Multijet and photon+jet measurements

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Introduction

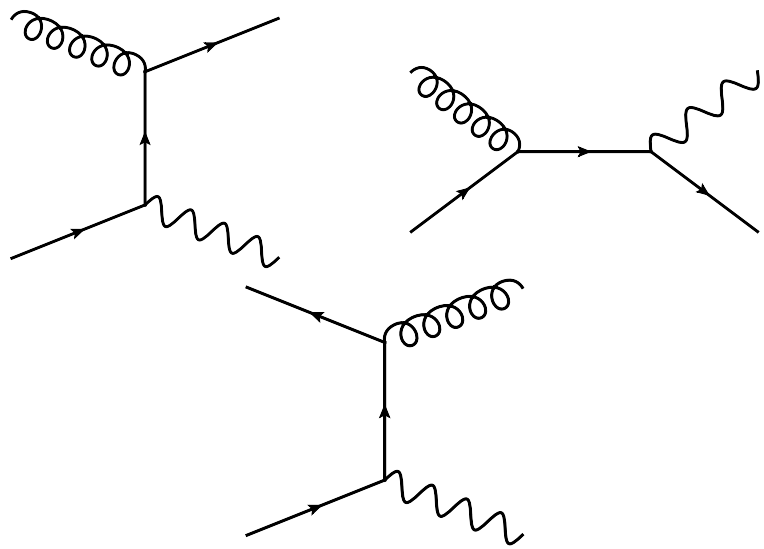
- Quantum chromodynamics (QCD), very rich and successful theory of strong interactions!
- Precise understanding of perturbative and non-perturbative QCD necessary for:
  - extraction of strong coupling constant α_s
  - testing pQCD in large phase-space volumes
  - modelling soft QCD physics
  - constraining parton distribution functions (PDFs)
  - all of the above $\rightarrow$ better Standard Model measurements and searches for physics beyond the Standard Model
- We present a summary of recent results by the CMS Collaboration on the following topics:
  - Measurement of differential cross sections for inclusive isolated-photon and photon+jets production in proton-proton collisions at $\sqrt{s} = 13$ TeV (Eur. Phys. J. C 79 (2019) 20);
  - Azimuthal separation in nearly back-to-back jet topologies in inclusive 2- and 3-jet events in pp collisions at $\sqrt{s} = 13$ TeV (Submitted to Eur. Phys. J. C, arXiv:1902.04374);

Measurement of differential cross sections for inclusive isolated photon and photon+jets production in proton-proton collisions at $\sqrt{s} = 13$ TeV (Eur. Phys. J. C 79 (2019) 20)

Differential cross sections sensitive to the parton density functions over a wide range of parton momentum fraction x and energy scale Q^2

Selection

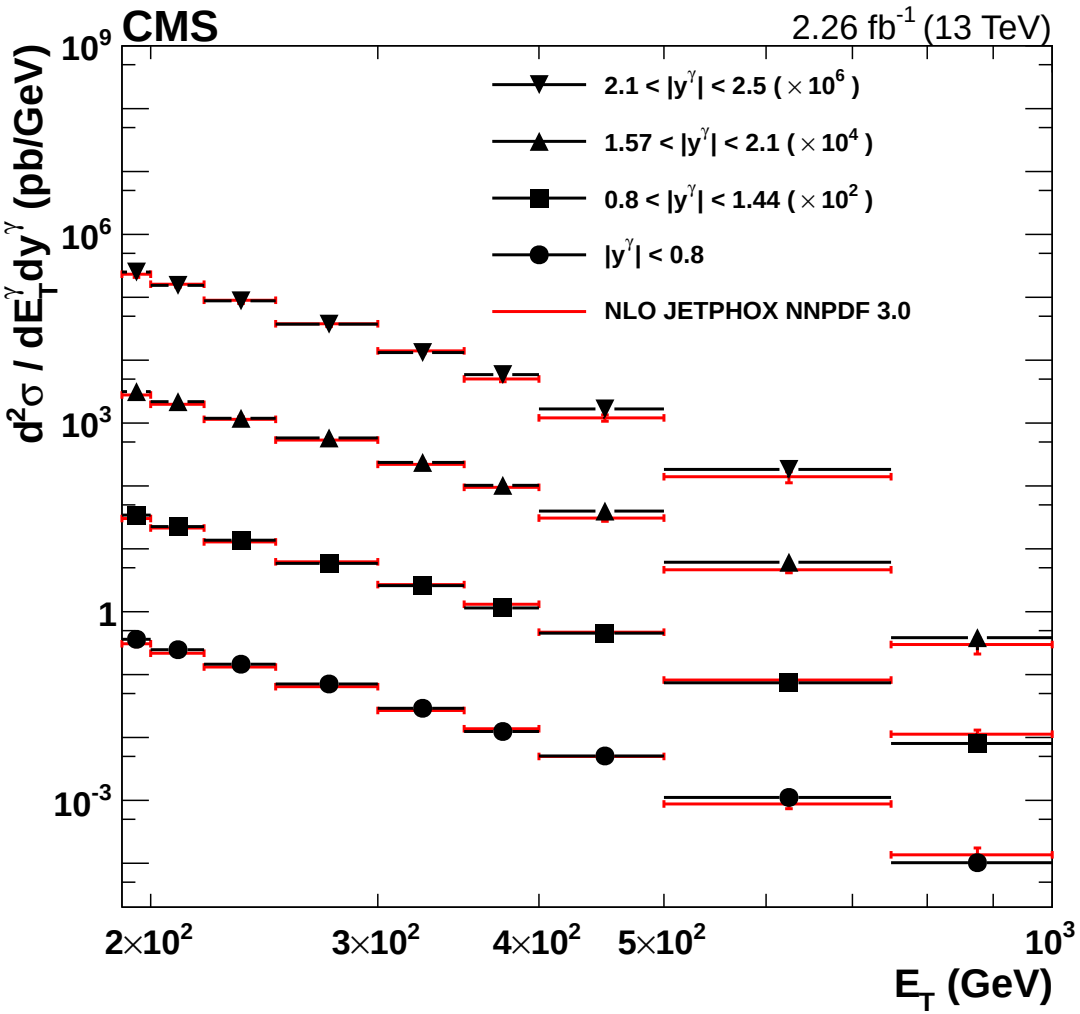
- Analysis based on 2.26 fb^{-1} of data collected in p-p collisions at 13 TeV;
- Sum of p_T of particles inside a cone of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around the photon is less than 5 GeV;
- At least one isolated photon with $E_T > 190$ GeV and $|\eta| < 2.5$;
- BDT (TMVA) to separate prompt-photons from neutral-meson decays (e.g., π^0, η)
- For photon+jet measurement: same photon selection as above and jet satisfies $p_T > 30$ GeV and $|y^{jet}| < 2.4$



Leading contributions to prompt-photon production:

- quark-gluon Compton scattering $qg \to q\gamma$
- quark-antiquark annihilation $q\bar{q} \to g\gamma$
- parton fragmentation $q\bar{q}(gg) \to X + \gamma$

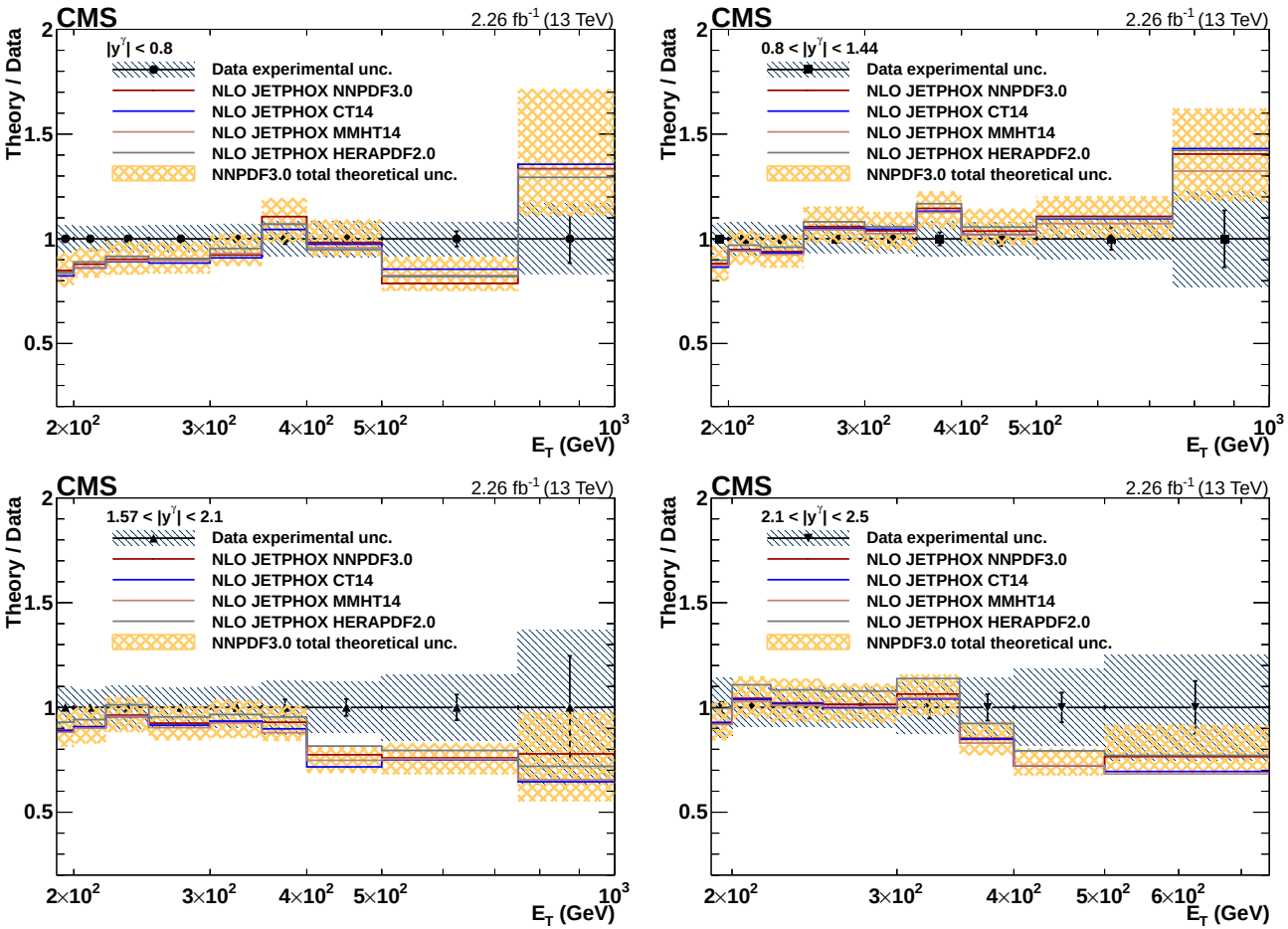
Double-differential cross-section measurement ($\gamma + X$)



$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y^\gamma \mathrm{d}E_T^\gamma} = \frac{\mathcal{U}(N^\gamma)}{\Delta y^\gamma \cdot \Delta E_T^\gamma \cdot \epsilon \cdot \mathrm{SF} \cdot L}$$

Observations

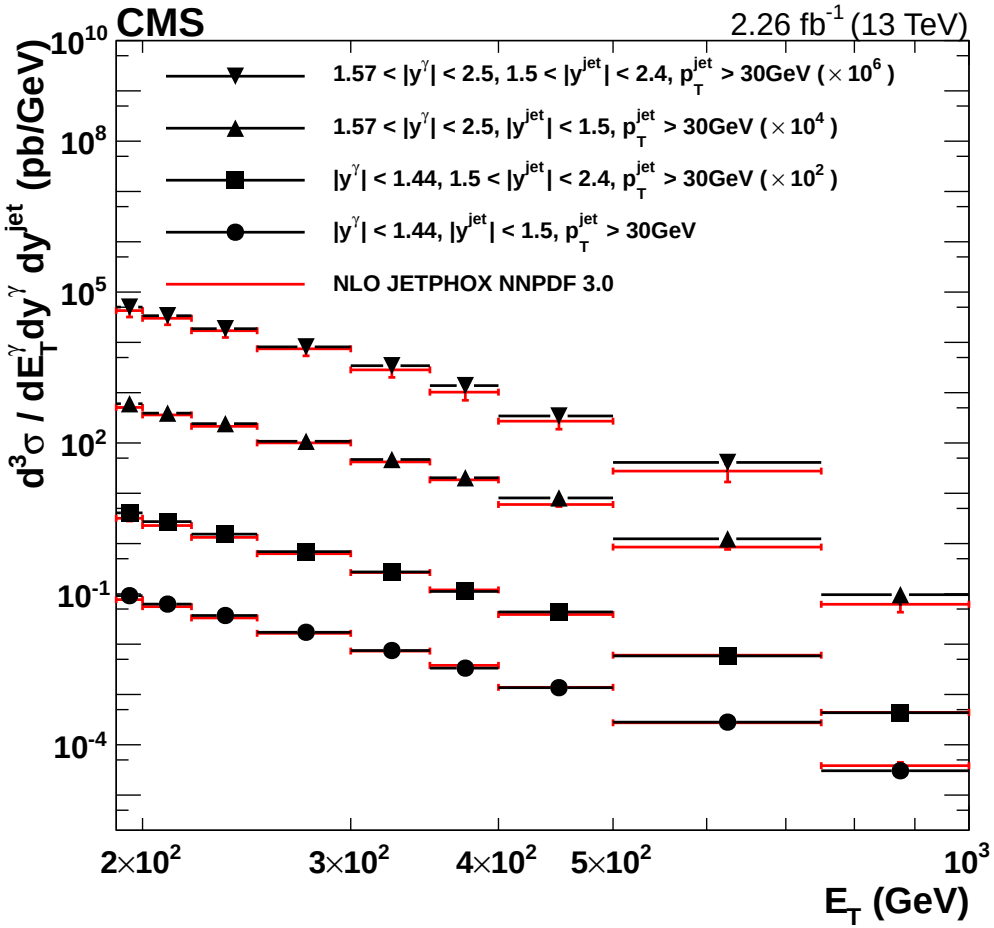
- Comparison with NLO QCD predictions (JETPHOX)
- Total theoretical uncertainties are evaluated as the quadratic sum of the scale, PDF, and α_s
- Tested with various PDF sets



Observations

- Tested predictions w/ various PDF sets (NNPDF3.0, CT14, MMHT14, HERAPDF2.0)
- Good compatibility between data and theo. predictions within uncertainties

Triple-differential cross-section measurement (γ + jet + X)



$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}y^\gamma \mathrm{d}E_T^\gamma \mathrm{d}y^{\mathrm{jet}}} = \frac{\mathcal{U}(N^\gamma)}{\Delta y^\gamma \cdot \Delta E_T^\gamma \cdot \Delta y^{\mathrm{jet}} \cdot \epsilon \cdot \mathrm{SF} \cdot L}$$

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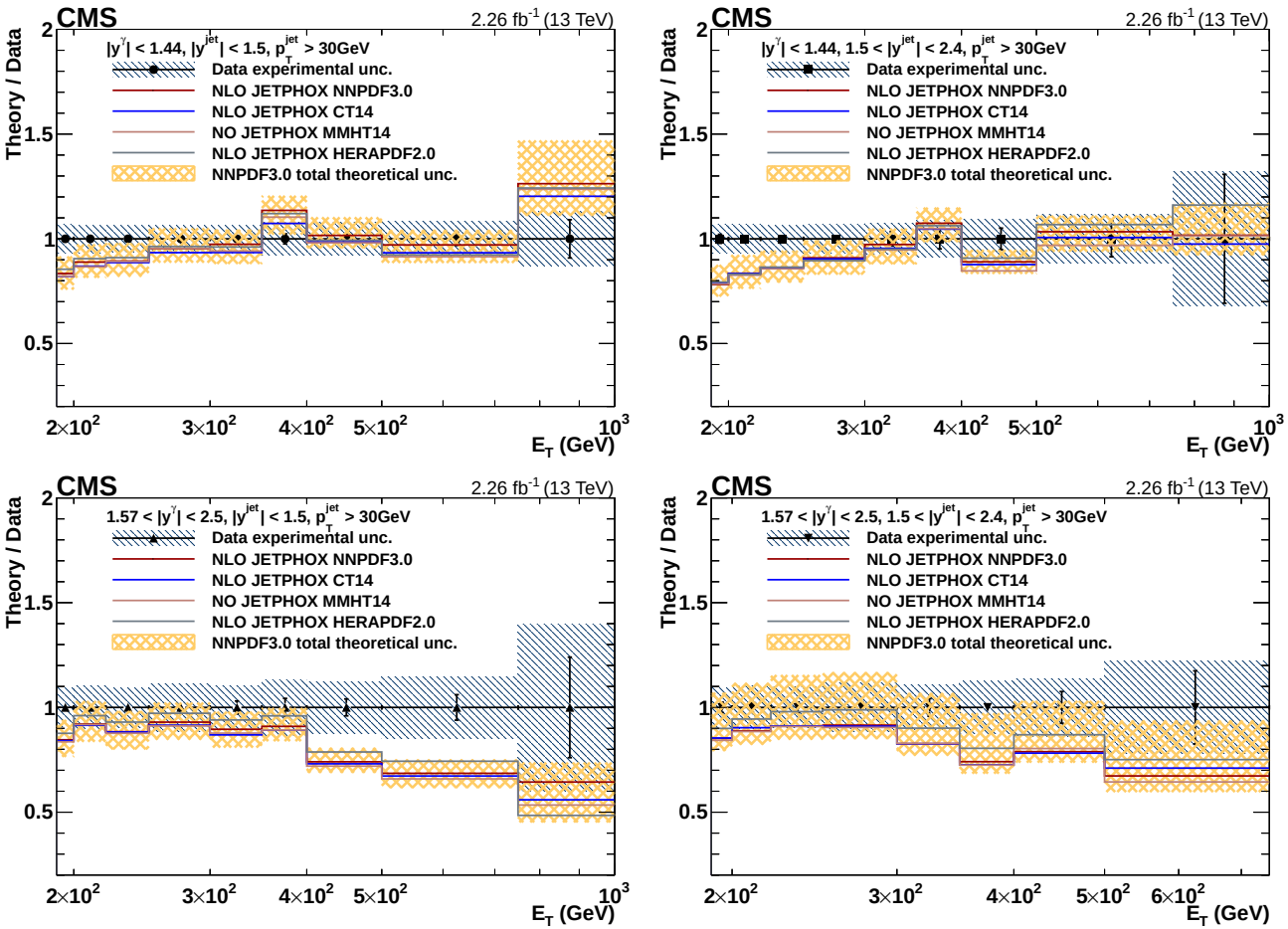

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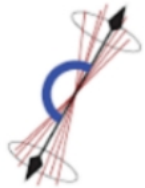
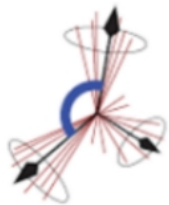
Azimuthal separation in nearly back-to-back jet topologies in inclusive 2- and 3-jet events in pp collisions at $\sqrt{s} = 13$ TeV (Submitted to Eur. Phys. J. C, arXiv:1902.04374)

Nearly back-to-back dijets as probe of resummation effects

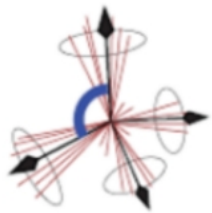
- At leading-order in pQCD, the leading two jets are produced back-to-back in the transverse plane ($\Delta\phi_{12} \equiv |\phi_{jet_1} - \phi_{jet_2}| = \pi$);
- Additional radiation generally induces azimuthal angle decorrelations and are described by higher-order corrections in pQCD;
- When the decorrelation is very small, $\Delta\phi_{12} \approx \pi$, pQCD fixed-order calculations become unstable, but can be cured with resummation of soft parton emissions to all orders in α_s
- Resummation is approximated with parton shower evolution (PS) embedded in Monte Carlo event generators
- **Nearly back-to-back dijet configurations highly sensitive to effects of soft initial- and final-state gluons**



$\Delta\varphi_{\mathrm{dijet}} = \pi$



$2\pi/3 \leq \Delta\varphi_{\mathrm{dijet}} < \pi$



$0 < \Delta\varphi_{\mathrm{dijet}} \ll \pi$

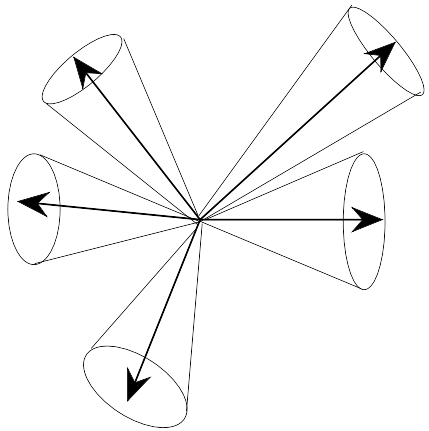
Analysis strategy

- Normalized differential cross-section in inclusive 2- and 3-jet production,

$$\frac{d\sigma}{\sigma_{p_T^{\max}} \mathrm{d}\Delta\phi_{12}}$$

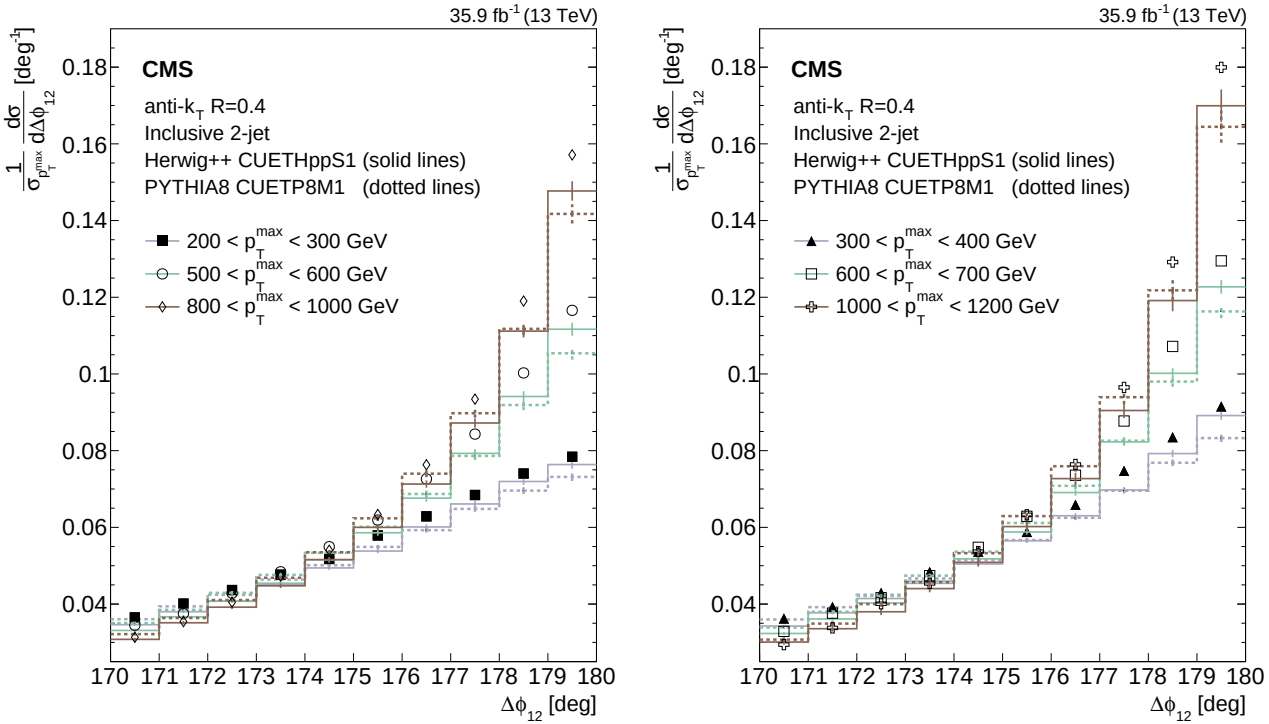
  for nearly back-to-back dijet configurations

- Compare with various MC generators (LO and NLO matrix elements) with different leading-log parton shower algorithms



Selection

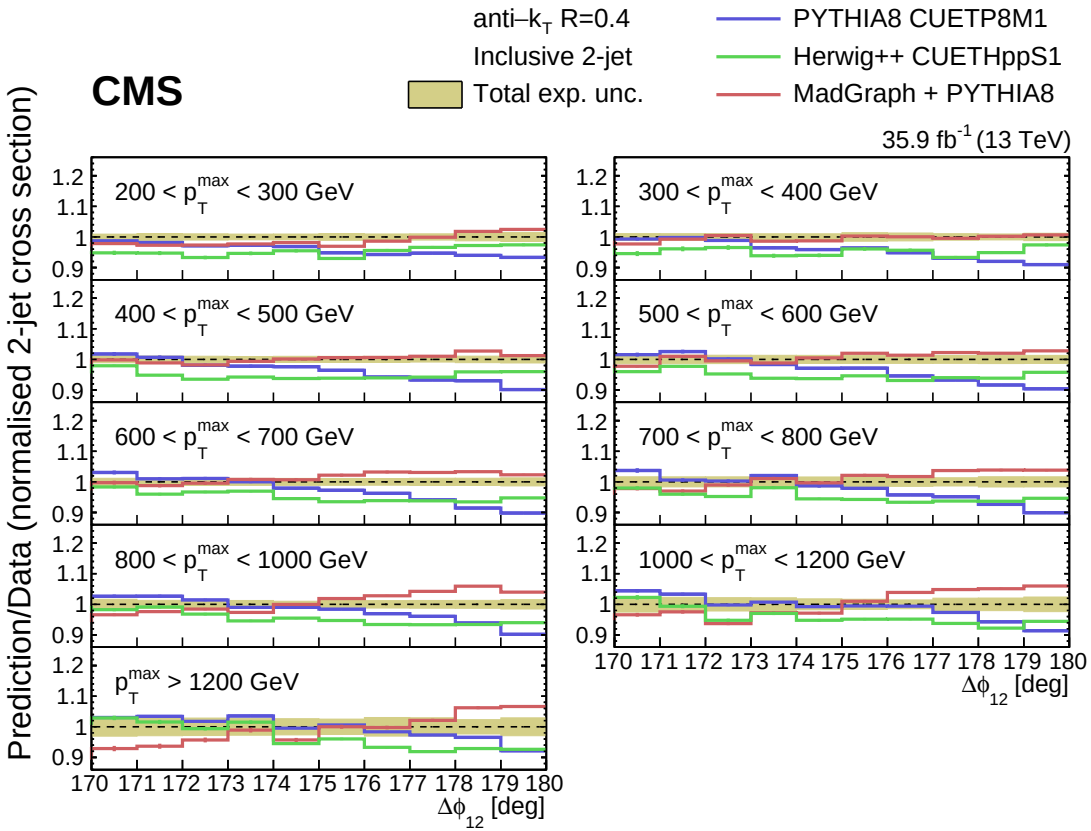
- Jets within rapidities $|y| < 5$;
- Leading two jets satisfy $p_{\mathrm{T}} > 100$ GeV and $|y| < 2.5$
- For inclusive 3-jet measurement, $p_{\mathrm{T,jet3}} > 30$ GeV and $|y_{\mathrm{jet3}}| < 2.5$



Normalized inclusive 2-jet $\Delta\phi_{12}$ distributions for different $p_T^{\max}$ values. Binning in $\Delta\phi_{12}$ per 1°.

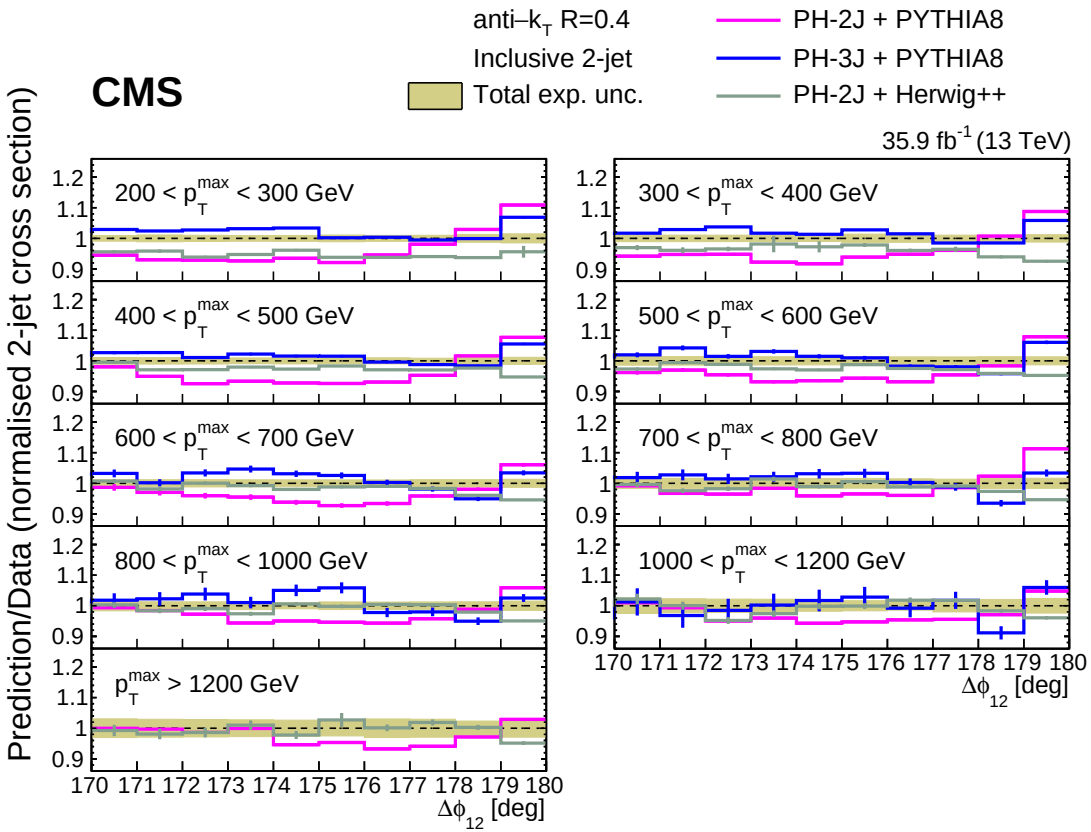
Observations

- Distributions peak steeply towards $\Delta\phi_{12} \approx 180°$ at larger transverse momenta $p_T^{\max}$
- Underestimation of $\leq$ 10% by LO HERWIG++ w/ CUETHppS1 tune and PYTHIA 8 w/ tune CUETP8M1 as $\Delta\phi \approx 180°$



Observations

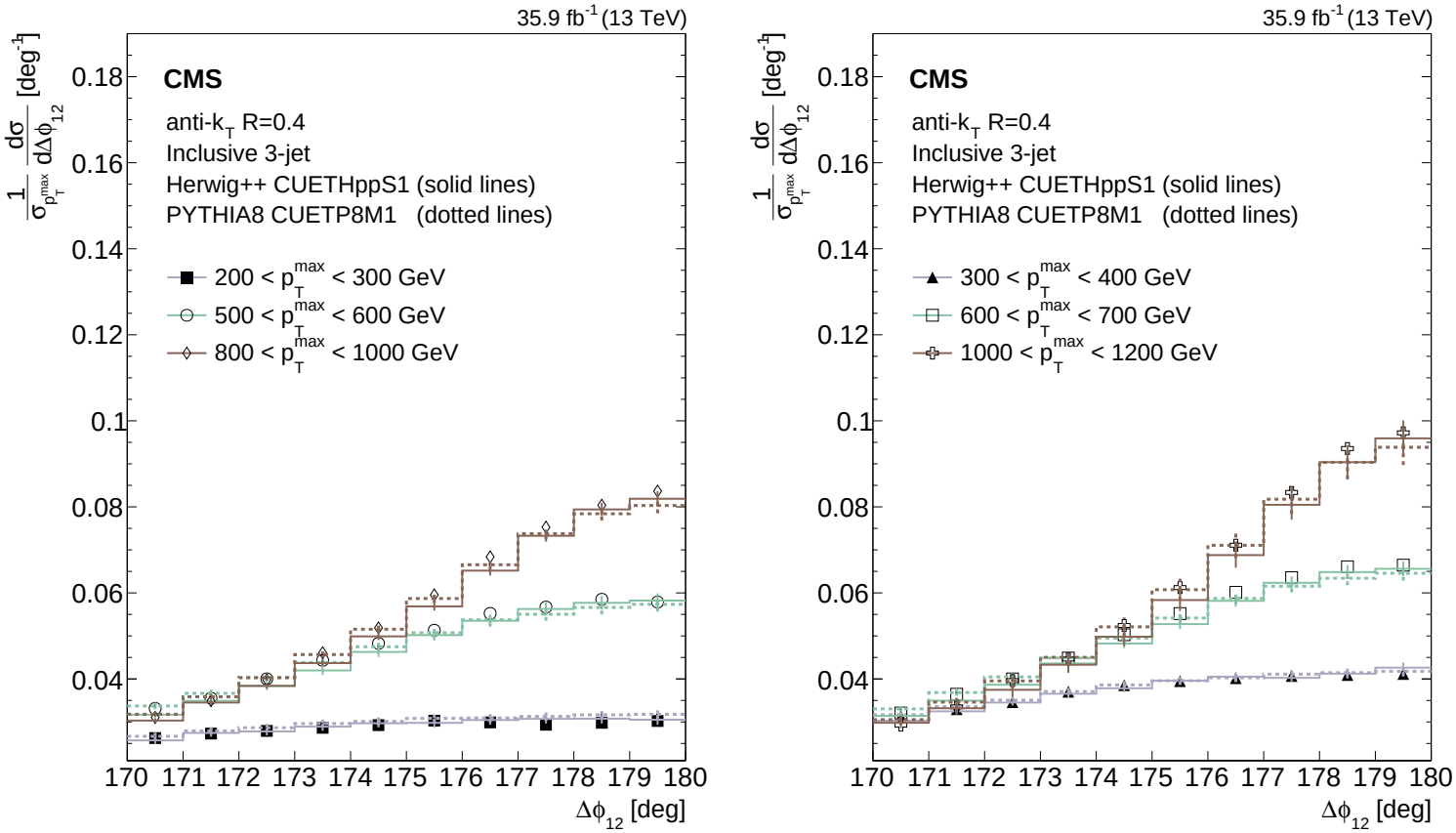
- MADGRAPH+PYTHIA8 describes data better than HERWIG++ w/ CUETHppS1 tune and PYTHIA 8 w/ tune CUETP8M1
- Predictions agree better at larger transverse momenta (and for $\Delta\phi_{12} \neq 180^\circ$), where resummation effects are small



Inclusive 2-jet azimuthal angle correlations compared to NLO calculations (POWHEG)

Observations

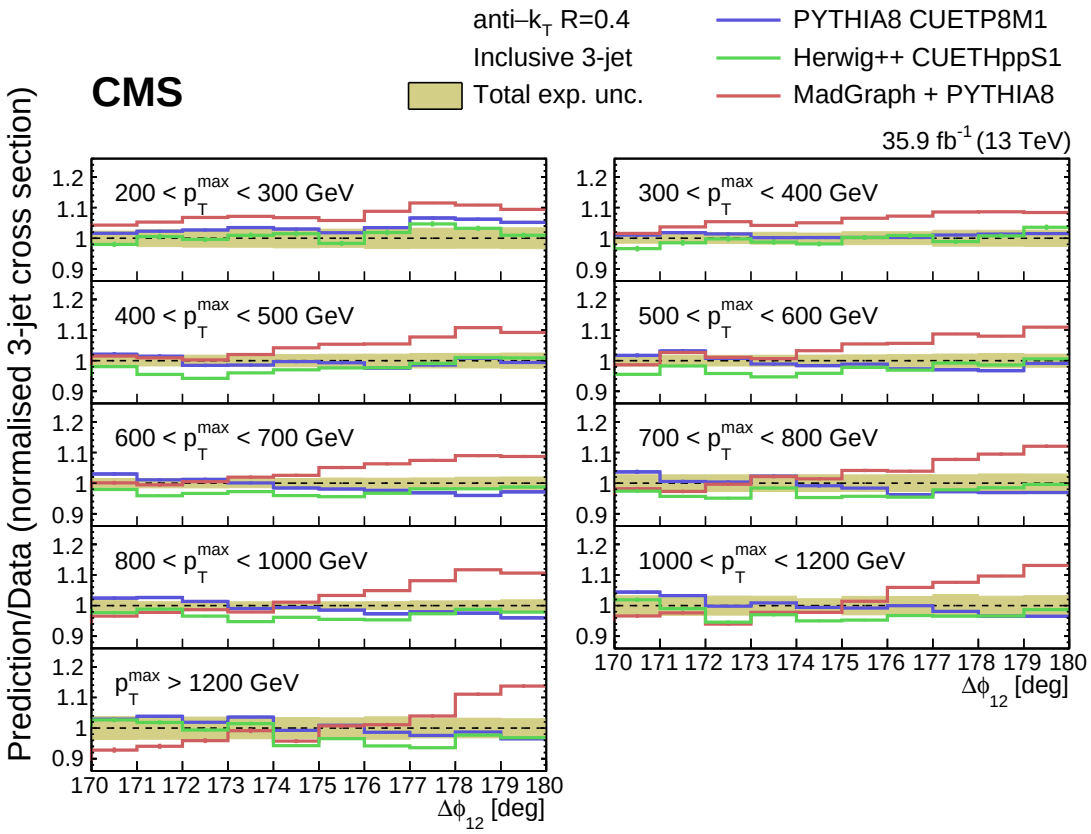
- Differences of order 10%, especially at $\Delta\phi_{12} \neq 180^\circ$
- Predictions agree better at larger transverse momenta (and for $\Delta\phi_{12} \neq 180^\circ$), where resummation effects are small
- PH-3J + PYTHIA 8 provides better overall description



Normalized inclusive 3-jet $\Delta\phi_{12}$ distributions for different $p_T^{\max}$ values

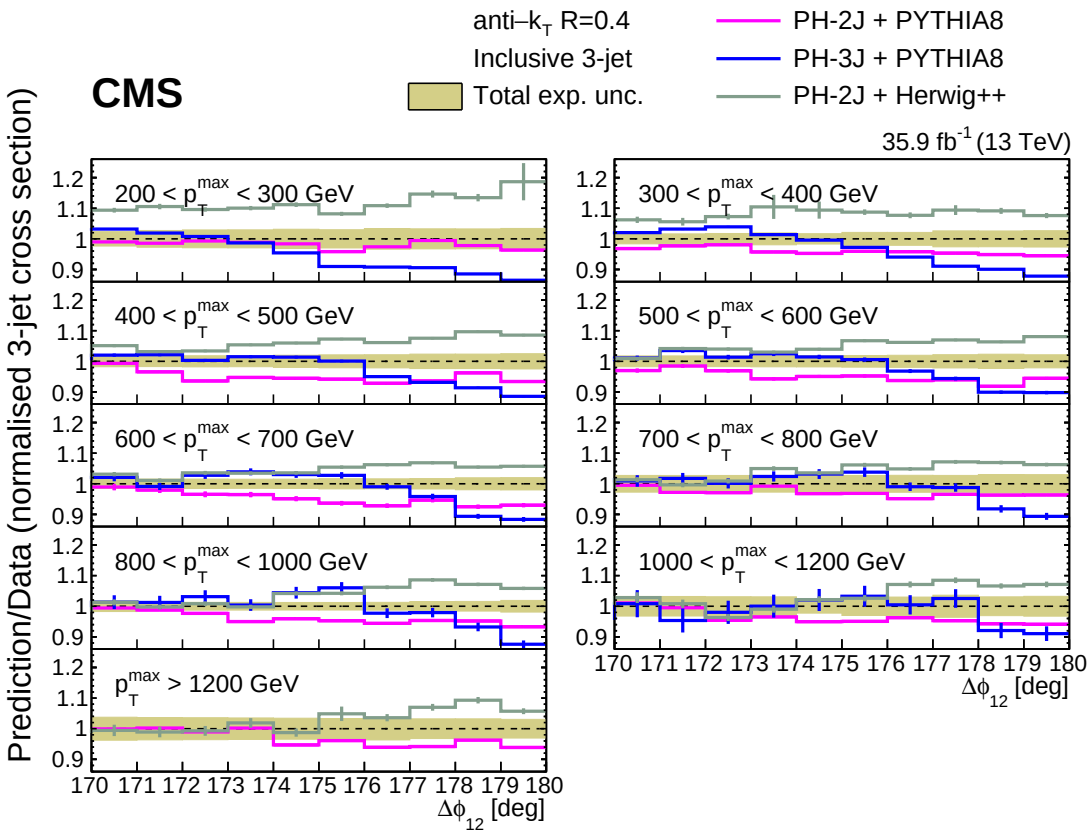
Observations

- $\Delta\phi_{12}$ distribution does not peak as steeply at $\Delta\phi_{12} \approx \pi$ due to presence of third jet
- PYTHIA 8 w/ tune CUETP8M1 and HERWIG++ w/ tune CUETHppS1 predictions in good agreement with data



Observations

- PYTHIA 8 w/ tune CUETP8M1 and HERWIG++ w/ tune CUETHppS1 predictions in good agreement with data
- MADGRAPH with PYTHIA 8 parton showers overestimates the data by less than 10%
- 2- and 3-jet measurements are not simultaneously described by any of models.



Inclusive 3-jet azimuthal angle correlations compared to NLO calculations (POWHEG)

Observations

- Differences of order 10% between PH-2J and PH-3J;
- Systematic overestimation of 5–10% by PH-2J+HERWIG++;
- PH-3J gives better description than PH-2J results at low- and high-p_T

Conclusions

- The LHC keeps enlarging our access to unexplored phase space to study strong interactions;
- Probes of perturbative and non-perturbative QCD predictions include the results presented today:
  - Measurement of differential cross sections for inclusive isolated-photon and photon+jets production in proton-proton collisions at $\sqrt{s} = 13$ TeV (Eur. Phys. J. C 79 (2019) 20);
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- State-of-the art calculations and measurements are becoming a reality!
- More incoming results in the near future!