Jet measurements at CMS

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On behalf of the CMS Collaboration

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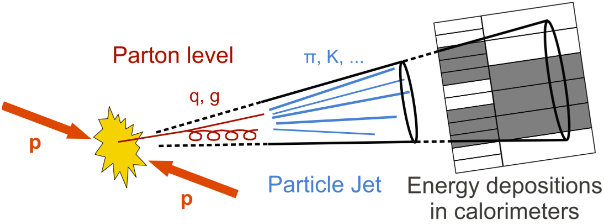


Studies of short and long distance aspects of the strong interaction at the LHC are essential for:

- Further tests of perturbative quantum chromodynamics (QCD).
- Better modeling of soft physics phenomena embedded in Monte Carlo (MC) generators.
- Improving constraints of parton distribution functions of the proton.
- Test resummation of large logarithms to all orders in α_s.
- All of the above is interesting on its own right, also help us better understand our backgrounds in searches for new physics.

Jet production (collimated spray of particles): benchmark process to understand QCD interactions.

New jet results since ICHEP 2018!

We present recent jet measurements in pp collisions by CMS:

- Dependence of inclusive jet production on the anti-k_T distance parameter in pp collisions at $\sqrt{s} = 13$ TeV, arXiv:2005.05159, *Submitted to JHEP*
- Measurement of angular and momentum distributions in multijet and Z+2 jet final states in pp collisions at $\sqrt{s} = 8$ and 13 TeV, CMS-PAS-SMP-17-008
- Study of hard color singlet exchange in dijet events with proton-proton collisions at $\sqrt{s} = 13$ TeV, CMS-PAS-SMP-19-006

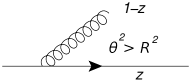
Tune in! More exciting jet-related studies by CMS presented at ICHEP 2020:

- V+jets presented by Sarah Malik today Tuesday July 28th.
- $V+$ heavy-flavor jets by Anton Stepennov today Tuesday July 28th.
- New phenomena using jets by Dimitrios Karasavvas today Tuesday July 28th.
- New jet tagging techniques by Dennis Schwarz on Wednesday July 29th.
- For jet substructure and boosted topologies join Deniz Cerci's talk on Thursday July 30th.

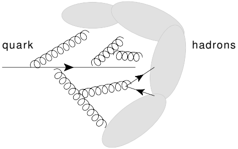
Different distance parameter R are sensitive to different parts of jet formation.

$\delta p_T \equiv$ "lost" transverse momentum outside jet cone at LO in small-radius approximation $R \ll 1$

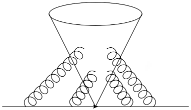
Parton shower: $(\delta p_T)_{\mathrm{PS}} \sim \ln(1/R)$



Hadronization: $(\delta p_T)_{\mathrm{HAD}} \sim R^{-1}$



Underlying event activity: $(\delta p_T)_{UE} \sim R^2$.



Analysis performed with data recorded in 2016 (35.9 fb^{-1}).

Jets have $84 < p_T < 1588$ GeV and $|y| < 2.5$, clustered with anti-k_t algorithm.

Double-differential inclusive jet cross section ratio:

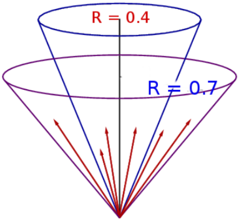
$$Ratio(R, 0.4) = \frac{d^2\sigma(R)}{dp_T dy} \Big/ \frac{d^2\sigma(R = 0.4)}{dp_T dy}$$

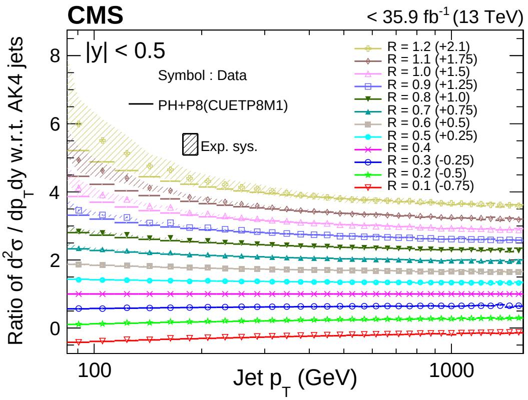
where $0.1 < R < 1.2$.

Cross section is corrected for detector effects and unfolded to stable-particle level with D'Agostini method.

→ Comparisons to LO (`Herwig++`,`Herwig7` `Pythia8`, `MadGraph`) and NLO (`PowHeg`, `NLOJET++` w/ and w/o NP correction) predictions.

AK4 chosen as reference because it is the standard R in CMS during Run-2

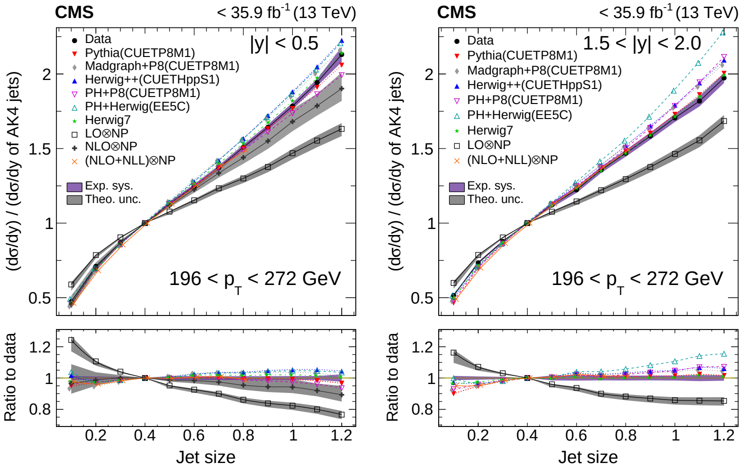




arXiv:2005.05159

- Curves are artificially displaced for visibility. Results are compared to NLO Powheg+Pythia8 (PH+P8) predictions (lines).
- Slope in the ratios at low p_T for larger R → Larger contributions from underlying event
- Flat ratio starting at $p_T \sim$ 200–300 GeV for most values of R.

Cross section ratios in central & forward region



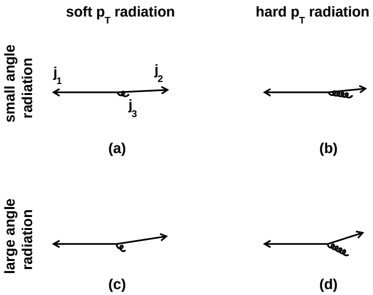
arXiv:2005.05159

- Central region $|y| < 0.5$ (**Left**) and forward region $1.5 < |y| < 2.0$ (**Right**).
- Best agreement achieved by NLO predictions in general R parameter range.
- NLO predictions slightly overshoot data at larger R values in forward region.

CMS-PAS-SMP-17-008

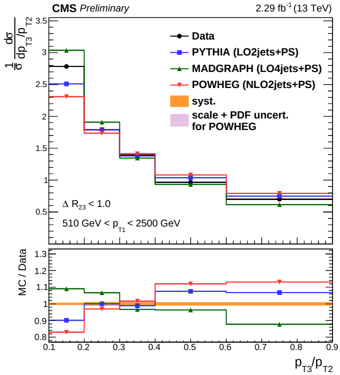
- Test regimes of validity of matrix element approach (harder parton splittings, wide angle emission) and parton shower approaches (soft collinear emissions).

- Main focus is on 3-jet event topology
- Interested in $\Delta R_{23} \equiv \sqrt{\Delta y_{23}^2 + \Delta \phi_{23}^2}$ and p_{T3}/p_{T2} distributions.
- Study based on 8 TeV (20 fb^{-1}) and 13 TeV (2.3 fb^{-1}) data. Part of the study is based on $Z+2$jet production (not covered in this talk).



3-jet event	selection
transverse momentum of the leading jet (j_1)	$p_{T1} > 510$ GeV
transverse momentum for each jet and rapidity for $j_{1,2}$	$p_T > 30$ GeV , $\|y_{1,2}\| < 2.5$
azimuthal angle difference between j_1 andj_2	$2.14 < \Delta\phi_{12} < \pi$
transverse momentum ratio between j_2 andj_3	$0.1 < p_{T3}/p_{T2} < 0.9$
angular distance between j_2 and j_3	$R_{jet} + 0.1 < \Delta R_{23} < 1.5$

Results on p_{T3}/p_{T2} at 13 TeV



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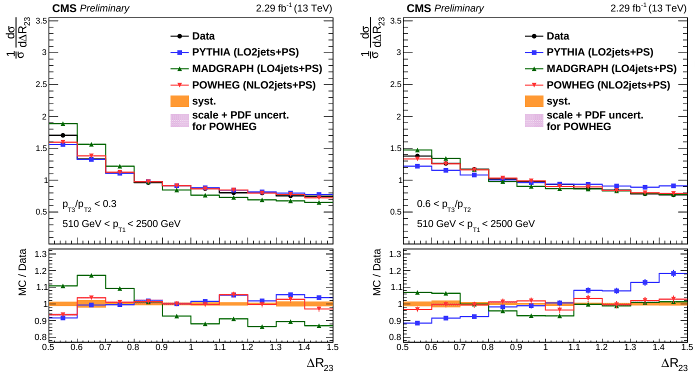
- **Left:** small-angle emissions $\Delta R_{23} < 1.0$ **Right:** wide-angle emissions $\Delta R_{23} > 1.0$.
- Powheg+Pythia8 (NLO2jets+PS) and Pythia8 (LO2jets+PS) are not able to describe data for small- and wide-angle emisisons in the soft- and hard-regimes in p_{T3}/p_{T2}.
- MadGraph (LO4jets + PS) is able to describe p_{T3}/p_{T2} spectra for wide-angle emissions $\Delta R_{23} > 1.0$. MadGraph does not describe well data for small-angle emissions $\Delta R_{23} < 1.0$.

Results on ΔR_{23} at 13 TeV



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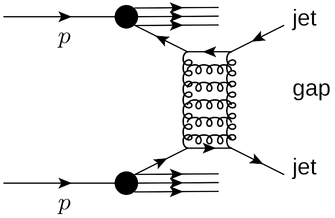
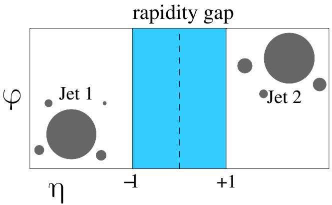
- **Left:** small $p_{T3}/p_{T2} < 0.3$ (soft splitting) **Right:** large $p_{T3}/p_{T2} > 0.6$ (hard splitting)
- `Powheg` (NLO2jets+PS) gives best agreement in ΔR_{23} for soft p_T and hard p_T regimes.
- Similar conclusion for 8 TeV results $\rightarrow$ No significant $\sqrt{s}$-dependence on matrix element method or parton shower approach (back-up slides).

Jet-gap-jet process as a probe of BFKL dynamics (CMS-PAS-SMP-19-006)





- In collisions with t-channel color singlet exchange between partons, color-flow is neutralized → Rapidity interval void of particle production between jets (rapidity gap). Jets are produced back-to-back with very little additional jet activity.

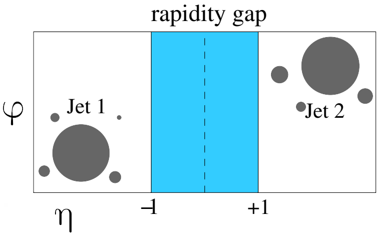
- In high-energy limit of QCD ($\hat{s} \gg -\hat{t} \gg \Lambda^2_{\mathrm{QCD}}$), color-singlet exchange corresponds to perturbative pomeron exchange (two-gluon ladder). Jet-gap-jet as a probe of Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution (resummation of $\alpha_s^n \log^n(\hat{s}/|\hat{t}|) \sim \mathcal{O}(1)$ terms).

- Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) dynamics are strongly suppressed in jet-gap-jet events (Sudakov form factor for gap) → Clean probe of BFKL dynamics.

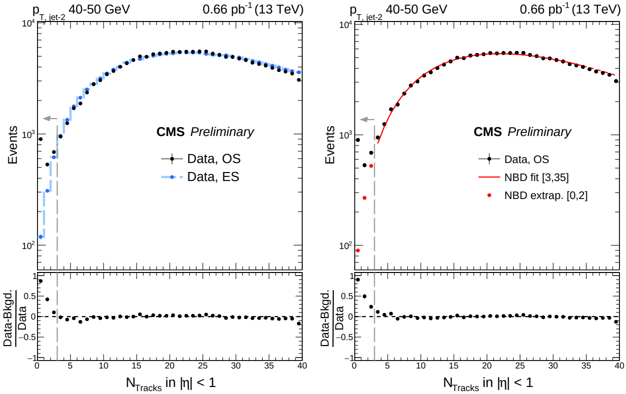
Analysis based on 2015 data $\sqrt{s} = 13$ TeV with low pileup (PU $\sim$ 0.05-0.10).

Event selection:

- Anti-k_t jets with $R = 0.4$.
- Leading two jets have $p_T > 40$ GeV and $1.4 < |\eta_{\mathrm{jet}}| < 4.7$ with $\eta_{\mathrm{j1}} \times \eta_{\mathrm{j2}} < 0$
  $\rightarrow$ Favors t-channel color singlet exchange.
- At most one reconstructed primary vertex $N^{PV} \leq 1$.

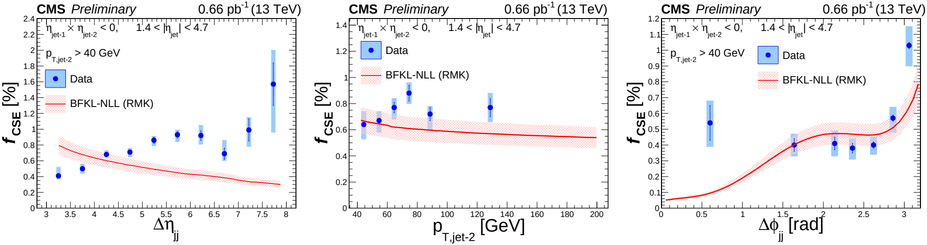


Pseudorapidity gap corresponds to absence of charged particle tracks between jets ($p_T^{\mathrm{ch}} > 200$ MeV & $|\eta| < 1$).



Standard dijet events dominate at high-multiplicities → Use as control region to estimate fluctuations at low multiplicities. Two data-based approaches:

- Orthogonal data sample: two jets on equal sides (ES) of the CMS detector, $\eta_{j1} \times \eta_{j2} > 0$. Normalize to events with jets in opposite sides (OS) of CMS, $\eta_{j1} \times \eta_{j2} < 0$, in $3 < N_{\text{Tracks}} < 40$.
- Negative binomial distribution (NBD) function: Fit data with NBD in $3 \leq N_{\text{Tracks}} \leq 35$, extrapolate down to $N_{\text{Tracks}} = 0$. (Baseline method)



CMS-PAS-SMP-19-006

- f_{CSE} generally increases with increasing $\Delta\eta_{\mathrm{jj}} \equiv |\eta_{\mathrm{j1}} - \eta_{\mathrm{j2}}|$. Weak dependence of f_{CSE} on $p_{\mathrm{T,j2}}$ within uncertainties. f_{CSE} increases at $\Delta\phi_{\mathrm{jj}} \equiv |\phi_{\mathrm{j1}} - \phi_{\mathrm{j2}}| \approx \pi$, uniform at $\Delta\phi_{\mathrm{jj}} < 2.7$. Typical values of $f_{\mathrm{CSE}} = 0.6$–1.0%.
- Comparison to Royon, Marquet, Kepka (RMK) model based on BFKL NLL calculations + LO impact factors (Phys. Rev. D 83.034036), and survival probability $|S|^2 = 0.1$.
- Challenging to describe all features of the measurement simultaneously $\rightarrow$ Guidance for further theory development.

- Jet measurements are crucial for our better understanding of strong interaction.
- Ratio of inclusive jet cross section as a function of R relative to $R = 0.4$ has been presented. NLO predictions, supplemented with parton shower and nonperturbative corrections, give the best agreement with data for most of the parameter range.
  arXiV:2005.05159, *submitted to JHEP*
- Multijet production allows us to test the regimes of validity of the matrix element approach and the parton shower algorithms. None of these approaches are able to describe the data in all regions of phase space simultaneously.
  CMS-PAS-SMP-17-008
- Events where radiation between the jets is suppressed at the 200 MeV scale (rapidity gap) are consistent with hard color singlet exchange. Present predictions based on the BFKL framework (resummation of large logarithms of energy in pQCD) are not able to describe all features of data.
  CMS-PAS-SMP-19-006
- Stay tuned for more CMS results!

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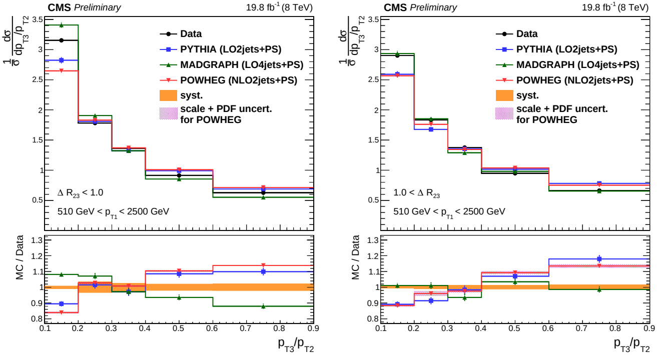
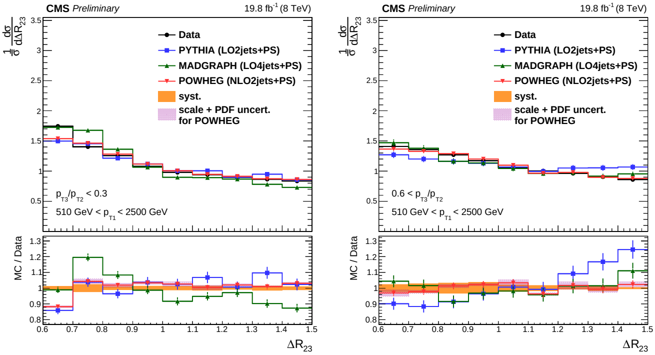
Back up



CMS-PAS-SMP-17-008

Left: p_{T3}/p_{T2} at small $\Delta R_{23} < 1.0$ **Right:** p_{T3}/p_{T2} at large $\Delta R_{23} > 1.0$.

Similar conclusion as in 13 TeV $\rightarrow$ No significant $\sqrt{s}$-dependence on matrix element method or parton shower approach.



CMS-PAS-SMP-17-008

Left: ΔR_{23} at small $p_{T3}/p_{T2} < 0.3$ (soft splitting) **Right:** ΔR_{23} at large $p_{T3}/p_{T2} > 0.6$ (hard splitting)

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