Diffractive results from CMS and TOTEM

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On behalf of the CMS and TOTEM Collaborations

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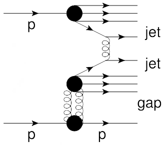
Recent selected results by CMS and CMS-TOTEM in diffraction:

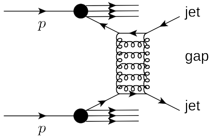
- Single-diffractive dijet production at $\sqrt{s} = 8$ TeV.
  CMS-TOTEM, arXiv:2002.12146, EPJC 80, 1164 (2020)

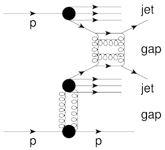
- Hard color-singlet exchange in dijet events ("jet-gap-jet") at $\sqrt{s} = 13$ TeV
  CMS-TOTEM, arXiv:2102.06945, PRD 104, 032009 (2021)

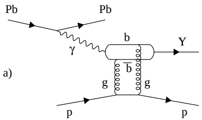
- Exclusive Υ production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
  CMS, arXiv:1809.11080,EPJC 79 (2019) 277

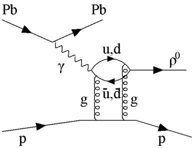
- Exclusive ρ production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
  CMS, arXiv:1902.01339, EPJC 79 (2019) 702

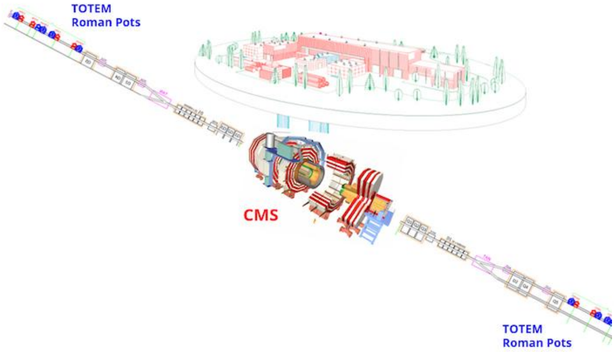












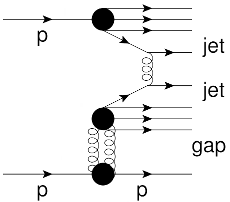
CMS:

- General purpose detector at IP5 of the CERN LHC.
- Tracking ($|\eta| < 2.5$), and hadronic and electromagnetic calorimetry ($|\eta| < 5.2$)
- Jets with $R = 0.4$ reconstructed within $|\eta^{\text{jet}}| < 4.7$.

TOTEM:

- Measurement of total cross section, elastic scattering, and soft and hard diffractive processes in pp collisions.
- **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.

CMS-TOTEM Collaborations, arXiv:2002.12146, EPJC 80, 1164 (2020)



- Diffractive structure function of the proton in an extended kinematic range. → **Poorly-understood part of the proton gluonic component.**
- **Universality of pomeron:** is the color-singlet object exchanged in ep collisions at HERA responsible for diffraction in pp collisions at the LHC?
- Constrain quark-gluon densities of the pomeron.
- Measure evolution of the survival probability with $\sqrt{s}$.

Analysis is based on very low pileup run with $\beta^* = 90$ m optics.

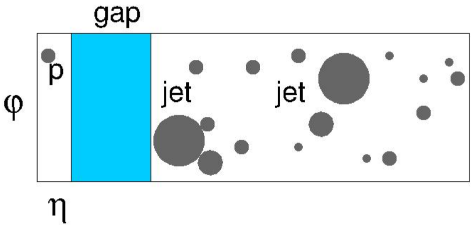
Jet selection requirements:

- Particle-flow jets with anti-k_T $R = 0.5$.
- Two highest p_T jets have $p_T > 40$ GeV in $|\eta| < 4.4$.

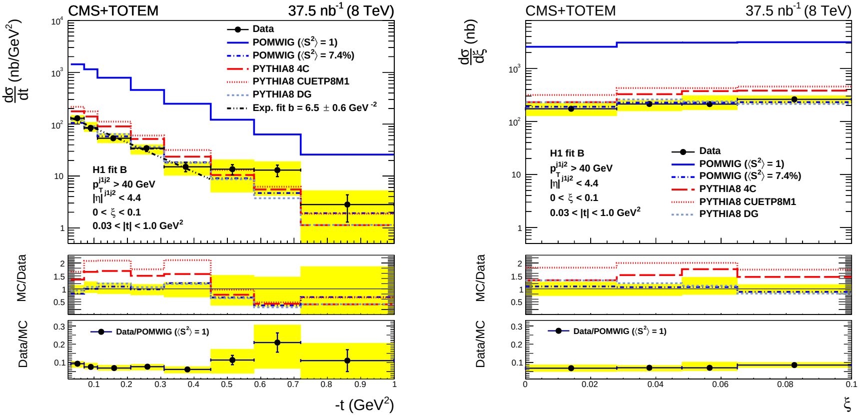
Proton requirements:

- At least one intact proton detected in the RPs (either arm).
- The fraction of beam energy lost by the proton must be $\xi_{\text{TOTEM}} \equiv \Delta p/p < 0.1$ ($x_{\mathbb{P}}$ in HERA language).
- The four-momentum transfer square at the proton vertex must be $-1 < t < -0.025$ GeV^2, where $t = (p_f - p_i)^2$.

No rapidity gap requirement! *Signature of diffraction is the intact proton.*

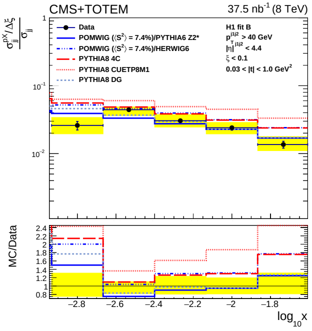


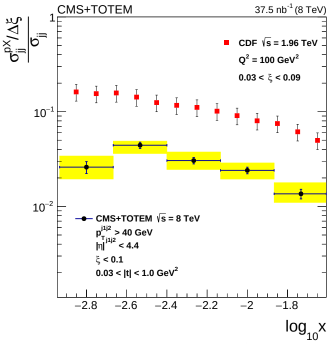
Measurement of differential cross sections in $|t|$ and ξ



Comparison w/ MC generators using various treatments of the survival probability. Predictions based on Regge factorization using the pomeron flux and diffractive PDFs from H1 2006 fit B.

- POMWIG with constant survival probability $\langle \mathcal{S}^2 \rangle = 7.4\%$ and no correction. Includes $\mathbb{P}$ and $\mathbb{R}$.
- PYTHIA8 4C and CUETP8M1 overshoot the data by a factor of $\approx$ 1.5–2. Only $\mathbb{P}$.
- Dynamical gap, based on matter distribution for MPI in $\mathbb{P}$p subsystem, describes the data without *ad hoc* normalization factors. C. Rasmussen, T. Sjöstrand, 10.1007/JHEP02(2016)142, arXiv:1512.05525.





Ratio $R = (SD/\Delta\xi)/INC$ versus x, where x is calculated with the jets

$$x^{\pm} \equiv \frac{1}{\sqrt{s}} \sum_{\mathbf{i=1}}^{\mathbf{3}} E^{\mathbf{jet\ i}} \pm p_z^{\mathbf{jet\ i}}$$

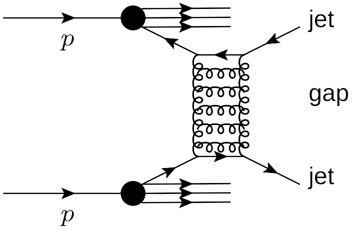
.

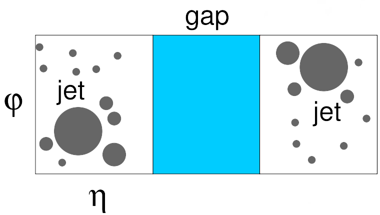
Comparison of R with different treatments of hard diffraction:

- POMWIG prediction with $\langle S^2 \rangle = 7.4\%$.
- PYTHIA8 4C, CUETP8M1 and dynamical gap (DG); no additional survival probability.

R at 8 TeV shows suppression w.r.t. measurement by CDF at 1.96 TeV. Consistent with an evolution of the survival probability with $\sqrt{s}$.

CMS-TOTEM Collaborations, arXiv:2102.06945, PRD 104, 032009 (2021)





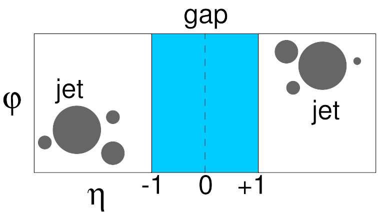
t-channel color-singlet exchange between partons (two-gluon exchange)
$\rightarrow$ η **interval void of particles between jets (pseudorapidity gap)**.

In the high-energy limit of QCD, process is expected to be described by **Balitsky–Fadin–Kuraev–Lipatov pomeron exchange**.
A. Mueller and W-K. Tang, PLB 284 (1992) 123.

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

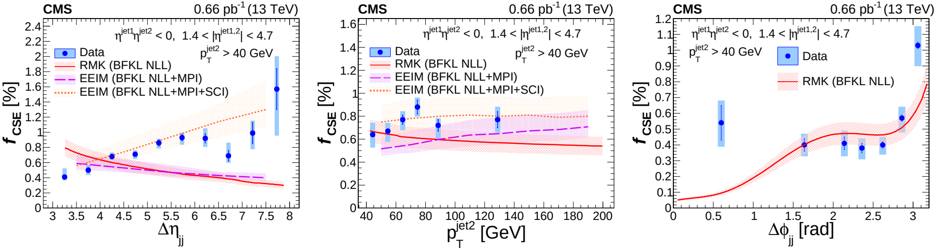
Analysis based on low-pileup data. Event selection:

- 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.**

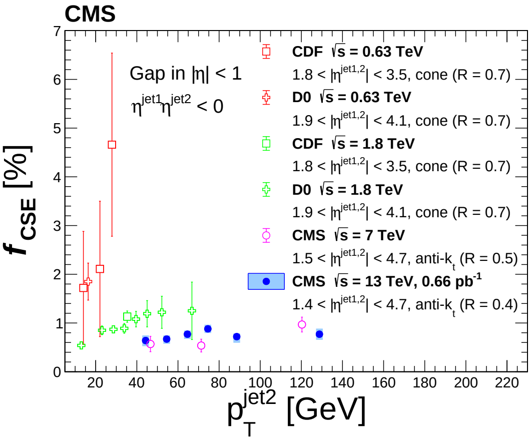


Pseudorapidity gap is defined via the multiplicity of charged particles N_{tracks} between the jets. Each charged particle has $p_T > 200$ MeV in $|\eta| < 1$.

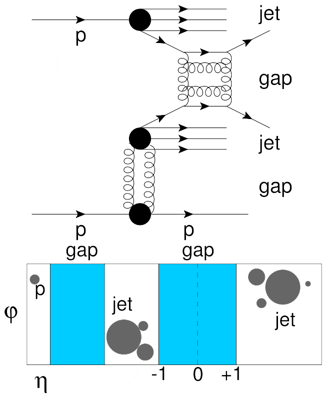
Results on color-singlet exchange fraction $f_{CSE} \equiv$ CSE dijets/INC dijets



- **Color-singlet exchange represents ≈ 0.6% of the inclusive dijet cross section for the probed phase-space.**
- 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 the uncertainties, **f_{CSE} stops decreasing with $\sqrt{s}$ at LHC energies**, in contrast to trend observed at lower energies 0.63 TeV → 1.8 TeV → 7 TeV.

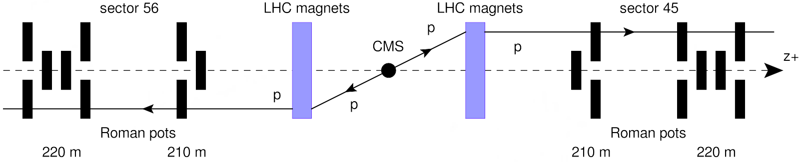


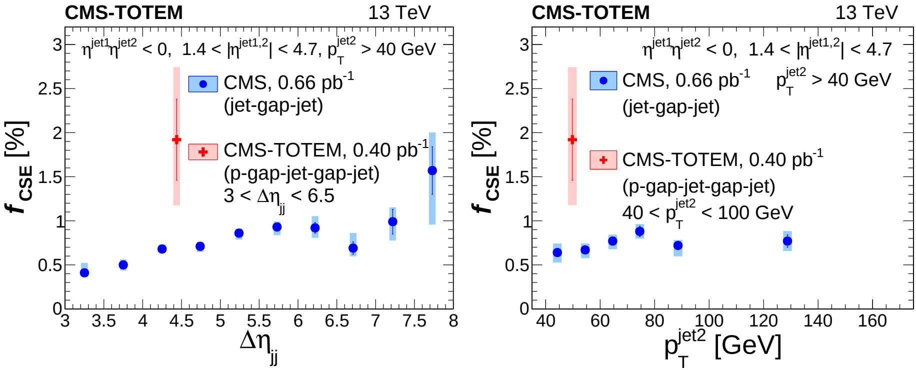
Better understand the role of spectator partons in the destruction of the central gap.

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

Proton requirements:

- The fraction of beam energy lost by the proton must be $\xi \equiv \Delta p/p < 0.2$.
- 4-momentum transfer at proton vertex $-4 < t < -0.025$ GeV^2, where $t = (p_f - p_i)^2$.





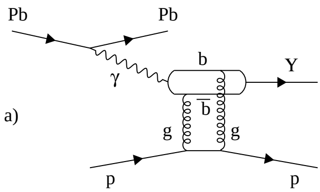
f_{CSE} fraction in p-gap-jet-gap-jet study is $2.91 \pm 0.70(\text{stat})^{+1.08}_{-1.01}(\text{syst})$ times larger than jet-gap-jet fraction, for similar dijet kinematics.

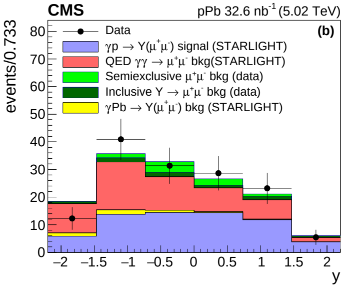
Abundance of events with a central gap is larger in events with intact protons.

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

CMS, arXiv:1809.11080,EPJC 79 (2019) 277

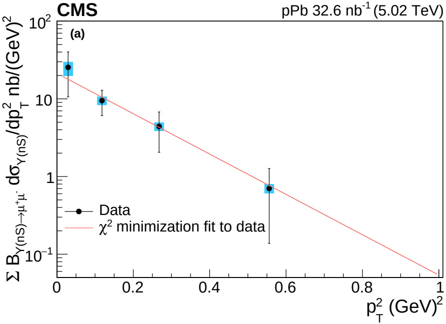
- **Virtual photon splits into color dipole that probes the proton structure $\gamma^* p \to \Upsilon p$**
- Photoproduction of quarkonia offers a clean probe of gluon densities of the proton (at LO in pQCD, $\sigma \propto [xg(x, Q^2)]^2$).
- One can probe $xg(x, Q^2)$ at $x = 10^{-4}$–10^{-2} at $Q^2 \approx m_\Upsilon^2 \gg \Lambda_{QCD}^2$.

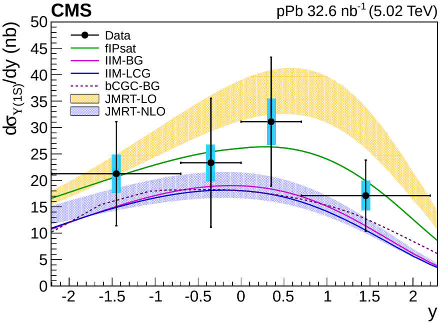




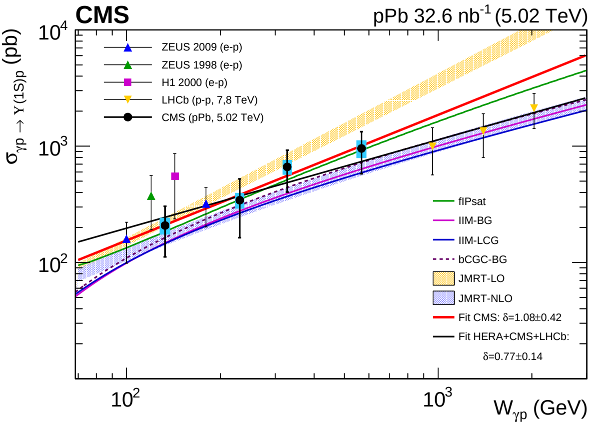
Focus on $\Upsilon \to \mu^+\mu^-$ channel. Event selection:

- Exactly two muon tracks of opposite charge associated to the primary vertex with $p_T^\mu > 3.3$ GeV and $0.1 < p_T^{\mu^+\mu^-} < 1$ GeV with $|\eta^\mu| < 2.2$. **No other tracks with $p_T > 0.1$ GeV.**
- No activity in $2.9 < |\eta| < 5.2$ with $E > 5 GeV$ and no neutrons detected in zero degree calorimeters (ZDCs).





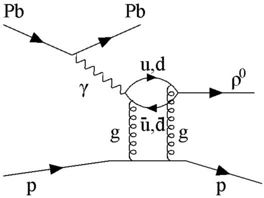
- Measure $d\sigma/p^2_{T,\Upsilon}$, where $p^2_{T,\Upsilon}$ is used a proxy for $t = (p_f - p_i)^2$.
- Extract slope of $b = 6 \pm 2.1$ (stat) ± 0.3 (syst) GeV^{-2} with $\exp(-bp^2_T)$ fit, in agreement with the value measured by ZEUS of $b = 4.3^{+2.0}_{-1.3}$ (stat) ${}^{+0.5}_{-0.6}$ (syst) GeV^{-2} at lower $W_{\gamma p}$.
- **Compared to various predictions based on different treatments of the low-x gluon densities of the proton.**

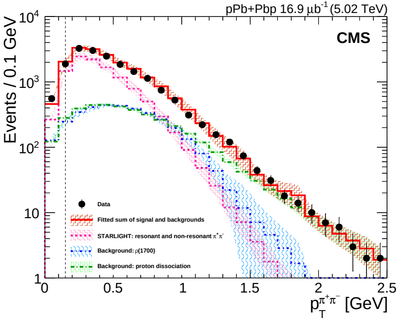


- Photon-proton center-of-mass energy $W_{\gamma p}^2 = 2E_p m_\Upsilon \exp(\pm y_\Upsilon)$ calculated in bins of $\langle y_\Upsilon \rangle$.
- A fit to the **CMS** data alone of the form $\sigma \propto W_{\gamma p}^{\delta}$ yields $\delta = 1.08 \pm 0.42$, consistent with the value reported by **ZEUS** of $\delta = 1.2 \pm 0.8$.
- $\sqrt{s_{\rm NN}} = 5.02$ **TeV pPb results cover region explored by H1, ZEUS, and LHCb results.**

CMS, arXiv:1902.01339, EPJC 79 (2019) 702

Color dipole size of $\rho^0(770)$ meson is expected to be larger than those of other vector mesons → possible enhancement of saturation effects.

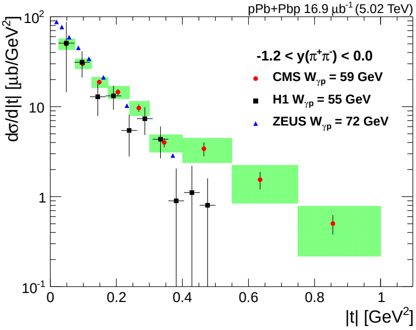


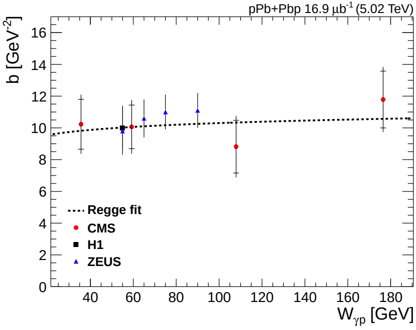


Focus on $\rho^0(770) \to \pi^+\pi^-$ channel.

Event selection:

- Exacly two high-purity tracks associated to primary vertex, $p_T^{\text{leading}} > 0.4$ GeV and $p_T^{\text{subleading}} > 0.2$ GeV in $|\eta| < 2.0$.
- No activity in forward hadronic $3.0 < |\eta| < 5.2$ with $E > 3$ GeV and no neutron activity in ZDC.

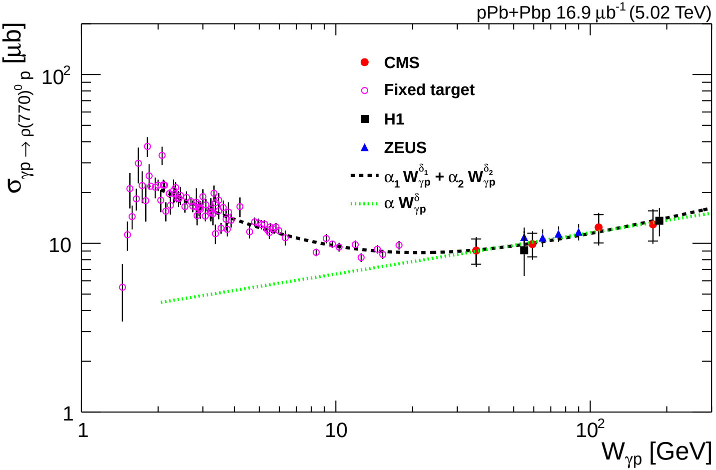




- Good agreement of the slope of $|t| \equiv p^2_{T,\pi^+\pi^-}$ between **H1**, **ZEUS**, and **CMS**. Slope extracted from $\exp(bt + ct^2)$ fit.
- Shrinkage of the b-slope with energy (Regge fit):

$$b = b_0 + 2\alpha' \ln(W_{\gamma p}/W_0)^2 \quad (1)$$

- **CMS:** $\alpha' = 0.28 \pm 0.11$ (stat) ± 0.12 (syst) GeV^{-2}, consistent with **ZEUS-only** value $\alpha' = 0.23 \pm 0.15$ (stat) ± 0.11 (syst) GeV^{-2}



- **Consistent with trend observed with HERA results at similar $W_{\gamma p}$.**
- Power-law fit to CMS and HERA $W_{\gamma p}^{\delta}$, with $\delta = 0.24 \pm 0.13$ (stat) ± 0.04 (syst).

Summary

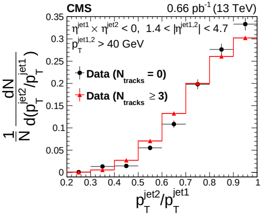
Unique opportunity to study the phenomenon of diffraction with CMS and TOTEM.

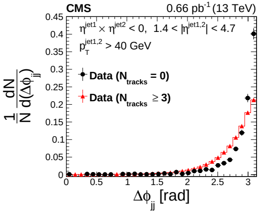
Testing properties and universality of diffractive interactions at different scales of momenta:

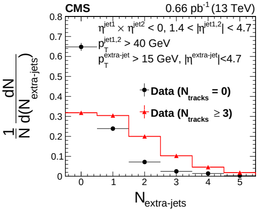
- Diffractive dijet production at $\sqrt{s} = 8$ TeV
- Hard color-singlet exchange in dijet events at $\sqrt{s} = 13$ TeV
- Exclusive ρ and Υ meson production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- Stay tuned for further studies!

Thanks!

DE-SC0019389







Normalized distributions in:

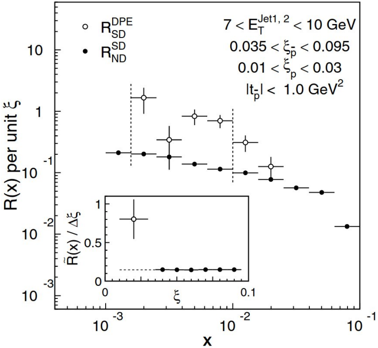
- $p_T^{\text{jet2}}/p_T^{\text{jet1}}$.
- $\Delta\phi_{\text{jj}} = |\phi^{\text{jet1}} - \phi^{\text{jet2}}|$
- Jet multiplicity $N_{\text{extra-jets}}$ for jets with $p_{T,\text{extra-jet}} > 15$ GeV.

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.

Predictions to exclusive Υ data

- The JMRT model [10], a pQCD approach that uses standard (collinear) PDFs with a skewness factor to approximate GPDs, including LO and NLO corrections, and a gap survival factor to account for the exclusive production;
- The factorized impact parameter saturation model, fIPsat, with an eikonalized gluon distribution function that uses the colour glass condensate (CGC) formalism to incorporate gluon saturation at low x [17, 18];
- the Iancu, Itakura and Munier (IIM) colour dipole formalism [63] with two sets of meson wave functions, boosted Gaussian (BG) and light-cone Gaussian (LCG), which also incorporate saturation effects [15, 16];
- the impact parameter CGC model (bCGC), which takes into account the t-dependence of the differential cross section, using the BG wave function [19, 64].



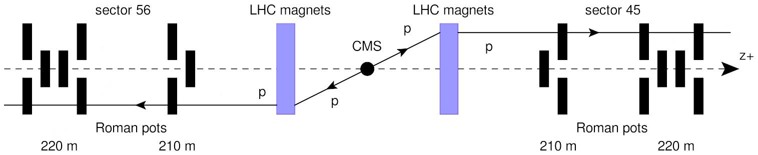
CDF studied double-pomeron exchange/single-diffractive dijet event ratios, compared them to single-diffractive/non-diffractive (**PRL85,4215**):

$\mathcal{R}$ = (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).

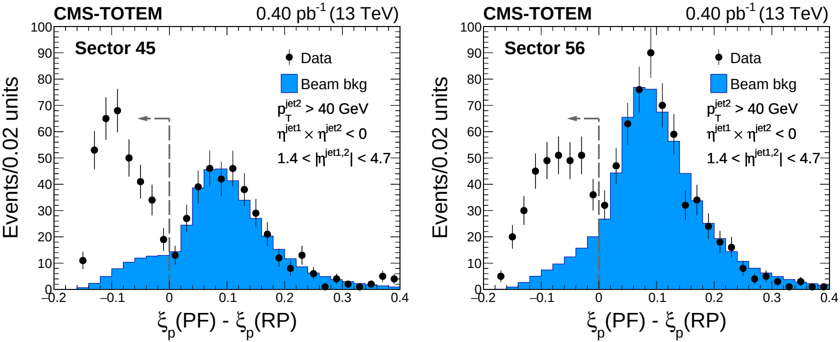
Source	Jet-gap-jet $\Delta\eta_{jj}$	Jet-gap-jet $p_{T,\text{jet-2}}$	Jet-gap-jet $\Delta\phi_{jj}$	Proton-gap-jet-gap-jet
Jet energy scale	1.0–5.0	1.5–6.0	0.5–3.0	0.7
Track quality criteria	6.0–8.0	5.4–8.0	1.5–8.0	8
Charged particle p_T threshold	2.0–5.8	1.6–4.0	1.1–5.8	11
Background subtraction method	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 $\xi \equiv \Delta p/p < 0.2$ 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.

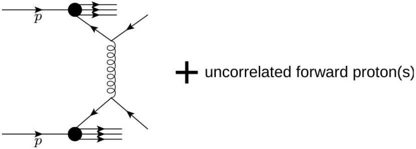


Estimated with event-mixing: inclusive dijet events paired with protons in zero-bias sample.

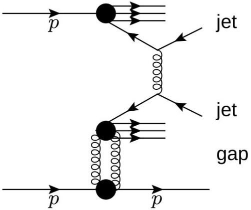
Requirement $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) < 0$ indicated by dashed line. Region $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) > 0$ is dominated by beam bkg contributions $\rightarrow$ Used as control region to estimate residual beam bkg in $\xi_p(\mathrm{PF}) - \xi_p(\mathrm{RP}) < 0$.

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).



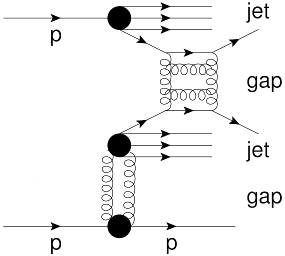
Standard diffractive dijet production with no central gap (p-gap-jet-jet topology):

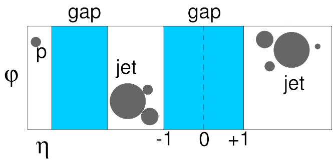


→ Fluctuations on particle multiplicity can lead to gaps. Needs to be subtracted (NBD and ES methods).

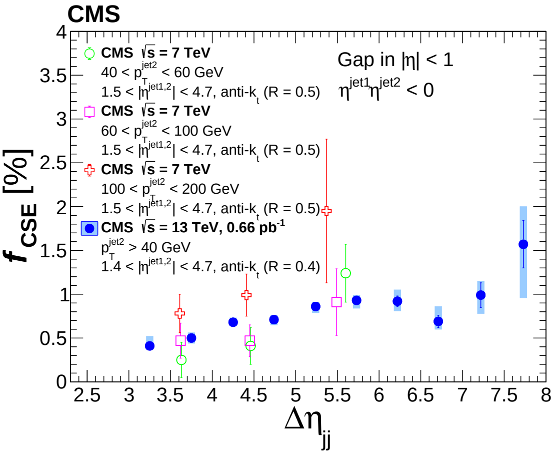
Soft-parton activity can destroy the central gap between the jets. This is parametrized with a gap survival probability, $|\mathcal{S}|^2$, **which is difficult to understand theoretically.**

In pp collisions with intact protons, soft-parton activity is largely suppressed → **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**.



- 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 $\Delta\eta_{jj}$**

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

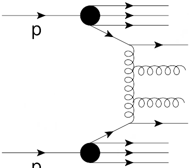
$$f_{\text{CSE}} \equiv \frac{N(N_{\text{tracks}} < 3) - N_{\text{bkg}}(N_{\text{tracks}} < 3)}{N_{\text{all}}} \equiv \frac{\text{color-singlet exchange dijet events}}{\text{all dijet events}}$$

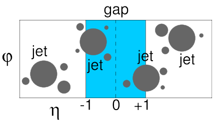
The fraction f_{CSE} is measured as a function of:

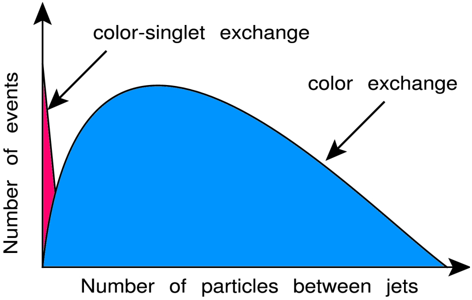
- $\Delta\eta_{\text{jj}} \equiv |\eta^{\text{jet1}} - \eta^{\text{jet2}}|$: Sensitive to expected BFKL dynamics, since it's related to resummation of large logs of s.
- $p_{\text{T}}^{\text{jet2}}$: Sensitive to expected BFKL dynamics; allows for comparison at lower $\sqrt{s}$.
- $\Delta\phi_{\text{jj}}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

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

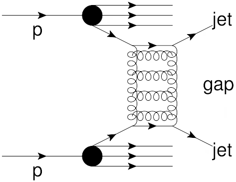
Color-exchange
(single-gluon in
t-channel)

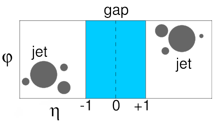






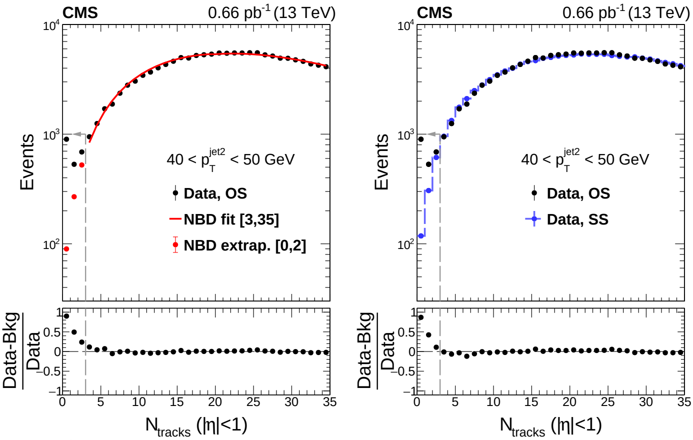
Color-singlet exchange
(two-gluon in t-channel)





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

Multiplicity of charged particles between the jets



Color-exchange events dominate at large $N_{\text{tracks}} \rightarrow$ 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 $N_{\text{tracks}} = 0$.