Collectivity signals in ultra-small collision systems at RHIC and the LHC

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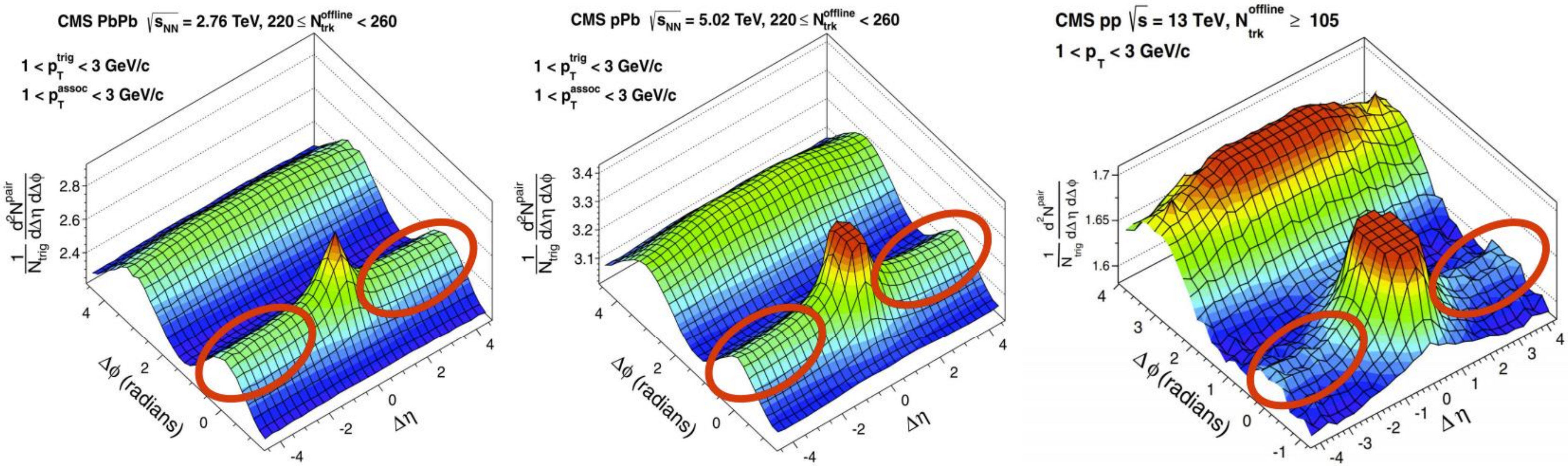
Azimuthal anisotropy



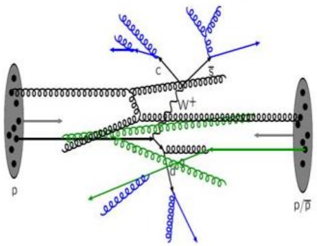
Clear collectivity signatures in many system sizes

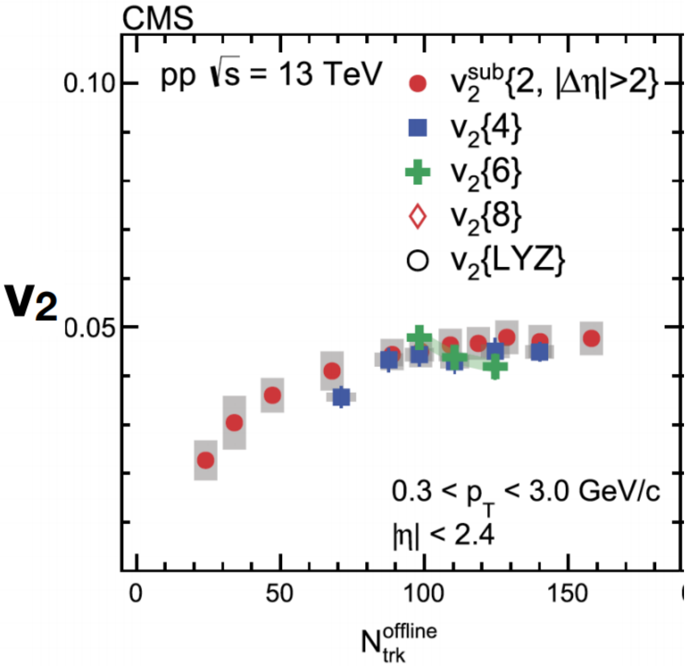
- Nearside ridge present in 2-particle correlation
- Precise measurements of v_n
- Multi-particle correlations → global correlation

arXiv:1305.0609 arXiv:1510.03068

Which small systems do we know flow?

pp





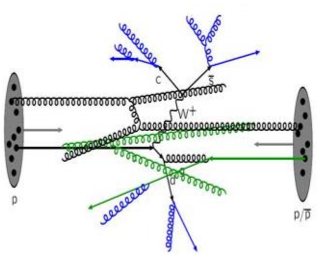
<u>Collectivity in ***pp***</u>

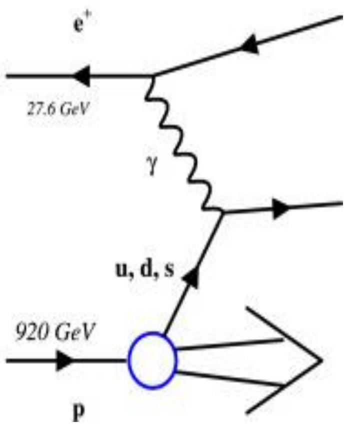
- Near-side ridge
- Multi-particle correlation
- Initial state geometry?

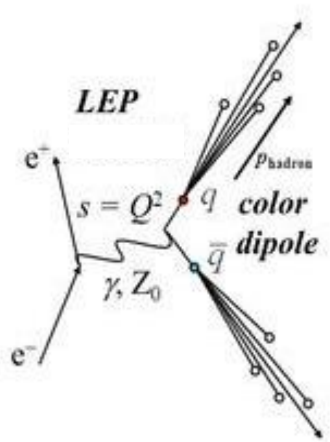
arXiv:1606.06198

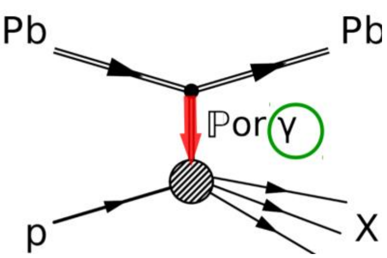
Which small systems do we know flow?

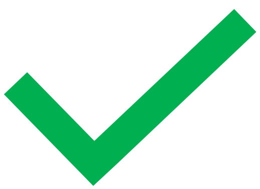
pp	e+*p*	$e^+ + e^-$	γ+*p*











Near-side ridge

Cumulants say v_2< 4%

[arXiv:1912.07431]

No near-side ridge

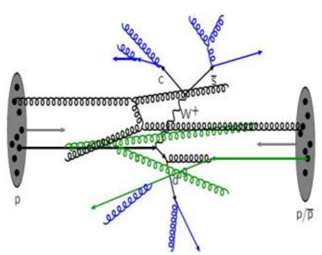
[arXiv:1906.00489]

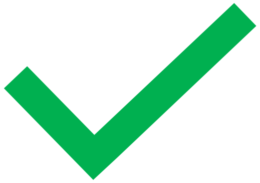
No near-side ridge

[CMS-PAS-HIN-18-008]

Which small systems do we know flow?

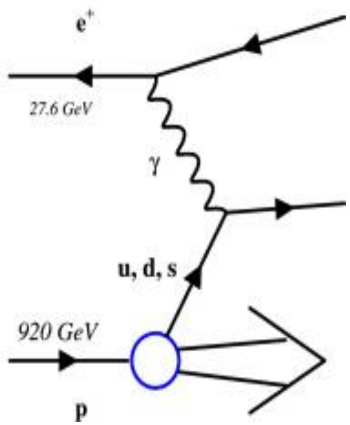
pp





Near-side ridge

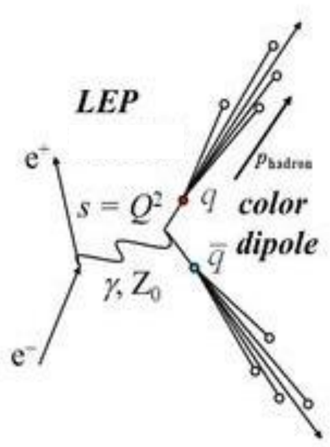
e+*p*



Cumulants
say v_2< 5%

arXiv:1912.07431

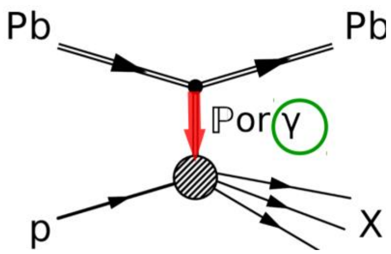
e⁺+e⁻



No
near-side ridge

arXiv:1906.00489

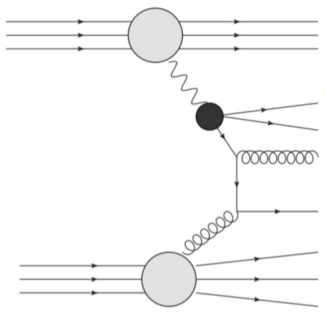
γ+*p*



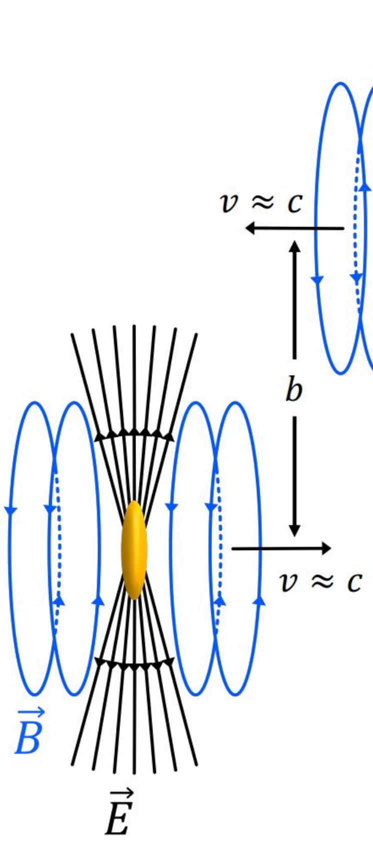
No
near-side ridge

CMS-PAS-HIN-18-008

γ+A



Photons in heavy ion collisions



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

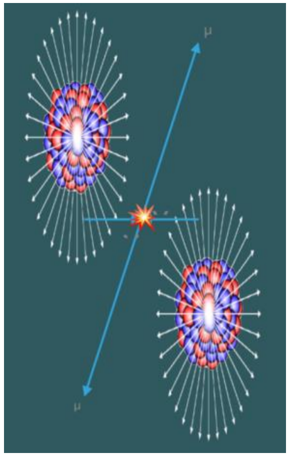
Equivalent photon approximation (EPA)
- EM field are a flux of quasi-real photons
- Developed by Fermi, Weizäcker, and Williams
- Implemented in STARLIGHT
- Differences with QED calculations

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

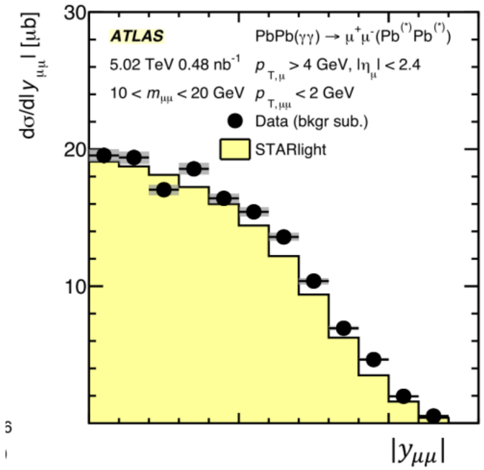
Brandenburg, GHP 2021 - good up-to-date review as well: arXiv:2103.16623

Ultra-peripheral collisions at the LHC

Steinberg, Initial Stages 2019



arXiv:2011.12211



Pure EM interactions

- For example, γγ→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

$$\Delta t \approx \frac{\hbar}{M_V c^2}$$

$$\gg$$

collision time

$$\Delta t \simeq b/(\gamma v)$$

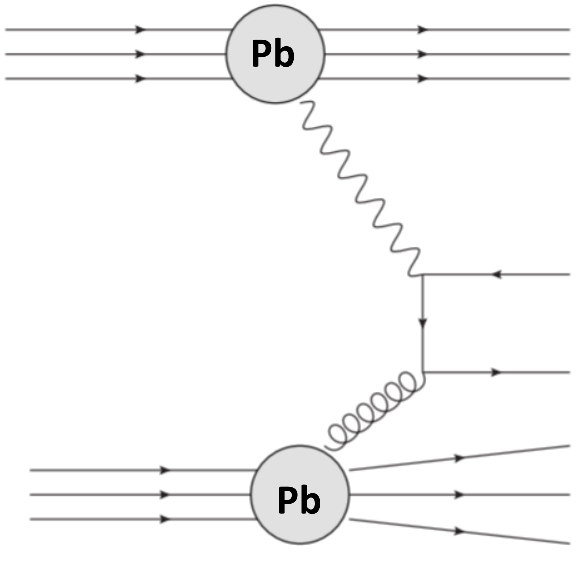
Photo-nucleus interactions

- Bare photon + vector meson wave function
- QCD diffractive vector meson production γ + A → A* + V
- Non-diffractive γ + A → X

Photonuclear interactions

Direct γA collisions

Photon couples directly to nuclear parton



Photonuclear interactions

Direct γA collisions

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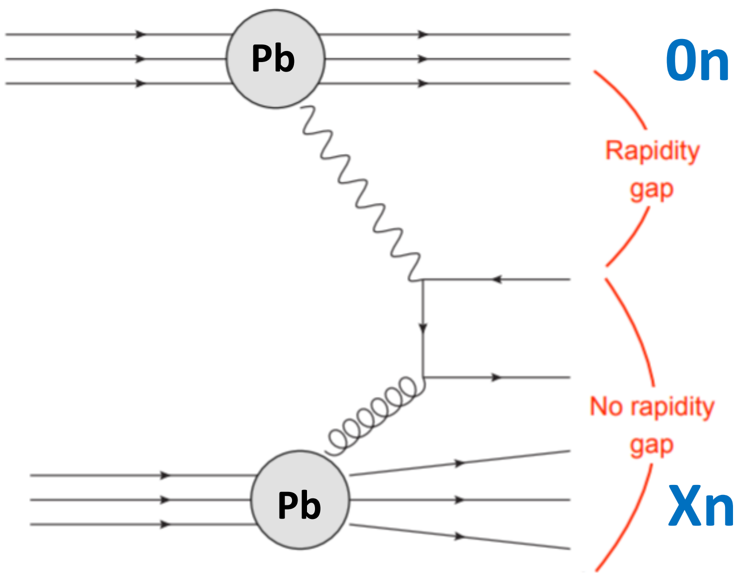
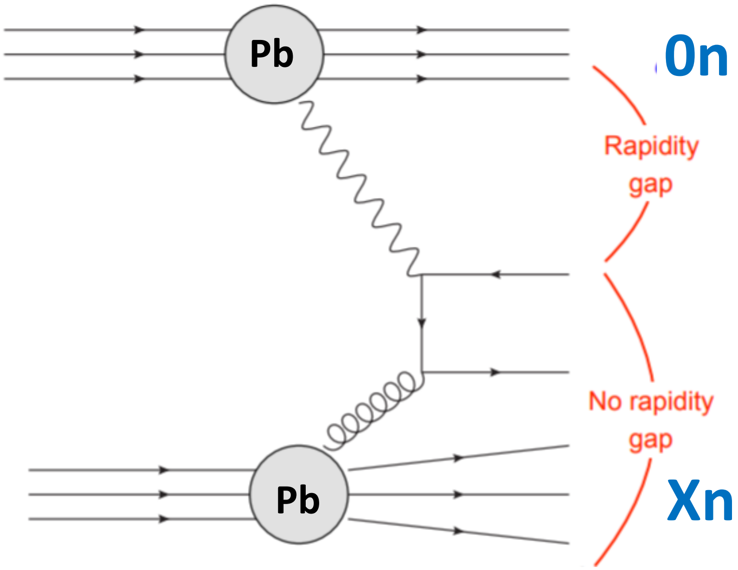
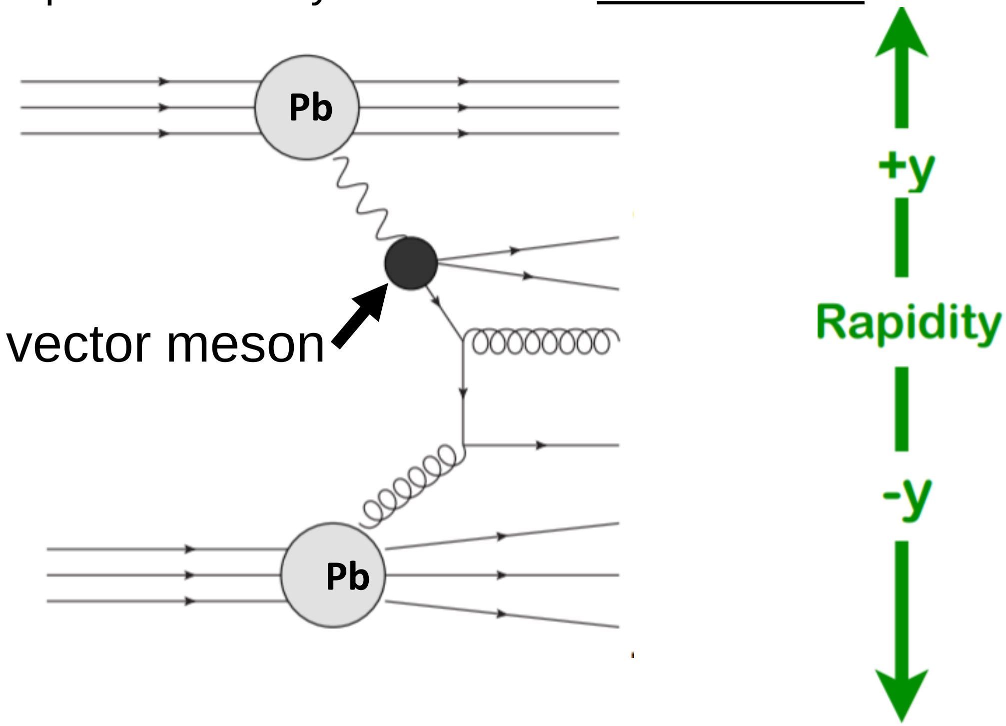


Photonuclear interactions

Direct γA collisions
Photon couples directly to nuclear parton



Resolved γA collisions
photon virtually resolved into hadronic state



Photonuclear interactions

Direct γA collisions

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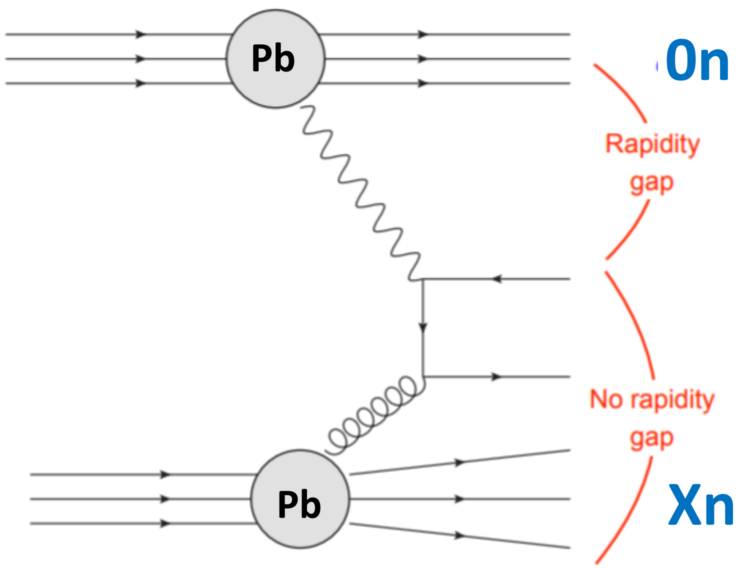

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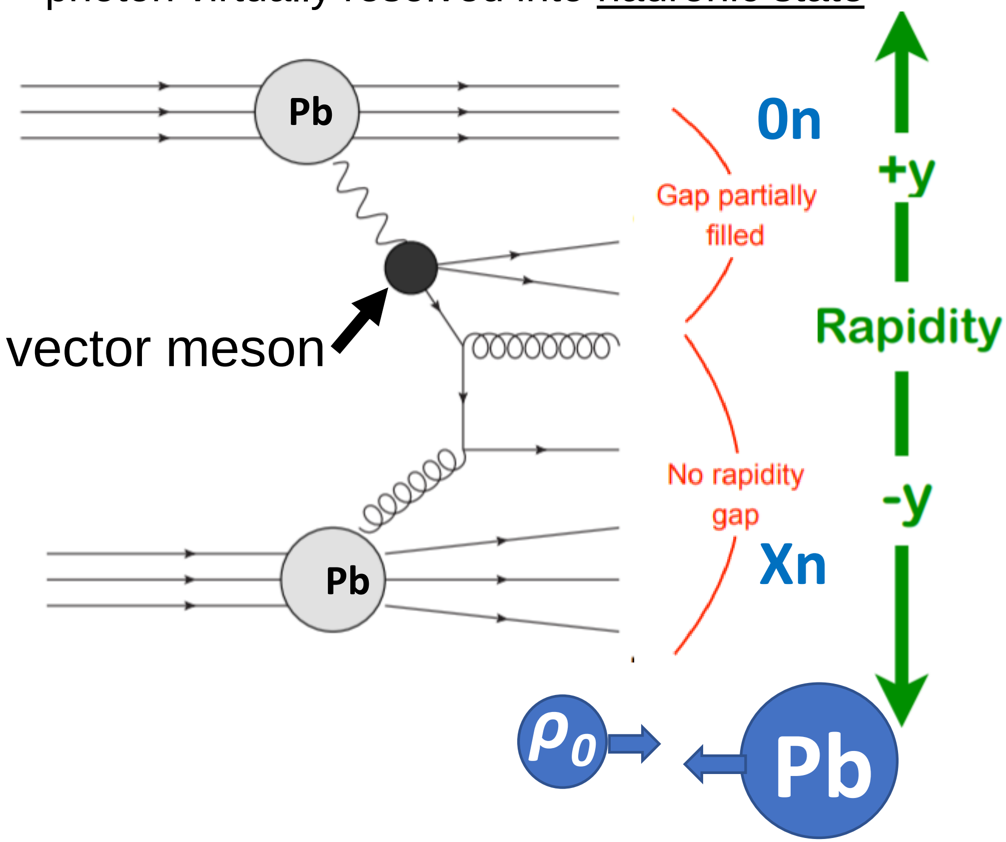


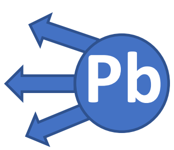
Select events based on primarily

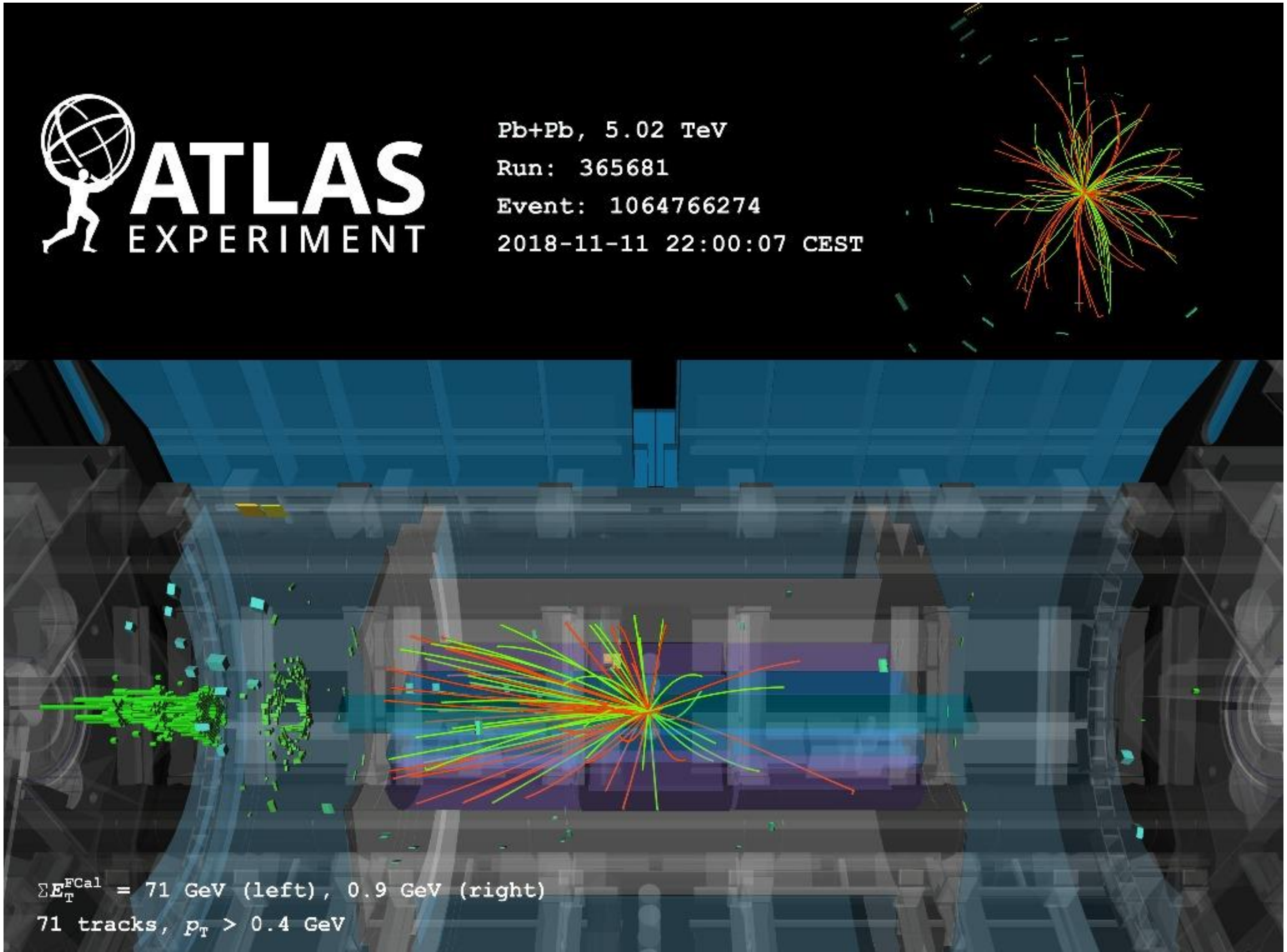
- Single-sided nuclear breakup "**0nXn**" (zero-degree calorimeter ZDC)
- Rapidity gaps

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

“High”-multiplicity photonuclear collisions

Pb going direction



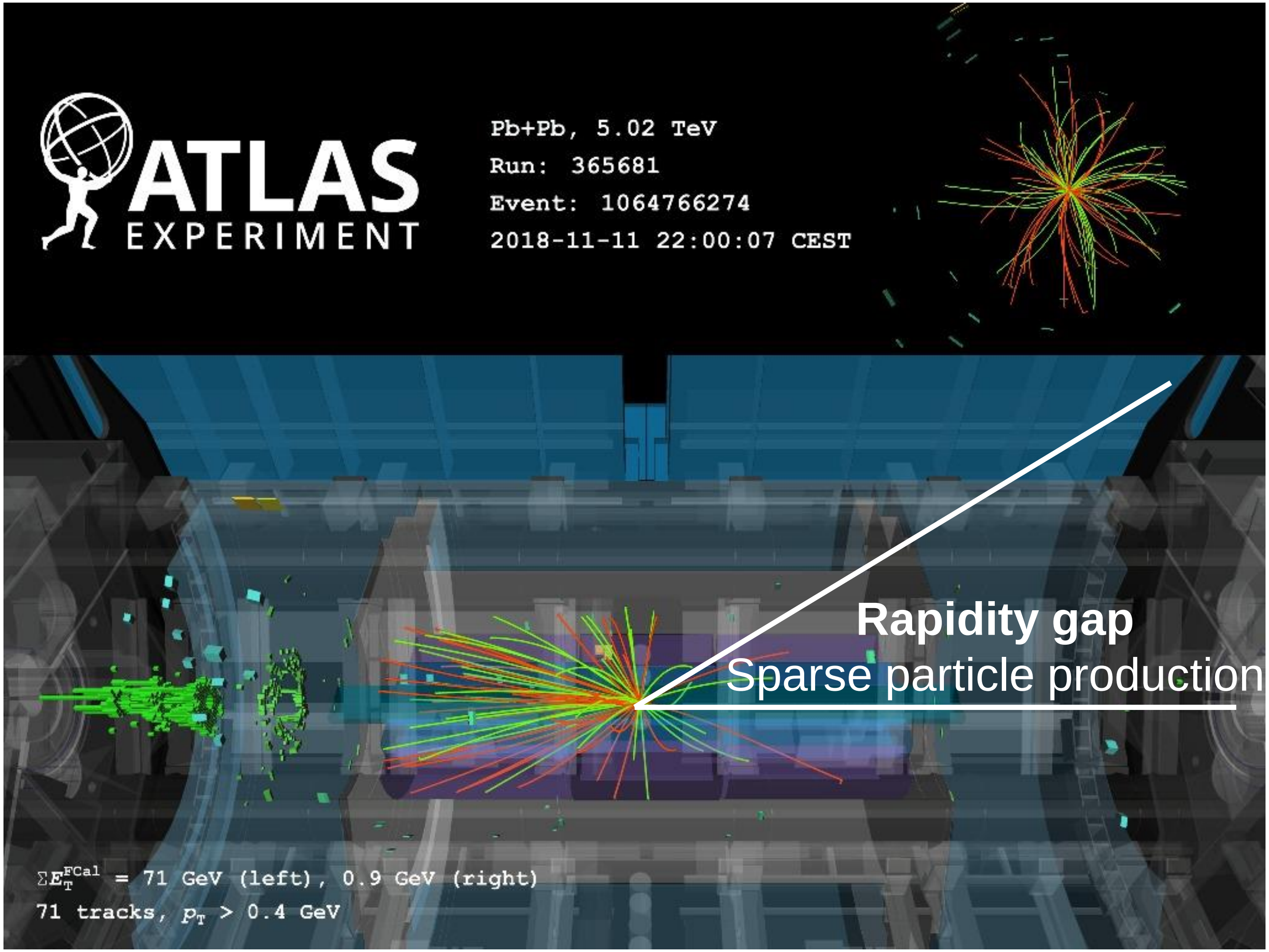


photon going direction

"High"-multiplicity photonuclear collisions

Pb going direction

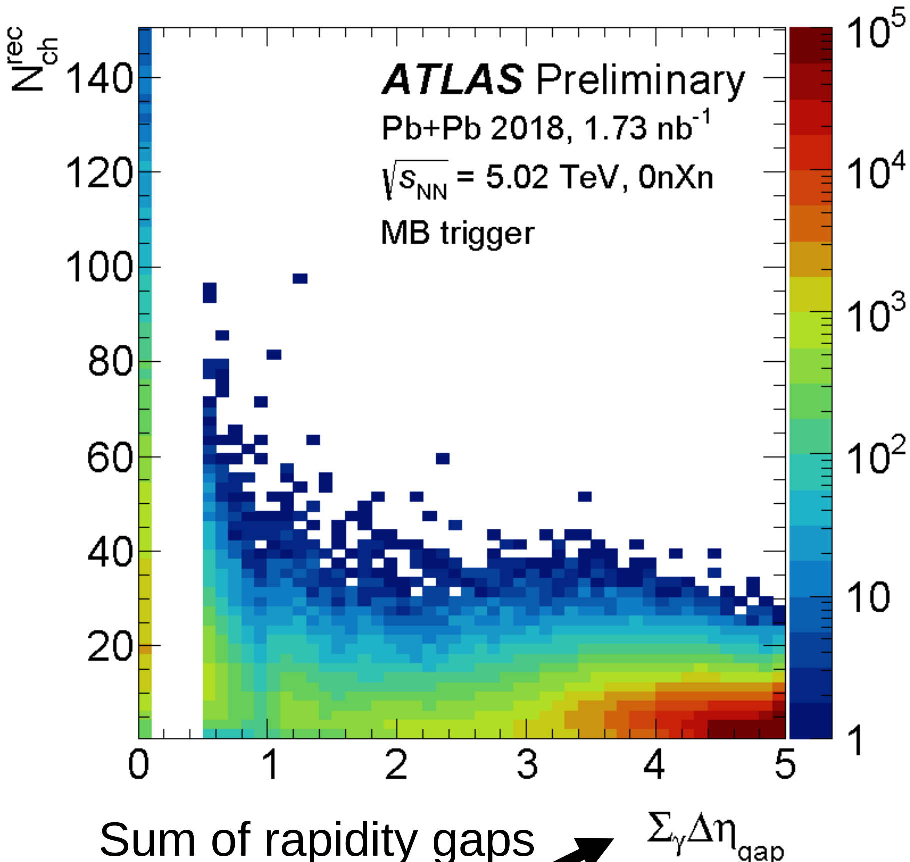
Xn



photon going direction

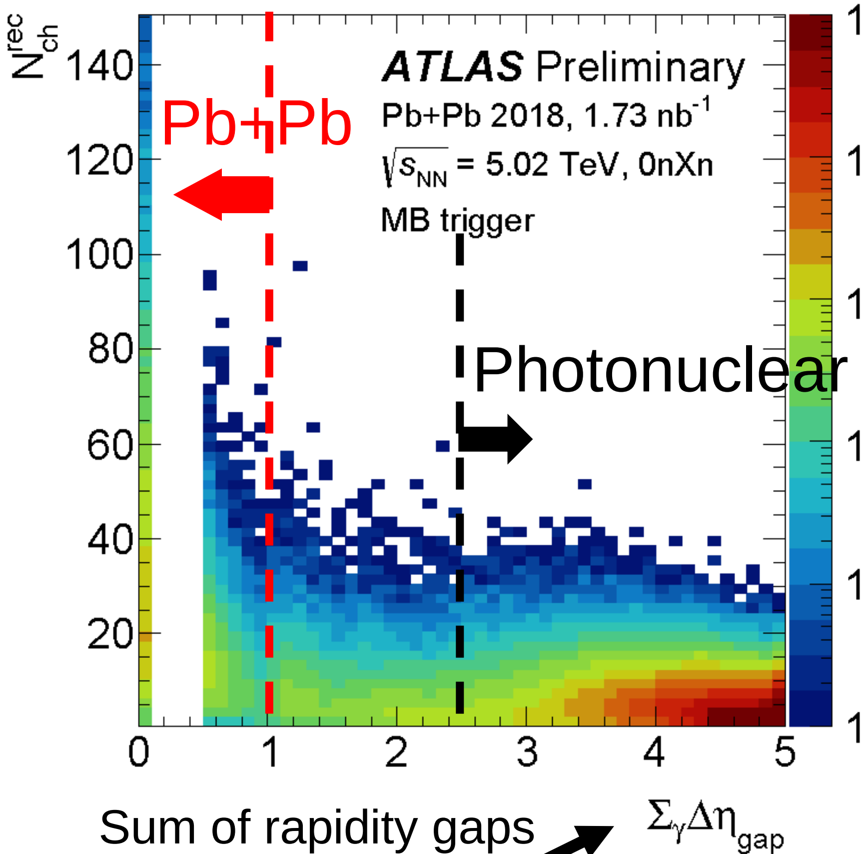
0n

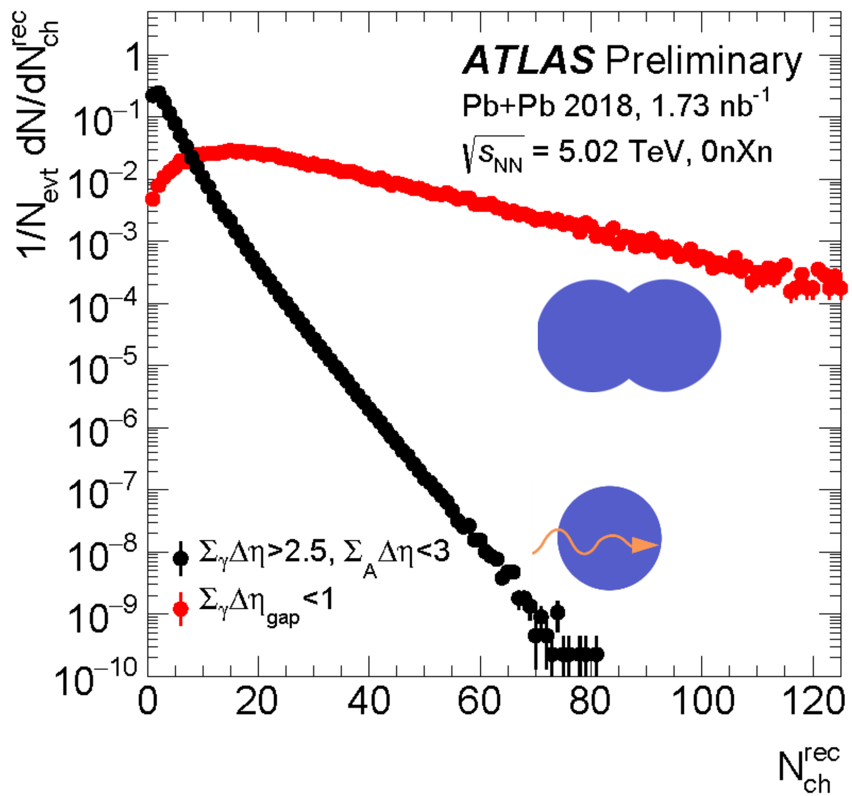
Photonuclear rapidity gaps $\Sigma_\gamma \Delta \eta$ and N_{ch}



Sum of rapidity gaps between particles greater than 0.5

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





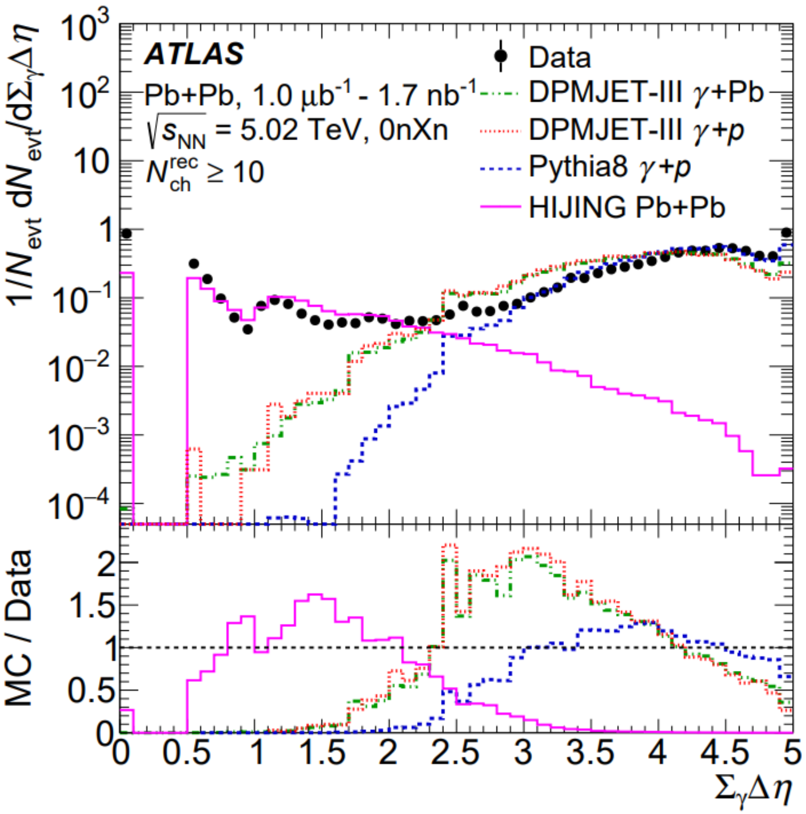
Sum of rapidity gaps between particles greater than 0.5

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

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

ATLAS-CONF-2019-022

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

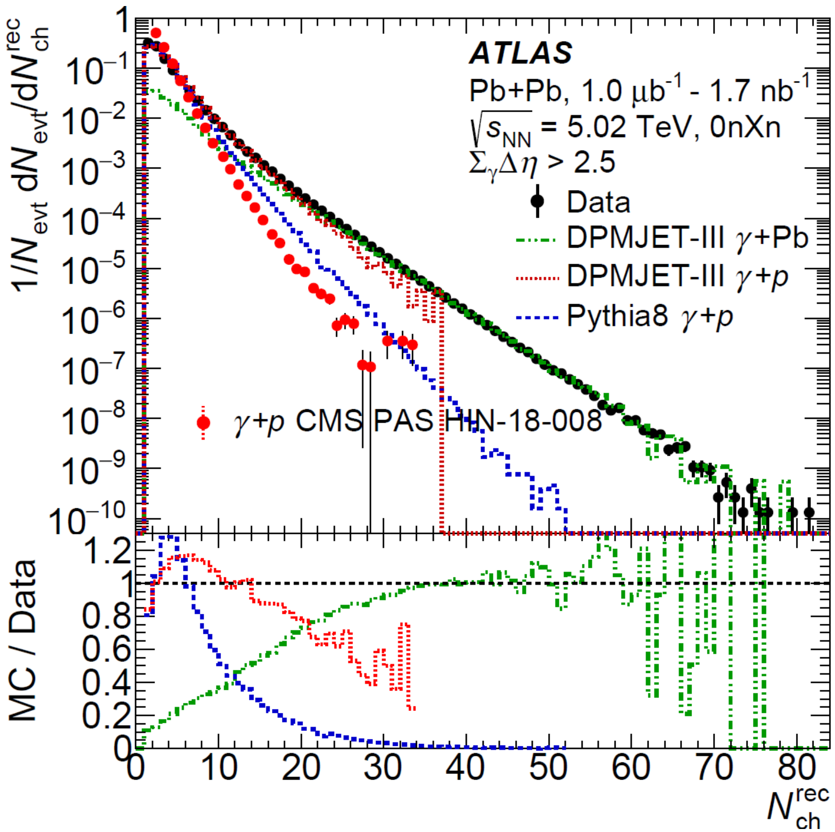
MC normalized to data in control regions

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

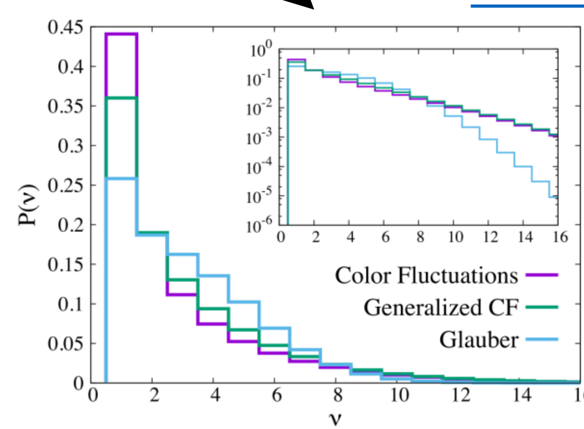
Rough N_{ch} comparison γ+A/*p*



Very rough N_{ch} comparison: different proton energy, acceptance and selection

- Future minimum-bias measurements would add fundamental understanding.
- Such measurements would also add to interesting hadron physics in color fluctuations and more.

arXiv:1605.06606

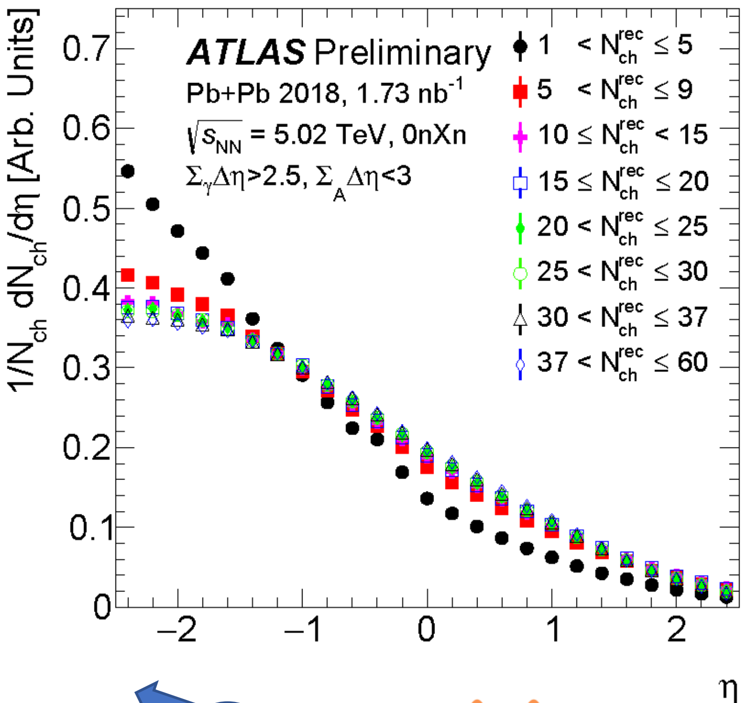


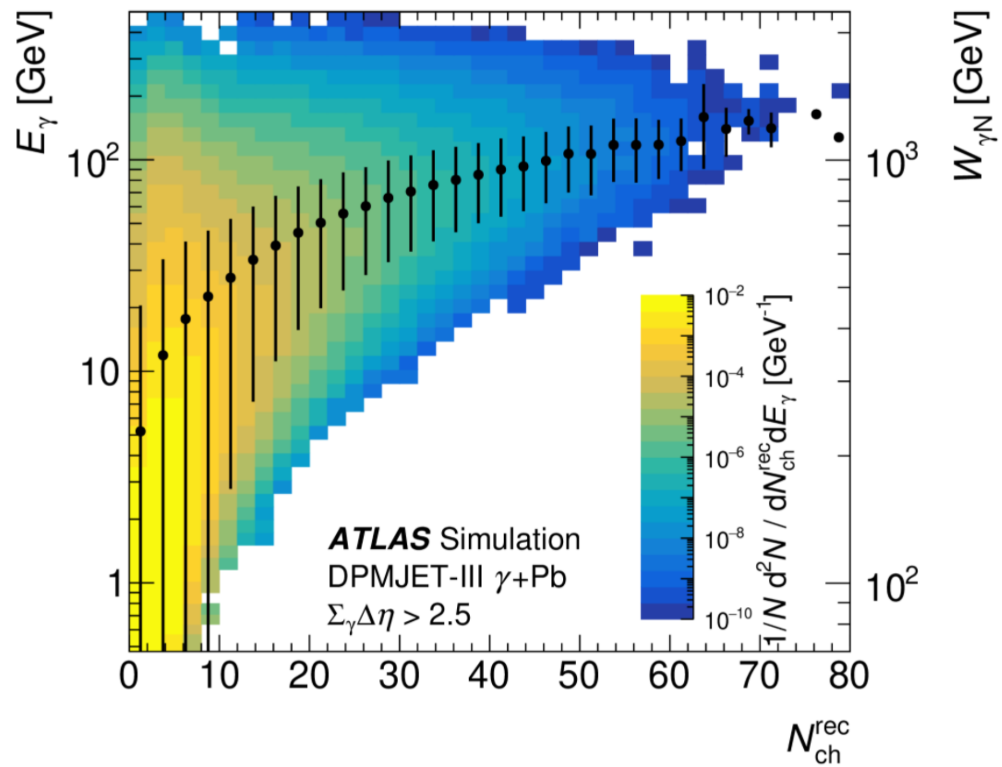
Number of wounded nucleons

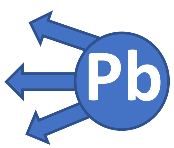
arXiv:2101.10771

dN_{ch}/dη in γA collisions

ATLAS-CONF-2019-022







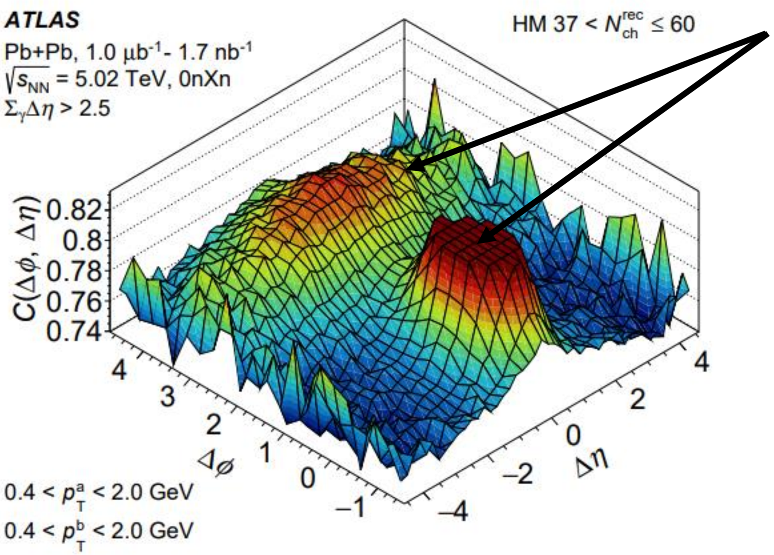
dN_{ch}/dη of photonuclear events - very similar shape with $N_{ch} \geq 10$

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

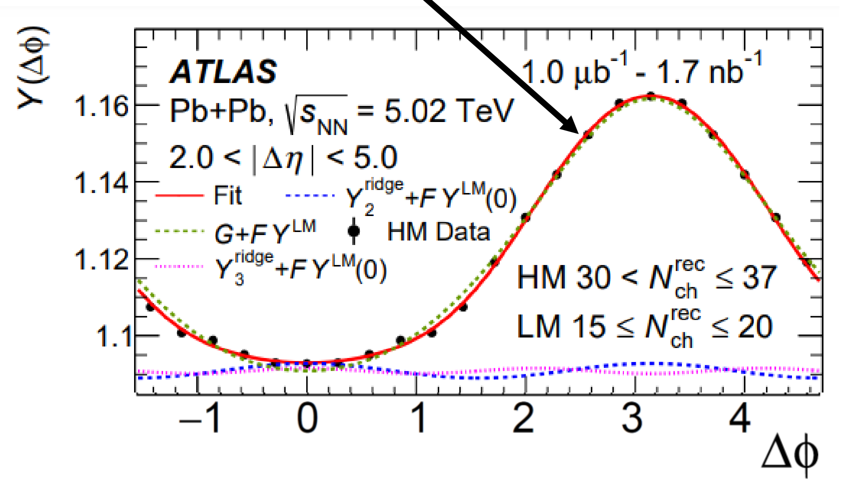
Away-side correlation

Momentum conservation

Jets

Termed "nonflow"

Not collective phenomenon



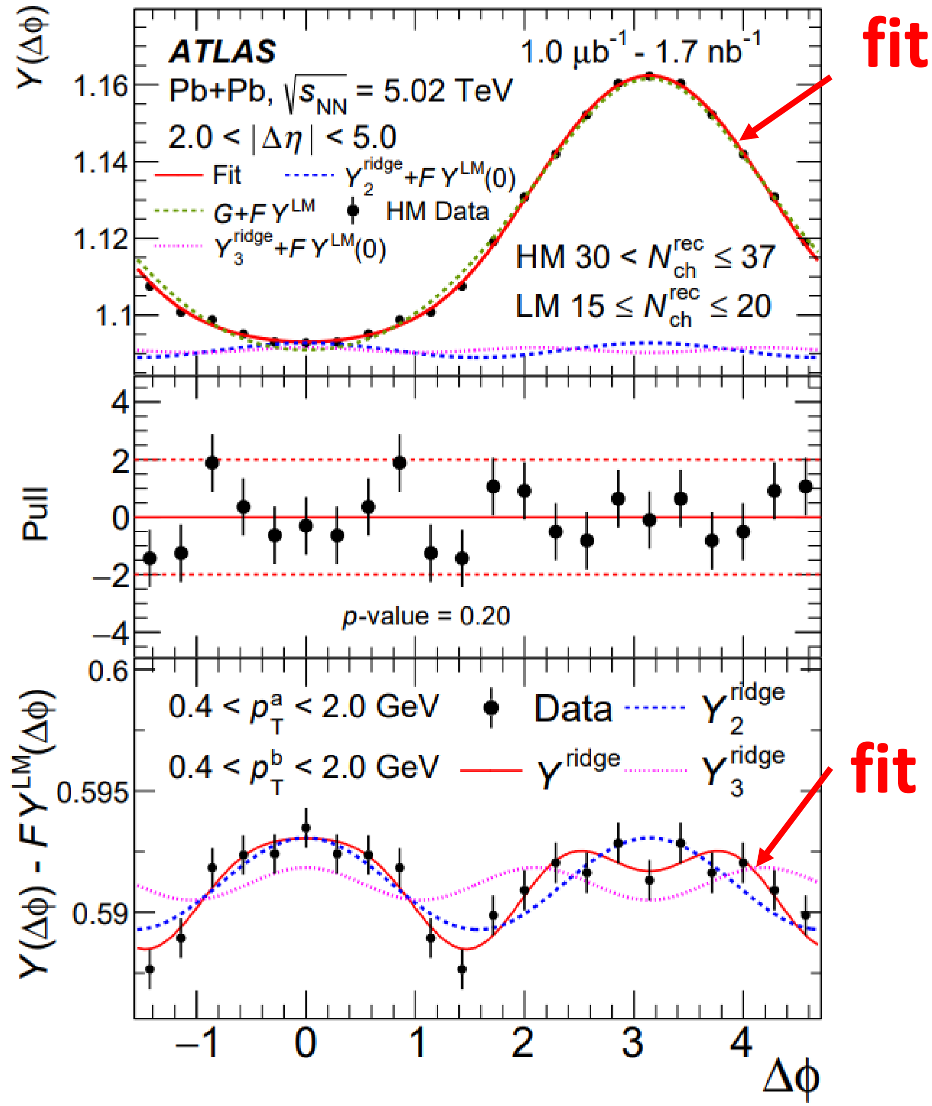
Need to remove nonflow

arXiv:2101.10771

Non-flow removal in γA correlations

High-multiplicity (HM) correlation data

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



arXiv:2101.10771

Non-flow removal in γA correlations

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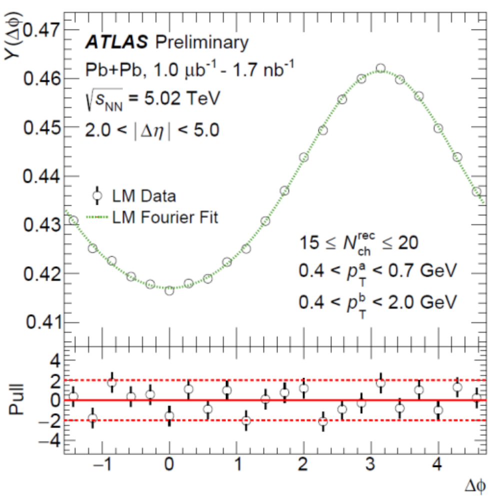
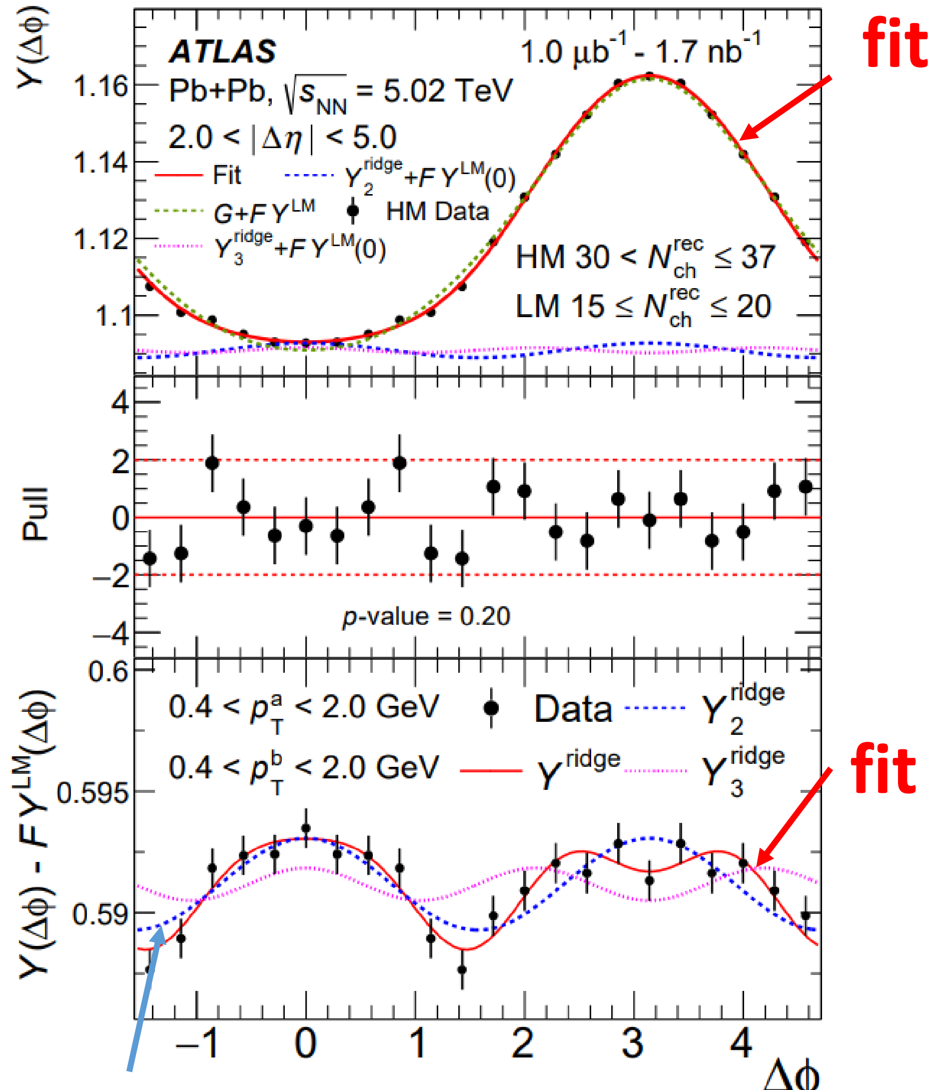


Nonflow subtraction

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

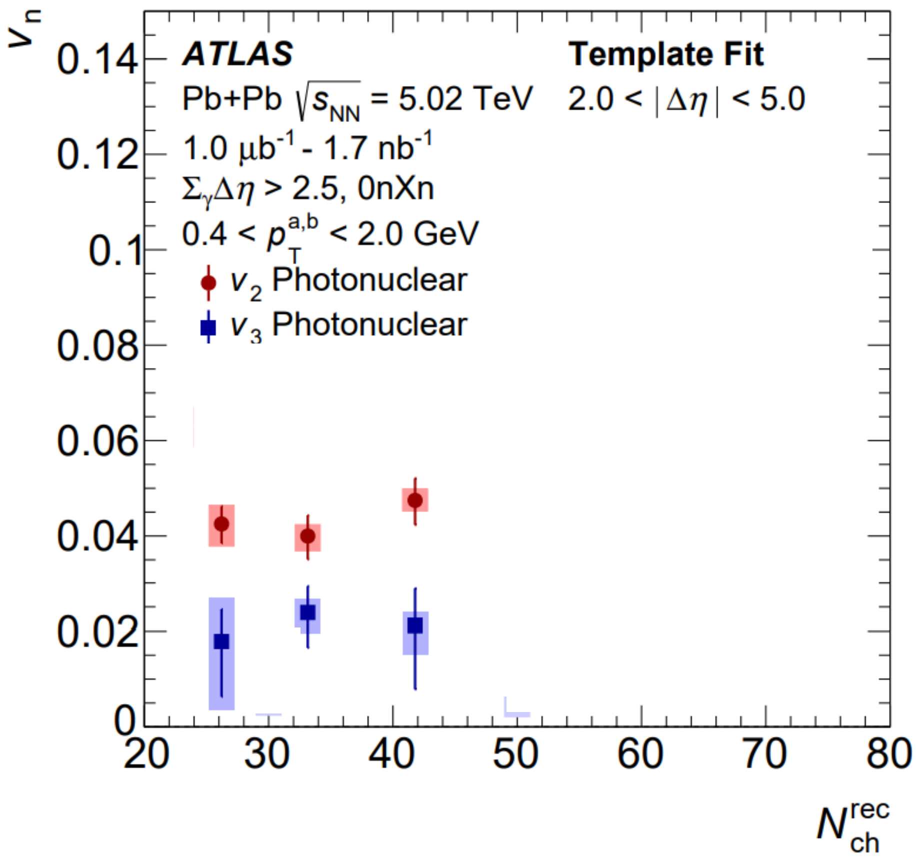
$$Y^{HM}(\Delta\phi) = FY^{LM}(\Delta\phi) + G\left\{1 + 2\sum_{n=2}^{3} v_{n,n}\cos(n\Delta\phi)\right\}$$



After nonflow subtraction clear cos(2Δϕ) modulation

arXiv:2101.10771

v_n in photonuclear collisions

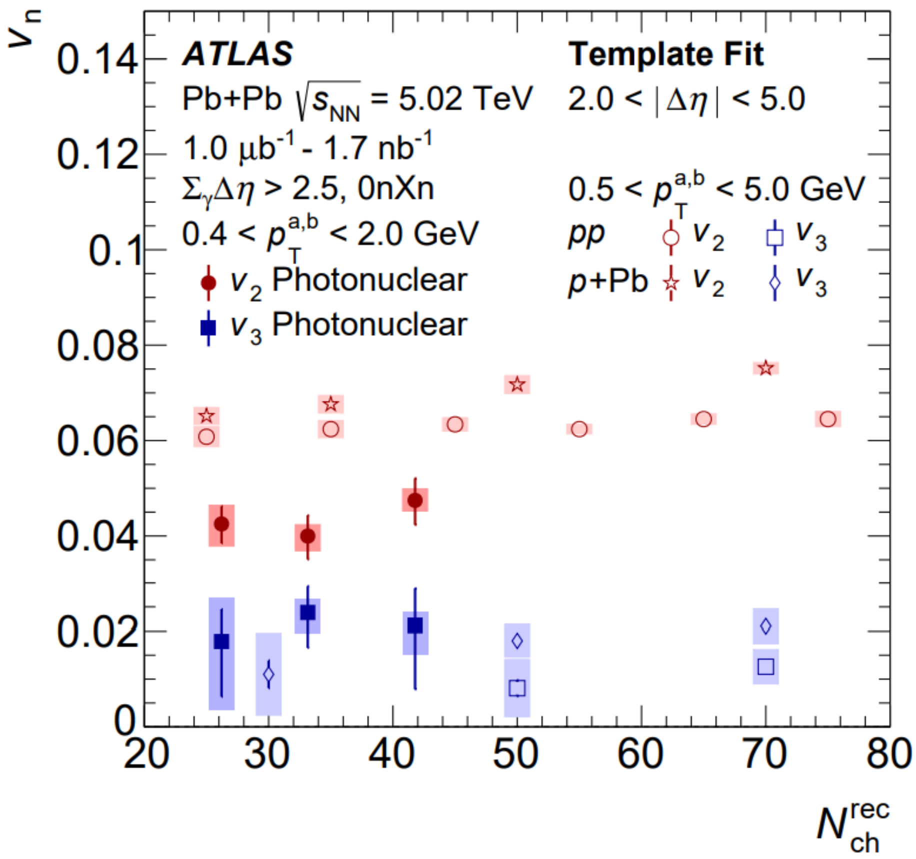


Significant nonzero v_2 and v_3 in photonuclear collisions

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

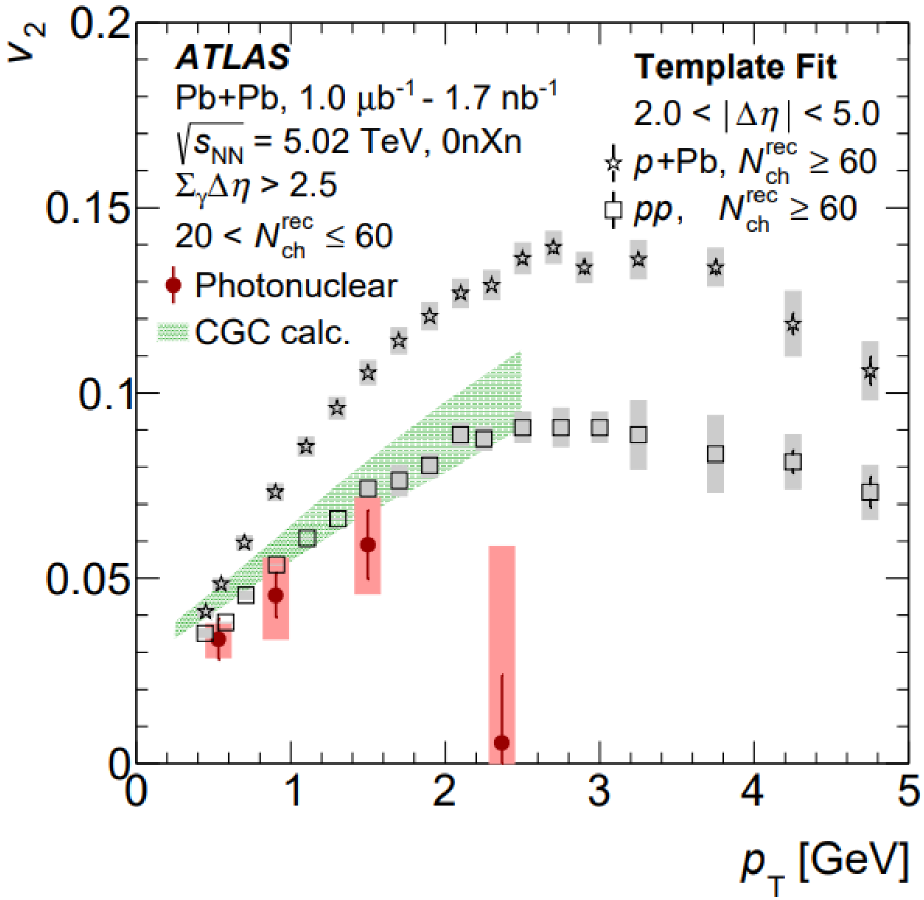
Flat $v_2(N_{ch})$ within statistical precision

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



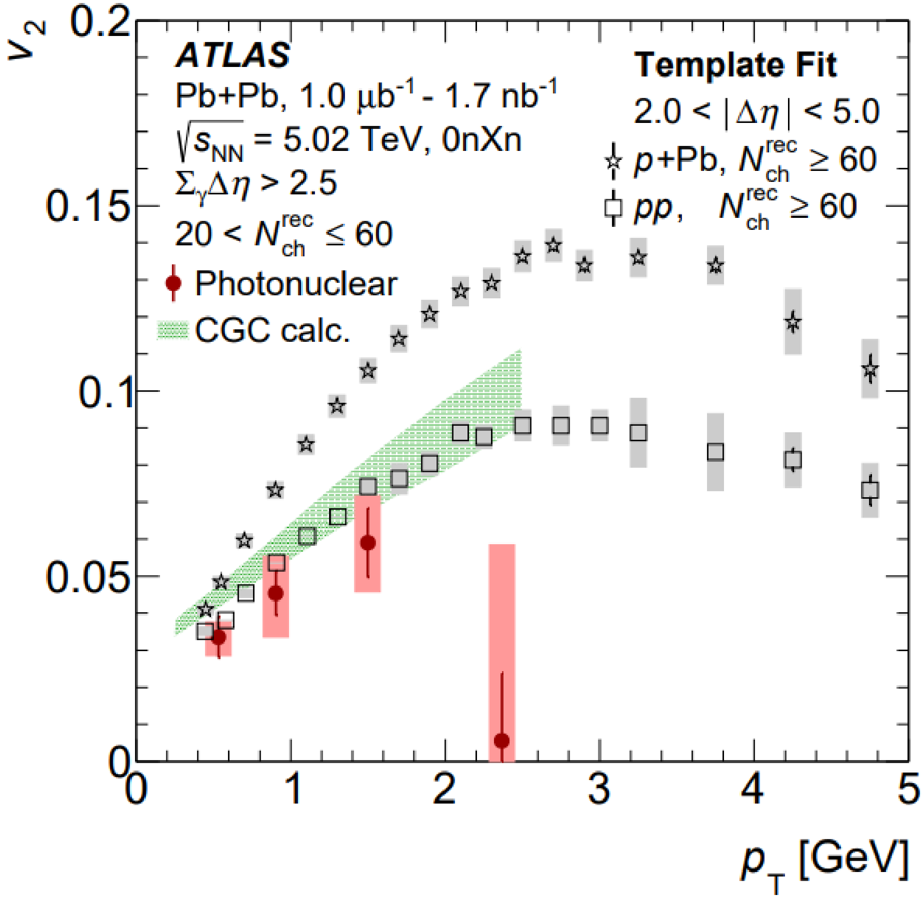
Similar trend in $v_2(p_T)$ as other hadronic systems.

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)

arXiv:2101.10771

$v_2(p_T)$ comparison with CGC calc.



Compared to Color Glass Condensate (CGC) framework calculation of γA $v_2(p_T)$ with $Q_s^2 = 5\ \mathrm{GeV}^2$ and $B_p^2 = 25\ \mathrm{GeV}^{-2}$

Model is consistent with data at low-p_T

Theory uncertainty from hadron fragmentation

arXiv:2008.03569

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 almost no 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.

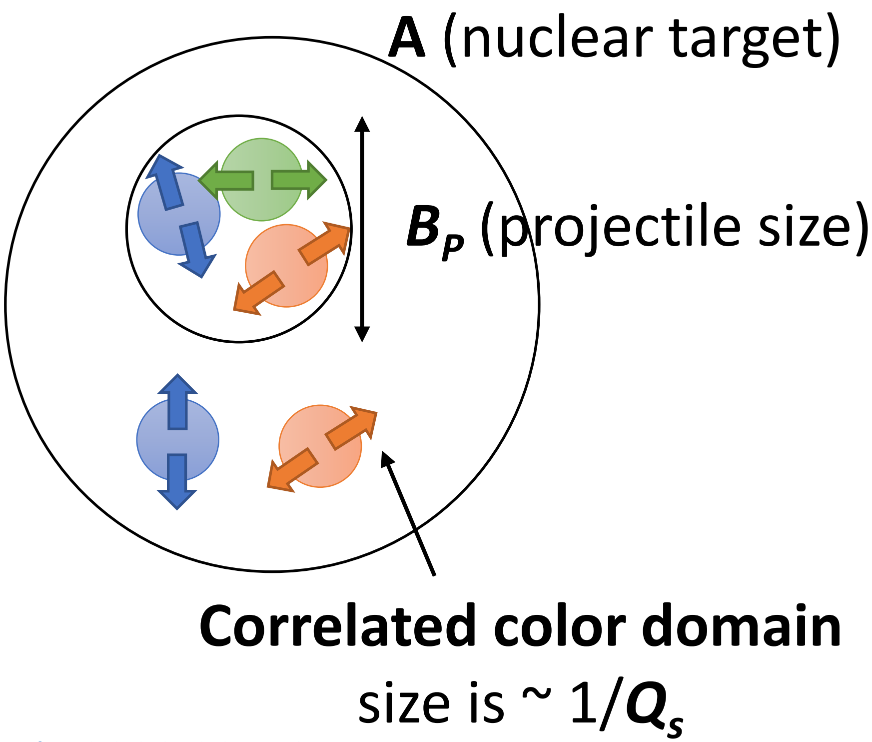
Initial state correlation

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

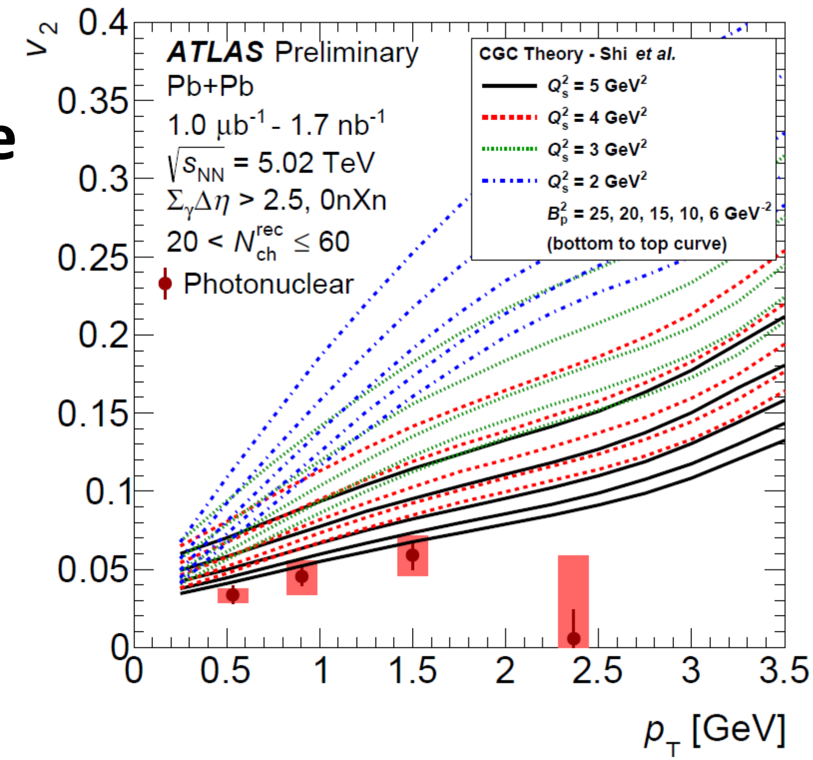
- A schematic CGC calculation is discussed in the next slide.

CGC model comparison

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



arXiv:2008.03569

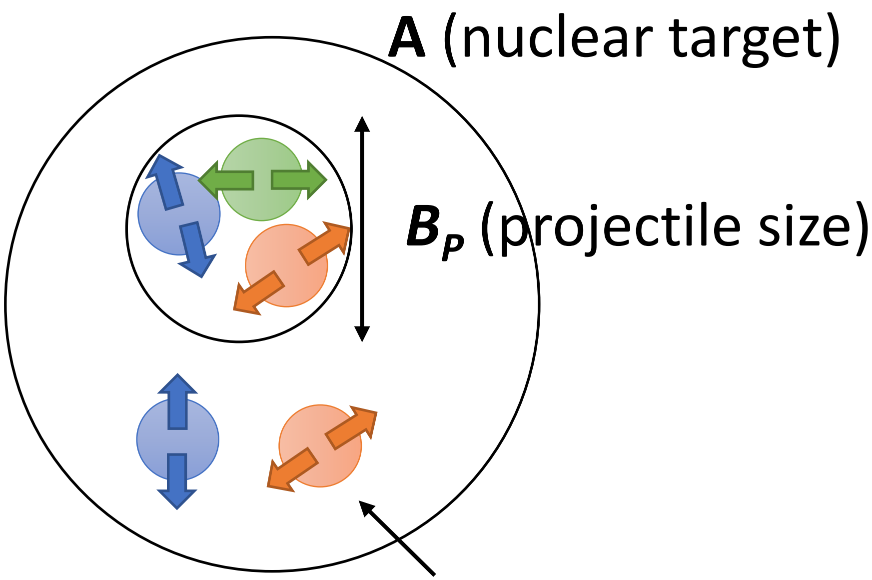


- Larger number of domains struck → lower v_2
- Quasi-real photon is predicted to have large B_P

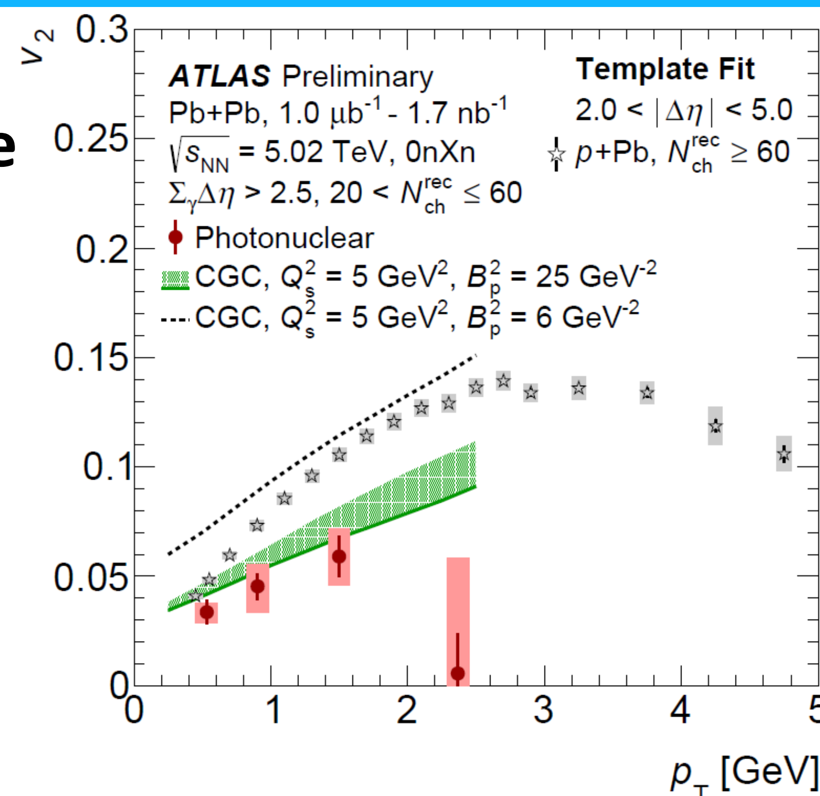
arXiv:2101.10771

CGC model comparison

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



Correlated color domain size is ~ $1/Q_s$

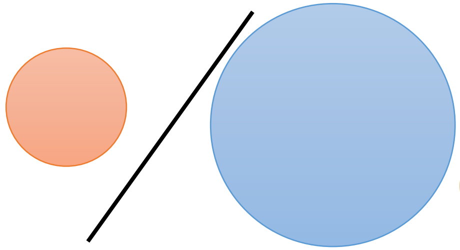


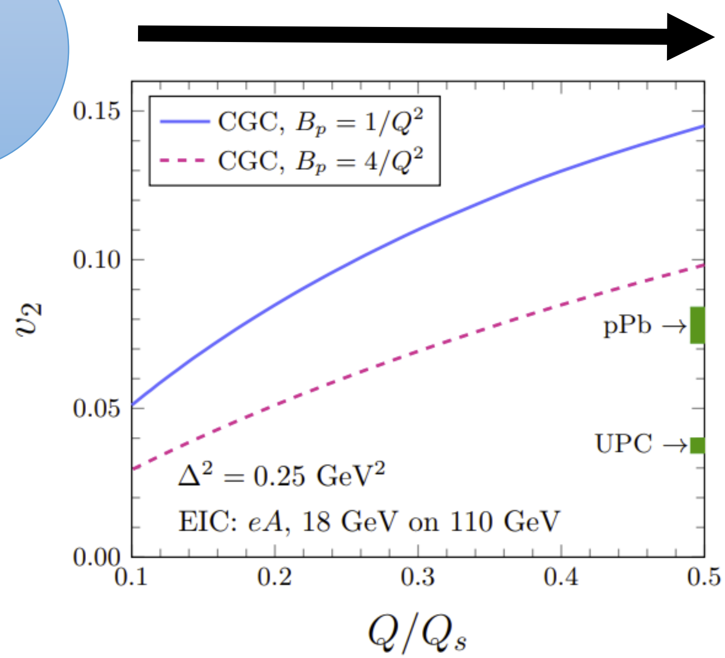
- Similar calculations describing p+Pb (arXiv:1808.09851)
- Difference in v_2 is a result of a smaller B_p^2 for a proton where $B_p^\gamma \sim 1/\Lambda_{QCD}$

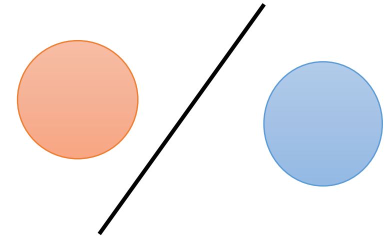
arXiv:2101.10771

CGC prediction at the EIC

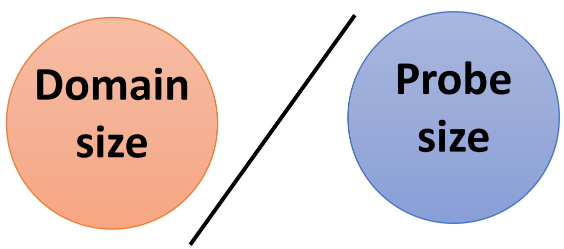
arXiv:2101.10771







Prediction only in low Q/Q_s regime

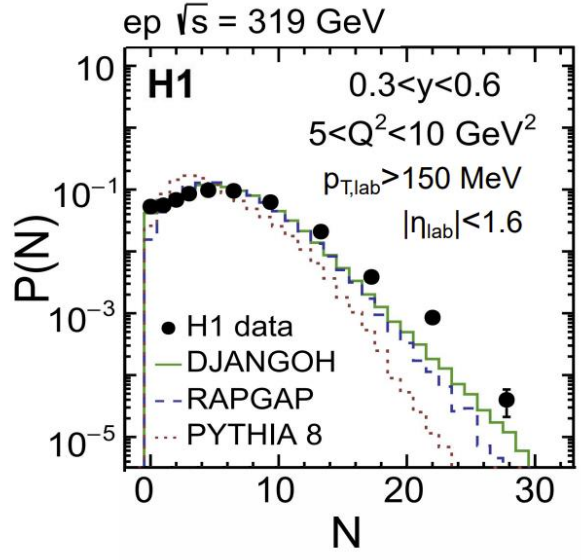


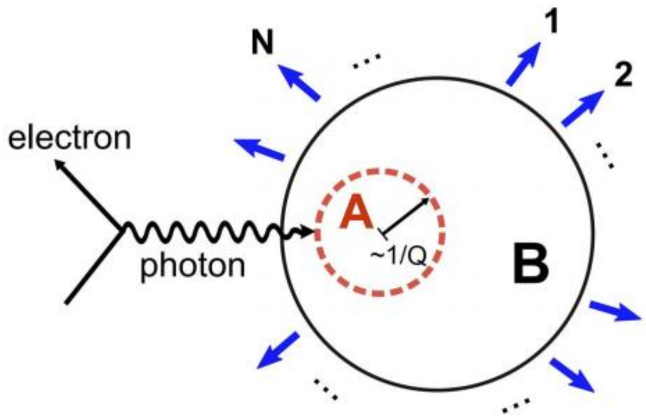
Deferring probe size would affect v_2 in a CGC or hydro picture

Constraints from DIS: *ep* at HERA

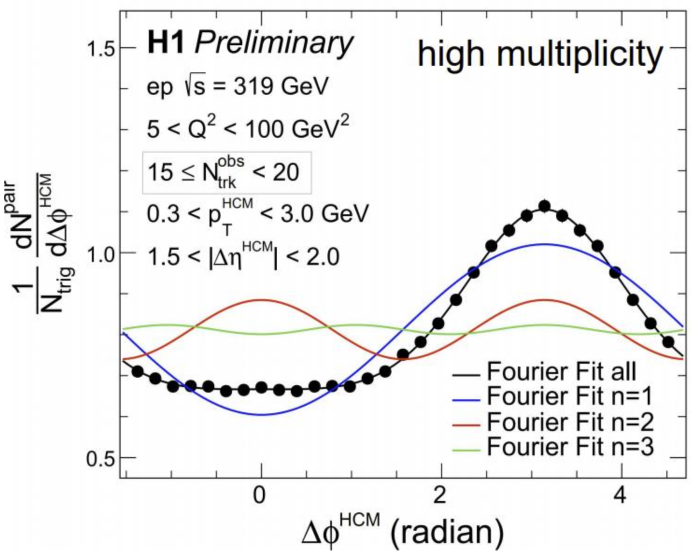
H1 detector at HERA *ep* collisions

- Dataset: 2006-2007
- Beam energy: E_e=27.6 GeV, E_p=920 GeV
- Much higher beam energy than CGC EIC predictions
- Lower multiplicites than LHC γA →





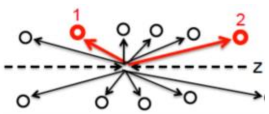
No near-side ridge →

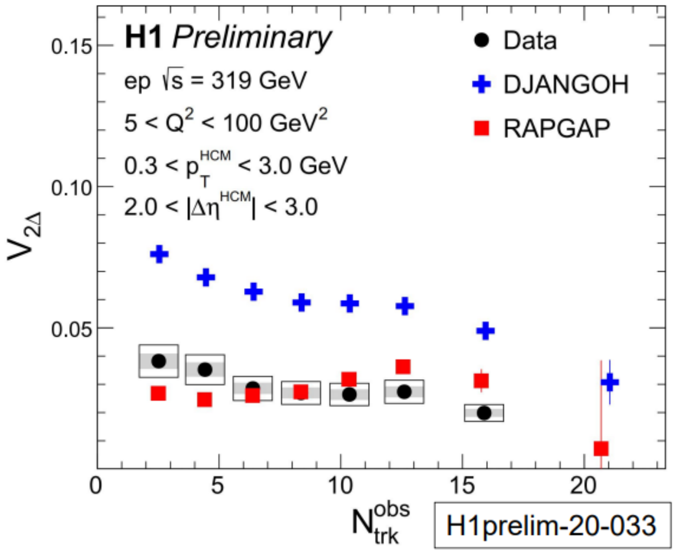


H1 searches in DIS and photoproduction

2-particle correlation →

- No nonflow removal
- Results **consistent with MC with no collectivity** (RAPGAP)



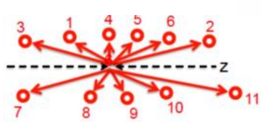


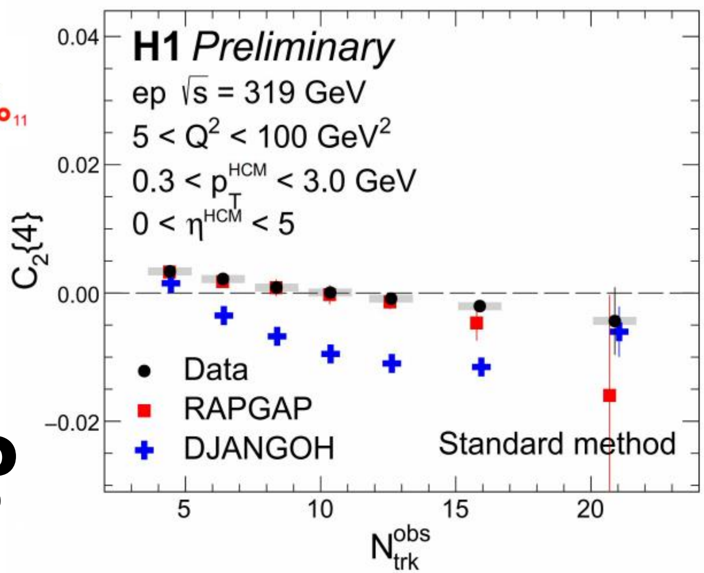
Multi-particle correlations →

- Suppresses nonflow
- Negative $C_2\{4\}$ is associated with flow-like signal

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

- **Consistent with MC w/o collectivity**



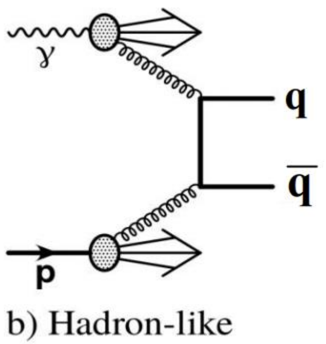


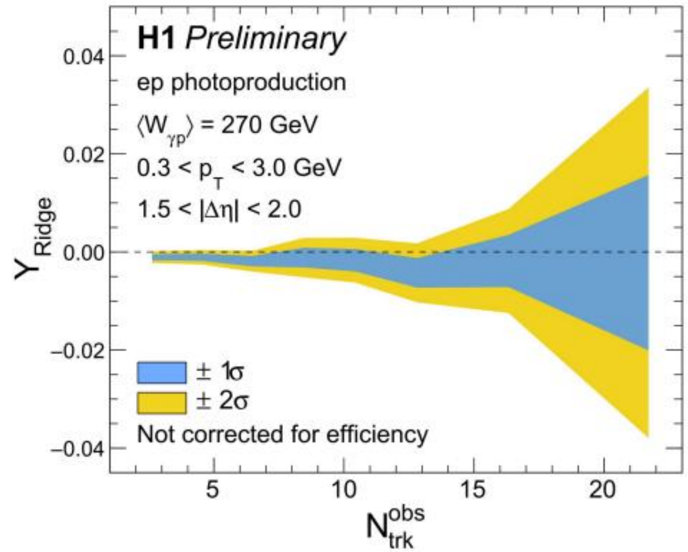
Extended geometry in DIS?

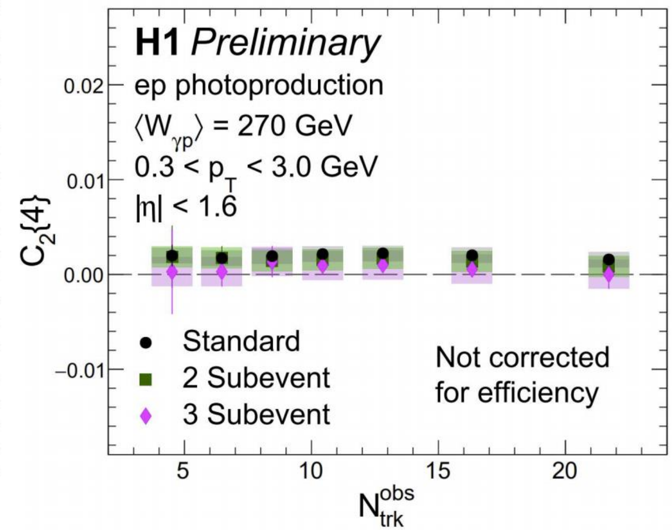
Chuan Sun, DIS 2021 H1prelim-20-033

H1 photoproduction results

ep photoproductio



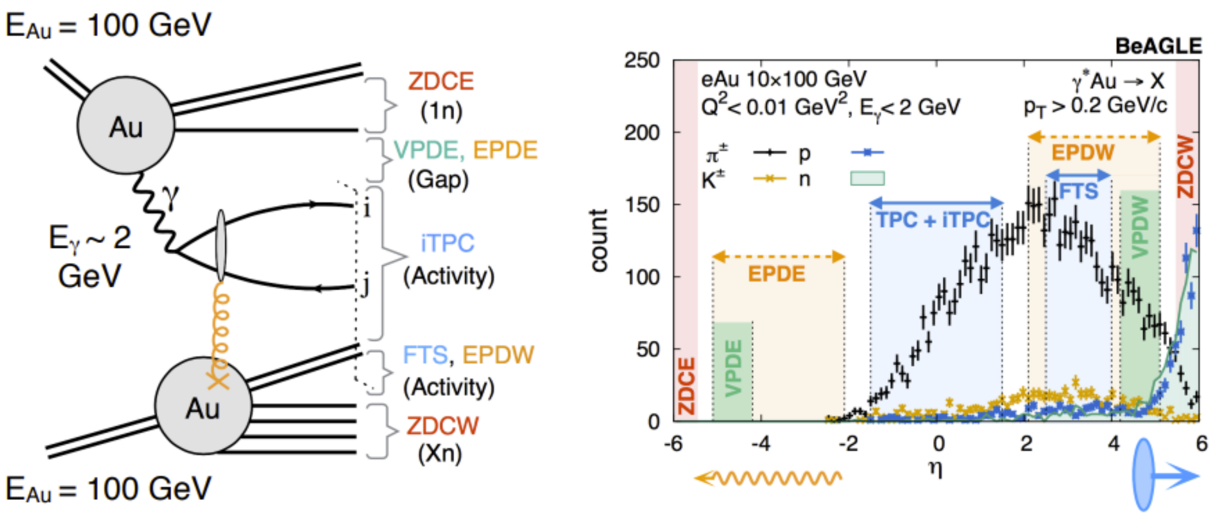




- 2-particle and multi-particle correlations indicate similar results as DIS (no obvious ridge yield)
- Q/Q_s is larger in *ep* photoproduction compared to γA at the LHC
- If applicable, the CGC calculation shown earlier would naively predict a larger v_2?
- Further studies could be more directly comparable such as similar treatment of nonflow in ep and multi-particle correlations in γA

γ +Au with STAR

Anticipated Run 2023 with Au+Au 200 GeV



If a high statistics Au+Au 200 GeV dataset if accumulated by STAR from the anticipated 2023 run of RHIC it will provide a golden opportunity to study photonuclear events with the forward upgrades. The same can be done in the photo production limit of e+A at EIC. Key measurements: 1. ridge 2. chemistry (pi/k/p yield) and how they change when compared to hadronic events at the same multiplicity.

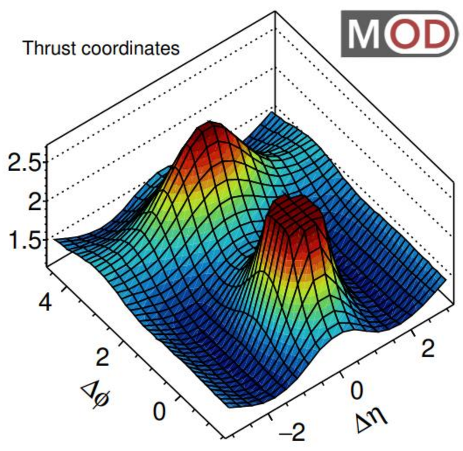
https://indico.bnl.gov/event/10184/contributions/47998/attachments/34717/56504/cfns_collectivity_
n_photonuclear_star_future_v1.pdf

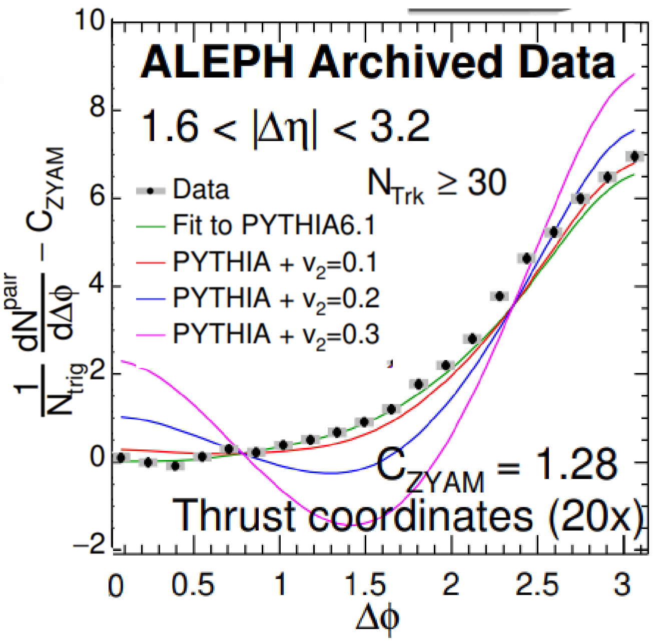
Collectivity searches in e^++e^-

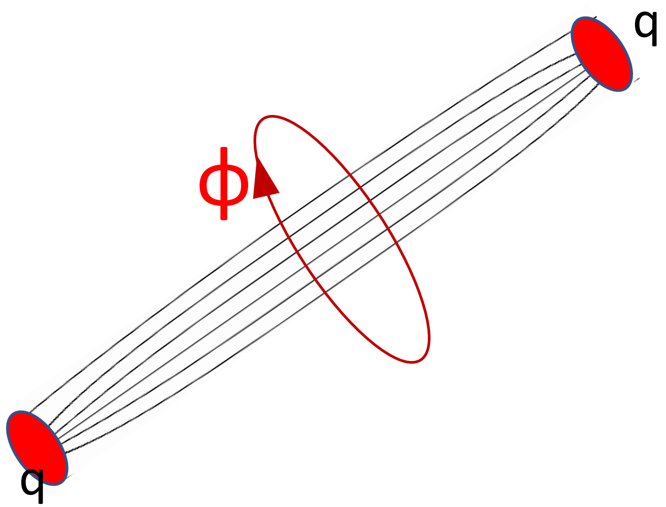
2-particle correlation in e^++e^-

arXiv:1906.00489

- Utilizes both detector coordinates and thrust coordinates (below)
- Large amount of nonflow – could it be removed?







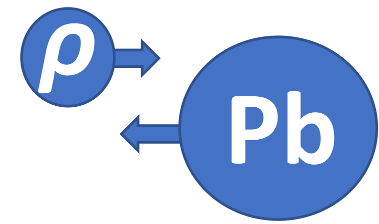
No obvious extended (in *η*) geometry in e^++e^-
Would not necessarily expect ridge even if collective effects exist

Conclusions

Results

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

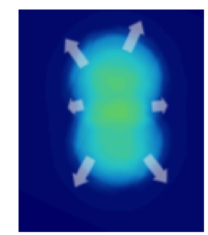
- Intuitive property of hadronic-like photonuclear collisions (photon → vector meson).



Theory

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

Quantitative comparison between e*p* photoproduction and γA

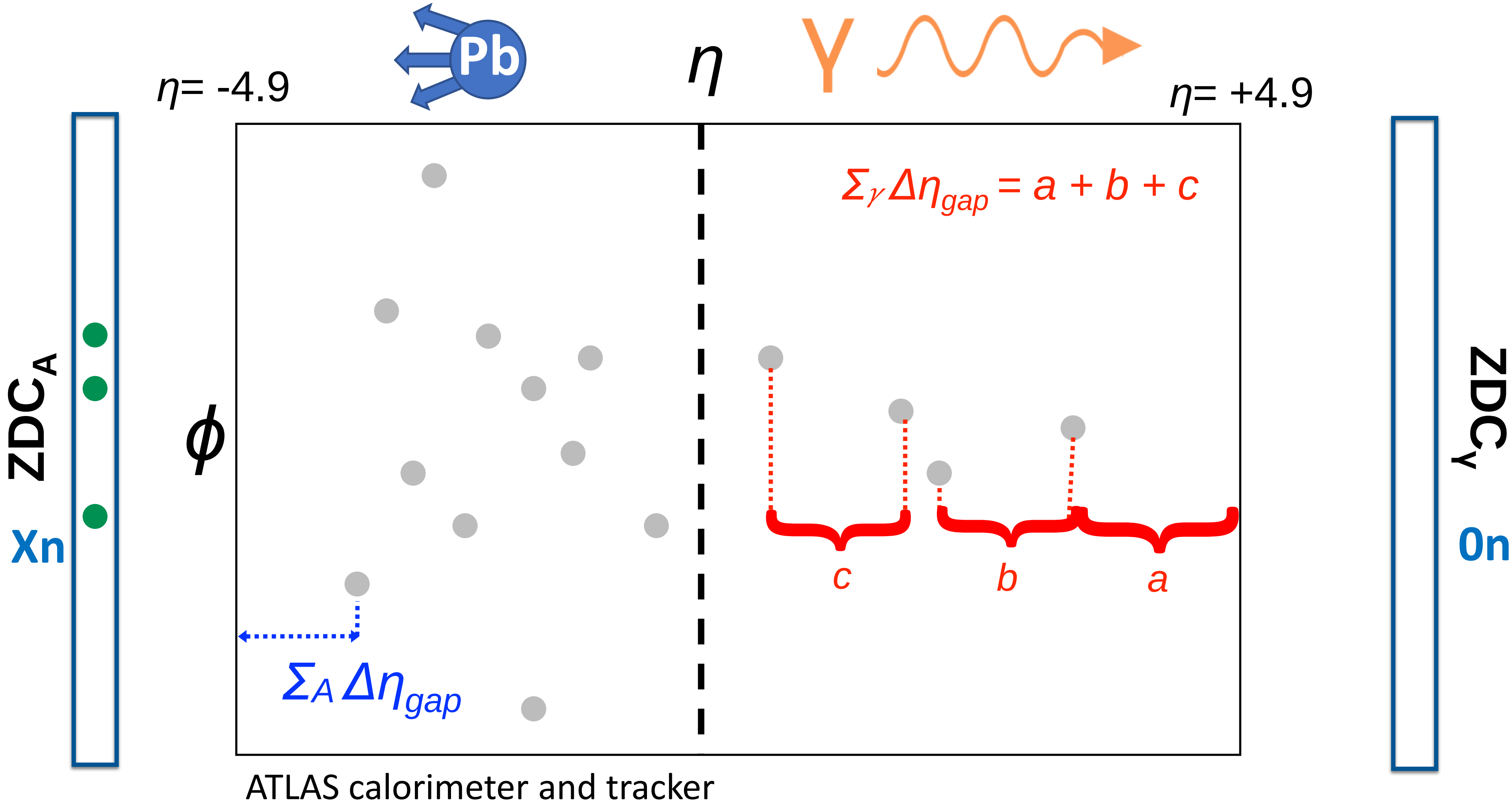


Future study in γA

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

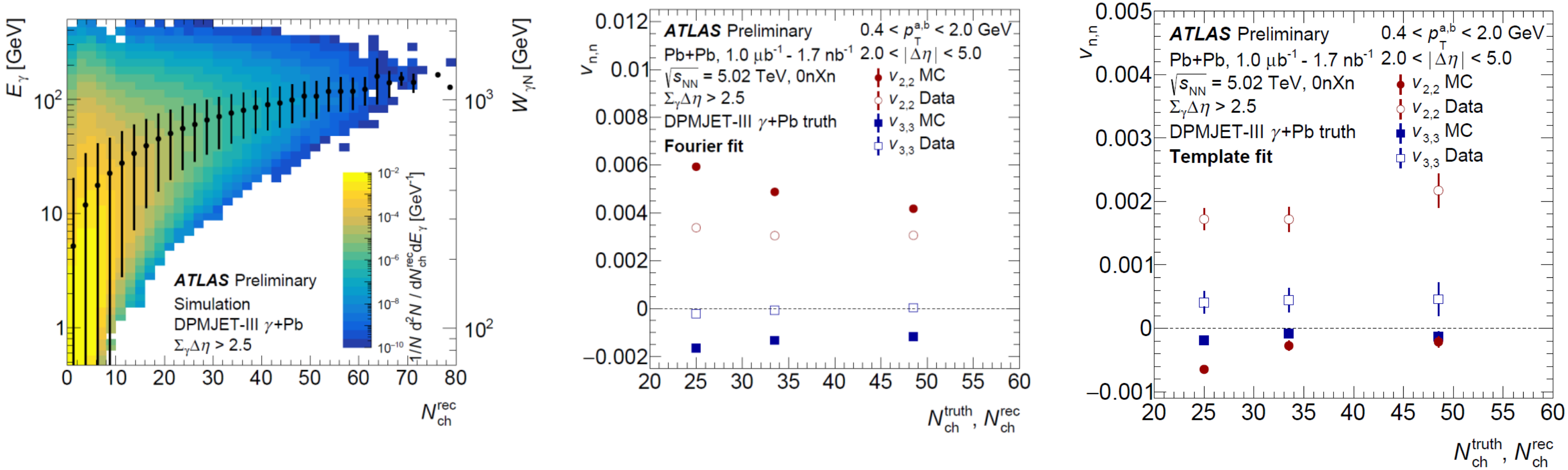
Thank you

Gap definition (detector roll-out)



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

Comparison to DPMJET-III

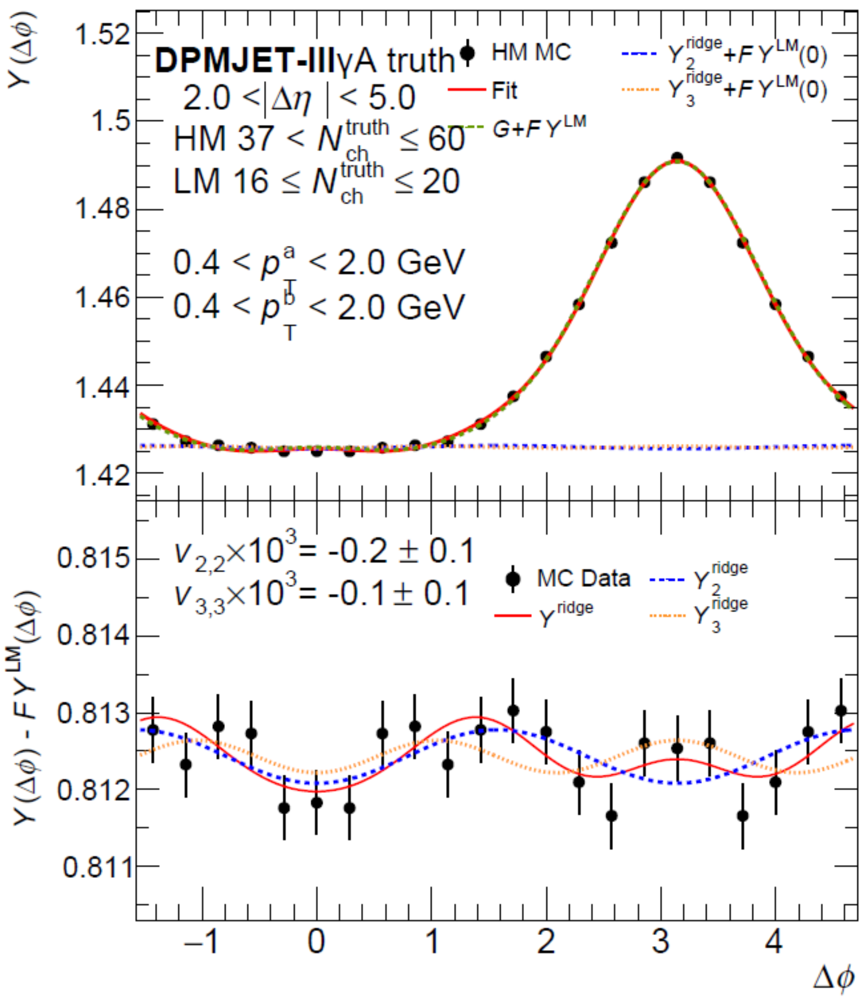


- DPMJET-III predicts the photon energy changes by about 1-2 standard deviations over the multiplicity range of the measurement and a doubling of the mean $W_{\gamma N}$ for 10 to 60 N_{ch}^{rec}.
- Large difference between measured $v_{n,n}$ before and after template nonflow subtraction for data and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

CERN-EP-2020-246

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.



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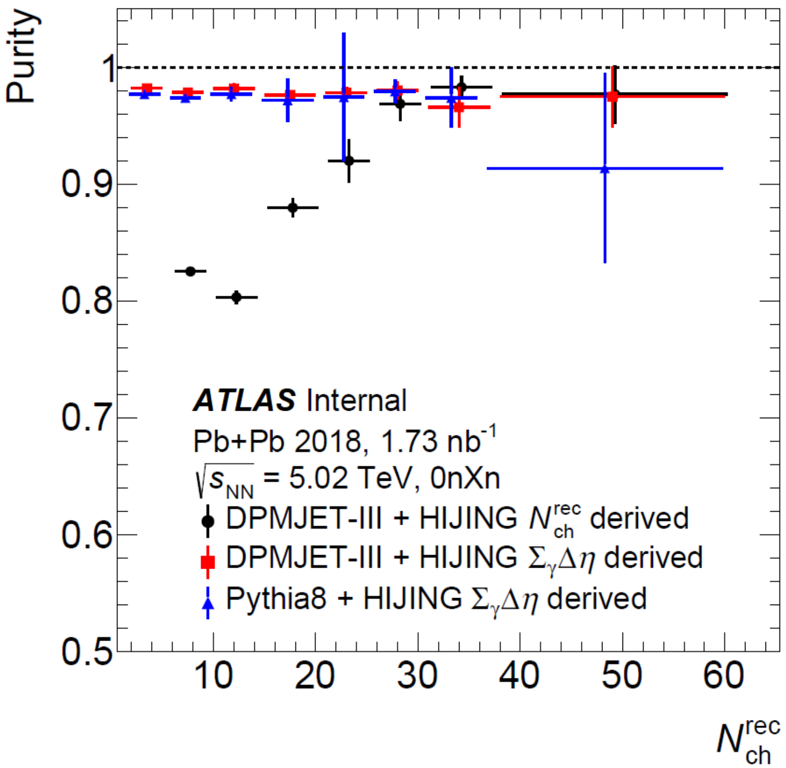
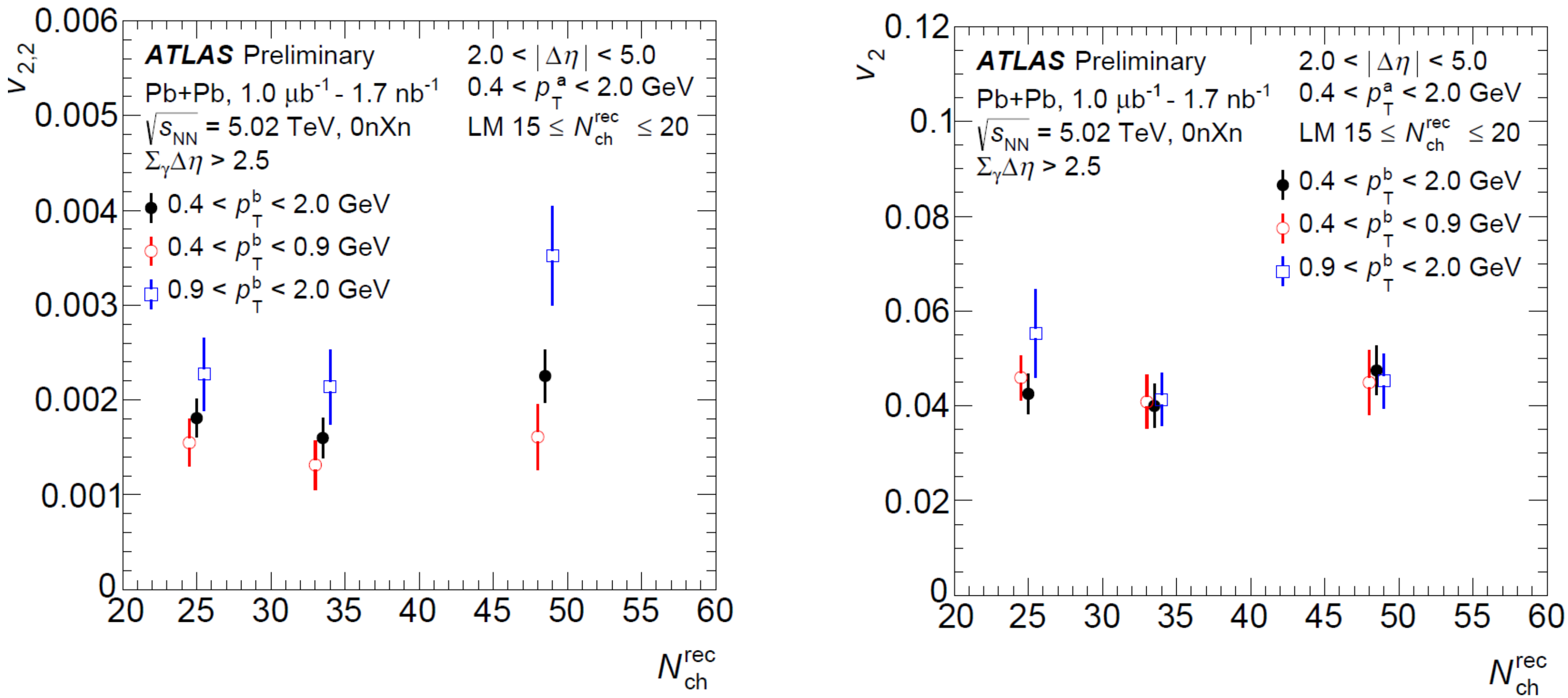
Purity of the photonuclear selection



- 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* $\Delta\phi$ 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.

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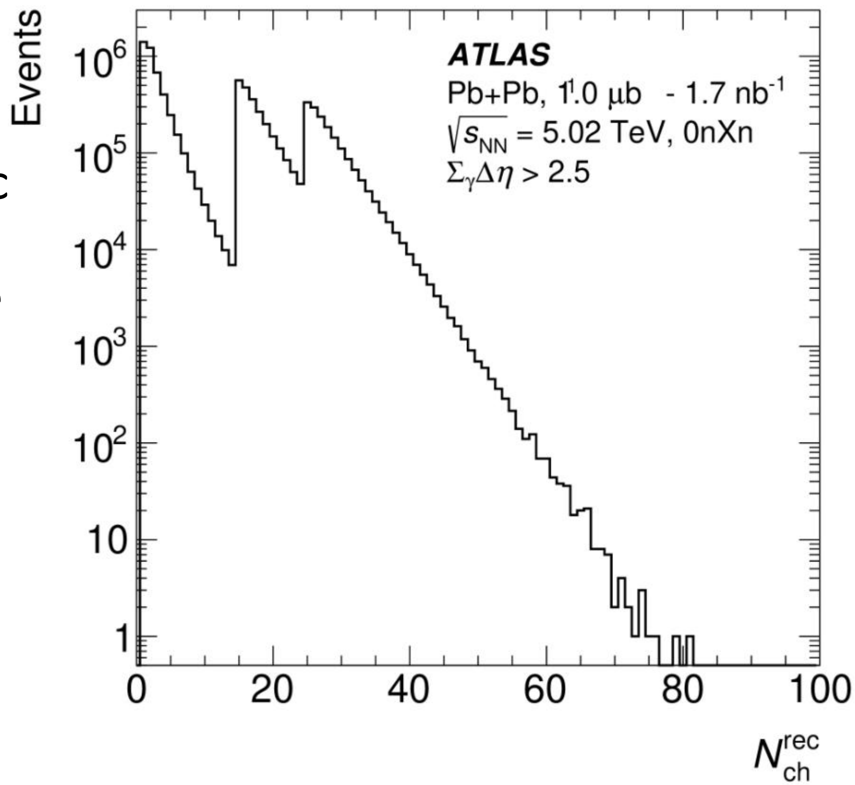
Triggering on photonuclear events

Triggering included

- Level-1 requirements on
  - Minimum event activity to collect high-multiplicity γA events
  - Maximum event activity to reject hadronic Pb+Pb collisions
  - Single-sided nuclear breakup (zero-degree calorimeter).
- High-level trigger requirements on
  - Minimum number of tracks to collect high-multiplicity events
  - Maximum energy in photon-going FCAL ($3.2 < \eta < 4.9$)



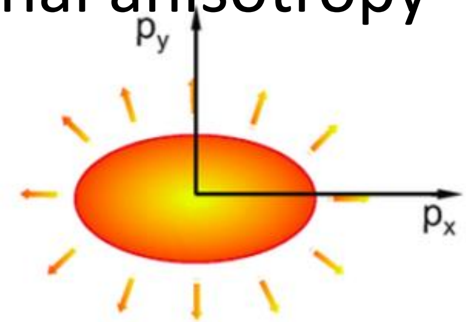
Due to trigger strategy, the high-statistics portion of the N_{ch} range is for $N_{ch} > 15$

arXiv:2101.10771

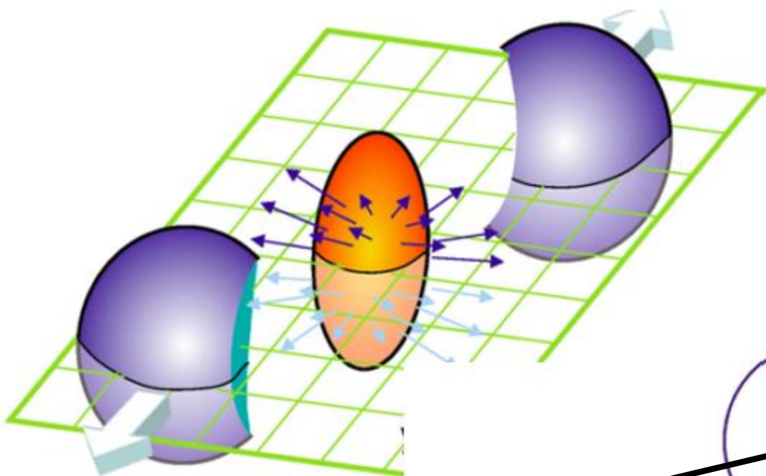
Origin of azimuthal anisotropy

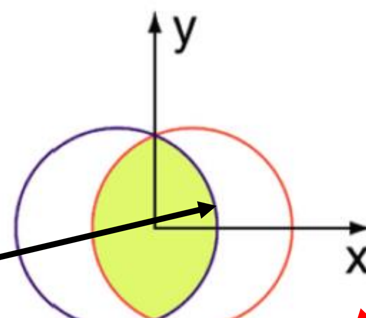
It has been largely established that hydrodynamic properties of the QGP governs many of the emergent phenomenon in HI

Initial geometry → Hydro → azimuthal anisotropy



final-state momentum anisotropies



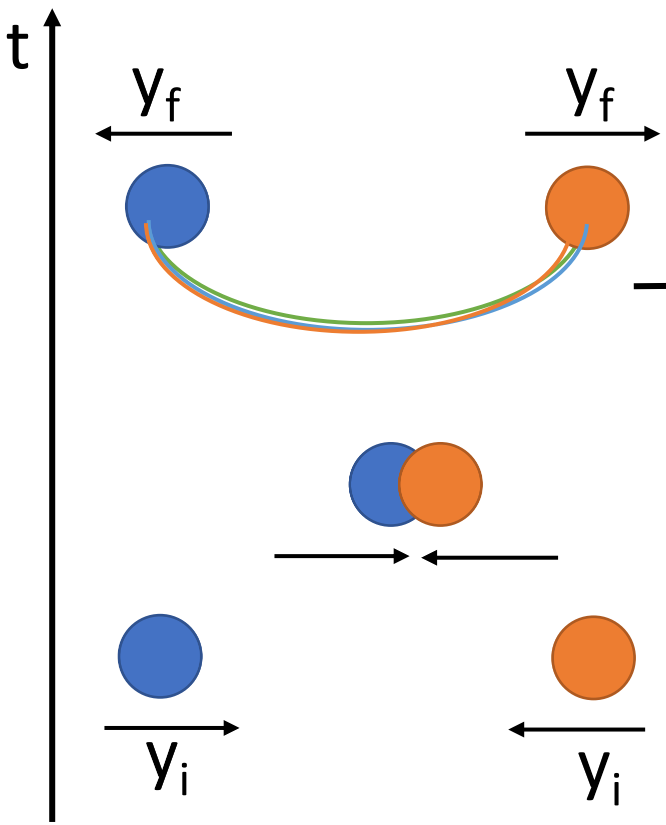


Hydrodynamic expansion

initial state geometry

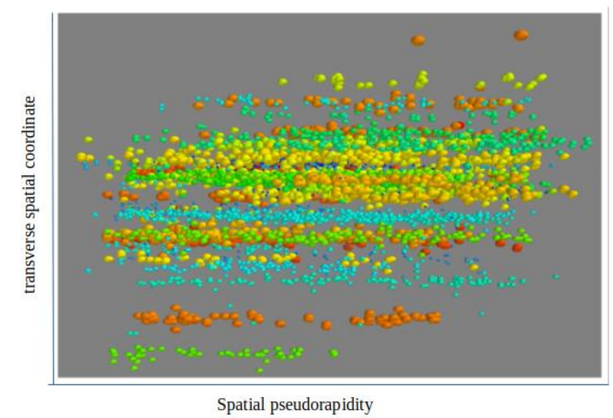
Average HI collision has elliptic initial energy deposition

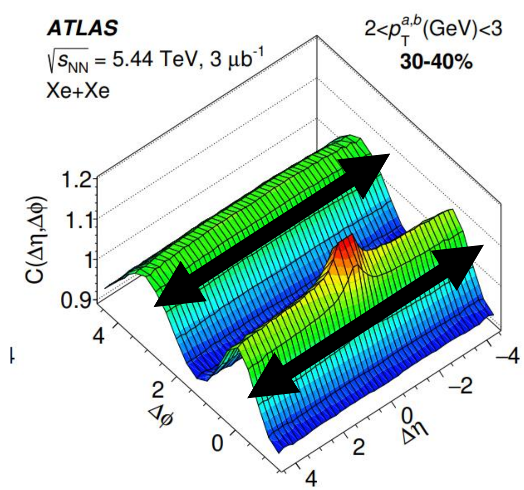
Long-range azimuthal anisotropy



Extended in transverse direction

arXiv:1511.04131



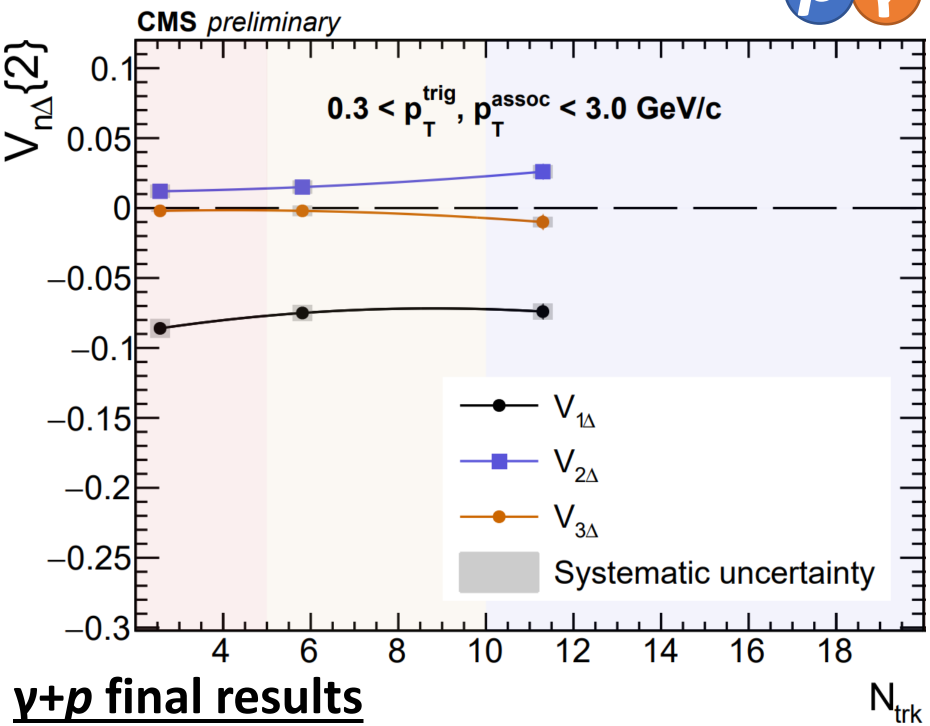


Long range in Δη

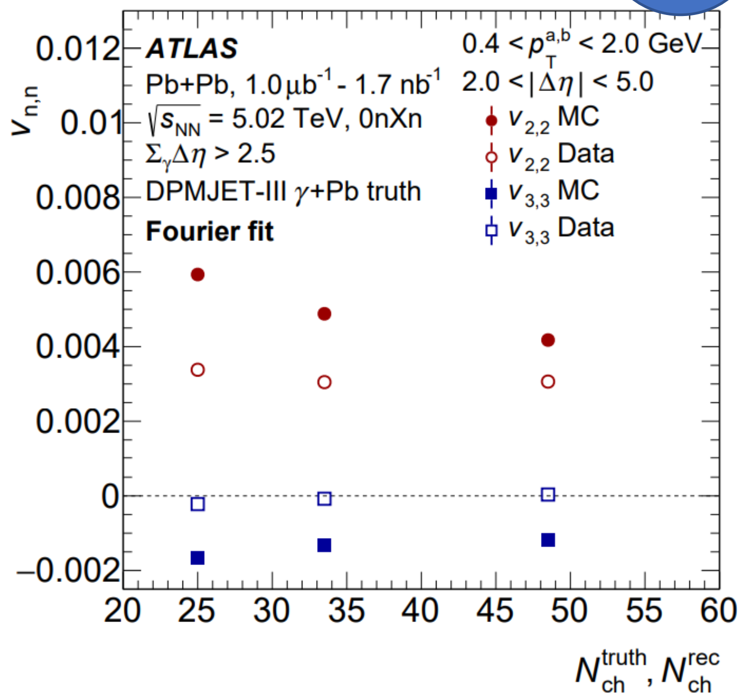
arXiv:1305.0609

Raw moments of 2PC (no non-flow removal)

CMS-PAS-HIN-18-008



arXiv:2101.10771

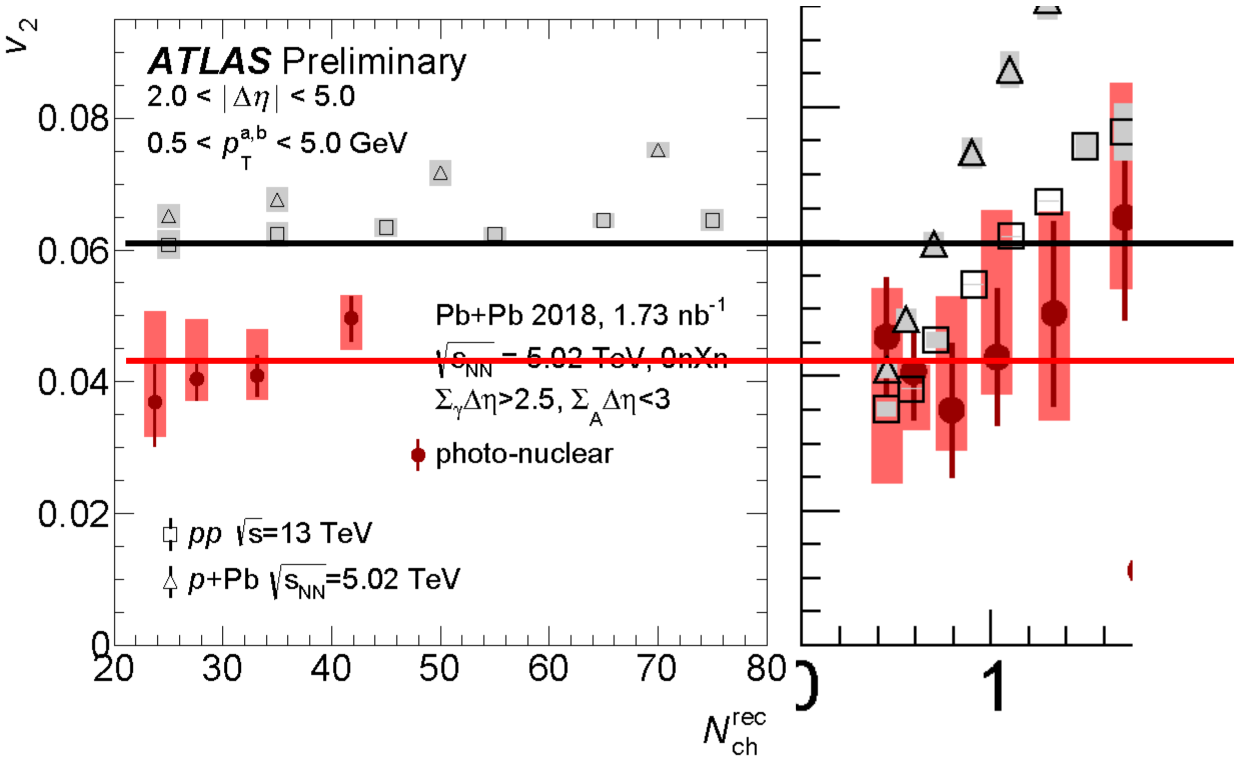


γ+*p* final results

- $v_{2,2}$ grows with N_{ch} – evidence of a dominant and N_{ch}-dependent-hardening jet shape
- Similar conclusion for $v_{3,3}$
- Although very different multiplicities, γ+*p* has a much stronger correlation than γ+A.

No trivial way of removing non-flow and require further study!

Consistency of N_{ch} and p_T in γA



Now on same y-axis scale

dN_{ch}/dη in γA collisions