Measurement of multijet production

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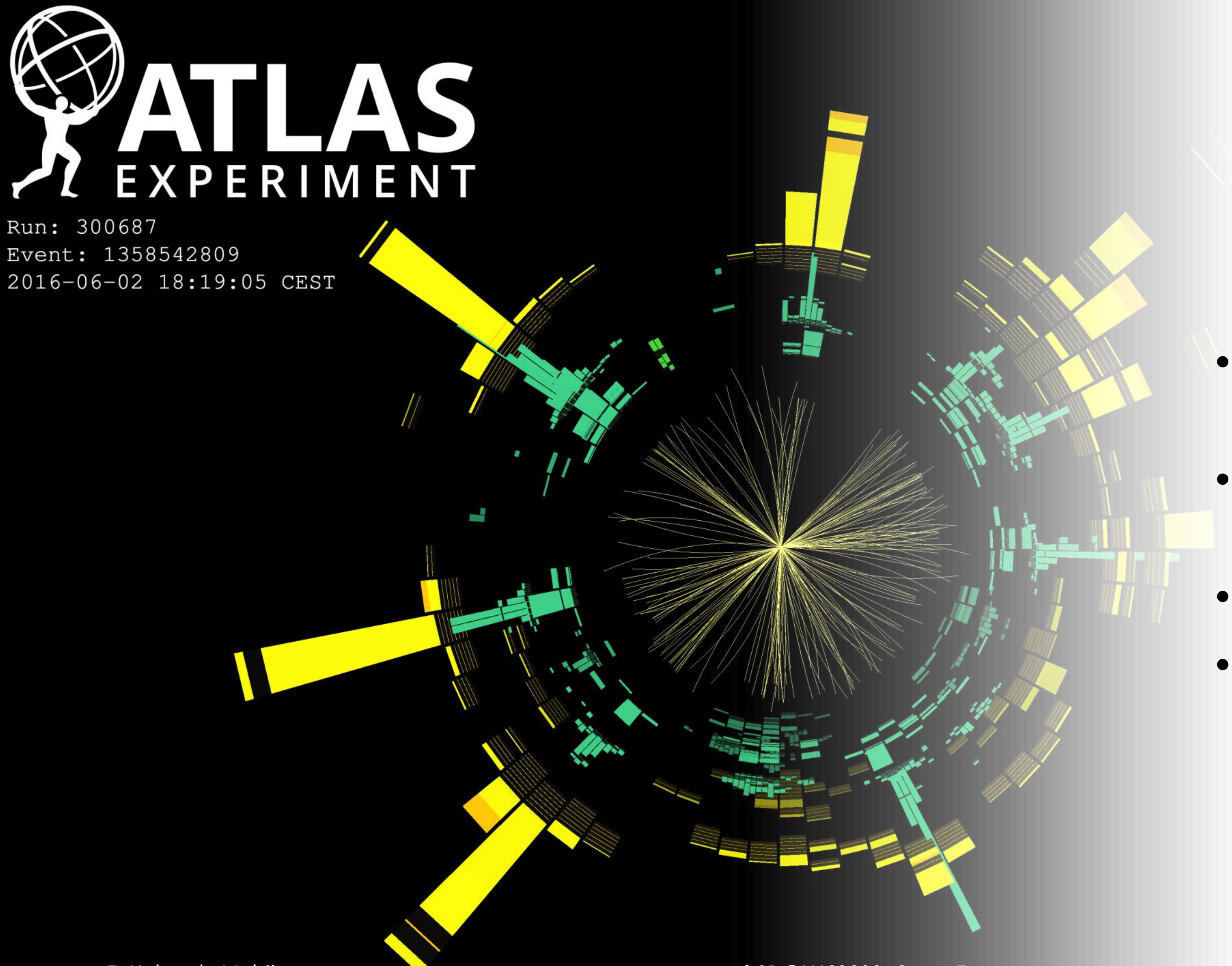
On behalf of CMS and ATLAS collaborations

QCD@LHC, Orsay, 2022



Motivation

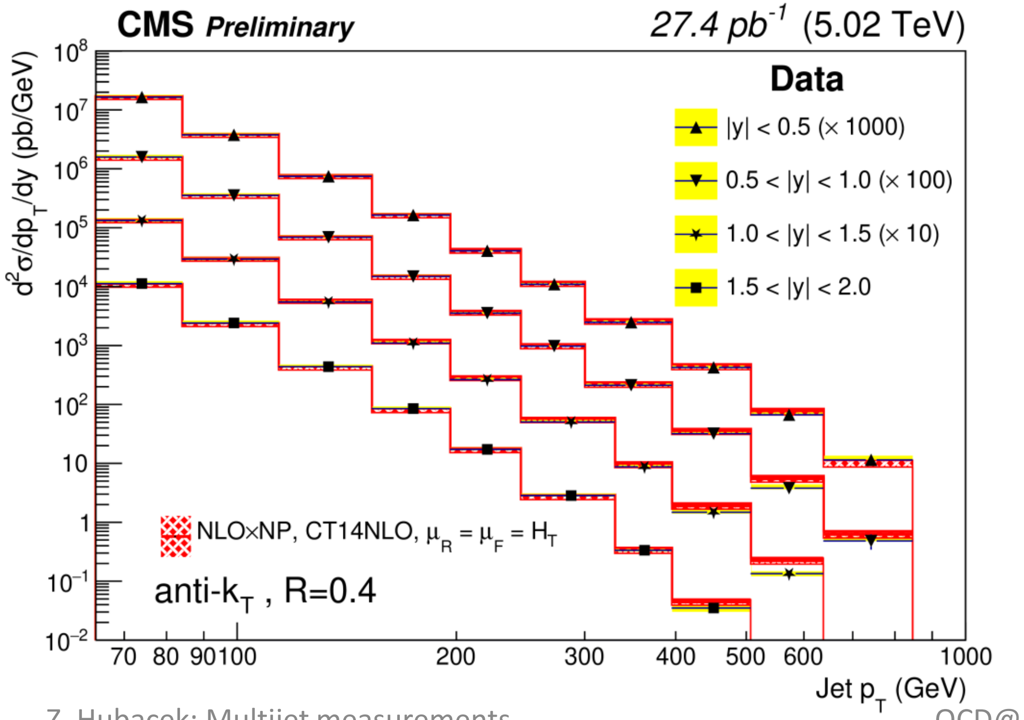
- Multijet measurements test various aspects of QCD
- Test of pQCD calculations (LO/NLO/NNLO)
- Parton shower modelling
- Determine QCD fundamental parameters

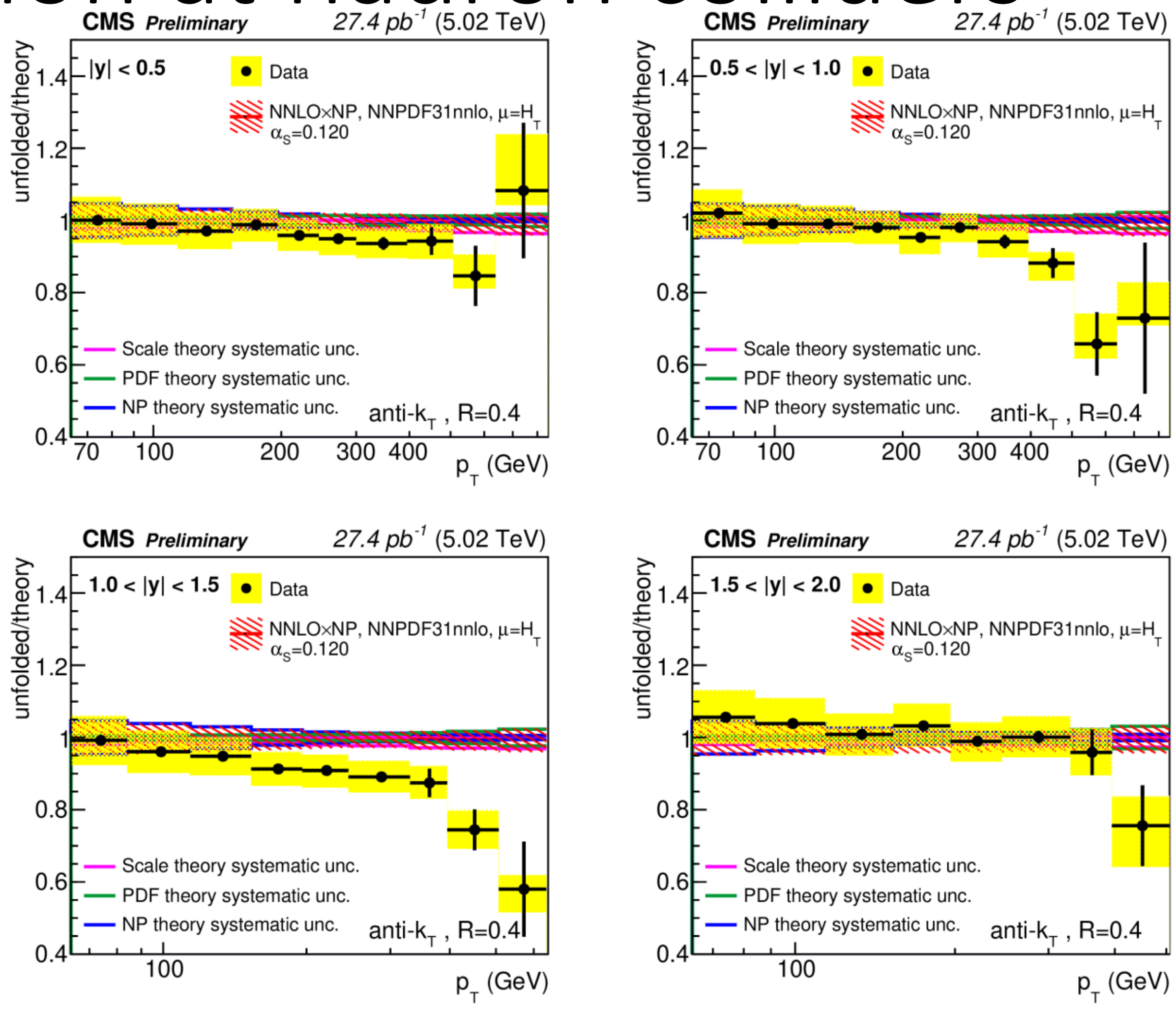
CMS, CMS-PAS-SMP-21-009

Inclusive jet cross section at hadron colliders

$$\frac{d^2\sigma}{dp_T d|y|} = \frac{N_{\text{jets}}}{\epsilon \mathcal{L} \Delta p_T \Delta |y|}$$

- “Standard candle measurement“ – measured at 2.76,5.02,7,8,13 TeV @LHC
- **NNLO state of the art now**

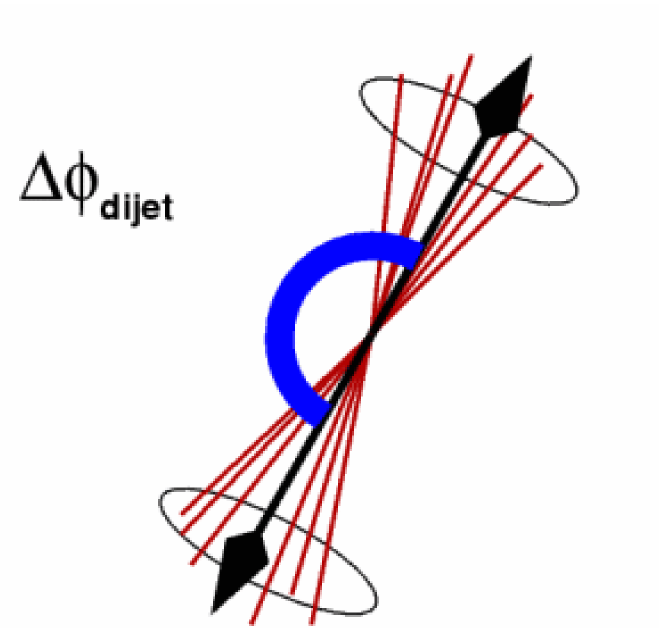




CMS-SMP-20-011 13 TeV updated with NNLO QCD fit

Extend to more than 2 jets

- Measure N-jet properties directly or indirectly
- At LO, 2 jets are produced back-to-back in the azimuthal angle



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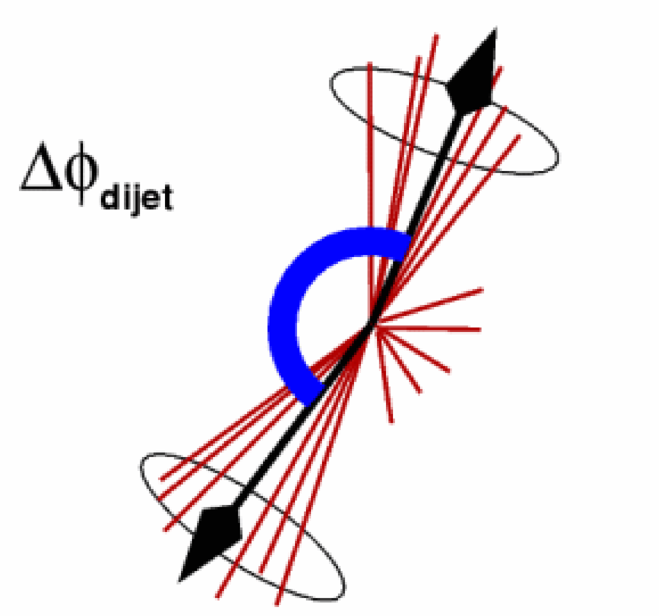

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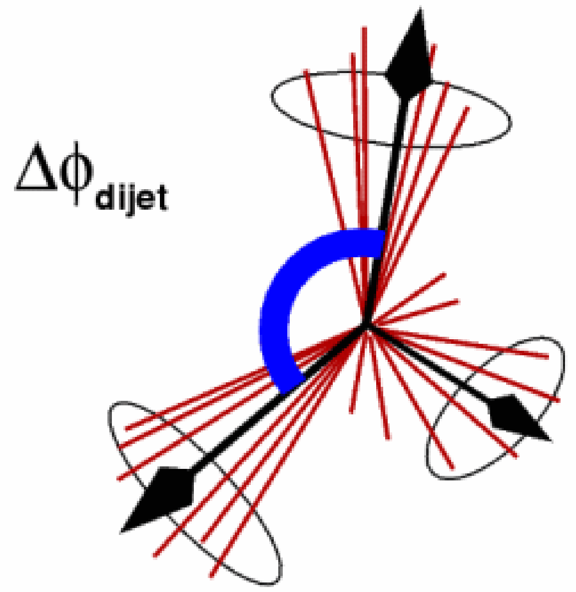
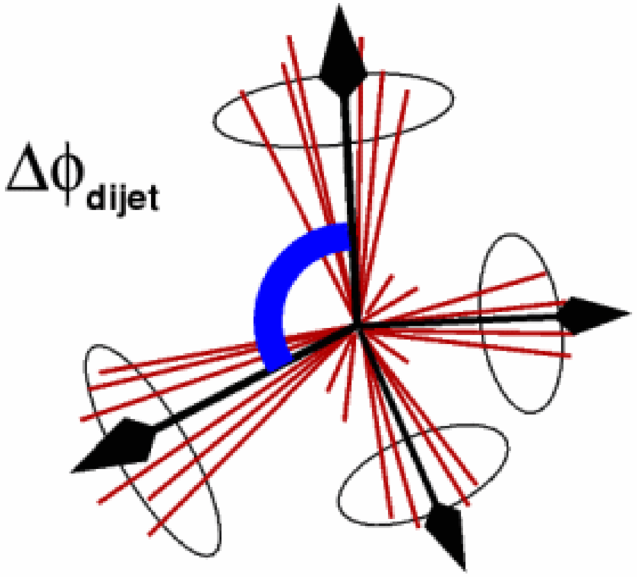
- 3rd jet production (2→3 process) restricts the phase space to $\boldsymbol{\Delta\phi > 2\pi/3}$



Extend to more than 2 jets

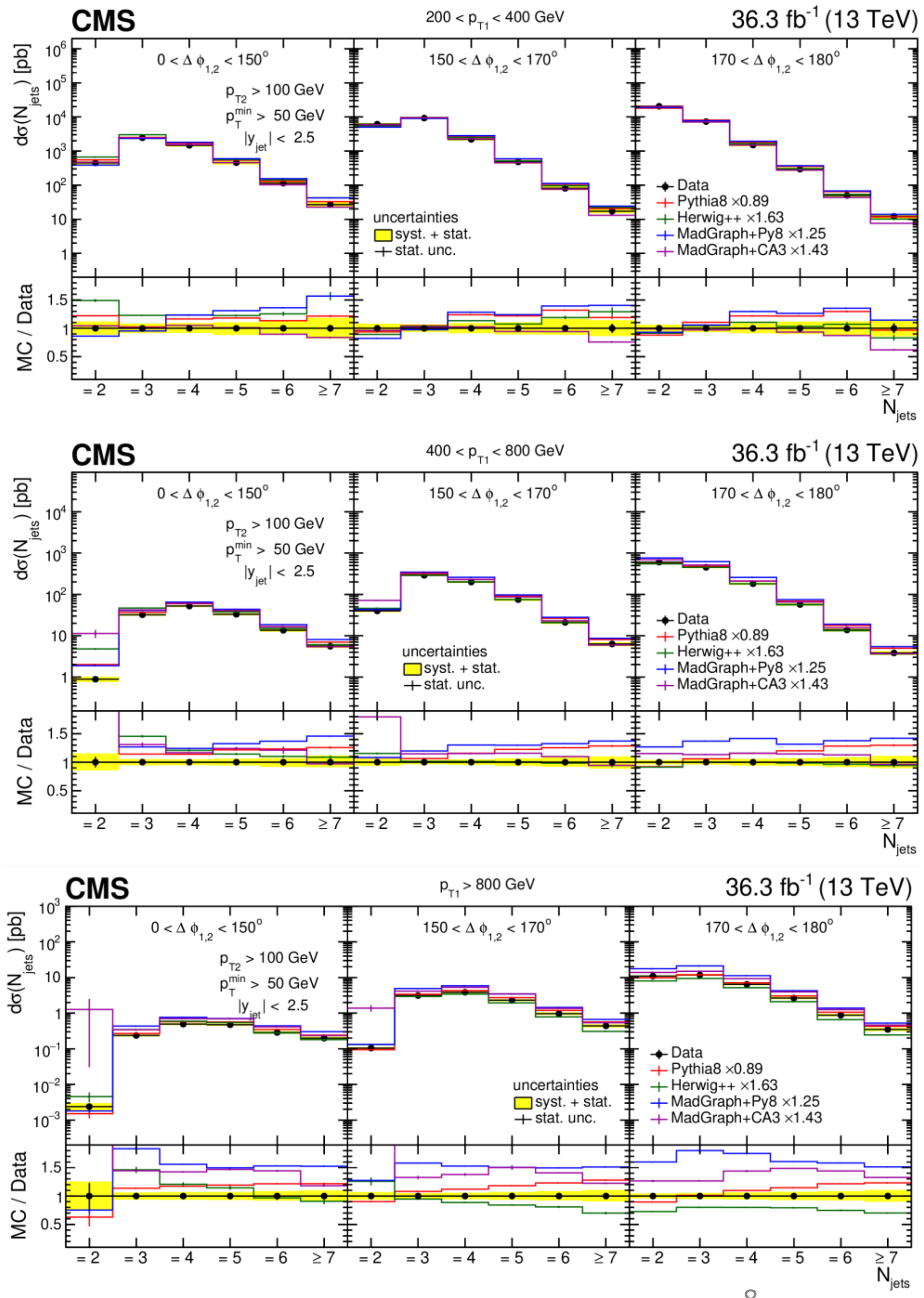
- Jet multiplicity and p_T in multijet events (CMS, Submitted to EPJC)
- Double parton scattering in 4 jet events (CMS, JHEP 01(2022) 177)
- Multijet event shapes (ATLAS, JHEP 01(2021) 188)
- Multijet event isotropies (ATLAS, ATLAS-CONF-2022-056)
- Extraction of α_S in transverse energy-energy correlations (ATLAS, ATLAS-CONF-2020-025)



NEW, CMS Submitted to EPJC

Jet multiplicity measurement

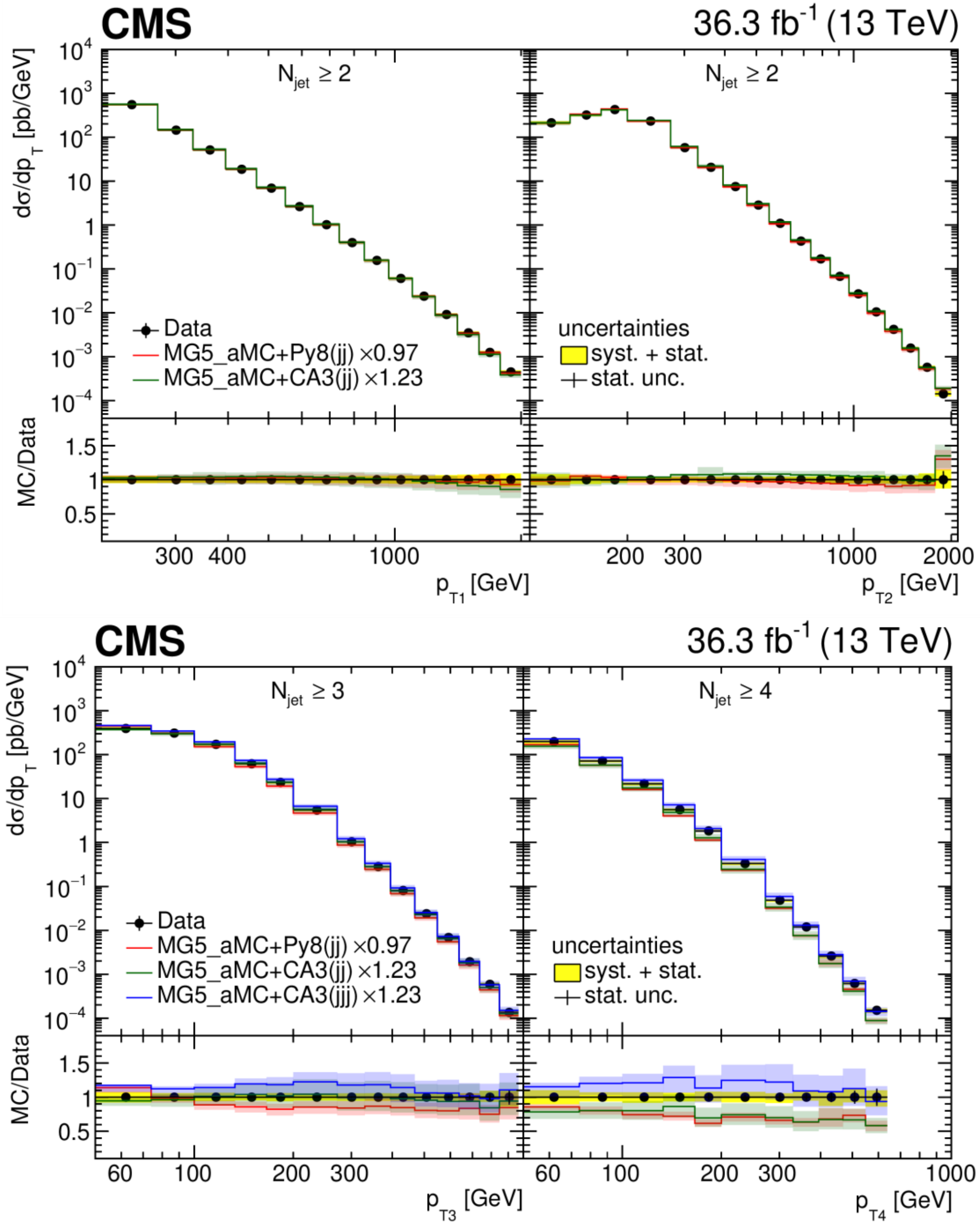
- Multiplicity of p_T>50 GeV jets measured in high p_T dijet events
- Also as a function of the azimuthal angle between the leading dijet
- Compared to LO/NLO ME predictions and also to NLO TMDs predictions



Generator	PDF	ME	Tune
PYTHIA8 [23]	NNPDF 2.3 (LO) [25]	LO $2 \to 2$	CUETP8M1 [24]
MADGRAPH+PY8 [4]	NNPDF 2.3 (LO) [25]	LO $2 \to 2, 3, 4$	CUETP8M1 [24]
MADGRAPH+CA3 [4]	PB-TMD set 2 (NLO) [1]	LO $2 \to 2, 3, 4$	—
HERWIG++ [26]	CTEQ6L1 (LO) [27]	LO $2 \to 2$	CUETHppS1 [24]
MG5_aMC+Py8 (jj)	NNPDF 3.0 (NLO) [31]	NLO $2 \to 2$	CUETP8M1 [24]
MG5_aMC+CA3 (jj)	PB-TMD set 2 (NLO) [1]	NLO $2 \to 2$	—
MG5_aMC+CA3 (jjj)	PB-TMD set 2 (NLO) [1]	NLO $2 \to 3$	—

Jet p_T distributions in multijet events

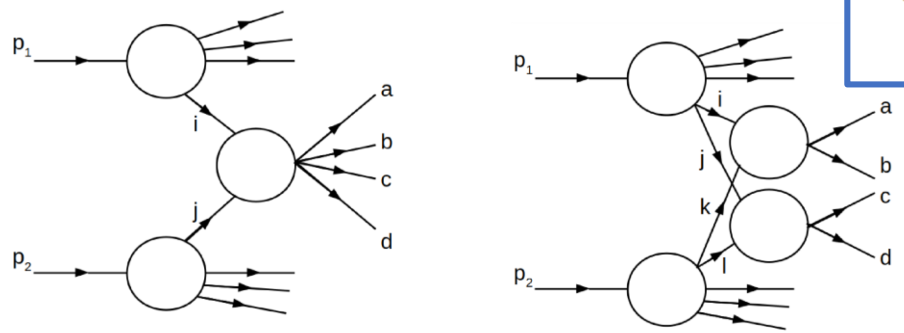
- Both jet multiplicity and p_T distributions not well described by LO generators
- NLO calculations describe multiplicities and p_T spectra reasonably well
- PB-TMD together with NLO used for the first time

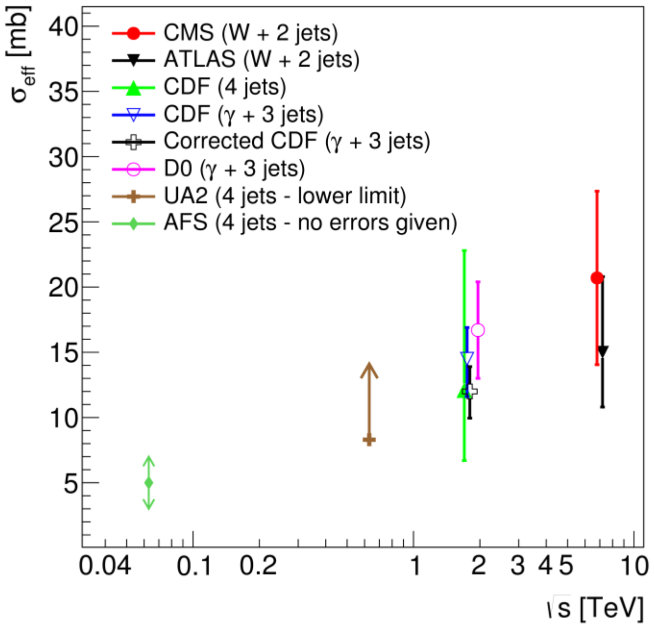


[CMS, JHEP 01 (2022) 177](https://doi.org/10.1007/JHEP01(2022)177)

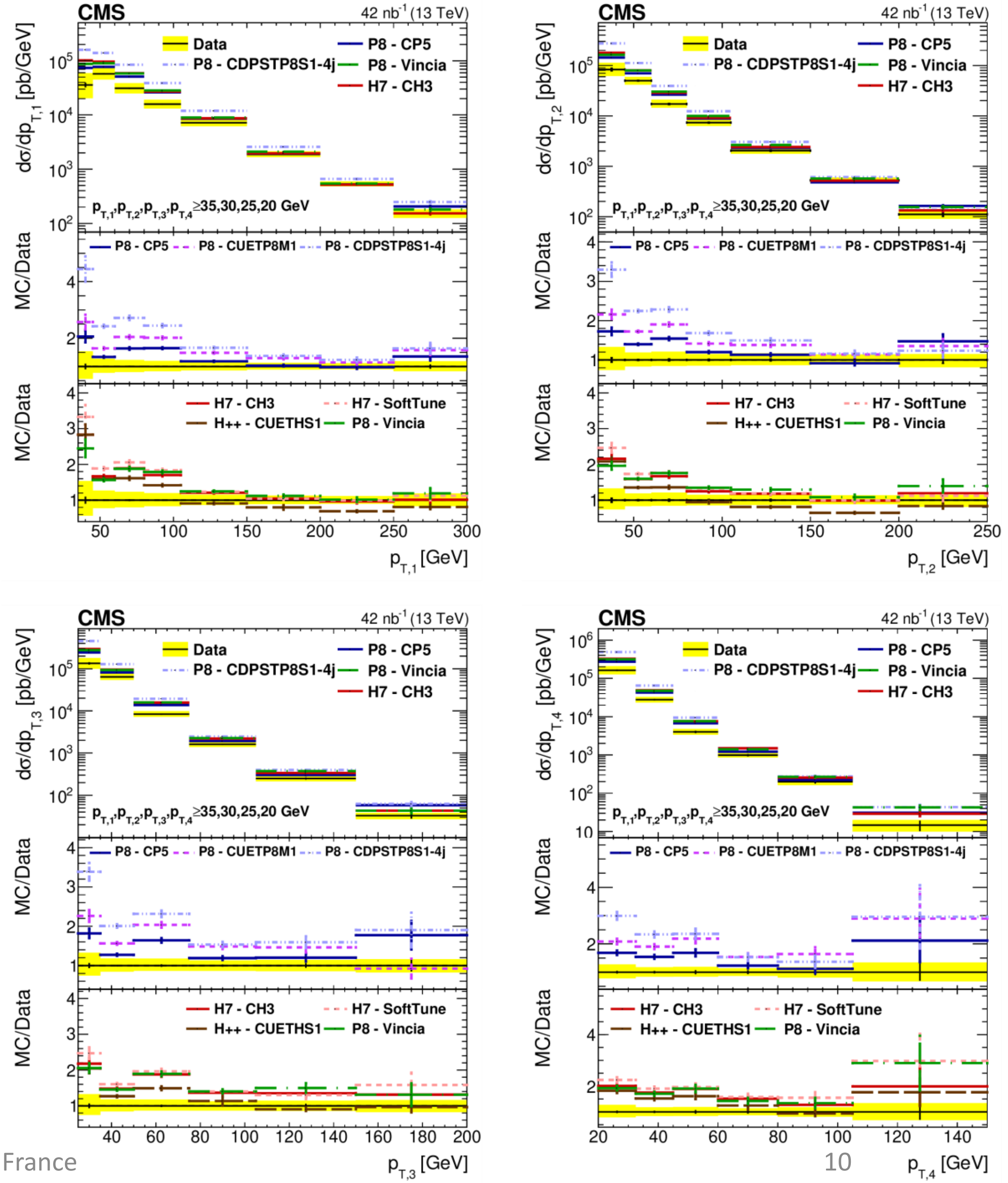
Double parton scattering in 4 jet events

$$\sigma^{DPS}_{A,B} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}.$$



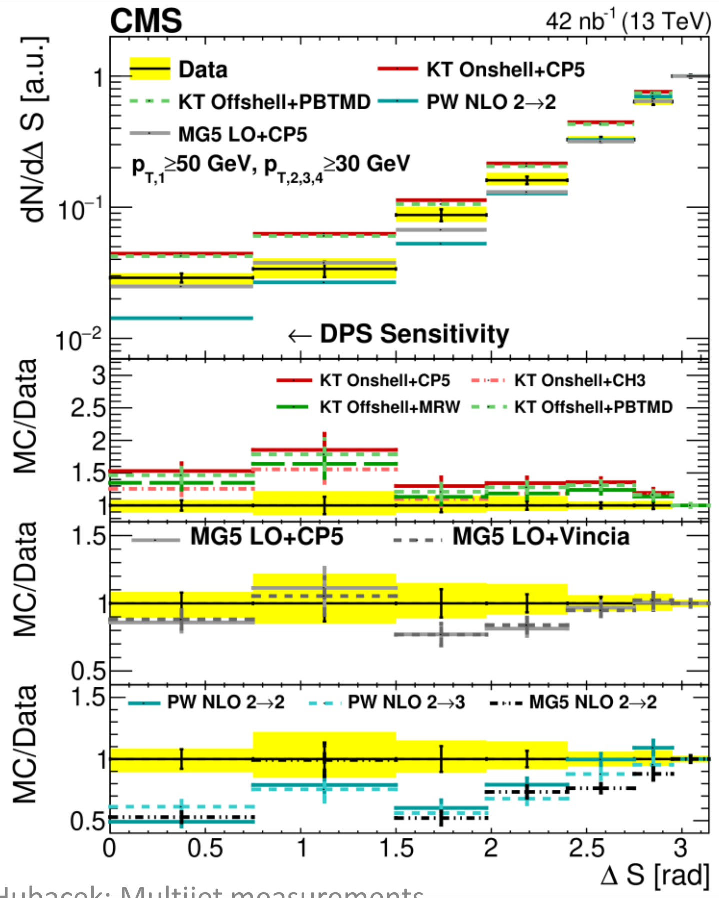


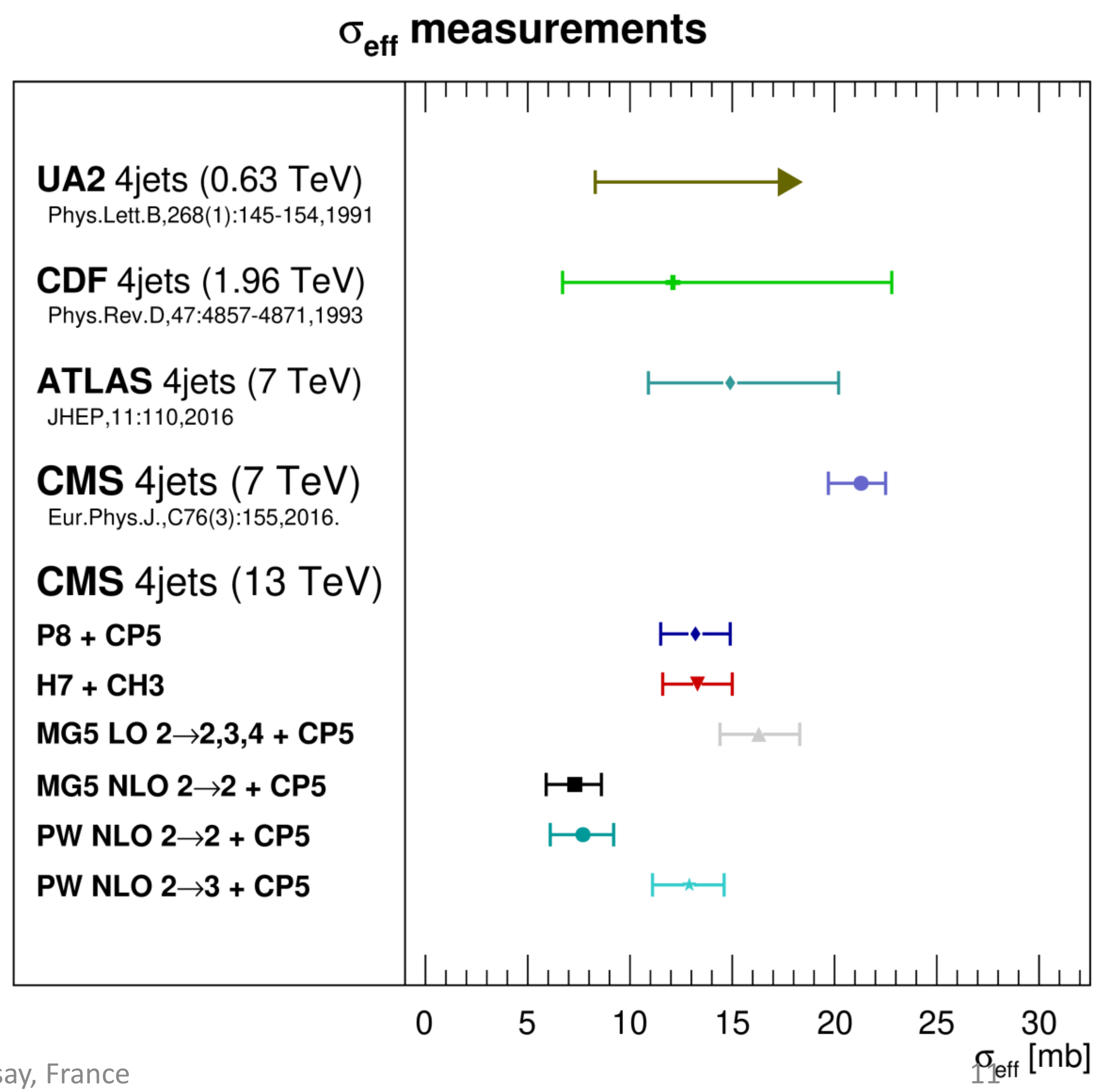
- 6 observables ($\Delta\phi_{Soft}=\Delta\phi_{34}$, Δp_{T34} for example) senstive to a difference between SPS and DPS
- Template method to extract DPS σ and σ_{eff}



DPS effective cross section

$$\Delta S = \arccos\left(\frac{(\vec{p}_{T,1} + \vec{p}_{T,2}) \cdot (\vec{p}_{T,3} + \vec{p}_{T,4})}{|\vec{p}_{T,1} + \vec{p}_{T,2}|\ |\vec{p}_{T,3} + \vec{p}_{T,4}|}\right).$$



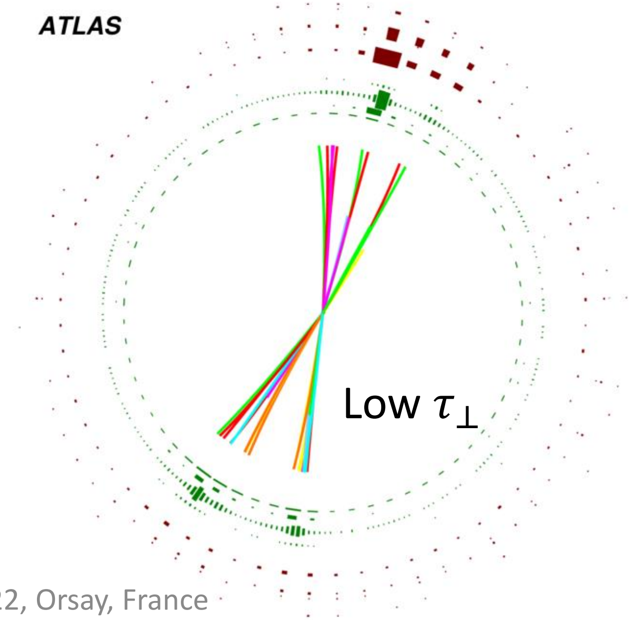


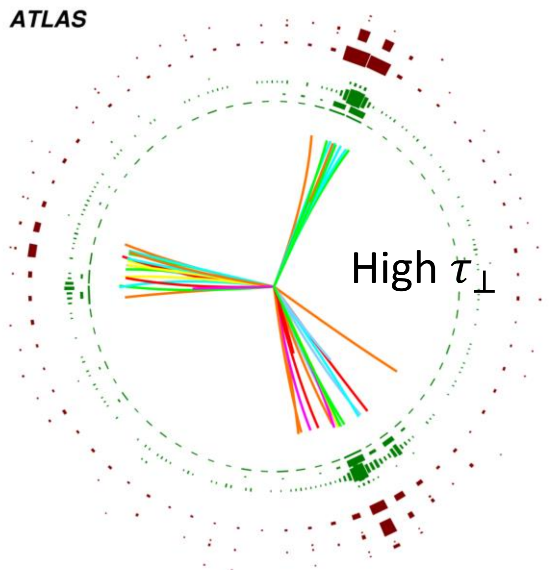
Event shapes

- Family of observables which characterize the event topology and/or energy flow in collider events
- **Thrust, thrust minor, sphericity, aplanarity**
- **Energy-energy correlations, event isotropies**

Example: **Transverse thrust** – thrust axis $n_{\perp}$ to which the projections of p_T are maximised, $0 \leq \tau_{\perp} < 1 - 2/\pi$

$$T_{\perp} = \max_{\hat{\boldsymbol{n}}_{\perp}} \frac{\sum_i |\boldsymbol{p}_{\mathrm{T}i} \cdot \hat{\boldsymbol{n}}_{\perp}|}{\sum_i p_{\mathrm{T}i}} \qquad \tau_{\perp} = 1 - T_{\perp}$$

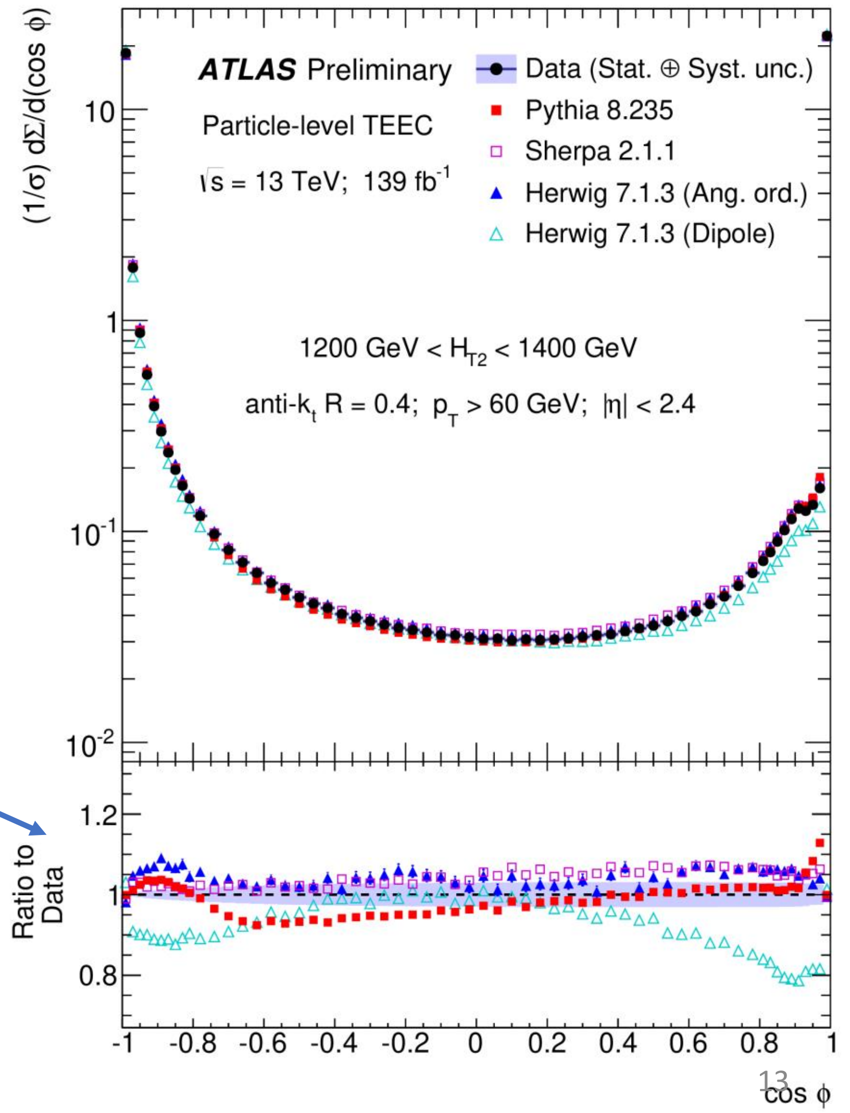




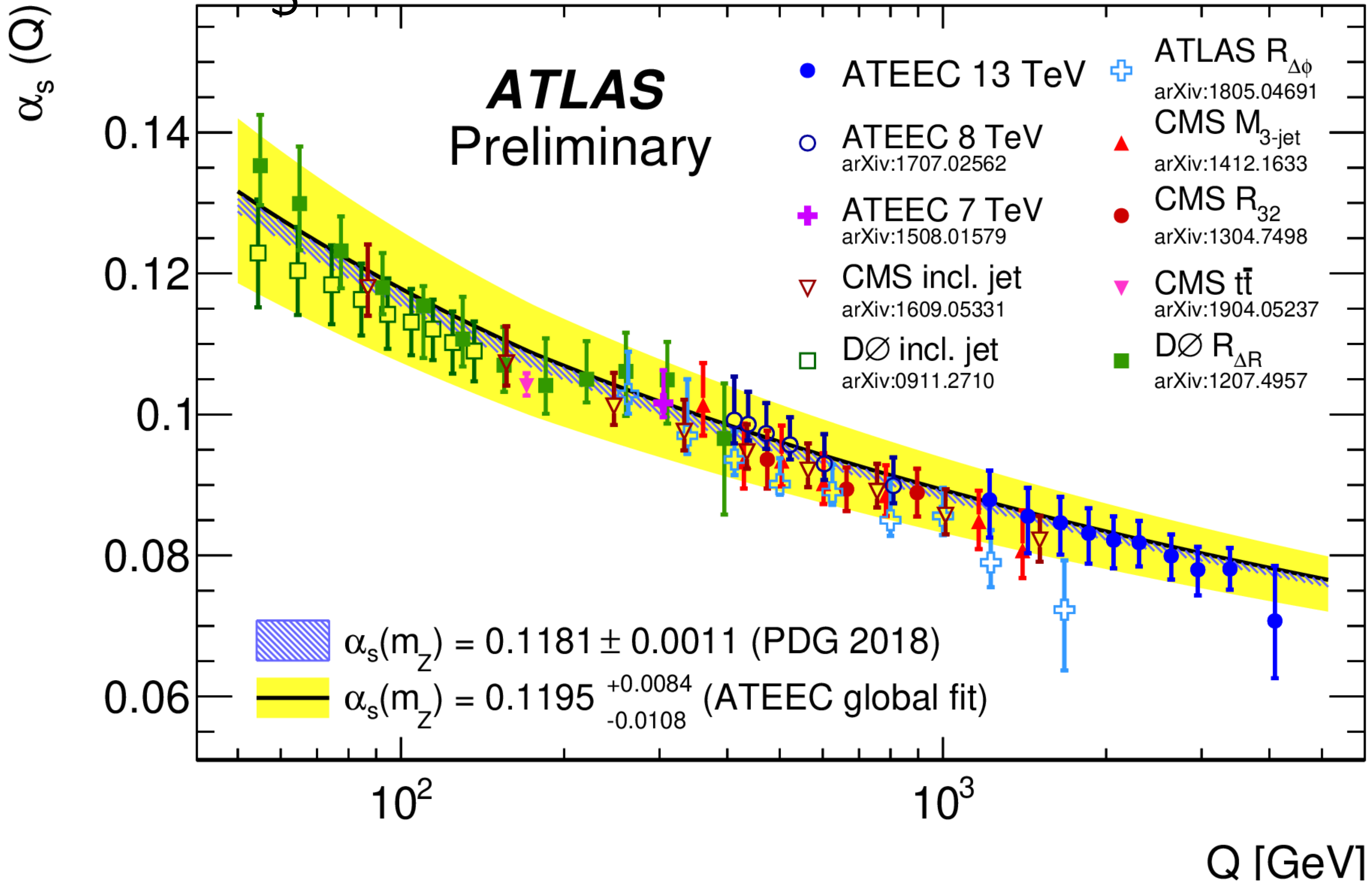
ATLAS, ATLAS-CONF-2020-025

Transverse energy energy correlations

- Transverse energy-weighted distribution of azimuthal differences between jet pairs
- RGE predicts running of α_S - deviation could be also a sign of new coloured fermions
- Also testing parton shower models



ATEEC and α_S extraction



$\mu_R = H_T$

TEEC: $\alpha_s(m_Z) = 0.1196 \pm 0.0001\ (\text{stat.}) \pm 0.0004\ (\text{syst.})^{+0.0071}_{-0.0104}\ (\text{scale}) \pm 0.0011\ (\text{PDF}) \pm 0.0002\ (\text{NP}),$

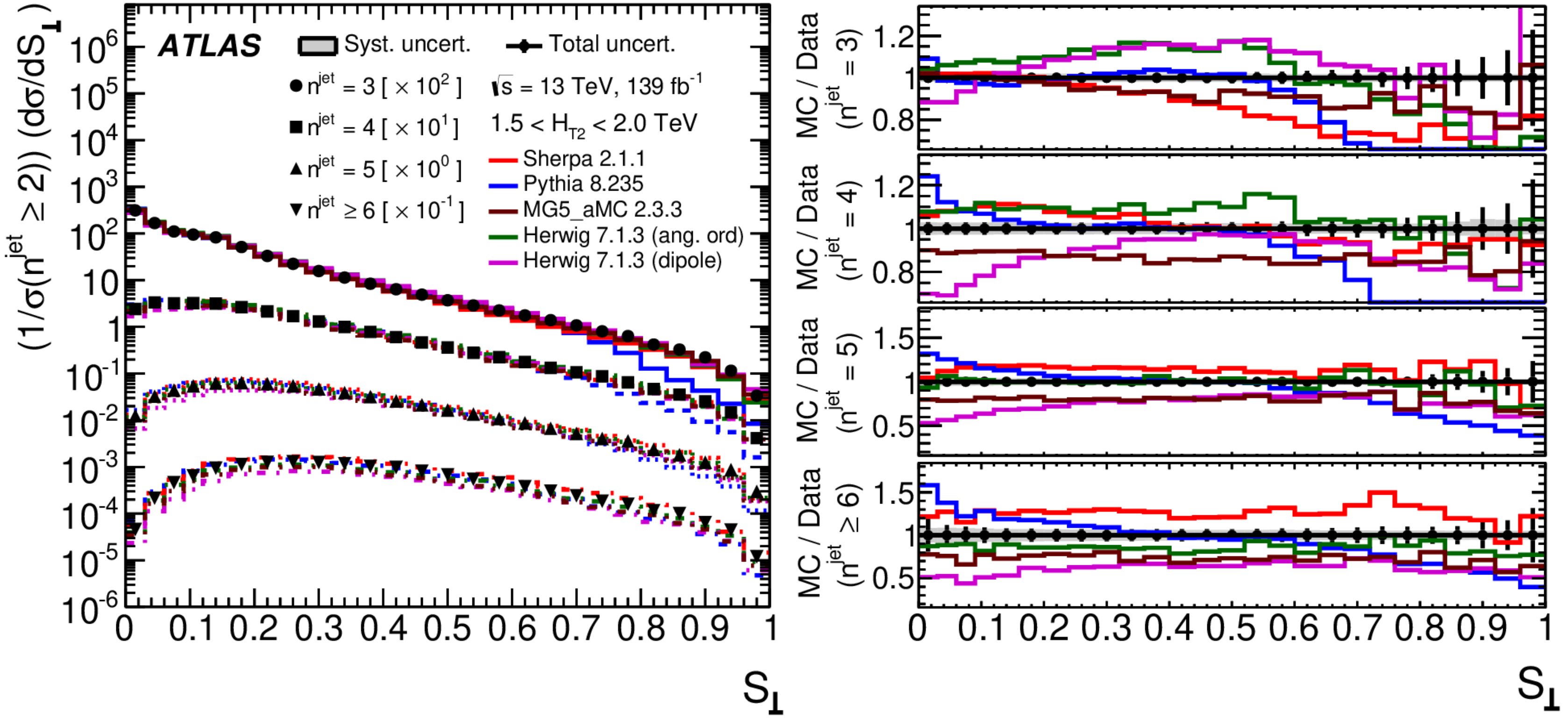
ATLAS, JHEP 01 (2021), 188

"Classical" event shapes

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

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

Where $\mu_1 > \mu_2$, $\mu_1 + \mu_2 = 1$ are eigenvalues of M_{xy}



- Measurement of **6 event shapes** also in **bins of jet multiplicity** and **bins of H_{T2}**
- At low jet multiplicities, Pythia, Sherpa predict less isotropic events than in data
- At higher jet multiplicities, the description is improved while discrepancy in normalisation is observed

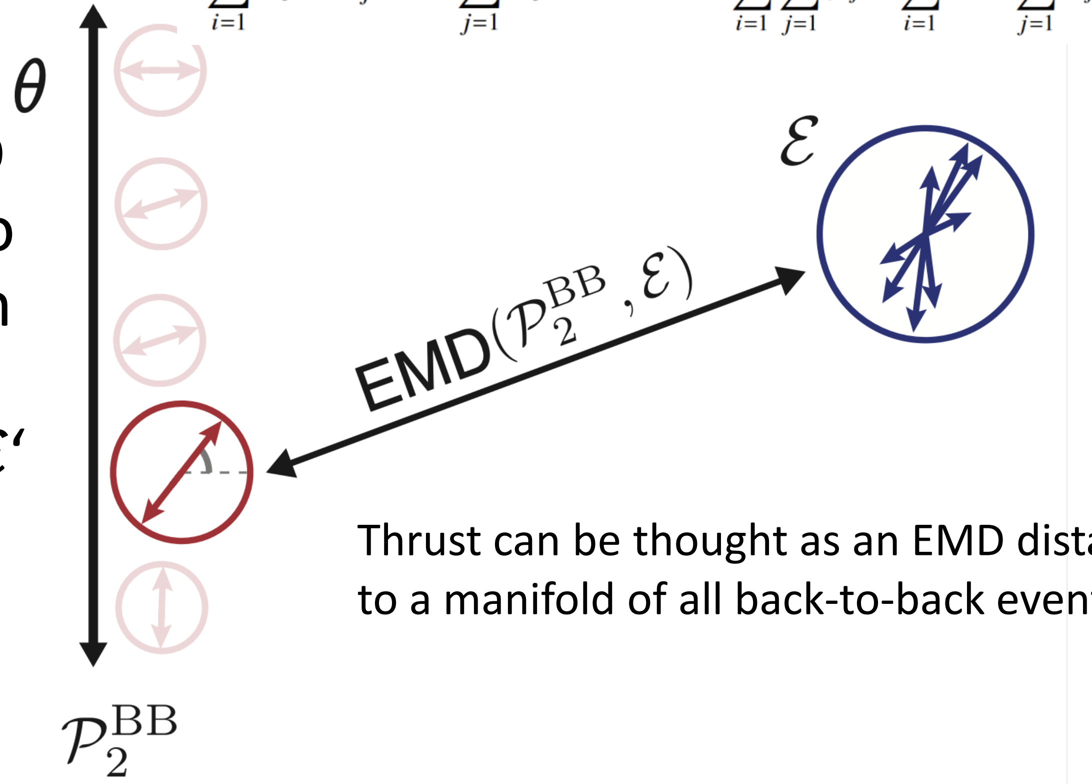
ATLAS-CONF-2022-056

Event shapes as a geometrical problem

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

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

- Event shapes together with other concepts unified through a geometric language JHEP07 (2020) 006
- Energy (Earth) mover‘s distance **EMD** = a measure of distance between two probability distributions (Wasserstein metric) = minimal amount of work to rearrange one event $\mathcal{E}$ into another $\mathcal{E}$‘



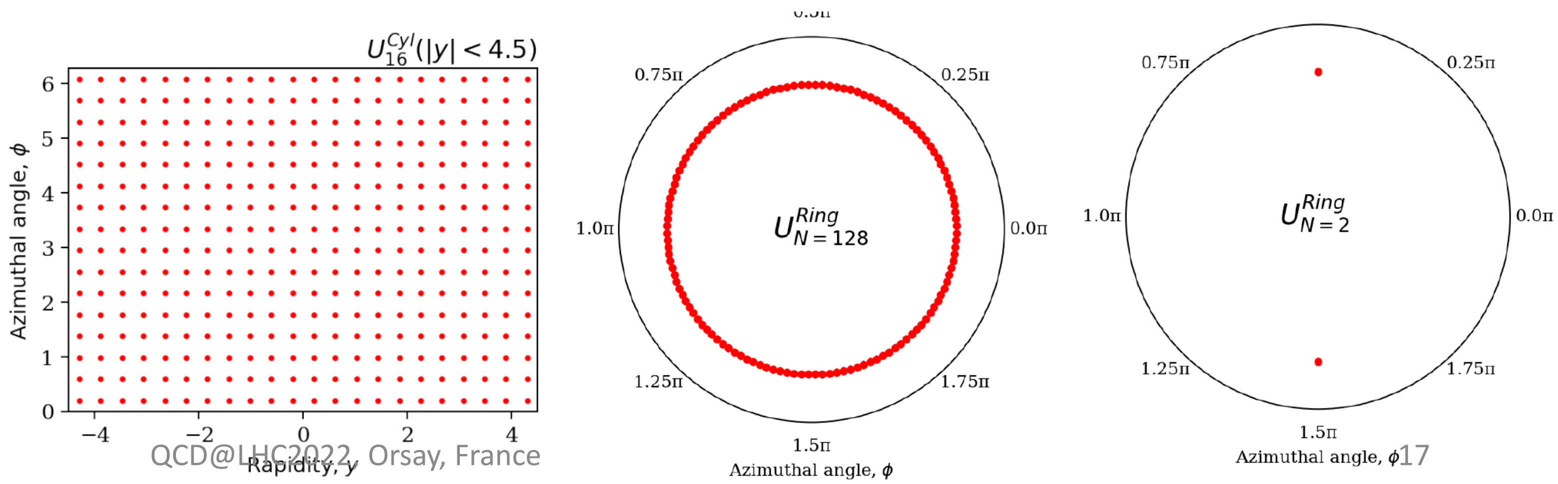
Thrust can be thought as an EMD distance to a manifold of all back-to-back events $\mathcal{P}_2^{BB}$

Novel event shapes – event isotropies

- EMD problem can be solved using **Optimal Transport** methods
- Event isotropies – how far is a collider event $\mathcal{E}$ from a symmetric radiation pattern $\mathcal{U}$, $\mathcal{J}$=EMD($\mathcal{E}$,$\mathcal{U}$) $\mathcal{J}\in[0,1]$
- Completely isotropic events $\mathcal{J}$=0

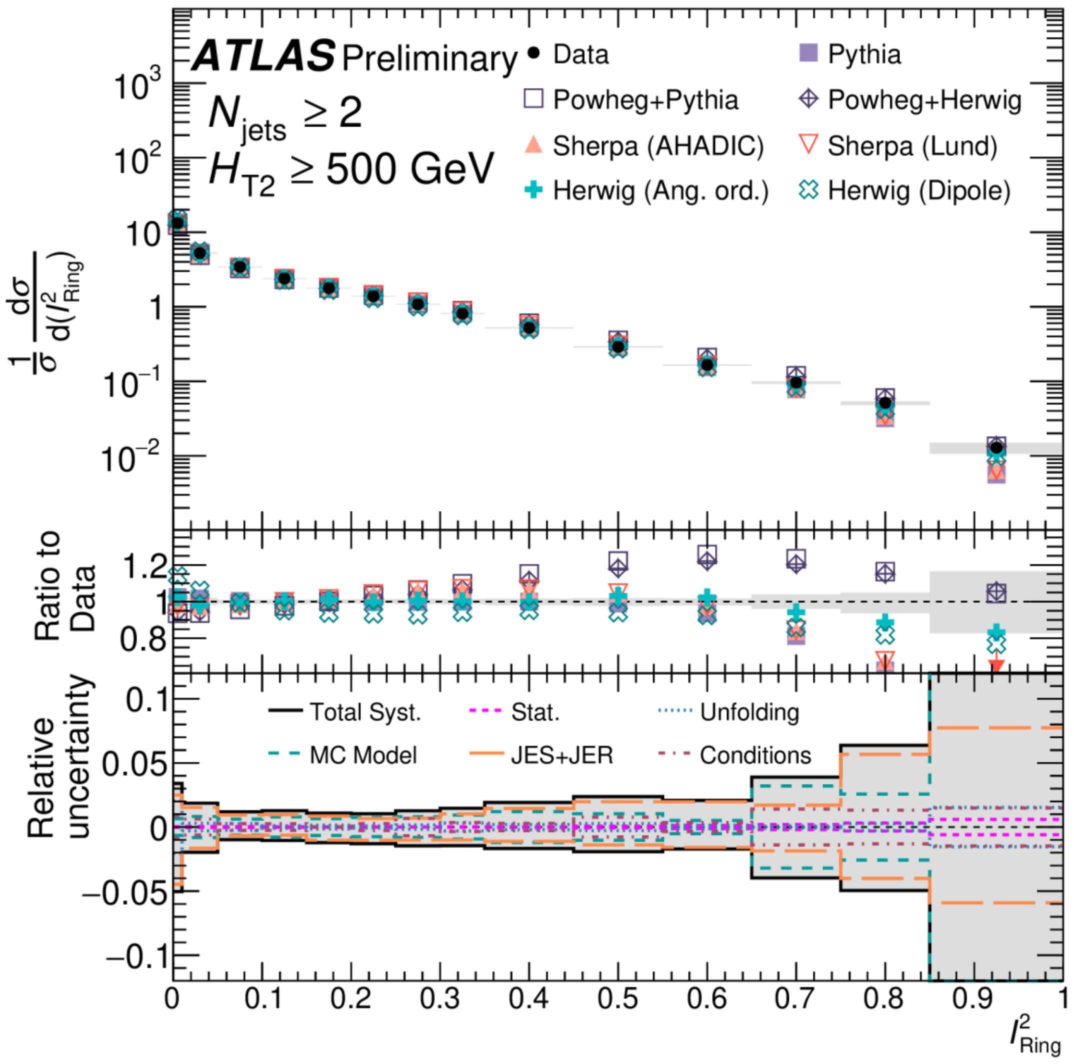
3 different $\mathcal{U}$ geometries considered

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)	$w_i^{\text{ring}} = p_{T\,i}/p_{T\,\text{tot}}$	$\theta_{ij}^{\text{ring}} = \frac{1}{1-\frac{1}{\sqrt{3}}}\left(1-\cos\phi_{ij}\right)$	$\mathcal{U}_2^{\text{ring}}$



Event isotropies – I^2_{Ring}

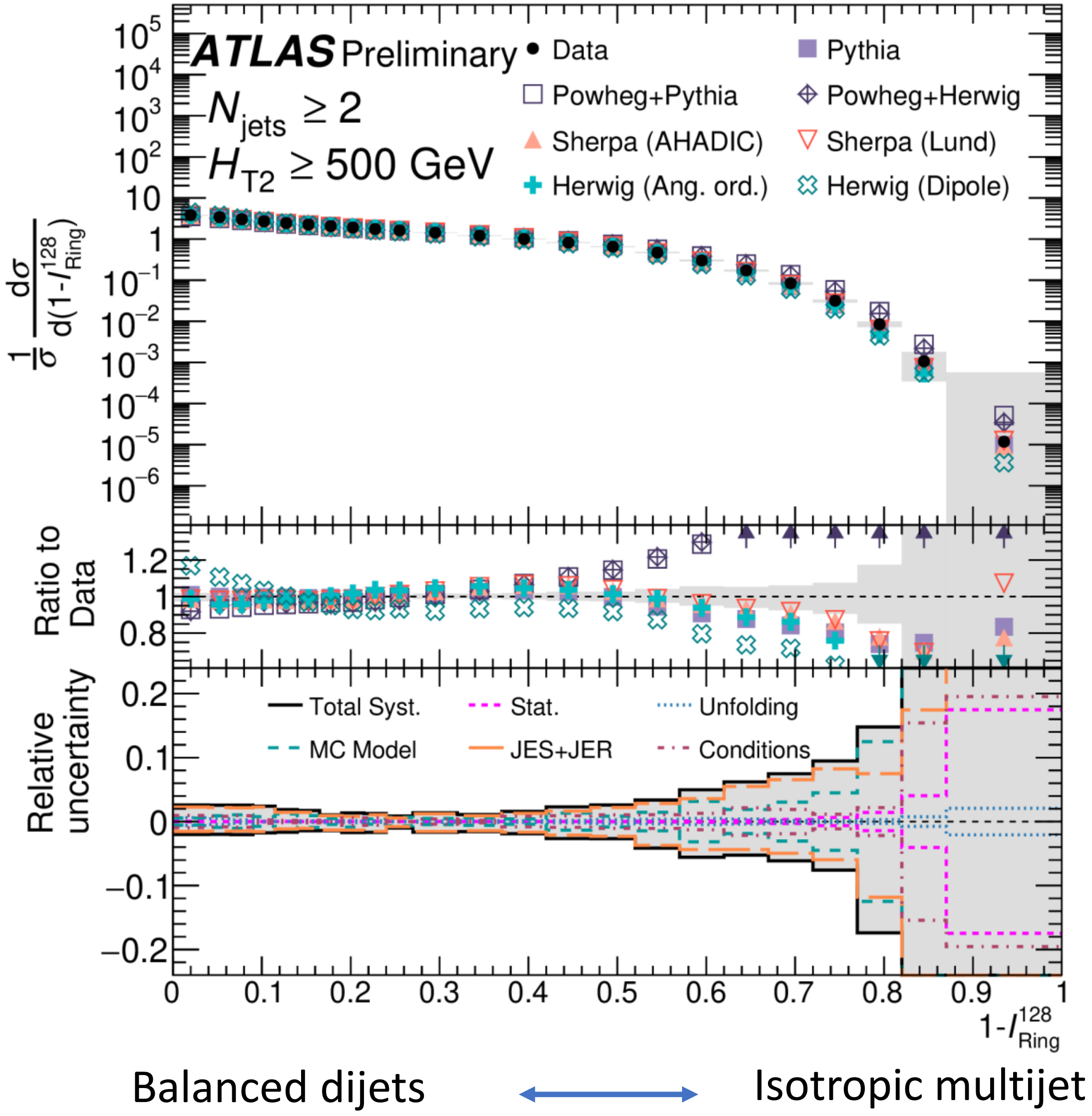
- $N_{jet} \geq 2$, $H_{T2} \geq 500$ GeV
- 3 isotropy observables binned in N_{jet} ($\geq$ 2,3,4,5) and H_{T2} ($\geq$ 500,1000,1500 GeV)
- Overall, the isotropic region is best described by NLO MC



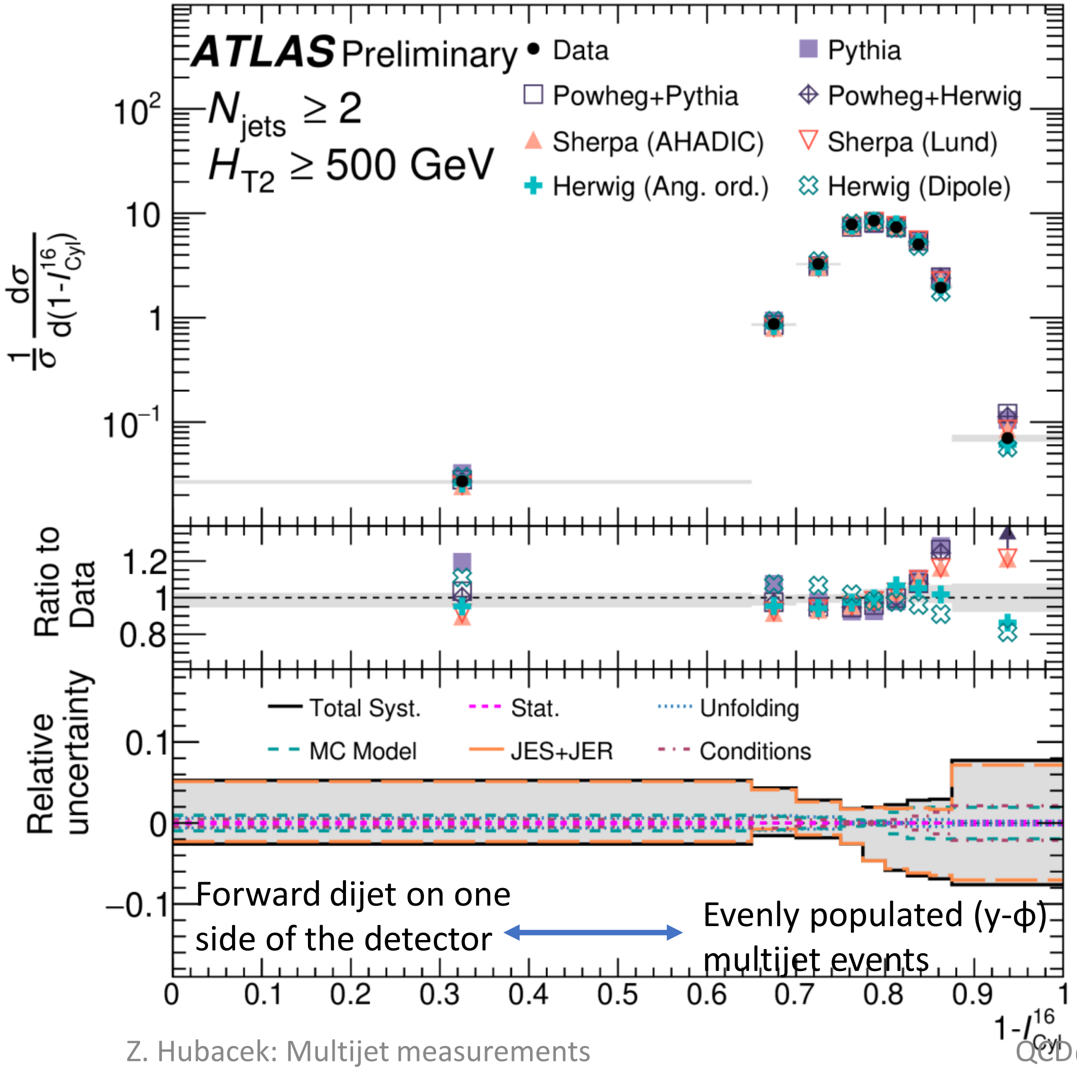
Well balanced dijets ⟷ Symmetric 3-jet event

Event isotropies – I_{Ring}^{128}

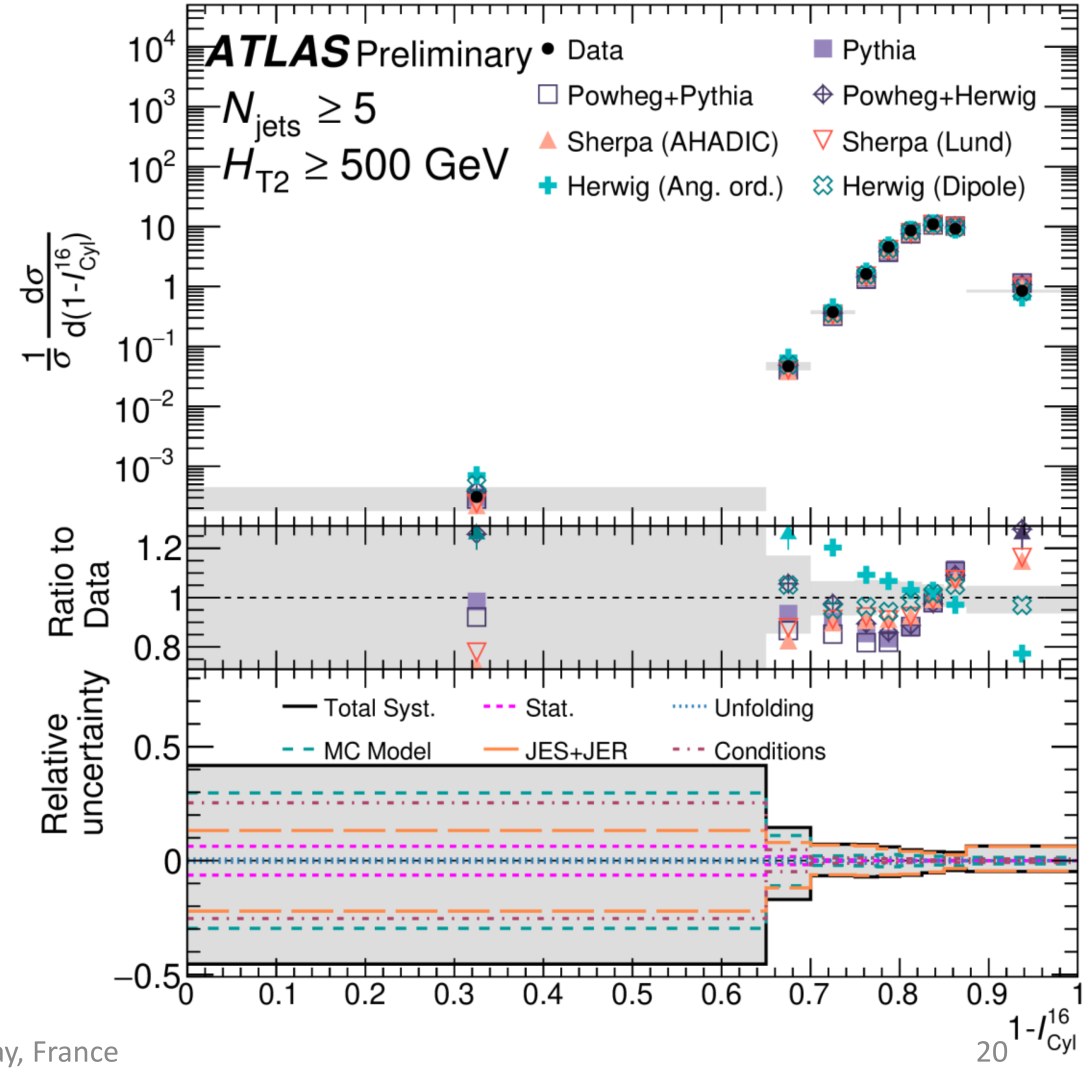
- Dynamic range – 6 orders of magnitude
- Quality of modelling very different from I_{Ring}^{2} (Powheg+Pythia/Herwig very different from other MC)
- Herwig dipole predicts relatively more dijet-like events than angular ordered



Event isotropies – I_{Cyl}^{16}



Jet multiplicity



Summary

- Presented recent QCD multijet studies of ATLAS and CMS collaborations
- Event shapes more complex than inclusive cross sections but allow testing more features of QCD radiation
- Agreement between data and simulations best in balanced, dijet-like systems and gets worse in more isotropic configurations