Searching for QGP Signatures in PhotoNuclear Collisions

arXiv: 2503.08181 [nucl-ex] HION-2024-02

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Nuclear Physics Seminars

Brookhaven National Laboratory, NY, USA

April 29, 2025

ATLAS EXPERIMENT

Outline

1) ***Charged Hadron Production***
in 5.02 TeV Pb+Pb photonuclear collisions.

2) ***Identified Hadron Production (K^0_S, Λ, Ξ^-)***
in 5.02 TeV Pb+Pb photonuclear collisions.

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EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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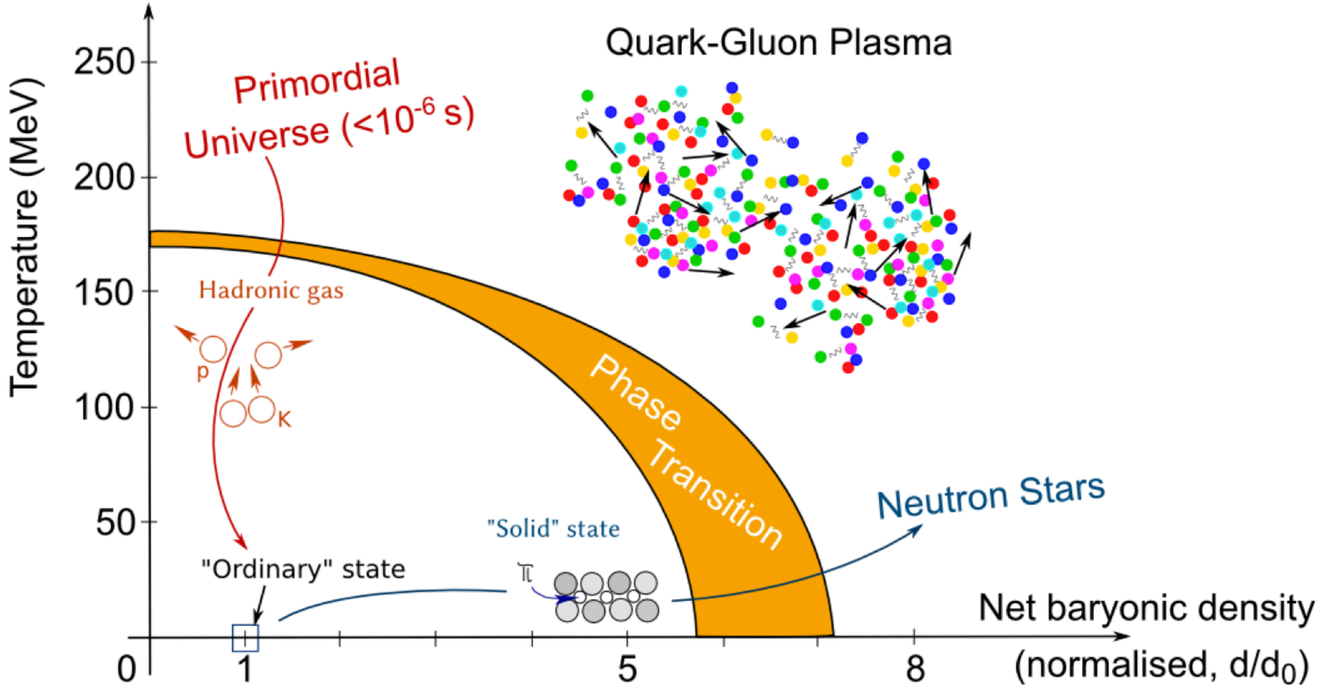
CERN-EP-2025-040
12th March 2025

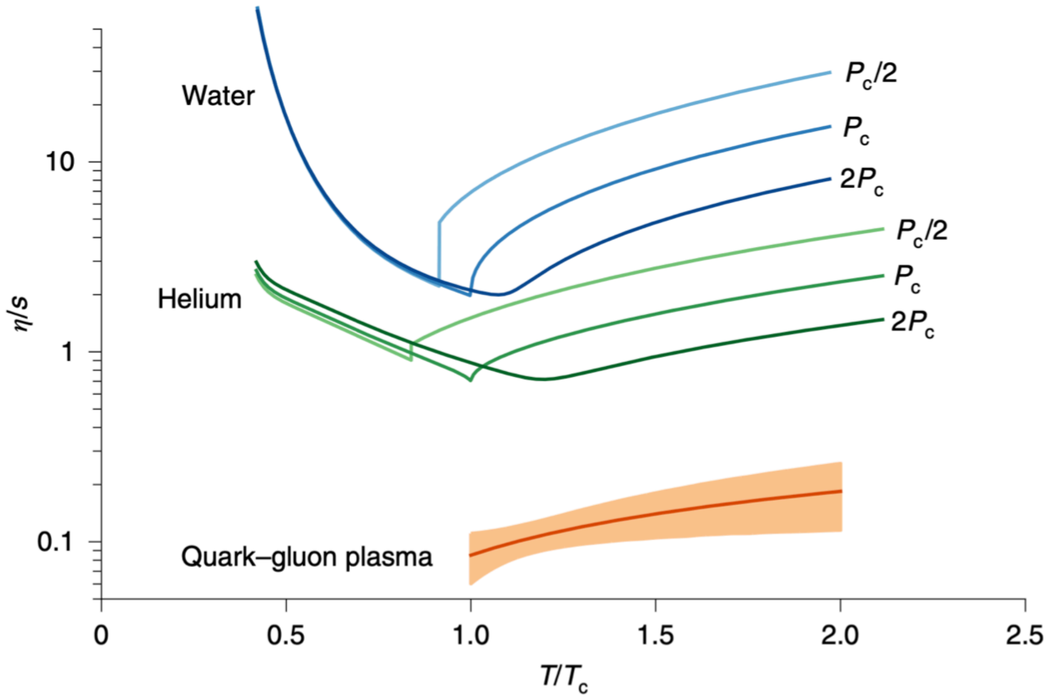
Charged-hadron and identified-hadron (K^0_S, Λ, Ξ^-) yield measurements in photo-nuclear Pb+Pb and p+Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV with ATLAS

The ATLAS Collaboration

This paper presents the measurement of charged-hadron and identified-hadron (K^0_S, Λ, Ξ^-) yields in photo-nuclear collisions using 1.7 nb^{-1} of $\sqrt{s_{\rm NN}}$ = 5.02 TeV Pb+Pb data collected in 2018 with the ATLAS detector at the Large Hadron Collider. Candidate photo-nuclear events are selected using a combination of tracking and calorimeter information, including the zero-degree calorimeter. The yields as a function of transverse momentum and rapidity are measured in these photo-nuclear collisions as a function of charged-particle multiplicity. These photo-nuclear results are compared with 0.1 nb^{-1} of $\sqrt{s_{\rm NN}}$ = 5.02 TeV p+Pb data collected in 2016 by ATLAS using similar charged-particle multiplicity selections. These photo-nuclear measurements shed light on potential quark-gluon plasma formation in photo-nuclear collisions via observables sensitive to radial flow, enhanced baryon-to-meson ratios, and strangeness enhancement. The results are also compared with the Monte Carlo DPMJET-III generator and hydrodynamic calculations to test whether such photo-nuclear collisions may produce small droplets of quark-gluon plasma that flow collectively.

QGP: The nearly perfect fluid





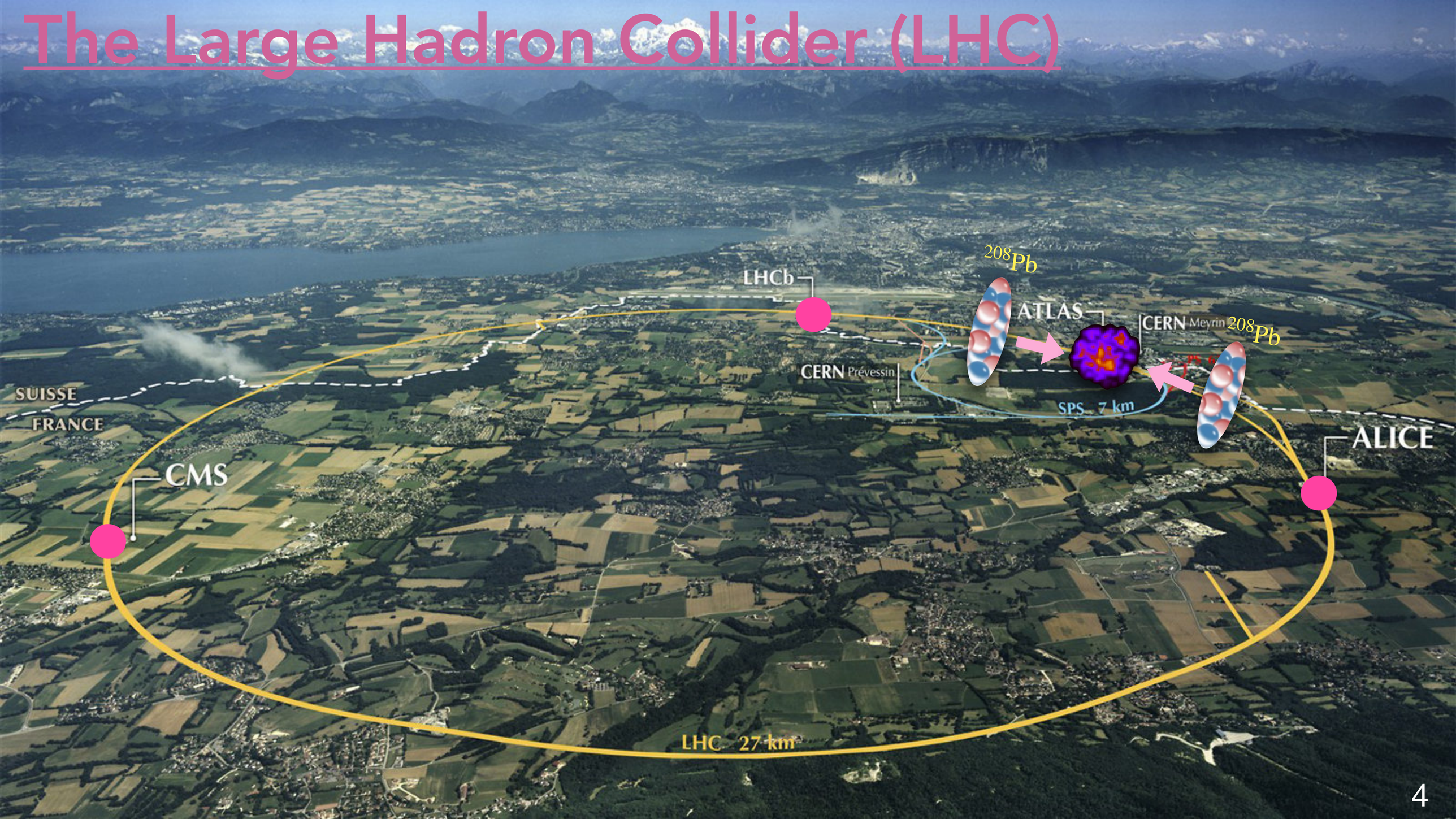
Nature Physics 15 (2019) 1113

Quark Gluon Plasma (QGP): *state of matter formed in the early universe* where quarks and gluons are deconfined.

QGP behave as a nearly perfect fluid: Experimental indications from **Au+Au collisions at RHIC** followed by **Pb+Pb collisions at LHC**.

Lowest specific shear viscosity (η/s) observed in nature so far!

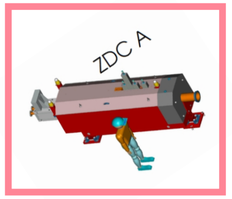
The Large Hadron Collider (LHC)



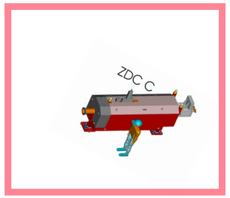
The ATLAS Detector

Tile/LAr Hadronic Calorimeter $|\eta| < 3.2$

LAr Forward Calorimeter $3.1 < |\eta| < 4.9$



Zero-degree calorimeter
$|\eta| > 8.3$



LAr EM Calorimeter $|\eta| < 3.2$

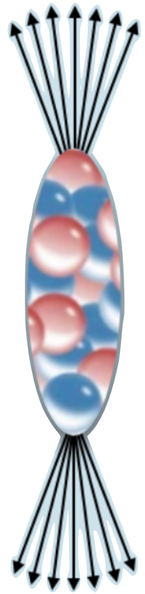
Inner detector tracker $|\eta| < 2.5$

ATLAS EXPERIMENT

Ultraperipheral Heavy-Ion Collisions

In heavy-ion collisions, the nuclei generate extreme strong electromagnetic (EM) fields

These EM fields correspond to a flux of quasi-real high energy photons; O(30 GeV) at LHC



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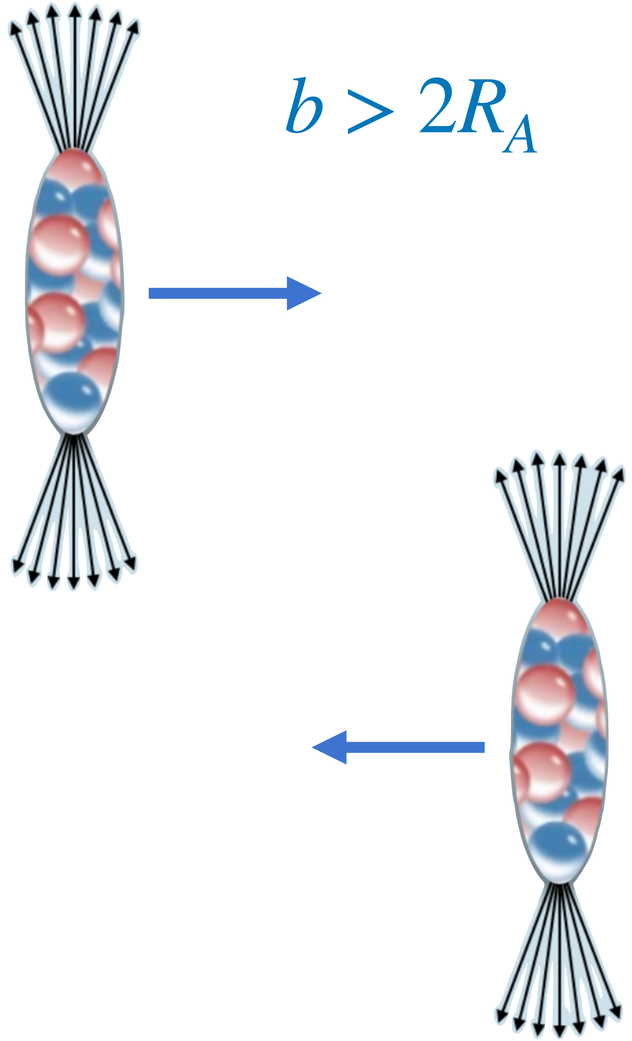

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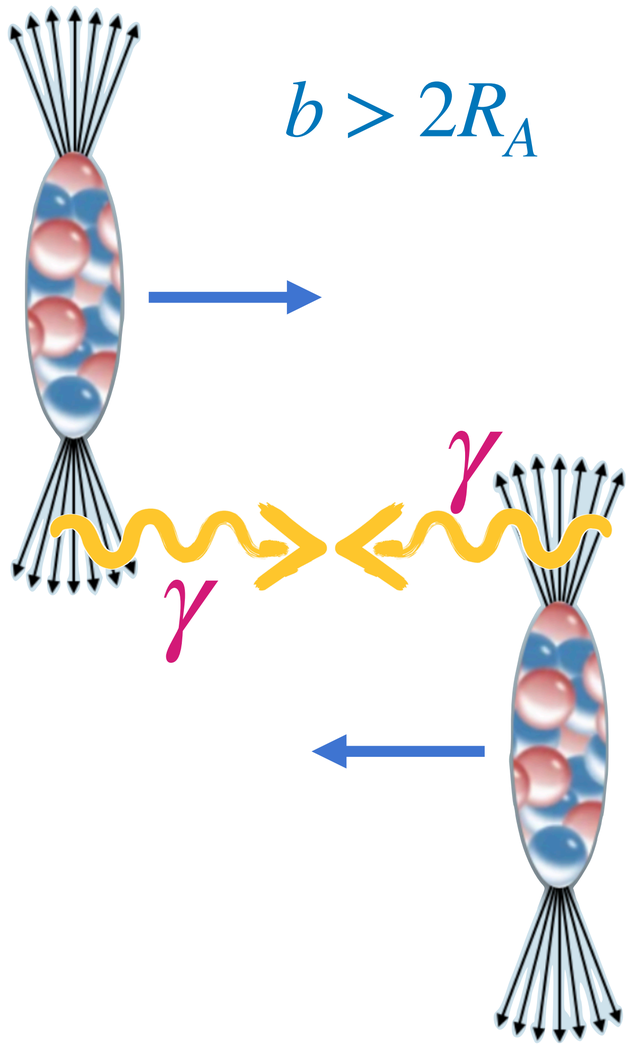

1) Photon-Photon interactions

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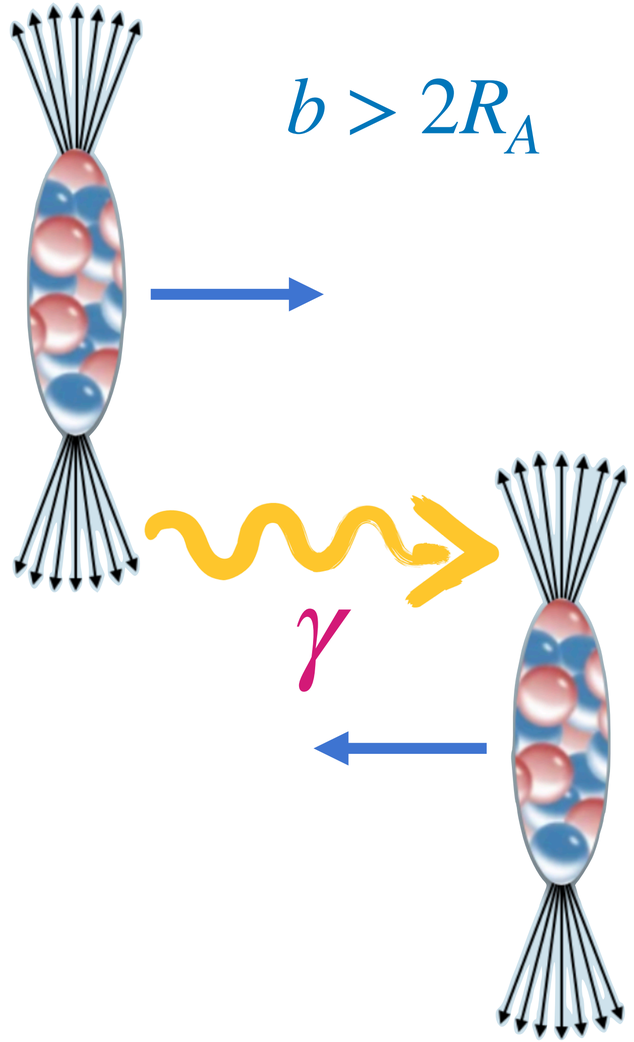
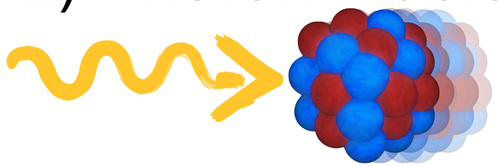


2) Photon-Nucleus interactions



Photon breaks up the other nuclei!

PhotoNuclear Collisions

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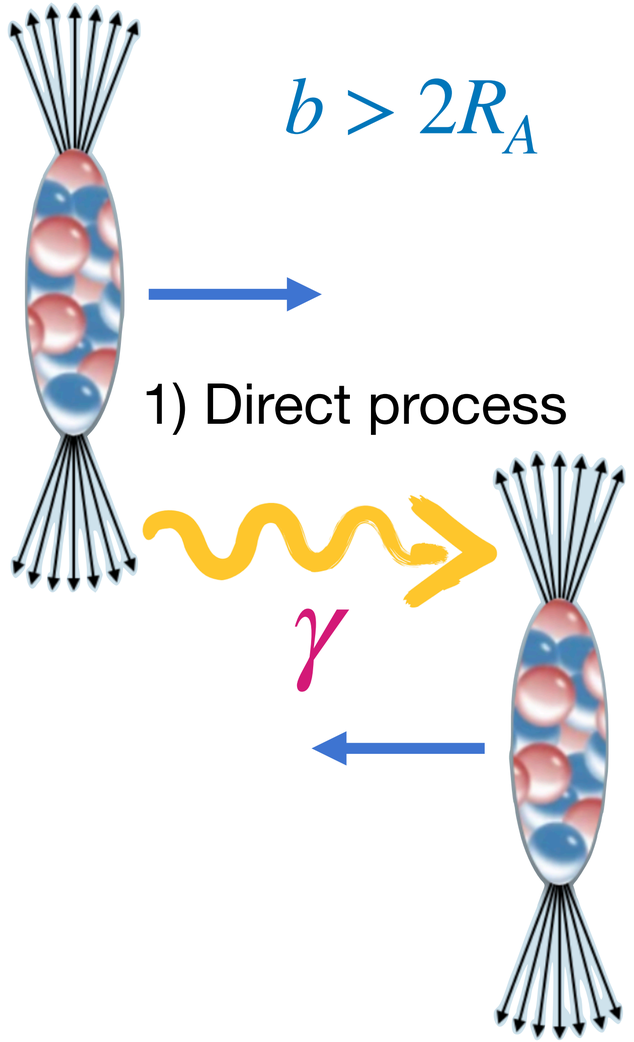

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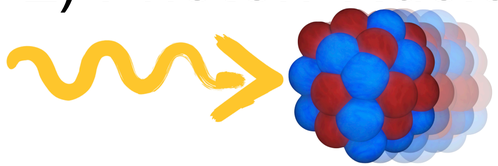

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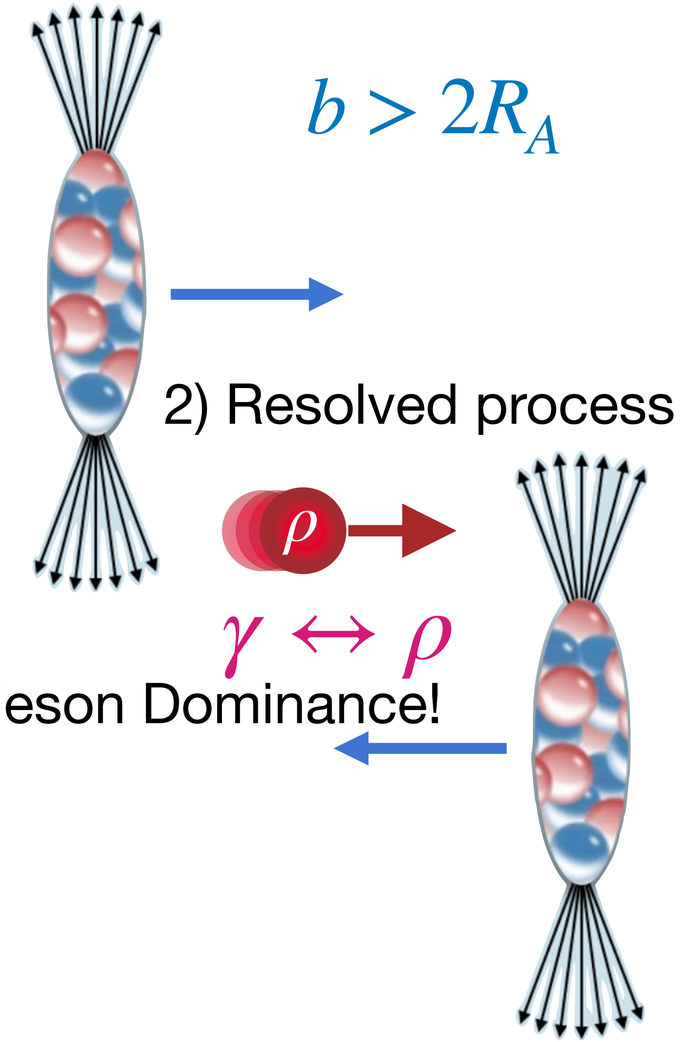

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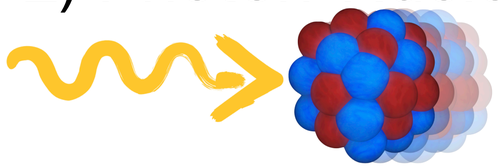

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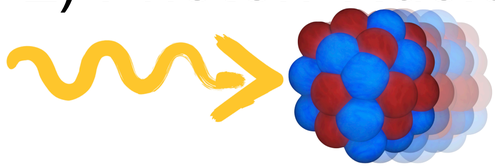

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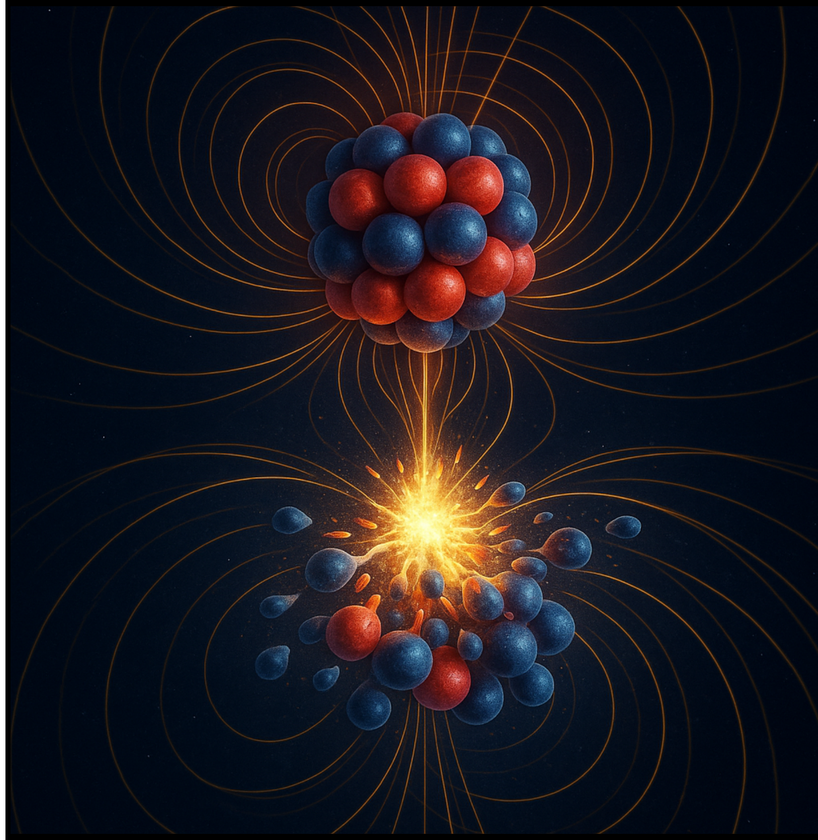
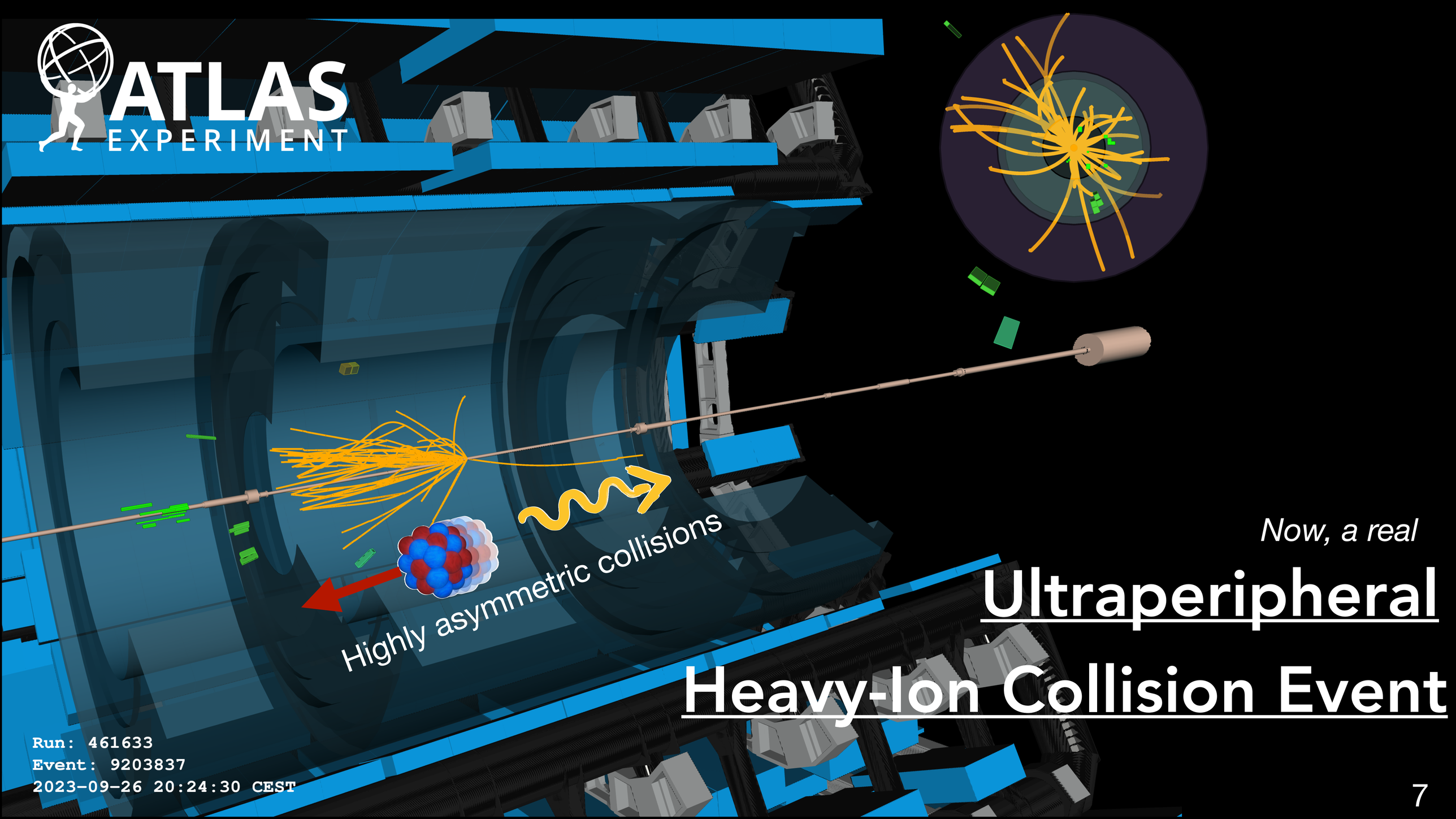


Nice job by ChatGPT!

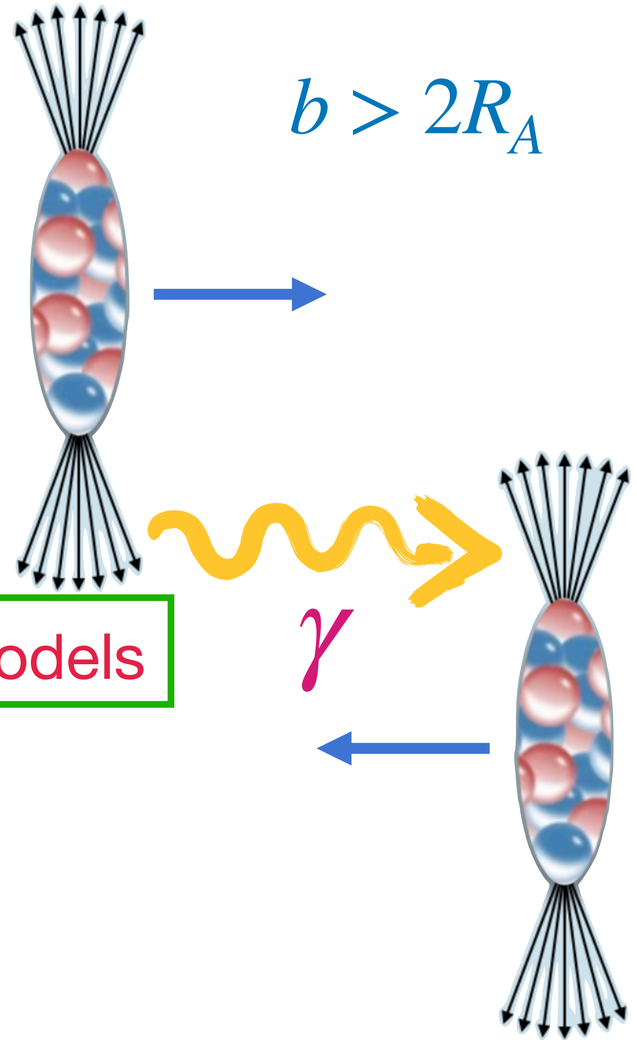


Now, a real

Ultraperipheral Heavy-Ion Collision Event

Characterization of PhotoNuclear Collisions

Modeling of photonuclear collisions are particularly challenging due to the event-to-event fluctuations of photon energies!



Characterizing photo-nuclear events places constraints on γA models

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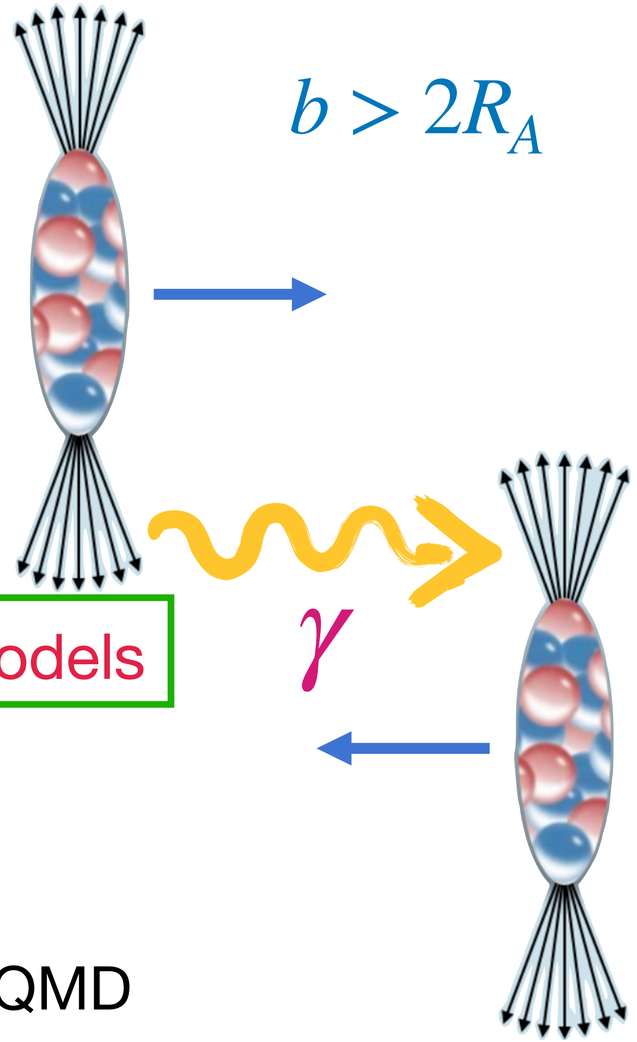


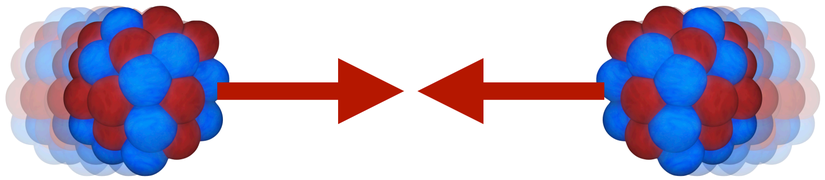
Characterizing photo-nuclear events places constraints on γA models

1. The Monte-Carlo model used: *DPMJET-III+STARLight γA*
   - Photon-flux from *STARLight*
   - *DPMJET-III* collides γA
2. Comparisons to hydrodynamic model: 3DGlauber+MUSIC+UrQMD

   Wenbin Zhao, Chun Shen, and Björn Schenke *Phys. Rev. Lett. 129, 252302*

We look forward to Pythia γA!

Flow in Heavy-Ion Collisions



A tiny drop of QGP is created in heavy-ion collisions and it expands like a fluid.

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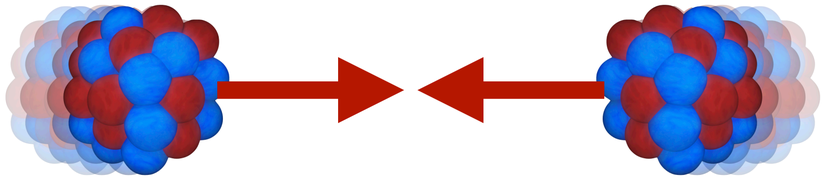

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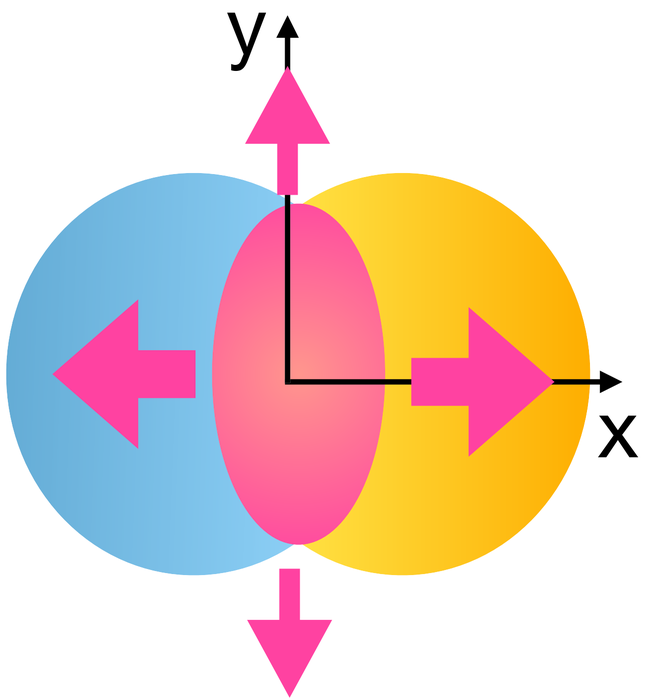

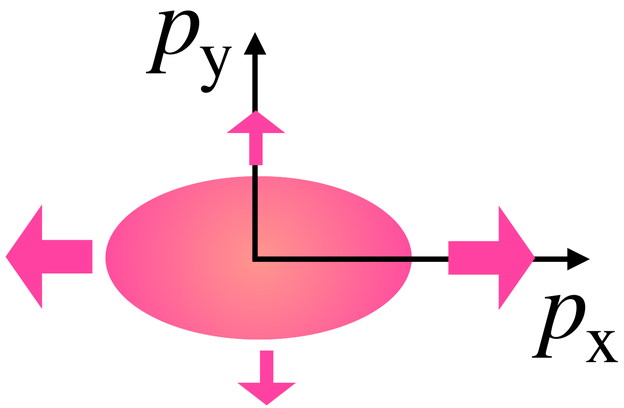

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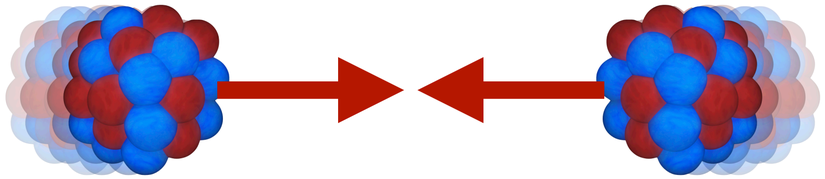

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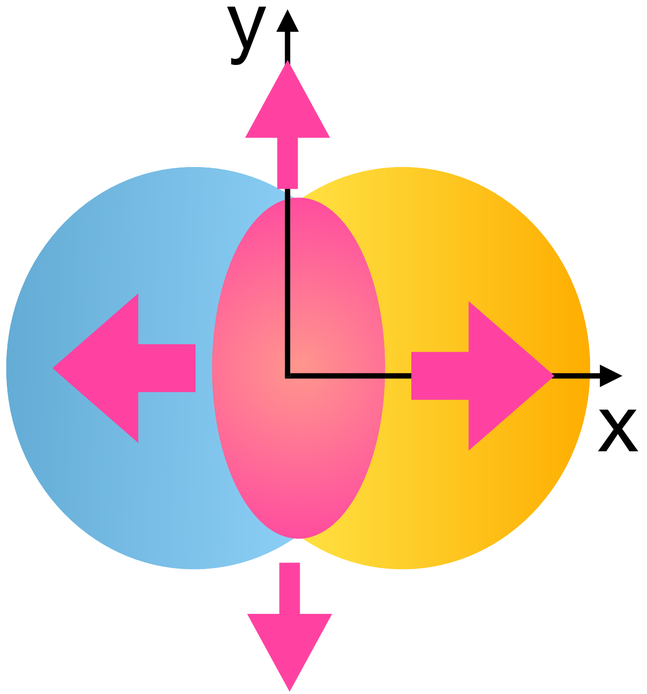
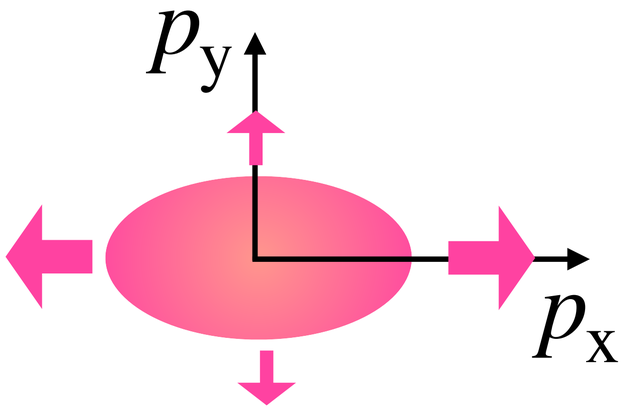
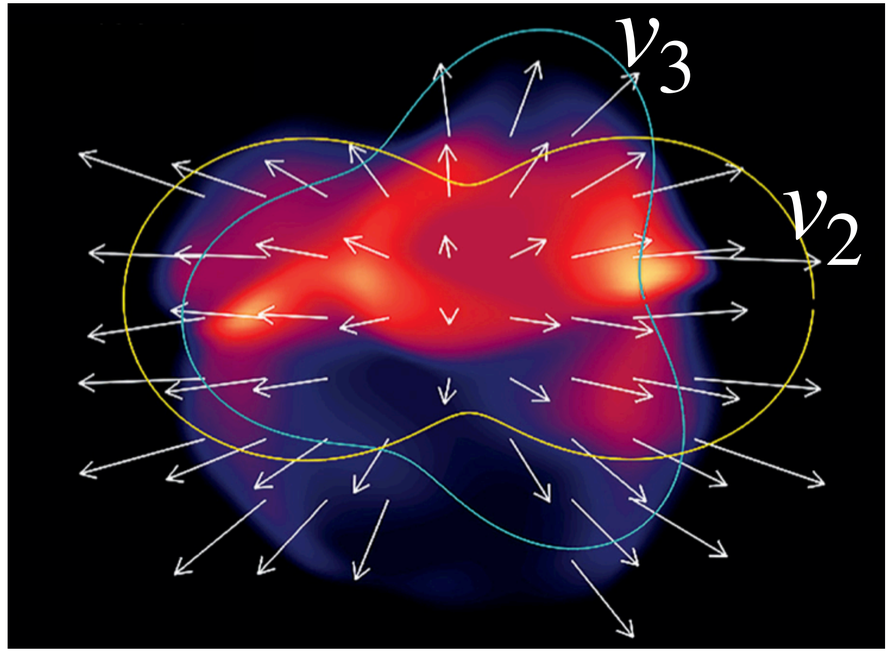


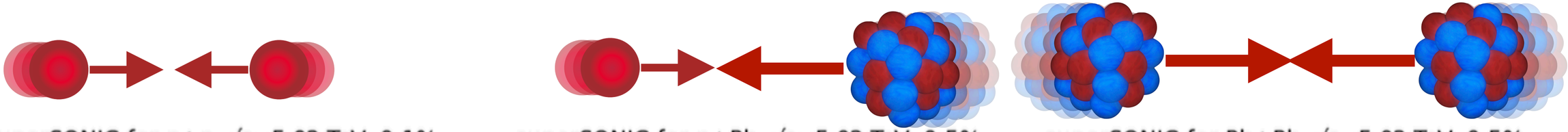




$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)]),$$

v_n: Flow coefficients

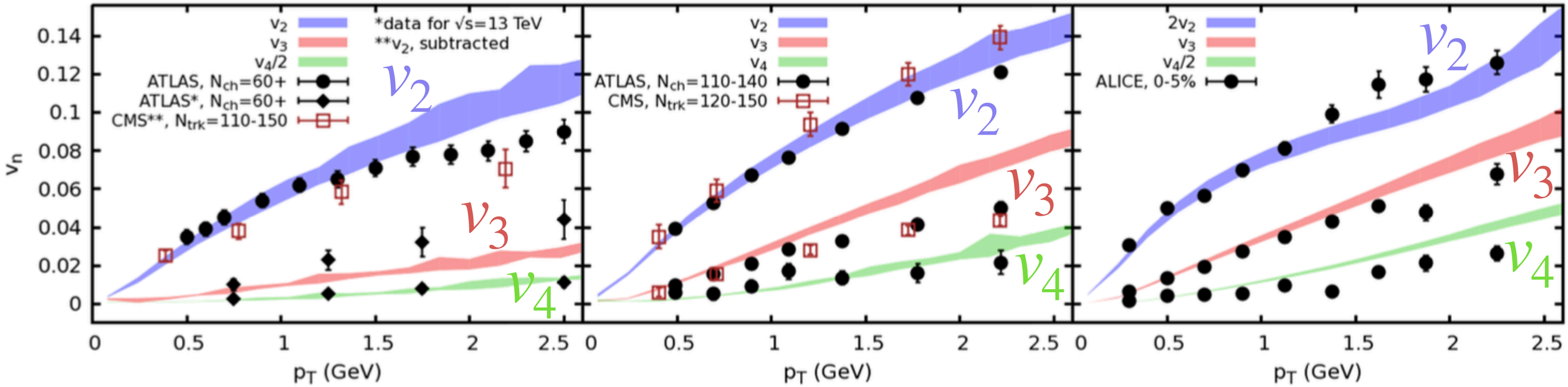
Flow in Small Systems



superSONIC for p+p, √s=5.02 TeV, 0-1%

superSONIC for p+Pb, √s=5.02 TeV, 0-5%

superSONIC for Pb+Pb, √s=5.02 TeV, 0-5%



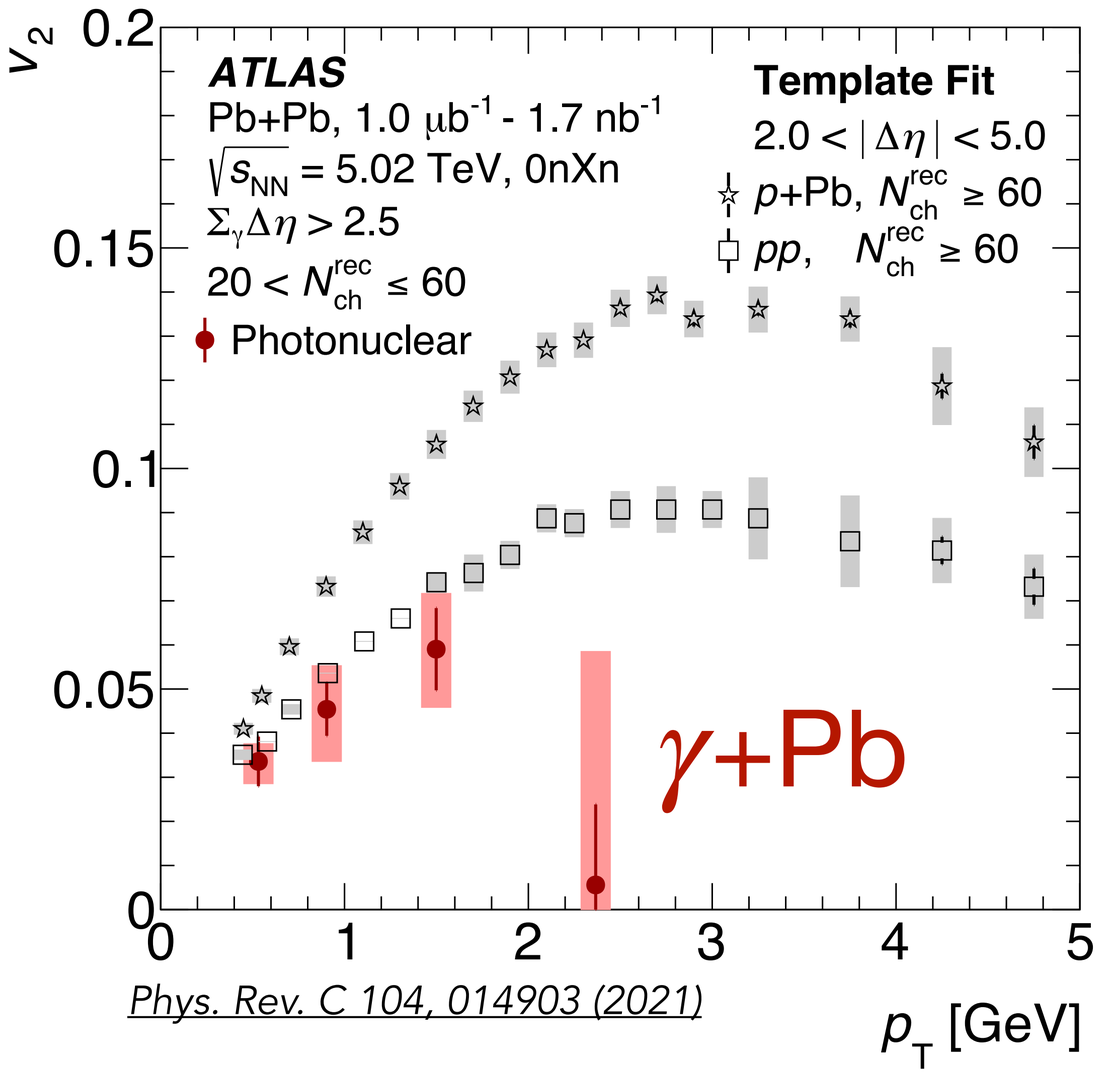
Theory: *Physics Letters B 774 (2017) 351–356*

ATLAS: *Physical Review C 90, 044906 (2014)*

Hydrodynamic models can successfully describe v_2, v_3, v_4

in systems of wide size ranges: *pp*, *p*Pb and Pb+Pb!

Flow in PhotoNuclear Collisions



Phys. Rev. C 104, 014903 (2021)

Collective flow (v_2) found by ATLAS in photo-nuclear collisions!

Do photo-nuclear events create QGP?

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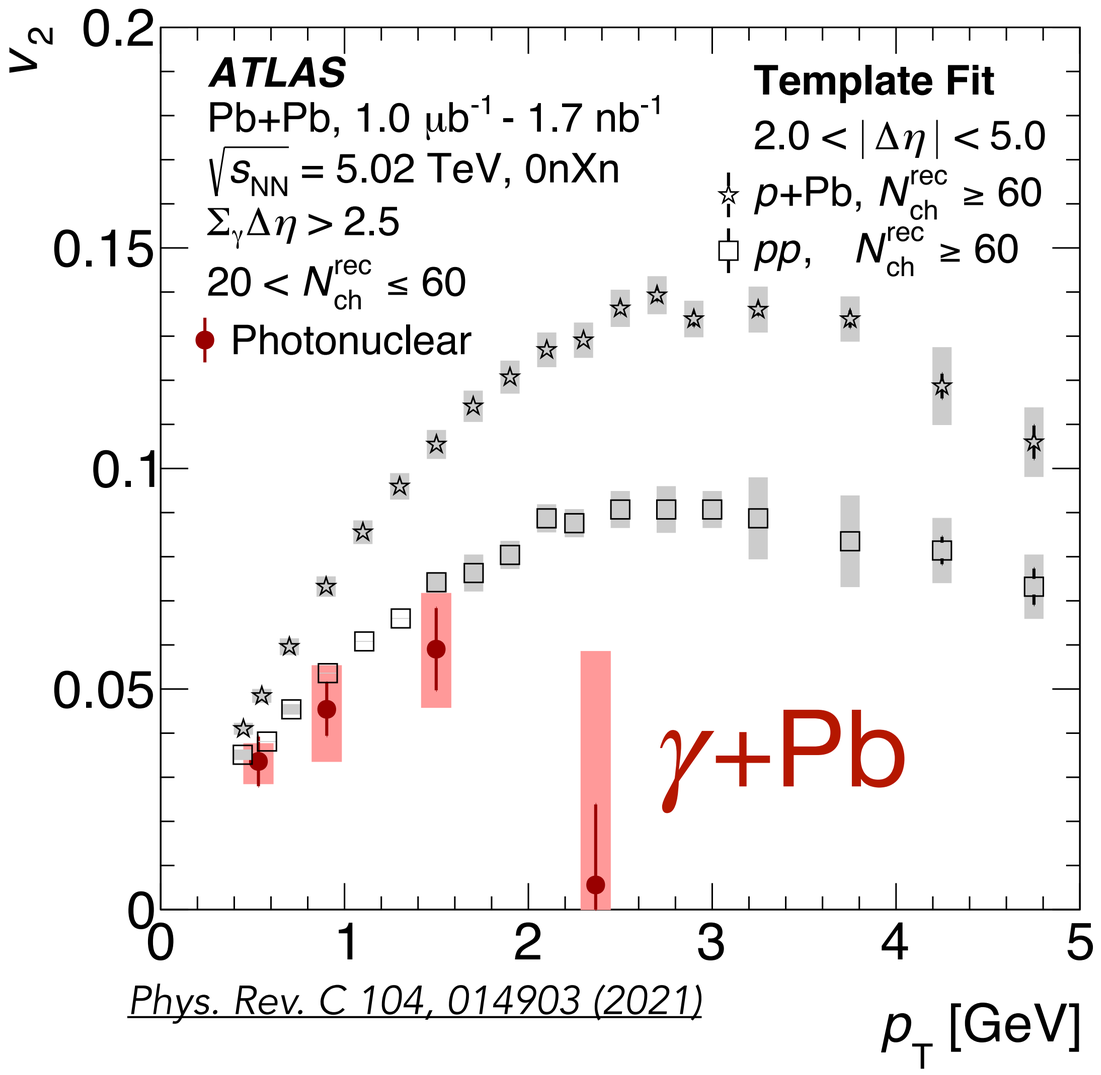

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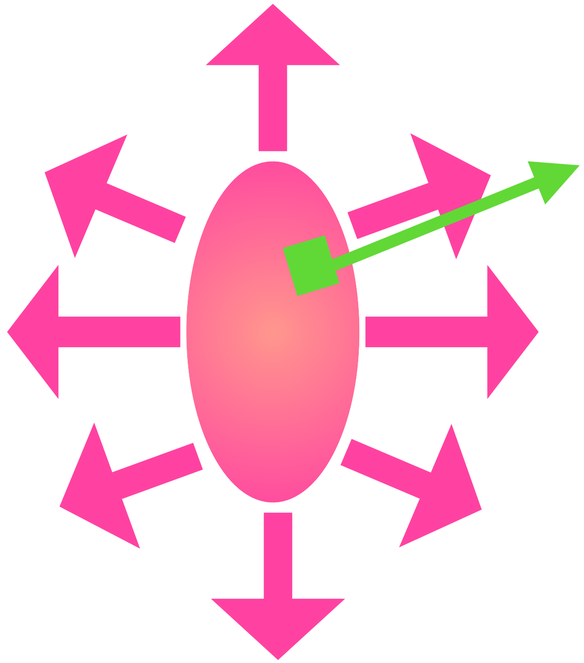
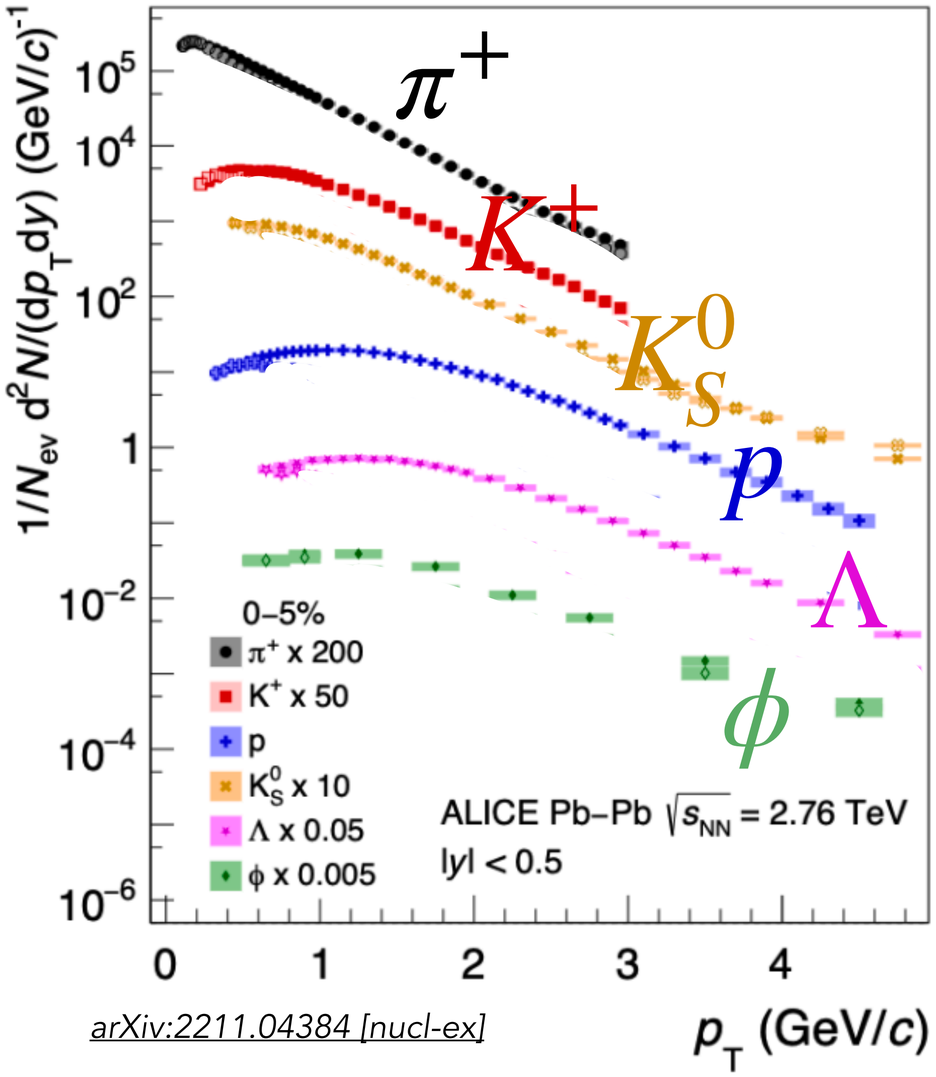
Radial flow? Baryon anomaly? Strangeness enhancement?

Radial flow

Due to the velocity boost, particles get pushed to higher p_{T}





arXiv:2211.04384 [nucl-ex]

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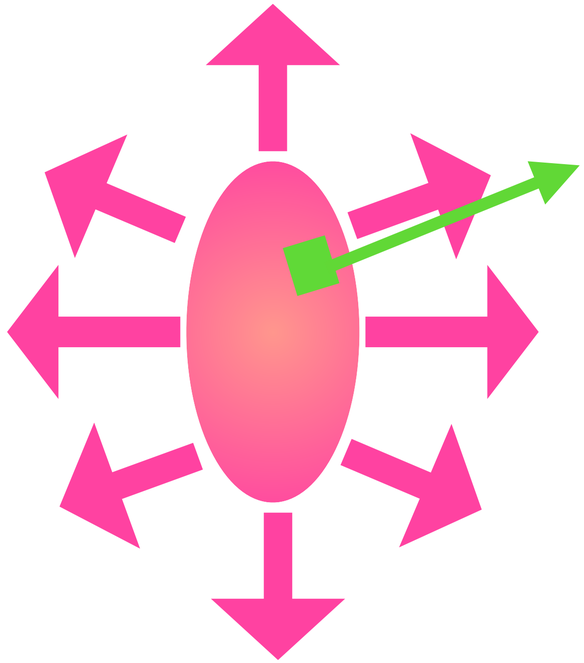

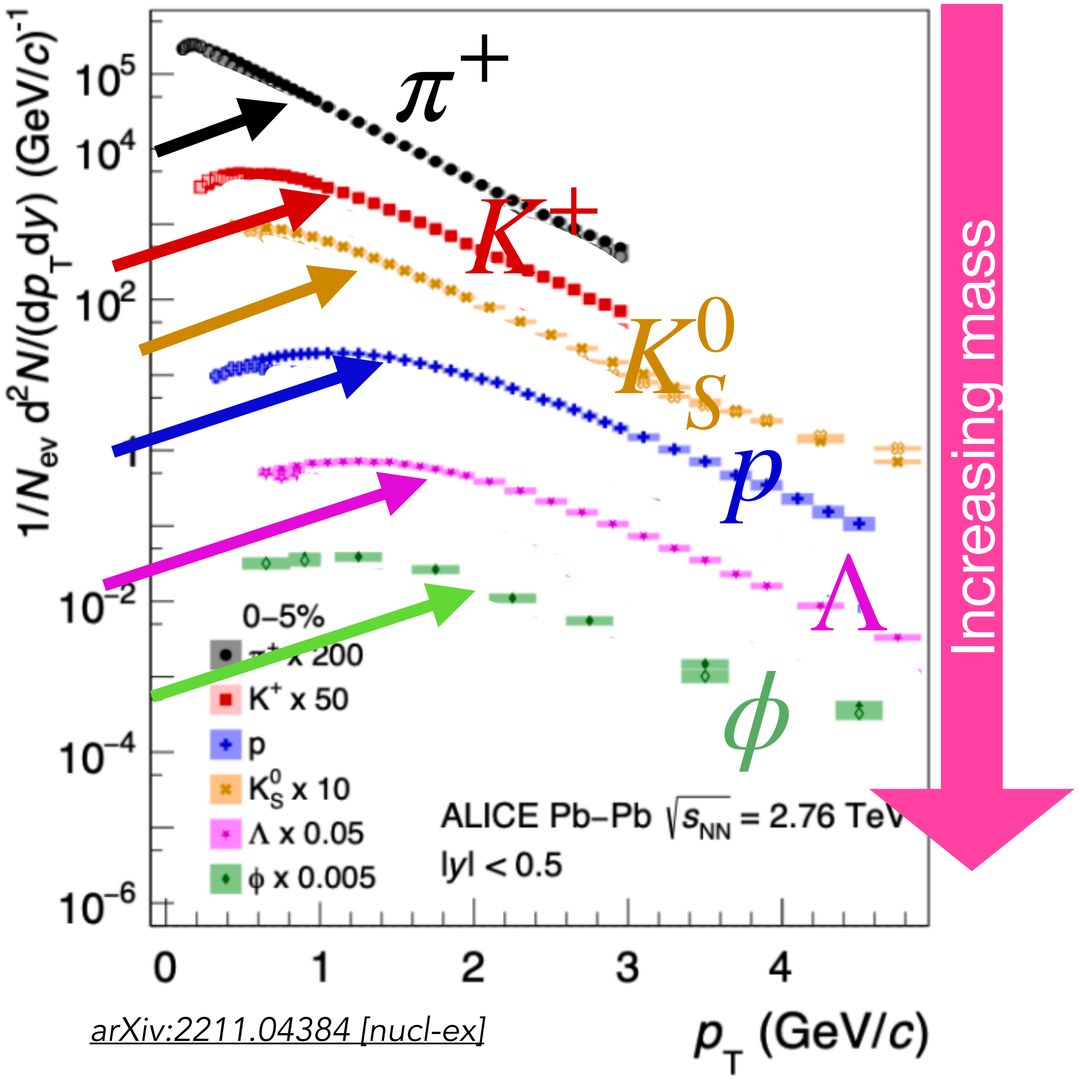

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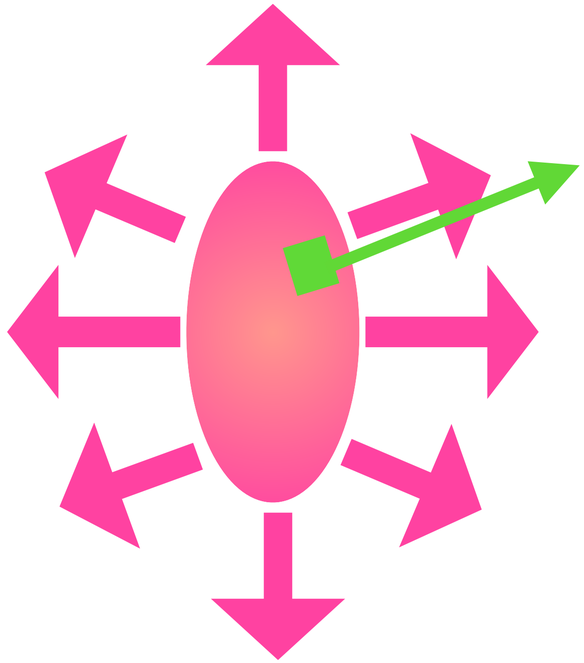
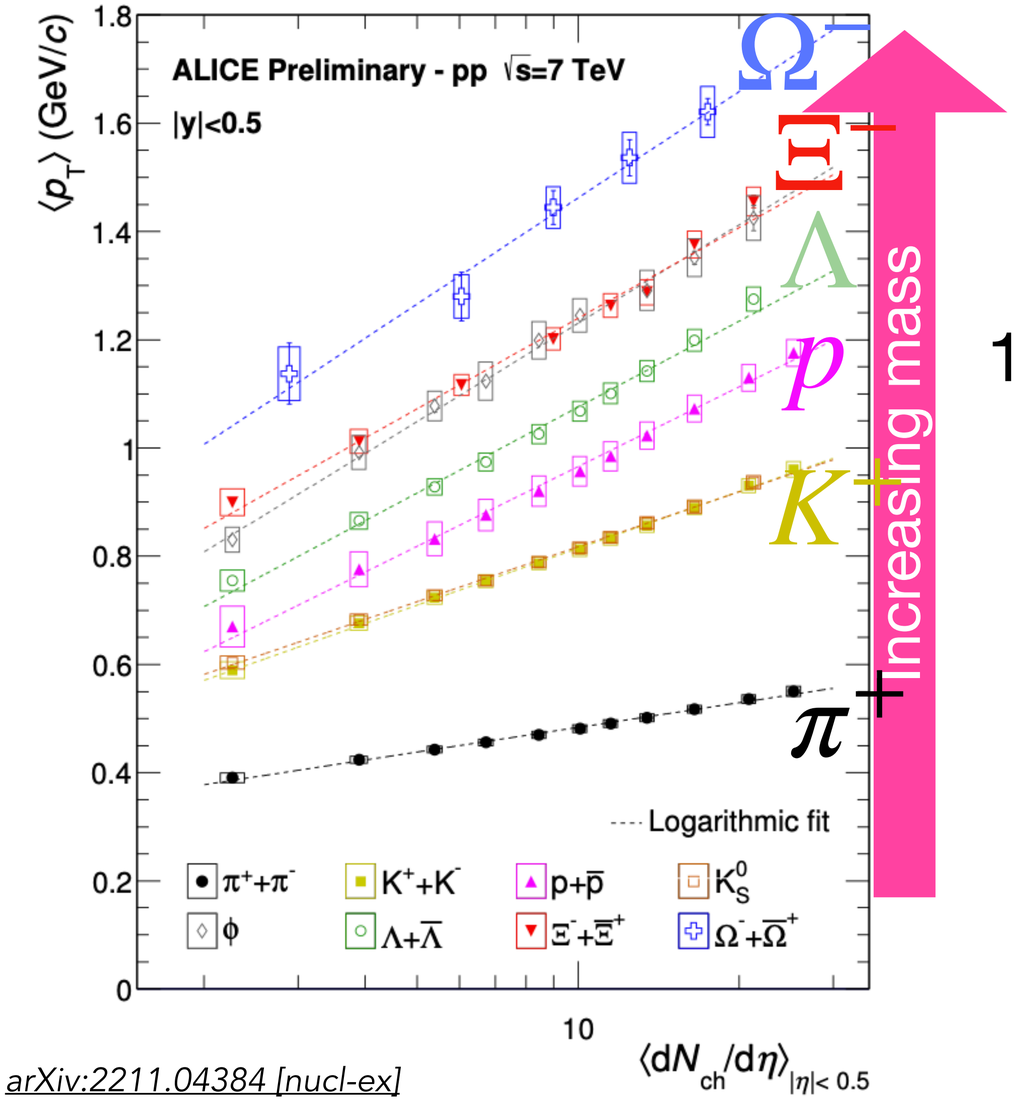


Radial flow can be quantified by $\langle p_{\mathrm{T}} \rangle$



1) Mass ordering

arXiv:2211.04384 [nucl-ex]

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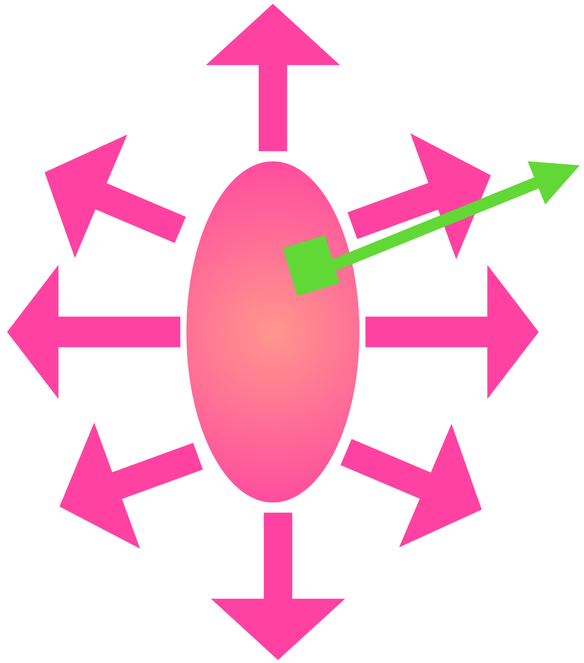

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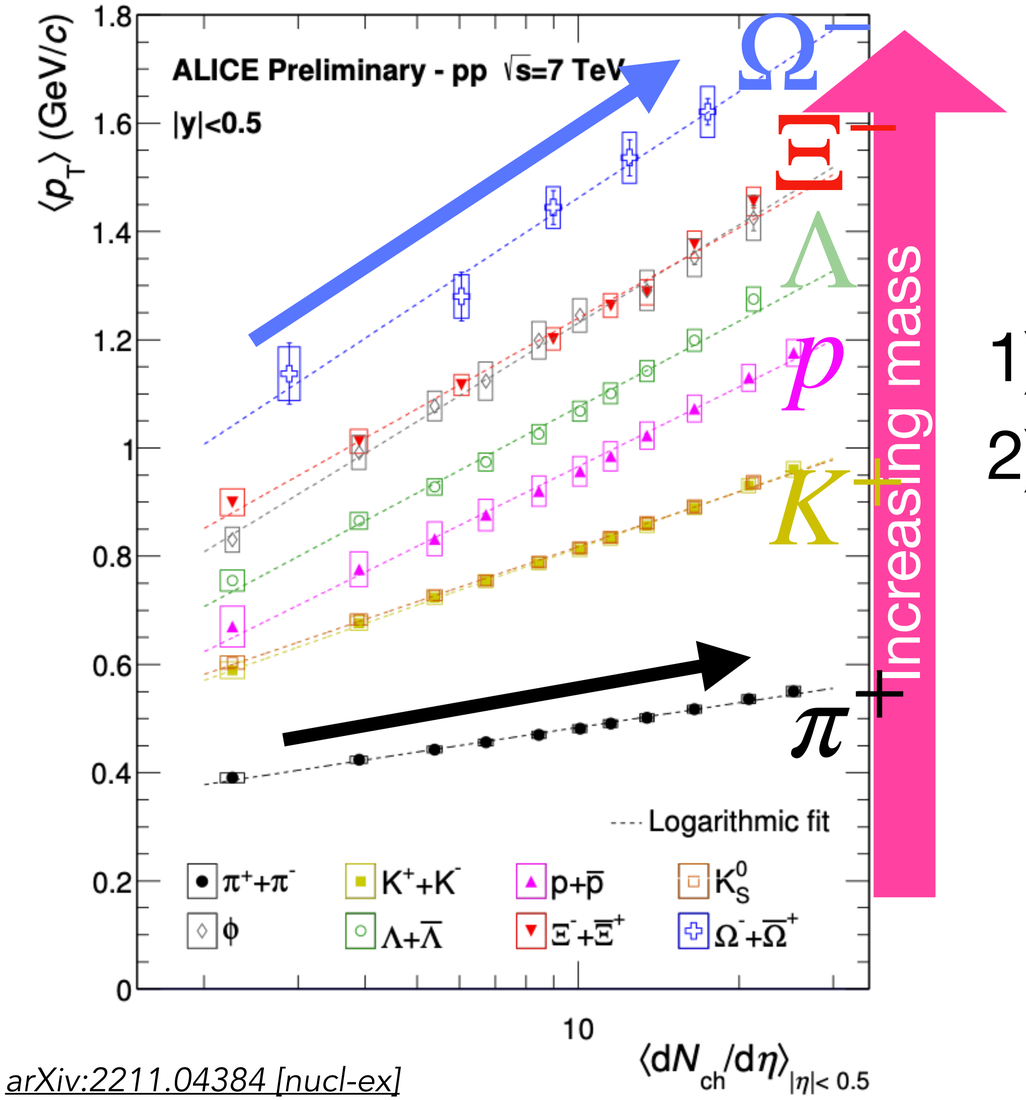
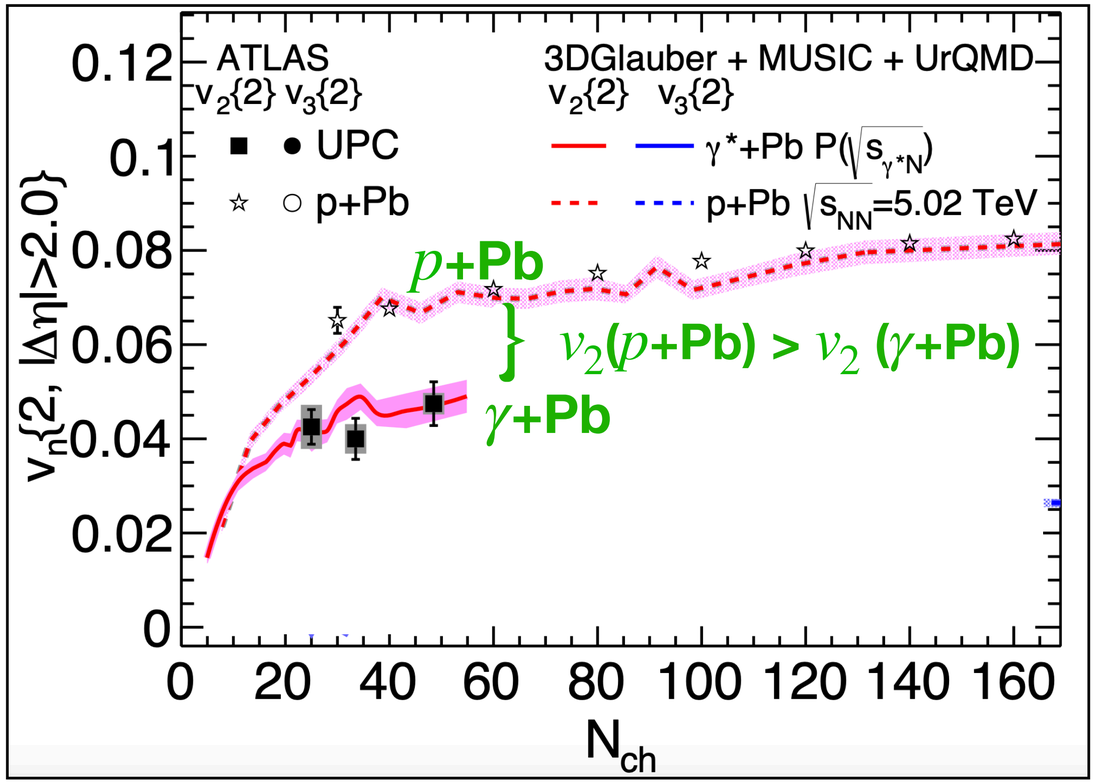


arXiv:2211.04384 [nucl-ex]

1) Mass ordering
2) Stronger multiplicity dependence for heavier particles

Radial flow: Hydro predictions for γ+Pb

3+1D hydrodynamics prediction Wenbin Zhao, Chun Shen, and Björn Schenke *Phys. Rev. Lett. 129, 252302*



v_2 lower in γ+Pb due to longitudinal decorrelation

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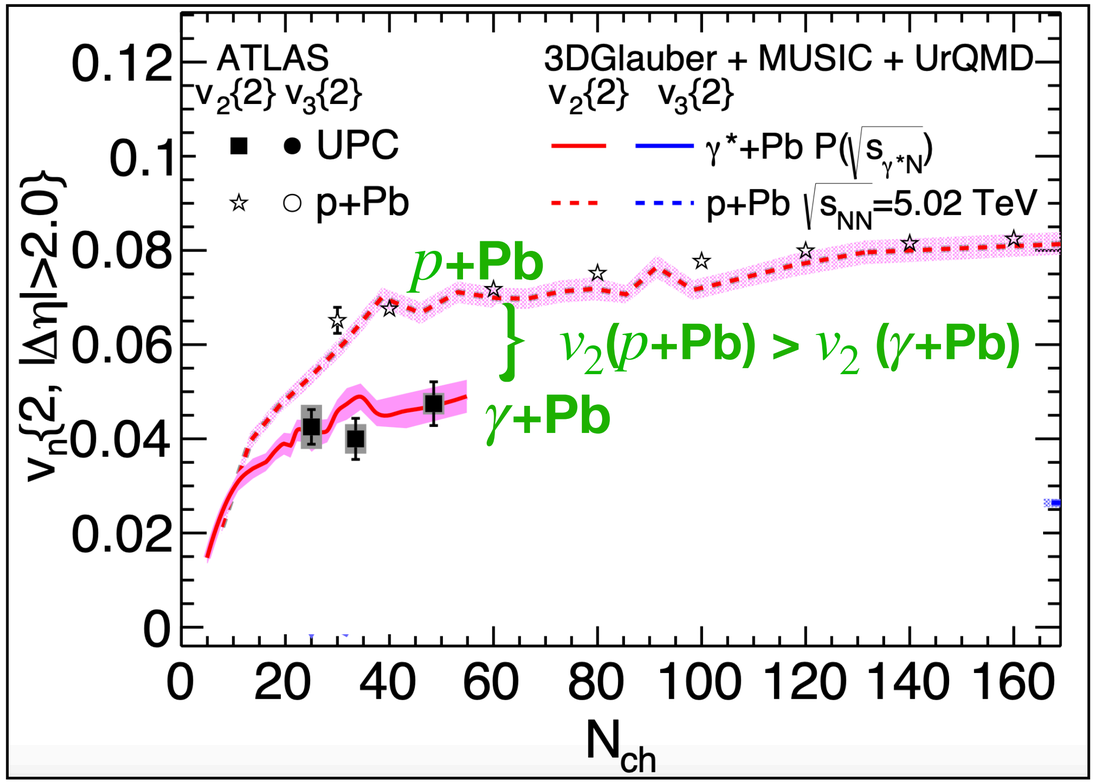

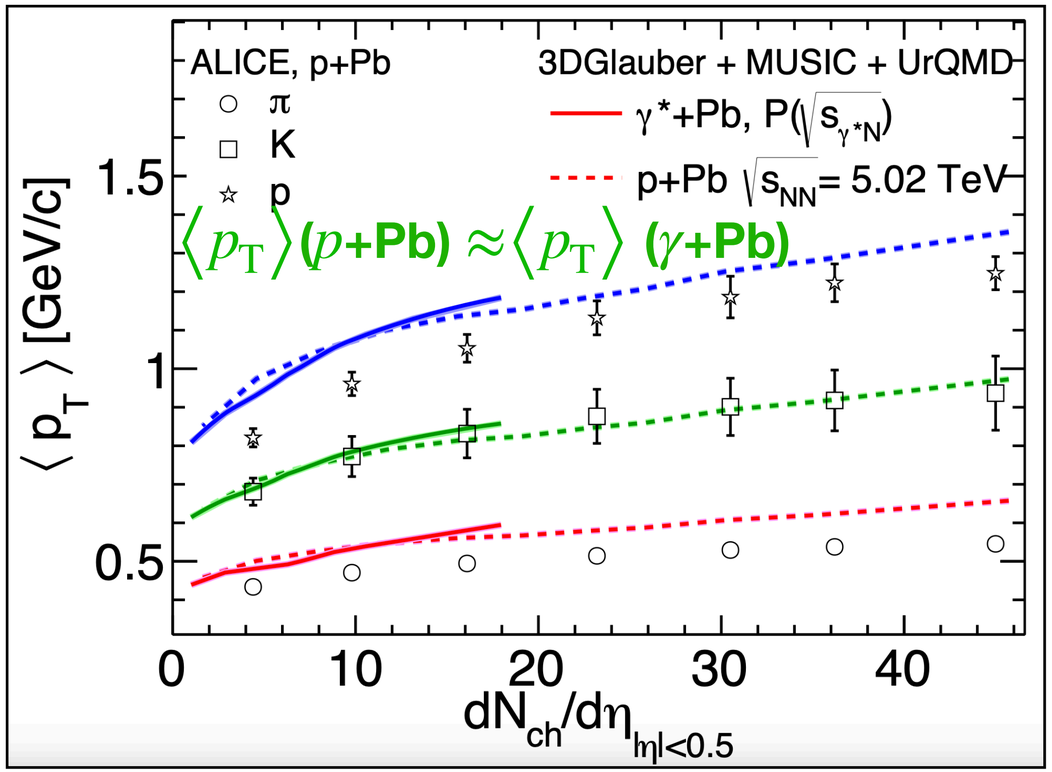

v_2 lower in γ+Pb due to longitudinal decorrelation $\langle p_T \rangle$ similar between p+Pb and γ+Pb!

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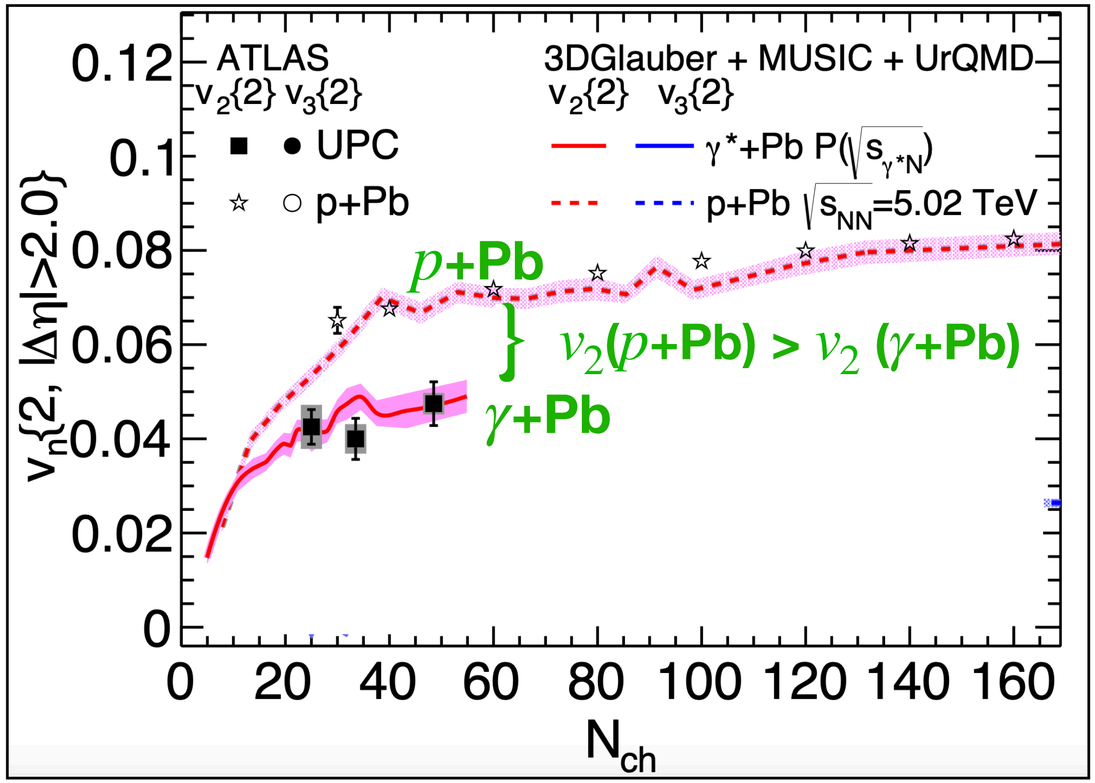
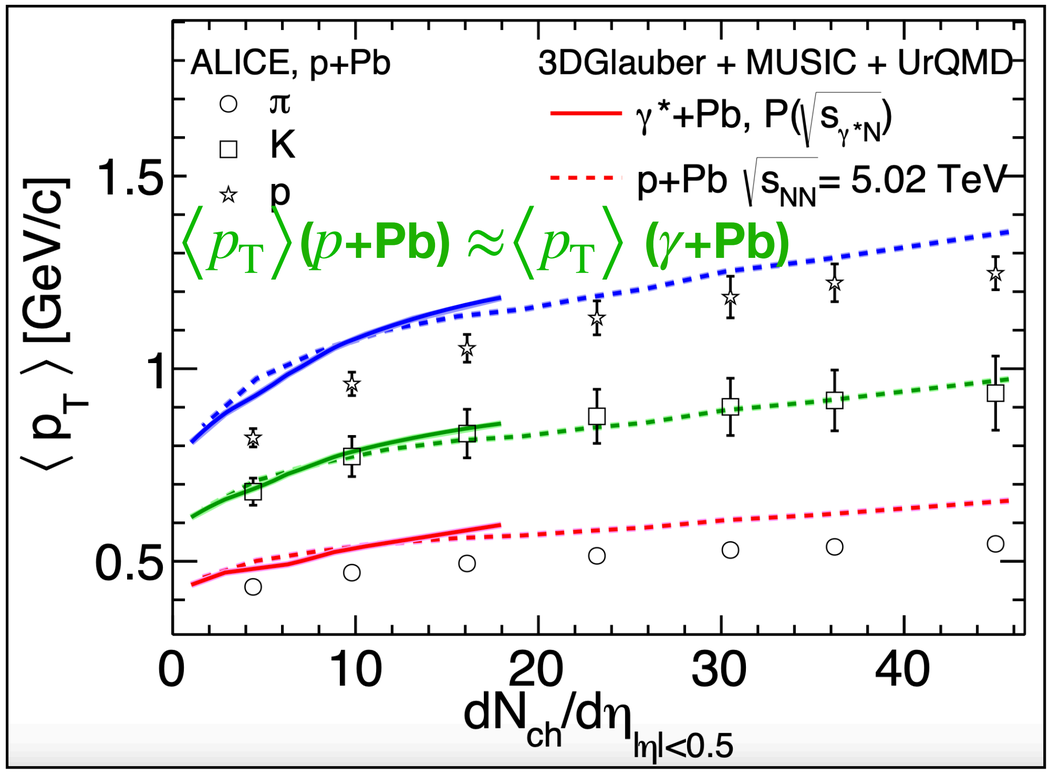
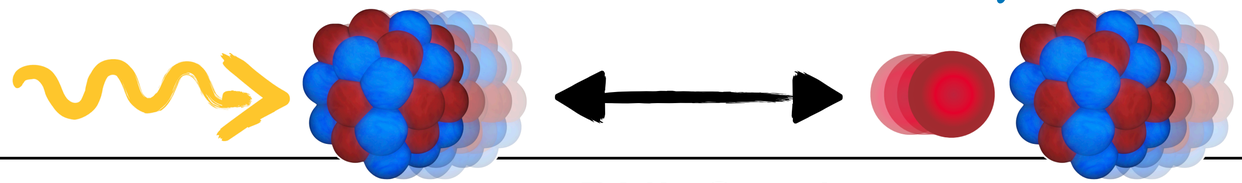


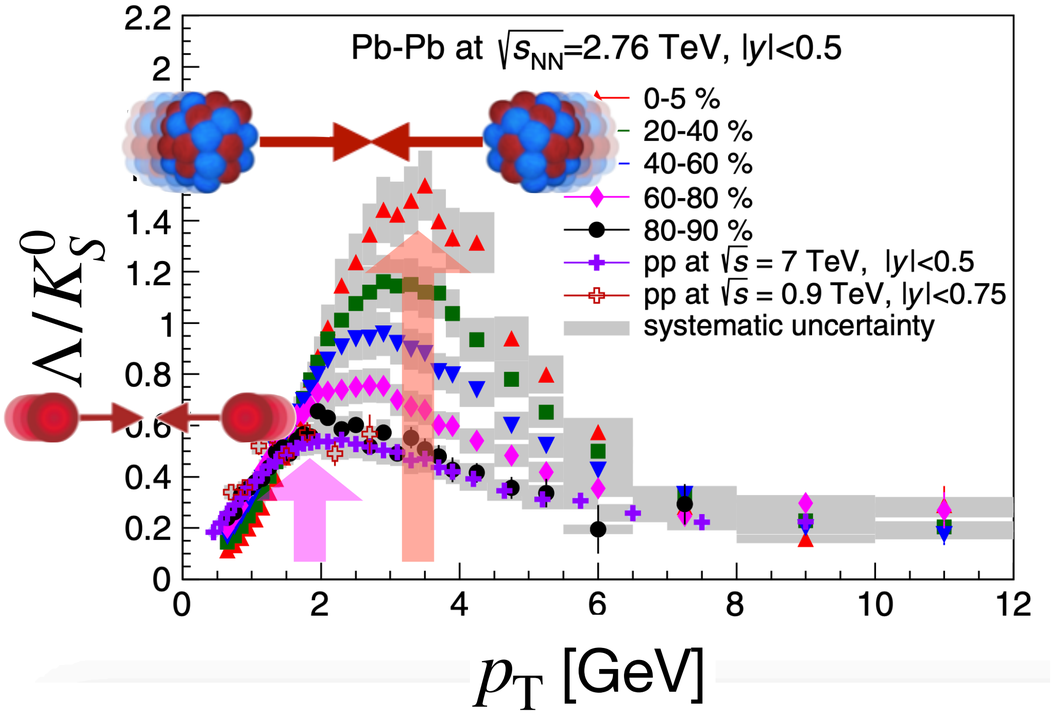


v_2 lower in γ+Pb due to longitudinal decorrelation $\langle p_T \rangle$ similar between p+Pb and γ+Pb!

Motivation to compare between γ+Pb and p+Pb!



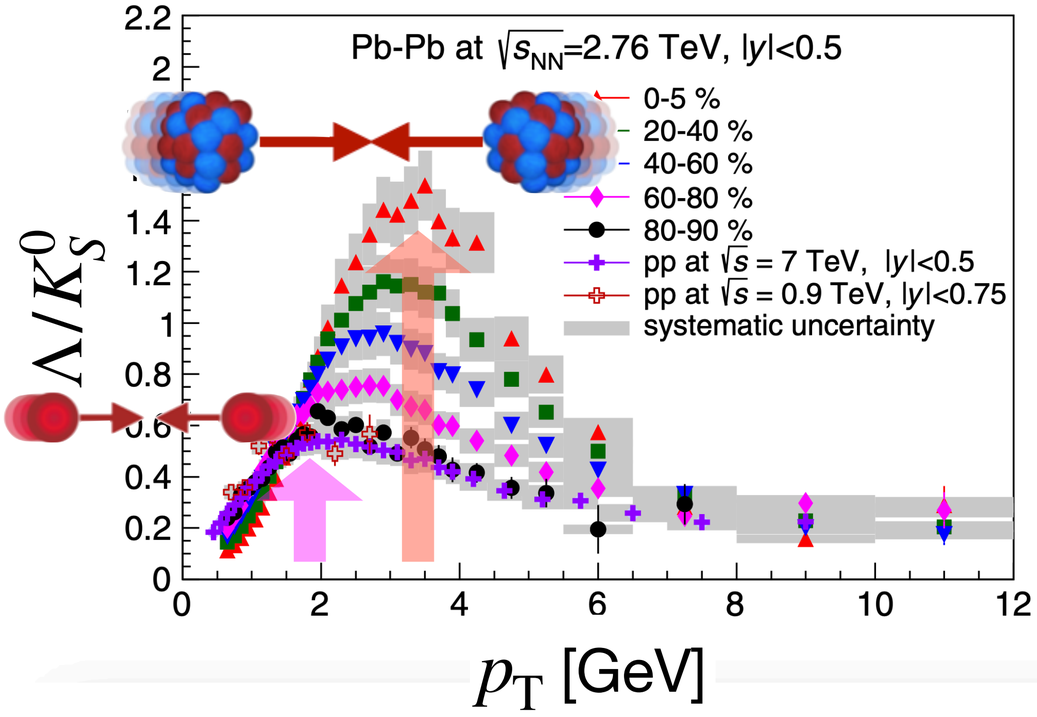
Baryon Anomaly



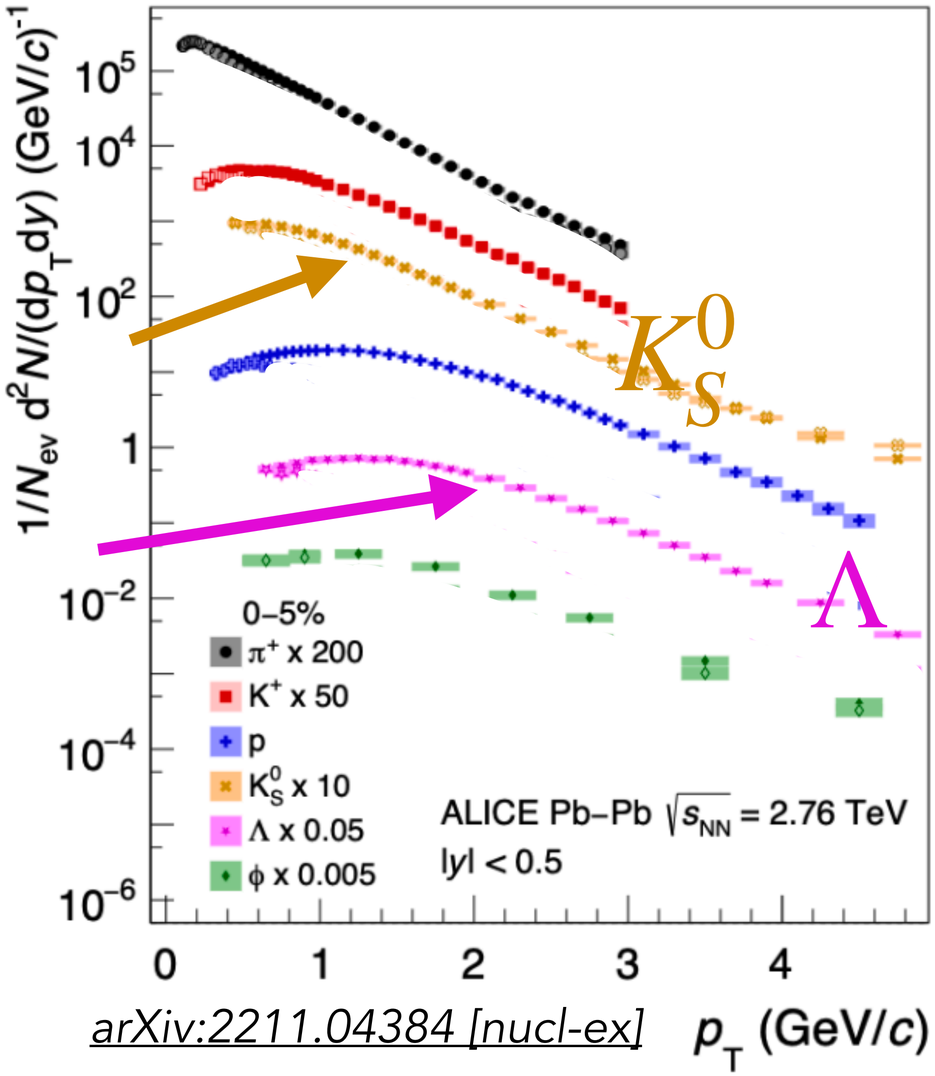
Phys. Rev. Lett. 111 (2013) 222301

Baryon Anomaly

1) Effects due to radial flow: Heavier Λ gets pushed to higher p_{T} compared to K^0_S



Phys. Rev. Lett. 111 (2013) 222301

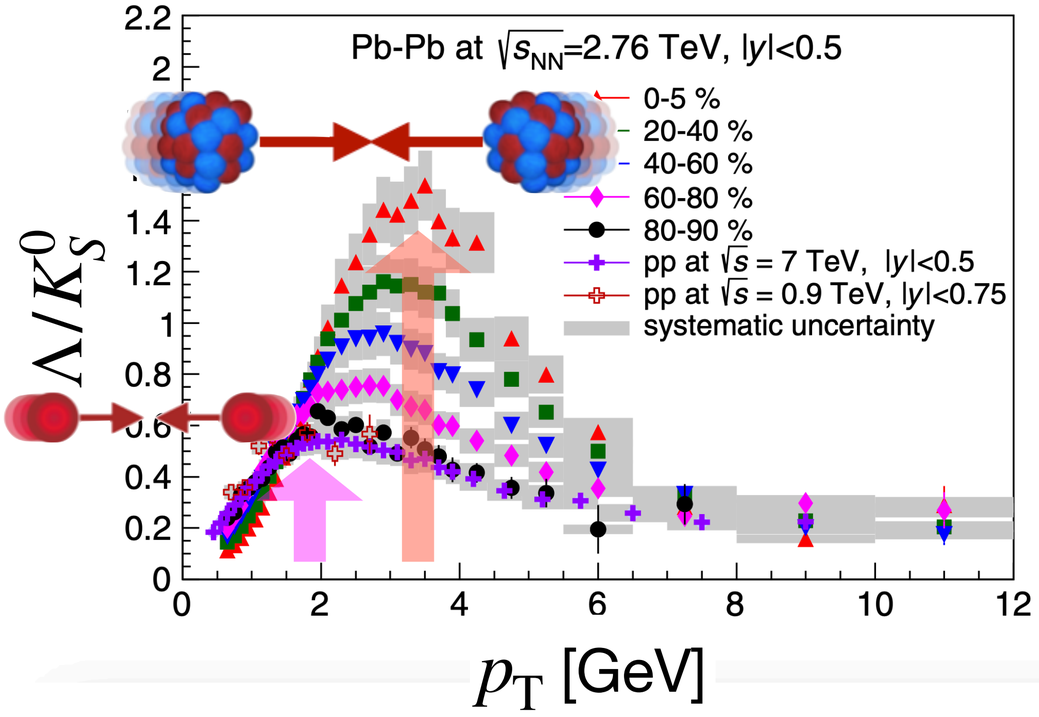


arXiv:2211.04384 [nucl-ex]

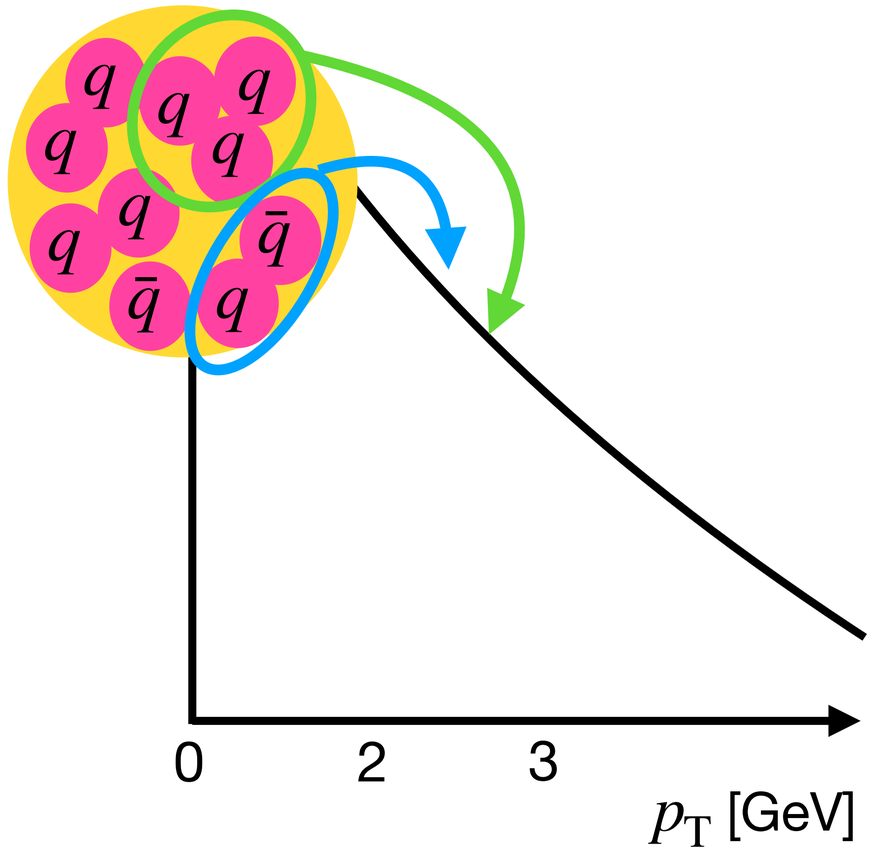
Baryon Anomaly

1) Effects due to radial flow: Heavier Λ gets pushed to higher p_{T} compared to K^0_S

2) Quark Coalescence model: Overlapping quarks in QGP combine to form baryons or mesons.



Phys. Rev. Lett. 111 (2013) 222301



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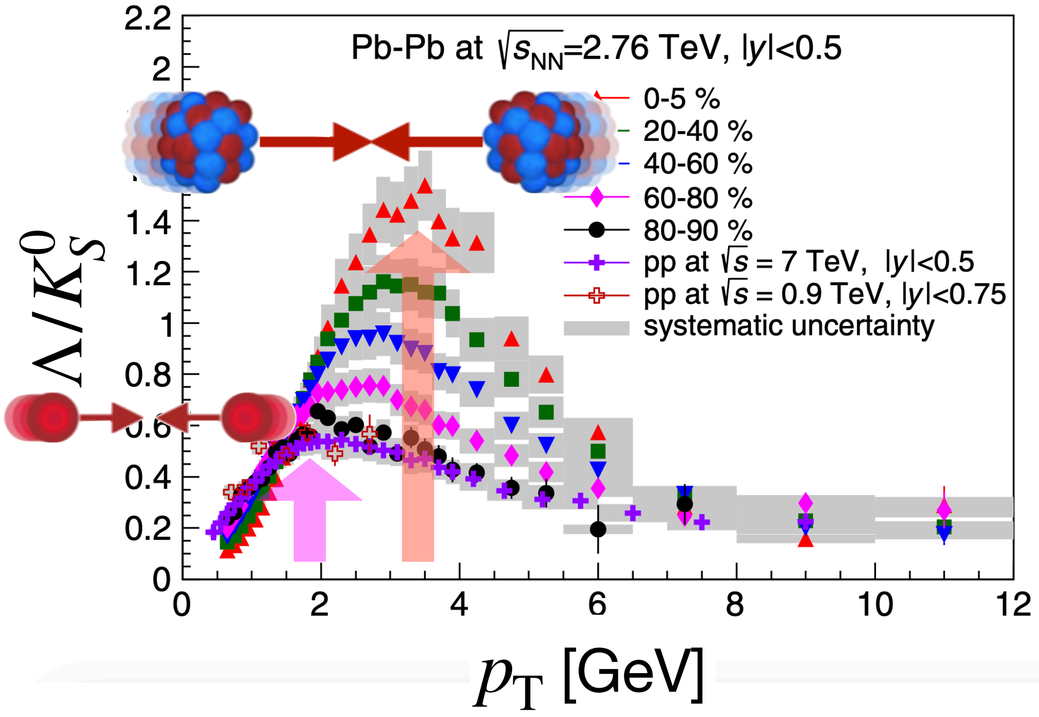
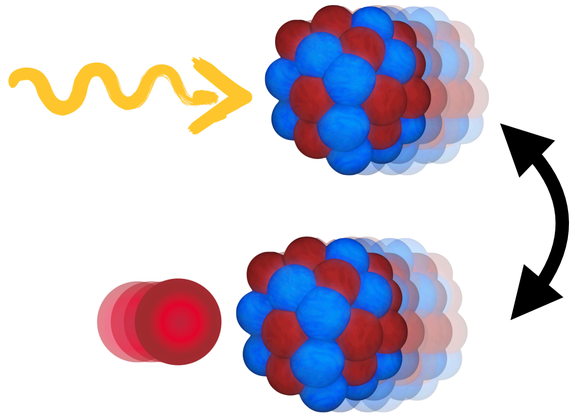
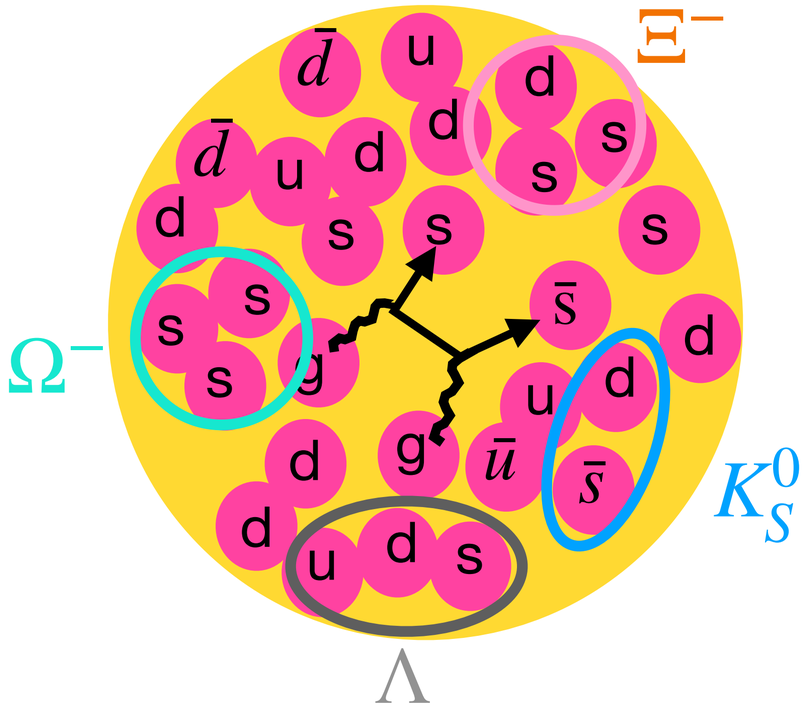


Phys. Rev. Lett. 111 (2013) 222301

How does γ+Pb compare to p+Pb ??

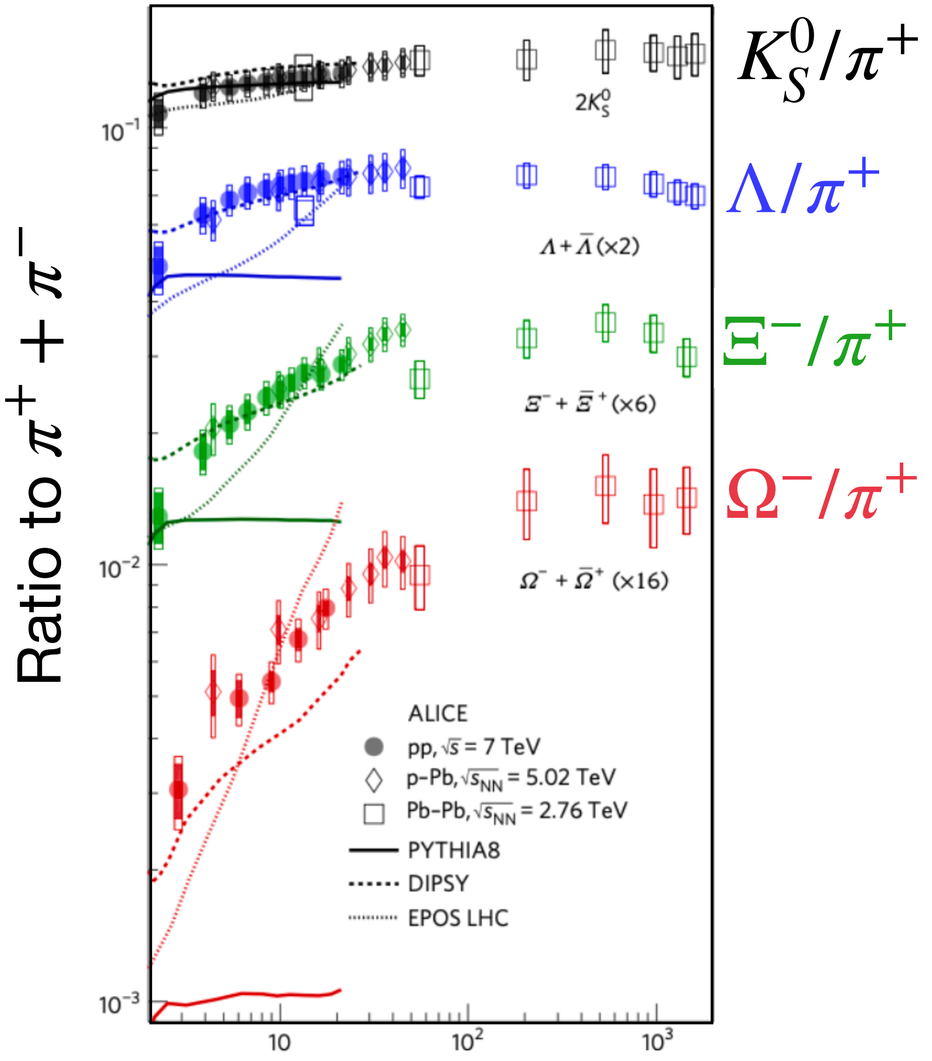


Strangeness Enhancement



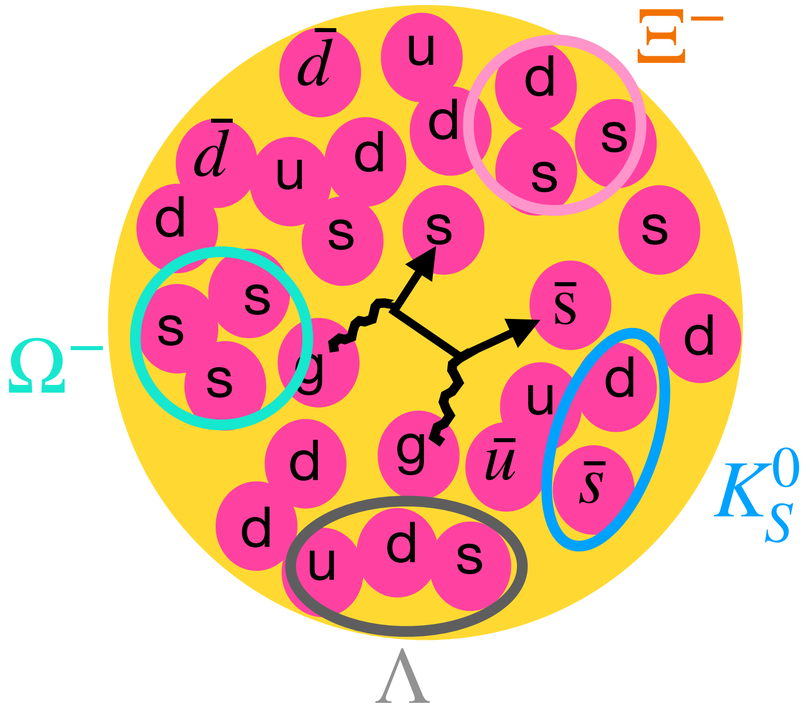
Dominance of gluonic channel and high gluon density in QGP produces abundance of strange hadrons

Historically, one of the first proposed observable for QGP formation



Nature Phys. 13, 535 (2017)

Strangeness Enhancement



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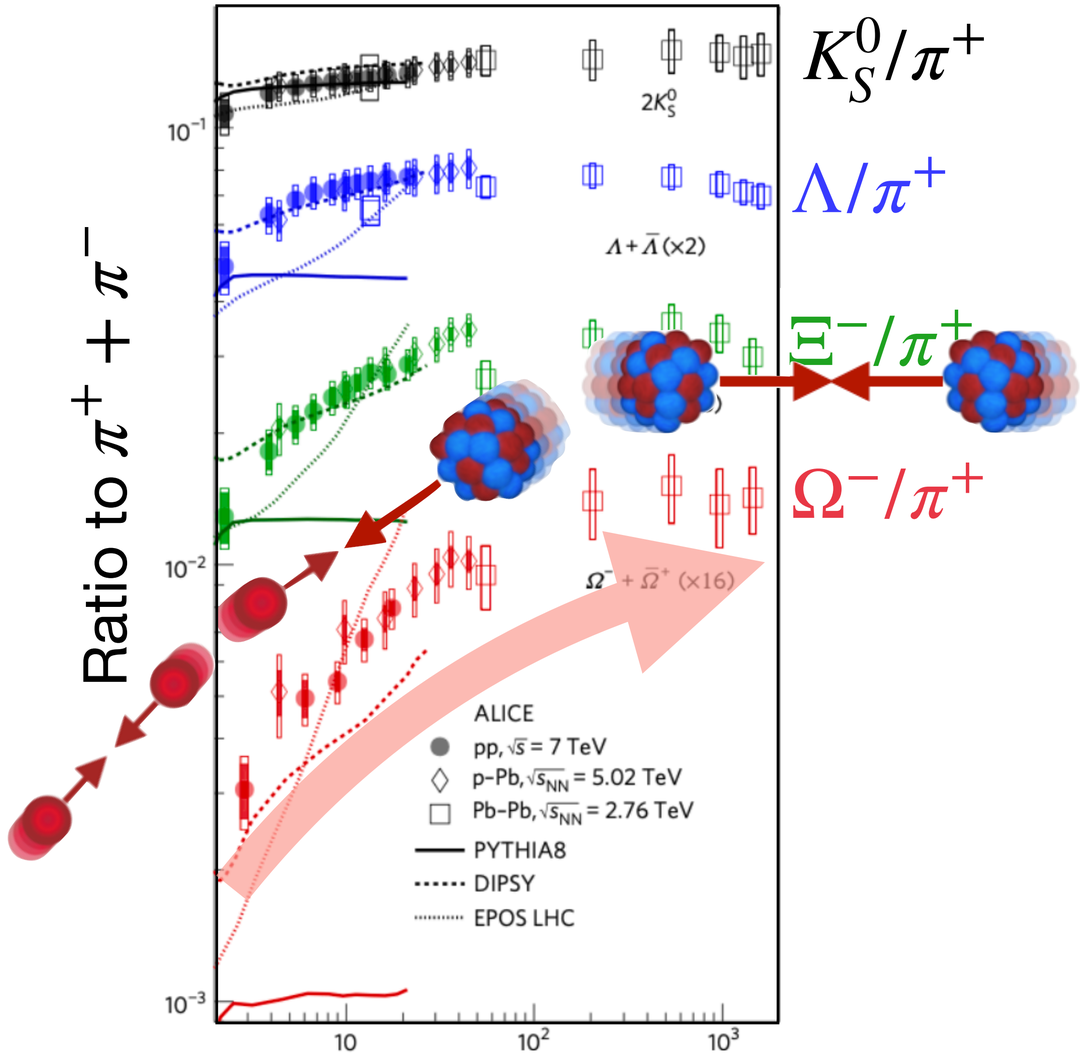

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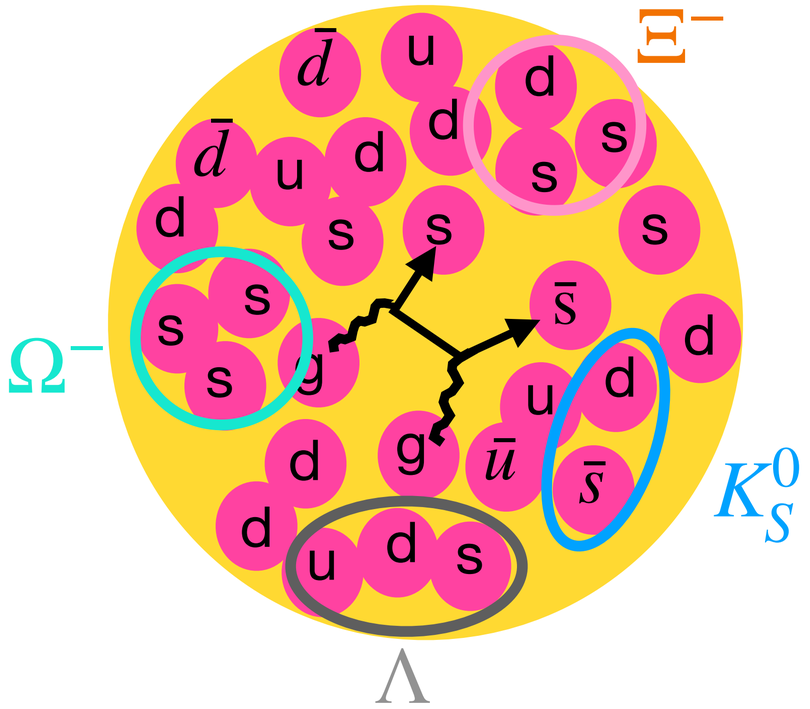

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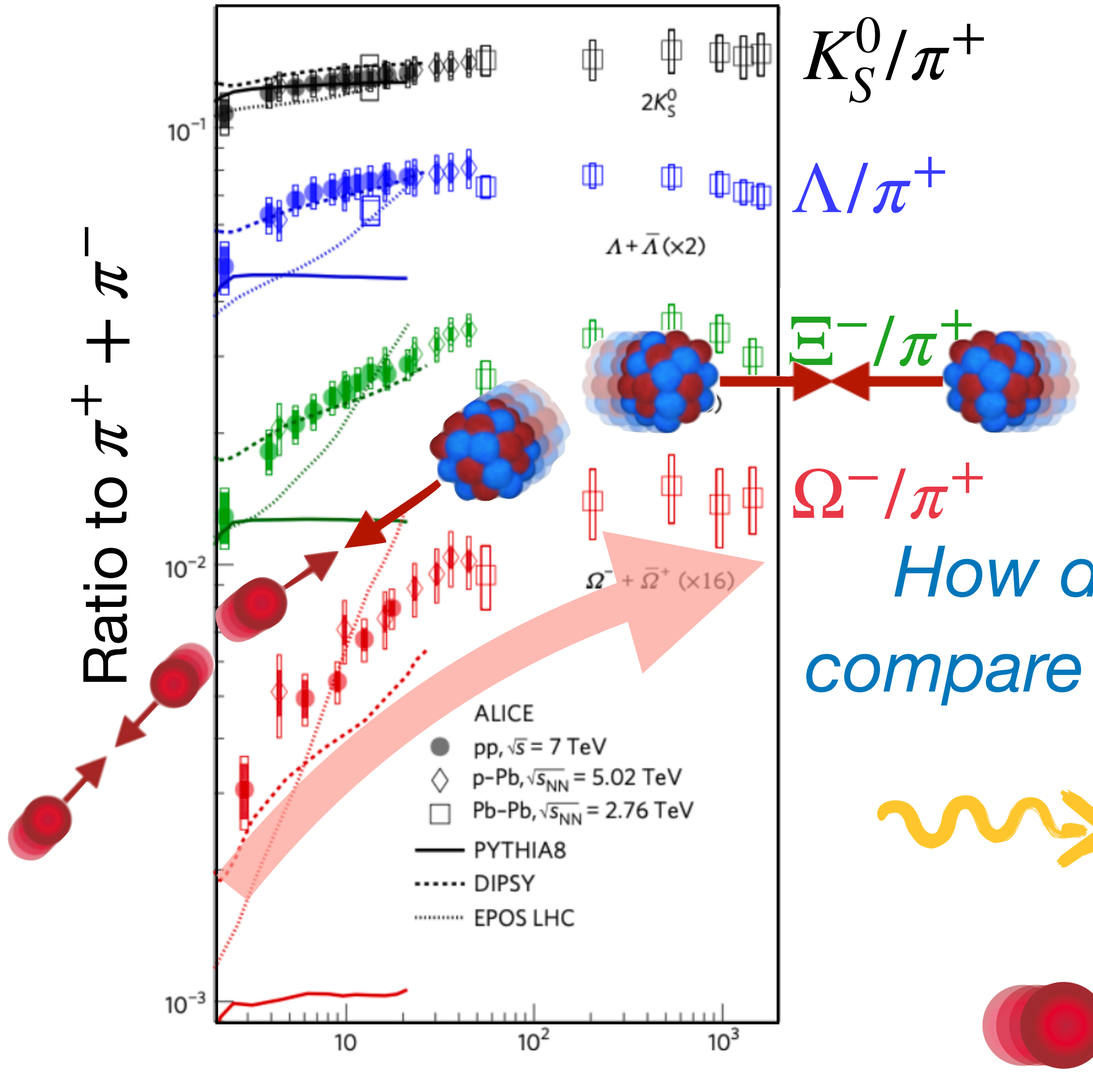
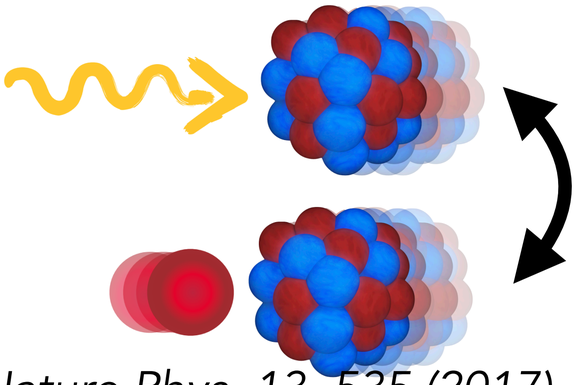
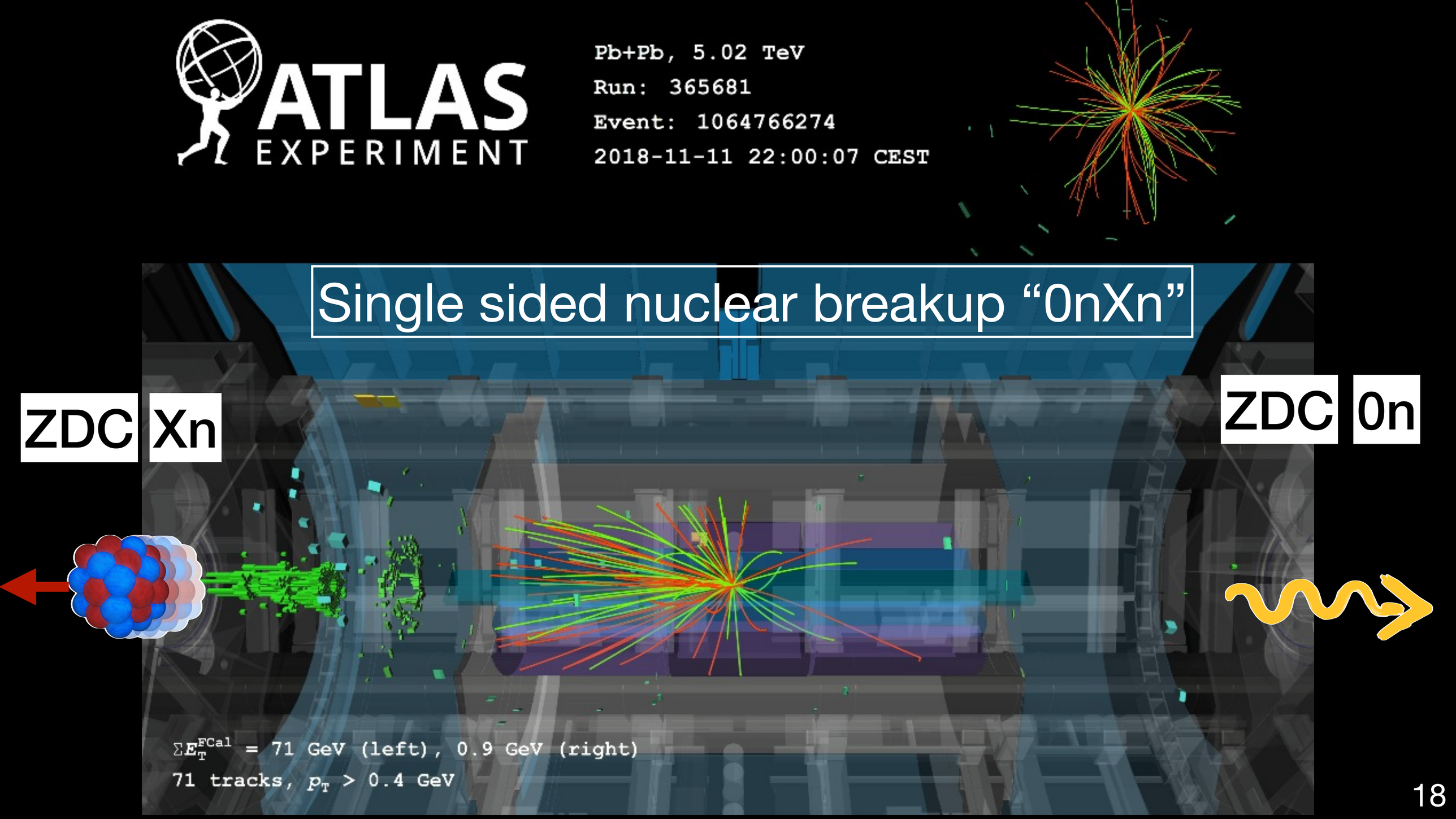


How does γ+Pb compare to p+Pb ??



Nature Phys. 13, 535 (2017)

Event Selection
and
Analysis Procedure


ATLAS EXPERIMENT
Pb+Pb, 5.02 TeV
Run: 365681
Event: 1064766274
2018-11-11 22:00:07 CEST
Single sided nuclear breakup “0nXn”
ZDC Xn
ZDC 0n
$\sum E_T^{FCal}$ = 71 GeV (left), 0.9 GeV (right)
71 tracks, p_T > 0.4 GeV

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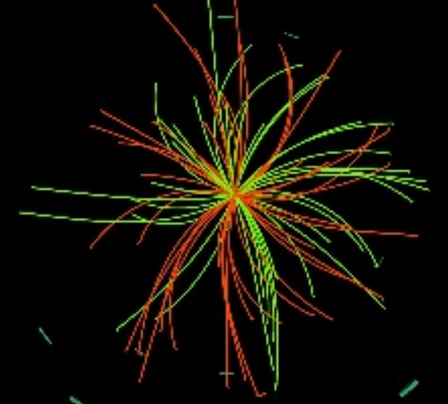


Single sided nuclear breakup “0nXn”

ZDC Xn

ZDC 0n

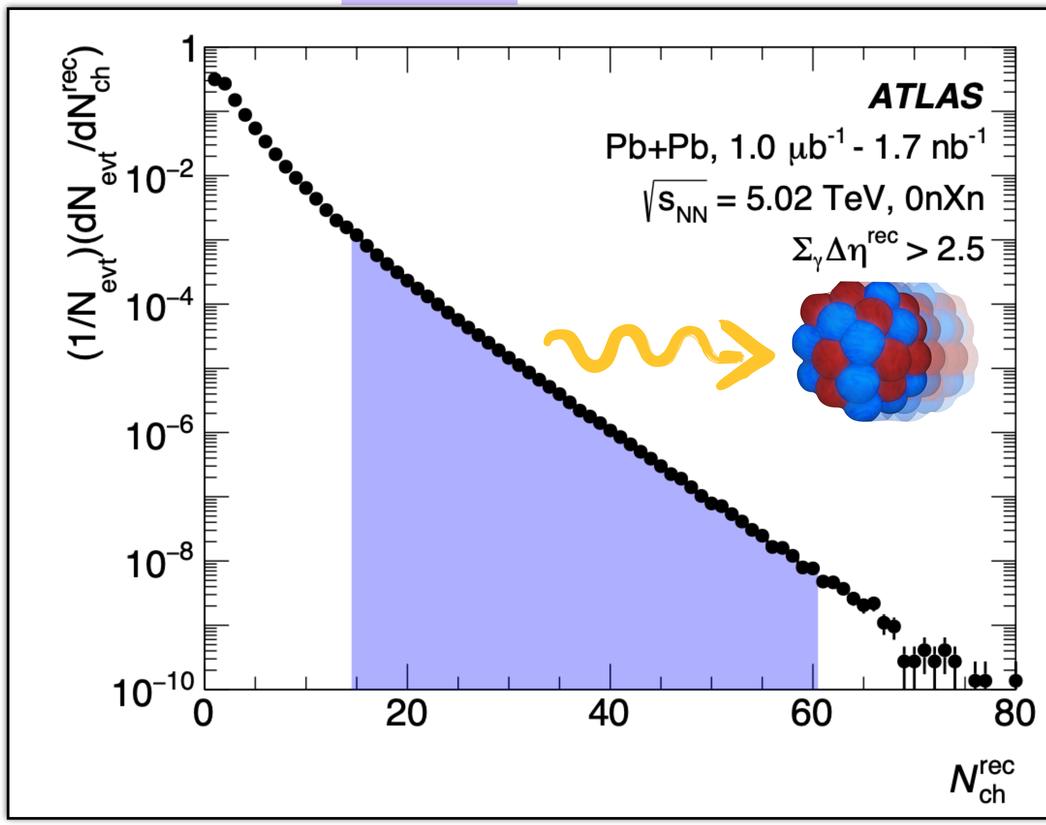
$$\sum_{\gamma} \Delta\eta^{\mathrm{rec}} > 2.5$$

Rapidity gap
Sparse particle production

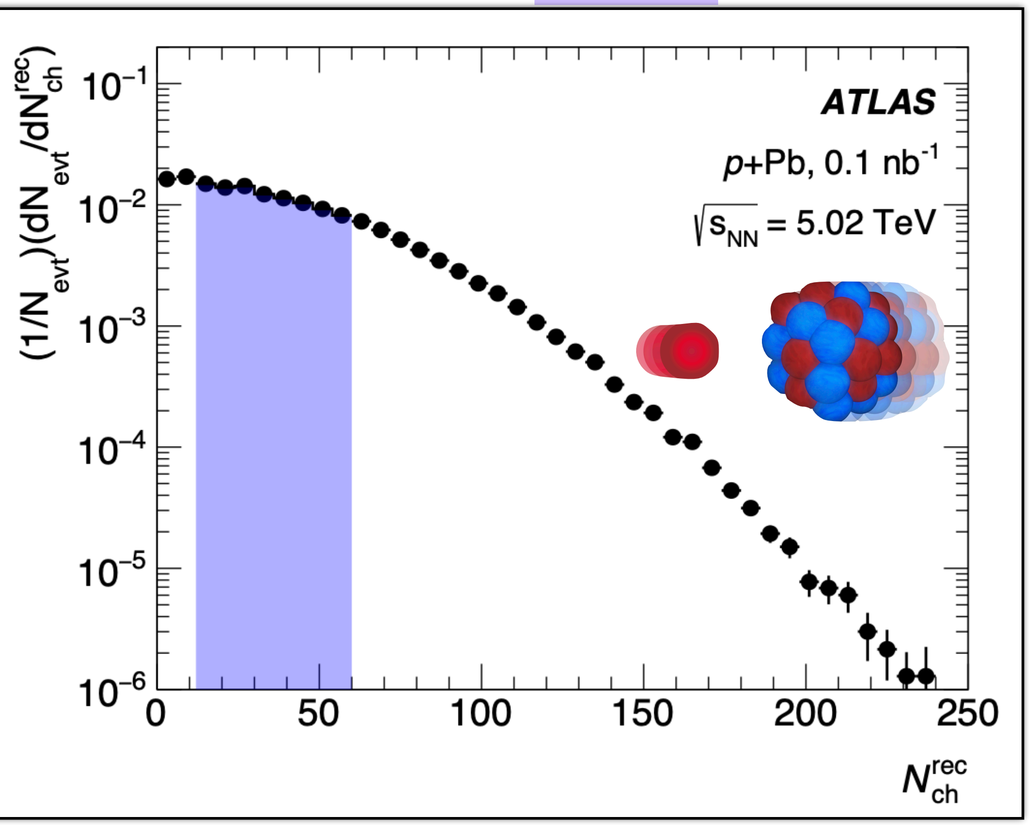
$\Sigma E_T^{\mathrm{FCal}}$ = 71 GeV (left), 0.9 GeV (right)
71 tracks, p_T > 0.4 GeV

Multiplicity selection

γ+Pb



p+Pb



Analysis event class: N_{ch}^{rec} integrated results are reported in the range: N_{ch}^{rec}: [25,60].
N_{ch}^{rec} differential results are reported in the range: N_{ch}^{rec}: [15,60].

* For later comparisons, N_{ch}^{rec} distribution in p+Pb is re-weighted to match that of γ+Pb.

Analysis Procedure

Charged-hadron analysis

Track Selection

- Tracks with $p_{\mathrm{T}} > 0.1$ GeV and $|\eta| < 2.5$, and a distance of closest approach to the reconstructed vertex in both longitudinal and transverse directions of less than 1.5 mm.

- Observables:

  Charged-hadron yields

$$Y_1(\eta, p_{\mathrm{T}}) = \frac{1}{N_{\mathrm{ev}}} \frac{\mathrm{d}N^2_{\mathrm{ch}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}$$

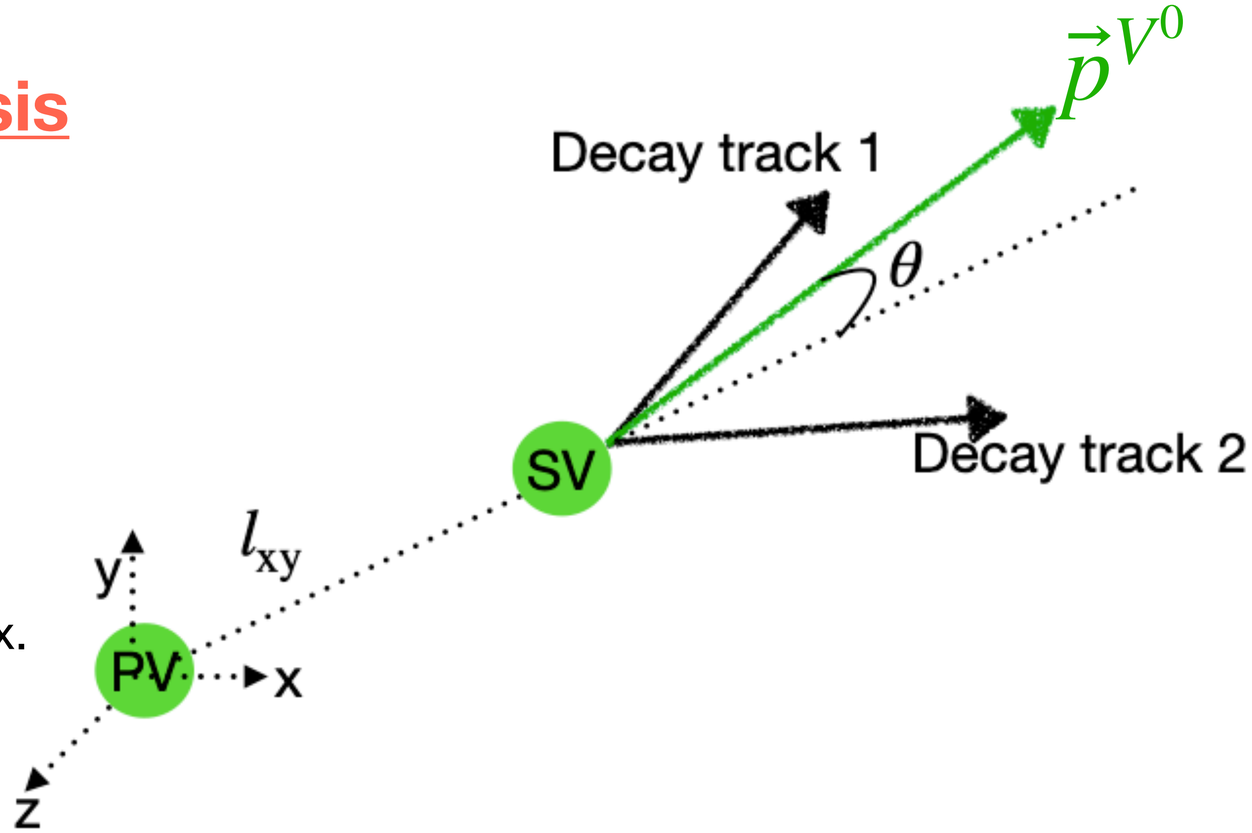
$$Y_2(\eta) = \frac{1}{N_{\mathrm{ev}}} \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}$$

- Tracks entering these observables in bins of p_{T} and η are corrected for reconstruction and selection inefficiency, and contribution of secondaries and fakes.

Analysis Procedure

Identified-hadron (K^0_S, Λ, Ξ^-) analysis

- Decay channels:
  - $K^0_S \rightarrow \pi^+ + \pi^-$
  - $\Lambda \rightarrow p + \pi^-$
  - $\Xi^- \rightarrow \Lambda + \pi^- \rightarrow p + \pi^- + \pi^-$
- Oppositely charged tracks with $p_T > 0.1$ GeV and $|\eta| < 2.5$ are fitted to a common secondary vertex.
- Reconstructed candidates are required to have:
  - K^0_S: $p_T > 0$ GeV
  - Λ: $p_T > 0.5$ GeV for |y| < 1.6, $p_T > 0.8$ GeV for 1.6 < |y| < 2.5
  - Ξ^-: $p_T > 1$ GeV, and |y| < 1.6
  - $\chi^2 < 15$
  - $\cos\theta > 0.999$
  - Optimized minimum values on $\left|L_{xy}/\sigma_{Lxy}\right|$ and $\left|p_T/\sigma_{p_T}\right|$

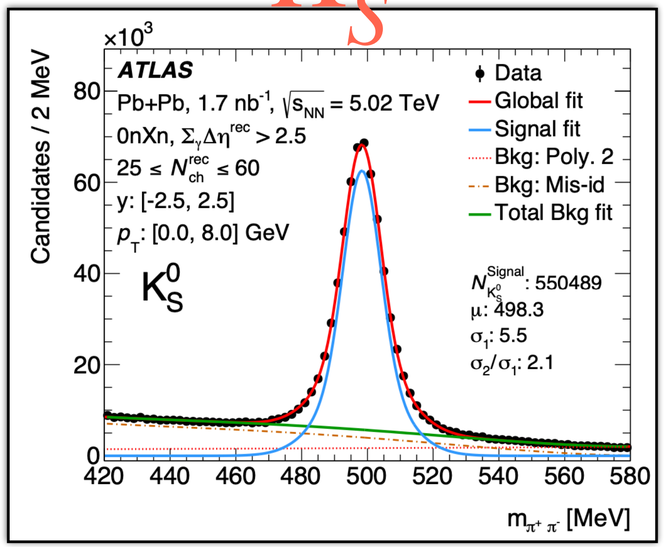


Analysis Procedure

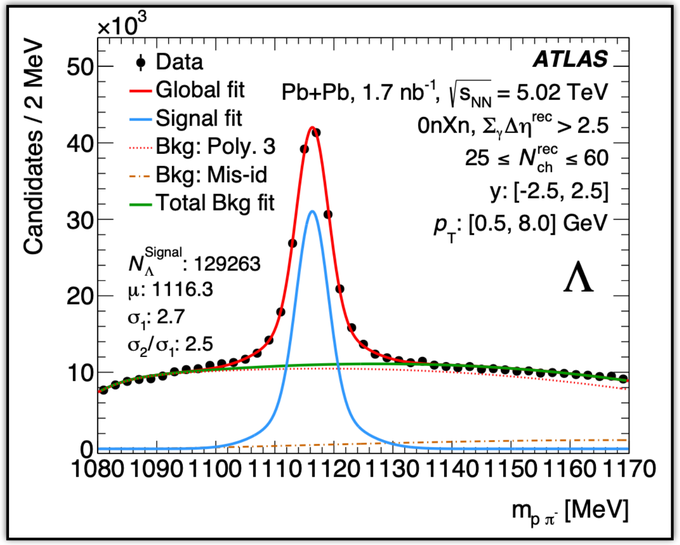
Identified-hadron (K^0_S, Λ, Ξ^-) analysis

- Signal yields can be very cleanly extracted from fits to the various invariant mass distributions.

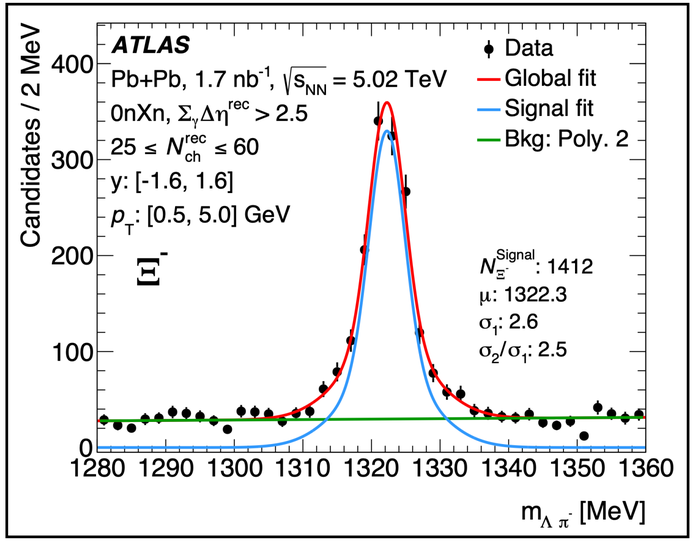
K^0_S



Λ



Ξ^-

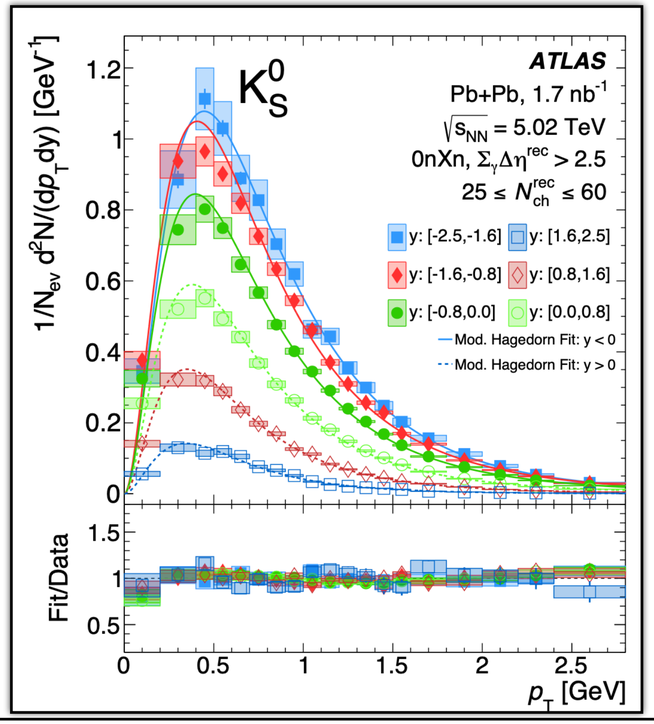


Analysis Procedure

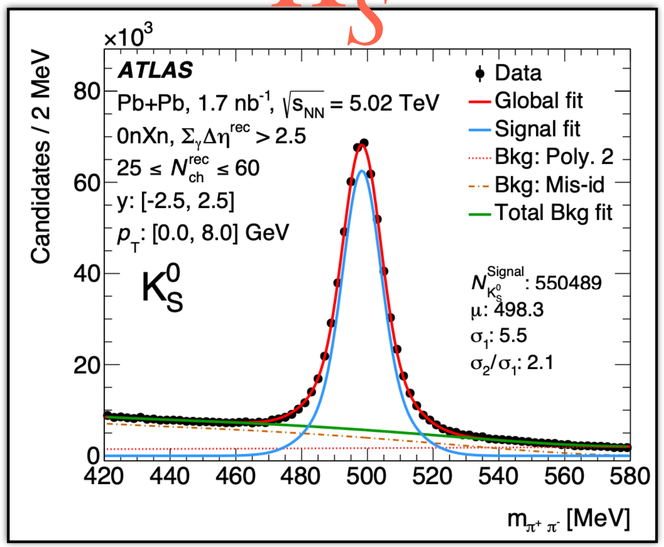
Identified-hadron (K^0_S, Λ, Ξ^-) analysis

- Signal yields can be very cleanly extracted from fits to the various invariant mass distributions.
- Signal yields are extrapolated to $p_T = 0$ GeV using Modified Hagedorn Fits:

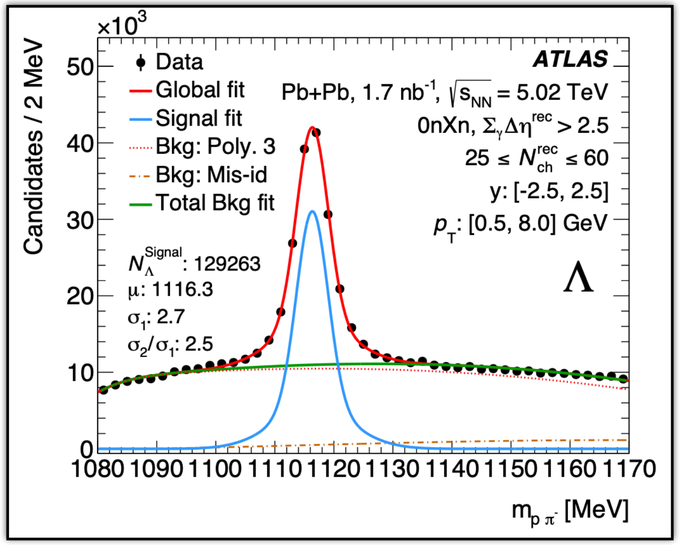
$$\frac{1}{N}\frac{dN}{dp_T} = A_1 \frac{p_T^2}{\sqrt{p_T^2 + m_0^2}} \left(1 + \frac{p_T}{p_1}\right)^{-n_1}$$



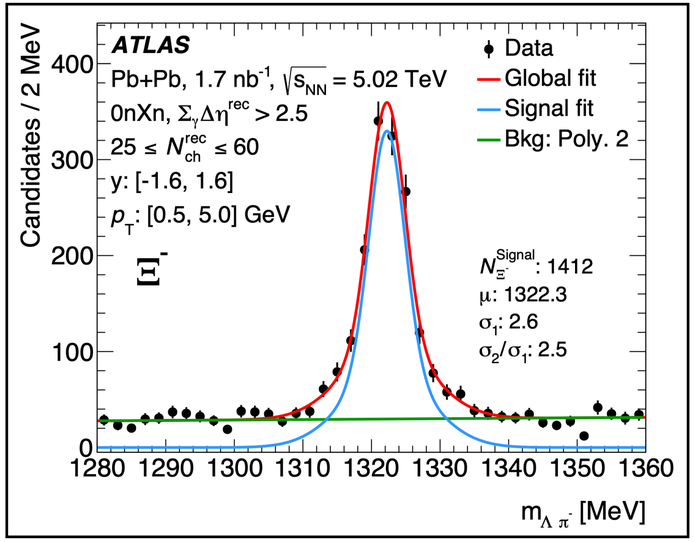
K^0_S



Λ

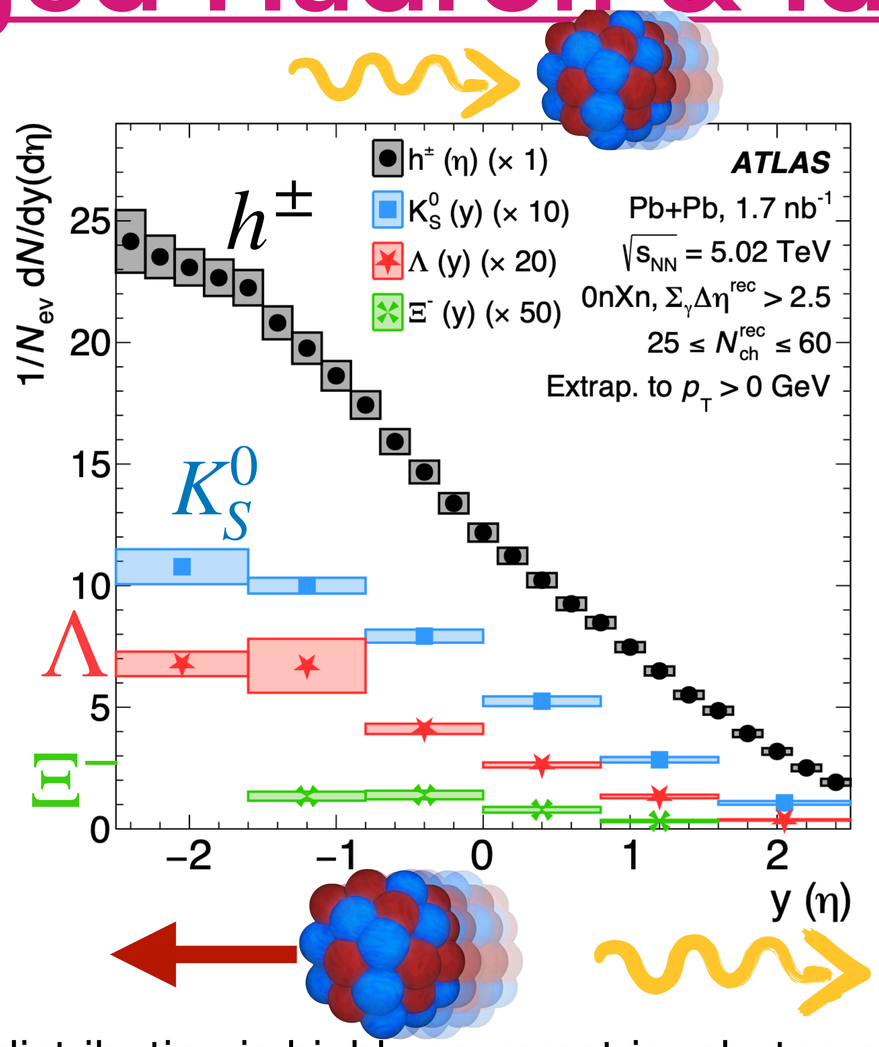


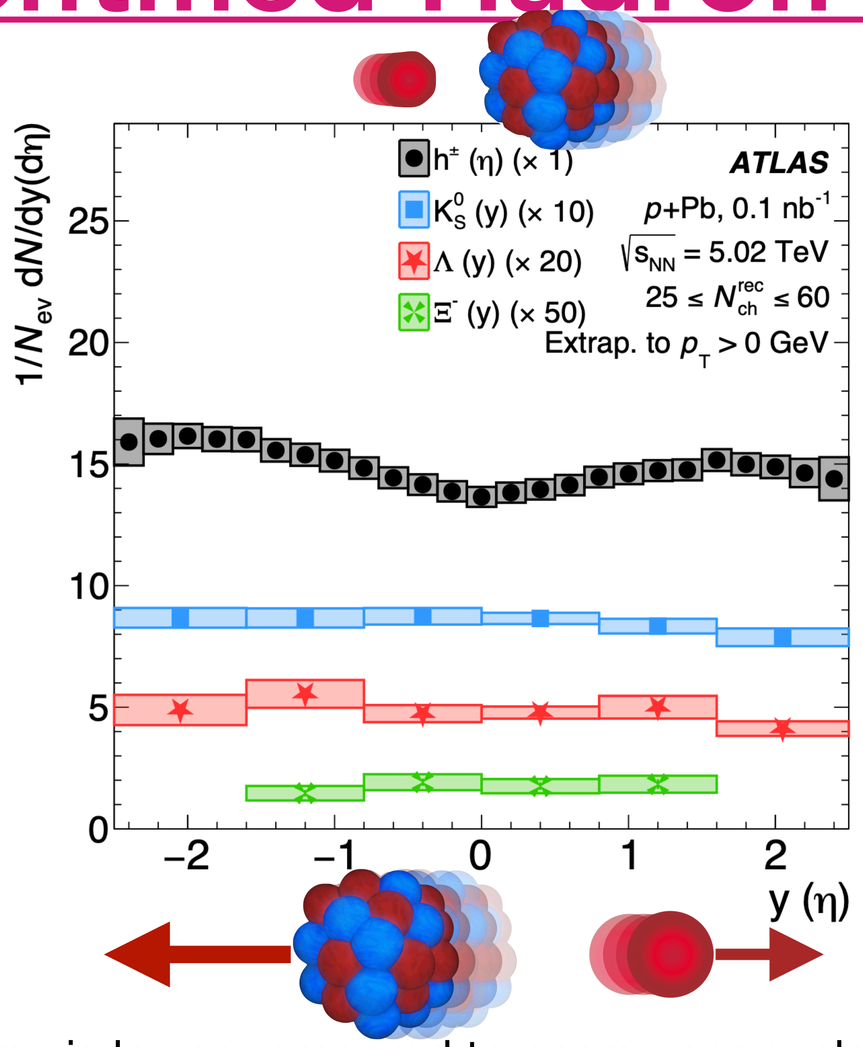
Ξ^-



Results

Charged Hadron & Identified Hadron Yields





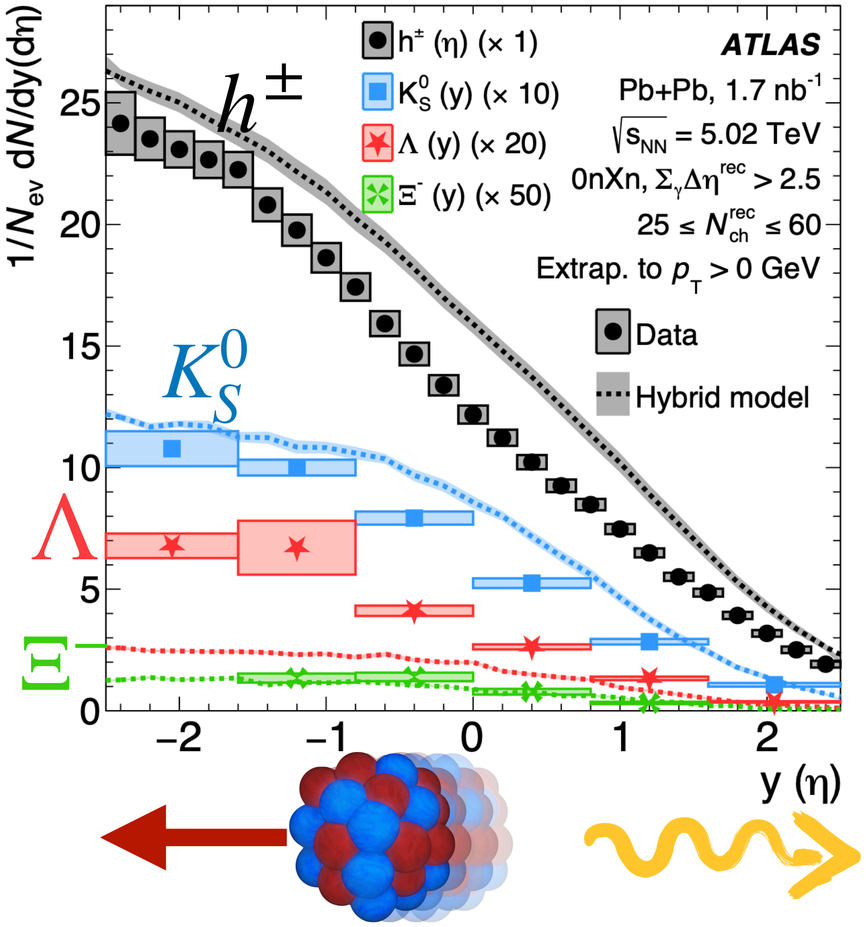
- γ+Pb distribution is highly asymmetric; photon energy is lower compared to energy per nucleon in Pb.

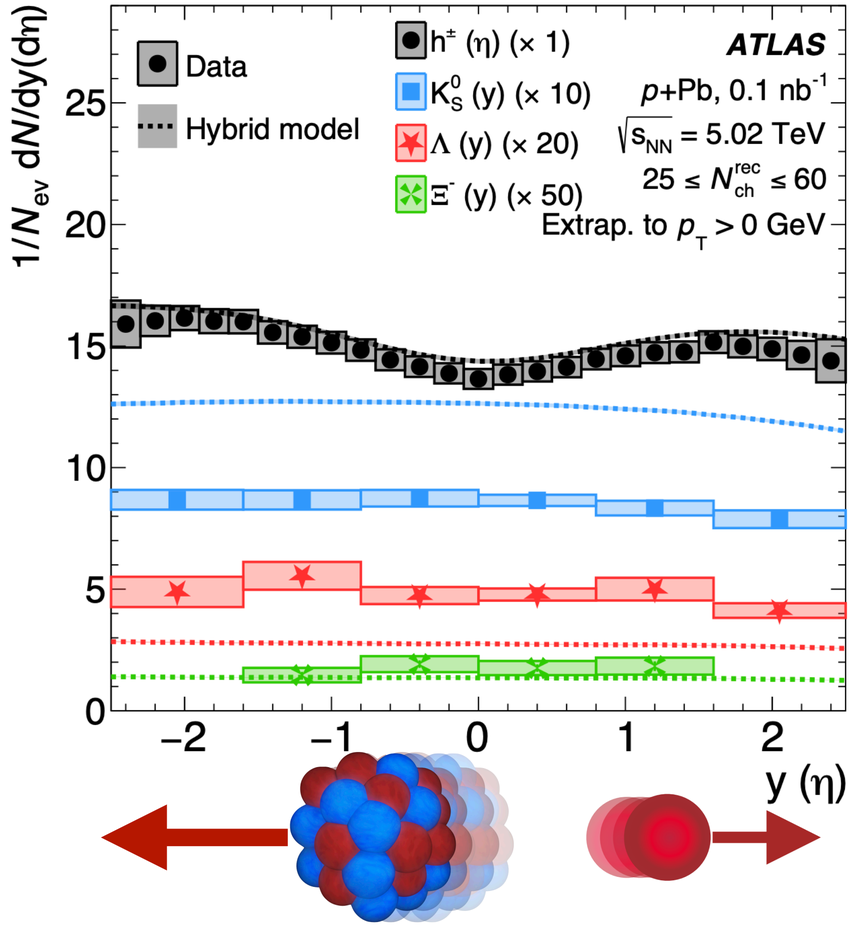
  p+Pb is nearly symmetric for selected low-multiplicity events.

  Given the extreme asymmetry, it is important to study γ+Pb properties in different η regions separately!

Charged Hadron & Identified Hadron Yields

Hybrid model with explicit QGP assumption and hydrodynamic expansion



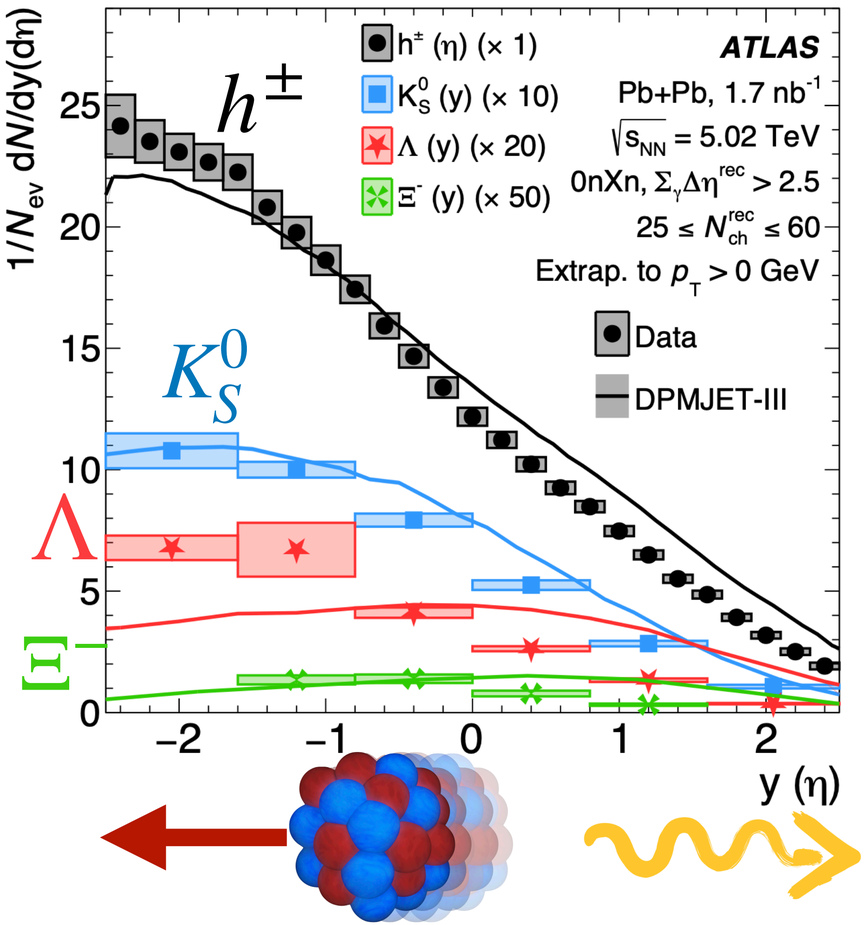


- Charged hadrons are well described in p+Pb, only qualitatively in γ+Pb.
- Over-predicts for K^0_S, under-predicts for Λ, describes Ξ^- well.

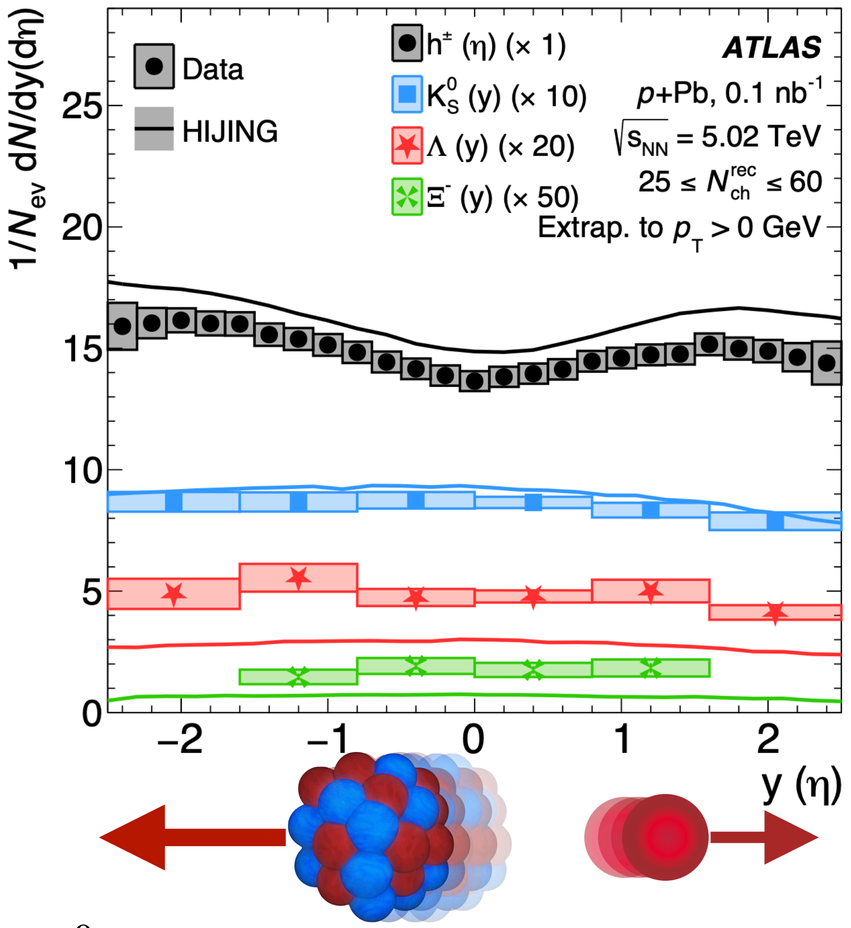
Charged Hadron & Identified Hadron Yields

Models with no QGP assumption

DPMJET-III model



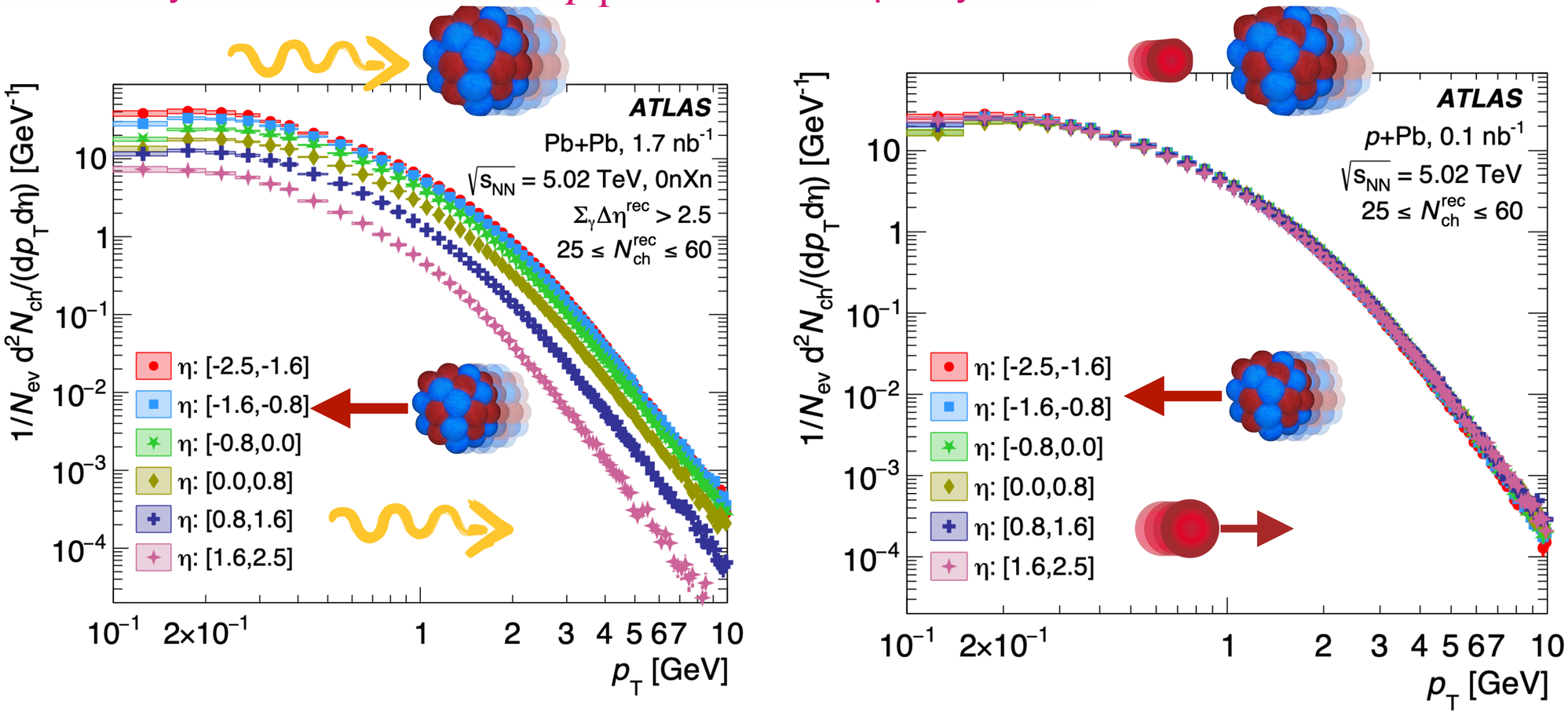
HIJING model



- Both calculations describe charged hadrons and K^0_S, and overall normalization at 15-25% level.
- In contrast, Λ and Ξ^- yields are poorly described: HIJING under-predicts by a factor of 2, DPMJET under-predicts at backward rapidity, over-predicts at forward rapidity.

Charged Hadron & Identified Hadron Yields

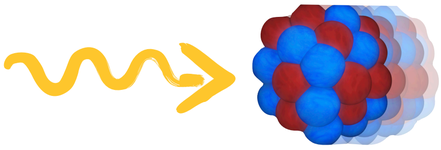
Charged hadron yield as a function of p_{T} in different rapidity slices

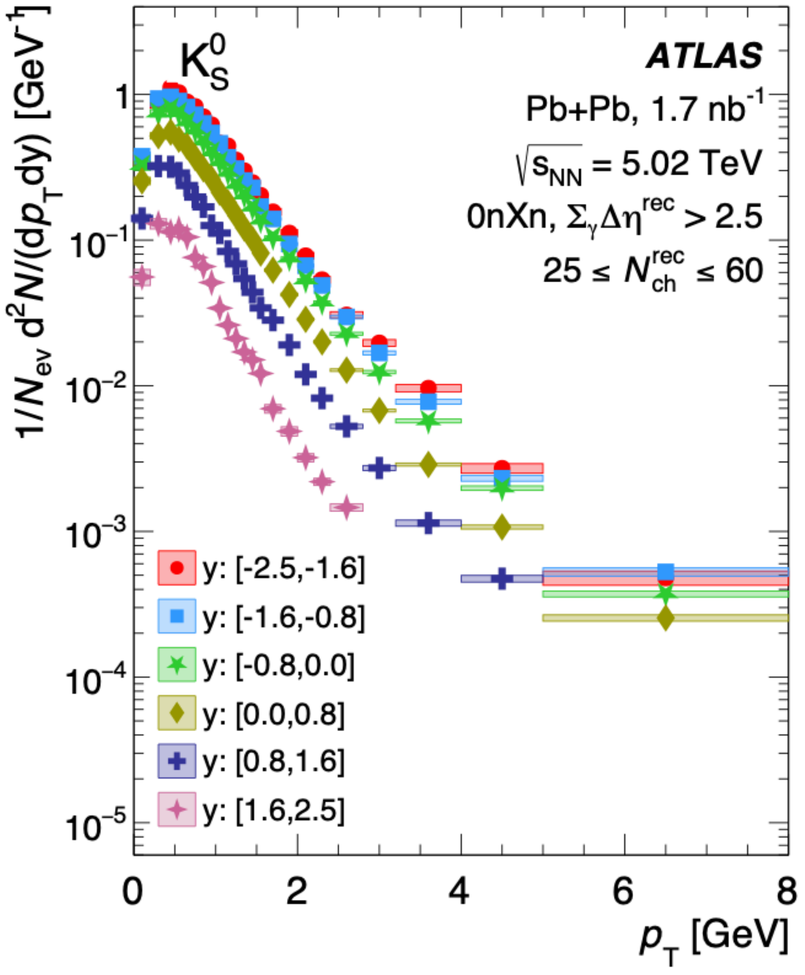


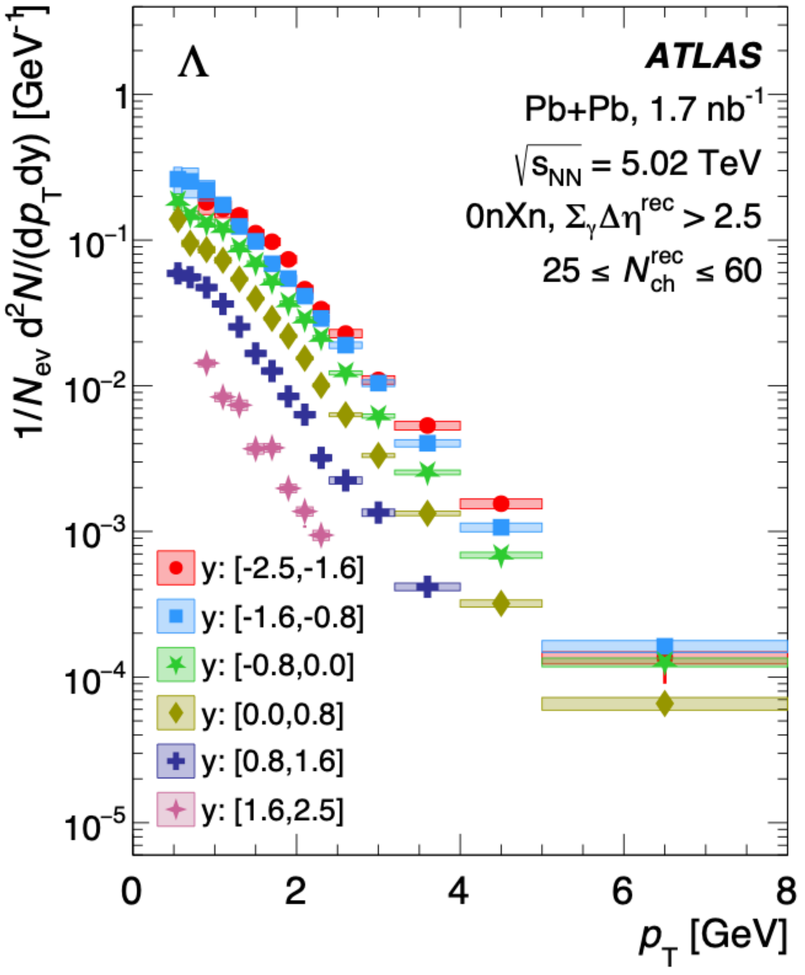
- γ+Pb distribution is highly asymmetric; p+Pb is nearly symmetric for selected low-multiplicity events.

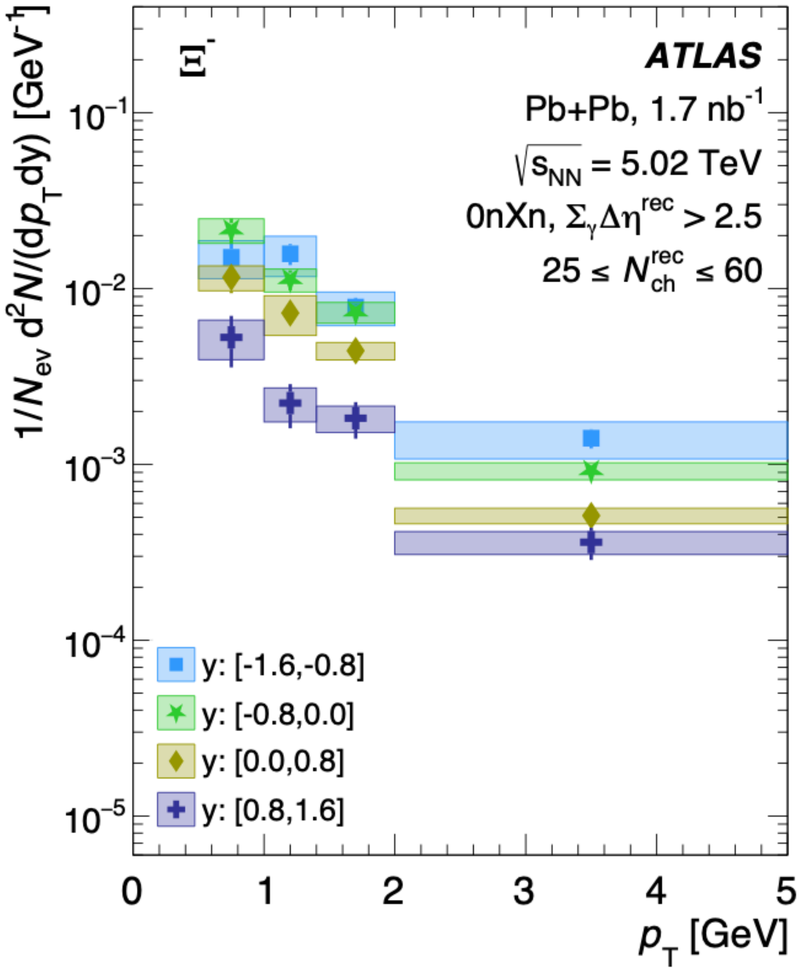
Charged Hadron & Identified Hadron Yields

Identified hadron yield as a function of p_T in different rapidity slices



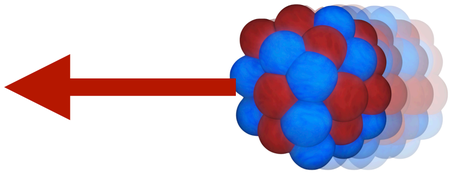




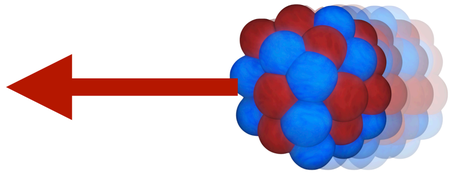


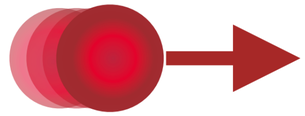
Radial Flow

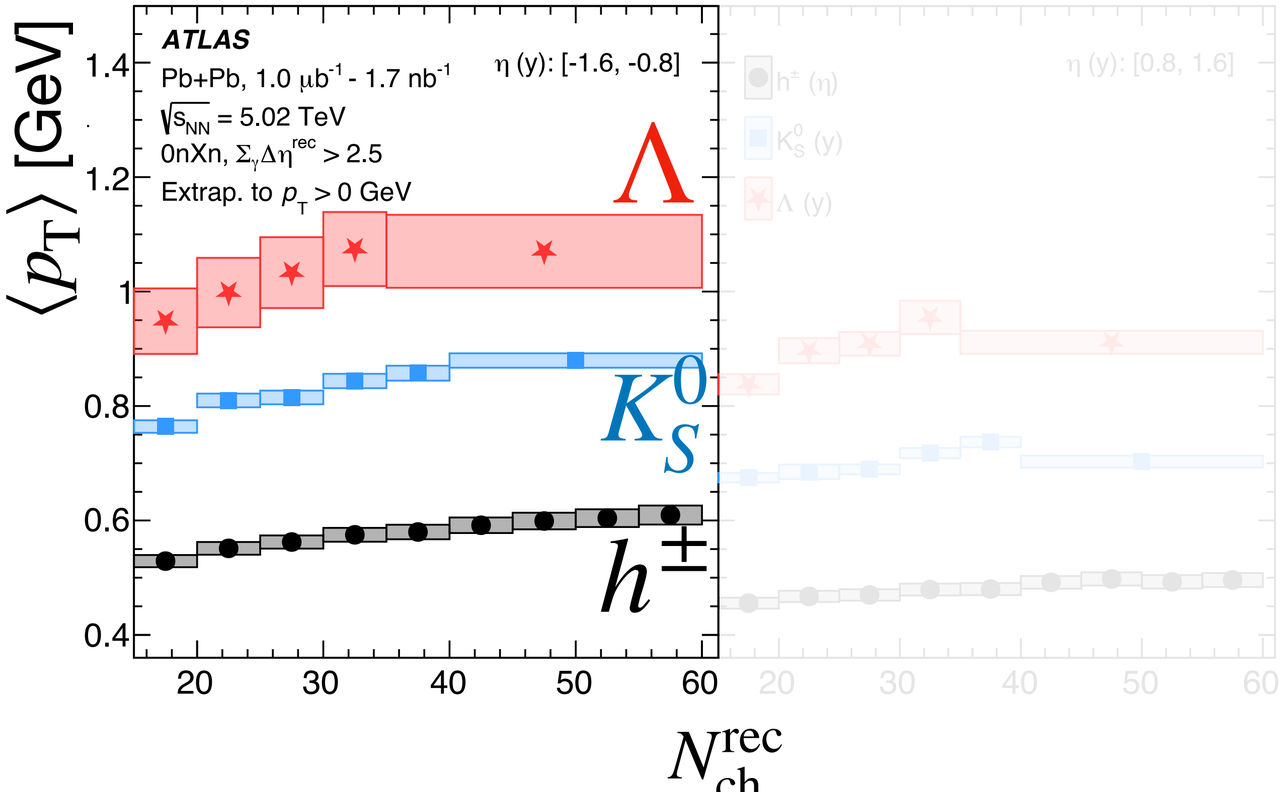
γ+Pb



p+Pb



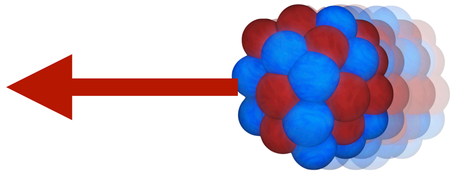




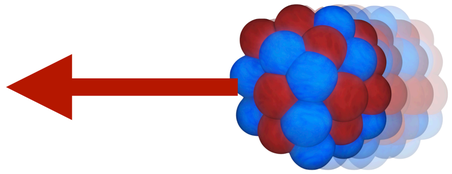
- $\langle p_T \rangle$ follows $\Lambda > K^0_S > h^{\pm}$, and clear multiplicity dependence

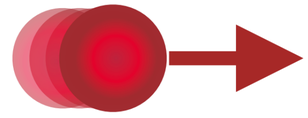
Radial Flow

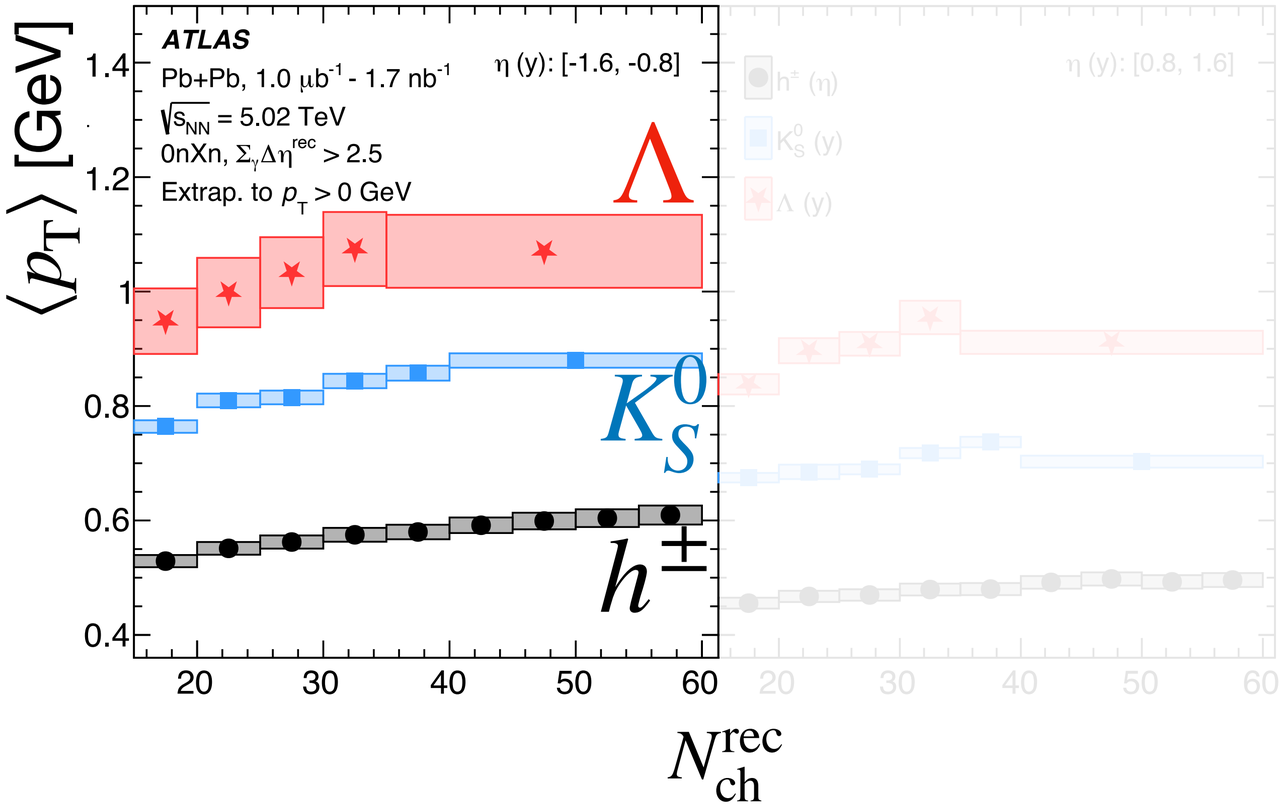
γ+Pb

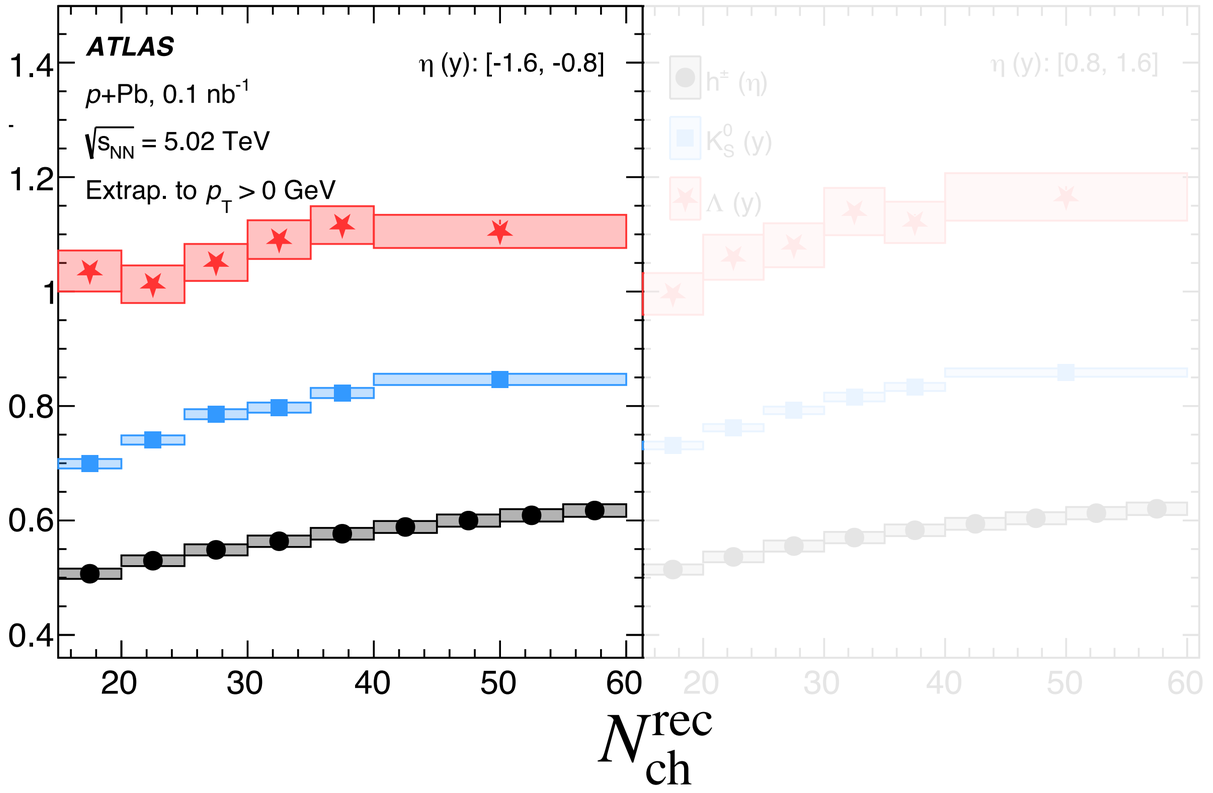


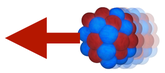
p+Pb





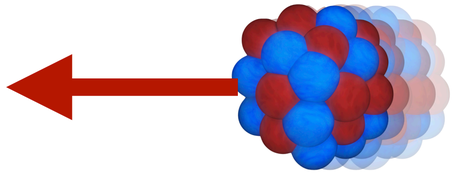




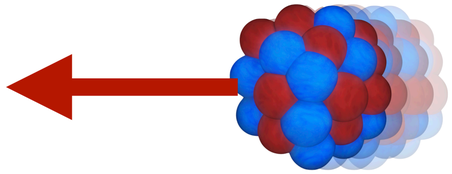
- In the Pb-going direction () similar amount of $\langle p_T \rangle$ between γ+Pb and p+Pb is observed.

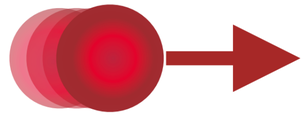
Radial Flow

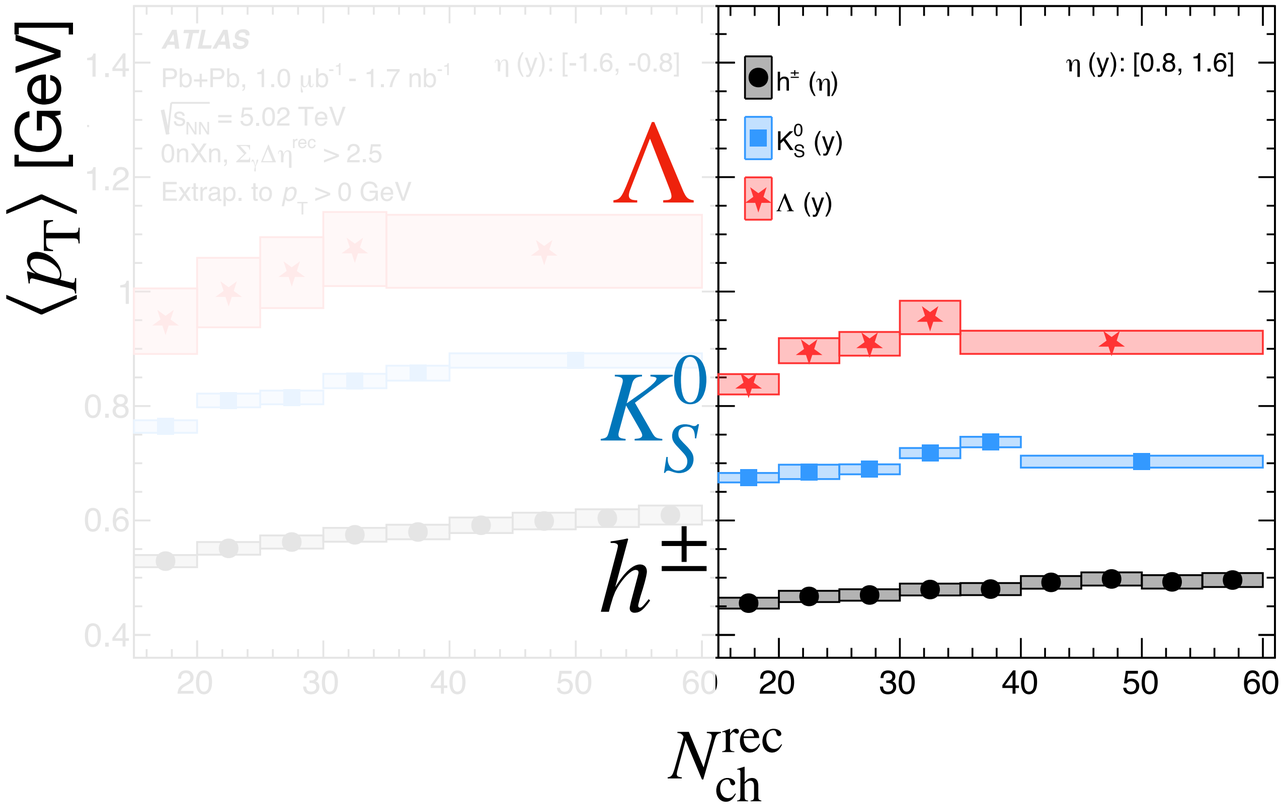
γ+Pb

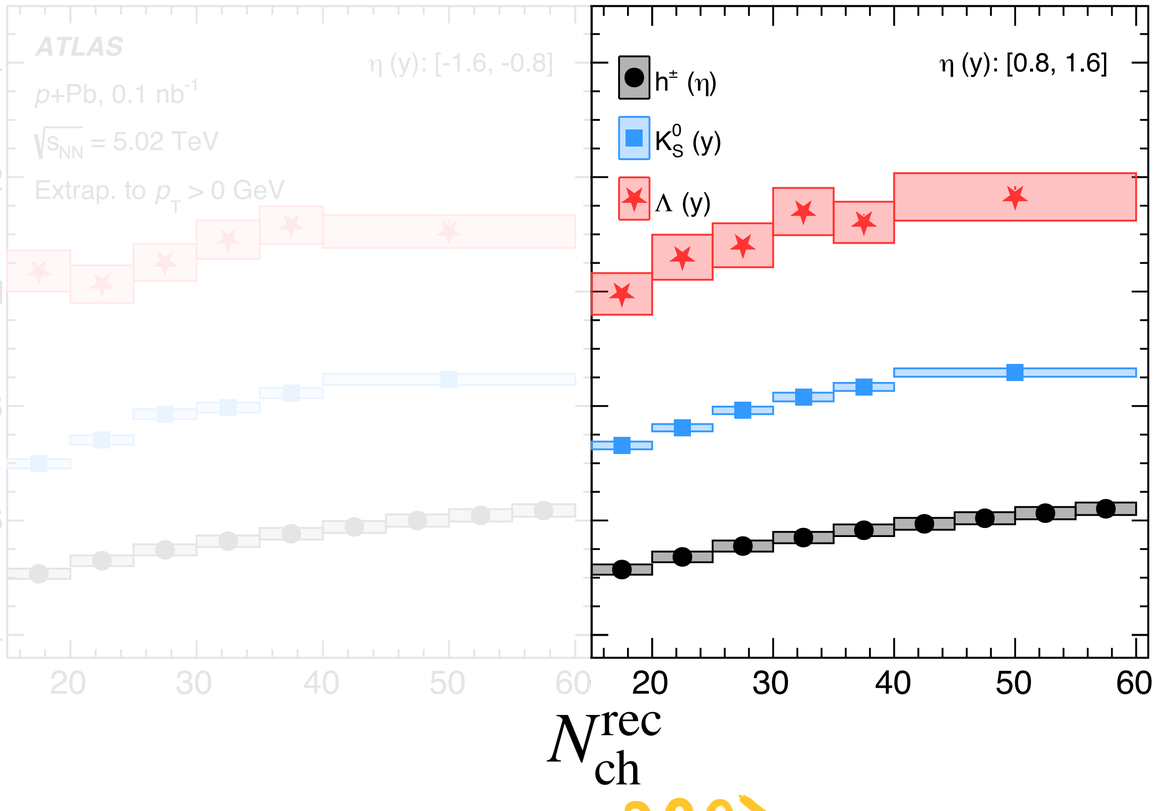


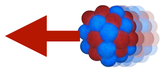
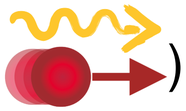
p+Pb









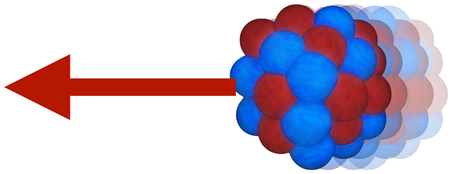
- In the Pb-going direction () similar amount of $\langle p_T \rangle$ between γ+Pb and p+Pb is observed.
- In the γ/p-going direction () lower amount of $\langle p_T \rangle$ is observed in γ+Pb compared to p+Pb.

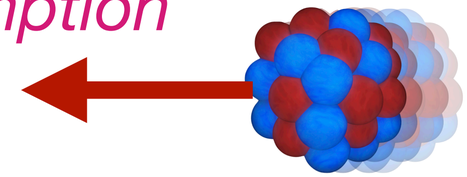
Radial Flow

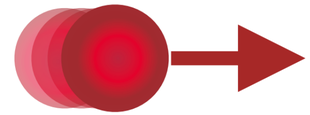
γ+Pb

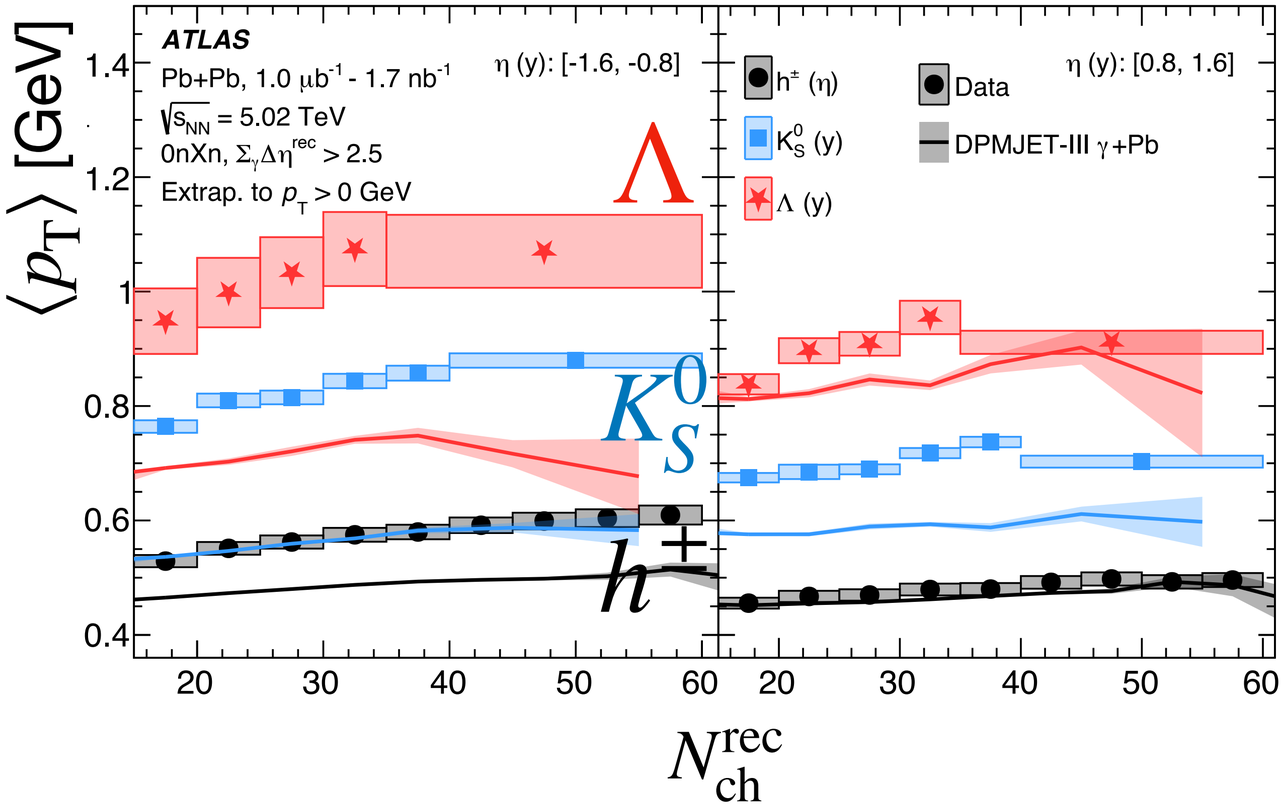
Models with no QGP assumption

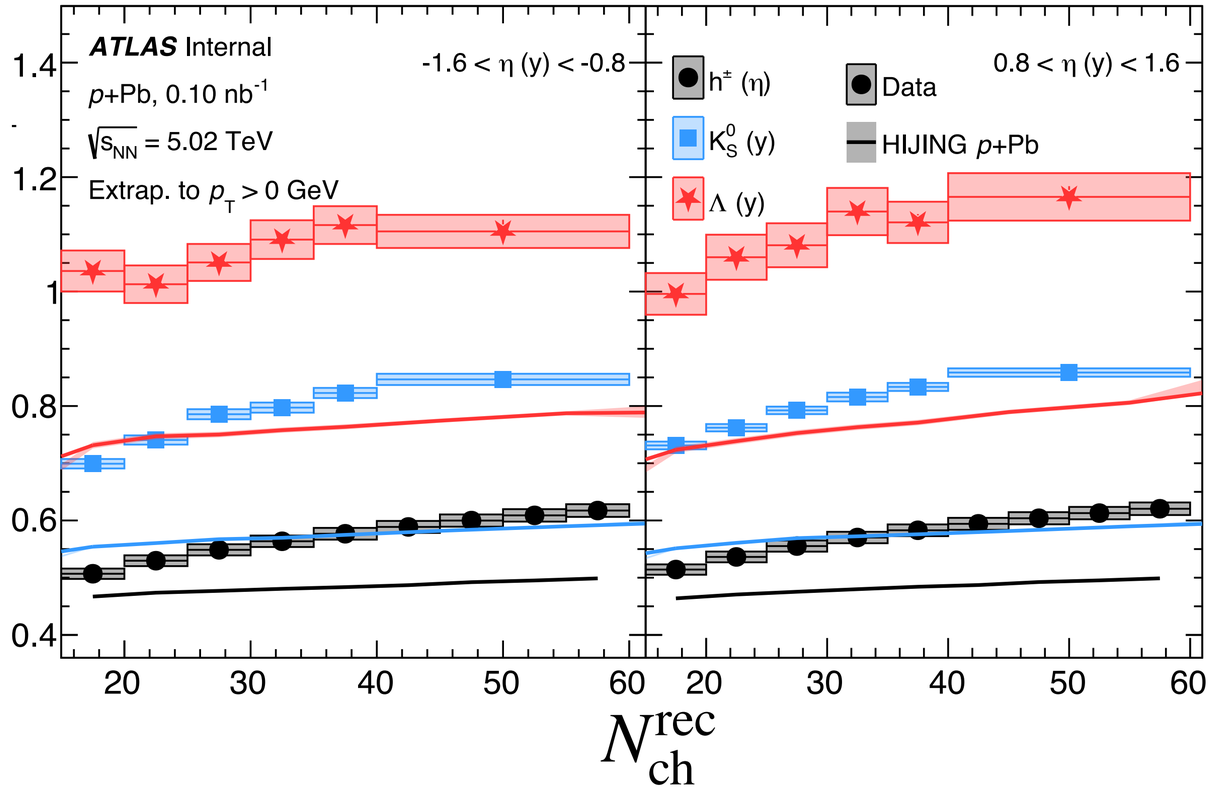
p+Pb











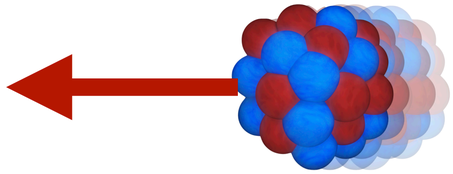
- Both DPMJET and HIJING models substantially under-predict the $\langle p_T \rangle$ of all particles
- Both models under-predict the difference in $\langle p_T \rangle$ between hadrons of difference masses.

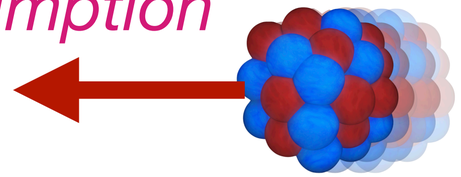
Radial Flow

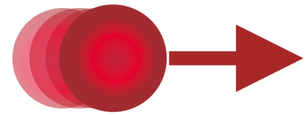
γ+Pb

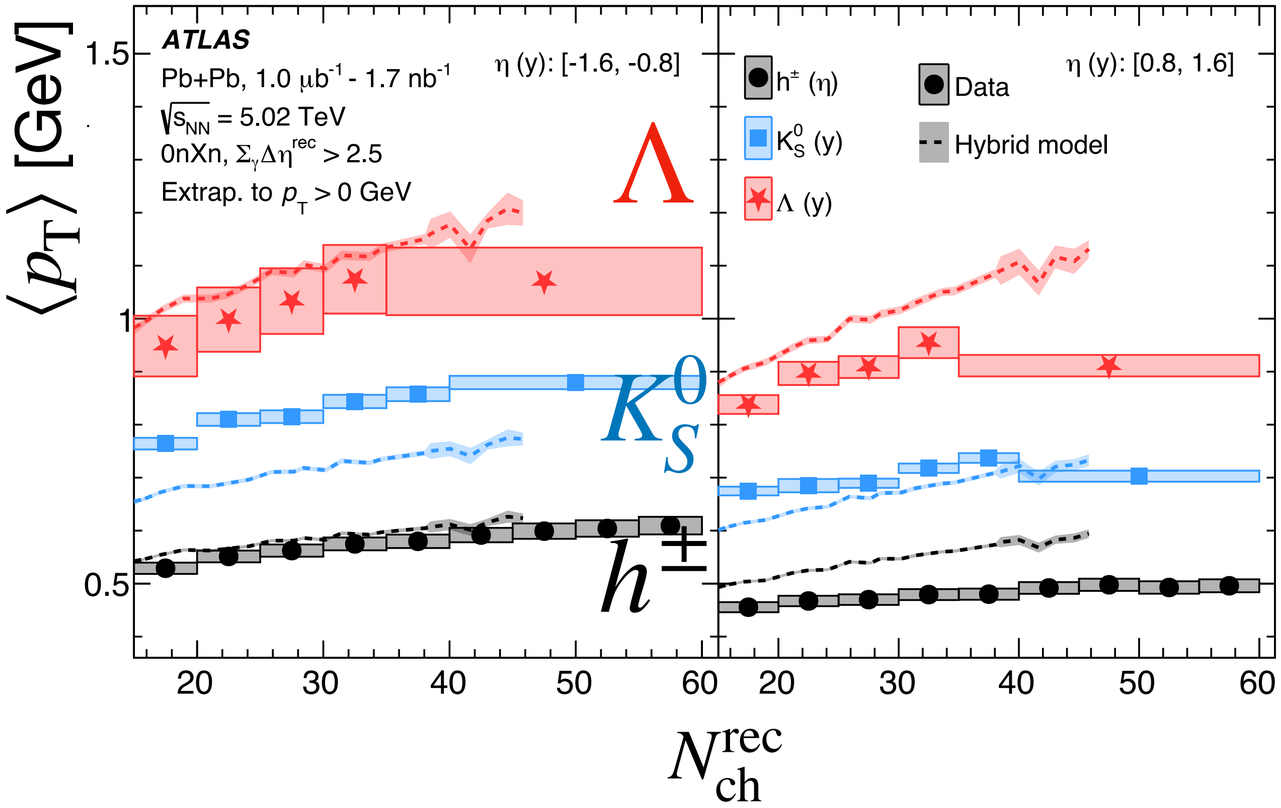
Hydrodynamic model with QGP assumption

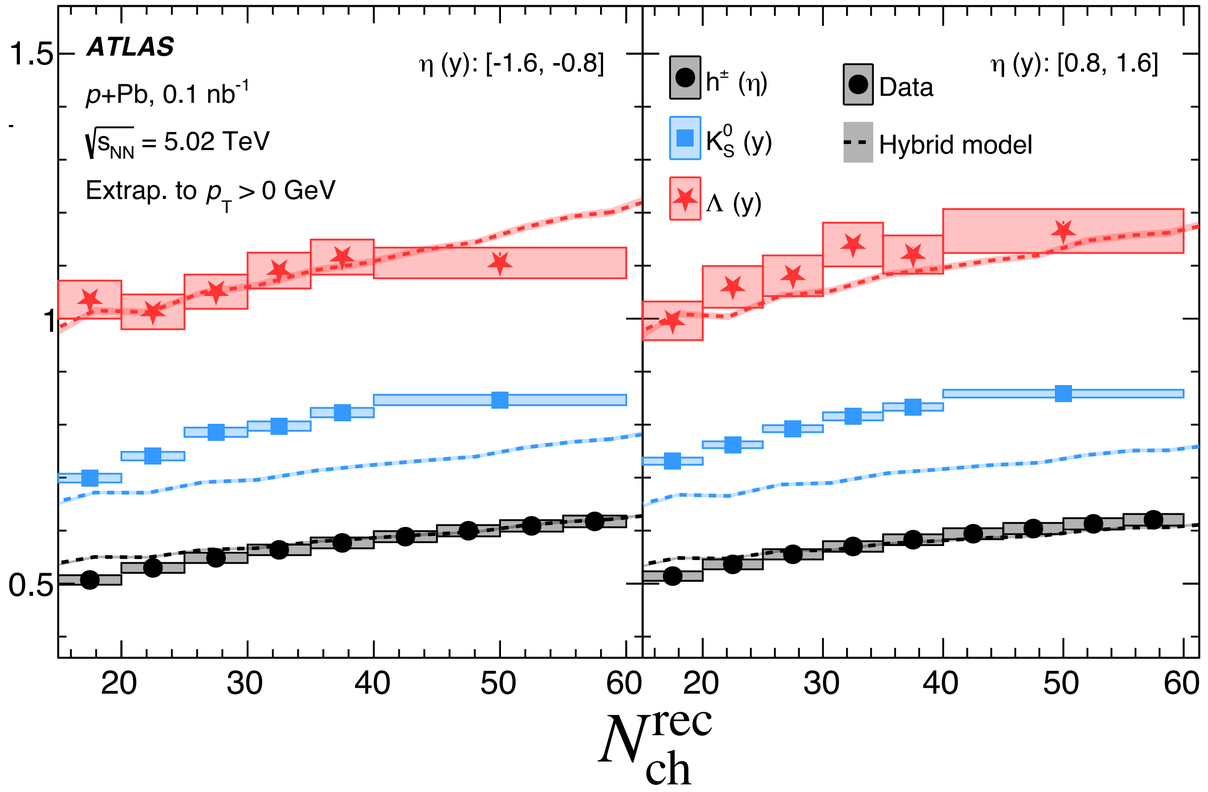
p+Pb











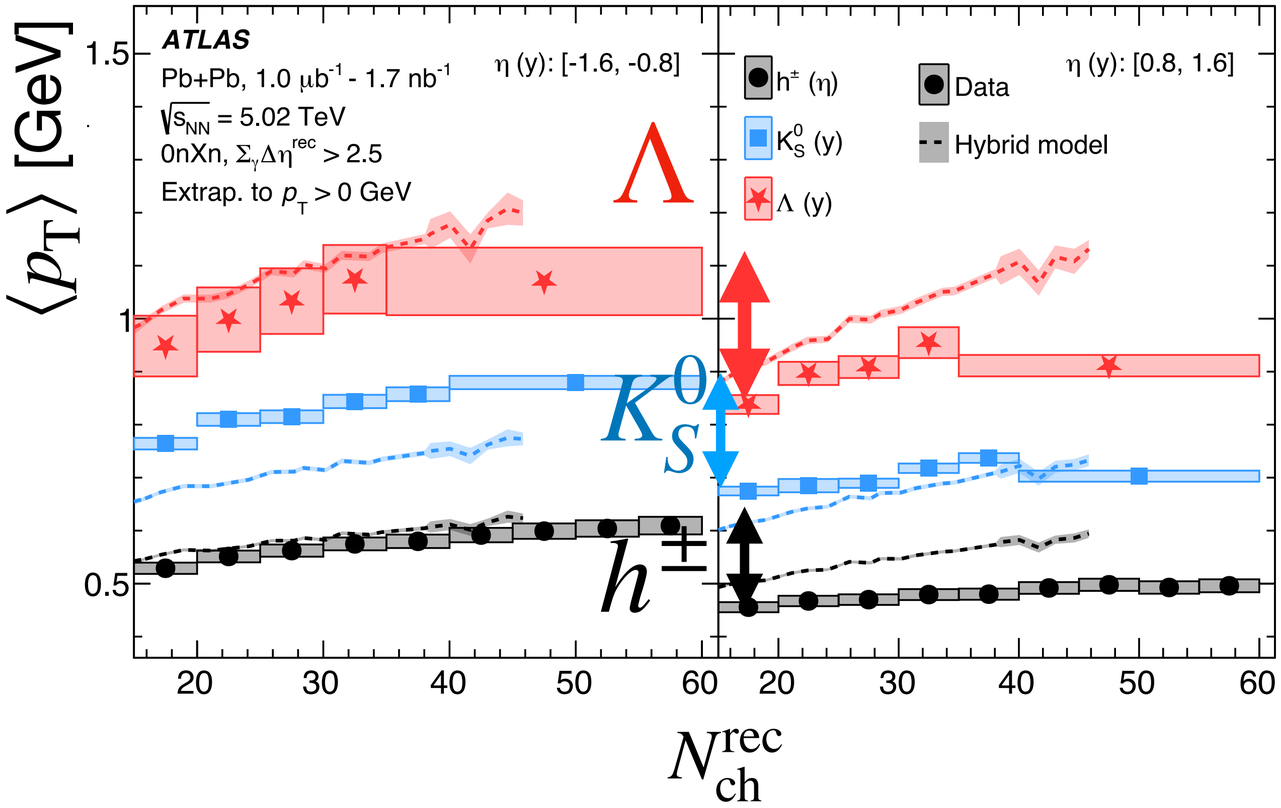
- Hydro model provides a reasonable description of $\langle p_T \rangle$ in both γ+Pb and p+Pb.
- However, K^0_S is under-predicted always. Stronger conclusions about QGP formations remains premature.

Radial Flow

γ+Pb

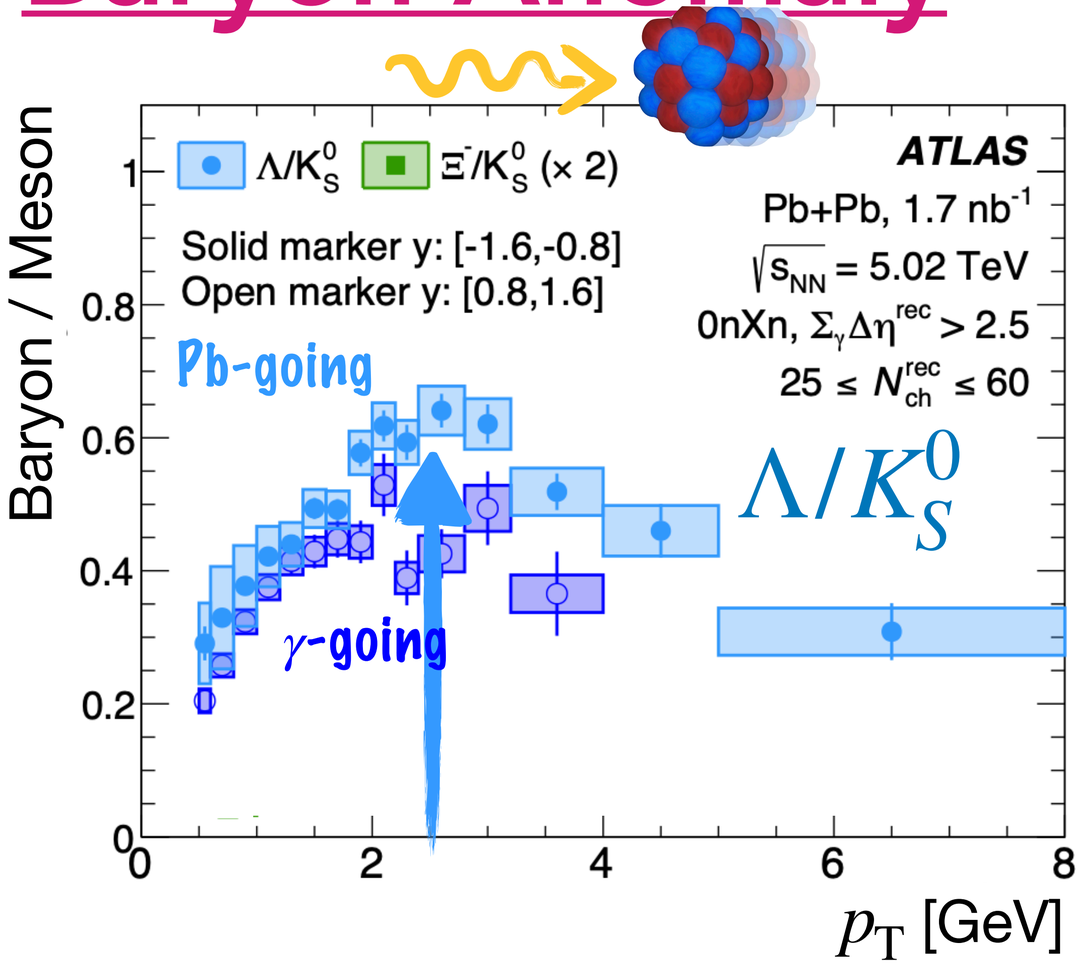
Hydrodynamic model with QGP assumption

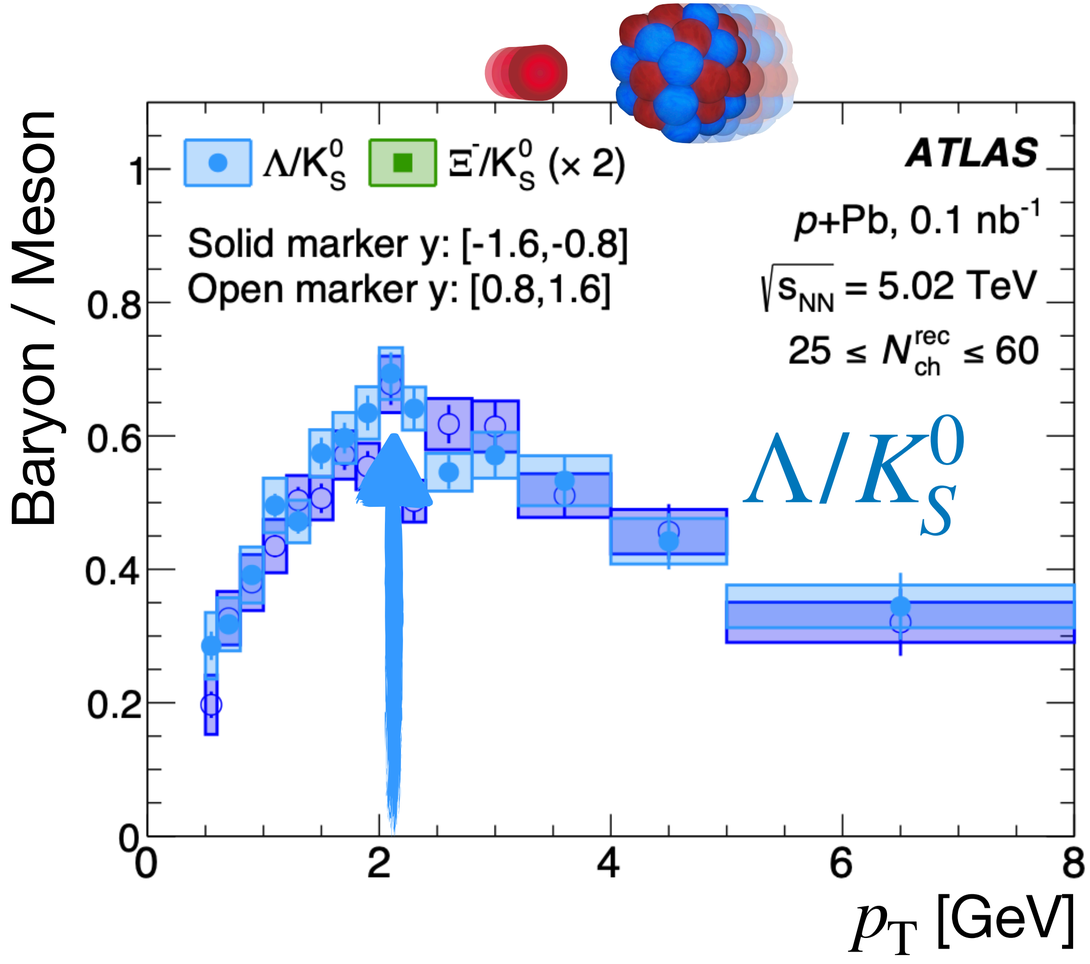
p+Pb



◉ Strong rapidity dependence for γ+Pb: $\langle p_T \rangle$ **Pb-going** > $\langle p_T \rangle$ **γ-going**

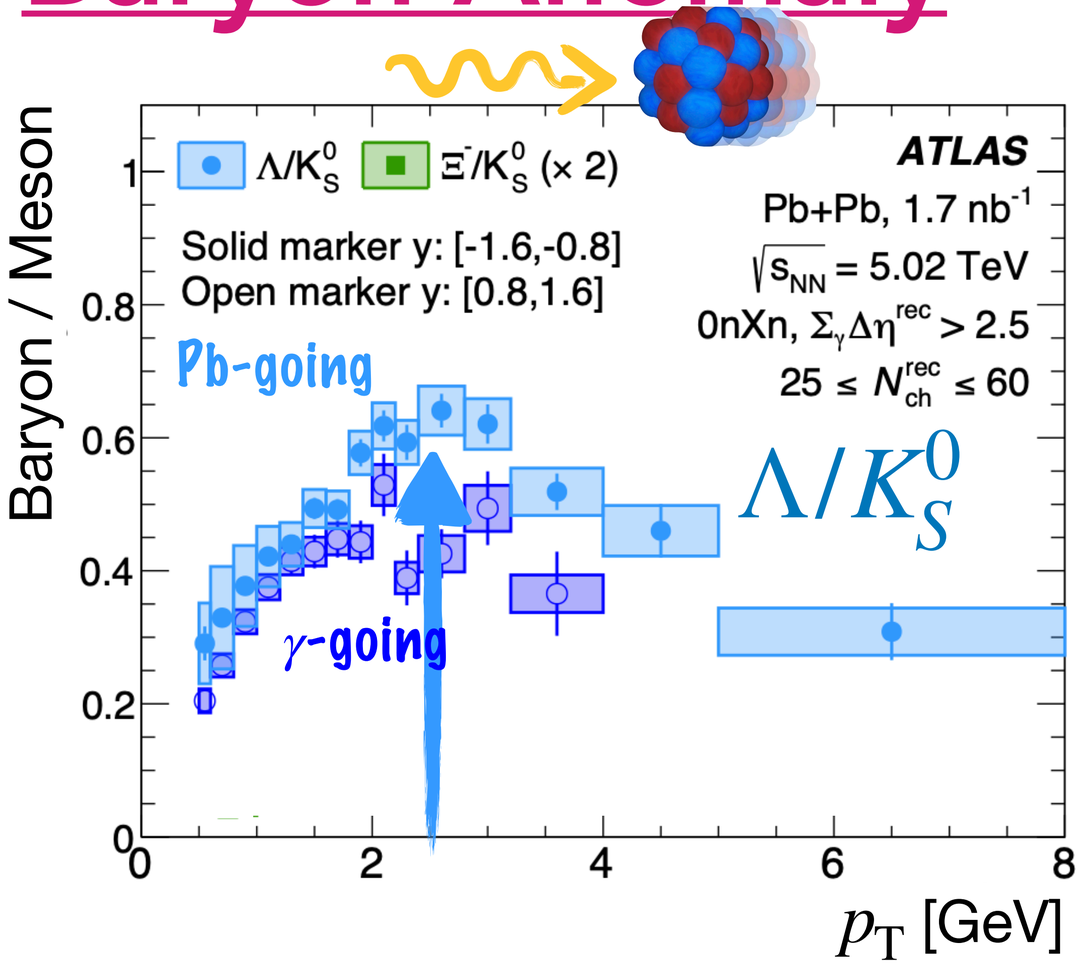
Baryon Anomaly

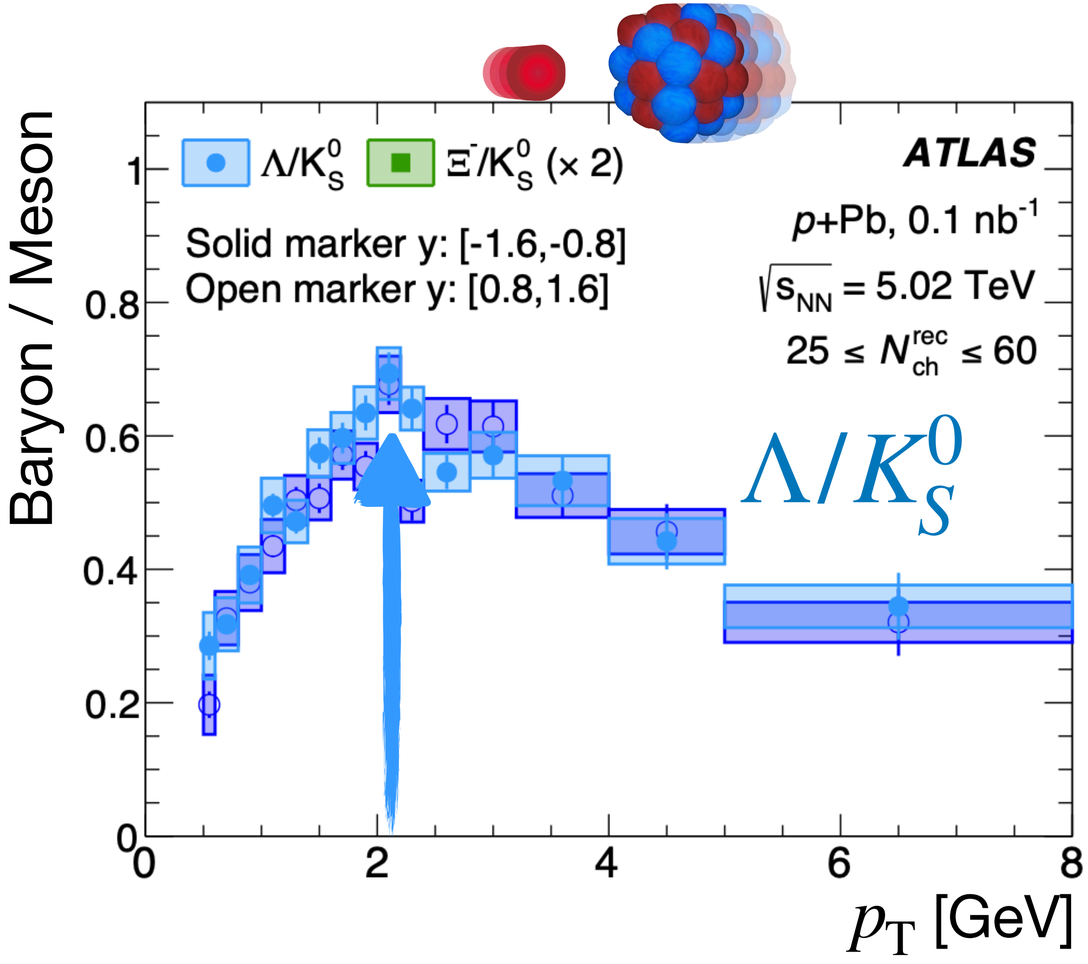




- Enhanced ratio at the intermediate p_T

Baryon Anomaly



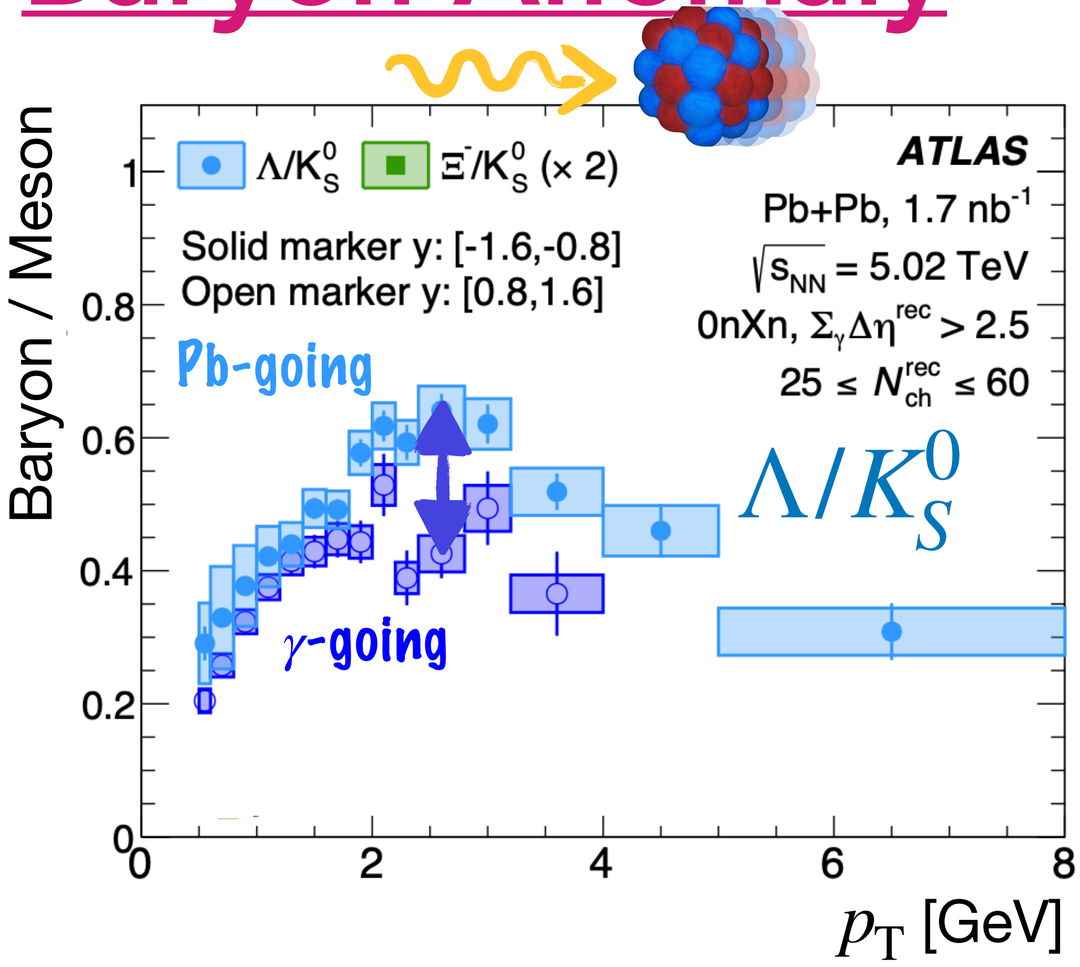


- Enhanced ratio at the intermediate p_T

◉ In the Pb-going direction ( ) similar amount of Λ/K^0_S between γ+Pb and p+Pb is observed.

◉ In the γ/p-going direction ( ) lower amount of Λ/K^0_S is observed in γ+Pb compared to p+Pb.

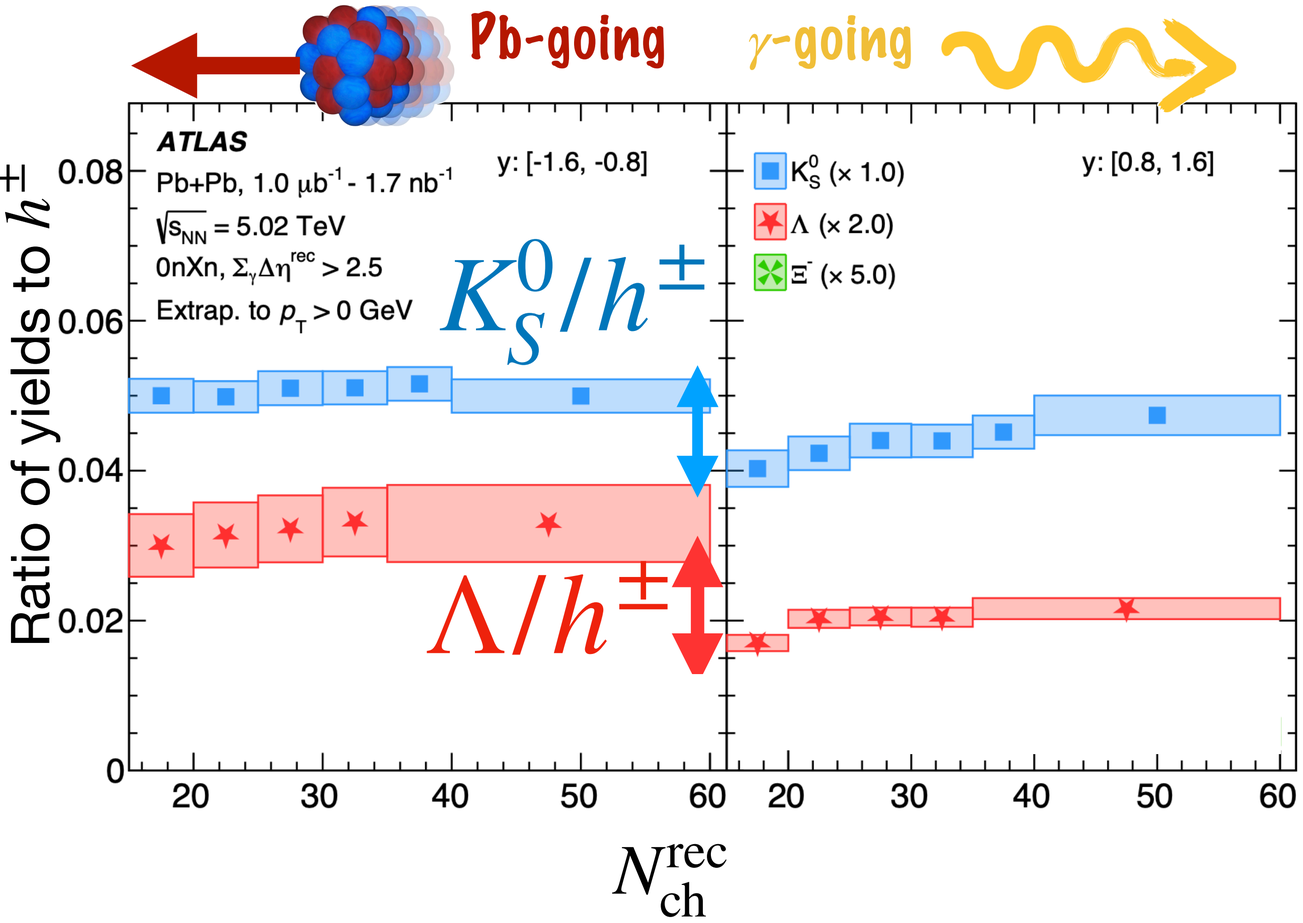
Baryon Anomaly



- Λ/K^0_S **Pb-going > γ-going**

Strong rapidity dependence !

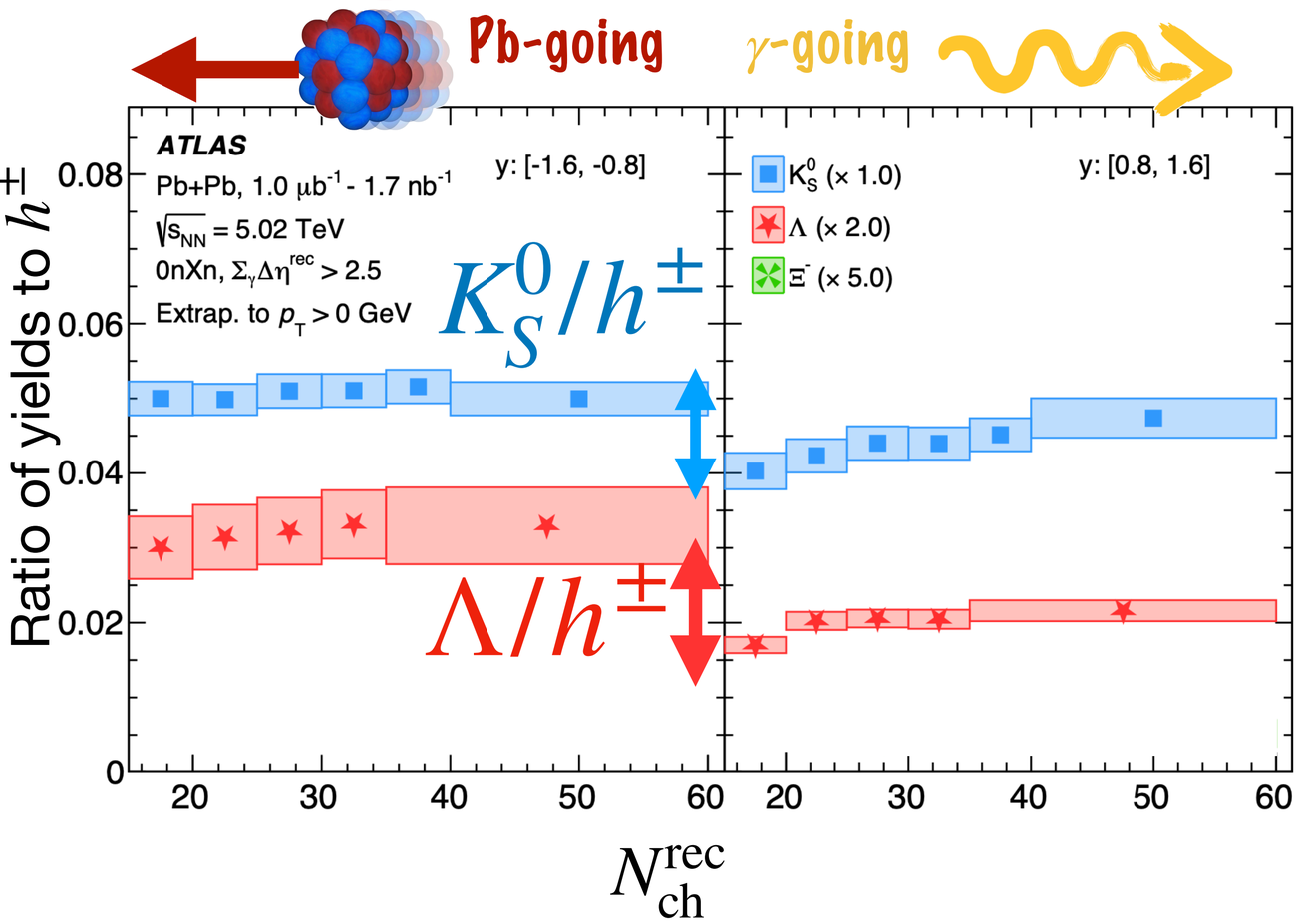
Strangeness Enhancement

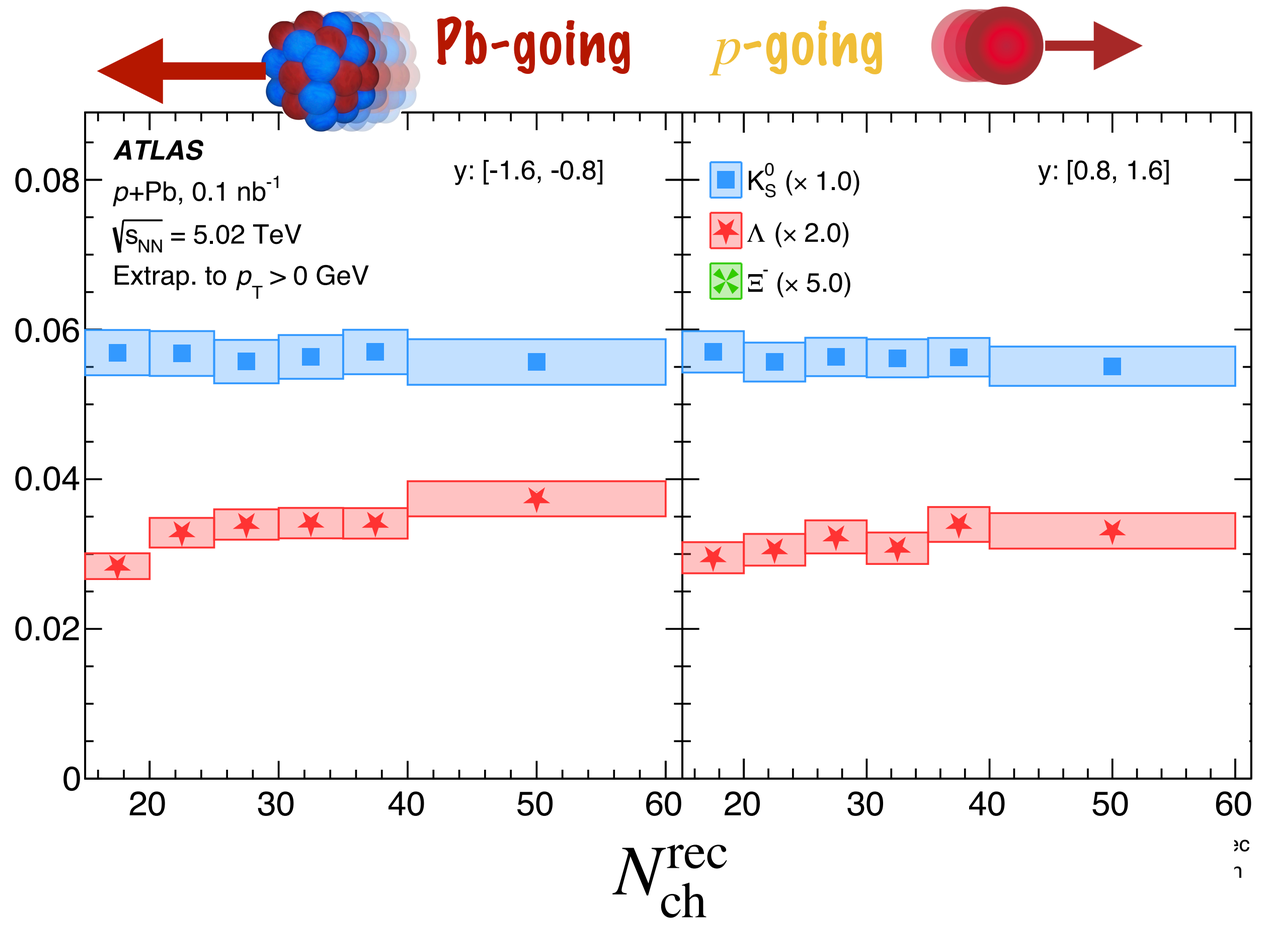


- $K^0_S/h^{\pm}$, $\Lambda/h^{\pm}$ **Pb-going > γ-going**

Strong rapidity dependence !

Strangeness Enhancement





- $K^0_S/h^{\pm}$, $\Lambda/h^{\pm}$ **Pb-going >** γ**-going**

Strong rapidity dependence !

◉ In the Pb-going direction ( ) similar amount of Λ/K^0_S between γ+Pb and p+Pb is observed.

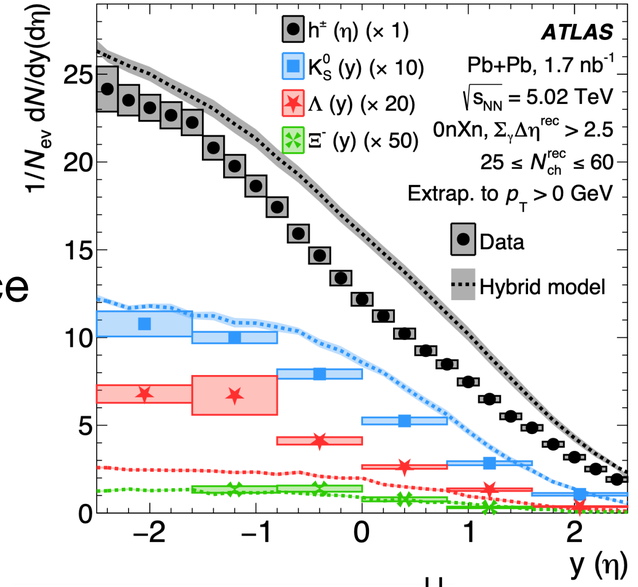
Conclusions

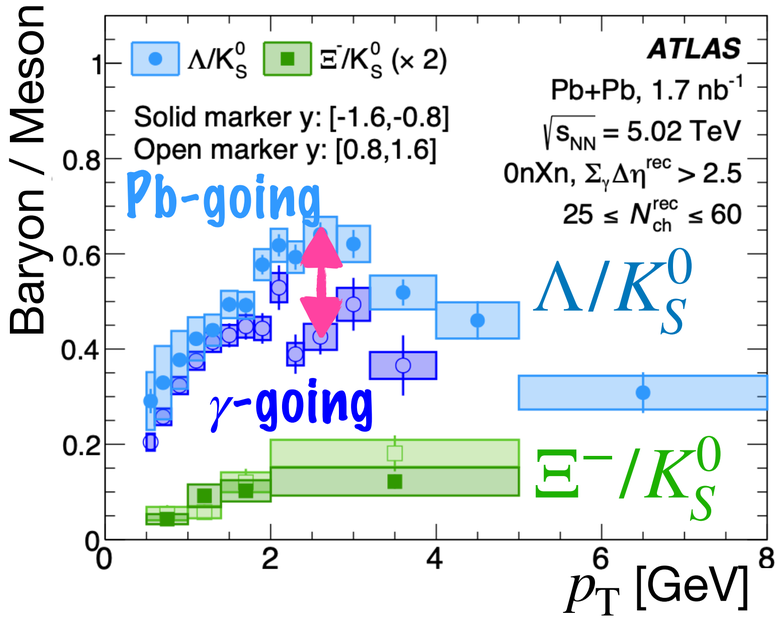
arXiv: 2503.08181 [nucl-ex]

- **First measurement** of strange hadron yields in photonuclear collisions

- γ+Pb events exhibit strong rapidity dependence in QGP-like signatures

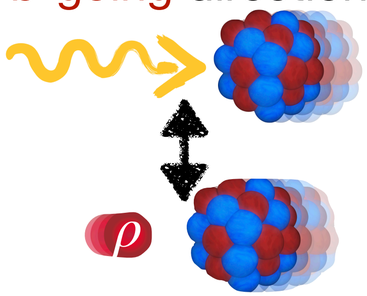
  $\langle p_T \rangle$, Λ/K^0_S **ratio,**
  strange hadrons/charged hadrons ratio
  Pb-going > γ-going



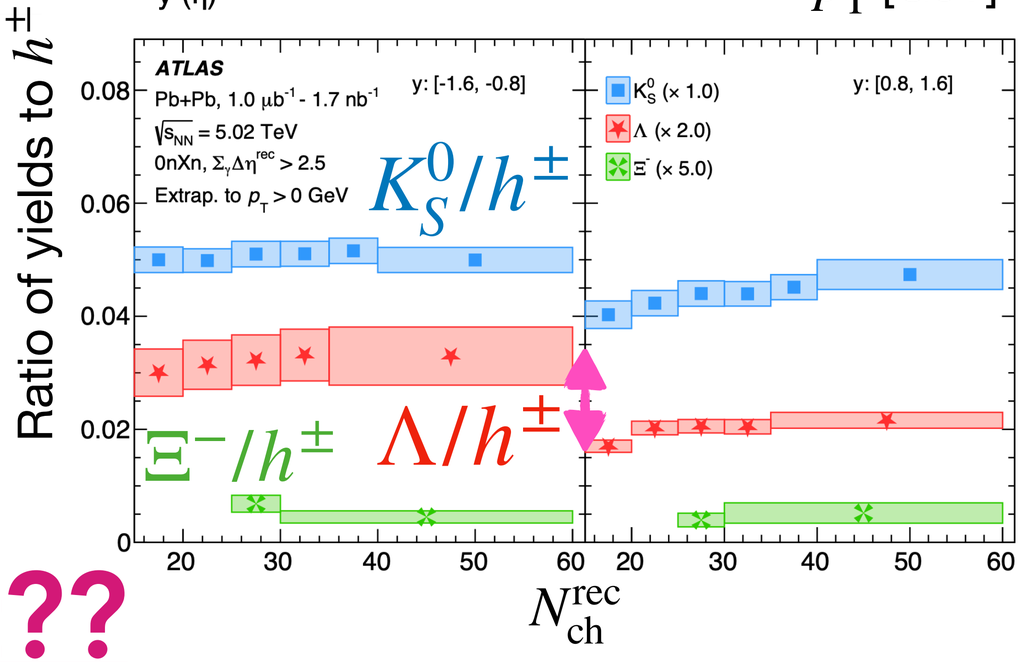


- Similar magnitude of QGP-like signals in Pb-going direction between γ+Pb and p+Pb

  γ+Pb collisions are dominated by vector meson dominance



- Stronger statements about QGP formation require more accurate theoretical comparisons.

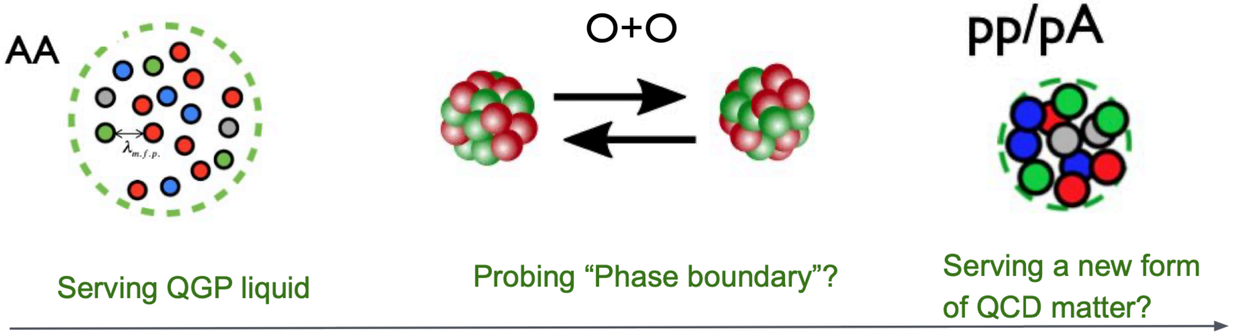


What's next??

Future Directions

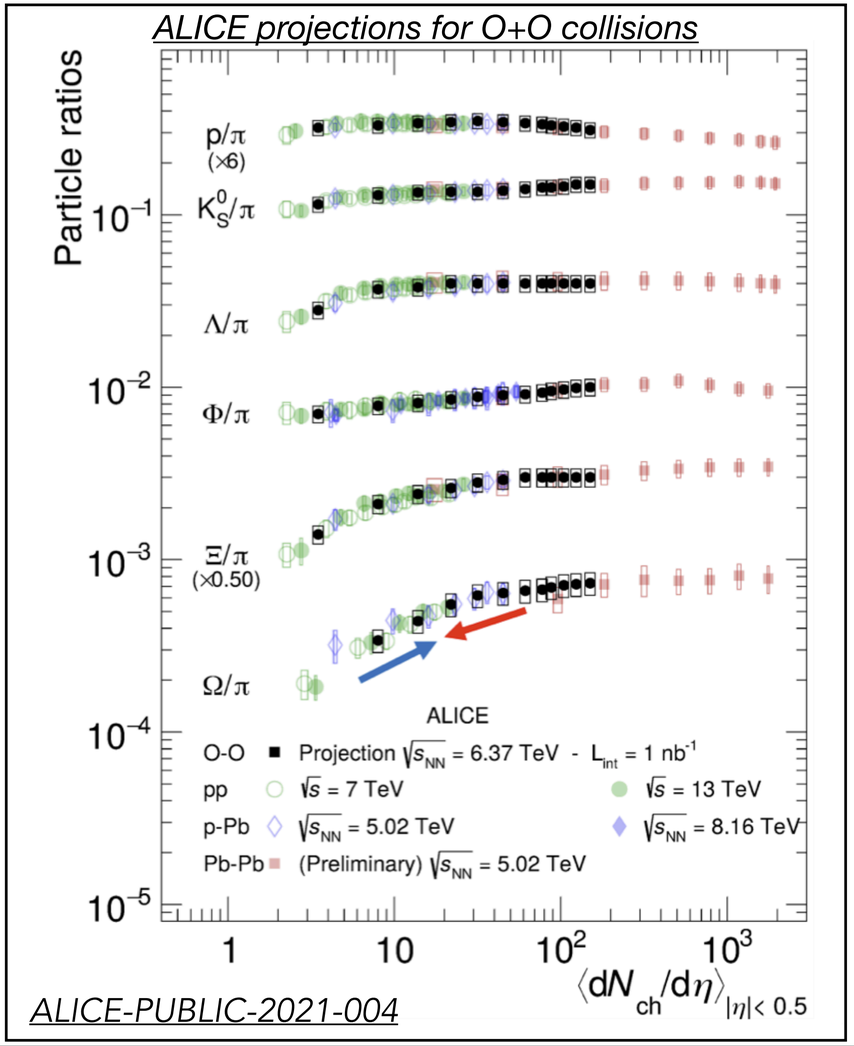
2025 → 2030 → 2035+

Upcoming O+O collisions at LHC



Broad range of multiplicity from pp to Pb+Pb covered by O+O

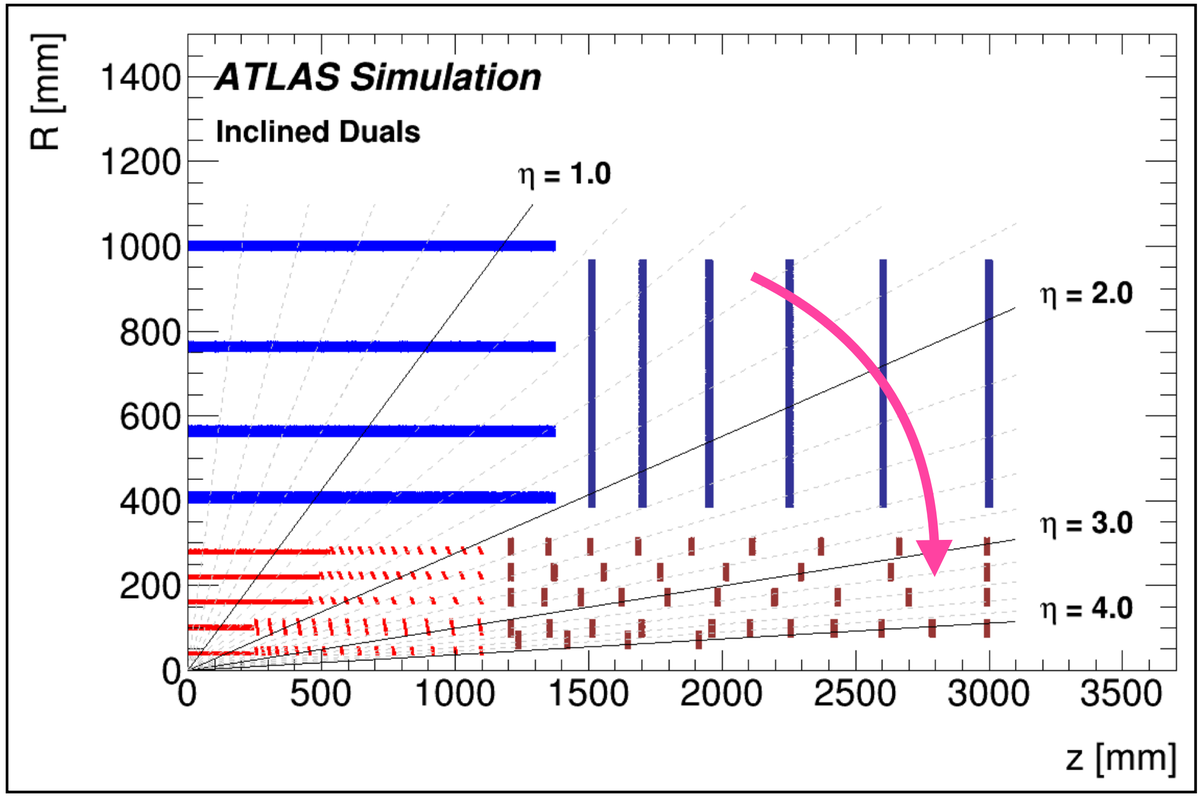
Wonderful opportunity to understand small systems !



Future Directions

2025 → 2030 → 2035+

LHC ATLAS/CMS Run4, major tracking upgrades: $|\eta| < 4.0$



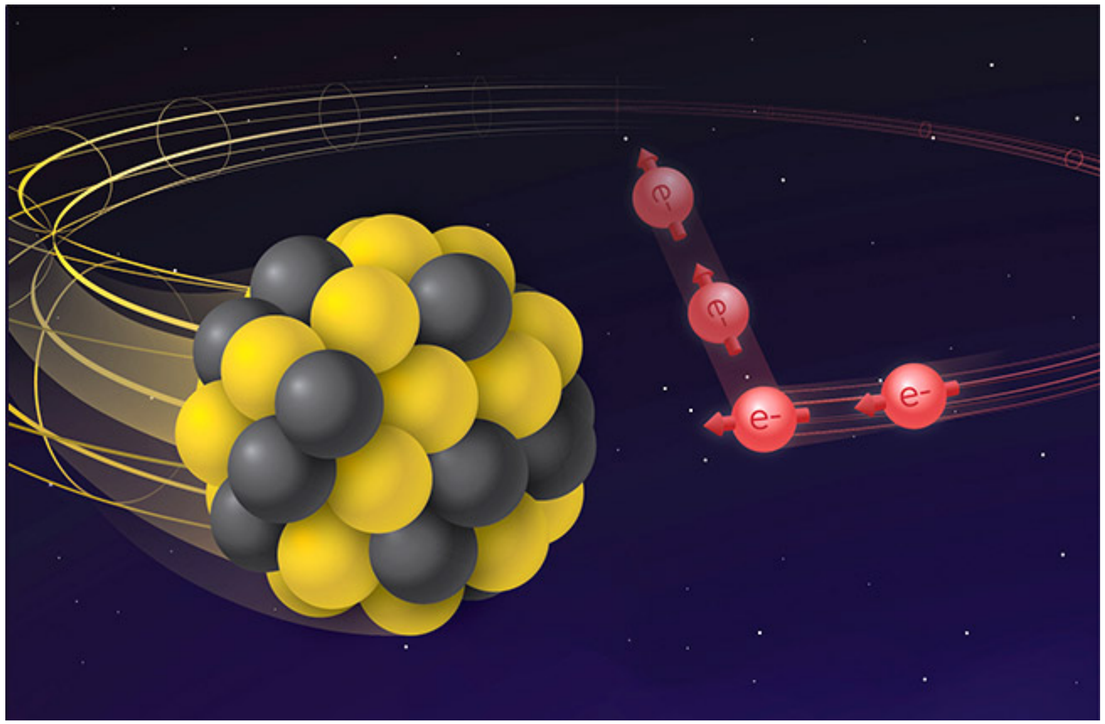
Extend UPC measurements to forward rapidity!

Future Directions

EIC: Future home at BNL

2025 2030 2035+

Electron-Ion Collider physics has close connections to UPC physics,
allows precise measurement of the energy and virtuality of the colliding photon!



Small systems test the limit of QGP formation.

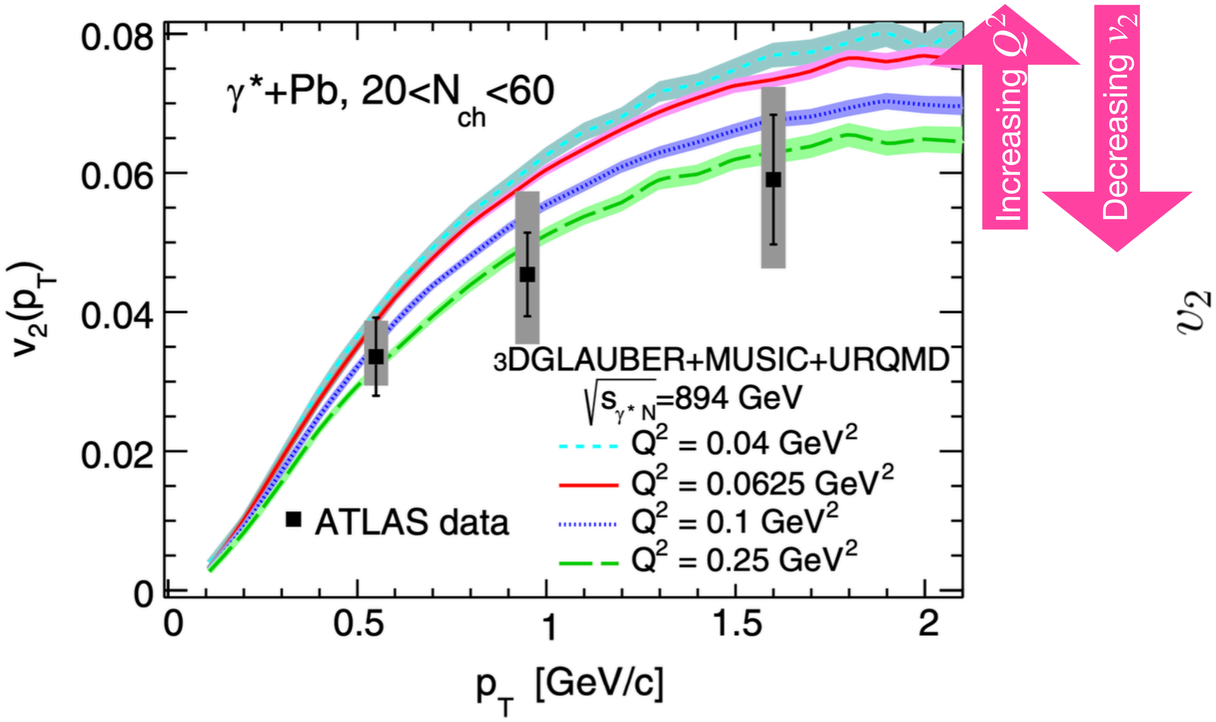
At EIC, one can use the photon virtuality as a dial to change the system size!

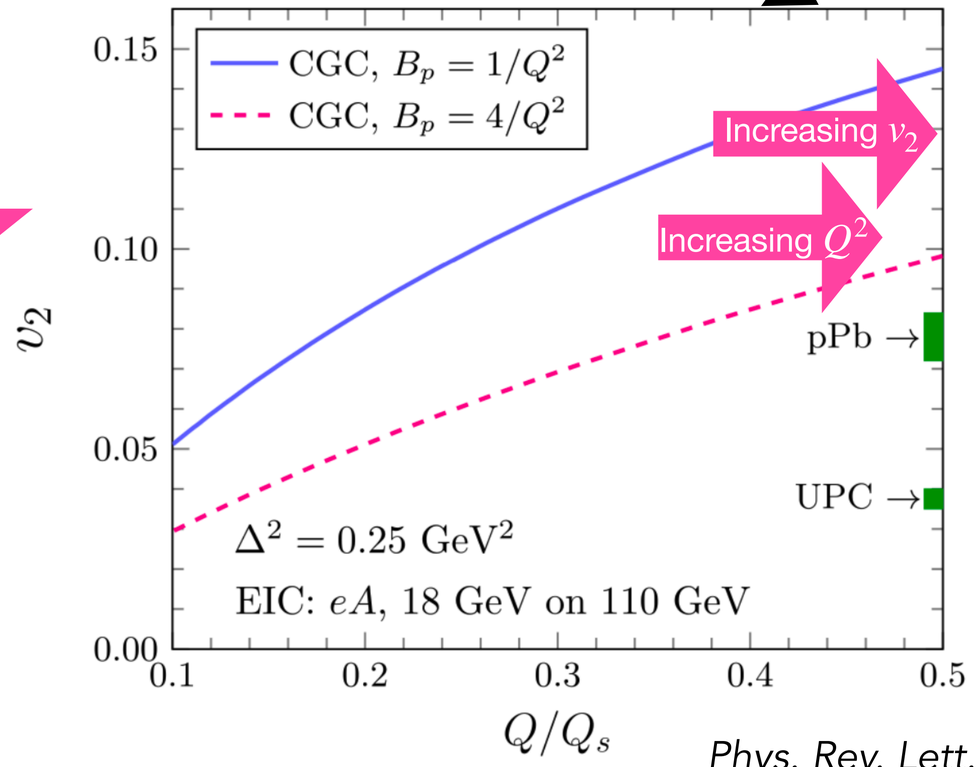
Future Directions

EIC: Future home at BNL

2025 2030 2035+

Predictions by hydrodynamic model and CGC, in opposite directions





Phys. Rev. Lett. 129, 252302

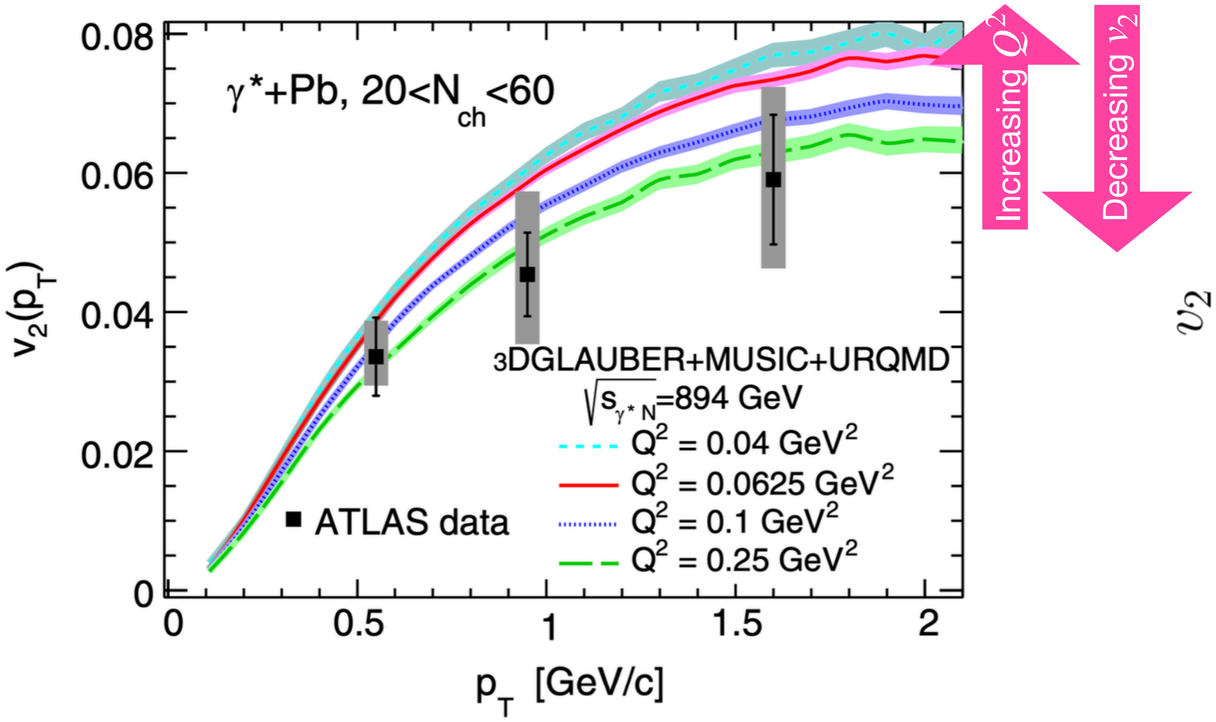
EIC can be a “tie-breaker” between the initial-state and final-state models!

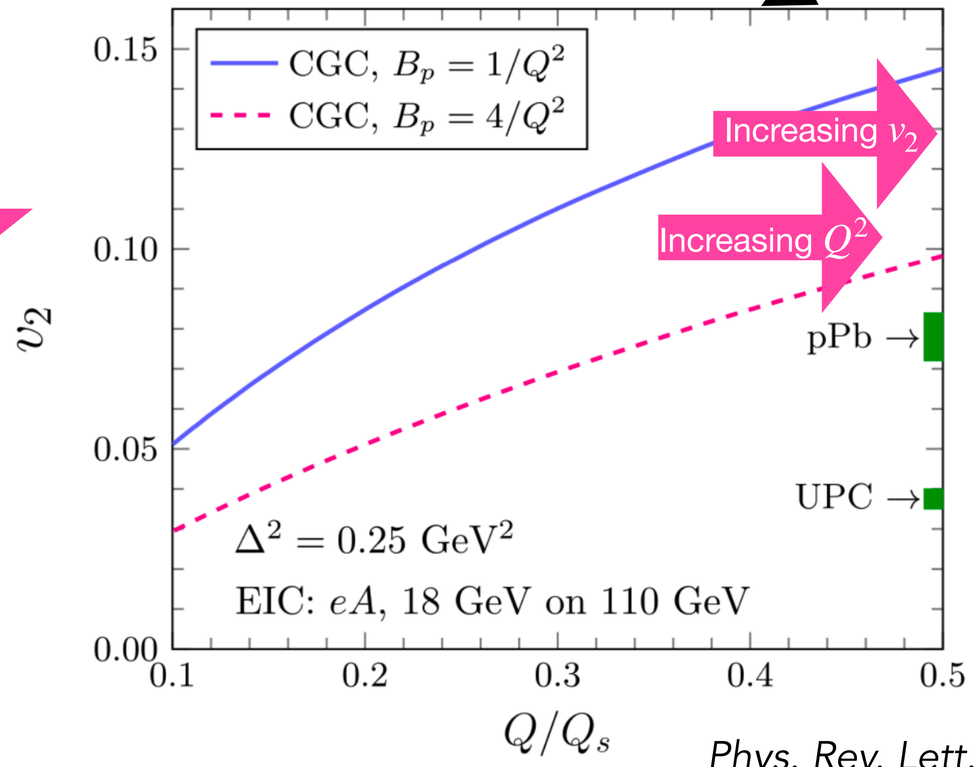
Future Directions

EIC: Future home at BNL

2025 2030 2035+

Predictions by hydrodynamic model and CGC, in opposite directions





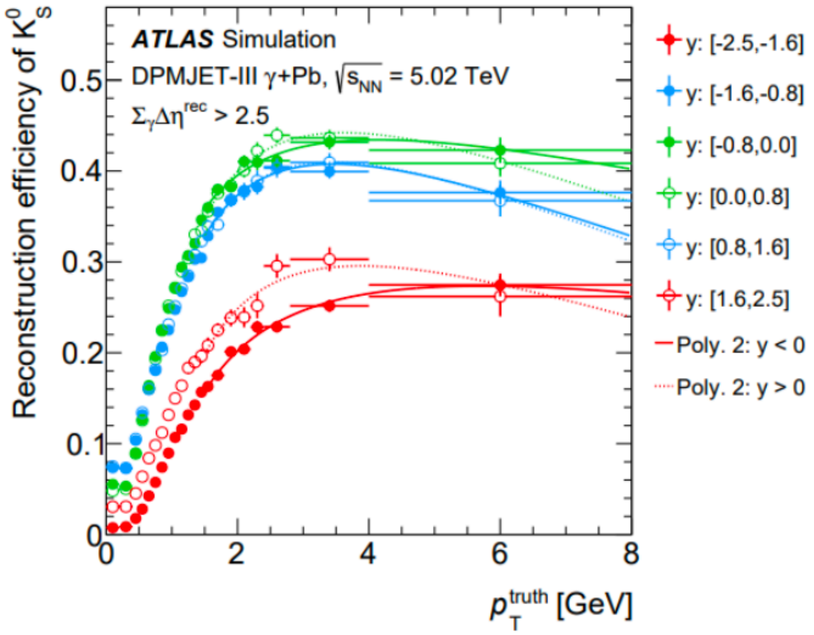
Phys. Rev. Lett. 129, 252302

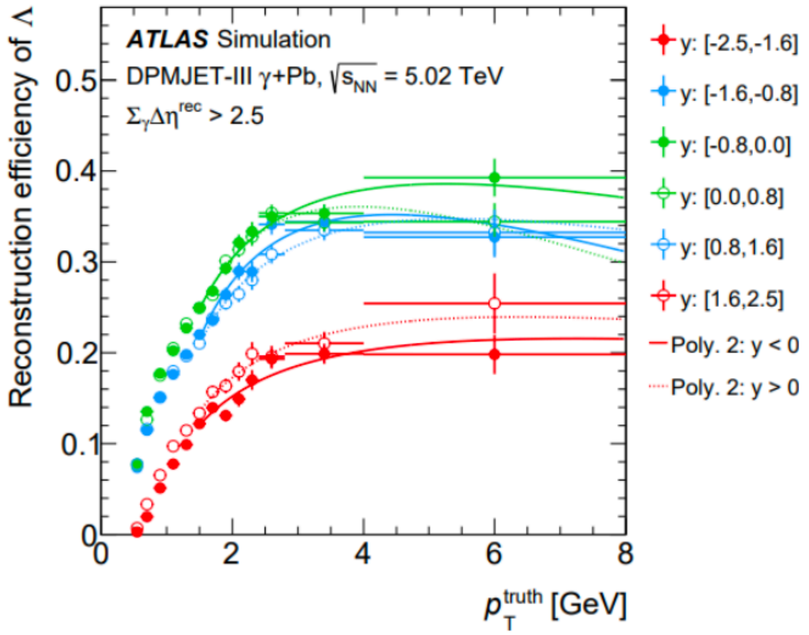
EIC can be a "tie-breaker" between the initial-state and final-state models!

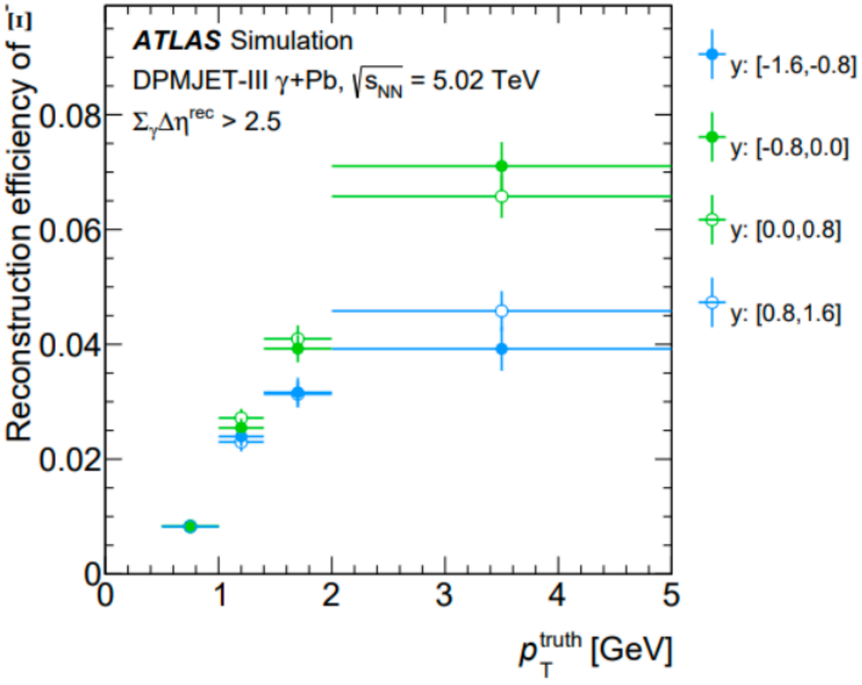
Thanks for listening!

Back up

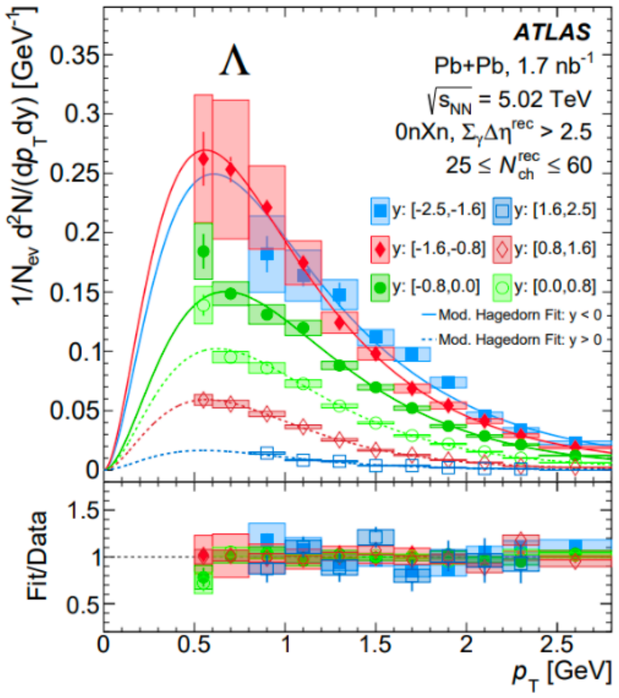
Reconstruction Efficiencies

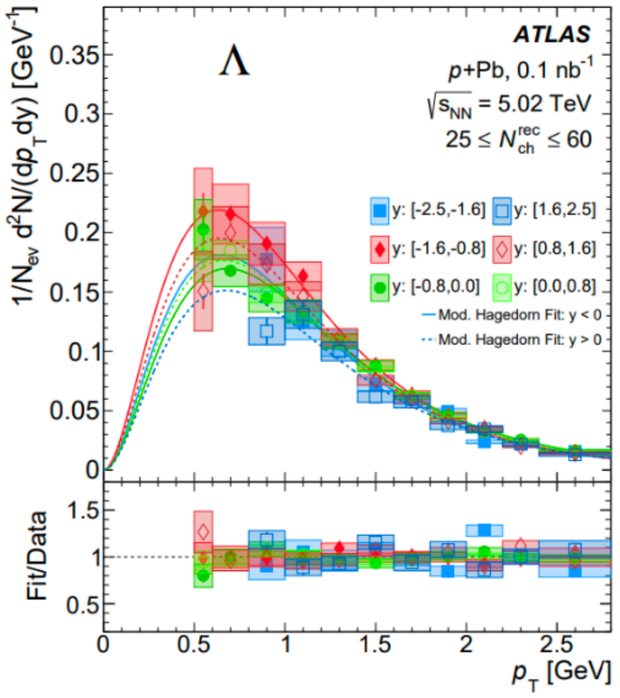


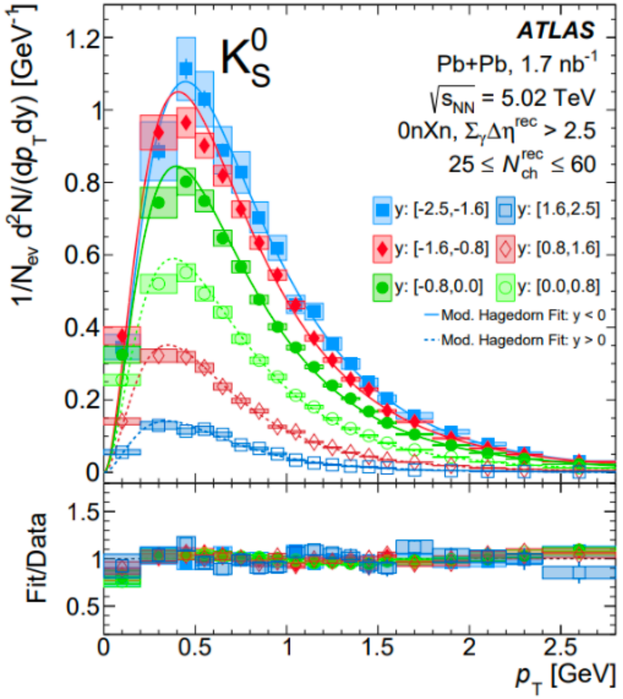


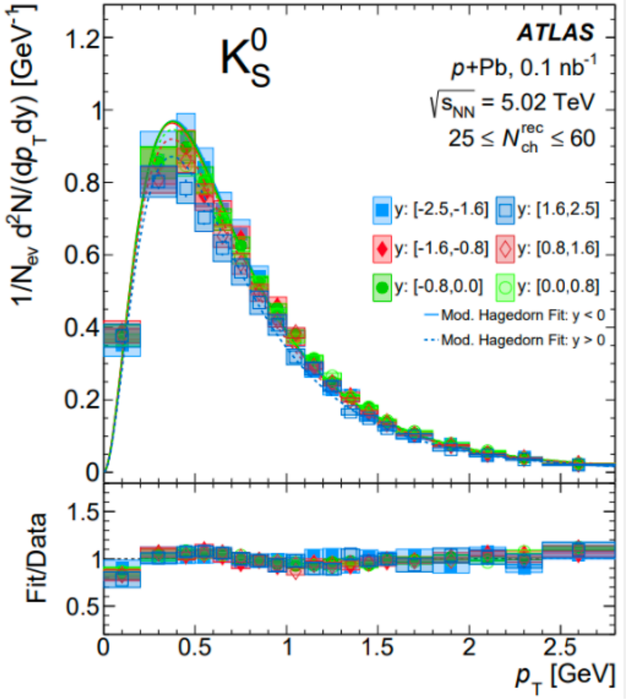


Extrapolation to $p_{\mathrm{T}} = 0$

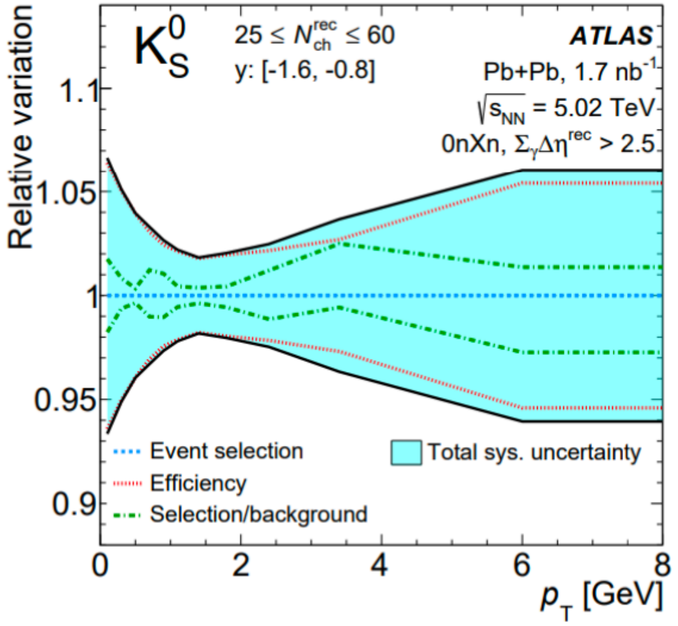


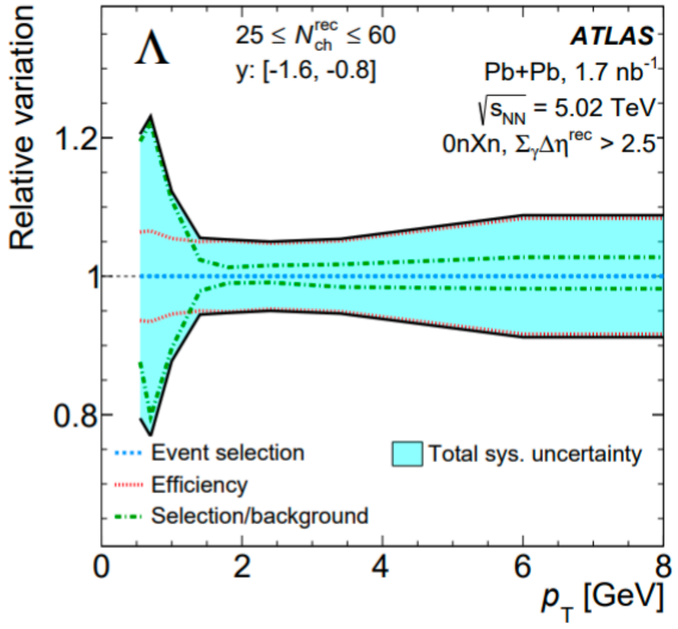


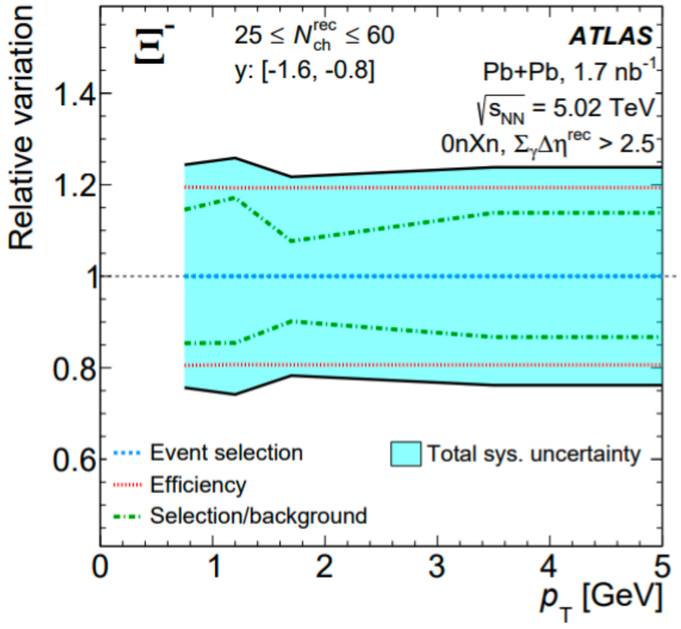


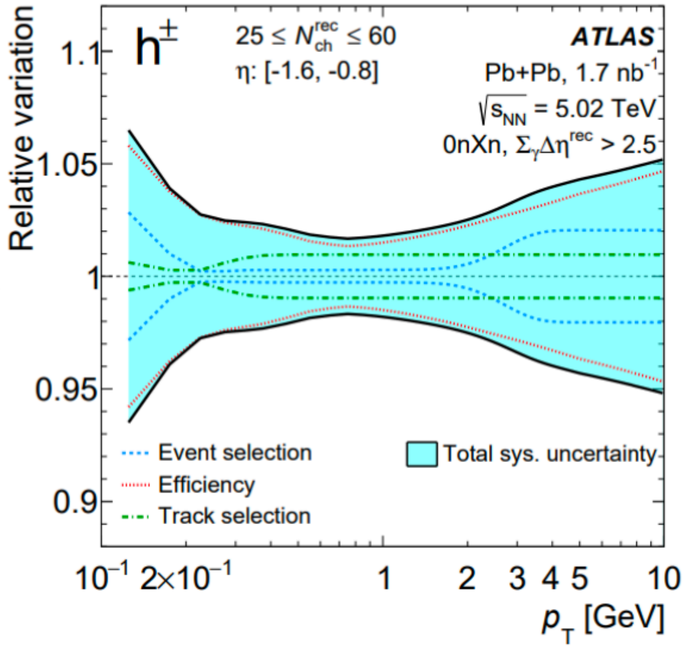


Systematic Uncertainties

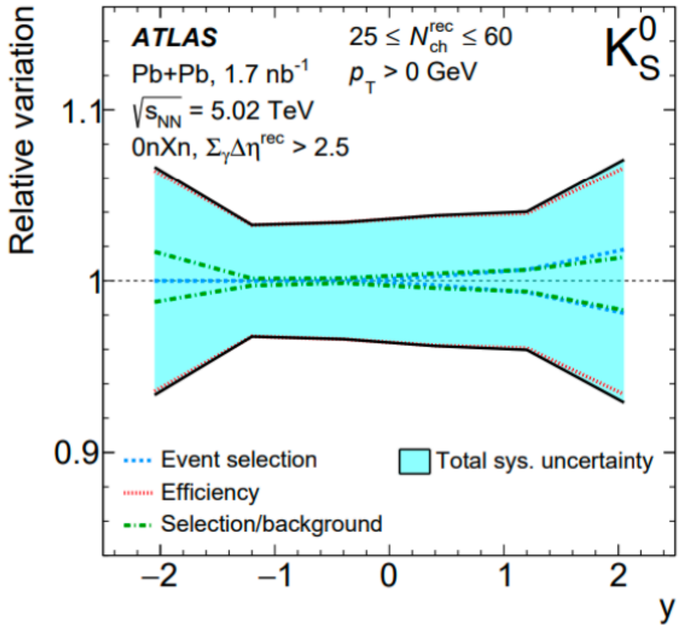


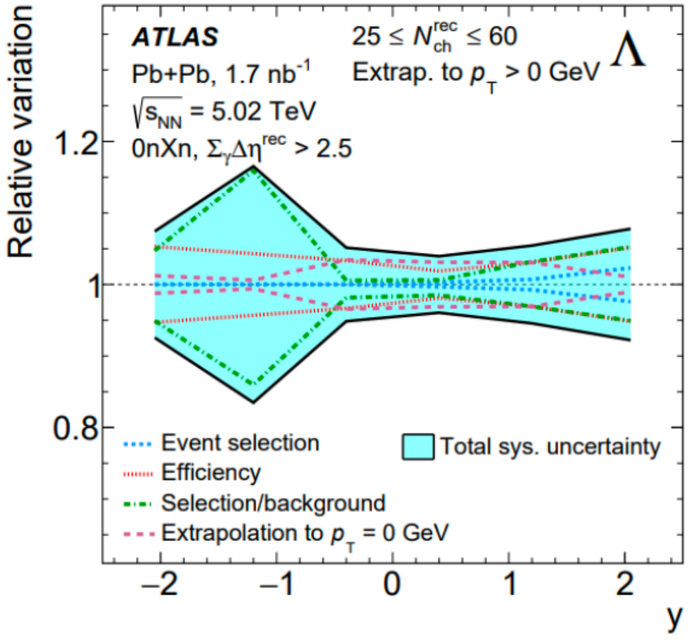


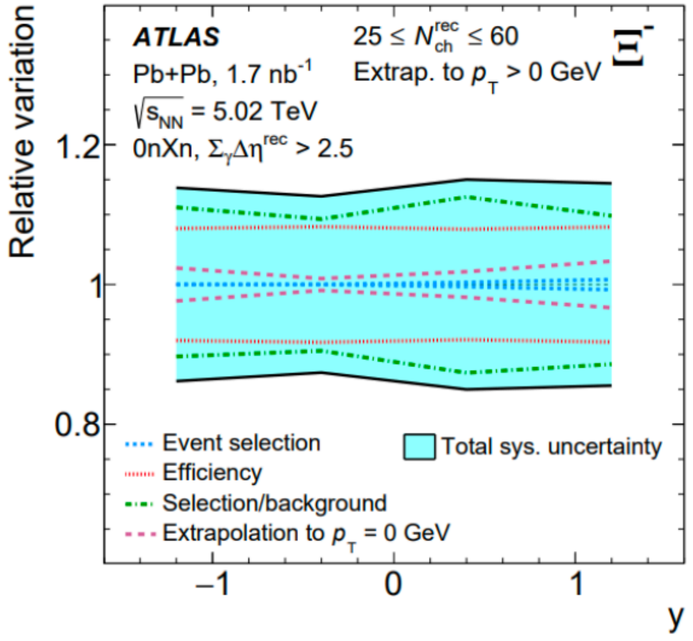


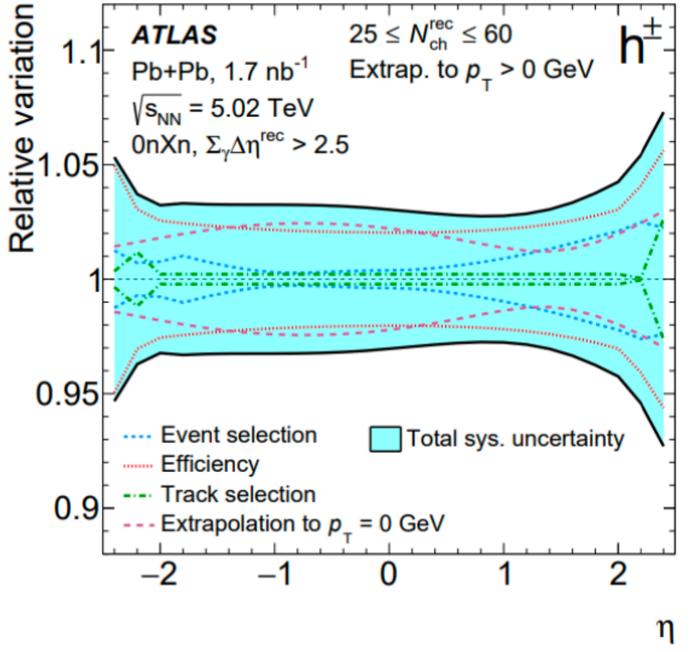


Systematic Uncertainties

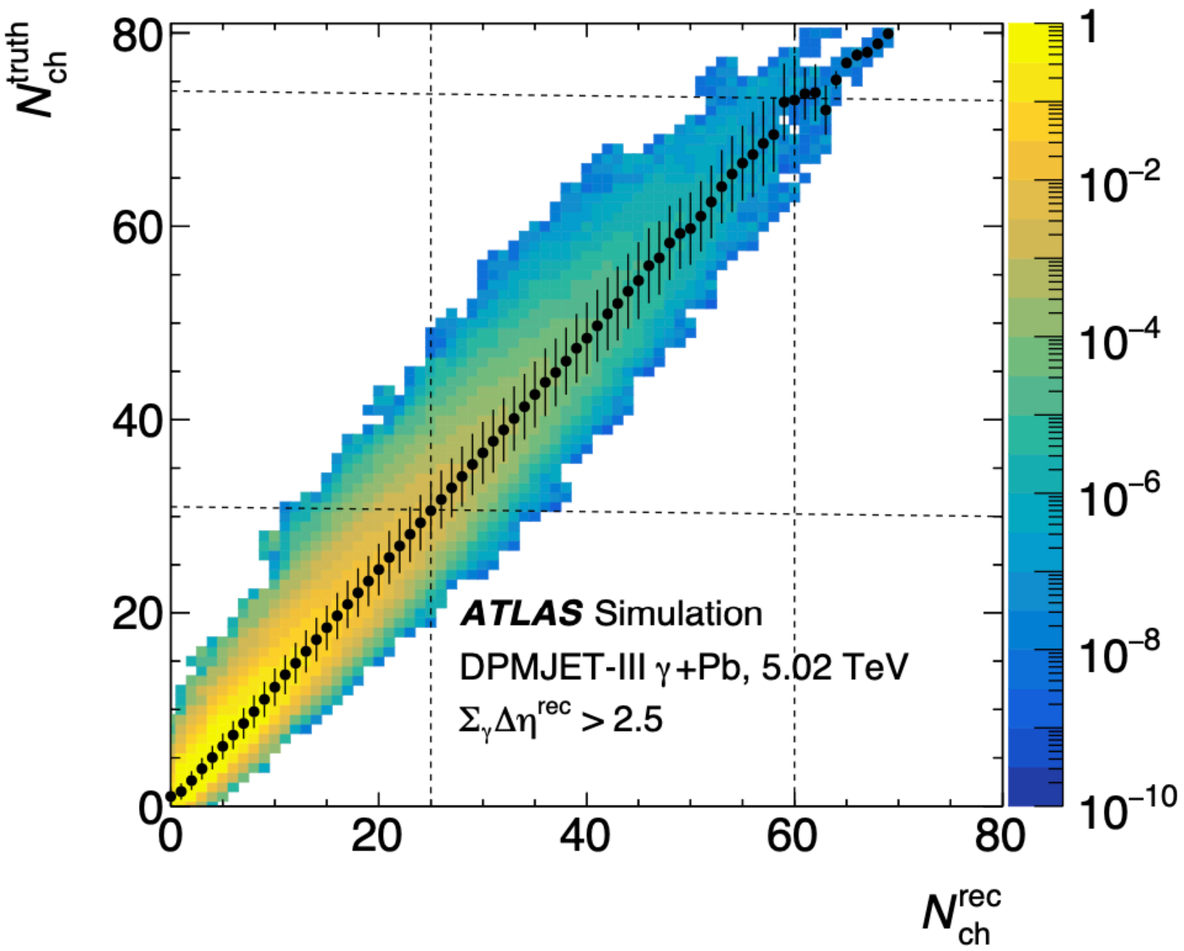




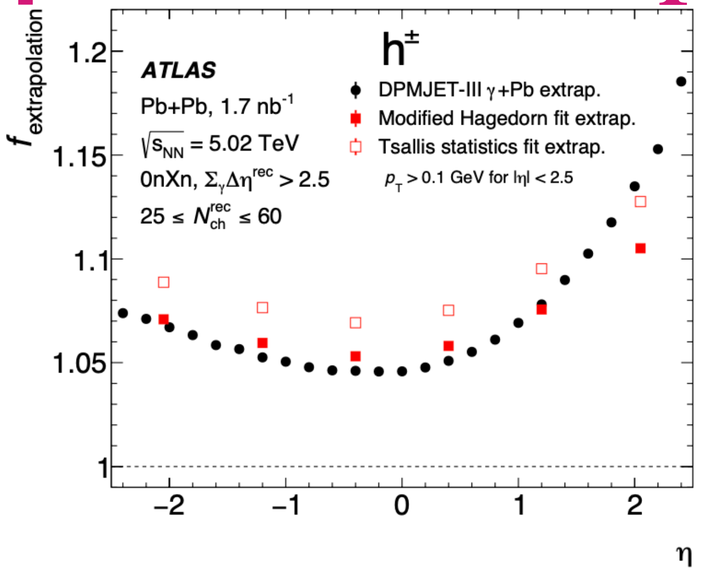


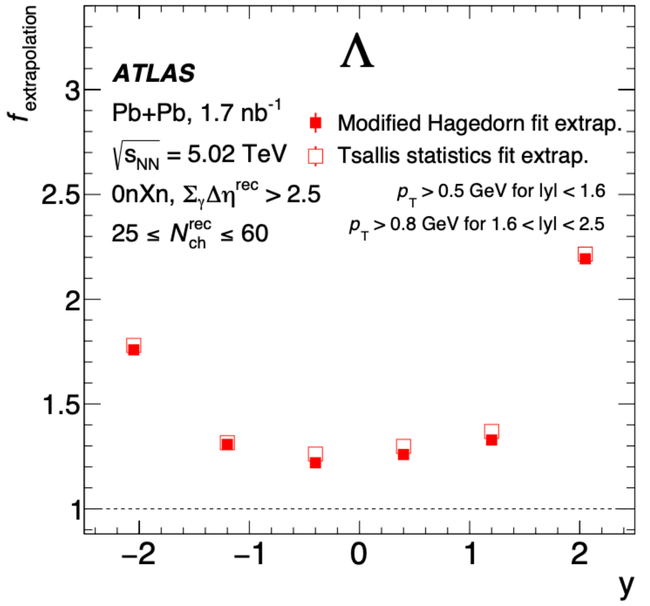


Multiplicity

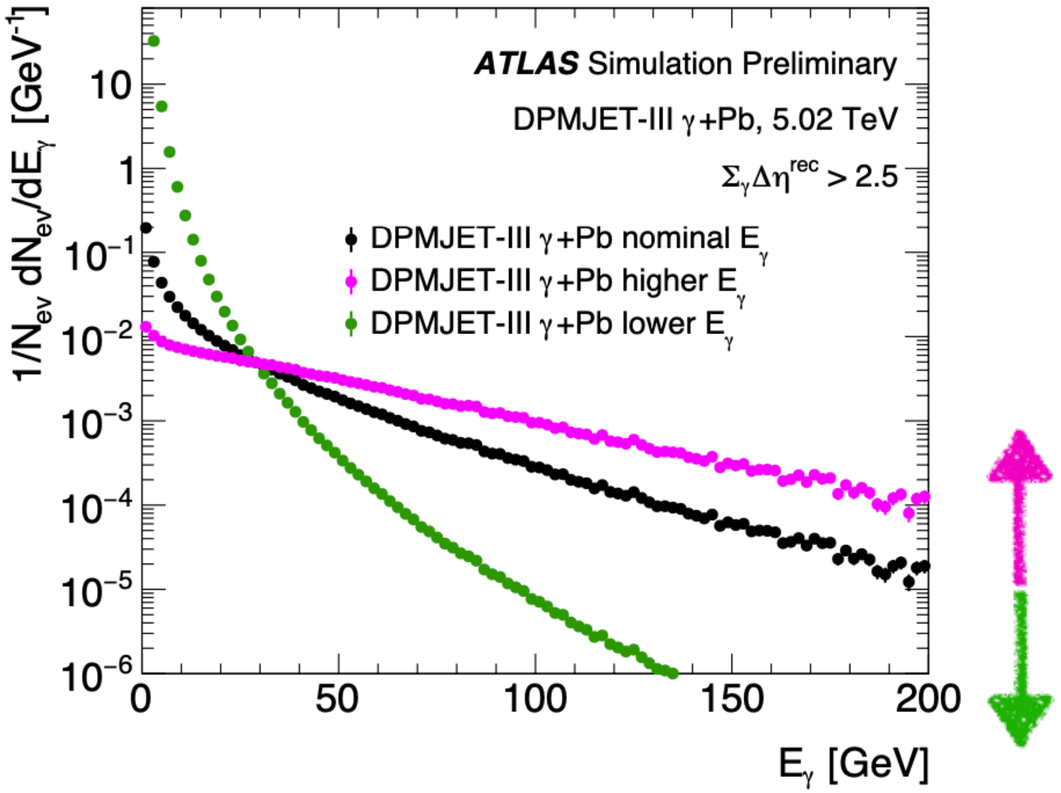


Extrapolation to $p_T = 0$



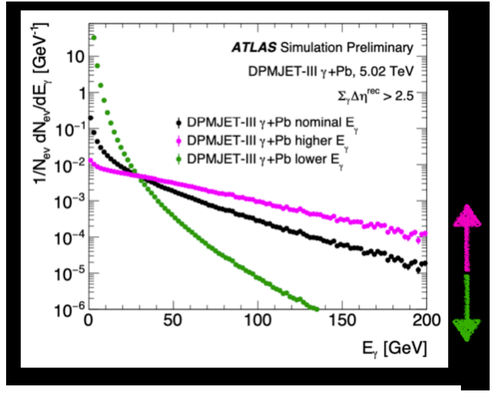


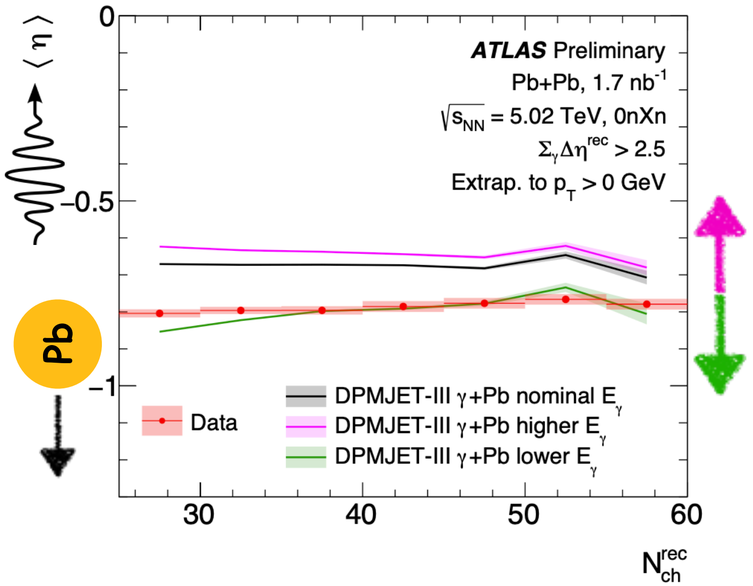
Study of photon energy and particle production

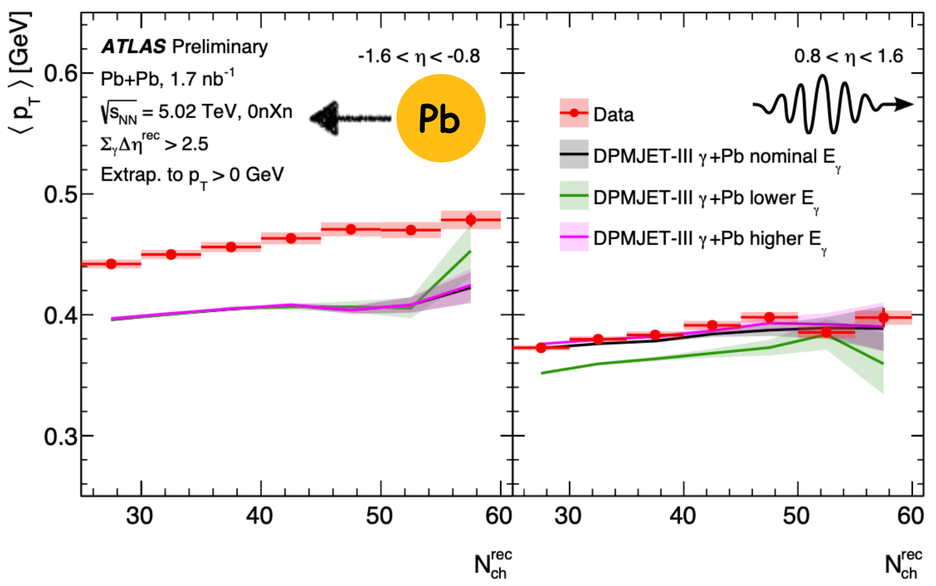


Arbitrarily re-weigh photon energy distribution to relatively allow:
1) more high-energy photons 2) more low-energy photons.

Study of photon energy and particle production







$\langle\eta\rangle$ is matched with "low-energy photon" re-weighting,

$\langle p_T\rangle$ couldn't be matched

💡 However, the very substantial energy re-weighting is quite likely ruled out by other Pb+Pb UPC measurements.