Relativistic Heavy Ions III - Unexpected results, new physics and the future

By the end of today's talk I aim for you to be able to discuss at dinner :

How measurement XYZ changed your "world view" of nuclear physics
How smaller doesn't always mean simpler
How much there is left to understand about heavy-ion collisions despite so many results already existing

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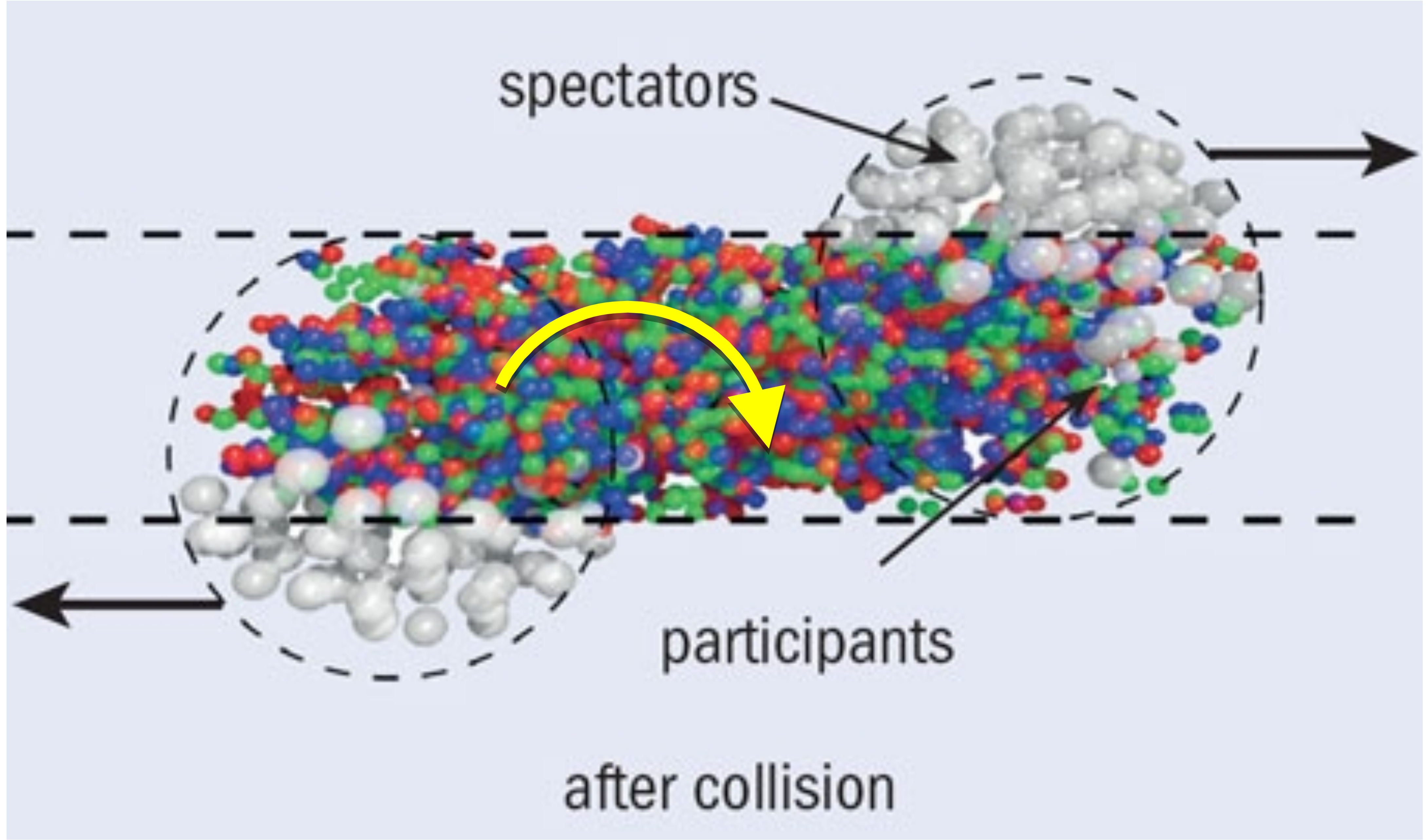
How much there is left to understand about heavy-ion collisions despite so many results already existing

(that secretly you now want to join the heavy-ion research community)

Other fascinating facts established about the QGP

The spinning QGP

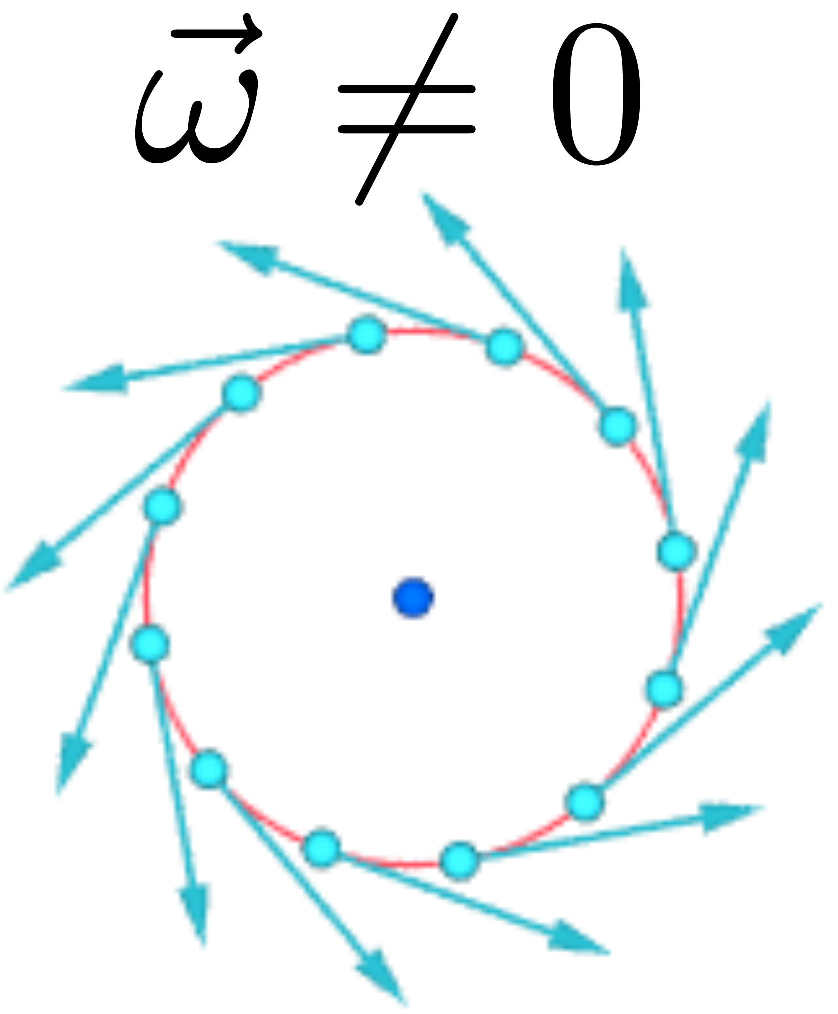


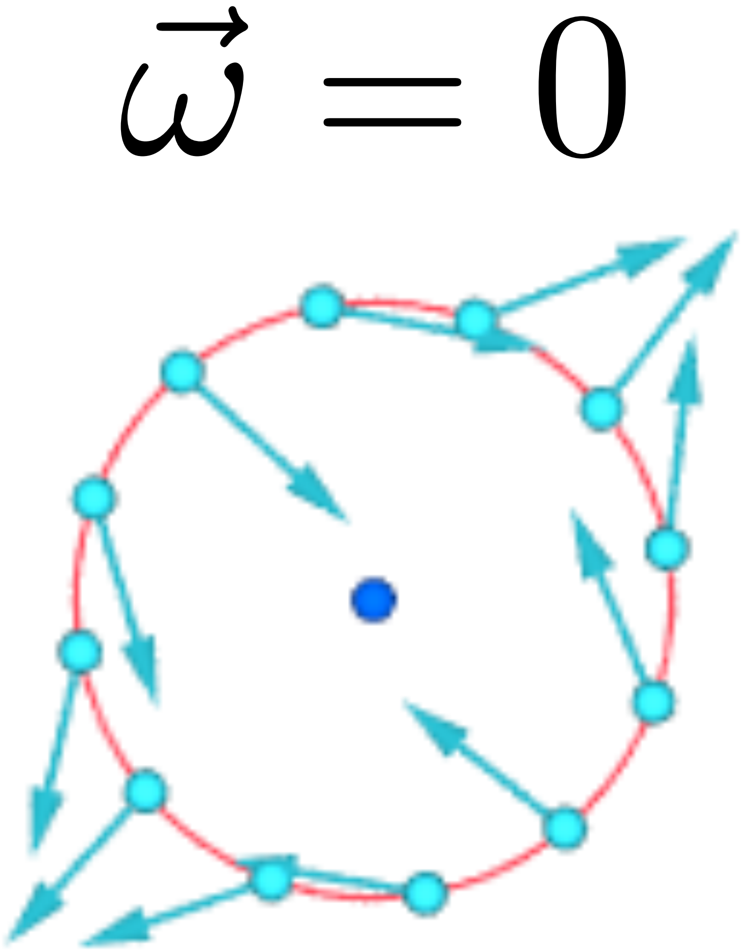
We generate a "spinning" QGP?

|L| ~ 10^5 in peripheral collisions

Spectators create a large B field

$$\vec{\omega} = (\vec{\nabla} \times \vec{v})/2$$





How does that affect fluid/transport?

Vorticity - local spinning motion

Viscosity dissipates vorticity to fluid at larger scales

Can we see any manifestation of this in the data?

Measuring Λ ***Global*** *Polarization*

Global polarization (alignment of spin with collision system angular momentum)

Direction of L:

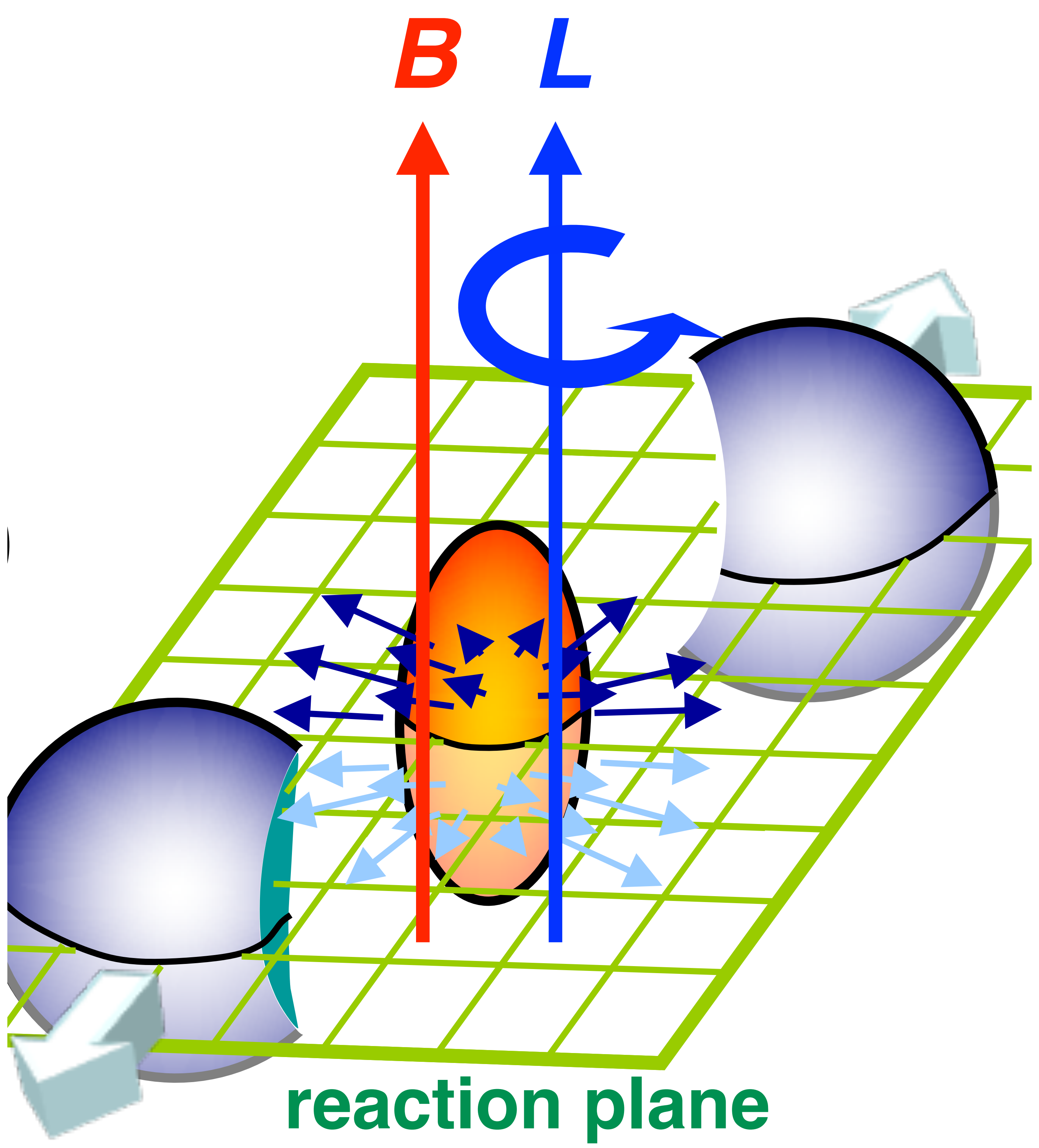
Estimate from 1st order reaction plane

Λ Polarization

Self analyzing

Decay p preferentially emitted in Λ spin direction

Decay $\bar{p}$ preferentially emitted against $\bar{\Lambda}$ spin direction



Λ and $\bar{\Lambda}$ spins aligned with L → Vortical or QCD spin-orbit

- Sigma feed-down goes with the primaries

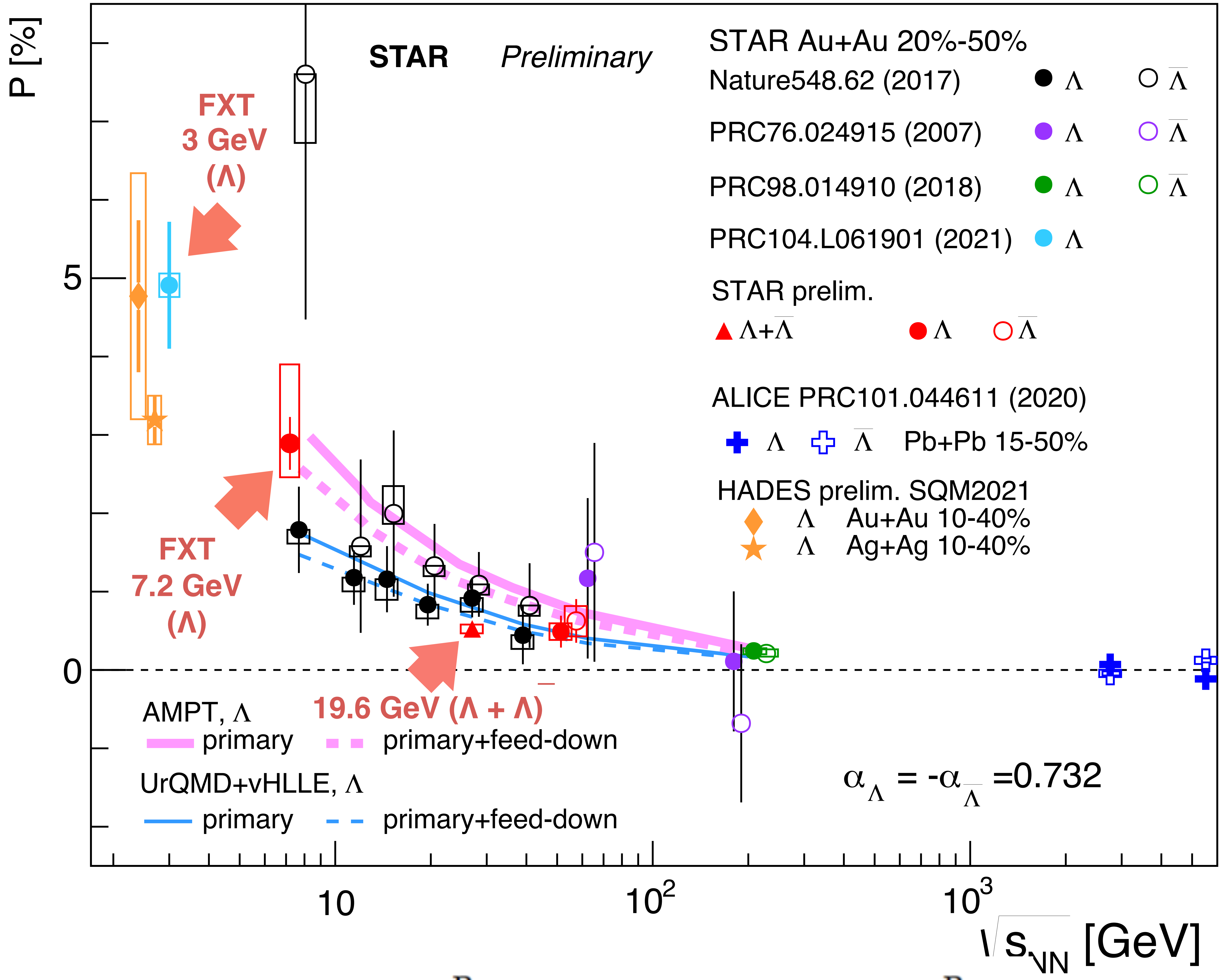
$$P_{vortical} = \frac{1}{2}(P_\Lambda + P_{\bar{\Lambda}})$$

Λ anti-aligned, $\bar{\Lambda}$ aligned with L → μ_H - B coupling

- Sigma feed-down tends to dampen the effect

$$P_{EM} = \frac{1}{2}(P_\Lambda - P_{\bar{\Lambda}})$$

Global Λ polarization



$$P_{\Lambda} \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_{\Lambda} B}{T} \qquad P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_{\Lambda} B}{T}$$

Precision measurements have now been made from $\sqrt{s_{NN}}$=3-5000 GeV:

QGP is non-central collisions is highly vortical: $\omega \sim 10^{22}\ s^{-1}$

How fast is that compared to the most powerful tornado?

a) slower

b) about the same

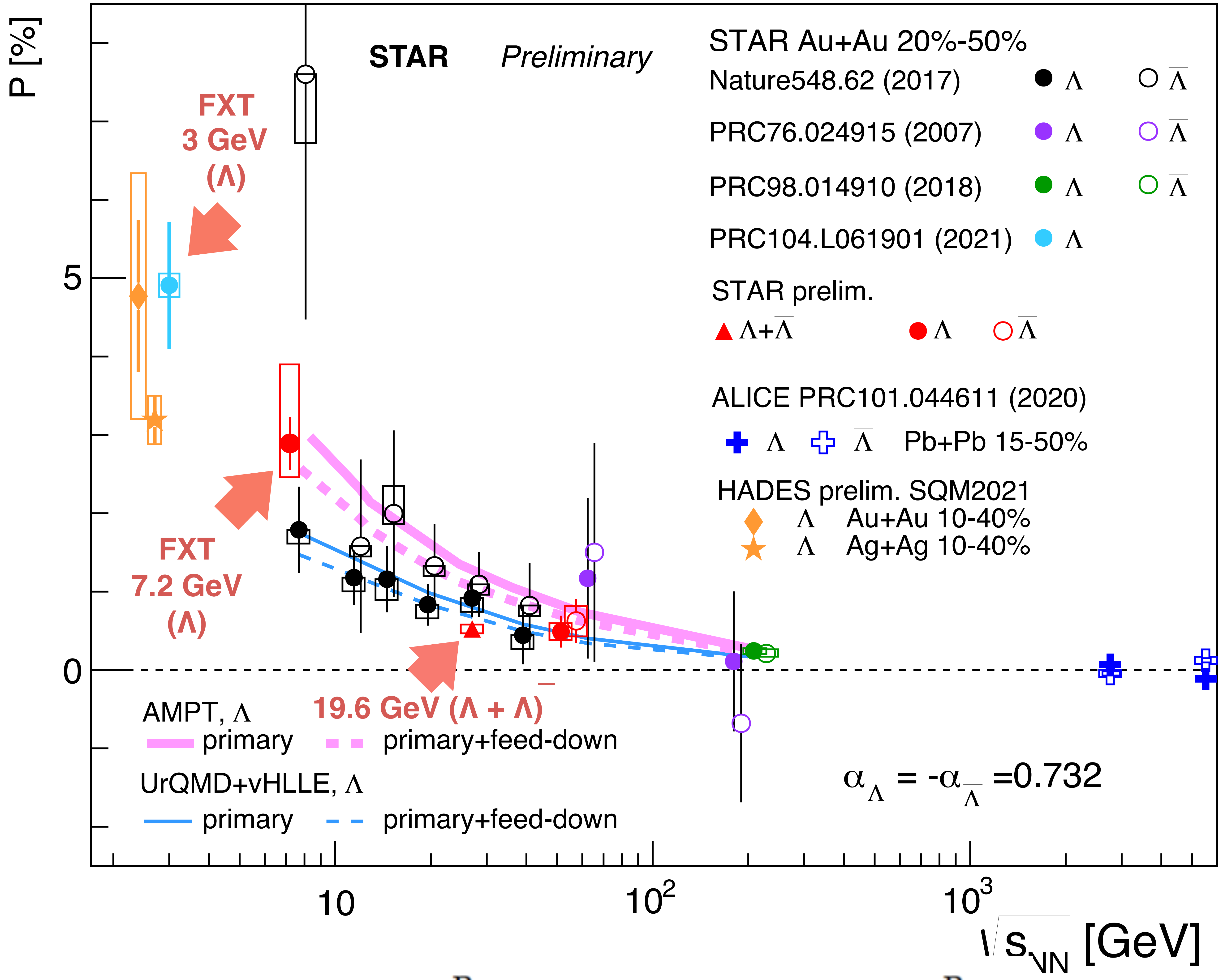
c) 1000 times faster

d) billion times fast

e) even faster

STAR:Nature 548, 62 (2017)

Global Λ polarization



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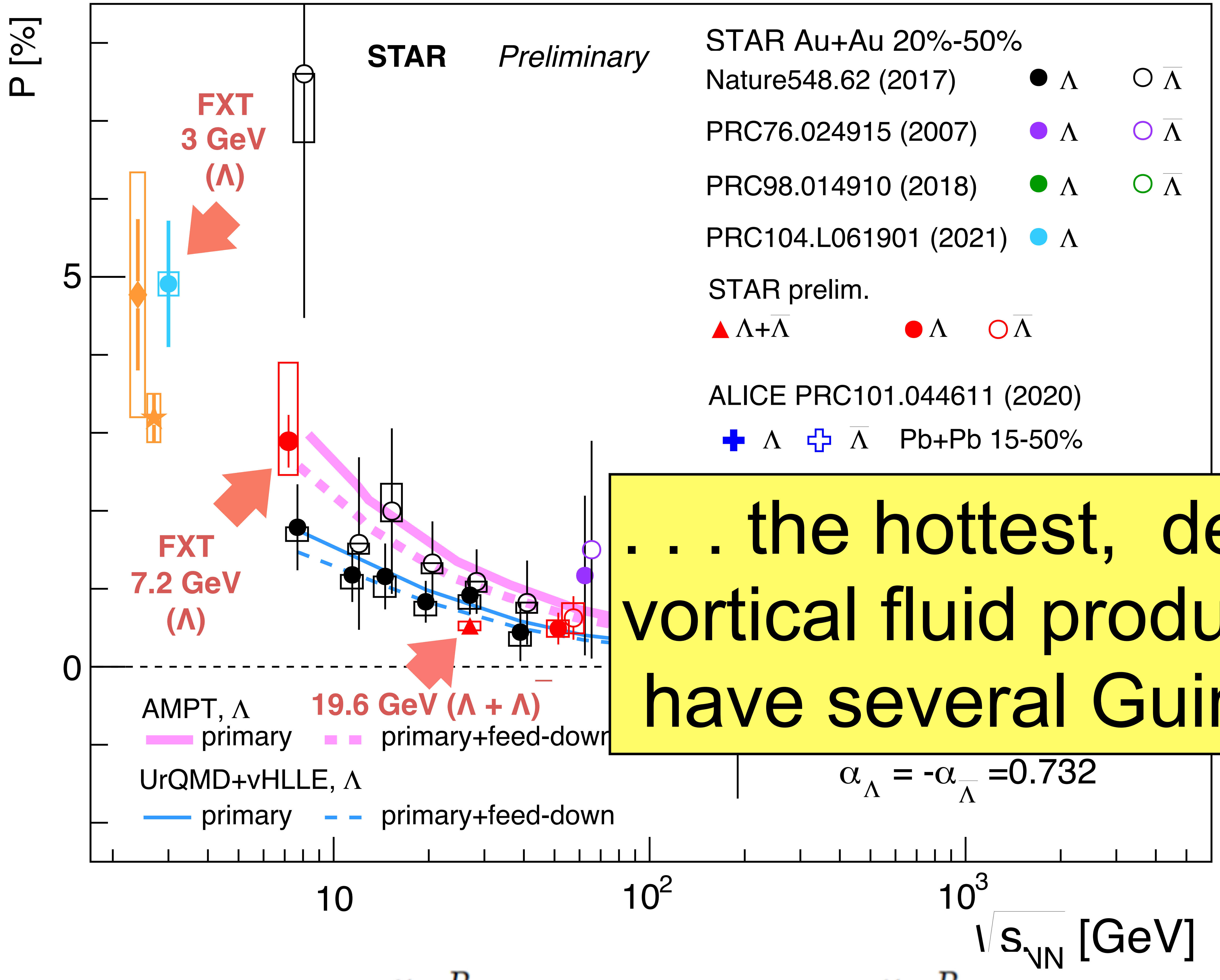

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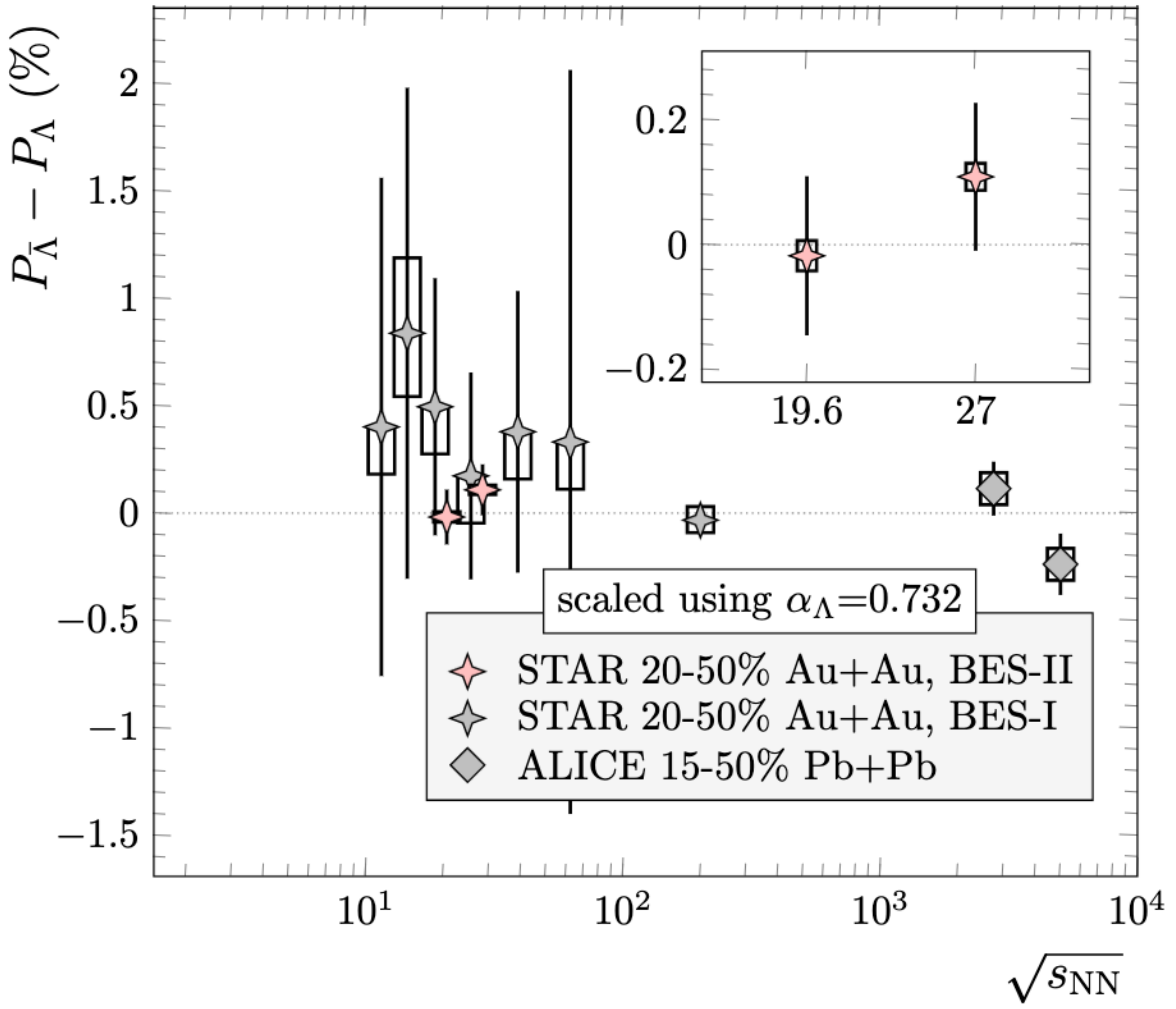
. . . the hottest, densest, least viscous, most vortical fluid produced in the laboratory . . . have several Guinness world records

d) billion times fast

e) even faster
ten billion trillion times faster

STAR:Nature 548, 62 (2017)

Splitting of hyperon polarization?



Late stage magnetic field should cause splitting in (anti)Λ polarization

No splitting observed over wide range of beam energies

At 95% confidence level late stage magnetic field

B(19.6 GeV) < 9.4×1012 *T*

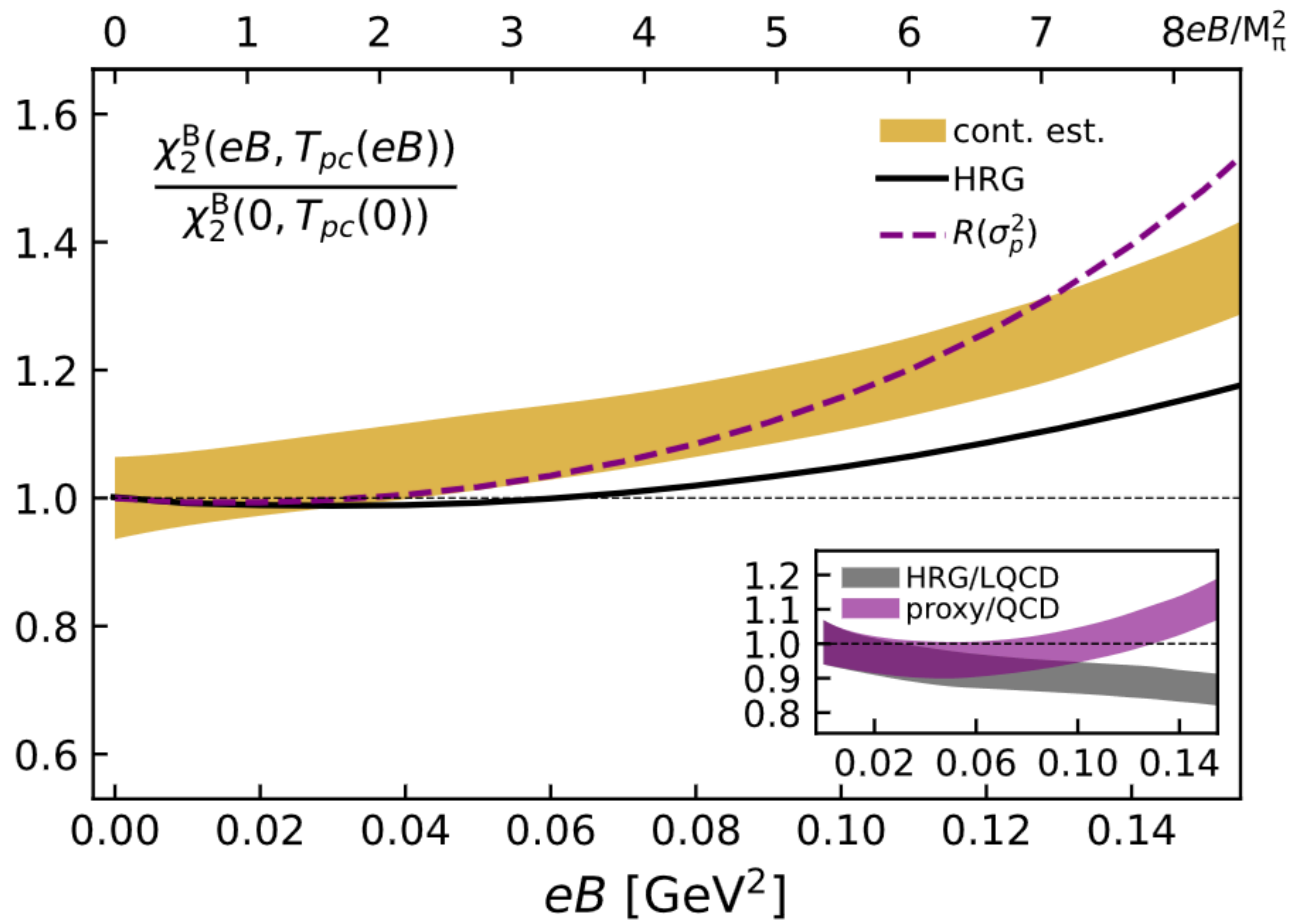
B (27 GeV)< 1.4x1013 *T*

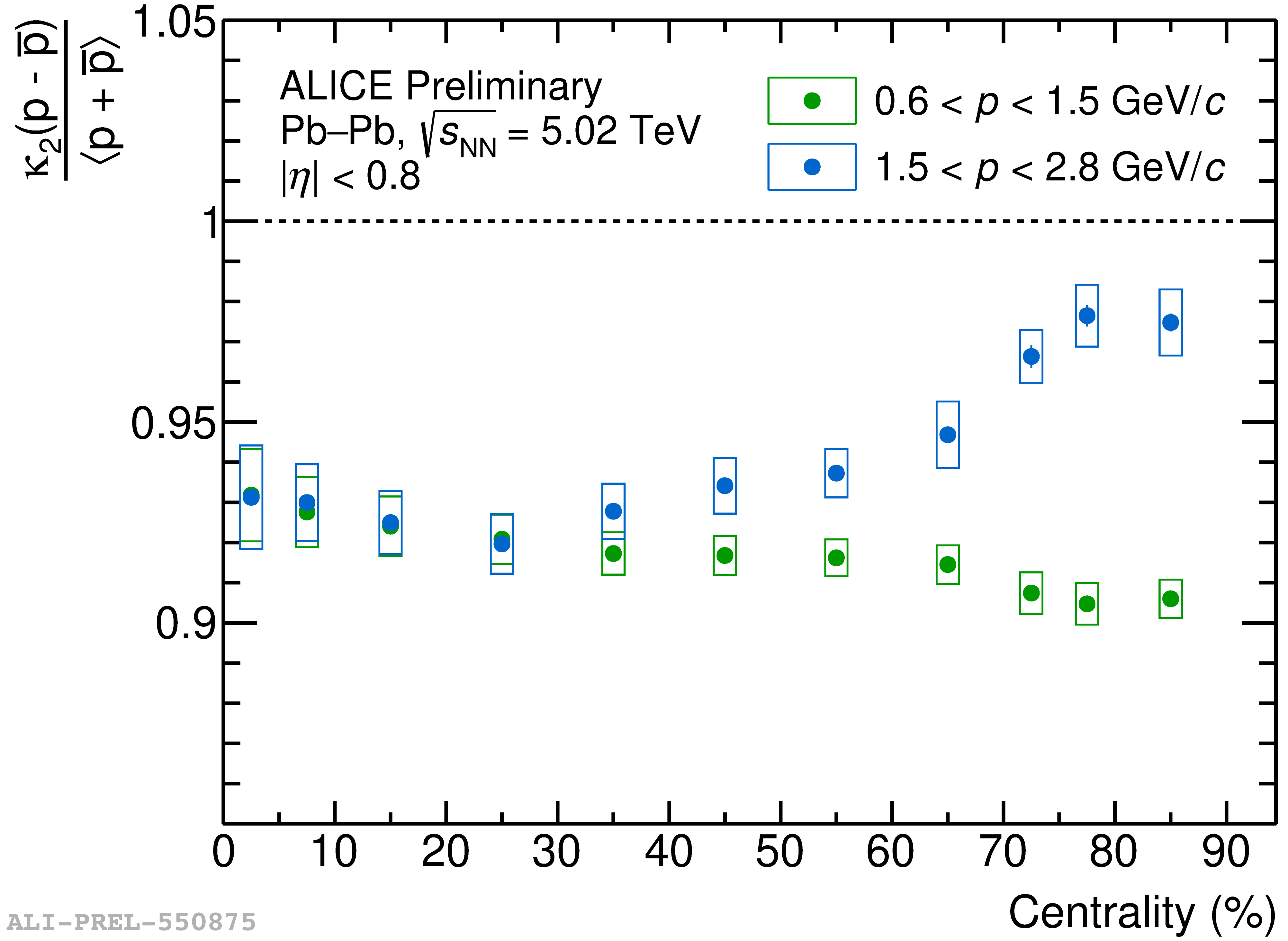
NB: Initial field 10^{14}-10^{16} T

Does magnetic field die away too quickly? Can we probe at earlier time?

Net-proton cummulants at LHC

Lattice calculations suggest susceptibilities sensitive to initial EM field





Fluctuation in high p range increases in peripheral events - B-field largest

More discussion with theory and measurement in pp needed

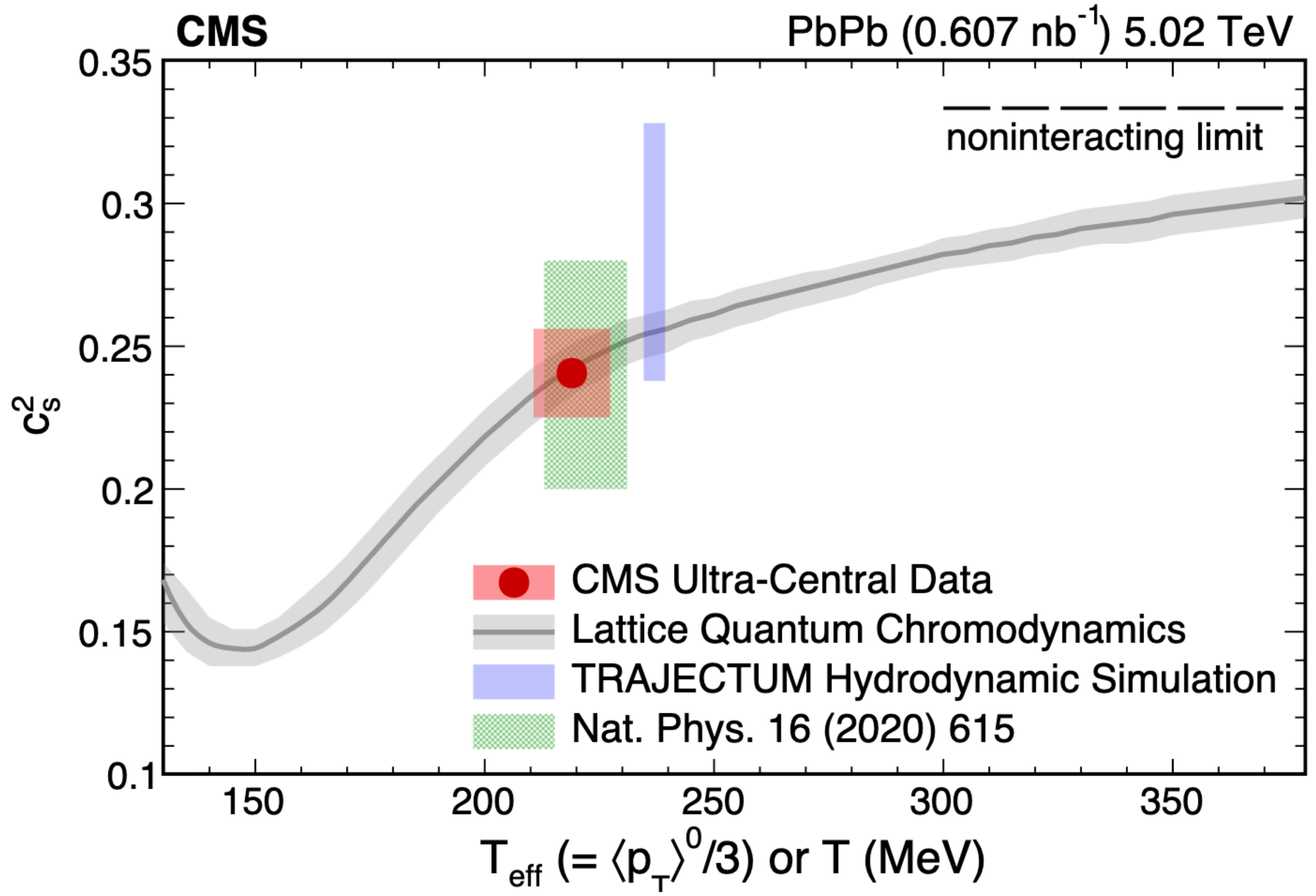
H.-T. Ding et al., PRL 132 (2024) 201903

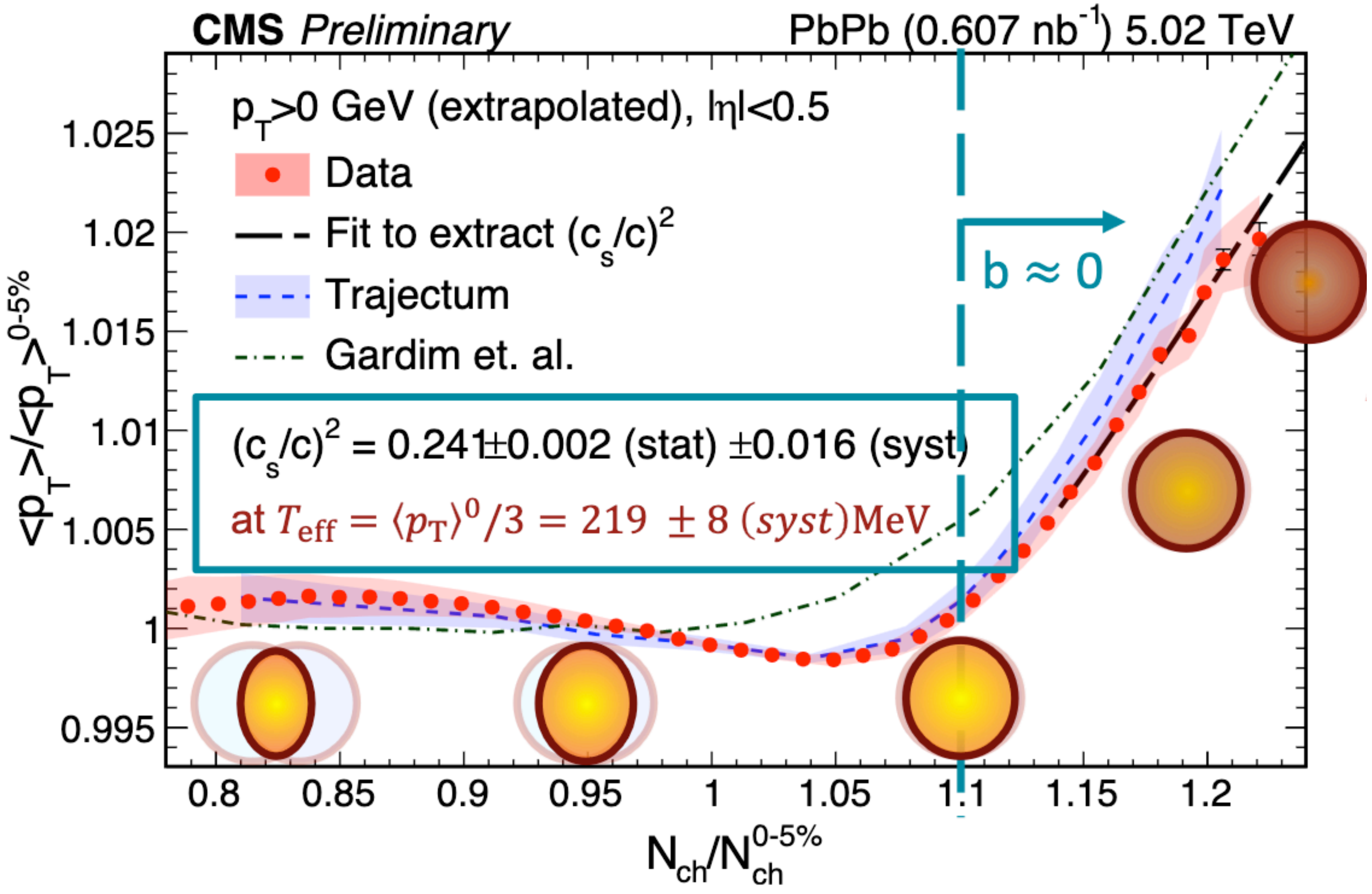
Speed of sound in QGP

Simple but elegant analysis

$$c_s^2 = \frac{dP}{d\varepsilon} = \frac{d\ln T}{d\ln s} = \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$$

Focus on ultra-central events - avoid geometry fluctuations

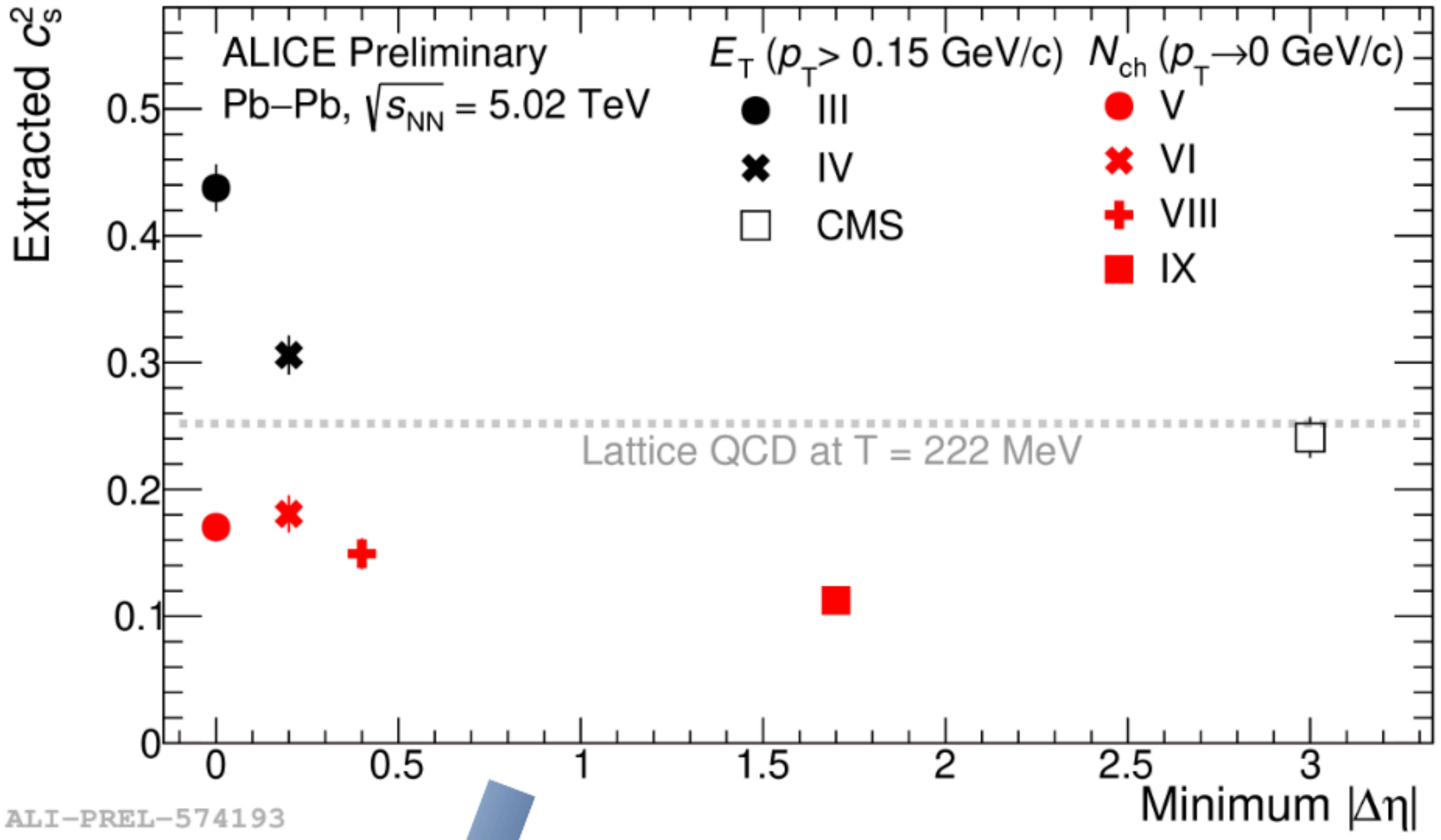




Data in excellent agreement with lattice QCD

CMS: Rep. Prog. Phys. 87 (2024) 077801

Speed of Sound: life is never that simple



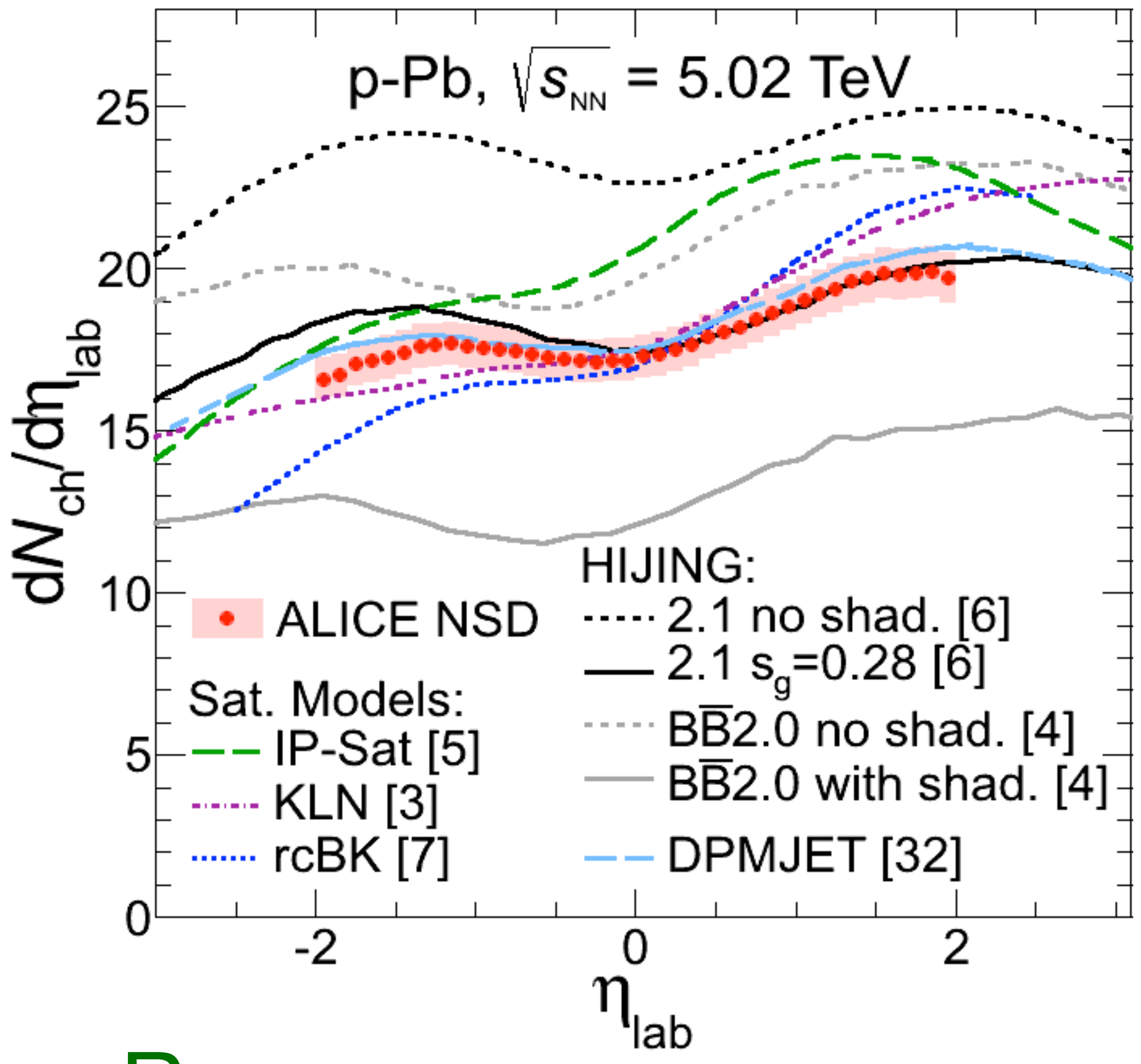
Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$	η gap
N_{ch} in TPC	I	$\lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.8$	0
	II	$0.5 \leq \lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.3$	0.3
E_T in TPC	III	$\lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.8$	0
	IV	$0.5 \leq \lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.3$	0.3
$N_{tracklets}$ in SPD	V	$\lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.8$	0
	VI	$0.5 \leq \lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.3$	0.3
	VII	$0.3 < \lvert\eta\rvert \leq 0.6$	$\lvert\eta\rvert \leq 0.3$	0
	VIII	$0.7 \leq \lvert\eta\rvert \leq 1$	$\lvert\eta\rvert \leq 0.3$	0.4
N_{ch} in V0	IX	$-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$	$\lvert\eta\rvert \leq 0.8$	1.7

Summary plot of extracted c_s^2 with different centrality estimators and various η separations between particles used for $\langle p_T \rangle$ and centrality

c_s^2 extracted depends strongly on centrality estimator - more studies needed

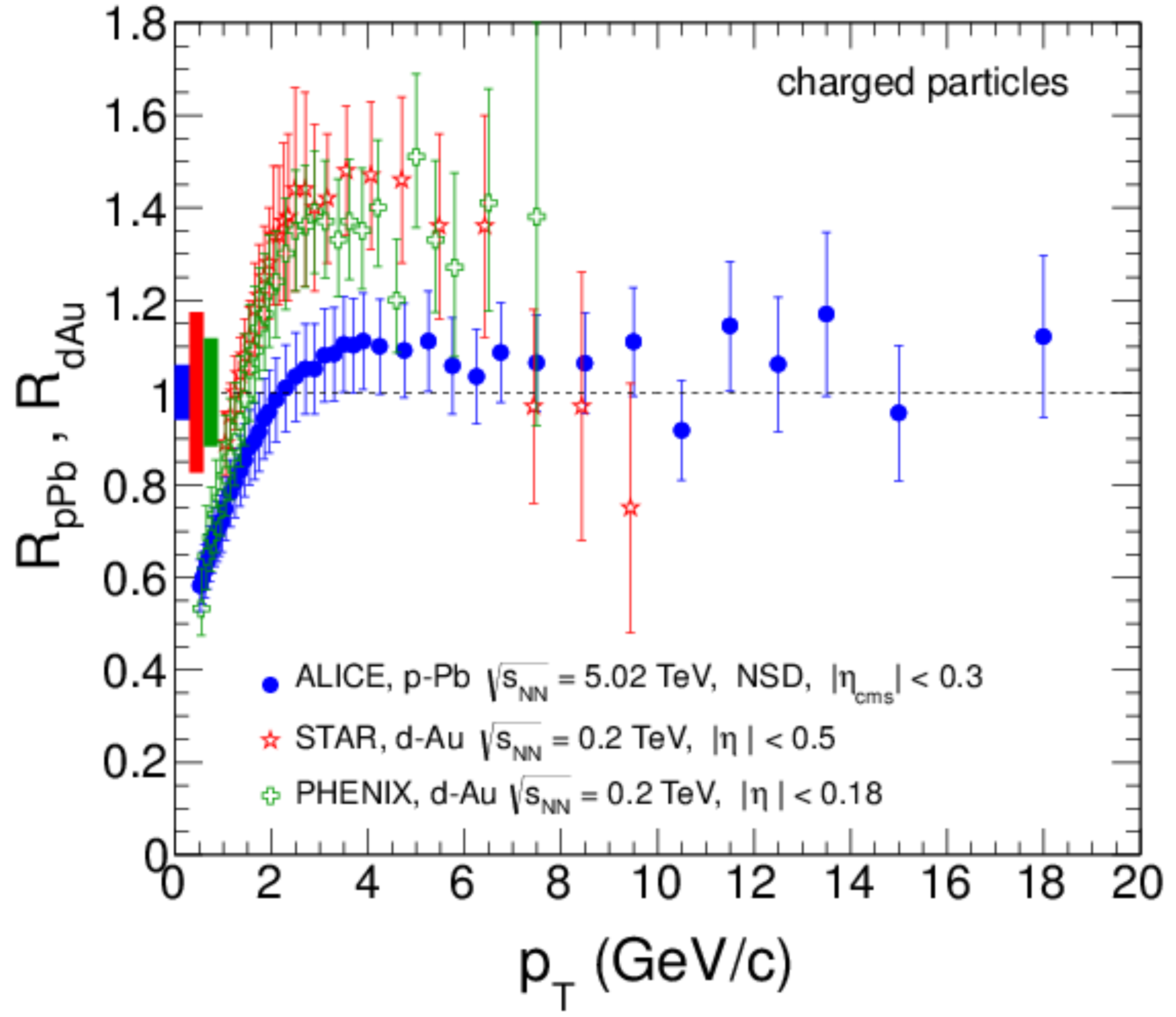
Moving to small systems

p-A: our control "Cold QCD" data



Rapidity distribution favors "shadowing" models

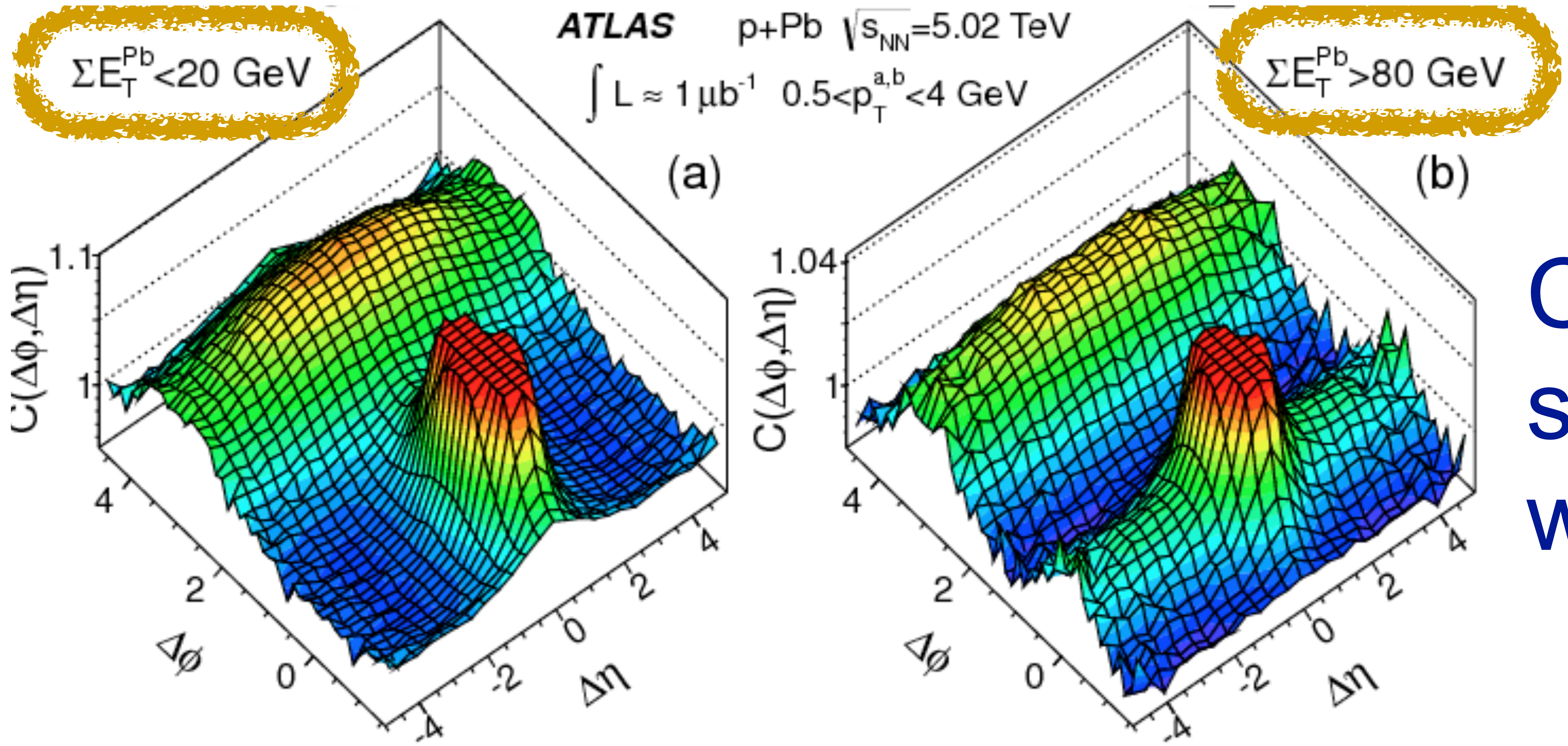
Initial state effects are small



R_{pA}
LHC : binary scaling
RHIC: small Cronin enhancement

ALICE: PRL 110, 032301 (2013), ALICE: PRL 110, 082302 (2013), STAR: PRL 91. 072304 (2003), PHENIX: PRL 91 (2003) 072303

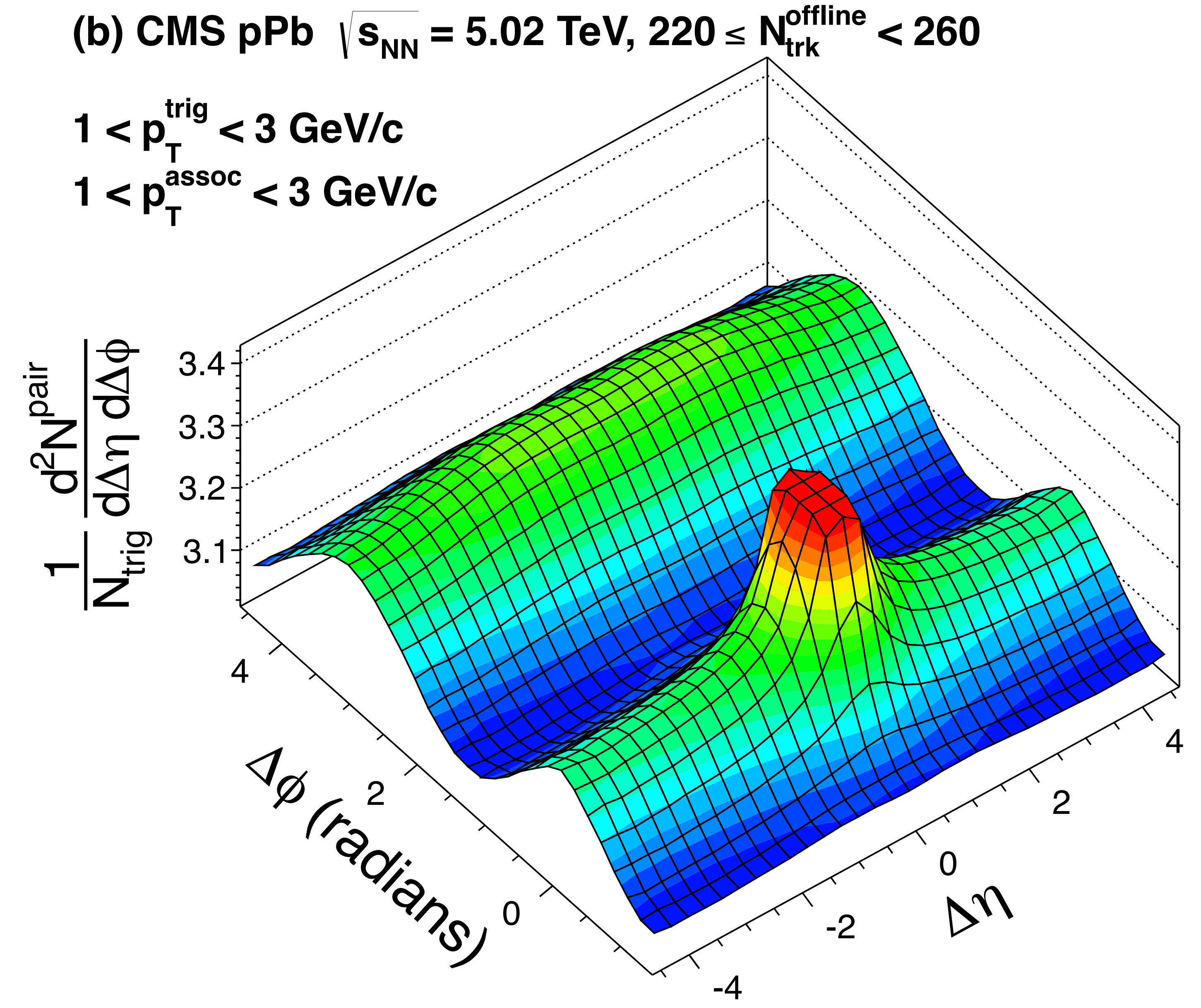
p-A: Our control starts to go out of control

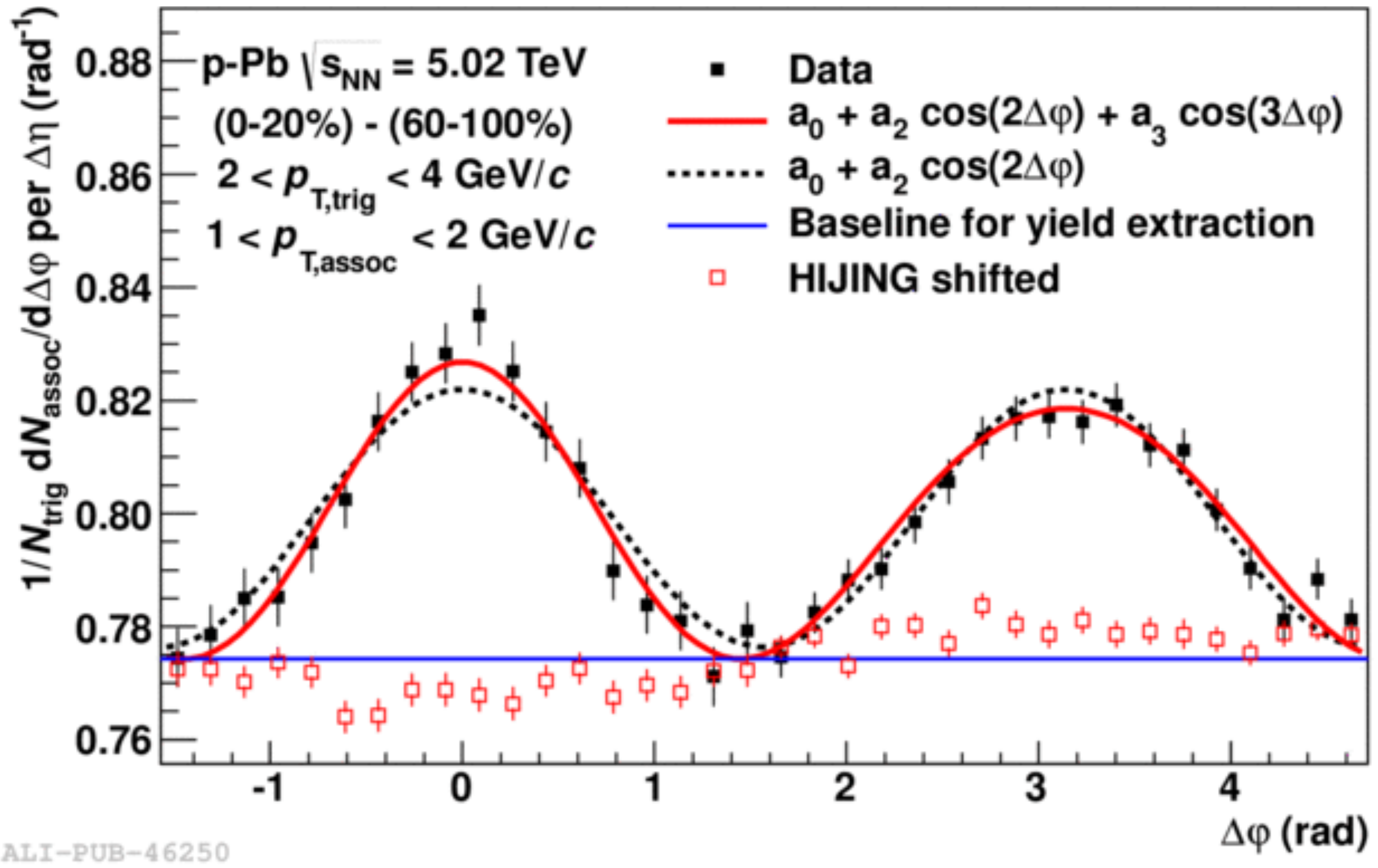


Decided to look at multiplicity separated p-Pb events

Correlations very similarity in shape and yield to those in A-A where attributed to collective flow

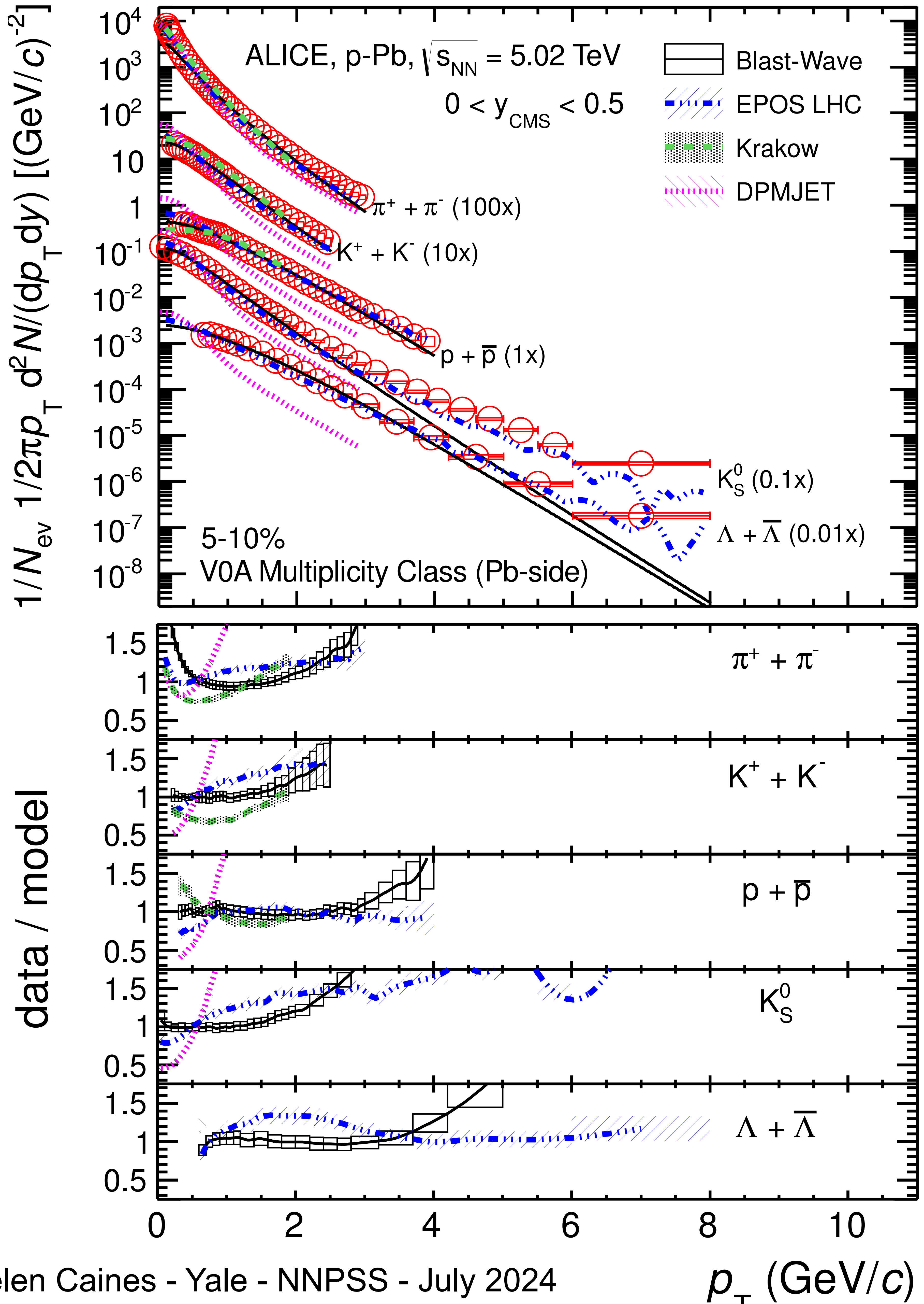
Flow in p-Pb ?





CMS: PLB 724 (2013) 312, ATLAS: PRL 110, 182302 (2013) ALICE: PLB 719 (2013) 29

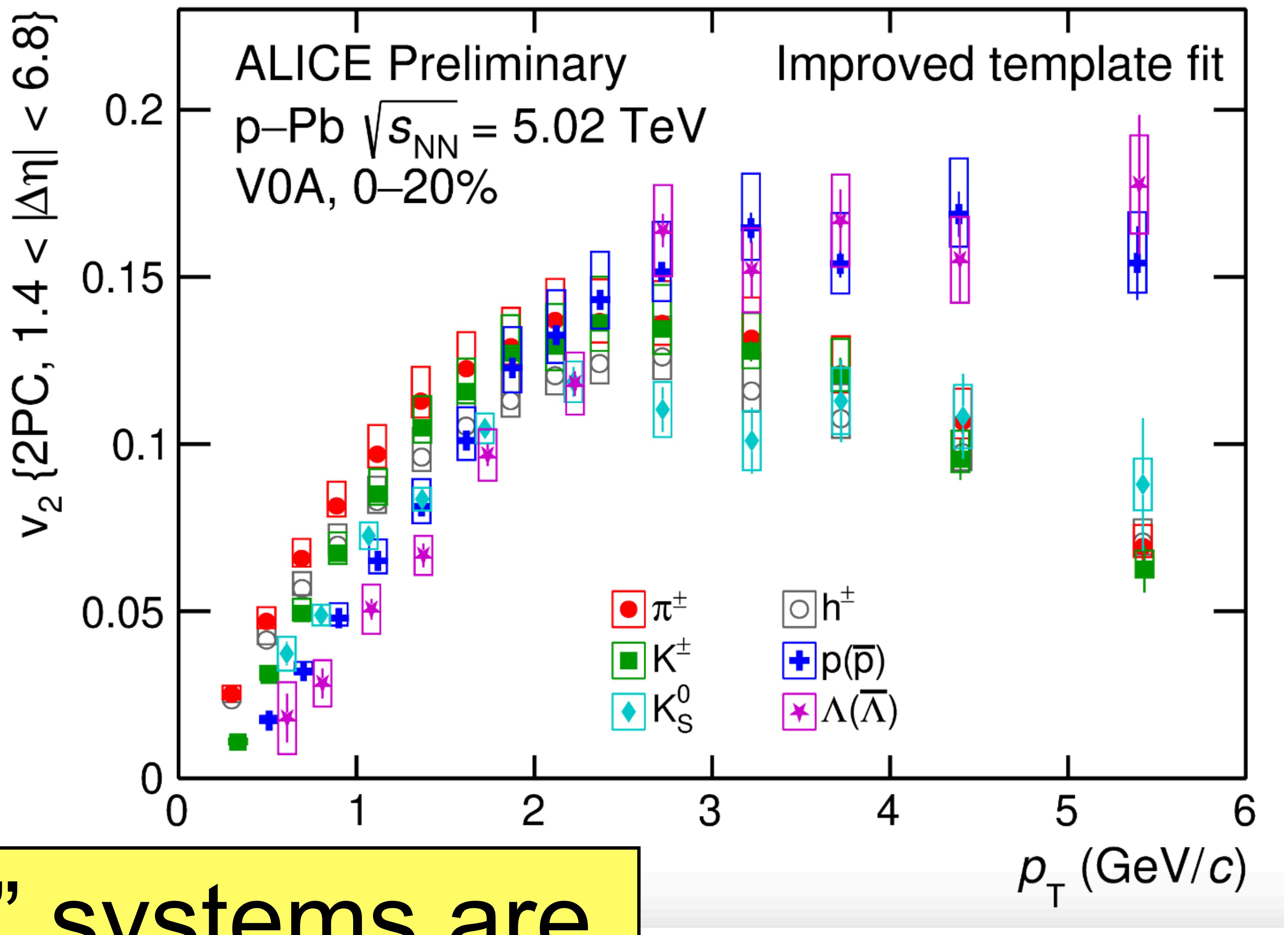
Evidence for flowing small systems grows



In p-Pb when Nch ≳ 50

Mass dependence of p_T spectra very similar to that in Pb-Pb

NQC scaling of v_2



Our "simple" systems are proving very complex!

ALICE: PLB (2014), 728, 25

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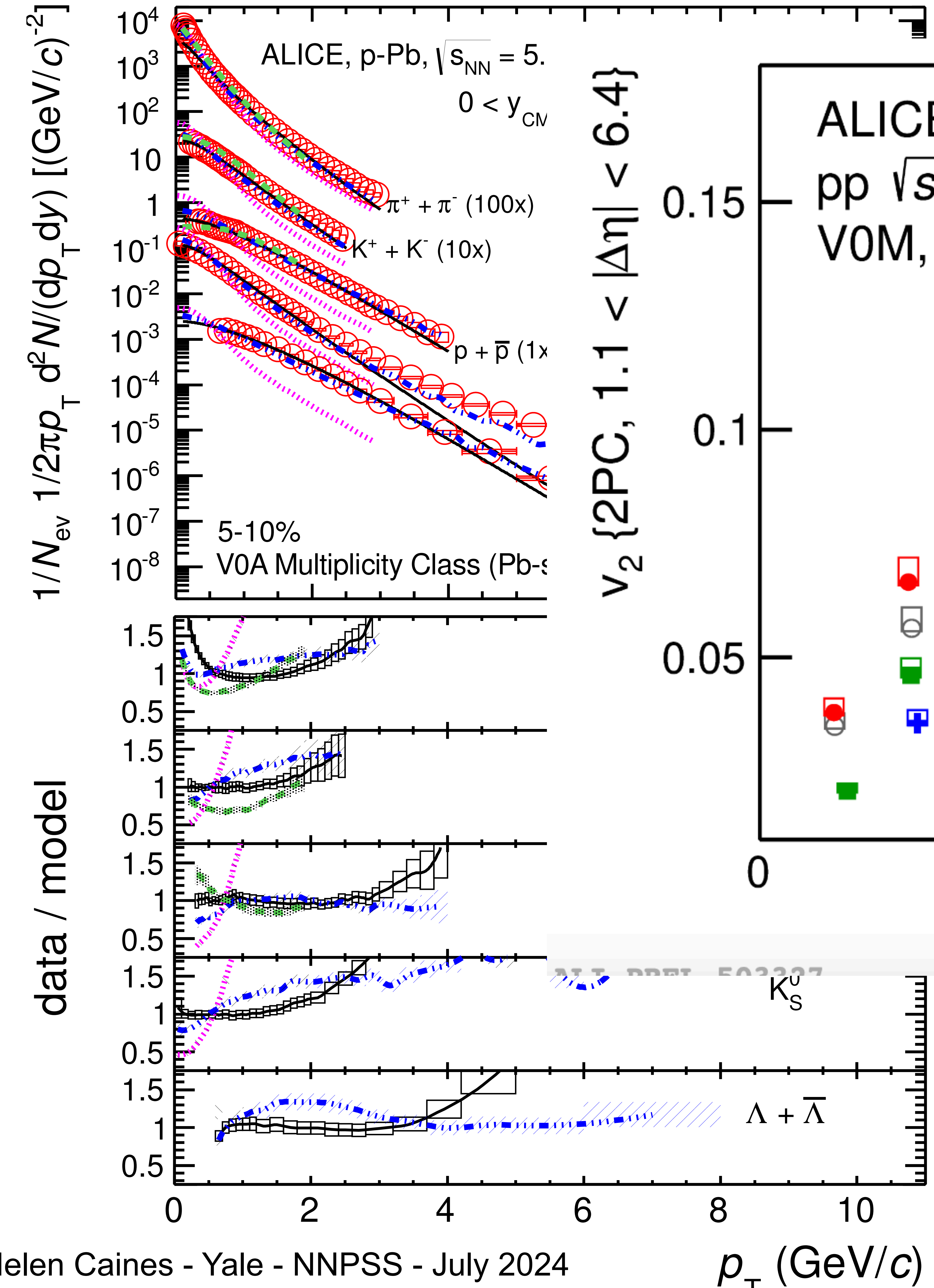
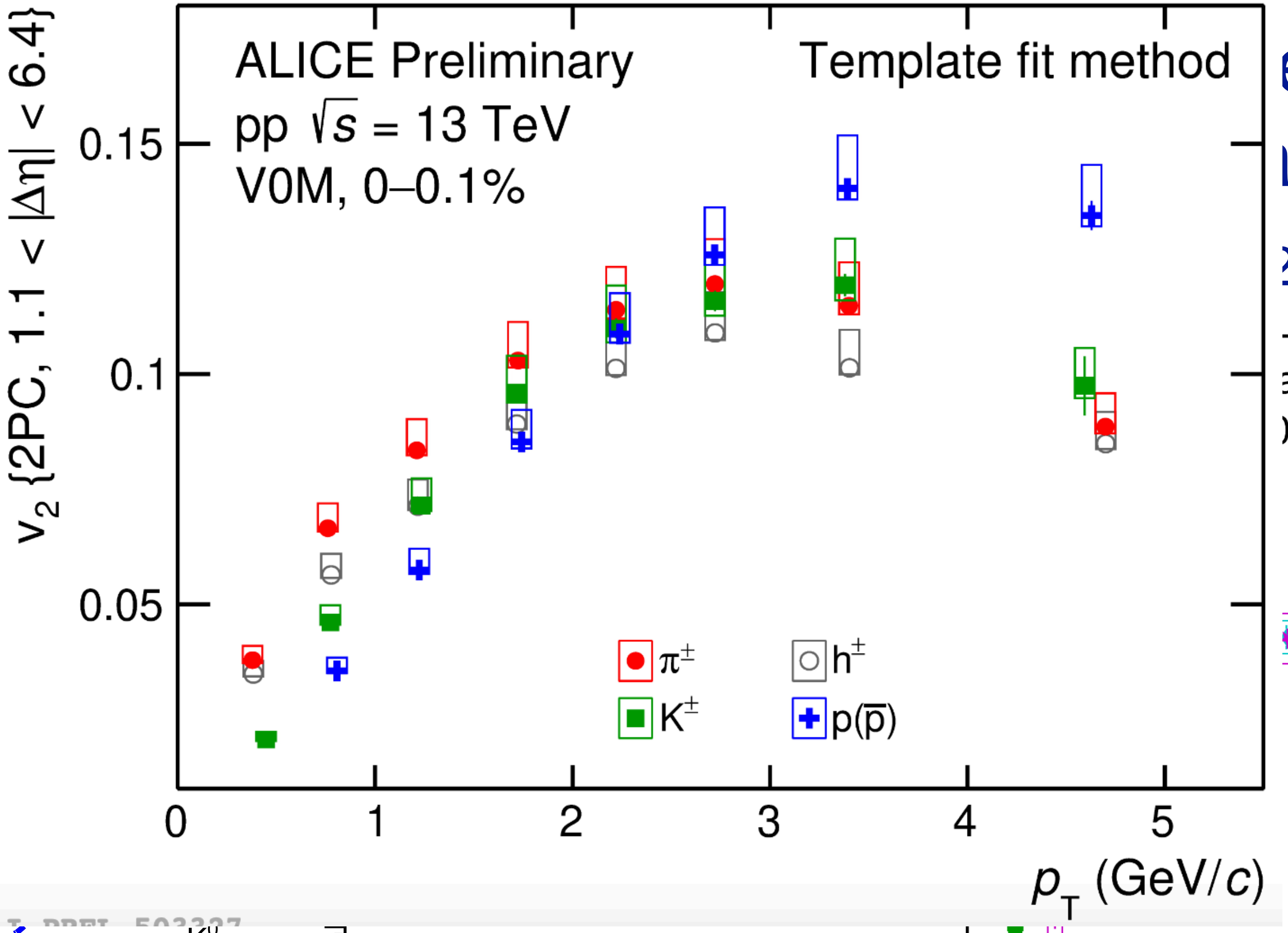


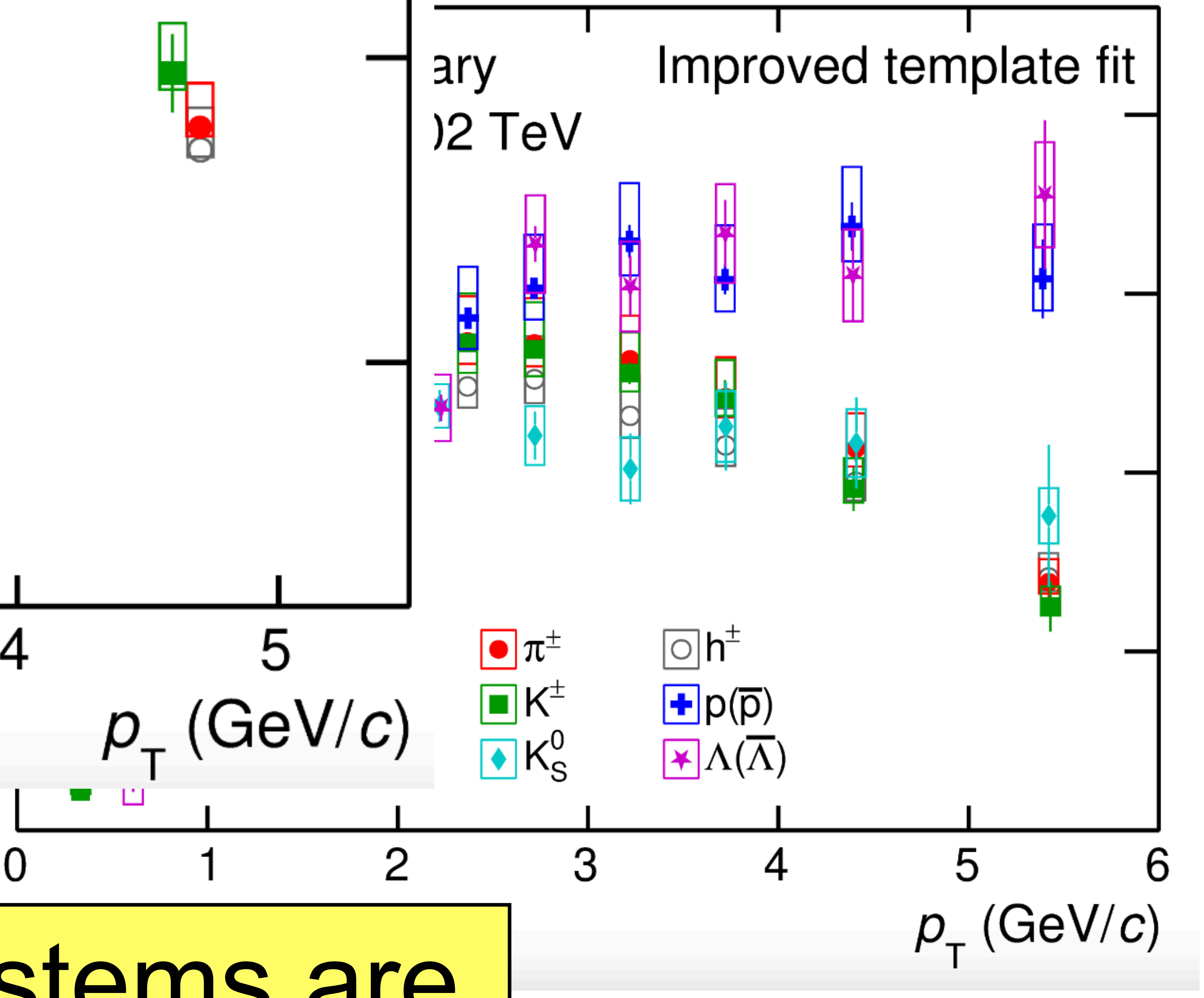
In p-Pb when Nch ≳ 50

e of p_T spectra

t in Pb-Pb

2





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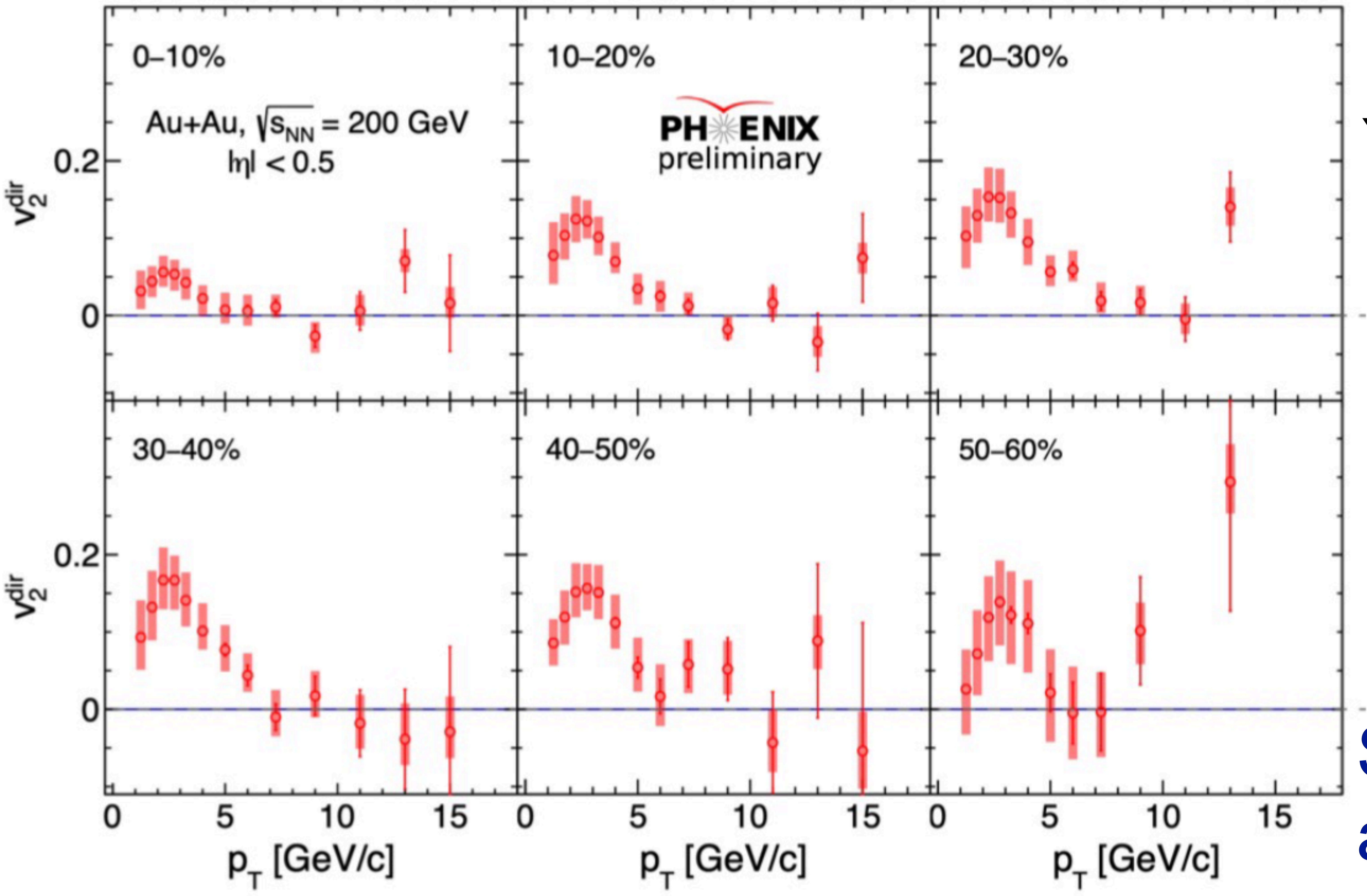
Can we ever turn flow off?

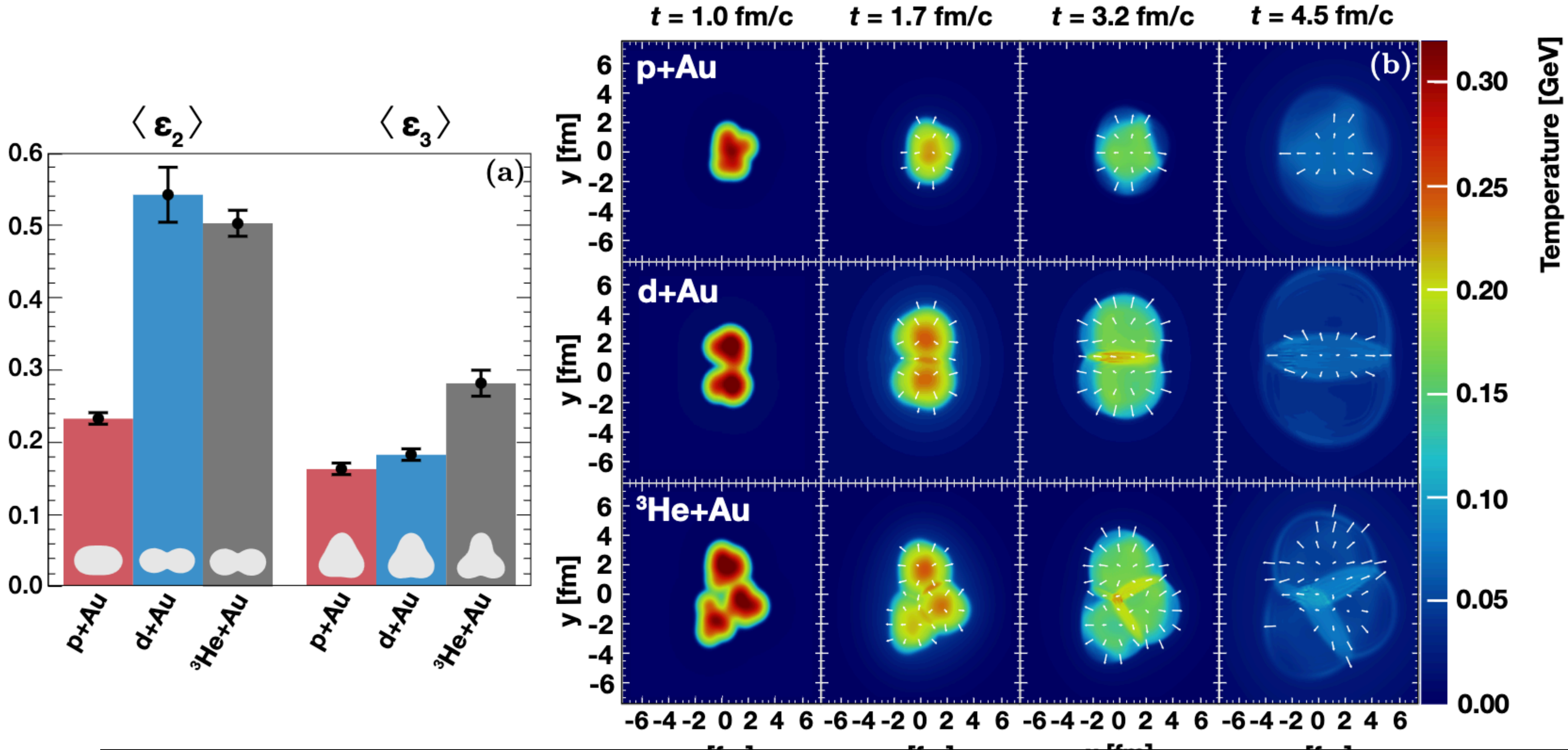


Yes! High p_T direct photons

Non-interacting probe doesn't exhibit collective motion

So we have to bite the bullet and tackle this
 - its (likely) not an analysis problem

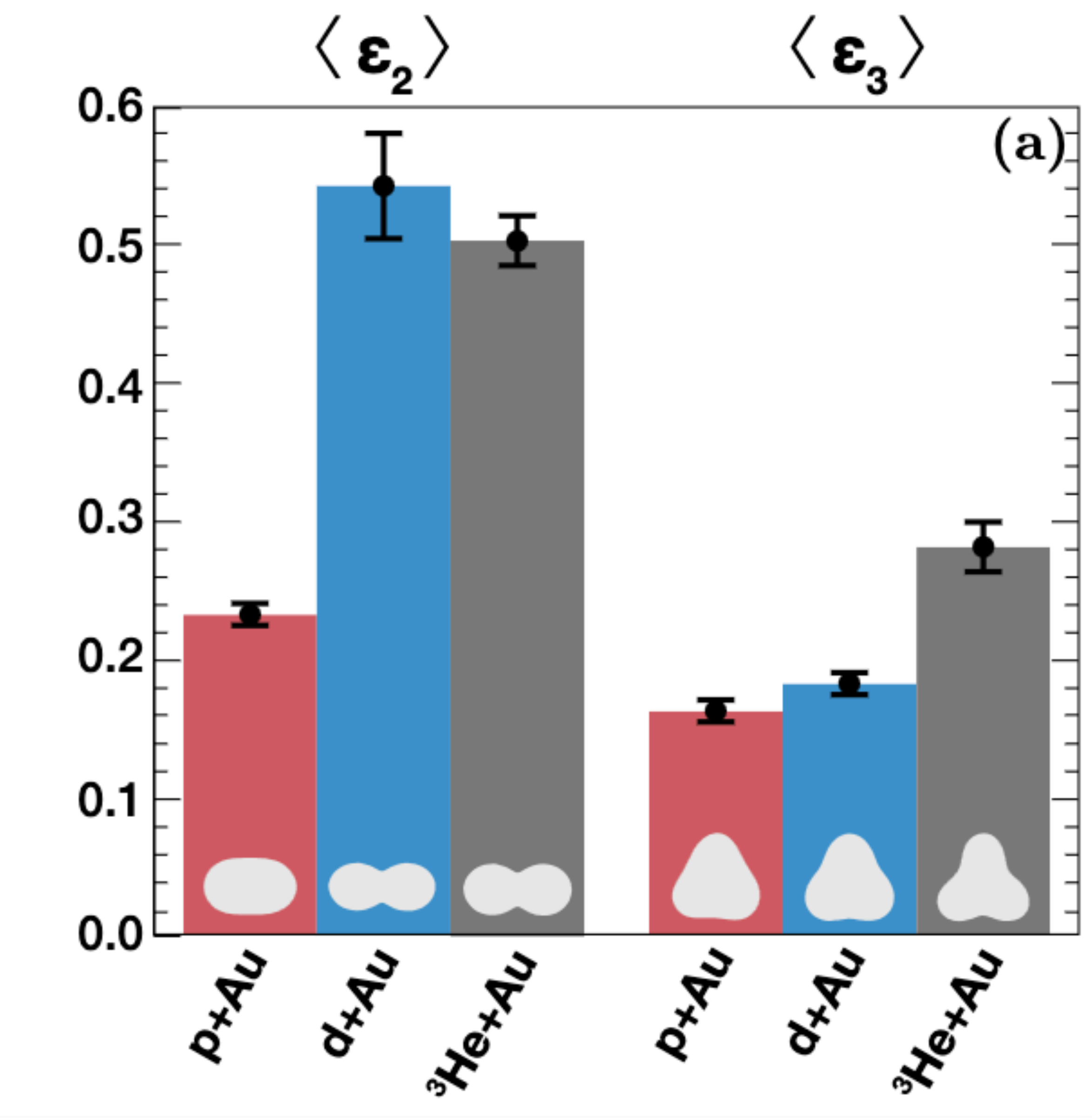
Testing for fluid in small systems

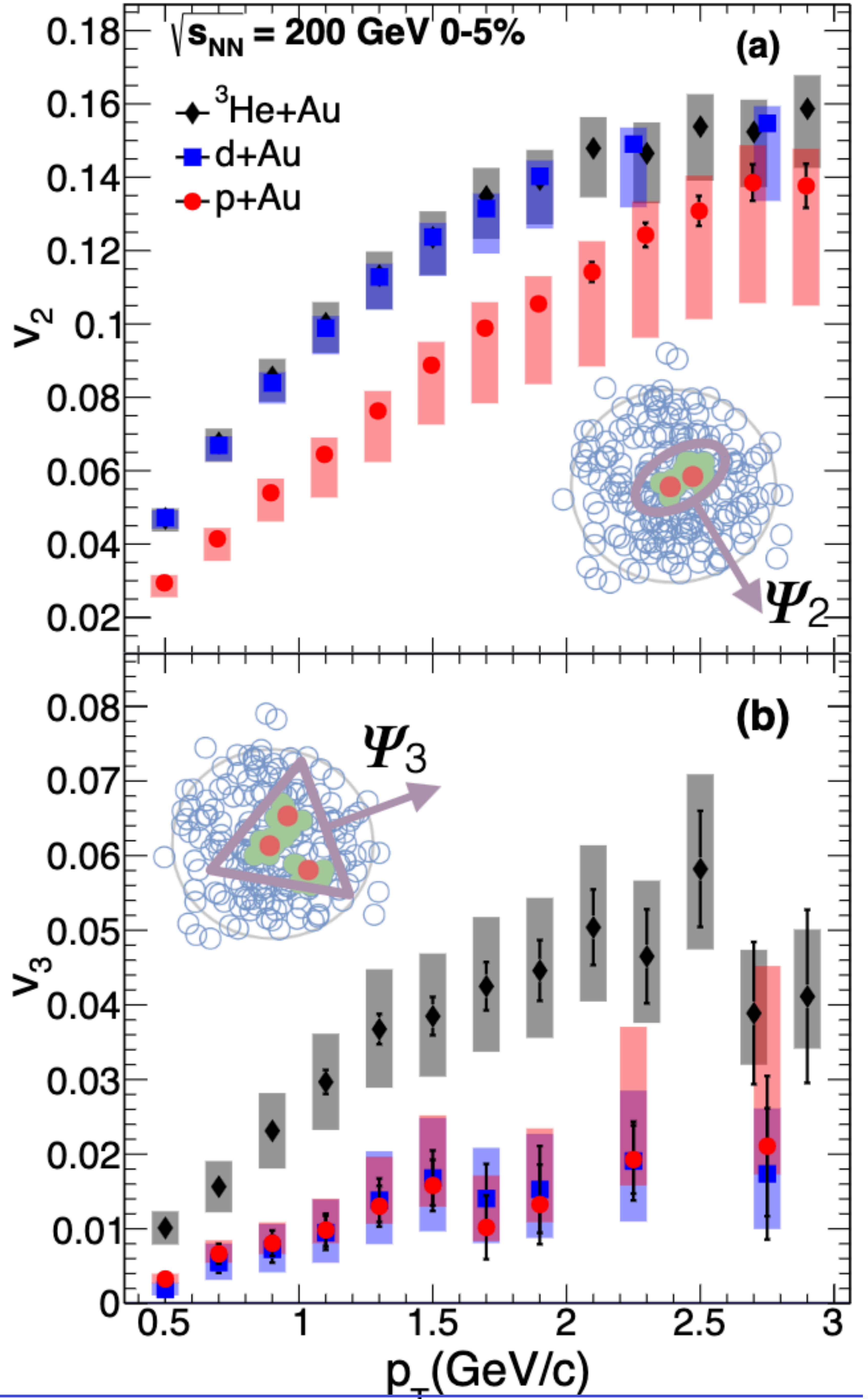


The proposal: p-Au, d-Au and ^{3}He-Au measurements would be the "ultimate test" of fluid behavior in small systems

PHENIX: Nature Physics 15, 214 (2019)

Control back under control



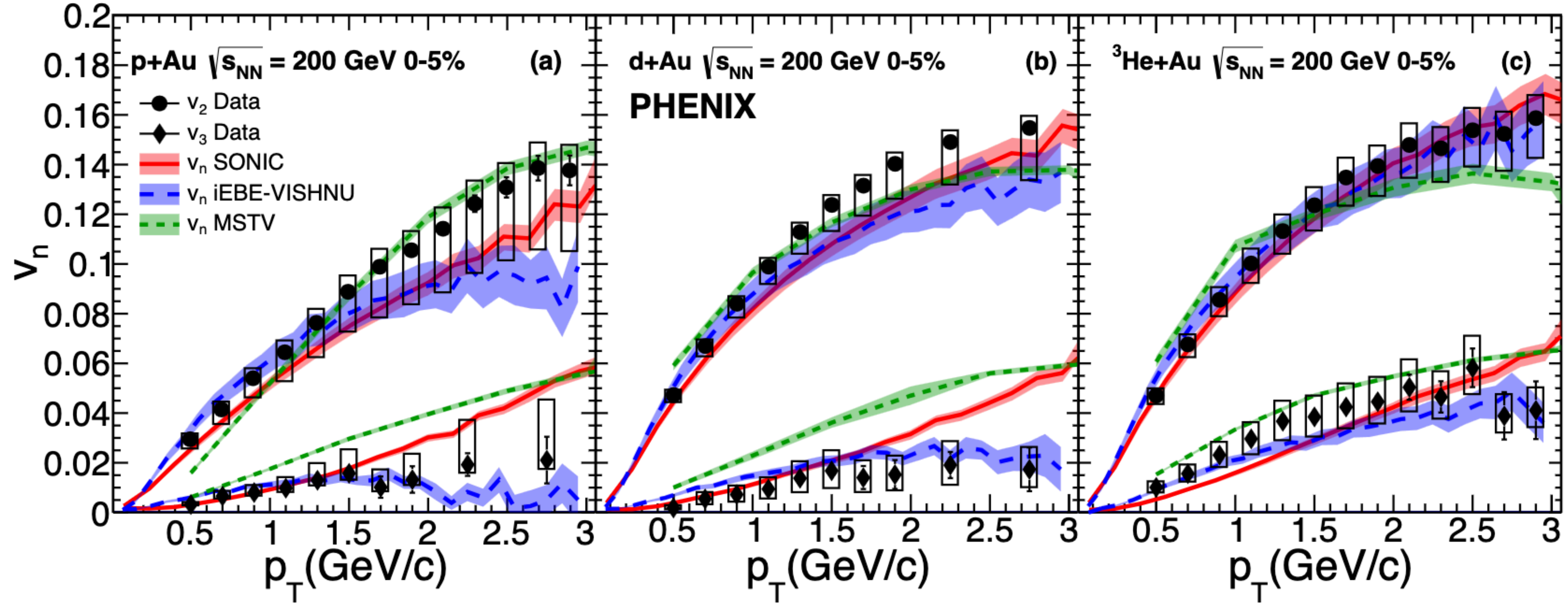


Elliptic flow seen in all systems!

Significantly higher v_3 in He^3-Au as expected

PHENIX: Nature Physics 15, 214 (2019)

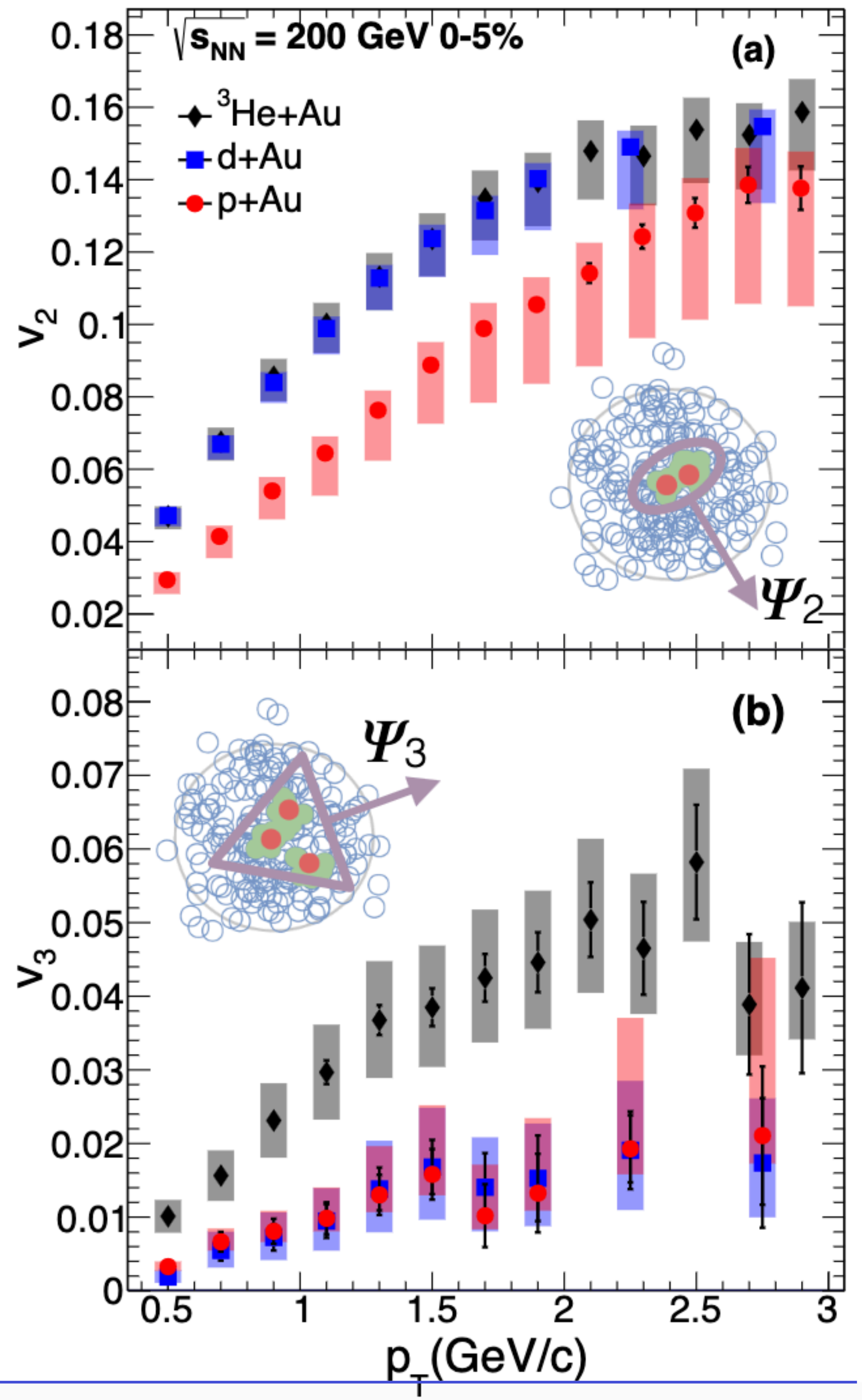
Control back under control



Elliptic flow seen in all systems!

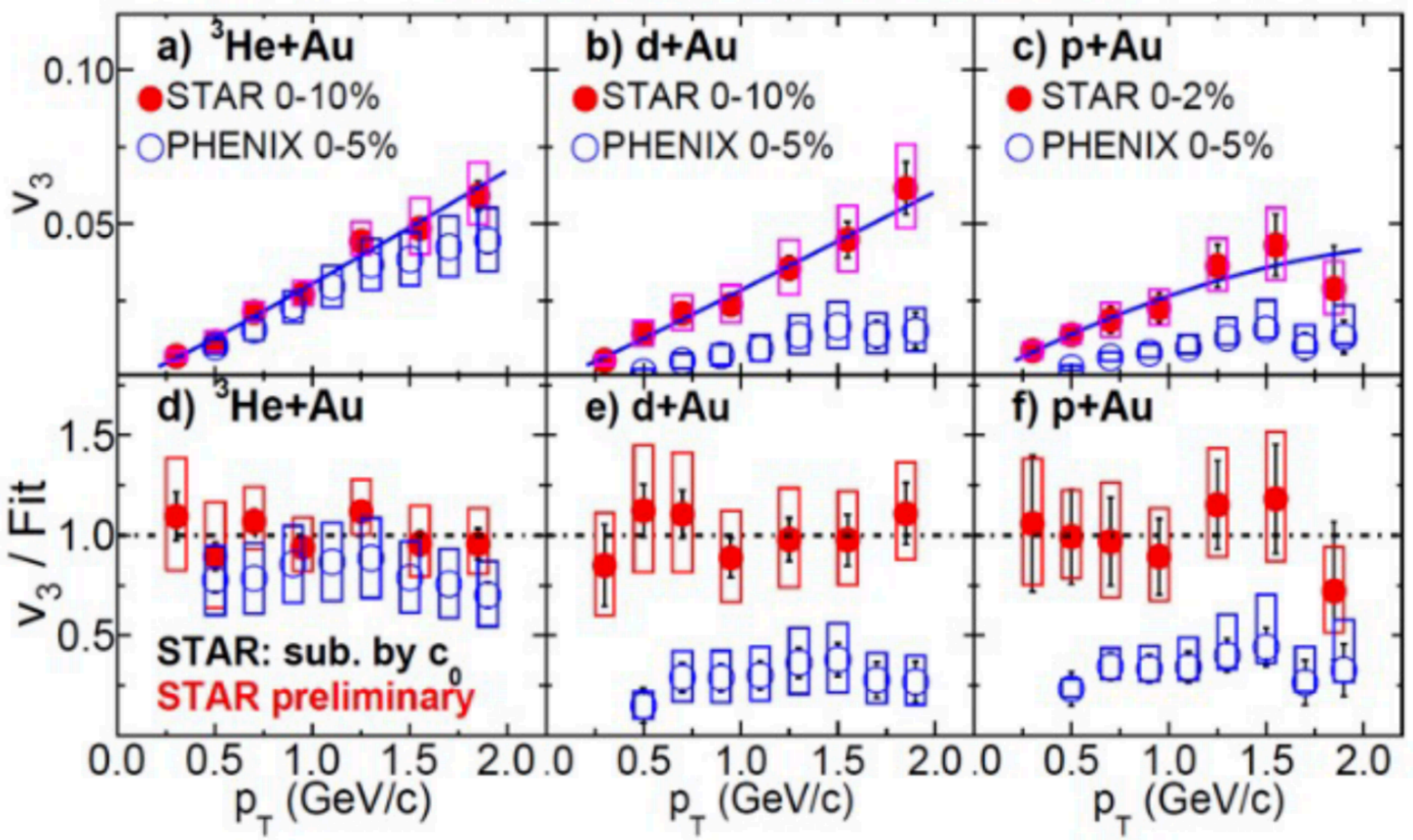
Significantly higher v_3 in He^3-Au as expected

Agreement with hydrodynamical calculations suggests systems really are flowing fluids



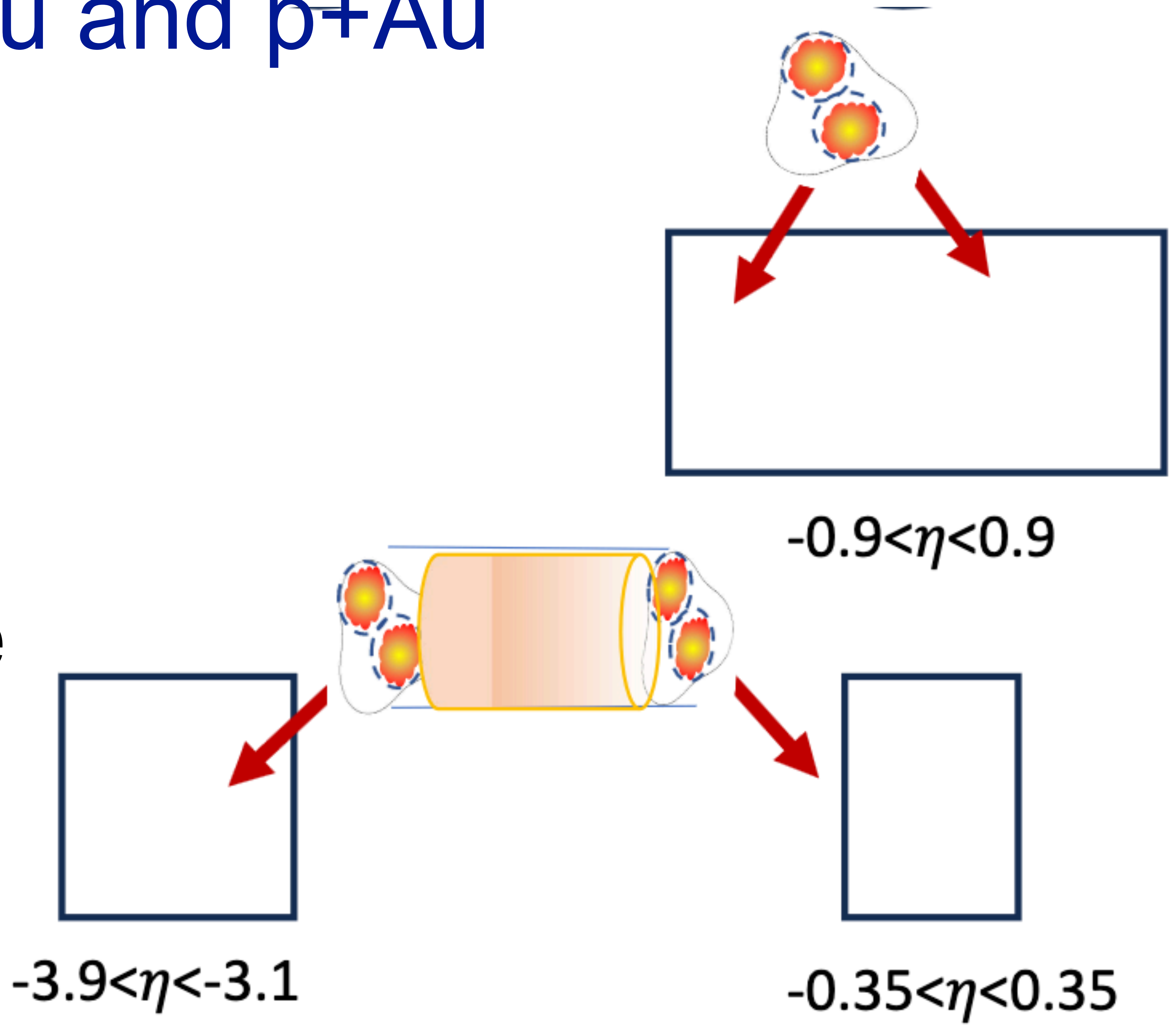
PHENIX: Nature Physics 15, 214 (2019)

but then STAR released results



v_2 results were consistent

v_3 results very different for d+Au and p+Au



Several differences in how analyses were done

- A key one being rapidity gap over which correlation measured

Both thought to be sufficient to allow unbiased measurement

STAR: PRL 130, 242301 (2023)

Solution potentially found

While neither experiment could perform analysis of the other theorists could model both

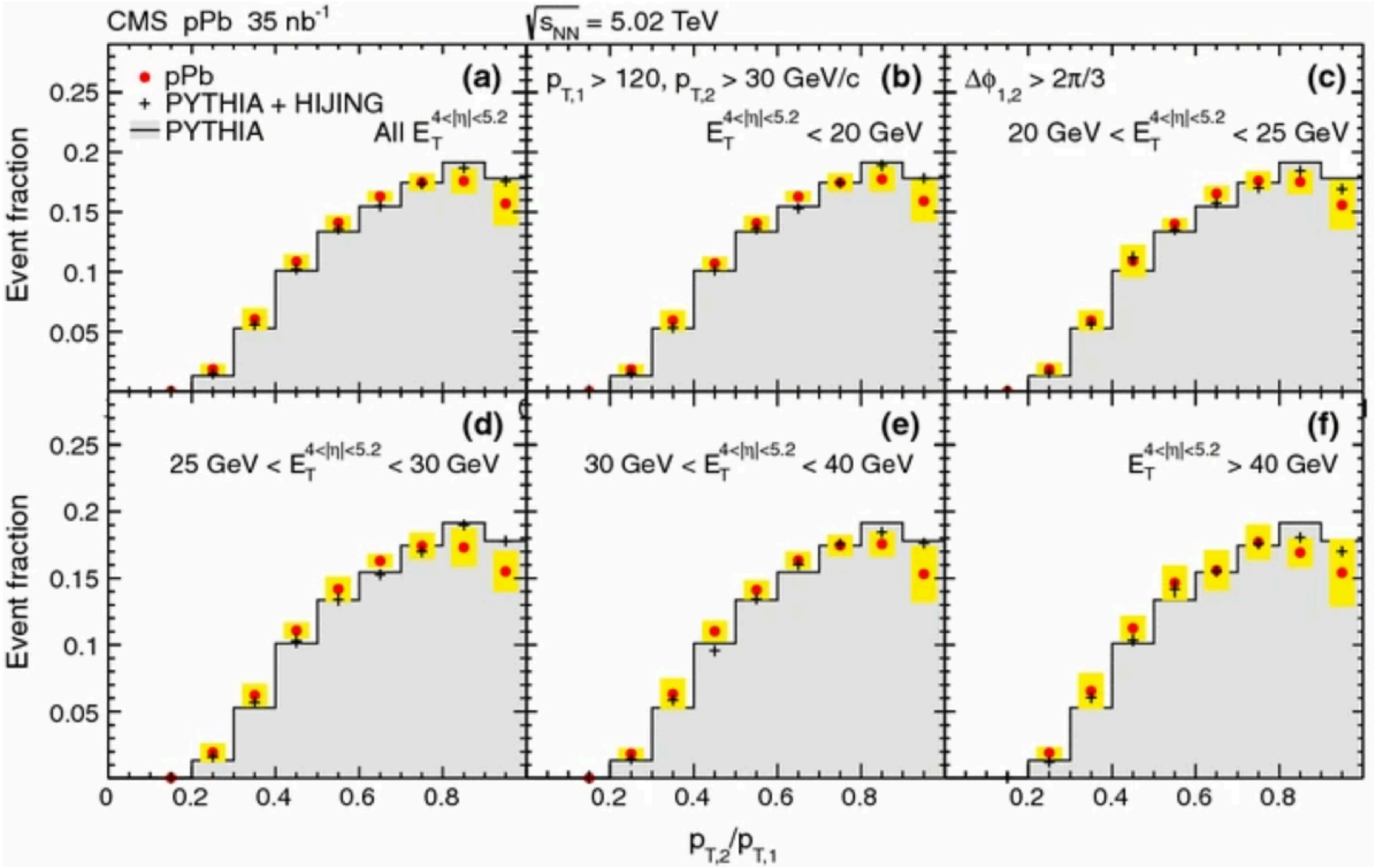
v_3 differences at RHIC largely due to use of different rapidity range but not all

O+O and new d+Au data taken

3+1D Hydro critical for comparisons
- medium not boost invariant over large rapidity ranges

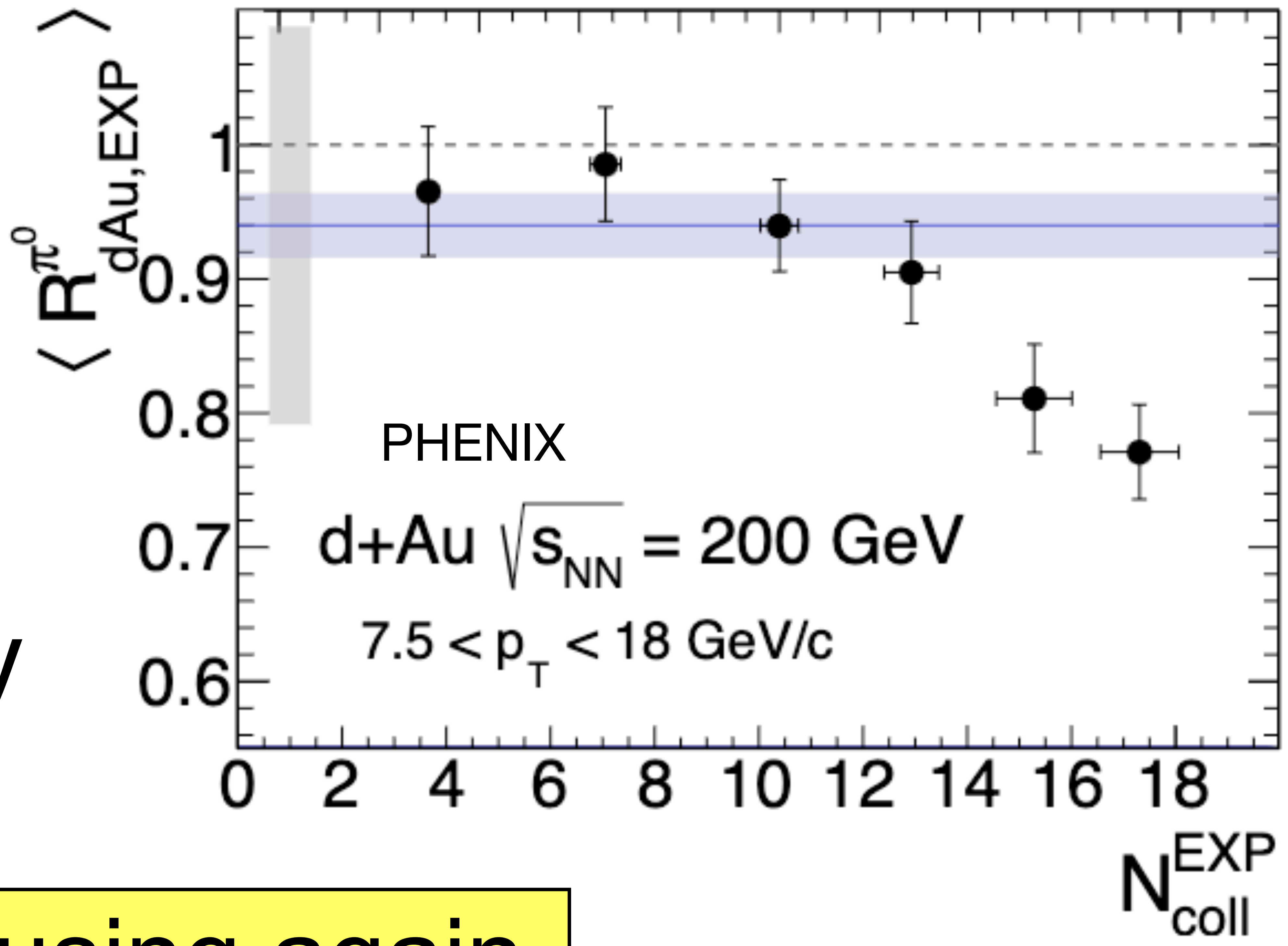
W. Zhao et al. PRC 107,(2023) 014904

Energy loss to medium?



CMS di-jet studies: no additional momentum imbalance observed

If there is a QGP in pA its too small to quench jets



PHENIX:

N_{bin} determined by forcing R_{dAu} γ to unity

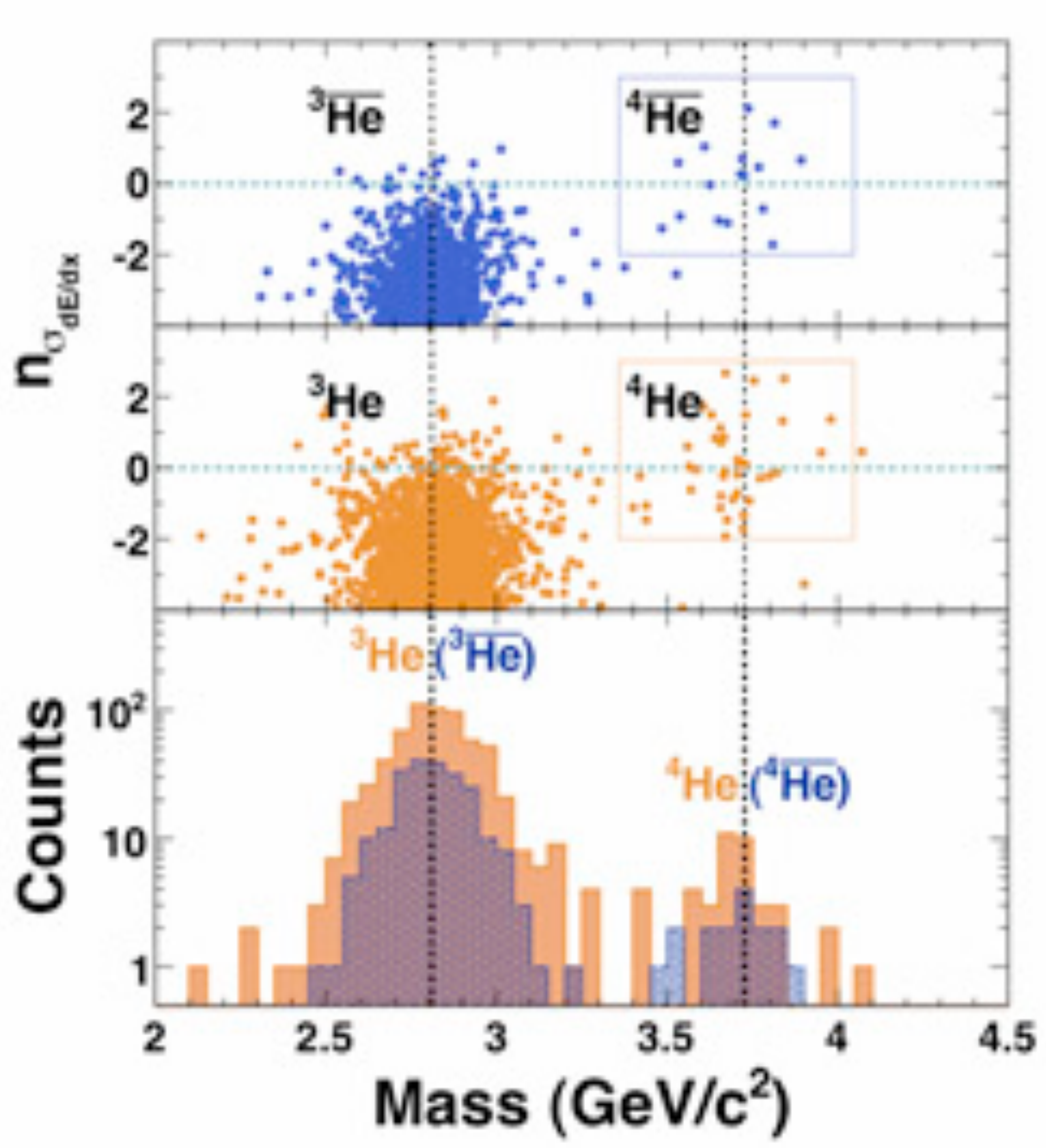
Strong suppression of π^0 in high multiplicity events

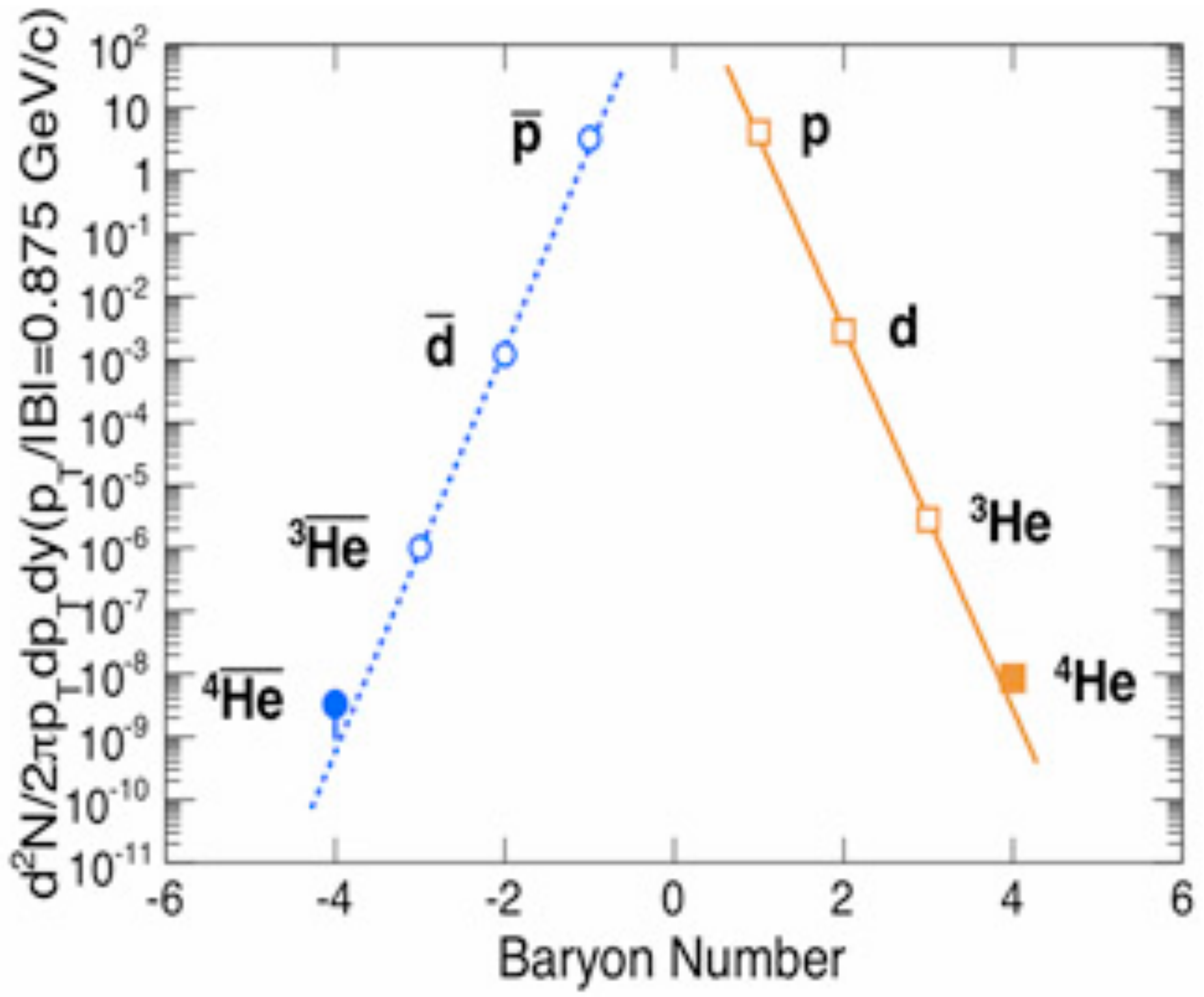
Interpretation confusing again

CMS: EPJC 74, 2951, (2014), PHENIX

Unexpected (but very cool) physics found along the way

First observation of anti-He⁴!





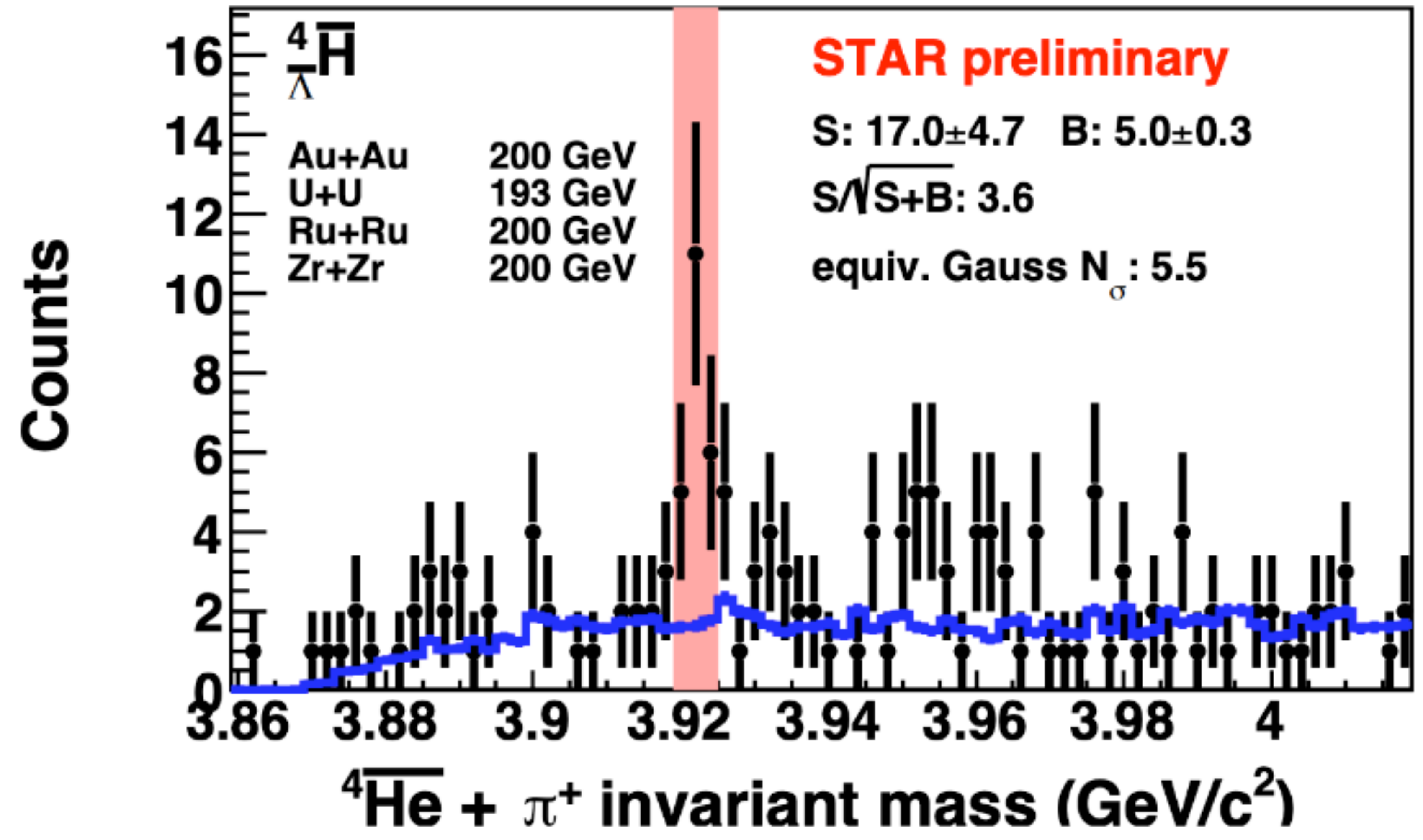
Matter and antimatter formed at same rate

Now know rates we should see anti-matter in space experiments

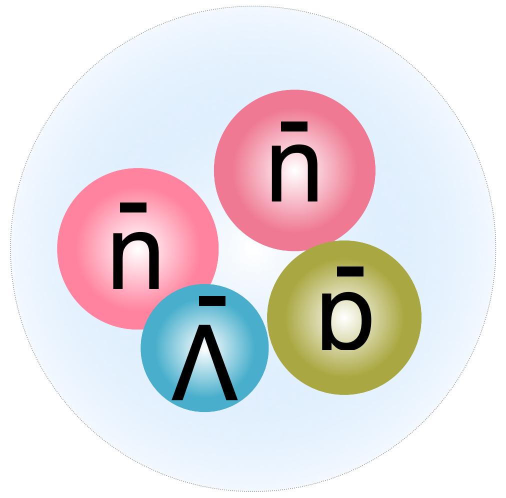
Fact that we are in a matter Universe not due to “problem” creating anti-matter

STAR: Nature **473** (2011) 353

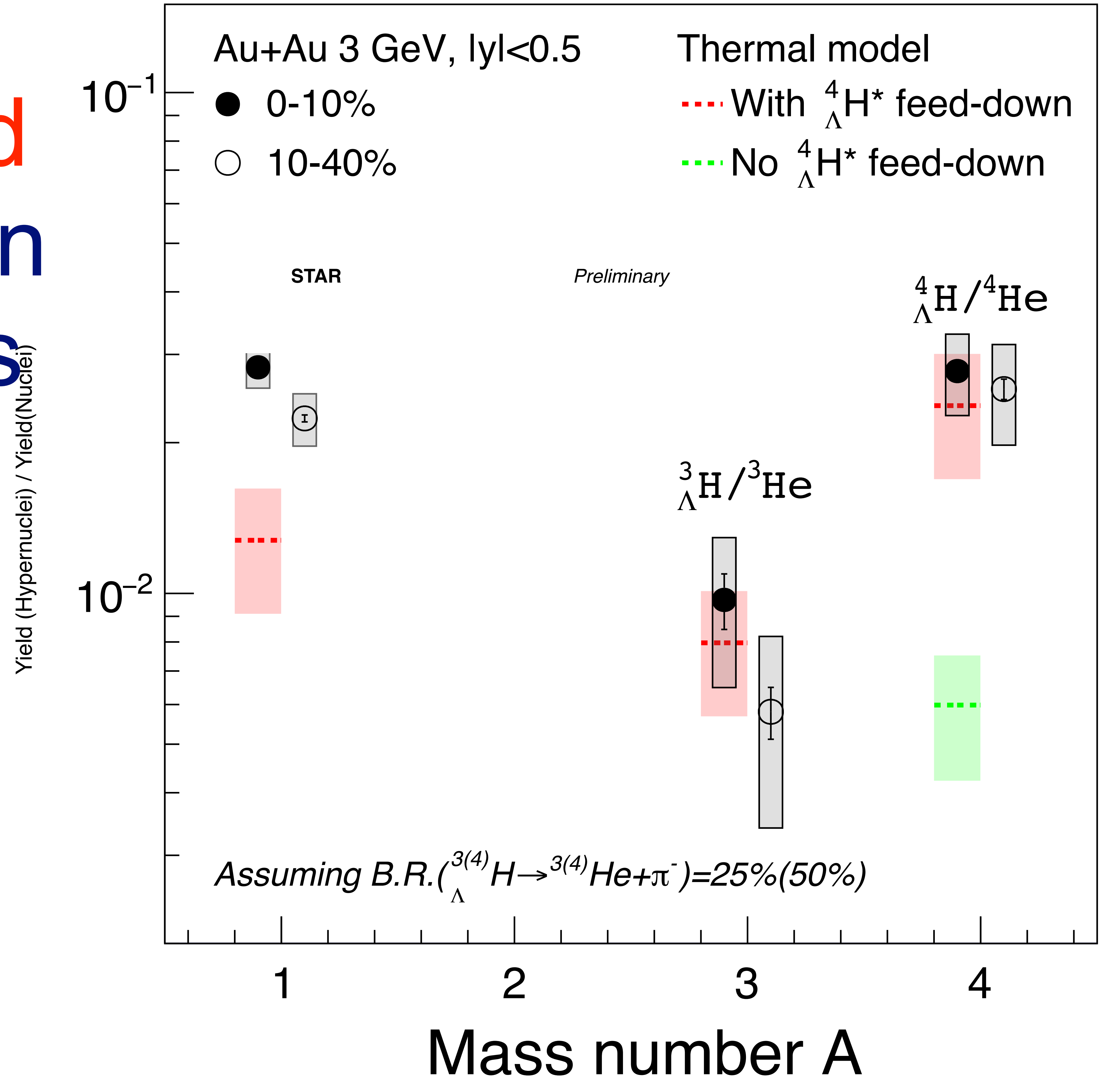
(anti)Hypernuclei are also created

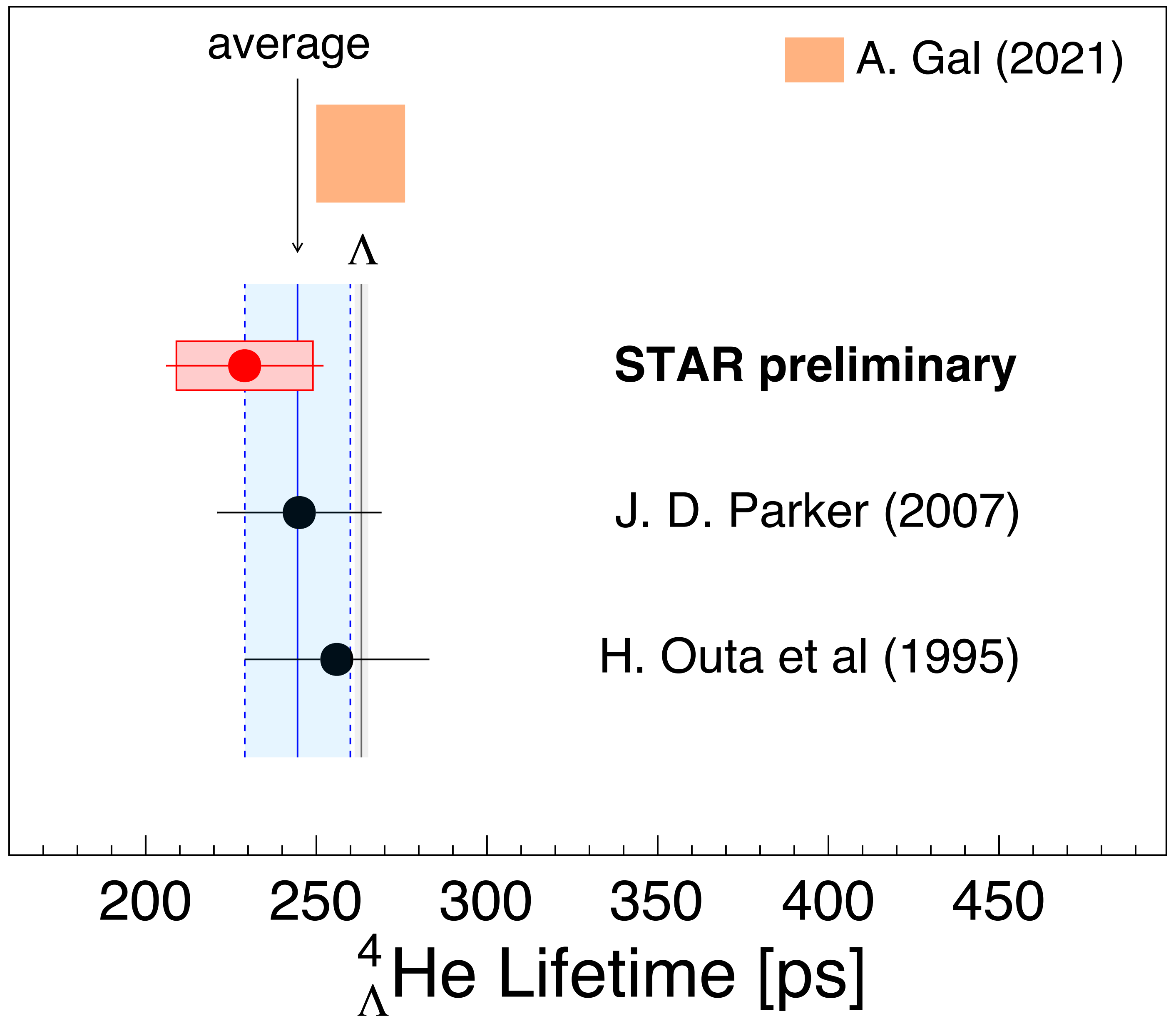


Anti-Hyper-Hydrogen-4



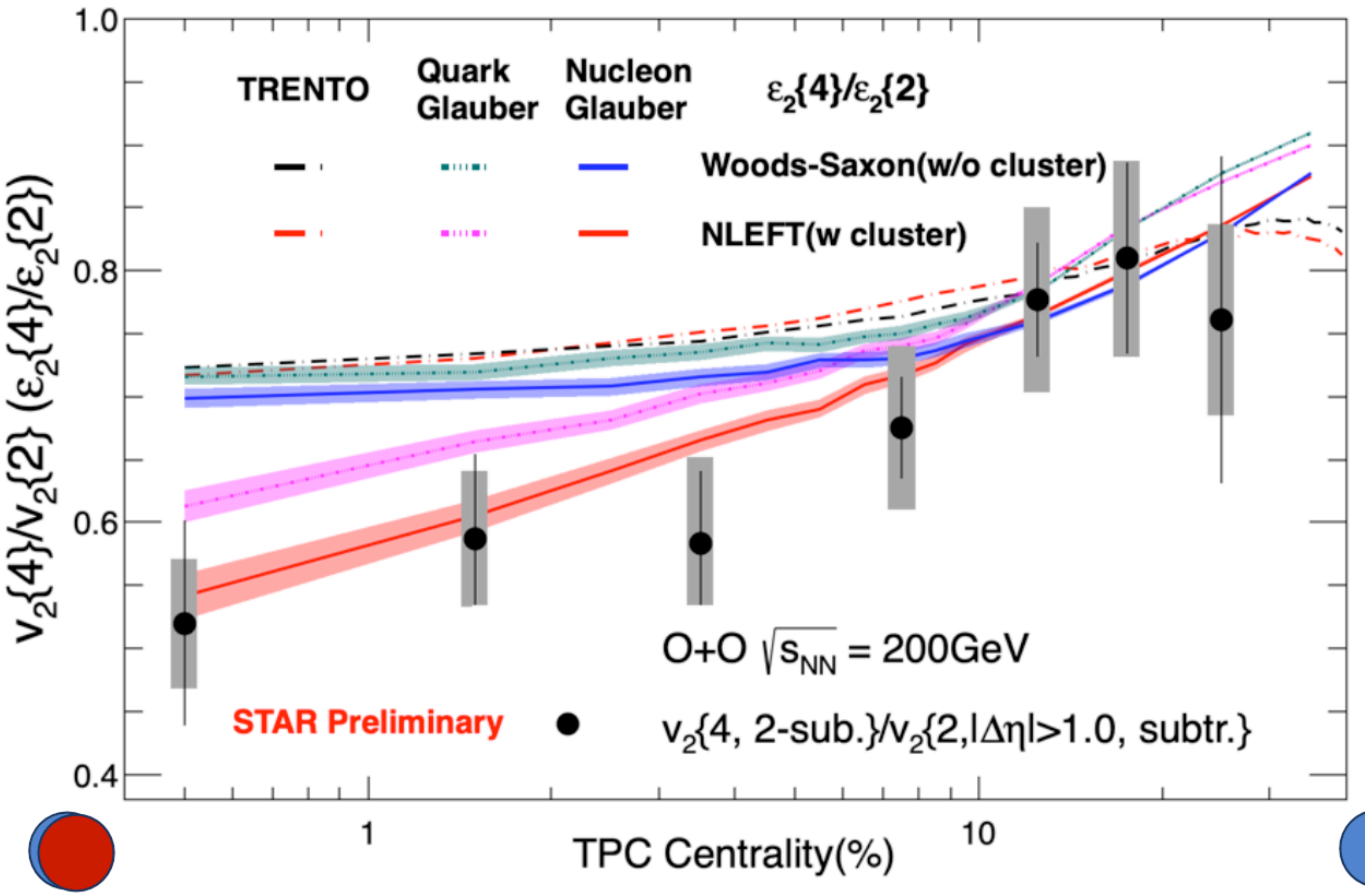
Evidence of formation of excited hypernuclei states in heavy ion collisions

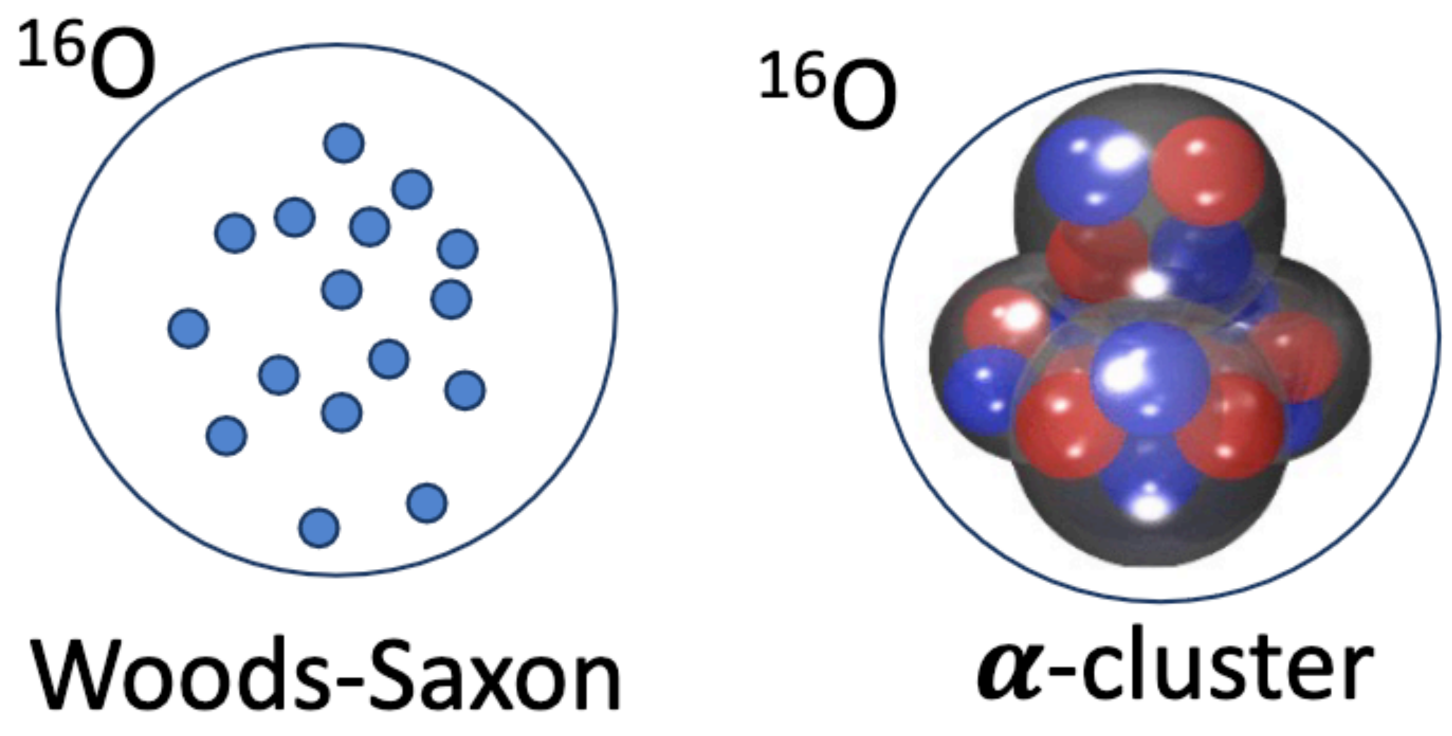




Hyper-Helium-4 lifetime measurement in heavy ion collisions

Substructure of oxygen





Data:

$v_2\{4\}/v_2\{2\}$ smaller in more central events :

fluctuations enhanced

Theory:

Enhanced fluctuations central events due to alpha clustering

Indication oxygen nucleus has alpha clusters

v_2 - measure of elliptical flow

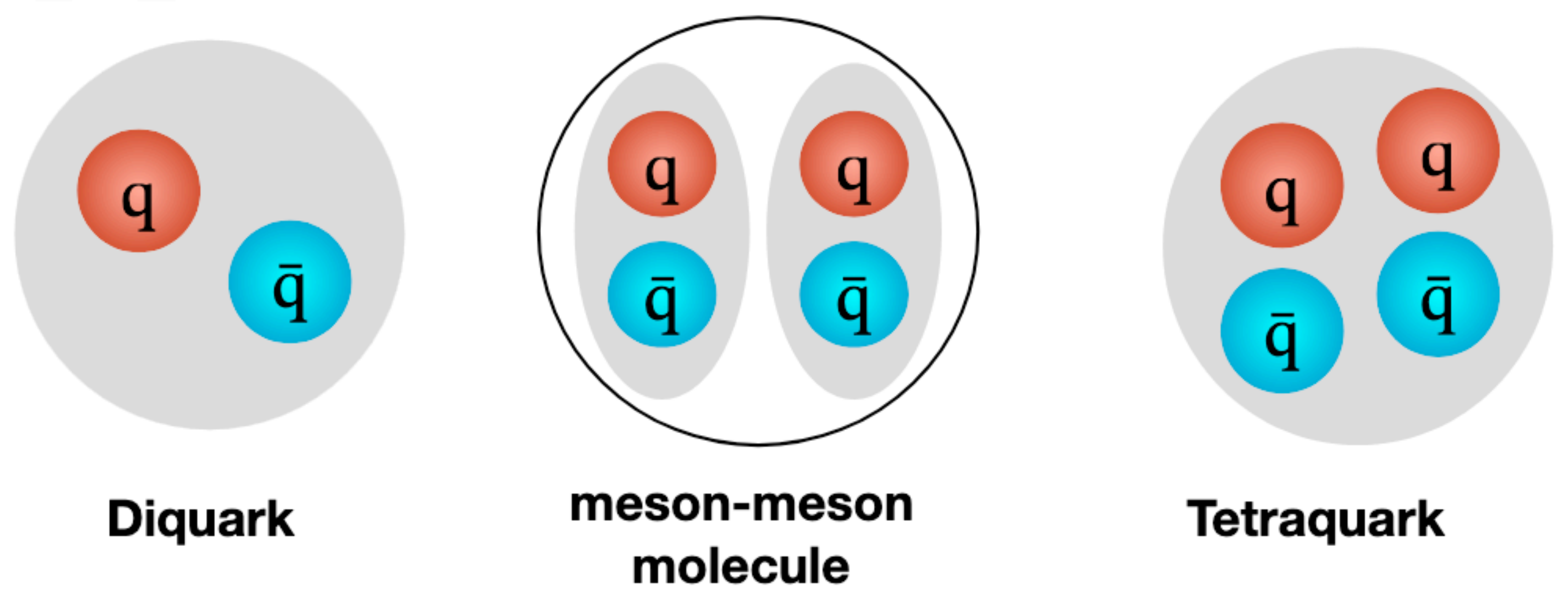
$v_2\{2\}$ - sensitive to fluctuations

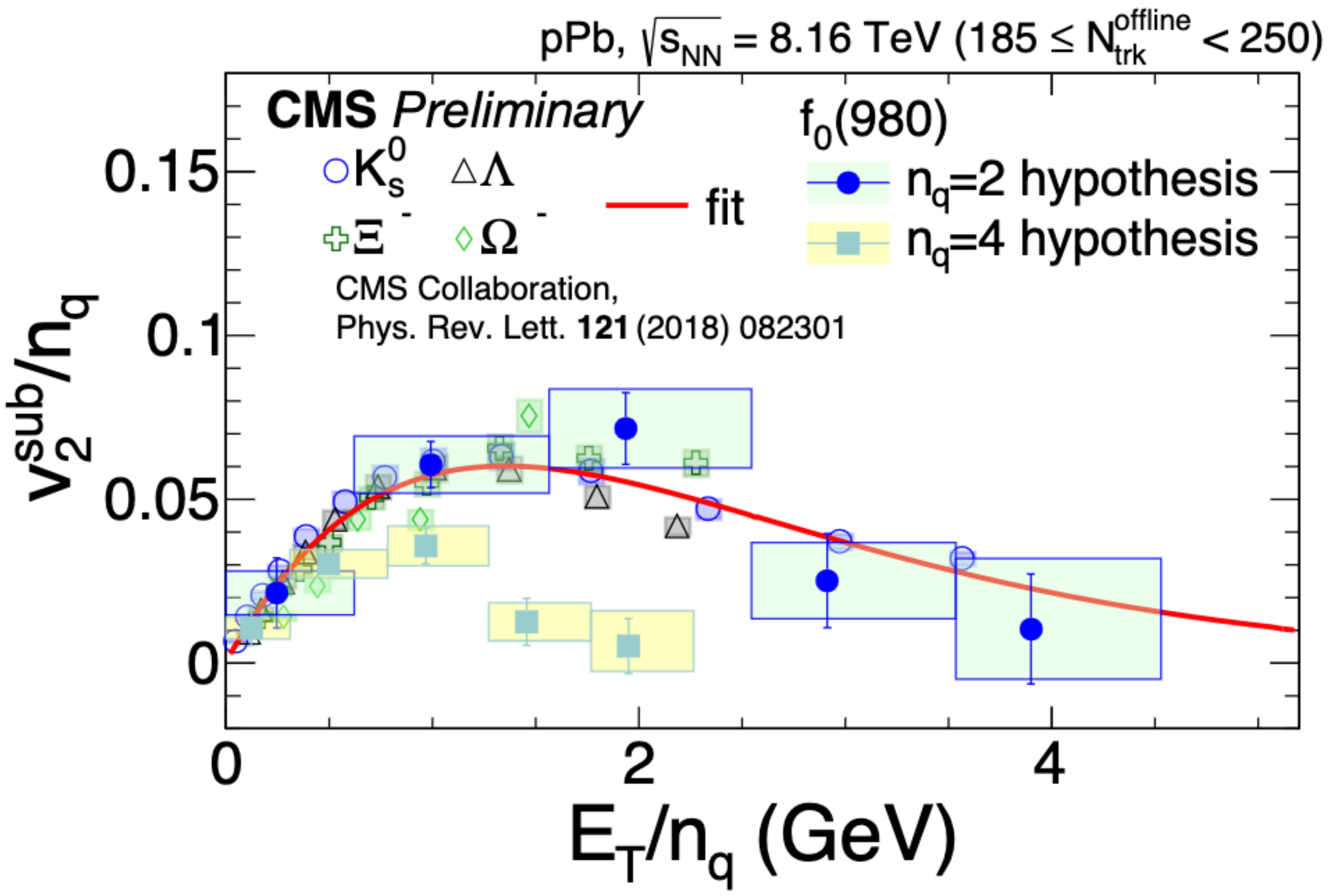
$v_2\{4\}$ - reduced sensitivity to fluctuations

$f_0(980)$ quark content

Longstanding question "is the f_0 a diquark, molecular, or tetraquark?"

Difficult/impossible question to answer theoretically - up to experiments to answer





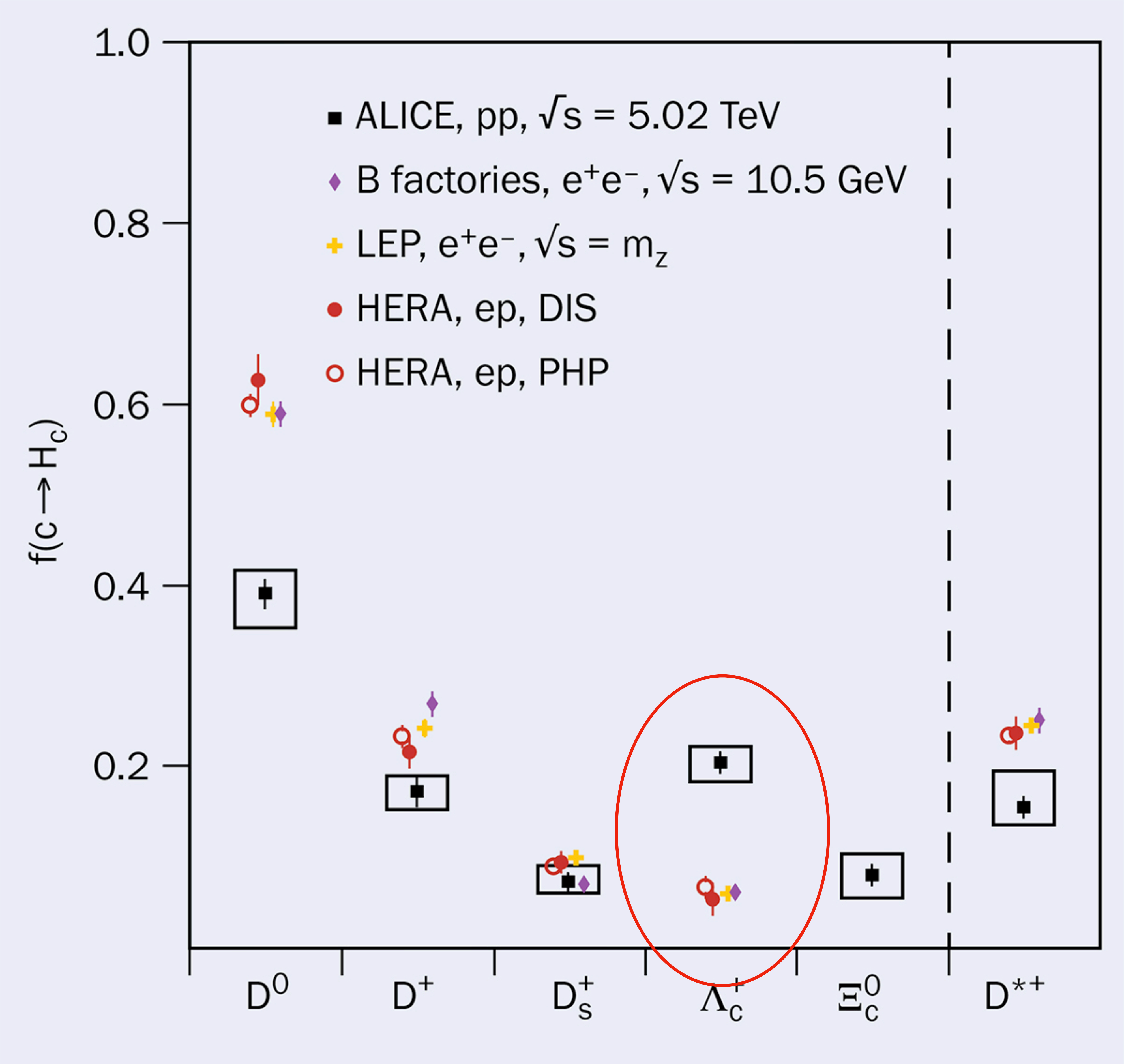
Elliptic flow:

Scales when $n_q = 2$

Suggests that f_0 is a diquark

Other results from low energy studies suggest otherwise
- debate continues

Is charm fragmentation universal?



Heavy-flavor yields computed in pQCD via convolution of

PDFs + partonic cross-section + FF

FF: typically parametrized from e^+e^-/ep measurements

Assumption that charm hadronization universal

$f(c \rightarrow H_c)$ from p+p collisions different to e^+e^- and ep data

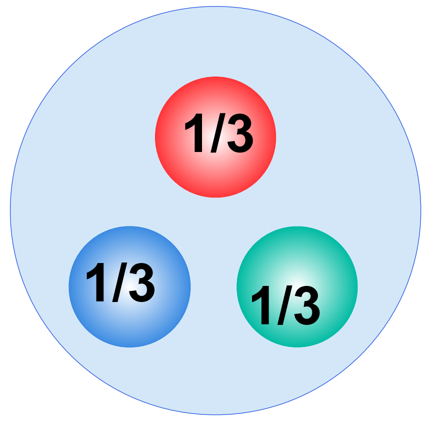
>3x more charm baryons than than in e^+e^- and ep

Assumption of universal (charm) fragmentation is not valid

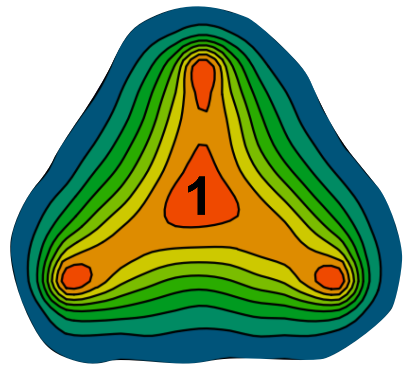
Note: LHC $c\bar{c}$ cross-section is consistent with pQCD predictions (although at upper limit)

ALICE: PRD 105, L011103 (2022)

What carries baryon number?



Quarks as baryon carriers?



Baryon-junction as baryon carrier?

fig: Suganuma et al. AIP Conf.Proc. 756 (2005) 1, 123

If baryon number carried by:
Valence quarks - B/Q = A/Z
Baryon junctions - B/Q > A/Z

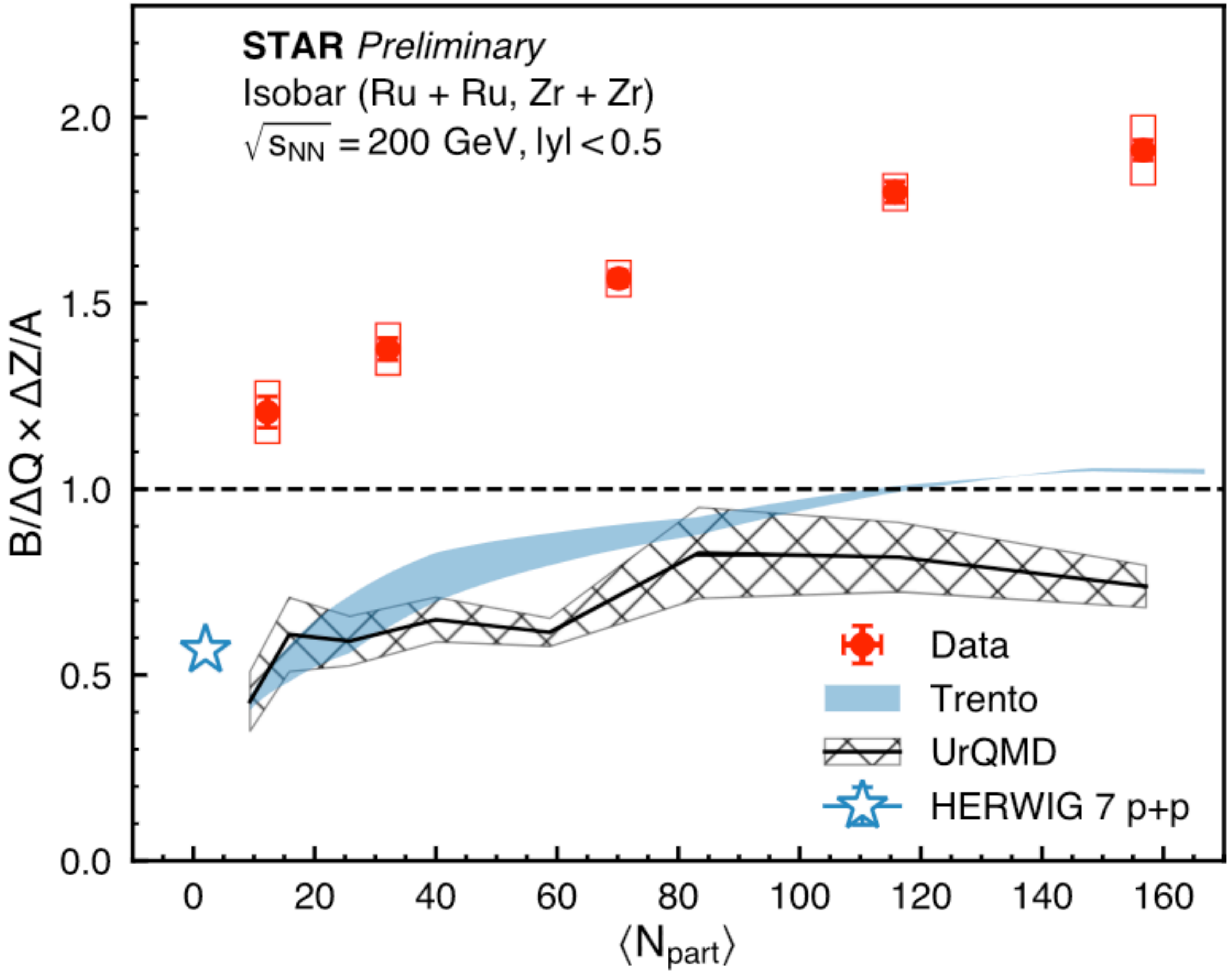
Use Isobar data:
Ru+Ru: A = 96, Z = 44
Zr+Zr: A = 96, Z = 40

$$B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$$

$$Q = \left(N_{\pi^+} + N_{K^+} + N_p\right) - \left(N_{\pi^-} + N_{K^-} + N_{\bar{p}}\right)$$

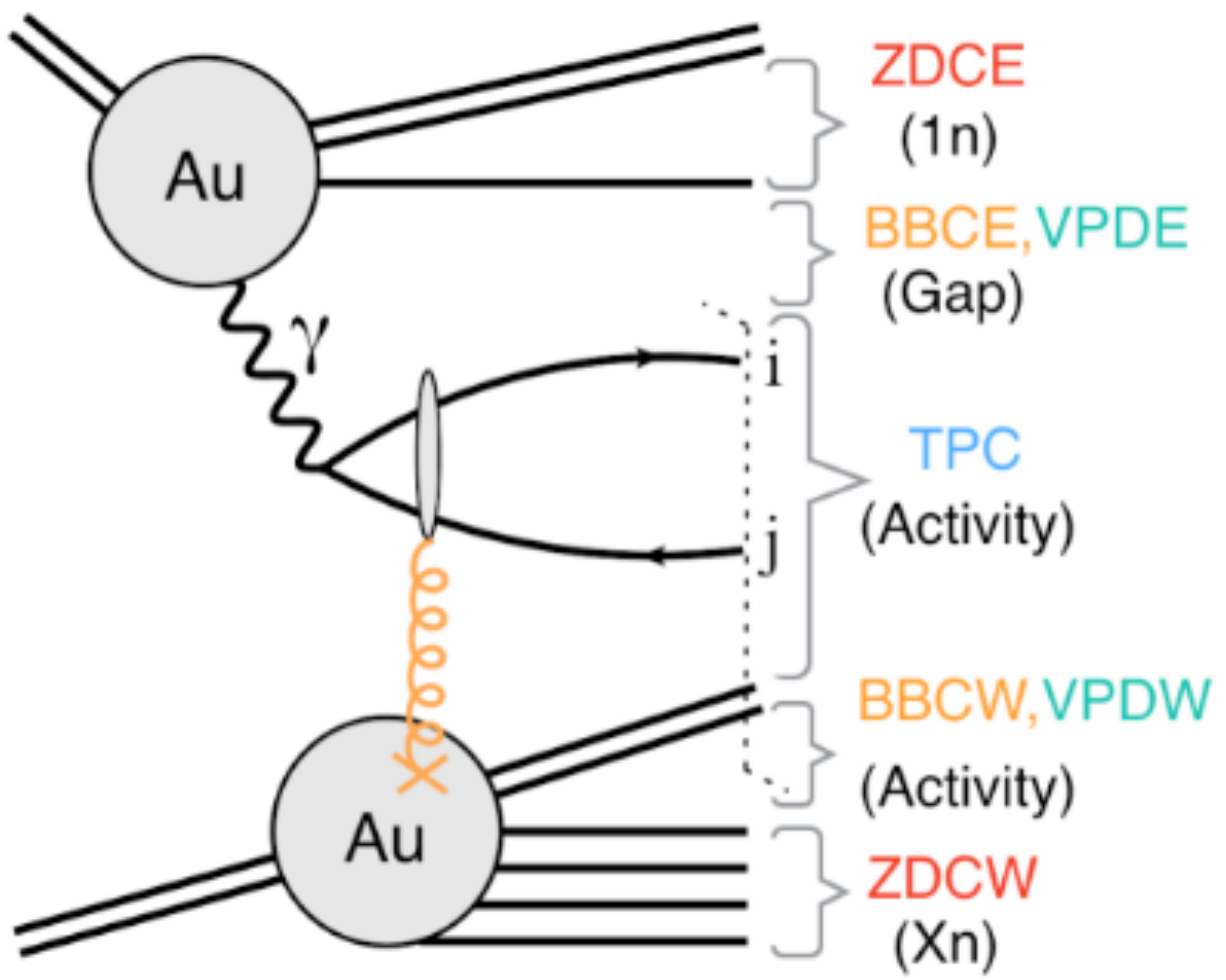
$\Delta Q = Q_{Ru} - Q_{Zr}$
$\Delta Z = Z_{Ru} - Z_{Zr}$

Measure B/ΔQ
Calculate A/ΔZ



Data currently favor baryon junctions

What carries the baryon number?

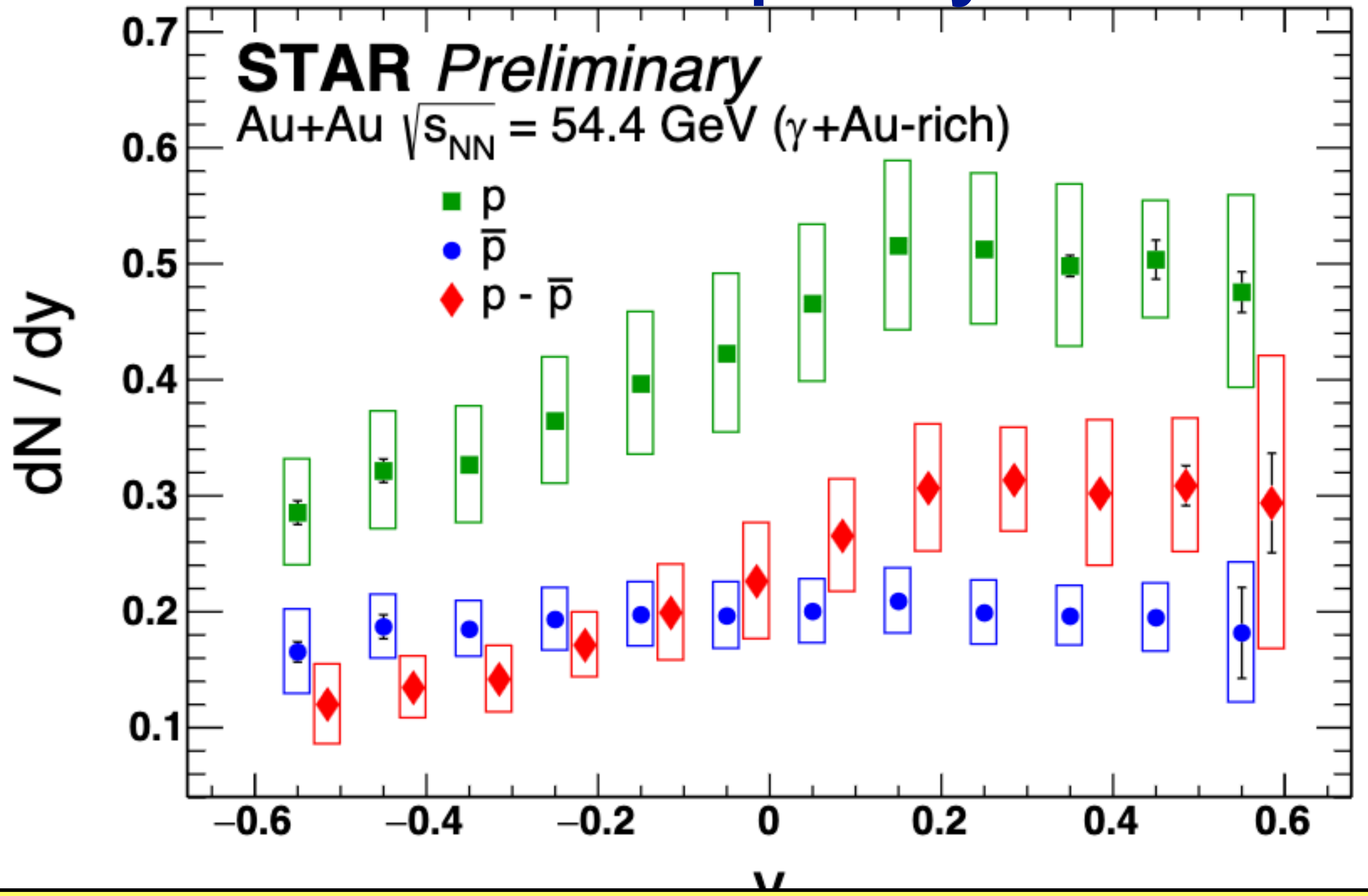


Study photonuclear events:

Very clean process, photon no B

Baryon number with valence quarks - very few baryons at mid-rapidity

Baryon junctions - more protons at mid-rapidity



y_{beam} = 4.06

Net proton yields

Valence quarks:

- $dN/d\Delta y \sim \exp(-2.4\Delta y)$ (PYTHIA)
- $\Delta y = Y_{beam} - y$

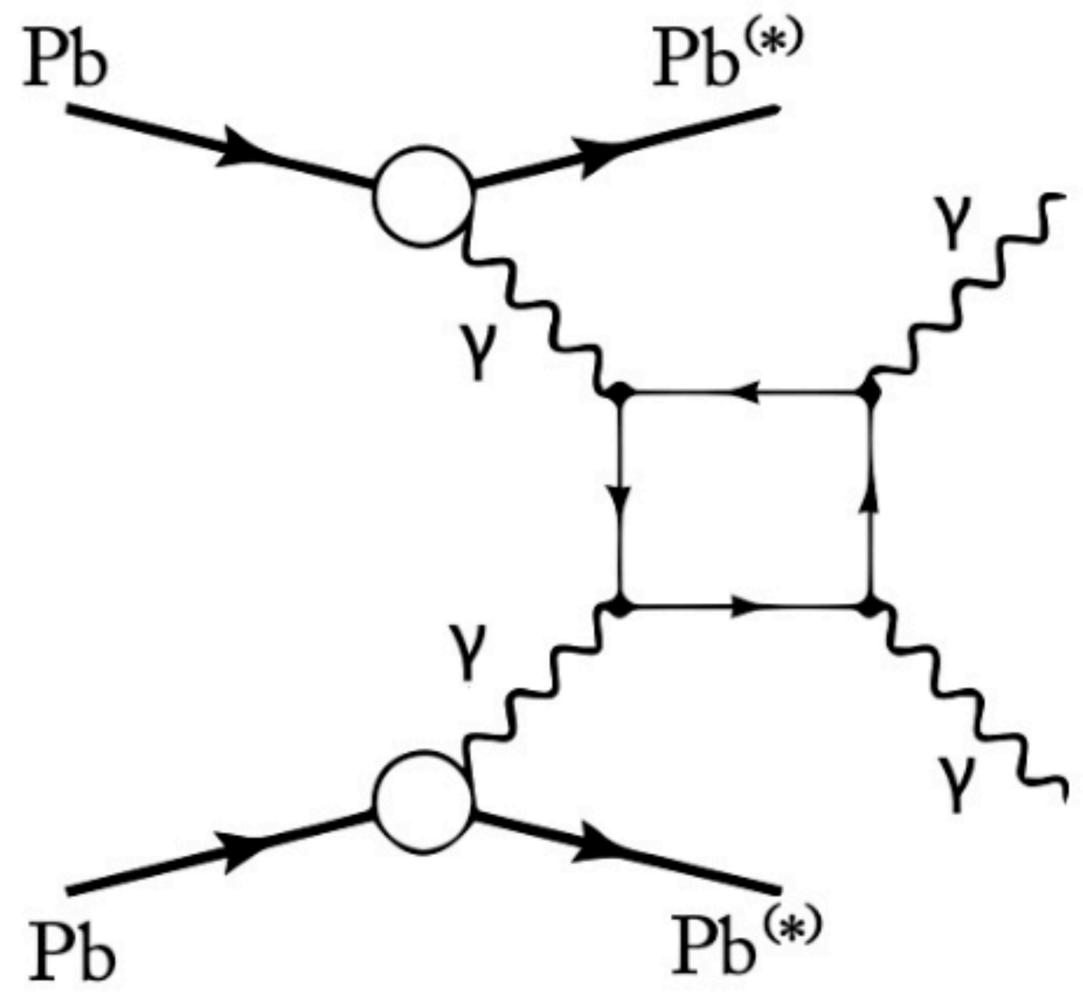
Slope from fit to data = -1.13 +- 0.32

Data inconsistent with valence quark expectations

Can we detect new physics via UPC?

UPC: Explosion in studies over past 10 Years

2017: Light-by-Light



Open Access | Published: 14 August 2017

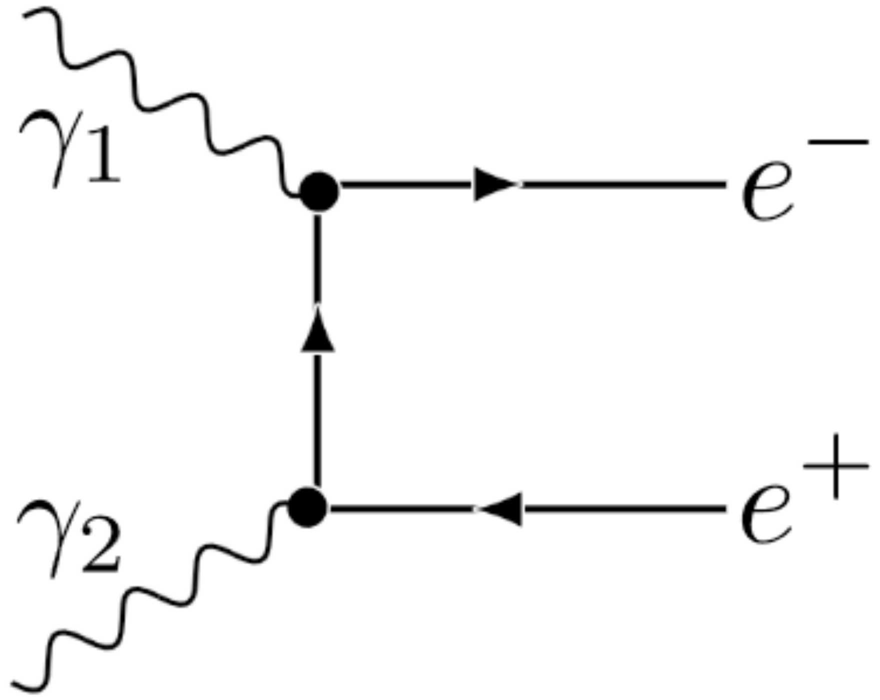
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

ATLAS Collaboration

Nature Physics **13**, 852–858 (2017) | Cite this article

41k Accesses | **185** Citations | **521** Altmetric | Metrics

2021: Breit-Wheeler



OUTPUTS FROM PHYSICAL REVIEW LETTERS

#42

of 37,322 outputs

2023: Entanglement Enabled Interference

ScienceAdvances AAAS

Article Metrics

? What is this page? | Embed badge | Share

Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

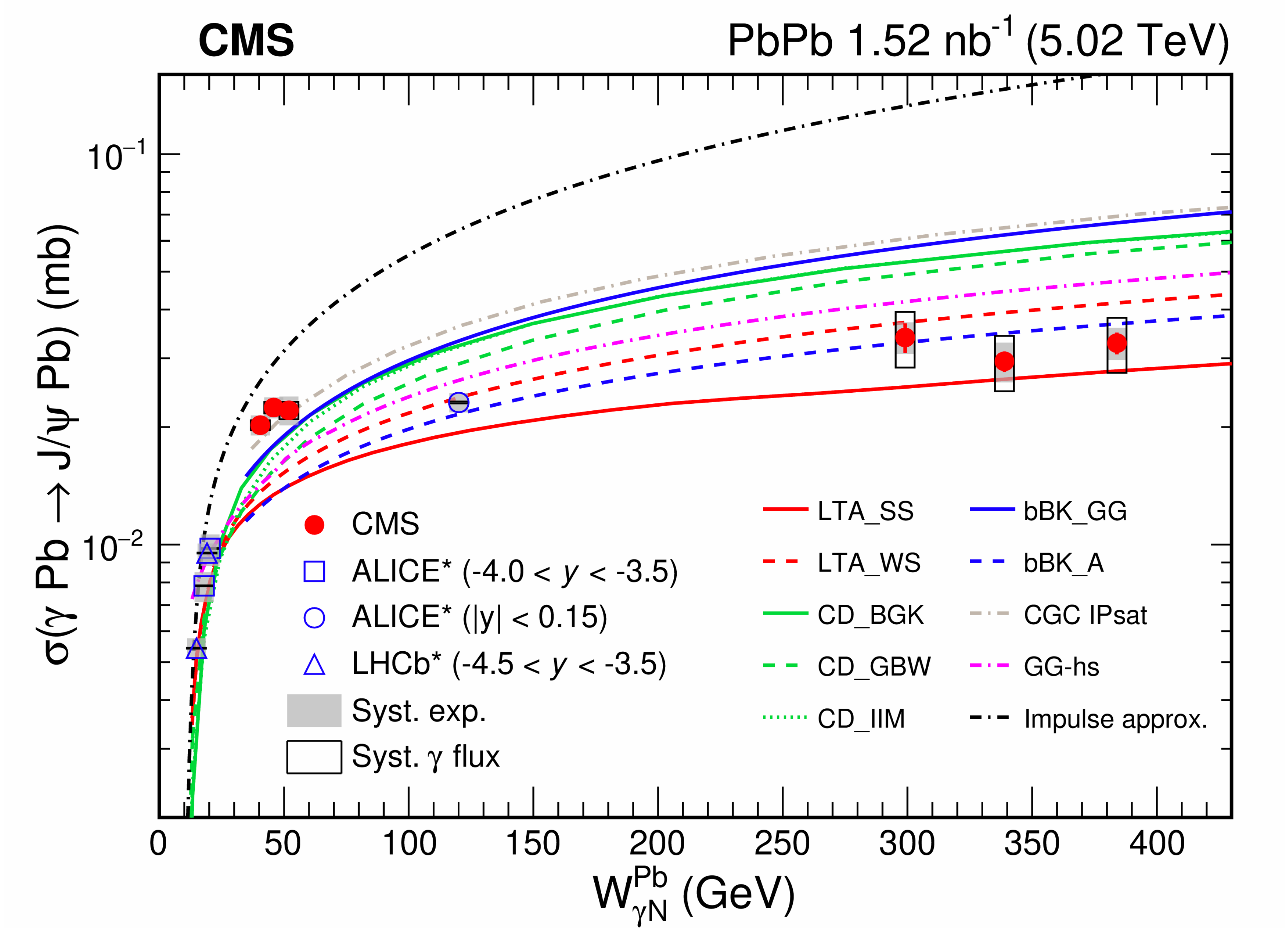
Overview of attention for article published in Science Advances, January 2023

Scientists See Quantum Interference between Different Kinds of Particles for First Time

A newly discovered interaction related to quantum entanglement between dissimilar particles opens a new window into the nuclei of atoms

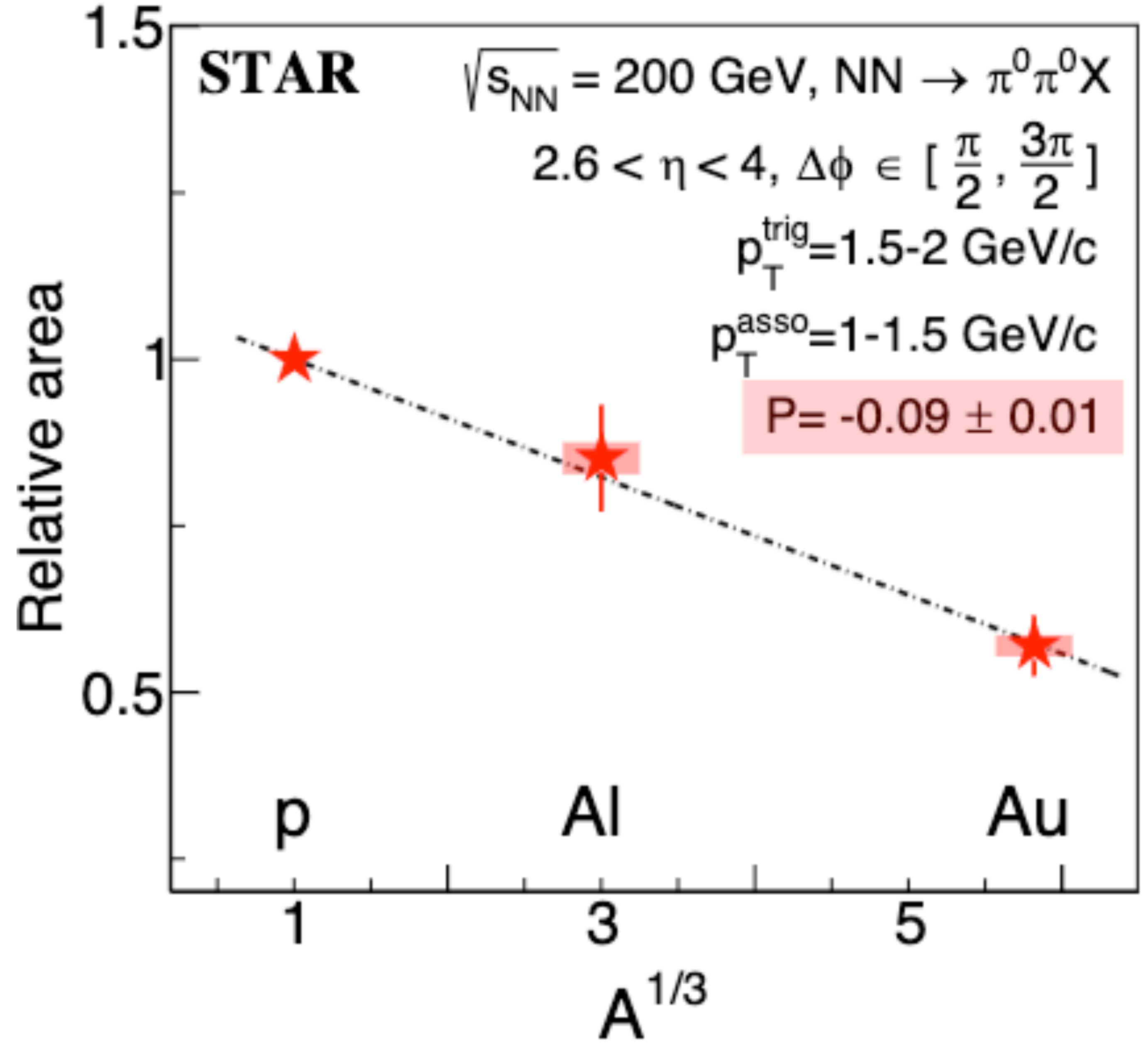
Exploiting both γγ and γ-A collisions

Evidence for gluon saturation



J/ψ photo-production:
- CMS (and ALICE) recently accessed new W (photon-nucleon CM) range
- Shape of coherent $\sigma_{\gamma A \to J/\psi A'}(W)$ not predicted by models
- Gluon saturation? black disk limit?

Suppression of di-π^0 correlations in p+A
- Dependence on A as predicted
- No broadening, not as predicted



Hints of saturation at RHIC and LHC

CMS: PRL 131 (2023) 262301, STAR: PRL 129, 092501 (2022)

Anomalous magnetic moment of τ lepton

Recent a_μ ($a_l = 1/2(g-2)l$) measurements challenge SM predictions.

If new physics and due to massive new particle, then τ would be much more sensitive

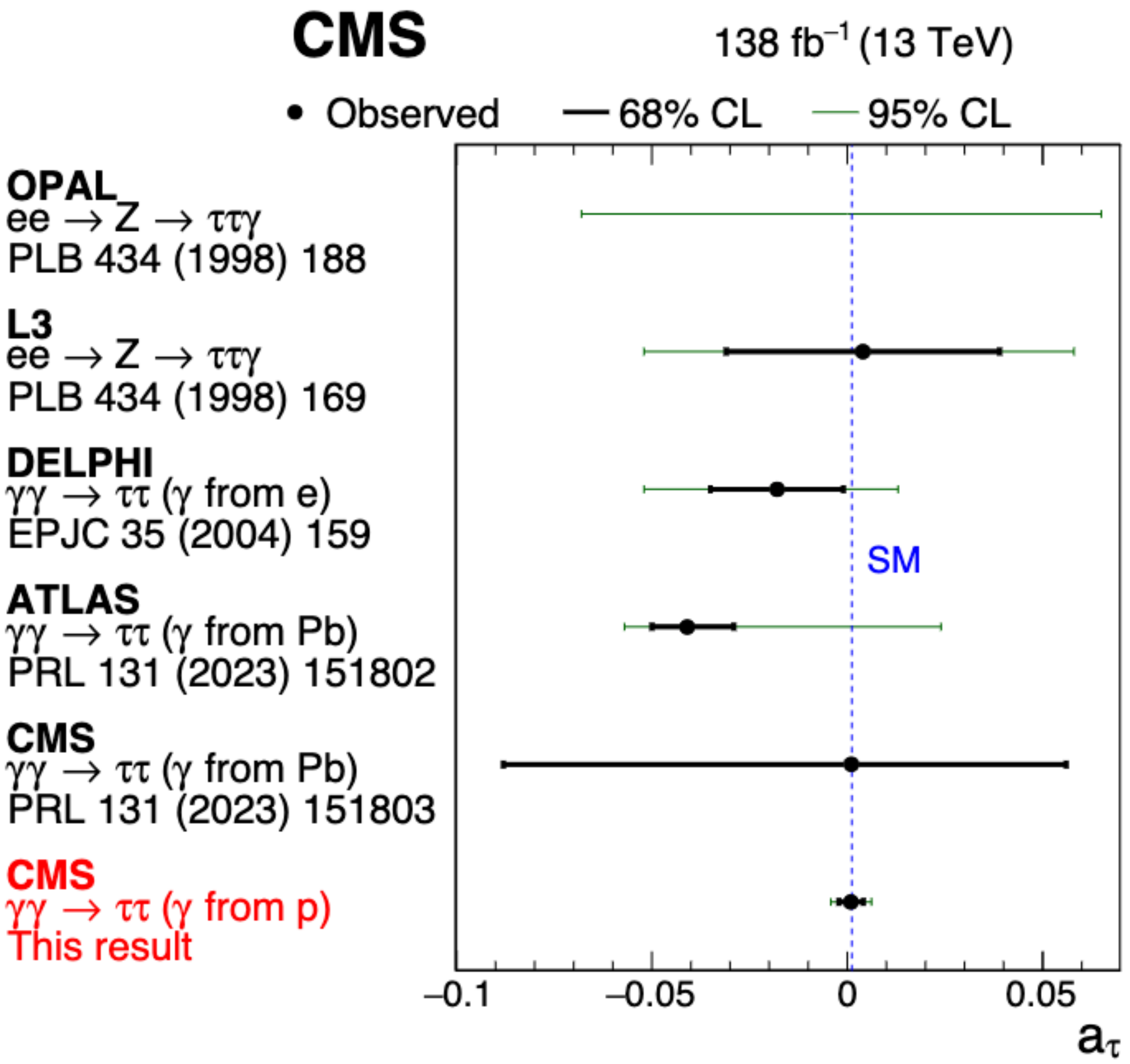
From p-p:

$a_\tau = 0.0009 + 0.031 - 0.0021$

(consistent with SM)

First uses of hadron-collider data to test EM properties of τ

Results competitive with existing lepton-collider constraints



CMS: arXiv:2406.03975

LHC: $\sqrt{s_{NN}}$ = 5.36 TeV

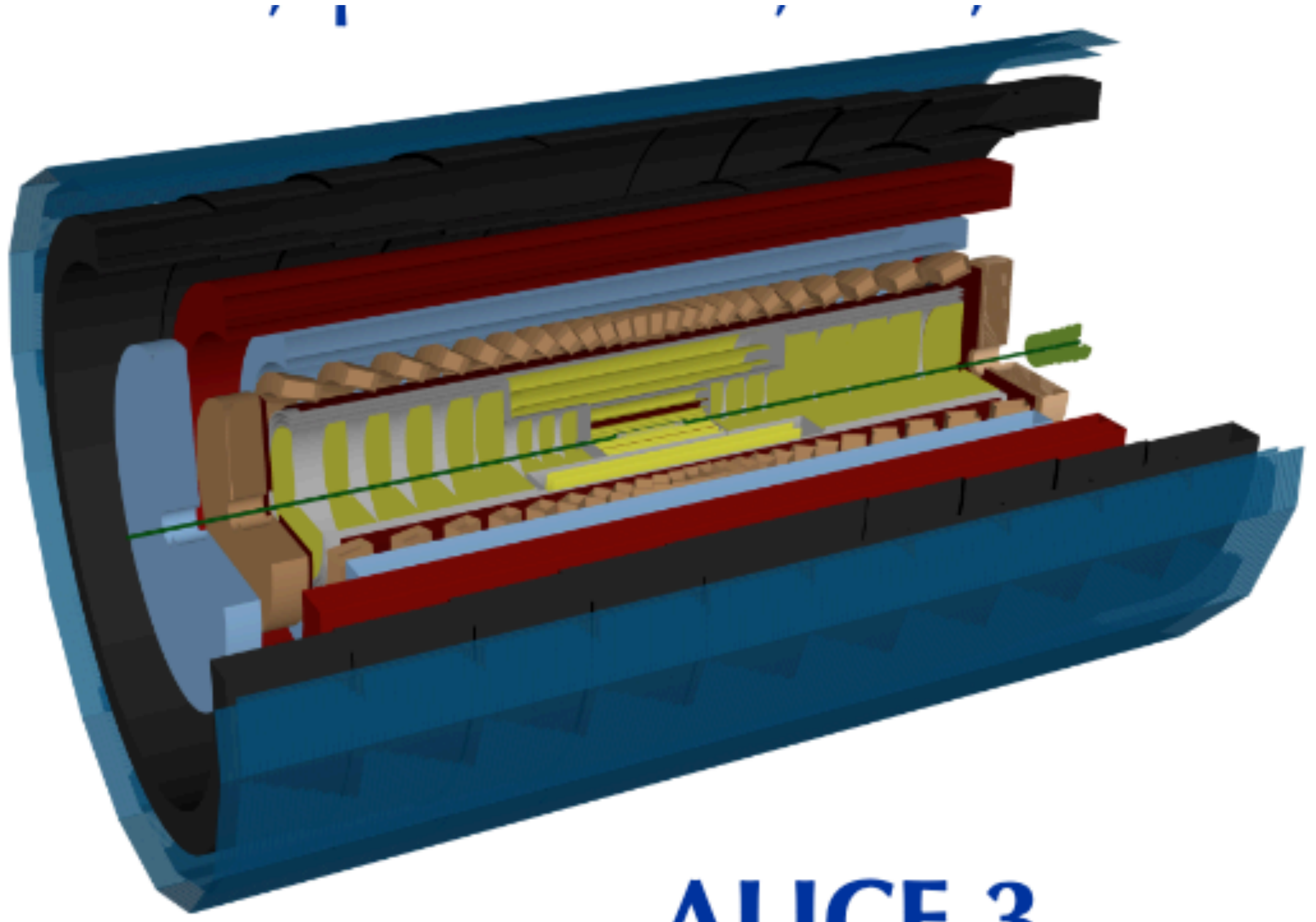
High luminosity for ions — HL-LHC — Higher luminosities for ions

LHC schedule	Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2025	Run 4 2029 - 2032	Run 5	Run 6
Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, OO, pPb, Pb-Pb	pp, pPb, Pb-Pb	pp, pA?, AA	pp, pA?, AA

ALICE, ATLAS, CMS, LHCb committed to continue taking HI data

all have upgrades planned

- highest energy density (> 12 GeV/fm³) and highest temperature (≳ 300 MeV)
- longest lifetime (≳ 10 fm/c)
- largest heavy-flavour yields (~200 $c/\bar{c}$ in central Pb-Pb)
- vanishing net-baryon density ($\mu_B \approx 0$)



ALICE 3

vertexing, tracking, TOF, RICH, ECal, μID, FCT

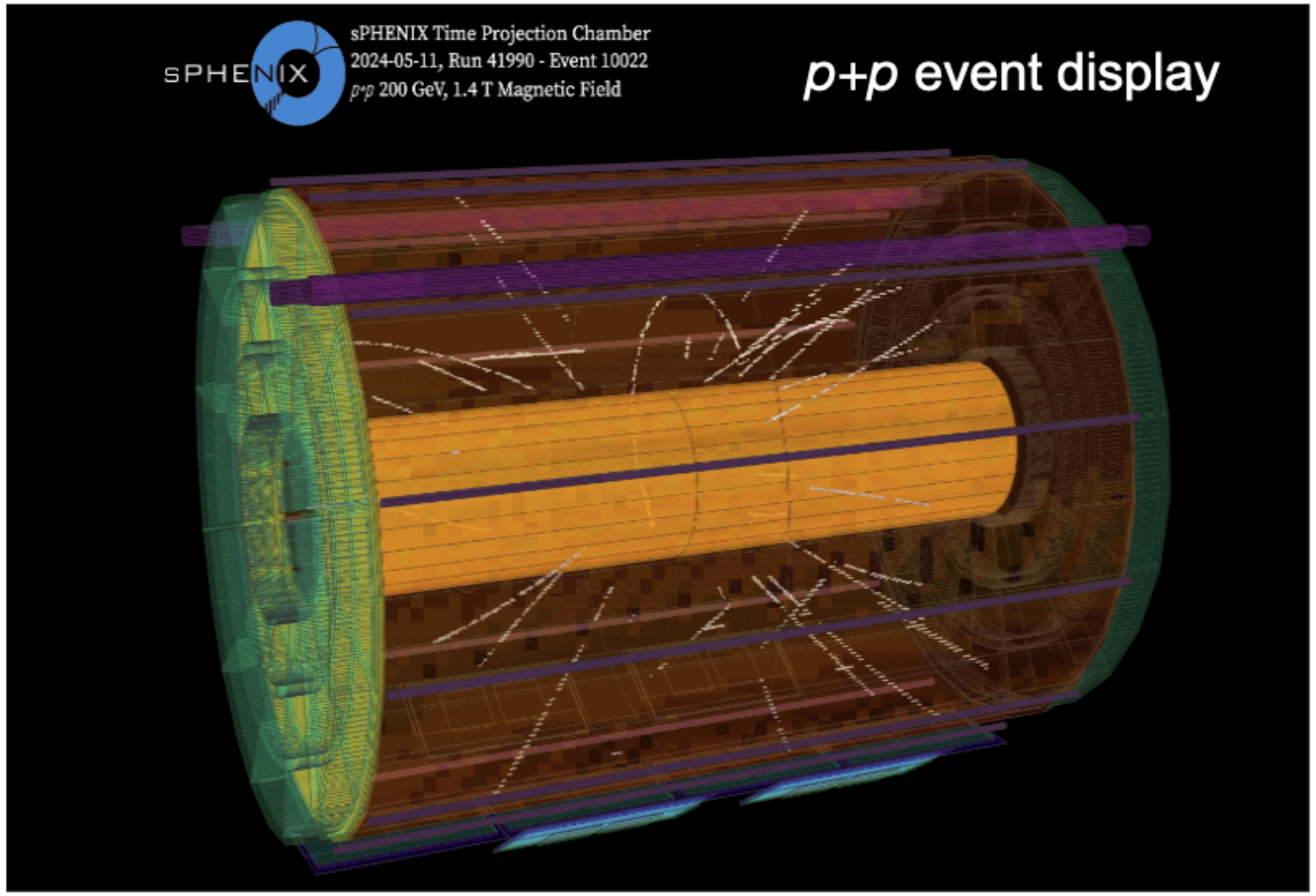
ALICE FOCAL for Run 4

ALICE3 - new detector focus on HF, chiral restoration, exotica … all multidimensionally

RHIC: $\sqrt{s_{NN}}$ = 200 GeV

New kid on the block: sPHENIX taking first data

- Photon and jet physics program with calorimeters in full swing
- Rare triggers operational
- DAQ rate > 15 kHZ
- Continued progress on TPC and full suite of tracking detectors



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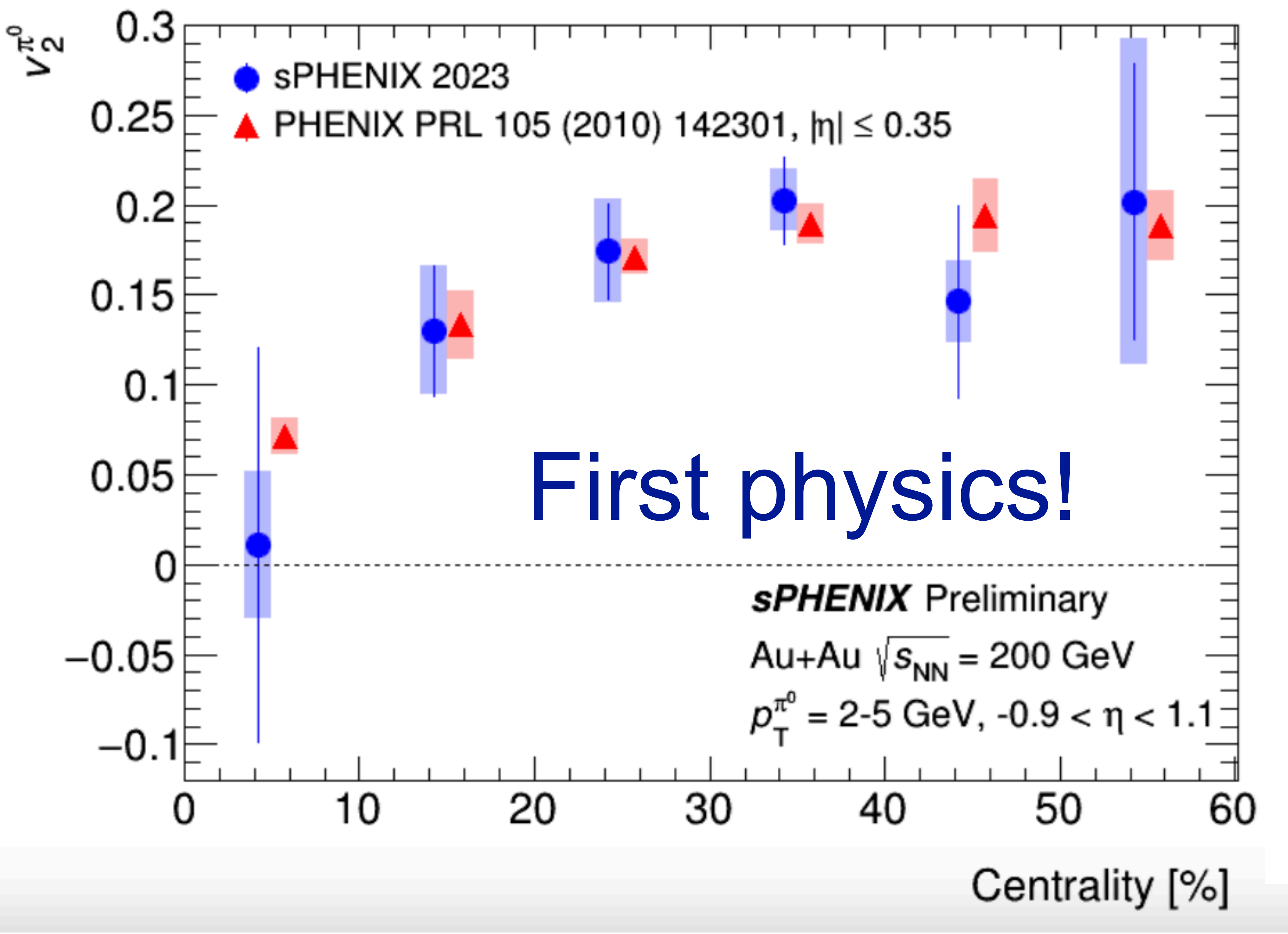

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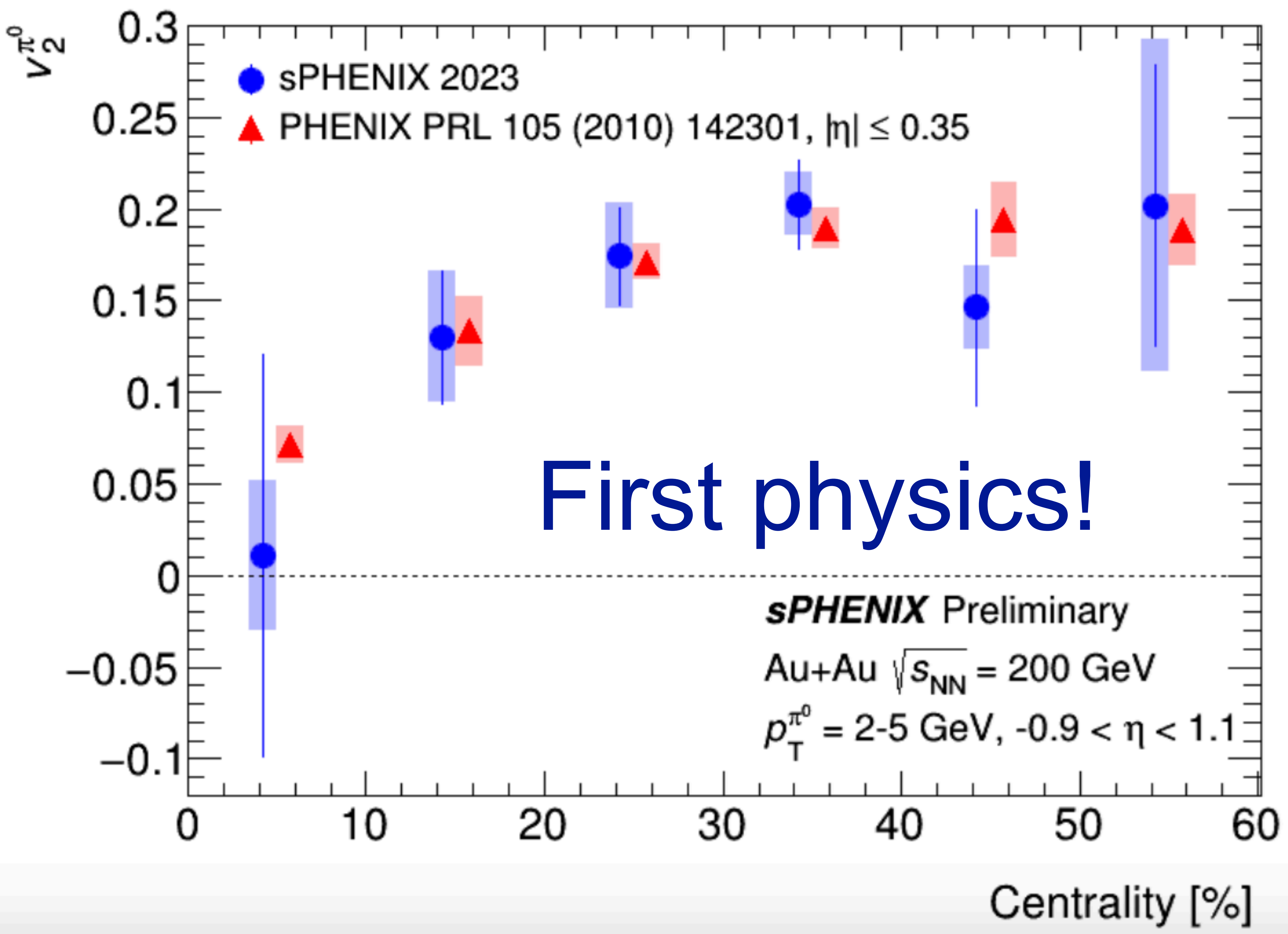
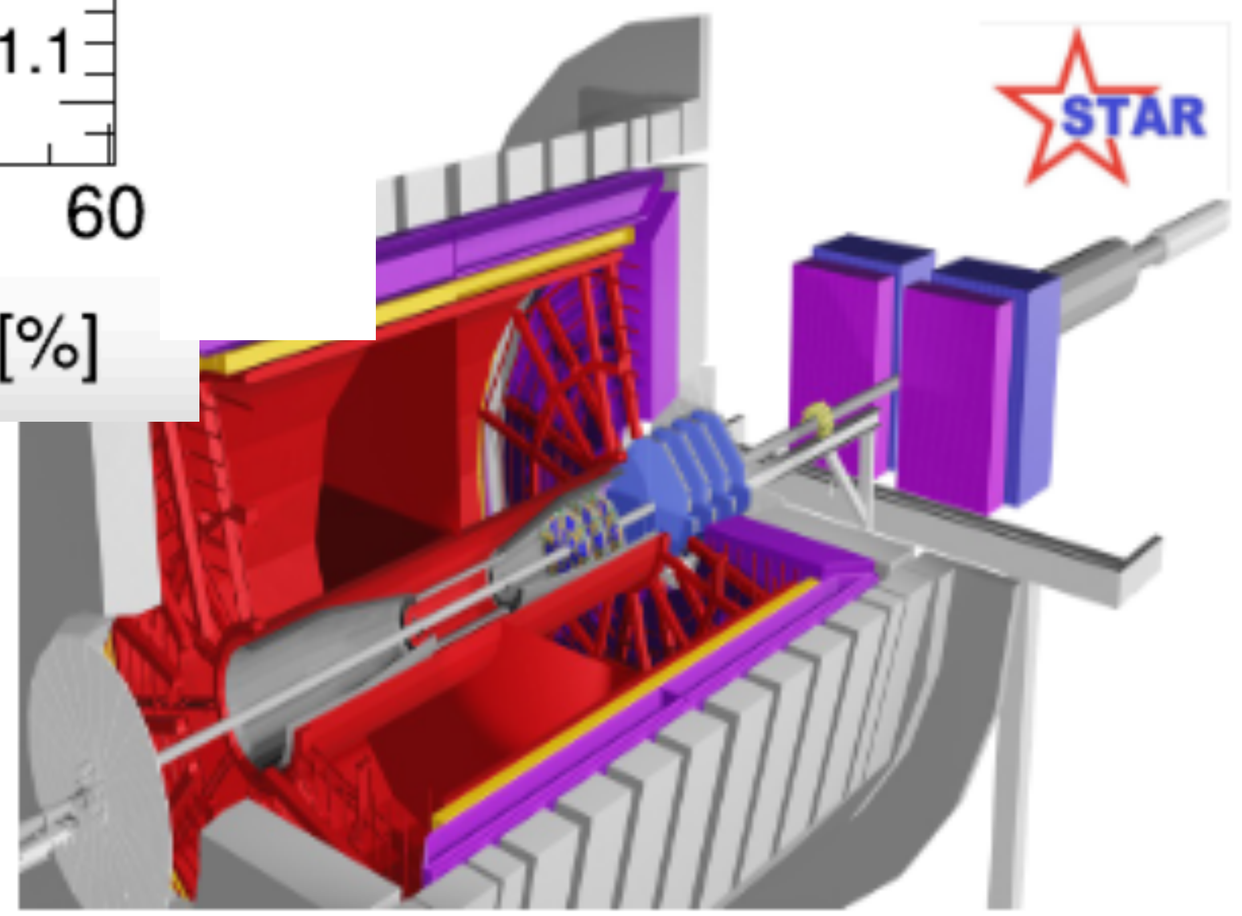
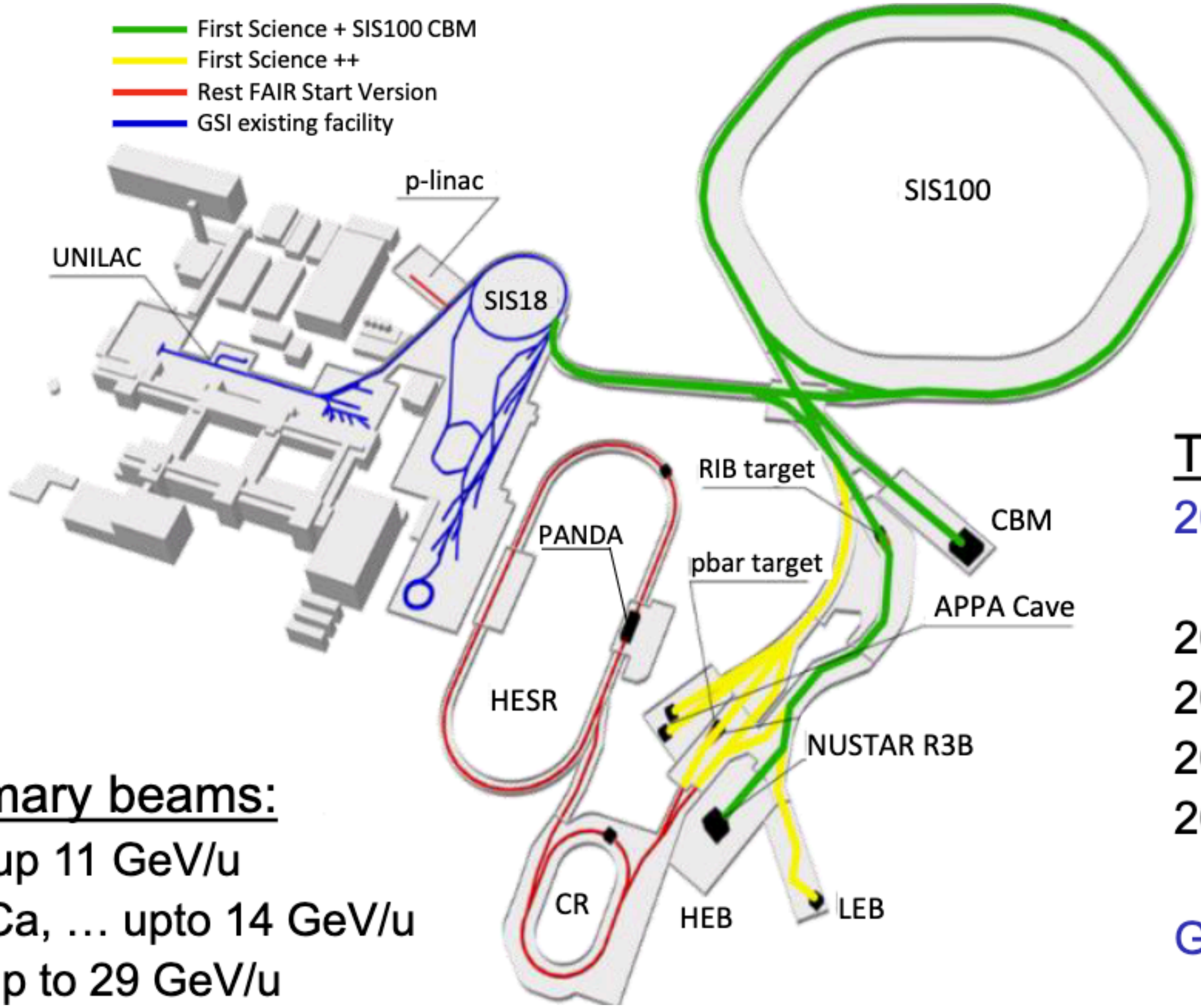


Senior scientist still going strong:
STAR exploiting at top energy upgrades from BES-II and new forward capabilities



CBM and HADES: $\sqrt{s_{NN}}$ = 2-5 GeV



Fixed target so very high rate experiment compared to RHIC

Timeline

2018 start of FAIR Phase-0 at upgraded GSI facilties
2023 concrete construction completed
2024 start of accelerator installation
2027 first experiments with S18 beam
2028 start of operation with SIS100

GSI facilities continue operation

SIS100 primary beams:

- 10^9/s Au up 11 GeV/u
- 10^9/s C, Ca, … upto 14 GeV/u
- 10^{11}/s p up to 29 GeV/u

Exploring high baryon density matter: EOS, hypernuclei, strangeness new threshold…

Outlooks

Bright future ahead

Next few years: New data from sPHENIX, STAR forward, LHC Run-3+4

Next-to-Next few years: ALICE-3, CBM@FAIR and the EIC

Lots left to discover and understand!

Among the open questions that remain are:

- What are the minimal conditions to create a QGP?
- Is there a Critical Point in the QCD phase diagram?
- Can we see evidence of chiral restoration?
- Can we determine additional properties such as its heat capacity, compression modulus, electric conductivity, color conductivity?
- What is the magnitude of the initial magnetic field?
- How is baryon number carried?