Di-jet production and signatures of collectivity in multiparticle photoproduction in UPC with the ATLAS detector

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on behalf of
the ATLAS Collaboration

Charles University
Prague

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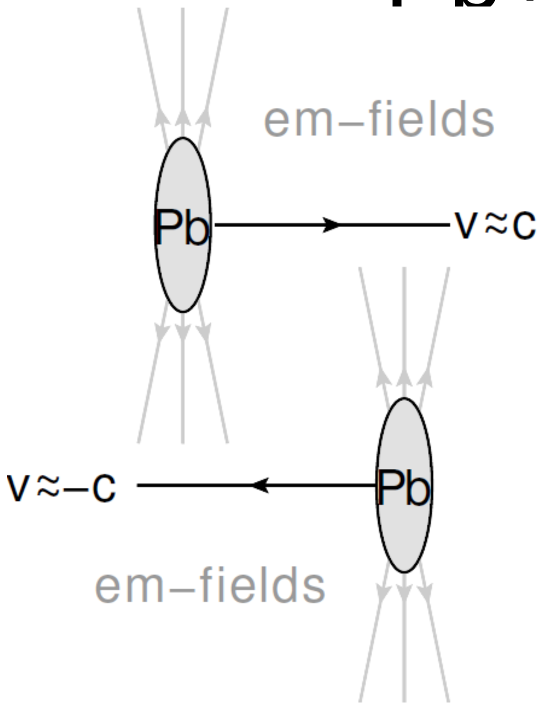
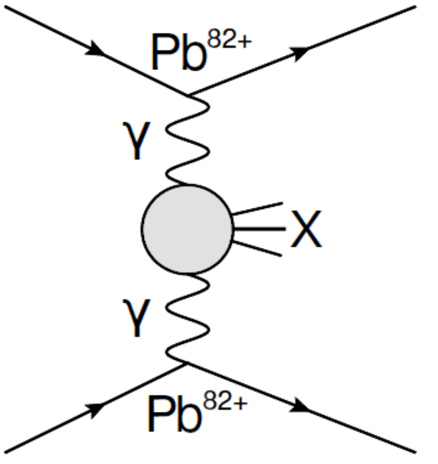
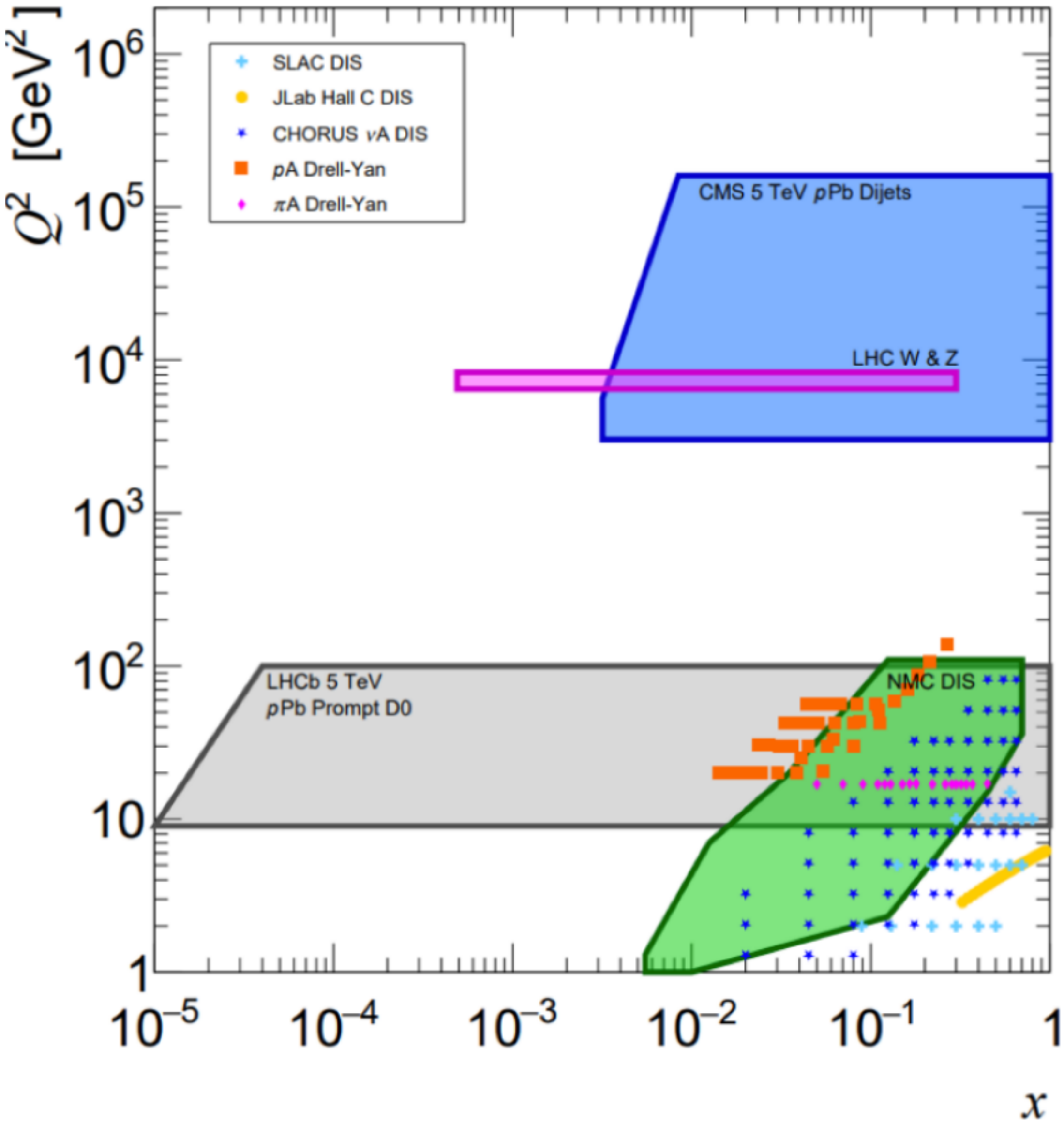
Ultraperipheral (UPC) Pb+Pb collisions





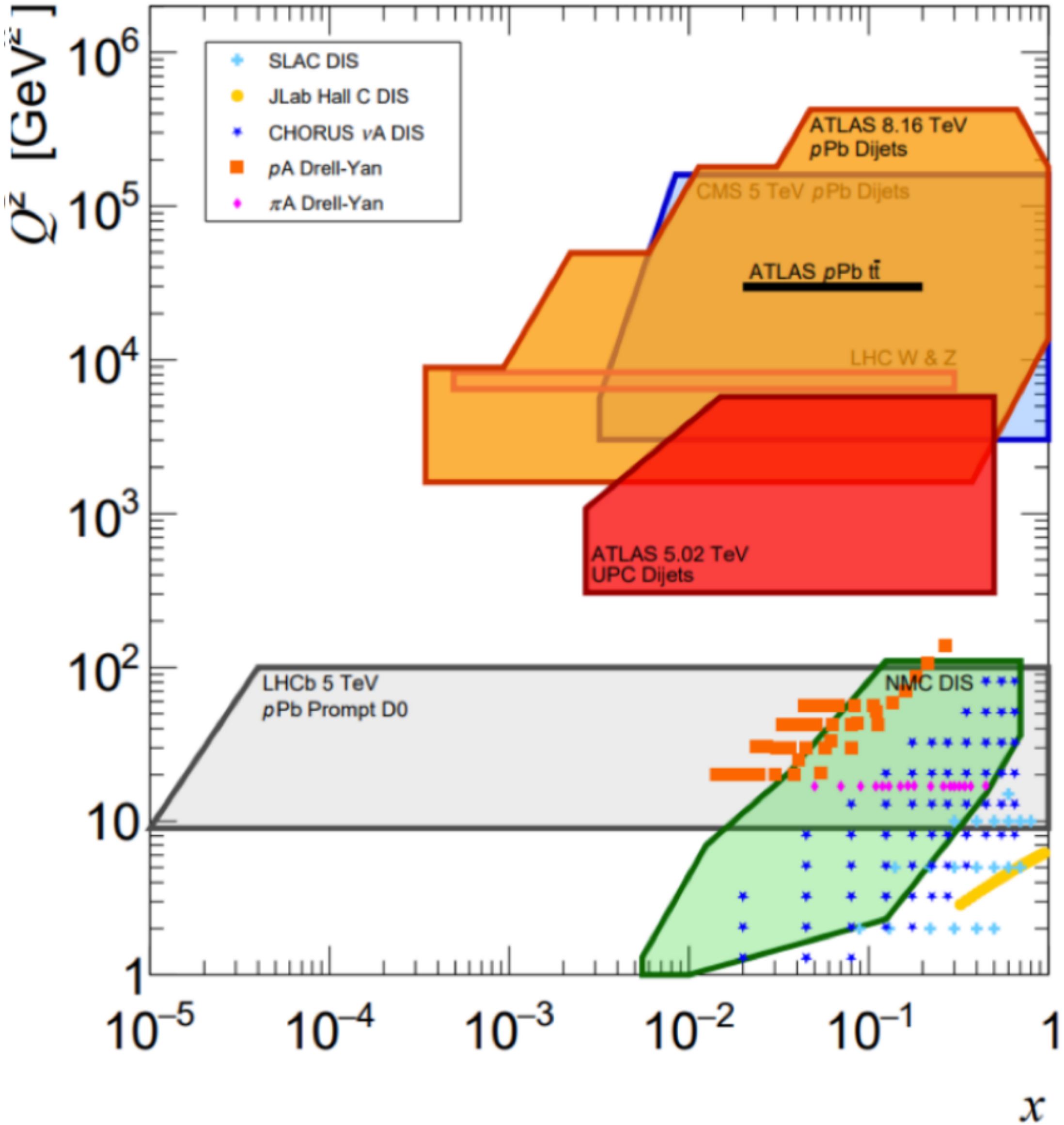
- Boosted protons / nuclei are **source of photons** of small virtuality ($Q^2<1/R^2=10^{-3}GeV^2$).
- Electromagnetic interactions **dominate** at large impact parameters => with Pb+Pb, the LHC turned into photon-photon collider.
- In this talk: study of dijets and collectivity in UPC.

Photo-nuclear jet production: motivation



- Mapping nuclear PDFs in wide range of Q^2, x space possible at the LHC.
- Large part of phase space not covered.

Photo-nuclear jet production: motivation

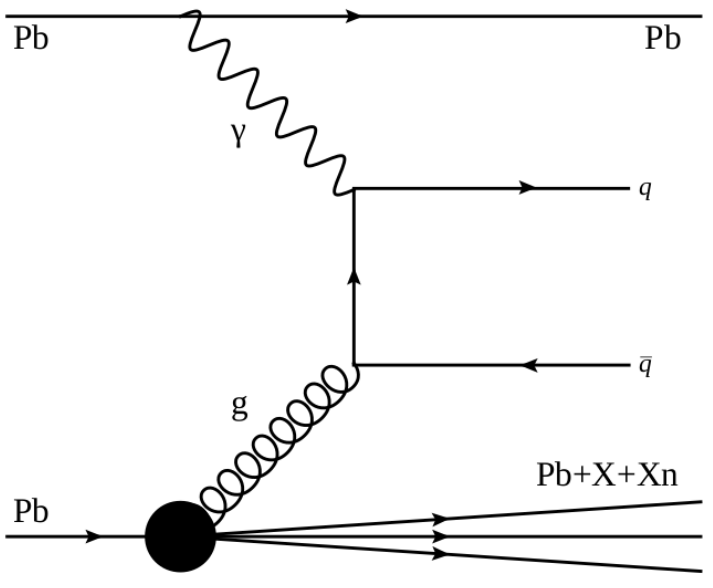


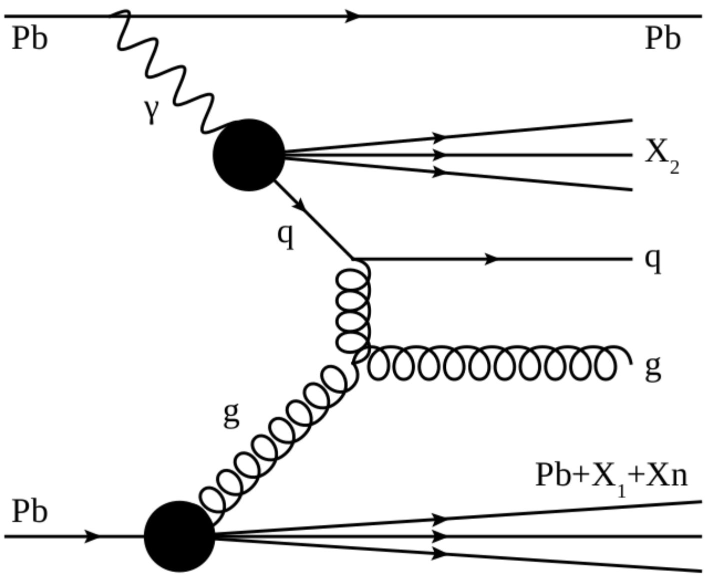
- Mapping nuclear PDFs in wide range of Q^2, x space possible at the LHC.
- Large part of phase space not covered.
- Photon-nuclear dijet measurements:
  - Can cover intermediate Q^2 region and large span of x.
  - Clean, DIS-like process

Photo-nuclear interactions

„Direct“

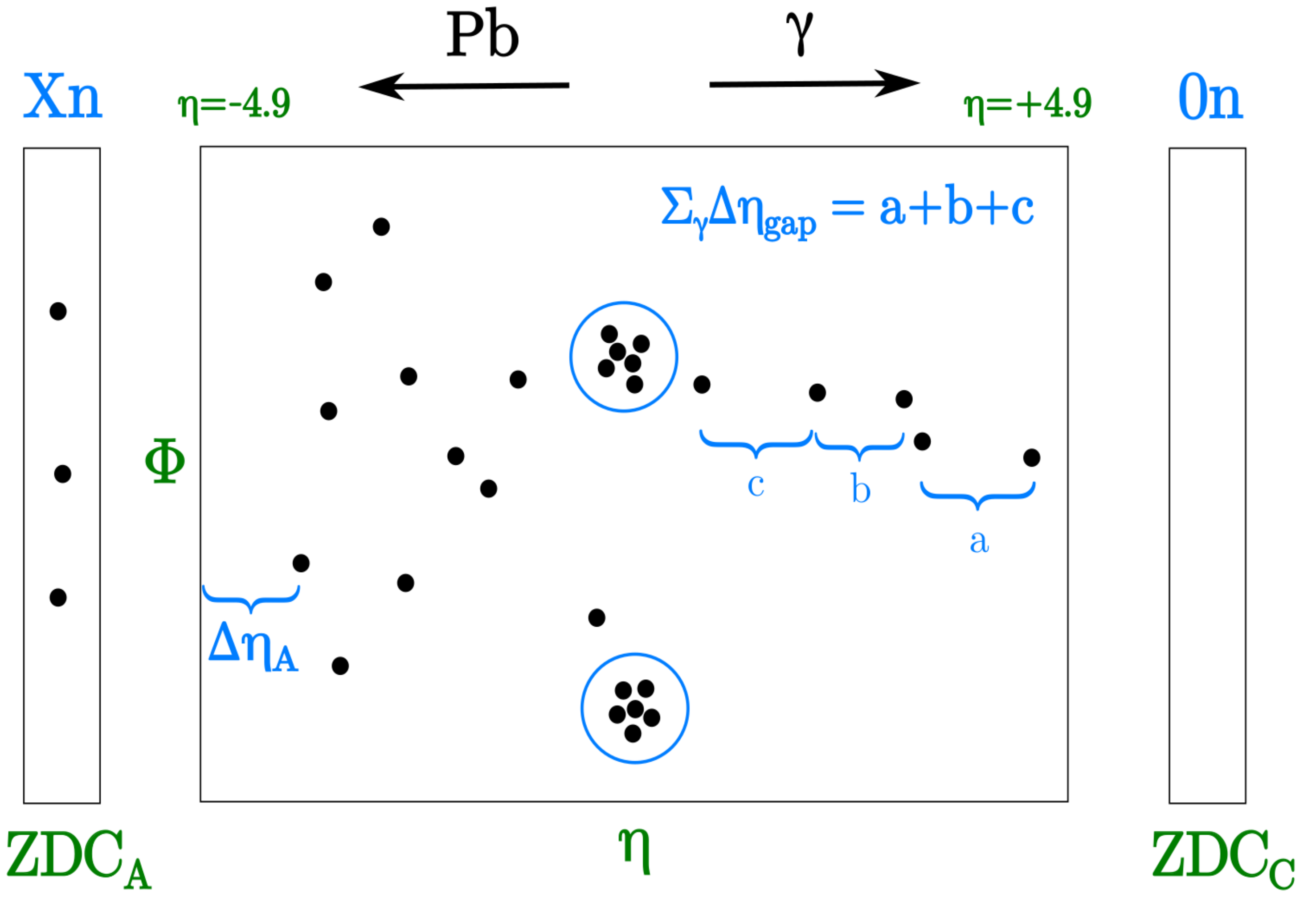
„Resolved“





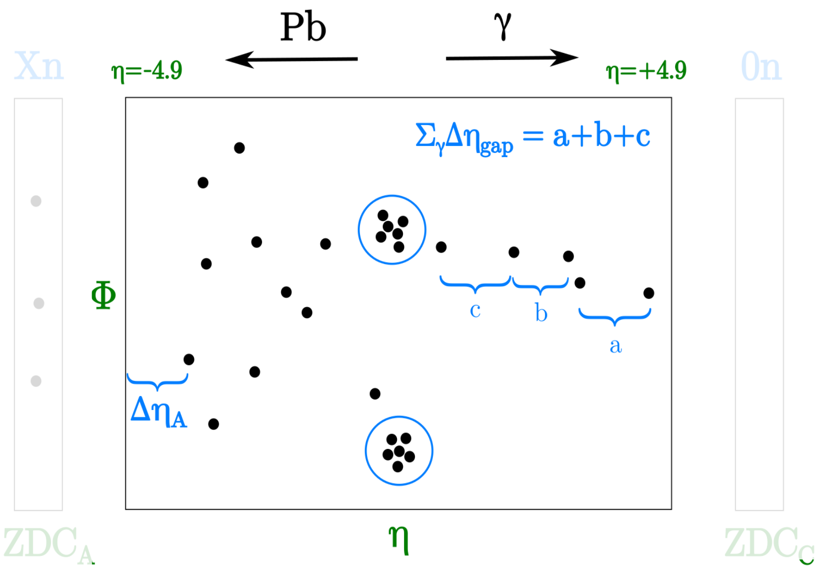
- Direct: photon directly couples to a parton.
- Resolved: photon resolved into hadronic state.

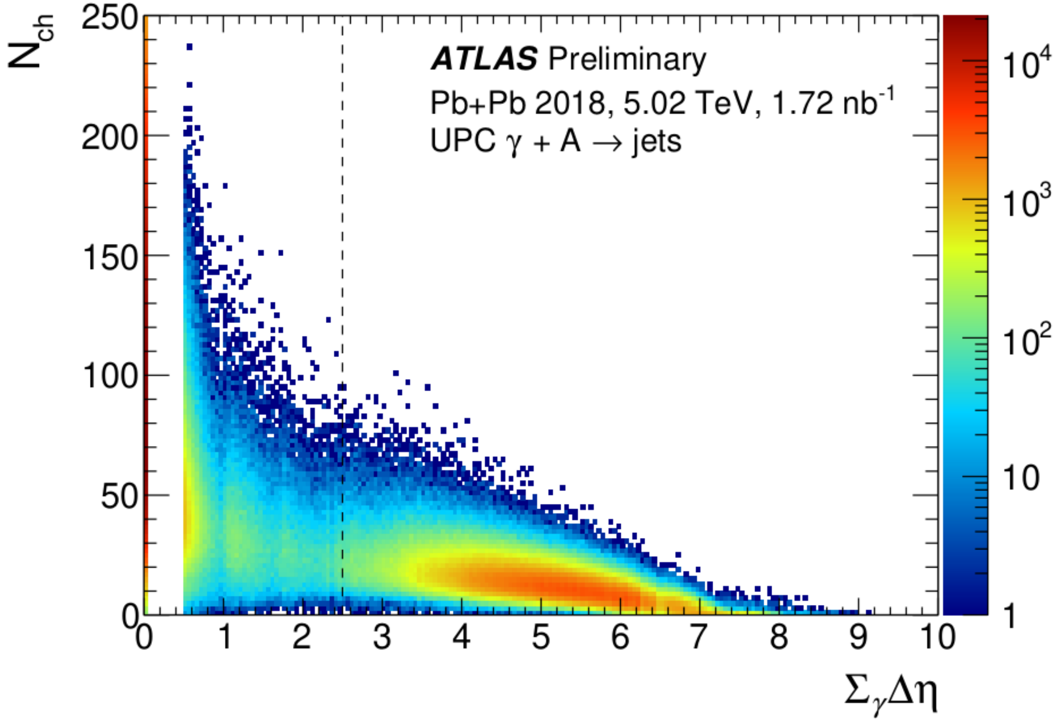
Event selection: two main tools



- Sum of rapidity gaps
- Signal from neutrons in Zero Degree Calorimeter

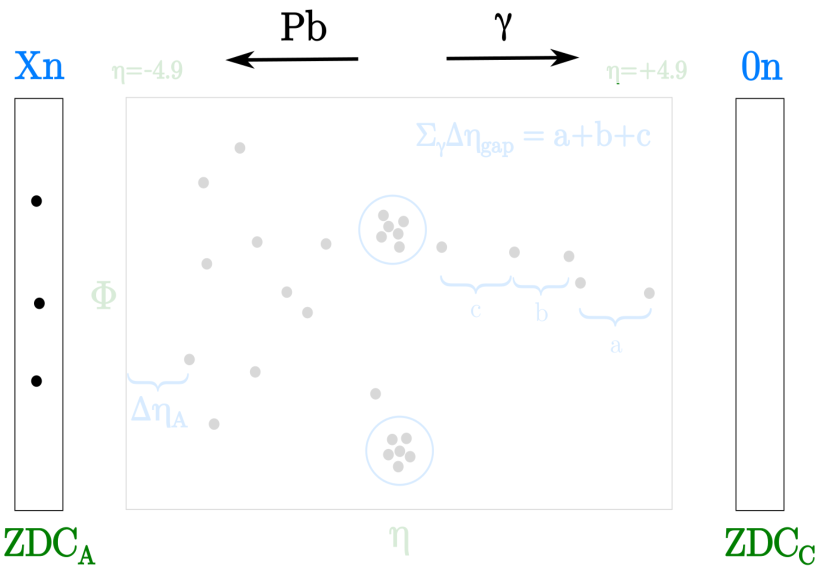
Event selection: rapidity gaps

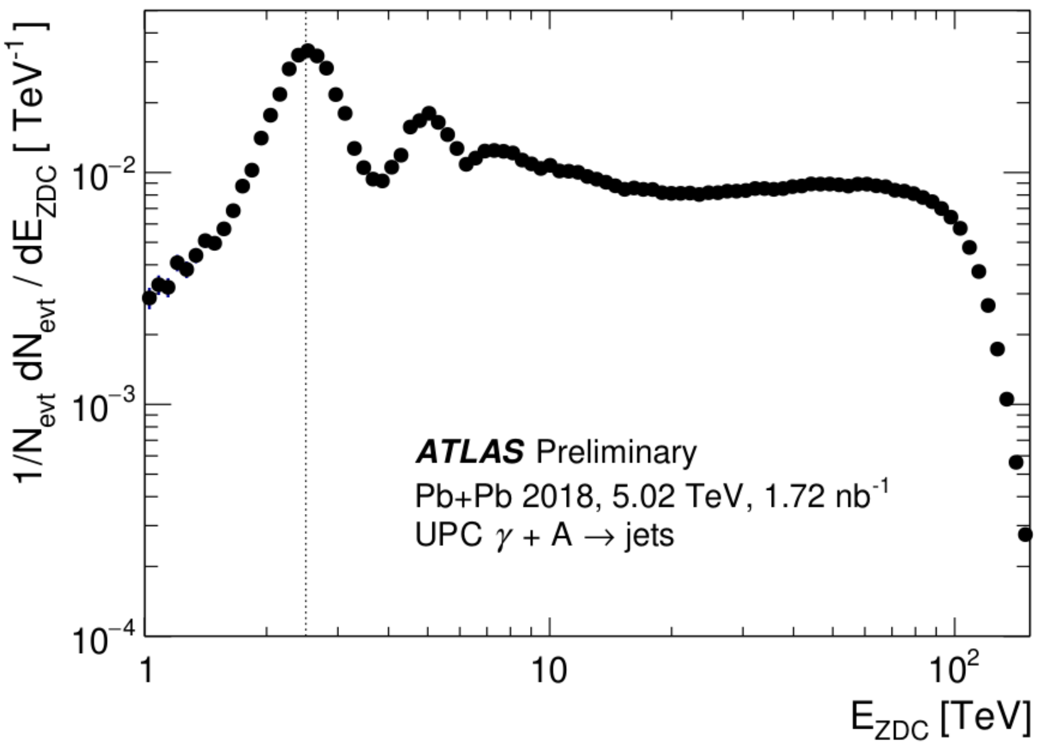




- $\Sigma_\gamma \Delta\eta_{gap} > 2.5$ … photon-nuclear events (large gaps and low N_{ch})
- $\Sigma_\gamma \Delta\eta_{gap} < 2.5$ … ordinary Pb+Pb events with dijets
- ($\Delta\eta_A < 3$)

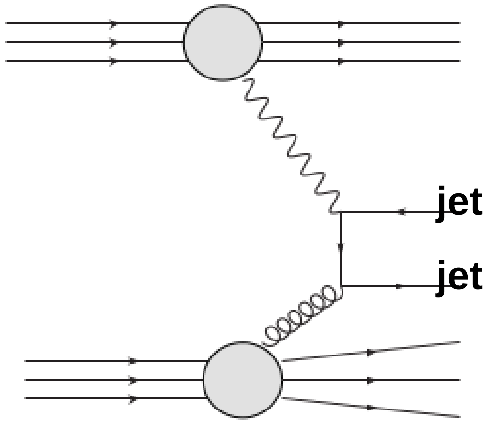
Event selection: ZDC





- Observed uncorrected ZDC energy in the Pb-going side
- Requiring signal from at least one neutron.

Observables



2 → 2 scattering limit:

$$H_T \equiv \sum_i p_{T\,i}$$ → ~ Q

$$x_A \equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}$$ → fraction of beam momentum carried by partons **in nucleus**

(in "direct" $x_A \sim x$)

$$z_\gamma \equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{+y_{\text{jets}}}$$ → fraction of beam momentum carried by partons **in photon**

(in "direct" $z_\gamma \sim$ DIS y)

… where

$$y_{\text{jets}} \equiv \frac{1}{2} \ln \left(\frac{\sum_i E_i + \sum_i p_{z\,i}}{\sum_i E_i - \sum_i p_{z\,i}} \right)$$

$$m_{\text{jets}} \equiv \left[\left(\sum_i E_i \right)^2 - \left| \sum_i \vec{p}_i \right|^2 \right]^{1/2}$$

… *i* goes through all the jets

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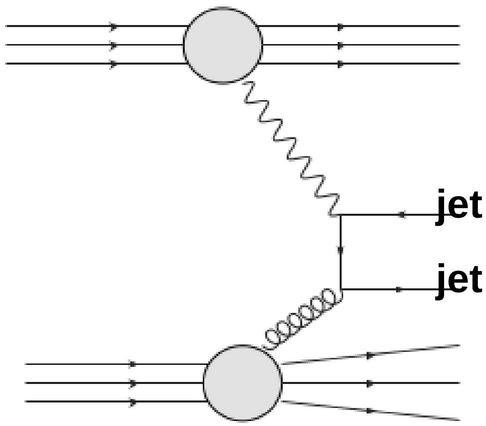

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… *i* goes through all the jets

$$\frac{d^3\sigma}{dH_T\, dx_A\, dz_\gamma}$$ . . . triple differential **cross-section** corrected to particle level

Emitting nucleus break up

- Selecting events with jets => selecting events with highest energy photons => bias towards low impact parameters as $E_\gamma \sim 1/b$ => high probability for the nucleus to **break up due to additional photon** exchanges.
- **Break up probability** can be quantified:

Nominal (but not unfolded)

$$f_{\text{no BU}} \equiv \frac{\mathrm{d}\sigma/\mathrm{d}z_\gamma|_{0nXn}}{\mathrm{d}\sigma/\mathrm{d}z_\gamma|_{XnXn} + \mathrm{d}\sigma/\mathrm{d}z_\gamma|_{0nXn}}$$

With just gap requirements

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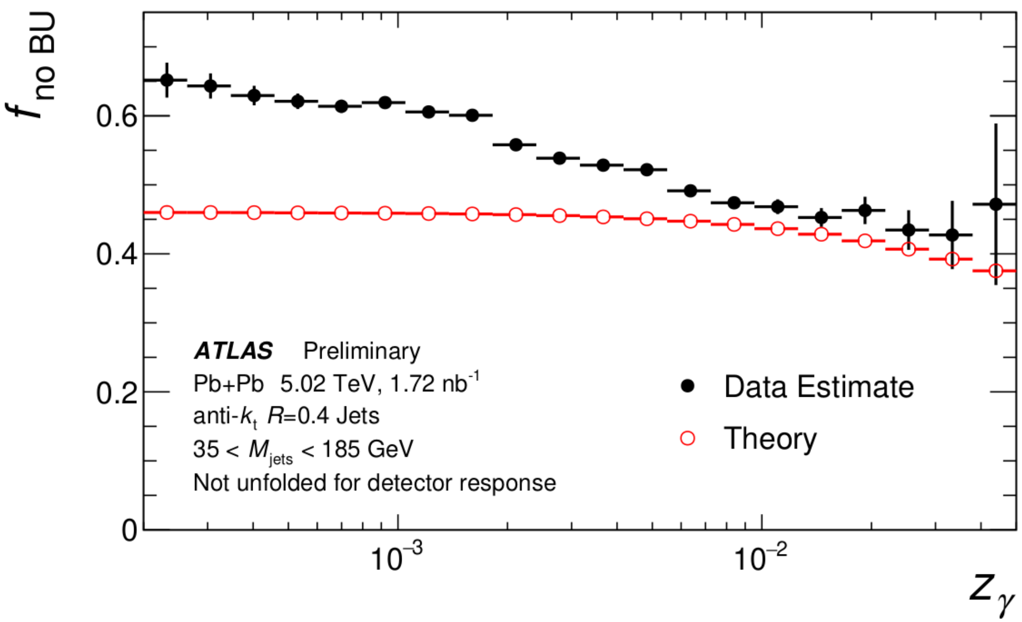
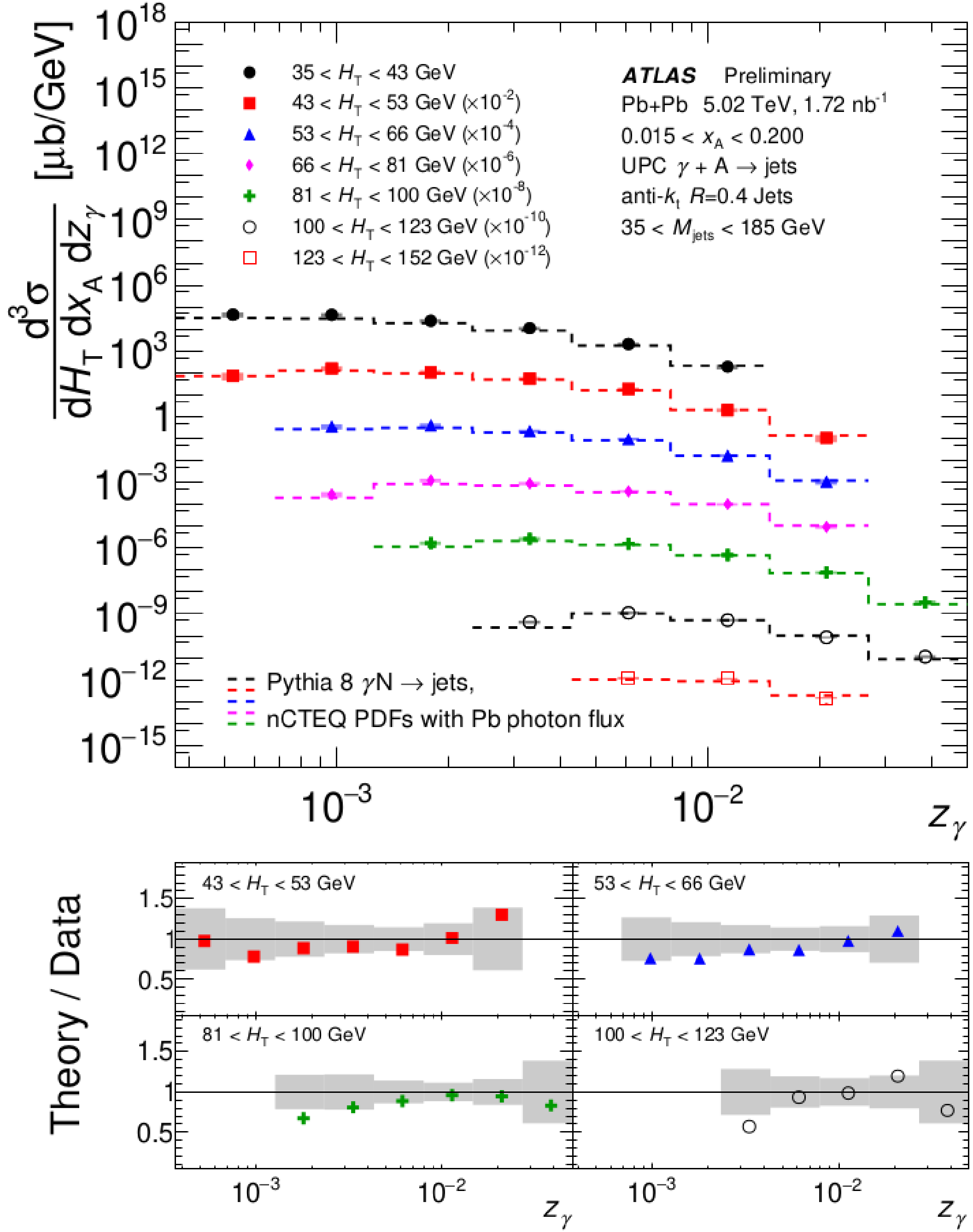


- **~50% probability** for emitting nucleus to break up
- Not included in PYTHIA 8 => room for **improvement of theoretical** description

- **PYTHIA 8 corrected** for these break up processes (done using calculations with input from STARLIGHT MC).

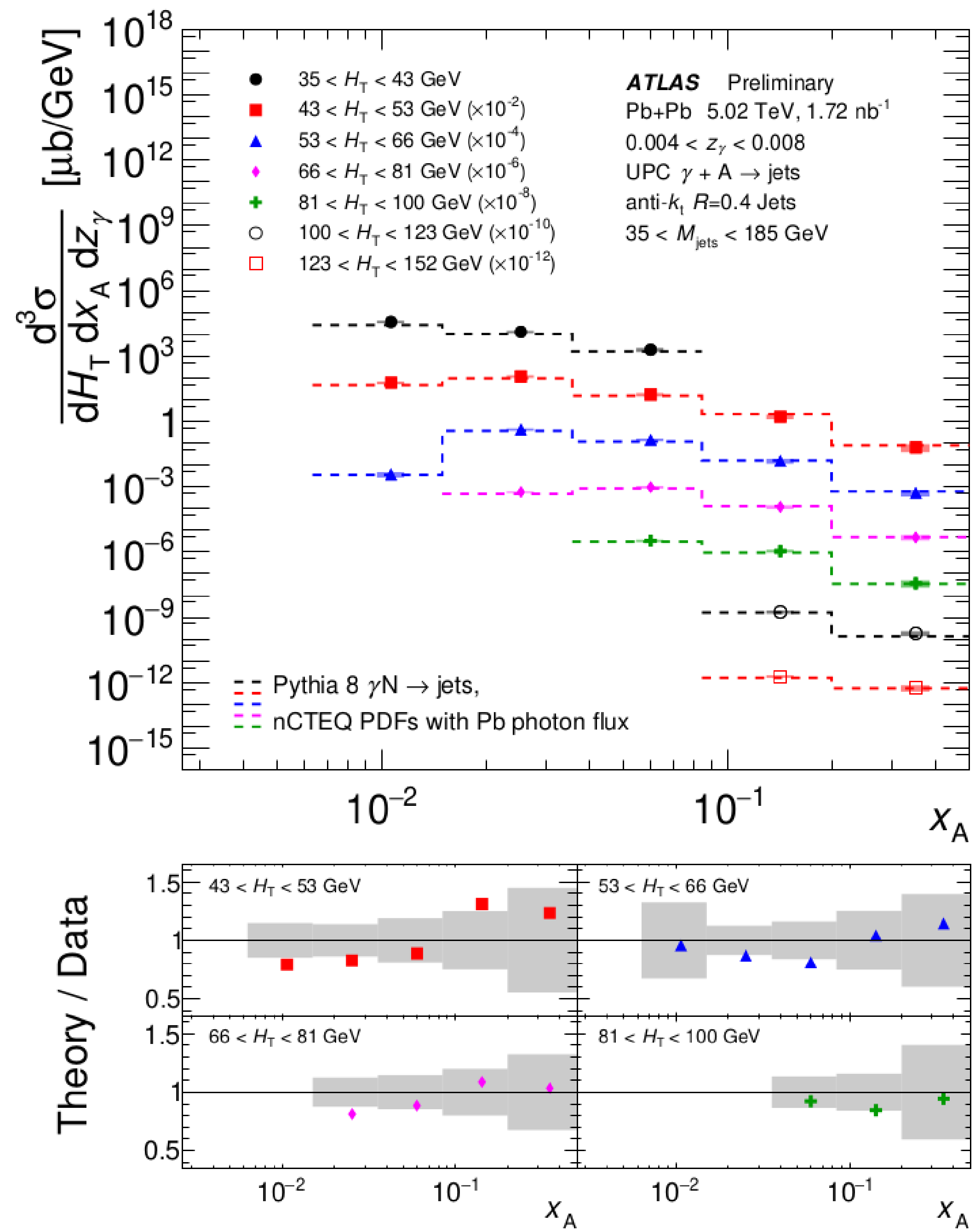
Results: narrow x_A region

- z_γ distributions for a **narrow x_A** region of large x_A ($0.015 < x_A < 0.2$).
- Primary sensitivity to **photon flux.**
- Results can constrain theory calculations of photon flux and nuclear break-up probability.



Results: scanning trough z_γ

- Low photon energy ($0.004 < z_\gamma < 0.008$) – access to **high x_A.**
- Higher photon energy ($0.008 < z_\gamma < 0.015$) – entering lower x_A region of **shadowing**.
- The highest photon energy ($0.015 < z_\gamma < 0.027$) – access to the **lowest x_A.**
- Data **consistent** with theory (PYTHIA8 + nCTEQ PDFs scaled for nuclear break-up).



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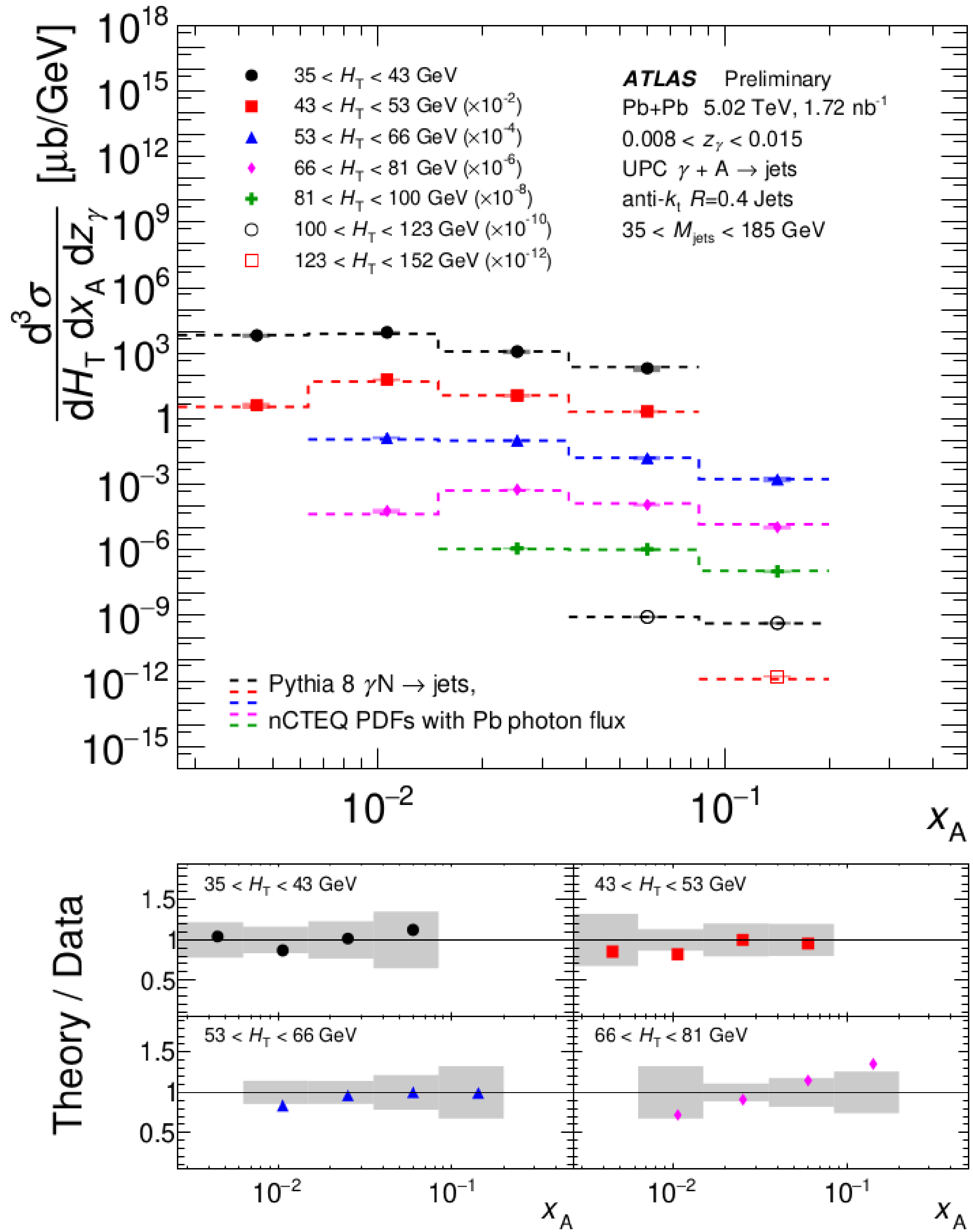

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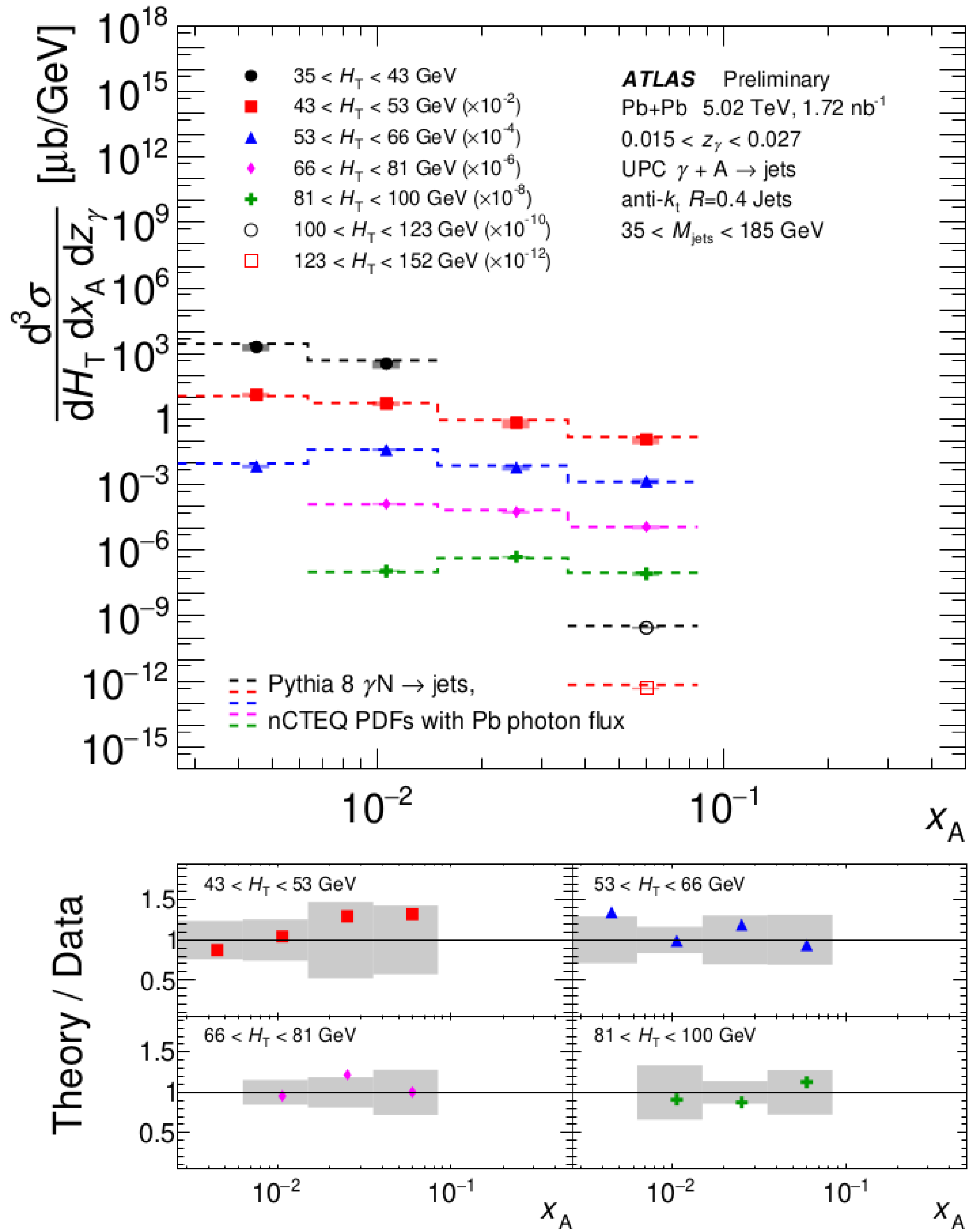

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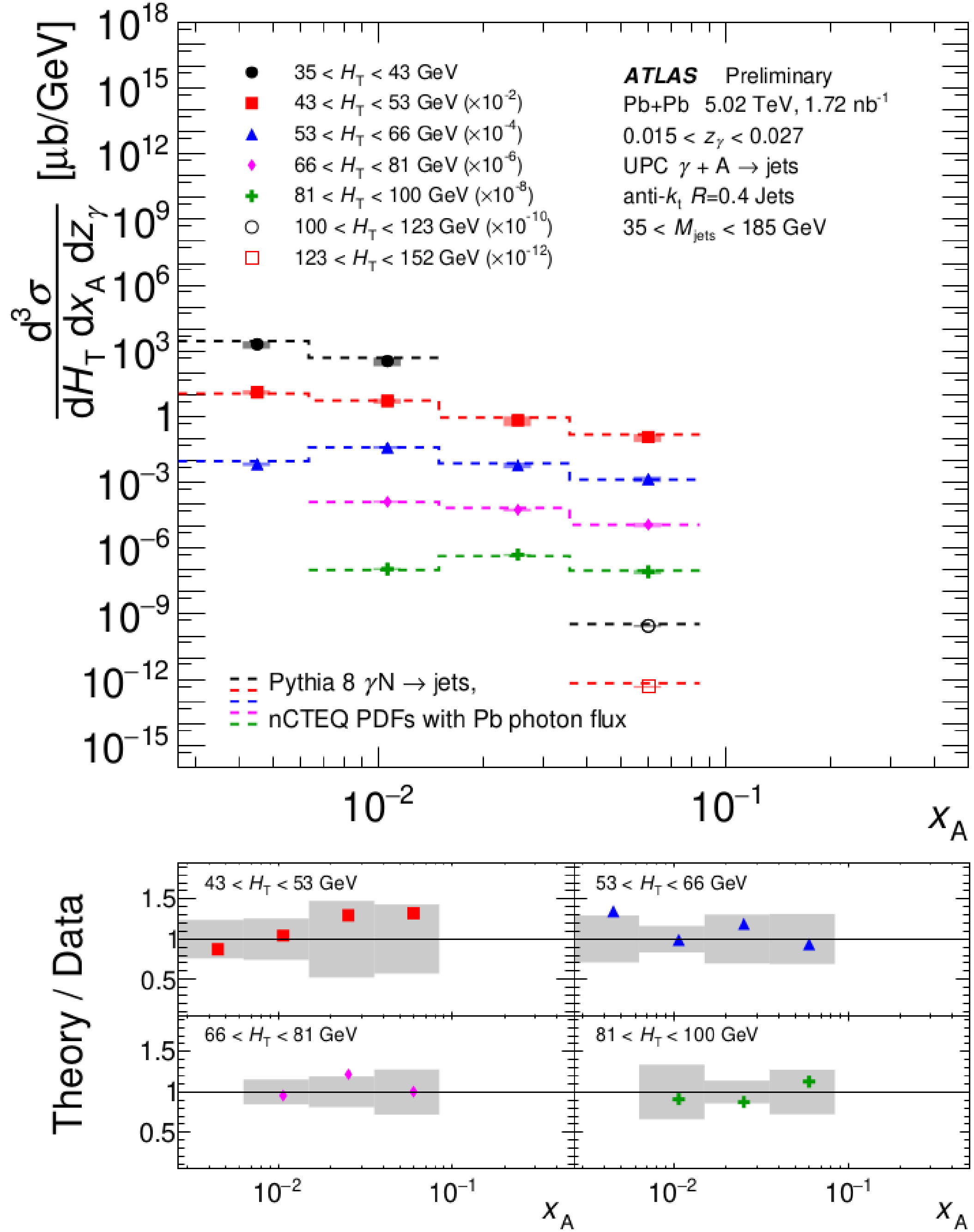
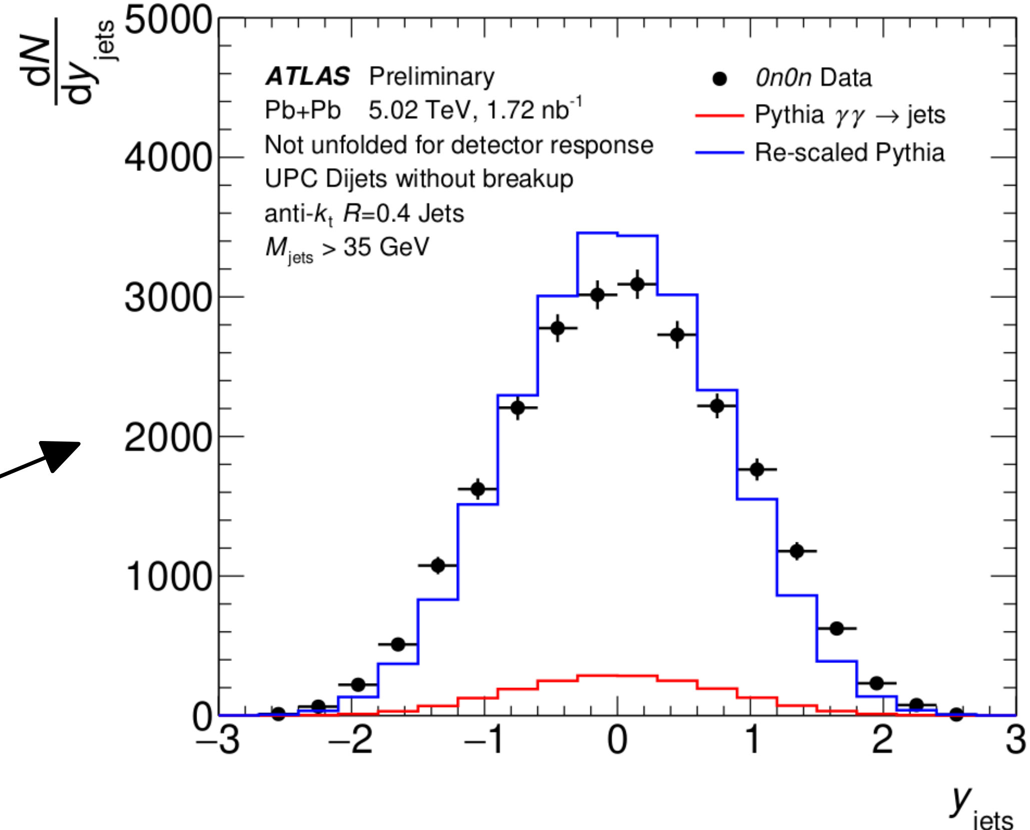


0n0n: Dijet production with no nuclear breakup

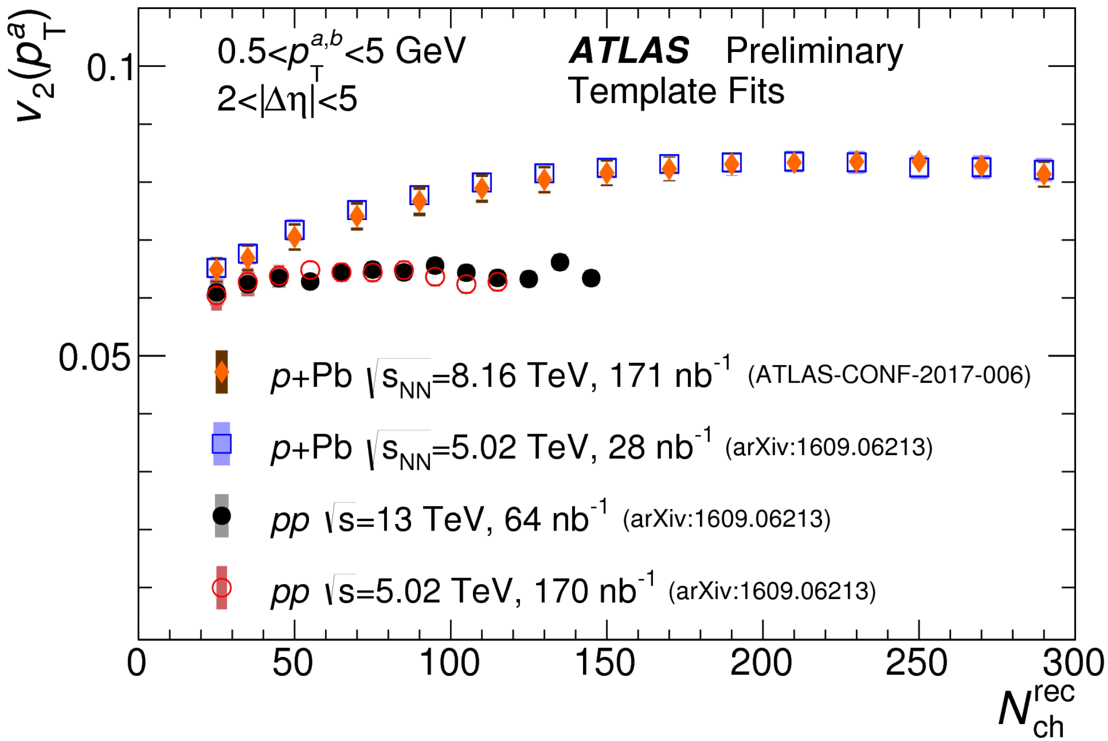
- As before but 0nXn ZDC requirement replaced by 0n0n = **no neutron at all** – characteristic for γγ scattering processes.
- Results compared with **PYTHIA.**
- Here, one example



- An order of magnitude smaller yield predicted by PYTHIA => indication that **γγ –> qq interaction is not dominant mechanism** for dijet production in events with no nuclear break up (=> diffractive processes?).

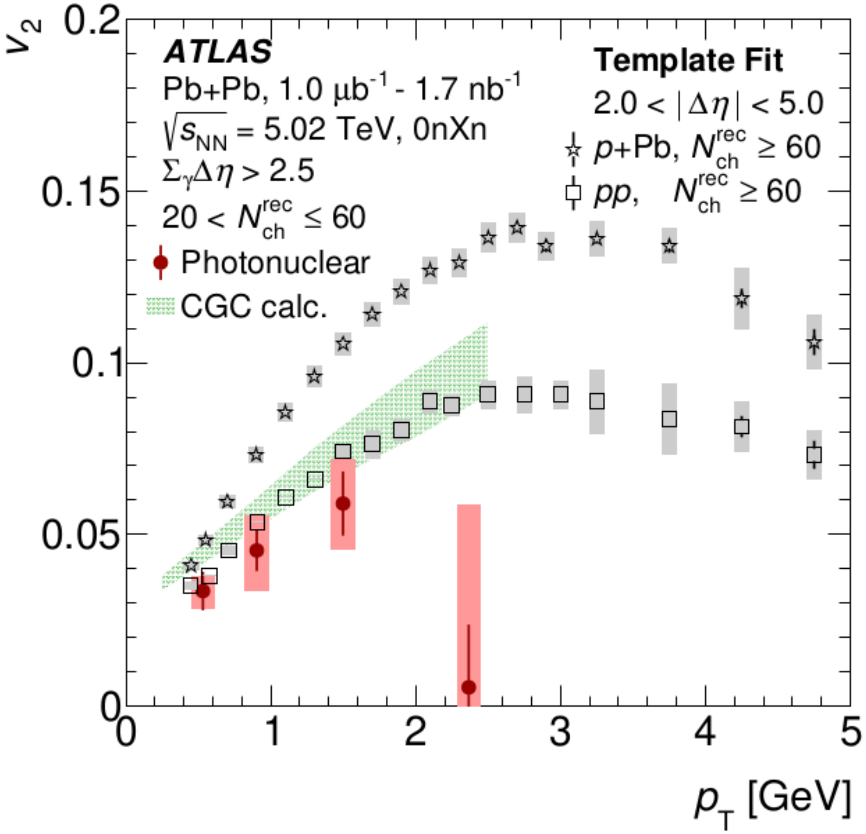
Collectivity in pp and p+Pb

- In high multiplicity p+Pb and p+p collisions, long **range two particle correlations** measured.
  - They can be quantified by Fourier expansion in azimuth => v_n – **Fourier coefficients**.
  - They can be understood as resulting from **collective behavior** of nuclear matter.



- Can we see such correlations in γ+Pb events?

Collectivity in UPC events: v_2, v_3



- **Significant v_2** observed, systematically smaller than in pp and p+Pb.
- **Theory** predicted v_2 based on **hadronic fluctuation** in γ interacting with Pb.
- **Non-zero v_3** seen as well. No significant multiplicity dependence seen.

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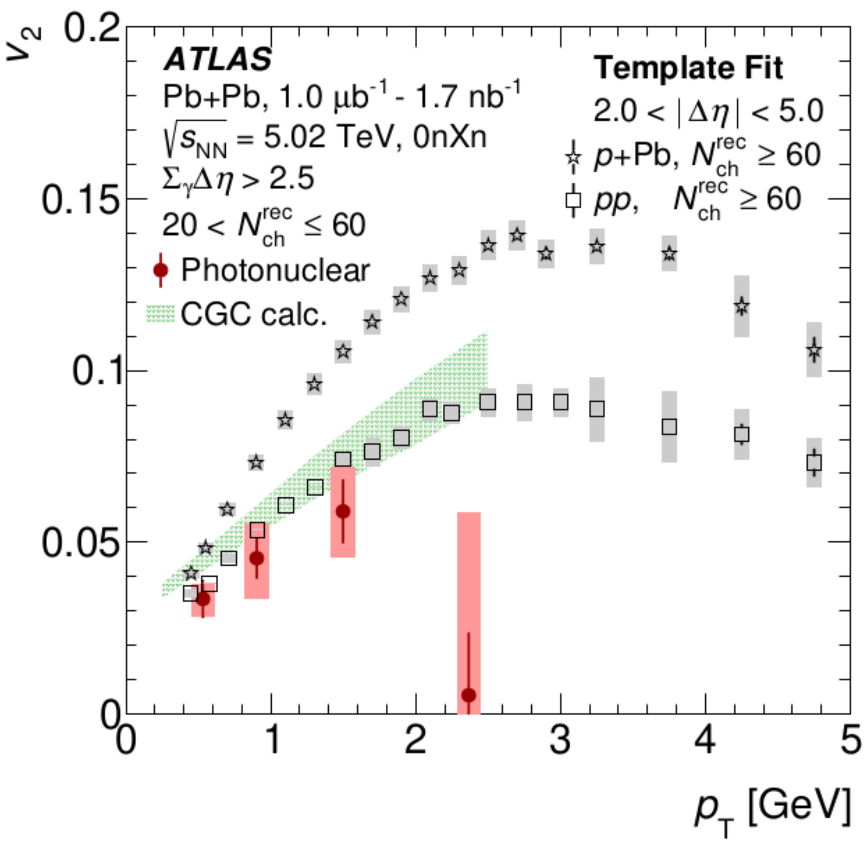

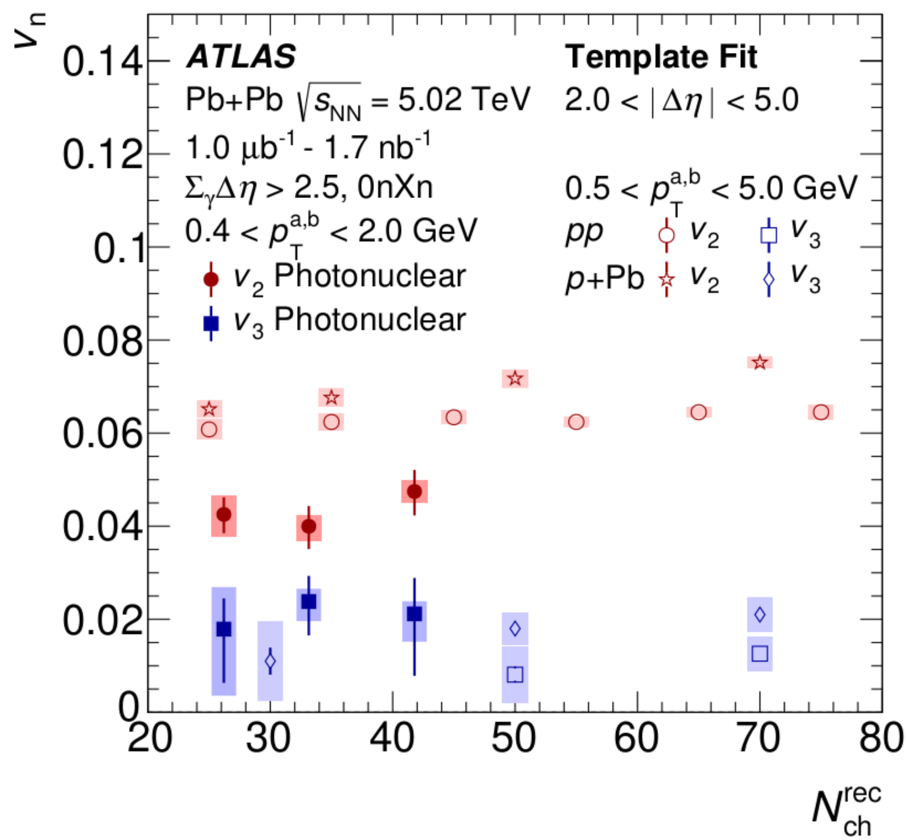

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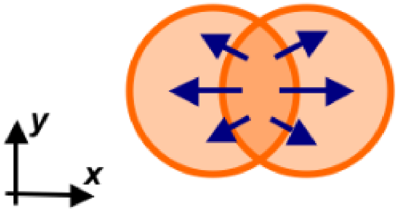
UPC Charged hadron yields

- Theory (3+1D hydrodynamics)* predicts that v_2(p+Pb) > v_2(γ+Pb) comes predominantly from the difference in the longitudinal structure of the collision, but the two system should have the **same radial flow** => should have the **same <p_T>**

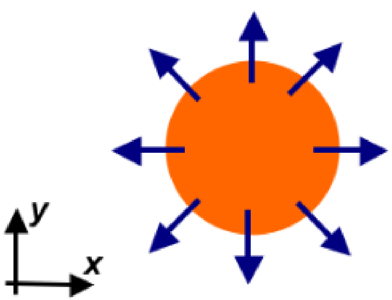
  => Measurement of charged hadron yield

- Charged hadron yields (p_T,η) measured and compared to **DPMJET-III** model and p+Pb data also to:
  - Constrain photon energy distribution
  - Constrain particle production modeling

Elliptic flow

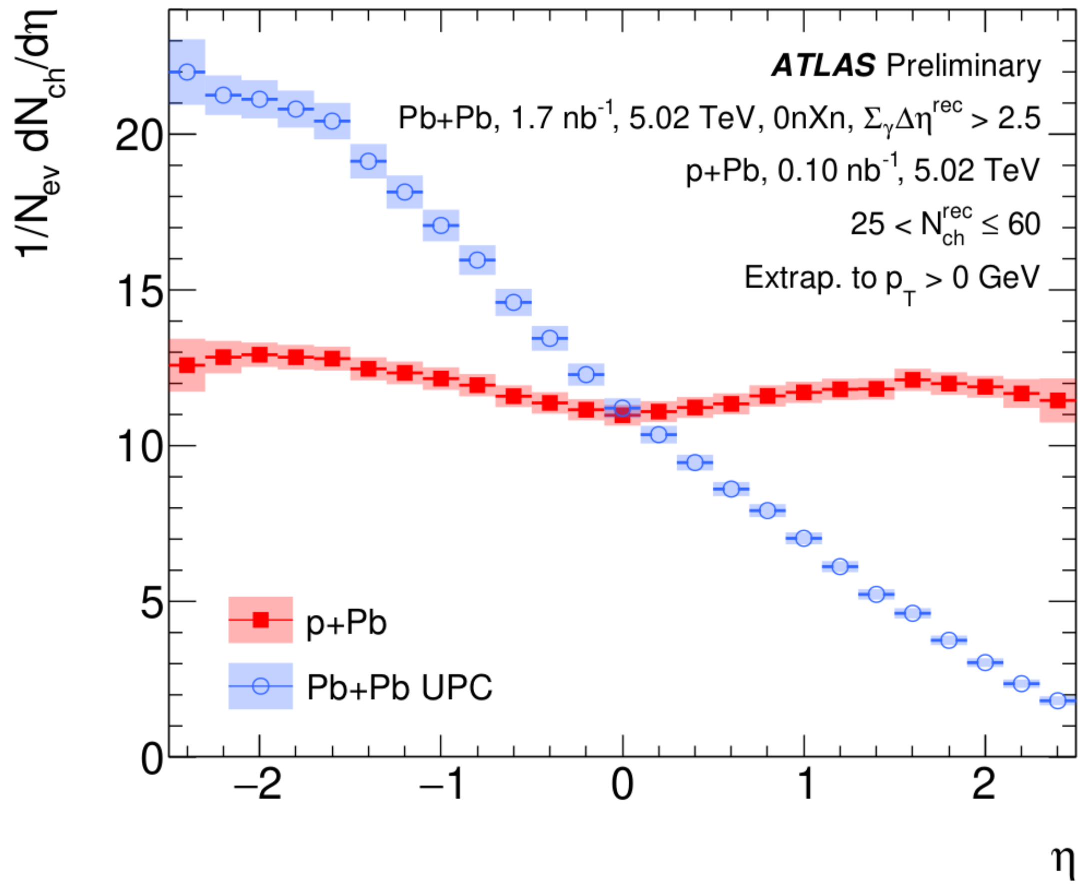


Radial flow



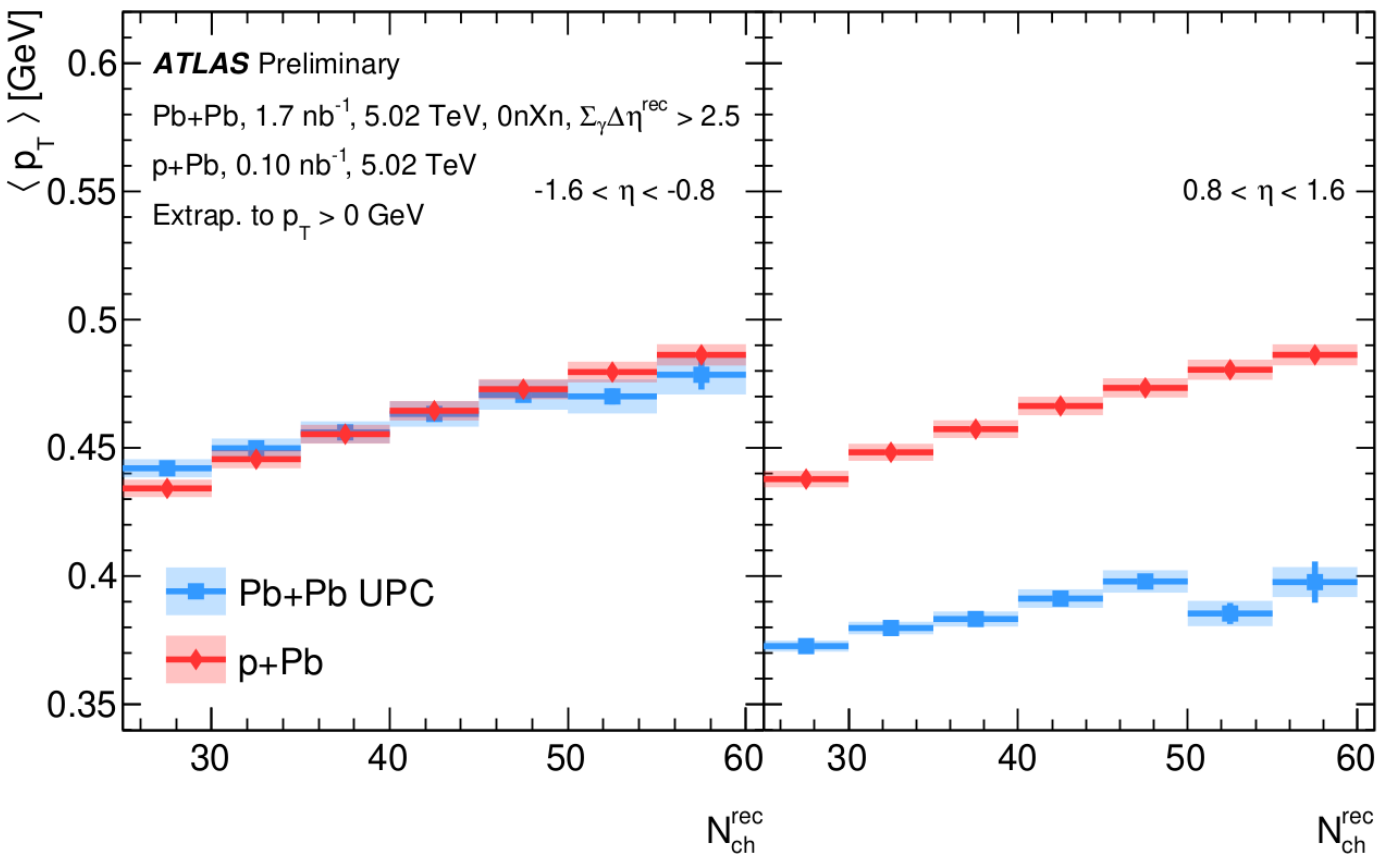
* PRL 129 (2022) 252302

UPC Charged hadron yields vs η



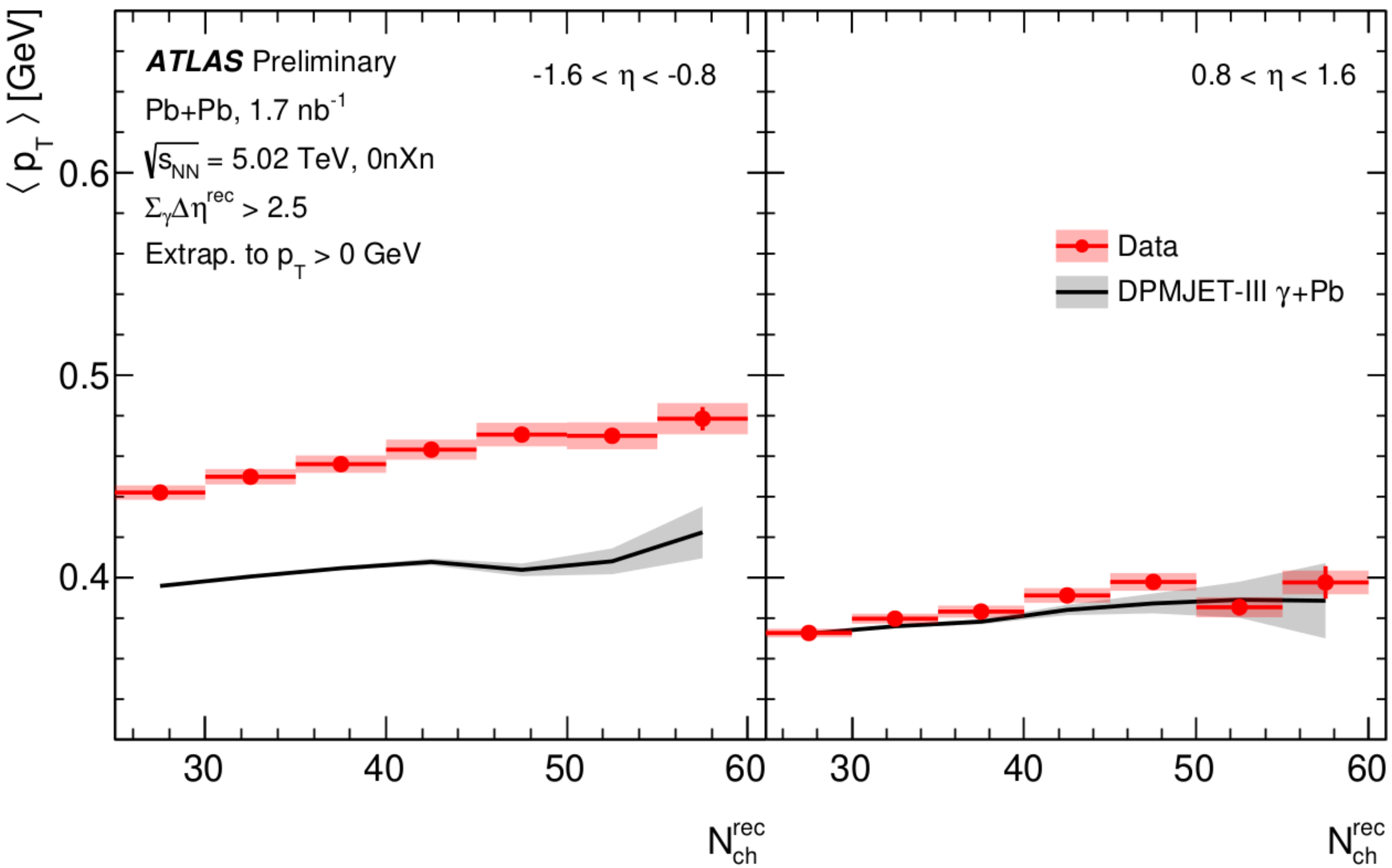
- Yields are **symmetric** in low multiplicity **p+Pb collisions** (low multiplicity events are pp-like)
- Yields are highly **asymmetric** in **γ+Pb events** ($E_{\gamma} < E_{Pb}$)

UPC Charged hadron <p_T> vs N_{ch}



- In lead-going side <p_T> **comparable** between p+Pb and γ+Pb.
- In photon-going side <p_T> **much lower** in γ+Pb – may be connected with the radial flow.

UPC Charged hadron <p_T> vs N_{ch}



- **Data in γ+Pb** compared to DPMJET-III which **under-predicts lead-going** rapidity region but describes well the photon-going region.

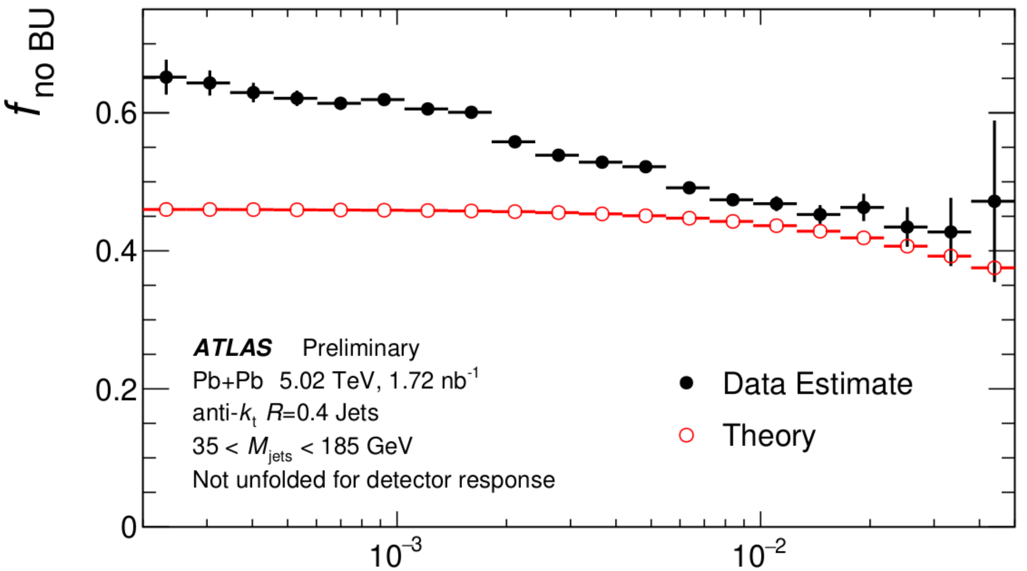
Summary

- Three measurements with UPC events from 5.02 TeV Pb+Pb collisions presented.
- Photonuclear dijet production (ATLAS-CONF-2022-021):
  - Studies nPDF in unexplored kinematic region.
  - Constrains photon flux modeling.
  - Shows a need for better understanding the nuclear breakup process as well as dijet production in events with no nuclear breakup.
- Collectivity in UPC events (PRC 104 (2021) 014903):
  - Significant v_2 and non-zero v_3.
- Charged hadron yields in UPC events (ATLAS-CONF-2023-059):
  - Measured to better understand the collectivity in UPC.
  - To constrain E_γ distributions and particle production modeling.

This work was supported by ERC-CZ grant LL2316

Backup slides

Emitting nucleus break up



$$f_{\text{no BU}} \equiv \frac{d\sigma/dz_\gamma|_{0nXn}}{d\sigma/dz_\gamma|_{XnXn} + d\sigma/dz_\gamma|_{0nXn}}$$

Theory: P8 + user's photon flux function (attribute of incident beam, not of the full system)

$$f_{\gamma/A} = d^3N_\gamma/dE_\gamma d^2s$$

$$F_{\gamma/A}^{\text{PYTHIA}}(E_\gamma) \equiv \int_{R_A}^{\infty} d^2s\, f_{\gamma/A}(E_\gamma, s)$$

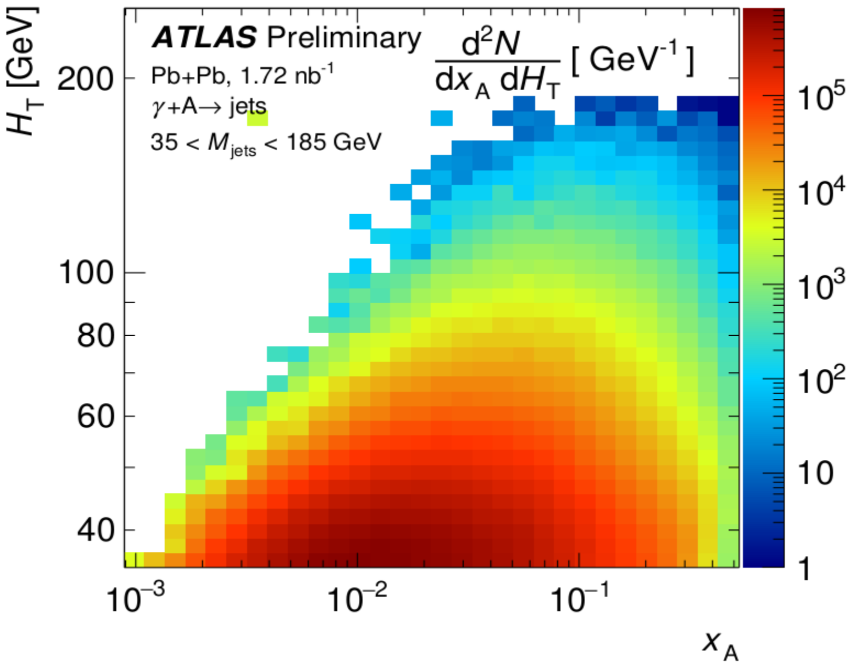
$$= \frac{2}{\pi}\frac{\alpha Z^2}{\beta_B^2}\frac{1}{E_\gamma}\left[u_R K_1(u_R)K_0(u_R) - \frac{u_R^2\beta_B^2}{2}\left(K_1^2(u_R) - K_0^2(u_R)\right)\right]$$

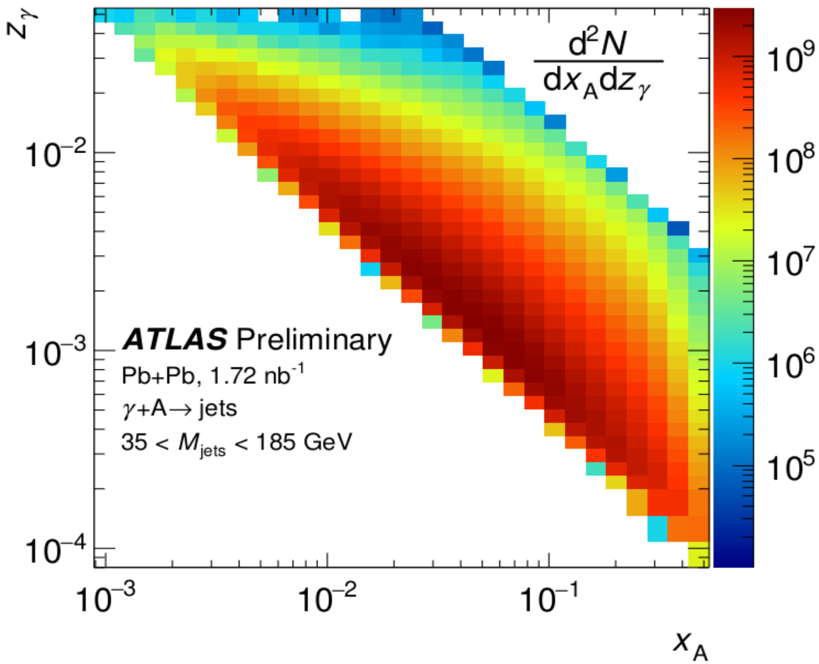
$$F_{\gamma/A}^{\text{eff}}(E_\gamma) \equiv \int d^2b\, d^2s_A P_{\text{no had}}(b) P_{\text{no EM}}(b) f_{\gamma/A}(E_\gamma, s) T_B(\vec{s}_A - \vec{b})$$

No breakup probabilities from STARLIGHT

$$H_\mathrm{T} \equiv \sum_i p_{\mathrm{T}\,i}$$

Observables





- z_γ and x_A highly correlated
- H_T not correlated with x_A or z_γ
- Final observable: triple differential cross-section corrected to particle level:

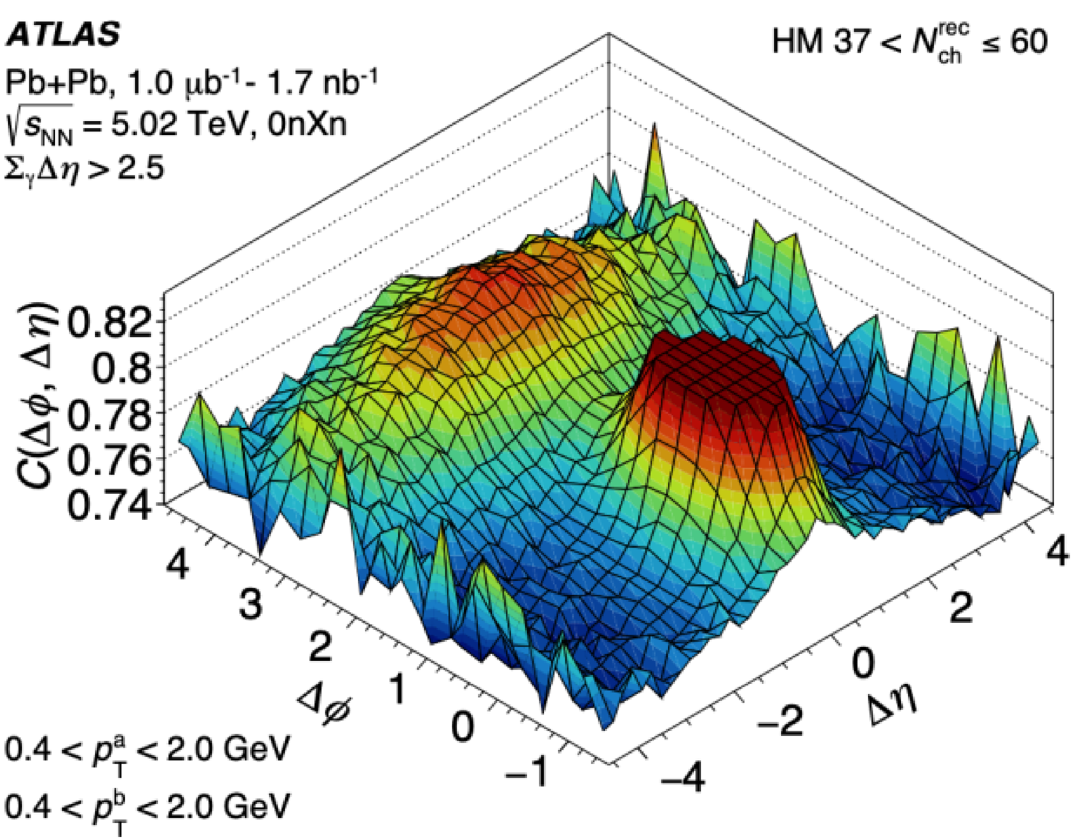
$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}H_\mathrm{T}\mathrm{d}x_\mathrm{A}\mathrm{d}z_\gamma} \equiv \frac{\Delta\sigma^\mathrm{unf}}{\Delta H_\mathrm{T}\Delta x_\mathrm{A}\Delta z_\gamma}$$

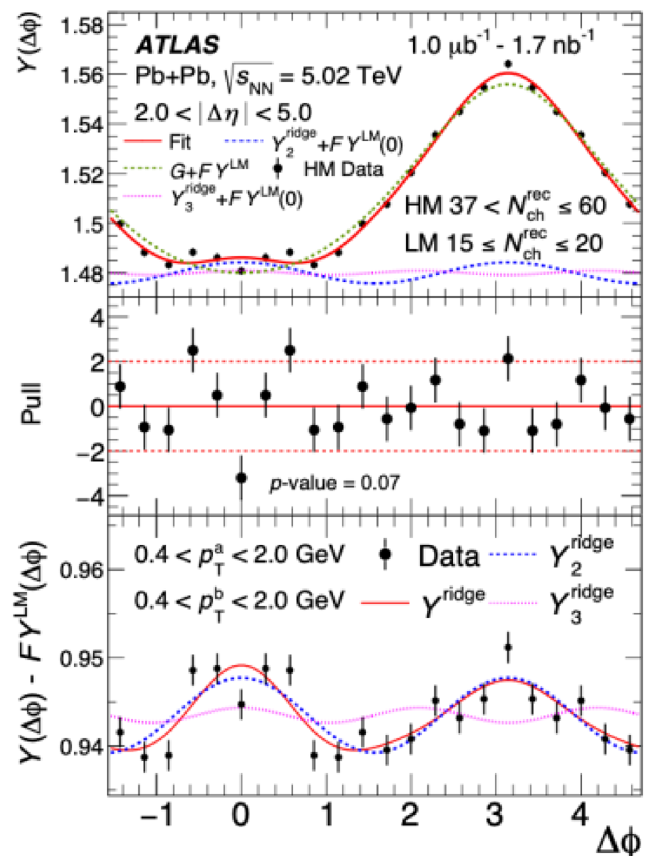
$$x_\mathrm{A} \equiv \frac{m_\mathrm{jets}}{\sqrt{s}} e^{-y_\mathrm{jets}}$$

$$z_\gamma \equiv \frac{m_\mathrm{jets}}{\sqrt{s}} e^{+y_\mathrm{jets}}$$

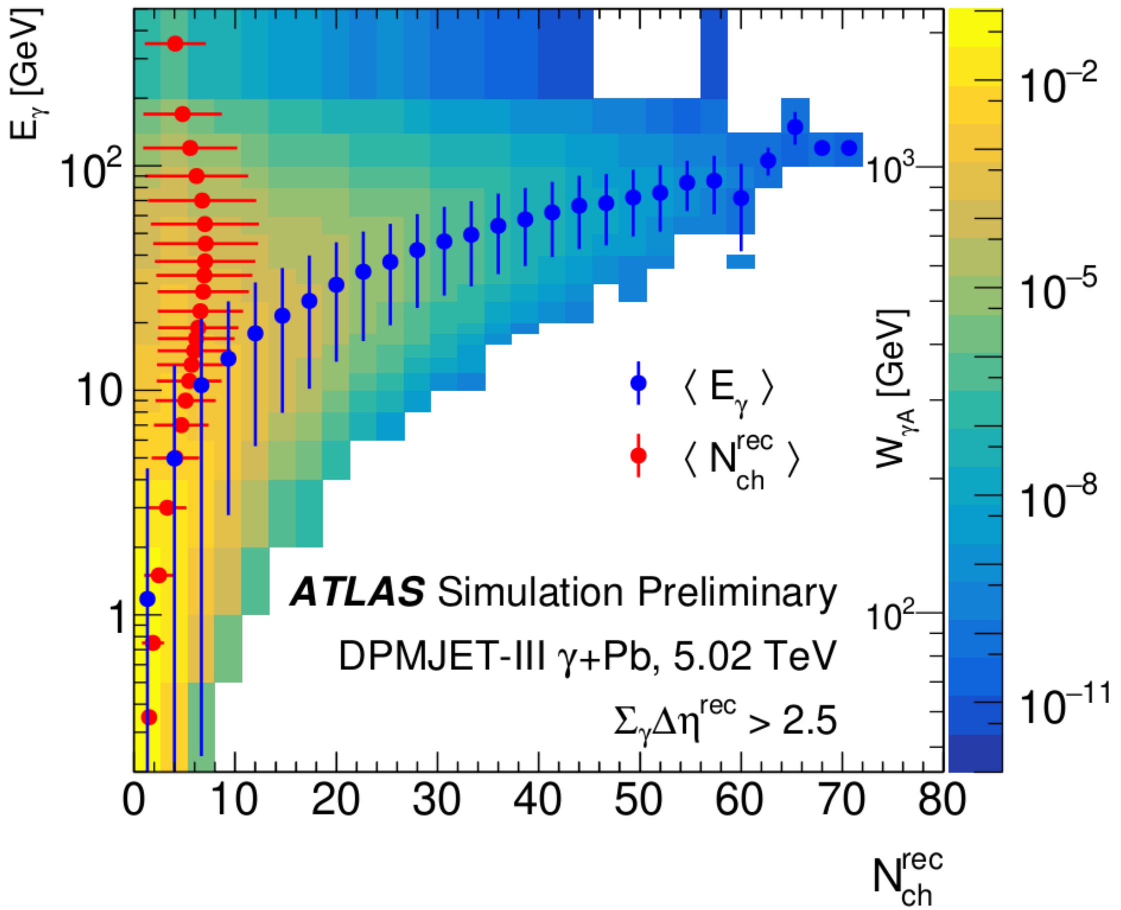
Collectivity in UPC events

- γ+Pb collisions, two particle correlations studied as a function of Δη and ΔΦ as in other systems.
- Template method used to extract flow coefficients, non-flow contribution subtracted using information from low multiplicity events.





E_γ in DPMJET-III



- Clear **correlation** between photon energy and charged particle yields.
- Measurement should improve understanding the **E_γ distribution**.