Collectivity probes in small systems and photoproduction studies at the LHC

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Diffraction and Low-x 2024

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Overview

Intact proton / nuclei

Intact protons or nuclei; photo/pomeron-induced processes

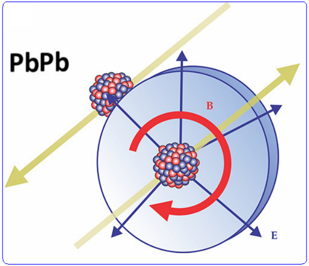
- **Ultra ($b \geq 2R_A$)/periperal collisions with large impact parameters;**

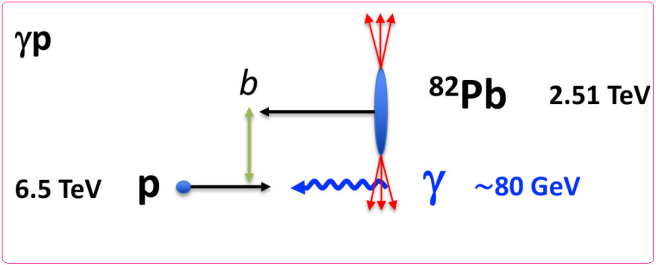
  Semiexclusive: $\rightarrow$ $\gamma/\mathbb{P}$-proton/Pb

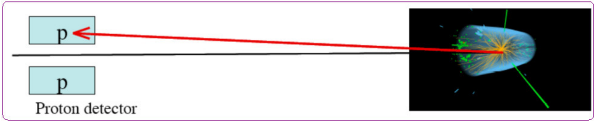
  Exclusive: $\rightarrow$ $\gamma\gamma$, γ-$\mathbb{P}$, $\mathbb{P}$-$\mathbb{P}$ in initial state

  $\rightarrow$ Photon/pomeron source (Pb or p) does not dissociate

A-A **p-A**







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

Pomeron Parton Density in Pythia

- **factorized into** **pomeron flux** **and** **pomeron structure function** **(Ingelman–Schlein model)**

  $\rightarrow F_2^{D(3)}(x_{\mathbb{P}}, \beta, Q^2) = f_{\mathbb{P}/p}(x_{\mathbb{P}}) F_2^{\mathbb{P}}(\beta, Q^2)$

- **Pythia8 options;** `SigmaDiffractive:PomFlux`, `PDF:PomSet` **combinations**

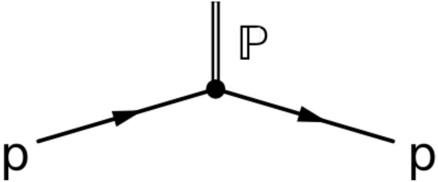
  → **Default**; PomSet = 6, PomFlux = 1

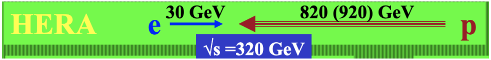
  → **H1 fit A**; PomSet = 3, PomFlux = 6

  → **H1 fit B**; PomSet = 6, PomFlux = 7

  → **Alternative from H1**; (`PomFlux = 8`)

Intact proton and pomeron



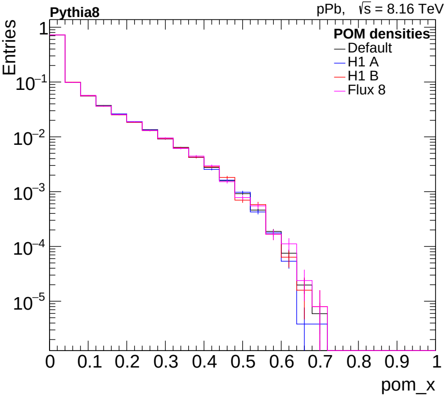


G.Ingelman and P. Schlein, Phys. Lett. B152 (1985) 256

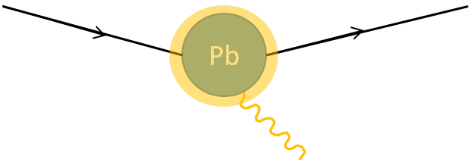
Pomeron PDF and flux in Pythia

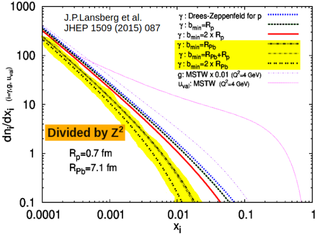
- **Pomeron energy fraction with respect proton energy (6.5 TeV)**

  → So far same reach between different PDFs, average ∼ 0.043



Photon flux; Equivalent Photon Approximation

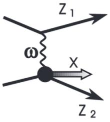


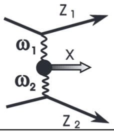


- Equivalent Photon Approximation (EPA)[1,2] ; cross-section can be factorized in terms of equivalent flux of photons with energy E_γ into colliding hadron
- Flux of quasireal photons, with intensity proportional to the square of its electric charge, Z^2

  → *Weizsäcker – Williams* power-law photon flux

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



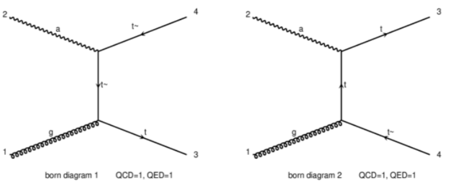


[1] arXiv:nucl-ex/0502005v2 here

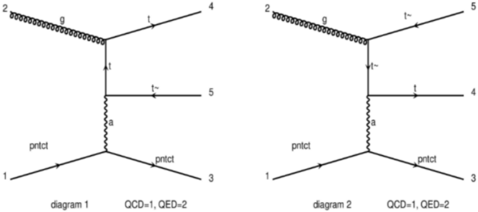
[2] doi:10.1103/PhysRevD.88.054025 here

Photon flux; Effective couplings [preliminary, work in progress]

- A. Bouzas, A. Cota, J. Murillo
- FeynRules were used to add intact proton ‘p_{ntct}’ to the SM in MG5



EPA

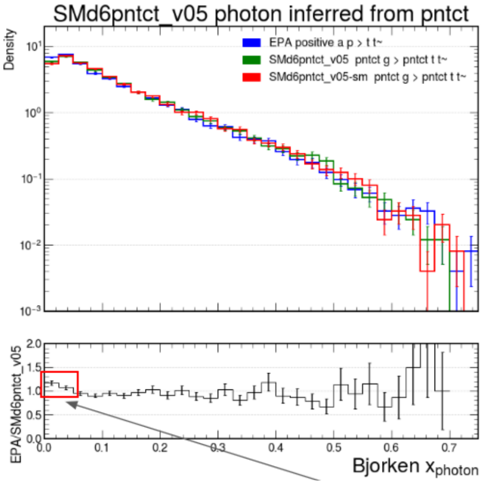


SMd6pntct_v05

`A. B., F. Larios, Phys. Rev. D 105 (2022) 115002`

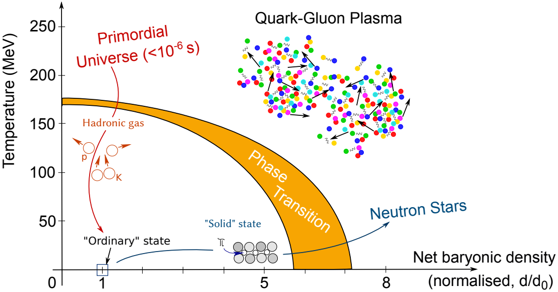
Photon flux; comparison with EPA [preliminary, work in progress]

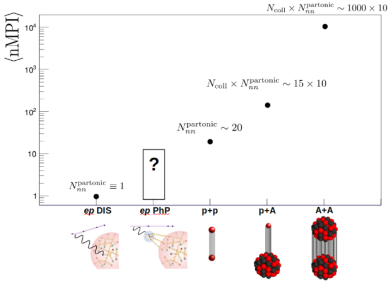
- A. Bouzas, A. Cota, J. Murillo
- So far consistency between EPA and QED tree level



Collectivity in diffractive processes within pPb collisions

- **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?

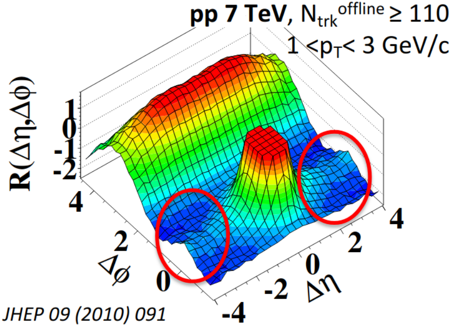




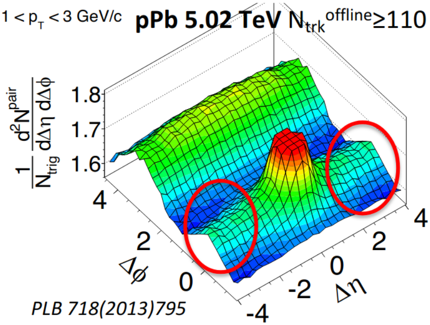
https://cds.cern.ch/record/2025215

D. Gangadharan, QM2022

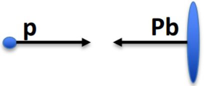
- Too small and simple to develop QGP-like collective behaviour?
  - → Minimal size and conditions for collectivity to emerge
- **Initial (CGC) effective model or Final (QGP) state effect?**
  - how small the interaction region can be until description of soft QCD breaks down?



JHEP 09 (2010) 091



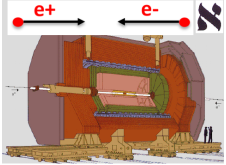
PLB 718(2013)795

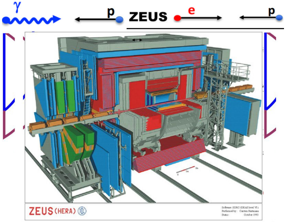


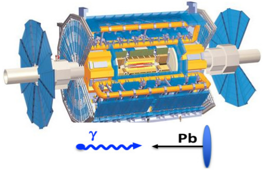
DOI: 10.1016/j.physletb.2011.01.024

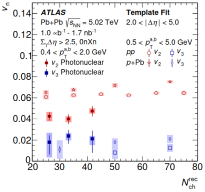
Recent collectivity probes with small systems

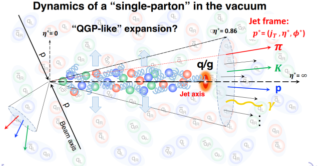
- **e^+e^-** → ALEPH (91 GeV, 208 GeV) and Belle (10.52 GeV)
- **ep** → ZEUS and H1 at HERA (318 GeV)
- **γp**
  - → ZEUS (318 GeV [ep]) (**JHEP 12 (2021) 102**)
  - → CMS (8.16 TeV [pPb]) (**PLB 844 (2023) 137905**)
- **pPb** → CMS (8.16 TeV [pPb])
- **γPb** → ATLAS (5.02 TeV [PbPb])





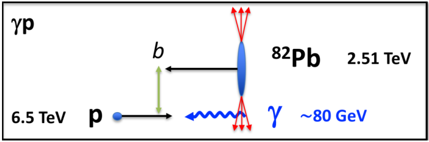


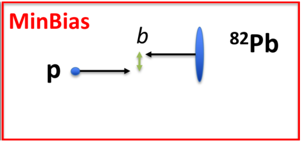


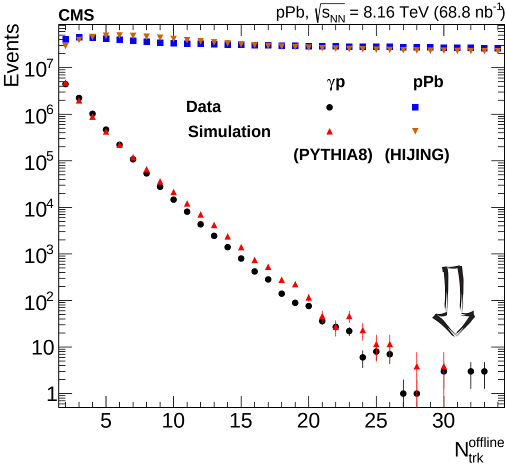


- **Intra-jets** → CMS (13 TeV [pp]) (**HIN-21-013-PAS**)

Limited multiplicity of charged particles in small systems



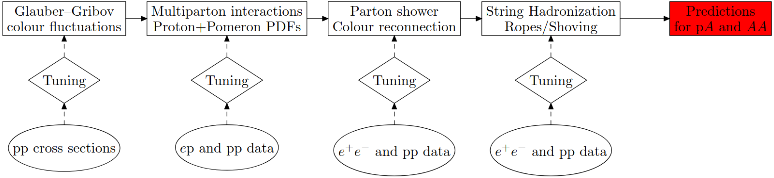




- Using PYTHIA8 to model γ flux from Pb nuclei
  - γp data consistent with prediction averages and reach
- Lower mean p_T and $N_{trk}^{offline}$ for γp than for pPb (same multiplicity range).
  - pPb events simulated with HIJING

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

- **Ongoing colaboration with Ilkka Helenius (Pythia8)**
- **Pythia8 with Angantyr model**



J. High Energ. Phys. (2018) 2018: 134

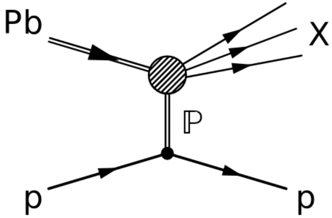
- **Pythia8 with Angantyr model and different pomeron density variations**

  → **Intact proton case**

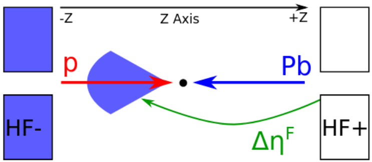
- **Presence of rapidity gap on the p-going side**

  - Activation of forward detectors on lead nucleus side and no activity on opposite side

pomeron-lead



Rapidity gap



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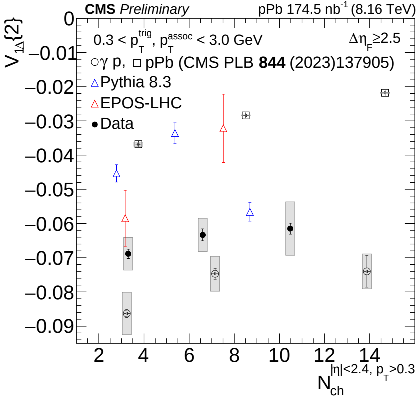
- **CMS-HIN-22-004, pPb data at 8.16 TeV**

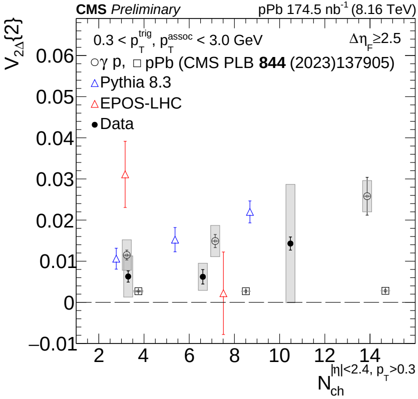
  $\rightarrow$ **proton at 6.5 TeV**

Comparison with Pythia8 model combining all diffractive contriobutions + ND

$V_{1\Delta}$



$V_{2\Delta}$

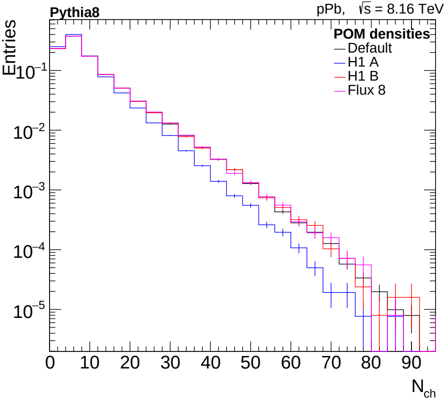


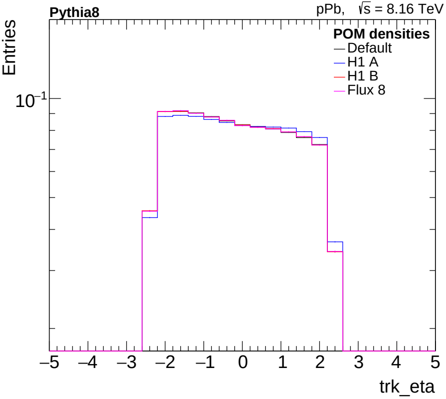
`Cross-section limits on HIN-18-019`

Returning to Pomeron-Lead interactions; produced charged particles

- **Pythia8 with Angantyr model** $\rightarrow$ **$\mathbb{P}$ density effect over N_{trk} and η**
- **N_{trk} and η in agreement so far for Default settings and H1 B Fit**
  - With difference with H1 A Fit at highest multiplicities
  - Stronger assymmetry in η distribution for H1 B Fit

Sample	Mean N_{ch}
Default	8.60
H1 A	7.61
H1 B	8.58
Flux8	8.60



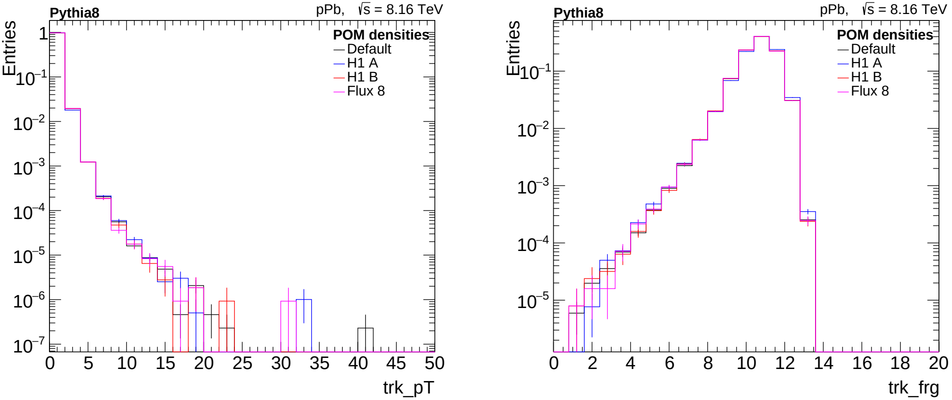


Pomeron-Lead interactions; Large rapidity gap

- Pythia8 with Angantyr model

  - p_T and $\Delta\eta^F$

- Indeed $\mathbb{P}$-Pb interaction leads to an empty side reflecting in a large $\Delta\eta^F$



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

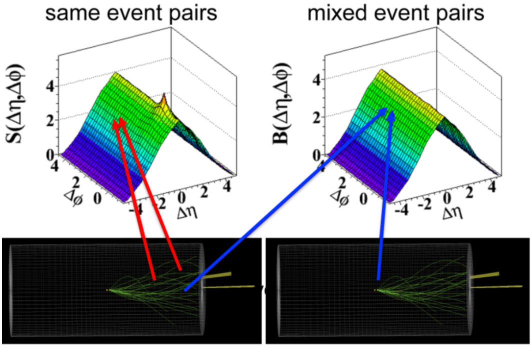
  → Correction for tracking inefficiency is applied to each charged particle

Signal pair distribution:

$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}$$

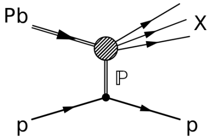
Background pair distribution:

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$



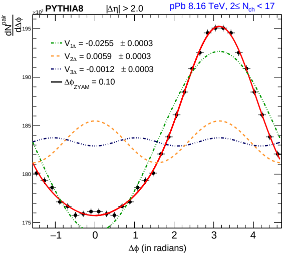
Fourier fits from 1D projection to long range $|\Delta\phi| > 2.0$

- Two particle correlations with **ℙ-Pb events**; **PYTHIA8** ℙ density + Angantyr
- 2D correlations are simmetrized around 0 and π
- Distributions are fitted over $\Delta\phi$ range $[0, \pi]$ to a Fourier decomposition series $\propto 1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)$, from where the measured $V_{n\Delta}$ are extracted

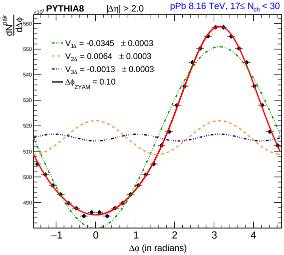


$\rightarrow \mathrm{N_{ch}} >$ categories with $\sim$even number of pairs

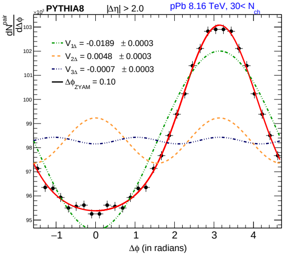
$2 \leq \mathrm{N_{ch}} < 17$



$17 \leq \mathrm{N_{ch}} < 30$

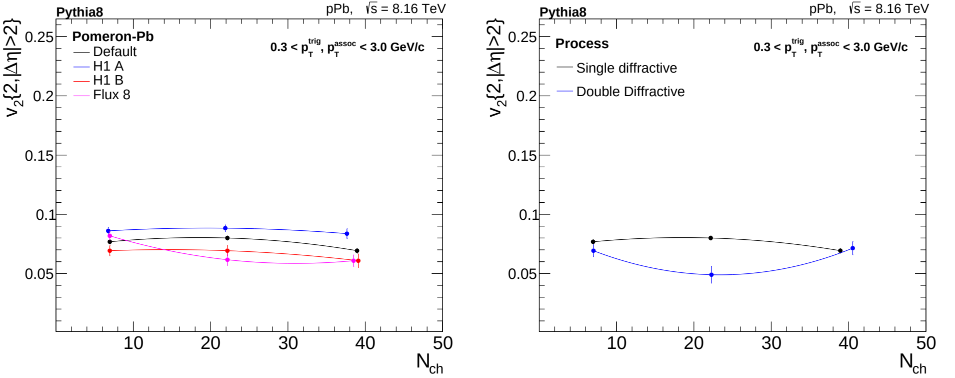


$\mathrm{N_{ch}} > 30$



v_2 anisotropy dependence with N_{trk}

- **Pythia8 with Angantyr model**
- **Fluxes have an impact on v_2 $\pm$ 10.4%**
- **SD and DD show**



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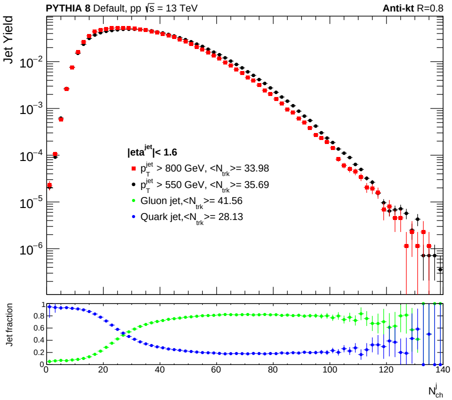
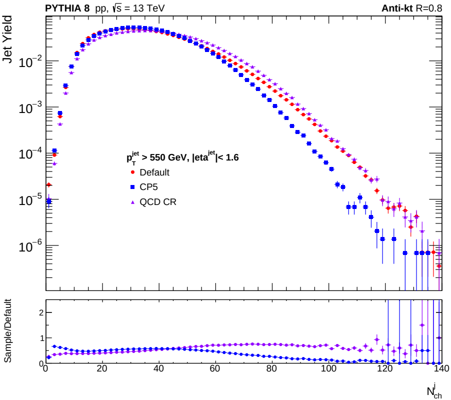
Intrajet collectivity and soft QCD tunes

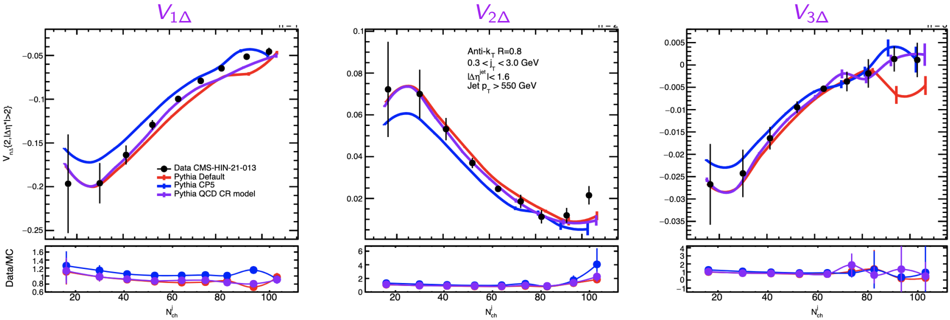
Intrajet N_{trk}

- **Intra jet N_{trk} can be categorised by parton flavor**
  - High energy jets $p_T > 500$ GeV
  - Gluon dominating high multiplicity region
- **N_{trk} distribution affected by Pythia tune settings**



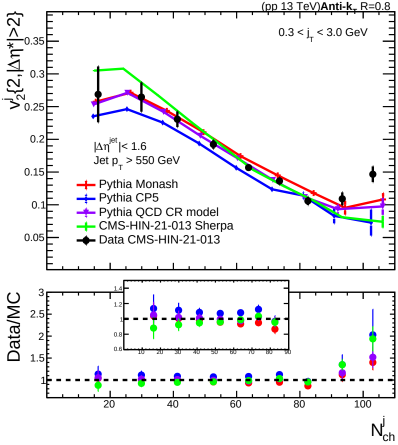


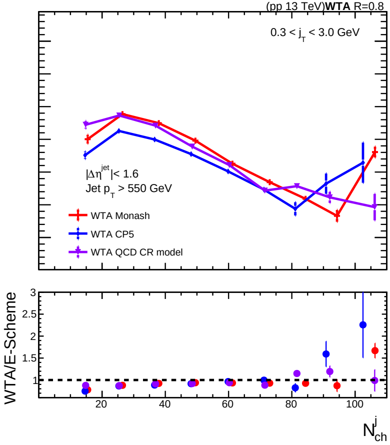
- Data from arXiv:2312.17103 compared with Pythia8 predictions with different tunes
- So far Monash and QCD CR more in agreement with data than Pythia CP5



Different tunes and frame of reference

- v_2 anisotropy modeled better by Monash and Pythia CR model
- Change to Winner-Take-All (WTA) model keep rersults consistent with E-Scheme up to N_{trk} $\sim$ 80 where Pythia CR keeps consistent and Pythia CP5 shows the highest variation





Summary and Outlook

- Several phenomena in photo-induced and diffractive proccesses yet to be studied
- Photon flux from QED tree level calculation consistent with EPA modeling
- Different pomeron density options with pomeron PDF and Flux affect the v_2 measurements

  - By $\sim$ 10%

- Predictions from the PYTHIA8 on intrajet v_2 data measurements with different tunes and frames of reference

  - Monash and QCD CR model in better agreement with Data

  - Measurements do not show signficant variation up to $N_{trk} \sim 80$ after performing measurements in WTA frame

  - Where QCD CR model shows the smallest variation

Thanks

Backup

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

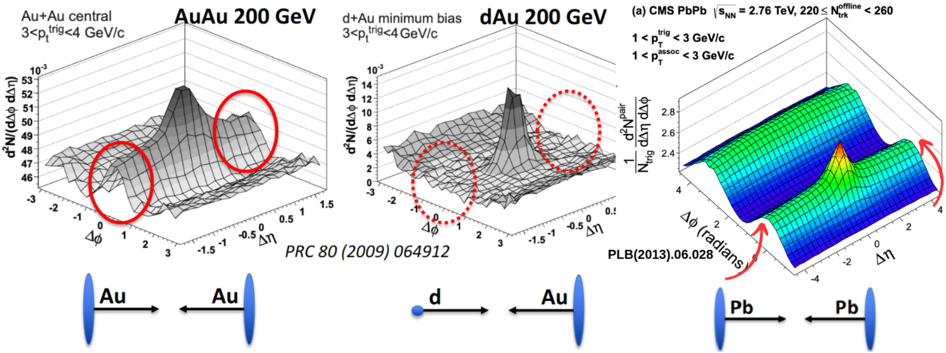
- Photon energies for lead ion at 2.76 TeV and proton at 7 TeV can reach values up to 80 GeV and 2.45 TeV respectively
- Photon energies at LHC, HL-LHC and FCC energies; larger reach for proton flux

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

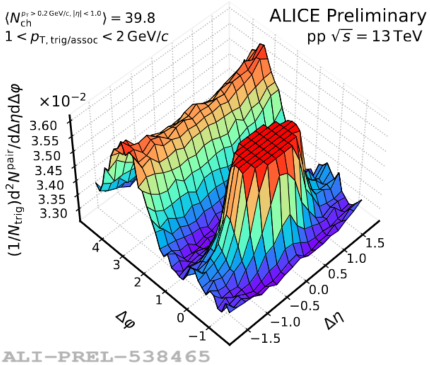
H.-S. Shao and D. d'Enterria, JHEP 2209 (2022) 248 arXiv:2207.03012[hep-ph]

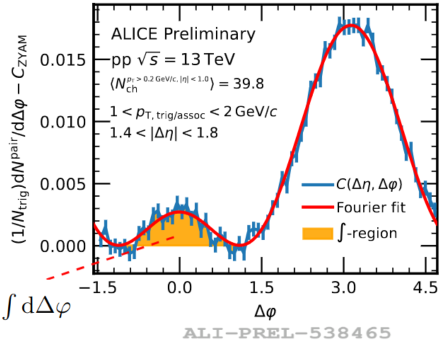
Collectivity and ridge in nuclear collisions AA

- 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



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



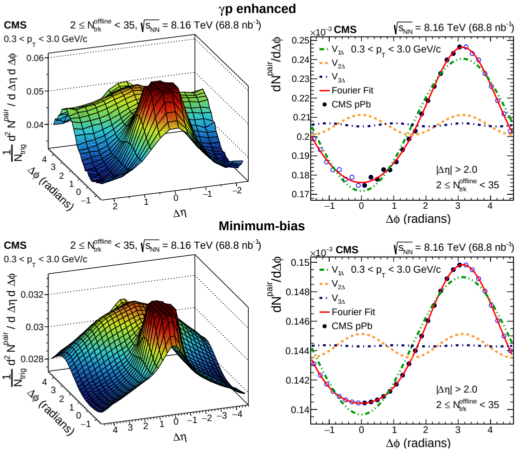


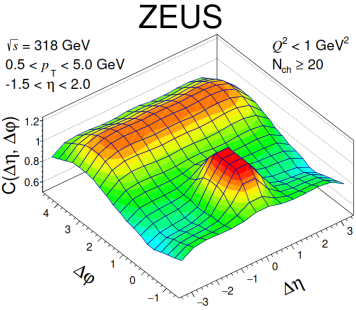
$$Y^{\mathrm{ridge}} = \int \mathrm{d}\Delta\varphi$$

Recontres de Moriond QCD 2023, Jasper Parkkila

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 $\propto 1 + \sum_n 2 V_{n\Delta} \cos(n\Delta\phi)$





(a) Photoproduction.

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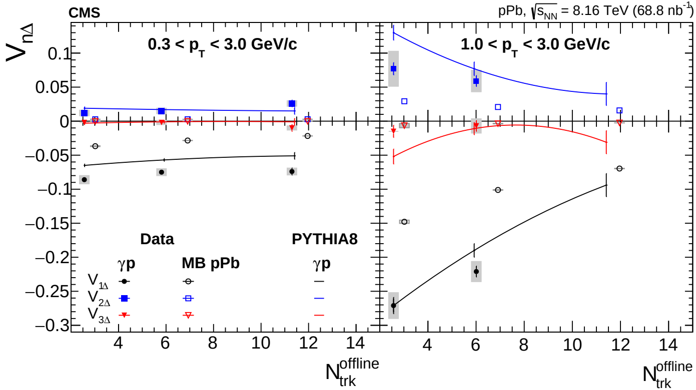
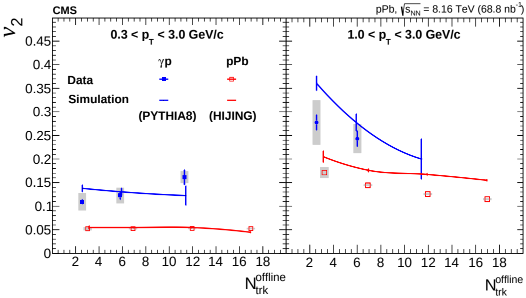
$V_{n\Delta}$ measurements with $|\eta| > 2.0$

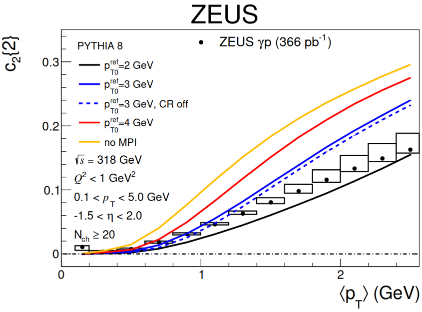
- $\rightarrow$ γp data measurements are consistent with model predictions that have no collective effects

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



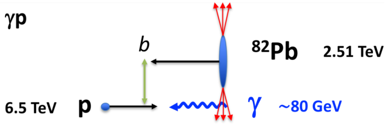
- At a given p_T and track multiplicity, v_2 is larger for γp-enhanced events than for MB pPb interactions
  - The magnitudes of both $V_{1\Delta}$ and $V_{2\Delta}$(v_2) increase with p_T
    $\rightarrow$ Similar response to p_T increase seen by ZEUS over $c_2\{2\}$
- Predictions from the PYTHIA8 model describe well the γp data within uncertainties

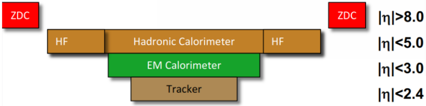


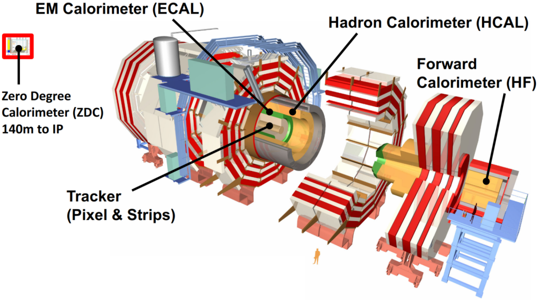


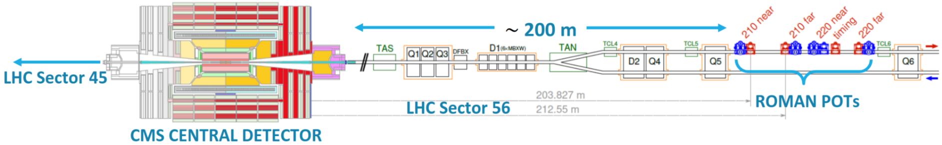
CMS forward detectors in Run 2

- 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





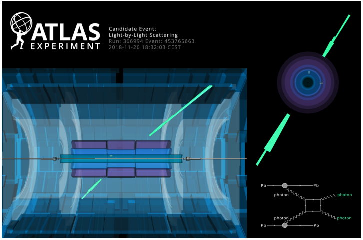


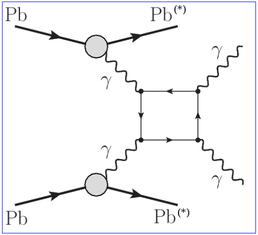


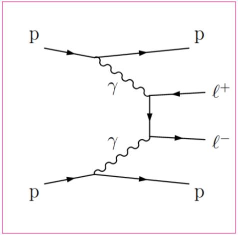
Evidence of Photo-induced processes in PbPb / pp at the LHC

- Evidence of light-by-light scattering

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







- Exclusive production of lepton pairs

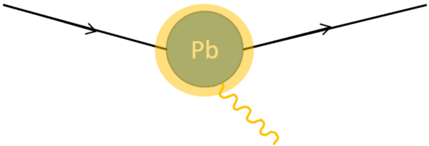
  - Scattered protons measured at CMS-TOTEM precision proton spectrometer (CT-PPS)

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

  JHEP07 (2018) 153

  - Light-by-light with protons

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

PHYSICAL REVIEW D 88, 054025 (2013)

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

Analytic approximation for equivalent photon flux from proton

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

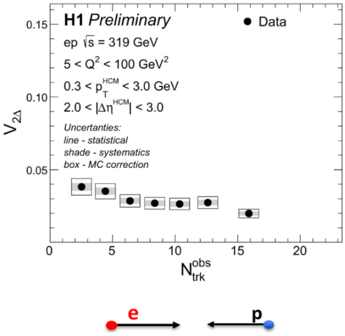
with the notation $\Omega = 1 + [(0.71\ \mathrm{GeV}^2)/Q^2_{\mathrm{min}}]$

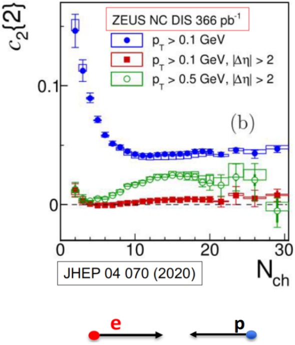
$$Q^2_{\mathrm{min}} = \omega^2/[\gamma_L^2(1 - 2\omega/\sqrt{s})] \approx (\omega/\gamma_L)^2$$

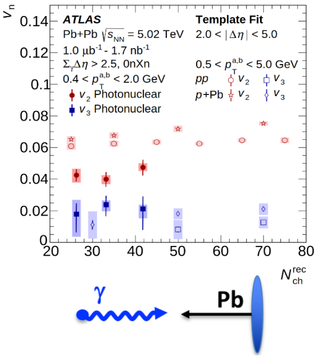
- γ_L is the lorentz boost of a single beam
  - Derived from *Weizsäcker – Williams* method
  - Using elastic proton from factor

PHYSICAL REVIEW D 88, 054025 (2013)

- 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

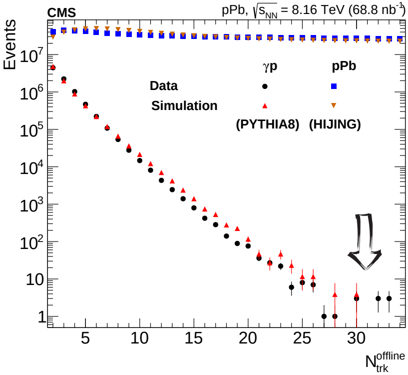
γp from pp and pPb; is track multiplicity consistent?

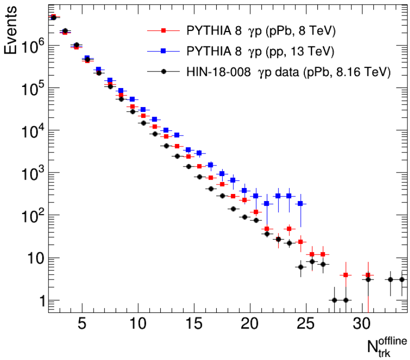
- EPA flux from proton instead of Pb nuclei
- Multiplicity distribution

$$< \mathrm{N_{trk}} >$$ PYTHIA8 pp sim) = 3.026 (1.5M events)

$$< \mathrm{N_{trk}} >$$ (PYTHIA8 pPb sim) = 2.89 (37M Events)

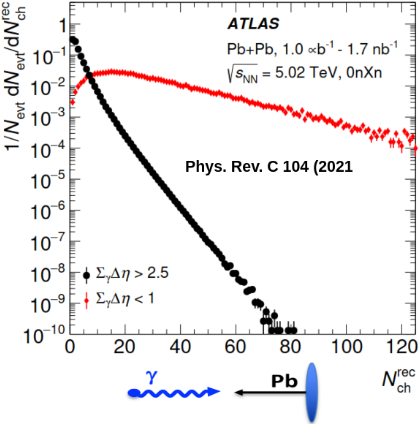
$$< \mathrm{N_{trk}} >$$ (pPb CMS Data) = 2.92

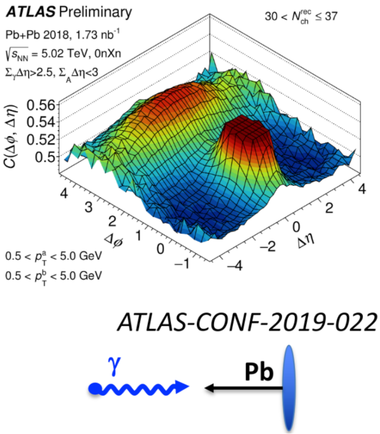




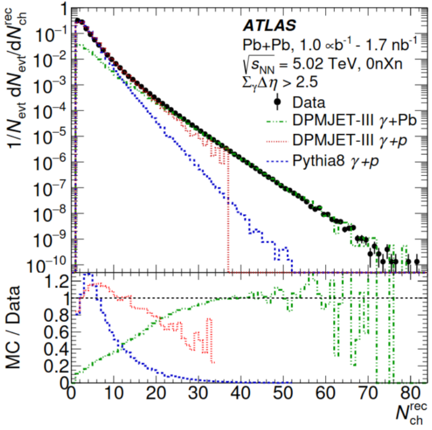
Recent probes in γPb; ATLAS at CERN within 5.02 TeV PbPb

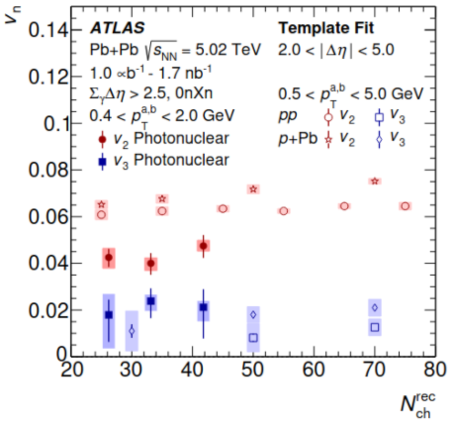
- Significant non-zero v_2
  - Substracting non-flow contribution using template fitting method

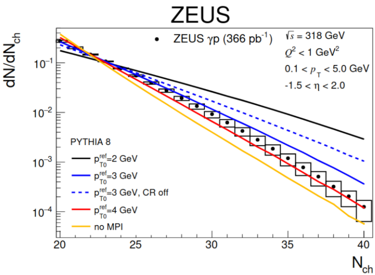




- Significant non-zero v_2
  - Substracting non-flow contribution using template fitting method

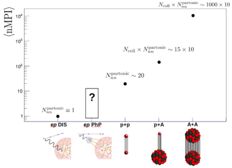


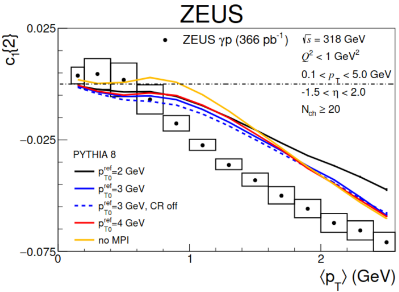


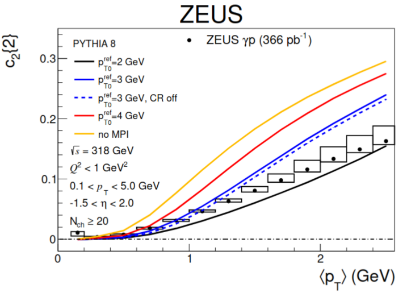


- No Multiparton Interactions (MPI) scenario disfavored

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







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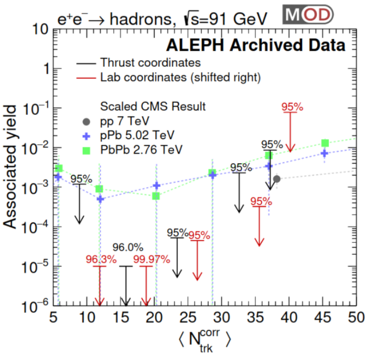
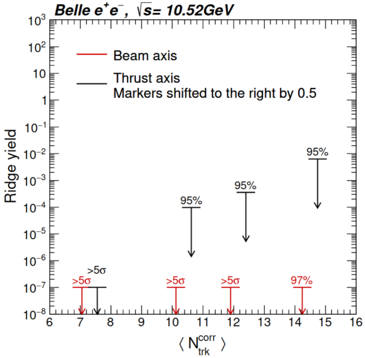
- Confidence limits on associated yield as a function of N_{trk} have been set





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