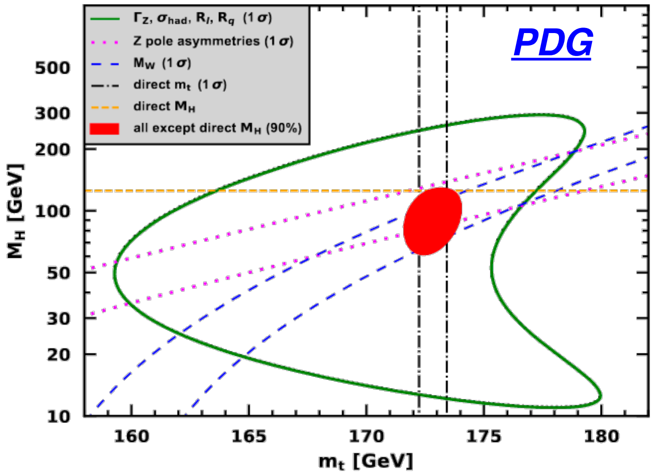
m_Z, G_F, α_{em}, (m_W, $sin^2\theta_W/sin^2\theta^{eff}_{lep}$, m_{top}, m_H)

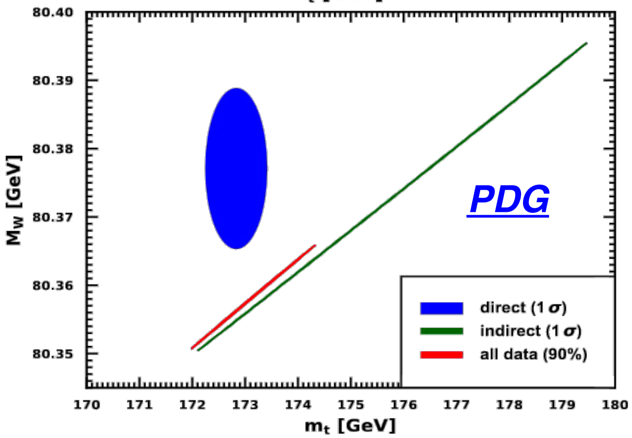
$$sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \qquad m_W^2 sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}$$



$$m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F m_Z^2}}\right)$$

$$\Delta r = -\frac{3\alpha cos_W^2 m_t^2}{16\pi sin_W^4 G_F m_W^2} + \frac{11\alpha}{48\pi sin_W^2} ln\frac{m_H^2}{m_W^2} + \cdots$$





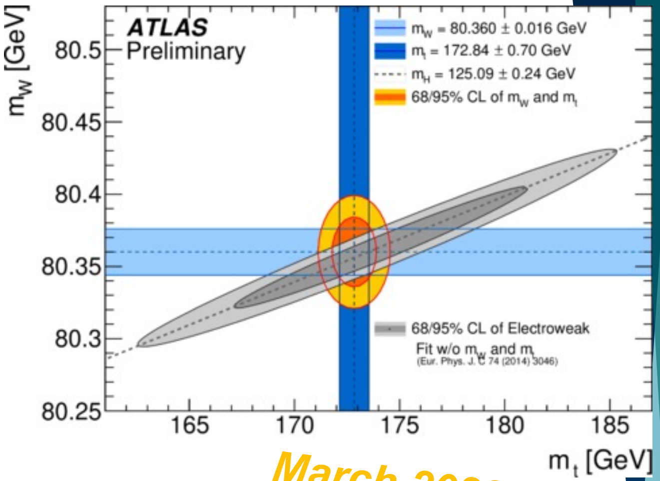
ATLAS W mass measurement

ATLAS, 7 TeV, 4.6 fb^{-1}
2023 Update: ATLAS-CONF-2023-004
2017 Measurement: *Eur. Phys. J. C 78 (2018) 110*

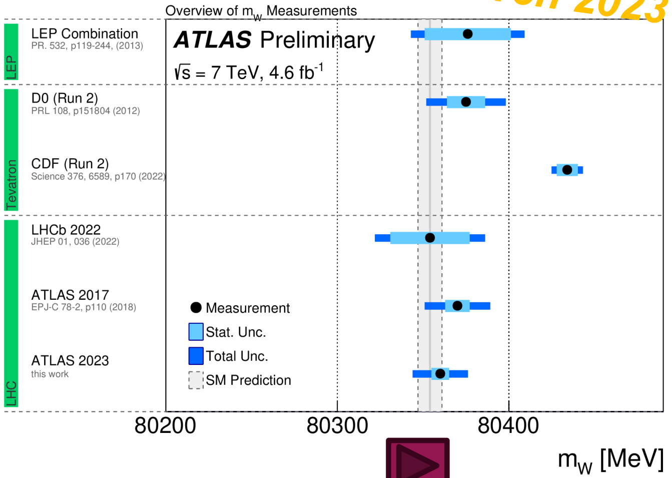
ATLAS W mass reanalysis: Reanalysis follows the same approach as 2017 analysis but using an improved fitting technique and updated PDFs.

Strategy & Updates:

- ✓ Leptonic (electron and muon) W decays ($W \to e/\mu+\nu$)
- ✓ Use dilepton p_T and m_T dependence on m_W
- ✓ Use signal MC templates obtained by reweighting the reference MC according to the Breit-Wigner parameterisation of W
- ✓ Z, $W \to \tau\nu$, VV, top background estimated using MC; data-driven multijet background
- ✓ Final m_W is obtained from separate p_T and m_T fit considering numerous event categories
- ✓ Rigorous checks of modelling have been performed:
  - ✓ PDF has been updated
  - ✓ Updated EW corrections
  - ✓ $p_T(W)$ validated with a dedicated measurement (see slide 8)
  - ✓ Updated calibrations and precise detector modelling



March 2023



Previous ATLAS result (2017):

$$m_W = 80370 \pm 19\ MeV$$

SM prediction:

$$m_W^{pred.} = 80354 \pm 7\ MeV$$

New ATLAS result:

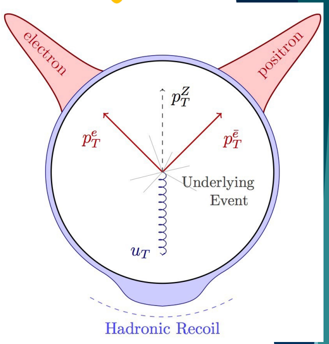
$$m_W = 80360 \pm 5(stat.) \pm 15(syst.) MeV = 80360 \pm 16 MeV$$

New result agrees slightly better with the SM prediction

Precise measurement of Z invisible width

NEW **July 2023** [Phys. Lett. B 842 (2023) 137563](#)
CMS, 13 TeV, 36.3 fb^{-1}

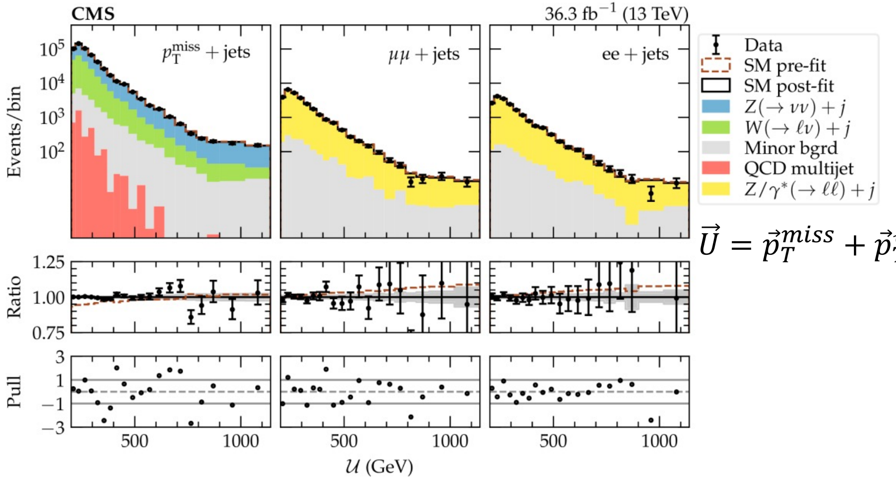
[ATL-COM-PHYS-2023-401](#) **August 2023** NEW
ATLAS, 13 TeV, 37 fb^{-1}



- ✗ First precise measurement of Z invisible width at a hadron collider from CMS
- ✗ Constraint on number of light neutrino species coupling to the Z boson
- ✗ Simultaneous fit of the hadronic recoil distribution in **Z→ll + jets** and MET+jets regions
  - Fit parameter scales Z->vv process relative to Z→ ll

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z\text{+jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z\text{+jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

Fit to the hadronic recoil distribution U (MET in case of Z->invisible)

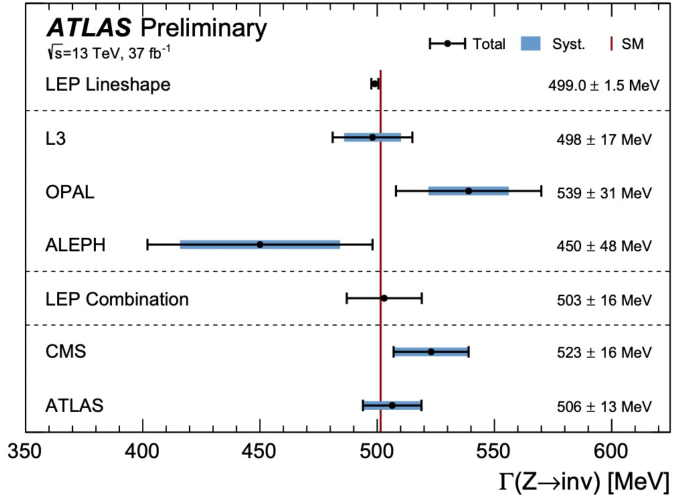


$$\vec{U} = \vec{p}_T^{\,miss} + \vec{p}_T^{\,\ell\ell}$$

CMS: $\Gamma_{inv} = 523 \pm 3(\text{stat}) \pm 16(\text{syst})\text{MeV}$

ATLAS: $\Gamma_{inv} = 506 \pm 2(\text{stat}) \pm 12(\text{syst})\text{MeV}$

LHC measurements competitive with the combined result of the direct measurements from the LEP



Probing N^nLO, resummed models: precise measurement of $p_T(W/Z)$ spectrum

- ✓ At LHC W/Z bosons production ➔ sensitive test of Quantum Chromodynamics (QCD)
- ✓ W/Z transverse momentum arises from higher order corrections to the leading order Drell–Yan processes, and from non-perturbative effects
  - ➢ At small $p_T(W/Z)$, where soft-gluon radiation is important, a resummation to all orders must be performed in order to obtain stable theoretical predictions and to describe the measurements
  - ➢ When $p_T(W/Z)$ increases, hard partonic radiation becomes important and associated jets can be measured, allowing the study of QCD contributions to W/Z production.
- ✓ Z-boson p_T spectrum ➔ straightforward through the transverse momentum of the pair of charged decay leptons $p_{T\ell\ell}$
- ✓ W-boson p_T spectrum ➔ much more significant challenge, as the decay neutrino escapes direct detection

CMS-SMP-21-003

CMS Measurement of Z+jet production cross section

$\sqrt{s}$ = 13 TeV L= 36.3 fb^{-1}

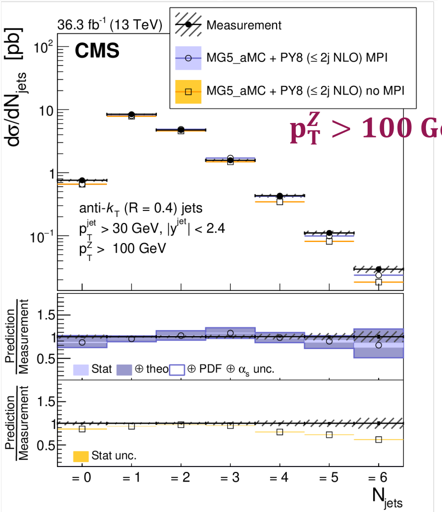
$Z \rightarrow \ell\ell$ + jets (ℓ=e or μ)

The multiplicity of jets with transverse momentum $p_T^{jet} > 30$ GeV is measured for different regions of the Z boson's $p_T(Z)$, from lower than 10 GeV to higher than 100 GeV.

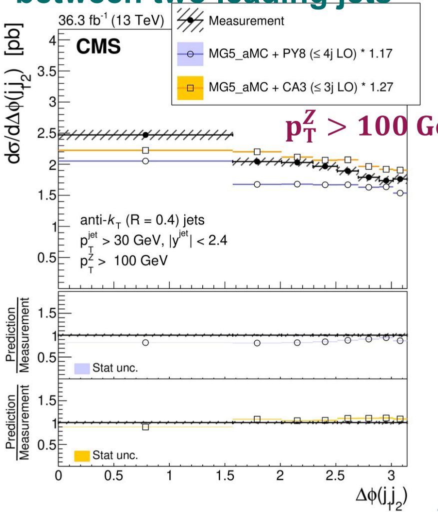
Z+jet measurements challenge theoretical predictions; a good agreement can be achieved by including contributions of multiparton interactions, parton showering, parton densities, as well as multijet matrix element merging.

The differential measurements provided help to disentangle the various contributions and illustrate where each contribution becomes important.

Jet multiplicity



Cross section as a function of $\Delta\varphi(j_1j_2)$ between two leading jets

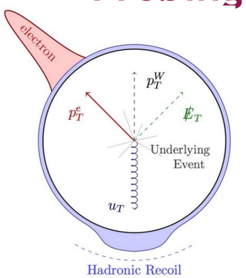


Probing N^nLO, resummed models: precise measurement of $p_T(W/Z)$ spectrum

ATLAS

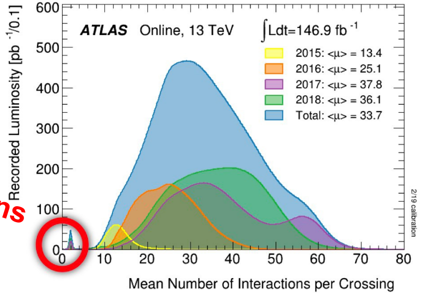
ATLAS-CONF-2023-028

May 2023



L= 255 pb^{-1} at √ s = 5.02 TeV; L=338 pb^{-1} at √ s = 13 TeV

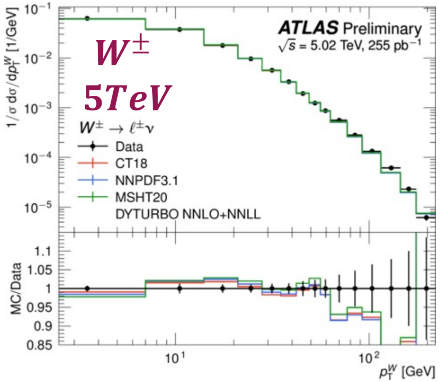
Precise modelling of $p_T(W)$ is important in reducing the uncertainty for m_W: hadronic recoil is the main limitation in $p_T(W)$ measurements and recoil resolution degrades with pileup

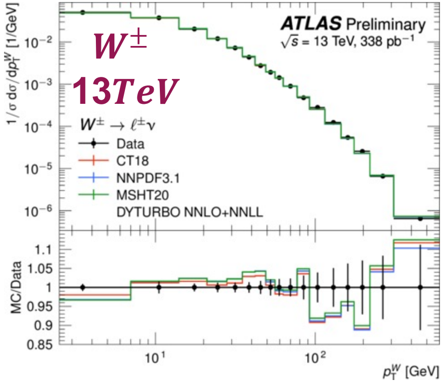


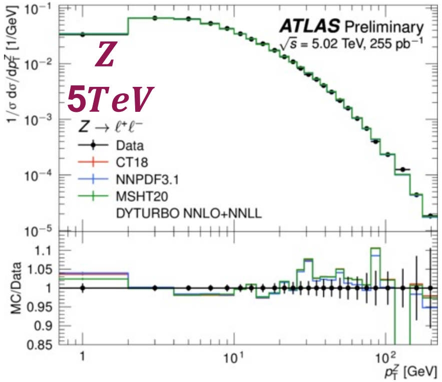
Precision measurements of $p_T(W^+, W^-, Z)$ and ratios at 13 and 5.02 TeV are performed using dedicated low-pileup runs with $< \mu >$~2

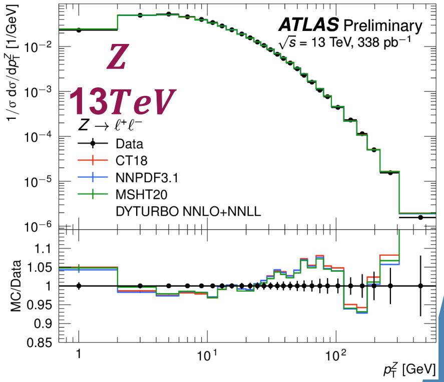
✓ W→ℓν and Z→ℓℓ (ℓ=e or μ)

Unfolded distributions are compared to QCD calculations based on parton shower Monte Carlo generators and analytical resummation









✓ ***MC predictions show common deficiencies for W/Z cross sections.***

✓ ***DYTURBO resummed predictions show best overall agreement, matching the data ~few percent level***

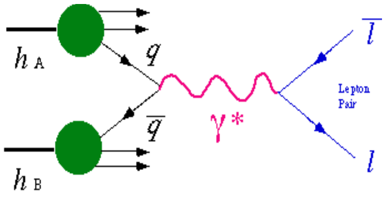
CMS Drell-Yan measurement

$\sqrt{s}$ = 13 TeV, L=36.3 fb^{-1}

Arxiv:2205.0489

July 2023

NEW

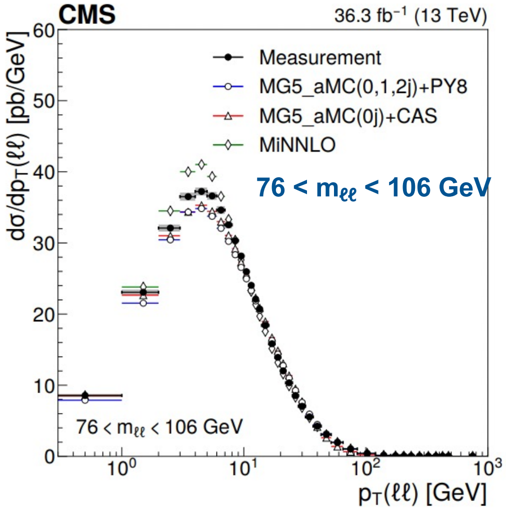


Double differential cross sections in m_{ll}, p_T, and $\varphi^*_\eta = tan\left(\frac{\pi-\Delta\varphi}{2}\right) sin(\theta^*_\eta)$

- Inclusive and >= 1 jet categories
- 5 m_{ll} bins. Fiducial region: p_T > 25 (20) GeV for leading (subleading) lepton, |η| < 2.4

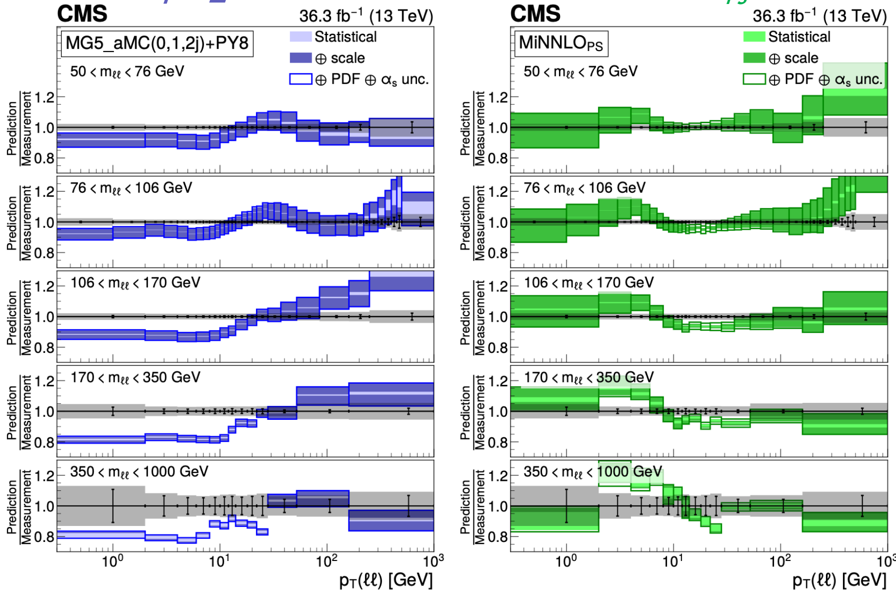
Measurement compared to large variety of theory predictions

Differential cross sections in p_T (ℓℓ)



The error bars on data points (black dots) correspond to the statistical uncertainty of the measurement and the shaded bands around the data points correspond to the total experimental uncertainty.

MadGraph5_aMC@NLO + PY8 | *$MiNNLO_{PS}$*



More in back up slides

Measurement compared with MadGraph5_aMC@NLO + PYTHIA 8 and $MiNNLO_{PS}$: NNLO ME and Pythia8 PS and MPI

The strong coupling strength α_s

The strong force is still the least well known interaction of nature α_s uncertainty ~ 1%

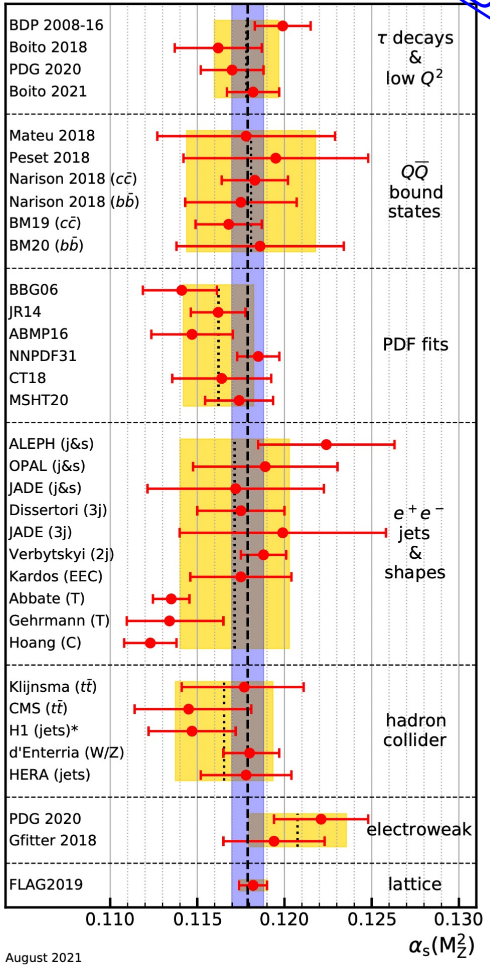
Impacts physics at the Planck scale:

- ✗ **EW vacuum stability, Grand Unification**
- ✗ **Is among the dominant uncertainties of several precision measurements at colliders**
- ✗ **Higgs couplings at the LHC**
- ✗ **EW precision observables at e+e- colliders**

World Average (PDG): $\alpha_s(m_Z) = 0.1179 \pm 0.0009$

Conventionally determined at the reference scale Q = m_Z
Decreases ("runs") as α_s~$\ln(Q_2 / \Lambda_2)^{-1}$

PDG



α_S from jets: Transverse Energy-Energy Correlation and Asymmetry in in multijet events

L= 139 fb^{-1} at $\sqrt{s}$ = 13 TeV **ATLAS**

arXiv:2301.09351

April 2023

TEEC:

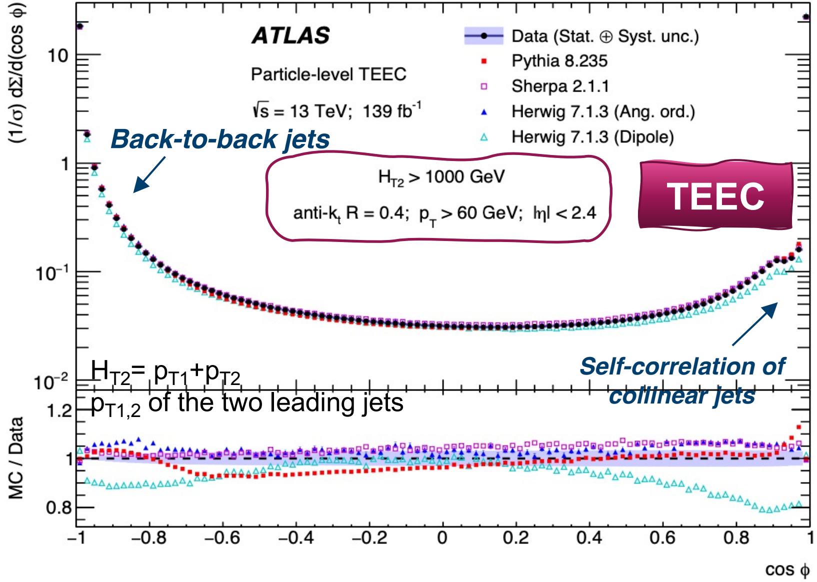
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d\cos\phi}x_{Ti}x_{Tj}dx_{Ti}dx_{Tj} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{Ti}E^A_{Tj}}{\left(\sum_k E^A_{Tk}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$

Difference between forward and backward part of TEEC

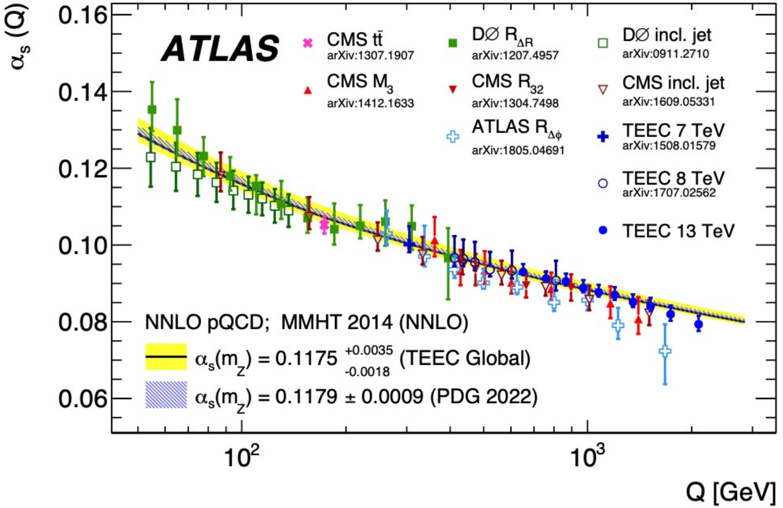
ATEEC:

$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

Generalization for hadronic collider



The total uncertainty is found to be of the order of 2% for the TEEC and 3% for the ATEEC



Leaving the value of α_s as a free parameter, it can be fitted as a function of H_T (using $Q = H_T/2$), show its running and obtain final combined values:

$\alpha_S(m_Z, \mathrm{TEEC})$ = **0.1175 ± 0.0006(exp.)+ 0.0034–0.0017(theo.)**

$\alpha_S(m_Z, \mathrm{ATEEC})$ = **0.1185 ± 0.0009(exp.)+ 0.0025–0.0012(theo.)**

α_S from jets: Transverse Energy-Energy Correlation and Asymmetry in in multijet events

CMS

SMP-22-015

August 2023

NEW

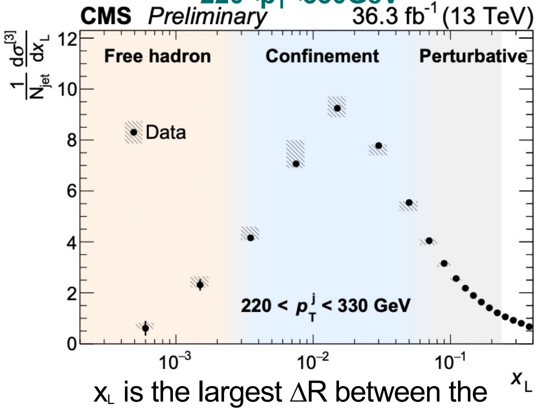
L= 36.3 fb^{-1} at $\sqrt{s}$ = 13 TeV

Two-point and three-point energy correlator jet substructure observables (E2C and E3C), using LHC 13 TeV data collected by the CMS experiment:

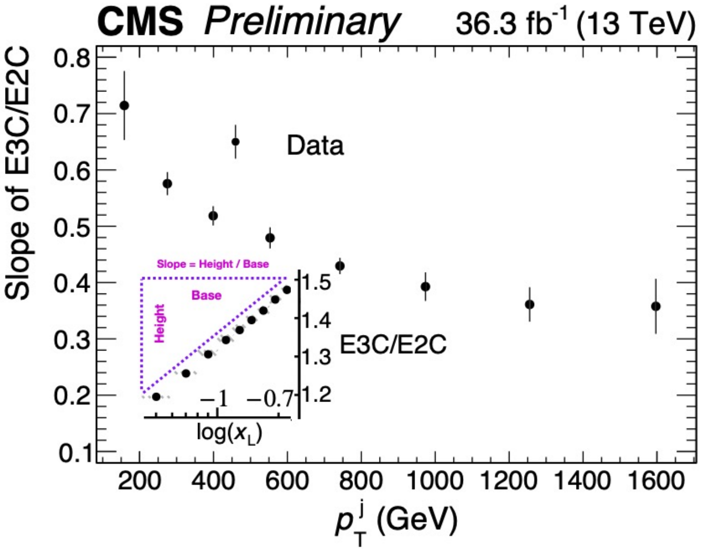
$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j}),$$

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

Unfolded data distribution of E3C using jets $220<p_T<330$GeV



x_L is the largest ΔR between the two or three particles



The fitted slopes of the E3C/E2C ratio data distributions as a function of jet p_T are used to illustrate the dependency of α_S on jet p_T.

The $\alpha_S(m_Z)$ value extracted from the ratio of the three-point and two-point correlators is:

$$\alpha_S(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

The most significant sources of uncertainty arise from the QCD scale in the theoretical calculation and the energy scales of the jet constituents.

The most precise α_s: Z (p_T)

ATLAS-CONF-2023-015
March 2023

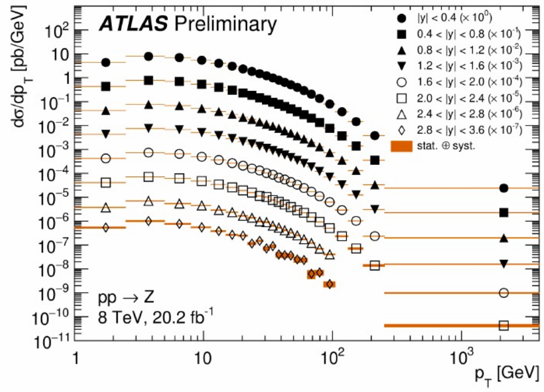
L= 20.2 fb^{-1} at $\sqrt{s}$ = 8 TeV

First precise measurement at the LHC in the full phase space for $pp \rightarrow Z \rightarrow \ell\ell (\ell = e$ or $\mu)$ at $\sqrt{s}$ = 8 TeV, L=20.2fb^{-1}

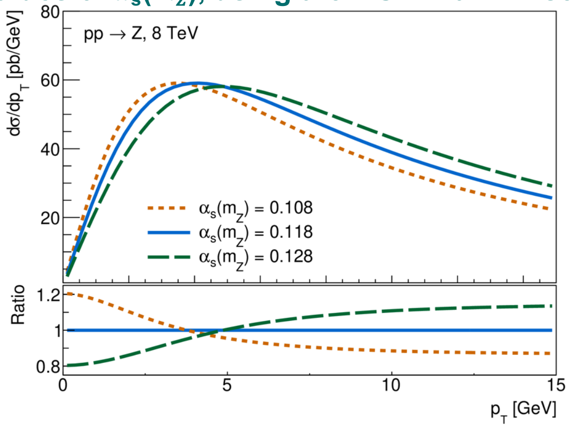
- *Negligible theory uncertainties, no extrapolation to full phase space*
- *Statistically limited*
- *Cross sections are parameters in fit to 176 bins of Z p_T-rapidity*
- Theory prediction from DYTurbo
- The Z-boson transverse-momentum distribution in the Sudakov region is not included in PDF fits, therefore largely reducing the issue of correlation of this α_S determination with simultaneous determination of PDFs and strong-coupling constant
- Evaluate a χ^2 that includes experimental and theory uncertainties, and at each value of α_s, a reweighting technique is used to get the PDFs that best fit the data
- Expected sensitivity 0.05%

This is the most precise to date and the first based on N⁴LLa+N³LO predictions in perturbative QCD

80<m_Z<100GeV & |y|<3.6



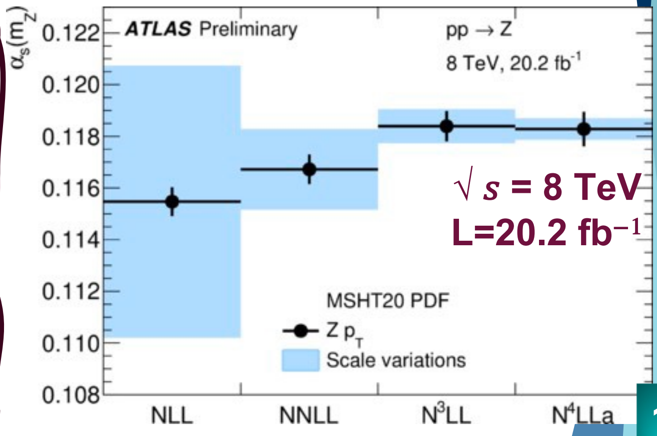
Z p_T predicted with DYTurbo at different values of $\alpha_s(m_Z)$, using the MSHT20 PDF set



This determination gathers all desirable features for high precision:

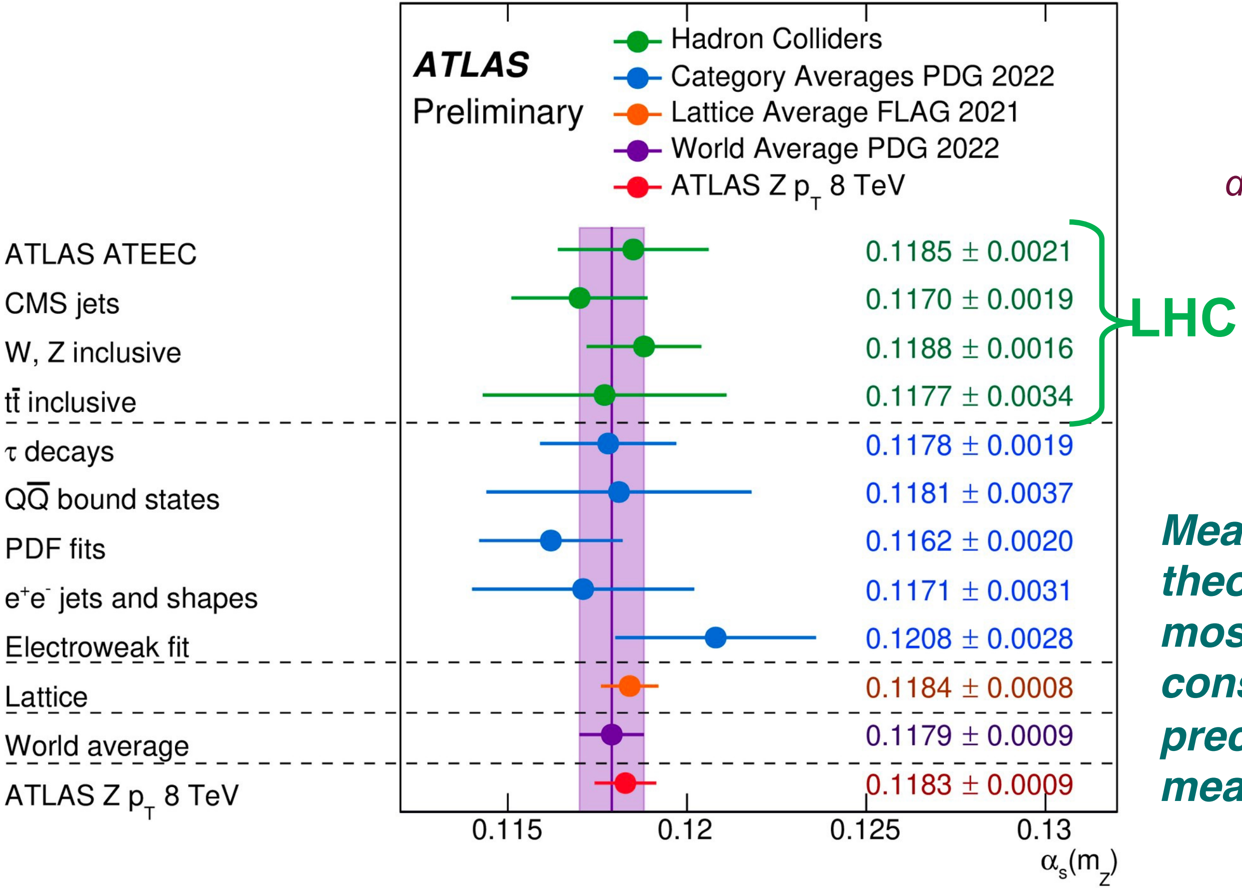
- large sensitivity compared to the experimental precision
- high perturbative accuracy of the theoretical predictions enabled by the computation of some perturbative corrections in QCD at four and five loops

$$\alpha_S = 0.11828^{+0.00089}_{-0.00094}$$



$\sqrt{s}$ = 8 TeV
L=20.2 fb^{-1}

α_s: global picture



$$\alpha_S = 0.11828^{+0.00089}_{-0.00094}$$

compatible with other determinations and with the world-average value

Measurement dominated by theory uncertainties, but most of them can be constrained with more precise cross-section measurements

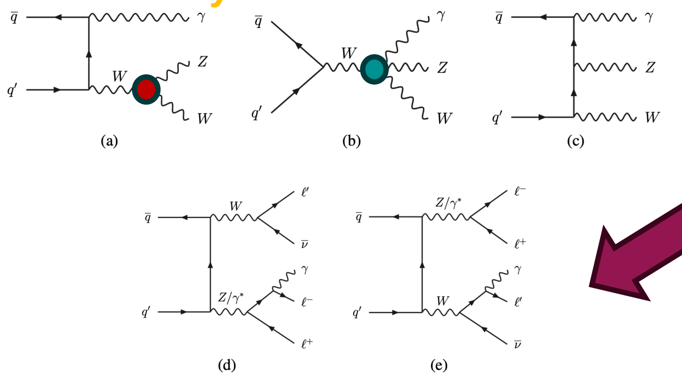
Triboson production

L= 139 fb^{-1} at $\sqrt{s}$ = 13 TeV

Test of the SM boson triple and quartic interaction

Atlas WZγ observation

May 2023

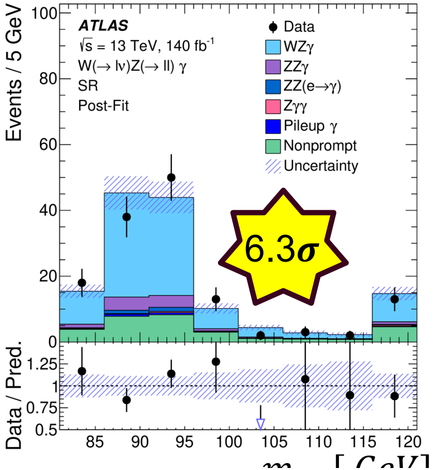


- W and Z leptonic decay
- Fiducial x-section measurement
- Kinematical cuts to reduce FSR process

Fiducial Cross-Section

ATLAS: 2.01 ±0.33 fb

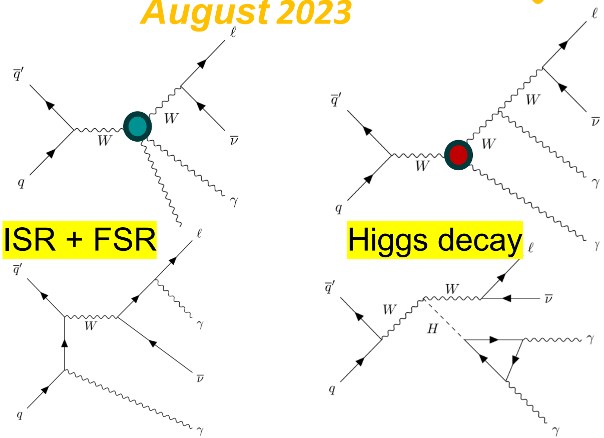
Theory: 1.05 ±0.06 fb

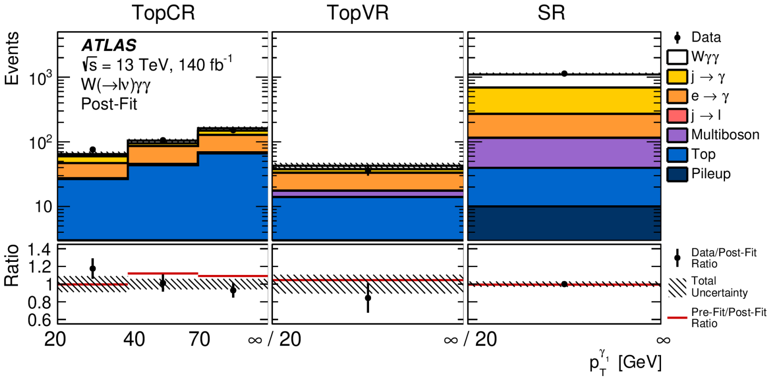


Atlas W$\gamma\gamma$ observation

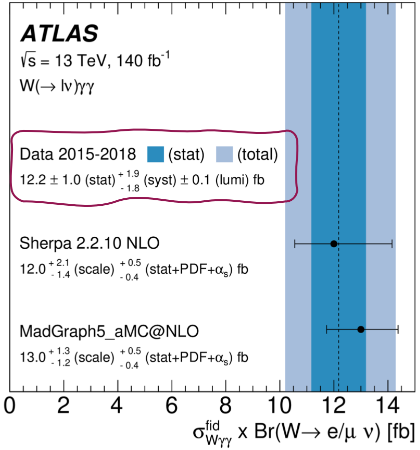
NEW

August 2023





The background-only hypothesis is rejected with an observed and expected significance of 5.6 standard deviations



CMS-PAS-SMP-22-006

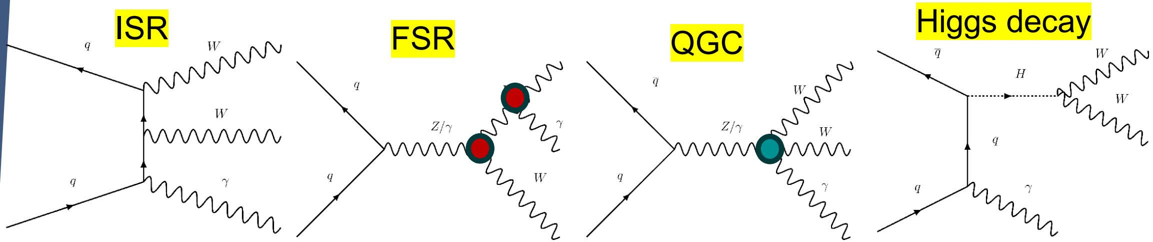
March 2023

Triboson production

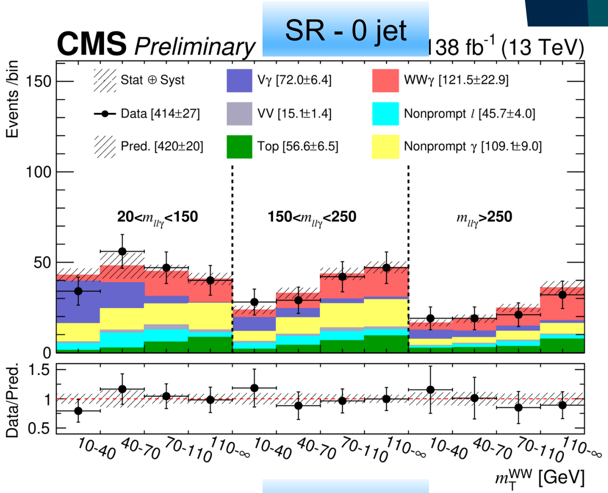
L= 138 fb^{-1} at $\sqrt{s}$ = 13 TeV

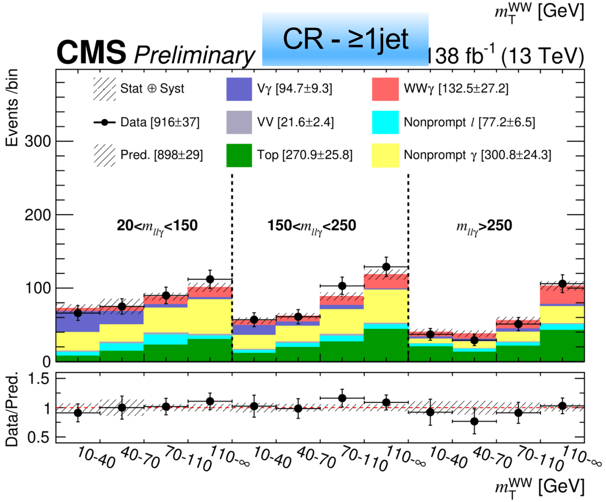
CMS WWγ observation

Test of the SM boson triple and quartic interaction



- 2 Control Regions: same-sign leptons and ≥ 1 bjet (TOP) have been defined to constrains experimental background from non prompt lepton and photon
- Extract signal using 2D fit to **m_T(WW)** and **m(llγ)** in SR and CRs
- **First observation of WWγ production at LHC with 5.6 (4.7) σ observed (expected) significance**





The measured fiducial cross section is:

σ = 6.0 ± 1.7fb fb

The theoretical prediction for the fiducial cross section is

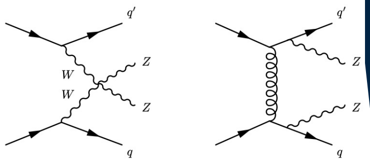
σ = 4.61 ± 0.34 (scale) ± 0.05 (PDF) fb NLO QCD MADGRAPH5 aMC@NLO

STDM-2020-02

August 2023

NEW

Vector boson scattering: Atlas ZZjj

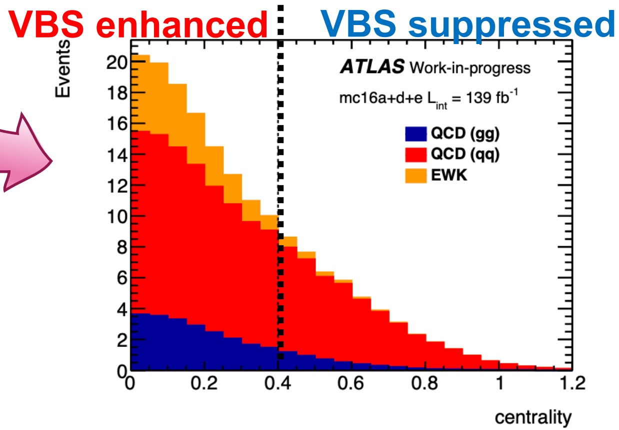


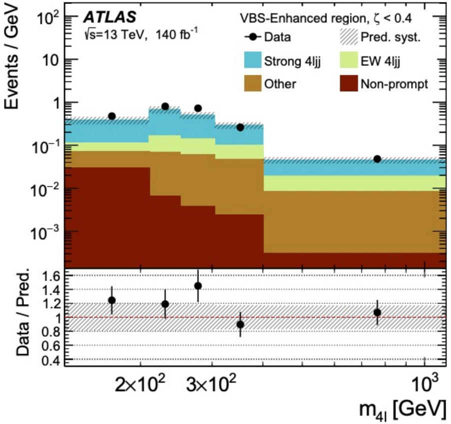
ZZ+jets production sensitive to both **EWK** (*WWZ and $WWZZ$ self-interactions*) and **strong** component (accuracy of perturbative QCD calculations)

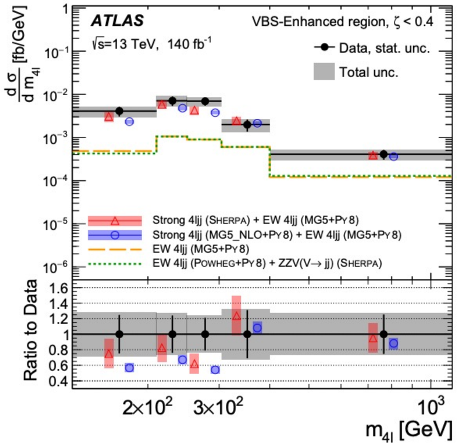
- Final state with 4 leptons in association with two jets
- EW and QCD components in two different fiducal regions: **VBS enhanced** and **VBS suppressed** based on 4l system **centrality ζ**

$$\zeta = \frac{|y_{quadruplet} - 0.5 * (y_{leading\ jet} + y_{sub-leading\ jet})|}{|y_{leading\ jet} - y_{sub-leading\ jet}|}$$

- **Differential cross section (unfolded) measurements** of inclusive ZZjj production with full Run 2 data set wrt different type of observables: m_{4l}, m_{jj}, $p_T(4l)$, $\Delta\phi jj, \vartheta^*_{12}, \vartheta^*_{34}$, $p_T(4ljj)$







Expected and observed limits D-8(6) operators on aQGC from 2D fit in m_{4l} and m_{jj}

Wilson coefficient	$\lvert\mathcal{M}_{d8}\rvert^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-0.98, 0.93]	[-1.00, 0.97]
	no	[-23, 17]	[-19, 19]
$f_{T,1}/\Lambda^4$	yes	[-1.2, 1.2]	[-1.3, 1.3]
	no	[-160, 120]	[-140, 140]
$f_{T,2}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-74, 56]	[-63, 62]
$f_{T,5}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-79, 60]	[-68, 67]
$f_{T,6}/\Lambda^4$	yes	[-3.9, 3.9]	[-4.1, 4.1]
	no	[-64, 48]	[-55, 54]
$f_{T,7}/\Lambda^4$	yes	[-8.5, 8.1]	[-8.8, 8.4]
	no	[-260, 200]	[-220, 220]
$f_{T,8}/\Lambda^4$	yes	[-2.1, 2.1]	[-2.2, 2.2]
	no	[-4.6, 3.1]×10^4	[-3.9, 3.8]×10^4
$f_{T,9}/\Lambda^4$	yes	[-4.5, 4.5]	[-4.7, 4.7]
	no	[-7.5, 5.5]×10^4	[-6.4, 6.3]×10^4

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\,\mathrm{Re}(\mathcal{M}_{SM}{}^* \mathcal{M}_{d8}) + |\mathcal{M}_{d8}|^2$$

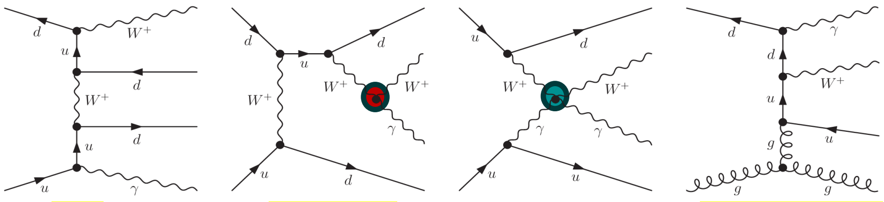
CMS-SMP-21-011

May 2023

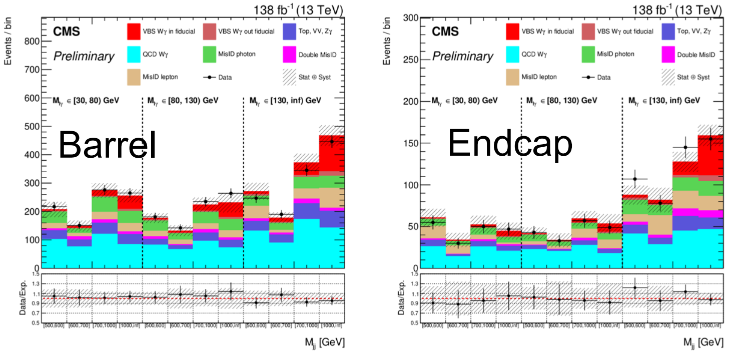
Vector boson scattering: CMS $W\gamma jj$

L= 138 fb^{-1} at $\sqrt{s}$ = 13 TeV

Test of the SM boson triple and quartic interaction



EW | EW TGC | VBS | QCD induced

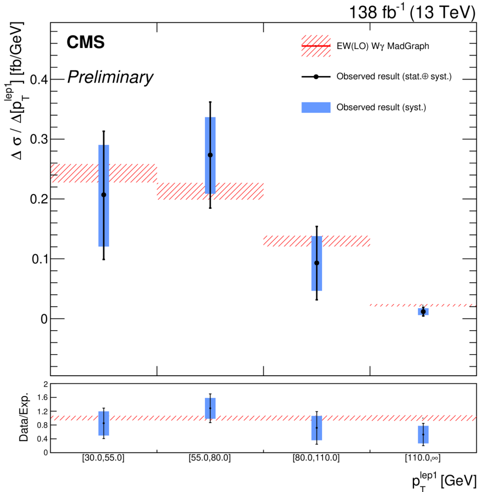


- Enahnce EW contribution using m_{jj} and $\Delta\eta$(jj) cuts
- Data driven estimation of backgrouns from misidentified photon and/or lepton in CRs (other baground from MC)
- Barrel/Endcap selection
- Extract signal using 2D fit to **m(jj)** and **m(lγ)** in SR and CRs
- First observation of $W\gamma jj$ production at LHC with 6 (6.8) σ observed (expected) significance

- Fiducial EW and EW+QCD cross section measurement

$$\sigma^{fid}_{EW} = 19.2^{+4.0}_{-3.9}\,fb \qquad \sigma^{fid}_{EW+QCD} = 90^{+11}_{-10}\,fb$$

Differential cross section measurements



Limits on anomalous quartic gauge couplings

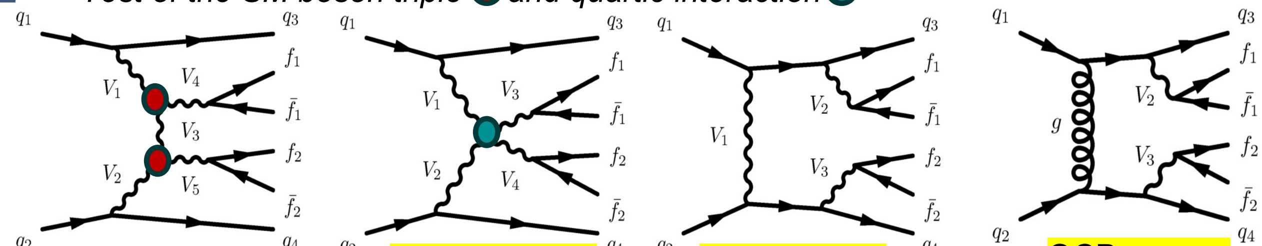
Expected. limit	Observed. limit	U_{bound}
$-5.1 < f_{M0}/\Lambda^4 < 5.1$	$-5.6 < f_{M0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M1}/\Lambda^4 < 7.4$	$-7.8 < f_{M1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M2}/\Lambda^4 < 1.8$	$-1.9 < f_{M2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M3}/\Lambda^4 < 2.5$	$-2.7 < f_{M3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M4}/\Lambda^4 < 3.3$	$-3.7 < f_{M4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M5}/\Lambda^4 < 3.6$	$-3.9 < f_{M5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T0}/\Lambda^4 < 0.51$	$-0.47 < f_{T0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T1}/\Lambda^4 < 0.31$	$-0.31 < f_{T1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T2}/\Lambda^4 < 0.92$	$-0.85 < f_{T2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T5}/\Lambda^4 < 0.31$	$-0.31 < f_{T5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T6}/\Lambda^4 < 0.25$	$-0.25 < f_{T6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T7}/\Lambda^4 < 0.68$	$-0.67 < f_{T7}/\Lambda^4 < 0.73$	3.1

most stringent limits to date on the aQGC

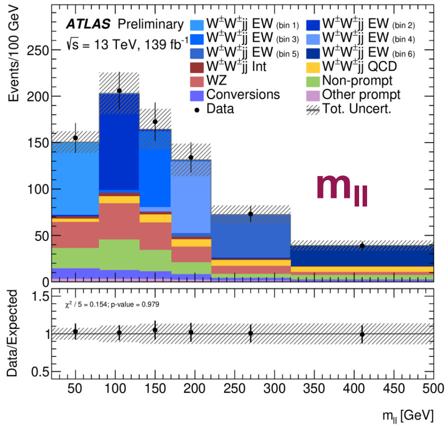
Vector boson scattering: same sign WWjj

L= 139 fb^{-1} at $\sqrt{s}$ = 13 TeV

Test of the SM boson triple and quartic interaction



EW VBS TGC | EW VBS QGC | EW non VBS | QCD induced

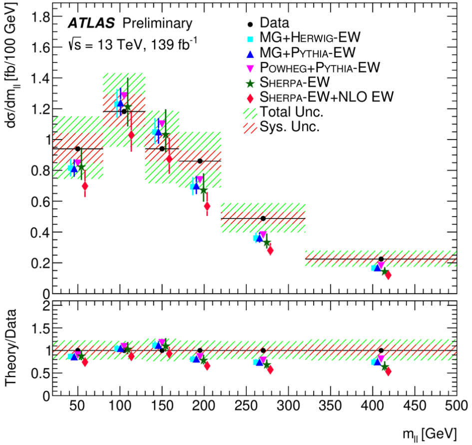


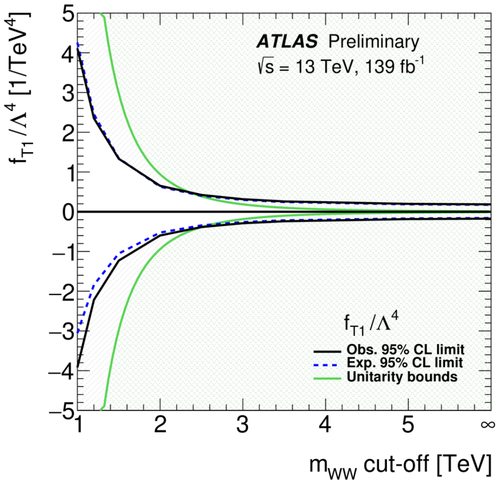
- ✓ The $W^{\pm}W^{\pm}jj$ final state has the largest ratio of electroweak to strong production cross sections compared to other VBS diboson processes
- ✓ The requirement of the presence of two same sign leptons significantly reduces SM backgrounds.

Limits on anomalous quartic gauge couplings

Unitarization: clipping method

Differential cross section measurements





Fiducial EW and EW+QCD cross section measurement

$$\sigma^{fid}_{EW} = 2.88 + 0.22(stat) + 0.19(syst)fb$$
$$\sigma^{fid}_{EW+QCD} = 3.35 + 0.22 + 0.20\ (syst)fb$$

Good agreement with the Standard Model predictions

Inclusive photon production

JHEP07(2023)086 *July 2023* (NEW)

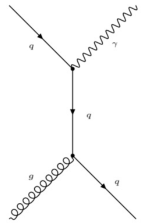
L= 139 fb^{-1} at $\sqrt{s}$ = 13 TeV

Measurement of inclusive isolated-photon cross section in ATLAS, using 139 fb^{-1} data of Run 2

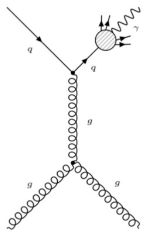
- Important measurement for test of pQCD
- Constraints on the **PDF** (especially for gluon-PDF, thanks to $qg \rightarrow q\gamma$)
- Photon produced through **two main processes**
  - **Direct process** → what we want to measure
  - **Fragmentation process** → Photons produced inside jets due to neutral mesons decays!
- Select isolated photons to remove photons from jets ➔ **isolation-cone radius (R): R= 0.2 and R=0.4**

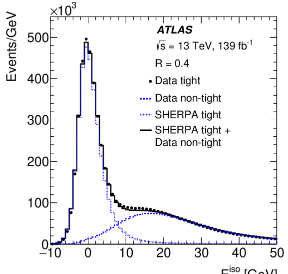
  ➔ two isolation radii and a more granular segmentation in photon pseudorapidity ➔ better determination of the proton parton distribution functions
- Non-prompt background estimated with ABCD method based on pass/fail ID and isolation criteria
- Next-to-leading-order QCD predictions from JETPHOX and SHERPA and next-to-next-to-leading-order QCD predictions from NNLOJET are compared to the measurements, using several parameterisations of the proton parton distribution functions.

Direct process



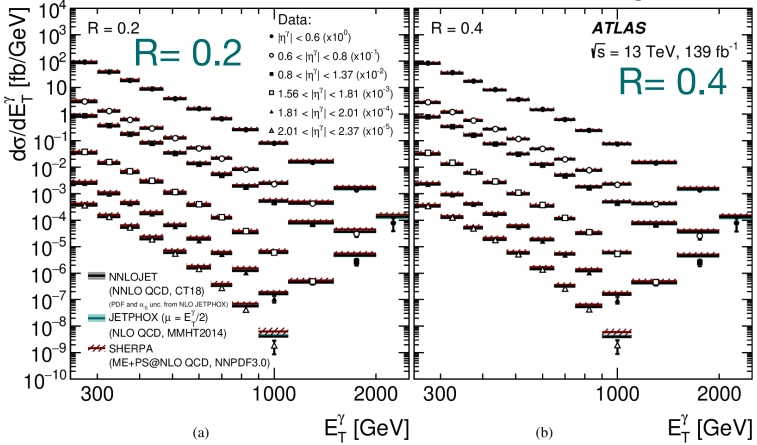
Fragmentation process

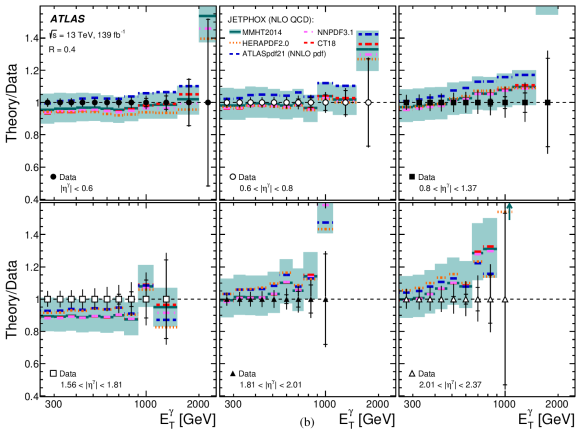




(b)

Unfold results in bins of |η$^{\gamma}$| and compare results with different pQCD predictions





The measured cross sections are well described by the fixed-order QCD predictions within the experimental and theoretical uncertainties in most of the investigated phase-space region.

Conclusions

LHC provides unique environment to test SM from precision measurement of the parameters and couplings to search for new observations and resonances:

- *Electroweak measurements provide a powerful way to explore nature ➔ LHC entered precision race with LEP measuring electroweak observables*
- *QCD process are fundamental for the understanding of the Standard Model ➔ both ATLAS and CMS have wide and innovative programs to study these processes*
- *Large dataset from Run 2:*
  - *allows for precise measurements of fundamental aspects, i.e. α_s or PDFs*
  - *numerous rare processes involving weak bosons are coming into view (all diboson channels, VBS, even photon-induced processes) ➔ Every first observation is a new laboratory to test the self consistency of the SM and to search for (in)direct evidence of New Physics*
- *Input and constraints to QCD theoretical models*
- *First observations of tri-boson processes ➔ tightening limits on EFT*
- Many more results that could not be presented in the allocated time…please give a look to:
  - ✦ ATLAS Public Results
  - ✦ CMS Public Results

Backup

ATLAS W mass measurement

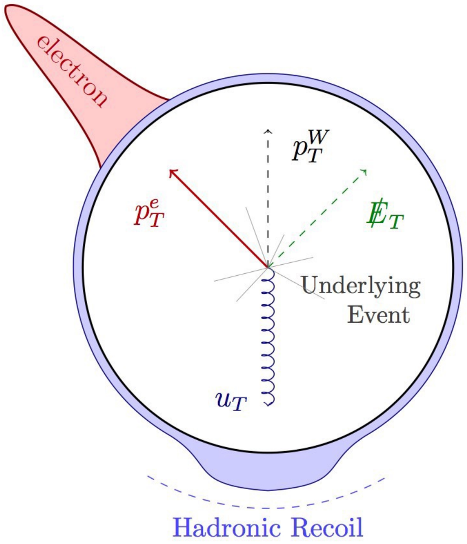
ATLAS, 7 TeV, 4.6 fb^{-1}
2023 Update: ATLAS-CONF-2023-004
2017 Measurement: *Eur. Phys. J. C 78 (2018) 110*

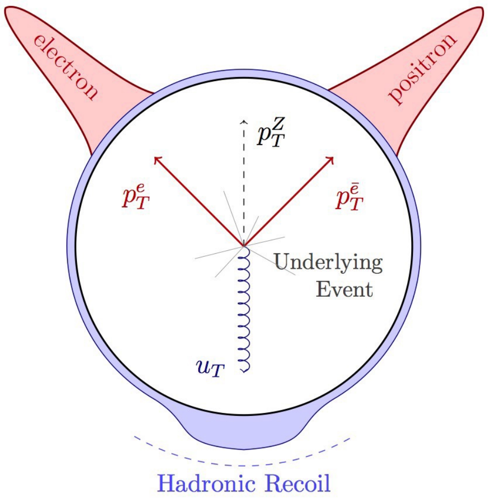
Strategy:

Lepton (electron/muon) + missing transverse energy (p_T^{miss})

Three observables:

$m_T, p_T^{\ell}, p_T^{miss}$





$Z \rightarrow ll$ events are used to calibrate signal events

$\vec{u}_T = \sum_i \vec{E}_{T,i}$ — $\vec{E}_{T,i}$ the vector of the transverse energy of cluster i

$\vec{p}_T^{miss} = -(\vec{p}_T^{\ell} + \vec{u}_T)$ — inbalance in the transverse plane

$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - cos\Delta\phi)}$$

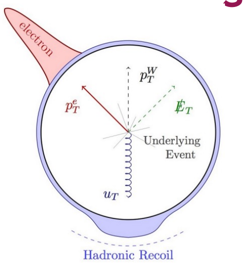
$\Delta\phi$ = azimuthal opening angle between charged lepton and missing transverse momentum

Probing N^nLO, resummed models: precise measurement of $p_T(W/Z)$ spectrum

ATLAS

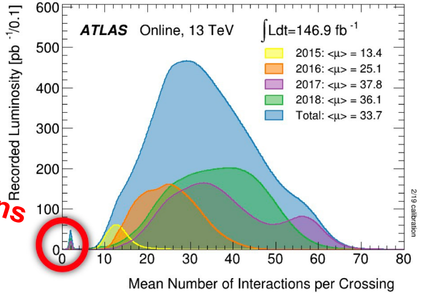
ATLAS-CONF-2023-028

May 2023



L= 255 pb^{-1} at √ s = 5.02 TeV; L=338 pb^{-1} at √ s = 13 TeV

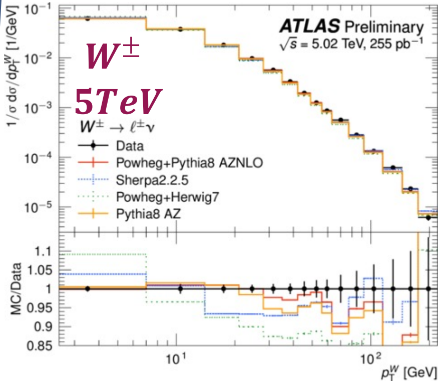
Precise modelling of $p_T(W)$ is important in reducing the uncertainty for m_W: hadronic recoil is the main limitation in $p_T(W)$ measurements and recoil resolution degrades with pileup

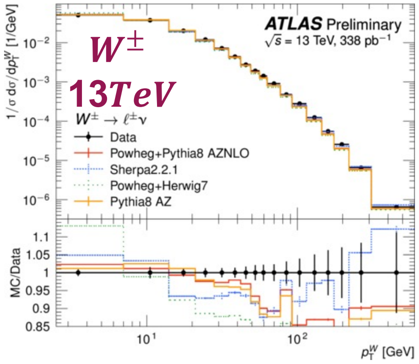


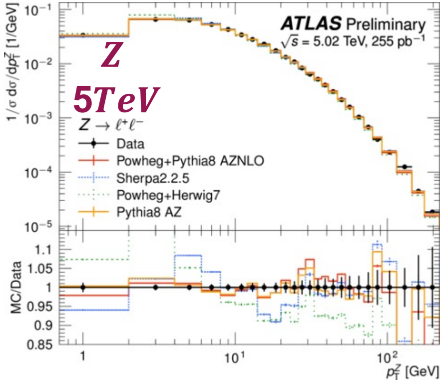
Precision measurements of $p_T(W^+, W^-, Z)$ and ratios at 13 and 5.02 TeV are performed using dedicated low-pileup runs with $< \mu >$~2

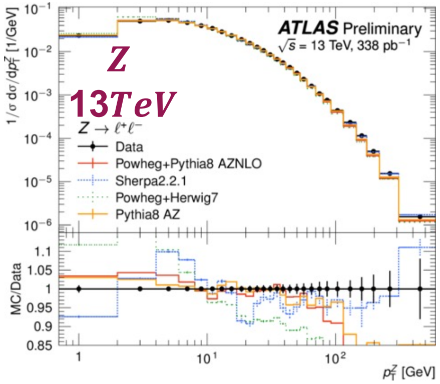
✓ W→ℓν and Z→ℓℓ (ℓ=e or μ)

Unfolded distributions are compared to QCD calculations based on parton shower Monte Carlo generators and analytical resummation









✓ ***MC predictions show common deficiencies for W/Z cross sections.***

✓ ***With ATLAS tune for PYTHIA showers the MC describe data reasonably at low p_T especially at √s=5.02 TeV***

CMS DY measurement

Arxiv:2205.0489

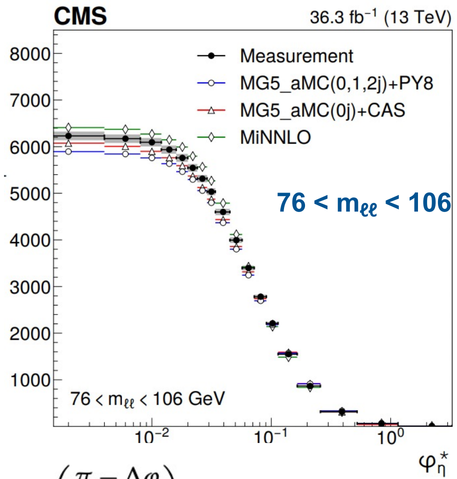
$\sqrt{s}$ = 13 TeV, L=36.3 fb-1

Double differential cross sections in m_{ll}, p_T, and ϕ^*_η

- Inclusive and >= 1 jet categories
- 5 m_{ll} bins. Fiducial region: p_T > 25 (20) GeV for leading (subleading) lepton, |η| < 2.4

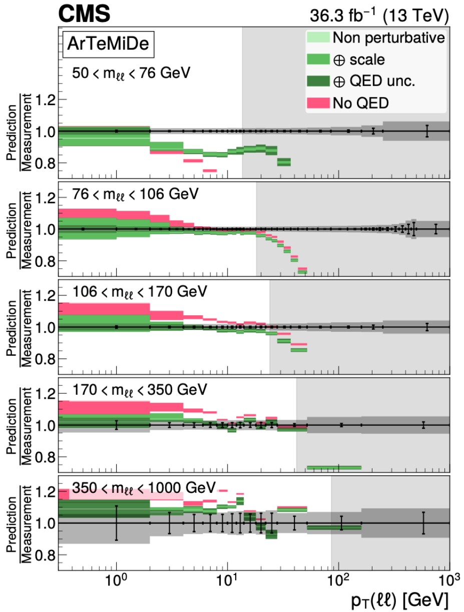
Measurement compared to large variety of theory predictions

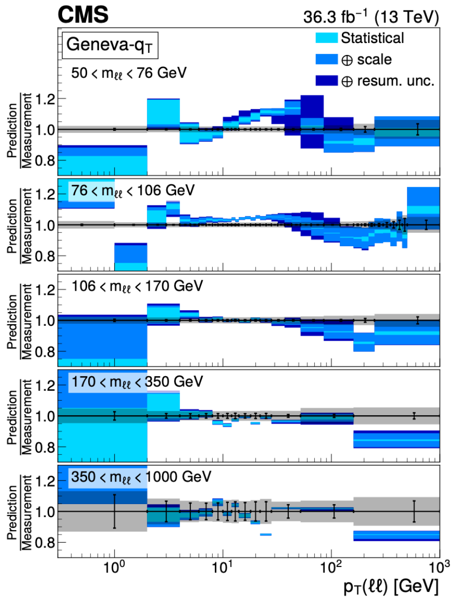
Differential cross sections in p_T ($\ell\ell$)



$$\varphi^*_\eta \equiv \tan\left(\frac{\pi - \Delta\varphi}{2}\right)\sin(\theta^*_\eta). \quad \cos(\theta^*_\eta) = \tanh\left[(\eta^- - \eta^+)/2\right]$$

The variable Δφ is the opening angle between the leptons in the plane transverse to the beam axis. The variable θ^*_η is the scattering angle of the dileptons with respect to the beam in the longitudinally boosted frame where the leptons are back to back.





Measurement compared with TMD based predictions (Parton-Branching with CASCADE3, ArTeMiDe) and resummed predictions with Geneva

α_S from jets: Transverse Energy-Energy Correlation and Asymmetry in in multijet events

arXiv:2301.09351

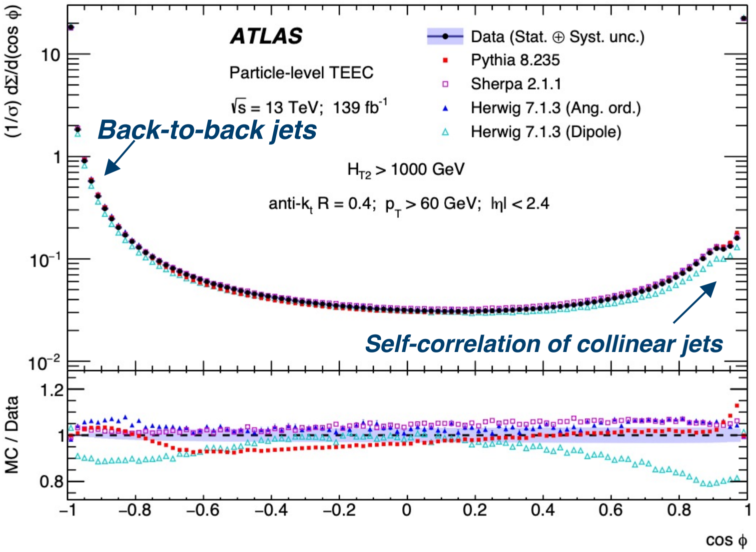
Transverse-energy distribution of azimuthal difference between jet pairs

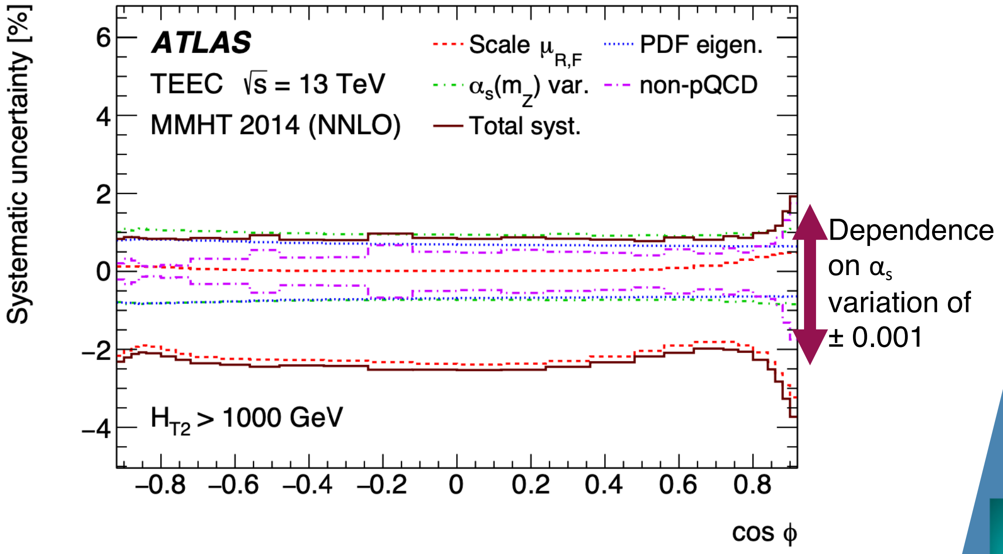
TEEC:
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d\cos\phi} x_{Ti}x_{Tj}dx_{Ti}dx_{Tj} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^{A}E_{Tj}^{A}}{\left(\sum_k E_{Tk}^{A}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$

Difference between forward and backward part of TEEC

ATEEC:
$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

Generalization for hadronic collider





α_S from jets: Transverse Energy-Energy Correlation (and Asymmetry)

Energy–energy correlation (EEC): event-shape observable, infrared safe

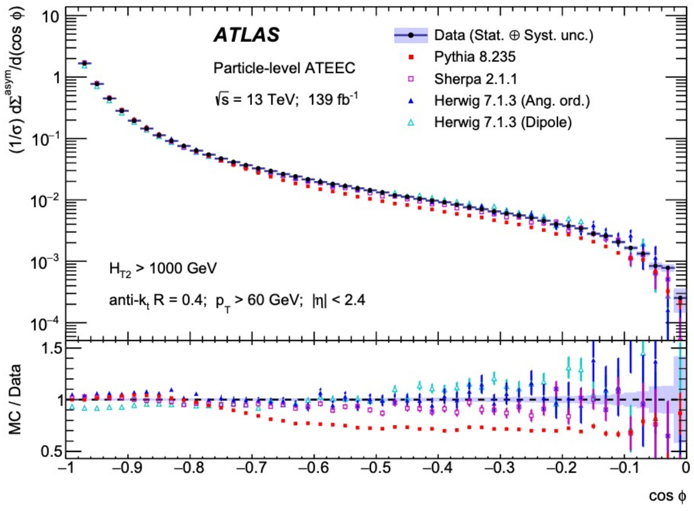
Transverse-energy weighted distribution of azimuthal difference between jet pairs [arXiv:2301.09351]

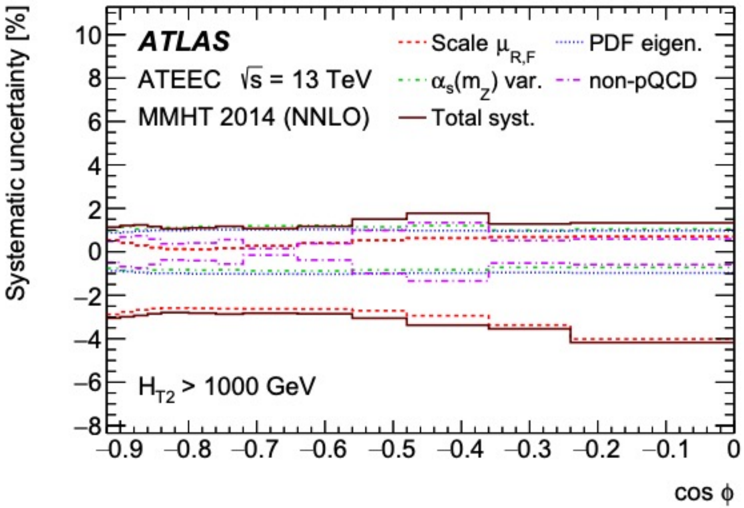
TEEC:
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d\cos\phi}x_{Ti}x_{Tj}dx_{Ti}dx_{Tj} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^{A}E_{Tj}^{A}}{\left(\sum_k E_{Tk}^{A}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$

Difference between forward and backward part of TEEC

ATEEC:
$$\frac{1}{\sigma}\frac{d\Sigma^{\text{asym}}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

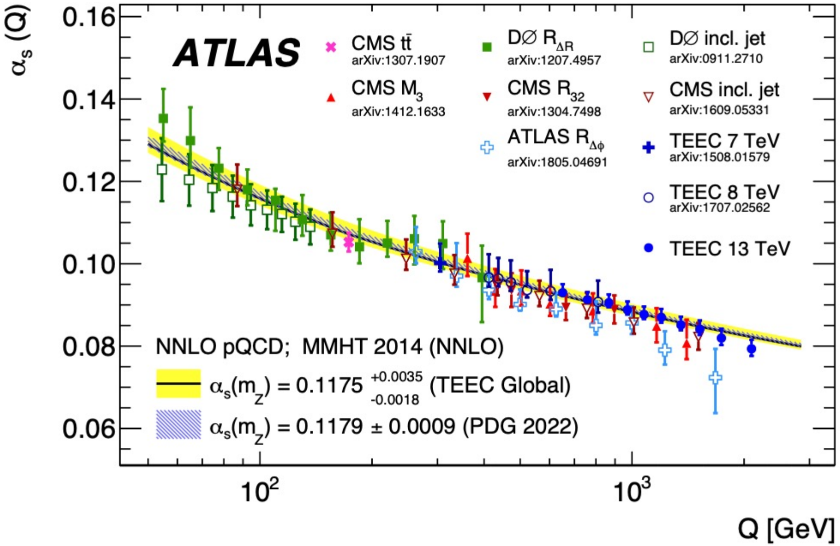
Generalization for hadronic collider

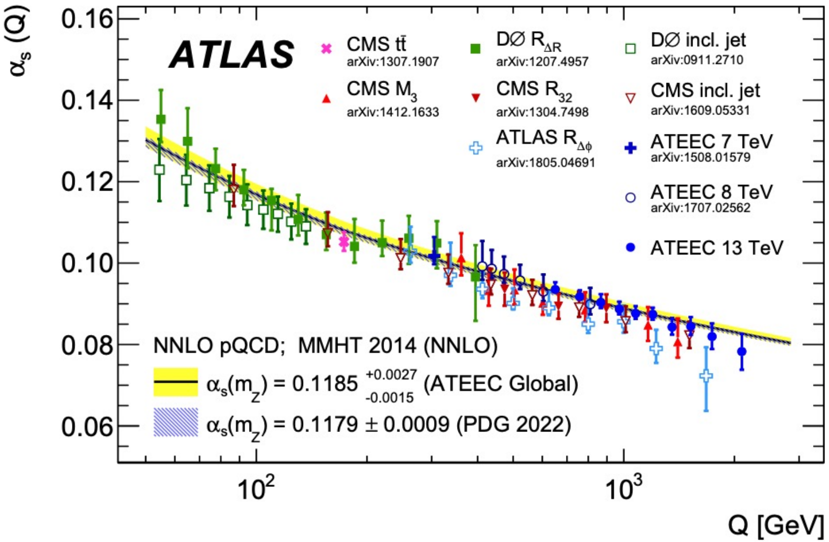




α_S from jets: Transverse Energy-Energy Correlation and Asymmetry in in multijet events

ATLAS L= 139 fb^{-1} at $\sqrt{s}$ = 13 TeV [arXiv:2301.09351]





Leaving the value of α_s as a free parameter, it can be fitted as a function of H_T (using $Q = H_T/2$), show its running and obtain final combined values:

$$\alpha_S(m_Z, \mathrm{TEEC}) = \mathbf{0.1175 \pm 0.0006(exp.) + 0.0034{-}0.0017(theo.)}$$
$$\alpha_S(m_Z, \mathrm{ATEEC}) = \mathbf{0.1185 \pm 0.0009(exp.) + 0.0025{-}0.0012(theo.)}$$

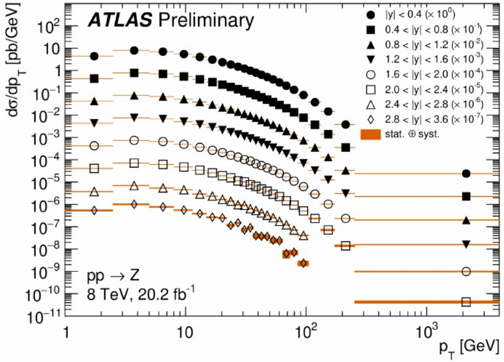
[ATLAS-CONF-2023-015](#)

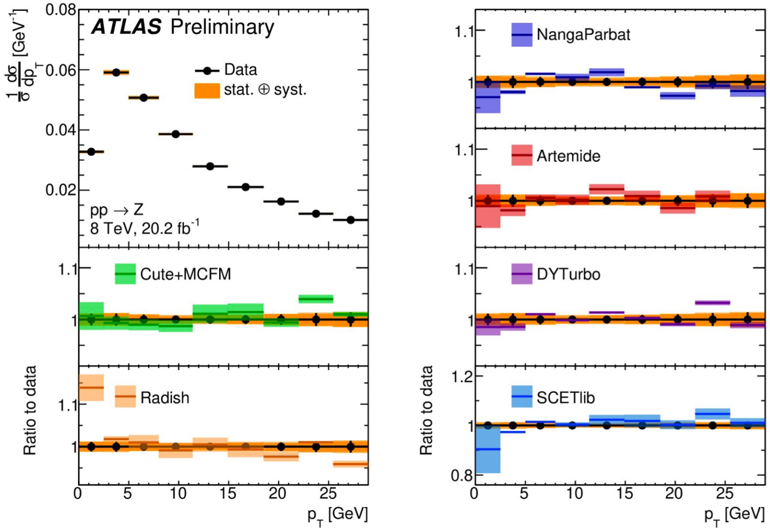
ATLAS full phase space Z measurement

First precise measurement at the LHC in the full phase space for $pp \rightarrow Z \rightarrow \ell\ell\,(\ell = e \text{ or } \mu)$ at $\sqrt{s} = 8$ TeV, L=20.2fb^{-1}

- ✗ *Negligible theory uncertainties, no extrapolation to full phase space*
- ✗ *Statistically limited*
- ✗ *Cross sections are parameters in fit to 176 bins of Z p_T-rapidity*

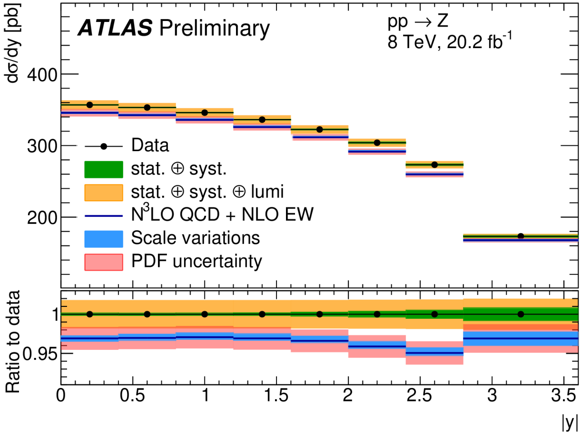
$80 < m_Z < 100$GeV & $|y| < 3.6$





p_T distribution in data vs various resummation codes. They all include approximate N⁴LL resummation and (apart from Artemis) fixed order α_S^3 contributions

Comparison between the dσ/dy measurements and N³LO QCD predictions obtained from DYTURBO using the recent aN³LO MSHT PDF set with experimental and theory uncertainties



Vector boson scattering: Atlas EFT interpretation WWjj and WZjj

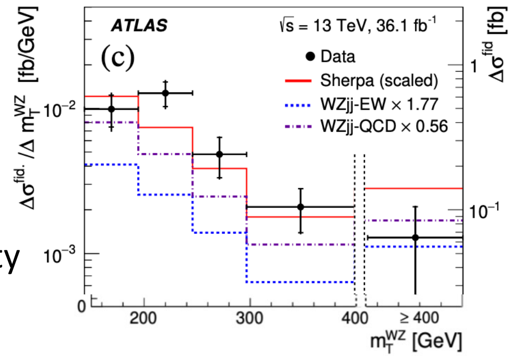
ATLAS PUB-2023-002

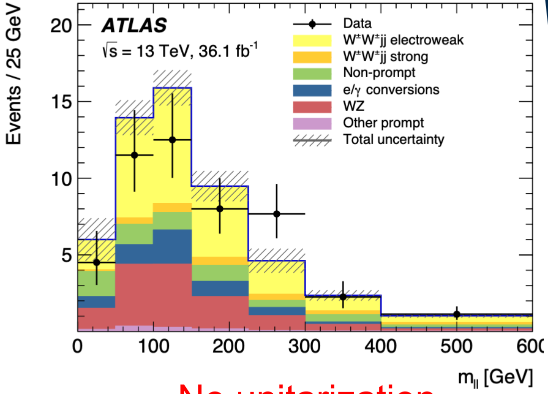
L= 36.1 fb^{-1} at $\sqrt{s}$ = 13 TeV

Combined **EFT** interpretation of **WWjj** (same-sign WW) and **WZjj** fully leptonic channels with partial Run2 dataset

Discriminating distributions:

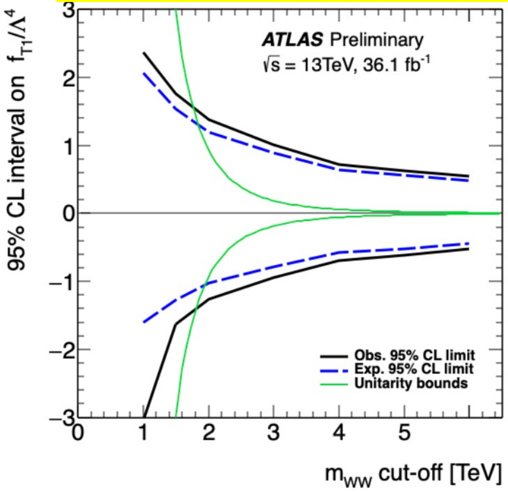
- **ssWW**: Reco-level m_{ll}
- **WZjj:** Differential distribution of m^{WZ}_T

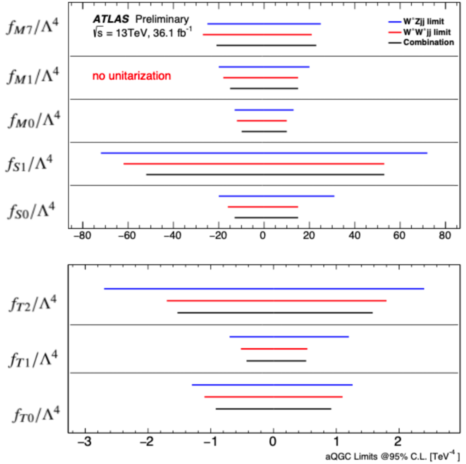




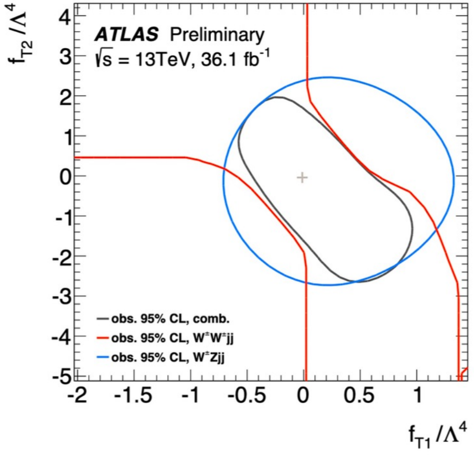
1 and 2D limits limits on D-8 operators in aQGC, experimental systematic uncertainty correlations included in combination

Unitarization: clipping method





No unitarization

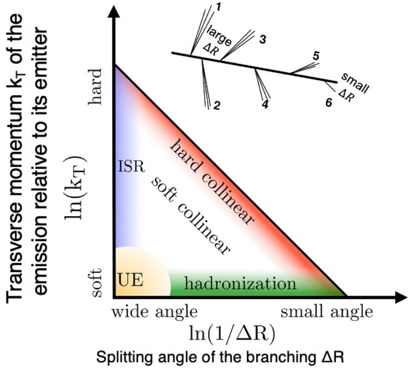


Measurement of the primary Lund jet plane density

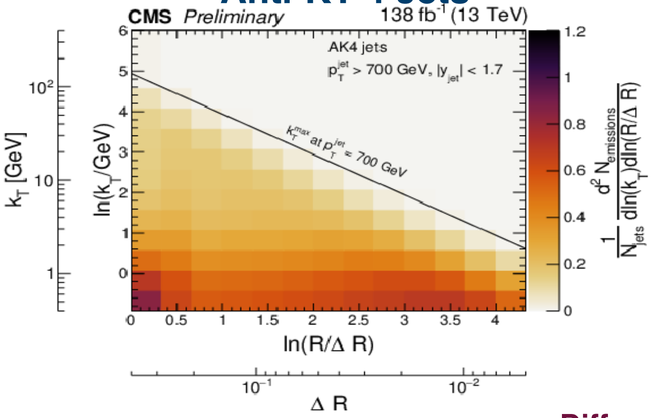
CMS PAS SMP-22-007 $\sqrt{s}$=13 TeV

Lund Jet Plane: representing QCD radiation in parton shower/internal structure of jets

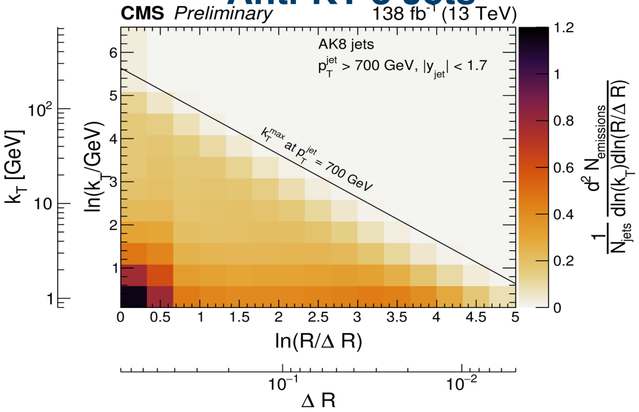
Representation of the phase space of 1 → 2 partonic splittings inside jets



Anti-KT 4 Jets

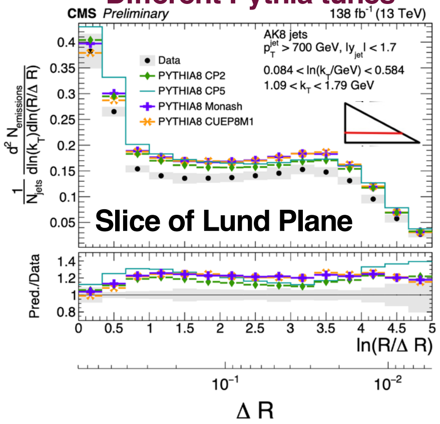


Anti-KT 8 Jets

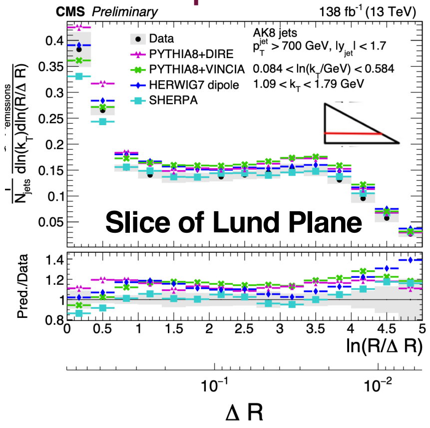


Measurement can be used as an input to improve the description from event generators and for future developments of parton showers with corrections beyond leading-logarithmic accuracy

Different Pythia tunes



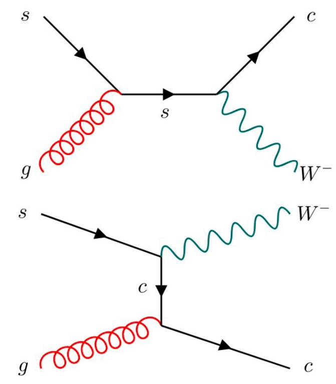
Different parton showers



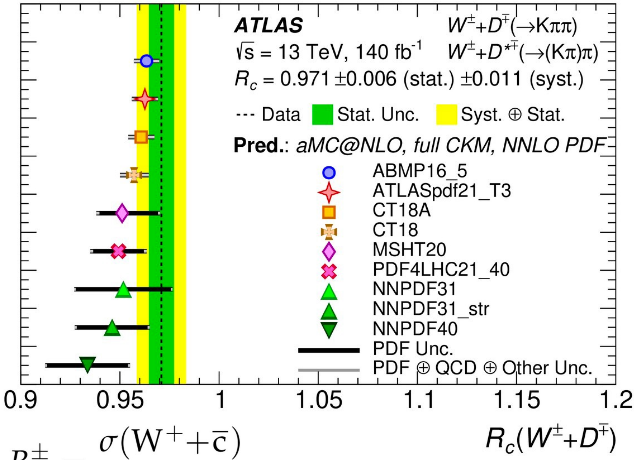
Similar studies from ATLAS published:
Phys. Rev. Lett. 124, 222002

ATLAS: STDM-2019-22
CMS: SMP-21-005

W+c Measurement

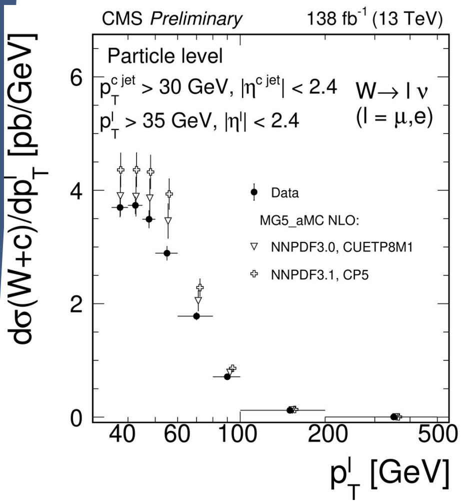


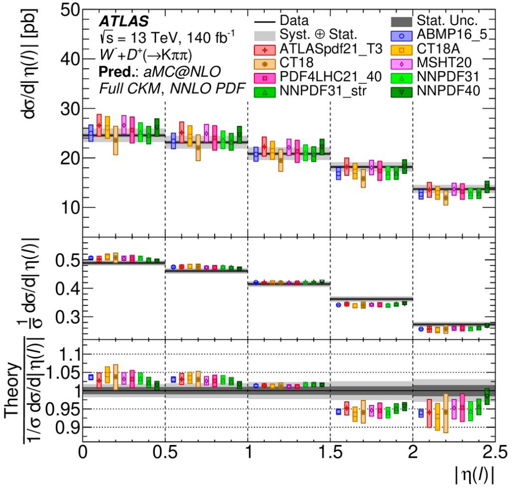
- *Constraints s-quark component of PDF* ➔ W+c major background in some measurements and searches at the LHC like *VH→cc searches*
- Precise measurements of W+c production used to verify the theoretical calculation and its modelling in the currently available Monte Carlo (MC) event generators.
- *Signal* ($W^+ + \bar{c}$ or $W^- + c$): W boson and charm quark always have opposite-sign electric charges
- *Background* (like heavy-flavor pair production or b-hadron production from ttbar events): equal rates for the production of leptons and $D^{(*)}$ with opposite-sign (OS) or same-sign (SS) charges
- signal obtained as the difference of the numbers of OS and SS candidates, and extrapolating the background estimate from SS candidates
- *Measurements suggest s-sbar asymmetry is small in the probed x,Q^2 region*



$$R_c^{\pm} = \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)}$$

Unfolded differential results





CMS $R^{\pm}_c$=0.950 ± 0.005 (stat) ± 0.010 (syst)
ATLAS $R^{\pm}_c$= 0.971±0.006(stat.)±0.011(syst.)