Measurements of long-range correlations in photon-hadron collisions at the LHC

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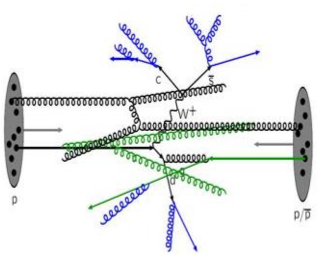
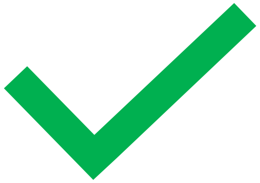
APS GHP, 2021, April. 16th

Which small systems do we know flow?

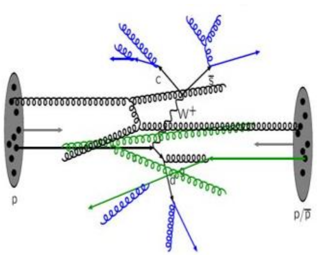
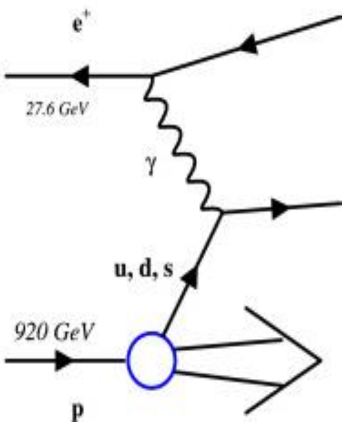
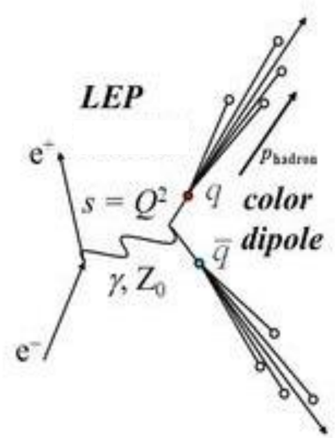
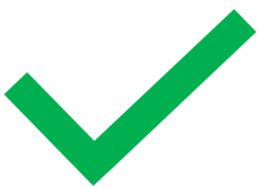
pp





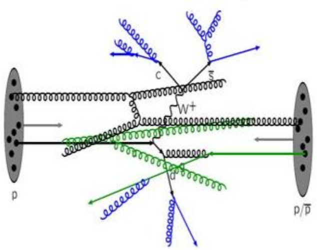
Near-side ridge

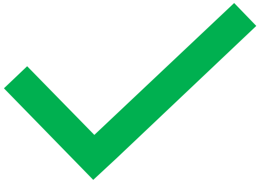
Which small systems do we know flow?

pp	e+*p*	$e^+ + e^-$
		
		
Near-side ridge	Cumulants say v_2< 4%	No near-side ridge
	arXiv:1912.07431	arXiv:1906.00489

Which small systems do we know flow?

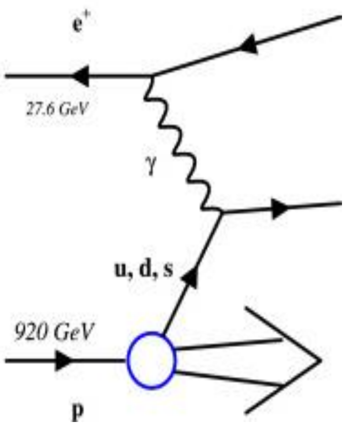
pp





Near-side ridge

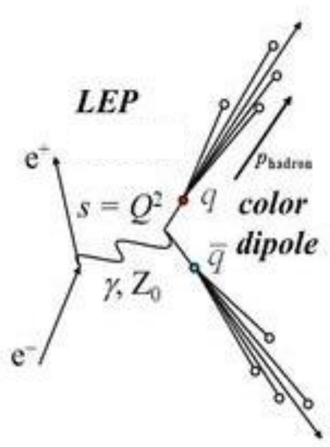
e+*p*



Cumulants
say v_2< 5%

arXiv:1912.07431

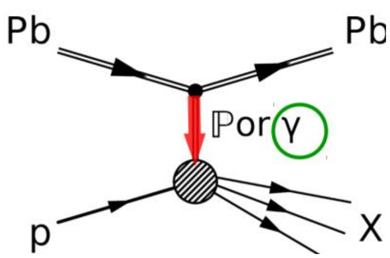
e^++e^-



No
near-side ridge

arXiv:1906.00489

γ+*p*



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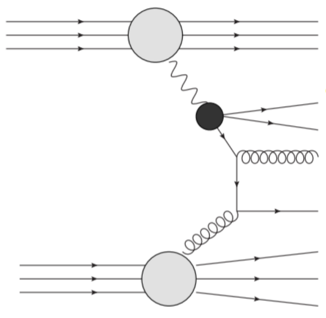
γ+A



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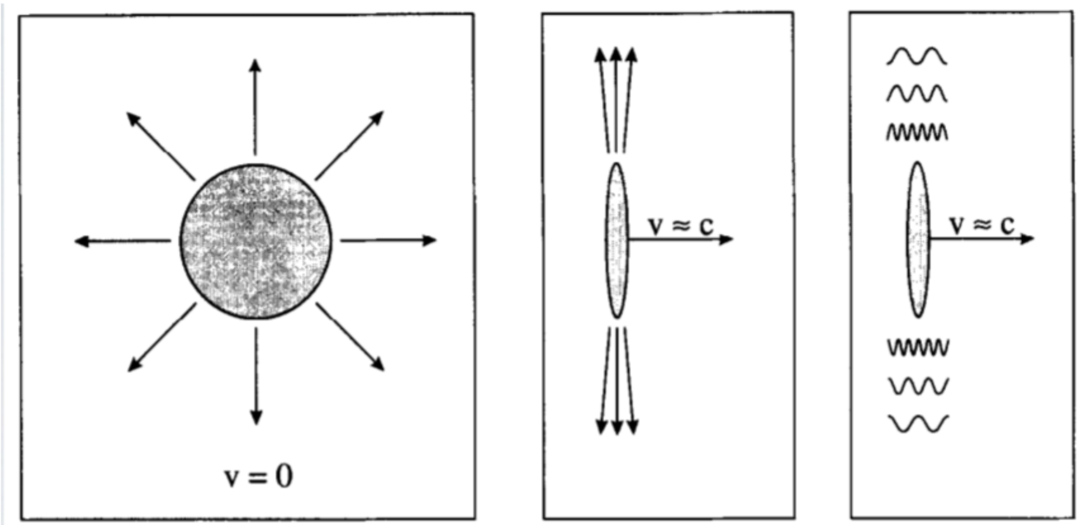
Ultra-peripheral collisions at the LHC

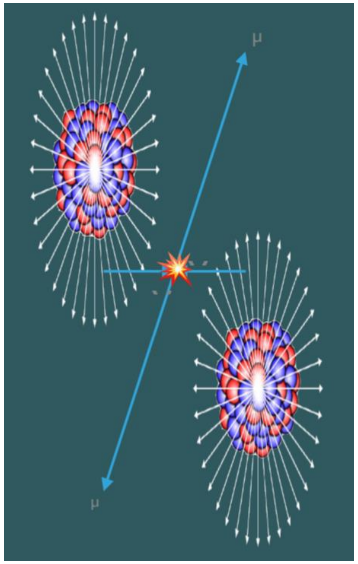


Coulomb fields of moving charges can be treated as an equivalent flux of photons which are boosted to high energies.

Photons reach energies of 10s of GeV with a 2.5 TeV Pb beam at the LHC

When $b > 2R_A$ two categories of interactions

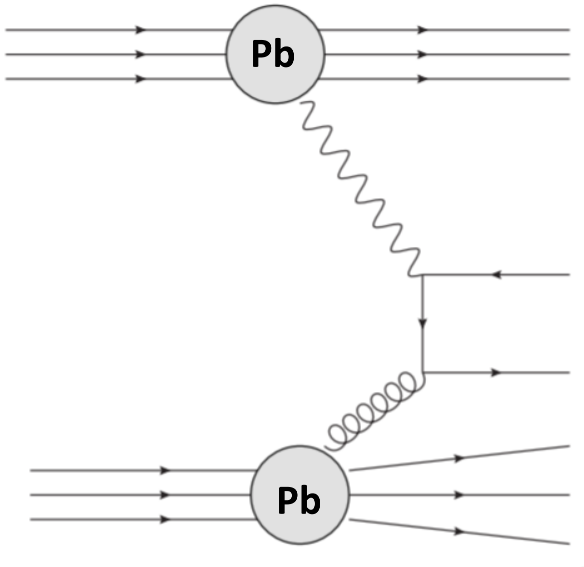
- Pure EM processes
  - γγ → γγ arXiv:1904.03536 & arXiv:2008.05355
  - γγ → μμ arXiv:2011.12211
- Photo-hadron interactions
  - γ + A → A* + V
  - γ + A → X



Photonuclear interactions

Direct γA collisions

Photon couples directly to nuclear parton



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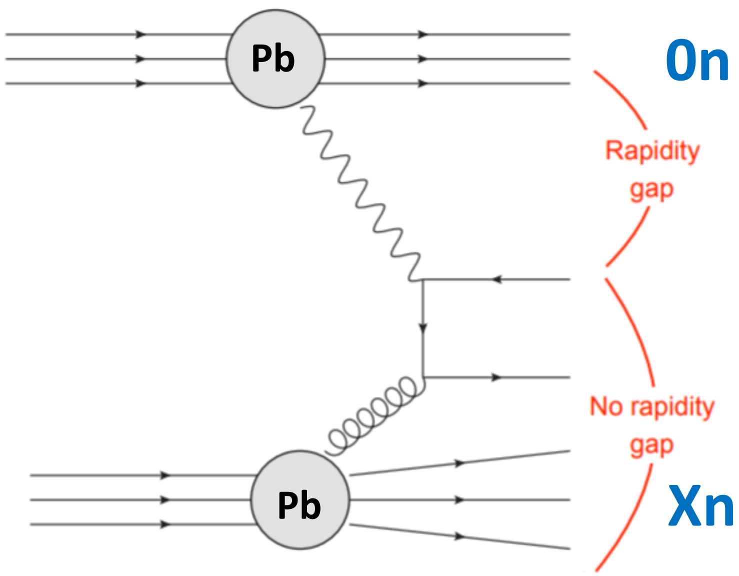
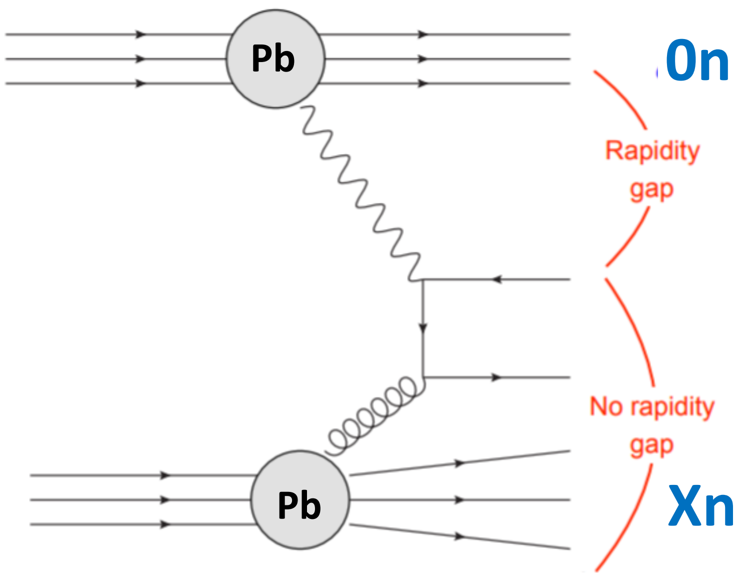
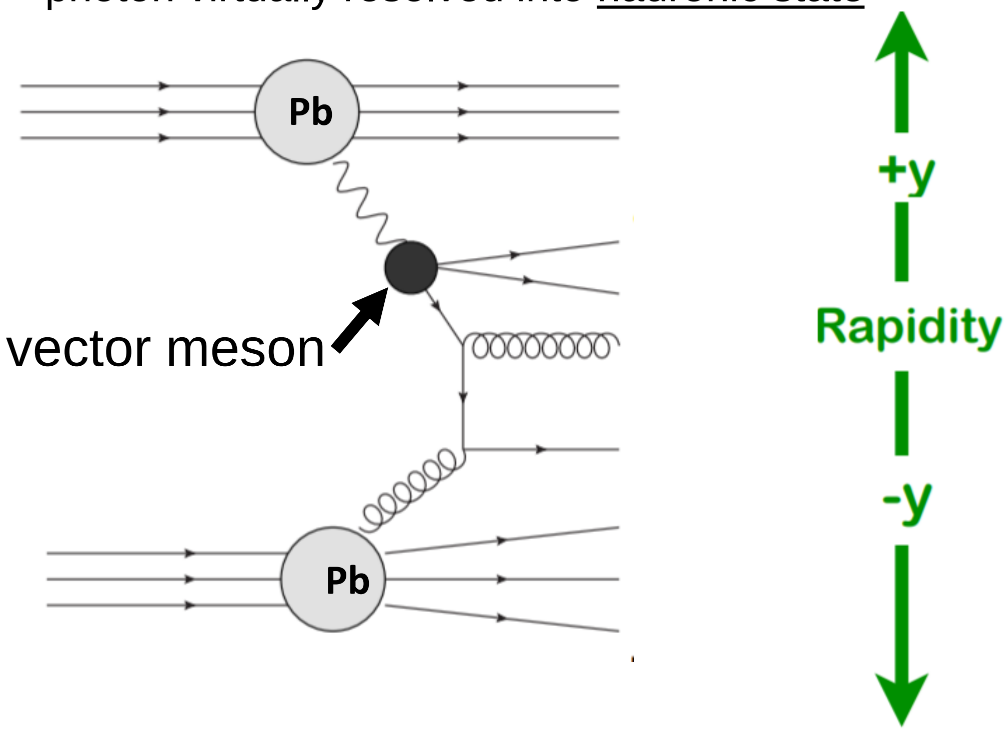


Photonuclear interactions

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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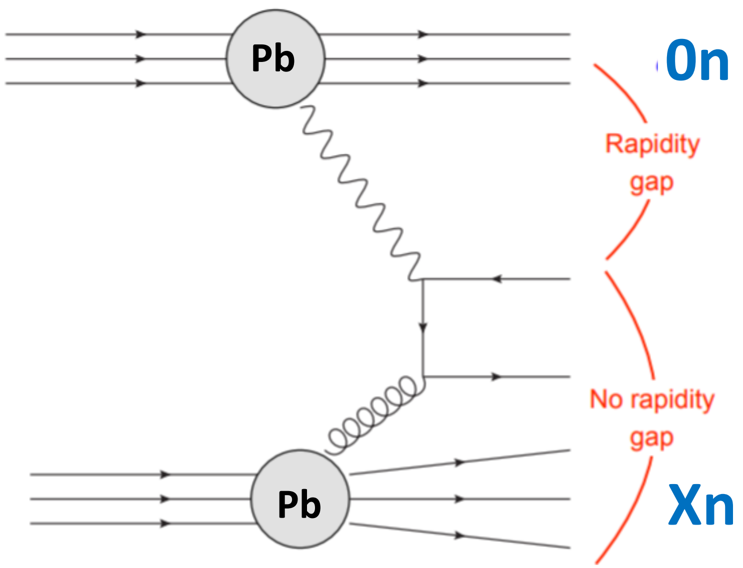
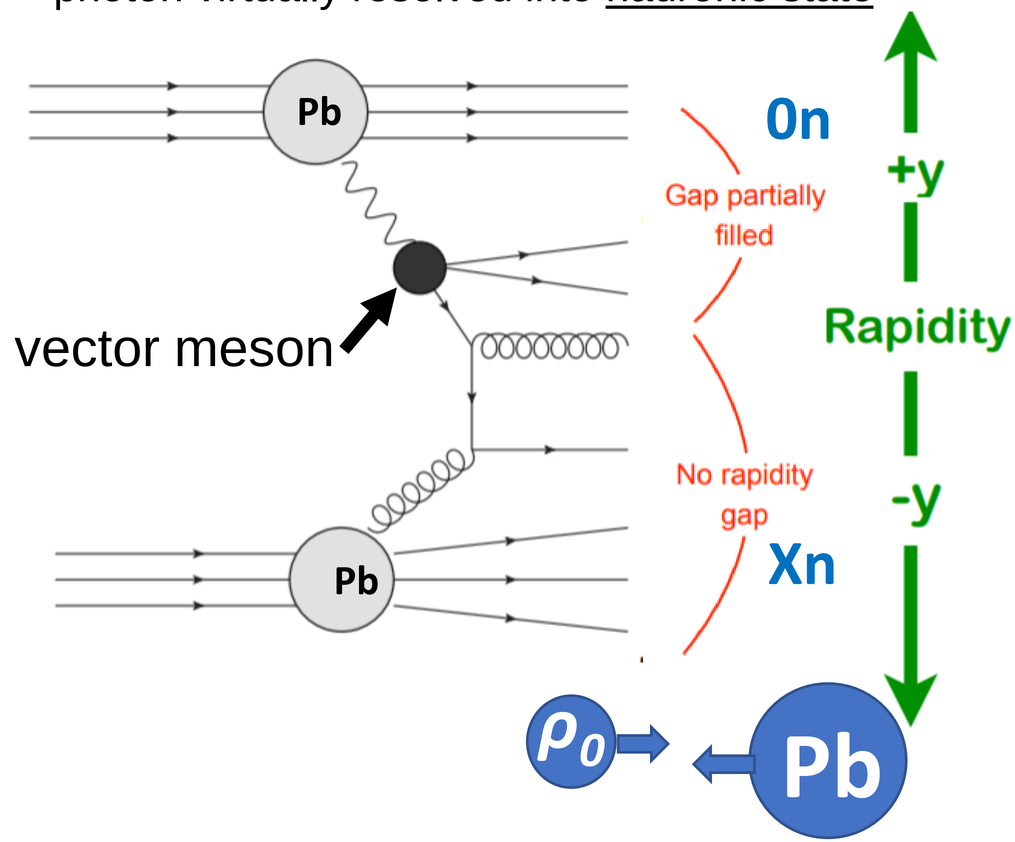


Resolved γA collisions

photon virtually resolved into hadronic state

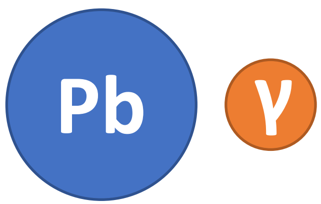


Select events based on primarily

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

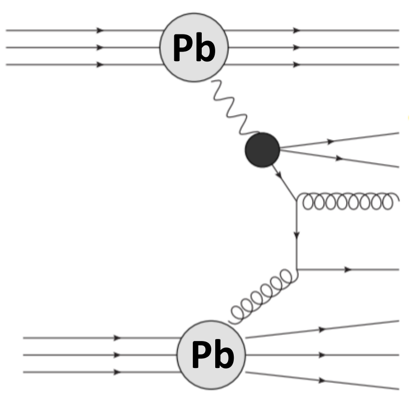
Minimum bias selection includes both but is dominated by resolved events.

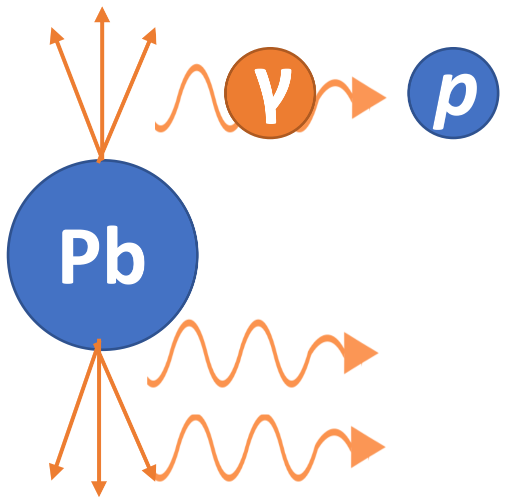
Presenting two measurements



2018 5.02 TeV Pb+Pb
Submitted to PRC
arXiv:2101.10771

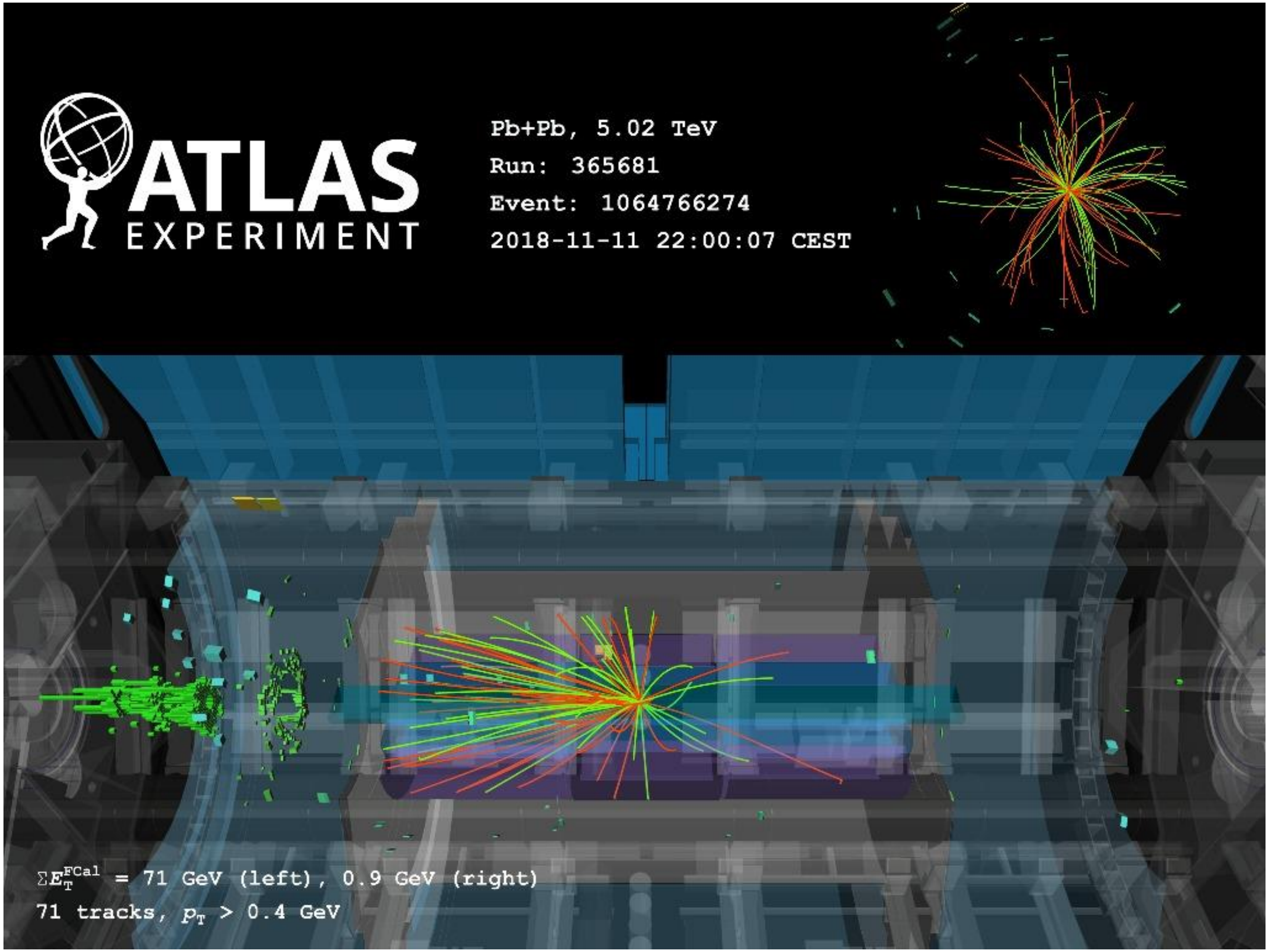
2016 8.16 TeV *p*+Pb
Preliminary
CMS-PAS-HIN-18-008





"High"-multiplicity photonuclear collisions

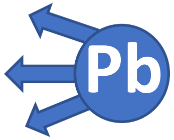
Pb going direction



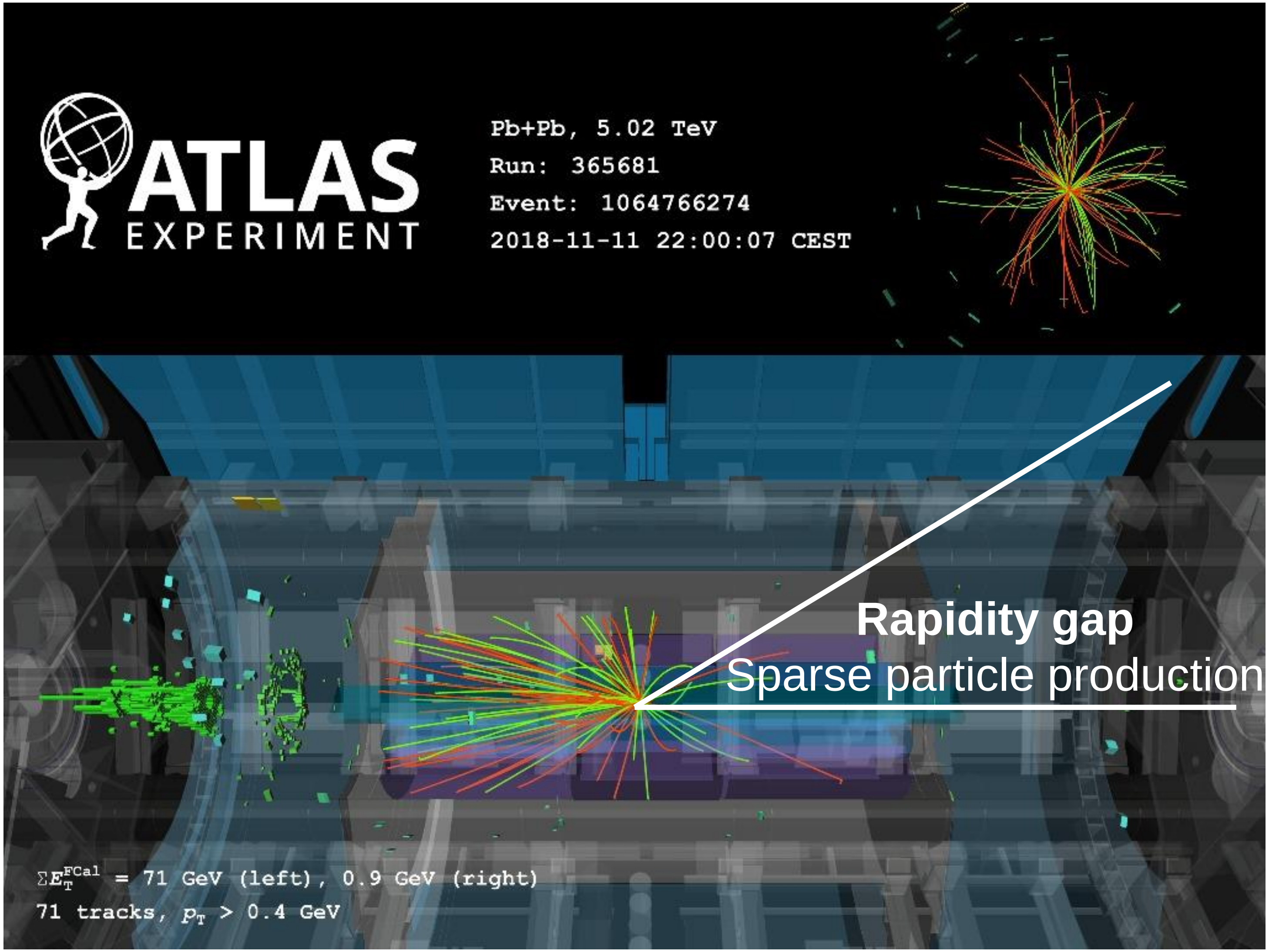
photon going direction

"High"-multiplicity photonuclear collisions

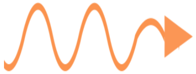
Pb going direction



Xn



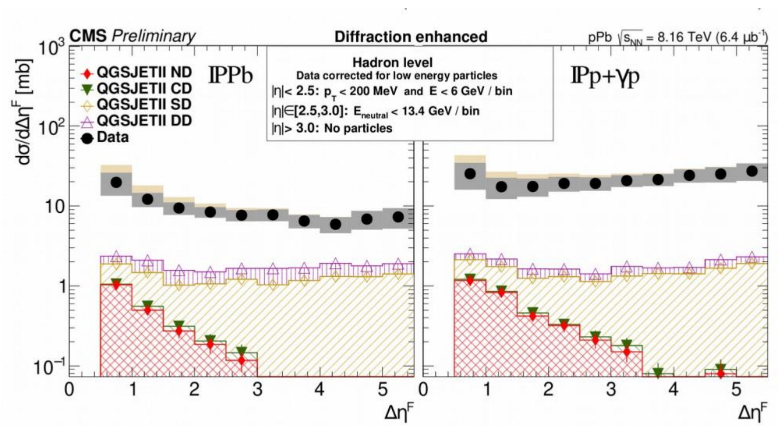
photon going direction



0n

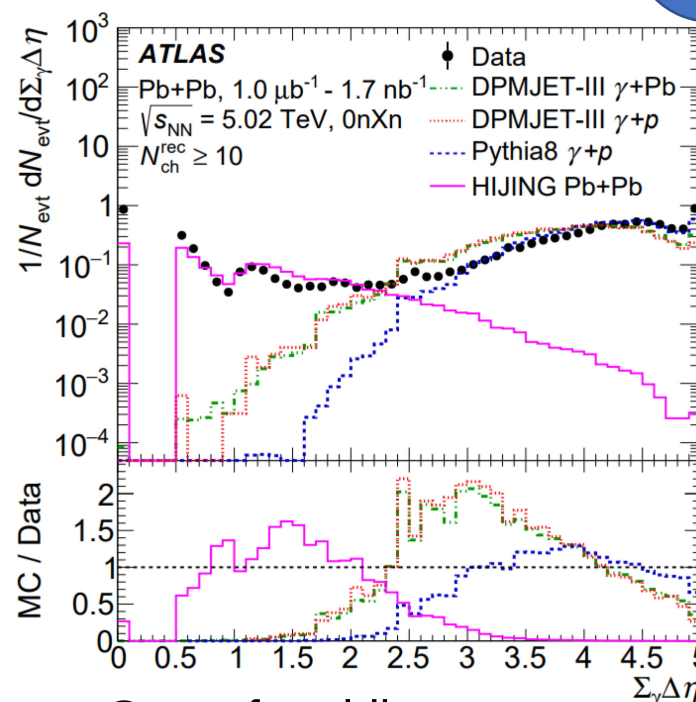
Rapidity gap selection

Reconstructed rapidity gaps are used for event selection of γ+A and γ+*p* (gap definitions are different).



Gap between detector edge and *η* bin with significant energy deposition. CMS has made a preliminary measurement of gap distributions.

CMS-PAS-HIN-18-019



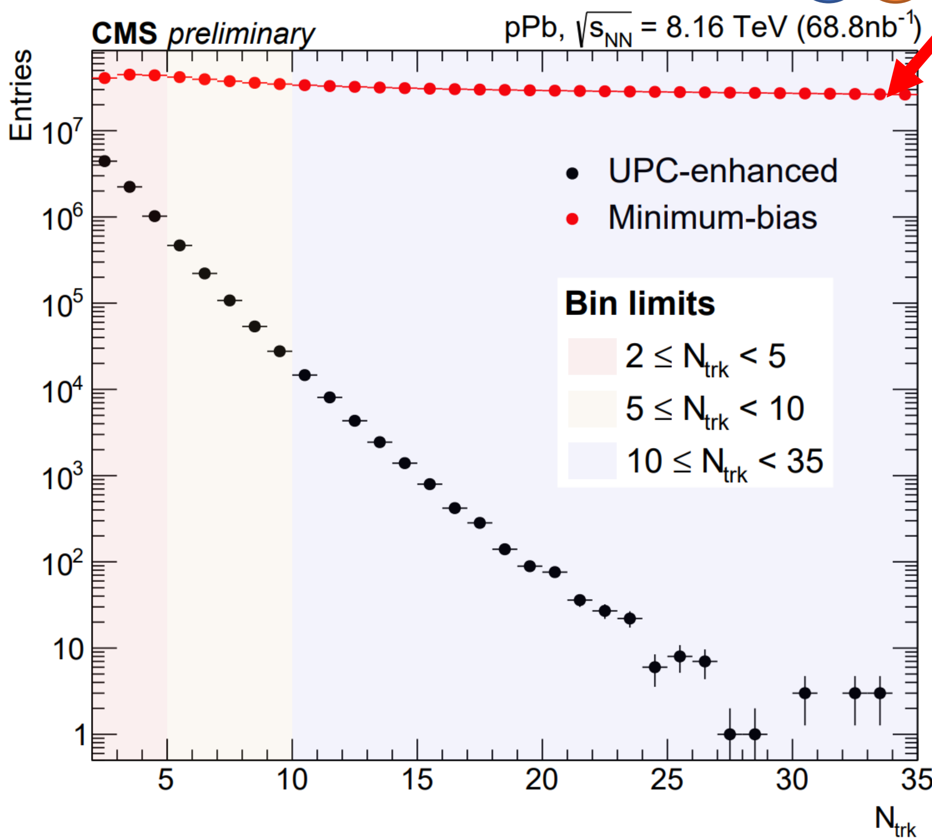
Sum of rapidity gaps between particles greater than Δη=0.5

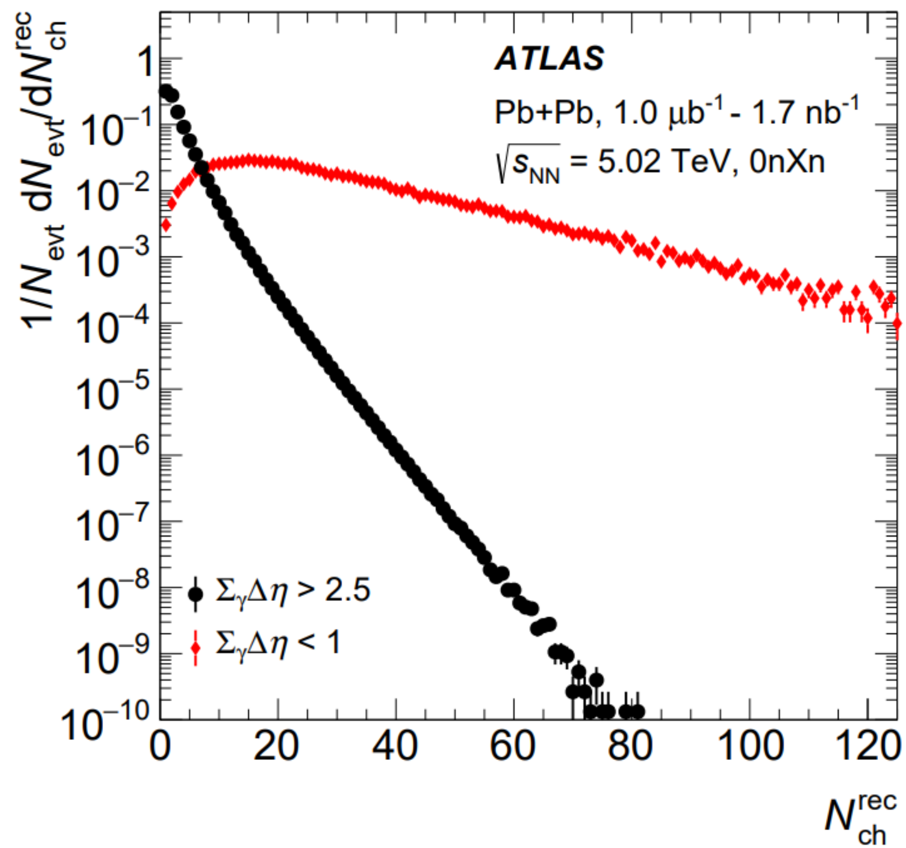
arXiv:2101.10771

Both MC comparisons indicate high purity γ+A/*p* samples

Charged-particle multiplicity

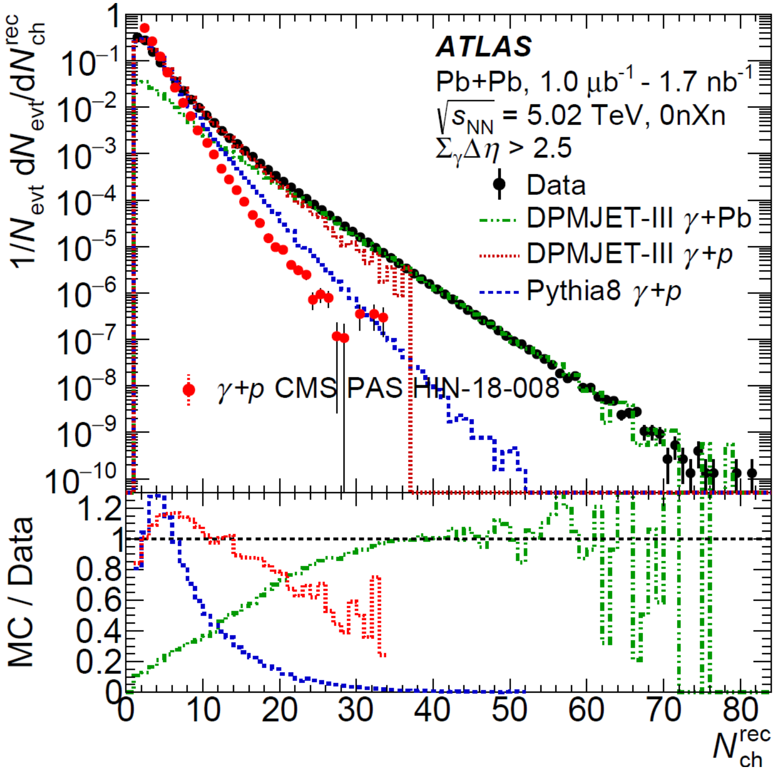
γ+A has a very steep multiplicity distribution and γ+*p* is even steeper compared to minimum-bias *p*+Pb.





CMS-PAS-HIN-18-008

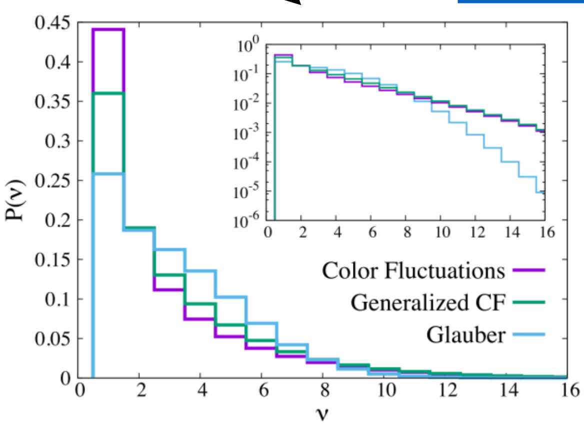
Rough N_{ch} comparison γ+A/*p*



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.

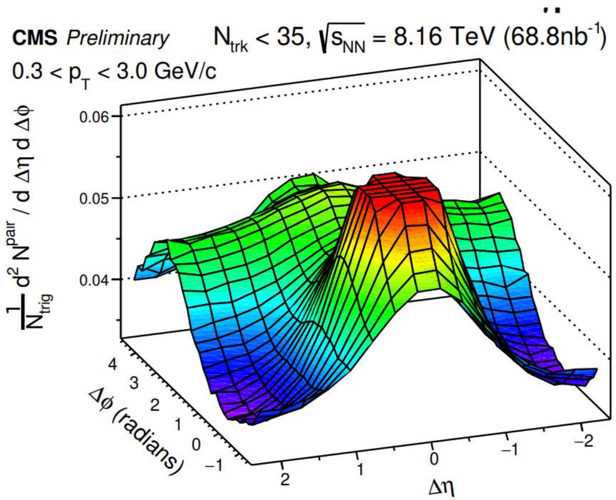
arXiv:1605.06606

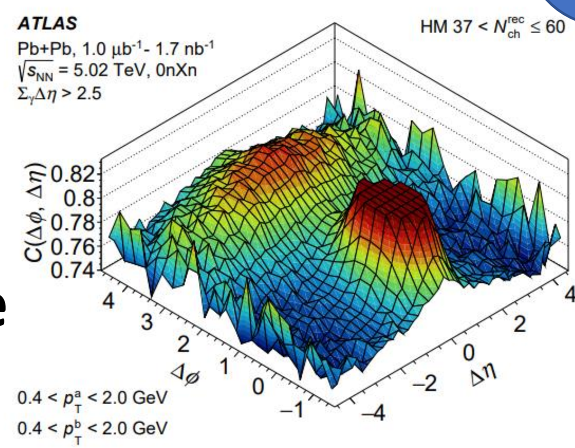


Number of wounded nucleons

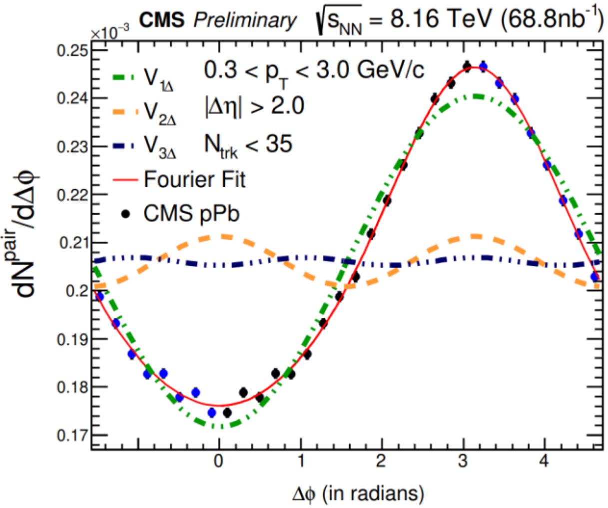
arXiv:2101.10771

Two-particle correlation of charged tracks





No clear nearside ridge



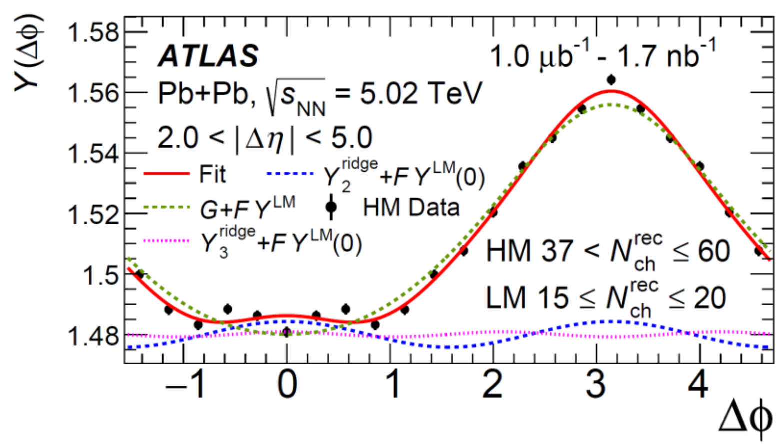
Away-side correlation

Momentum conservation

Jets

Not collective phenomenon

Termed "non-flow"



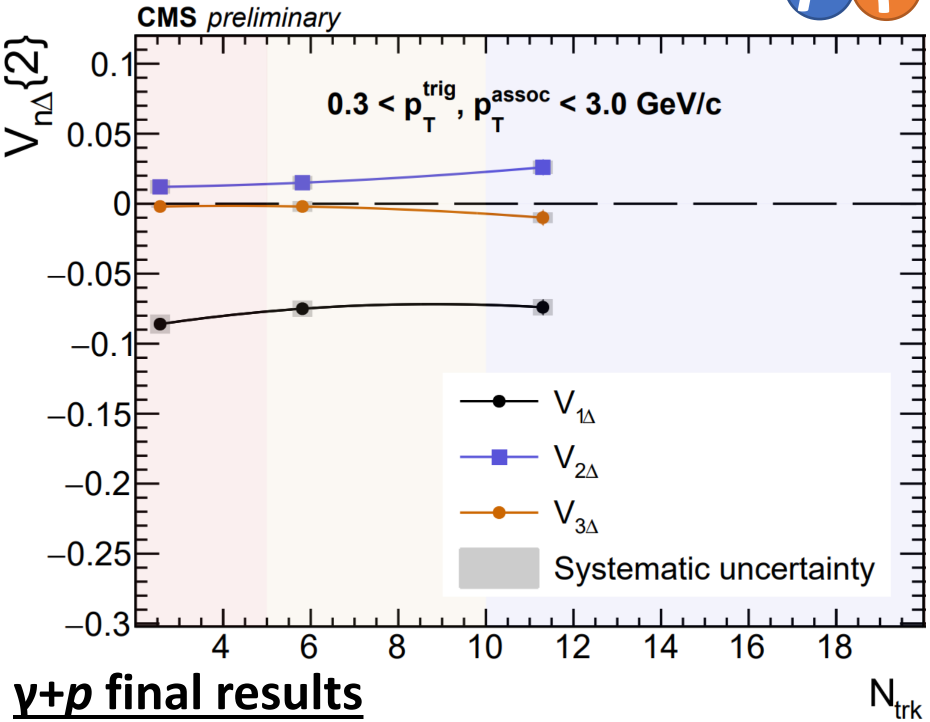
CMS-PAS-HIN-18-008

Need to remove non-flow

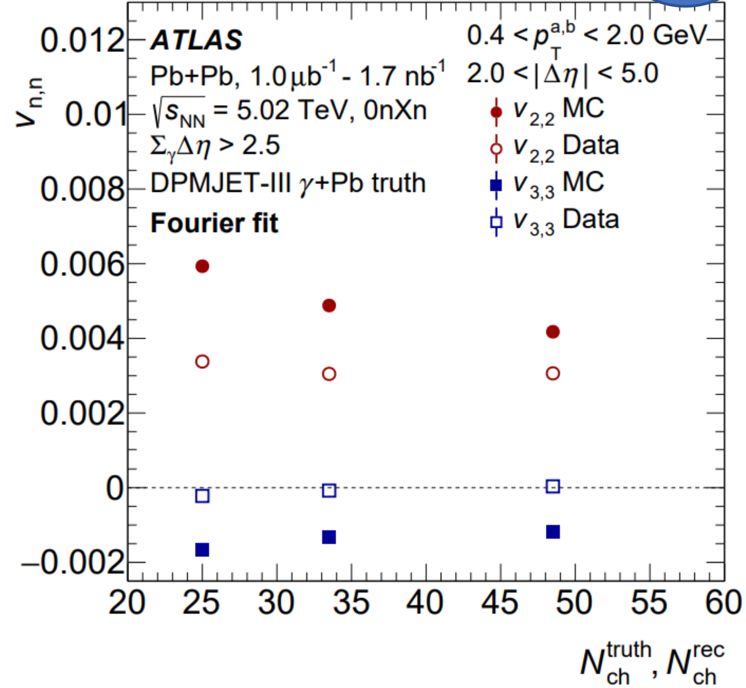
arXiv:2101.10771

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!

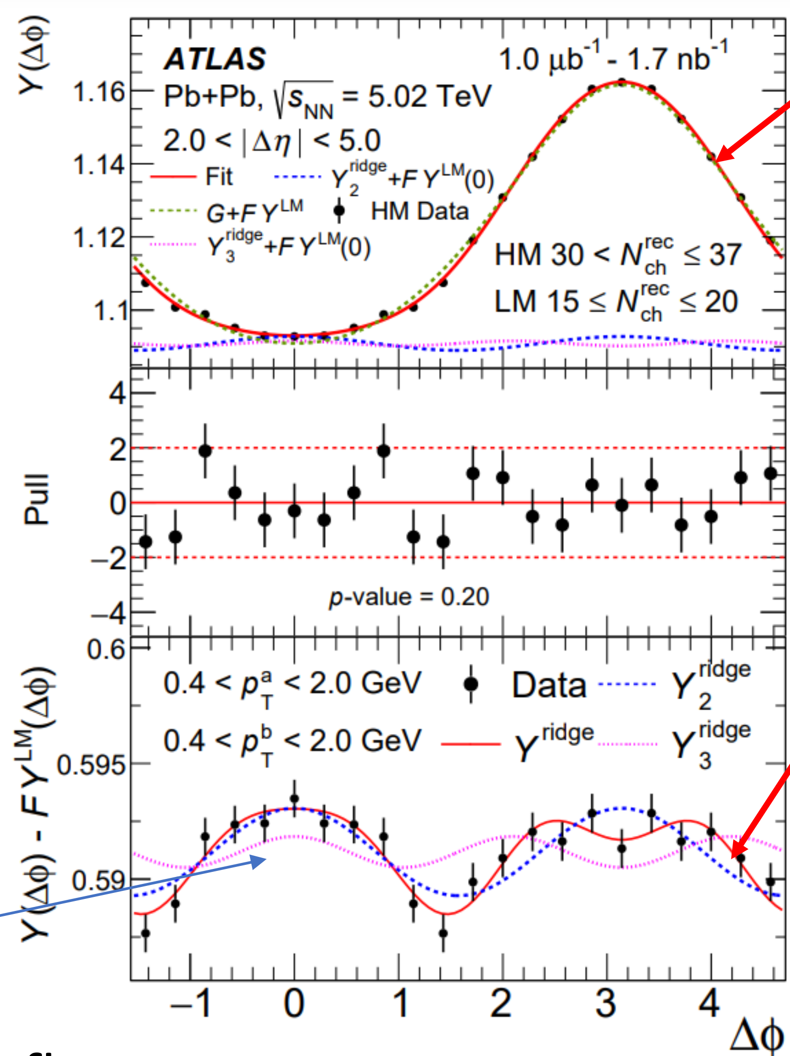
Non-flow removal in γA correlations

High-multiplicity (HM) correlation data

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

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

HM – (scaled LM) removes nonflow



fit

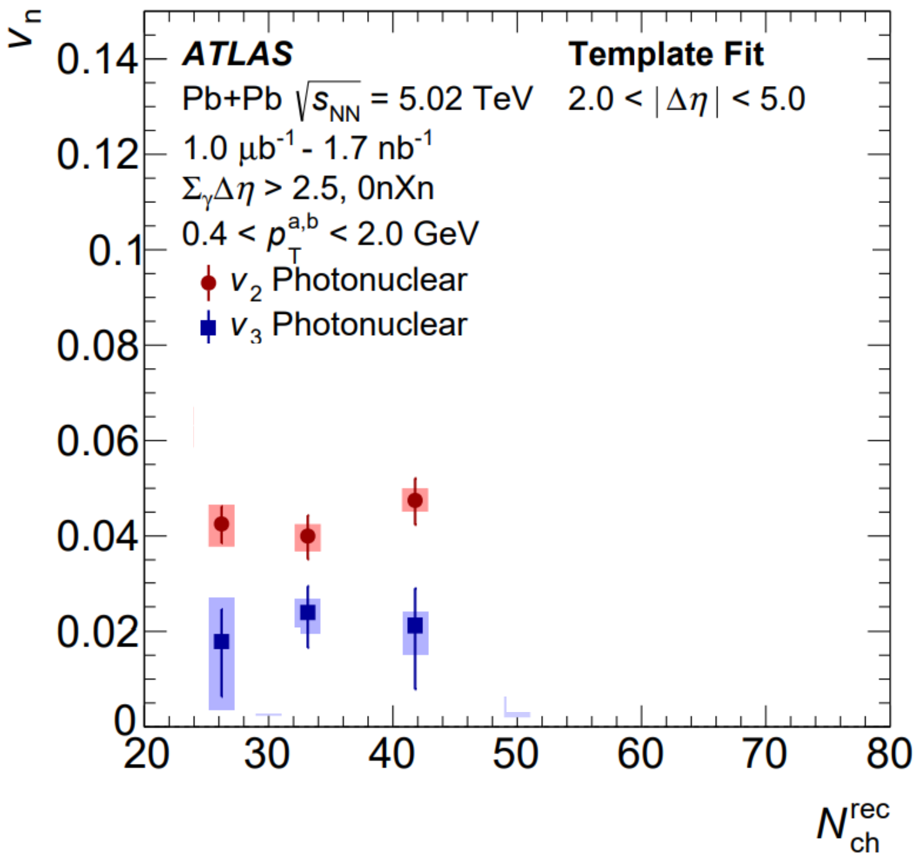
fit

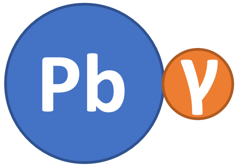
Clear **cos(2Δϕ)** modulation

Same technique used in *pp* and *p*+Pb flow measurements

arXiv:2101.10771

v_n in photonuclear collisions



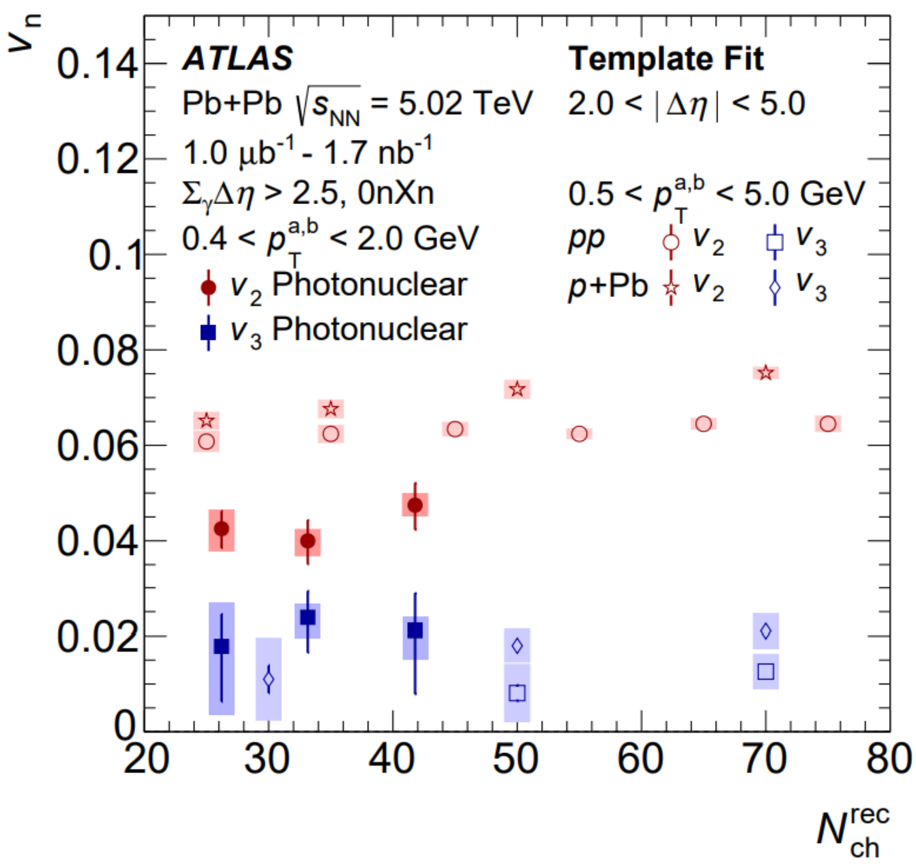


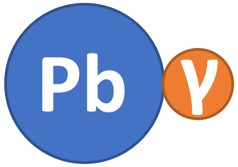
Significant nonzero v_2 and v_3 in photonuclear collisions

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

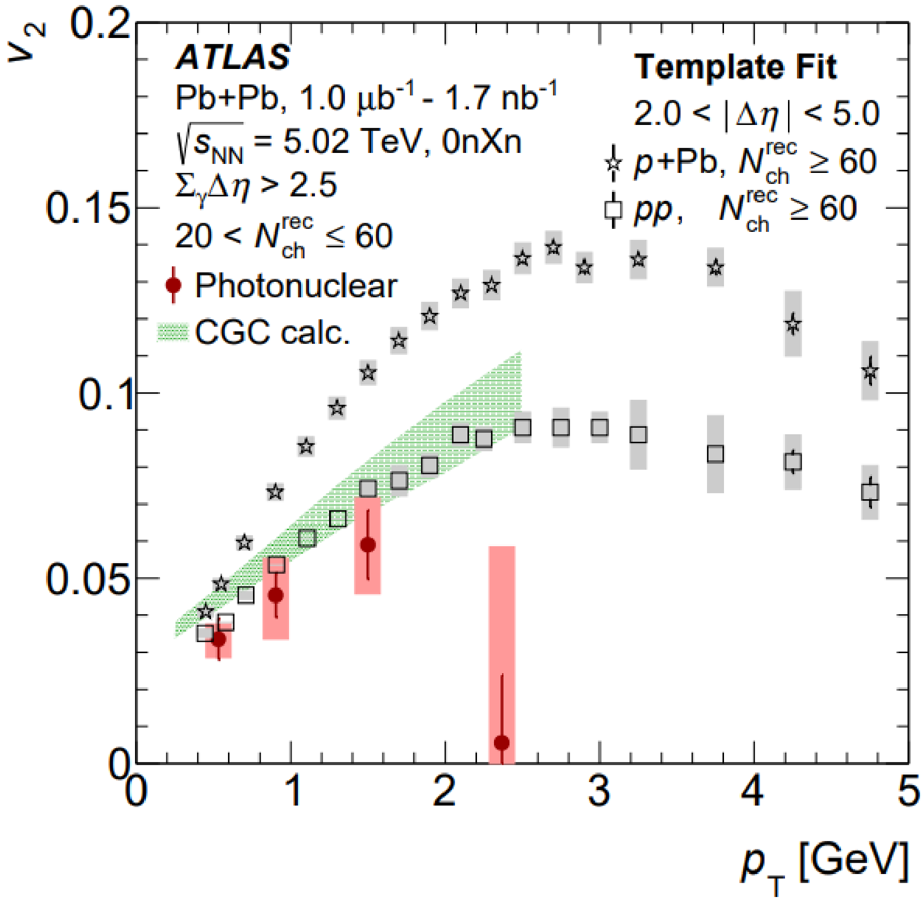
Flat $v_2(N_{ch})$ within statistical precision

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



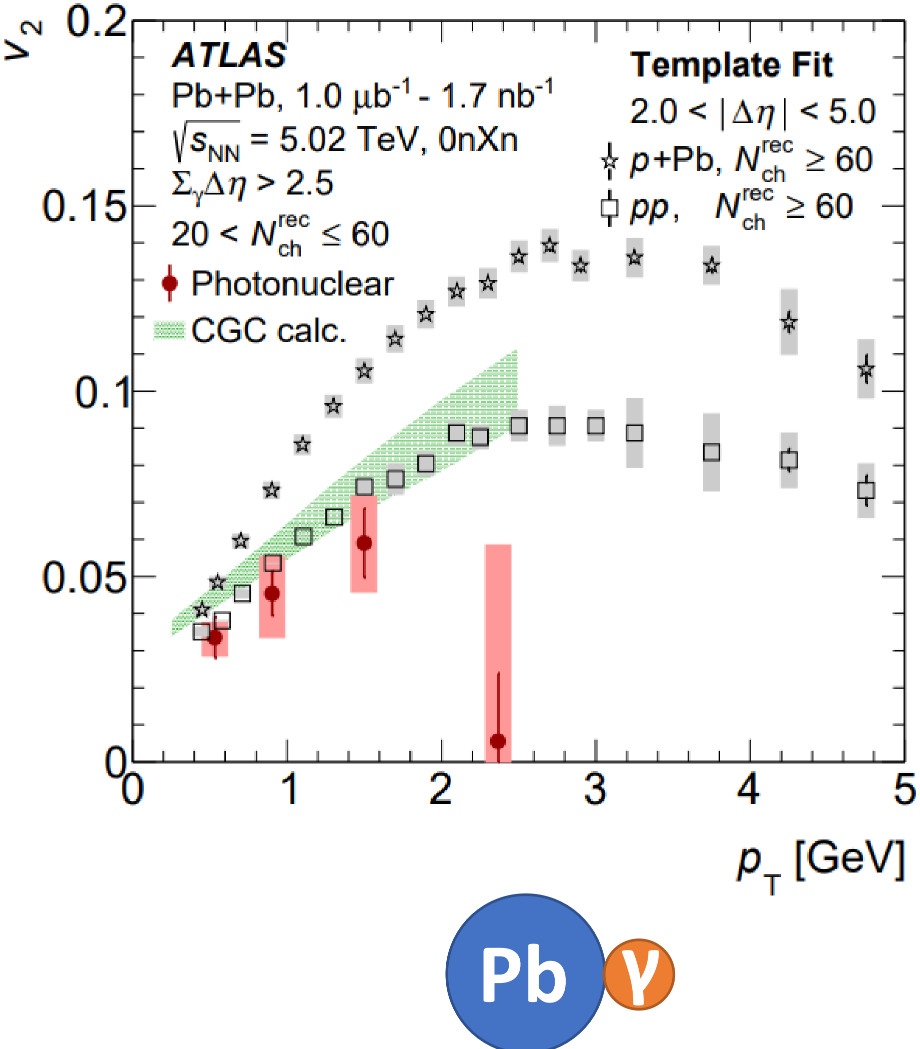
Similar trend in $v_2(p_T)$ as other hadronic systems.

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 GeV² and B_p^2 = 25 GeV⁻²

Model is consistent with data at low-p_T

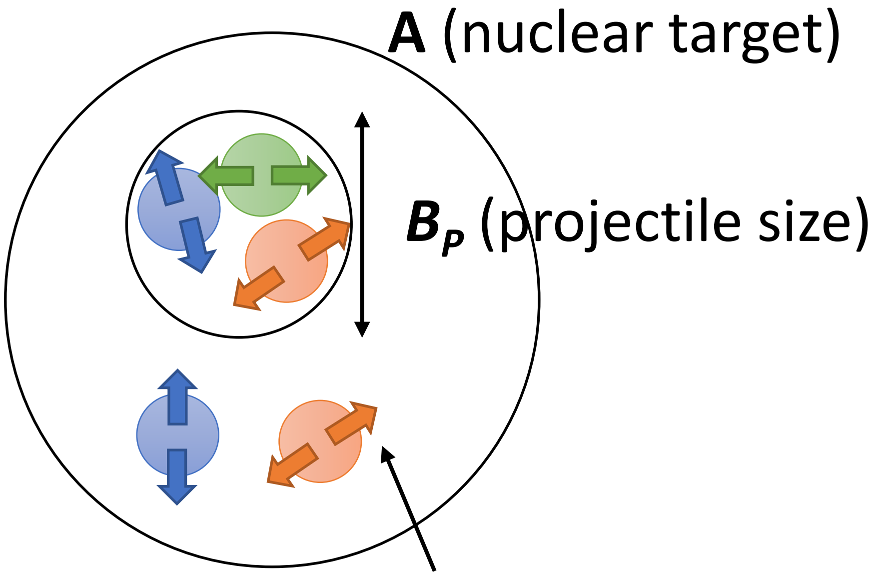
Theory uncertainty from hadron fragmentation

arXiv:2008.03569

arXiv:2101.10771

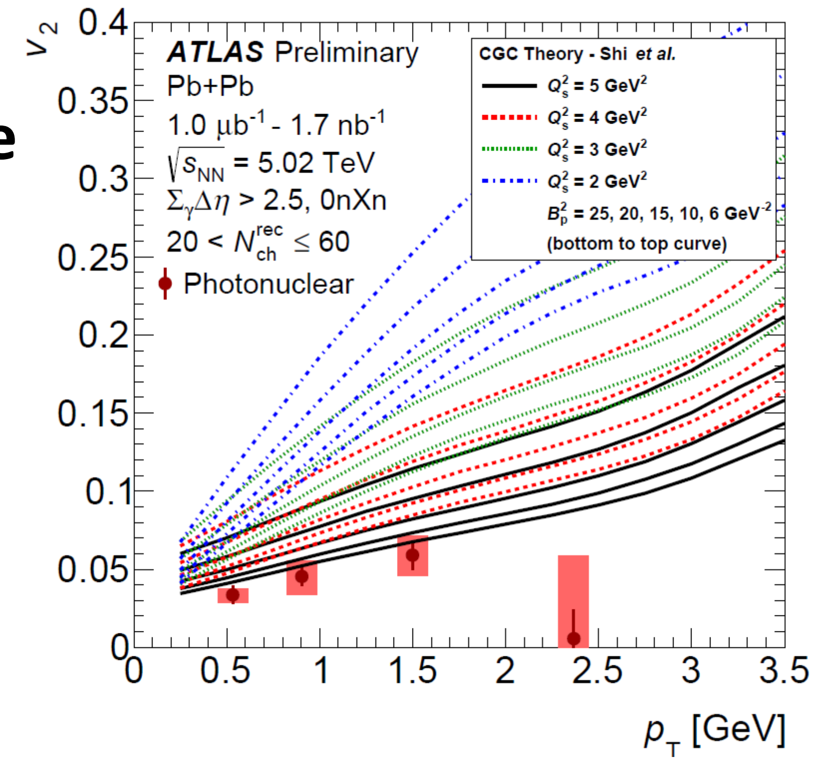
CGC model comparison

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



Correlated color domain
size is ~ $1/Q_s$

arXiv:2008.03569

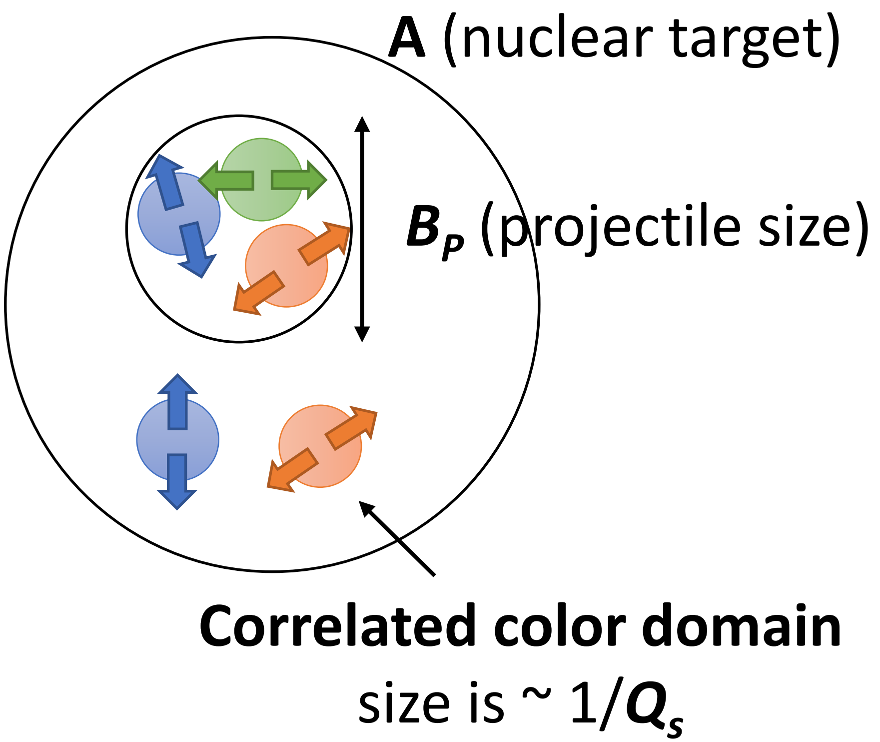


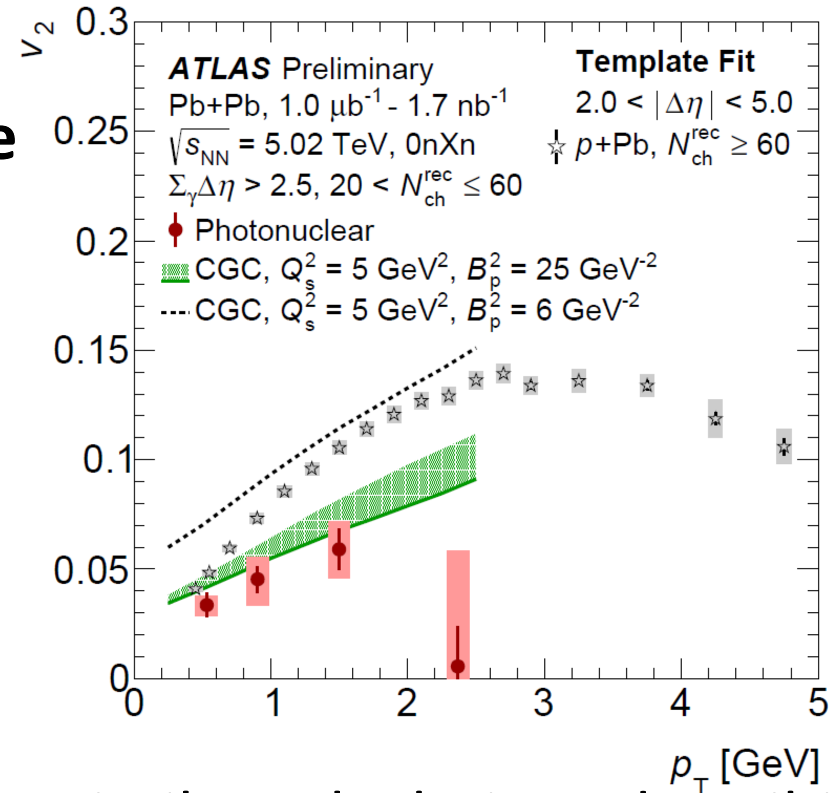
- Larger number of domains struck →lower v_2
- Quasi-real photon is predicted to have large B_P

arXiv:2101.10771

CGC model comparison

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





- 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 $B_p^\gamma \sim 1/\Lambda_{QCD}$

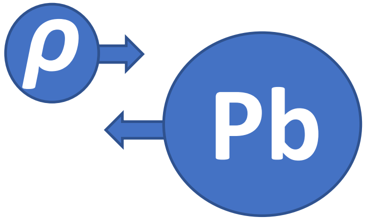
arXiv:2101.10771

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).

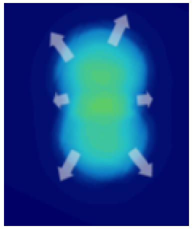


Preliminary results of γ+*p* show raw correlations with no nearside ridge and correlations consistent with non-flow.

Theory

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

Prediction for collectivity in γ+*p* given γ+A?

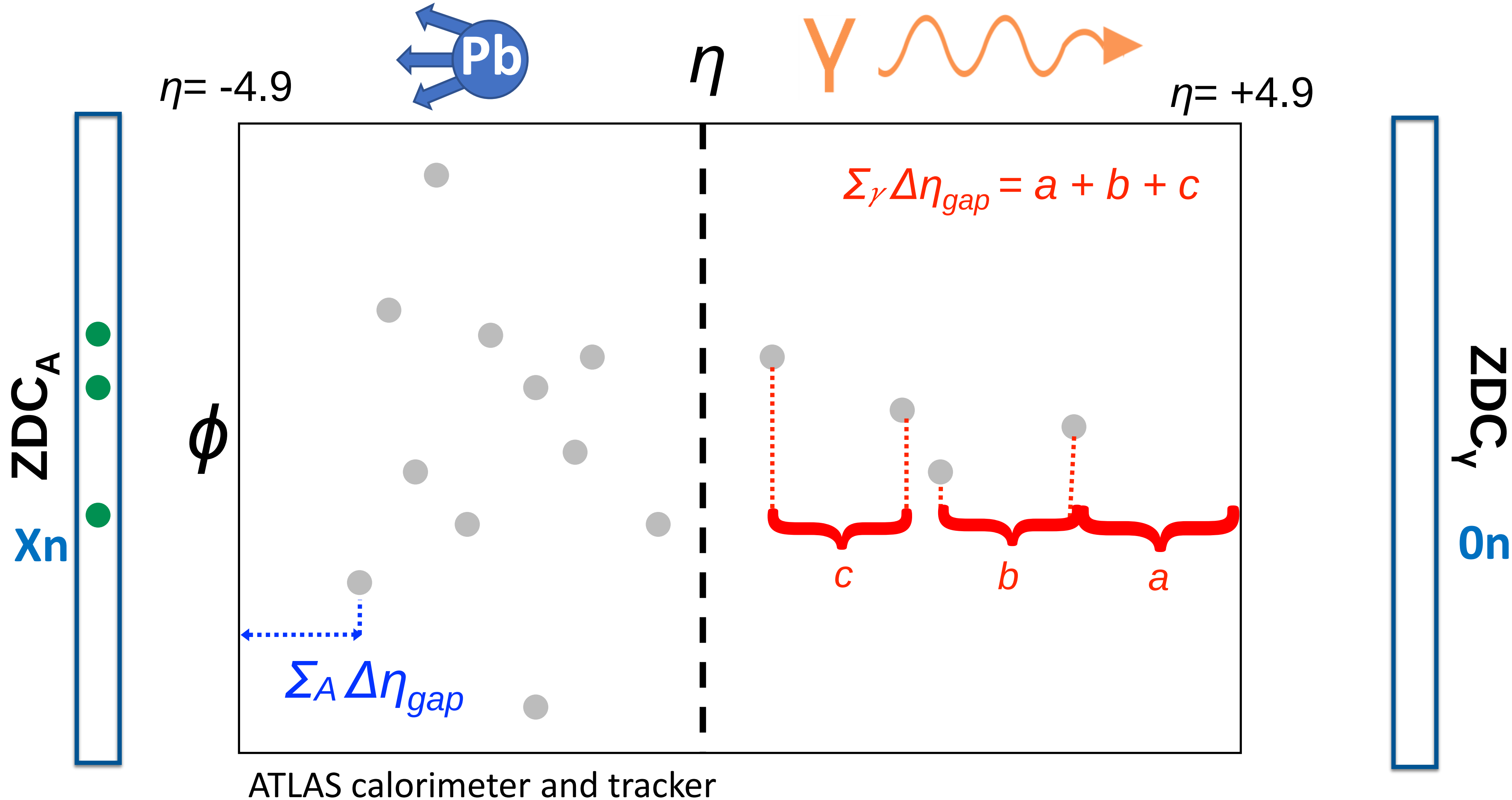


Future study

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

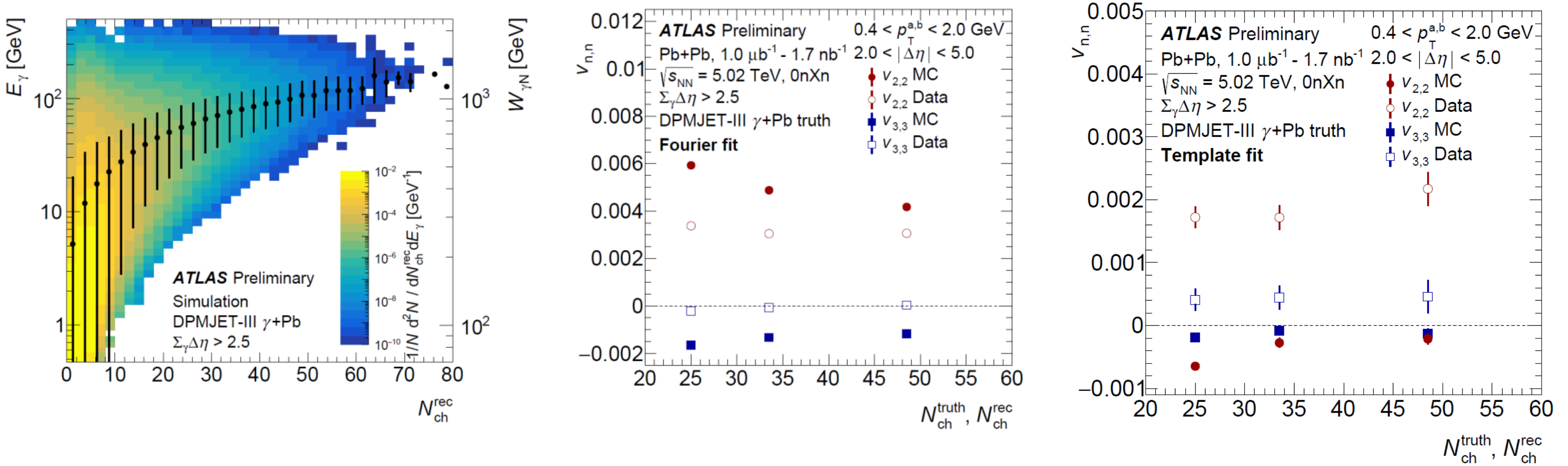
Thank you

Gap definition (detector roll-out)



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

Comparison to DPMJET-III

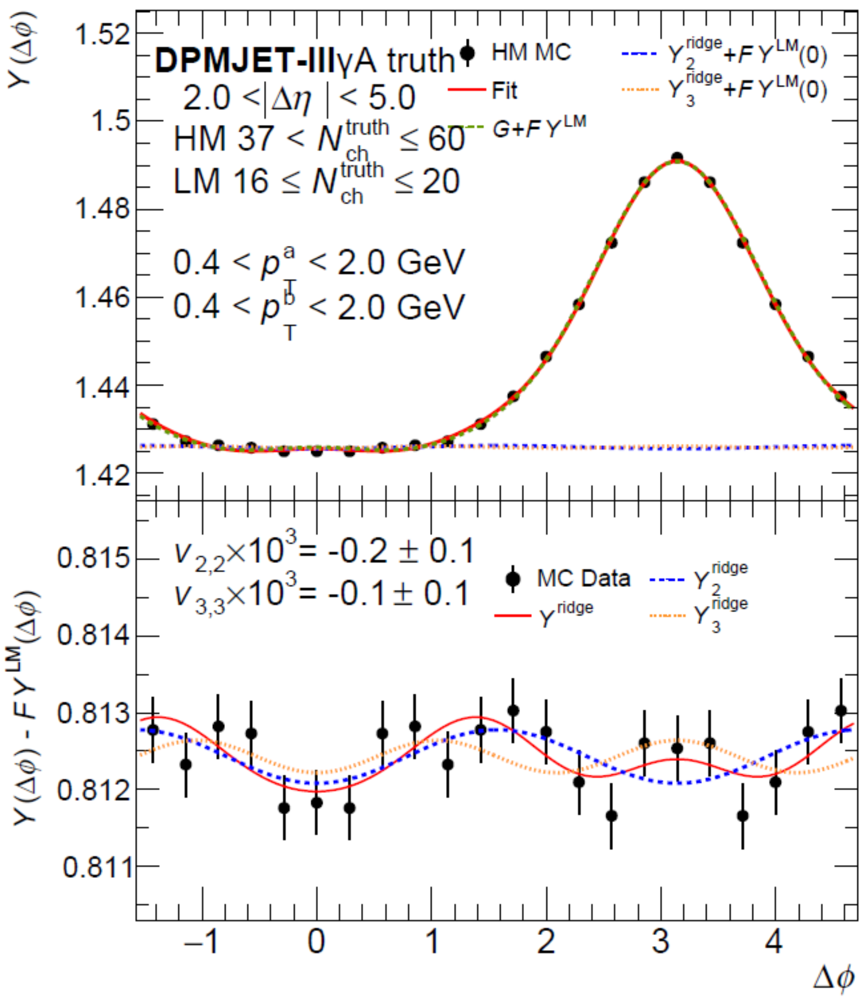


- DPMJET-III predicts the photon energy changes by about 1-2 standard deviations over the multiplicity range of the measurement and a doubling of the mean $W_{\gamma N}$ for 10 to 60 N_{ch}^{rec}.
- Large difference between measured $v_{n,n}$ before and after template nonflow subtraction for data and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

CERN-EP-2020-246

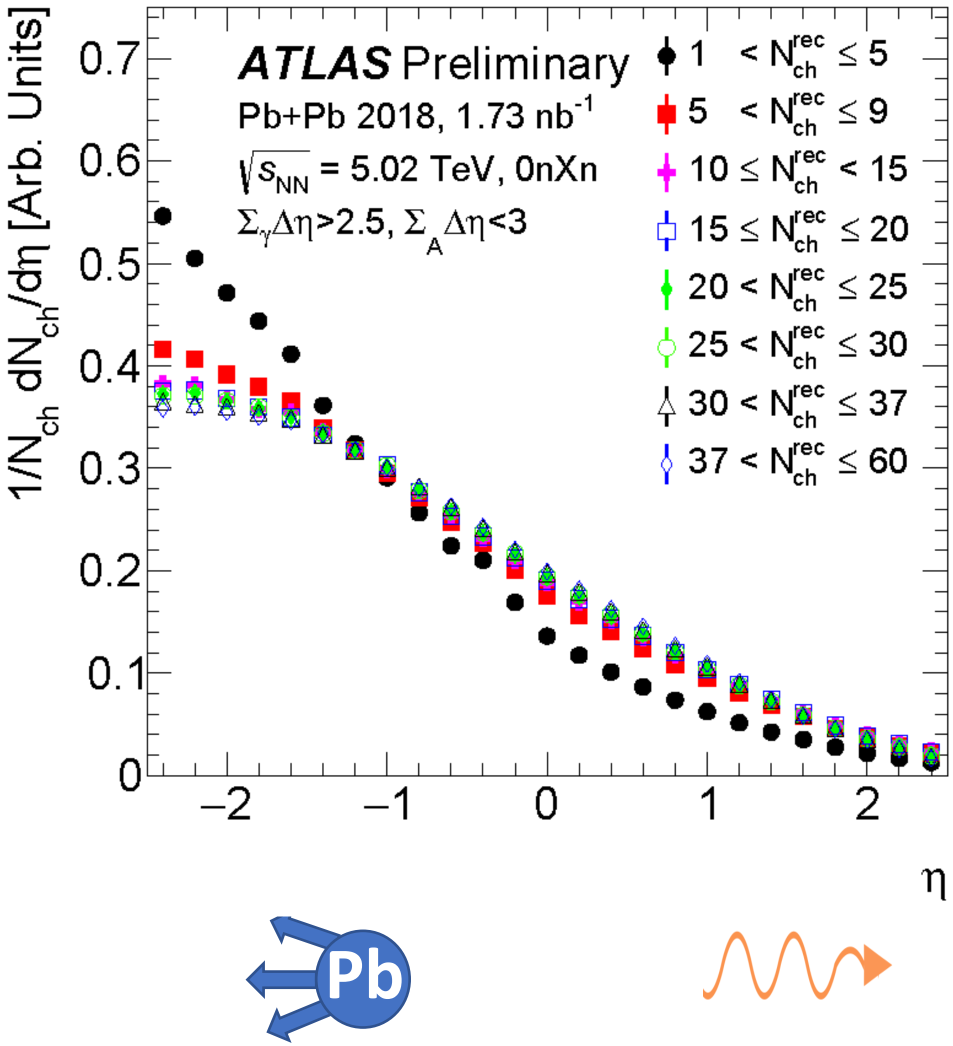
DPMJET-III 2PC example

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.



CERN-EP-2020-246

dN_{ch}/dη in γA collisions

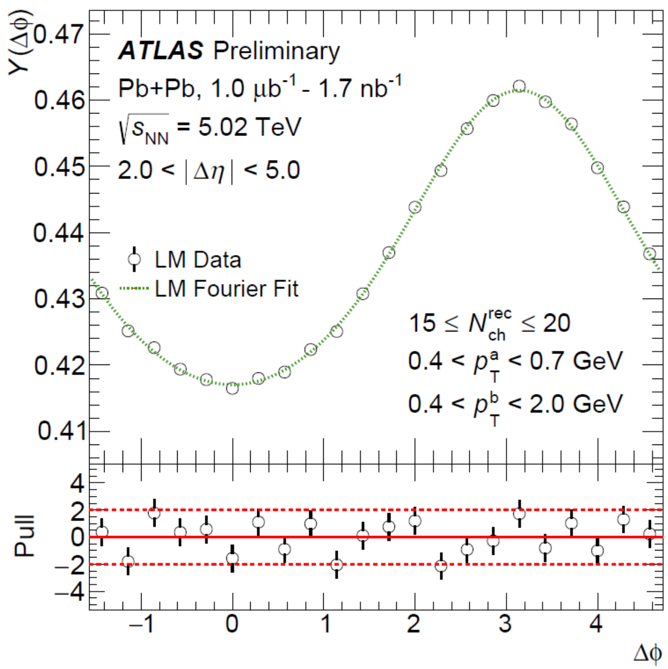


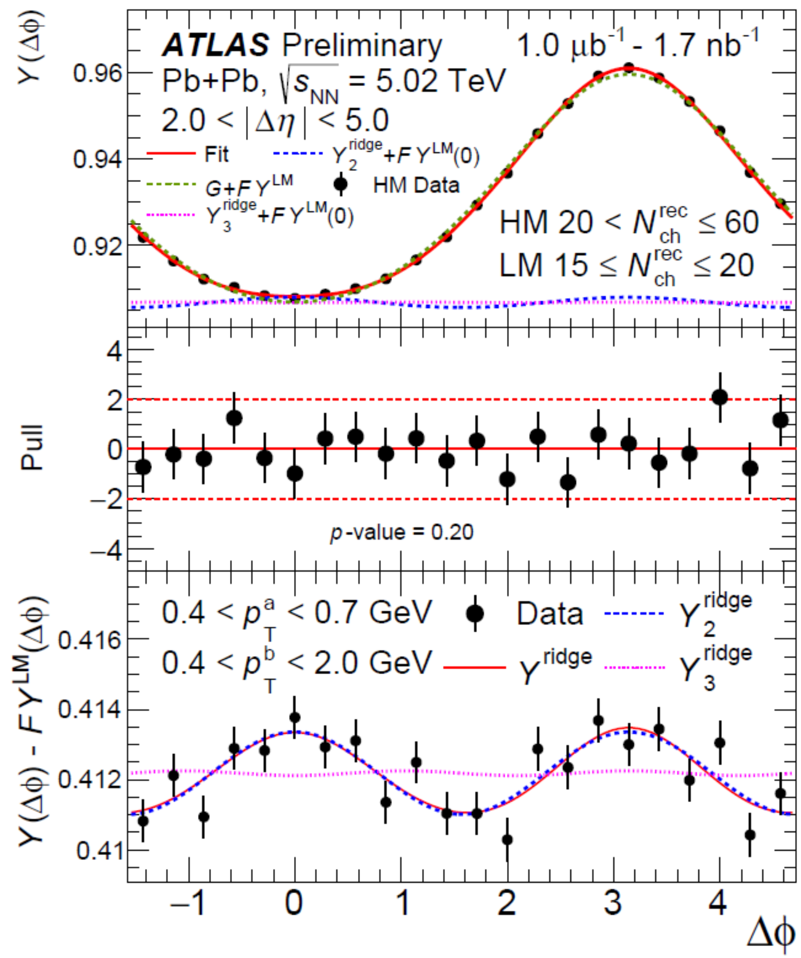
- dN_{ch}/dη of events passing the photonuclear event selection.

- Very similar shape dN_{ch}/dη for events with $N_{ch}^{rec} \geq 10$.

ATLAS-CONF-2019-022

ATLAS template fitting method





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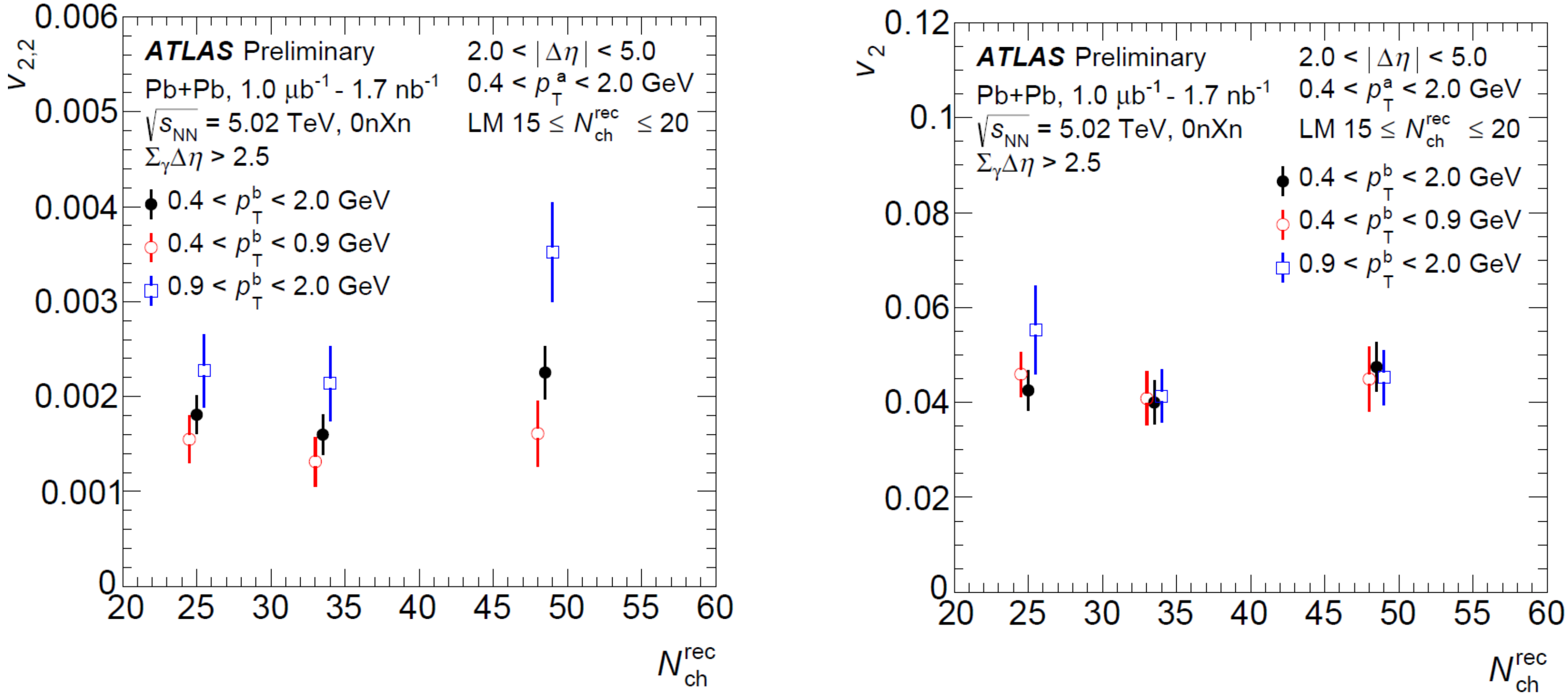
Factorization $v_2(N_{ch})$



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

$v_2(N_{ch})$ 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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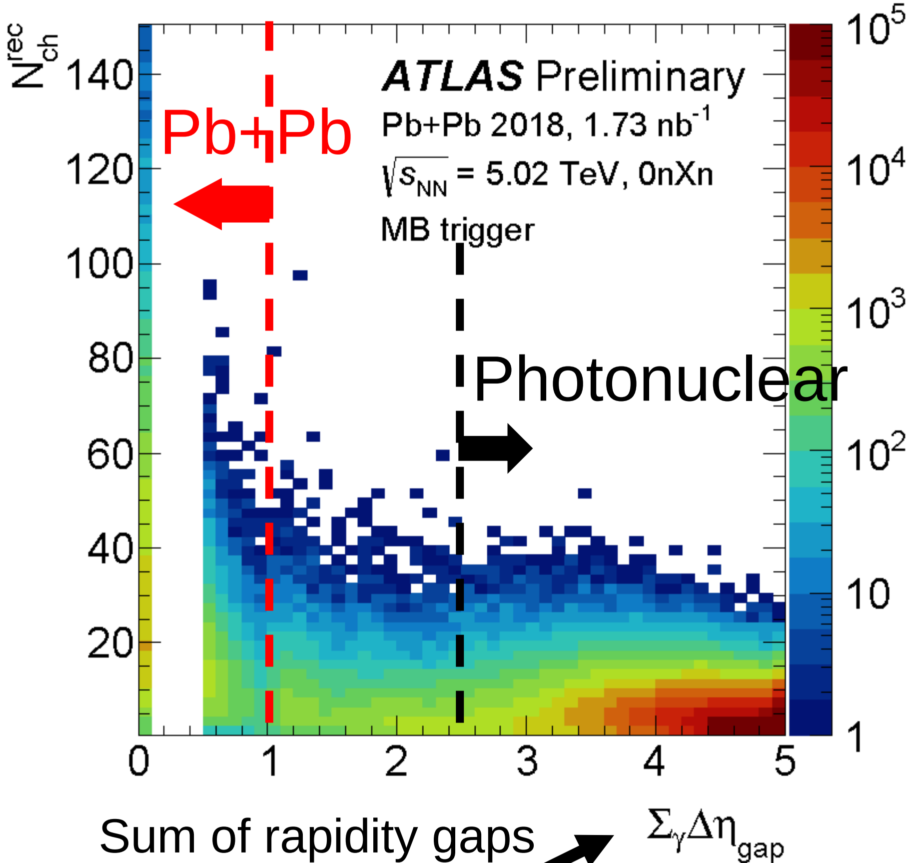
Triggering on photonuclear events

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

Triggering included

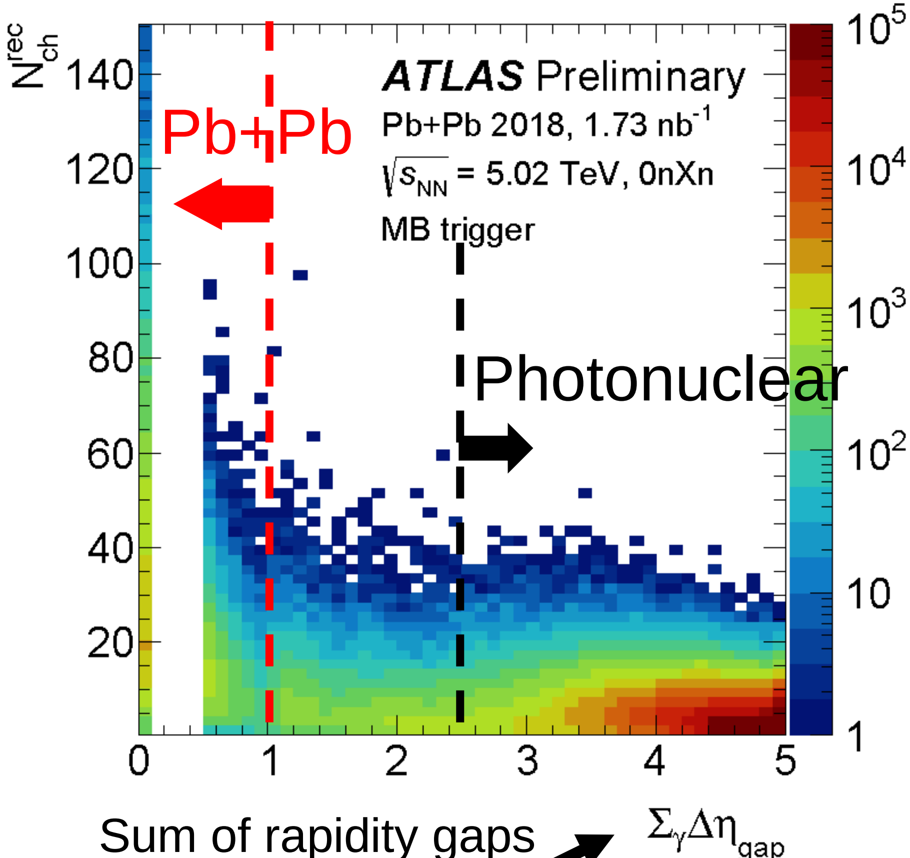
- Level-1 requirements on
  - Minimum event activity to collect high-multiplicity γA events
  - Maximum event activity to reject Pb+Pb collisions
  - Single-sided nuclear breakup (zero-degree calorimeter).
- High-level trigger requirements on
  - Minimum number of tracks to collect high-multiplicity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

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

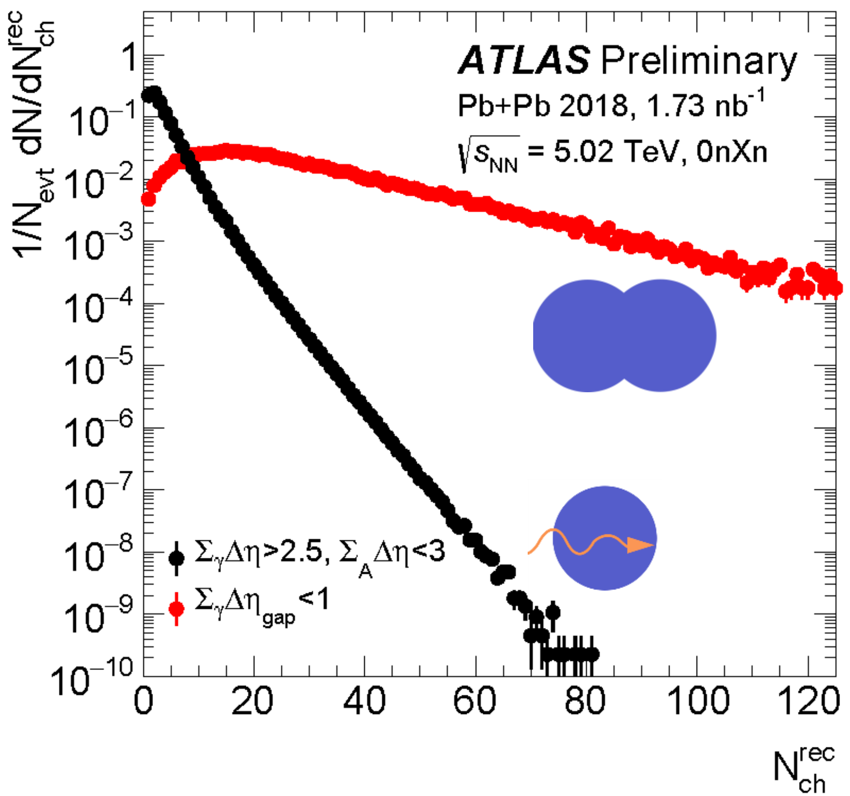


Sum of rapidity gaps between particles greater than 0.5

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.

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