

Hard color-singlet exchange in dijet events in proton-proton collisions at $\sqrt{s} = 13$ TeV in CMS and TOTEM

Based on CERN-EP-2020-229, [arXiv:2102.06945](https://arxiv.org/abs/2102.06945), *submitted to Phys. Rev. D*

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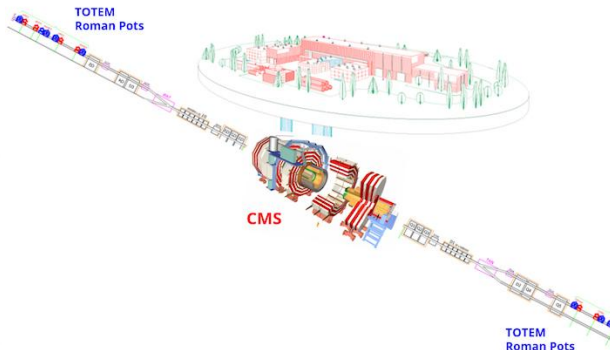
On behalf of the CMS and TOTEM Collaborations

XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects
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DE-SC0019389

- ▶ The CMS and TOTEM detectors.
- ▶ Hard color-singlet exchange in dijet events (“jet-gap-jet”) as a probe of Balitsky–Fadin–Kuraev–Lipatov dynamics.
- ▶ 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 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 $\approx 220\text{m}$ 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 $\hat{s} \gg -\hat{t} \gg \Lambda_{\text{QCD}}^2$, where \hat{s} , \hat{t} are the Mandelstam variables at parton-level.

Here, **the fixed-order pQCD approach breaks down**.

The perturbative expansion should be rearranged (symbolically) as,

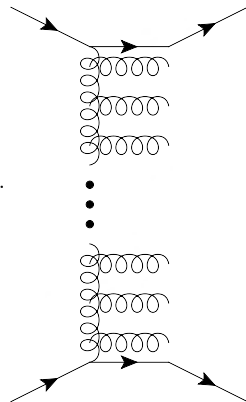
$$d\hat{\sigma} \sim \alpha_s^2 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|} \right) + \alpha_s^3 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|} \right) + \alpha_s^4 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|} \right) + \dots$$

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

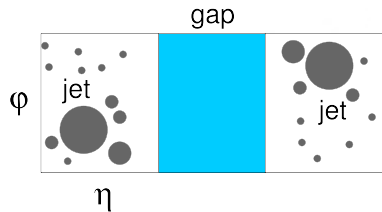
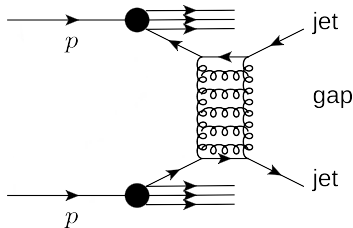
Resummation of large logarithms of \hat{s} to all orders in α_s is done via **Balitsky-Fadin-Kuraev-Lipatov (BFKL)** evolution equations of pQCD.

Very important test of QCD; very challenging to isolate experimentally

Detailed theory discussion presented by Federico Deganutti in the [previous talk](#).



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



t -channel color-singlet exchange between partons (two-gluon exchange)

→ **pseudorapidity interval void of particle production between jets (pseudorapidity gap).**

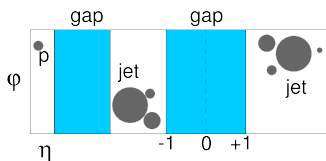
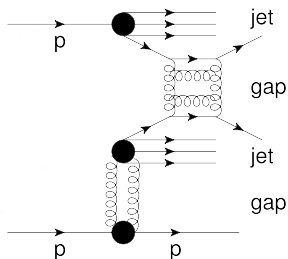
In the high-energy limit, this corresponds to **perturbative pomeron exchange** (BFKL two-gluon ladder exchange). A. Mueller and W-K. Tang, Phys. Lett. B 284 (1992) 123.

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi dynamics are strongly suppressed in events with pseudorapidity gaps (Sudakov form factor to suppress radiation in gap).

Detailed theory description of the jet-gap-jet process by Federico Deganutti in the [previous talk](#).

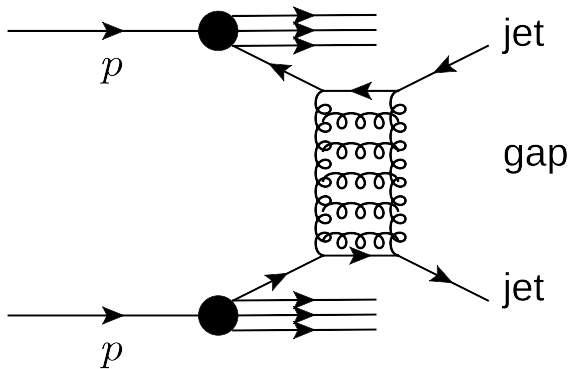
Although there is a short-distance mechanism for gap formation, **soft-parton activity can destroy the central gap between the jets**. This is parametrized by means of a gap survival probability, $|S|^2$, **which is difficult to understand theoretically**.

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



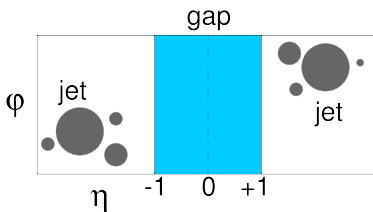
Addressed in study with CMS-TOTEM combined analysis (SMP-19-006, [arXiv:2102.06945](https://arxiv.org/abs/2102.06945)).
Second part of this talk.

Turning to CMS measurement



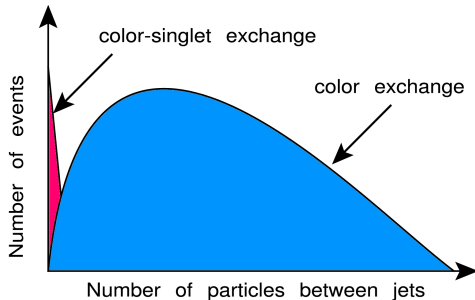
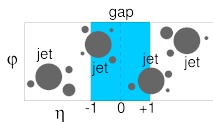
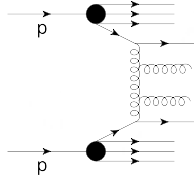
Analysis based on 13 TeV low-luminosity with special optics $\beta^* = 90$ m pp collision data collected by CMS and TOTEM in 2015 (pileup of 0.05-0.10). Event selection:

- ▶ 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 $\eta^{\text{jet1}} \eta^{\text{jet2}} < 0$
→ **Favors t -channel color-singlet exchange.**
- ▶ At most one reconstructed primary vertex, $N_{PV} \leq 1$, to suppress residual pileup contributions.

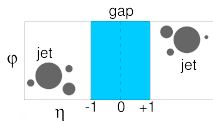
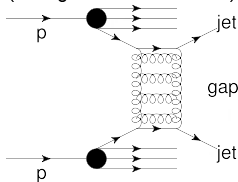


Pseudorapidity gap is defined by means of the charged particle multiplicity N_{tracks} between the leading two jets. Each charged particle has $p_T > 200$ MeV in $|\eta| < 1$.

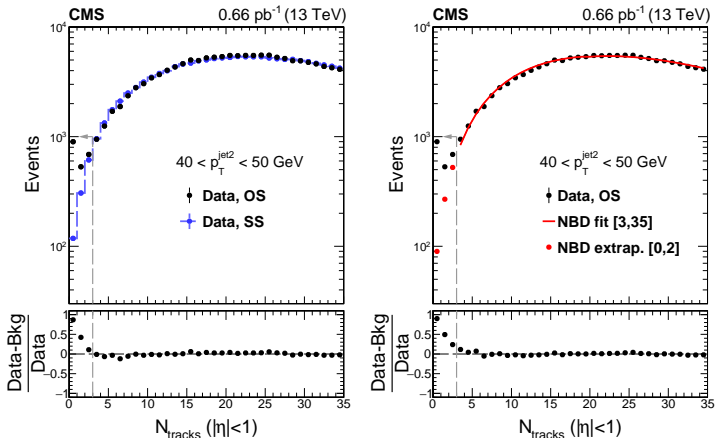
Color-exchange
(single-gluon in t -channel)



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



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



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

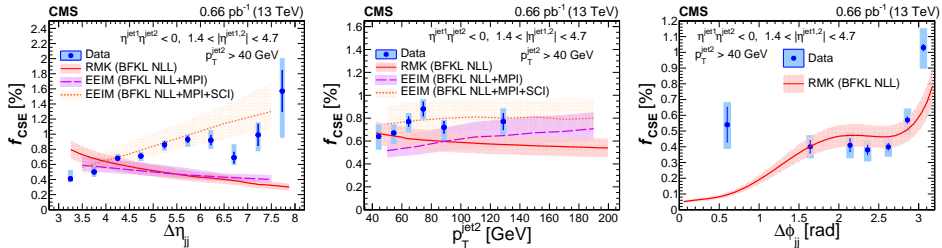
- **Control dijet sample:** two jets on the same-side (SS) of the CMS detector, $\eta^{\text{jet1}}\eta^{\text{jet2}} > 0$. Normalize to events with jets in opposite sides (OS) of CMS, $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$, in $N_{\text{tracks}} > 3$.
- **Negative binomial distribution (NBD) function:**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

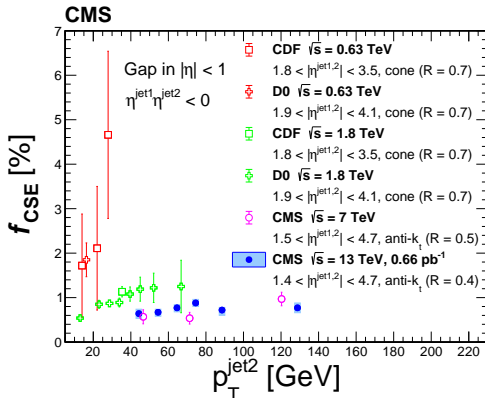
$$f_{\text{CSE}} \equiv \frac{N(N_{\text{tracks}} < 3) - N_{\text{bkg}}(N_{\text{tracks}} < 3)}{N_{\text{all}}} \equiv \frac{\text{color-singlet exchange dijet events}}{\text{all dijet events}}$$

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

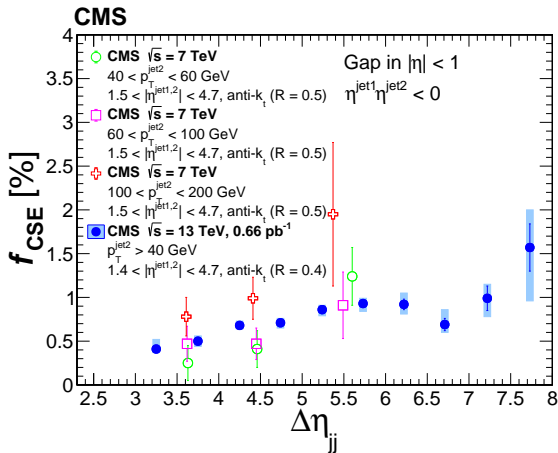
- ▶ **Pseudorapidity difference between the jets**, $\Delta\eta_{jj} \equiv |\eta^{\text{jet1}} - \eta^{\text{jet2}}|$. Sensitive to expected BFKL dynamics, since it's related to resummation of large logs of s .
- ▶ **Subleading jet transverse momentum**, $p_{\text{T}}^{\text{jet2}}$. Sensitive to expected BFKL dynamics.
- ▶ **Azimuthal angle difference between the leading jets**, $\Delta\phi_{jj} \equiv |\phi^{\text{jet1}} - \phi^{\text{jet2}}|$. Sensitive to deviations of $2 \rightarrow 2$ scattering topology.



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

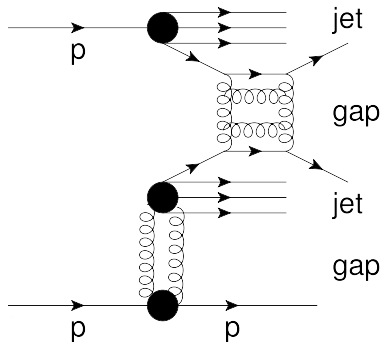


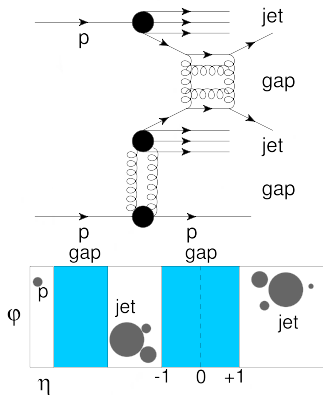
- ▶ Measurement of jet-gap-jet events at four different \sqrt{s} in $p\bar{p}$ and pp collisions at **0.63 TeV**, **1.8 TeV**, **7 TeV**, and **13 TeV** (this measurement).
- ▶ Generally, f_{CSE} is expected to decrease with increasing \sqrt{s} , due to an increase in spectator parton activity with \sqrt{s}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



- CMS 7 TeV analysis performed in three bins of $p_{\text{T}}^{\text{jet2}}$ 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



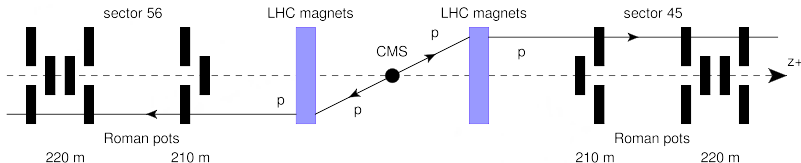


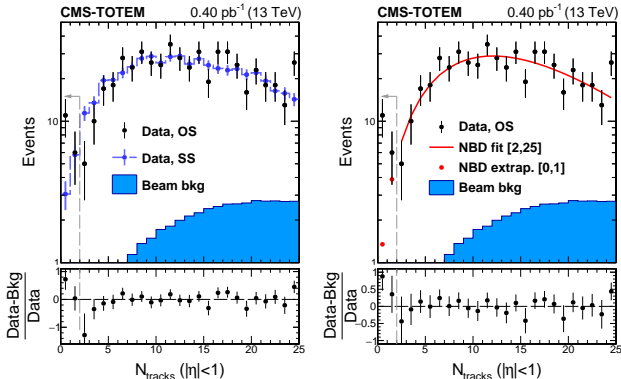
Better understand the role of spectator partons in the destruction of the central gap.

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 $-4 < t < -0.025 \text{ GeV}^2$, where $t = (p_f - p_i)^2$ of the proton.



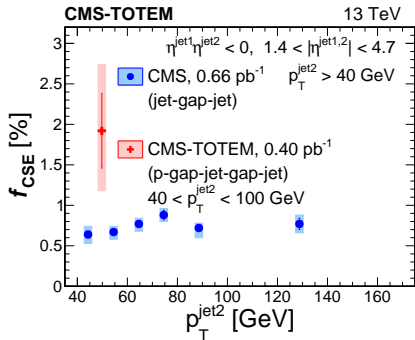
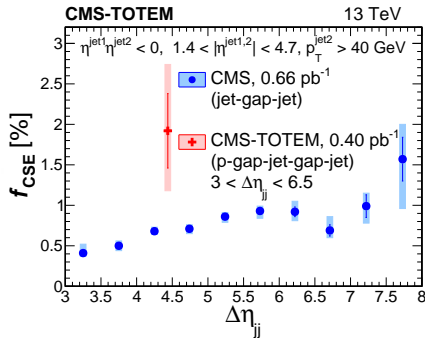


Similar techniques to estimate background from fluctuations in particle multiplicity:

- **Control dijet sample:** Two jets in same side w.r.t. fixed η region. The η interval needs to be adjusted to account for boosts in SD dijet events (0.8 units in η).
- **Negative binomial distribution (NBD) approach:** NBD is fit in $2 < N_{\text{tracks}} < 25$, and extrapolated down to $N_{\text{tracks}} = 0$. Different fit range accounts for lower mean N_{tracks} in events with intact protons.

Excess of events at low charged particle multiplicities → 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.**

Unique opportunity to study hard color-singlet exchange at the CERN LHC.

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

- ▶ About 0.5% of dijet events are produced by hard color-singlet exchange.
- ▶ No further suppression between 7 and 13 TeV results is observed.

Jet-gap-jet events with intact protons:

- ▶ **First study of this process.** Allows for the possibility of future differential measurements.
- ▶ 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.

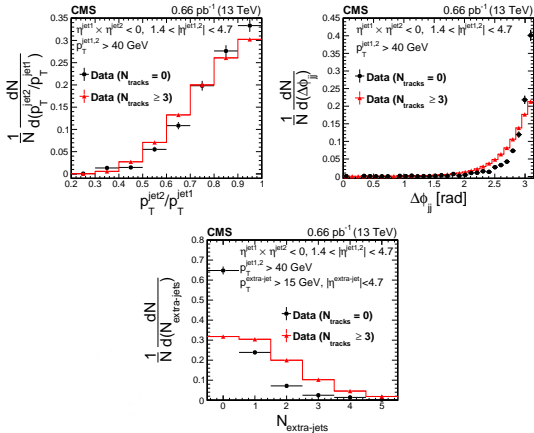
Paper has been submitted to PRD ([arXiv:2102.06945](https://arxiv.org/abs/2102.06945)).

Thanks!



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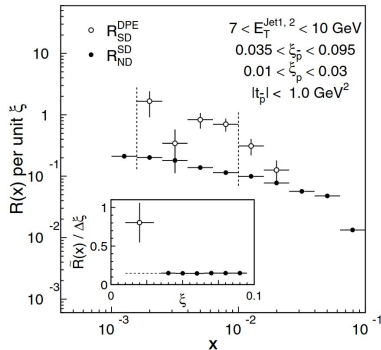


Normalized distributions in:

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

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.



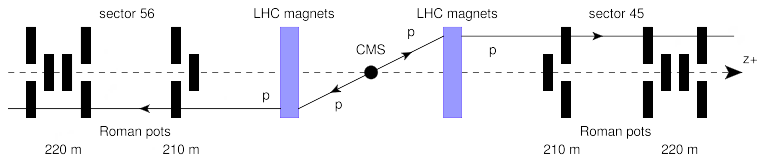
CDF studied double-pomeron exchange/single-diffractive dijet event ratios, compared them to single-diffractive/non-diffractive (**PRL85,4215**):

$\mathcal{R} = (DPE/SD) / (SD/ND) = 5.3 \pm 1.9$, 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-jet).

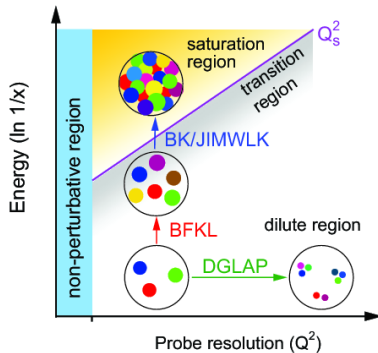
Source	Jet-gap-jet			Proton-gap-jet-gap-jet
	$\Delta\eta_{jj}$	$p_{T,jet-2}$	$\Delta\phi_{jj}$	
Jet energy scale	1.0–5.0	1.5–6.0	0.5–3.0	0.7
Track quality criteria	6.0–8.0	5.4–8.0	1.5–8.0	8
Charged particle p_T threshold	2.0–5.8	1.6–4.0	1.1–5.8	11
Background subtraction method	4.7–14.6	2–14.6	12.0	28.3
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, $0 < x < 20\text{mm}$ and $8 < |y| < 30\text{mm}$, for horizontal RPs, $7 < x < 25\text{mm}$ and $|y| < 25\text{mm}$.
- ▶ Proton fractional momentum loss is $\xi_p(\text{RP}) < 0.2$ and four-momentum transfer square is $0.025 < -t < 4 \text{ GeV}^2$. Based on acceptance studies + validity of optical functions.
- ▶ To suppress beam bkg contribution (pileup+beam halo), additional cut $\xi_p(\text{PF}) - \xi_p(\text{RP}) < 0$, where $\xi_p(\text{PF}) = \frac{\sum_i E_{i\pm p_{z,i}}}{\sqrt{s}}$ is the proton fractional momentum loss reconstructed with PF candidates of CMS. The \pm is the sign of the intact proton η .

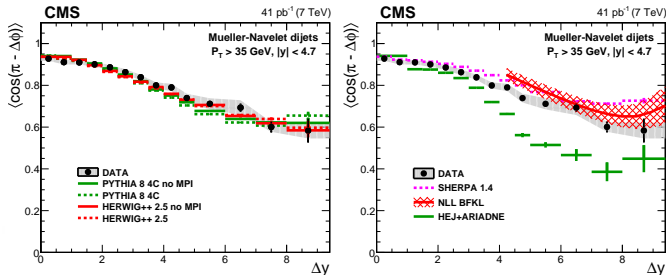
A total of 336 and 341 events in sector 45 and sector 56, respectively, satisfy the above selection requirements + dijet selection requirements.



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 $\alpha_s^n \ln^n(1/x_{Bj})$) \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!

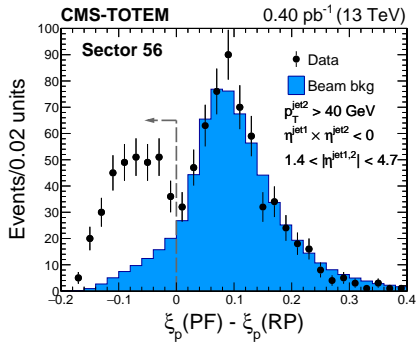
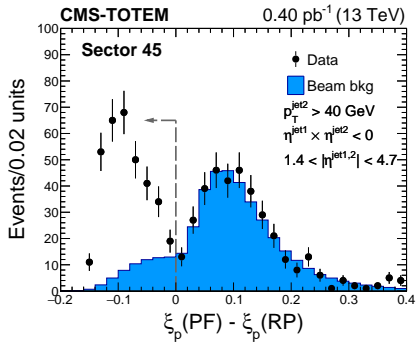


CMS, JHEP 08 (2016) 139, arXiv:1601.06713

Some standard probes of BFKL dynamics:

- ▶ $\Delta\phi$ decorrelations in Mueller–Navelet jets (Plot above)
- ▶ Exclusive vector meson production ($\gamma^* p \rightarrow Vp$) at large $W_{\gamma p}$, with $V = J/\psi, \psi(2s), \Upsilon, \dots$
- ▶ PDFs at small- x_B at small momentum transfer $Q^2 > \Lambda_{\text{QCD}}^2$.

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.



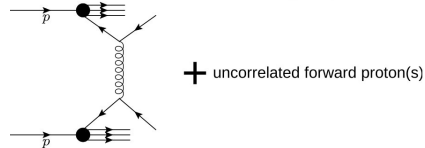
Estimated with event-mixing: inclusive dijet events paired with protons in zero-bias sample.

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

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

Inclusive dijet production + uncorrelated proton from residual pileup or beam halo activity (estimated 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).

