Diffractive and forward physics measurements by CMS and CMS-TOTEM

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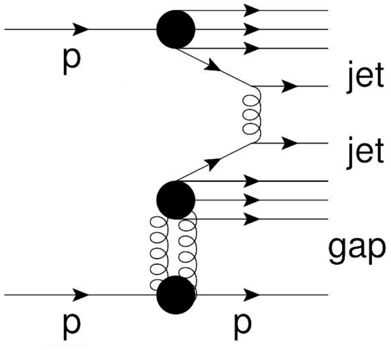
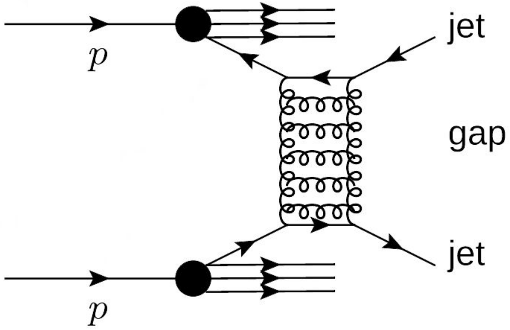
What does CMS have to say on small-x and diffraction?

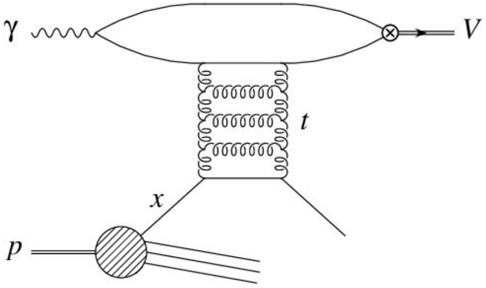
Selection of results in pp and pPb collisions by CMS from the last 2+ years (⚠️ personal bias). ***G. Krintiras will cover CMS diffraction and UPC results in PbPb; M. Pitt discussed photon-induced processes with proton tagging.***



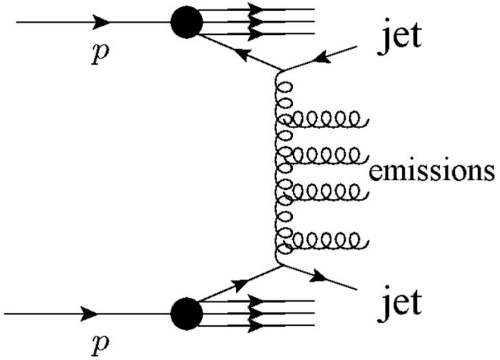
Diffractive dijet with an intact proton



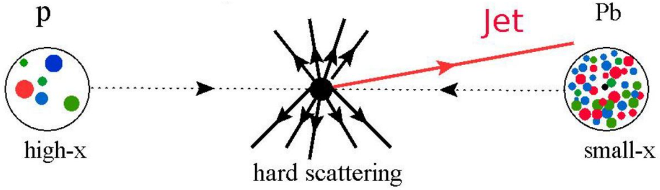
Jet-gap-jet



Diffractive vector meson

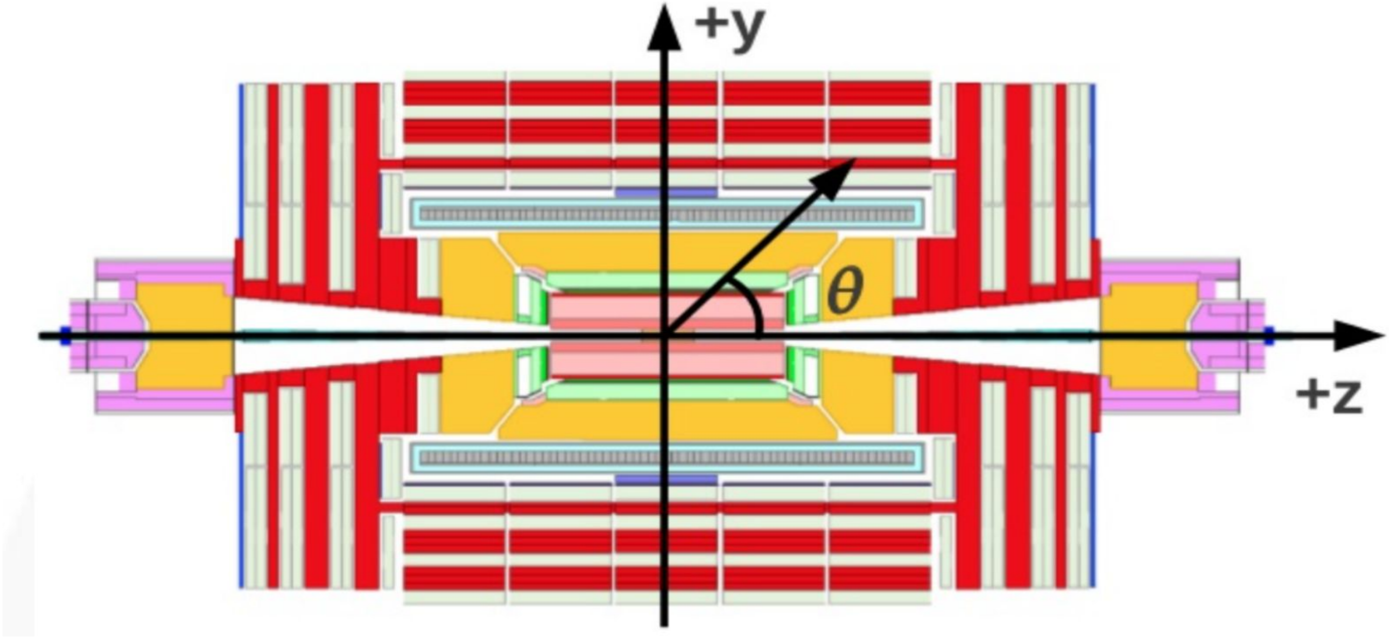


Mueller-Navelet jets



Forward jet measurement

CMS detector

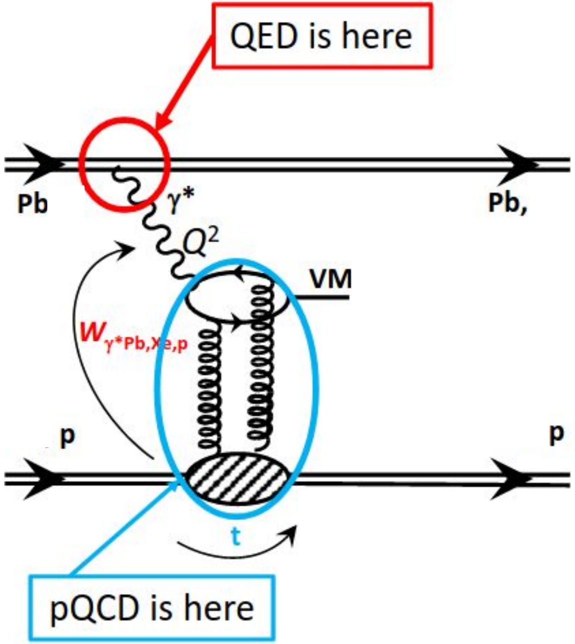


Tracker & muon chambers acceptance up to $|\eta| < 2.5$; **p_T > 200 MeV for tracks**
hadronic calorimeter coverage up to $|\eta| < 5.2$; **noise threshold E ≳ 5 GeV in fwd region**

Jet reconstruction spans wide range in $|\eta| < 4.7$ and as low as $p_T > 20$ GeV

Exclusive vector meson production in pPb collisions

Quasi-real photon exchange from Pb ion fluctuates into a color dipole that probes the proto .



At LO in pQCD,

$$\sigma(\gamma^* p \to Vp) \sim [\, g(x, Q^2 = m_V^2)\,]^2$$

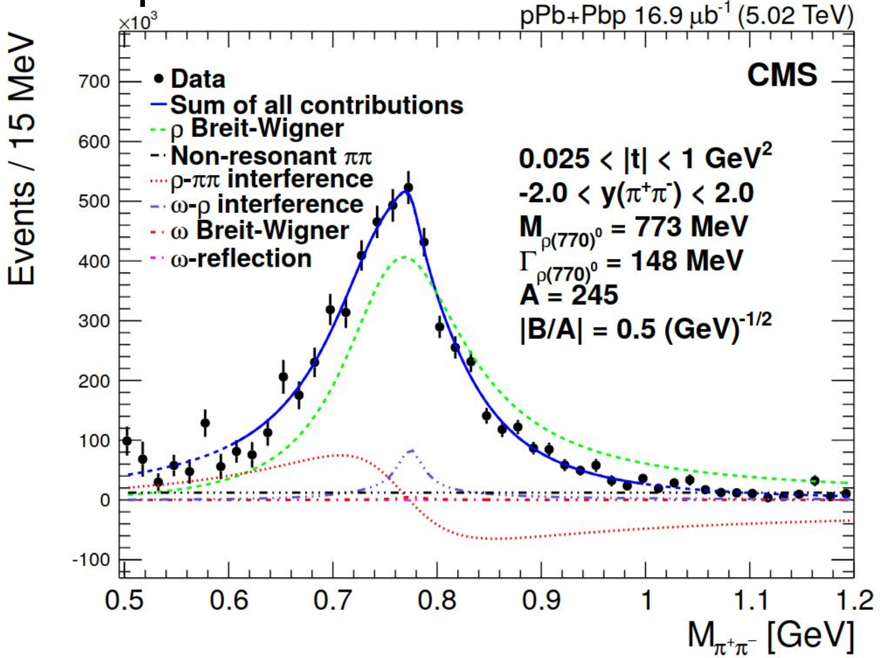
In principle, strong sensitivity to small-x evolution of gluon PDFs

(NB: this is no longer true at NLO, *as discussed by V. Guzey in this conference*)

Physics *a la* EIC at the LHC (energetic “photon” beam, smaller photon virtualities)

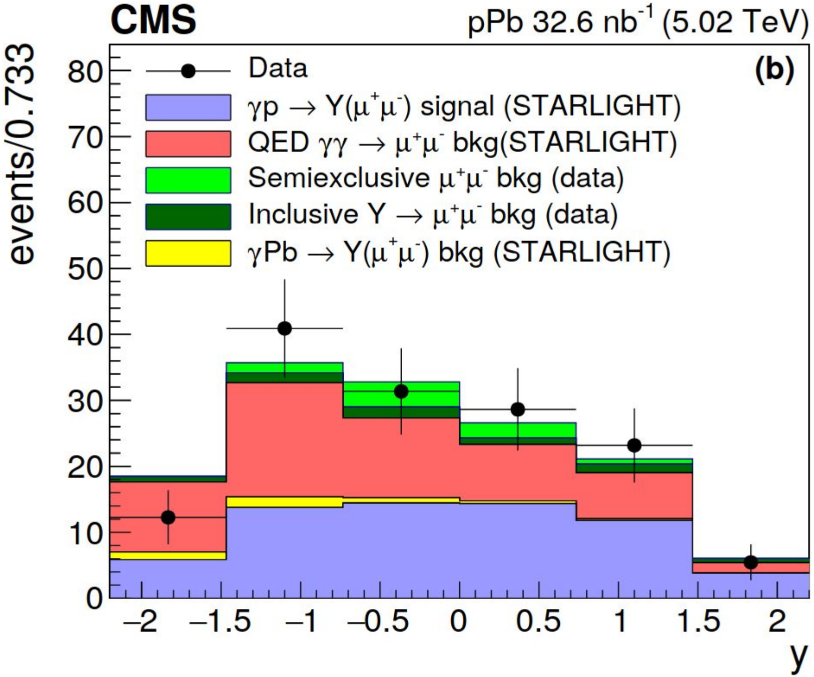
Exclusive vector meson production in 5.02 TeV pPb collisions

excl. $\rho^0 \to \pi^+\pi^-$ CMS, EPJC 79 (2019) 702



Exclusive ρ requires special treatment of backgrounds (+ interference with other states).

excl. $\Upsilon \to \mu^+\mu^-$ CMS, EPJC 79 (2019)



Critical to control **$\gamma\gamma \to \mu^+\mu^-$ background**

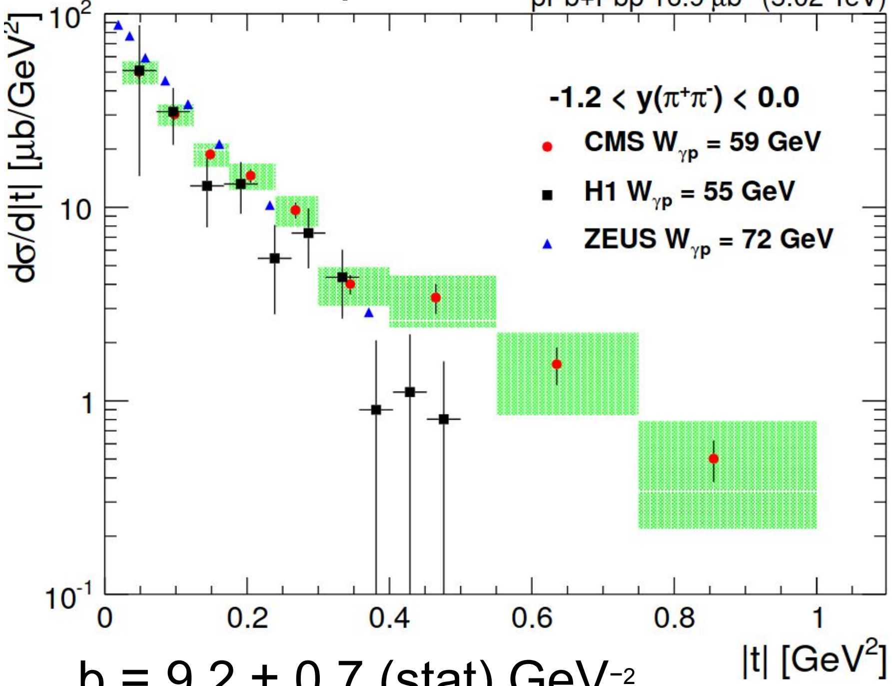
Different masses of vector mesons allows us to scan different color dipole sizes and different pQCD scales
→ ***Necessary if we want to establish universality properties.***

|t| distributions (corrected for smearing effects)

One can use the p_T^2 of the vector meson as a proxy for |t|.

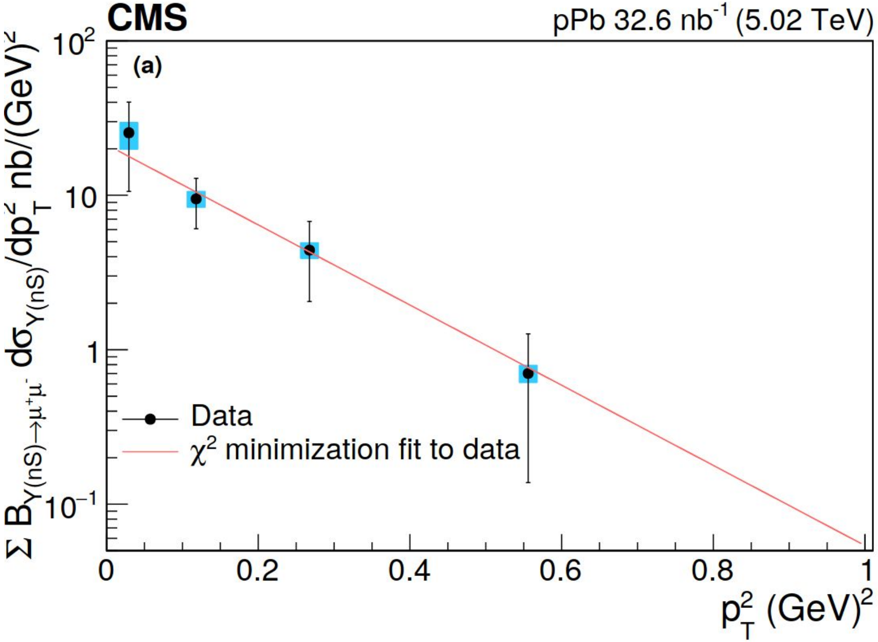
Provides info on impact parameter space (*b* and *t* are Fourier conjugate variables)

exclusive ρ^0 CMS, EPJC 79 (2019) 702



$b = 9.2 \pm 0.7$ (stat) GeV^{-2}

exclusive Υ CMS, EPJC 79 (2019)

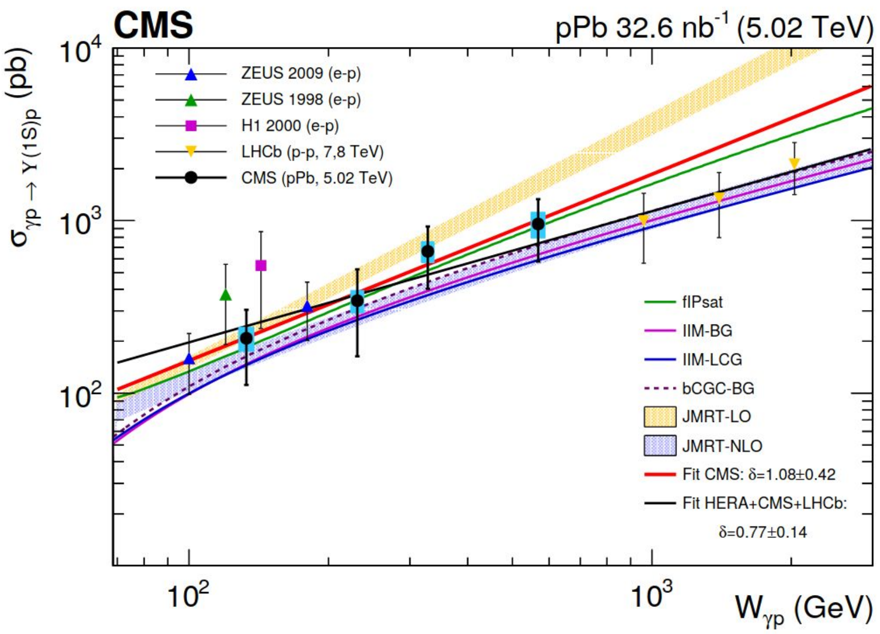


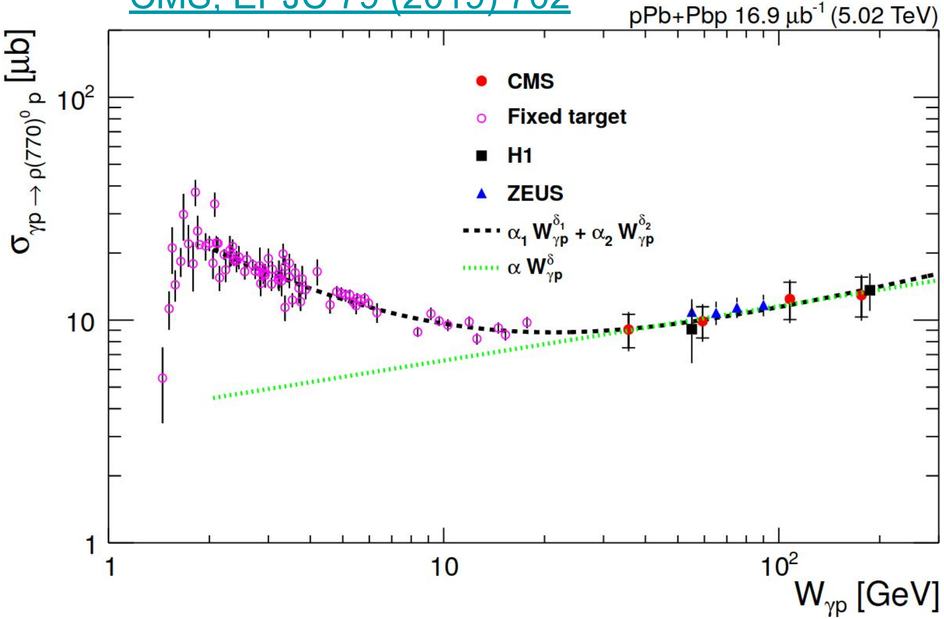
$b = 6.0 \pm 2.1$ (stat) ± 0.3 (syst) GeV^{-2}

Cross section in γ*p frame

Cross sections in pPb frame can be “unfolded” to photon-proton frame using the photon flux from the Pb ion as an input for a given rapidity bin.

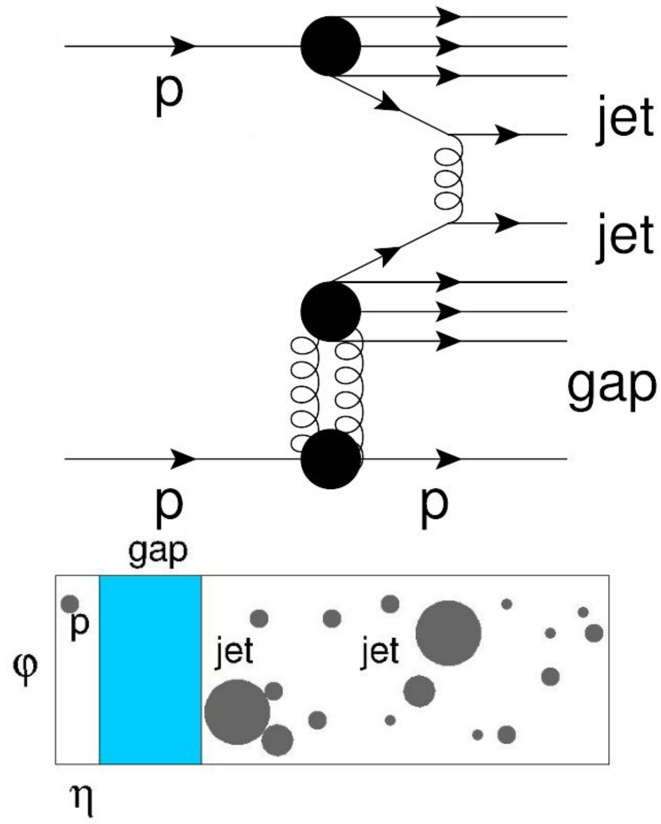
CMS, EPJC 79 (2019) 702





HERA+LHC data consistent with linear evolution. To probe non-linear evolution effects, one needs to increase beam energy or increase number of nucleons (***see G. Krintira’s talk on PbPb***).

Hard diffraction with intact protons detected in Roman pots of TOTEM



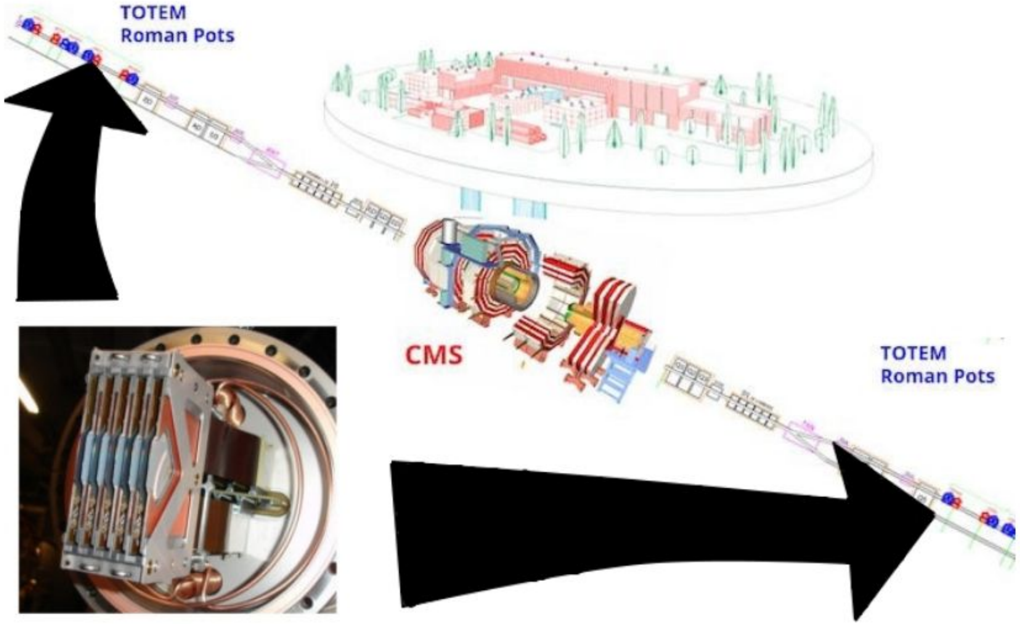
Intact proton is an unambiguous signature of diffraction

Proton detection gives direct access to:

- Four-momentum transfer at the proton vertex |t| (0.03 < $|t|$ < 1 GeV^2)
- Fractional momentum loss ξ ($x_{\mathbb{P}}$ in HERA notation), proxy for the energy carried away by the pomeron/reggeon exchange. (0.0 < ξ < 0.1 for Run-1 analysis)

CMS-TOTEM setup

Roman pots:
Near-beam Si tracker
detectors



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.

|t| distribution for single-diffractive jets

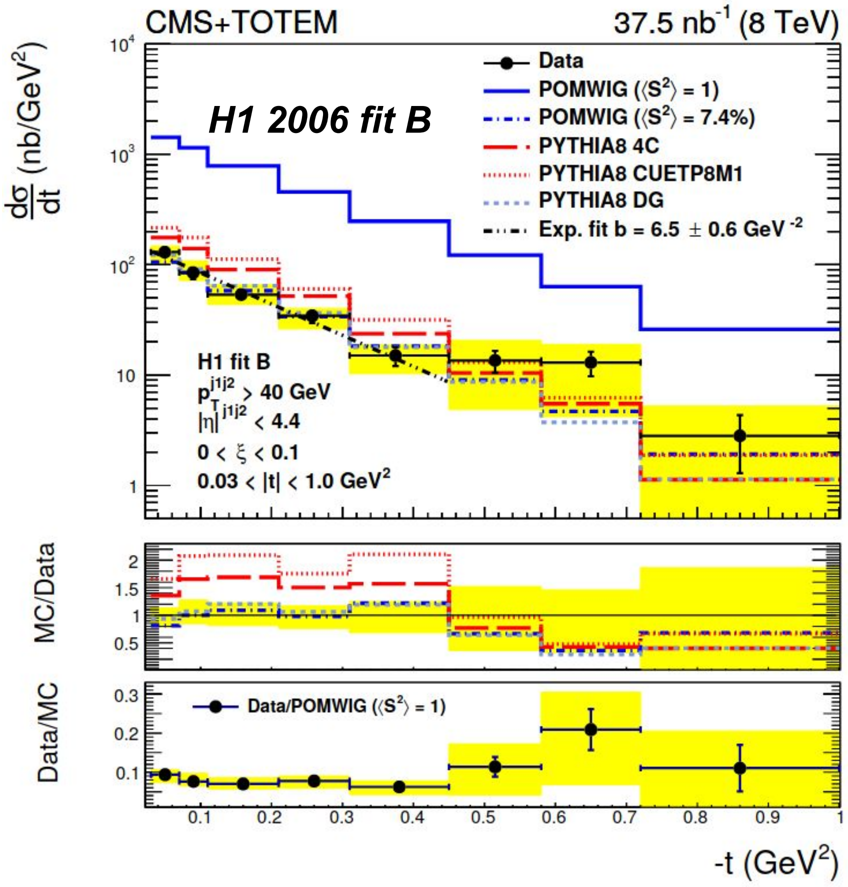
CMS-TOTEM, EPJC 80, 1164 (2020)

Exponential slope *b = 6.5 ± 0.6 GeV* $^{-2}$ consistent with other hard diffraction probes.

Bare POMWIG overshoots data (requires **survival probability of 7.4%**), ***stronger factorization breaking compared to CDF***.

PYTHIA8 predictions systematically off by a factor of ~2 at low |t|.

PYTHIA8 with dynamical gap (DG) model correctly describes the rate and shape of the distribution, ***no additional correction factor.***

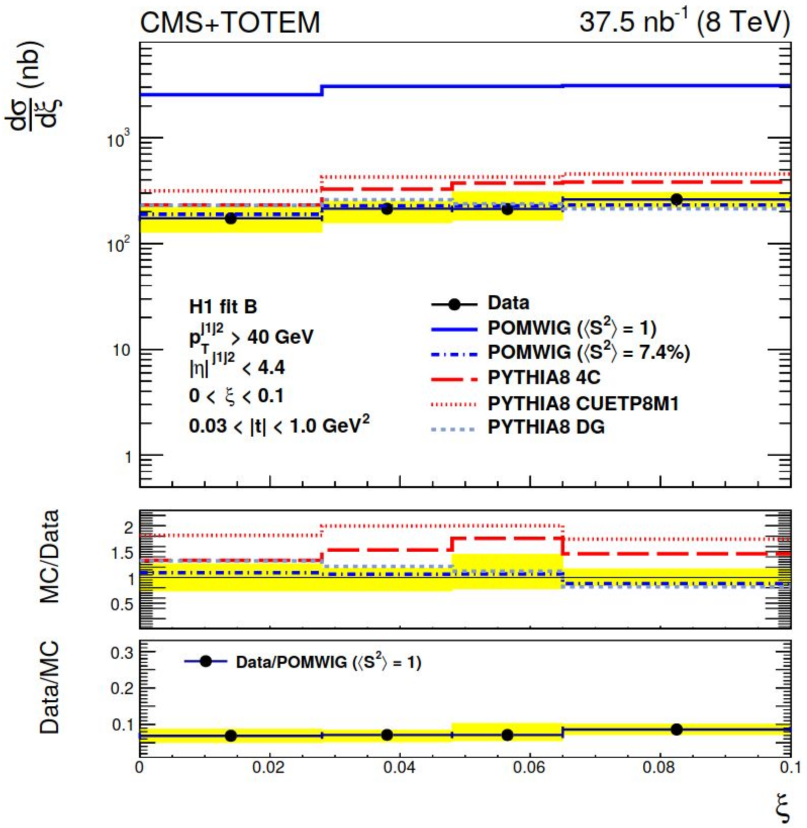


Fractional momentum loss ξ ($x_{\mathbb{P}}$ in HERA notation) CMS-TOTEM, EPJC 80, 1164 (2020)

H1 2006 fit B

Significantly extending reach based on forward gaps only ξ < 0.01.

Pomeron and reggeon exchange (**POMWIG**) yield the same shapes as pomeron-only (**PYTHIA8**).



Data corrected to particle-level

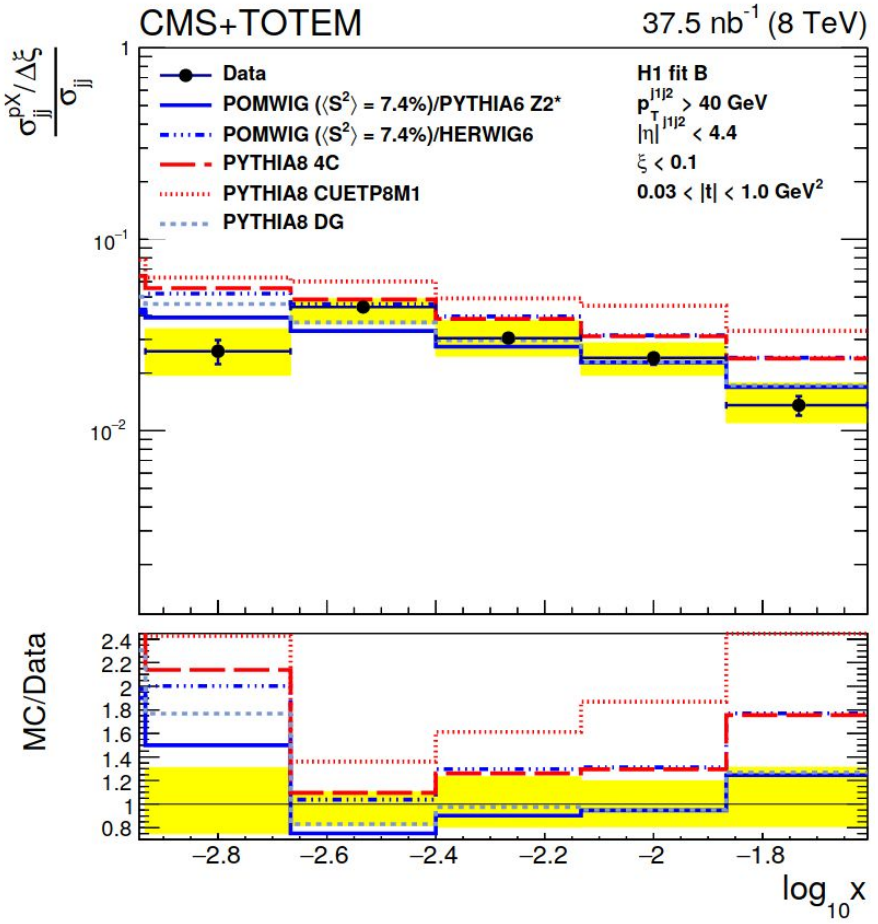
CMS-TOTEM, EPJC 80, 1164 (2020)

Proxy for parton momentum fraction can be estimated from jets kinematics:

$$x^{\pm} = \frac{\sum_{\text{jets}} \left(E^{\text{jet}} \pm p_z^{\text{jet}}\right)}{\sqrt{s}},$$

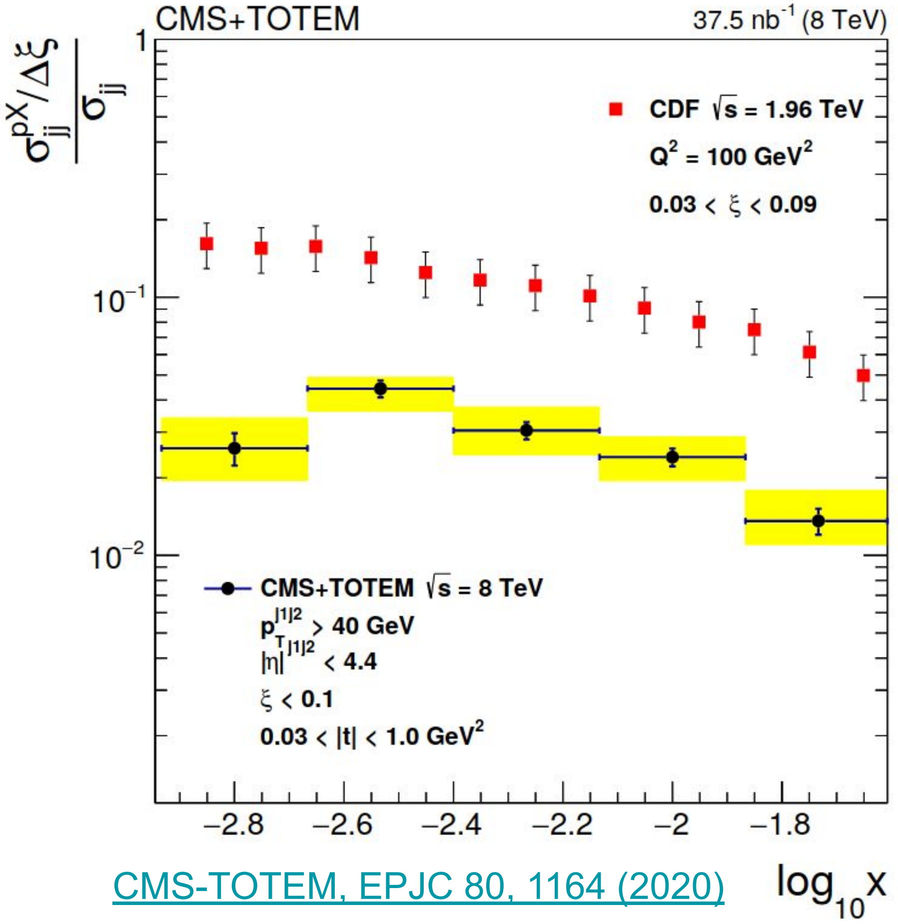
POMWIG (with a survival probability of 7.4%) describe qualitatively well the shapes.
PYTHIA8 predictions off at high- and low-*x*.

PYTHIA8 with dynamical gap correctly describes the rate in data, no additional suppression factor is needed.



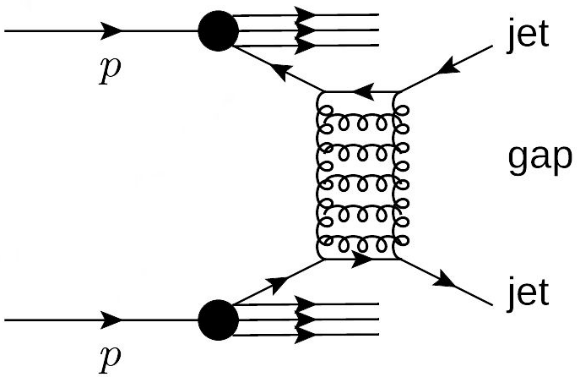
Suppression of single-diffractive jets as a function of √s

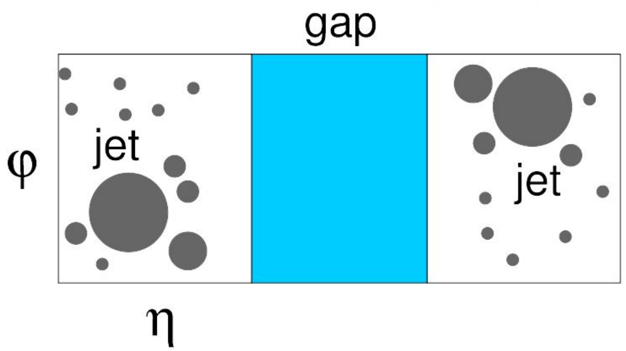
Fraction of diffractive jets decreases with energy (**Tevatron → LHC**), qualitatively expected from survival probability dependence on √s.



[CMS-TOTEM, EPJC 80, 1164 (2020)]

Mueller-Tang jets (a.k.a., “jet-gap-jet”)



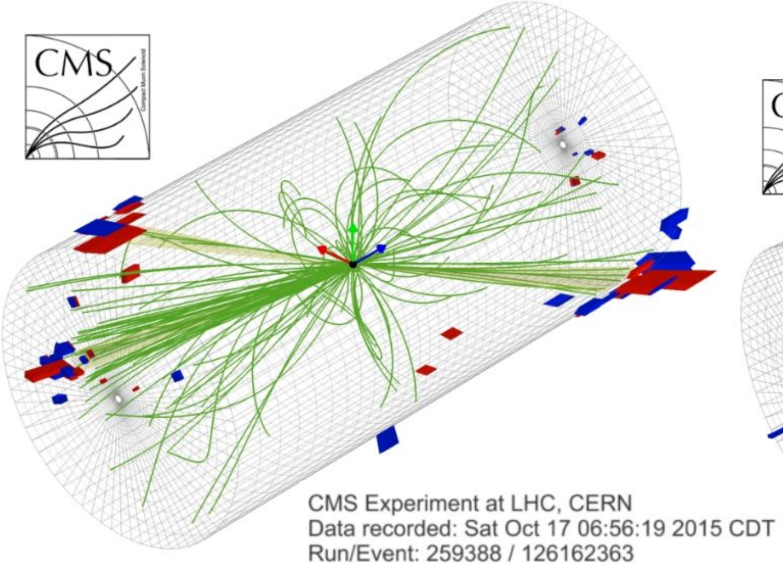


t-channel color-singlet exchange between partons → ***rapidity gaps between final-state jets***

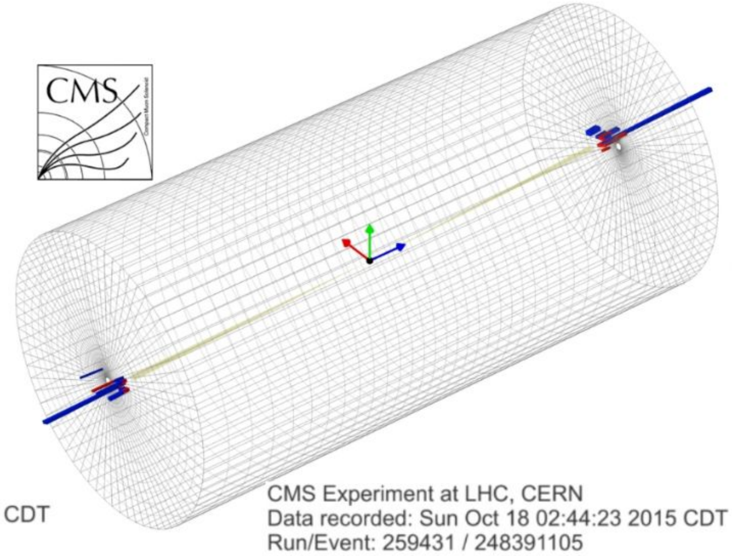
In the high-energy limit (large $\Delta\eta_{jj}$), it is expected to be mediated by **BFKL pomeron exchange**. A. Mueller and W-K. Tang, PLB 284 (1992) 123.

Experimentally, a signal with a controllable QCD background.

CMS event displays (low pileup data)



Color-exchange event candidate
(Background-like)



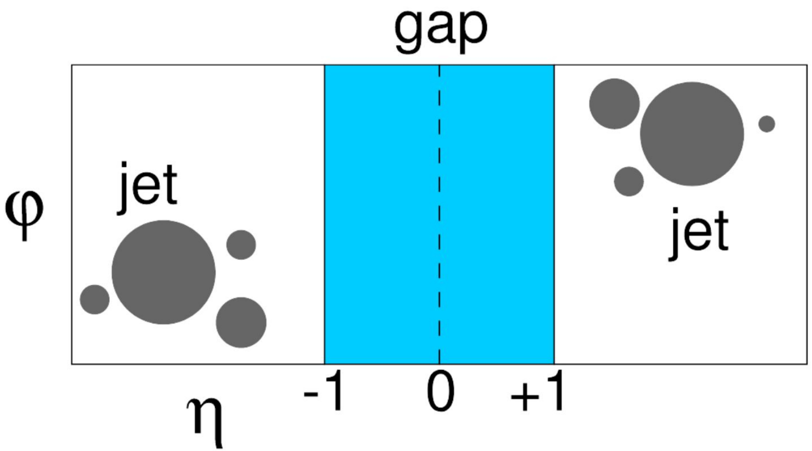
Color-singlet exchange event candidate
(Signal-like)

tracks with pT > 0.2 GeV are plotted here.

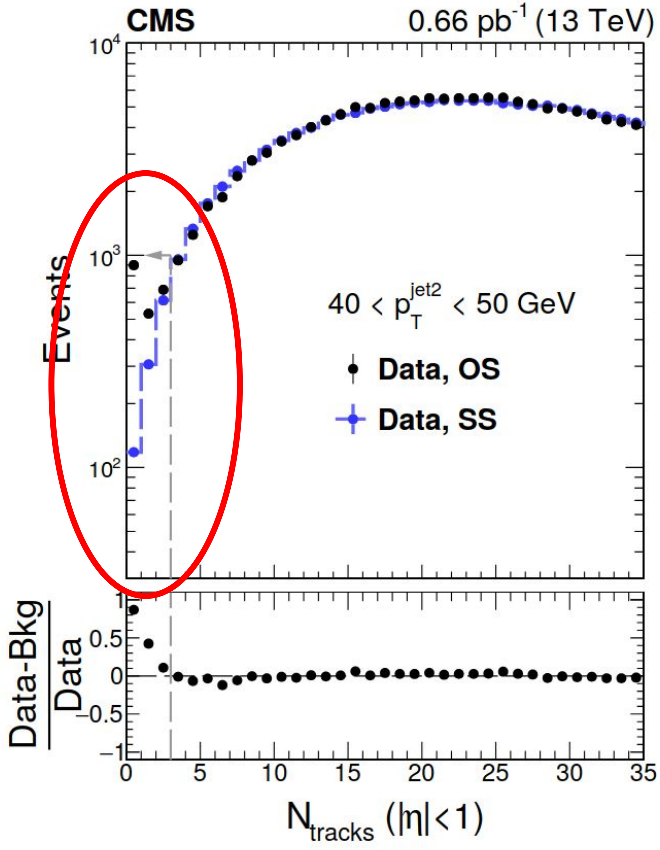
Rapidity gap definition

CMS-TOTEM PRD 104, 032009 (2021)

Number of charged-particles with p_T> 200 MeV in $-1 < \eta < 1$ is measured, ***rapidity gap corresponds to absence of N_{tracks}.***

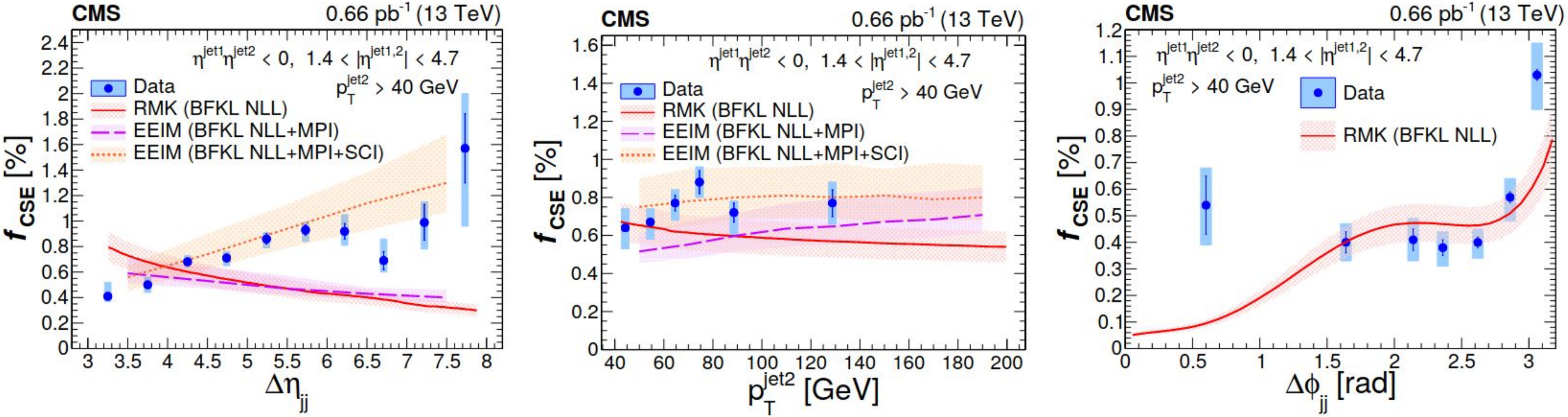


Each jet has $|\eta_{jet}| > 1.4$, with $\eta_{jet1} * \eta_{jet2} < 0$, with p_T>40 GeV.



Residual color-octet background is subtracted with data-driven methods.

Color-singlet fraction f_{CSE} by CMS at 13 TeV



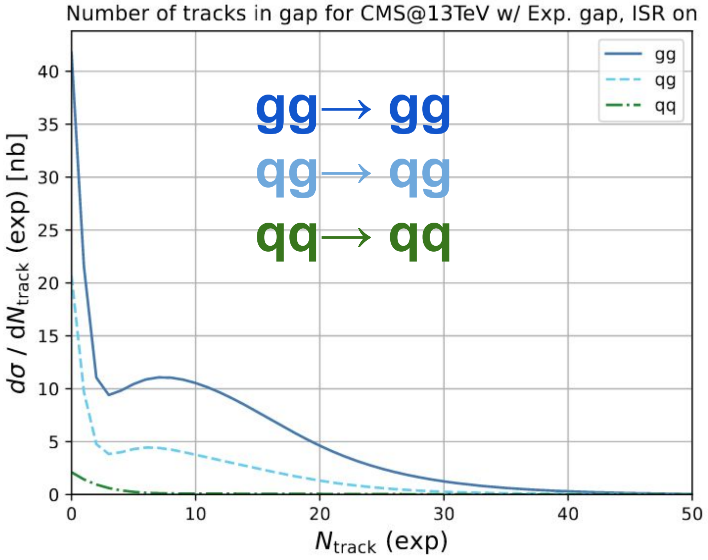
CMS-TOTEM PRD 104, 032009 (2021)

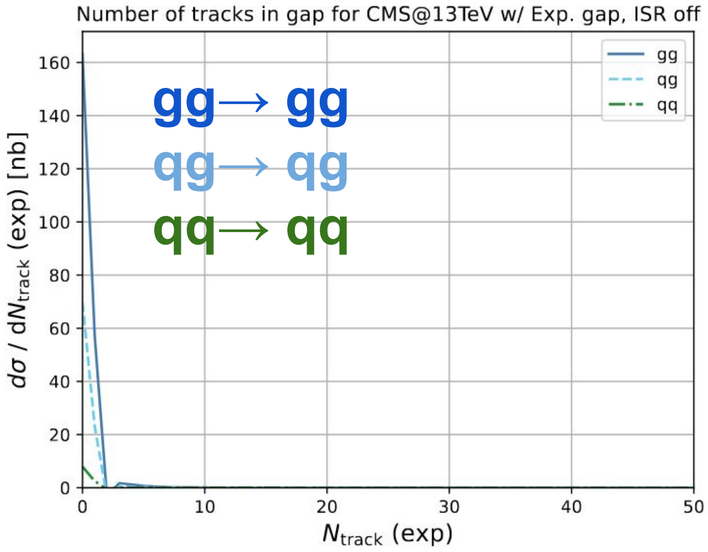
About 0.6% of dijets are produced by hard color-singlet exchange, contribution neglected in modern MC generators.

Pure BFKL predictions (**or pure BFKL + MPI**) get the trend with data wrong as a function of $\Delta\eta_{jj}$ (Royon, Marquet, Kepka, PRD 83:034036, 2011)

BFKL + soft-color interaction for gap survival probability correctly describes $\Delta\eta_{jj}$ trend (Ekstedt, Enberg, Ingelman, Motyka, arXiv:1703.10919)

Number of particles in the gap for color-singlet signal events





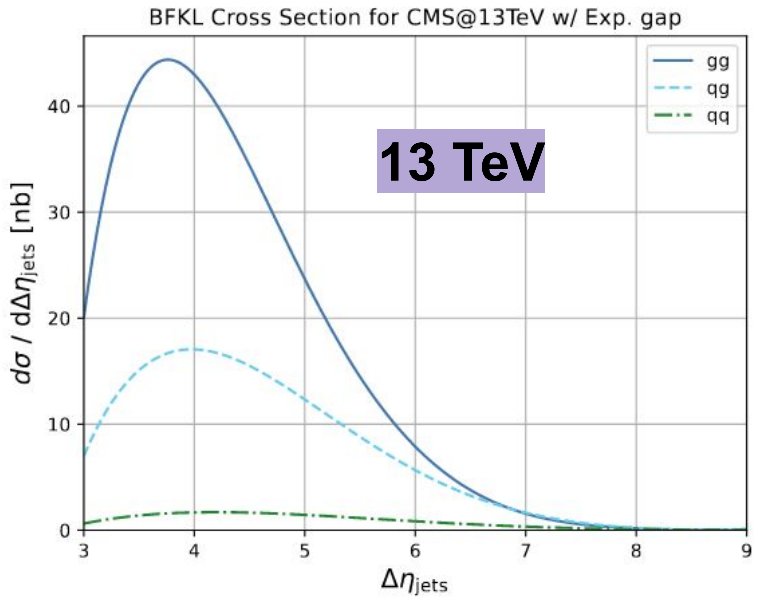
`ISR = on` → more particles between the jets.

`ISR = off` → fewer particles between the jets (unclustered wide-angle hadrons).

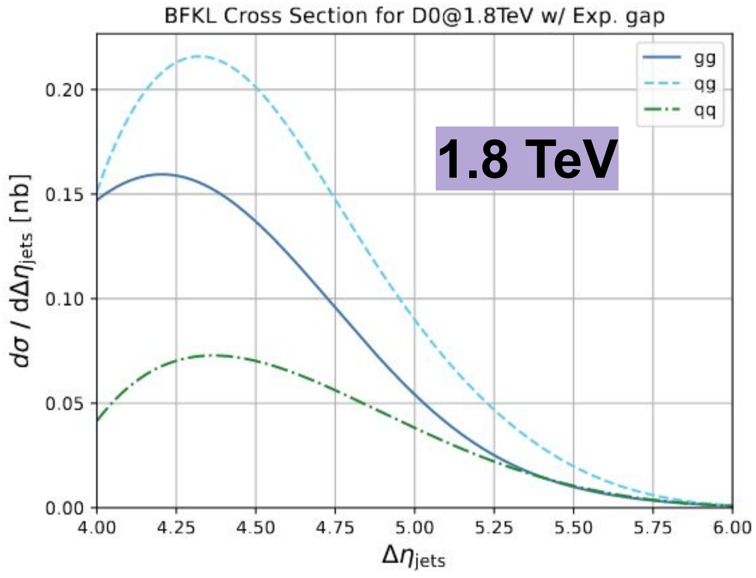
Unexpected sensitivity to ISR in central pseudorapidities.

CB, P. Gonzalez, M. Klasen, J. Salomon, C. Royon, JHEP 08 (2022) 250

PDFs ⊗ color structure for color-singlet exchange ⊗ BFKL kinematical dependence



13 TeV



1.8 TeV

At 13 TeV, $gg \to gg$ dominates over $qg \to qg$ and $qq \to qq$.

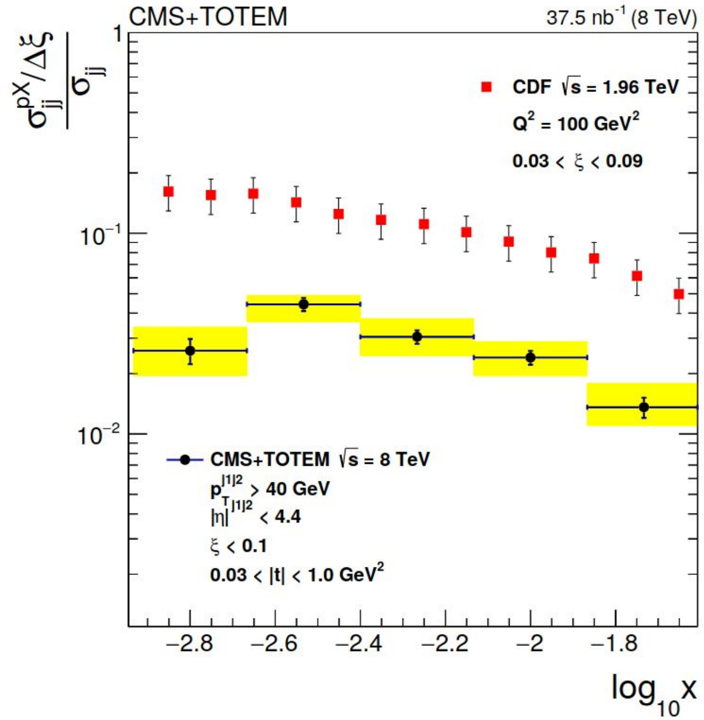
At 1.8 TeV, $qg \to qg$ dominates over $gg \to gg$ and $qq \to qq$.

CB, P. Gonzalez, M. Klasen, J. Salomon, C. Royon, JHEP 08 (2022) 250

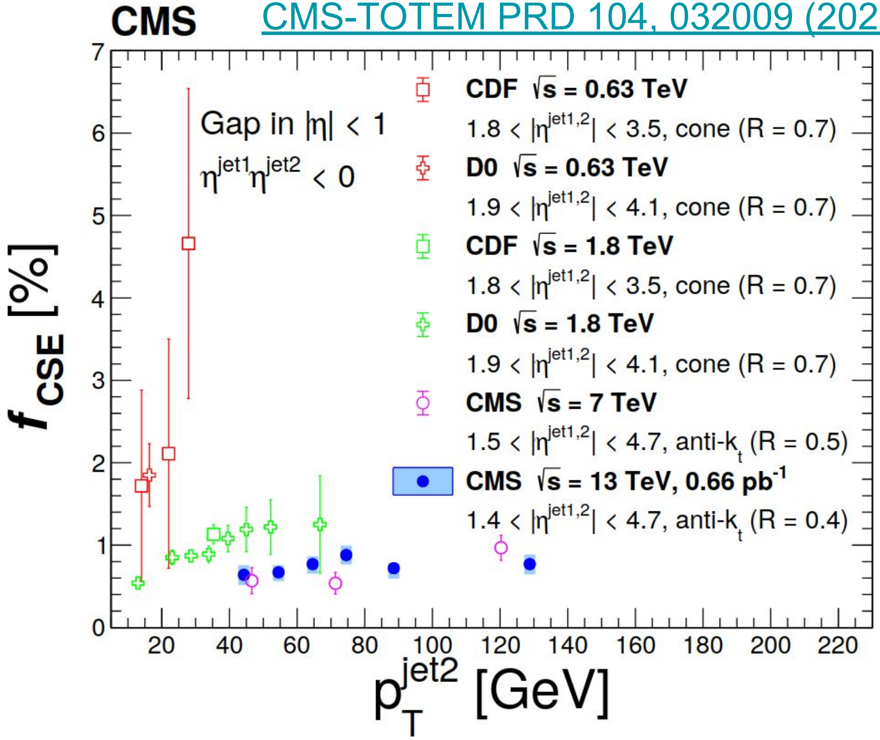
At 13 TeV, we are more sensitive to ISR effects for gluon-gluon processes.

Suppression of jet-gap-jet fraction with √s

CMS-TOTEM, EPJC 80, 1164 (2020)



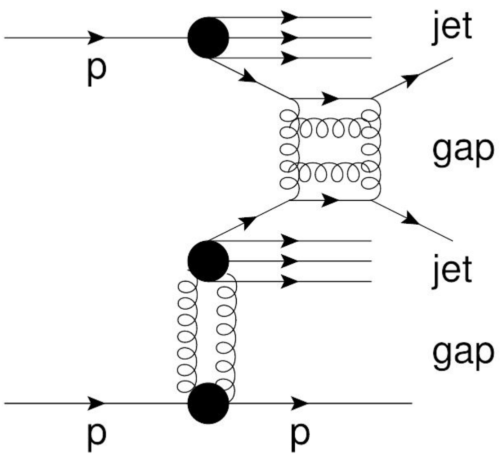
CMS-TOTEM PRD 104, 032009 (2021)

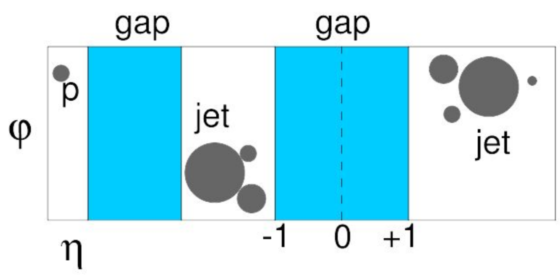


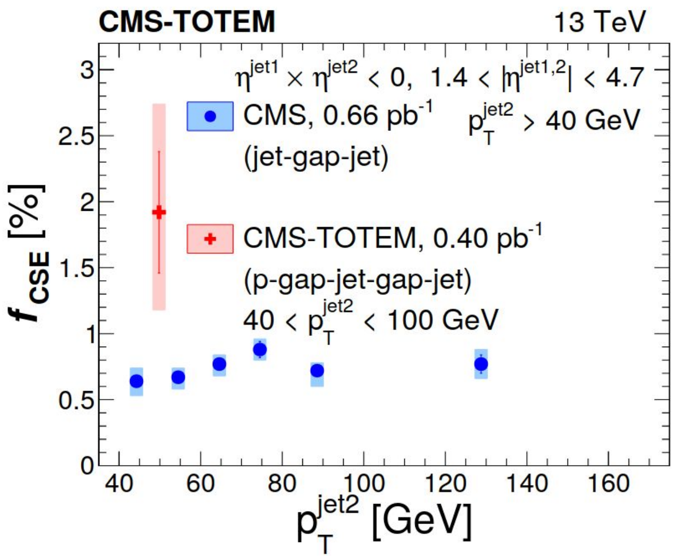
Decrease from Tevatron to LHC energies, ***consistent with diffractive dijet trend***

Gap between jets with intact proton

CMS-TOTEM PRD 104, 032009 (2021)





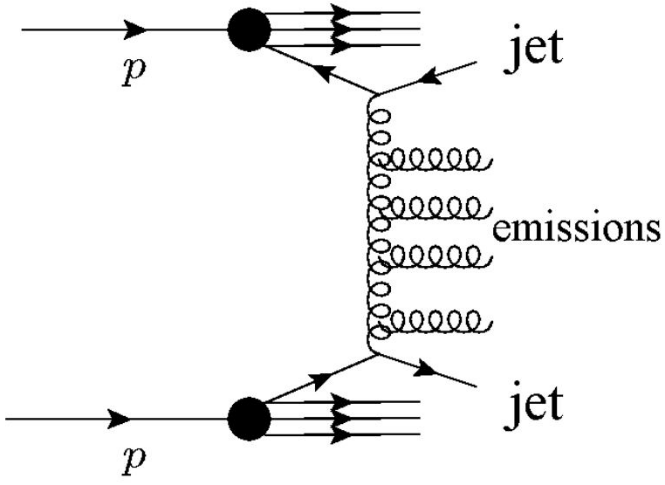


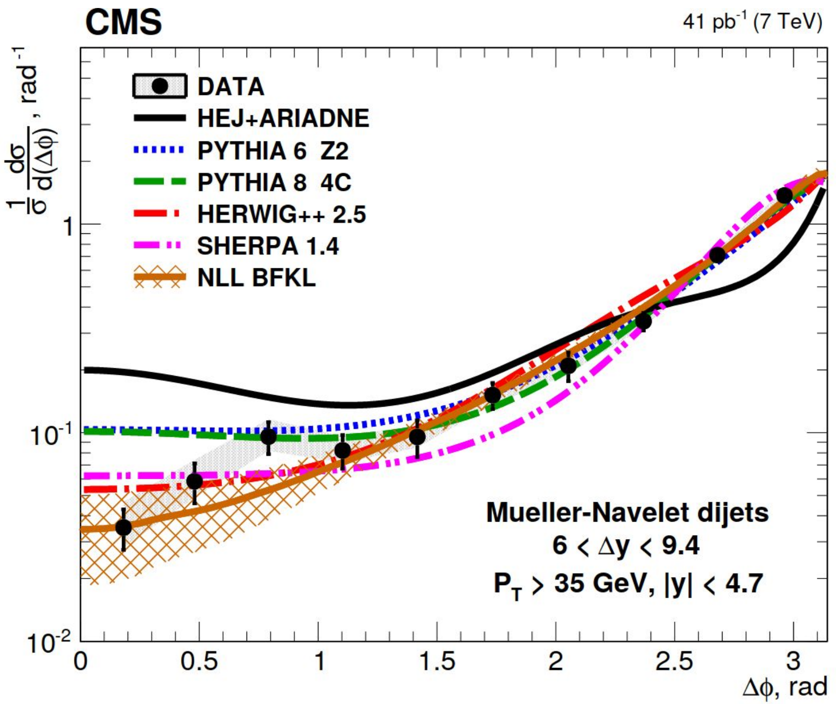
Partial restoration of factorization; intact proton enhances the probability that the central gap “survives” the collision.

Analogous to restoration of factorization observed by CDF Collaboration for double-pomeron exchange/single-diffractive dijets.

Mueller-Navelet jets at 7 TeV

CMS, JHEP 08 (2016) 139



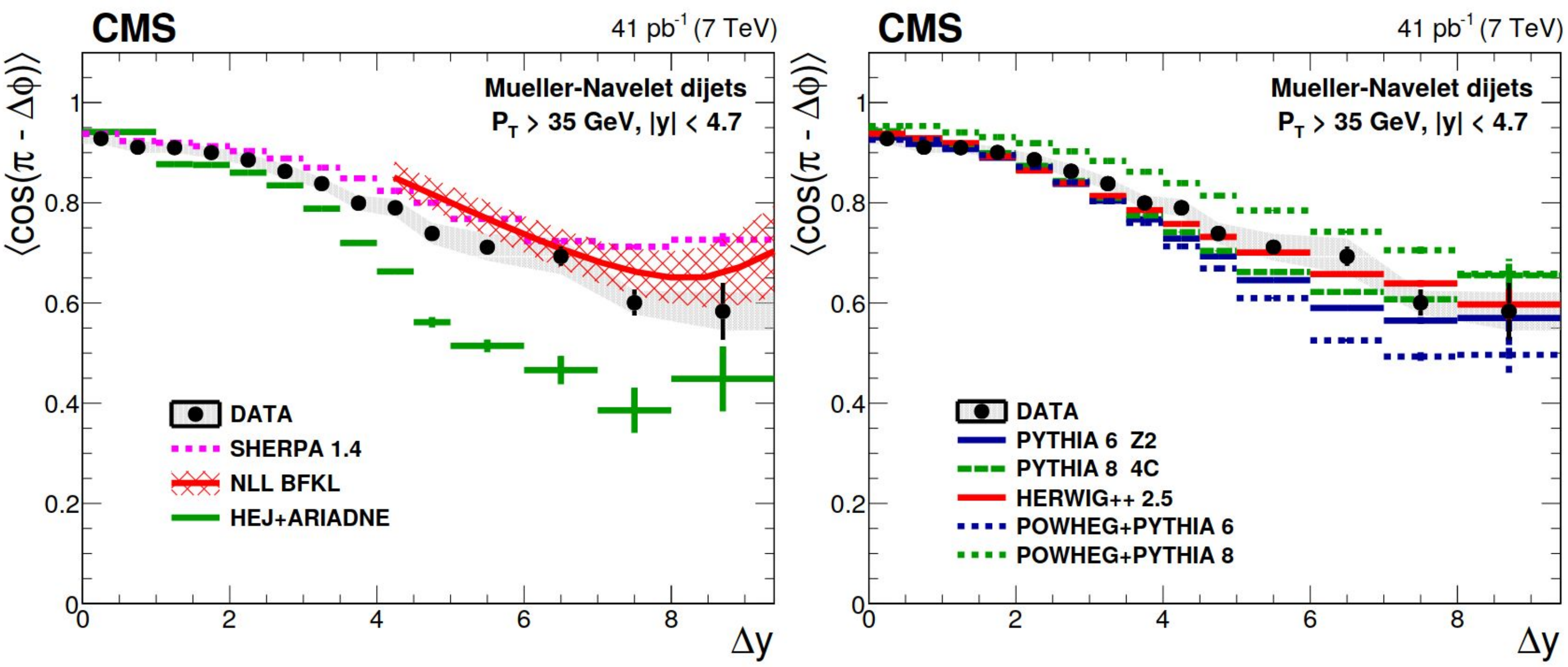


Forward-backward dijet configuration (BFKL limit) → Phase-space for additional radiation.

Multiple-gluon emissions induce large angular decorrelations between the forward-backward jets.

Fourier coefficients as a function of Δy

CMS, JHEP 08 (2016) 139



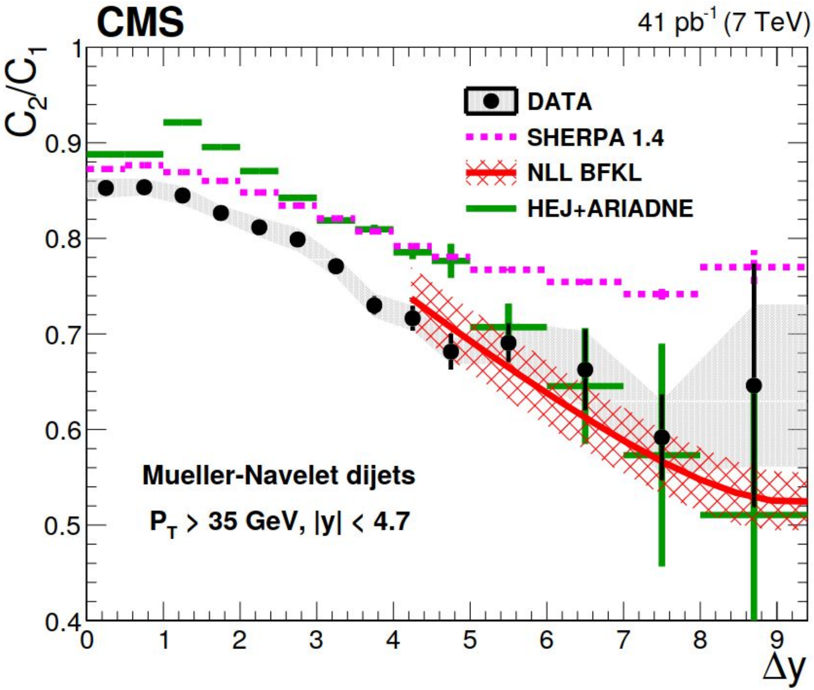
Predictions based on **BFKL resummation at NLL** are consistent with the data.

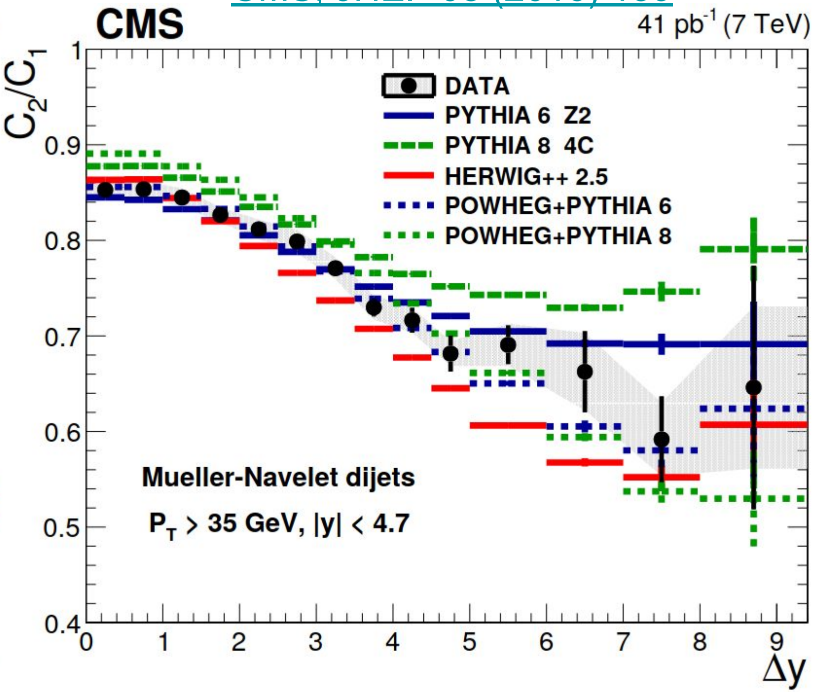
MC predictions based on fixed order pQCD + parton shower envelop the data in the entire Δy range.

New observables required? Or could 7 TeV → 13.6 TeV change help probe BFKL limit?

Ratios of Fourier coefficients for further discrimination

CMS, JHEP 08 (2016) 139

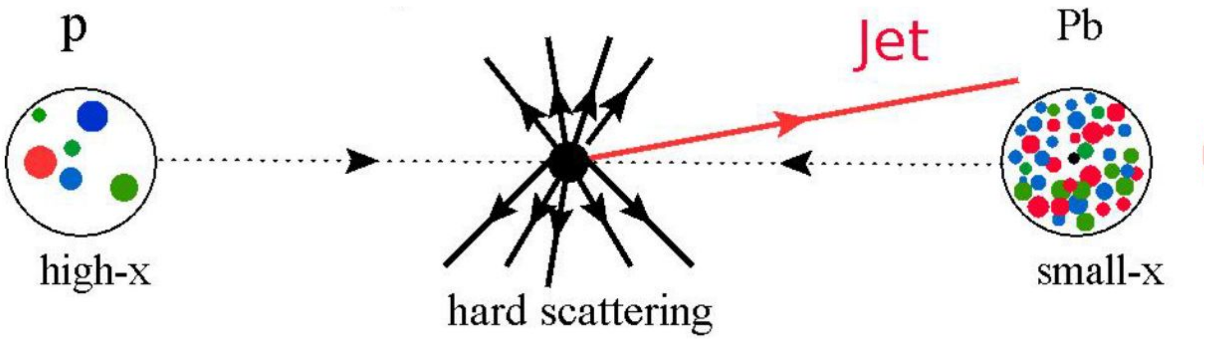




BFKL calculations consistent with data. Nevertheless, fixed order pQCD + PS still does a great job throughout the entire range.

Would 7 TeV → 13.6 TeV help? New observables? Asymmetric jet p_T cuts can help suppress DGLAP-like radiation.

Forward single jet spectra in proton-Pb collisions



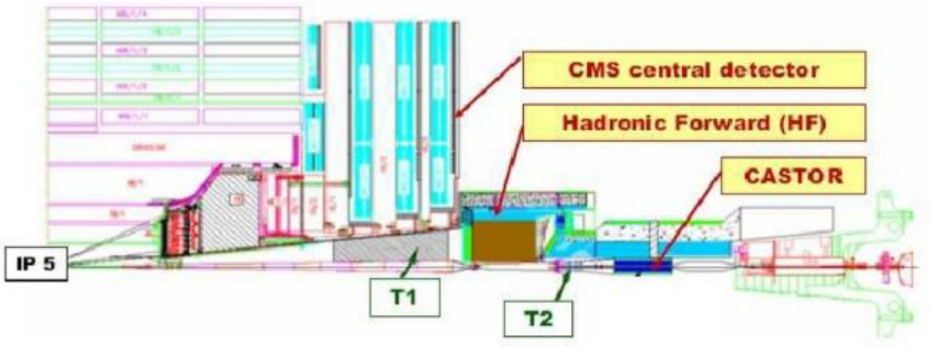
High-*x* parton from proton, low-*x* parton from Pb ion.

Saturation scale enhanced by $A^{1/3} \sim 6$ relative to proton, potentially making it experimentally accessible at the LHC.

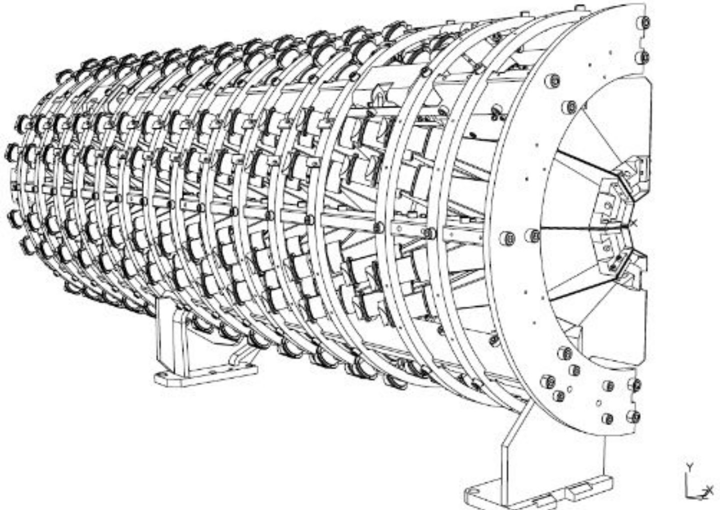
Requires *very* forward calorimetry + jet calibration under control.

CASTOR calorimeter to extend η acceptance

Forward calorimeter with unique access to low-*x* and low Q^2 kinematics at the LHC ($-6.6 < \eta < -5.2$, jet $p_T \sim 3$ GeV).



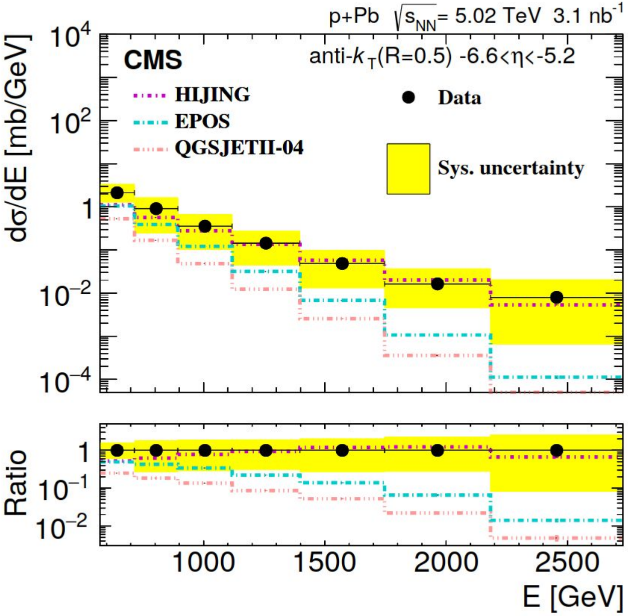
Calorimeter installed in special runs (low PU pp, pPb, and PbPb)

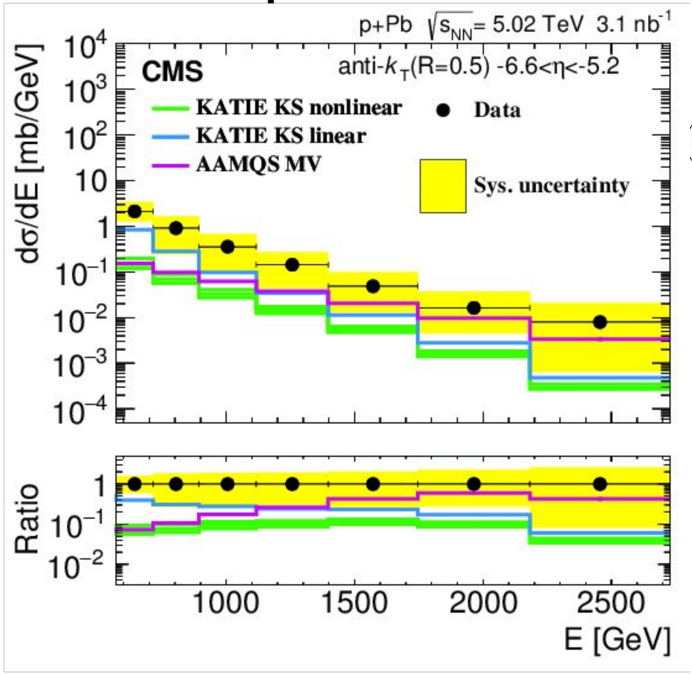


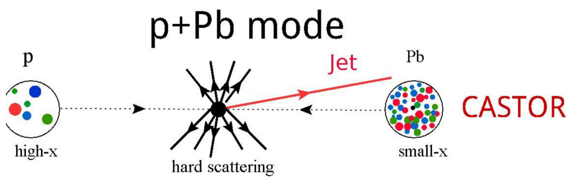
Calorimeter introduced initially to search for Centauro events, not optimized for jet physics. ***No η-segmentation.***

Inclusive jet cross section in pPb mode

[CMS, JHEP 05 (2019) 043]







$$p_T = E/\cosh(\eta)$$

EPOS and **QGSJETII** incorporate saturation effects via pomeron self-interactions. **HIJING** implements nuclear shadowing parametrically.

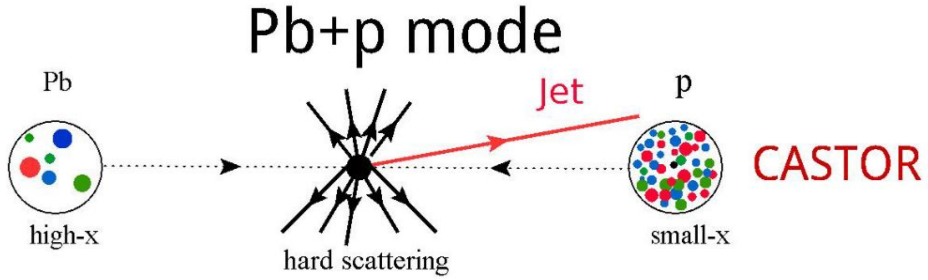
KATIE predictions (TMD-based, 2→1 matrix elements **linear evolution with BFKL eqn.** or **non-linear evolution with BK eqn.**)

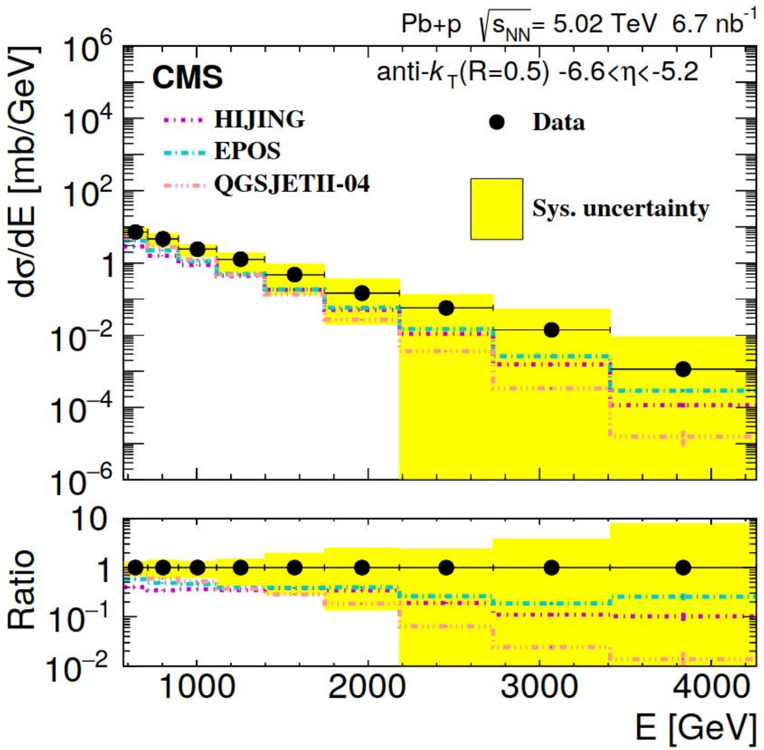
AAMQS MV (TMD-based, 2 → 1 matrix elements, **non-linear evolution with BK eqn.**)

Predictions based on saturation effects undershoot the data. Missing fragment remnants in forward region?

Control measurement (Pb+p mode)

CMS, JHEP 05 (2019) 043





Jet detected on incoming proton-beam side.

MC-based predictions undershoot the data at low energies (down to ~40%).

Large uncertainties at higher energies due to alignment uncertainty and unfolding model dependence.

Summary

- Numerous measurements of hard-scale forward and diffractive processes, corrected to stable-particle level.

- So far no “smoking gun” signature of small-x evolution in forward jet data or diffractive vector meson production in pp and pPb collisions in CMS.

- ***Trade-off between clean experimental signatures/observables and control over the phenomenology.***

High-energy limit of QCD

In the limit $\hat{s} \gg -\hat{t} \gg \Lambda^2_{QCD}$, the fixed order pQCD expansion breaks down.

It can be rearranged (symbolically) as,

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

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

Large logarithms are resummed with Balitsky–Fadin–Kuraev–Lipatov (BFKL) resummation to all orders in α_s .

Same gluon radiation pattern emerges in the proton/nucleus ***(small-x evolution***).