Jet and Photon Measurements using the ATLAS detector

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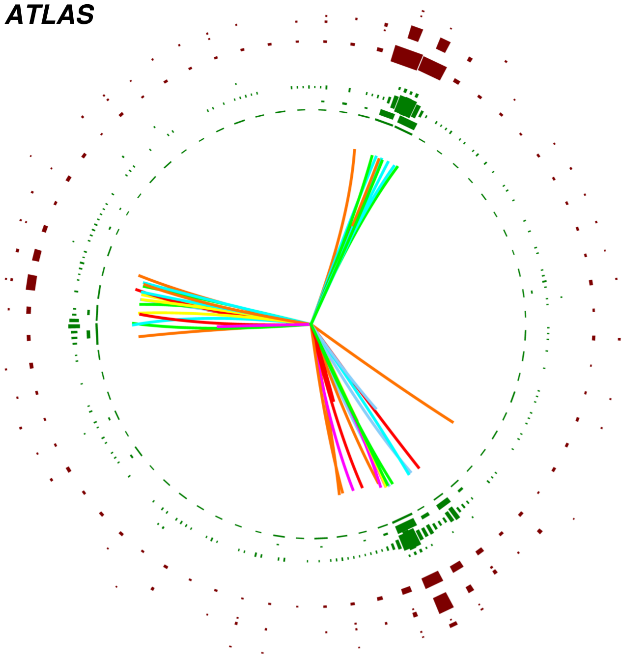
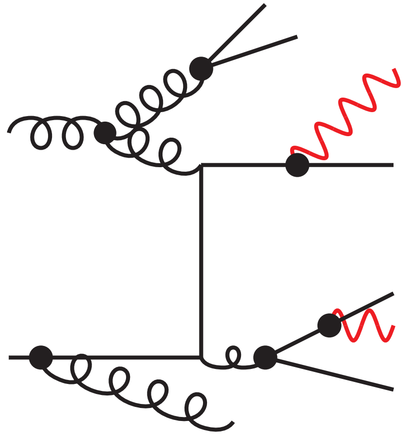
ATLAS EXPERIMENT

Introduction

- Jet and photon signatures provide testing ground for QCD
  - Multi-jet events ubiquitous in hadron-hadron collisions
  - all LHC measurements benefit from good knowledge of these processes



- three recent ATLAS measurements with the full LHC run-2 139 fb^{-1} @ 13 TeV:
  - $\alpha_s(m_z)$ from Transverse Energy-Energy Correlations (ATLAS-CONF-2020-025)
  - Hadronic event shapes at high H_T (JHEP 01 (2021) 188)
  - Diphoton production (ATLAS-CONF-2020-024)



Transverse Energy Energy Correlation (TEEC) Measurement

- Measured in events with $H_{T2} = p_{T,1} + p_{T,2} > 1$ TeV
- Normalised quantity averaged over all N_{evt} multi-jet events in the sample

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\Phi} = \frac{1}{N_{evt}}\sum_{i=1}^{N_{evt}}\frac{1}{\Delta\cos\Phi}\sum_{a,b\ \text{pairs in}\ \Delta\Phi}^{N_{jets}}\frac{2E^i_{Ta}E^i_{Tb}}{(E^i_T)^2}$$

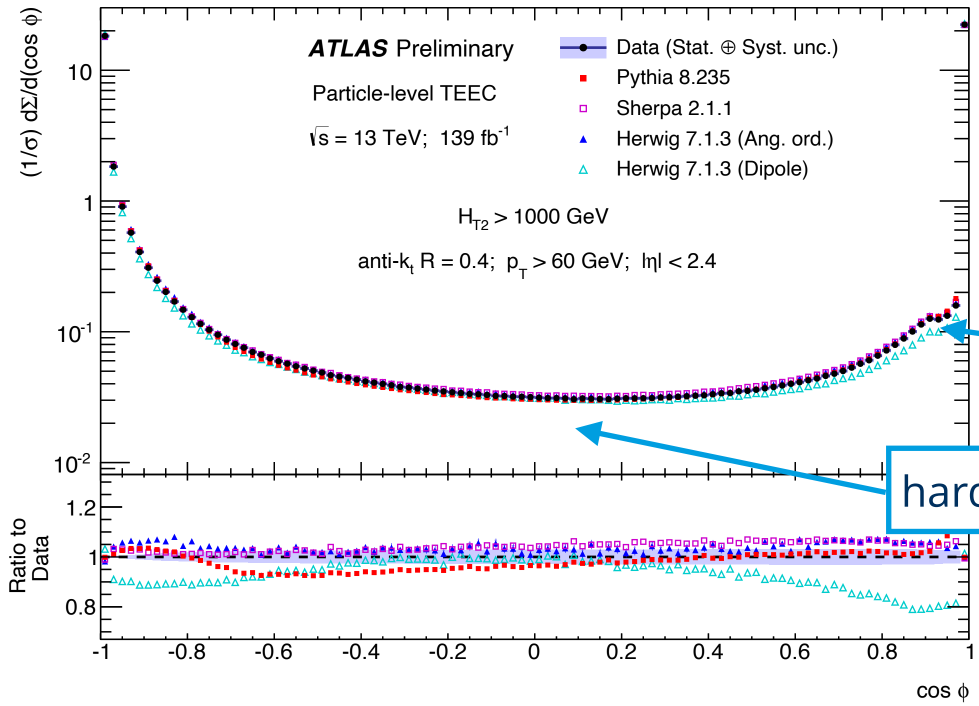
Asymmetric part is measured in addition (reduced uncertainties)

$$\frac{d\Sigma^{asym}}{d\cos\Phi} = \left.\frac{d\Sigma}{d\cos\Phi}\right|_{\Phi} - \left.\frac{d\Sigma}{d\cos\Phi}\right|_{\pi-\Phi}$$

- NLO pQCD calculations of observable able to describe the data
  - enables precision measurement of α_s

back-to-back

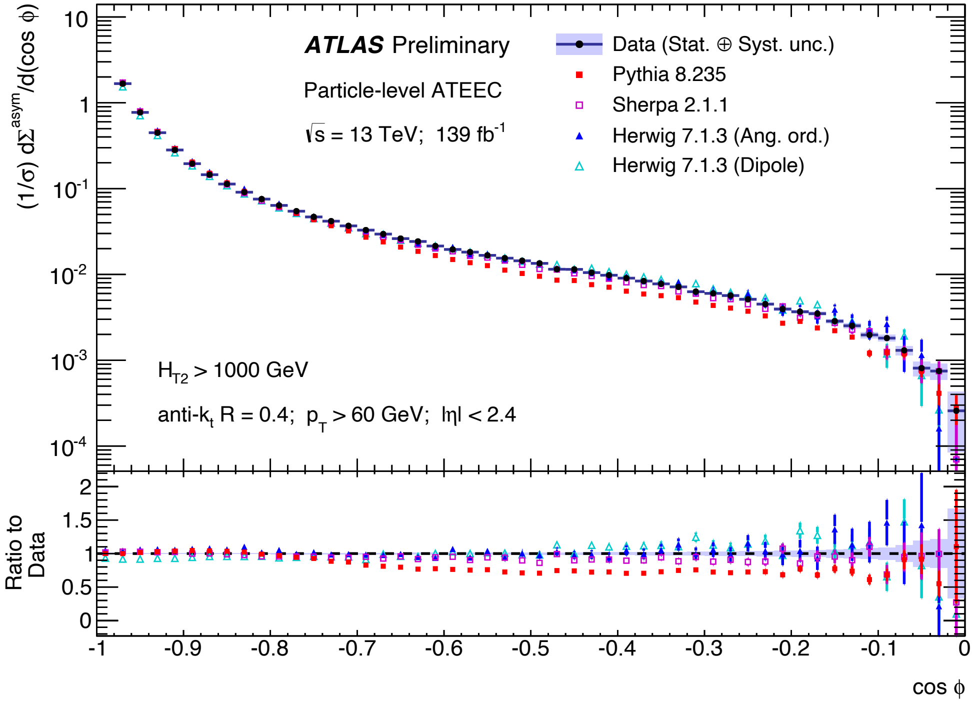
self-correlation



jet-radius kink

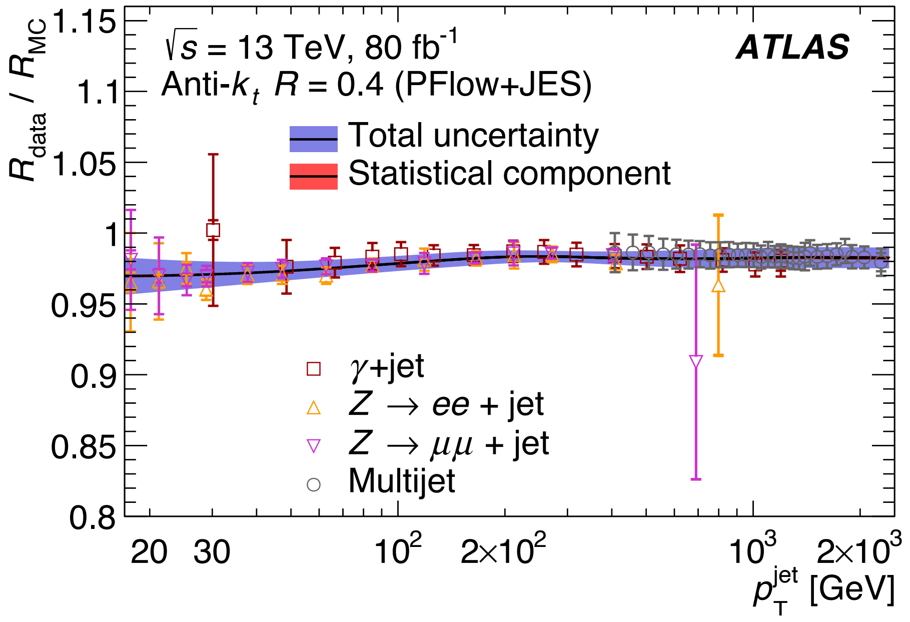
hard wide-angle

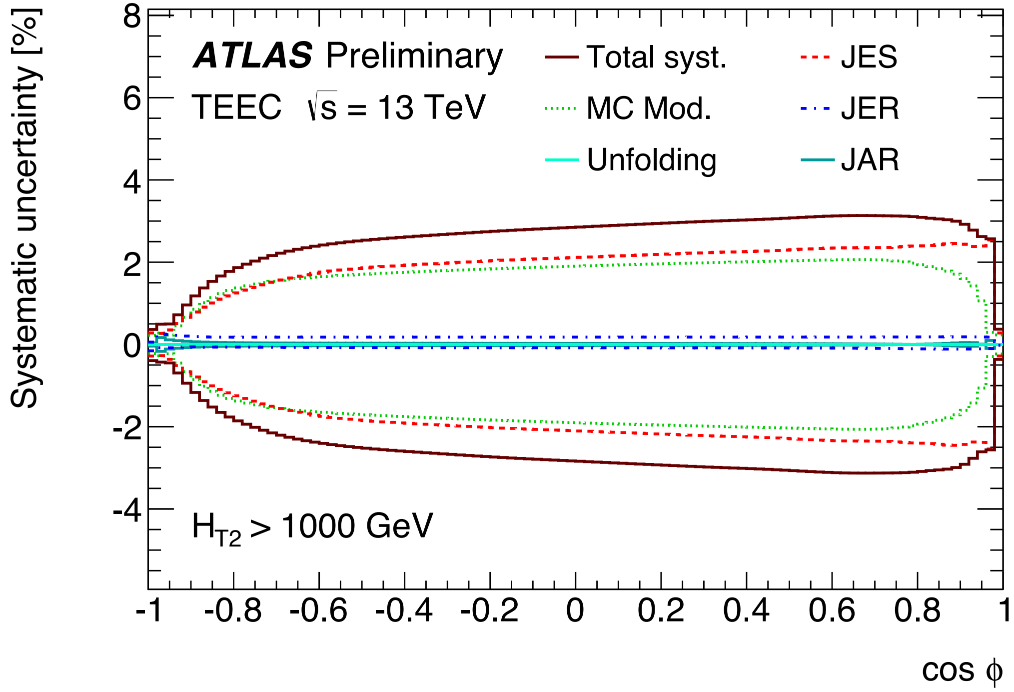
hard wide-angle

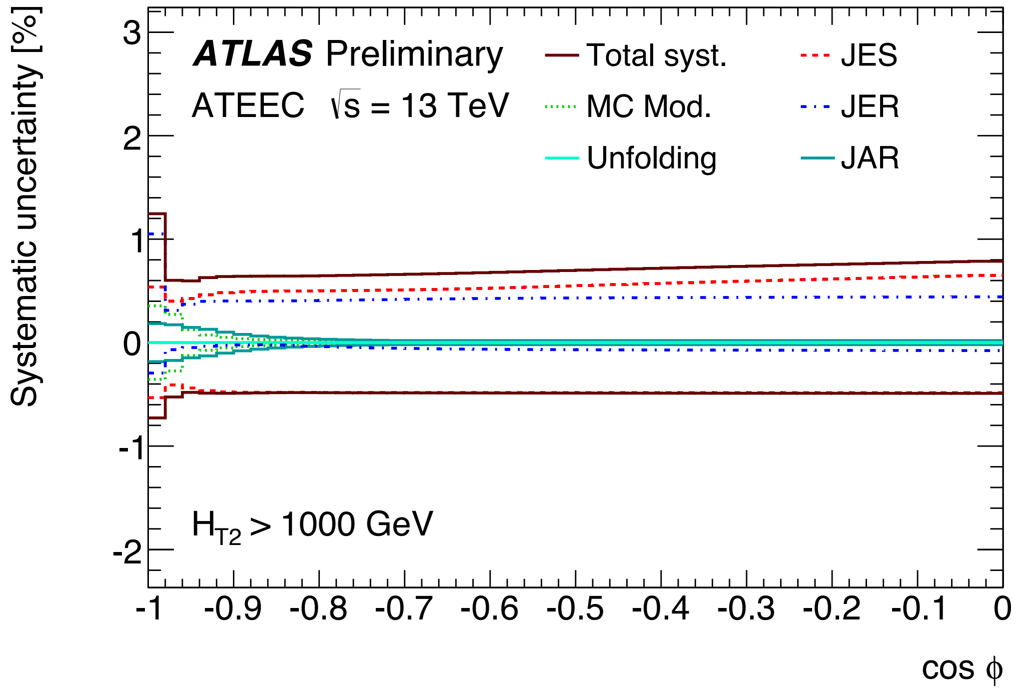


(A)TEEC Experimental Uncertainties

- data unfolded to particle level using iterative bayesian unfolding
- percent level experimental uncertainties
- profit from high precision of Jet Energy Scale and Resolution measurements (CERN-EP-2020-083)
- uncertainties on e.g. MC modeling partially cancel for Asymmetric TEEC observable





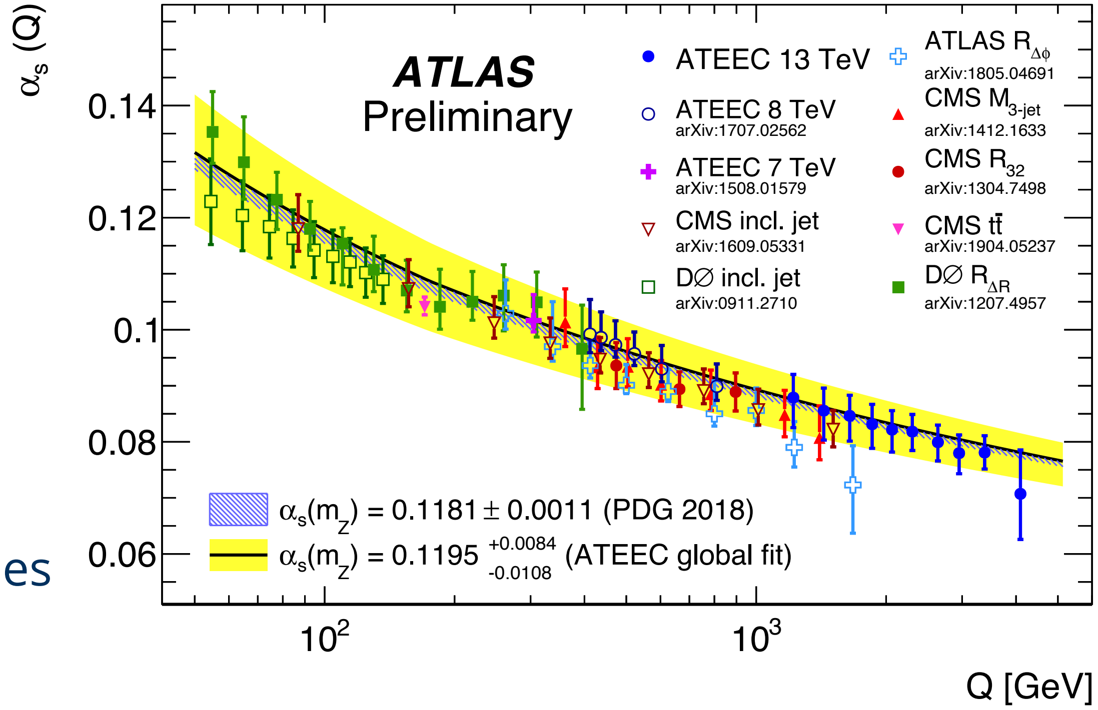


Determination of α_s with TEEC

- unfolded data are compared to NLO pQCD calculations
- predictions are fit to data extracting α_s in different bins of $H_{T2} = p_{T,1} + p_{T,2}$
  - $\alpha_s(Q)$ measured up to Q > 3 TeV
- compatibility of $\alpha_s(Q)$ with expectation from renormalisation group equations can constrain BSM scenarios (Nucl.Phys.B 936 (2018))
  - all bins yield compatible values of $\alpha_s(m_Z)$
- inclusive fit to all bins:

$$\alpha_s(m_Z) = 0.1196 \pm 0.0004 \text{ (exp.) } {}^{+0.0072}_{-0.0105} \text{ (theo.)}$$

- compatible with $\alpha_s(m_Z)$ world average from from PDG
  - theory uncertainties limiting precision
  - NNLO calculations are needed to reduce scale uncertainties

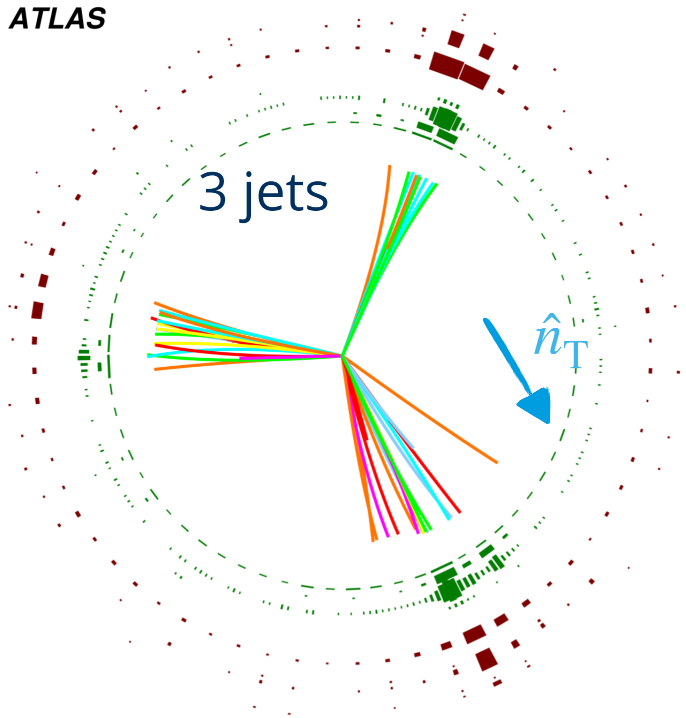


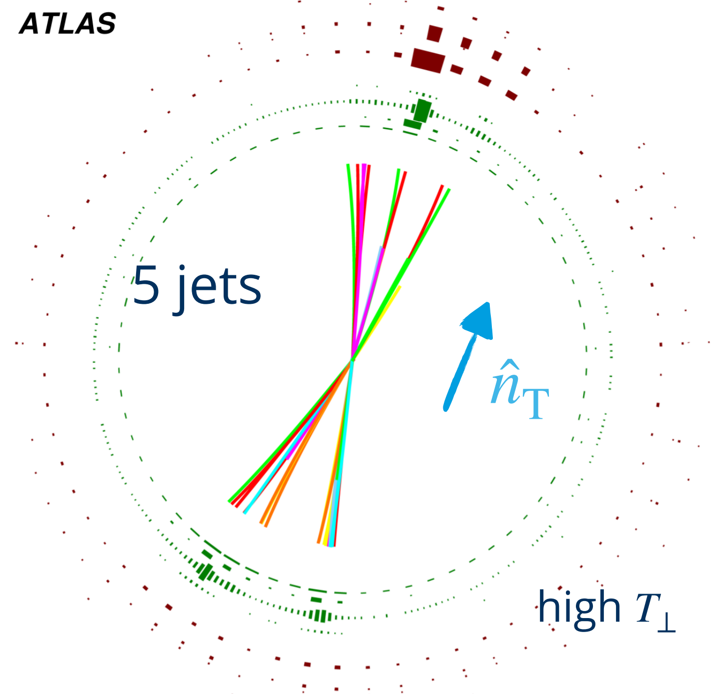
Event shapes at large momentum transfer

- previous ATLAS measurement @ 7 TeV with 35 pb^{-1} in events $H_{T2} = p_{T,1} + p_{T,2} > 500$ GeV (Eur. Phys. J. C (2012) 72: 2211)
- new measurement @ 13 TeV with 139 fb^{-1} in $H_{T2} > 1$ TeV events
  - factor of 4000 more data at higher energies
  - triple differential measurement of 6 event shape variables (event shape $\otimes n_{jet} \otimes H_{T2}$)
  - $n_{jet} = 2,3,4,5$ and ≥ 6, H_{T2} in $[1.0,1.5), [1.5,2.0,), [2.0,2.5]$ TeV
- event shapes quantify (transverse) sphericity, planarity and alignment with thrust axis

thrust axis $\hat{n}_T$ direction maximising $\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|$

Transverse Thrust $T_\perp = \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i |\vec{p}_{T,i}|}$



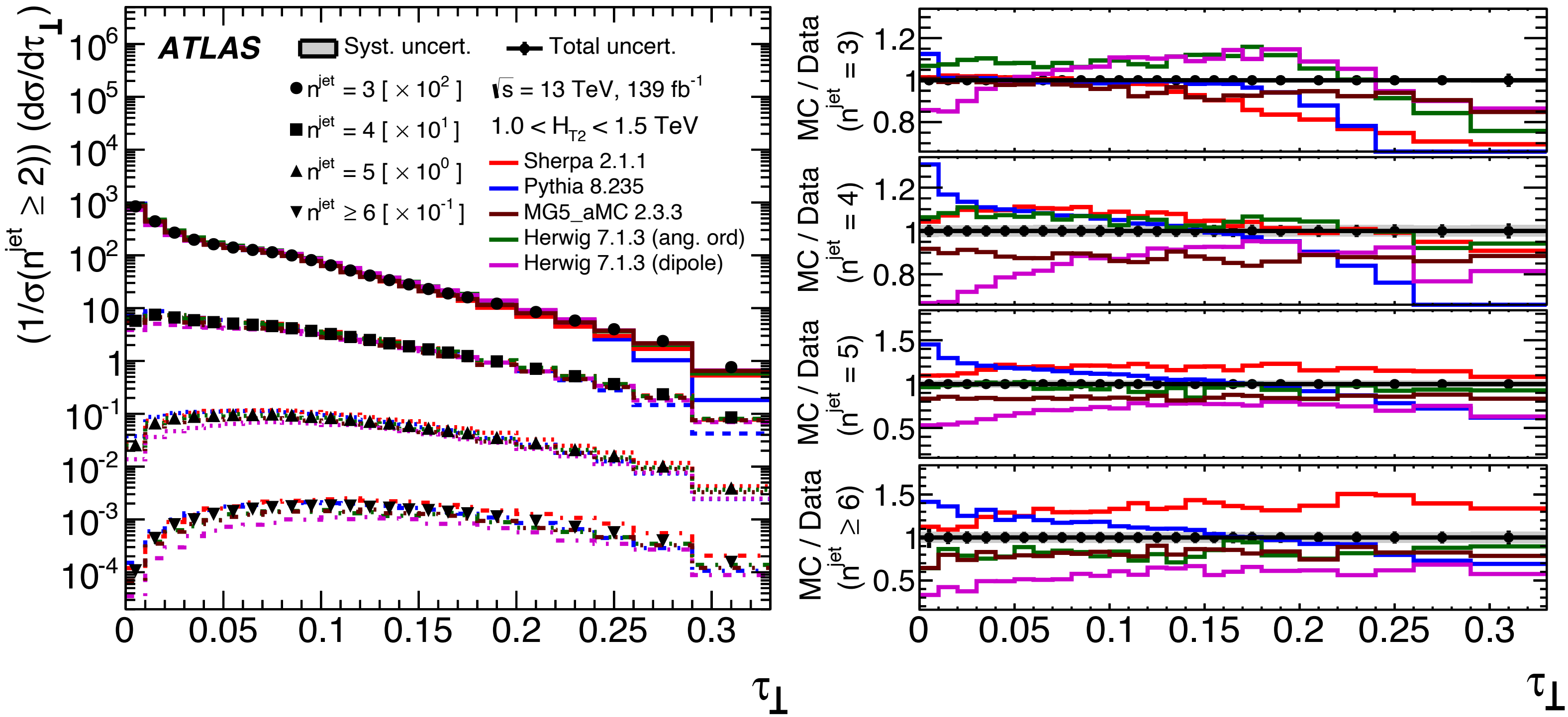


Results of the Event Shape Measurement

- data unfolded using iterative bayesian unfolding correcting efficiencies and resolution effects
- compare cross sections normalised in each H_{T2} bin
- none of the generators able to describe the data well everywhere
  - general underestimation of amount of isotropic events
  - overestimation of back-to-back configurations by Pythia
  - underestimation of back-to-back in HERWIG with Dipole Shower (partially better with Angle-ordered shower)
  - overestimation of high-jet multiplicity by Sherpa
  - MG5_aMC describe shapes at low $\tau_\perp$, but offset as a function of n_{jet}
- all results also available on HEPData (link)

Generator	ME order	FS partons	PDF set	Parton shower	Scales μ_R, μ_F	$\alpha_s(m_Z)$
PYTHIA	LO	2	NNPDF 2.3 LO	p_T-ordered	$(m_{T3} \cdot m_{T4})^{\frac{1}{2}}$	0.140
SHERPA	LO	2,3	CT14 NNLO	CSS (dipole)	$H(s,t,u)$ $[2 \to 2]$ CMW $[2 \to 3]$	0.118
MG5_aMC	LO	2,3,4	NNPDF 3.0 NLO	p_T-ordered	m_T	0.118
HERWIG	NLO	2,3	MMHT2014 NLO	Angle-ordered Dipole	$\max_i \{p_{Ti}\}_{i=1}^{N}$	0.120

$\tau_\perp = 1 - T_\perp$



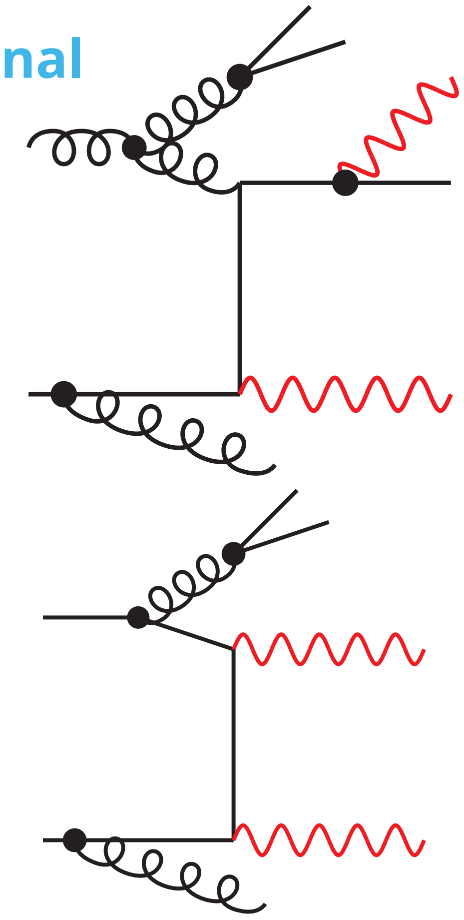
back-to-back → isotropic

Diphoton Measurement

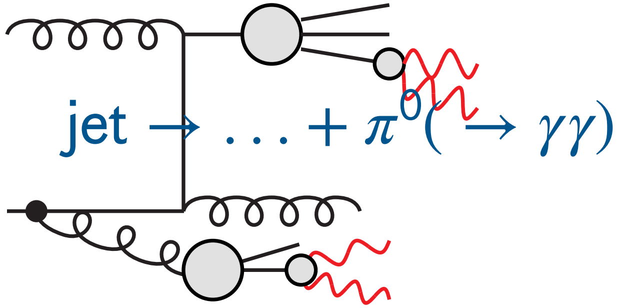
- use photons as precision probes of the QCD process
- measurement of **prompt** + **isolated** photon pair production
  - not from the decay of a hadron ($\pi^0 \to \gamma\gamma$) main background
  - isolated from additional activity
    - necessary experimentally to distinguish from background
    - required for higher order pQCD calculations
- measure differential cross section as a function of several kinematic variables
  - E_{T,γ_1}, E_{T,γ_2}, $m_{\gamma\gamma}$, $p_{T,\gamma\gamma}$, $a_{T,\gamma\gamma}$, ϕ^*_η, $\pi - \Delta\phi_{\gamma\gamma}$, $|\cos\theta^*_\eta|^{(CS)}$

- 139 fb^{-1} @ 13 TeV provide factor ~14 higher statistics inclusively compared to previous 20.2 fb^{-1} @ 8 TeV ATLAS measurement

signal

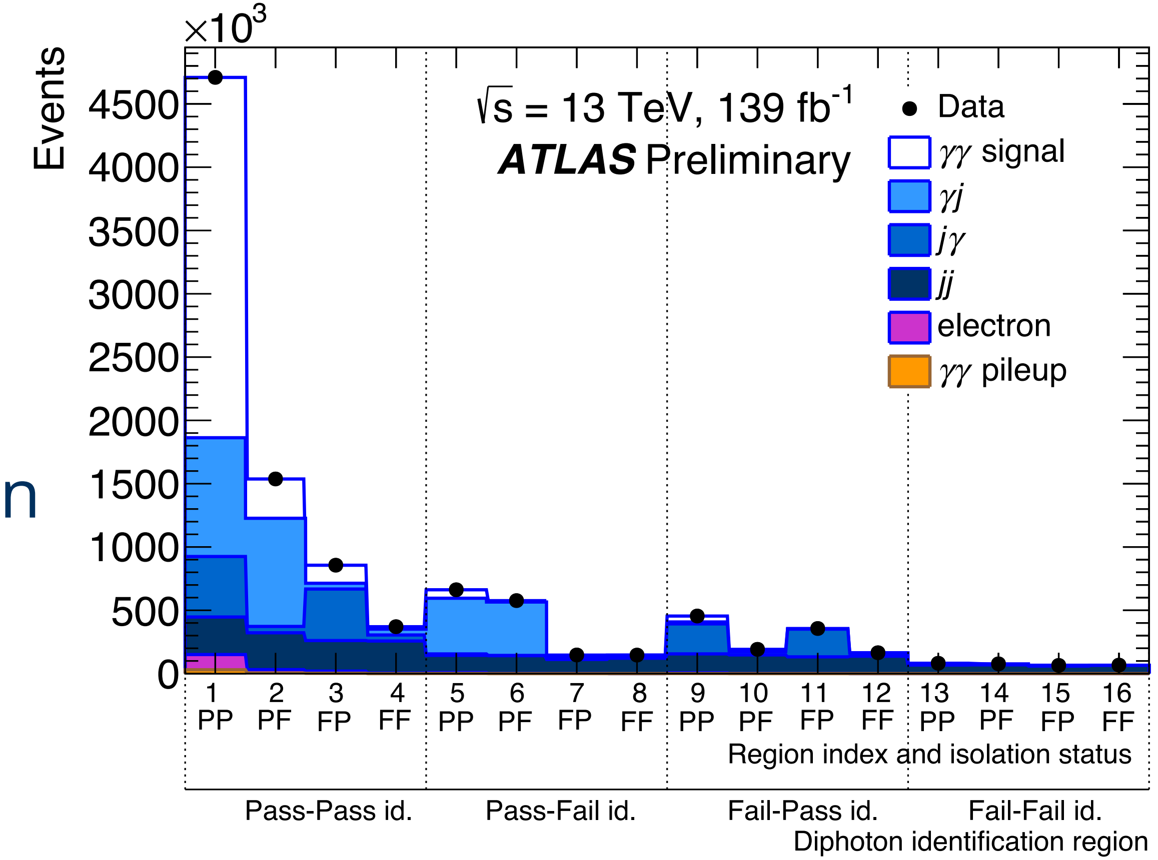


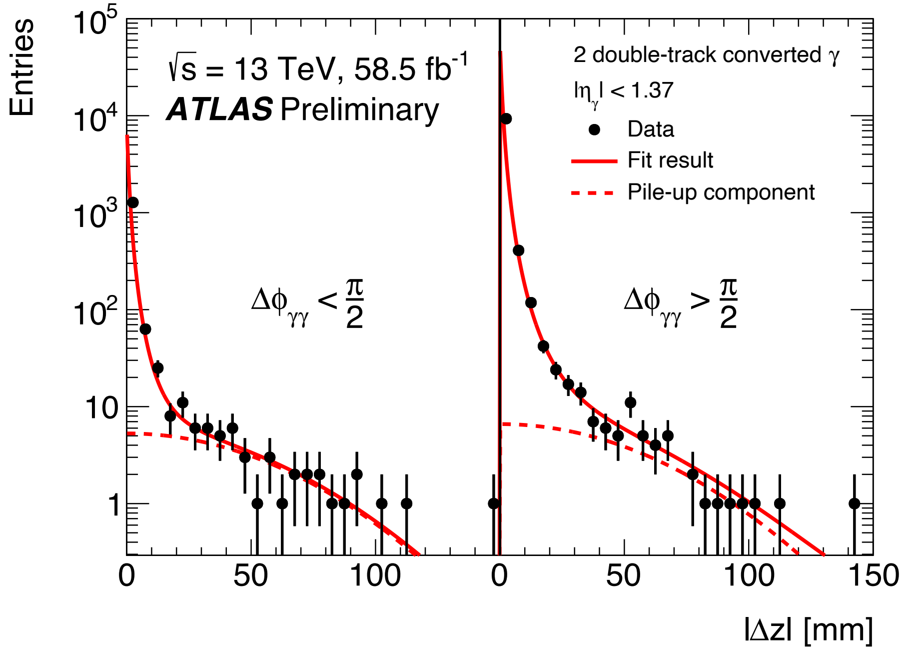
main background



Diphoton Backgrounds

- 60% $\gamma\gamma$ signal
- 36% γ-jet and jet-jet events
  - estimated data-driven based on photon isolation and identification
- 2.6% electrons: mostly from $Z/\gamma^* \to ee$





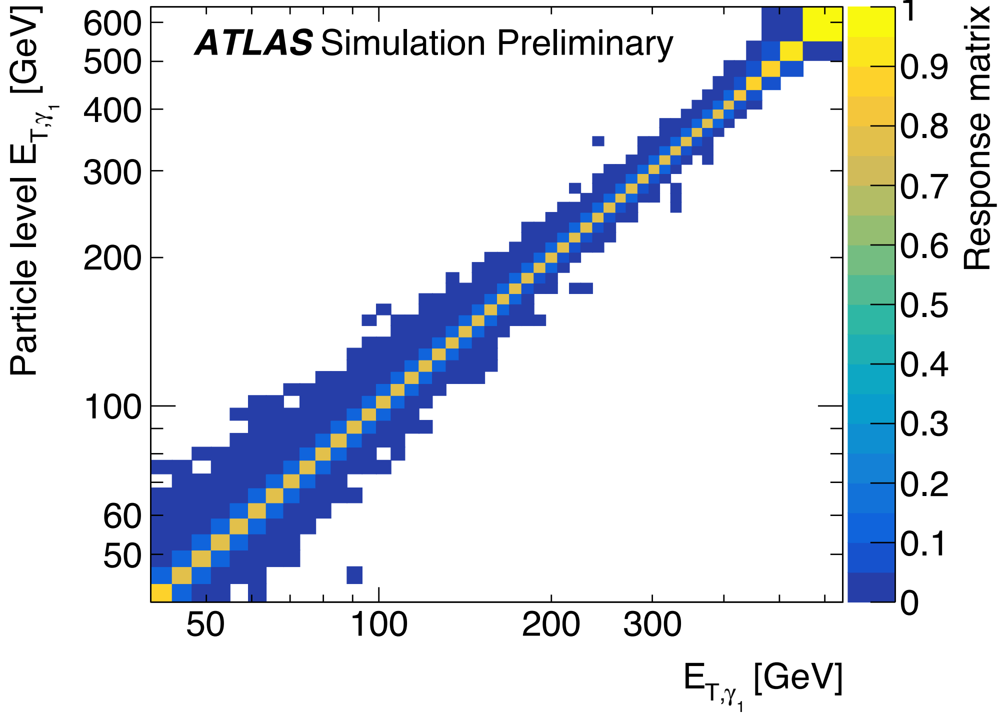
- 0.6% pileup: 2 x γj events from different interaction vertices ($\gamma\gamma$)
  - estimated from events with $\gamma \to e^+e^-$ conversion in the inner detector

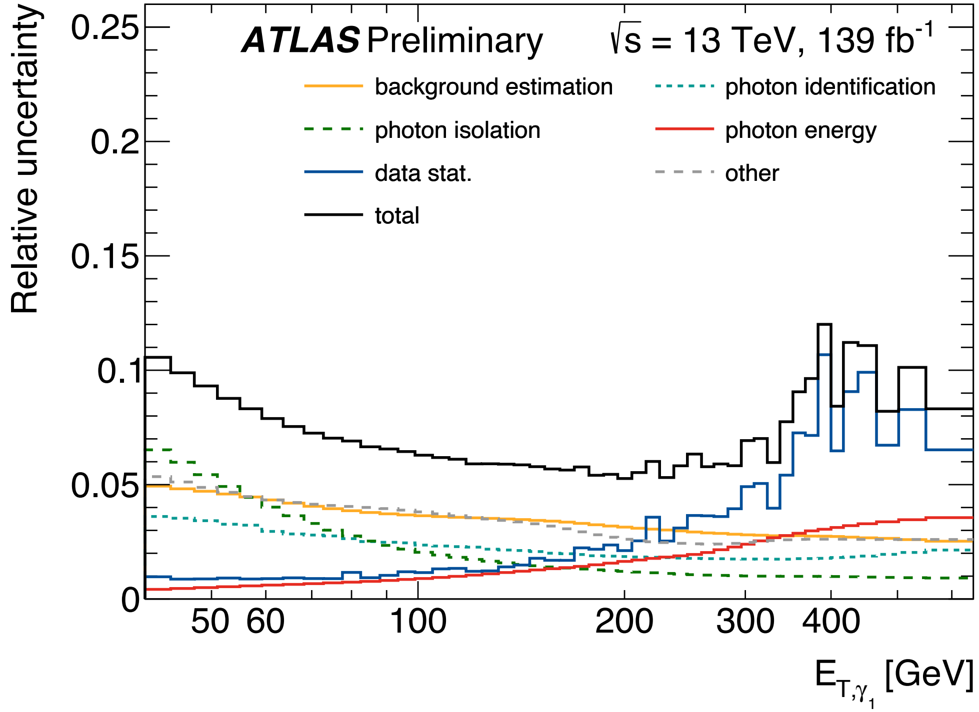
Diphoton Unfolding

- correct for detector efficiencies and resolution effects using **iterative bayesian unfolding**
  - determine particle level differential cross sections in the fiducial phase-space

Selection	Detector level	Particle level
Photon kinematics	$E_{\mathrm{T},\gamma_{1(2)}} > 40(30)\ GeV$,	$\|\eta_\gamma\| < 2.37$ excluding $1.37 < \|\eta_\gamma\| < 1.52$
Photon identification	tight	stable, not from hadron decay
Photon isolation	$E_{\mathrm{T},\gamma}^{\mathrm{iso},0.2} < 0.05 \cdot E_{\mathrm{T},\gamma}$	$E_{\mathrm{T},\gamma}^{\mathrm{iso},0.2} < 0.09 \cdot E_{\mathrm{T},\gamma}$
Diphoton topology	$N_\gamma \geq 2, \quad \Delta R_{\gamma\gamma} > 0.4$	

- excellent detector resolution for photons allows for fine binning
- leading uncertainties related to:
  - photon isolation detector efficiency
  - jet background estimation

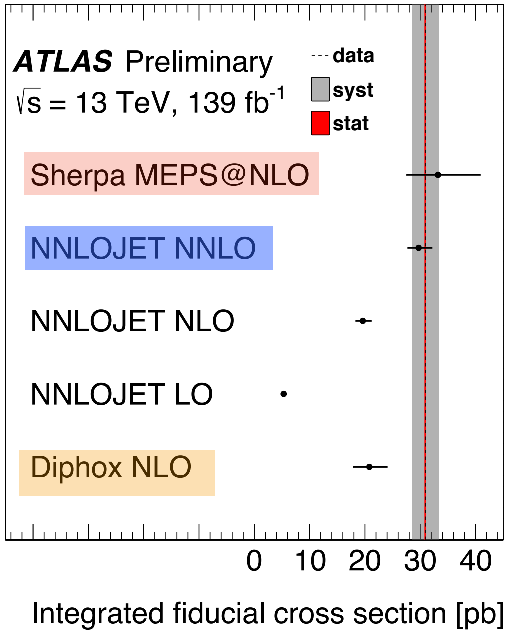




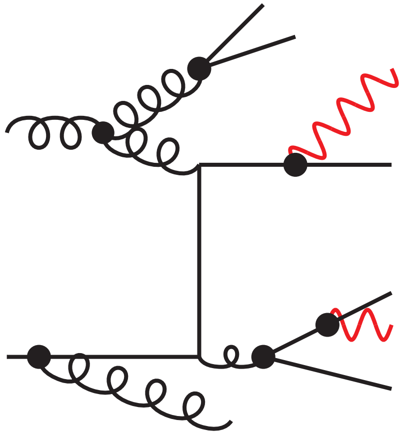
Diphoton Results

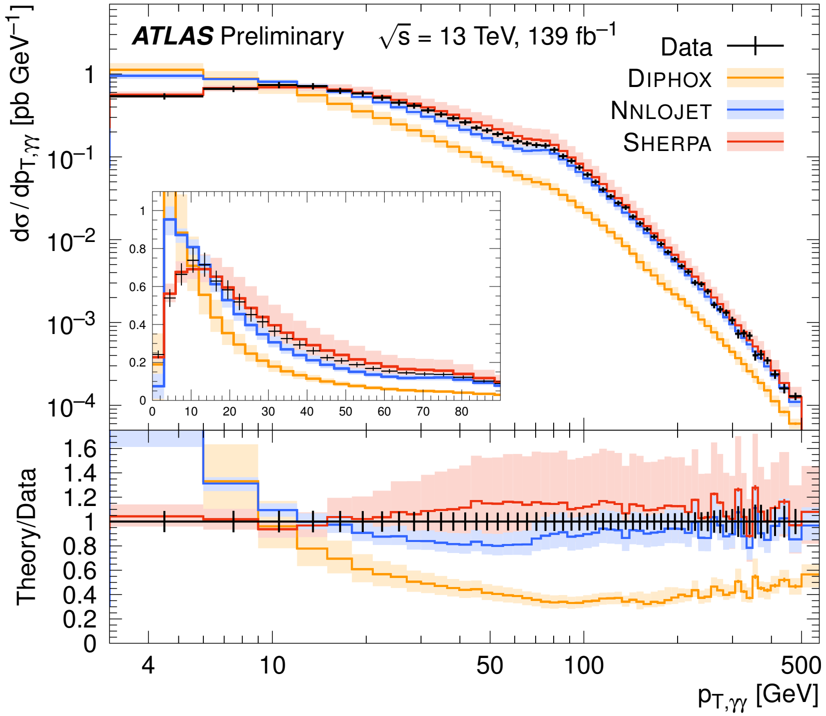
- unfolded data compared to predictions

	fixed order accuracy $\gamma\gamma$	$+1j$	$+2j$	$+3j$	$+\geq 4j$	$gg \to \gamma\gamma$	fragmentation γj	jj	QCD res.	NP eff.
DIPHOX	NLO	LO	-	-	-	LO	NLO		–	–
NNLOJET	NNLO	NLO	LO	-	-	LO	–	–	–	–
SHERPA	NLO		LO		PS	LO	ME+PS		PS	✓



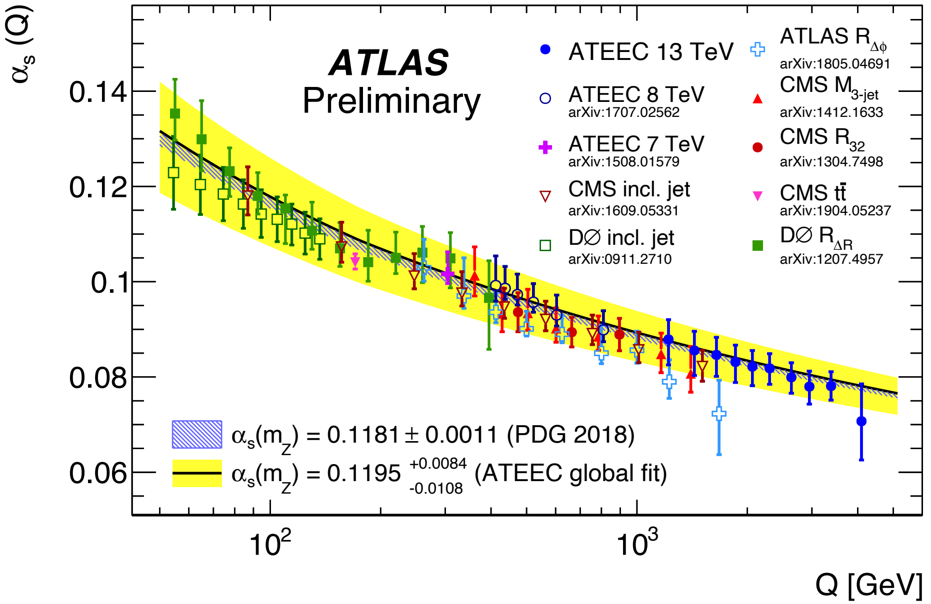
- slow convergence of perturbative series
- NNLO pQCD calculations and Sherpa describe data well at high $p_{T,\gamma\gamma}$
  - $\gamma\gamma + 2j$ indispensable for good description
- parton shower needed for phase space regions sensitive to soft-gluon radiation (e.g. low $p_{T,\gamma\gamma}$)

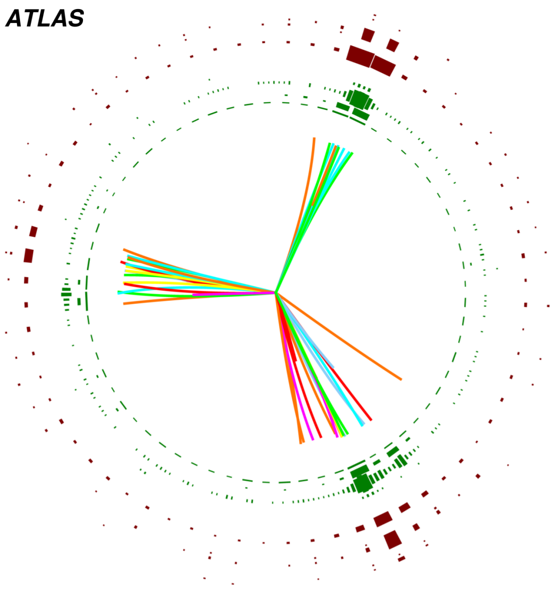


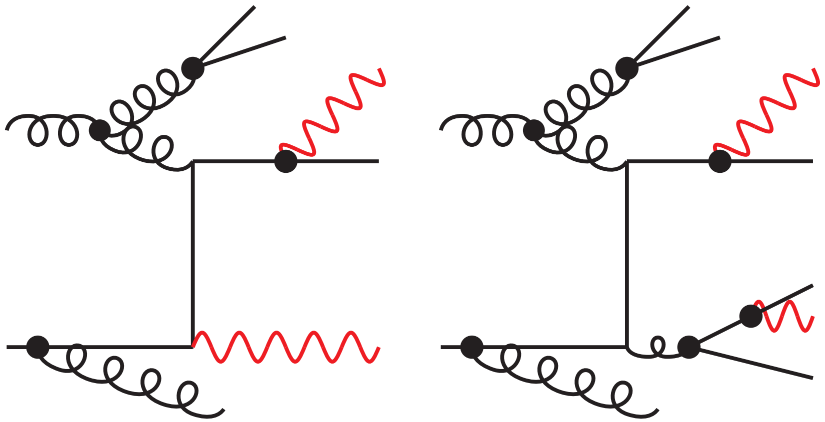


Summary

- selection of recent ATLAS jet and photon measurements
  - ✳ precise determination of $\alpha_s(m_Z)$ using transverse energy energy correlation (TEEC)
    - extends range of $\alpha_s(Q)$ measurement to multi TeV
  - ✳ measurement of event shapes at high p_T
    - provides very granular triple-differential information to check validity of e.g. MC generators
  - ✳ measurement of diphoton production
    - check accuracy of QCD predictions of main background for e.g. Higgs measurement







Backup

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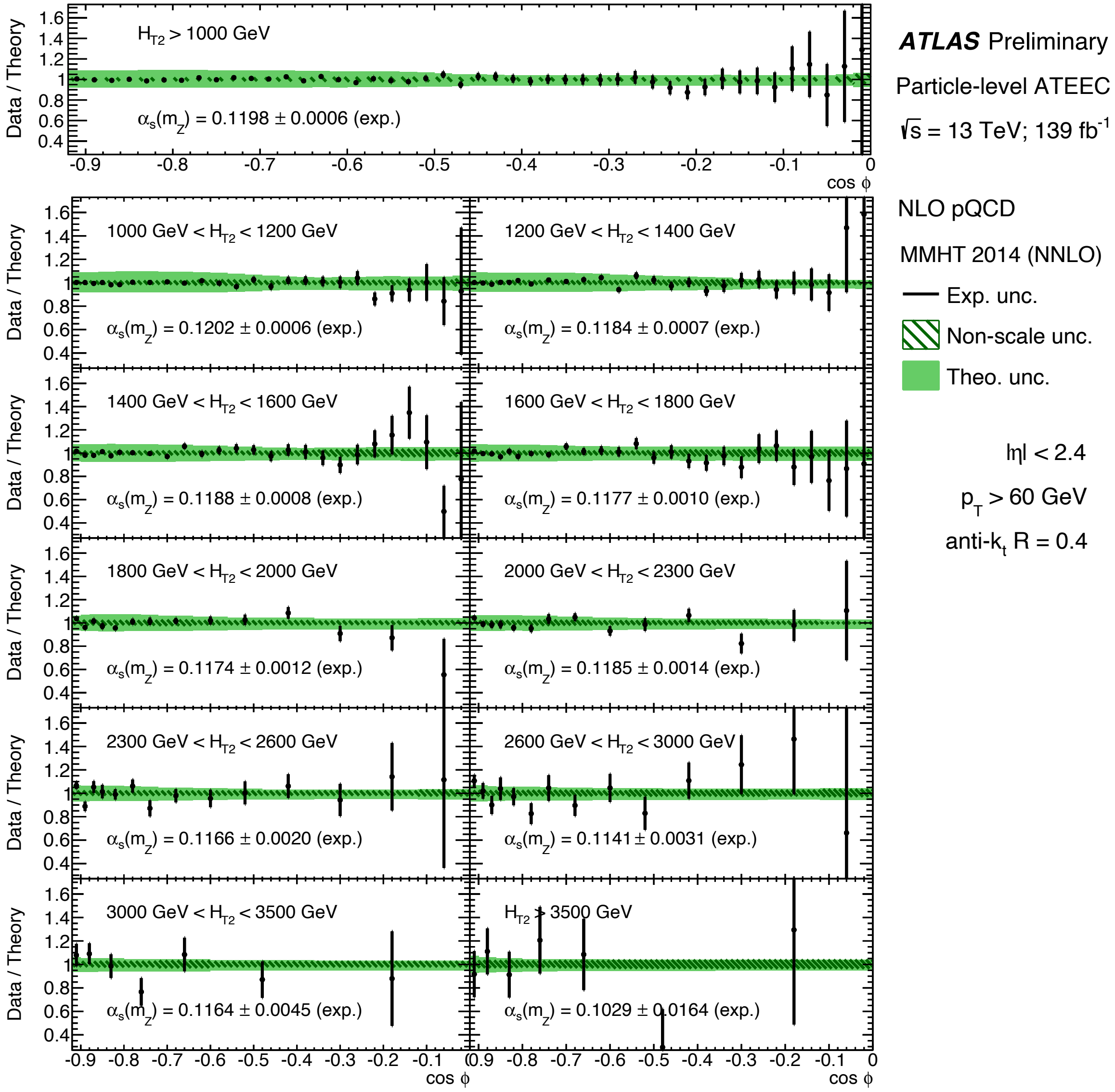
Determination of α_s with TEEC



Event shapes

- shapes based on eigenvalues $\lambda_1 > \lambda_2 > \lambda_3$ of M_{xyz} tensor

$$M_{xyz} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} & p_{x,i}p_{z,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 & p_{y,i}p_{z,i} \\ p_{z,i}p_{x,i} & p_{z,i}p_{y,i} & p_{z,i}^2 \end{pmatrix}$$

Sphericity $S = \frac{3}{2}(\lambda_2 + \lambda_3)$ **Aplanarity** $A = \frac{3}{2}\lambda_3$

$$D = 27(\lambda_1\lambda_2\lambda_3) \qquad C = 3(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)$$

- shape based on eigenvalues $\mu_1 > \mu_2$ of transverse M_{xy} tensor

$$M_{xy} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{x,i}p_{y,i} & p_{y,i}^2 \end{pmatrix}$$

transverse Sphericity $S_\perp = \frac{2\mu_2}{\mu_1 + \mu_2}$