Jets separated by a rapidity gap

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Outline

- Jets separated by a pseudorapidity gap as a probe of BFKL dynamics (experimental + theory status).
- My hope is to invite folks to join phenomenology efforts, as well as to assess possible studies by other experiments, so we can get a global picture of the jet-gap-jet process in particular and BFKL in general.
- Will discuss 13 TeV results from a recent study by CMS and TOTEM Collaborations (preliminary results CMS-PAS-SMP-19-006).
- Thoughts/discussion at the end of the presentation (mostly from a CMS experimentalist point of view).

In fixed-order pQCD, we calculate cross sections in powers of $\alpha_s(Q^2) \ll 1$, symbolically represented by

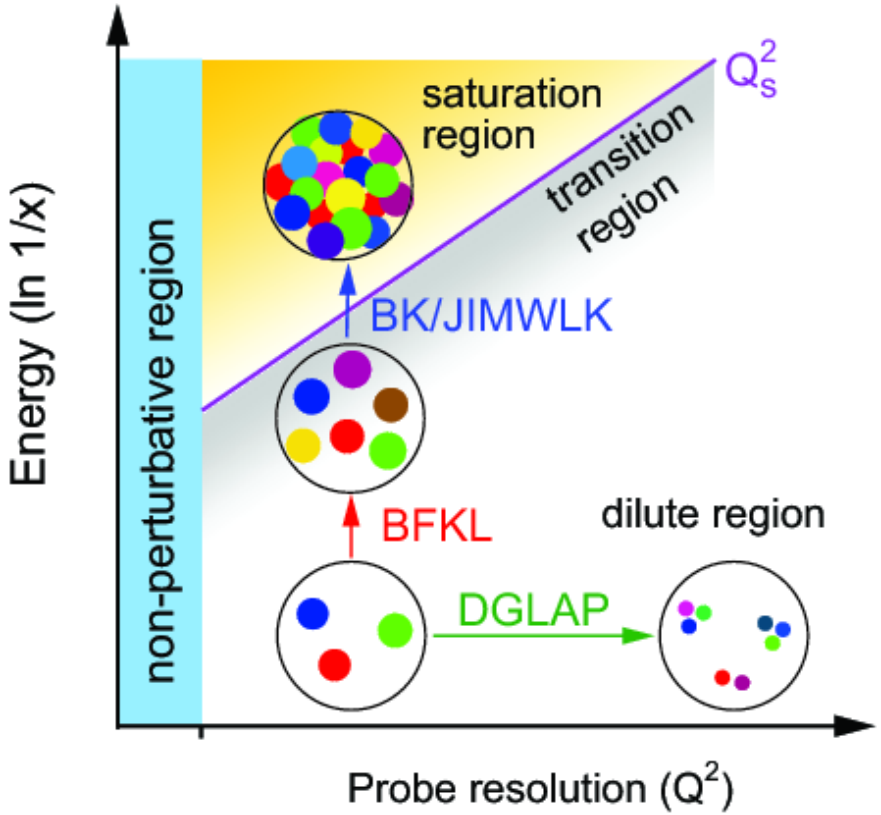
$$\mathrm{d}\hat{\sigma} \sim \alpha_s^2 + \alpha_s^3 + \alpha_s^4 + \dots$$

In the high-energy limit however, where $\hat{s} \gg -t \gg \Lambda^2_{\mathrm{QCD}}$, the perturbative expansion can be rearranged (symbolically) as,

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

where $\hat{s}$, $\hat{t}$ are the Mandelstam variables at parton-level, and $\alpha_s \ln\left(\frac{\hat{s}}{-\hat{t}}\right) = \alpha_s \Delta y \lesssim 1$.
Resummation of large logarithms of energy to all orders in α_s is needed. The Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution equation resums large logarithms of energy to all orders in α_s. Resummation known up to next-to-leading-logarithm (NLL) approximation.

Proton wavefunction in x and Q^2



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.

Probes of BFKL dynamics

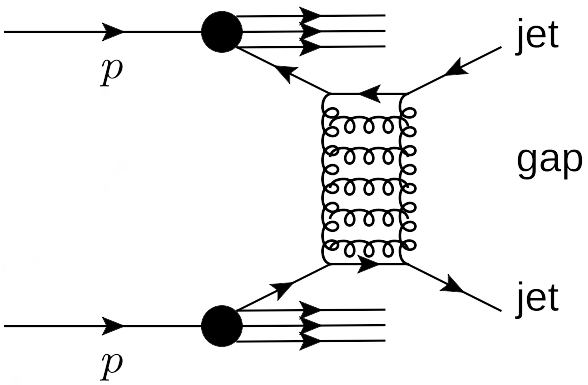
Standard probes of BFKL dynamics:

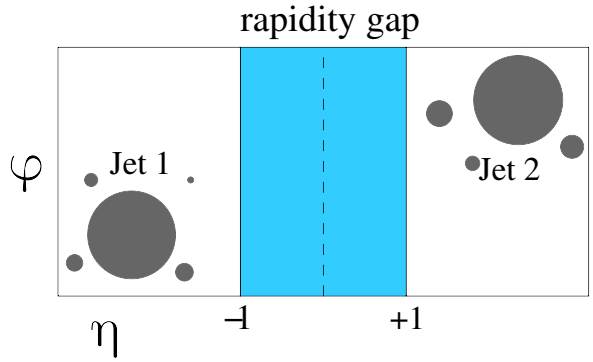
- Mueller-Navelet jets.
- Exclusive vector meson production $\gamma^* p \to Vp$.
- PDFs at small-x_{Bj} and small Q^2.

Generally difficult to separate from other higher-order corrections, such as DGLAP evolution. Processes where DGLAP evolution is expected to be suppressed may aid to unambiguously identify BFKL dynamics.

Ideally, we want a set of processes that may all be sensitive to BFKL dynamics, so we are sure we have a good theoretical grasp of possible underlying BFKL radiation pattern.

Jet-gap-jet process as a probe of BFKL dynamics





In standard dijet production, net color-flow leads to particle production over wide intervals of rapidity between jets.

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

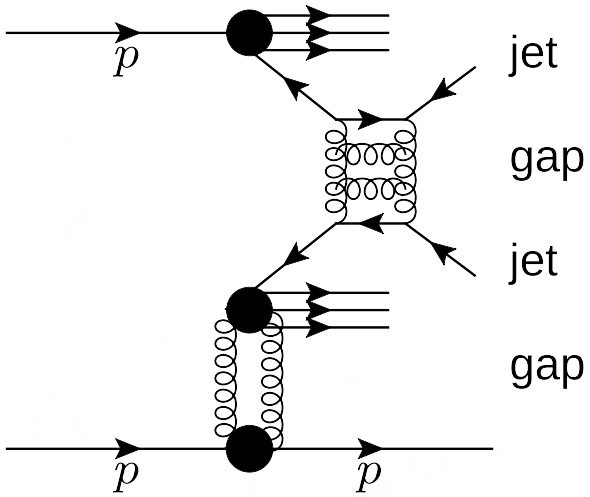
In the BFKL limit of QCD, color-singlet exchange corresponds to perturbative pomeron exchange (BFKL two-gluon ladder exchange). Jet-gap-jet process was first proposed by A. Mueller and W-K. Tang Phys. Lett. B284,123 (1992) as a probe of BFKL evolution.

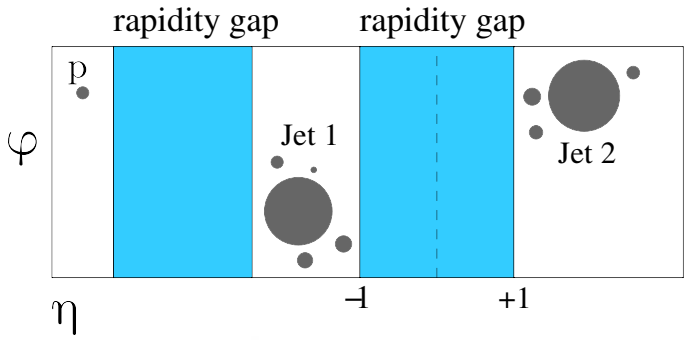
DGLAP dynamics are strongly suppressed in events with pseudorapidity gap (Sudakov form factor to suppress radiation in gap).

Gap survival probability

Although there is a short-distance physics mechanism for rapidity gap formation (pomeron exchange), soft-parton activity can destroy the rapidity gap signature. This is usually parametrized by means of survival probability $|\mathcal{S}|^2$, which reduces the visible cross section of jet-gap-jet events. Difficult to understand theoretically.

In collision events with intact protons, soft-parton activity is largely reduced $\rightarrow$ Central gap is more likely to "survive" (C. Marquet, C. Royon, M. Trzebiński, R. Žlebčík Phys.Rev. D 87, 034010 (2013)).





Addressed in study with CMS-TOTEM combined analysis. **First time a proton-gap-jet-gap-jet topology is studied!**.

Previous experimental studies at HERA, Tevatron, and LHC

Usually, one considers cases where the two jets are separated by a large rapidity interval. The rapidity gap is then defined as the absence of calorimeter tower or charged particles with energies above noise level between the jets.

We have over 20+ years of experimental analyses on jet-gap-jet events:

HERA:
ZEUS: Phys. Lett. B369 (1996), H1: EPJC 24, 517 (2002)

Tevatron:
CDF: 1.8 TeV Phys.Rev.Lett. 74, 855 (1995), 1.8 TeV Phys.Rev.Lett. 80, 1156 (1998), 0.63 TeV Phys. Rev. Lett. 81, 5278 (1998).

D0: 1.8 TeV Phys.Rev.Lett. 72, 2332 (1994), 1.8 TeV Phys.Rev.Lett. 76, 734 (1996), 0.63&1.8 TeV Phys.Lett. B440 189 (1998)

LHC:
CMS: 7 TeV EPJC 78,242 (2018), 13 TeV CMS-PAS-SMP-19-006 / TOTEM-NOTE-2020-001 (Paper in preparation).

Theory & phenomenology status (to the best of my knowledge)

Jet-gap-jet phenomenology studies based on BFKL calculations include corrections up to BFKL@NLL + jet impact factors@LO: O. Kepka, C. Marquet, C. Royon Phys.Rev. D83.034036 (2011), R. Enberg, G. Ingelman, L. Motyka Phys.Lett.B524,273 (2002), A. Ekstedt, R. Enberg, G. Ingelman arXiv:1703.10919 B. Cox, J. Forshaw and L. Lönnblad JHEP9910, 023 (1999), L. Motyka, A.D. Martin, M.G. Ryskin Phys.Lett. B524 107 (2002).

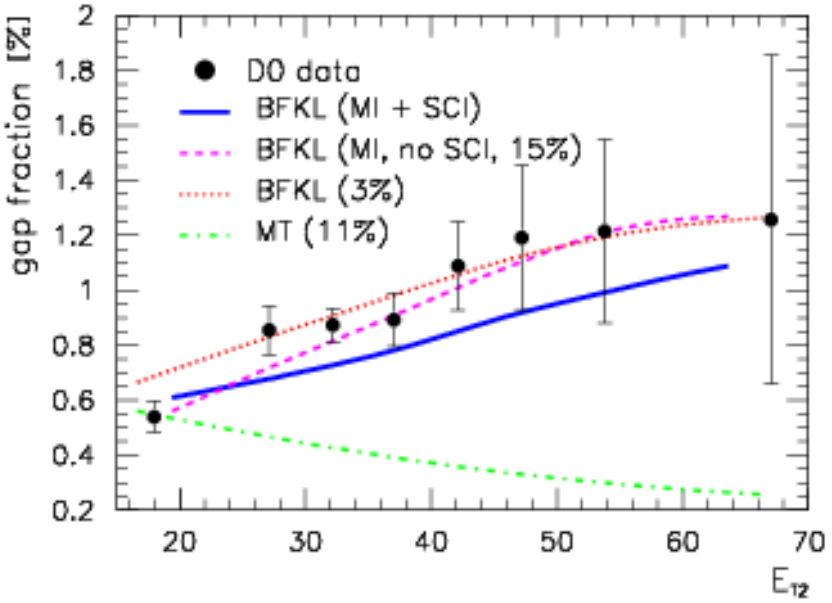
Part of survival probability estimated with MPI (I. Babiarz, R. Staszewski, A. Szczurek Phys.Lett.B 771,532 (2017)), also MPI supplemented with soft color interactions (R. Enberg, G. Ingelman, L. Motyka Phys.Lett.B524,273 (2002), A. Ekstedt, R. Enberg, G. Ingelman, arXiv:1703.10919).

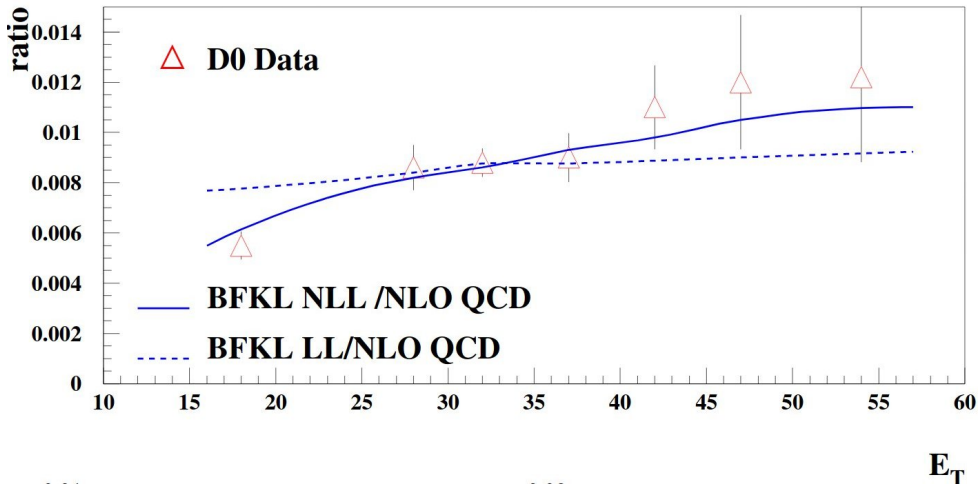
Jet-gap-jet NLO impact factors calculated by M. Hentschinski, Madrigal-Martínez, B. Murdaca, A. Sabio-Vera: Nucl. Phys. B887, 309 (2014), Nucl.Phys. B889, 549 (2014), PLB 735,168 (2014).

NLO impact factors have yet to be implemented for phenomenology studies to complete the NLO calculation (BFKL@NLL + impact factors@NLO). Efforts by D. Colferai, F. Deganutti, C. Royon, T. Raben on this direction (private communication), and by U. of Münster colleagues (M. Klasen, J. Salomon, P. González, M. Kampshoff).

Generally, jet-gap-jet phenomenology studies are very challenging.

Comparison w/ D0 results on gap fraction (example)





R. Enberg, G. Ingelman, L. Motyka Phys.Lett.B524,273 (2002) O. Kepka, C. Marquet, C. Royon Phys.Rev. D83.034036 (2011)

Predictions based on BFKL framework seem to be consistent with fraction of jet-gap-jet events vs. E_T^{jet} by D0 Coll. (Phys.Lett. B440 189 (1998)).

Turning to CMS 13 TeV study

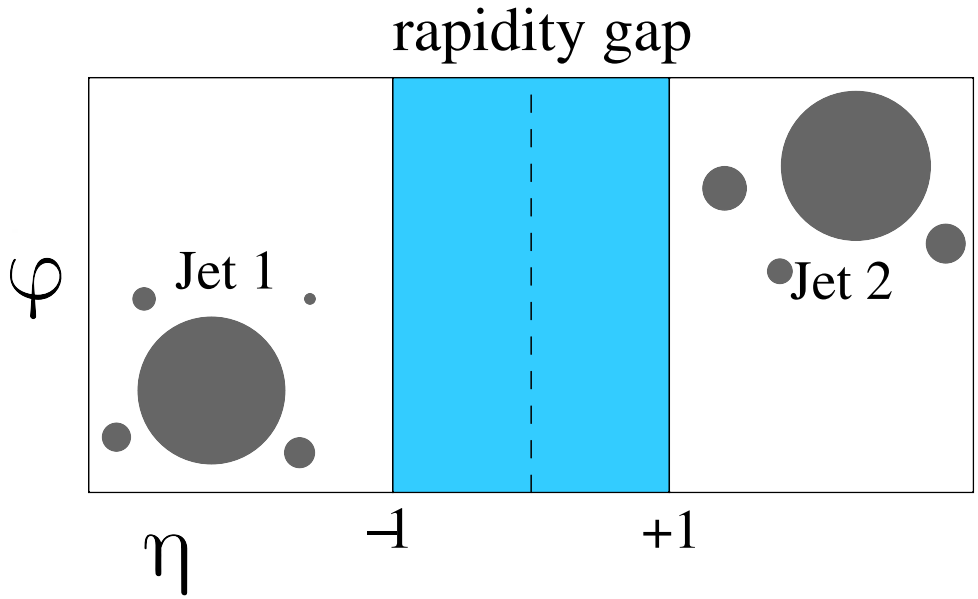
Analysis based on 13 TeV low-luminosity high-β^* pp collision data collected in 2015 (pileup of 0.05-0.10). Events selected with inclusive dijet trigger with $p_{\mathrm{T,\ jet\text{-}2}} > 32$ GeV in $|\eta_{\mathrm{jet}}| < 4.7$ (unprescaled).

Dijet event selection:

- Particle-flow jets, clustered with anti-k_t algorithm with $R = 0.4$.
- Leading two jets have $p_T > 40$ GeV each.
- Leading jets satisfy $1.4 < |\eta_{\mathrm{jet}}| < 4.7$ and $\eta_{\mathrm{jet\text{-}1}} \times \eta_{\mathrm{jet\text{-}2}} < 0$
  $\rightarrow$ Favors t-channel color singlet exchange.
- At most one reconstructed primary vertex to suppress residual pileup contributions.

There are 362,915 events satisfying these requirements.

Experimental definition of central gap

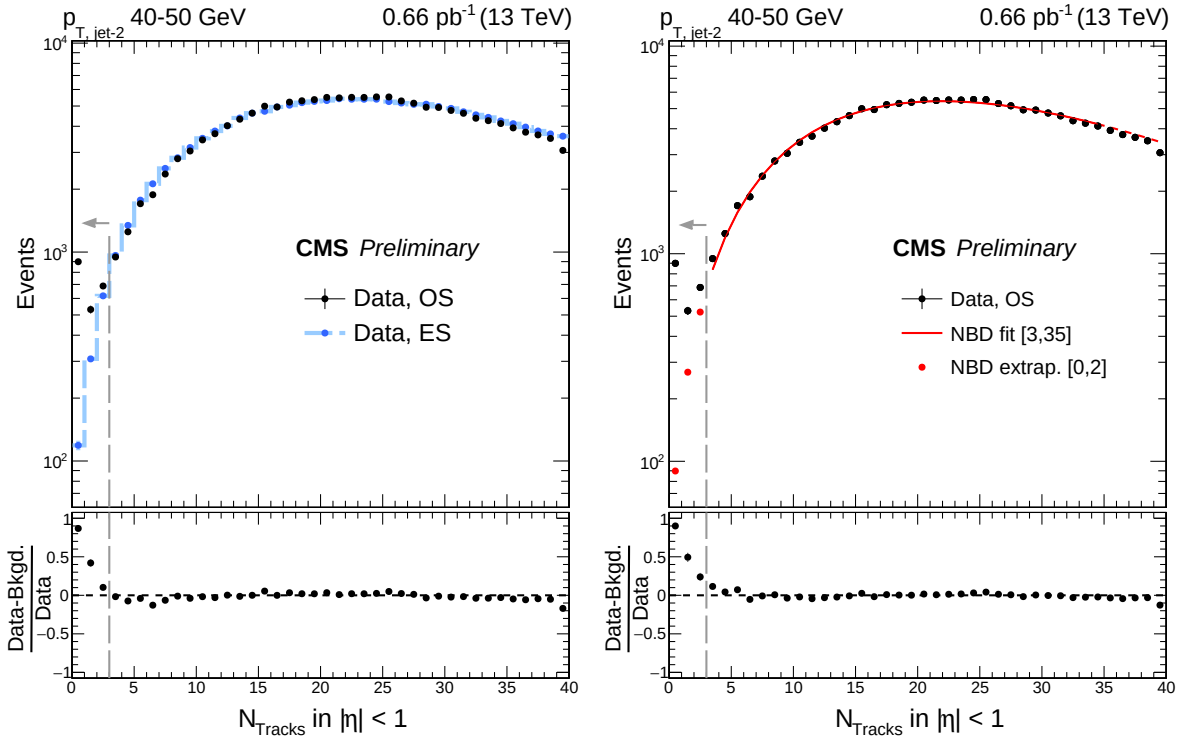


Pseudorapidity gap is defined by means of the charged particle multiplicity N_{tracks} between the leading two jets.

Each charged particle track has $p_T > 200$ MeV in $|\eta| < 1$.

Pseudorapidity gap corresponds to absence of charged particle tracks between jets.

Multiplicity of charged particles between jets (CMS-PAS-SMP-19-006)



Color-exchange dijet events dominate at high-multiplicities $\rightarrow$ 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, $\eta_{\text{jet-1}} \times \eta_{\text{jet-2}} > 0$. Normalize to events with jets in opposite sides (OS) of CMS, $\eta_{\text{jet-1}} \times \eta_{\text{jet-2}} < 0$, 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)

Observable: color-singlet exchange fraction f_{CSE}

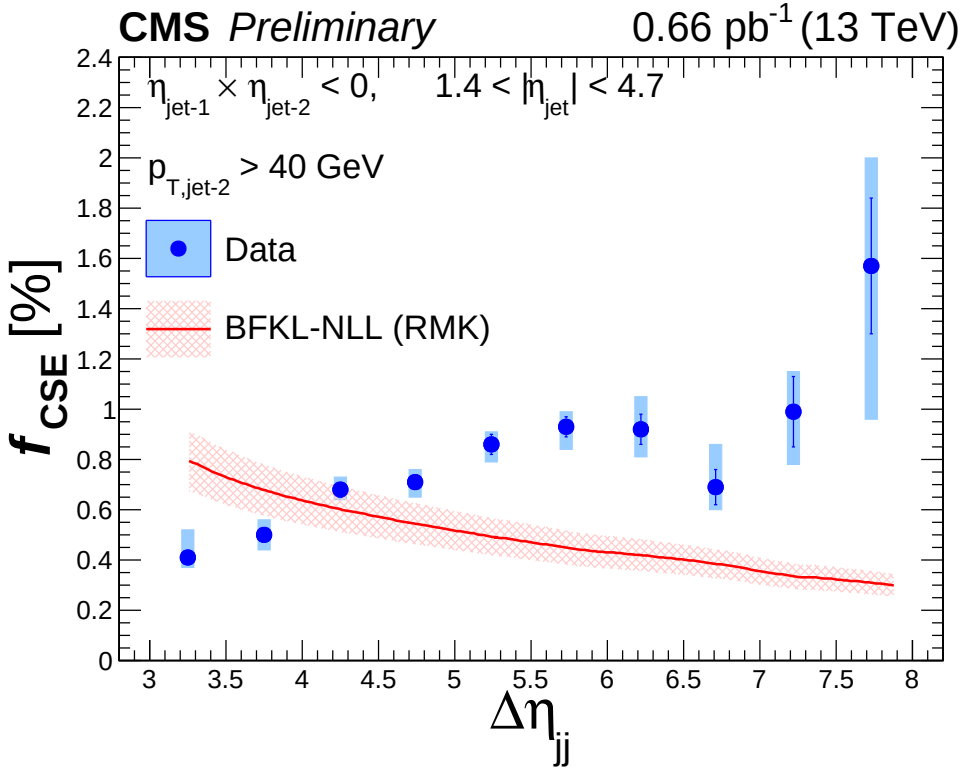
We extract f_{CSE} based on the charged particle multiplicity distribution between the jets ($f_{CSE} \equiv$ Fraction of excess of events above color-exchange bkg in $N_{Tracks} < 3$).

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

- Pseudorapidity difference between the jets, $\Delta\eta_{jj} \equiv |\eta_{\text{jet-1}} - \eta_{\text{jet-2}}|$. Sensitive to expected BFKL dynamics.
- Subleading jet transverse momentum, $p_{T,\,\text{jet-2}}$. Sensitive to expected BFKL dynamics.
- Azimuthal angle difference between the leading jets, $\Delta\phi_{jj} \equiv |\phi_{\text{jet-1}} - \phi_{\text{jet-2}}|$. Sensitive to deviations of $2 \to 2$ scattering topology.

Results on color-singlet exchange fraction f_{CSE} vs. $\Delta\eta_{jj}$

$\Delta\eta_{jj}$	$\langle\Delta\eta_{jj}\rangle$	f_{CSE} [%]
3 – 3.5	3.24	$0.41 \pm 0.02^{+0.11}_{-0.04}$
3.5 – 4	3.75	$0.50 \pm 0.02^{+0.06}_{-0.06}$
4 – 4.5	4.25	$0.68 \pm 0.02^{+0.05}_{-0.03}$
4.5 – 5	4.74	$0.71 \pm 0.03^{+0.04}_{-0.05}$
5 – 5.5	5.24	$0.86 \pm 0.04^{+0.03}_{-0.06}$
5.5 – 6	5.73	$0.93 \pm 0.04^{+0.05}_{-0.08}$
6 – 6.5	6.22	$0.92 \pm 0.06^{+0.11}_{-0.09}$
6.5 – 7	6.71	$0.69 \pm 0.07^{+0.15}_{-0.05}$
7 – 7.5	7.22	$0.99 \pm 0.14^{+0.07}_{-0.15}$
7.5 – 8	7.73	$1.57 \pm 0.27^{+0.34}_{-0.55}$

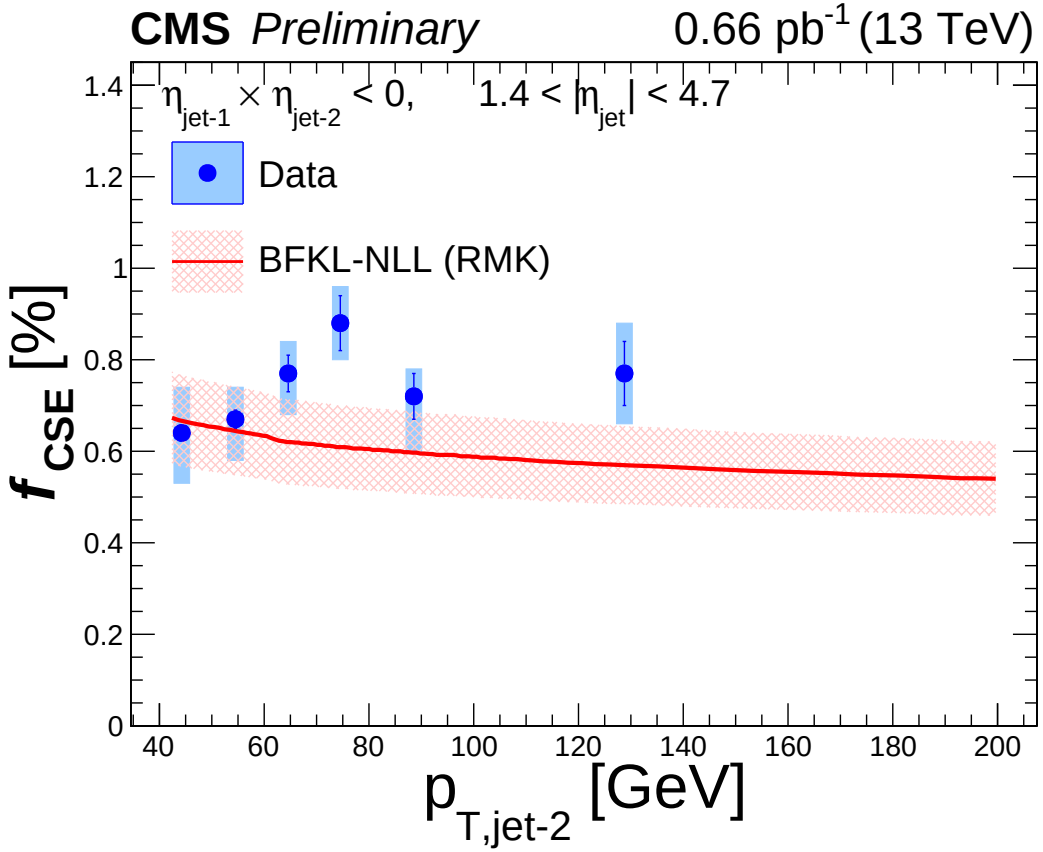


CMS-PAS-SMP-19-006

- Bars represent stat uncertainties, boxes represent stat + syst uncertainties.
- f_{CSE} generally increases with increasing $\Delta\eta_{jj}$.
- Comparisons to Royon, Marquet, Kepka (RMK) model based on BFKL NLL calculations + LO impact factors (**PRD**83.034036), and survival probability $|S|^2 = 0.1$.
- RMK model predicts a decreasing fraction with increasing $\Delta\eta_{jj}$, in disagreement with the trend observed in data $\rightarrow$ Guidance for further theory development.

Results on color-singlet exchange fraction f_{CSE} vs $p_{T,jet\text{-}2}$

$p_{T,jet\text{-}2}$ [GeV]	$\langle p_{T,jet\text{-}2} \rangle$ [GeV]	f_{CSE} [%]
40 – 50	44.3	$0.64 \pm 0.01^{+0.10}_{-0.11}$
50 – 60	54.5	$0.67 \pm 0.02^{+0.07}_{-0.09}$
60 – 70	64.6	$0.77 \pm 0.04^{+0.06}_{-0.08}$
70 – 80	74.5	$0.88 \pm 0.06^{+0.06}_{-0.05}$
80 – 100	88.6	$0.72 \pm 0.05^{+0.04}_{-0.11}$
100 – 200	128.8	$0.77 \pm 0.07^{+0.08}_{-0.09}$

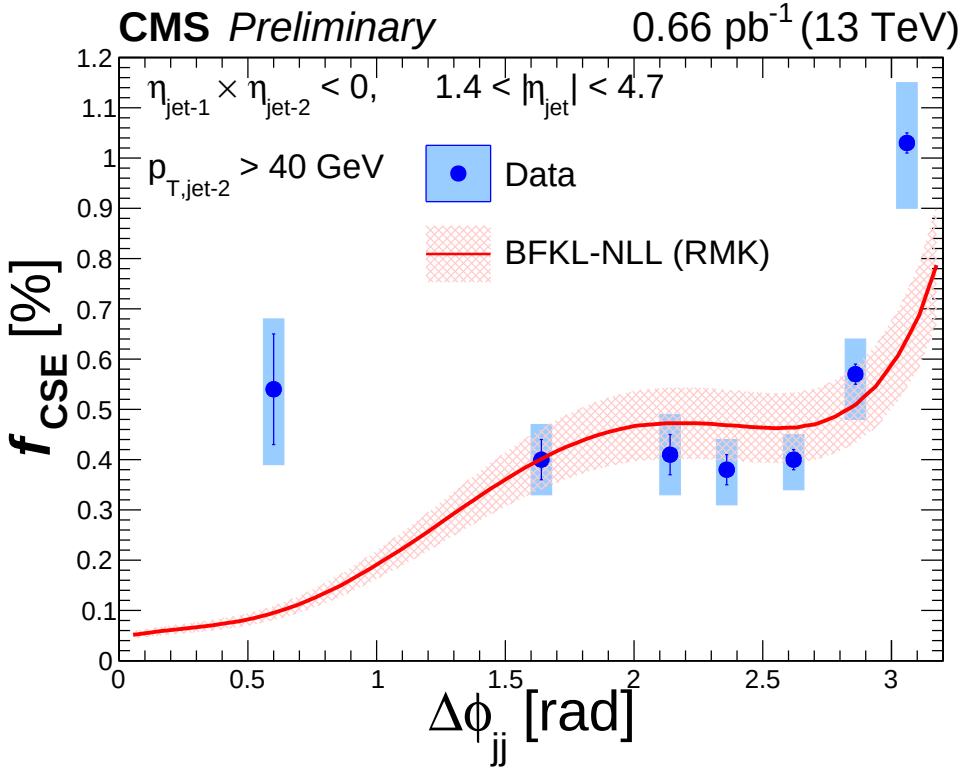


CMS-PAS-SMP-19-006

- Weak dependence of f_{CSE} on $p_{T,jet\text{-}2}$ in data within uncertainties with fractions of $f_{CSE} = 0.7$–0.8%.
- Comparison with RMK model, which predicts a weak dependence of f_{CSE} vs $p_{T,jet\text{-}2}$. Agreement with data, within uncertainties.

Results on color-singlet exchange fraction f_{CSE} vs. $\Delta\phi_{jj}$

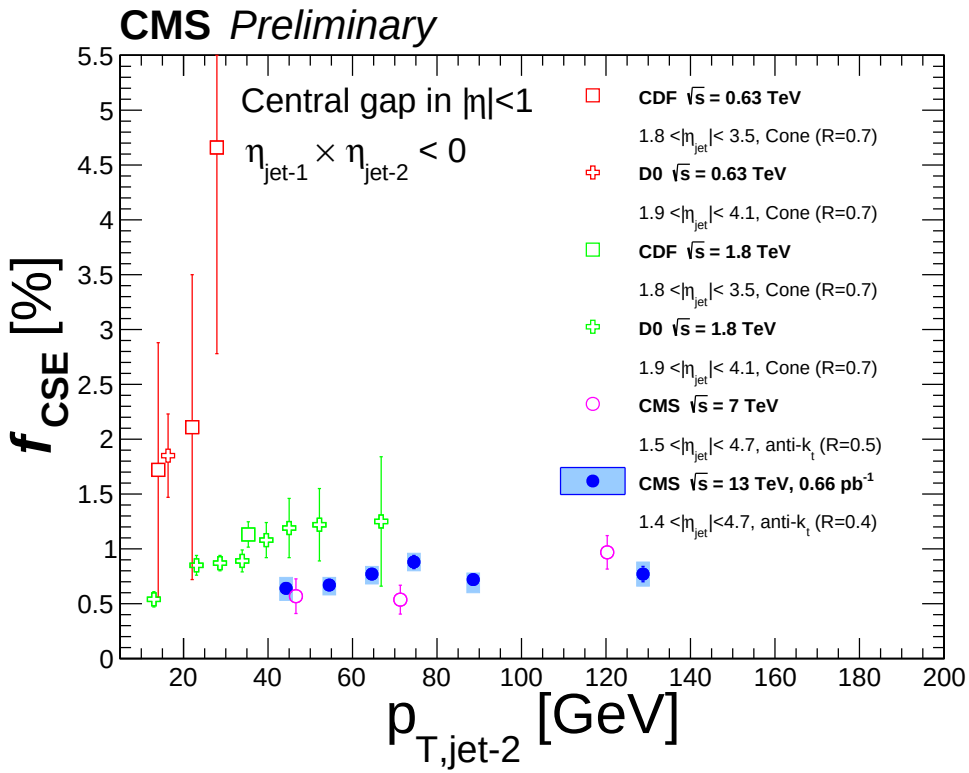
$\Delta\phi_{jj}$ [rad]	$\langle\Delta\phi_{jj}\rangle$	f_{CSE} [%]
$0-1$	0.60	$0.54 \pm 0.11^{+0.09}_{-0.10}$
$1-2$	1.64	$0.40 \pm 0.04^{+0.06}_{-0.06}$
2 - 2.25	2.14	$0.41 \pm 0.04^{+0.07}_{-0.07}$
$2.25-2.5$	2.36	$0.38 \pm 0.03^{+0.05}_{-0.06}$
$2.5-2.75$	2.62	$0.40 \pm 0.02^{+0.05}_{-0.06}$
$2.75-3$	2.86	$0.57 \pm 0.02^{+0.07}_{-0.09}$
$3-\pi$	3.06	$1.03 \pm 0.02^{+0.12}_{-0.13}$



CMS-PAS-SMP-19-006

- Fraction f_{CSE} peaks at $\Delta\phi_{jj} = \pi$, indicative of underlying quasielastic parton-parton scattering.
- Jet-gap-jet and inclusive dijet events decorrelate at similar rates for $\Delta\phi_{jj} < 2.75$, within uncertainties.
- Comparison with RMK model. Predicts increase of f_{CSE} as $\Delta\phi_{jj} \to \pi$, and a suppression as $\Delta\phi_{jj} \to 0$. Underestimates data by $\approx 10\%$ at $\Delta\phi_{jj} = \pi$. Underestimates data for $\Delta\phi_{jj} < 1$.

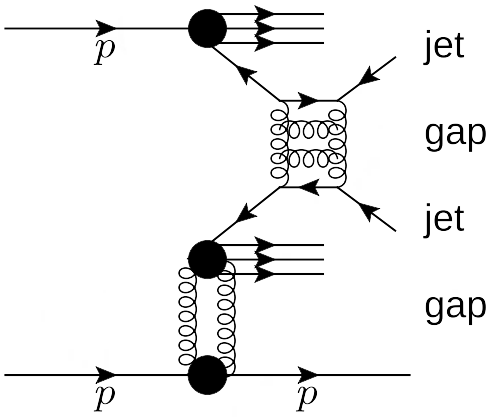
Comparison to previous measurements

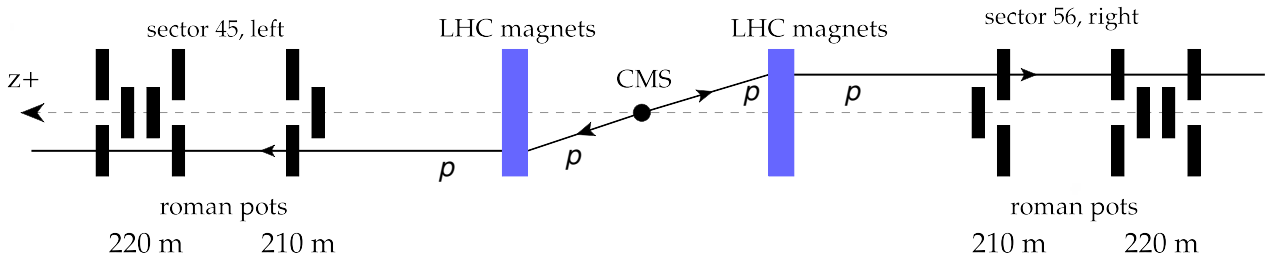


CMS-PAS-SMP-19-006

- Jet-gap-jet events at four different energies in $p\bar{p}$ and pp collisions at 0.63 TeV, 1.8 TeV, 7 TeV, and 13 TeV (this measurement).
- Generally, gap survival probability $|\mathcal{S}|^2$ is expected to decrease with increasing $\sqrt{s}$, due to an increase in spectator parton activity with $\sqrt{s}$.
- Within uncertainties, gap fractions 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.

Turning to study with leading protons (CMS-TOTEM)



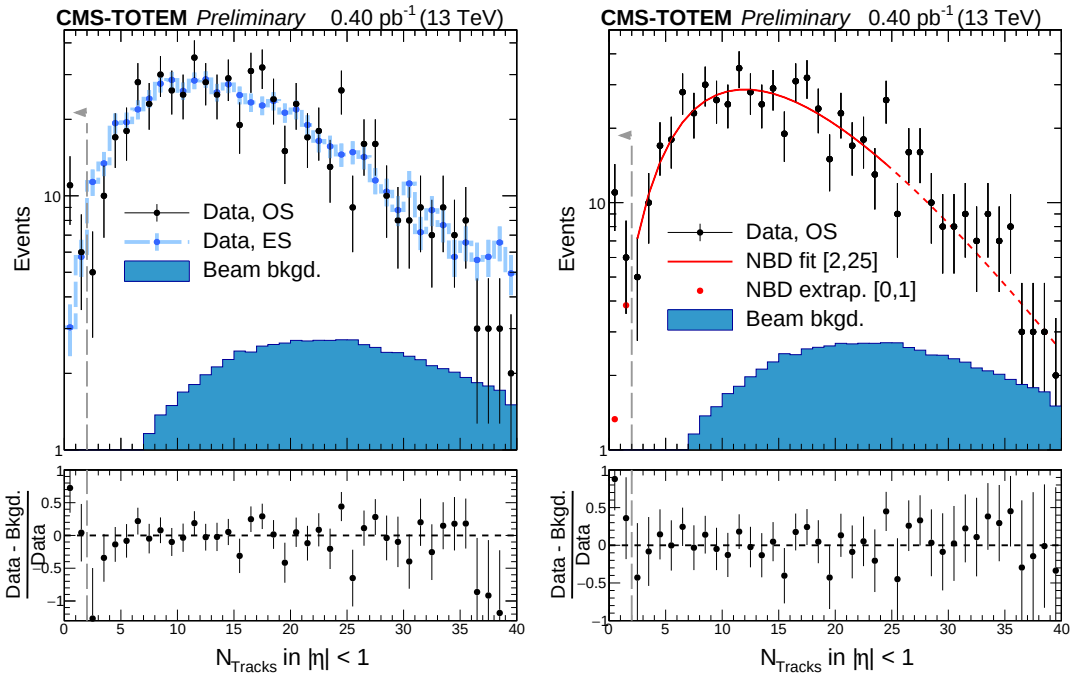


Based on a subsample of events with leading protons detected with TOTEM roman pots.

- Same dijet event selection requirement on central gap as with standard jet-gap-jet study.
- Forward proton detection with TOTEM roman pot detectors, which allows measurement of:
  - At least one proton on either side.
  - Proton fractional momentum loss is $\xi_p(\text{RP}) < 0.2$ and four-momentum transfer square is $-4.000 < t < -0.025$ GeV^2.
  - 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 reconstructed with particle-flow candidates of CMS. The $\pm$ is the sign of the leading proton η.

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

Charged particle multiplicity between jets + leading proton



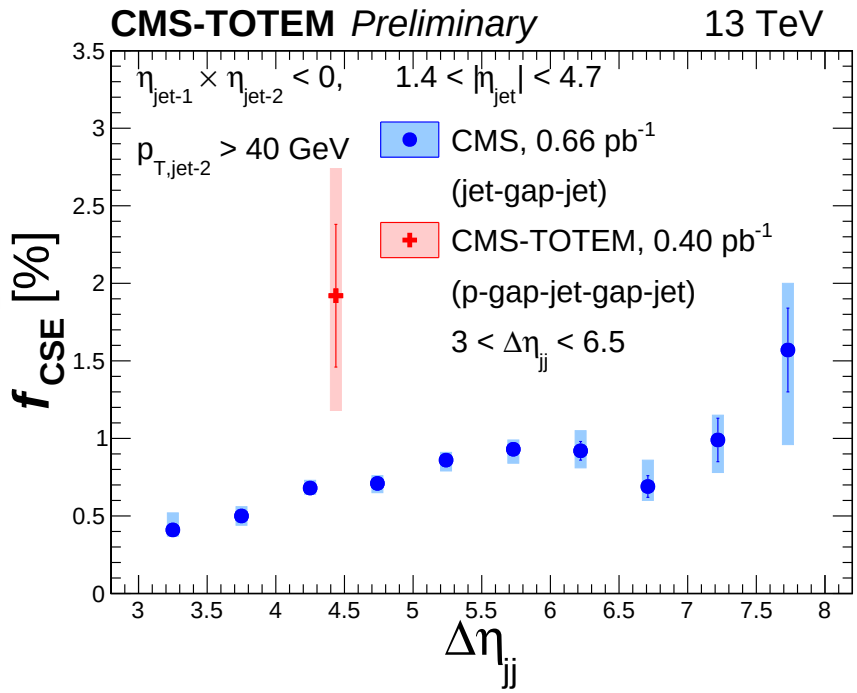
Solid histogram represents beam-bkg + dijet production.

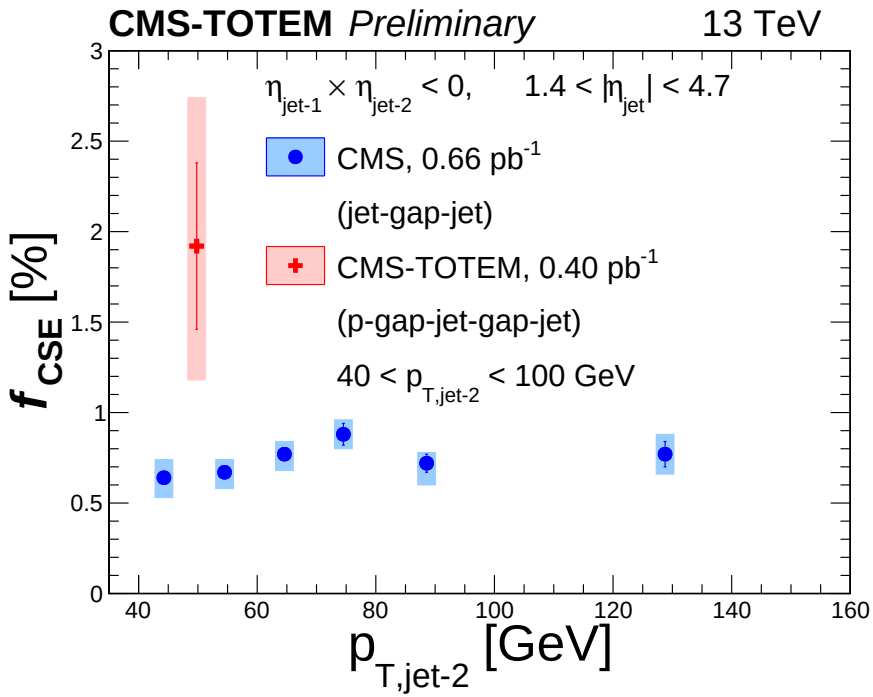
Similar techniques to estimate background from fluctuations in particle multiplicity:

- Orthogonal dijet sample approach: Two jets in same side w.r.t. fixed η region. Interval needs to be adjusted to account for boosts in SD dijet events (0.8 units in η).
- 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.

Both approaches lead to an excess of events at low charged particle multiplicities $\rightarrow$ First time these events are studied!

Results on p-gap-jet-gap-jet





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

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

Lower spectator parton activity in events with intact protons $\rightarrow$ Better chance of central gap surviving the collision.

Some thoughts/questions for discussion (Part I)

- We have had evidence for jet-gap-jet events at various experiments at HERA, Tevatron, and now at the LHC. The production rate represents a small fraction of the inclusive dijet cross section (order 0.5–1%, not negligible!). This process, however, remains ill understood.
- Next steps on pheno: completion of jet-gap-jet cross section calculation at NLO supplemented with appropriate survival probability effects.
- How could we better isolate possible BFKL dynamics effects? $\rightarrow$ Better observables, or other collider probes (in ep, eA collisions?). Measurement with intact proton shows that we can partially suppress soft-parton exchanges, but we are limited by luminosity to do differential studies.
- Is suppression of gap fraction with $\sqrt{s}$ expected?

Some thoughts/questions for discussion (Part II)

- What if we do not get agreement with completion of BFKL NLO calculation?
- Is BFKL pomeron exchange the *only* way of understanding these events? Or are missing an alternative mechanism for rapidity gap generation?
- How about other processes potentially sensitive to same mechanism? For instance, it was proposed to study J/Ψ pair production, with the reconstructed J/Ψ separated by a rapidity gap (see e.g. V.P. Goncalves, M.V.T. Machado EPJ C28,71 (2003), V. P. Goncalves, B. D. Moreira, F. S. Navarra EPJ C76,103 (2016)).

Some of these issues are being addressed with colleagues at U. of Münster (M. Klasen, J. Salomon, P. González, M. Kampshoff), U. of Florence (D. Colferai), and U. of Kansas (C. Royon, F. Deganutti, Z. Warner, CB), and plan to have it as part of the Snowmass 2021 work.

Letter of Interest in preparation.

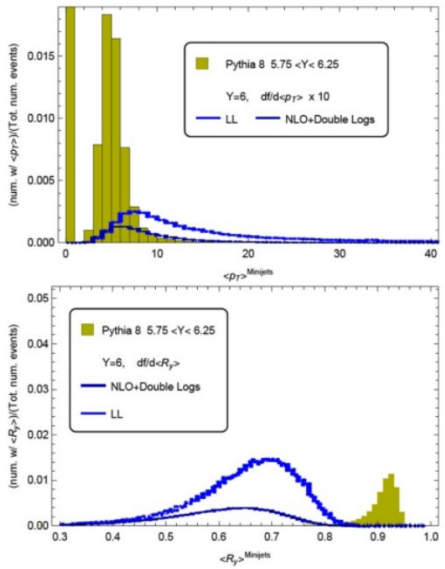
Lastly... A few more words on less inclusive observables

Study interjet activity in Mueller-Navelet jets to further discriminate DGLAP dynamics w.r.t. BFKL dynamics $\rightarrow$ Possibly more discrimination power w.r.t. $\Delta\phi_{jj}$ correlations. BFKLex generator (A. Sabio-Vera, G. Chachamis, JHEP02 064 (2016)), for instance, can be used to calculate these quantities.

BFKL dynamics: looking for less inclusive variables

$$\langle p_T \rangle = \frac{1}{N}\sum_{i=1}^{N} |p_{Ti}|$$

$$\langle R_y \rangle = \frac{1}{N+1}\sum_{i=1}^{N+1} \frac{y_i}{y_{i-1}}$$



- Looking for multiple gluon emission along ladder characteristic of BFKL: number, p_T, rapidity distributions of "minijets"
- Comparison between BFKL-ex MC and pythia/herwig to find best variables: collaboration with A. Sabio Vera, D, Gordo, G. Chachamis, F. Deganutti, T. Raben

Slide by C. Royon

$\langle R \rangle$ is the average of the ratio of rapidities of adjacent jets.
$\langle p_T \rangle$ is the average of transverse momentum of the minijets.
BFKL predictions in blue.
DGLAP predictions in yellow.

Summary

Unique opportunity to study hard color singlet exchange:

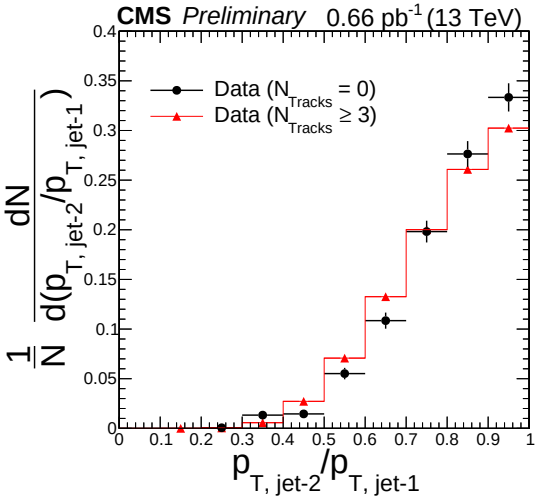
- Jet-gap-jet events at 13 TeV. Comparison to BFKL based calculations and to previous measurements by CDF, D0 and CMS at lower $\sqrt{s}$. Need further interpretation.
- First study of p-gap-jet-gap-jet events, where the leading proton is tagged with the TOTEM RPs. Larger fraction of events with a central gap, allows for interpretation in terms of reduced spectator parton activity in events with leading protons.
- Many questions/issues to be addressed for Snowmass 2021.

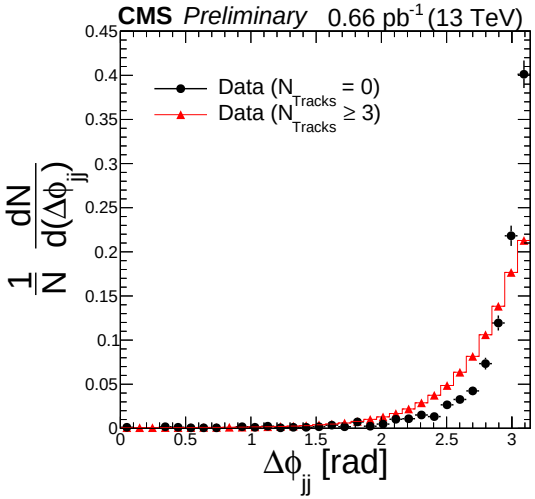
Thanks!

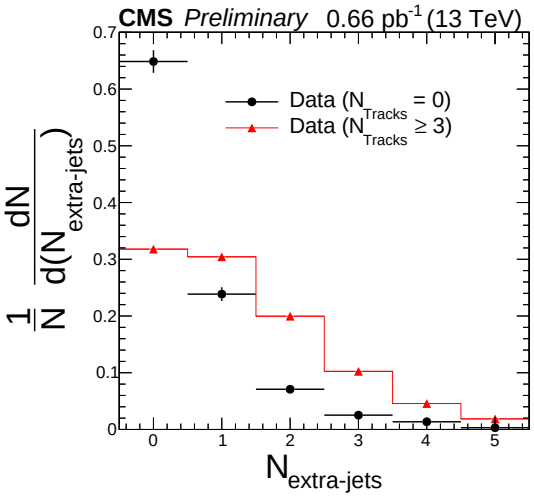
Back up

Back up

Kinematic properties of jet-gap-jet candidates vs incl. dijet events







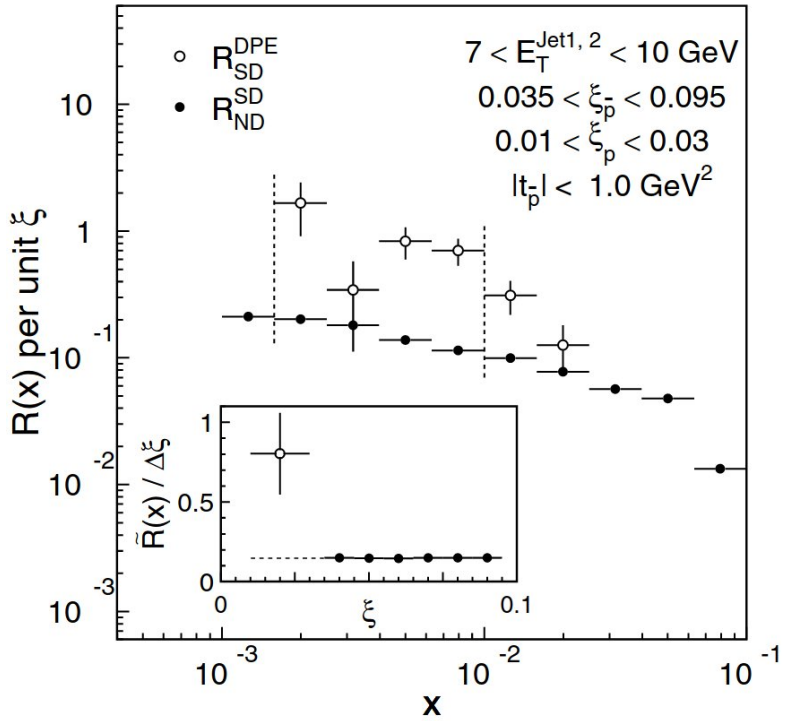
Normalized distributions in:

- $p_{\mathrm{T,jet\text{-}2}}/p_{\mathrm{T,jet\text{-}1}}$.
- $\Delta\phi_{\mathrm{jj}} = |\phi_{\mathrm{jet\text{-}1}} - \phi_{\mathrm{jet\text{-}2}}|$
- Jet multiplicity $N_{\mathrm{extra\text{-}jets}}$ for jets with $p_{\mathrm{T,extra\text{-}jet}} > 15$ GeV.

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

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 ± 1.9, different from factor of 1 expected from factorization. Comparison of gap-jet-jet-gap/gap-jet-jet topology.

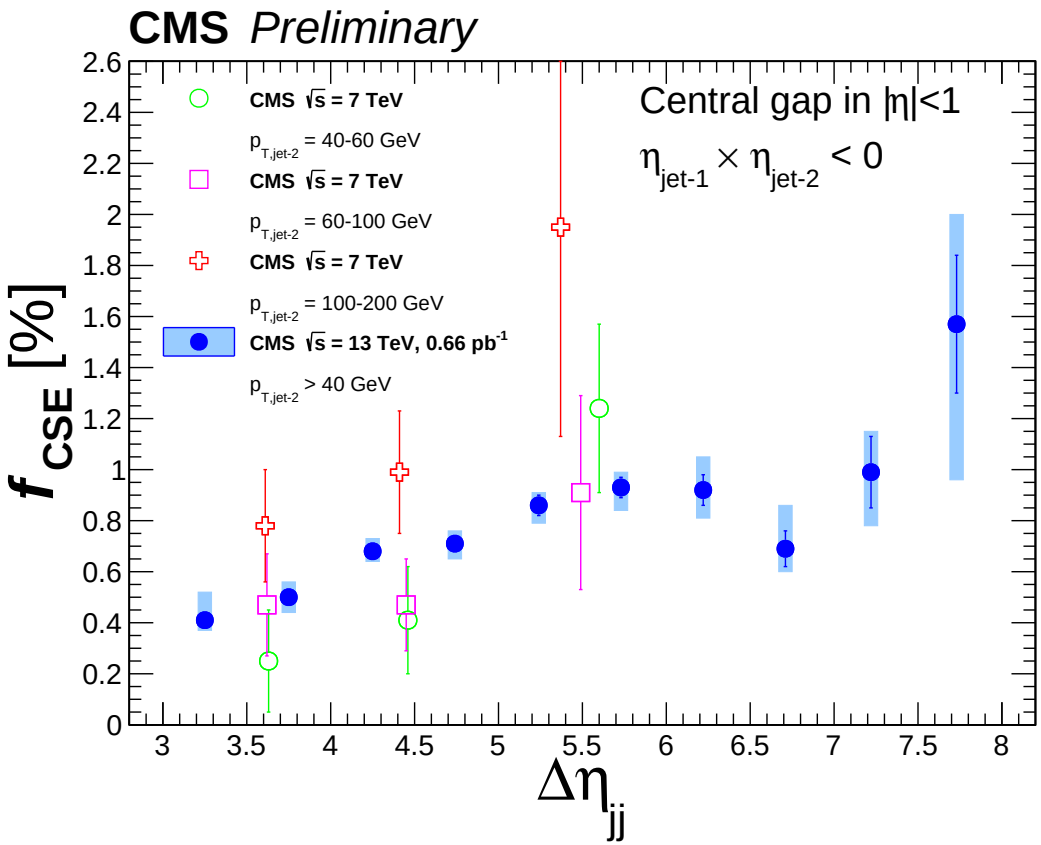
Present CMS-TOTEM result finds a similar effect for a different two-gap topology (proton-gap-jet-gap-jet).

Systematic uncertainty table summary

Source	Jet-gap-jet			Proton-gap-jet-gap-jet
	$\Delta\eta_{jj}$	$p_{T,\text{jet-2}}$	$\Delta\phi_{jj}$	
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

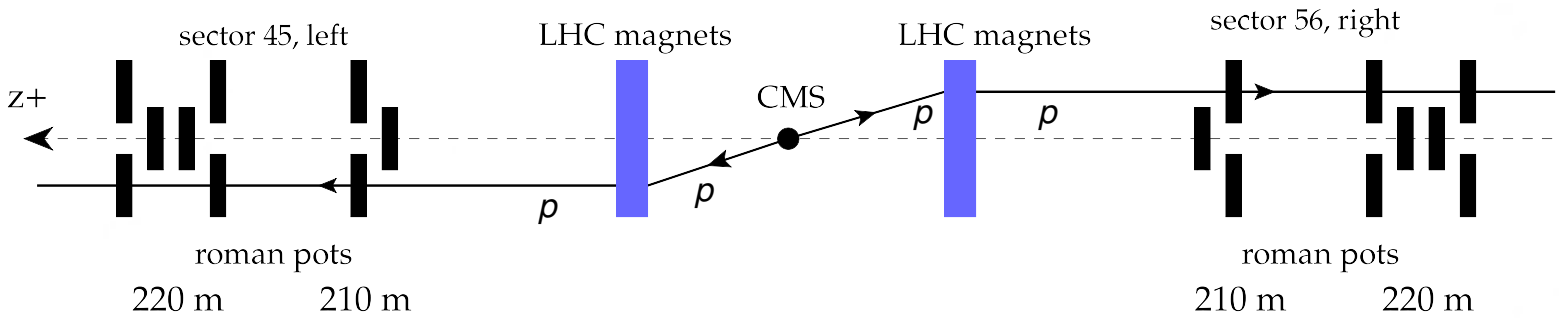
Relative systematic uncertainties in percentage on f_{CSE}. Uncertainty range is representative of the variation found in the jet-gap-jet fraction in bins of the kinematic variables of interest.

f_{CSE} vs. $\Delta\eta_{jj}$ between 7 TeV and 13 TeV CMS results



- 7 TeV analysis performed in three bins of $p_{T,\text{jet-2}}$ and three bins of $\Delta\eta_{jj}$ = 3–4, 4–5,5–7 (**EPJC**78(2018)242)
- Trend of increasing f_{CSE} with $\Delta\eta_{jj}$ observed at 7 TeV is confirmed with present 13 TeV results.
- New results reach previously unexplored values of $\Delta\eta_{jj}$ → Very important to understand hard color singlet exchange.

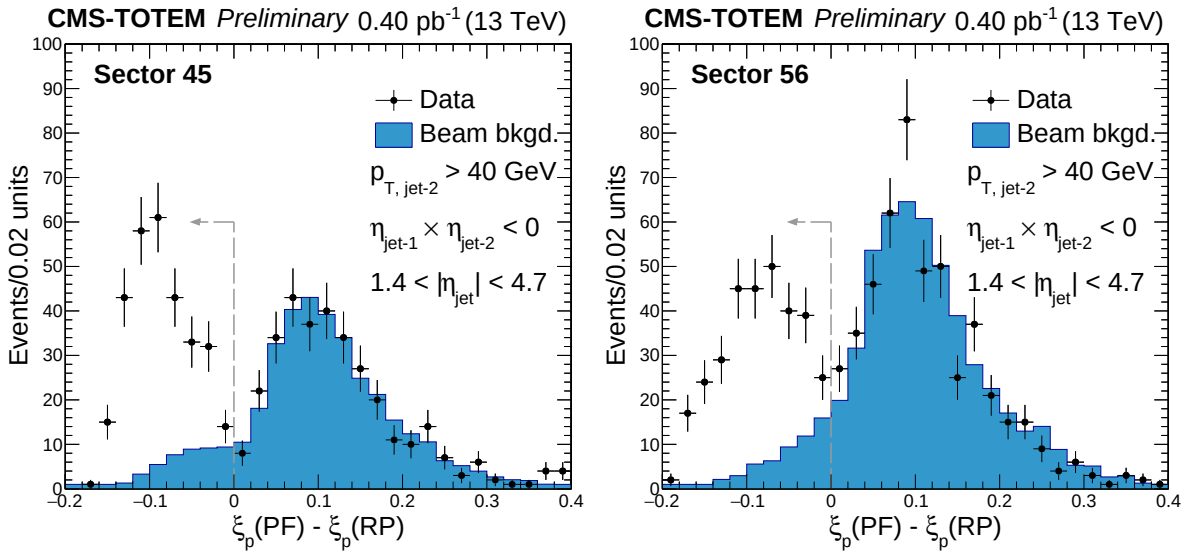
Proton selection



- 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 $\xi_p(\text{RP}) < 0.2$ 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 $\xi_p(\text{PF}) - \xi_p(\text{RP}) < 0$, 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 leading proton η.

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

Beam background



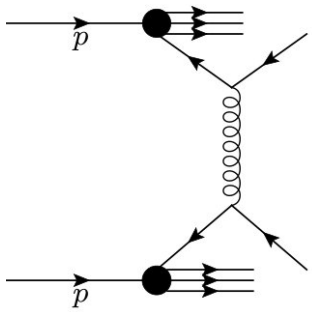
Estimated with event-mixing: inclusive dijet events paired with protons in zero-bias sample.

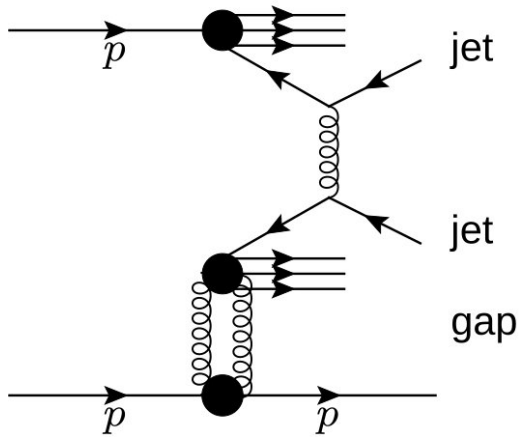
Requirement $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) < 0$ indicated by dashed line. Region $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) > 0$ is dominated by beam bkg contributions $\rightarrow$ Used as control region to estimate residual beam bkg in $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) < 0$.

Beam background contributes 13.6% and 15.2% for protons in sector 45 and 56 in $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) < 0$, respectively. Consistent with results in FSQ-12-033.

Background contributions to p-gap-jet-gap-jet events

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):



+ uncorrelated forward proton(s)

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