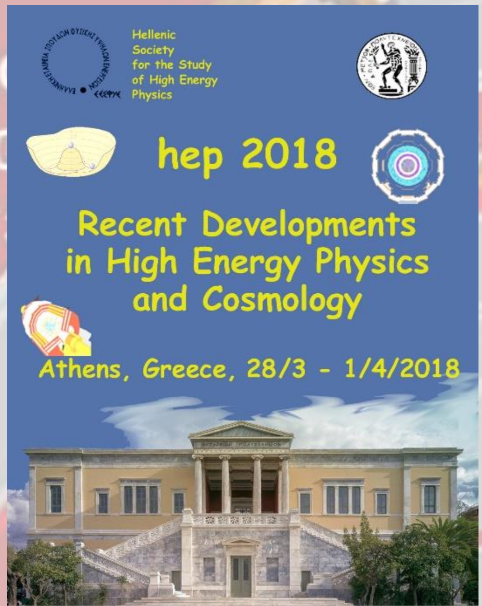


Azimuthal Correlations for Inclusive 2-jet, 3-jet and 4-jet events in pp collisions at $\sqrt{s}$ = 13 TeV with CMS

Paris Gianneios

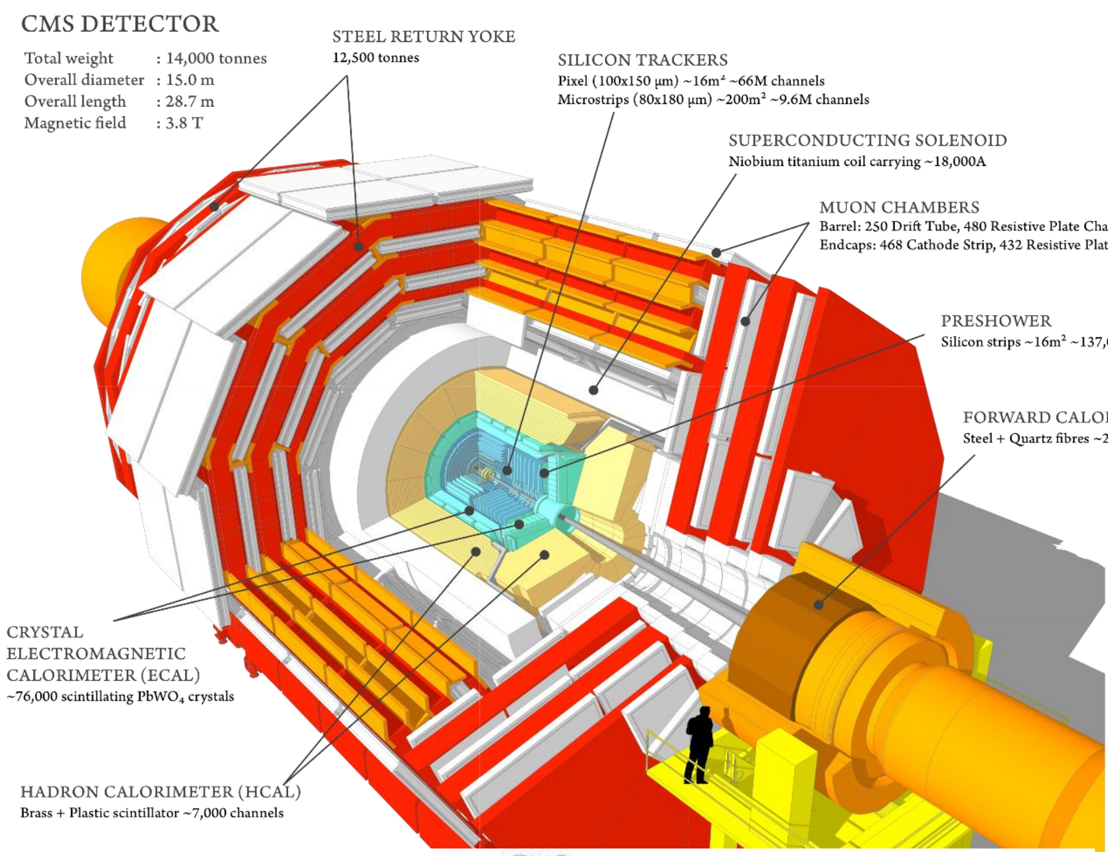
University of Ioannina

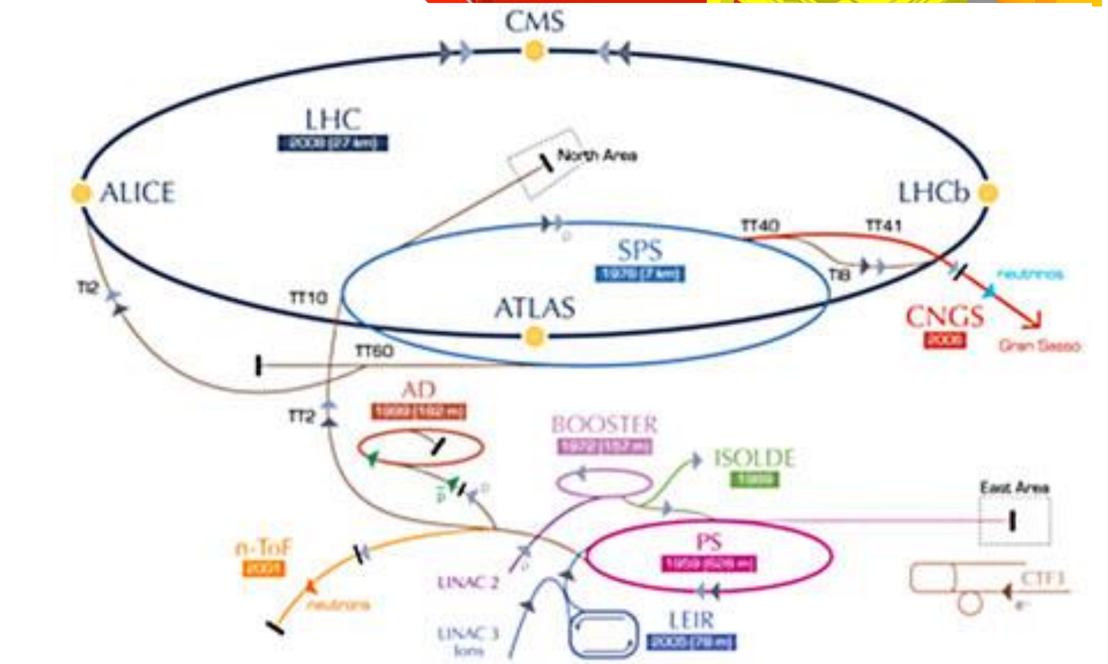
29th March 2018, HEP Athens

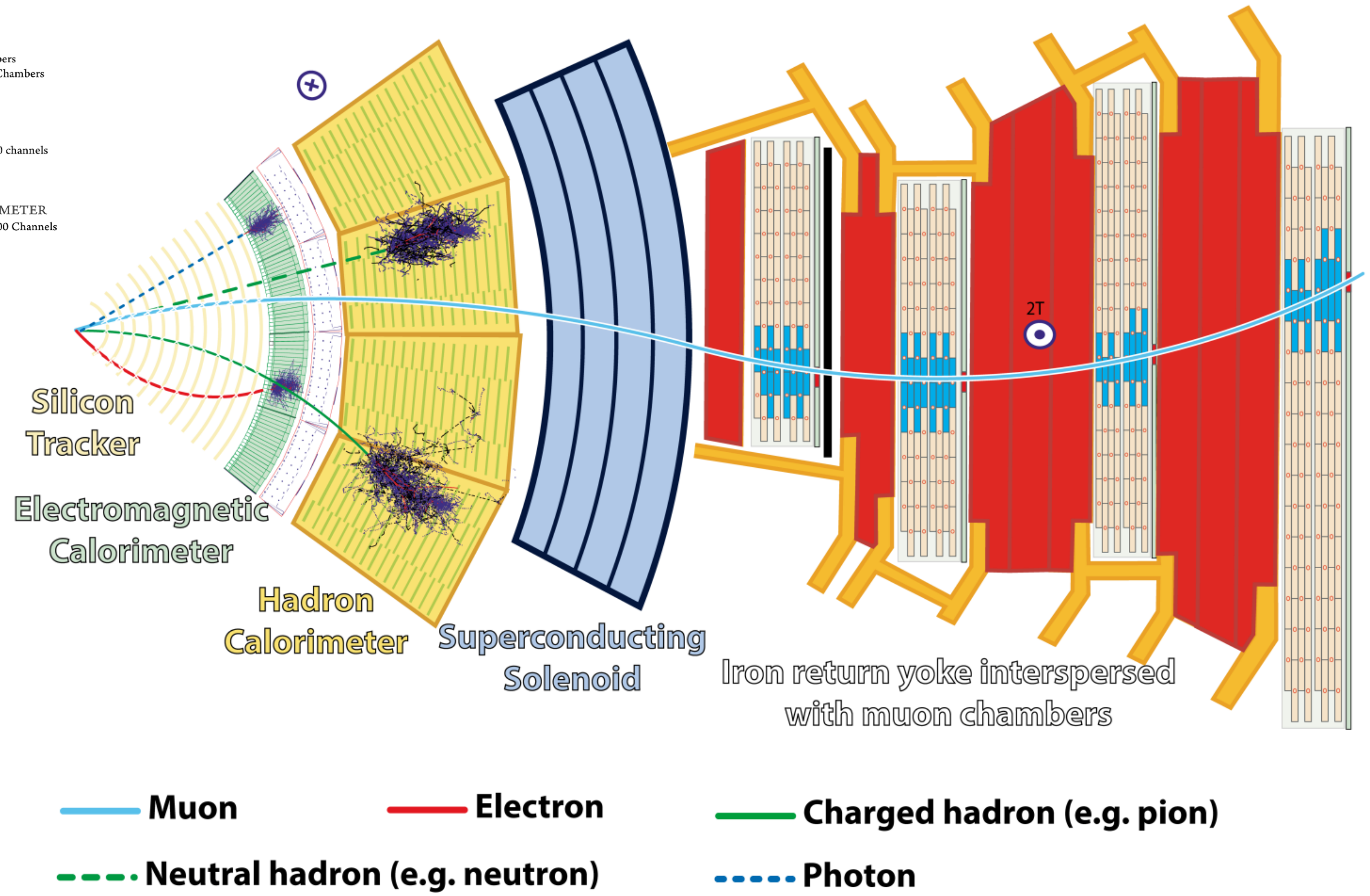
Outline

1. CMS Detector
2. Jet Physics with CMS
3. Motivation for this Measurement
4. The Measurement
5. Summary

CMS Detector

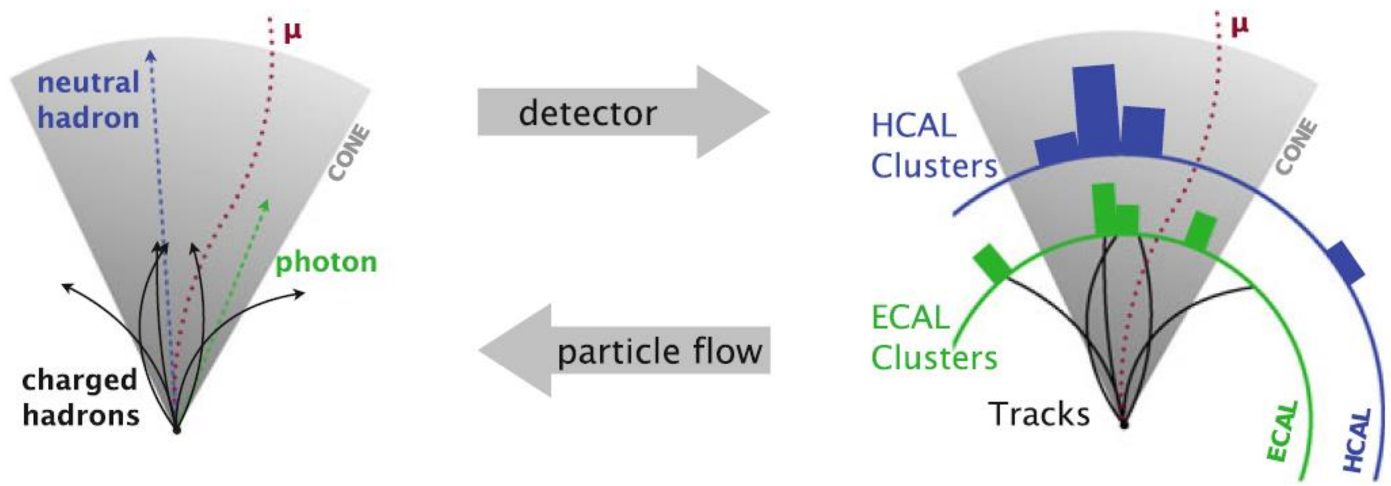


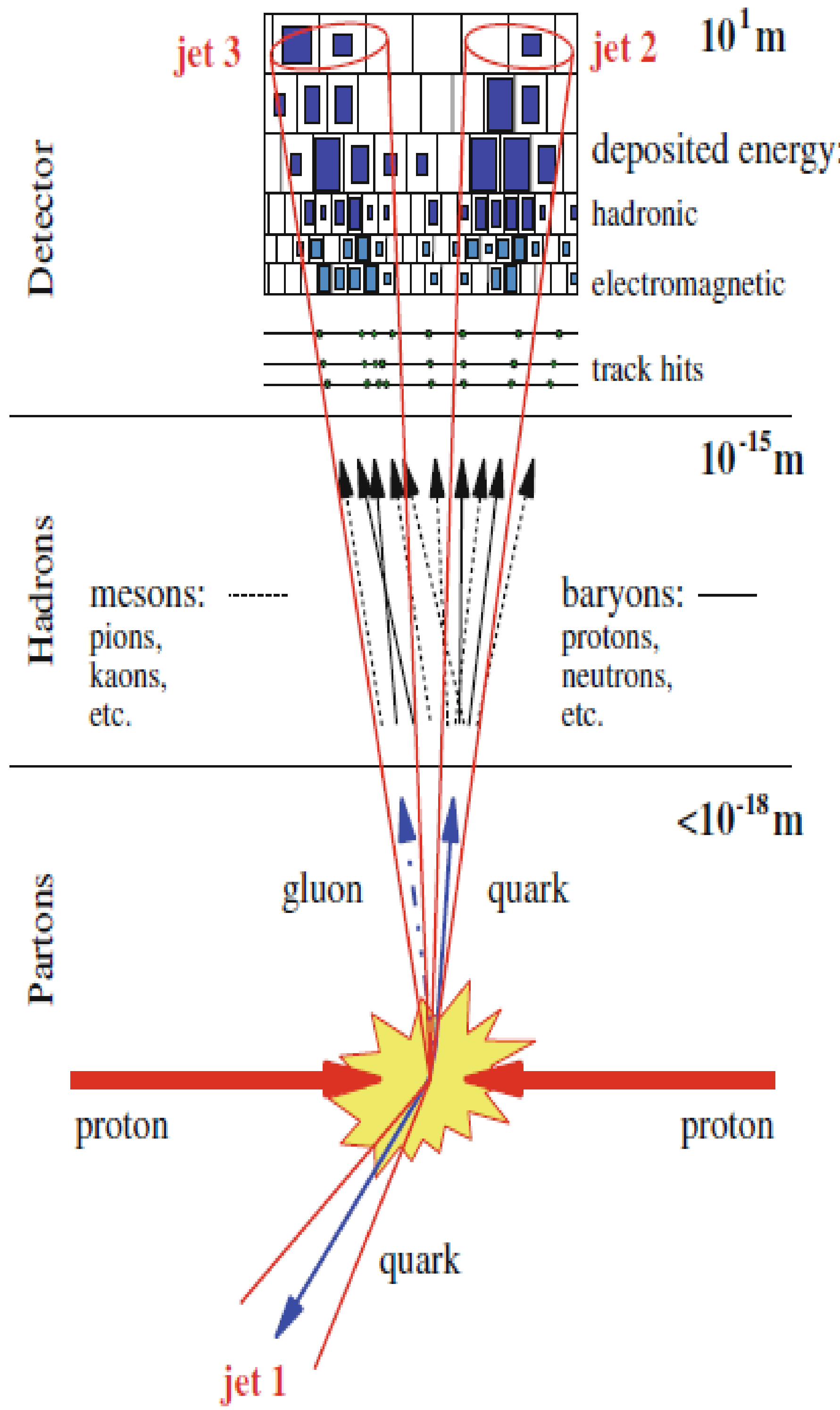




Jet Physics with CMS

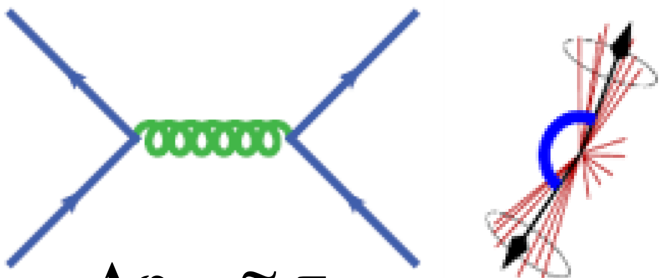
- pp DIS ➡ 2 or more outgoing partons ➡ radiation ➡ parton shower ➡ hadronization ➡ "stream" of hadrons in the direction of initial parton : ***Jet***
- Jet algorithm: a mathematical prescription which decides whether a measured object belongs to a jet or not.
  Anti-kt algorithm : standard jet algorithm at the LHC
- Anti-kt algorithm requires as input a list of particles in order to cluster them into final jets:
  PF Algorithm



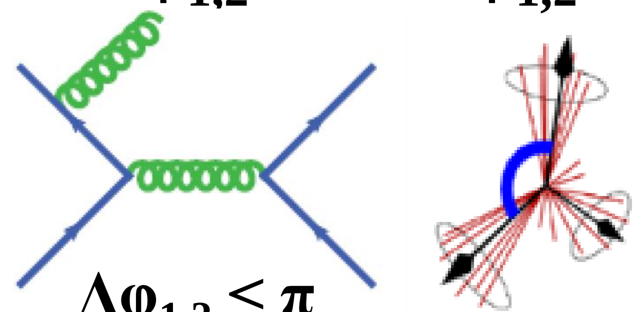


Motivation for this measurement

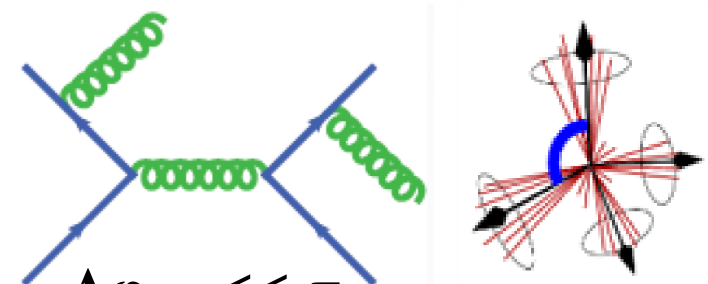
- Azimuthal angle $\Delta\varphi_{1,2}$ between the 2 leading jets is sensitive to radiation effects of quarks & gluons => **can be used for testing pQCD and for MC tuning:**
  - At **LO** the two leading jets are back-to-back: $\boldsymbol{\Delta\varphi_{dijet} \approx \pi}$, while higher order corrections cause azimuthal decorrelation of jets: $\boldsymbol{\Delta\varphi_{1,2} < \pi}$ **,** $\boldsymbol{\Delta\varphi_{1,2} << \pi}$



$\Delta\varphi_{1,2} \approx \pi$



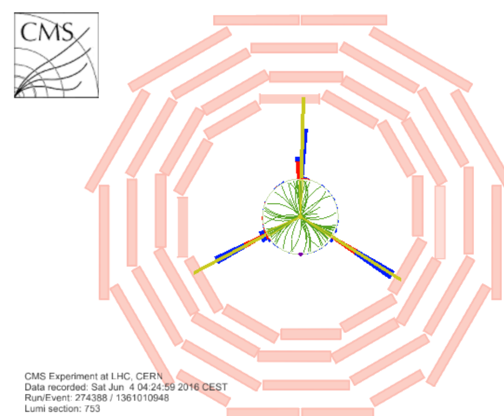
$\Delta\varphi_{1,2} < \pi$

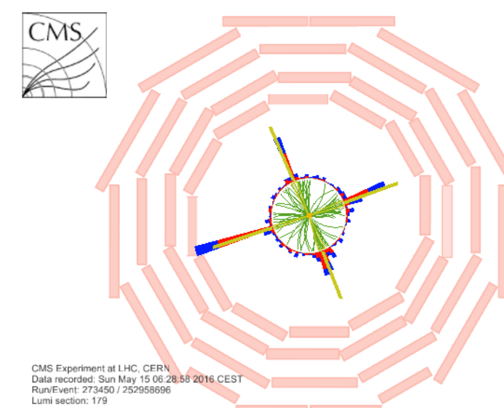


$\Delta\varphi_{1,2} << \pi$

- **Compare the 13TeV results to a similar measurement at 8TeV:**
  - Extend the 8 TeV measurement (only 2-jet topologies) to 3-jet and 4-jet topologies.

- **Measure a new observable $\Delta\varphi_{2j}^{min}$ for 3-jet and 4-jet topologies which also probes the emission of extra partons.**





Observables and event selection

- Measurement of two observables for several regions of p_T^{max}:

(A) $\frac{1}{\sigma_{1,2}} \frac{d\sigma_{1,2}}{d\Delta\varphi_{1,2}}$ **(B)** $\frac{1}{\sigma_{2j}^{min}} \frac{d\sigma_{2j}^{min}}{d\Delta\varphi_{2j}^{min}}$

- Measurement of observable (A) for inclusive 2,3 and 4 jet topologies and observable (B) for inclusive 3 and 4 jet topologies.

- Data collected with CMS experiment: full 2016 statistics $\mathcal{L}_{int}$=35.9 fb^{-1} at $\sqrt{s} = 13\ TeV$ with single-jet high level triggers:

Trigger choice for each region of p_T^{max}

HLT p_T threshold (GeV)	140	200	320	400	450
p_T^{max} region (GeV)	200–300	300–400	400–500	500–600	>600
$\mathcal{L}$ (fb^{-1})	0.024	0.11	1.77	5.2	36

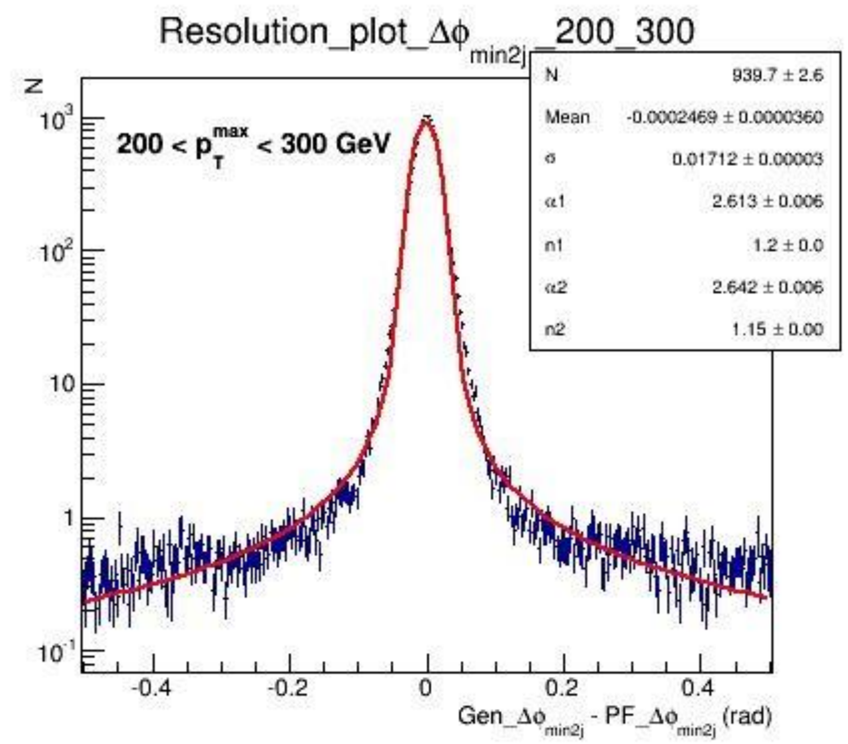
- Event selection :
  - Events with at least one good primary vertex, apply tight JetID on each jet.
  - Consider jets up to $|y| < 5$ and with $p_T > 100\ GeV$
    - Inclusive 2-jet events : $|y_1|, |y_2| < 2.5$
    - Inclusive 3-jet events : $|y_1|, |y_2|, |y_3| < 2.5$
    - Inclusive 4-jet events : $|y_1|, |y_2|, |y_3|, |y_4| < 2.5$

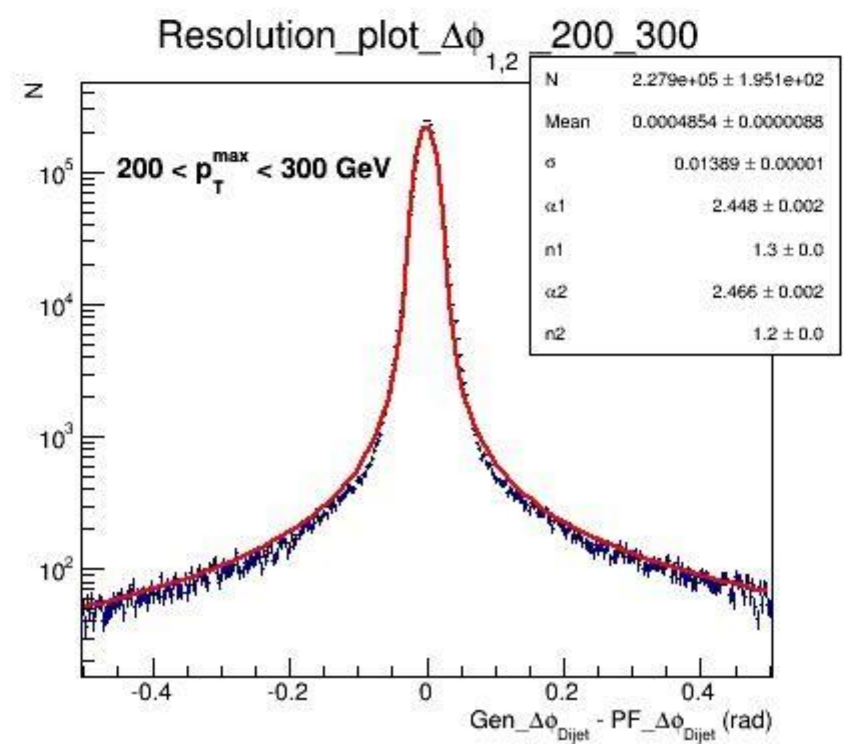
Δφ resolution studies

- Δφ resolution studies:
  - are taken into account in the binning definition
  - are used to perform the unfolding of the measurement
  - are performed using Monte Carlo event generators using the difference between generated and reconstructed Δφ.

p_T^{max} (GeV)	Gen_$\Delta\phi_{12}$−PF_$\Delta\phi_{12}$ (rad) PYTHIA8 CUETM1	Gen_$\Delta\phi_{2j}^{min}$−PF_$\Delta\phi_{2j}^{min}$ (rad) PYTHIA8 CUETM1
200-300	0.014	0.017
300-400	0.012	0.016
400-500	0.010	0.014
500-600	0.009	0.013
600-700	0.008	0.013
700-800	0.008	0.012
800-1000	0.007	0.011
1000-1200	0.007	-
>1000	0.007	0.011
>1200	0.007	

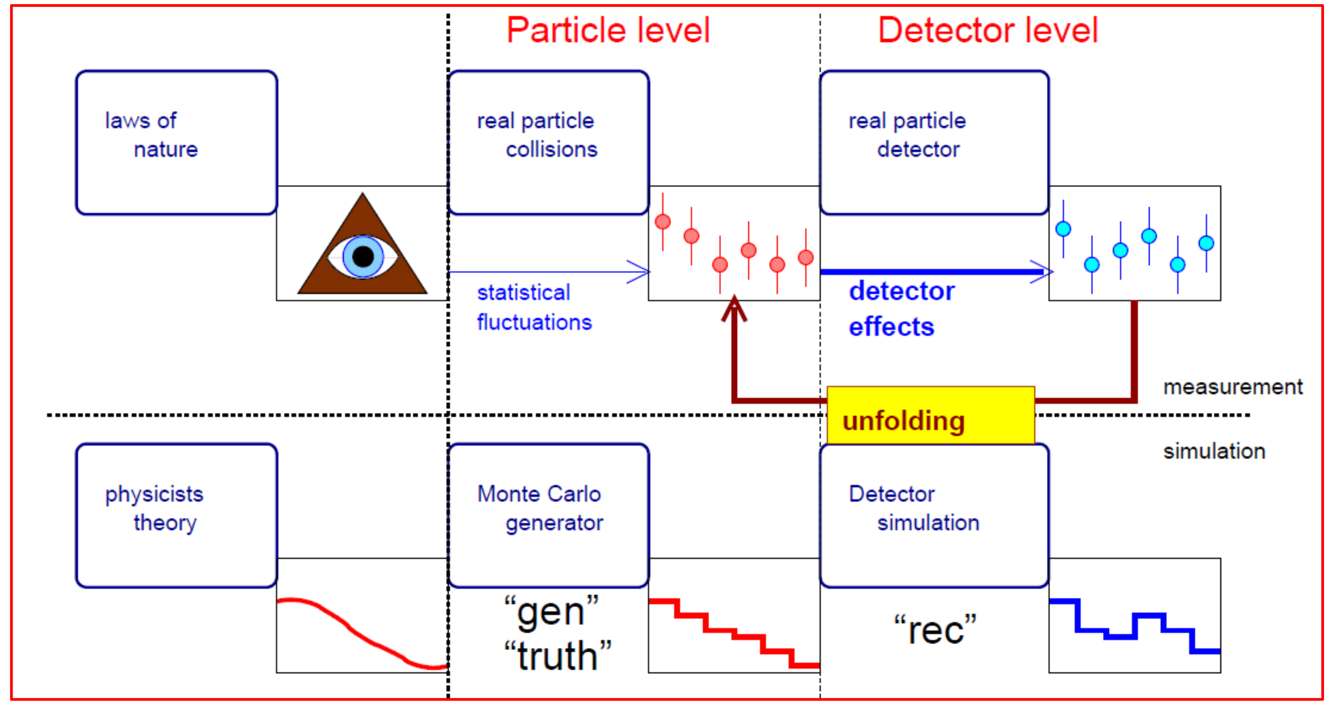
- Resolution ranges from 0.017 rads (1°) to 0.007 rads (0.4°). The bin width used in the measurements of $\Delta\varphi_{1,2}$ and $\Delta\varphi_{2j}^{min}$ is 0.087 rads (5°) ≈ 5 to 12 times larger than the resolution.



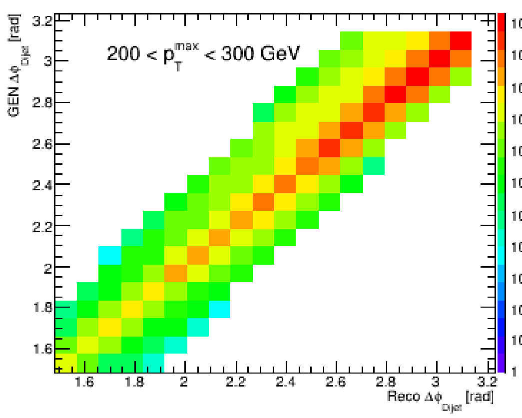


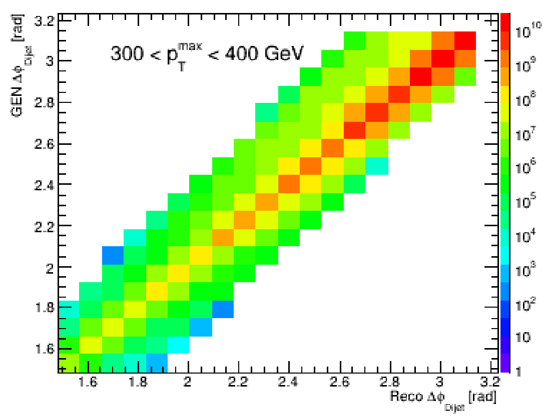
Data Unfolding

- Measurement at reconstructed (detector) level needs to be corrected for detector smearing effects => direct comparison :
  - Data vs Monte Carlo at particle level
  - Data vs Data from other exp. e.g ATLAS



- Unfolding based on the matrix inversion algorithm with RooUnfold package:
  1. Build a response matrix (RM) that maps the true distribution onto the measured one using a Toy MC for larger statistics :





  - Events generated in flat Δφ spectrum
  - Weight these events by the cross sections at gen level from Pythia CUETM1 => True distributions
  - Smear the true distributions with Δφ resolution => measured distributions.

  2. Use the matrix inversion method and obtain the unfolded distributions.

- The unfolded distributions differ from the distributions at the detector level by 1 to 4% .

Systematics

Three main sources of systematic uncertainties:

- Systematic uncertainty due to unfolding:
  - Model dependence ➡ build new response matrices using the generator level from Herwig++ or Madgraph and repeat the unfolding ~ 0.2% .
  - Δφ resolution uncertainty ➡ change Δφ resolution by ±10 % , construct new response matrices and redo the unfolding < 0.2% .

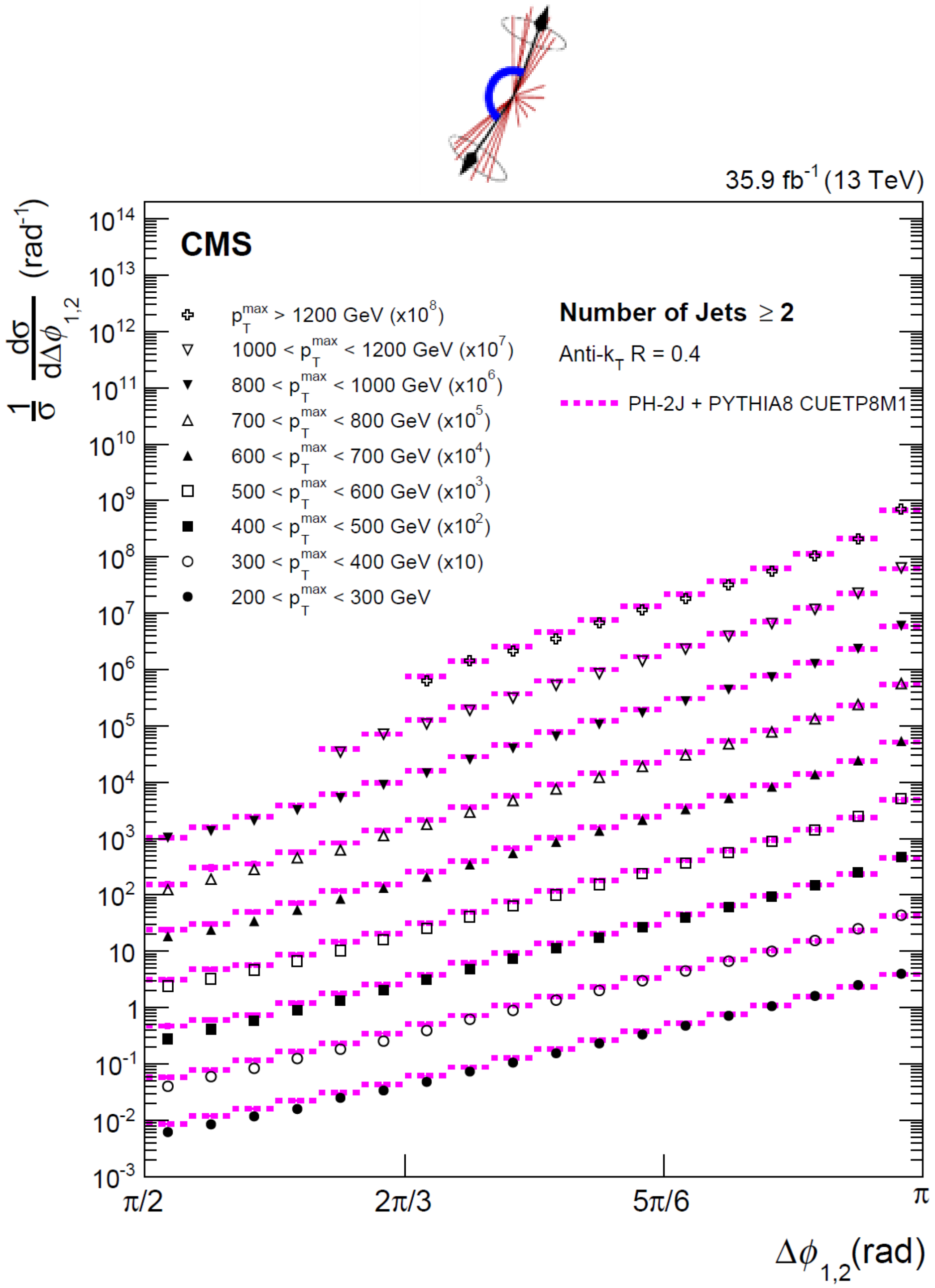
- Systematic uncertainty due to Jet Energy Scale (JES) calibration:
  - The sensitivity of the measurement to JES uncertainty estimated by changing all jets p_T as $p_T = p_T(1 \pm 1\sigma)$ and compare the new cross sections with those with nominal JES value
    $\Delta\varphi_{1,2}$: ranges from 3% at π/2 to 0.1% at π.
    $\Delta\varphi_{2j}^{min}$: ranges from 0.1 to 1% for 3-jet topologies & from 0.1 to 2% for 4-jet topologies

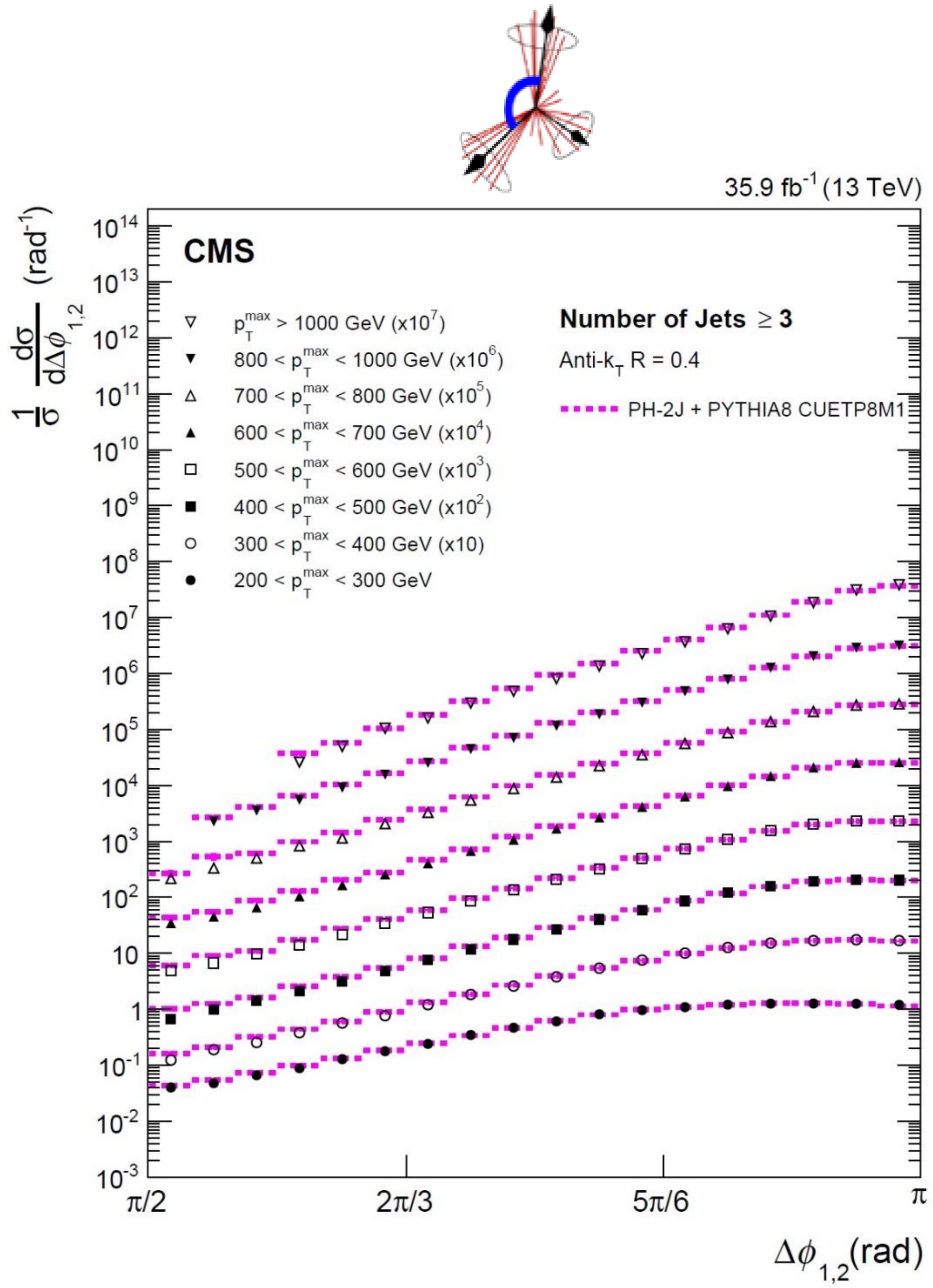
- Systematic uncertainty due to Jet Energy Resolution (JER):
  - Use of Pythia8 for p_T resolution and varying its parameters within their uncertainties
    $\Delta\varphi_{1,2}$: ranges from 1% at π/2 to 0.1% at π.
    $\Delta\varphi_{2j}^{min}$: < 0.5% .

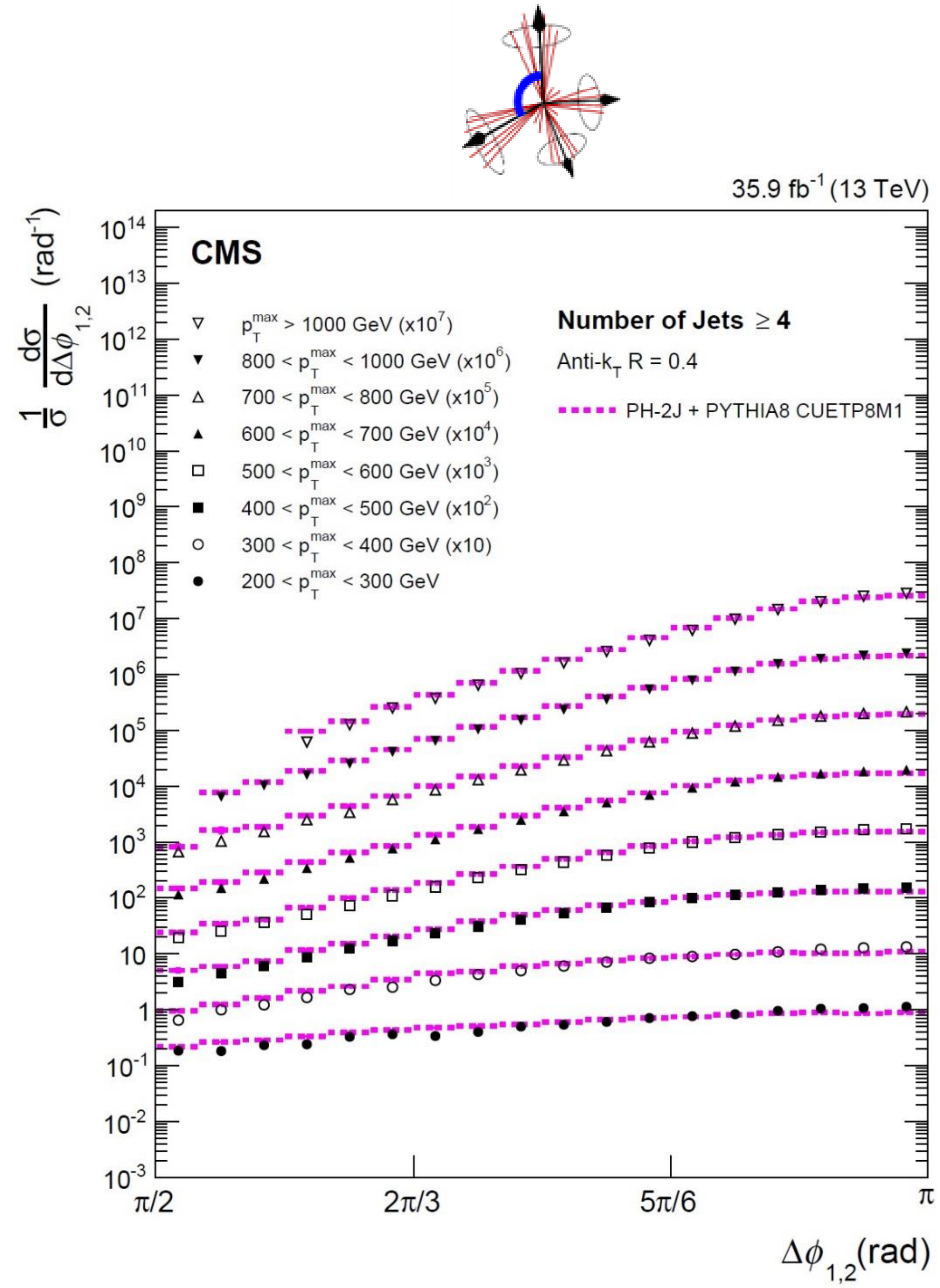
Monte Carlo event generators

Generator	Simulated diagrams	Showering	Hadronization	Tune	PDF set
Pythia8	LO $2 \rightarrow 2$	Order in pT	Lund string model	CUETP8M1	NNPDF2.3LO
Herwig++	LO $2 \rightarrow 2$	Angular order	Cluster fragmentation	CUETHppS1	CTEQ6L1
MadGraph	LO $2 \rightarrow 2$ LO $2 \rightarrow 3$ LO $2 \rightarrow 4$	Pythia8 MLM matching	Pythia8	CUETP8M1	NNPDF2.3LO
Powheg	NLO $2 \rightarrow 2$ LO $2 \rightarrow 3$	Pythia8 Herwig++	Pythia8 Herwig++	CUETP8M1 CUETHppS1	NNPDF2.3LO
Powheg	NLO $2 \rightarrow 3$ LO $2 \rightarrow 4$	Pythia8	Pythia8	CUETP8M1	NNPDF2.3LO
Herwig7	NLO $2 \rightarrow 2$ LO $2 \rightarrow 3$	Angular order	Cluster fragmentation	H7-UE-MMHT	MMHT2014

Inclusive 2-jets, 3-jets and 4-jets $\Delta\phi_{1,2}$

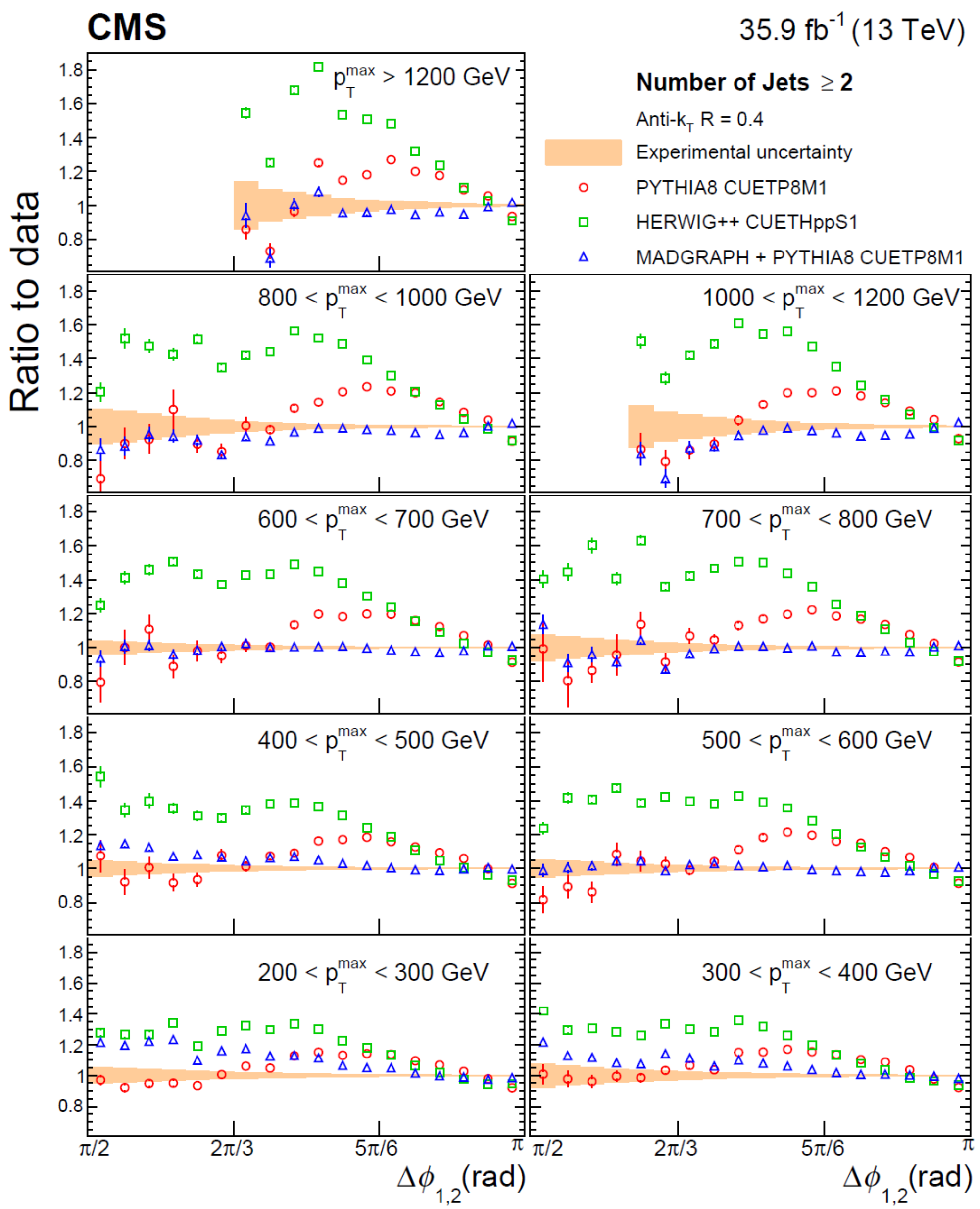


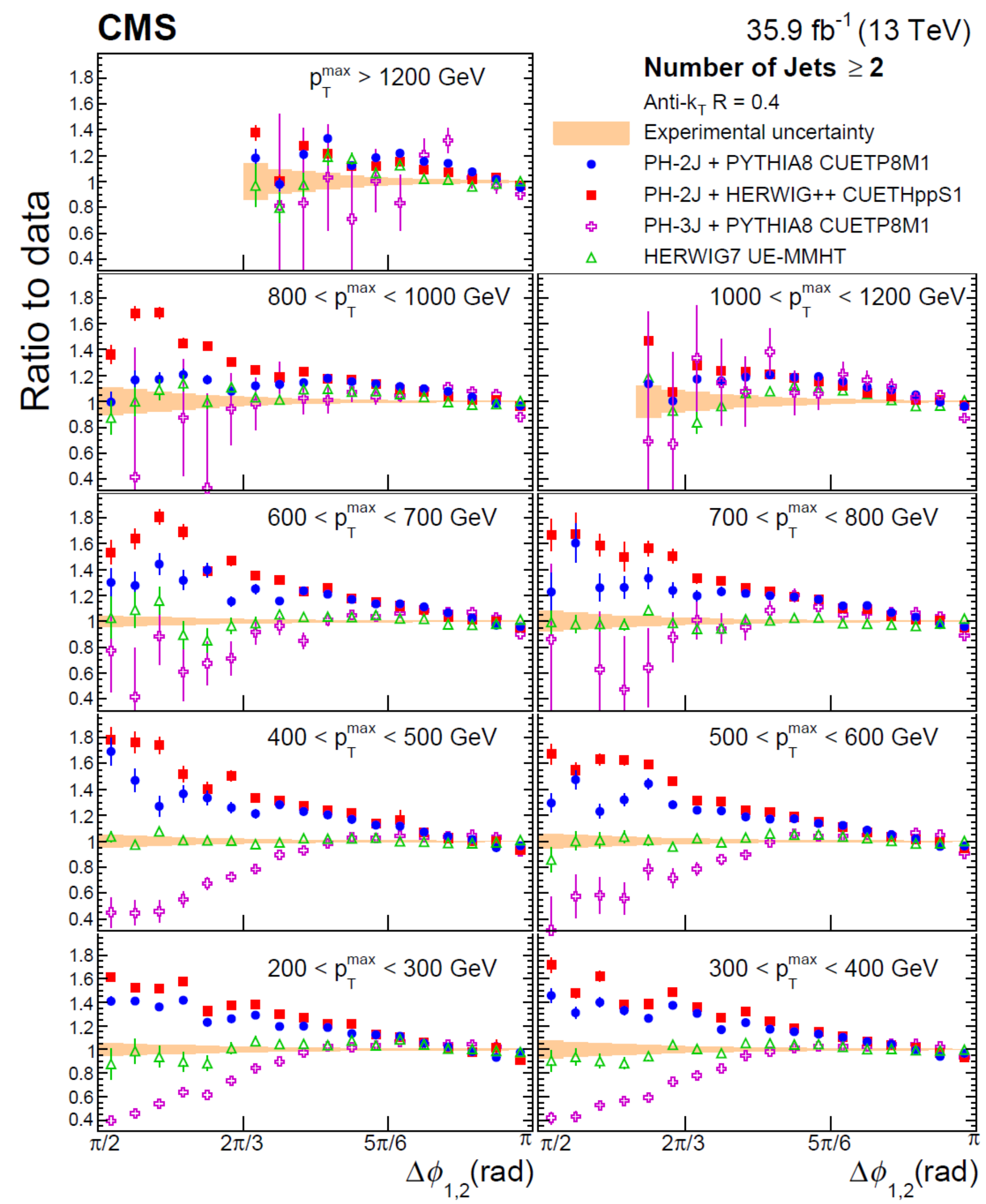




Incl 2-jets: $\Delta\varphi_{1,2}$ strongly peaked at π and become steeper with increasing p_T^{max}.
Incl 3-jets (& 4-jets): $\Delta\varphi_{1,2}$ smoother close to π since dijets (& 3-jets) are not included.

Inclusive 2-jets : $\Delta\phi_{1,2}$

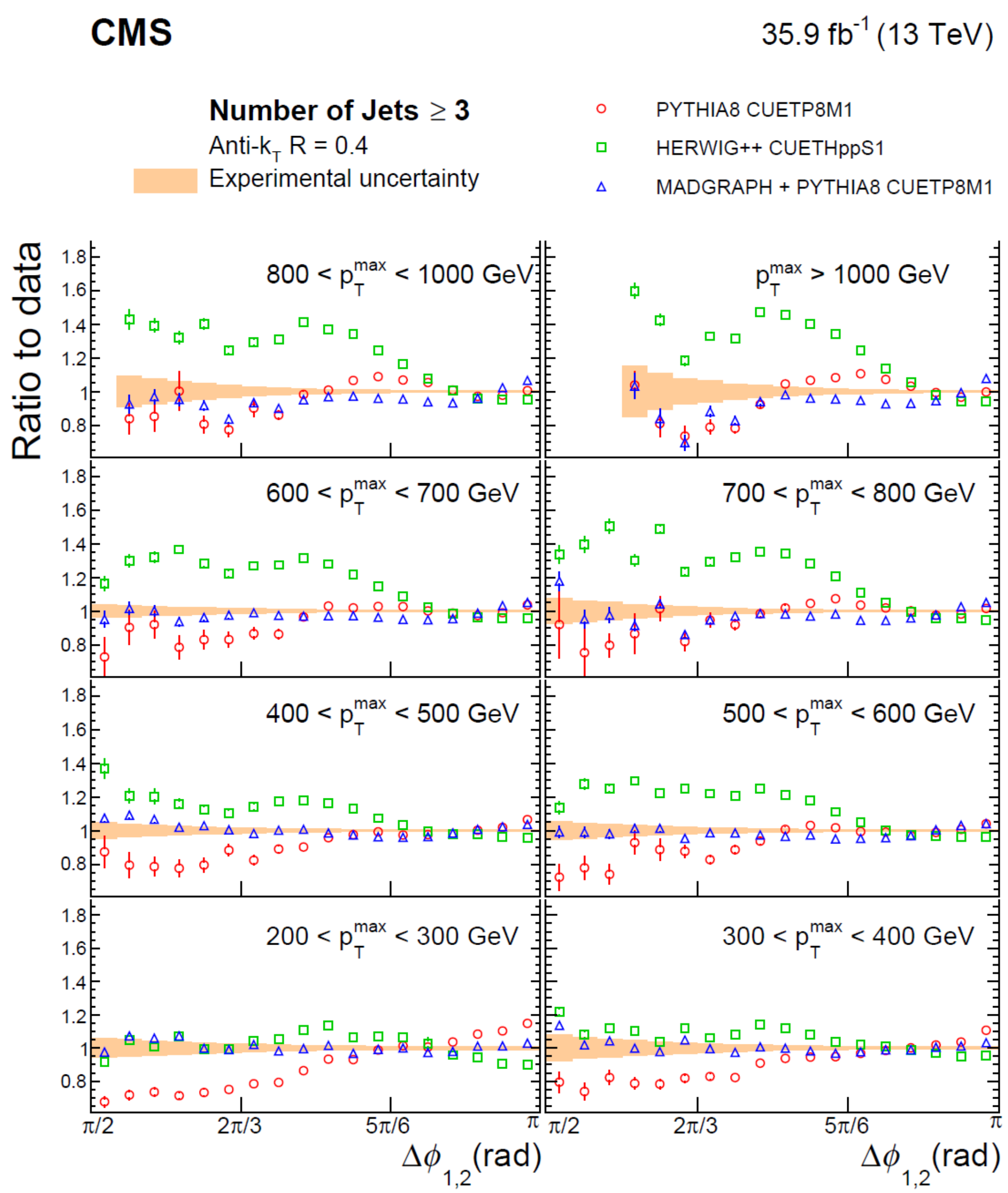


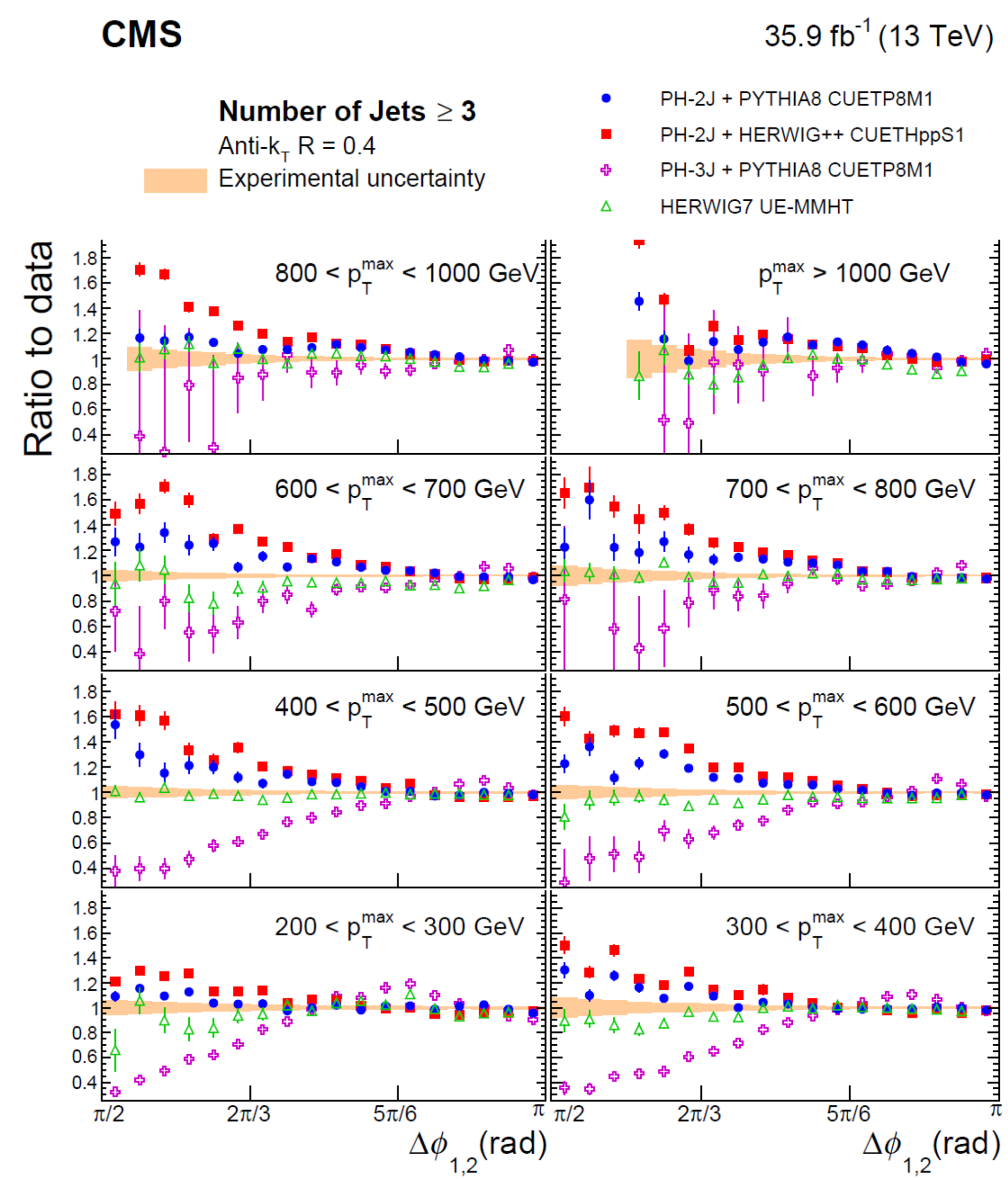


- Herwig++ exhibits the largest deviations
- Pythia8 behaves better
- Best description by Madgraph

- PH-2J and PH-3J exhibit large deviations
- Best description by H7

Inclusive 3-jets : $\Delta\phi_{1,2}$

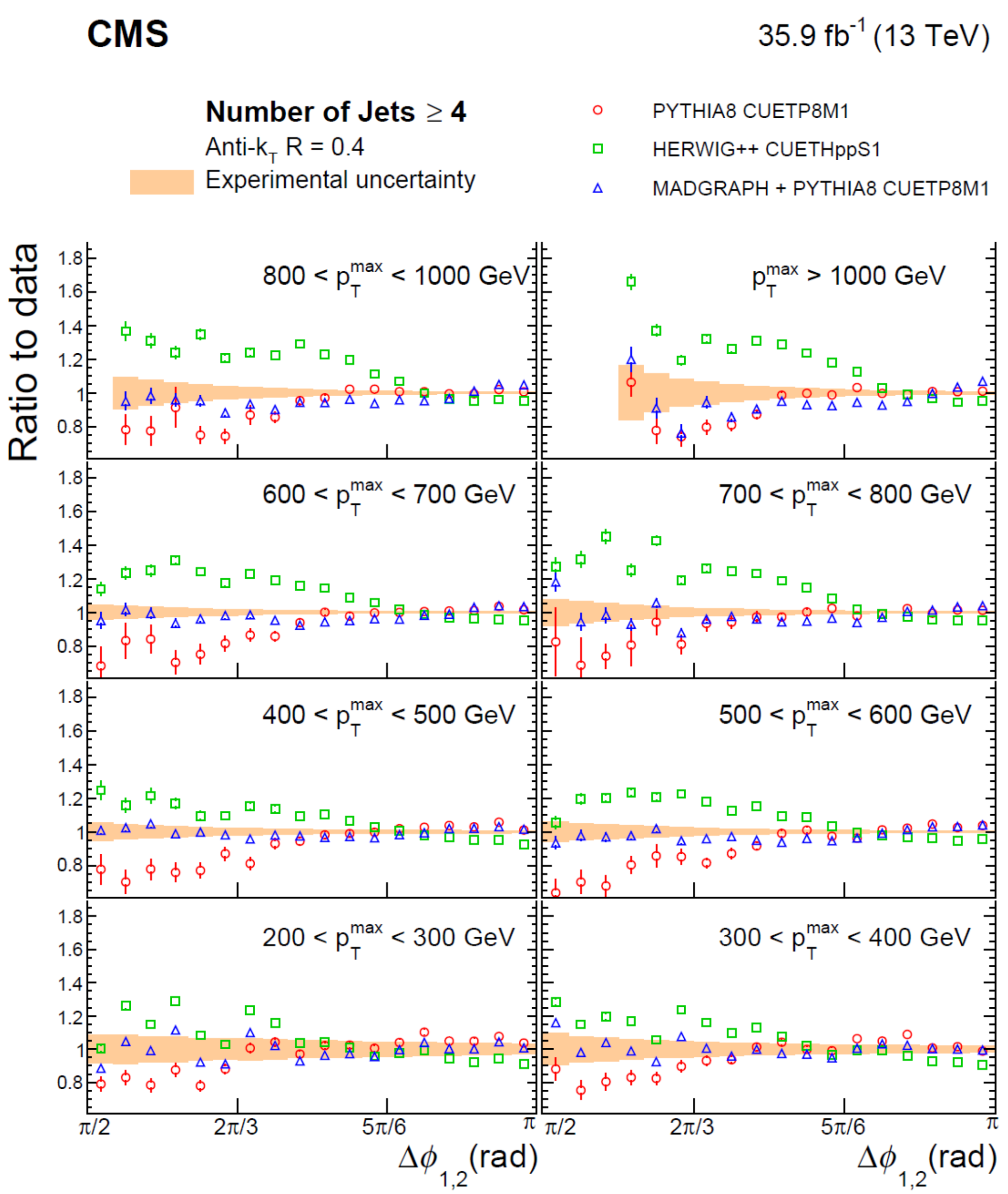


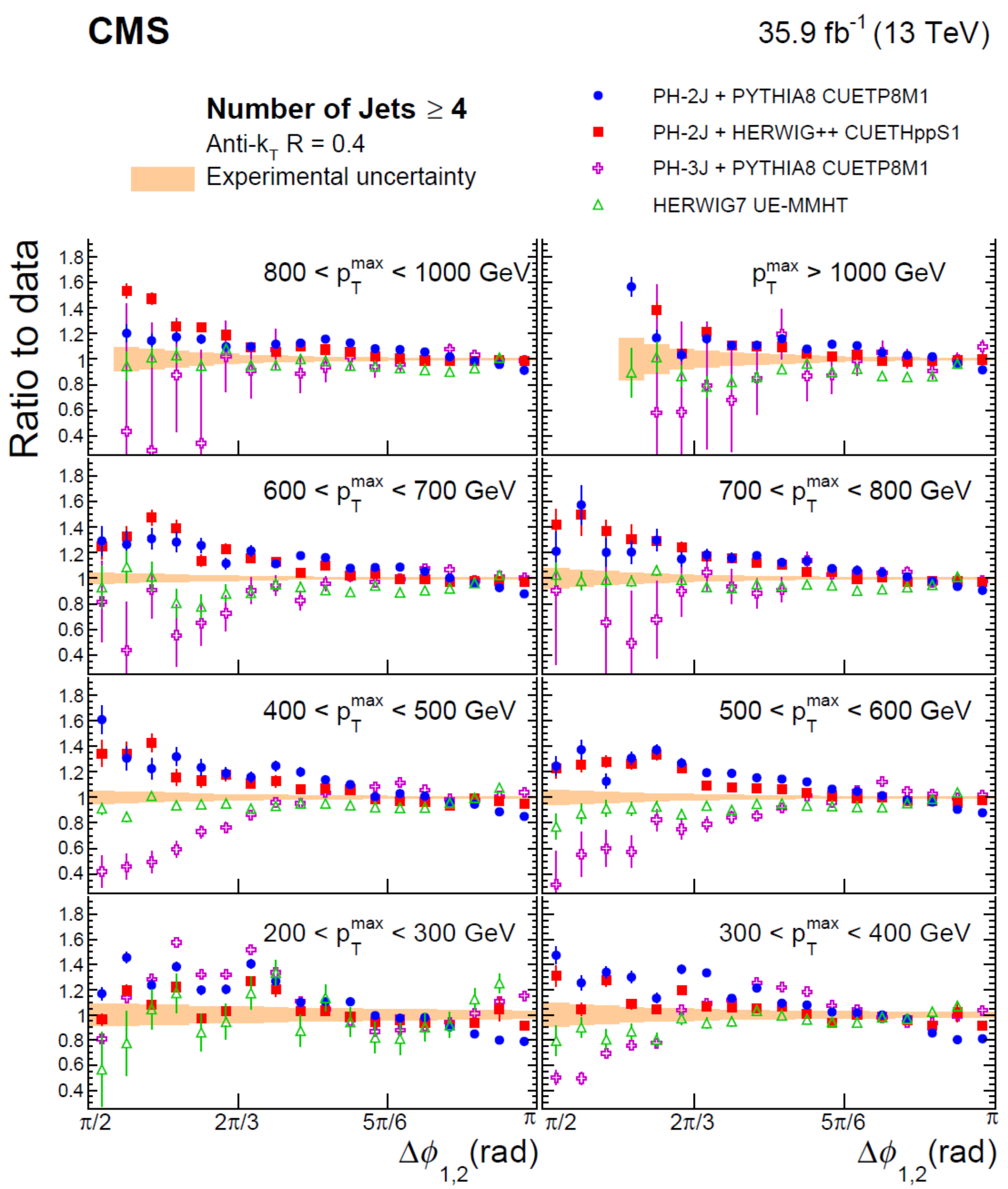


- Herwig++ exhibits the largest deviations
- P8 behaves different close to $\pi/2$ than in 2-jet
- Best description by Madgraph

- PH-2J and PH-3J exhibit large deviations
- Best description by H7

Inclusive 4-jets : $\Delta\phi_{1,2}$

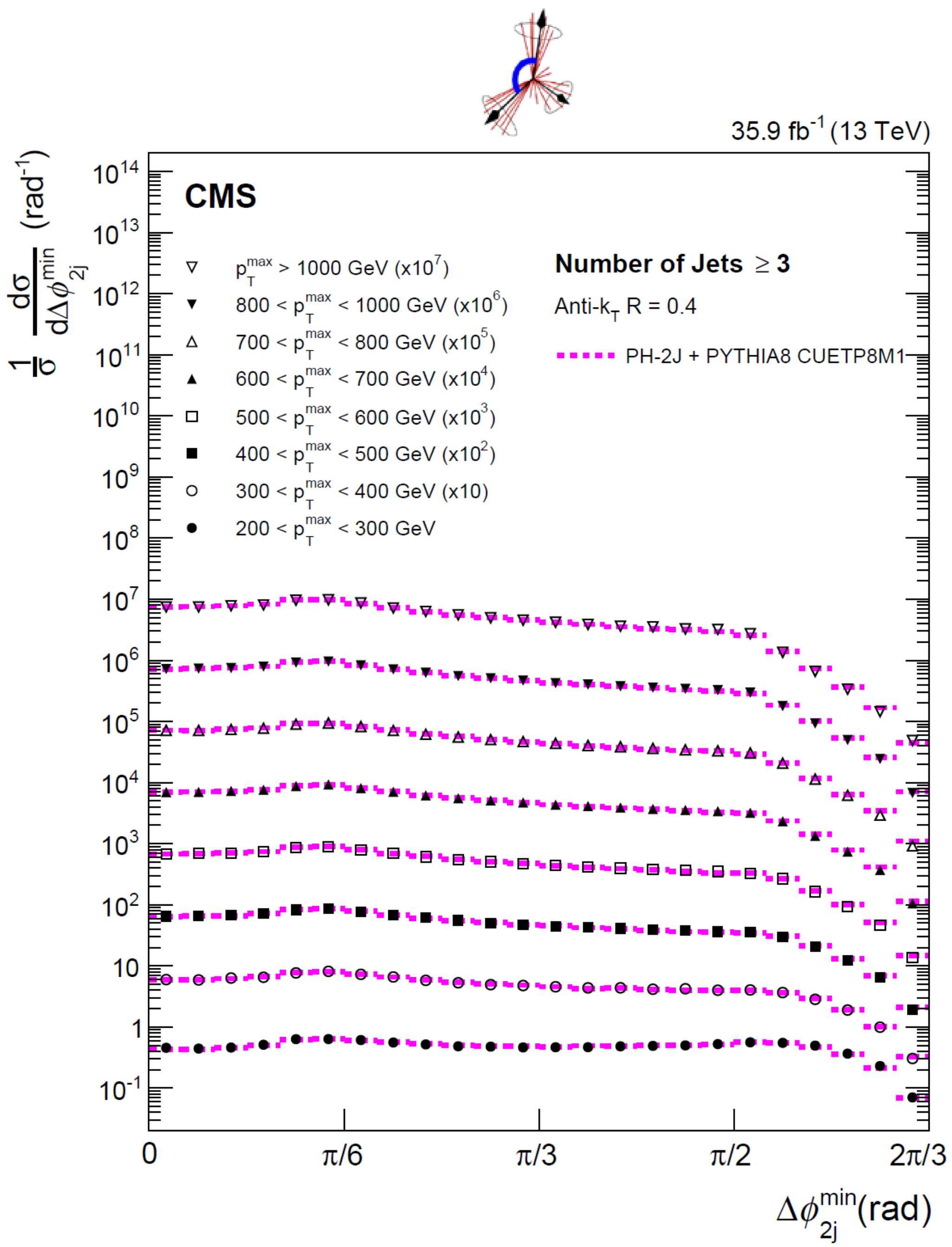


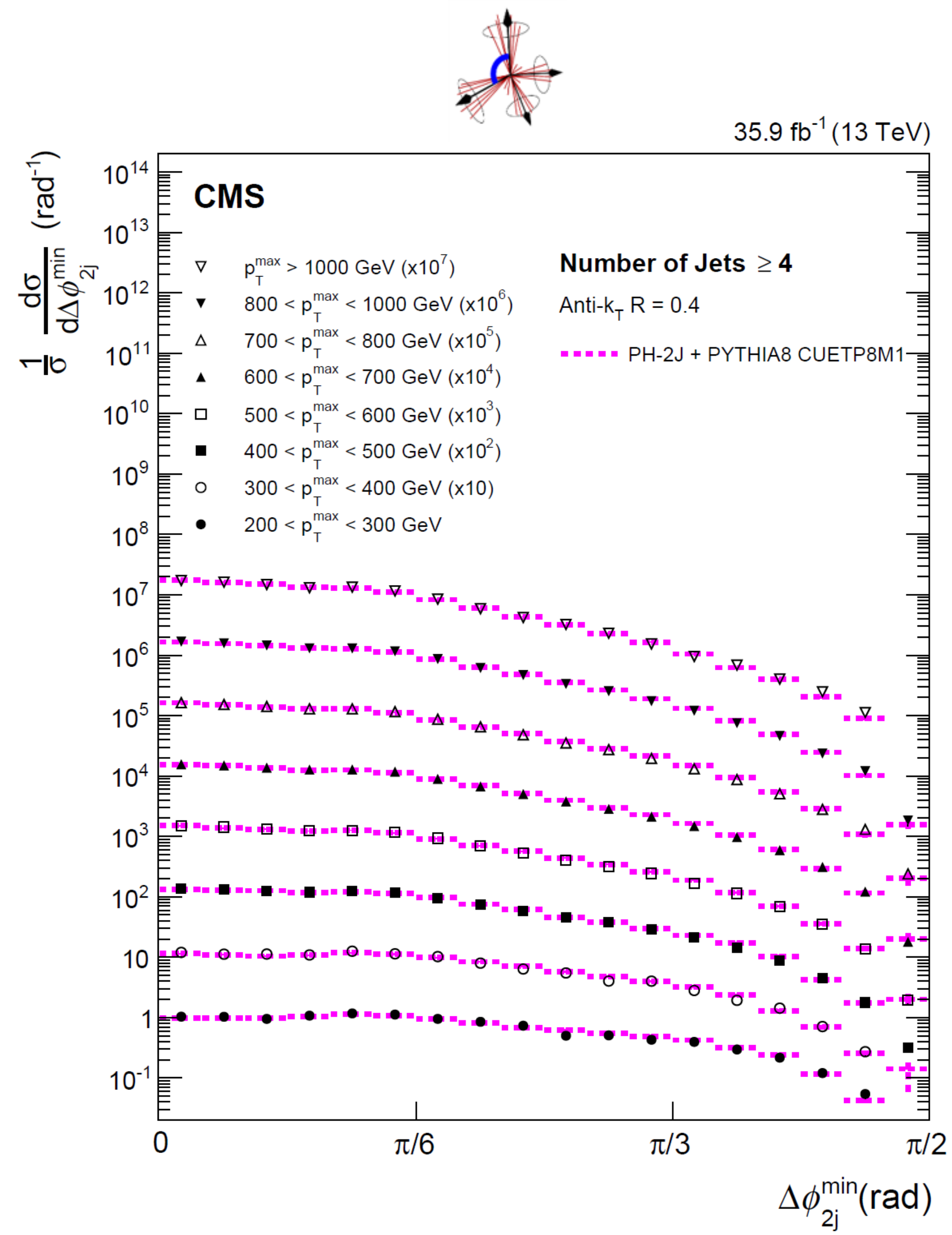


- Herwig++ exhibits the largest deviations
- P8 behaves different close to $\pi/2$ than in 2-jet
- Best description by Madgraph

- PH-2J and PH-3J exhibit large deviations
- Best description by H7

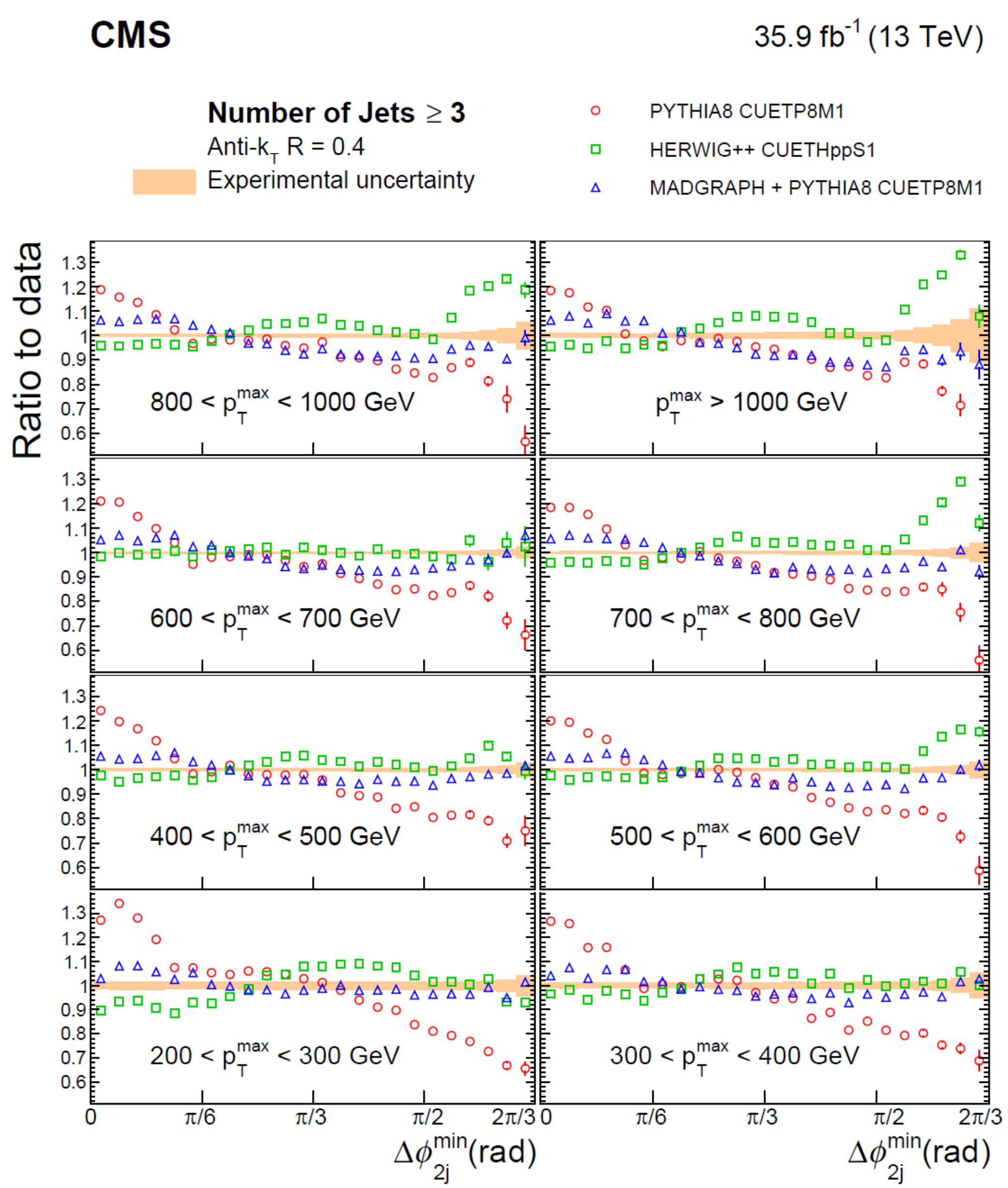
Inclusive 3-jets and 4-jets $\Delta\varphi_{2j}^{min}$

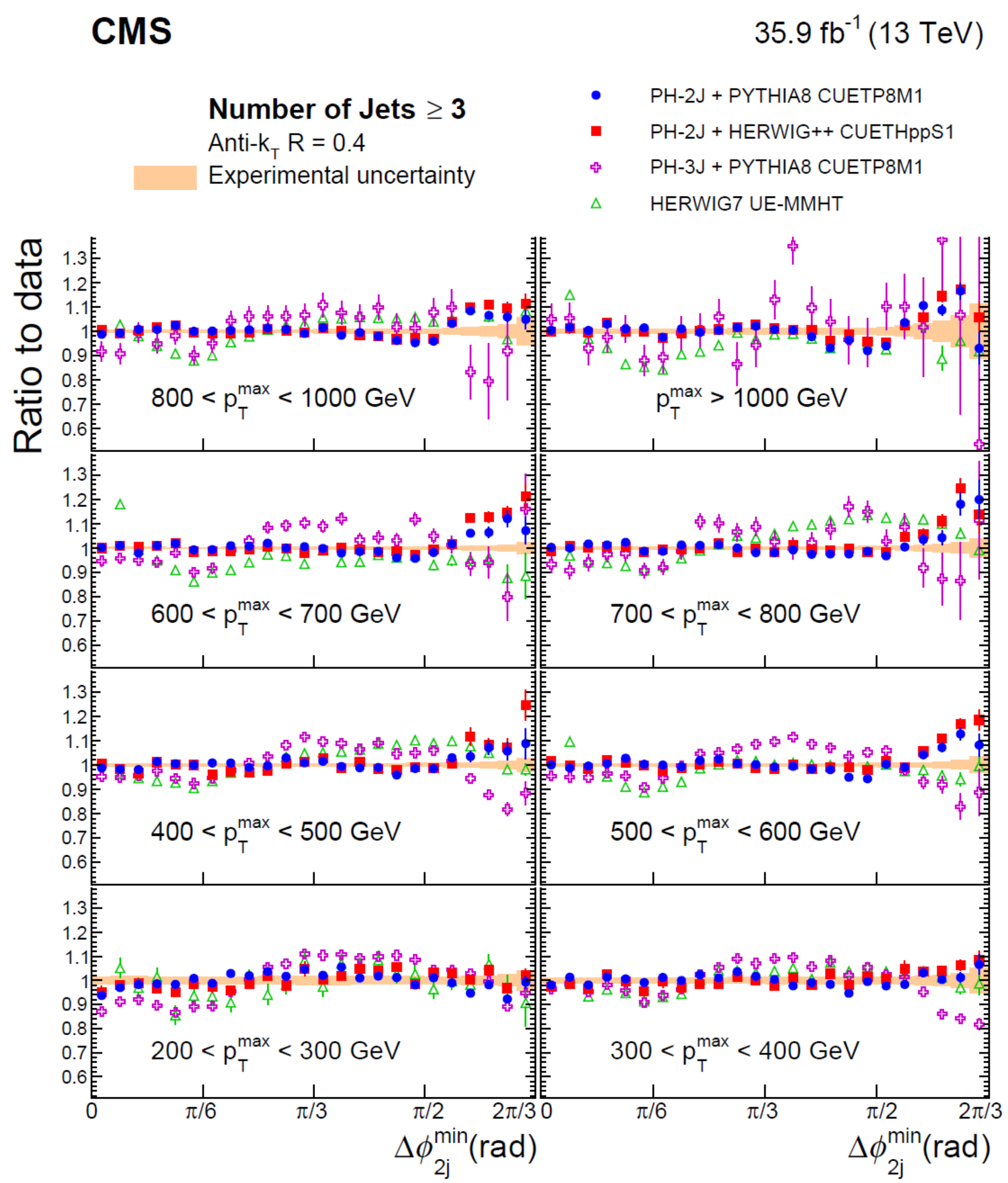




- Distributions are almost flat and decrease slowly on the right with maximum value for incl. 3-jets at $2\pi/3$ ("star-shape" configuration) & for incl. 4-jets at $\pi/2$ ("cross" configuration).

Inclusive 3-jets : $\Delta\varphi_{2j}^{min}$

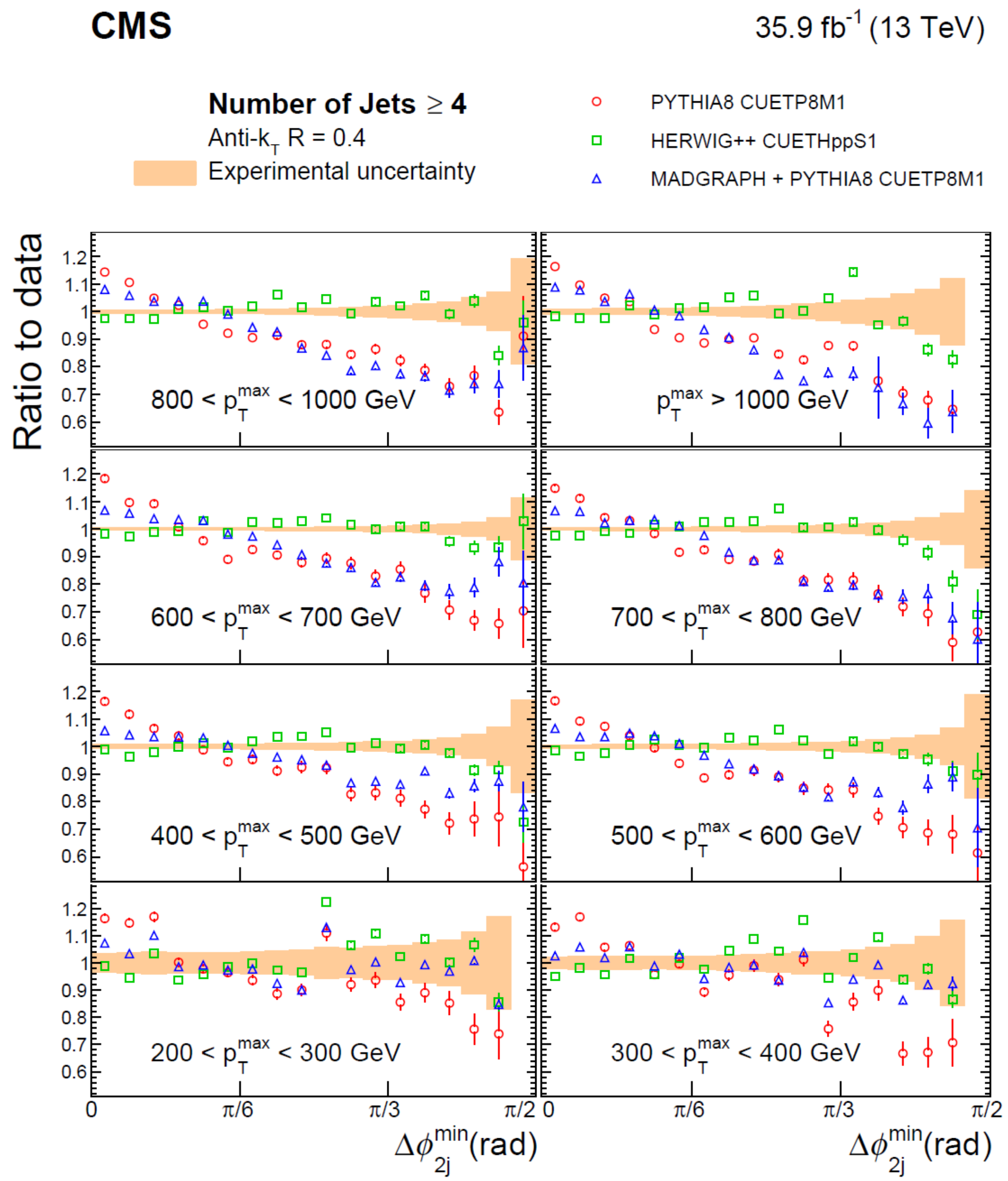


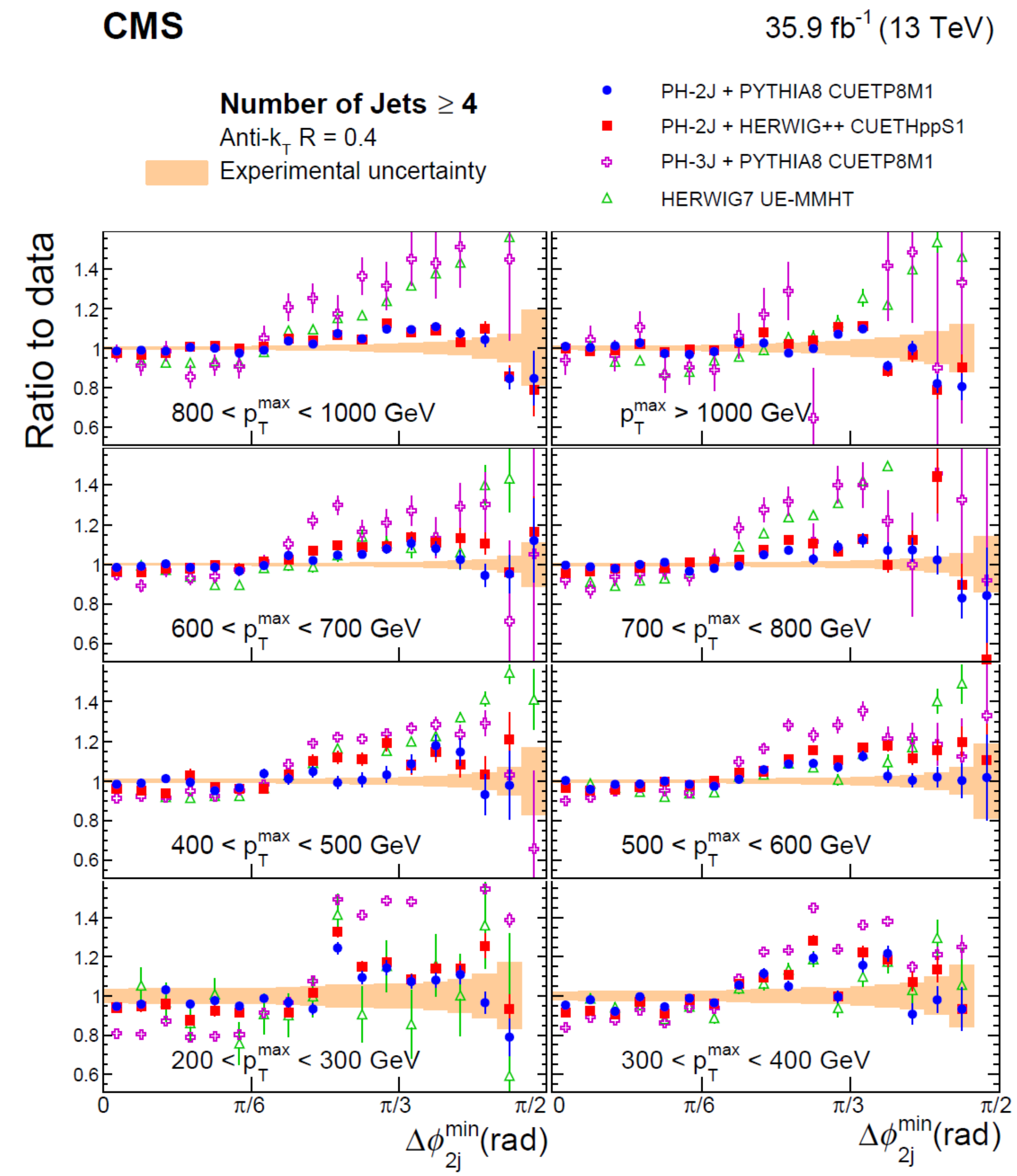


- Pythia8 fails to describe the data
- Herwig++ and Madgraph provide reasonable description of the data

- PH-2J provides the best description

Inclusive 4-jets : $\Delta\varphi_{2j}^{min}$





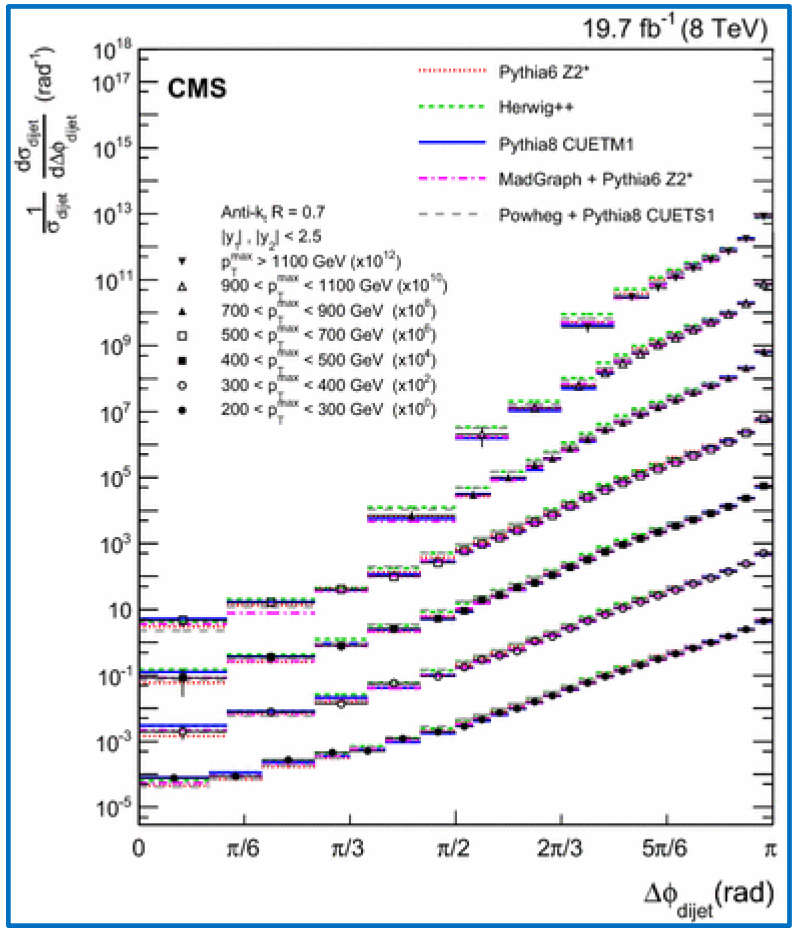
- Pythia8 and Madgraph fail to describe the data
- Herwig++ provides reasonable description

- PH-2J provides the best description

Summary

- First results for multi-jets azimuthal correlations at 13 TeV [arxiv:1712.05471](https://arxiv.org/abs/1712.05471)
- Very good detector performance (resolution < 1°) and very precise measurement (uncertainties of the order of few %).
- Extension of 8 TeV measurement for $\Delta\varphi_{1,2}$ at 13 TeV: very similar behavior of the observable here.
- Measurement of $\Delta\varphi_{1,2}$ observable also in 3-jet and 4-jet topologies and introduction of a new observable $\Delta\varphi_{2j}^{min}$ for these topologies.
- Comparison to predictions from MC event generators:
  - Madgraph with 4 partons best description among LO MC.
  - H7 best description for $\Delta\varphi_{1,2}$ and PH-2J for $\Delta\varphi_{2j}^{min}$

8 TeV measurement



https://doi.org/10.1140/epjc/s10052-016-4346-8

Still a challenge to describe in detail multi-jet correlations!

Thank you for you attention

BackUp

Measurements of Azimuthal correlations

- D0 collaboration in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV
https://arxiv.org/abs/hep-ex/0409040
https://arxiv.org/abs/1212.1842

- Atlas collaboration in pp collisions at $\sqrt{s}$ = 7 TeV
https://arxiv.org/abs/1102.2696

- CMS collaboration in pp collisions at $\sqrt{s}$ = 7 TeV
https://arxiv.org/abs/1101.5029

- CMS collaboration in pp collisions at $\sqrt{s}$ = 8 TeV
https://arxiv.org/abs/1602.04384

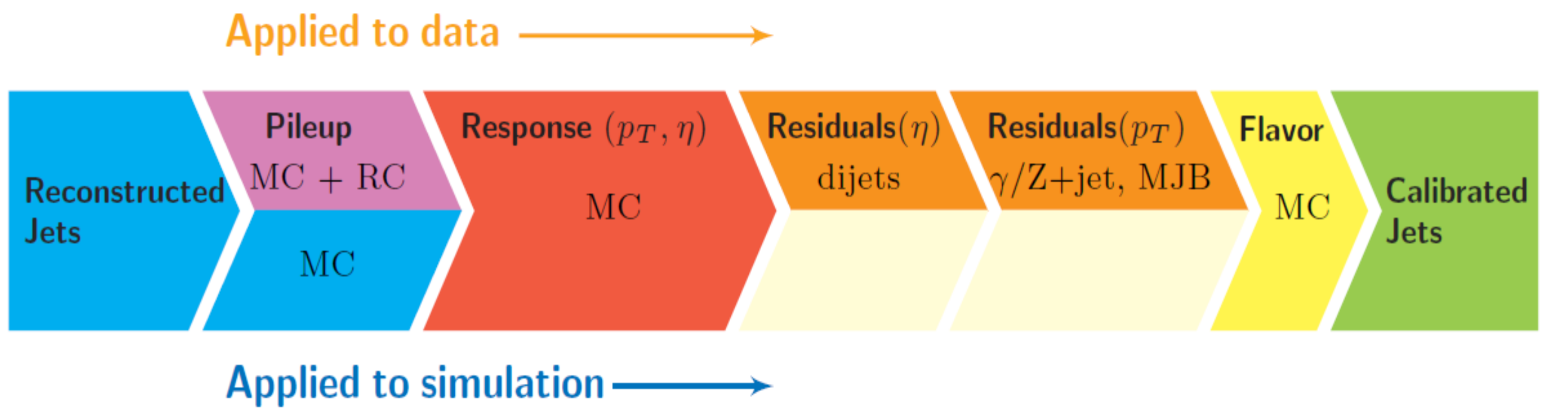
- Atlas collaboration in pp collisions at $\sqrt{s}$ = 8 TeV
https://arxiv.org/abs/1411.1855
https://arxiv.org/abs/1509.07335

Datasets and Software

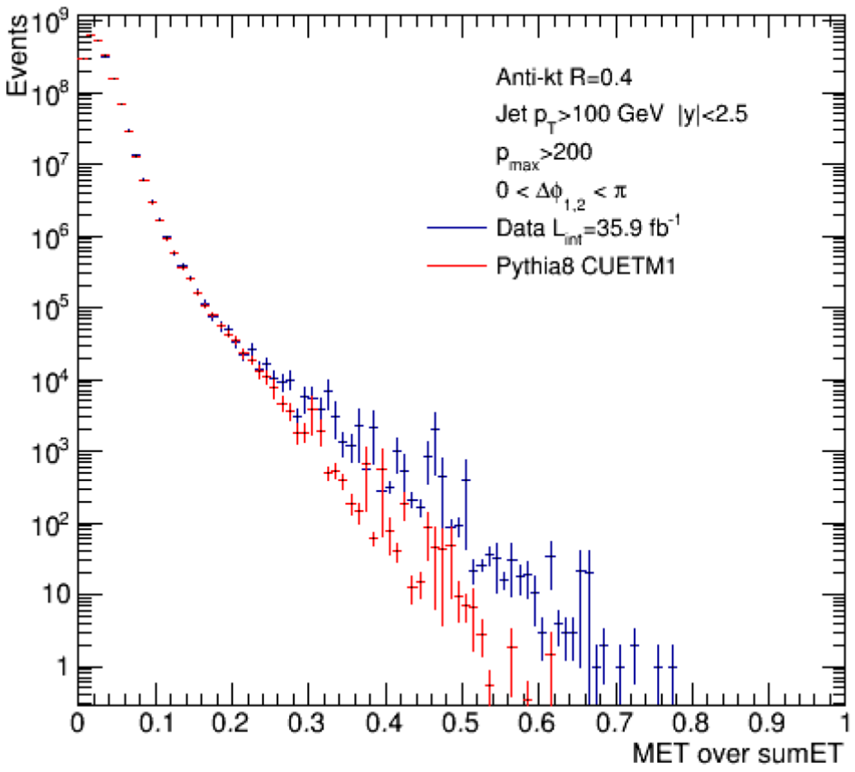
- 2016 Data with CMS experiment at $\sqrt{s} = 13\ TeV$ with 25 ns bunch spacing:
  - RUN B : /JetHT/Run2016B-23Sep2016-v3/AOD
  - RUN C : /JetHT/Run2016C-23Sep2016-v1/AOD
  - RUN D : /JetHT/Run2016D-23Sep2016-v1/AOD
  - RUN E : /JetHT/Run2016B-23Sep2016-v1/AOD
  - RUN F : /JetHT/Run2016F-23Sep2016-v1/AOD
  - RUN G : /JetHT/Run2016G-23Sep2016-v1/AOD
  - RUN H : /JetHT/Run2016H-PromptReco-v2/AOD

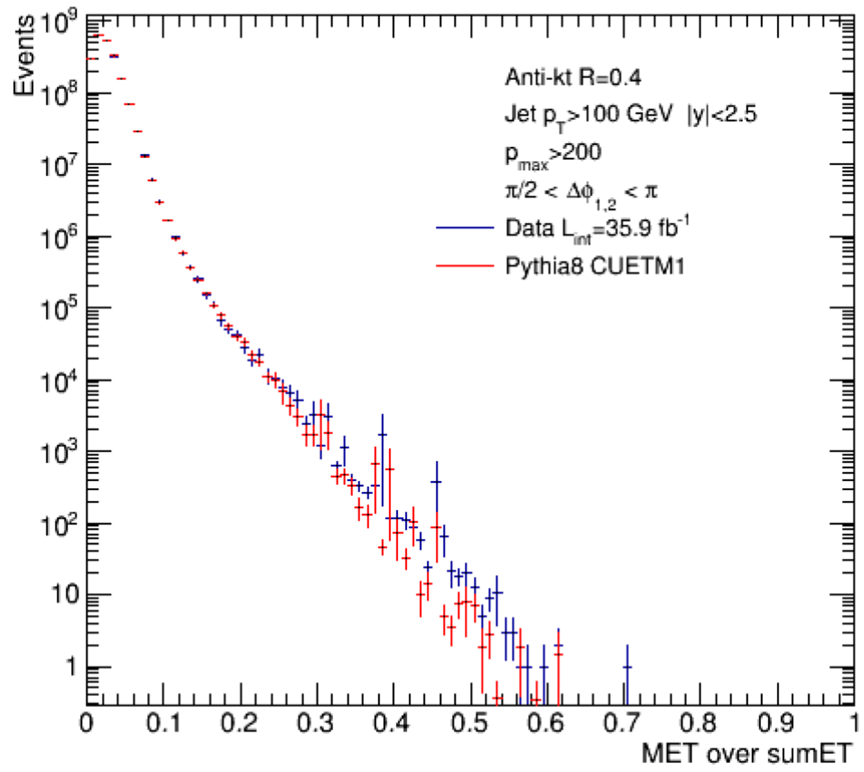
- CMSSW_8_0_x

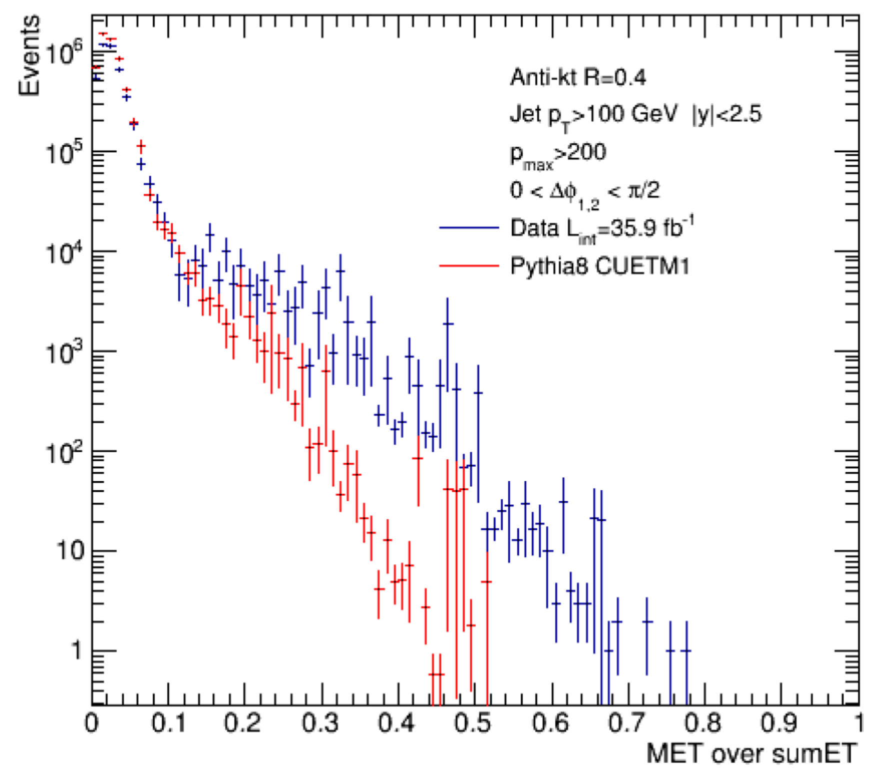
- JECs from JetMet group: Summer16_23Sep2016(RUN)3



MET/SumE_T


Events
Anti-kt R=0.4
Jet p_T>100 GeV |y|<2.5
p_{max}>200
$0 < \Delta\phi_{1,2} < \pi$
Data L_{int}=35.9 fb^{-1}
Pythia8 CUETM1
MET over sumET

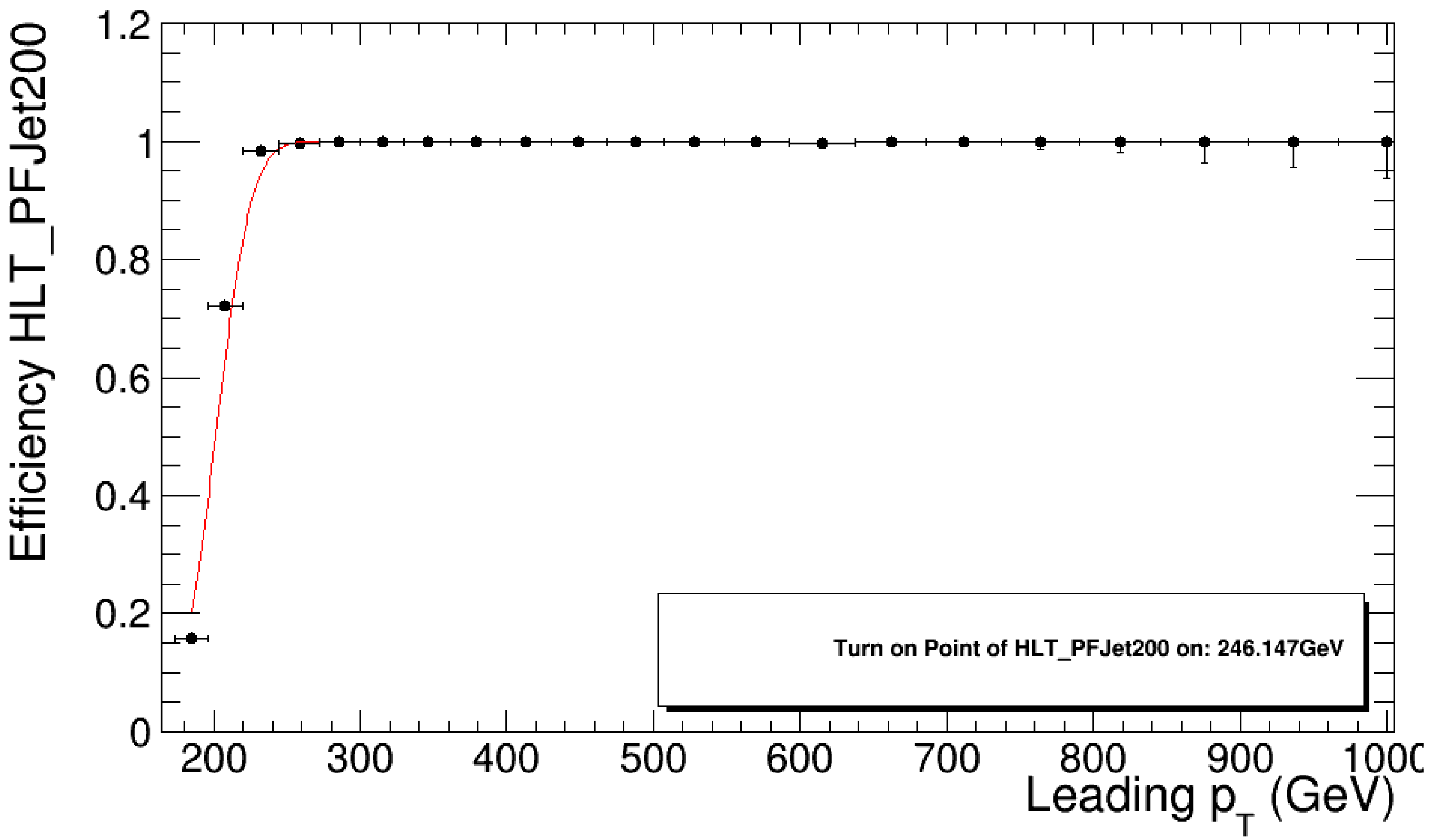

Events
Anti-kt R=0.4
Jet p_T>100 GeV |y|<2.5
p_{max}>200
$\pi/2 < \Delta\phi_{1,2} < \pi$
Data L_{int}=35.9 fb^{-1}
Pythia8 CUETM1
MET over sumET


Events
Anti-kt R=0.4
Jet p_T>100 GeV |y|<2.5
p_{max}>200
$0 < \Delta\phi_{1,2} < \pi/2$
Data L_{int}=35.9 fb^{-1}
Pythia8 CUETM1
MET over sumET

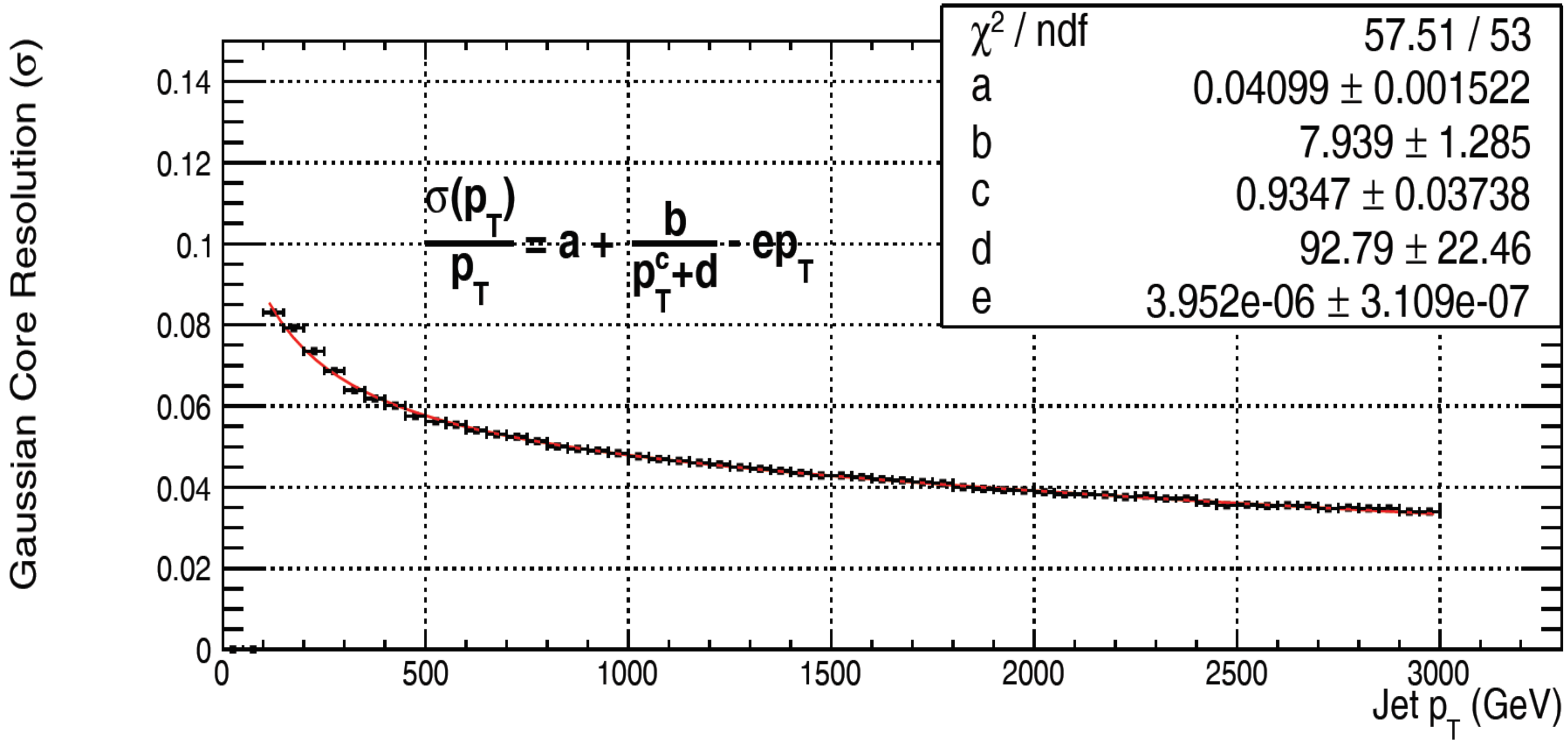
HLT_PFJet80, HLT_PFJet140, HLT_PFJet200, HLT_PFJet260, HLT_PFJet320, HLT_PFJet400, HLT_PFJet450, HLT_PFJet500

HLT Triggers	Lumi (fb^{-1})	Turn-on-points (GeV)	p_T^{max} region
HLT_PFJet80	0.003	104	
HLT_PFJet140	0.024	175	200-300 GeV
HLT_PFJet200	0.104	246	300-400 GeV
HLT_PFJet260	0.592	308	
HLT_PFJet320	1.765	374	400-500 GeV
HLT_PFJet400	5.171	472	500-600 GeV
HLT_PFJet450	35.877	519	>600 GeV
HLT_PFJet500	35.877	588	

$$eff_{HLT\_PFJet200} = \frac{HLT\_PFJet200}{HLT\_PFJet140}$$



Jet Energy Resolution



https://twiki.cern.ch/twiki/bin/viewauth/CMS/JetResolution

JER Scaling factors and Uncertainty for 13 TeV (2015 and 2016)

Values are reported below:

Spring16_25nsV10 (80X, 2016, BCD+GH PromtReco) DATA/MC SFs

abs(eta) region	0.0–0.5	0.5-0.8	0.8–1.1	1.1-1.3	1.3–1.7	1.7 - 1.9	1.9–2.1	2.1 - 2.3	2.3 - 2.5	2.5–2.8	2.8-3.0	3.0-3.2	3.2-5.0
Data/MC SF	1.109 +-0.008	1.138 +-0.013	1.114 +-0.013	1.123 +-0.024	1.084 +-0.011	1.082 +-0.035	1.140 +-0.047	1.067 +-0.053	1.177 +-0.041	1.364 +-0.039	1.857 +-0.071	1.328 +-0.022	1.16 +-0.029