Overview of public Standard Model measurements

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on behalf of the ATLAS SM group

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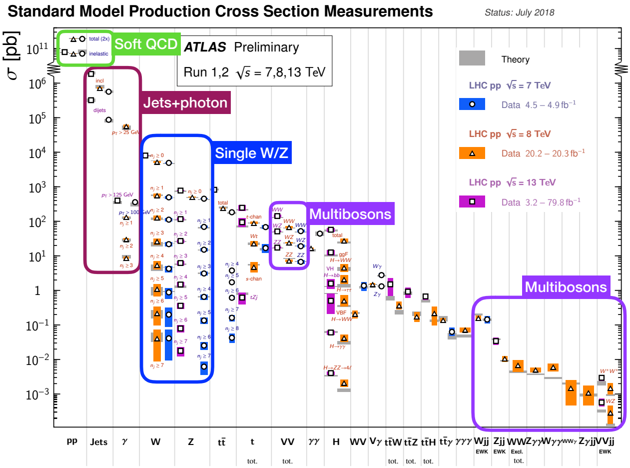
Introduction



Test Standard Model on wide phase-space range.

The results give an input for

- Measurements of SM **EWK parameters**
- **EFT** constraints
- **PDF** constraints
- Test of **pQCD**
- Probing **non-pQCD**

Lots of interplay between applications of various measurements.

All ATLAS SM public results: link

Measurements of electroweak parameters

Effective leptonic weak mixing angle

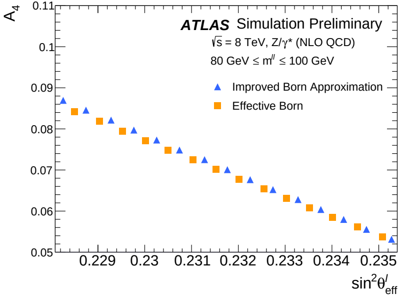
Drell-Yan cross-section $q\bar{q} \to Z/\gamma^* \to \ell\ell$ is expanded as a sum of 9 harmonic polynomials:

$$\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}} \Big\{(1+\cos^2\theta) + \frac{1}{2} A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\Big\}.$$

A_4 (and A_3) sensitive to weak mixing angle

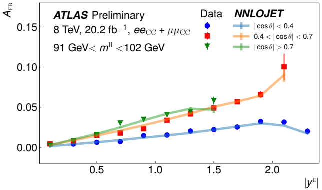
The angular coefficients A_{0-7} are extracted from the data by fitting templates of the polynomial terms.

- Measurement in 3 channels: central-central ee and $\mu\mu$, central-forward ee, binned in mass and rapidity
  → **reduces** the dominant source of systematics arising from PDFs
- Extract $\sin^2\theta^{\ell}_{\text{eff}}$ by parametrising A_4 in likelihood via a linear interpolation model from A_4 vs $\sin^2\theta^{\ell}_{\text{eff}}$ predictions.



Predicted variation of A_4 as a function of $\sin^2\theta^{\ell}_{\text{eff}}$

→ *Cross-check* of the $\sin^2\theta^{\ell}_{\text{eff}}$ extraction is performed with A_{FB} measurement from triple-differential DY CS



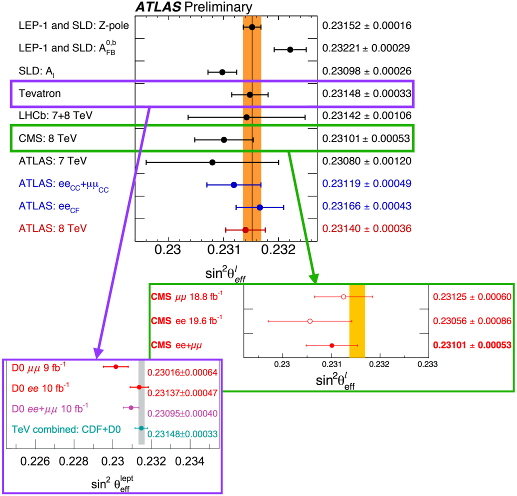
Effective leptonic weak mixing angle

$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23140 \pm 0.00021(\text{stat.}) \pm 0.00024(\text{PDF}) \pm 0.00016(\text{syst.})$$

$\times 10^{-5}$

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
	Uncertainties in measurements				
PDF (meas.)	8	9	7	6	4
p_T^Z modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

- Measurement uncertainty 36×10^{-5}
- Central-forward is the most precise channel, 1.5M events, (13.5 CC ee+$\mu\mu$)

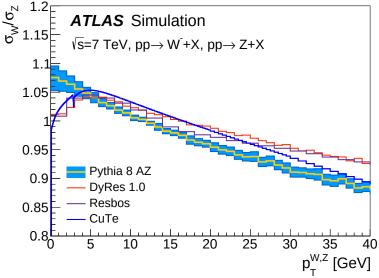


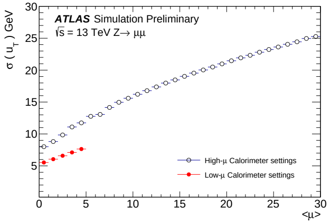
W mass measurement and prospects for p_T^W

Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

stat. = 6.8 MeV exp. syst = 10.6 MeV mod. syst =13.6 MeV

m_W = 80370 +- 19 MeV



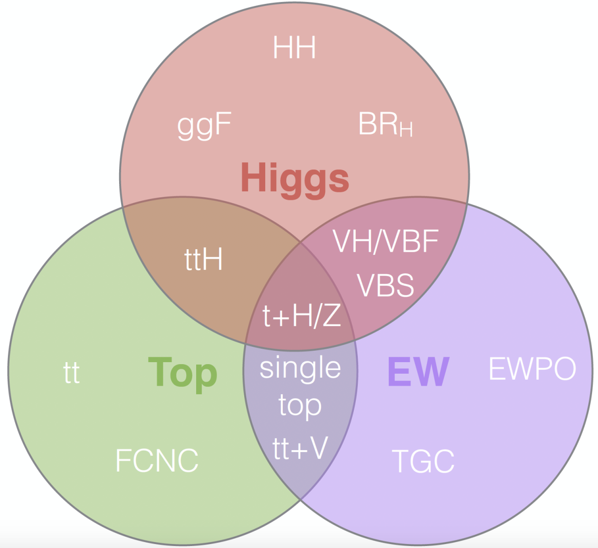


- An issue in modeling of the W/Z p_T was observed in m_W measurement: only (N)LL parton shower predictions are in agreement with the data ($u_{||}^{\ell}$, p_T^Z), all resummed calculations *fail* to describe the observed distributions.

- Goal: a measurement of p_T^W with 5 GeV bins to have **direct probe** of the W/Z p_T ratio (target @ 1% unc.)
  → need recoil resolution of the same order.
- Pileup degrades the resolution of the recoil
  → in low-μ environment is a great opportunity for this measurement.

Measurements relevant for EFT

EFT: Key players



Status of SM measurements

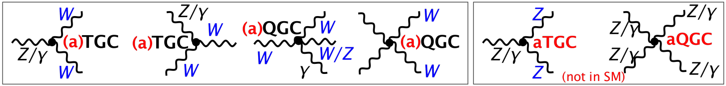
Inclusive diboson channels are extensively studied - variety of results are available.

Rare processes:

VBS	$W^{\pm}W^{\pm}jj$	$WZjj$	$WW/WZjj$	$\gamma\gamma \to W^{+}W^{-}$	$Z\gamma jj$	$ZZjj$
VBF	Zjj	Wjj				
Tribosons	$Z\gamma\gamma$	$W\gamma\gamma$	$WV\gamma$	$\gamma\gamma\gamma$	WWW	

- A fruitful start of Run2 data analyses for Vector Boson Scattering (**VBS**): observations of 2 processes.
- Vector Boson Fusion **(VBF)**: significance well above 5σ.
- **Tribosons**: No 13 TeV results yet. Run1 achievements: one observation and one evidence.
- Differential results are available for inclusive dibosons, VBS, VBS and triboson measurements.

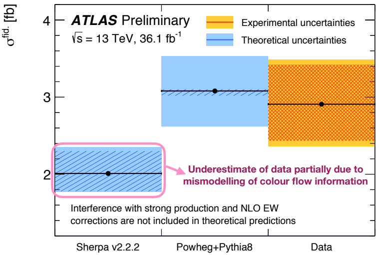
Constraints on
anomalous triple gauge couplings (aTGCs): dibosons and VBF
anomalous quartic gauge couplings (aQGCs): VBS and tribosons



Latest VBS results

[ATLAS-CONF-2018-030](#)
[ATLAS-CONF-2018-033](#)

$W^{\pm}W^{\pm}jj$-EW: observed significance 6.9σ (4.6σ exp.)



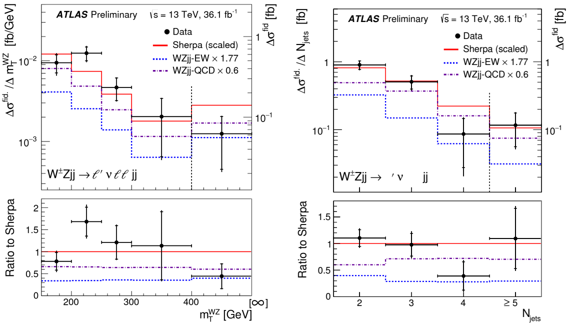
Measured fiducial cross-section of EWK production:

$\sigma^{\text{fid}}_{\text{Data}} = 2.95 \pm 0.49(\text{stat.}) \pm 0.23(\text{syst.})$ fb

→ *information needed for EFT interpretation to be published*

$WZjj$-EW: observed significance 5.6σ (3.3σ exp.)

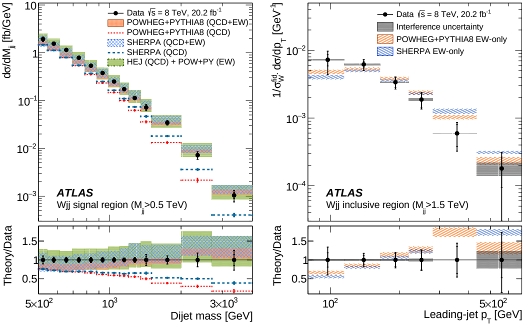
First observation of WZjj-EW!



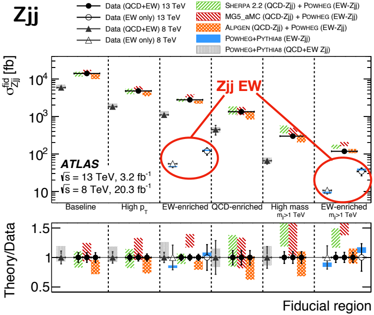
- Measured EWK cross-section in fiducial PS
- First differential results for EWK+QCD production: variables **sensitive to aQGCs**: m_T^{WZ}, $\sum p_T^{\ell}$, $\Delta\phi(W,Z)$ and variables **sensitive to pQCD** ($N_{\text{jets}}(p_T > 40)$ GeV, $N^{\text{gap}}_{\text{jets}}(p_T > 25)$ GeV, m_{jj}, $\Delta\phi(j_1, j_2)$, $\Delta y(j_1, j_2)$)

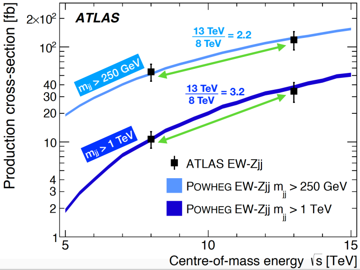
Status of VBF results

Wjj



Zjj





- Measurements in several fiducial regions.
- Differential cross sections of EW and EW+QCD processes: variables distinguishing QCD and EW production, and observables sensitive to aTGCs.

Missing NLO electroweak corrections!

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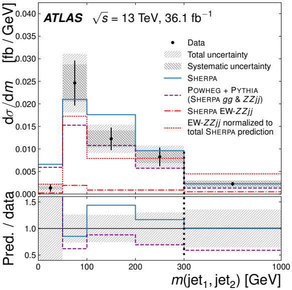
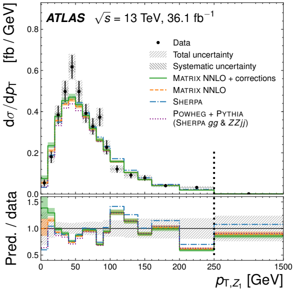
- Most of the inclusive diboson channels provide results for **differential CSs**.
- Include distributions sensitive to aTGCs.

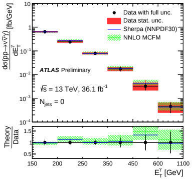
$ZZ \to 4\ell$ results:

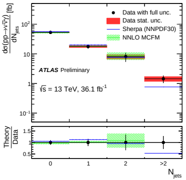
- $ZZ \to 4\ell$ CS is measured as a function of 20 observables.
  $\to$ *Most of them for the first time!*
- m(jet1,jet2) is particularly sensitive to the EWK-ZZjj process
- p_T of leading Z boson is sensitive for aTGC searches.

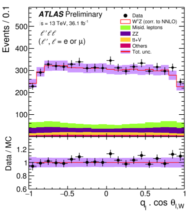


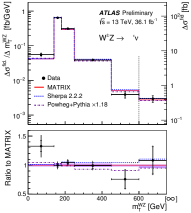


More differential diboson results:







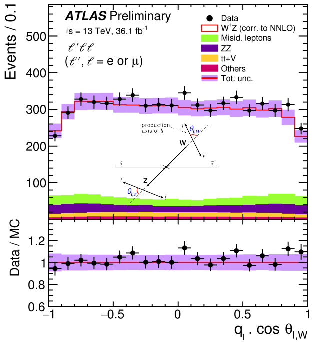


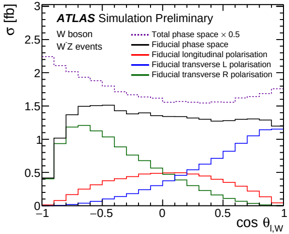
W and Z polarisation in diboson events

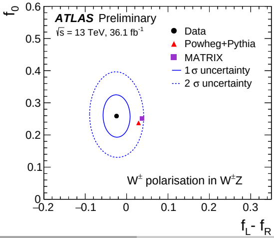
- Measurement of $W_0 Z$ and WZ_0 production in inclusive diboson events.
- Template fit to angular distribution in data.
- $f_0^W = 0.26 \pm 0.06$, $f_0^Z = 0.24 \pm 0.04$
- Observed significance for longitudinal polarisation in W bosons: 4.2σ (3.8σ exp), measurement of longitudinal polarisation in Z bosons.
- Dominated by statistical uncertainties.

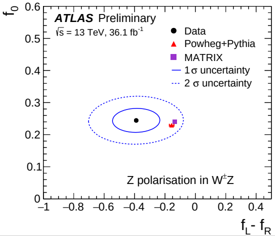
→ Future measurements: $W_0 Z_0$ and $W_0 Z_0 \to W_0 Z_0$ production

→ A promising avenue for new physics searches!





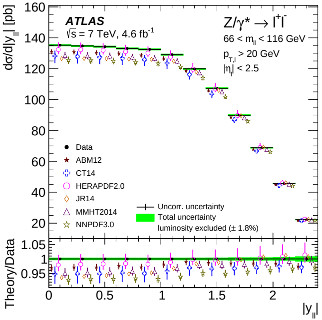


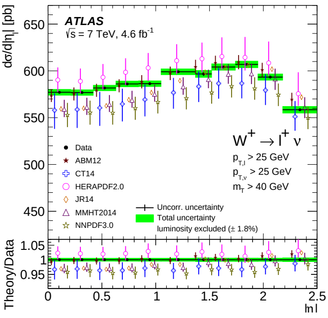


PDF-sensitive measurements/ Testing pQCD

ATLAS measurements sensitive to PDFs

Measurement	PDF sensitivity
Inclusive W, Z and asymmetries	Quark flavor separation (u, d, s)
High mass Drell-Yan	sea quarks at high-x, photon PDFs
Low mass Drell-Yan	low-x, resummation effects
W, Z, W/Z + jets	Medium x gluon
W with charm quarks	Direct sensitivity to s-quarks
$\gamma/Z + c, b$ production	c, b quarks, intrinsic charm
p_T^Z	Gluon sensitivity
$t\bar{t}$ production (total, differential)	Gluon (α_s)
Single top production	Gluon and b quark
Inclusive jet, dijet, trijets	High x quarks and gluon (α_s)
Isolated photons	Medium and high x gluon





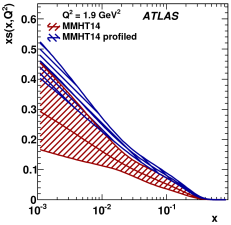
Precision:
Z: 0.32%, W^+: 0.6%, W^-: 0.5%

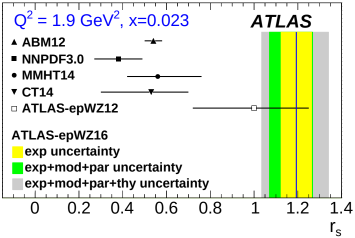
→ Better than NNLO QCD + NLO EW theory

- **Differential measurements** are nearly as precise as integrated CS
- A sensitive test of lepton universality
- Competitive measurement of $|V_{cs}|$ of the CKM matrix

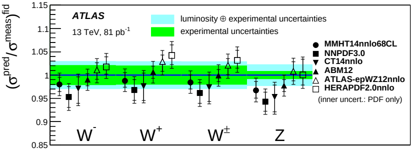
- ATLAS-epWZ16 is provided
- Light quark pdf constraints
- Confirmation of unsuppressed strange-quark density

$$r_s = \frac{s+\bar{s}}{2\bar{d}} = \mathbf{1.19} \pm 0.07(\text{exp}) \pm$$
$$\pm 0.02(\text{mod})^{+0.02}_{-0.01}(\text{par})$$

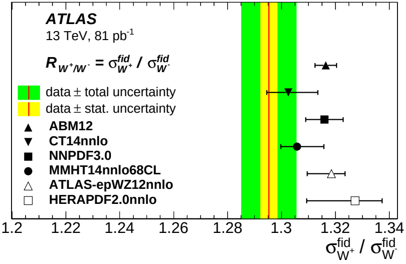




More W/Z results



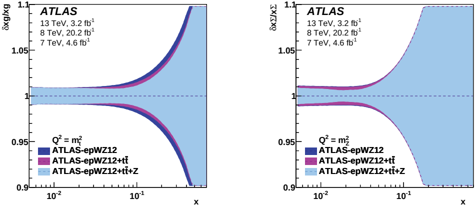
Cross section ratio measurements: partial cancellation of systematics

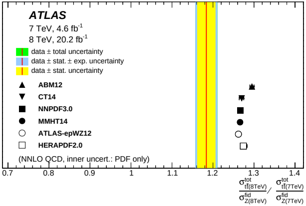


→ sensitive to u_V and d_V at low x

$t\bar{t}/Z$ ratios @ 7, 8, and 13 TeV:

- cancellation of luminosity and some systematic unc.
- Z: constraint of light-quark-sea and gluon densities
- $t\bar{t}$ contributes to gluon density constraint → significant power to constraint gluon density at $x \sim 0.1$ and total light-quark sea at $x < 0.02$

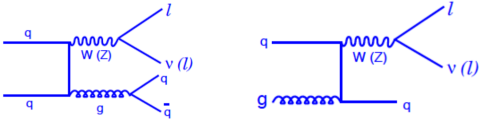




Double ratio: sensitive tests of the SM predictions
→ *tension* with observed predictions is 3-4σ

V+jets measurements

- V+jets production is dominated by strong interactions:
  - Precision test of pQCD: test state-of-the-art pQCD calculations
  - Impact on PDFs understanding
  - Background to SM measurements, Higgs and New Physics: important validation of the Matrix Element+Parton Shower MCs
  - Input for MC tuning



W/Z+jets

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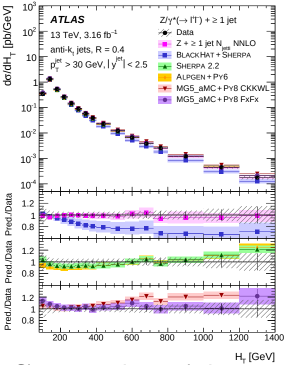
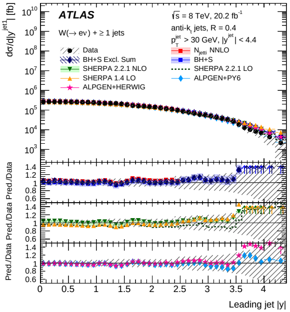
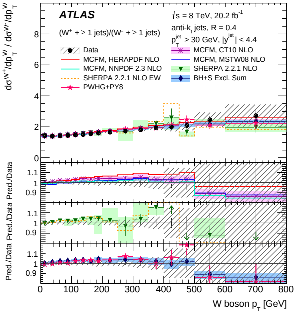
Z+jets @ 13 TeV



W+jets @ 8 TeV



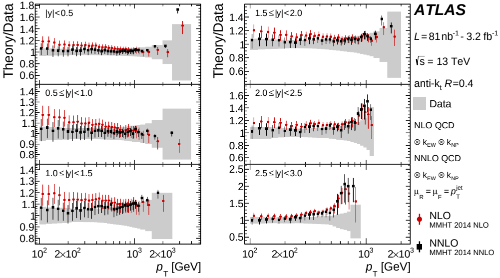


→ Clean experimental signature.
→ $H_T = \sum_{\text{leptons, jets}} |p_T|$: inclusive quantity commonly used to set the scale, discriminant in BSM searches.
→ Important test of recent NNLO calculations.

→ Differential CSs for $W+\geq 1j$: *sensitivity* to H/O corrections and to PDFs
→ Differential CSs for $W+\geq 2j$: *sensitivity* to hard parton radiation at large angles, and ME/PS merging schemes

→ W^+/W^- asymmetry, **high precision**: many experimental and theoretical uncertainties cancel out.
→ Valuable input for u-, d-, and gluon PDFs.

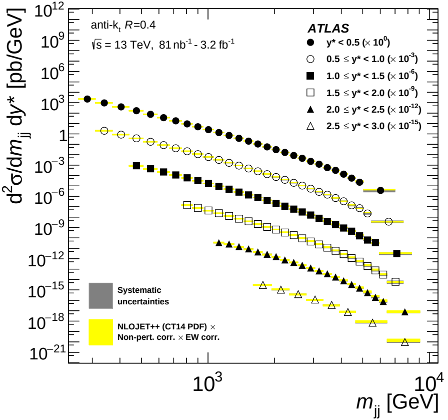
- **Inclusive jet** CS is measured 2d (p_T^{jet}, $|y^{\text{jet}}|$)
- Measurement up to $p_T < 3.5$ TeV.



χ^2/dof all $\lvert y \rvert$ bins	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
p_T^{max}	419/177	431/177	404/177	432/177	475/177
p_T^{jet}	399/177	405/177	384/177	428/177	455/177

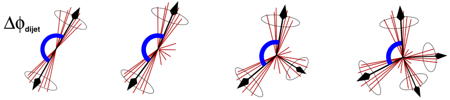
- Tension between data and NLO theory in a global fit using all p_T and $|y|$ bins. Already seen in previous 8 TeV data
  $\rightarrow$ *sensitive to assumptions on correlations for two-point systematics*
- First comparison with NNLO: improved description for $\mu_R = \mu_F = p_T^{jet}$

- Double-differential **dijet** CS (m_{jj}, y^*)
  $y^* = |y_1 - y_2|/2$
- Measurement up to $m_{jj} < 9$ TeV.

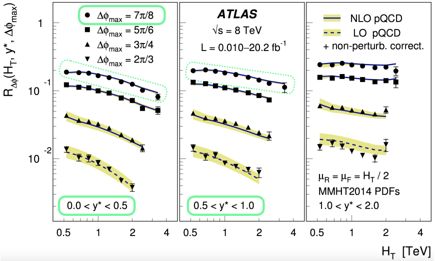


- NLO pQCD predictions and data agree within uncertainties.

Dijet azimutal decorrelation



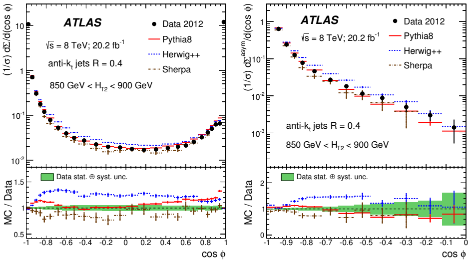
Measure quantity $R_{\Delta\phi}$: fraction of dijet events with $\Delta\phi_{\text{dijet}} < \Delta\phi^{\text{max}}_{\text{dijet}}$ in all dijet events, as a function of H_T: $R_{\Delta\phi}(H_T) \rightarrow \alpha_s(Q = H_T/2)$



- **High precision**, many experimental and theoretical uncertainties cancel.
- Extract α_s using $\Delta\phi^{\text{max}}_{\text{dijet}} = 7\pi/8$ - most reliable pQCD predictions.

Transverse energy-energy correlations (TEEC) - energy-weighted *angular distribution* of jet pairs. An alternative event shape variable for hadron colliders, not affected by soft divergences.

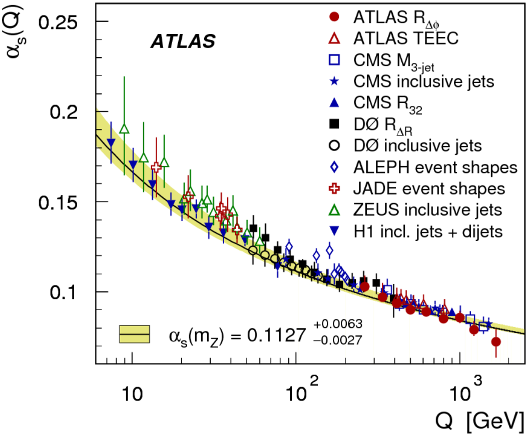
- Shape of TEEC observables (and its asymmetry) depends on α_s and not very sensitive to PDFs



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

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

α_s results



$R_{\Delta\phi}$:

$\alpha_S(m_Z)$	Total uncert.	Statistical	Experimental correlated	Non-perturb. corrections	MMHT2014 uncertainty	PDF set	$\mu_{R,F}$ variation
0.1127	${}^{+6.3}_{-2.7}$	± 0.5	${}^{+1.8}_{-1.7}$	${}^{+0.3}_{-0.1}$	${}^{+0.6}_{-0.6}$	${}^{+2.9}_{-0.0}$	${}^{+5.2}_{-1.9}$

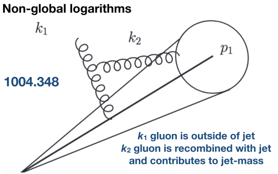
TEEC and ATEEC:

$$\alpha_s(m_Z) = 0.1162 \pm 0.0011\ (\text{exp.})\ {}^{+0.0076}_{-0.0061}\ (\text{scale}) \pm 0.0018\ (\text{PDF}) \pm 0.0003\ (\text{NP})$$

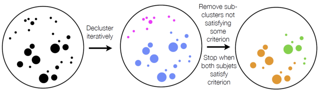
$$\alpha_s(m_Z) = 0.1196 \pm 0.0013\ (\text{exp.})\ {}^{+0.0061}_{-0.0013}\ (\text{scale}) \pm 0.0017\ (\text{PDF}) \pm 0.0004\ (\text{NP})$$

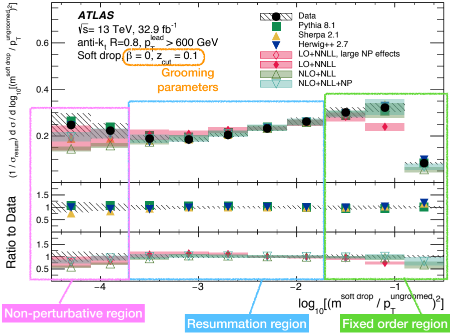
→ Precision of α_s measurements is mainly limited by the scale dependence of NLO pQCD predictions

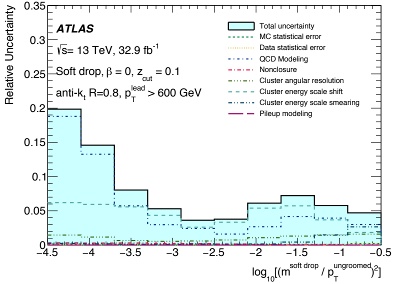
- Jet mass is used for constructing taggers of boosted Z/W/H hadronic decays: crucial for ATLAS search program.
- Presence of non-global logarithms prevented from calculations beyond LL.
- Soft-drop is a jet grooming procedure to remove soft and wide angle radiation from a jet. Formally insensitive to non-global logarithms.
- Recent soft-drop mass calculations at LO + NNLL and NLO + NLL



Measurement of dimensionless mass $\rho^2 = m^{\text{soft drop}} / p_T^{\text{ungroomed}}$ in dijet events; unfolded to particle-level

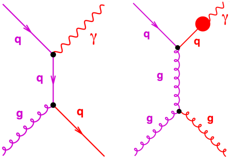




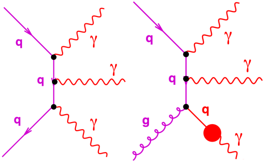


Testing pQCD with photons

- Measurements of the production of high p_T prompt photons in association with jets in hadron colliders provide
  - tests of pQCD predictions in a *cleaner reaction* than jet production
  - constraints on the proton PDFs (*flavour content* when jets are tagged)
  - input to understand the background to Higgs production and BSM searches
    $\rightarrow$ validation of Monte Carlo models



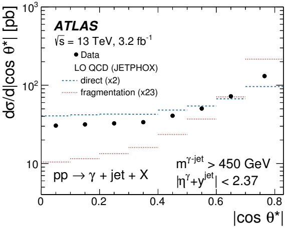
isolated single-photon plus (HF) jet



isolated triphoton production

Testing pQCD with photons

photon+jet @ 13 TeV
Phys. Lett. B 780 (2018) 578

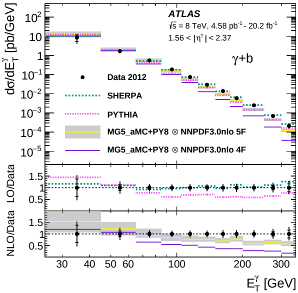


→ **gluon exchange** $\propto (1 - |\cos\theta^*|)^{-2}$

→ **quark exchange** $\propto (1 - |\cos\theta^*|)^{-1}$

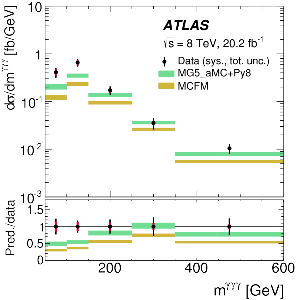
- Test of QCD dynamics with angular correlations between the γ and the jet → shape of data much closer to direct-photon than to fragmentation processes. Consistent with dominance of t-channel quark exchange.

photon+HF @ 8 TeV
Phys. Lett. B 776 (2018) 295



- Probe of HF content of the proton → mismodeling of high E_T^{γ}: increase of gluon-splitting contribution (appears only at tree level in the 5F NLO predictions) - *higher order calculations are needed.*

triphoton @ 8 TeV
Phys. Lett. B 781 (2018) 55



- Test of pQCD with rare SM processes → improved modelling of triphoton production is needed: MCFM at NLO underestimates data by factor of 2. **No NNLO** calculations are available.

Soft QCD

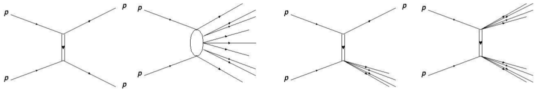
Measurement of inelastic pp cross section

Phys. Rev. Lett. 117 (2016) 182002

- Inelastic cross section is a fundamental quantity that cannot be calculated with perturbative QCD
- Observed rise of σ_{inel} with $\sqrt{s}$
  → energy dependence cannot be predicted directly by QCD
  → need to be constrained by measurements.
- $\sigma_{\text{inel}}^{\text{fid.}}$ is measured using events tagged in Minimum Bias counters $2.07 < |\eta| < 3.86$ for $\xi = M_x^2/s > 10^{-6}$.
- $f_D = (\sigma_{SD} + \sigma_{DD})/\sigma_{\text{inel}}$ is poorly known and differs between models.
- The fraction of single-sided events, R_{SS}, is related to f_D and used to tune f_D in models.

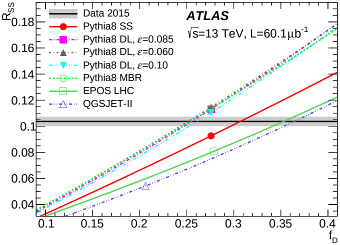
$$\sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{inelastic}}$$

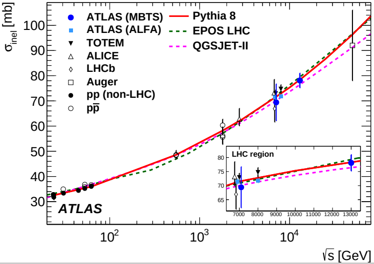
$$\sigma_{\text{inelastic}} = \sigma_{\text{non-diffractive}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}}$$



- Extrapolation to the full PS using 7 TeV measurements to minimise model dependence.

13 TeV: $\sigma_{\text{inel}} = 78.1 \pm 0.6\ (\text{exp.}) \pm 1.3\ (\text{lum.}) \pm 2.6\ (\text{extrap.})$ mb.





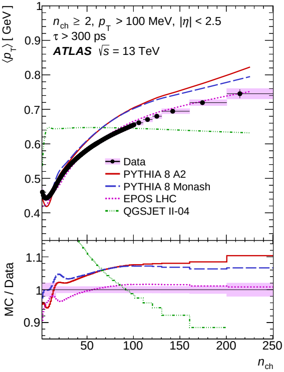
Minimum bias and underlying event

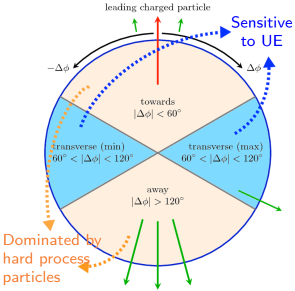
Minimum bias: any inelastic events

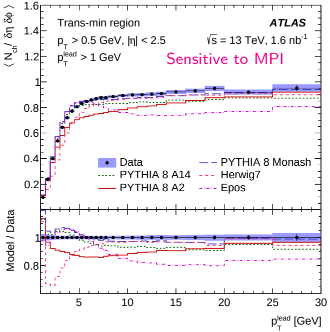
- Measurement of distributions of charged particles with $p_T > 100$ MeV, $|\eta| < 2.5$

Underlying event: soft processes accompanying hard interactions (ISR, FSR, MPI, CR, BR, ...)

- Distributions of charged particles with $p_T > 500$ MeV in events with at least one charged particle with $p_T > 1$ GeV







Level of MC variation >> uncertainty of the measurement! systematic mismodeling is observed
→ An important input for MC tuning.
→ Can improve precision of m_W measurement.

Summary

- Rich physics program; probing all from soft to hard interactions.
- Outstanding precision of EW parameters, many new ideas are still to be implements.
- Start testing rare SM processes - promising for new physics searches.
- Precision of many measurements challenges pQCD and non-pQCD predictions.
- Improvements in precision of many measurements **require theory input**.

- Most of the measurements are implemented in RIVET, data available at HEPDATA.