Measurements of event properties and correlations in multi jet events in CMS

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On behalf of the CMS Collaboration

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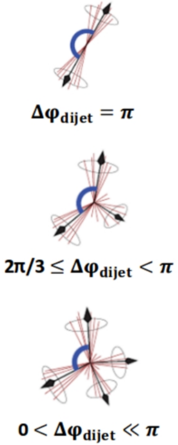
Introduction

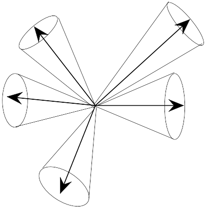
- Quantum chromodynamics (QCD), very rich and successful theory of strong interactions!
- Precise understanding of perturbative and non-perturbative QCD necessary for:
  - extraction of strong coupling constant α_s
  - testing pQCD in large phase-space volumes
  - modelling soft QCD physics
  - constraining 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 analyses:
  - 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**);
  - Event shape variables measured using multijet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV (**JHEP 12 (2018) 117**);

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 algorithms (PS) embedded in Monte Carlo event generators
- **Nearly back-to-back dijet configurations highly sensitive to effects of soft initial- and final-state gluons**





Analysis strategy

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

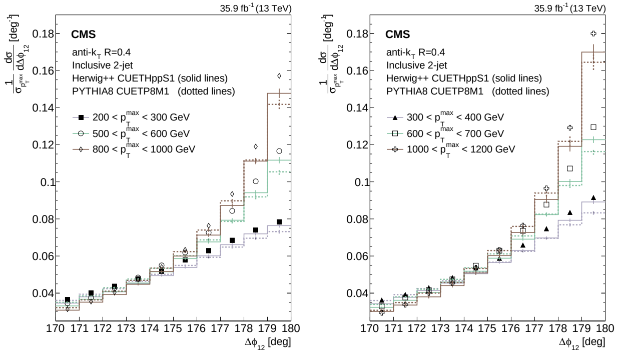
$$\frac{d\sigma}{\sigma_{p_{\mathrm{T}}^{\mathrm{max}}}\,\mathrm{d}\Delta\phi_{12}}$$

for nearly back-to-back dijet configurations, where $p_{\mathrm{T}}^{\mathrm{max}}$ is the leading jet p_{T}.

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

Selection

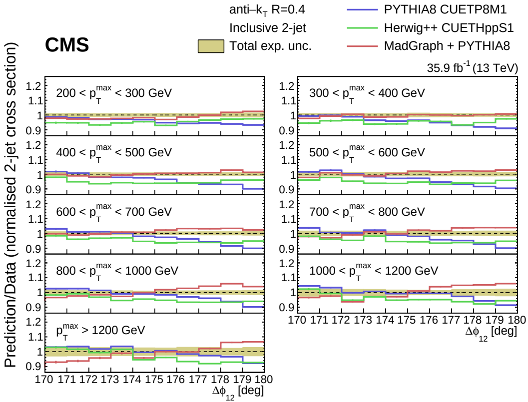
- 13 TeV pp collisions with 36 fb^{-1} of data, collected with various single-jet triggers.
- anti-k_t particle-flow jets with $R = 0.4$.
- Offline, leading two jets satisfy $p_{\mathrm{T}} > 100$ GeV and $|y| < 2.5$.
- For inclusive 3-jet measurement, $p_{\mathrm{T,jet3}} > 30$ GeV and $|y_{\mathrm{jet3}}| < 2.5$.



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

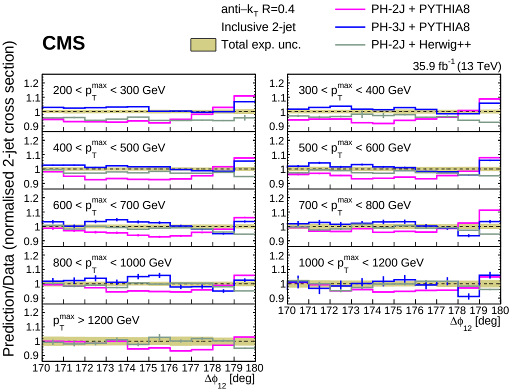
Observations

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



Observations

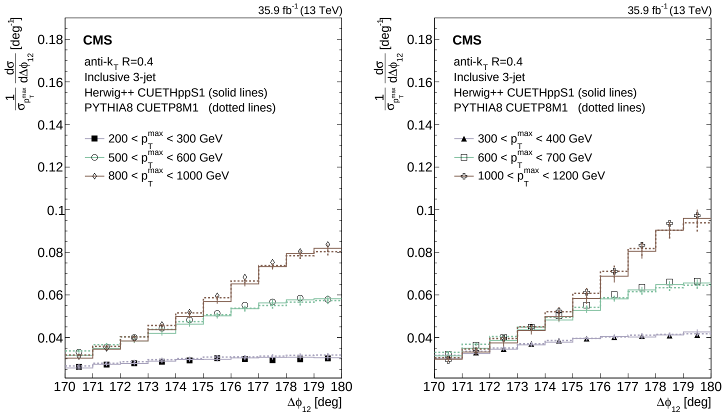
- MADGRAPH+PYTHIA8 describes data better than HERWIG++ w/ CUETHppS1 tune and PYTHIA 8 w/ tune CUETP8M1 for $p_T^{max} < 700$ GeV.
- Predictions agree better at larger transverse momenta (and for $\Delta\phi_{12} \neq 180^\circ$), where resummation effects are small



Inclusive 2-jet azimuthal angle correlations compared to 2 $\rightarrow$ 2 and 2 $\rightarrow$ 3 NLO calculations in POWHEG (PH-2J and PH-3J)

Observations

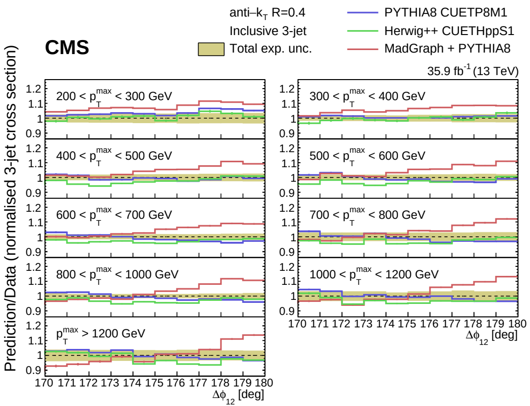
- Differences of order 5–10%, particularly at $\Delta\phi_{12} = 180^\circ$
- Predictions agree better at larger transverse momenta (and for $\Delta\phi_{12} \neq 180^\circ$), where resummation effects are small.
- PH-3J + PYTHIA8 provides better description than PH-2J results



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

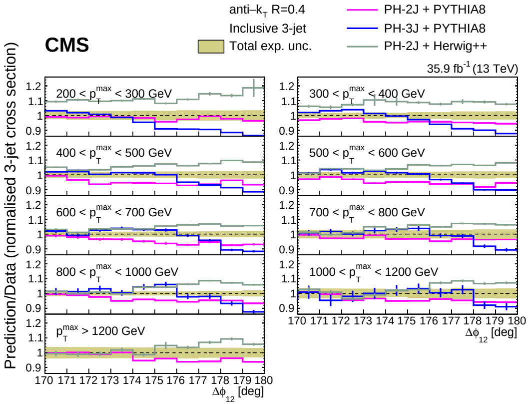
Observations

- $\Delta\phi_{12}$ 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+PYTHIA8 overestimates the data by less than 10%
- 2- and 3-jet measurements cannot be described simultaneously by any of these models.



Inclusive 3-jet azimuthal angle correlations compared to 2 → 2 and 2 → 3 NLO calculations with POWHEG (PH-2 and PH-3)

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

Event shape variables measured using multijet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV (JHEP 12 (2018) 117);

Event shape variables (ESV) in multijet events

Four infrared-safe variables ESVs sensitive to the flow of energy in hadronic final states are studied:

- **Complement of transverse thrust $\tau_\perp$:**

$$\tau_\perp = 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i p_{T,i}}$$

  where $\tau_\perp = 0$ for back-to-back dijet configurations and $\tau_\perp = 1 - 2/\pi$ for spherical multijet events. Thrust axis is along $\hat{n}_T$.

- **Total jet broadening B_{Tot}:**

$$B_X = \frac{1}{2P_T} \sum_i p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$$

  where X is the upper U (lower L) region defined by $\vec{p}_{T,i} \cdot \hat{n}_T > 0$ ($\vec{p}_{T,i} \cdot \hat{n}_T < 0$). η_X and ϕ_X are p_T-weighted pseudorapidities and azimuthal angles. The total jet broadening is given by

$$B_{\text{Tot}} = B_U + B_L$$

- **Total jet mass ρ_{Tot}:**
  Normalized squared invariant mass of the jets in U and L regions,

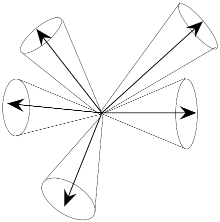
$$\rho_X \equiv \frac{M_X^2}{P^2}$$

  where M_X is the invariant mass of jets in region X and $P \equiv \sum p_{\text{T},i}$. The total jet mass is defined as,

$$\rho_{\text{Tot}} \equiv \rho_U + \rho_L$$

- **Total transverse jet mass ρ^T_{Tot}:** Calculation of ρ_{Tot} with transverse components.

These ESVs yield higher values for multijet spherical-like events, and lower values for back-to-back dijet events.



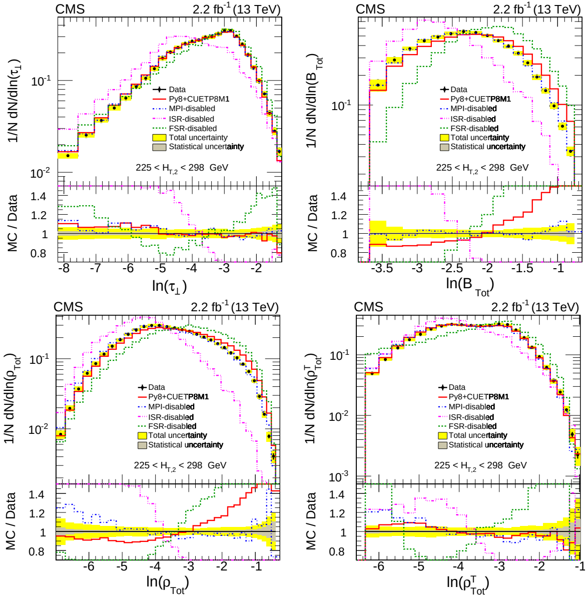
Selection

- 2.2 fb^{-1} of data collected in 13 TeV in 2015;
- Inclusive dijet triggers with various $H_{T,2} \equiv \frac{1}{2} \cdot (p_{T,\text{jet 1}} + p_{T,\text{jet 2}})$ thresholds
- Collection of anti-k_t particle-flow jets with $R = 0.4$.
- Events are required to have at least three jets with $p_T > 30$ GeV within $|\eta| < 2.4$ each.
- Three jets are used for the calculation of the ESVs:
  - Two leading p_T jets;
  - Third jet with highest recoil off the leading two jets;

Analysis strategy

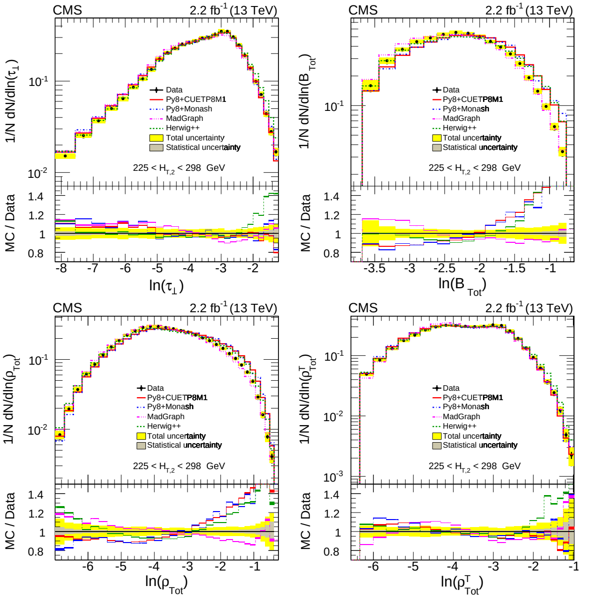
- Study ESV variables ρ_{tot}, $\rho^{\text{T}}_{\text{tot}}$, $\tau_{\perp}$, B_{tot} in bins of $H_{T,2}$ in terms of normalized cross-sections.
- Compare with predictions from pQCD, as well as the impact of soft physics, initial- and final-state radiation effects
- Predictions based on PYTHIA8 w/ Monash and CUETP8M1 tunes, MADGRAPH+PYTHIA8 and HERWIG++

Sensitivity of ESVs to MPI, ISR and FSR (PYTHIA8+CUETP8M1)



- Small effects of FSR and MPI on ESVs.
- ISR is very important to describe spherical-like multijet topologies.

Comparison with different generators ($225 < H_{T,2} < 298$ GeV)

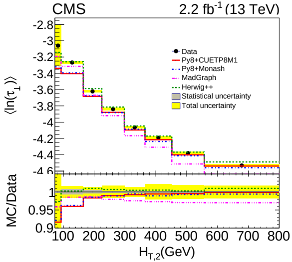


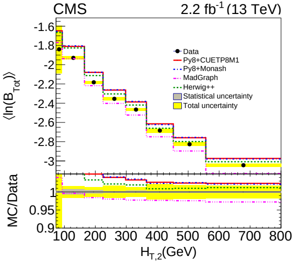
PYTHIA8 agrees well with data for $\tau_\perp$ and $\rho^T_{\rm tot}$ (sensitive to transverse plane energy-flow)

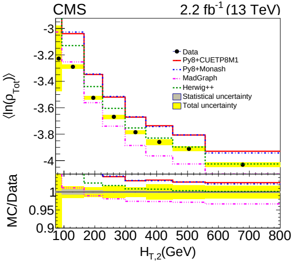
PYTHIA8 progressively deviates from measurement at larger values of the $B_{\rm tot}$ and $\rho_{\rm tot}$ (sensitive to longitudinal and transverse energy-flow)

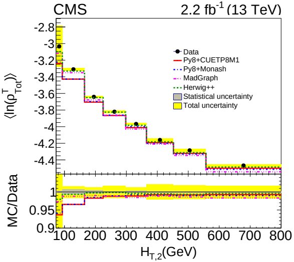
MADGRAPH has better performance on all four ESVs cases.

Average ESVs vs $H_{T,2}$









Average of ESVs drop at larger $H_{T,2}$.

→ Back-to-back topologies are favored at larger $H_{T,2}$.

MadGraph and Herwig++ provide good description on all four ESVs cases.

Benchmark generators agree better with data at larger $H_{T,2}$.

Summary

- 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:
  - 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);
  - Event shape variables measured using multijet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV (JHEP 12 (2018) 117);
- These results provide very important inputs for future Monte Carlo generator tunes and further development of parton-shower algorithms.
- More incoming results in the near future!

General observations on ESVs results

- Disabling ISR results in a very large shift of the ESVs to lower values (less spherical-like nature of multijet events);
- Energy-flow in transverse plane is modelled well in Monash and CUETP8M1 tunes of PYTHIA8 (good description of $\tau_\perp$ and $\rho^{\mathrm{T}}_{\mathrm{tot}}$ variables), but longitudinal energy-flow is modelled better by HERWIG++ and MADGRAPH.
- HERWIG++ and MADGRAPH show good agreement with data for all four ESVs studied and better than PYTHIA8 w/ CUETP8M1 or Monash tunes for the ρ_{tot} and B_{Tot};