

# Measurements of inclusive 2-jet, 3-jet and 4-jet azimuthal correlations in pp collisions at $\sqrt{s} = 13$ TeV

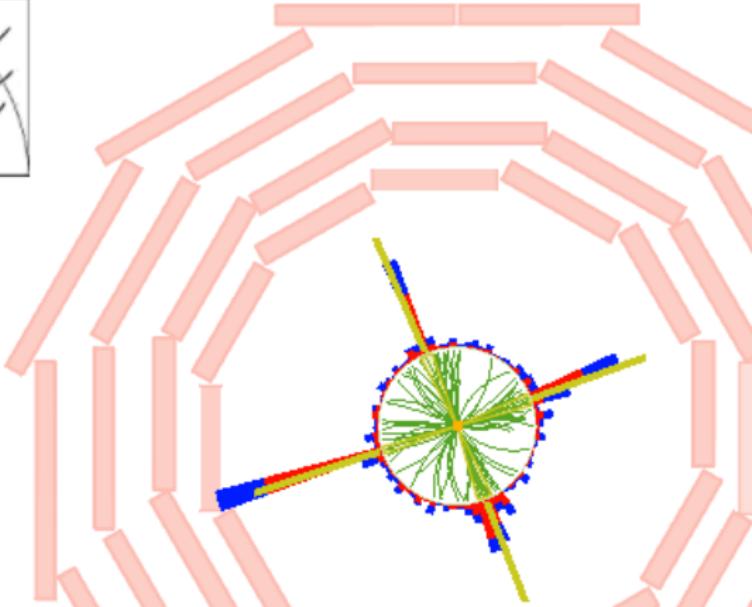
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on behalf of the CMS collaboration.

<sup>1</sup>Deutsches Elektronen-Synchrotron (DESY)

April 2017



# Outline

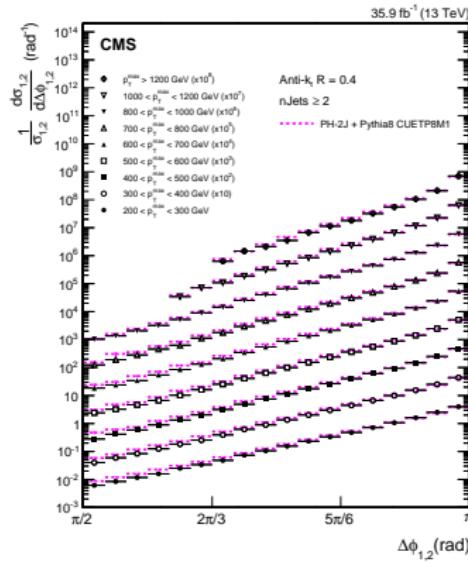


CMS Experiment at LHC, CERN  
Data recorded: Sun May 15 06:28:58 2016 CEST  
Run/Event: 273450 / 252958696  
Lumi section: 179

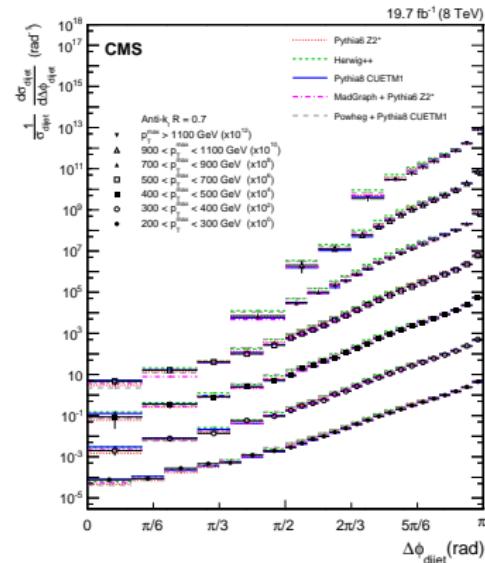
# Motivation

- Comparing the 13 TeV results to a similar measurement at 8 TeV.
- Extending the 8 TeV measurements to 3-jet and 4-jet topologies.
- Measuring new  $\Delta\phi_{2J}^{min}$  observable for 3-jet and 4-jet topologies which also probes the emission of extra partons.

## Present Analysis



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# Observables

- Normalized inclusive 2-jet, 3-jet and 4-jet differential cross section:

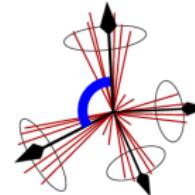
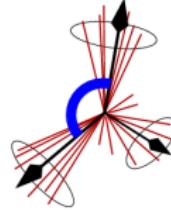
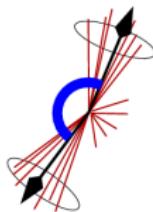
$$\frac{1}{\sigma_{1,2}} \frac{d\sigma_{1,2}}{d\Delta\phi_{1,2}} \quad (1)$$

- Normalized inclusive 3-jet and 4-jet differential cross section:

$$\frac{1}{\sigma_{2J}^{min}} \frac{d\sigma_{2J}^{min}}{d\Delta\phi_{2J}^{min}} \quad (2)$$

# Jet reconstruction and event selection

- Data collected with the CMS experiment.
- Full 2016 statistics  $L_{int} = 35.9 \text{ fb}^{-1}$  at  $\sqrt{s} = 13 \text{ TeV}$ .
- Jets reconstruction: **anti-k<sub>t</sub>**  $R = 0.4$
- Event selection
  - Jets with  $p_T > 100 \text{ GeV}$
  - 2 jet events:  $|y_1|, |y_2| < 2.5$
  - 3 jet events:  $|y_1|, |y_2|, |y_3| < 2.5$
  - 4 jet events:  $|y_1|, |y_2|, |y_3|, |y_4| < 2.5$
- Slices in  $p_T$  of the leading jet:  $200 < p_T^{max} < 4000 \text{ GeV}$ .



# $\Delta\phi$ Resolution studies

- Resolution ranges from  $0.014\text{rad}$  ( $0.8^\circ$ ) for low  $p_T^{\max}$ , to  $0.007\text{rad}$  ( $0.4^\circ$ ) towards high  $p_T^{\max}$

$p_T^{\max}$ (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	

# Unfolding

- Unfolding of the measured distribution:
  - Distributions corrected for detector resolution and unfolded to the level of final-state particles.
  - Response matrix maps the predicted distribution onto the measured one.
  - Unfolding procedure is based on the matrix inversion algorithm.

# Systematics

- Three main sources of systematics were considered:
  - Unfolding
  - Jet Energy Scale (JES) uncertainties.
  - Jet Energy Resolution (JER) uncertainties.

# Jet Energy Scale and Jet Energy Resolution systematic uncertainties

- Jet Energy Scale (JES) uncertainties
  - By studying inclusive jet, top,  $\gamma$ +jet, Z+jet samples.
  - Sensitivity to JES uncertainties is studied by changing jets transverse momentum.
  - $\Delta\phi_{12}$  JES:  $\sim 3\%$  close to  $\pi/2$  and  $0.1\%$  close to  $\pi$ .
  - $\Delta\phi_{2j}^{min}$  JES:  $\sim 0.1\%$  for low  $\Delta\phi_{2j}^{min}$  and  $2\%$  for high  $\Delta\phi_{2j}^{min}$ .
- Jet Energy Resolution (JER) uncertainties
  - By studying the smearing from particle to detector level in MC samples.
  - $\Delta\phi_{12}$  JER:  $\sim 1\%$  close to  $\pi/2$  and  $0.1\%$  close to  $\pi$ .
  - $\Delta\phi_{2j}^{min}$  JER:  $<0.5\%$ .

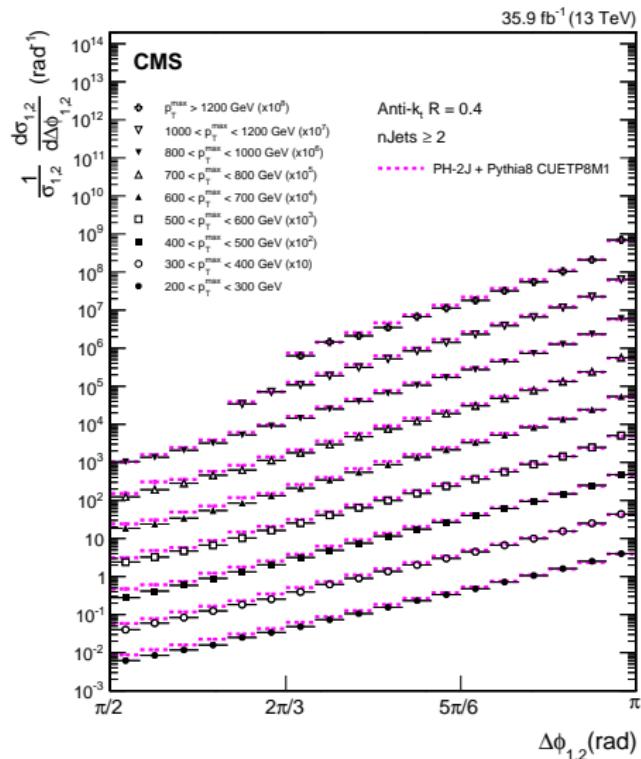
# Systematics - Unfolding

- Model dependence.
  - New response matrices with Herwig++ and MadGraph.
  - Uncertainties:  $\sim 0.2\%$ .
- $\Delta\phi$  resolution uncertainty.
  - Change  $\Delta\phi$  resolution by  $\pm 10\%$  (motivated by the observed difference between data and simulation) and construct new response matrices.
  - uncertainties  $< 0.1\%$ .

# Theory predictions

Generator	Order	Showering	Hadronization	Tune
Pythia8	LO 2→2	Order in $p_T$	Lund String model	CUETP8M1 based on NNPDF2.3LO
Herwig++	LO 2→2	Angular order	Cluster Fragmentation	CUETHppS1 based on CTEQ6L1
MadGraph	LO 2→2, 2→3, 2→4	Pythia8 MLM matching	Pythia8	CUETP8M1
Powheg	NLO Dijet NNPDF30nlo PDF	Pythia8 Herwig++	Pythia8 Herwig++	CUETP8M1 CUETHppS1
Powheg	NLO TriJet NNPDF30nlo PDF	Pythia8	Pythia8	CUETP8M1
Herwig7	NLO Dijet MMHT2014 PDF	Angular order	Cluster Fragmentation	UE-MMHT

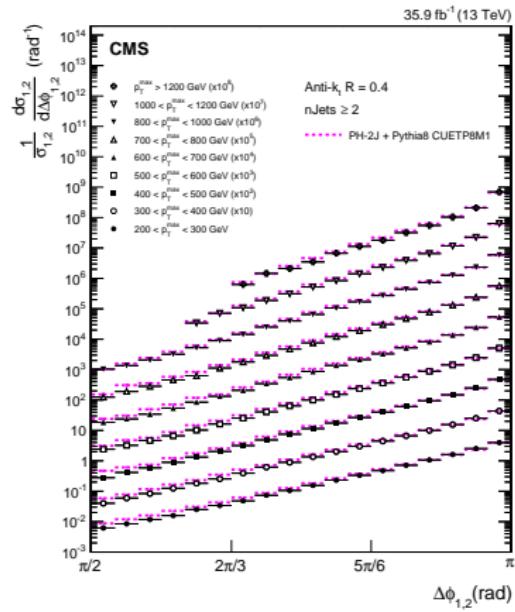
# Inclusive 2-jets $\Delta\phi_{1,2}$



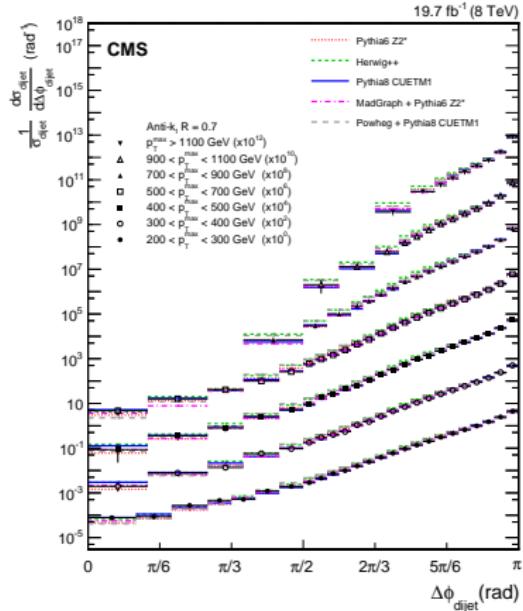
- Incl 2-jets: The  $\Delta\phi_{1,2}$  are strongly peaked at  $\pi$  and become steeper with increasing  $p_T^{\max}$ .
- Error bars on the data points: quadratic sum of statistical and systematic uncertainties.

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

Present Analysis

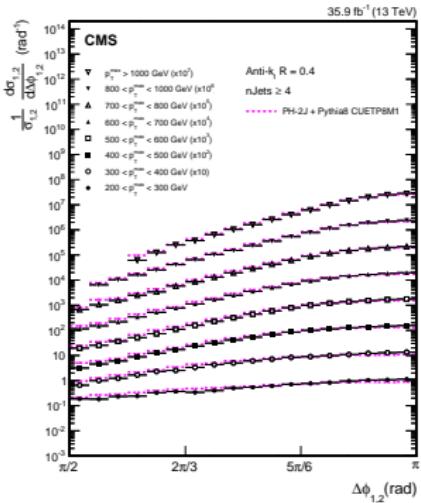
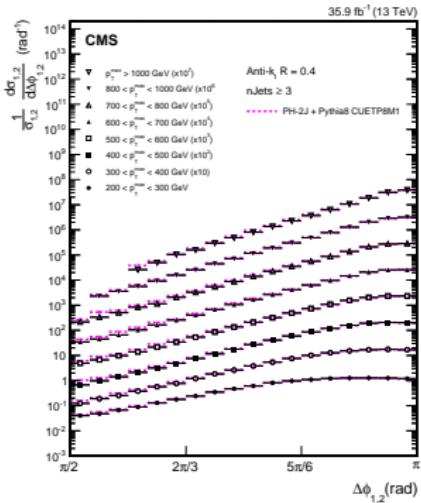
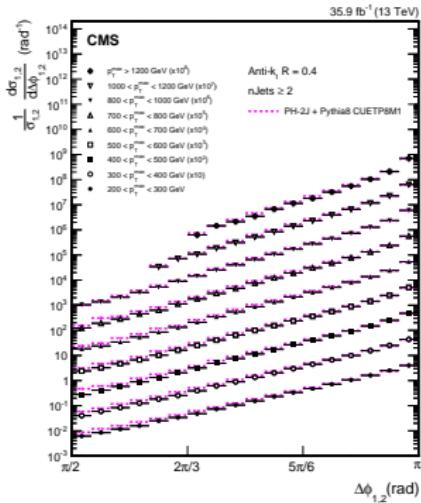
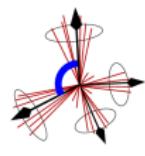
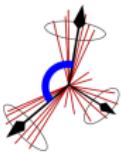
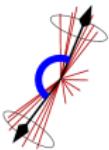


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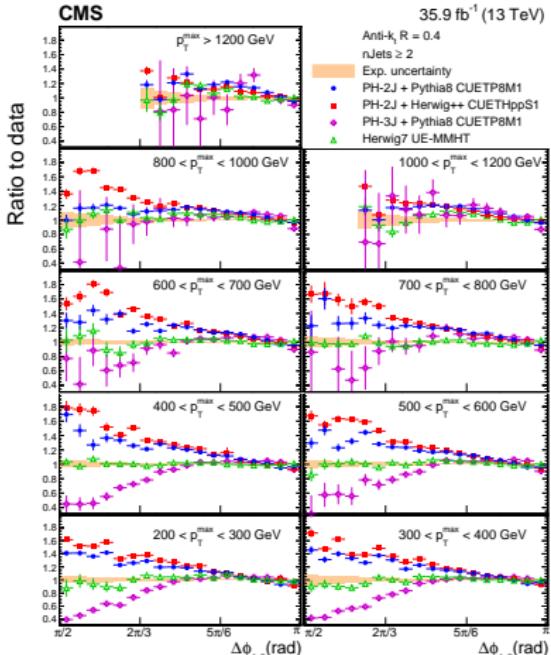
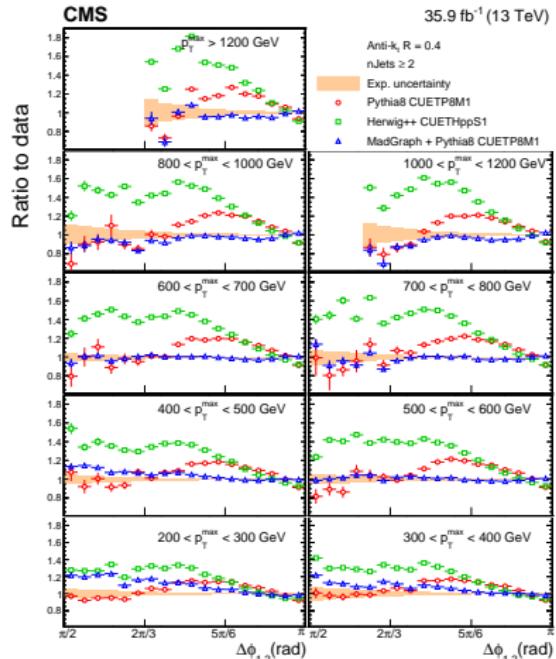
- Results from 8TeV analysis are consistent with those from the present study at 13TeV.
- They are consistent with NLO+PS predictions

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



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

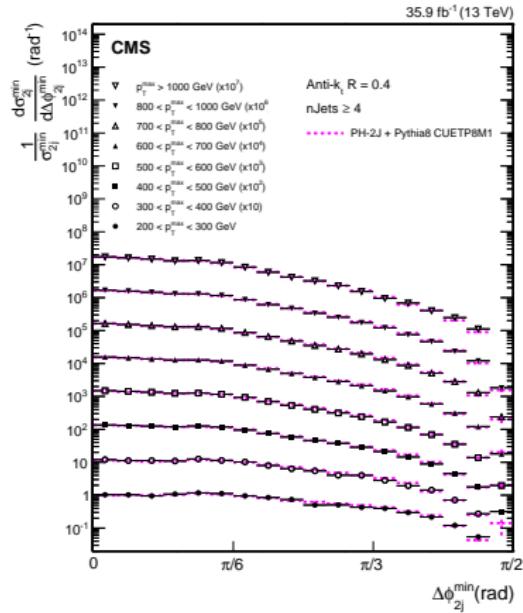
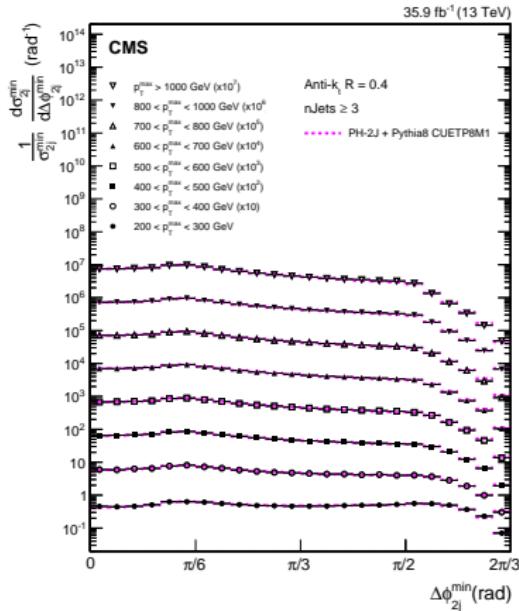
# Inclusive 2-jets: $\Delta\phi_{1,2}$



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

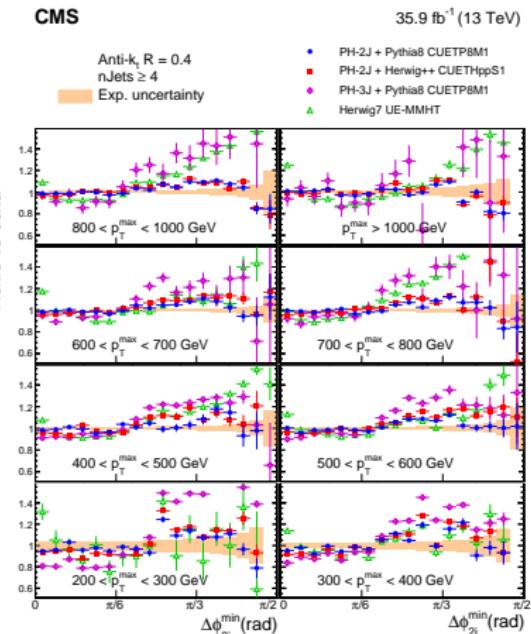
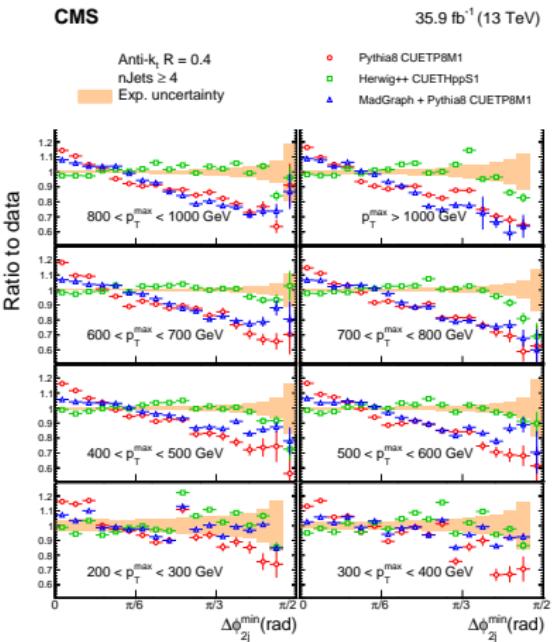
- PH-2J and PH-3J exhibit large deviations.
- Best description by H7.

# Inclusive 3-jets and 4-jets $\Delta\phi_{2J}^{\min}$



Distributions are close to be flat and decrease slowly on the right.

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



- Pythia8 and MadGraph fail to describe data.
- Herwig++ provides a reasonable description of the data.

- PH-2J provides the best description.

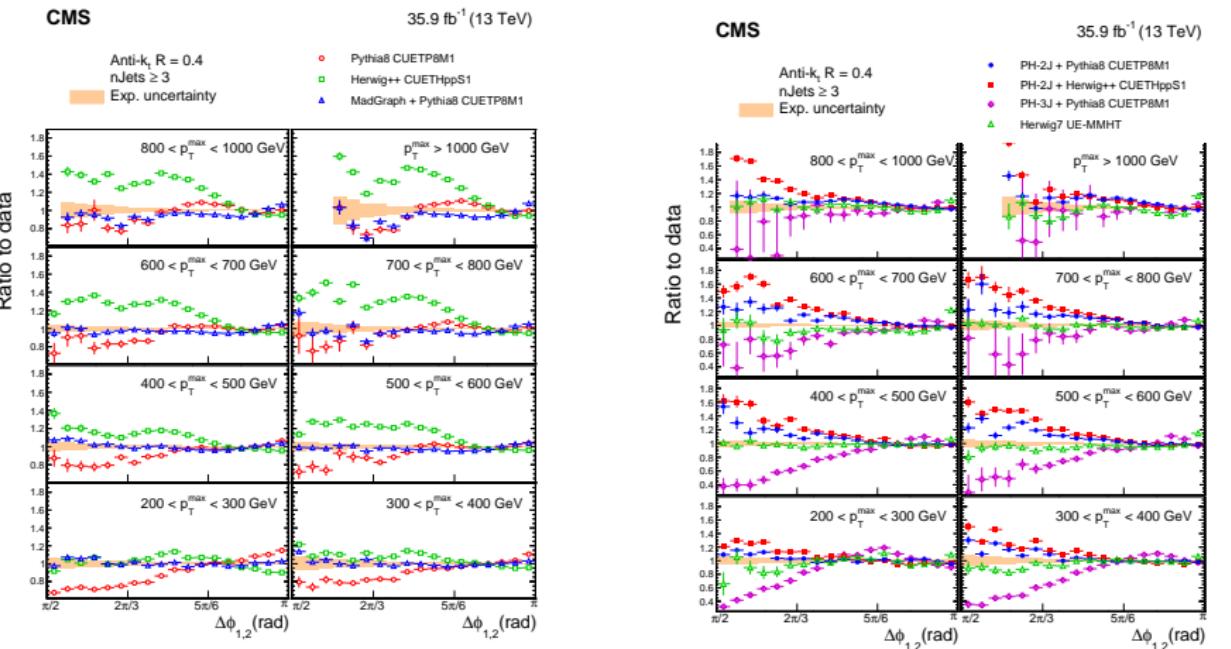
# Summary

- First 13TeV results multi-jets azimuthal correlations.
- Very good detector performance (resolution  $< 0.8^\circ$ ).
- Very precise measurement was done (uncertainties of the order of few %)
- Similar behaviour as in 8TeV was observed.
- Comparisons with theory predictions:
  - Madgraph with 4 partons performs best among LO generators.
  - PH-3jet+PS performing is surprisingly not so good.
  - H7 describes best  $\Delta\phi_{1,2}$  among NLO generators. Why is not PH-2jet+PS doing well?
  - Still a challenge to describe in detail multijet correlations.
- More details in the public PAS [▶ Link](#)

Thank you for your attention.



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



- Herwig++ exhibits the largest deviations.
- Pythia8 behaves differently than in the 2-jet case close to  $\pi/2$ .
- Best description by MadGraph.

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

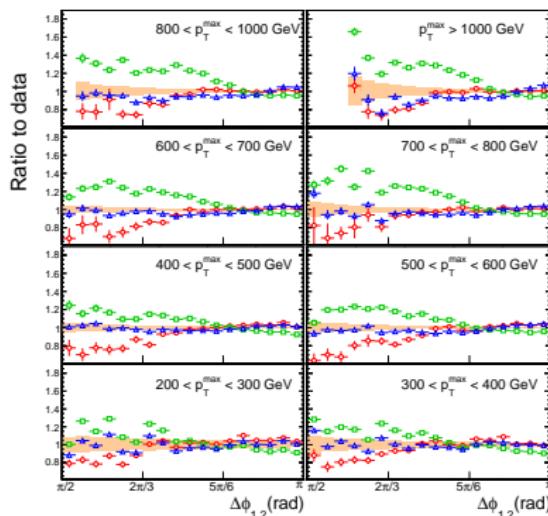
# Inclusive 4-jets: $\Delta\phi_{1,2}$

CMS

35.9  $\text{fb}^{-1}$  (13 TeV)

Anti- $k_t$ ,  $R = 0.4$   
 $n\text{Jets} \geq 4$   
 Exp. uncertainty

- Pythia8 CUETP8M1
- Herwig++ CUETHppS1
- △ MadGraph + Pythia8 CUETP8M1

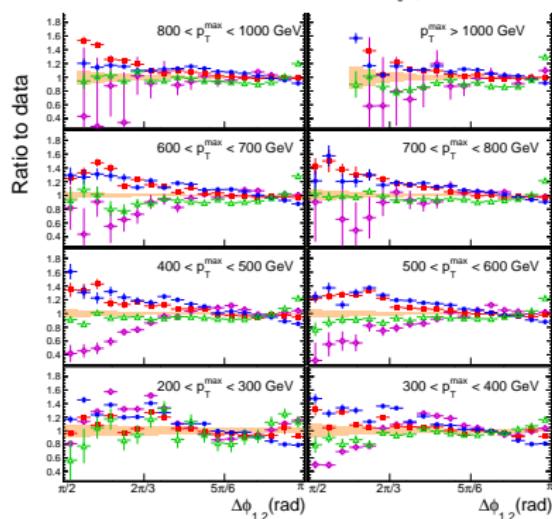


CMS

35.9  $\text{fb}^{-1}$  (13 TeV)

Anti- $k_t$ ,  $R = 0.4$   
 $n\text{Jets} \geq 4$   
 Exp. uncertainty

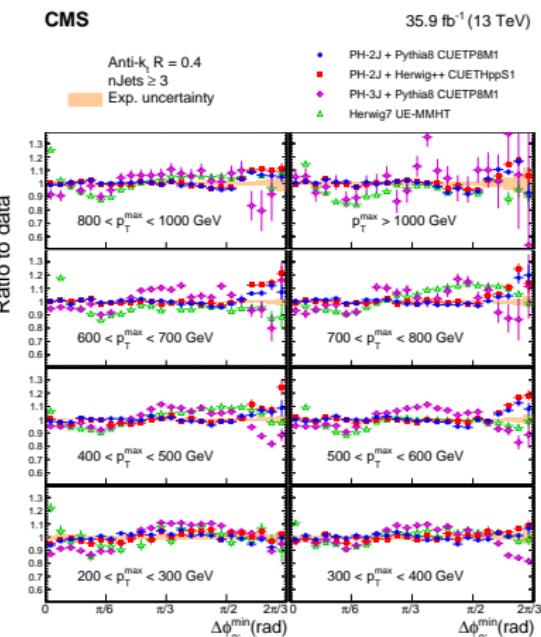
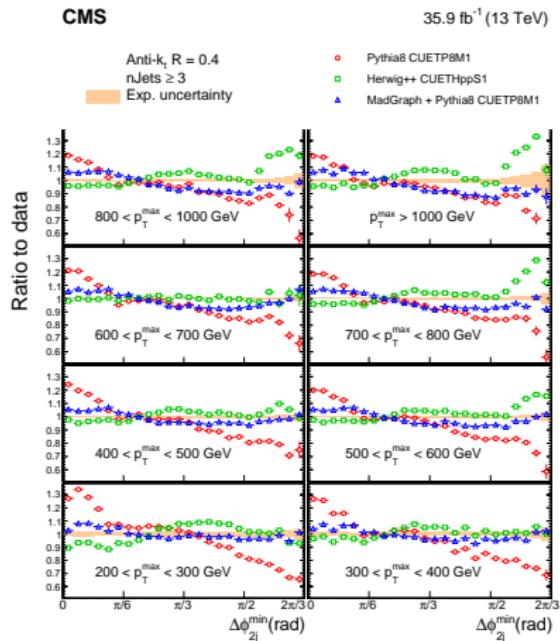
- PH-2J + Pythia8 CUETP8M1
- PH-2J + Herwig++ CUETHppS1
- PH-3J + Pythia8 CUETP8M1
- ▲ Herwig7 UE-MMHT



- Herwig++ exhibits the largest deviations.
- Pythia8 behaves differently than in the 2-jet case close to  $\pi/2$ .
- MadGraph performs very good.

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

# Inclusive 3-jets: $\Delta\phi_{2J}^{\min}$



- Pythia8 fails to describe data.
- Herwig++ and MadGraph provide a reasonable description of the data.

- PH-2J provides the best description.