Hard diffraction with hadronic final states with (mostly) CMS

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Diffraction and gluon saturation at the LHC and the EIC

June 10th-14th 2024

Outline

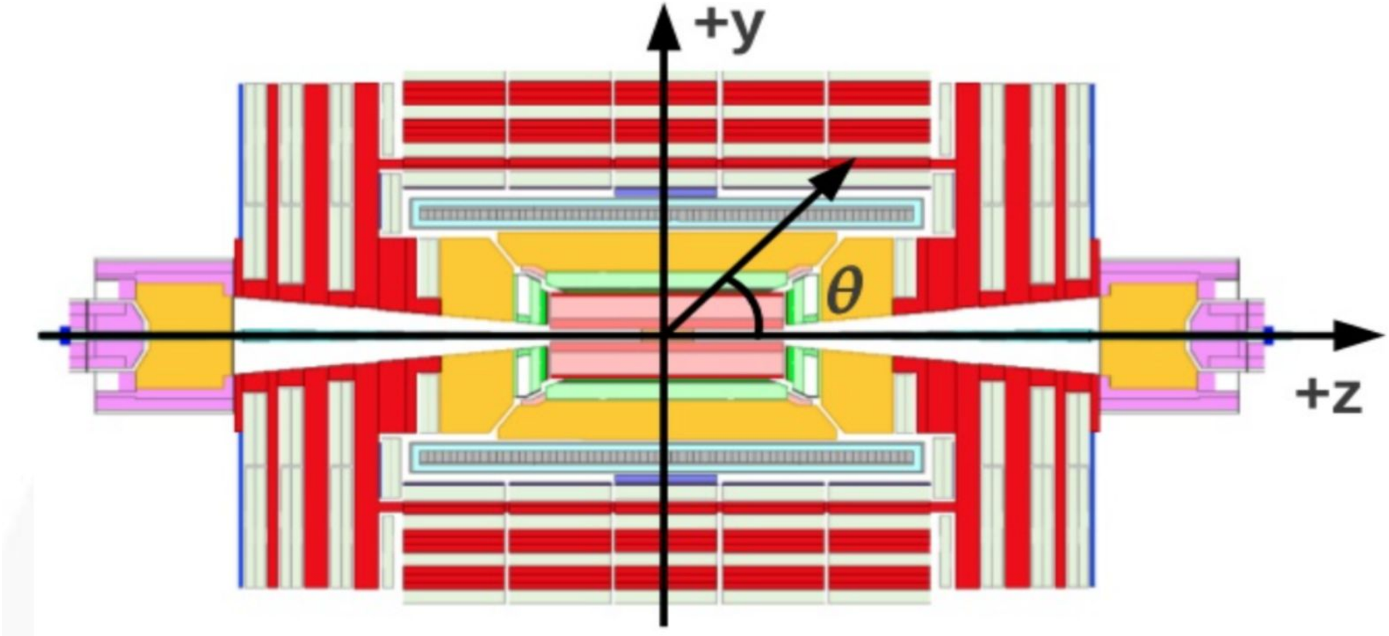
Mostly discuss four LHC results:

- ATLAS & CMS photonuclear jets in PbPb
  (ATLAS-CONF-2022-021, **CMS, Phys. Rev. Lett. 131 (2023) 051901**)

- Single-diffractive dijets in pp collisions (ATLAS, CMS)
  CMS-TOTEM, Eur. Phys. J. C 80, 1164 (2020)

- Jet-gap-jet, (CMS-TOTEM)
  CMS-TOTEM PRD 104, 032009 (2021)

CMS detector recap



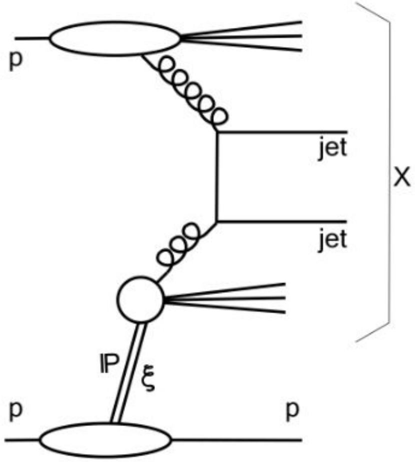
Tracker & muon chambers acceptance up to $|\eta| < 2.5$; **p_T > 200 MeV for tracks**
hadronic calorimeter coverage up to $|\eta| < 5.2$; **noise threshold E $\gtrsim$ 5 GeV in fwd region**

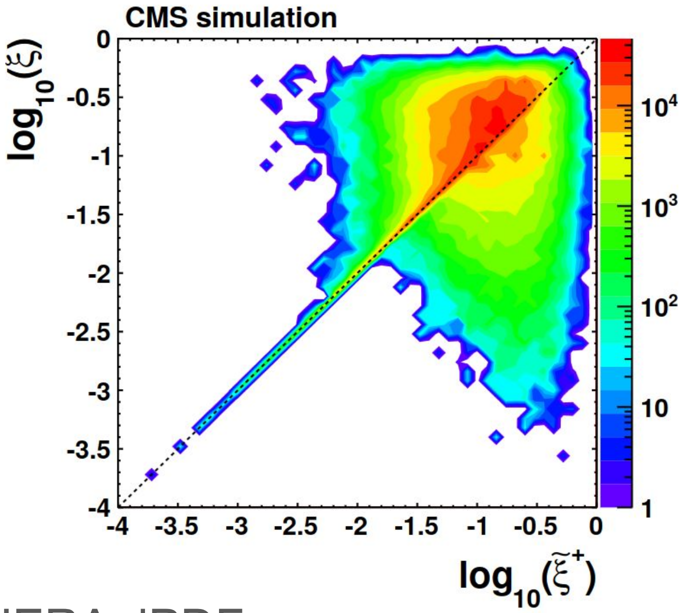
Jet reconstruction spans wide range in $|\eta| < 4.7$ and as low as $p_T > 20$ GeV

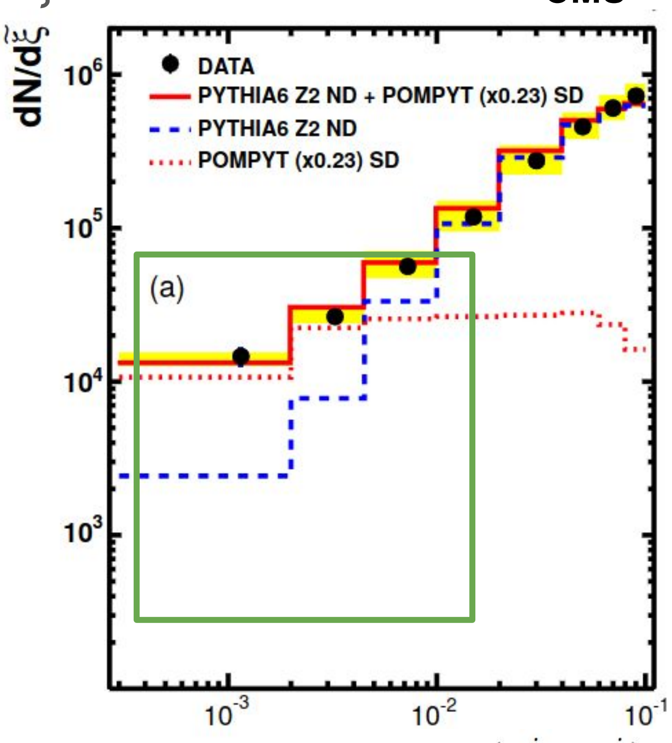
Run-1 measurements of diffractive jets (no Roman pots)

Larger rapidity gaps ⇔ smaller $\xi \sim \ln(1/\Delta\eta_{gap})$;

~20% nondiffractive contamination for $\xi \sim 10^{-4}$–10^{-2}





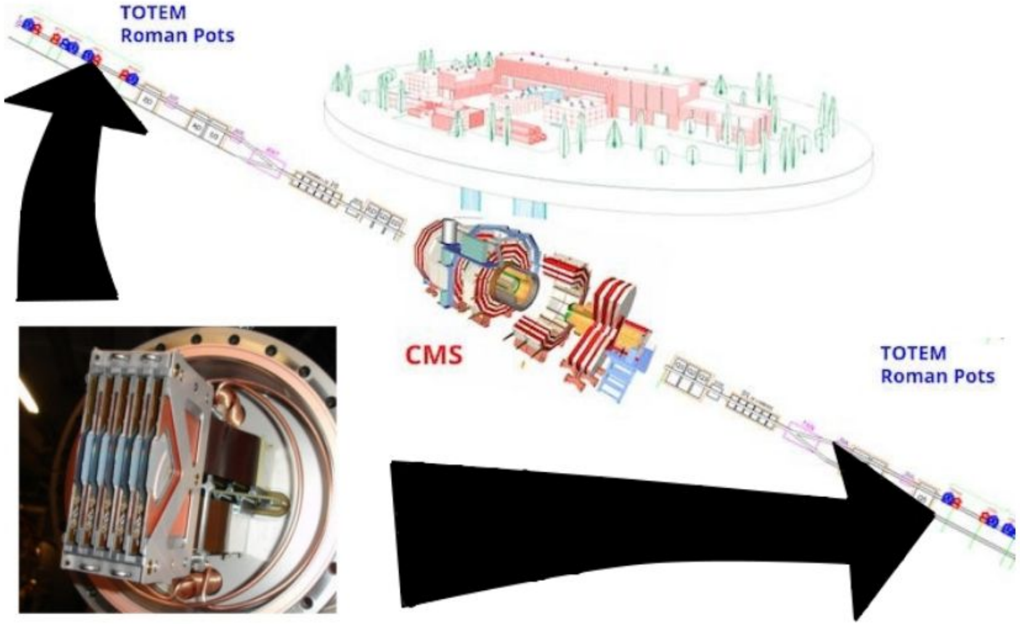


testing universality of HERA dPDFs,
understanding factorization breaking at LHC

$$x_{\mathbb{P}} == \tilde{\xi}^{\pm} = \frac{\sum (E^i \pm p_z^i)}{\sqrt{s}},$$

CMS, Phys. Rev. D 87 (2013) 012006
ATLAS, Phys. Lett. B 754 (2016) 214

CMS-TOTEM setup



Roman pots:
Near-beam Si tracker detectors

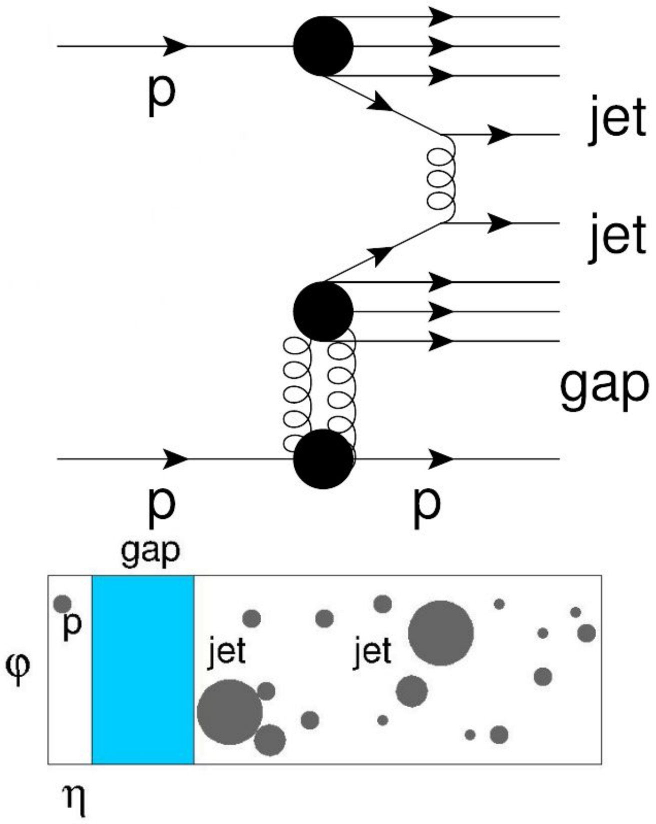
CMS:

- 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.

Hard diffraction with intact protons (CMS+TOTEM)



Intact proton is an unambiguous signature of diffraction

Gives access to:

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

  ($0.0 < \xi < 0.1$ for Run-1 in high-β*,
  up to $\xi \sim 0.2$ in Run-2)

|t| distribution for single-diffractive jets

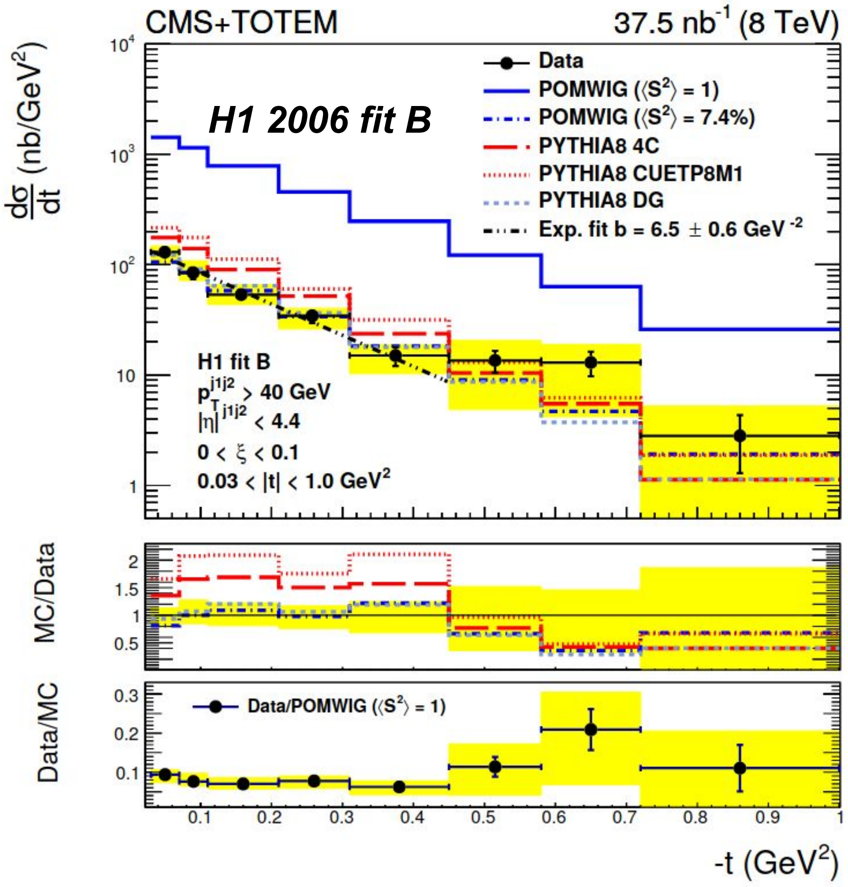
[CMS-TOTEM, EPJC 80, 1164 (2020)]

Exponential slope $b = 6.5 \pm 0.6\ GeV^{-2}$ consistent w/ other hard diffractive probes (e.g., exclusive VM)

Bare POMWIG overshoots data (**survival probability of 7.4%**)

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***

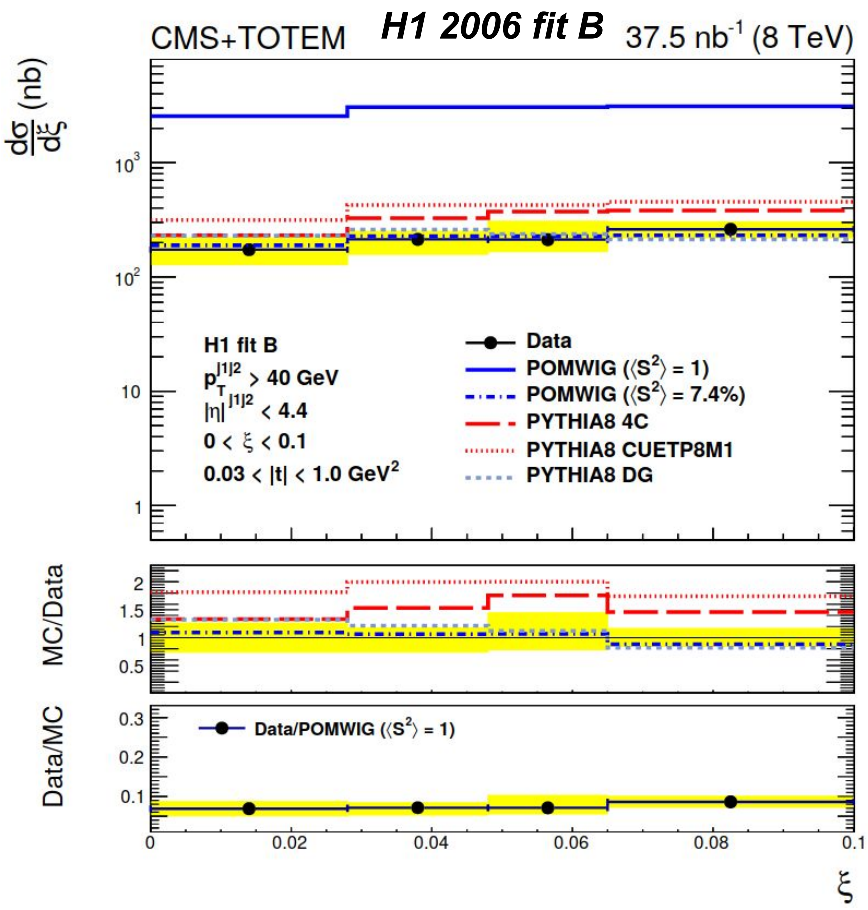


Fractional momentum loss ξ

CMS-TOTEM, EPJC 80, 1164 (2020)

Significantly extending reach based on forward gaps only $\xi < 0.01$

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



Data corrected to particle-level

CMS-TOTEM, EPJC 80, 1164 (2020)

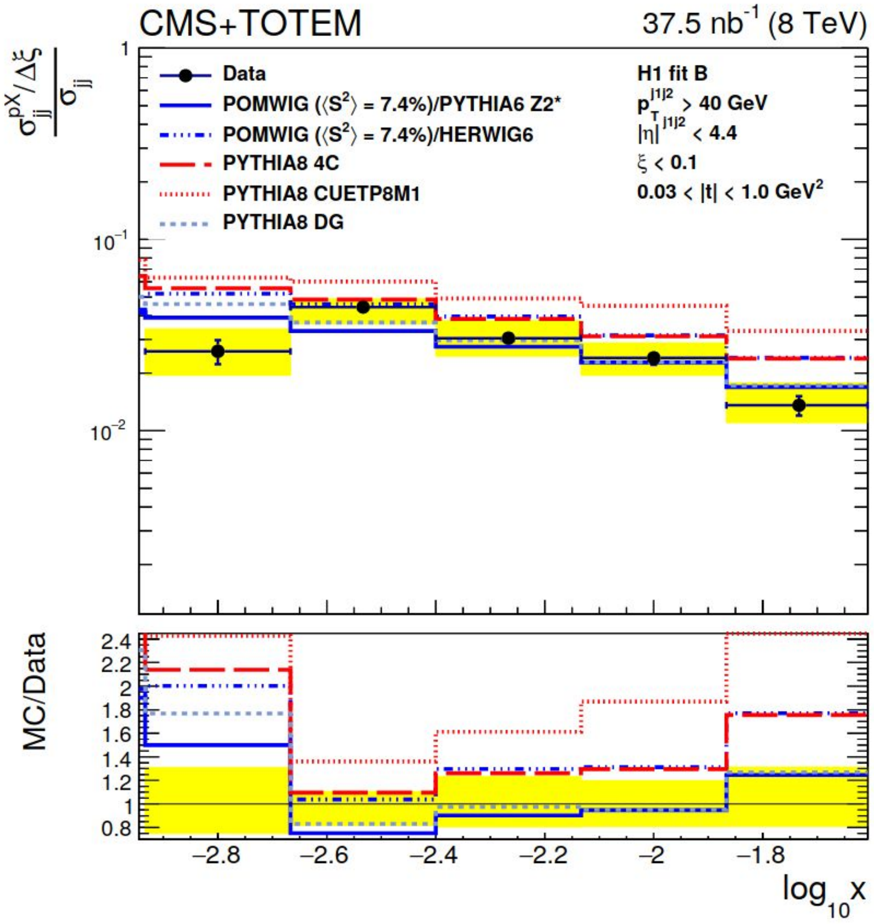
Proxy for Bjorken-x from all jets:

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

POMWIG (pomeron & reggeon exchanges) describes qualitatively well the shapes

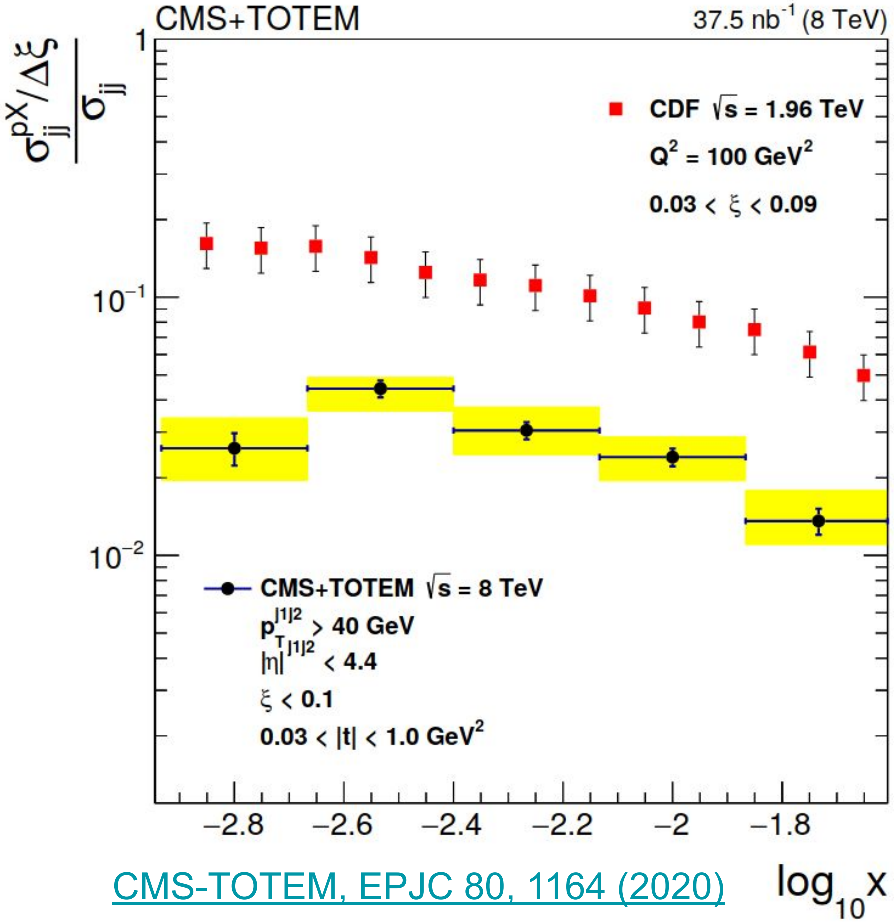
PYTHIA8 (pomeron-only) predictions off at high- and low-*x*.

PYTHIA8 with "dynamical gap" (pomeron-only) describes the observed rate, no need for fudge factors



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

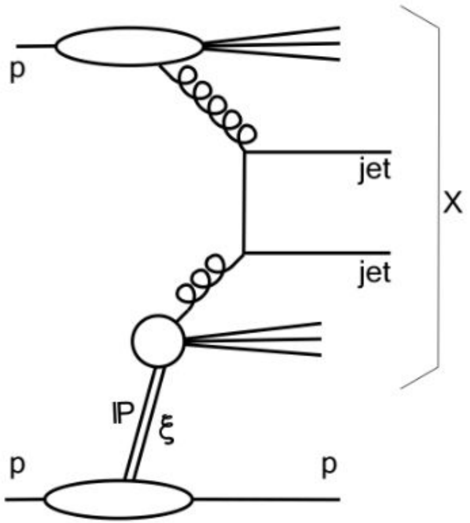
Fraction of diffractive jets decreases with energy (**Tevatron → LHC**), qualitatively expected from survival probability dependence on √s.



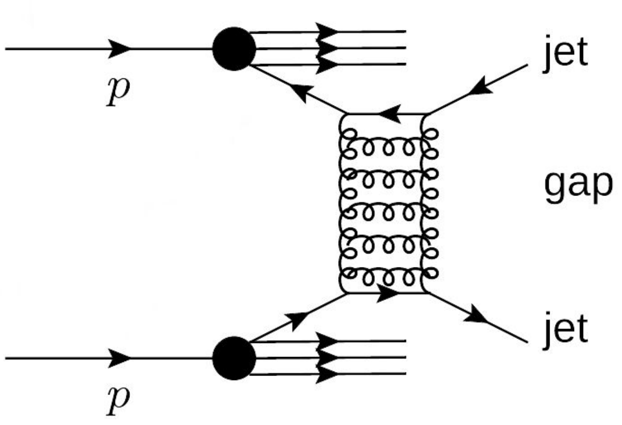
CMS-TOTEM, EPJC 80, 1164 (2020)

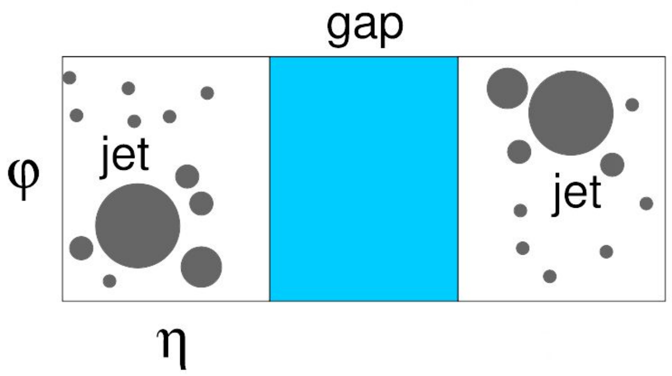
Lesson/thoughts:

- Rapidity gap based diffraction gives access to $10^{-4} < \xi < 10^{-2}$
- Diffractive jets at LHC energies consistent with pomeron-only exchange ($0 < \xi < 10^{-1}$, with Roman pots)
- Stronger suppression at LHC than at CDF
- How can it be extended?



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



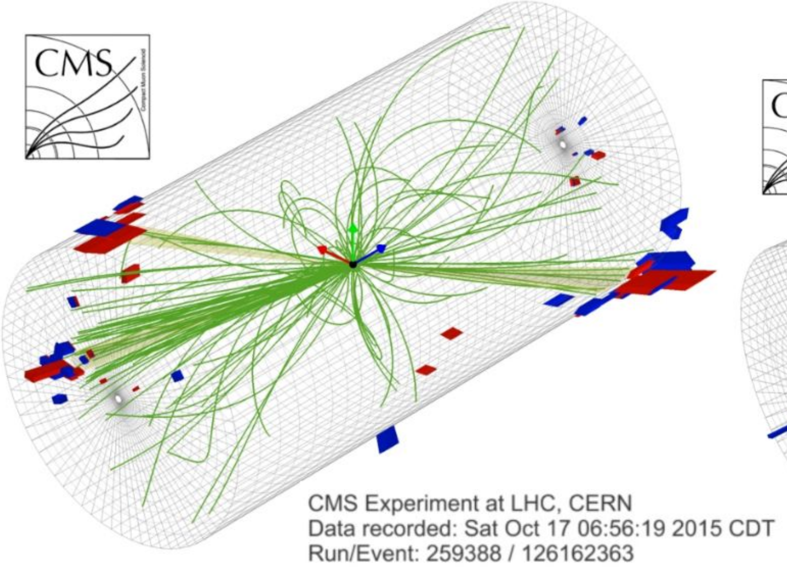


t-channel color-singlet exchange between partons → ***rapidity gaps between final-state jets***

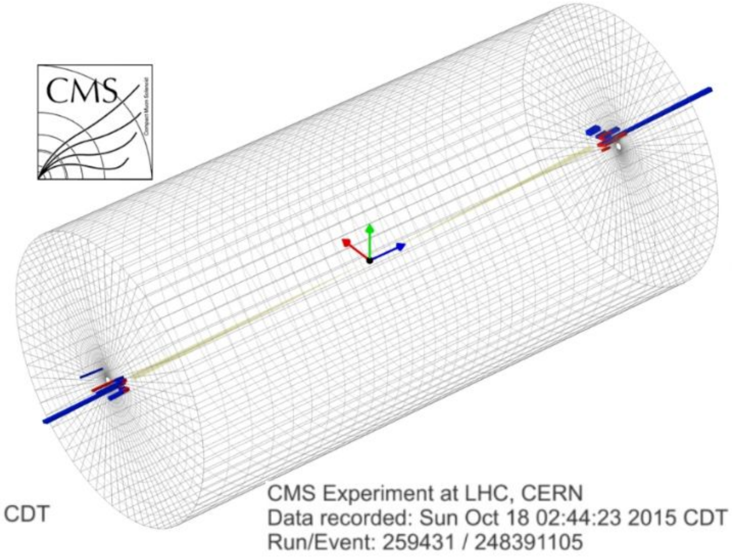
In the high-energy limit (large $\Delta\eta_{jj}$), it is expected to be mediated by **BFKL pomeron exchange**. A. Mueller and W-K. Tang, PLB 284 (1992) 123.

Experimentally, a signal with a controllable QCD background.

CMS event displays
(single proton-proton collisions)



Color-exchange event candidate
(Background-like)



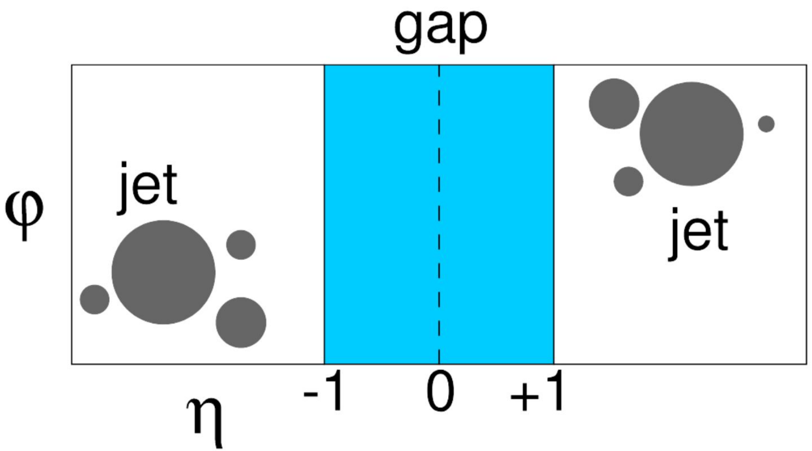
Color-singlet exchange event candidate
(Signal-like)

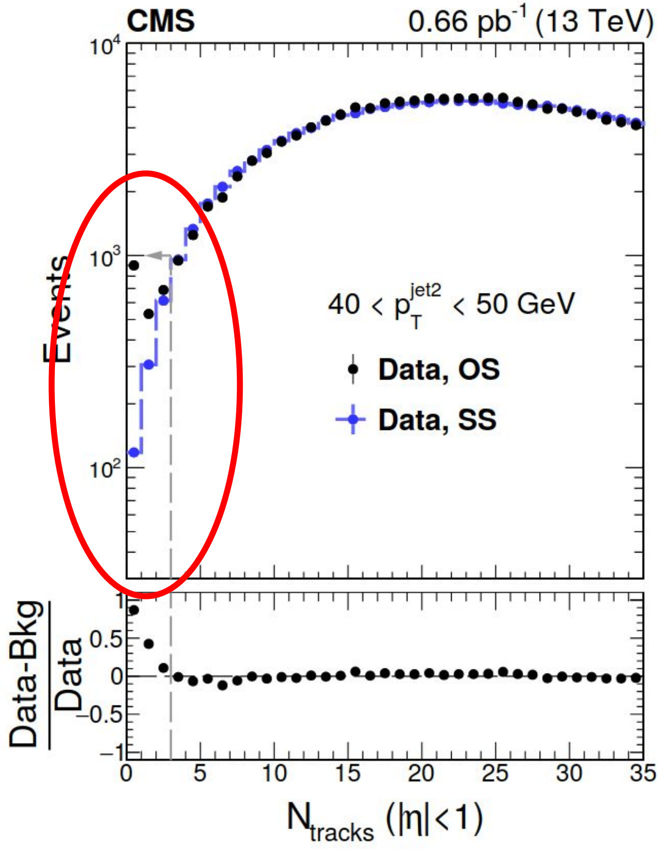
tracks with pT > 0.2 GeV are plotted here.

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}.***

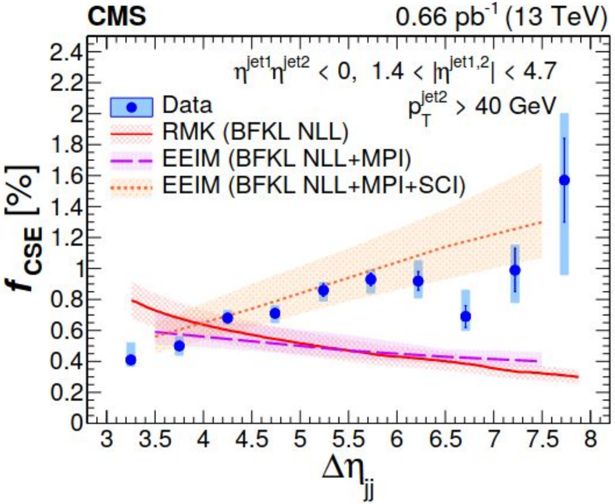


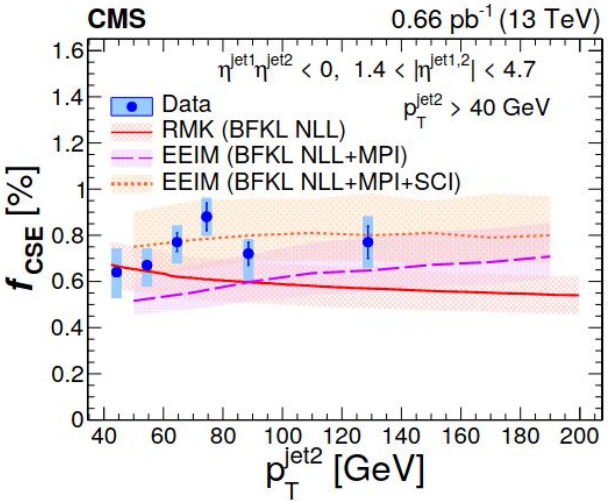


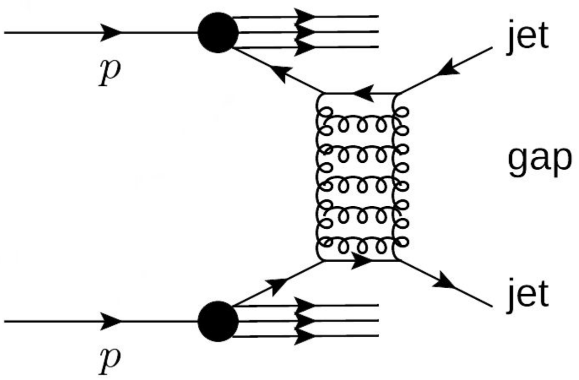
Each jet has $|\eta_{jet}| > 1.4$, with $\eta_{jet1} * \eta_{jet2} < 0$, with p_T>40 GeV.

Color-octet fluctuations subtract

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







CMS-TOTEM PRD 104, 032009 (2021)

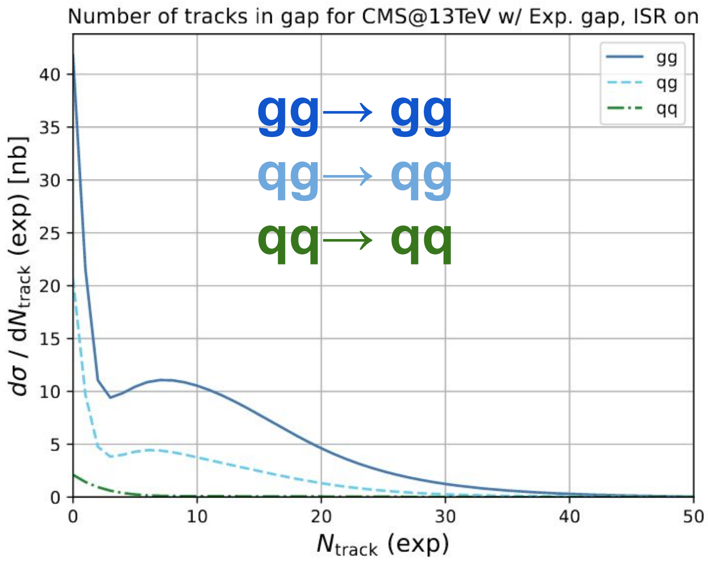
About ~0.7% of dijets are produced by hard color-singlet exchange

Pure BFKL predictions 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)

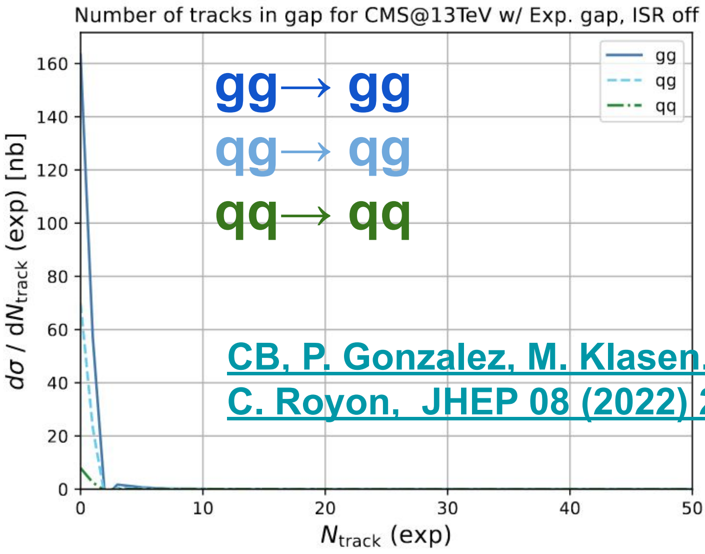
ISR “screens” central gap between Mueller–Tang jets

ISR on → central gap is destroyed



ISR = on → more particles between the jets.

ISR off → central gap remains



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

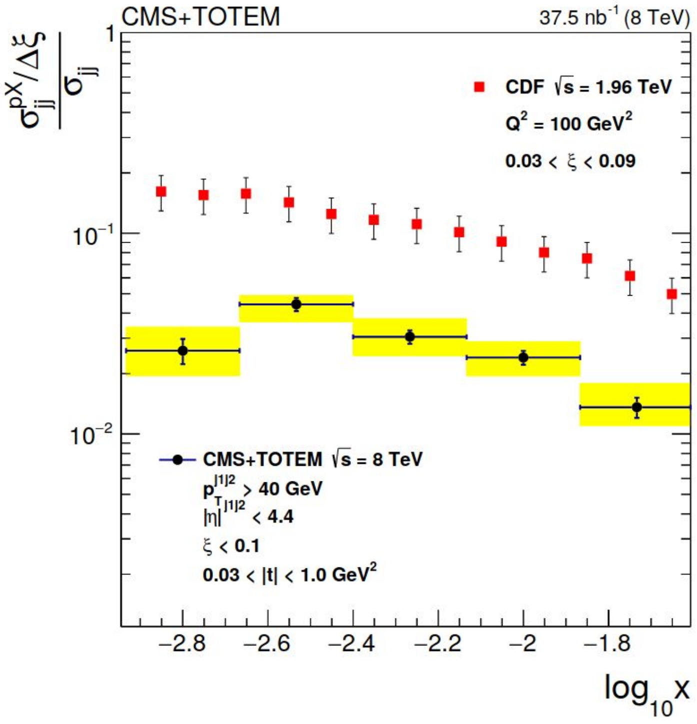
ISR = off → fewer particles between the jets (unclustered wide-angle hadrons).

Unexpected (?) sensitivity to ISR at central pseudorapidities

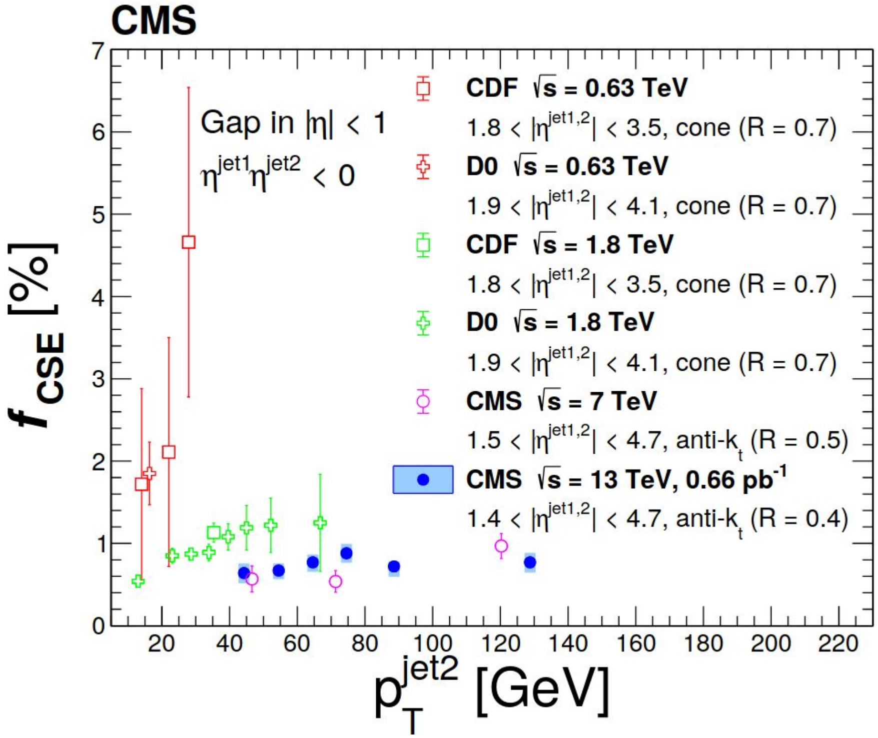
(see talk by C. Royon next!)

Suppression of jet-gap-jet fraction with √s

CMS-TOTEM, EPJC 80, 1164 (2020)



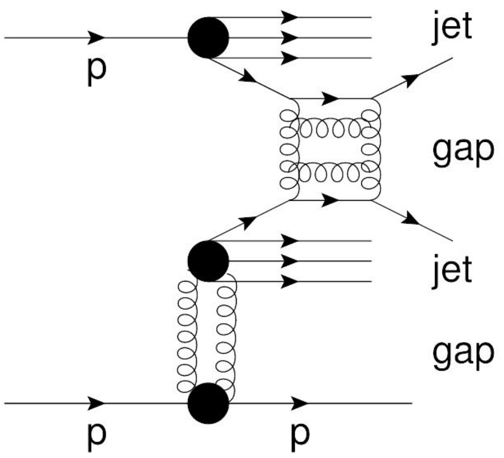
CMS-TOTEM PRD 104, 032009 (2021)

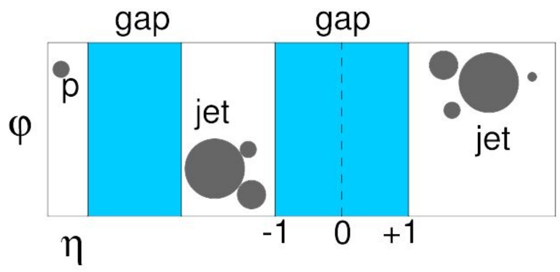


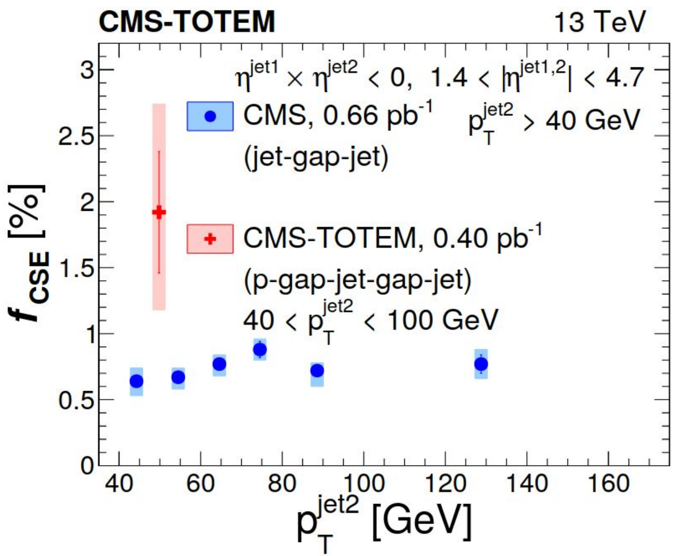
Decrease from Tevatron to LHC energies, ***consistent with single-diffractive dijet trend***

Gap between jets with intact proton

CMS-TOTEM PRD 104, 032009 (2021)



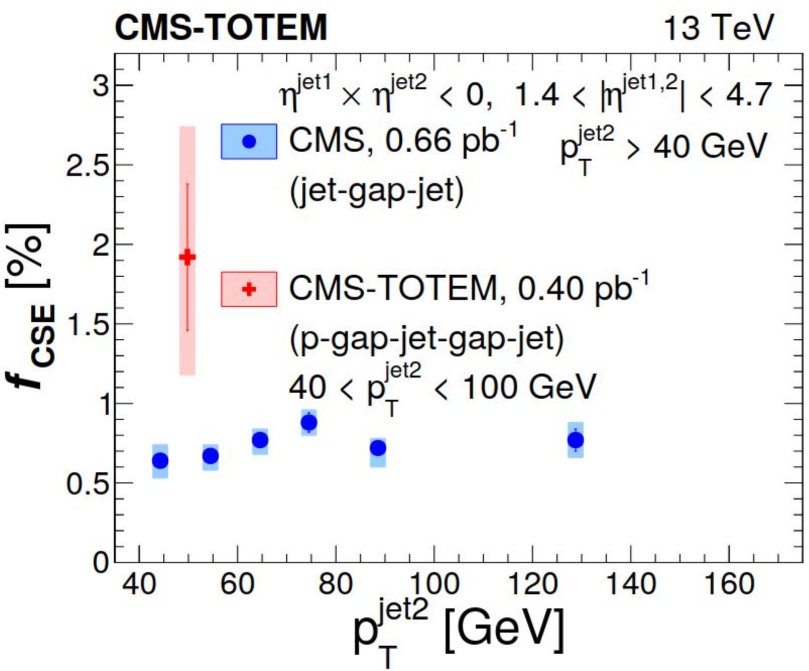


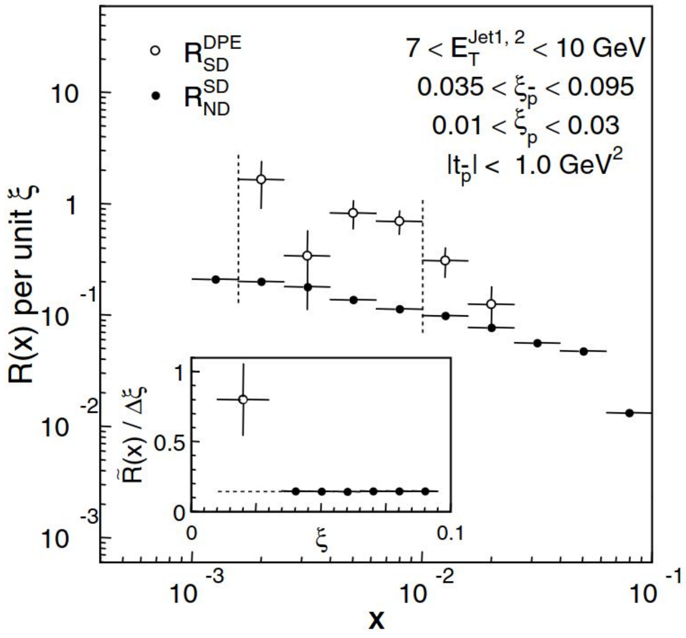


Partial restoration of factorization; intact proton enhances the probability that the central gap “survives” the collision.

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

Similar enhancement in other two-gap diffractive topologies





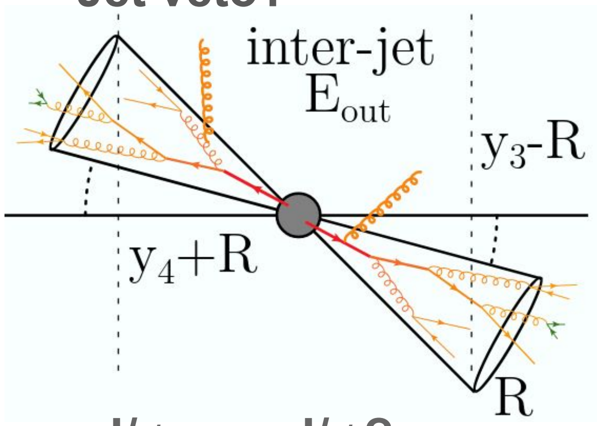
[CMS-TOTEM PRD 104, 032009 (2021)]

[CDF PRL 85 (2000) 4215 for double-pomeron jets/single-diffractive dijets]

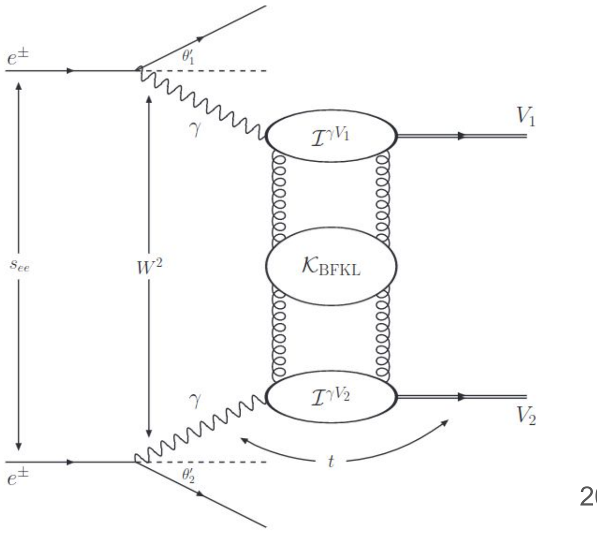
Lessons/thoughts:

- Clear “jet-gap-jet” signal in data
- Enhancement when tagging intact proton compatible with other topologies (DPE/SD dijet double-ratios by CDF)
- Central gap introduces nontrivial sensitivity to ISR & color-flow effects (according to Pythia8!)
- Mueller–Tang spin-offs that retain sensitivity to genuine pQCD effects?

Jet veto?

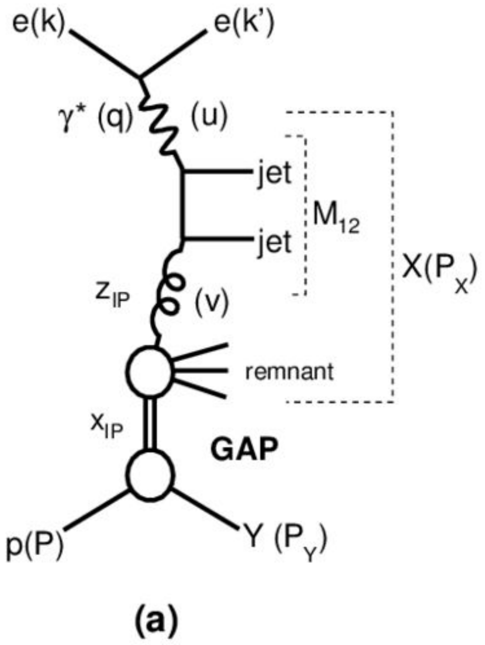


J/ψ-gap-J/ψ?

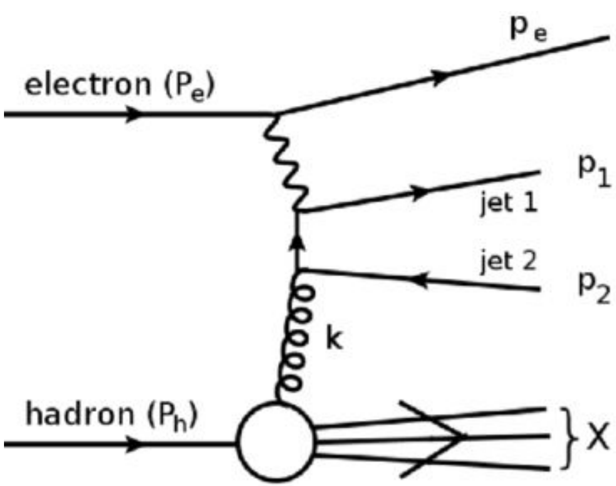


Dijet photoproduction (resolved or direct)

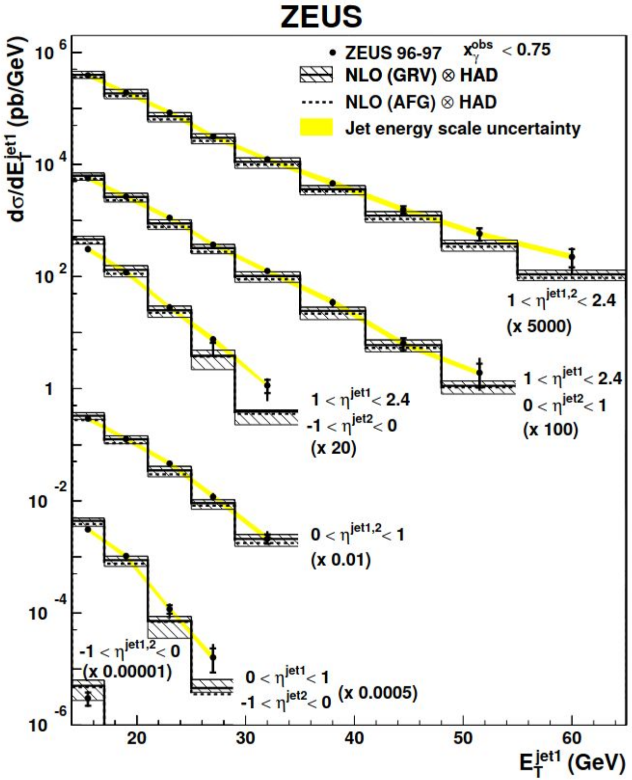
Thoroughly measured at HERA, what about the LHC?



Diffractive photoproduction



Photoproduction



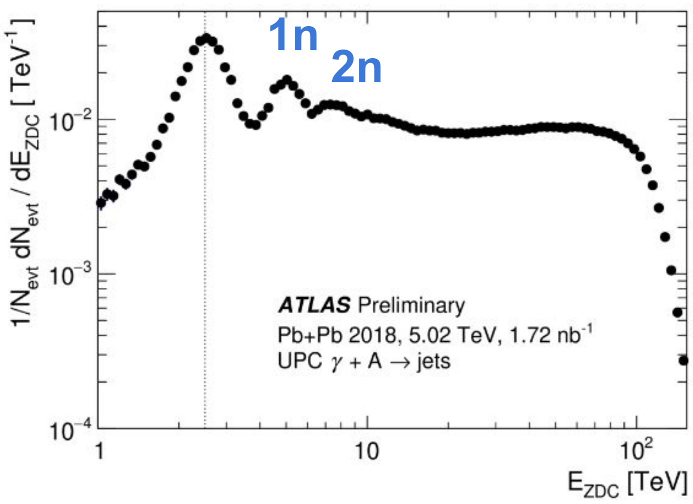
ZEUS, arXiv:0112029

Photonuclear dijet in ATLAS in PbPb at 5.02 TeV

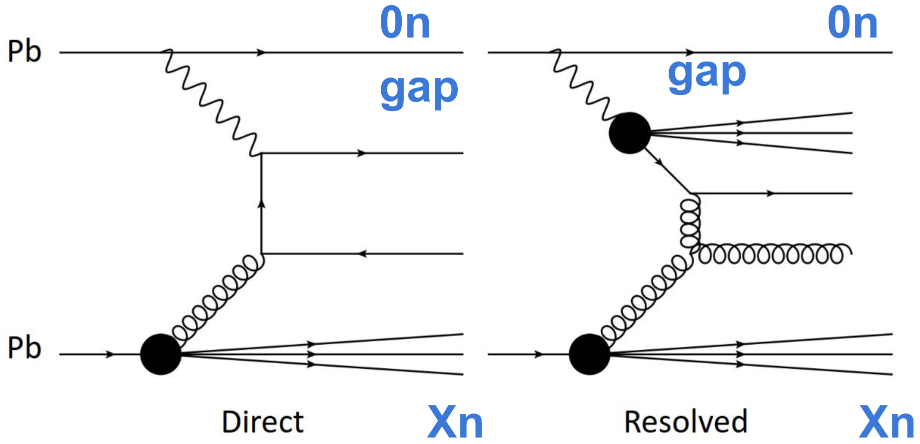
Forward neutrons on zero degree calorimeter to tag photon emission (**0nXn, X > 0**) + rapidity gap

ZDC helps clean up event from “hadronic” dijet (peripherals)

0n (no breakup)



ZDC energy spectrum



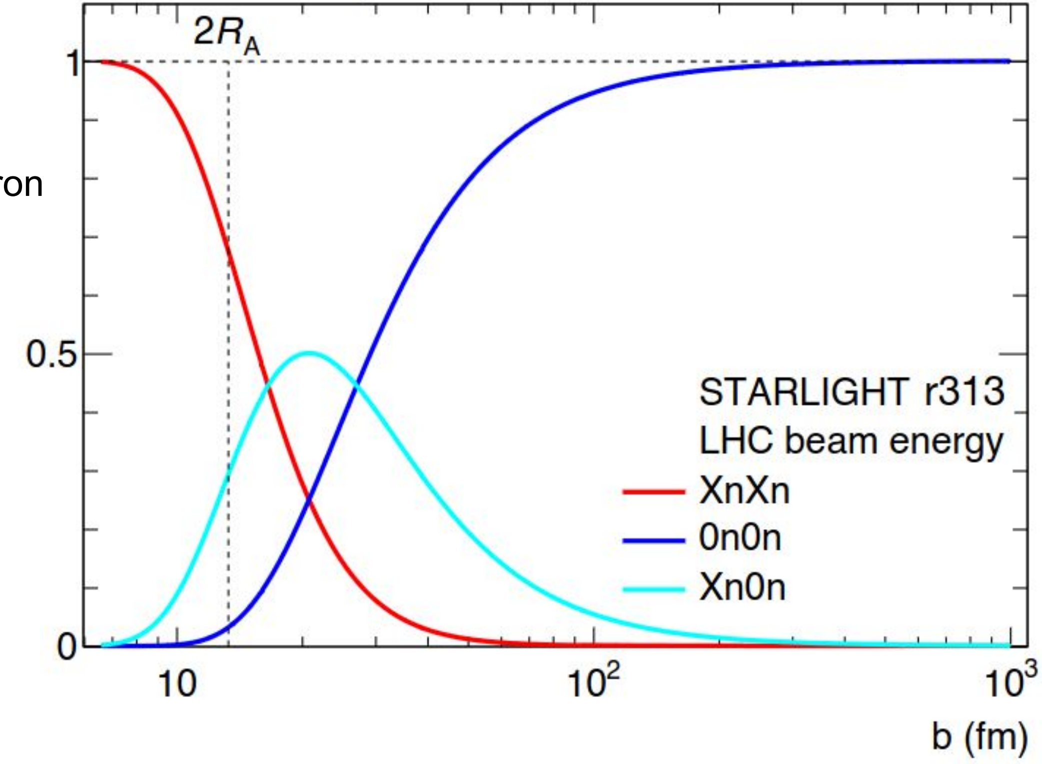
Probe of gluon nuclear PDFs at small-x and perturbative Q^2

>= 2 jets with $p_{T,jet}$ > 15 GeV, up to acceptance $|\eta_{jet}| < 4.4$

In general, ZDC topology "filters" different impact parameters, which affects the photon flux modeling

Klein, Steinberg, Ann Rev Nucl Part Sci Vol. 70:323-354

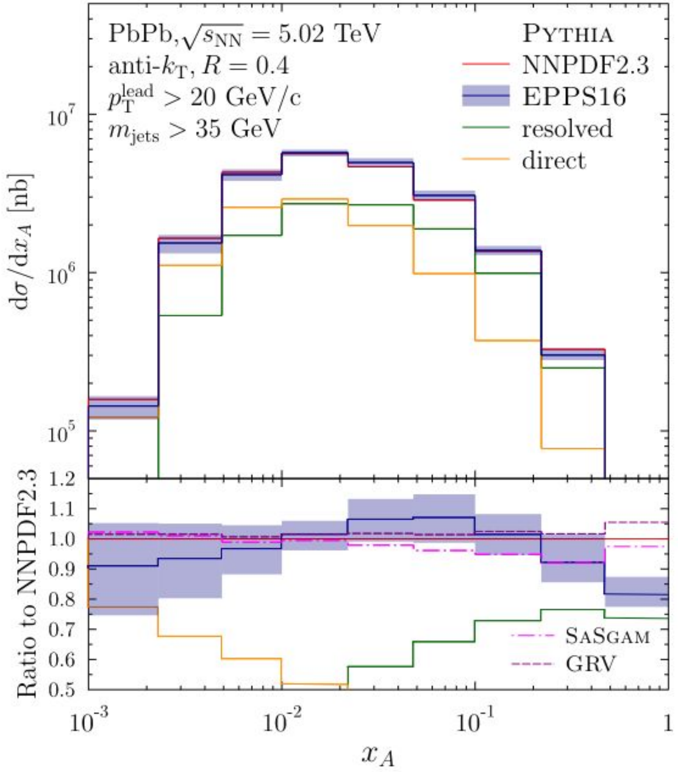
Probability
of fwd neutron



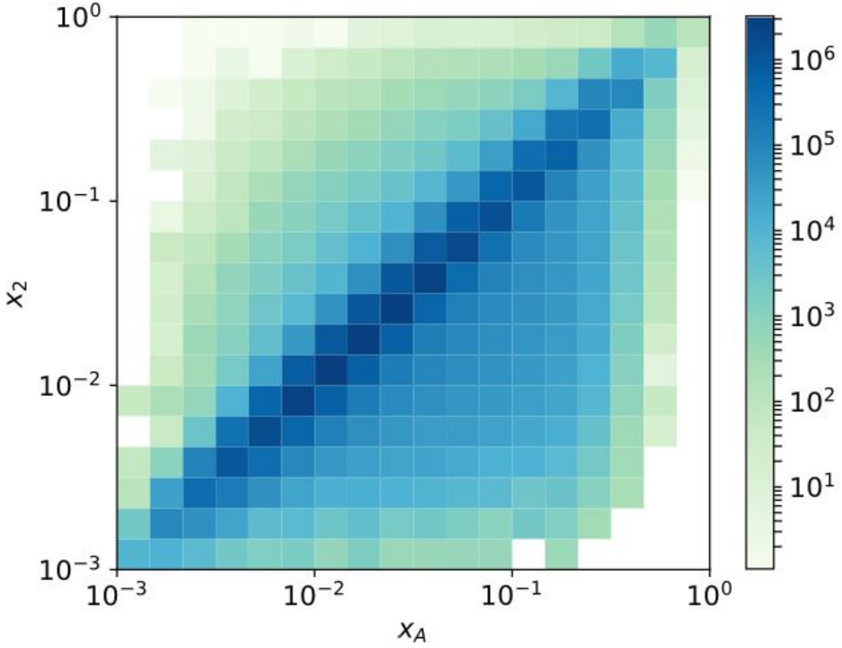
$$x_A \equiv \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}}$$

Jet-based proxy for parton momentum fraction wrt Pb nucleus

small x_A dominated by **direct photoproduction**, high x_A by **resolved photoproduction**



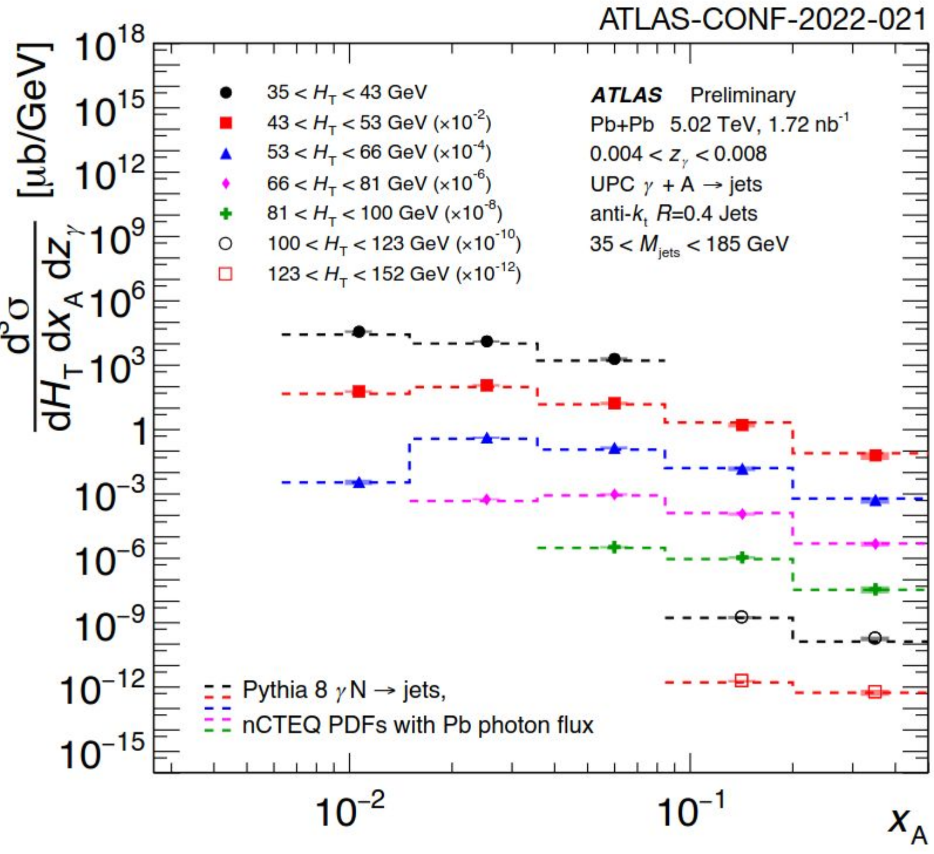
x_A strongly correlated with x_2 used in nPDF evaluation



I. Helenius, arXiv:1811.10931

Triple differential cross section measurement (ATLAS)

ATLAS-CONF-2022-021



Unfolded to particle-level, reported for three variables

$$H_T \equiv \sum_i p_T^i \qquad x_A \equiv \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}} \qquad z_\gamma \equiv \frac{M_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}$$

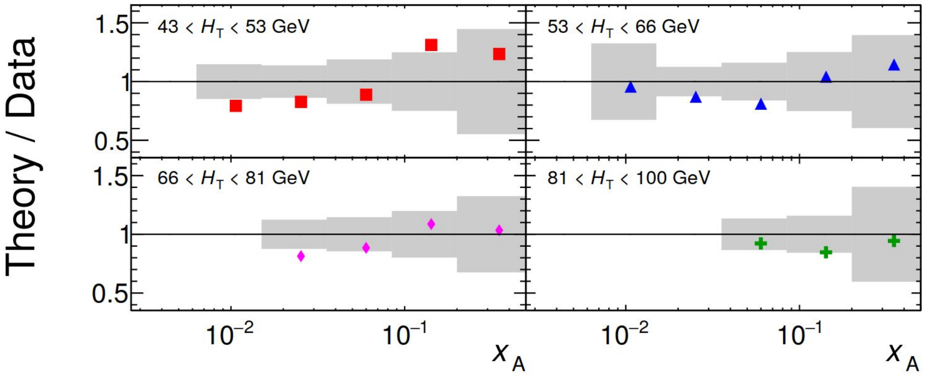
~Q^2 — parton momentum fraction wrt target — momentum fraction carried by photon

Precision limited by jet calibration unc.

(**particle-flow low p_T jets are hard to calibrate!**)

Triple differential cross section measurement (ATLAS)

ATLAS-CONF-2022-021



Fully unfolded to particle-level, reported for three variables

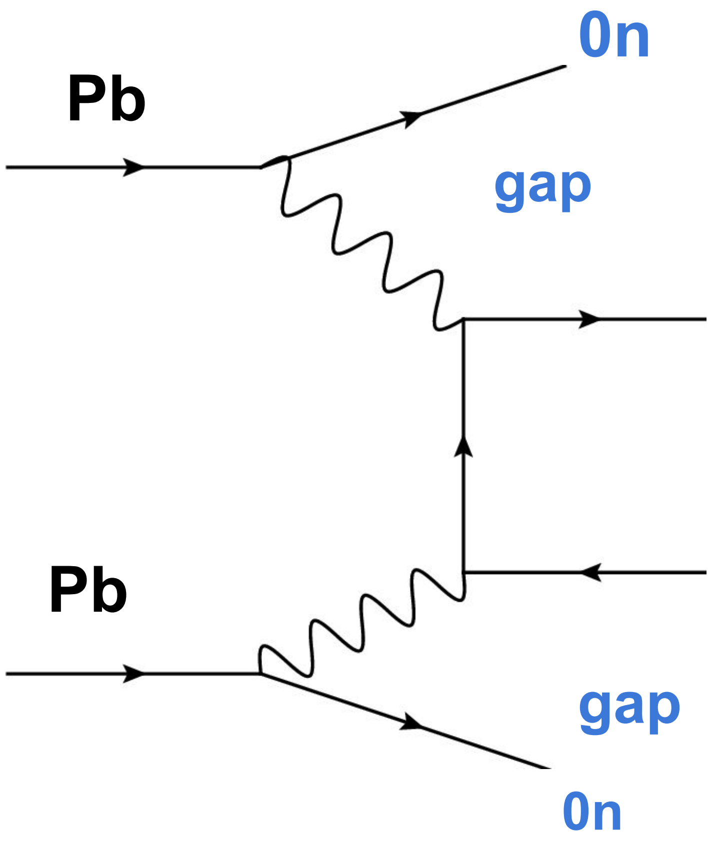
$$H_T \equiv \sum_i p_T^i \qquad x_A \equiv \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}} \qquad z_\gamma \equiv \frac{M_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}$$

~Q^2 | parton momentum fraction wrt target | momentum fraction carried by photon

Experimental precision currently limited by jet energy scale uncertainty

(**particle-flow low p_T jets are hard to calibrate!**)

Exclusive* dijet with 0n0n + two rapidity gaps [ATLAS]

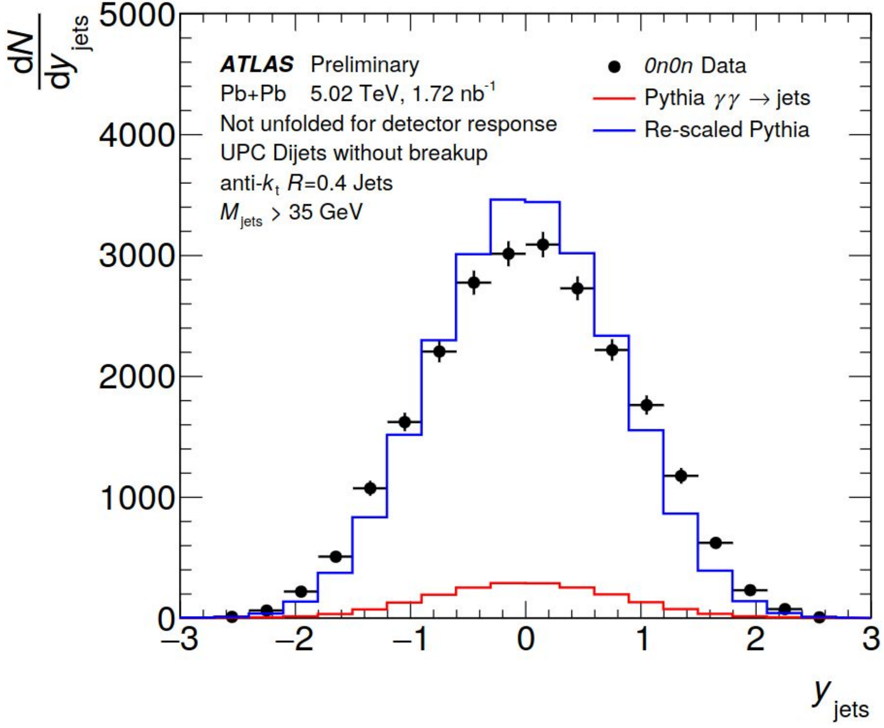


One would expect
QED $\gamma\gamma \to$ qqbar to dominate
(large photon flux)

NB:
"Exclusive" up to detector-noise,
& jet p_T threshold

Exclusive dijet with 0n0n + two rapidity gaps [ATLAS]

ATLAS-CONF-2022-021

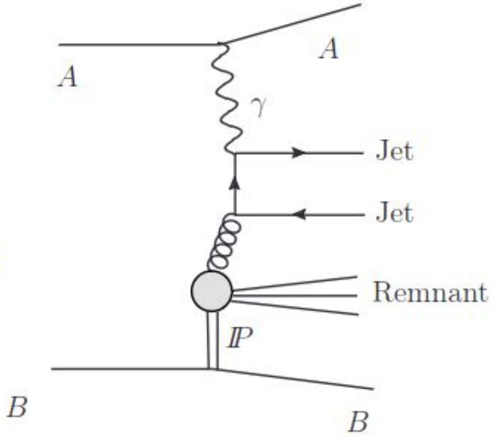


NB: Uncorrected distributions

Pure **QED ɣɣ→qqbar** contribution accounts only for 10% of the observed rates in data

Could be due to coherent diffractive photoproduction of dijets in PbPb: V. Guzey, M. Klasen, arXiv:1603.06055

If so, could be used as a probe of saturation:



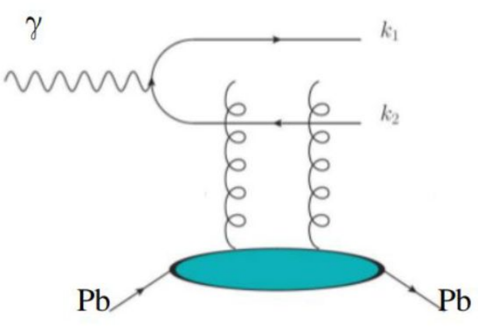
H. Mäntysaari, N. Mueller, F. Salazar, B. Schenke, PRL 124, 112301 (2020)

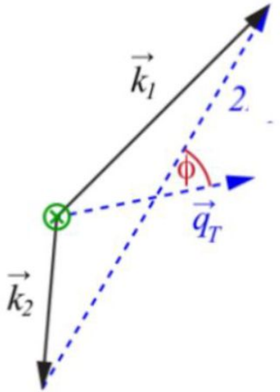
E. Iancu, A.H. Mueller, D.N. Triantafyllopoulos, S.Y. Wei, arXiv:2304.12401

Exclusive dijet production in PbPb (CMS)

Proposed to probe elliptic polarization of gluons in unpolarized nuclei,

Hatta, et al, PRL 116, 202301 (2016)





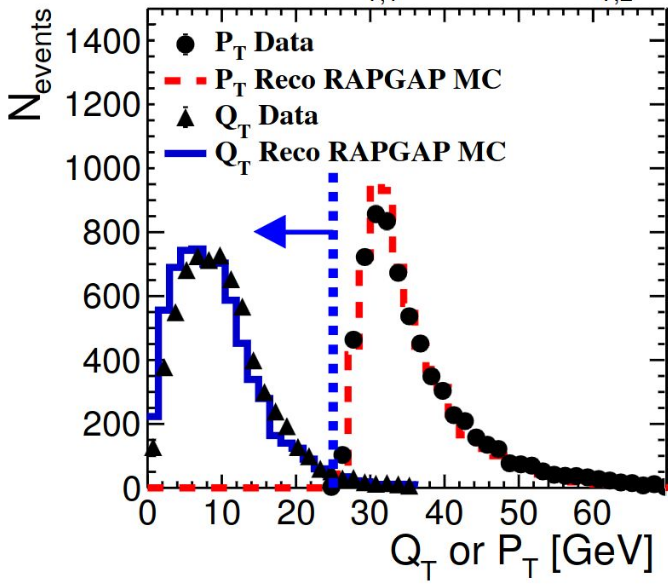
Vector sum of 2 jets:

$$\vec{Q}_T = \vec{k}_1 + \vec{k}_2$$

Vector difference of 2 jets:

$$\vec{P}_T = \frac{1}{2}(\vec{k}_1 - \vec{k}_2)$$

CMS, PRL 131 (2023) 051901



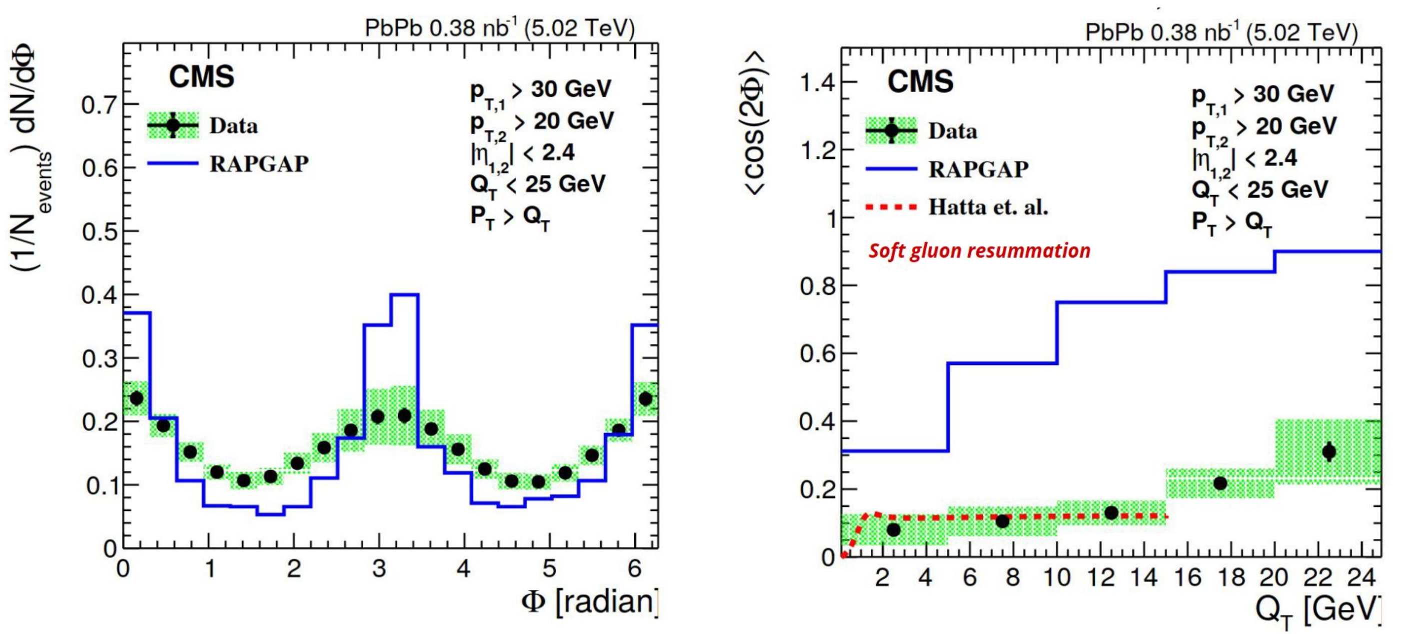
angular correlation between P_T and Q_T vectors sensitive to polarization

$$v_2 = \langle \cos(2\phi) \rangle,$$

$$\cos(\phi) = \vec{Q}_T \cdot \vec{P}_T / (\| \vec{Q}_T \| \cdot \| \vec{P}_T \|)$$

CMS exclusive dijet angular correlations

CMS, PRL 131 (2023) 051901



Calculations with out-of-cone soft radiation effects are able to describe the data.

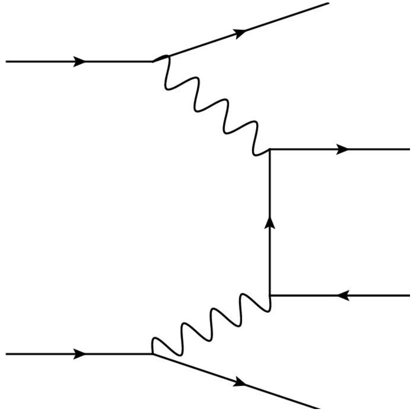
No experimental sensitivity to polarization effects

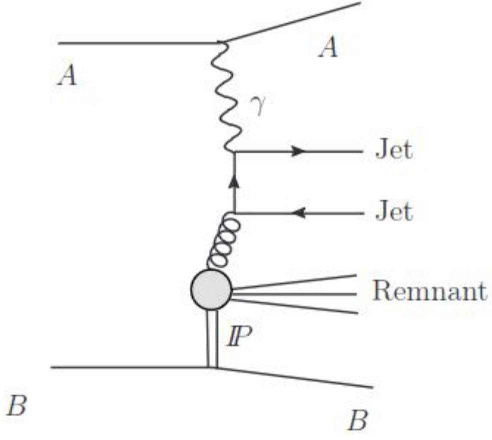
Lessons/thoughts:

- QED rate accounts for ~10%
  of 0n0n exclusive dijet rate in PbPb (ATLAS),
  is remaining 90% coherent diffractive?

- Observables proposed to be sensitive to gluon elliptic polarization are sensitive to final-state radiation effects

- Measurements challenge low p_T jet calibration!
  Other "hard" probes?
  (see Gian Michele Innocenti's talk!)





Summary

- Run-1 & Run-2 results on hard diffraction & photoproduction with jets

- **Trade-offs between clean experimental signatures and control over calculations**

- Interested on feedback on different decisions (low p_T jets, rapidity gap definitions, ZDC & Roman pot tagging, …)