Mueller–Navelet jets and jet-gap-jet events with the CMS and TOTEM experiments

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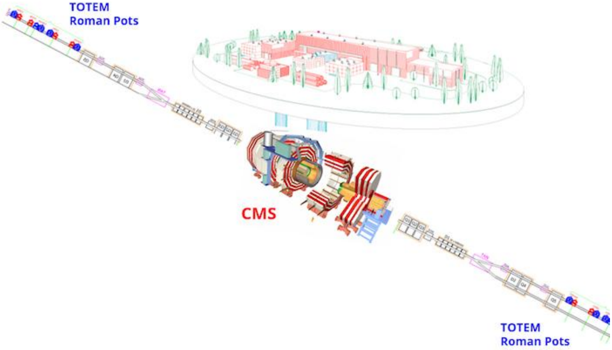
DE-SC0019389

- The CMS and TOTEM detectors.
- Mueller–Navelet jets at $\sqrt{s} = 7$ TeV (arXiv:1601.06713, JHEP08(2016)139).
- Hard color-singlet exchange in dijet events ("jet-gap-jet") at $\sqrt{s} = 13$ TeV (arXiv:2102.06945, *accepted by PRD*)
  - Jet-gap-jet events in proton-proton collisions at $\sqrt{s} = 13$ TeV ("CMS-only" analysis).
  - Jet-gap-jet events with an intact proton at $\sqrt{s} = 13$ TeV (CMS-TOTEM combined analysis).
- Summary



CMS:

- General purpose detector at IP5 of the CERN LHC.
- Tracking ($|\eta| < 2.5$), and hadronic and electromagnetic calorimetry ($|\eta| < 5.2$)
- Jets reconstructed within $|\eta^{\text{jet}}| < 4.7$.

TOTEM:

- **Roman pots:** Forward tracking detectors at $\approx$ 220m w.r.t. IP5 that measure the protons scattered at small angles w.r.t. the beam.
- Measurement of total cross section, elastic scattering, and soft and hard diffractive processes in pp collisions.

The high-energy limit is defined by $\hat{s} \gg -\hat{t} \gg \Lambda^2_{\text{QCD}}$, where $\hat{s}$, $\hat{t}$ are the Mandelstam variables at parton-level, **the fixed-order pQCD approach breaks down**.

The perturbative expansion should be rearranged (symbolically) as,

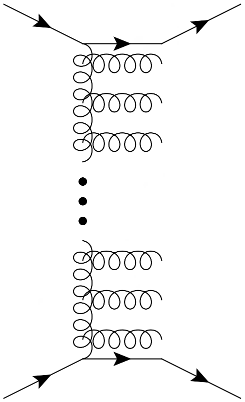
$$d\hat{\sigma} \simeq \alpha_s^2 \sum_{n=0}^{\infty} \alpha_s^n \ln^n\left(\frac{\hat{s}}{|\hat{t}|}\right) + \alpha_s^3 \sum_{n=0}^{\infty} \alpha_s^n \ln^n\left(\frac{\hat{s}}{|\hat{t}|}\right) + \alpha_s^4 \sum_{n=0}^{\infty} \alpha_s^n \ln^n\left(\frac{\hat{s}}{|\hat{t}|}\right) + \ldots$$

such that $\alpha_s^n \ln^n(\hat{s}/|\hat{t}) \lesssim 1$.

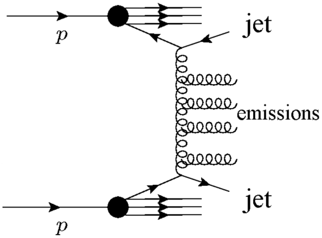
Resummation of large logarithms of $\hat{s}$ to all orders in α_s via **Balitsky-Fadin-Kuraev-Lipatov (BFKL)** evolution equations of pQCD.

Very important test of QCD; very challenging to isolate experimentally

Detailed theory discussion previously presented by Dmitri Ivanov.



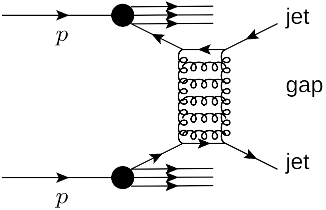
Multi-gluon ladder diagrams contribute significantly in the high-energy limit

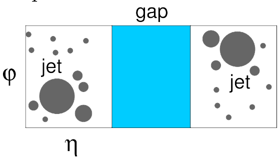


Mueller–Navelet jets:
Events where the two outermost jets are largely separated by a large interval in $\Delta y \equiv |y_{\text{jet1}} - y_{\text{jet2}}| \gg 1$.

At large Δy, the $\Delta\phi$ decorrelations between MN jets are stronger due to increased parton emission with the available phase-space.

$\Delta\phi$ decorrelations are expected to be strong in the BFKL picture.

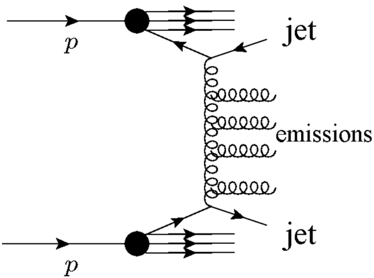


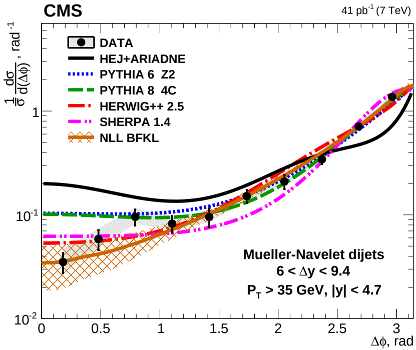


Mueller–Tang jets:
Events with two jets separated by a rapidity gap (hard color-singlet exchange).

In $\Delta y \equiv |y_{\text{jet1}} - y_{\text{jet2}}| \gg 1$, it is expected to be described by perturbative pomeron exchange.

arXiv:1601.06713, JHEP08(2016)139

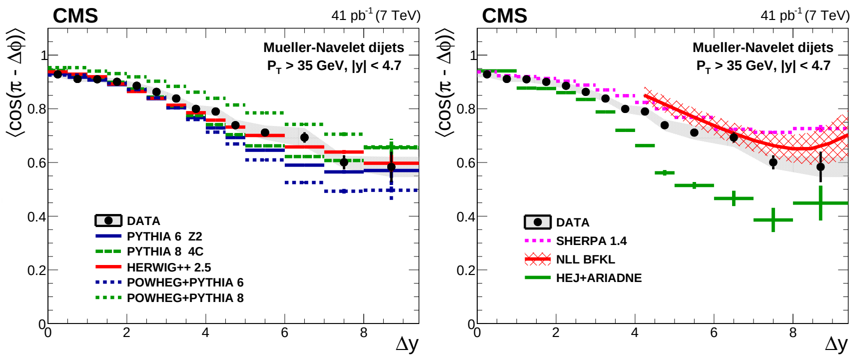




Analysis based on low pileup 7 TeV data. The Mueller–Navelet jets have $p_T > 35$ GeV and $|y| < 4.7$, anti-k_T jets with $R = 0.5$.

Characterize $\Delta\phi$ decorrelations as a function of $0 < \Delta y < 9.4$.

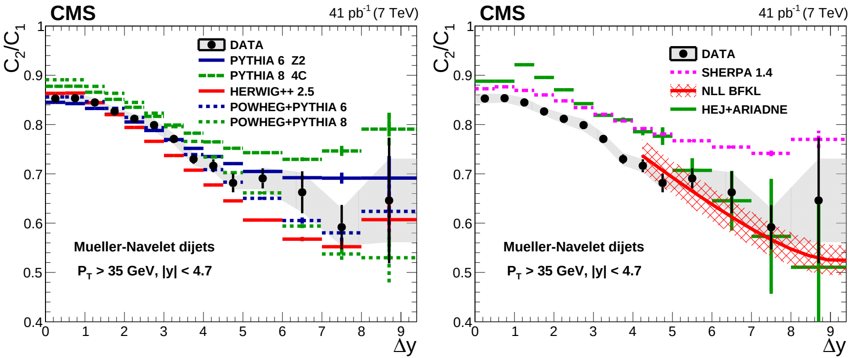
Average cosine of $\Delta\phi$ vs. $\Delta y \equiv |y_{\text{jet1}} - y_{\text{j2}}|$



$$\cos(\pi - \Delta\phi) = 1 \iff \text{back-to-back jets}$$
$$\cos(\pi - \Delta\phi) = 0 \iff \text{collinear jets}$$

- BFKL at NLL + NLO impact factor calculations describe data at large Δy within uncertainties.
- PYTHIA6, PYTHIA8, HERWIG++ (DGLAP splitting functions) are able to describe data over wide range in Δy within uncertainties.
- POWHEG+PYTHIA6 and POWHEG+PYTHIA8 (NLO + PS) underestimates or overestimates data at large Δy, respectively.

Other $\langle\cos[n(\pi - \Delta\phi)]\rangle$ can be found in arXiv:1601.06713, JHEP08(2016)139.

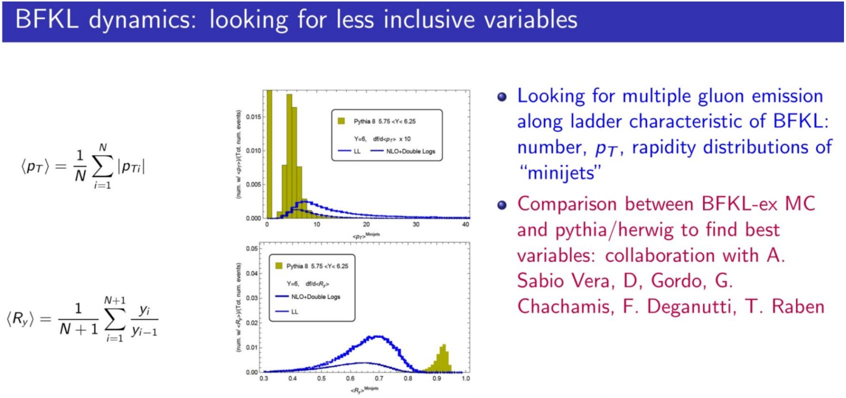


where $C_n \equiv \langle \cos[n(\pi - \Delta\phi)] \rangle$ is the n-th Fourier coefficient of the expansion of $\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}$.

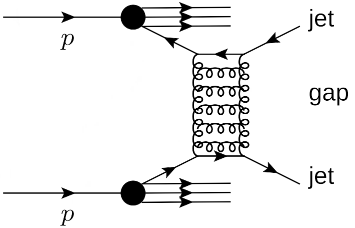
- BFKL at NLL + NLO impact factor calculations describe data at large Δy within uncertainties (B. Ducloué, L. Szymanowski, S. Wallon, JHEP 1305(2013) 096)
- SHERPA is not able to describe simultaneously the C_2/C_1 ratios and C_n coefficients versus Δy.
- PYTHIA6, POWHEG+PYTHIA6 are able to describe data over wide range in Δy within uncertainties.
- HERWIG++, PYTHIA8, POWHEG+PYTHIA8 slightly overshoot or undershoot data at large Δy, respectively.

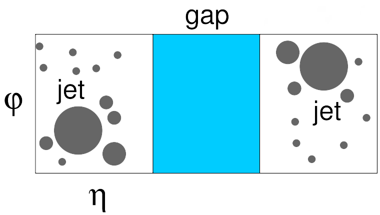
Other ratio C_3/C_2 can be found in arXiv:1601.06713, JHEP08(2016)139.

- Difficult to clearly disentangle the onset of BFKL dynamics from other QCD perturbative and nonperturbative effects in Mueller–Navelet jets.
- A possibility for future measurements could be a combination of $\Delta\phi$ analysis and minijet-based observables (A. Sabio Vera, G. Chachamis, `BFKLex`, JHEP02 (2016) 064).



Slide by C. Royon





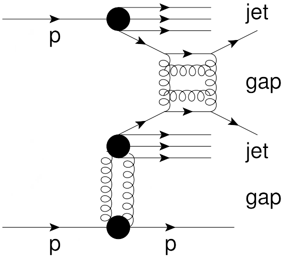
t-channel color-singlet exchange between partons (two-gluon exchange)
$\rightarrow \eta$ **interval void of particles between jets (pseudorapidity gap)**.

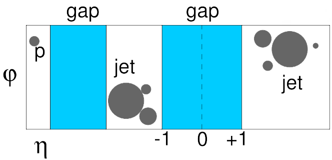
In the high-energy limit, this corresponds to **perturbative pomeron exchange** (BFKL two-gluon ladder exchange).

DGLAP dynamics are strongly suppressed in events with pseudorapidity gaps (Sudakov form factor to suppress radiation in gap).

Soft-parton activity can destroy the central gap between the jets. This is parametrized with a gap survival probability, $|\mathcal{S}|^2$, **which is difficult to understand theoretically.**

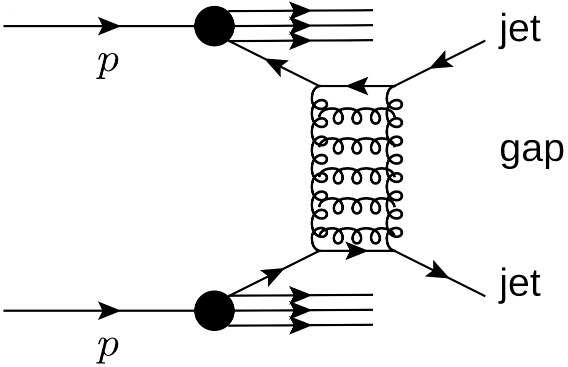
In pp collisions with intact protons, soft-parton activity is largely suppressed $\rightarrow$ **Central gap more likely to "survive"** (Marquet, Royon, Trzebiński, Žlebčík, Phys.Rev. D 87, 034010 (2013)).





Addressed in study with CMS-TOTEM combined analysis (arXiv:2102.06945). **Second part of the analysis**.

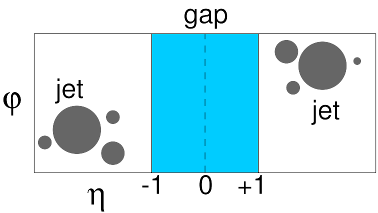
Turning to CMS measurement



CMS-TOTEM Collaborations, arXiv:2102.06945, *accepted by PRD*

Analysis based on low-pileup data. Event selection:

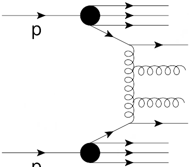
- Particle-flow, anti-k_t jets $R = 0.4$.
- Two highest p_T jets have $p_T > 40$ GeV each.
- Leading two jets satisfy $1.4 < |\eta_{\text{jet}}| < 4.7$ and $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$
  $\rightarrow$ **Favors t-channel color-singlet exchange.**

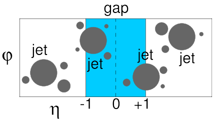


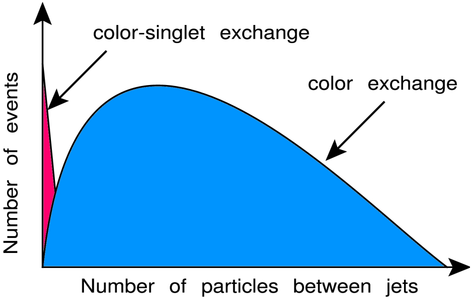
Pseudorapidity gap is defined by means of the charged particle multiplicity N_{tracks} between the leading two jets. Each charged particle has $p_T > 200$ MeV in $|\eta| < 1$.

Need to distinguish color-exchange from color-singlet exchange contributions

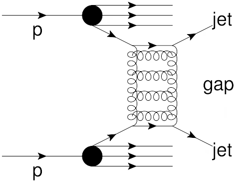
Color-exchange (single-gluon in t-channel)

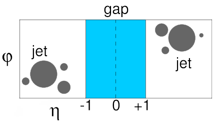






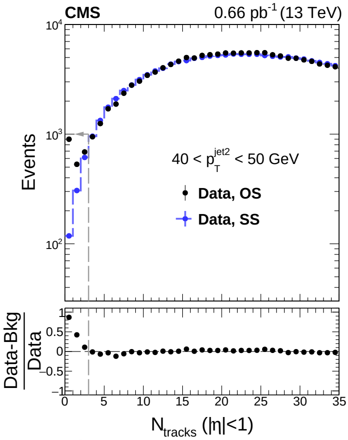
Color-singlet exchange (two-gluon in t-channel)

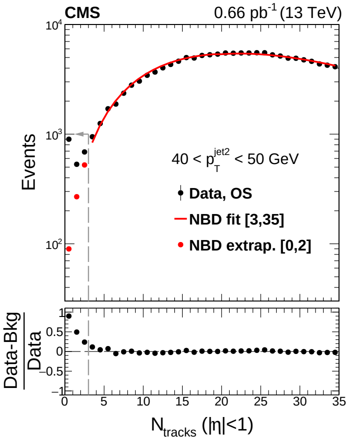




Color-exchange fluctuations at low-multiplicities need to be properly treated.

Multiplicity of charged particles between the jets





Color-exchange events dominate at large N_{tracks} $\rightarrow$ Use as control region to estimate fluctuations at low N_{tracks}. Two data-based approaches:

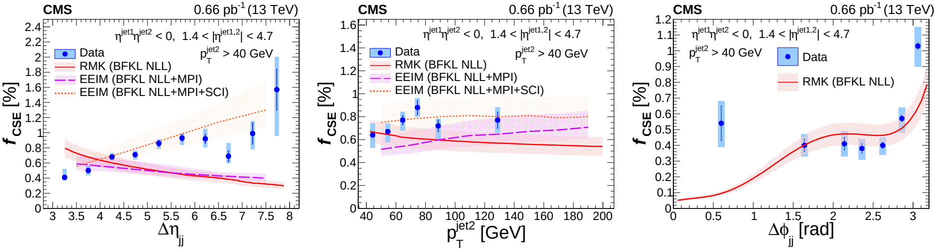
- Control dijet sample: two jets on the same-side (SS) of the CMS detector, $\eta^{\text{jet1}}\eta^{\text{jet2}} > 0$. Normalize to events with jets in opposite sides (OS) of CMS, $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$, in $N_{\text{tracks}} > 3$.
- Negative binomial distribution (NBD) function: Fit data with NBD in $3 \leq N_{\text{tracks}} \leq 35$, extrapolate down to $N_{\text{tracks}} = 0$. (Baseline method)

We extract the fraction f_{CSE} based on the charged particle multiplicity between the jets:

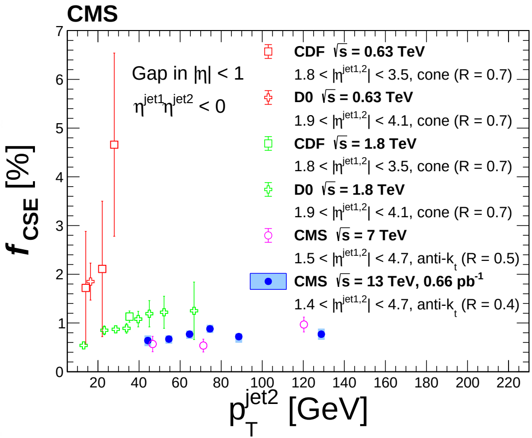
$$f_{\mathrm{CSE}} \equiv \frac{N(N_{\mathrm{tracks}} < 3) - N_{\mathrm{bkg}}(N_{\mathrm{tracks}} < 3)}{N_{\mathrm{all}}} \equiv \frac{\text{color-singlet exchange dijet events}}{\text{all dijet events}}$$

The fraction f_{CSE} is measured as a function of:

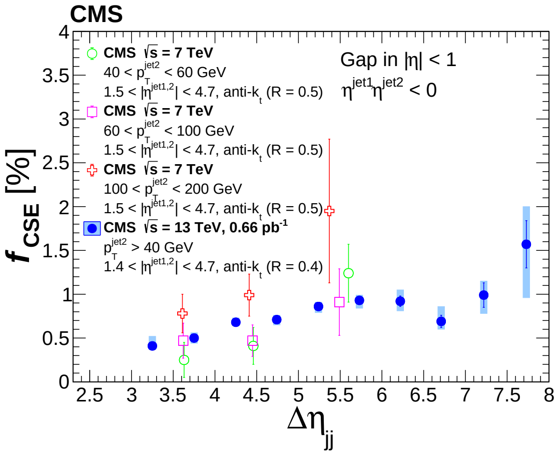
- $\Delta\eta_{\mathrm{jj}} \equiv |\eta^{\mathrm{jet1}} - \eta^{\mathrm{jet2}}|$: Sensitive to expected BFKL dynamics, since it's related to resummation of large logs of s.
- $p_{\mathrm{T}}^{\mathrm{jet2}}$: Sensitive to expected BFKL dynamics; allows for comparison at lower $\sqrt{s}$.
- $\Delta\phi_{\mathrm{jj}} \equiv |\phi^{\mathrm{jet1}} - \phi^{\mathrm{jet2}}|$: Sensitive to deviations of $2 \to 2$ scattering topology of color-singlet exchange.



- **Color-singlet exchange represents ≈ 0.6% of the inclusive dijet cross section for the probed phase-space.**
- Bars represent stat uncertainties, boxes represent stat + syst uncertainties.
- Comparison w/ calculations based on BFKL NLL resummation + LO impact factors:
  - **Royon, Marquet, Kepka** (RMK) predictions (Phys. Rev. D 83.034036 (2011), arXiv:1012.3849), with survival probability $|S|^2 = 0.1$.
  - **Ekstedt, Enberg, Ingelman, Motyka** (EEIM) predictions (Phys. Lett. B 524:273 and arXiv:1703.10919) with MPI to simulate $|S|^2$, also be supplemented with soft-color interactions (SCI).
- **Challenging to describe theoretically all aspects of the measurement simultaneously.**

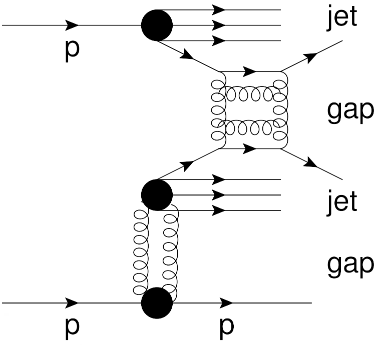


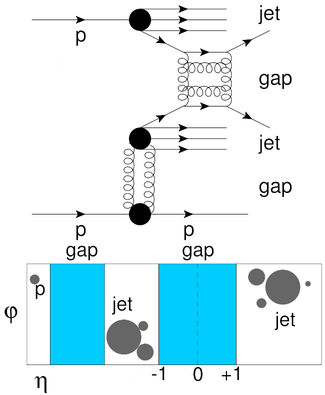
- Measurement of jet-gap-jet events at four different $\sqrt{s}$ in $p\bar{p}$ and pp collisions at 0.63 TeV, 1.8 TeV, 7 TeV, and 13 TeV (this measurement).
- Generally, f_{CSE} is expected to decrease with increasing $\sqrt{s}$, due to an increase in spectator parton activity with $\sqrt{s}$.
- Within uncertainties, f_{CSE} stop decreasing with $\sqrt{s}$ at LHC energies, in contrast to trend observed at lower energies 0.63 TeV → 1.8 TeV → 7 TeV.



- CMS 7 TeV analysis performed in three bins of p_T^{jet2} and three bins of $\Delta\eta_{jj} = 3$–4, 4–5,5–7 (CMS, **EPJC** 78 (2018) 242)
- **Trend of increasing f_{CSE} with $\Delta\eta_{jj}$ is confirmed with new 13 TeV results.**
- **New results reach previously unexplored values of $\Delta\eta_{jj}$**

Turning to CMS-TOTEM combined measurement



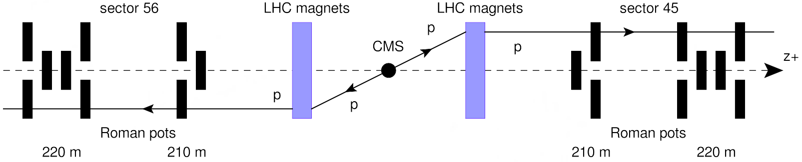


Better understand the role of spectator partons in the destruction of the central gap.

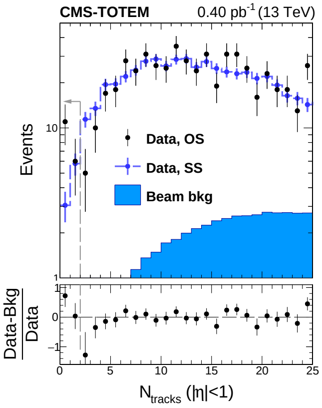
Same dijet and central gap definitions as with CMS-only analysis.

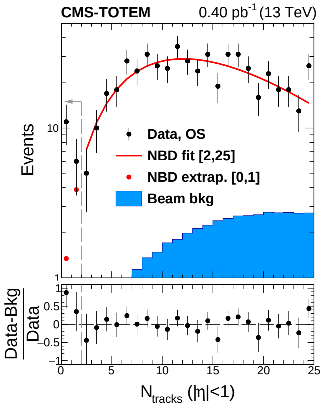
Proton requirements:

- The fraction of beam energy lost by the proton must be $\xi_p(\text{RP}) < 0.2$
- The four-momentum transfer square at the proton vertex must be $-4 < t < -0.025$ GeV^2, where $t = (p_f - p_i)^2$ of the proton.



Charged particle multiplicity between jets + intact proton



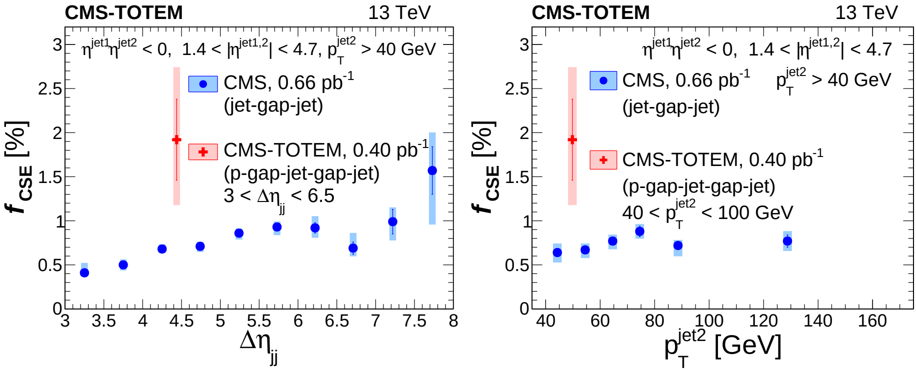


Similar techniques to estimate background from fluctuations in N_{tracks}:

- Control dijet sample: Two jets in same side w.r.t. fixed η region. η interval is be adjusted to account for SD dijets boosts.
- Negative binomial distribution (NBD) approach: NBD is fit in $2 < N_{\text{tracks}} < 25$, and extrapolated down to $N_{\text{tracks}} = 0$.

Excess of events at low N_{tracks} $\rightarrow$ For the first time these events are studied!

Filled histogram represents beam background contribution.



f_{CSE} fraction in p-gap-jet-gap-jet study is $2.91 \pm 0.70(\text{stat})^{+1.02}_{-0.94}(\text{syst})$ times larger than jet-gap-jet fraction, for similar dijet kinematics.

Abundance of events with a central gap is larger in events with intact protons.

Lower spectator parton activity in events with intact protons → **Better chance of central gap surviving the collision.**

Summary

Unique opportunity to probe BFKL dynamics in jet production at the CERN LHC.

Mueller–Navelet jet analysis at 7 TeV:

- BFKL calculations at NLL with NLO impact factors are able to describe the data at large Δy.
- Challenging to disentangle other higher-order corrections; calls for new family of observables for future measurements.

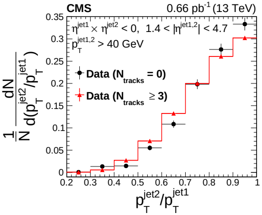
Analysis of jet-gap-jet events at 13 TeV:

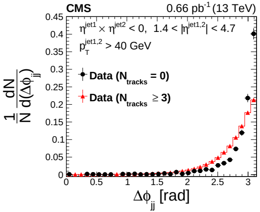
- About 0.6% of dijet events are produced by hard color-singlet exchange.
- **No further suppression between 7 and 13 TeV results is observed.**
- BFKL NLL calculations with **LO** impact factor are not able to describe all aspects of the measurement simultaneously. Description improves with SCI and MPI supplements.
- Can NLO impact factor give different trend? Maybe process is combination of perturbative and nonperturbative effects.

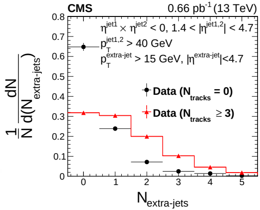
Jet-gap-jet events with intact protons:

- **First study of this process.** Allows for the possibility of future differential measurements with larger luminosity.
- Hard color-singlet exchange fraction f_{CSE} is $2.91 \pm 0.70(\text{stat})^{+1.02}_{-0.94}$ larger than that in standard jet-gap-jet events.

Thanks!







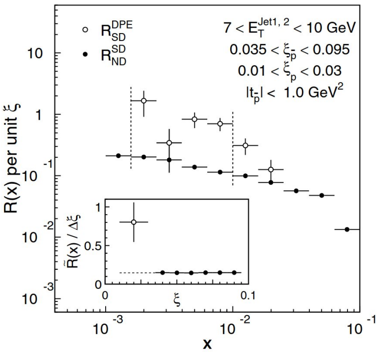
Normalized distributions in:

- $p_T^{\text{jet2}}/p_T^{\text{jet1}}$.
- $\Delta\phi_{\text{jj}} = |\phi^{\text{jet1}} - \phi^{\text{jet2}}|$
- Jet multiplicity $N_{\text{extra-jets}}$ for jets with $p_{T,\text{extra-jet}} > 15$ GeV.

Jet-gap-jet candidates with $N_{\text{tracks}} = 0$ and events dominated by color-exchange dijet events with $N_{\text{tracks}} \geq 3$.

Distributions reflect underlying quasielastic parton-parton scattering process topology.

Consistent with other two-rapidity gap topology



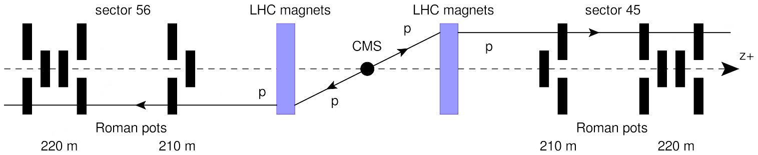
CDF studied double-pomeron exchange/single-diffractive dijet event ratios, compared them to single-diffractive/non-diffractive (**PRL85,4215**):

$\mathcal{R}$ = (DPE/SD) / (SD/ND) $= 5.3 \pm 1.9$, different from factor of 1 expected from factorization. Comparison of gap-jet-jet-gap/gap-jet-jet topology.

Present CMS-TOTEM result finds a similar effect for a different two-gap topology (proton-gap-jet-gap-jet).

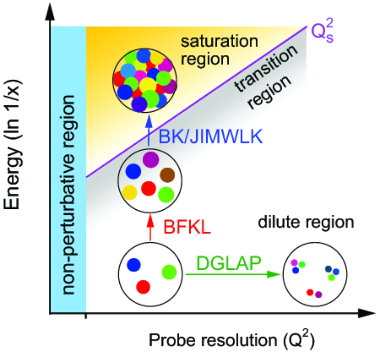
Source	Jet-gap-jet $\Delta\eta_{jj}$	Jet-gap-jet $p_{T,\,jet\text{-}2}$	Jet-gap-jet $\Delta\phi_{jj}$	Proton-gap-jet-gap-jet
Jet energy scale	1.0–5.0	1.5–6.0	0.5–3.0	0.7
Track quality criteria	6.0–8.0	5.4–8.0	1.5–8.0	8
Charged particle p_T threshold	2.0–5.8	1.6–4.0	1.1–5.8	11
Background subtraction method	4.7–14.6	2–14.6	12.0	28.3
NBD fit parameter	0.8–2.6	0.6–1.7	0.1–0.6	7
NBD fit interval	—	—	—	12.0
Calorimeter energy scale	—	—	—	5.0
Horizontal dispersion	—	—	—	6.0
Fiducial selection requirements	—	—	—	2.6
Total	6.8–22.0	8.3–14.9	12.0–17.1	33.4

Relative systematic uncertainties in percentage on f_{CSE}. Uncertainty range is representative of the variation found in the jet-gap-jet fraction in bins of the kinematic variables of interest.



- At least one proton on either side.
- Track-impact point cuts (x, y) based on acceptance studies. For vertical RPs, $0 < x < 20$mm and $8 < |y| < 30$mm, for horizontal RPs, $7 < x < 25$mm and $|y| < 25$mm.
- Proton fractional momentum loss is $\xi_p(\mathrm{RP}) < 0.2$ and four-momentum transfer square is $0.025 < -t < 4$ GeV^2. Based on acceptance studies + validity of optical functions.
- To suppress beam bkg contribution (pileup+beam halo), additional cut $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) < 0$, where $\xi_p(\mathrm{PF}) = \frac{\sum_i E_i \pm p_{z,i}}{\sqrt{s}}$ is the proton fractional momentum loss reconstructed with PF candidates of CMS. The $\pm$ is the sign of the intact proton η.

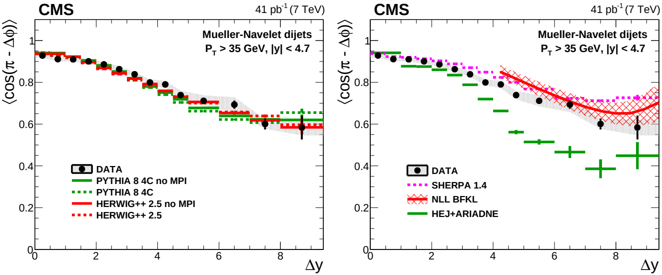
A total of 336 and 341 events in sector 45 and sector 56, respectively, satisfy the above selection requirements + dijet selection requirements.



Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP): Evolution in Q^2 (resummation of $\alpha_s^n \ln^n(Q^2/Q_0^2)$) $\rightarrow$ Resolving "smaller" partons with larger Q^2 at fixed x_{Bj}.

BFKL: Evolution in x_{Bj} (resummation of $\alpha_s^n \ln^n(1/x_{\mathrm{Bj}})$) $\rightarrow$ Larger parton densities at smaller x_{Bj} at fixed Q^2.

Very important to understand parton densities QCD evolution in (x, Q^2) plane; need as many experimental probes of QCD evolution effects as possible!

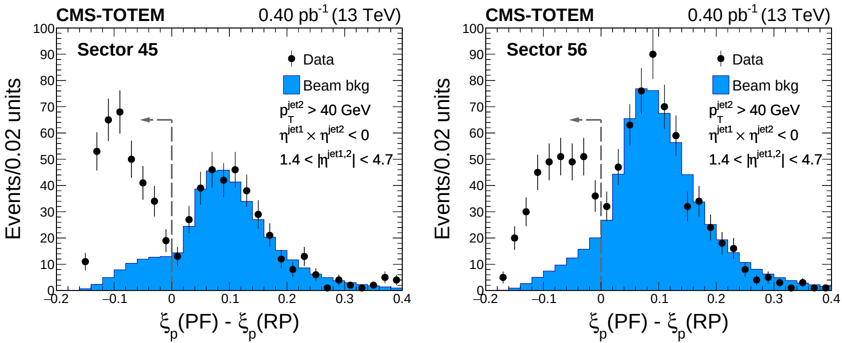


CMS, JHEP 08 (2016) 139, arXiv:1601.06713

Some standard probes of BFKL dynamics:

- $\Delta\phi$ decorrelations in Mueller–Navelet jets (Plot above)
- Exclusive vector meson production ($\gamma^* p \to Vp$) at large $W_{\gamma p}$, with $V = J/\psi, \psi(2s), \Upsilon, \ldots$.
- PDFs at small-x_{Bj} at small momentum transfer $Q^2 > \Lambda^2_{\mathrm{QCD}}$.

It is generally difficult to isolate BFKL from other higher-order effects, such as DGLAP evolution. Processes where DGLAP evolution is expected to be suppressed may aid to unambiguously identify BFKL dynamics.

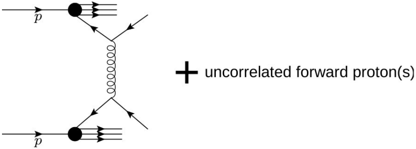


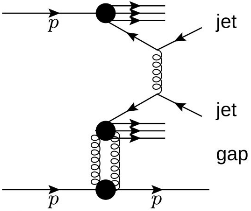
Estimated with event-mixing: inclusive dijet events paired with protons in zero-bias sample.

Requirement $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) < 0$ indicated by dashed line. Region $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) > 0$ is dominated by beam bkg contributions $\rightarrow$ Used as control region to estimate residual beam bkg in $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) < 0$.

Beam background contributes 18.7 and 21.5% for protons in sector 45 and 56 in $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) < 0$, respectively.

Inclusive dijet production + uncorrelated proton from residual pileup or beam halo activity (estimade from data).
Standard diffractive dijet production with no central gap (p-gap-jet-jet topology):





→ Fluctuations on particle multiplicity can lead to gaps. Needs to be subtracted (NBD and ES methods).