Opportunities with jets in photoproduction at the LHC

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GDR QCD workshop on coherence/incoherence in hadronic & diffractive collisions at DIS and at hadron colliders, Oct 11th – 12th 2023

European Research Council

Outline

Mostly discuss three LHC results:

- ATLAS photonuclear dijet measurement in PbPb (ATLAS-CONF-2022-021)

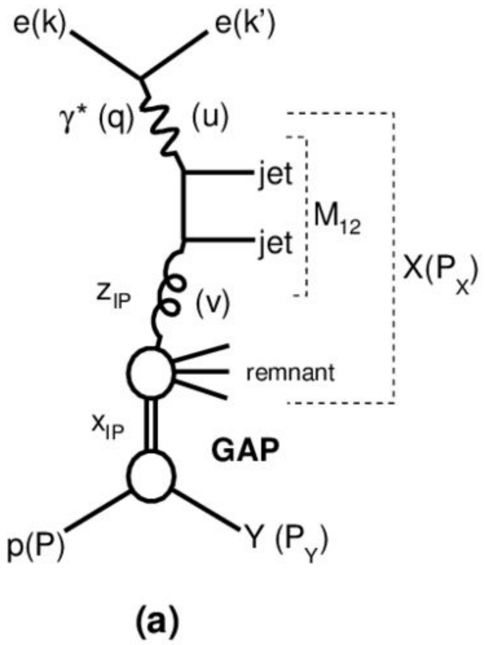
- CMS diffractive dijet photoproduction in PbPb (**CMS, Phys. Rev. Lett. 131 (2023) 051901**)

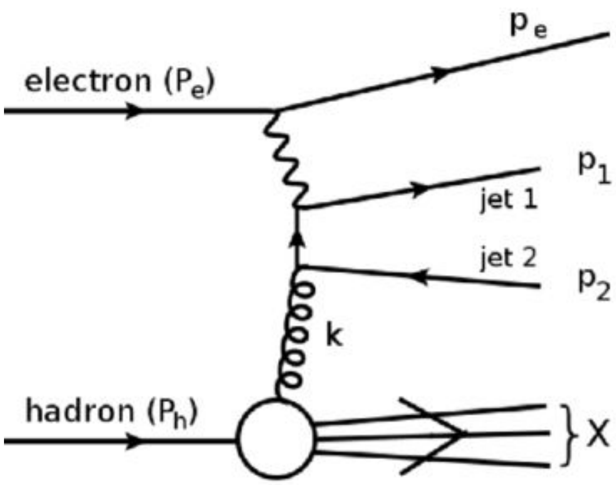
- CMS-TOTEM single-diffractive dijet with proton tagging (CMS-TOTEM, Eur. Phys. J. C 80, 1164 (2020))

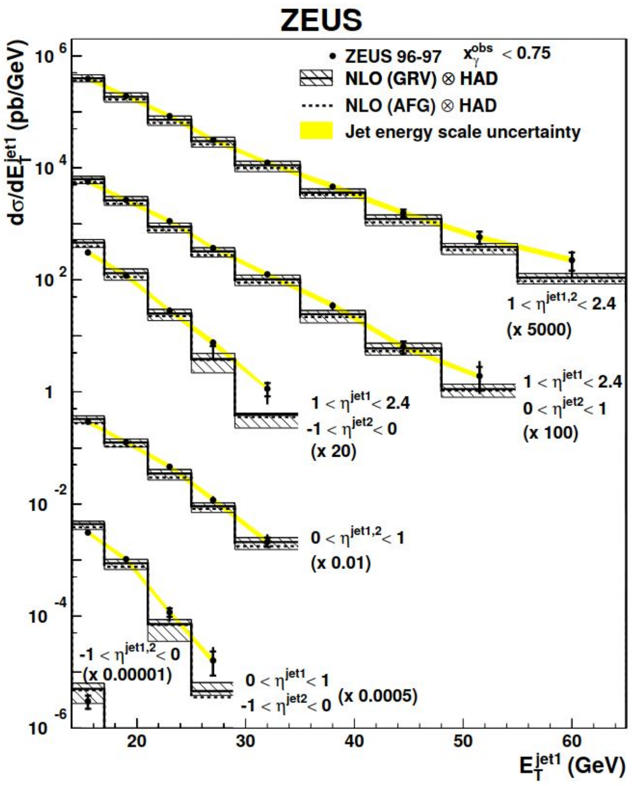
Some thoughts on the experimental challenges and opportunities throughout the presentation

Dijet photoproduction

Detailed measurements at HERA, what about the LHC?







ZEUS, arXiv:0112029

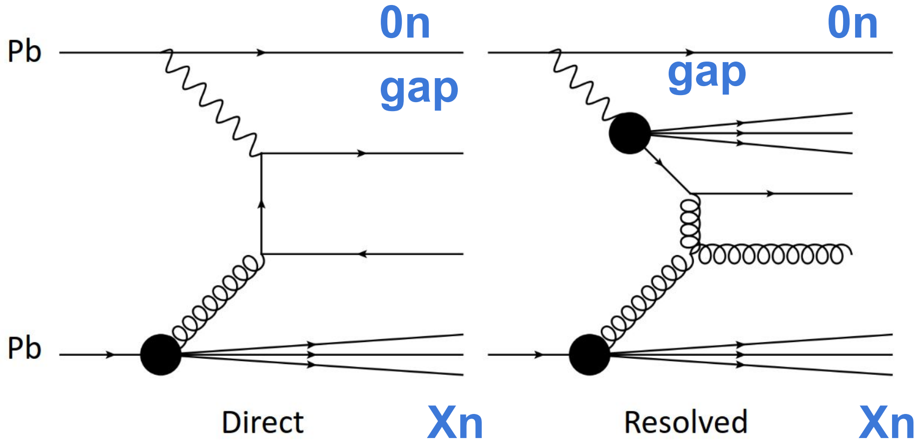
Diffractive photoproduction

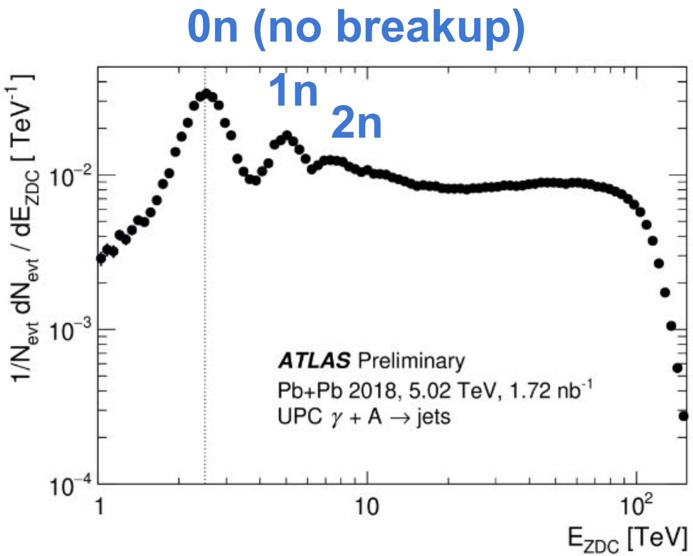
Photoproduction

Photonuclear dijet in ATLAS in PbPb at 5.02 TeV

Forward neutrons on ZDC to tag photon emission (0n Xn, X > 0) + rapidity gap

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





ZDC energy spectrum

Sensitivity to resolved and direct dijet photoproduction

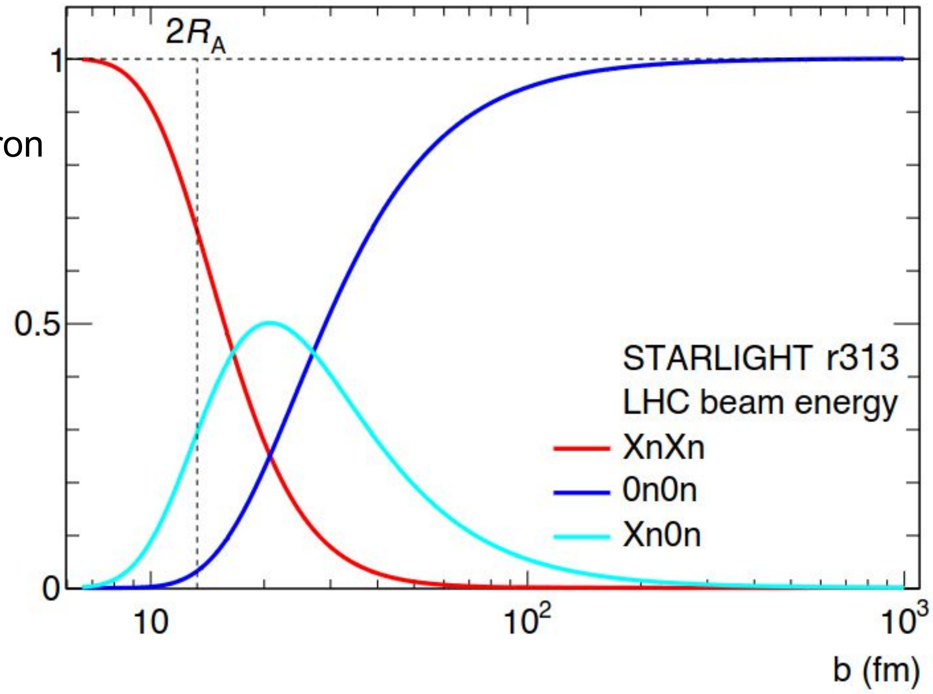
Clean probe of gluon nuclear PDFs at small-x and perturbative Q^2

At least 2 jets with p_T > 15 GeV, allowed to go up to acceptance $|\eta|<4.4$

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

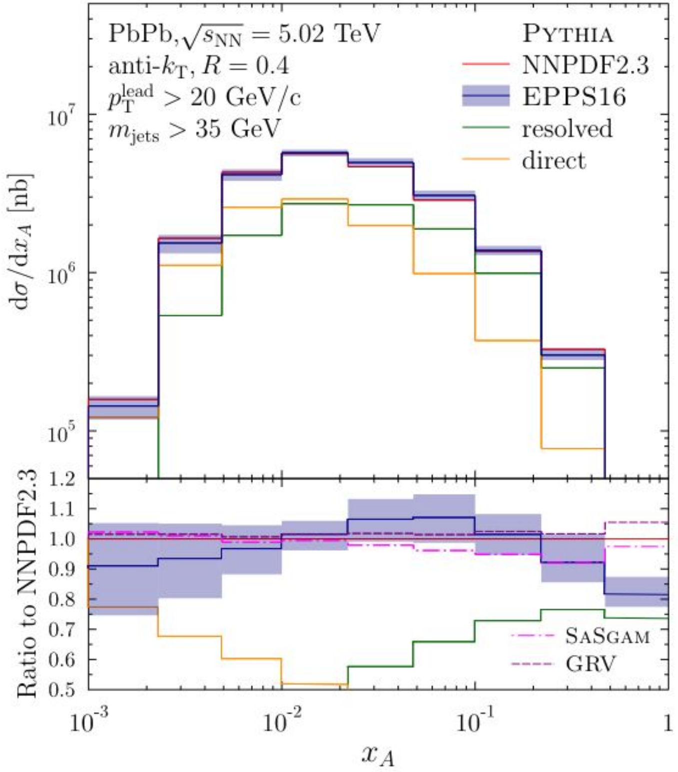


In ATLAS, the photon flux of PYTHIA8 is reweighted to take into account this bias for photonuclear dijet predictions

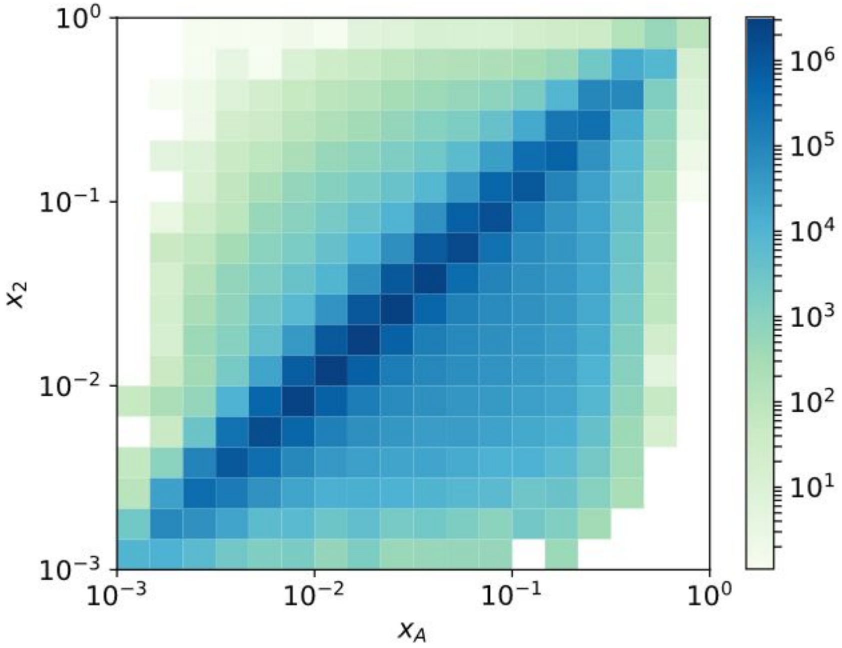
$$x_A \equiv \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}}$$

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

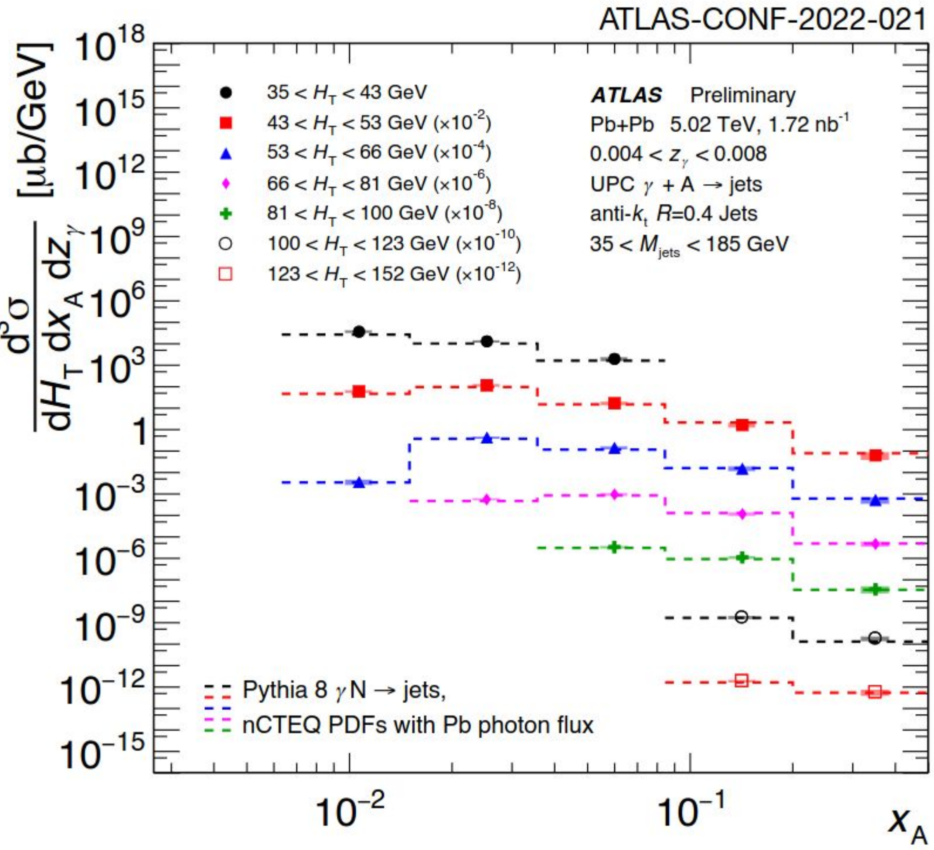


C. Balden

I. Helenius, arXiv:1811.10931

Triple differential cross section measurement (ATLAS)

ATLAS-CONF-2022-021



Fully unfolded to particle-level, reported for three variables

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

$\sim Q^2$ — 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!**)

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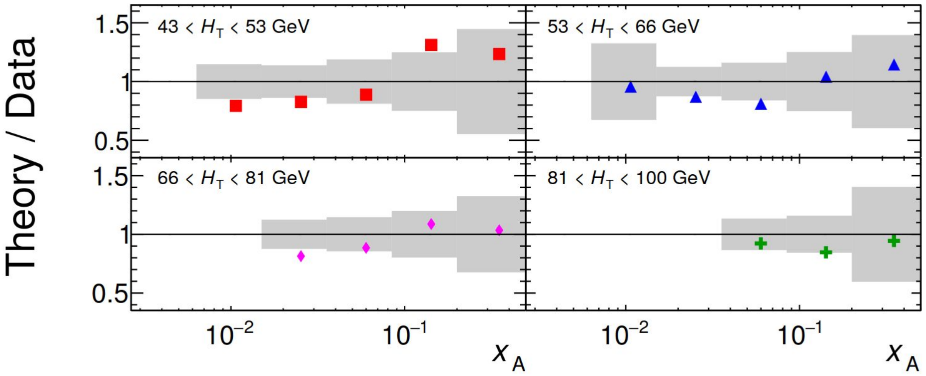

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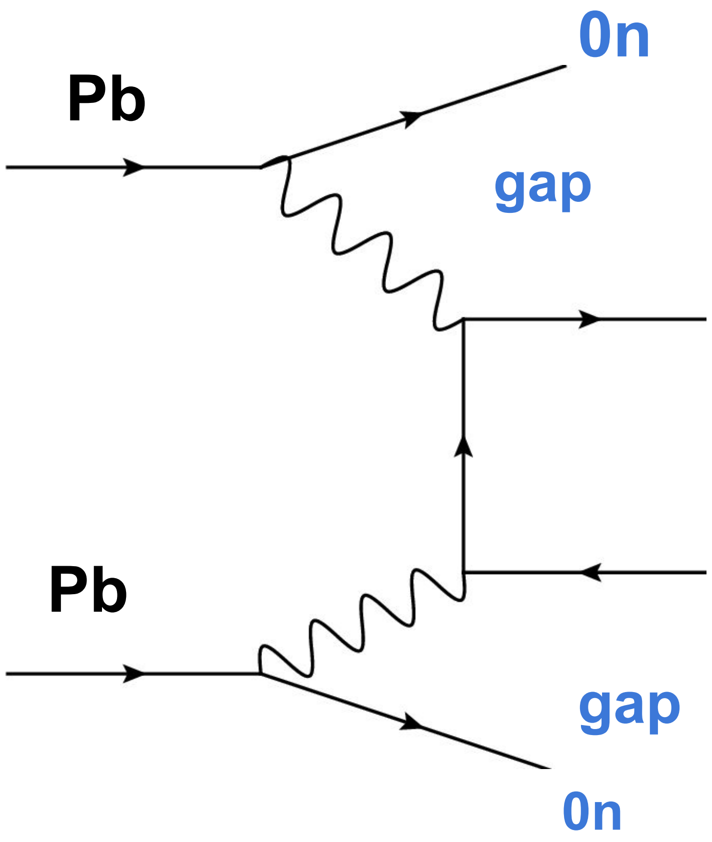
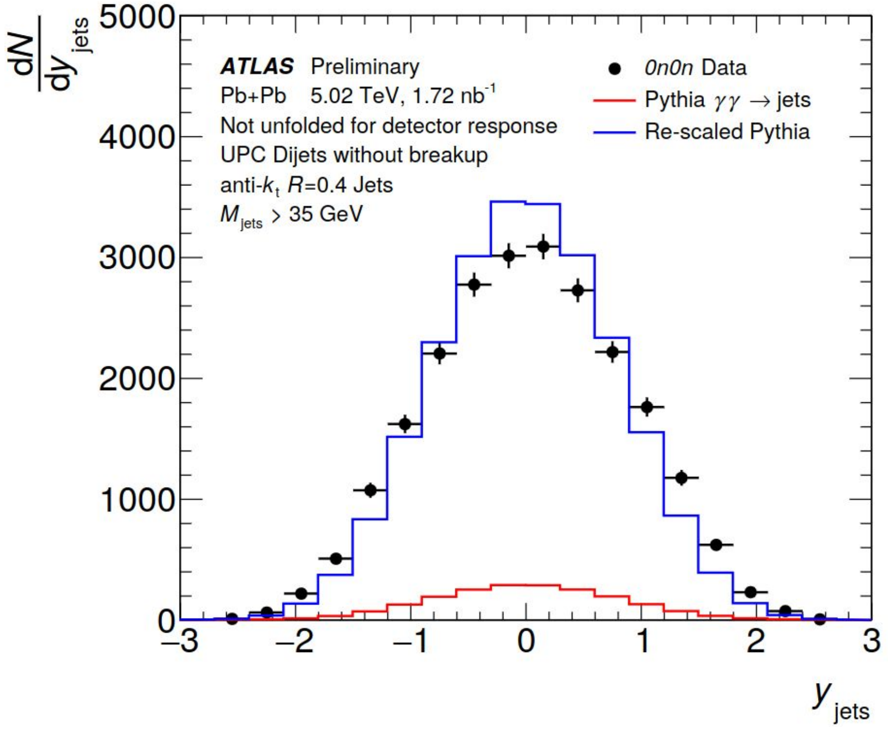
Exclusive dijet with 0n0n + two rapidity gaps (ATLAS)



Naïvely, one would expect **QED ɣɣ→qqbar** to dominate (large photon flux)

Exclusive dijet with 0n0n + two rapidity gaps

ATLAS-CONF-2022-021

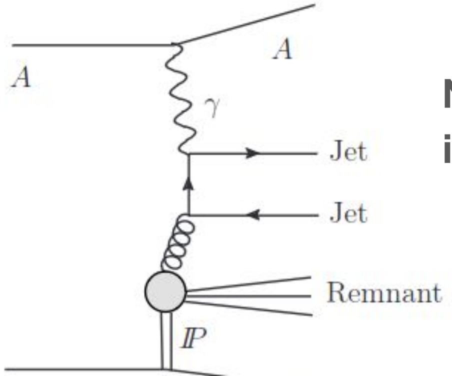


NB: Uncorrected distributions

Pure **QED γγ→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:
E. Iancu, A. Mueller, D. Triantafyllopoulos, S.Y. Wei, arXiv:2304.12401



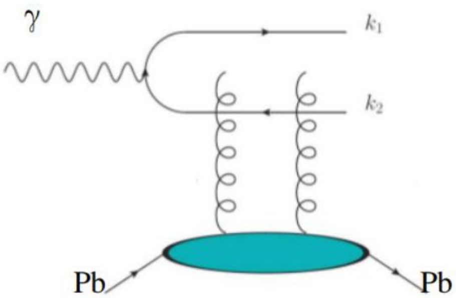
Needs to be investigated further!

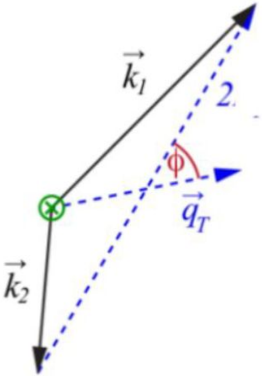
Exclusive dijet production in PbPb (CMS)

Proposed to probe elliptic polarization of gluons in unpolarized nuclei,

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

CMS, PRL 131 (2023) 051901



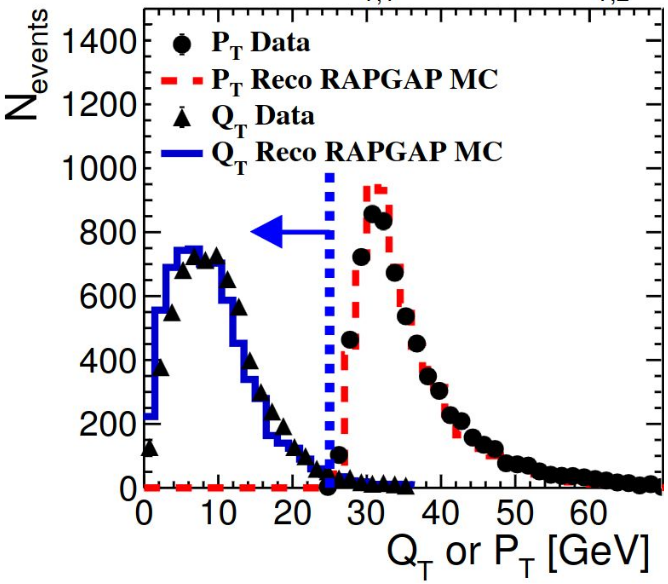


Vector sum of 2 jets:

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

Vector difference of 2 jets:

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



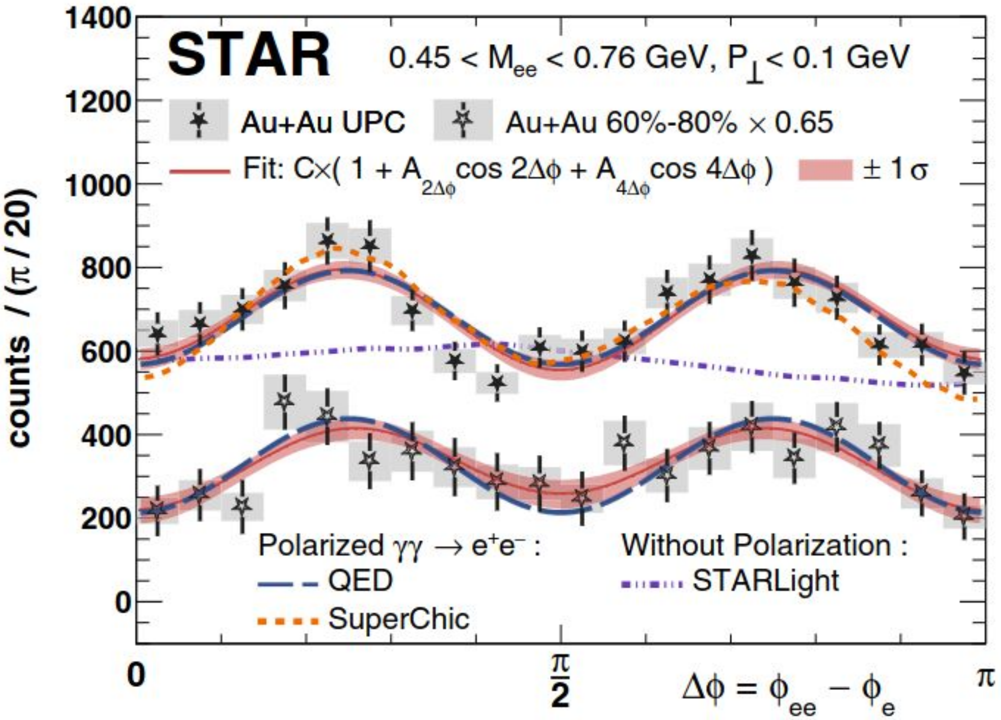
angular correlation between P_T and Q_T vectors sensitive to polarization

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

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

Analogous strategy used in γγ→e⁺e⁻ (STAR)

$$\cos\phi = (\vec{p_{T1}} + \vec{p_{T2}}) \cdot (\vec{p_{T1}} - \vec{p_{T2}}) / (|\vec{p_{T1}} + \vec{p_{T2}}| \times |\vec{p_{T1}} - \vec{p_{T2}}|)$$

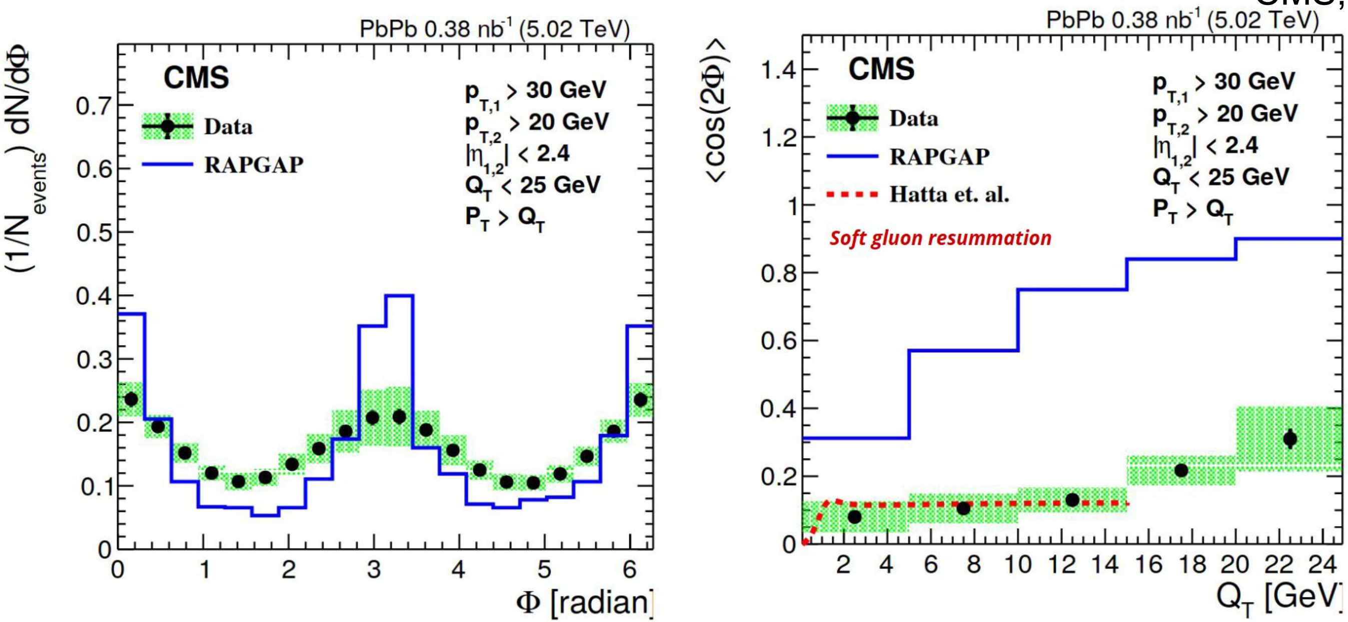


STAR, Phys. Rev. Lett. 127, 052302

linear polarization of quasi-real photons in exclusive dielectron events induce azimuthal angular correlations

CMS exclusive dijet angular correlations

CMS, PRL 131 (2023) 051901

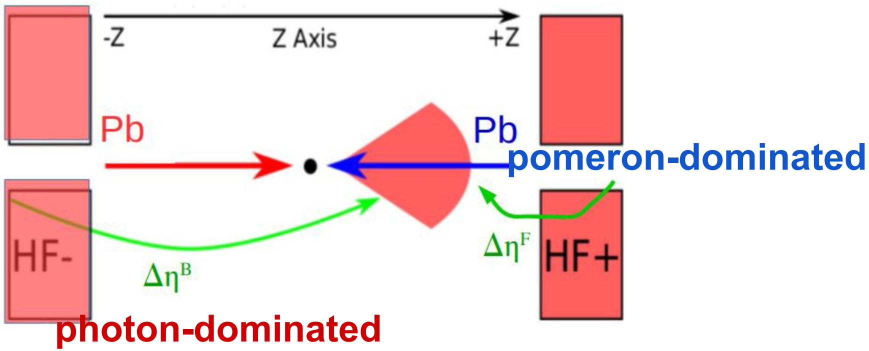


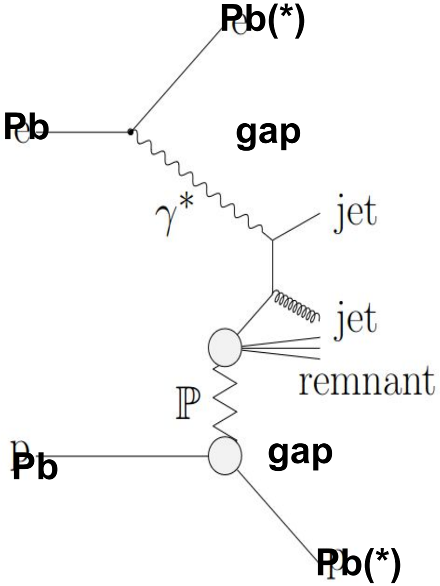
Calculations with out-of-cone radiation effects (not present in **RAPGAP** generator) are able to describe the data. No experimental sensitivity to polarization effects.

In the future, one could consider using larger R jets (mitigates nonglobal logs), ZDC for further purification, scan for different categories of p_T/Q_T

Two-fold ambiguity in symmetric PbPb collisions

Don’t know which Pb emitted the photon event-by-event



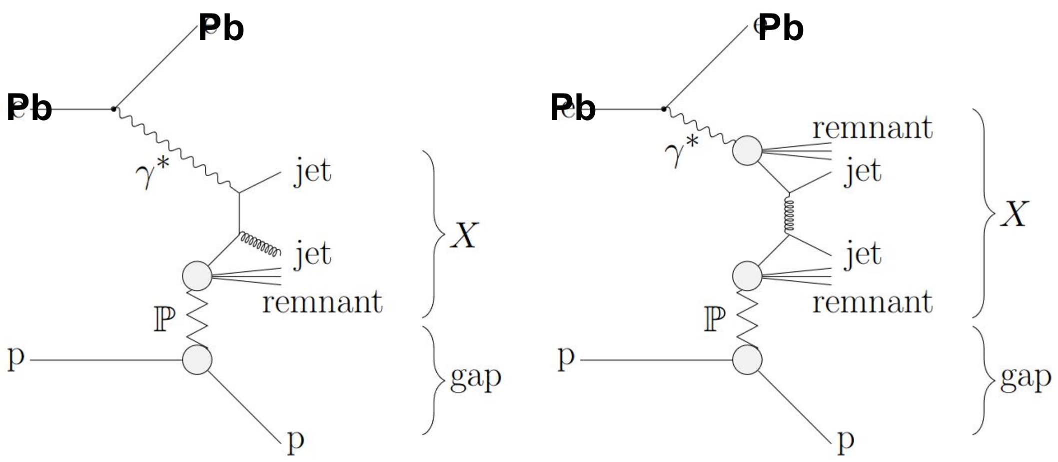


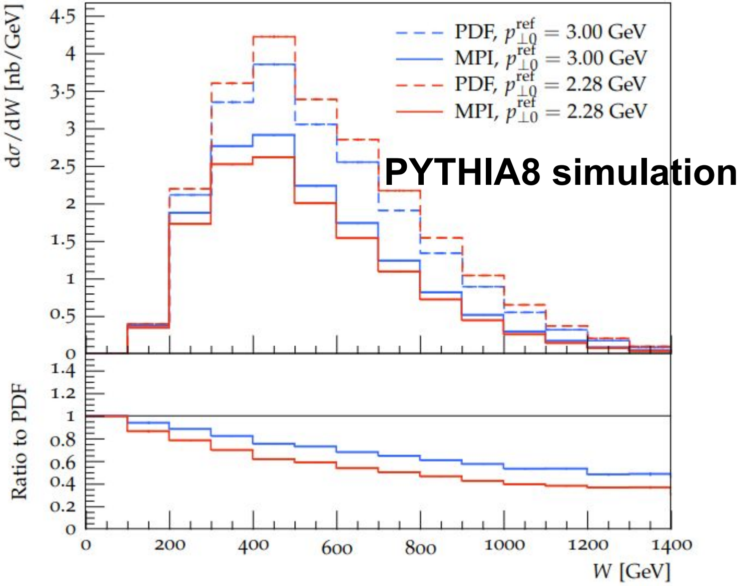
In CMS, ambiguity was suppressed by selecting boosted dijet configurations

(It has been suggested that one could use the direction of the third jet to identify photon emitter, could we also use ZDC for disentanglement as done for PbPb -> Pb(*) J/ψ Pb(*)?)

Diffractive dijet photoproduction in proton-lead (HERA-like)

[Ilkka Helenius, arXiv:2107.07389](https://arxiv.org/abs/2107.07389)





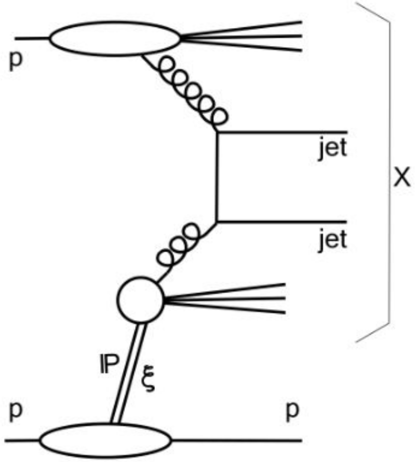
A measurement of the cross section would be interesting to revisit open questions in diffraction since HERA times (eg, is factorization broken in hard diffractive DIS?)

Useful baseline also for PbPb to quantify nuclear modification of diffractive PDFs with data

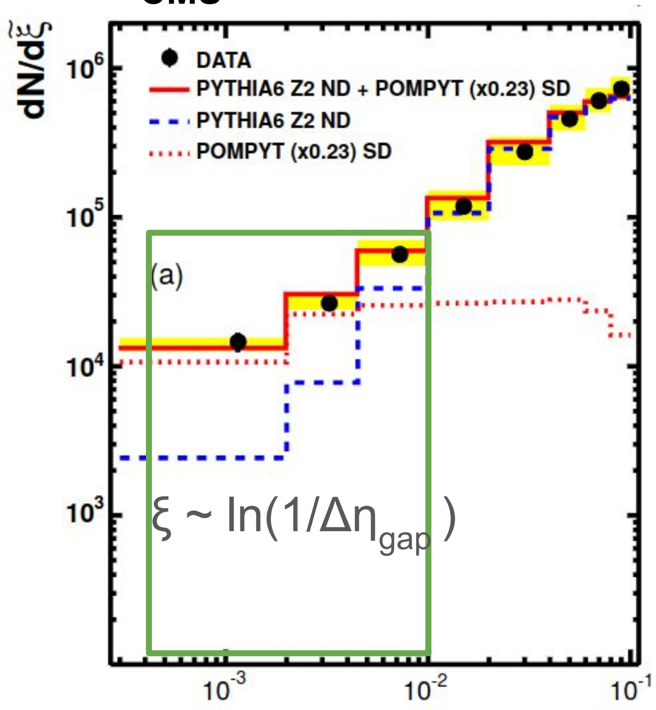
Existing 2016 pPb data could be used for this in ATLAS/CMS
(ZDC operational in 2016 pPb)

Nondiffractive contamination with large rapidity gaps

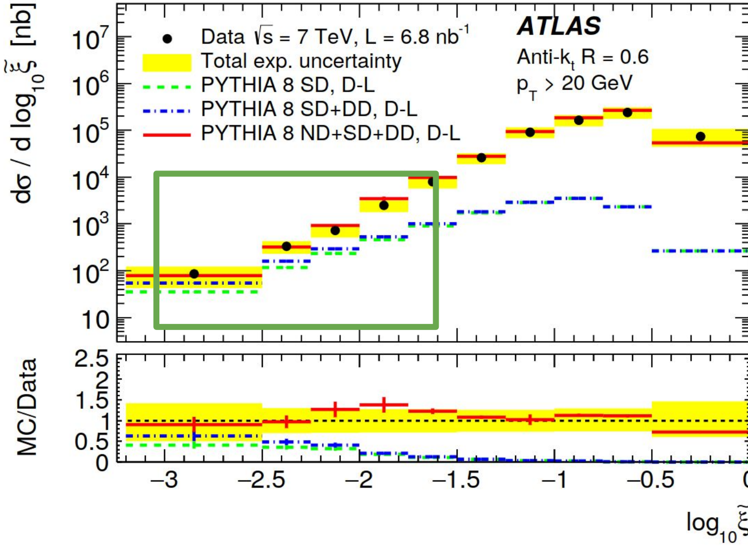
Nondiffractive/photoproduction events can mimic rapidity gaps with fluctuations (~20% contamination for single-diffractive dijet with large rapidity gaps in pp)



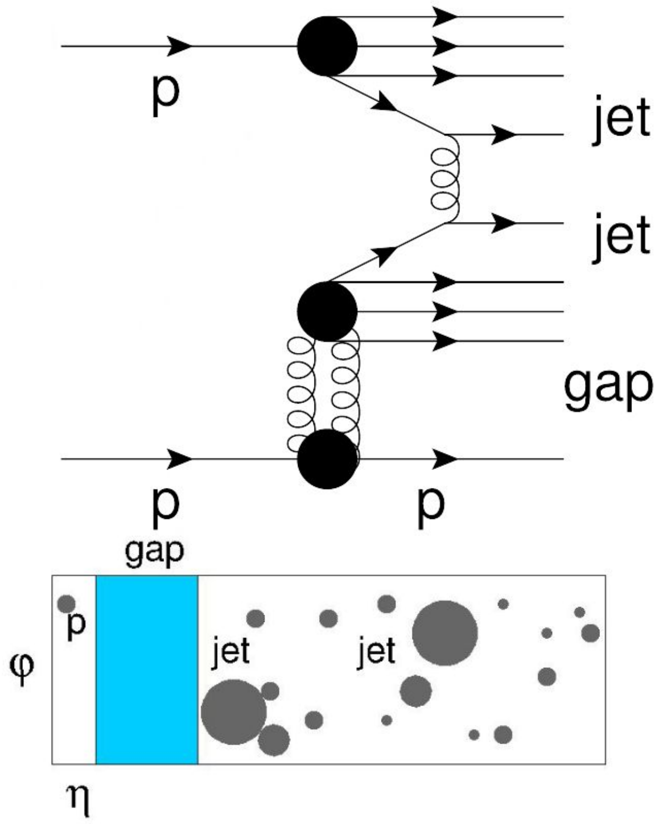
CMS



$x_P == \tilde{\xi}$



Hard diffraction with intact protons detected in Roman pots of TOTEM



Intact proton is a more direct 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. ($0.0 < \xi < 0.1$ for Run-1 analysis)

|t| distribution for single-diffractive jets

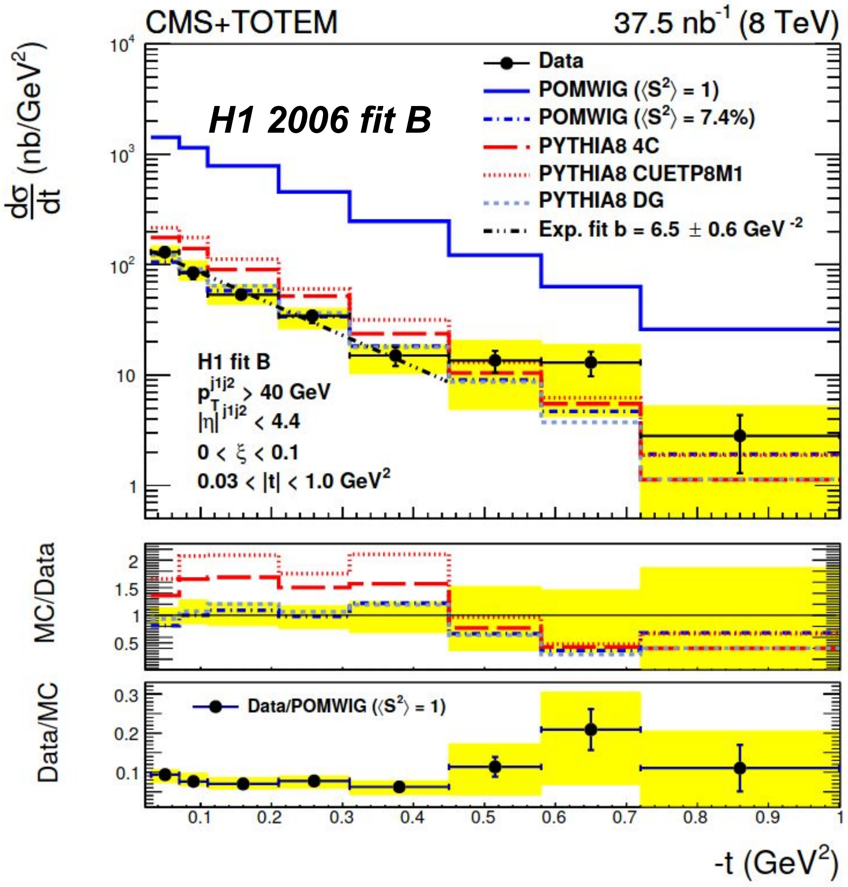
CMS-TOTEM, EPJC 80, 1164 (2020)

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|

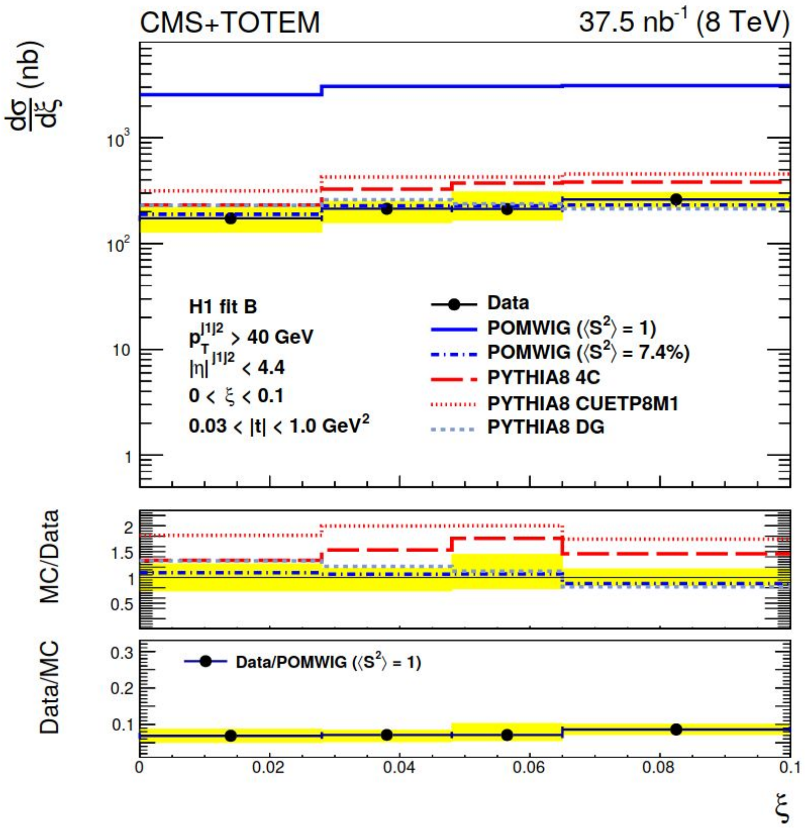
PYTHIA8 with dynamical gap (DG) model correctly describes the rate and shape of the distribution, ***no additional correction factor***



Fractional momentum loss ξ ($x_{\mathbb{P}}$ in HERA notation)

CMS-TOTEM, EPJC 80, 1164 (2020)

H1 2006 fit B



Proton tagging allows to probe larger values of ξ ~ 0.1, whereas rapidity gaps restrict you to ξ ~ 10^{-3}– 10^{-2}

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

Challenges and considerations

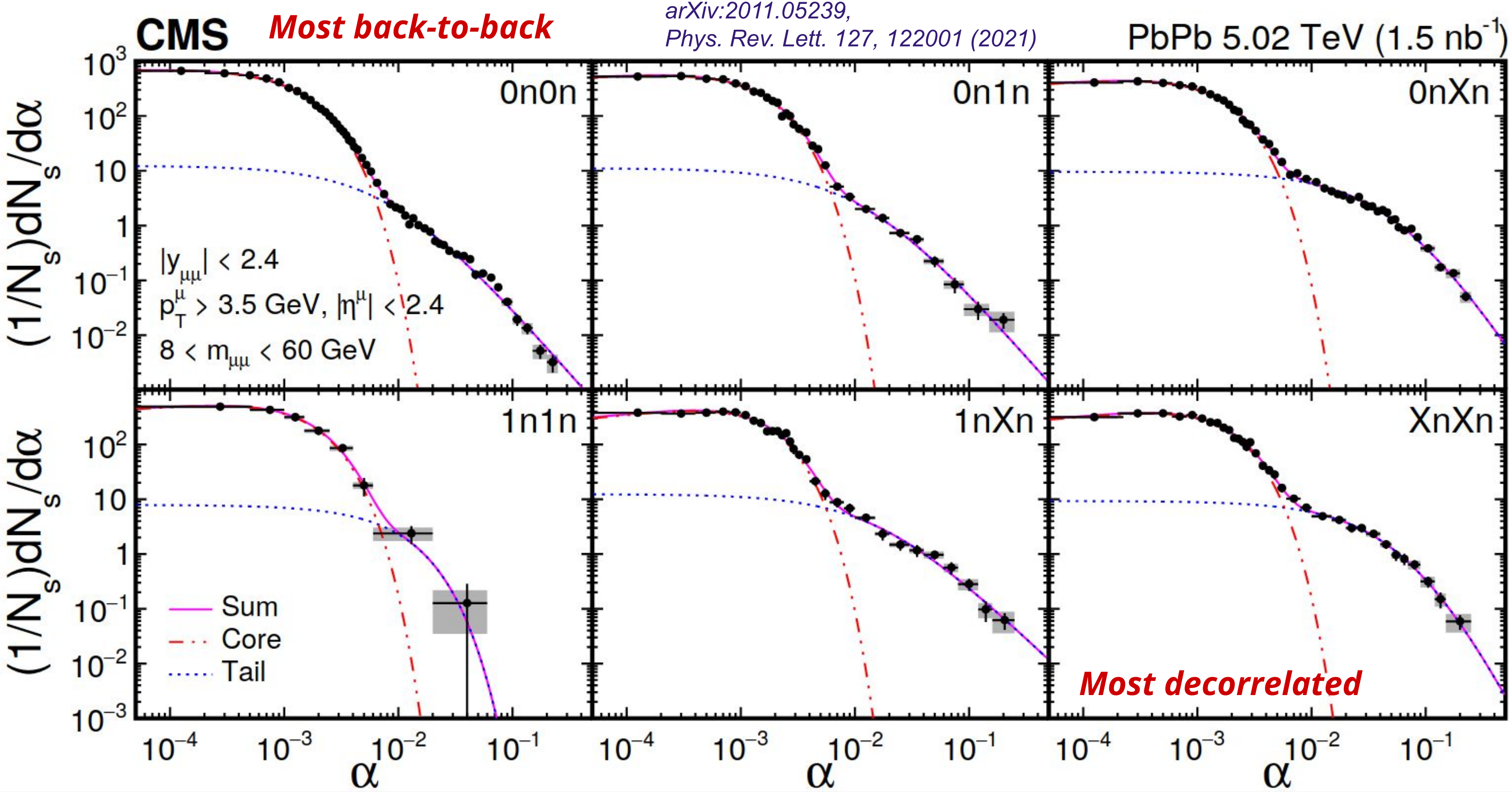
- rapidity gaps are less stringent over time due to radiation damage on forward hadron calorimeters
- ZDC can be used to suppress hadronic bkg and rely less on rapidity gaps, in exchange of a bias on the photon flux
- **Need a handle on diffractive contributions;** exclusive dijet with 0n0n suggests that QED-only contribution is not enough, could it be only explained with a large coherent diffractive dijet contribution?
- Low p_T jet calibration is highly nontrivial for ATLAS/CMS (lowest p_T is 15 GeV), if we want to probe saturation we have to think of ways of improving calibration or use other perturbative probes as proxies for jets

Summary

- Photonuclear dijets have been measured at the LHC by ATLAS and CMS
- Photoproduction (+ diffraction) with hadronic final states (jets) requires both careful experimental and theoretical considerations
- Opportunities for dijet photoproduction in pPb collisions with existing 2016 pPb data
- Coherent diffractive dijet photoproduction

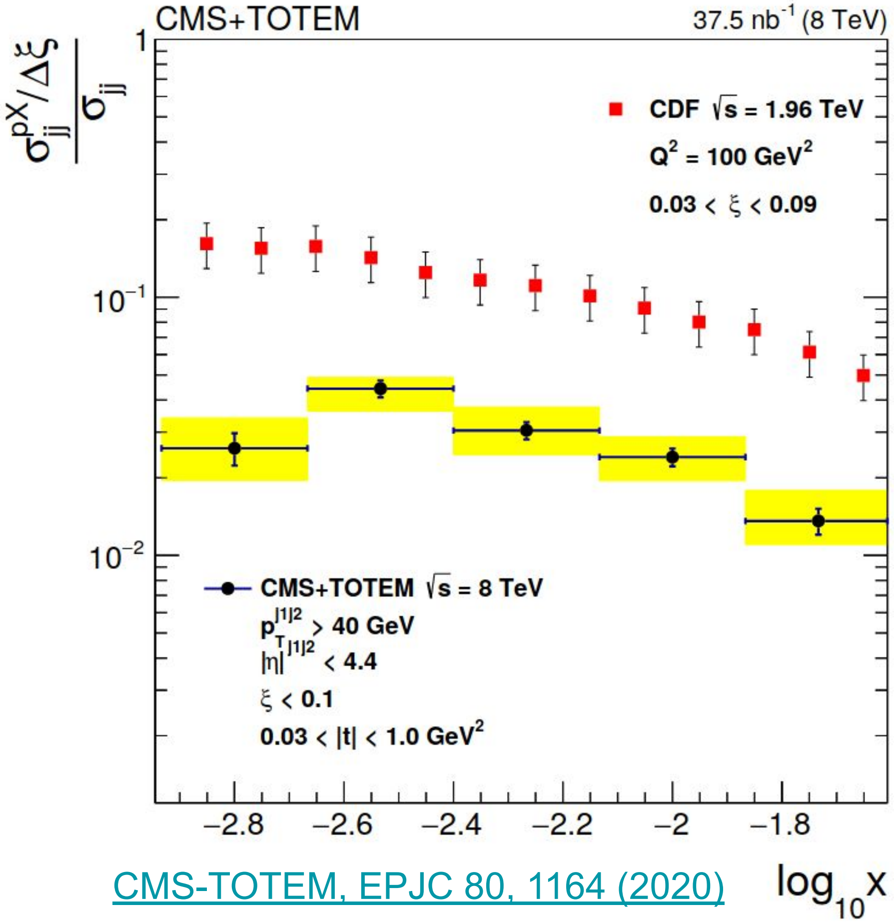
Forward neutron multiplicities modulate azimuthal angular correlations between muon pairs

arXiv:2011.05239,
Phys. Rev. Lett. 127, 122001 (2021)



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)

Data corrected to particle-level

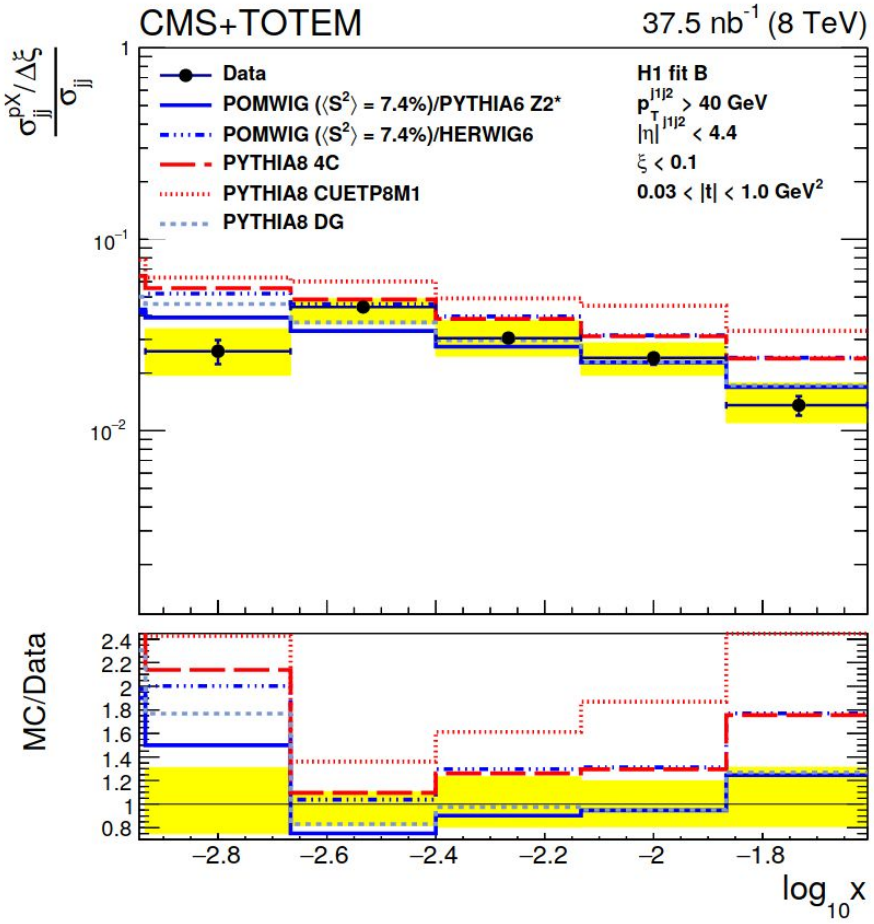
CMS-TOTEM, EPJC 80, 1164 (2020)

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

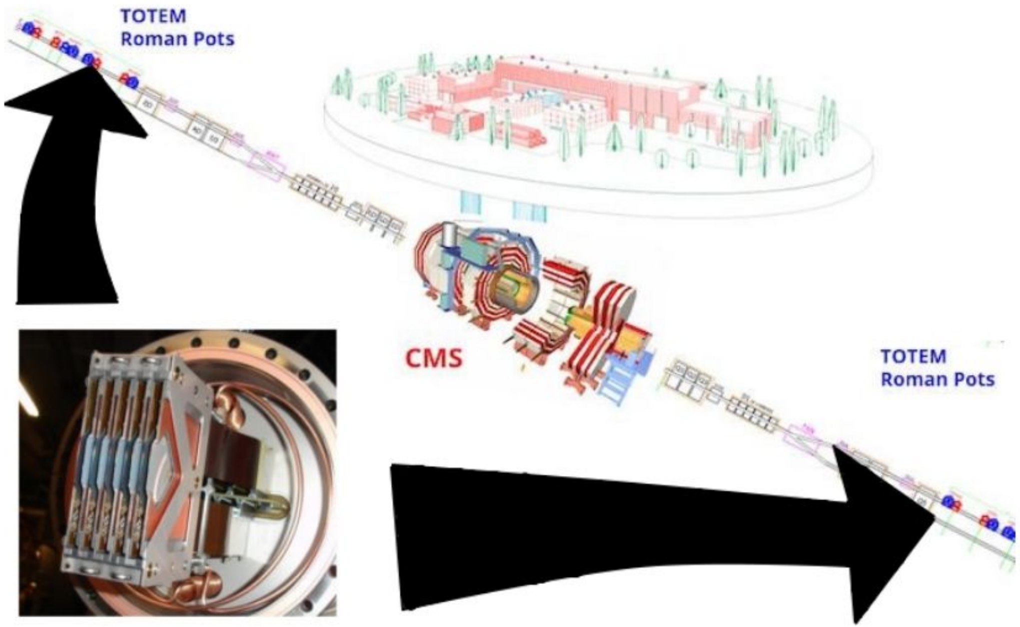
$$x^{\pm} = \frac{\sum_{\text{jets}} \left(E^{\text{jet}} \pm p_z^{\text{jet}}\right)}{\sqrt{s}},$$

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.



CMS-TOTEM setup



Roman pots:
Near-beam Si tracker detectors

CMS:

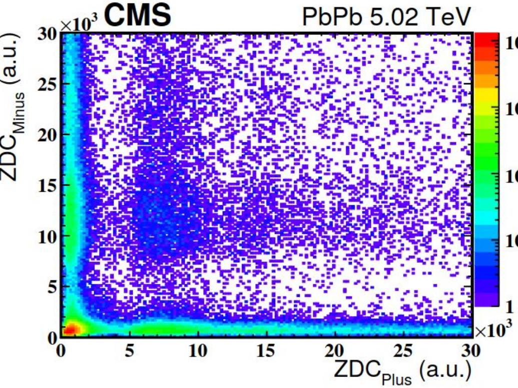
- General purpose detector at IP5 of the CERN LHC.
- Jets with $R = 0.4$ reconstructed within $|\eta^{\text{jet}}| < 4.7$.

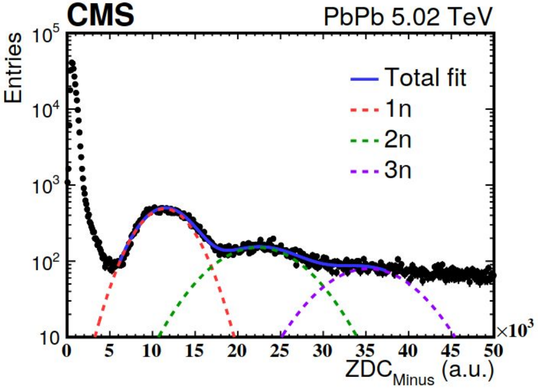
TOTEM:

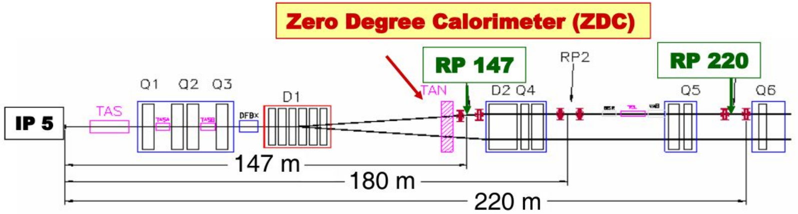
- **Roman pots:** Forward tracking detectors at $\approx$ 220m w.r.t. IP5 that measure the protons scattered at small angles w.r.t. the beam.

Forward neutron multiplicity ⇔ impact parameter “filter”

Softer photon-exchange in addition to hard scattering → forward neutrons from nuclear breakup
Events can be categorized w.r.t. Zero Degree Calorimeter (**ZDC**) activity (0n0n, 0nXn, XnX n, with X = 1, 2, ...)





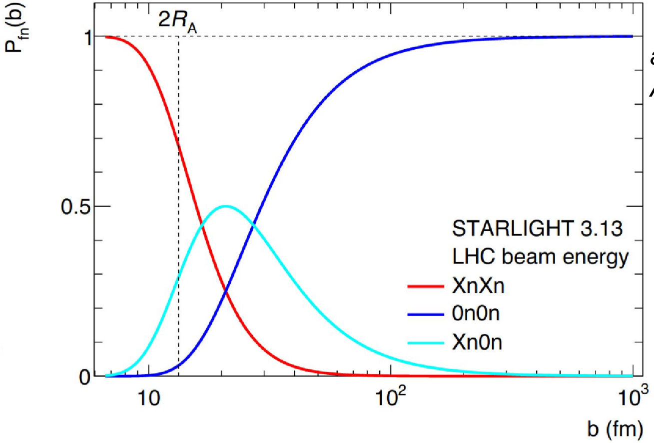


Phys. Rev. Lett. 127, 122001 (2021)

arXiv:2011.05239, Phys. Rev. Lett. 127, 122001 (2021)

Selection of a specific ZDC topology is also filtering on a range of impact parameters.

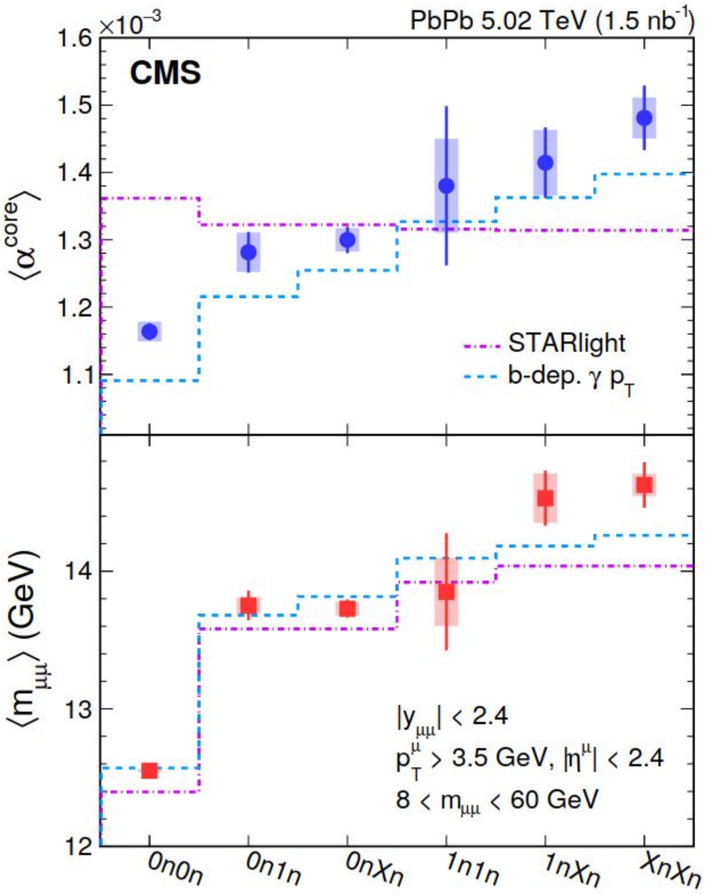
Xn0n or XnXn select smaller impact parameters than 0n0n!



arXiv:2005.01872, S. Klein, P. Steinberg, Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

Significant dependence of impact parameter with forward neutron multiplicities.

arXiv:2011.05239, Phys. Rev. Lett. 127, 122001 (2021)



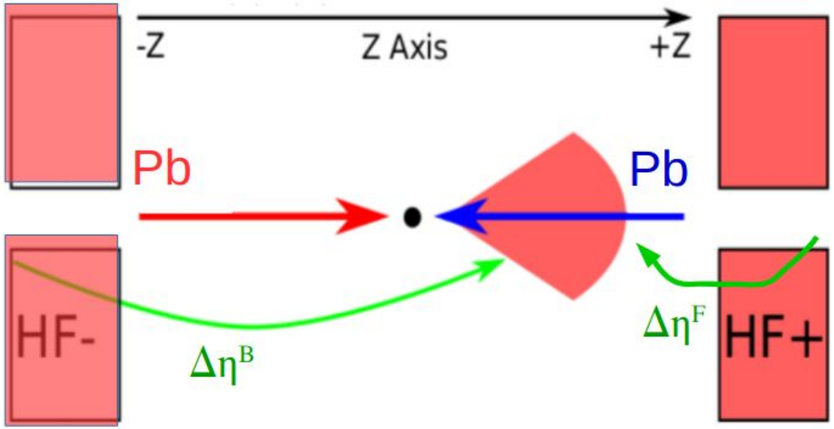
- Each muon has $p^{\mu}_{T} > 3.5$ GeV, $|\eta^{\mu}| < 2.4$, and the pair $8 < m^{\mu\mu} < 60$ GeV, $|y^{\mu\mu}| < 2.4$.
- Strong correlation between neutron multiplicities with$\langle m^{\mu\mu} \rangle$and the mean value of the acoplanarity $\alpha = 1 - |\Delta\varphi^{\mu\mu}|/\pi$ near the back-to-back region ($\langle \alpha_{core} \rangle$).
- Comparison to **STARlight** (pure back-to-back muon pairs, no initial-state p_T ``kicks'')
- Data agrees with QED calculation ***only when it incorporates the b-dependence of the initial photon pT (``kicks'')*** (**blue line**, calculation by J. Brandenburg, W. Li, L. Ruan, Z. Tang, Z. Xu, S. Yang, W. Zha, arXiv:2006.07365)

Event selection

- anti-kT R = 0.4 particle-flow jets.

- Two jets with $|\eta| < 2.4$, $p_T^{lead} > 30$ GeV and $p_T^{sublead} > 30$ GeV > 20 GeV.

- Hadronic activity is vetoed in backward and forward regions
(2.8 < $|\eta|$ < 5.2) above the calorimeter noise threshold.



Symmetric PbPb beams: ***which Pb ion emits a pomeron and which one emits a photon?***

Enrich sample in gamma-pomeron -> dijet interactions by selecting dijet boosted topologies (*cf* **RAPGAP** simulation).

Rapidity gap definition:

A forward gap $\Delta\eta^F$ = 2.4-ηmax, where ηmax is the η of the farthest track with $p_T > 0.2$ GeV (*associated to pomeron exchange).*

A larger backward gap $\Delta\eta^B > \Delta\eta^F$ (*associated to the photon exchange)*

Symmetrized configuration is analyzed and combined

Event selection requirements

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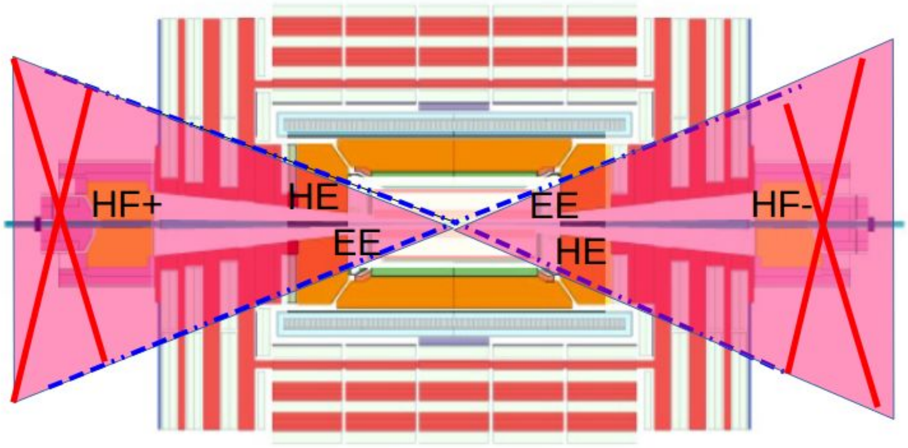

arXiv:2205.00045