Measurements of collectivity in photonuclear collisions with ATLAS

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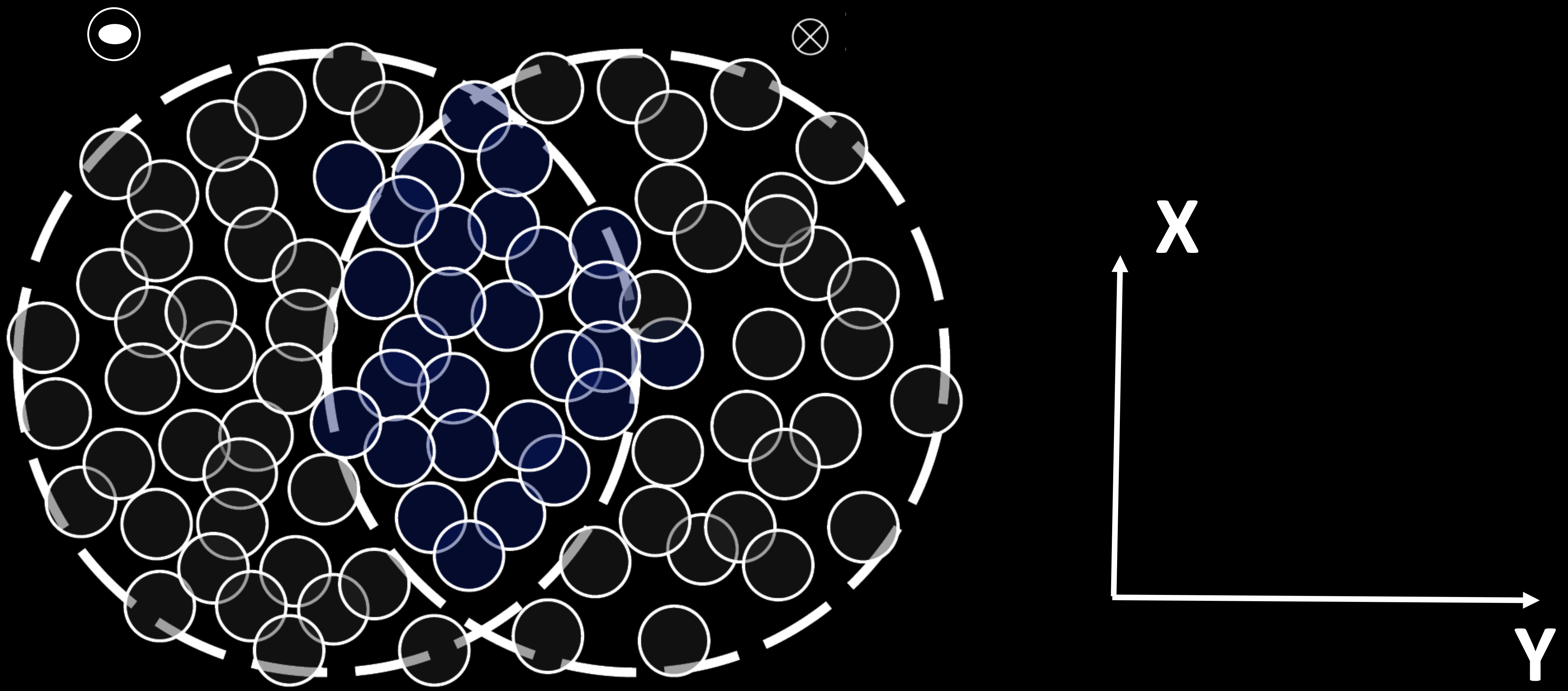
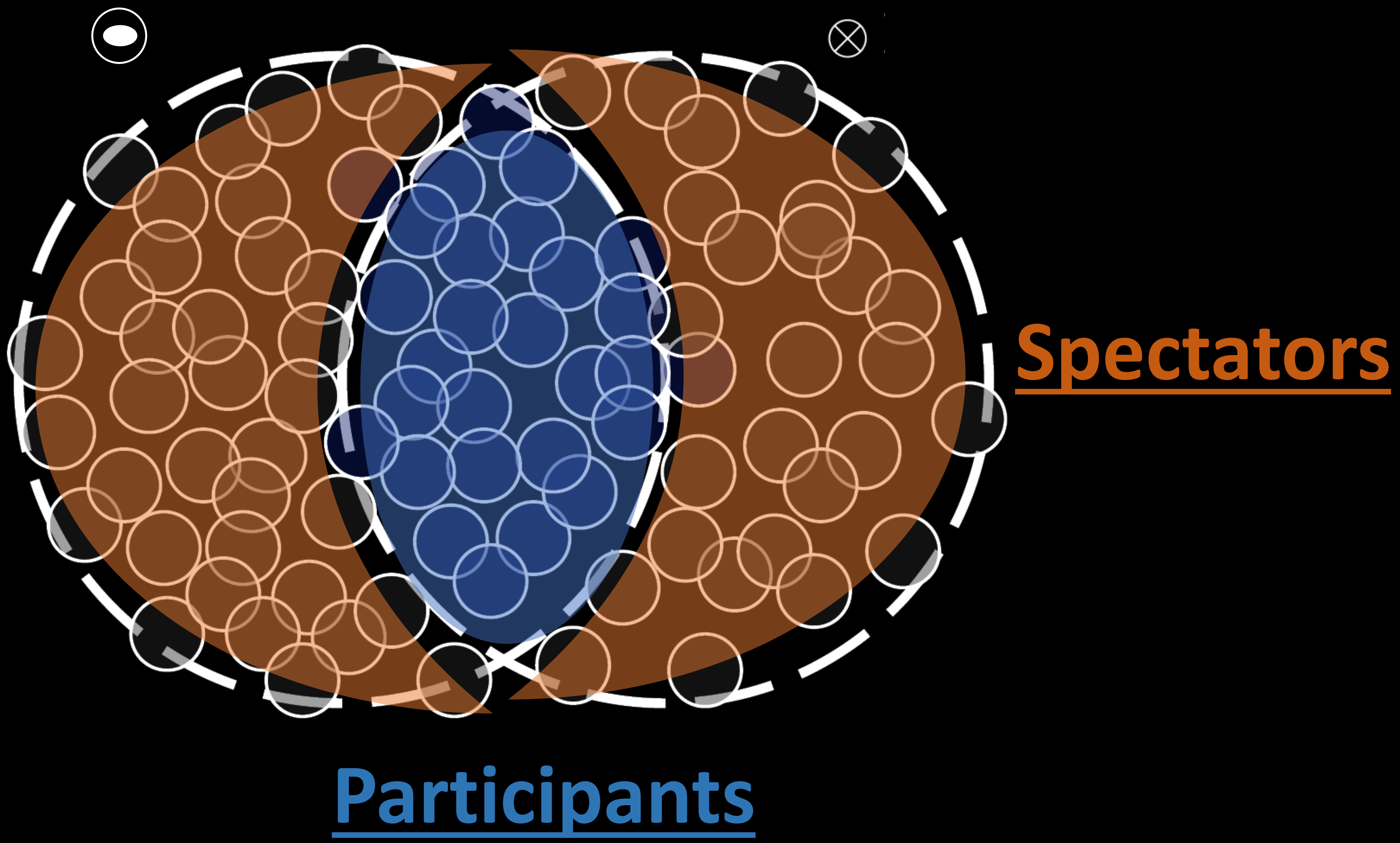
GHP Mar. 16th , 2025

Dennis Perepelitsa

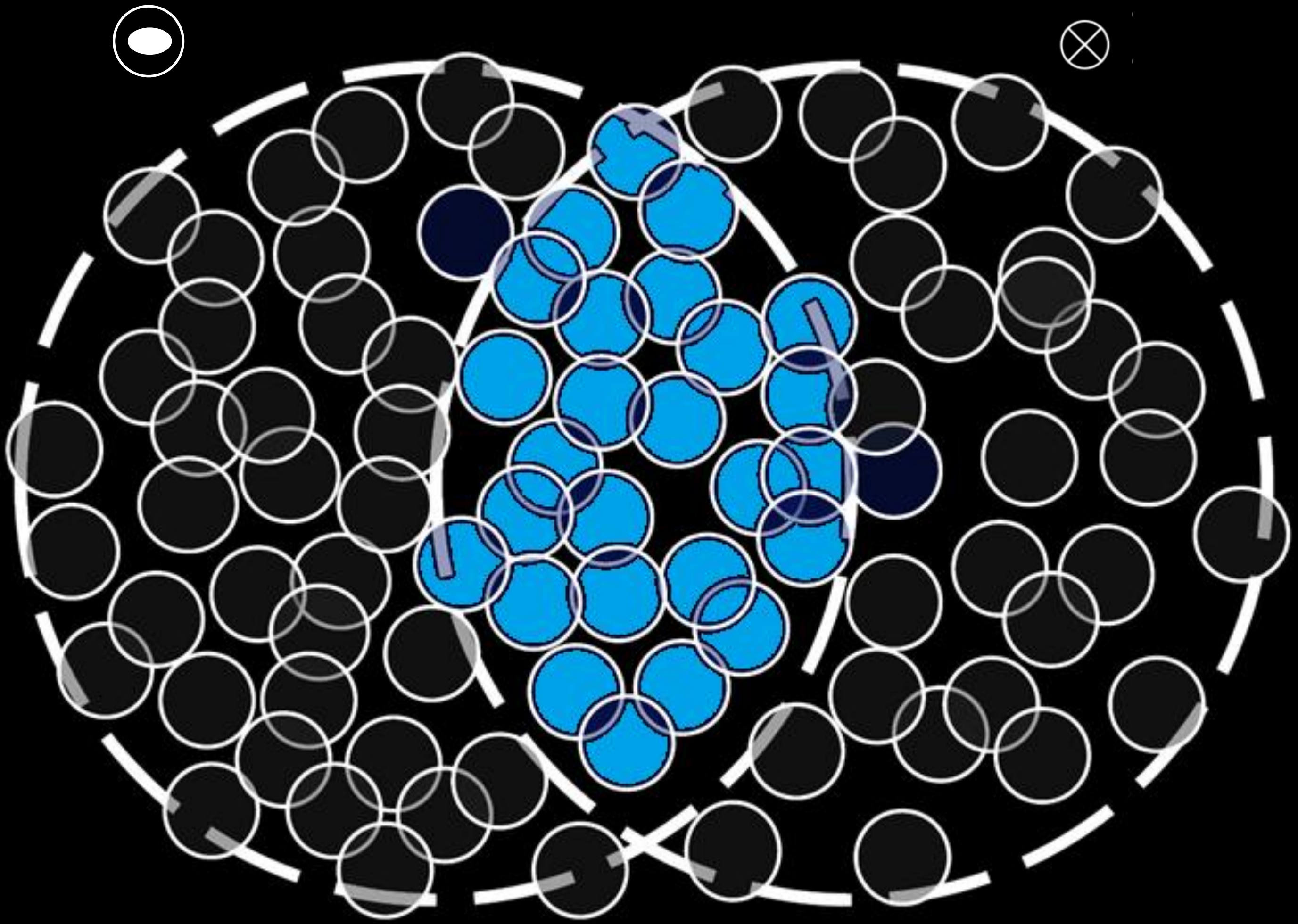
Jamie Nagle

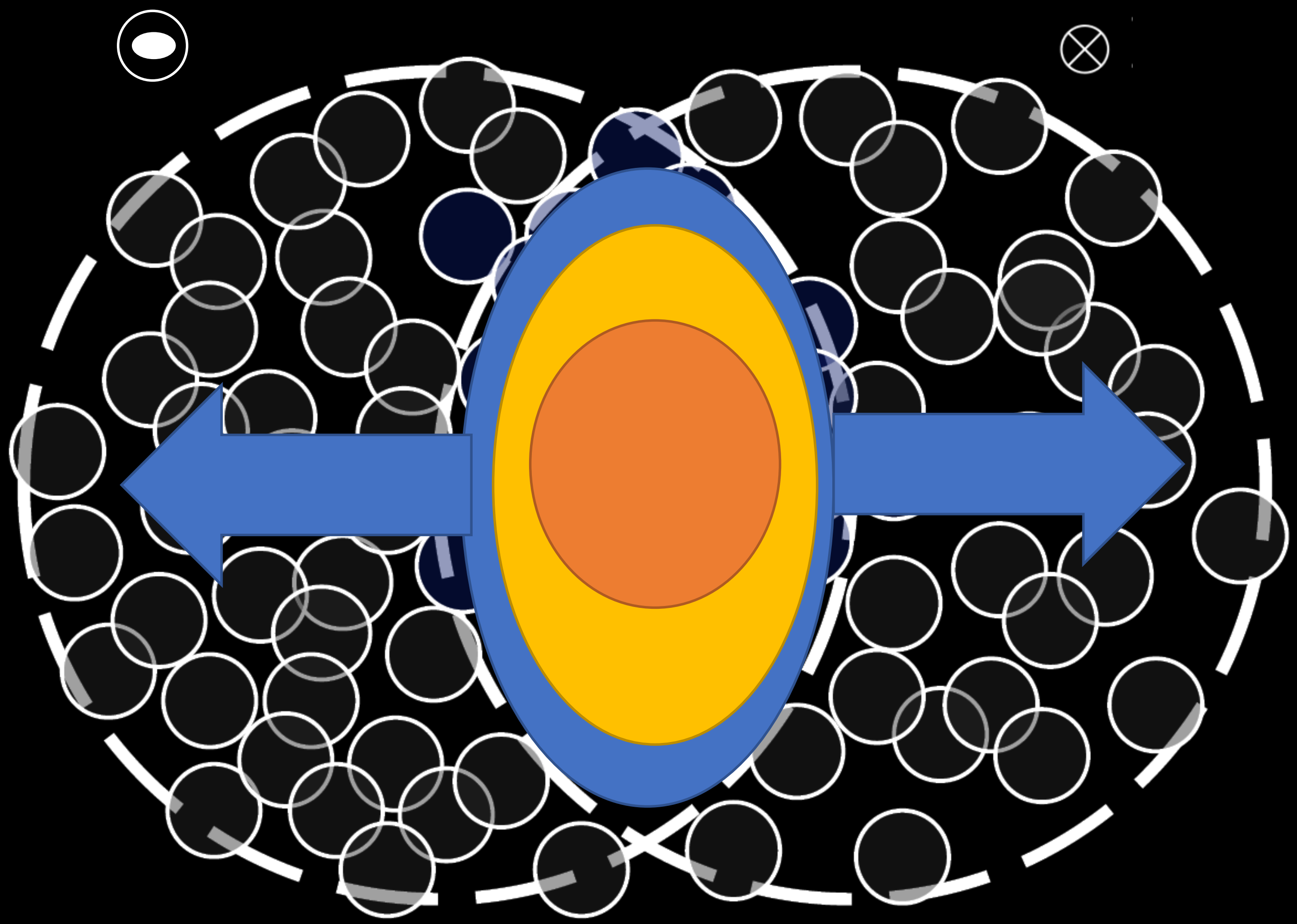
Special thanks to **Sruthy Das** who I am showing some new results from


X
Y

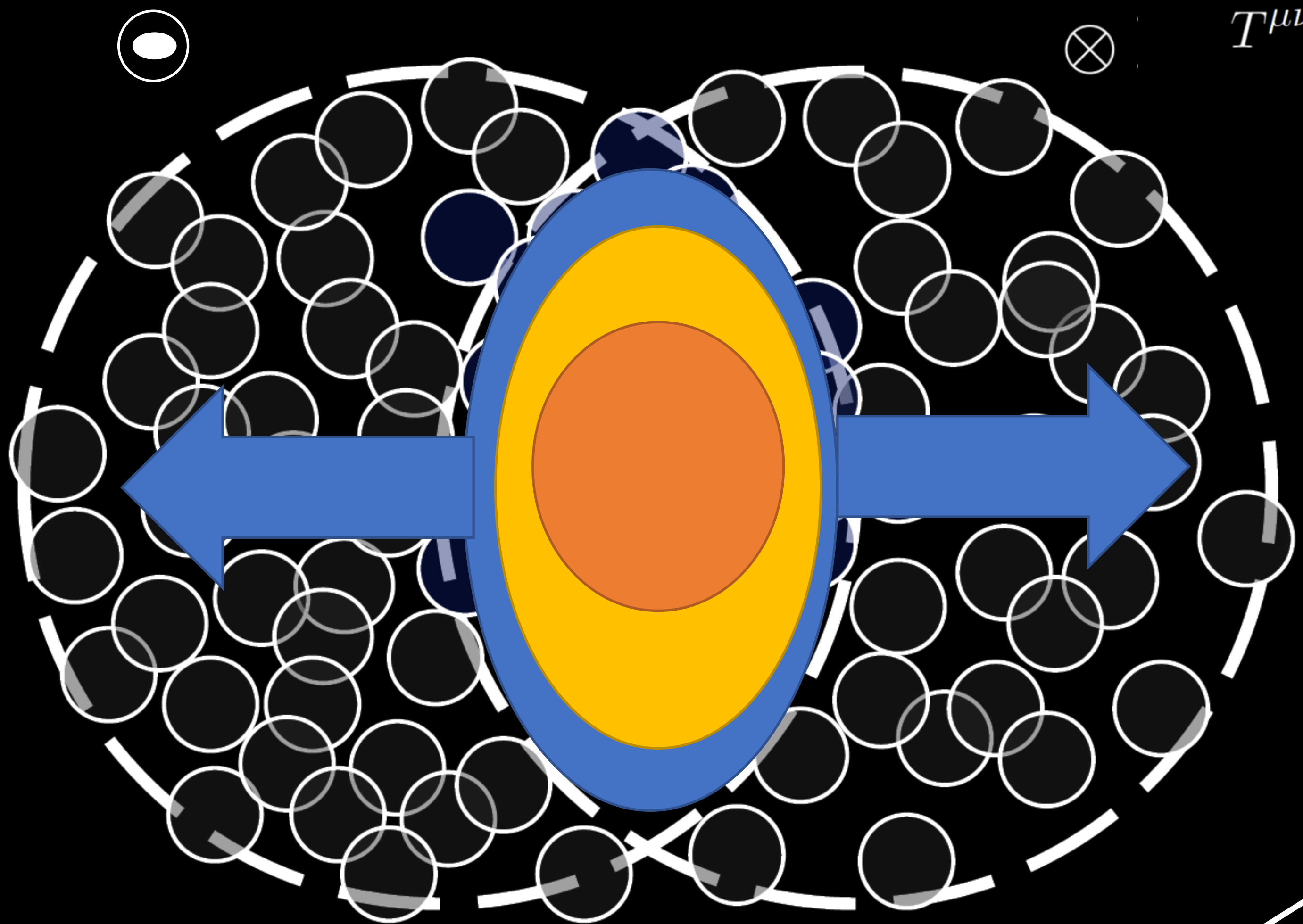

Spectators
Participants

Initial state





Viscous Hydrodynamics

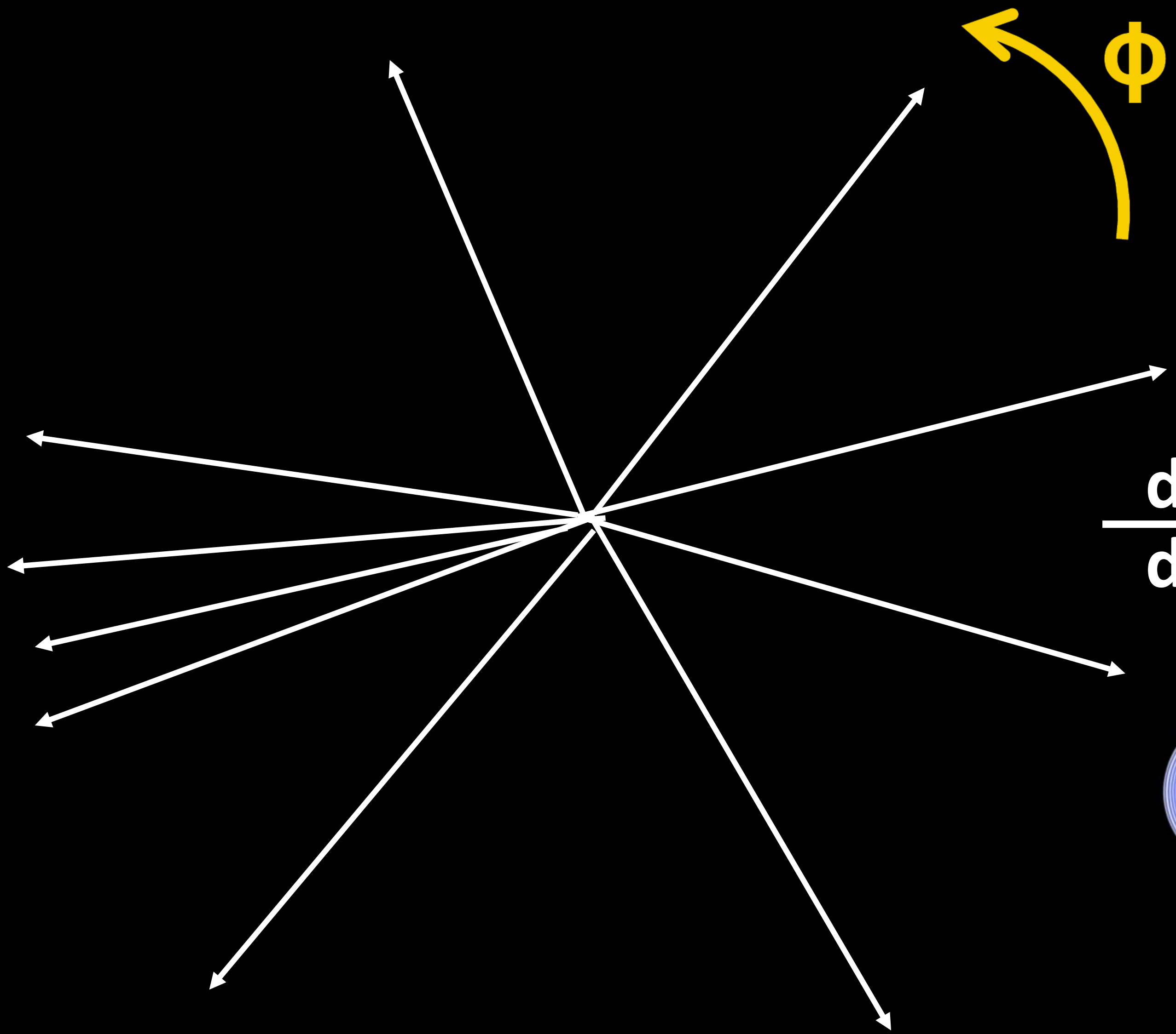


$$T^{\mu\nu} = \underbrace{\epsilon u^\mu u^\nu + P[\epsilon]\Delta^{\mu\nu}}_{\text{Ideal Hydro}} \underbrace{- \eta[\epsilon]\sigma^{\mu\nu} - \zeta[\epsilon]\Delta^{\mu\nu}\nabla^\perp_\lambda u^\lambda}_{\text{Viscous Hydro}}$$

Equation of state $P[\epsilon]$

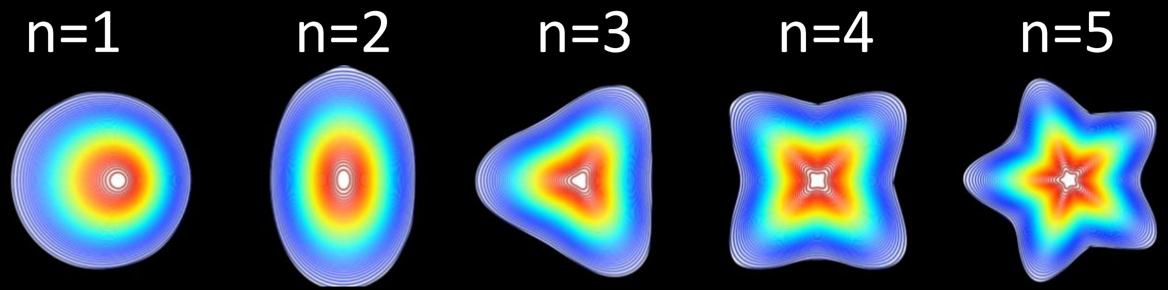
transport coefficients $\eta[\epsilon]$ $\zeta[\epsilon]$.

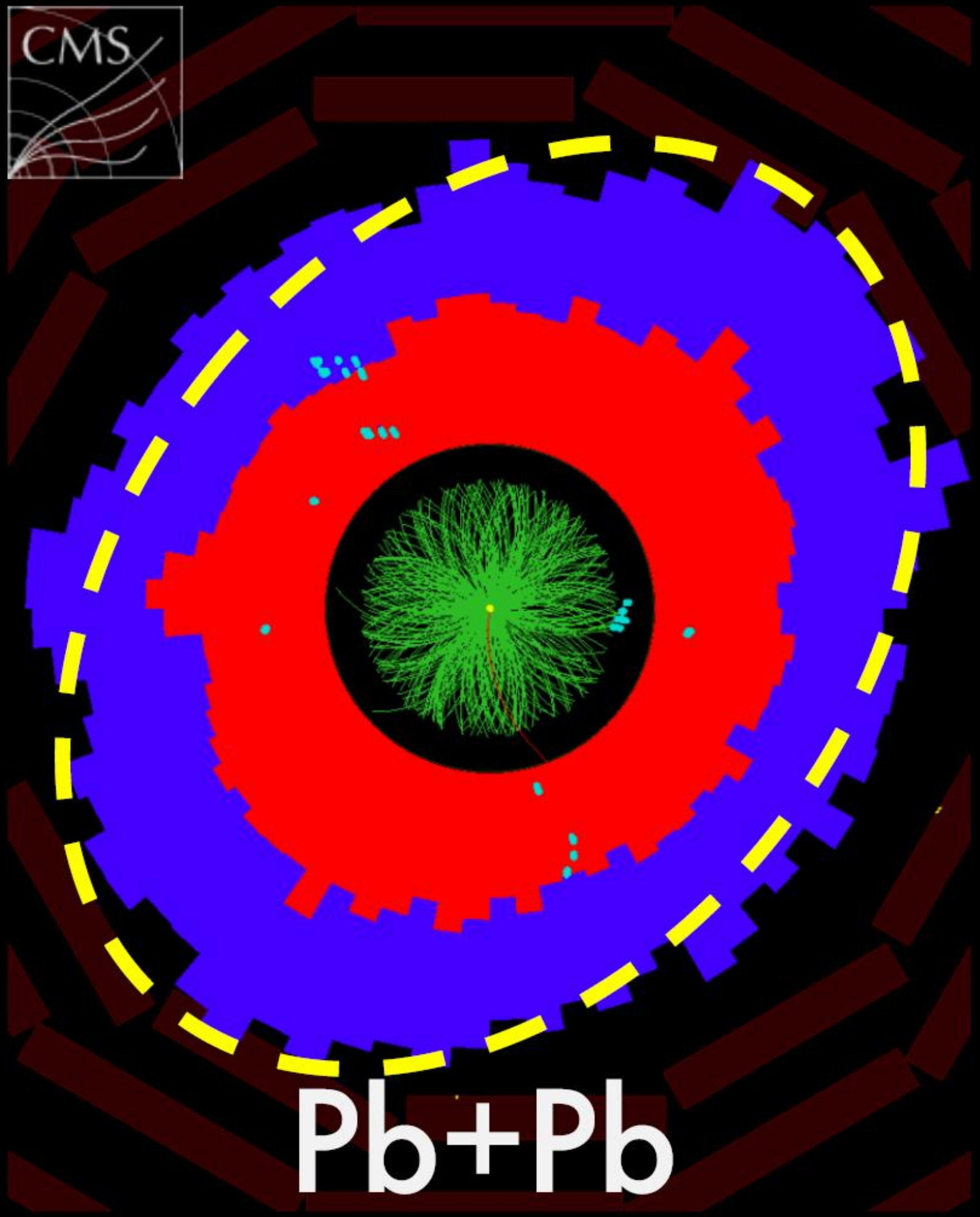
Initial state → **Hydro** → Momentum anisotropy



Azimuthal anisotropy

$$\frac{dN}{d\phi} \ \alpha \ 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_3\cos(3\phi) + \ldots$$

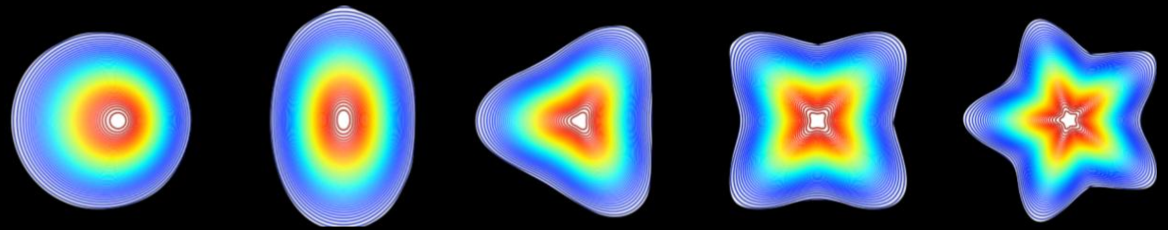




Single-particle azimuthal anisotropy

$$\frac{dN}{d\phi} \propto 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_3\cos(3\phi) + \ldots$$

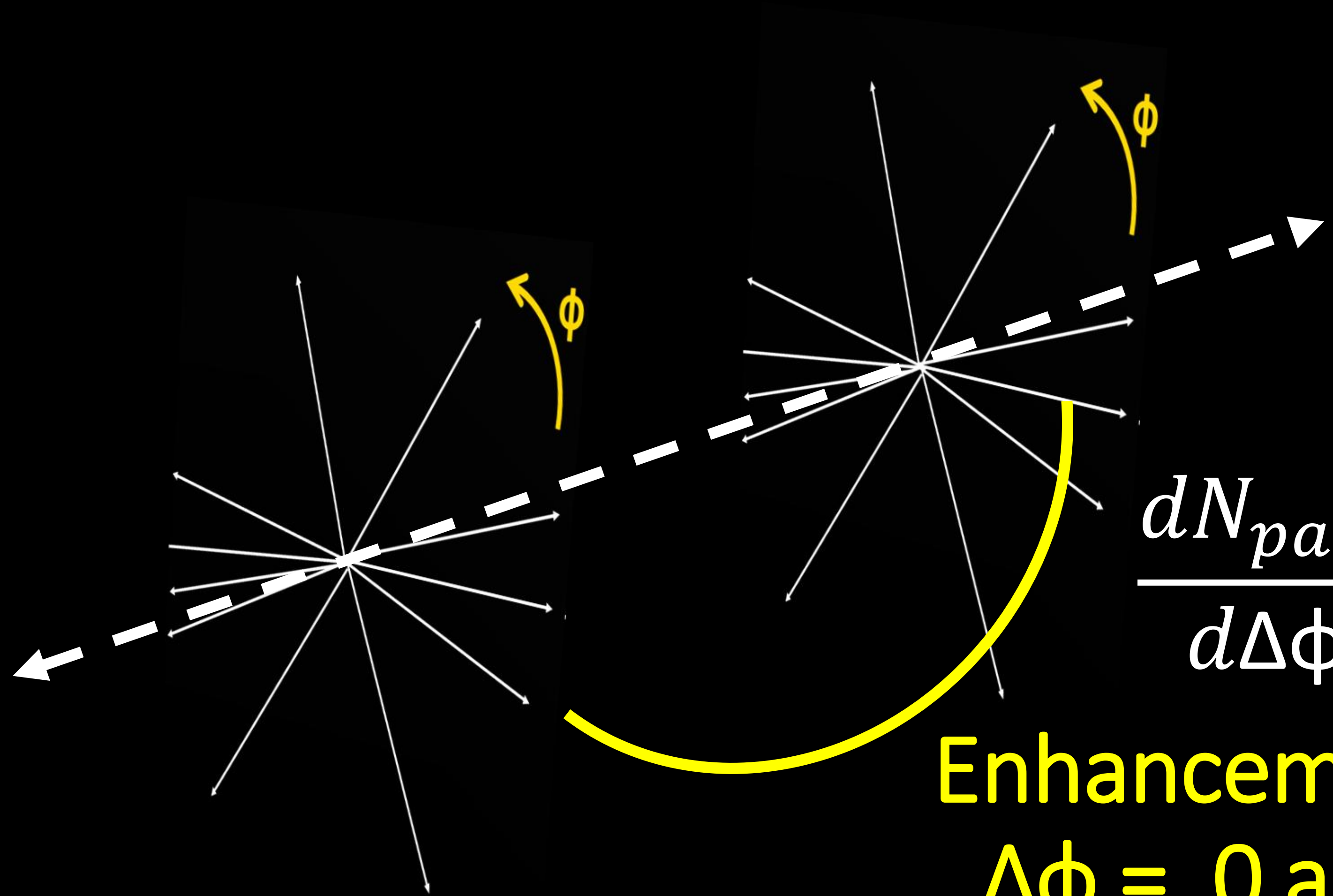
n=1 n=2 n=3 n=4 n=5



Two-particle correlation

For the purposes of this talk

All charged particle tracks



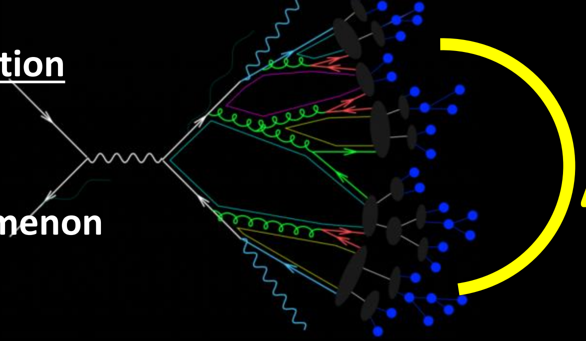
rapidity

$$\frac{dN_{pair}}{d\Delta\phi} \alpha\ 1 + 2v_{2,2}\cos(2\Delta\phi) + .$$

Enhancement at
$\Delta\phi = 0$ and π

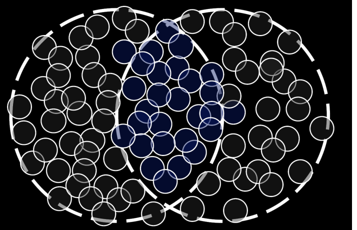
System size

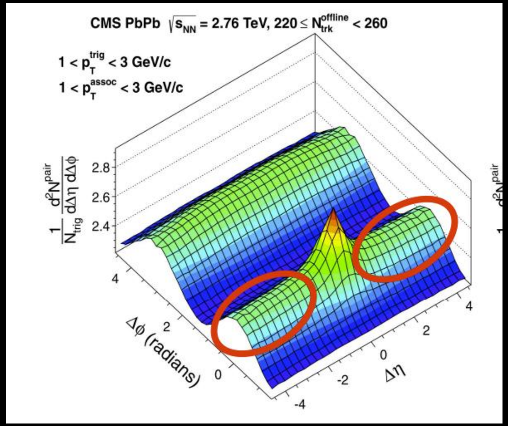
Momentum conservation
Jets & particle decays
Termed "nonflow"
Not collective phenomenon



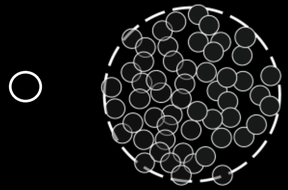
$\Delta\phi = \pi$

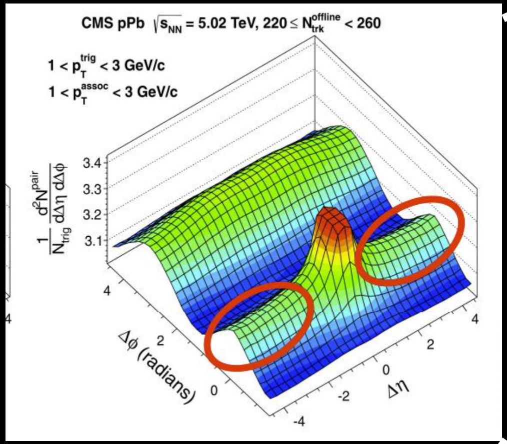
Pb+Pb

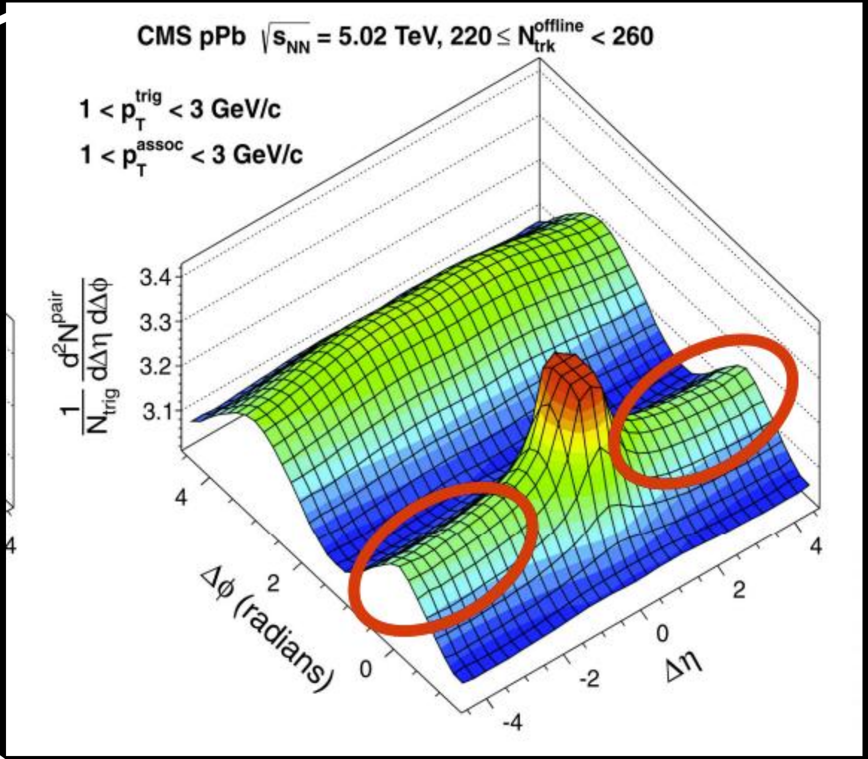




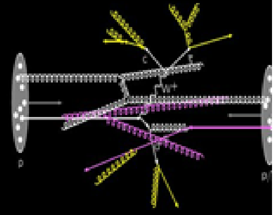
p+Pb

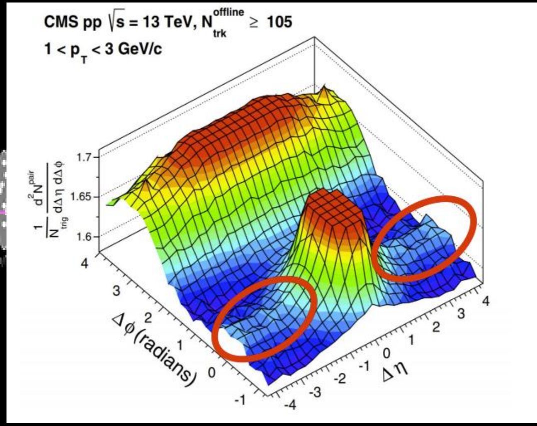


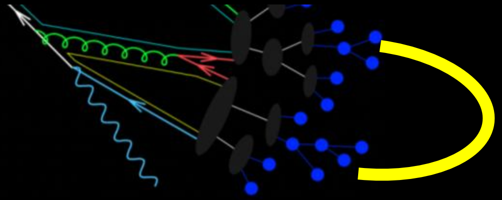




pp



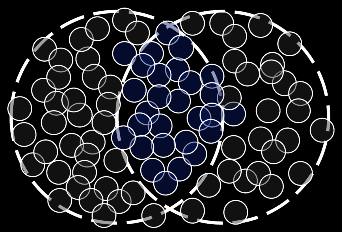




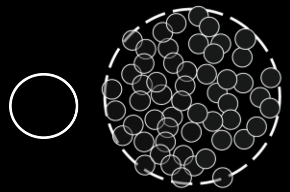
$\Delta\phi < 2$
$\Delta\eta < 2$

System size

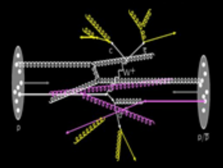
Pb+Pb



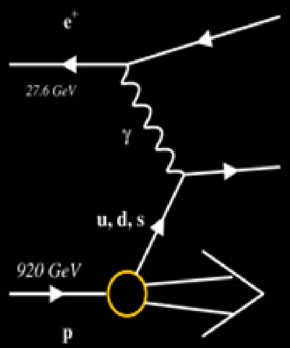
p+Pb



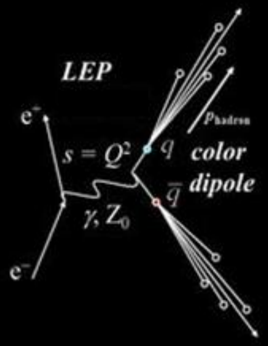
pp



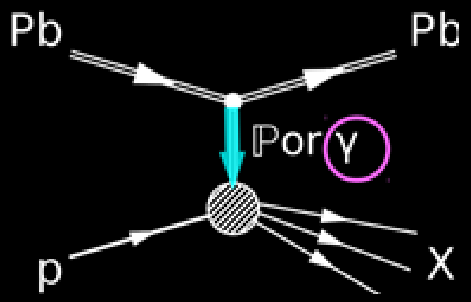
e+*p*



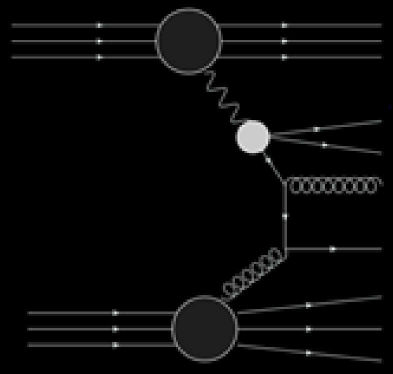
$e^+ + e^-$



γ+*p*



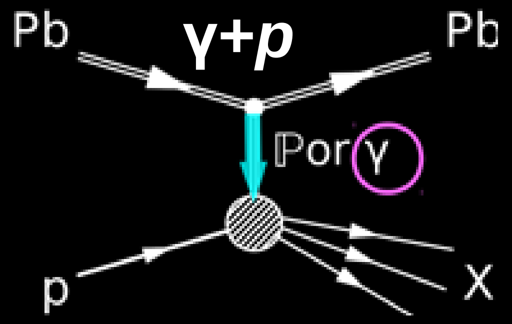
γ+A

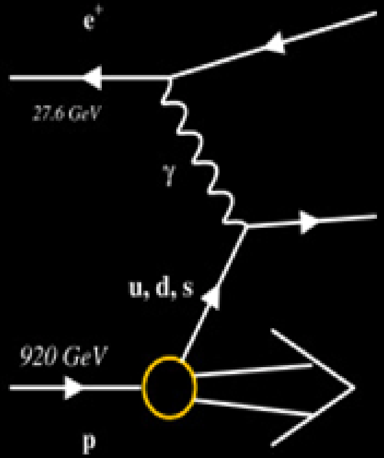


Recent measurements

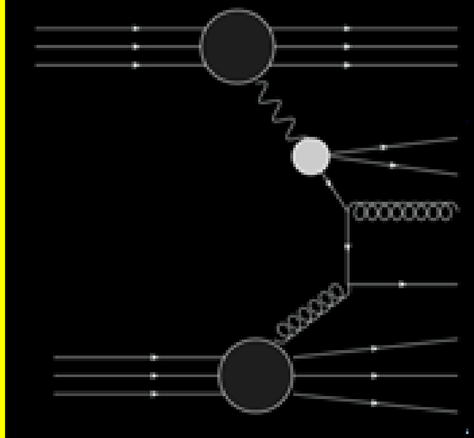
Today

e+*p*

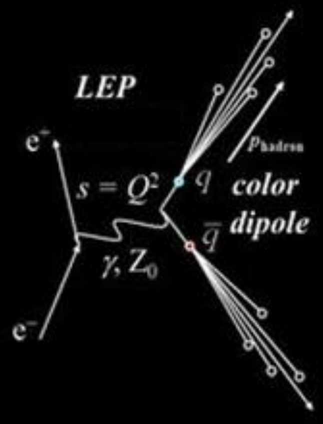




γ+A



$e^+ + e^-$



γ+*p* collectivity
arXiv:2204.13486

Preliminary

arXiv:2106.12377

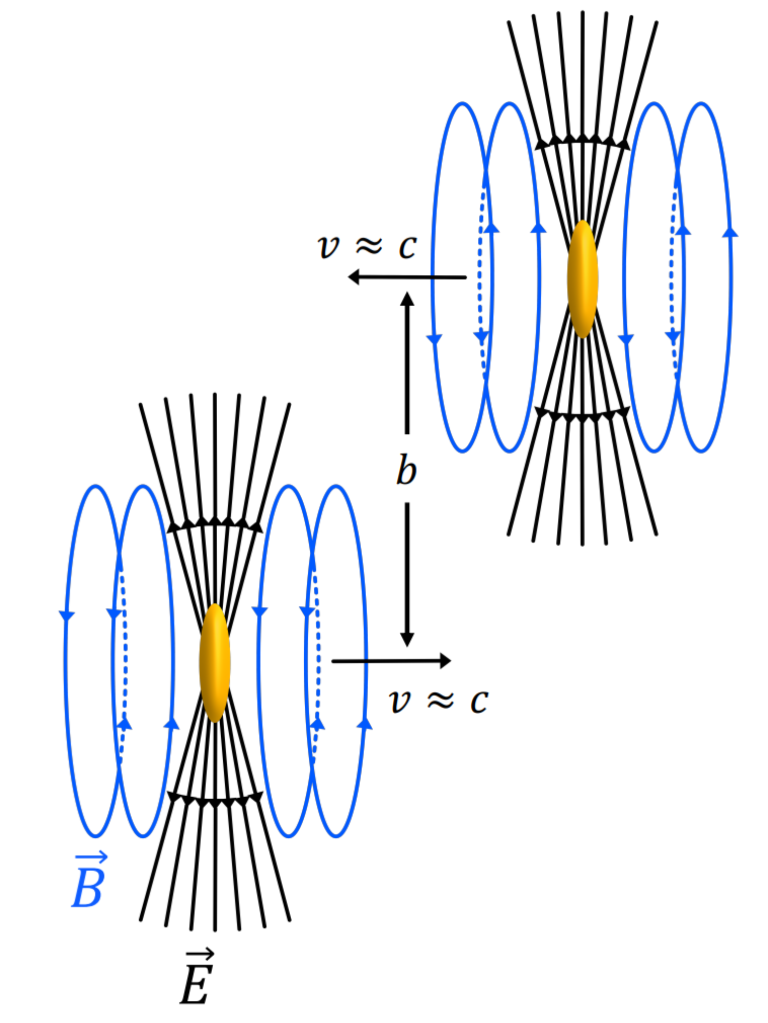
γ+A collectivity
arXiv:2101.10771

ICHEP22 talk

QM22 talk

Ultra-peripheral collisions

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, SuperChic
- Differences with full QED calculations
- **Quasi-real photon**

	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- good up-to-date review as well: arXiv:2103.16623

Photon wave function

Low (Q^2 = 0) virtuality photons

$$|\gamma\rangle = \sqrt{Z_3}\,|\gamma_{\text{bare}}\rangle + \sum_{V=\rho^0,\omega,\phi} \frac{\sqrt{4\pi\alpha_{\text{EM}}}}{f_V}|V\rangle + \frac{\sqrt{4\pi\alpha_{\text{EM}}}}{f_{q\bar{q}}}|q\bar{q}\rangle$$

Total wave function

Bare photon

Interacts via EM force

Point-like

Vector meson component

Interacts via QCD

Extended QCD substructure

Two-photon interactions

$$|\gamma\rangle \otimes |\gamma\rangle$$

Photon-nucleus interactions

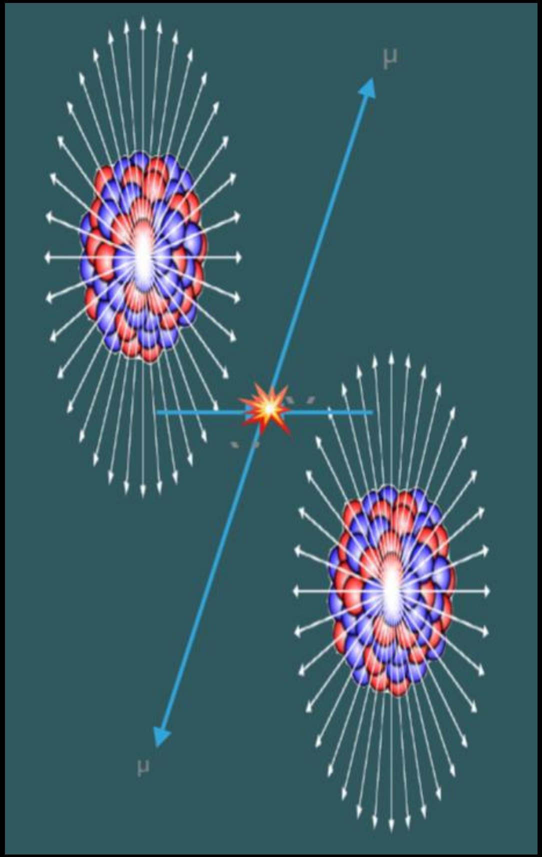
$$|\gamma\rangle \otimes \text{Pb}$$

Two-photon interactions

$|\gamma_{bare}\rangle \otimes |\gamma_{bare}\rangle$

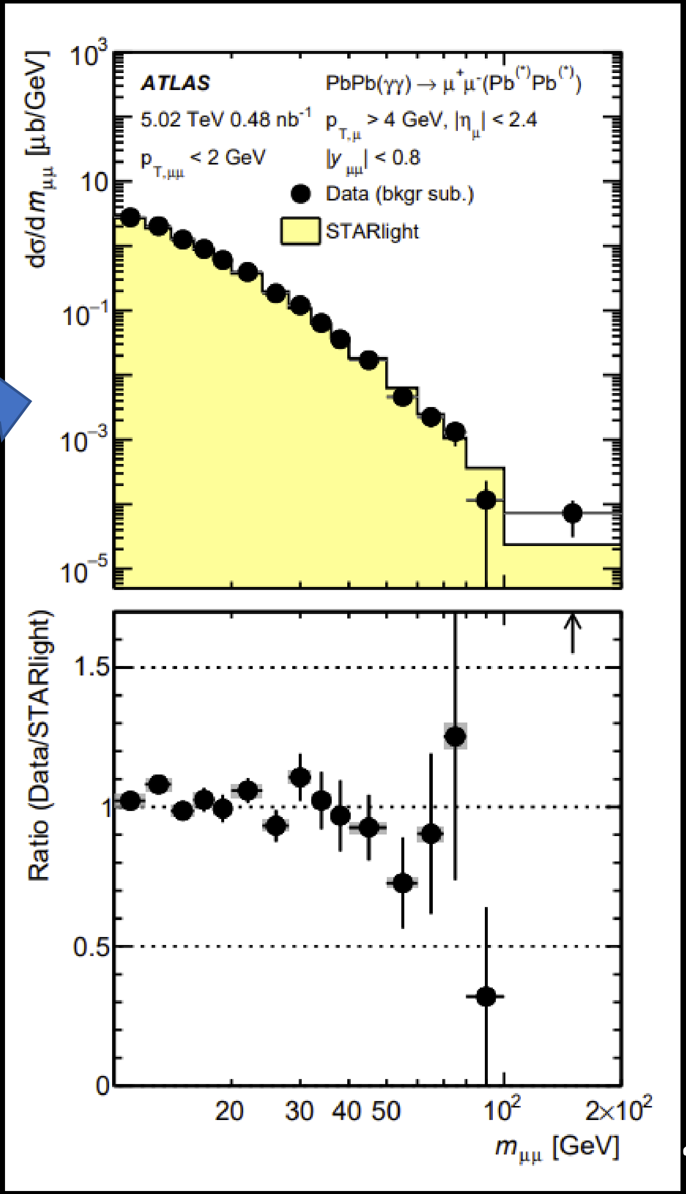
arXiv:2011.12211

Steinberg, Initial Stages 2019



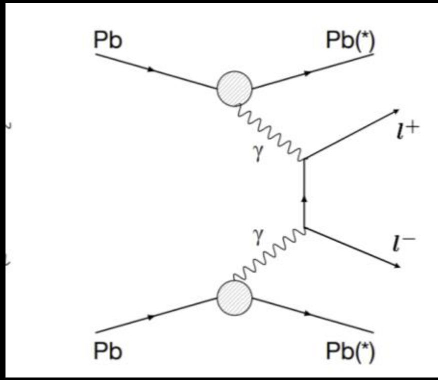
Pure EM interactions

- Back-to-back products
- Precision tests of EPA and QED calculations of photon flux
- Good agreement with **EPA**

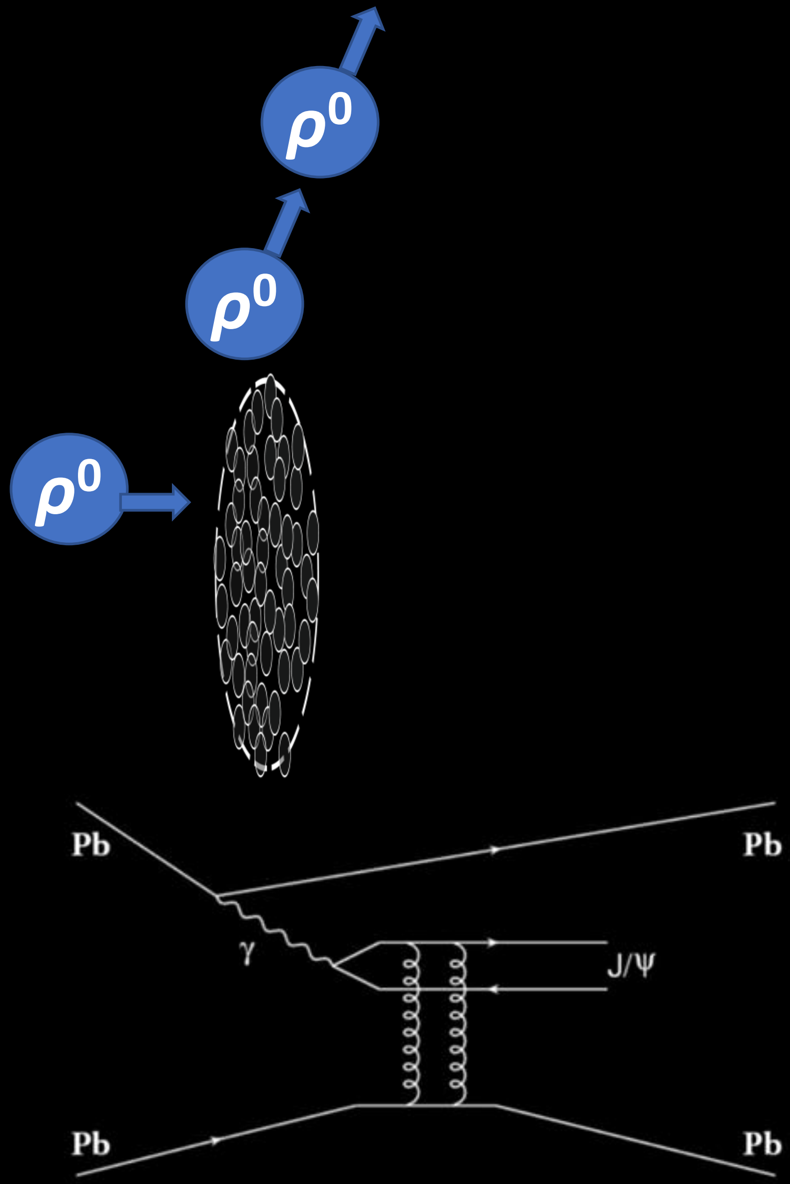


Examples

- Pure EM processes
  - γγ → γγ arXiv:1904.03536 & arXiv:2008.05355
  - γγ → μμ arXiv:2011.12211
  - γγ → ττ arXiv:2204.13478
  - γγ →ee *arXiv:2207.12781*
  - γγ →*MM* arXiv:2408.11035

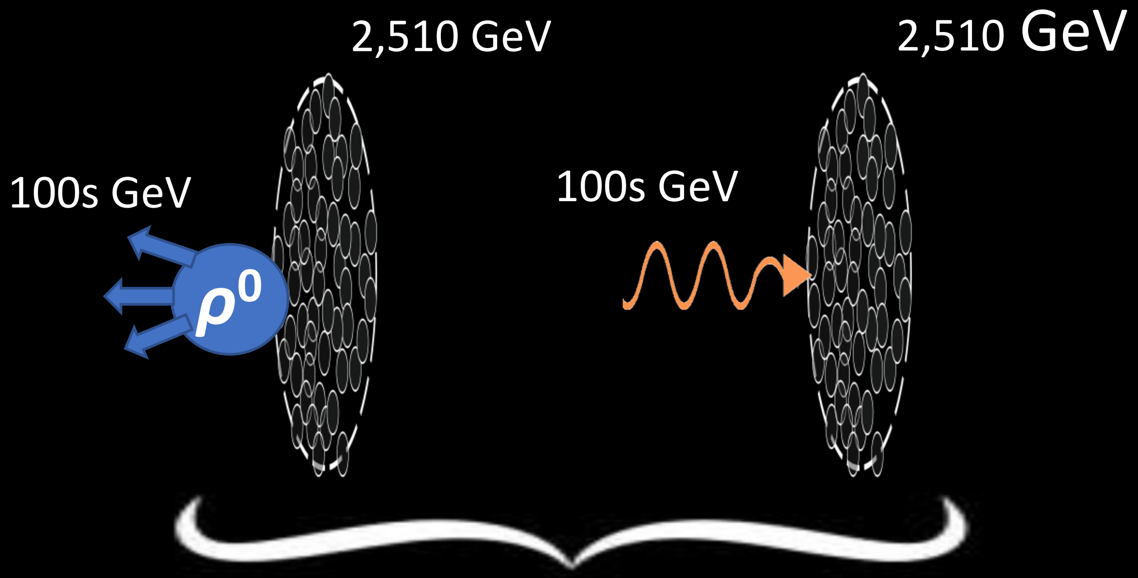


Single-photon interactions



Quasi-elastic: $\gamma + A \rightarrow A^* + V$

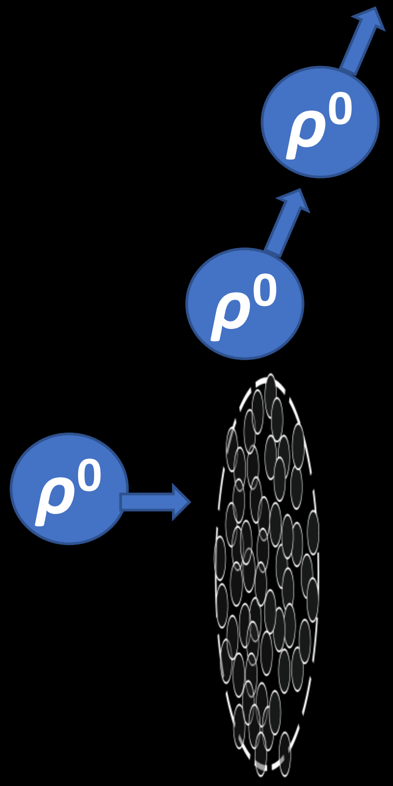
Single photon interactions

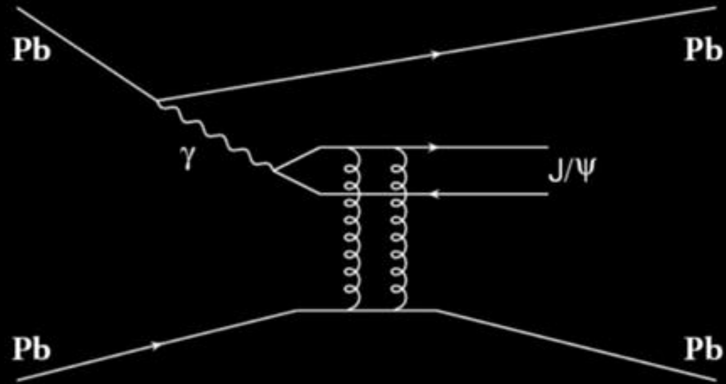


Non-diffractive/DIS interactions

Exchange of QCD quantum numbers

QCD particle production

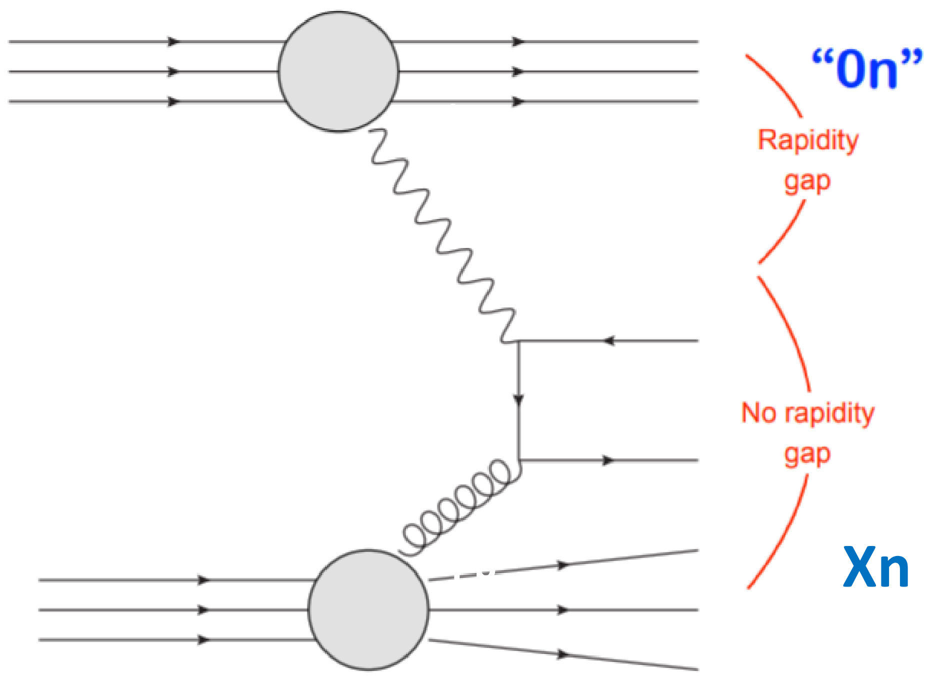




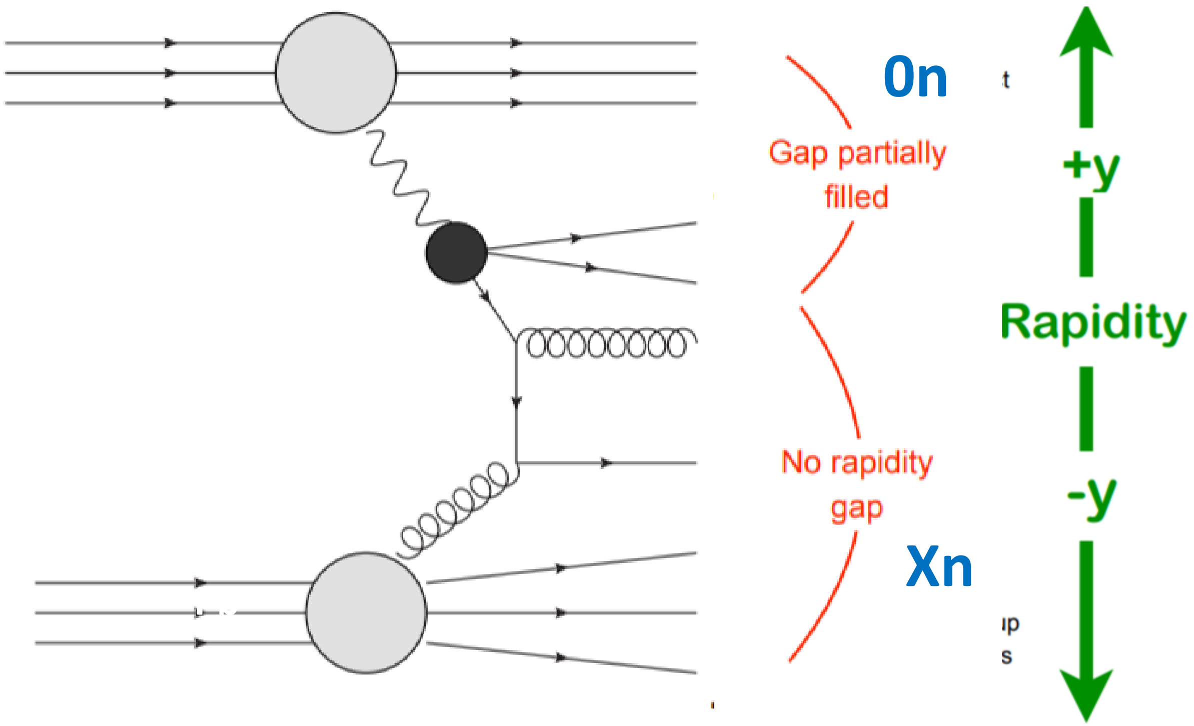
Quasi-elastic: $\gamma + A \rightarrow A^* + V$

Photonuclear collisions

Direct γA collisions
Photon couples directly to nuclear parton

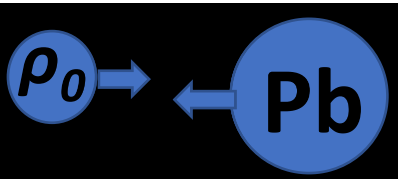


Resolved γA collisions
photon virtually resolved into hadronic state



Select events based on primarily

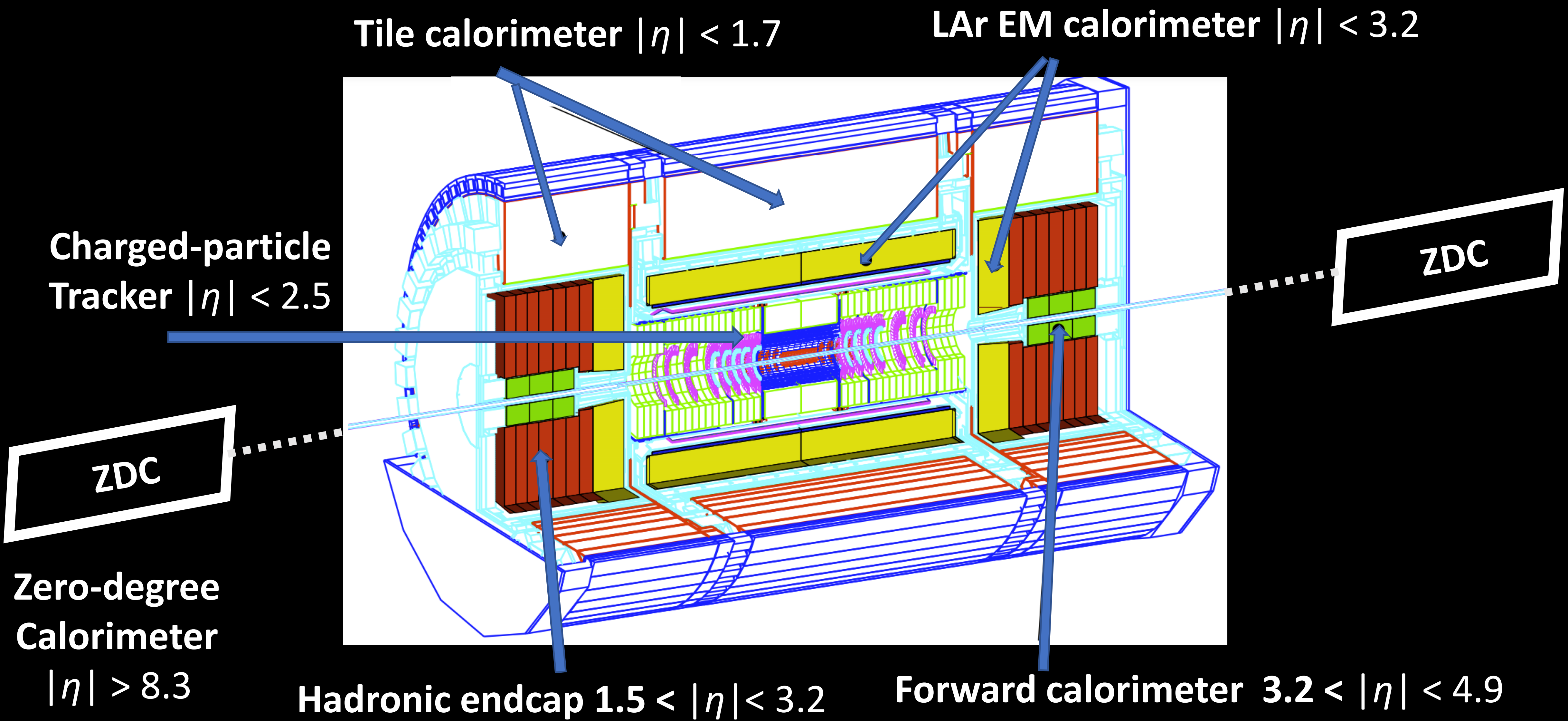
- Single-sided nuclear breakup “**0nXn**” (zero-degree calorimeter ZDC)
- Rapidity gaps



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

A Toroidal LHC ApparatuS
(ATLAS)

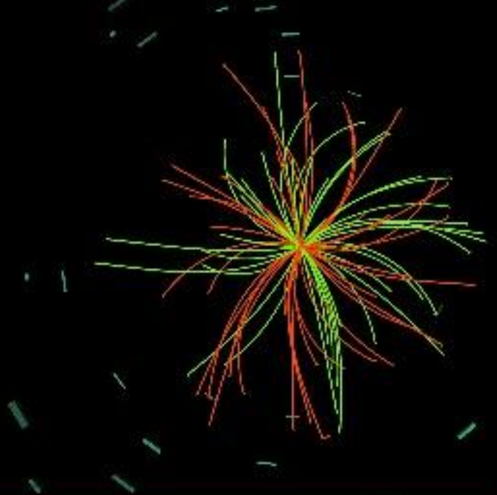
ATLAS detector



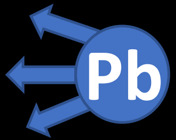
Photonuclear collisions
in
ATLAS

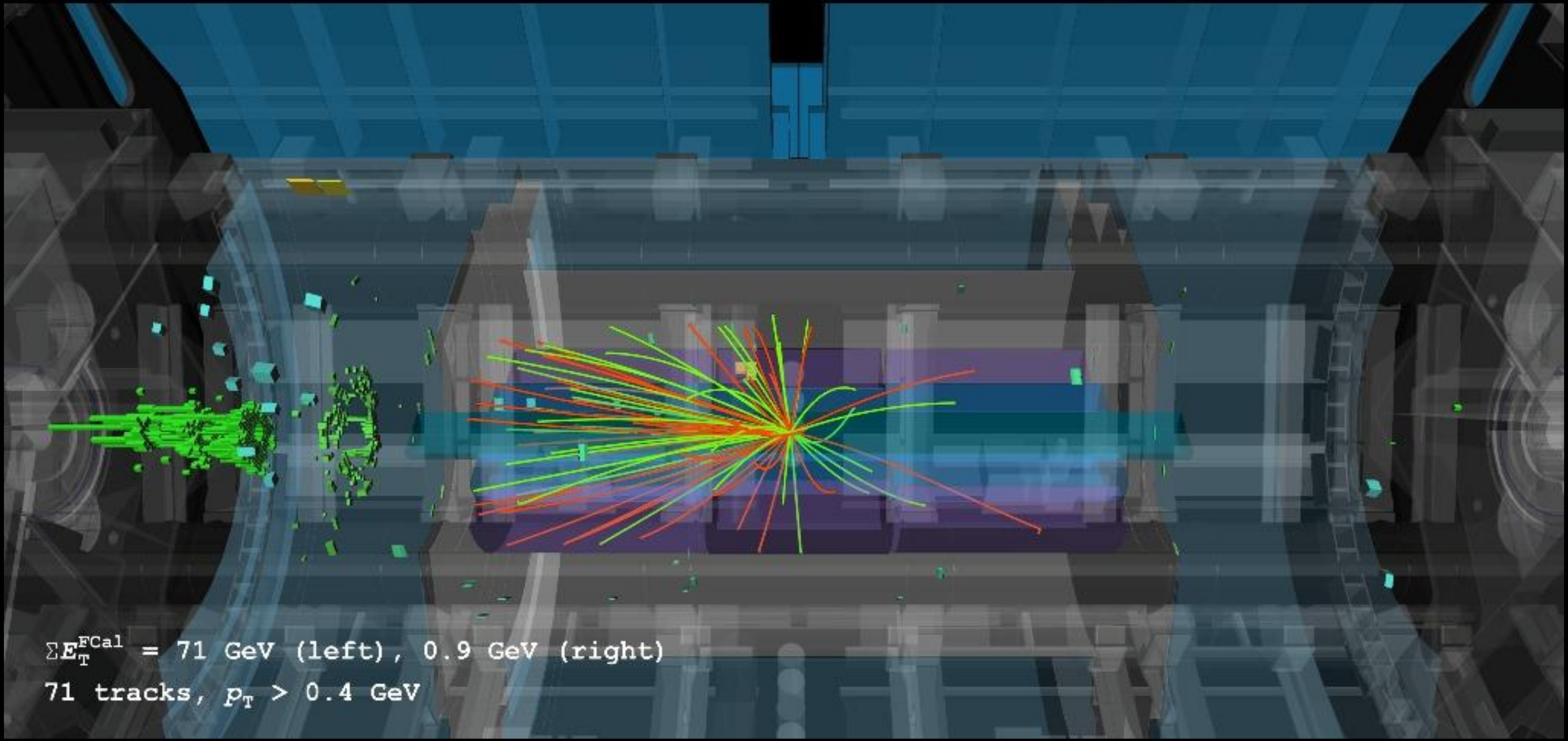
ATLAS EXPERIMENT

Pb+Pb, 5.02 TeV
Run: 365681
Event: 1064766274
2018-11-11 22:00:07 CEST



Pb going direction





photon going direction

ATLAS EXPERIMENT

Pb+Pb, 5.02 TeV
Run: 365681
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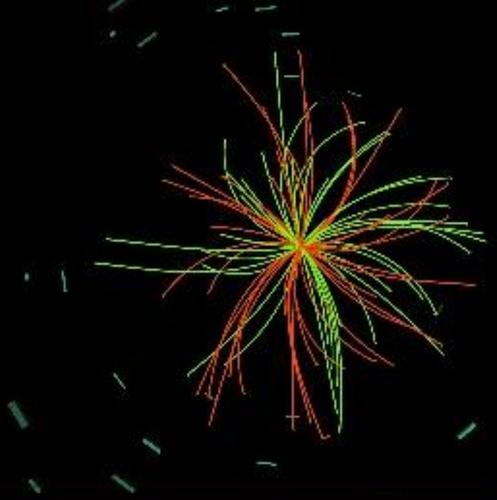
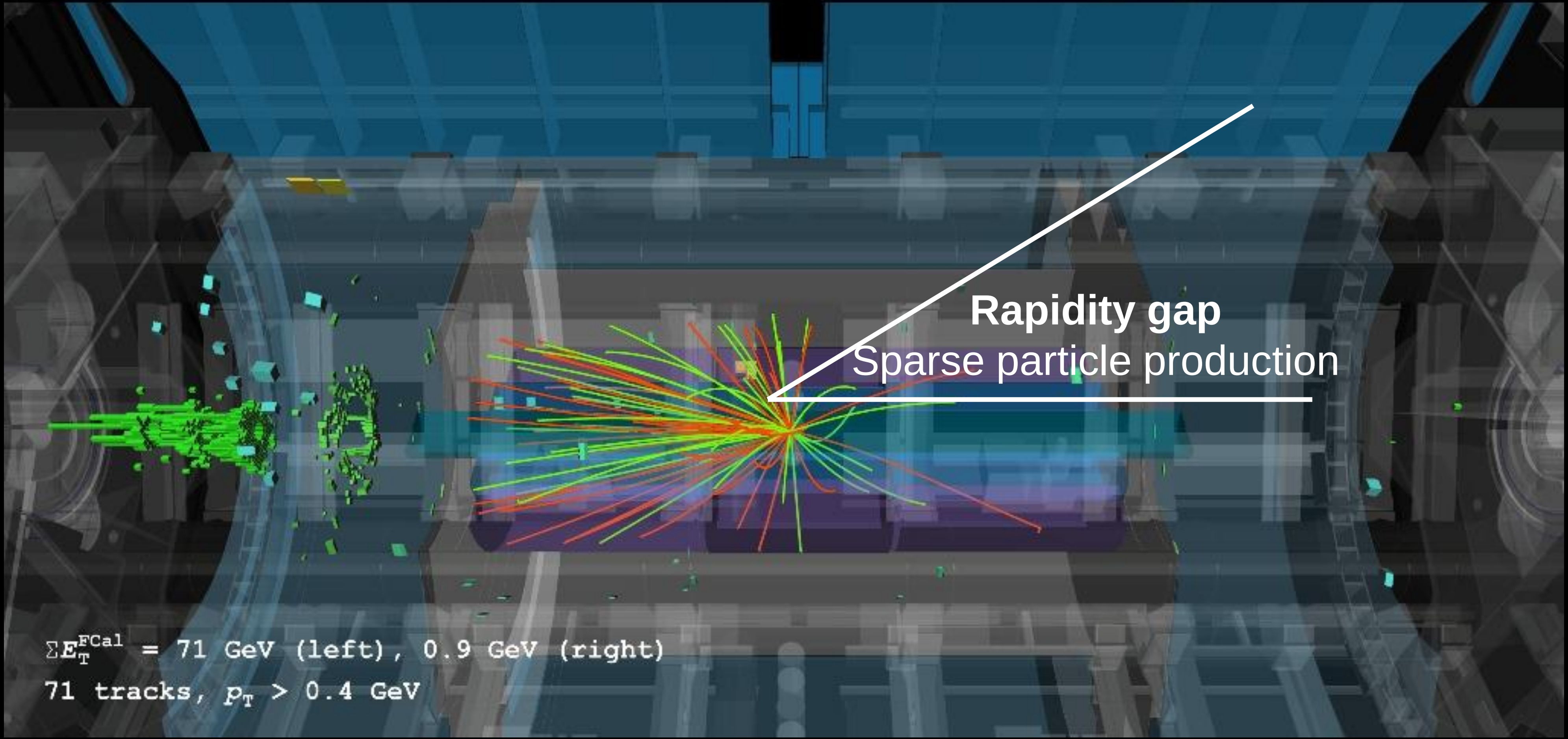


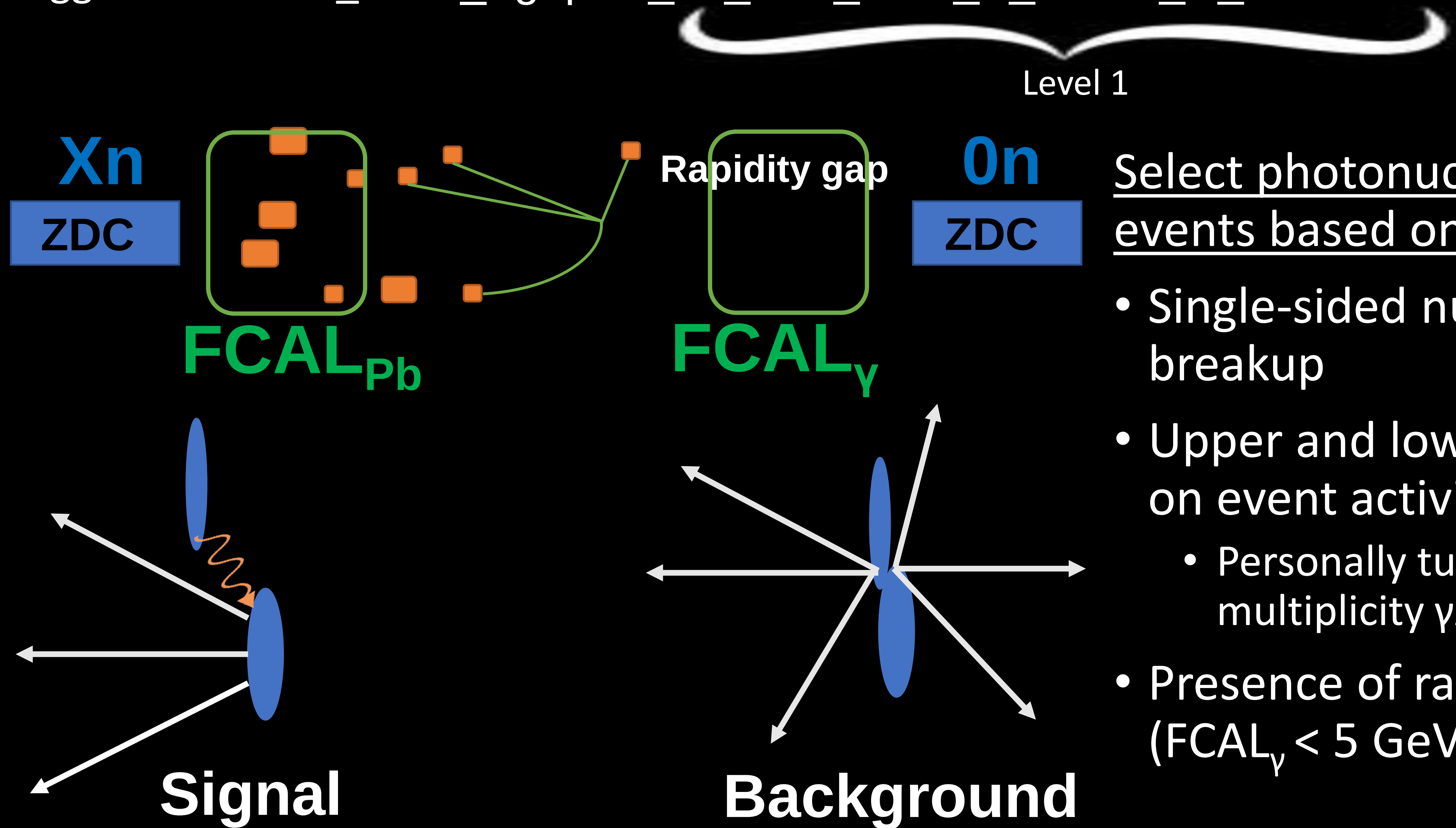
Pb going direction



photon going direction

Collecting photonuclear events

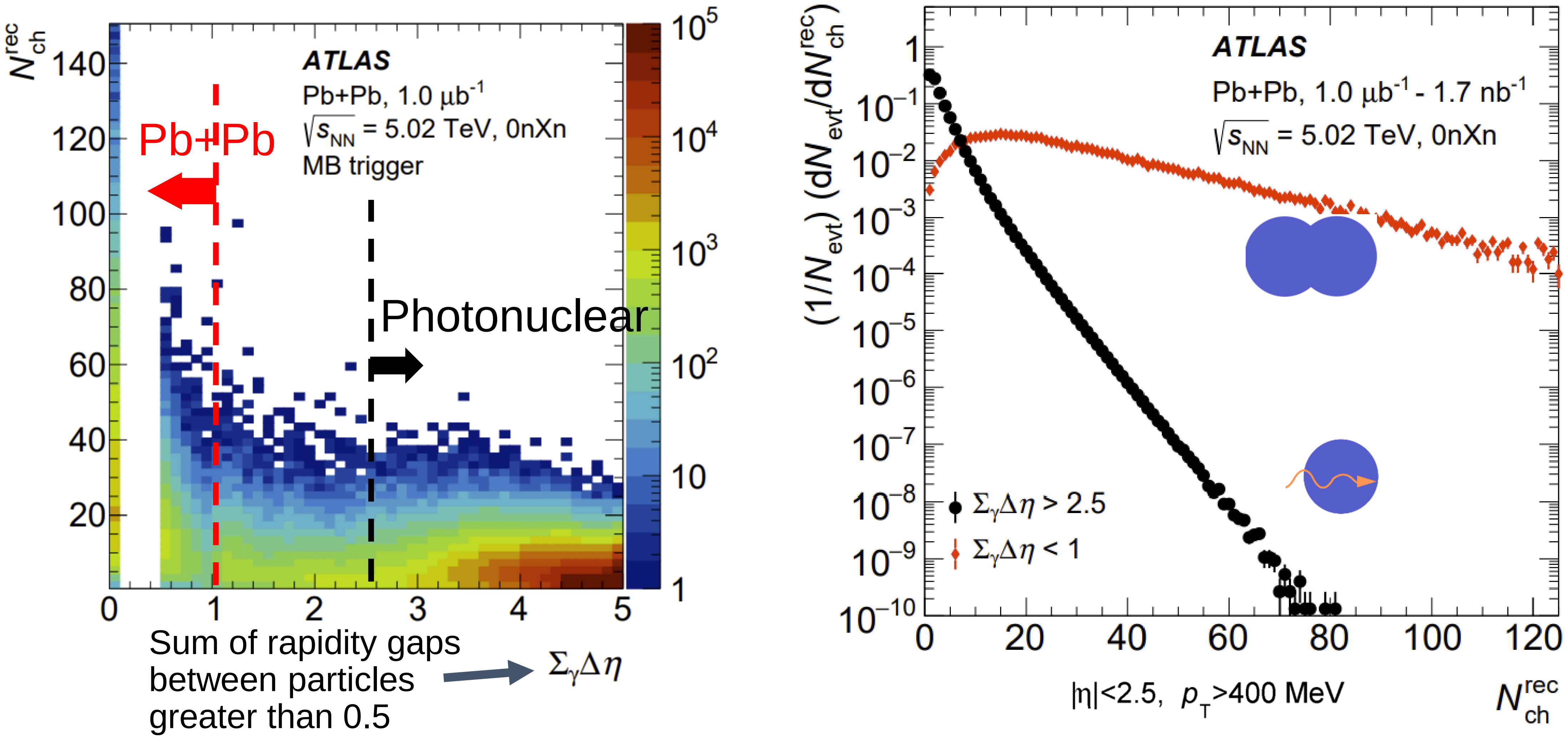
Trigger name: HLT_trk25_FgapC5_L1_TE3_ZDC_A_VZDC_C_VTE200 ???



Select photonuclear events based on

- Single-sided nuclear breakup
- Upper and lower bound on event activity
  - Personally tuned for high-multiplicity γA
- Presence of rapidity gaps ($FCAL_{\gamma}$ < 5 GeV)

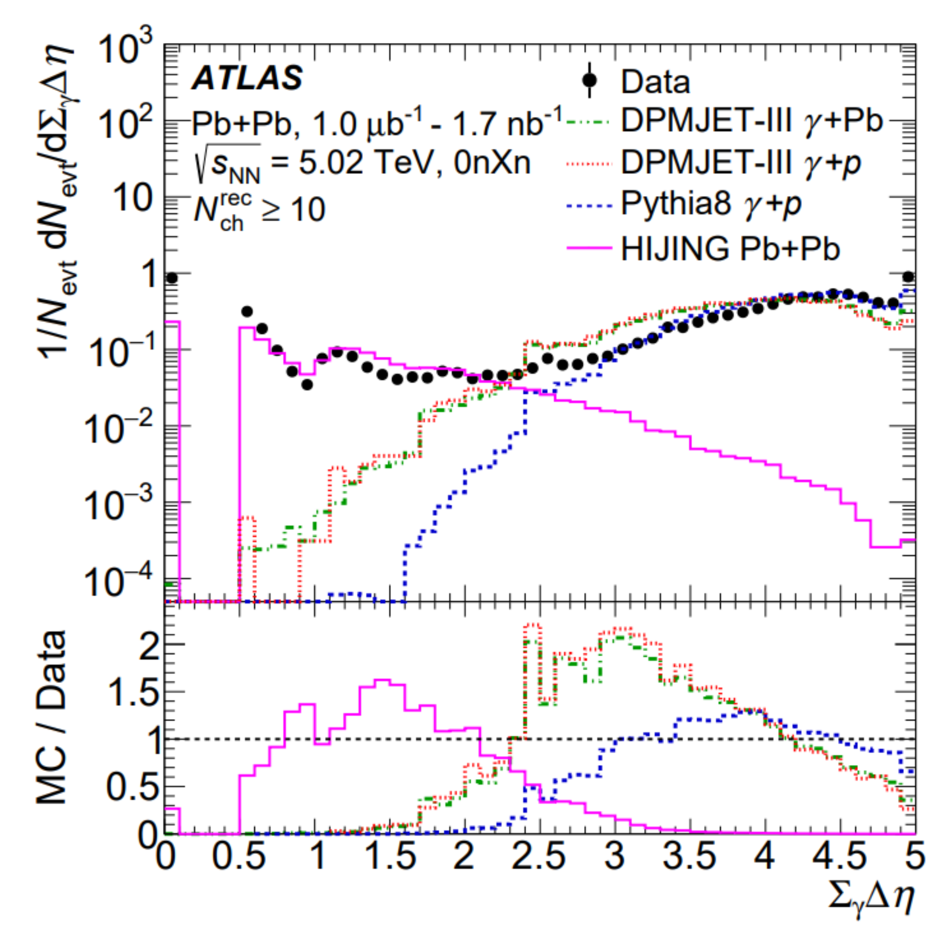
Rapidity gaps $\Sigma_\gamma\Delta\eta$ and N_{ch}



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

arXiv:2101.10771

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

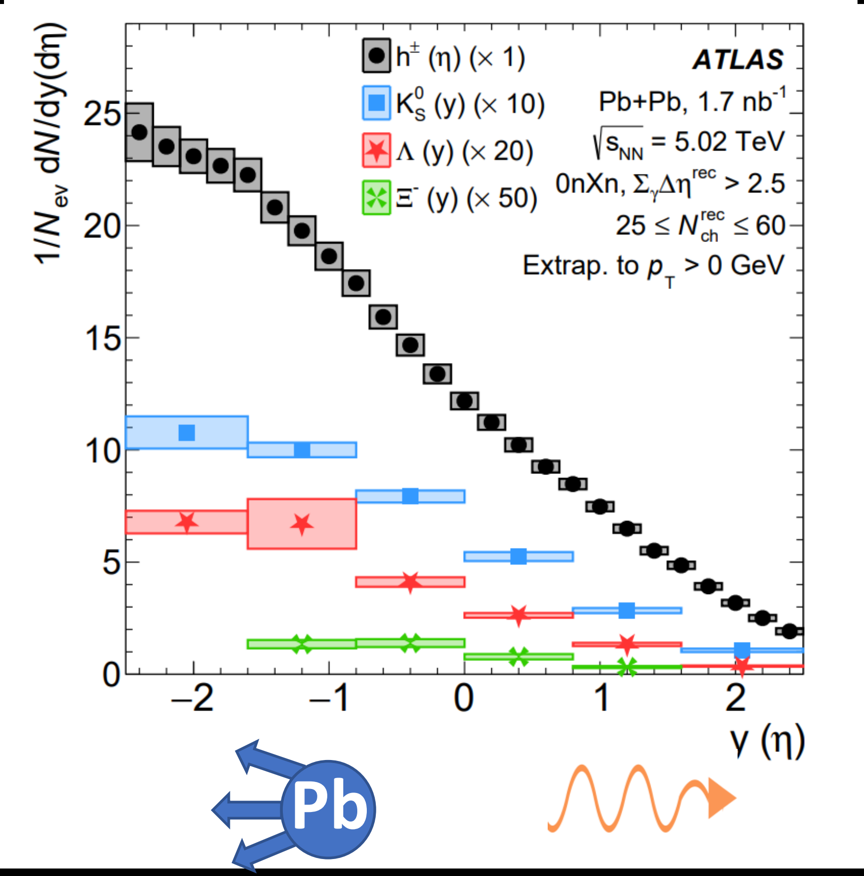
MC normalized to data in control regions

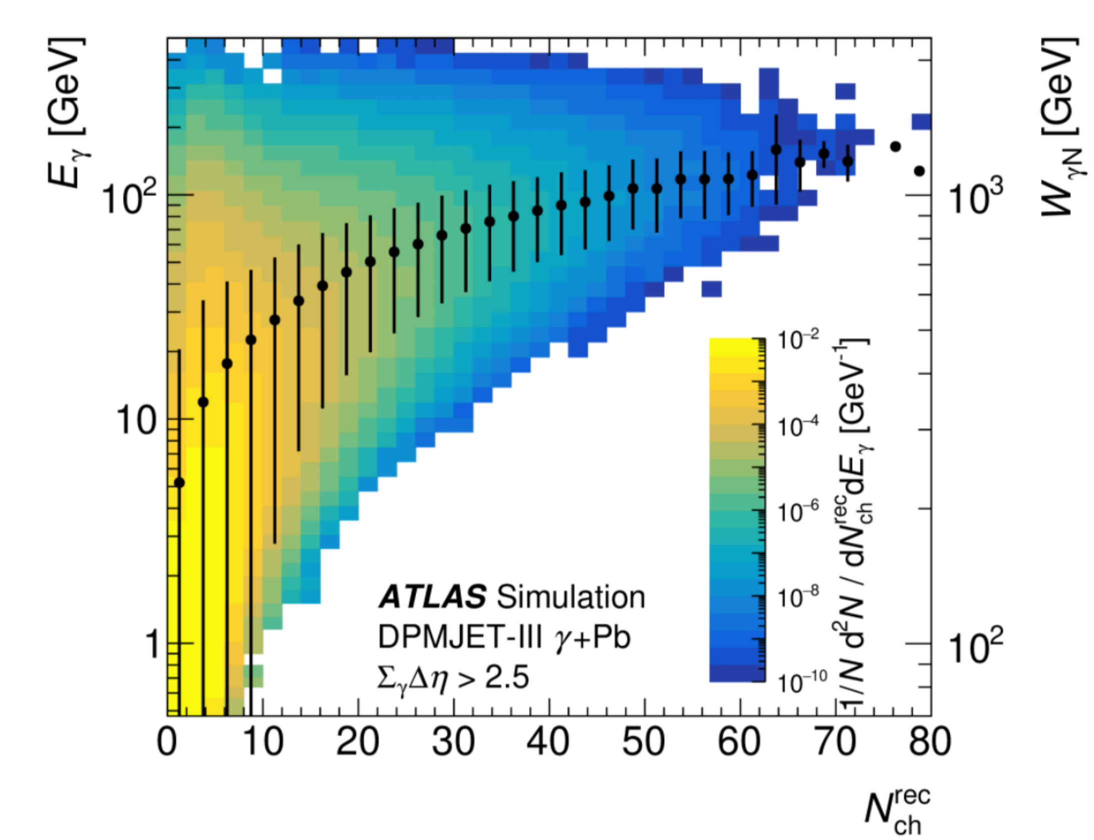
Qualitative agreement with MCs, PYTHIA being the most compatible

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

arXiv:2101.10771

$dN_{ch}/d\eta$ in γA collisions





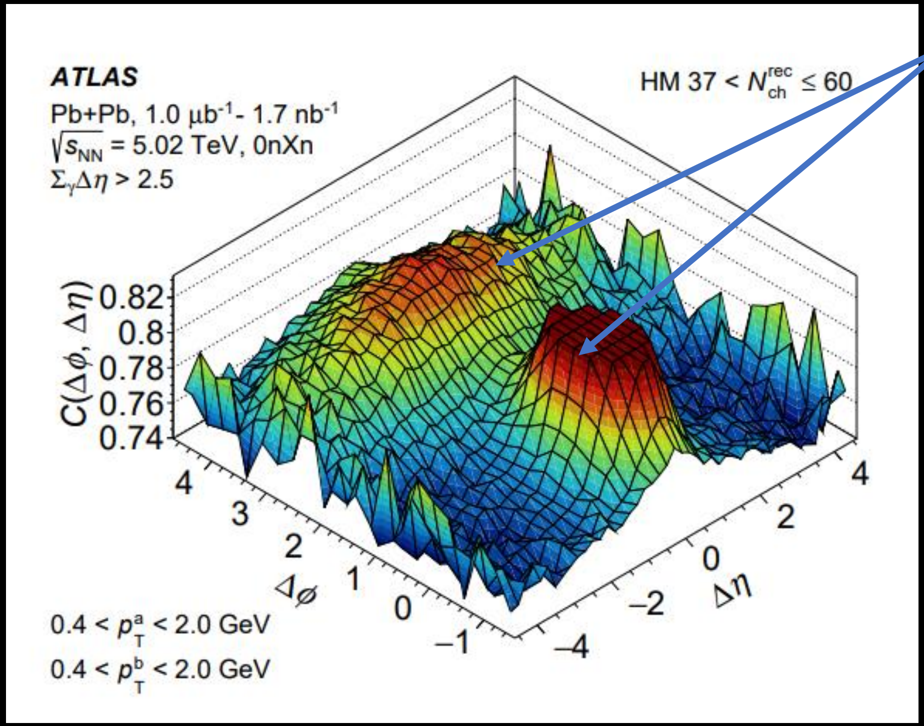
$dN_{ch}/d\eta$ of photonuclear events - very similar shape with $N_{ch} \geq 10$

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 $dN_{ch}/d\eta$

arXiv:2101.10771

Two-particle correlations and non-flow

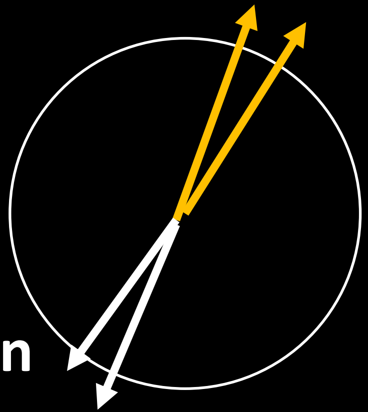


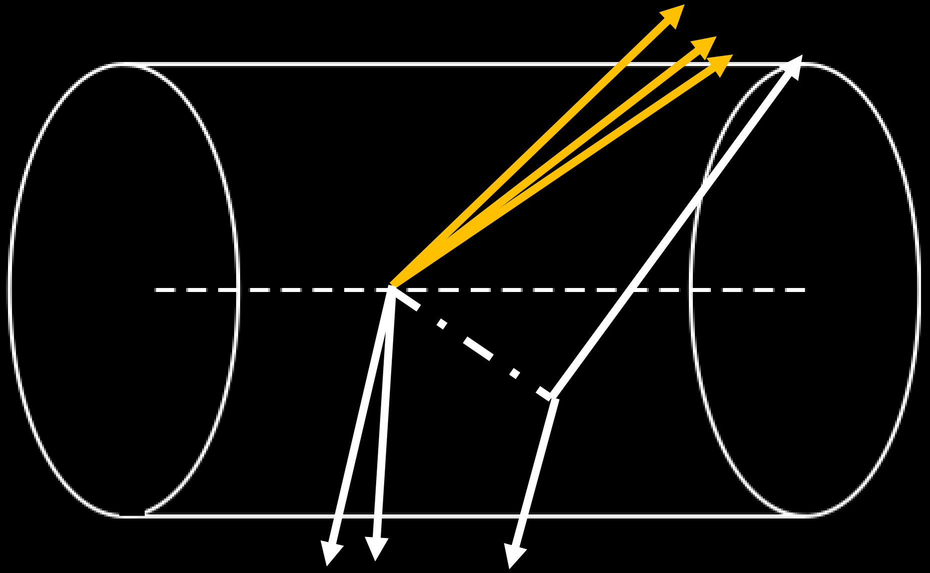
Momentum conservation

Jets & particle decays

Termed "nonflow"

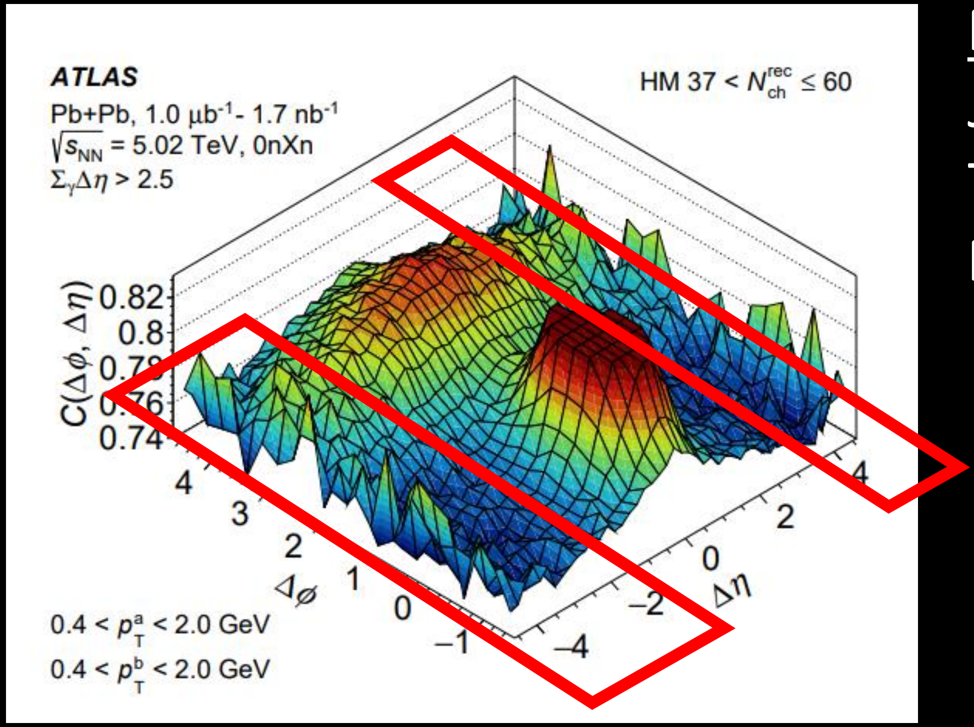
Not collective phenomenon





arXiv:2101.10771

Two-particle correlations and non-flow



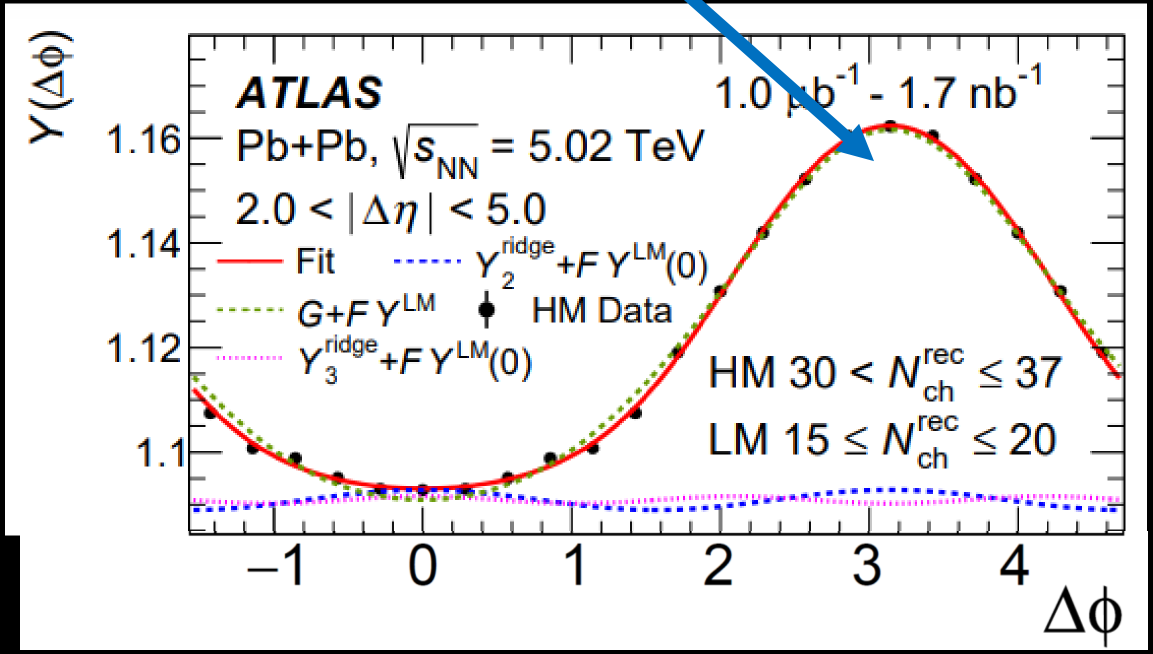
No clear
nearside ridge

Momentum conservation

Jets & particle decays

Termed "nonflow"

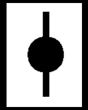
Not collective phenomenon

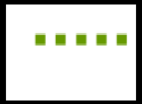


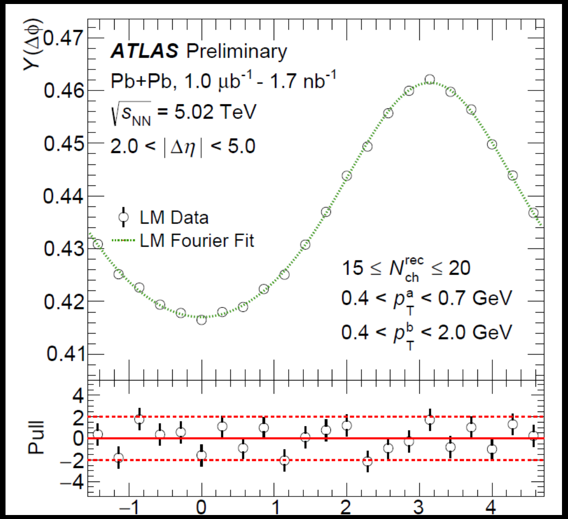
Need to remove nonflow

arXiv:2101.10771

Non-flow removal in γA correlations


High-multiplicity (HM) correlation data

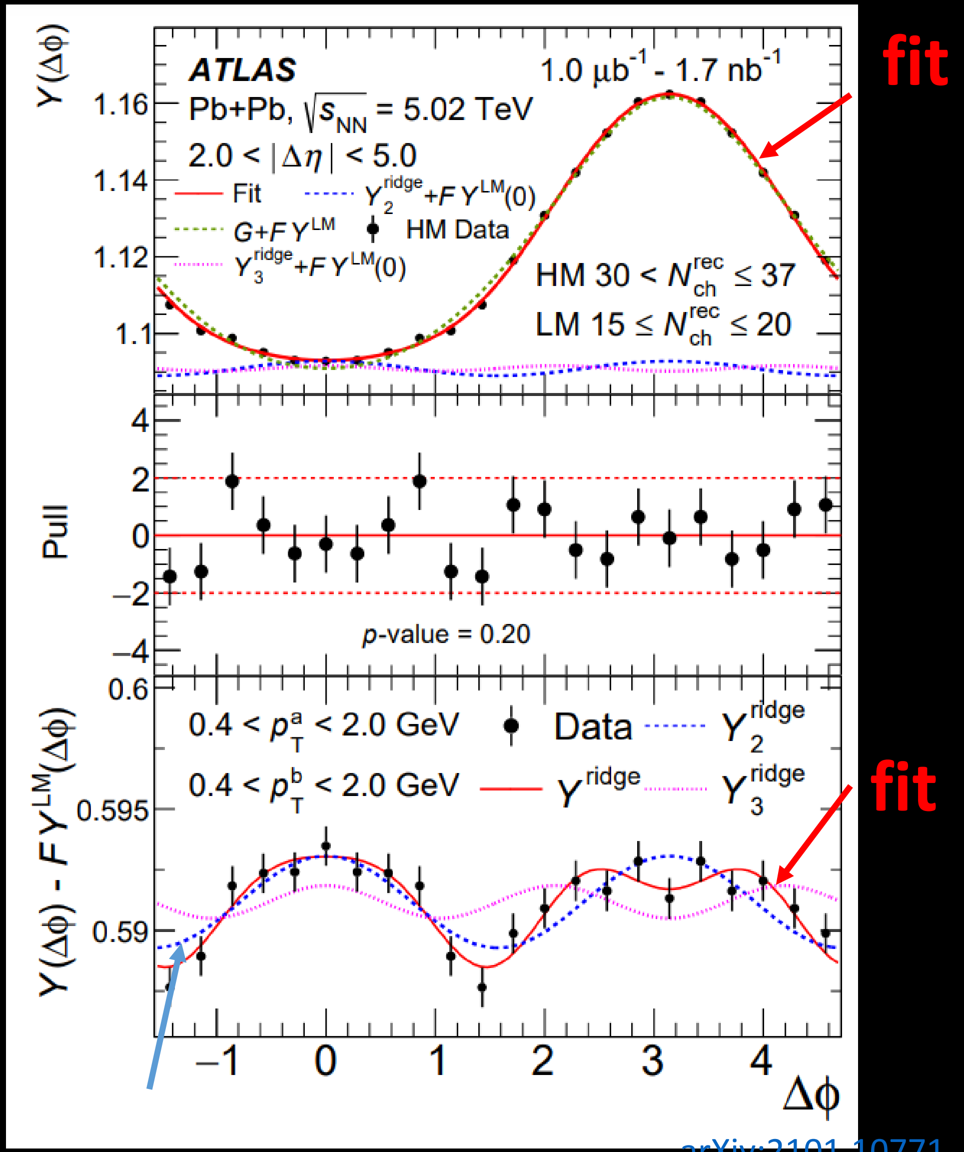

Low multiplicity (LM) template for jet/non-flow correlation



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

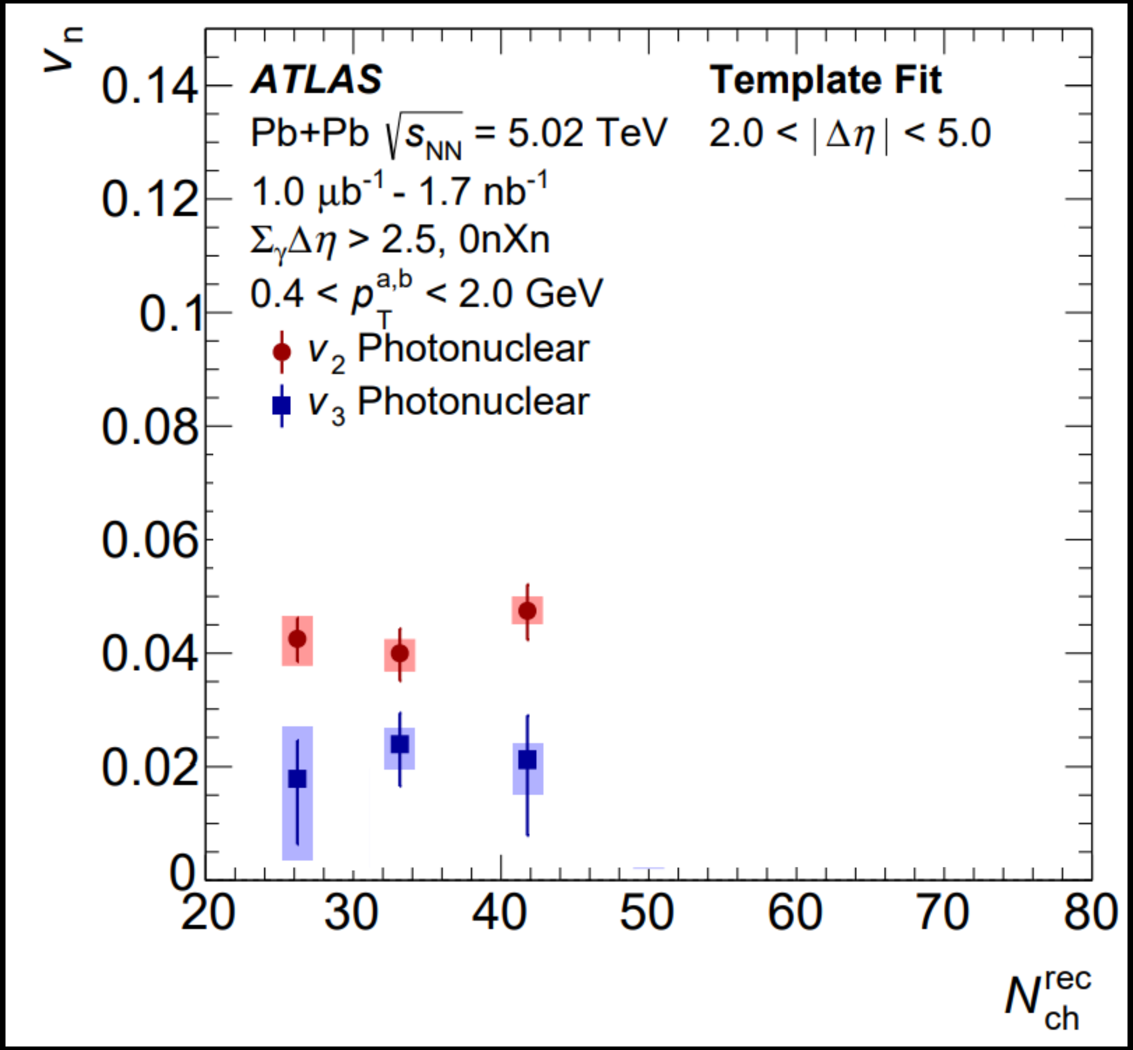
$$Y^{\mathrm{HM}}(\Delta\phi) = F Y^{\mathrm{LM}}(\Delta\phi) + G\left\{1 + 2\sum_{n=2}^{3} v_{n,n}\cos(n\Delta\phi)\right\}$$



arXiv:2101.10771

After nonflow subtraction clear cos(2Δϕ) modulation

v_n in photonuclear collisions

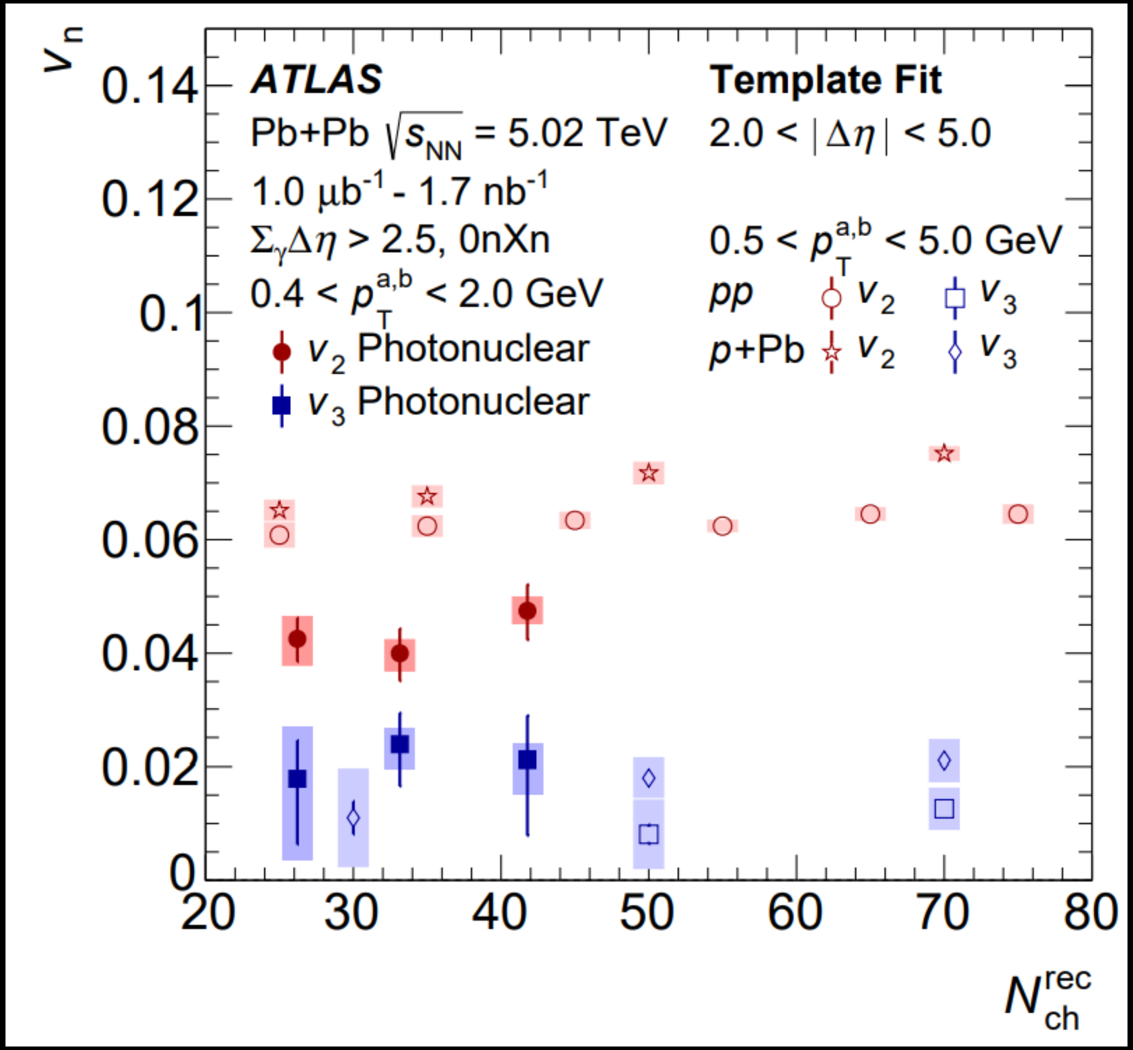


Significant nonzero v_2 and v_3 in photonuclear collisions

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

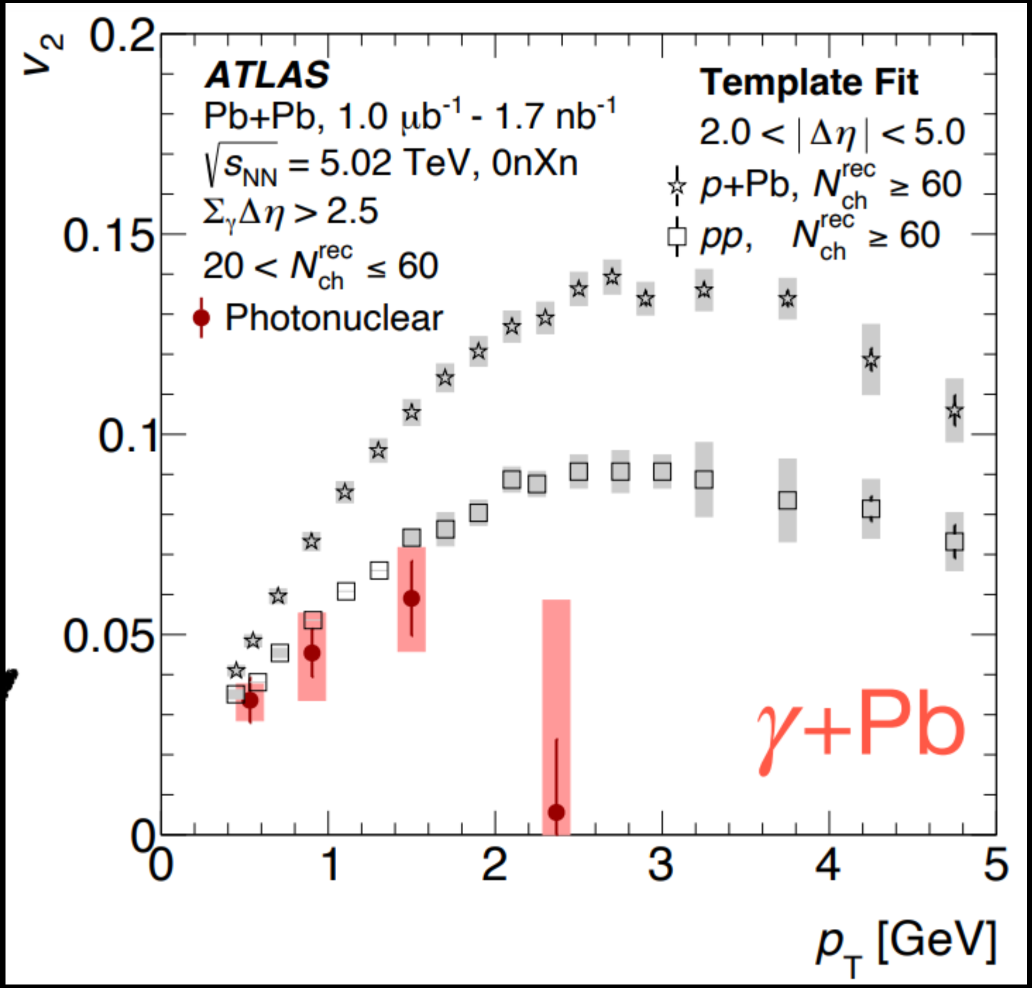
Flat $v_2(N_{ch})$ within statistical precision

γA has significantly lower v_2 than *pp*

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

arXiv:2101.10771

v_n in photonuclear collisions



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)

(3+1)D hydrodynamic model comparison

Collectivity in Ultra-Peripheral Pb+Pb Collisions at the Large Hadron Collider

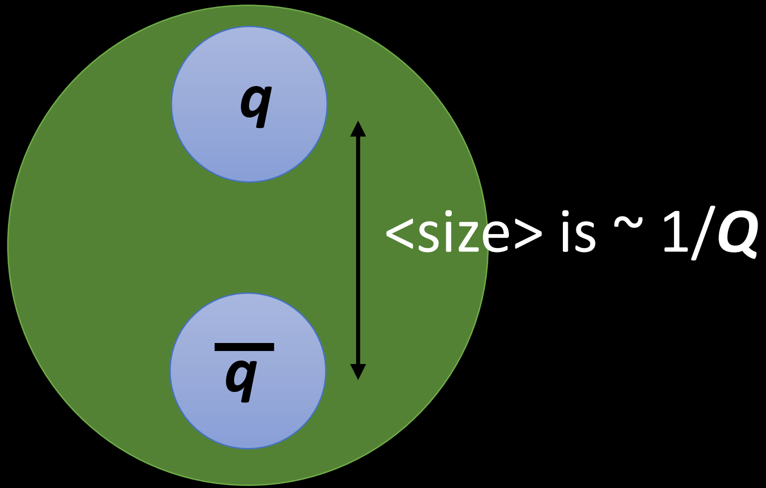
Wenbin Zhao,[1] Chun Shen,[1,2] and Björn Schenke[3]

Initial state

$$|\gamma\rangle = \sqrt{Z_3}\,|\gamma_{\rm bare}\rangle + \sum_{V=\rho^0,\omega,\phi} \frac{\sqrt{4\pi\alpha_{\rm EM}}}{f_V}\,|V\rangle + \frac{\sqrt{4\pi\alpha_{\rm EM}}}{f_{q\bar{q}}}\,|q\bar{q}\rangle$$

Rho Wave function:

Gaussian hot spots



Rho PDF:

Defines the longitudinal extent of energy deposition

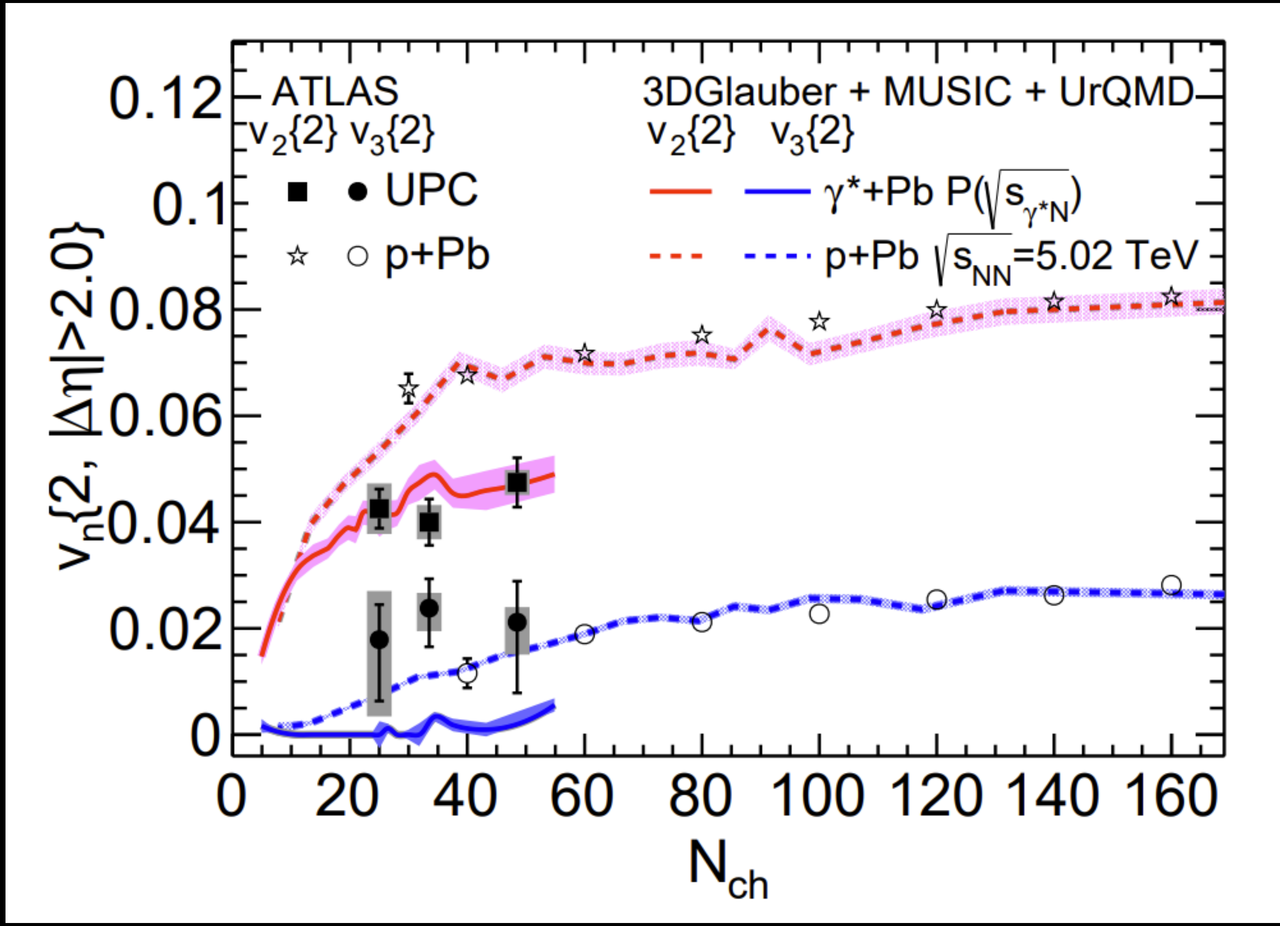
$$xv^{\rm VM} = N_v x^{\alpha}(1-x)^{\beta}$$

Final state

Viscous Hydrodynamics

(3+1)D MUSIC+UrQMD

New γ+Pb theory comparisons



Nonzero γPb v_2

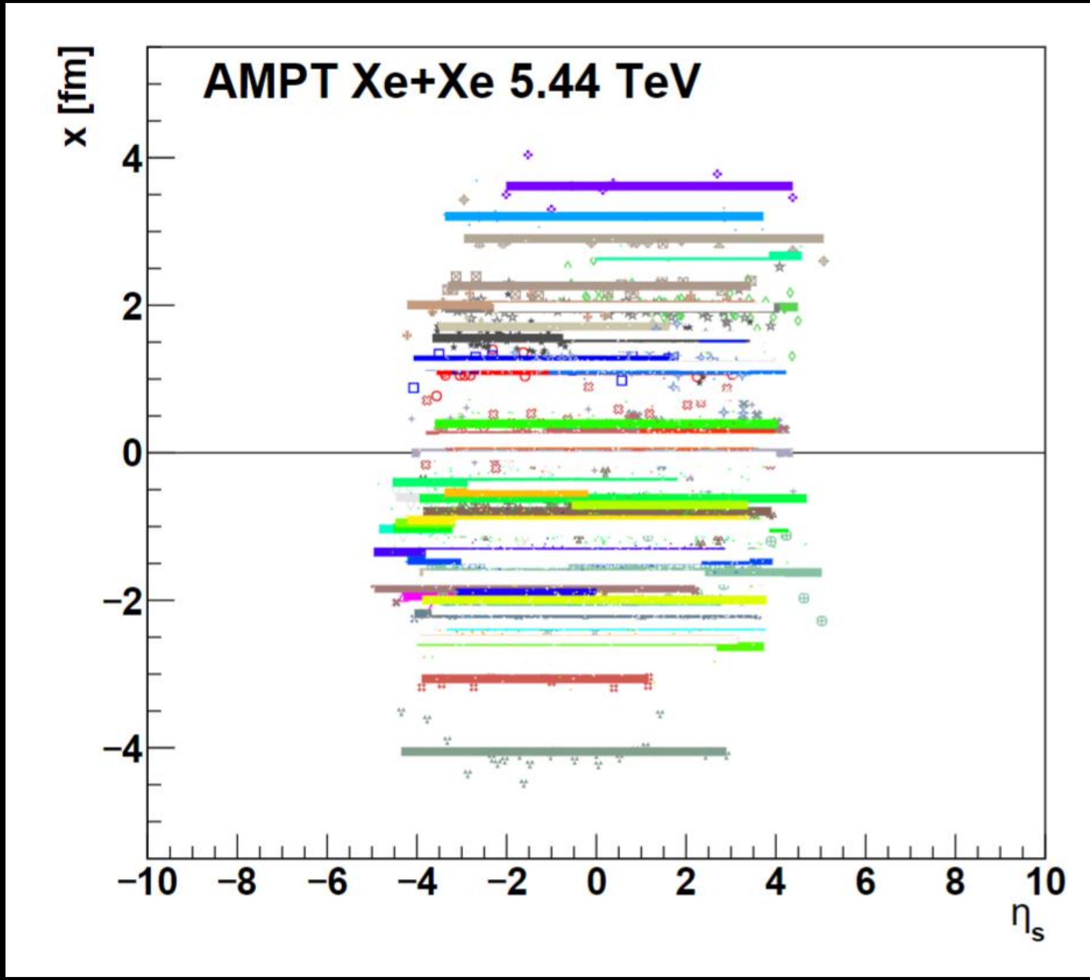
comparison to
3DGlauber + MUSIC +UrQMD

Why is
v_2 (γ *Pb) < v_2 (pPb)
Correlations performed in forward rapidity in γPb suppresses observed collectivity

arXiv:2203.06094 arXiv:2101.10771

Why is γPb v_2 smaller

- Correlations in small systems are performed with a rapidity gap between the particles
- The event plane can fluctuate between these rapidities, which decreases the observed v_2
- This effect is larger at forward rapidities.
- Because γPb is so boosted the "forward rapidities" are probes relative to other systems with the ATLAS detector.



Why is γPb v_2 smaller

EPJ Web of Conferences 276, 01002 (2023) SQM22

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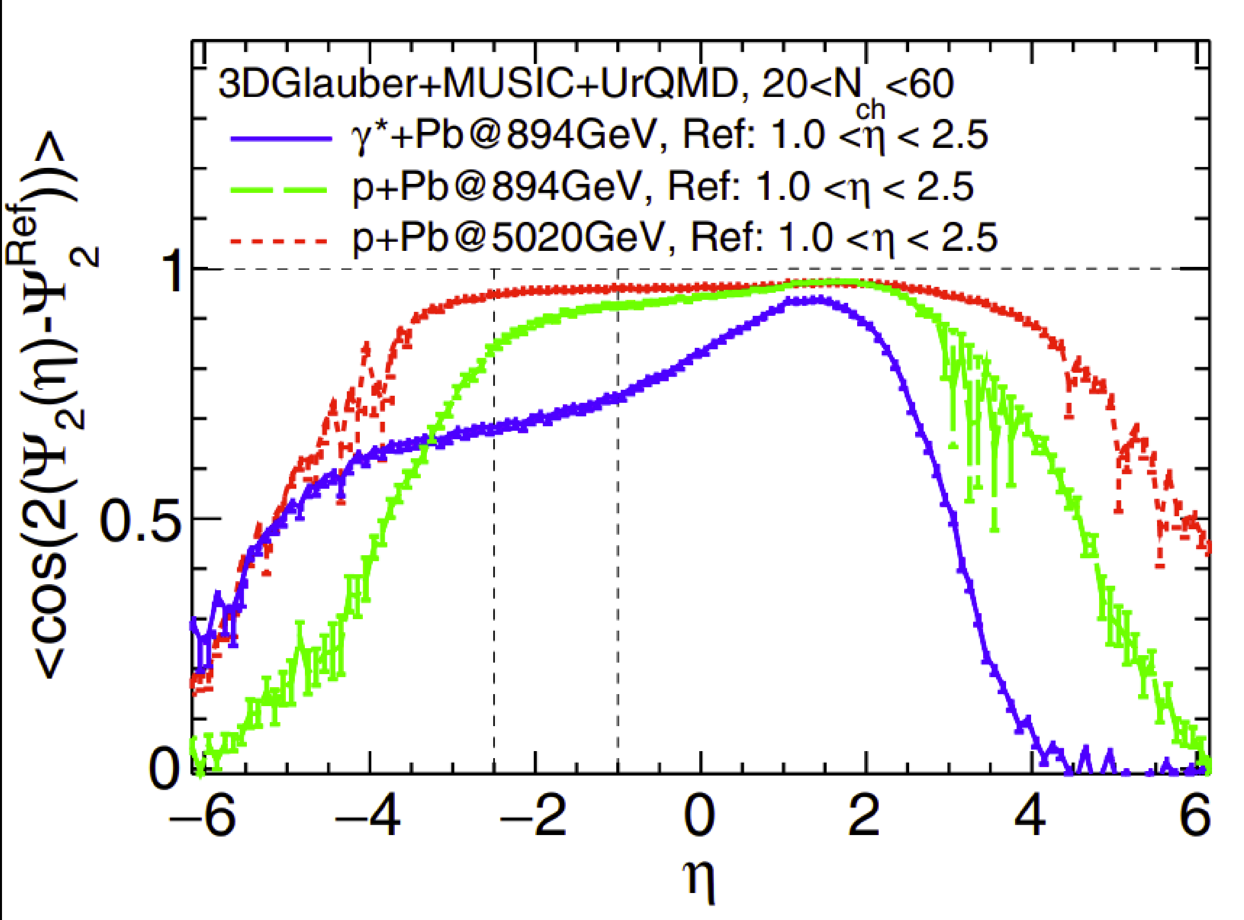


Measurements of longitudinal decorrelation

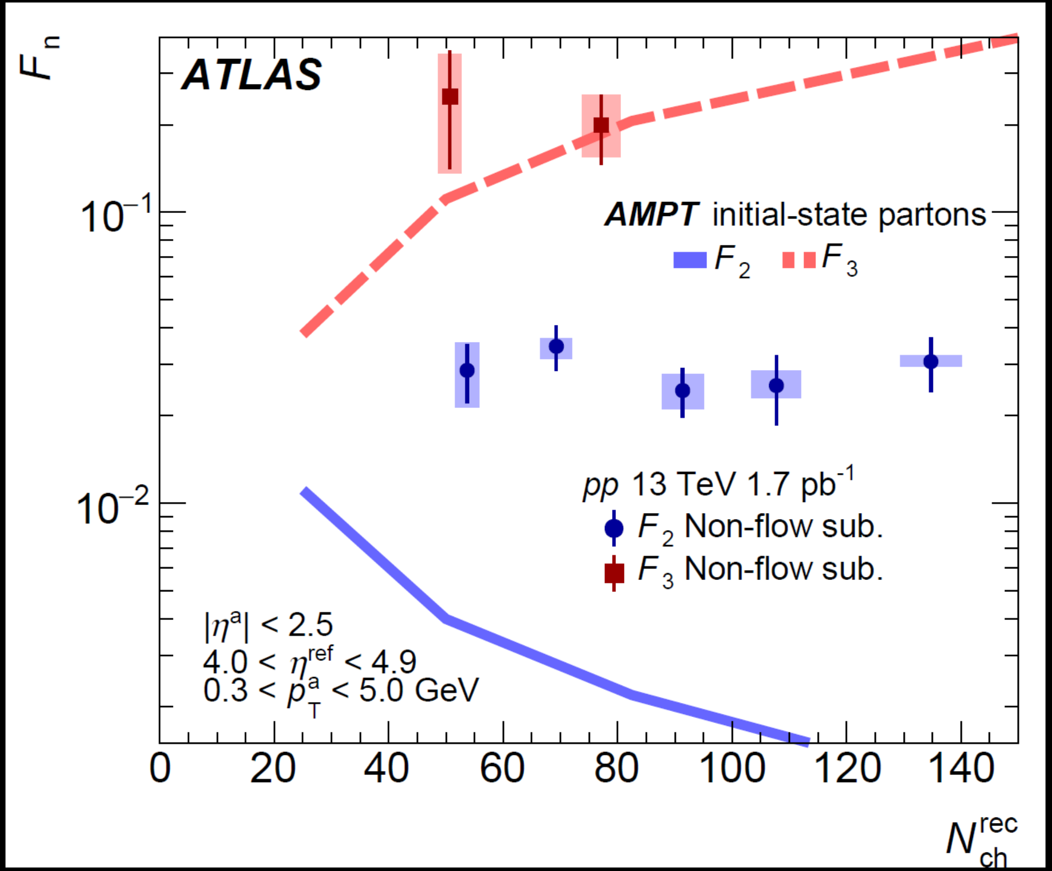
arXiv:2308.16745

F_n is the fractional change in $v_{n,n}$ per a unit rapidity

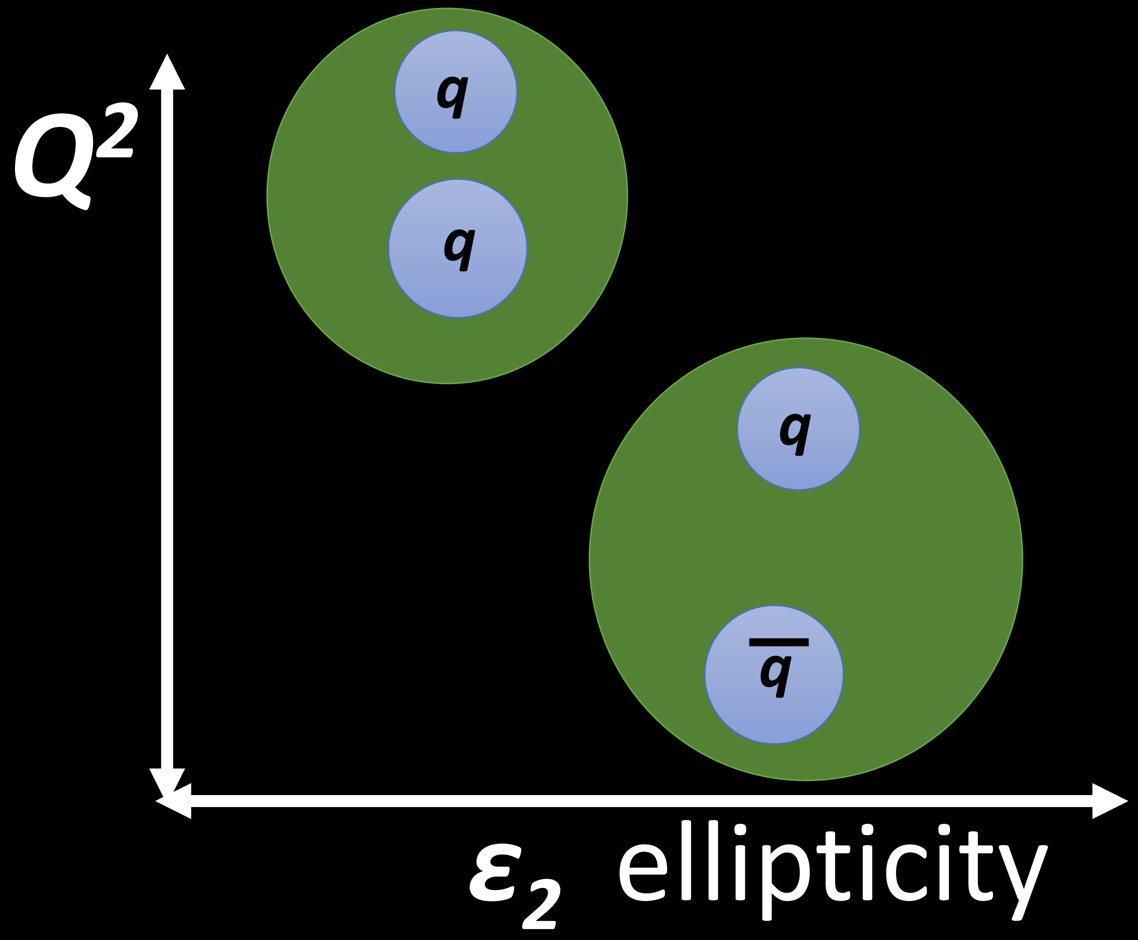
It characterizes longitudinal decorrelation effects well

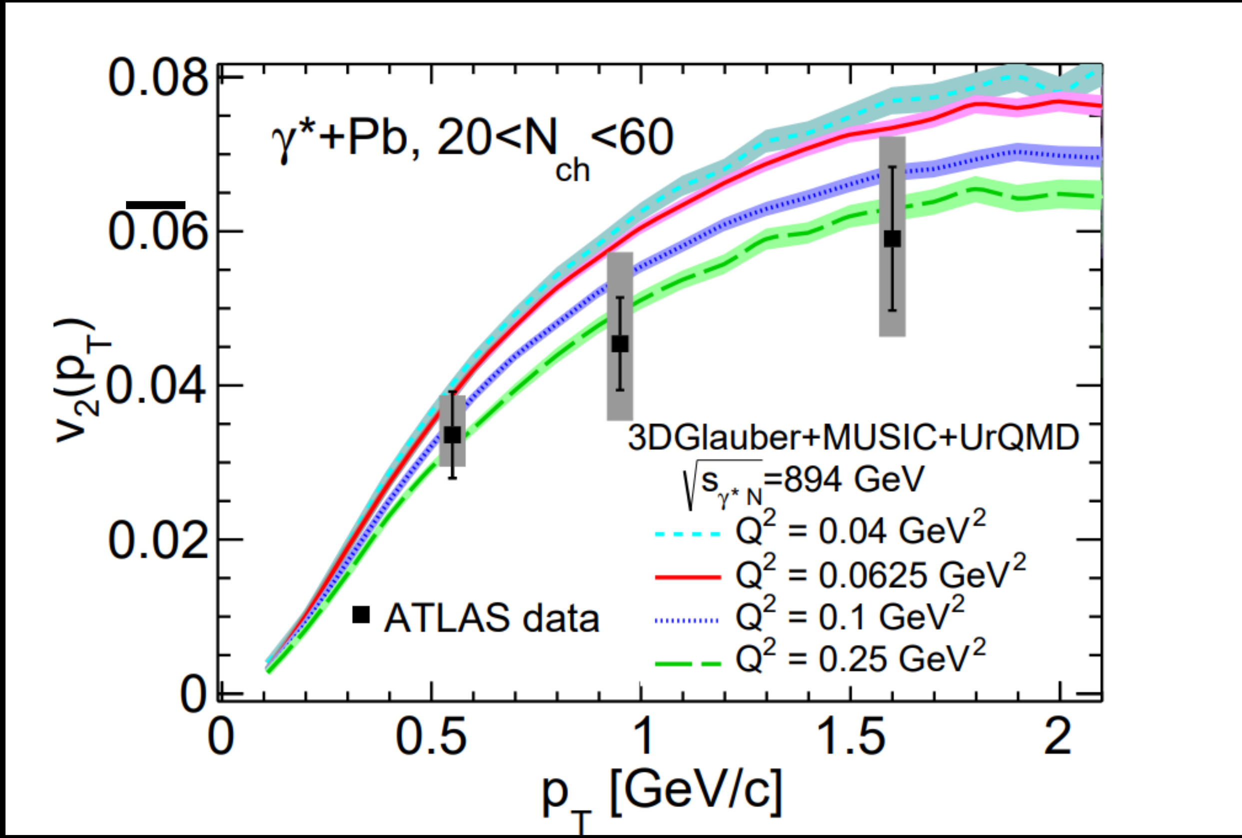
This class of measurements probes the shape of the initial state energy density

First decorrelation measurement in small systems



3+1D Hydrodynamic model comparison in γA

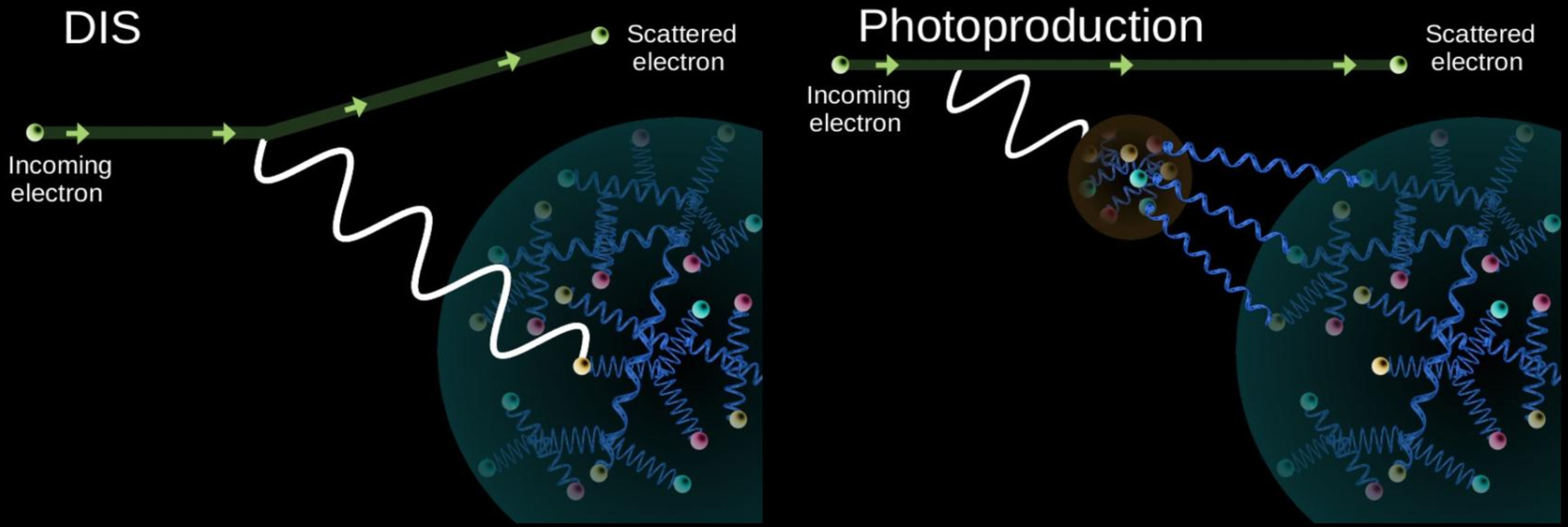


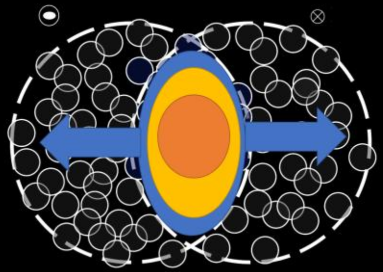


Changes in probe virtuality affects the shape of initial energy density

No direct access to Q^2 in UPC γA

Azimuthal anisotropy in eA collisions?





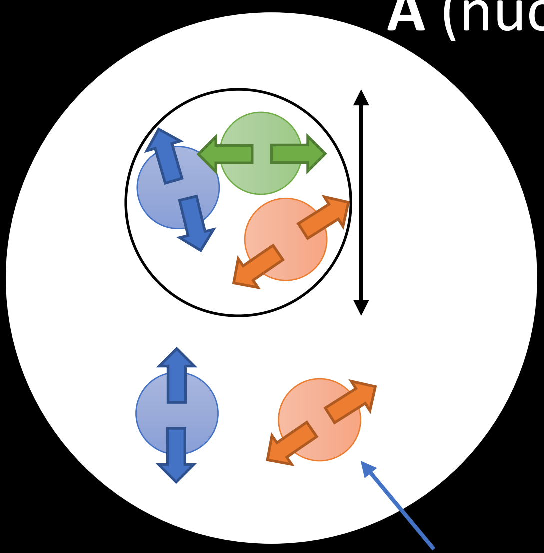
- DIS: Point-like interaction region would suggest little geometry
- Photoproduction: photon mostly fluctuates to a vector meson and interacts hadronically with the target. This provides an energy deposit with a transverse extent and possible elliptic geometry.
- Q^2 range in the previous slide should be accessible by EPIC at the EIC

CGC model comparison

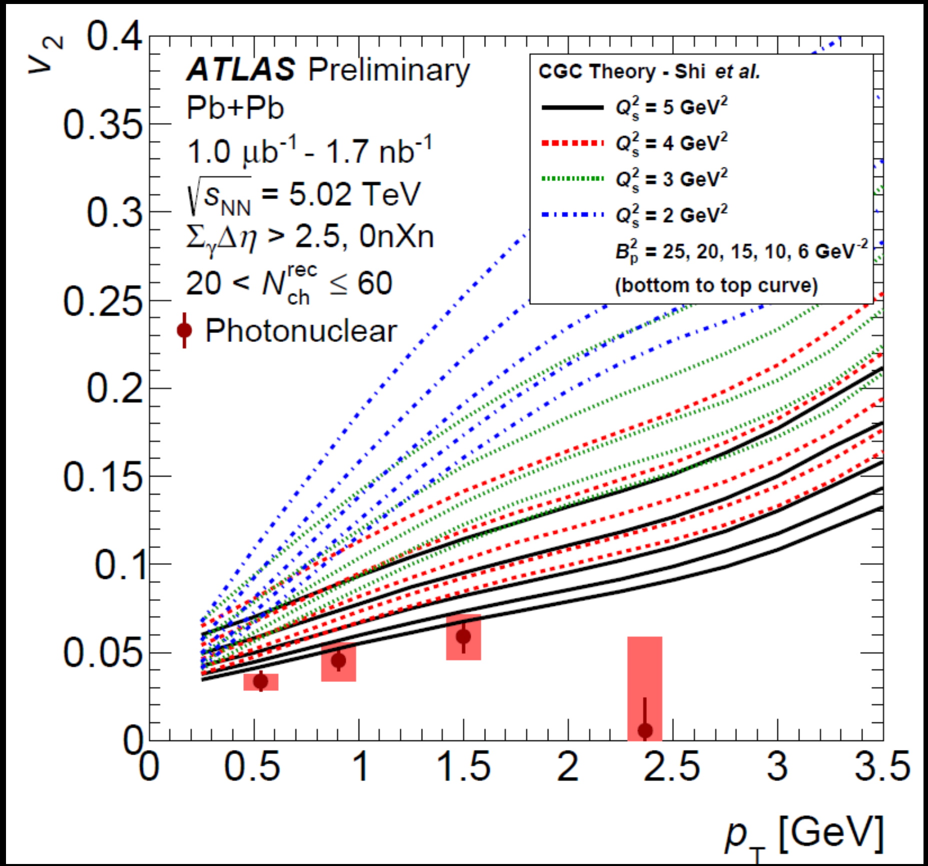
Color Glass Condensate model calculation containing **initial-state correlations** which gives rise to nonzero v_2

A (nuclear target)

$\boldsymbol{B_P}$ (projectile size)

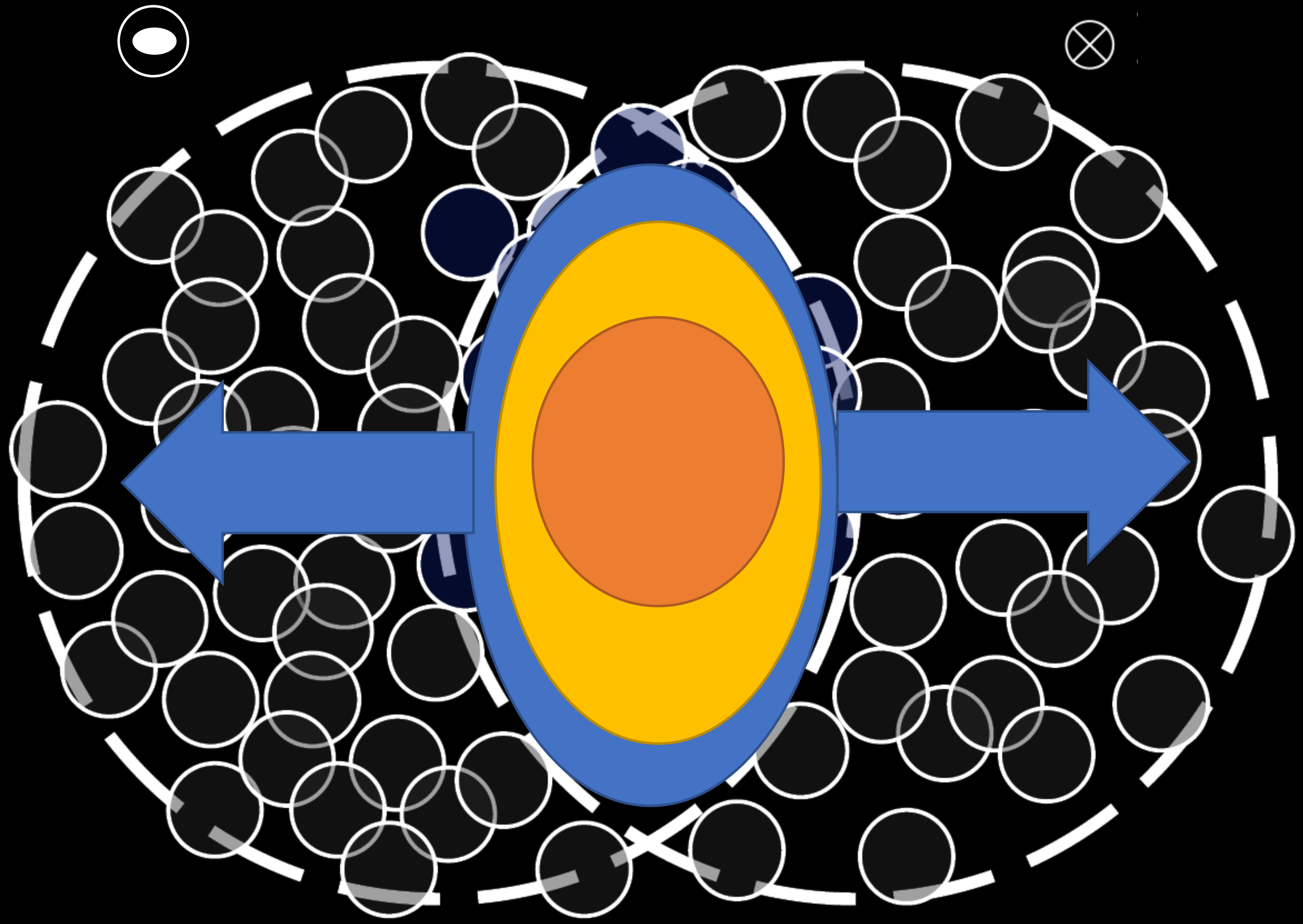


Correlated color domain
size is ~ $1/\boldsymbol{Q_s}$



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

arXiv:2101.10771



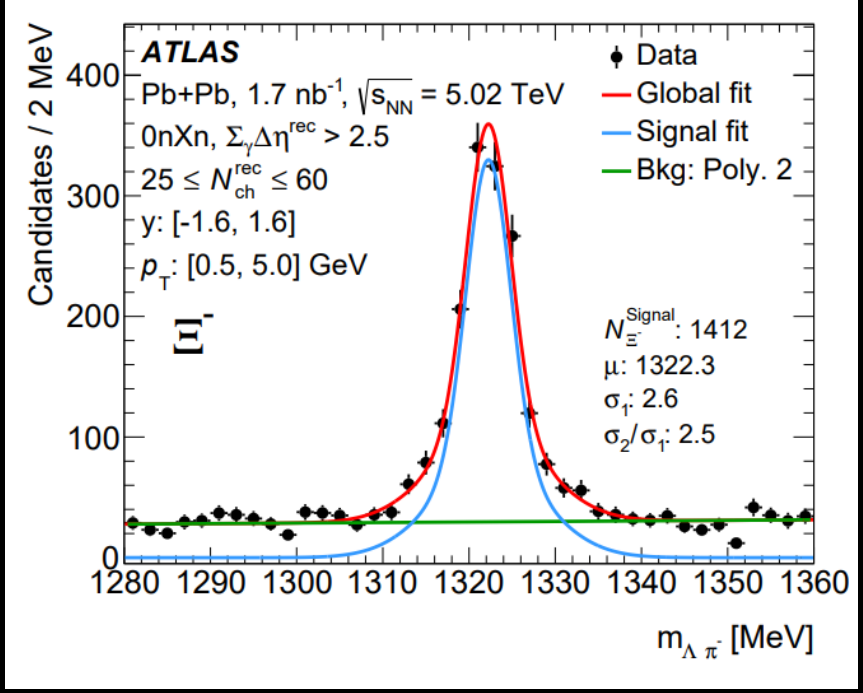
QGP phase

Radial flow

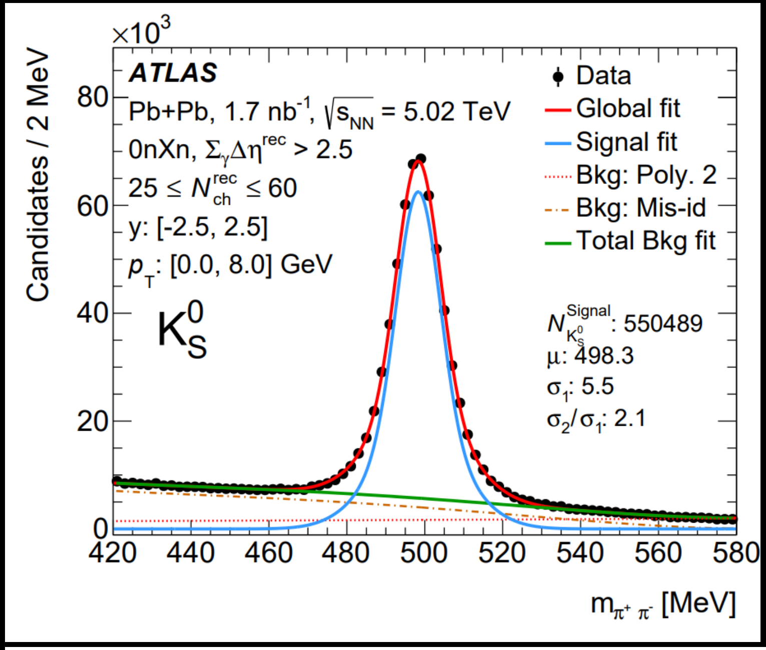
Populating QCD degrees of freedom, strangeness

Strangeness enhancement in γA

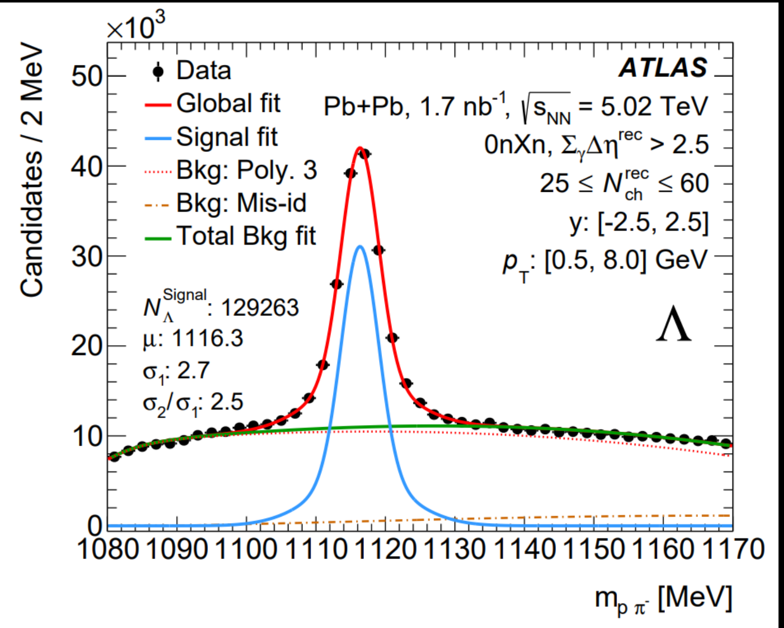
- Strangeness enhancement, baryon anomaly, baryon stopping…
- Novel incoming quantum numbers in *γ*Pb
- Plots of displaced vertex identified particle candidates in *γ*Pb



Ξ^-

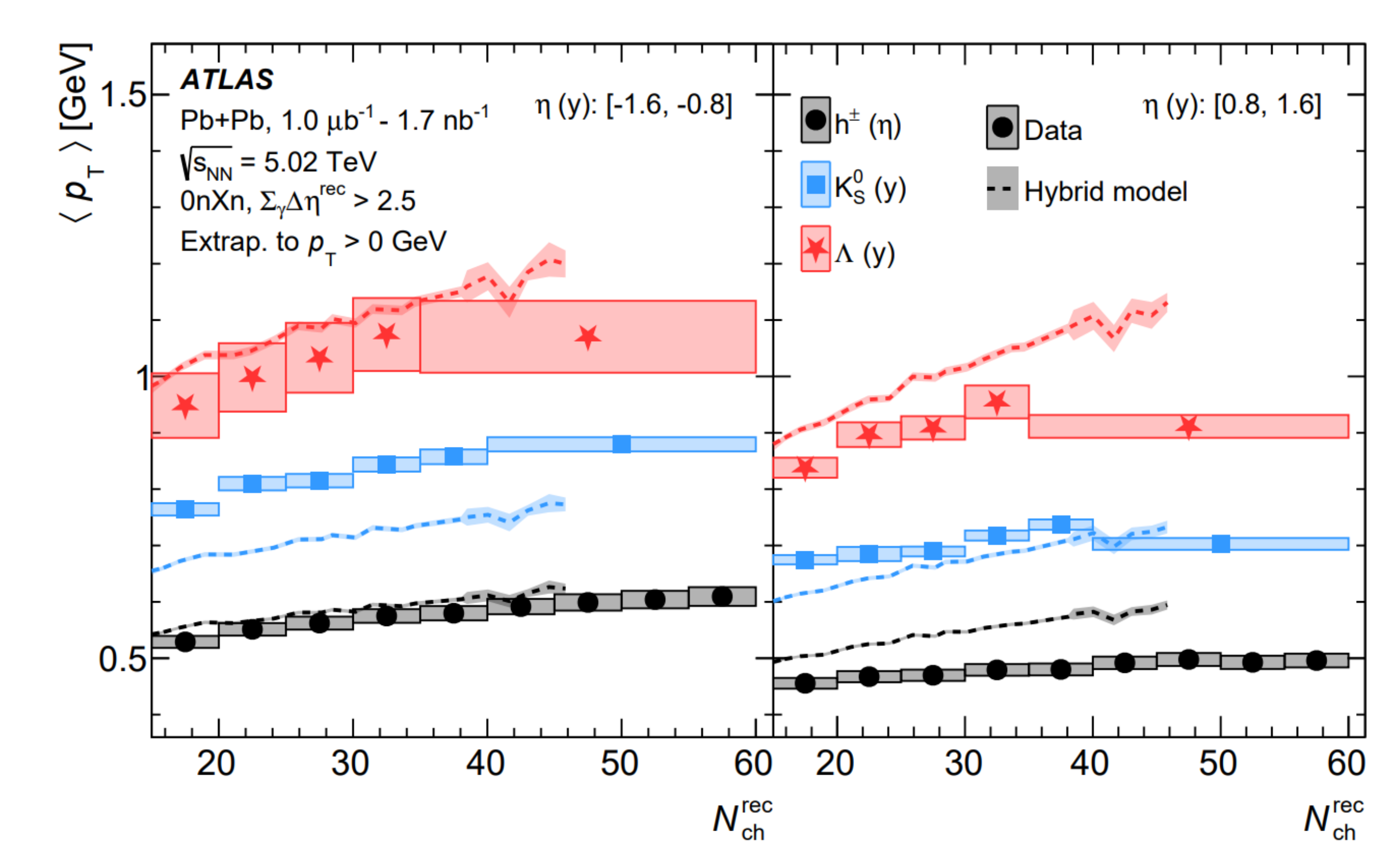


K_S^0

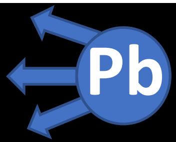


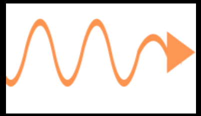
Λ

Identified particle <pT> in *γA*



- <pT> with $_{Nch}$
  - Higher energy density achieved in higher multiplicity collisions leads to stronger radial expansion.
  - Thought of as a signature of QGP formation
- Larger <pT> in the Pb-going direction
- Qualitative agreement with the Hydro model excluding K_S^0
  - Common in these new data-model comparisons



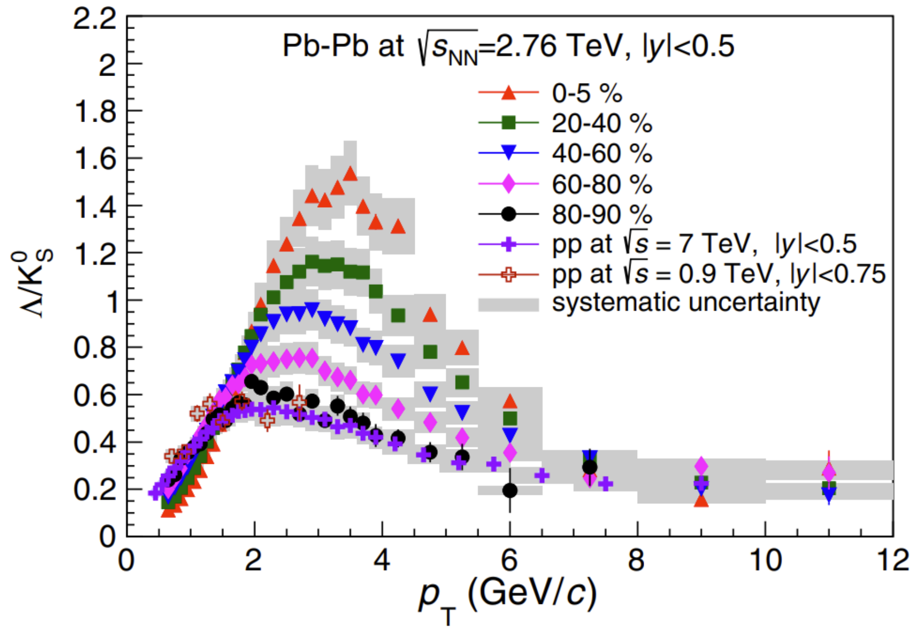


arXiv:2503.08181

Behavior in data is consistent with qualitative picture of radial flow

Baryon anomaly in *γA*

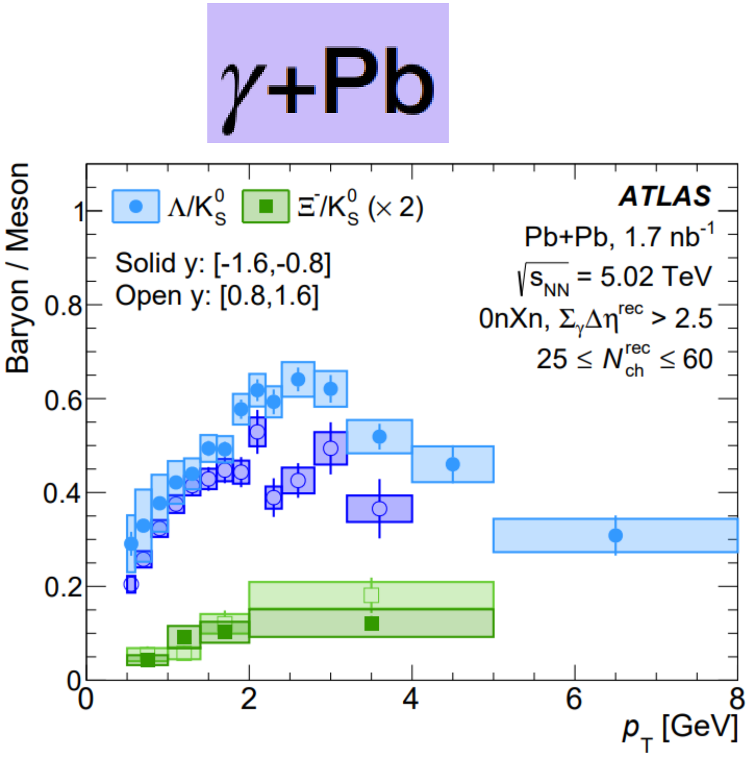
Phys. Rev. Lett. **111**, 222301

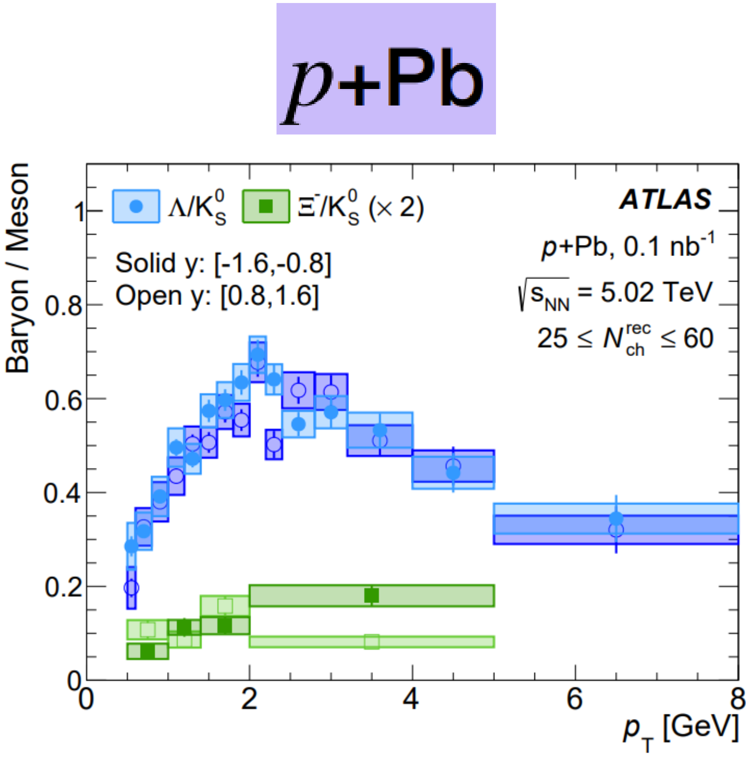


- Larger hydrodynamic push to baryons as the QGP velocity field cools into hadrons
- Observe large baryon enhancement at mid-pT in *γA,* similar to pPb
- Possibly see larger baryon enhancement in the Pb going direction

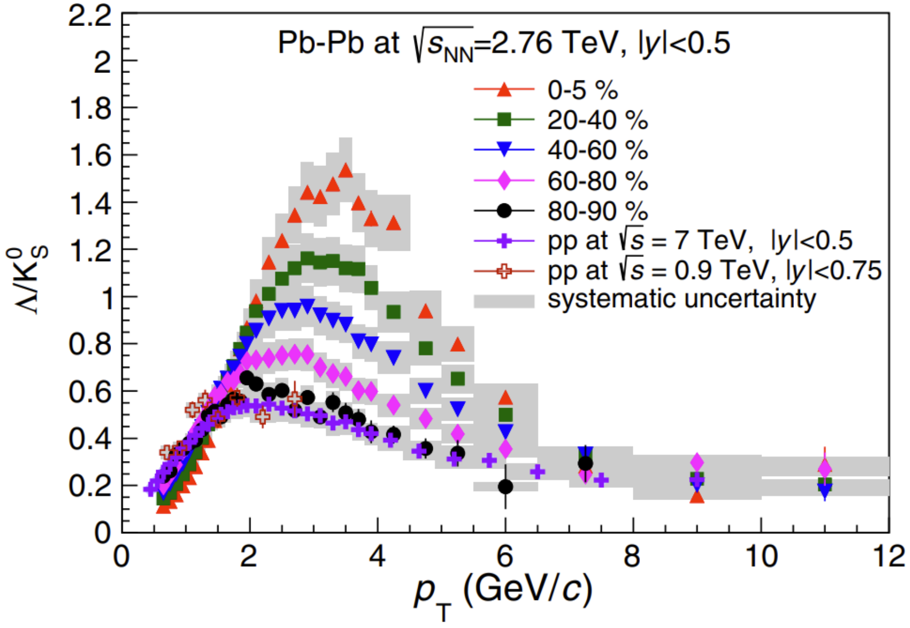
Baryon anomaly in γA

arXiv:2503.08181





Phys. Rev. Lett. **111**, 222301



- Larger hydrodynamic push to baryons as the QGP velocity field cools into hadrons
- Observe large baryon enhancement at mid-pT in γA, similar to pPb
- Possibly see larger baryon enhancement in the Pb going direction

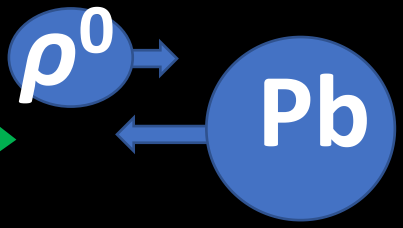
Observe large baryon enhancement at mid-pT in *γA*, similar to pPb

Conclusion

Results

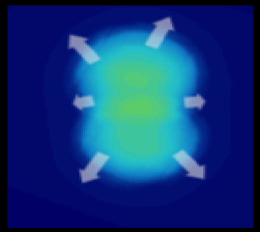
Photonuclear v_n has a similar order of magnitude and trends as other previously measured hadronic systems

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



Theory comparisons

Quantitative agreement with hydrodynamic models which translates initial geometric anisotropy to final-state momentum anisotropy through final-state interaction e.g. hydro



Compared to schematic CGC calculation

New results in identified hadrons

New ATLAS measurements probing strangeness enhancement, baryon anomaly and radial flow

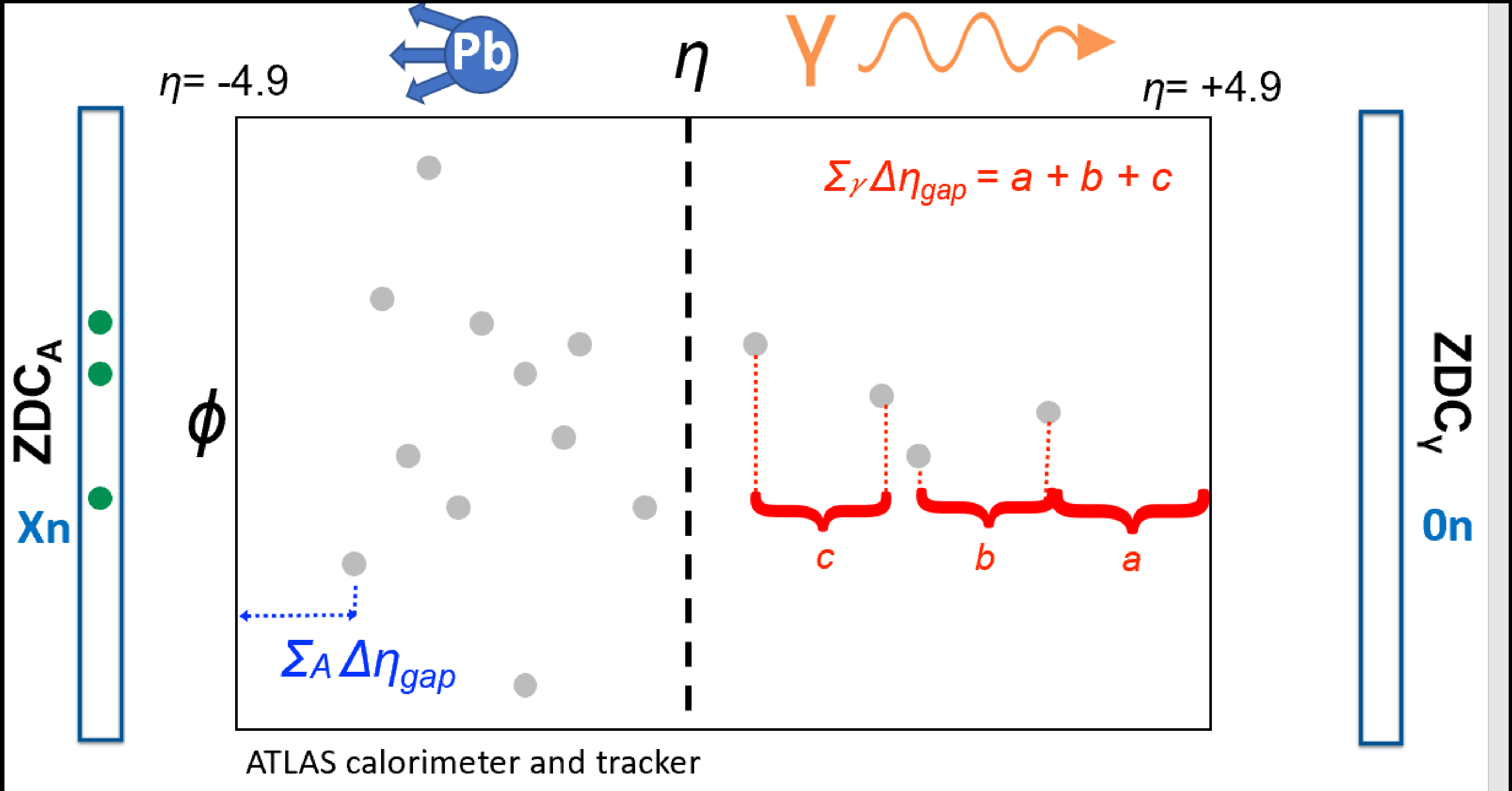
Future study

In Run 3 ATLAS has collected 2-3x more high-multiplicity γA data!

Explore photon Q^2 and tunable probe size at the EIC

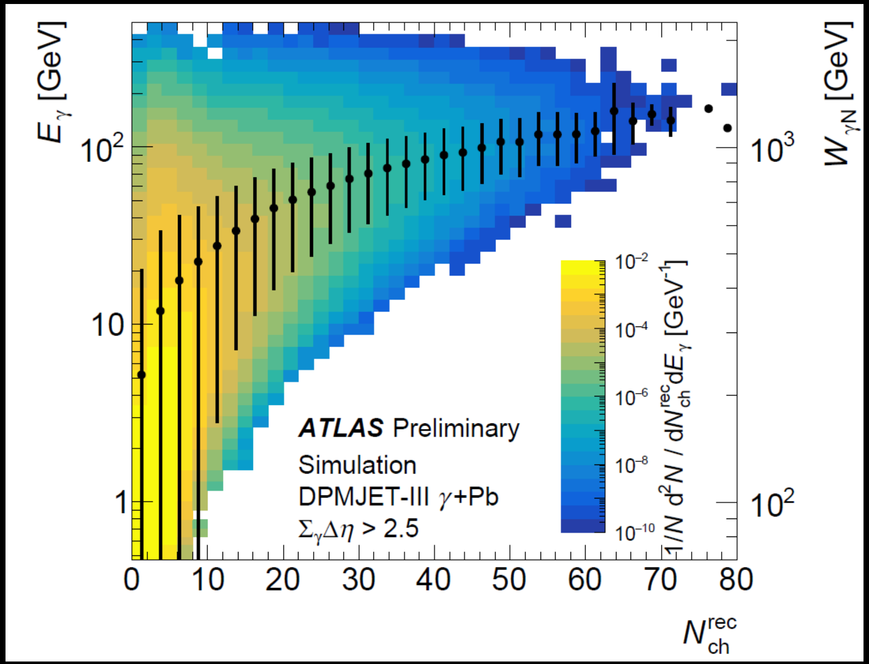
Thank you

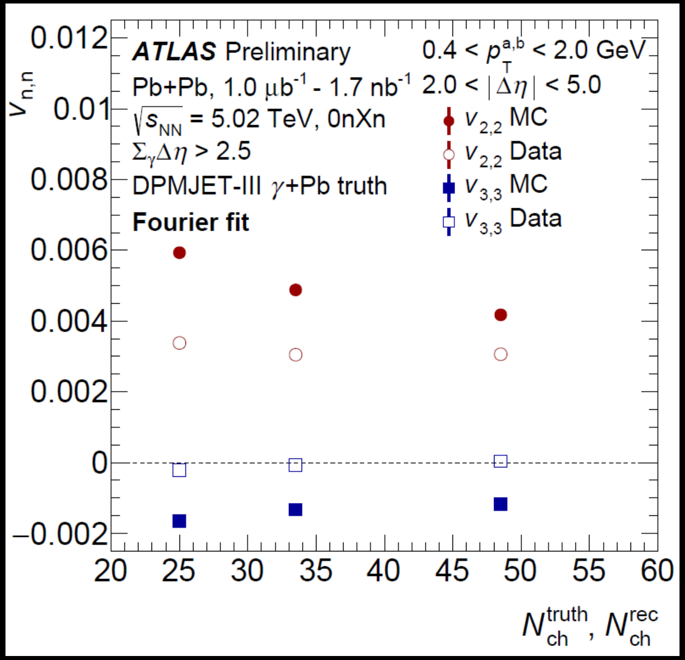
Sum of gaps

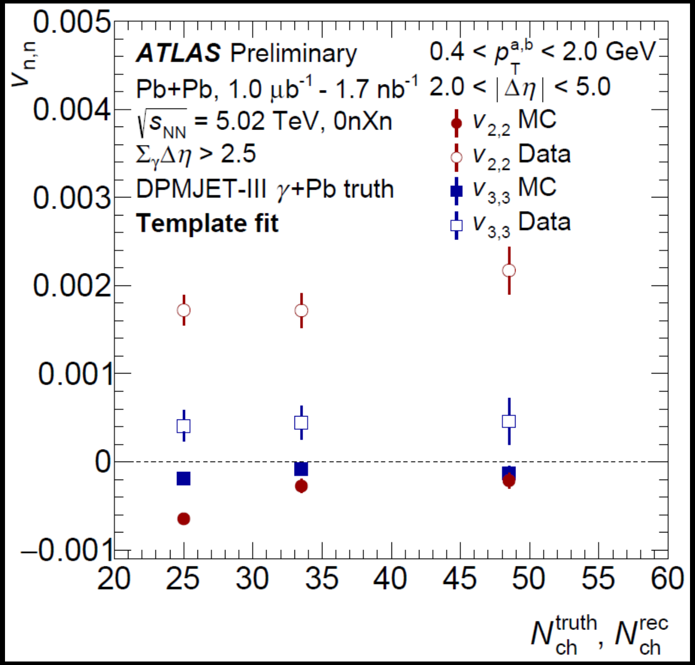


Event Selection: $\Sigma\Sigma_\gamma \Delta\eta_{gap} > 2.5$

Comparison to DPMJET-III





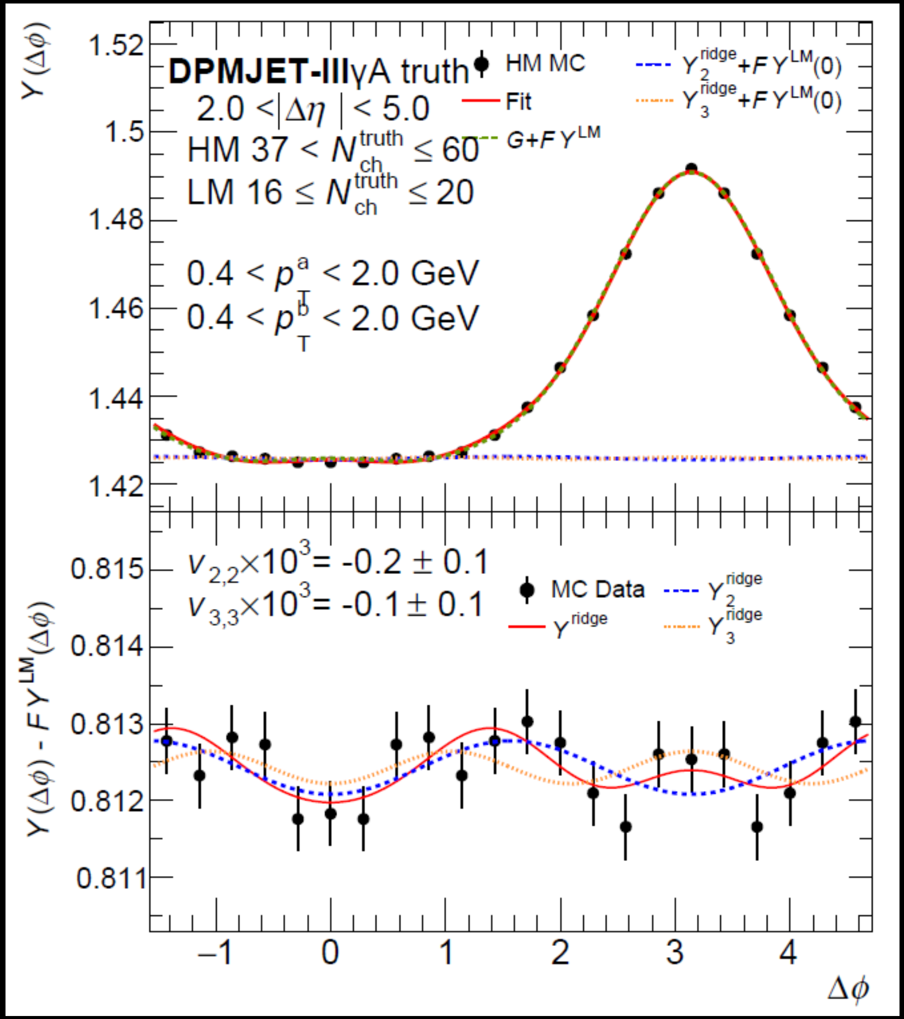


- DPMJET-III predicts the photon energy changes by about 1-2 standard deviations over the multiplicity range of the measurement and a doubling of the mean $W_{\gamma N}$ for 10 to 60 N_{ch}^{rec}.
- Large difference between measured $v_{n,n}$ before and after template nonflow subtraction for data and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

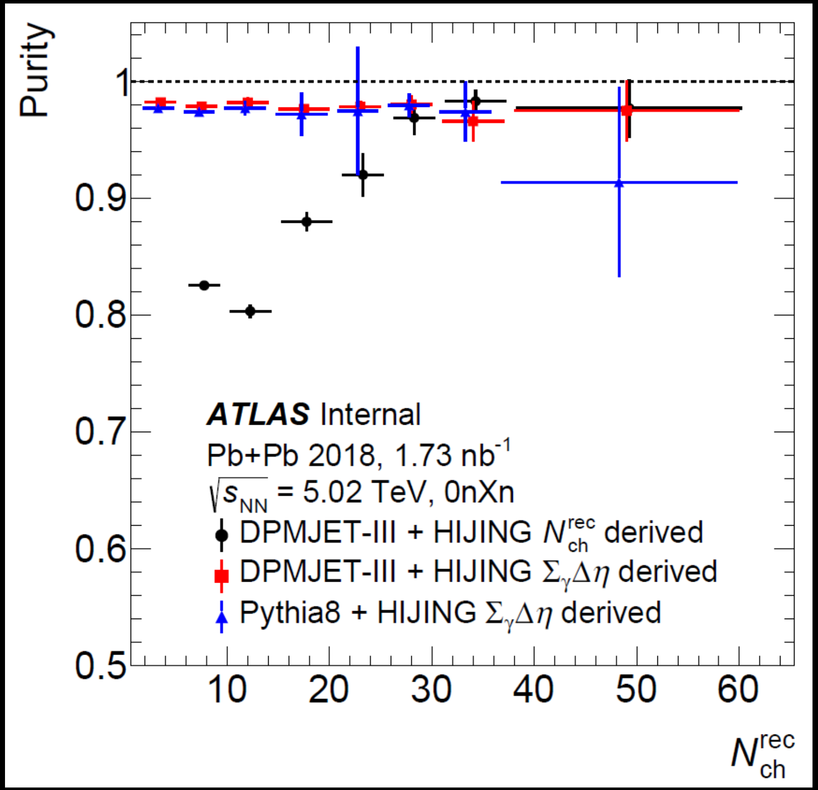
CERN-EP-2020-246

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.

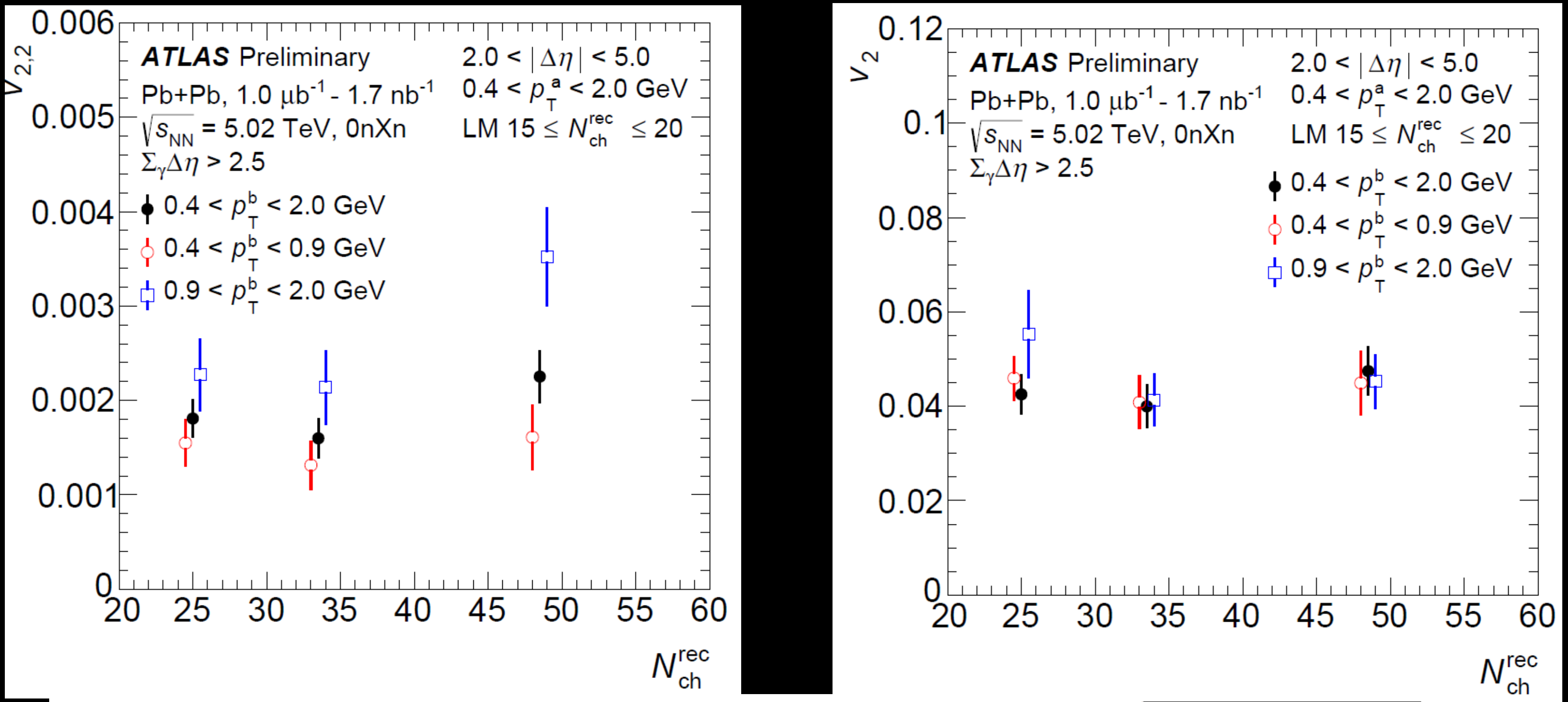


Purity of the photonuclear selection



- 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.