Search for elliptic azimuthal anisotropies in photon-proton interactions using rapidity gaps at pPb collisions with the CMS experiment

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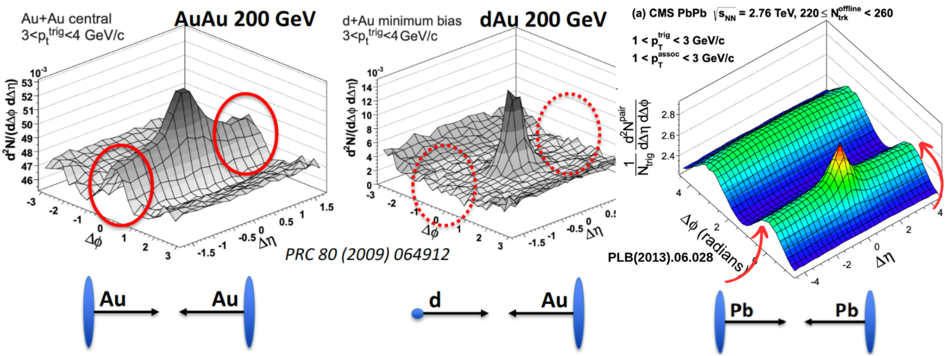
Overview

1. Collectivity features and probes in small systems
2. Ultraperipheral collisions (UPCs) and the photon flux
3. CMS experiment and forward detectors
4. Correlation probes in γ-proton interactions
5. Summary and outlook

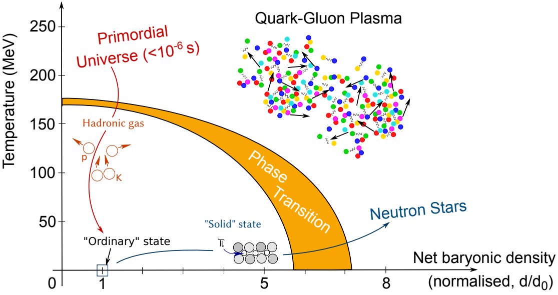
Collectivity and ridge in nuclear collisions AA

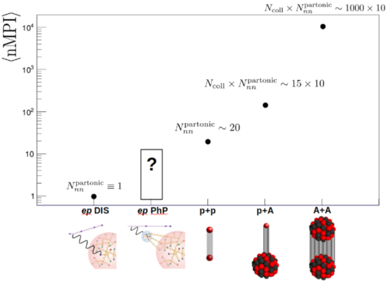
- Emerges in the two-particle correlation functions
  - Long-range spatial correspondence → [collective behaviour of final-state particles]
  - Observed in large collision systems (AA) → **[ridge-like shape in data]**
  - First probes over smaller collision systems (dAu)
- Evidence of collectivity and one of the features of QGP; Relativistic fluid dynamics



Quark gluon plasma (QGP) and collectivity

- **Medium properties and hydrodynamic behavior** → **Look into smaller systems**
- **Initial and final state effects**
  - Long range correlations induced by color fluctuations? (CGC)
  - gluon saturation in the initial state?



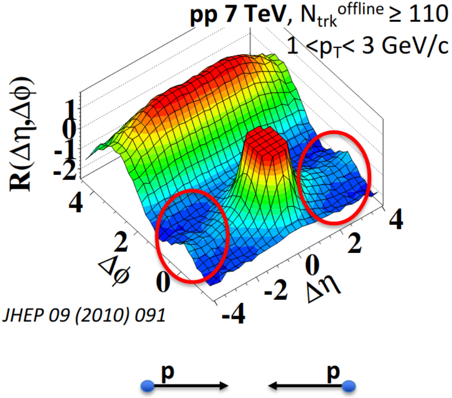


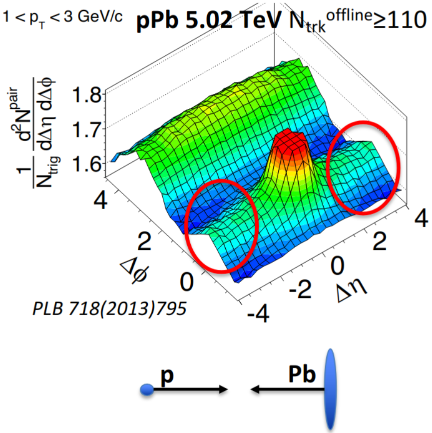
https://cds.cern.ch/record/2025215

D. Gangadharan, QM2022

Unexpected signs of collectivity seen in pp and pPb at the LHC

- Too small and simple to develop QGP-like collective behaviour?
  → Minimal size and conditions for collectivity to emerge
- **Initial (CGC) effective model or Final (QGP) state effect?**
  - how small the interaction region can be until description of soft QCD breaks down?

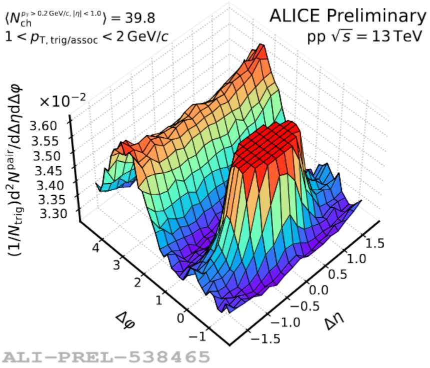


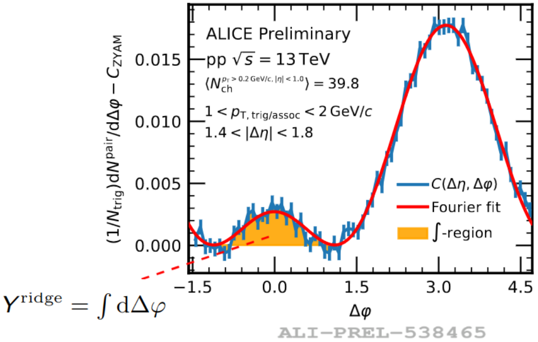


DOI: 10.1016/j.physletb.2011.01.024

Collectivity signatures at low proton-proton multiplicity

- ▶ **Significant near-side ridge at very low pp multiplicity** → **Identify emergence mechanisms**
  - Down to a range from ∼ 8 to 20
  - Compatible with CMS results

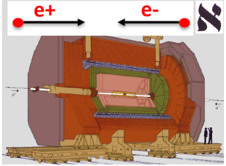




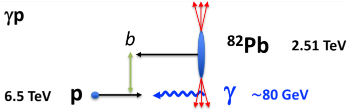
Recontres de Moriond QCD 2023, Jasper Parkkila

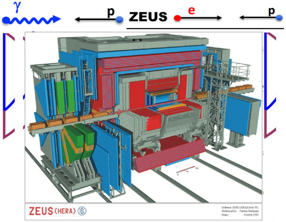
Recent collectivity probes with small systems

- **e^+e^-** → ALEPH (91 GeV, 208 GeV) and Belle (10.52 GeV)

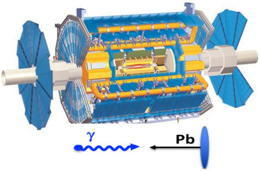


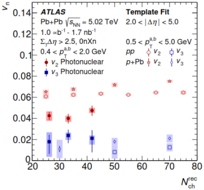
- **ep** → ZEUS and H1 at HERA (318 GeV)
- **γp**
  - → ZEUS (318 GeV [ep]) (**JHEP 12 (2021) 102**)
  - → CMS (8.16 TeV [pPb]) (**PLB 844 (2023) 137905**)

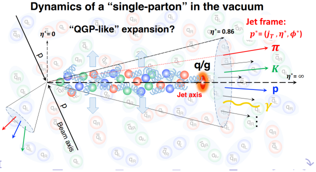




- **γPb** → ATLAS (5.02 TeV [PbPb])



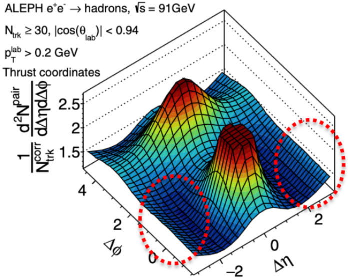




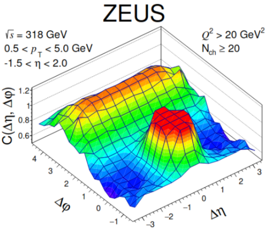
- **Inside jets** → CMS (13 TeV [pp]) (**HIN-21-013-PAS**)

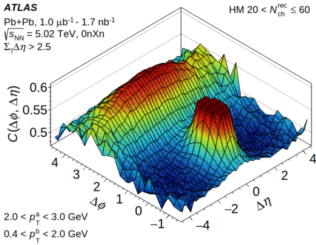
No sign of significative ridge in e^+e^-, ep and γ-Pb

- No significant near side ridge so far
  - → Very low multiplicities for ee, ep and γp systems
  - → Higher multiplicity in γPb allowing nonflow substraction

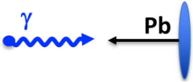


PRL 123 (2019) 212002





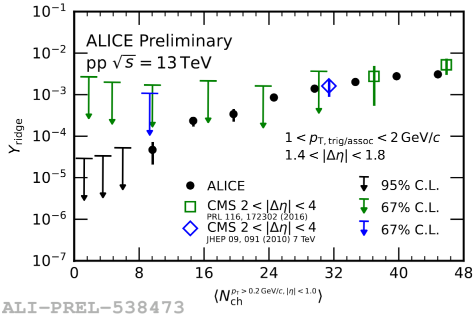
PRC 104, 014903 (2021)

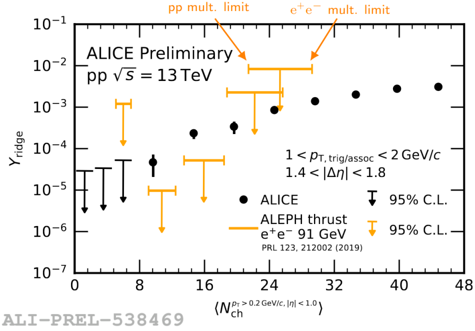


DOI: 10.1016/j.physletb.2011.01.024

Studying ridge significance e^+e^- vs proton-proton

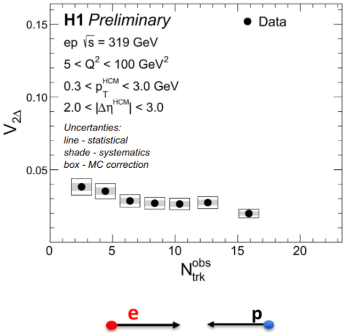
- First probes investigating significance of near side ridge at low multiplicity
  - → CMS results consistent with ALICE recent observations
- First direct comparisons between ee and pp systems
  - → ee upper limits point to lower significance if any

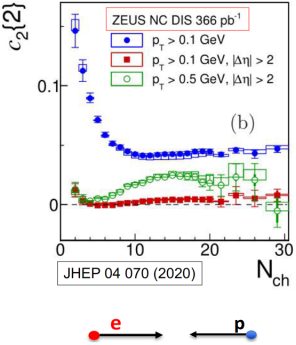


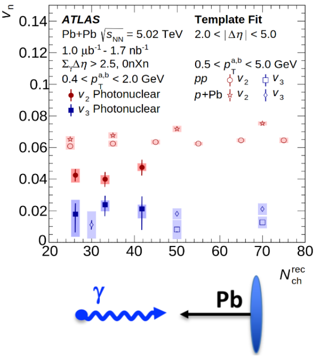


Studying azimuthal correlations ep vs γp

- Significant correlation coefficients as a function of multiplicity
  - → Very low multiplicities for ee, ep and γp systems
  - → Higher multiplicity in γPb allowing nonflow substraction







ATLAS: PRC 104, 014903 (2021)

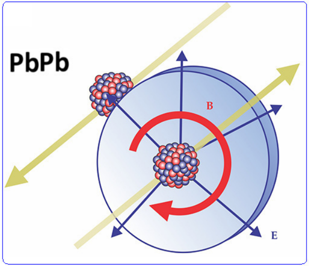
H1: QM 2022, Chuan Sun

Ultraperipheral collisions (UPCs) and the photon flux

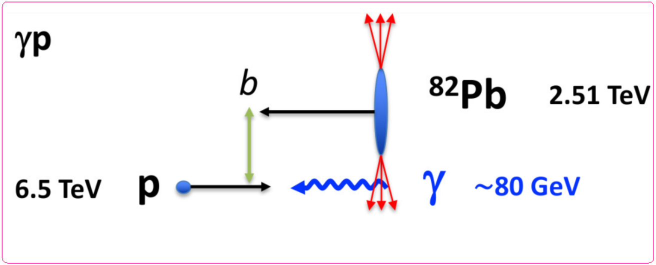
Intact protons or lead nuclei; source of photo-induced processes

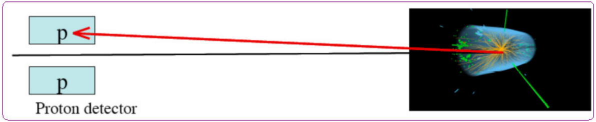
- **Ultraperipheral collisions (UPC's) with large impact parameters; ($b > 2R_A$)**
  - → γ-proton/Pb and $\gamma\gamma$ initial state processes
  - → Photon source (Pb or p) does not dissociate

A-A



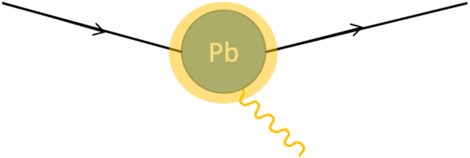
p-A

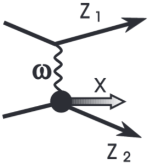


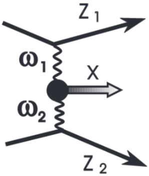


https://doi.org/10.1063/PT.3.3727

Equivalent Photon Approximation; Intact protons or lead nuclei;







- Equivalent Photon Approximation (EPA)[1,2] ; cross-section can be factorized in terms of equivalent flux of photons with energy E_γ into colliding hadron
- Flux of quasireal photons, with intensity proportional to the square of its electric charge, Z^2

  → *Weizsäcker – Williams* method

  → Proton flux: further corrections proposed: `Nucl. Phys. B 974, 115645 (2022)`

[1] arXiv:nucl-ex/0502005v2 here
[2] doi:10.1103/PhysRevD.88.054025 here

EPA fluxes implemented in simulations packages

- **PYTHIA8**
  - EPA and radial parameters in Nucleus2gamma object
  - Exclusive and semiexclusive processes
  - Available softQCD processes to simulate MB events within photoproduction
- **STARLIGHT**
  - $\gamma\gamma$ and $\gamma\mathbb{P}$ interactions between nuclei and protons
  - Variety of final states to $\mu^+\mu^-$, $\tau^+\tau^-$, e^+e^-, ρ^0, J/ψ, υ ..
- **Madgraph**
  - EPA flux for proton, with exclusive and semiexclusive production at NLO
- **Gamma-UPC**
  - Exclusive $\gamma\gamma$ processes with variable A number of nucleons and EPA models
    - Improved Weizsaecker-Williams Approx [hep-ph/9310350]
    - Effective W/Z/A Approx [2111.02442]
    - edff [2207.03012]
    - chff [2207.03012]

Photon from Pb nuclei with energy up to $\sim$ 80 GeV

- Photon energies for lead ion at 2.76 TeV and proton at 7 TeV can reach values up to 80 GeV and 2.45 TeV respectively
- Photon energies at LHC, HL-LHC and FCC energies; larger reach for proton flux

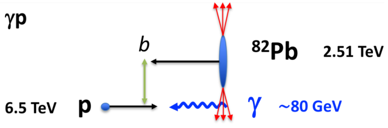
System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	$E_{beam1} + E_{beam2}$	γ_L	R_A	E_γ^{max}	$\sqrt{s_{\gamma\gamma}^{max}}$
Pb-Pb	5.52 TeV	5 nb^{-1}	2.76 + 2.76 TeV	2960	7.1 fm	80 GeV	160 GeV
Xe-Xe	5.86 TeV	30 nb^{-1}	2.93 + 2.93 TeV	3150	6.1 fm	100 GeV	200 GeV
Kr-Kr	6.46 TeV	120 nb^{-1}	3.23 + 3.23 TeV	3470	5.1 fm	136 GeV	272 GeV
Ar-Ar	6.3 TeV	1.1 pb^{-1}	3.15 + 3.15 TeV	3390	4.1 fm	165 GeV	330 GeV
Ca-Ca	7.0 TeV	0.8 pb^{-1}	3.5 + 3.5 TeV	3760	4.1 fm	165 GeV	330 GeV
O-O	7.0 TeV	12.0 pb^{-1}	3.5 + 3.5 TeV	3760	3.1 fm	240 GeV	490 GeV
p-Pb	8.8 TeV	1 pb^{-1}	7.0 + 2.76 TeV	7450, 2960	0.7, 7.1 fm	2.45 TeV, 130 GeV	2.6 TeV
p-p	14 TeV	150 fb^{-1}	7.0 + 7.0 TeV	7450	0.7 fm	2.45 TeV	4.5 TeV
Pb-Pb	39.4 TeV	110 nb^{-1}	19.7 + 19.7 TeV	21 100	7.1 fm	600 GeV	1.2 TeV
p-Pb	62.8 TeV	29 pb^{-1}	50. + 19.7 TeV	53 300, 21 100	0.7,7.1 fm	15.2 TeV, 600 GeV	15.8 TeV
p-p	100 TeV	1 ab^{-1}	50. + 50. TeV	53 300	0.7 fm	15.2 TeV	30.5 TeV

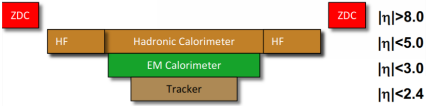
H.-S. Shao and D. d'Enterria, JHEP 2209 (2022) 248 arXiv:2207.03012[hep-ph]

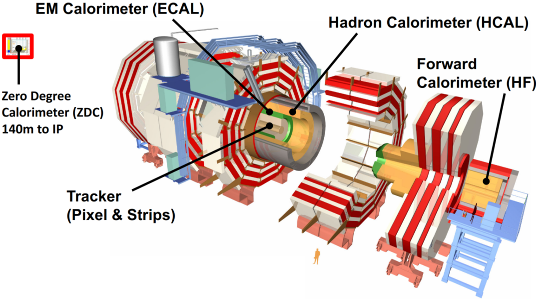
CMS experiment and forward detectors

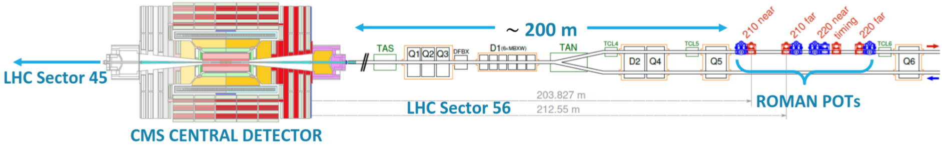
CMS forward detectors in Run 2

- Zero Degree (ZDC) and Hadronic Forward (HF) calorimeters for Pb and protons respectively
- CMS Particle Flow energies to constrain activity as a function of η
- CT-PPS spectrometer for pp runs





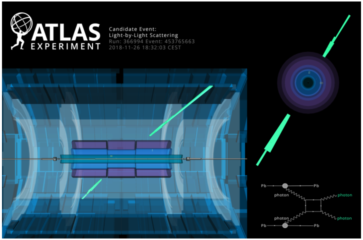


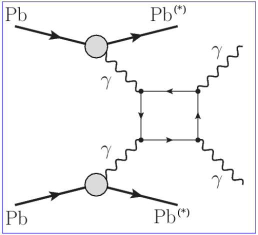


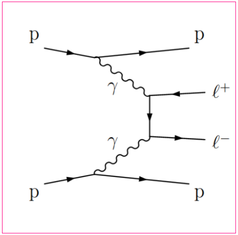
Evidence of Photo-induced processes in PbPb / pp at the LHC

- Evidence of light-by-light scattering

  CMS-FSQ-16-012 Phys. Lett. B 797 (2019) 134826







- Exclusive production of lepton pairs

  - Scattered protons measured at CMS-TOTEM precision proton spectrometer (CT-PPS)

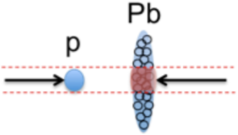
  - Observed for first time at the LHC in pp collisions at $\sqrt{s} = 13$ TeV

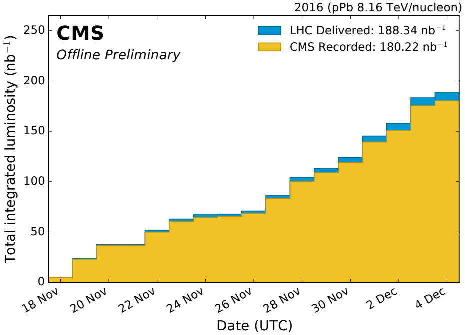
  JHEP07 (2018) 153

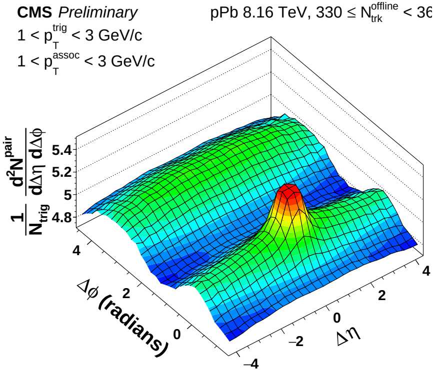
Correlation probes in γ-proton interactions

Confirming collectivity features with proton-lead (pPb) at 8 TeV

- Most energetic pPb collisions so far at the LHC
- Consistent results at 5.02 and 8.16 TeV



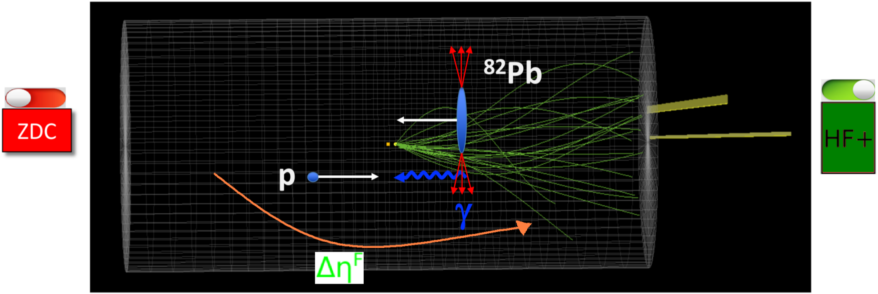




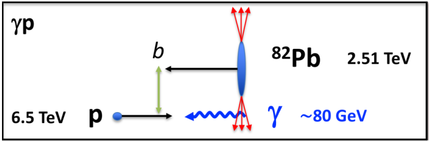
Phys. Rev. Lett. 120, 092301

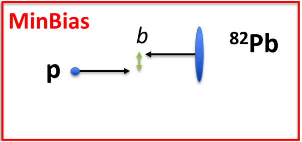
Event selection

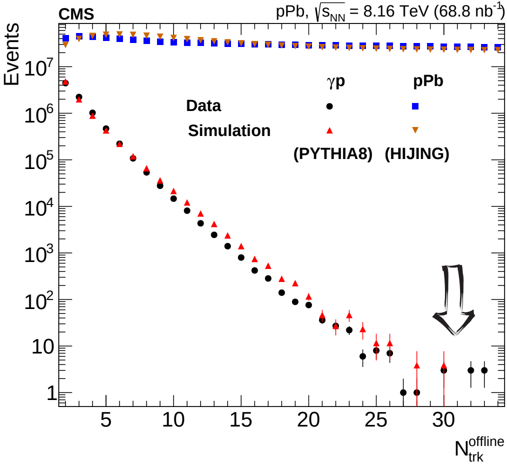
- HF calorimeter measures activity on the proton side while no neutrons are detected by ZDC calorimeter consistent with intact Pb nucleus source of the γ flux.
- Particle flow energies and track objects used to isolate events with large forward rapidity gap ($\Delta\eta^F$) $\rightarrow$ $5.0 < \Delta\eta^F < 7.5$



Limited multiplicity of charged particles in γp interactions







- For first time using `PYTHIA8` to model γ flux from Pb nuclei

  - γp data consistent in $N_{\mathrm{trk}}^{\mathrm{offline}}$ with prediction

- Mean p_{T} and $N_{\mathrm{trk}}^{\mathrm{offline}}$ are smaller for γp sample than for pPb (same multiplicity range).

  - pPb events simulated with `HIJING`

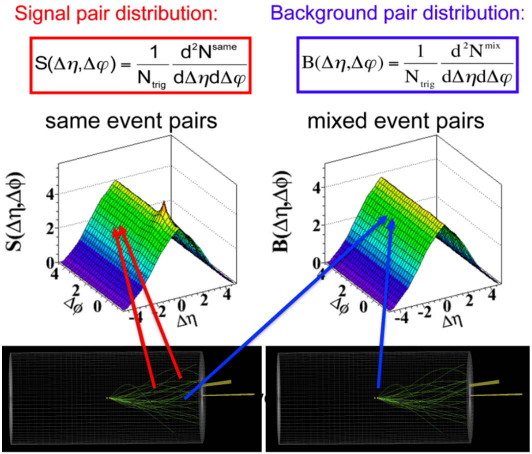
Sample	$2 \leq N_{\mathrm{trk}}^{\mathrm{off}} < 35$
γp-enhanced	2.9
γp-simulated	2.9
MB	16.6
MB-simulated	15.7

Two-dimensional (2D) angular correlation distribution

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

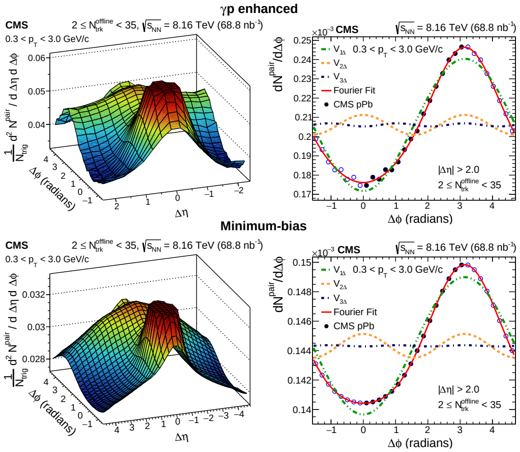
- $\frac{B(0,0)}{B(\Delta\eta,\Delta\phi)}$ is the pair acceptance correction to the signal distribution

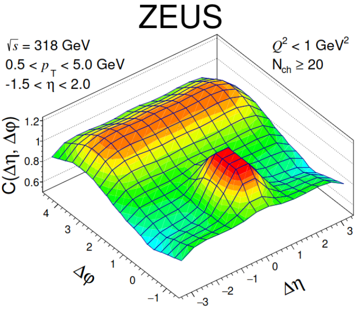
  → Correction for tracking inefficiency is applied to each charged particle



One-dimensional (1D) projection and decomposition

- No ridge so far for γp system in CMS and ZEUS probes
- Fitted over the $\Delta\phi$ range $[0, \pi]$ to a Fourier decomposition series $\propto 1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)$





(a) Photoproduction.

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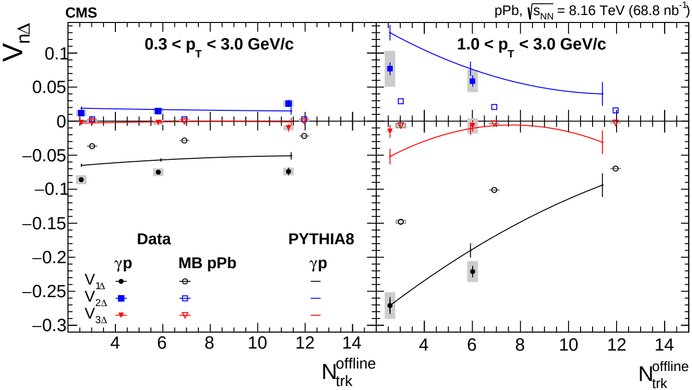
$V_{n\Delta}$ measurements with $|\eta| > 2.0$

- $\rightarrow$ γp data measurements are consistent with model predictions that have no collective effects

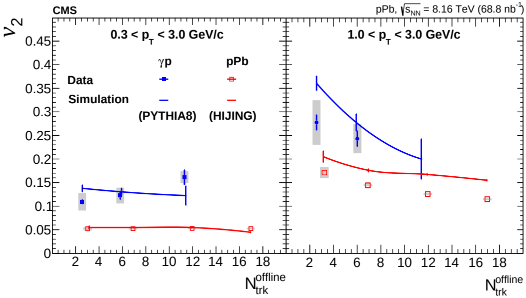
p_T range		$2 \le N_{trk}^{offline} < 5$	$5 \le N_{trk}^{offline} < 10$	$10 \le N_{trk}^{offline} < 35$
	$V_{1\Delta}$	-0.086 ± 0.006	-0.075 ± 0.005	-0.074 ± 0.007
$0.3 < p_T < 3.0\,\mathrm{GeV}/c$	$V_{2\Delta}$	0.012 ± 0.004	0.015 ± 0.004	0.026 ± 0.006
	$V_{3\Delta}$	-0.002 ± 0.001	-0.002 ± 0.004	-0.010 ± 0.006
		$2 \le N_{trk}^{offline} < 5$	$5 \le N_{trk}^{offline} < 35$	
	$V_{1\Delta}$	-0.271 ± 0.021	-0.221 ± 0.017	
$1.0 < p_T < 3.0\,\mathrm{GeV}/c$	$V_{2\Delta}$	0.077 ± 0.027	0.059 ± 0.017	
	$V_{3\Delta}$	-0.015 ± 0.009	-0.007 ± 0.013	

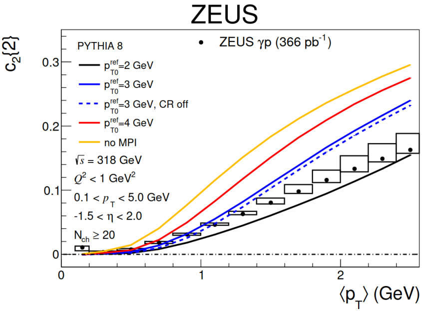


v_2 elliptic anisotropy measurements with $|\eta| > 2.0$

- At a given p_T and track multiplicity, v_2 is larger for γp-enhanced events than for MB pPb interactions
  - The magnitudes of both $V_{1\Delta}$ and $V_{2\Delta}$(v_2) increase with p_T

    $\rightarrow$ Similar response to p_T increase seen by ZEUS over $c_2\{2\}$
- Predictions from the PYTHIA8 model describe well the γp data within uncertainties

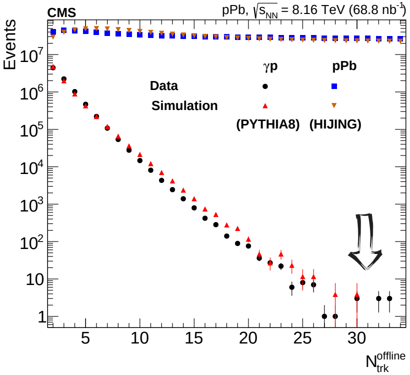


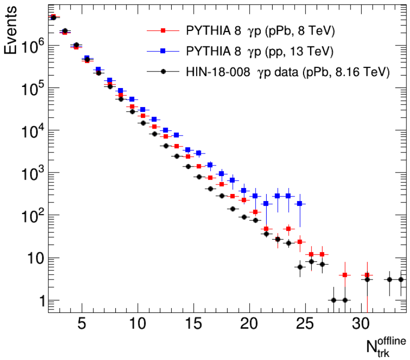


γp from pp and pPb; is track multiplicity consistent?

- EPA flux from proton instead of Pb nuclei
- Multiplicity distribution

$$< \mathrm{N_{trk}} > \text{PYTHIA8 pp sim)} = 3.026 \text{ (1.5M events)}$$
$$< \mathrm{N_{trk}} > \text{(PYTHIA8 pPb sim)} = 2.89 \text{ (37M Events)}$$
$$< \mathrm{N_{trk}} > \text{(pPb CMS Data)} = 2.92$$





Summary and Outlook

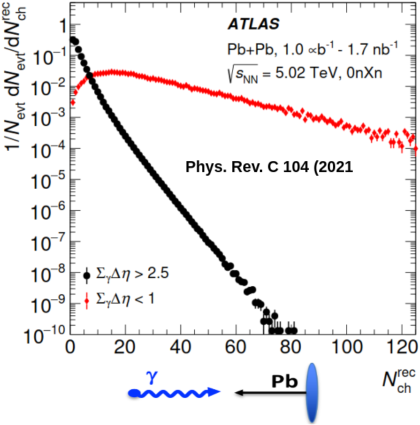
- Predictions from the `PYTHIA8` model describe well the γp system within uncertainties
  - $\rightarrow$ This suggests the data are dominated by noncollective effects
  - $\rightarrow$ Within the present experimental sensitivity, no significant collectivity signal is observed
  - $\rightarrow$ Limited multiplicity and response to p_T consistent with what has been seen by ZEUS in γp and ep studies

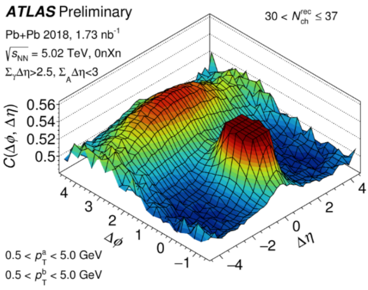
- For small systems there is need to identify mechanisms responsable for observed trends and values over distinct angular coefficients
  - \- Confirmation over pp collective features and significant ridge down to $N_{\text{trk}} \sim 10$
  - \- Significant v_2 and observed by ATLAS after non flow substraction

Thanks

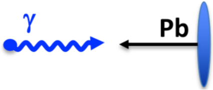
Backup

- Significant non-zero v_2
  - Substracting non-flow contribution using template fitting method



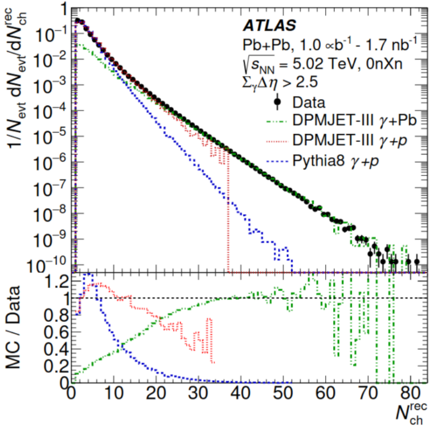


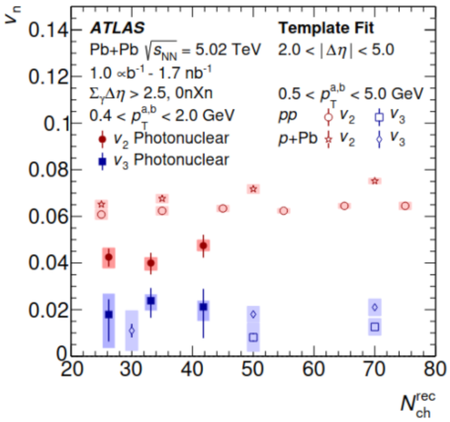
ATLAS-CONF-2019-022



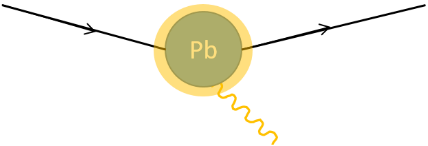
Recent probes in γPb; ATLAS at CERN within 5.02 TeV PbPb

- Significant non-zero v_2
  - Substracting non-flow contribution using template fitting method





Photon flux, dN/dω from nuclei



Analytic approximation for equivalent photon flux from nuclei

$$\frac{dN}{d\omega}\bigg|_A = \frac{2Z^2\alpha_{em}}{\pi\omega}\left[\bar{\eta}K_0(\bar{\eta})K_1(\bar{\eta}) - \frac{\bar{\eta}^2}{2}\mathcal{U}(\bar{\eta})\right]$$

where $K_0(\eta)$ and $K_1(\eta)$ are the modified Bessel functions

$$\bar{\eta} = \omega(R_{h_1} + R_{h_2})/\gamma_L \quad \text{and} \quad \mathcal{U}(\bar{\eta}) = K_1^2(\bar{\eta}) - K_0^2(\bar{\eta})$$

- γ_L is the lorentz boost of a single beam
  - $R_p = 0.6$fm and $R_A = 1.2\text{A}^{1/3}$
  - Absortive corrections can be disregarded at b $> R_{h1} + R_{h2}$
  - At b $< R_{h1} + R_{h2}$ the photon flux is zero

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Photon flux can be modelled with gamma-UPC

- **gamma-UPC**: '*Automated generation of exclusive photon-photon processes in ultraperipheral proton and nuclear collisions with varying form factors*'

  H.-S. Shao and D. d'Enterria, JHEP 2209 (2022) 248 arXiv:2207.03012[hep-ph]

- Different configurations of nuclei and pp, pA and AA collisions can be set:

Nucleus	A	Z	R_A [fm]	a_A [fm]	w_A
O	16	8	2.608	0.513	–0.051
Ar	40	18	3.766	0.586	–0.161
Ca	40	20	3.766	0.586	–0.161
Kr	78	36	4.5	0.5	0
Xe	129	54	5.36	0.59	0
Pb	208	82	6.624	0.549	0

Photon flux, $dN/d\omega$ from proton

Analytic approximation for equivalent photon flux from proton

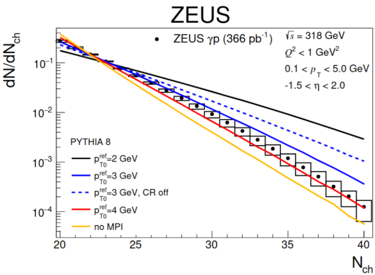
$$\frac{dN}{d\omega}\bigg|_p = \frac{\alpha_{\rm em}}{2\pi\omega}\left[1+\left(1-\frac{2\omega}{\sqrt{s}}\right)^2\right] \times\left(\ln\Omega-\frac{11}{6}+\frac{3}{\Omega}-\frac{3}{2\Omega^2}+\frac{1}{3\Omega^3}\right)$$

with the notation $\Omega = 1 + [(0.71\ {\rm GeV}^2)/Q^2_{\rm min}]$

$$Q^2_{\rm min} = \omega^2/[\gamma_L^2(1-2\omega/\sqrt{s})] \approx (\omega/\gamma_L)^2$$

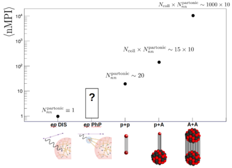
- γ_L is the lorentz boost of a single beam
  - Derived from *Weizsäcker – Williams* method
  - Using elastic proton from factor

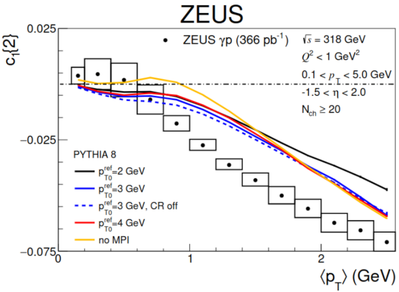
PHYSICAL REVIEW D 88, 054025 (2013)

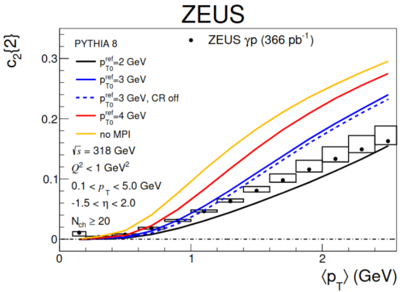


- No Multiparton Interactions (MPI) scenario disfavored

  - 4-particle cumulant positive in ep photoproduction and negative in non-central heavy-ion collisions







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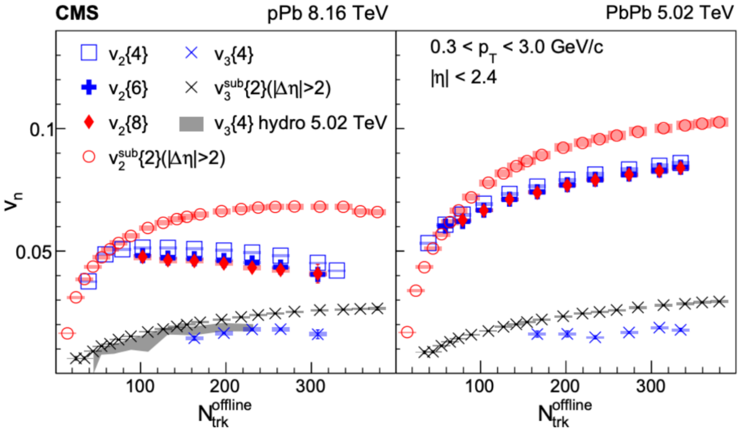
Small vs large collision systems

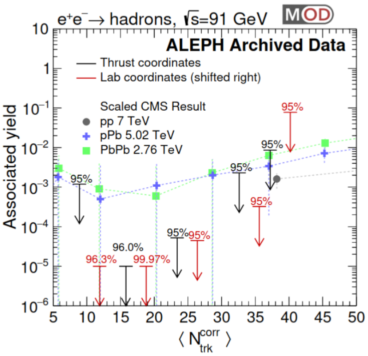
- Origin of the ridge in small systems?
  - Natural question is whether such signatures persist in even smaller collision systems
  - Final state effect?, Pure fluctuations? CGC?

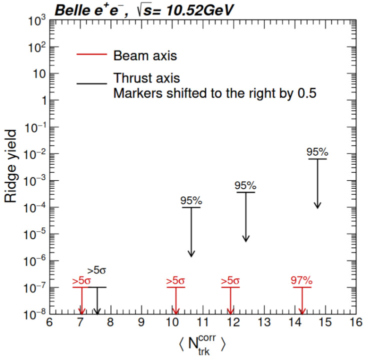


PRC 101 (2020) 014912

Recent probes in e^+e^-; ALEPH (91 GeV) and Belle (10.52 GeV)

- Confidence limits on associated yield as a function of N_{trk} have been set





Phys. Rev. Lett. 123, 212002 (2019)
arXiv:2201.01694 [hep-ex]