# Recent results on diffractive and exclusive processes with heavy ion collisions at the CMS Experiment

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**On behalf of the CMS Collaboration**

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# Outline

- **Diffraction and inclusive $\gamma$p in pPb collisions @8 TeV**
  - Understanding the high energy limit of QCD
  - Useful for Cosmic ray physics Monte Carlo tuning

- **Two particle correlations in inclusive UPC pPb @8 TeV**
  - Search for elliptic azimuthal anisotropies in inclusive $\gamma$p

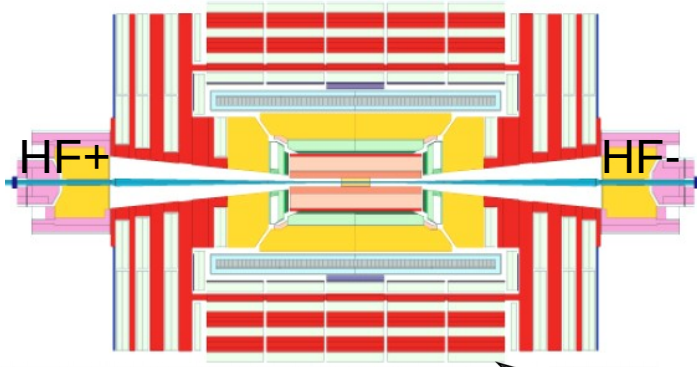
- **Exclusive dijet production in UPC PbPb @5 TeV**
  - First step to access novel features of gluon distributions

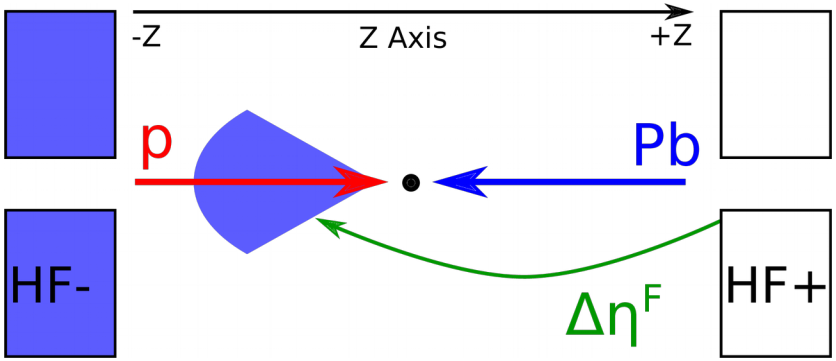
# First measurement of diffraction in pPb @8 TeV

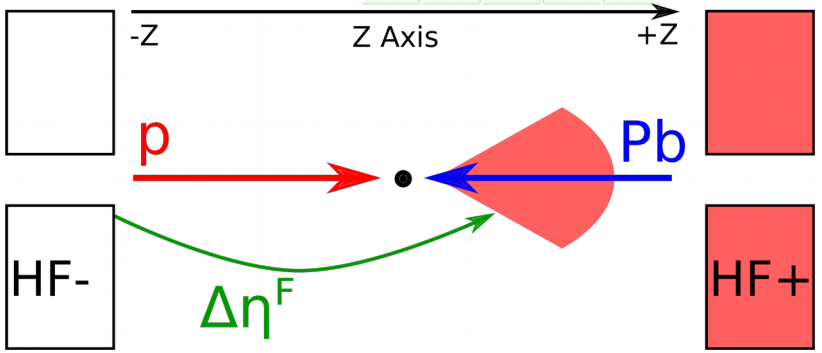
(CMS-PAS-HIN-18-019)

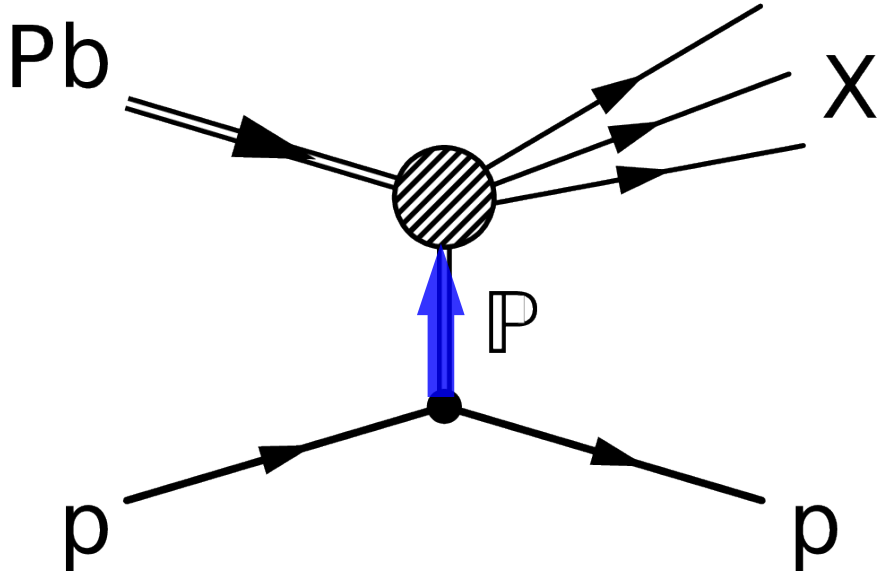
# Diffraction in pPb @8 TeV (CMS-PAS-HIN-18-019)

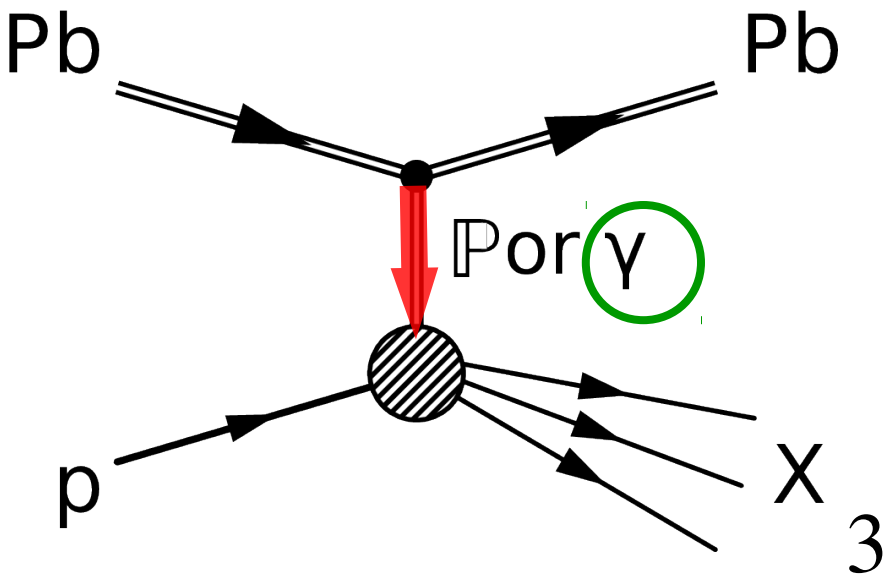
- 3.9 μb$^{-1}$ for pPb and 2.5 μb$^{-1}$ for Pbp
- MB events, at least one tower in Hadronic Forward (HF) Calorimeter > 10 GeV ($3.0 < |\eta| < 5.2$)
- Single Diffractive (SD) IPPb and IPp events are characterized by large rapidity gaps



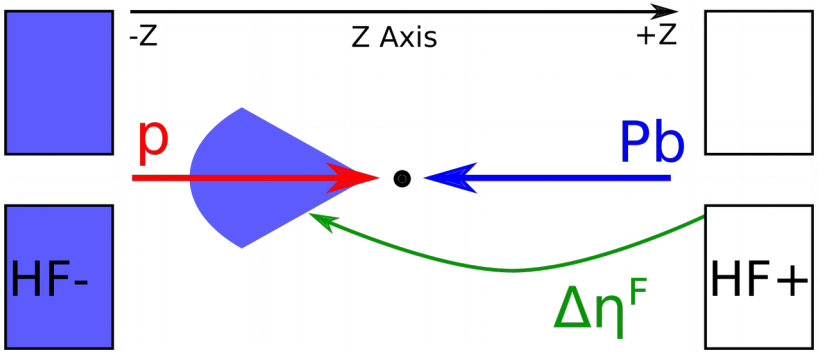



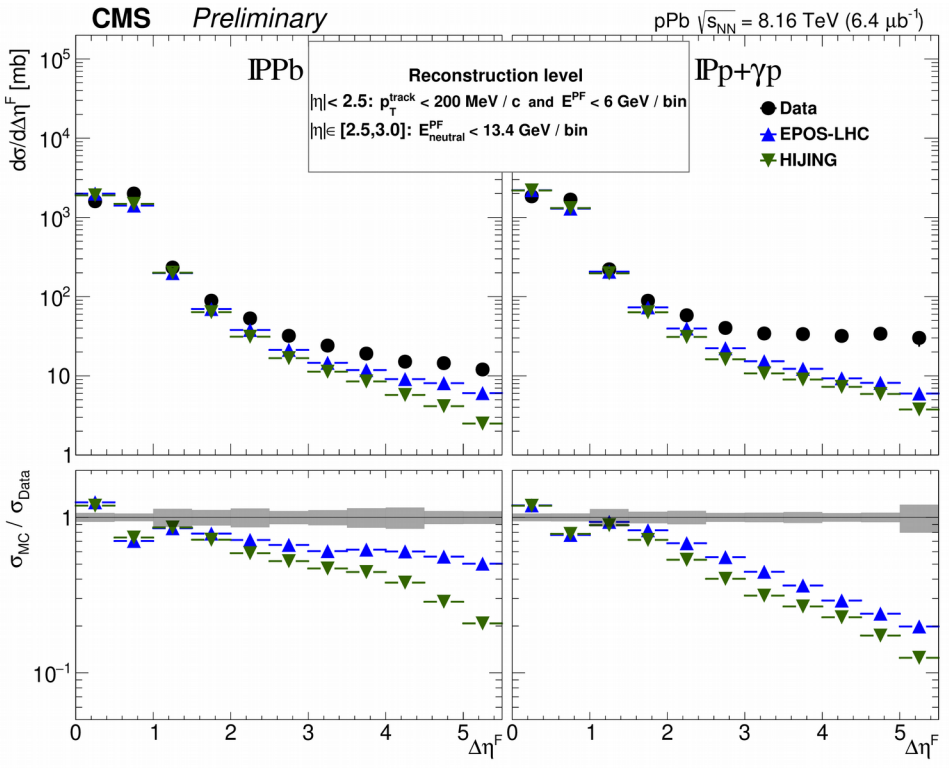
# Diffraction in pPb @8 TeV (CMS-PAS-HIN-18-019)

- Central detector $|\eta| < 3.0$ divided into 12 bins in rapidity
- No track with $p_T > 200$ MeV, total energy of Particle Flow-candidates below 6 GeV for $|\eta| < 2.5$
- Neutral hadrons below 13.4 GeV for $2.5 < |\eta| < 3.0$

Rapidity Gap $\Delta\eta^F$ is the distance from $\eta = 3.0$ to the first non empty bin




Rapidity Gap distribuion $\Delta\eta^F$:

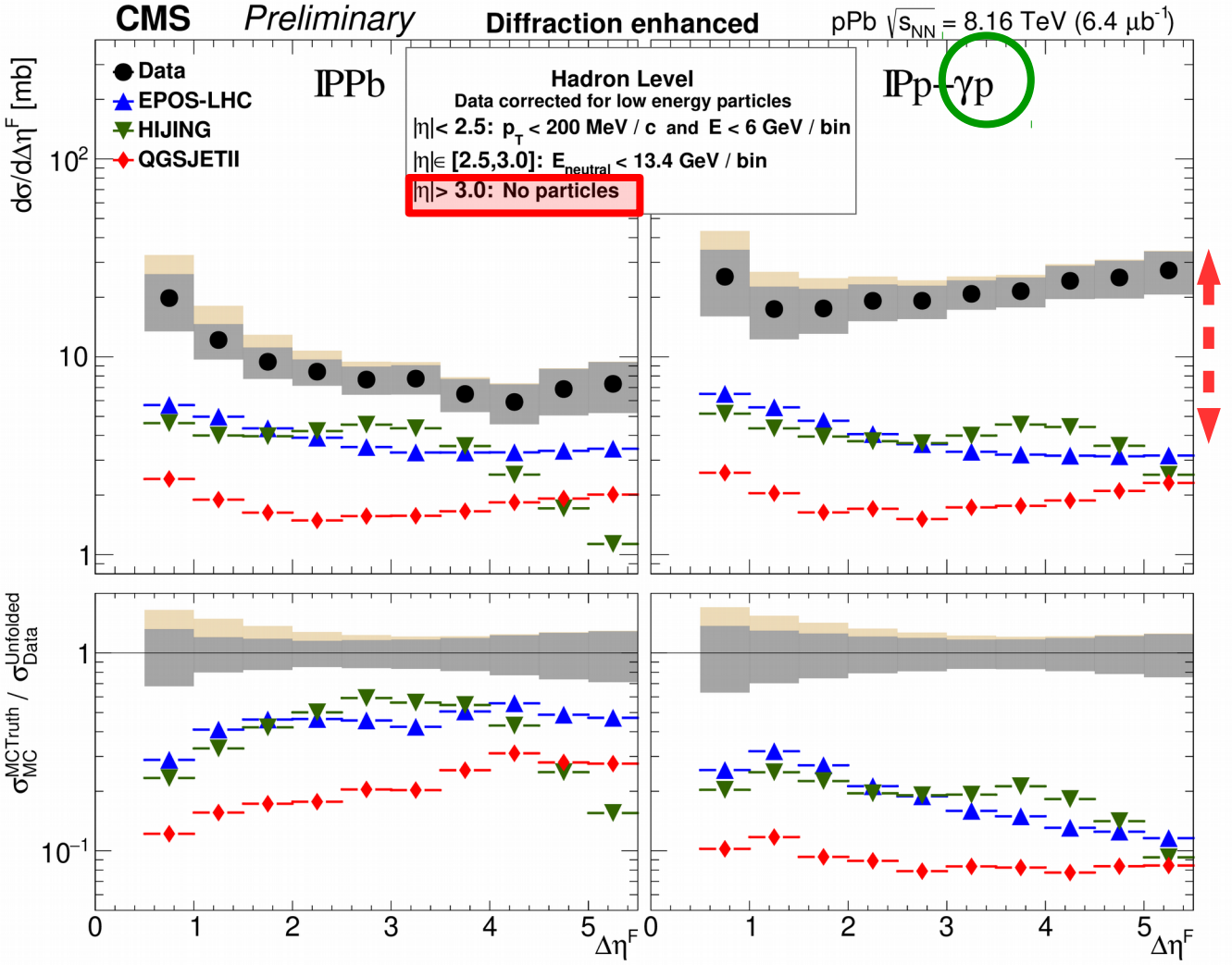



$\Delta\eta^F < 2$ are dominated by non-diffractive events

# Diffraction in pPb @8 TeV (CMS-PAS-HIN-18-019)

Extended rapidity gap from the central detector $|\eta| < 3.0$ to the HF calorimeter $3.0 < |\eta| < 5.2$:

Enhanced sensitivity to diffractive events.




Strong contribution from γp events

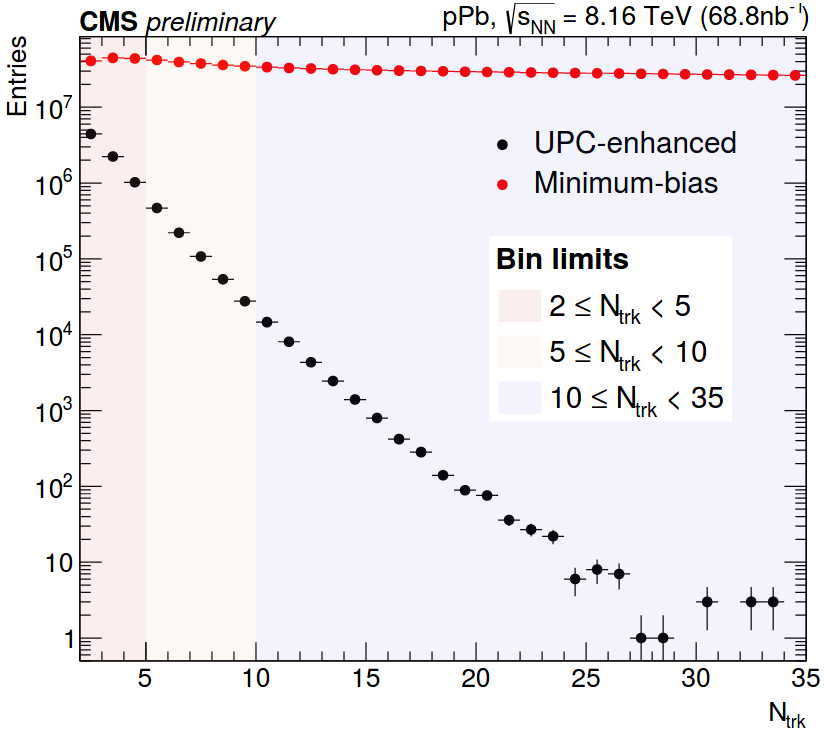
EPOS-LHC and QGSJET II below the data, but describe its shape

First measurement of two-particle correlations in inclusive UPC in pPb @8 TeV

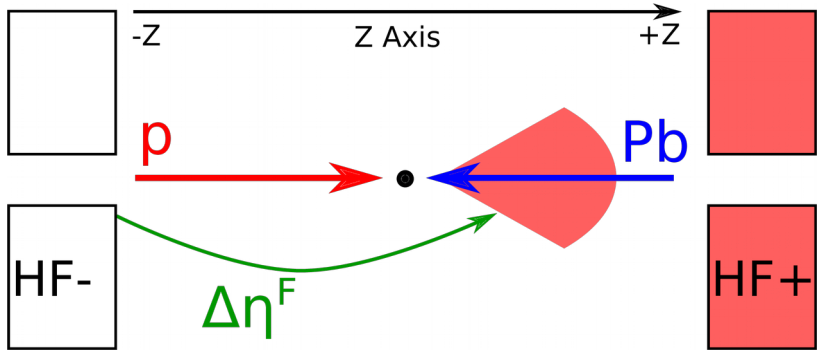
(CMS-PAS-HIN-18-008)

# Two-particle correlations in inclusive UPC in pPb @8 TeV (CMS-PAS-HIN-18-008)

- **MB-sample**: Both HF± with at least one tower > 3 GeV
- **UPC-enhanced sample**: HF+ with at least one tower > 10 GeV
  - No track with $p_T$ > 200 MeV, total energy of PF-candidates below 6 GeV for $|\eta| < 2.5$
  - Neutral hadrons below 13.4 GeV for $2.5 < |\eta| < 5.0$
  - Events with rapidity gap $5.0 < \Delta\eta^F < 7.5$ are selected




UPC sample is limited to $N_{trk} < 35$



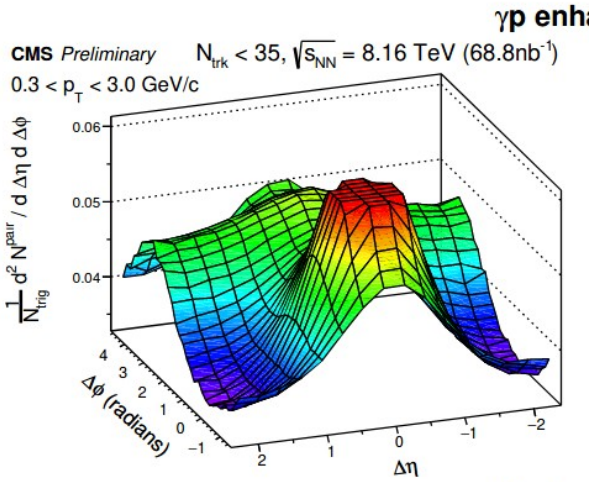

Rapidity gap selection used for the Diffractive analysis

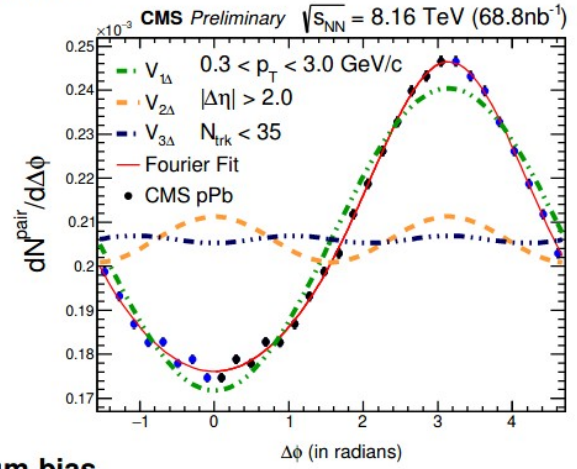
# Two-particle correlations in inclusive UPC in pPb @8 TeV (CMS-PAS-HIN-18-008)

- Tracks $0.3 < p_T < 3.0$ GeV in $|\eta| < 2.4$ are studied

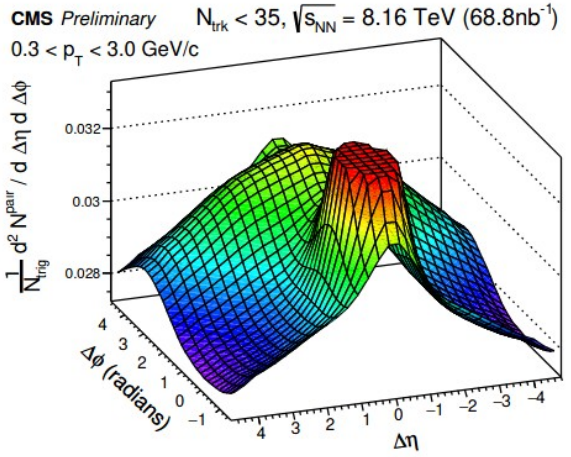
$$\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2N^{\text{pair}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

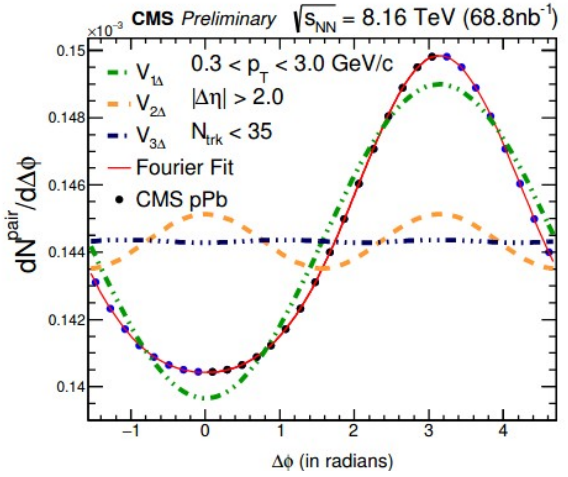
γp




MB



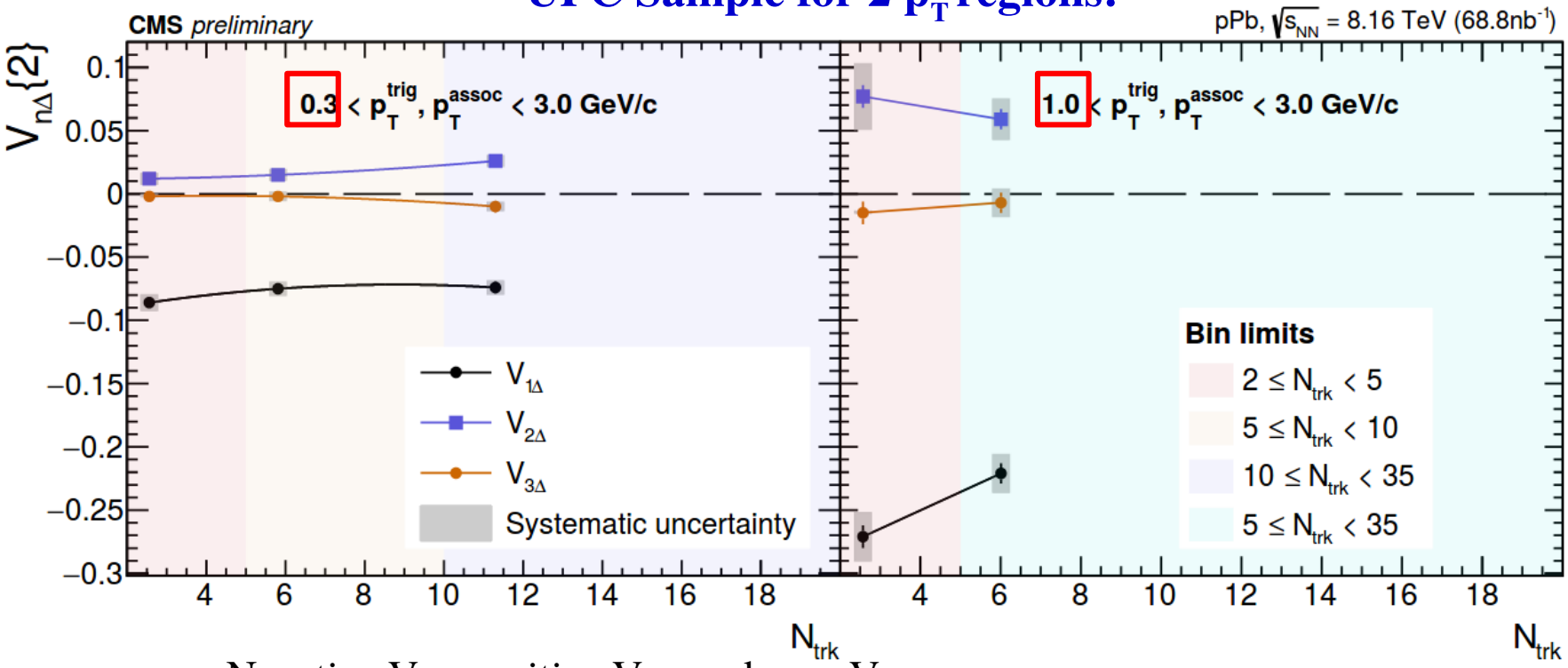




Both the γp and MB distributions have significant two-particle Fourier coefficients $V_{1\Delta}$ and $V_{2\Delta}$

# Two-particle correlations in inclusive UPC in pPb @8 TeV (CMS-PAS-HIN-18-008)

- Systematic uncertainties:
  - Rapidity Gap Selection $\Delta\eta^F$: [4.5, 5.0)
  - Trigger efficiency
  - Tracking inefficiency
  - Primary vertex position

**UPC Sample for 2 $p_T$ regions:**



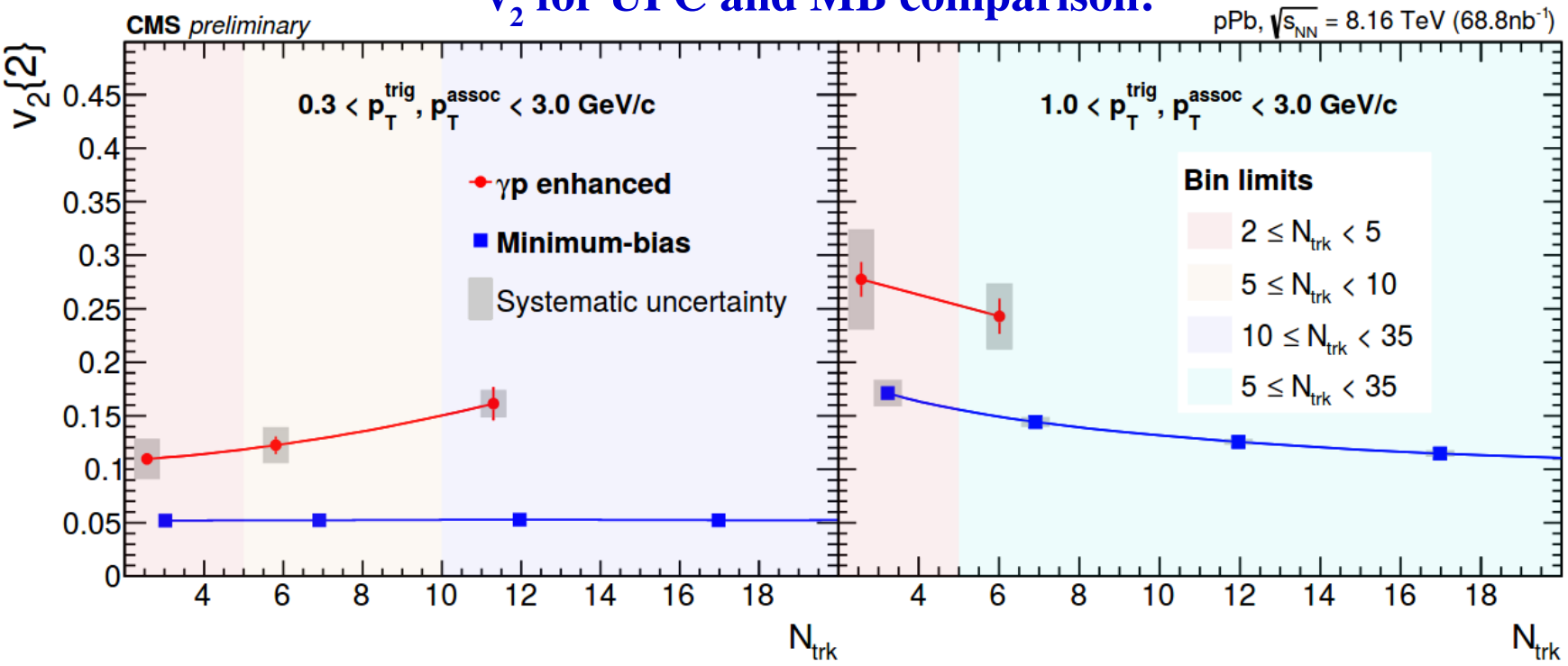

Negative $V_{1\Delta}$, positive $V_{2\Delta}$, and zero $V_{3\Delta}$

No strong $N_{trk}$ dependence

# Two-particle correlations in inclusive UPC in pPb @8 TeV (CMS-PAS-HIN-18-008)

If factorisation is assumed single-particle azimuthal anisotropy Fourier coefficients $v_2$ can be extracted as $v_n = \sqrt{V_{n\Delta}}$

**$v_2$ for UPC and MB comparison:**




$v_2\{2\}$ increases with $p_T$ for both MB and UPC data samples

$v_2\{2\}$ is larger in the UPC sample

$v_2$ from inclusive UPC events seems to be strongly affected by jet-like correlations

# First measurement of exclusive dijets in UPC PbPb @5 TeV

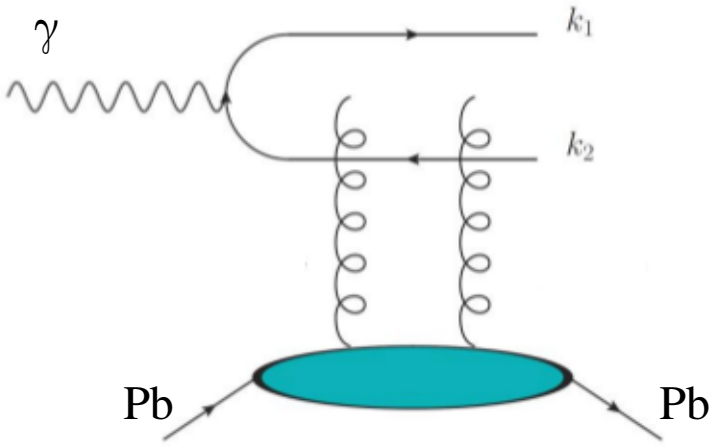
(CMS-PAS-HIN-18-011)

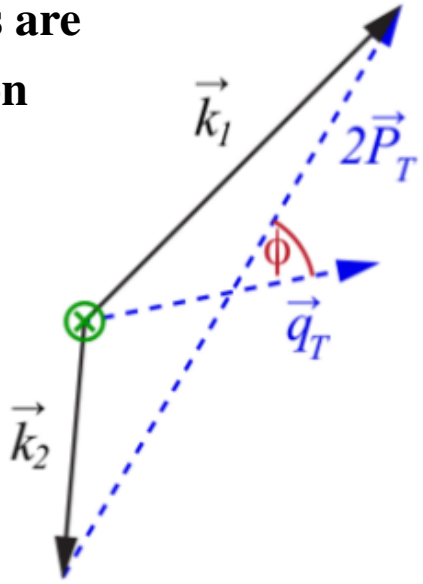
# Exclusive dijets in UPC PbPb @5 TeV

## (CMS-PAS-HIN-18-011)

Exclusive dijet photoproduction is the only process directly sensitive to the Wigner gluon distribution. e.g., Y. Hatta, B.-W. Xiao, and F. Yuan, *Phys. Rev. Lett. 116, 202301 (2016)*

**Wigner and Husimi gluon distributions are the most fundamental gluon distribution**




Vector sum of 2 jets:

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

Vector difference of 2 jets:

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

**Elliptic gluons**: predicted non-trivial angular correlations of the gluon Wigner distributions. Depend on impact parameter and gluon transverse momentum.

The magnitude of the spatial momentum anisotropy is measured by the second Fourier harmonic of the azimuthal distribution

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

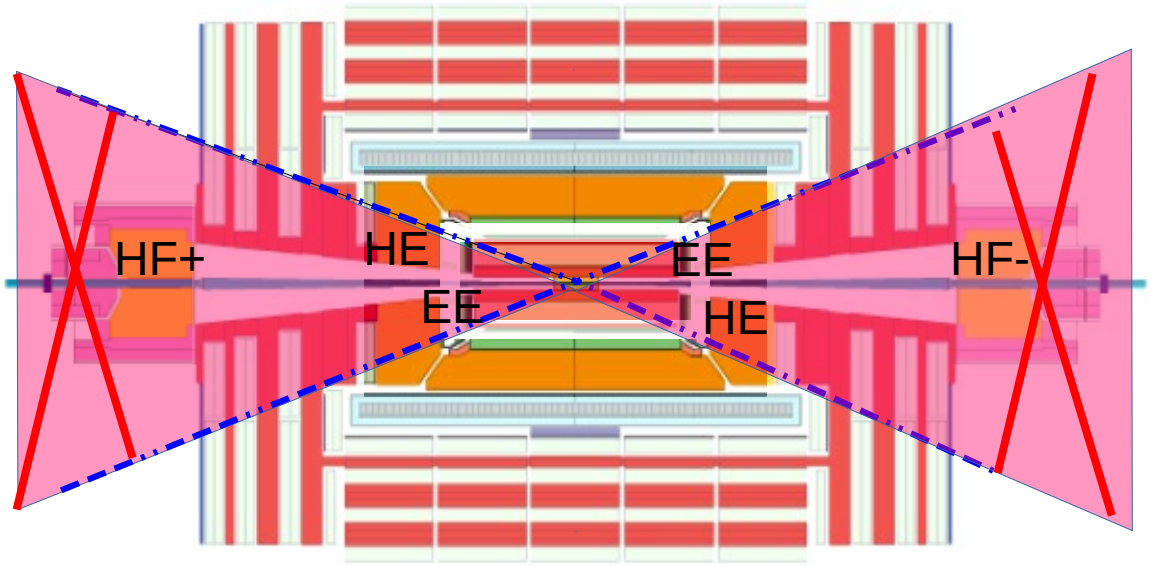
where φ is the angle between $P_T$ and $Q_T$:

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

# Exclusive dijets in UPC PbPb @5 TeV

## (CMS-PAS-HIN-18-011)

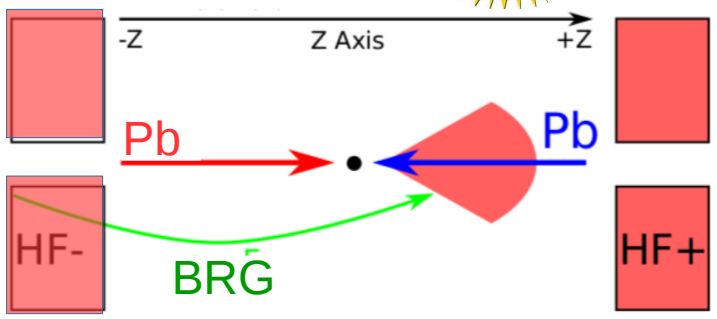
- Analysis selections (part I):
  - At least one track in the central tracker
  - Particle flow jets using the anti-$k_t$ algorithm with R=0.4
  - Only two jets $|\eta_{lab}| < 2.4$, $p_{T,1} > 30$ GeV, $p_{T,2} > 20$ GeV
  - Veto activity in the forward region ($2.8 < |\eta| < 5.2$): HF, HE and EE calorimeters




RAPGAP MC extensively exploited for **ep** collisions at HERA
is used for modelling exclusive dijet photoproduction via photon-gluon fusion

# Exclusive dijets in UPC PbPb @5 TeV

## (CMS-PAS-HIN-18-011)




Rapidity Gap Selection: No track with $p_T > 0.2$ GeV, $|\eta| < 2.5$

$\gamma$ + Pb → jet + jet + Pb events are asymmetric in rapidity.

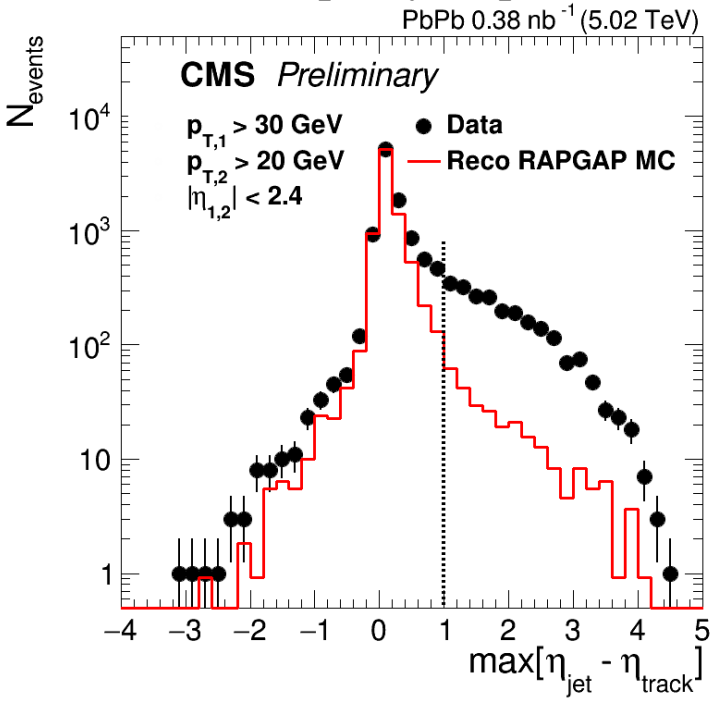
Two separate data sets are defined:

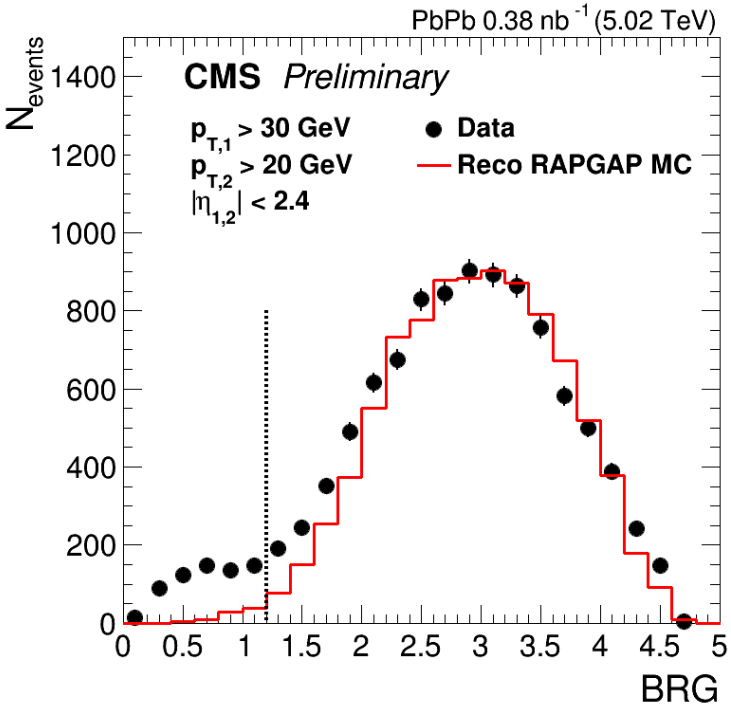
one of them has BRG > FRG, and the other FRG > BRG

Samples are merged by changing the rapidity sign of the jets in the FRG > BRG dataset.

No tracker activity far from the jets to reject non-exclusive and two-photon processes.

- $\max[\eta_{jet} - \eta_{track}] < 1$
- Backward Rapidity Gap (BRG) > 1.2

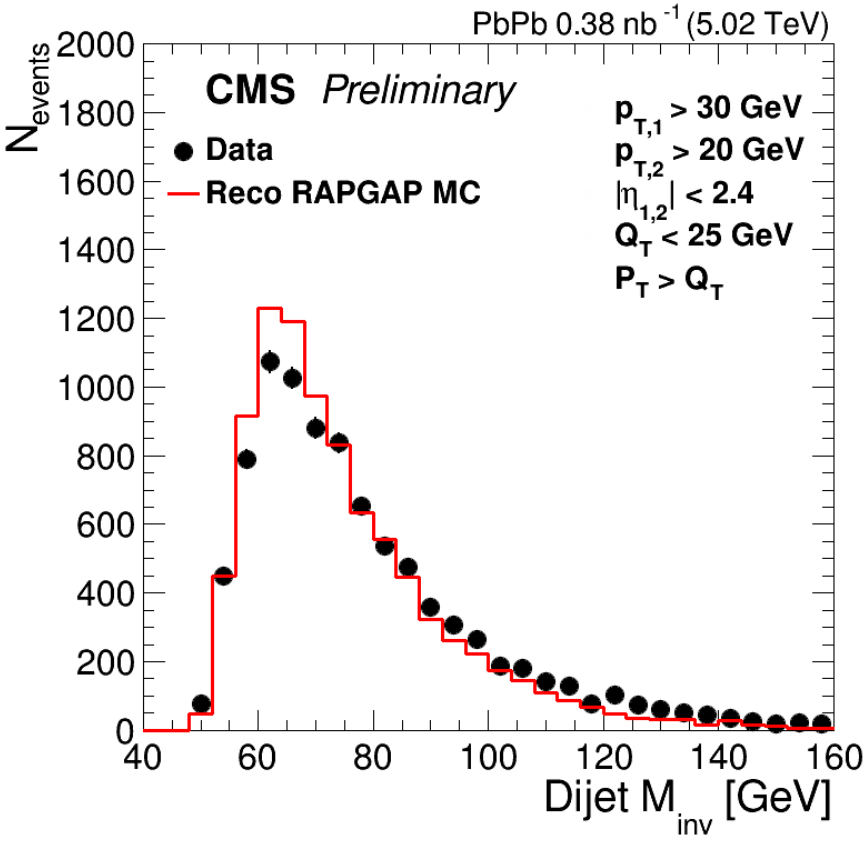


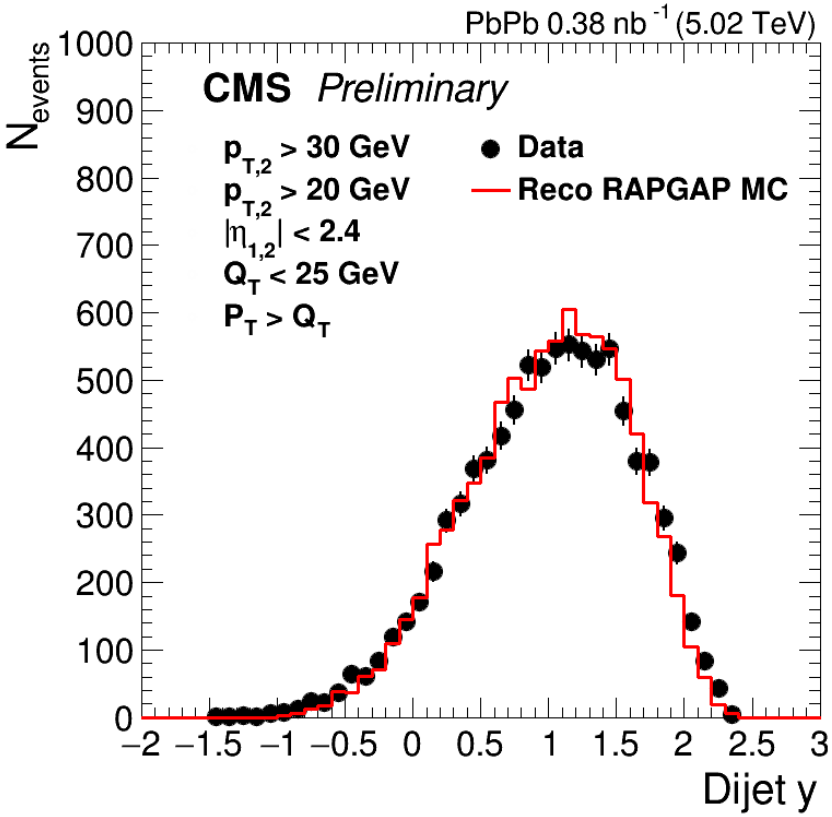



# Exclusive dijets in UPC PbPb @5 TeV

(CMS-PAS-HIN-18-011)

Dijet kinematics



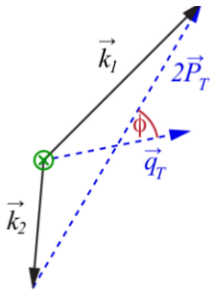

Good agreement between data and MC.

Photon flux in RAPGAP correctly tuned for the UPC $\gamma$Pb data.

# Exclusive dijets in UPC

## (CMS-PAS-HIN-18-011)

## Dijet kinematics

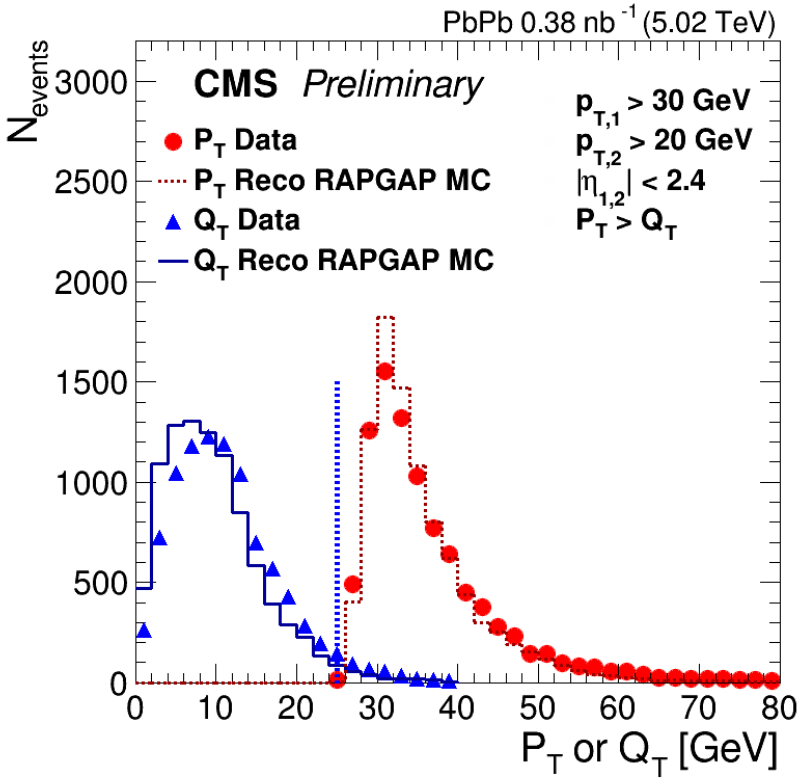


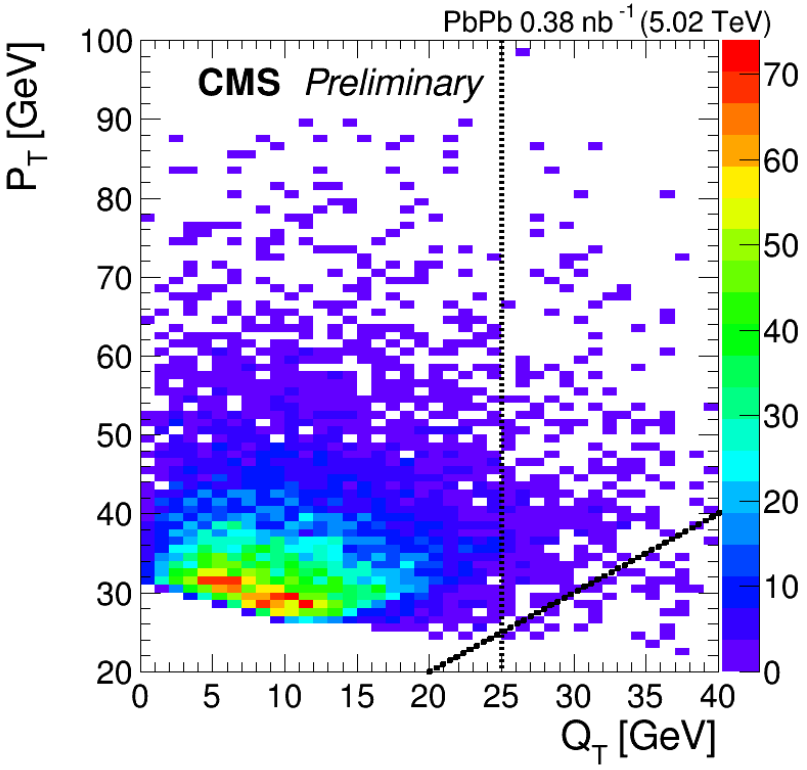

Vector sum of 2 jets:

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

Vector difference of 2 jets

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




The measurement is performed in $Q_T < 25$ GeV

***9290*** dijet events pass all analysis selections.

$P_T > Q_T$ : "back-to-back limit"

# Exclusive dijets in UPC PbPb @5 TeV

(CMS-PAS-HIN-18-011)

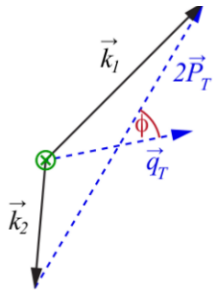
## Systematic uncertainties:

- Jet Energy Scale Correction (JES): ±2%
- Jet Energy Scale non-closure (JESnc): -5%
- Jet Energy Resolution (JER): 15% for 20 GeV jets
- Jet Angular Resolution (JAR): 0.03 for 20 GeV jets
- Rapidity Gap Selection (PUR): BRG > [0,2]
- Trigger Efficiency (TR)

| $Q_T$ [ GeV ] | JES | JESnc | JER | JAR | PUR | TR | Total |
|---|---|---|---|---|---|---|---|
| 0-5 | 0.042 | 0.011 | 0.008 | 0.009 | 0.002 | 0.009 | 0.046 |
| 5-10 | 0.036 | 0.021 | 0.004 | 0.006 | 0.008 | 0.008 | 0.044 |
| 10-15 | 0.027 | 0.017 | 0.007 | 0.004 | 0.007 | 0.009 | 0.035 |
| 15-20 | 0.021 | 0.020 | 0.032 | 0.003 | 0.001 | 0.006 | 0.044 |
| 20-25 | 0.008 | 0.029 | 0.091 | 0.002 | 0.006 | 0.008 | 0.096 |

# Exclusive dijets in UPC PbPb @5 TeV

(CMS-PAS-HIN-18-011)



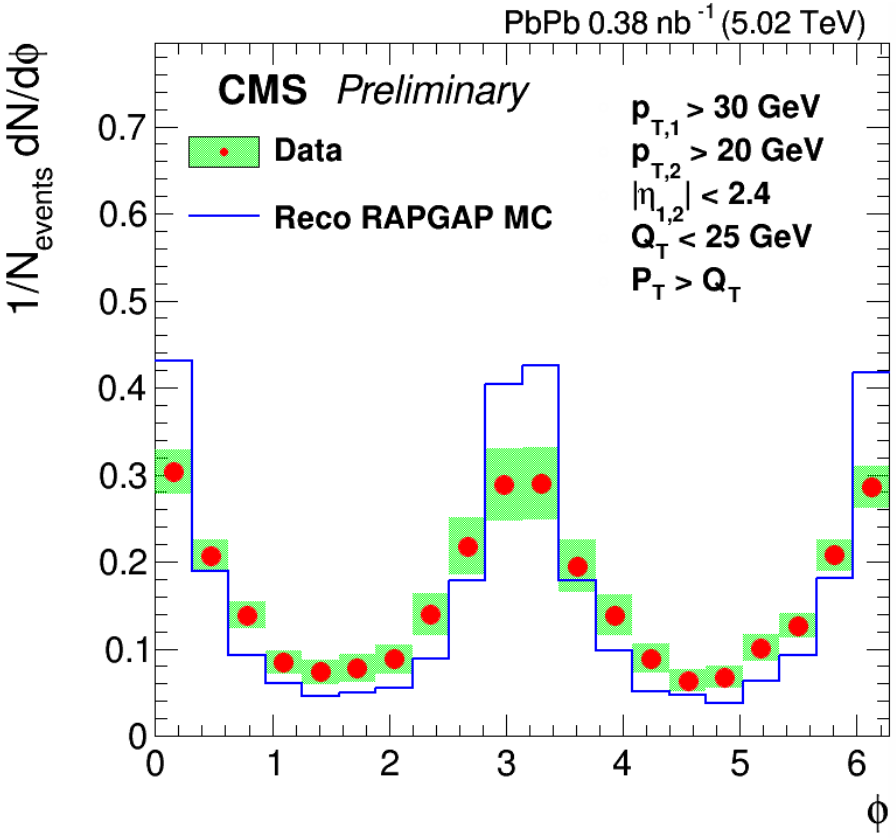

Vector sum of 2 jets:

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

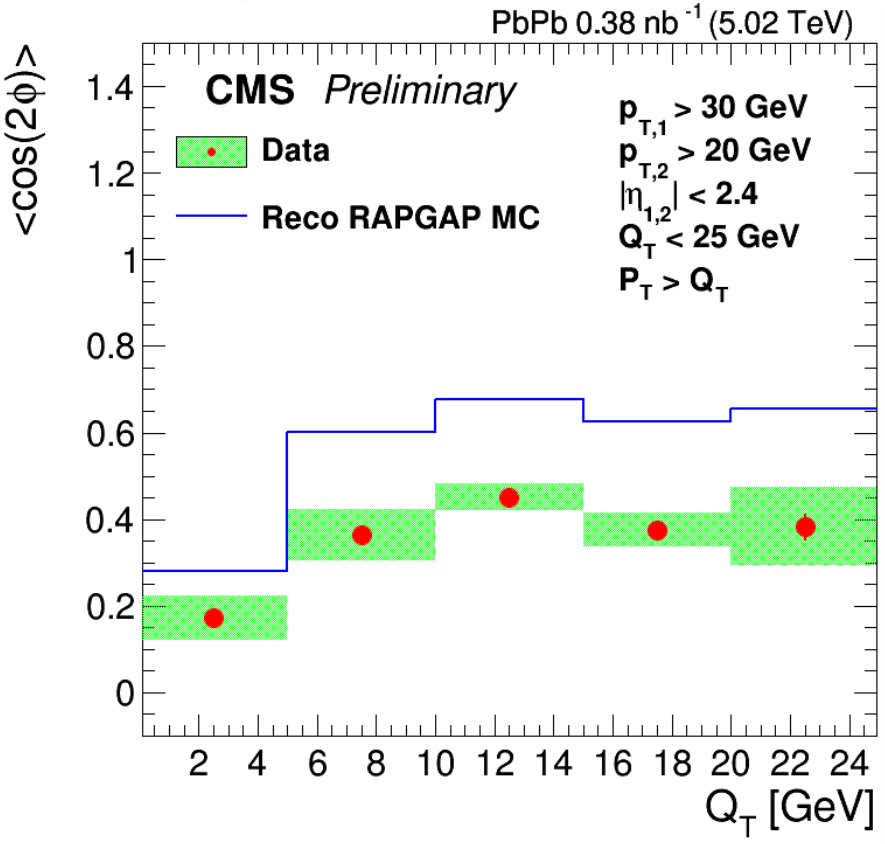
Vector difference of 2 jets

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

NEW!




Similar trend between data and RAPGAP, but RAPGAP prediction is above the data.

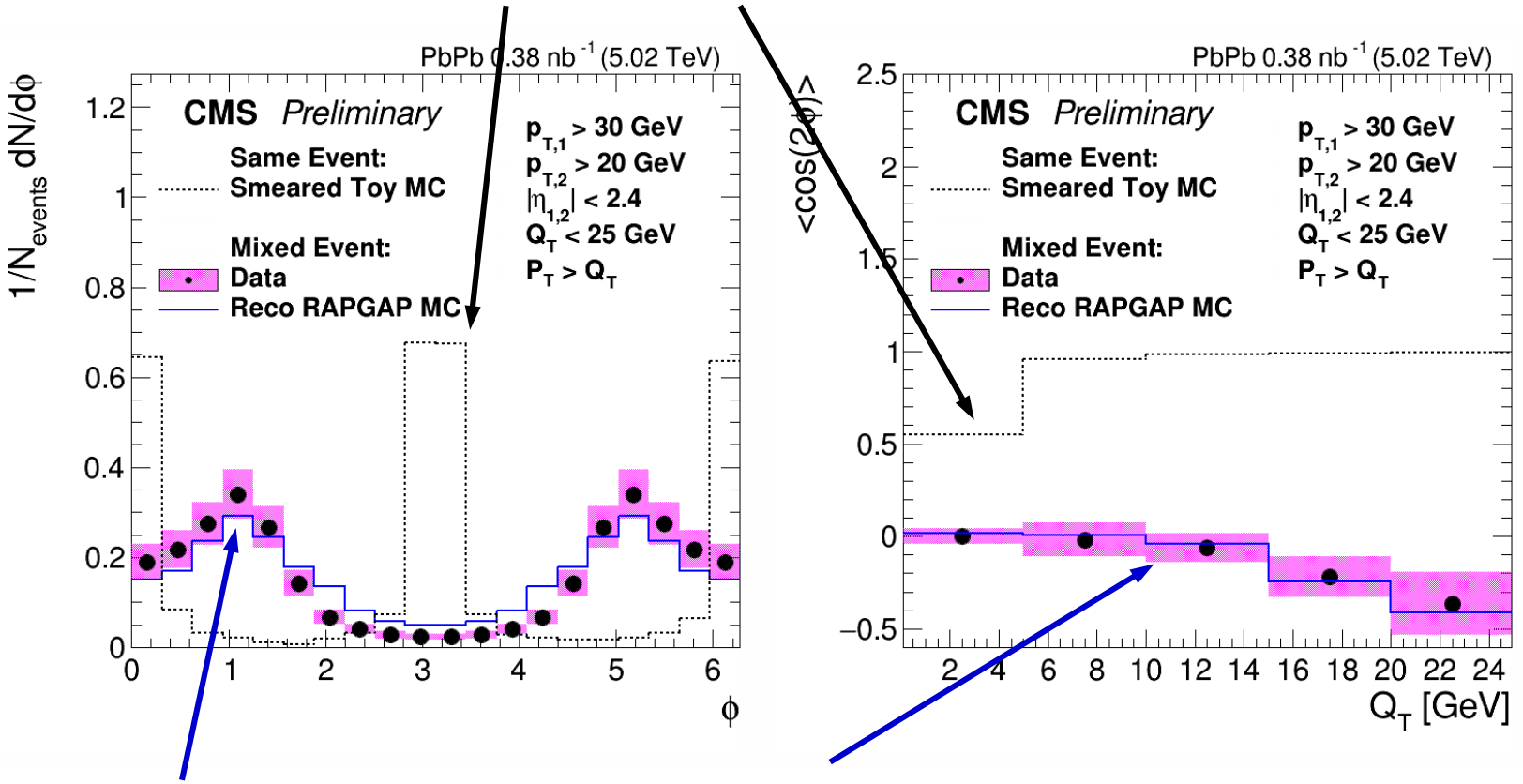



<cos(2φ)> reaches a constant value ~0.5 at $Q_T$ > 10 GeV

# Exclusive dijets in UPC PbPb @5 TeV
(CMS-PAS-HIN-18-011)

Analysis cross checks

**Toy MC**: back-to-back jets with detector resolution effects <cos(2φ)> → 1

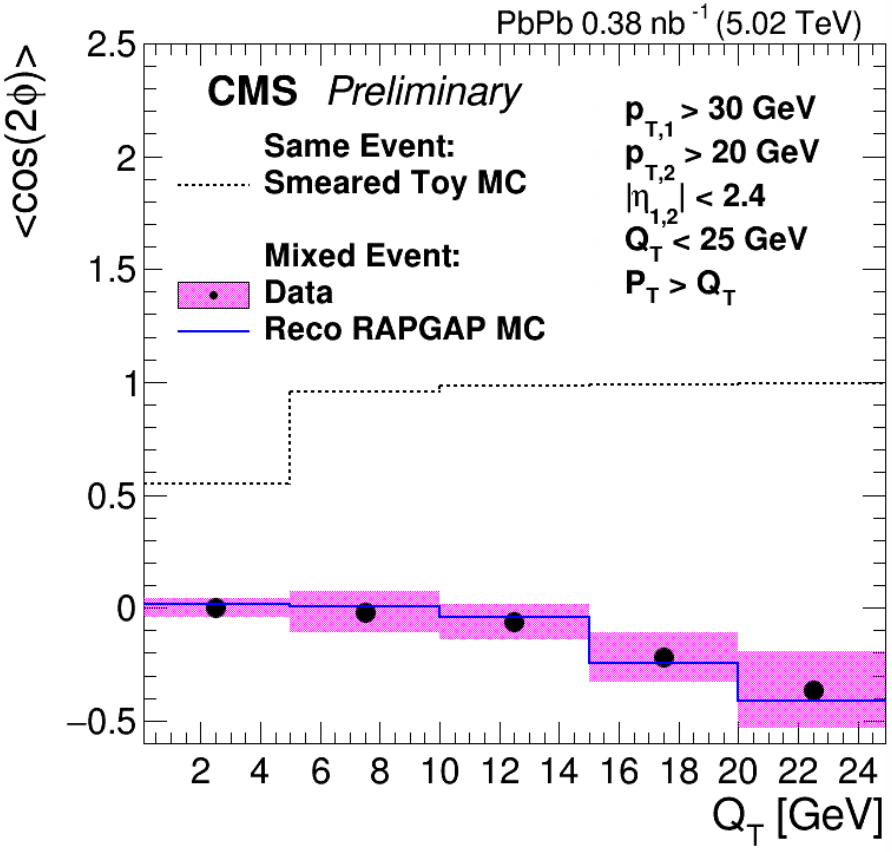


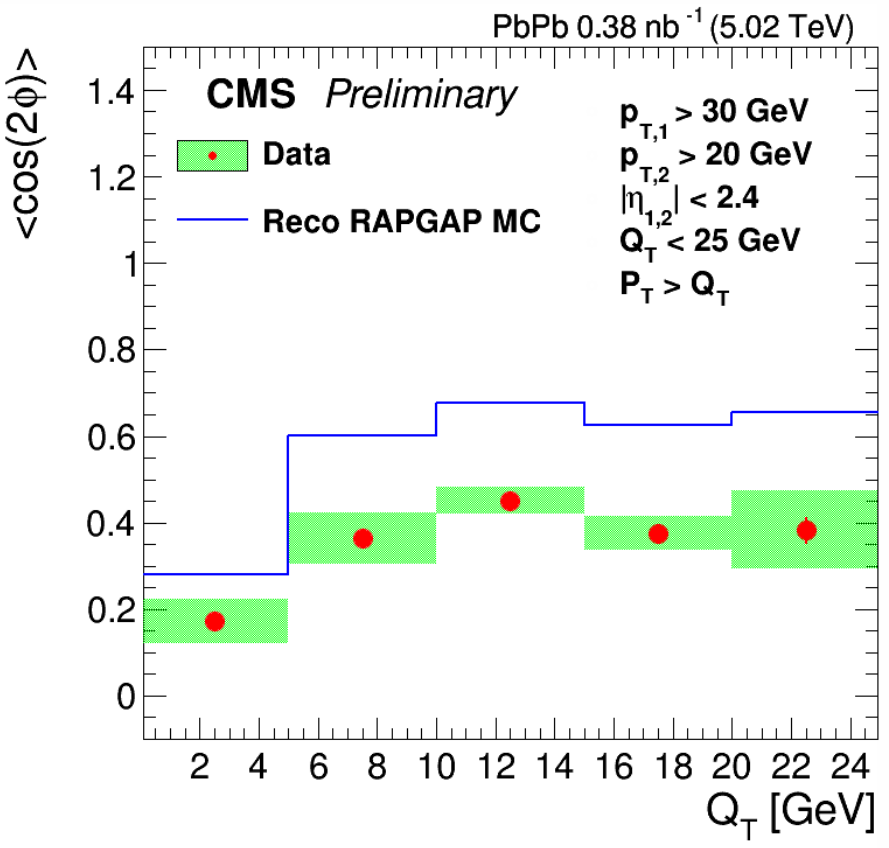

**Mixed events** have no physical correlation (mixing with other 5 selected events):
negative <cos(2φ)> value

# Exclusive dijets in UPC PbPb @5 TeV

(CMS-PAS-HIN-18-011)

<cos(2φ)> in data is below back-to-back expectation and RAPGAP prediction

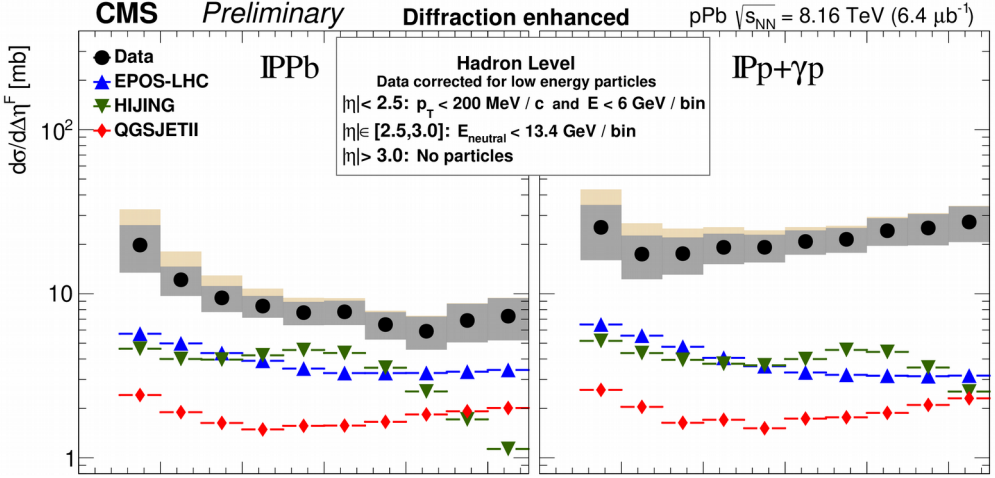


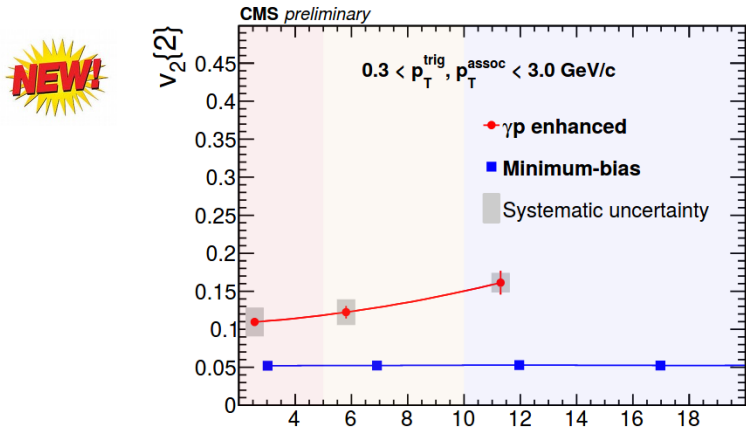

Data calls for theorists to explain the observed $Q_T$ dependence.

# Summary

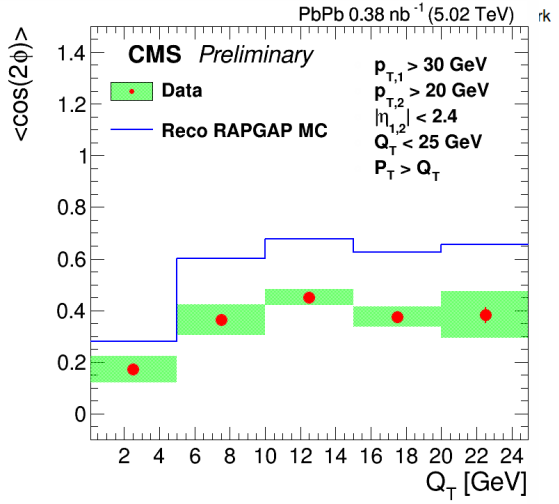
- **First measurement of diffraction in pPb collisions at 8 TeV**
  - Strong contribution from $\gamma$p events in IPp+$\gamma$p topology




- **First measurement of two-particle correlations in inclusive UPC pPb collisions at 8 TeV**
  - Non-zero $v_2$ and larger than in MB, strong effect of jet like correlations




- **First measurement of azimuthal anisotropy from UPC Dijets in PbPb at 5 TeV**
  - $Q_T$ dependence of <cos(2φ)> in data not described by RAPGAP MC prediction, and below back-to-back dijets
  - First (and essential) step to extract the gluon Wigner/Husimi distributions, believed to be most fundamental gluon distribution



Thank you for your attention!

# CMS results on UPCs - published

- "Coherent J/$\psi$ photoproduction in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with the CMS experiment", Phys. Lett. B 772 (2017) 489
- "Measurement of exclusive $\rho(770)^0$ photoproduction in ultraperipheral pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV", Eur. Phys. J. C 79 (2019), no. 8, 702
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# CMS results on UPCs
# New Preliminary from summer 2020

- *"Angular correlations in exclusive dijet photoproduction in ultra-peripheral PbPb collisions at* $\sqrt{s_{NN}} = 5.02$ *TeV"*

CMS-PAS-HIN-18-011

- *"First measurement of the forward rapidity gap distribution in pPb collisions at* $\sqrt{s_{NN}} = 8.16$ *TeV"*

CMS-PAS-HIN-18-019

- *"Search for elliptic azimuthal anisotropies in* $\gamma p$ *interactions within ultra-peripheral pPb collisions at* $\sqrt{s_{NN}} = 8.16$ *TeV"*

CMS-PAS-HIN-18-008

- *"Observation of forward neutron multiplicity dependence of dimuon acoplanarity in ultra-peripheral PbPb collisions at* $\sqrt{s_{NN}} = 5.02$ *TeV"*

CMS-HIN-19-014