Measurement of multijet events and photon production with ATLAS

L. Carminati (Università degli Studi e INFN di Milano)
on behalf of the ATLAS collaboration

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Quick outline

Two very recent interesting QCD measurements from ATLAS will be presented :

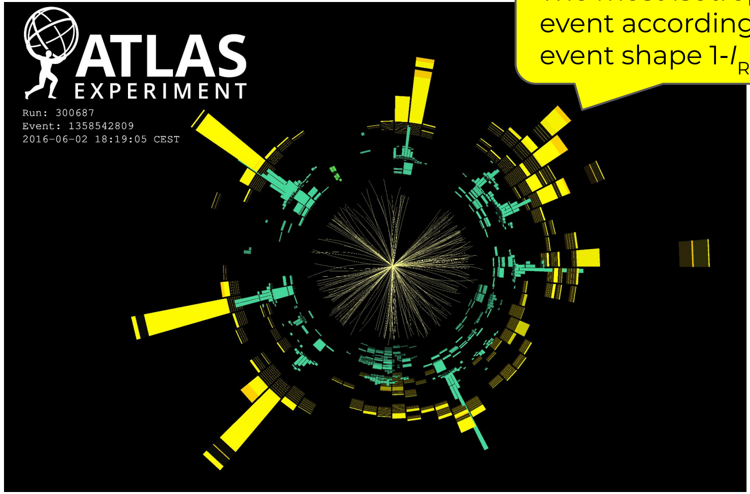
- ❑ Measurements of multijet event isotropies using optimal transport with the ATLAS detector (August 2022)

- ❑ Inclusive-photon production and its dependence on photon isolation in *pp* collisions at $\sqrt{s}$ = 13 TeV using 139 fb−1 of ATLAS data (September 2022) ATLAS-CONF-2022-065 (to appear soon)

Multi-jet event shapes

- Event shapes are a family of observables used to describe the flow of energy in collider events
  - provide stringent tests of perturbative QCD (stress our understanding of pQCD, MC improvements)
  - could be used in the search for physics beyond the SM where multijet events are typically a background

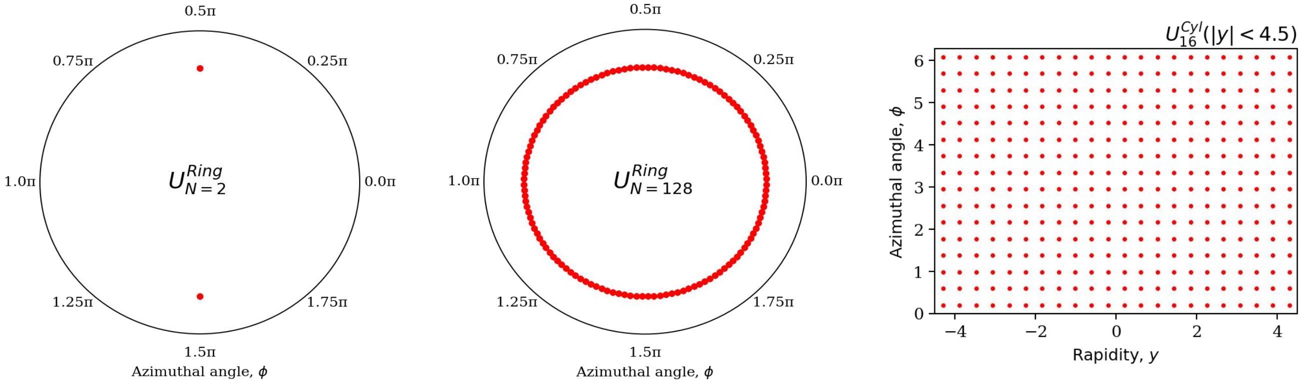
- A novel class (JHEP 08 (2020) 084) of event-shape observables was recently proposed that quantifies the isotropy of collider events. These observables are broadly called *event isotropy*
  - Measure how 'far' a collider event is from a symmetric radiation pattern in terms of a well defined metric (Wasserstein distance).
  - Event isotropies are more sensitive to isotropic radiation patterns than other event shapes, isolating events with larger multiplicities of objects that are isotropically distributed.
  - Event isotropy observables are complementary to canonical event shapes such as thrust, sphericity,and spherocity, which were designed to quantify how closely collider events resemble 'pencil-like' dijet events.



The most isotropic event according to the event shape $1\text{-}I_{\text{Ring}}^{128}$

Energy-Mover's distance

- Consider a reference configuration and try to quantify how far is a given event from the reference configuration (need a metric !)



- EMD$_\beta$(Ɛ,Ɛ') = the minimum amount of 'work' necessary to transport one event Ɛ with M particles into another Ɛ' of equal energy with M' particles, by movements of energy f_{ij} from particle $i \leq$ M in one event to particle $j \leq M'$ in the other

$$\text{EMD}_\beta(\mathcal{E}, \mathcal{E}') = \min_{\{f_{ij} \geq 0\}} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} \theta_{ij}^{\beta},$$

E_{tot} = total event energy
f_{ij} = normalized energy transfer
θ_{ij}^{β} = angular weighted distance

$$\sum_{i=1}^{M} f_{ij} = E'_j, \qquad \sum_{j=1}^{M'} f_{ij} = E_i, \qquad \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} = \sum_{i=1}^{M} E_i = \sum_{j=1}^{M'} E_j = E_{\text{tot}}$$

Analysis details

- Data from LHC *pp* collisions collected in 2015–2018 with the ATLAS detector (Run 2, 139 fb^{-1})
- Detector-level jets are reconstructed from particle-flow objects with anti-*kt* R=0.4 algorithm.
  - required to have a p_T > 60 GeV and a rapidity $|y| < 4.5$ to be retained for study.
- Events are required to have at least two selected jets (Njet ≥ 2) and to satisfy $H_{T2} \geq 400$ GeV ($H_{T2} = p_{T,1}+p_{T,2}$) to be included in the analysis.
- Data are unfolded using an Iterative Bayesian Unfolding (IBU) procedure
- Systematic uncertainties :
  - Statistical+Unfolding: related to both data and MC statistics via the bootstrapping method plus non-closure uncertainty using a data-driven reweighting procedure.
  - MC Model: related to the choice of MC models when performing the unfolding procedure. HERWIG with angle-ordered parton shower rather than nominal PYTHIA.
  - JES+JER: all sources of uncertainty originating from the jet energy scale and jet energy resolution. The JER uncertainty dominates this category in nearly all cases

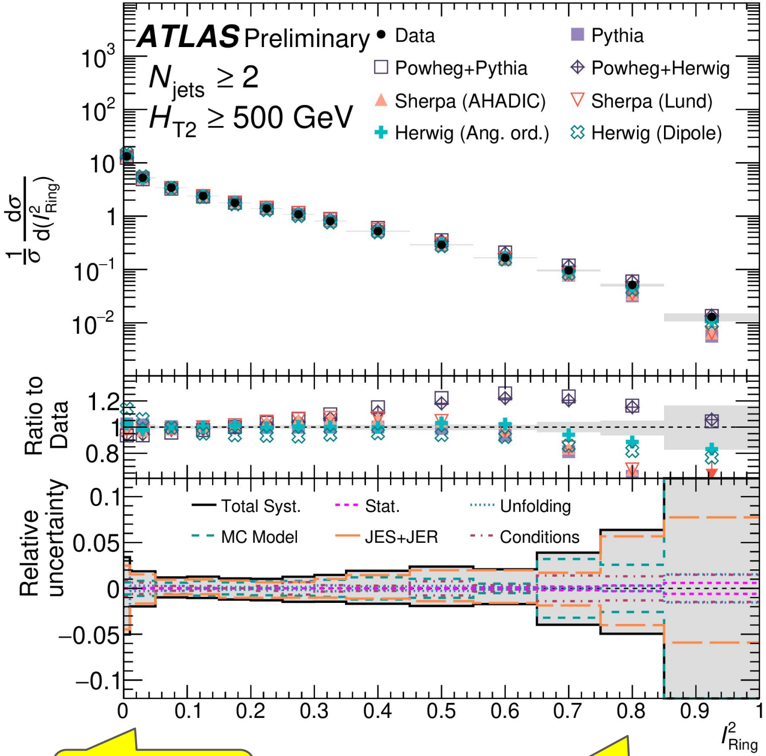
Theoretical predictions

MC generator	Matrix elements	Parton Shower	Hadronisation	PDFs
Pytha 8.230 (nominal)	2->2 LO	Dipole-style p_T-ordered	Lund string	NNPDF 2.3
Powheg V2 + Pythia 8.235	2->2 NLO	Dipole-style p_T-ordered	Lund string	NNPDF30NLO
Herwig 7.1.3	2->2 NLO ; 2->3LO	Angle-ordered	Cluster	MMHT2014NLO
Herwig 7.1.3	2->2 NLO ; 2->3LO	Dipole	Cluster	MMHT2014NLO
Sherpa 2.2.5	2->2 LO	CSS	Cluster (AHADIC)	CT14NNLO
Sherpa 2.2.5	2->2 LO	CSS	Lund string (via Pythia 6.4)	CT14NNLO
Powheg+Herwig 7	2->2 NLO	Angle-ordered	Cluster	NNPDF30NLO

Results : I_{ring}^2

back-to-back ⟵ ⟶ isotropic

- As expected modelling works typically best for back-to-back events, degrades for higher values.
- Leading-order Pythia and Sherpa predictions describe the back-to-back and intermediate range of the distribution well, but under-predict the cross-section for the most isotropic events.
- Overall NLO generators look best in the isotropic region.
- Not sensitive to hadronization models (in the sherpa samples).
- Dominant uncertainty from Jet Energy Resolution and MC signal modelling

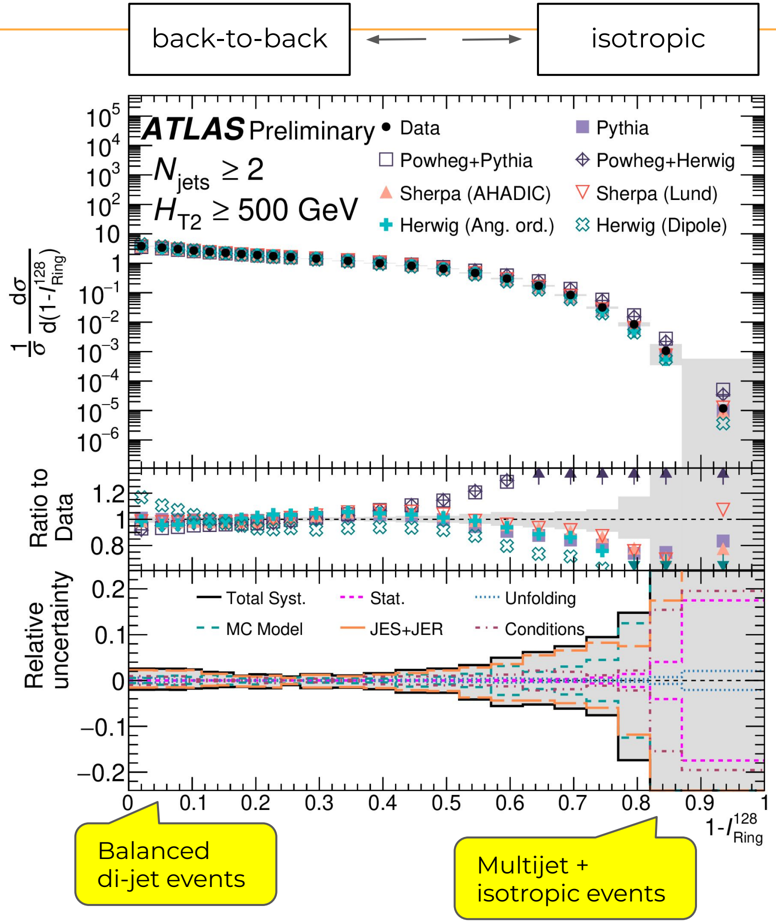


Balanced di-jet events

Symmetric “mercedes-like” events

Results : 1-I_{ring}^{128}

- The Powheg+Pythia and Powheg+Herwig predictions overestimate the measured cross-section for isotropic events while all other predictions underestimate it.
- Large differences between the Herwig angle-ordered and dipole shower models: the dipole model predicts relatively more dijet-like events than than the angle-ordered model, and correspondingly fewer isotropic events.
- No significant differences between the Sherpa hadronization models, although they seem to better match the measured data for larger values of $1 - I_{ring}^{128}$
- The JES/JER systematics and signal MC modelling are the main source of uncertainties.
  - systematic related to the effect of disabled tile calo modules also becomes large.
  - Non-negligible statistical uncertainty for the most isotropic events
- Many more plots in the note (also in exclusive Njet and H_T regions)

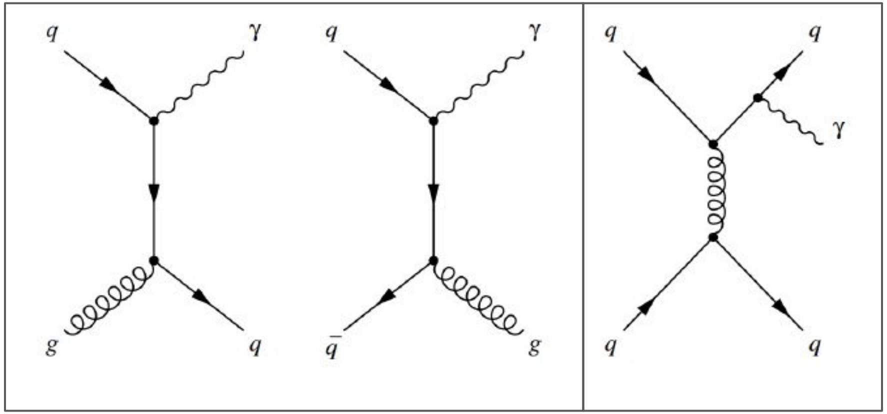


Prompt photons production at the LHC

Prompt photon production provides a testing ground for pQCD in a cleaner environment than e.g. di-jet production since it's less affected by hadronization effects. Sensitive to gluon PDF

The production of high-p_T prompt-photons (i.e. photons not coming from hadron decays) proceeds at LO via two mechanisms: direct processes and fragmentation processes

Direct processes



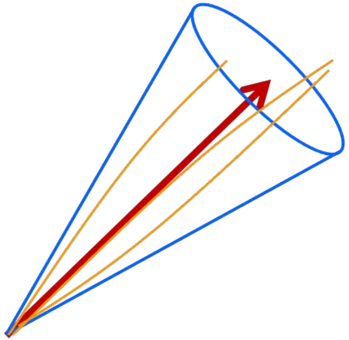
Fragmentation processes

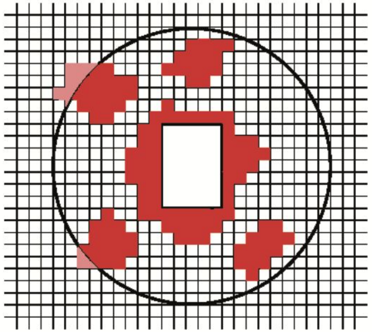
- ❑ Fragmentation contribution typically cumbersome to calculate and relies on 'fragmentation functions' that must be determined from comparisons with data
- ❑ Huge background from photons coming from high-p_T π^0 produced in jets fragmentation : typically an isolation criterium is applied which stresses a bit the reliability of perturbative calculations

Measurements of prompt photon production at ATLAS

The measurements rely on full Run 2 dataset (L = 139 fb^{-1}) collected by the ATLAS detector from 2015 to 2018

- Trigger: $E_T^\gamma > 140$ GeV photon fulfilling loose identification criteria (lowest un-prescaled photon trigger menu)
- At least one photon with: $E_T^\gamma > 250$ GeV and $|\eta_\gamma| < 2.37$, excluding the $1.37 < |\eta_\gamma| < 1.56$ region.
- Tight photon identification requirements
- Photon isolation: E_T^{iso} (R = 0.2 or 0.4) $< 4.2 \cdot 10^{-3} E_T^\gamma + 4.8$ GeV (corrected for leakage and ambient energy density)

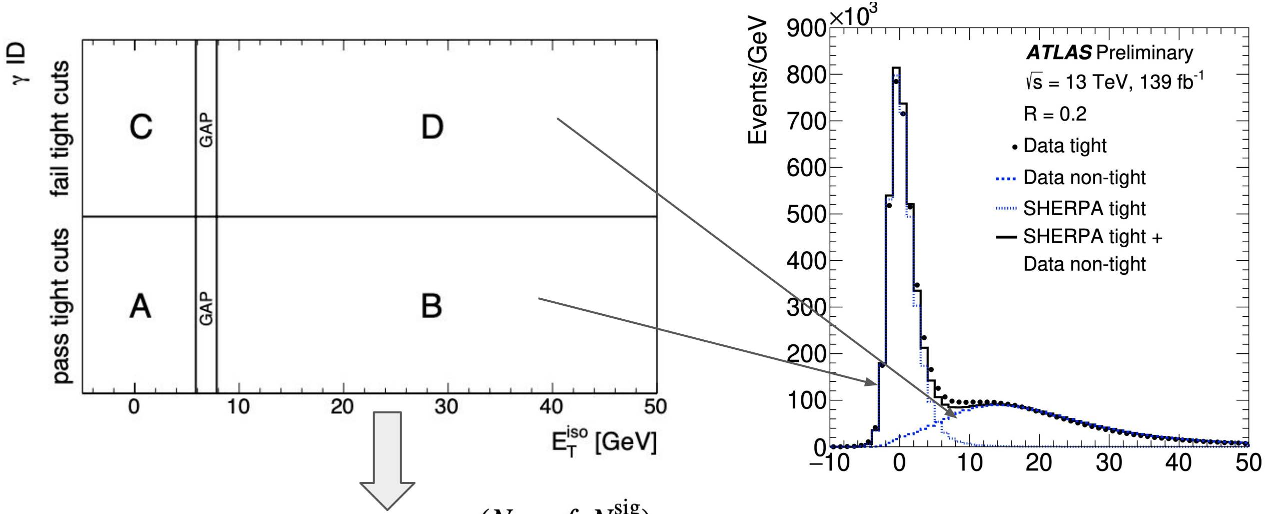




- Data are unfolded at particle level using a bin-by-bin method
- Measure inclusive isolated-photon production cross sections as functions of E_T^γ in 6 bins of photon pseudorapidity η_γ
- Measure ratios of inclusive isolated-photon production cross sections with different cone radiuses as functions of E_T^γ in 6 bins of photon pseudorapidity η_γ

Background subtraction

- Background from multijet events with one jet misidentified as photon estimated using appropriate control regions (ABCD) method : non-isolated and non-tight (identification) control regions



$$N_A^{\mathrm{sig}} = N_A - R^{\mathrm{bg}} \cdot (N_B - f_B N_A^{\mathrm{sig}}) \cdot \frac{(N_C - f_C N_A^{\mathrm{sig}})}{(N_D - f_D N_A^{\mathrm{sig}})}$$

  - Measured purity of the selected sample always > ~95%

- Small (sub–%) background from electrons faking photons accounted for as a systematic uncertainty

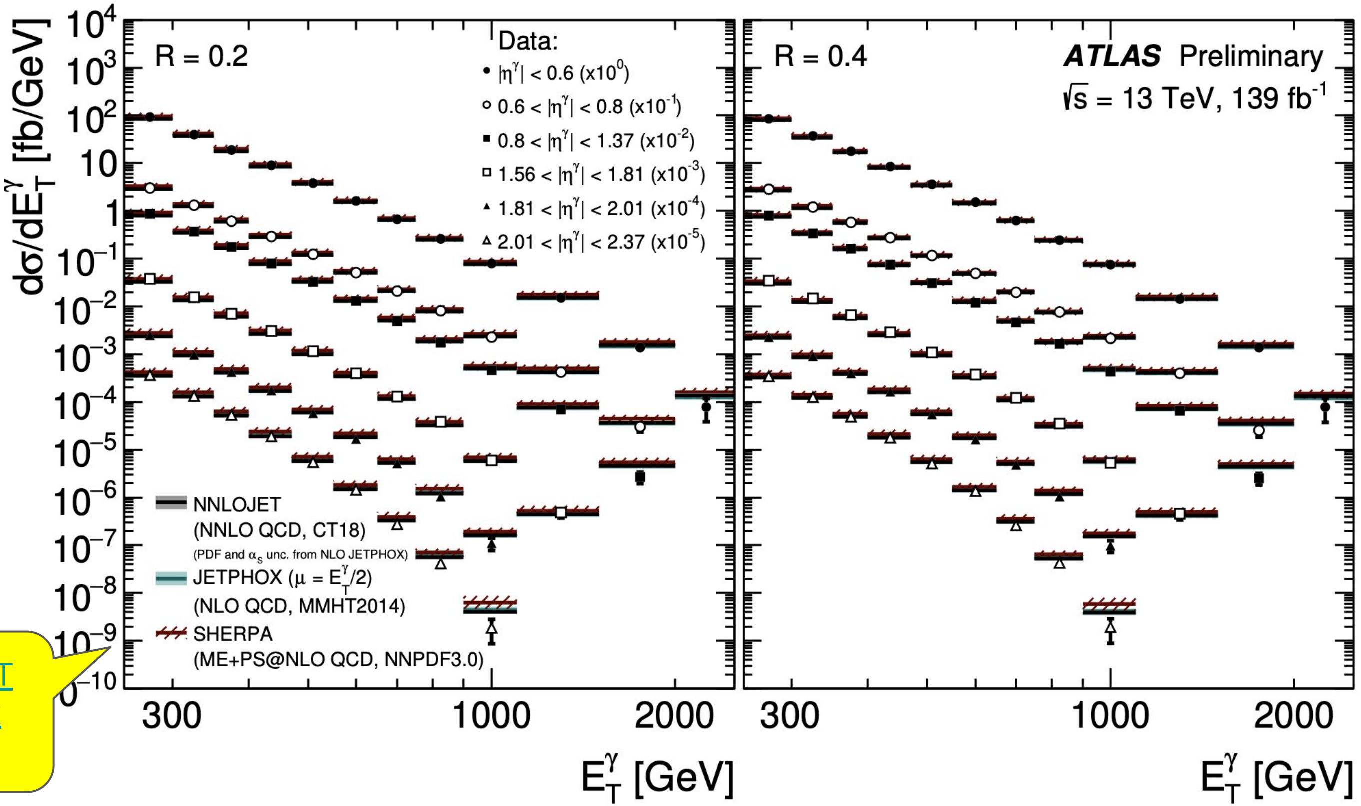
MC predictions

The results are compared with several MC predictions (both particle and parton level) and different PDF sets

Program	Order in α_s	Fragmentation	Parton shower	Isolation method	PDF	Particle level
JETPHOX	NLO	yes	no	fixed cone	– MMHT2014 – CT18 – NNPDF3.1 – HERAPDF2.0 – ATLASpdf21	no
SHERPA 2.2.2	NLO for $\gamma + (1, 2)$-jet LO for $\gamma + (3, 4)$-jet	no	yes	hybrid	NNPDF3.0	yes
NNLOJET	(N)NLO	yes	no	fixed cone	CT18NNLO	no

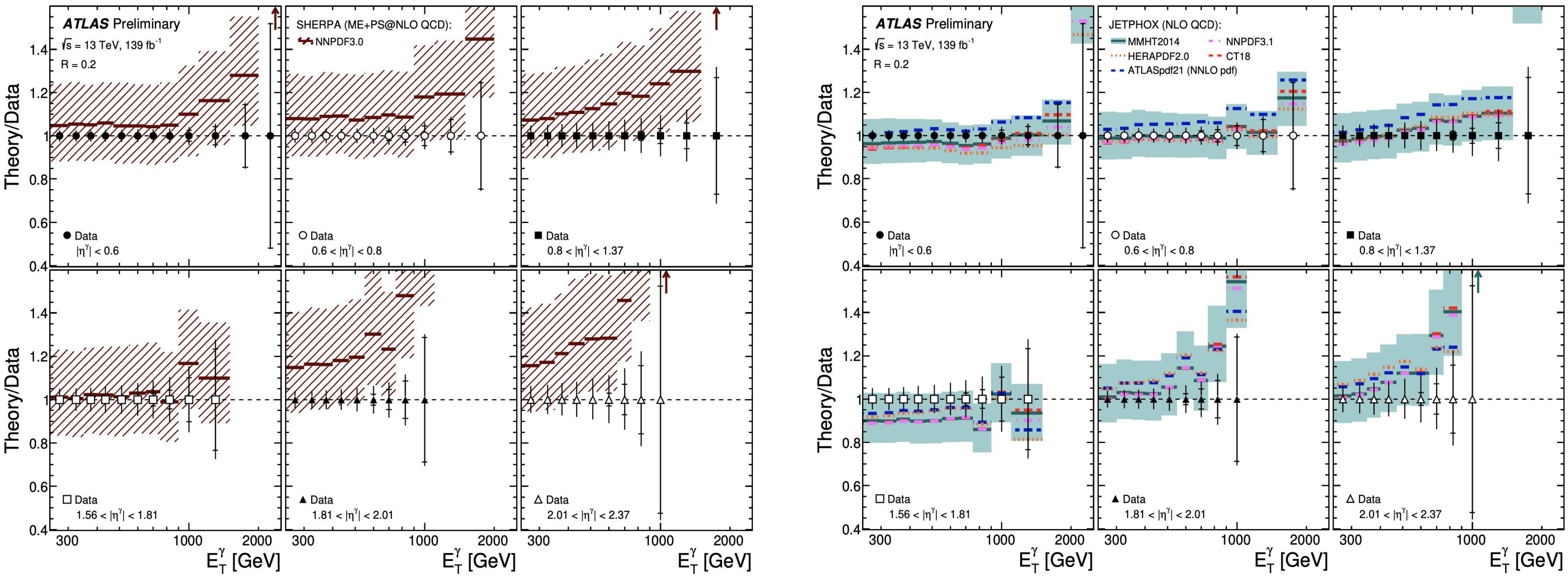
Results : measured differential cross sections

Each differential measurement spans ~6 order of magnitude



NNLOJET
JetPhox
Sherpa

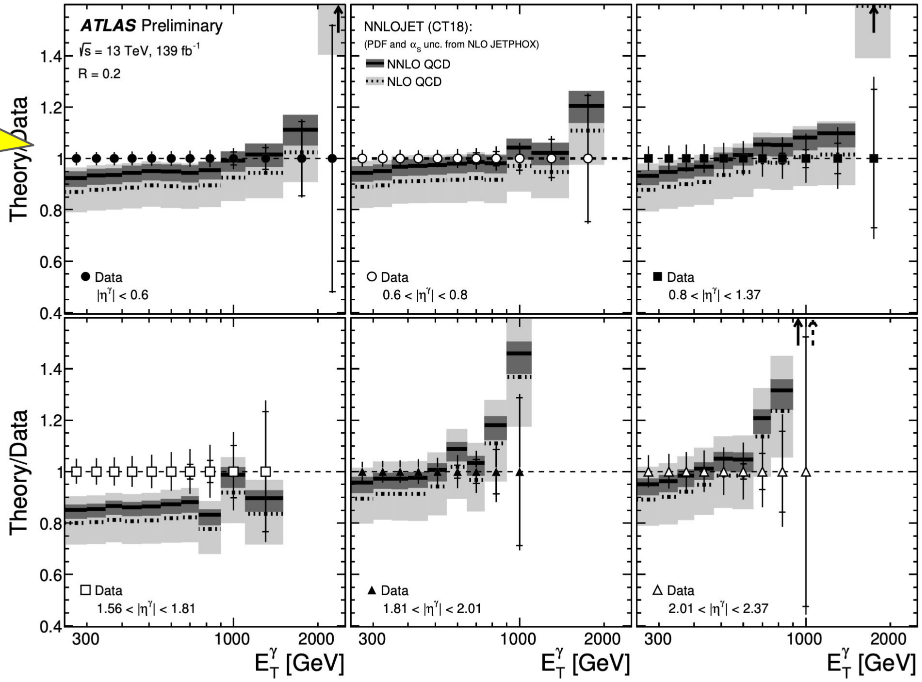
Results : measured differential cross sections



- ❏ Measurements uncertainty dominated by systematics up to ~ 1 TeV
- ❏ NLO QCD predictions are found to provide an adequate description of the data within the experimental and theoretical uncertainties. The comparison of data and theory is limited by the theoretical scale uncertainties
- ❏ Exp systematic uncertainties are smaller than the theo uncertainties over the full investigated phase space.
- ❏ The measurements have the potential to further constrain the gluon PDFs,

Results : measured differential cross sections

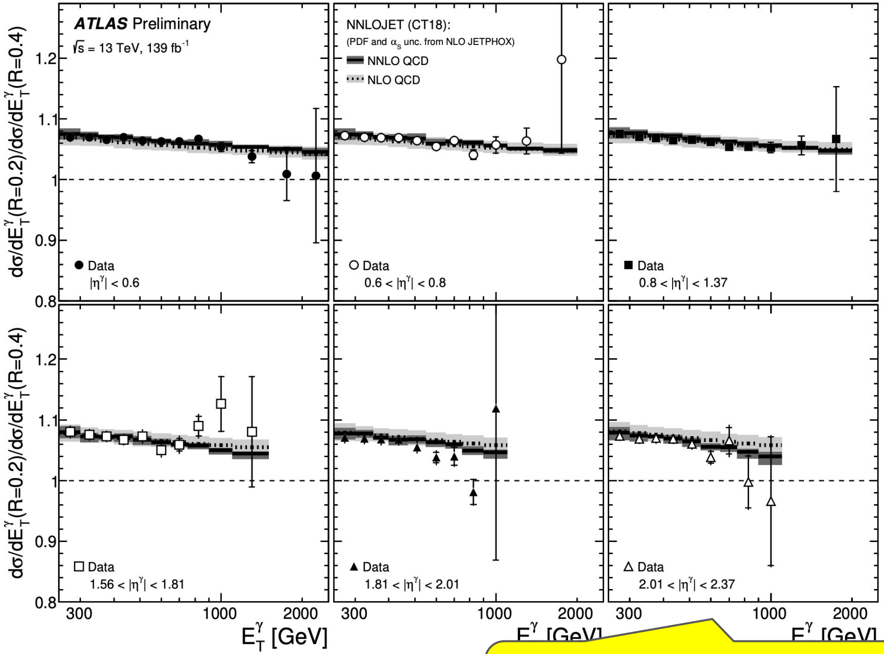
Sizeable reduction of the scale uncertainty from NNLO calculation

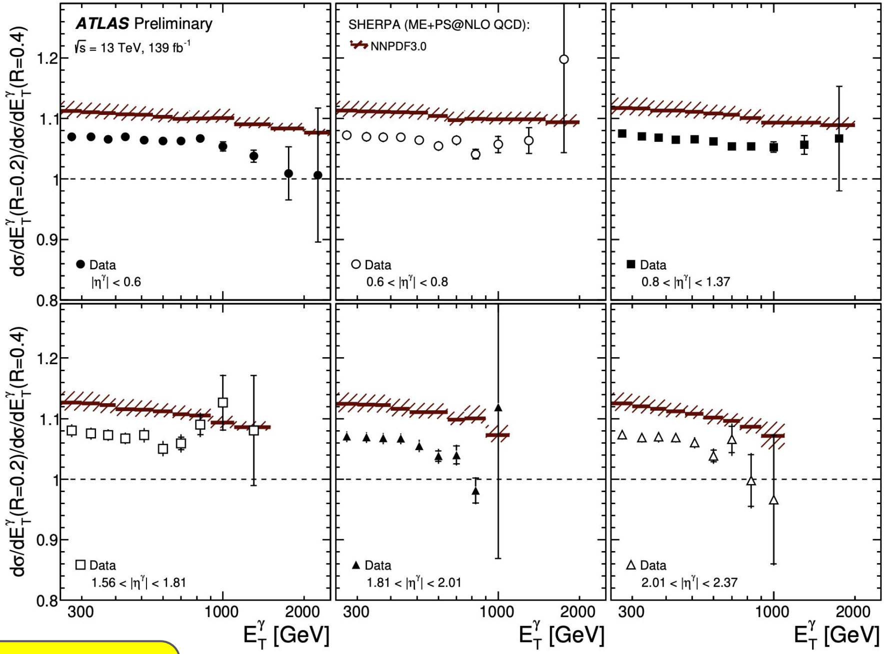


NNLO QCD predictions (including direct- and fragmentation-photon components) are compared to the differential cross sections. For both cone radii, the NNLO predictions give a good description of the data within the uncertainties, except in the region 1.56 < |ηγ| < 1.81, where the calculations underestimate the data.

Results : ratios of differential cross sections with different isolation cones

Ratios of differential cross sections with different cone radii allows to investigate very precisely the handling of the fragmentation contribution: the theoretical and (most of) the experimental uncertainties in the ratio are estimated as fully correlated for both isolation-cone radii





Systematic uncertainty (both theoretical and experimental) below the % level !

Conclusions

Two new interesting measurements released by the ATLAS collaboration have been discussed:

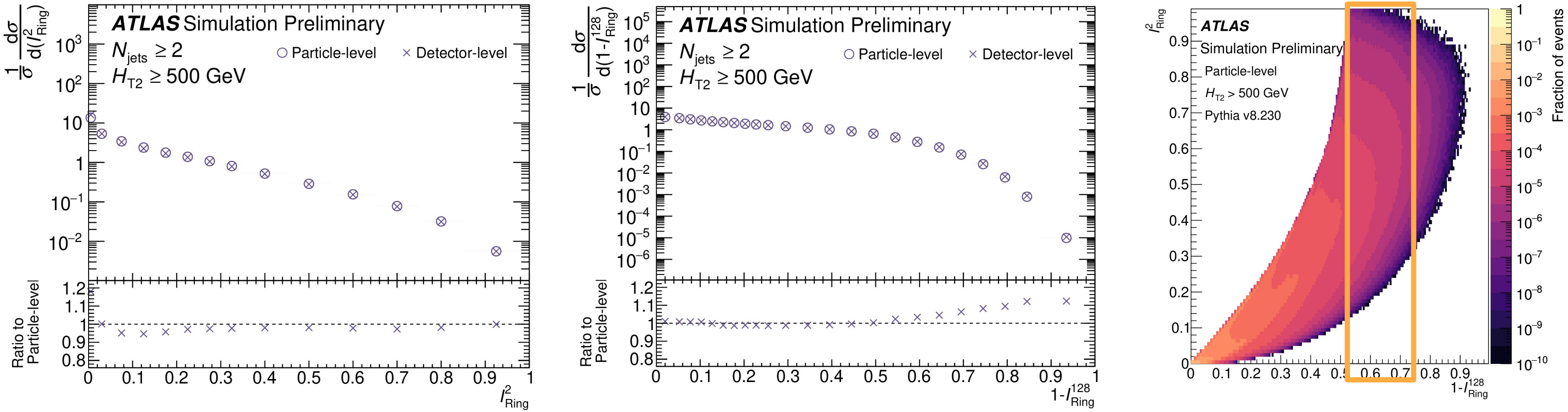
- A first measurement of novel event shape observables (*event isotropy)* has been performed.
  - They are capable of exposing a remote piece of QCD phase space that is difficult to model and relevant to many searches for physics beyond the Standard Model.
  - The measured data are compared to several state-of-the-art MC event generators:
    - Agreement between data and simulations tends to be best in balanced, dijet-like arrangements and deteriorates in more isotropic configurations.
    - Dipole geometry (I_{Ring}^{2}): the NLO MC predictions generally outperform those at LO.
    - Ring geometry (I_{Ring}^{128}) : no single MC generator accurately describes the full distribution.
    - Cylinder geometry (I_{cyl}^{16}) : complex observable not well-predicted by any MC generator.

- New measurement of inclusive isolated-photon cross sections using full Run 2 dataset: the measured data are compared to several state-of-the-art MC event generators predictions obtained with different PDF sets
  - NNLO calculations give in general a good description of the data within the uncertainties
  - Ratios of cross sections with different isolation cones : insights in the fragmentation component description, uncertainties at the % level

These measurements provide useful inputs for improving our understanding of QCD. They can be used in future **Monte Carlo tuning** campaigns and other studies of QCD (including PDF fits).

Event isotropies

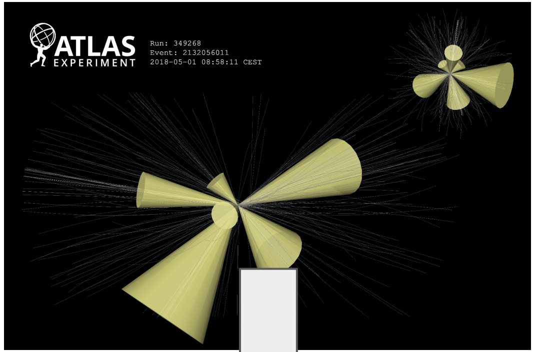
back-to-back ↔ isotropic   back-to-back ↔ isotropic

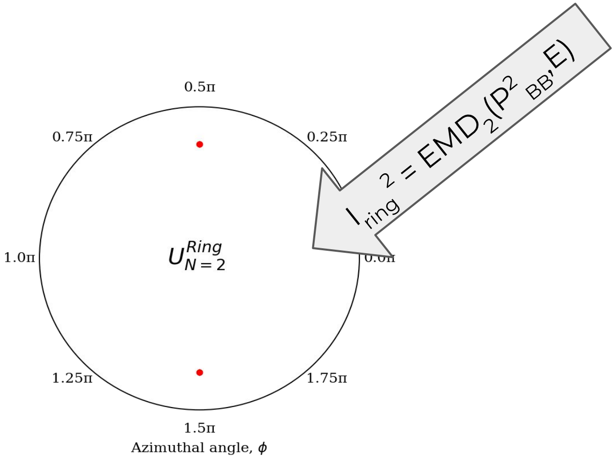


I_{Ring}^{2} and I_{Ring}^{128} take extreme values for ***qualitatively different*** events: I_{Ring}^{128} takes extreme values for much *rarer* multijet final states (***increased dynamic range***).

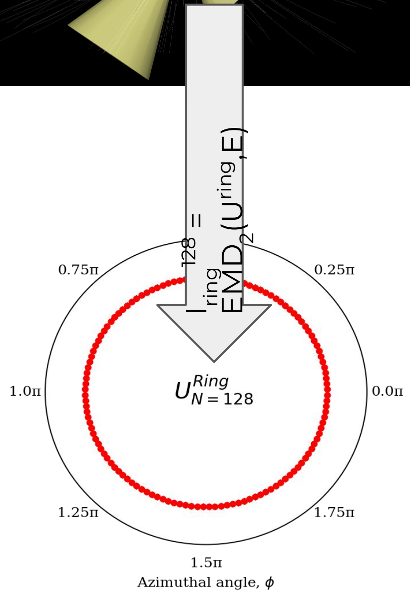
- Events that saturate I_{Ring}^{2} only have intermediate I_{Ring}^{128} values
- I_{Ring}^{128} saturated by “perfectly (and only perfectly) isotropic events.”
- New event shapes provide additional testing grounds for pQCD prediction !

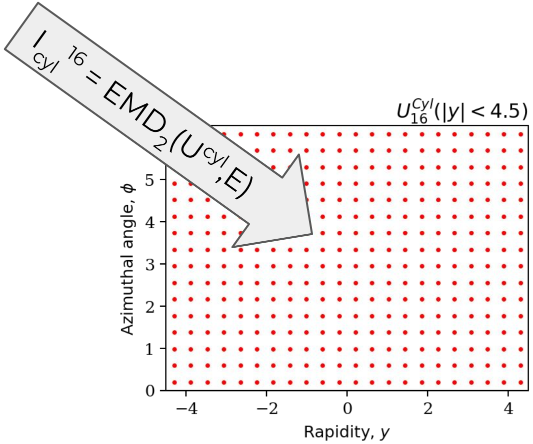
Energy-Mover's distance





This is equivalent to the usual transverse thrust





All shape variables in [0,1] by construction

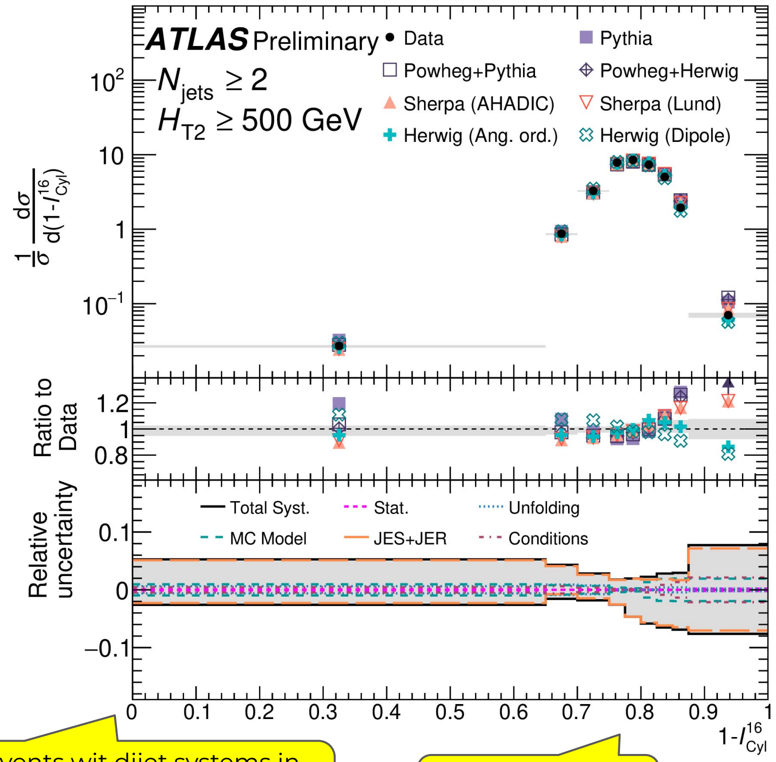
More on EMD

Geometry	Energy Weight	Ground Measure	$\mathcal{U}$
Cylinder	$w_i^{\text{cyl}} = p_{T\,i}/p_{T\,\text{tot}}$	$\theta_{ij}^{\text{cyl}} = \frac{12}{\pi^2+16y_{\text{max}}^2}\left(y_{ij}^2 + \phi_{ij}^2\right)$	$\mathcal{U}_N^{\text{cyl}}(\lvert y\rvert < y_{\text{max}})$
Ring	$w_i^{\text{ring}} = p_{T\,i}/p_{T\,\text{tot}}$	$\theta_{ij}^{\text{ring}} = \frac{\pi}{\pi-2}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_N^{\text{ring}}$
Ring (Dipole)	$w_i^{\text{ring}} = p_{T\,i}/p_{T\,\text{tot}}$	$\theta_{ij}^{\text{ring}} = \frac{1}{1-\frac{1}{\sqrt{3}}}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_2^{\text{ring}}$

Table 1: The different geometries used to define event isotropy, with their corresponding energy weights, ground measures, and default quasi-uniform configurations, adapted from Reference (where the dipole geometry was not considered explicitly).

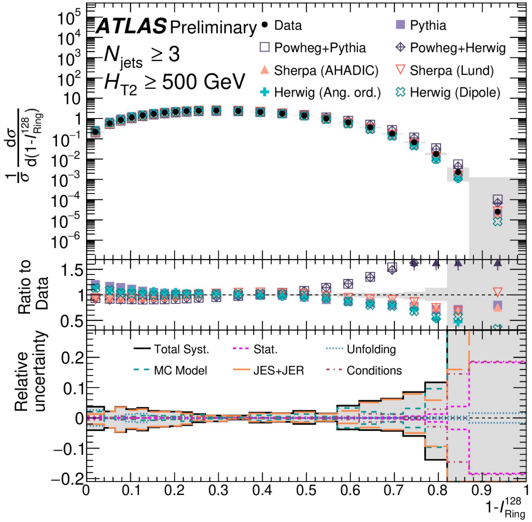
Results : 1-I_{cyl}^{16}

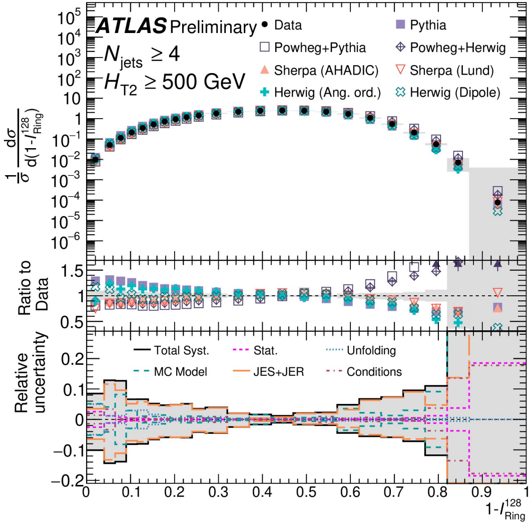
- None of the MC predictions accurately describe this complex observable, although the best descriptions occur near the peak of the distribution around $1 - I_{cyl}^{16}$ ~ 0.8.
- The Herwig angle-ordered and dipole parton shower models predict distributions that have a peak at respectively larger and smaller values than that observed in the measured data.
- The predictions from the Pythia, Powheg+Pythia and Powheg+Herwig samples are consistent except at low values, where the Pythia sample over-estimates the observed cross-section.
- No sensitivity to the hadronization models implemented in Sherpa is observed.
- Jet Energy Resolution uncertainty dominates the total uncertainty band

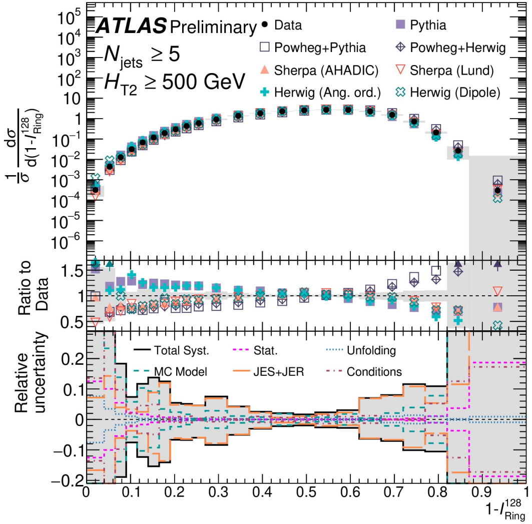


Many more possible comparisons: N_{jets} dependence

Average isotropy intuitively increases with jet multiplicity.







- Large jet multiplicities can highlight larger differences between MCs : eg in back-to-back region
  - Herwig 7 Dipole > Angle-ordered for NJets>=2
  - Herwig 7 Dipole < Angle-ordered for NJets>=5.
- Herwig Dipole PS ~ agree often with Powheg+Pythia/ Herwig predictions in the back-to-back region
- Pythia often overpredicts back-to-back cross section