Testing the strong force with photons and jets

SM@LHC 2023, Fermilab, Batavia, Illinois, USA

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MANCHESTER 1824
The University of Manchester

ATLAS EXPERIMENT

CMS

Overview

LHC Jet & Photon Physics
(Selected Run 2 results)

Perturbative Radiation
Fixed-order Predictions

Soft + Colinear Radiation
Resummed Predictions

Non-perturbative radiation
Models of Hadronisation, colour reconnection, MPI/UE, etc.

- Photon and jet cross-section measurements are **stringent tests of QCD predictions**, both analytical and Monte Carlo.
  - Typically, **multi-faceted measurements** that probe multiple aspects of our understanding across a wide range of energy scales.

Overview

LHC Jet & Photon Physics
(Selected Run 2 results)

… A LOT OF ACTIVITY IN THIS AREA DURING RUN 2!

Perturbative Radiation
Fixed-order Predictions

CMS
Inclusive jets

ATLAS, CMS
Event Shapes

CMS
Jet multiplicity

CMS
Photon+jet

ATLAS
Diphoton

ATLAS, CMS
Inclusive photon

ATLAS
(A)TEECs

ATLAS
Multijet event isotropies

Soft + Colinear Radiation
Resummed Predictions

ALICE
Dead cone

CMS
Soft-Drop Mass

ATLAS, CMS
Lund jet plane

ATLAS
Soft-Drop Observables

ATLAS
JSS in *W*/*t* jets

CMS
JSS angularities

Non-perturbative radiation
Models of Hadronisation, colour reconnection, MPI/UE, etc.

ALICE
Lund jet plane

ALICE
2-point Correlators

ALICE
JSS in D0-tagged jets

LHCb
JSS of Z-tagged jets

ATLAS
Frag. Functions

ALICE
Groomed jet mass

ATLAS
B Fragmentation

ALICE
N_{SD}, z_g, θ_g

ALICE
Jet axis deflection

LHCb
J/Ψ in jets

Overview

LHC Jet & Photon Physics
(Selected Run 2 results)

Today, I'll focus mostly on measurements that are being used to improve models of perturbative QCD.

Perturbative Radiation

Fixed-order Predictions

Soft + Colinear Radiation

Resummed Predictions

Non-perturbative radiation

Models of Hadronisation, colour reconnection, MPI/UE, etc.

THIS TALK!

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Related Talks at SM@LHC!

Christian Baldenegro Barrera (CMS),
Jet substructure & fragmentation at the LHC
Monday, 11h00

Joey Huston (CTEQ, ATLAS)
Status overview of global PDF fits
Wednesday, 9h00

Francesco Giuli (ATLAS),
α_S from pT,Z and 2→3 jet predictions @NNLO
Wednesday, 8h00

Florian Herren (Sherpa)
Progress on Parton Showers
Wednesday, 9h30

Perturbative Radiation
Fixed-order Predictions

Soft + Colinear Radiation
Resummed Predictions

Non-perturbative radiation
Models of Hadronisation, colour reconnection, MPI/UE, etc.

This Talk!

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Inclusive jets

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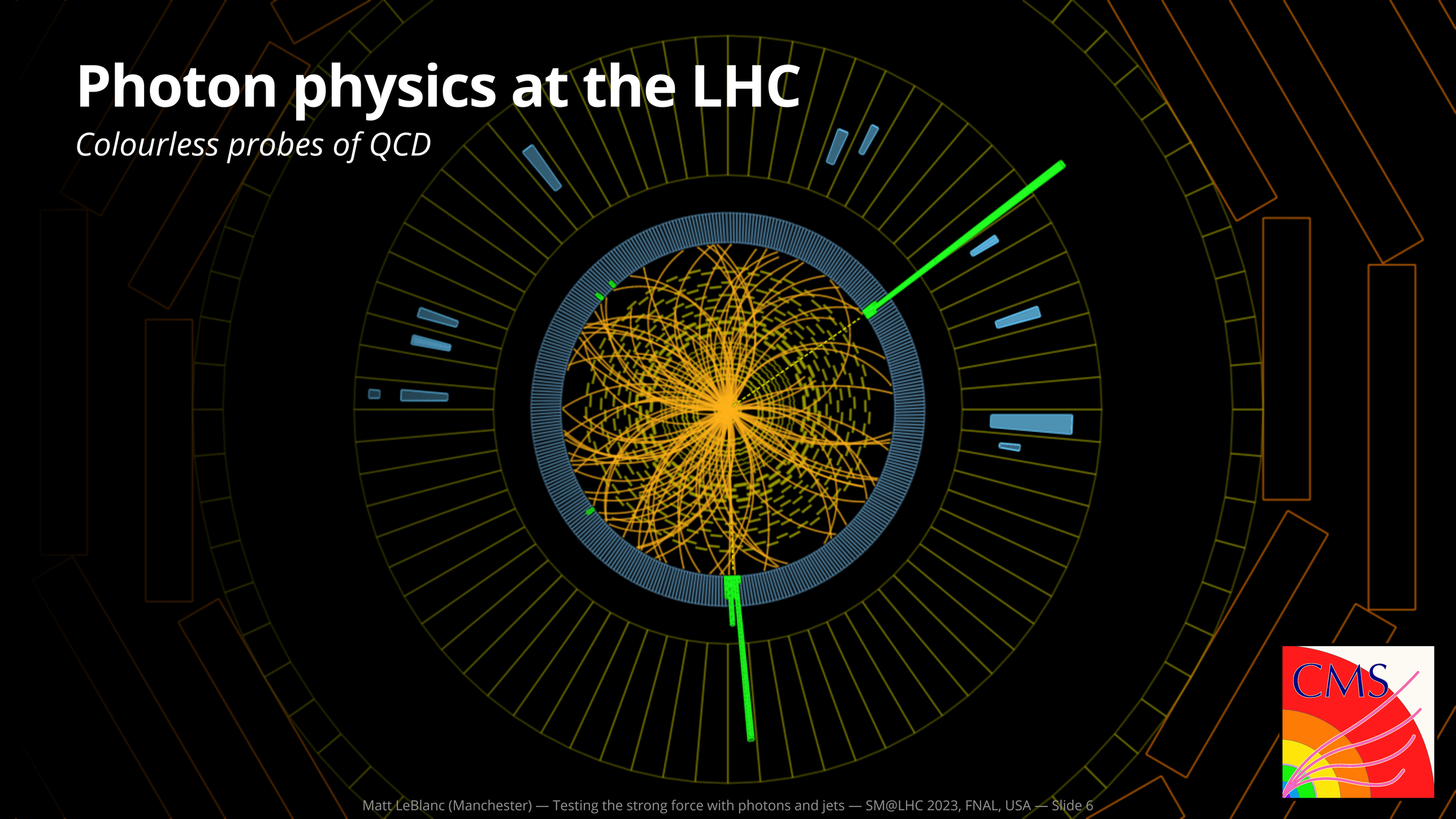
Photon physics at the LHC

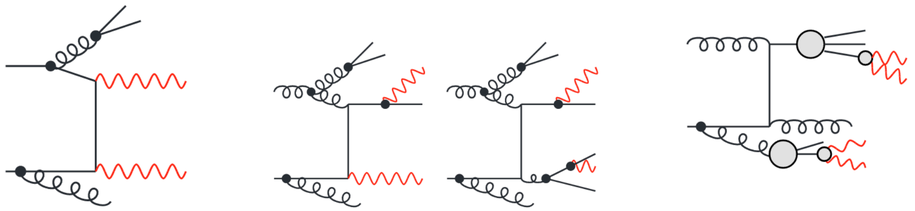
Colourless probes of QCD



Inclusive/isolated γ

ATLAS 2302.00510, CMS 1807.00782.

- Photon production tests QCD while minimising sensitivity to non-perturbative processes (hadronisation, colour reconnection, *etc.*)
- Major experimental challenge for photon cross-section measurements: estimation of multijet background (high-p_T π^0 decays).

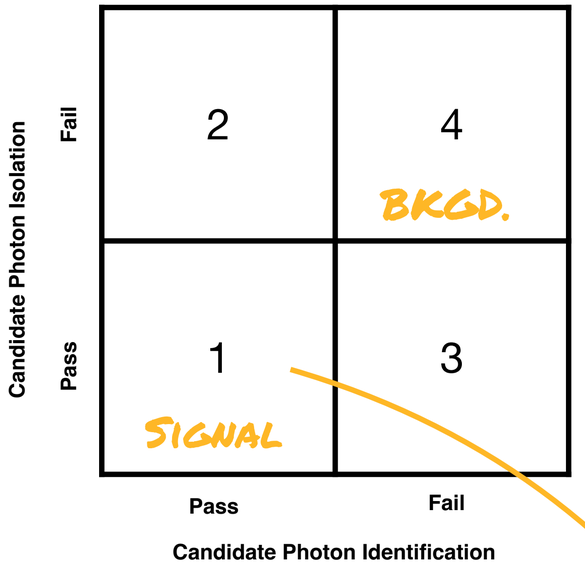


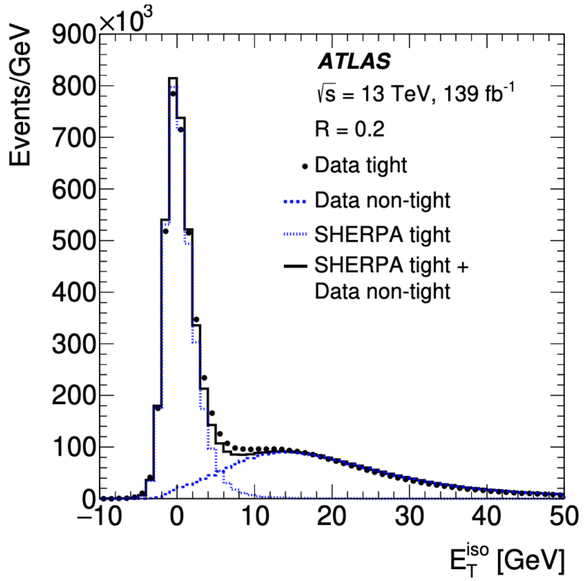
✓ Direct Photons

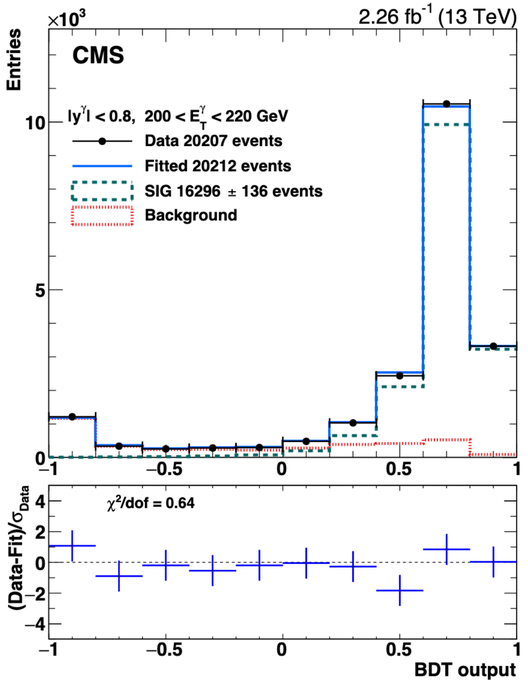
✓ Fragmentation Photons

✗ "Non-prompt" Photons ($\pi^0 \to \gamma\gamma$)

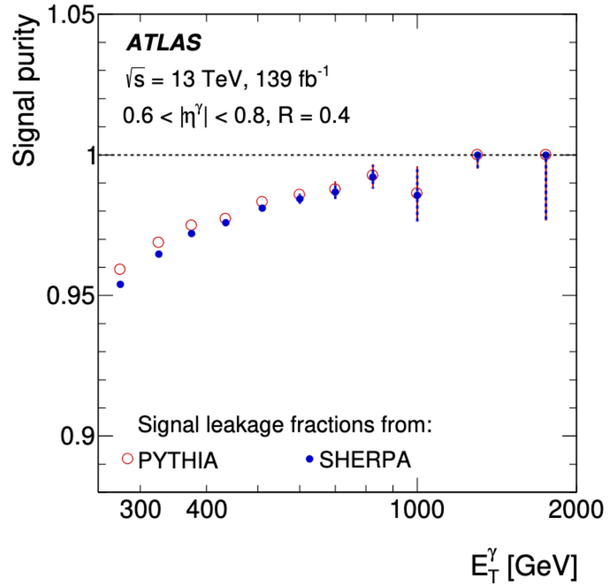
- Double-sideband estimation in photon **identification** and **isolation** used by both ATLAS and CMS.
- *Subleading backgrounds: electrons faking photons, pile-up photons.*







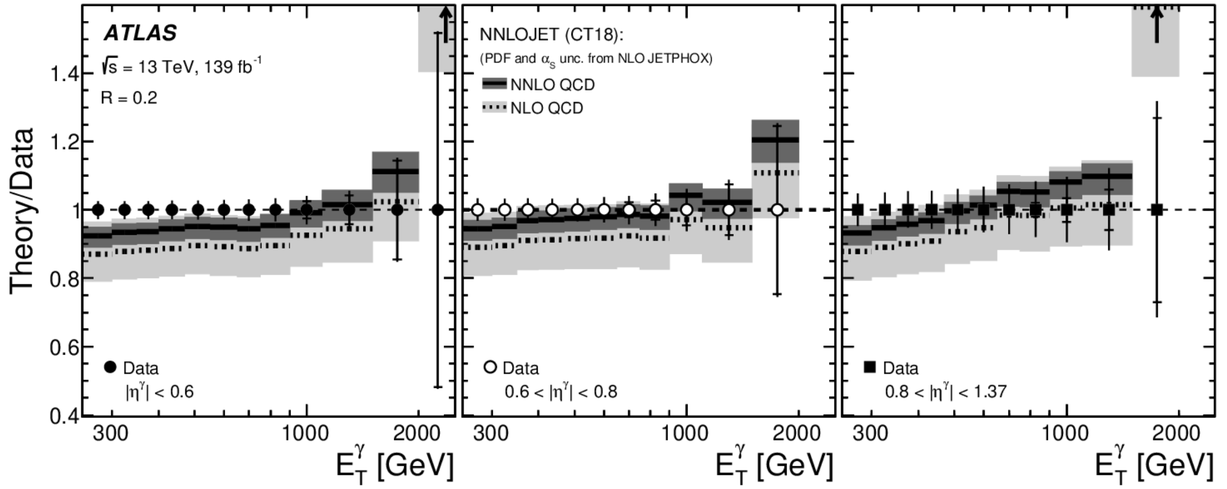
"Signal Leakage Fractions" from MC account for signal contamination in ATLAS control regions

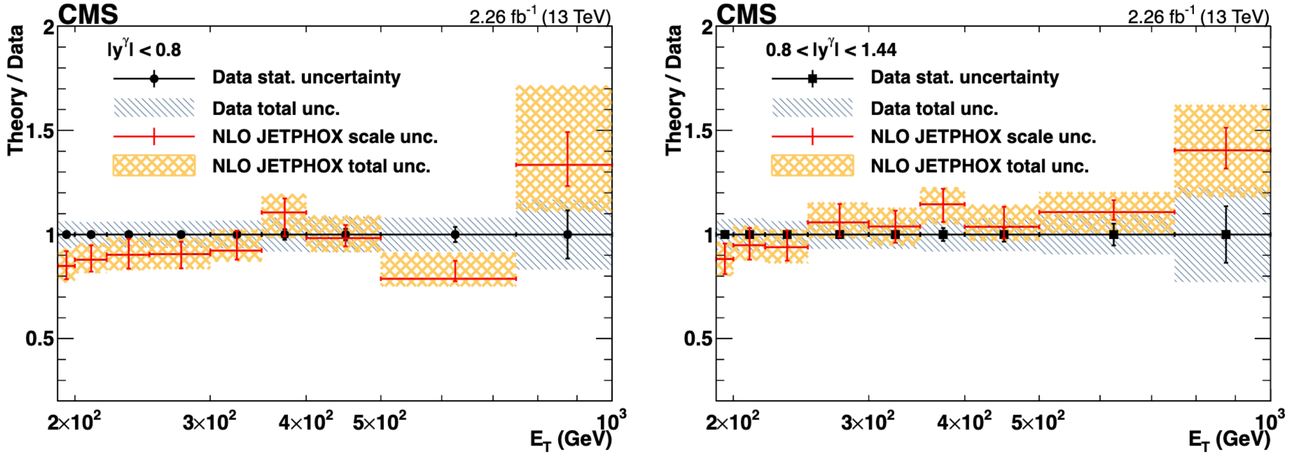


Inclusive/Isolated *γ*, *γ*+jet Cross-Sections

ATLAS 2302.00510, CMS 1807.00782.

- Measured cross-section compared to pQCD predictions across a broad range of transverse energy and rapidity bins.
  - Good agreement generally observed between data and NLO (both), NNLO (ATLAS) theory.
- Dominant uncertainty from photon energy scale (ATLAS), background estimation (CMS).

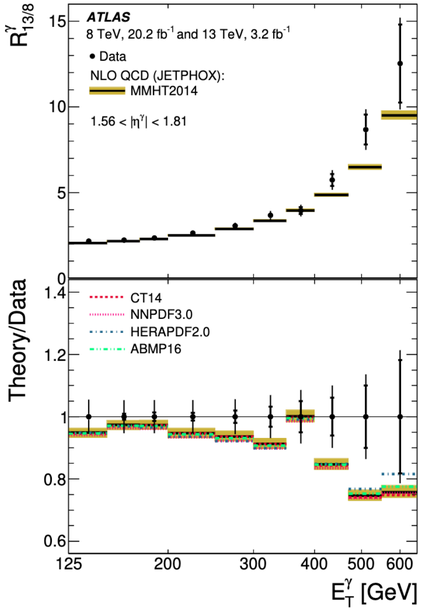




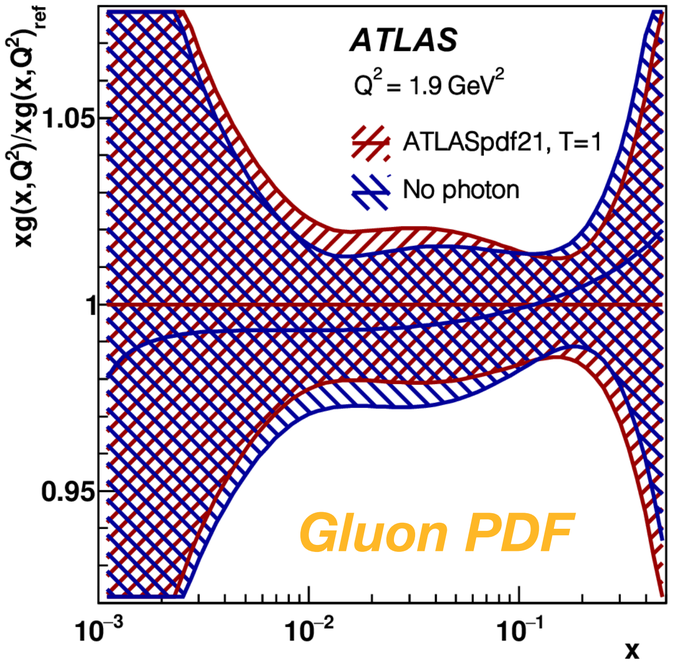
Inclusive/Isolated *γ*, *γ*+jet Cross-Sections

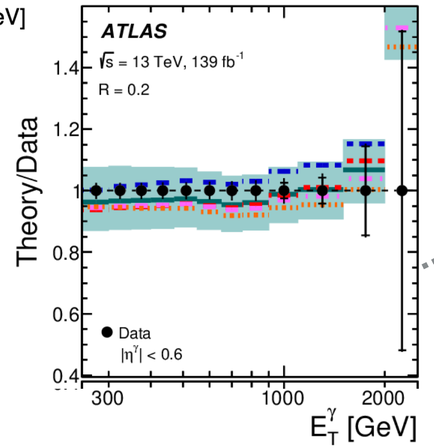
ATLAS 2302.00510, CMS 1807.00782.
For more on PDFs: ATLAS 2112.11266, 13 TeV / 8 TeV photon cross-section ratio: 1901.10075

- Measured cross-section compared to pQCD predictions across a broad range of transverse energy and rapidity bins.
  - Good agreement generally observed between data and NLO (both), NNLO (ATLAS) theory.
- Dominant uncertainty from photon energy scale (ATLAS), background estimation (CMS).
- Main production mechanism $qg \rightarrow q\gamma$, leads to gluon PDF sensitivity.
  - Measured data no longer in tension with other inputs to global PDF fits (20+ year tension)!



13 TeV / 8 TeV cross-section ratio had only 3.2 fb⁻¹ of 13 TeV data!





Full Run 2 impact?
Improved statistical power & experimental precision!

Inclusive/Isolated *γ*, *γ*+jet Cross-Sections

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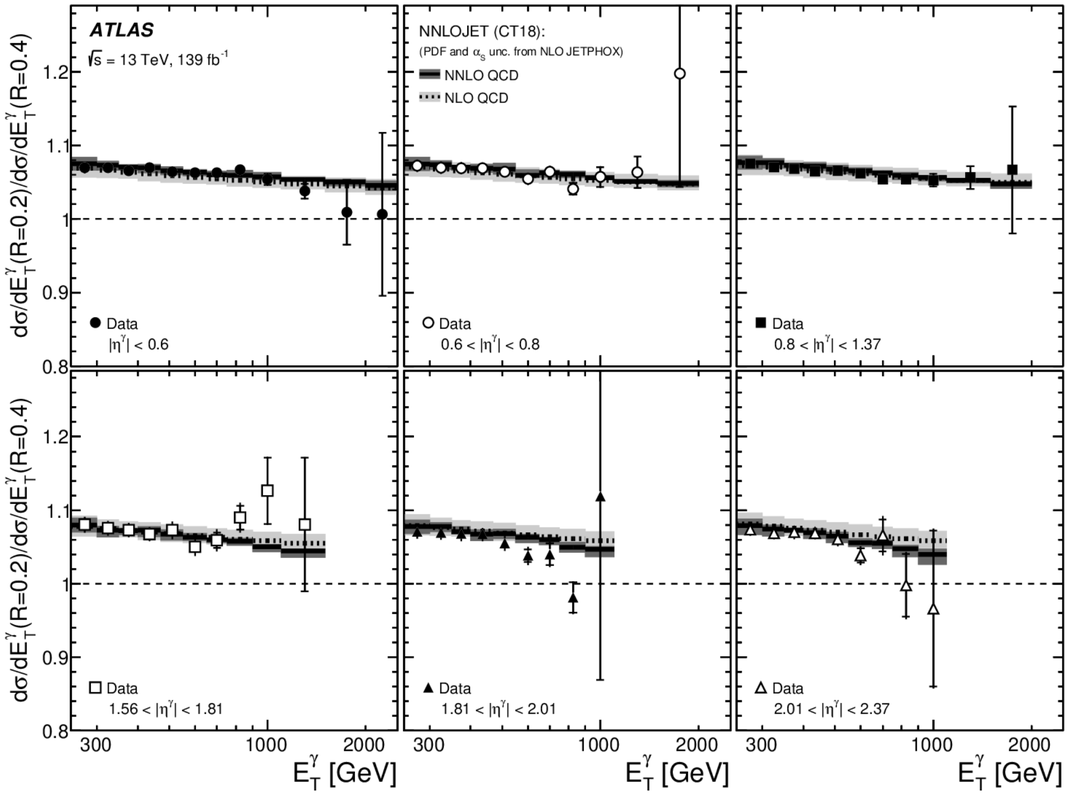
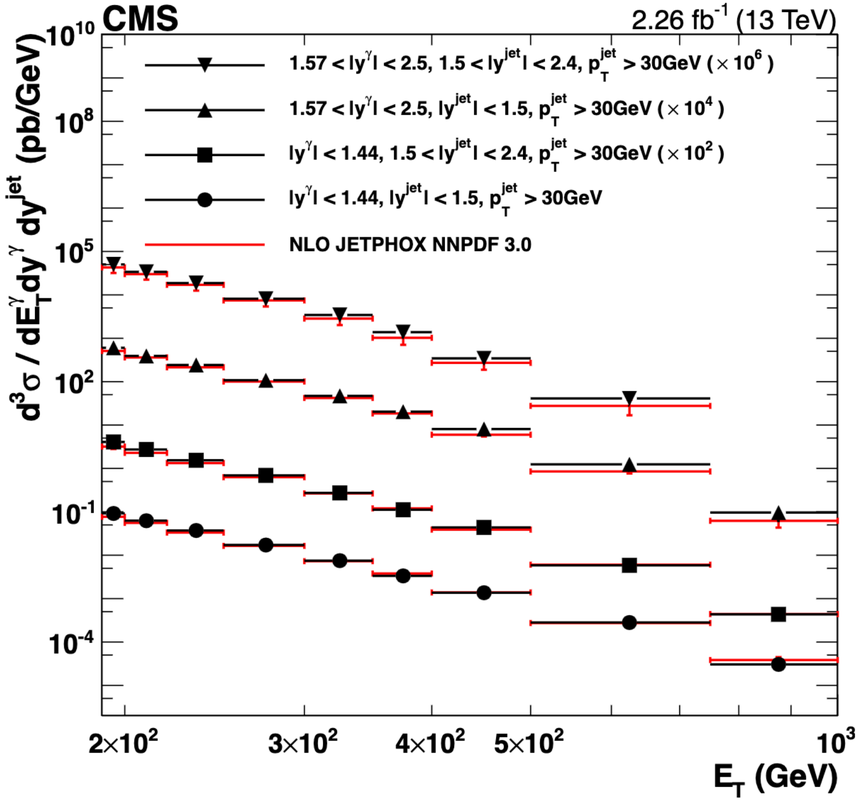




ATLAS : cross-section *vs.* isolation radius *R*

Investigates dependence of fiducial cross-section on isolation-cone radius *R*.

No *R*-dependence at LO → direct test of higher-order contributions!

CMS measured *γ*+jet cross-section at 13 TeV

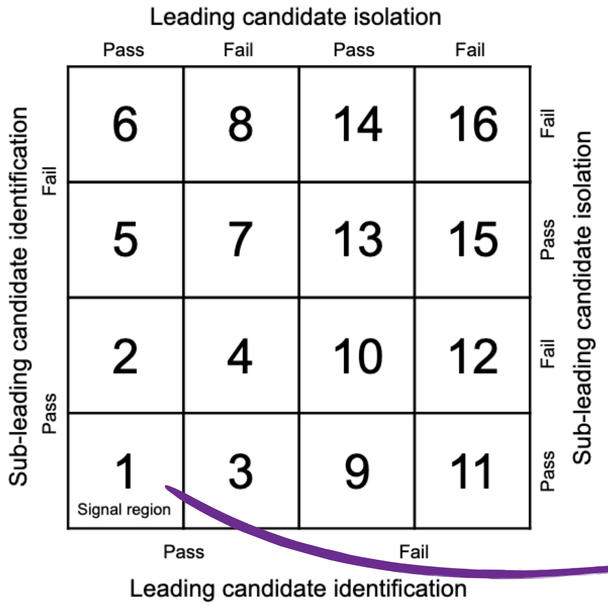
Run 2 centre-of-mass energy greatly extends kinematic reach of measurement vs. 7 TeV results (previously ended at 400 GeV)

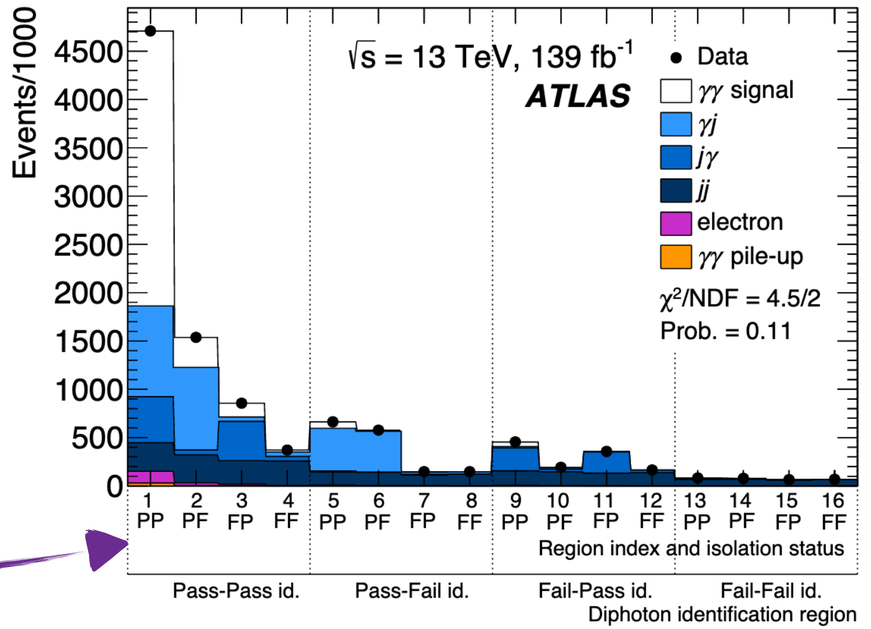
→ good agreement between data & NLO in central region!

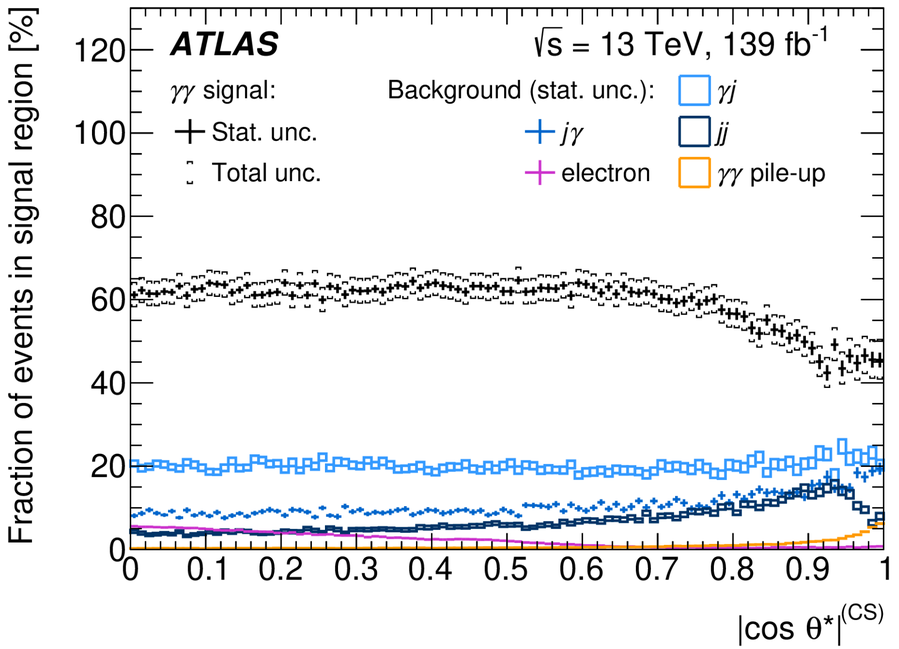
Diphotons ($\gamma\gamma$)

ATLAS 2107.09330

- Continuum diphotons are a **critical Higgs background!**
  - Sophisticated predictions, need *in situ* validation
- Main experimental challenge : **data-driven background estimation** of non-prompt photons from jets.
  - Signal contribution from Poisson likelihood fit in uncorrelated Iso & ID observables, *for each photon, for each measurement bin.*
- Several simple & complex observables measured, probing different QCD effects.
- Small but interesting **background of photons from uncorrelated pile-up interactions**.
  - Data-driven estimate from converted photons in ID (~0.5% of available diphoton events can be used).
  - Extrapolate PV *z*-position from calorimeter pointing & conversion vertex information.







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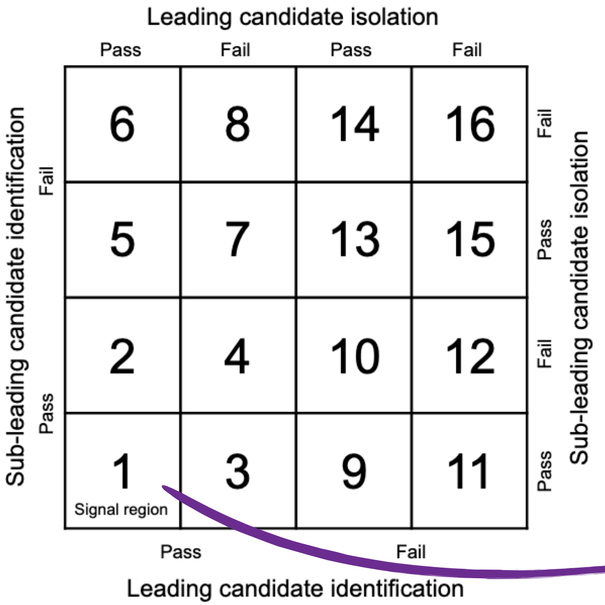
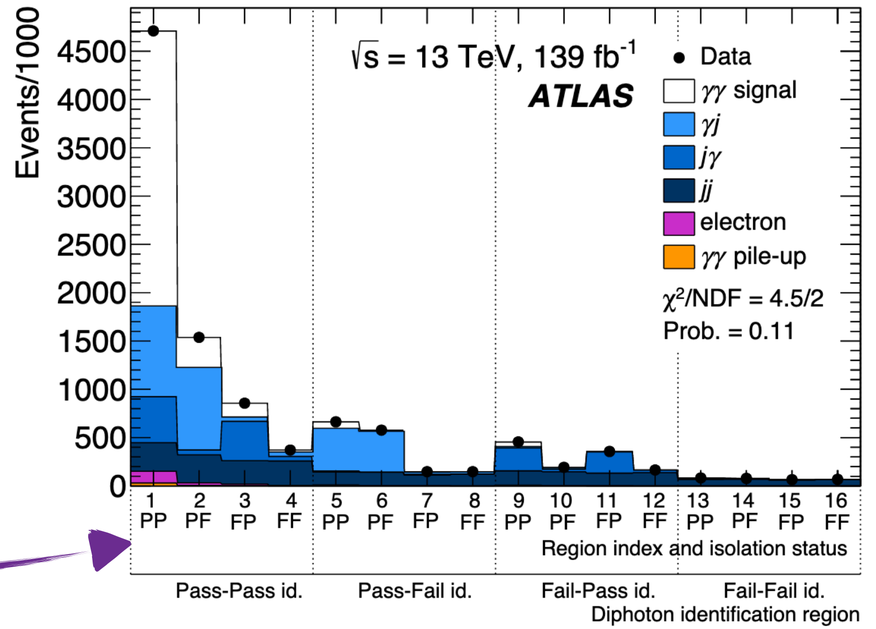
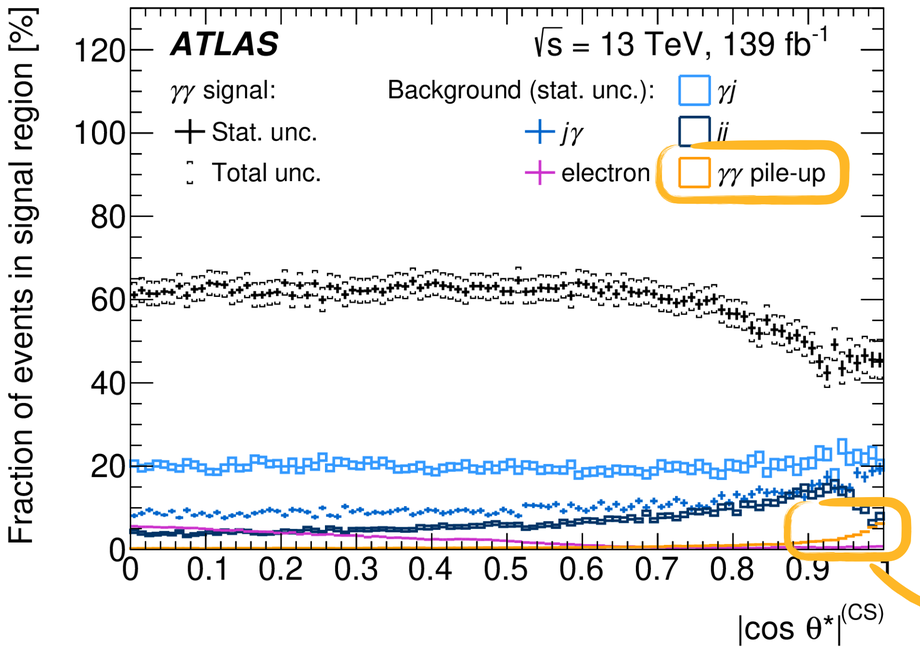
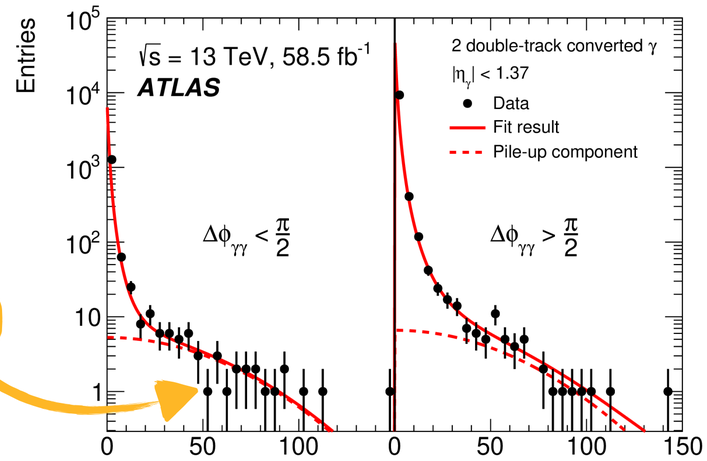






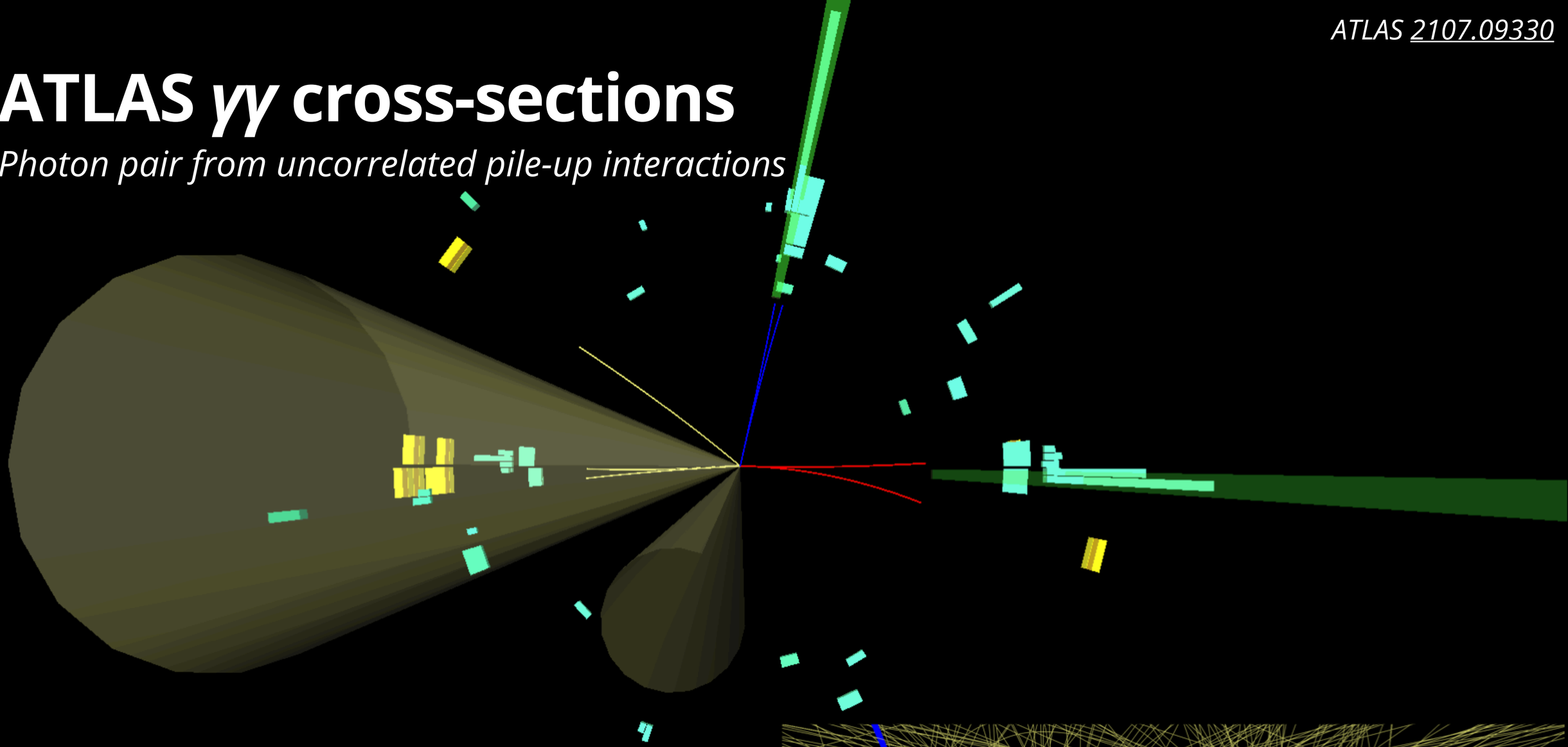
Uncorrelated pile-up γγ: largest contribution ~6% at high $|\cos\theta^*|^{(CS)}$



ATLAS 2107.09330

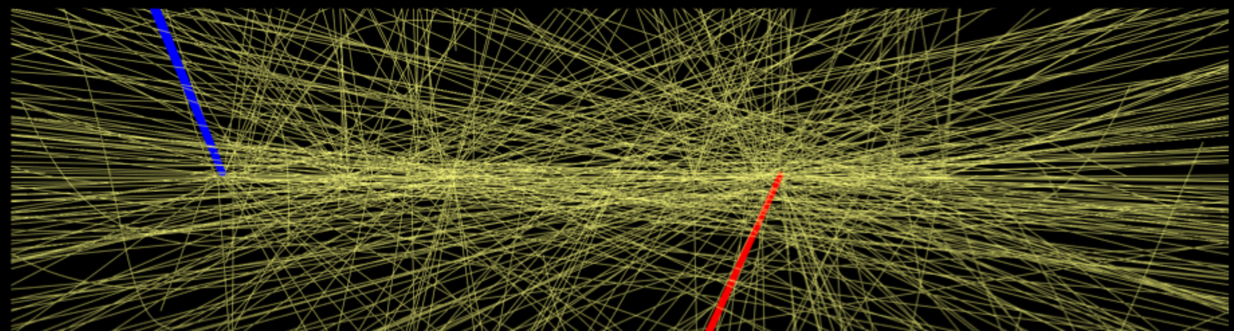
ATLAS *γγ* cross-sections

Photon pair from uncorrelated pile-up interactions



ATLAS EXPERIMENT

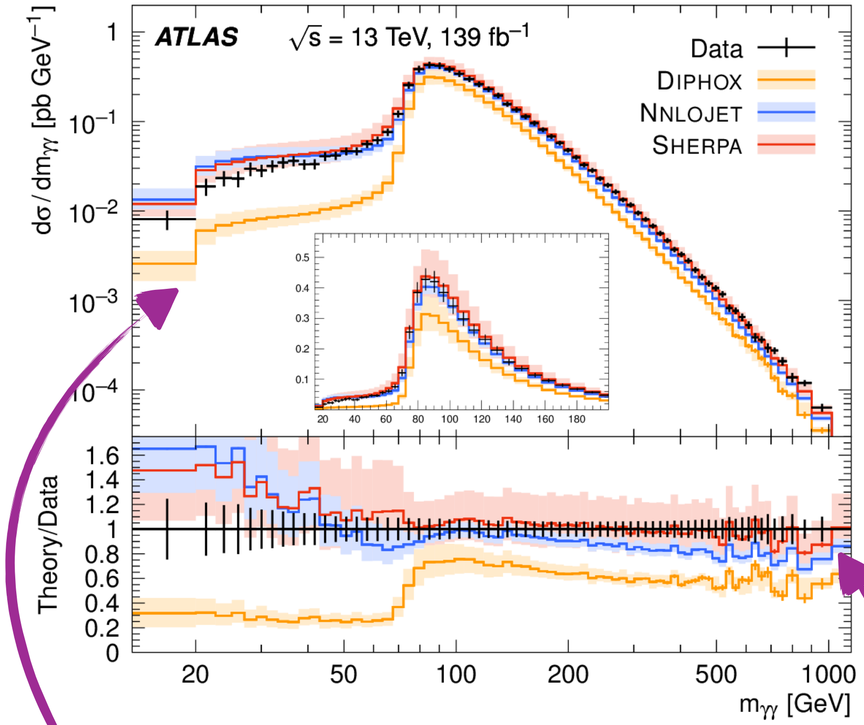
Run: 349451
Event: 680807571
2018-05-03 01:22:08 CEST



$\gamma\gamma$: results

ATLAS 2107.09330

	Fixed-order accuracy						Fragmentation		QCD	NP
	$\gamma\gamma$	$+1j$	$+2j$	$+3j$	$+\geq 4j$	$gg \to \gamma\gamma$	single	double	res.	effects
DIPHOX	NLO	LO	-	-	-	LO	NLO		–	–
NNLOJET	NNLO	NLO	LO	-	-	LO	–	–	–	–
SHERPA	NLO		LO		PS	LO	ME+PS		PS	✓



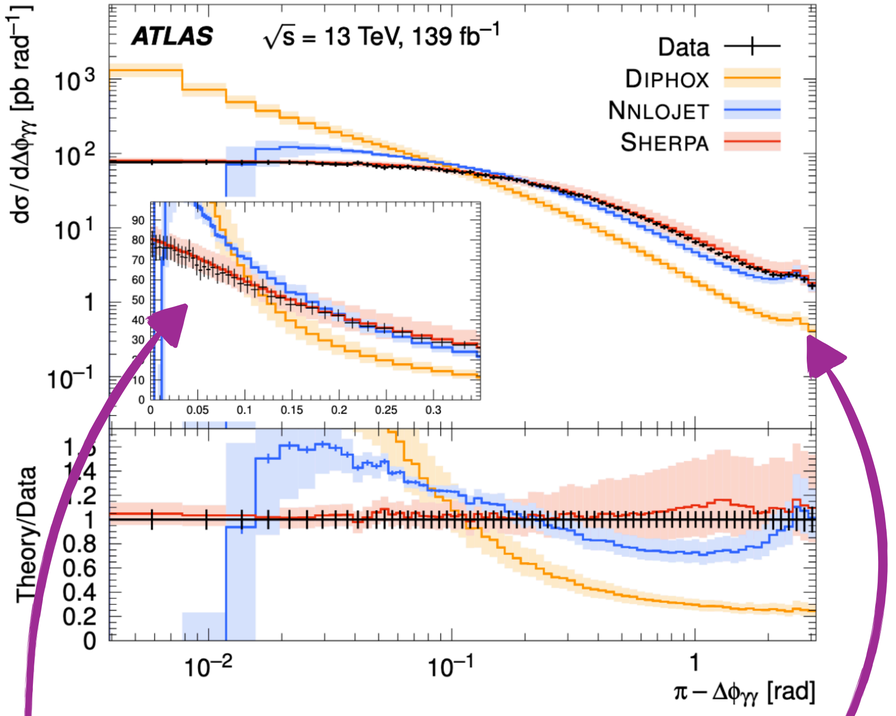
Low $m_{\gamma\gamma}$ region kinematically suppressed, populated by $\gamma\gamma$+multijets.

Benefits greatly from NNLO & multi-leg Sherpa treatment.

NNLO & NLO predictions underestimate high-$m_{\gamma\gamma}$ region.

Main systematics from background fit.

Statistically-limited in distribution tails.



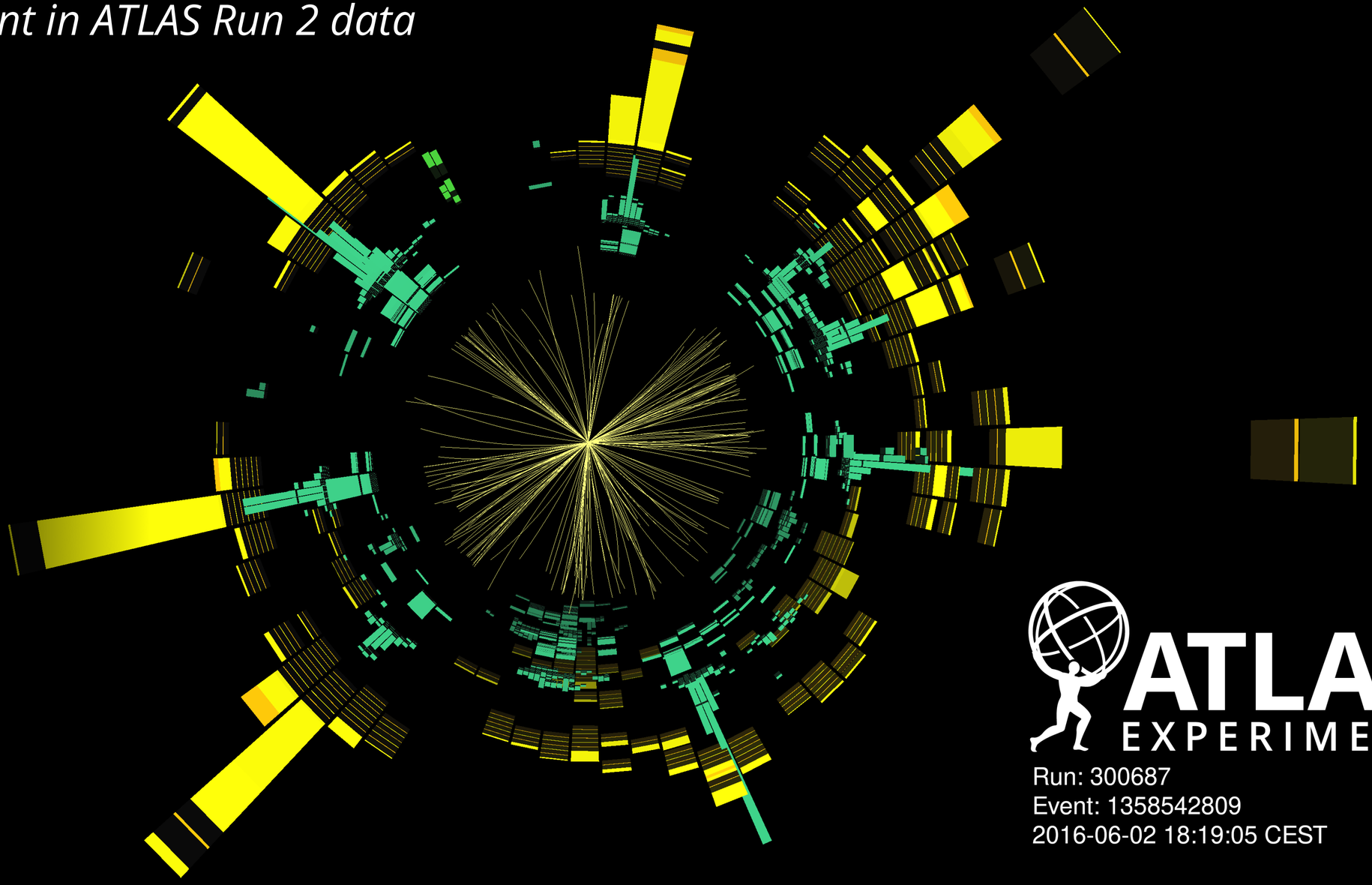
Back-to-back : sensitive to soft/ collinear emissions.

PS resummation in Sherpa needed to reliably model.

NNLO improves agreement for larger azimuthal decorrelations.

Multijet cross-section measurements

Most ‘isotropic’ event in ATLAS Run 2 data



ATLAS EXPERIMENT

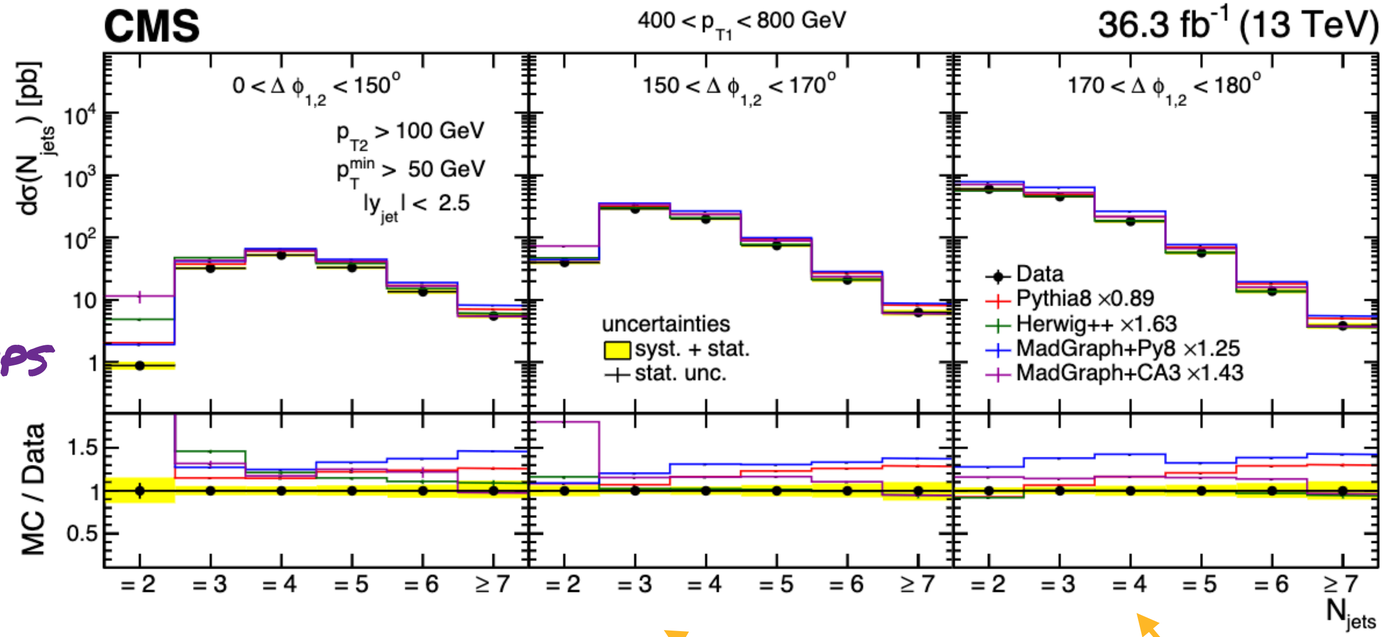
Run: 300687
Event: 1358542809
2016-06-02 18:19:05 CEST

N_{Jets} & p_T

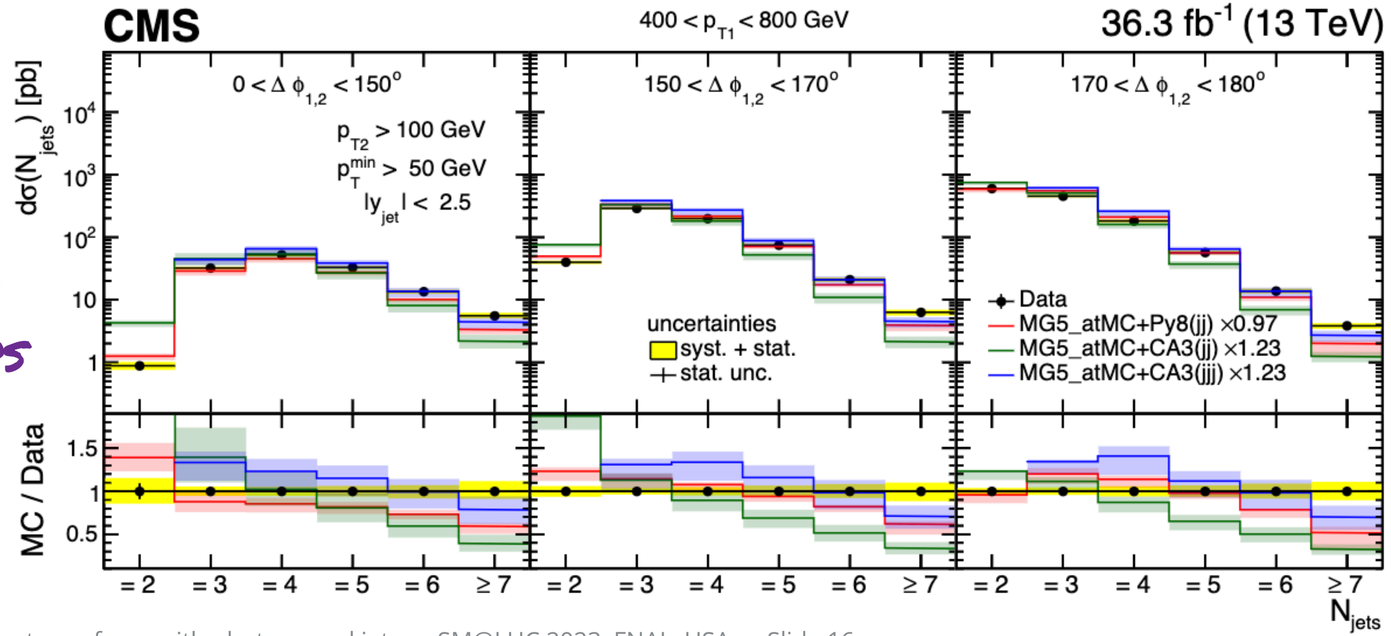
CMS 2210.13557

- Measurement of **jet multiplicity and p_T** in multijet events, **differential in leading jet p_T and dijet azimuthal separation** (shown).
  - Interpolating between 2- and 3+-jetty tpoologies.
    - Sensitive to higher-order QCD effects
  - **Compared to LO & NLO MC setups.**
    - **LO Herwig++** performs well for more collimated topologies!
    - **LO** & **NLO MG5_atMC+CA3** predictions include **transverse-momentum dependent parton densities** (PB-TMD) & PS
      → fewer tuneable parameters than other MC setups.
- Experimental **Jet Energy Scale** most relevant source of uncertainty.

LO SETUPS



NLO SETUPS

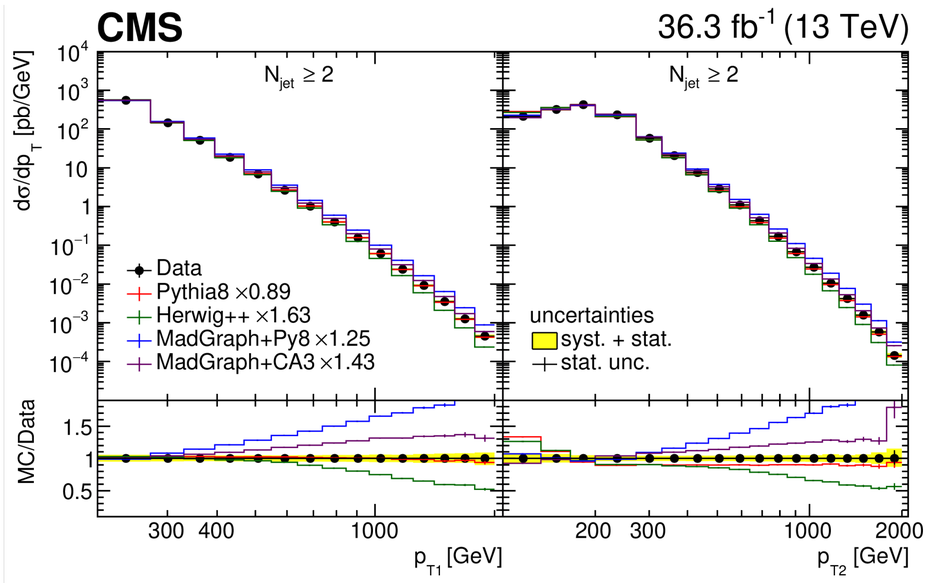


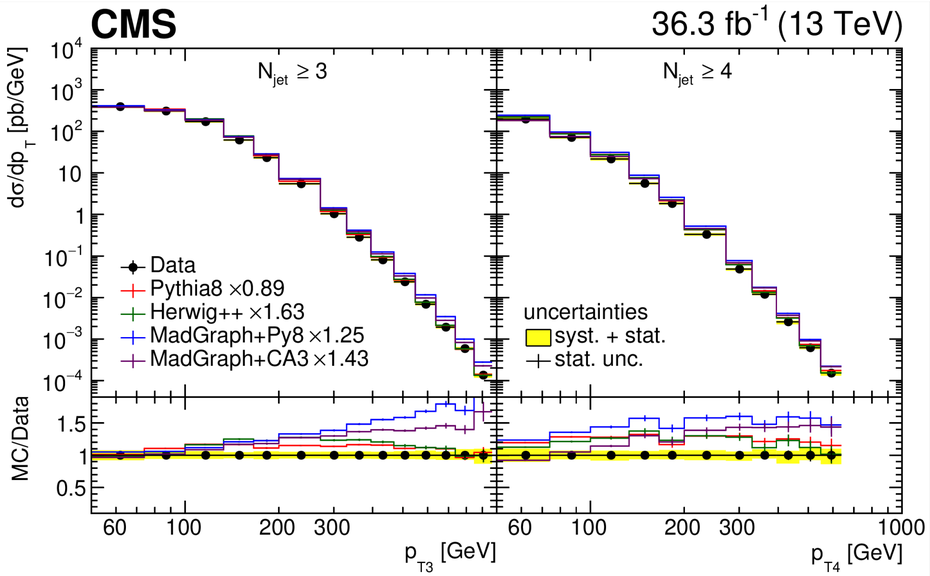
N_{Jets} & p_T

CMS 2210.13557

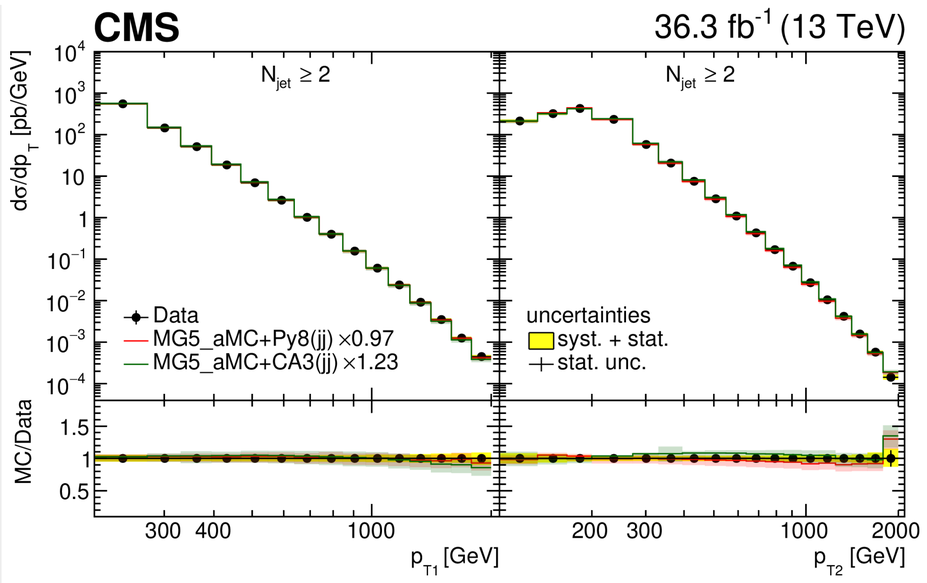
- Comparison of **measured p_T spectra for four leading jets** to LO (left) and NLO (right) predictions.
  - **NLO MG5_aMC+Py8** prediction provides accurate estimate of normalisation *(SF 0.97x)*.
  - 3-jet NLO **MG5_aMC+CASCADE3** describes radiation beyond leading jet pair “very well”!
  - Uncertainties from μ_R,μ_F variations in NLO predictions cover data/MC differences.
- Experimental **Jet Energy Scale** most relevant source of uncertainty.

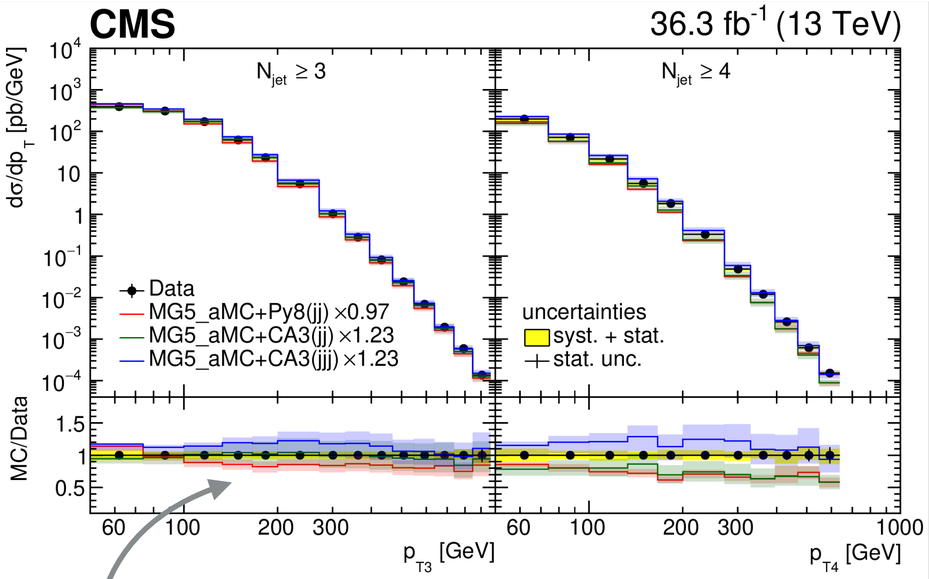
Leading-Order MC Setups





Next-to-Leading-Order MC Setups





Bands on NLO predictions indicate uncertainty from μR, μF variation.

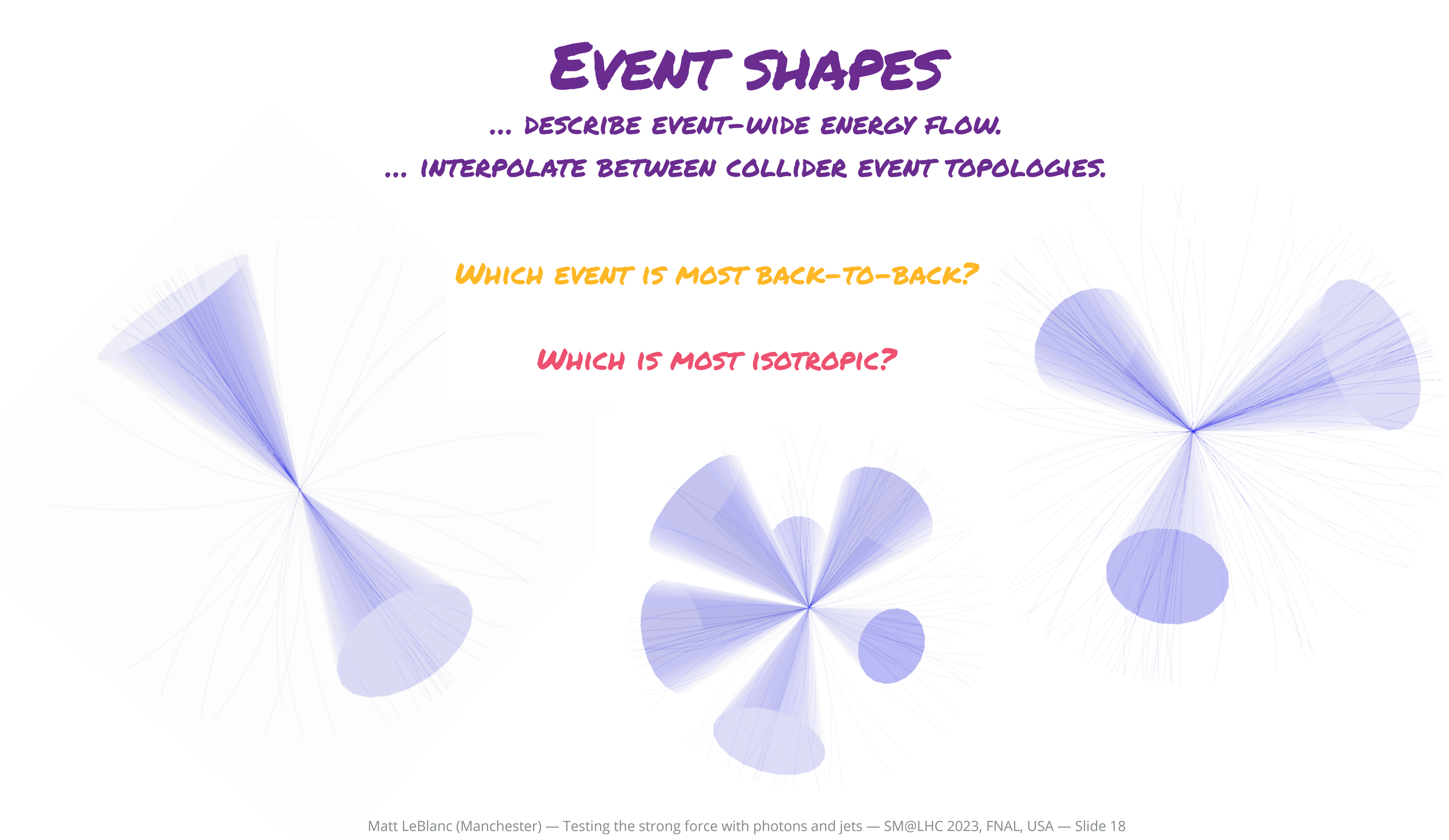
Event shapes

... describe event-wide energy flow.

... interpolate between collider event topologies.

Which event is most back-to-back?

Which is most isotropic?



Event Shapes

CMS 1811.00588, ATLAS 2007.12600

- A staple of QCD, event shapes describe the energy flow in particle collisions.
  - Widespread applications over 50 years, including gluon observation @ PETRA, α_S extractions at LEP, MC tuning and improvement, *etc., etc.*
  - Testbed data for theoretical predictions and Parton Shower Monte Carlo (PSMC) programs.
- ATLAS and CMS have both revisited Event Shapes during Run 2.
  - Larger dataset allows **multi-differential measurements**.
  - Both measurements using **calibrated R=0.4 jets** as inputs to Event Shape calculations.
    - Good precision due to **excellent jet performance!**
      - *For latest, see e.g. ATLAS 2303.17312* (new!)

	ATLAS	***CMS***
Inputs	Calibrated jets	Calibrated jets
Differential binning	H_{T2}, N_{jet} (incl. & excl.)	H_{T2}
Dataset	140 fb^{-1}	2.2 fb^{-1}
Transverse Thrust	✓	✓
Transverse thrust (minor)	✓	
Transverse Sphericity	✓	
C-parameter	✓	
D-parameter	✓	
Total jet broadening		✓
Total jet mass		✓
Total transverse jet mass		✓

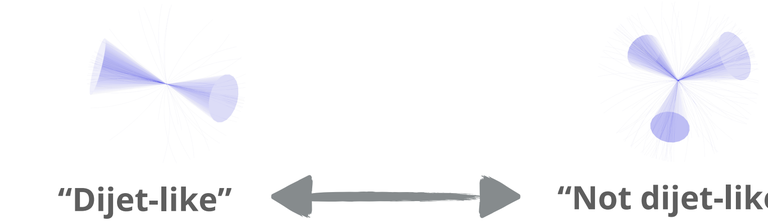
Transverse thrust

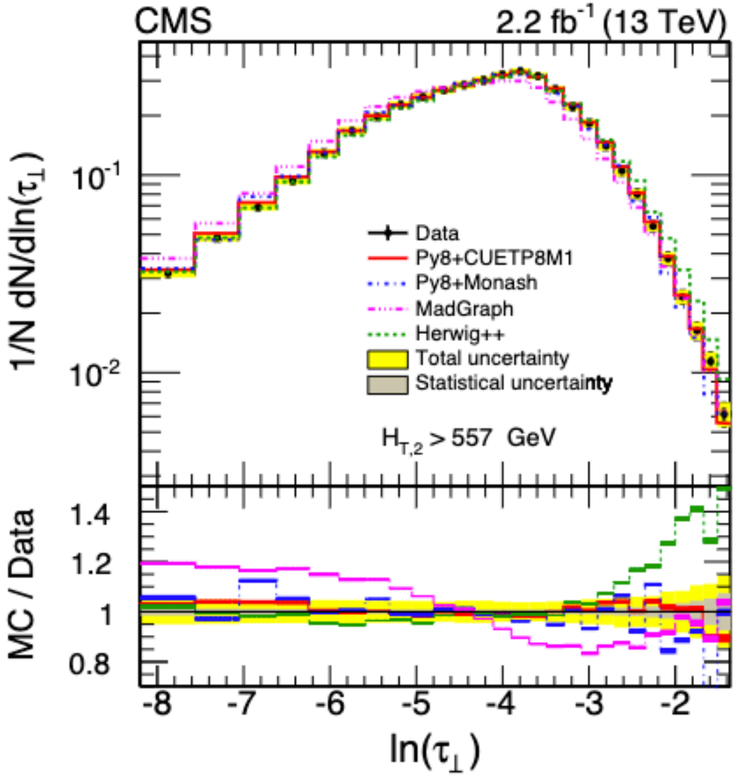
CMS 1811.00588, ATLAS 2007.12600

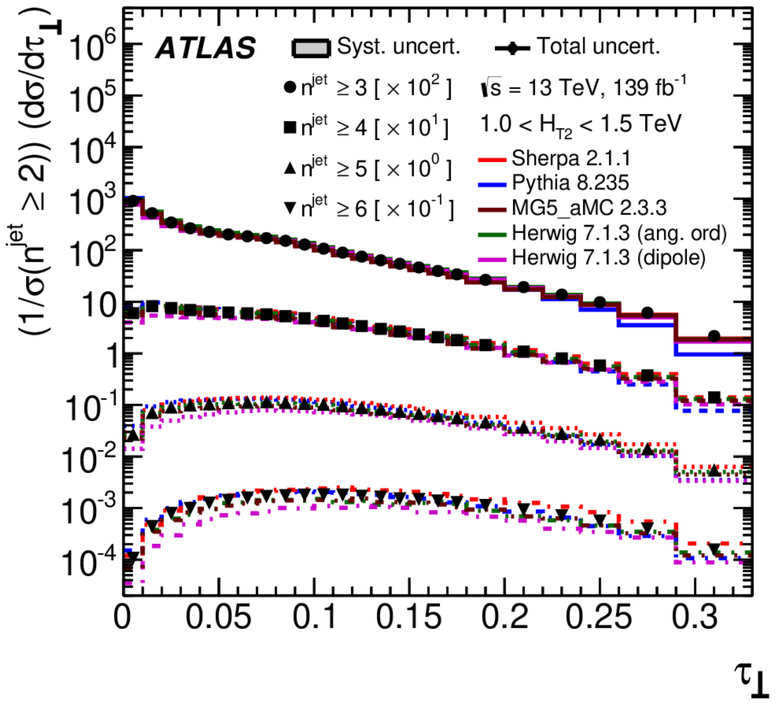
"How *dijet-like* is the event?"

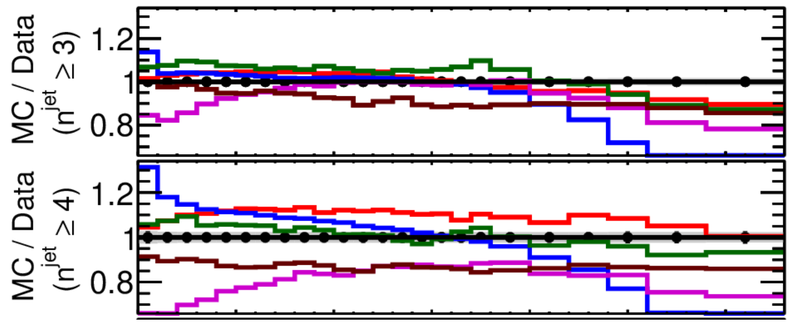
$$T_\perp = \max_{\hat{n}_\mathrm{T}} \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}_\mathrm{T}|}{\sum_i |\vec{p}_{\mathrm{T},i}|}; \qquad T_m = \frac{\sum_i |\vec{p}_{\mathrm{T},i} \times \hat{n}_\mathrm{T}|}{\sum_i |\vec{p}_{\mathrm{T},i}|}$$

- ATLAS and CMS measurements complementary
  - high- *vs.* low-pT focus
- LO+LL MC generators struggle to describe non-dijet-like region adequately.
  - Agreement slightly better for **NLO H7** and multi-leg **Sherpa 2.1.1** setups.
  - Agreement improves with increasing energy scale, as events become more collimated (refer to publications).









Aplanarity

ATLAS 2007.12600

“How *planar* is the event?”

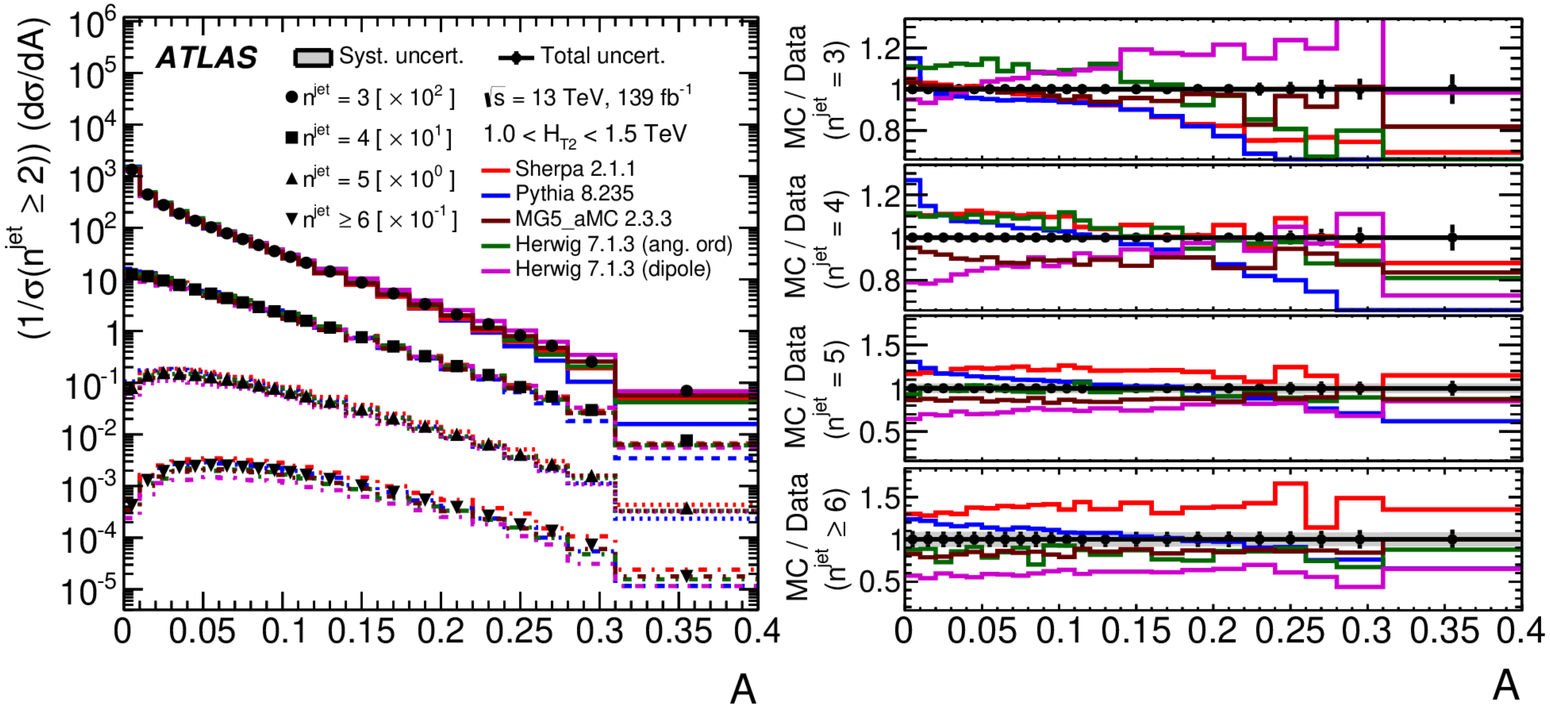
$$\mathcal{M}_{xyz} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} & p_{x,i}p_{z,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 & p_{y,i}p_{z,i} \\ p_{z,i}p_{x,i} & p_{z,i}p_{y,i} & p_{z,i}^2 \end{pmatrix} \quad S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

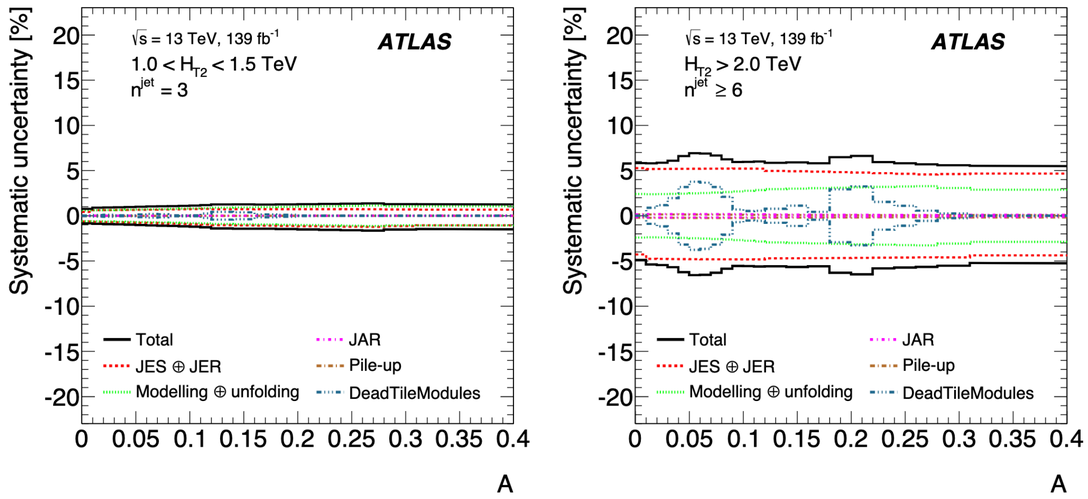
EIGENVALUE OF LINEARISED SPHERICITY TENSOR:

$$A = \frac{3}{2}\lambda_3$$

- Agreement in normalisation degrades as jet multiplicity increases (also seen for other observables).
- Sensitive to **perturbative physics** in PS alg.
  - NLO H7 **angle-ordered** and **dipole** showers disagree for both small & large values.
  - **Pythia** does not predict enough planar 3- and 4-jet events.
  - **MG5_aMC@NLO** performs well, even at higher N_{Jet}!

"Planar” ⟷ “Not planar”





Precision of Event Shape measurements generally limited by the Jet Energy Scale and choice of MC Model for unfolding.

Total jet broadening

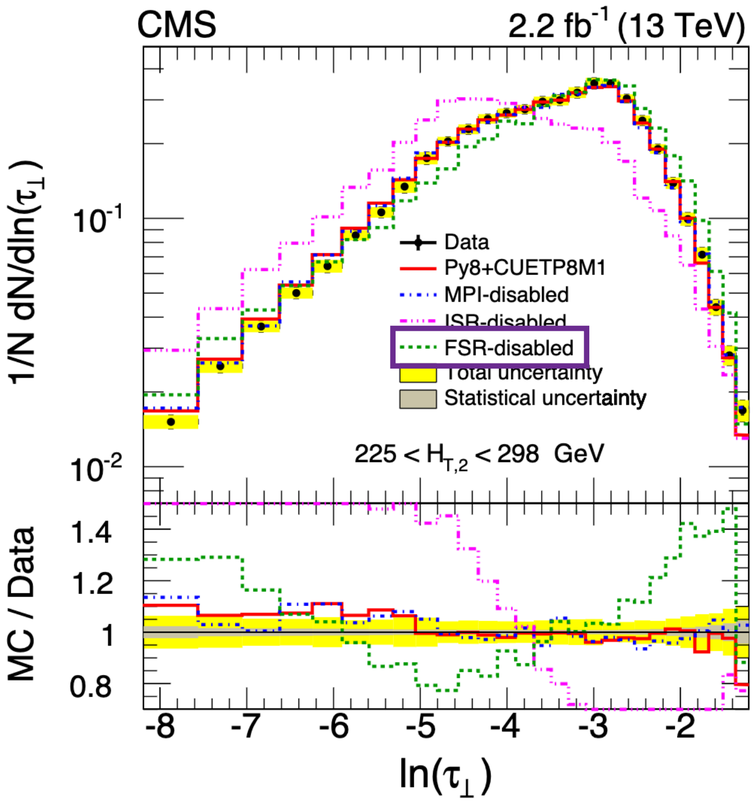
CMS 1811.00588

"How *distributed* is energy within the thrust hemispheres?"

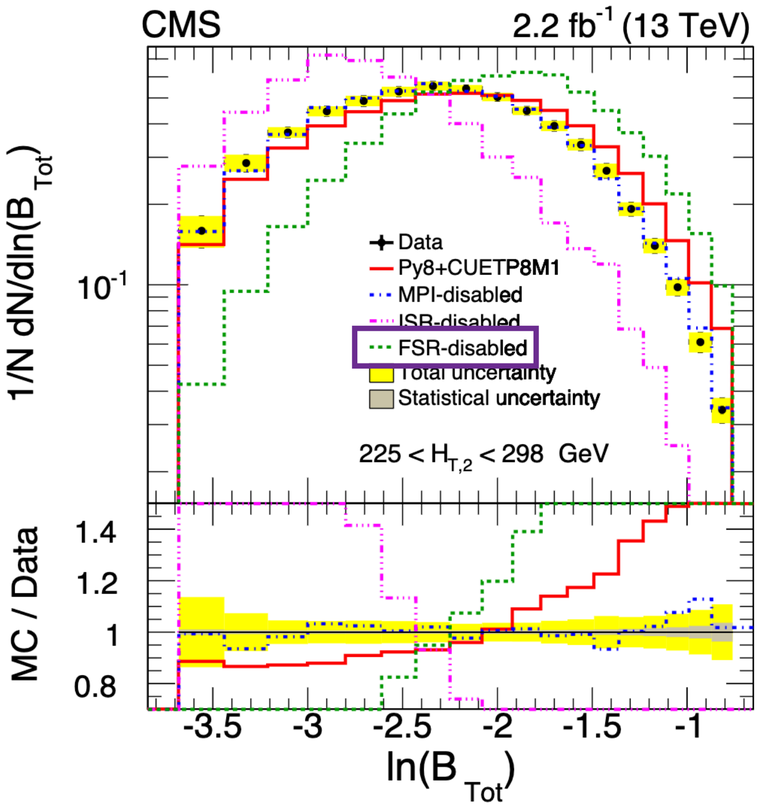
$$B_X \equiv \frac{1}{2\,P_T} \sum_{i \in X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2},$$

- Event Shapes like Broadening are sensitive to npQCD effects (hadronisation / FSR, etc.).
- Improvement in data / MC agreement generally seen as energy scale increases.
  - Radiation becomes more collimated / 'back-to-back,' easier for LO+PS predictions.

Transverse Thrust



Total Broadening



Broadening is more sensitive to ISR/FSR treatment!

Total jet broadening

CMS 1811.00588

"How *distributed* is energy within the thrust hemispheres?"

$$B_X \equiv \frac{1}{2\,P_T} \sum_{i \in X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2},$$

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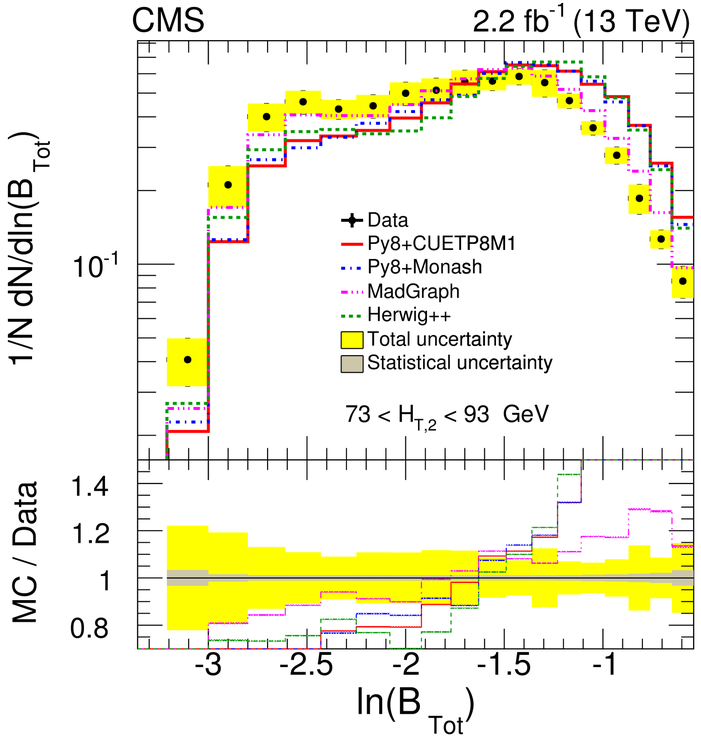
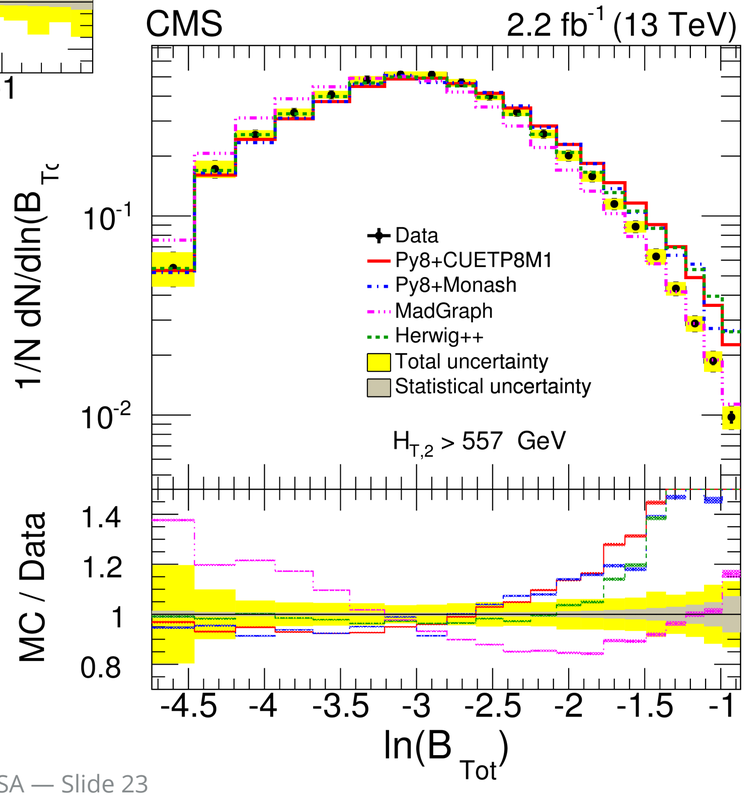


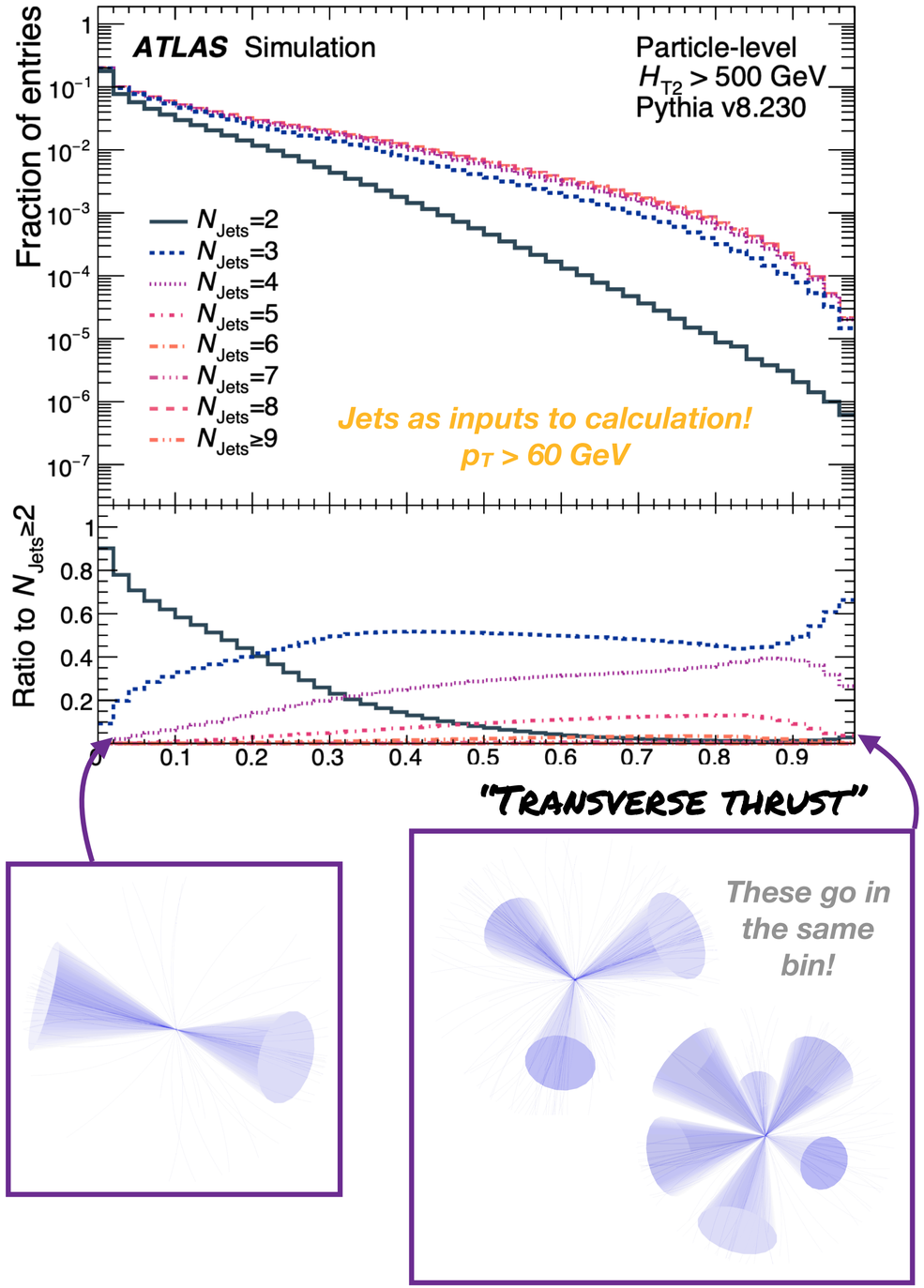
INCREASE HT2 ... EVENT BECOMES MORE "BACK-TO-BACK" BETTER DESCRIPTION!



Energy-Mover's Distance (EMD)

Komiske, Metodiev & Thaler, 1902.02346, 2004.04159
Cesarotti & Thaler, 2004.06125

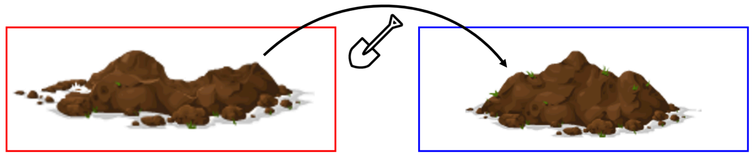
- Event shapes like Thrust identify back-to-back events, not isotropic ones.



Energy-Mover's Distance (EMD)

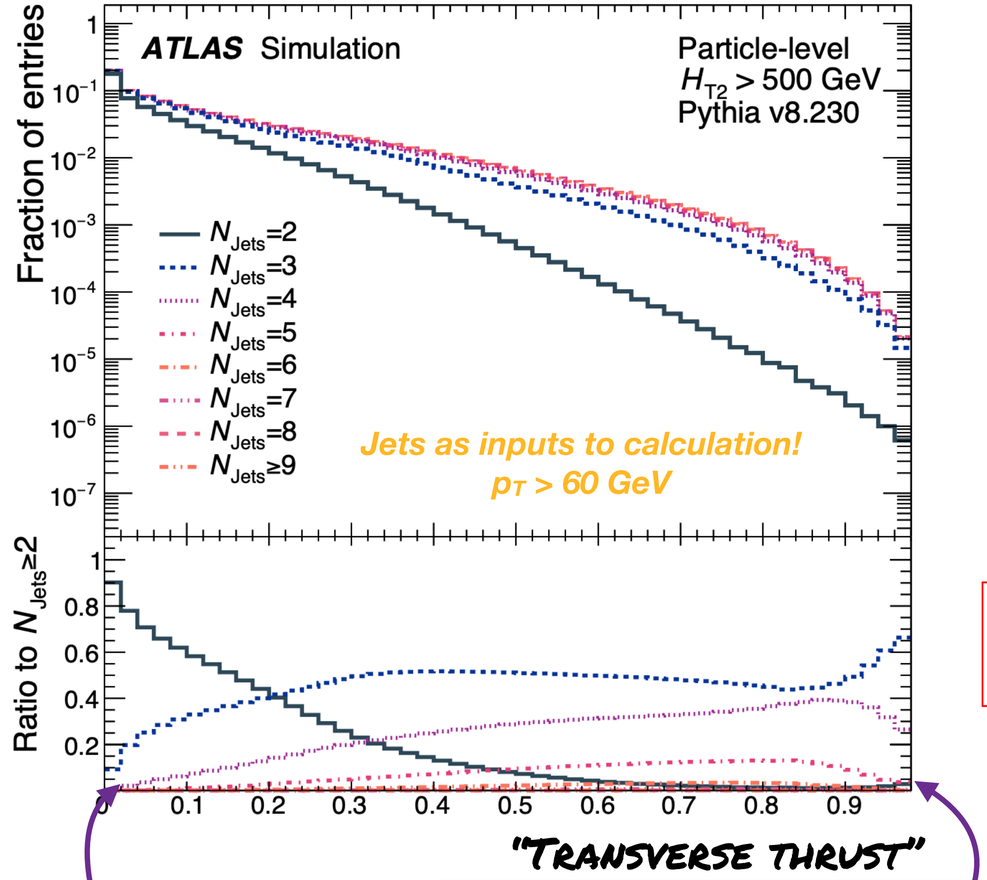
Komiske, Metodiev & Thaler, 1902.02346, 2004.04159
Cesarotti & Thaler, 2004.06125

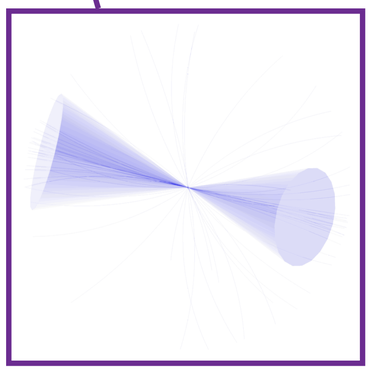
- Event shapes like Thrust identify back-to-back events, not isotropic ones.
  - To isolate rarer QCD configurations, we can use a new tool: an **IRC-safe distance metric** between collider radiation patterns.
    - EMD defined as the **minimum 'work' required to re-arrange one event into another**.

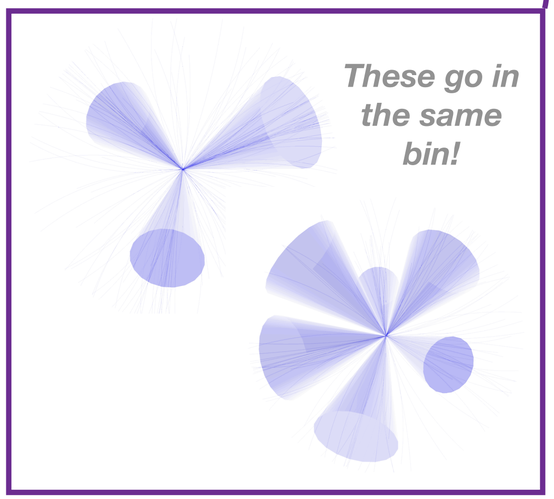


$$\mathrm{EMD}_\beta(\mathcal{E},\mathcal{E}') = \min_{\{f_{ij}\geq 0\}} \sum_{i=1}^{M}\sum_{j=1}^{M'} f_{ij}\theta_{ij}^{\beta}$$

      - a.k.a. the **Earth-Mover's Distance** or ***p*-Wasserstein** class of metrics.
- **Interdisciplinary tool, used for QCD analysis!**
  - EMDs used often in **computer vision**: problems solved w/ **Optimal Transport** techniques.
    - Common tools/libraries… 1, 2, 3
      - Some have been adapted for HEP! 4, 5
- EMDs used in 2004.06125 to **construct new event-shape observables** for certain BSM models … *utility for QCD studies?*

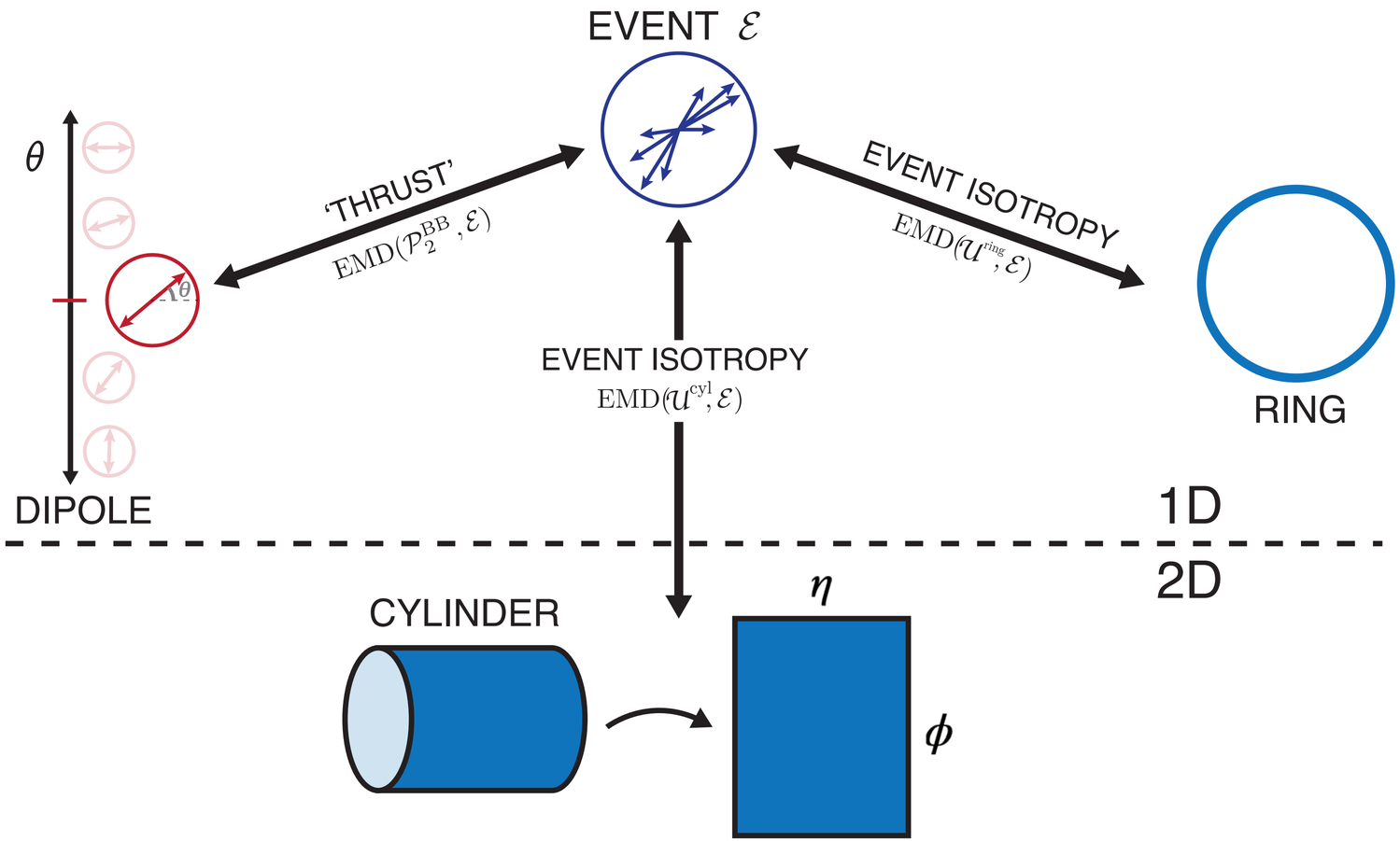






Event Isotropy: event shapes via Optimal Transport (OT)

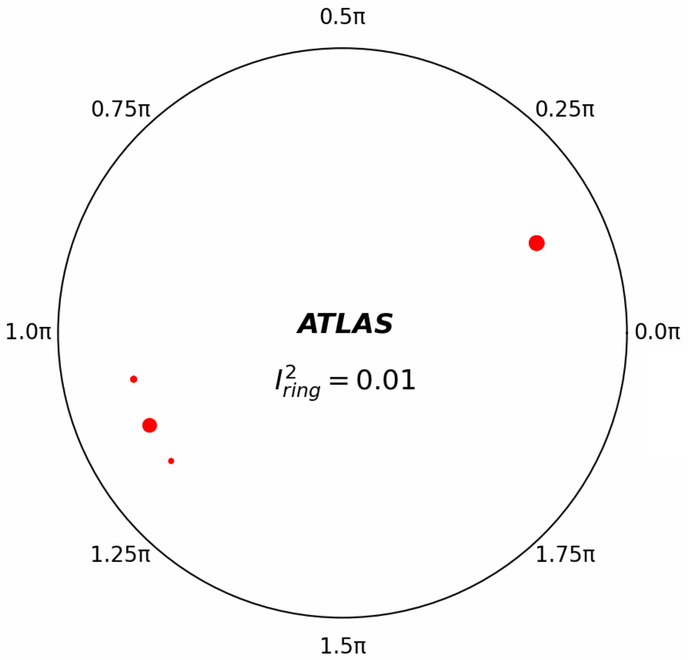
Cesarotti & Thaler, 2004.06125
***ATLAS** 2305.16930*

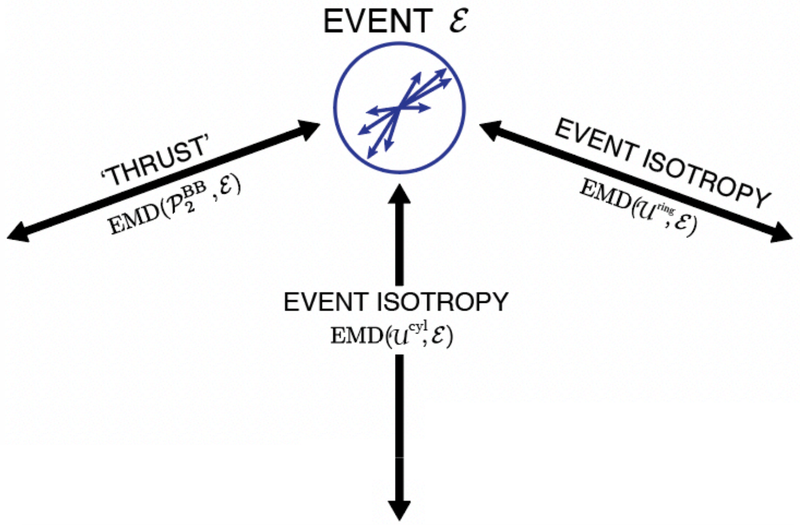


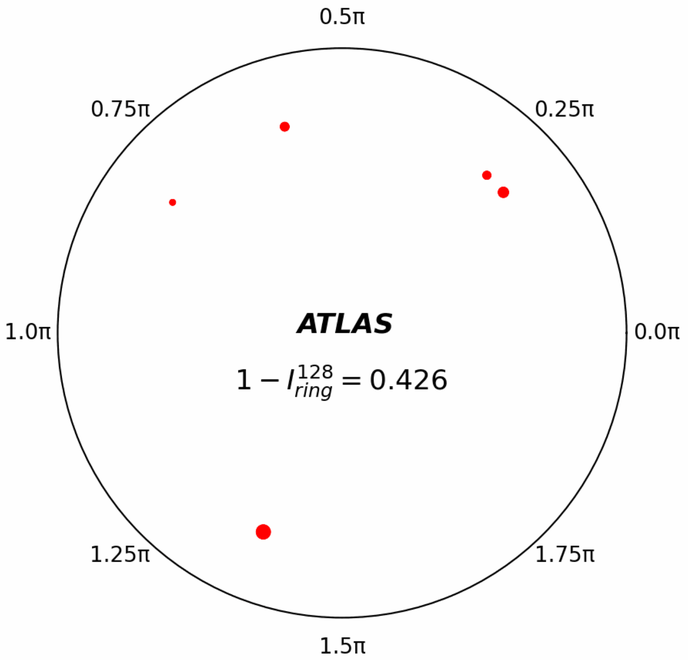
- **3 EMDs measured per-event:**
  - Two most-distant 1D configurations conserving transverse momentum.
  - 2D extension of isotropy into rapidity-phi space (**IsoCyl16**).
- Used ***R*=0.4 PFlow jets** ($p_{\mathrm{T}} > 60$ GeV, $|y| < 4.4$) as inputs to EMD calculations.
- Measurements in inclusive bins of **jet multiplicity** and $\boldsymbol{H_{\mathrm{T2}} = p_{\mathrm{T},1} + p_{\mathrm{T},2}}$.

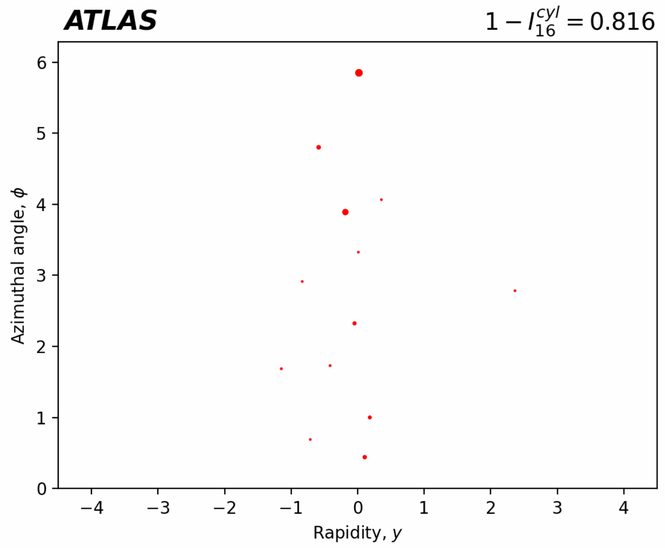
Visualisation of Optimal Transport calculations

ATLAS *2305.16930*





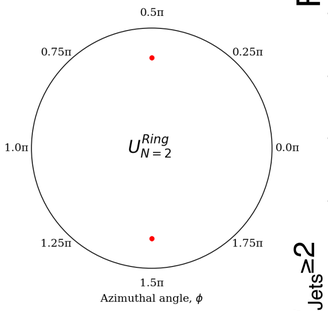


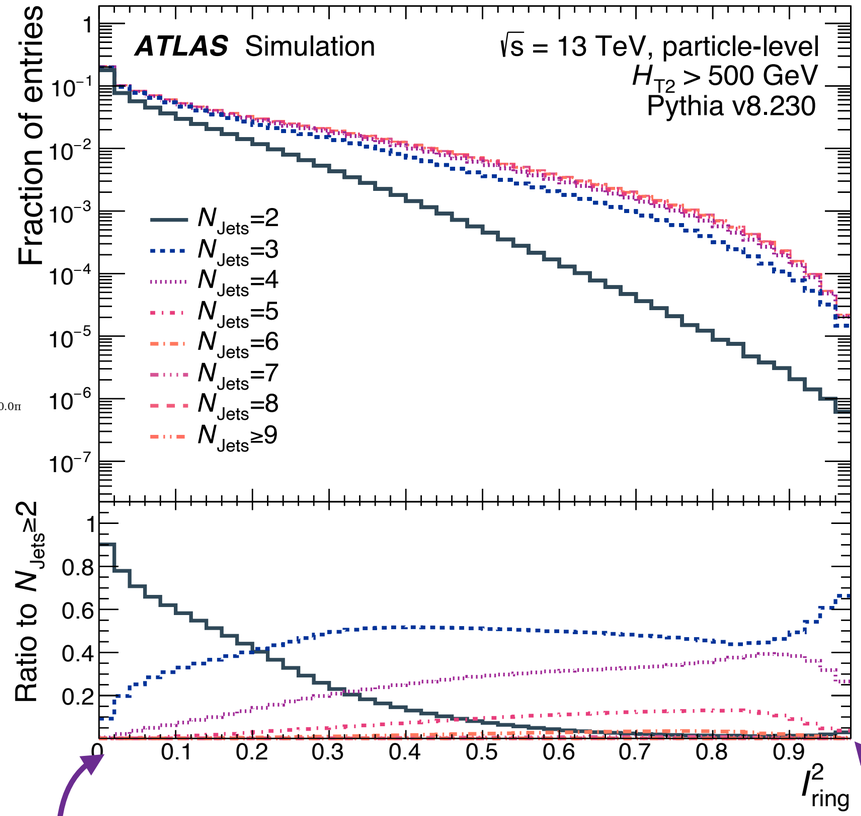


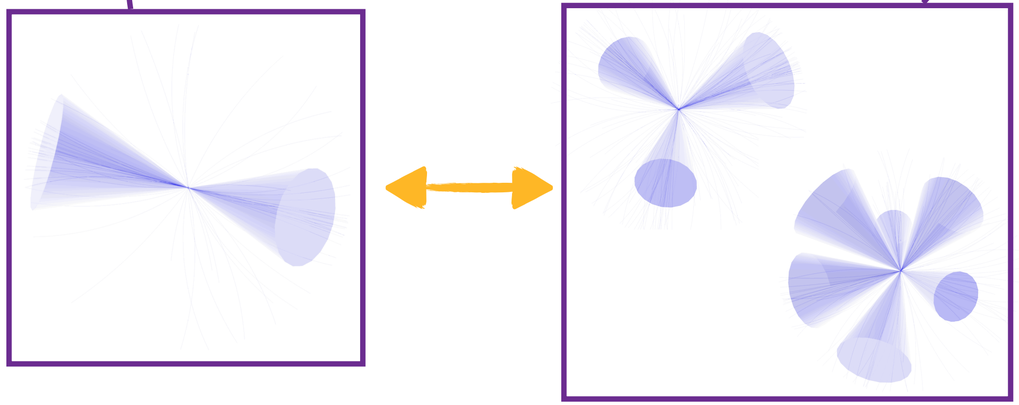
Animations are at this link :
https://cernbox.cern.ch/index.php/s/rYYF20n3je2rtXI

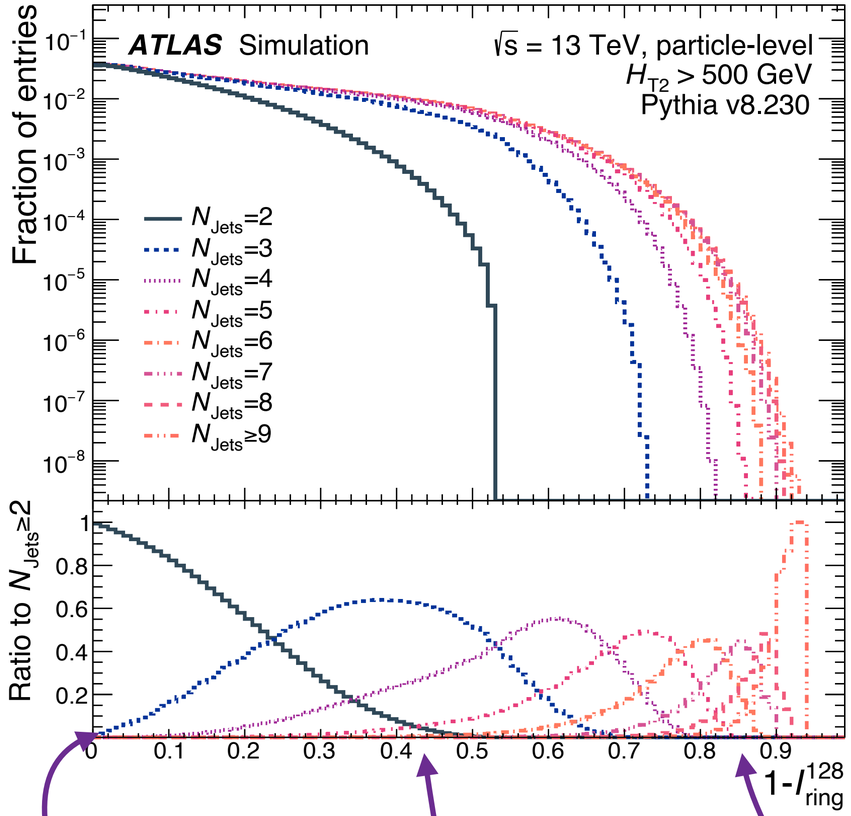
Phenomenology of different reference geometries...

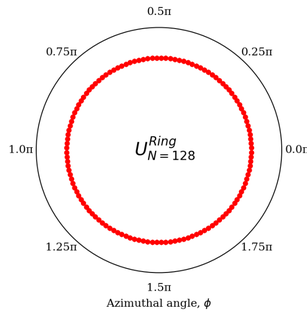
ATLAS 2305.16930

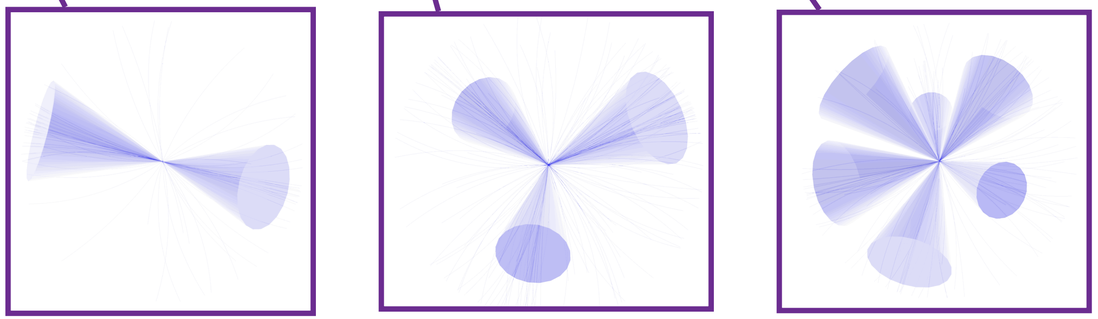






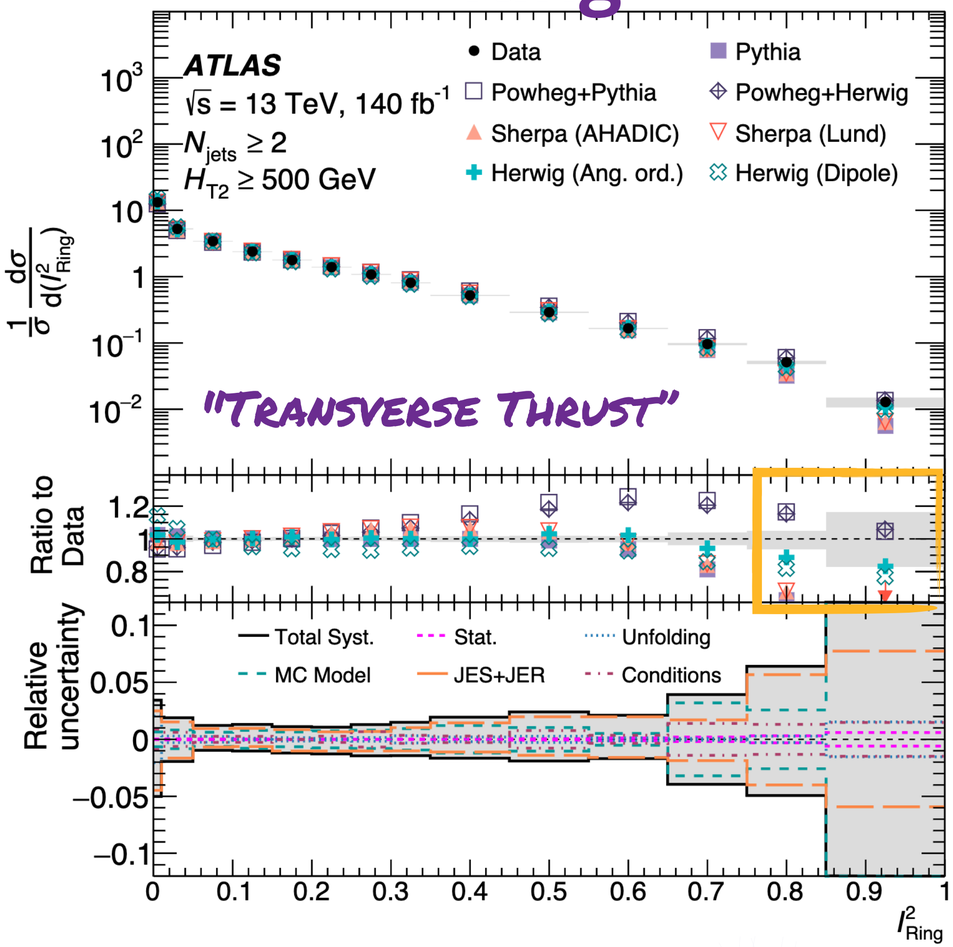




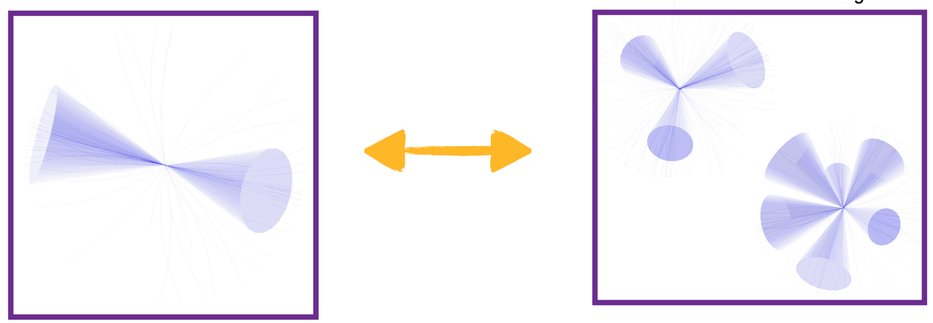


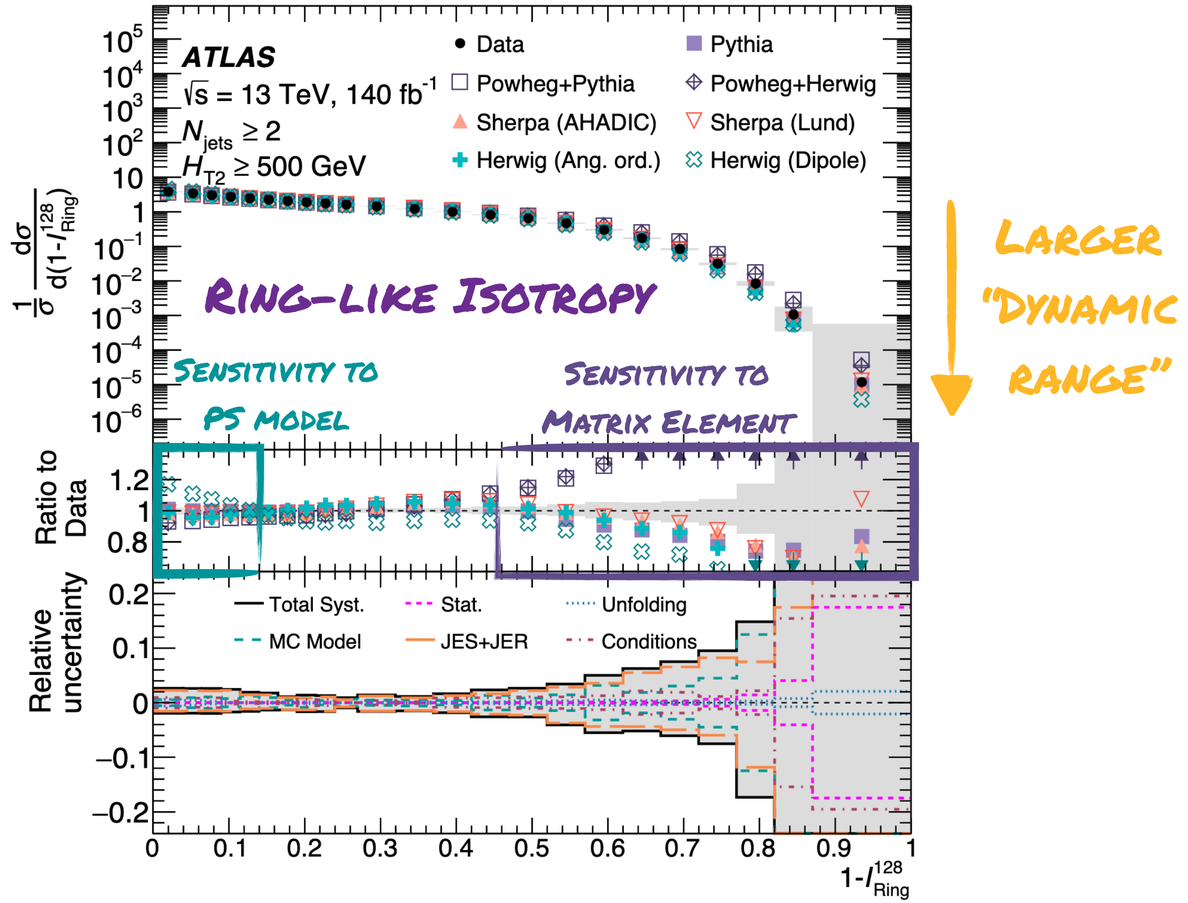
Results: I_{Ring}^{2} and I_{Ring}^{128}

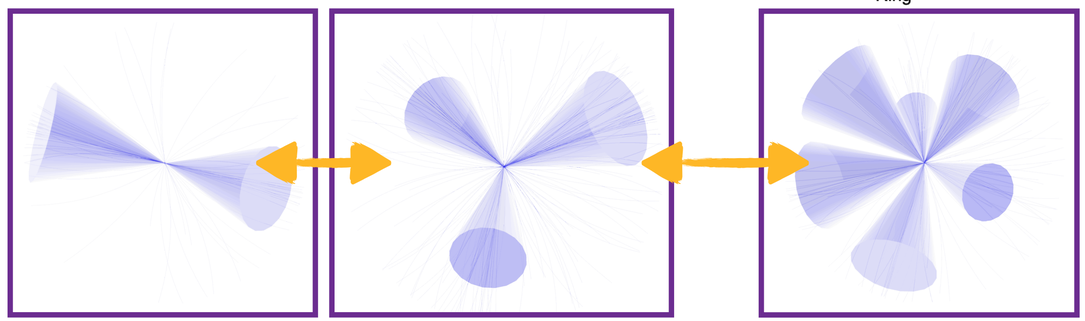
ATLAS 2305.16930



NLO performs best for 3-jet events

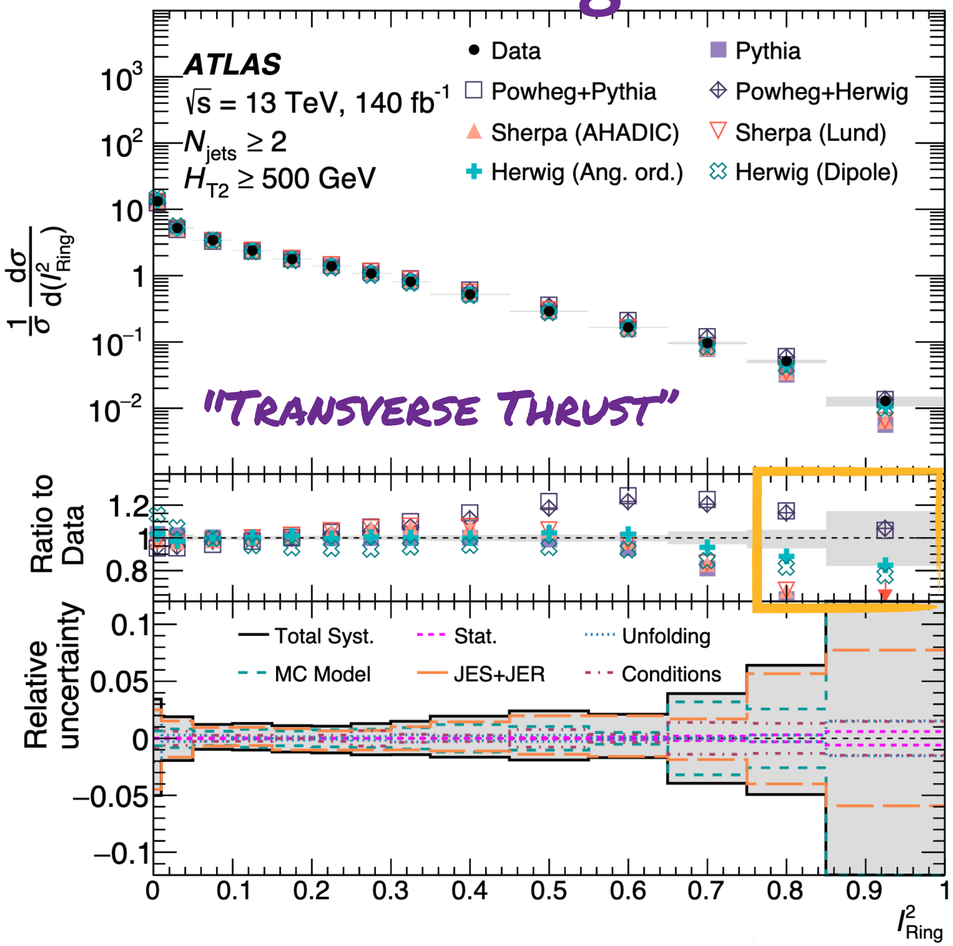




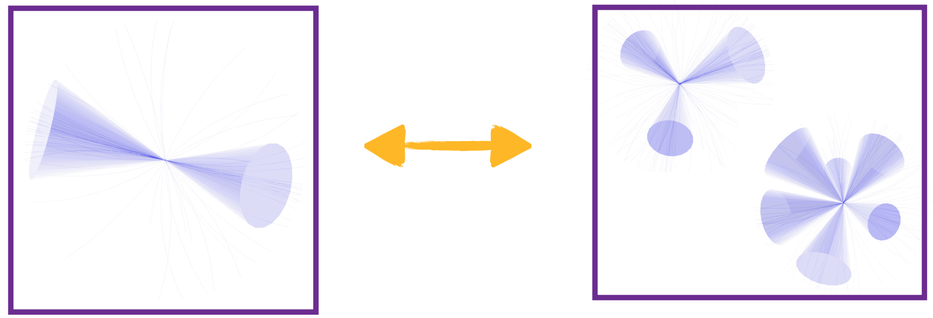


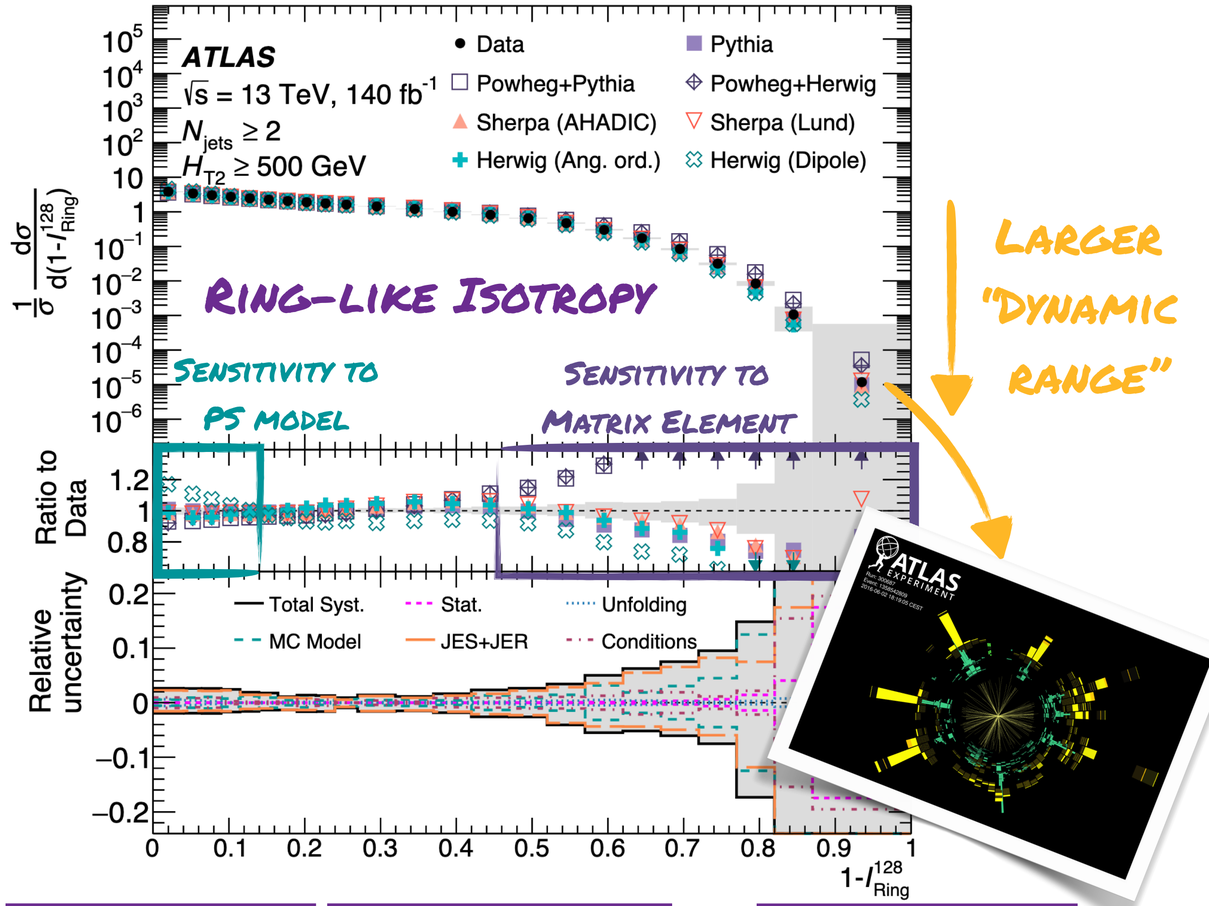
Results: I_{Ring}^2 and I_{Ring}^{128}

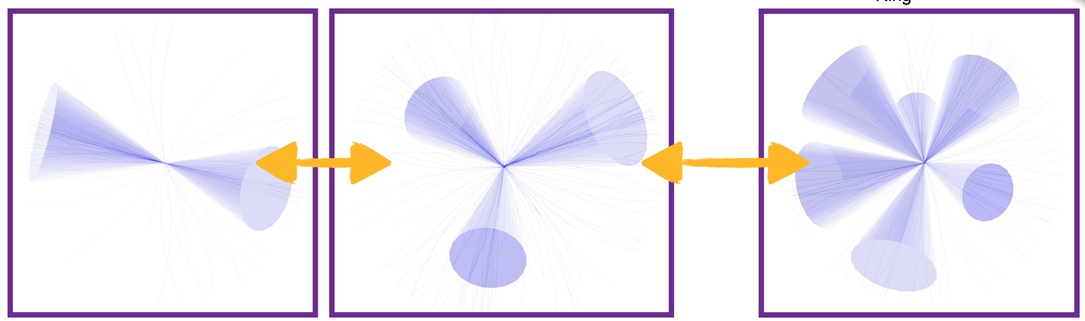
ATLAS 2305.16930



NLO performs best for 3-jet events





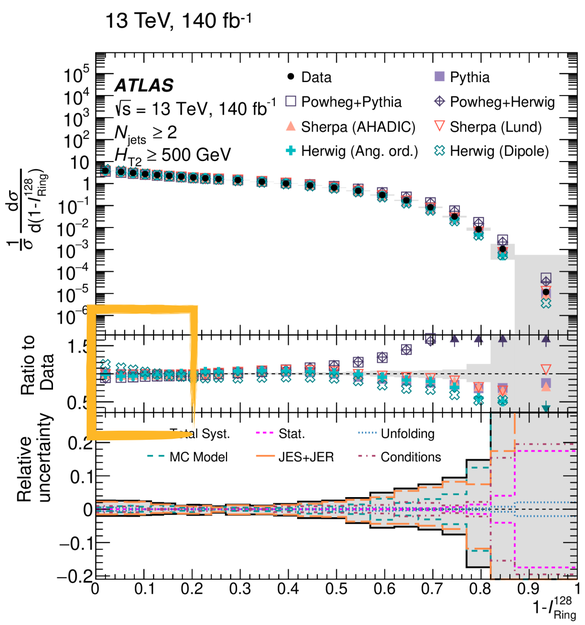


Results: I_{Ring}^{128} *vs.* N_{jets}

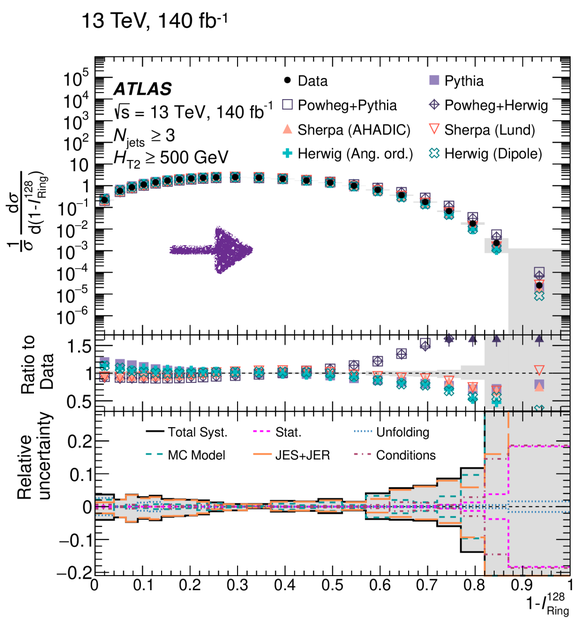
ATLAS *2305.16930*

Increase minimum jet requirement

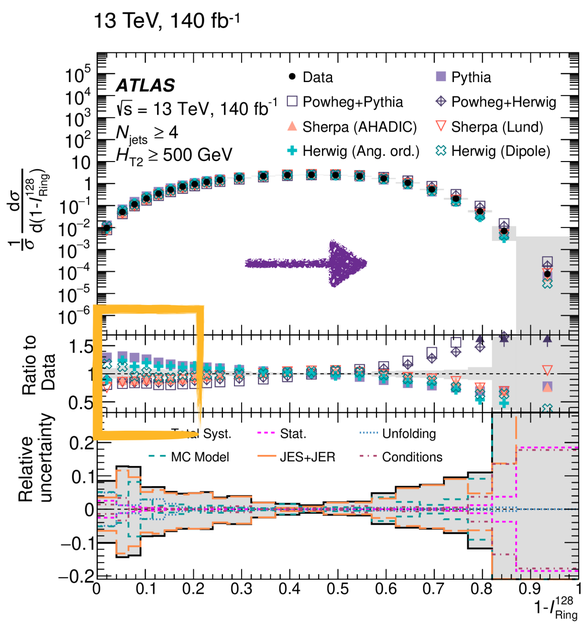
N>=2



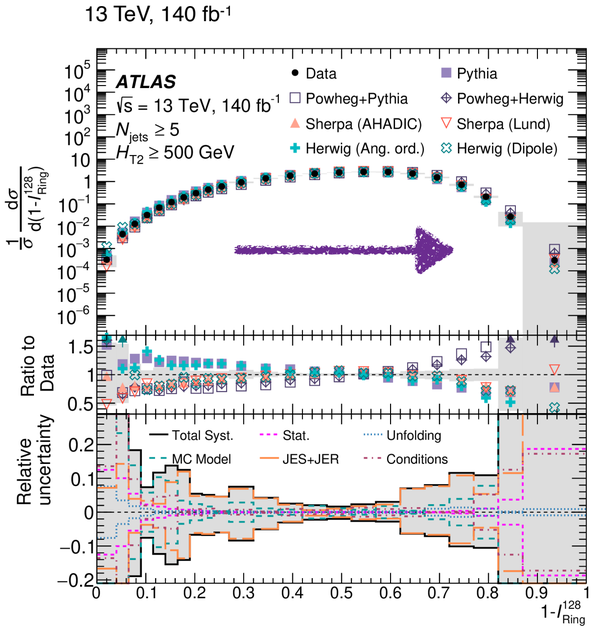
N>=3



N>=4



N>=5



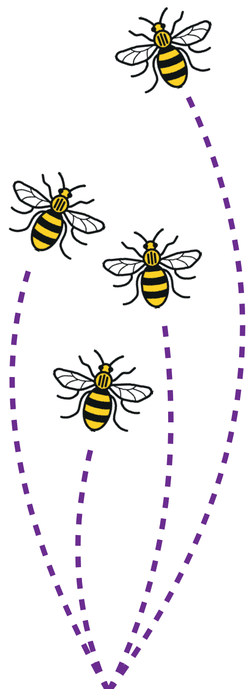
Data/MC disagreement deteriorates at "dijet-like" end: soft activity in the event increases difficulty for MC generators

Events become more isotropic as Njets is increased (as expected!)

Concluding remarks

Testing the strong force with photons & jets

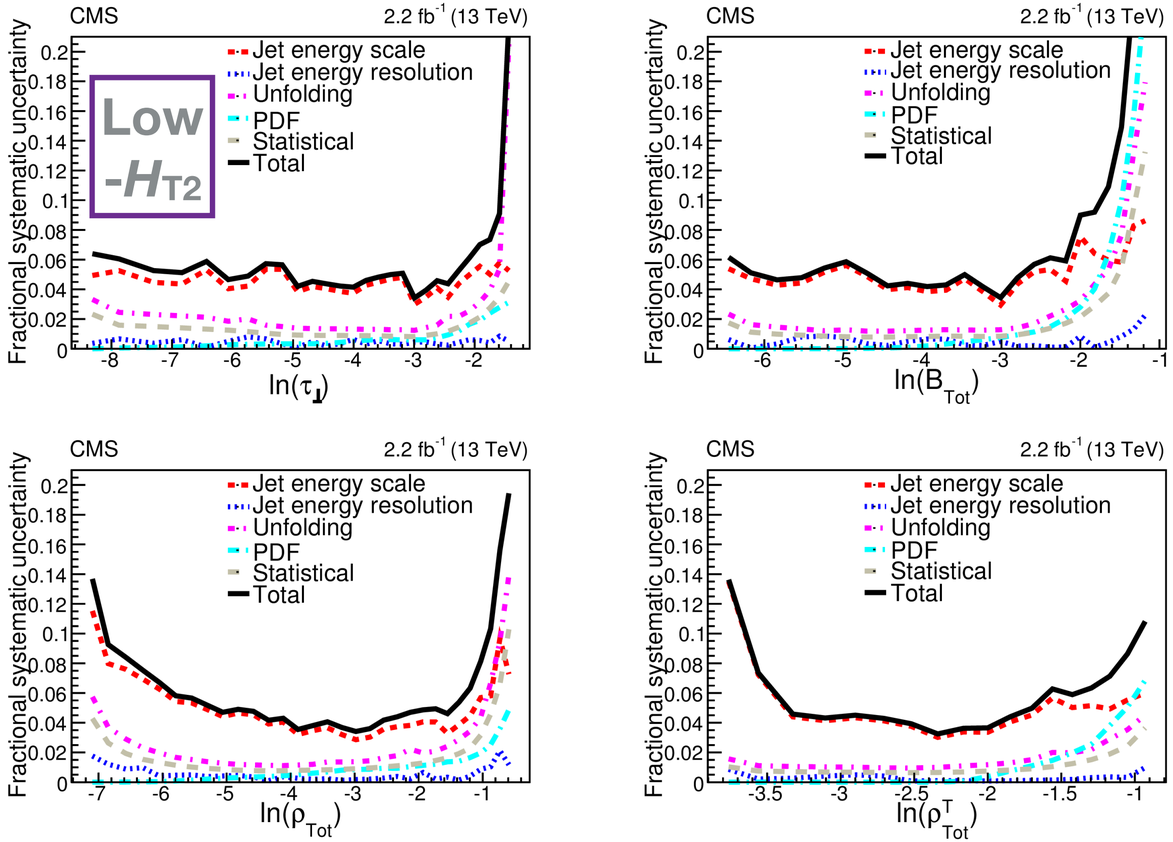
- **Photon and jet cross-section measurements provide stringent tests of QCD predictions.**
  - Typically, **multi-faceted measurements** that probe multiple aspects of our understanding:
    - Strong coupling, PDFs, MC modelling, analytic predictions (fixed-order, resummed), non-perturbative models (hadronisation), *etc.*
      - Be sure to check out **F. Giuli's talk about extractions of the strong coupling at the LHC** (Wed., 8h00) and **J. Huston's talk about Global PDF fits** (Wed., 9h00)!
  - Run 3 is an opportunity for **experimental & theoretical physicists to collaborate** and improve our understanding & tools **before the HL-LHC era starts!**
    - New analyses w/ novel properties resulting from direct collaboration between these communities.
    - Lots of theoretical activity towards **more accurate parton shower Monte Carlos** : **Report by F. Herren!** (Wed., 9h30)
      - … commissioning with experimental data will be an exciting opportunity!

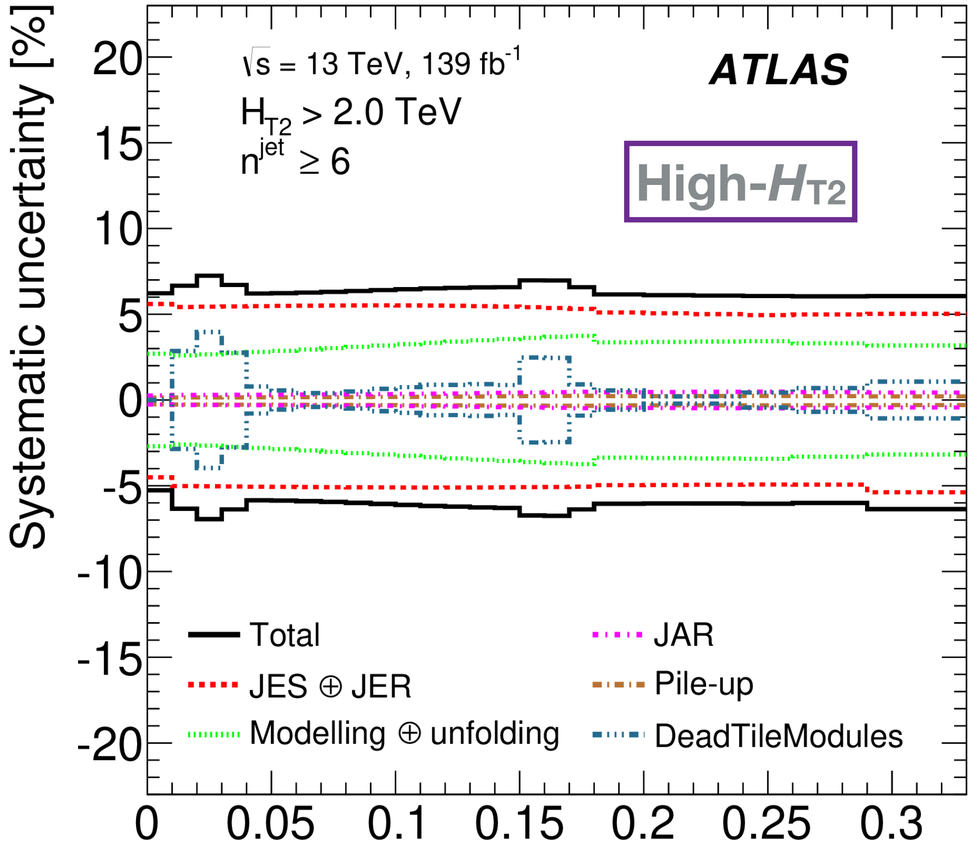



Thanks for
Listening!

Event Shapes: Systematics

ATLAS 2007.12600, CMS 1811.00588





Leading systematics consistently from JES (Driven by modelling differences in JES response) or MC modelling (differences in choice of generator for unfolding procedure).