Creating the smallest fluid in the universe with a single photon

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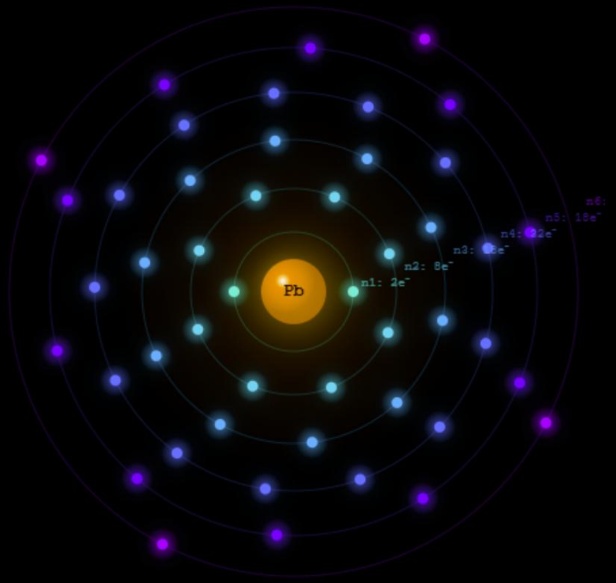
Thesis work at University of Colorado Boulder

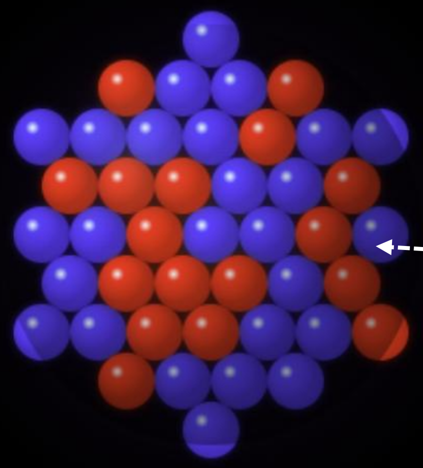
Sambamurti Lecture July 30th, 2026

Pb atom



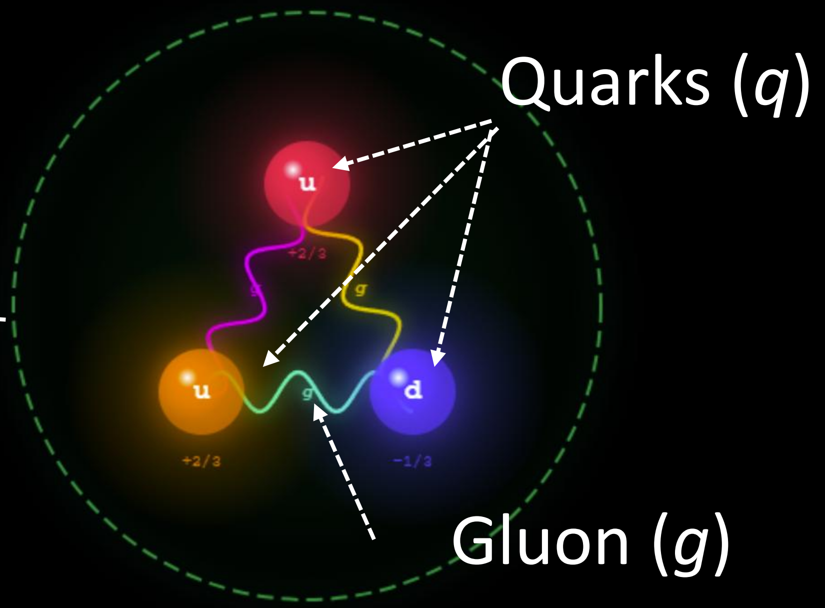
Contains electrons and a nucleus

Pb nucleus

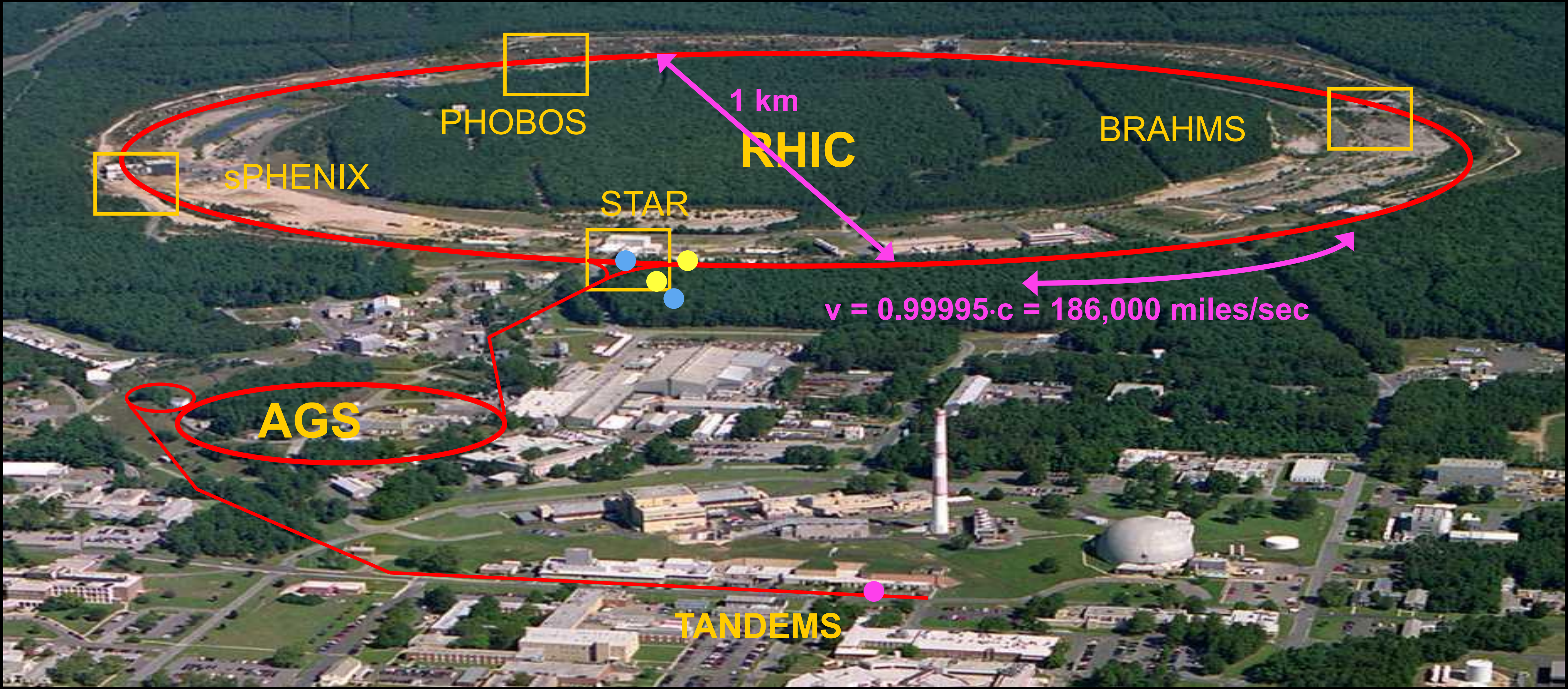


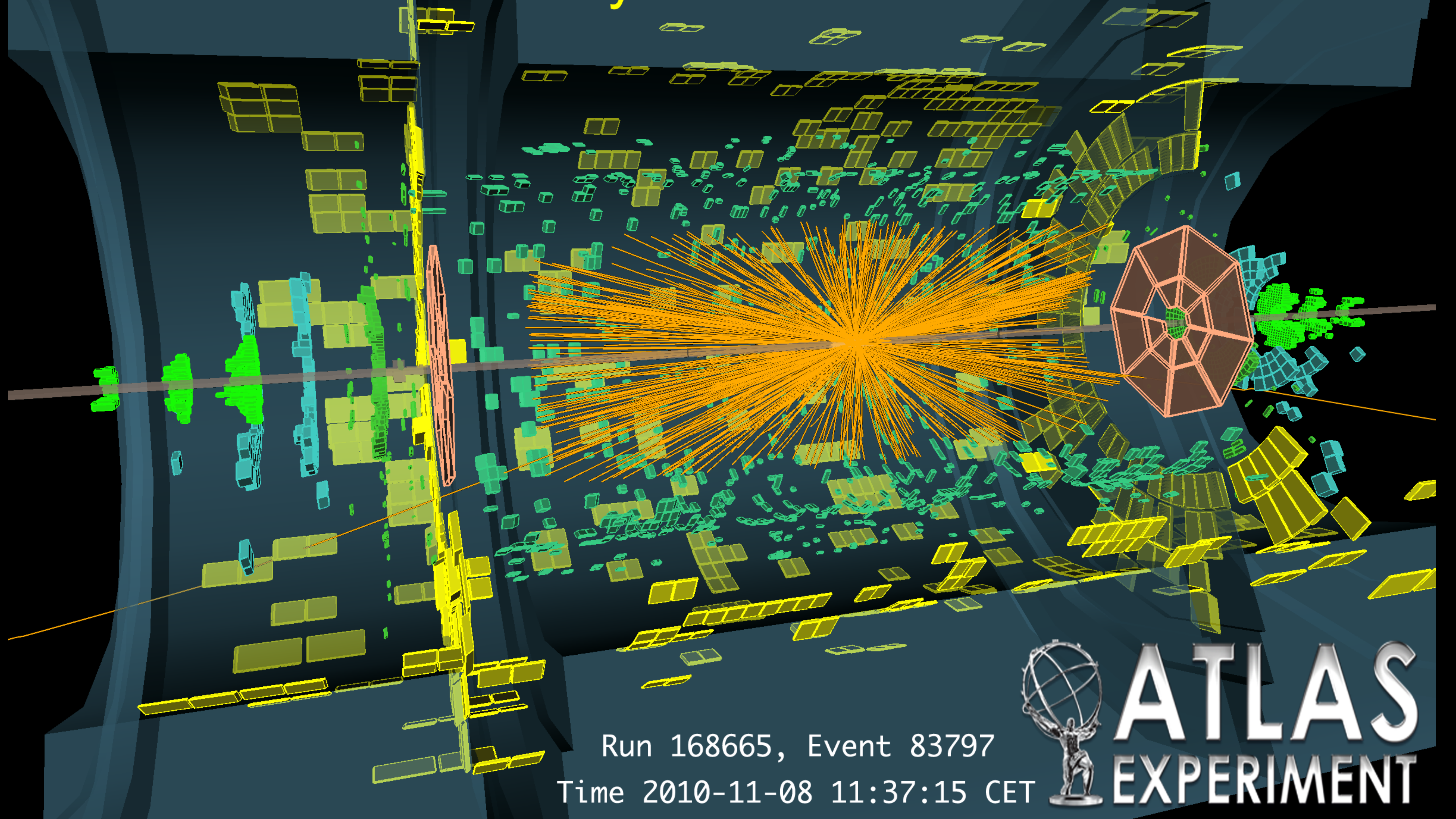
Contains *nucleons* (protons and neutrons)

Proton



Contains quarks and gluons
Quark content dictates whether it's a proton, neutron or other *hadron*
Gluons are the *glue* which binds the quarks together

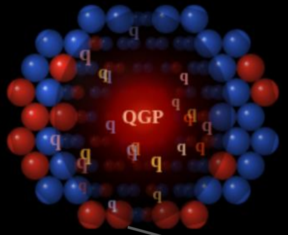

PHOBOS
1 km
RHIC
BRAHMS
sPHENIX
STAR
v = 0.99995·c = 186,000 miles/sec
AGS
TANDEMS

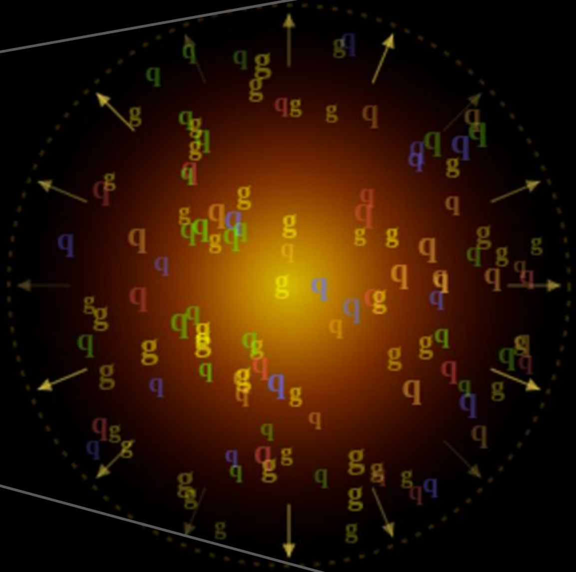

Run 168665, Event 83797
Time 2010-11-08 11:37:15 CET
ATLAS
EXPERIMENT

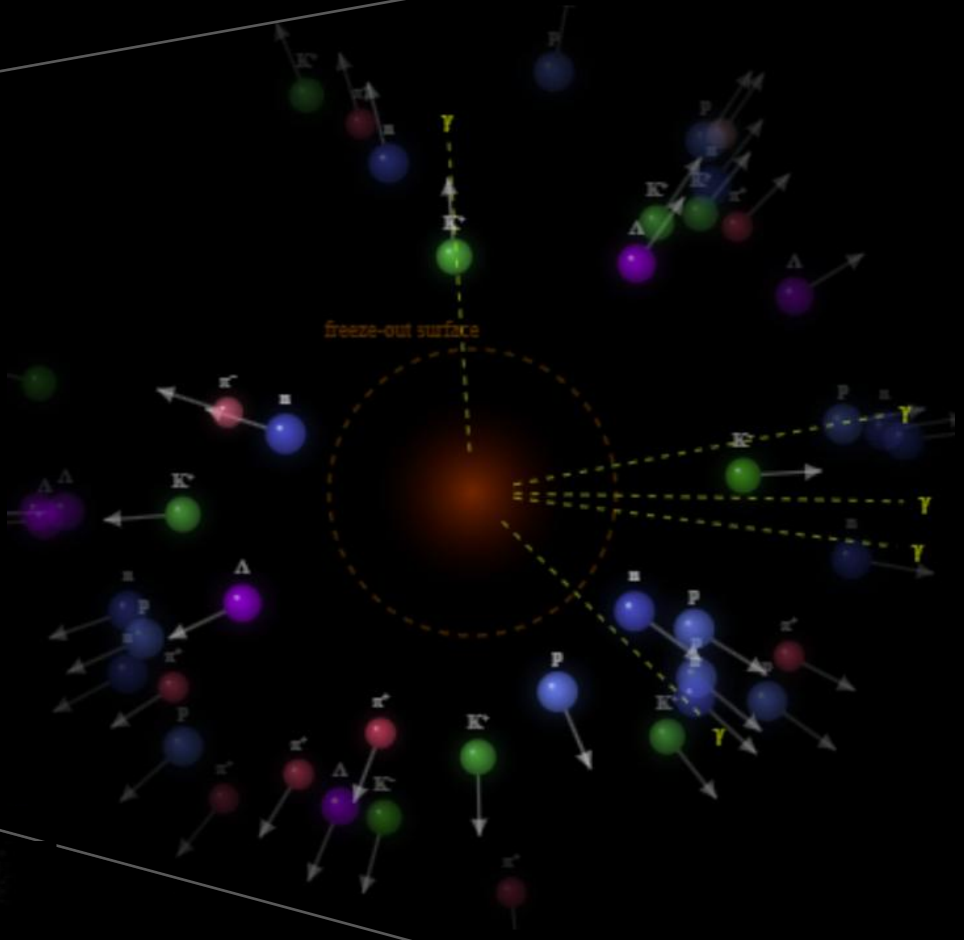
Reaches the critical temperature and forms back into hadrons like protons

Quark gluon plasma (QGP) expands and cools

Collision!
Nucleons melt into quarks and gluons

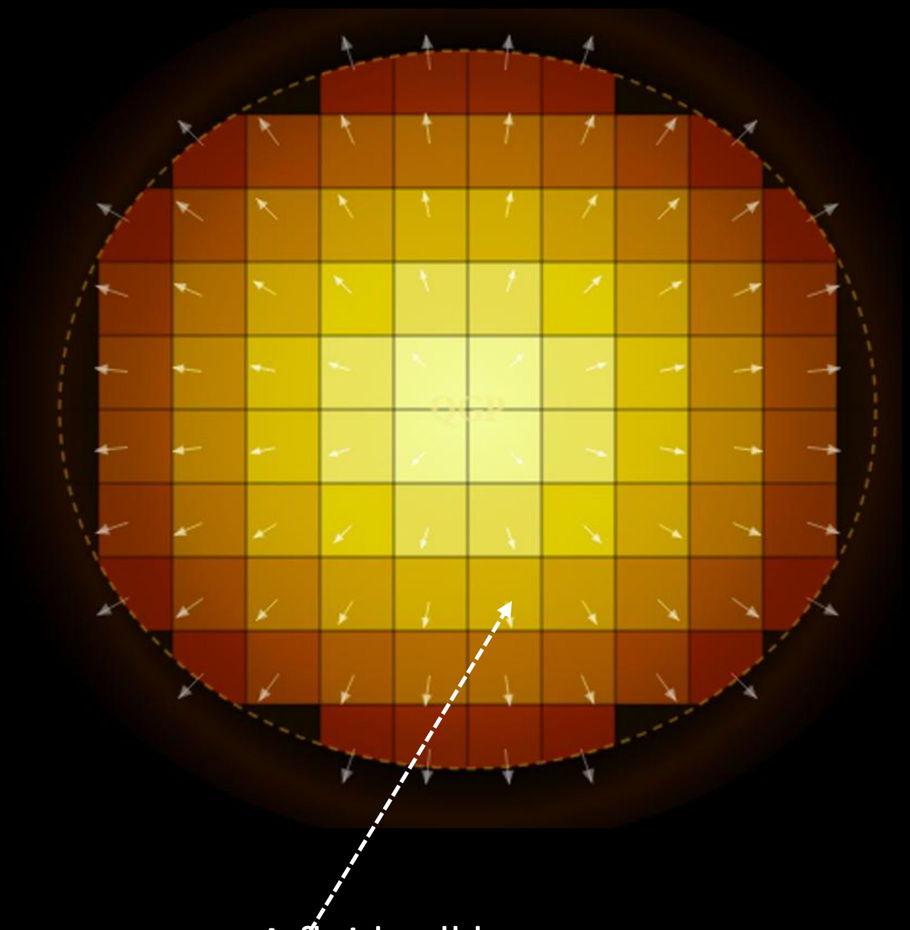






1×10^{-23} seconds
5×10^{12} °C

The QGP expands like a fluid!



A fluid cell has,
a pressure, temperature and velocity.

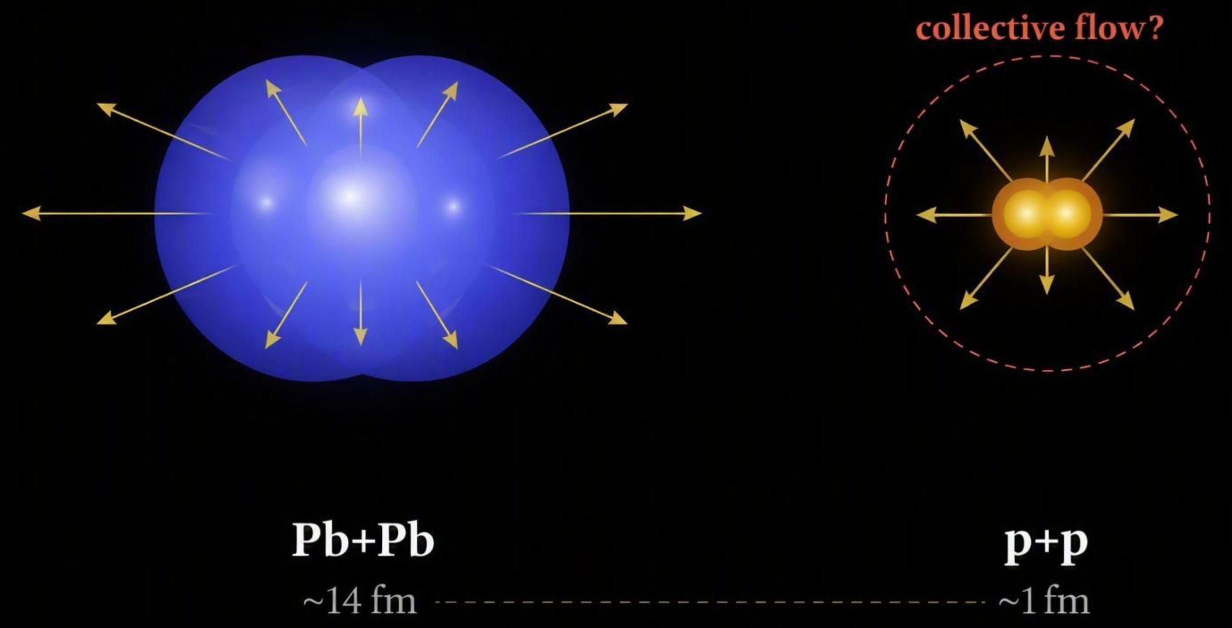
- **A fluid flows and equalizes internally — fast**
  - particles interact so frequently that local temperature & pressure are fully descriptive
- **Not all matter is a fluid — it depends on how often particles collide**
  - few interactions → non-interacting gas
  - many interactions → liquid
- The same math that describes ocean currents describes the QGP

Do small systems flow?

Large systems (Pb+Pb) clearly form QGP and flow collectively

Small systems are a stress test of everything we think we know

If hydro works here, why? If it doesn't, where does it break?

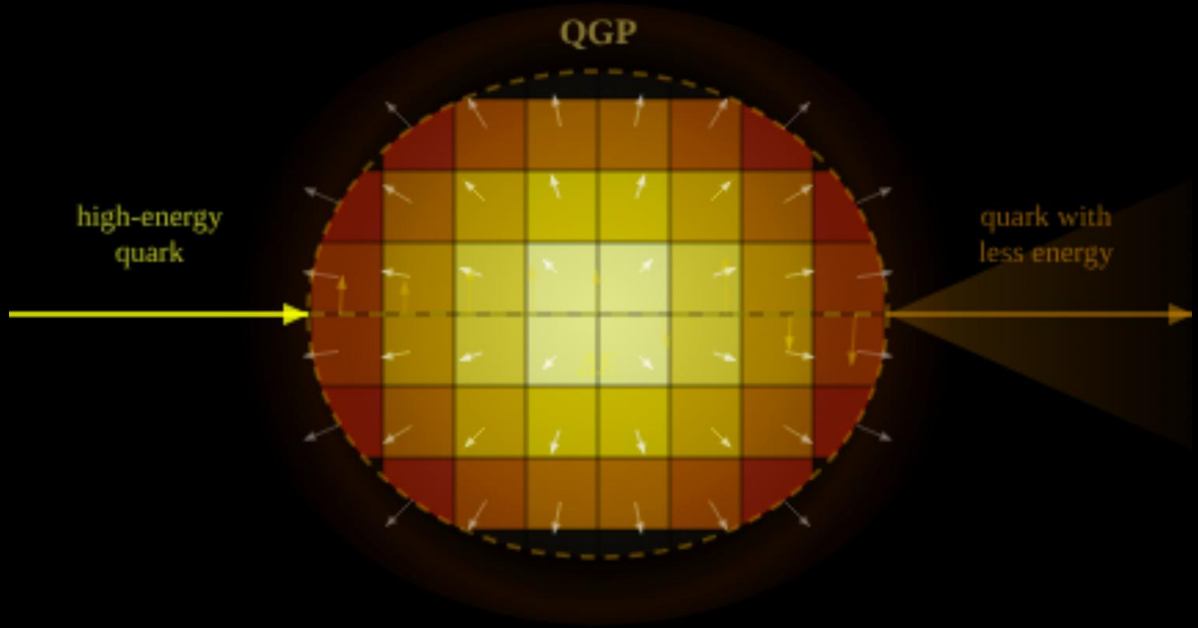


Probing the QGP with high energy quarks

High-energy quarks lose energy traversing the QGP

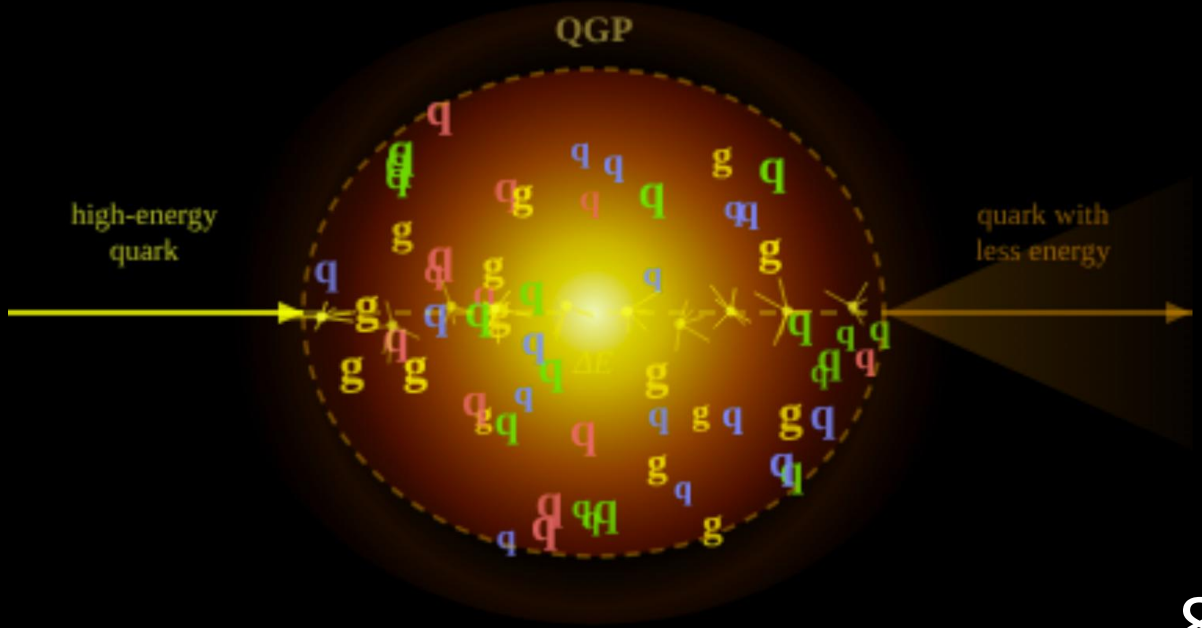
Fluid picture

Like a bullet through water, they smoothly lose energy

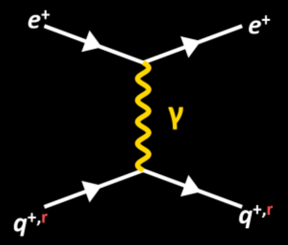


Particle picture

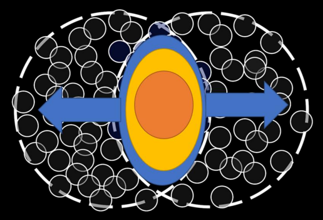
Loses energy in discrete collisions with the quarks/gluons of the QGP



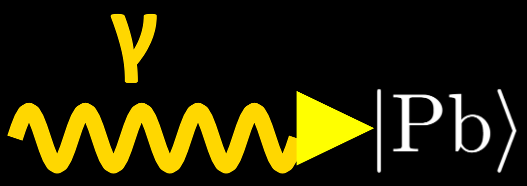
Today's roadmap



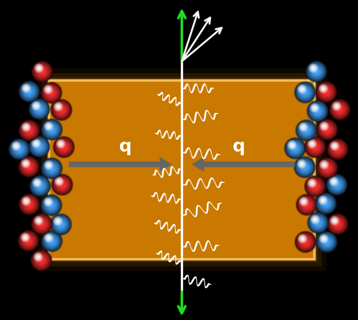
1. Particle physics background
   - Quarks and gluons are strongly coupled making theory challenging



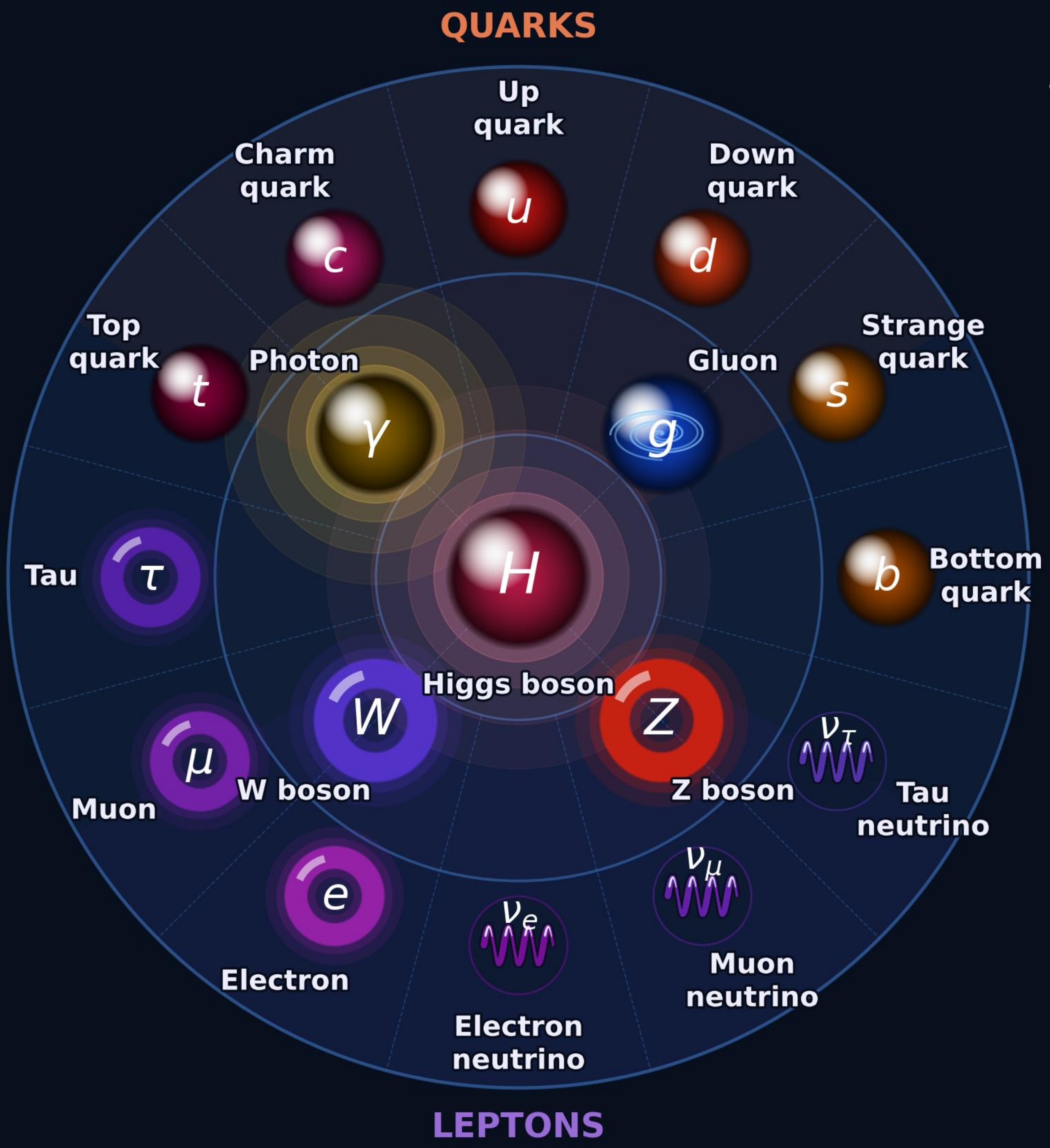
2. Relativistic heavy ion collisions and the QGP



3. Photonuclear and other ultraperipheral collisions
   - ATLAS measurement of photonuclear



4. Probing the QGP with high energy quarks

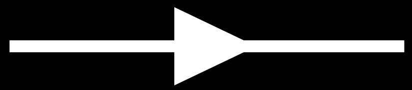


Standard model

What we need for today

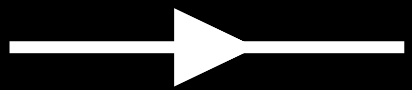
- *e*: electron

e^+



- *q*: any quark

q^+



- *g*: gluons

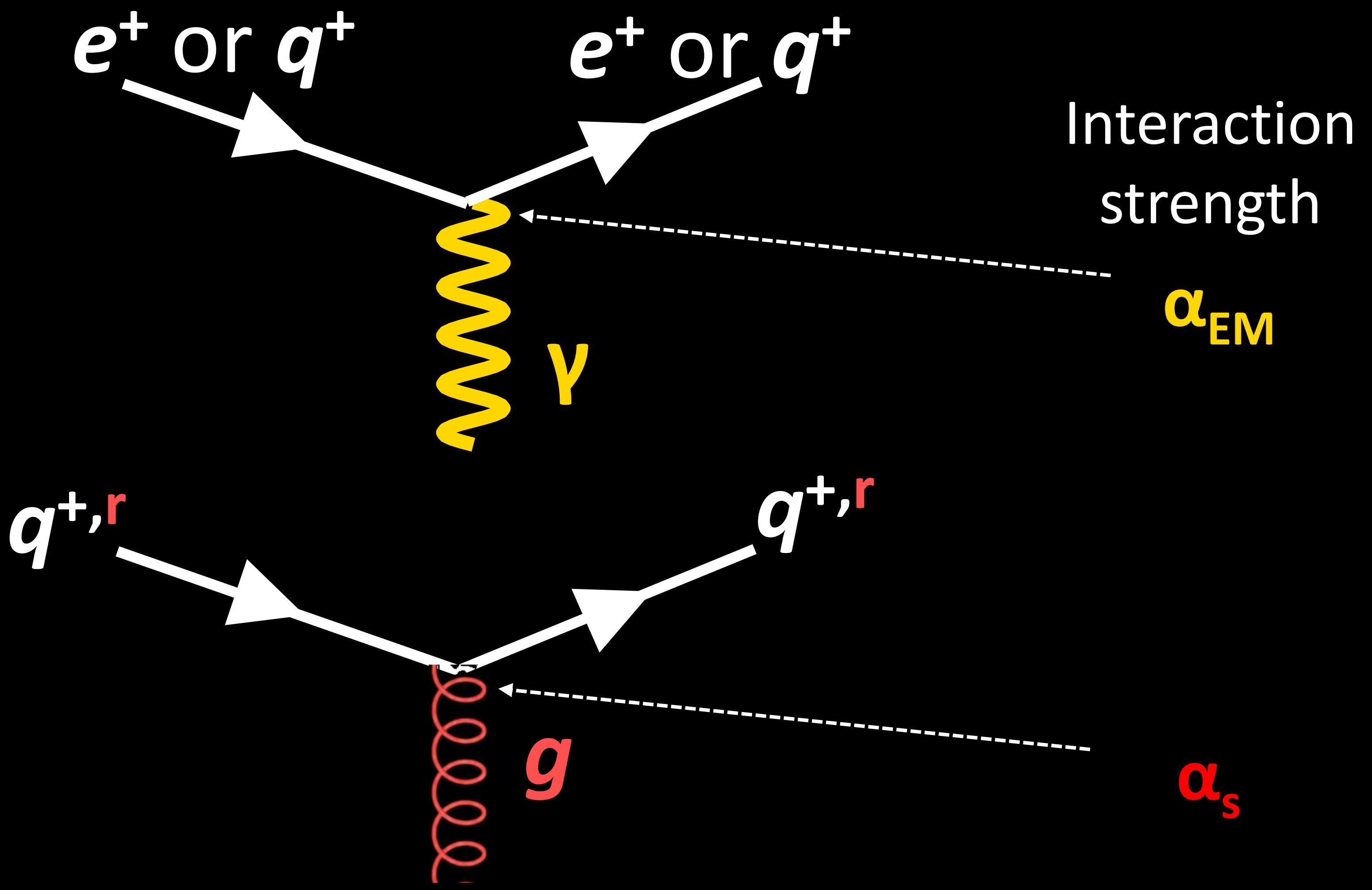
g

- *γ*: photon

γ

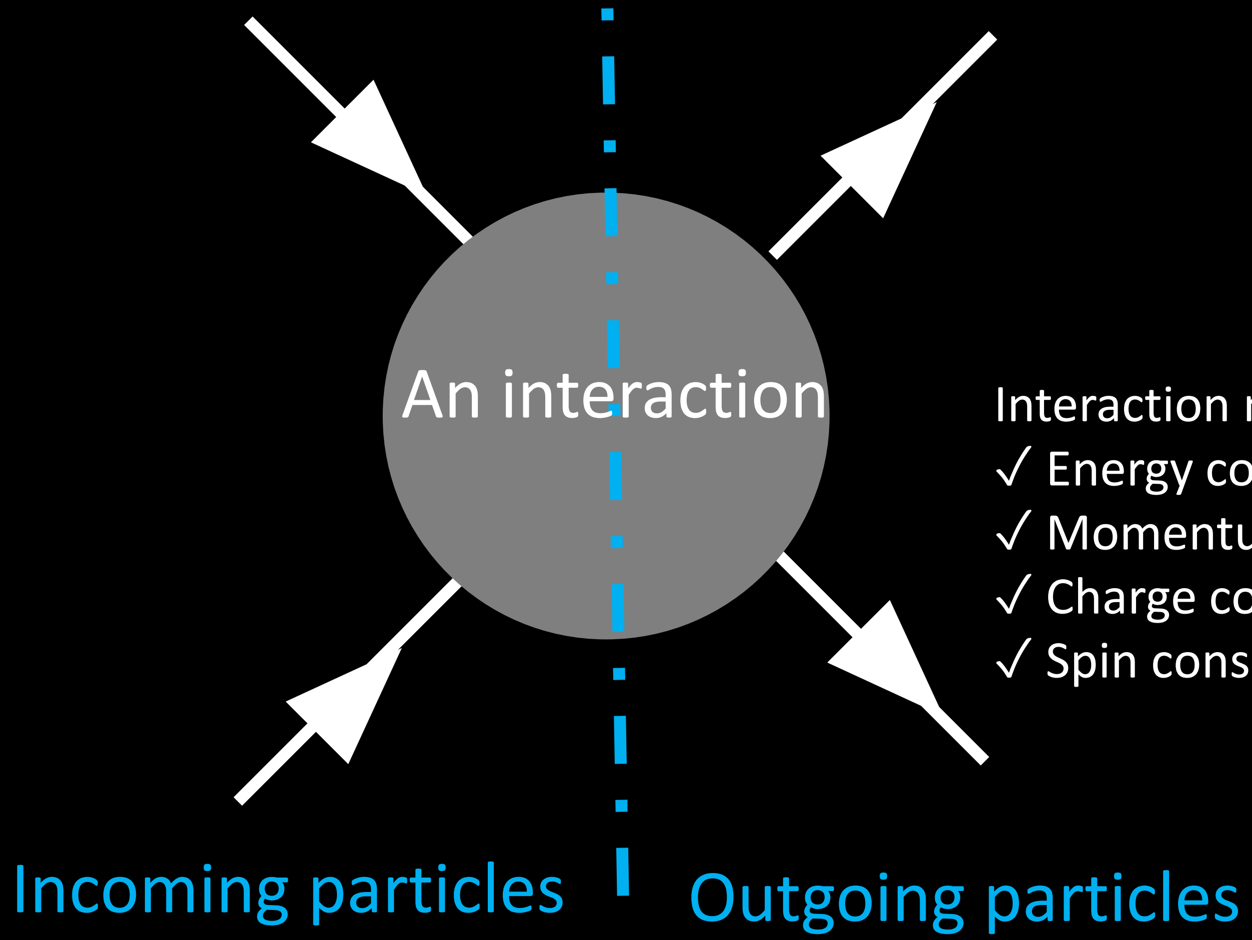
Four fundamental forces

- Electromagnetic force
  - Photons and particles with electric charge
- Strong nuclear force
  - Gluons and quarks which both have “color” charge (red, blue, and green)
- Weak force
- Gravity



Quantum field theory and Feynman diagrams

The most precise and straightforward tool for calculations of phenomena in the standard model and beyond



Interaction must obey things like

✓ Energy conserved
✓ Momentum conserved
✓ Charge conserved
✓ Spin conserved

Many allowed diagrams

↓

Add amplitudes

↓

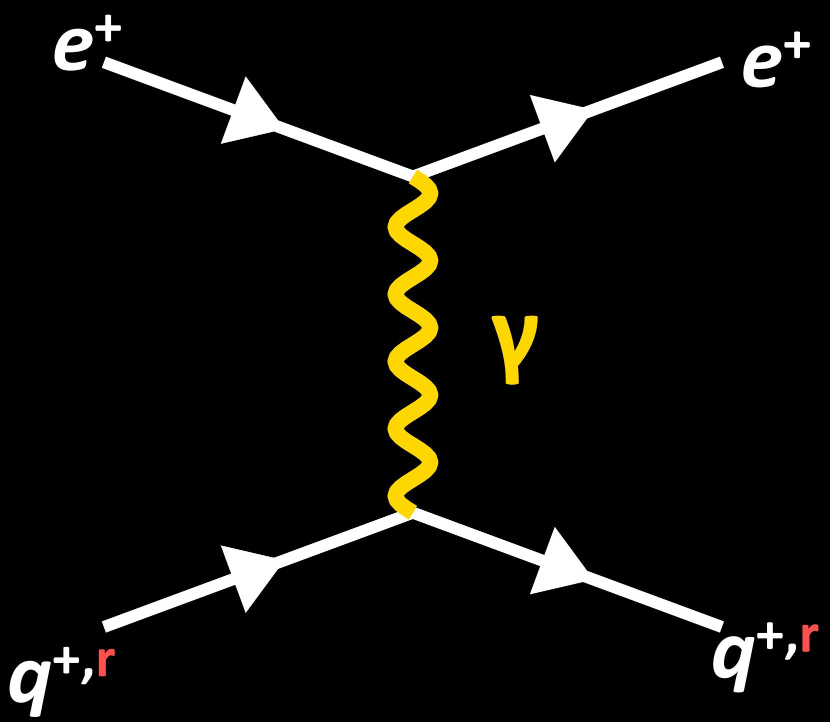
Square

↓

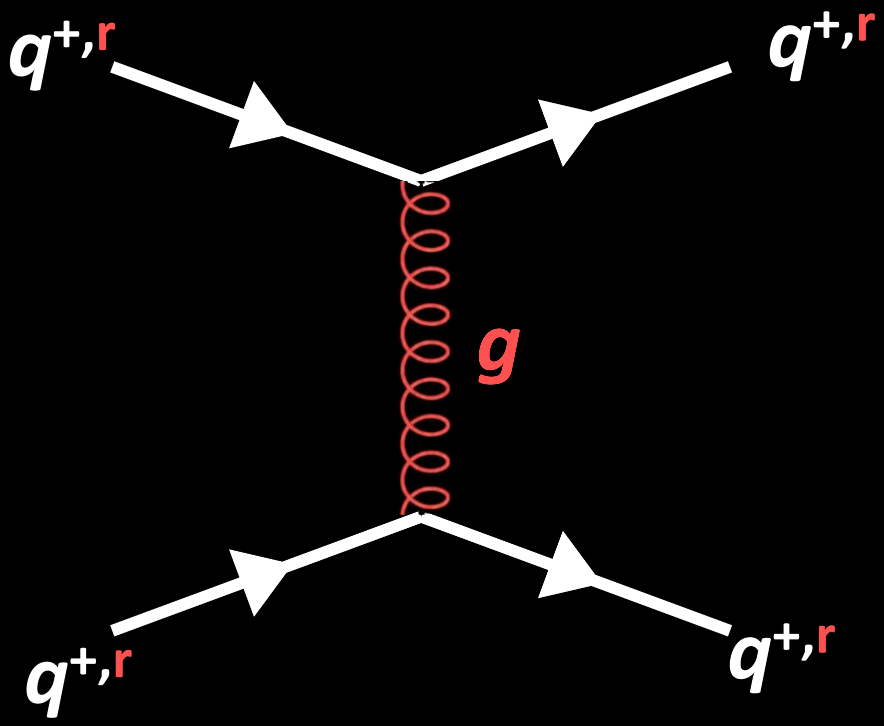
Probability

Feynman Diagrams

Electromagnetic force

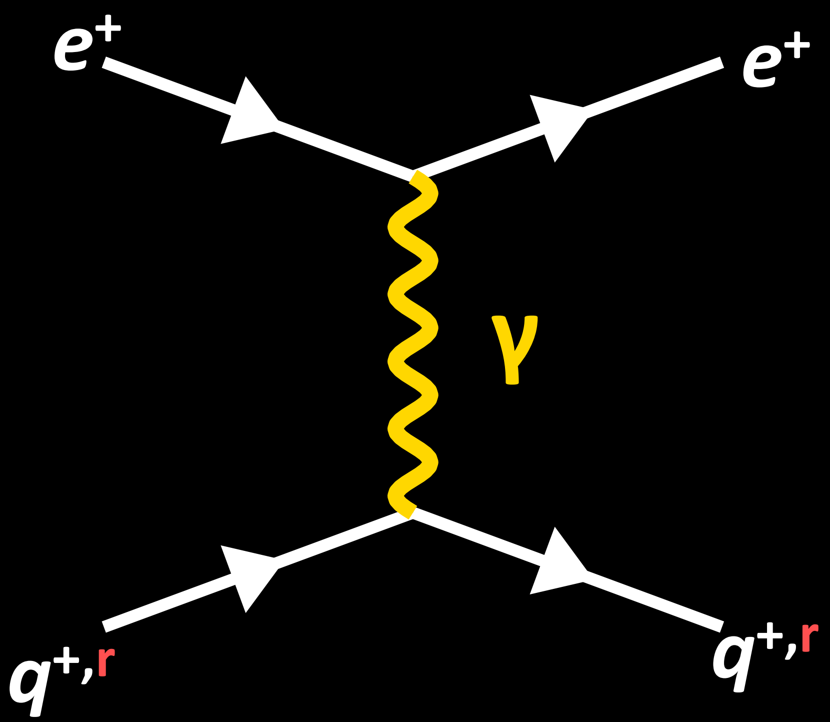


Strong nuclear force



Vertex Factors & Probability

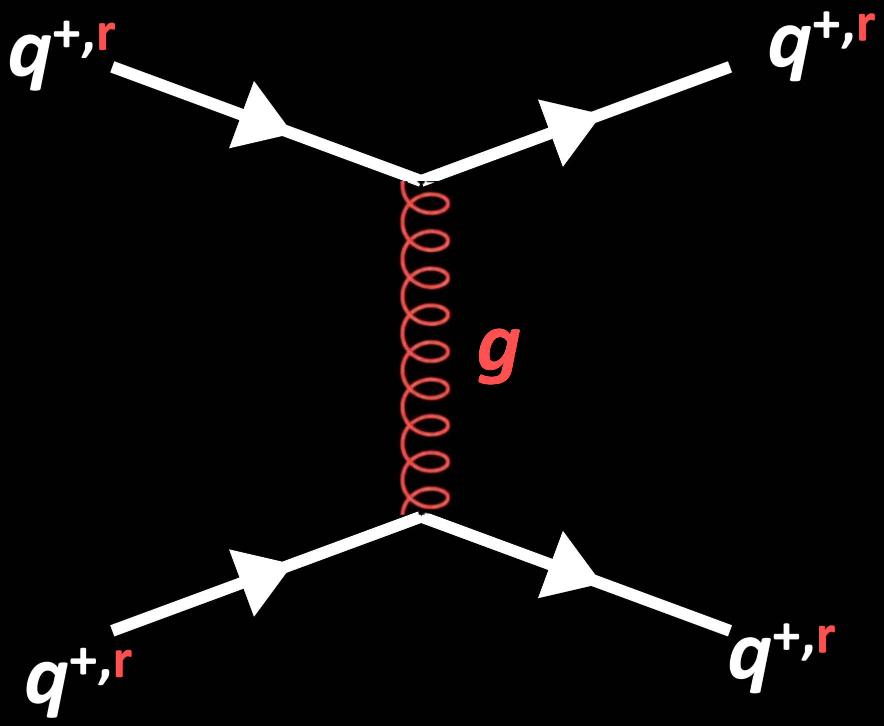
Electromagnetic force



↳ Each vertex contributes one factor of the coupling constant

$P \propto \alpha^2$ ($\alpha \approx 1/137$, so $\alpha^2 \approx 5\times10^{-5}$)

Strong nuclear force

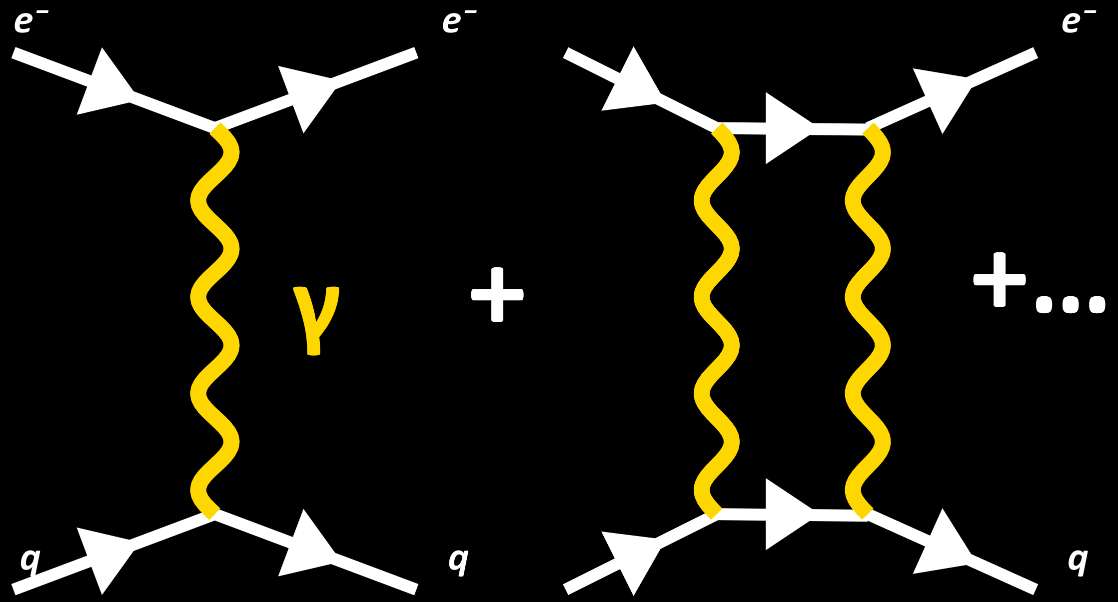


↳ Each vertex contributes one factor of the coupling constant

$P \propto \alpha s^2$ ($\alpha s \approx 1$ at low energy!)

Higher-Order Interactions (adding amplitudes)

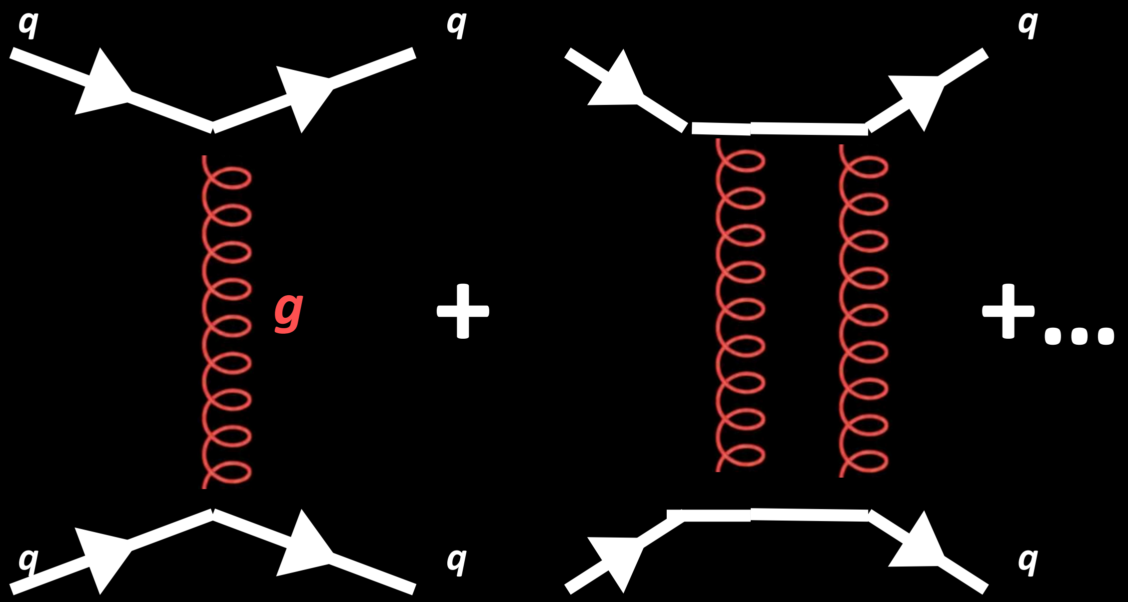
Electromagnetic force



$\propto \alpha_{EM}^{2}$ $\propto \alpha_{EM}^{4}$

$\alpha_{EM} \approx 1/137 \ll 1$ → each new order is ~(1/137)× smaller → series converges!

Strong nuclear force

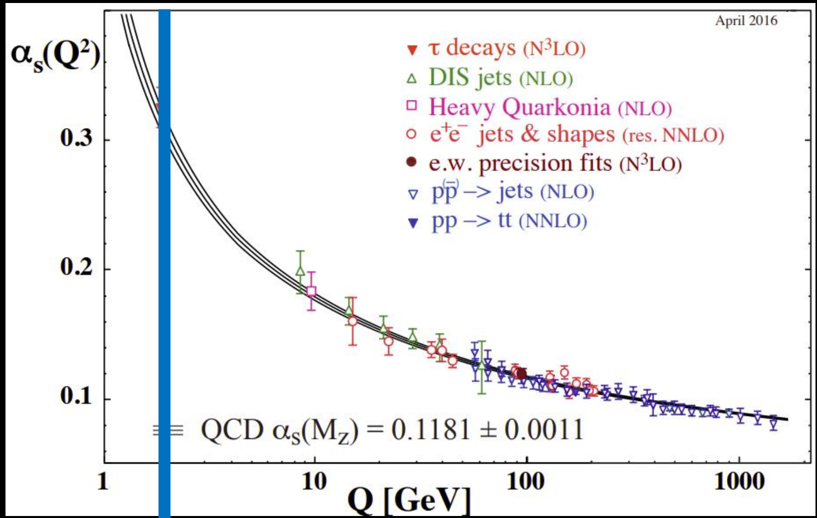


$\propto \alpha_{s}^{2}$ $\propto \alpha_{s}^{4}$

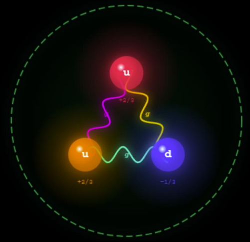
$\alpha_{s} \approx 1$ → every order contributes equally → series does NOT converge!

Important phenomena are challenging theoretically

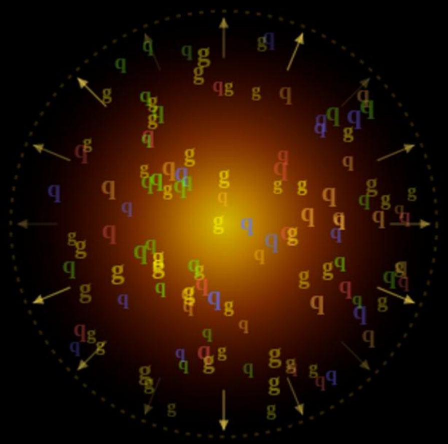
- At low momentum transfers α_s is large making perturbative calculations impossible



Strong coupling | Weak coupling



Low energy gluons in the proton → Why we are building the EIC

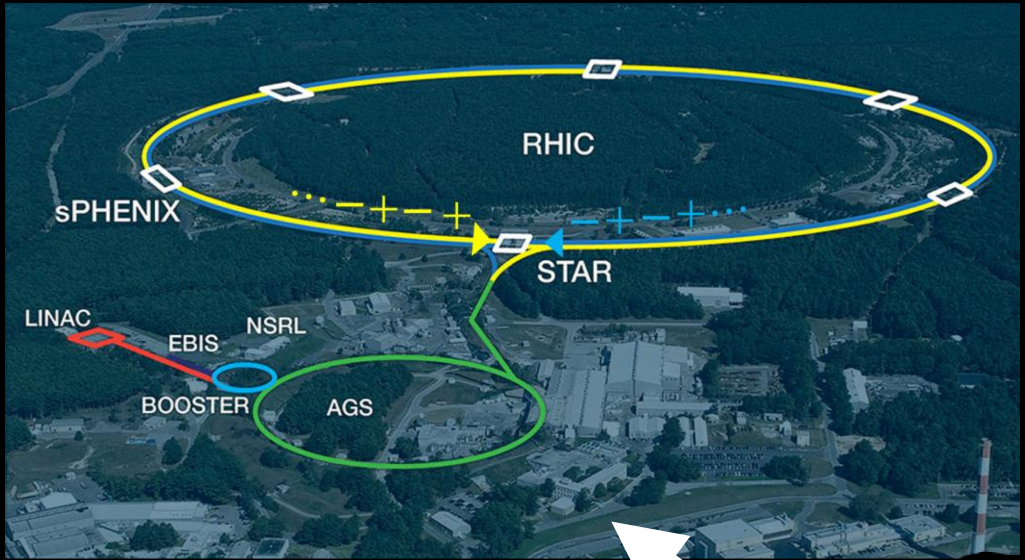


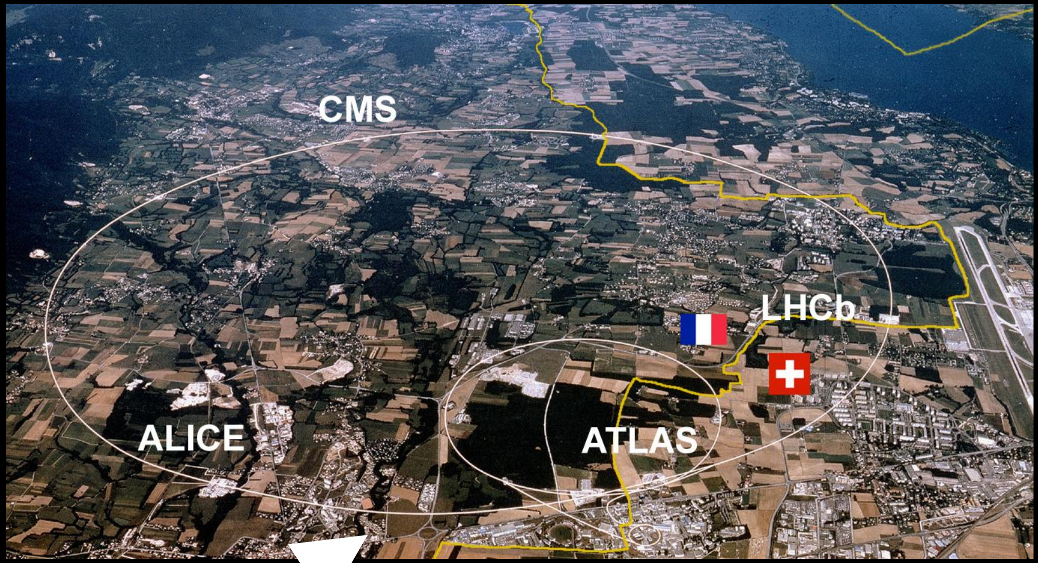
Homogeneous sea of quarks and gluons over a wide temperature range → Why we built RHIC

A high energy quark shooting through this sea → Why we built sPHENIX

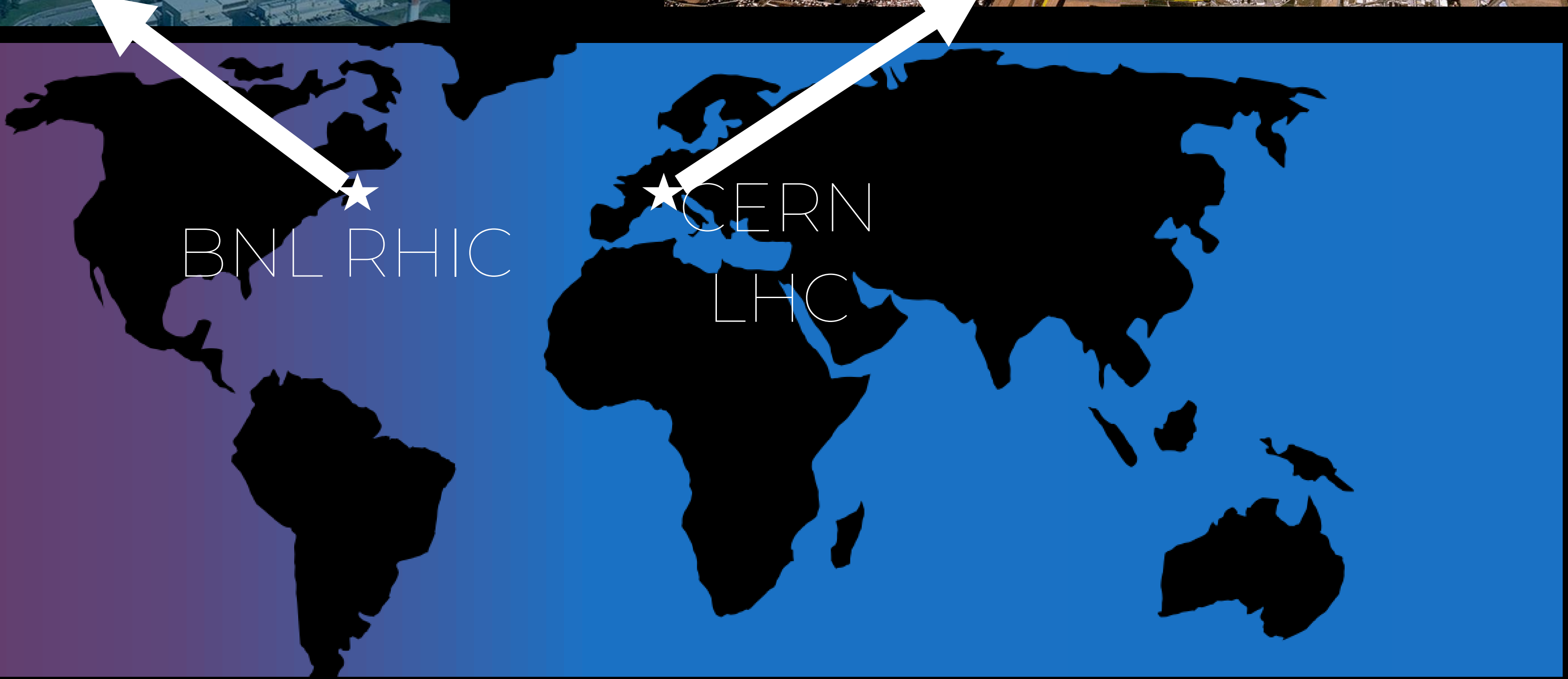
Heavy ion collisions

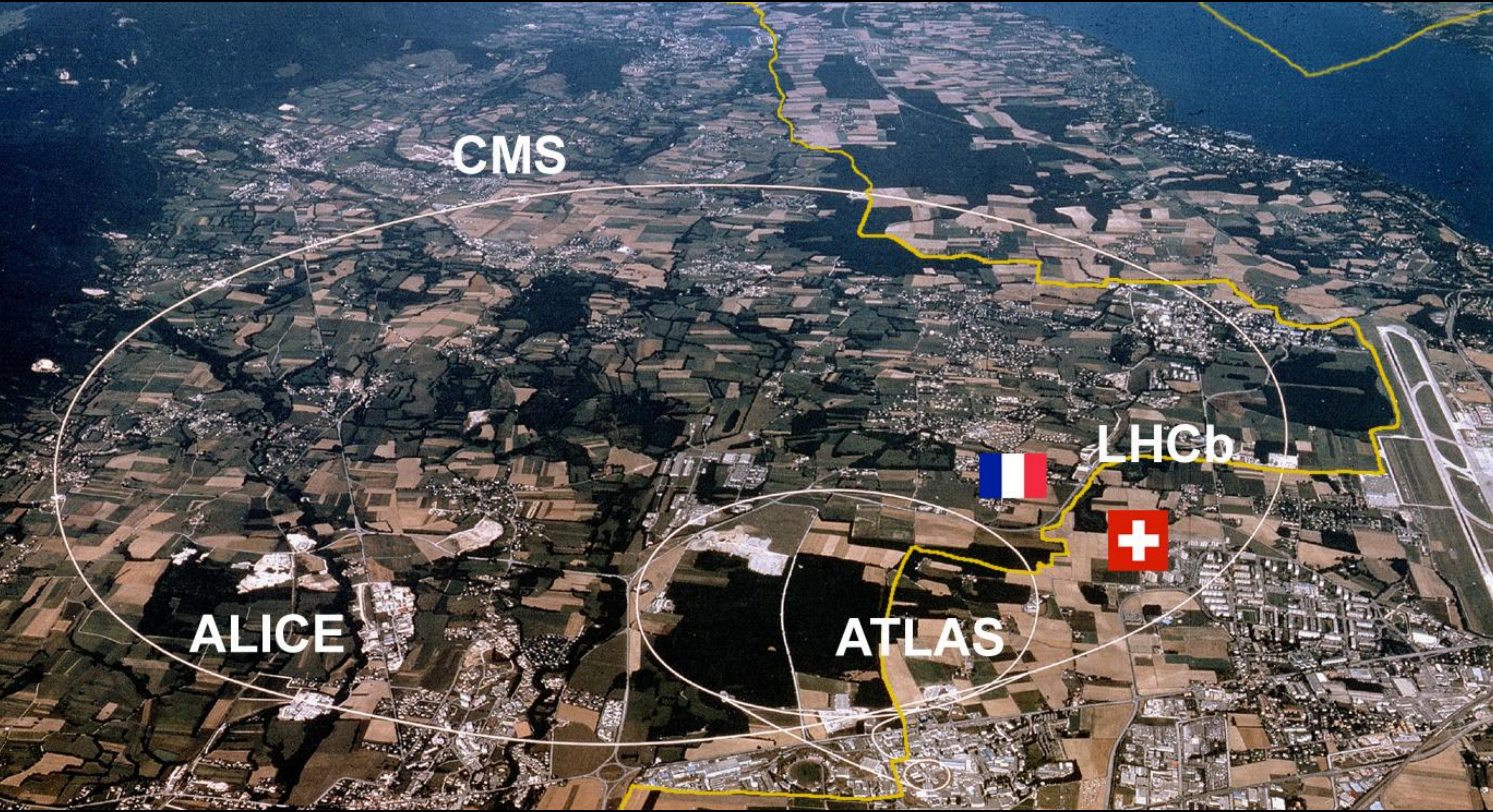
The creation of the flowing quark gluon plasma

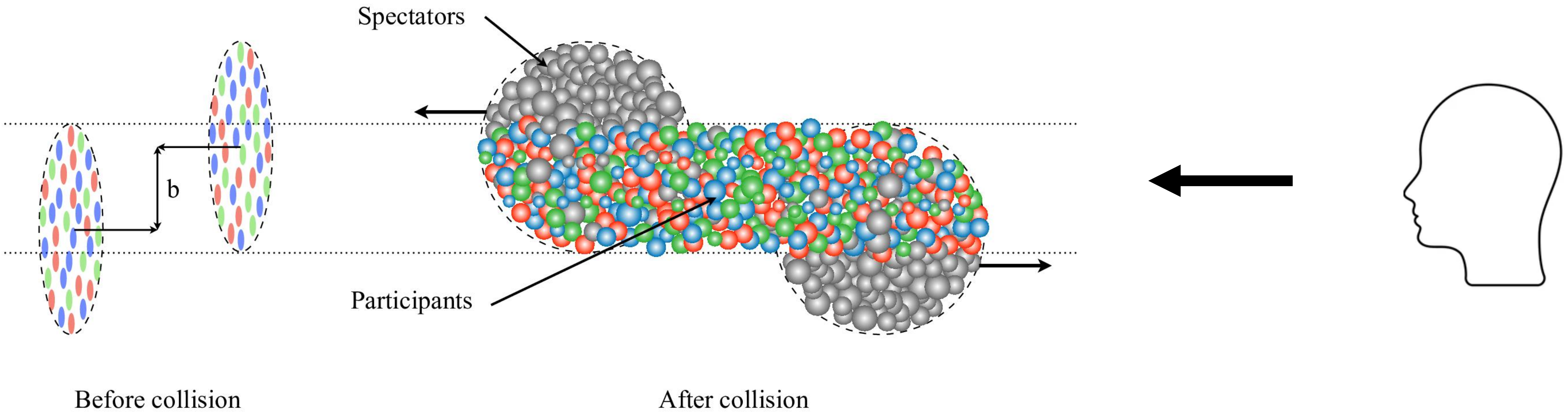




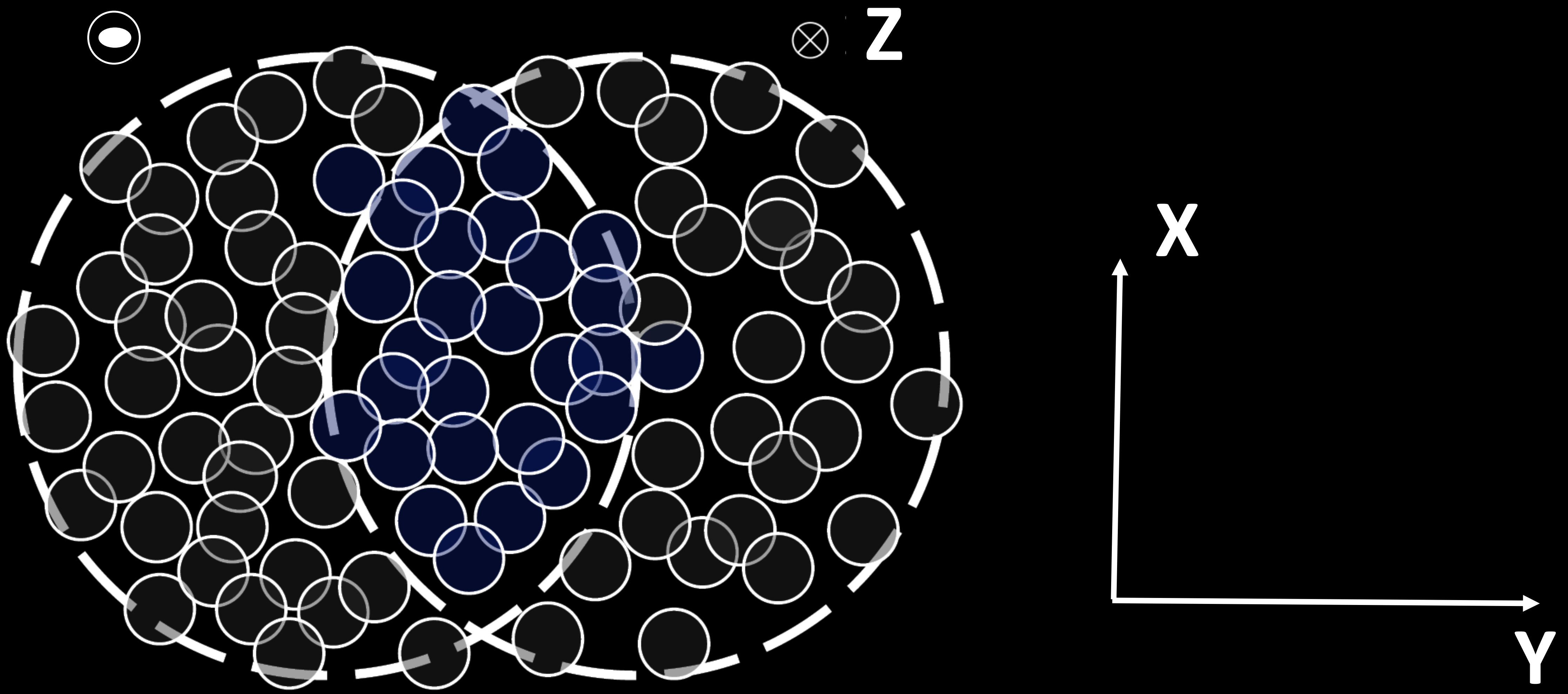
High Energy Heavy Ion Colliders around the world

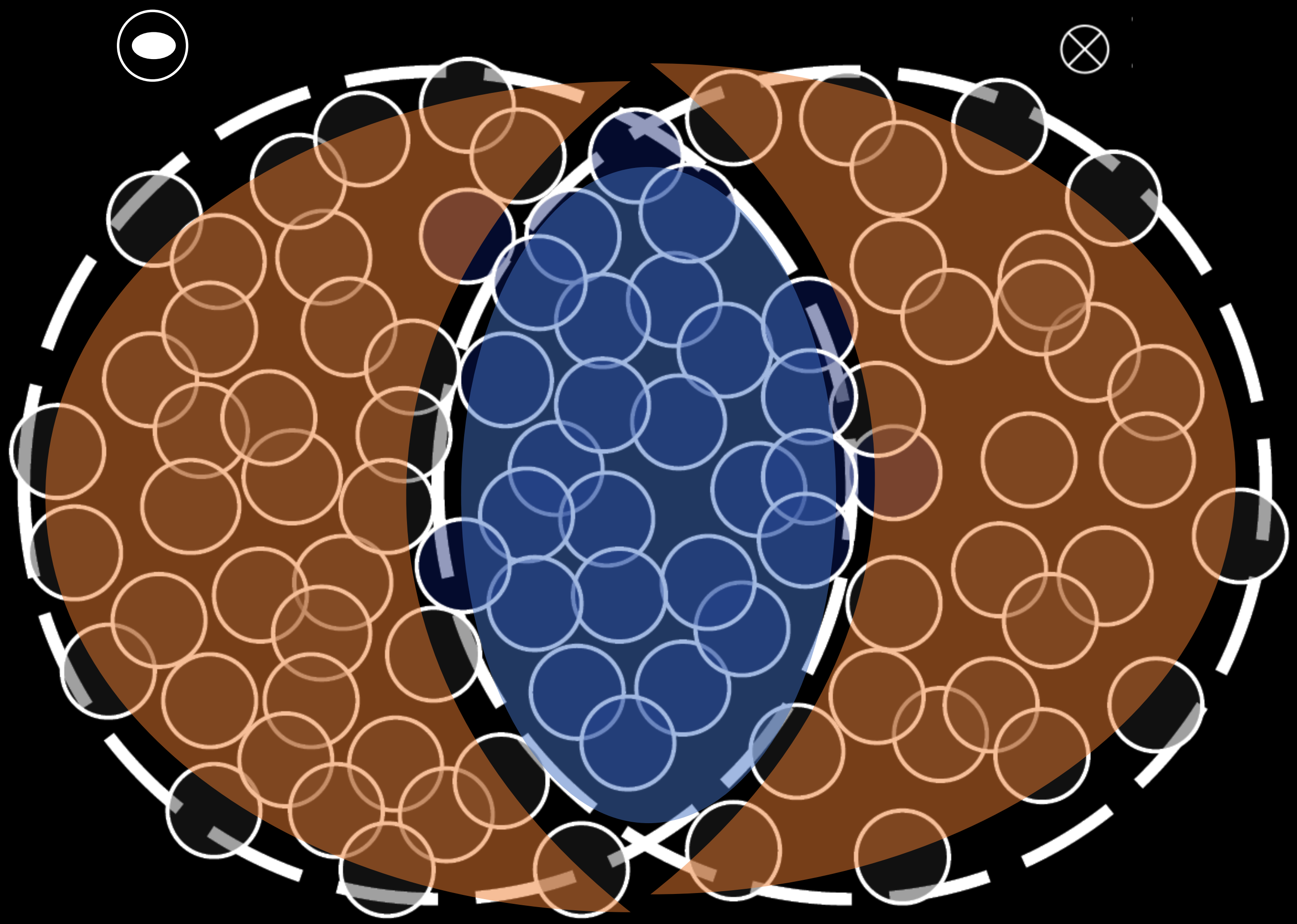



CMS
LHCb
ALICE
ATLAS

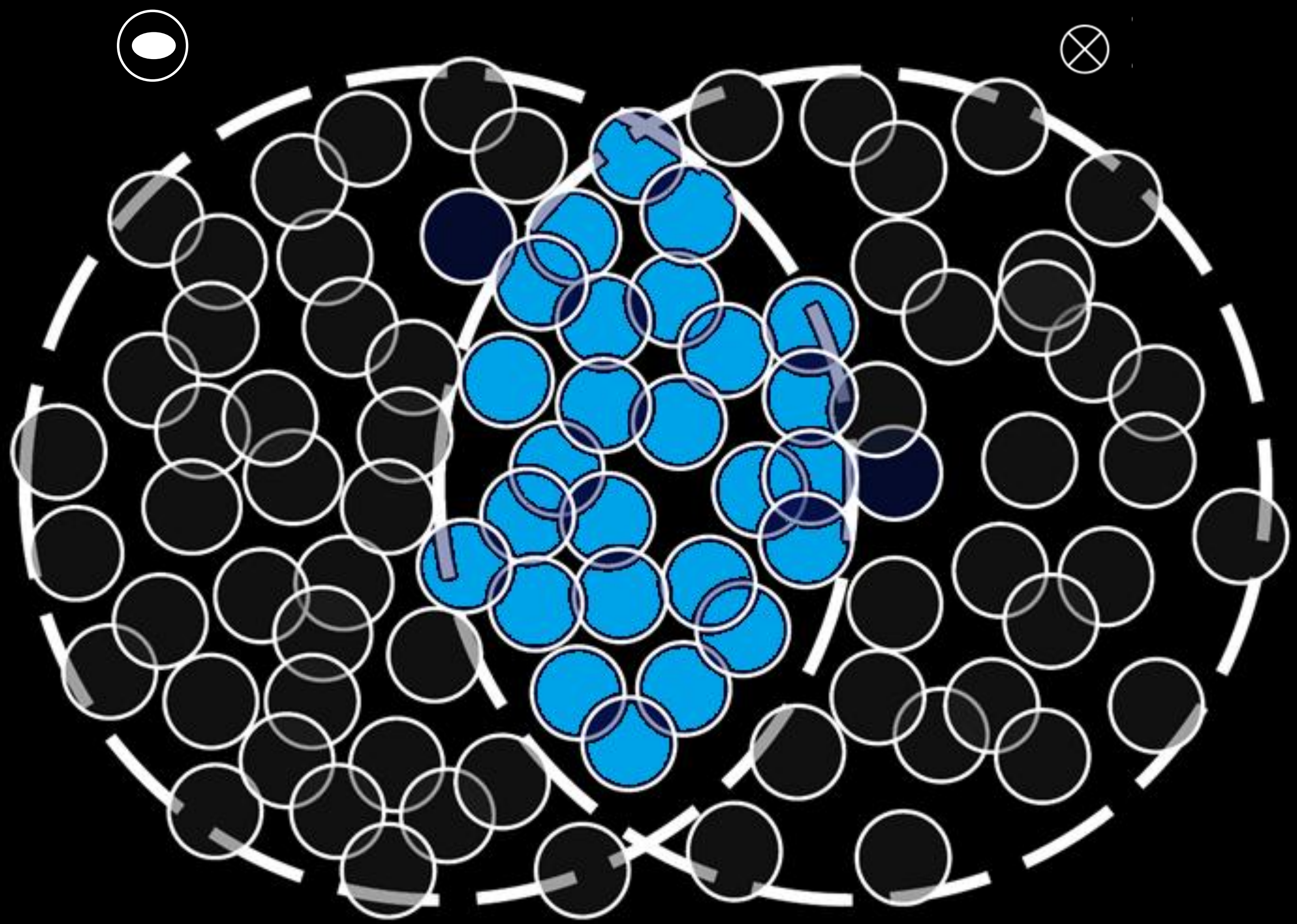


Spectators
b
Participants
Before collision
After collision

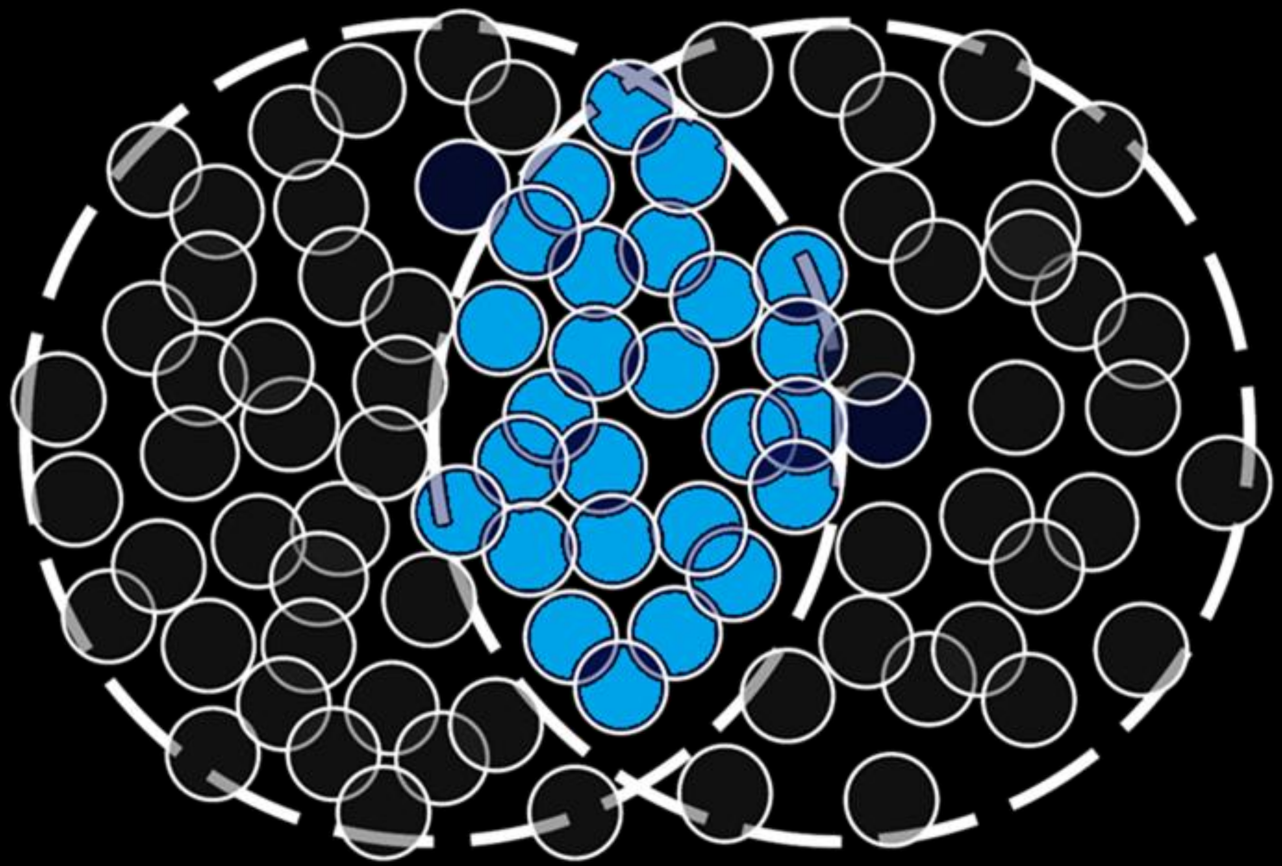

Z
X
Y


Spectators
Participants

Initial state



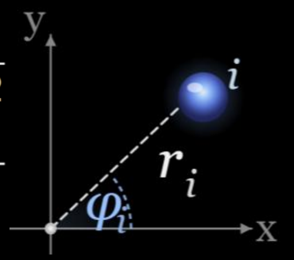
Initial state of heavy ion collisions

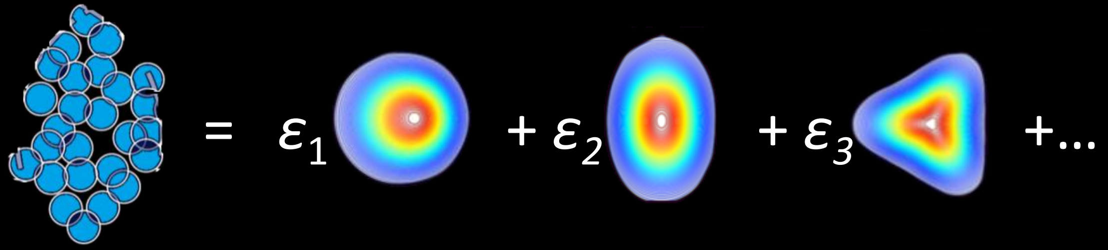


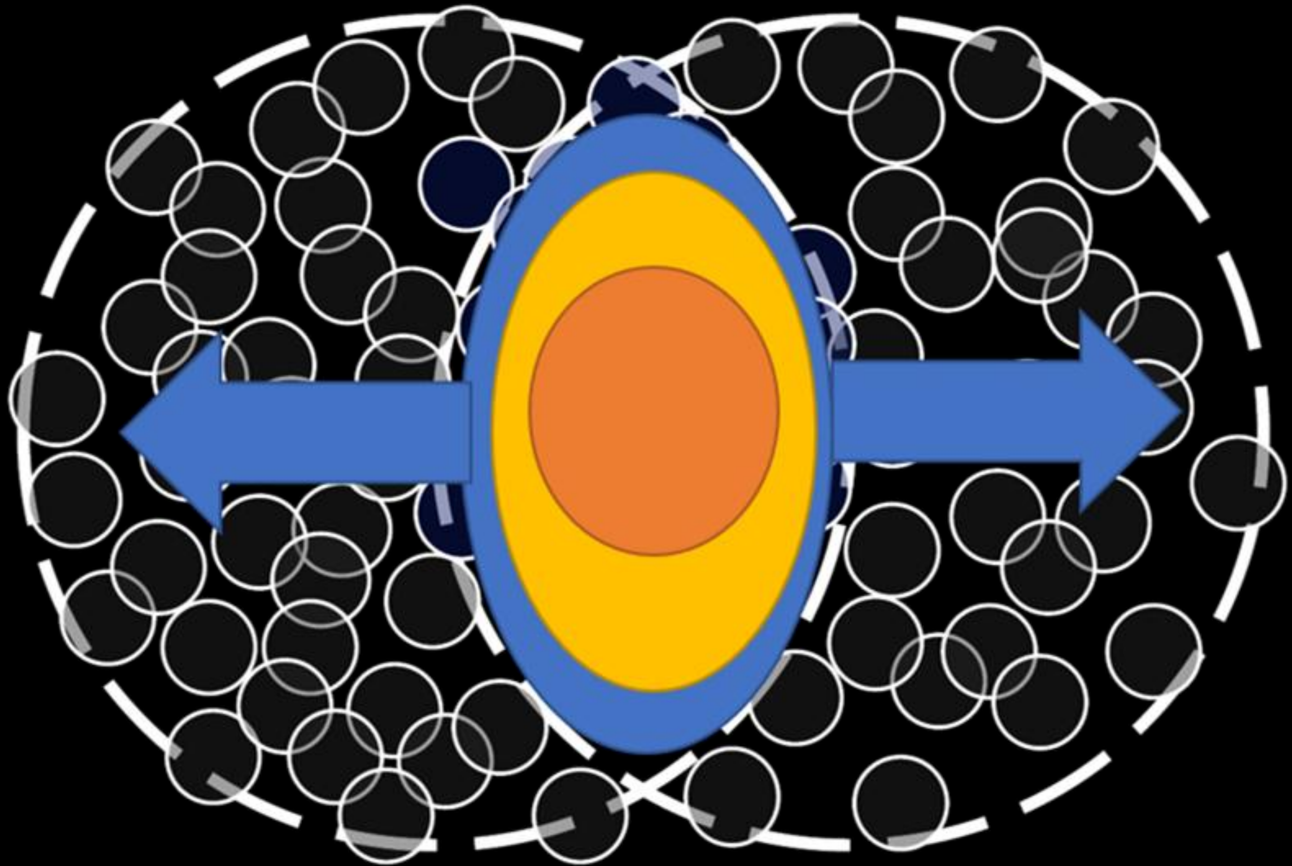
Parametrize spatial anisotropy

The "eccentricity"

$$\varepsilon_n = \frac{\sqrt{\langle r_i^n \cos(n\varphi_i)\rangle^2 + \langle r_i^n \sin(n\varphi_i)\rangle^2}}{\langle r_i^n \rangle}$$







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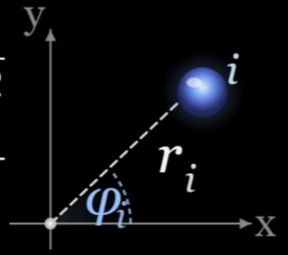
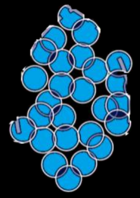


<u>Viscous Hydrodynamics</u>

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + P[\epsilon]\Delta^{\mu\nu} - \eta[\epsilon]\sigma^{\mu\nu} - \zeta[\epsilon]\Delta^{\mu\nu}\nabla^\perp_\lambda u^\lambda$$

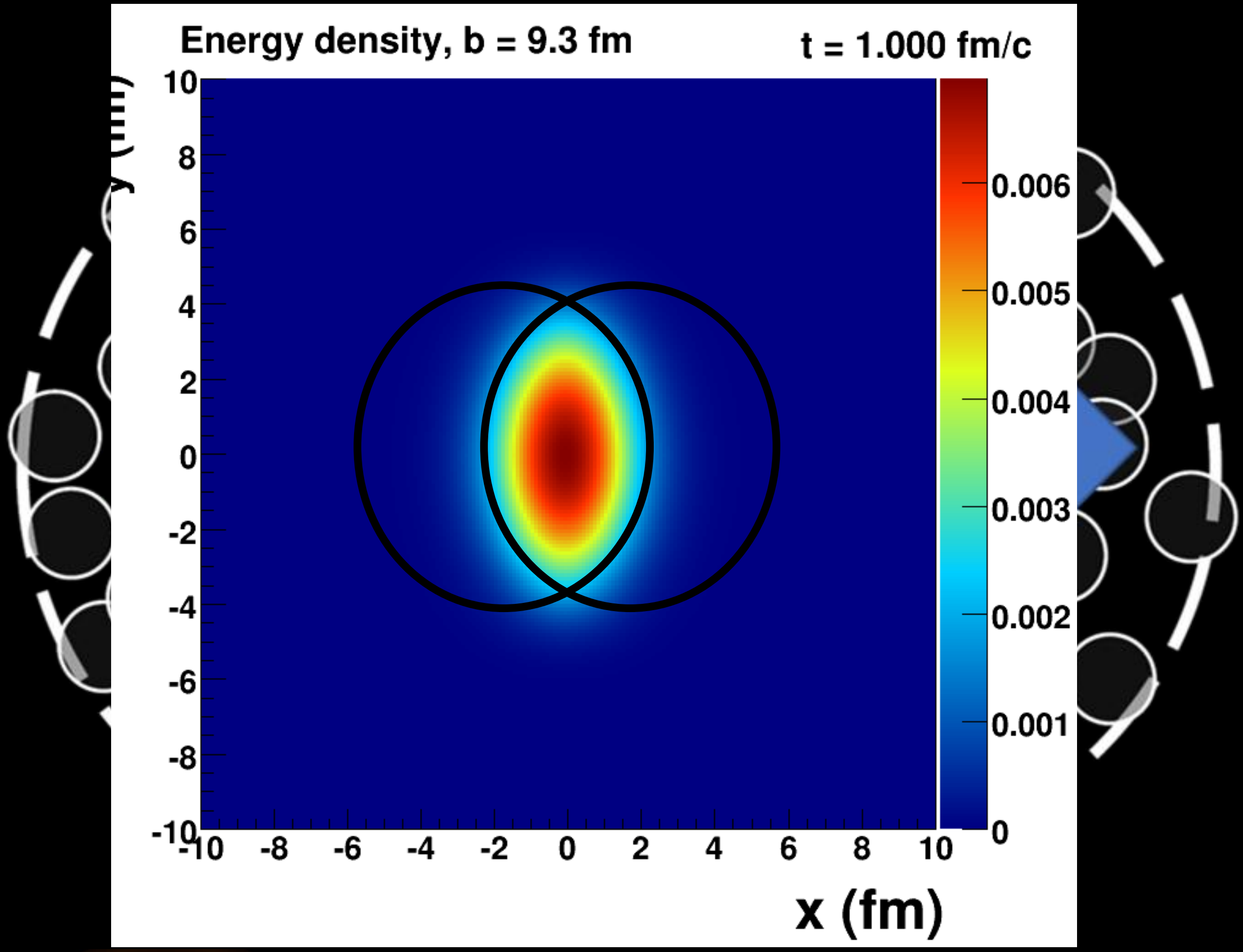
<u>Equation of stae:</u> $P[\epsilon]$ relates pressure (P), enrgy (ϵ), temperature, and entropy (s)

<u>Transport coefficients:</u> shear viscosity (η), bulk viscosity (ζ)



<u>Initial state</u> → **Hydrodynamic expansion**

ε_n



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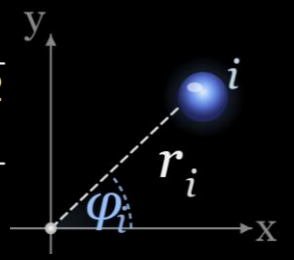

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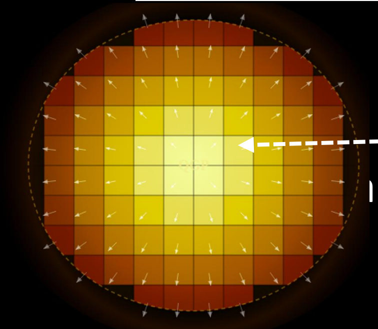
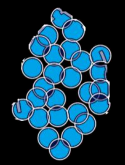


A fluid cell has, pressure, temperature and velocity (***u***).

All we need for hydro

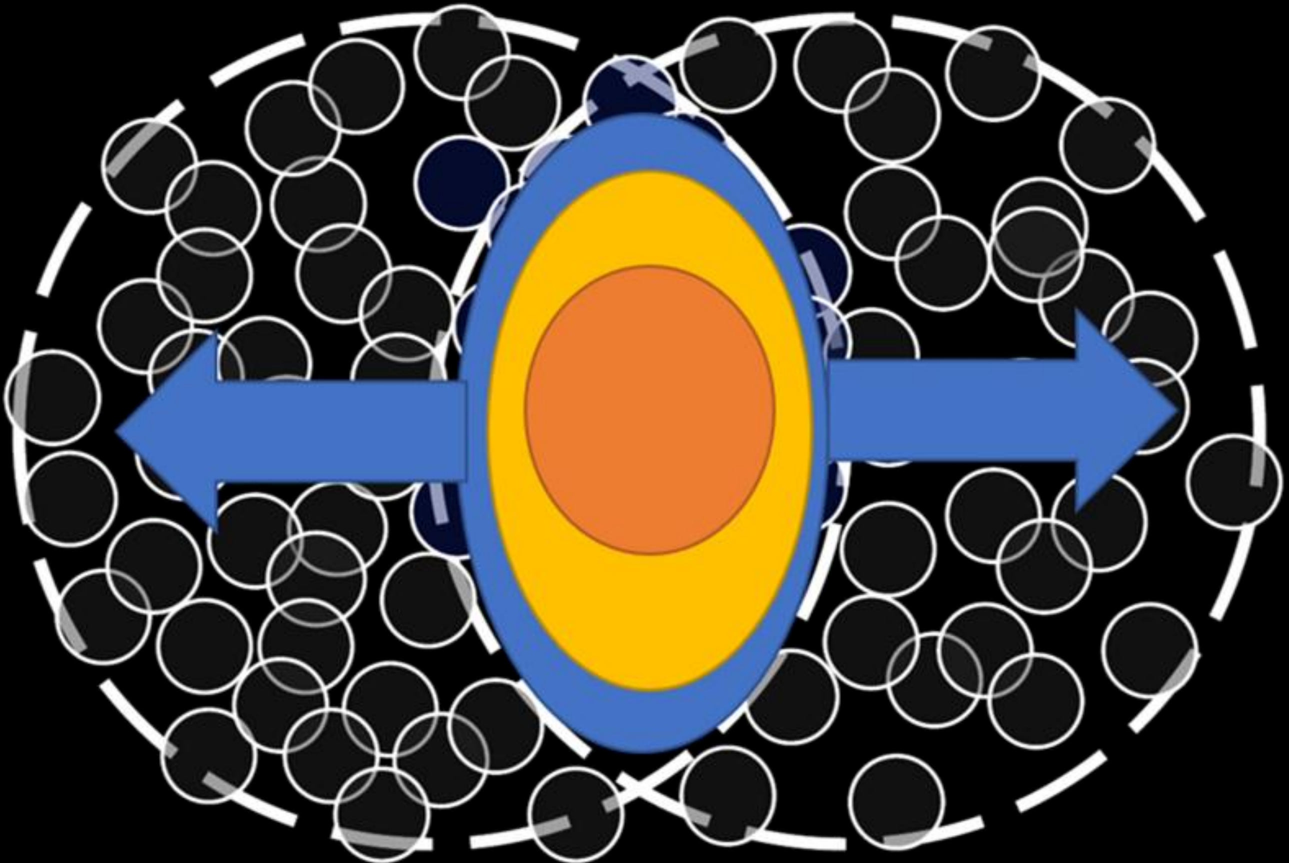
Initial conditions



u(t=0) = 0

Fluid properties

P[e] & shear/bulk viscosity



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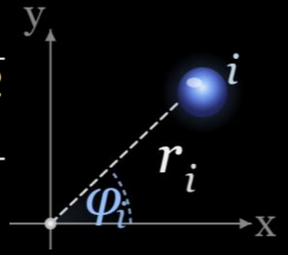

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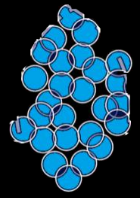

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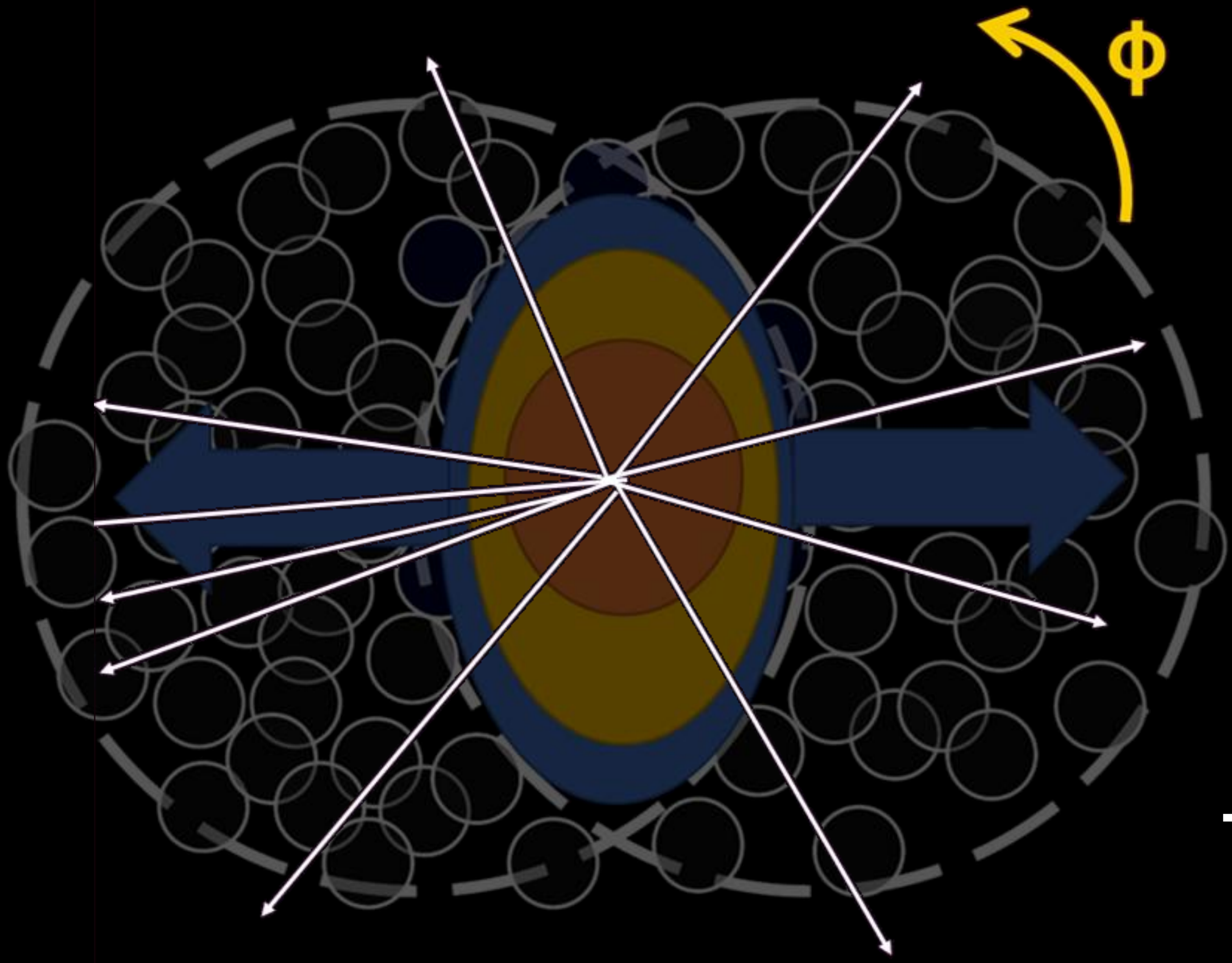

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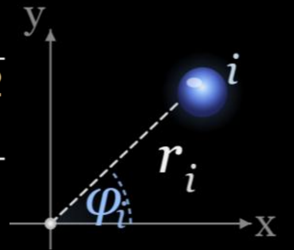

Viscous Hydrodynamics

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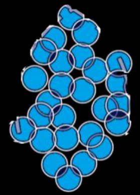
Azimuthal Momentum anisotropy

$$\frac{dN}{d\varphi} \;\alpha\; 1 + 2\boldsymbol{v_1}\cos(\phi) + 2\boldsymbol{v_2}\cos(2\phi) + 2\boldsymbol{v_3}\cos(3\phi) + \dots$$



Initial state → **Hydrodynamic expansion** → **Momentum anisotropy**

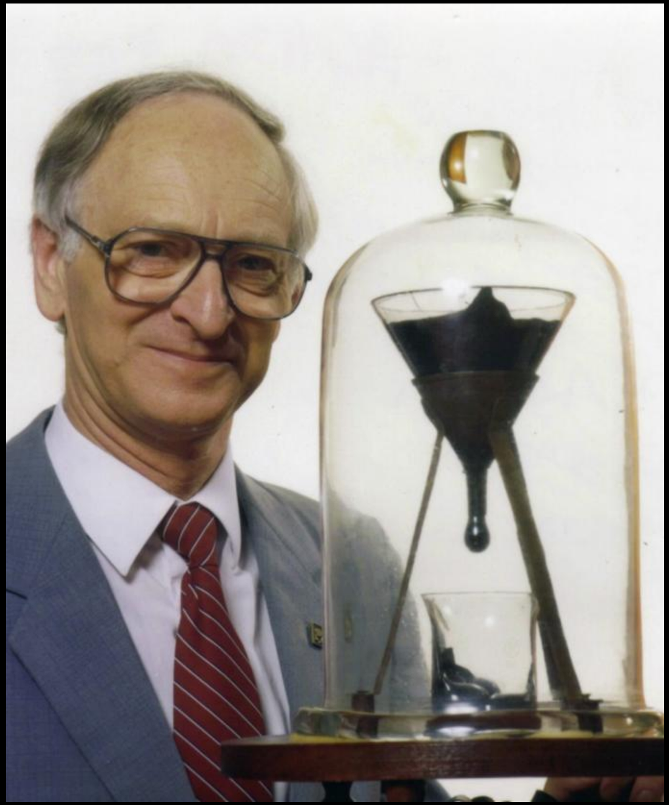
ε_n

$v_n \simeq \kappa_n \varepsilon_n$

v_n

Hydro can model lots of things!

Many things can be described by hydro: water, billiard balls, glass, pitch tar, etc. That doesn't prove we have created a QGP

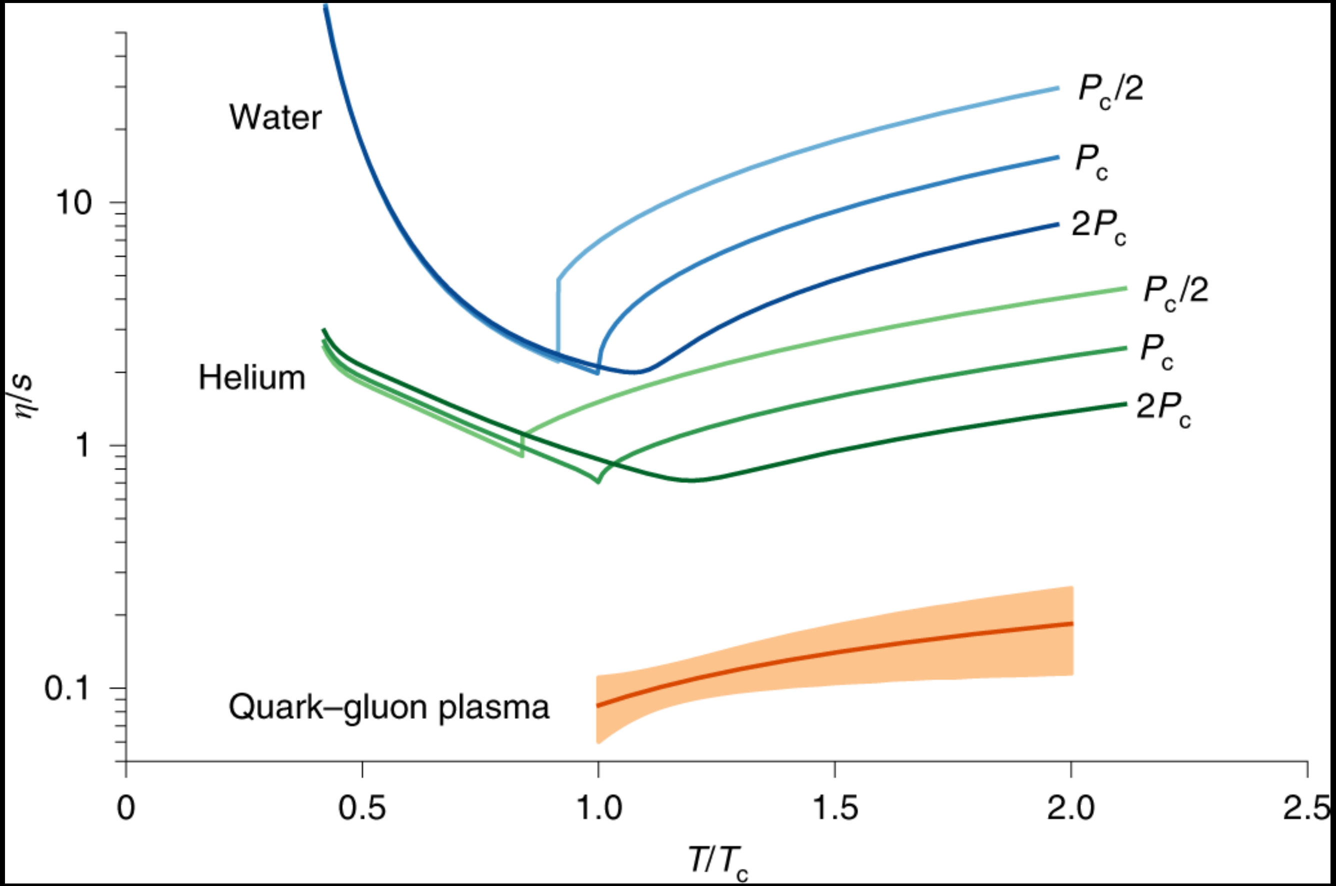


- **World's longest-running lab experiment:** Set up by Thomas Parnell in 1927
- **Pitch**, a tar-derived resin that looks solid — is actually a fluid roughly **230 billion times more viscous than water**
- **Only nine drops in ~95 years:** Drops have fallen in **1938, 1947, 1954, 1962, 1970, 1979, 1988, 2000, and 2014**

Substance	Temperature	Viscosity (cp)
Air	18°C	0.018
Water	0°C	1.8
Water	20°C	1
Water	100°C	0.28
Glycerin	20°C	1500
Mercury	20°C	1.6
n-Pentane	20°C	0.23
Argon	85K	0.28
He^4	4.2K	0.033
Superfluid He^4	< 2.1K	0
Glass		$> 10^{15}$

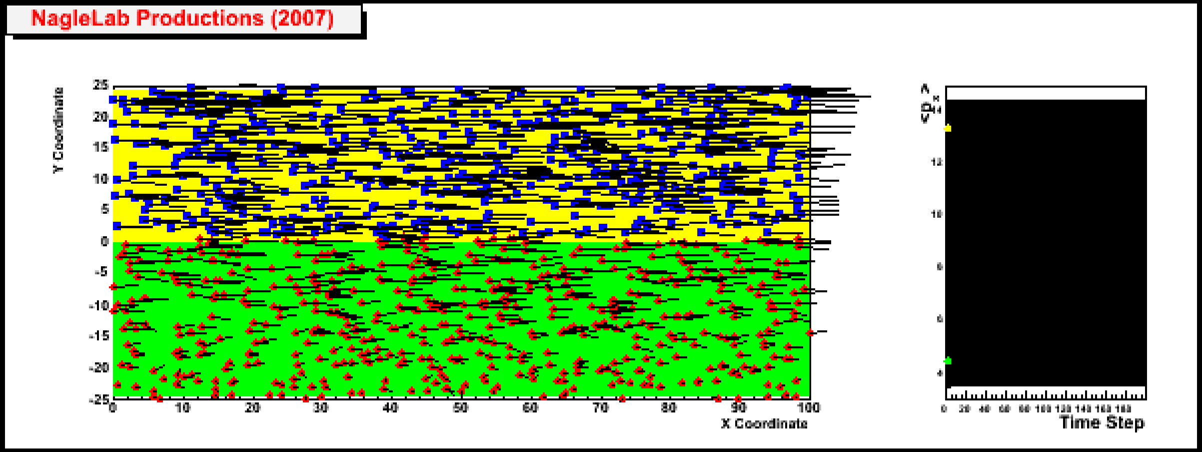
Measured QGP viscosity

- Measured η/s: the smallest suitably normalized shear viscosity
  - Need to divide by something like the density, *s* (entropy)
- Measured viscosity is in line with expectations for QGP
- One of the main pillars supporting confidence in creating the QGP in heavy ion collisions

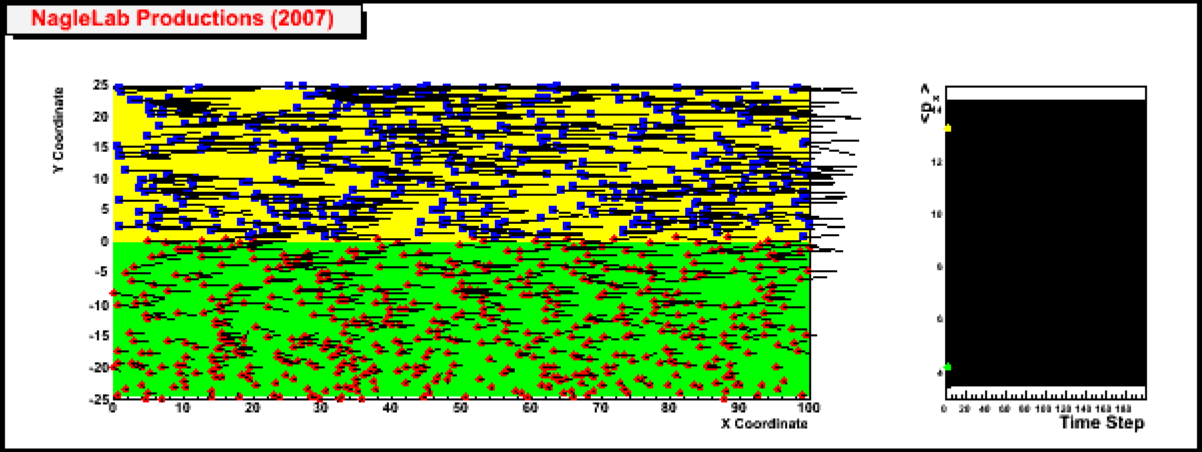


Why a low viscosity

Weak coupling = Large viscosity



Strong coupling = Small viscosity



Inhibited diffusion
↓
Small viscosity
↓
Perfect fluid
↓
Strongly Coupled QGP

How small a system can flow?

$$T^{\mu\nu} = \underbrace{\epsilon u^\mu u^\nu + P[\epsilon]\Delta^{\mu\nu}}_{\text{Zeroth order hydro}} \underbrace{- \eta[\epsilon]\sigma^{\mu\nu} - \zeta[\epsilon]\Delta^{\mu\nu}\nabla^\perp_\lambda u^\lambda}_{\text{First order hydro}} + \ldots$$

Perfect fluid

Heavy ion collisions are large enough to be well modeled by first order hydrodynamics

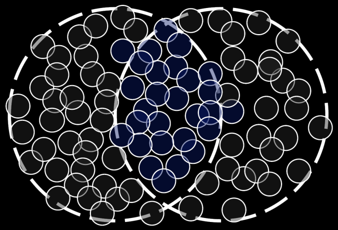
The smaller the system, the larger the corrections at first order, second order, …

Does the series converge?

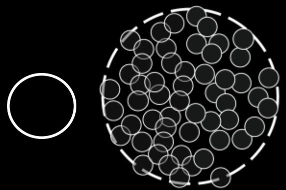
This is the fundamental question of small systems

System size

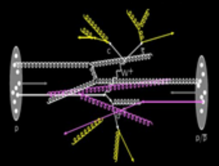
Pb+Pb



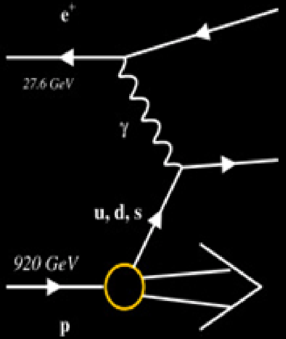
p+Pb



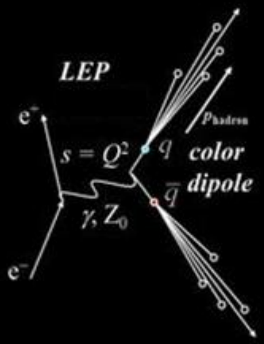
pp



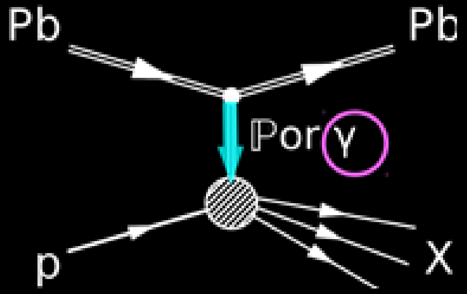
e+*p*



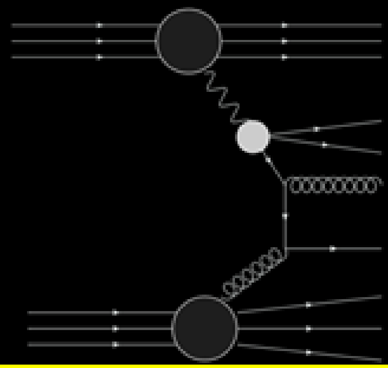
e^++e^-



γ+*p*

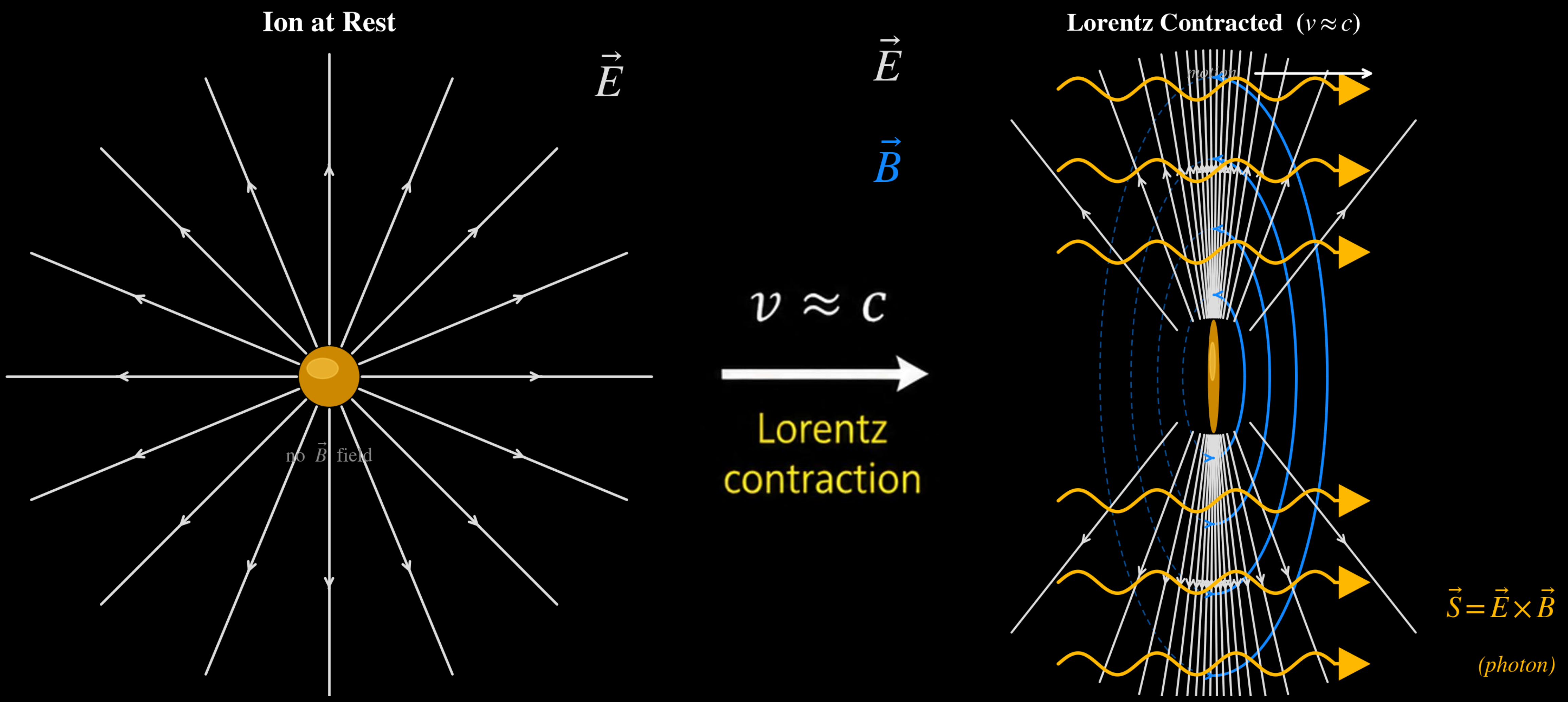


γ+A

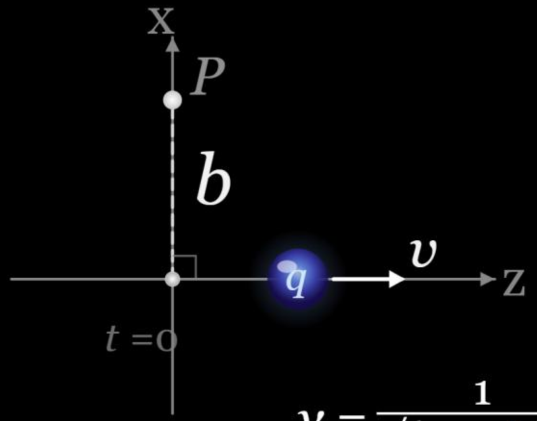


Ultra-peripheral collisions

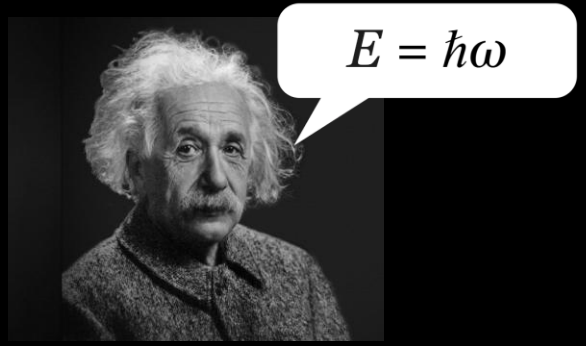
Electromagnetic fields of Relativistic ion



EM fields of moving charges



$$\gamma = \frac{1}{\sqrt{(1- v^2/c^2)}}$$



$$\vec{E}(t) = \begin{cases} E_x = \dfrac{q}{4\pi} \dfrac{\gamma b}{(b^2 + v^2\gamma^2 t^2)^{3/2}}, \\ E_z = -\dfrac{q}{4\pi} \dfrac{v\gamma t}{(b^2 + v^2\gamma^2 t^2)^{3/2}} \end{cases}$$

- EM field a distance *b* away as the charge *q* passes

$$\vec{E}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \vec{E}(t)\, e^{i\omega t}\, dt$$

- Fourier transform: express the ***E***(t) as set of waves with frequency ω

$$\frac{dI}{d\omega} = 4\pi |\vec{E}(\omega)|^2$$

- Calculate energy per unit frequency

$$N(\hbar\omega) = \frac{1}{\hbar^2\omega} \frac{dI}{d\omega}$$

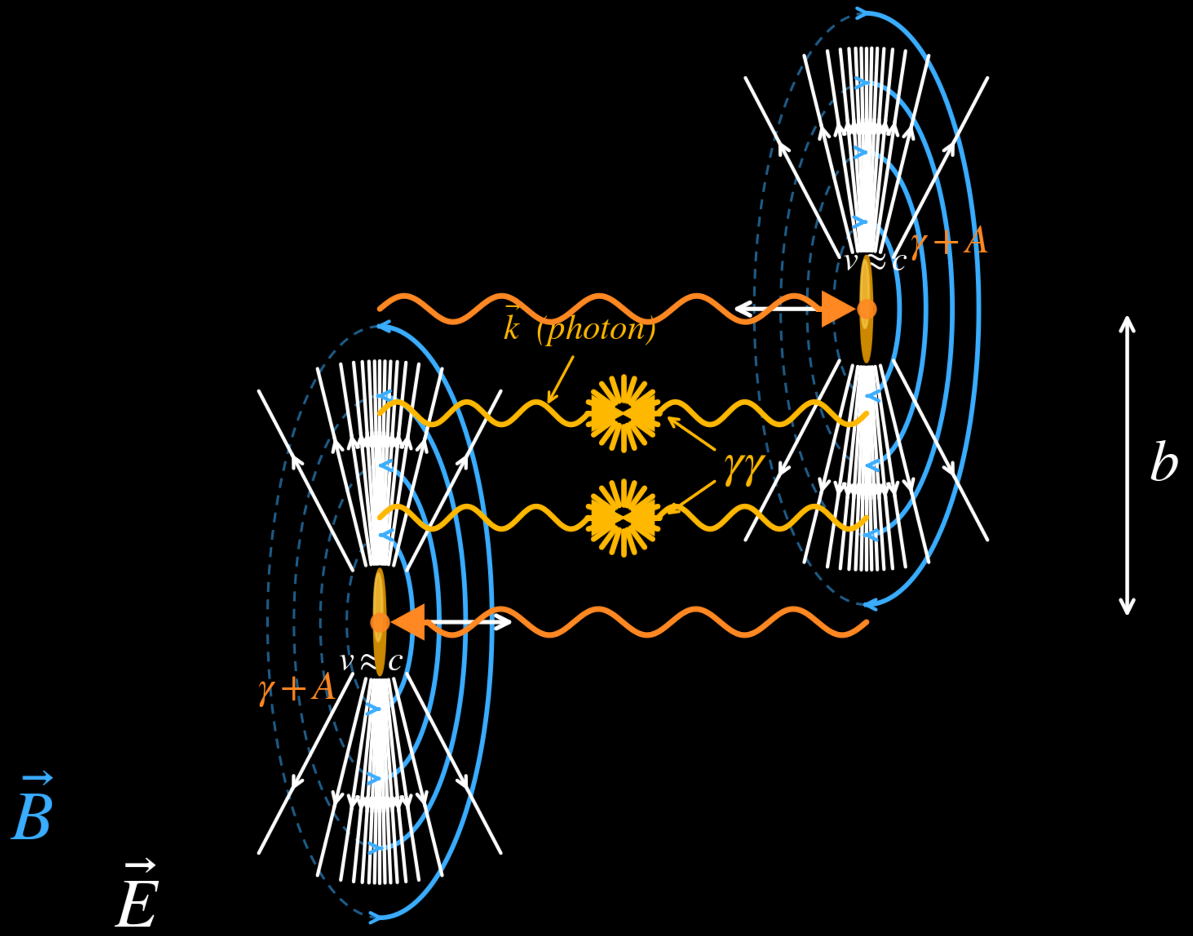
- Convert into number density of photons

$$N(\hbar\omega) = \frac{q^2}{4\pi} \frac{1}{\omega} \frac{1}{\pi^2 v^2 b^2} \left(\frac{\omega b}{\gamma v}\right)^2 \left[K_1^2\left(\frac{\omega b}{\gamma v}\right) + \frac{1}{\gamma^2} K_0^2\left(\frac{\omega b}{\gamma v}\right)\right]$$

- Full photon flux where $K_{1,0}$ are Bessel's functions

Very accurate description of photon energy spectrum from "basic" E&M

EM fields in collision



Equivalent photon approximation (EPA)

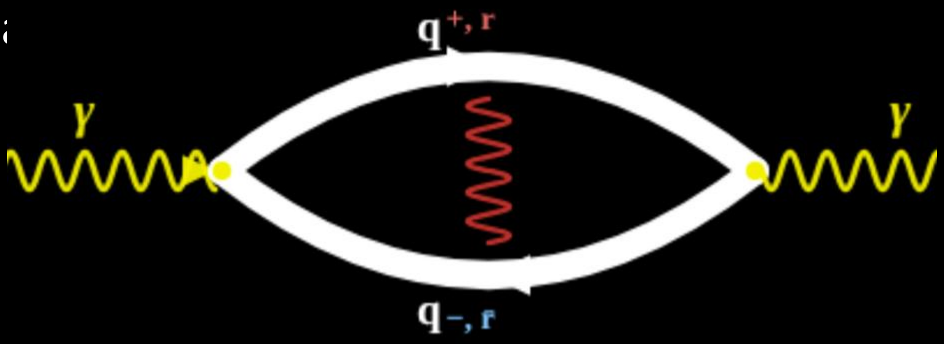
- EM field is a flux of quasi-real photons
- Developed by Fermi, Weizsäcker, and Williams
- Implemented in STARLIGHT, SuperChic

	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

At the LHC/RHIC we can study the most energetic photon interaction in the world

The structure of the photon

The photon can undergo quantum fluctuations into other st

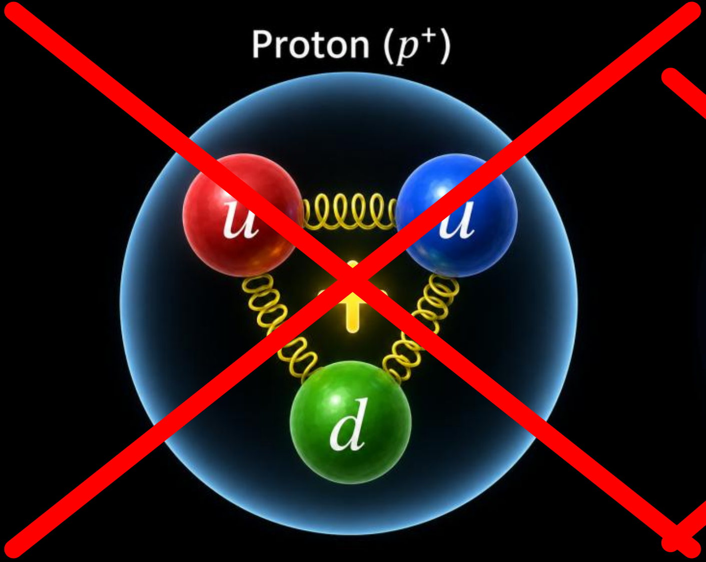


Quantum doesn't mean there are no rules!!

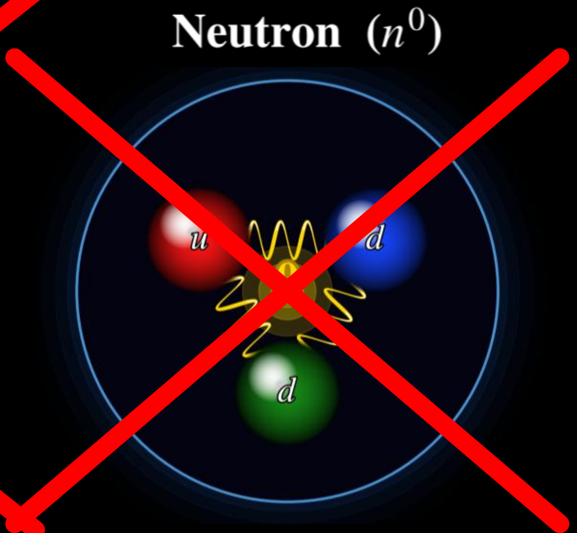
Consider two

1. Charge conservation
2. Angular momentum conservation

Which hadrons can a photon fluctuate into?

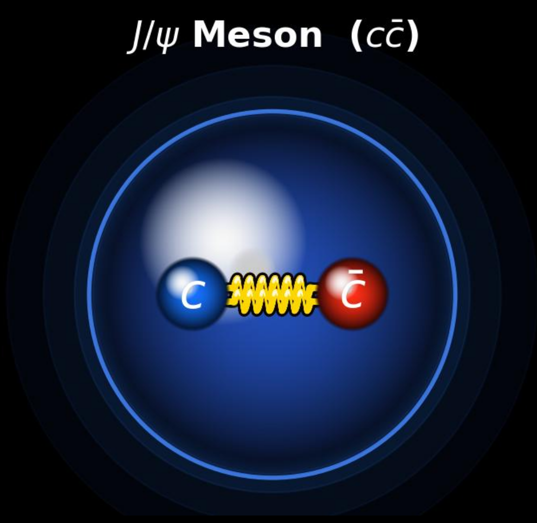


m = 938.3 MeV/c²
J = ½ ħ

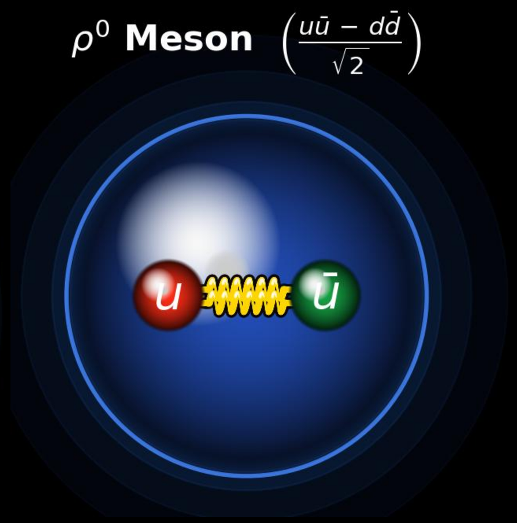


m = 939.6 MeV/c²
J = ½ ħ

Vector mesons



m = 3096.9 MeV/c²
J = 1 ħ



m = 775.3 MeV/c²
J = 1 ħ

Photon wave function

Low (Q^2 = 0) virtuality photons

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

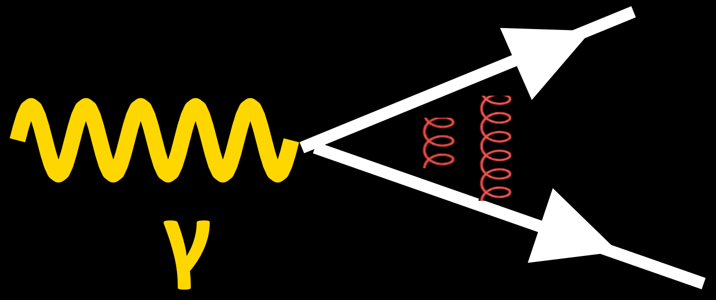
Where $\langle\gamma|\gamma\rangle = 1$

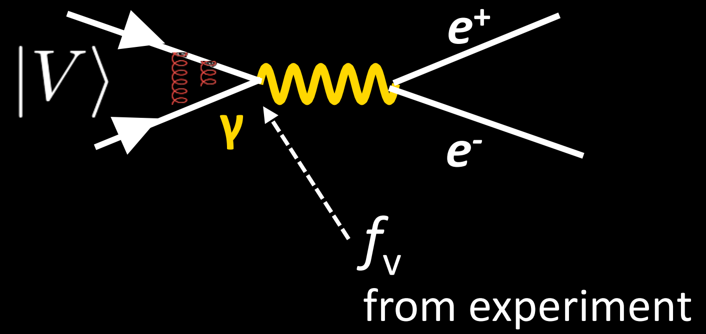
$$Z_3 = 1 - \sum_{V=\rho^0,\,\omega,\,\phi} \left(\frac{\sqrt{4\pi\alpha_{\mathrm{EM}}}}{f_V}\right)^2 - \cdots$$

Total wave function

Bare photon

Vector meson component





Two-photon interactions

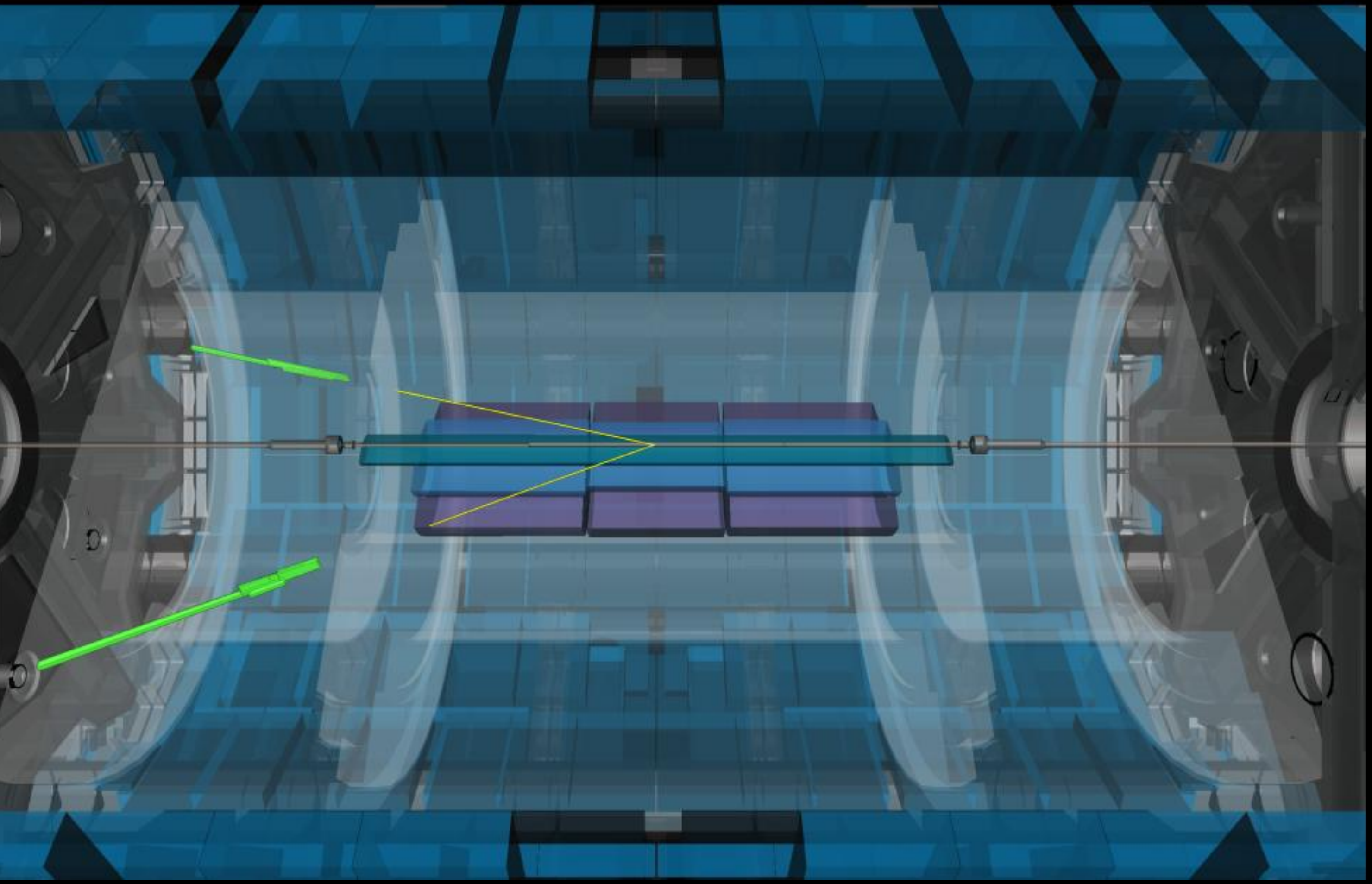
$$|\gamma\rangle \otimes |\gamma\rangle$$

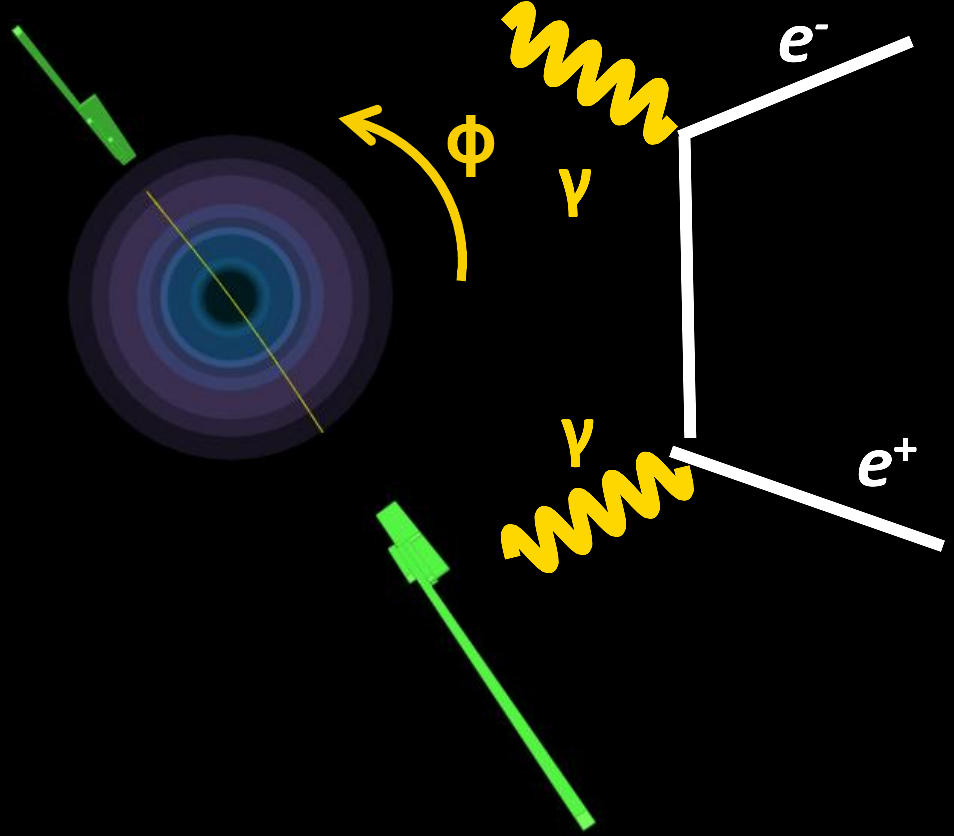
Photon-nucleus interactions

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

Two-photon interactions

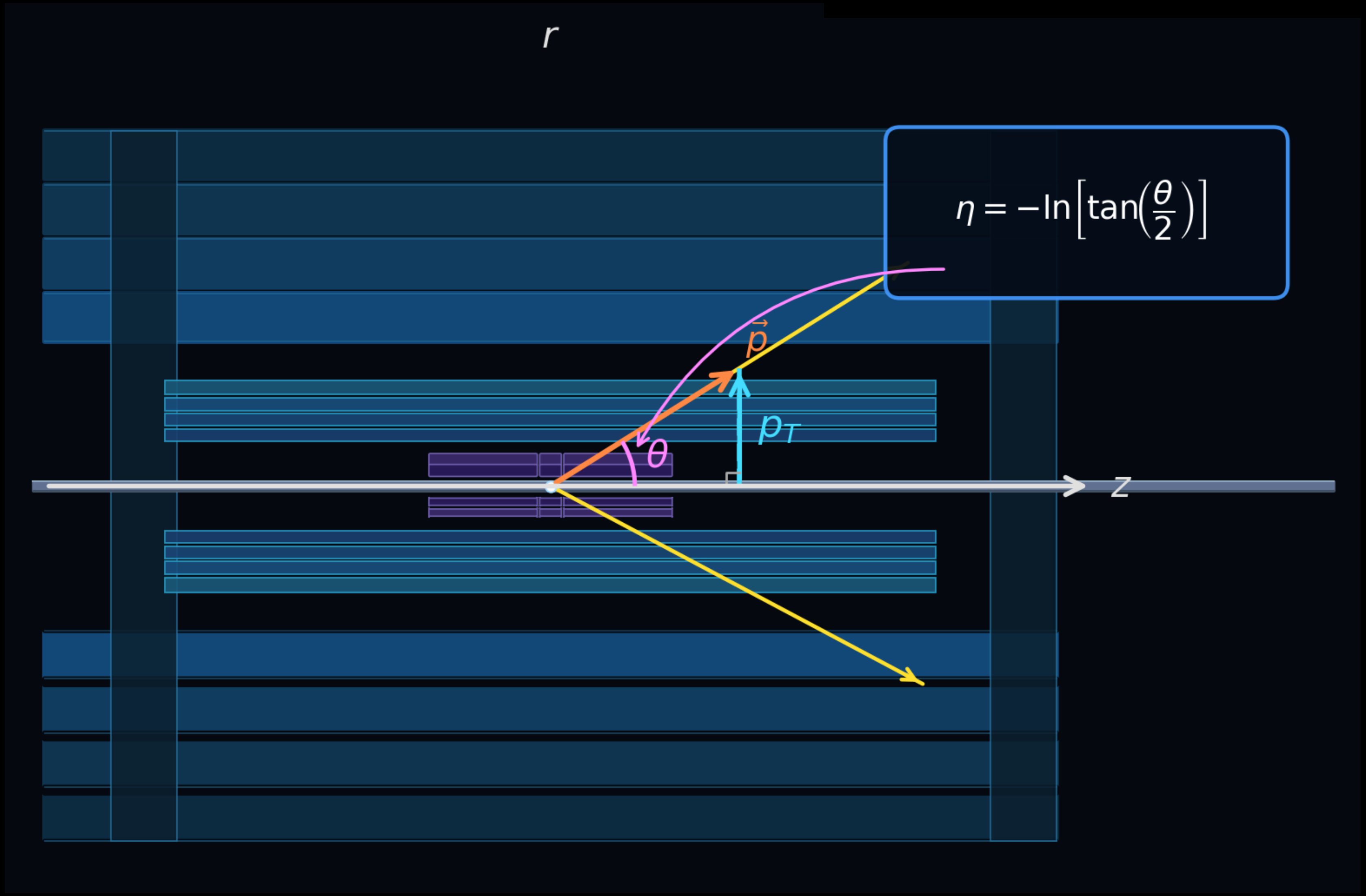
$$|\gamma_{\text{bare}}\rangle \otimes |\gamma_{\text{bare}}\rangle$$

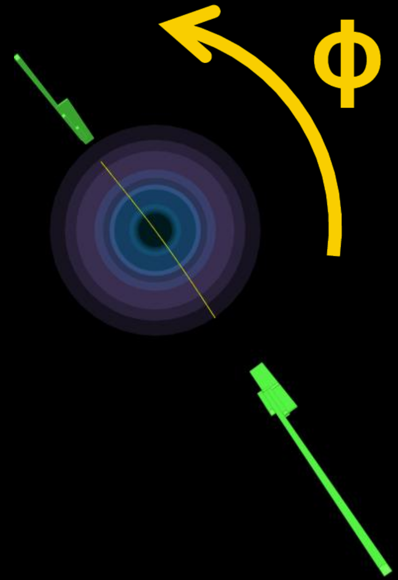




Two-photon interactions

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





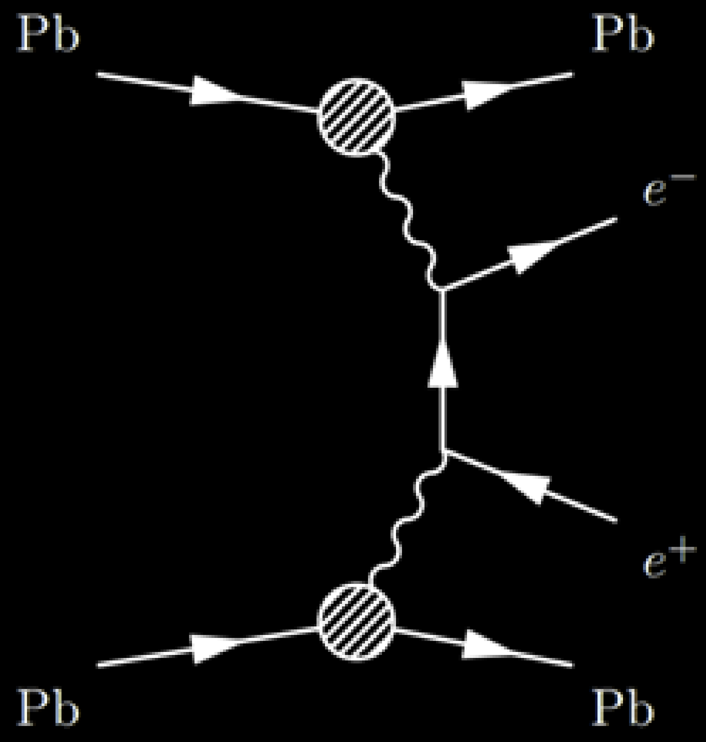
Two-photon interactions

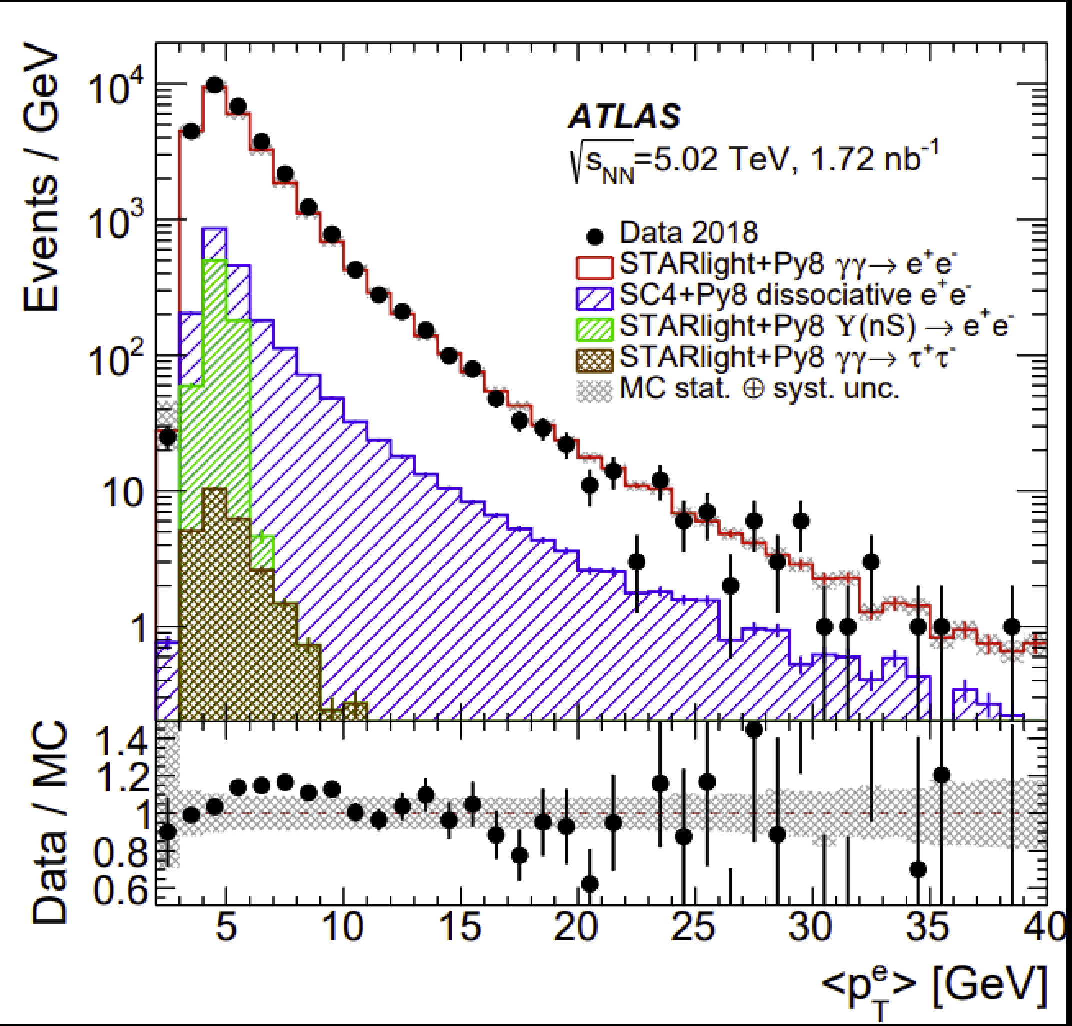
$|\gamma_{\mathrm{bare}}\rangle \otimes |\gamma_{\mathrm{bare}}\rangle$

Pure EM interactions

- Back-to-back products
- Good agreement with **EPA**

γγ →ee [arXiv:2207.12781]





Other photon-photon interactions

$|\gamma_{\text{bare}}\rangle \otimes |\gamma_{\text{bare}}\rangle$ γγ →ee, and many others

- Pure EM measurements by ATLAS
  - 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

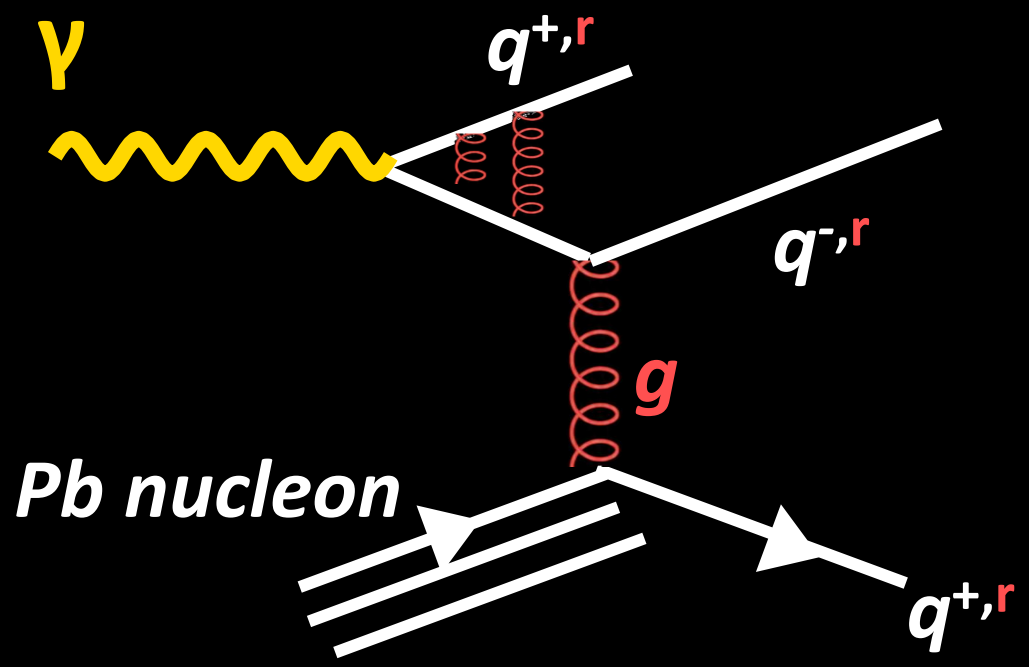
$|V\rangle \otimes |V\rangle$ Not been measured

$|\gamma_{\text{bare}}\rangle \otimes |V\rangle$ Not been measured

Comparing photonuclear interactions

Resolved photonuclear collision

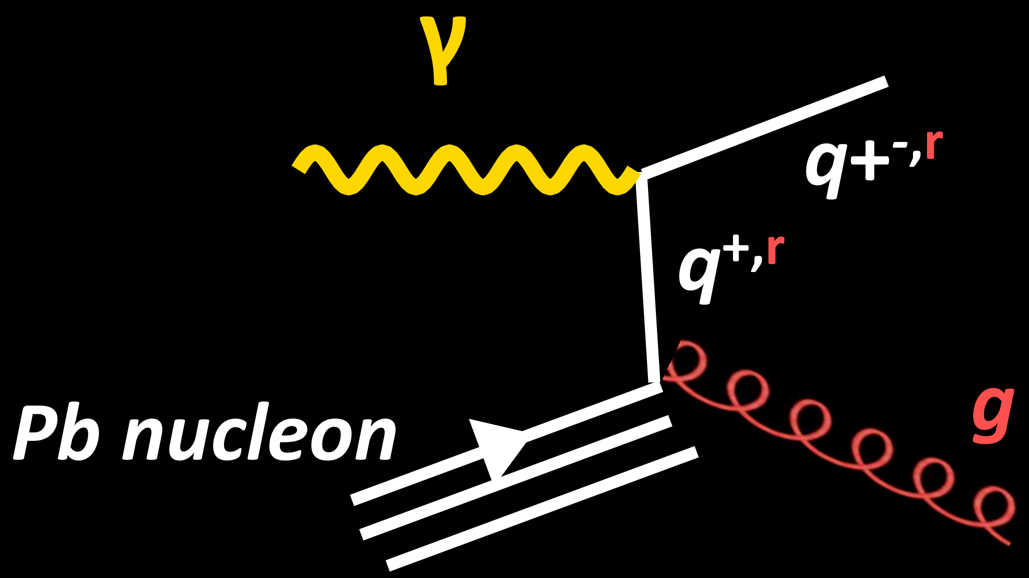
$$|V\rangle \otimes |\mathrm{Pb}\rangle$$



Probability $\propto \alpha_s^2 \alpha_{EM}$

Direct photonuclear collision

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

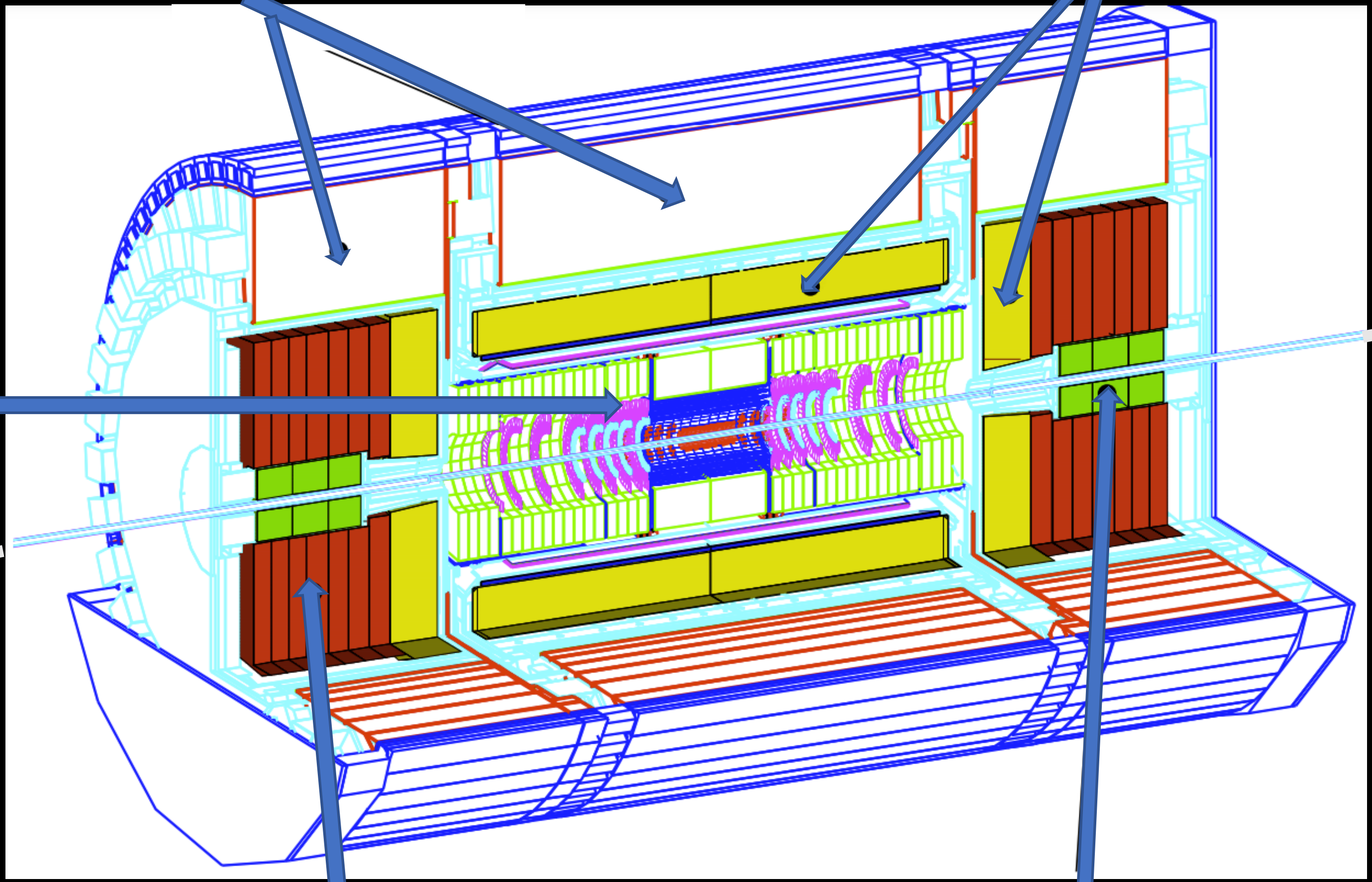


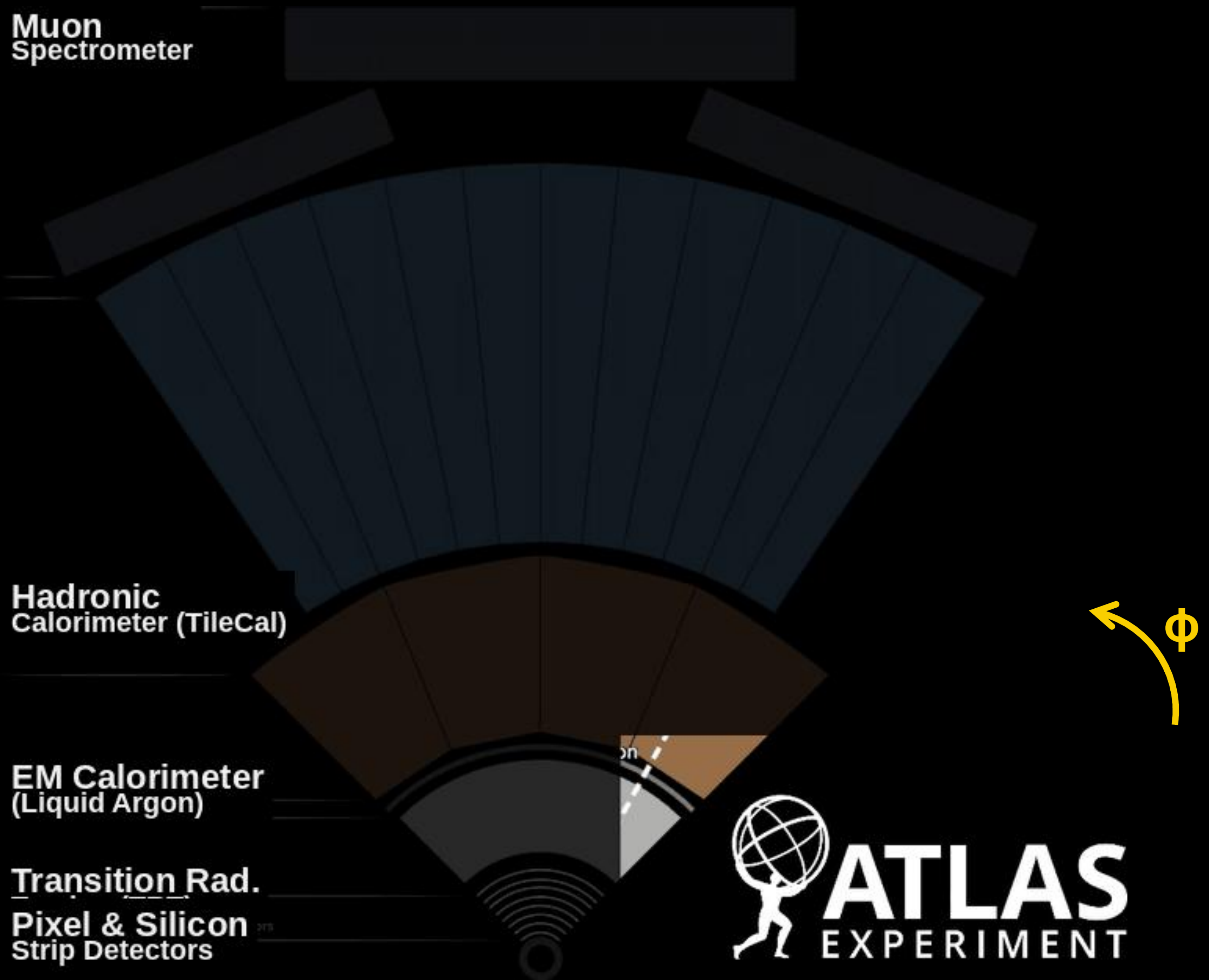
Probability $\propto \alpha_s \alpha_{EM}$

Both processes contribute a similar order of magnitude

Measuring photonuclear events with ATLAS

A Toroidal LHC ApparatuS (ATLAS)



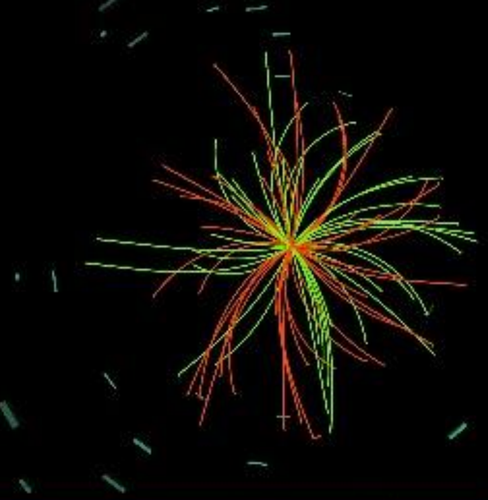


Trackers of charged particles

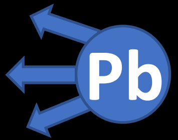
ATLAS EXPERIMENT

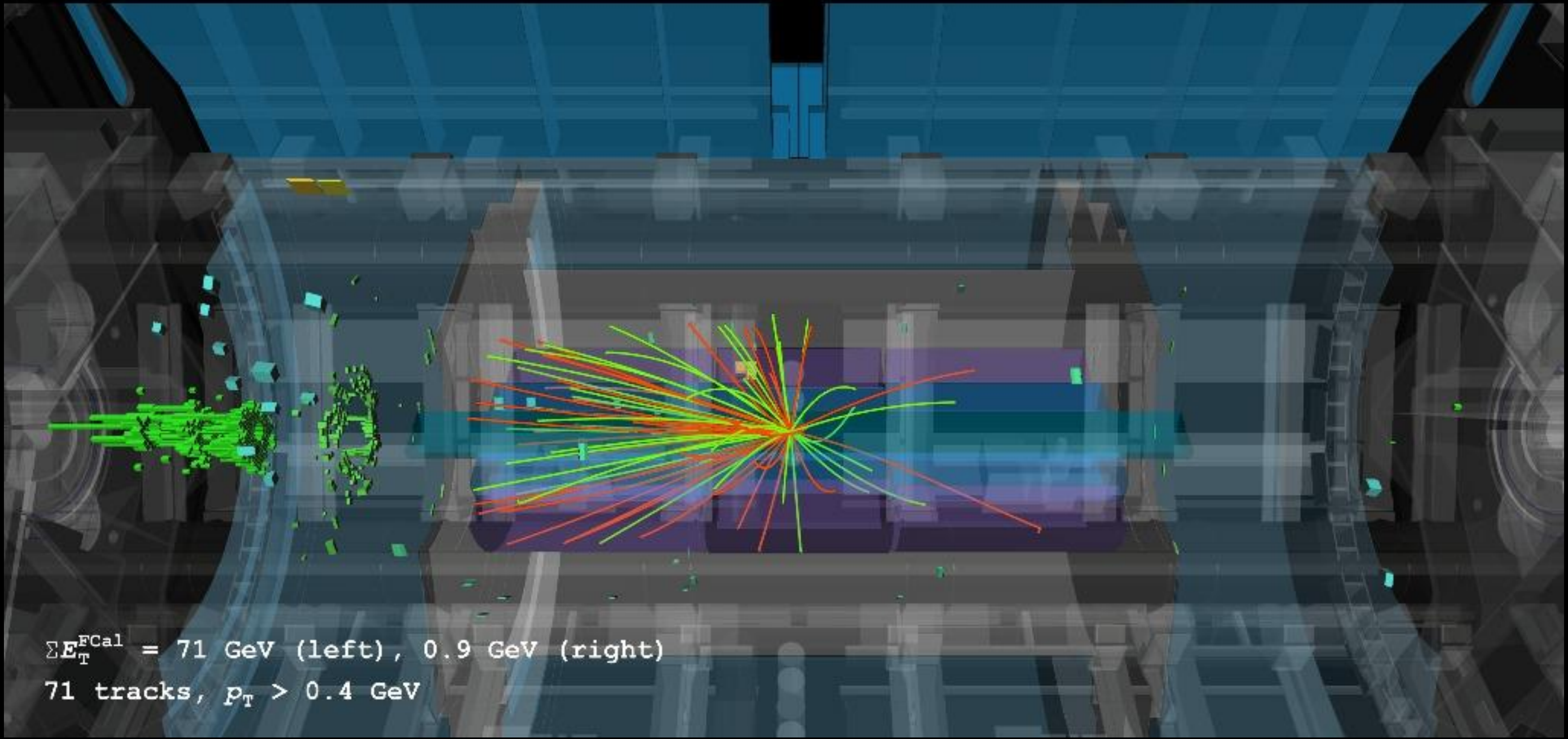
ATLAS EXPERIMENT

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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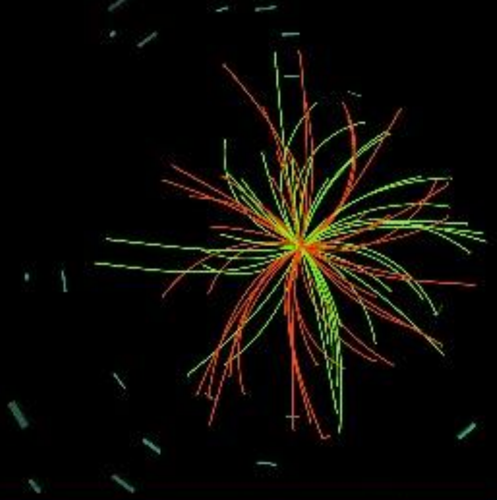
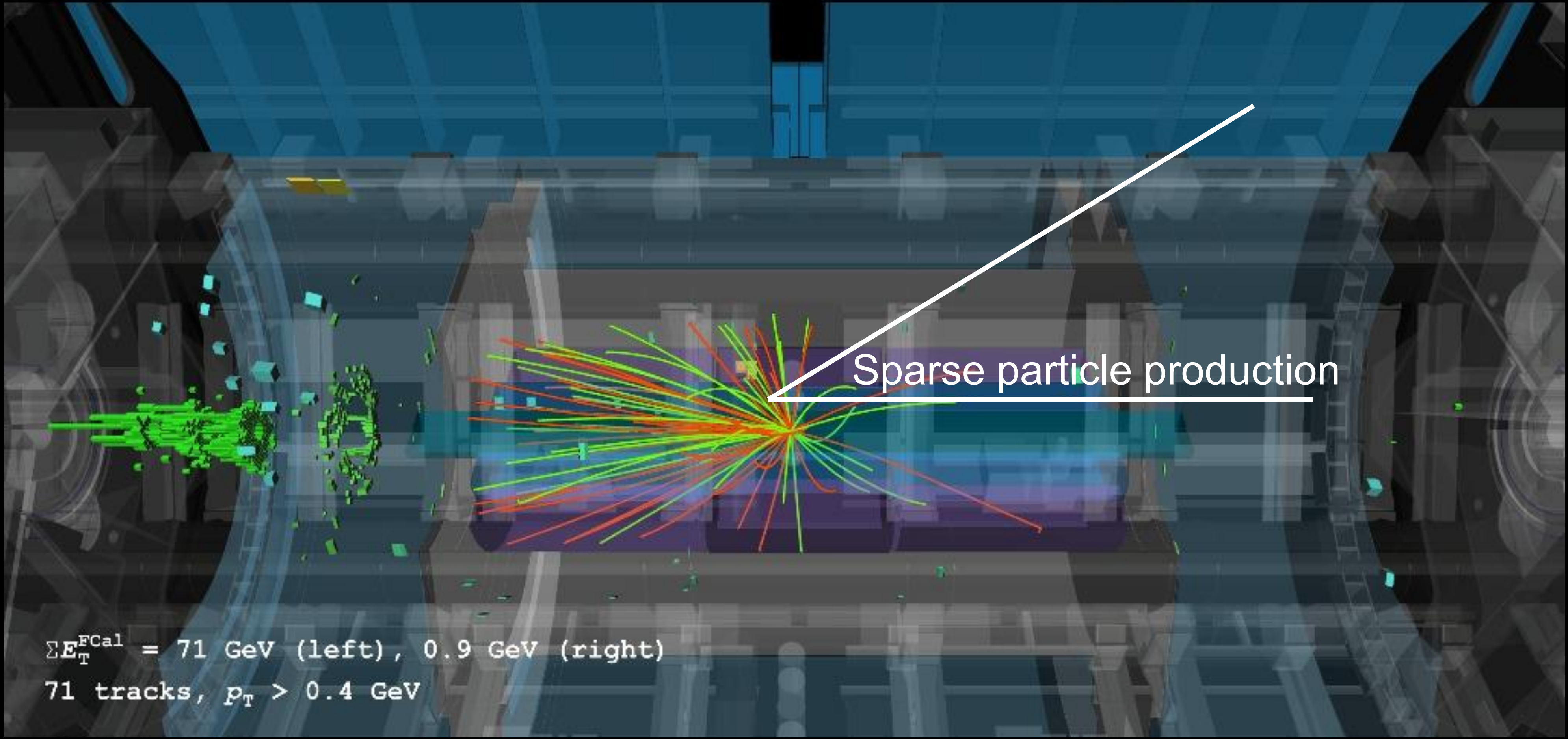
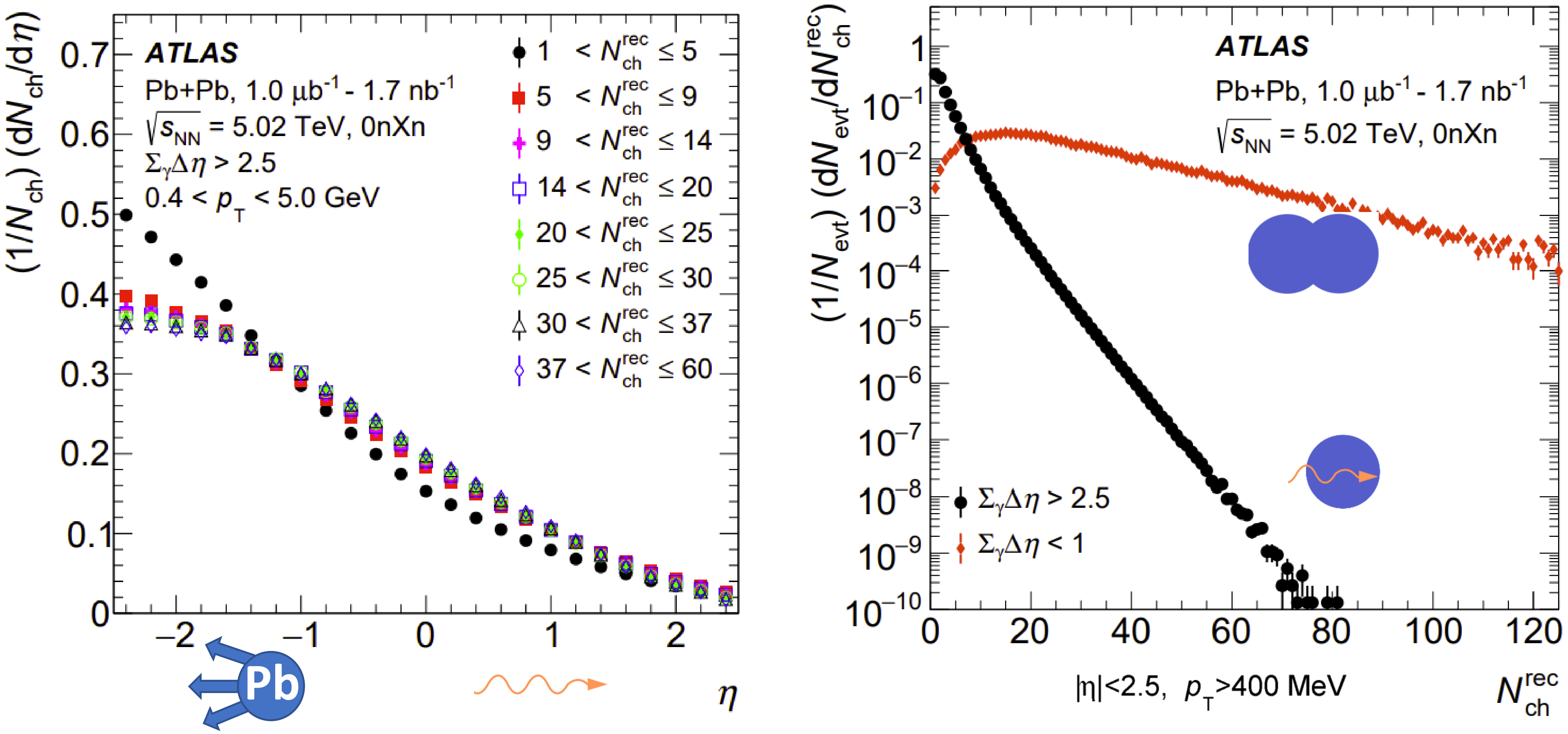


Pb going direction



photon going direction

Charge particle η distribution and N_{ch}



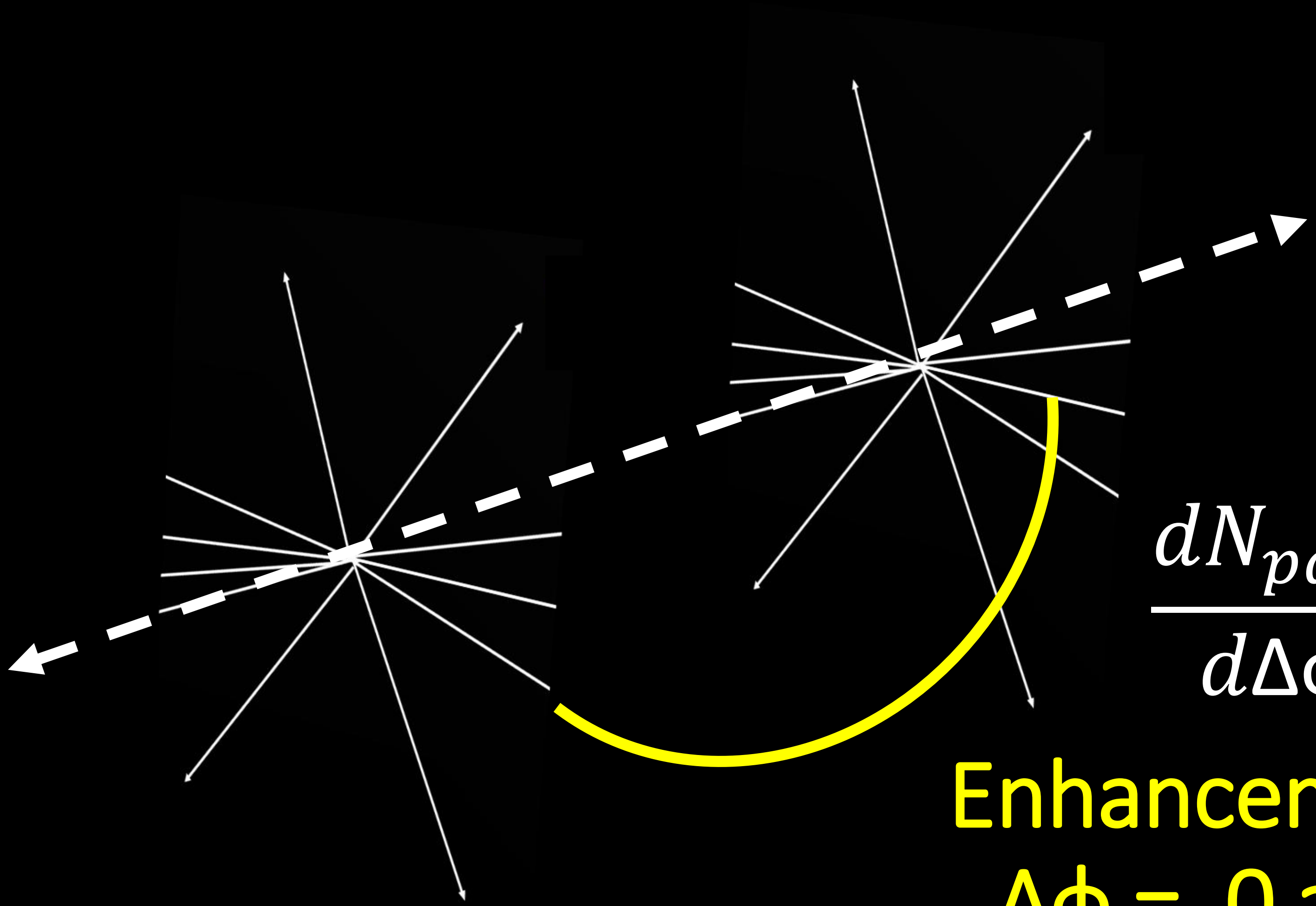
Photonuclear events have less particle production in the photon-going direction and a steeply falling multiplicity distribution.

arXiv:2101.10771

Two-particle correlation

For the purposes of this talk

All charged particle tracks



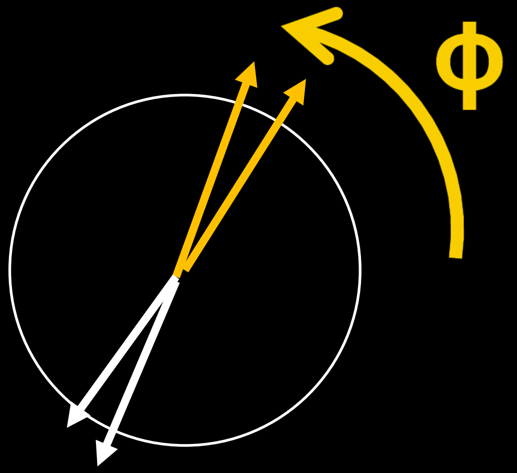
rapidity

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

Enhancement at

$\Delta\phi = 0$ and π

Two-particle correlations and non-flow

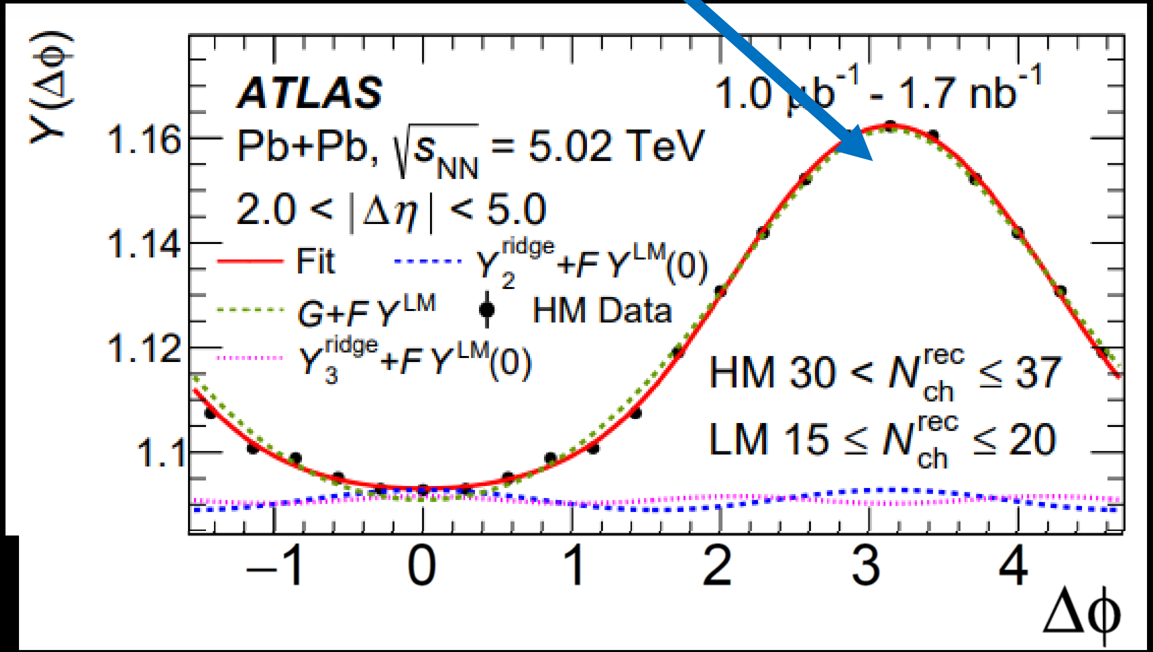


Momentum conservation

Jets & particle decays

Termed "nonflow"

Not collective phenomenon

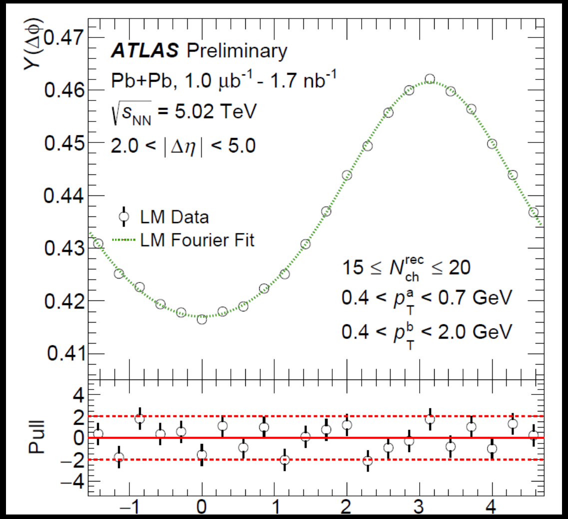


arXiv:2101.10771

Non-flow removal in γPb correlations

High-multiplicity (HM) correlation data

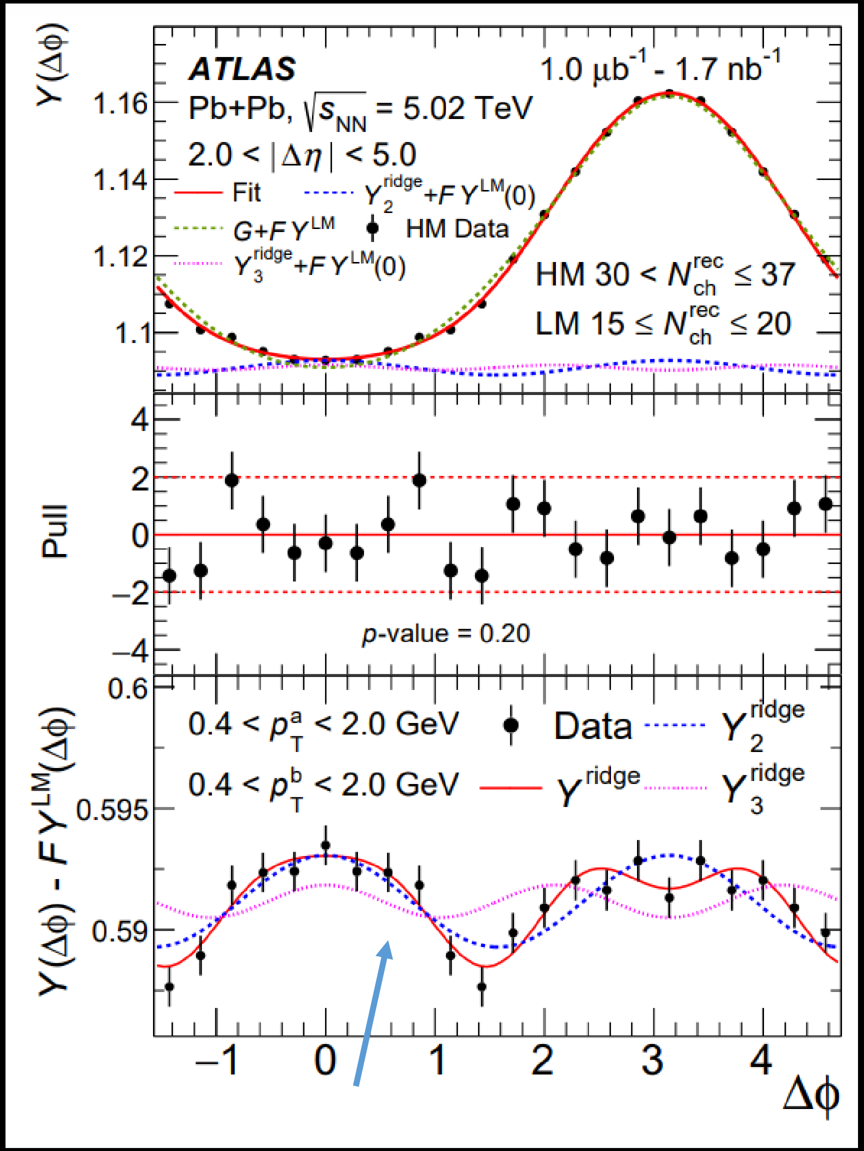
Low multiplicity (LM)
template for jet/non-flow correlation

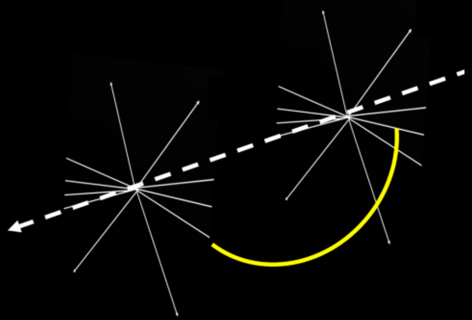


<u>Nonflow subtraction</u>

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

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

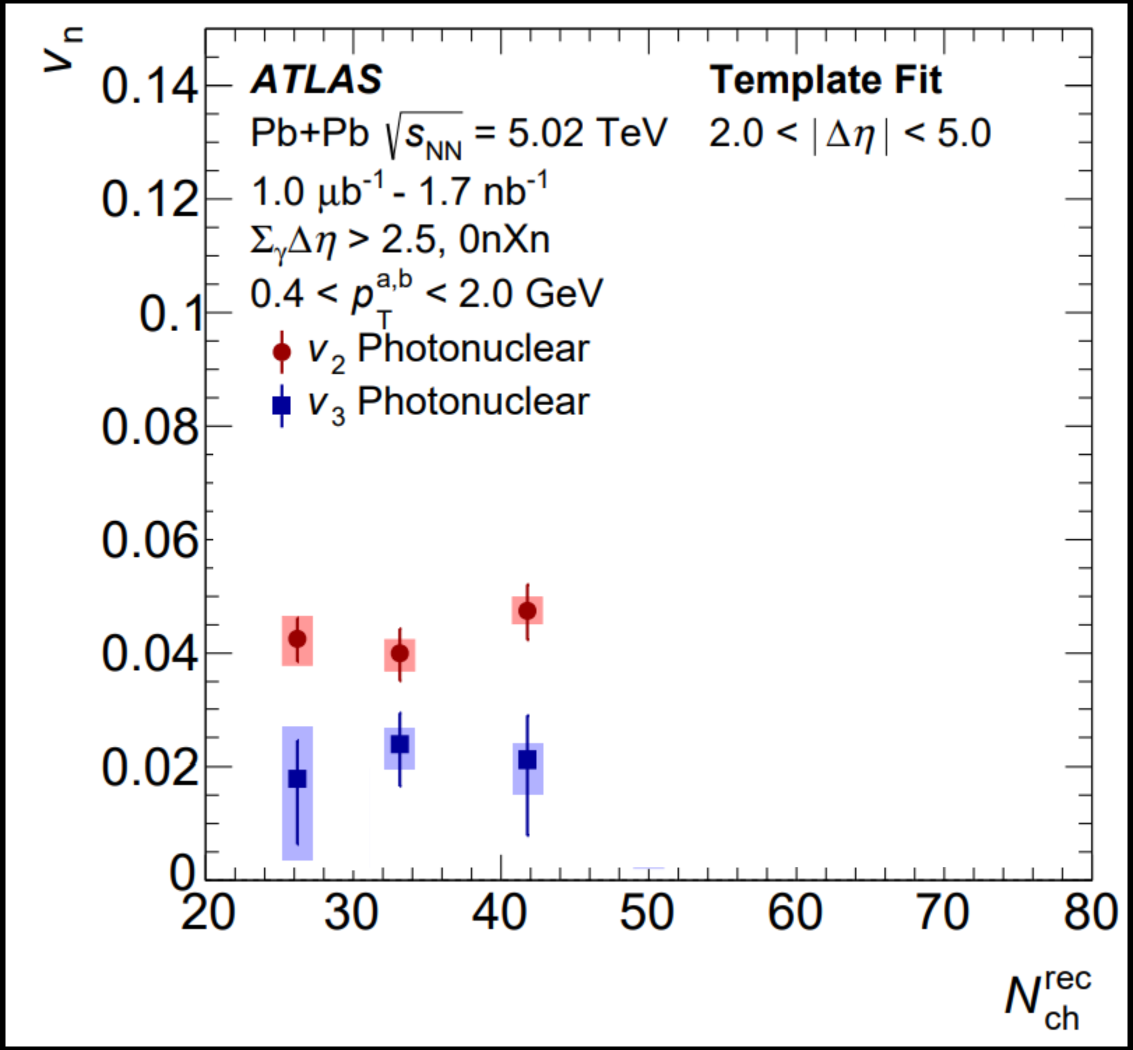




After nonflow subtraction clear cos(2Δϕ) modulation

arXiv:2101.10771

v_n in photonuclear collisions



Significant nonzero v_2 and v_3 in photonuclear collisions

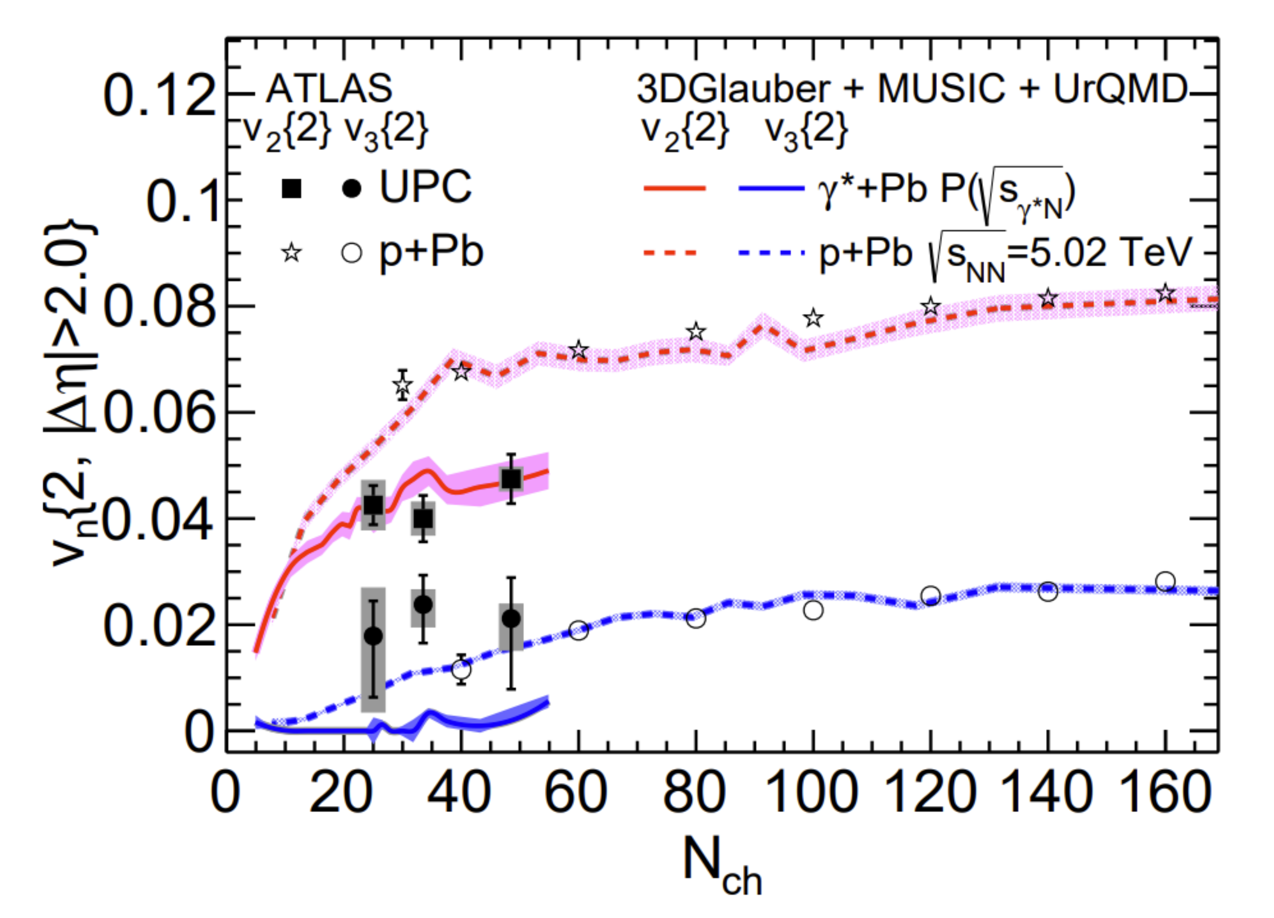
Flat $v_2(N_{ch})$ within statistical precision

Nonzero triangularity, v_3

System with 20-30 particles shows hydrodynamic response

arXiv:2101.10771

γ+Pb theory comparisons



arXiv:2203.06094 arXiv:2101.10771

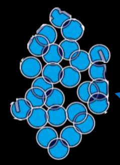
Nonzero γPb v_2

comparison to hydrodynamics
"3DGlauber + MUSIC +UrQMD"

Using shear viscosity = 0.08

All we need for hydro

Initial conditions



u(t0) = 0

Fluid properties

P[e] & shear/bulk viscosity

?

$$v_n \simeq \kappa_n \varepsilon_n$$

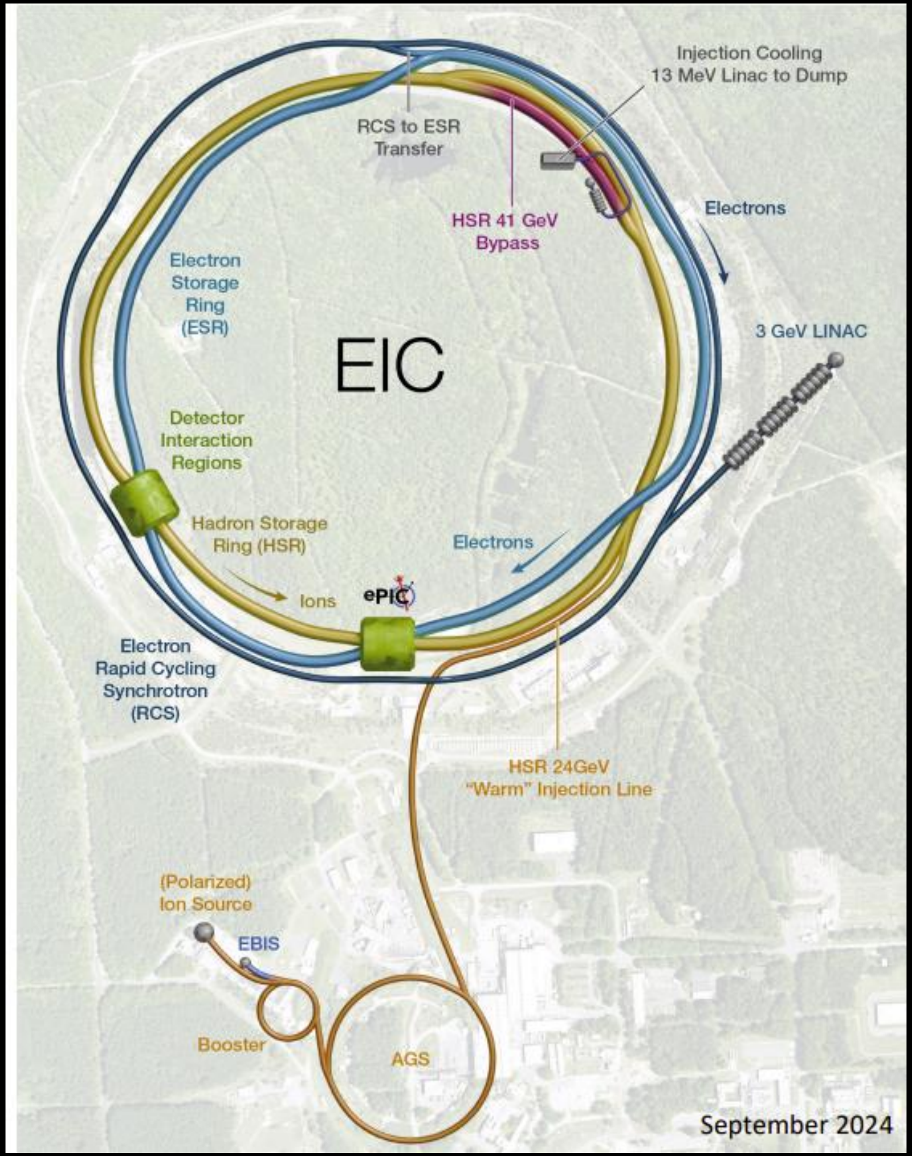
Great hydrodynamic description of γ+Pb with QGP fluid properties

The Electron Ion Collider at BNL

Even smaller QGP?

With even more precision?

The Electron Ion Collider



- First collisions and early physics around 2034/5

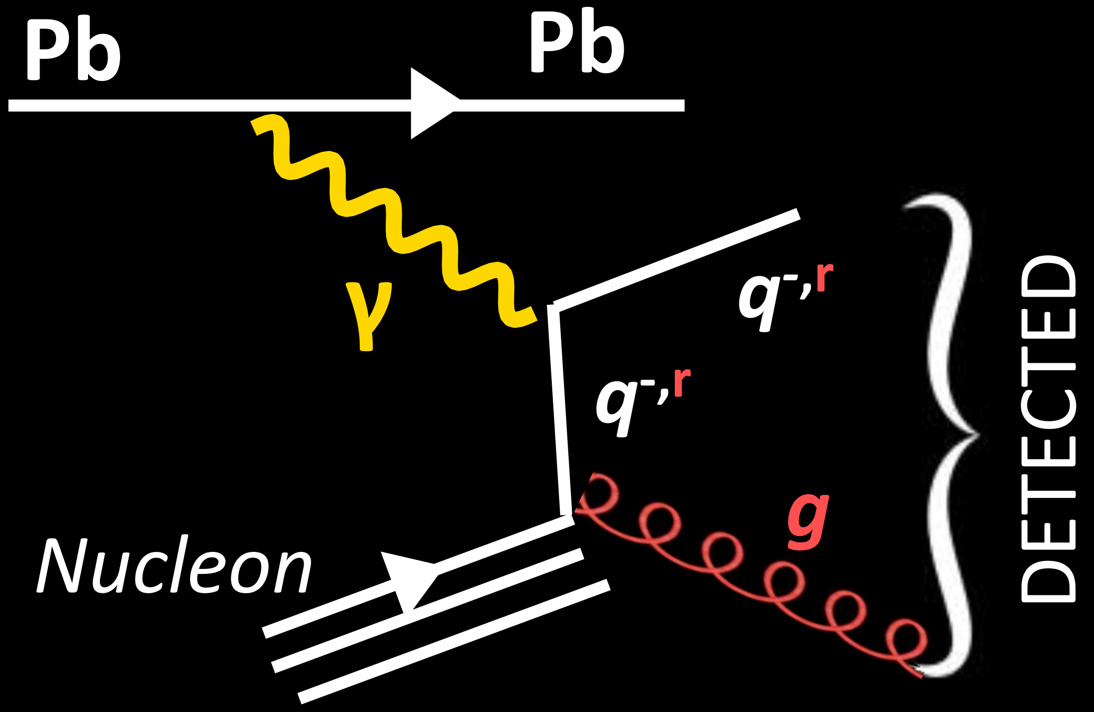
Big physics questions

- What happens to the gluon density in nuclei?
- How do the nucleon properties (mass & spin) emerge?

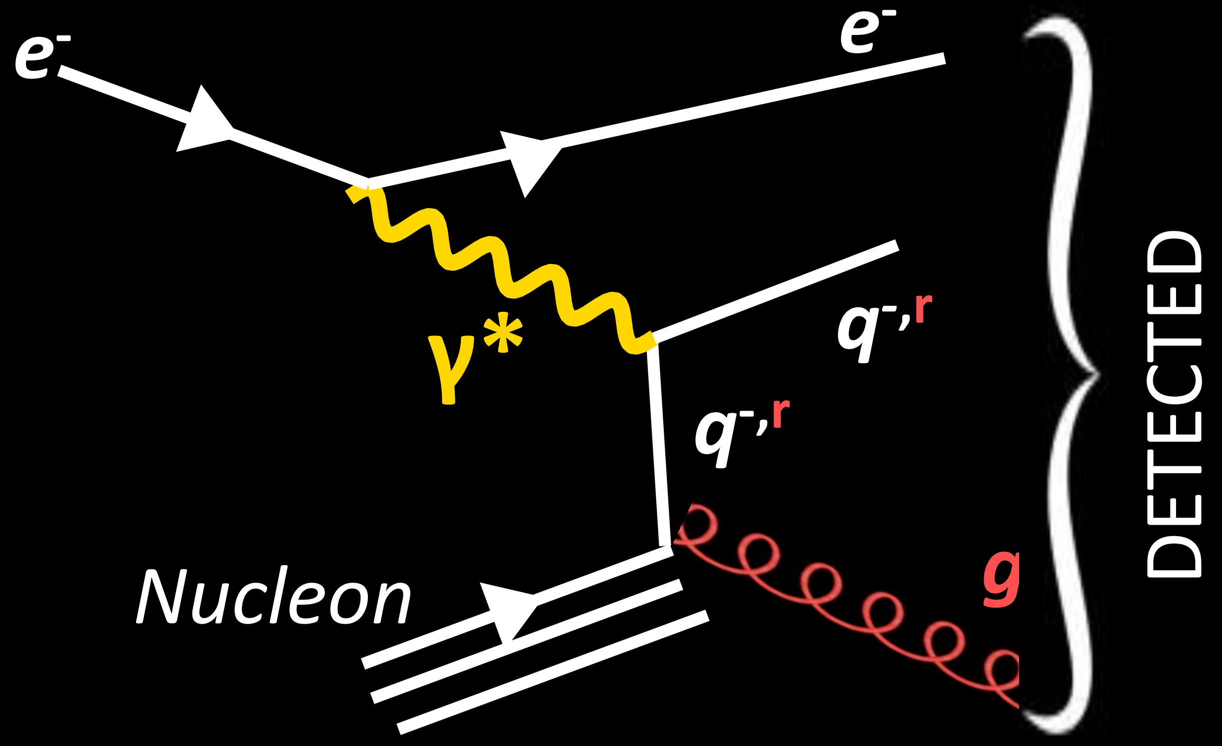
- See Abhay Deshpande's summer lecture talk

Comparing photonuclear interactions

γA at LHC and RHIC

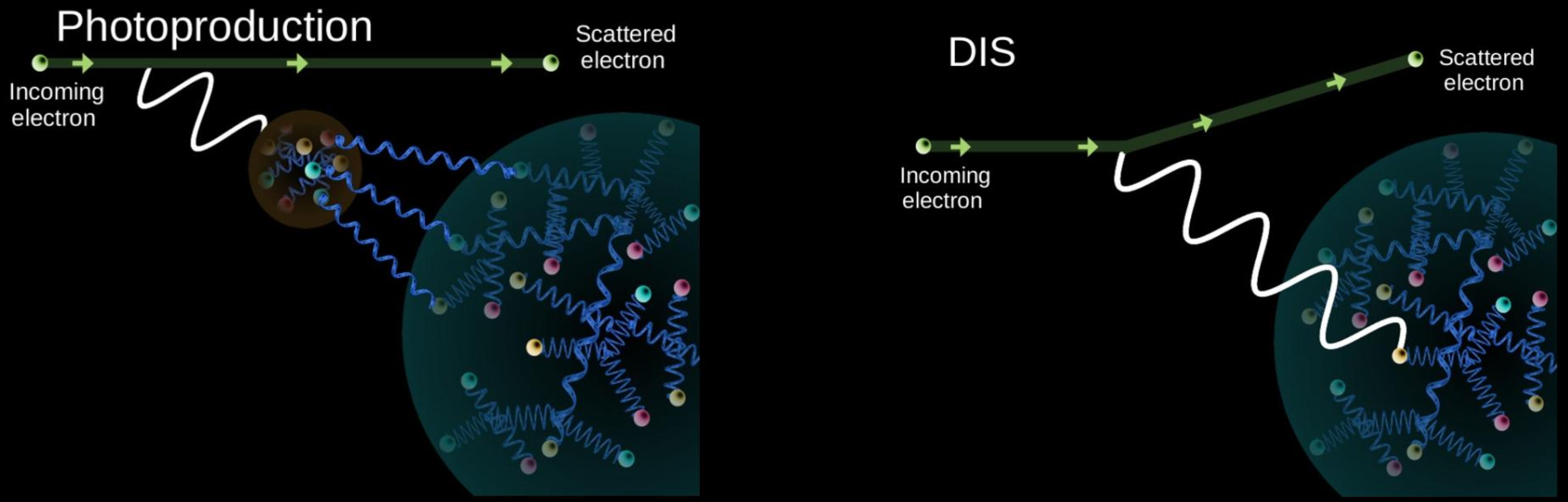


eA at the EIC

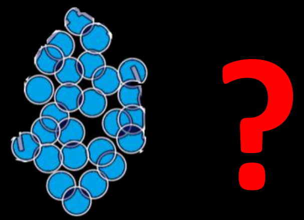


We can select varying mixtures of direct/resolved with detected electron

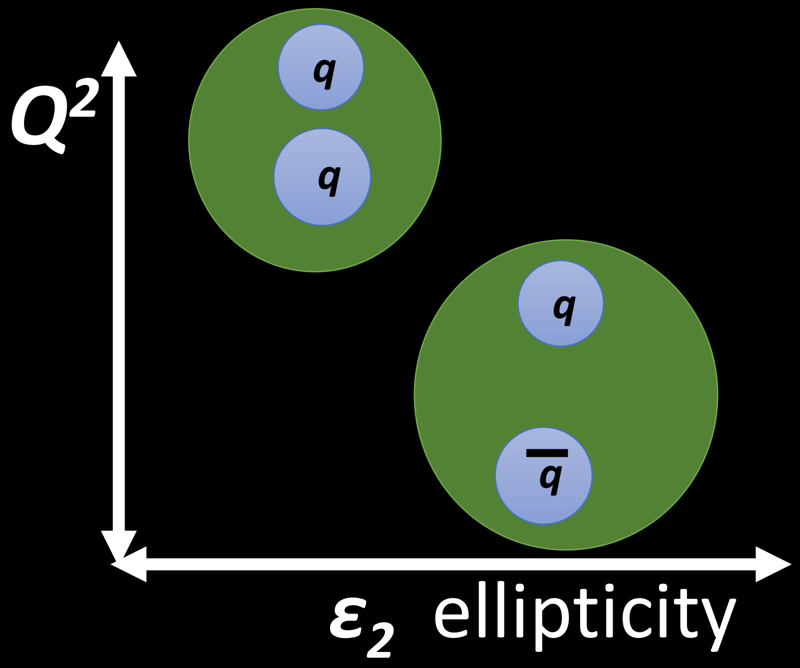
Initial state geometry in eA collisions?

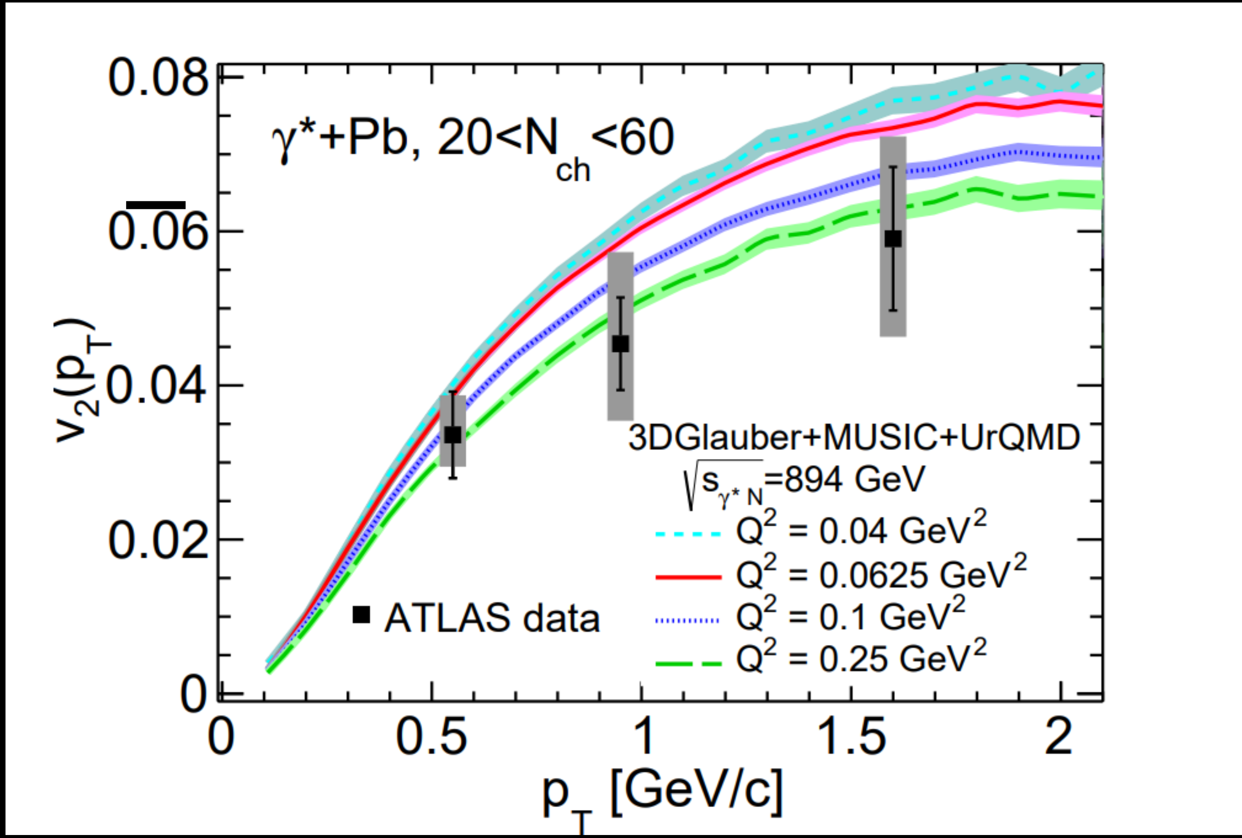


- $|\gamma_{\text{bare}}\rangle$ Point-like interaction region would suggest little geometry
- $|V\rangle$ provides an energy deposit with a transverse extent and possible elliptic geometry.



3+1D Hydrodynamic model comparison in γA





Changes in probe virtuality affect the shape of initial energy density

No direct access to Q^2 in UPC γA

$$Q^2 = -(k - k')^2 = 4E_e E'_e \sin^2\left(\frac{\theta_e}{2}\right)$$

Example: 100 GeV e on 2.5 TeV Pb

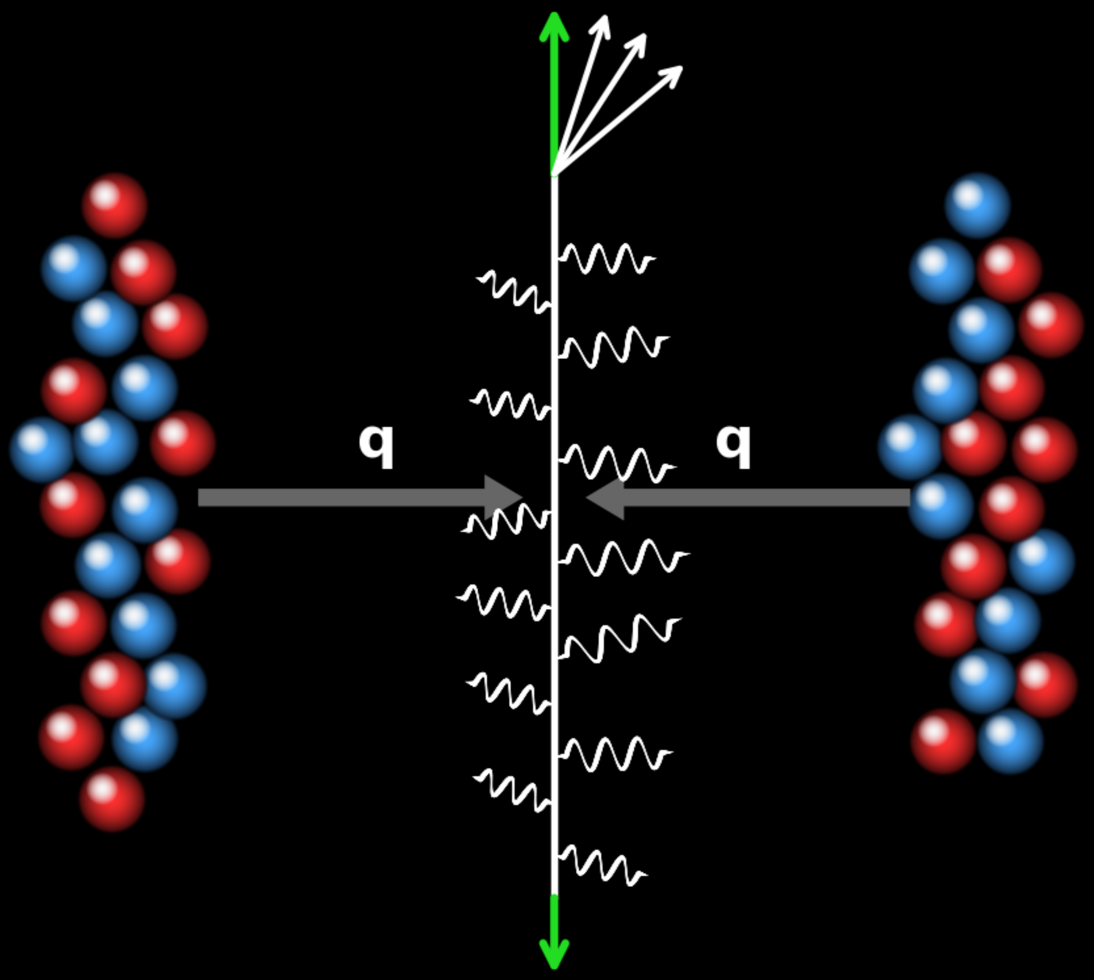
Q^2 = 0.25 – 0.04 GeV^2

Deflection angle 0.0014 – 0.00056

The sPHENIX Experiment

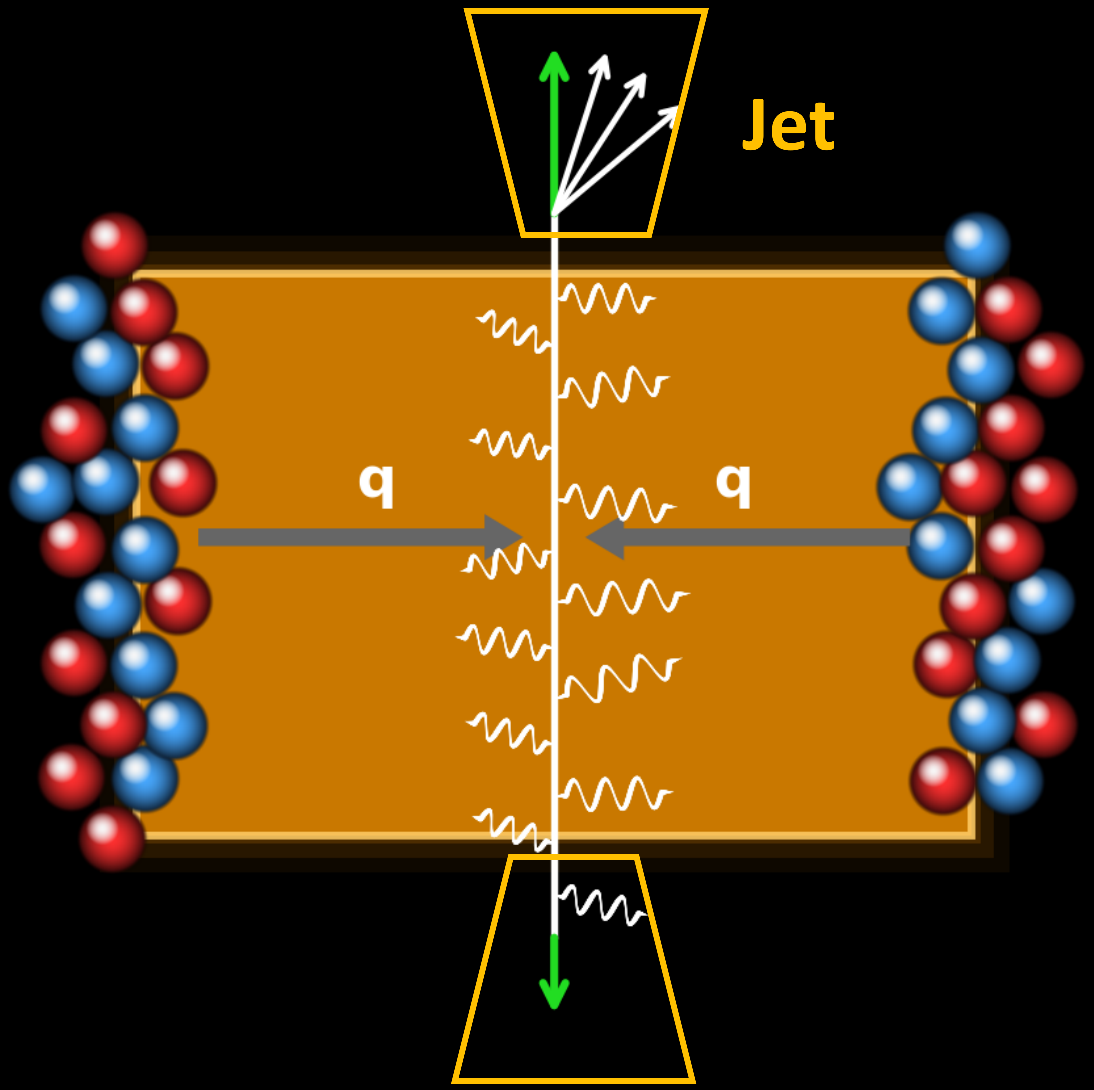
Studying the QGP with high-energy quarks & gluons

Source of high-energy quarks and gluons



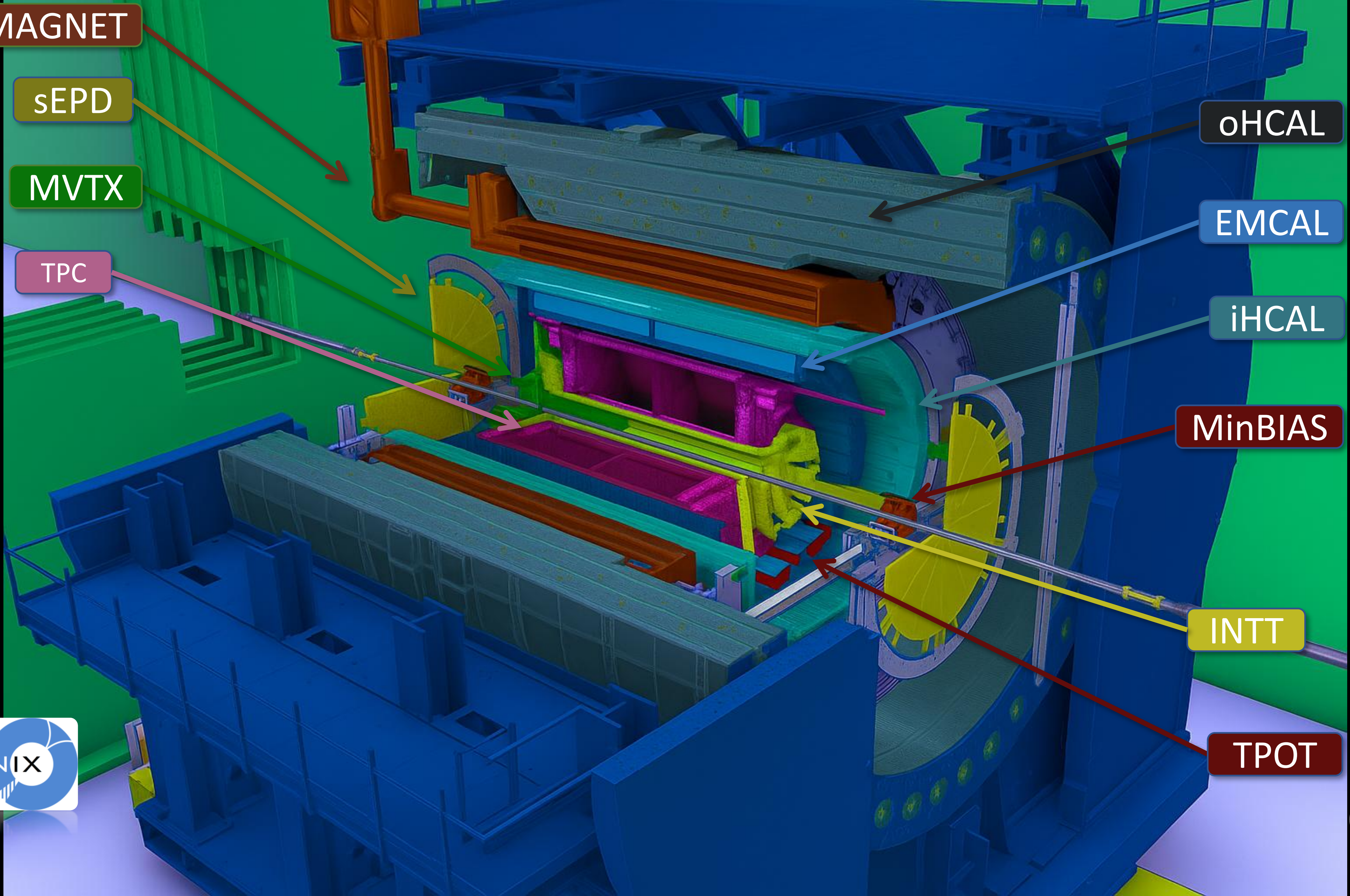
Rare hard energetic scattering leading to high energy particles

High-energy quarks/gluons and the QGP



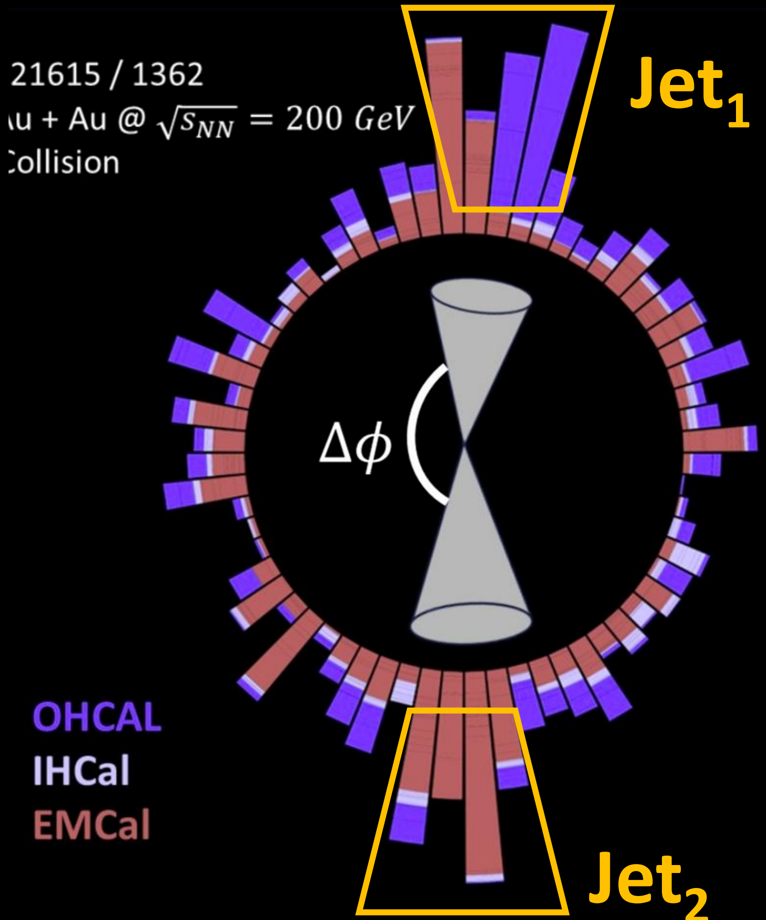
Rare hard energetic scattering leading to high energy particles

Energy loss occurs while traversing through the medium


MAGNET
sEPD
MVTX
TPC
oHCAL
EMCAL
iHCAL
MinBIAS
INTT
TPOT
sPHENIX

sPHENIX jet event

Event recorded last year



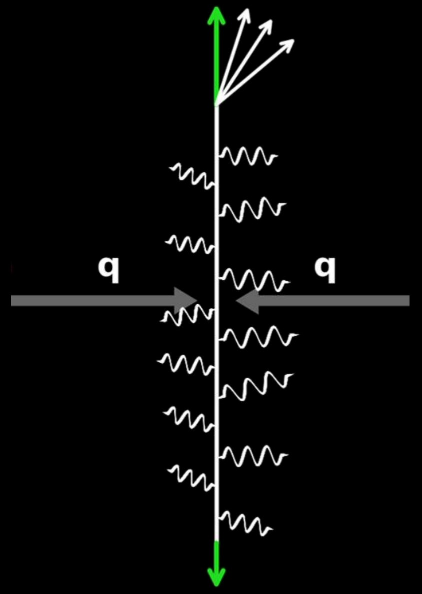
$$x_J = \frac{\text{Jet}_2\, p_T}{\text{Jet}_1\, p_T}$$

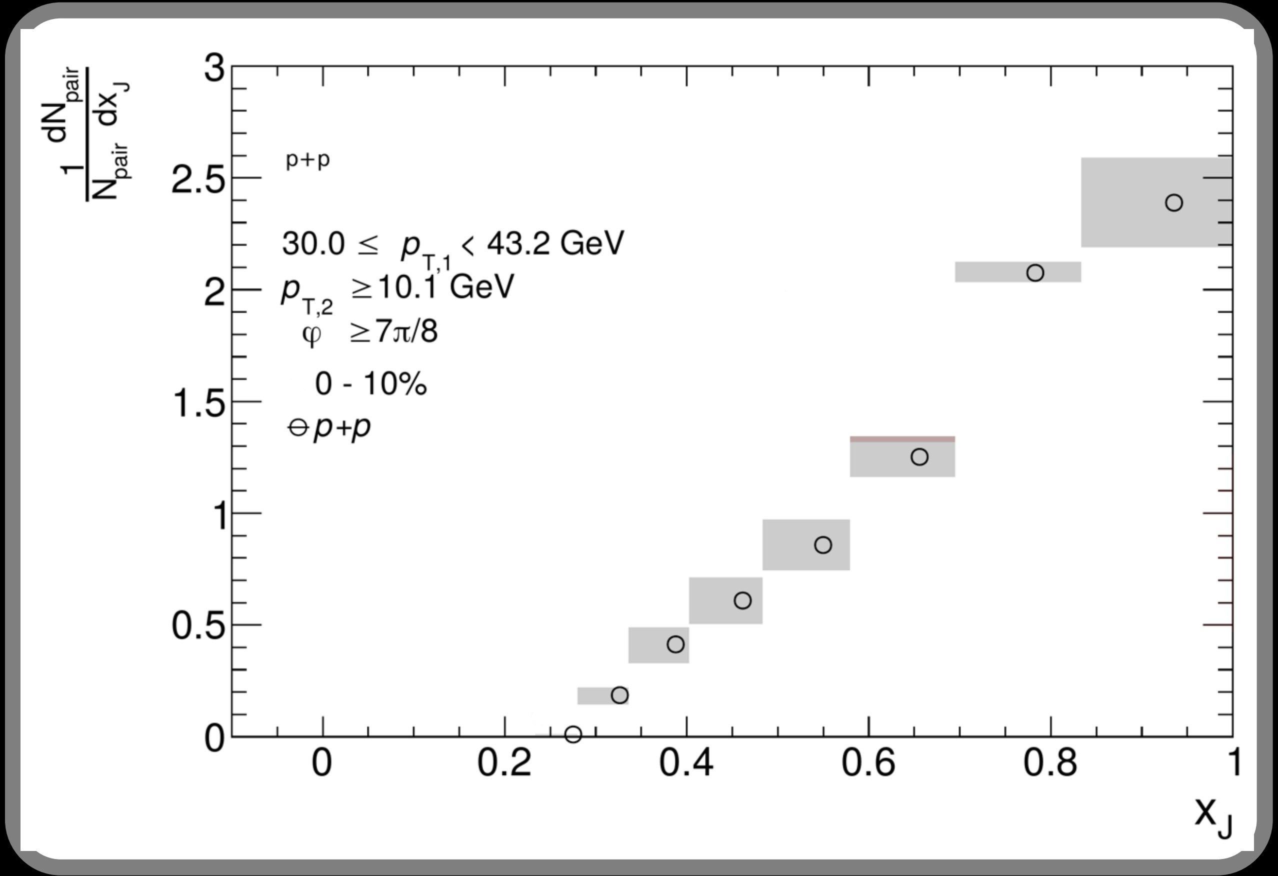
Higher energy jet in the denominator, $x_J < 1$

sPHENIX p+p jet x_J

$$x_J = p_{T,2}/p_{T,1}$$ Where p_{T1} is the leading jet

- No QGP effects in *pp*
- x_j close to 1



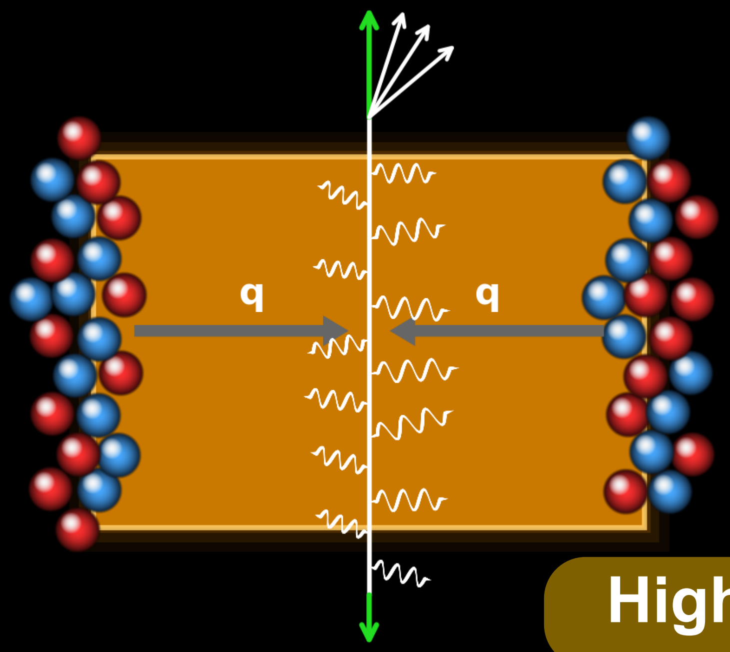


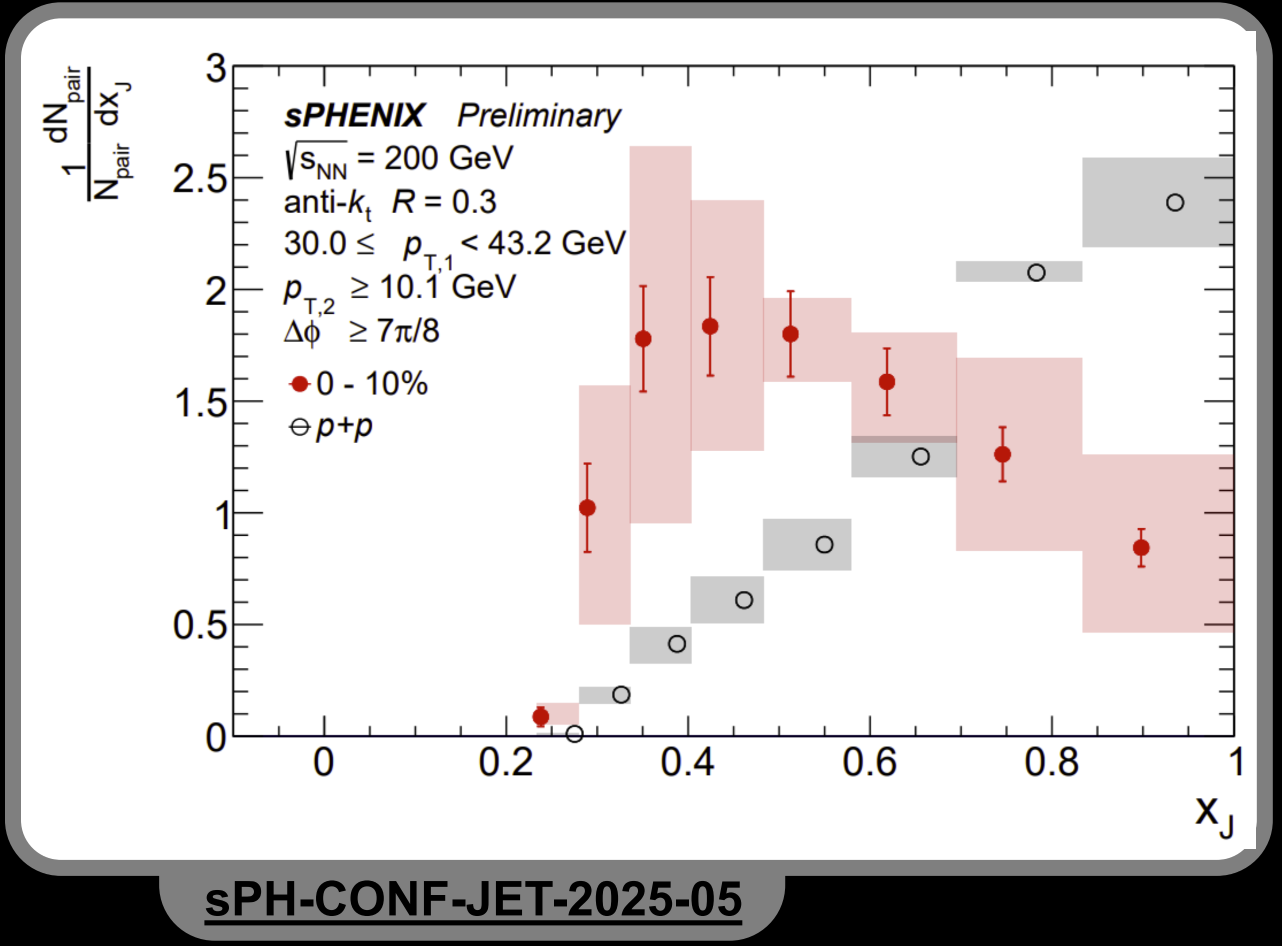
sPHENIX Au+Au jet x_J

$$x_J = p_{T,2} / p_{T,1}$$

Where p_{T1} is the leading jet

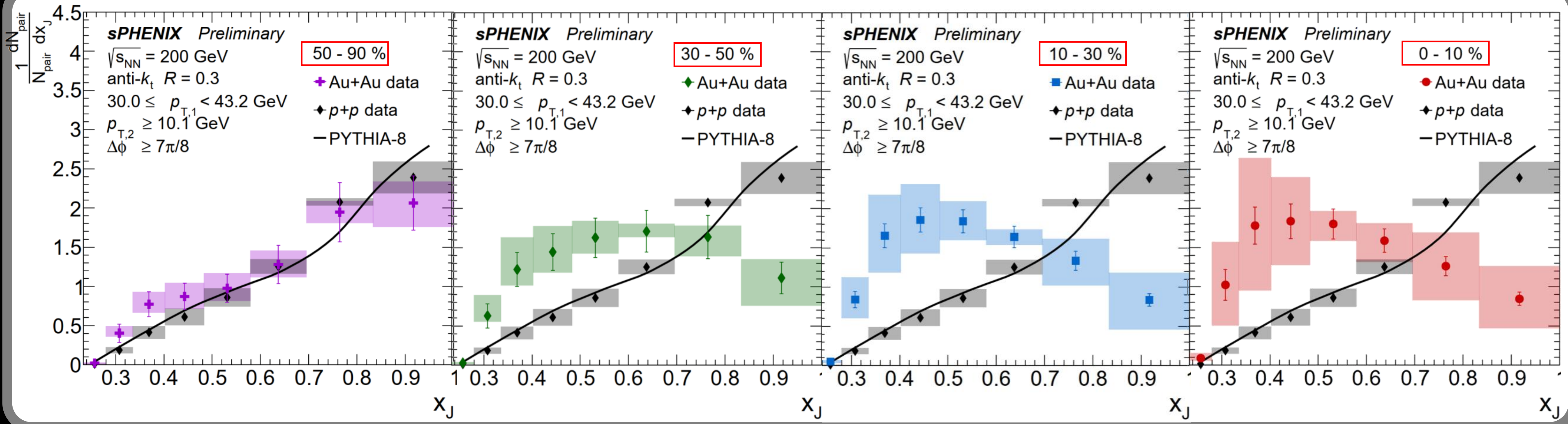
- x_j around 0.5



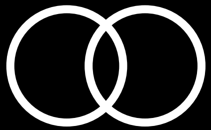


High-energy quarks/gluons lose energy in the QGP

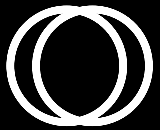
Au+Au dijet x_J centrality dependence



sPH-CONF-JET-2025-05 **IS Talk Link**



Centrality



Conclusion

Results

Photonuclear collision measurements show evidence of hydrodynamic flow of the QGP

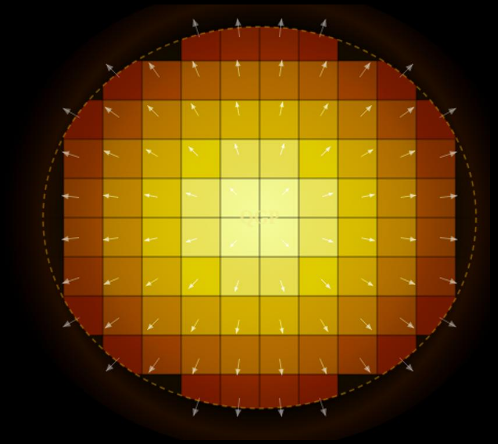
Many measurements in small systems show this

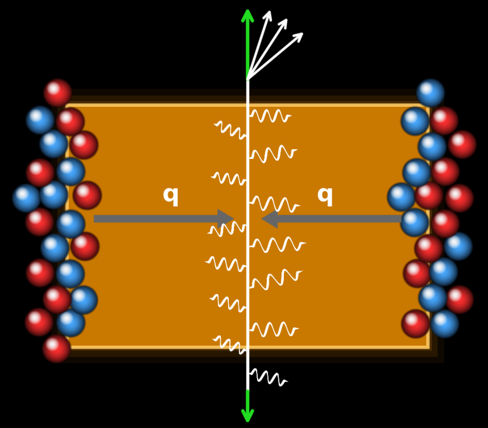
Future/current theoretical and experimental questions

Why is hydrodynamics accurate in this extreme scenario?

Can we measure a breakdown?

First measurements of jet energy loss from sPHENIX





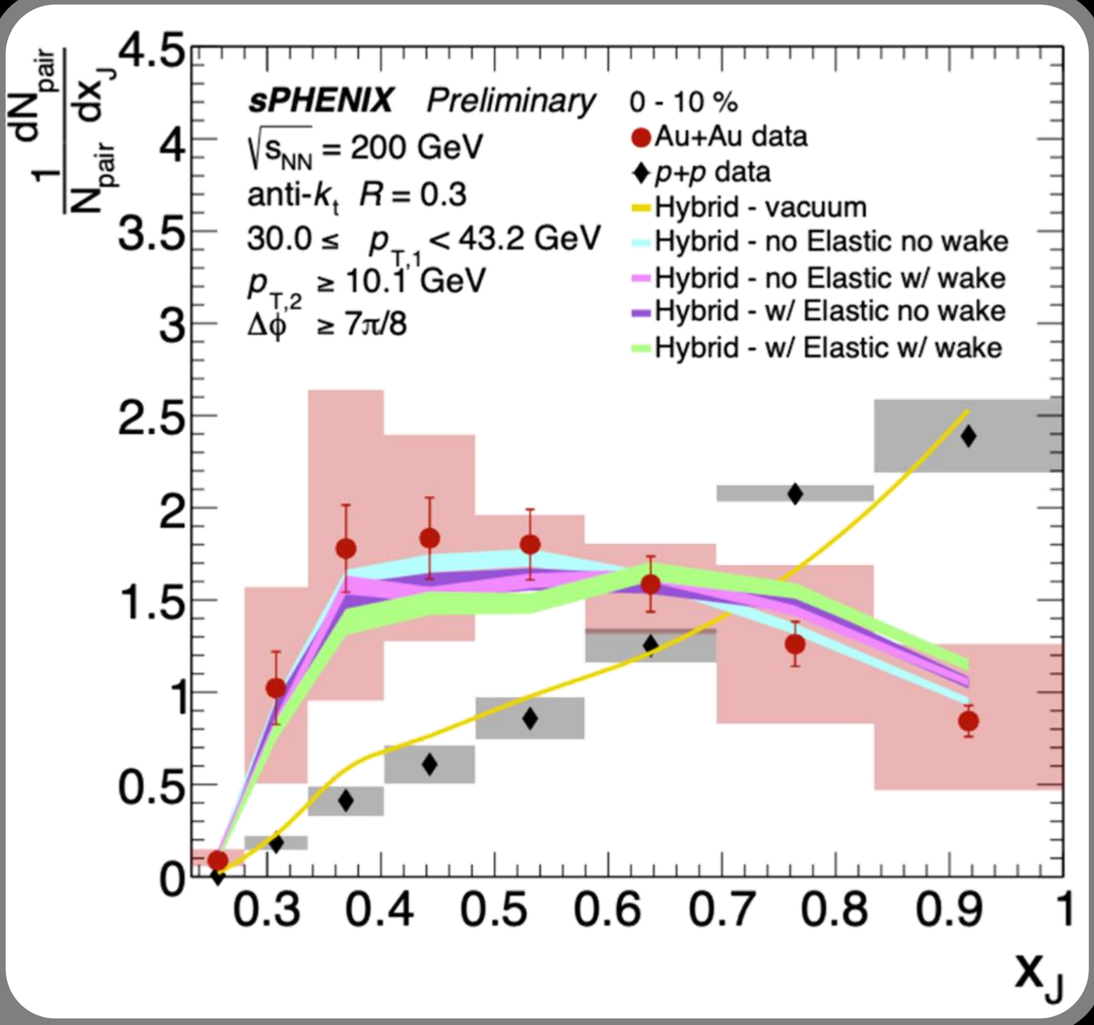
Thank you

Au+Au dijet x_J

- Consistent with all hybrid model predictions with various forms of medium response

- All of these calculations, with various physical effects turned on and off, agree within the uncertainties (red shaded bands) of the data

We need more precise data
or
Need a different observable where the physical phenomena make more of an impact.

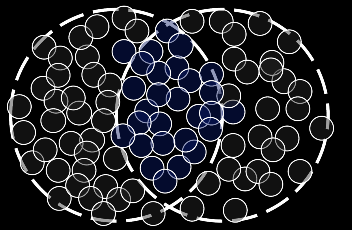


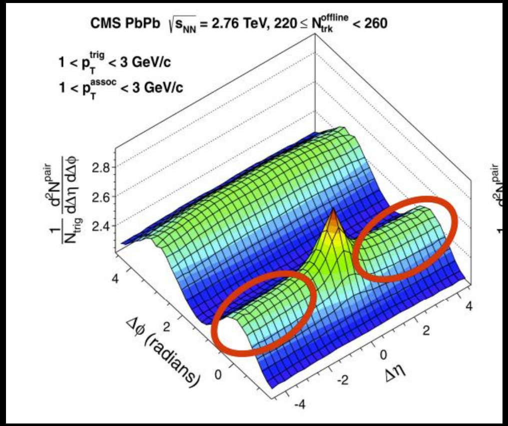
sPH-CONF-JET-2025-05 IS Talk Link

Motivates additional measurements

System size

Pb+Pb



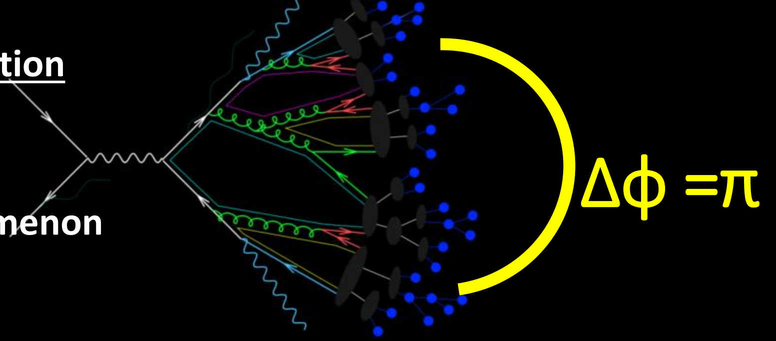


Momentum conservation

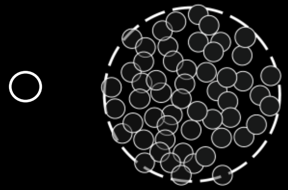
Jets & particle decays

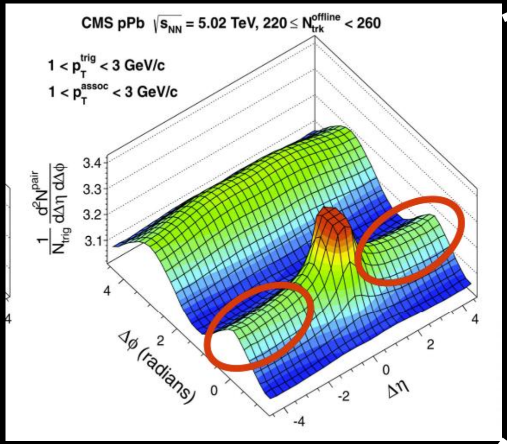
Termed "nonflow"

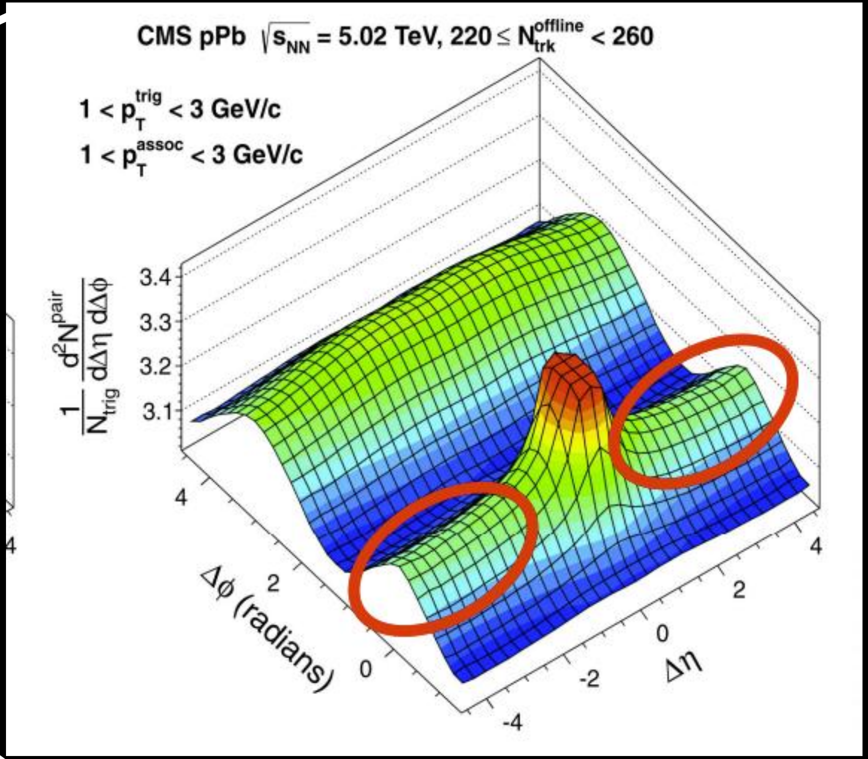
Not collective phenomenon



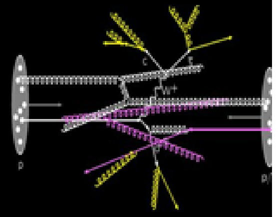
p+Pb

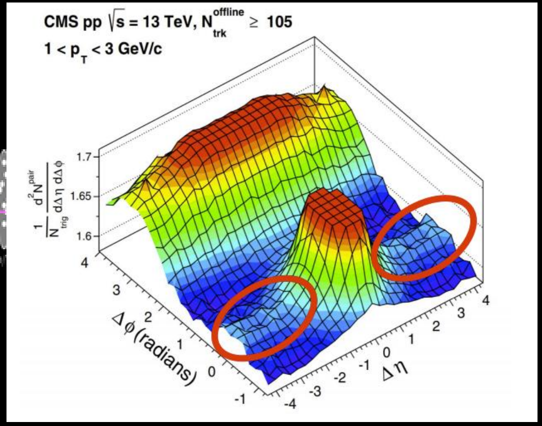


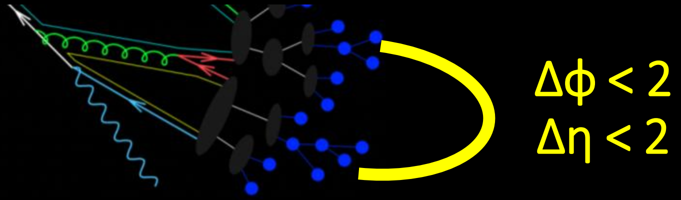




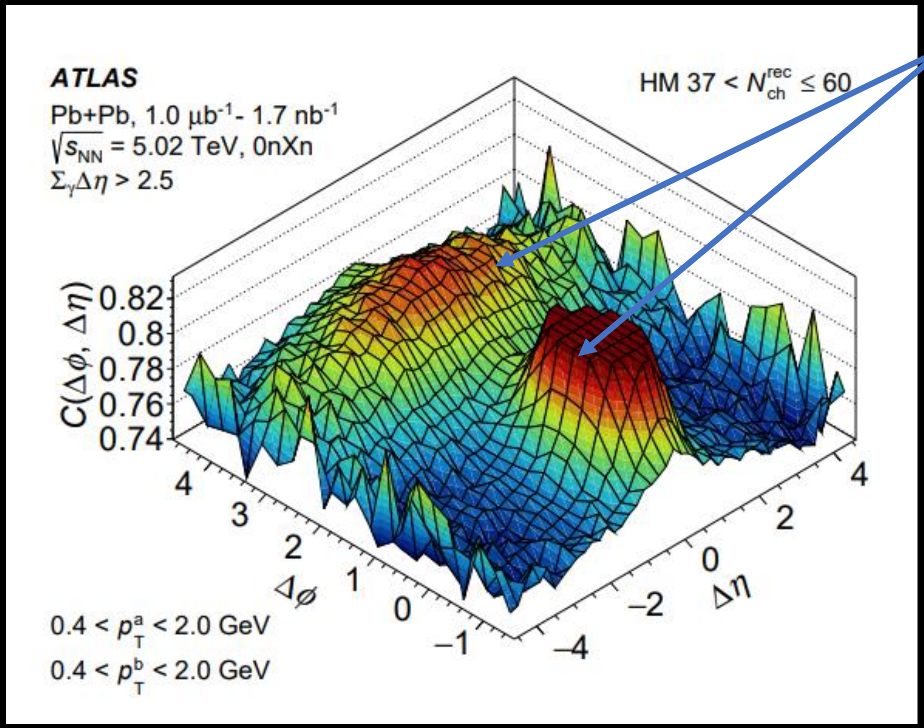
pp







Two-particle correlations and non-flow

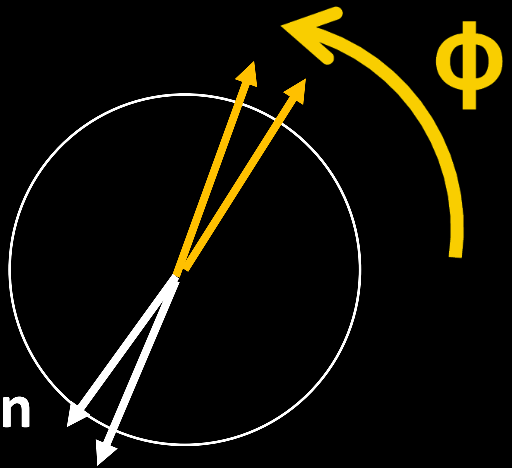


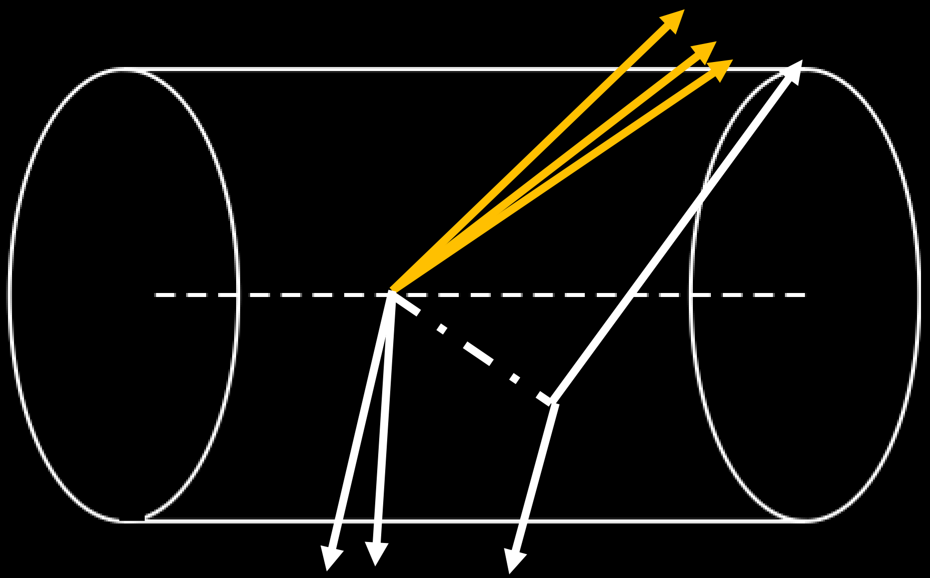
Momentum conservation

Jets & particle decays

Termed "nonflow"

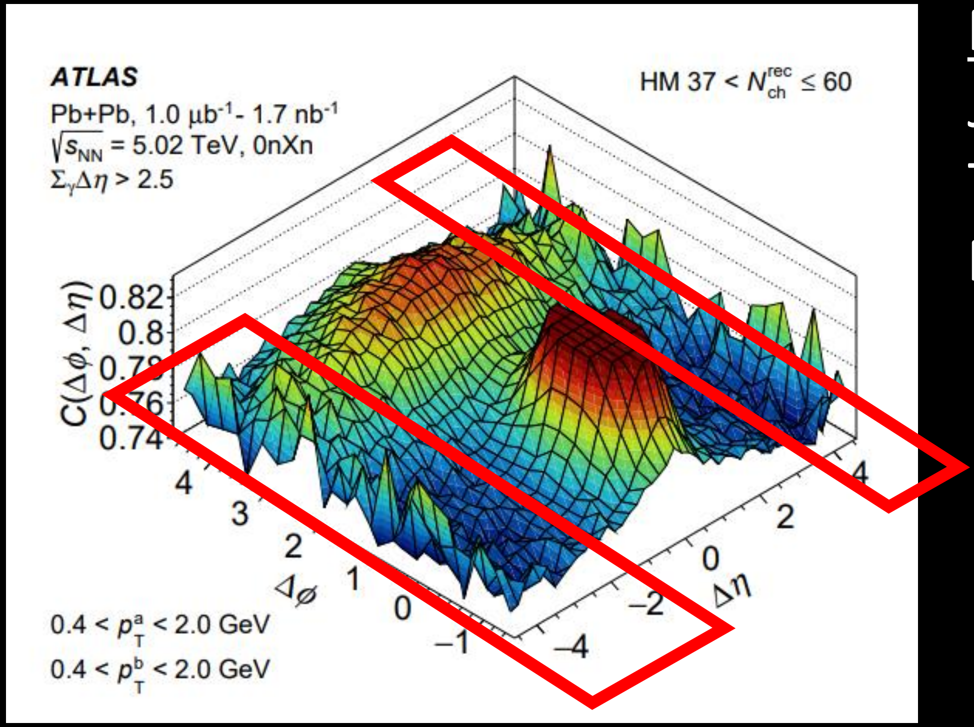
Not collective phenomenon





arXiv:2101.10771

Two-particle correlations and non-flow



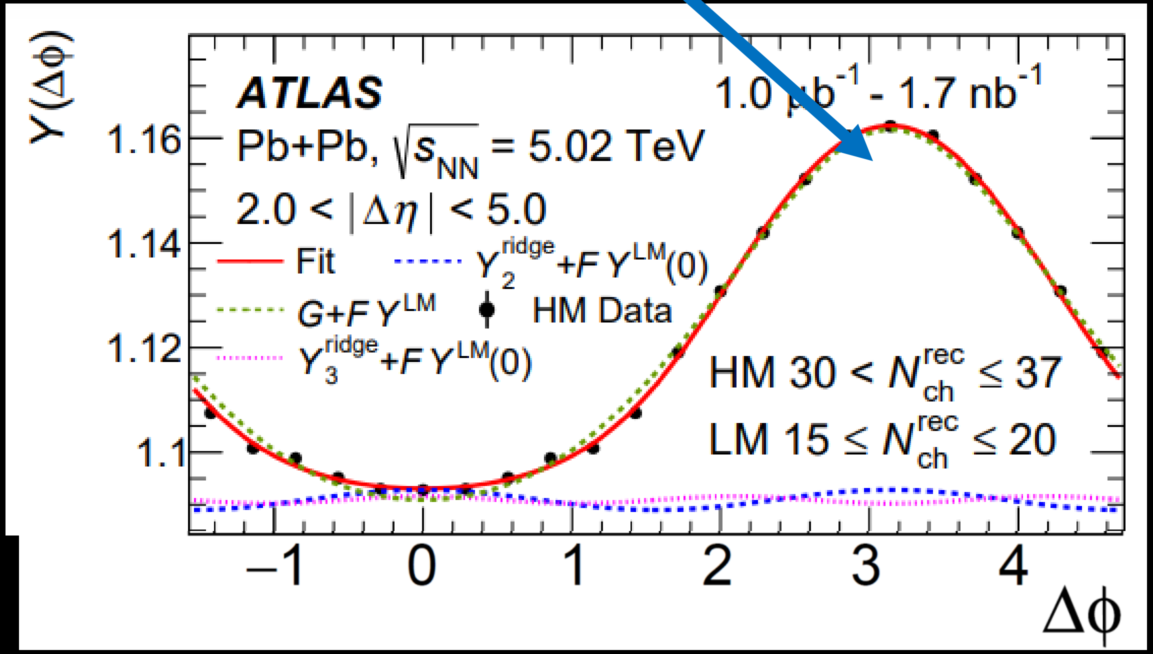
No clear nearside ridge

Momentum conservation

Jets & particle decays

Termed "nonflow"

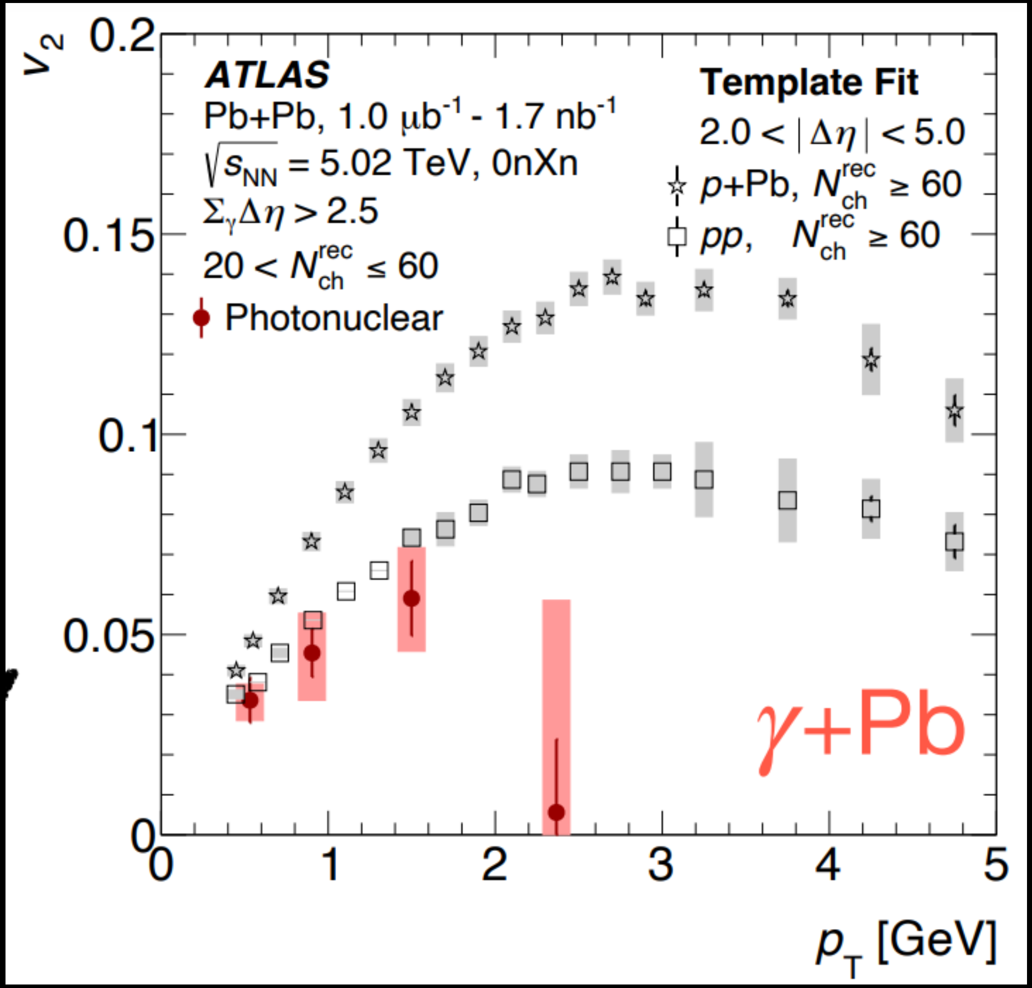
Not collective phenomenon



Need to remove nonflow

arXiv:2101.10771

v_n in photonuclear collisions



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

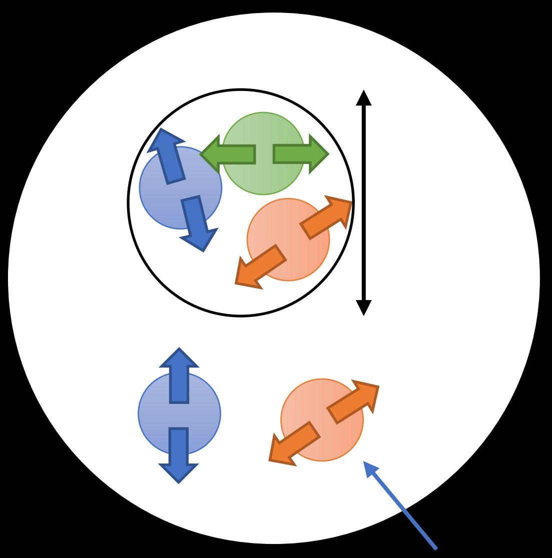
Similar low-p_T behavior as *pp* and *p*+Pb but systematically lower.

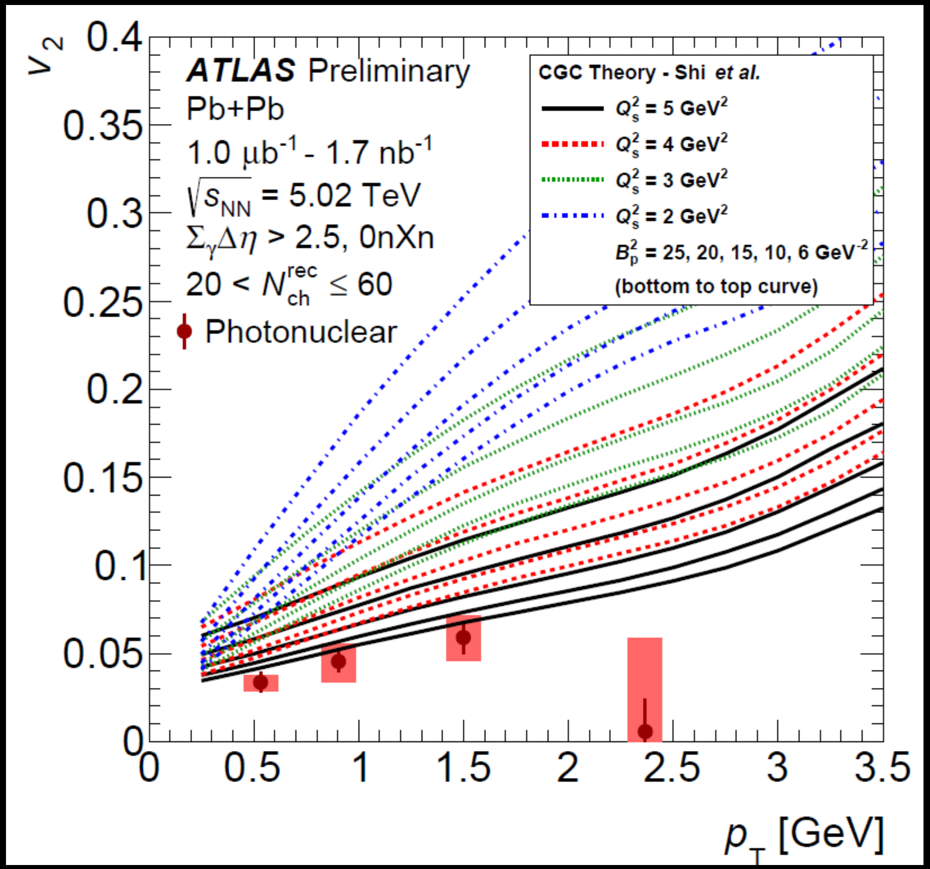
High-p_T v_2 is falling to large negative values (see backup) which is from the over-subtraction of nonflow. This effect is present in *pp* but is larger and sets in at lower p_T in γA (ATLAS-CONF-2020-018)

arXiv:2101.10771

CGC model comparison

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





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

arXiv:2101.10771

(3+1)D hydrodynamic model comparison

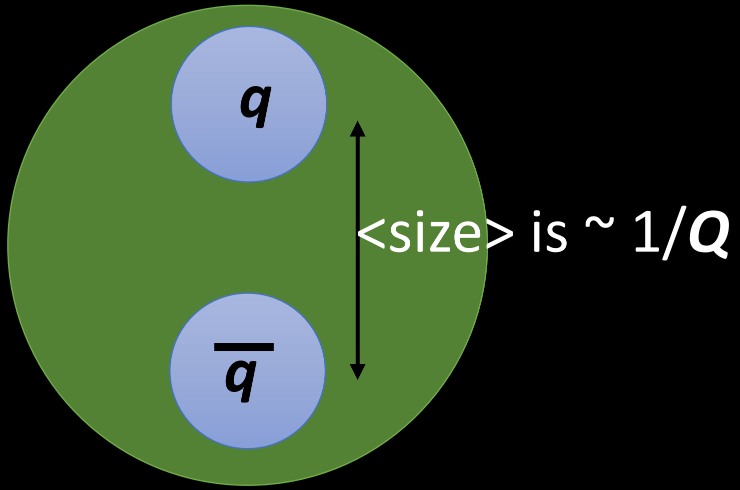
Collectivity in Ultra-Peripheral Pb+Pb Collisions at the Large Hadron Collider

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

Initial state

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

Rho Wave function:
Gaussian hot spots



Rho PDF:
Defines the longitudinal extent of energy deposition

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

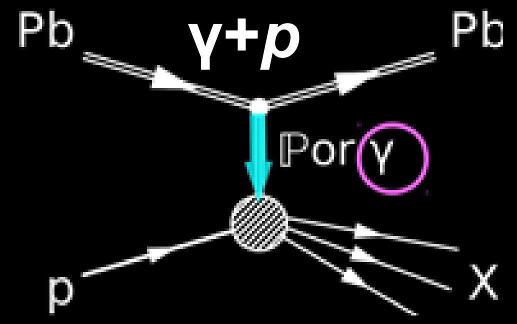
Final state

Viscous Hydrodynamics

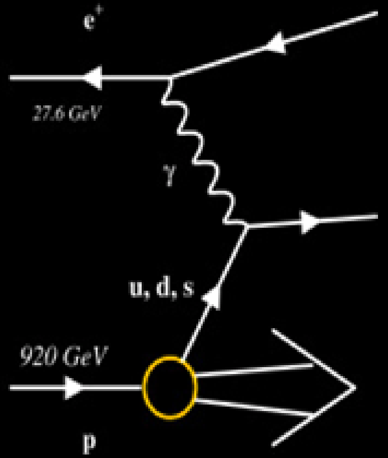
(3+1)D MUSIC+UrQMD

Recent measurements

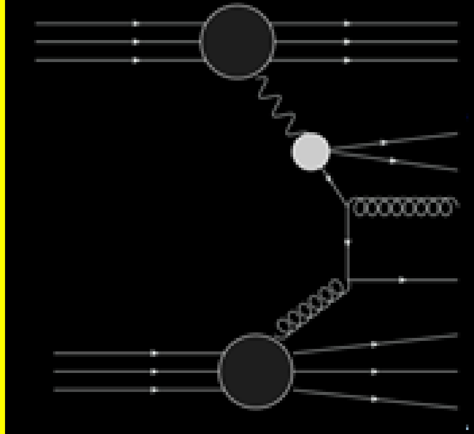
Today



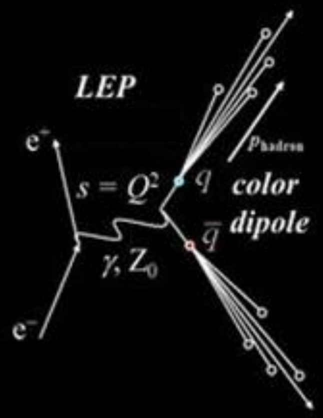
e+p



γ+A



$e^+ + e^-$



γ+*p* collectivity
arXiv:2204.13486

Preliminary

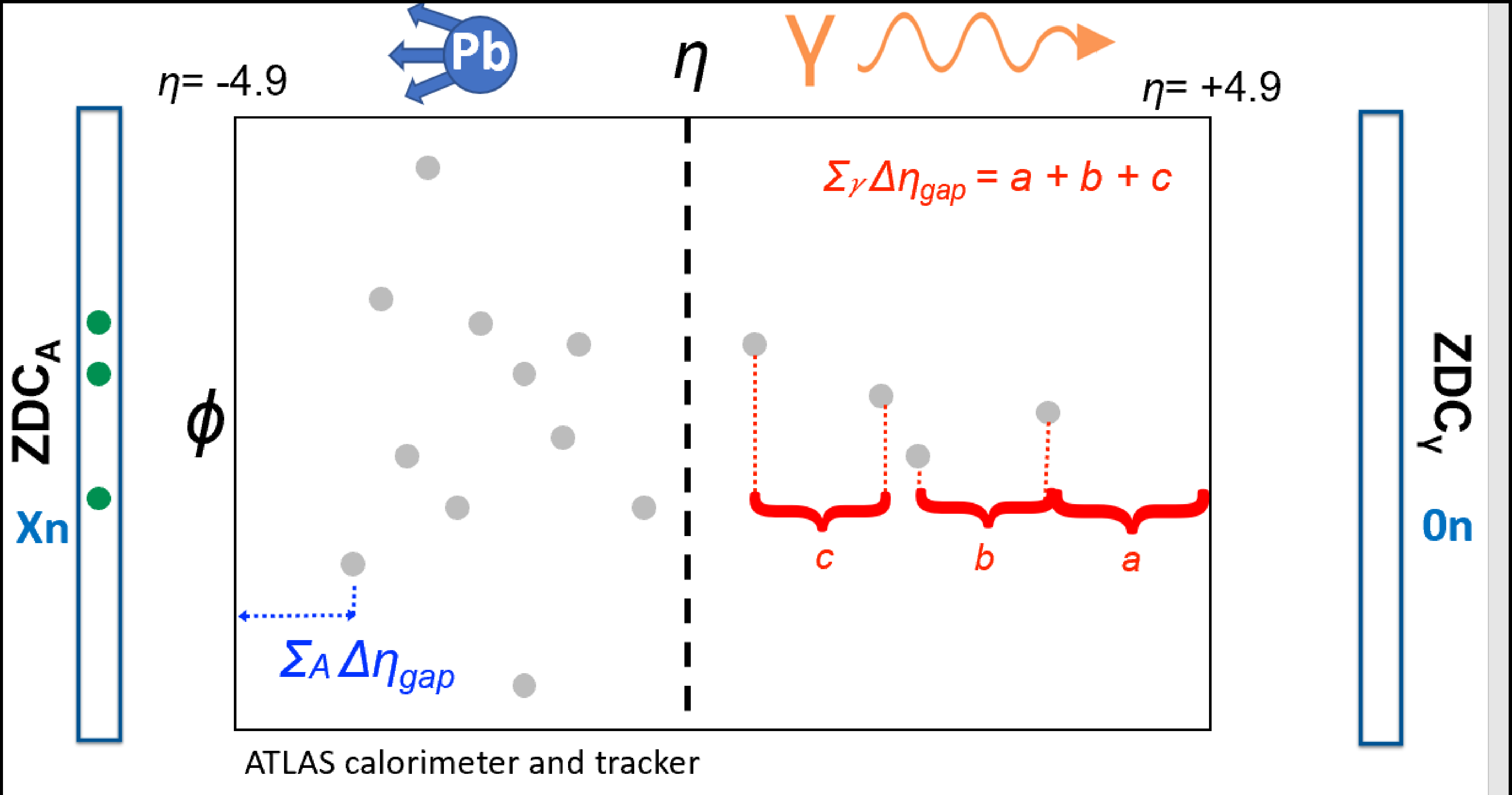
arXiv:2106.12377

γ+A collectivity
arXiv:2101.10771

ICHEP22 talk

QM22 talk

Sum of gaps

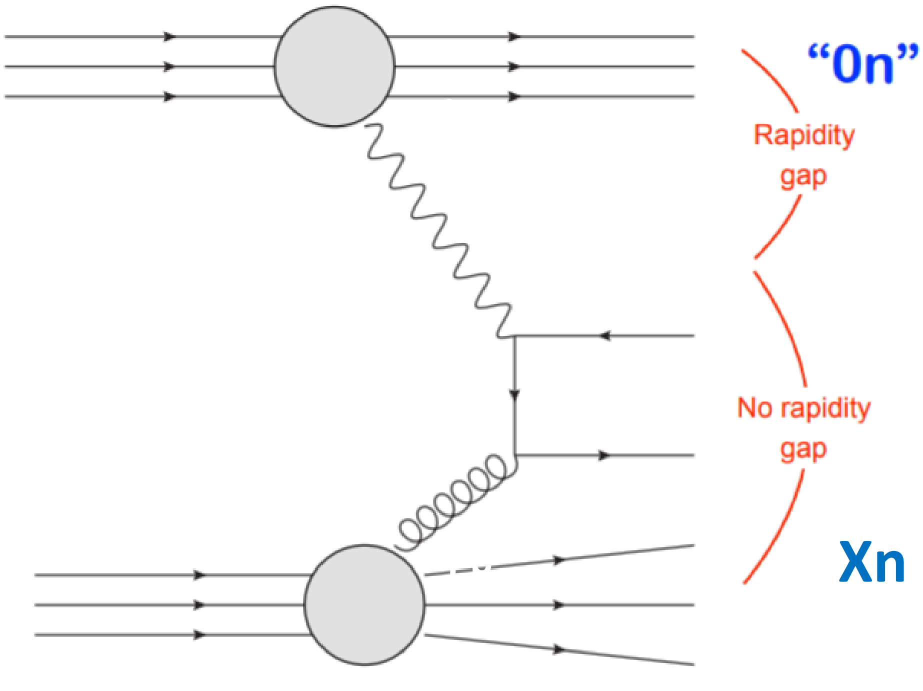


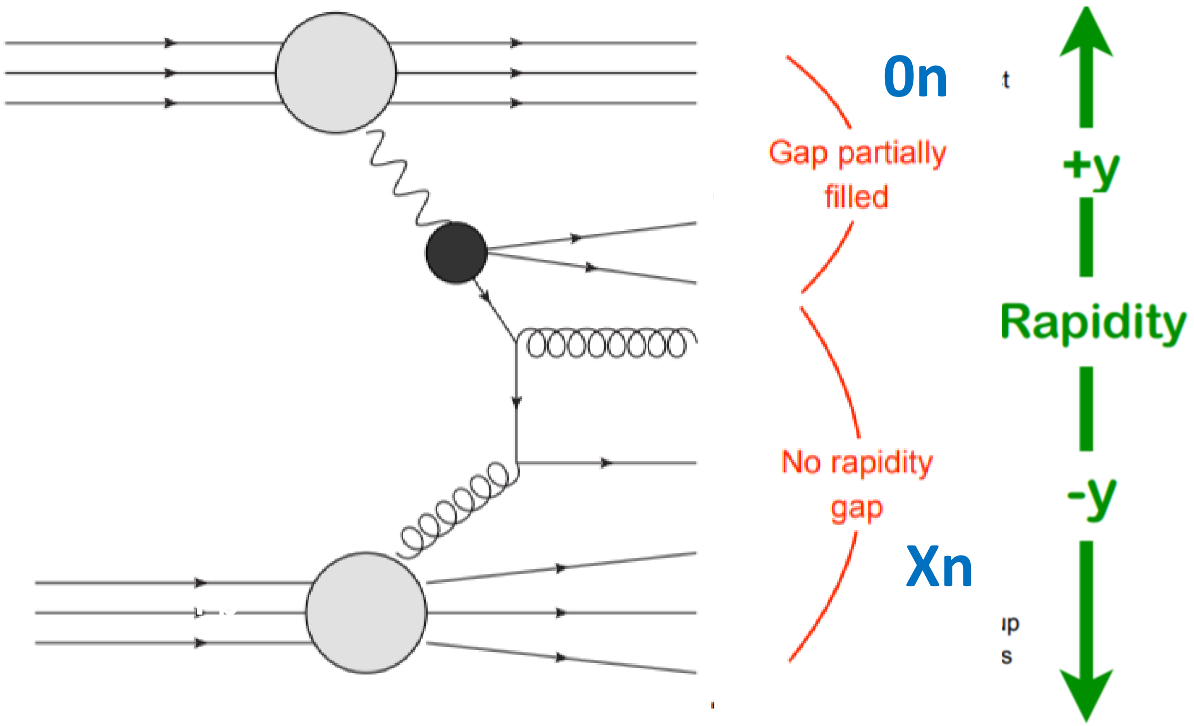
Event Selection: $\Sigma\Sigma_\gamma \Delta\eta_{gap} > 2.5$

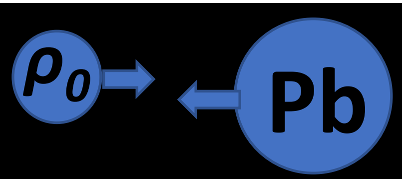
Photonuclear collisions

Direct γA collisions
Photon couples directly to nuclear parton

Resolved γA collisions
photon virtually resolved into hadronic state



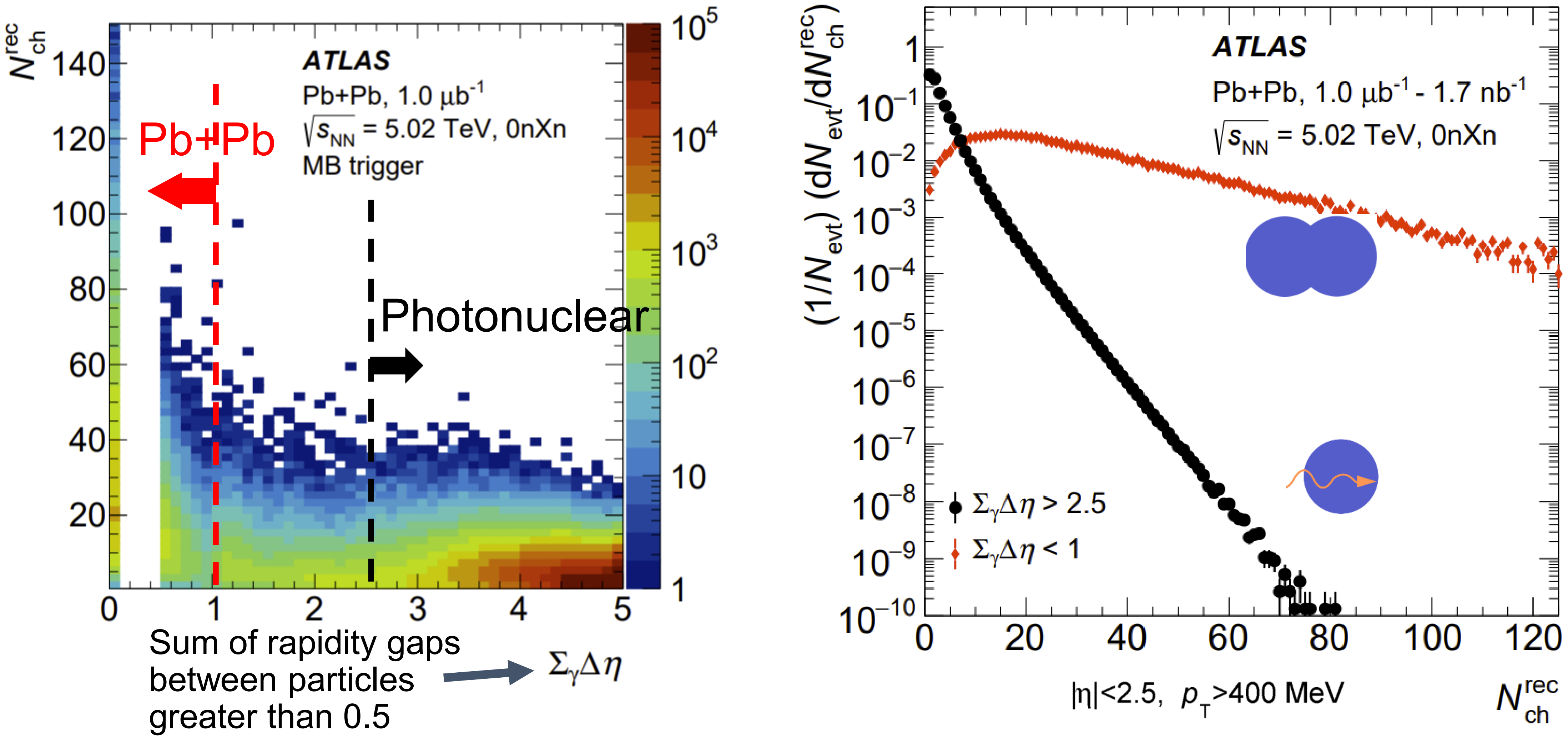




Select events based on primarily
- Single-sided nuclear breakup "**0nXn**" (zero-degree calorimeter ZDC)
- Rapidity gaps

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

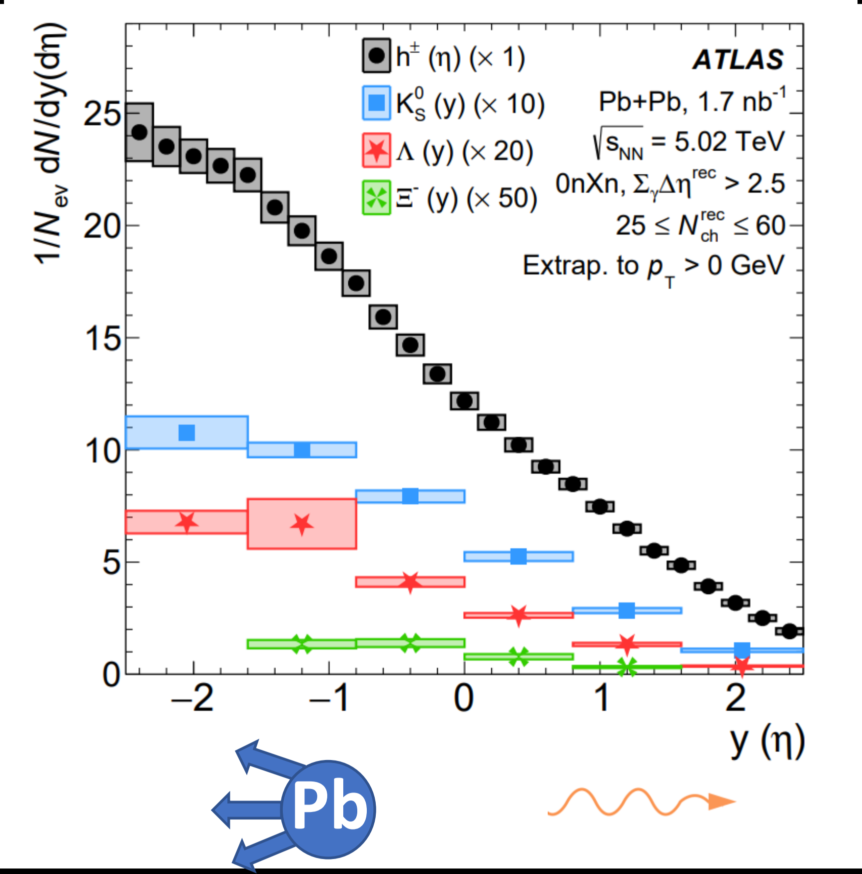
Rapidity gaps $\Sigma_\gamma \Delta\eta$ and N_{ch}

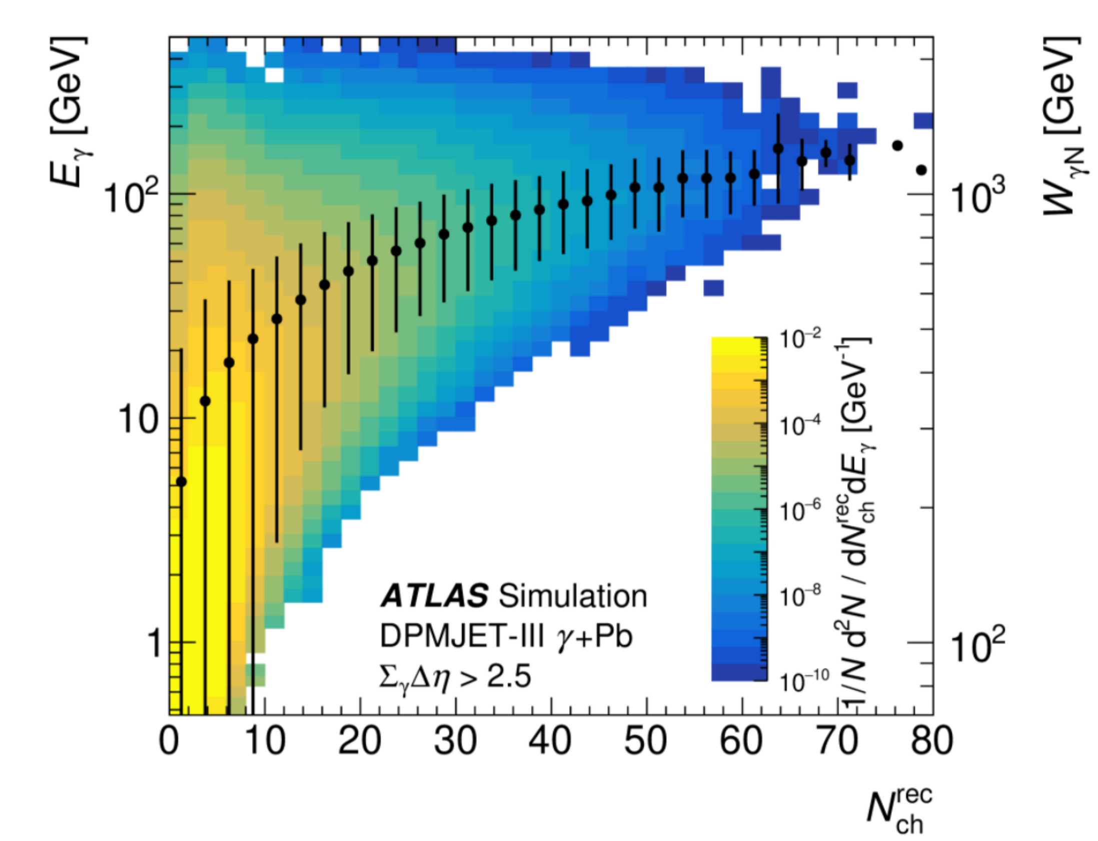


Photonuclear events have large rapidity gaps in the photon-going direction and a steeply falling multiplicity distribution.

arXiv:2101.10771

$dN_{ch}/d\eta$ in γA collisions





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

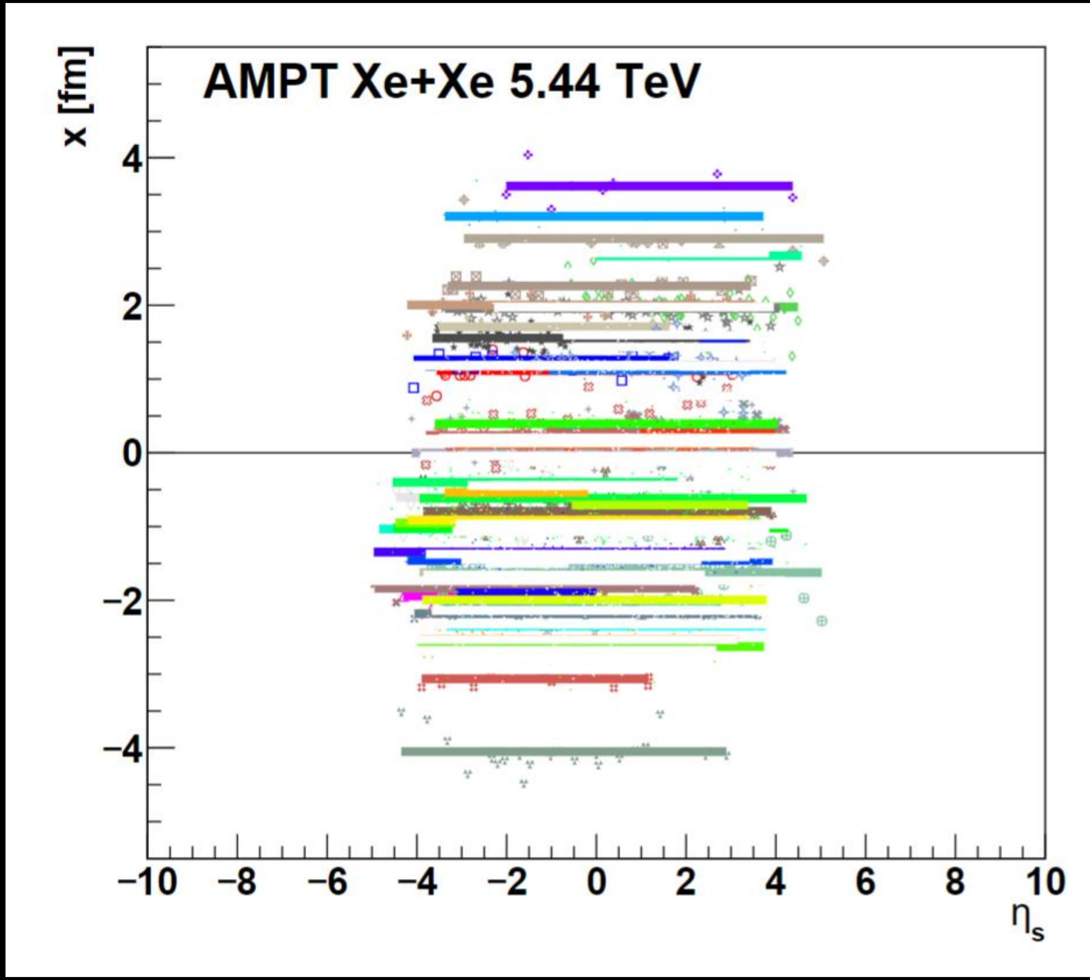
MC comparison shows 200 GeV to 1 TeV CM energy ($W_{\gamma N}$)

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

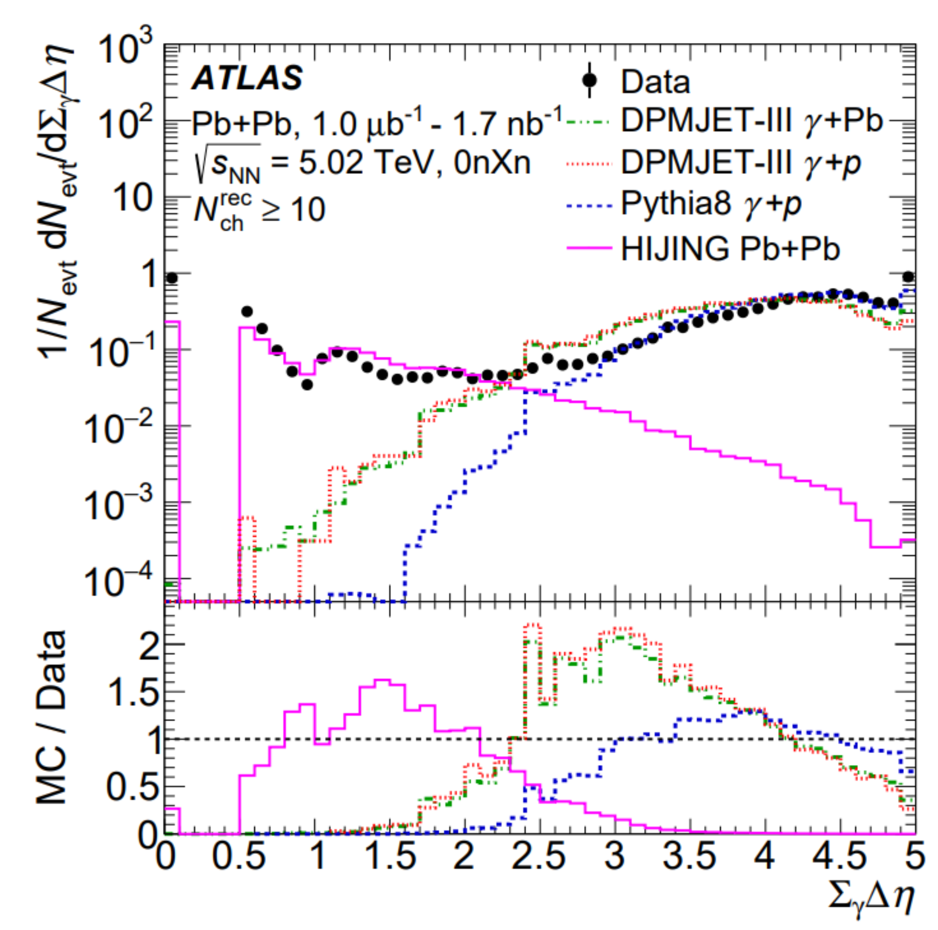
arXiv:2101.10771

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.



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

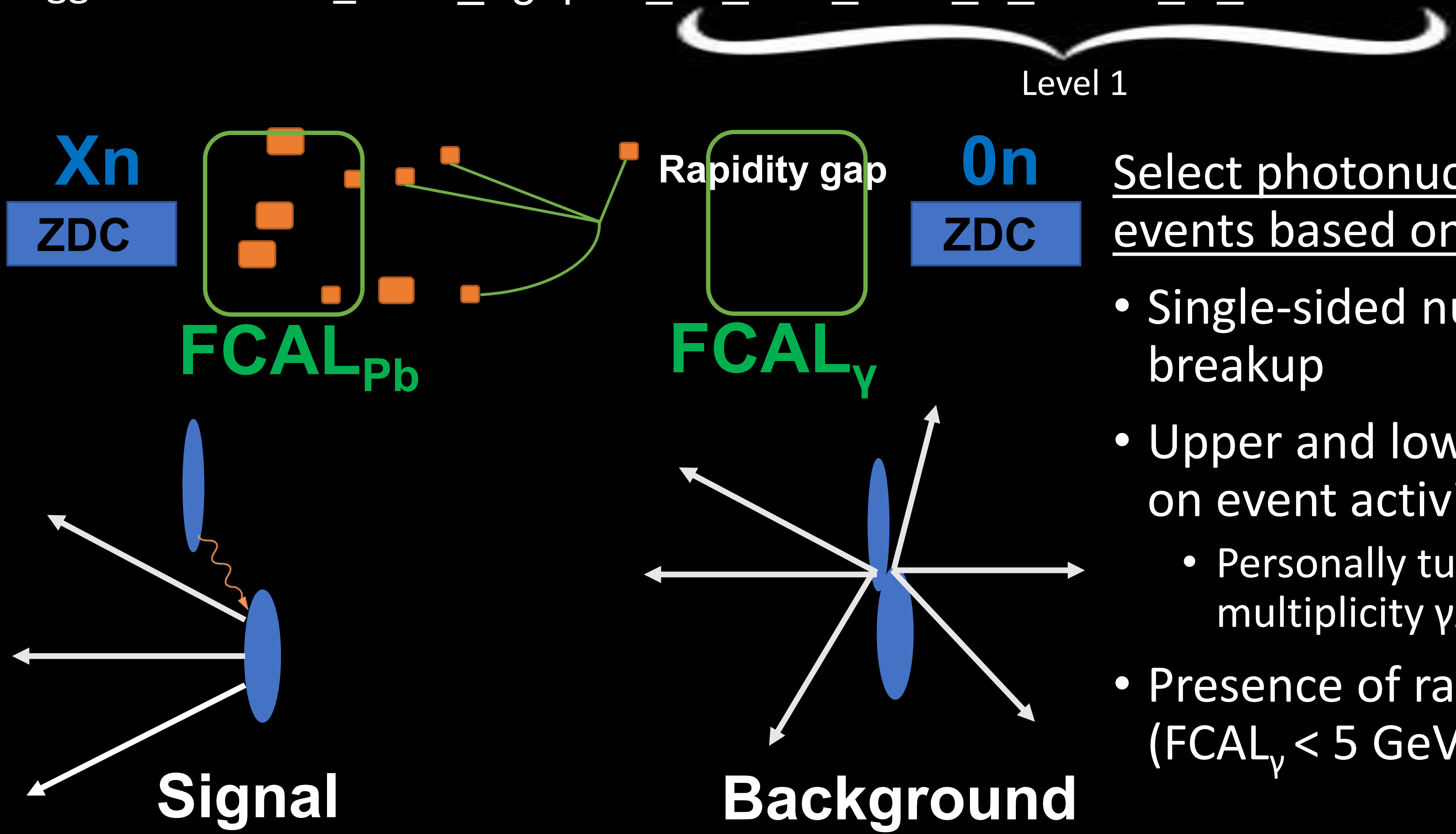
Qualitative agreement with MCs, PYTHIA being the most compatible

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

arXiv:2101.10771

Collecting photonuclear events

Trigger name: HLT_trk25_FgapC5_L1_TE3_ZDC_A_VZDC_C_VTE200 ???



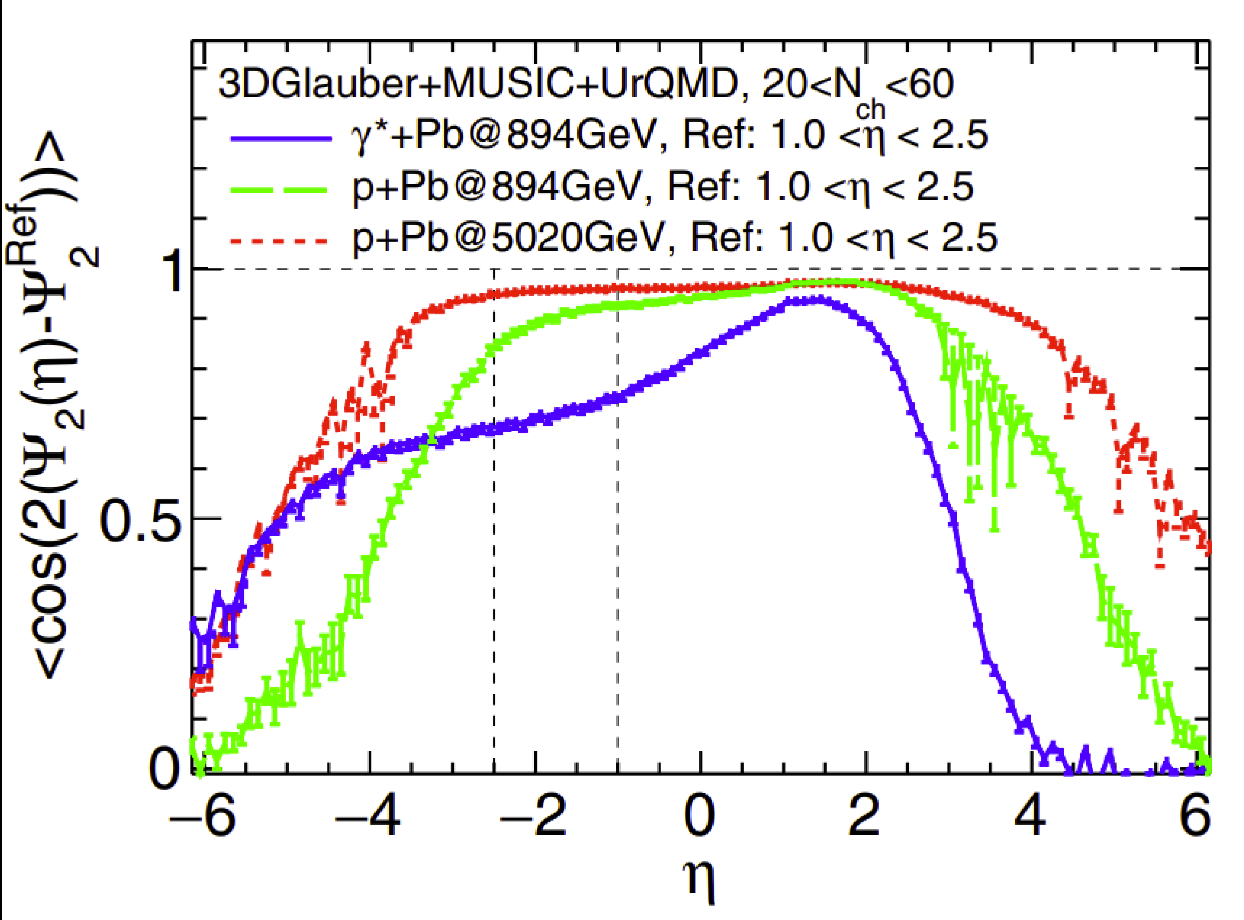
Select photonuclear events based on

- 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)

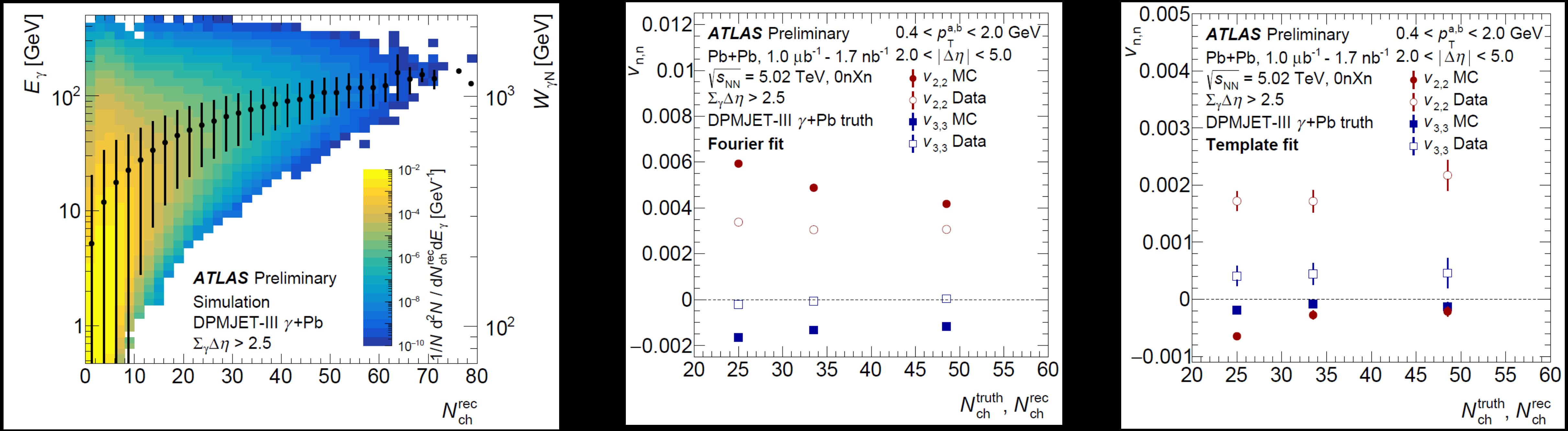
Why is γPb v_2 smaller

EPJ Web of Conferences 276, 01002 (2023) SQM22

- 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.



Comparison to DPMJET-III

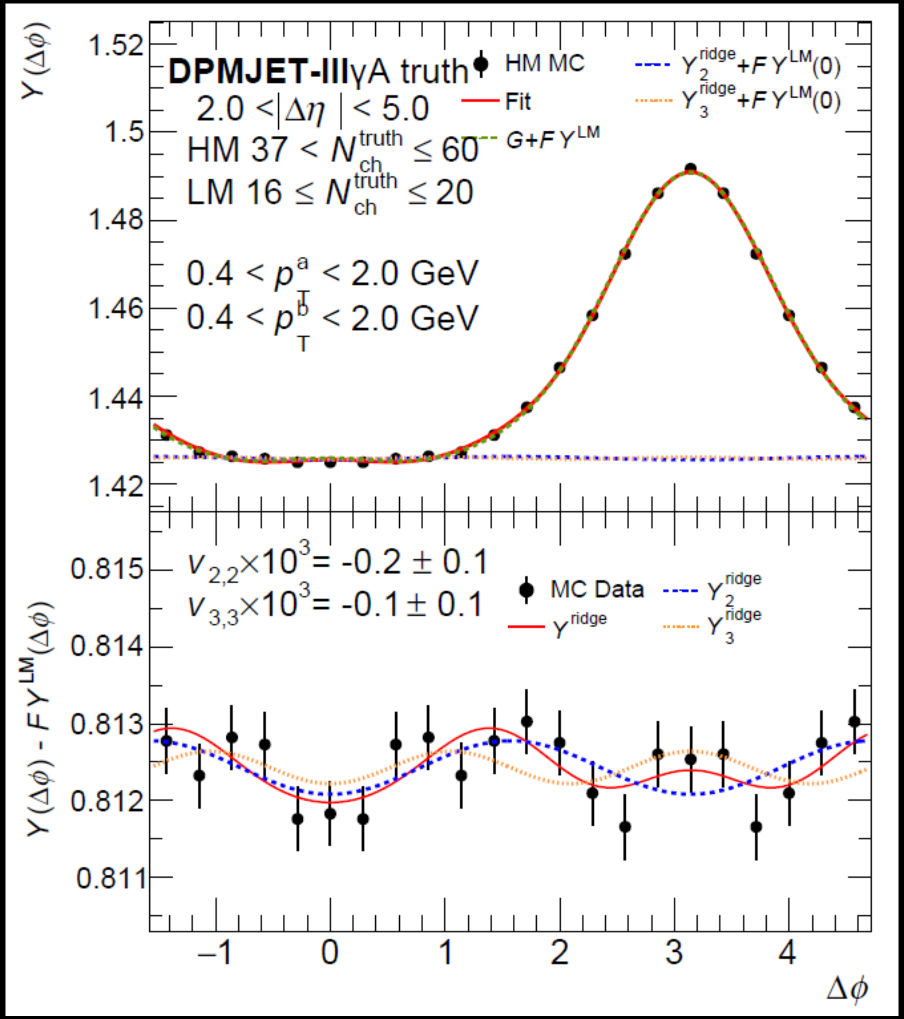


- DPMJET-III predicts the photon energy changes by about 1-2 standard deviations over the multiplicity range of the measurement and a doubling of the mean $W_{\gamma N}$ for 10 to 60 N_{ch}^{rec}.
- Large difference between measured $v_{n,n}$ before and after template nonflow subtraction for data and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

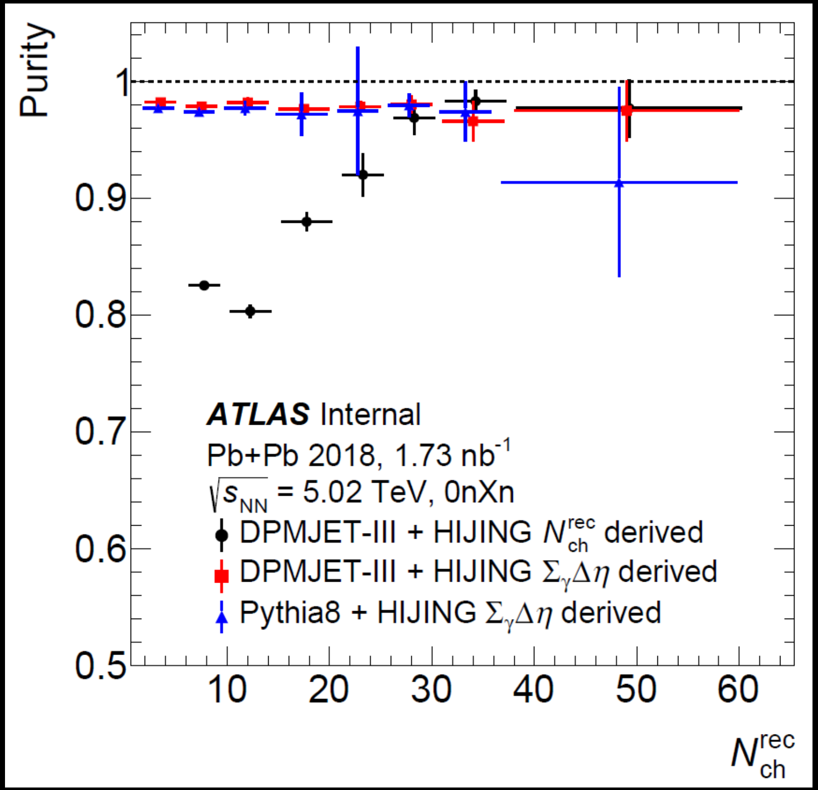
CERN-EP-2020-246

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.

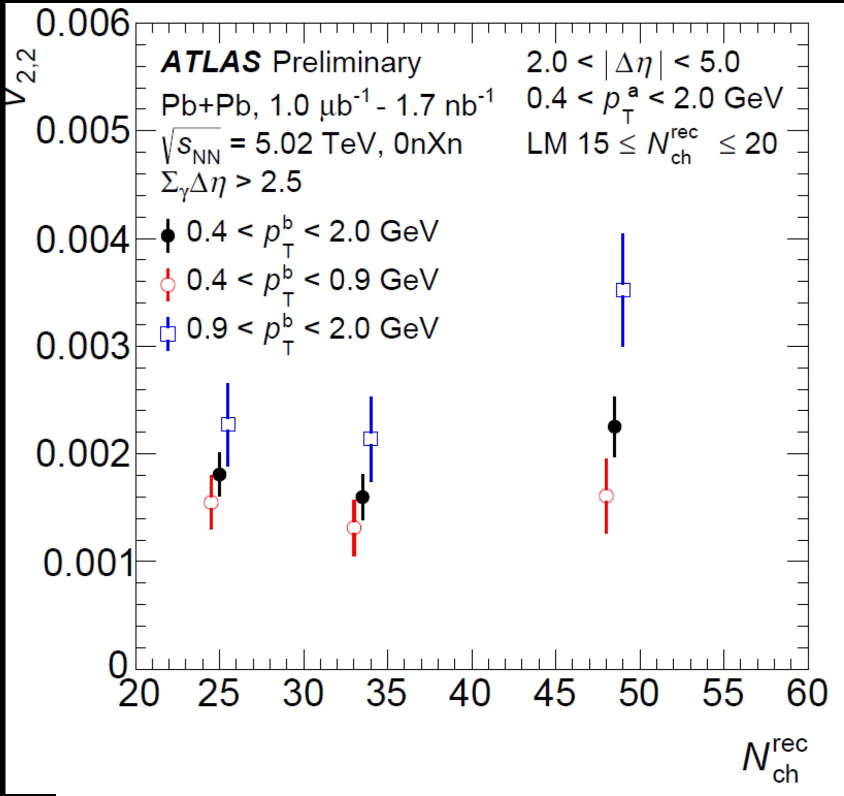


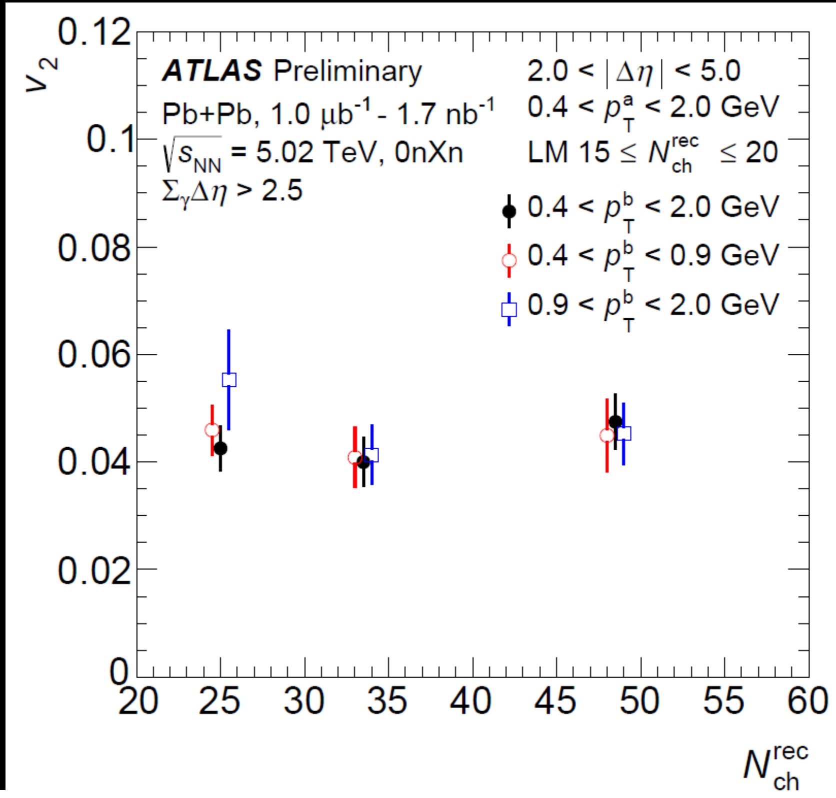
Purity of the photonuclear selection



- 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.

Measurements of longitudinal decorrelation

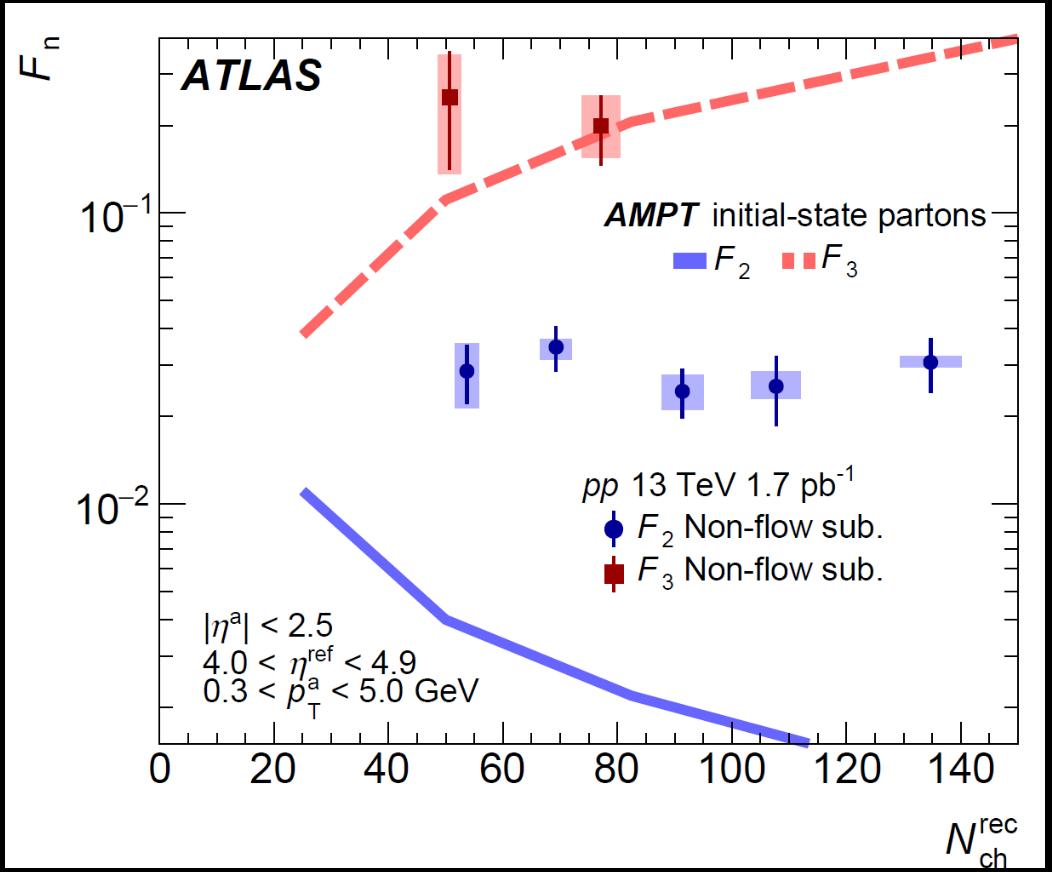
F_n is the fractional change in $v_{n,n}$ per a unit rapidity

It characterizes longitudinal decorrelation effects well

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

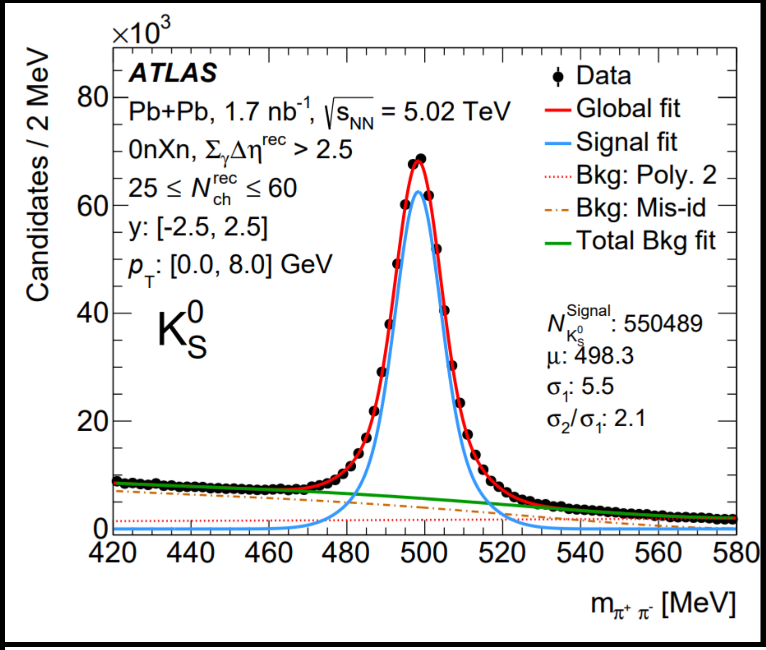
First decorrelation measurement in small systems

arXiv:2308.16745

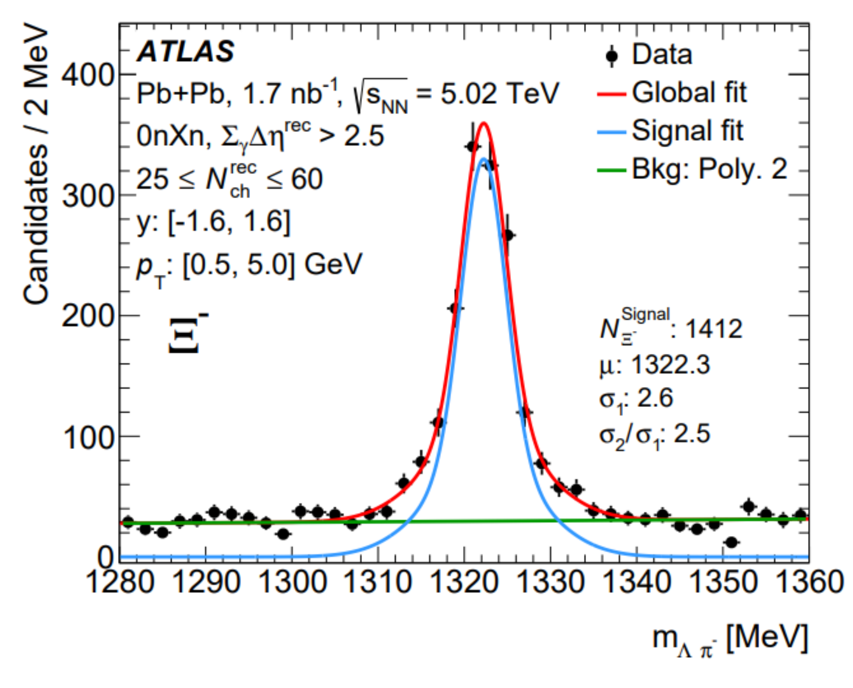


Strangeness enhancement in γA

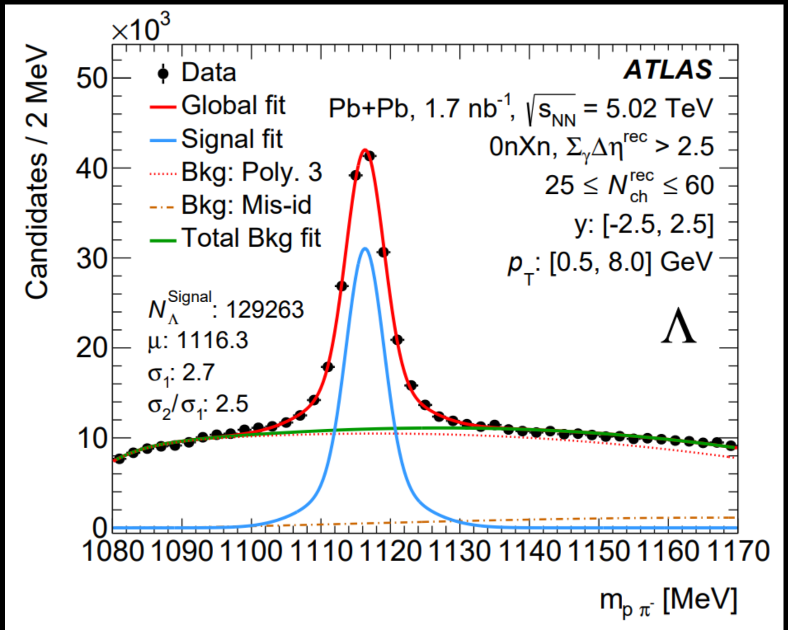
- Strangeness enhancement, baryon anomaly, baryon stopping…
- Novel incoming quantum numbers in γPb
- Plots of displaced vertex identified particle candidates in γPb



K_S^0

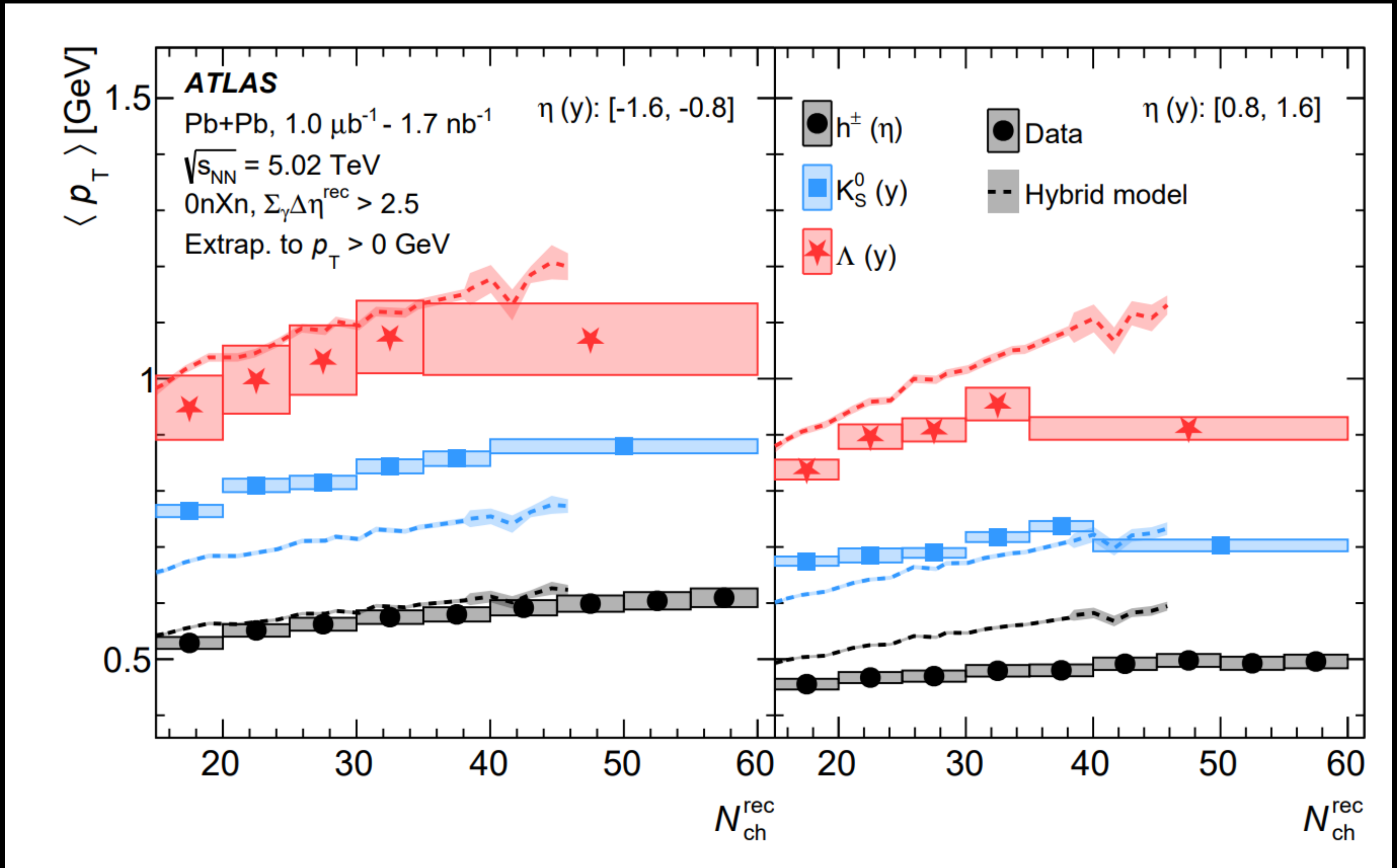


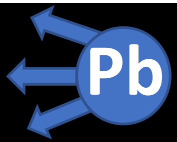
Ξ^-



Λ

Identified particle <pT> in *γA*





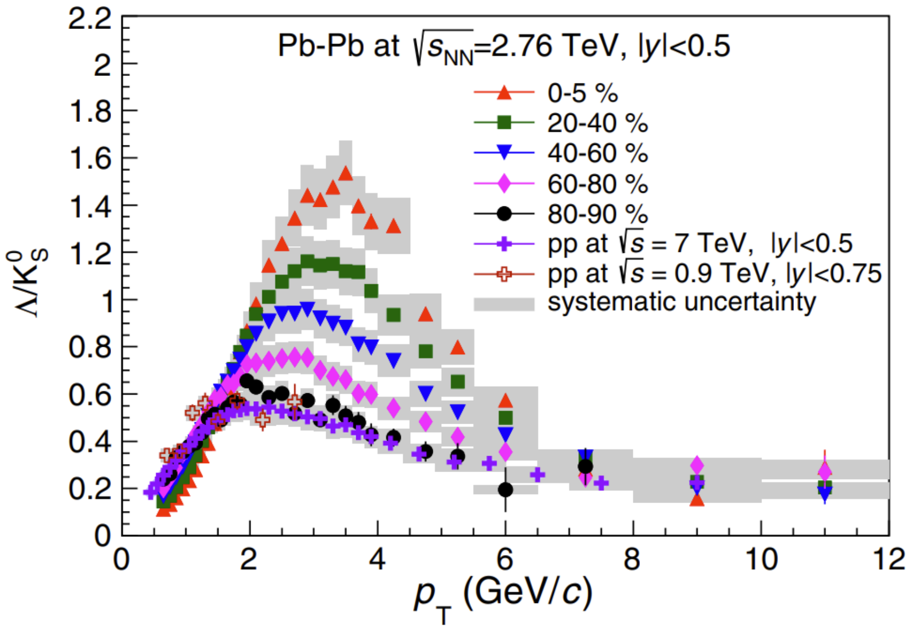
- <pT> with $_{Nch}$
  - Higher energy density achieved in higher multiplicity collisions leads to stronger radial expansion.
  - Thought of as a signature of QGP formation
- Larger <pT> in the Pb-going direction
- Qualitative agreement with the Hydro model excluding K_S^0
  - Common in these new data-model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

arXiv:2503.08181

Behavior in data is consistent with qualitative picture of radial flow

Baryon anomaly in *γA*

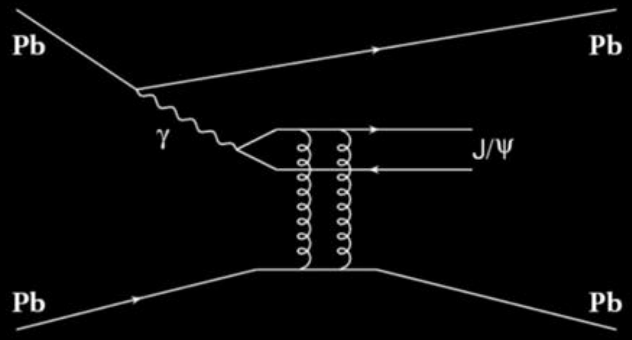
Phys. Rev. Lett. **111**, 222301

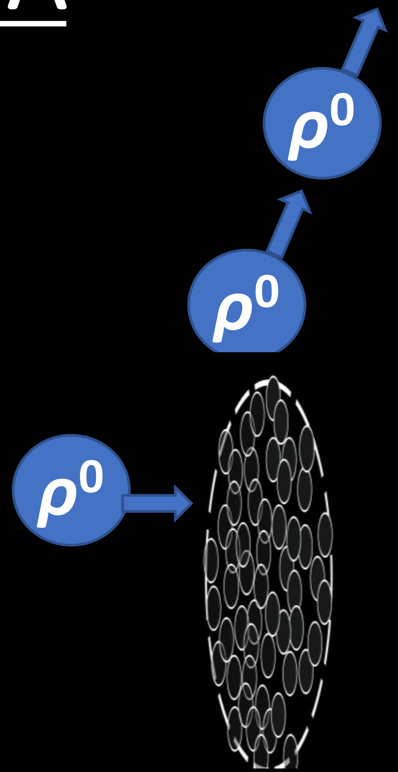


- Larger hydrodynamic push to baryons as the QGP velocity field cools into hadrons
- Observe large baryon enhancement at mid-pT in *γA,* similar to pPb
- Possibly see larger baryon enhancement in the Pb going direction

Single-photon interactions V+A

$|V\rangle \otimes |\mathrm{Pb}\rangle$





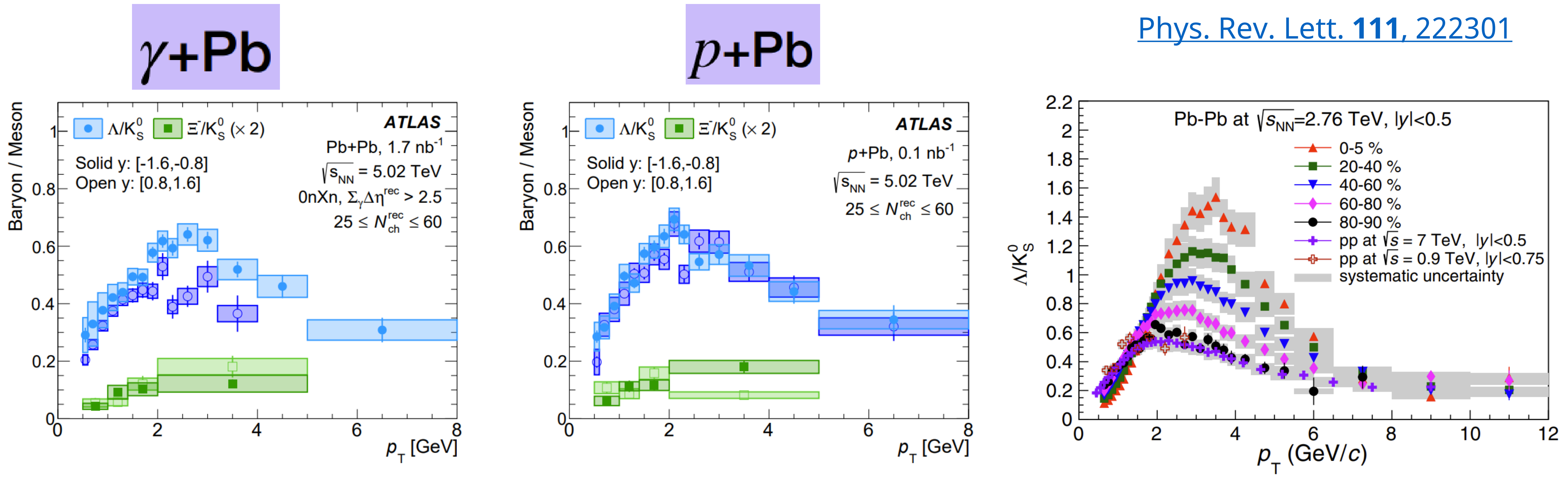
Elastic scattering: V + A → A + V

Example measurement of vector meson production

Baryon anomaly in γA

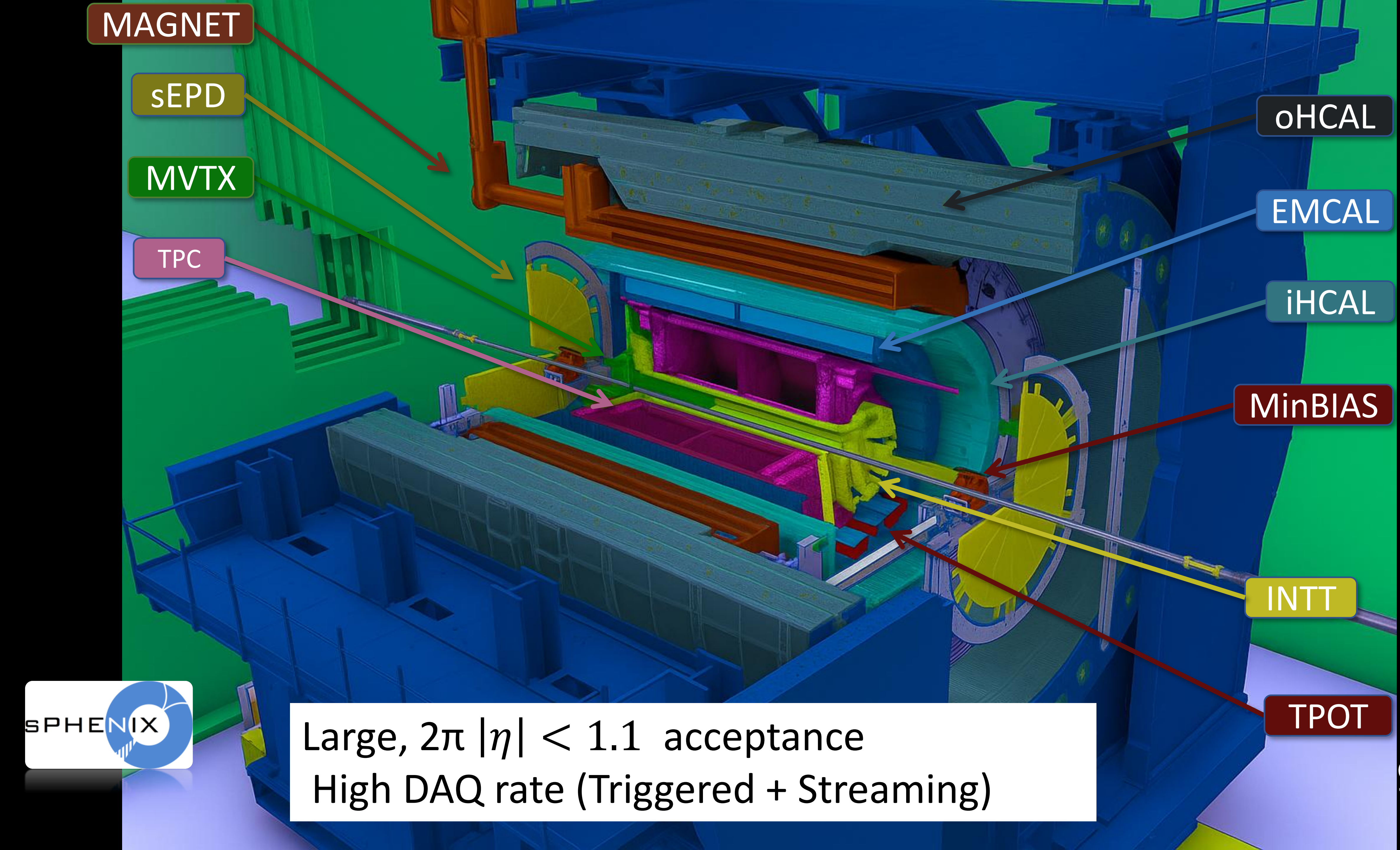
arXiv:2503.08181

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

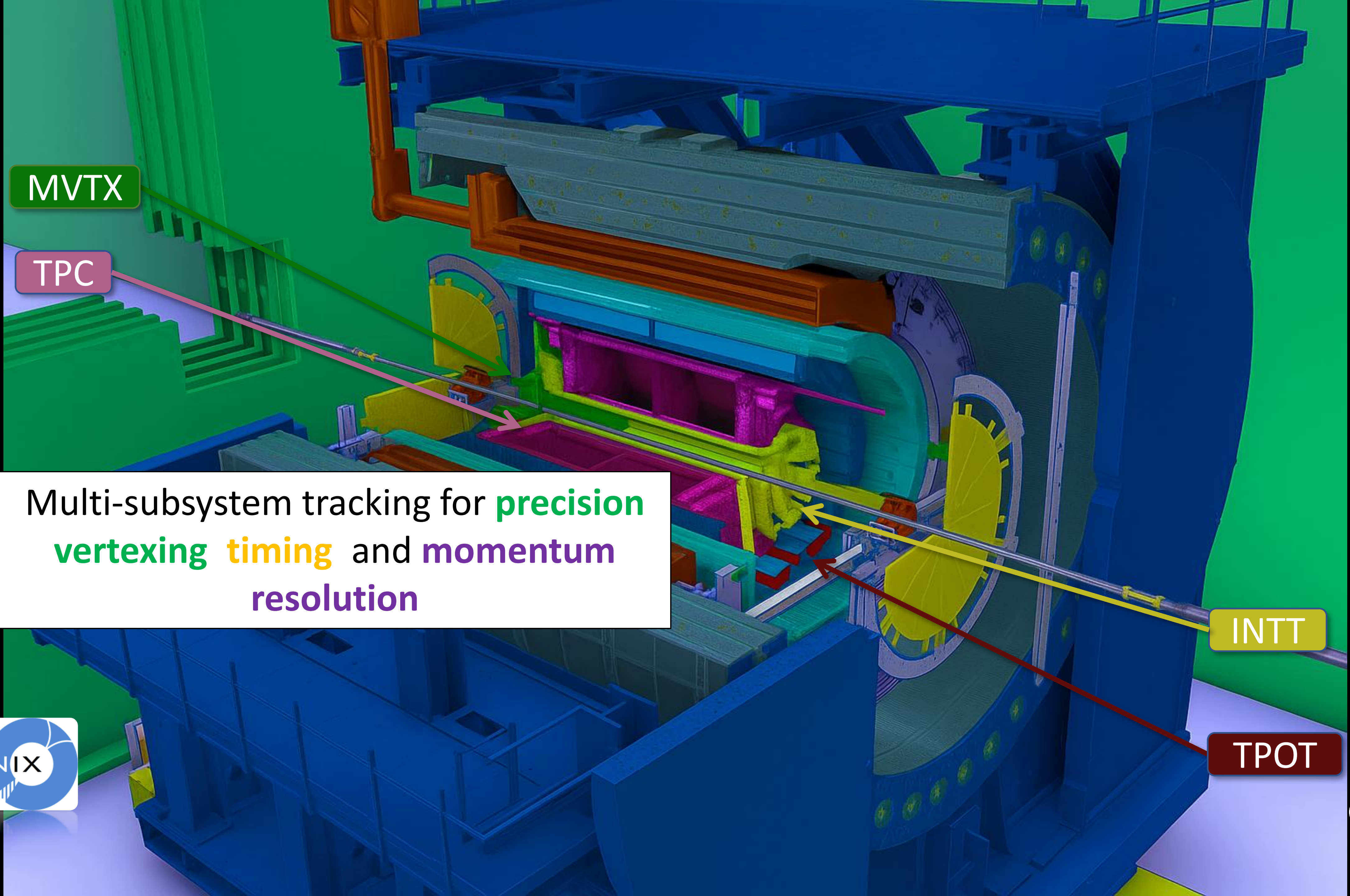


- Larger hydrodynamic push to baryons as the QGP velocity field cools into hadrons
- Observe large baryon enhancement at mid-pT in γA, similar to pPb
- Possibly see larger baryon enhancement in the Pb going direction

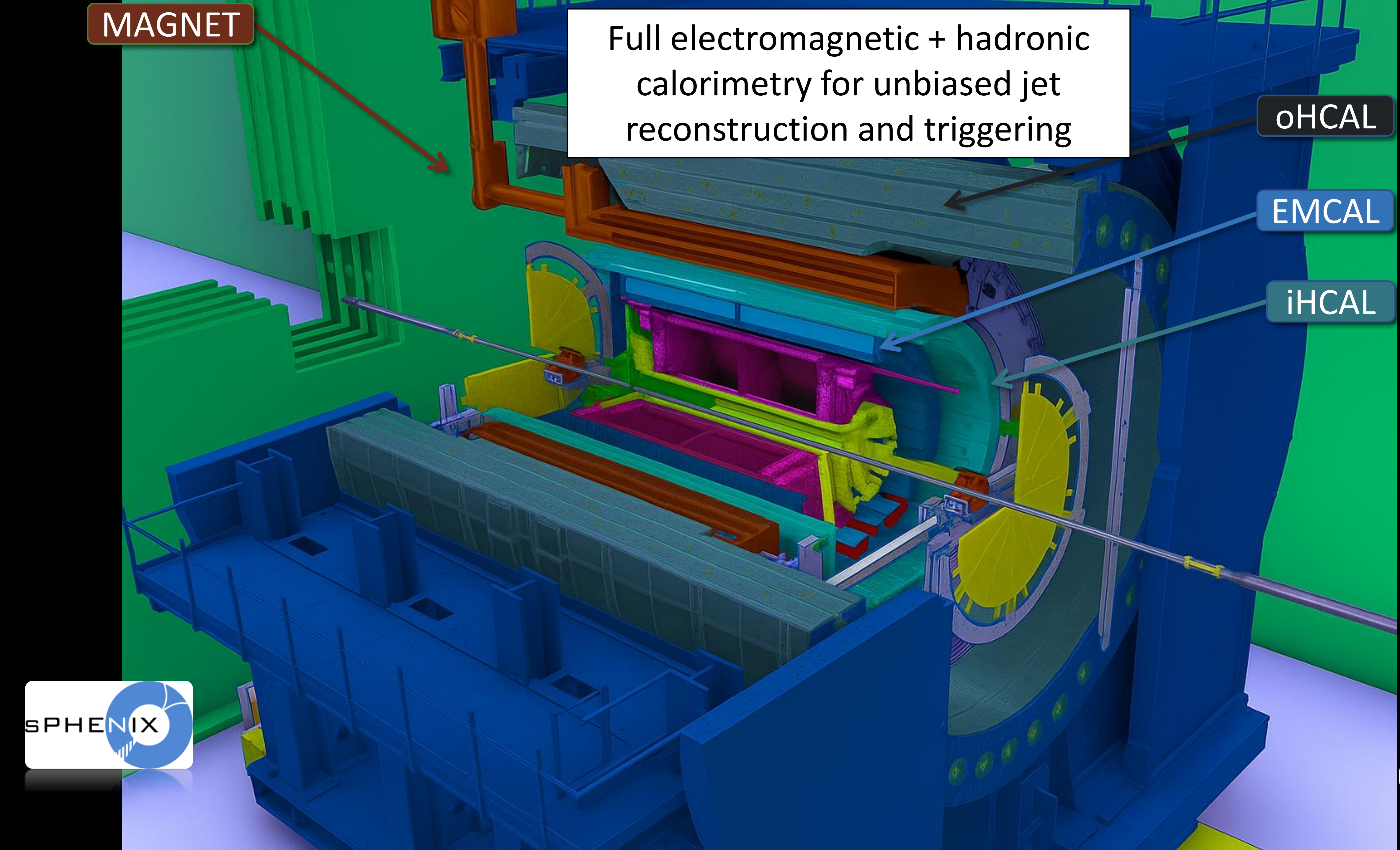
Observe large baryon enhancement at mid-pT in *γA*, similar to pPb

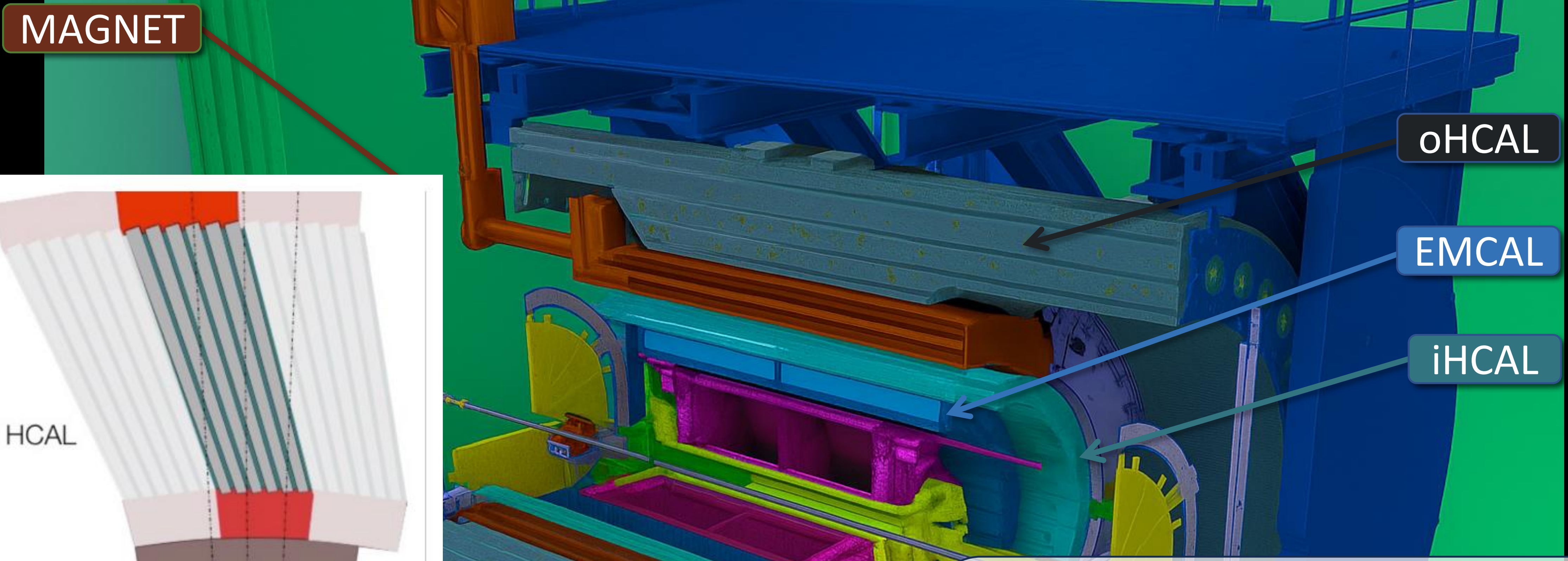


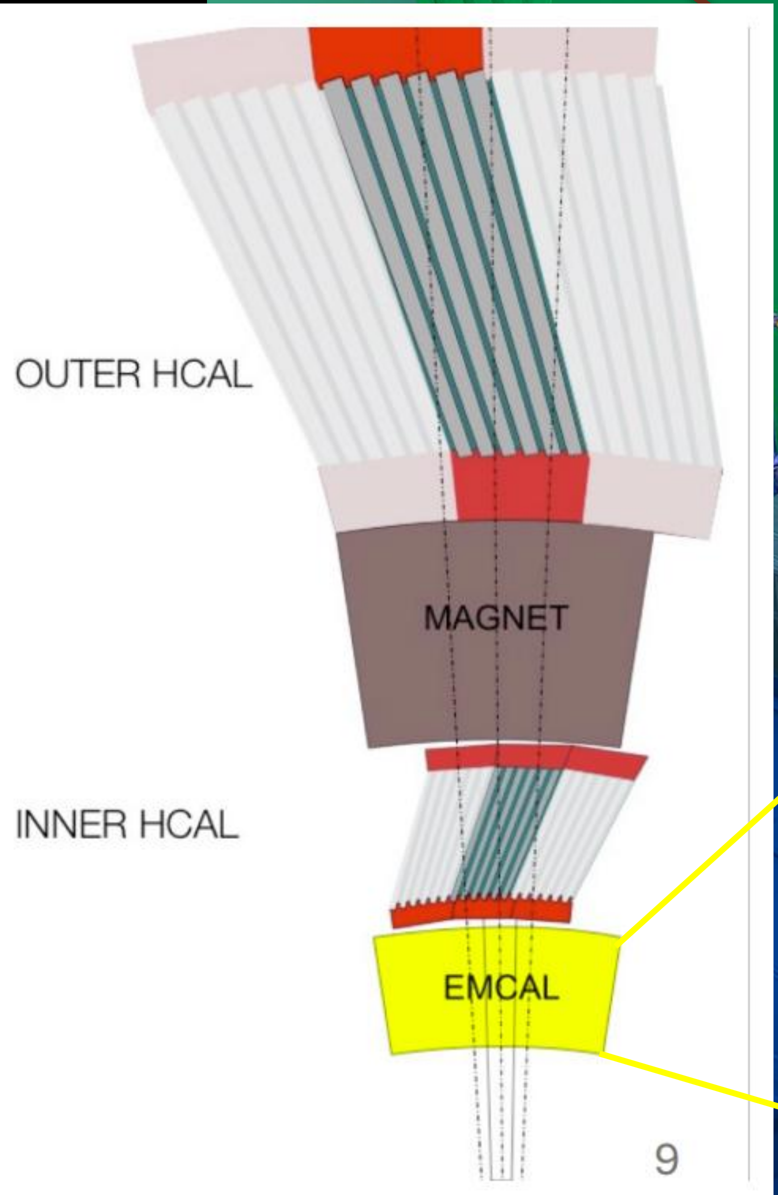
Large, 2π $|\eta| < 1.1$ acceptance
High DAQ rate (Triggered + Streaming)

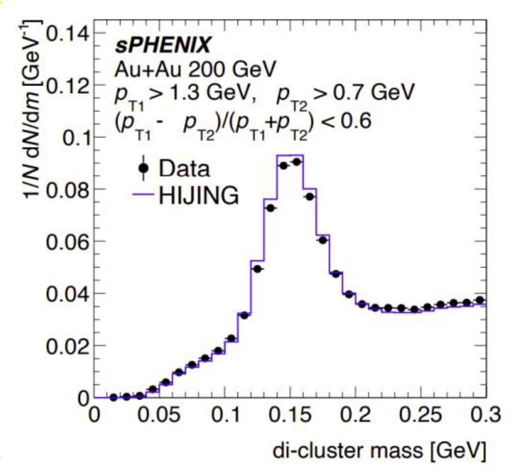


Multi-subsystem tracking for **precision vertexing** **timing** and **momentum resolution**


MAGNET
Full electromagnetic + hadronic calorimetry for unbiased jet reconstruction and triggering
oHCAL
EMCAL
iHCAL
sPHENIX



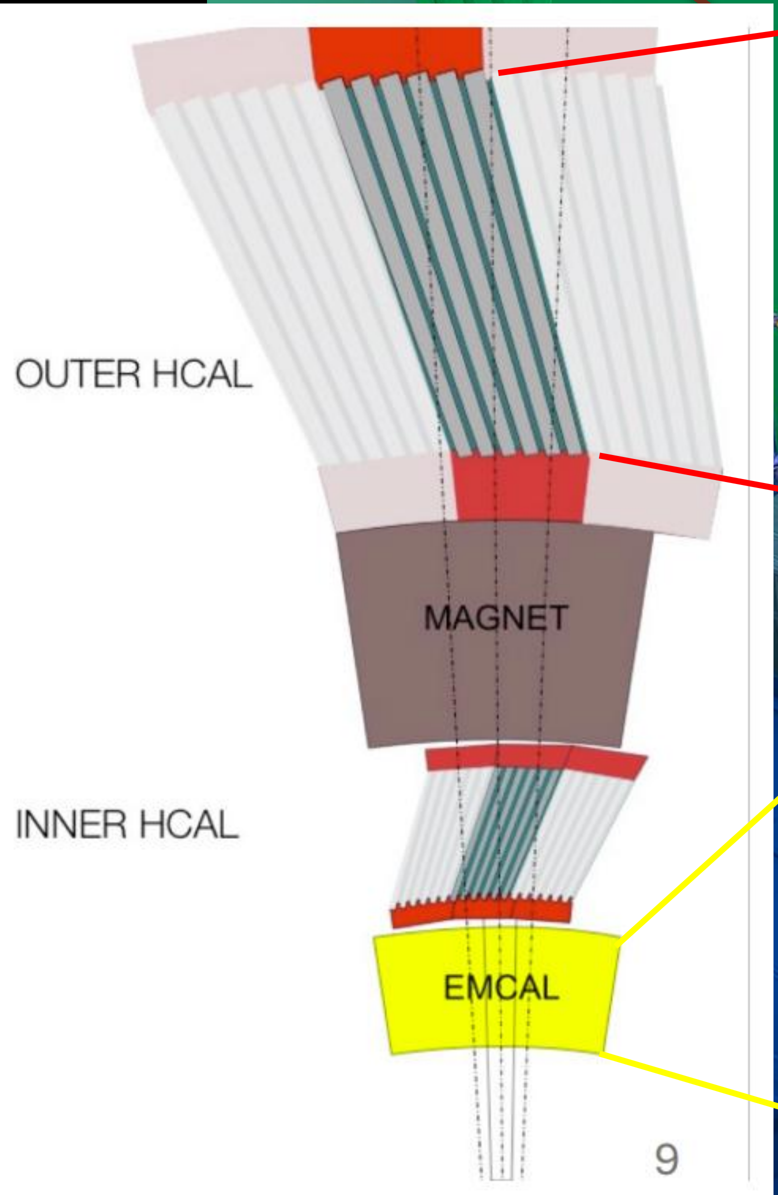


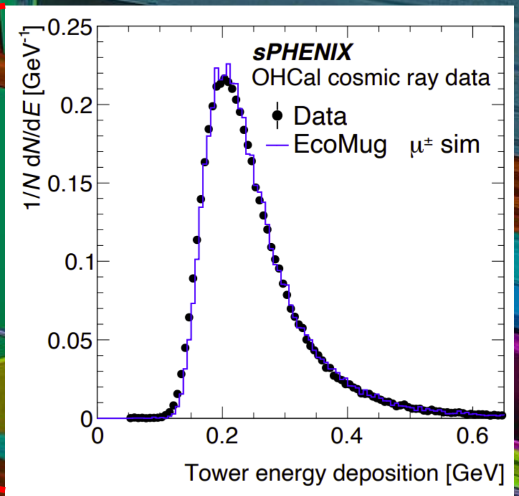


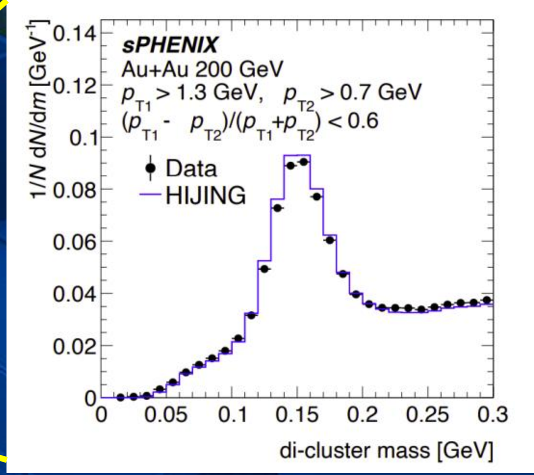
EMCal

- $\Delta\phi \times \Delta\eta$: 0.025x0.025
- Tungsten-scintillating fiber sampling calorimeter
- Projective geometry
- Calibration: $\pi^0 \rightarrow \gamma\gamma$ mass peak to match between data and simulation

MAGNET







Phys. Rev. C 112, 024908

oHCAL

EMCAL

iHCAL

HCal

- $\Delta\phi x \Delta\eta$: 0.1x0.1
- Steel-plate scintillating-tile sampling calorimeter
- Projective geometry
- Calibration: compare measured MIP peak from cosmic ray muons in data to simulation

EMCal

- $\Delta\phi x \Delta\eta$: 0.025x0.025
- Tungsten-scintillating fiber sampling calorimeter
- Projective geometry
- Calibration: $\pi^0 \rightarrow \gamma\gamma$ mass peak to match between data and simulation