Study of hard color singlet exchange in dijet events with pp collisions at $\sqrt{s} = 13$ TeV

CMS-PAS-SMP-19-006/TOTEM-NOTE-2020-001

Cristian Baldenegro (cbaldenegro@ku.edu)
The University of Kansas

December 8, 2020

Zimányi School Winter Workshop 2020

DE-SC0019389

High energy limit of QCD

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

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

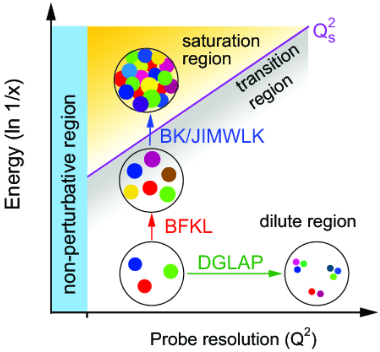
In the high-energy limit ($\hat{s} \gg -\hat{t} \gg \Lambda^2_{\mathrm{QCD}}$), the perturbative expansion can be rearranged (symbolically) as,

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

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-logarithmic (NLL) accuracy.

Proton wavefunction in x and Q^2

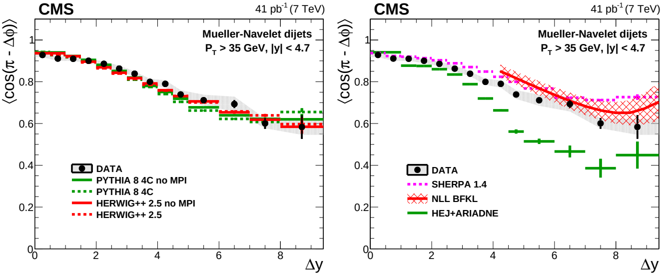


Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP): Evolution in Q^2 (resummation of $\alpha_s^n \ln^n(Q^2/Q_0^2)$) → Resolving "smaller" partons with larger Q^2 at fixed x_{Bj}.

BFKL: Evolution in x_{Bj} (resummation of $\alpha_s^n \ln^n(1/x_{\mathrm{Bj}})$) → 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!

Probing BFKL dynamics



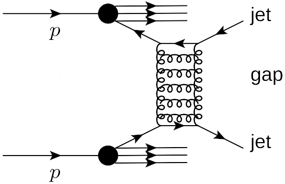
CMS Collaboration, arXiv:1601.06713, JHEP 08 (2016) 139

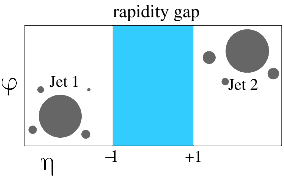
Examples of standard probes of BFKL dynamics:

- $\Delta\phi$ decorrelations in Mueller–Navelet jets (very forward-backward jets). (Plot above)
- Exclusive vector meson production ($\gamma^* p \to Vp$) at large $W_{\gamma p}$.
- PDFs at small-x_{Bj} at small momentum transfer.

Generally difficult to isolate BFKL 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.

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.

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

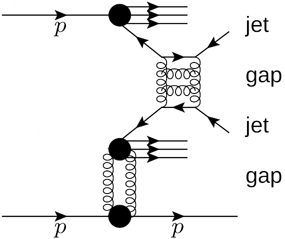
In the BFKL limit of QCD, color-singlet exchange corresponds to perturbative pomeron exchange (BFKL two-gluon ladder exchange). Jet-gap-jet process was first proposed by A. Mueller and W-K. Tang (Phys. Lett. B284,123 (1992)) as a probe of BFKL evolution.

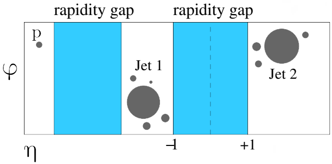
Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) dynamics are strongly suppressed in events with pseudorapidity gaps (Sudakov form factor to suppress radiation in gap).

Gap survival probability

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

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



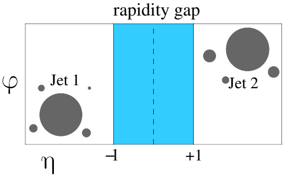


Addressed in study with CMS-TOTEM combined analysis. **First time a proton-gap-jet-gap-jet topology is studied!**.

Jet-gap-jet @ 13 TeV study by CMS and TOTEM (CMS-PAS-SMP-19-006)

Analysis based on 13 TeV low-luminosity, high-β^* pp collision data collected in 2015 (pileup of 0.05-0.10). Event selection:

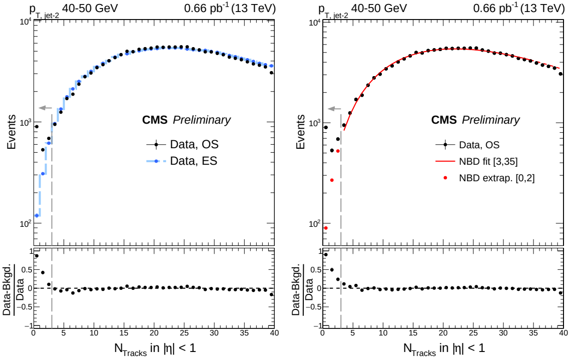
- Particle-flow anti-k_t jets with $R = 0.4$.
- Two leading jets have $p_T > 40$ GeV each.
- Leading jets satisfy $1.4 < |\eta_{\text{jet}}| < 4.7$ and $\eta_{\text{jet-1}} \times \eta_{\text{jet-2}} < 0$
  $\rightarrow$ Favors t-channel color singlet exchange.
- At most one reconstructed primary vertex 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 $|\eta| < 1$.

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 → Use as control region to estimate fluctuations at low multiplicities. Two data-based approaches:

- Orthogonal data sample (left): 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 (right): Fit data with NBD in $3 \leq N_{\text{Tracks}} \leq 35$, extrapolate down to $N_{\text{Tracks}} = 0$. (Baseline method)

Hard color singlet exchange fraction f_{CSE}

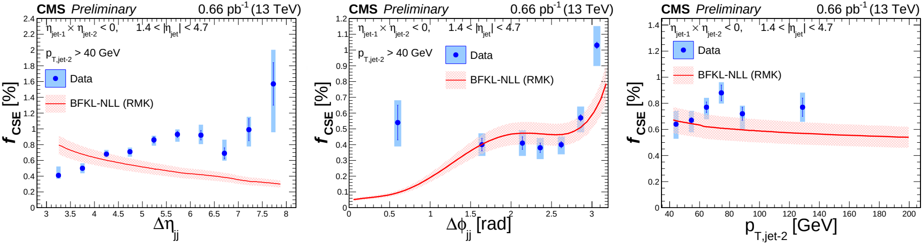
We the fraction f_{CSE} based on the charged particle multiplicity distribution between the jets:

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

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

- Pseudorapidity difference between the jets, $\Delta\eta_{\mathrm{jj}} \equiv |\eta_{\text{jet-1}} - \eta_{\text{jet-2}}|$. Sensitive to expected BFKL dynamics, since it's related to resummation of large logs of s.
- Subleading jet transverse momentum, $p_{\mathrm{T,\,jet\text{-}2}}$. Sensitive to expected BFKL dynamics.
- Azimuthal angle difference between the leading jets, $\Delta\phi_{\mathrm{jj}} \equiv |\phi_{\text{jet-1}} - \phi_{\text{jet-2}}|$. Sensitive to deviations of 2 → 2 scattering topology.

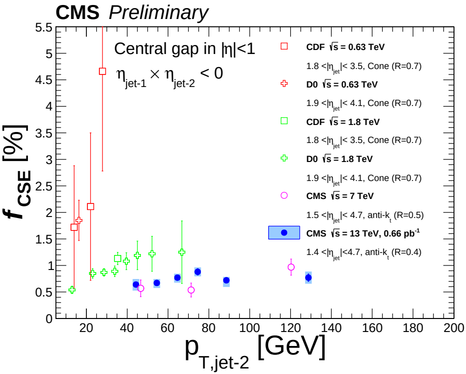
Results on color-singlet exchange fraction f_{CSE}



CMS-PAS-SMP-19-006

- Bars represent stat uncertainties, boxes represent stat + syst uncertainties.
- $f_{\text{CSE}} = 0.5$–1.0%. f_{CSE} increases with $\Delta\eta_{\text{jj}}$, with $\Delta\phi_{\text{jj}} \approx \pi$, and is weakly dependent on $p_{\text{T,jet-2}}$.
- Comparisons with Royon, Marquet, Kepka (RMK) predictions based on BFKL NLL calculations + LO impact factors (Phys. Rev. D 83.034036), and $|S|^2 = 0.1$.
- Challenging to describe theoretically all aspects of the measurement simultaneously.

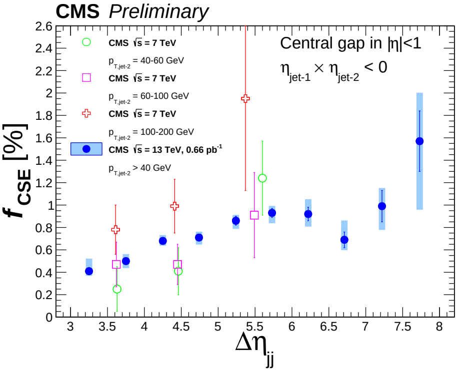
Comparison to measurements at lower $\sqrt{s}$



CMS-PAS-SMP-19-006

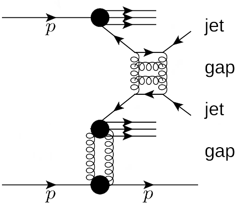
- Jet-gap-jet events at four different energies in $p\bar{p}$ and pp collisions at 0.63 TeV, 1.8 TeV, 7 TeV, and 13 TeV (this measurement).
- Generally, gap survival probability $|\mathcal{S}|^2$ is expected to decrease with increasing $\sqrt{s}$, due to an increase in spectator parton activity with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

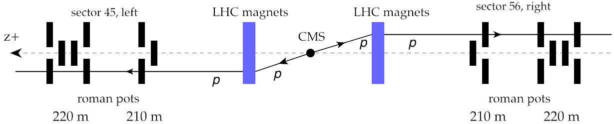
f_{CSE} vs. $\Delta\eta_{\mathrm{jj}}$ between 7 and 13 TeV CMS results



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

Turning to study with leading protons (CMS-TOTEM)





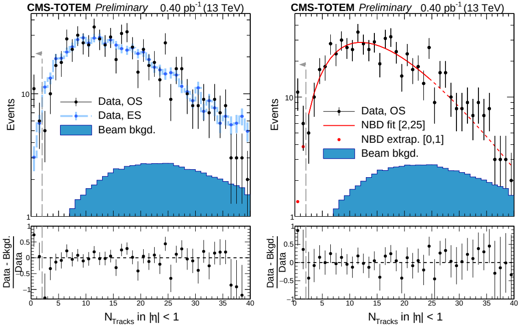
Based on a subsample of events that have leading protons detected with TOTEM roman pots.

Same dijet event selection + central gap definition as before.

Intact proton selection:

- Proton fractional momentum loss is $\xi_p(\text{RP}) < 0.2$ and four-momentum transfer square is $-4 < t < -0.025$ GeV^2.
- To suppress beam background, we cut on $\xi_p(\text{PF}) - \xi_p(\text{RP}) < 0$, 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 ± is the sign of the leading proton η.

Charged particle multiplicity between jets + leading proton



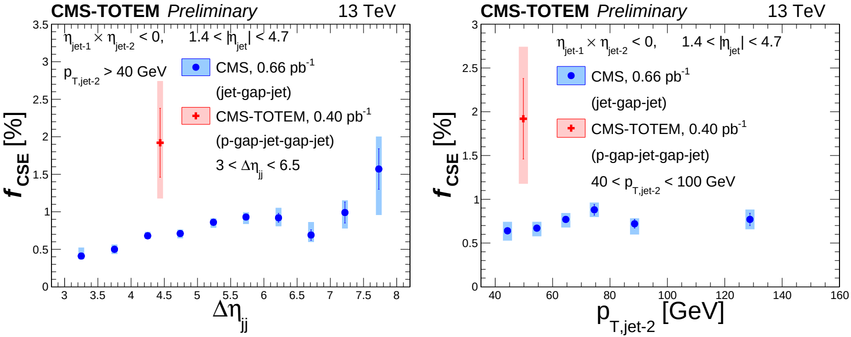
Solid histogram represents beam-bkg + dijet production.

Similar techniques to estimate background from fluctuations in particle multiplicity:

- Orthogonal dijet sample approach (left): 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 (right): 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 → For the first time these events are studied!

Results on p-gap-jet-gap-jet



CMS-PAS-SMP-19-006

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

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

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

Summary

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

Observation 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.
- NLL BFKL calculation is not able to describe all aspects of the measurement simultaneously.

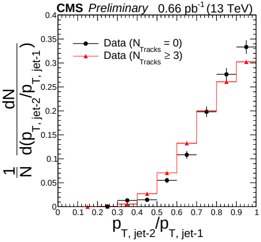
Jet-gap-jet events with intact protons:

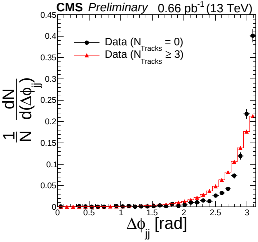
- First observation of this process experimentally.
- Hard color singlet exchange fraction f_{CSE} is $2.91 \pm 0.70(\mathrm{stat})^{+1.01}_{-0.94}$ larger than that in standard jet-gap-jet events.
- Corresponding paper will be submitted for publication soon.

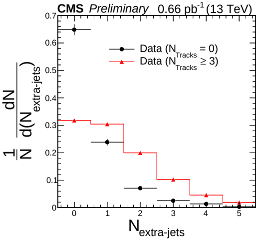
Thanks!

DE-SC0019389

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







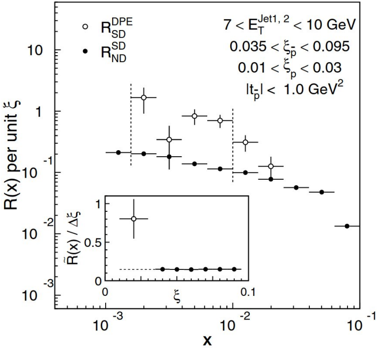
Normalized distributions in:

- $p_{\mathrm{T,jet\text{-}2}}/p_{\mathrm{T,jet\text{-}1}}$.
- $\Delta\phi_{\mathrm{jj}} = |\phi_{\mathrm{jet\text{-}1}} - \phi_{\mathrm{jet\text{-}2}}|$
- 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

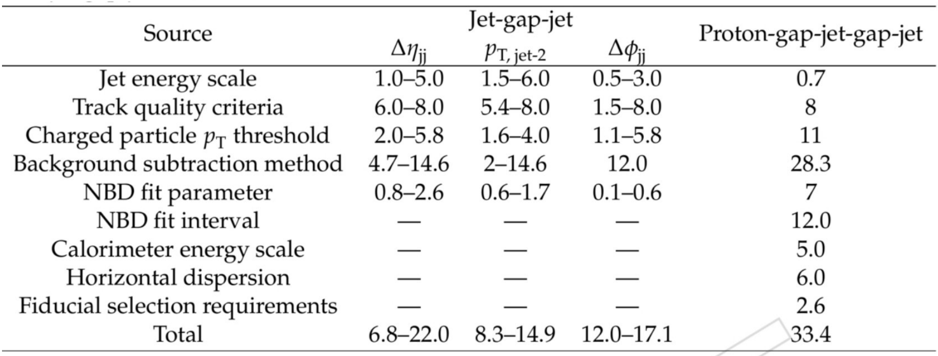


CDF studied double-pomeron exchange/single-diffractive dijet event ratios, compared them to single-diffractive/non-diffractive (**PRL85,4215**):

$\mathcal{R}$ = (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).

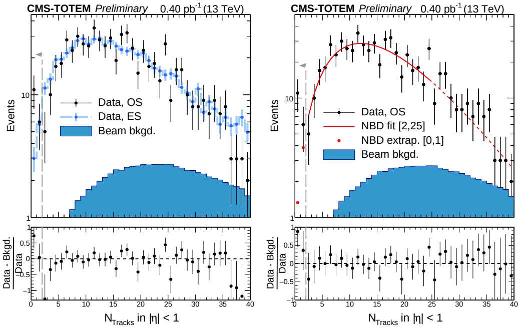
Systematic uncertainty table summary



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.

Charged particle multiplicity between jets + leading proton



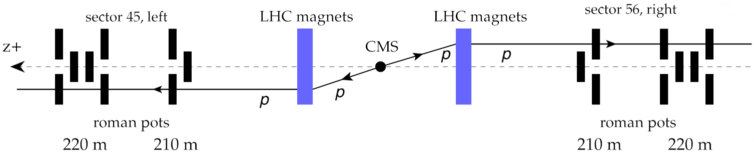
Solid histogram represents beam-bkg + dijet production.

Similar techniques to estimate background from fluctuations in particle multiplicity:

- Orthogonal dijet sample approach (left): 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 (right): NBD is fit in $2 < N_{\mathrm{Tracks}} < 25$, and extrapolated down to $N_{\mathrm{Tracks}} = 0$. 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 → For the first time these events are studied!

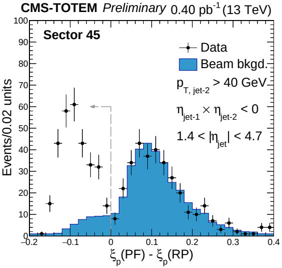
Proton selection

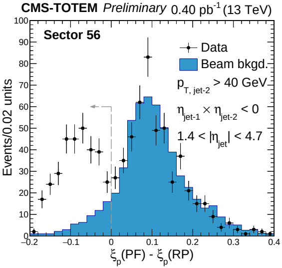


- At least one proton on either side.
- Track-impact point cuts $(x,\ y)$ based on acceptance studies. For vertical RPs, $0 < x < 20$mm and $8 < |y| < 30$mm, for horizontal RPs, $7 < x < 25$mm and $|y| < 25$mm.
- Proton fractional momentum loss is $\xi_p(\text{RP}) < 0.2$ and four-momentum transfer square is $0.025 - t < 4\ \text{GeV}^2$. 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 ± 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





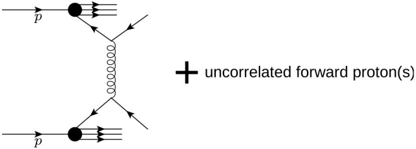
Estimated with event-mixing: inclusive dijet events paired with protons in zero-bias sample.

Requirement $\xi_p(\text{PF}) - \xi_p(\text{RP}) < 0$ 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 13.6% and 15.2% for protons in sector 45 and 56 in $\xi_p(\text{PF}) - \xi_p(\text{RP}) < 0$, 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):



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