Hard color-singlet exchange in dijet events at $\sqrt{s} = 13$ TeV

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Forward QCD: open questions and future directions

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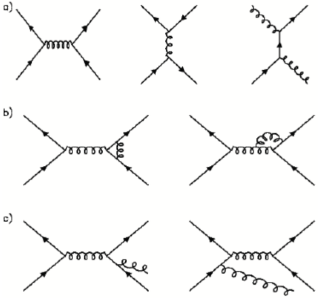
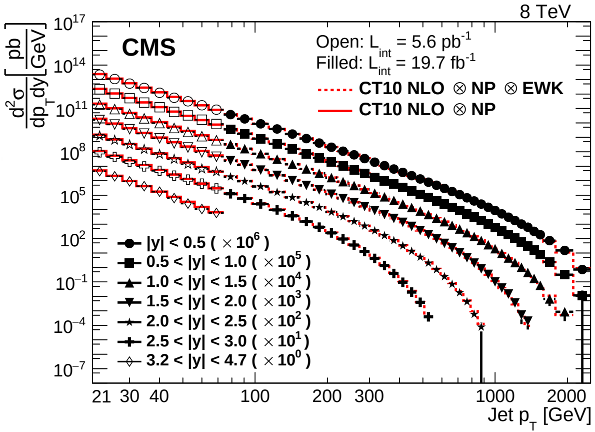
Standard "fixed-order" perturbation theory machinery



In fixed-order pQCD, we calculate the hard cross sections in powers of $\alpha_s \ll 1$, *symbolically* (ignoring pre-factors) represented by

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

Calculations are known at leading order (LO), next-to-LO (NLO), next-to-NLO (N^2LO), and in very few cases for next-to-NNLO (N^3LO).



CMS, JHEP 03 (2017) 156, arXiv:1609.05331

Fixed-order pQCD has been rigorously tested in inclusive jet cross section measurements at HERA (ep), the Tevatron ($p\bar{p}$), and the LHC (pp).

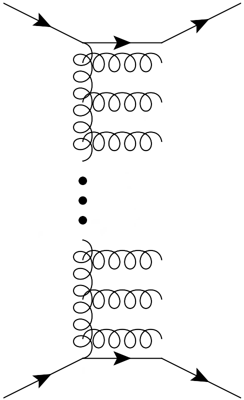
Perturbative calculations supplemented with parton shower and non-perturbative QCD effects are very successful.

Regime of interest: $\hat{s} \gg -\hat{t} \gg \Lambda^2_{QCD}$, where $\hat{s}$ and $\hat{t}$ are the square of the center-of-mass energy and four-momentum transfer at parton-level.

$\rightarrow$ **Fixed-order pQCD approach breaks down**.

The perturbative expansion should 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 $\alpha_s^n \ln^n \left(\hat{s}/|\hat{t}|\right) \lesssim 1$ with $\alpha_s \approx 0.1$.

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.

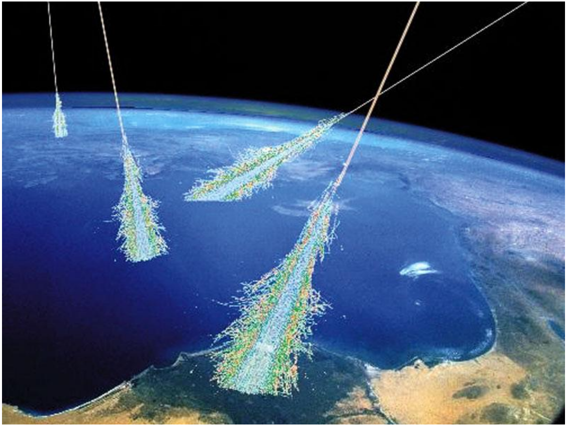
Very important test of QCD; very challenging to isolate experimentally

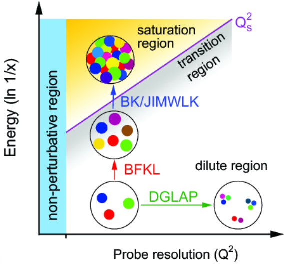
The onset of BFKL dynamics is at large $\Delta y = \ln(\hat{s}/|\hat{t}|)$.

According to BFKL, $\hat{\sigma} \propto \hat{s}^{0.5}$ at LL.

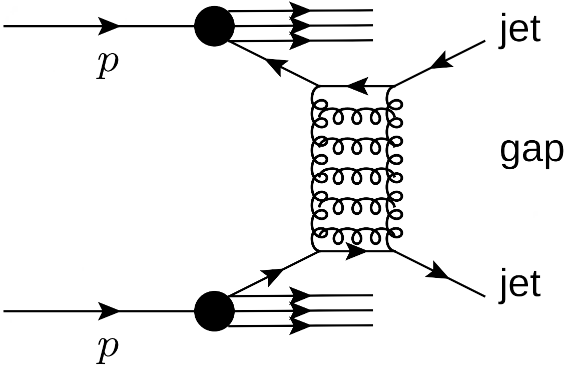
Why should we care about the high energy limit of QCD anyway?

- **Important test of QFT framework**.
- **Cosmic ray physics:** cosmic ray interactions with the atmosphere can occur at the multi-TeV scale and beyond. **The strong force dominates.**
- **Small-x limit:** Evolution of proton and PDFs at small-x is described by BFKL (before onset of parton saturation). **Important topic of study at the future Electron Ion Collider.**

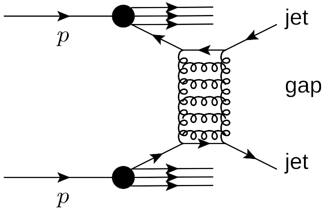


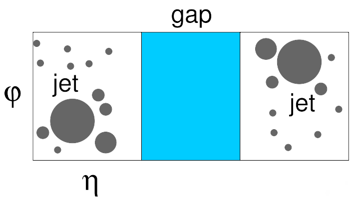


Turning to CMS measurement



arXiv:2102.06945, *Phys. Rev. D* 104, 032009 (2021)





Very clean experimental signature!

t-channel color-singlet exchange between partons (two-gluon color-singlet exchange)
→ **pseudorapidity interval devoid 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.

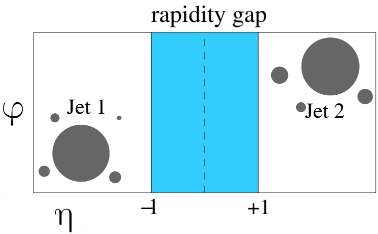
Other higher-order corrections, e.g., parton splittings cf DGLAP evolution, are strongly suppressed in events with gaps (Sudakov form factor).

rapidity gaps ⇔ pomeron exchange ⇔ diffraction

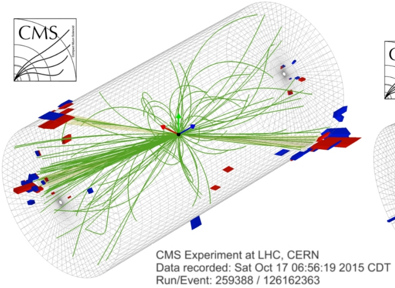
Low-PU conditions to reconstruct rapidity gaps and suppress forward PU jets.

Offline event selection:

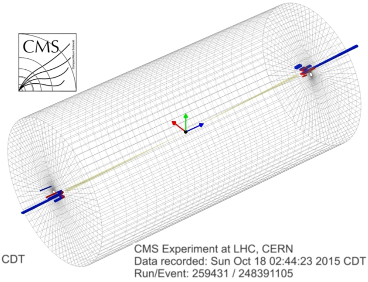
- Particle-flow, anti-k_t jets $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$.
- At most one primary vertex (PU suppression).
- **Two highest p_T jets have $p_T > 40$ GeV each.**
- **Two highest p_T jets must have** $1.4 < |\eta_{\text{jet}}| < 4.7$ **and** $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$
  $\rightarrow$ Favors t-channel exchanges.



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



Color-exchange event candidate
(Background-like)

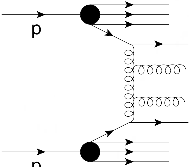


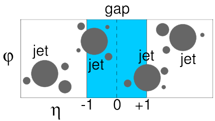
Color-singlet exchange event candidate
(Signal-like)

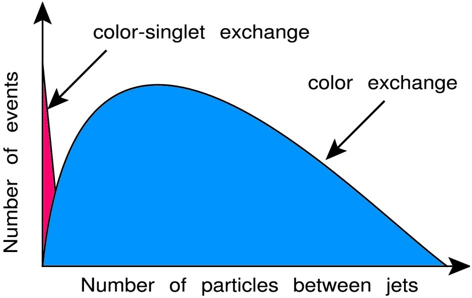
Leading two jets $p_T > 40$ GeV, all other jets $p_T > 15$ GeV, calorimeter towers with $E > 1$ GeV, high-purity charged-particle tracks with $p_T > 200$ MeV

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

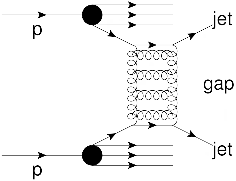
Color-exchange
(single-gluon in t-channel)

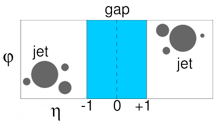






Color-singlet exchange
(two-gluon in t-channel)

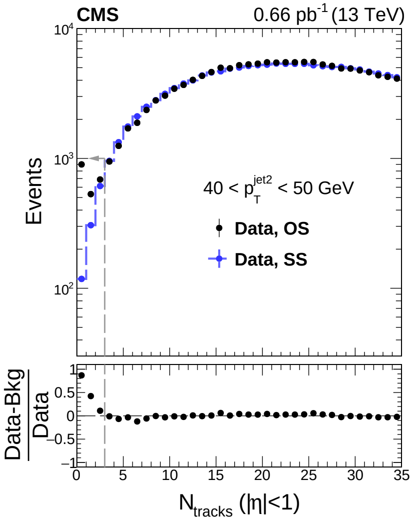




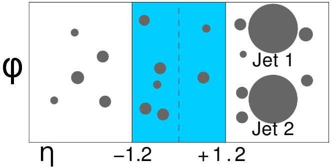
Color-exchange dijet fluctuations at low-multiplicities need to be properly treated.

To avoid model-dependent Monte Carlo predictions, **we used data-based methods to estimate the fluctuations of color-exchange events.**

Approach 1: Same-side (SS) dijets

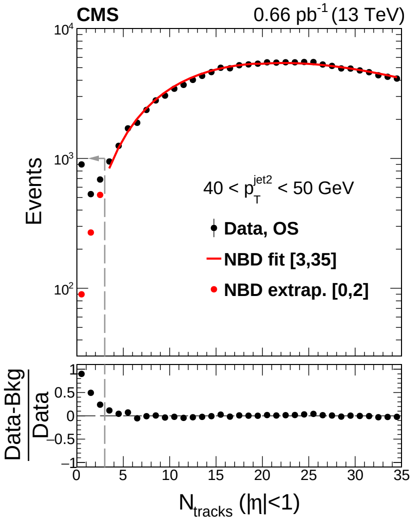


Sharp excess of events at $N_{\text{tracks}} < 3$.



- **Use sample of two jets on the same-side (SS), $\eta^{\text{jet1}}\eta^{\text{jet2}} > 0$.** The resulting N_{tracks} is enriched in color-exchange events.
- Normalize N_{tracks} distribution of SS to the one of opposite-side (OS) jets, $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$, at large N_{tracks}.
- **The η interval and η_{jet} of the jets in SS are optimized to match the N_{tracks} of the OS sample.**
- Minimum forward particle activity to suppress single-diffractive jet contributions ($3 < |\eta| < 5.2$, $E > 5$ GeV).

Approach 2: negative binomial distribution (NBD) function fit



Sharp excess of events at $N_{\text{tracks}} < 3$.

- **Fitted data with NBD in $3 \leq N_{\text{tracks}} \leq 35$, extrapolate down to $N_{\text{tracks}} = 0$.**
- NBDs are good empirical models of N_{ch} distributions in hadron-hadron collisions.
- **Validated the NBD method with trijet data, with SS dijets, and with Monte Carlo events (PYTHIA8 QCD jets).**
- Studied the stability of bkg. when changing fit N_{tracks} interval, other functional forms (eg double NBD), ...

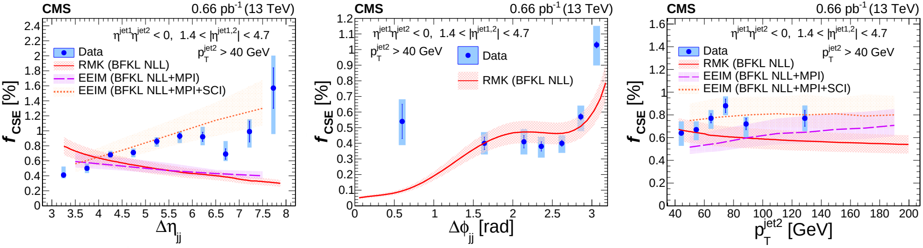
We extract f_{CSE} based on the N_{tracks} analysis between the jets:

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

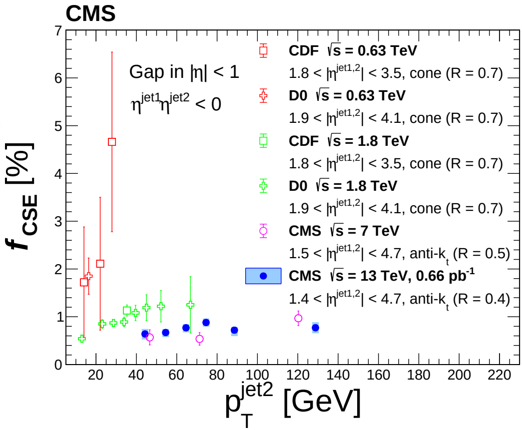
f_{CSE} is measured as a function of:

- $\Delta\eta_{\text{jj}} \equiv |\eta^{\text{jet1}} - \eta^{\text{jet2}}|$: 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.
- $\Delta\phi_{\text{jj}} \equiv |\phi^{\text{jet1}} - \phi^{\text{jet2}}|$: Sensitive to deviations of $2 \to 2$ scattering topology.

Results on color-singlet exchange fraction f_{CSE}

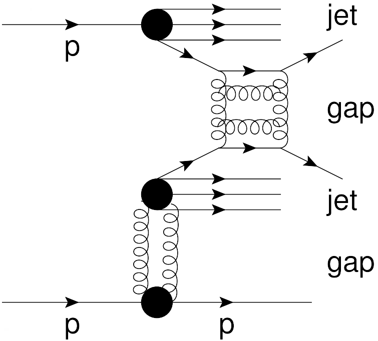


- **Color-singlet exchange represents ≈ 0.6% of the inclusive dijet cross section for the probed phase-space.**
- Comparisons to BFKL predictions (resummation at next-to-leading logarithmic accuracy):
  - Royon, Marquet, Kepka (RMK) predictions and gap survival probability $|S|^2 = 0.1$.
  - Ekstedt, Enberg, Ingelman, Motyka (**EEIM**) predictions with multiple-parton interactions (MPI), also supplemented with soft-color interactions (SCI).
- **Challenging to describe theoretically all aspects of the measurement simultaneously.**
- Existing perturbative calculations are partially NLO; one needs to incorporate NLO order impact factors to complete it (M. Hentschinski, J.D. Madrigal Martínez, B. Murdaca, A. Sabio Vera, Nucl.Phys. B889 (2014) 549, Nuclear Physics B887 (2014) 309)). See talk by F. Deganutti for efforts in this direction.



- 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, f_{CSE} has been observed (and 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 $\rightarrow$ 1.8 TeV $\rightarrow$ 7 TeV.

Turning to CMS-TOTEM combined measurement



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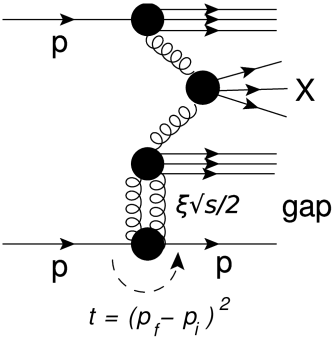


Color-singlet exchange off the proton

Most hard QCD processes are from single parton-parton collisions.

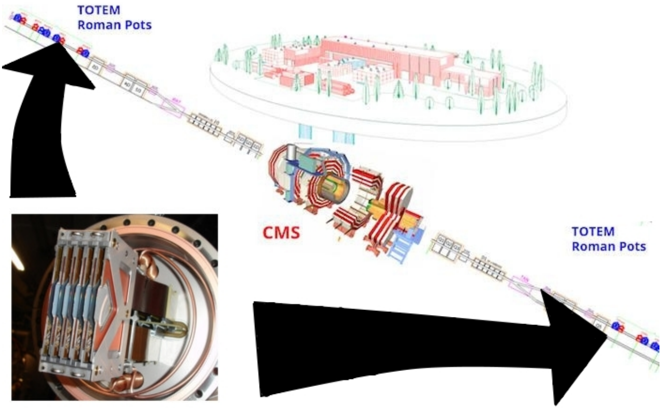
A fraction of the hard QCD processes are mediated by **color-singlet multiparton exchange from the proton** (two-gluons at LO QCD).

These are known as **hard diffractive** processes.

The protons may remain **intact** and be detected very far from the interaction point.

Two additional kinematic variables:

- The fraction of beam momentum carried away by the pomeron exchange, $\xi \equiv \Delta p/p$.
- Square of four-momentum transfer at the proton vertex, $t \equiv (p_f - p_i)^2$.

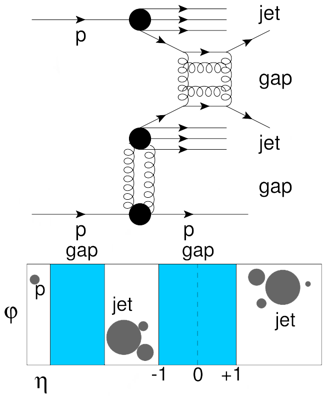


CMS:

- General purpose detector at IP5 of the CERN LHC.
- Jets with $R = 0.4$ reconstructed within $|\eta^{\text{jet}}| < 4.7$.

TOTEM:

- **Roman pots:** Forward tracking detectors at $\approx$ 220m w.r.t. IP5 that measure the protons scattered at small angles w.r.t. the beam.

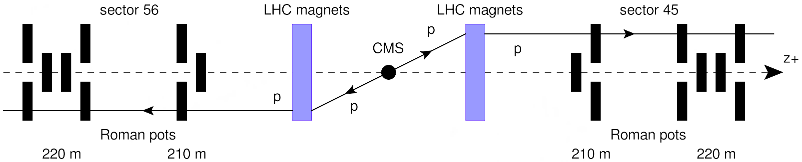


Better understand the role of spectator partons in the destruction of the central gap.

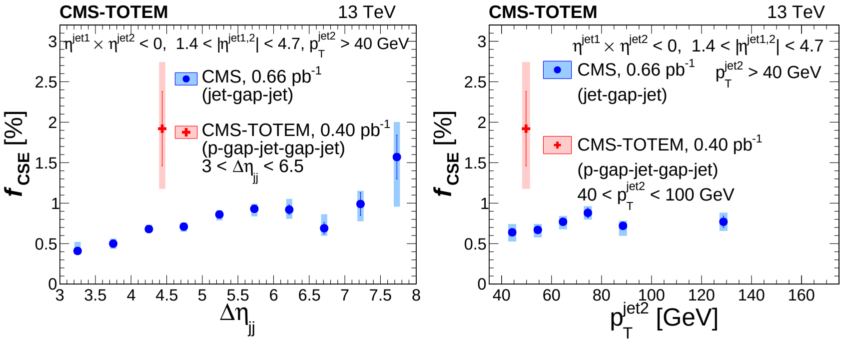
Same dijet and central gap definitions as with CMS-only analysis.

Additional requirements:

- ≥ 1 intact proton.
- $\xi_p(\text{RP}) < 0.2$ and $-4 < t < -0.025$ GeV^2 (+ fiducial RP requirements).



Results on p-gap-jet-gap-jet



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.

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

Future low-PU runs with dedicated trigger w/ more lumi to study process differentially.

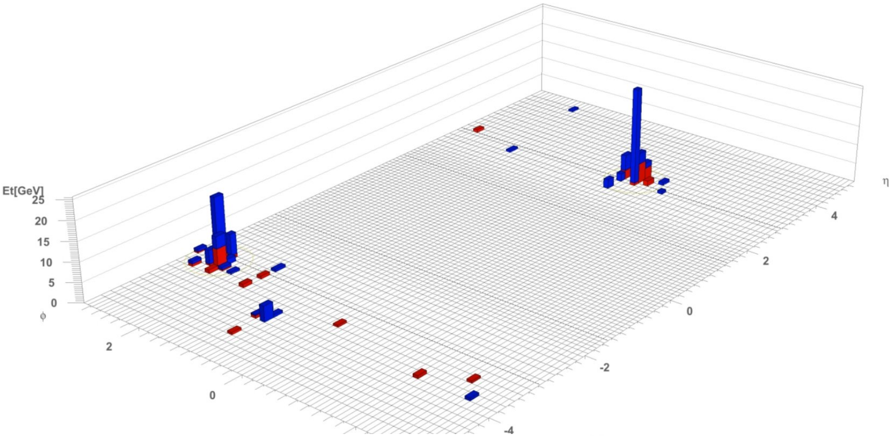
CMS and TOTEM measurements:

- We measured hard color-singlet exchange dijet events at $\sqrt{s} = 13$ TeV with CMS and TOTEM data (arXiv:2102.06945, *Phys. Rev. D* 104, 032009 (2021))

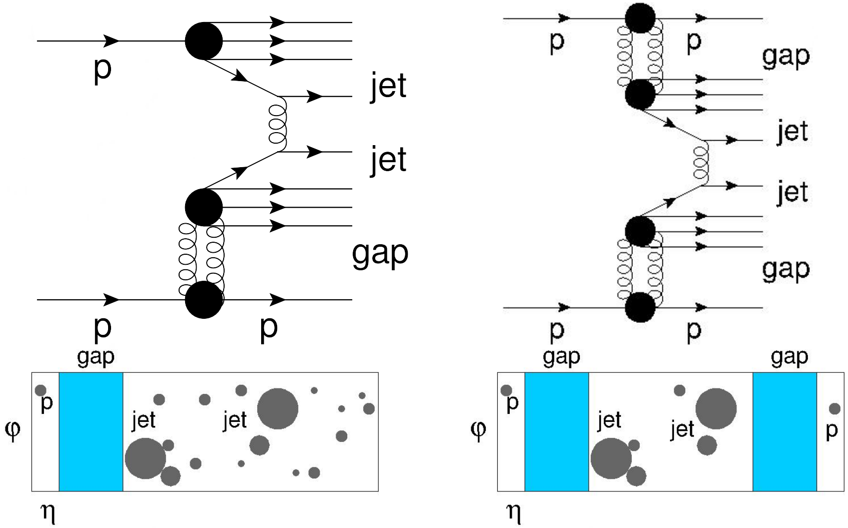
- About 0.6% of dijet events are produced by hard color-singlet exchange (subprocess absent in Monte Carlo simulations).

- First measurement of jet-gap-jet with protons w/ CMS-TOTEM. f_{CSE} in this sample is larger than in CMS-only.

Thank you!



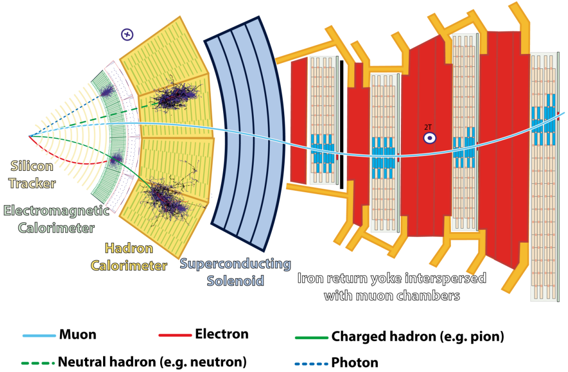
Hard diffractive dijet production at 13 TeV with CMS and TOTEM

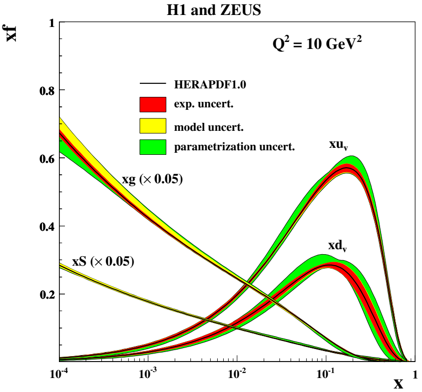


CMS-TOTEM work in progress

CMS is a general purpose detector at the LHC ring.

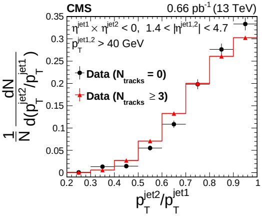
Several subdetector components dedicated to measure **most of the decay debris of proton-proton collisions in a $\approx 4\pi$ solid angle region**.

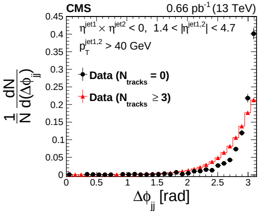


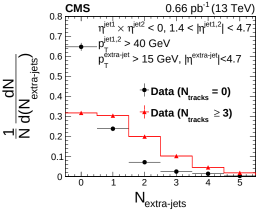


At small-x, small-Q^2, the gluon densities grow rapidly (driven by parton splitting $g \to gg$ or $q \to qg$ at low-x) $\to$ Regime of validity of BFKL evolution.

At very small-x and Q^2, one should expect that not only we have gluon splitting ($g \to gg$), but also gluon recombination ($gg \to g$) to avoid violation of unitarity. This is described by another set of QCD evolution equations (Balitsky-Kovchegov or Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov and Kovner equations).







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 $N_{\text{tracks}} \geq 3$.

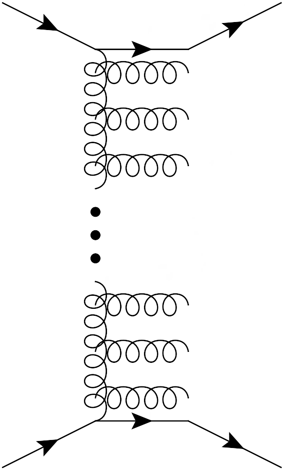
Distributions reflect underlying quasielastic parton-parton scattering process topology.

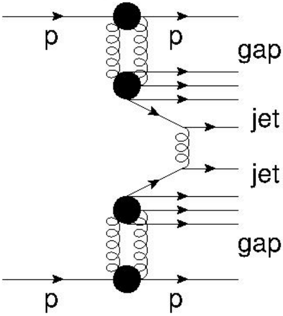
In the leading logarithm approximation, only diagrams where parton emissions are *strongly ordered in rapidity*, with similar p_T, contribute to the cross section in the high energy limit:

$$y_1 \ll y_2 \ll y_3 \ll \cdots \ll y_{n-2} \ll y_{n-1} \ll y_n$$

$$p_{T,1} \approx p_{T,2} \approx p_{T,3} \approx \ldots p_{T,n-2} \approx p_{T,n-1} \approx p_{T,n} \gg \Lambda_{QCD}$$

The contributions in the leading logarithm approximation are dominated by gluon branching.

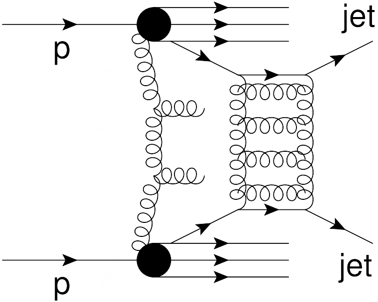


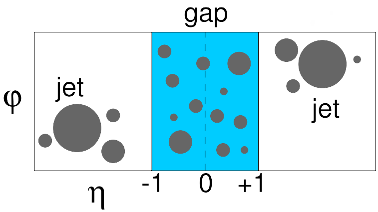


Pomeron exchange from each colliding proton leading to two high p_T jets.

- **Process has not been studied with the detection of the two intact hadrons.**
- These events are cleaner than their single-diffractive or non-diffractive dijet counterparts.
- Process is key to study the breakdown of factorization of hard diffractive reactions.
- Same selection requirements, except that we require ***exactly two protons.***

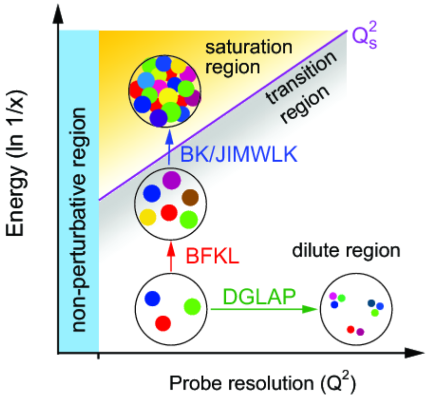
Although there is a short-distance physics mechanism for gap formation (pomeron exchange), spectator parton activity can destroy the central gap.





This is parametrized by means of a survival probability, $|\mathcal{S}|^2$, which reduces the visible cross section of jet-gap-jet events. Difficult to understand theoretically. $|\mathcal{S}|^2 = \mathcal{O}(10\%)$ at the LHC

The central η gap signature can be destroyed by multiple-parton interactions or rearrangement of the color field by soft-parton exchanges.



Owing to universality of strong interactions, QCD evolution equations of high-energy scattering arise also in PDF evolution in parton momentum fraction x at hard energy scales Q.

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

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

Balitsky–Fadin–Kuraev–Lipatov (BFKL) evolution

All-orders resummation in α_s is done via the Balitsky–Fadin–Kuraev–Lipatov (BFKL) evolution equations. Resummation is known at leading logarithmic (LL) accuracy ($\alpha_s^n \ln^n(\hat{s}/|\hat{t}|)$ terms) and next-to-LL (NLL) accuracy ($\alpha_s^n \ln^{n-1}(\hat{s}/|\hat{t}|)$ terms).

The BFKL equation (in Mellin space), which emerges upon the resummation of logs, is symbolically represented by:

$$\omega \mathcal{G}_\omega = \mathbb{I} + \mathcal{K} \otimes \mathcal{G}_\omega \qquad (1)$$

$\mathcal{G}_\omega$ is known as the BFKL Green's function, and encodes the all-orders resummation of logarithms, ω is a complex angular momentum variable, $\mathcal{K}$ is the BFKL kernel, and $\otimes$ represents a convolution.

By solving for $\mathcal{G}_\omega$ (in terms of the eigenfunctions of $\mathcal{K}$), one can then calculate the corresponding scattering amplitude by means of an **inverse** Mellin transform to momentum space.

A famous prediction by BFKL resummation is that scattering amplitudes should scale as

$$\mathcal{M} \propto \hat{s}^\lambda$$

where $\lambda = 4\ln(2)\alpha_s N_C/\pi \approx 0.5$ in the LL approximation.

Hard partonic cross sections scale with a power of $\hat{s}$ in the high energy limit of QCD.

Similar QCD evolution equations

Similar set of resummation techniques are used for square momentum transfer Q^2. This resummation is done via the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations.

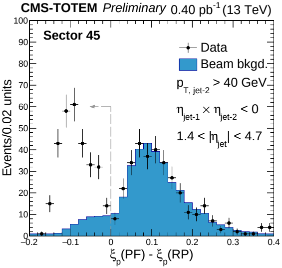
DGLAP evolution equations are the bread-and-butter of PDF evolution for the LHC physics program (PDF at low Q_0^2 is "evolved" to another PDF at $Q^2 > Q_0^2$).

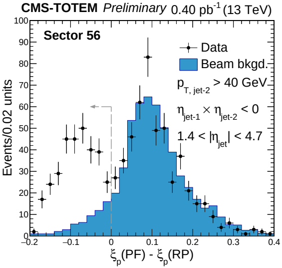
DGLAP dynamics are approximated in parton shower algorithms embedded in standard Monte Carlo generators (Pythia8, Herwig, Sherpa, ...) for numerical resummation of collinear parton splittings.

In the DGLAP picture, parton splittings strongly ordered in p_{T} contribute in the leading logarithm approximation,

$$y_1 < y_2 < y_3 < \cdots < y_{n-2} < y_{n-1} < y_n$$

$$p_{T,1} \gg p_{T,2} \gg p_{T,3} \gg \ldots p_{T,n-2} \gg p_{T,n-1} \gg p_{T,n} \gg \Lambda_{\mathrm{QCD}}$$



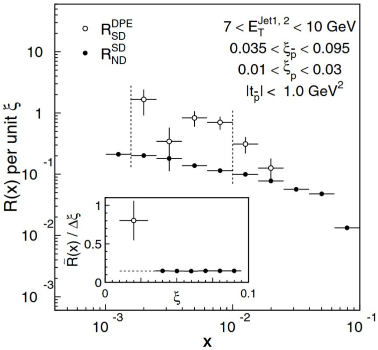


Estimated with event-mixing: inclusive dijet events paired with protons in zero-bias sample.

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.

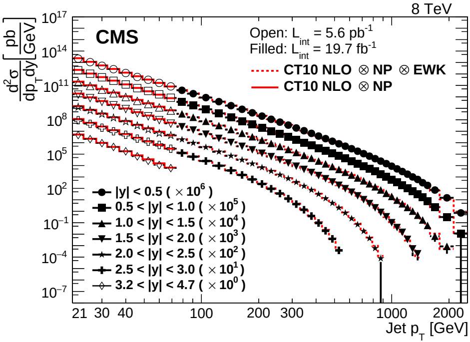
Consistent with other two-rapidity gap topology



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

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

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



CMS, JHEP 03 (2017) 156, arXiv:1609.05331

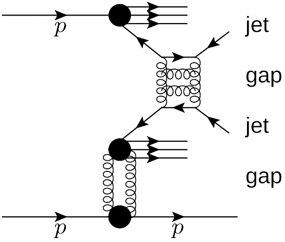
Fixed-order pQCD has been rigorously tested in inclusive jet cross section measurements at the Tevatron and LHC.

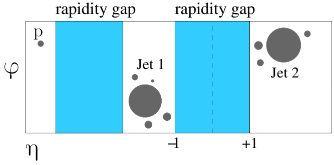
Perturbative calculations supplemented with parton shower and soft QCD effects (underlying event activity, beam remnants, hadronization, . . .), are generally very successful in describing jet production over various collision energies for numerous jet p_T and y configurations.

These precision measurements test the rapidity y and p_T ranges where fixed-order pQCD approaches can be trusted.

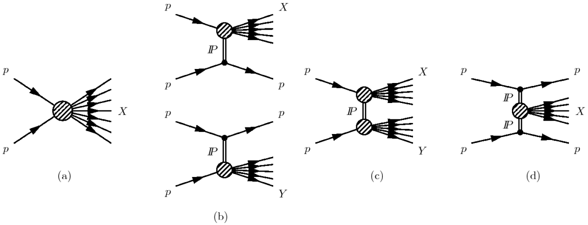
Gap survival probability

In pp collisions with intact protons, spectator-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!** Will discuss on second part of this talk.

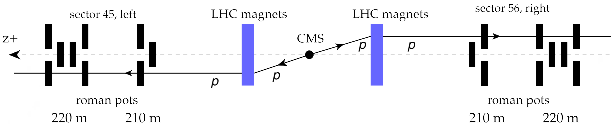


TOTEM shares the same interaction point as CMS (IP5) at the LHC. TOTEM studies a special class of physics, known as diffractive physics:

- Total hadronic cross section measurement, $\sigma_{\mathbf{tot}}$.
- Elastic cross section measurement ($pp \to pp$).
- Single- and central-diffraction $pp \to pX$ and $pp \to pXp$, where X corresponds to many soft particles.

Occassionally, CMS and TOTEM collect data together in dedicated runs to do special physics together (central, harder particles in CMS, and forward, intact protons in TOTEM).

TOTEM Roman pot detectors



Near-beam (a few mm close to the beam) silicon tracking detectors hosted in vacuum vessels (Roman pots) inserted in the LHC beam pipe. Designed to not disrupt the operation of the LHC.

Accelerator magnetic lattice (magnetic dipoles & quadrupoles), which are designed to manipulate the LHC beam optics, can be also used as an effective proton momentum spectrometer.

Protons that have lost a small fraction of their original beam-momentum will be separated from beam-momentum protons.

Precise knowledge of the magnetic lattice → Reconstruction of intact proton kinematics.

Two important kinematic variables:

- Fractional momentum loss of the proton, $\xi = \Delta p/p$.
- Four-momentum transfer square at the proton vertex, $t = (p_f - p_i)^2$.