Measurements of long-range azimuthal anisotropy in photonuclear collisions with ATLAS

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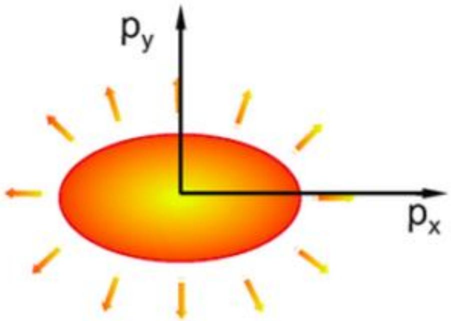
EPS-HEP, July 29th 2021

Origin of azimuthal anisotropy

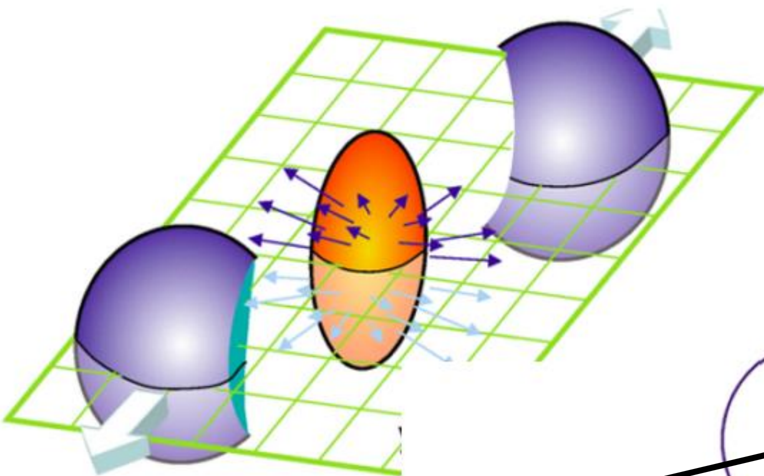
It has been largely established that hydrodynamic properties of the QGP governs many of the emergent phenomenon in heavy ions

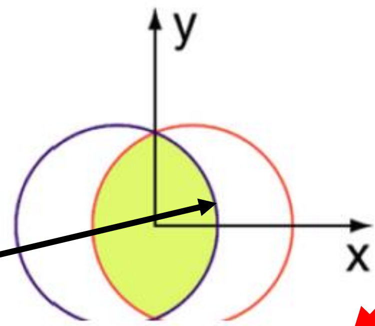
Initial spatial anisotropy → hydro → final momentum anisotropy



final-state momentum anisotropies

Hydrodynamic expansion



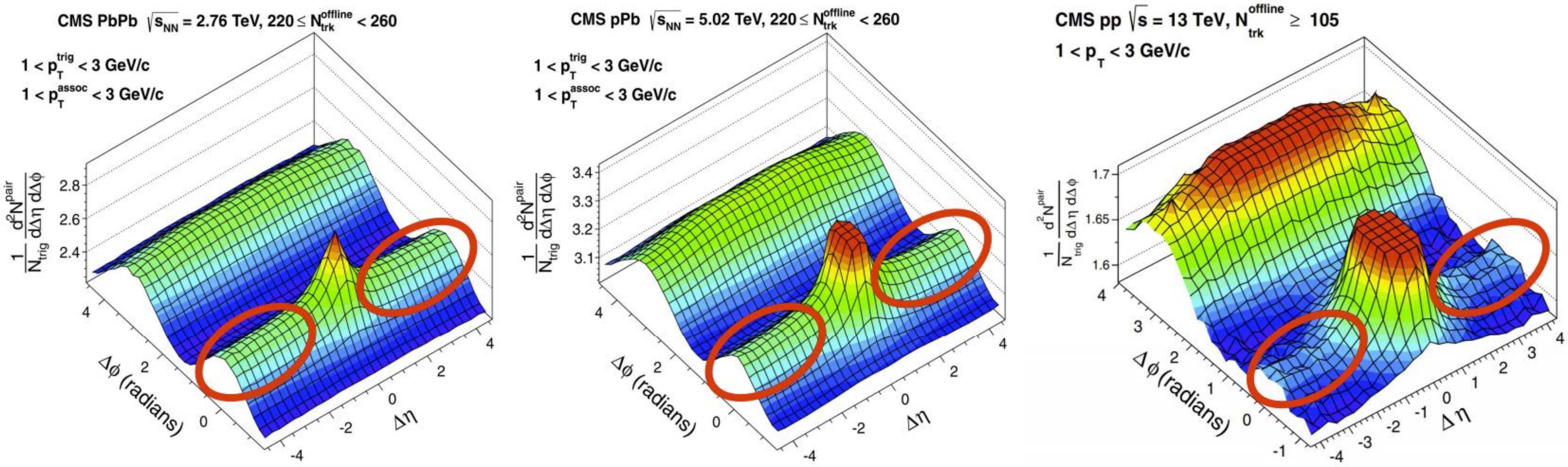


Average heavy ion collision has elliptic initial energy deposition

initial state geometry

Azimuthal anisotropy

Long-range (in η) azimuthal anisotropy leads to the "**ridge**" in the 2-particle correlation



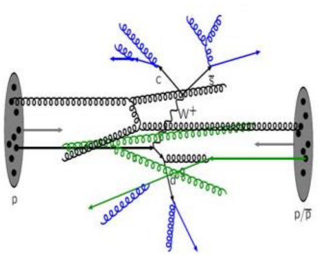
Clear collectivity signatures in many system sizes

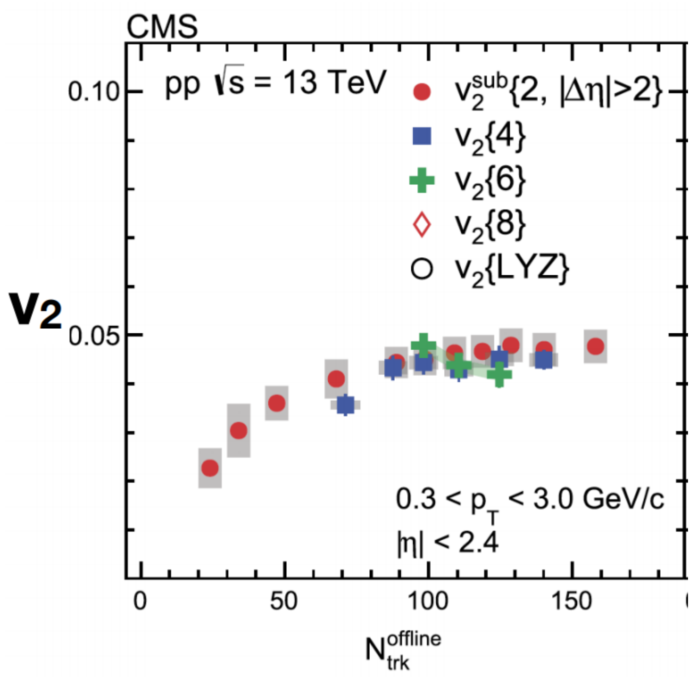
- Nearside ridge present in 2-particle correlation
- Precise measurements of v_n
- Multi-particle correlations → global correlation

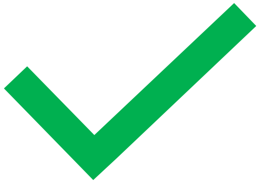
arXiv:1305.0609 arXiv:1510.03068

Which small systems do we know flow?

pp







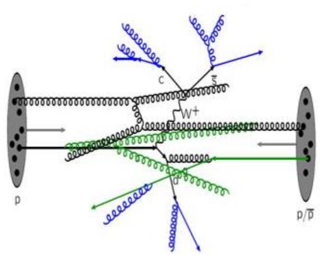
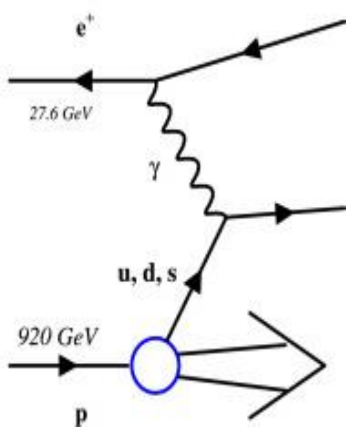
Collectivity in ***pp***

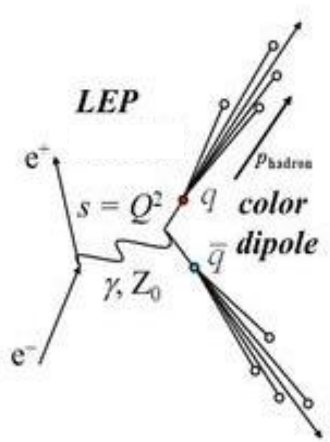
- Near-side ridge
- Multi-particle correlation
- Initial state geometry?

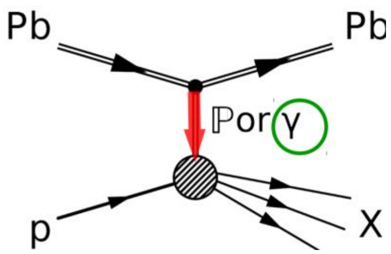
arXiv:1606.06198

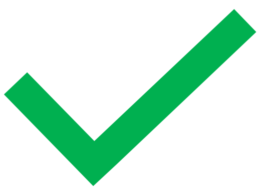
Which small systems do we know flow?

pp	e+*p*	$e^+ + e^-$	γ+*p*







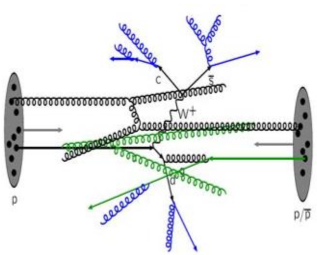
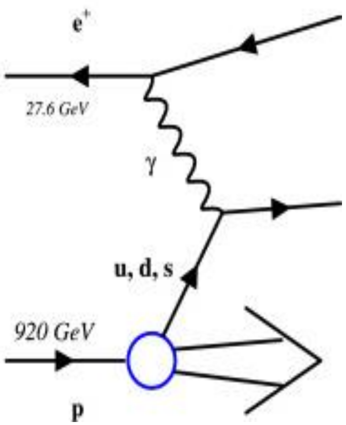
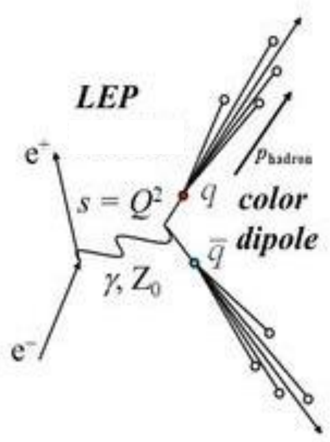
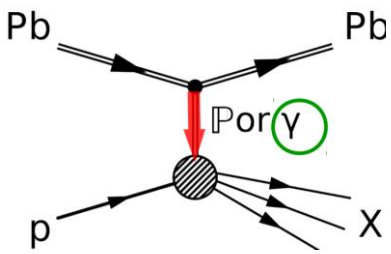
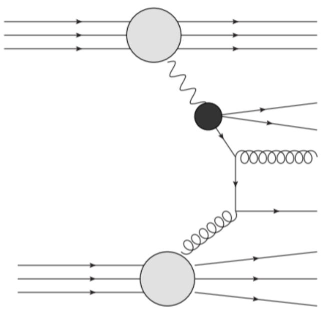
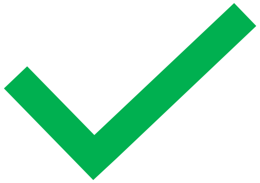

Near-side ridge

Cumulants say v_2< 4%
arXiv:2106.12377

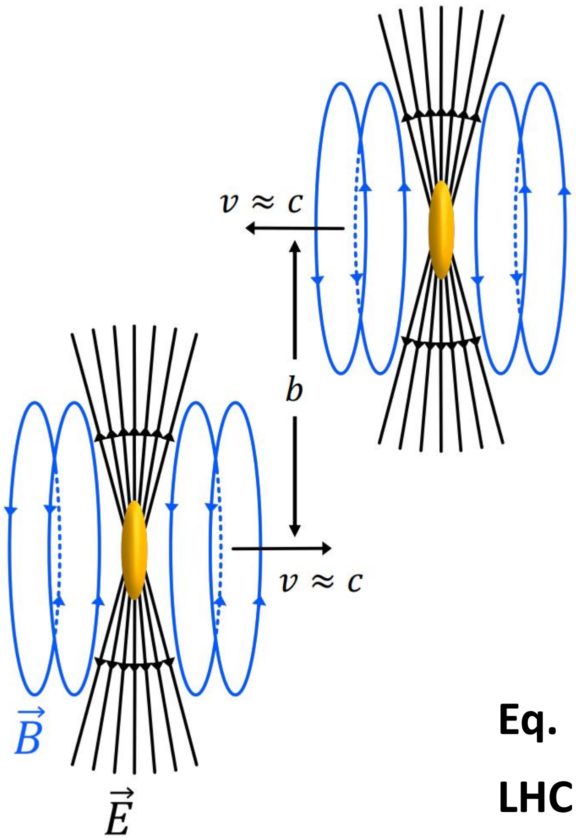
No near-side ridge
arXiv:1906.00489

No near-side ridge
CMS-PAS-HIN-18-008

Which small systems do we know flow?

pp	e+*p*	e^++e^-	γ+*p*	γ+A
				
				
Near-side ridge	Cumulants say v_2< 4%	No near-side ridge	No near-side ridge	
	arXiv:2106.12377	arXiv:1906.00489	CMS-PAS-HIN-18-008	

Photons in heavy ion collisions



Lorentz contracted electromagnetic fields of moving charges can be treated as a flux of photons.

Equivalent photon approximation (EPA)

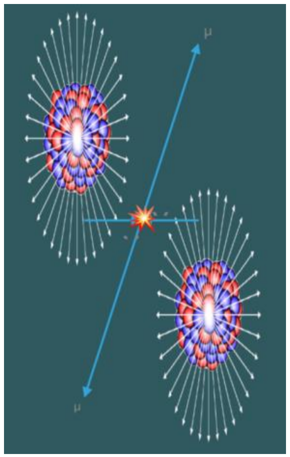
- EM field are a flux of quasi-real photons
- Developed by Fermi, Weizäcker, and Williams
- Implemented in STARLIGHT
- Differences with QED calculations

	E_γ proj. frame	E_γ lab frame	$W_{\gamma N}$
Eq.	$1/(2*1.2\ A^{1/3}\ \text{fm})$	$\gamma/(1.2\ A^{1/3}\ \text{fm})$	$\sqrt{(4E_\gamma E_N)}$
LHC	30 MeV	160 GeV	1.7 TeV
RHIC	30 MeV	6 GeV	50 GeV

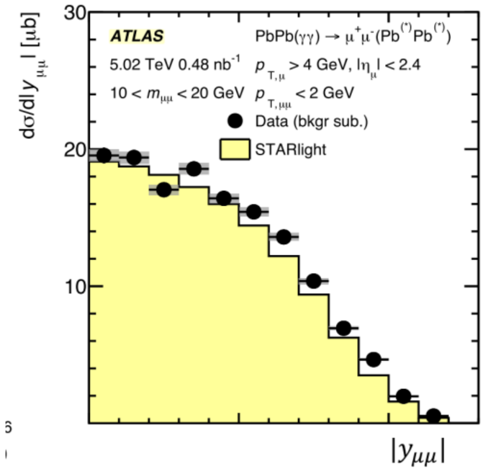
Brandenburg, GHP 2021 - good up-to-date review as well: arXiv:2103.16623

Ultra-peripheral collisions at the LHC

Steinberg, Initial Stages 2019



arXiv:2011.12211



Pure EM interactions

- For example, $\gamma\gamma \rightarrow l^+l^-$
- Precision tests of EPA and QED calculations of photon flux
- Active area of research
  - b dependence of photon p_T
  - Photon polarization arXiv:2103.16623

Vector meson quantum fluctuation $\gg$ collision time

$$\Delta t \approx \frac{\hbar}{M_V c^2} \gg \Delta t \simeq b/(\gamma v)$$

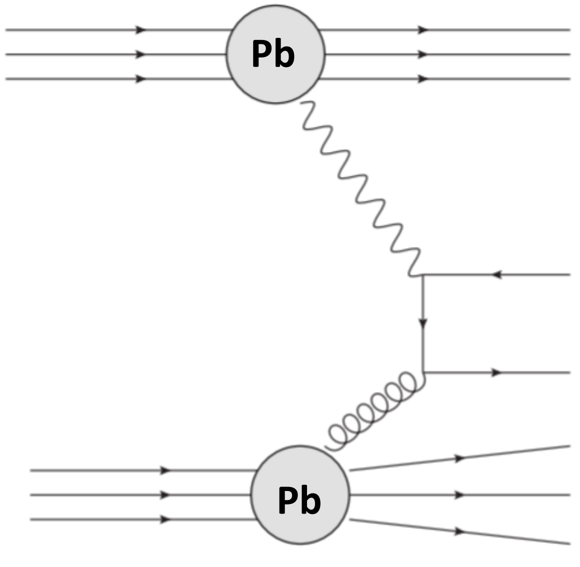
Photo-nucleus interactions

- Bare photon + vector meson wave function
- QCD diffractive vector meson production $\gamma + A \rightarrow A^* + V$
- Non-diffractive $\gamma + A \rightarrow X$

Photonuclear interactions

Direct γA collisions

Photon couples directly to nuclear parton



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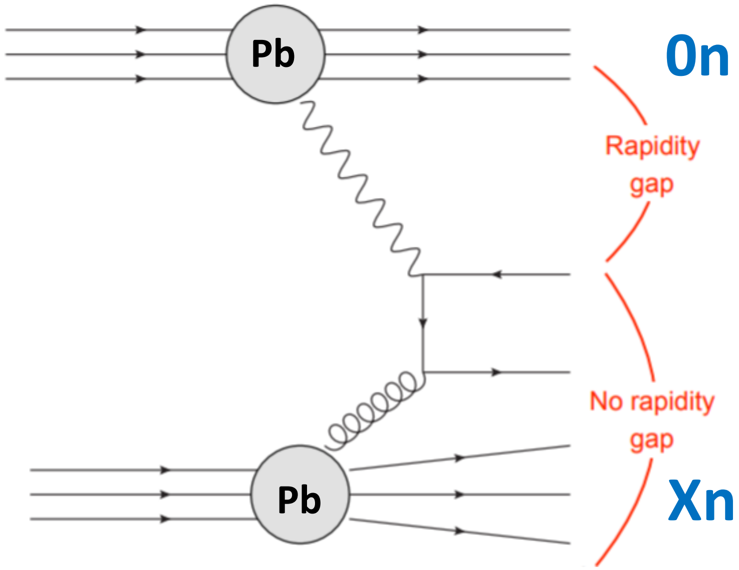

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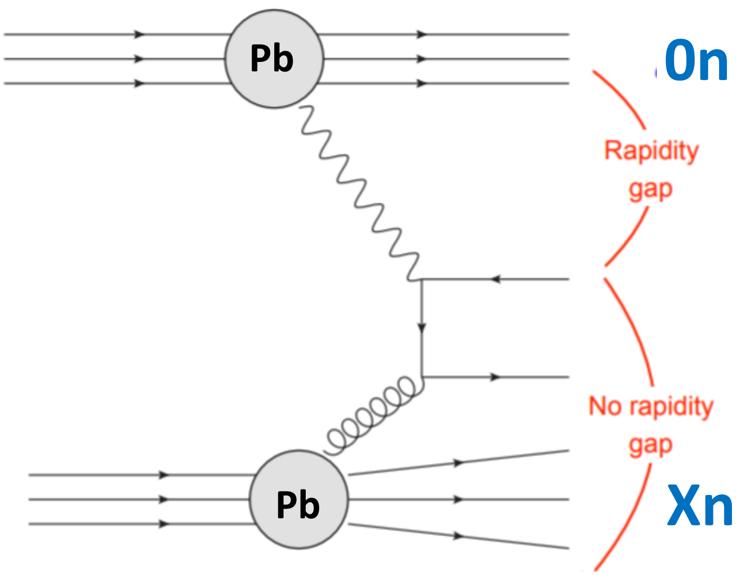
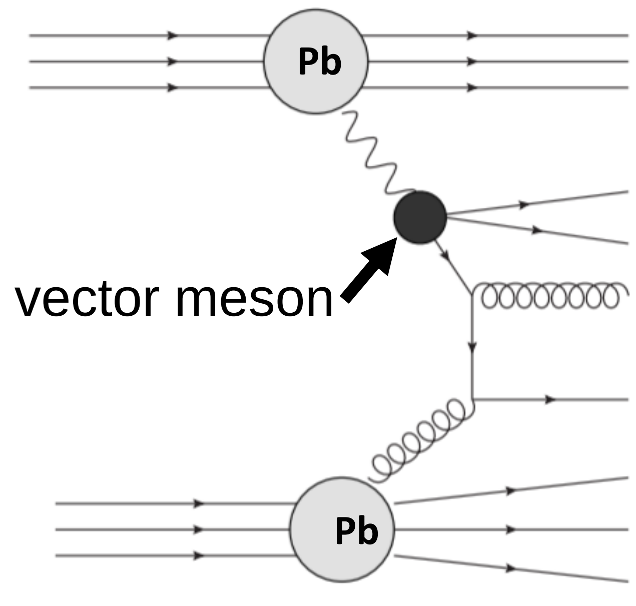


Resolved γA collisions

photon virtually resolved into <u>hadronic state</u>



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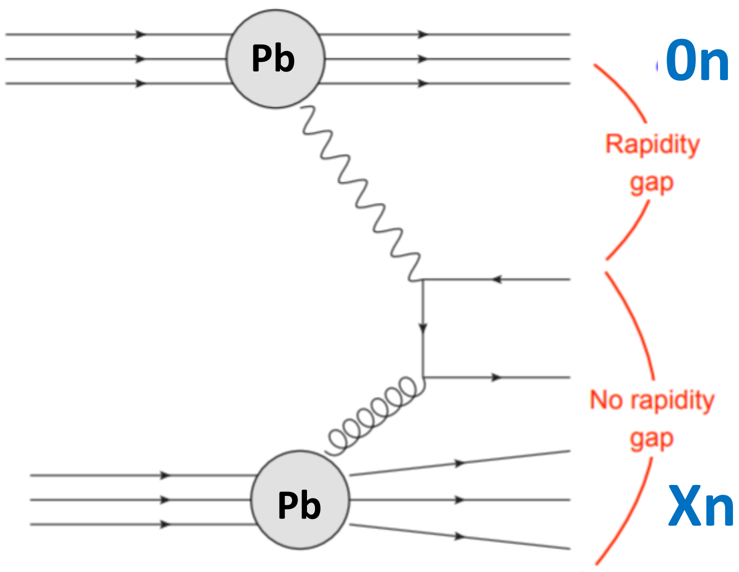
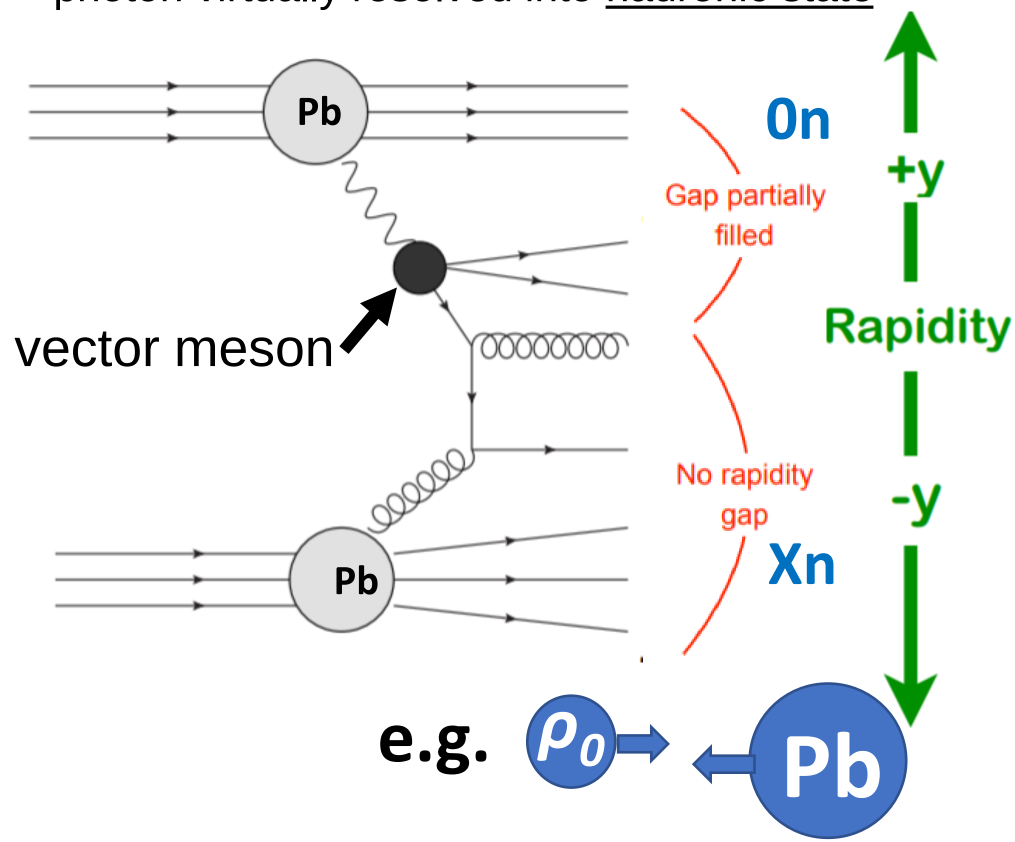




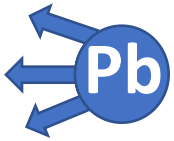
Select events based on primarily

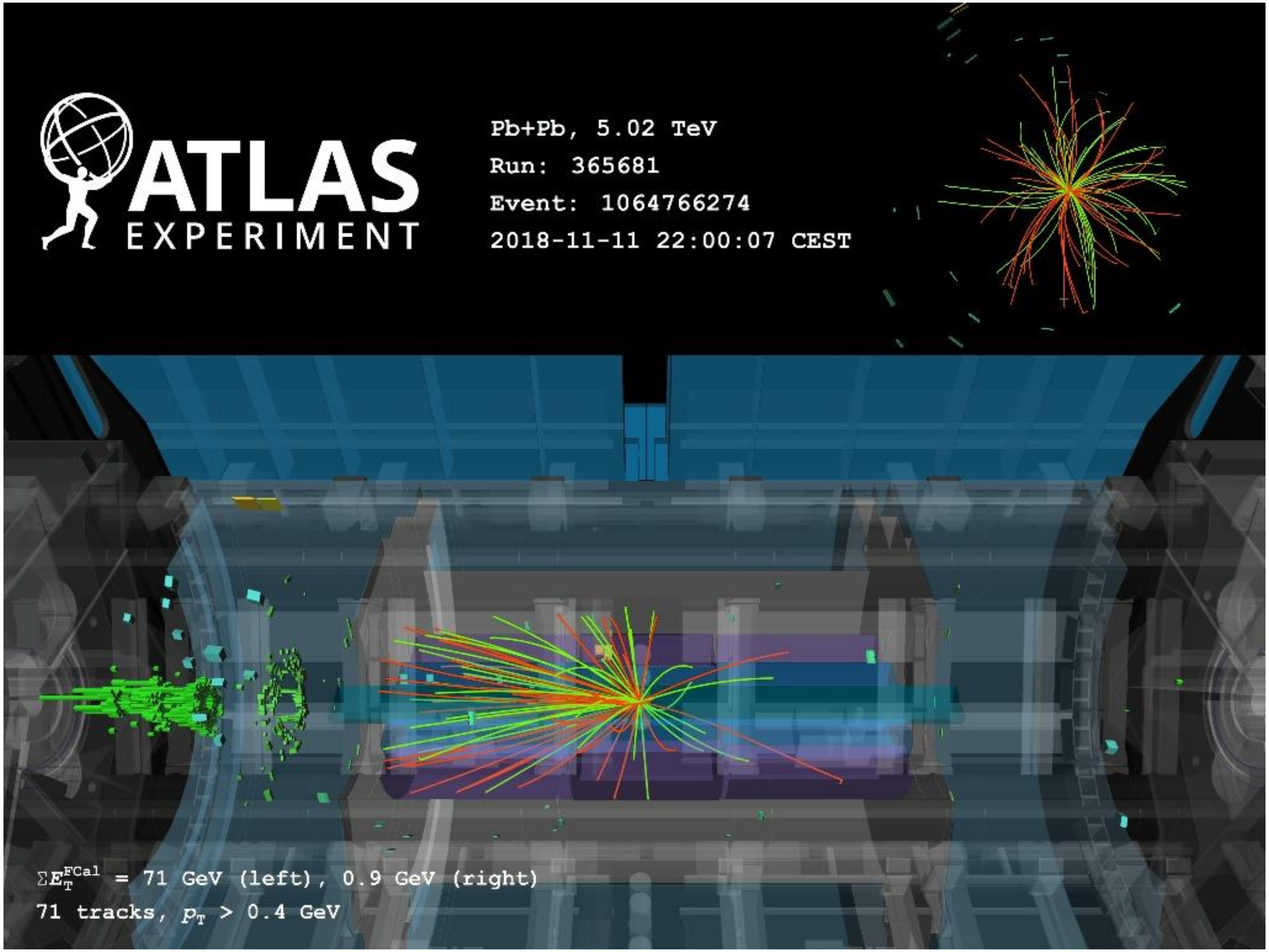
- Single-sided nuclear breakup “**0nXn**” (zero-degree calorimeter ZDC)
- Rapidity gaps

Minimum bias selection includes both but is dominated by resolved events.

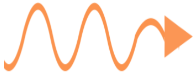
"High"-multiplicity photonuclear collisions

Pb going direction





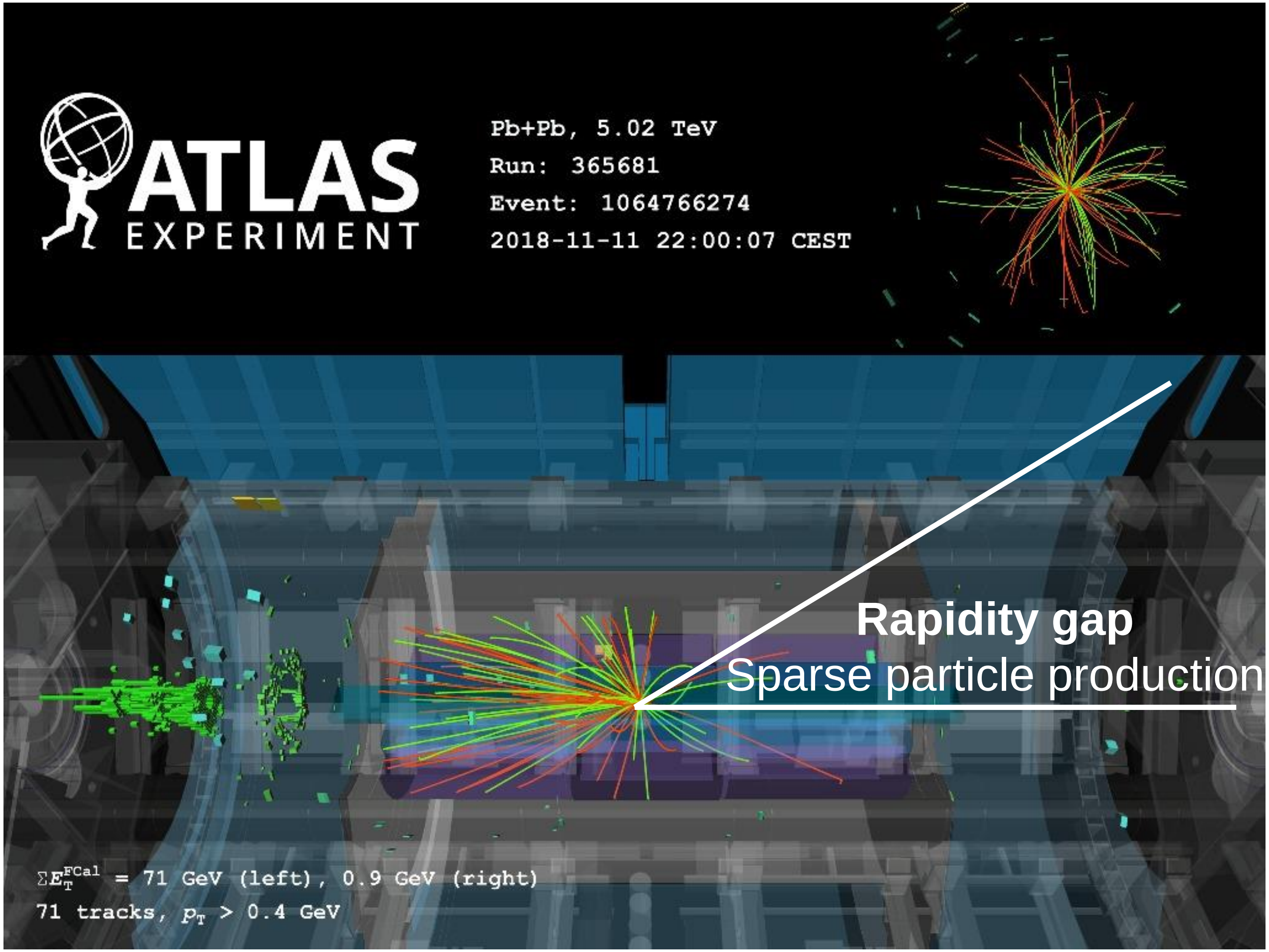
photon going direction



"High"-multiplicity photonuclear collisions

Pb going direction

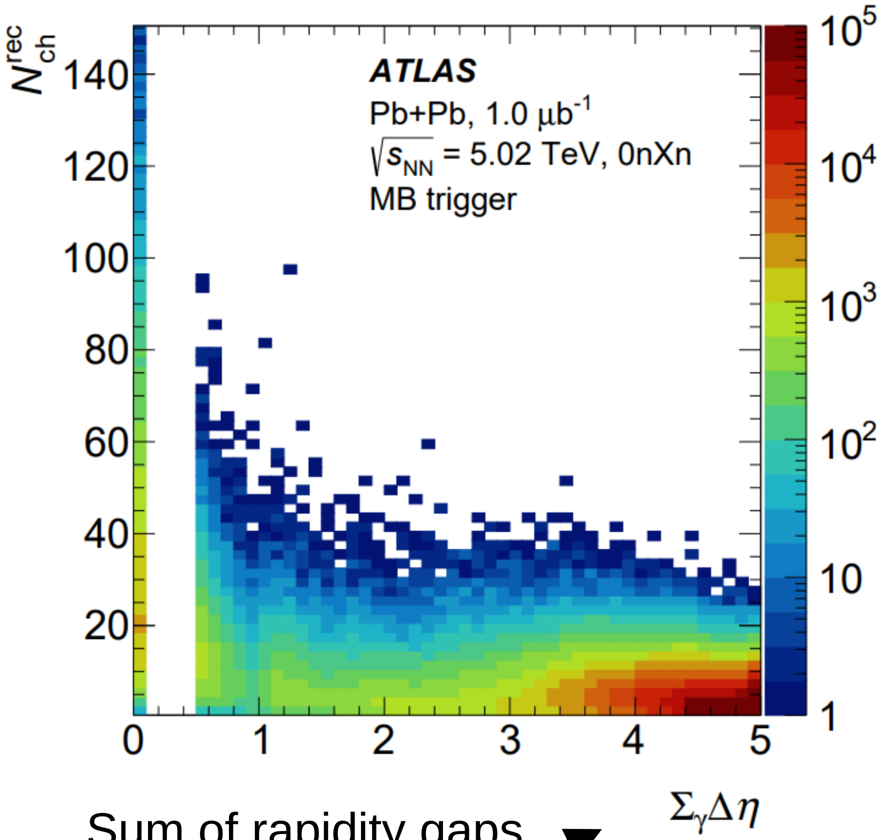
Xn



photon going direction

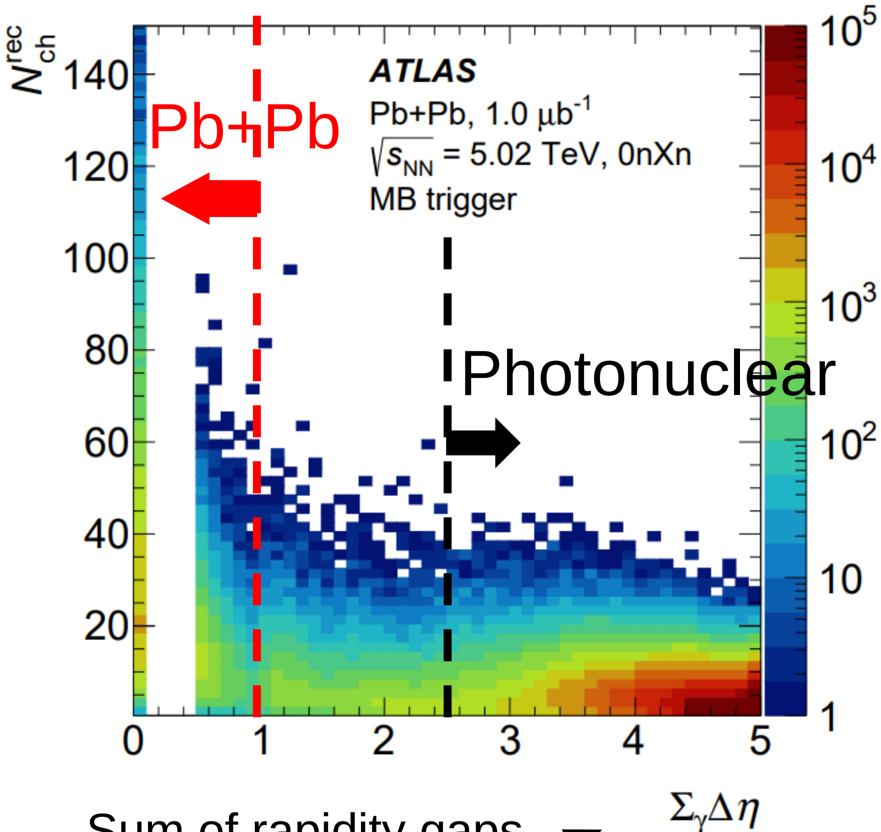
0n

Photonuclear rapidity gaps $\Sigma_\gamma \Delta\eta$ and N_{ch}



Sum of rapidity gaps between particles greater than 0.5

Photonuclear rapidity gaps $\Sigma_{\gamma}\Delta\eta$ and N_{ch}



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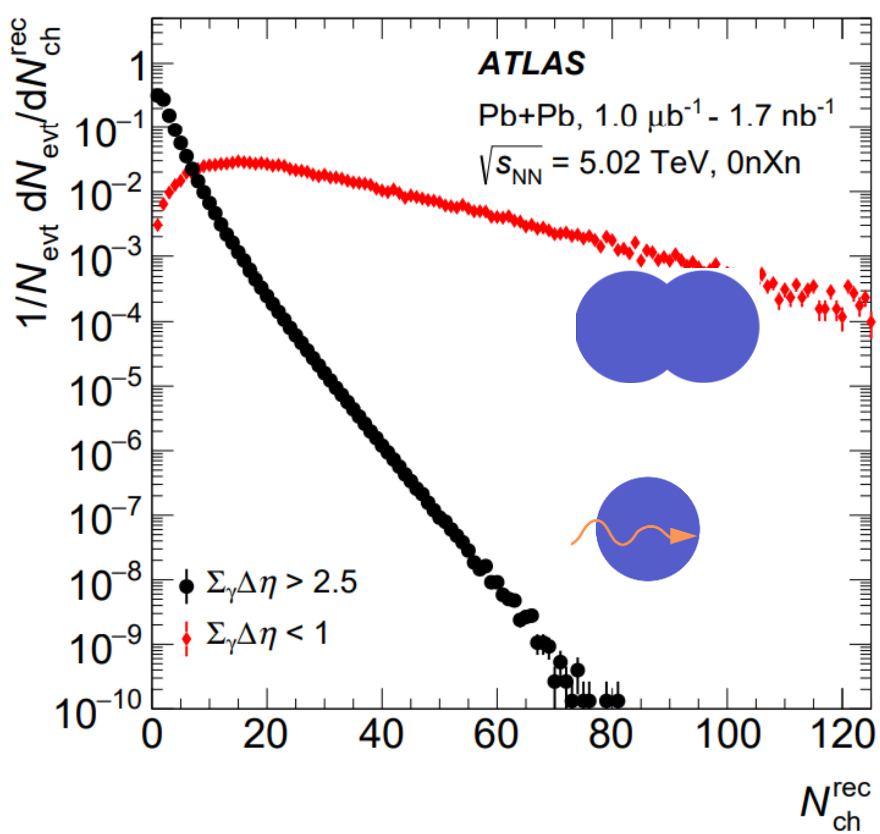


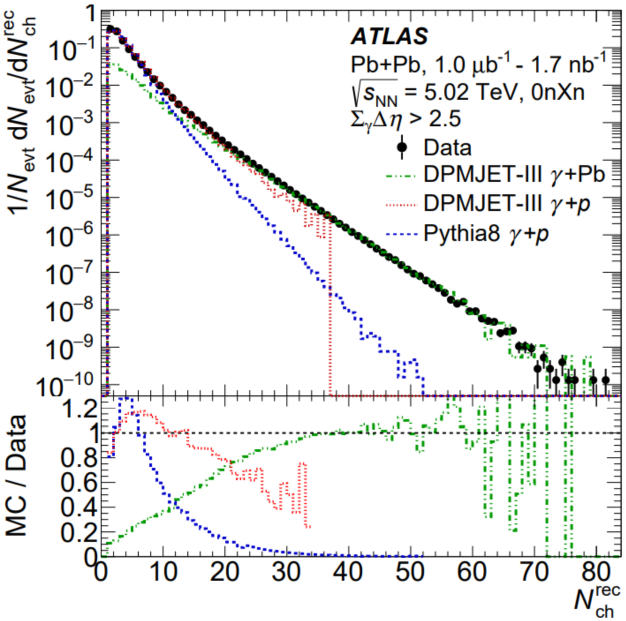
$|\eta|<2.5$, $p_T>400$ MeV

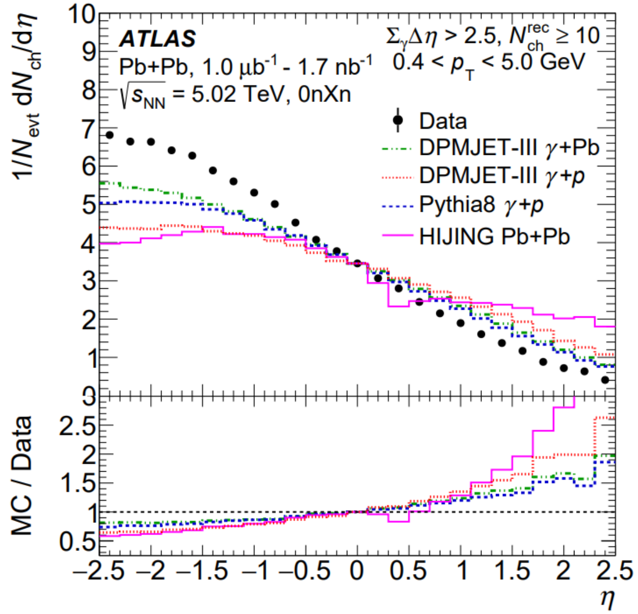
Photonuclear events have large rapidity gaps in the photon-going direction and a steeply falling multiplicity distribution.

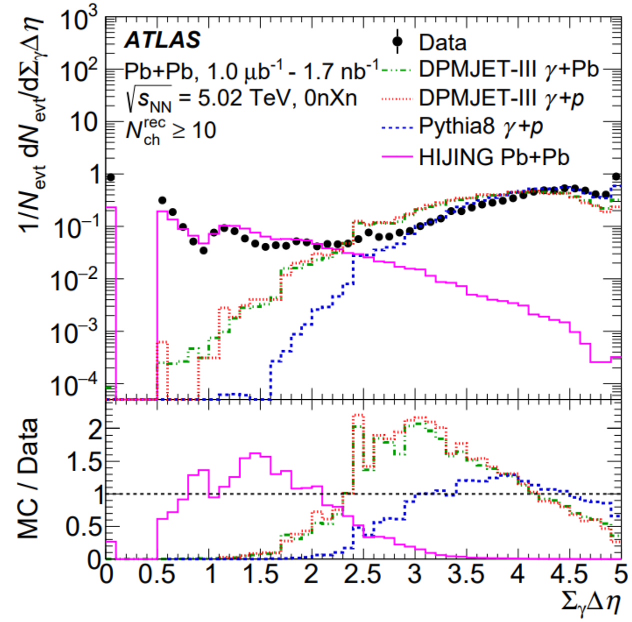
arXiv:2101.10771

Photonuclear event properties

Several data-MC comparisons included in our results





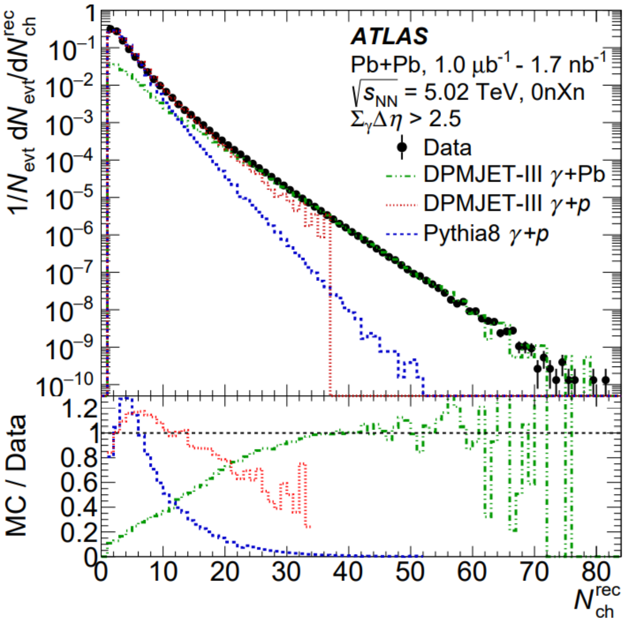


N_{ch} $dN_{ch}/d\eta$ $\Sigma_\gamma \Delta\eta$

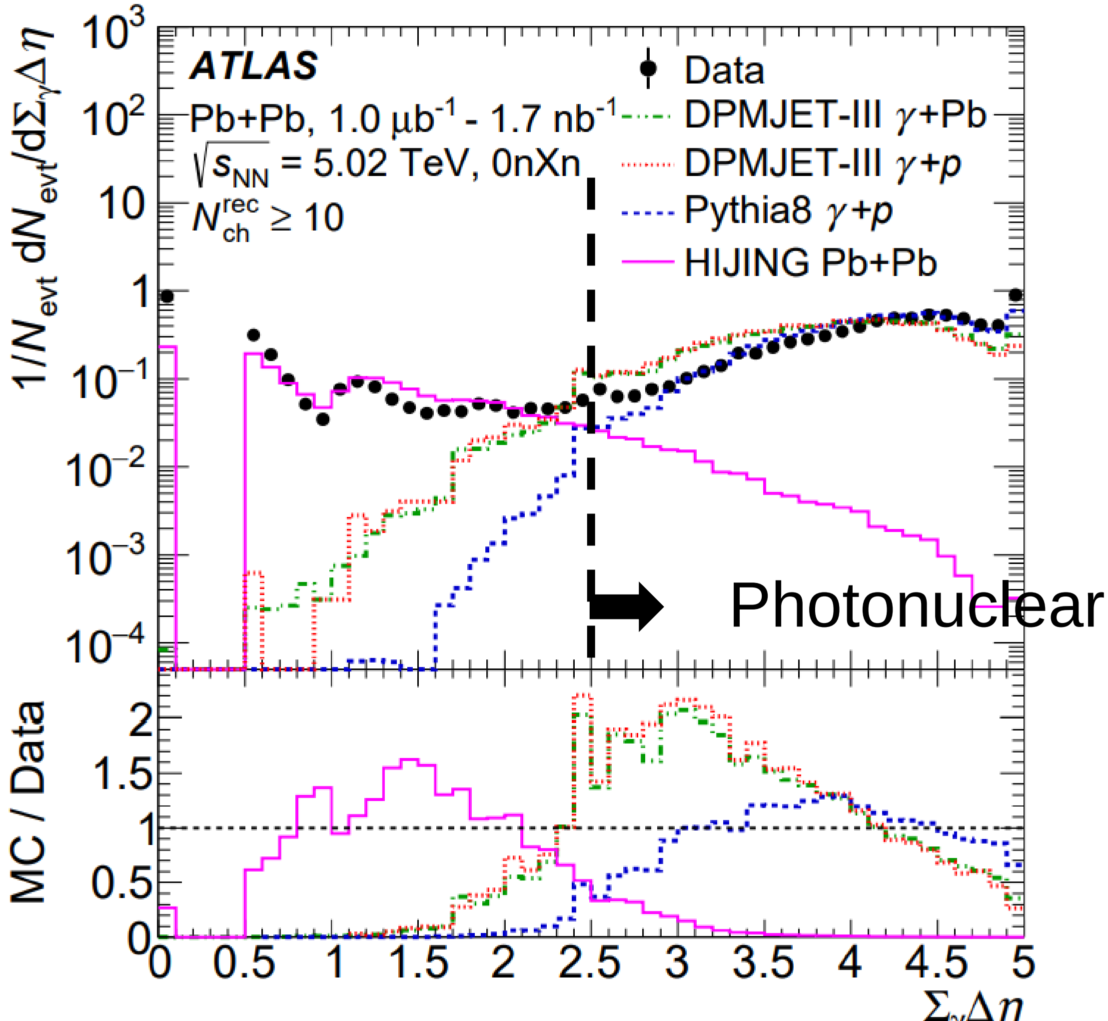
arXiv:2101.10771

Photonuclear event properties

Several data-MC com



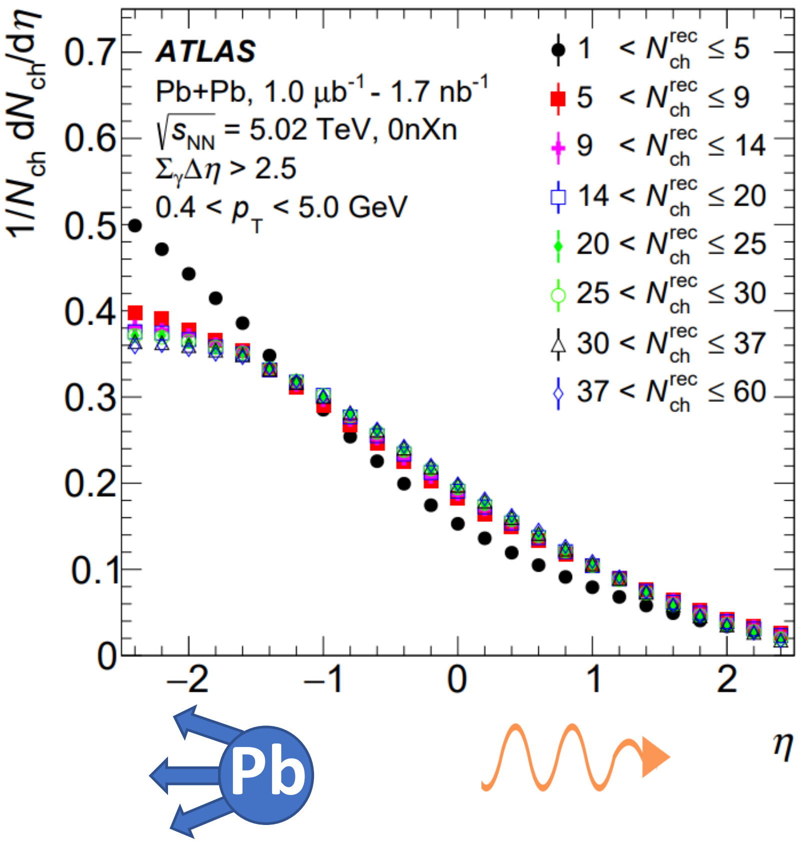
N_{ch}

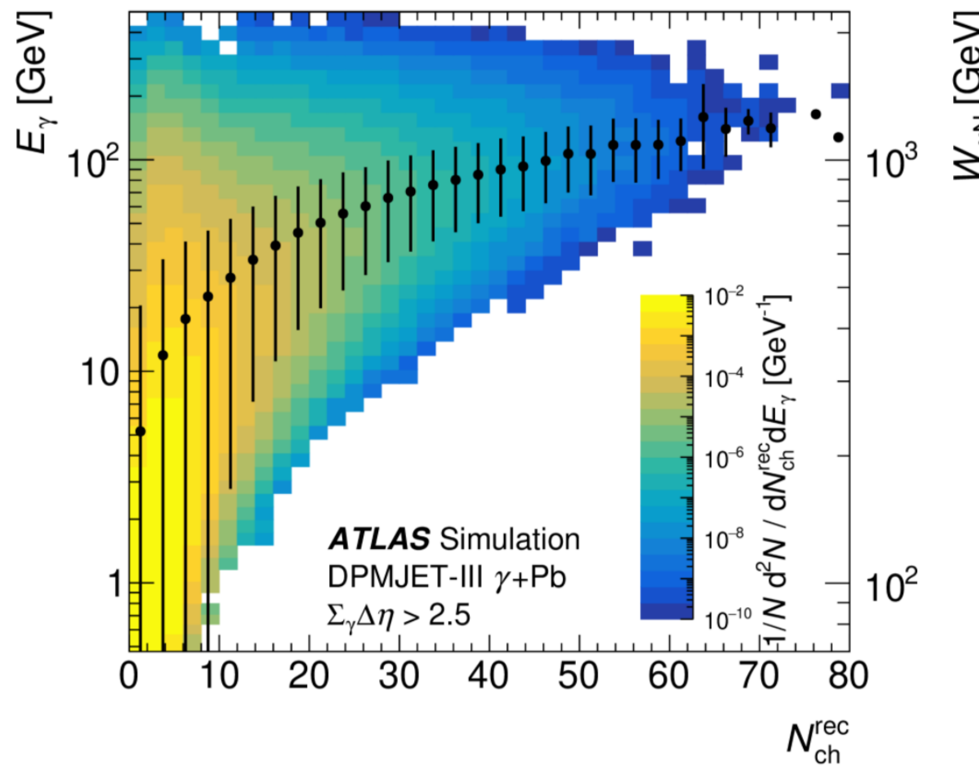


> 97% purity across N_{ch} range of analysis

arXiv:2101.10771

dN_{ch}/dη in γA collisions





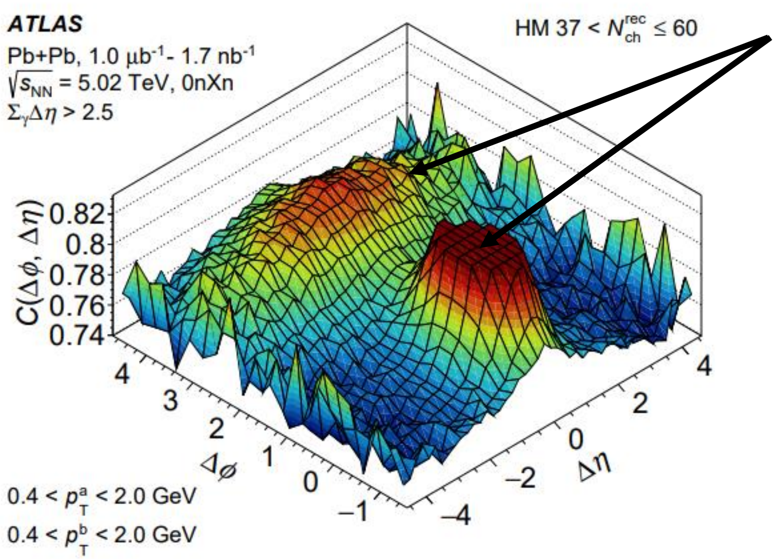
dN_{ch}/dη of photonuclear events - very similar shape with $N_{ch} \geq 10$

MC comparison show 200 GeV to 1 TeV CM energy ($W_{\gamma N}$)

$W_{\gamma N}(N_{ch})$ trend comports with N_{ch} trend in data dN_{ch}/dη

arXiv:2101.10771

2-particle correlation of charged tracks



No clear nearside ridge

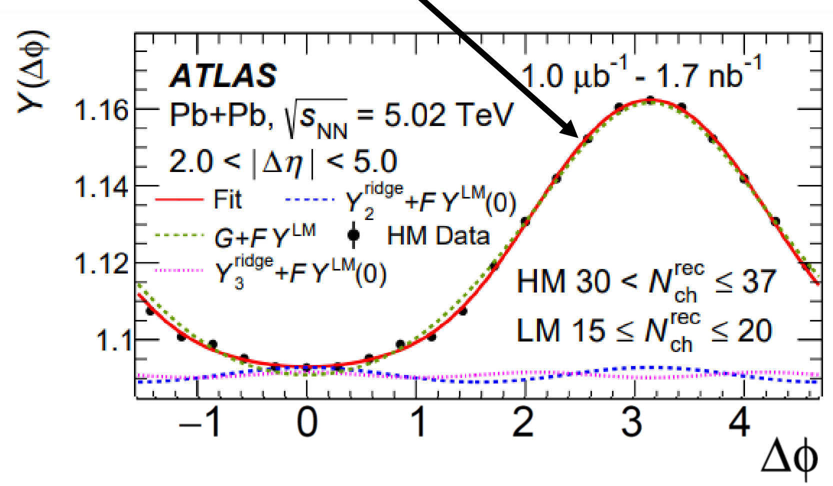
Away-side correlation

Momentum conservation

Jets

Termed “nonflow”

Not collective phenomenon

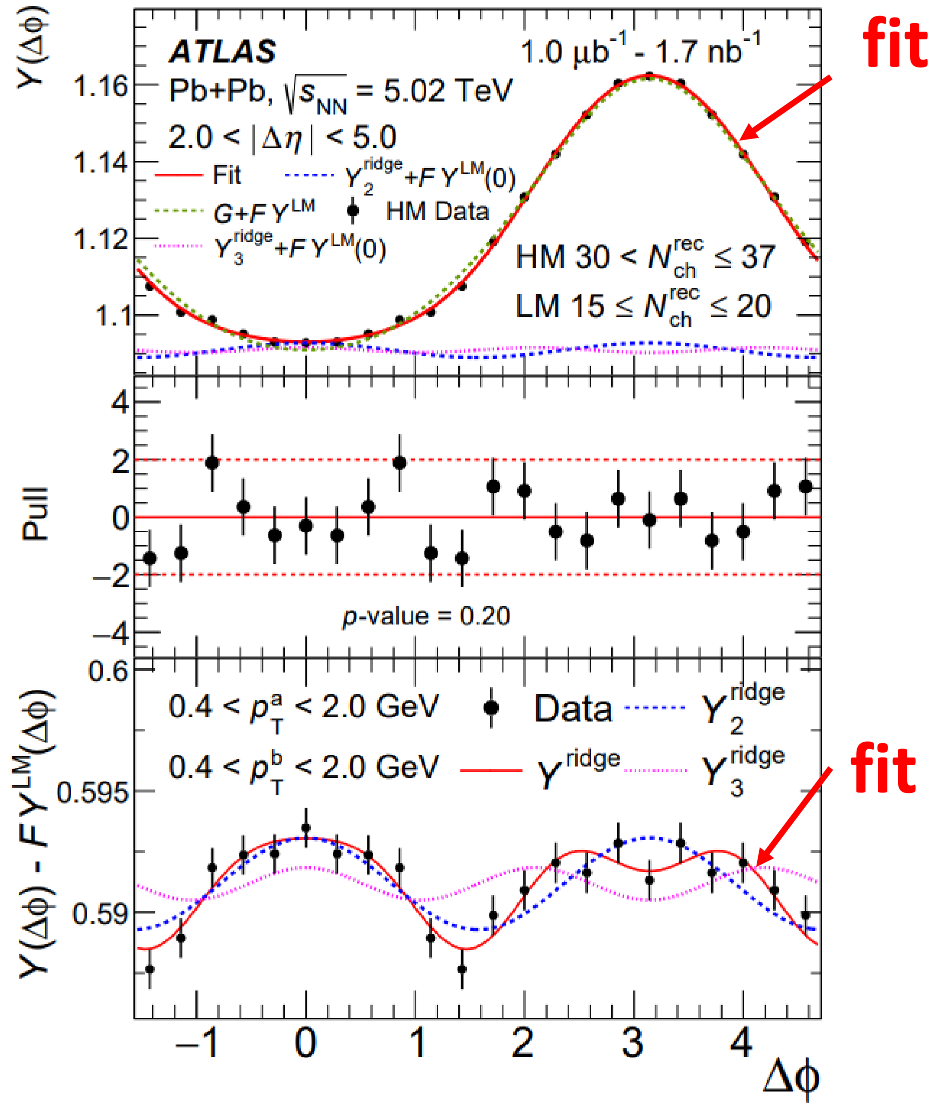


Need to remove nonflow

arXiv:2101.10771

Non-flow removal in γA correlations

- High-multiplicity (HM) correlation data
- Low multiplicity (LM) template for jet/non-flow correlation



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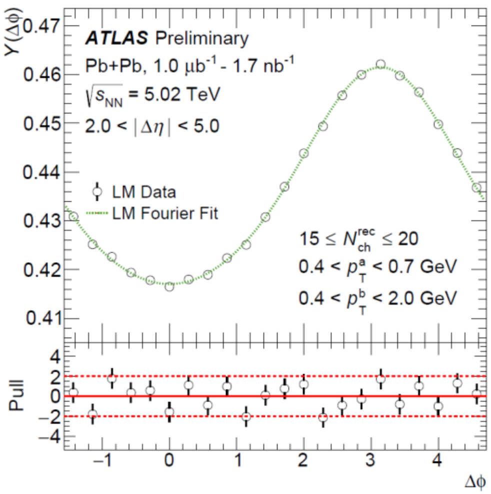
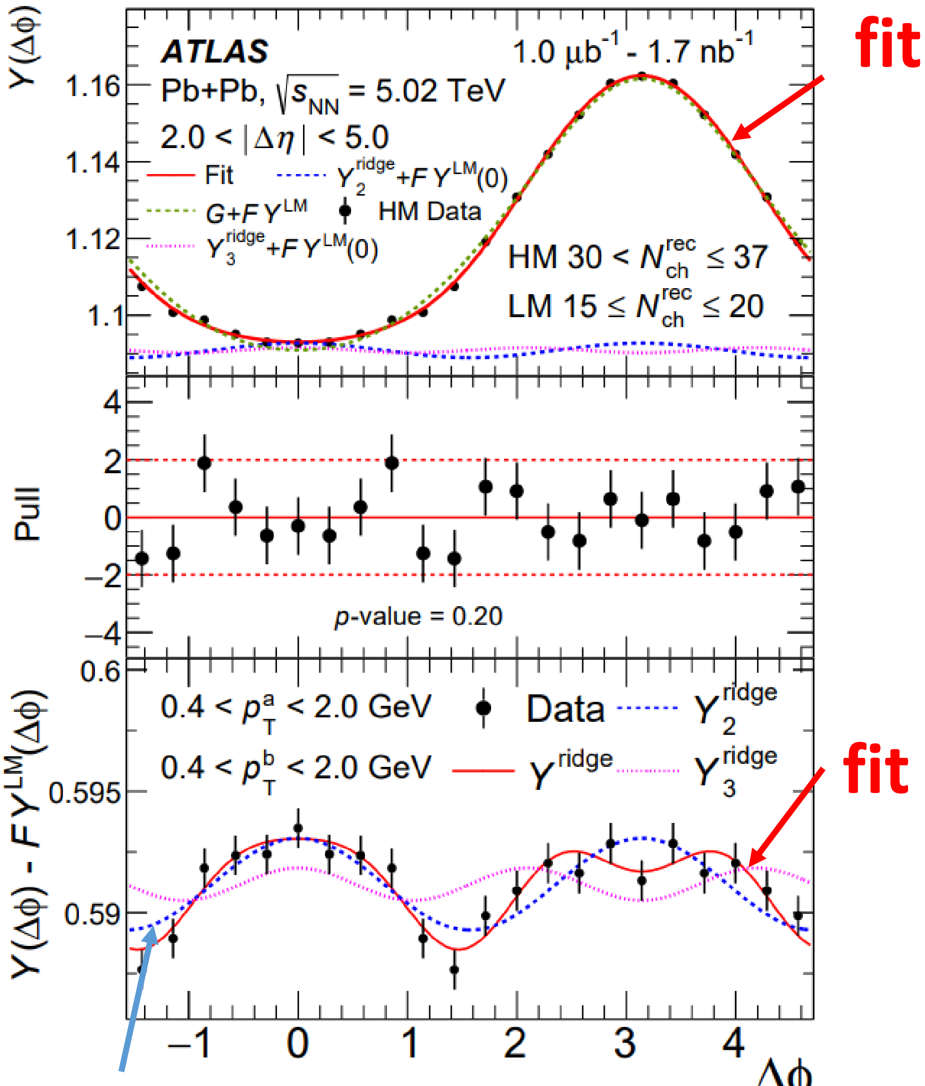


<u>Nonflow subtraction</u>

- HM fit with LM data and flow coef.
- HM and LM assumed to have same flow shape
- Different LM selection leads to similar results

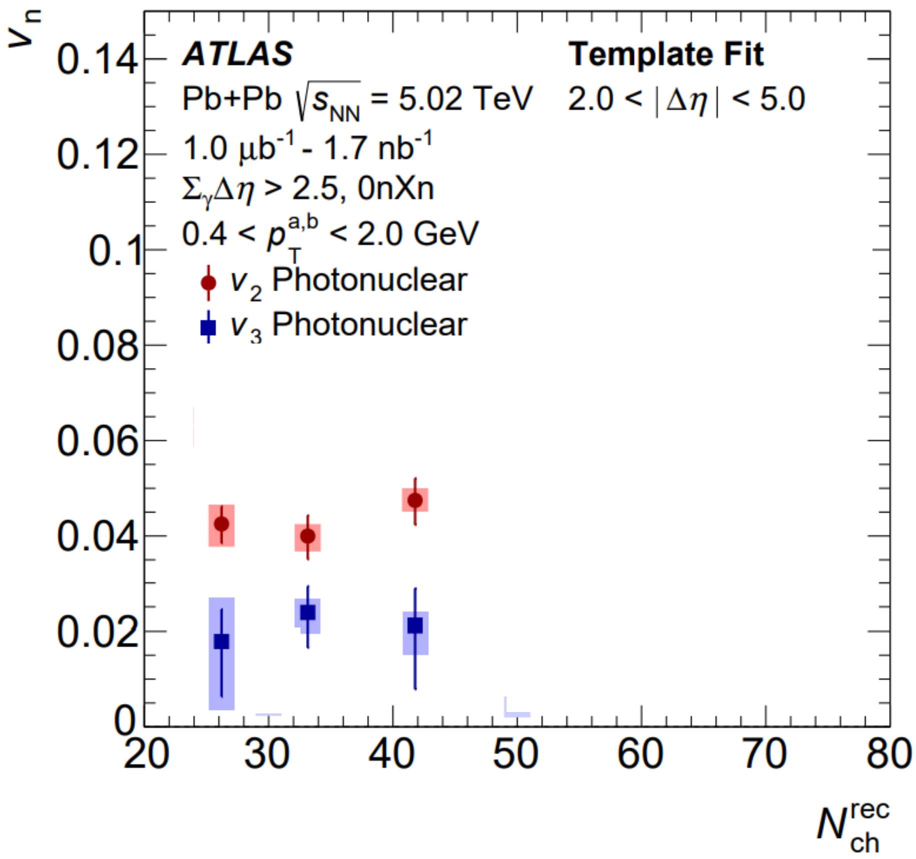
$$Y^{HM}(\Delta\phi) = FY^{LM}(\Delta\phi) + G\left\{1 + 2\sum_{n=2}^{3} v_{n,n}\cos(n\Delta\phi)\right\}$$



After nonflow subtraction clear cos(2Δϕ) modulation

arXiv:2101.10771

v_n in photonuclear collisions

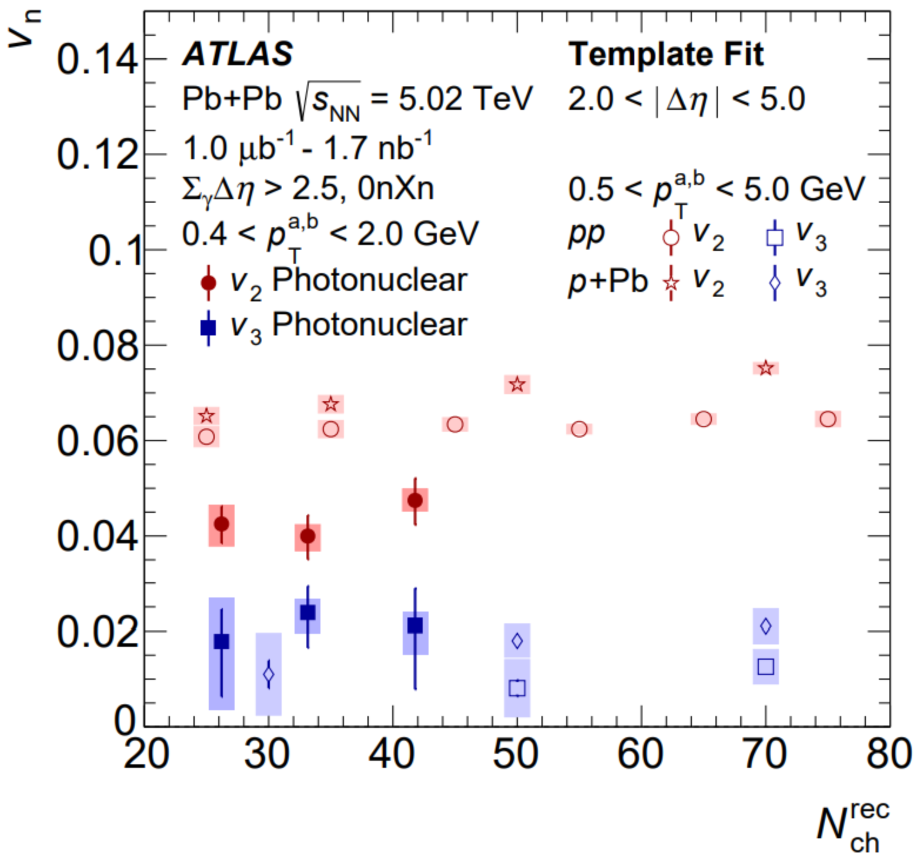


Significant nonzero v_2 and v_3 in photonuclear collisions

Flat $v_2(N_{ch})$ within statistical precision

arXiv:2101.10771

v_n in photonuclear collisions



Significant nonzero v_2 and v_3 in photonuclear collisions

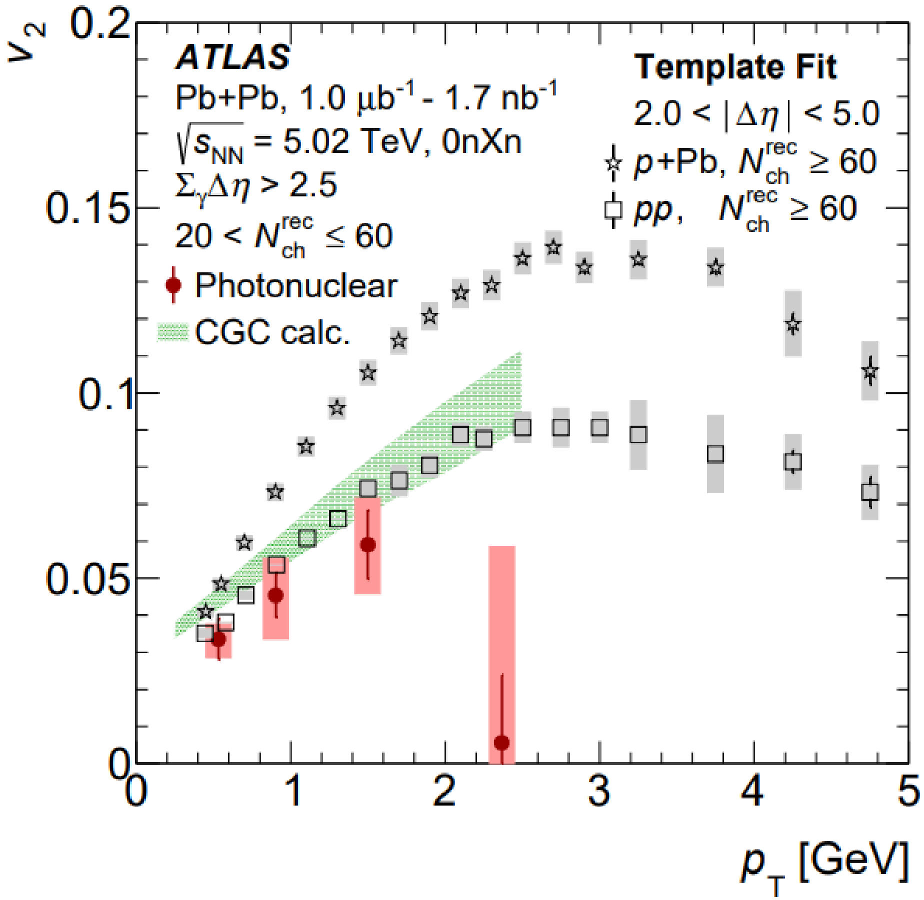
Flat $v_2(N_{ch})$ within statistical precision

Changing *pp* to $0.4 < p_T < 2.0$ is predicted to lower *pp* v_2 by ~10% which does not lead to agreement between *pp* and γA

Consistent v_3 between γA and *pp* given large uncertainties on both

arXiv:2101.10771

$v_2(p_T)$ comparison with *pp* and *p*+Pb



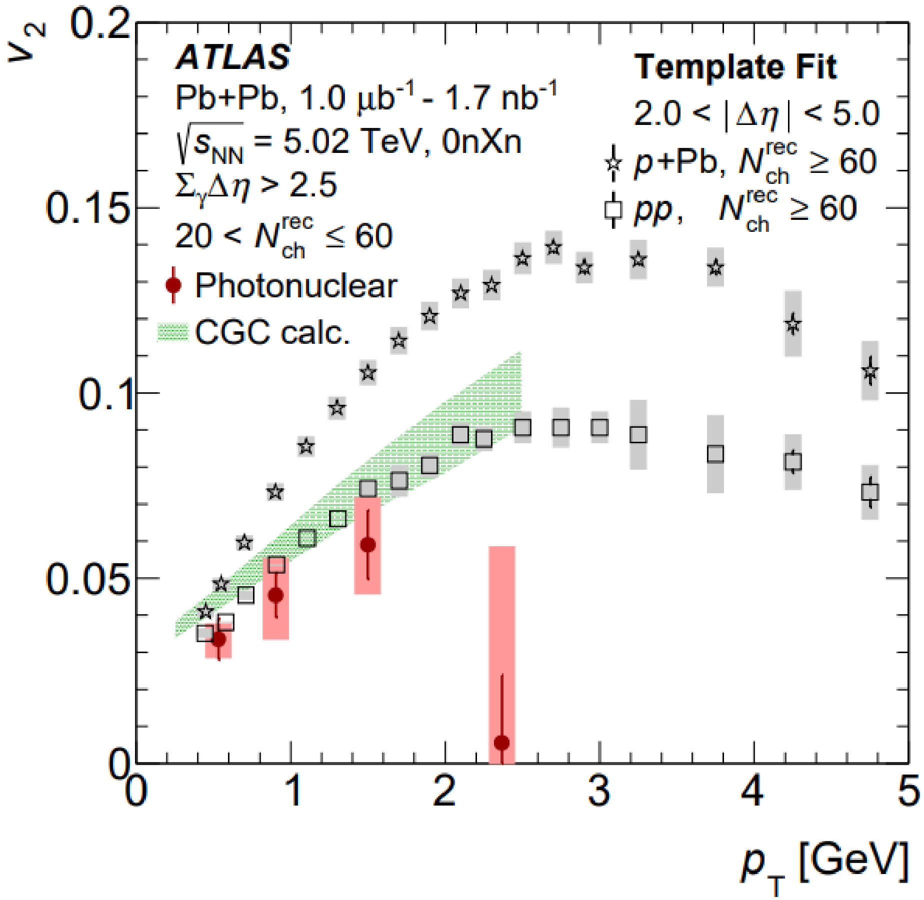
arXiv:2101.10771

Similar trend in $v_2(p_T)$ as other hadronic systems.

Similar low-p_T behavior as *pp* and *p*+Pb but systematically lower.

High-p_T v_2 is falling to large negative values (see backup) which is from the over-subtraction of nonflow.
This effect is present in *pp* but is larger and sets in at lower p_T in γA (ATLAS-CONF-2020-018)

$v_2(p_T)$ comparison with CGC calc.



Compared to Color Glass Condensate (CGC) framework calculation of γA $v_2(p_T)$ with Q_s^2 = 5 GeV² and B_P^2 = 25 GeV⁻²

Model is consistent with data at low-p_T

Theory uncertainty from hadron fragmentation

arXiv:2008.03569

arXiv:2101.10771

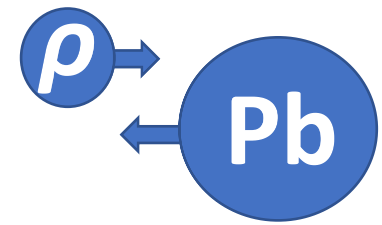
Conclusions

Results

Photonuclear v_n has a similar order of magnitude and trends as other previously measured hadronic systems

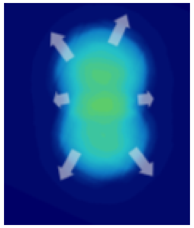
Intuitive property of hadronic-like photonuclear collisions (photon $\rightarrow$ vector meson).

e.g.



Theory

Compared to CGC model and are interested in models which include **final-state effects**.



Future study

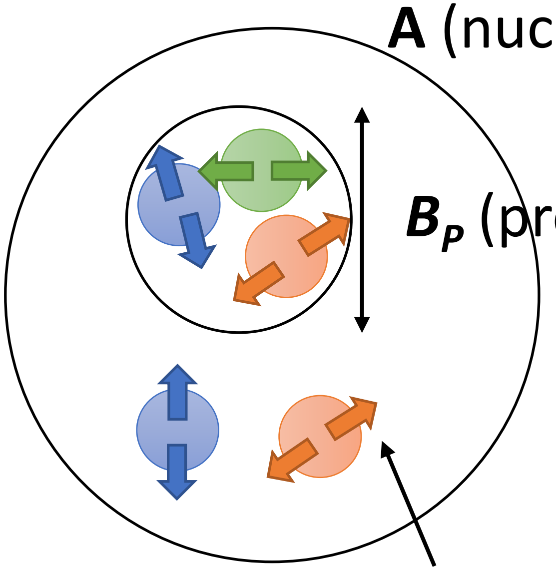
Difference with *pp* might be a consequence of (and further studied by) CM energy, CM-frame rapidity acceptance, decorrelations effects, and multi-particle correlations

Thank you

CGC model comparison

Color Glass Condensate model calculation containing **initial-state correlations** which gives rise to nonzero v_2

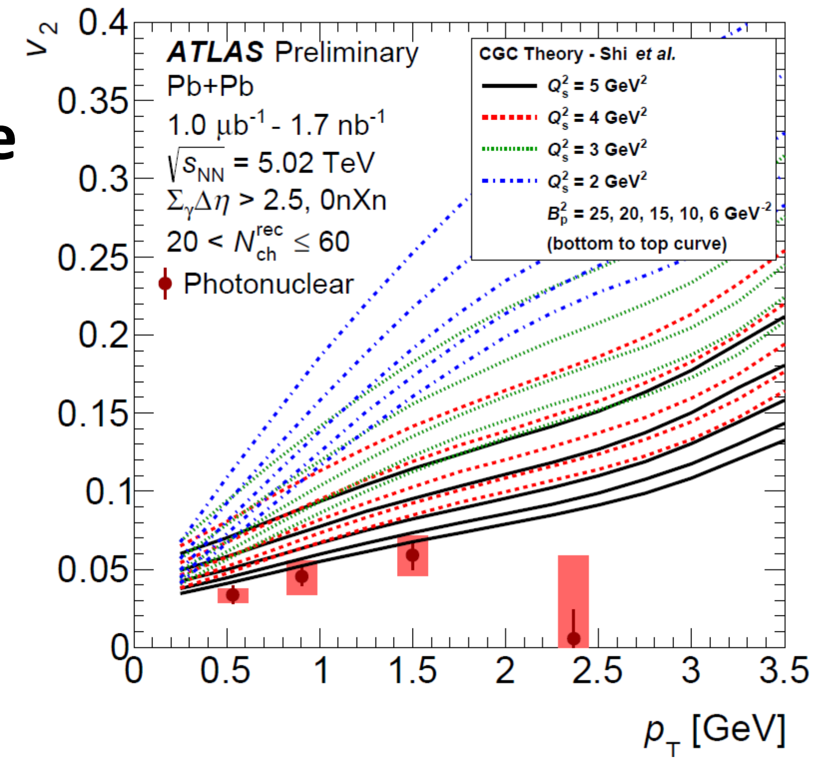
A (nuclear target)



$\boldsymbol{B_P}$ (projectile size)

Correlated color domain

size is ~ $1/\boldsymbol{Q_s}$



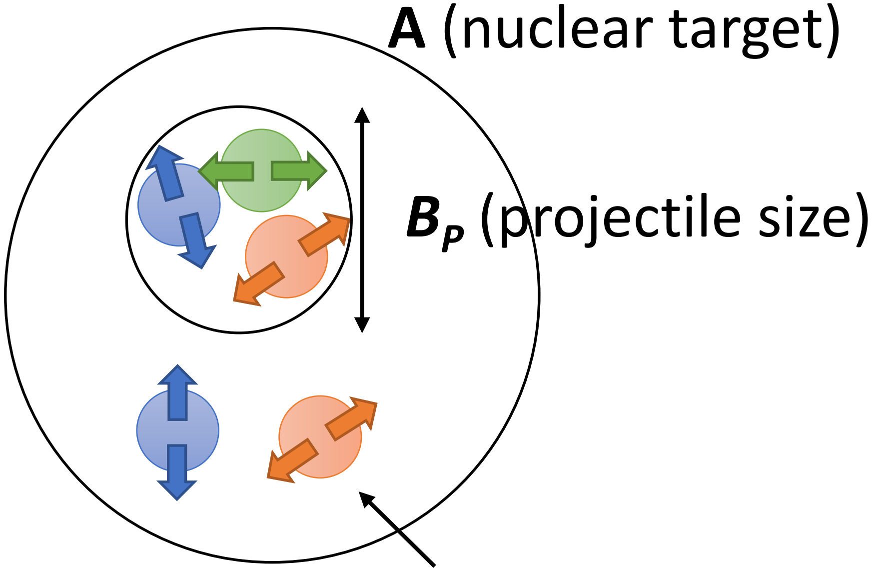
- Larger number of domains struck → lower v_2
- Quasi-real photon is predicted to have large B_P

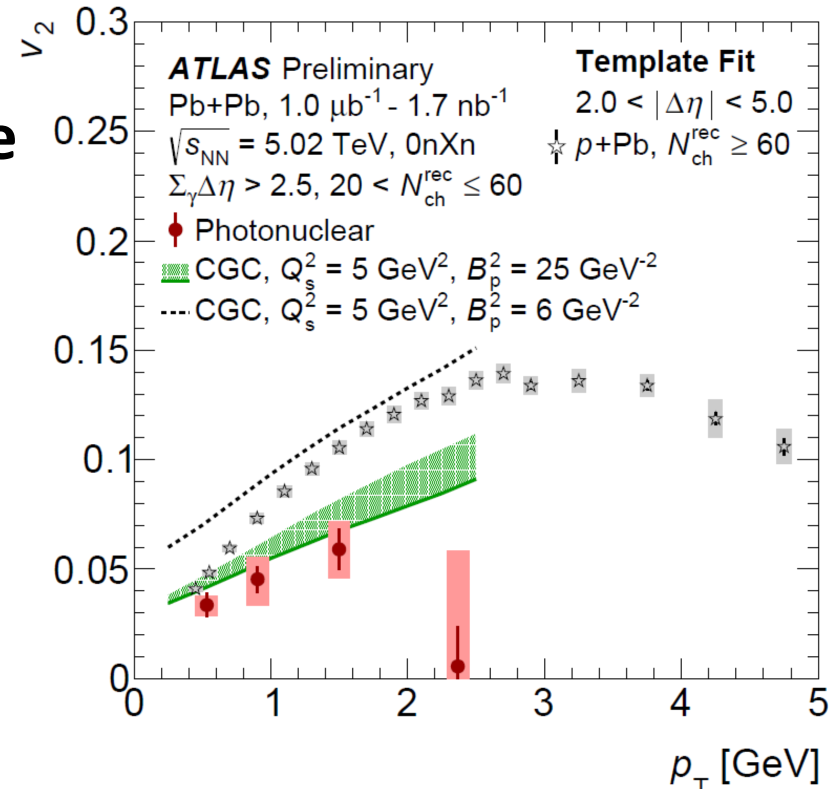
arXiv:2008.03569

arXiv:2101.10771

CGC model comparison

Color Glass Condensate model calculation containing **initial-state correlations** which gives rise to nonzero v_2





- Similar calculations describing p+Pb (arXiv:1808.09851)
- Difference in v_2 is a result of a smaller B_p^2 for a proton where $B_p^\gamma \sim 1/\Lambda_{QCD}$

arXiv:2101.10771

Origin of γA ridge

Final state effects

Initial-state geometry → hydro → final-state anisotropy has described simultaneously many systems

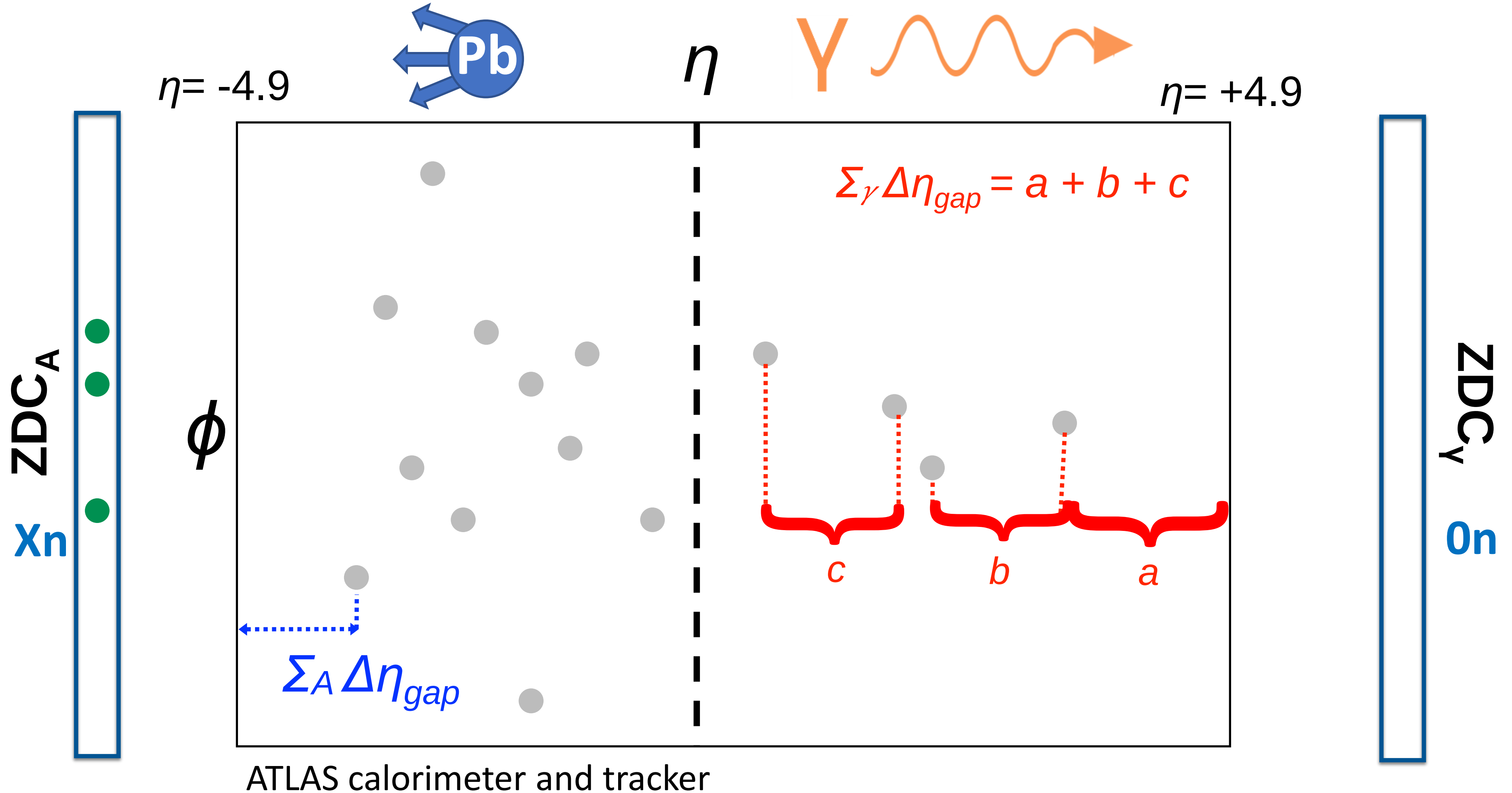
- In small systems the initial geometry is largely determined by fluctuation
- We ran a constituent quark model, 2 vs 3 quarks on Pb and found a very modest difference in ε_2 and ε_3.
- In that sense, one might expect similar results for *p*+Pb and rho+Pb at fixed multiplicity.
- A more complete calculation is needed also considering the bare photon portion of the wave function, color fluctuations, possible correlations between the impact parameter and photon energy etc.

Initial state correlation

Less success in the description of a diverse set of observables.

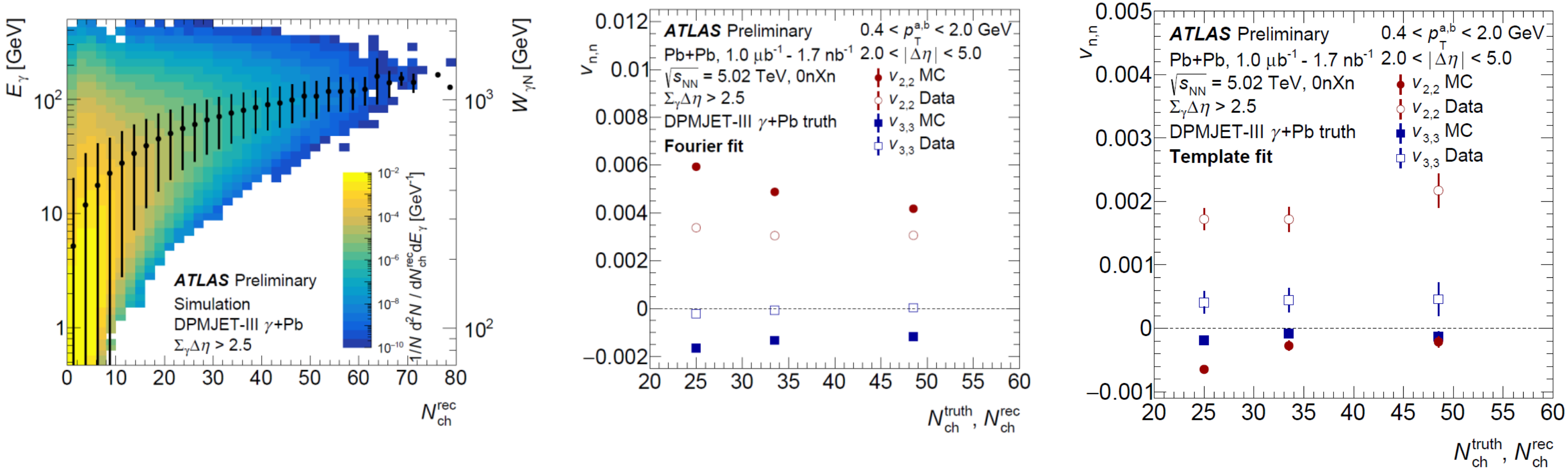
- A schematic CGC calculation is discussed in the next slide.

Gap definition (detector roll-out)



Event Selection: $\Sigma\Sigma_{\gamma}\Delta\eta_{gap} > 2.5$

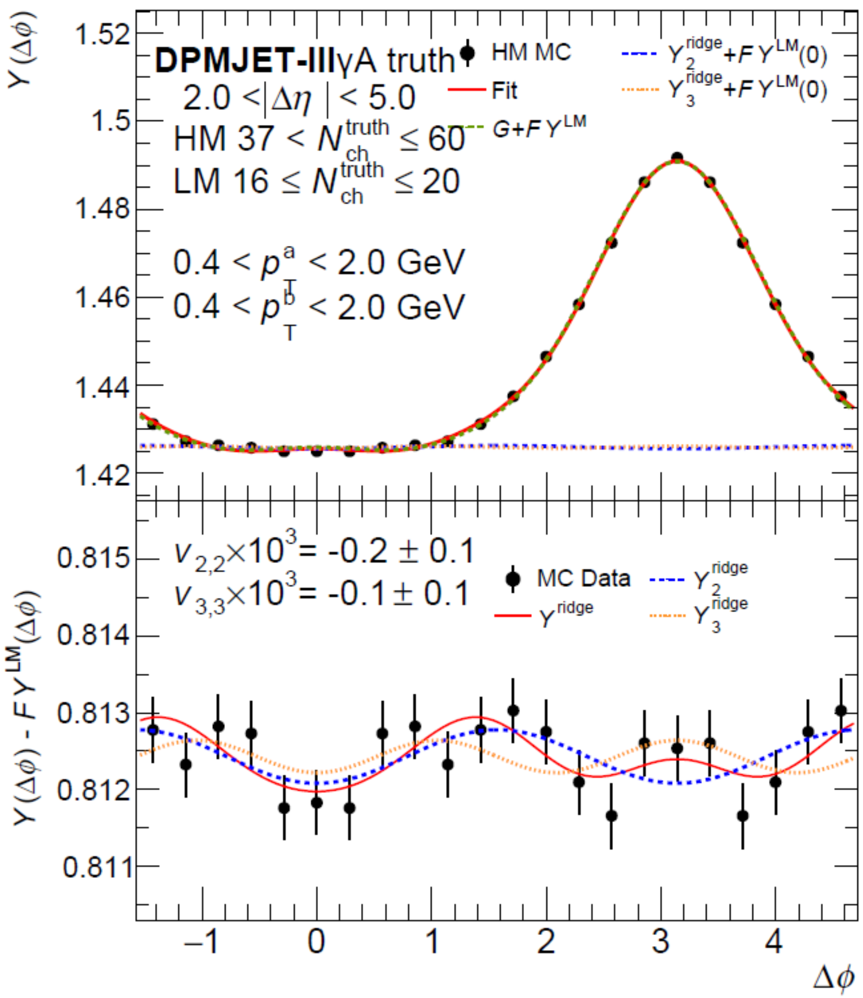
Comparison to DPMJET-III



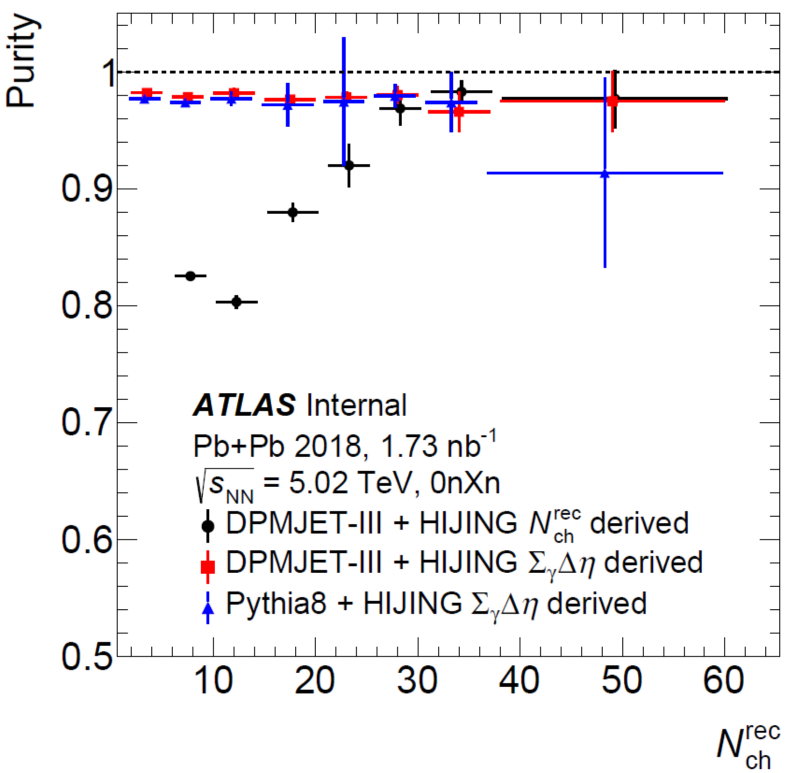
- DPMJET-III predicts the photon energy changes by about 1-2 standard deviations over the multiplicity range of the measurement and a doubling of the mean $W_{\gamma N}$ for 10 to 60 N_{ch}^{rec}.
- Large difference between measured $v_{n,n}$ before and after template nonflow subtraction for data and DPMJET-III.
- Small negative $v_{2,2}$ after template fit

DPMJET-III 2PC example

More jet-like away side in DPMJET-III than in data. This produces the larger unsubtracted $v_{2,2}$ seen on the previous slide. Small remaining modulation after nonflow subtraction seen in the lower panel. DPMJET-III is of limited use in modeling the soft correlations in photonuclear events.

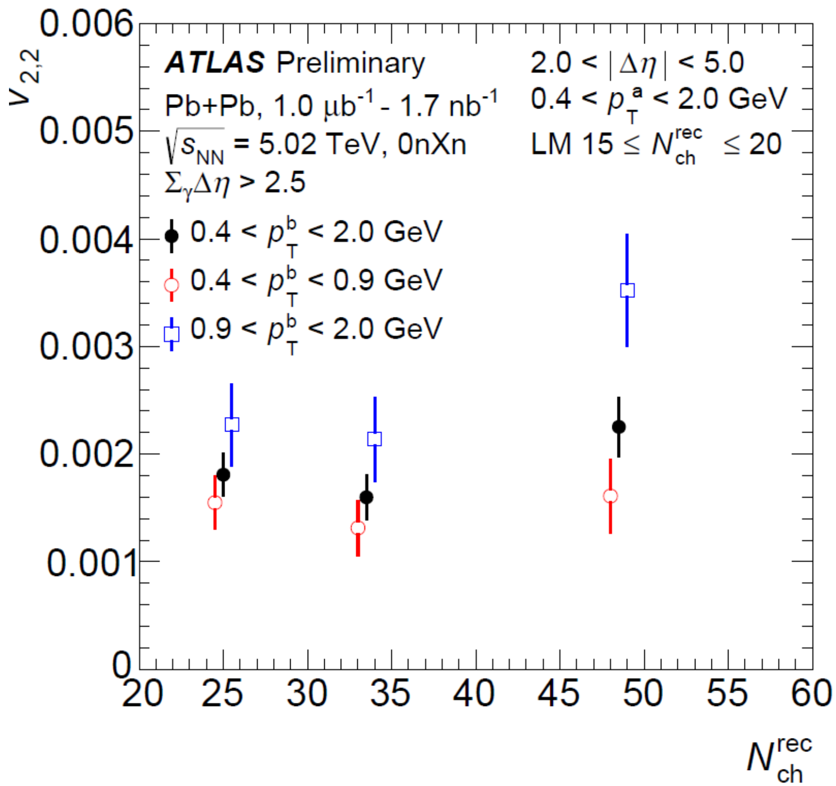


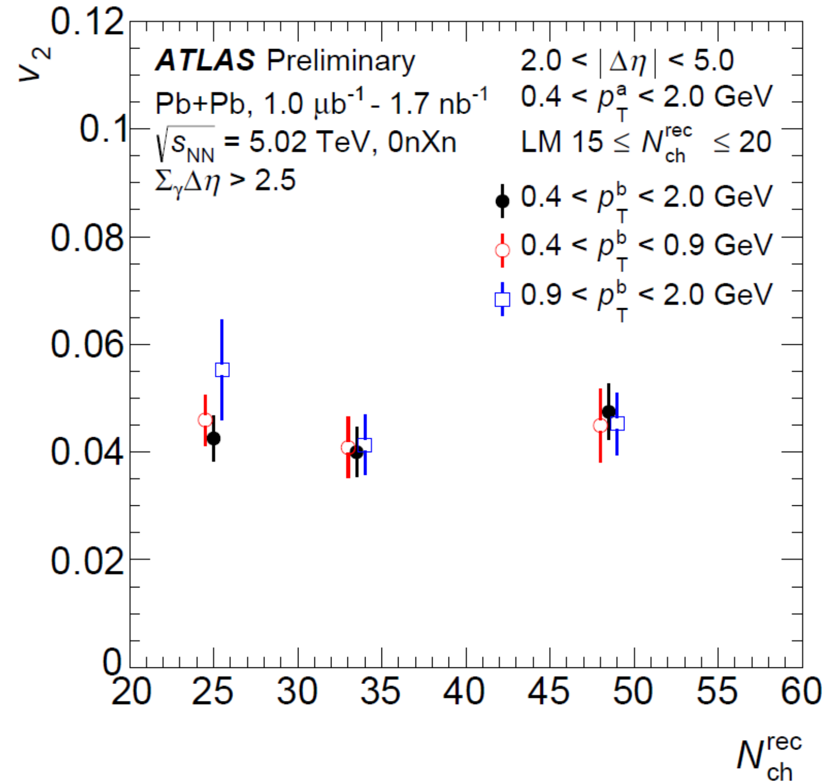
Purity of the photonuclear selection



- A two-component fit was performed (signal MC) + (background MC) to data distributions to determine the purity.
- The N_{ch} and $\Sigma_{\gamma}\Delta\eta$ distributions were used.
- A conservative approach was taken and the worst purities were used to assess possible effects.
- A *pp* Δϕ correlation with the same selections was subtracted (according to the bins purity) from the photonuclear data as a systematic variation and the sensitivity is included in the final result.

Factorization $v_2(N_{ch})$



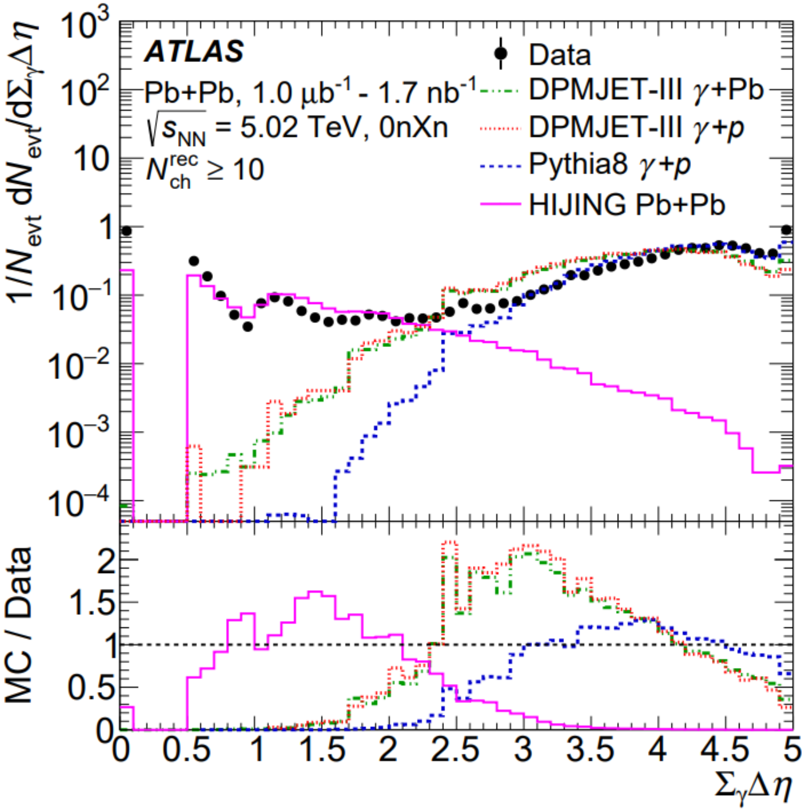


$$v_n(p_T^a) = v_{n,n}(p_T^a, p_T^b)/v_n(p_T^b) = v_{n,n}(p_T^a, p_T^b)/\sqrt{v_{n,n}(p_T^b, p_T^b)}$$

$v_2(N_{ch})$ shows insensitivity to associated particle p_T range. This is consistent with a hydrodynamic paradigm where particle anisotropies are generated from a single-particle flow vector for all p_T.

CERN-EP-2020-246

Rapidity gap comparison to MC



- DPMJET-III γ+A
  - Photon flux generated by STARLIGHT
  - DPMJET simulates γA collision
- DPMJET-III γ+*p*
  - Utilizes a Pb+Pb photon flux from STARLIGHT
  - Serves as a comparison to PYTHIA8
- PYTHIA8 γ+*p*
  - Reweighted to STARLIGHT flux
- HIJING Pb+Pb background MC

MC normalized to data in control regions

Qualitative agreement with MCs, PYTHIA being the most compatible

Indicates high purity γ+A sample for $\Sigma_\gamma \Delta\eta > 2.5$

arXiv:2101.10771