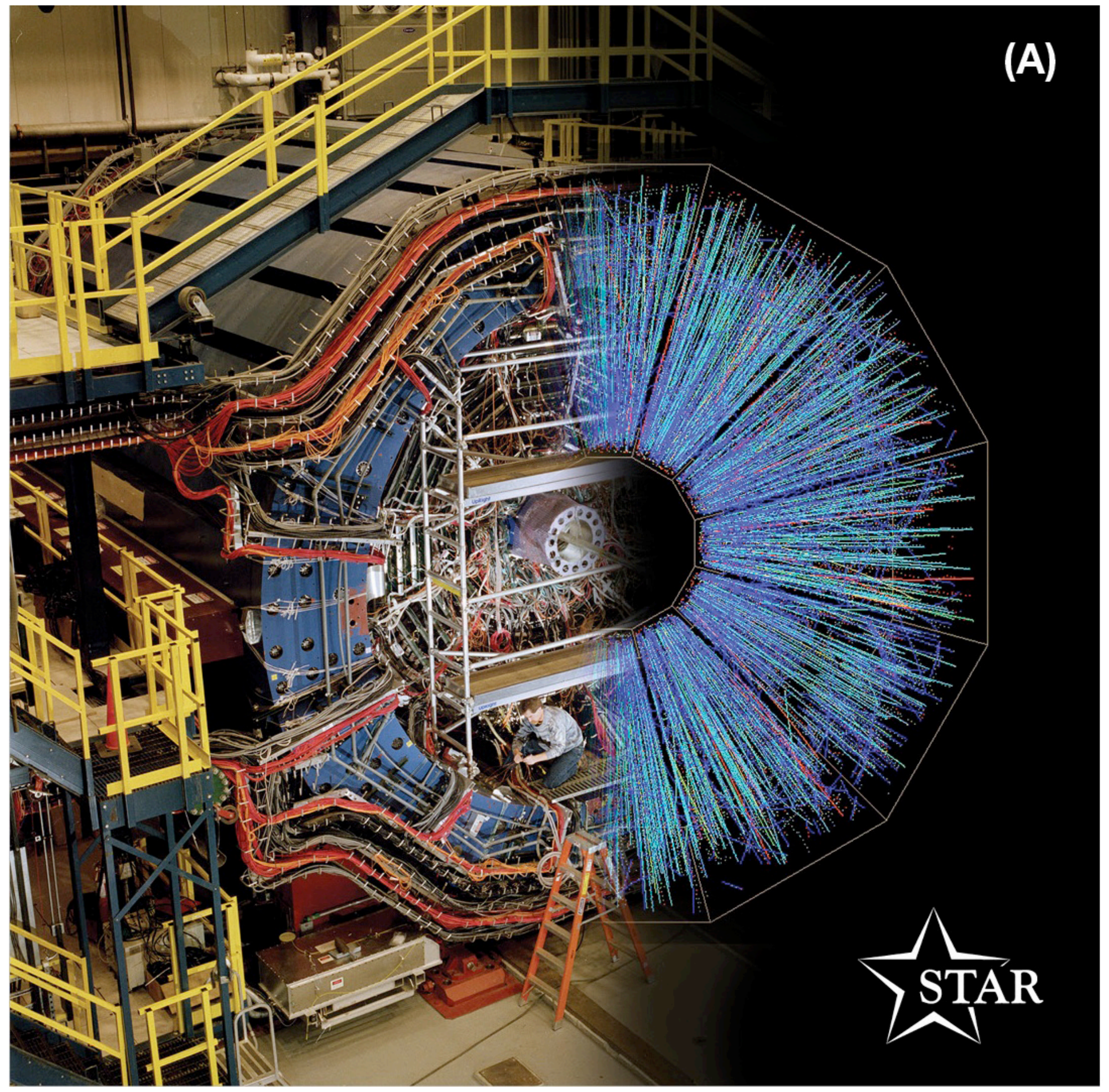
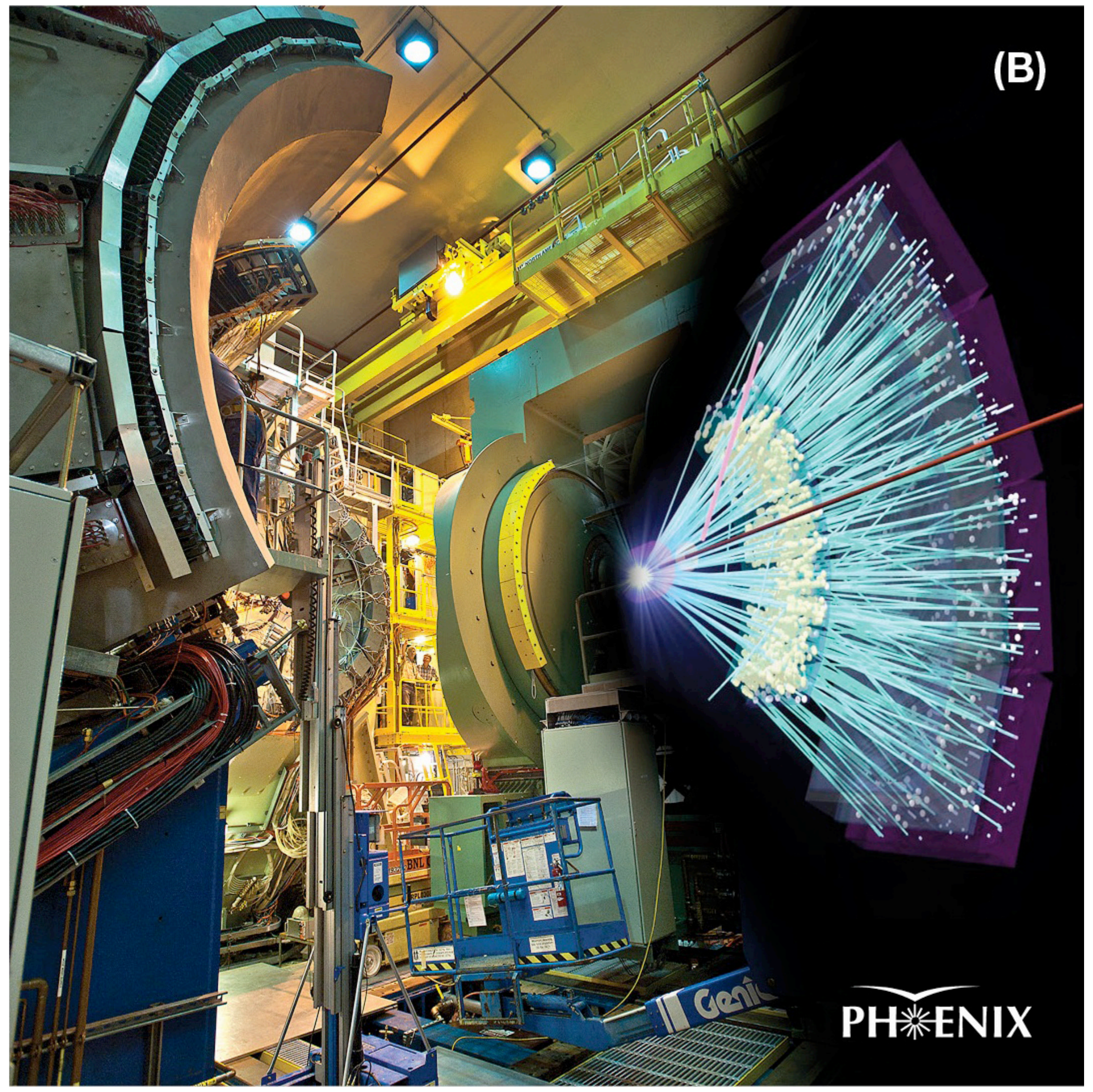


U.S. DEPARTMENT OF ENERGY
Office of Science

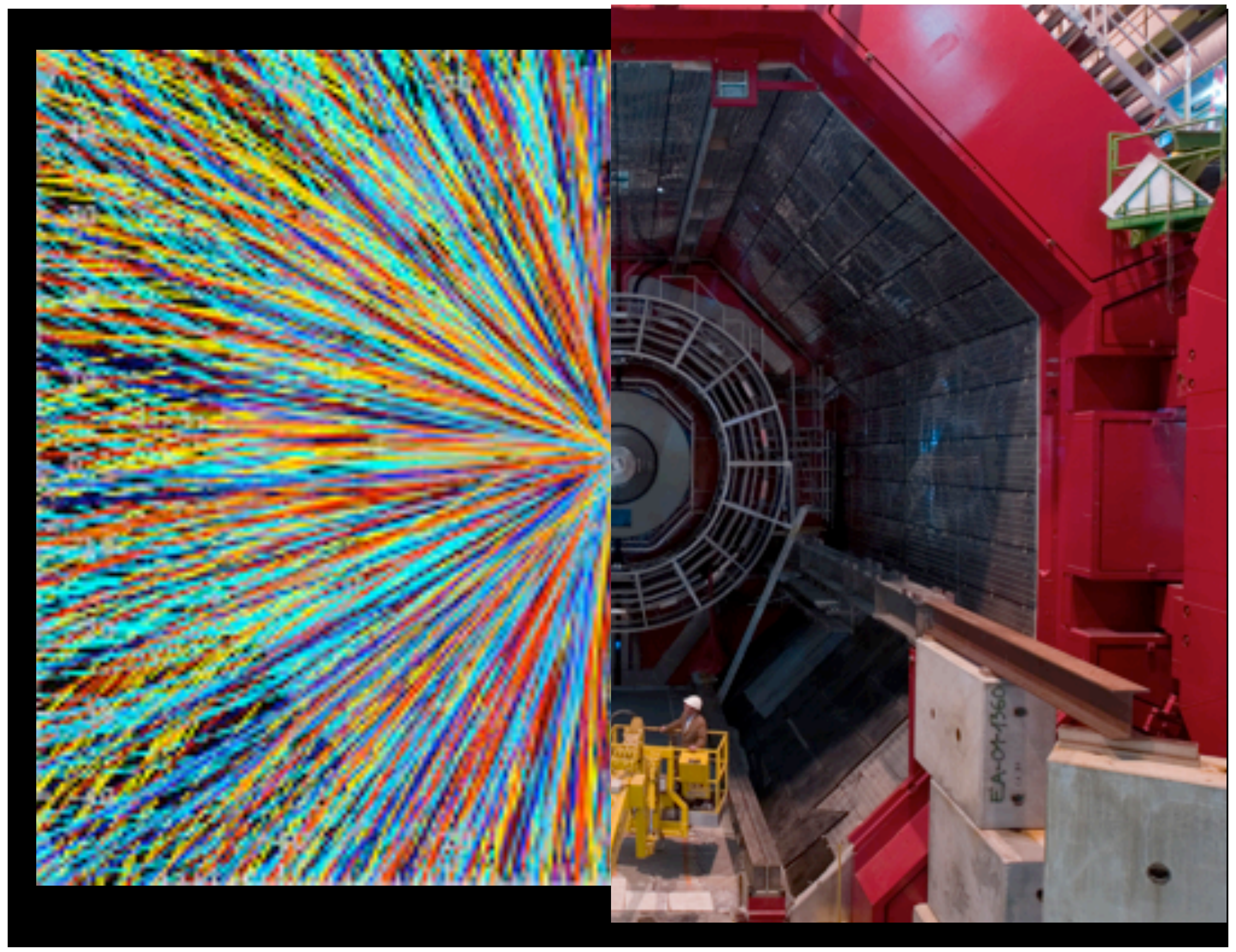
LUX ET VERITAS

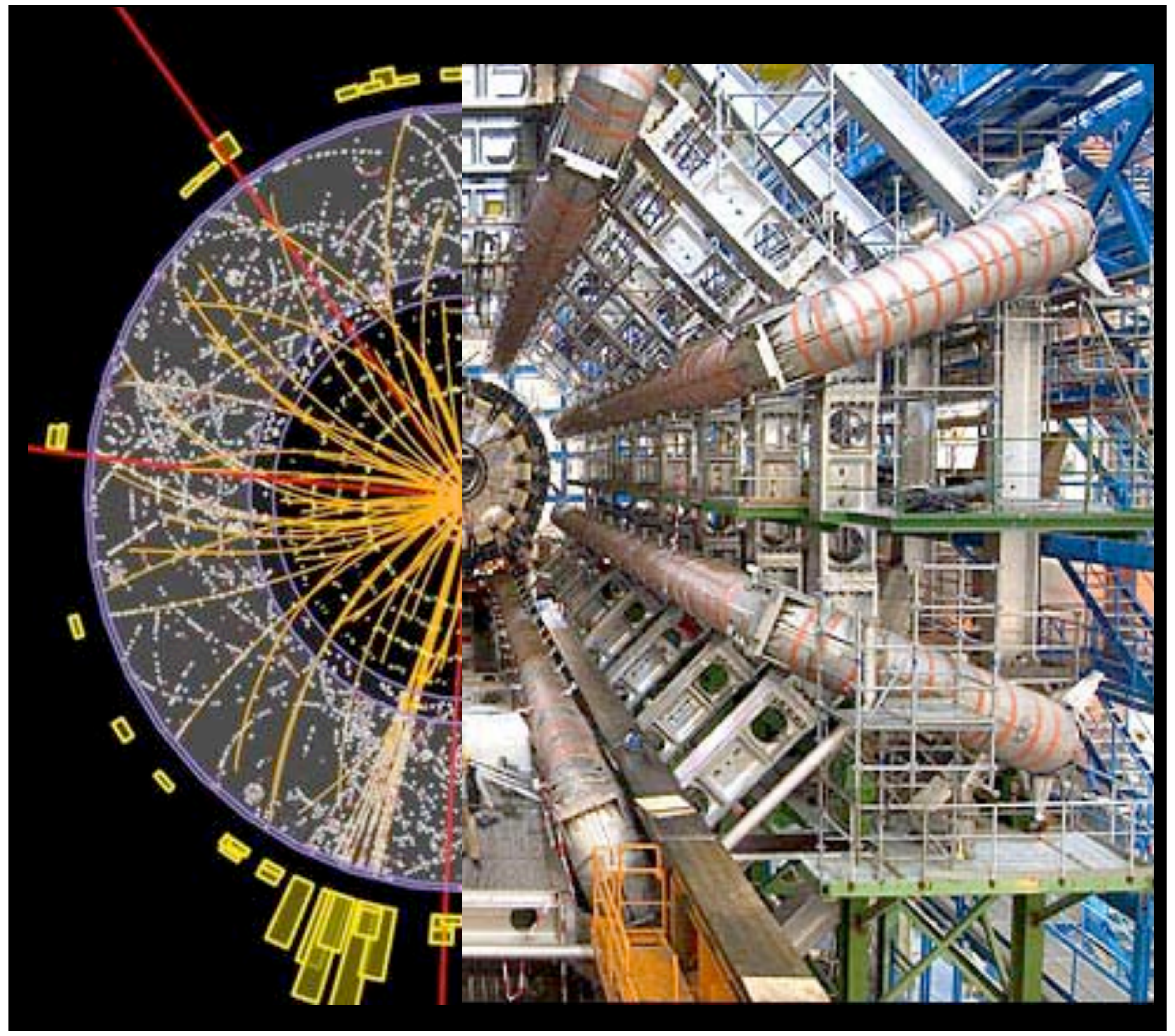
Wright Laboratory

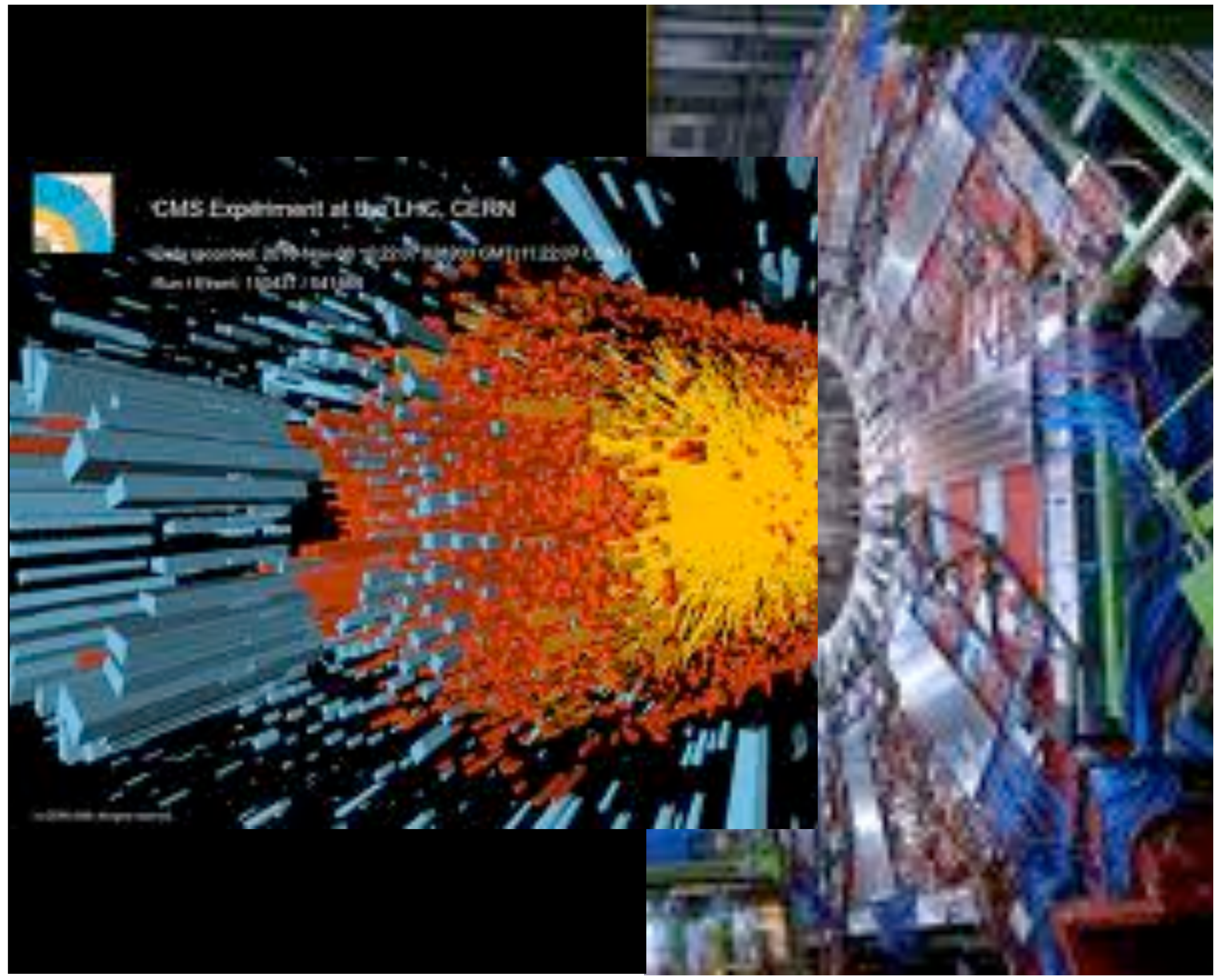


Hot QCD: Heavy ion physics at RHIC and the LHC

Helen Caines (she/her), Wright Lab, Yale University

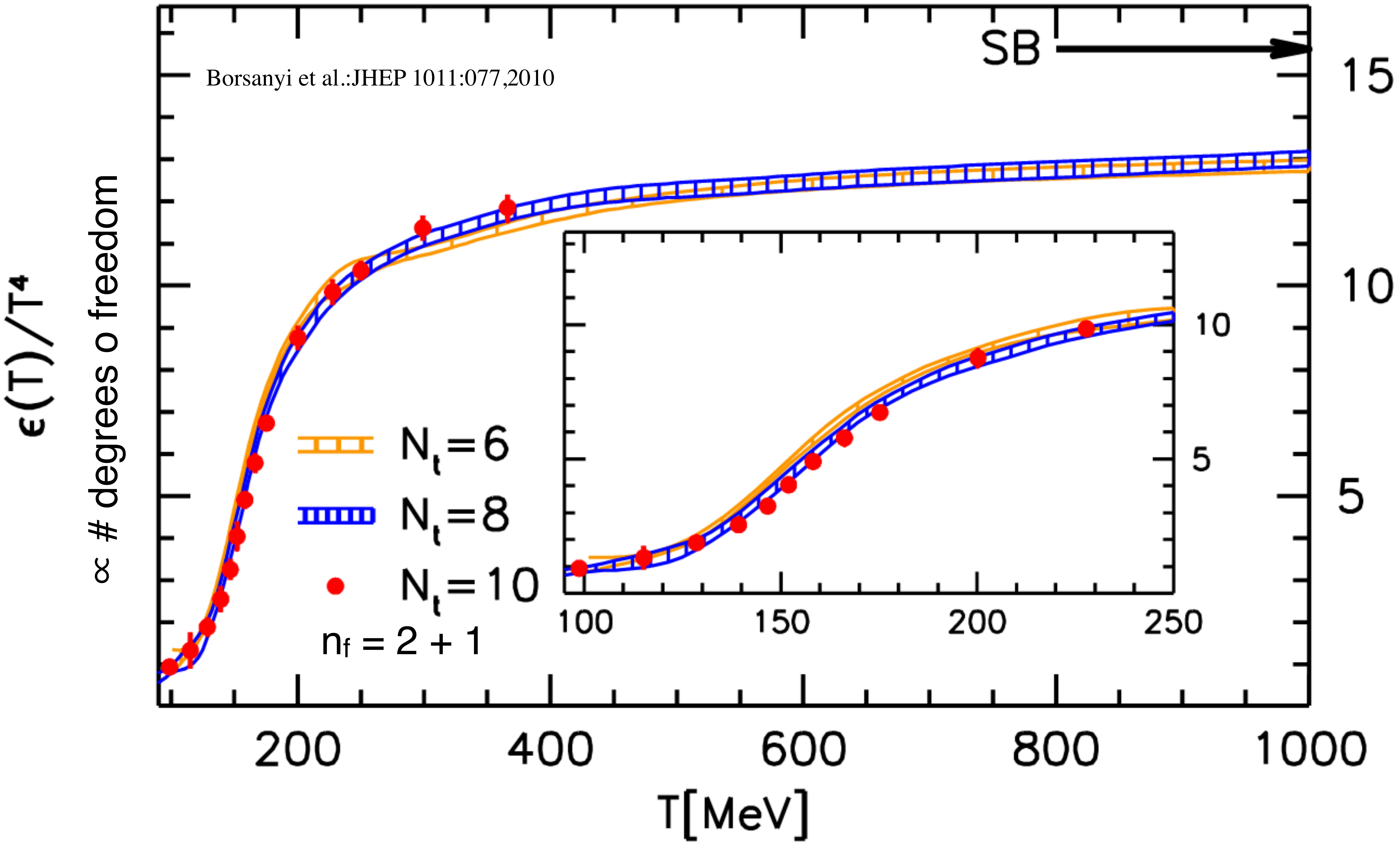






Midsummer QCD School, Saariselkä, Finland, July 2024

Goal of Hot QCD in a nutshell



Number of degrees of freedom increases by factor 10 at T~150 MeV → quarks and gluons

Lattice calculations: rapid smooth cross-over at $\mu_B \sim 0$

$T_{pc} \approx 156.5 \pm 1.5$ MeV

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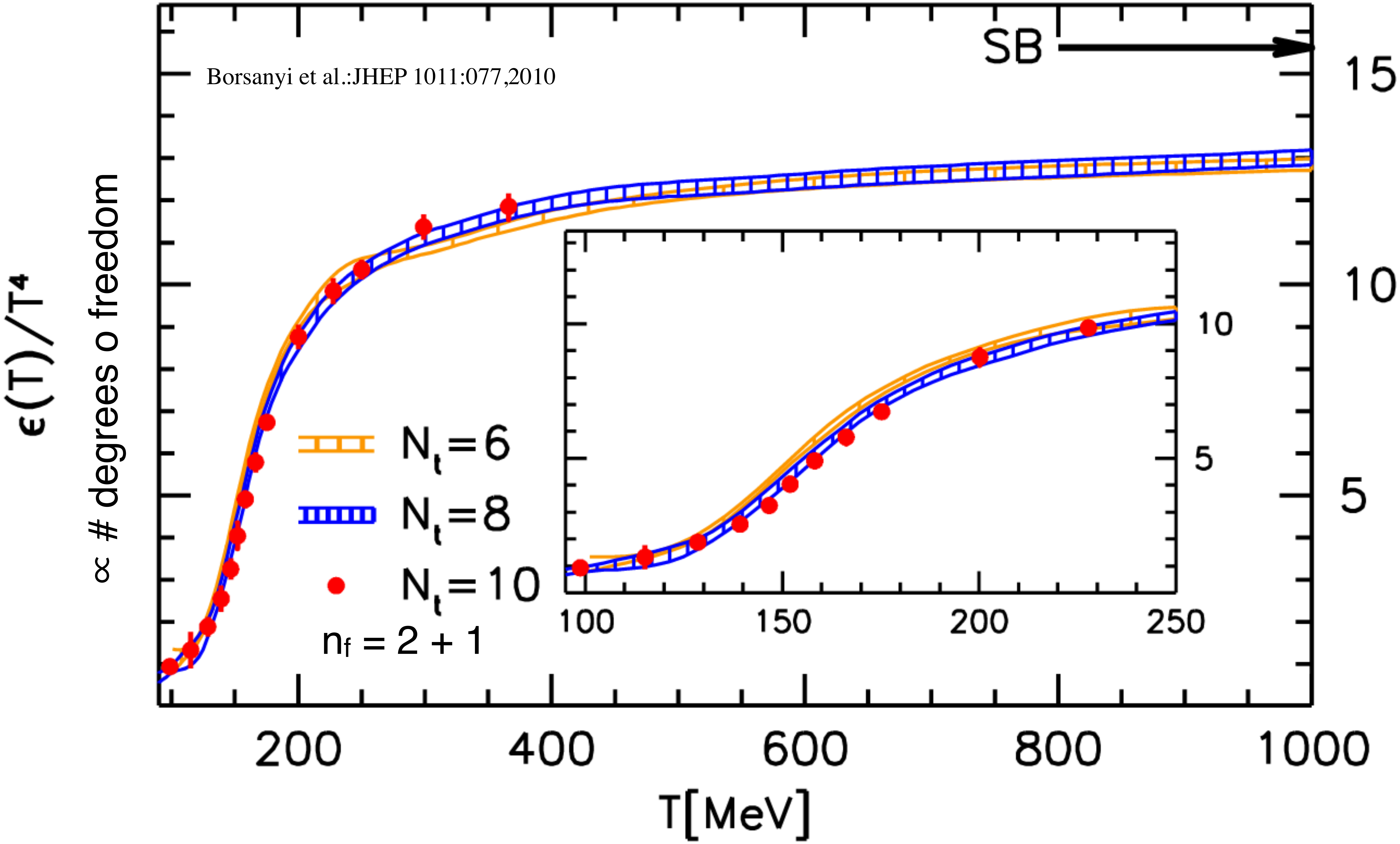

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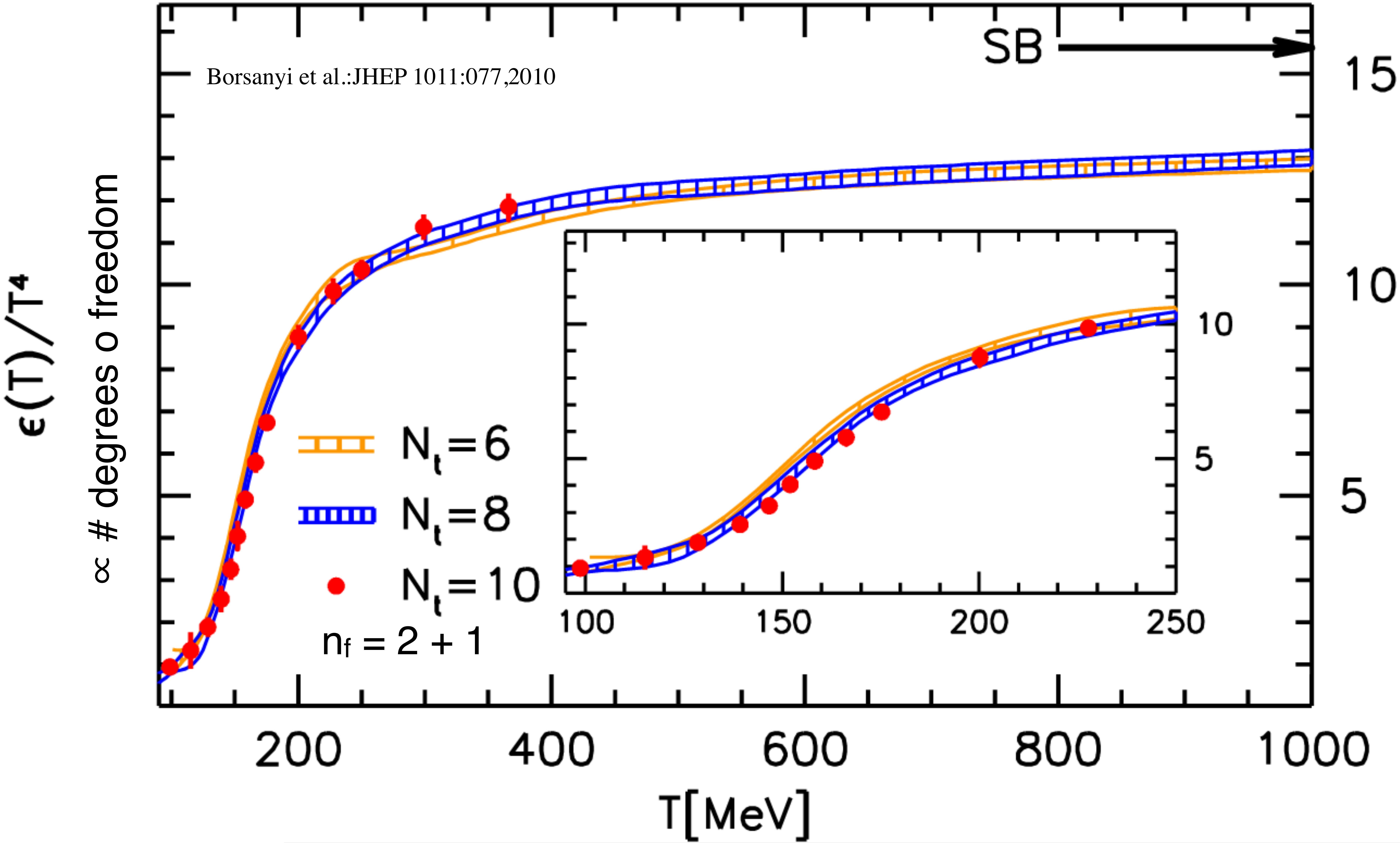
Borsanyi et al.:JHEP 1011:077,2010

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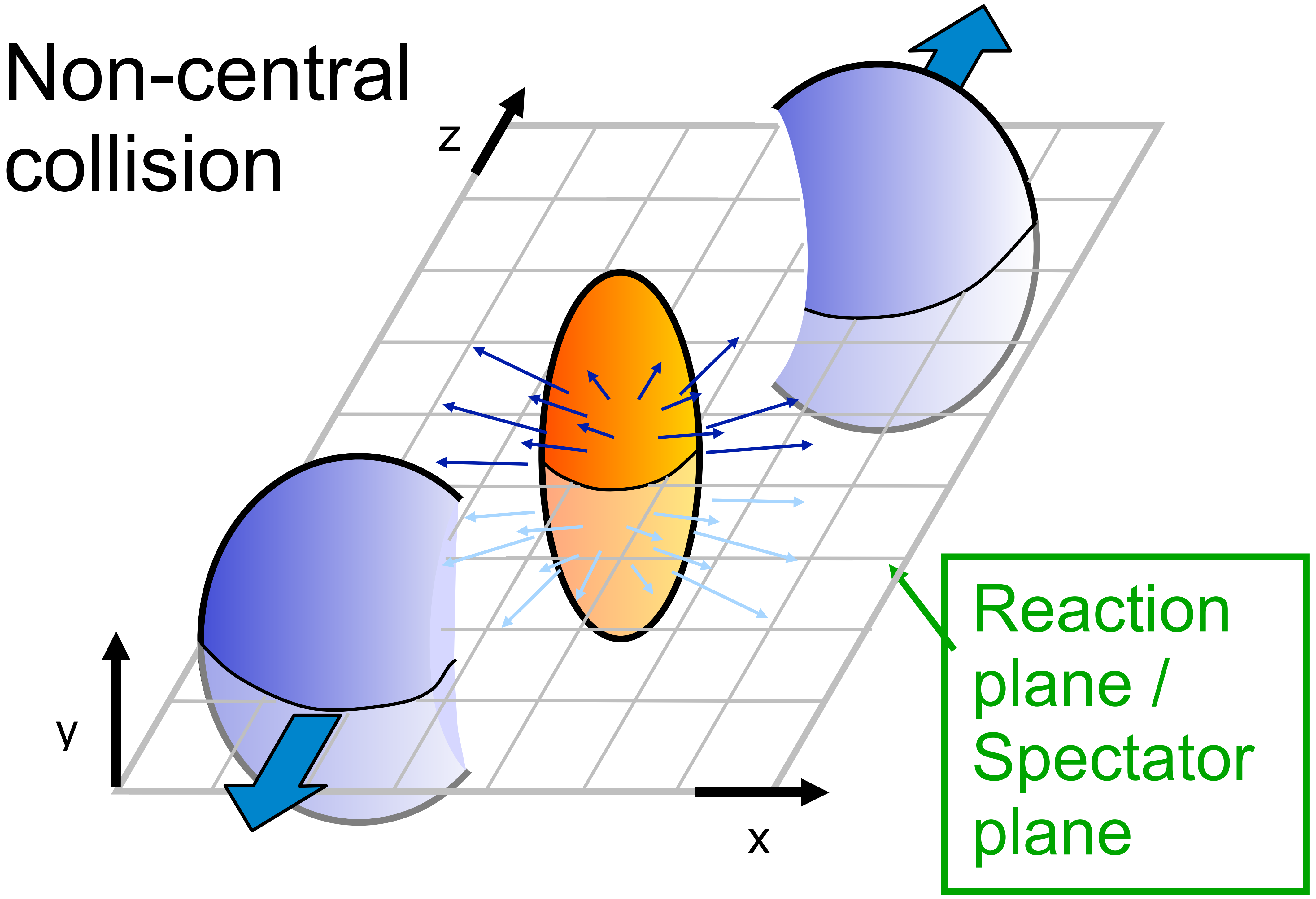
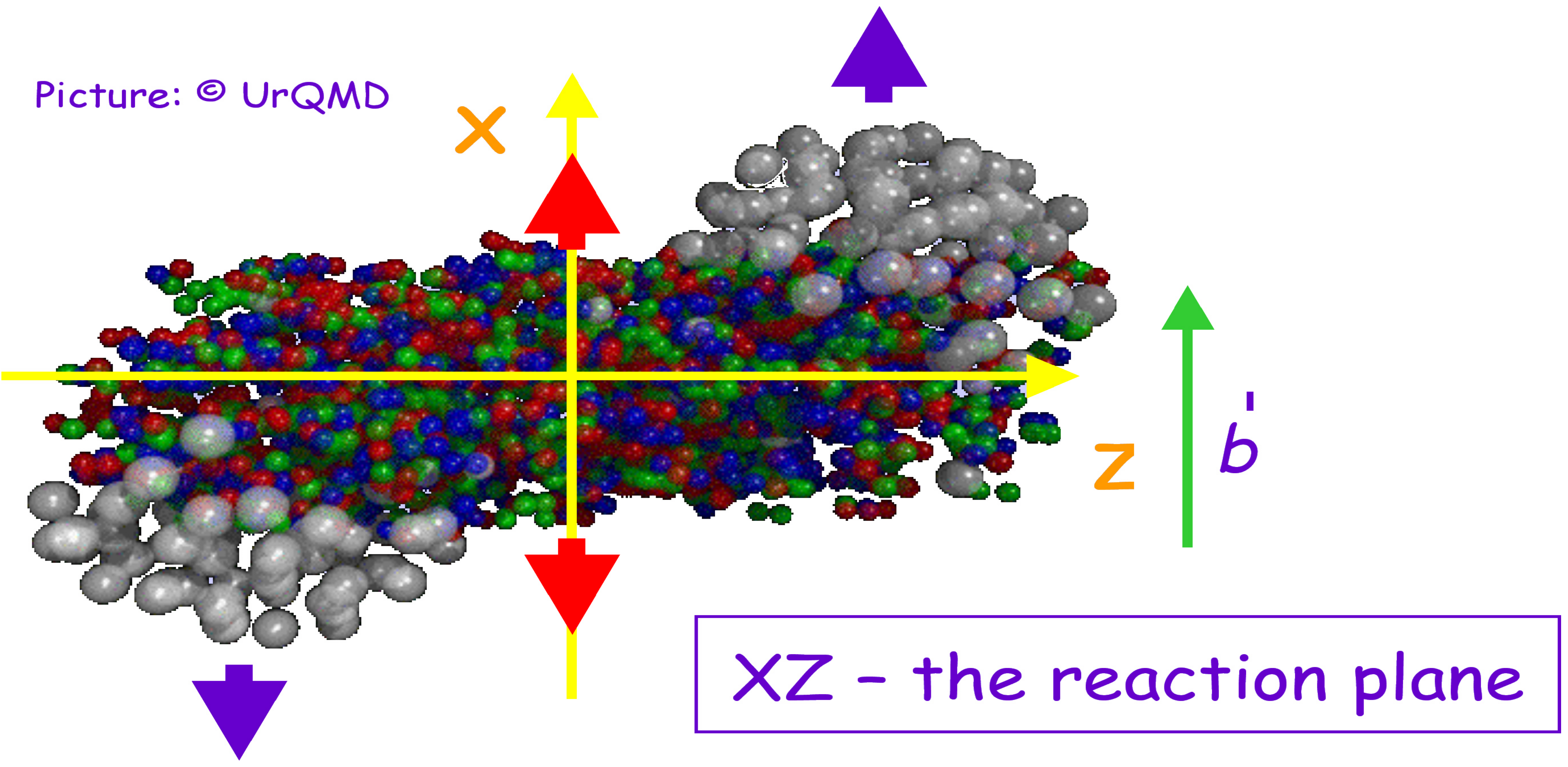
$\varepsilon_{pc} \approx 0.70$ GeV/fm^3

Such conditions can be created in Heavy Ion collisions at RHIC and LHC

Terminology of a heavy-ion collision



Reaction plane / Spectator plane



XZ - the reaction plane

“<u>peripheral</u>” collision ($b \sim b_{max}$)

“<u>central</u>” collision ($b \sim 0$)

Number of participants (N_{part}):

number of incoming nucleons (participants) in overlap region

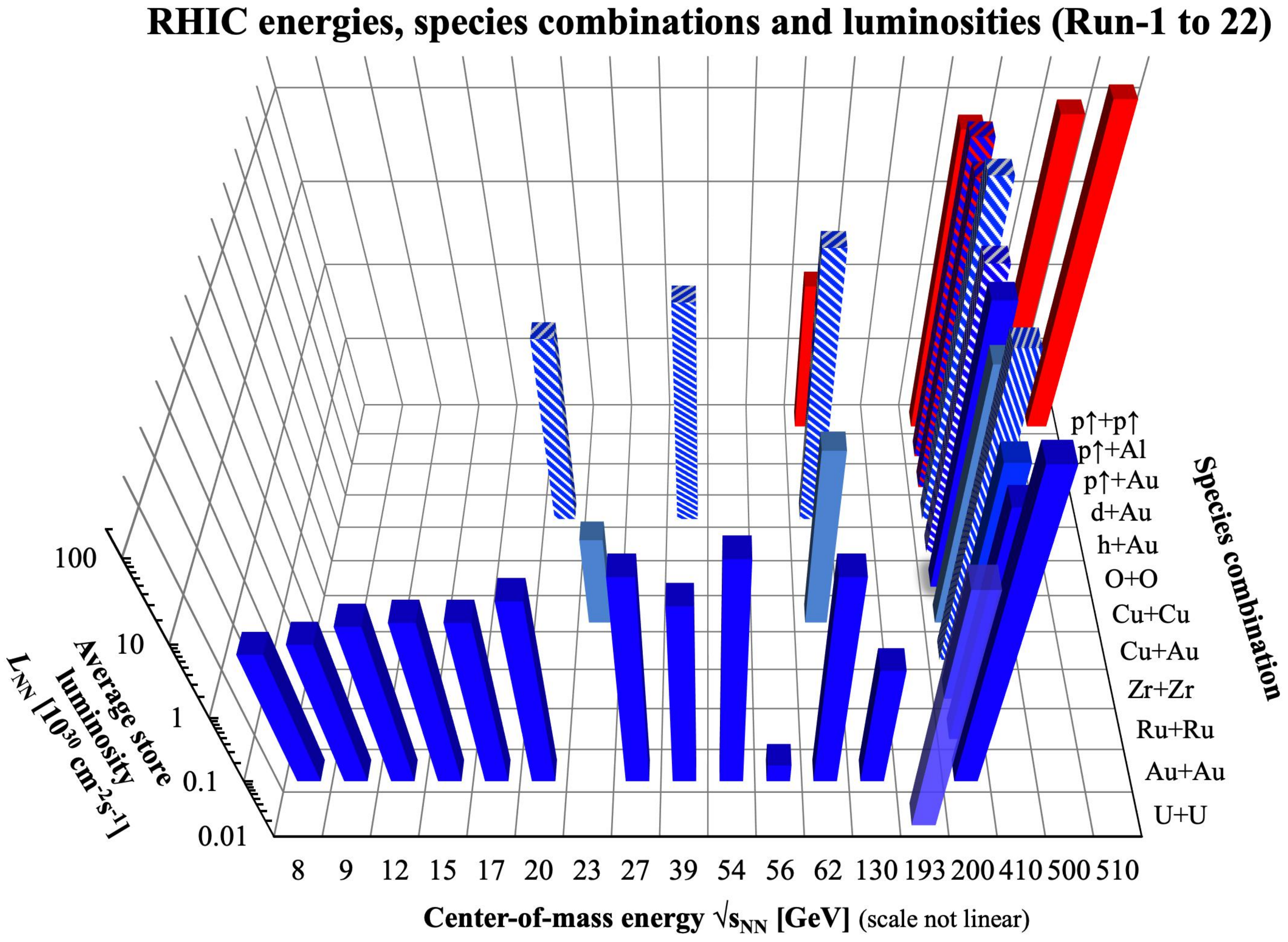
Number of binary collisions (N_{bin}):

number of equivalent inelastic nucleon-nucleon collisions

$N_{bin} \geq N_{part}$

More central collisions produce more particles

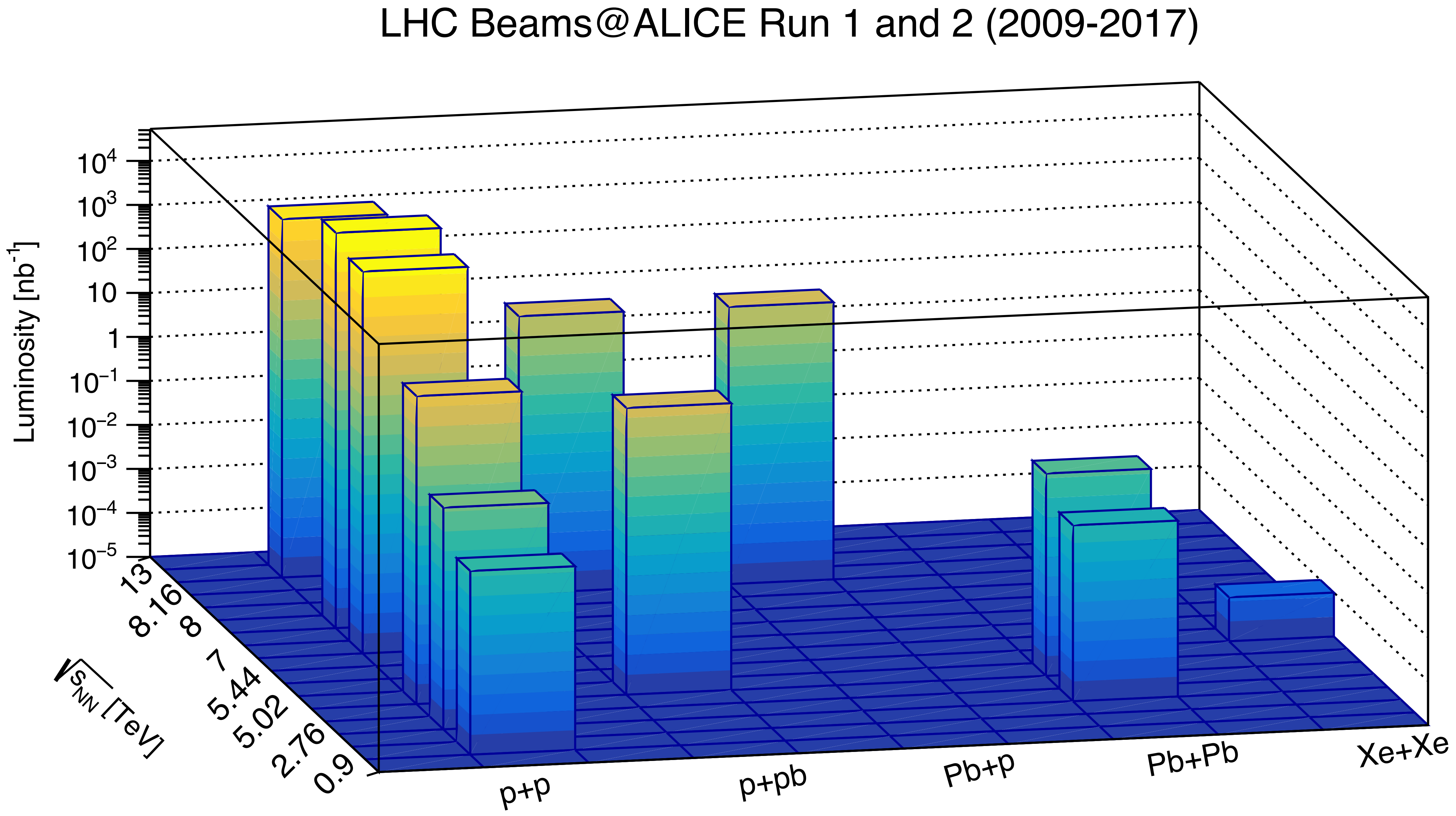
Wealth of data available



RHIC (beam energy scan, different nuclei):

U+U, Au+Au, Ru+Ru, Zr+Zr, Cu+Cu, O+O, Cu+Au, He^3+Au, d+Au, p+Au, p+Al, p+p

Mostly at 200 GeV but Au+Au from 3-200 GeV



LHC (top energy, rare probes):

Pb+Pb, Xe+Xe, p+Pb, p+p

For Pb+Pb mostly at 5.02 TeV

HUGE datasets

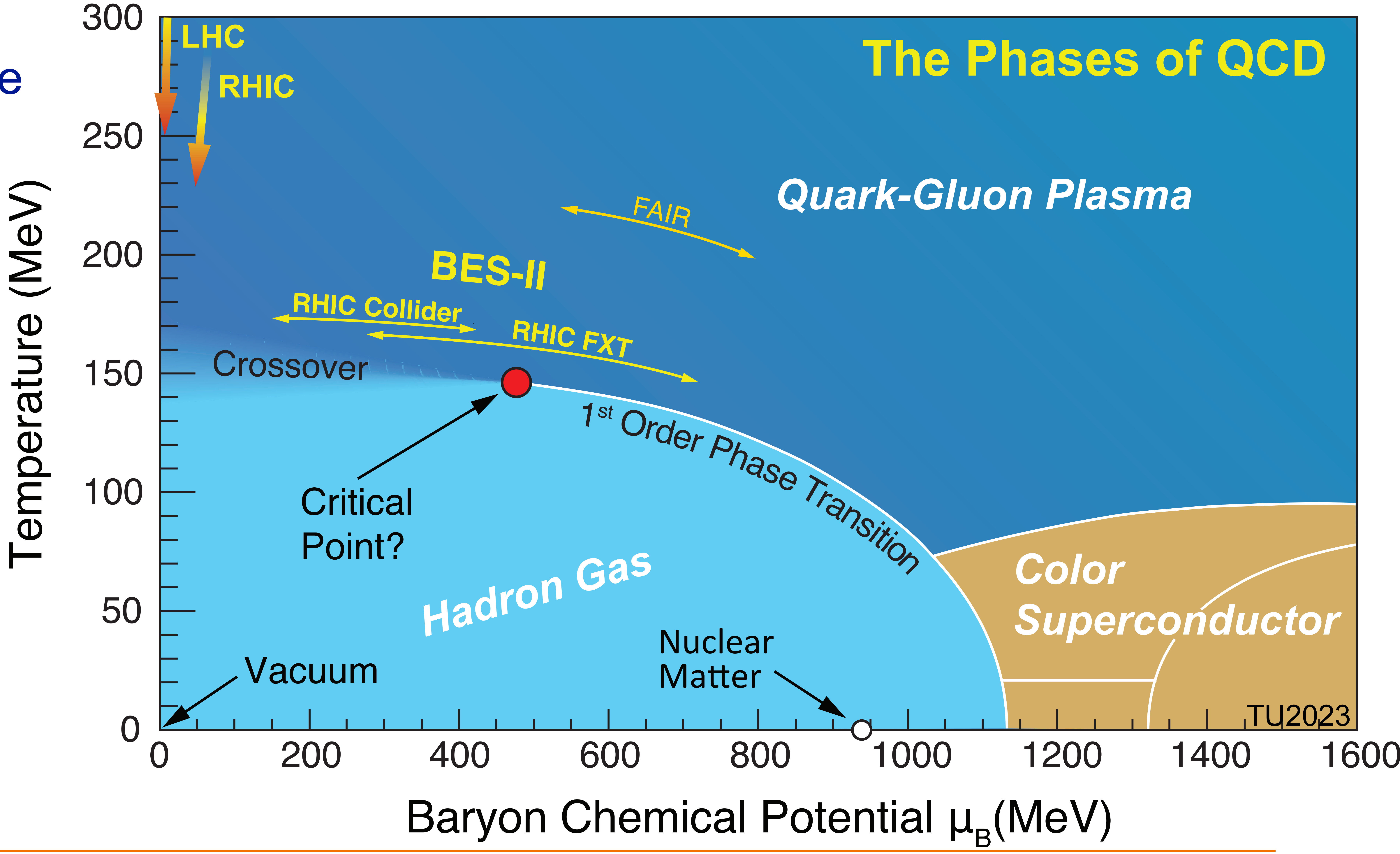
(significantly bigger at ATLAS and CMS)

Complimentary datasets

The phase diagram of QCD

Cross-over at low μ_B

Very hard to extrapolate off $\mu_B = 0$ axis



The phase diagram of QCD

Cross-over at low μ_B

Very hard to extrapolate off $\mu_B = 0$ axis

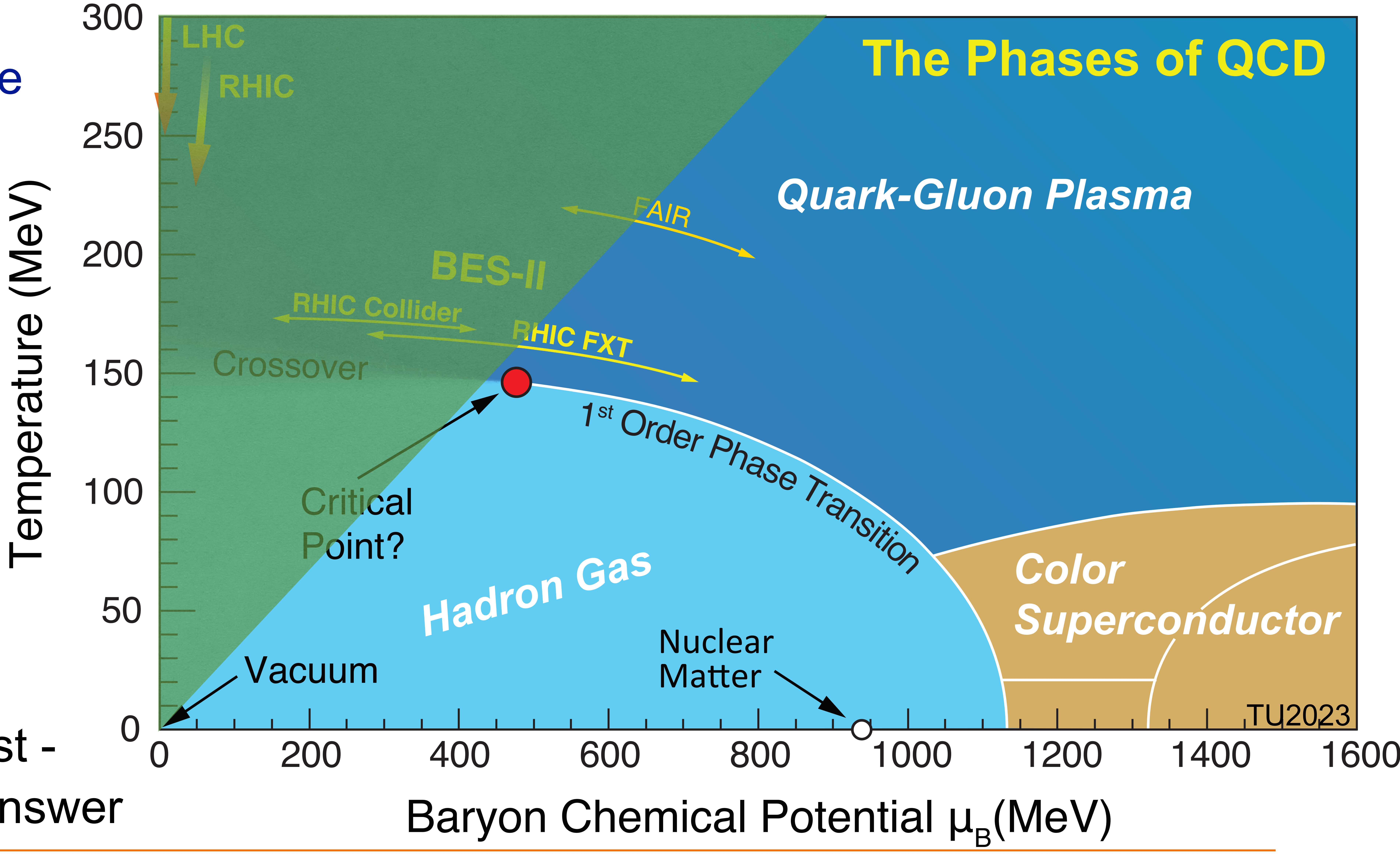
Disfavor QCD critical point at $\mu_B/T < 3$

Several calculations settling on CP at

T~90-100 MeV
μ_B~500-600 MeV

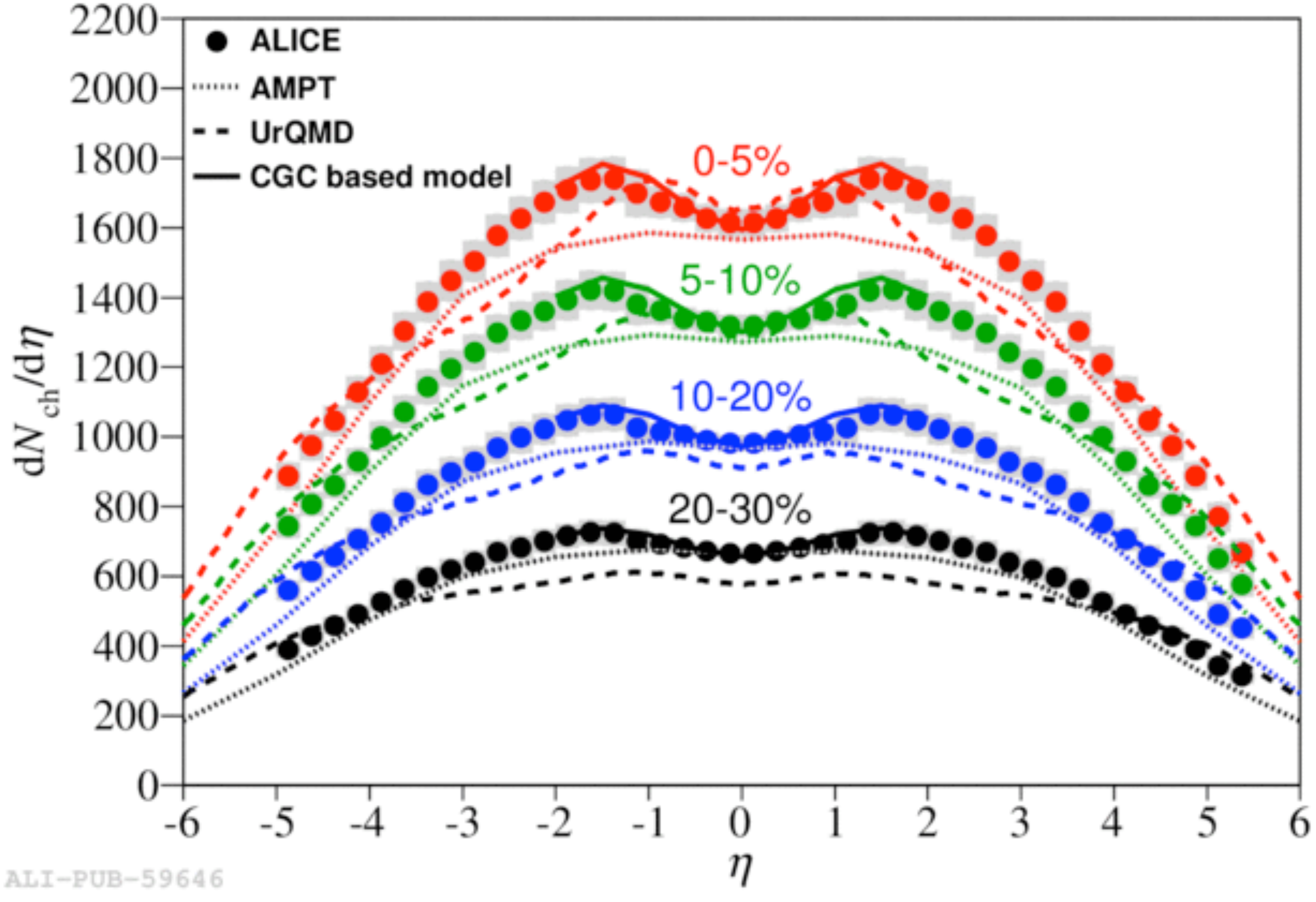
$\sqrt{s_{NN}}$ = 3-5 GeV

CP might also not exist - needs experimental answer



Do we create the necessary initial conditions?

Energy density in central collisions



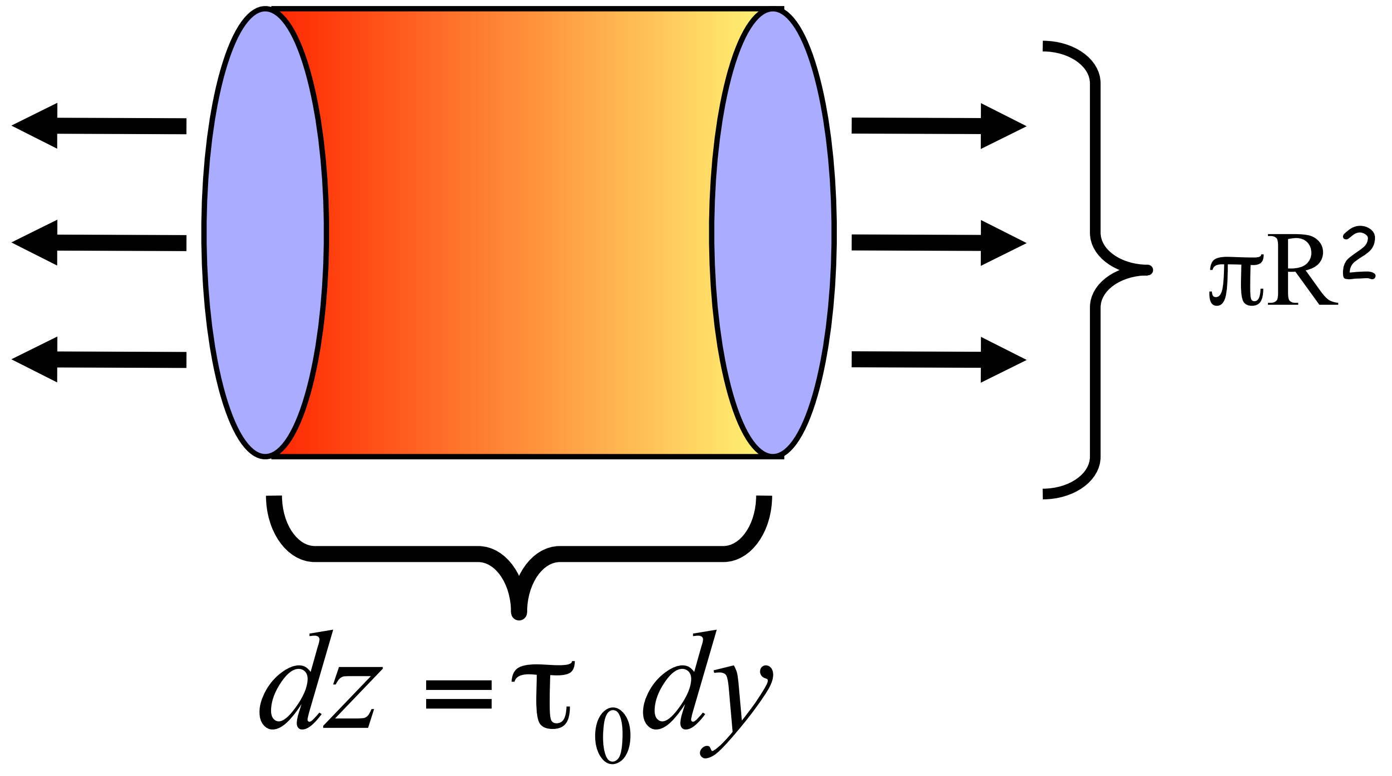
Bjorken-Formula for Energy Density:

$$\epsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{3}{2} \frac{dN_{ch}}{d\eta} \langle p_T \rangle$$

Radius of medium

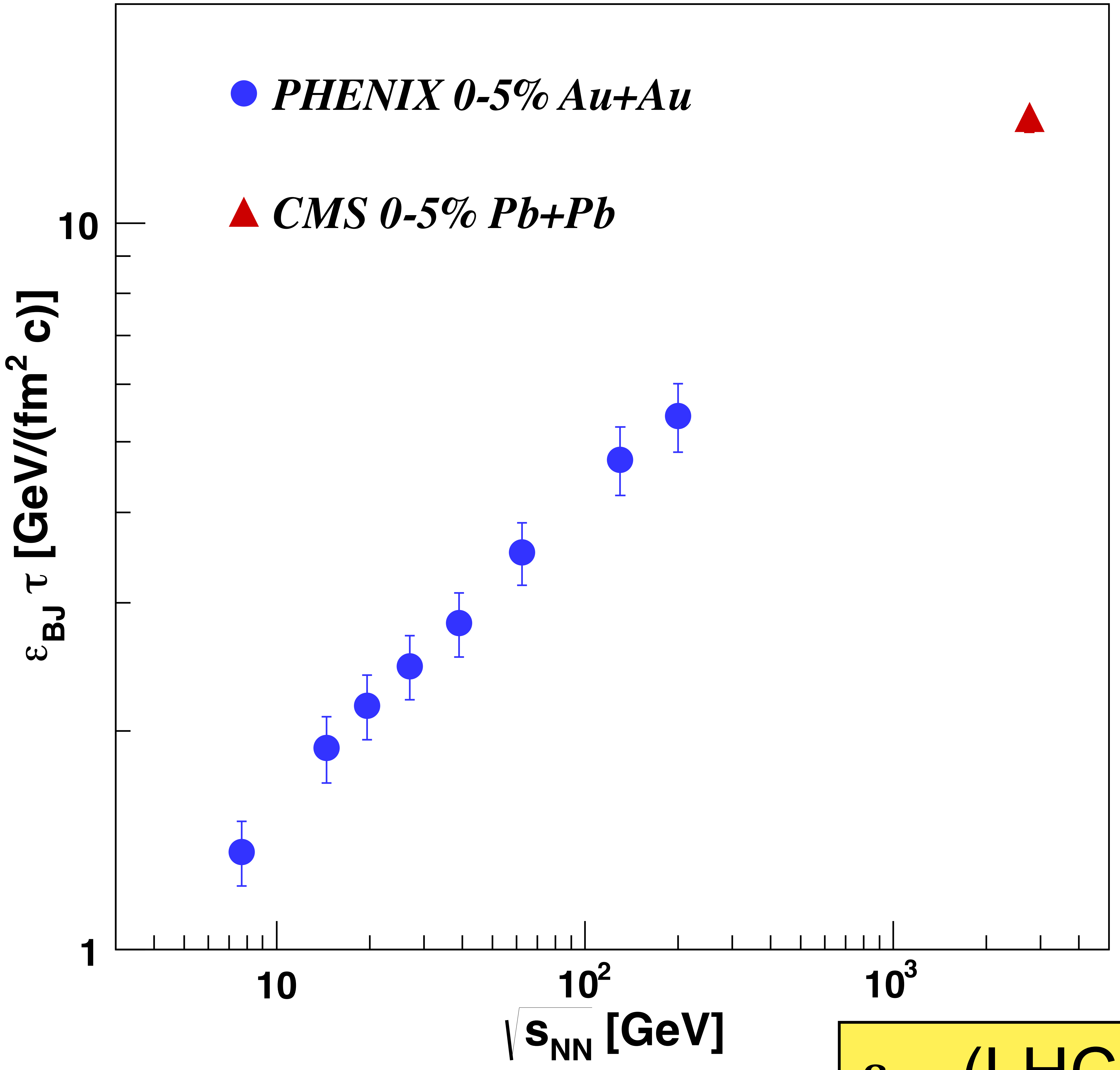
R~7 fm

Time it takes to thermalize system



ALICE: PLB 726, 610 (2013),

Energy density in central collisions



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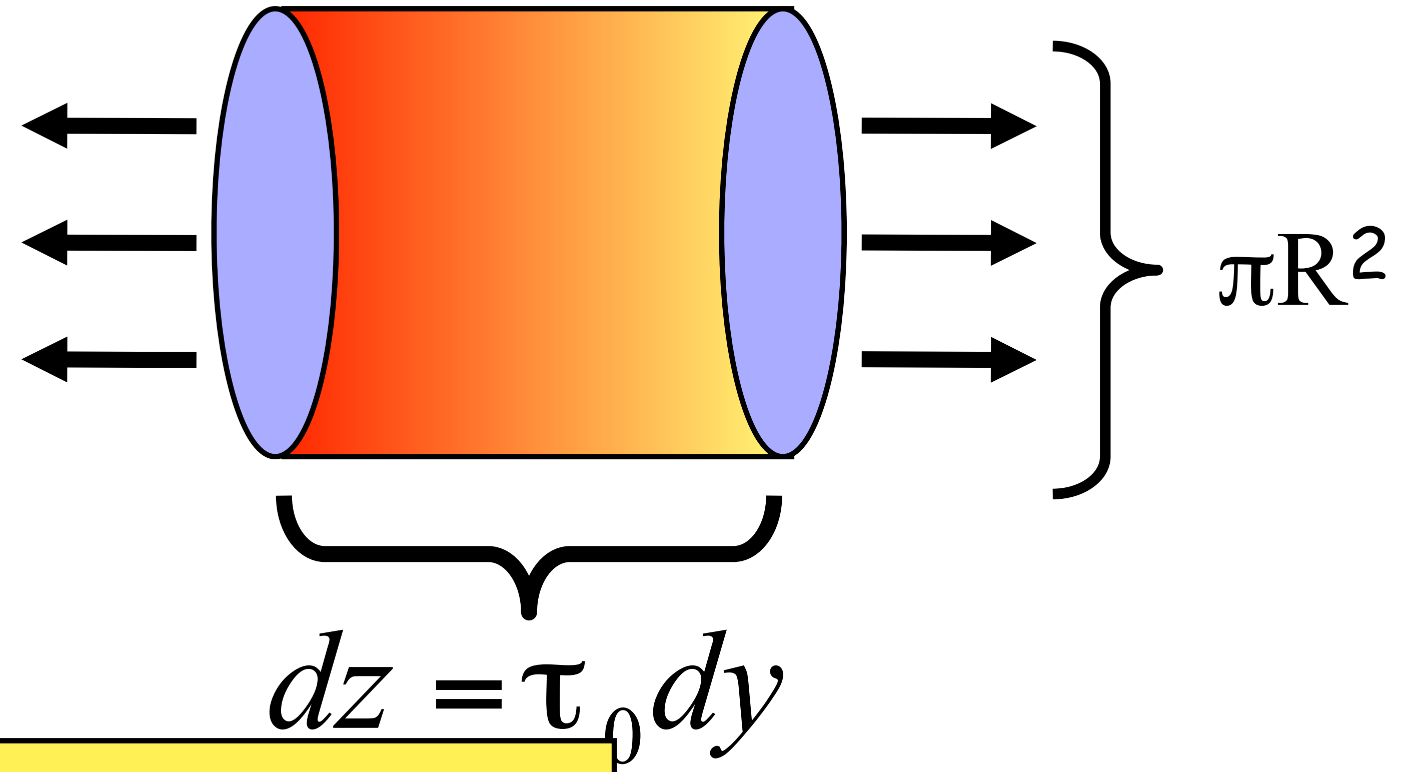

$\langle p_T\rangle$ ~ 650 MeV

τ_0 ~ 1fm

ε_{BJ} (LHC) ≈ 10 GeV/fm^3
~75 times normal nuclear density
~ 15 times > $\varepsilon_{critical}$ (lattice QCD)

ALICE: PLB 726, 610 (2013), PHENIX: PRC 93, 024901 (2016)

10 GeV/fm^3. Is that a lot?

In a year, U.S.A (known energy hog) uses ~100 quadrillion BTUs of energy (1 BTU raises 1 lb water 1° F = 1 burnt match = 1,055 J). What size cube would you need to pack this energy into to produce equivalent energy density?

A. A cube ~1 m high by 100 367 km^2 (approximately the area of Lapland)?

B. A cube ~1 cm x ~30 cm x ~20 cm (approximately size of your laptop)

C. A cube ~1 mm x ~1 mm x ~0.1 mm (approximate size of snowflake)

D. A cube ~5 μm x ~5 μm x ~5 μm (smaller than cross-section of your hair)

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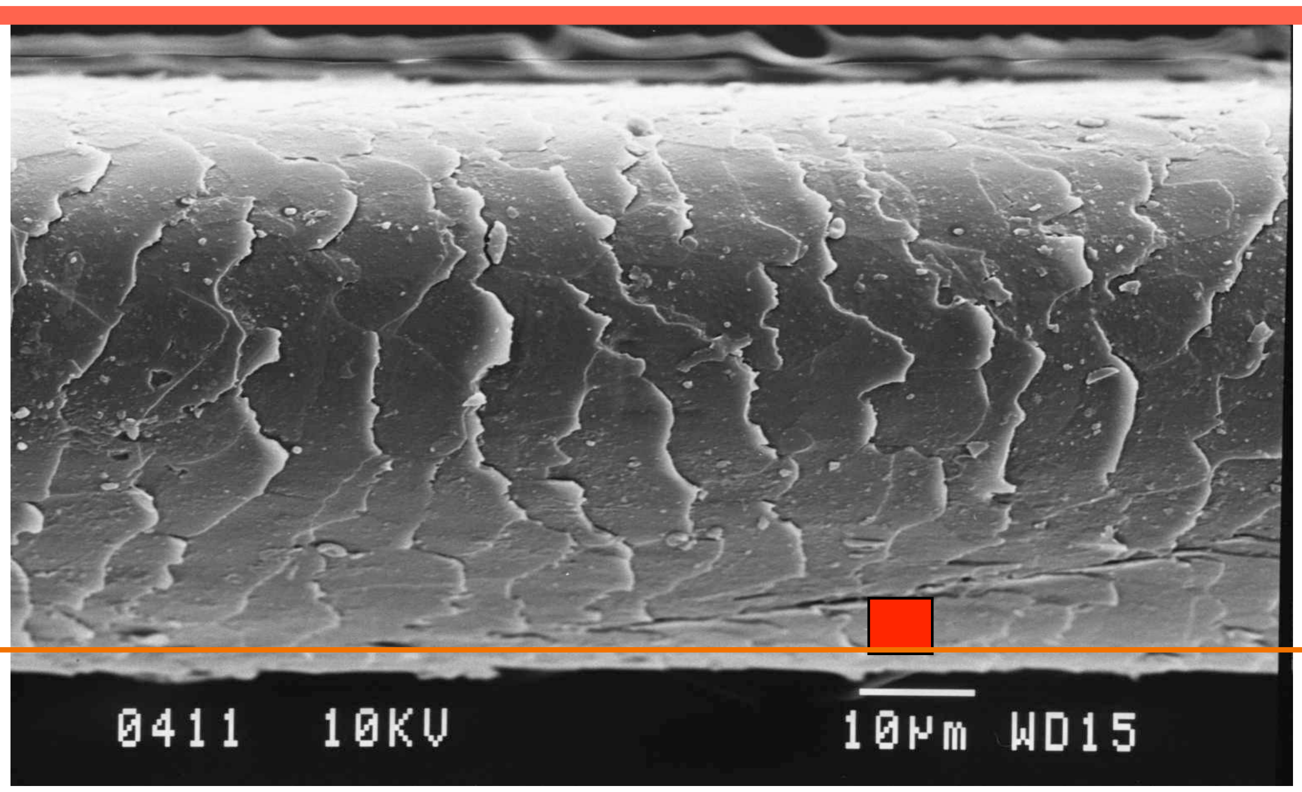

Temperature of chemical freeze-out

Number of particles of a given species related to temperature

$$dn_i \sim e^{-(E-\mu_B)/T} d^3p$$

Assume all particles described by same temperature T and μ_B

One ratio (e.g., $\bar{p}$ / p) determines μ_B /T :

$$\frac{\bar{p}}{p} = \frac{e^{-(E-\mu_B)/T}}{e^{-(E-\mu_B)/T}} = e^{-2\mu_B/T}$$

A second ratio (e.g., K / π) provides T → μ

$$\frac{K}{\pi} = \frac{e^{-E_K/T}}{e^{-E_\pi/T}} = e^{-(E_K-E\pi)/T}$$

Then all other hadronic ratios (and yields) defined

ALICE: arXiv:2211.04384

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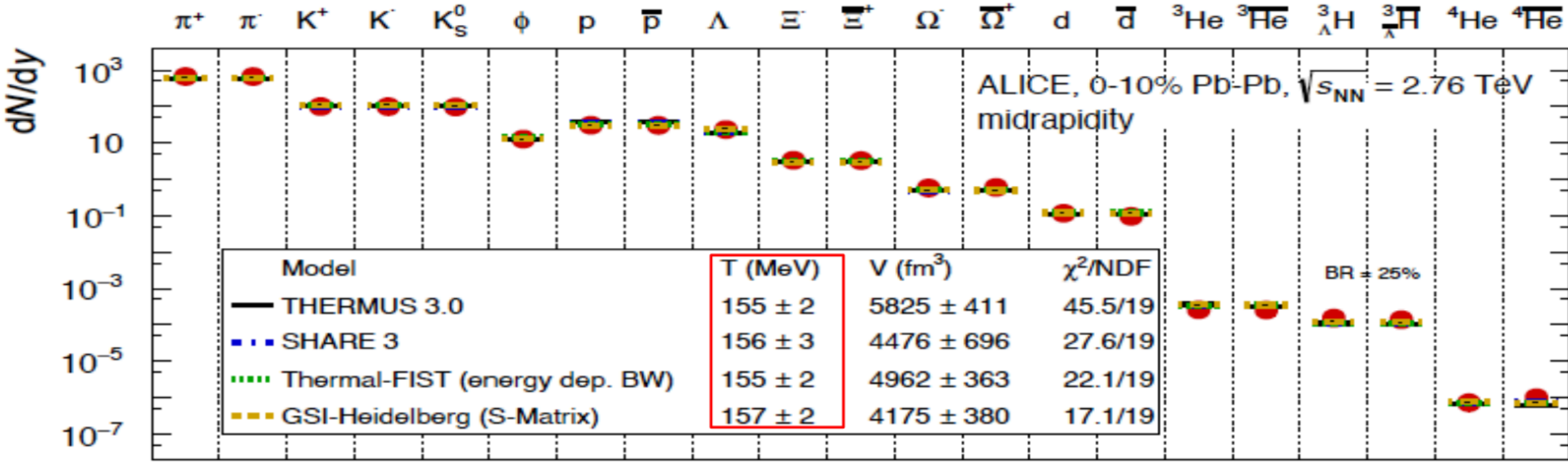


Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 3.0	155 ± 2	5825 ± 411	45.5/19
SHARE 3	156 ± 3	4476 ± 696	27.6/19
Thermal-FIST (energy dep. BW)	155 ± 2	4962 ± 363	22.1/19
GSI-Heidelberg (S-Matrix)	157 ± 2	4175 ± 380	17.1/19

Chemical Freeze-out temperature T_{ch} close to that of T_{pc} at top energies

But this is the T at which hadronic ratios are fixed.

What about initial T?

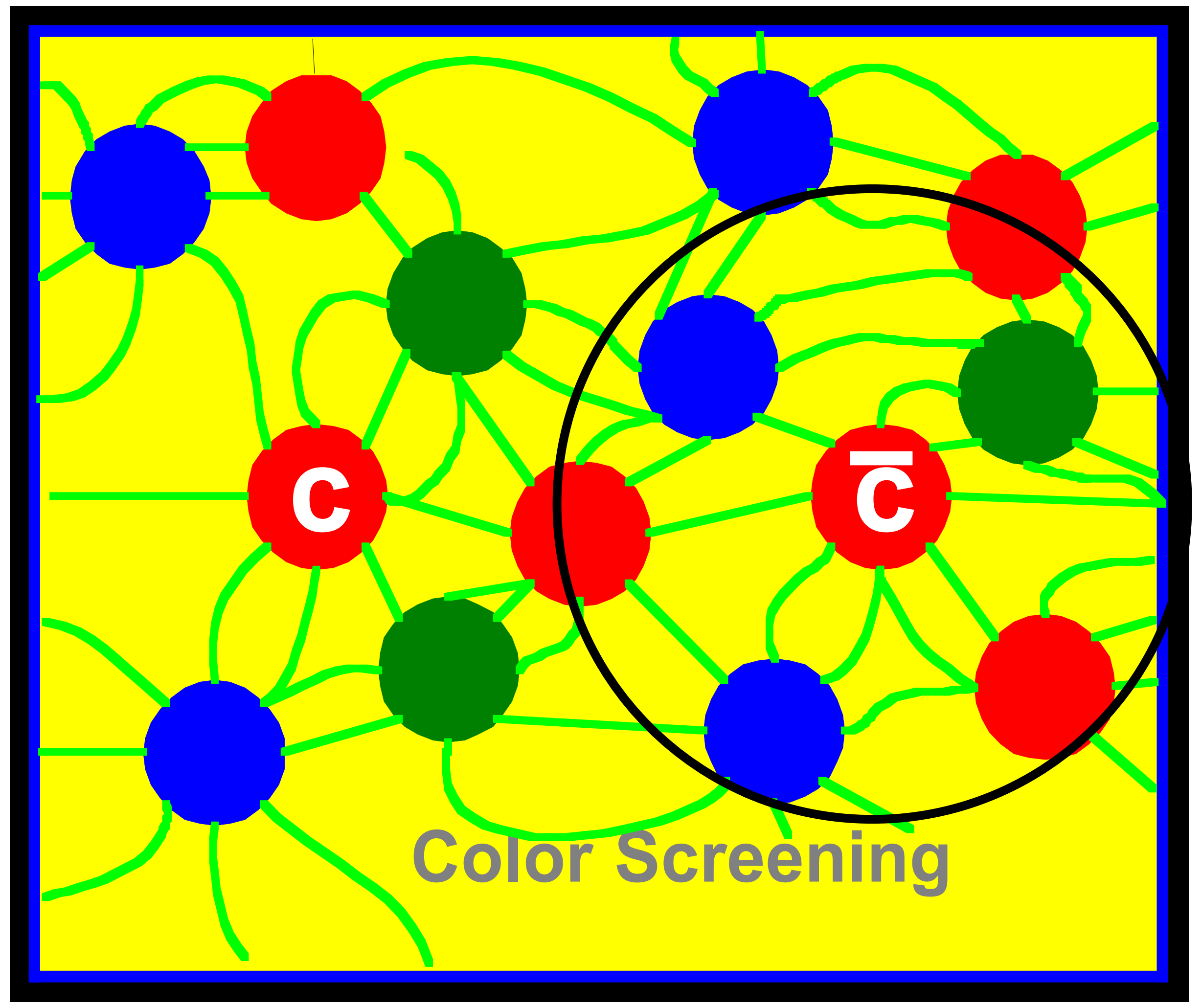
ALICE: arXiv:2211.04384

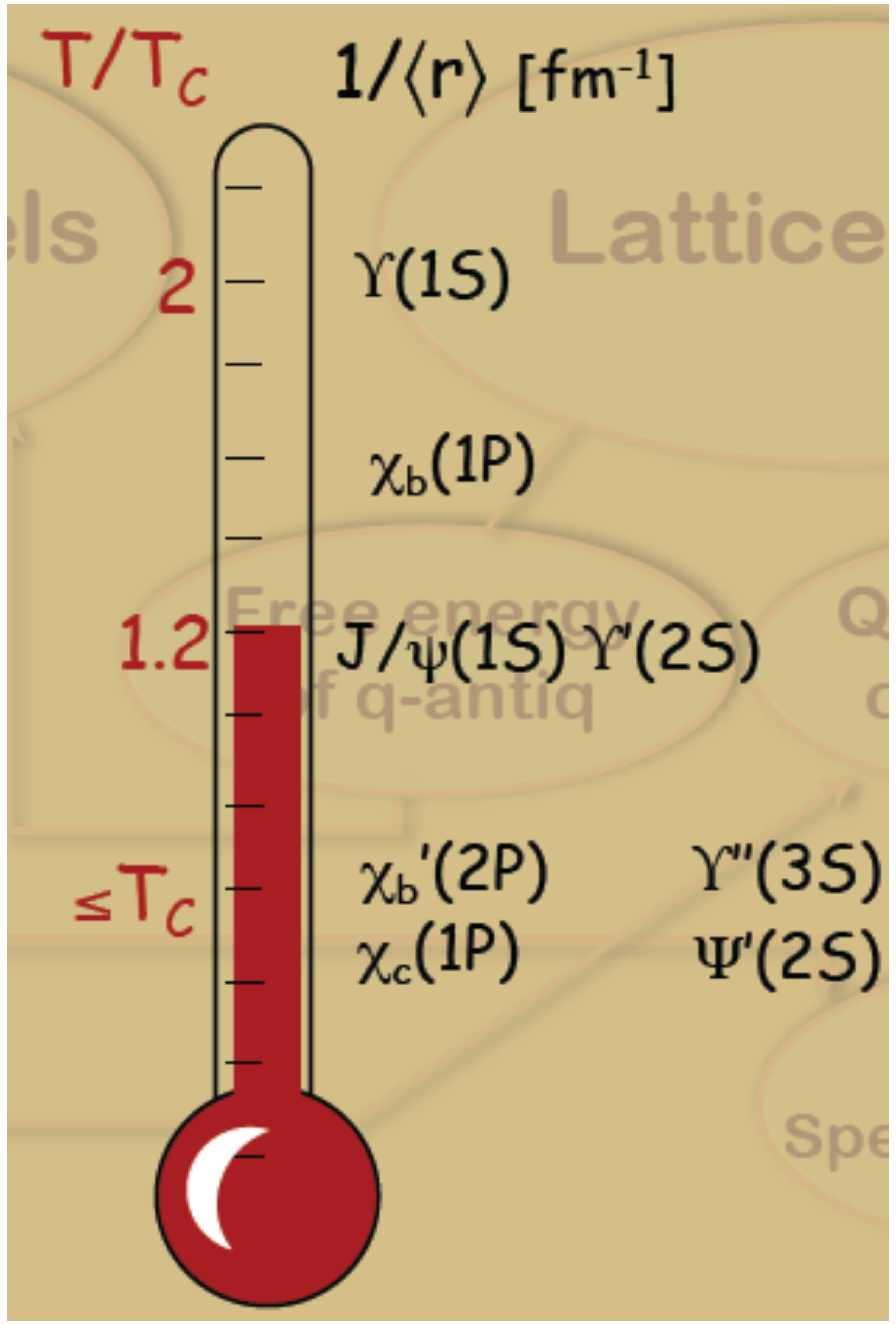
Quarkonia - QGP thermometers

Formed only in the very early stages of the collision due to their high masses

Color screening of static potential between heavy quarks

(Matsui and Satz, *PLB* **178** (1986) 416)





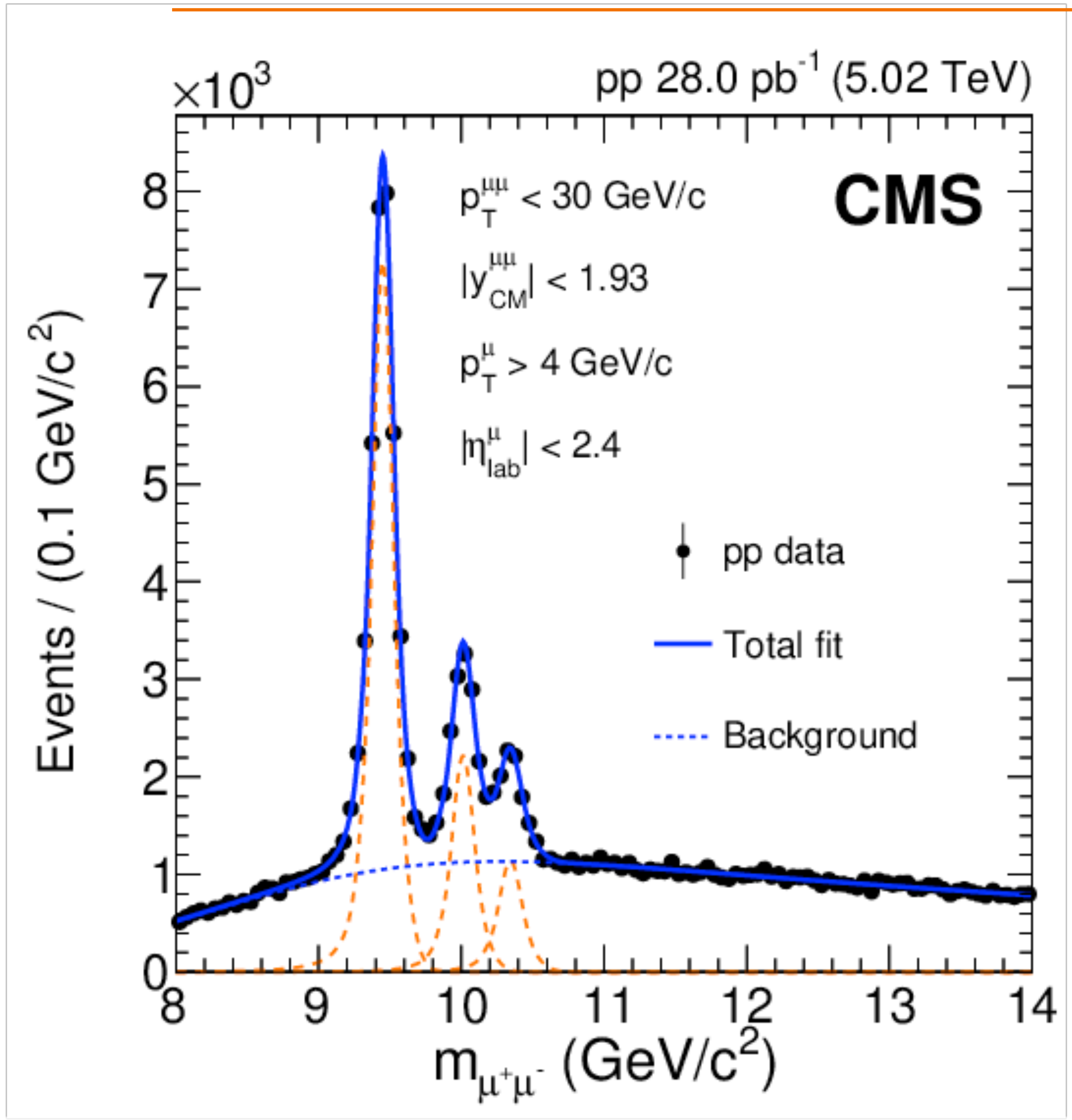
Charmonia: J/ψ, Ψ', χc

Bottomonia: ϒ(1S), ϒ(2S), ϒ(3S)

	$E_{binding}$ (GeV)
J/ψ	0.64
ψ'	0.05
χ_c	0.2
ϒ(1S)	1.1
ϒ(2S)	0.54
ϒ(3S)	0.31

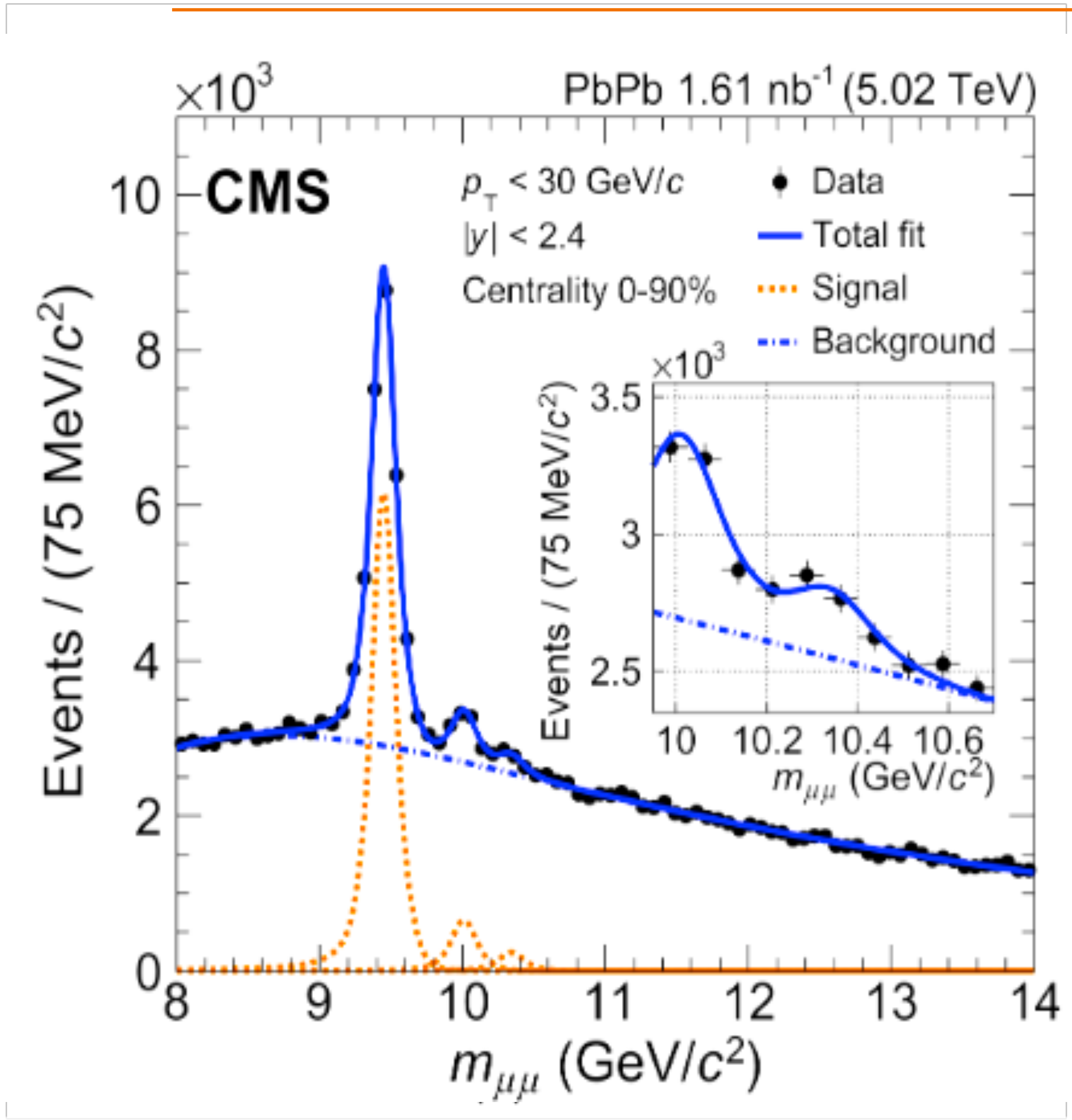
Suppression determined by T and binding energy

Sequential melting of quarkonia



CMS: PRL 109 (2012) 222301, PLB 835 (2022) 137397, STAR: PRL 130 (2023) 11230

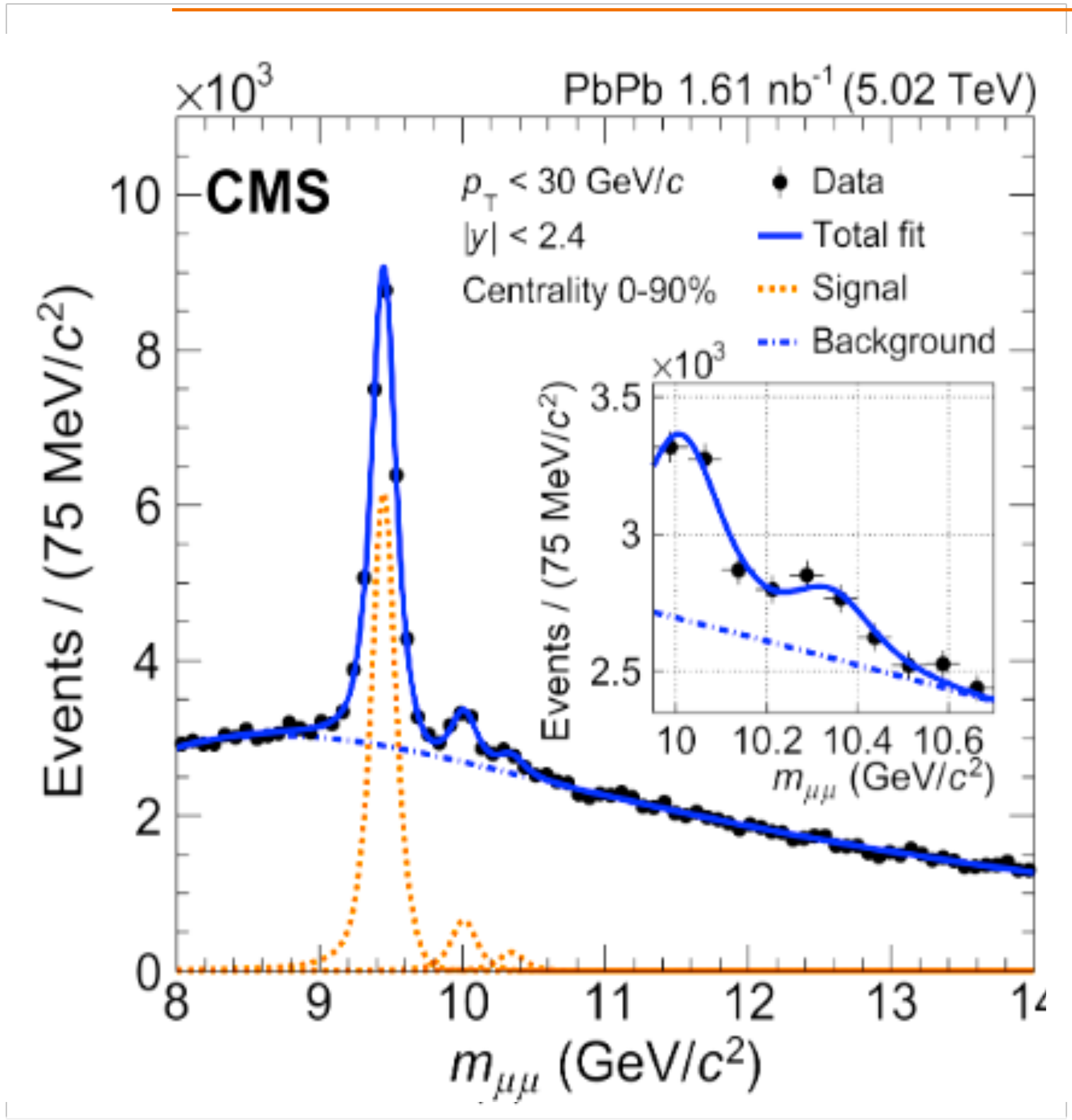
Sequential melting of quarkonia

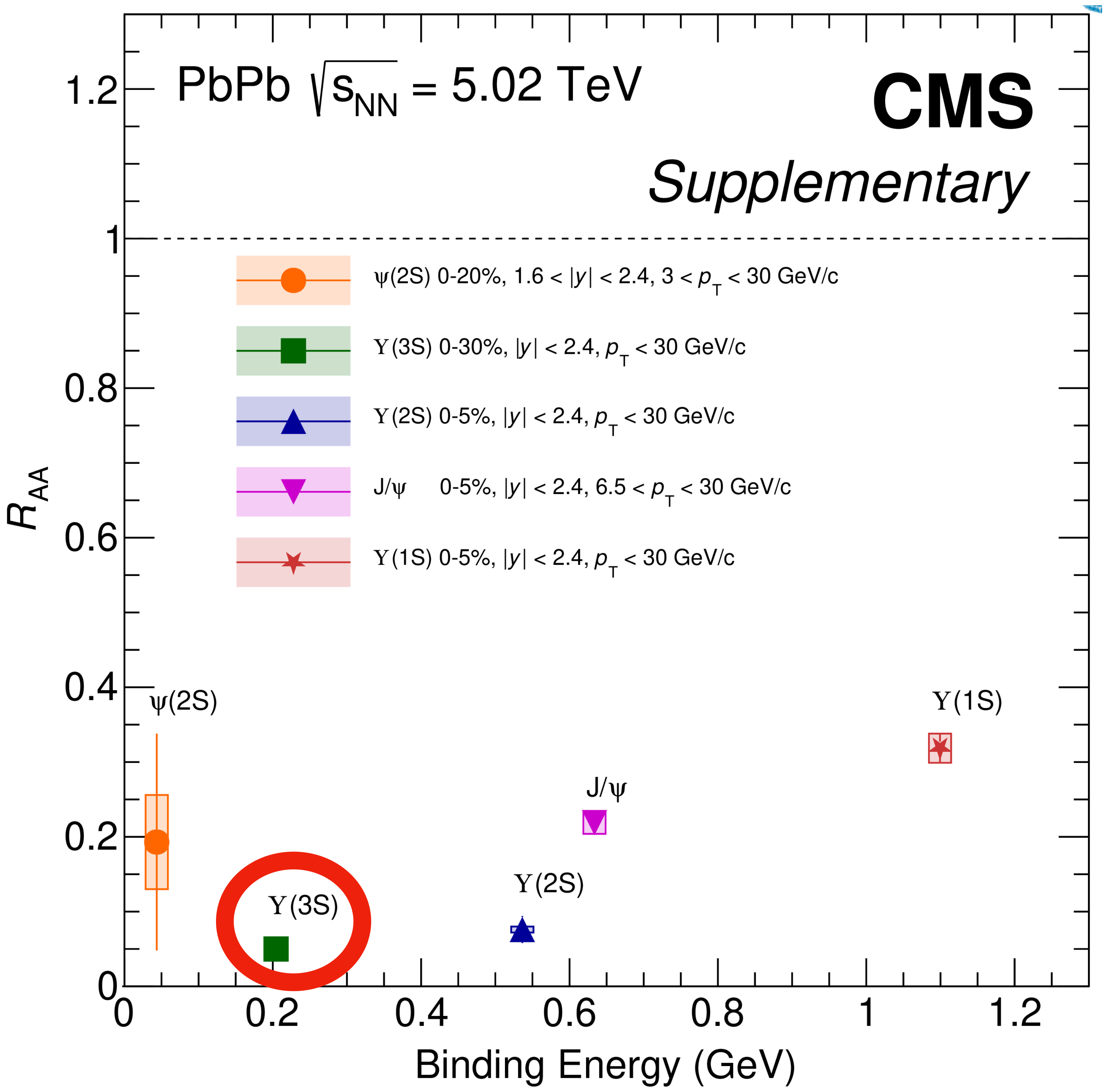


Lightly bound states almost completely gone
Tightly bound states have mostly melted at LHC energies

CMS: PRL 109 (2012) 222301, PLB 835 (2022) 137397, STAR: PRL 130 (2023) 11230

Sequential melting of quarkonia





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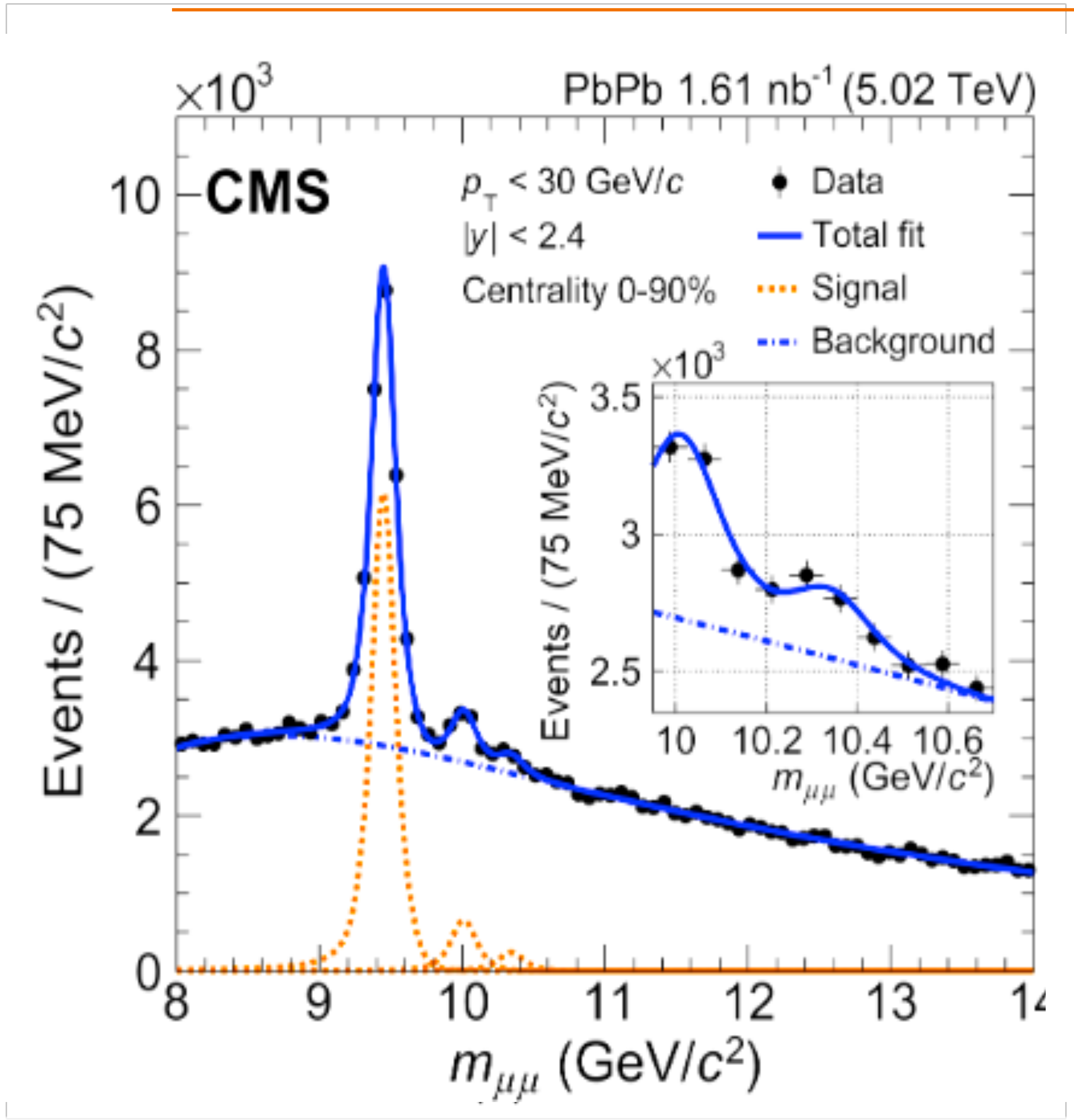
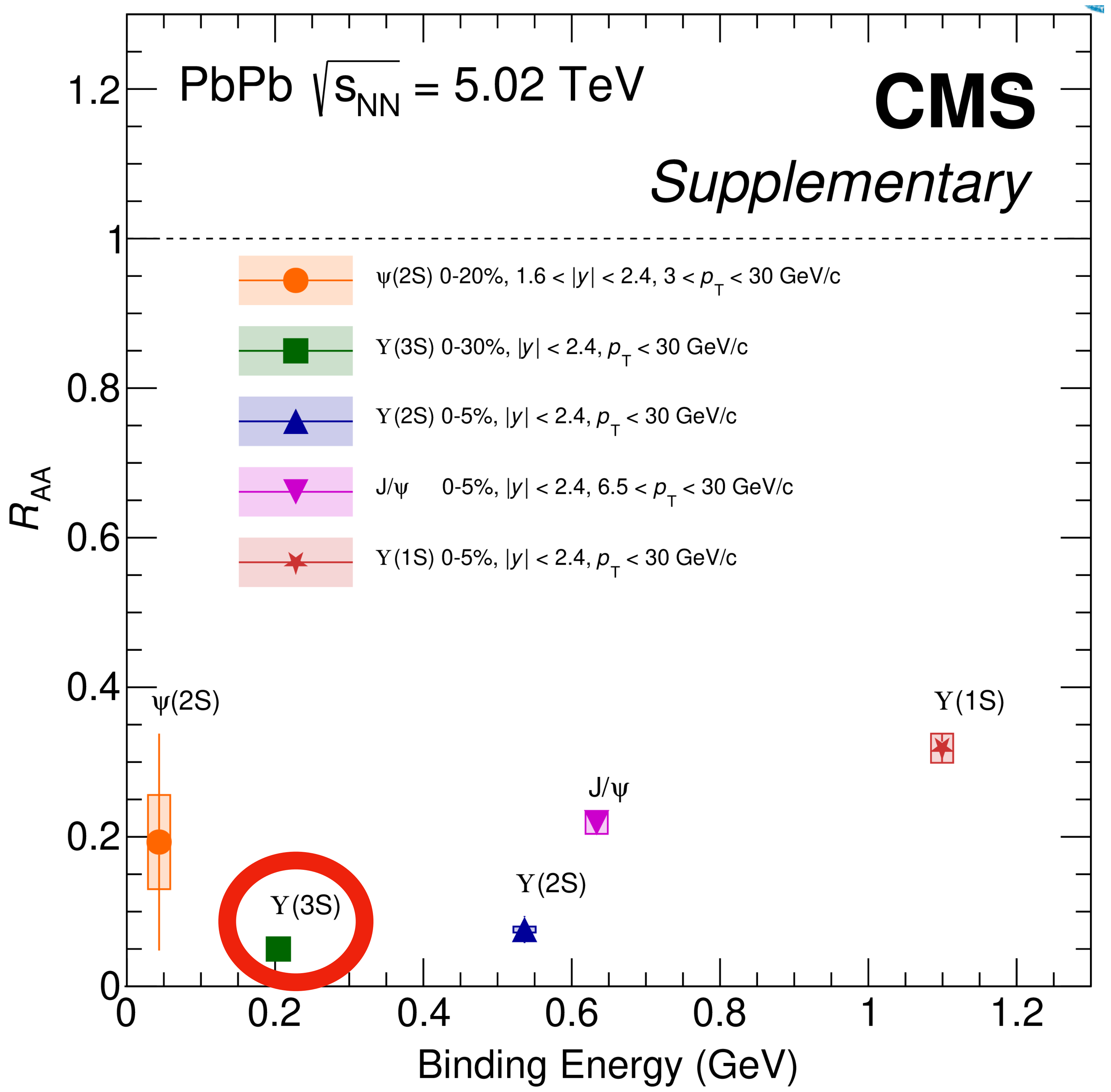
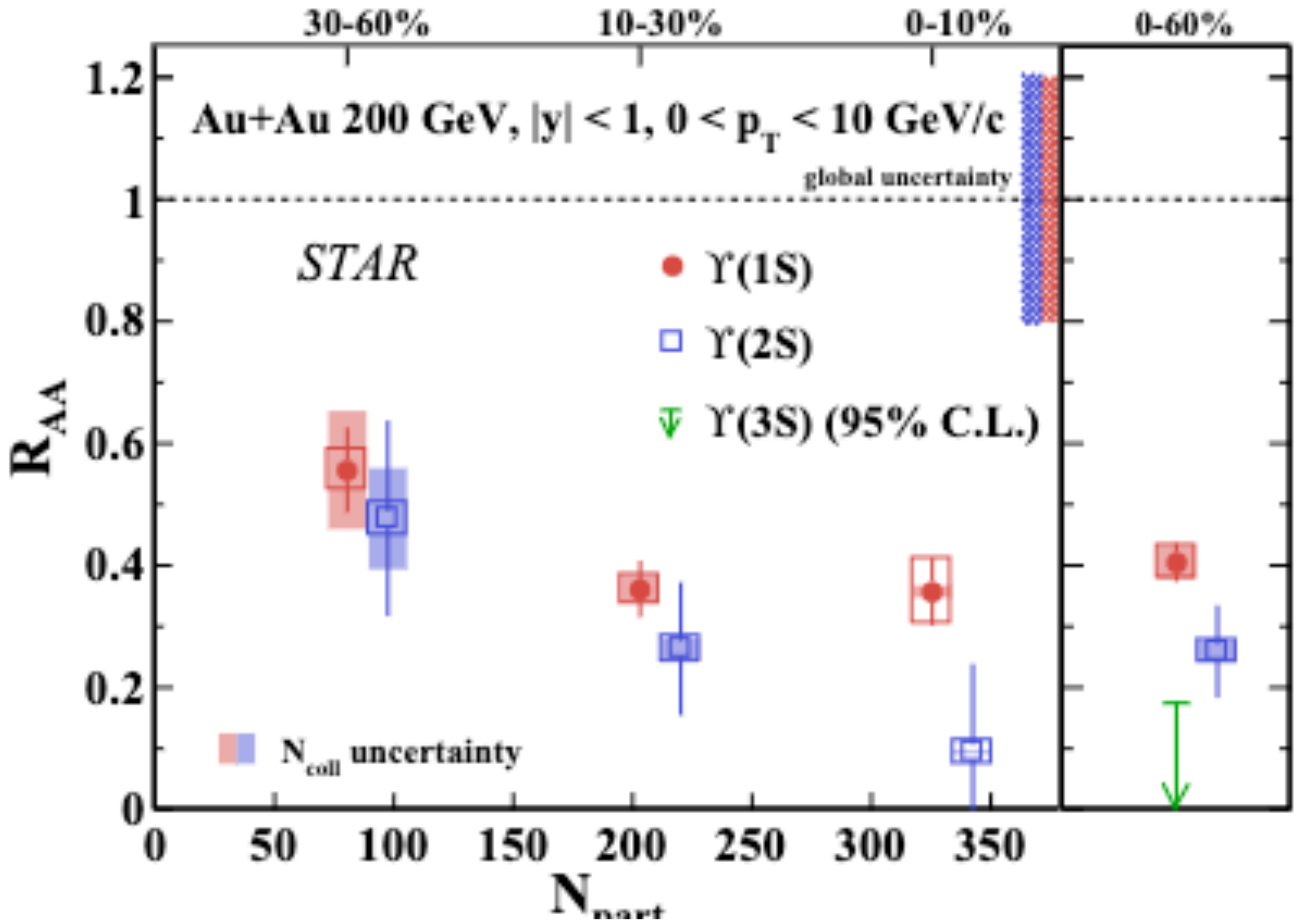






Lightly bound states almost completely gone

Tightly bound states have mostly melted at LHC energies

and top RHIC

T > 1.5 T_c ~ 300 MeV

CMS: PRL 109 (2012) 222301, PLB 835 (2022) 137397, STAR: PRL 130 (2023) 11230

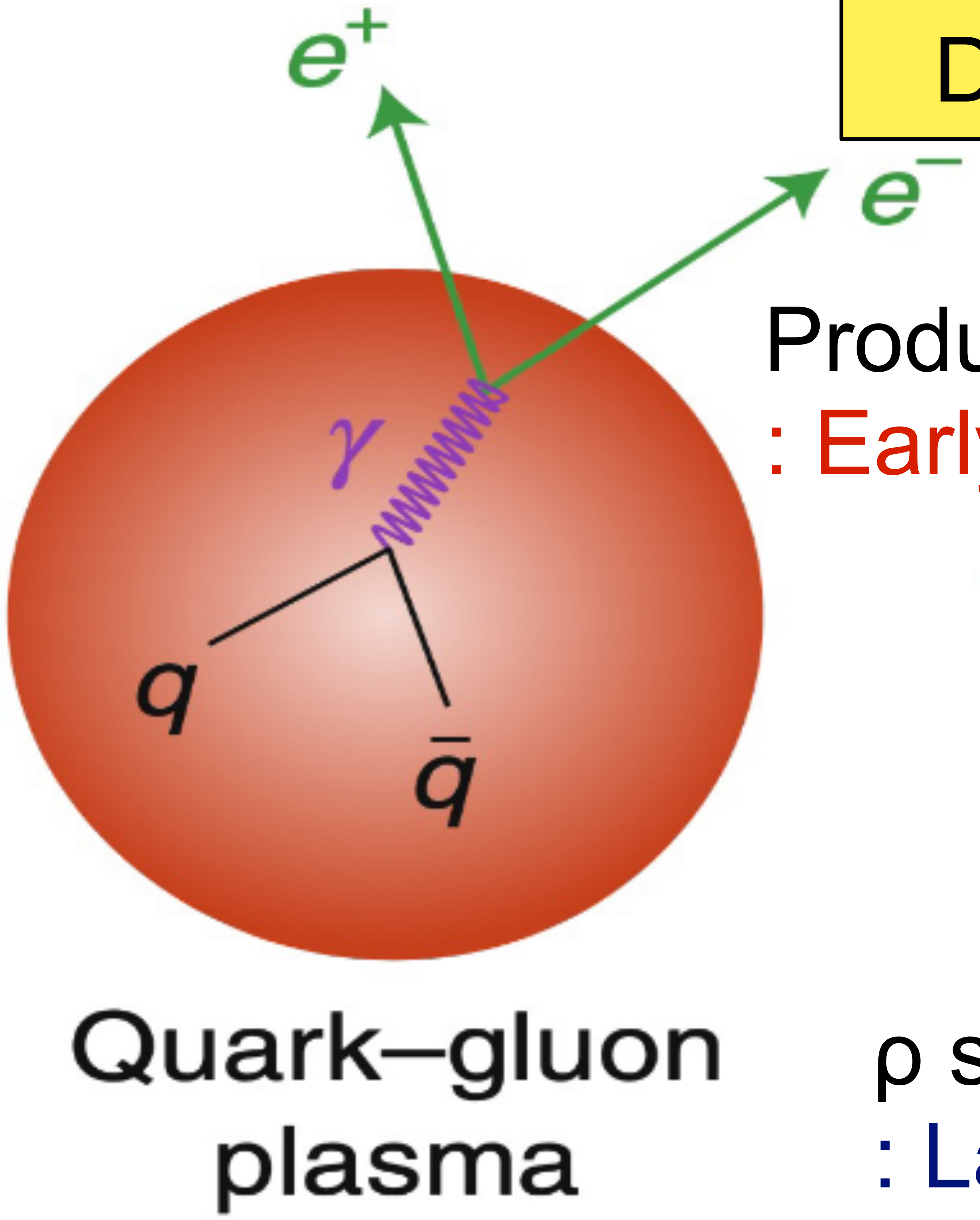
Extracting the initial T: non-interacting probe

Di-leptons probe medium over its whole evolution.

Escape medium without interacting (no color charge)

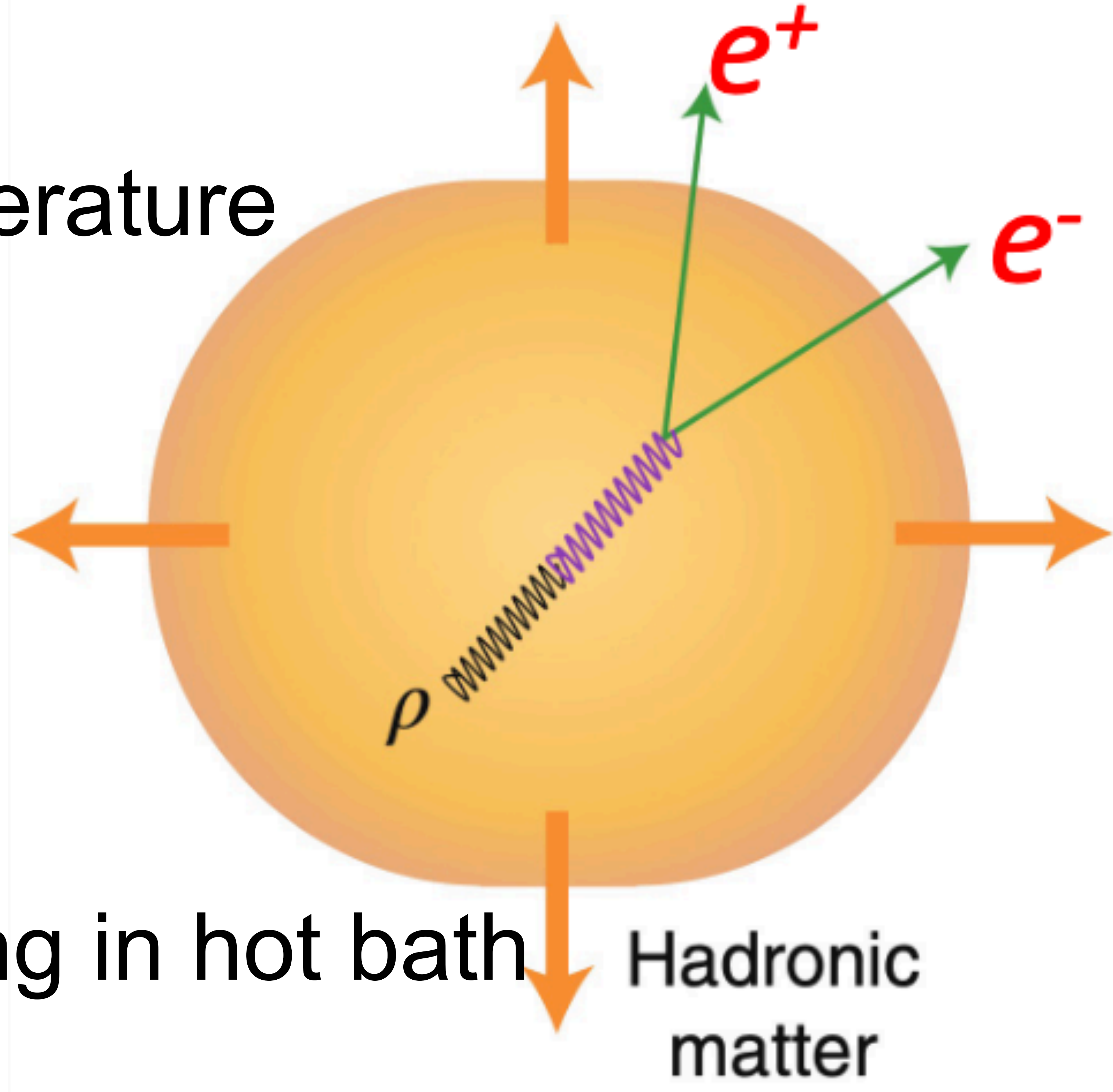
Two for the price of one:

Different di-lepton invariant mass ranges probe different times

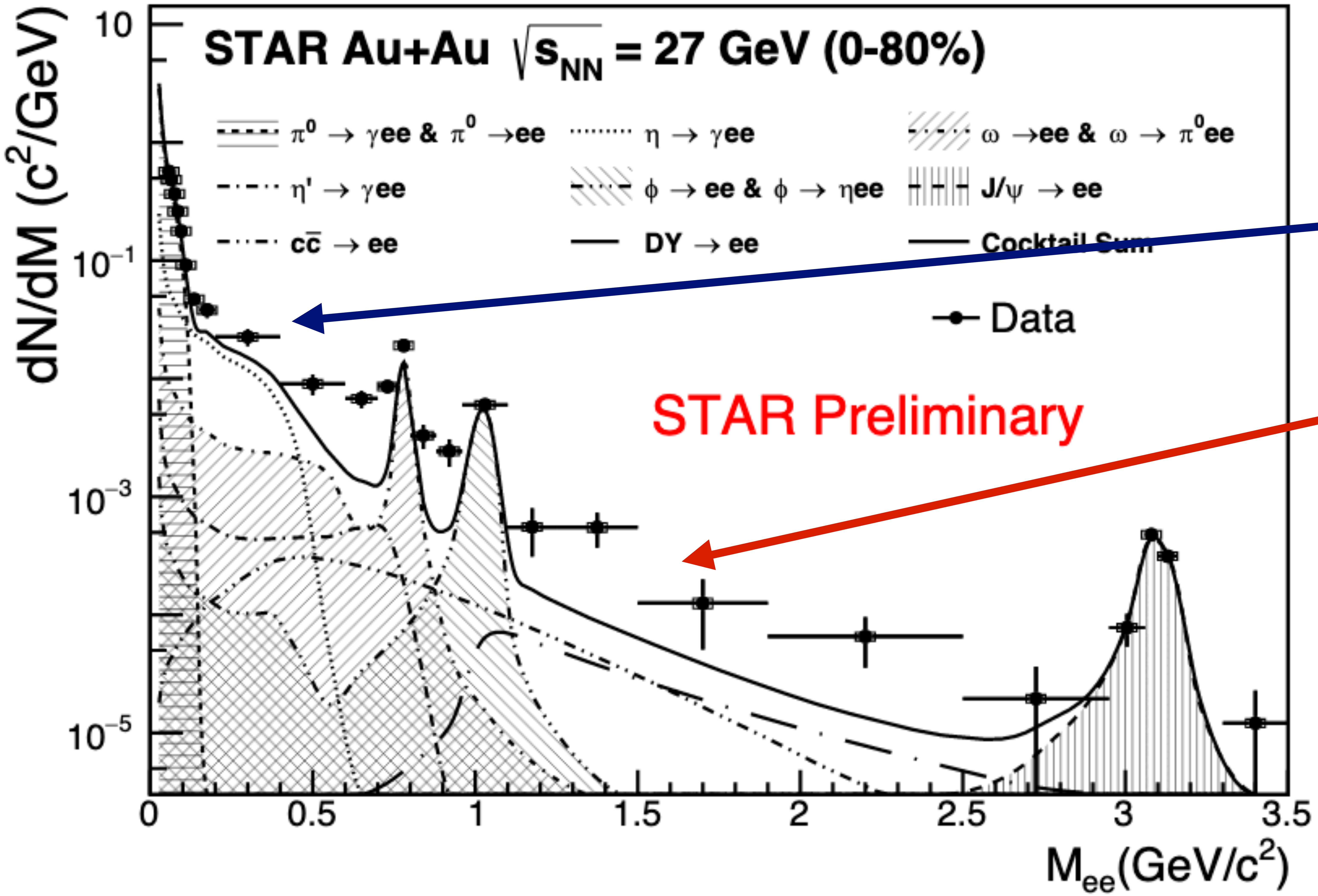


Production rate proportional to QGP temperature
: Early time measurement

ρ spectral function broadens when sitting in hot bath
: Later time measurement



Extracting the signal

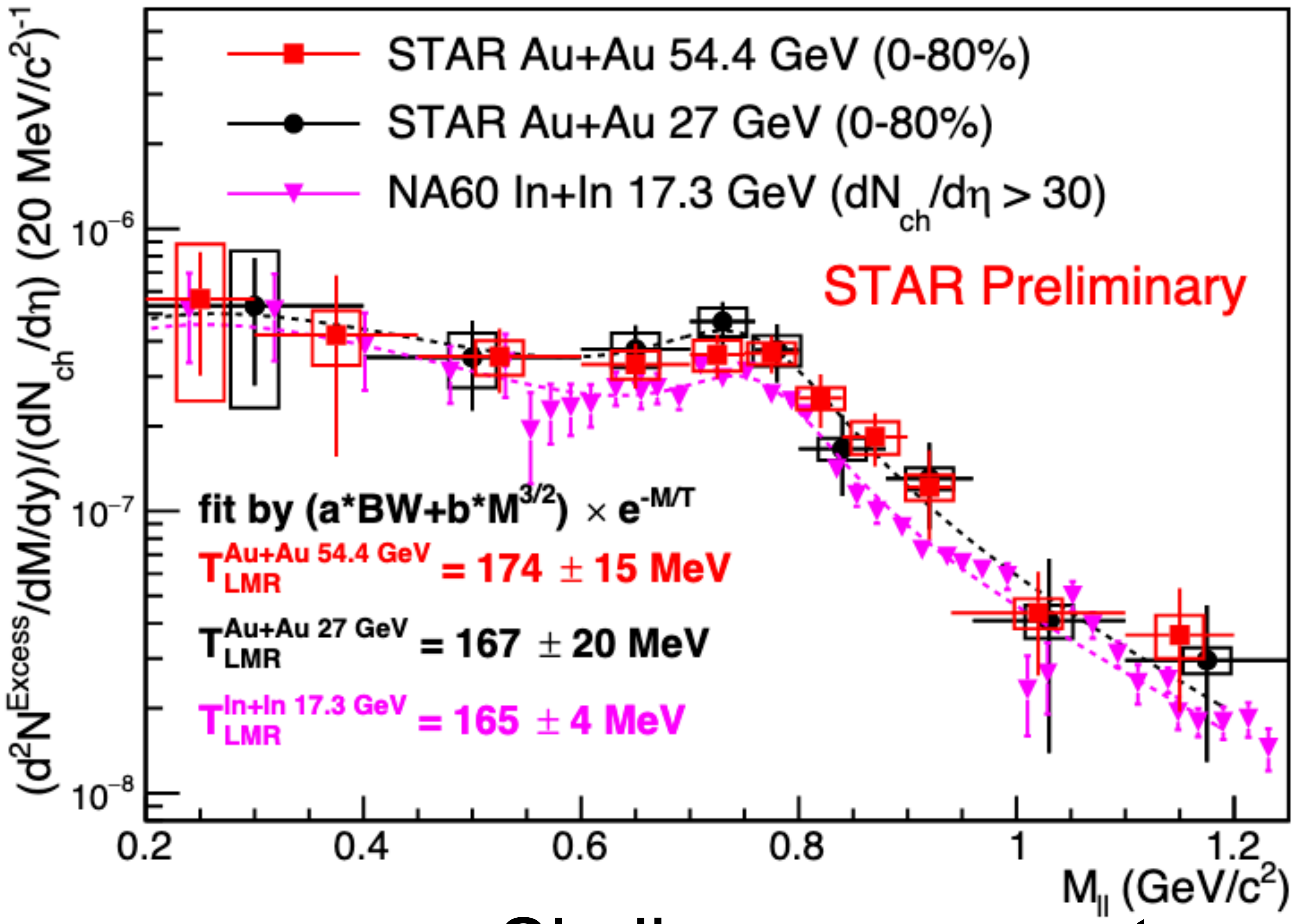


Low mass range

Intermediate mass range

Clear enhancement for LMR and IMR

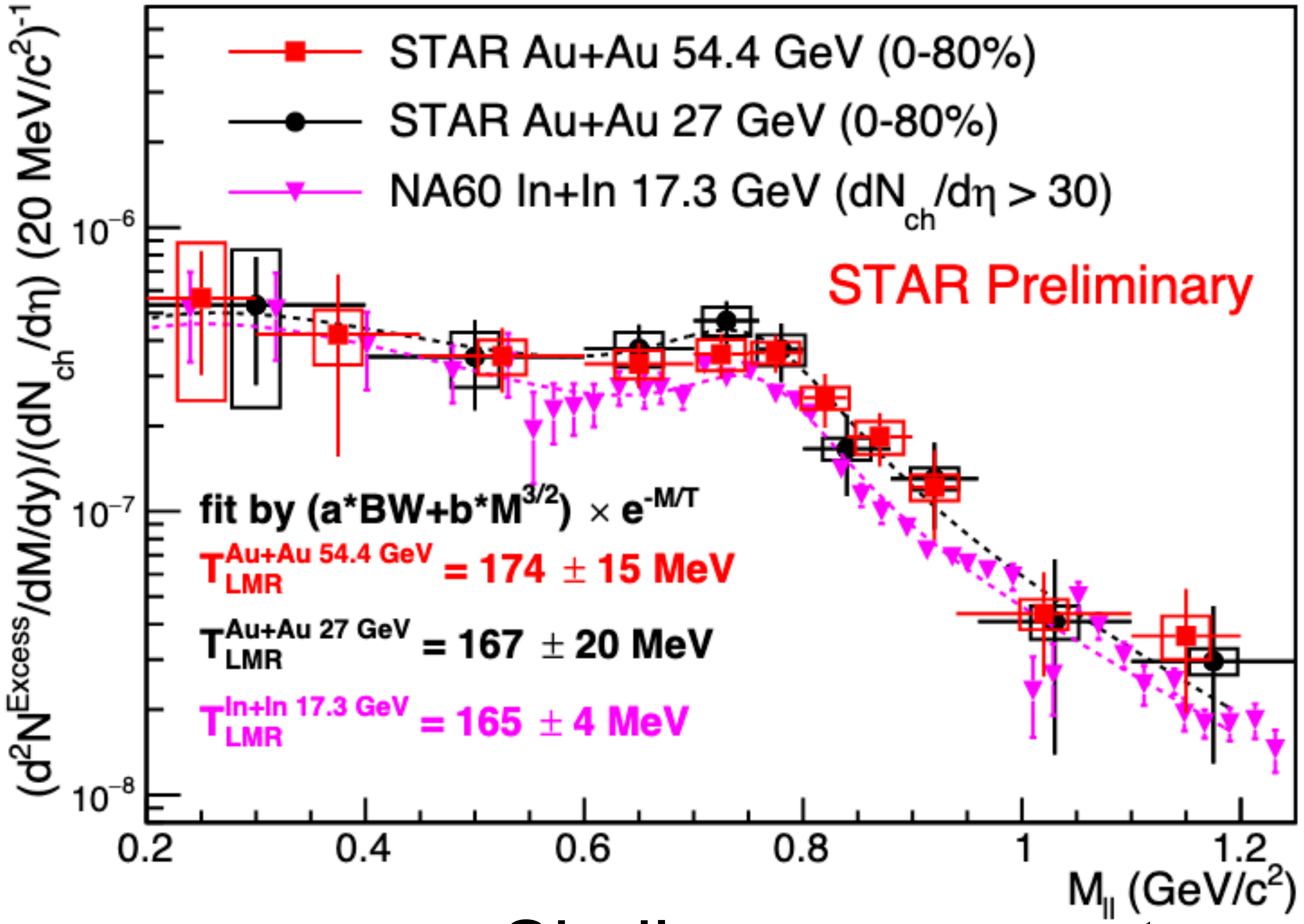
Extracting the temperatures

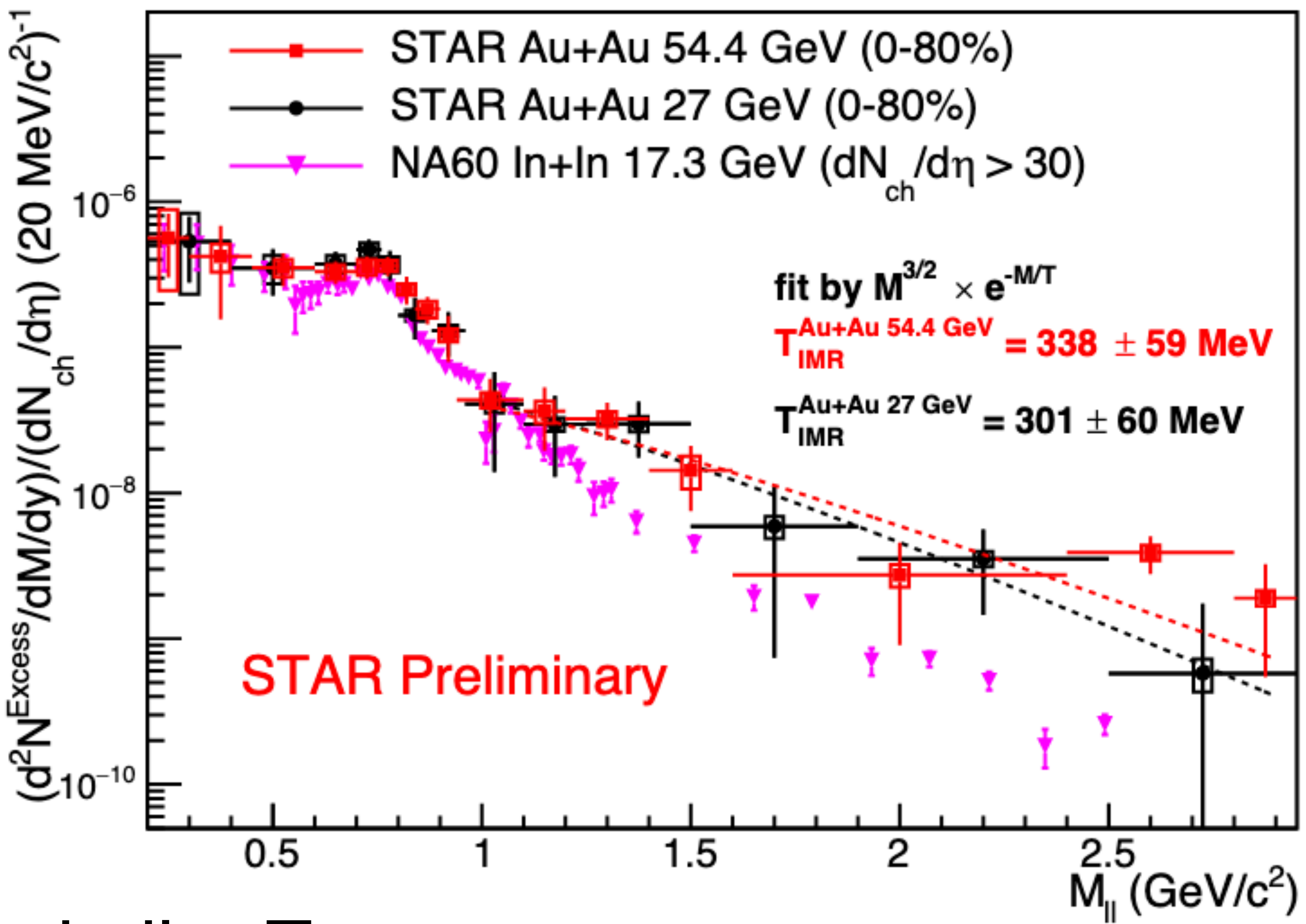


Low mass range: Similar mass spectrum, similar T,
in-medium ρ produced & broadened in similar heat bath from $\sqrt{s_{NN}}$ =17-56 GeV

STAR: arXiv: 2402.01998

Extracting the temperatures





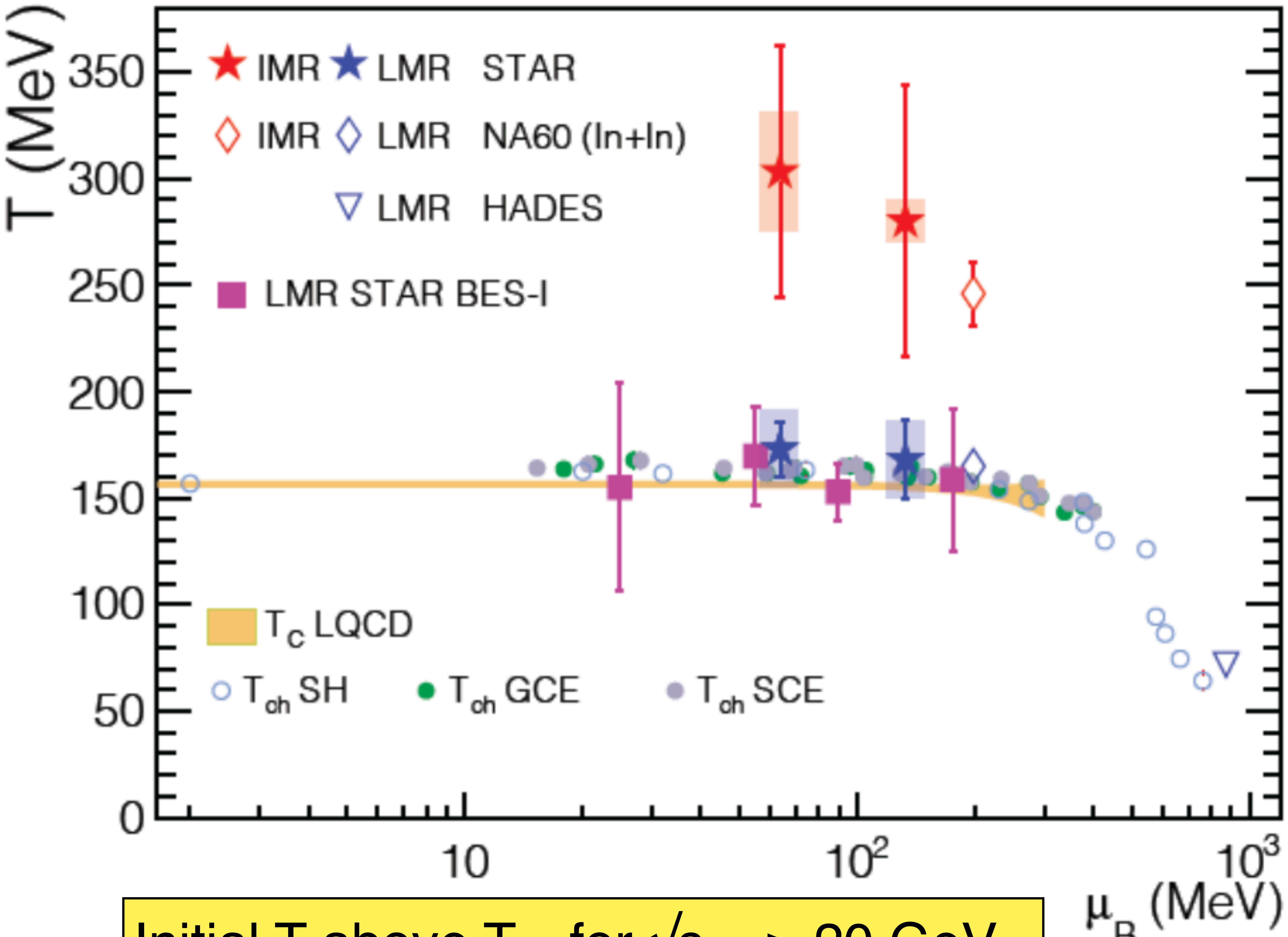
Low mass range: Similar mass spectrum, similar T,
in-medium ρ produced & broadened in similar heat bath from
$\sqrt{s_{NN}}$ =17-56 GeV

Intermediate mass range: T($\sqrt{s_{NN}}$ =54.6) = 338 ± 59 MeV ~ T($\sqrt{s_{NN}}$ =27) = 301± 60 MeV
T($\sqrt{s_{NN}}$ =17) ~ 246 MeV

Different medium below 20 GeV?

STAR: arXiv: 2402.01998

Phase diagram summary



Initial T above T_{pc} for $\sqrt{s_{NN}} > 20$ GeV

Higher chemical potentials at lower $\sqrt{s_{NN}}$

Hadronization occurs at ~170 MeV
T_{pc} from lattice
(chemical fits and dileptons)

At top RHIC energies (and LHC)
Initial temperature >300 MeV
(Quarkonia and photons)

Above $\sqrt{s_{NN}}$ ~ 30 GeV
Initial temperature >300 MeV
Potentially dropping below 20 GeV
(dileptons)

STAR: arXiv: 2402.01998

How hot is ~200 MeV ?

A. Approximately the same as the hottest recorded T in Finland (~37.2 °C Liperi, July 29, 2010)

B. Approximately that of molten gold (~1000 °C)

C. Approximately that of the center of the sun (~15 million °C)

D. Approximately that of a supernova (~10 billion °C)

E. Even hotter

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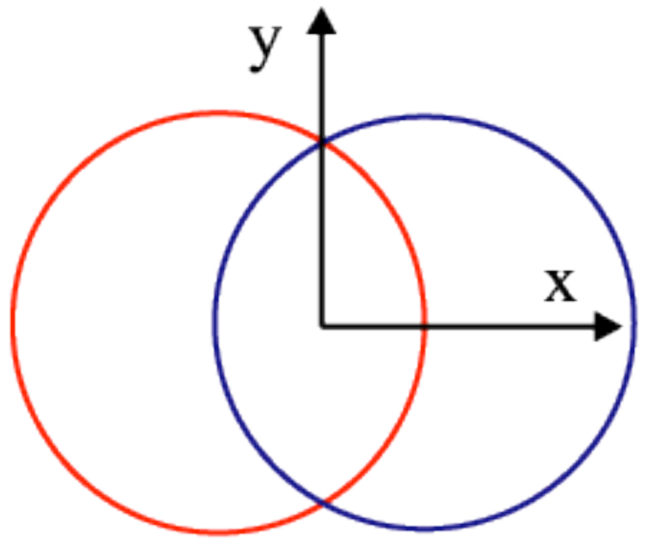
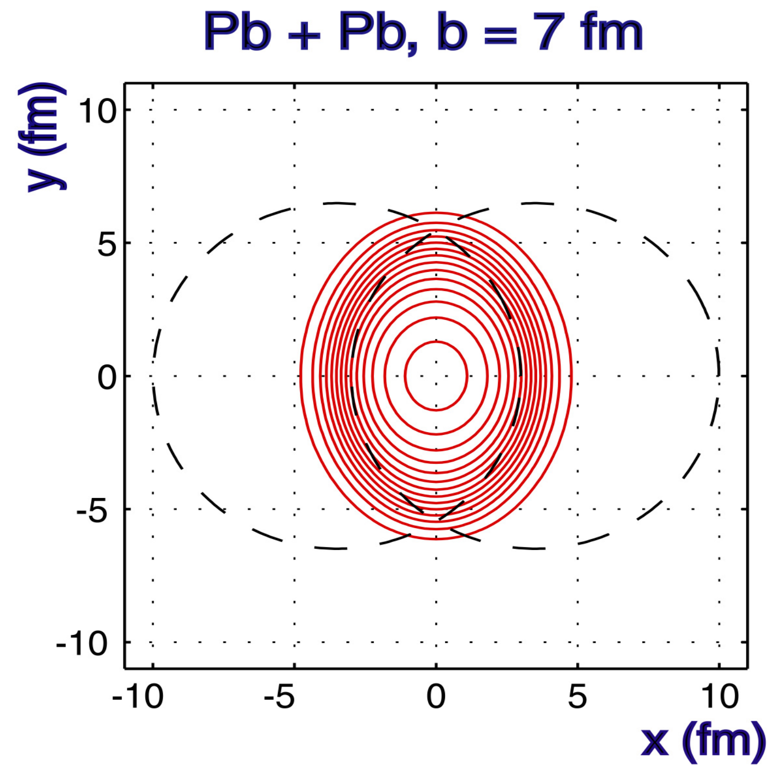
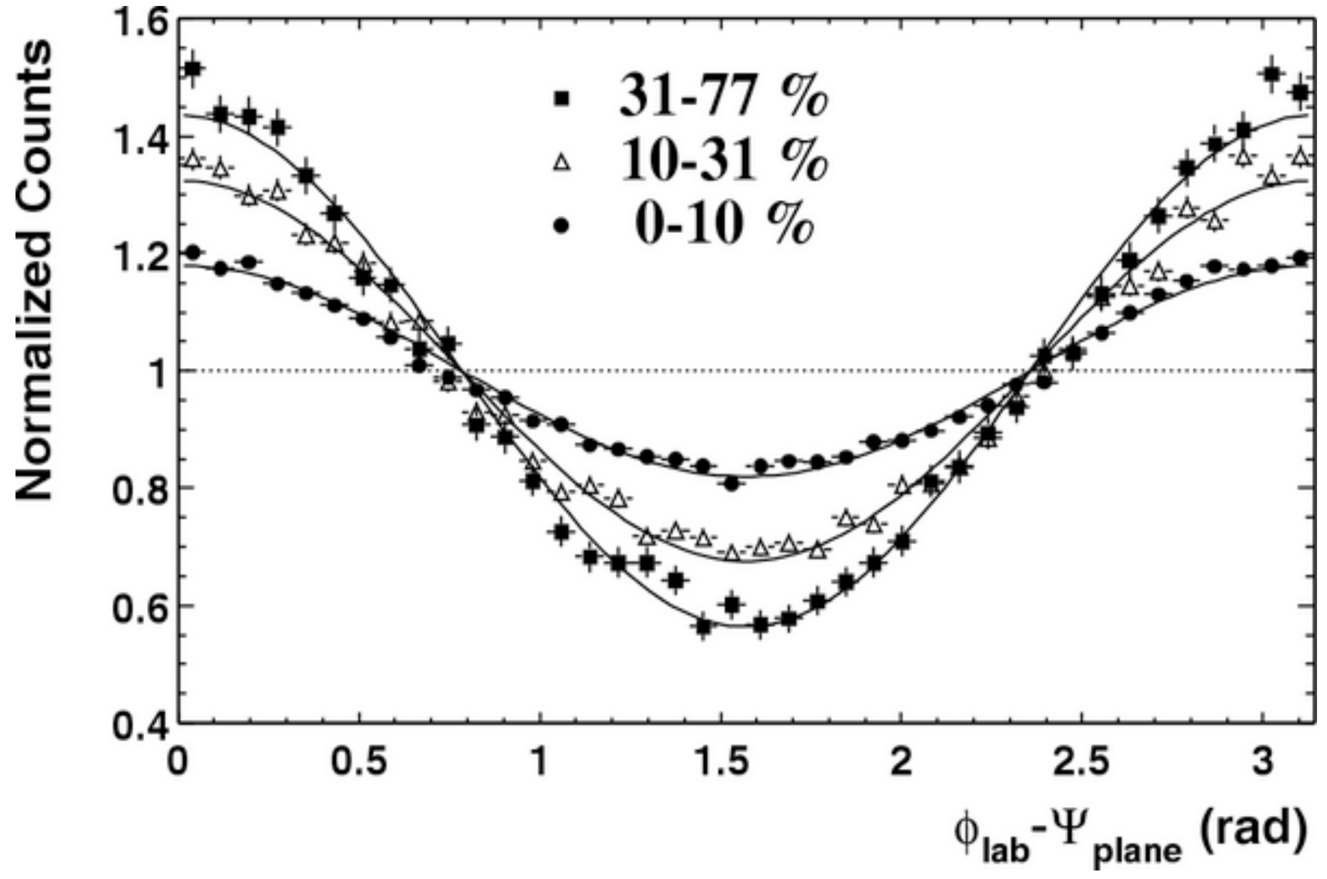
D. Approximately that of a supernova (~10 billion °C)

E. Even hotter ~0.1 trillion °C

QGP: fluid or gas or plasma?





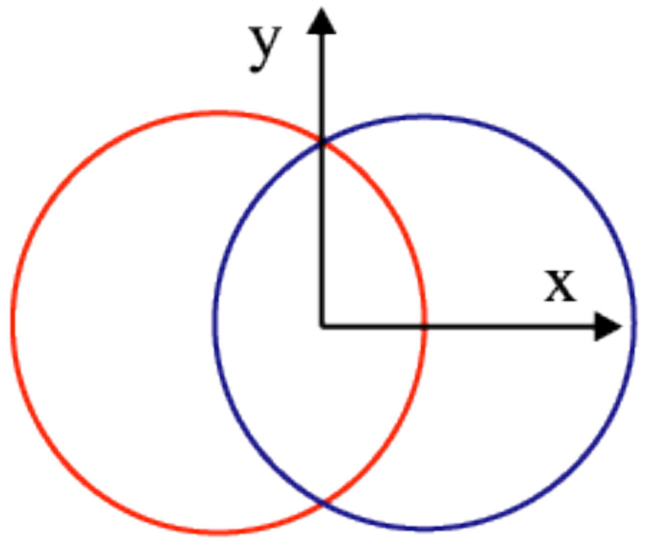


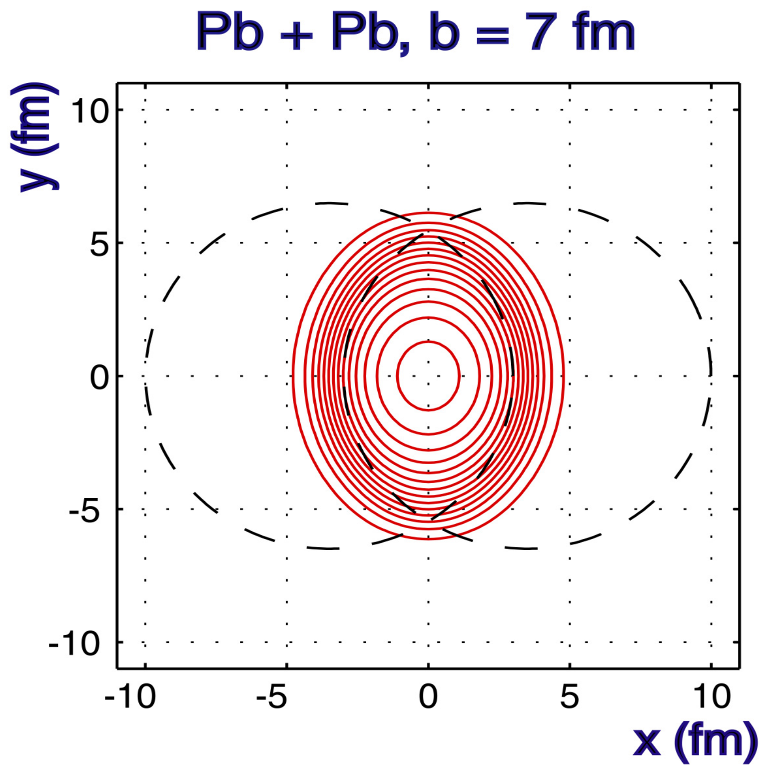
Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum space

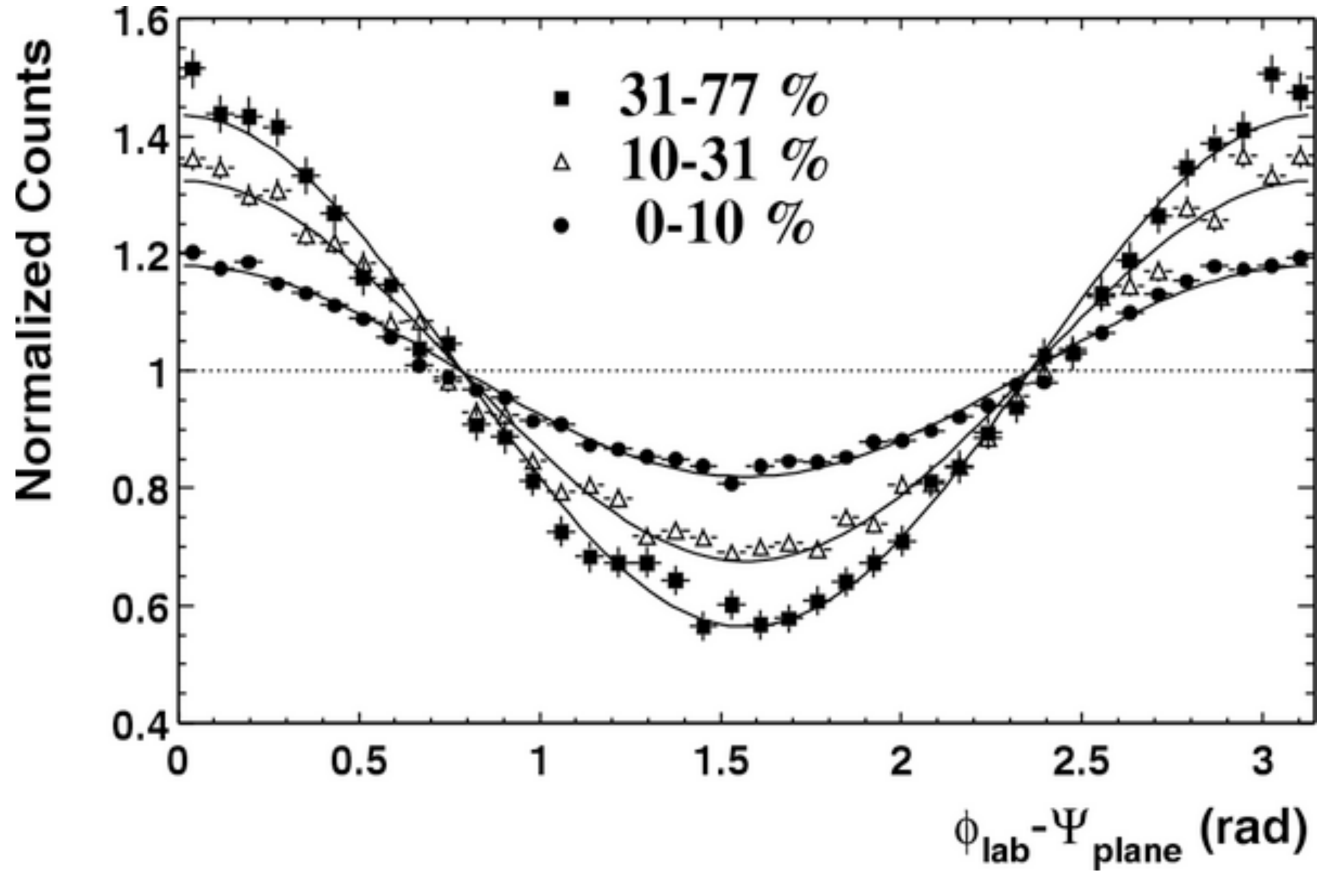
$$dN/d\phi \propto 1+2\, v_1(p_T)\cos(\phi-\Psi_R) + 2\, v_2(p_T)\cos(2(\phi-\Psi_R))\ldots\ ] \quad \phi=\mathrm{atan}(p_y/p_x)$$

v_1: directed flow, v_2: elliptic flow

QGP: fluid or gas or plasma?







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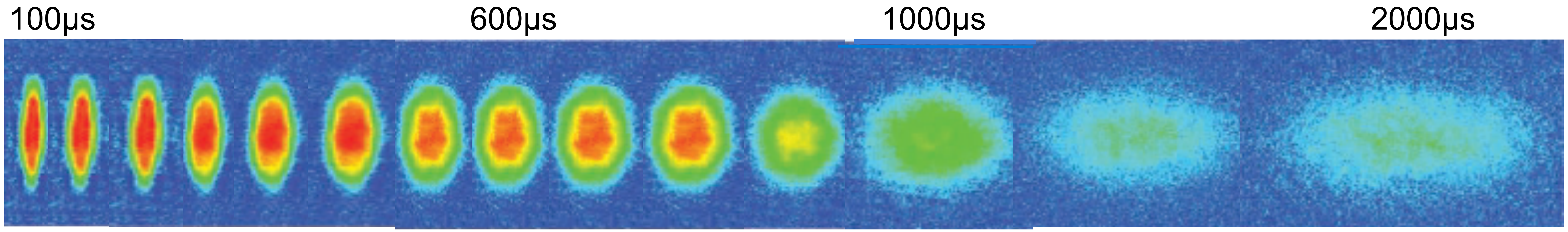
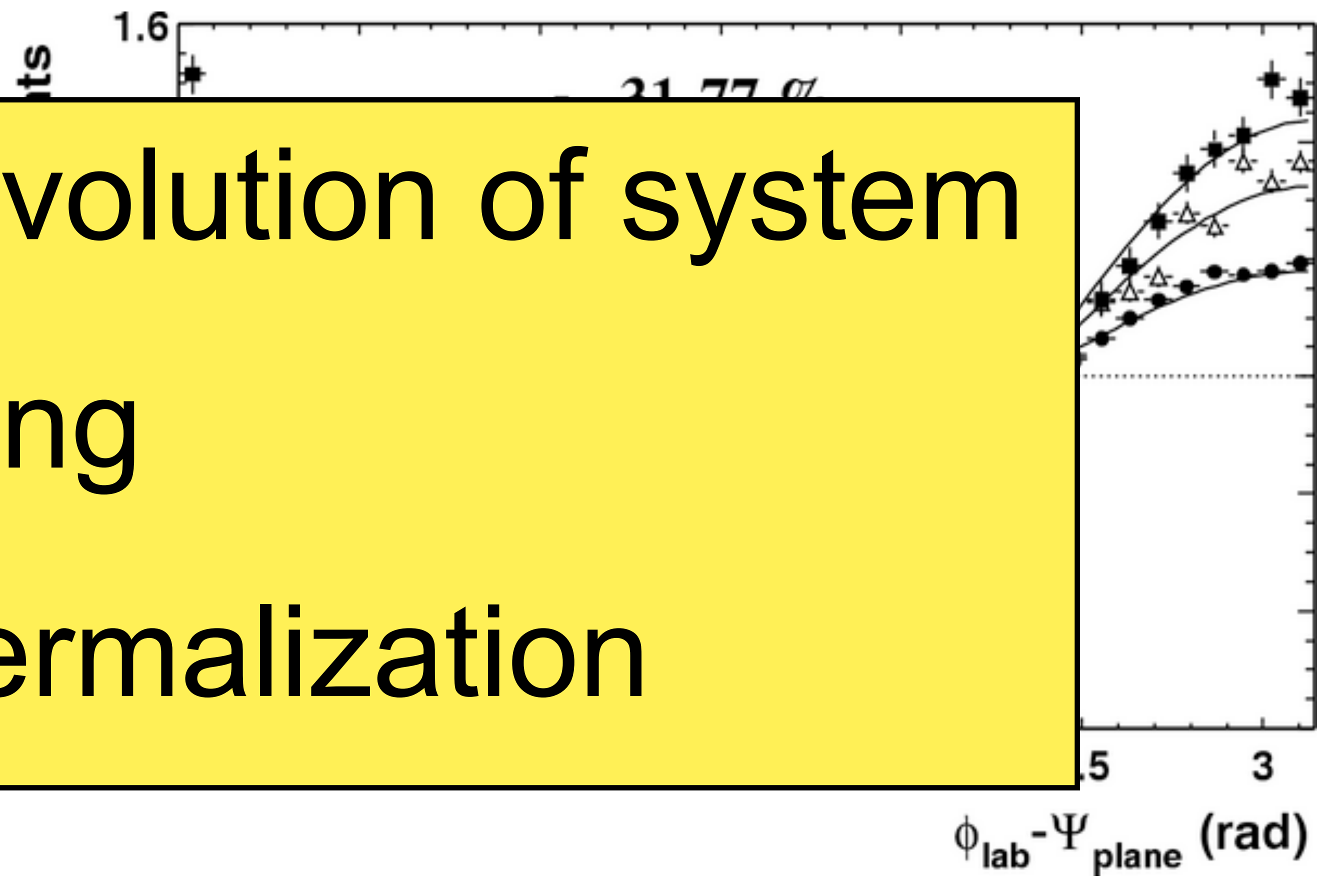


Time

–M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

QGP: fluid or gas or plasma?

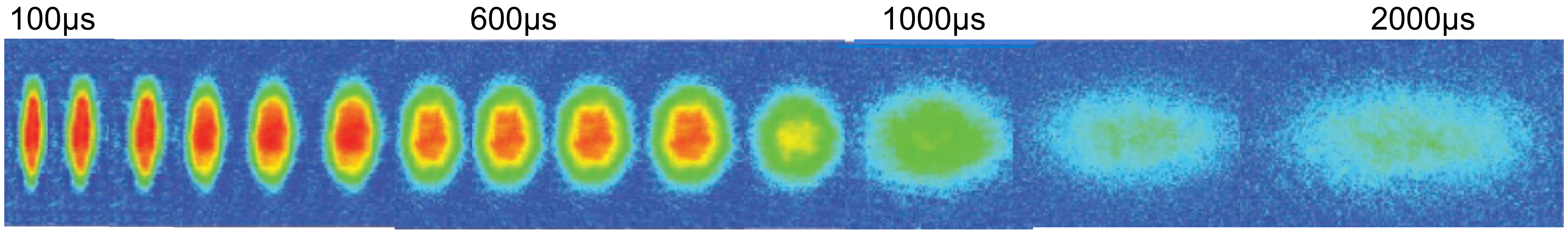


Elliptic flow observable sensitive to early evolution of system

Mechanism is self-quenching

Large v_2 is an indication of ***early*** thermalization

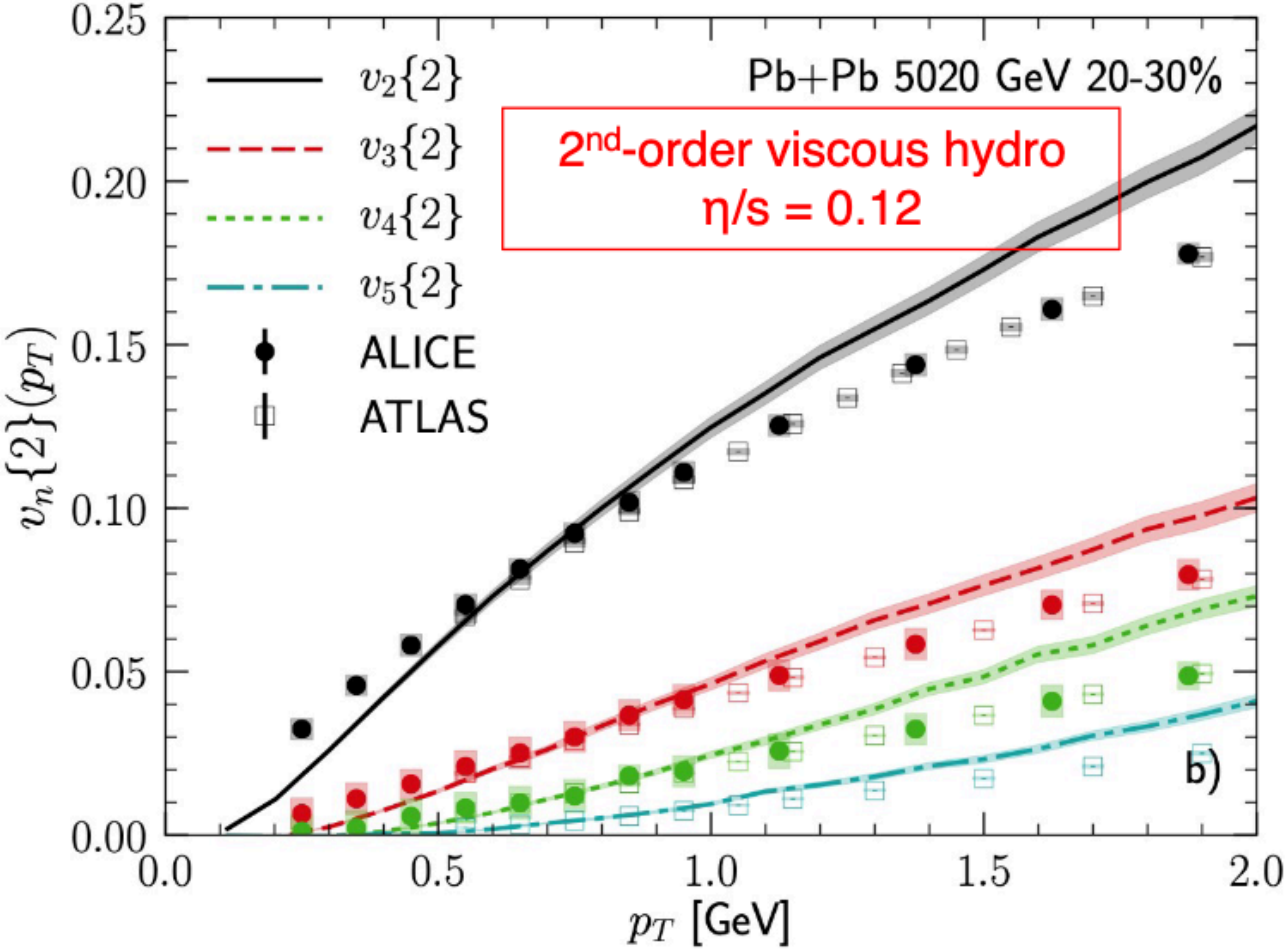
Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum space



→ Time

–M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Its a fluid



Data well described by hydrodynamical models with very low viscosity to entropy ratio

A near-perfect fluid!

Higher odd v_n terms dominantly due to event-by-event geometrical fluctuations

B. Schenke, C. Shen, P. Tribedy PRC 102, 044905 (2020)

Evidence for partonic degrees of freedom

Elliptic flow is additive

If partons are flowing the *complicated* observed flow pattern in $v_2(p_T)$ for hadrons

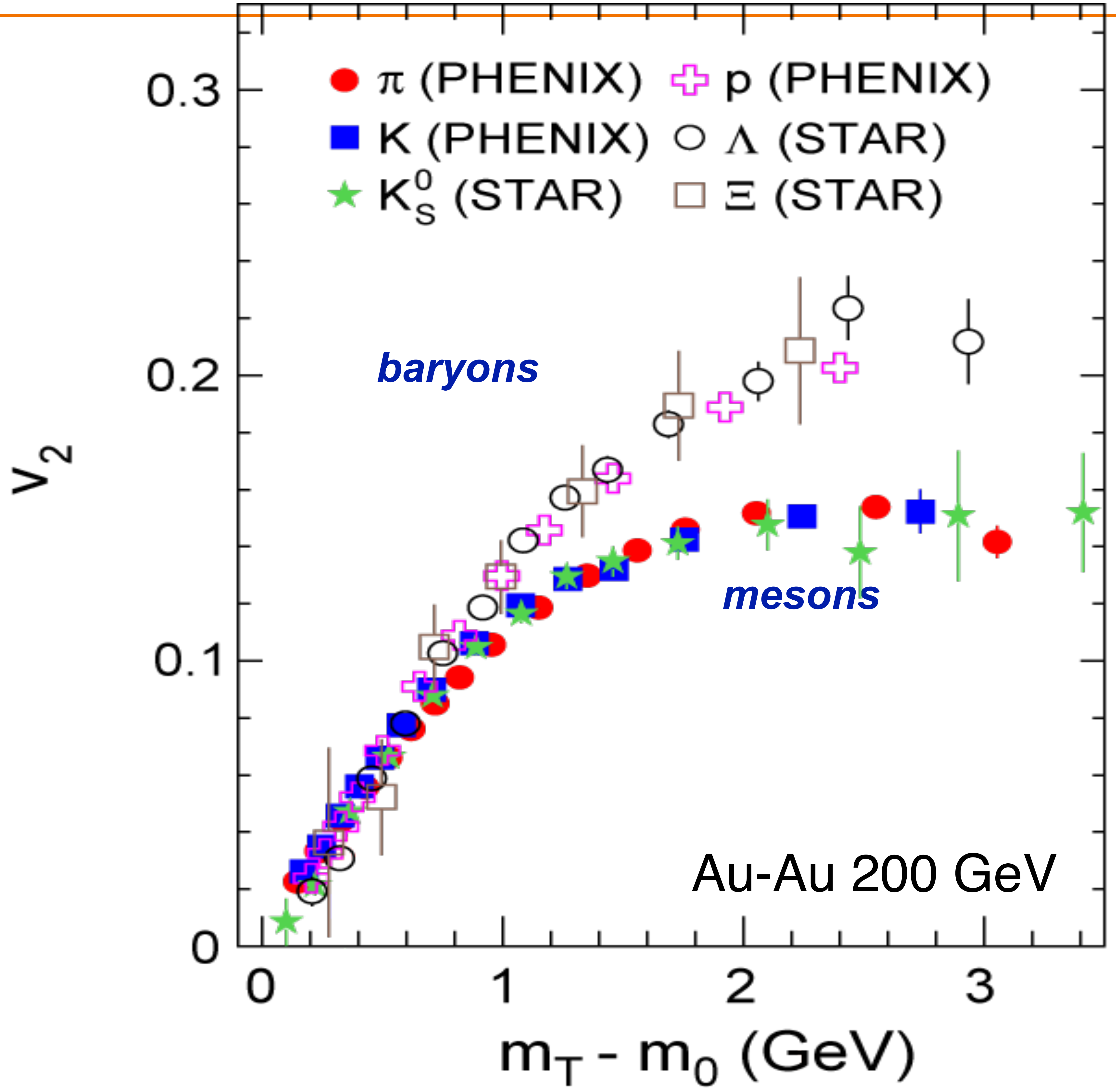
$$\frac{d^2N}{dp_T d\phi} \propto 1+2\, v_2(p_T)\cos(2\phi)$$

should become *simple* at the quark level

$p_T \rightarrow p_T/n$

$v_2 \rightarrow v_2/n$

n = (2, 3) for (meson, baryon)



$$m_T = \sqrt{p_T^2 + m_0^2}$$

STAR: PRL 95 (2005) 122301, PHENIX: PRL 98 (2007) 162301

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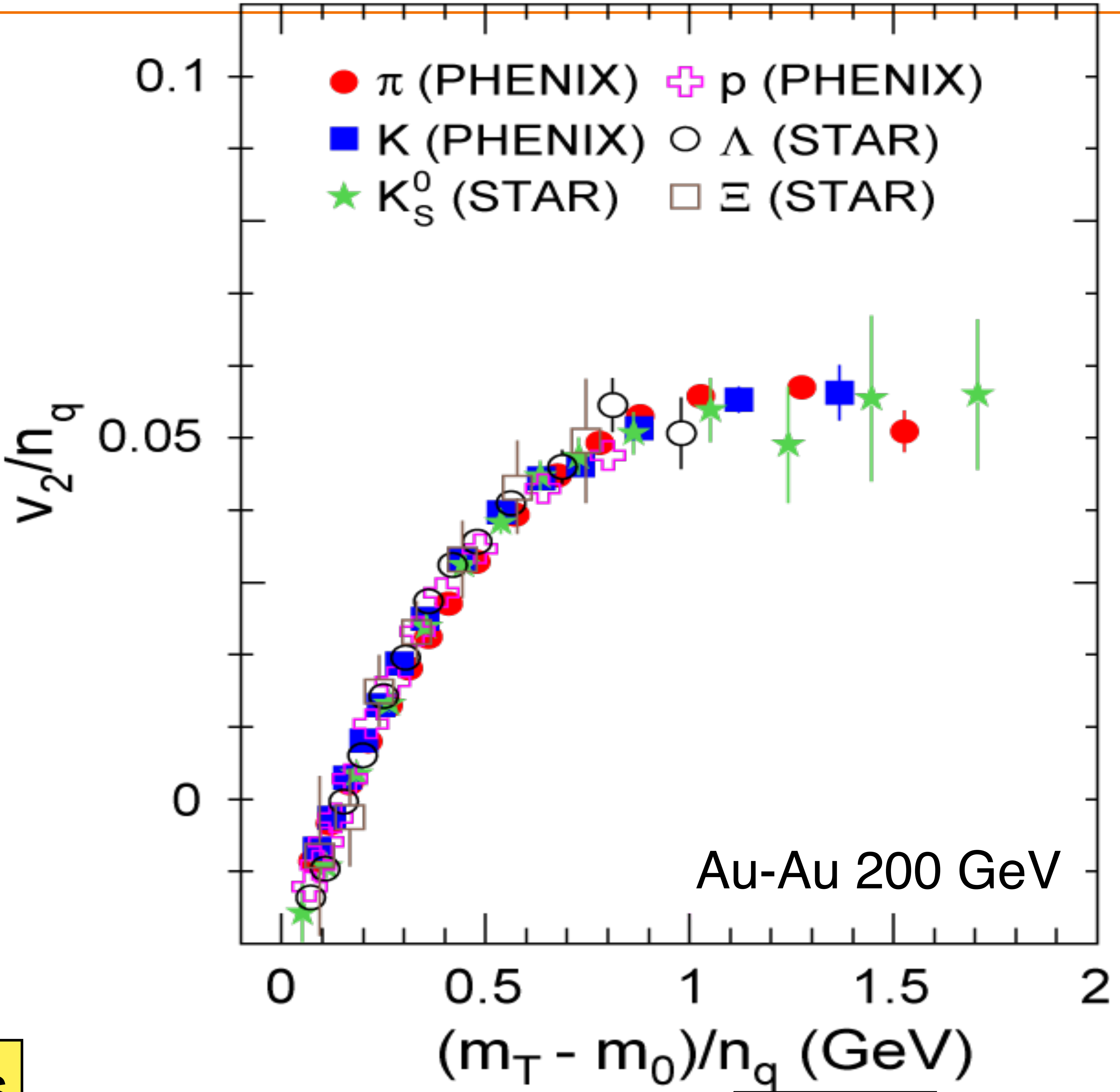
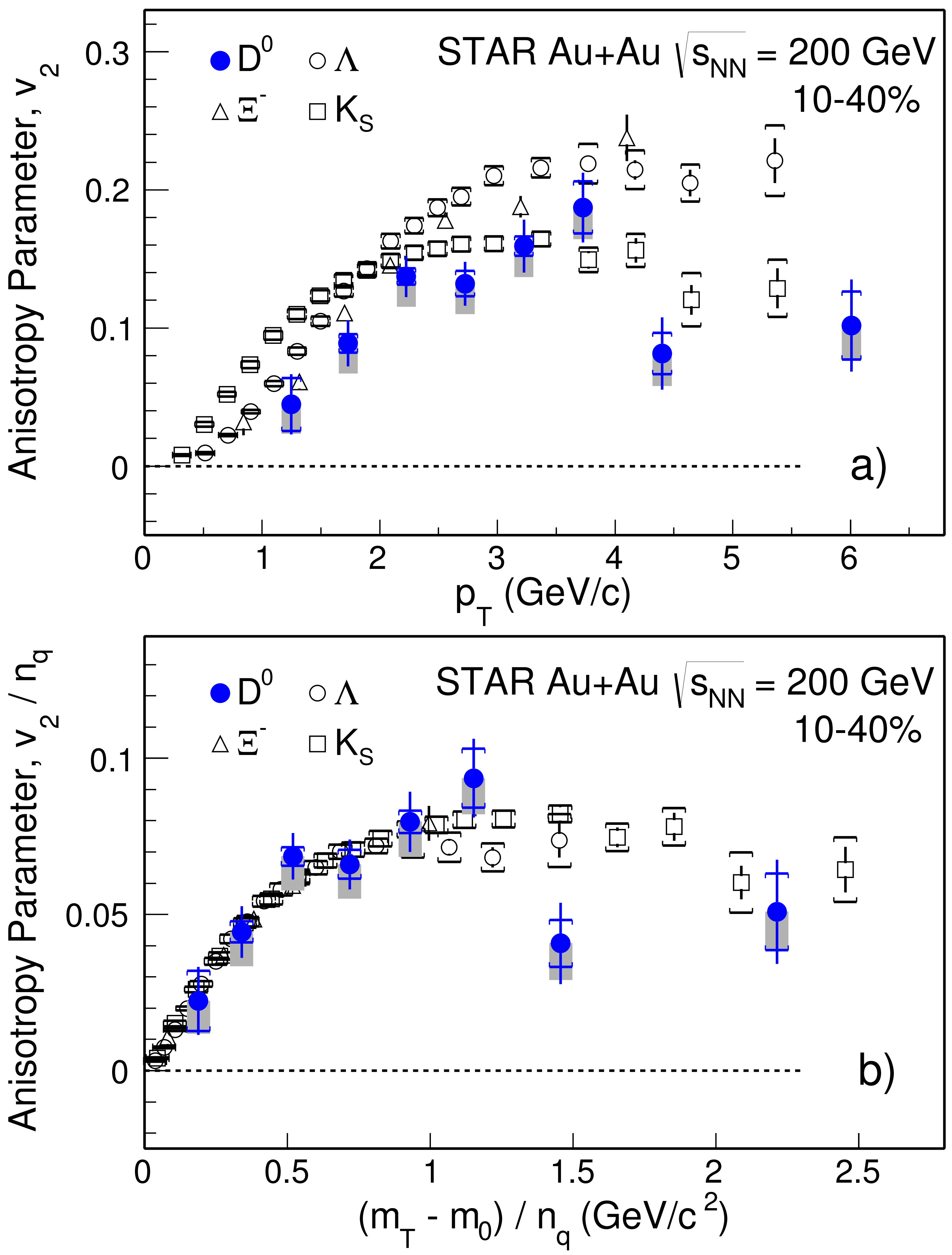
Constituents of QGP are partons

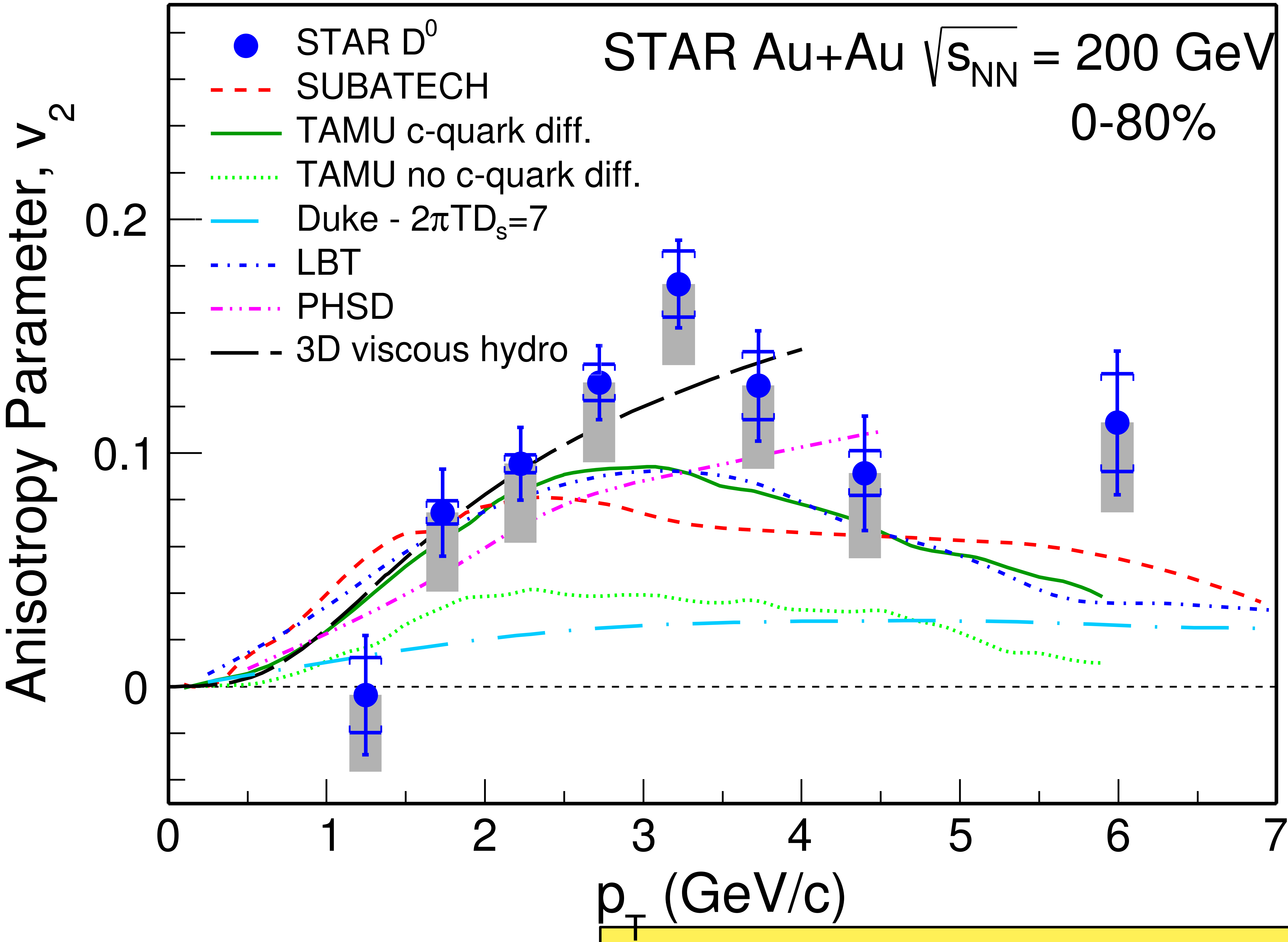


$$m_T = \sqrt{p_T^2 + m_0^2}$$

STAR: PRL 95 (2005) 122301, PHENIX: PRL 98 (2007) 162301

Charm quarks are also thermalized





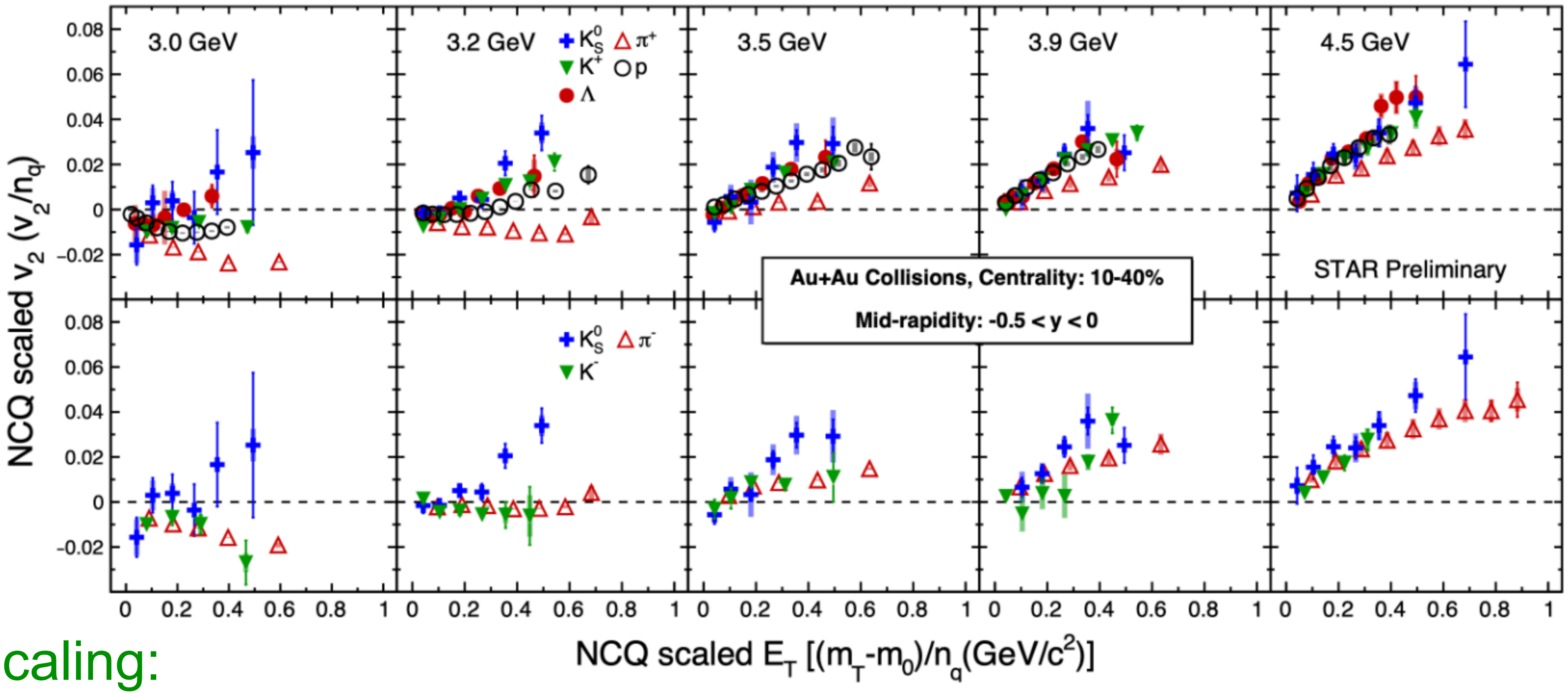
Clear mass ordering p_T < 2GeV/c

NCQ scaling of charm
- thermalization of heavy quarks

STAR: PRL 118 (2017) 212301

Disappearance of partonic collectivity

Hadronic interaction



Partonic collectivity

NCQ scaling:

Fails at $\sqrt{s_{NN}}$ = 3.2 GeV and lower

Gradually restores up to $\sqrt{s_{NN}}$ = 4.5 GeV

Evident from $\sqrt{s_{NN}}$ = 7.7 GeV onwards

Partonic : $\sqrt{s_{NN}} > 5$ GeV

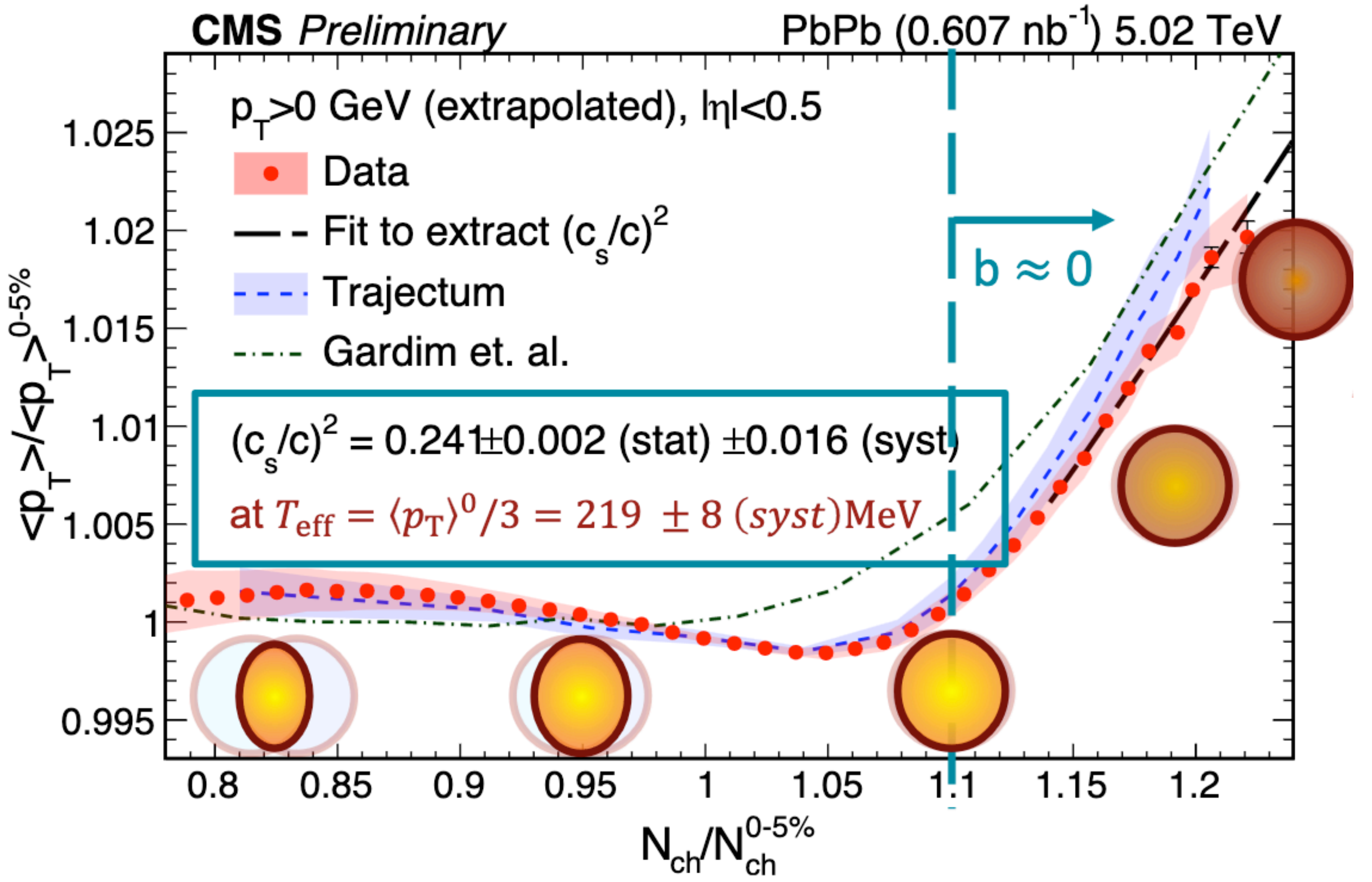
Hadron dominated : $\sqrt{s_{NN}} < 3.2$ GeV

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



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

Speed of sound in QGP

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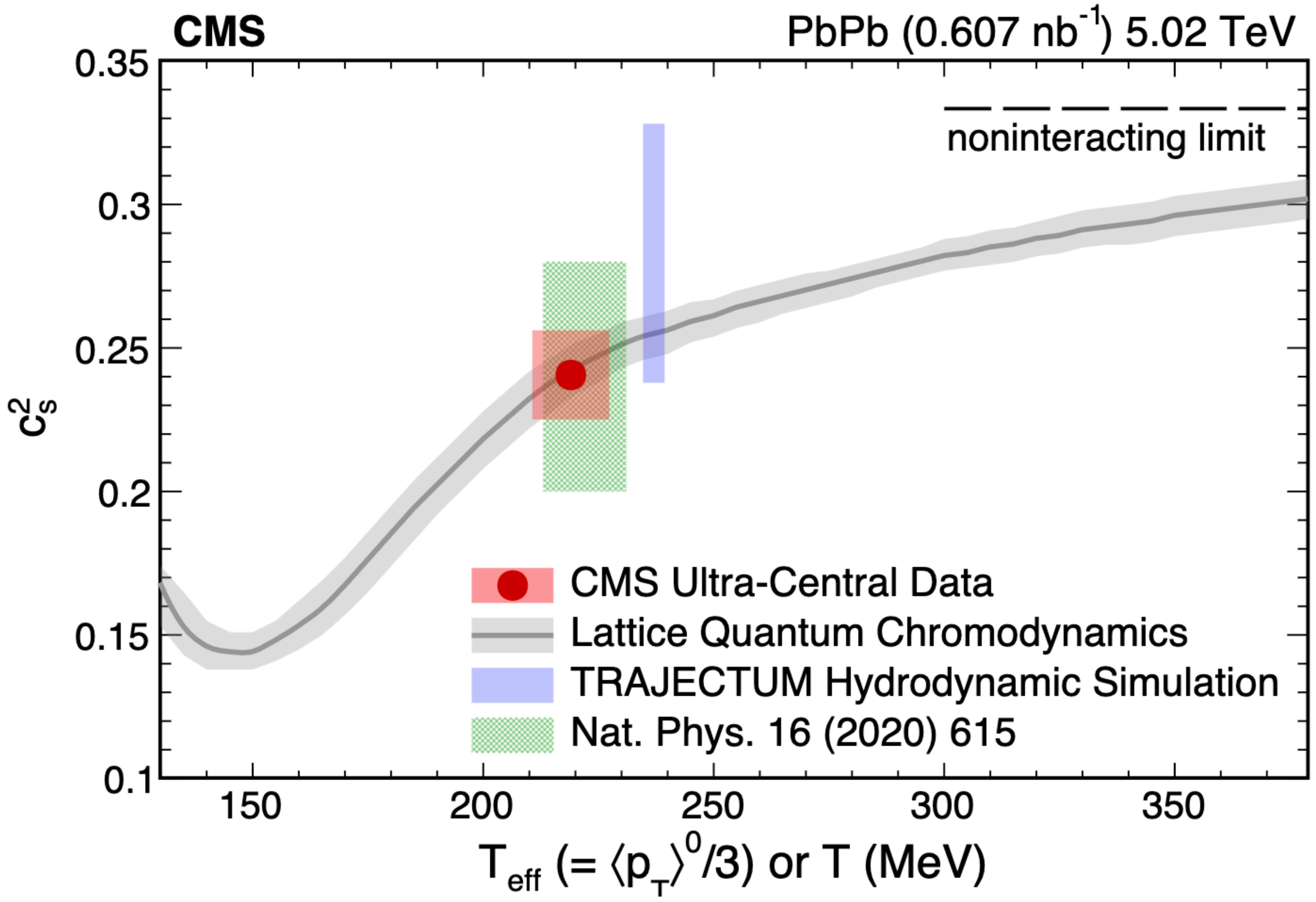
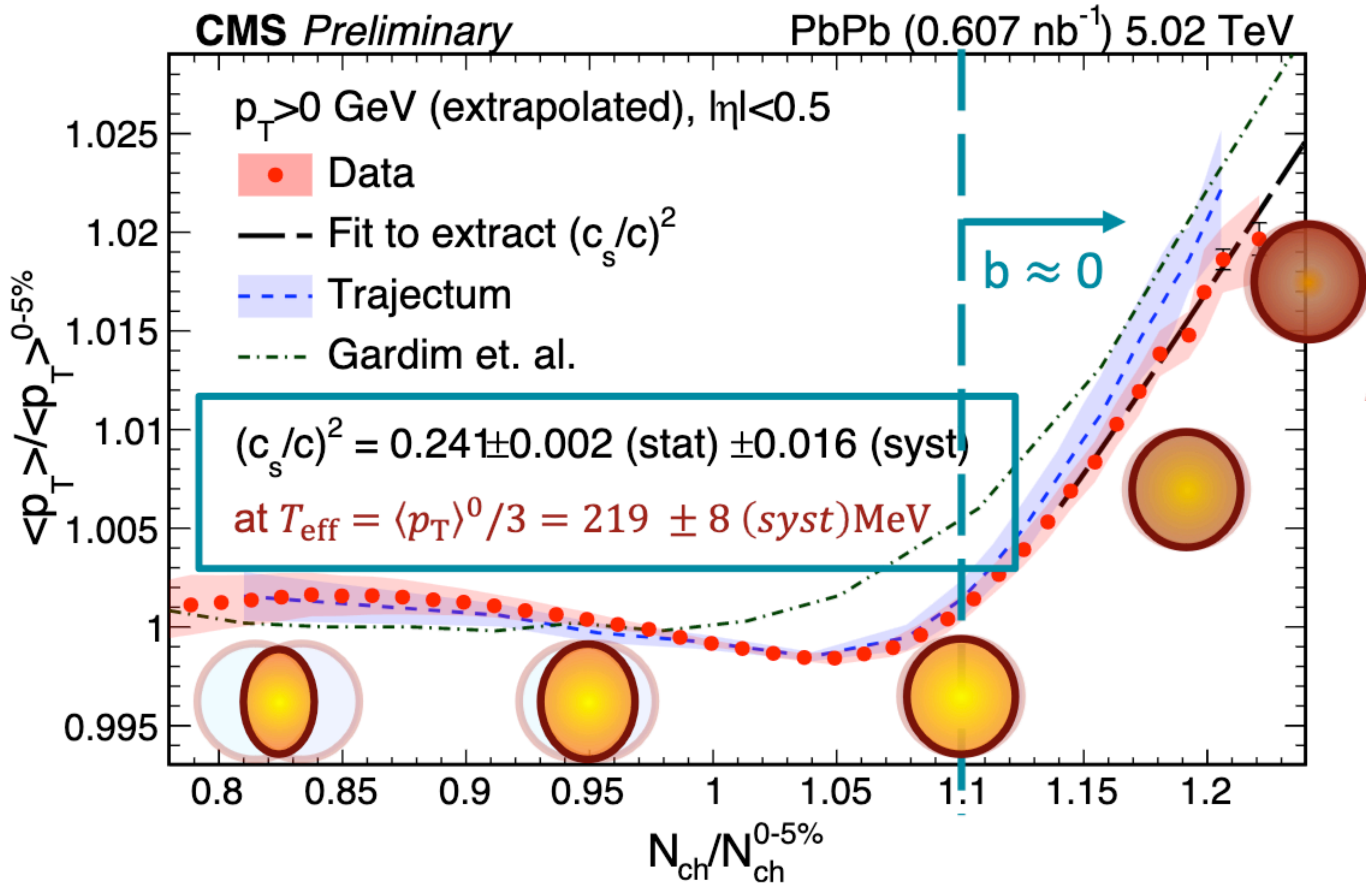




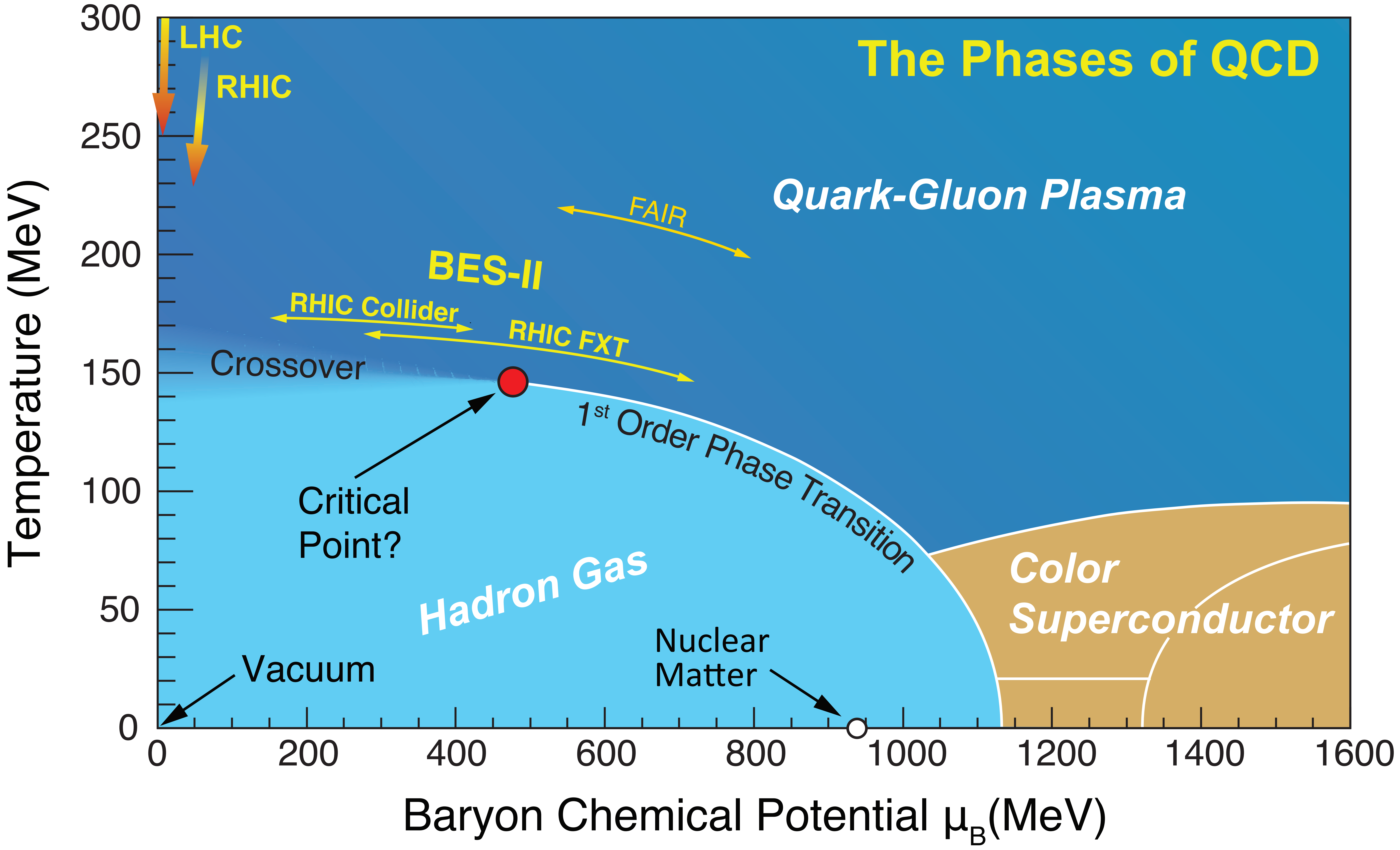
Data in excellent agreement with lQCD EoS

New data from ALICE suggest picture might be a bit more complicated

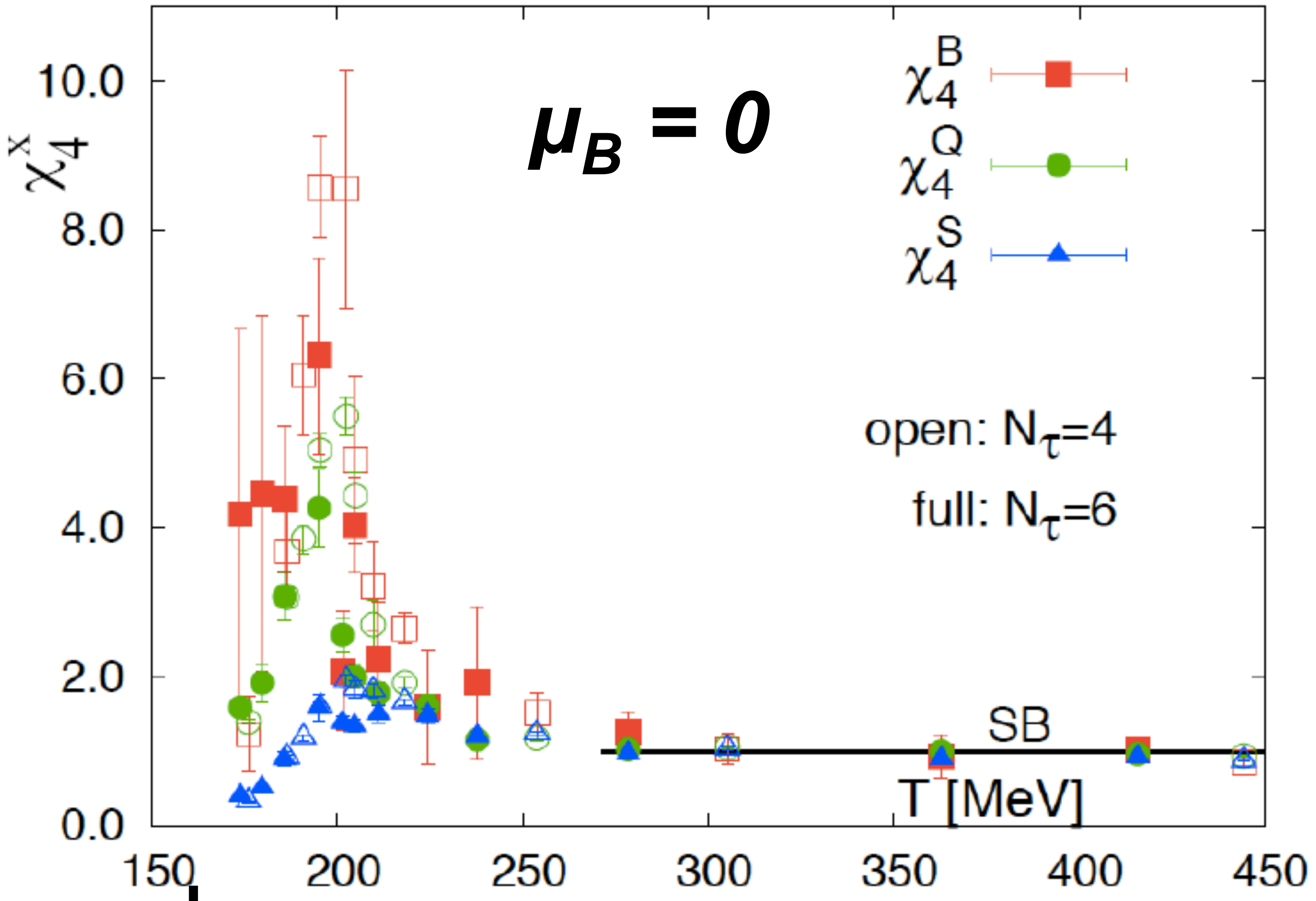
CMS: Rep. Prog. Phys. 87 (2024) 077801

Is there a Critical Point?

Back to the phase diagram



Searching for a Critical Point



Critical Points:

divergence of susceptibilities

e.g. magnetism transitions

divergence of correlation lengths

e.g. critical opalescence

Lattice QCD:

Divergence of susceptibilities for conserved quantities (B,Q,S) at critical point

Searching for a Critical Point

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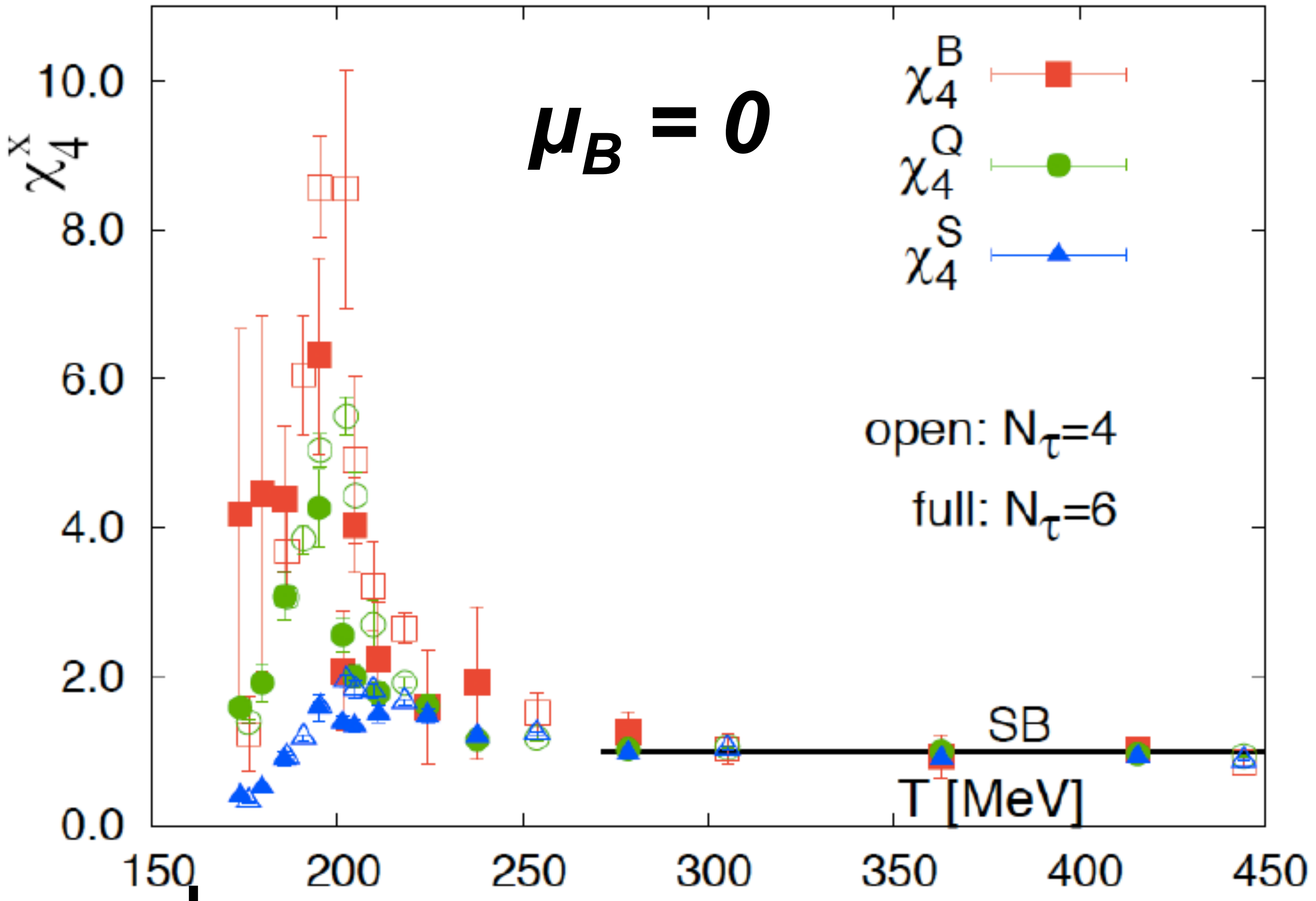

Lattice QCD:

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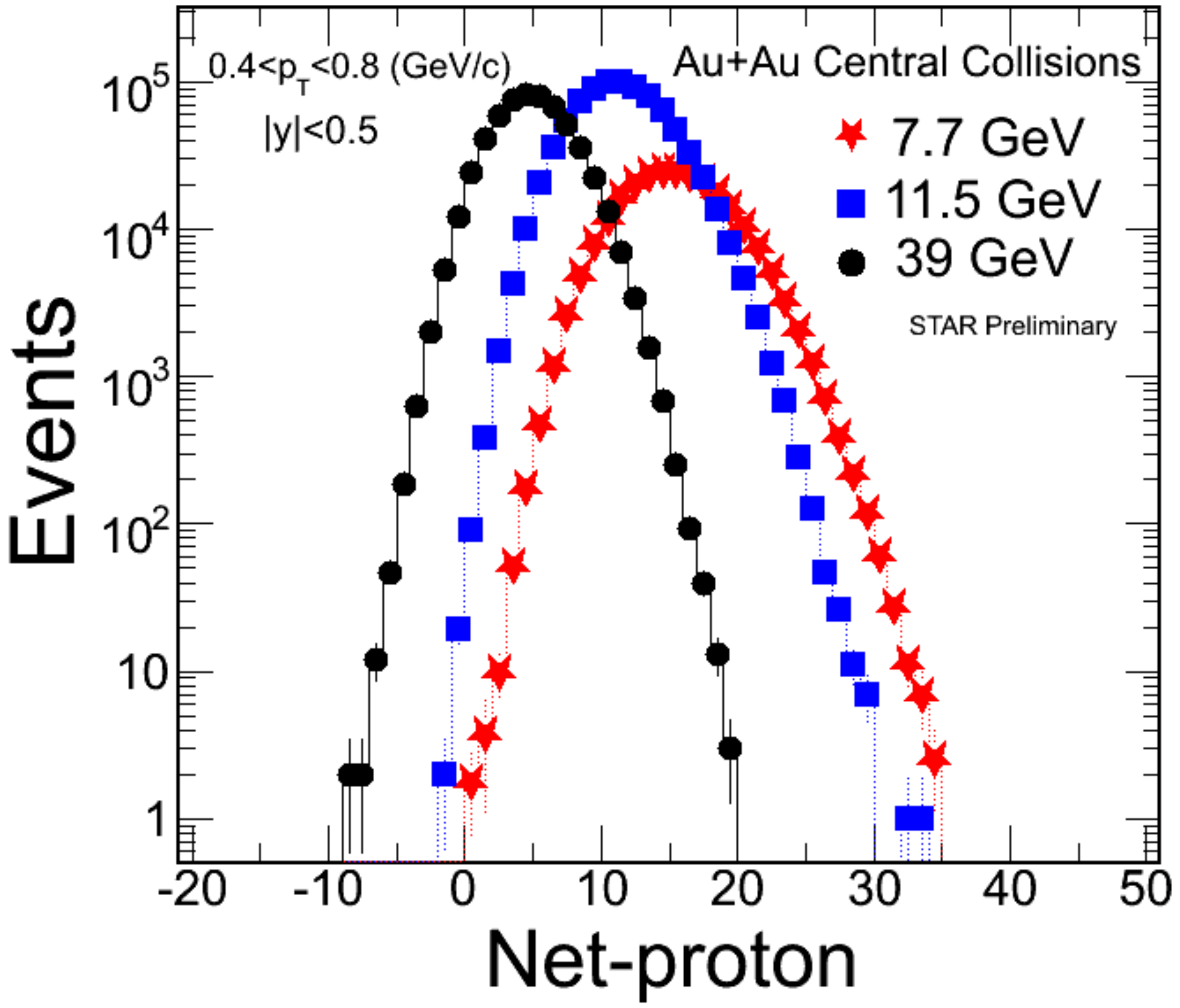

Divergences of conserved quantities may survive in the final state

Non-gaussian fluctuations of net-baryon density

Searching for CP

Particle number density, N/V = $n_k(T,\mu_k) = \frac{d_k}{(2\pi)^3}\int \mathrm{d}^3\vec{p}\,\frac{1}{(-1)^{B_k+1}+\exp((\sqrt{\vec{p}^{\,2}+m_k^2}-\mu_k)/T)}$ = $(\partial p/\partial\mu_k)_T$

Theoretically susceptibilities of conserved quantities (B,Q,S) can be calculated :

$$\chi_{lmn}^{BSQ} = \frac{\partial^{l+m+n}(p/T^4)}{\partial(\mu_B/T)^l\,\partial(\mu_S/T)^m\,\partial(\mu_Q/T)^n}.$$

δN = N - ⟨N⟩

Experiment measure event-by-event distribution of conserved quantities

Focus on net-proton as proxy for net-baryon

Take ratios to remove volume and T dependence

$$\text{mean:} \quad M = \langle N\rangle = VT^3\chi_1,$$

$$\text{variance:} \quad \sigma^2 = \left\langle(\delta N)^2\right\rangle = VT^3\chi_2,$$

$$\text{skewness:} \quad S = \frac{\left\langle(\delta N)^3\right\rangle}{\sigma^3} = \frac{VT^3\chi_3}{(VT^3\chi_2)^{3/2}},$$

$$\text{kurtosis:} \quad \kappa = \frac{\left\langle(\delta N)^4\right\rangle}{\sigma^4} - 3 = \frac{VT^3\chi_4}{(VT^3\chi_2)^2},$$

M. Stephanov. PRL 107:052301(2011)

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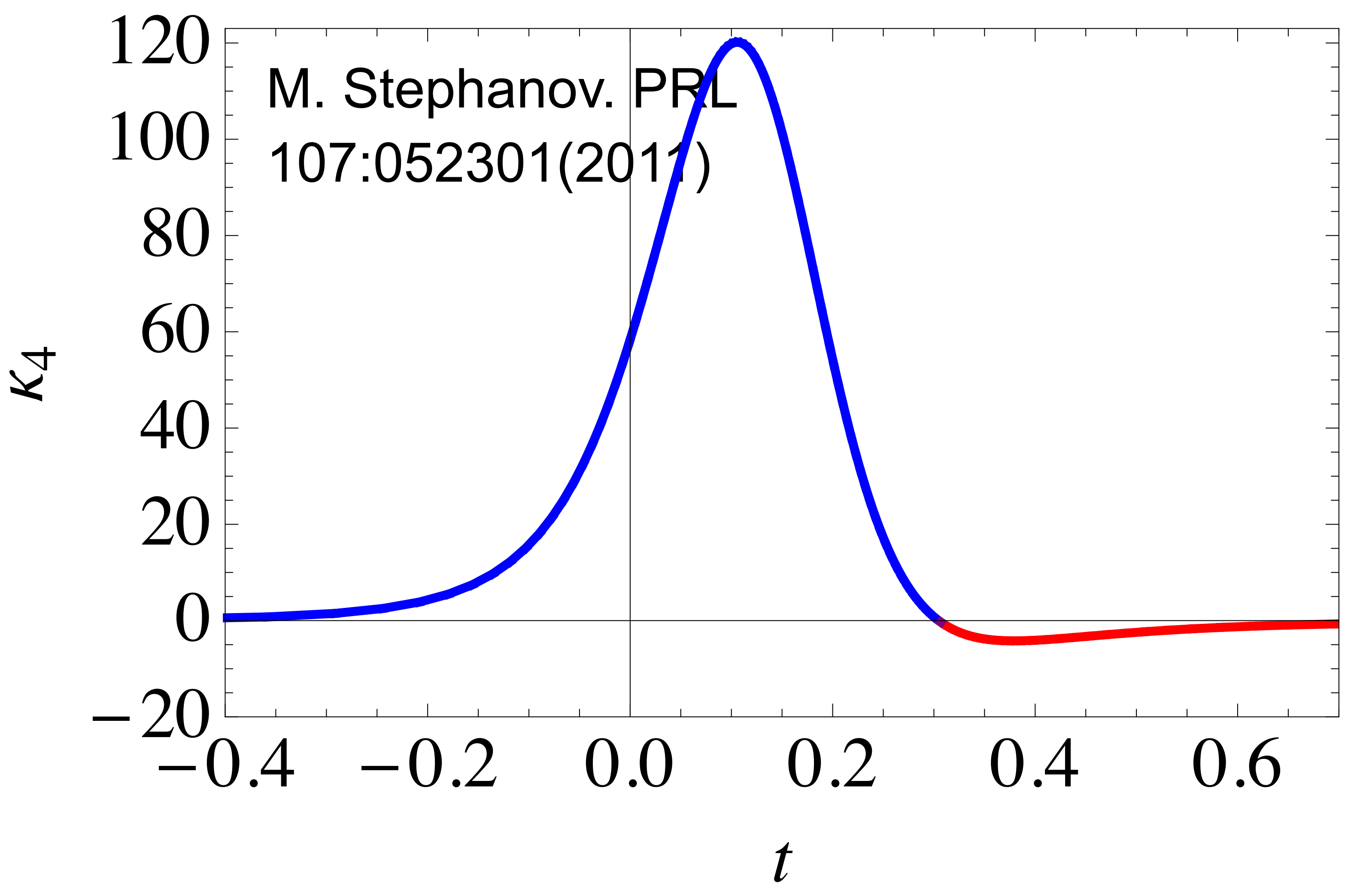
Kurtosis x Variance^2 ~ $\chi^{(4)}/\chi^{(2)}$

(Kurtosis - 4th moment - “tailiness” of distribution)

M. Stephanov. PRL 107:052301(2011)

Presence of Critical Point?



Correlation lengths diverge →

Net-p $\kappa\sigma^2$ diverge

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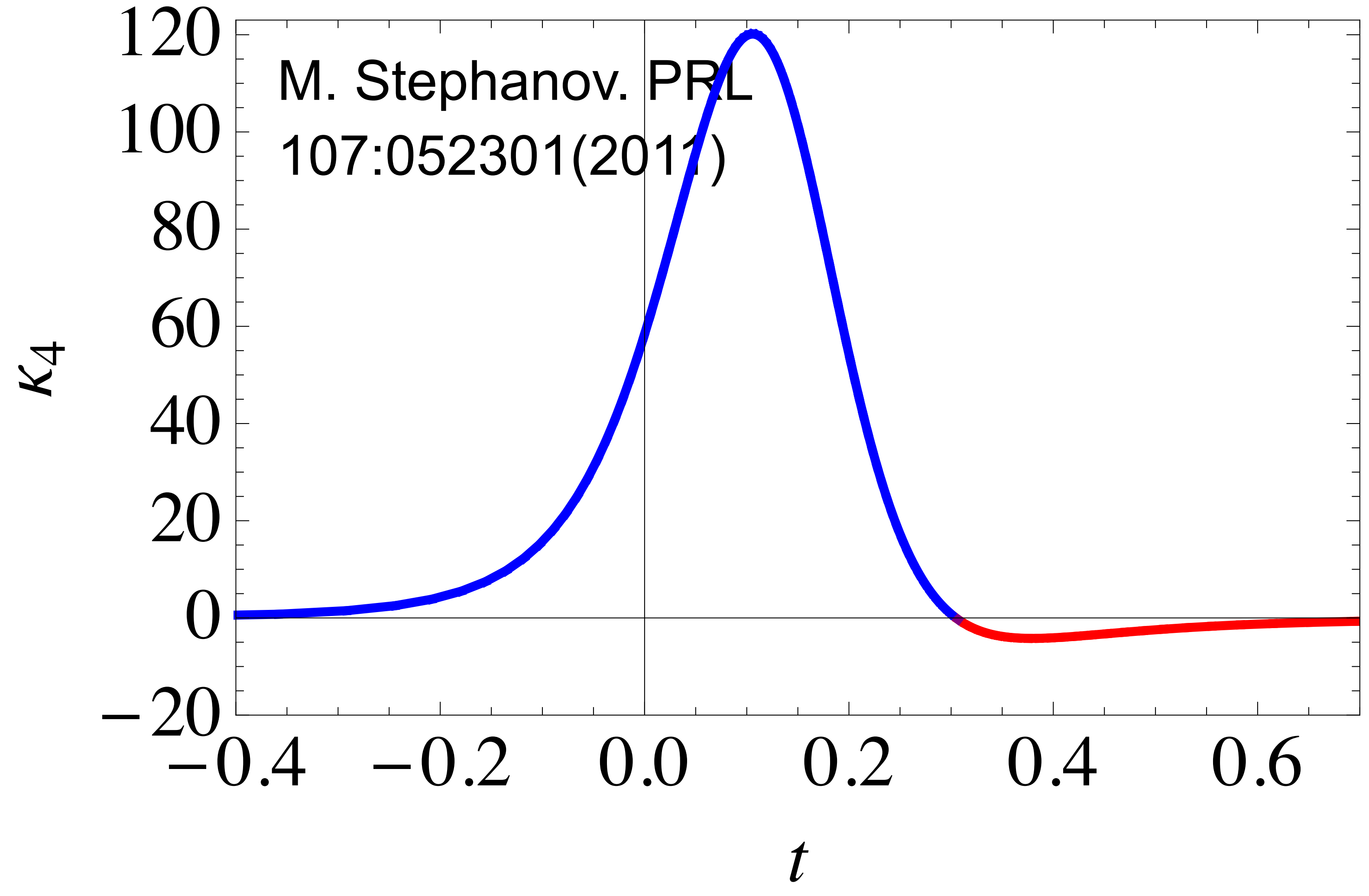

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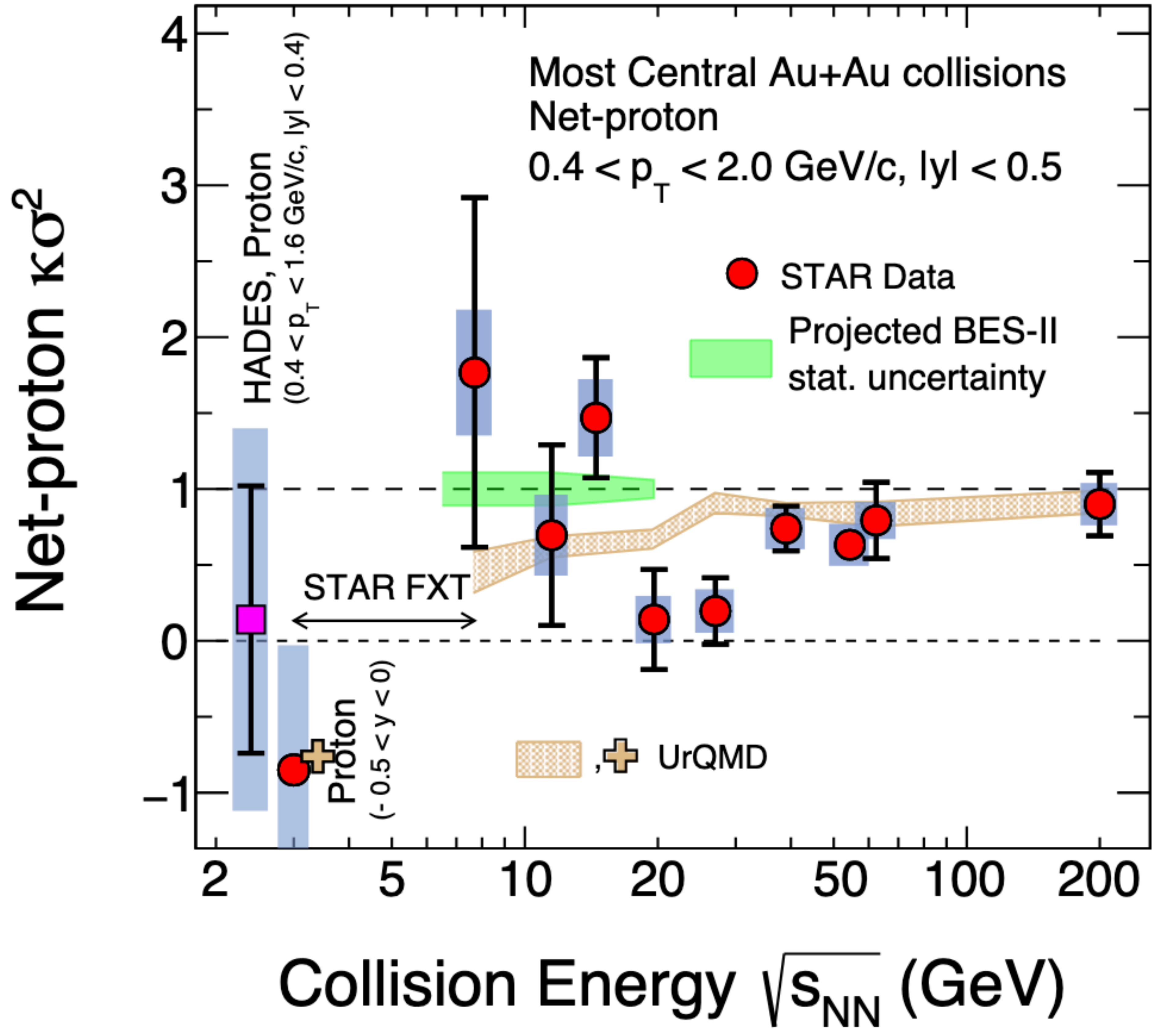
Net-p $\kappa\sigma^2$ diverge

Top 5% central collisions:

- Non-monotonic behavior
- Enhanced p_T range → enhanced signal
- Not see in peripheral data

UrQMD (no Critical Point):

- shows suppression at lower energies
  - due to baryon number conservation



STAR: PRL **126** (2021) 92301, PRC **104** (2021) 024902 , PRL **127** (2021) 262301, PRL **128** (2022) 202303

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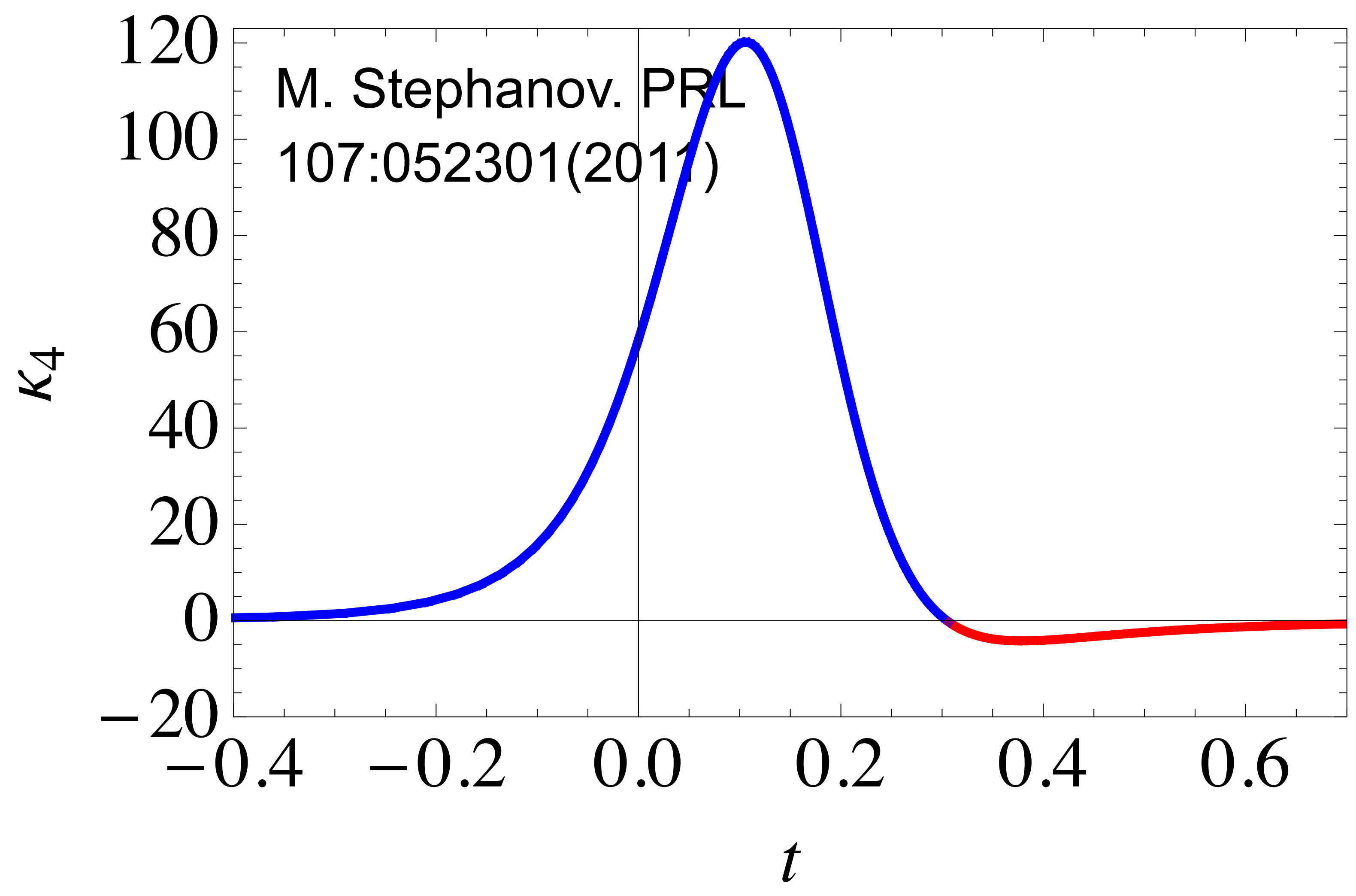
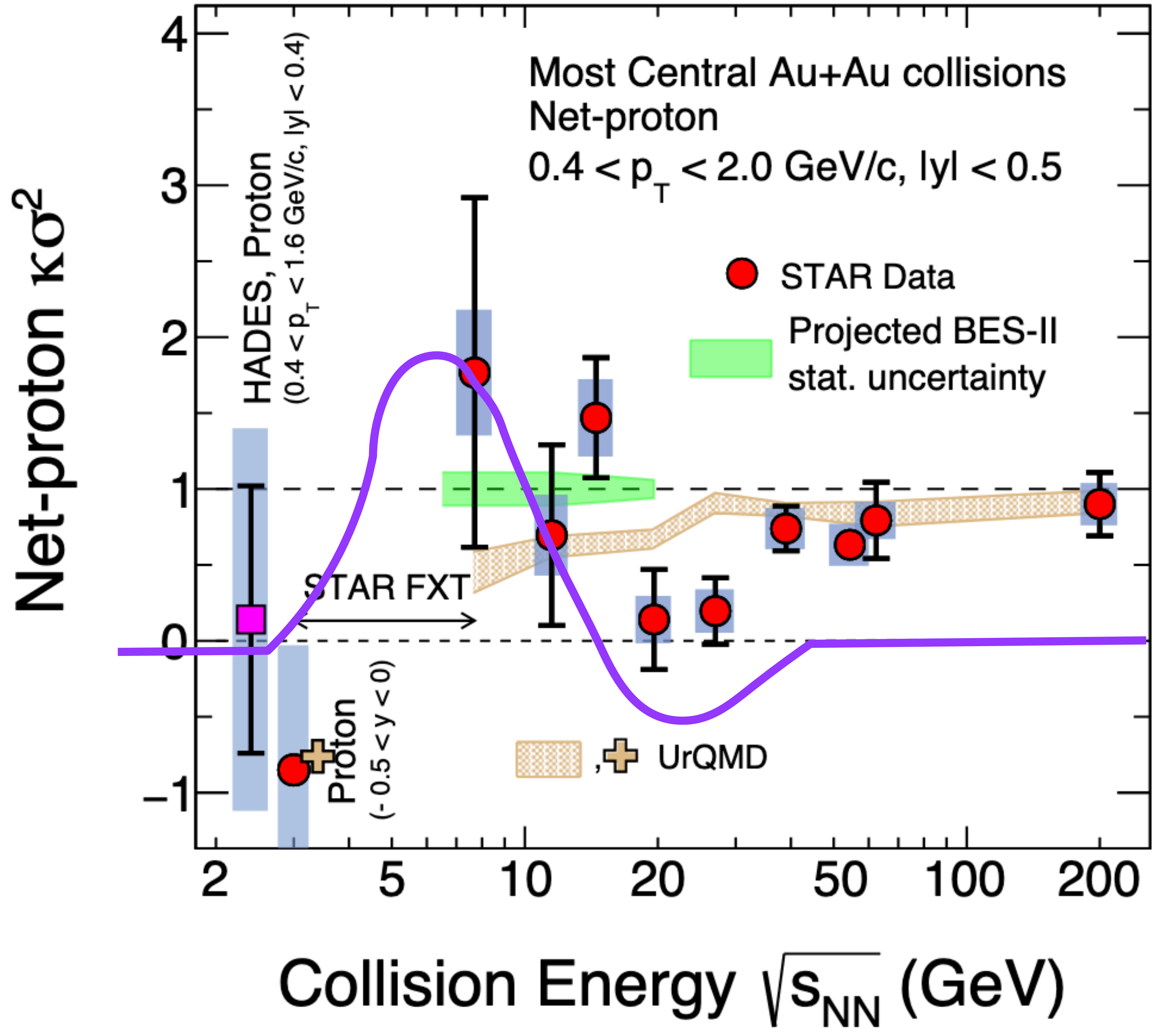


Correlation lengths diverge → Net-p $\kappa\sigma^2$ diverge

Hints of Critical fluctuations
More data needed



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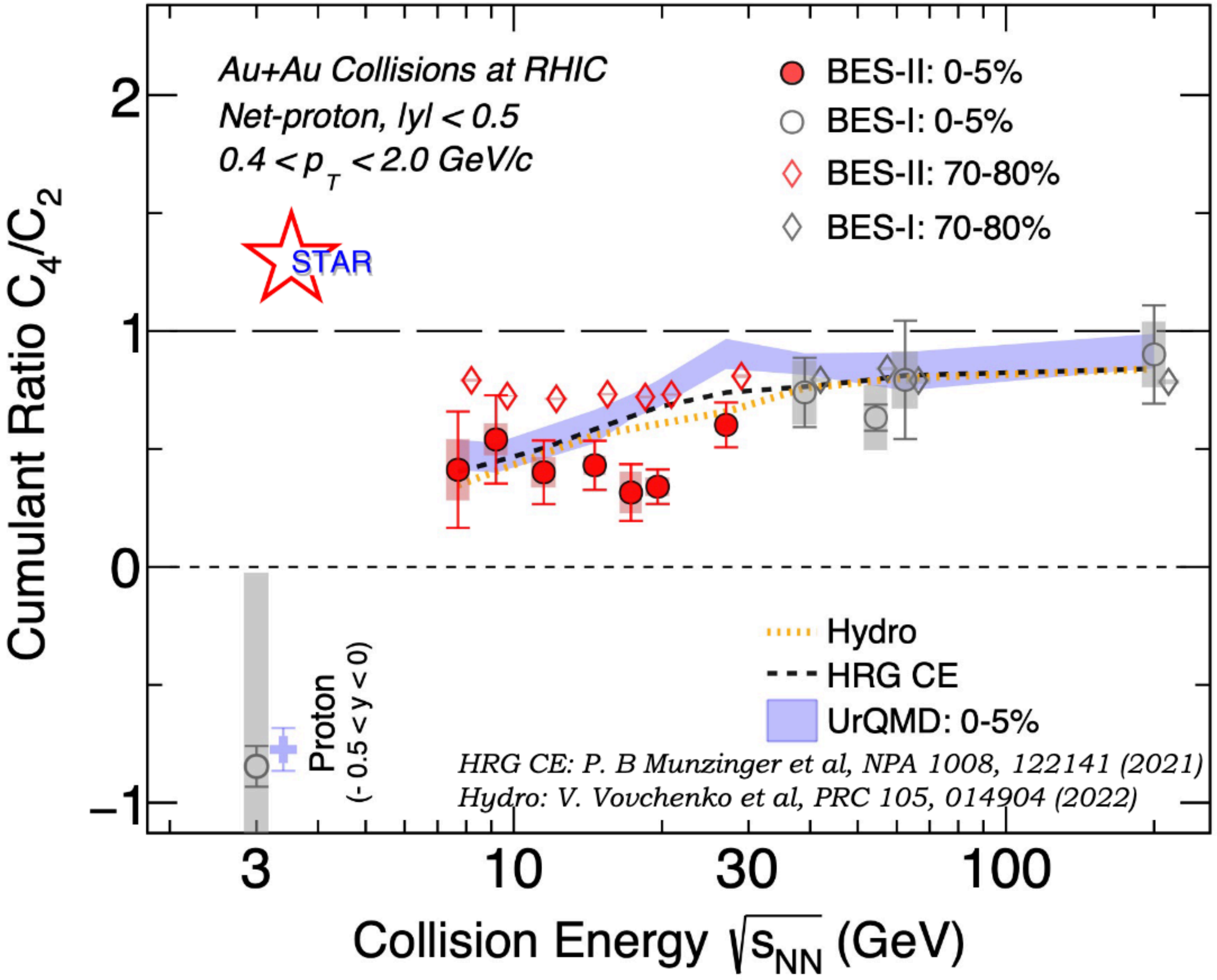
BES-II data released this month



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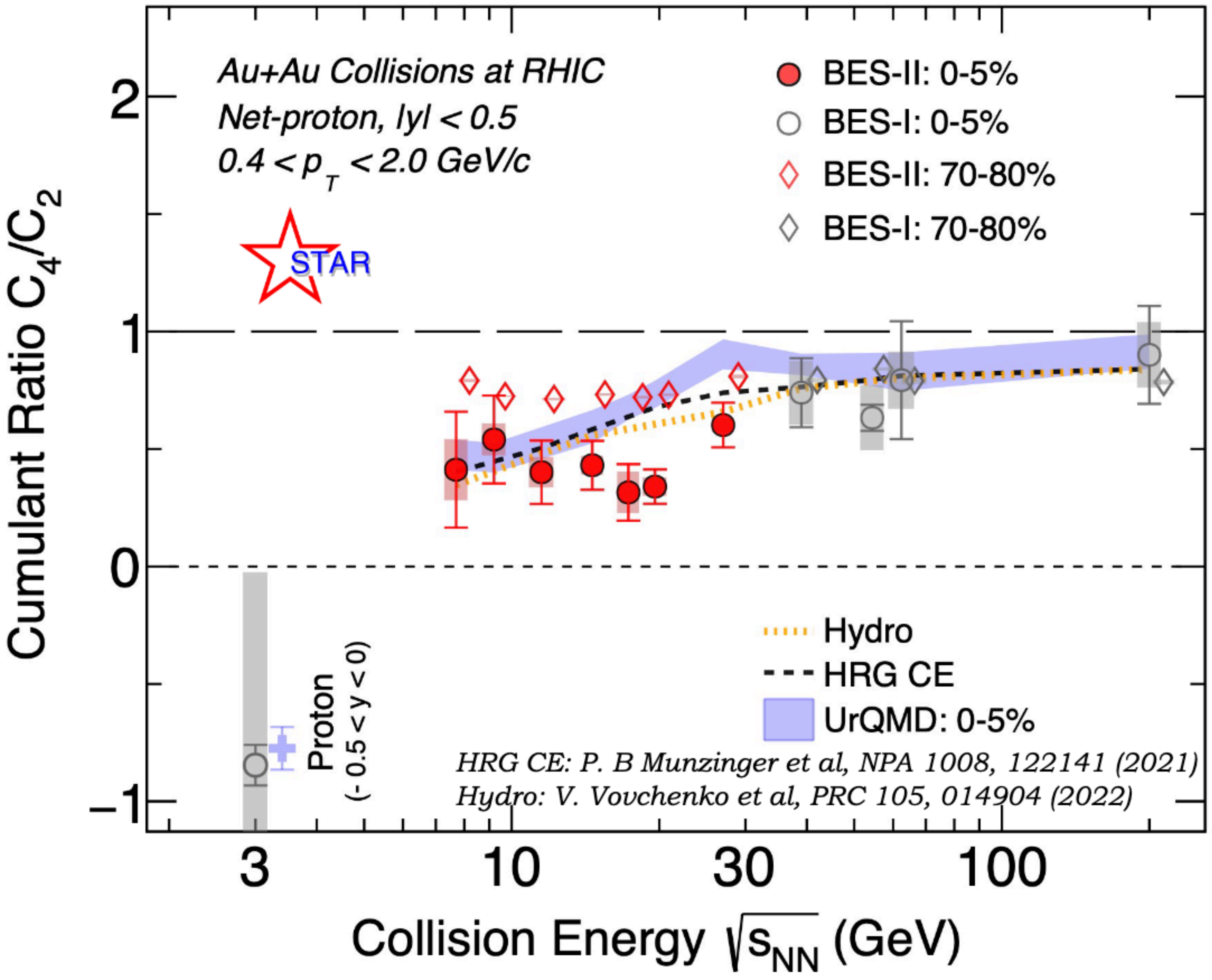
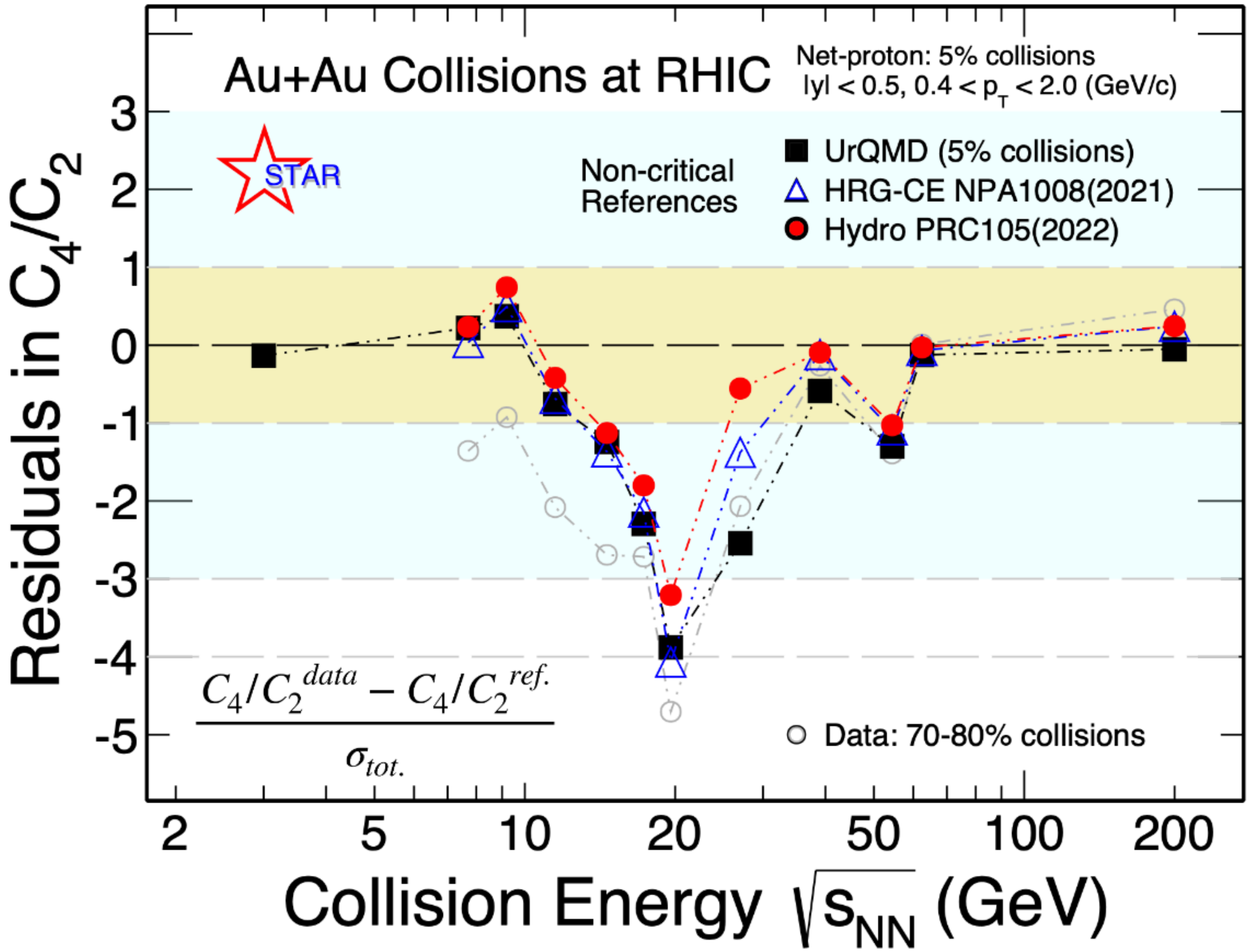




C_4/C_2 ($\kappa\sigma^2$) minimum around ~20 GeV comparing to non-CEP models and 70-80% data

Maximum deviation: 3.2 − 4.7σ at ~ 20 GeV

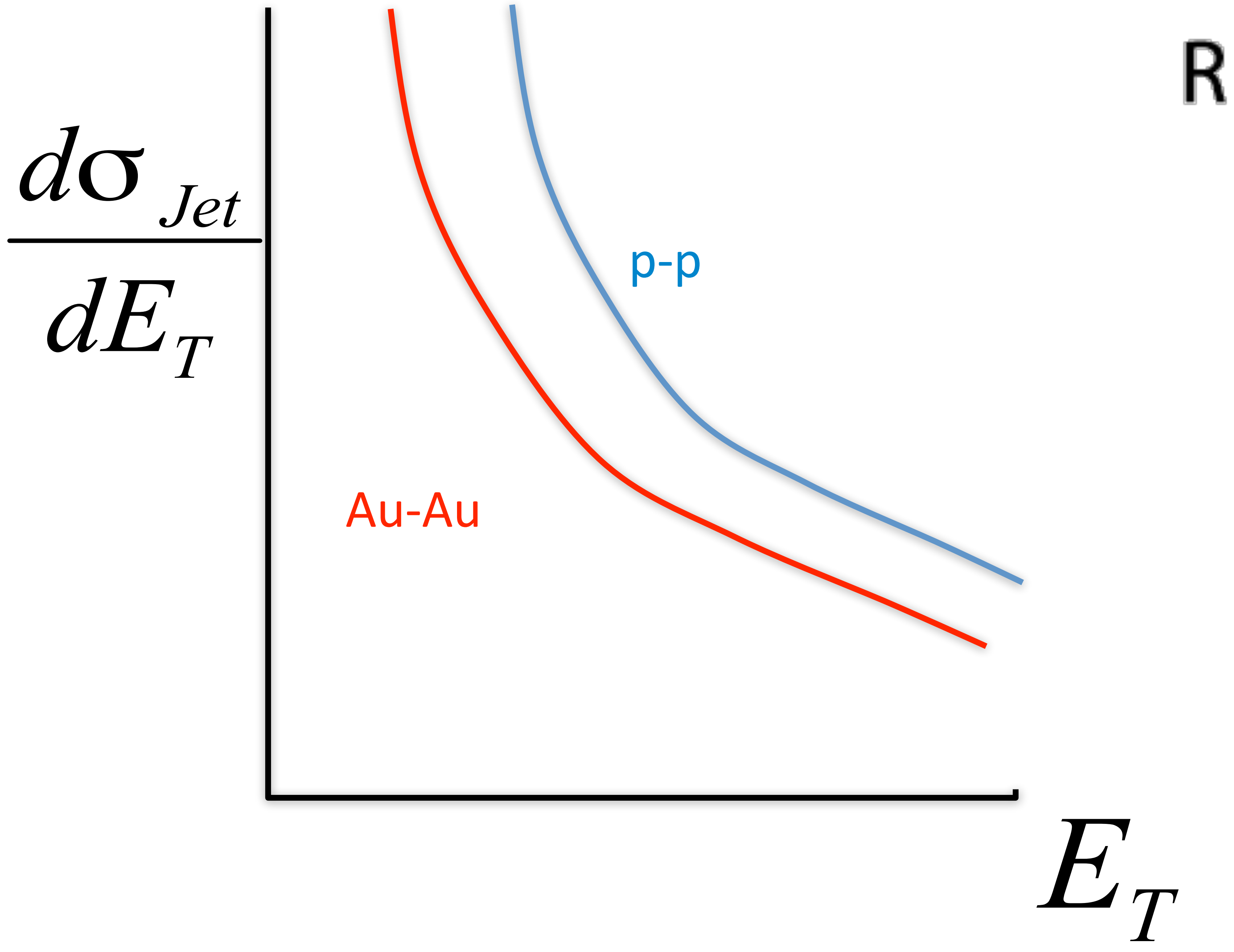
Can we understand the nature of parton interactions with the QGP?

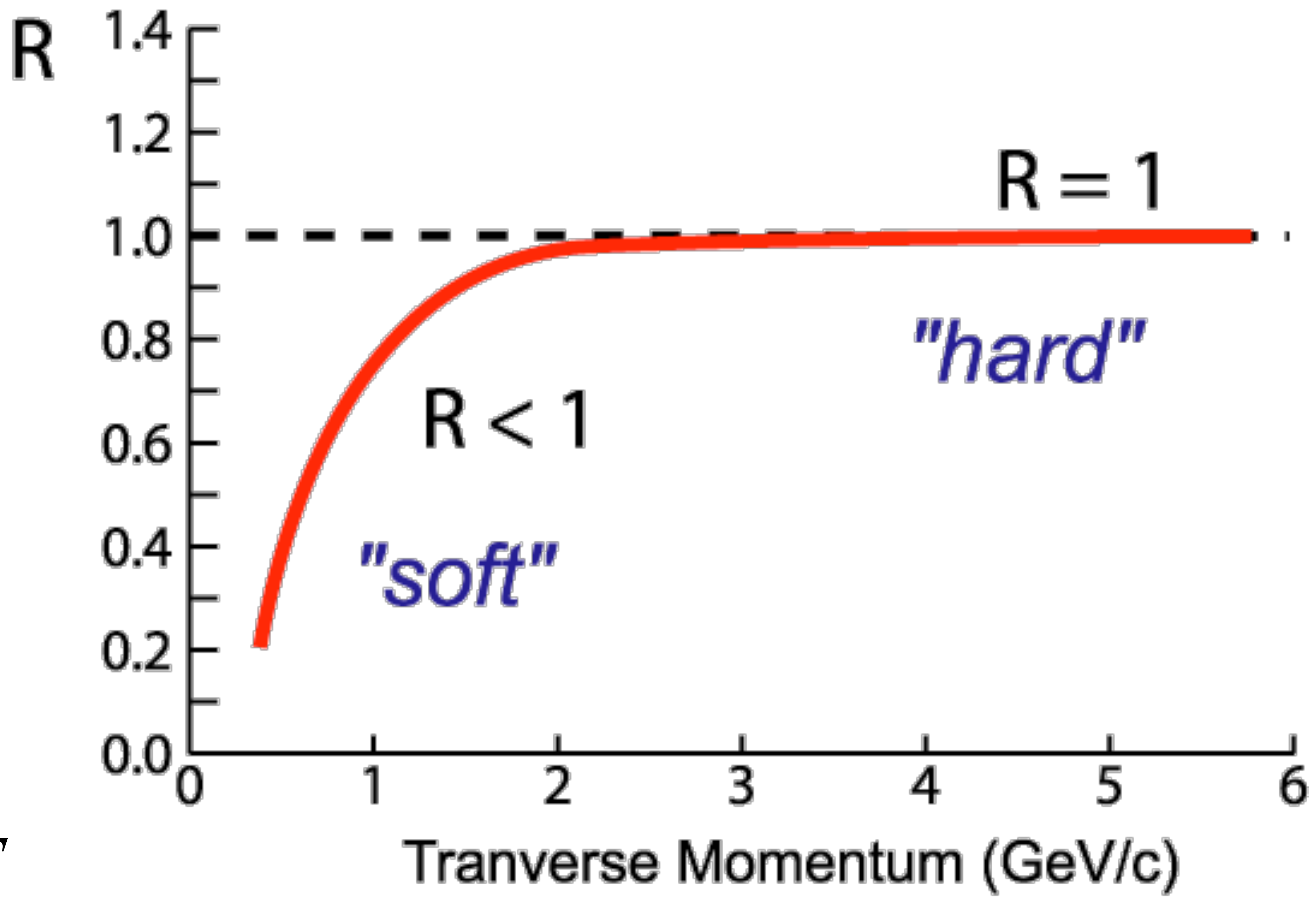
How do partons interact with the QGP?

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p)\times\langle N_{coll}\rangle}$$

Average number of p+p collisions in A+A collision





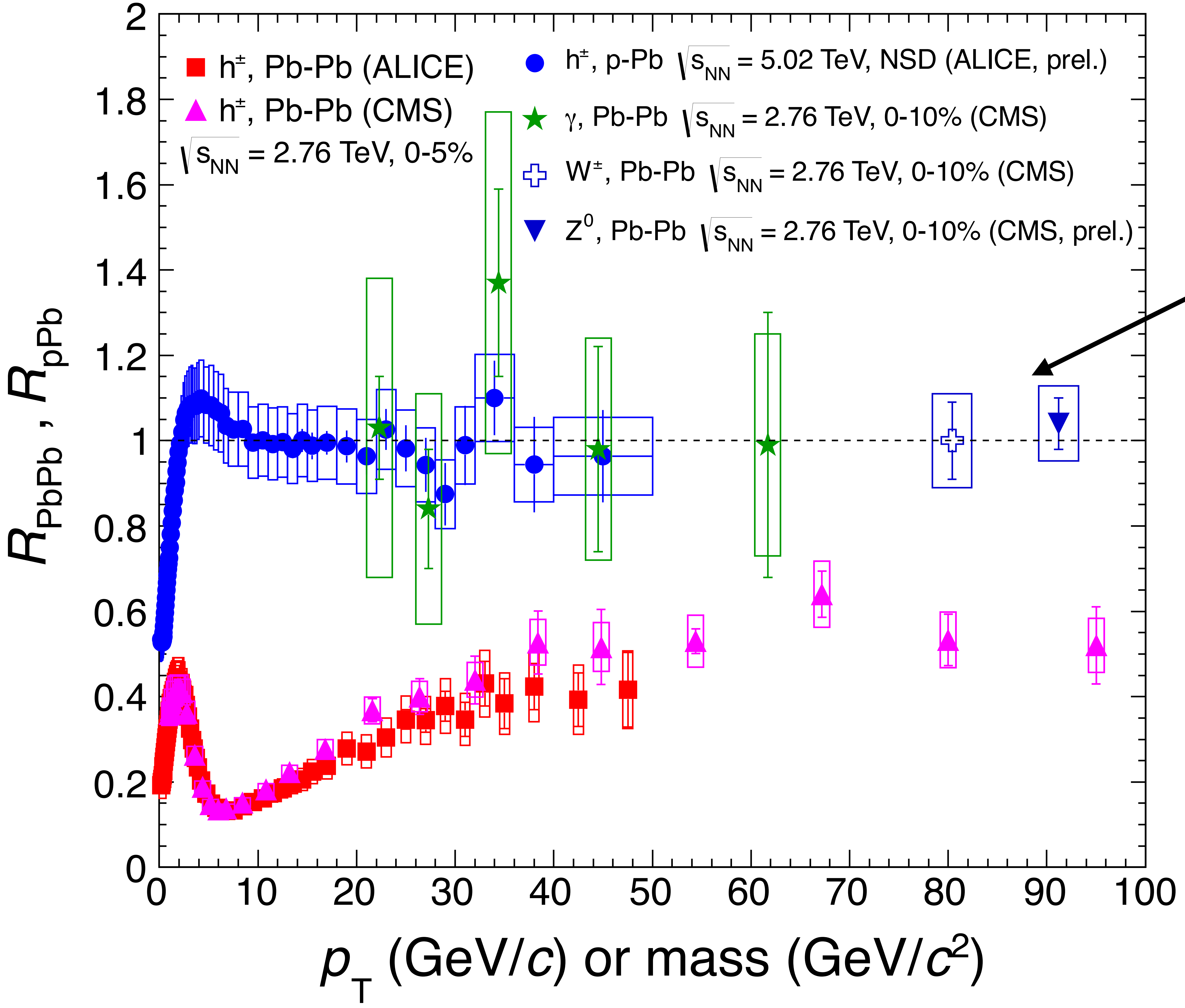
No “Effect”:

R < 1 at small momenta - production from thermal bath

R = 1 at higher momenta where hard processes dominate

R<1 at high p_T if QGP affecting partons’ propagation

Strong “jet quenching” observed



Colorless objects should not interact with colored QGP

show no suppression

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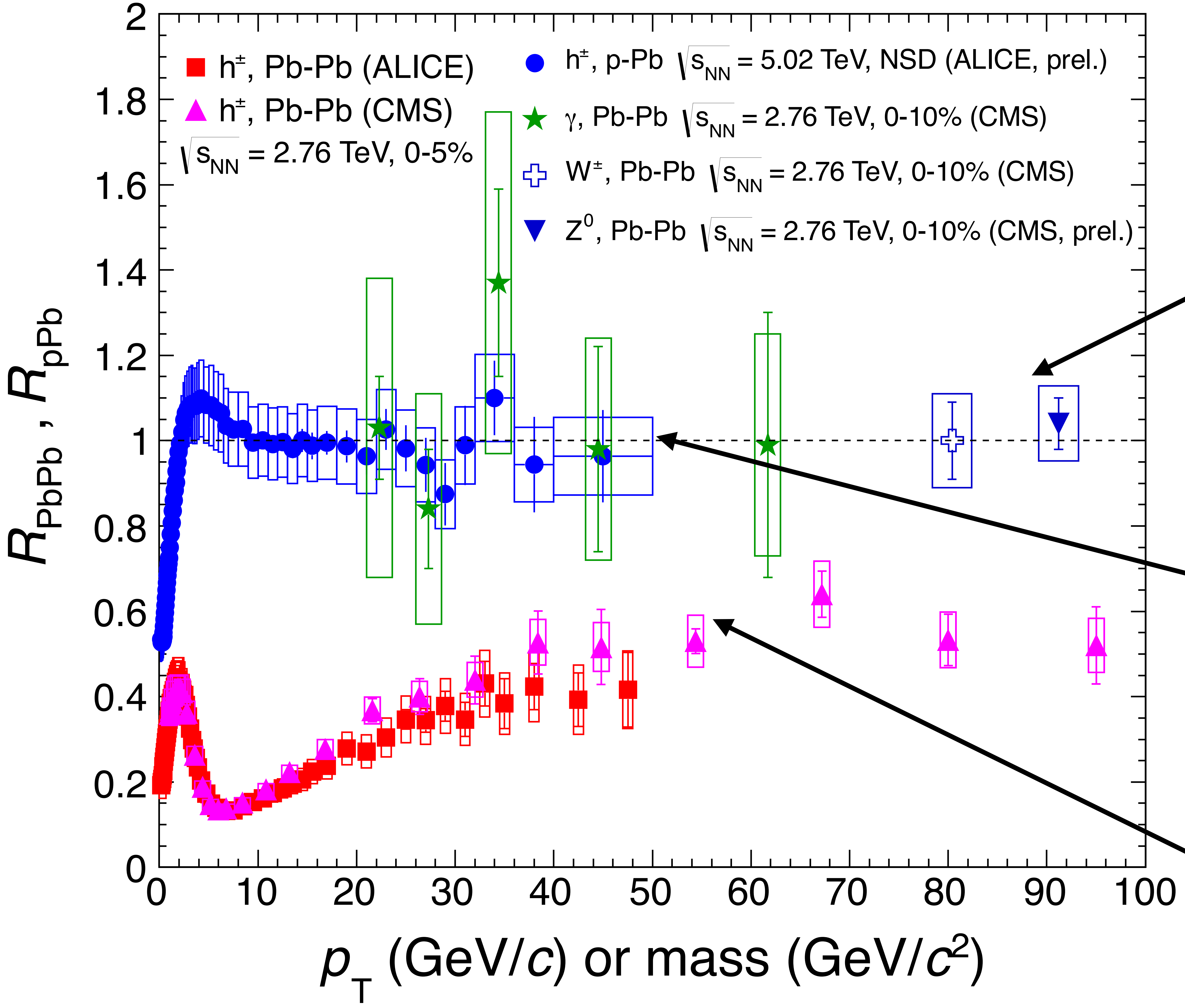


Colorless objects should not interact with colored QGP

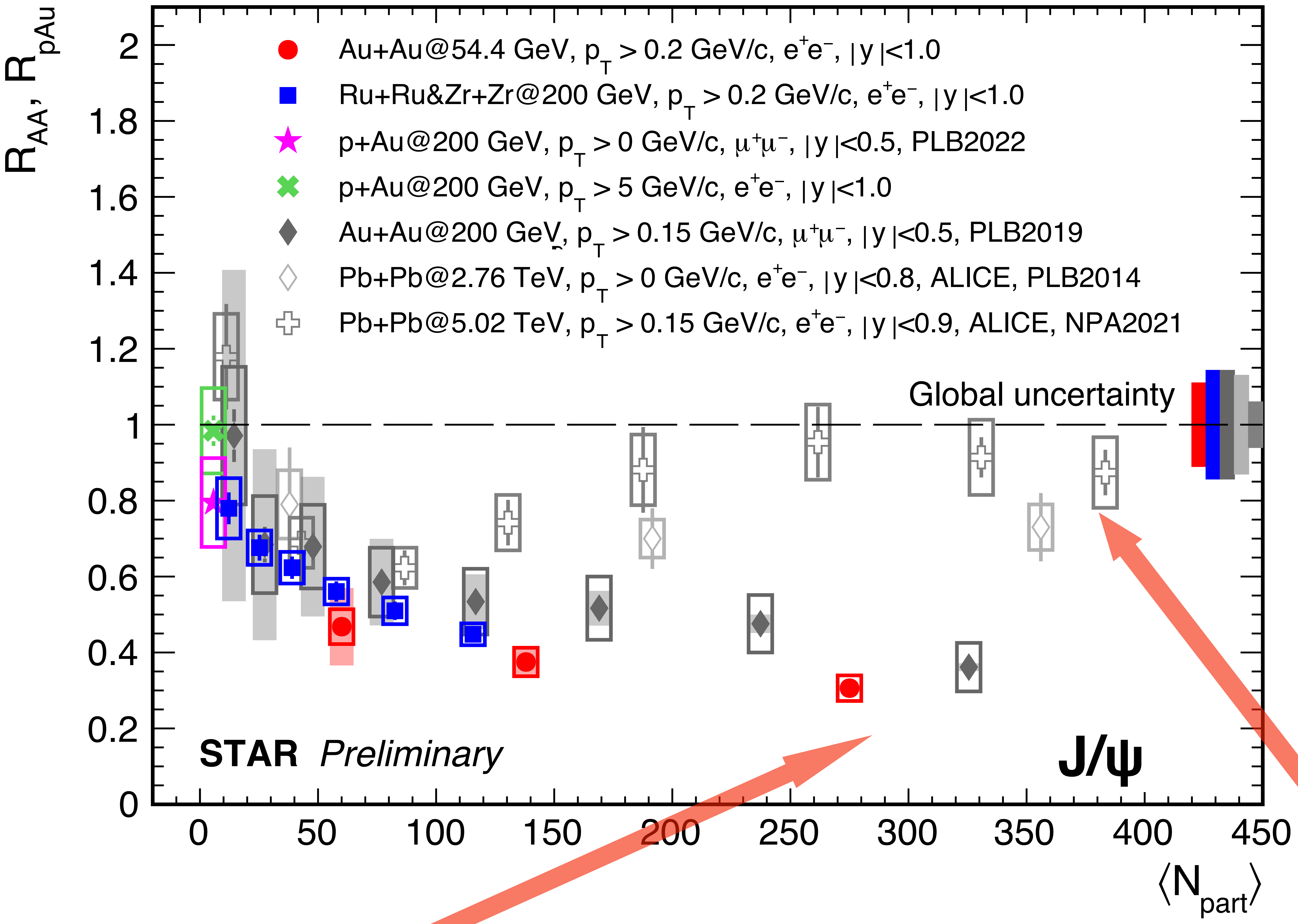
show no suppression

Minimum bias p+Pb collisions don’t form QGP

R_{pPb} shows no suppression

QGP opaque to colored objects - its a strongly coupled medium

What about charmonia?

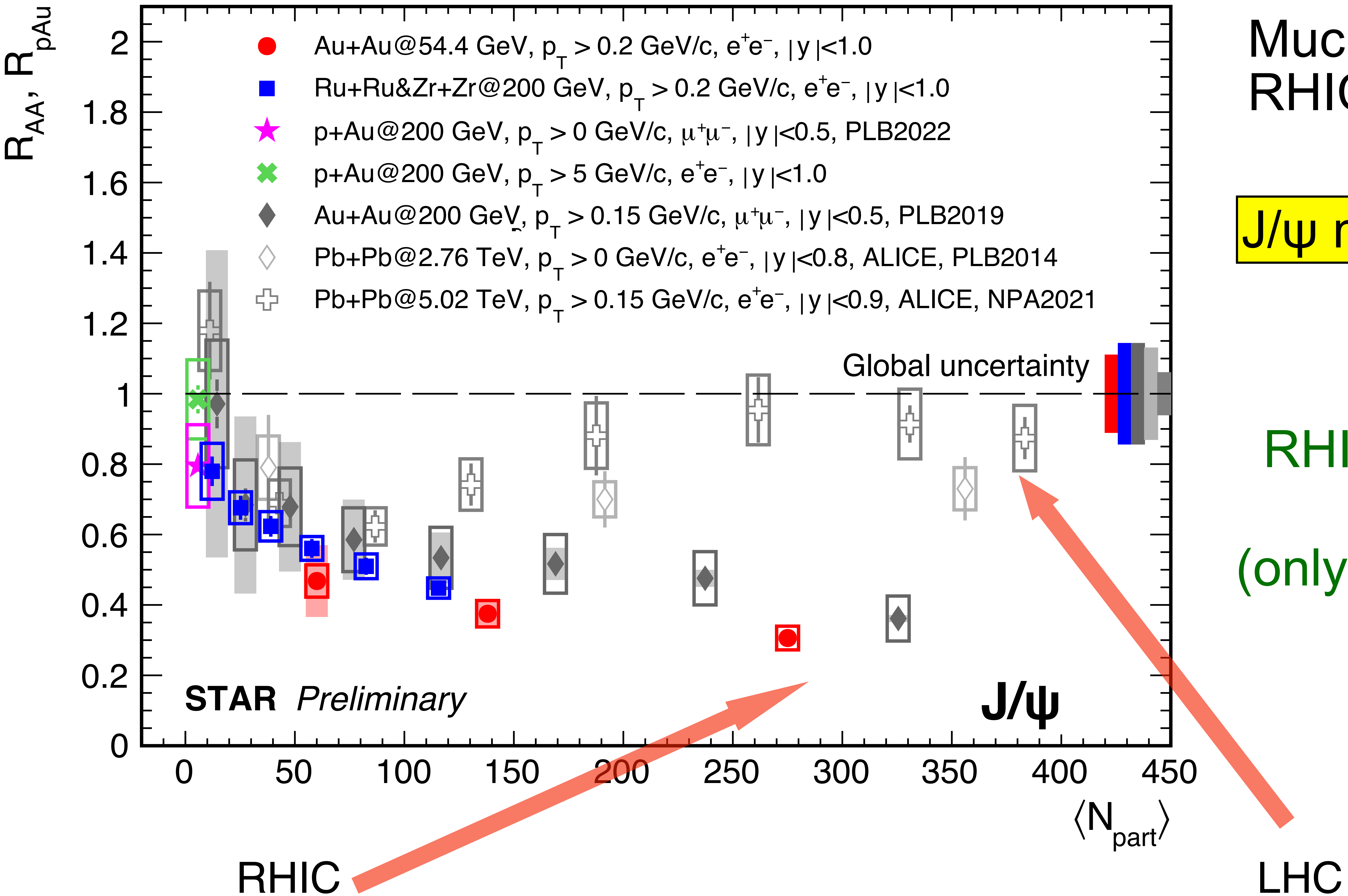


Much more suppression at RHIC than at the LHC!

RHIC

LHC

What about charmonia?



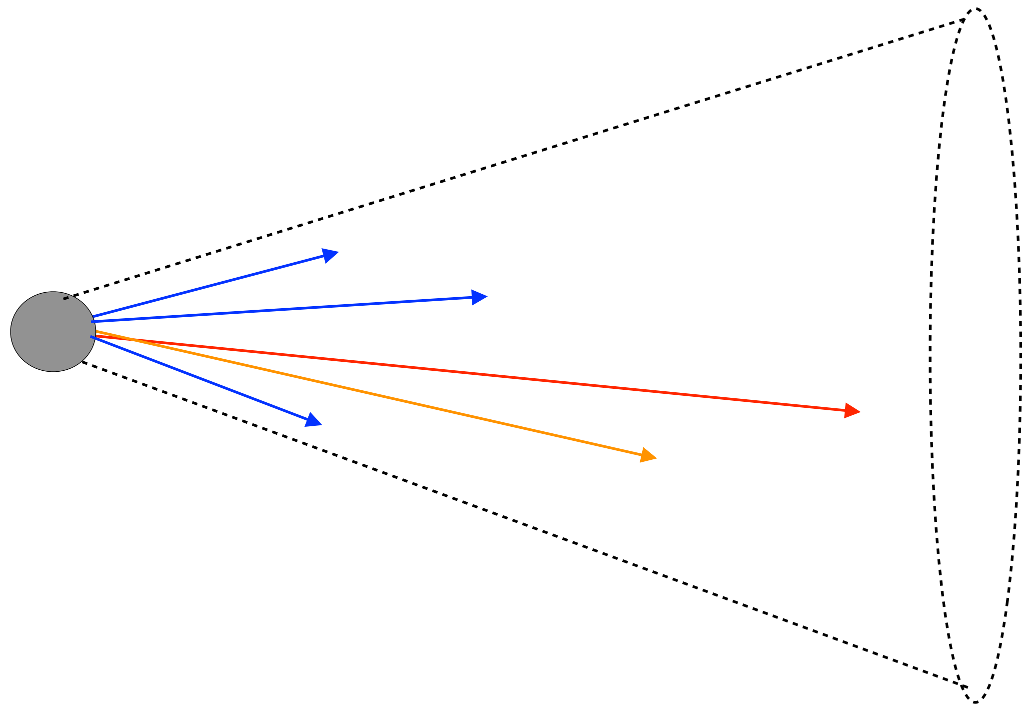
Much more suppression at RHIC than at the LHC!

J/ψ melts but also regenerates

RHIC much less regeneration in the medium
(only a few c quarks created, once melted don't reform)

What about looking at jets?

p and E MUST be conserved even with quenched jets



Can we restore “quenched” energy by looking at jets?

Study nuclear modification factor (R_{AA}) of jets

ATLAS: PLB 790 (2019) 108

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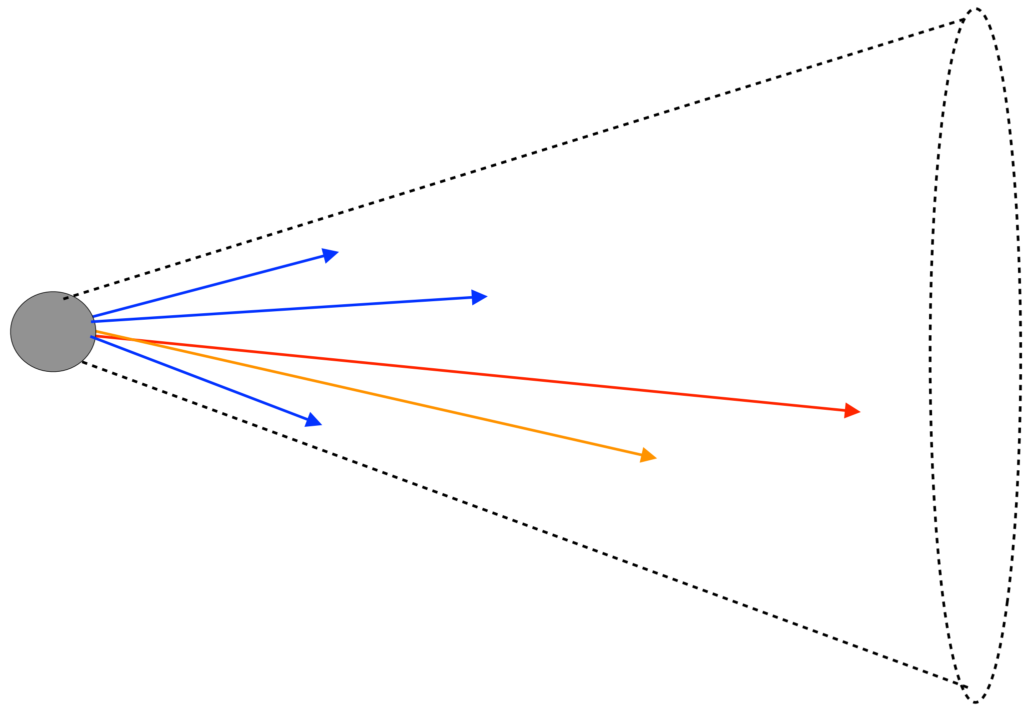

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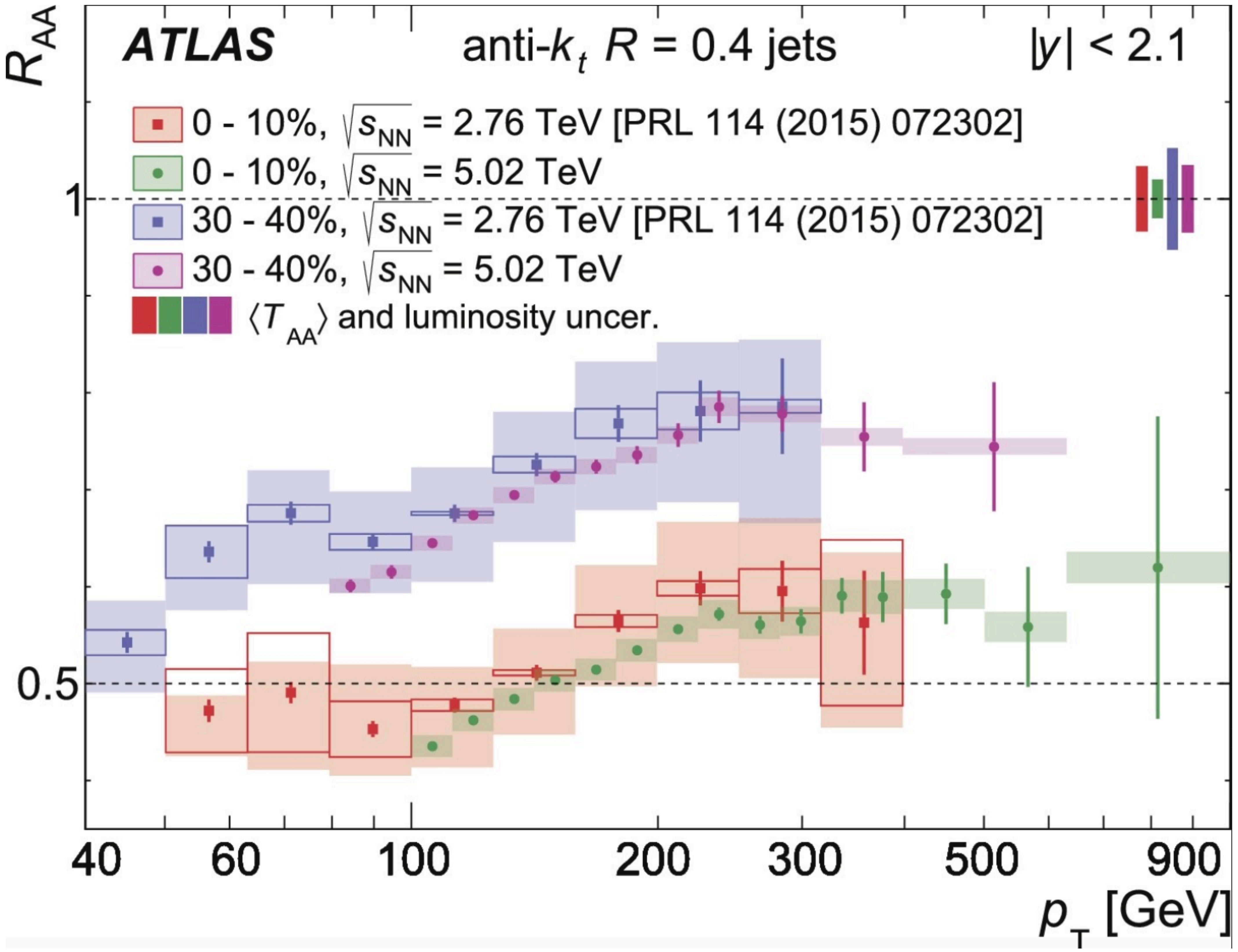


Quenched energy not recovered

R_{AA}(5 TeV) ~ R_{AA}(2.76 TeV)

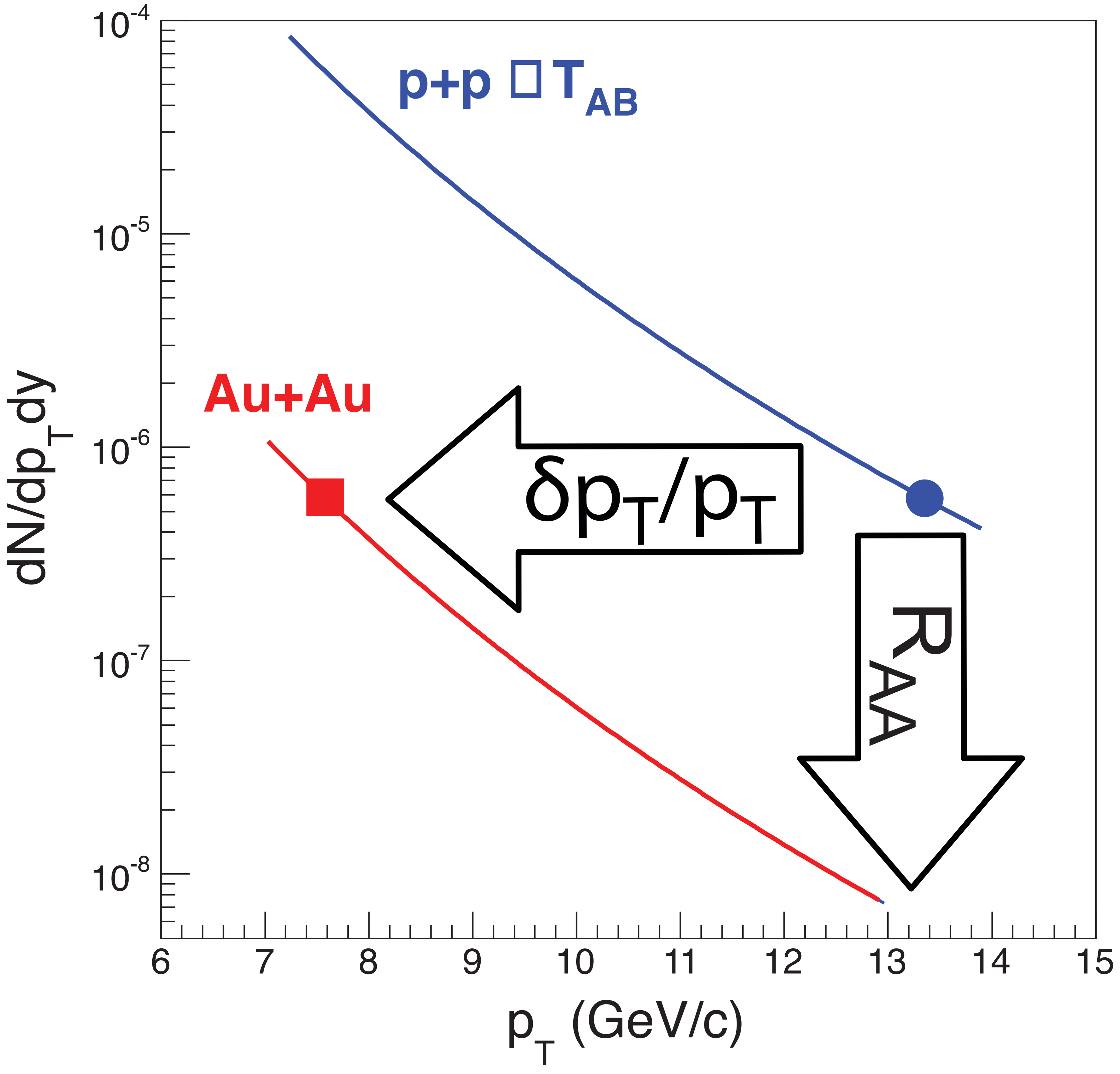
Compensating effects of higher E_{loss} and flatter p_T spectrum

ATLAS: PLB 790 (2019) 108

Opaqueness/stopping power of QGP

Measure fractional momentum loss

$\delta p_T/p_T$ instead of R_{AA}



ATLAS: PLB 846 (2023) 138154

Opaqueness/stopping power of QGP

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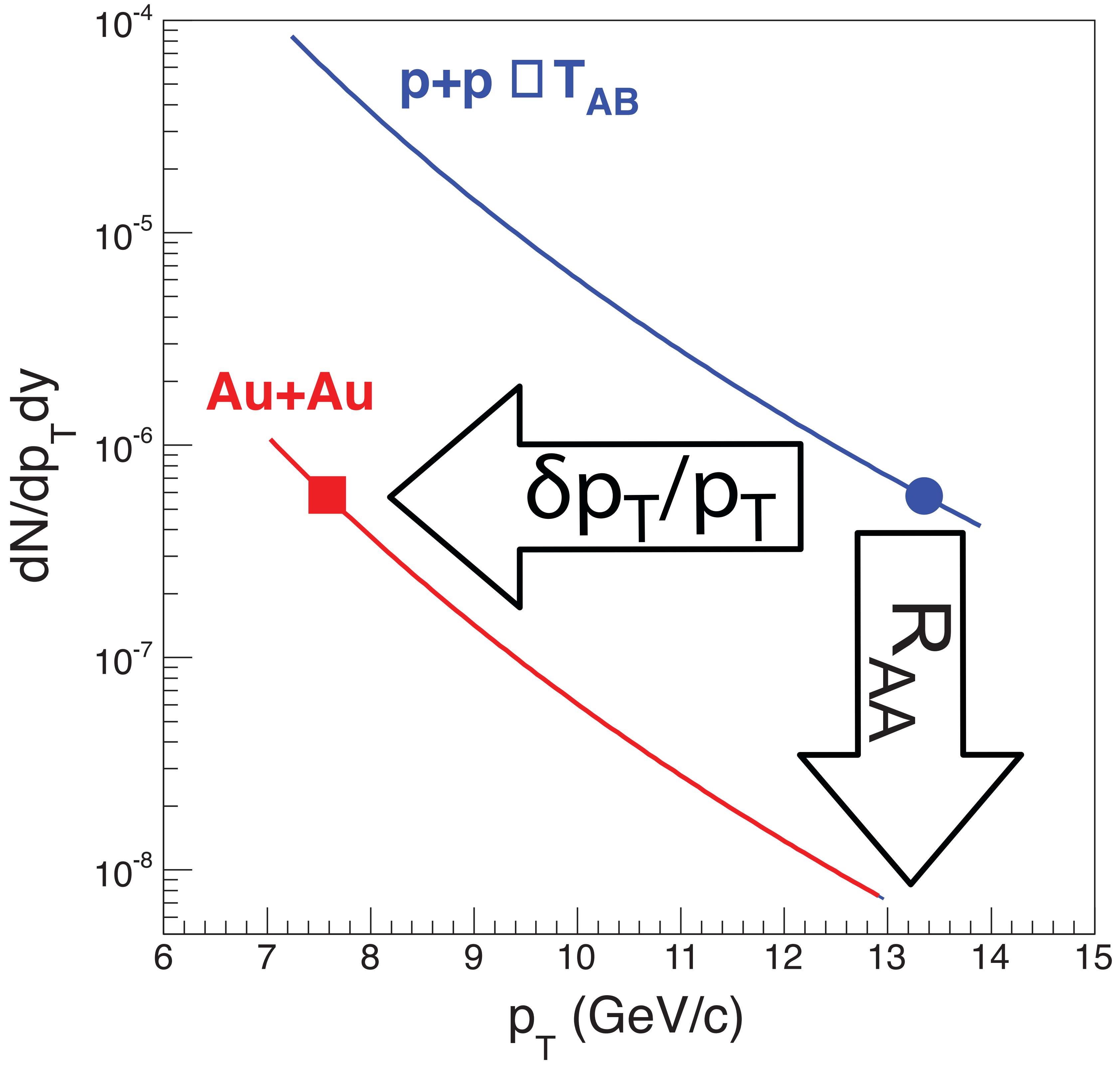

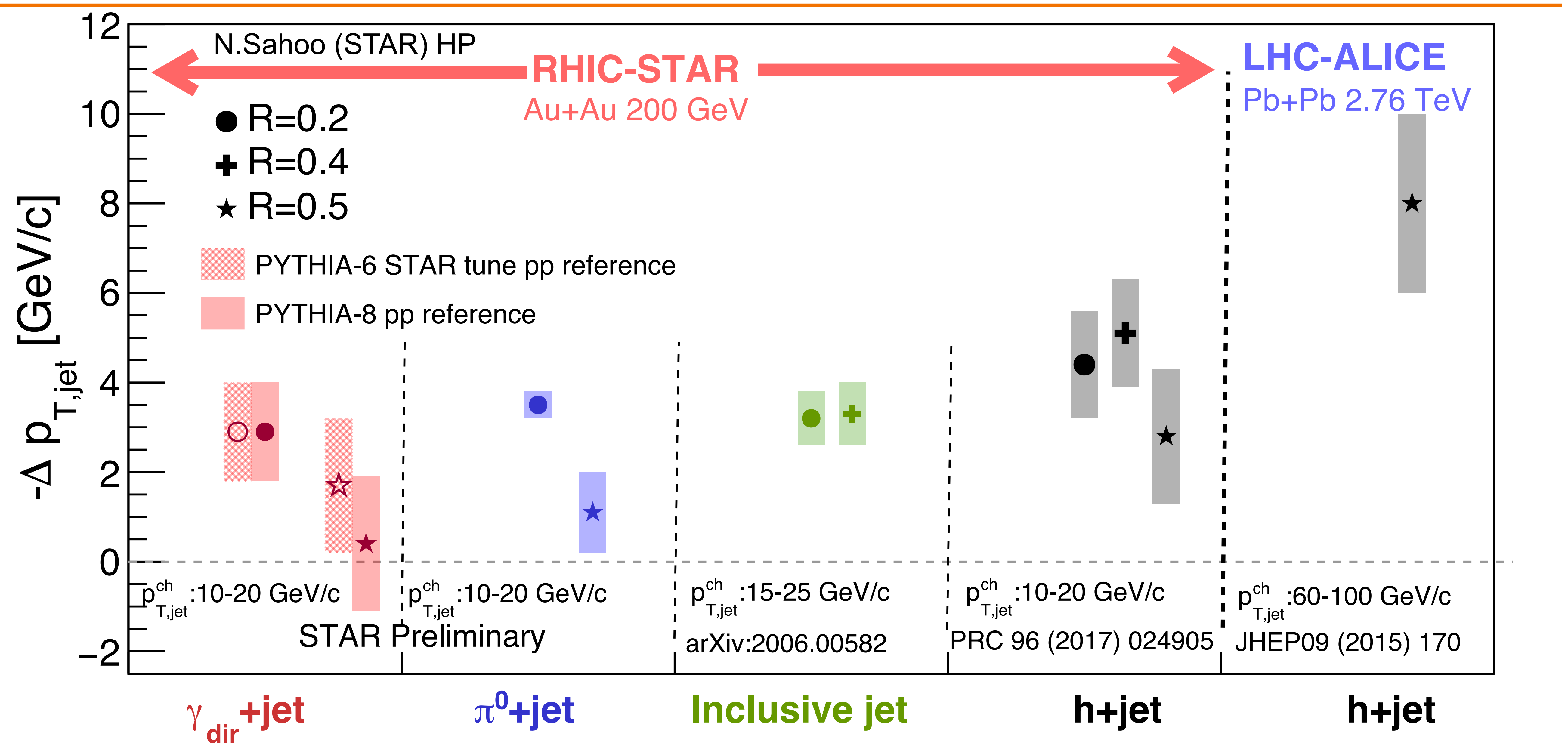

ATLAS: PLB 846 (2023) 138154

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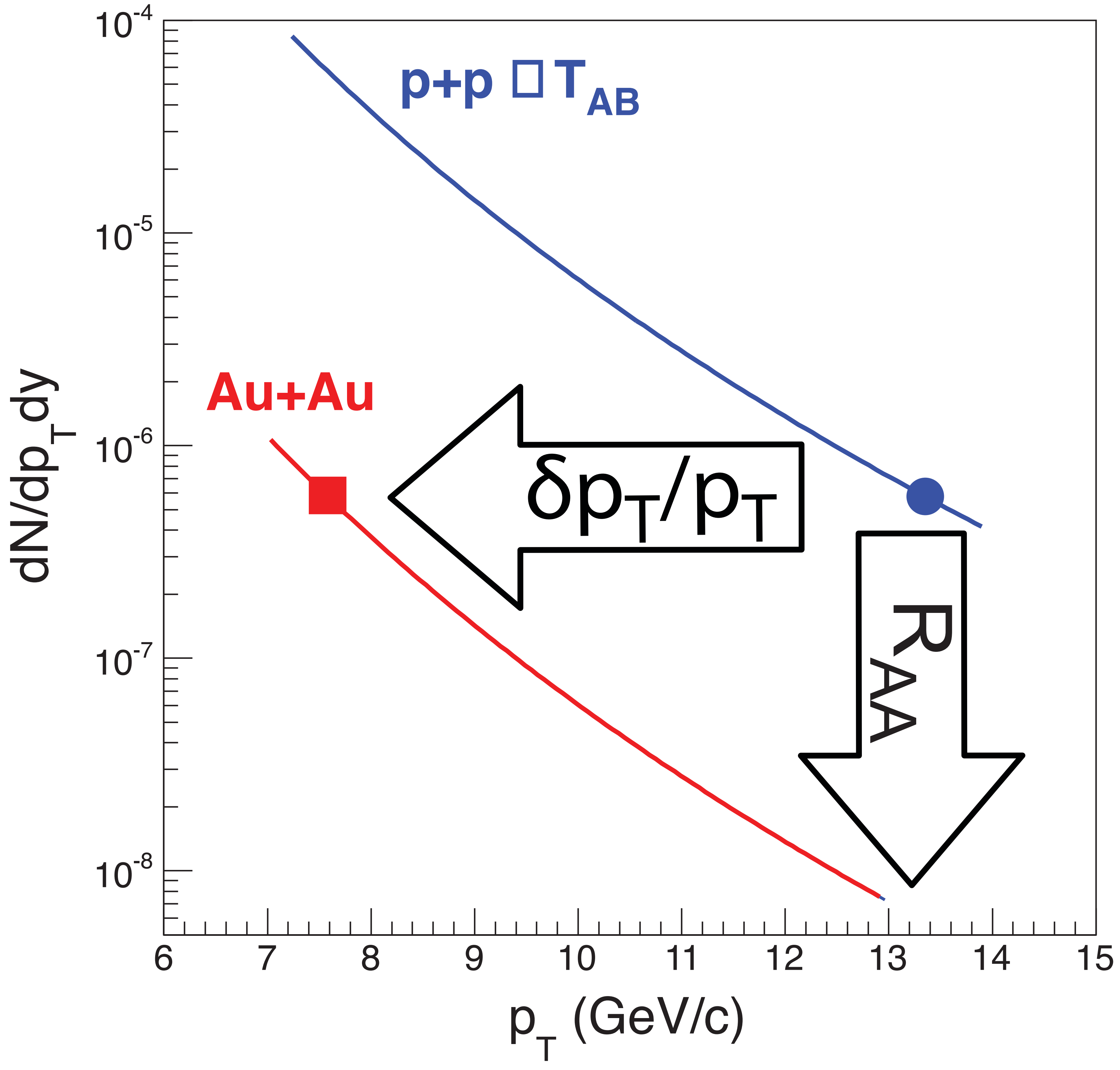
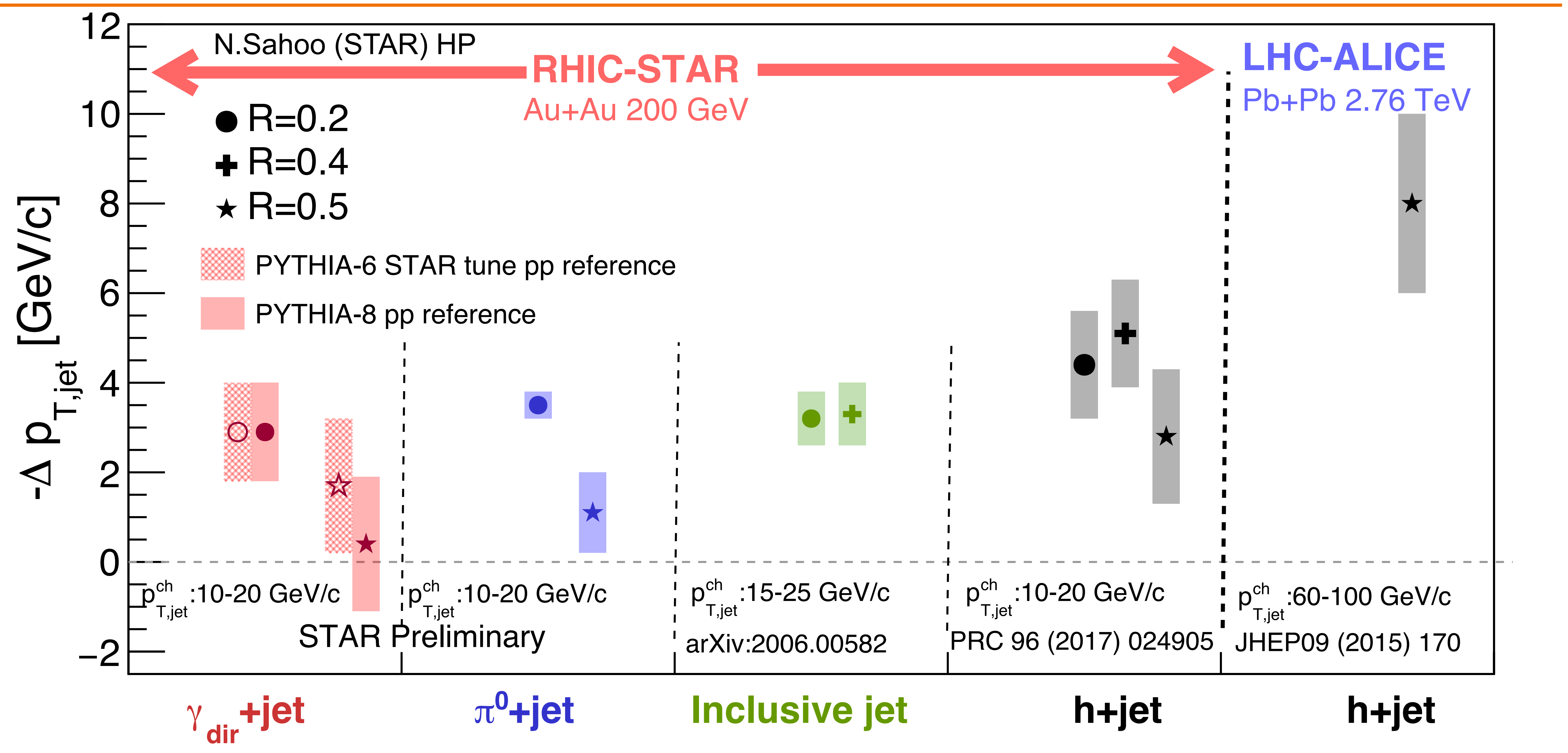
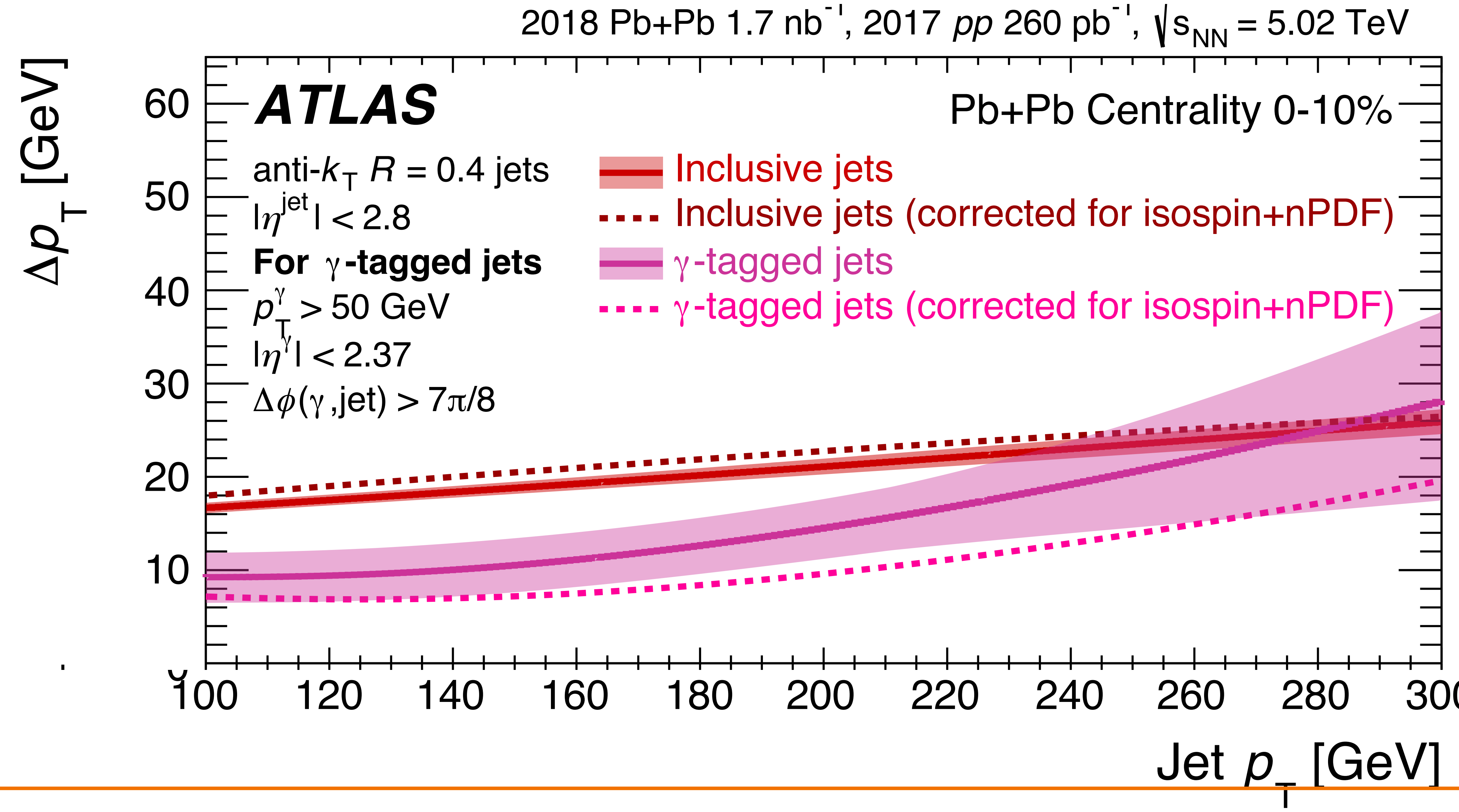


Δp_T (RHIC) < Δp_T (LHC)
Δp_T (quark) < Δp_T (g)

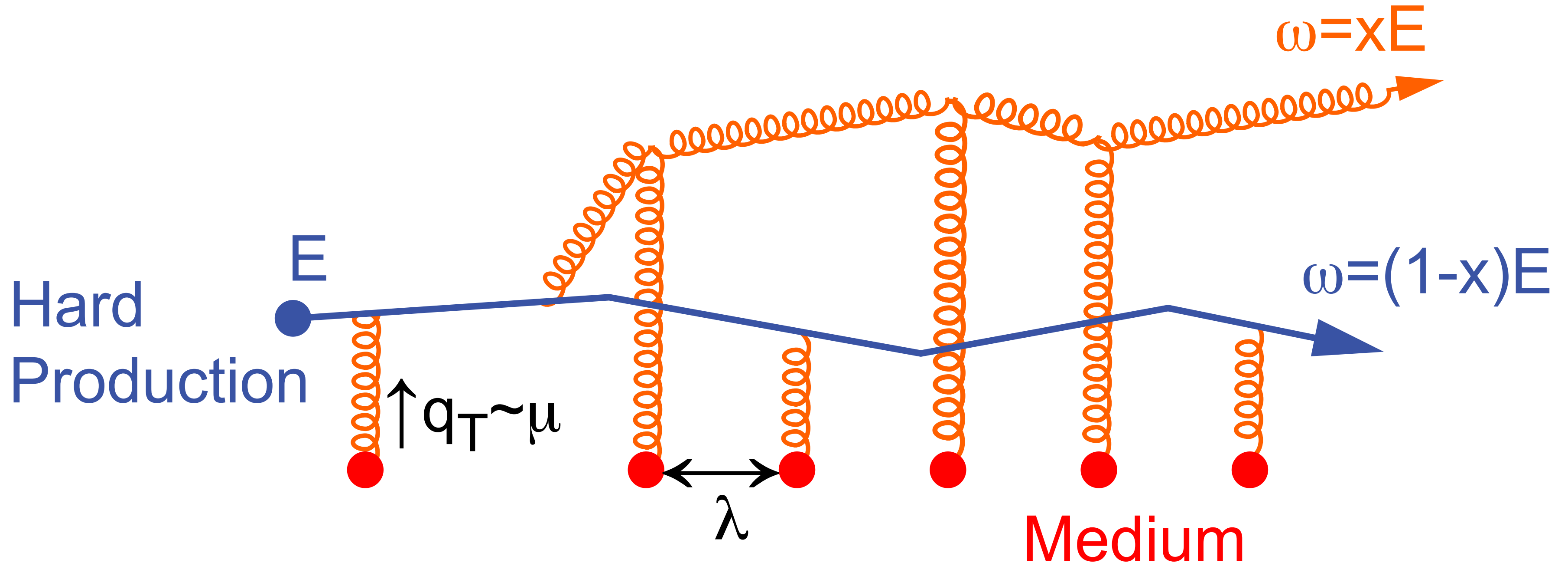




ATLAS: PLB 846 (2023) 138154

So what is happening?

Jet quenching understood to arise from elastic and inelastic interactions of partons with QGP, with coherence effects playing an important role



Modification of Jet Structure

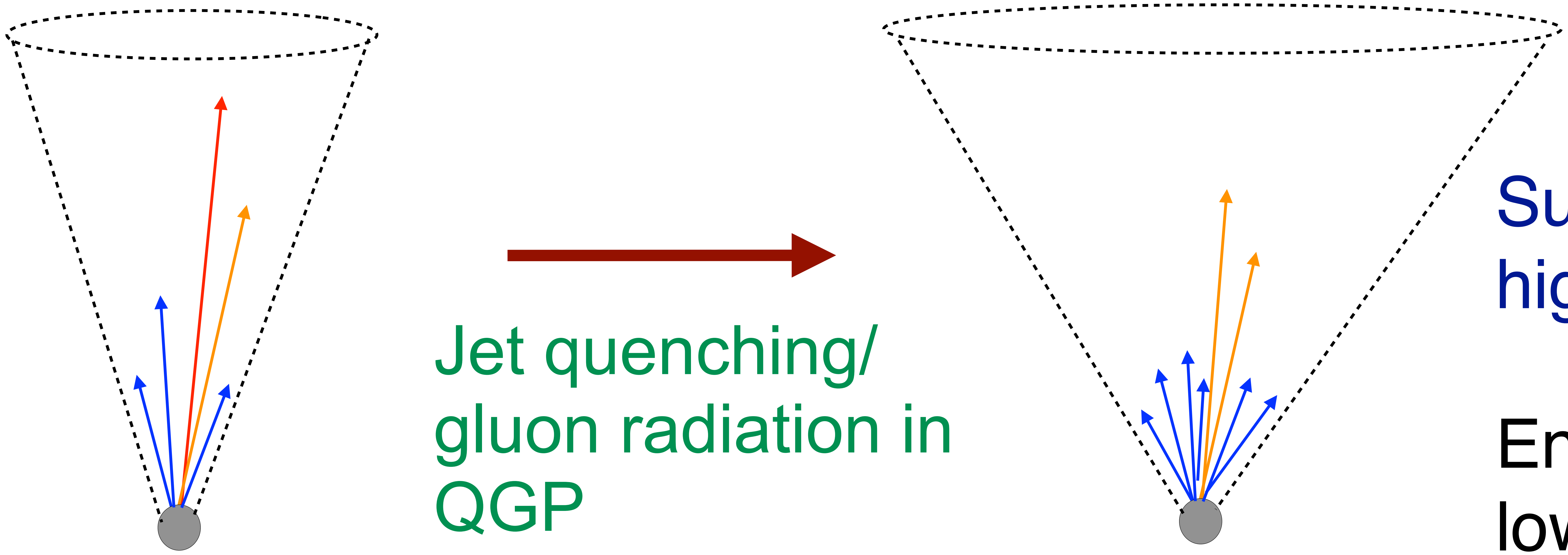
Jet in vacuum

E^{Jet}_{Vacuum}

Jet in medium

$E^{Jet}_{Medium}=E^{Jet}_{Vacuum}$

Jet broadening

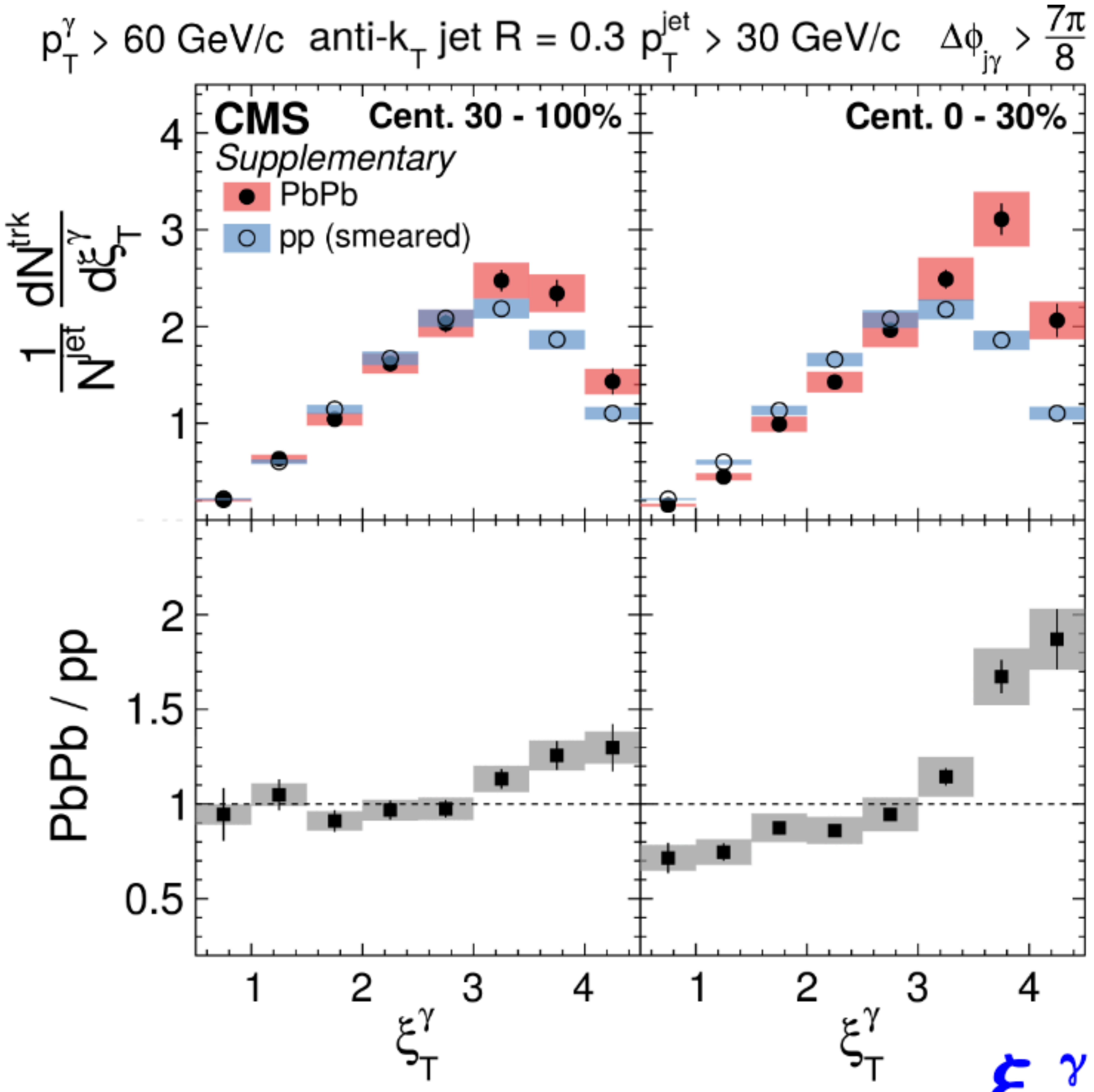


Jet quenching/ gluon radiation in QGP

Suppression of high-p_T particles

Enhancement of low-p_T particles

Where does the energy go?



ξ_T^γ

Reconstruct jet recoiling from high p_T photon

- since photons don't interact "know" initial parton energy

Examine fragmentation hadrons

$$\xi_T^\gamma = \ln\left[-|\vec{p}_T^{\,\gamma}|^2/(\vec{p}_T^{\,trk}\cdot\vec{p}_T^{\,\gamma})\right]$$

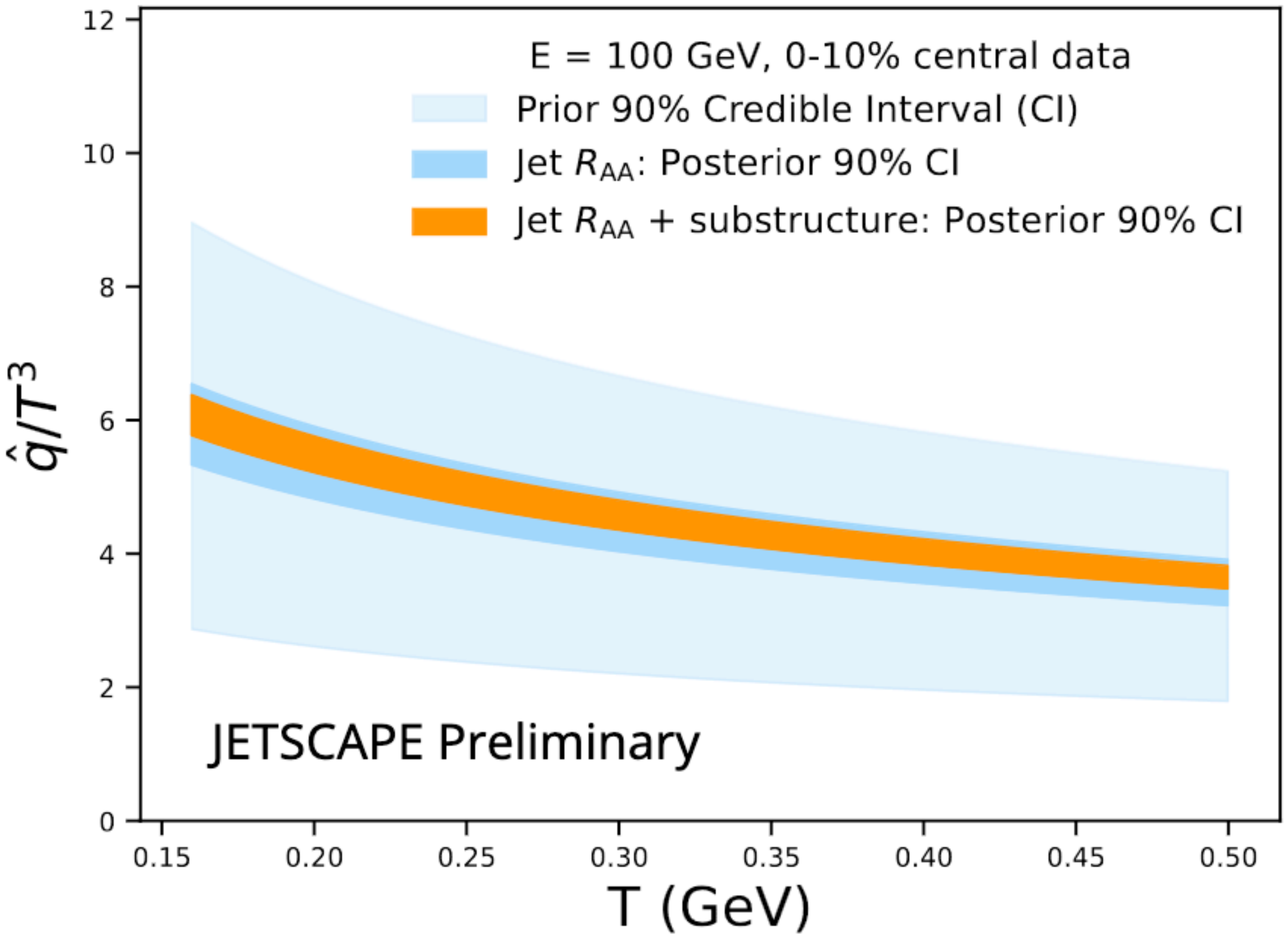
- take ratio Pb+Pb/p+p

"Lost" hard particles emerge as multiple soft particles

- Jet substructure is highly modified
- Particles emerge at large R and low p_T

CMS: PRL121,(2018) 242301

Determining QGP transport properties



Advances continue - especially via JETSCAPE (but not only) - exploit bayesian inference

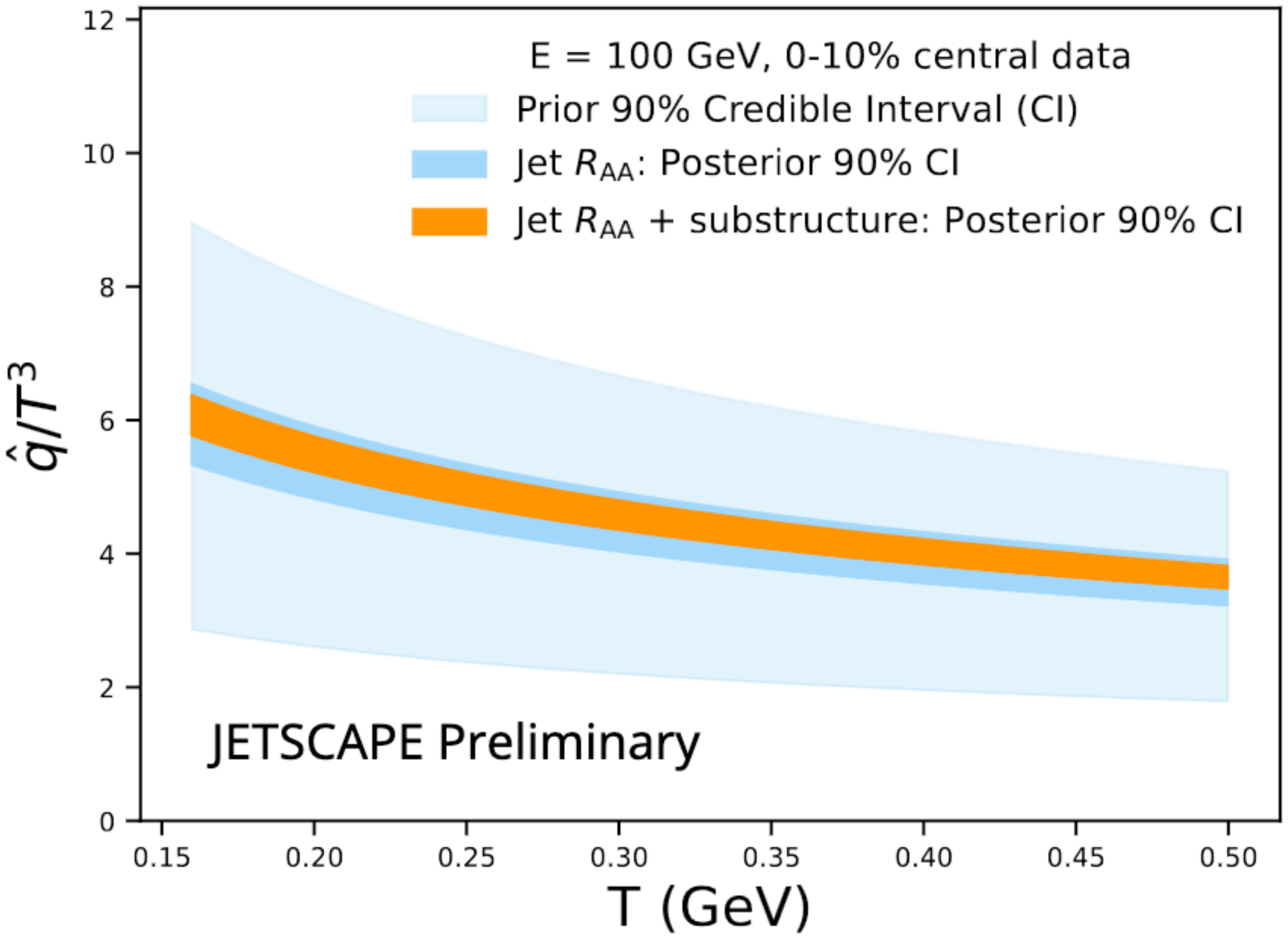
Now includes jet R_{AA} and substructure measurements

$\hat{q} = Q^2/L$ Q - mtm transfer to medium
L - path length

Most precise estimate to-date

Does the T evolution explain differences at RHIC and the LHC?

Determining QGP transport properties



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Most precise estimate to-date

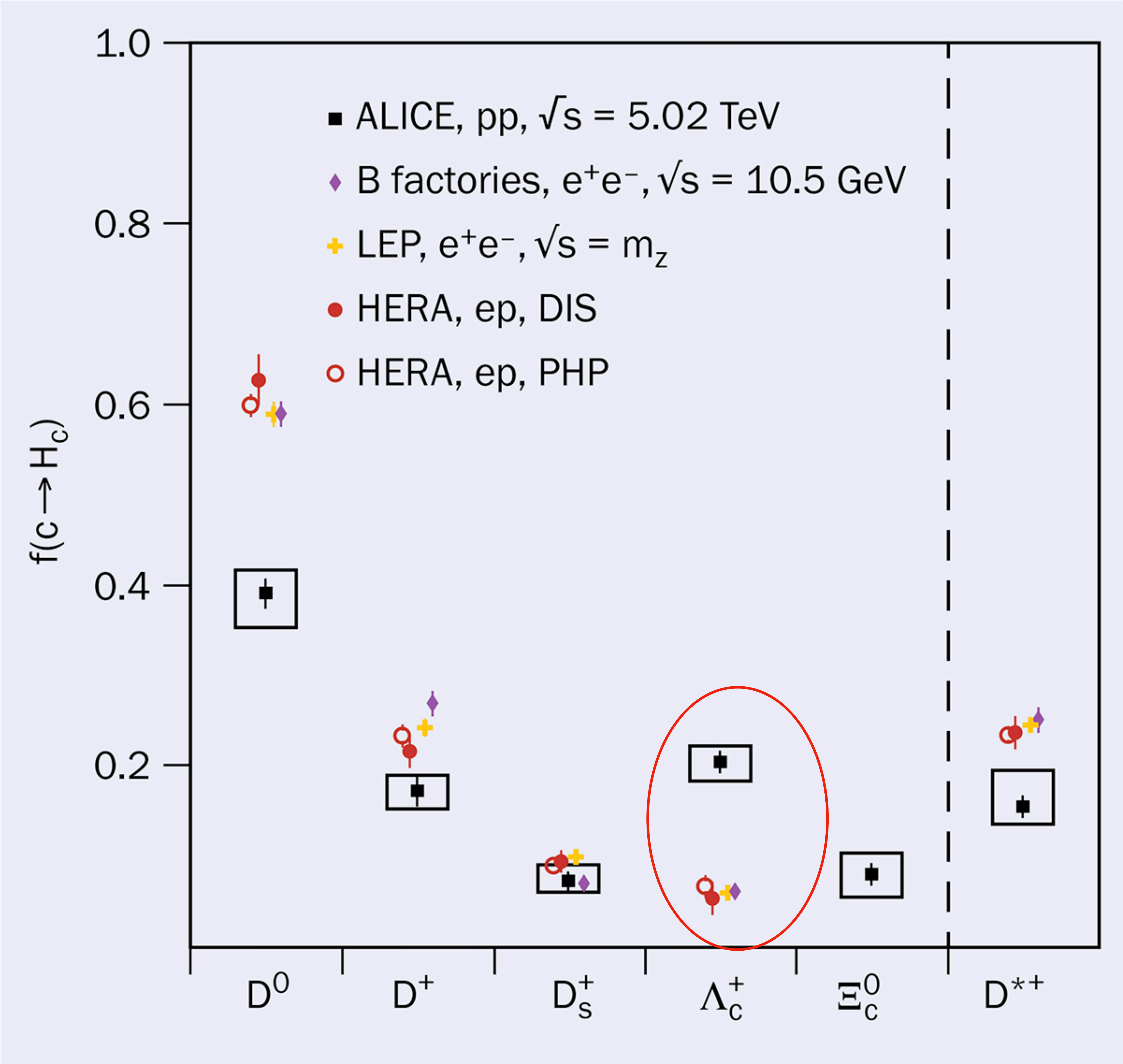
Does the T evolution explain differences at RHIC and the LHC?

Some physics missing?
Uncertainties incorrect?
Theory uncertainty critical?
All of the above?

Some tension when include hadron R_{AA}

Unexpected physics found along the way

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 → H_c) from p+p collisions different to e^+e^- and ep data

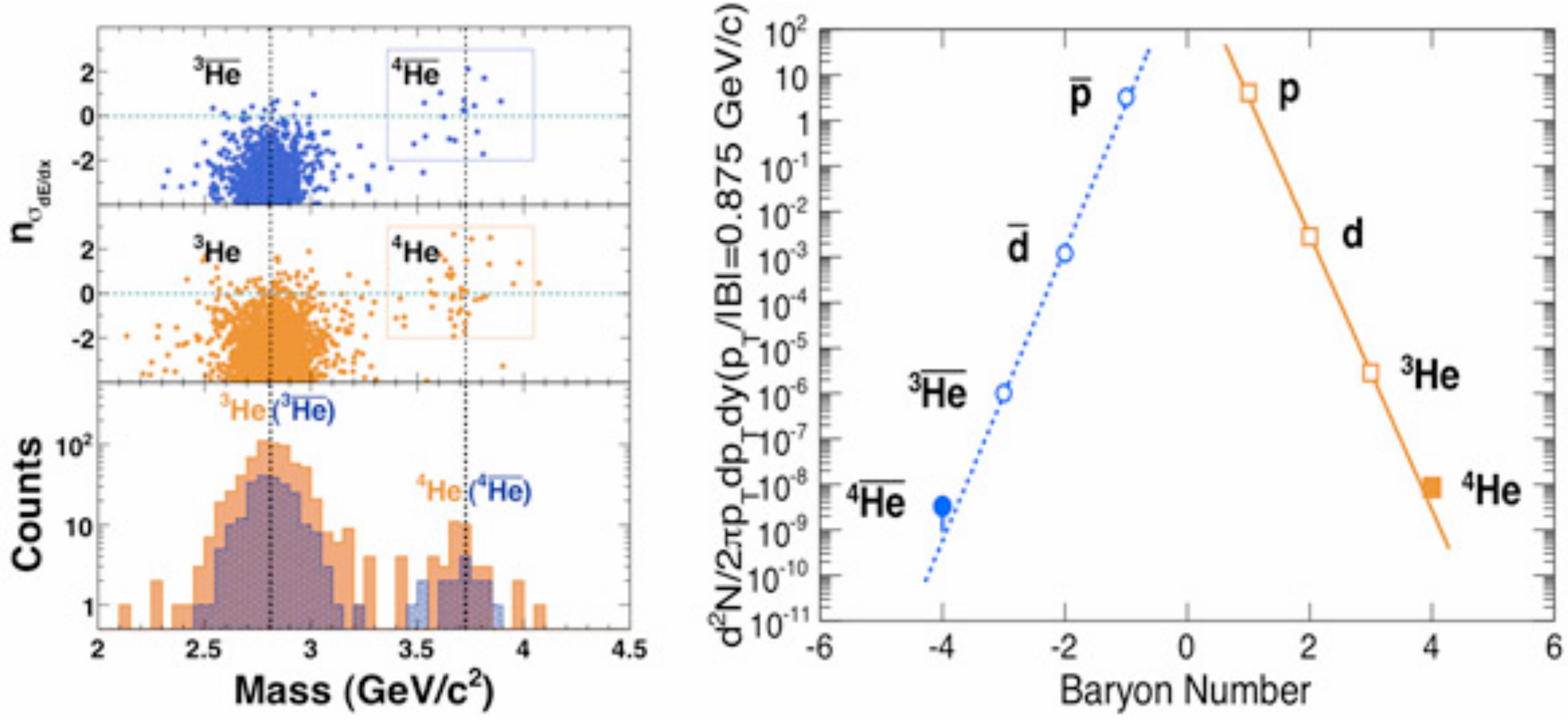
>3x more charm baryons than than in e^+e^- and ep

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)

First observation of anti-He^4!



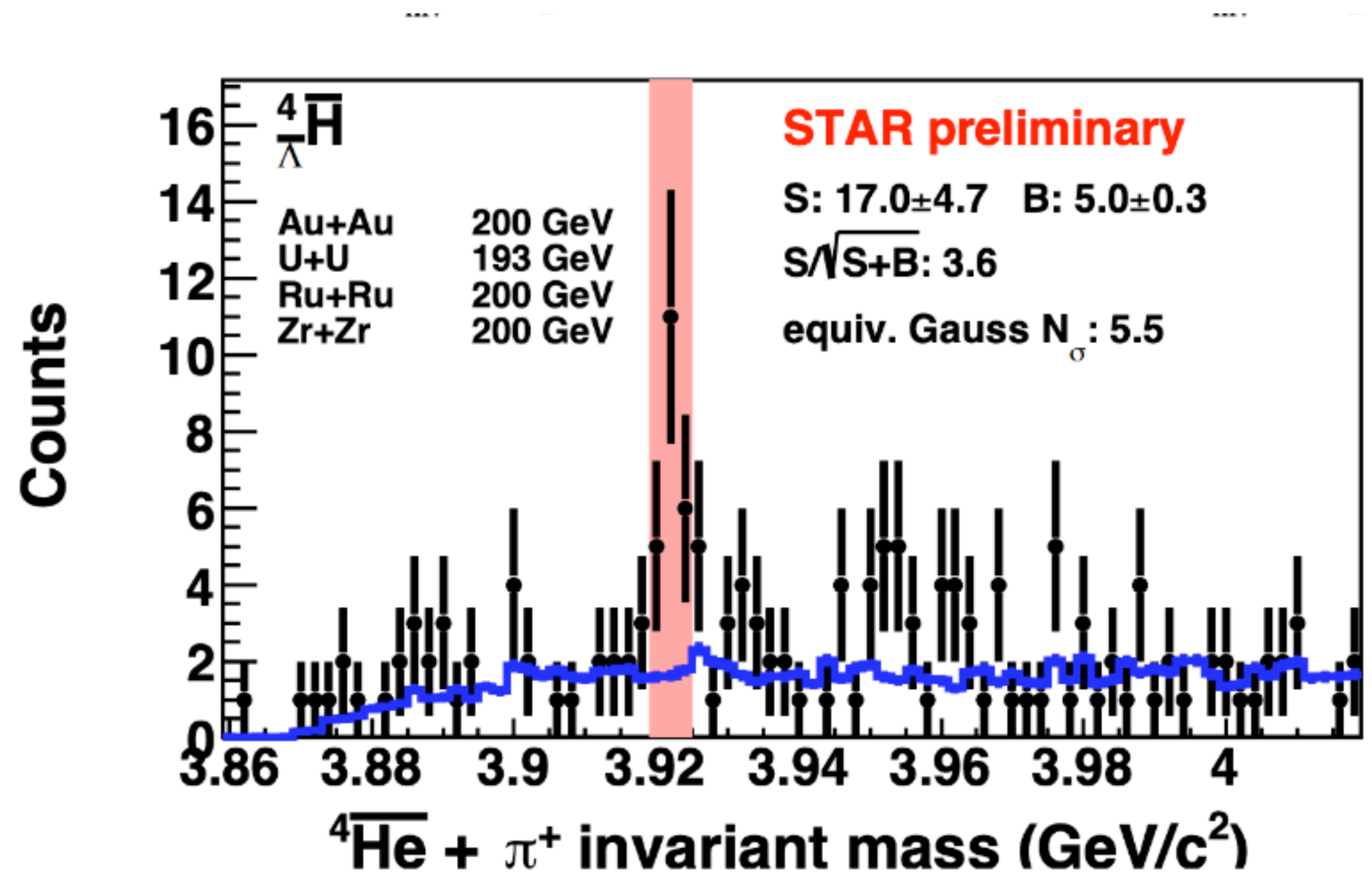
Matter and antimatter formed at same rate

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

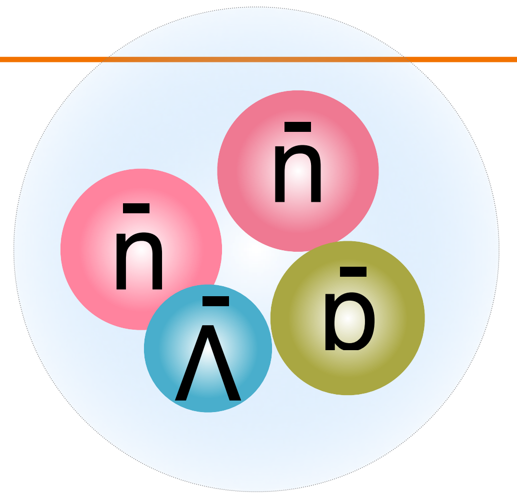
Fact that we are in a matter Universe not due to “problem” creating anti-matter

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

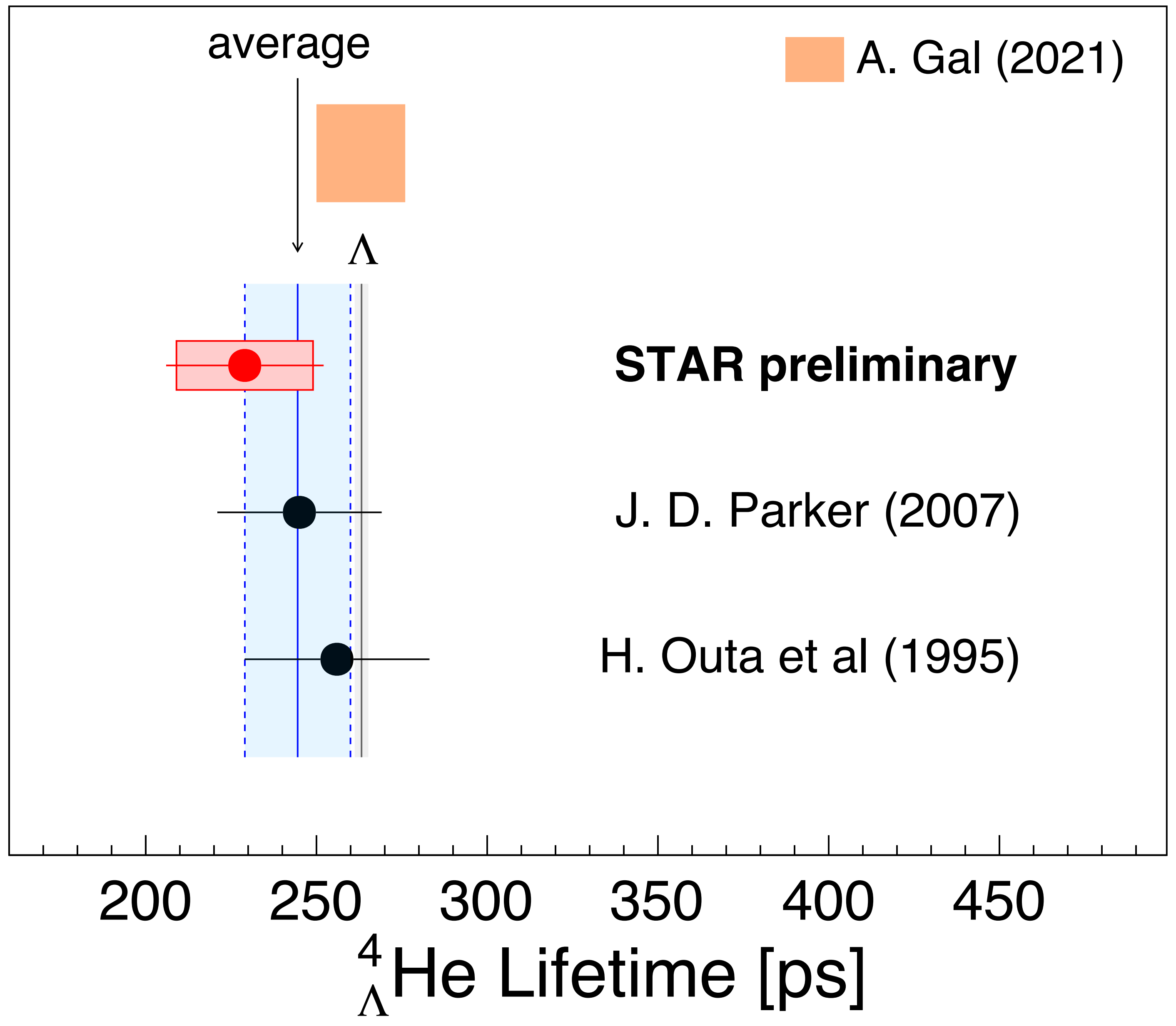
(anti)Hypernuclei are also created



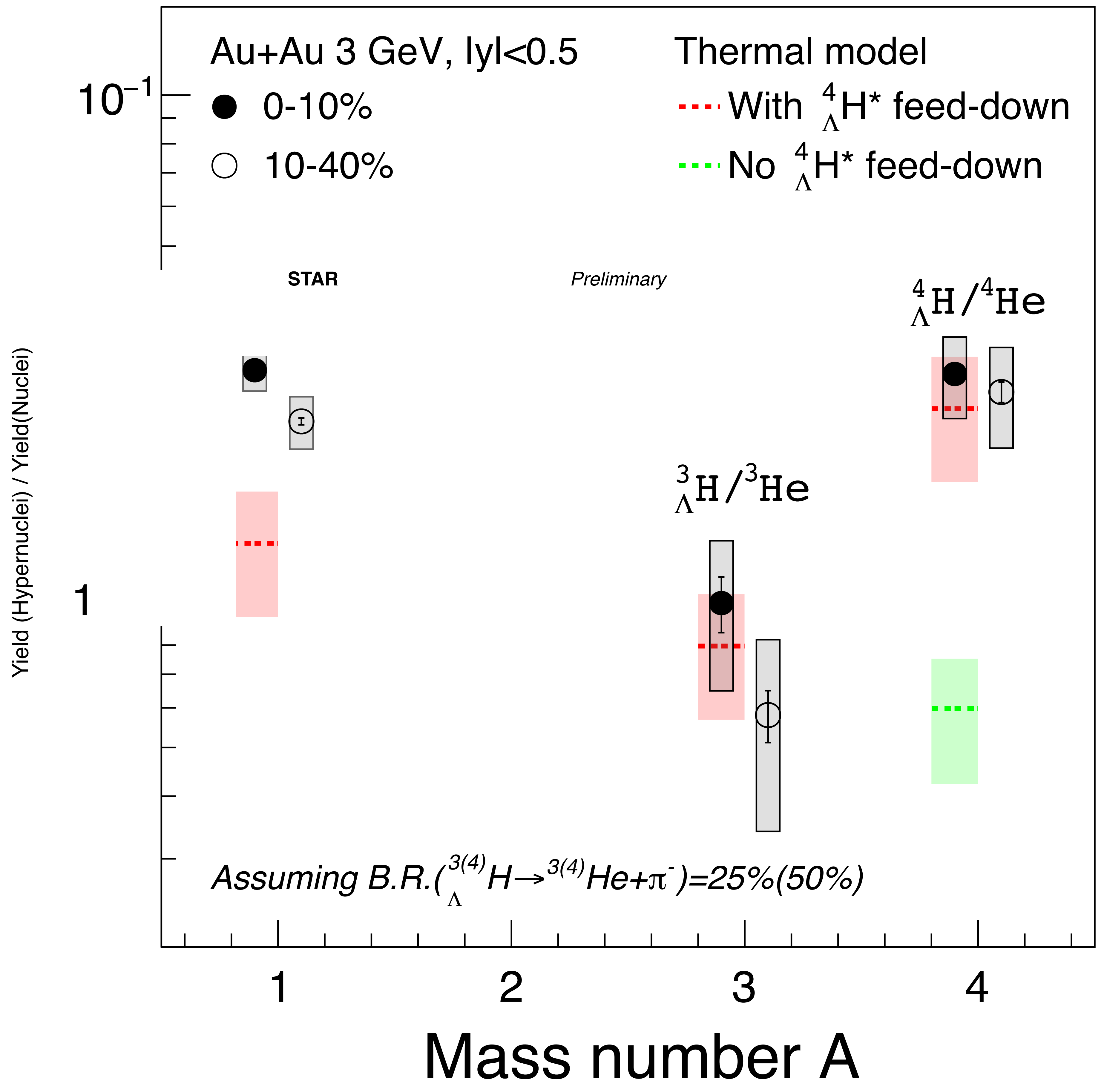
Anti-Hyper-Hydrogen-4



Evidence of formation of excited hypernuclei states in heavy ion collisions



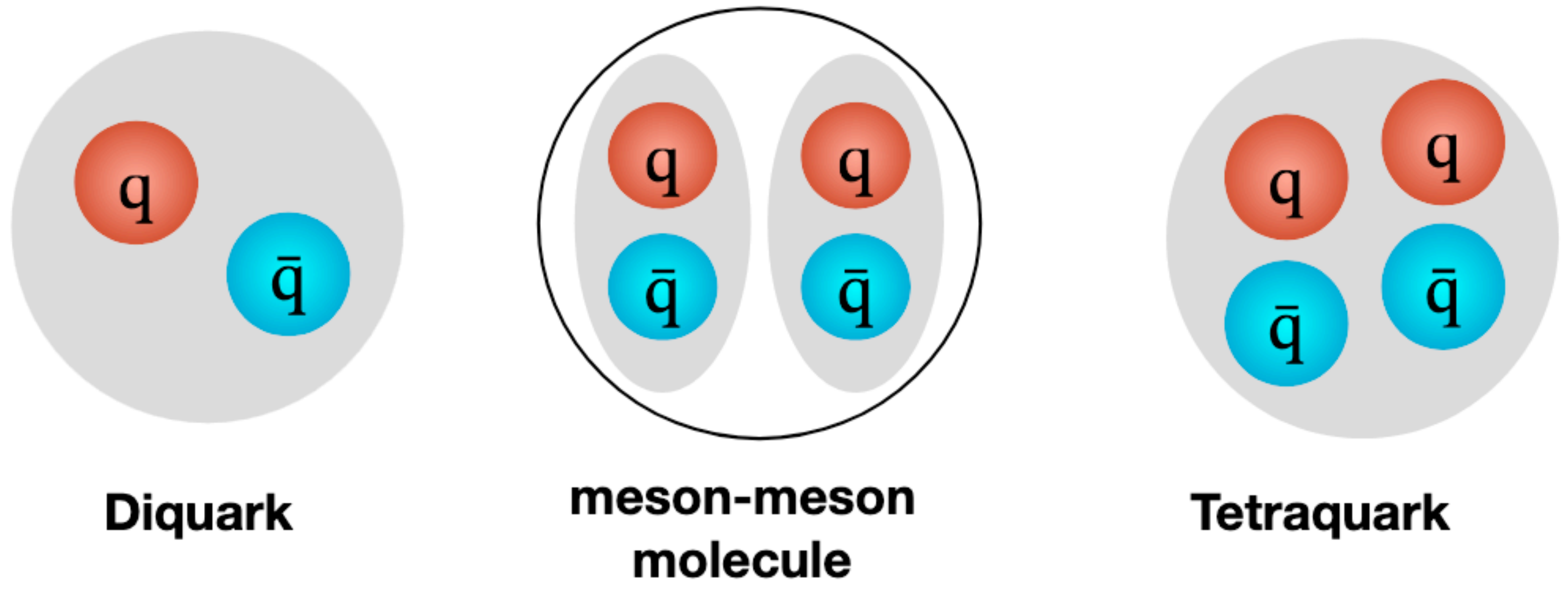
Hyper-Helium-4 lifetime measurement in heavy ion collisions



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



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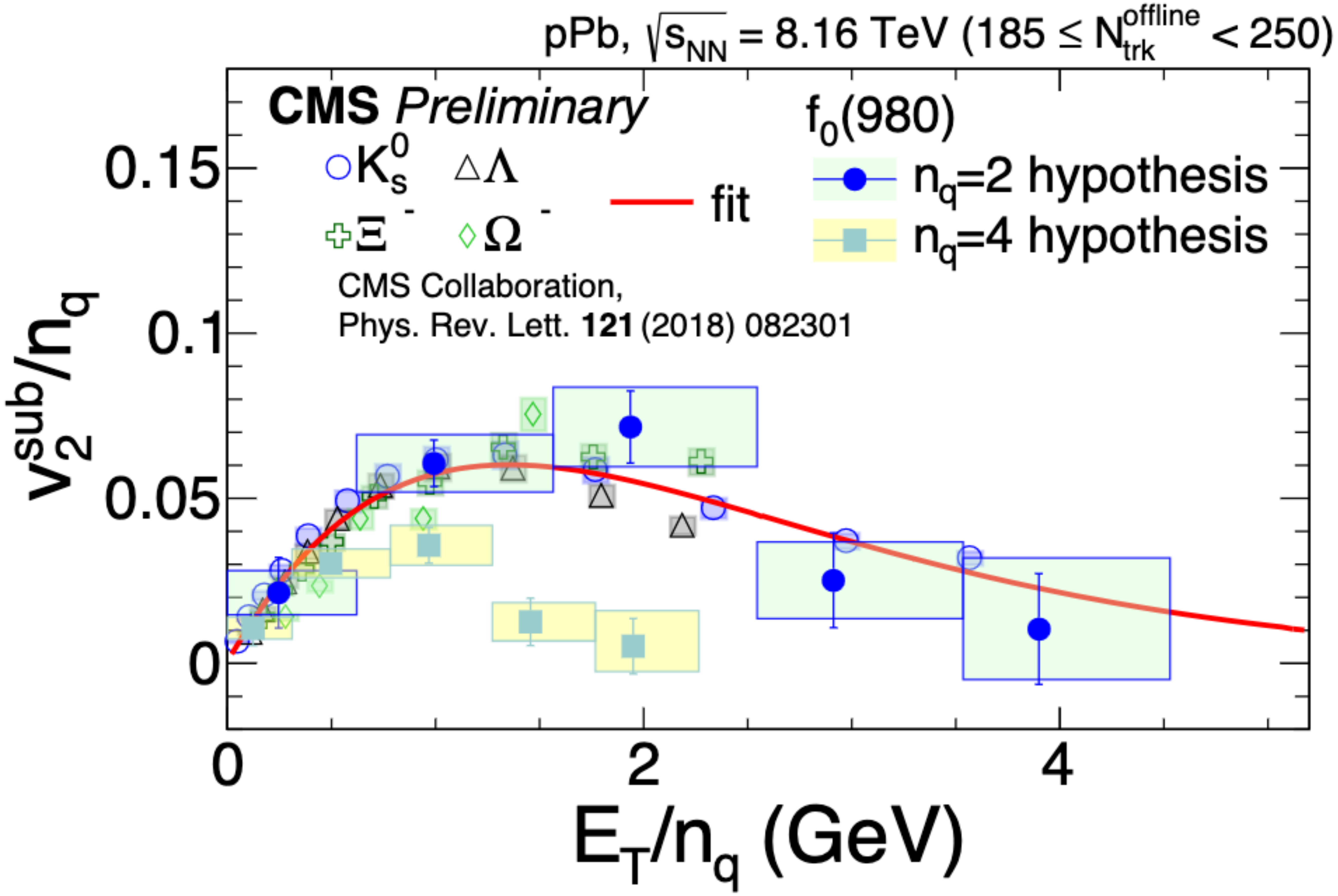
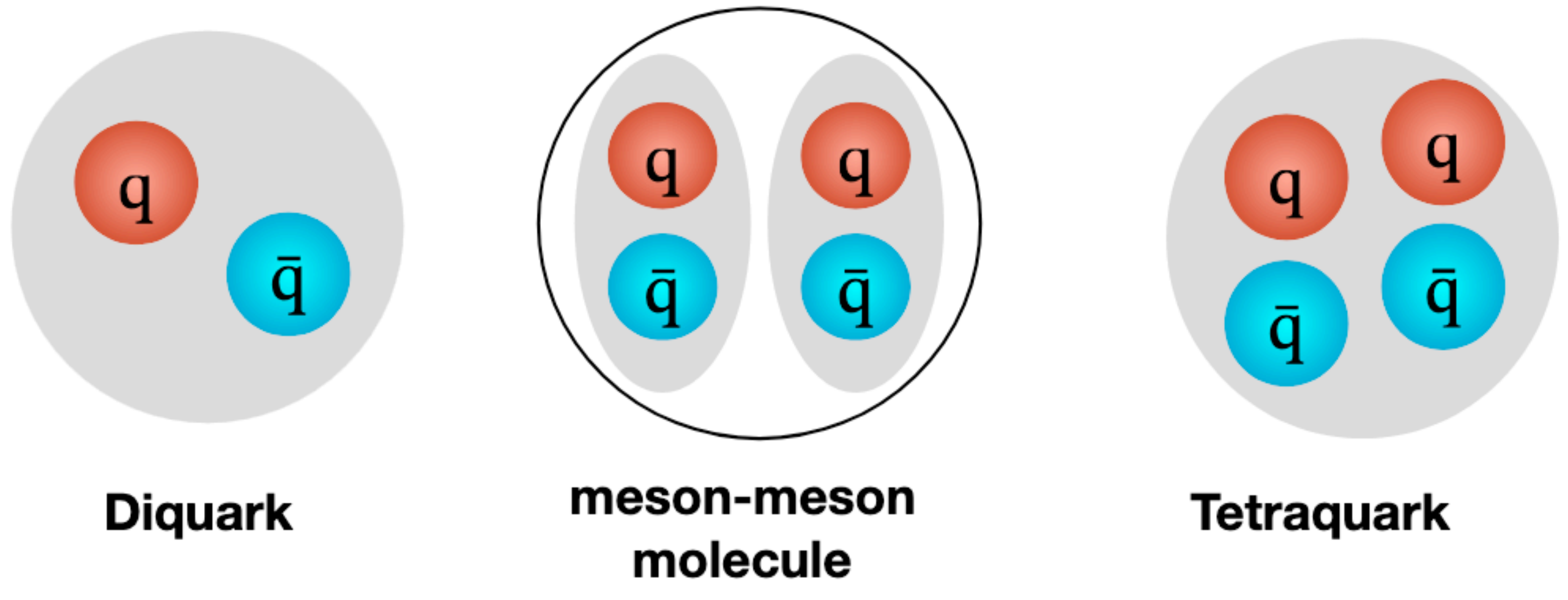




In p-Pb

Elliptic flow:

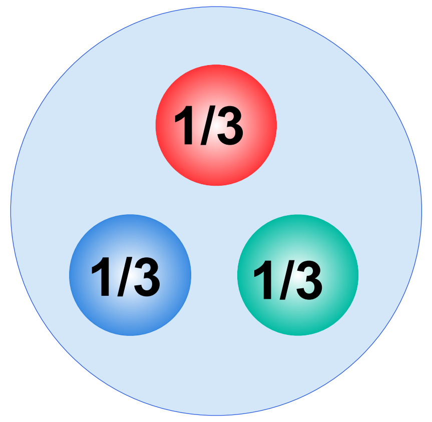
Scales when n_q = 2

Suggests that f_0 is a diquark

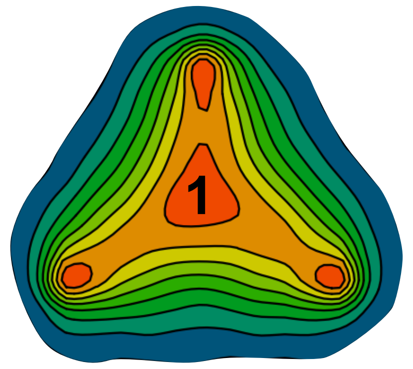
Low energy results suggest otherwise

- debate continues

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 from STAR:

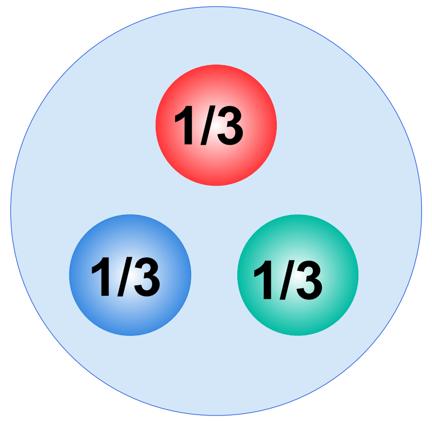
Ru+Ru: A = 96, Z = 44
Zr+Zr: A = 96, Z = 40

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

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

$\Delta Q = Q_{Ru} - Q_{Zr}$ Measure $B/\Delta Q$
$\Delta Z = Z_{Ru} - Z_{Zr}$ Calculate $\Delta Z/A$

What carries baryon number?



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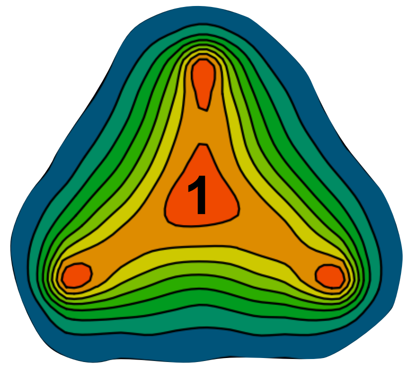

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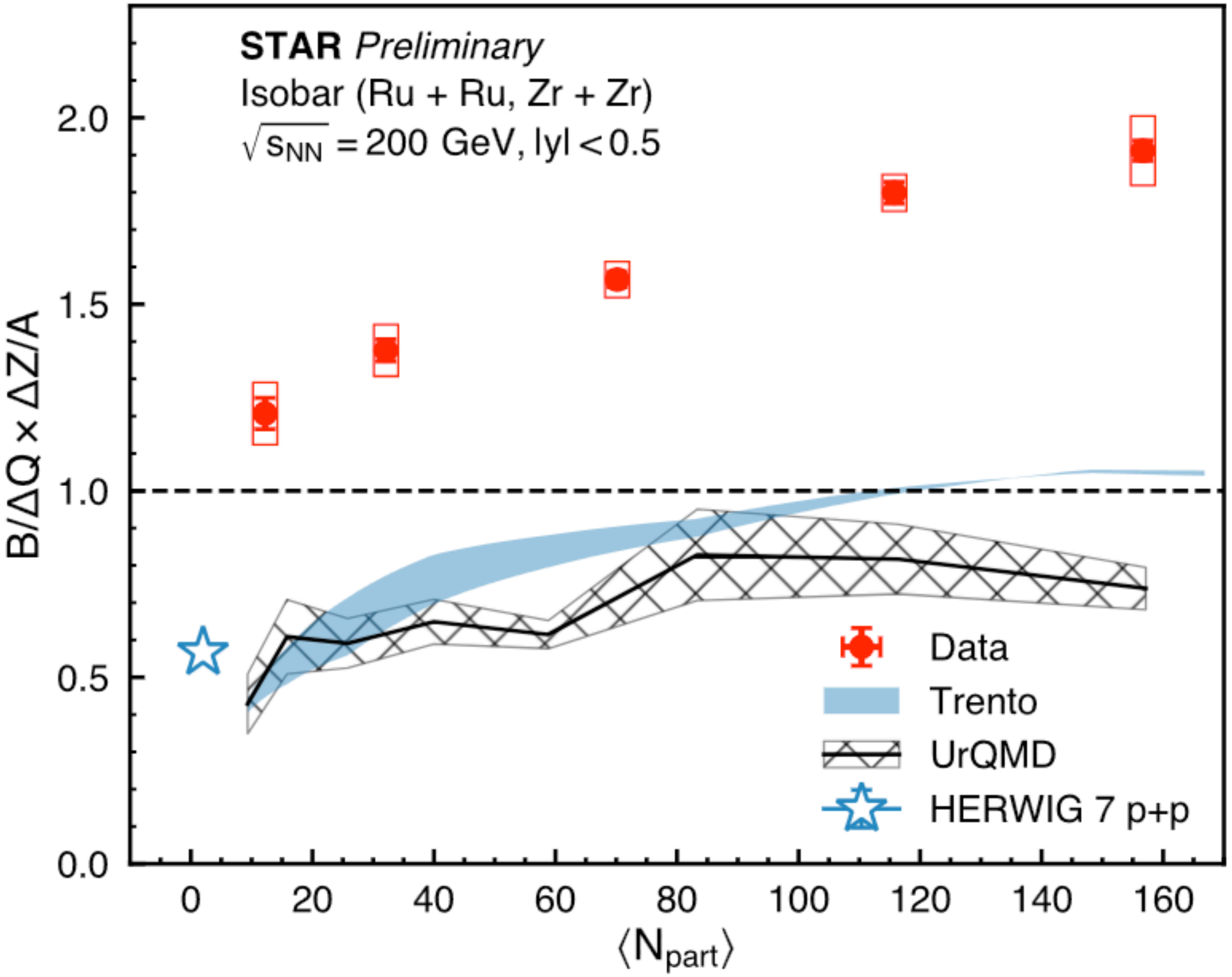
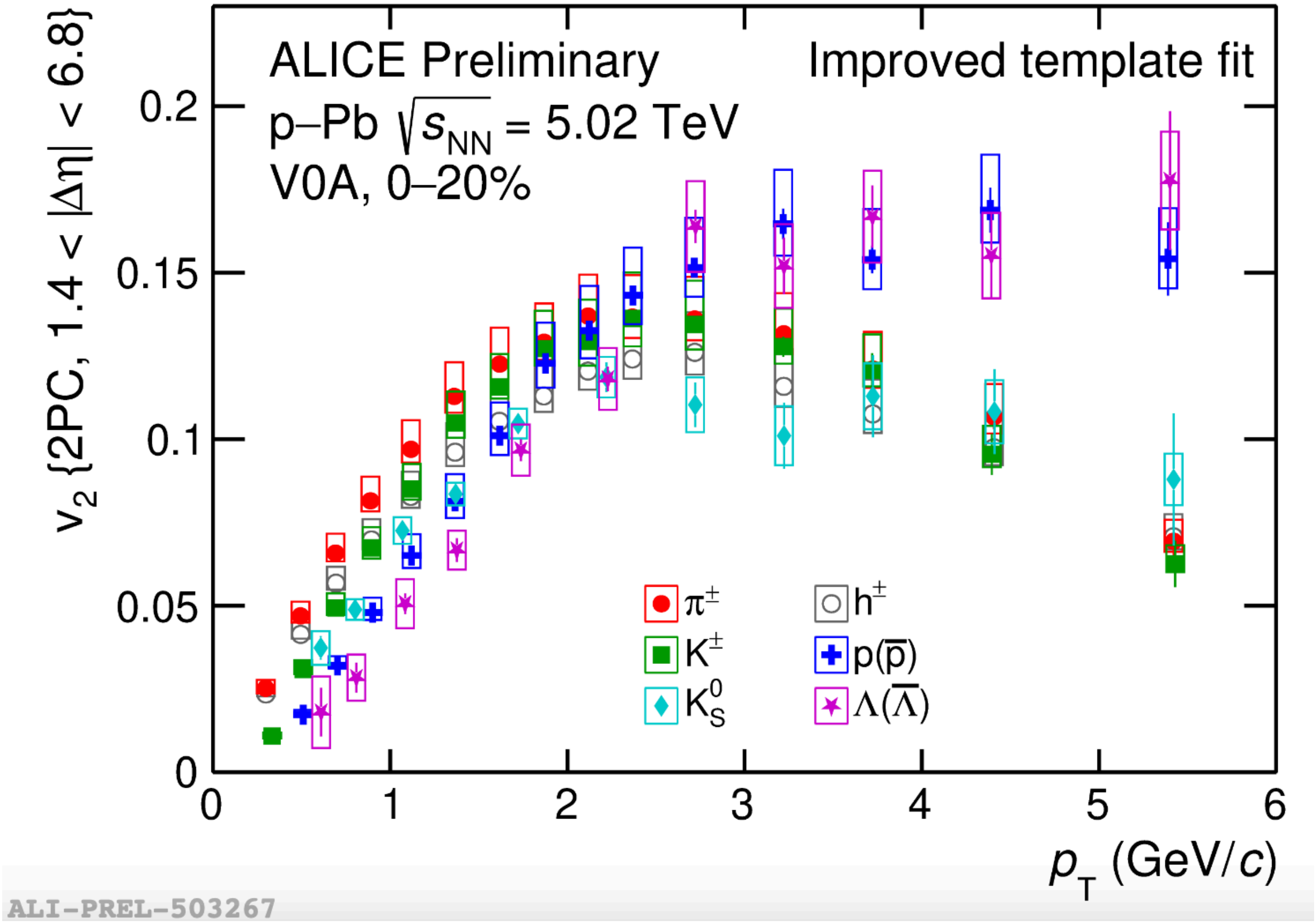


Data currently favor baryon junctions

Small system complexity



Initially thought p+A - “cold” matter baseline

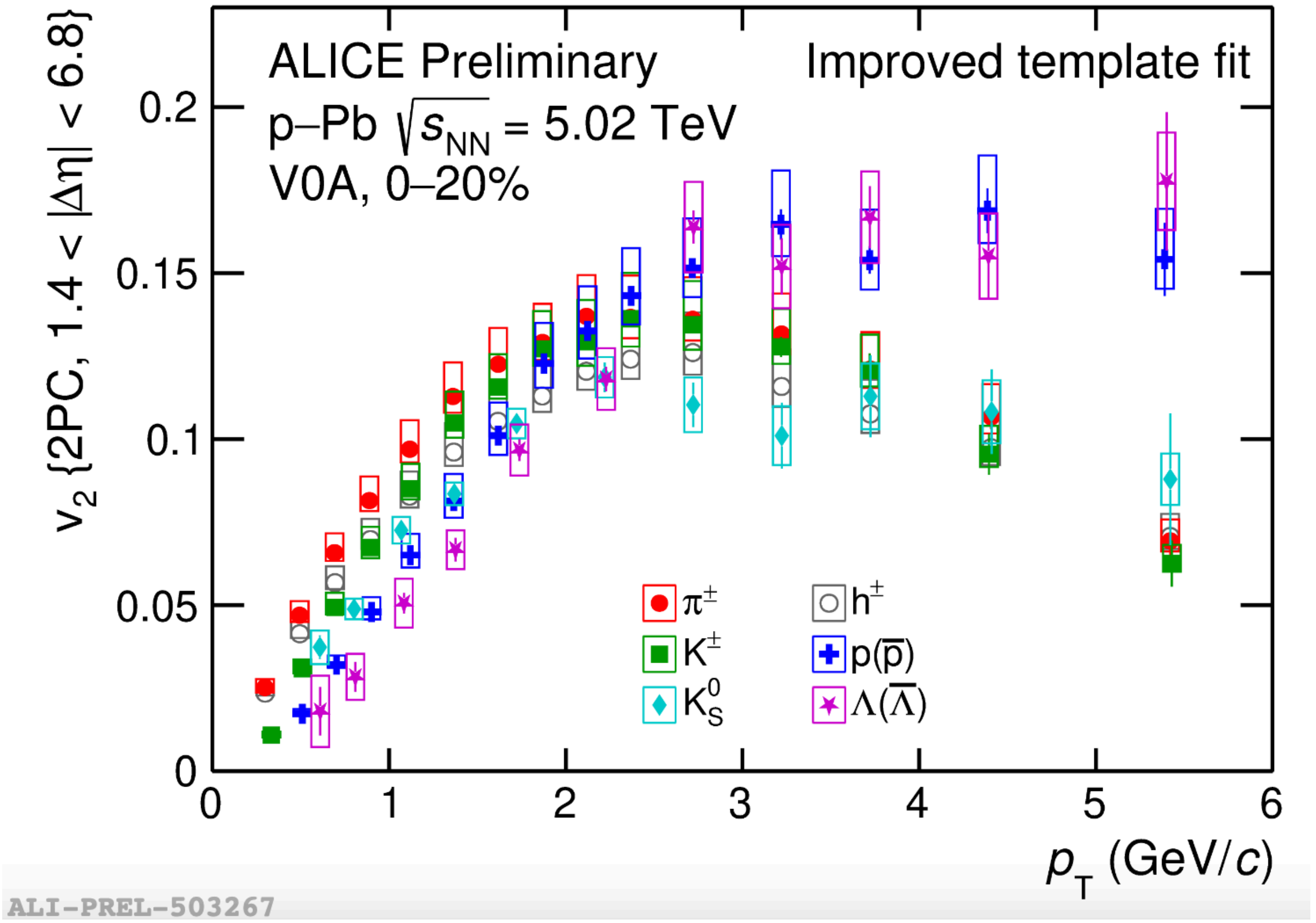
But:

Clear collective motion signals now observed at LHC and RHIC

Intermediate p_T - NCQ scaling

ATLAS: PRL 131 (2023) 072301

Small system complexity



Initially thought p+A - “cold” matter baseline

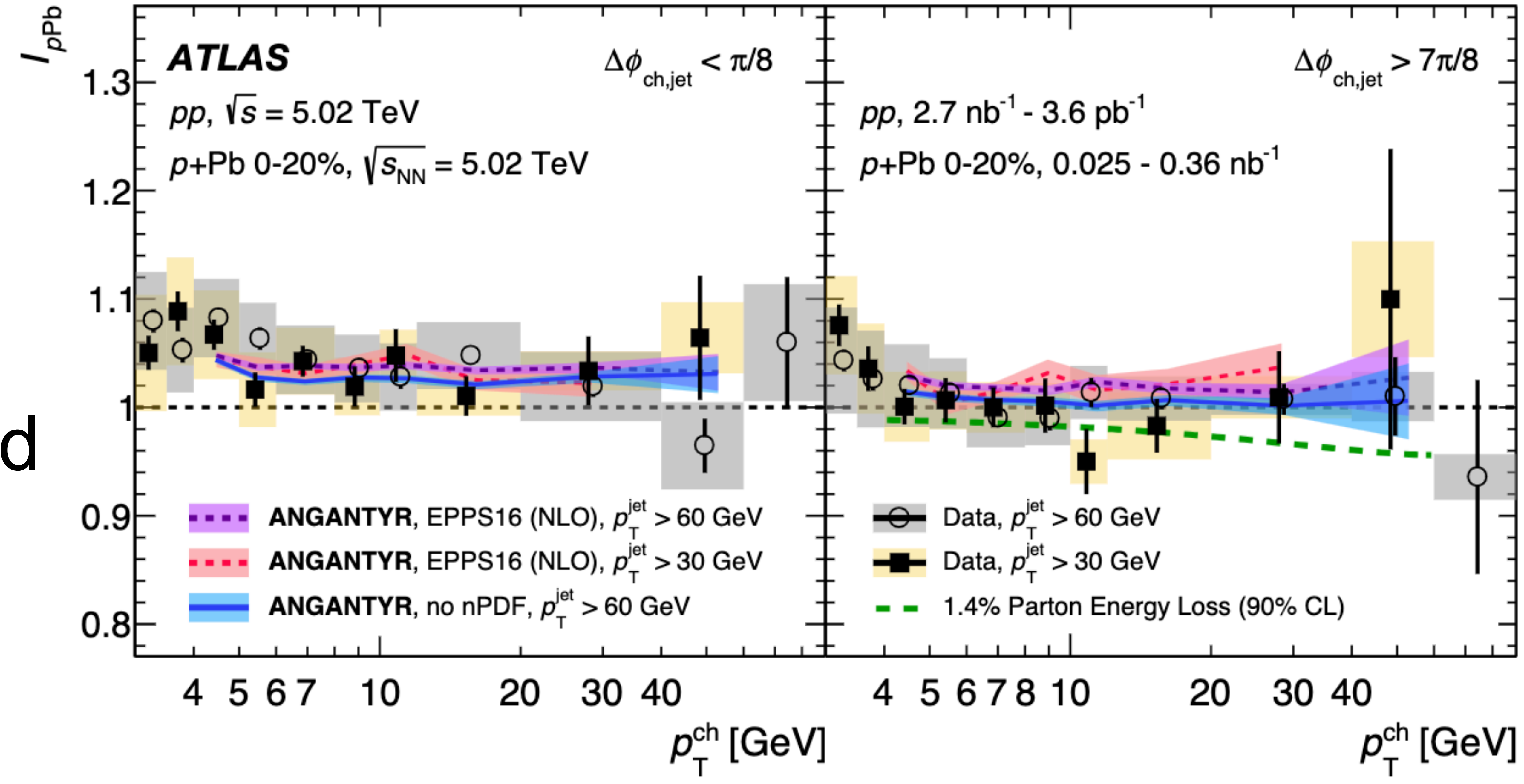
But:

Clear collective motion signals now observed at LHC and RHIC

Intermediate p_T - NCQ scaling

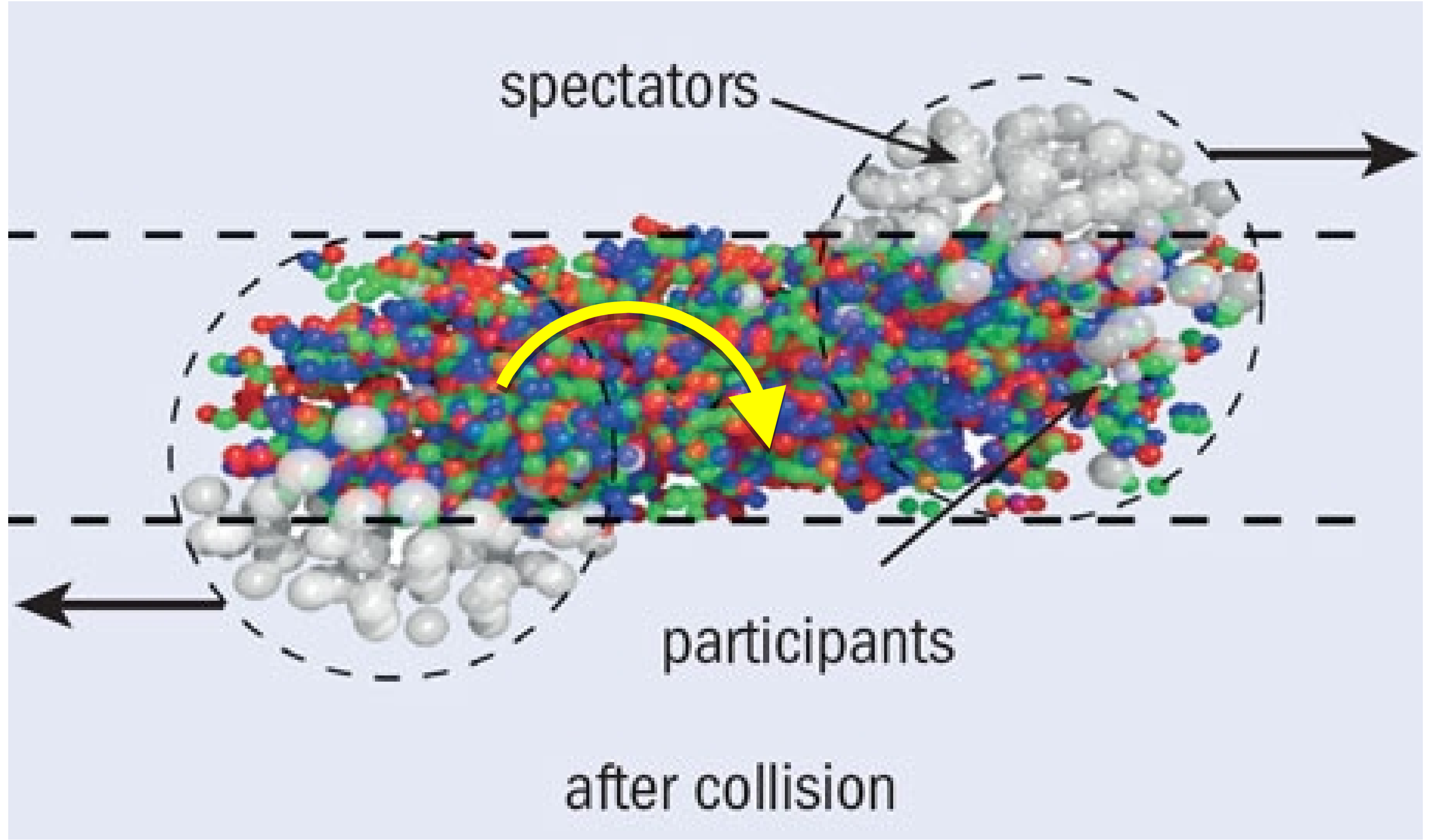
No clear signs of jet quenching reported

Do we make a very small QGP in more central p+A events?



ATLAS: PRL 131 (2023) 072301

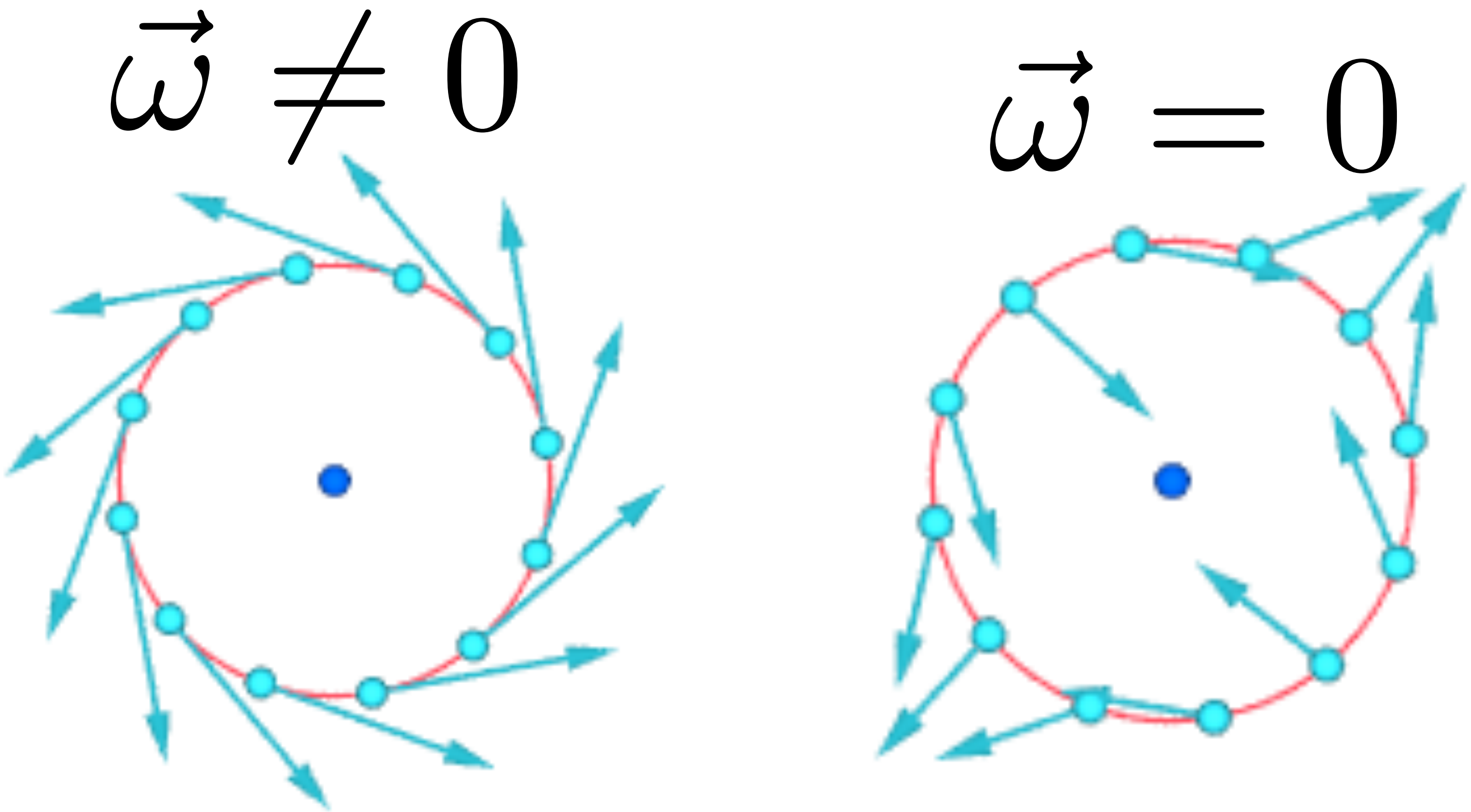
The spinning QGP



|L| ~ 10^5 in peripheral collisions

We generate a "spinning" QGP?

Spectators create a large magnetic field



How does that affect fluid/transport?
Vorticity - local spinning motion

$$\vec{\omega} = \vec{\nabla} \times \vec{v}$$

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:

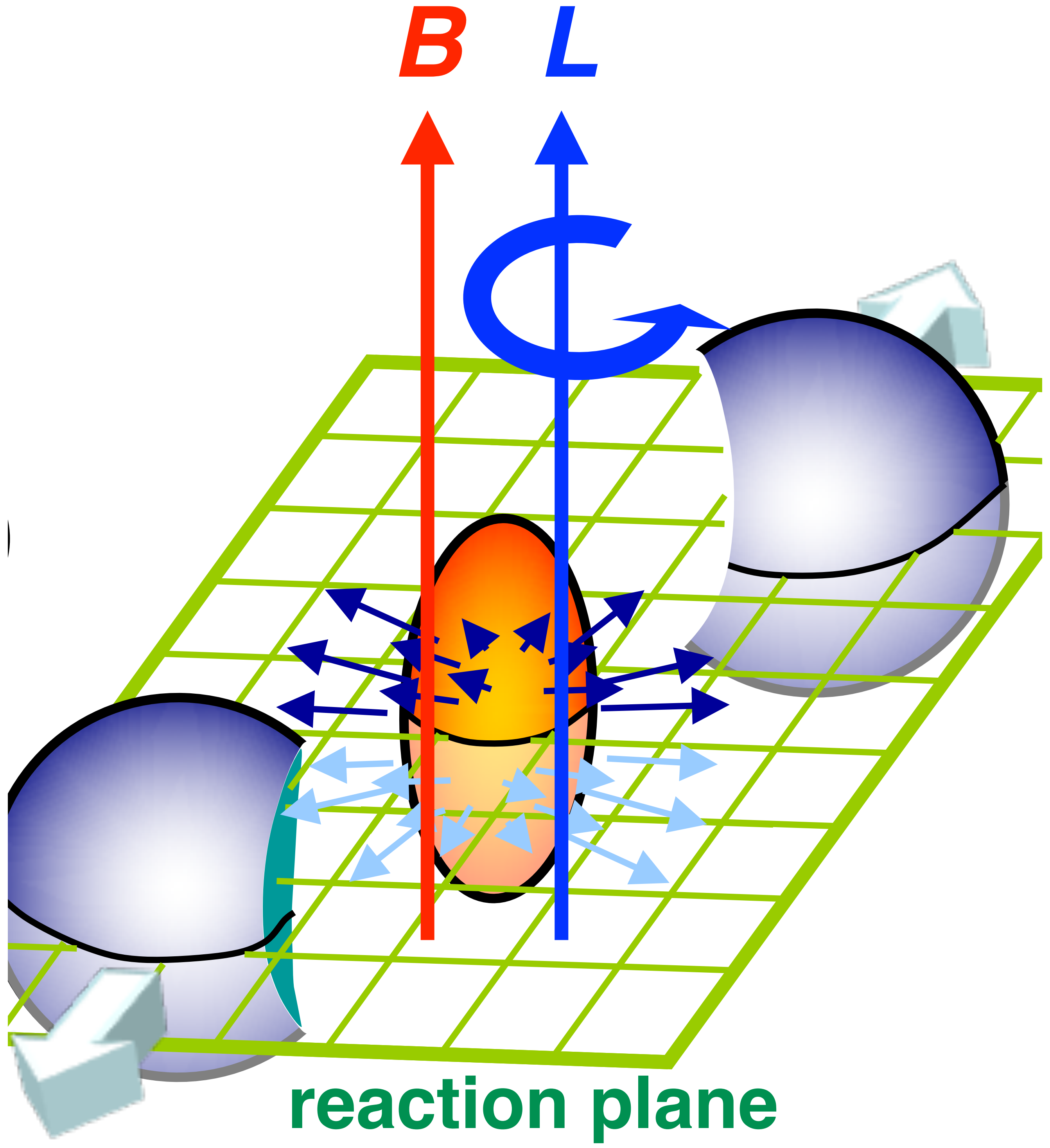
Estimate from 1st order reaction plane

Λ Polarization

Self analyzing

Decay p preferentially emitted in Λ spin direction

Decay anti-proton preferentially emitted against anti-Λ spin direction



Λ and anti-Λ spins aligned with L → Vortical or QCD spin-orbit

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

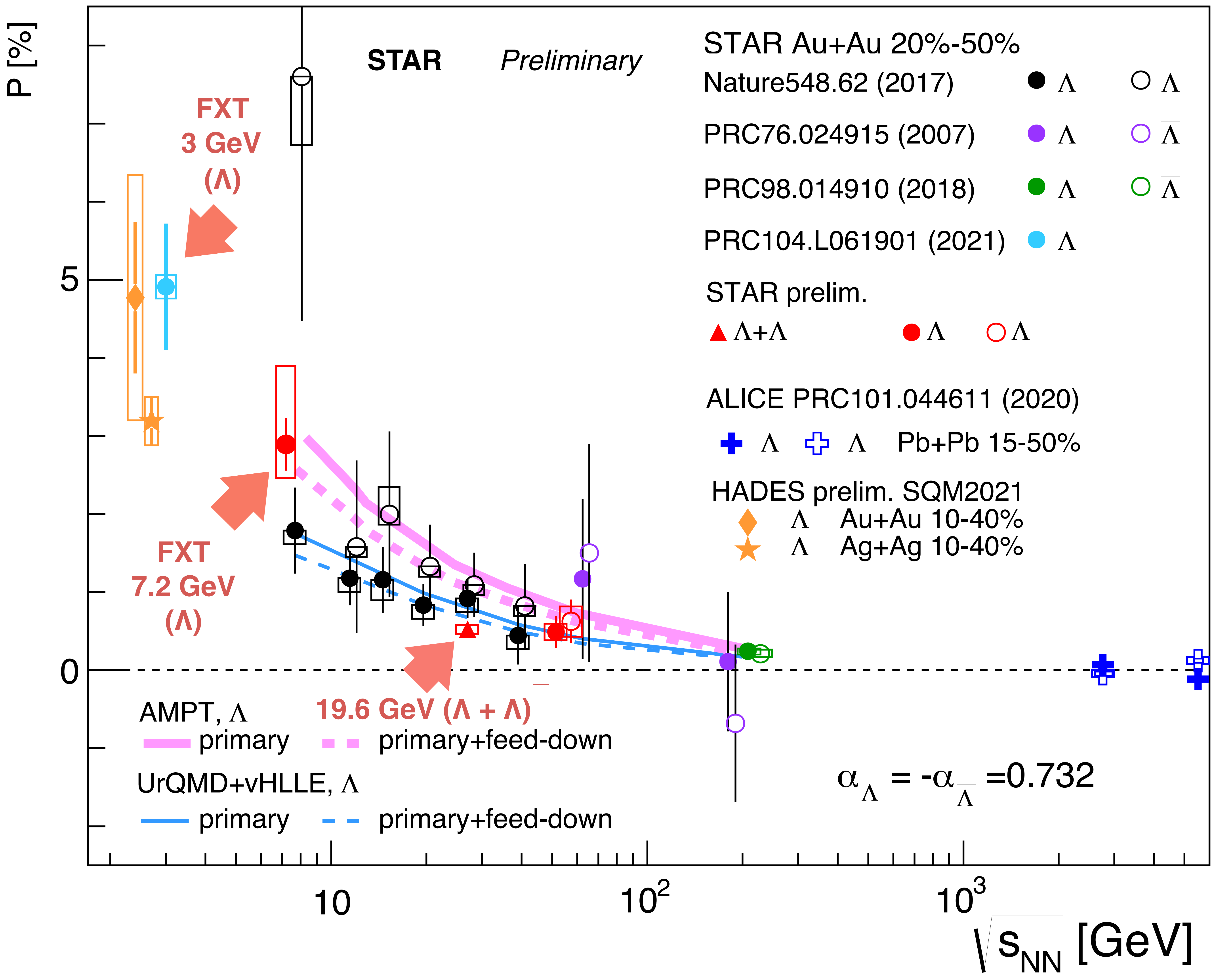
- Sigma feed-down tends to dampen the effect

Λ anti-aligned, anti-Λ aligned with L → μ_H - B coupling

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

- Sigma feed-down goes with the primaries

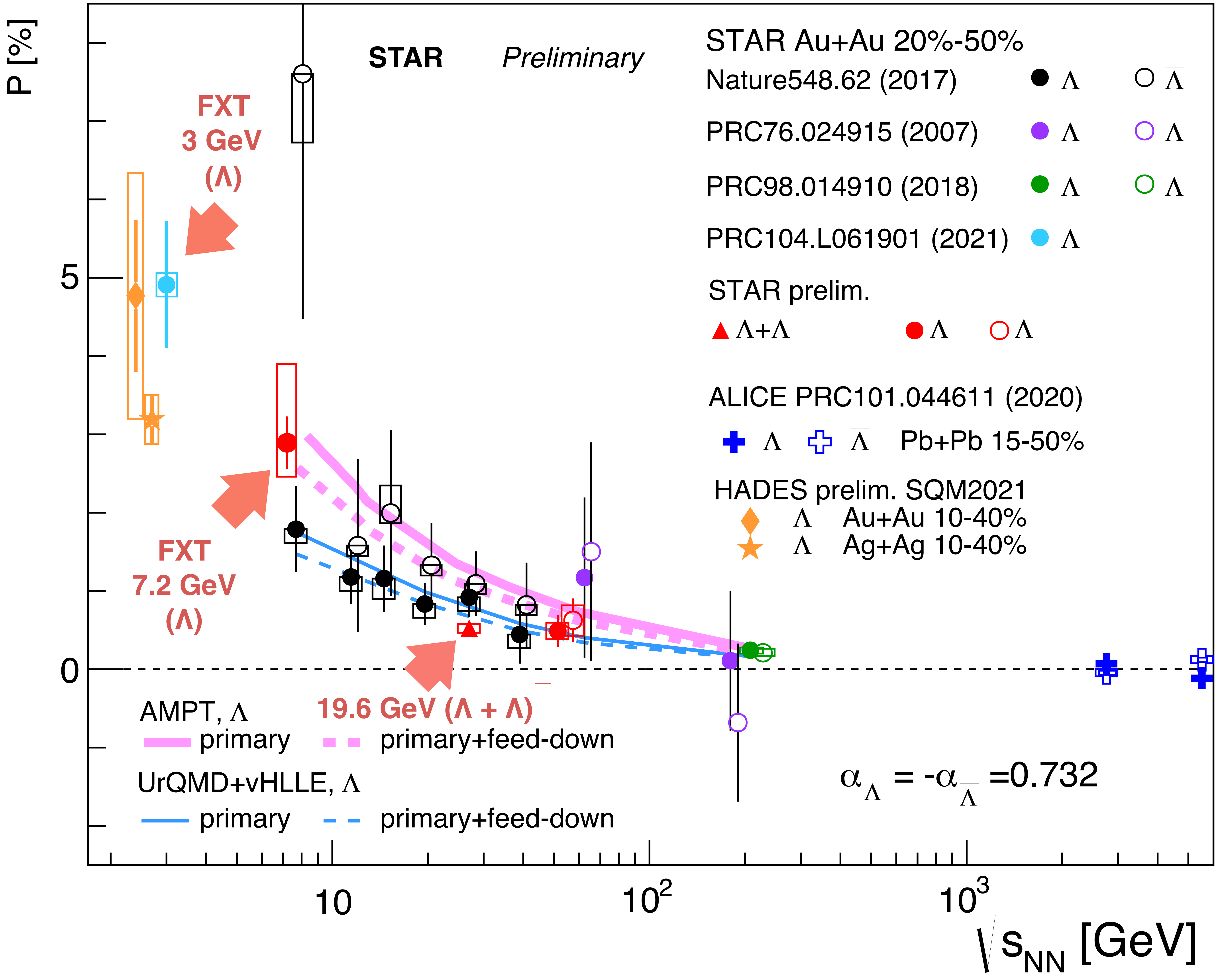
Global Λ polarization



Precision measurements have now been made from 3-5000 GeV:

Highly vortical fluid:
$\omega \sim 10^{22}\ s^{-1}$

Global Λ polarization



Precision measurements have now been made from 3-5000 GeV:

Highly vortical fluid:
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How fast is that compared to the most powerful tornado?

a) slower

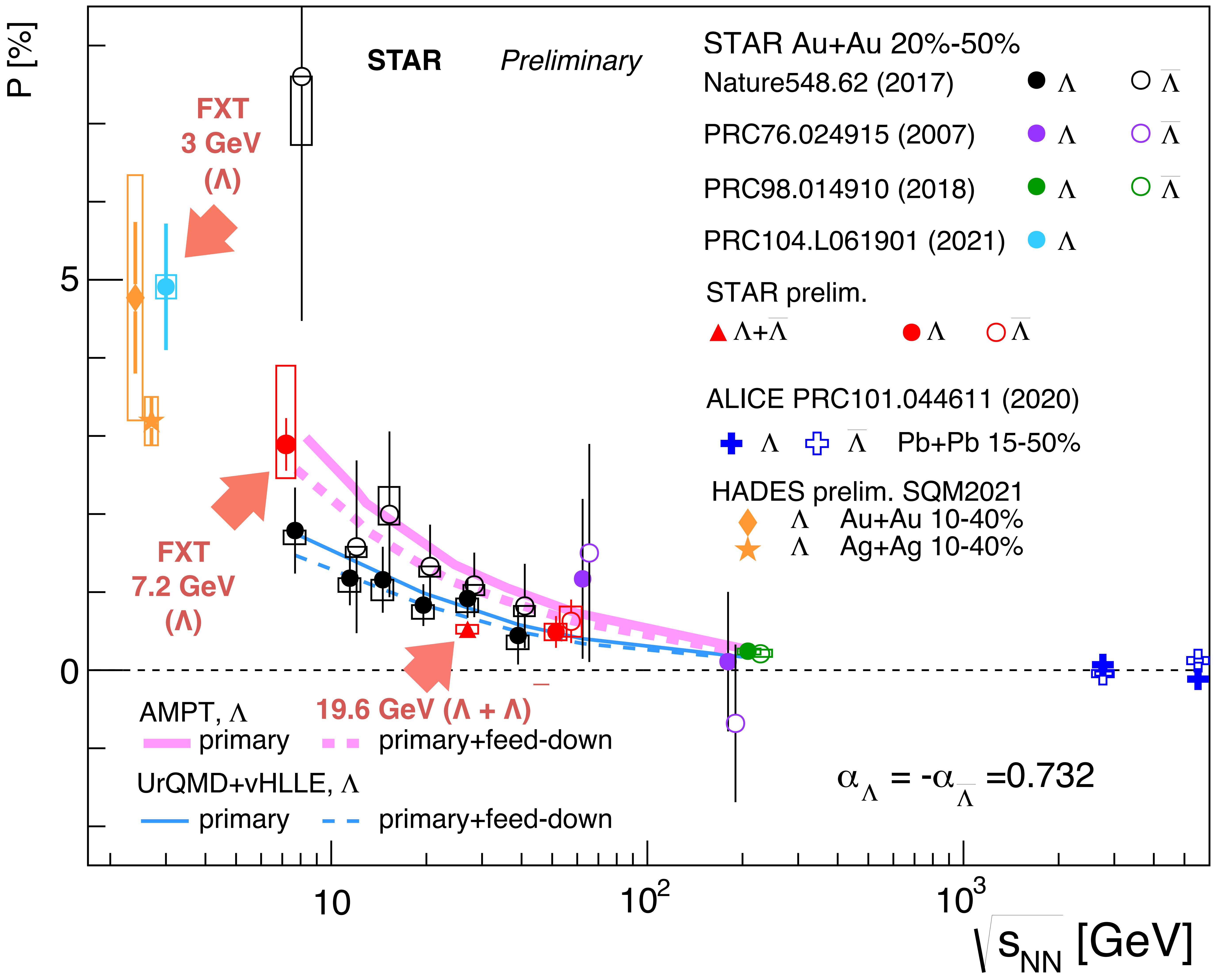
b) about the same

c) 1000 times faster

d) billion times fast

e) even faster

Global Λ polarization



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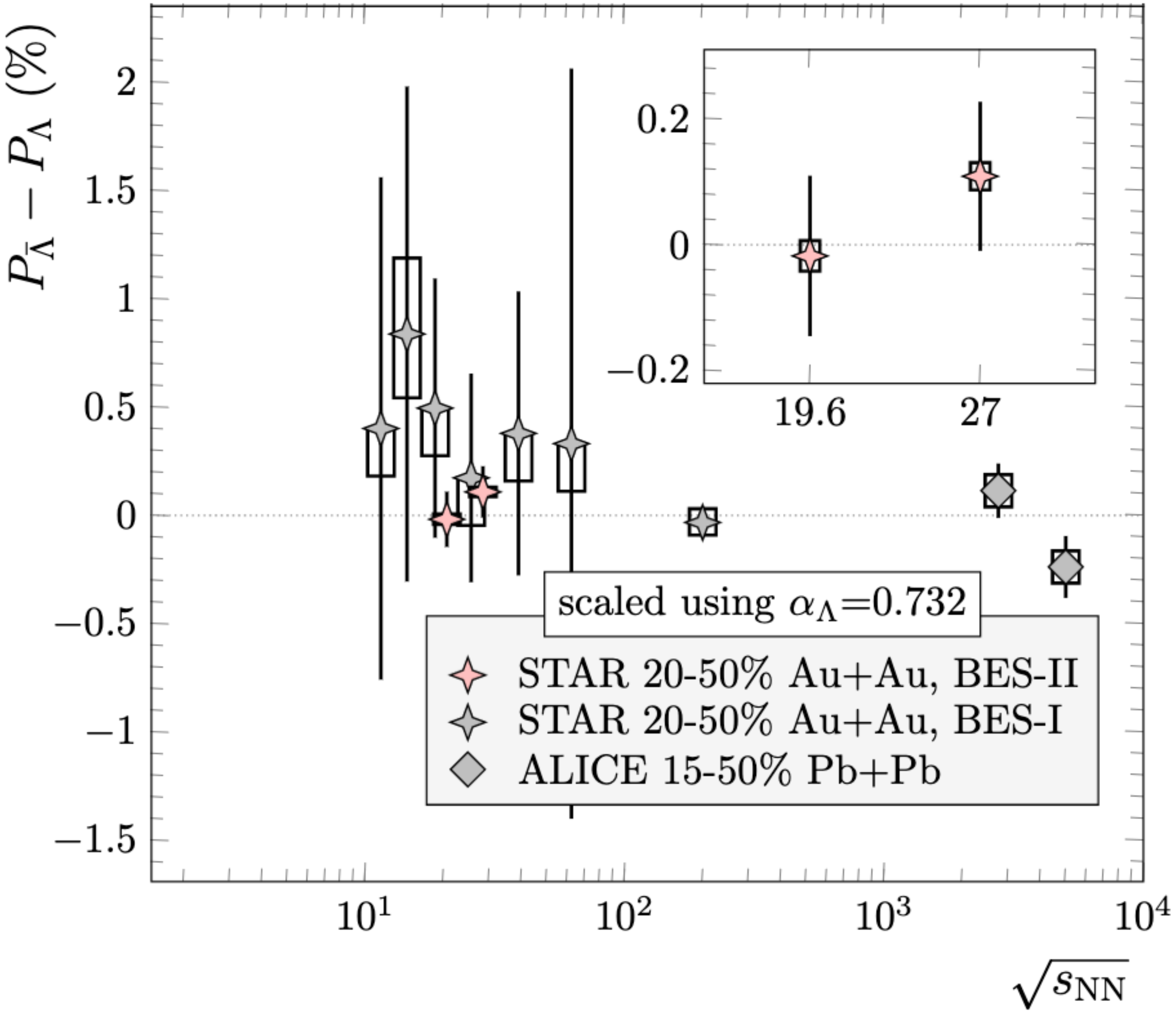
d) billion times fast

e) even faster

ten billion trillion times faster

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

(Initial field 10^{14}-10^{16} T)

B(19.6 GeV) < 9.4×10^{12} T

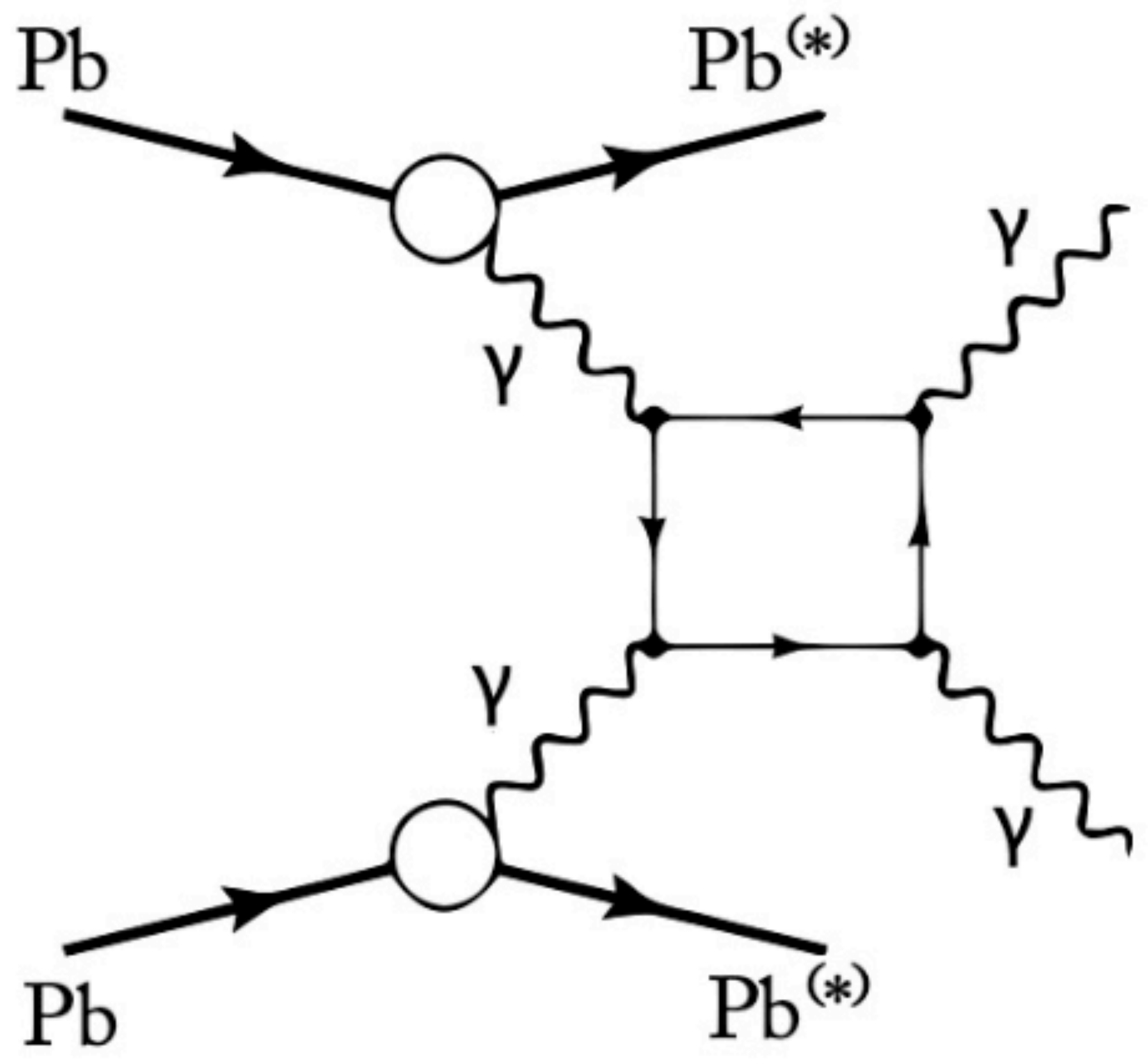
B (27 GeV)< $1.4\text{x}10^{13}$ T

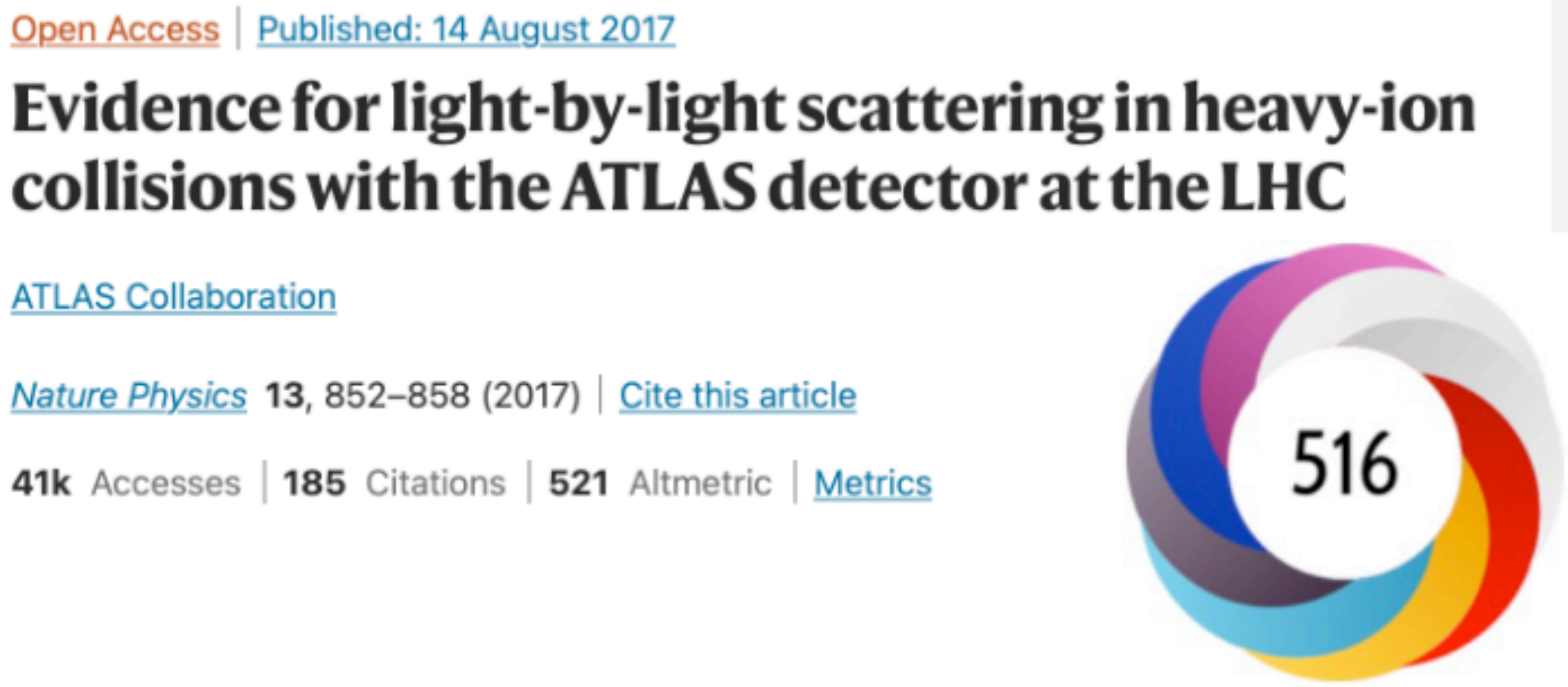
Does magnetic field die away too quickly?
Can we probe at earlier time?

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

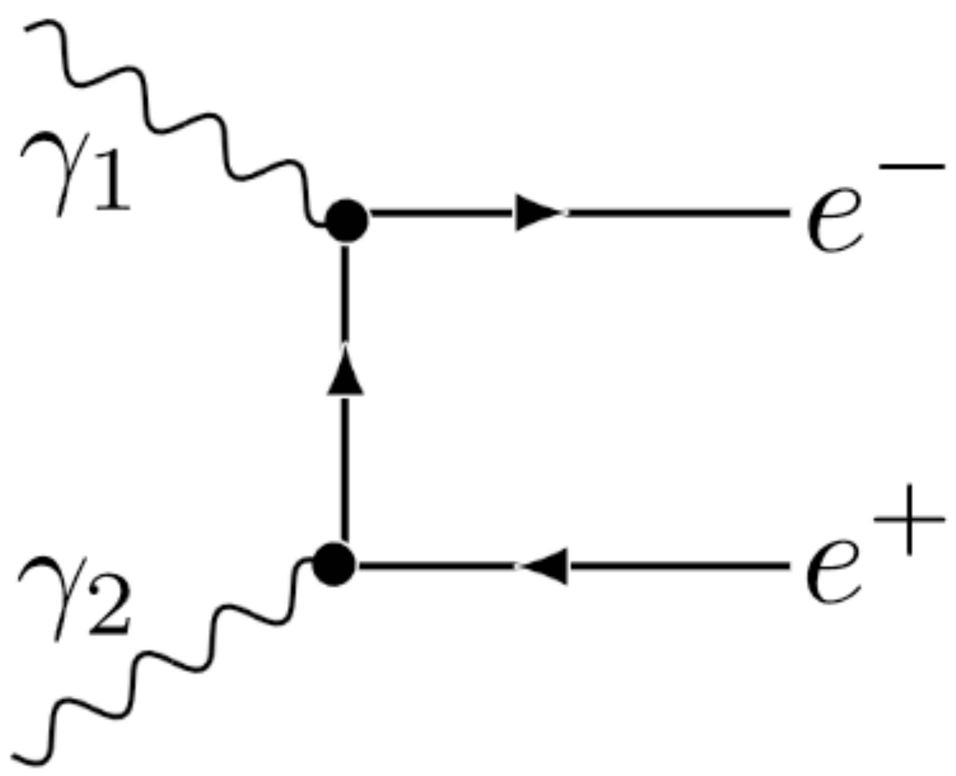
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

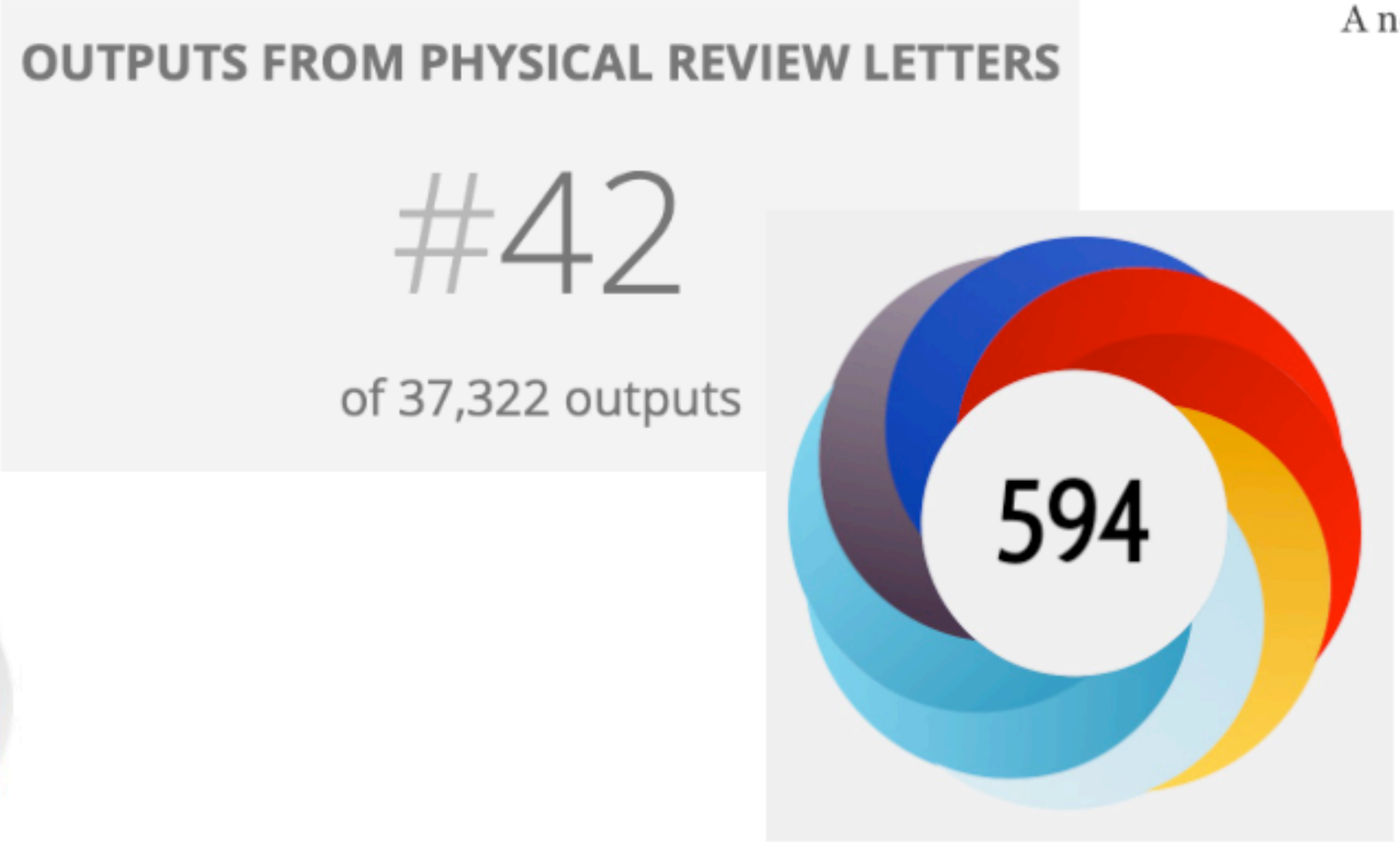
ATLAS Collaboration

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

Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

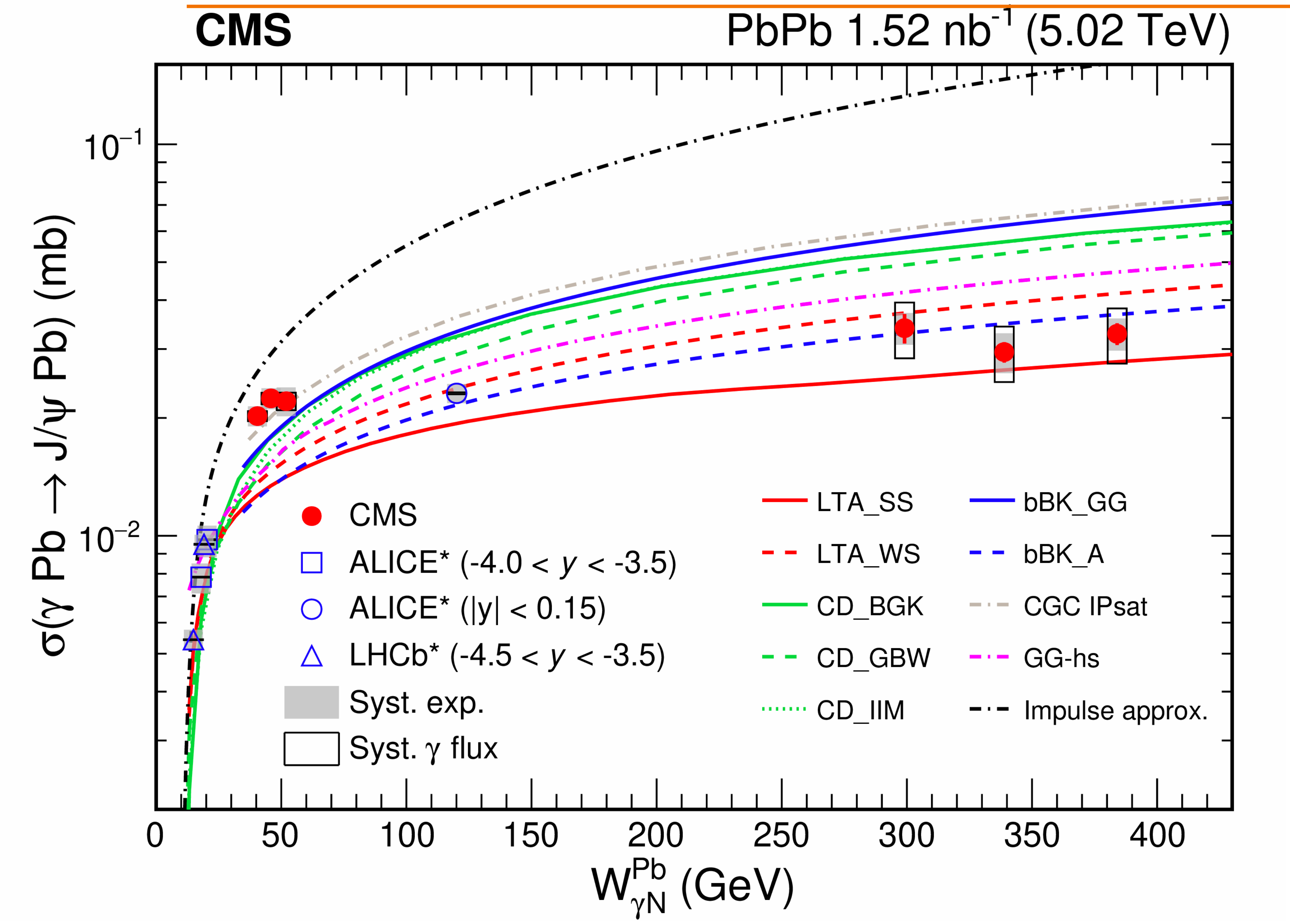
Overview of attention for article published in Science Advances, January 2023

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 $\sigma_{\gamma A \rightarrow J/\psi A'}(W)$ not predicted by models
- Gluon saturation? black disk limit?

CMS: PRL 131 (2023) 262301,

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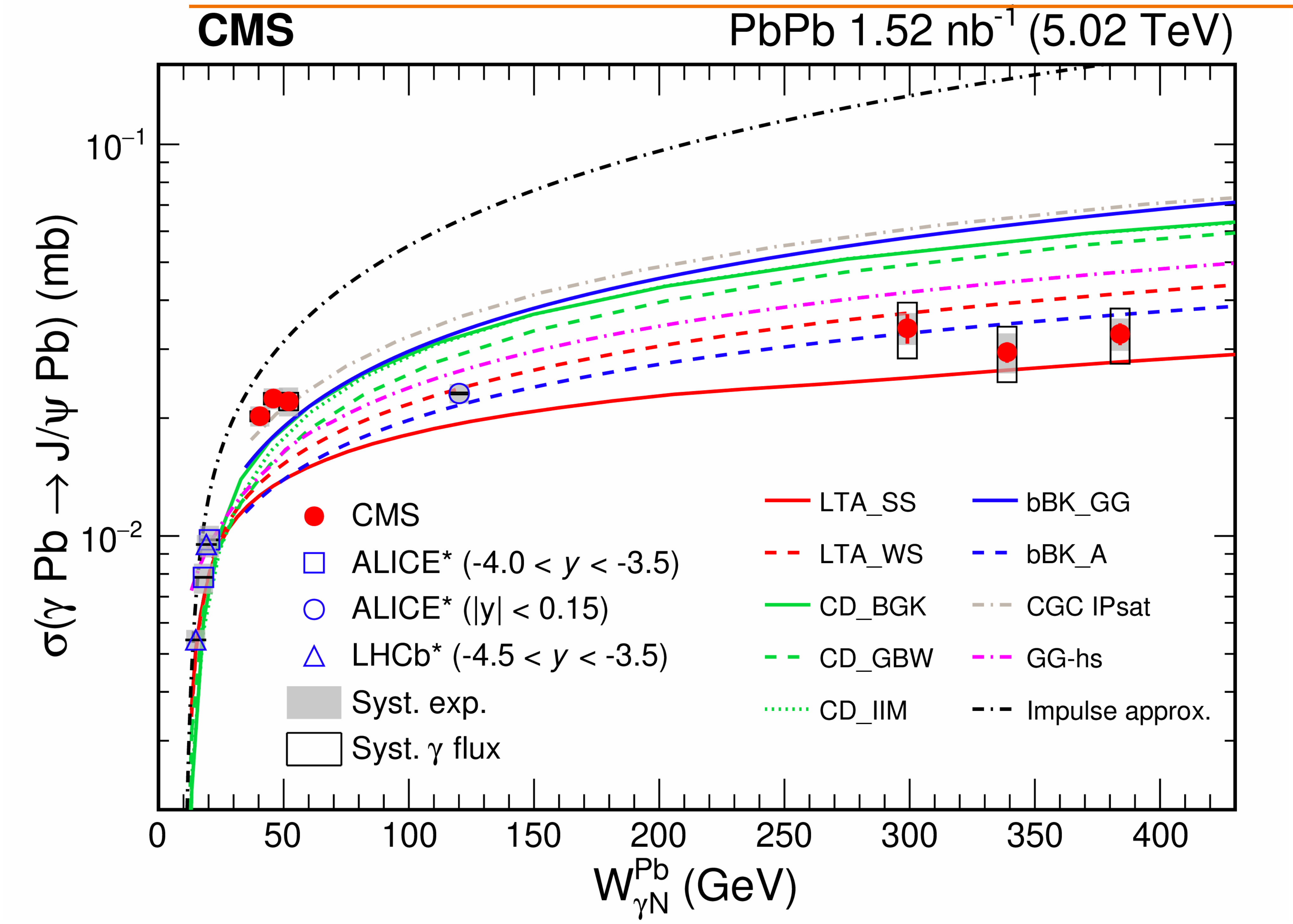

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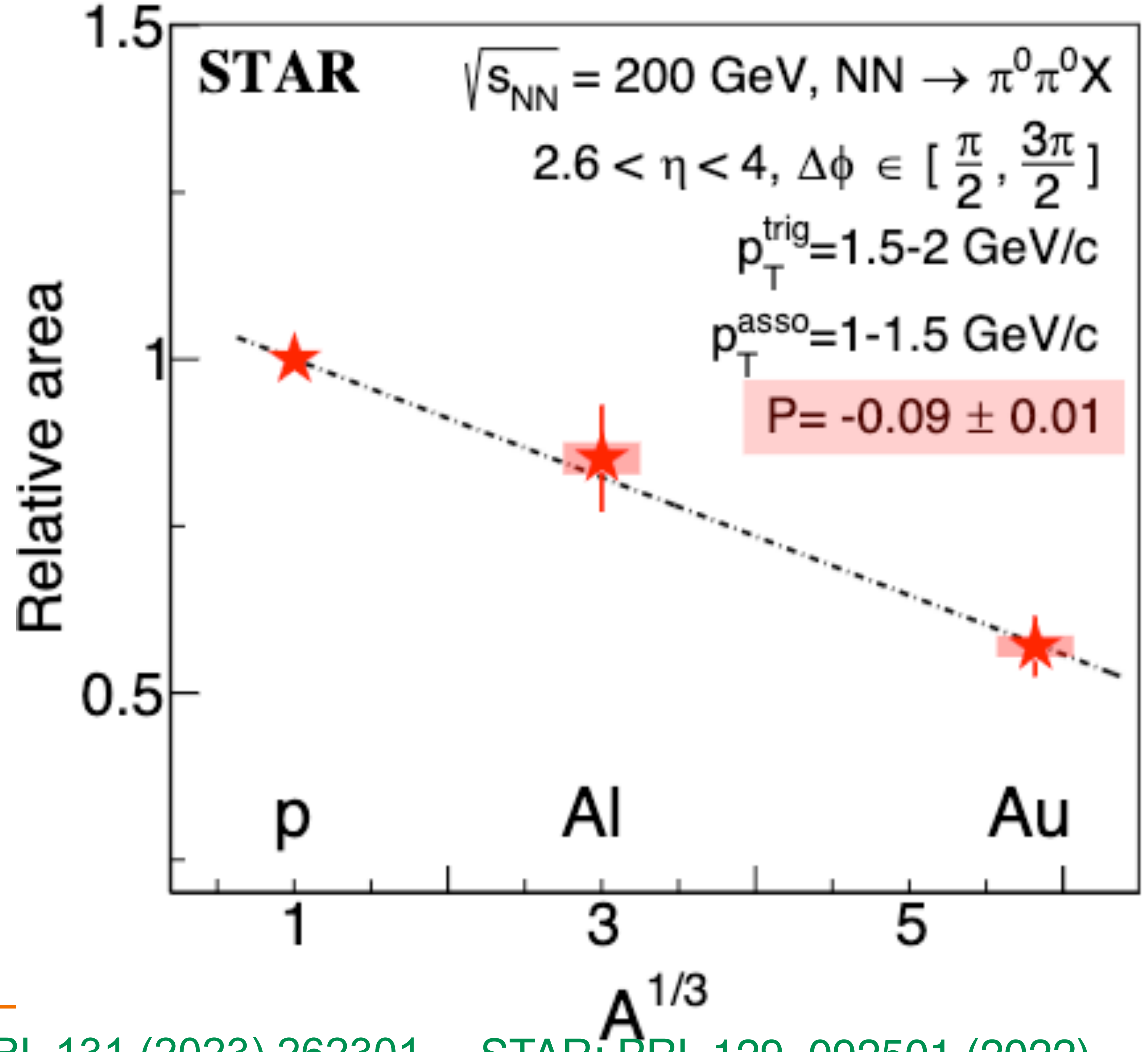


Suppression of di-π^0 correlations in p+A

- 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

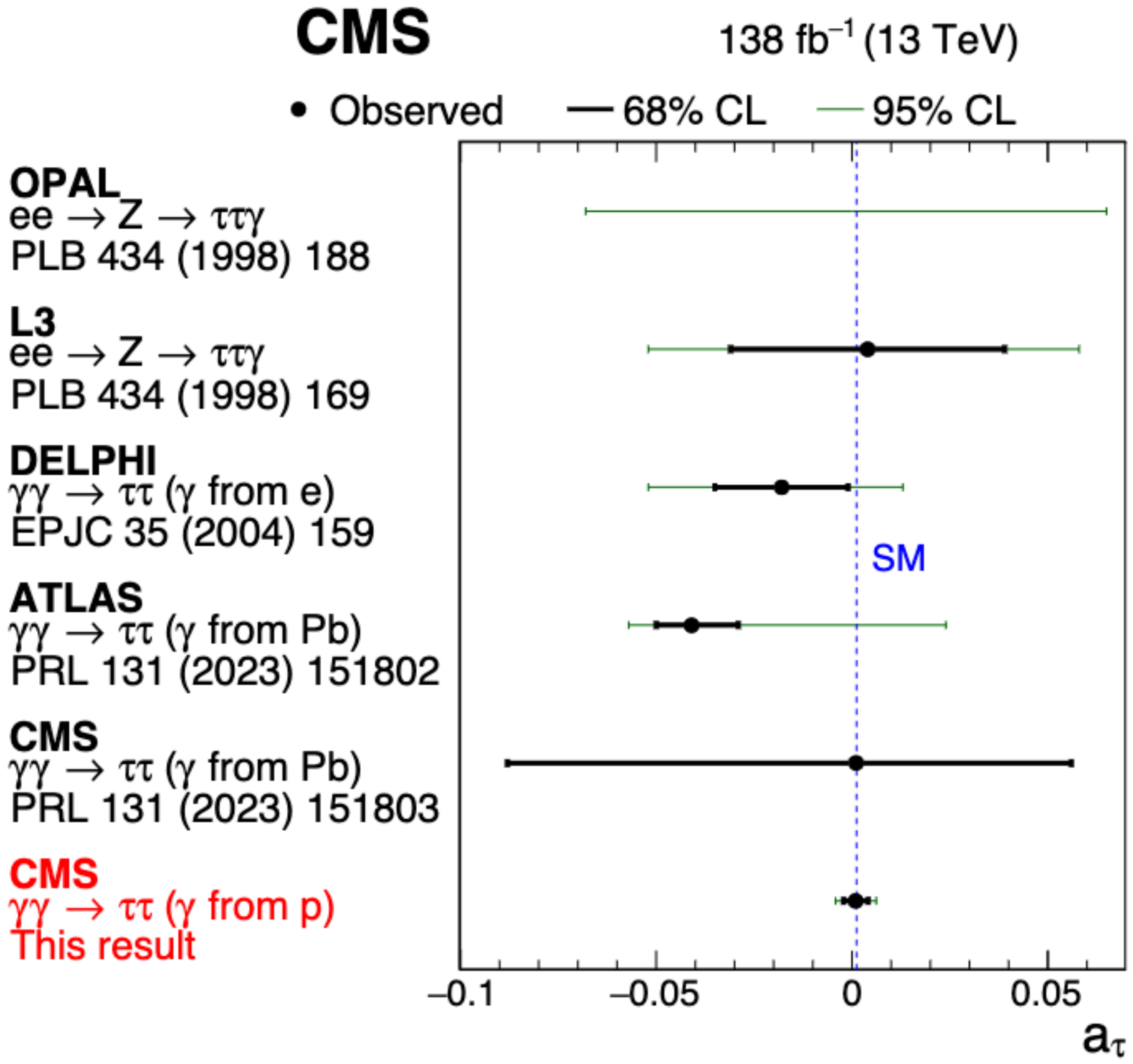
From p+p:

$a_\tau = 0.0009 + 0.031 - 0.0021$

(consistent with SM)

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

Results are competitive with existing lepton-collider constraints



CMS: arXiv:2406.03975

Summary

Wealth of high quality data across $\sqrt{s_{NN}}$, species and centralities has conclusively shown that a QGP is formed are allowing detailed studies that highlight underlying physics we could previously gloss over

Much is now understood about this unique state of matter

We have uncontrovertibly established that:

- the QGP is a dense and opaque and initially very how
- the QGP is highly vortical
- the QGP flows almost as a perfect liquid (very small shear and bulk viscosity)
- the relevant degrees of freedom are those of quarks and gluons
- equilibration/thermalization is first achieved in the QGP and persists through to chemical freeze out

Outlooks

Bright future ahead

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

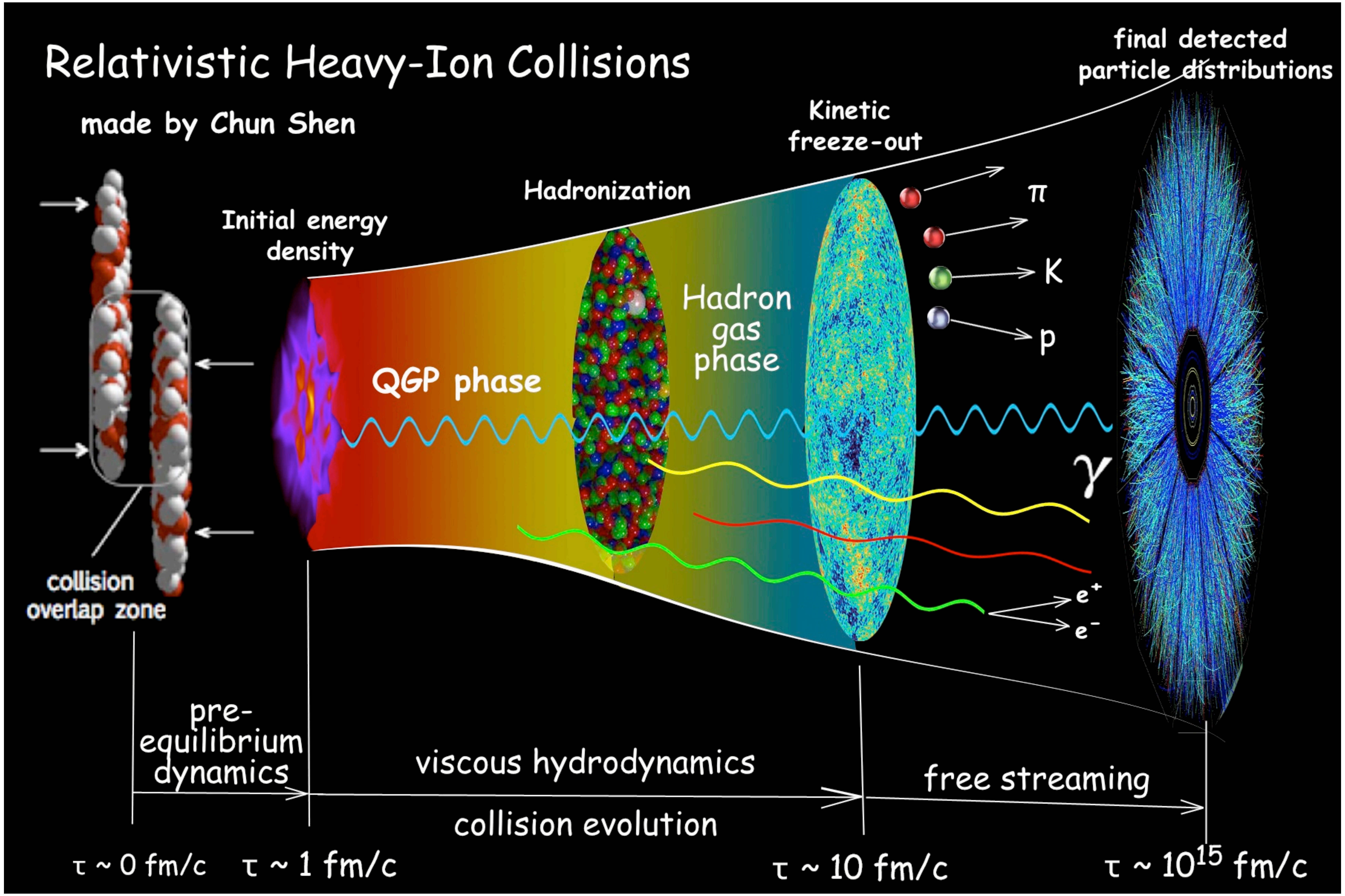
Next-to-Next few years: EIC, ALICE-3, and CBM@FAIR

Lots left to discover!

Of 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?

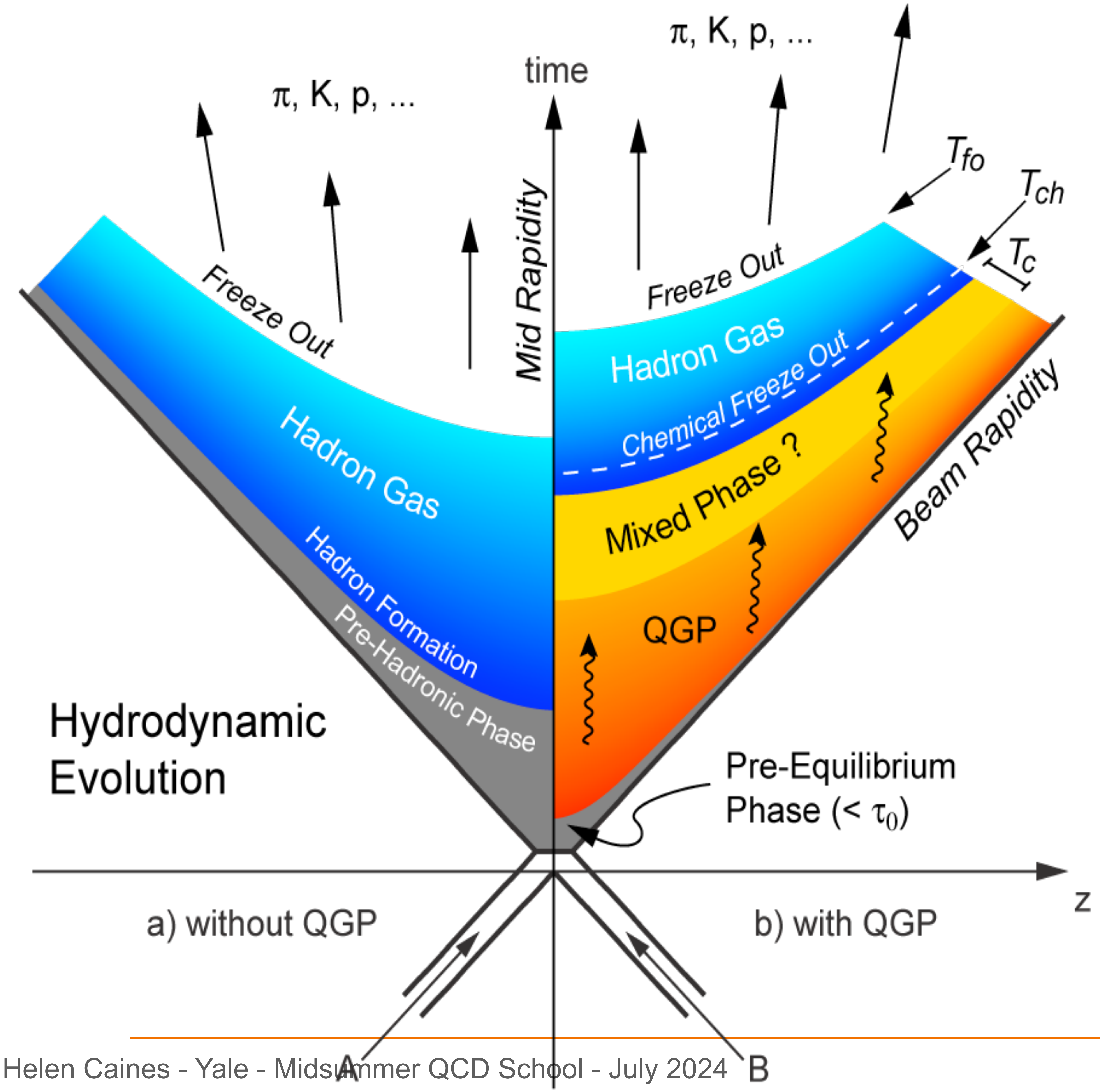
Timeline of a heavy-ion collision



Can only measure final state particles and photons

How to probe the earlier stages?

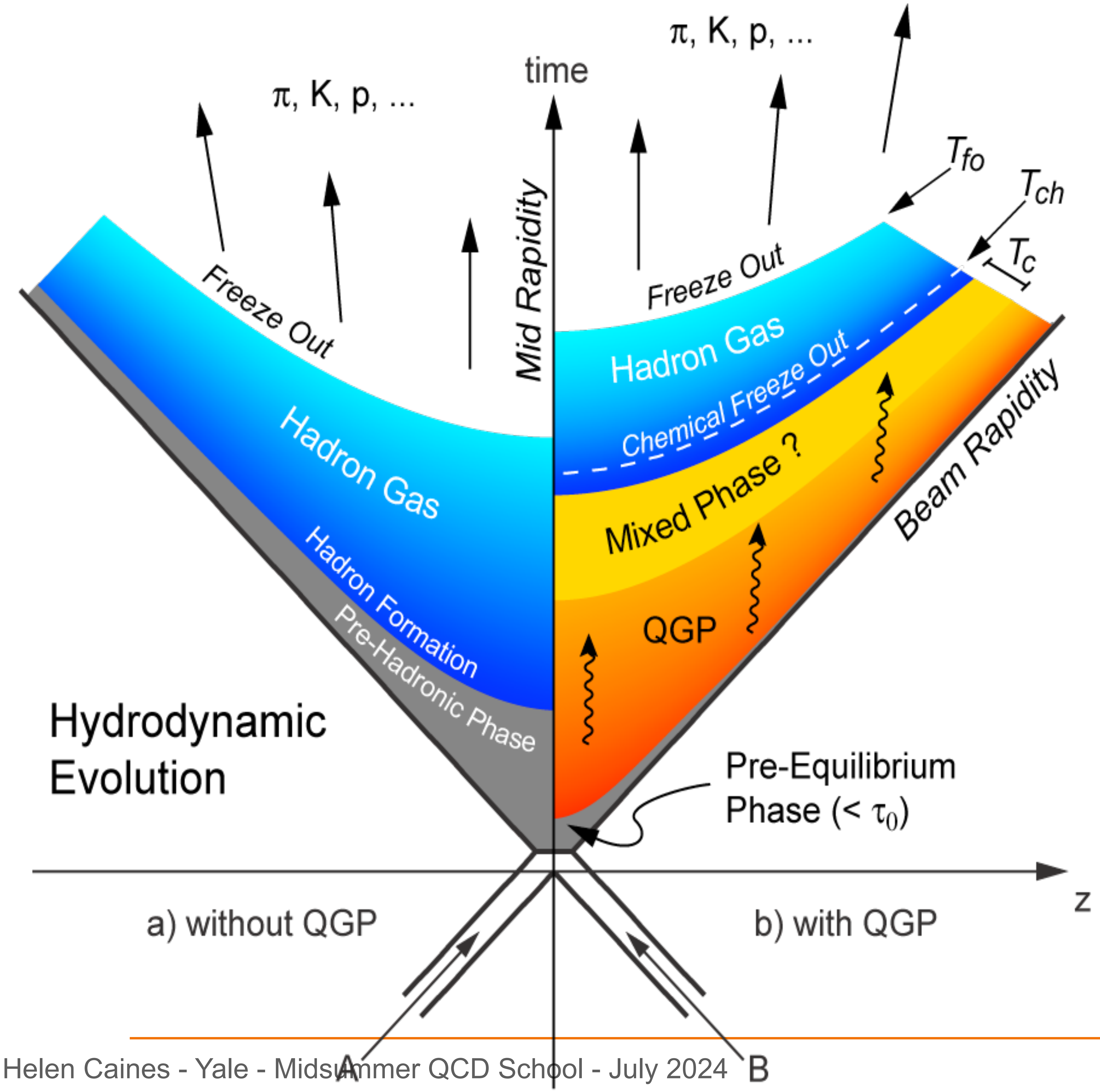
The phase transition in the laboratory



Chemical freeze-out:
  ($T_{ch} \leq T_c$): inelastic scattering ceases

Kinetic freeze-out:
  ($T_{fo} \leq T_{ch}$): elastic scattering ceases

The phase transition in the laboratory



Chemical freeze-out:
($T_{ch} \leq T_c$): inelastic scattering ceases

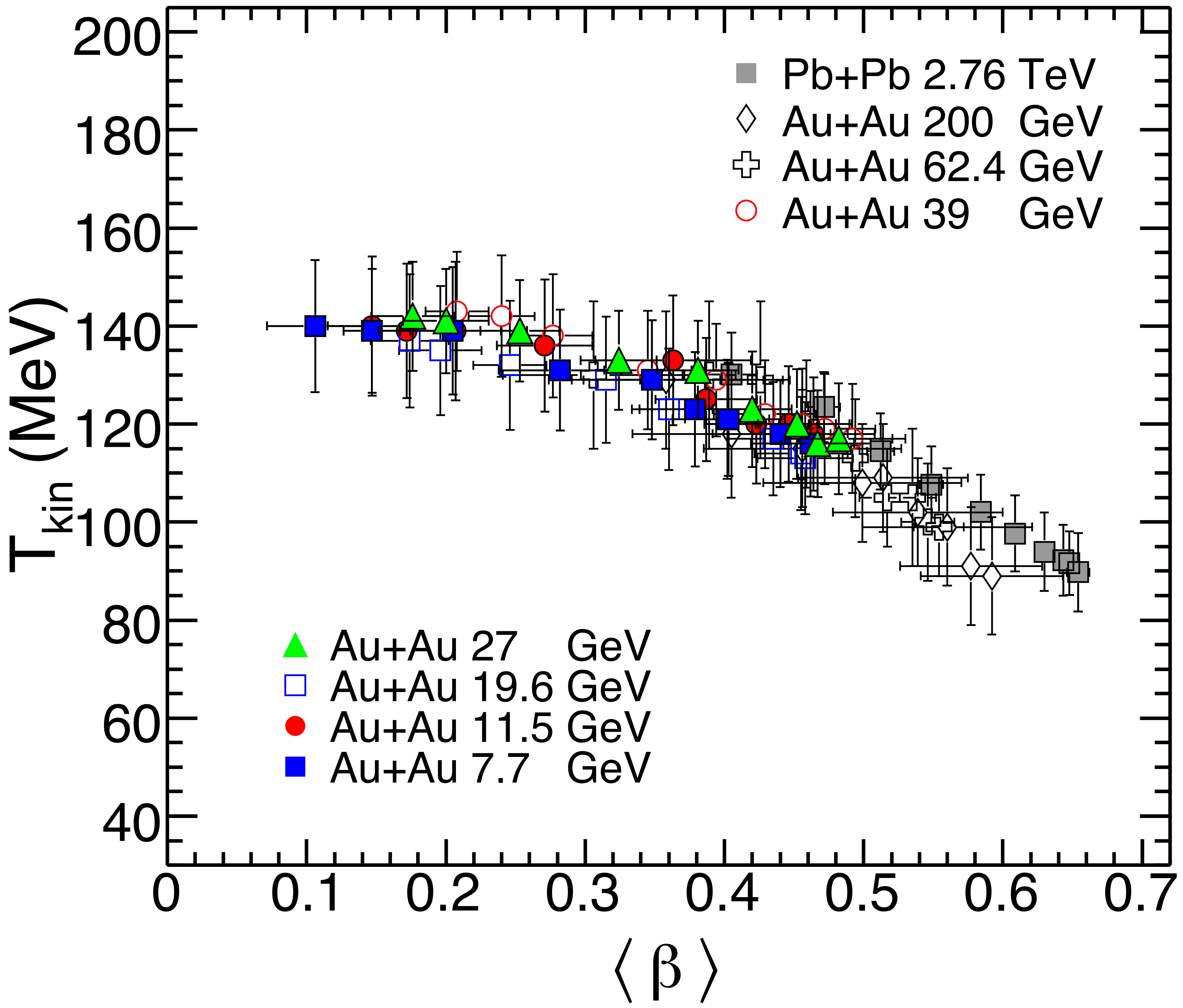
Kinetic freeze-out:
($T_{fo} \leq T_{ch}$): elastic scattering ceases

Energy density is a necessary but **not** sufficient condition

$\varepsilon(\sqrt{s} = 7$ TeV pp LHC) >>
$\varepsilon(\sqrt{s} = 200$ GeV Au-Au RHIC)

Thermal Equilibrium ⇒
many constituents

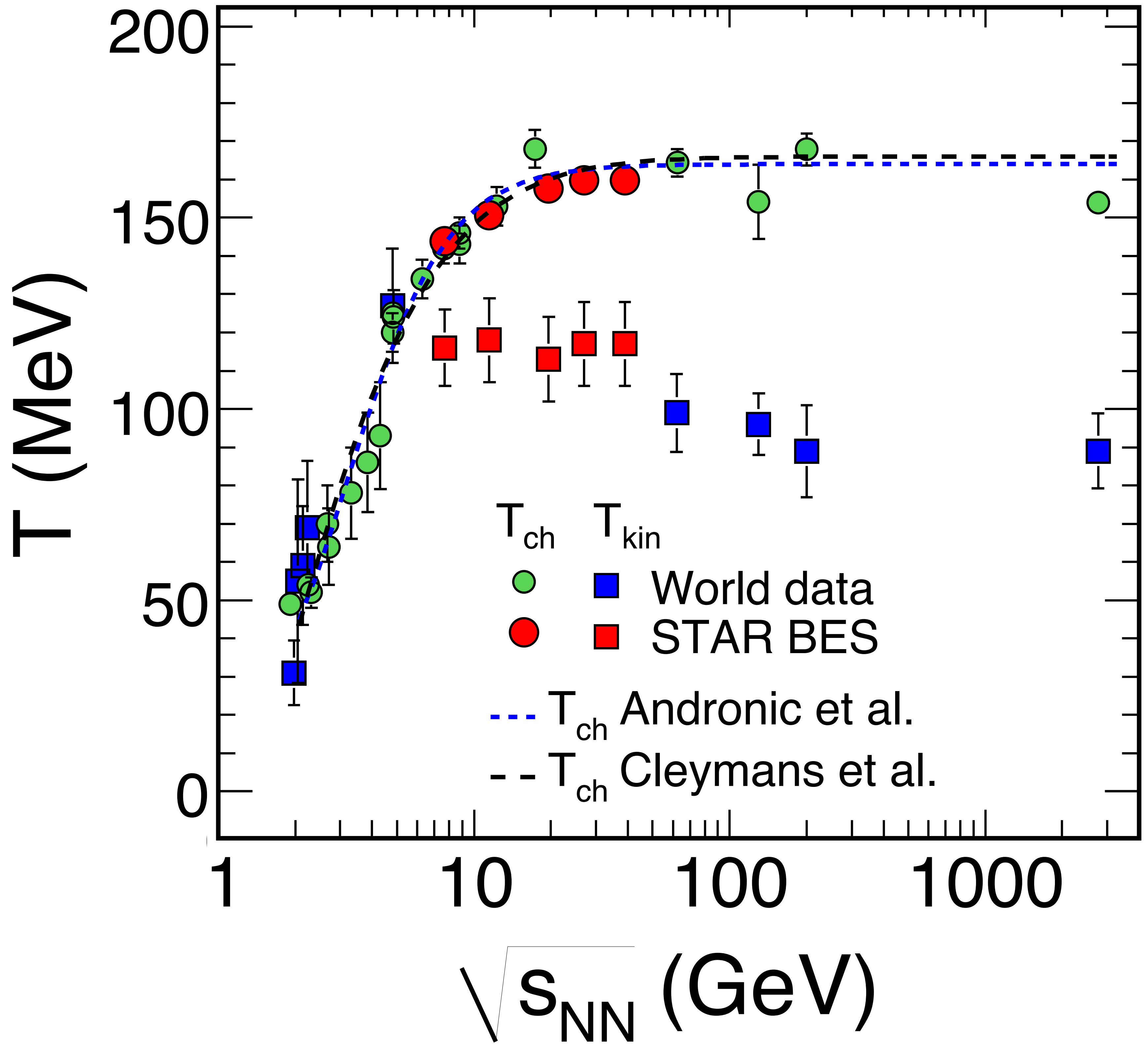
Establishing the "basics": Kinetic freeze-out



Stronger collectivity at higher √s

Central collisions:

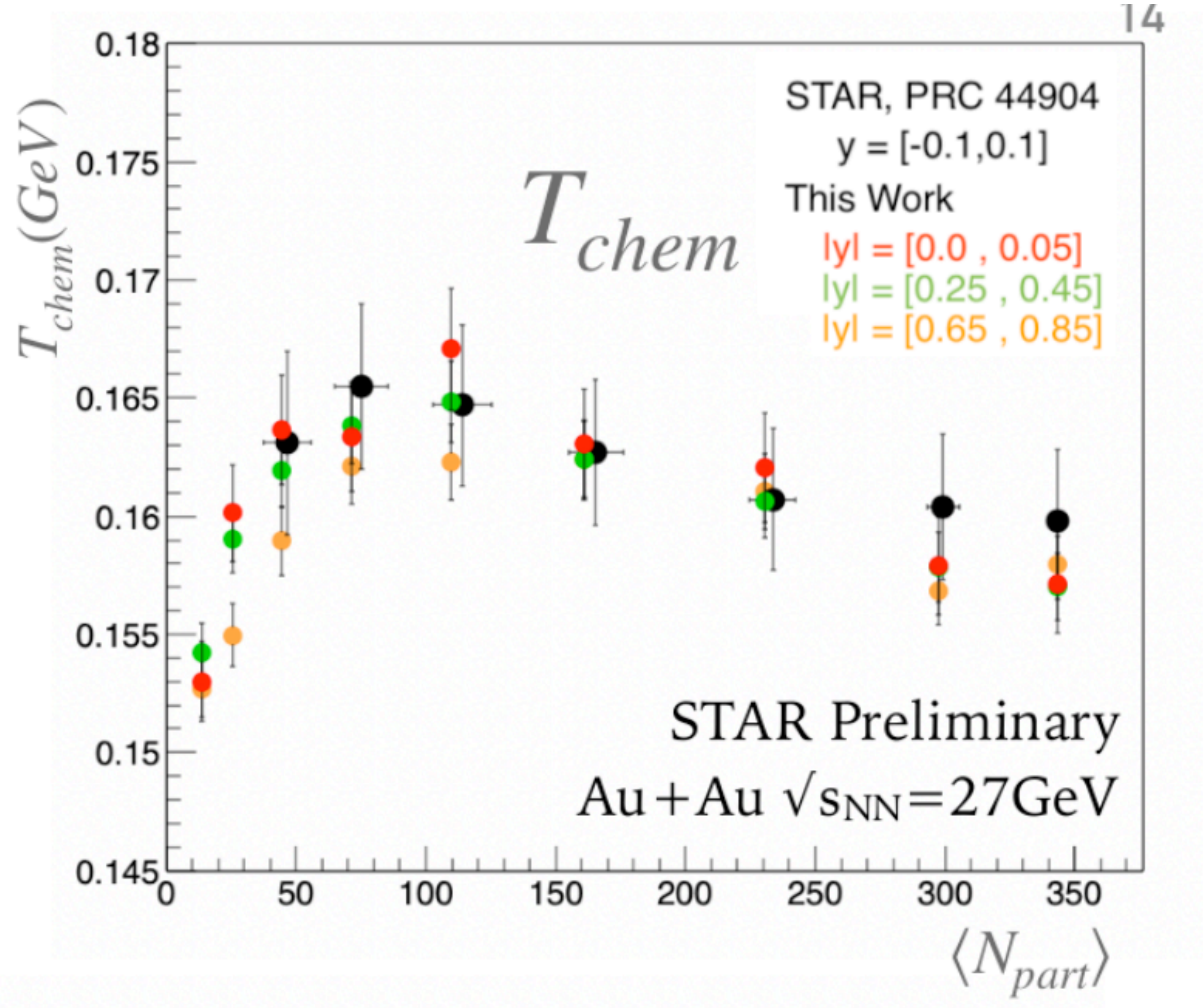
Lower T→ higher β

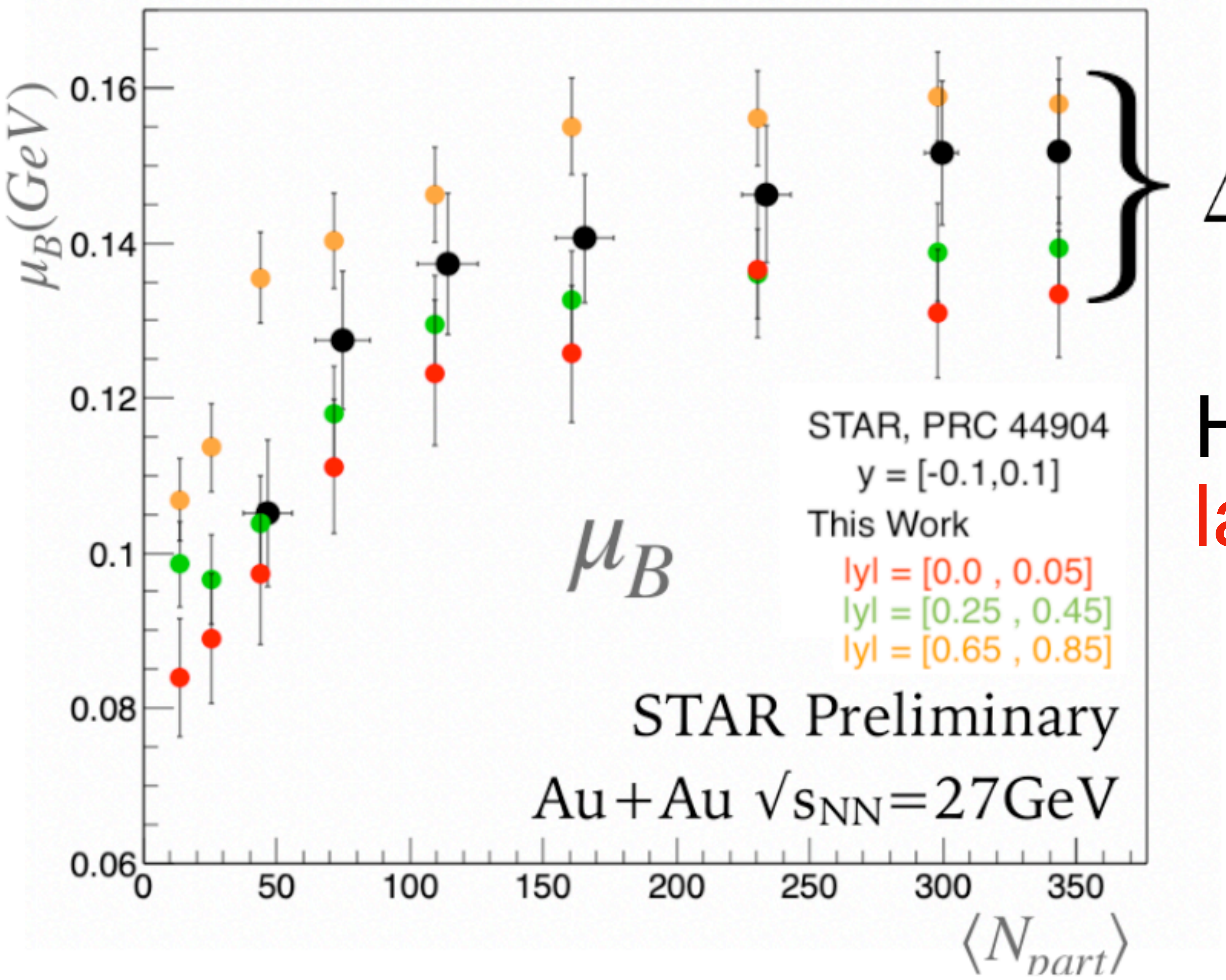


T_{kin}~T_{ch} below √s ~ 7 GeV

Varying trajectory through the phase diagram?

With BES-II statistics and new TPC acceptance can explore rapidity dependence





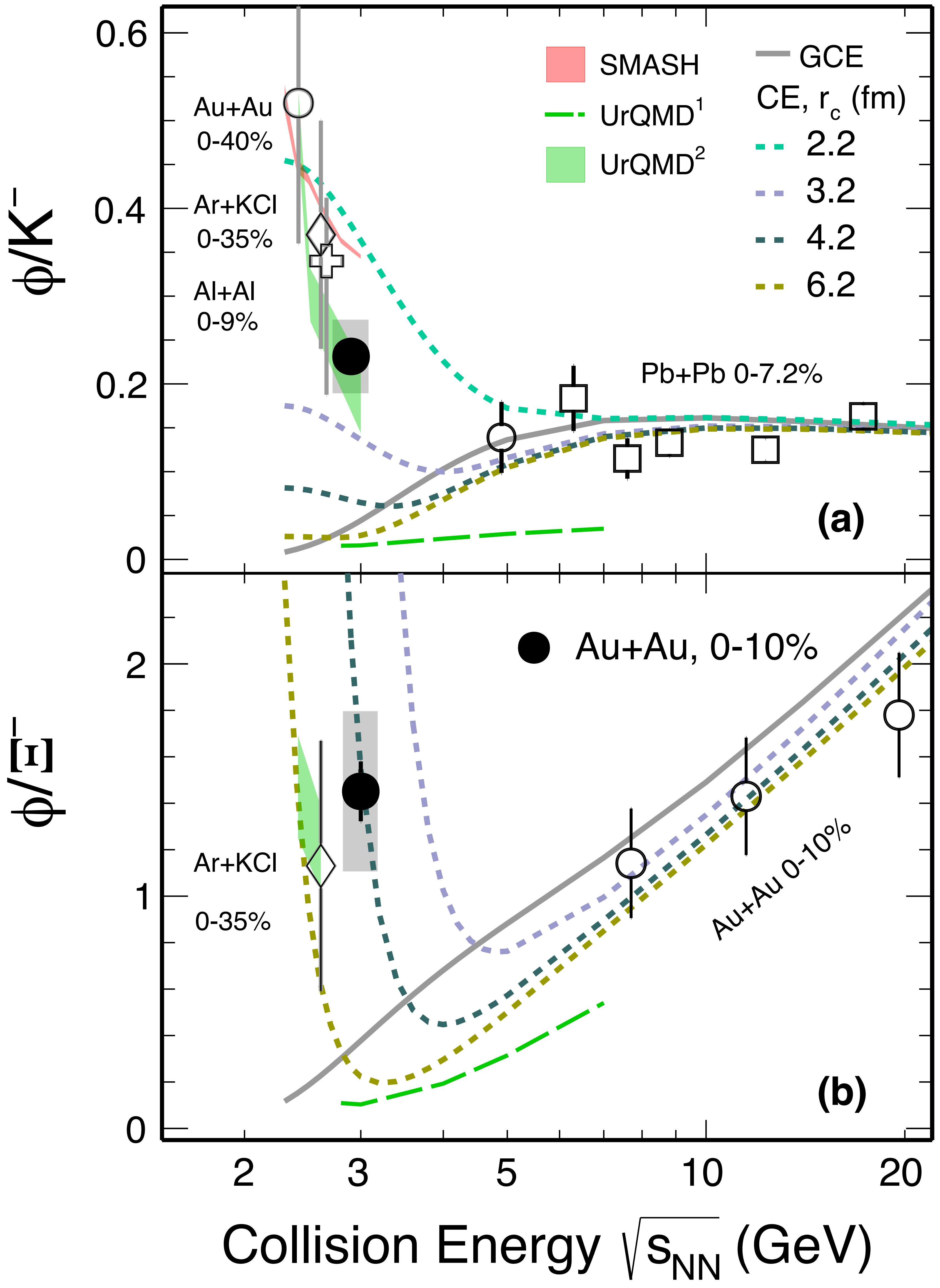
$\Delta\mu_B$

Higher rapidity —>
larger μ_B, similar T_{ch}

Next step: Compare mid-rapidity/low $\sqrt{s_{NN}}$ and high rapidity/high $\sqrt{s_{NN}}$

Chemical freeze-out parameters match but initial conditions differ.
Can we see the difference imprinted elsewhere?

Probing (grand)canonical production



Things change at $\sqrt{s_{NN}}$ = 3 GeV

Collision energy:

below threshold for Ξ

very close to threshold for ϕ

Local treatment of strangeness conservation crucial

Small strangeness correlation radius preferred

$r_c \leq 4.2$ fm

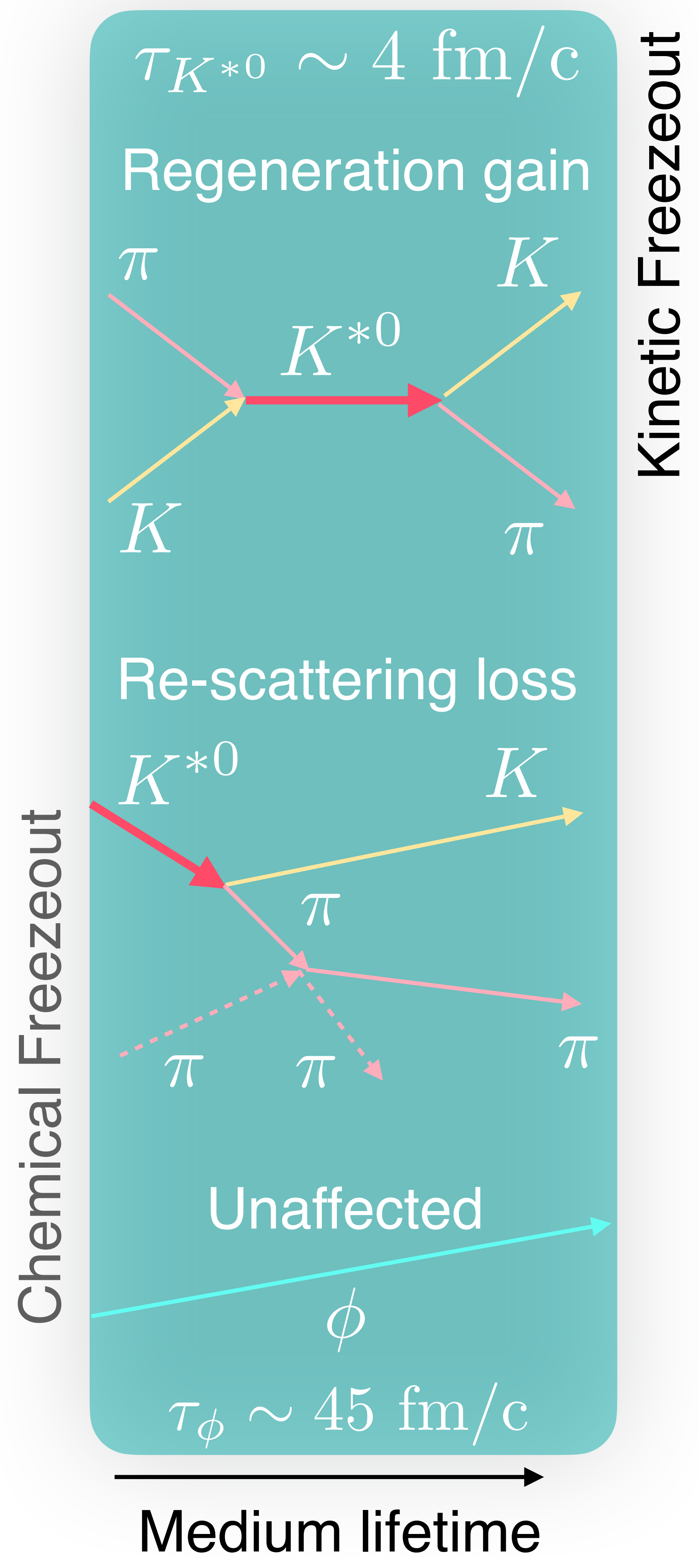
CE cannot simultaneously describe ϕ/K^- and ϕ/Ξ^- ratios

significant change in strangeness production at this low energy

T_{ch} = 72.9 MeV and μ_B = 701.4 MeV

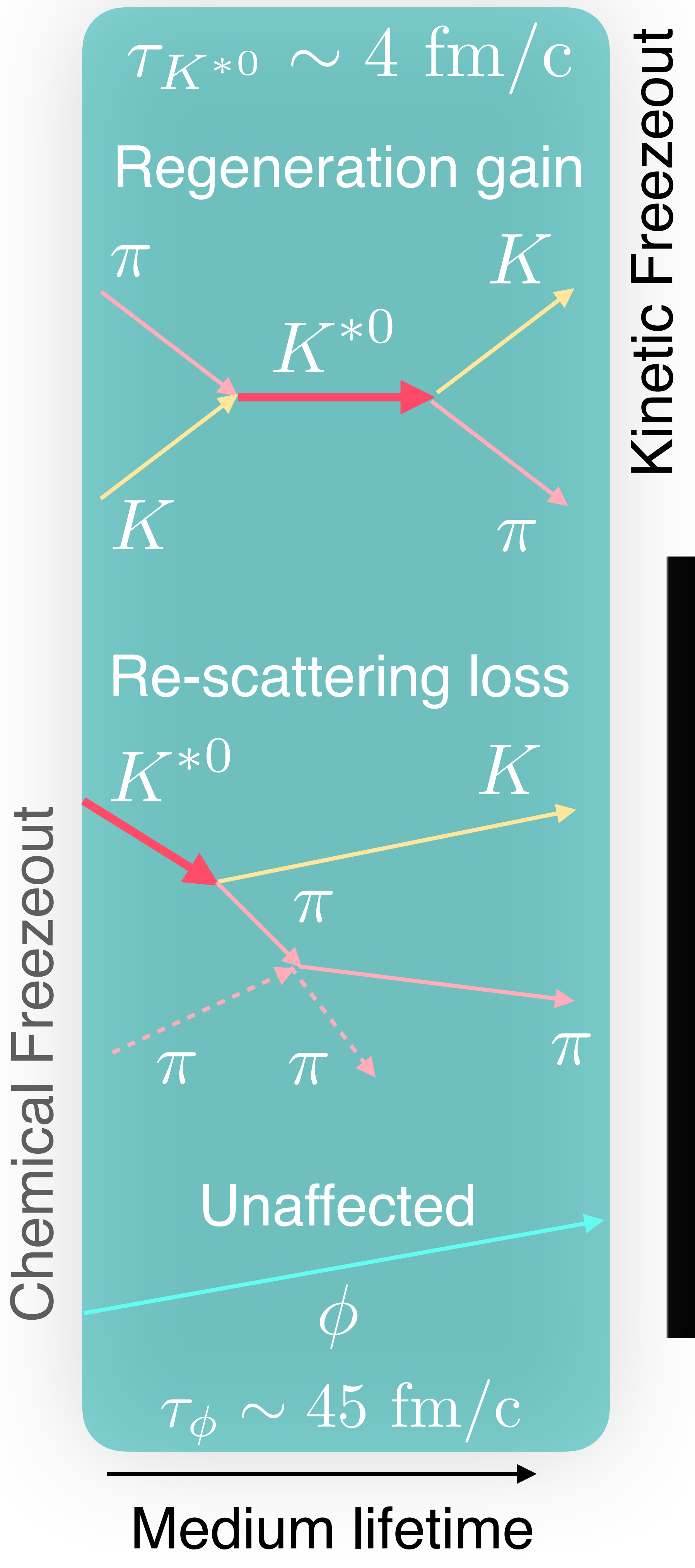
STAR: PLB **831** (2022) 137152

Strange resonance production



Resonance/non-resonance probes hadronic phase between chemical and kinetic freeze-out

Strange resonance production



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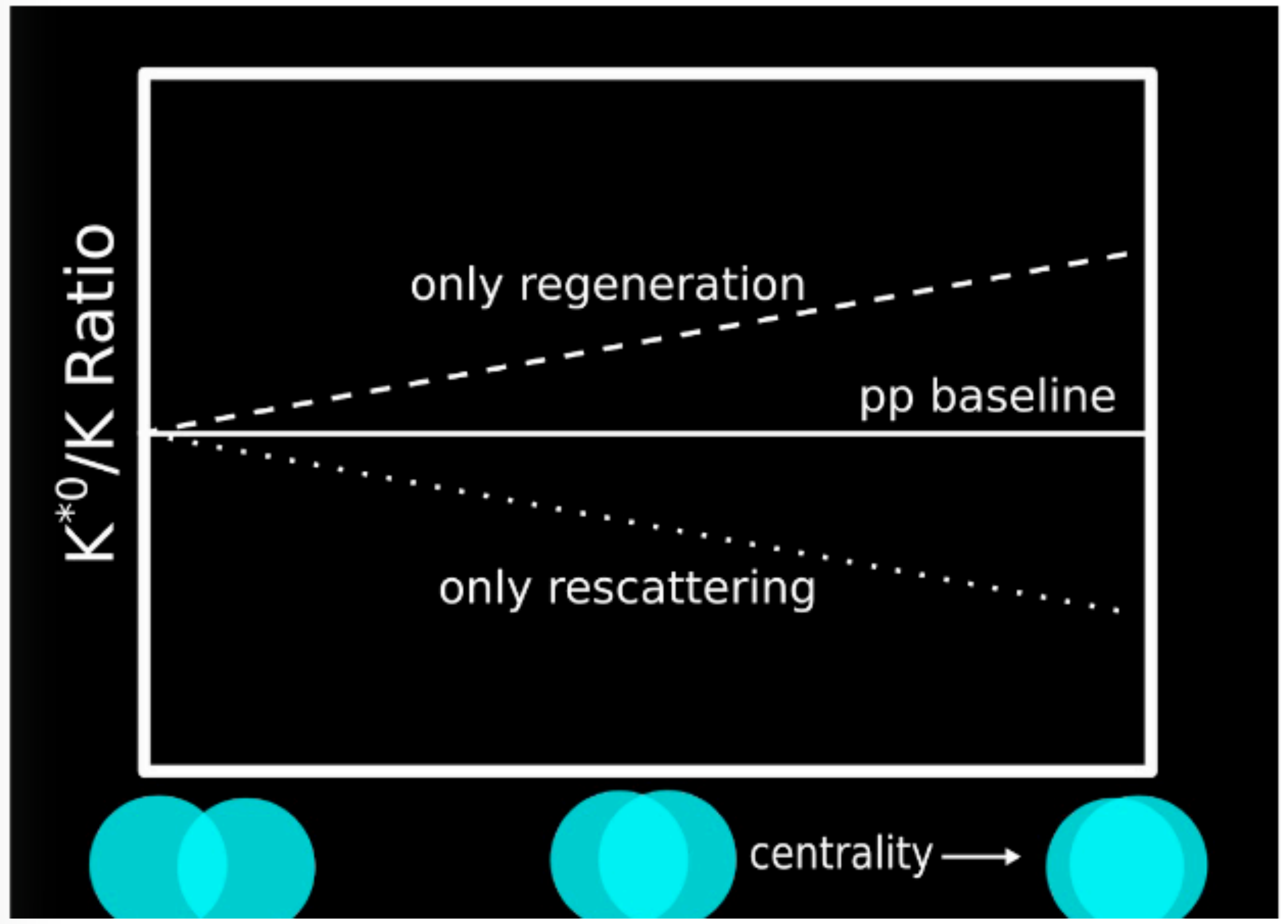

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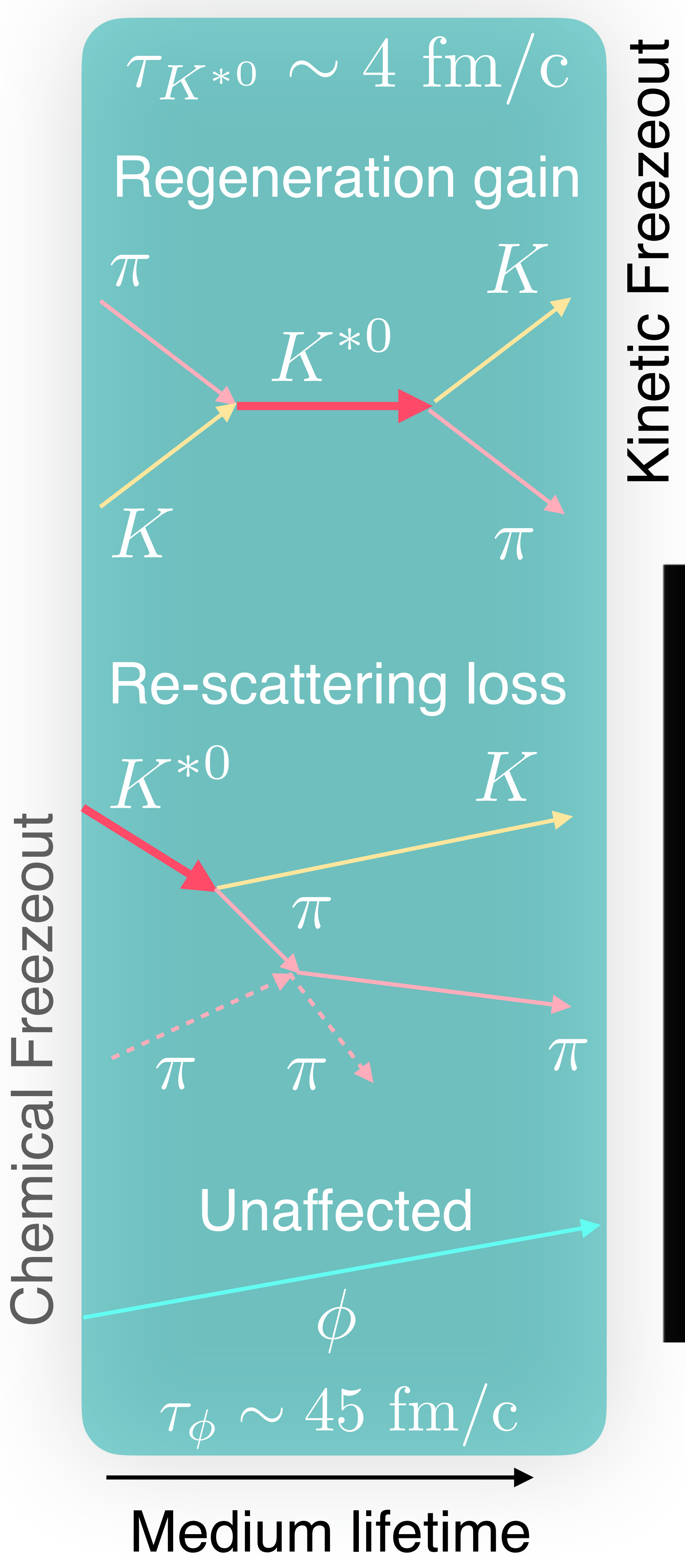

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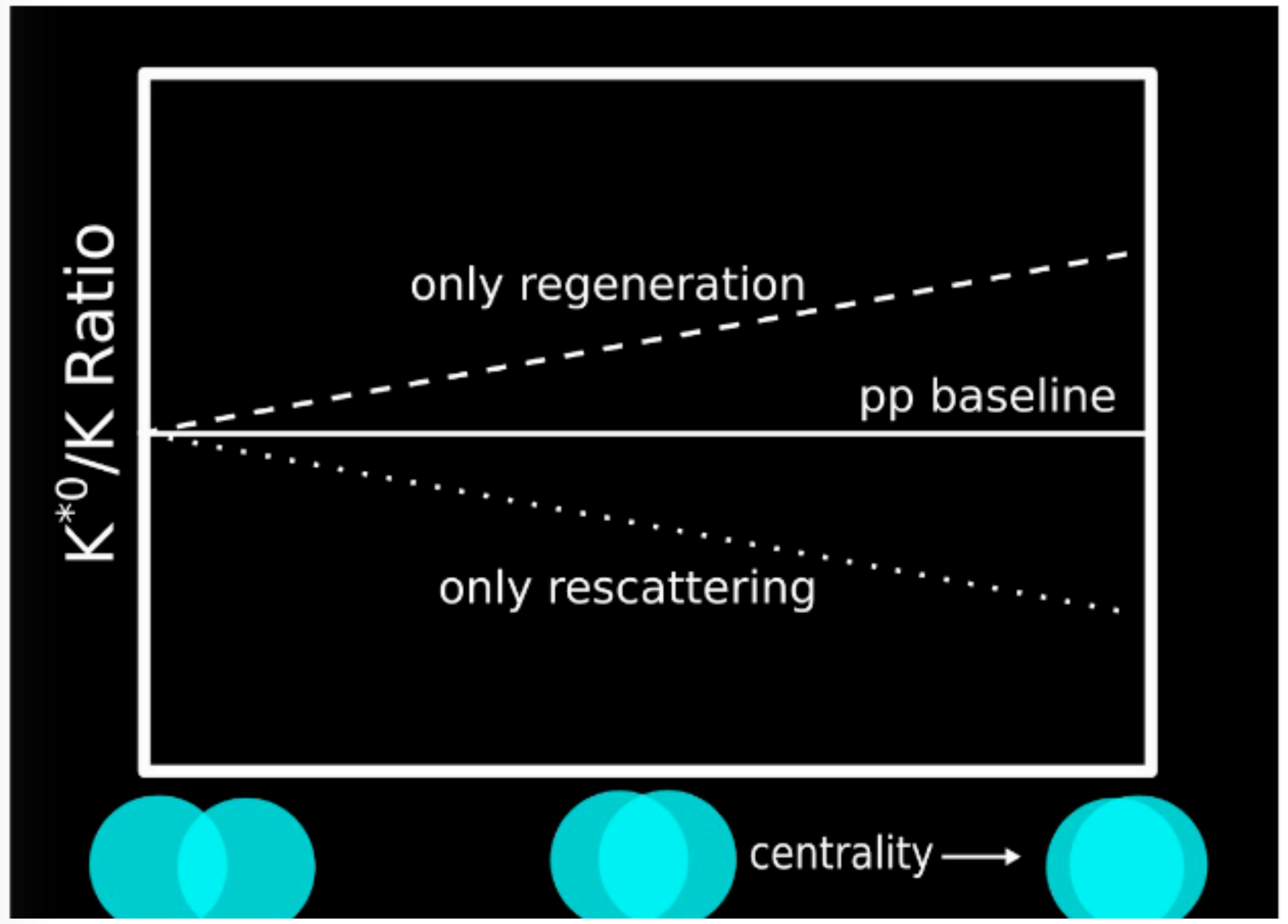
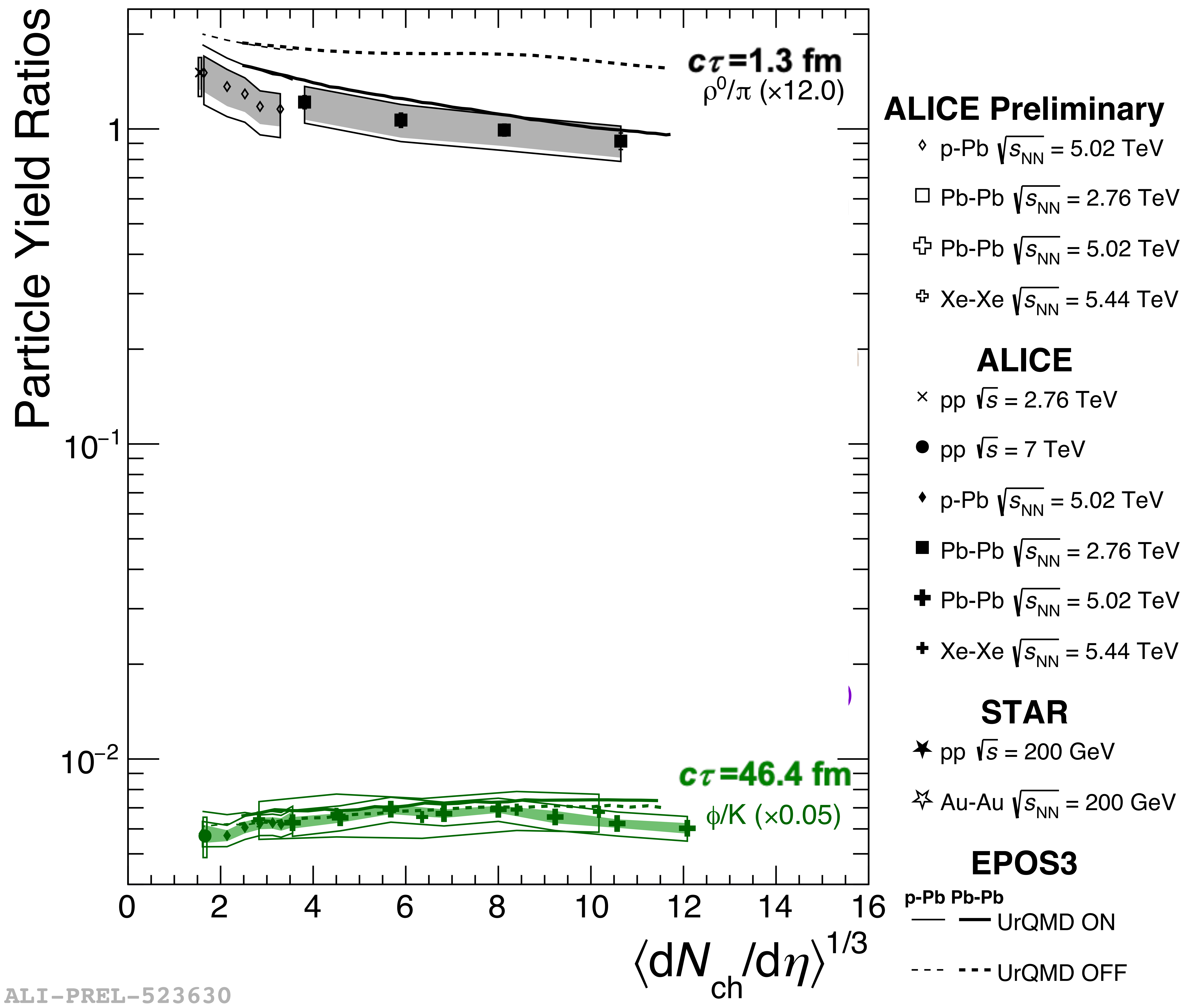
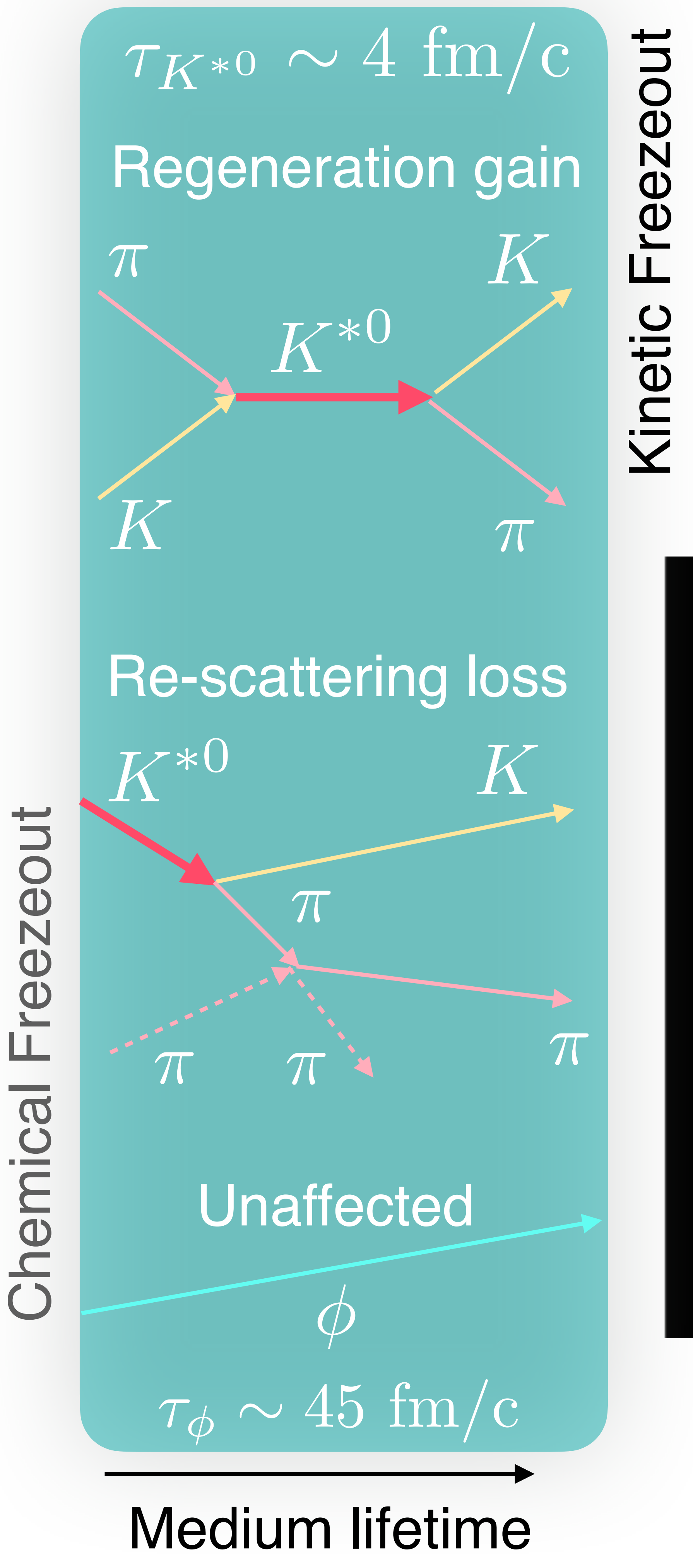
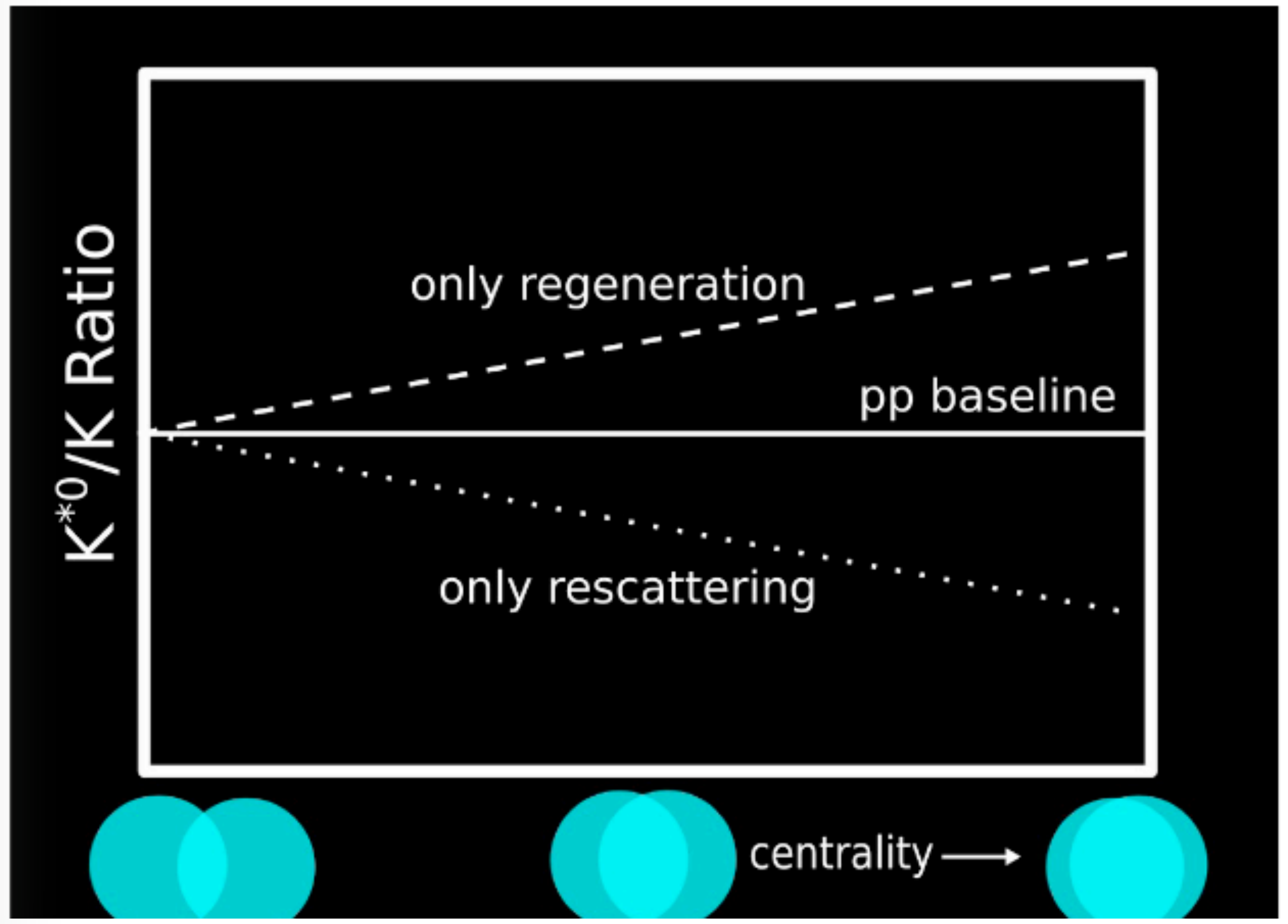


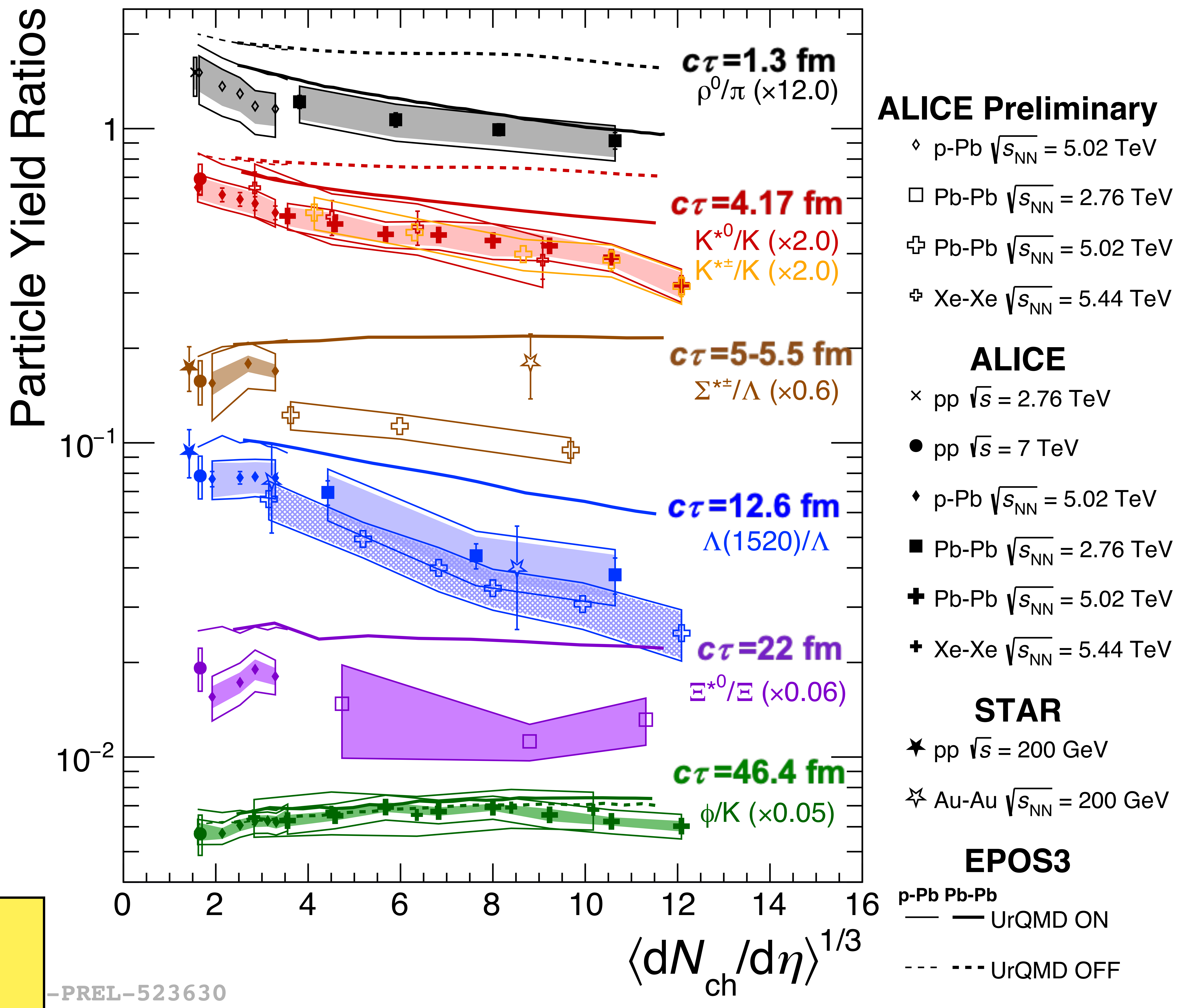


Strange resonance production



Resonance/non-resonance probes hadronic phase between chemical and kinetic freeze-out





Ratios suggest hadronic phase is long, rescattering cross-section also important

Softening of Equation of State

Fermi-Landau initial conditions with ideal hydro expansion : $c_s^2 = \partial P/\partial \varepsilon$

$c_s^2 = 0$ for a sharp phase transition

Softest Point: minimum in c_s^2

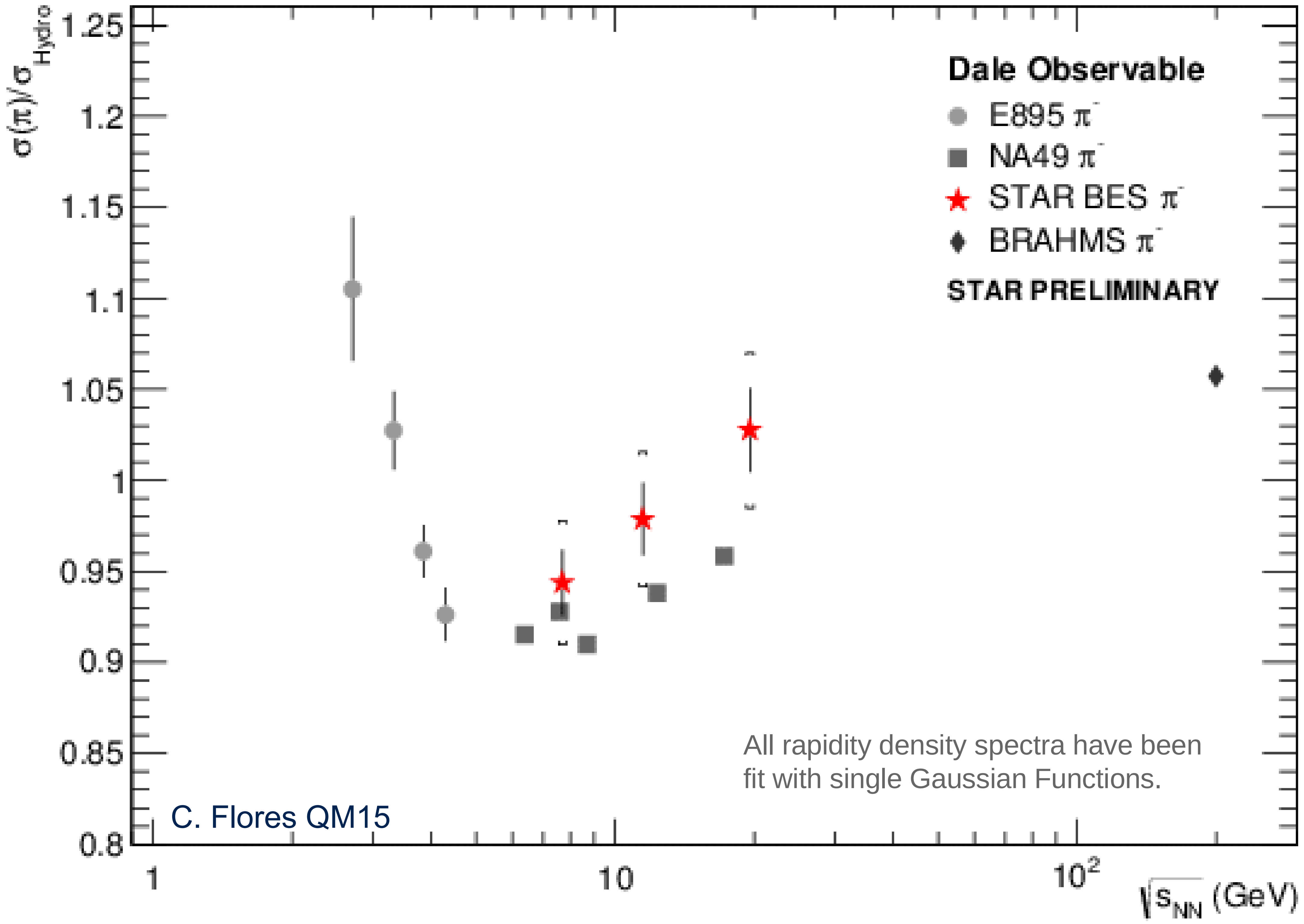
$$\frac{dn}{dy} = \frac{K s_{NN}^{1/4}}{\sqrt{2\pi\sigma_y^2}} e^{-\frac{y^2}{2\sigma_y^2}} \qquad \sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln\left(\frac{\sqrt{s}}{2m_N}\right)$$

Minimum observed at √s = ~7 GeV

Minimum in the speed of sound?

$c_s^2 \sim 0.26$

Indication of softening of EoS?



All rapidity density spectra have been fit with single Gaussian Functions.

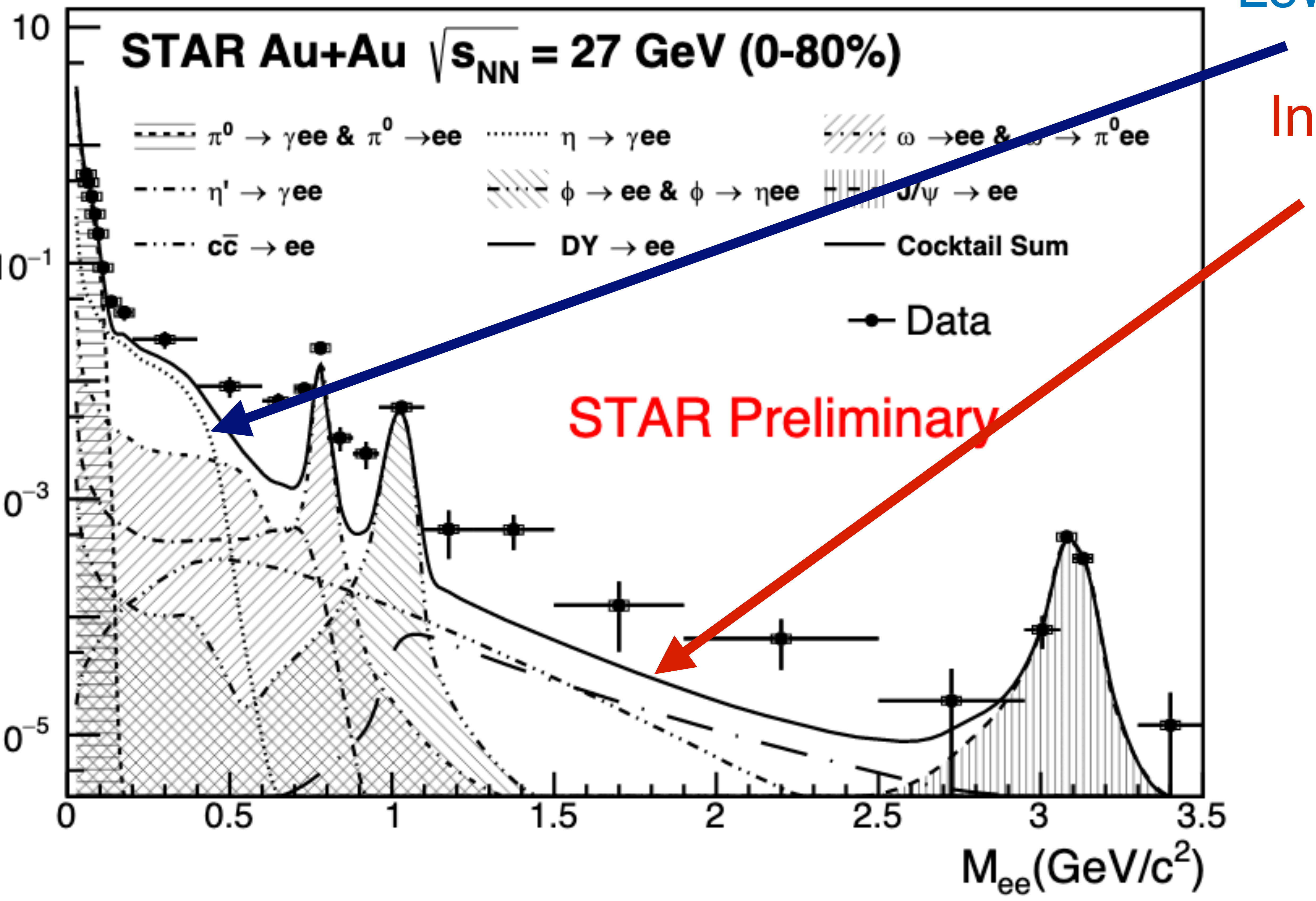
C. Flores QM15

E895: J. L. Klay et al, PRC 68, 05495 (2003)
NA49: S. V. Afanasiev et al. PRC 66, 054902 (2002)
BRAHMS: I.G. Bearden et al., PRL 94, 162301

NA61/SHINE see minima in similar place for pp data

Confirm c_s in other ways?

Significant enhancement above cocktail

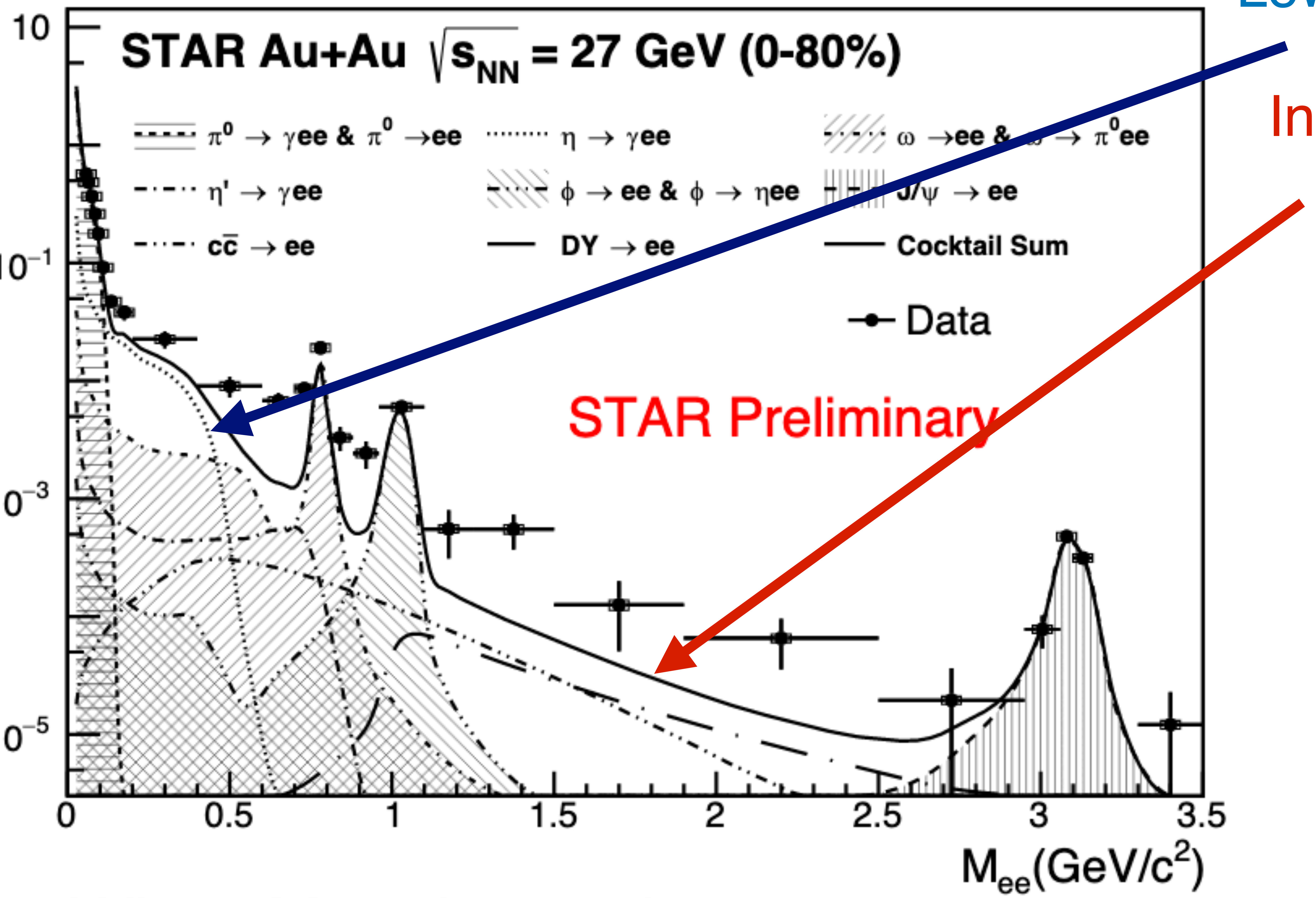


Low mass range

Intermediate mass range

Clear enhancement for LMR and IMR

Significant enhancement above cocktail



Low mass range

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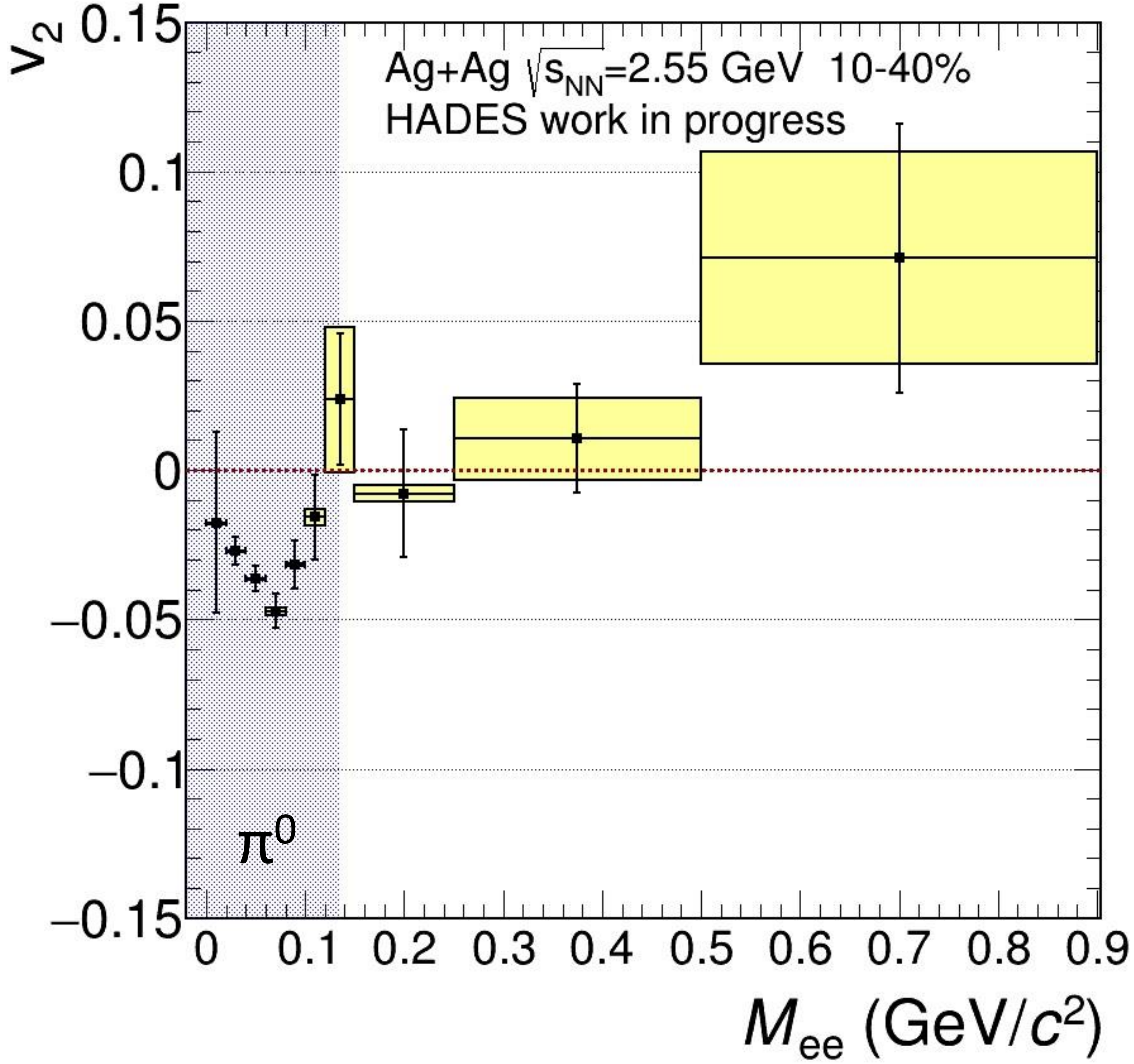
Clear enhancement for LMR and IMR



When M_{ee} above pion mass:

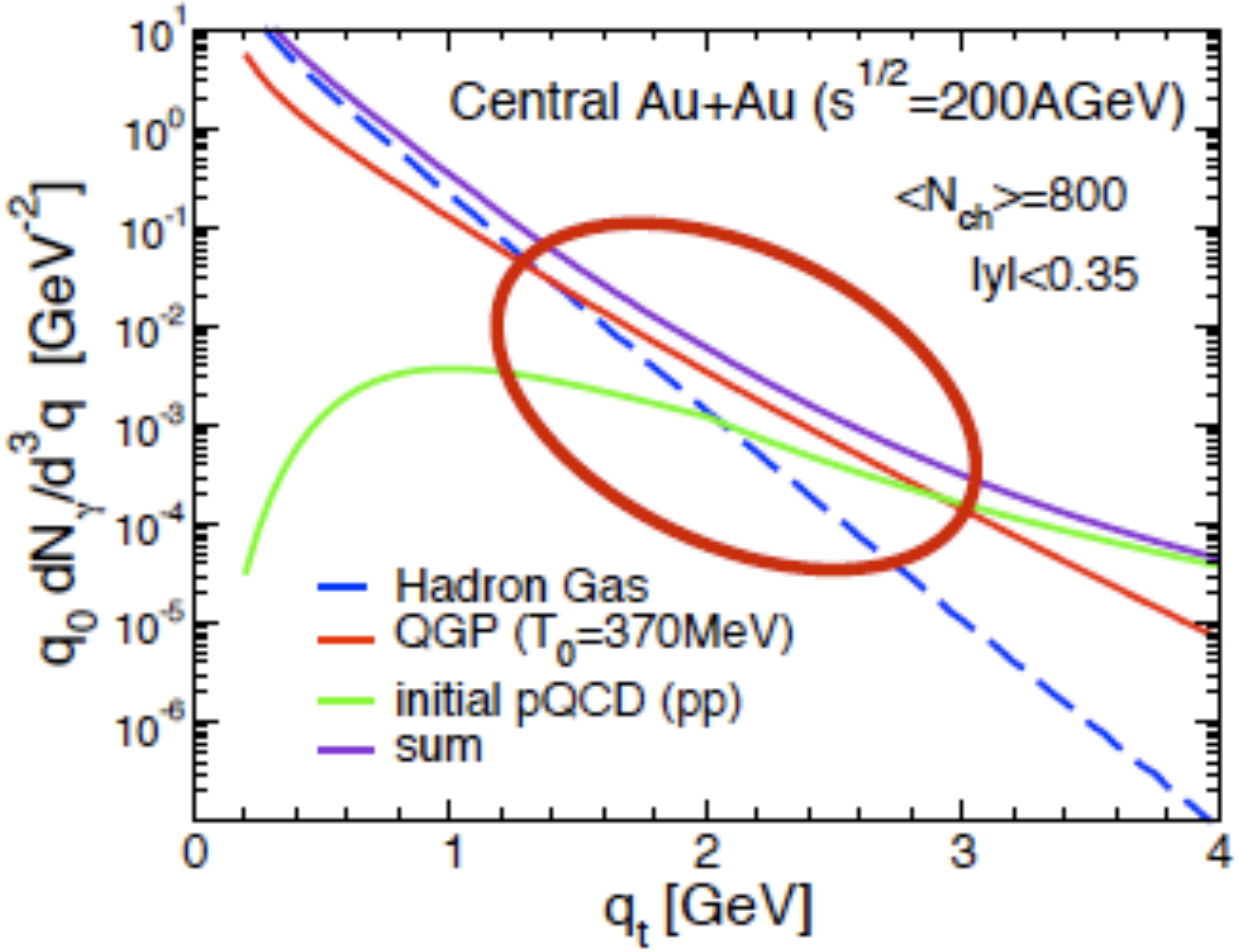
no collectivity exhibited

We've identified a penetrating probe with no boost

Estimating the initial temperature

Direct Photons:

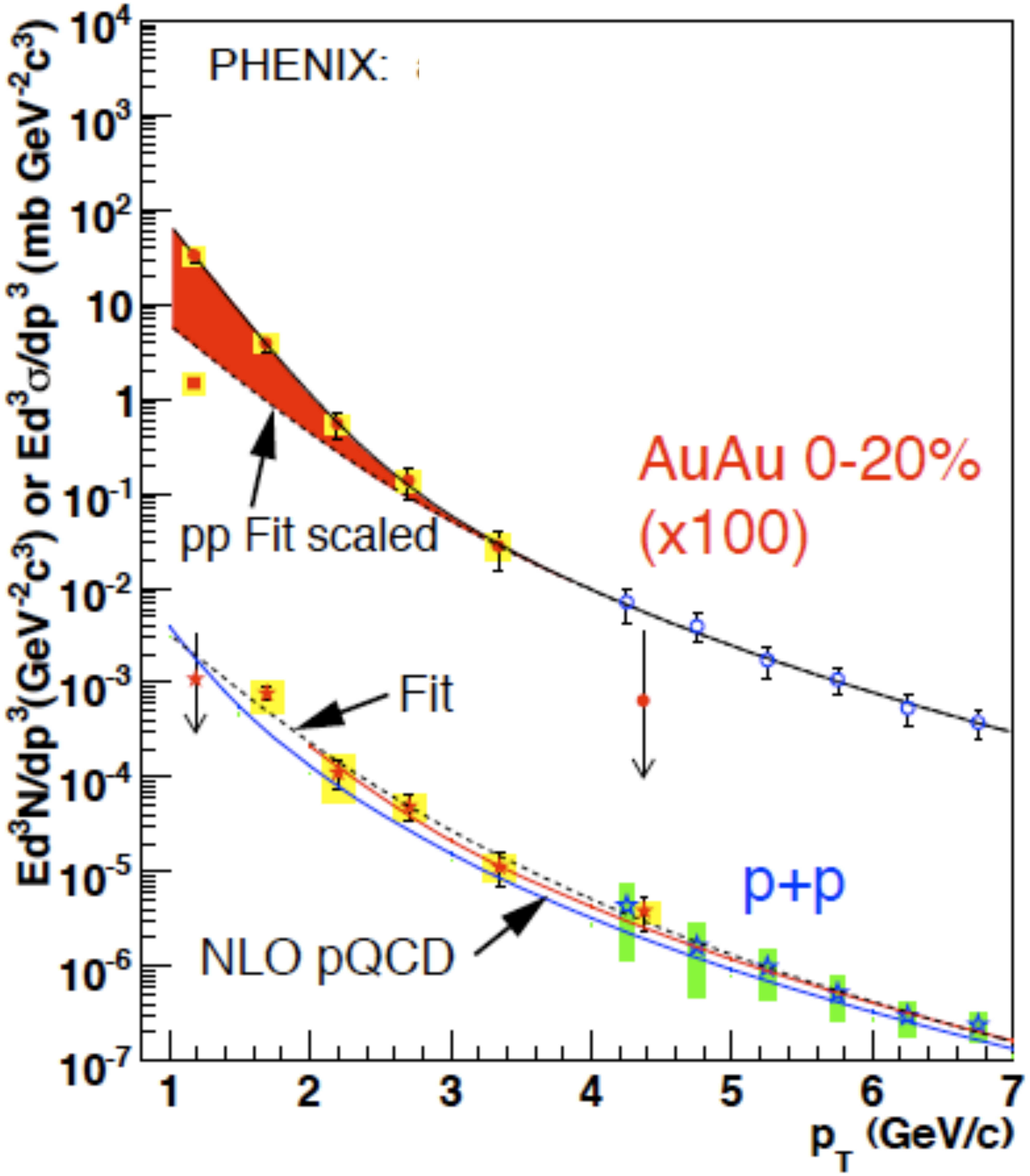
- no charge or color → don't interact with medium
- emitted over all lifetime → convolution of all T



Theory well developed

QGP dominates: 1< p_T < 3 GeV/c

HIC: surpass critical temperature



After background subtraction:

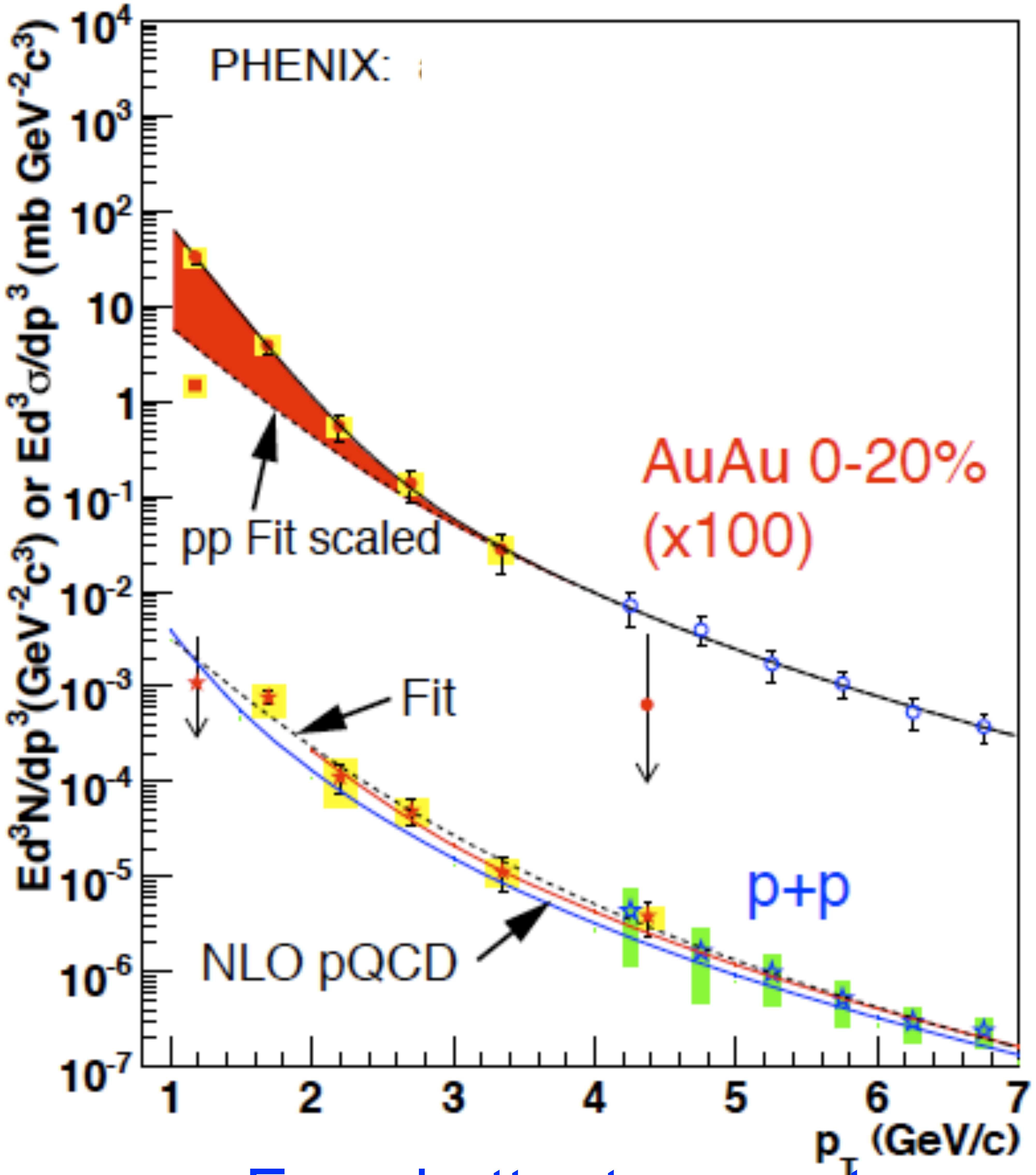
Emission rate and shape consistent with that from a hot thermally equilibrated medium

Hydro models fit to data
T_{RHIC} = 300 - 600 MeV
> 2^*T_c
τ = 0.15-0.6 fm/c

Large uncertainty due to correlated pair background i.e. jets

PHENIX: PRL 104 (2010) 132301

HIC: surpass critical temperature



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Large uncertainty due to correlated pair background i.e. jets

Even hotter temperatures extracted at the LHC

PHENIX: PRL 104 (2010) 132301

Presence of a Critical Point?

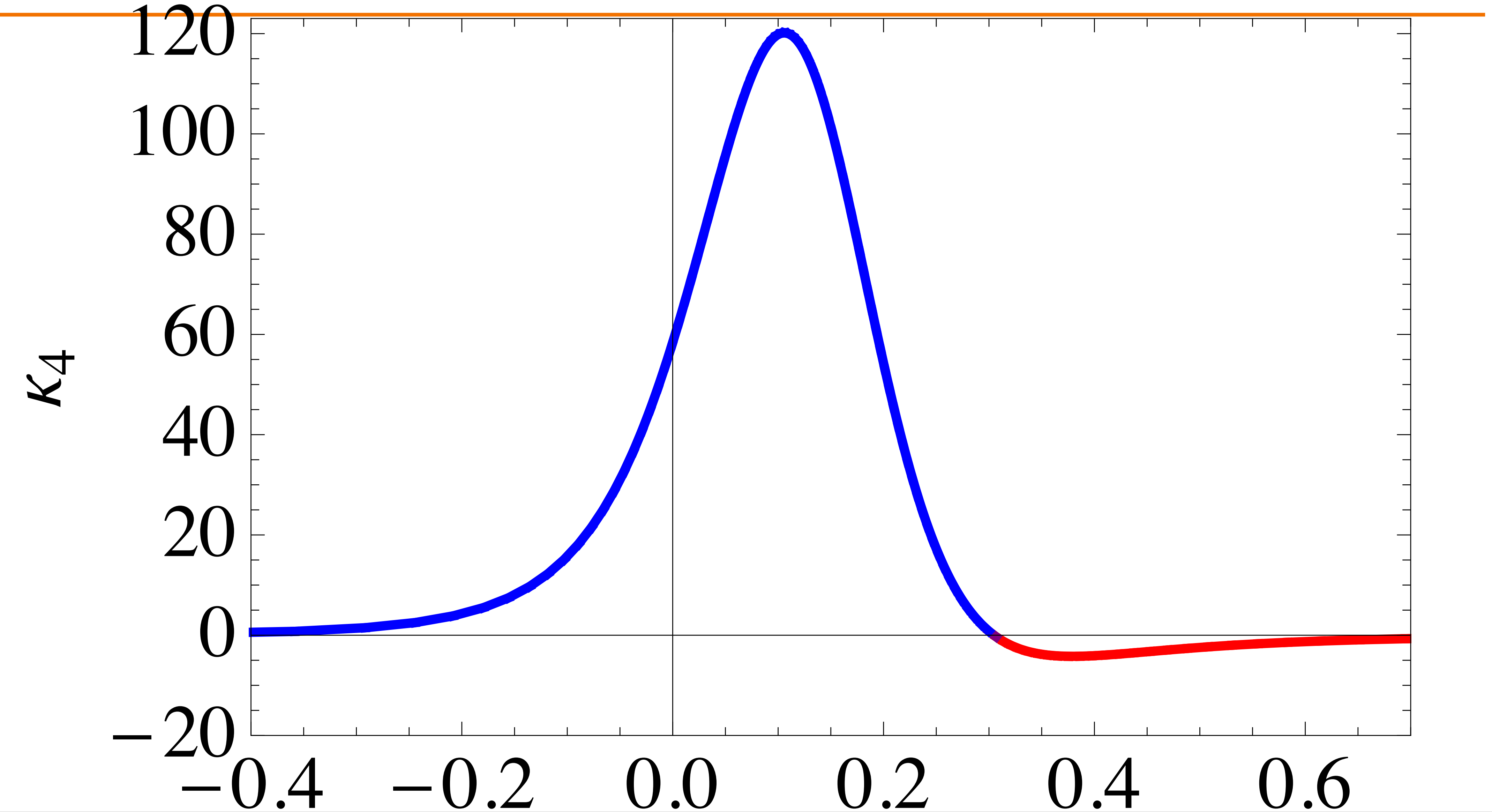
Critical Points:

divergence of susceptibilities

e.g. magnetism transitions

and divergence of correlation lengths

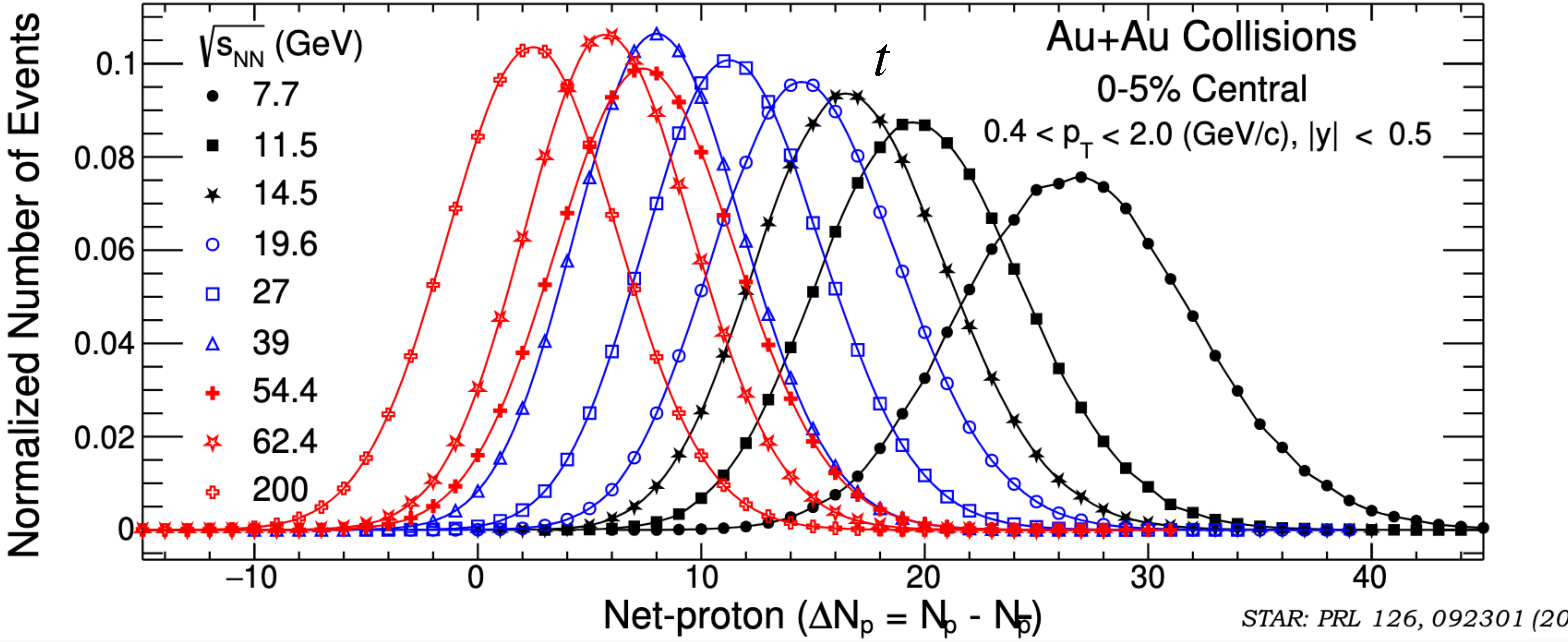
e.g. critical opalescence



In HI:
Large event-by-event fluctuations of conserved quantities (Q,B S) as the non-equilibrium correlation length, ξ, diverges

Correlation lengths diverge →

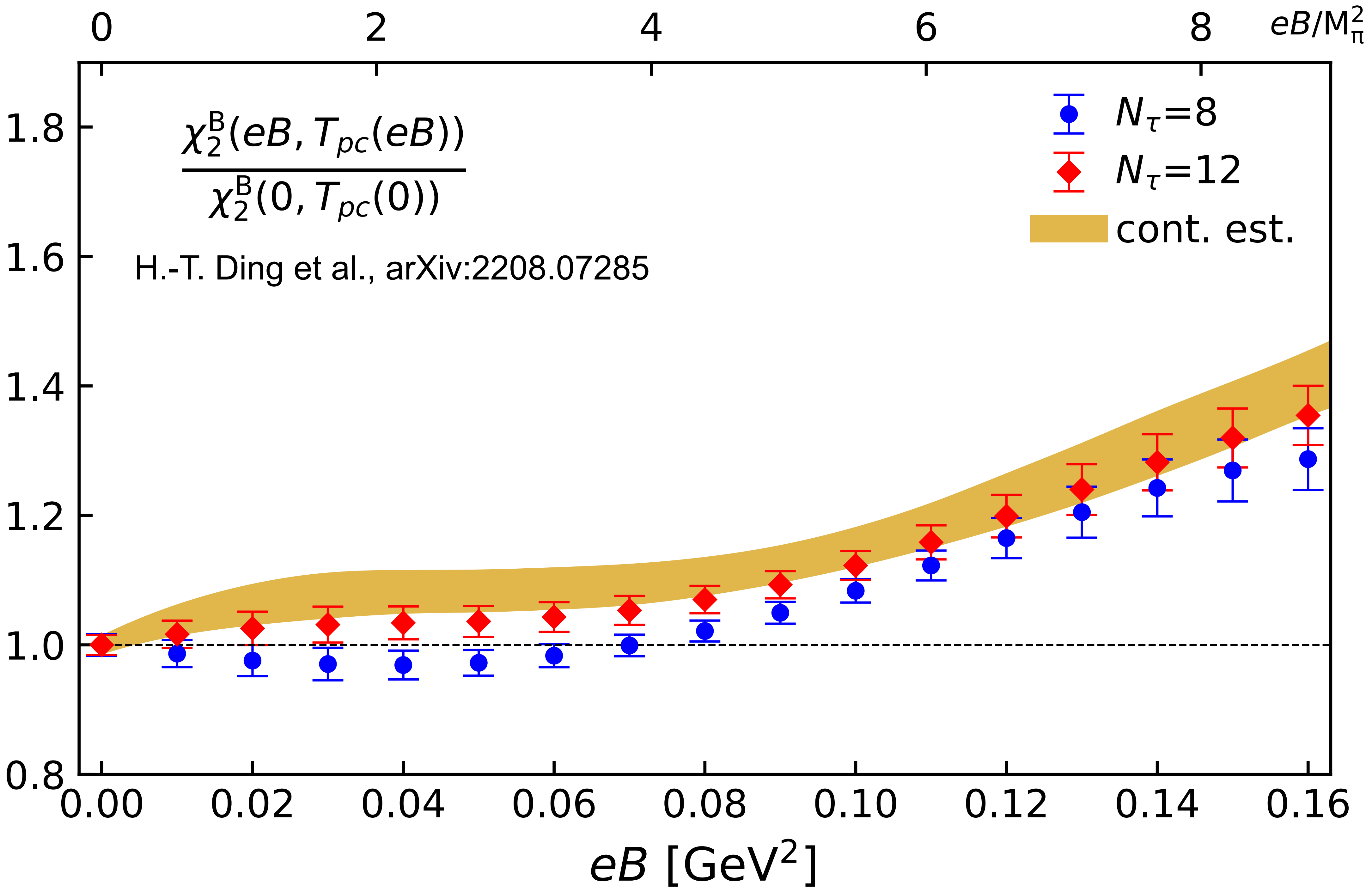
Net-p $\kappa\sigma^2$ diverge



STAR: PRL **126** (2021) 92301
STAR: PRL 127 (2021) 262301

Net-proton cummulants at LHC

Lattice calculations suggest susceptibilities sensitive to initial EM field



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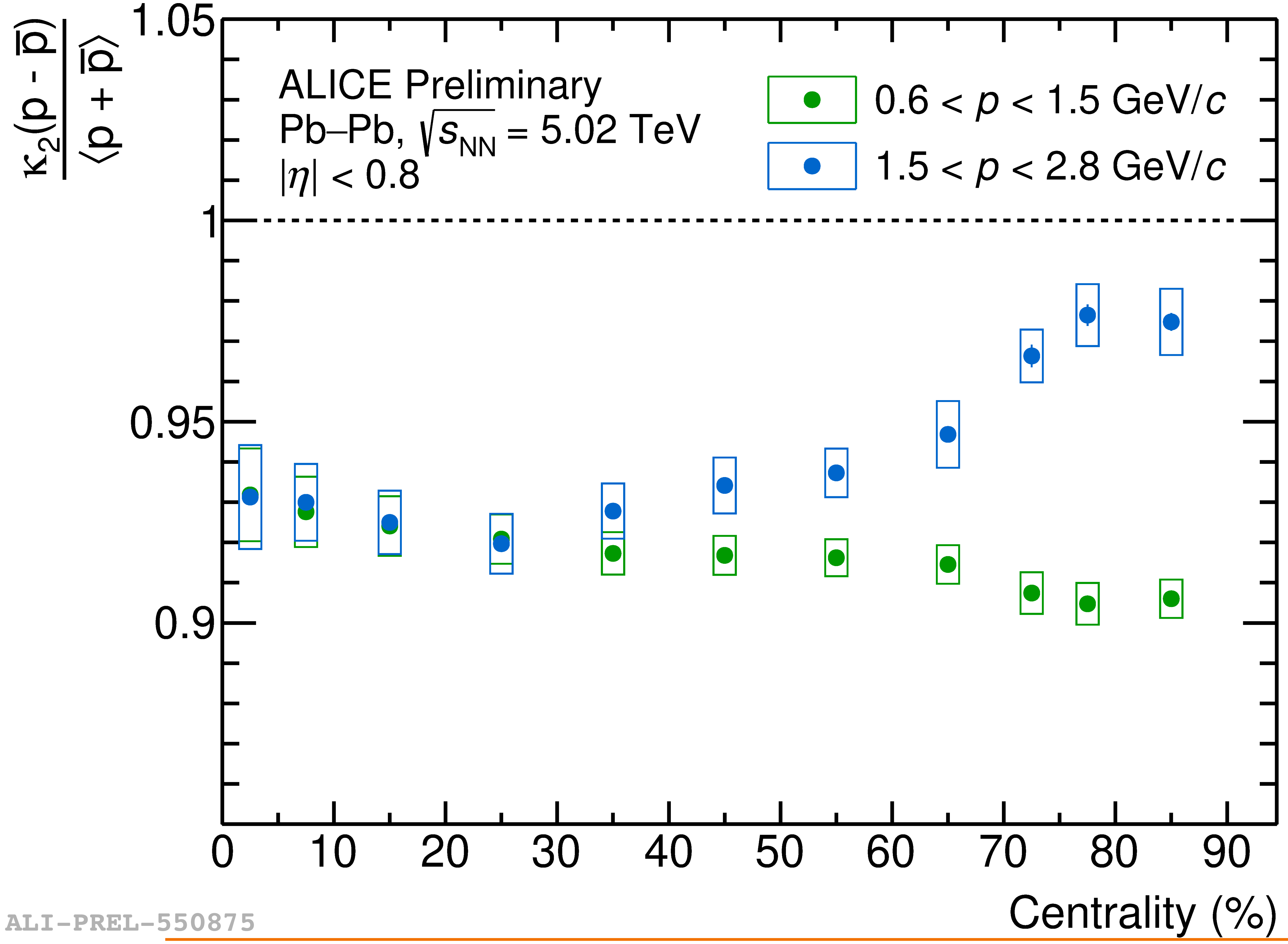
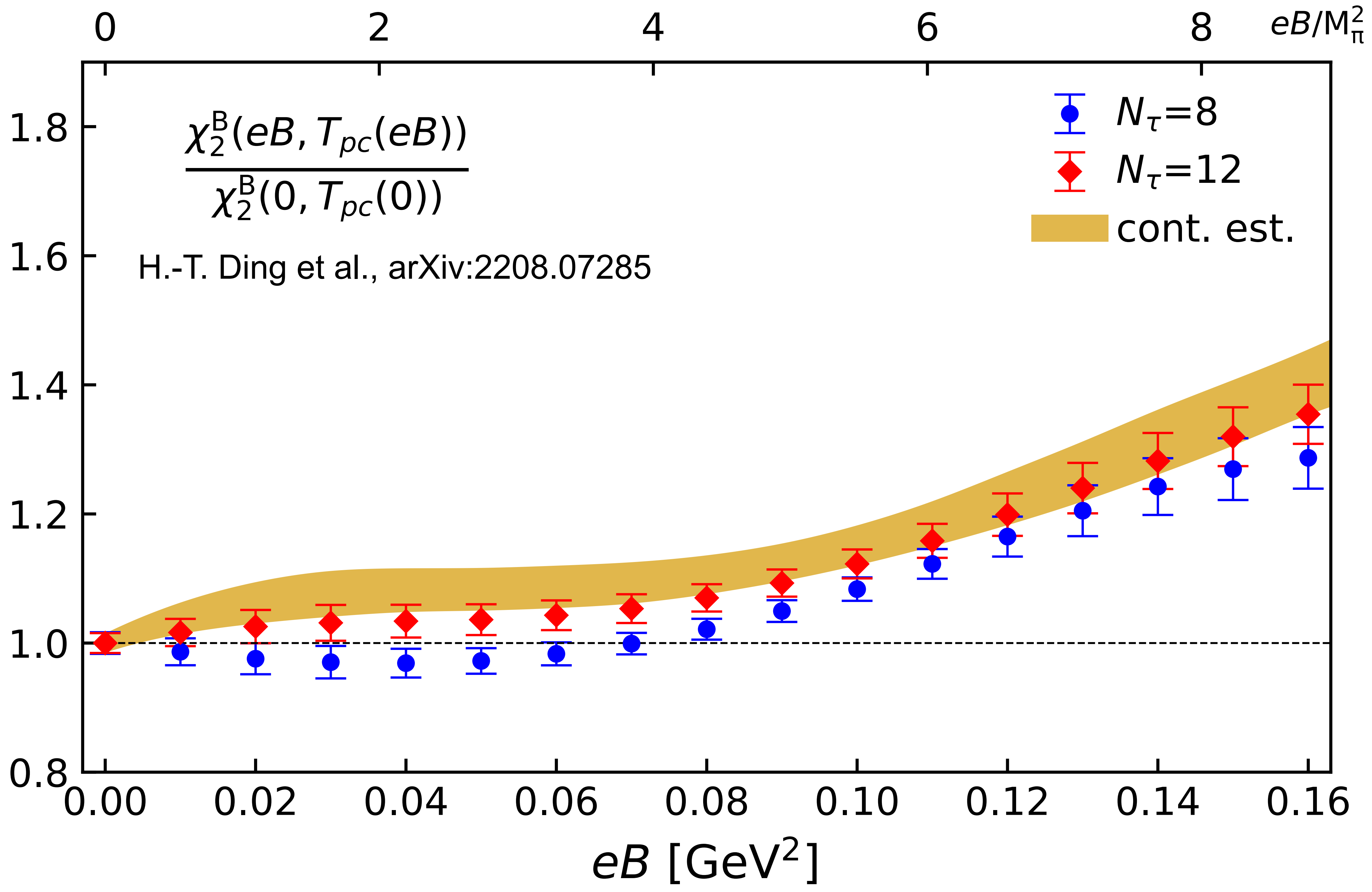


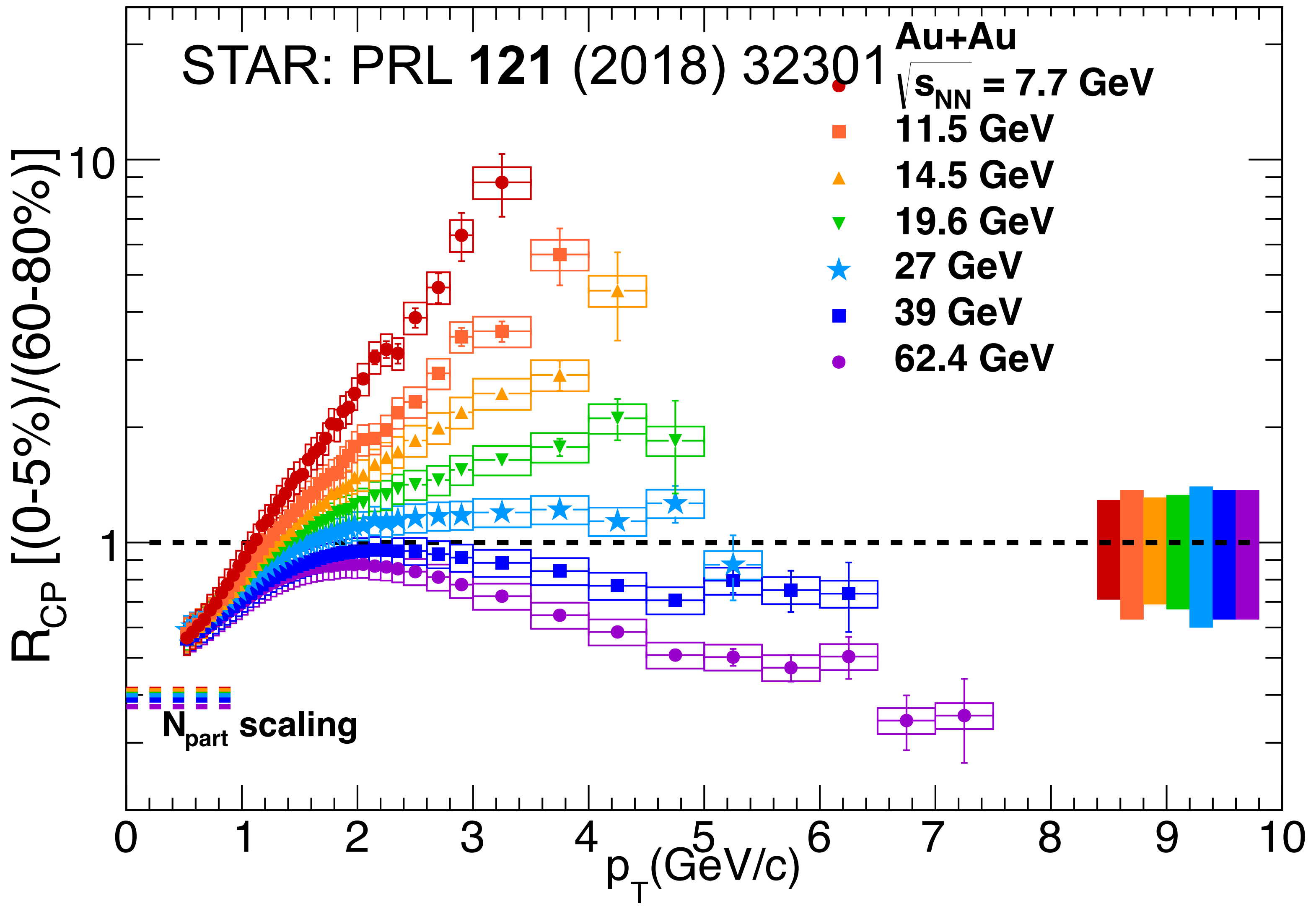


First measurement above 2 GeV/c

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

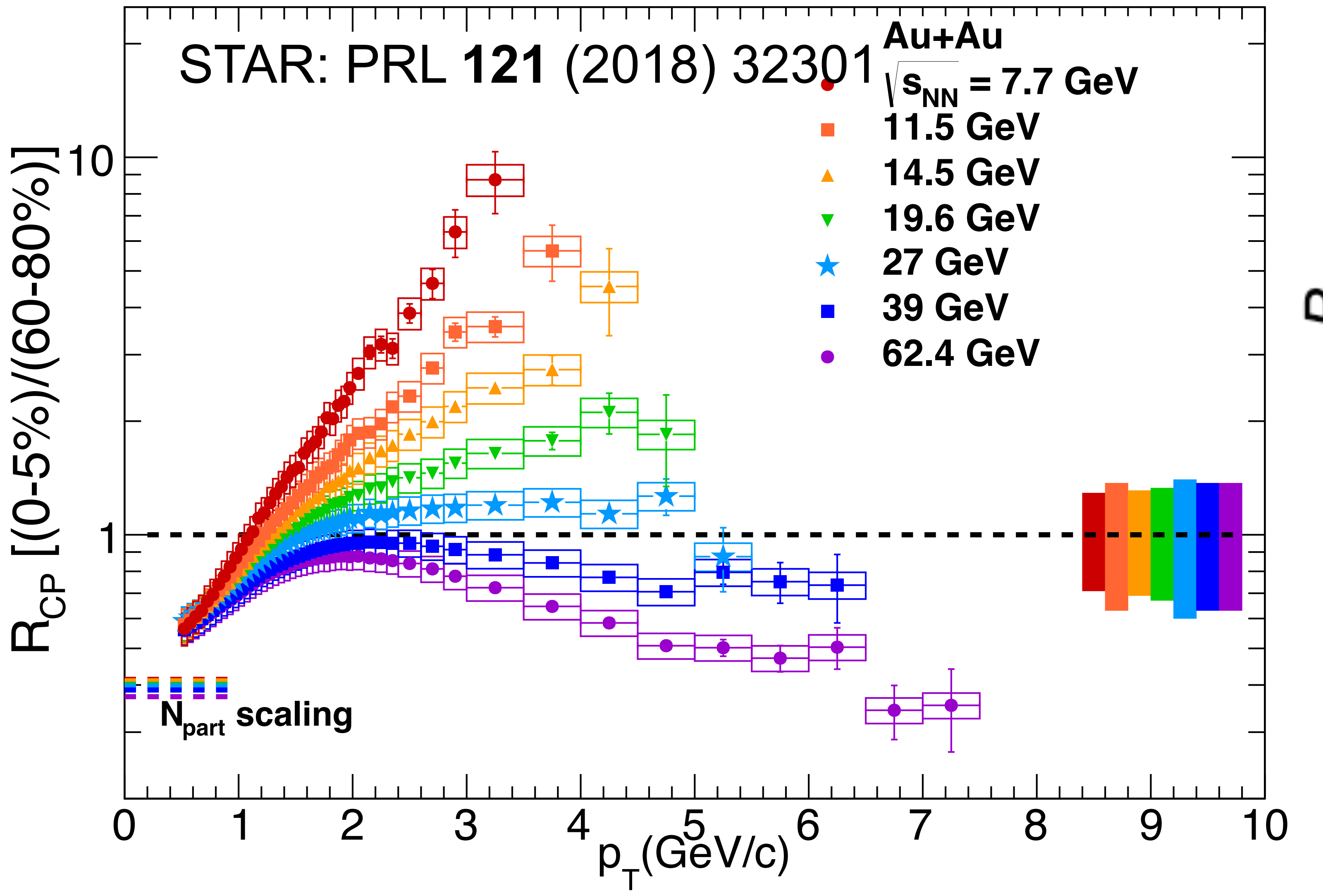
More discussion with theory and measurement in pp needed

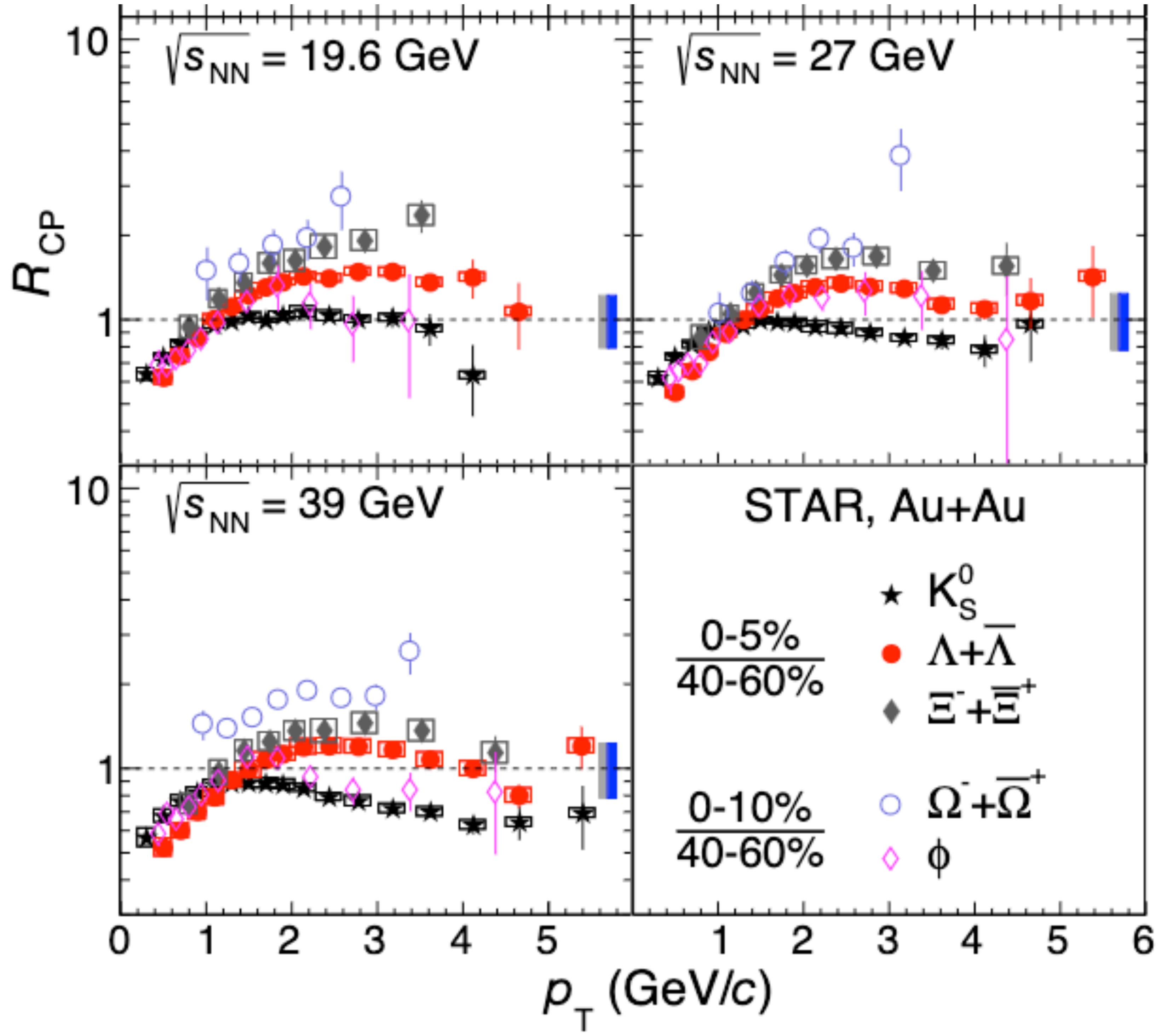
Nuclear modification of light species



For $\sqrt{s_{NN}}$ > 27 GeV suppression observed

Nuclear modification of light species

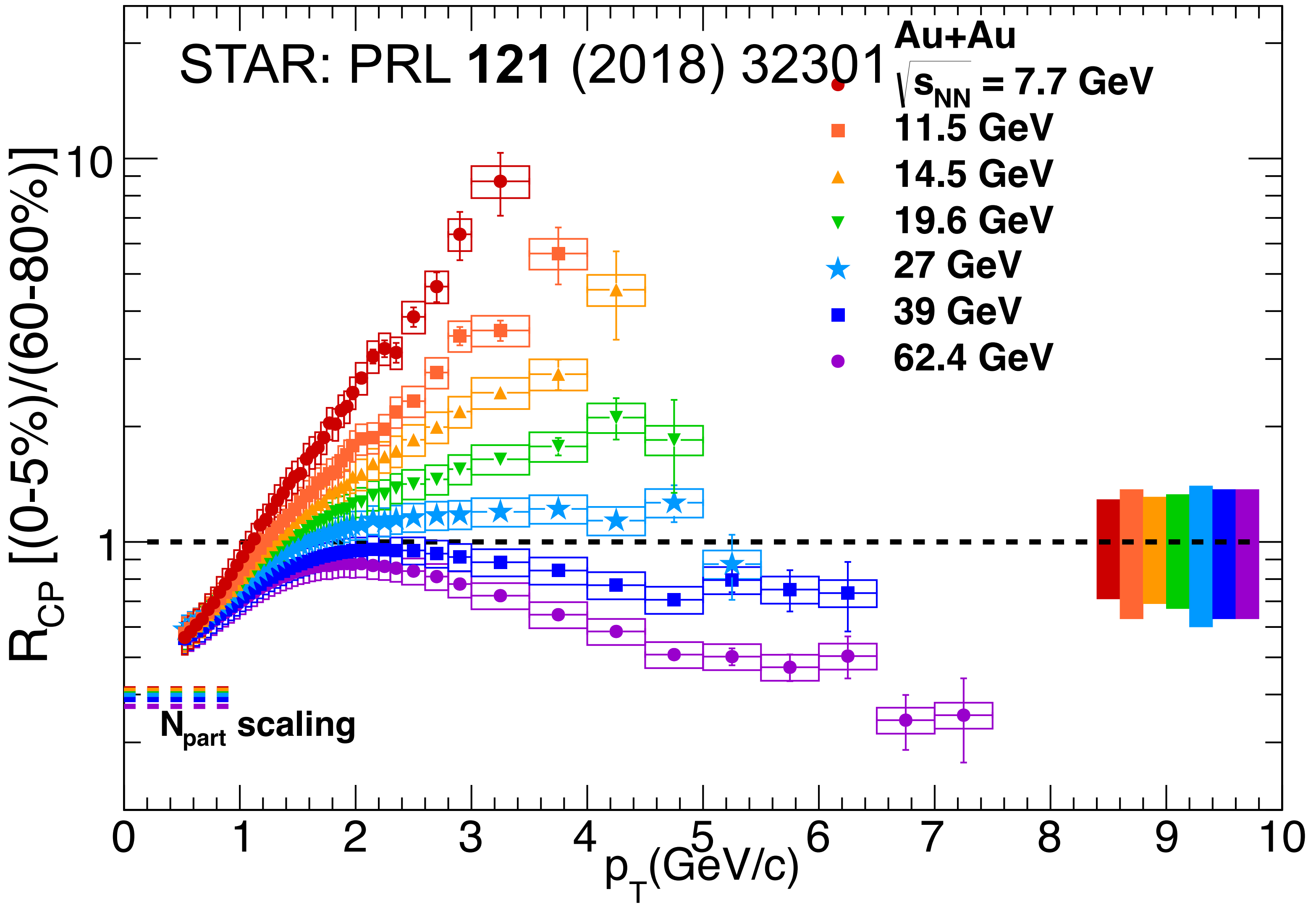


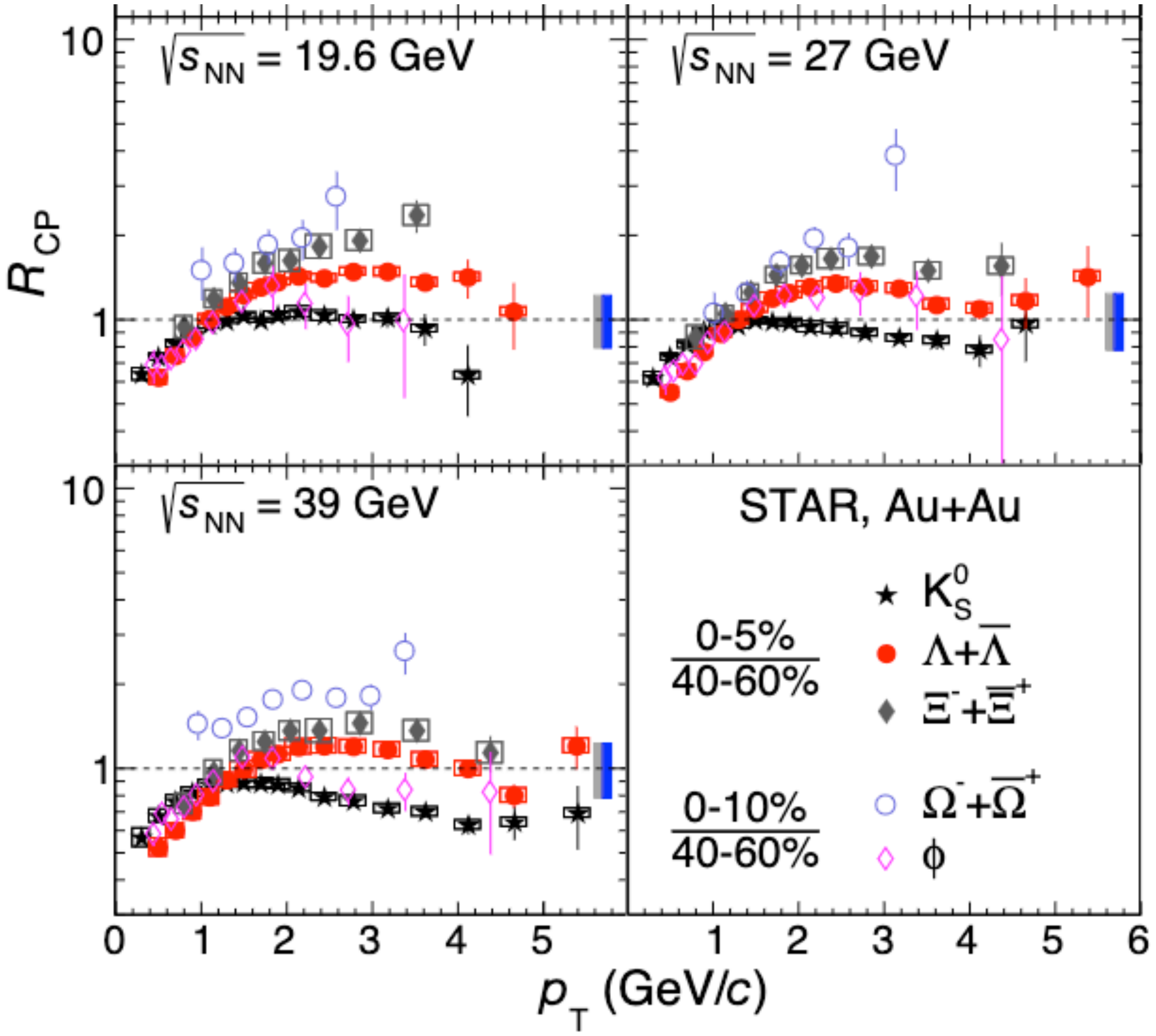


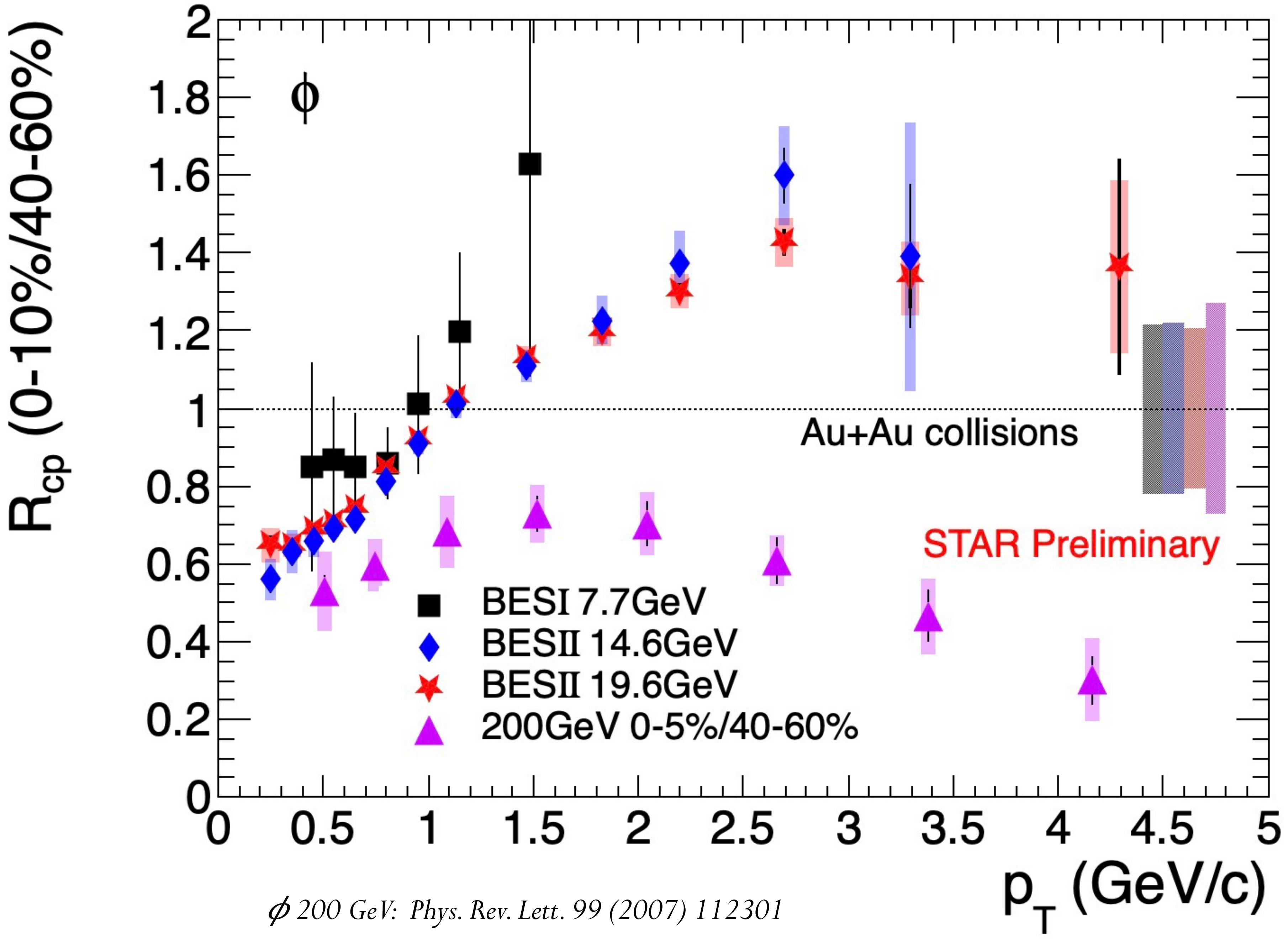
For $\sqrt{s_{NN}}$ > 27 GeV suppression observed

Differences for baryons and mesons

Nuclear modification of light species







ϕ 200 GeV: Phys. Rev. Lett. 99 (2007) 112301

For $\sqrt{s_{NN}}$ > 27 GeV suppression observed

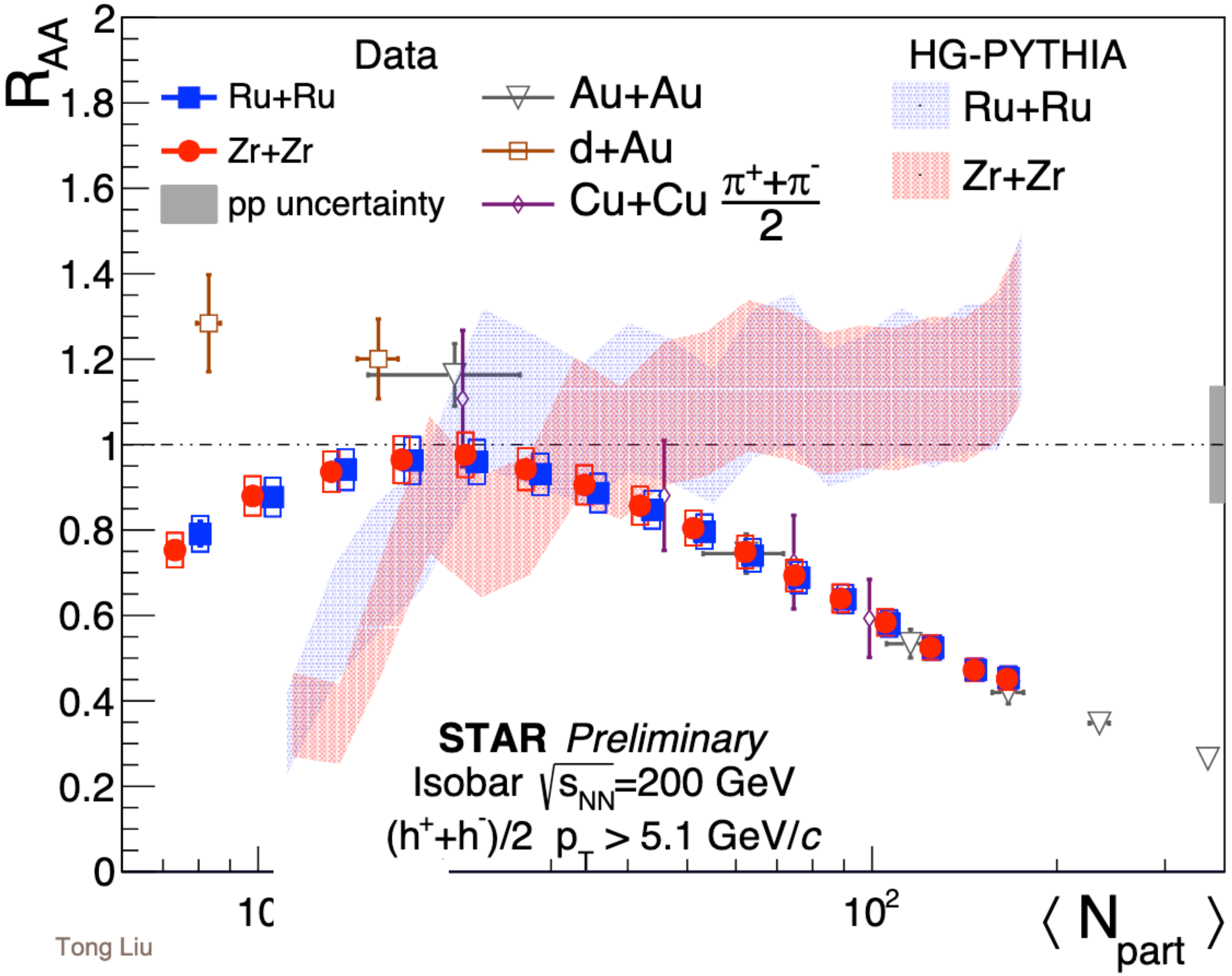
Differences for baryons and mesons

New ϕ data indicate mass not baryon/meson effect?

Is flow hiding E_{loss}?

How to disentangle?

Precision quenching measurements



Tong Liu

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

R_{AA} in 0-60% central events (N_{part}>20) decrease with N_{part}

Same R_{AA} at same N_{part} regardless of system

Deviation from trend starting at $N_{part} \lesssim 20$

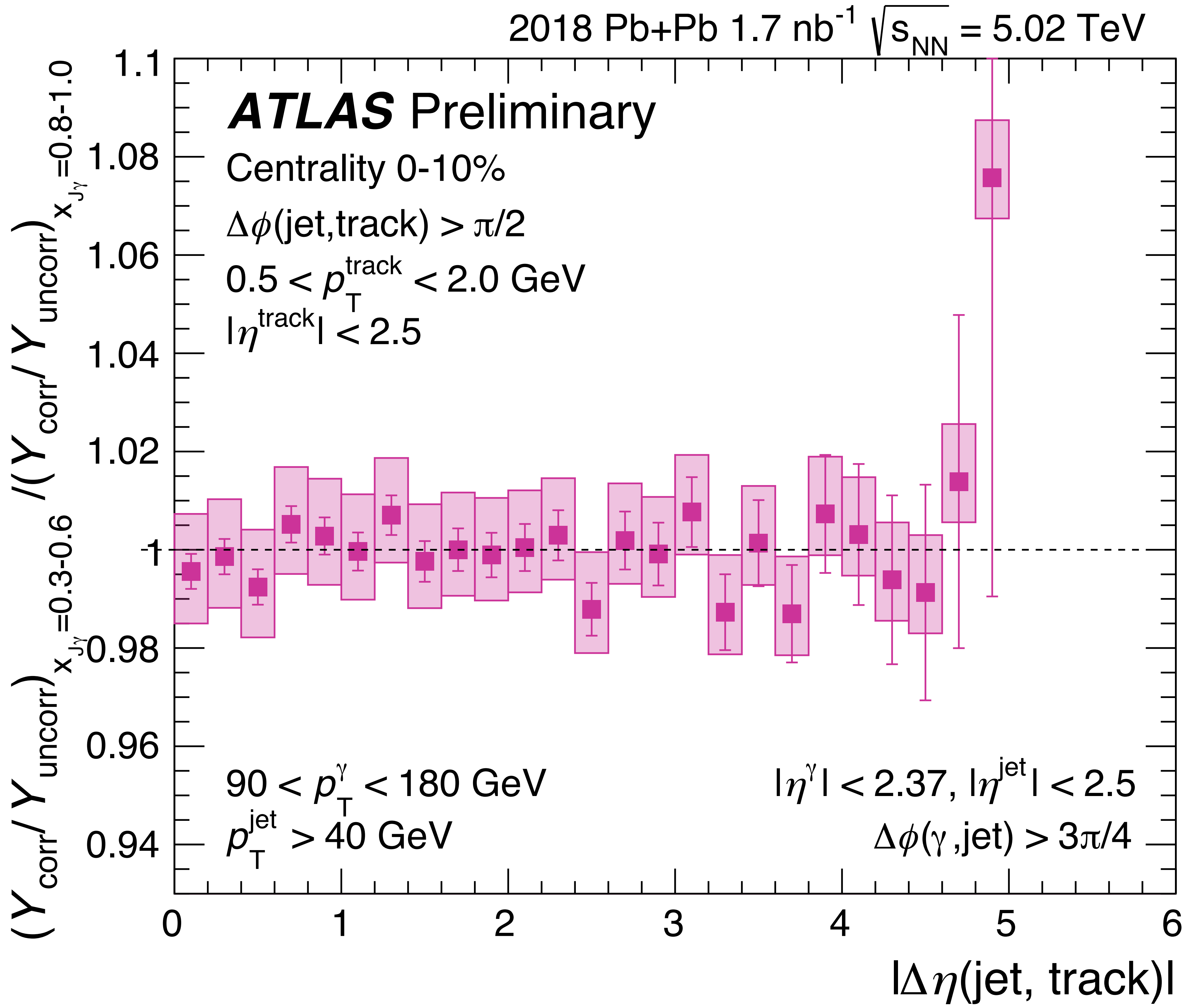
Event selection bias in peripheral events causes artificial suppression?

- HG-PYTHIA qualitatively gets trend but predicts steeper drop

Jet quenching linear with log(N_{part})

STAR: PRL 91, 172302 (2003), PRL 91, 072304 (2003),
PRC 81, 054907 (2010) Loizides & Morsch, PLB 773 (2017) 408-4

Diffusion Wake or Not?



Lost jet energy generates diffusion wake

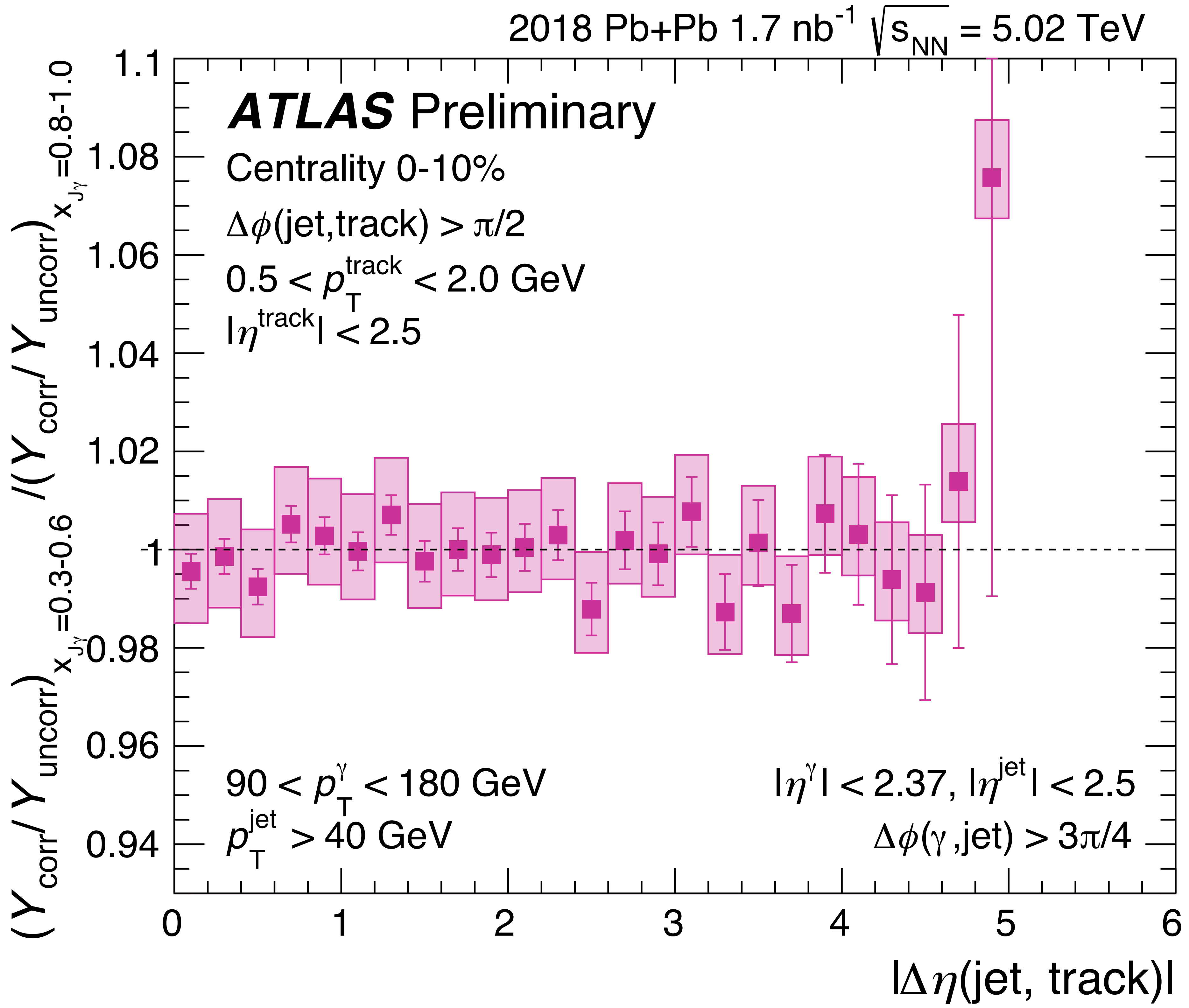
—> Depleted particle production in γ direction

—> Wake larger when x_J smaller

At 95% CL wake < 0.8% perturbation of bulk

(note CoLBT predicts 0.2%)

Diffusion Wake or Not?



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At 95% CL wake < 0.8% perturbation of bulk

(note CoLBT predicts 0.2%)

Jets recoiling off of a high p_T trigger hadron

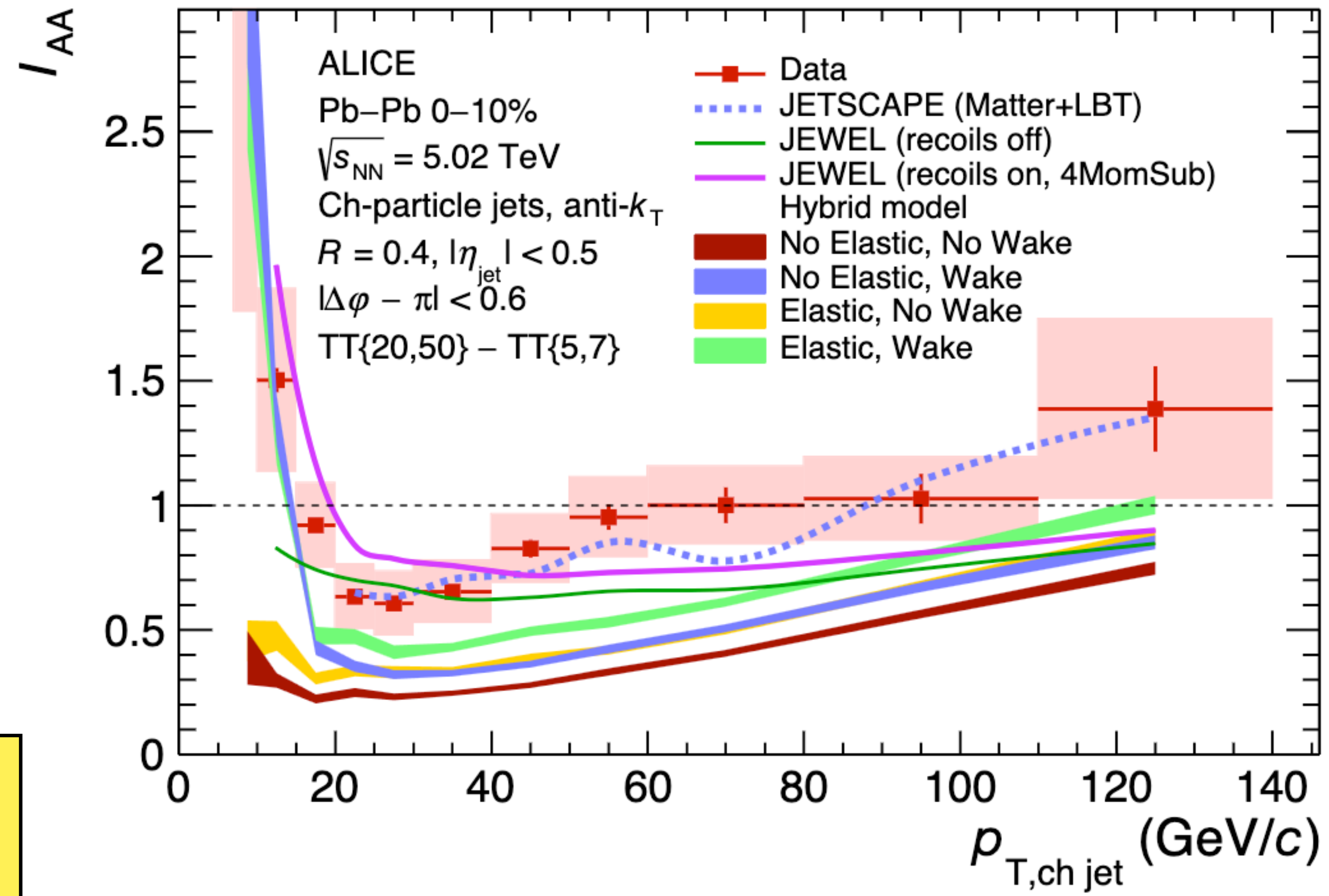
Shape of I_{AA} best reproduced when wake included

Shape not sensitive to Moliere/elastic scattering

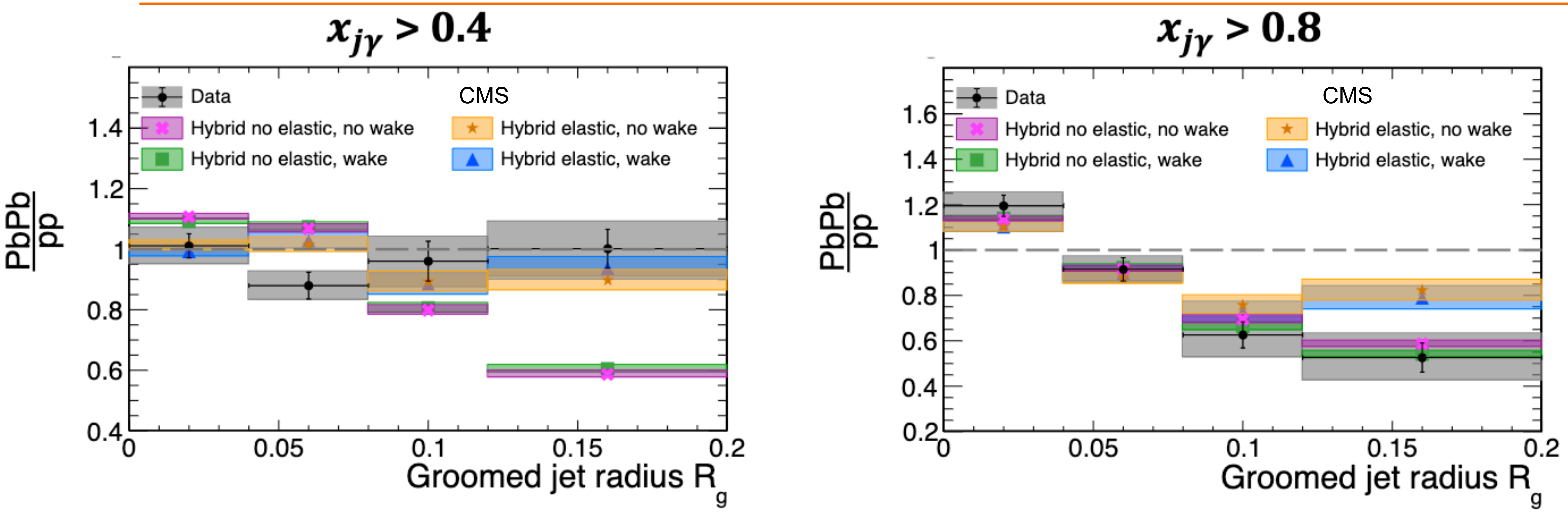
Different sensitivities?

Proposal better to look at groomed substructure?

What is wake and what's soft gluon emission



Selection Bias Rather Than Decoherence?



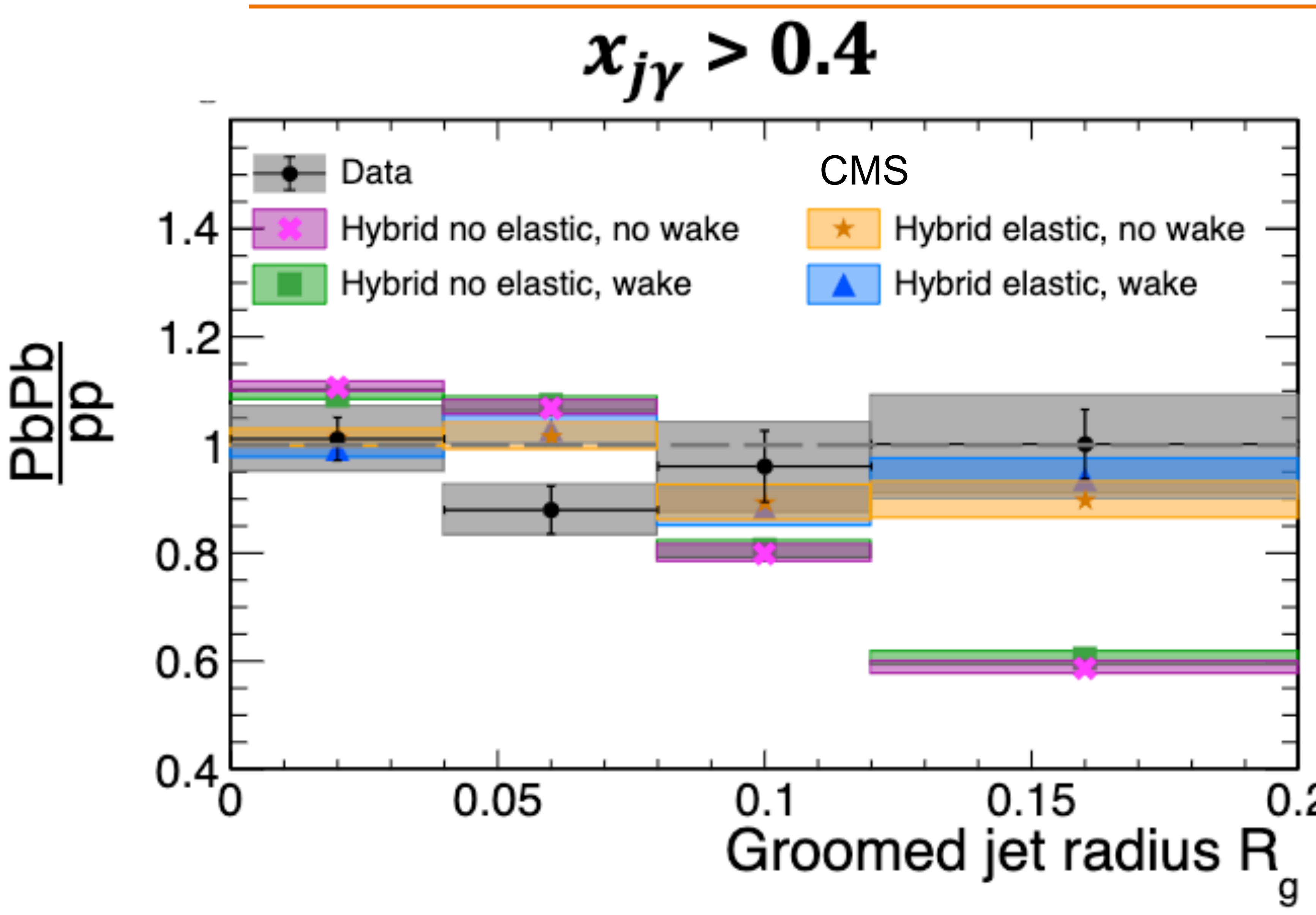
γ-jet: Use photon to select initial not quenched energy

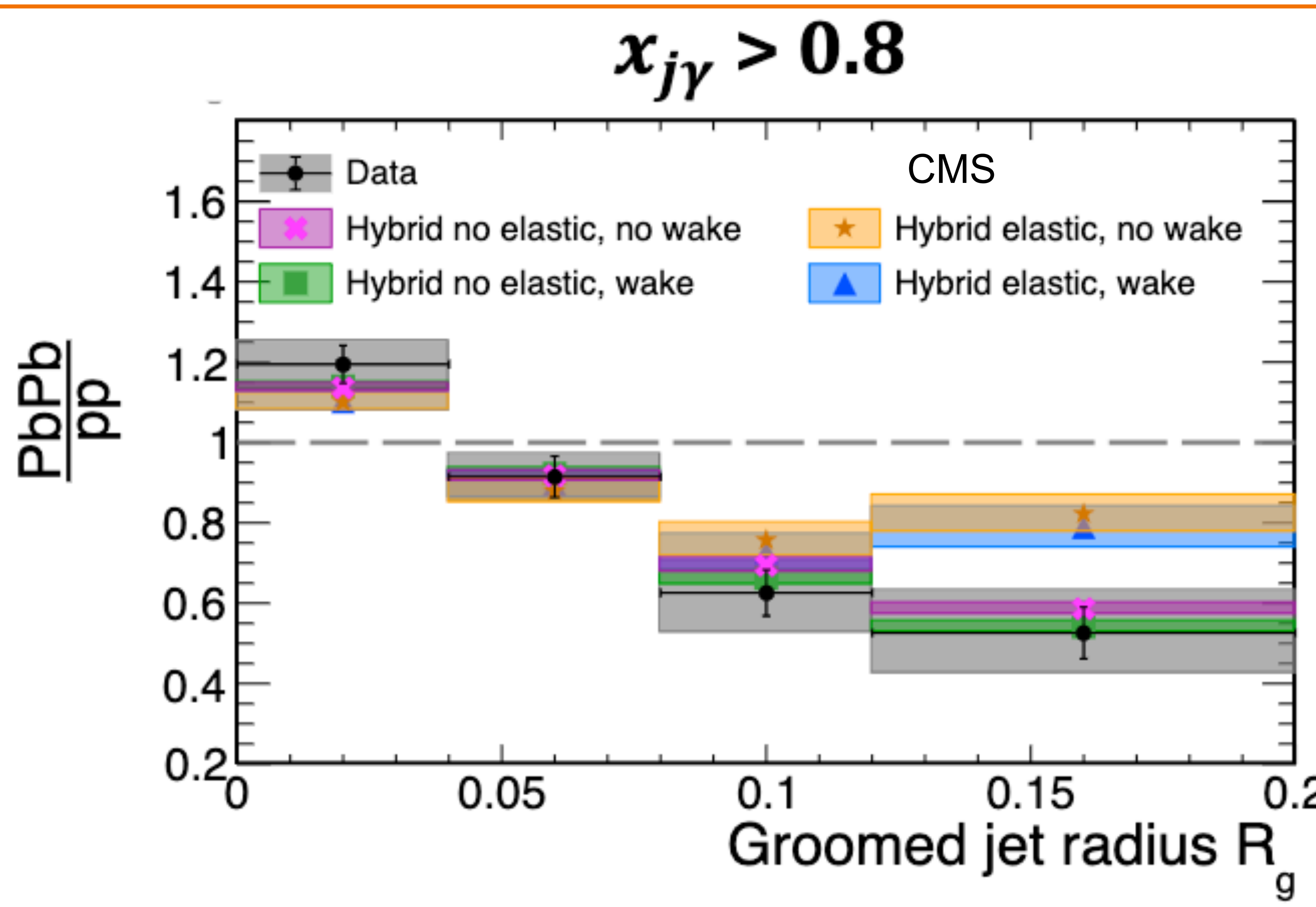
"All" x_J: No biasing on amount of E_{Loss}, no R_g dependence in PbPb/pp ratio

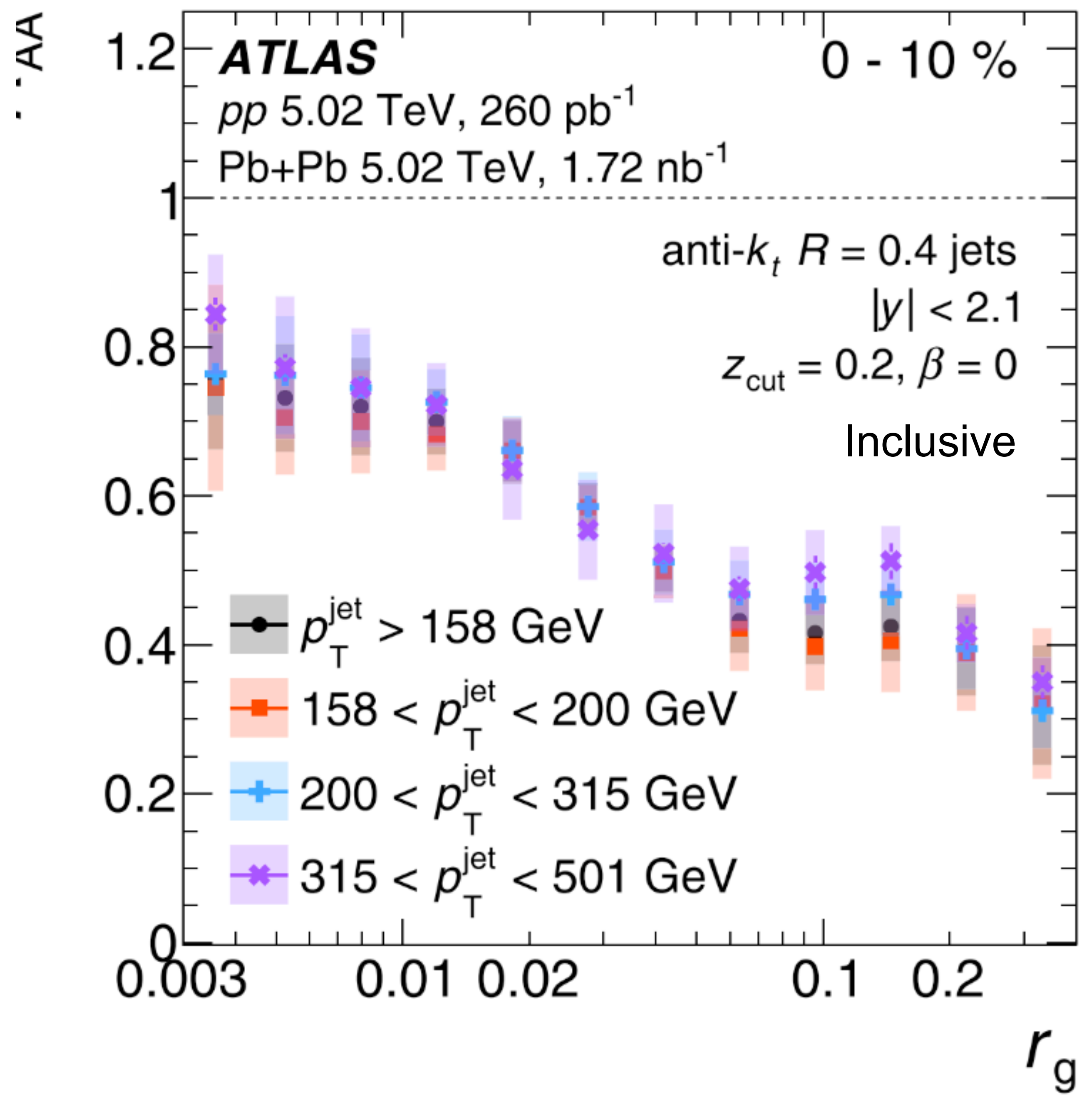
Balanced x_J: Bias towards jets with E_{Loss}=0, wide R_g jets disfavored

M. Park

Selection Bias Rather Than Decoherence?







γ-jet: Use photon to select initial not quenched energy

"All" x_J: No biasing on amount of E_{Loss}, no R_g dependence in PbPb/pp ratio

Balanced x_J: Bias towards jets with E_{Loss}=0, wide R_g jets disfavored

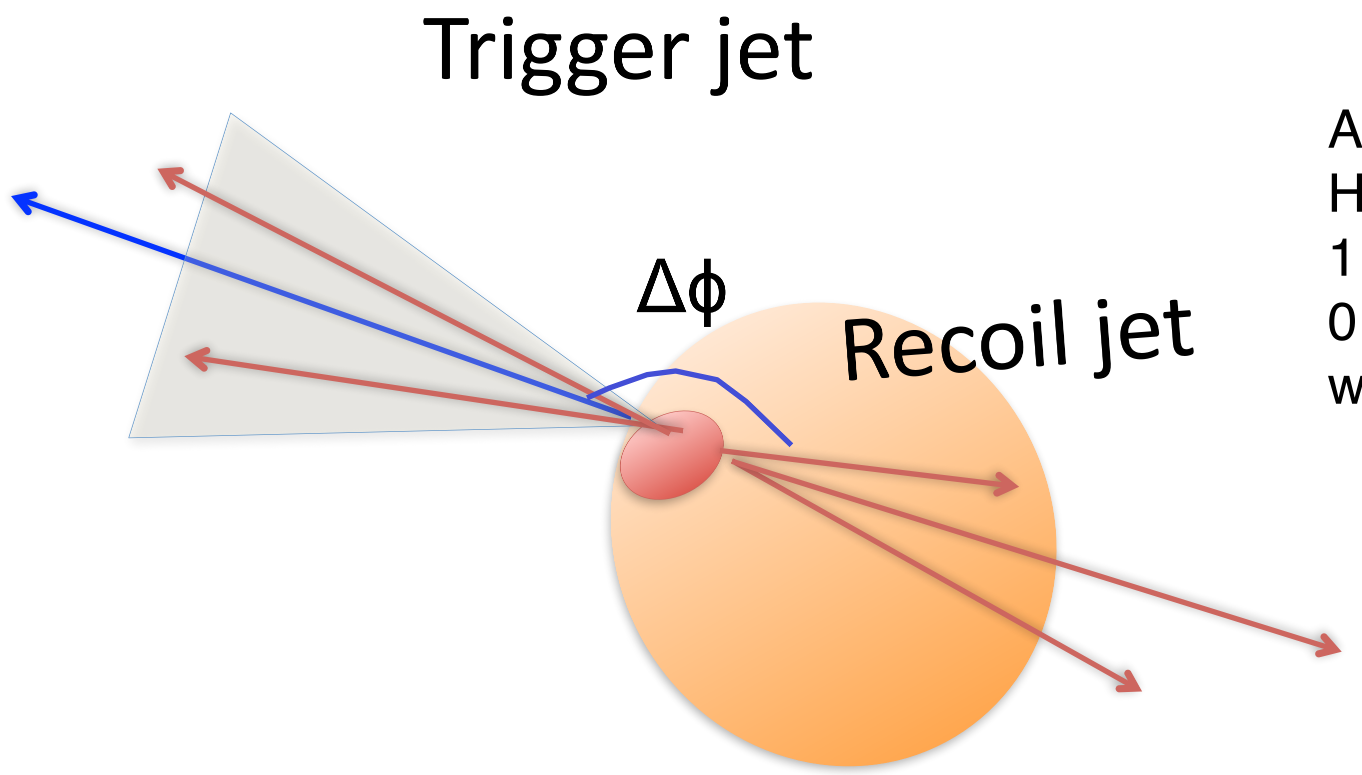
Inclusive: select via jet p_T after quenching

Inclusive jet: wide R_g jets disfavored. E_{Loss} higher so shifted to lower jet p_T

Now we know there is a bias, can we use it to our favor as has been done at RHIC?

M. Park

Where does lost energy go?

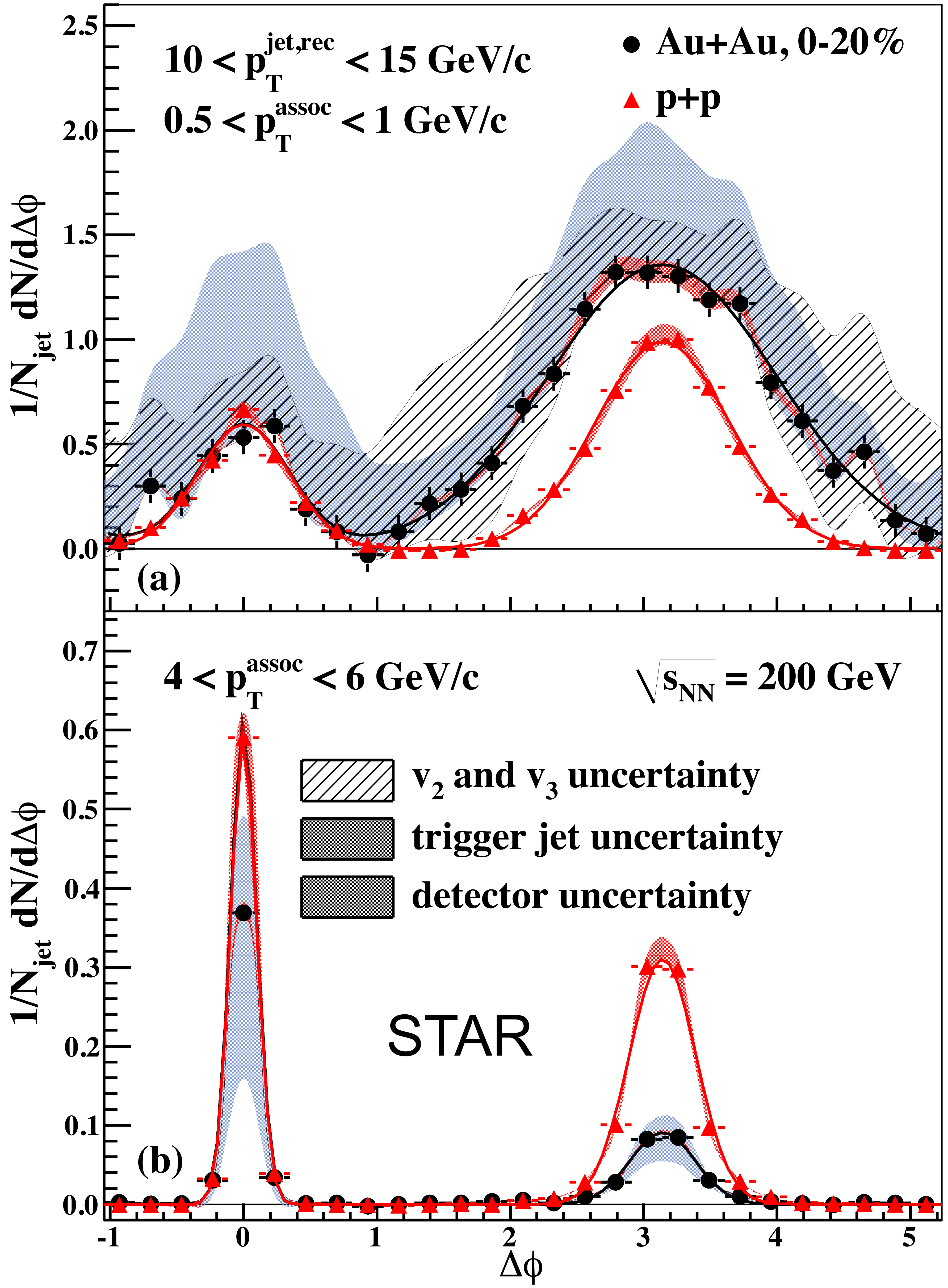


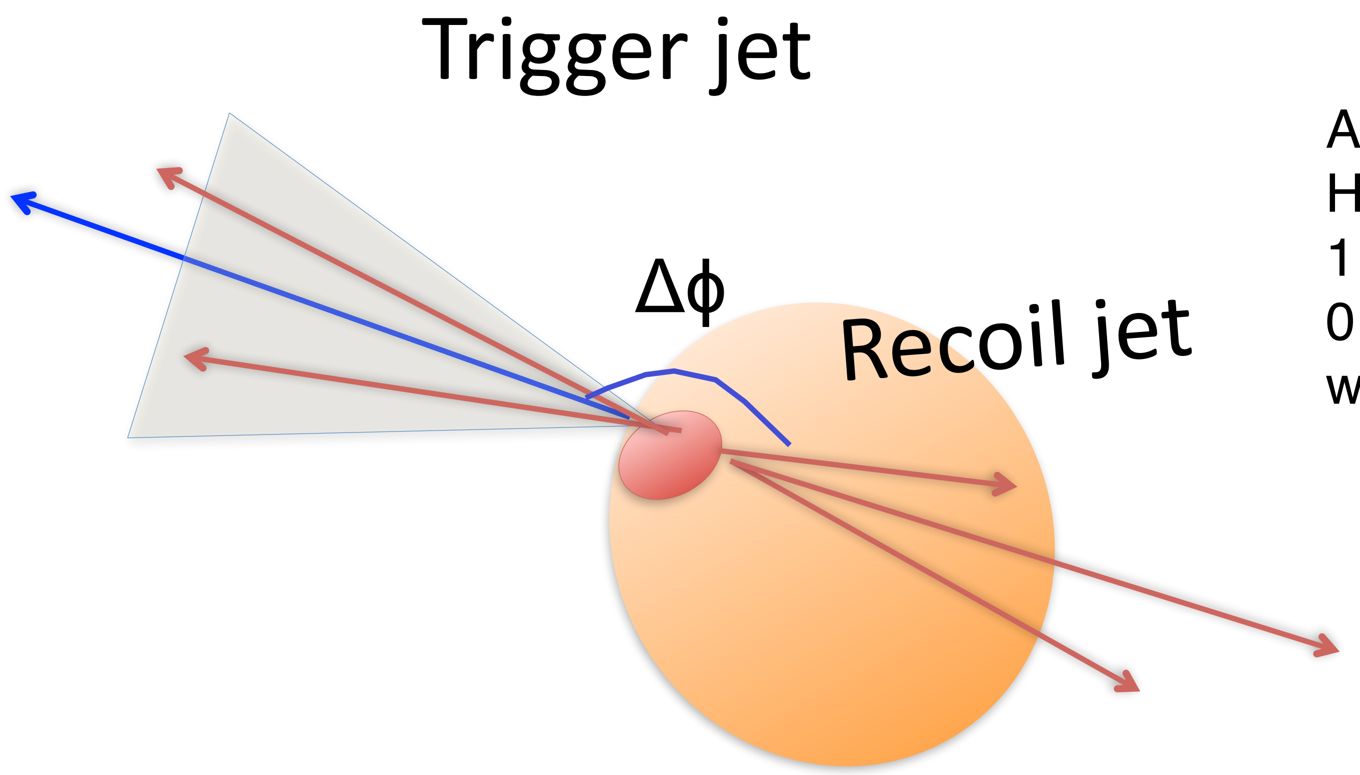
Au+Au 0-20%
High Tower Trigger
1 tower
0.05x0.05 (ηxϕ)
with E_t> 5.4 GeV

Jet trigger:
Anti-k_T,
R=0.4,
$pt_{,rec}$(jet) using
$p_{t,}$(particle)>2 GeV

STAR:PRL 112 (2014) 122301

Where does lost energy go?





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R=0.4,
$p_{t,rec}$(jet) using
$p_{t,}$(particle)>2 GeV

Away-side: Broadening
Softening

E remains correlated to jet axis but at large angles

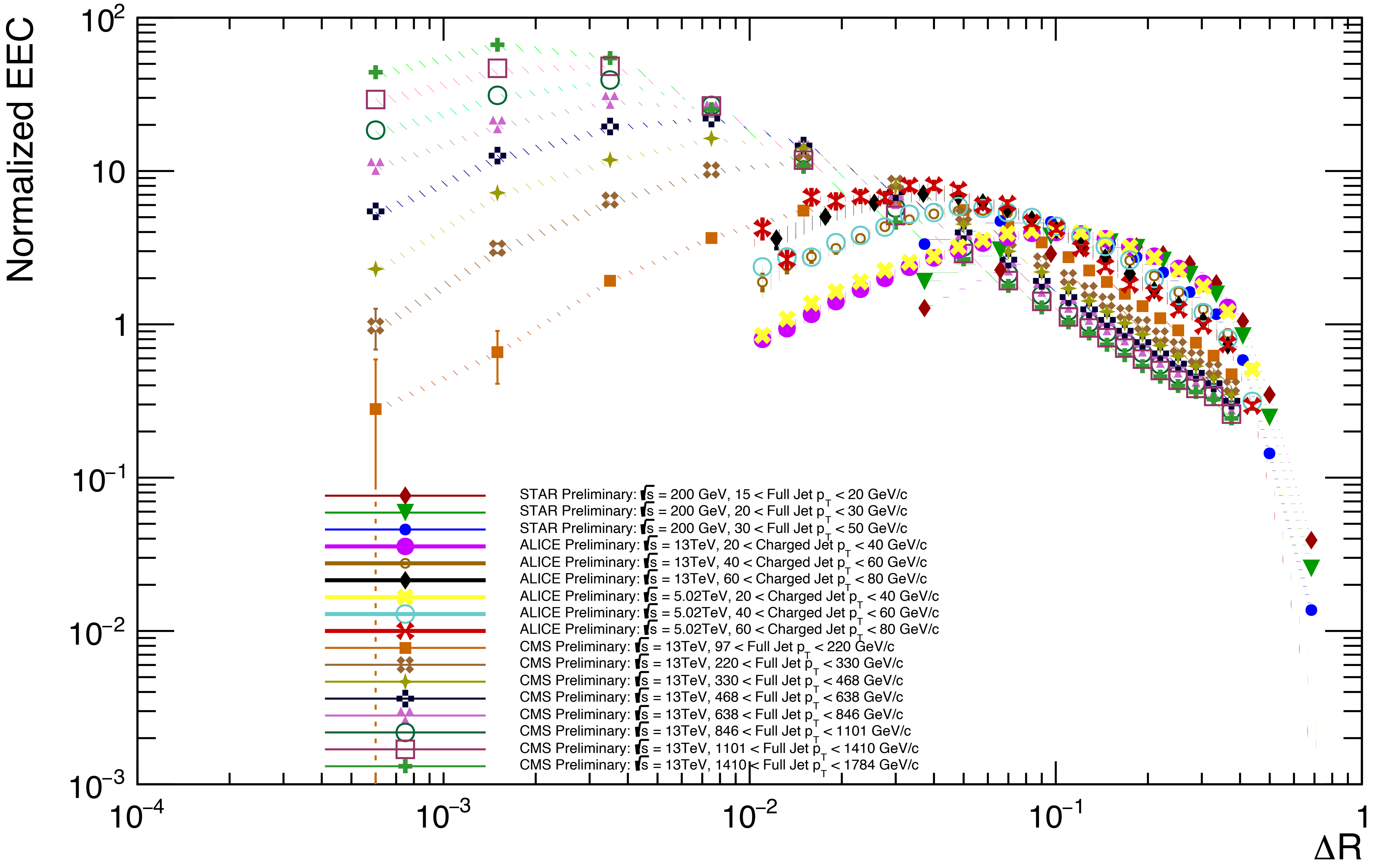
Direct measurement of modified fragmentation due to presence of QGP

STAR:PRL 112 (2014) 122301

Probing energy flow in jets

N-point Energy Correlators

Perturbative region grows as jet p_T increases

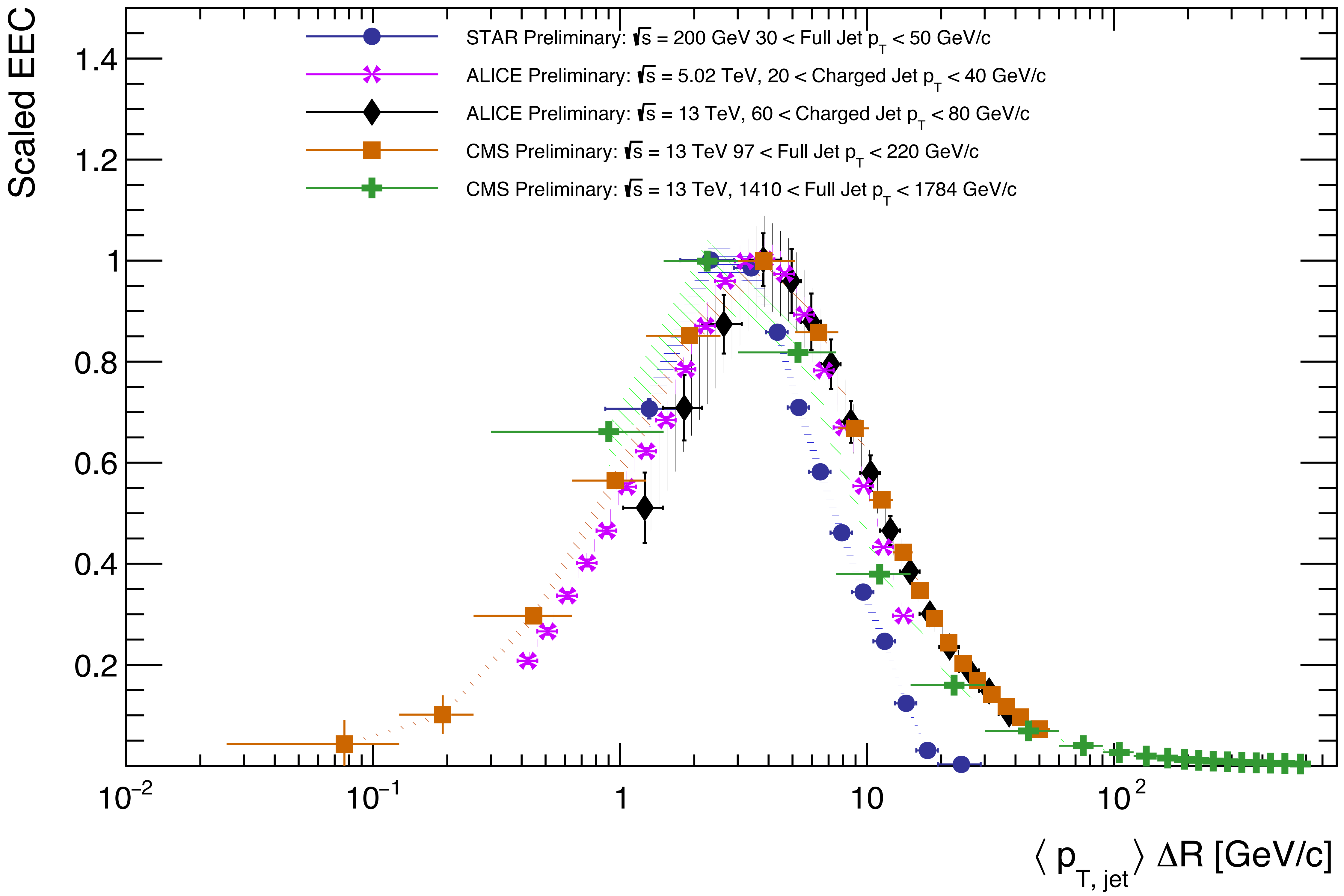


Probing energy flow in jets

N-point Energy Correlators

Perturbative region grows as jet p_T increases

Scaling by jet p_T: universal transition point
- HF jets' transition point affected deadcone



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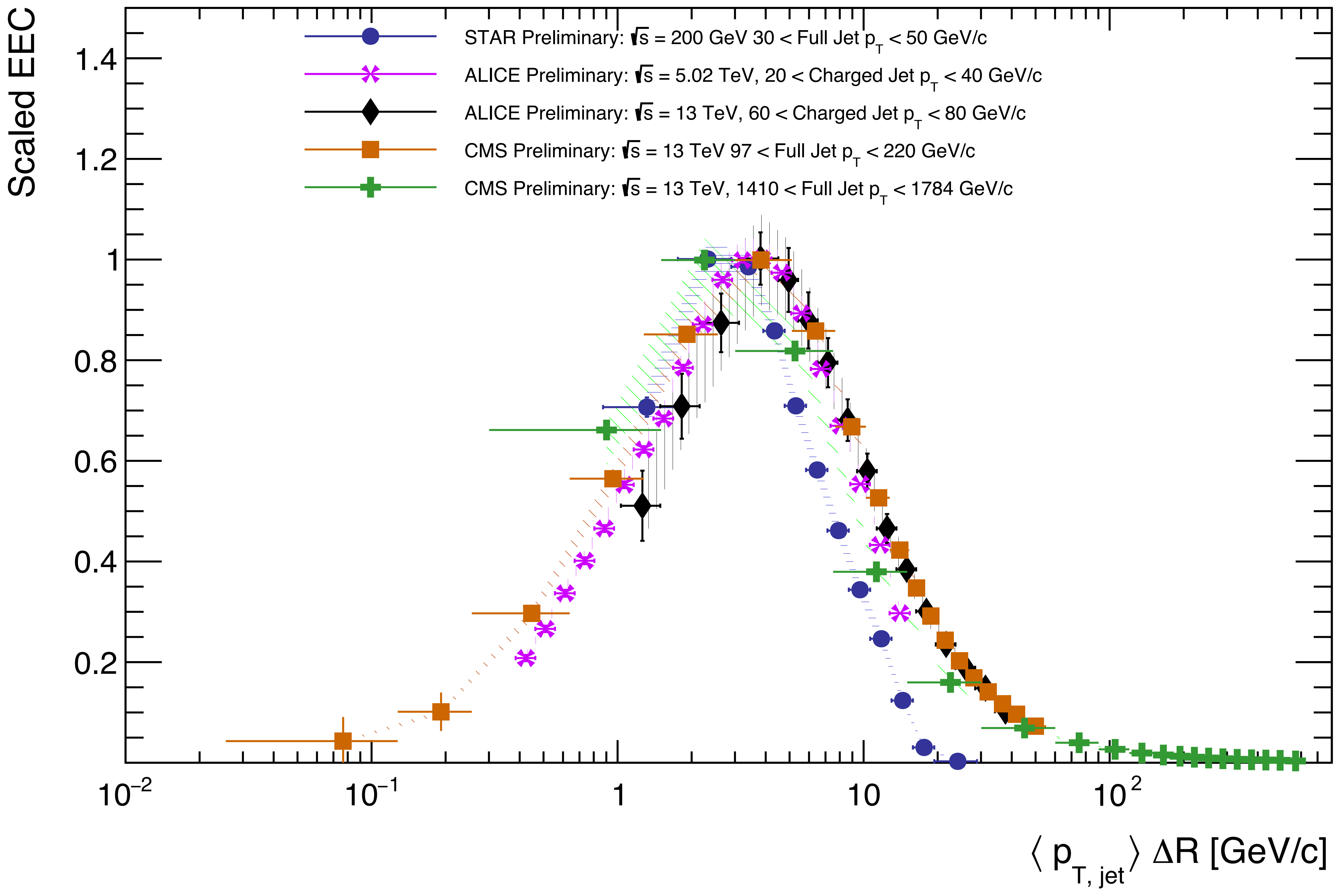
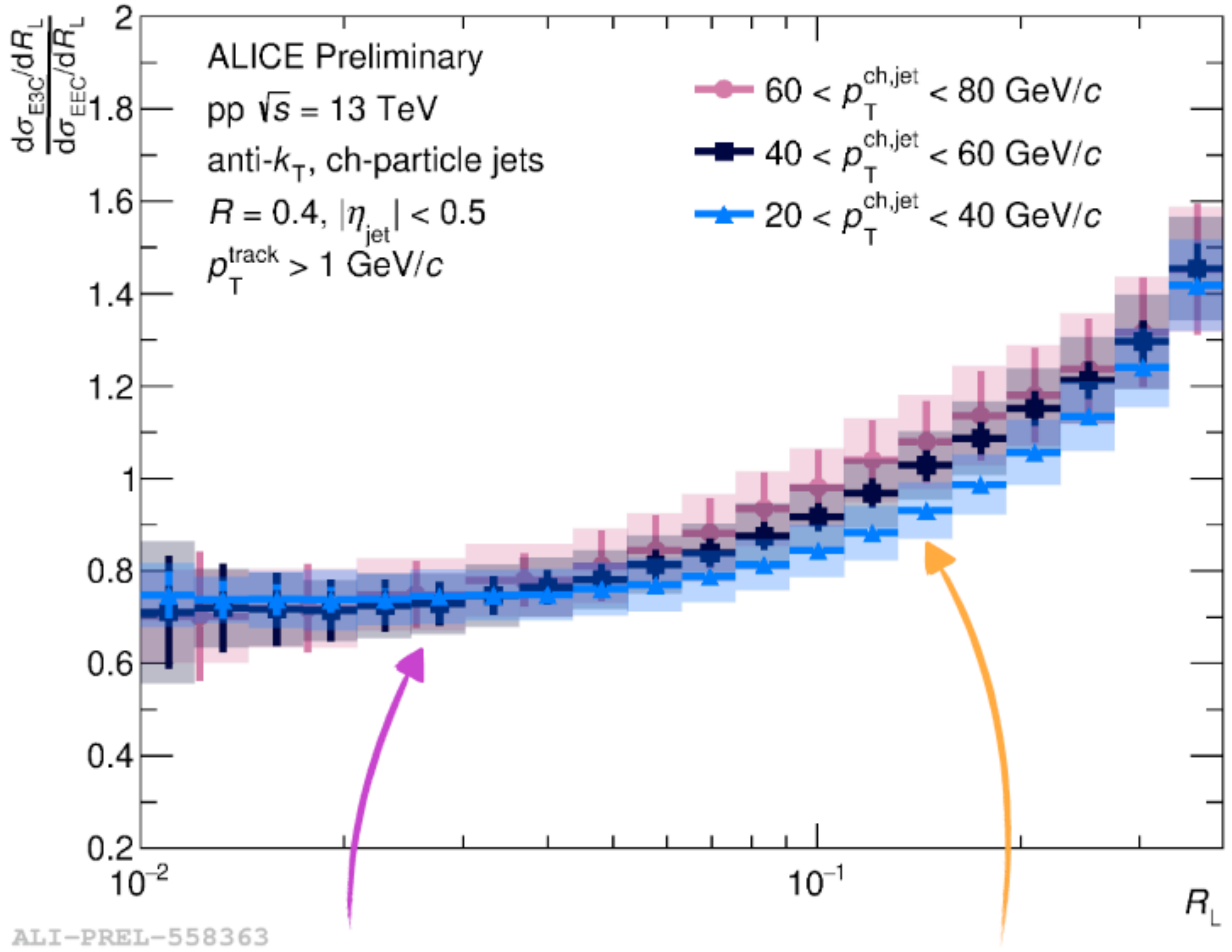




Free hadron scaling region

Perturbative scaling region

Ratio of 3-point/2-point correlators:

Decrease in slope at large ΔR with increasing jet p_T consistent with running of α_s

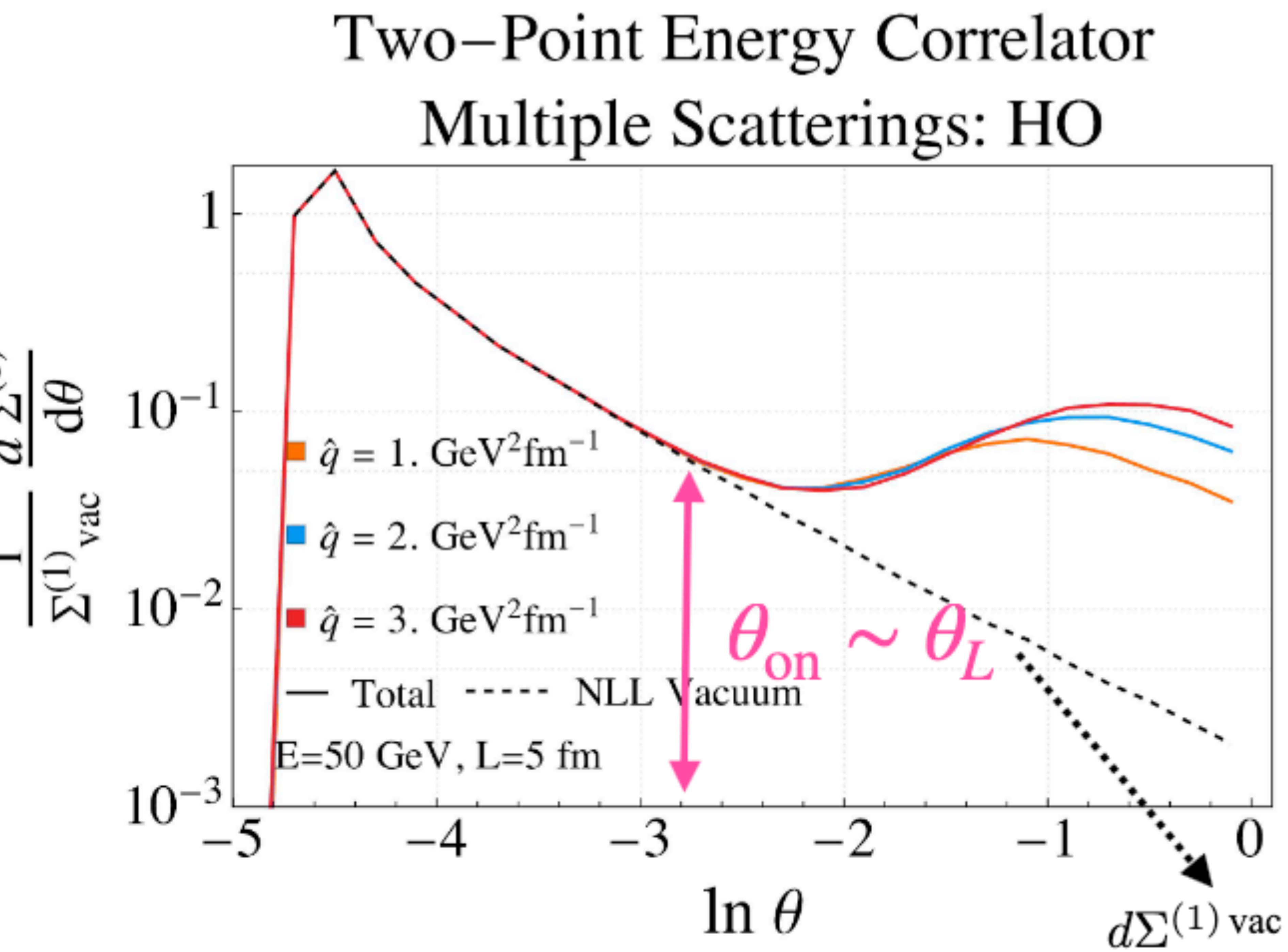
ENC behavior understood in vacuum from 15 -1784 GeV

Sensitivity to medium effects

First study using static toy model and no background

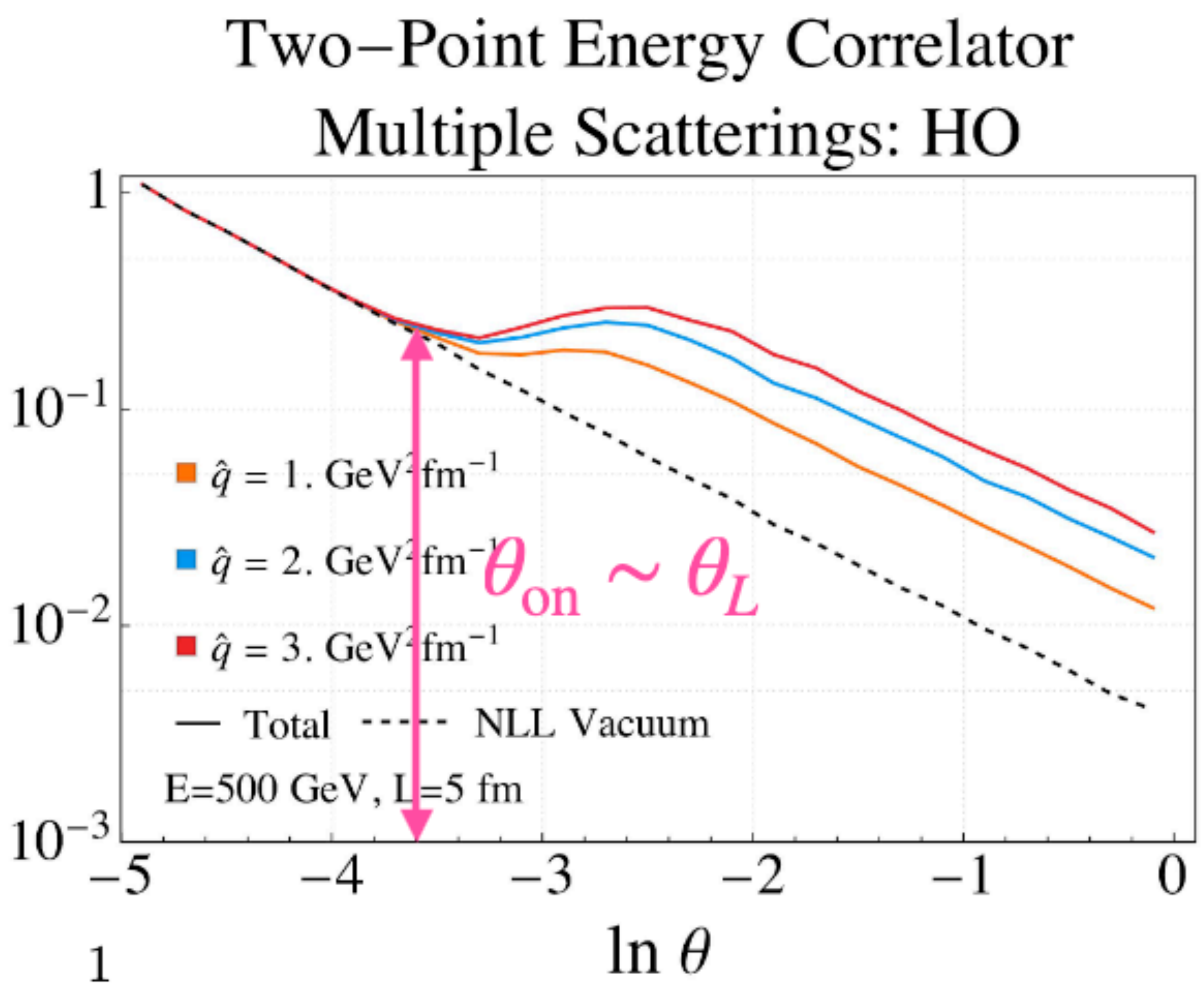
θ_c - decoherence angle, θ_L - where formation time longer than L

$\theta_L \gg \theta_c \left(E \ll \hat{q}L^2\right)$



$$\frac{d\Sigma^{(1)\,\text{vac}}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

$\theta_L \ll \theta_c \left(E \gg \hat{q}L^2\right)$



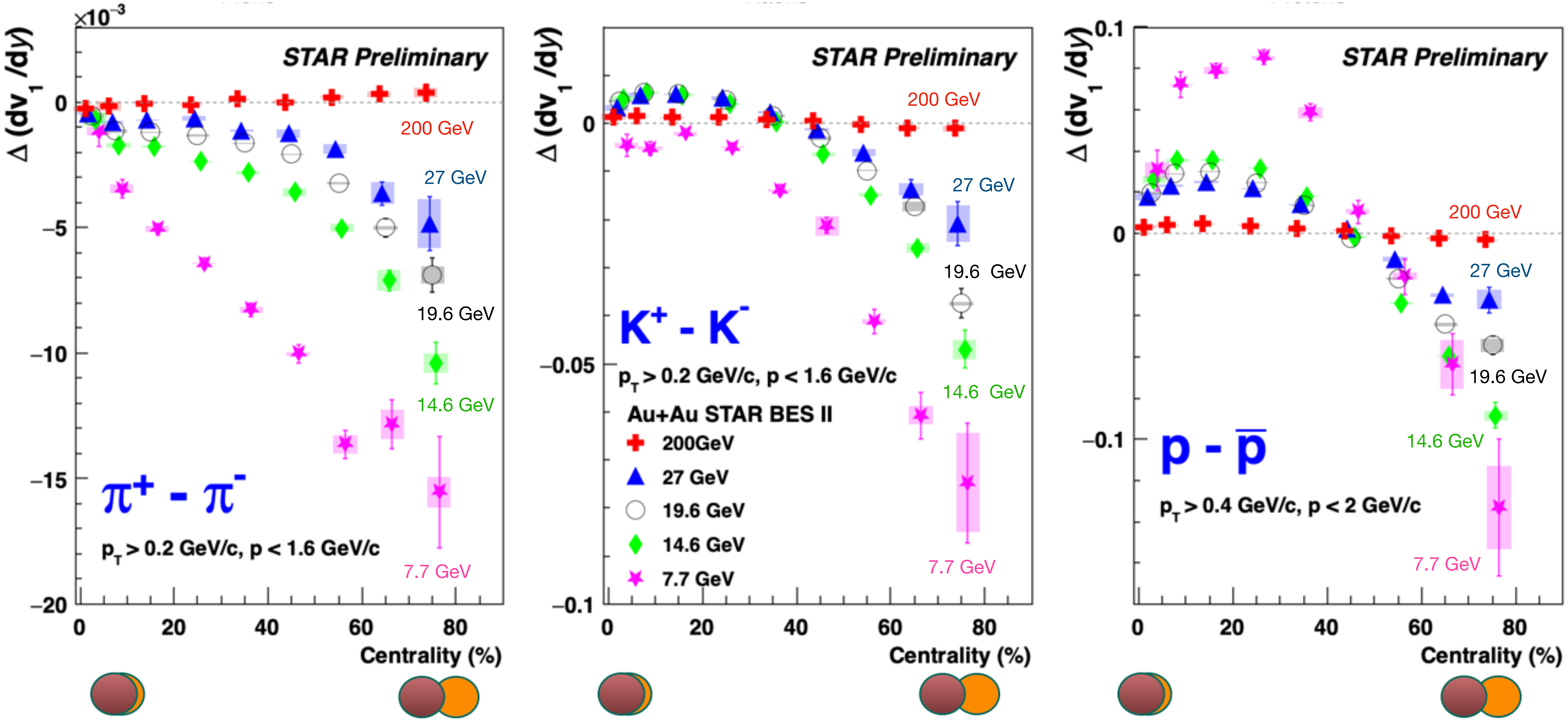
Medium-induced radiation effects only at small angles

θ_{onset} independent of $\hat{q}$

How does more realistic simulation look?

Collaborations hard at work on these measurements, expect first results soon

Directed flow difference

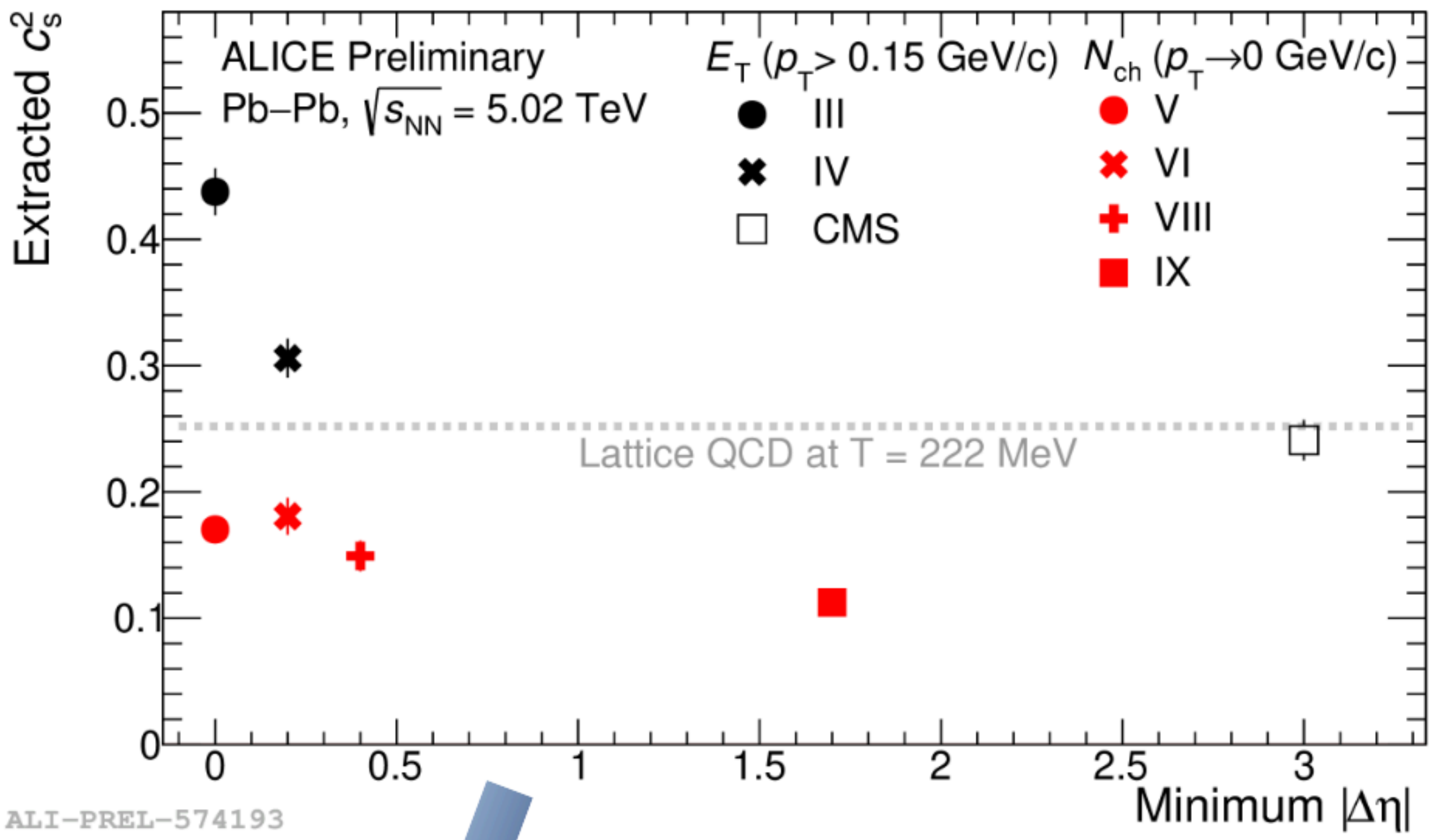


Different effects can/do dominate in different regimes - Have precision to hopefully disentangle

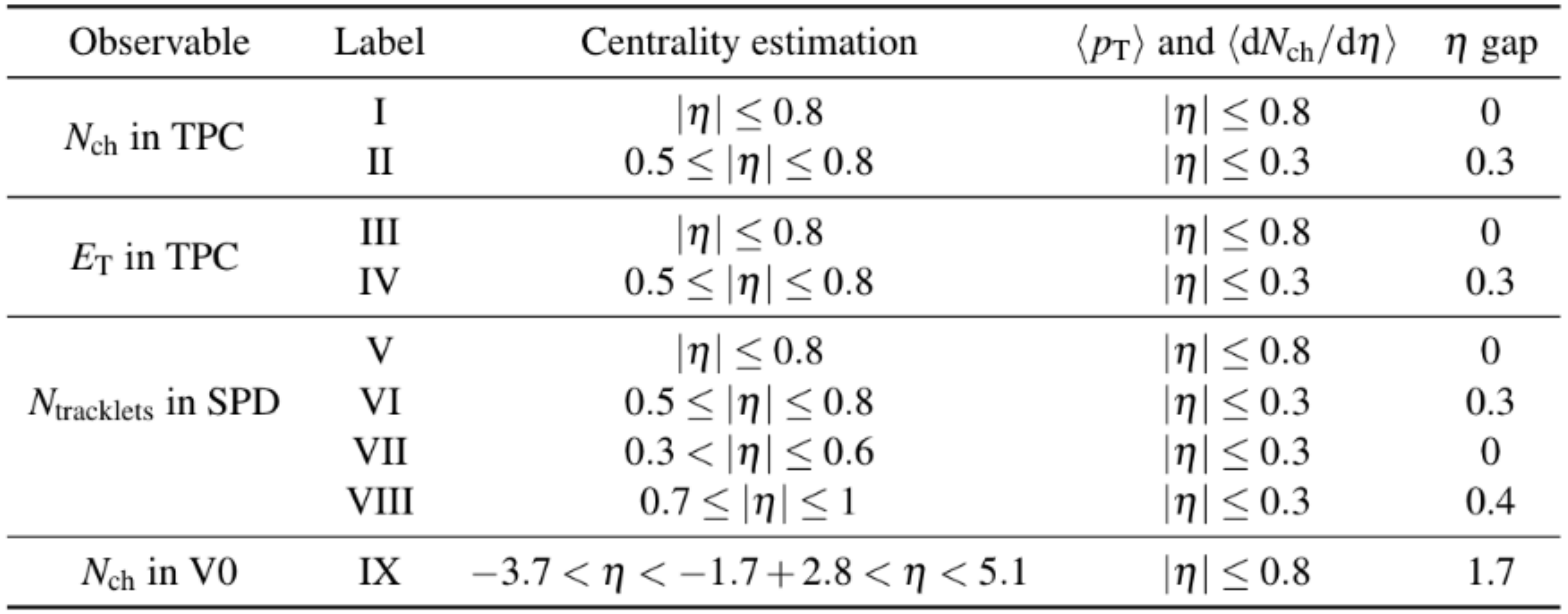
Difference in particle-anti-particle slope:

Increases with decreasing centrality - Higher B-field
Increases with decreasing beam energy - Increasing crossing time
Has species dependence - transported vs created quarks

Speed of Sound: ALICE



ALI-PREL-574193



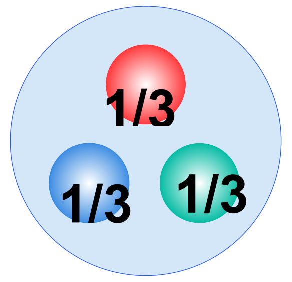
Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$	η gap
N_{ch} in TPC	I	$\lvert\eta\rvert \le 0.8$	$\lvert\eta\rvert \le 0.8$	0
	II	$0.5 \le \lvert\eta\rvert \le 0.8$	$\lvert\eta\rvert \le 0.3$	0.3
E_T in TPC	III	$\lvert\eta\rvert \le 0.8$	$\lvert\eta\rvert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

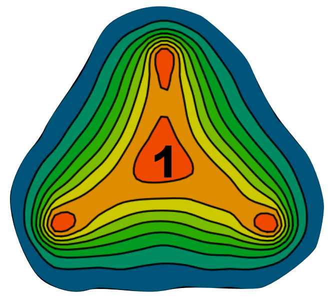
The extraction is heavily **dependent on the choice of centrality estimator**

A significant difference in forward versus midrapidity centrality determination and from the bias of the centrality estimator

What carries the baryon number?

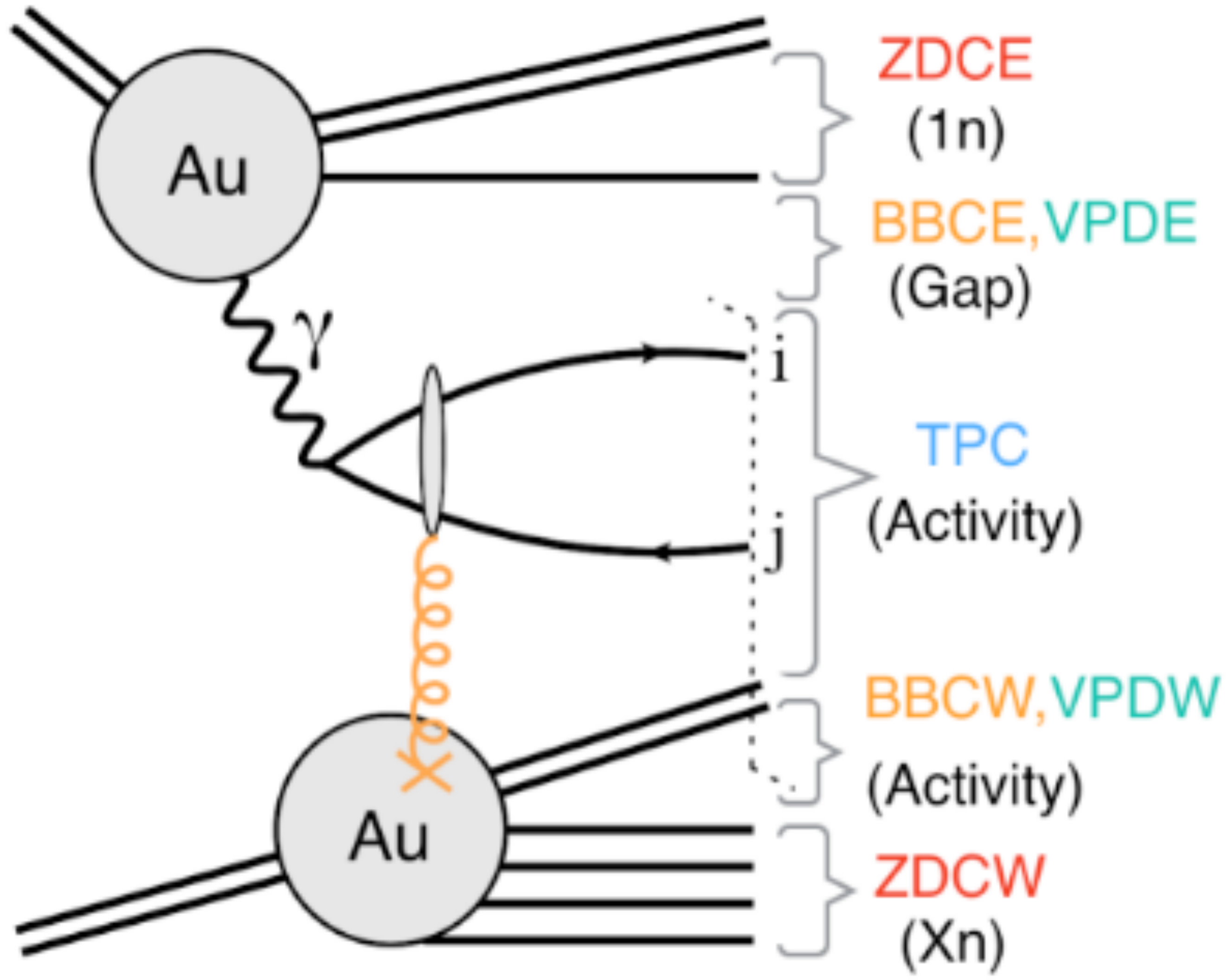


Quarks as baryon carriers?



Baryon-junction as baryon carrier?

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

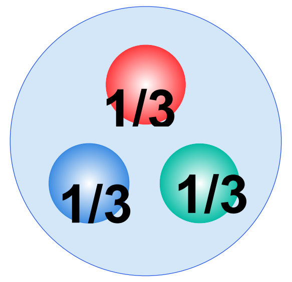


Study photonuclear events:
Very clean process

Baryon number in 3 valence quarks - no stopped baryons

Baryon junctions - produce midrapidity proton

What carries the baryon number?



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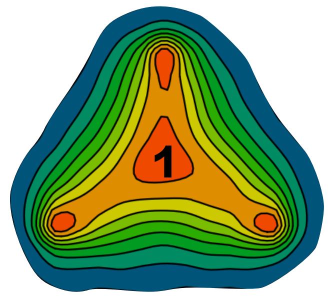

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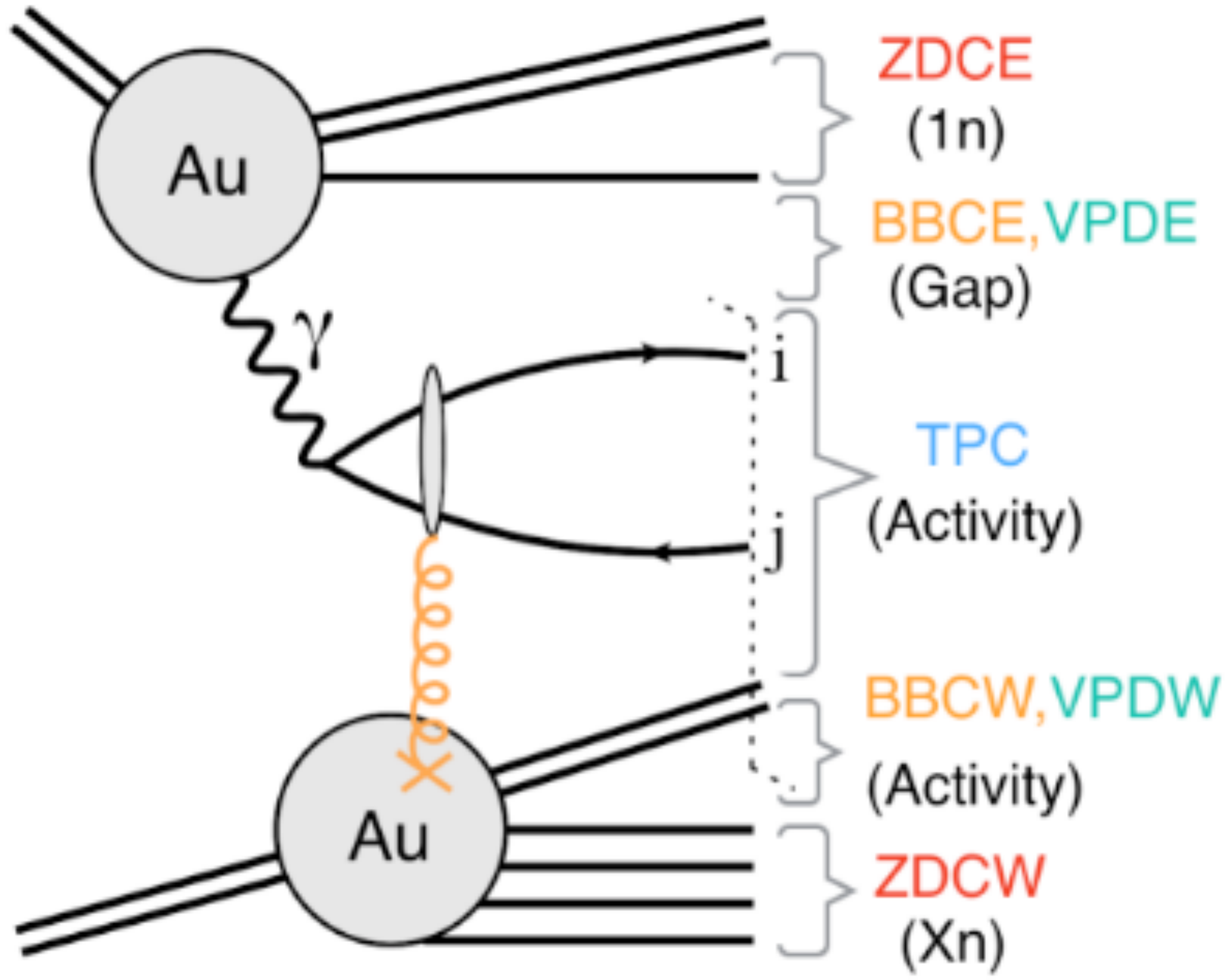
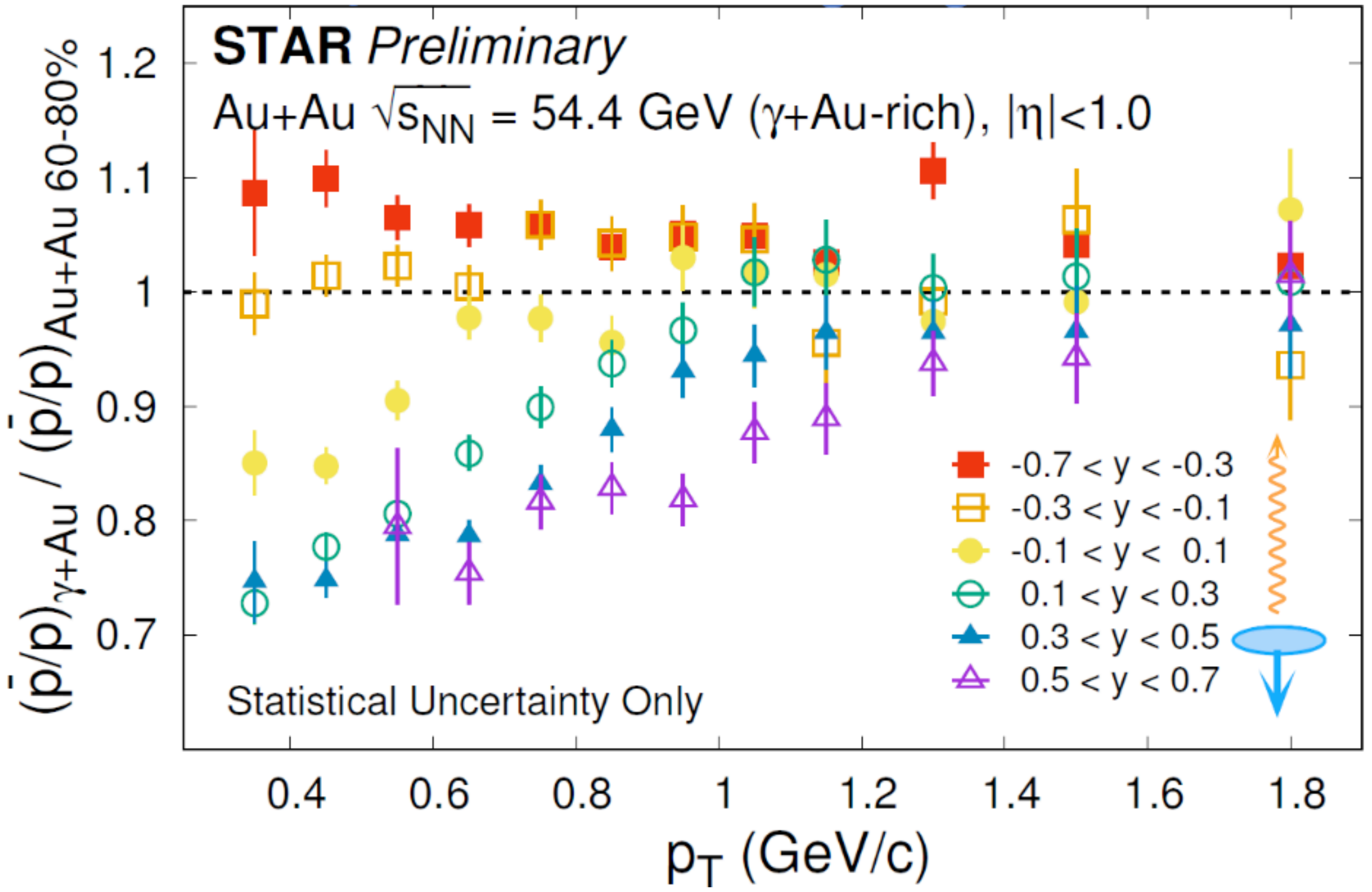


Study photonuclear events:
Very clean process

Baryon number in 3 valence quarks - no stopped baryons

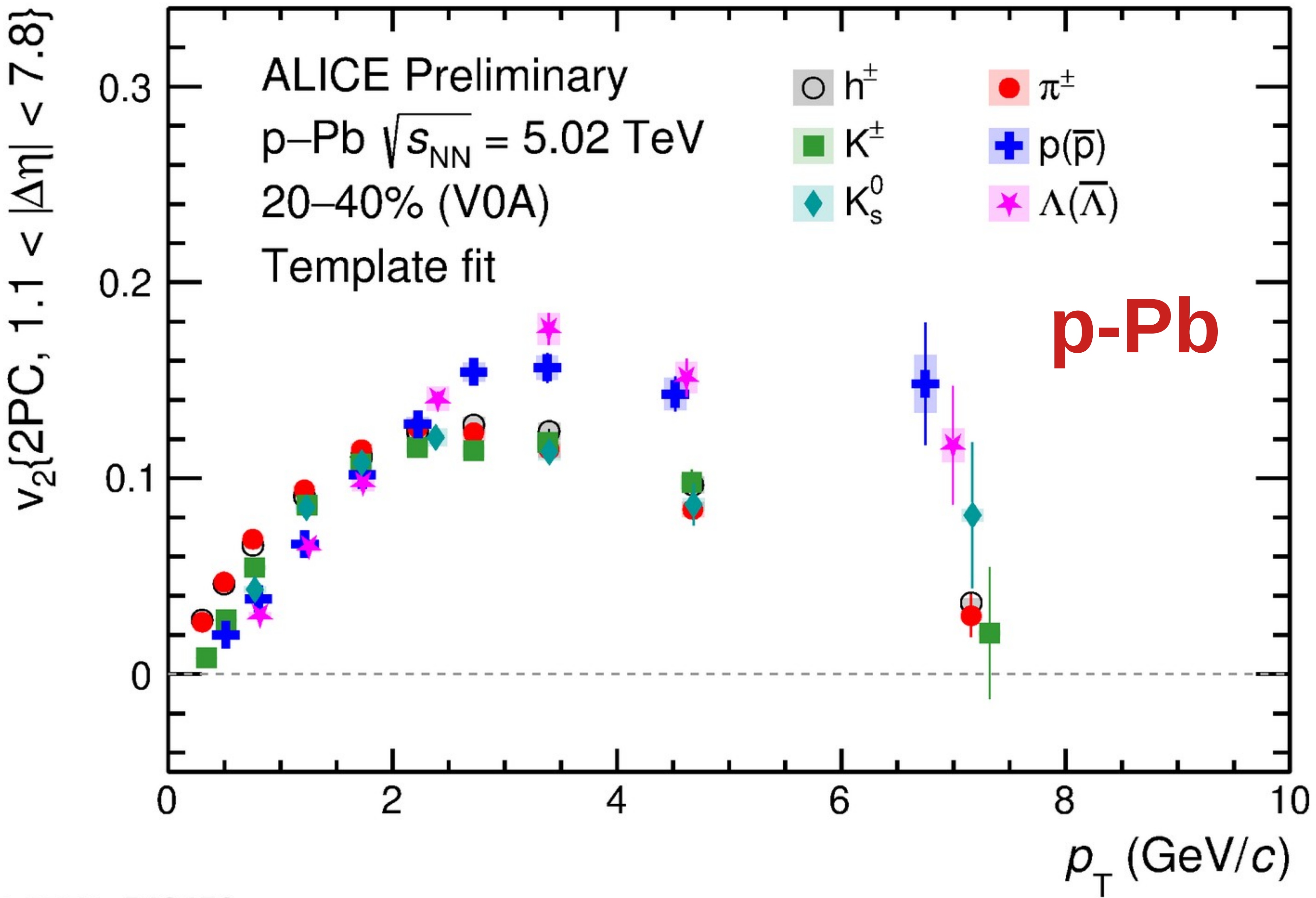
Baryon junctions - produce midrapidity proton



stronger rapidity dependent stopping in γ+Au than peripheral Au+Au at approximately same multiplicity

Path towards a microscopic understanding of what carries baryon number & how it is stopped

Small system flow



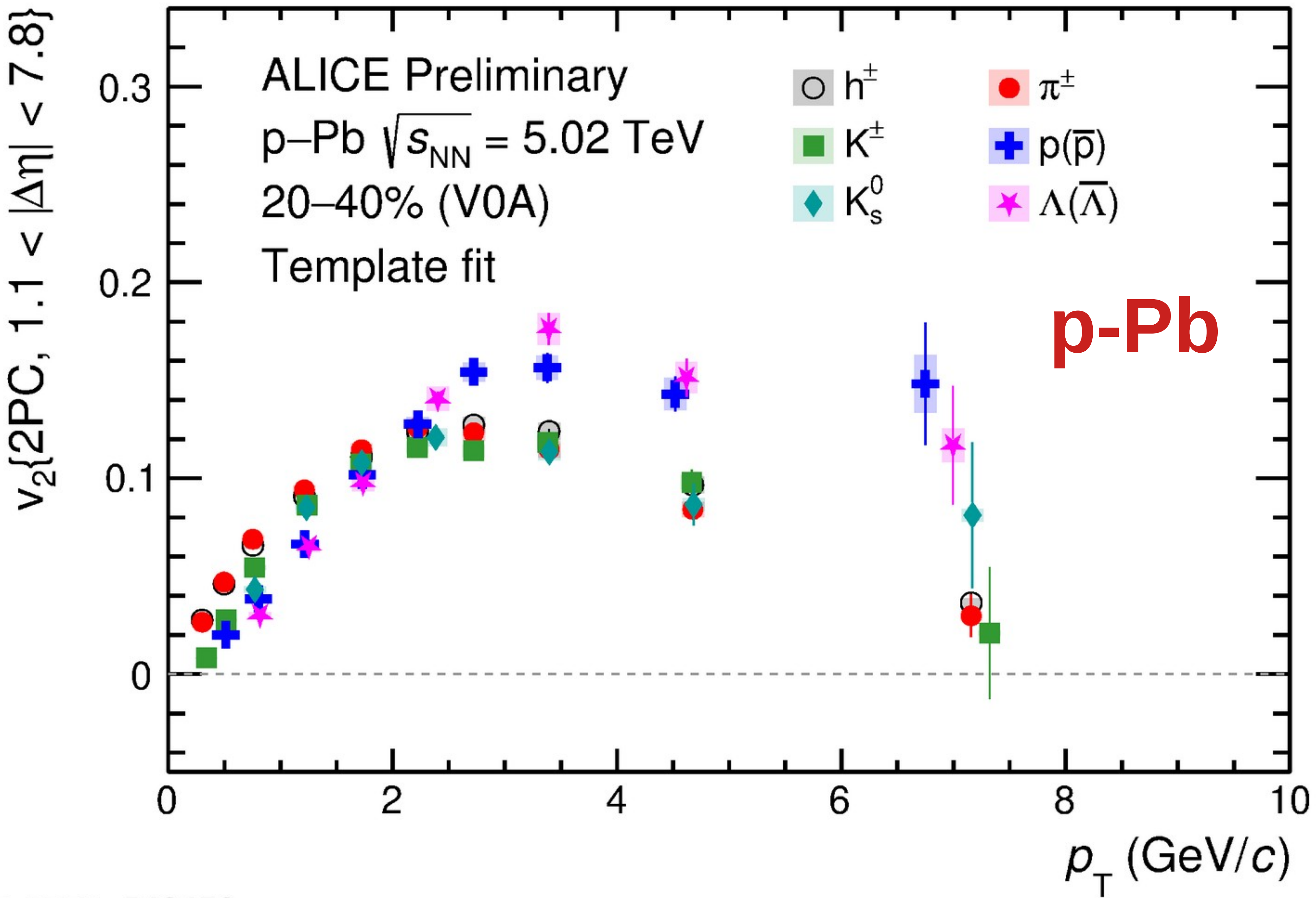
ALI-PREL-543472

Low p_T - mass ordering

Intermediate p_T - NCQ scaling

B. Schenke, M.Zhao

Small system flow



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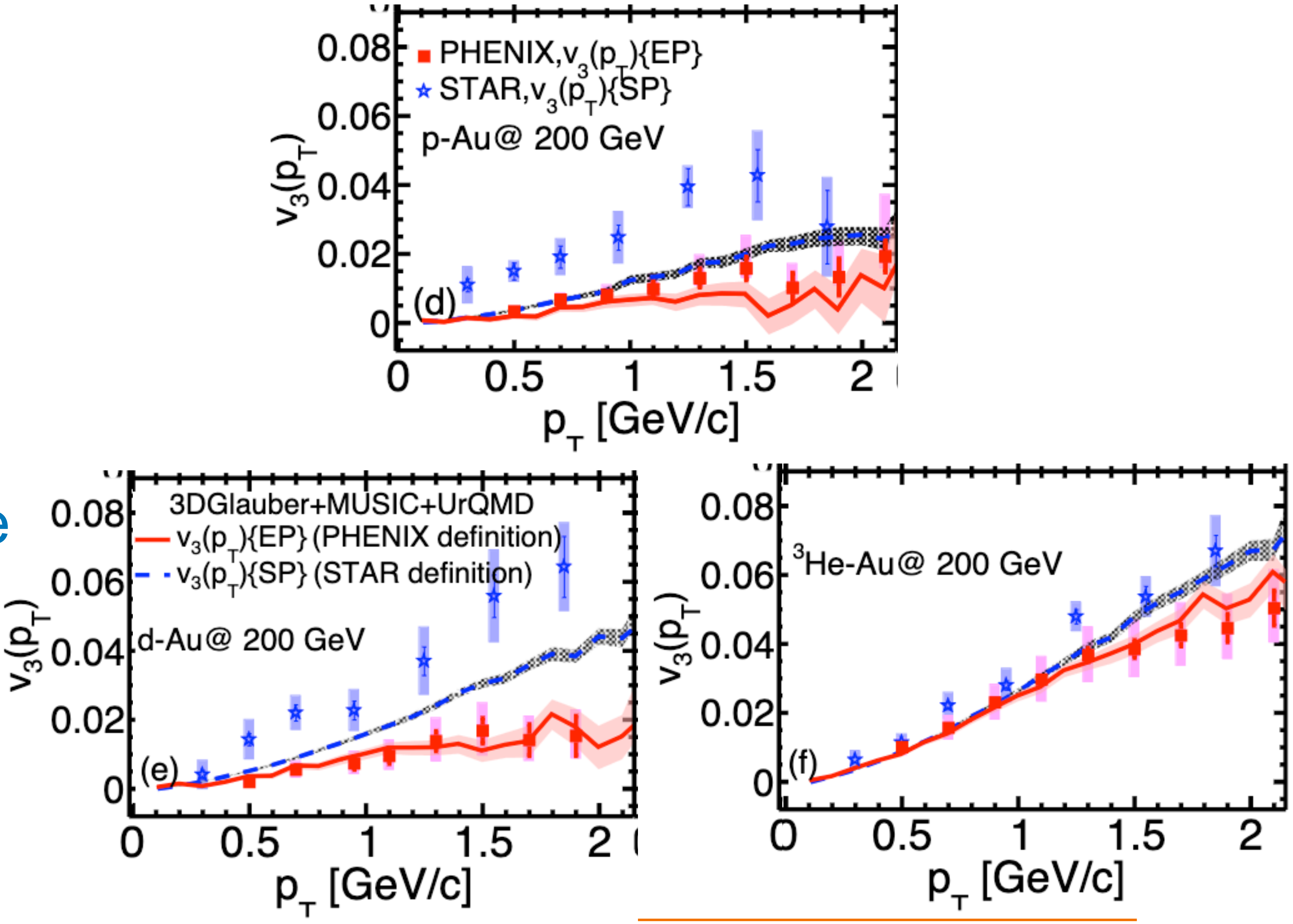
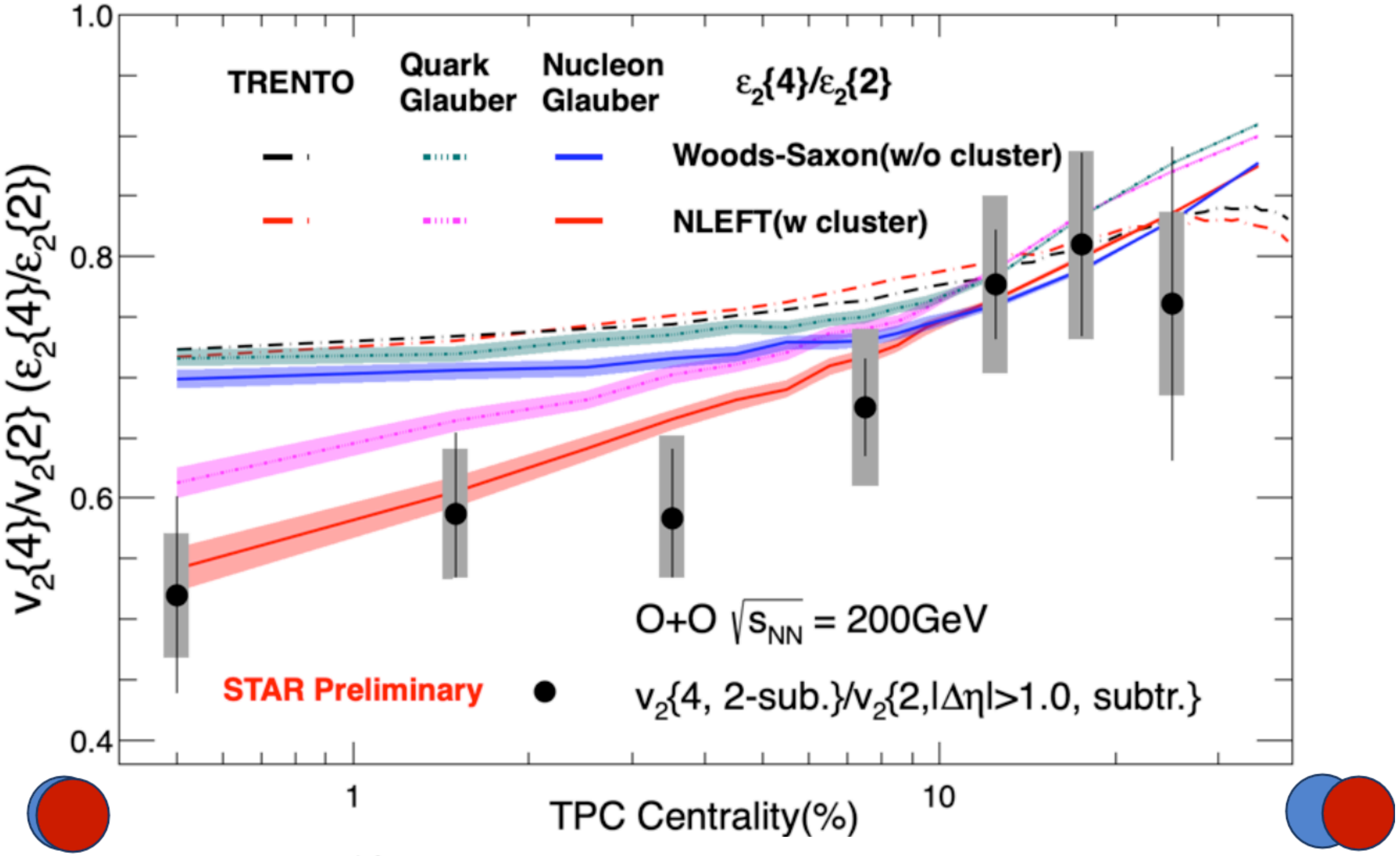


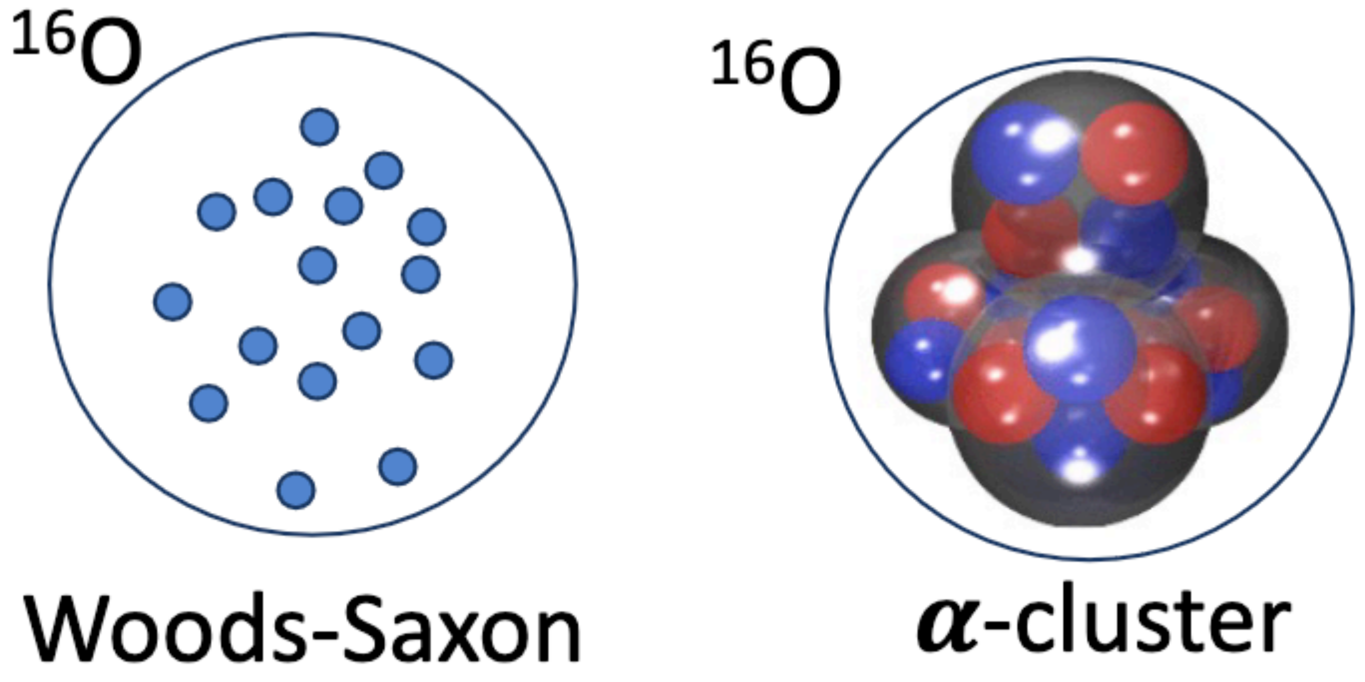
v_2 and v_3 differences at RHIC largely due to use of different rapidity ranges

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

B. Schenke, M.Zhao

Substructure of oxygen





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

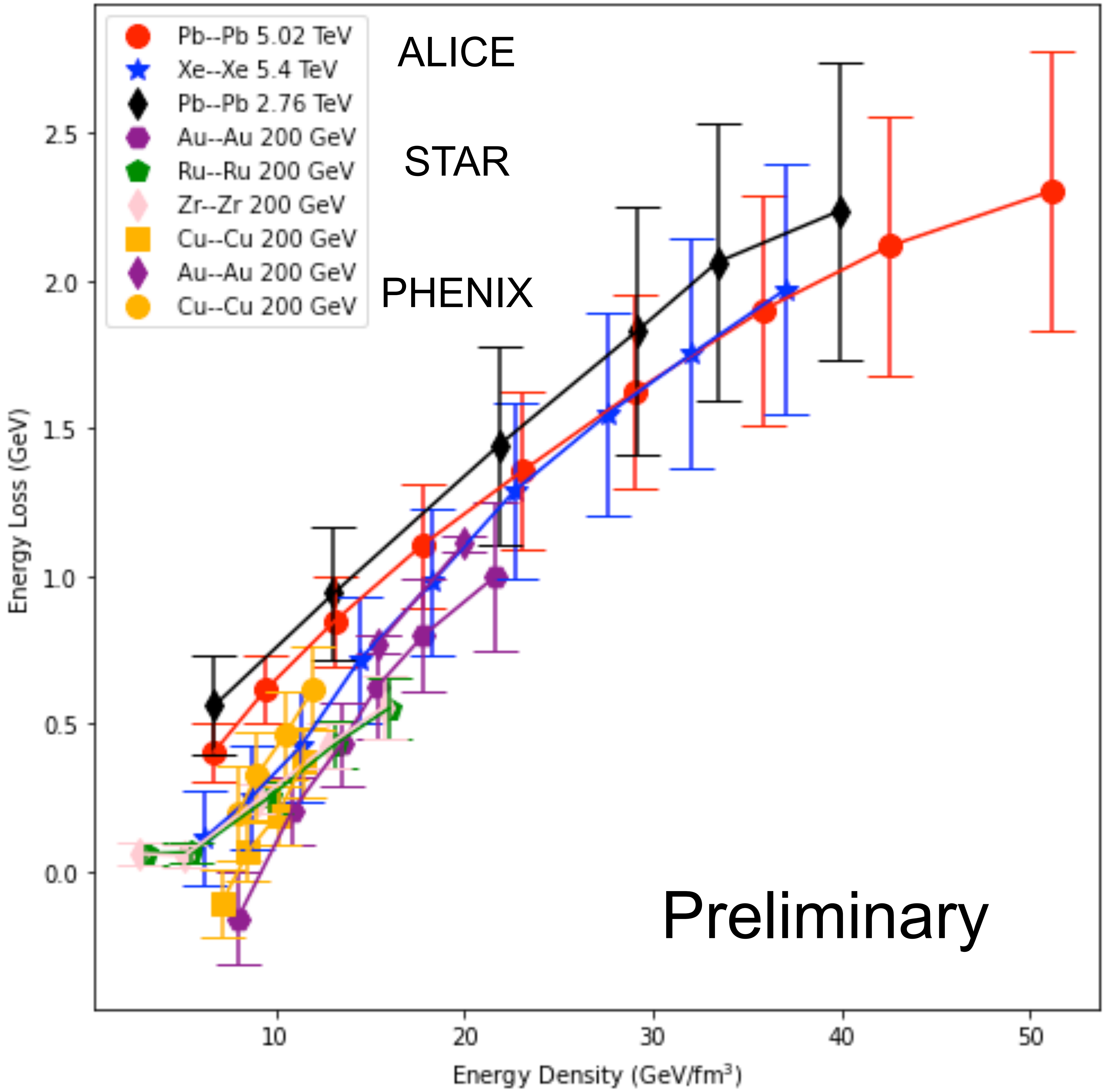
$v_2\{4\}$ - reduced sensitivity to fluctuations

Data:
in central event but fluctuations enhanced, (v_2 reduced overall)

Theory:
Alpha clusters enhance fluctuations

Data strongly favor alpha-clustering

Energy loss vs energy density



E_{Loss} from: shift of p_T spectra

Approximate energy density from:

$dN_{ch}/d\eta \longrightarrow dS/dy \longrightarrow s_f \tau_f = dS/dy/A_T = s_{init} \tau_{init}$

$$\varepsilon_{init} = 3/4\ s_{init}\, T_{int}$$

Given number of approximations reasonably reasonable correlation between E_{Loss} and ε_{init} over different species and collision energies

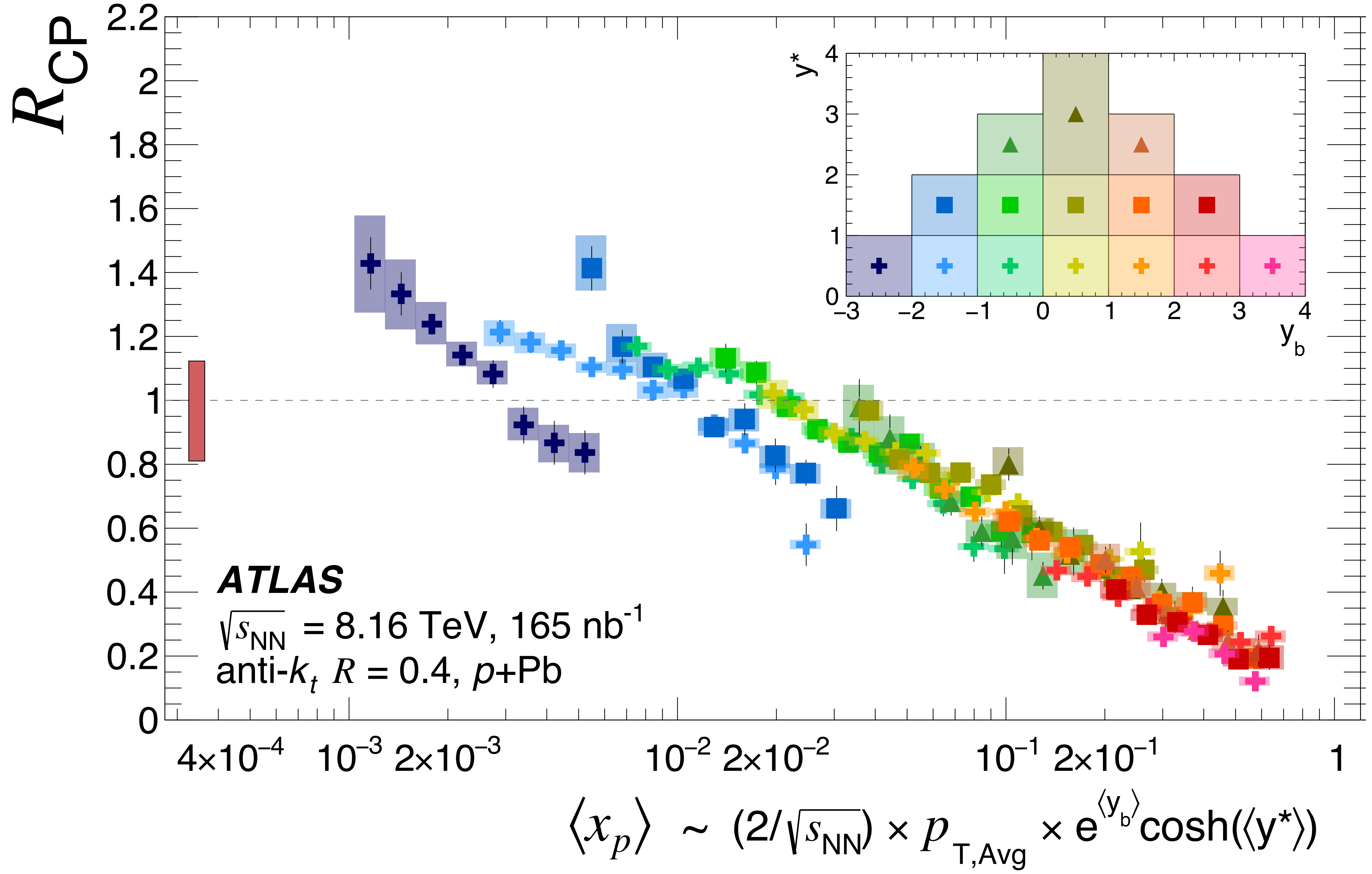
Link between entropy and charged particle density very sensitive to viscosity.

Maybe worth more careful calculation?

More details on estimates see 2308.05743 J. Harris & B. Muller

T. Hachiya, S. Schlichting

Energy loss to p(d)-Au medium?



ATLAS di-jet studies: centrality dependence of jet yield initial (x_p), not final, state effect!

CMS: no di-jet imbalance, no E_{Loss}

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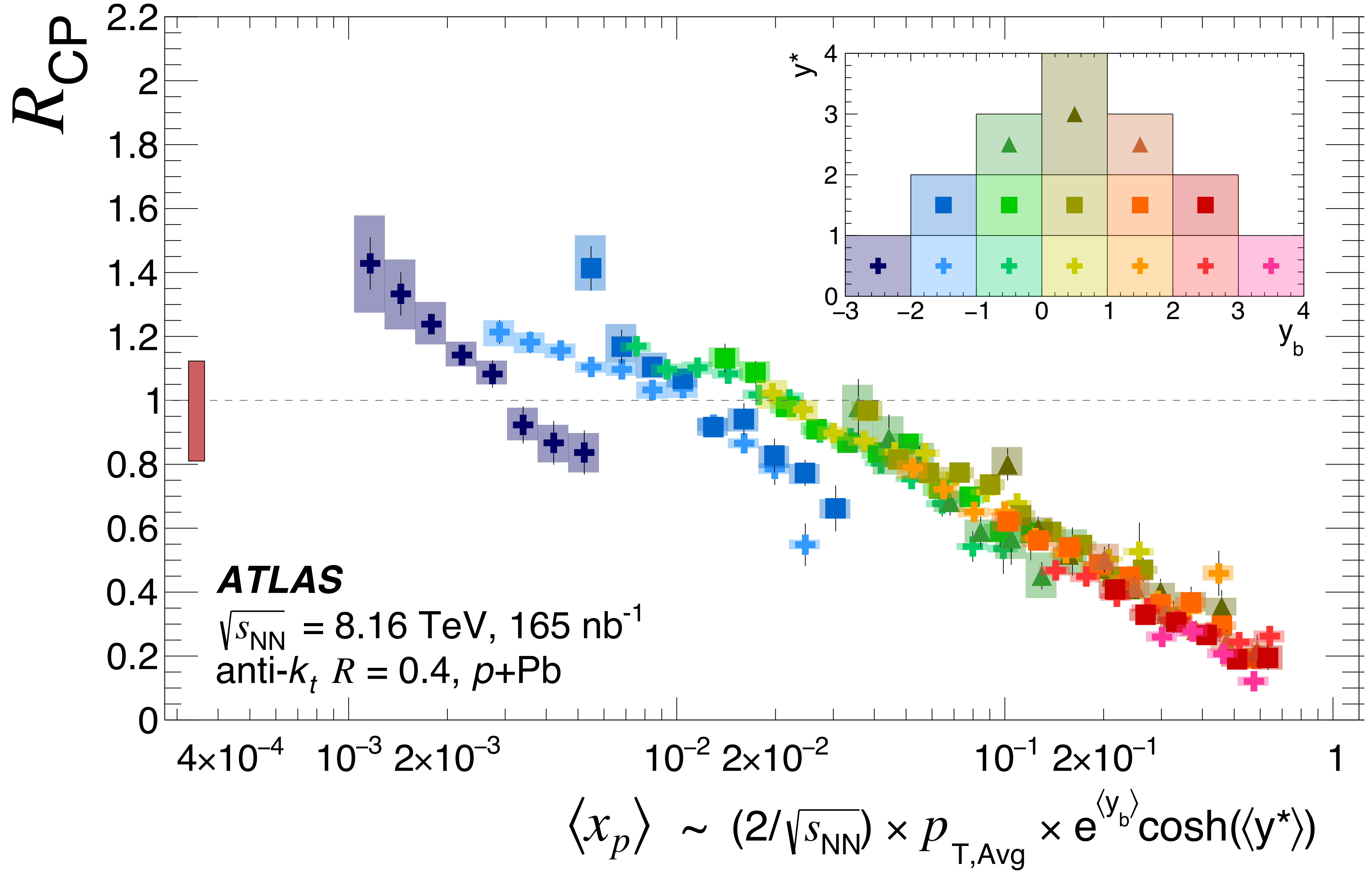

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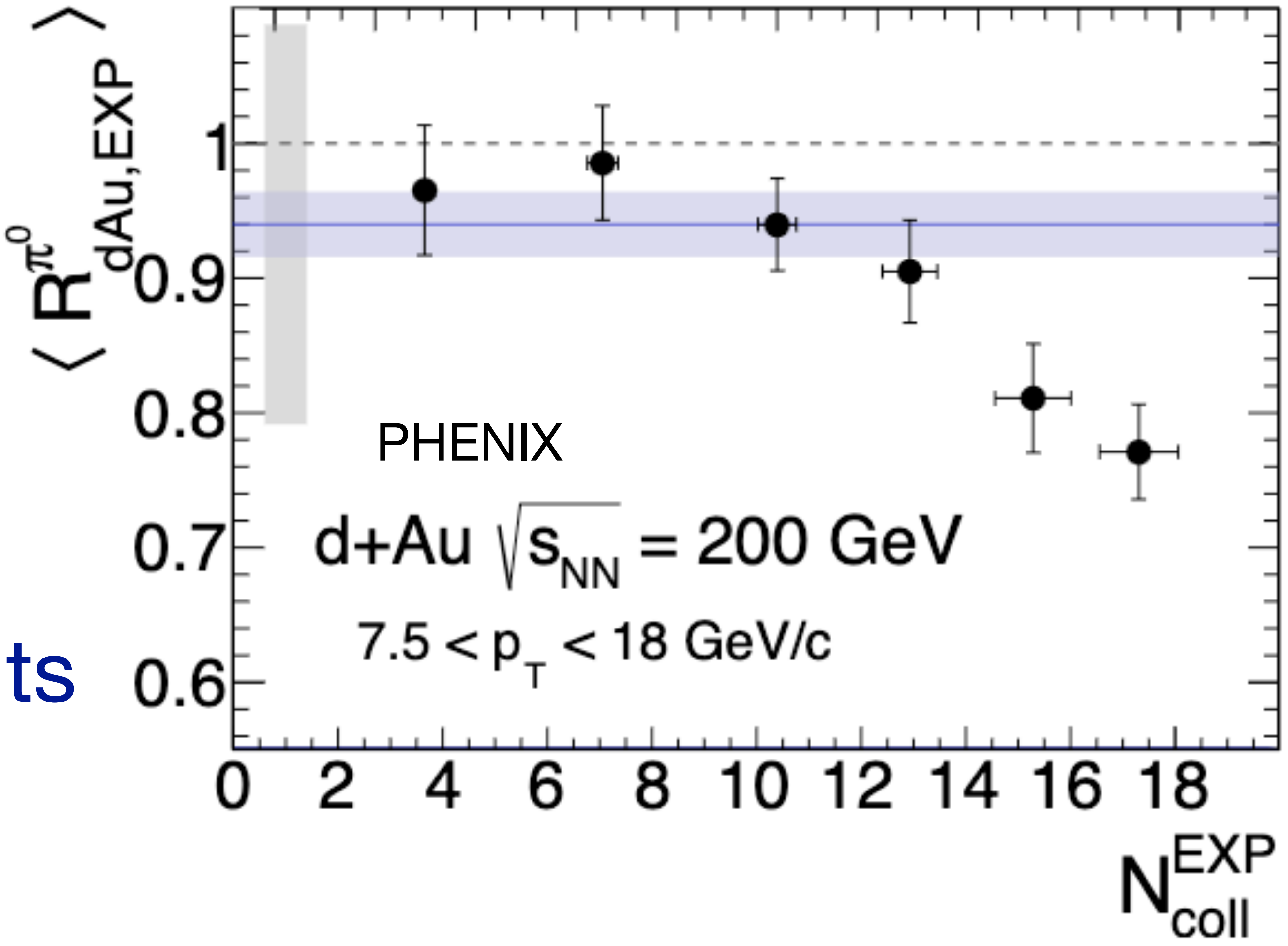
PHENIX:

Show usual techniques to determine N_{bin}

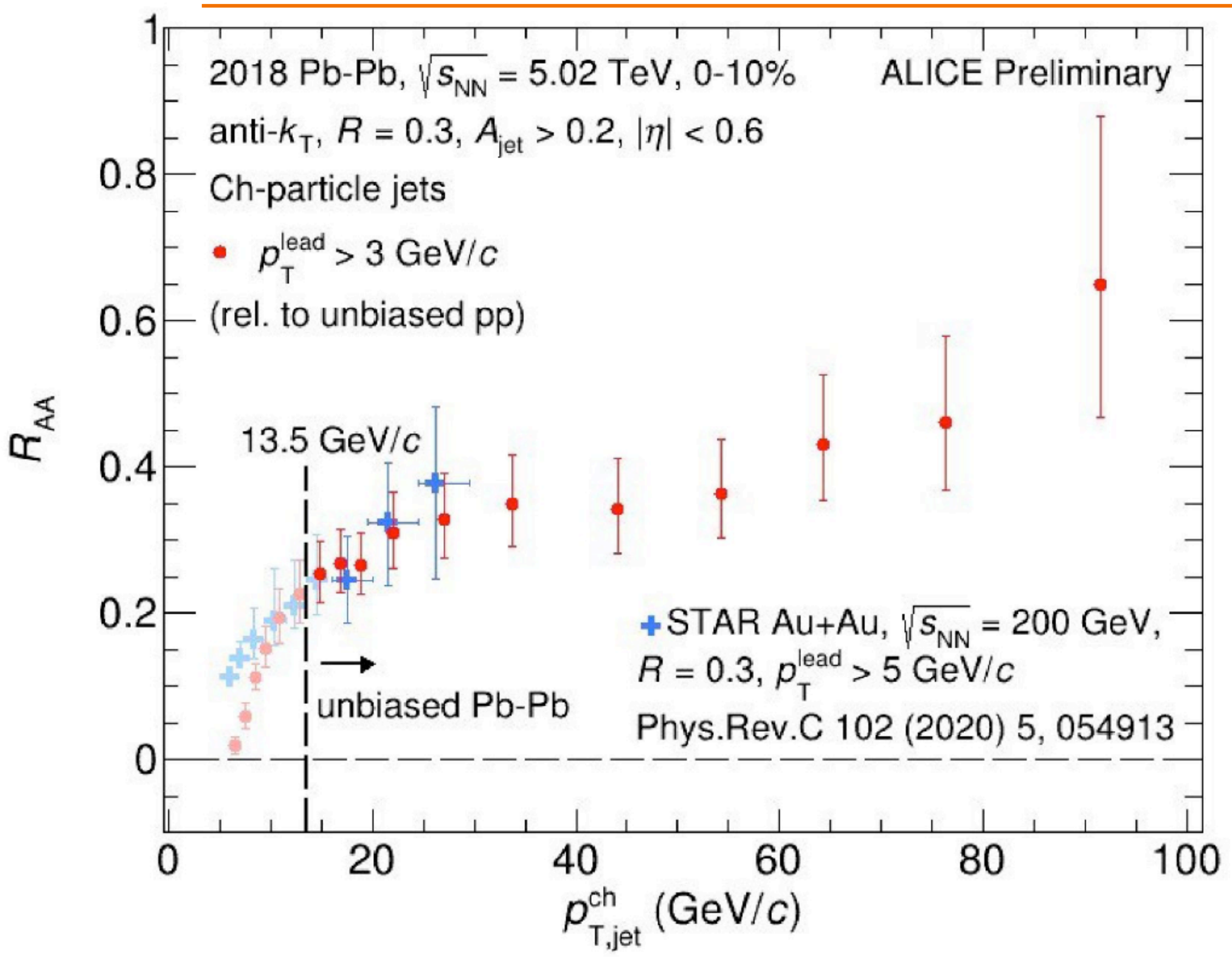
so now determine by forcing R_{dAu} γ to unity

Strong suppression of π^0 in high multiplicity events



Not clear there’s a consistent picture across collision energies yet

Nuclear modification of jets



Charged jet results at same p_T for RHIC and LHC (N.B. scale by ~1.5 to get to full jet equivalent p_T)

Similar R_{AA} for both collision energies

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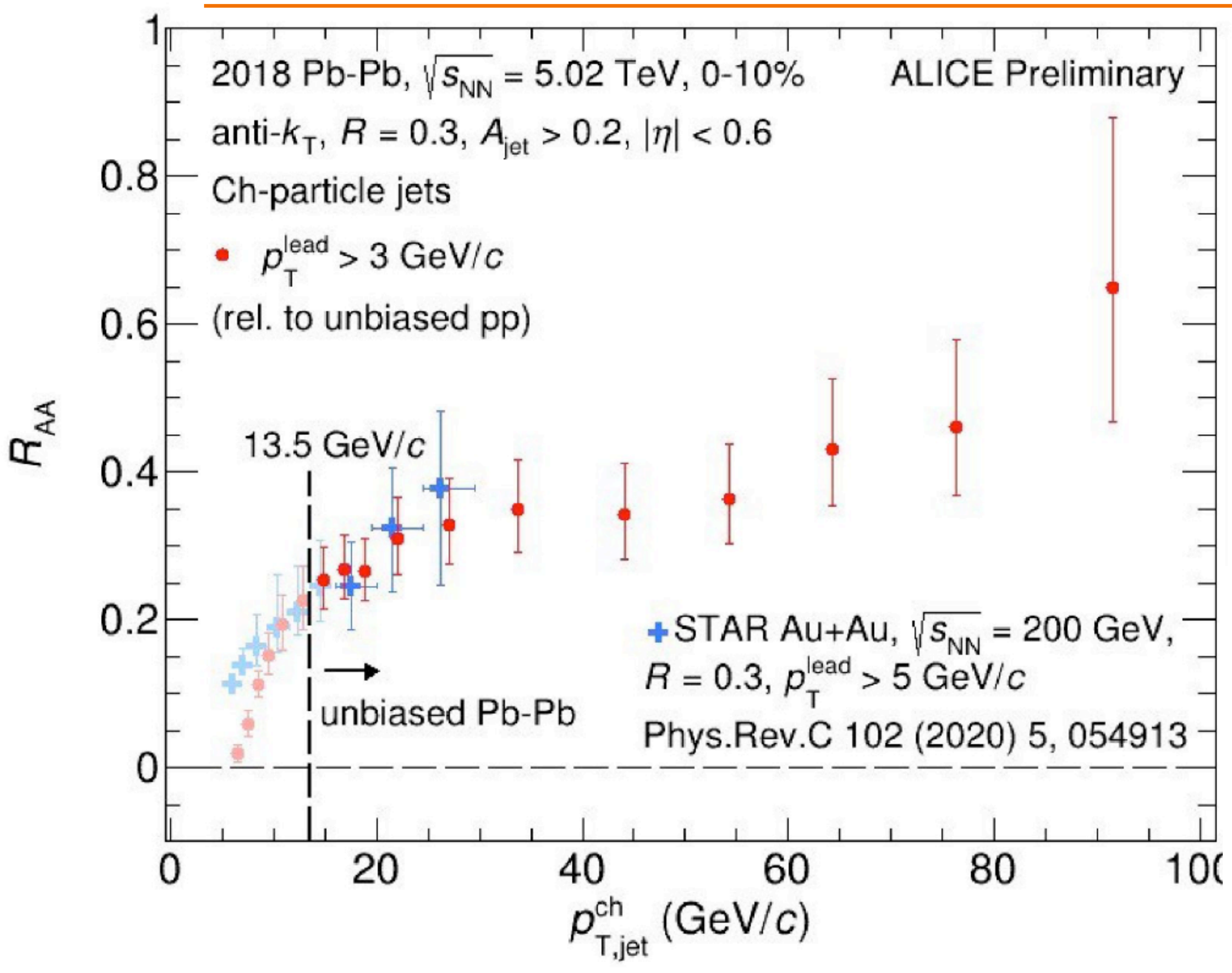

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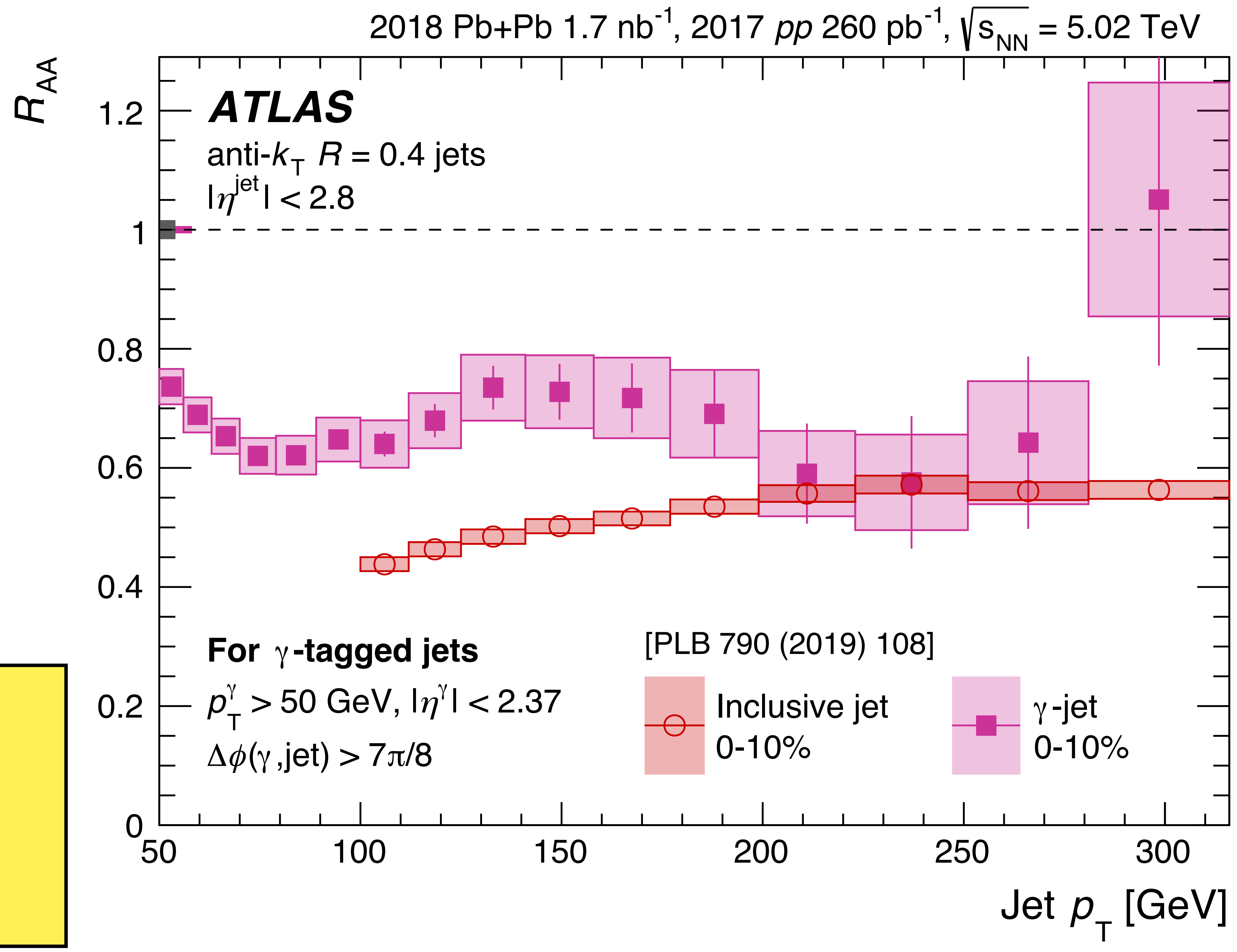


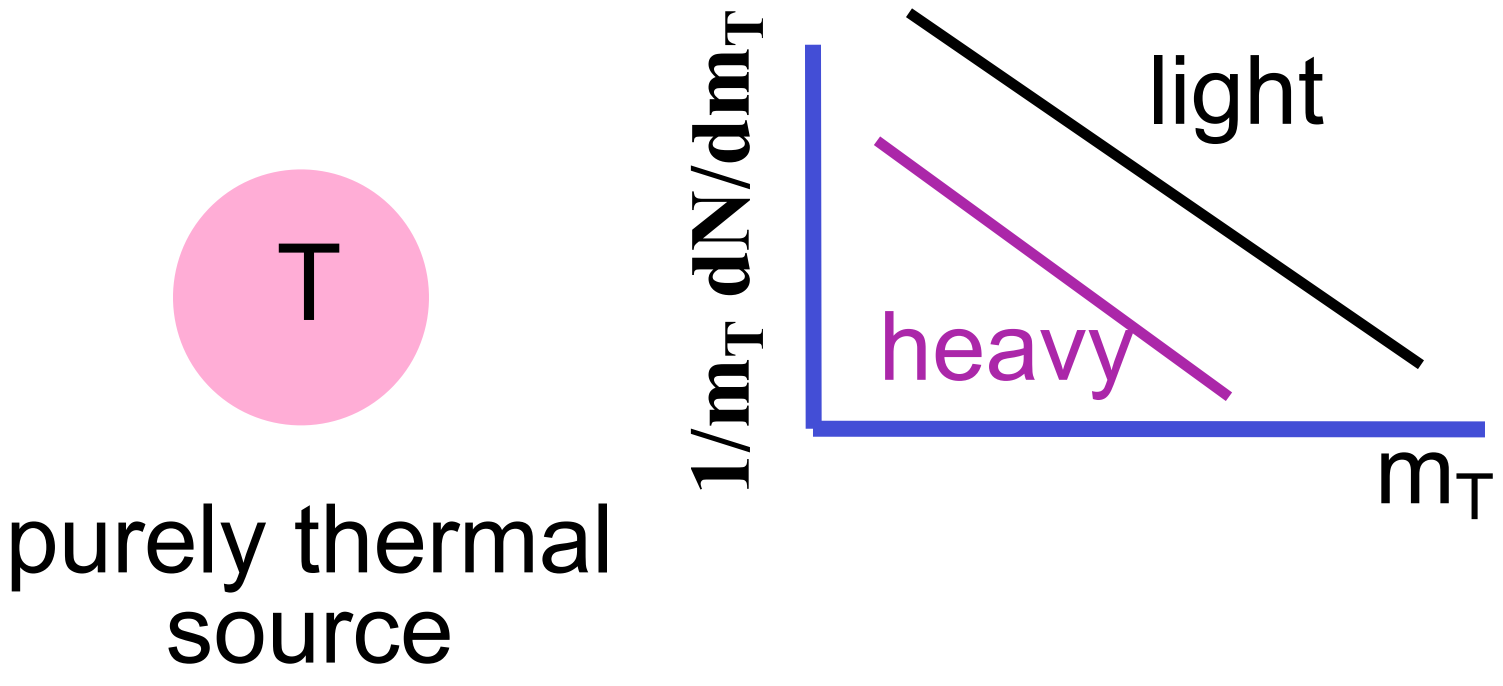
~ 80% quark jets

~ 40—50 % quark jets

Clear difference in R_{AA} for inclusive and γ-tagged jets

In both cases interpretation complicated due to differing slopes of pp baselines

Kinematics after last scattering



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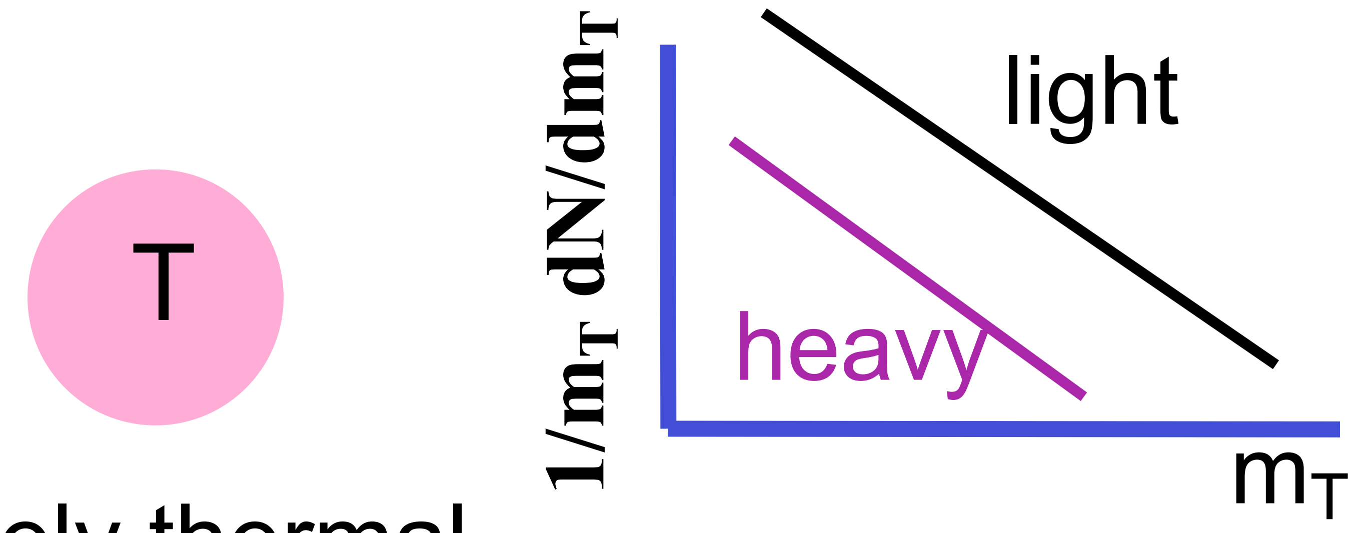
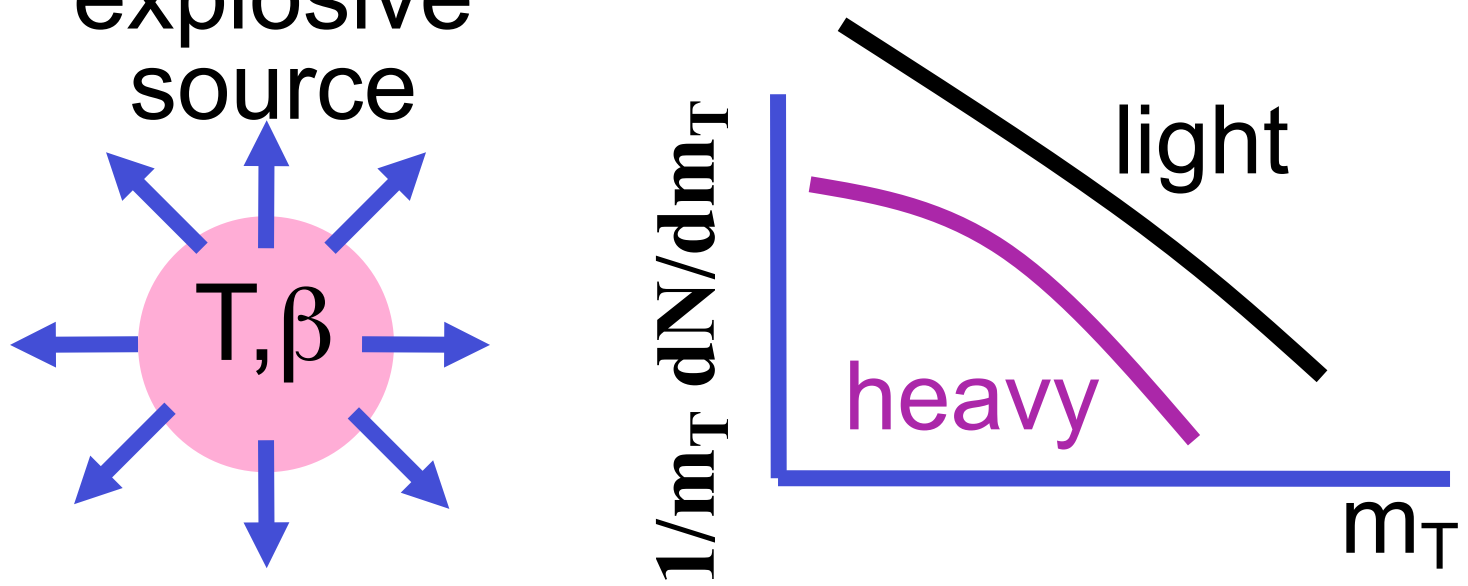


purely thermal
source

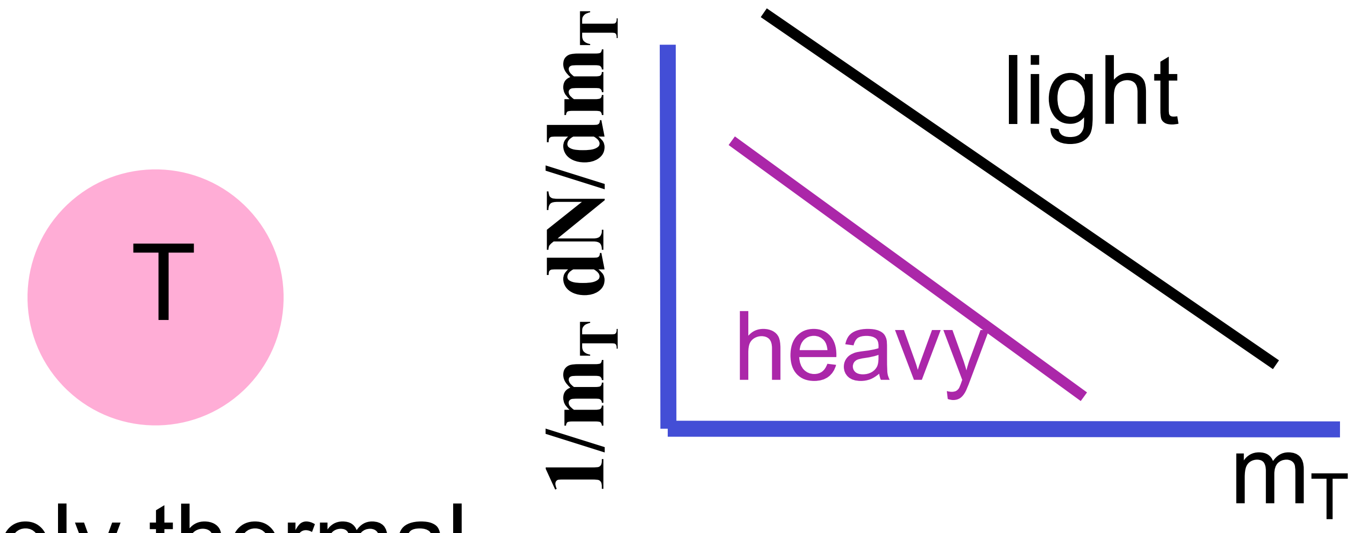
explosive
source



$m_T = (p_T^2 + m^2)^{½}$

Different spectral shapes for
particles of differing mass
→ strong collective radial flow

Kinematics after last scattering



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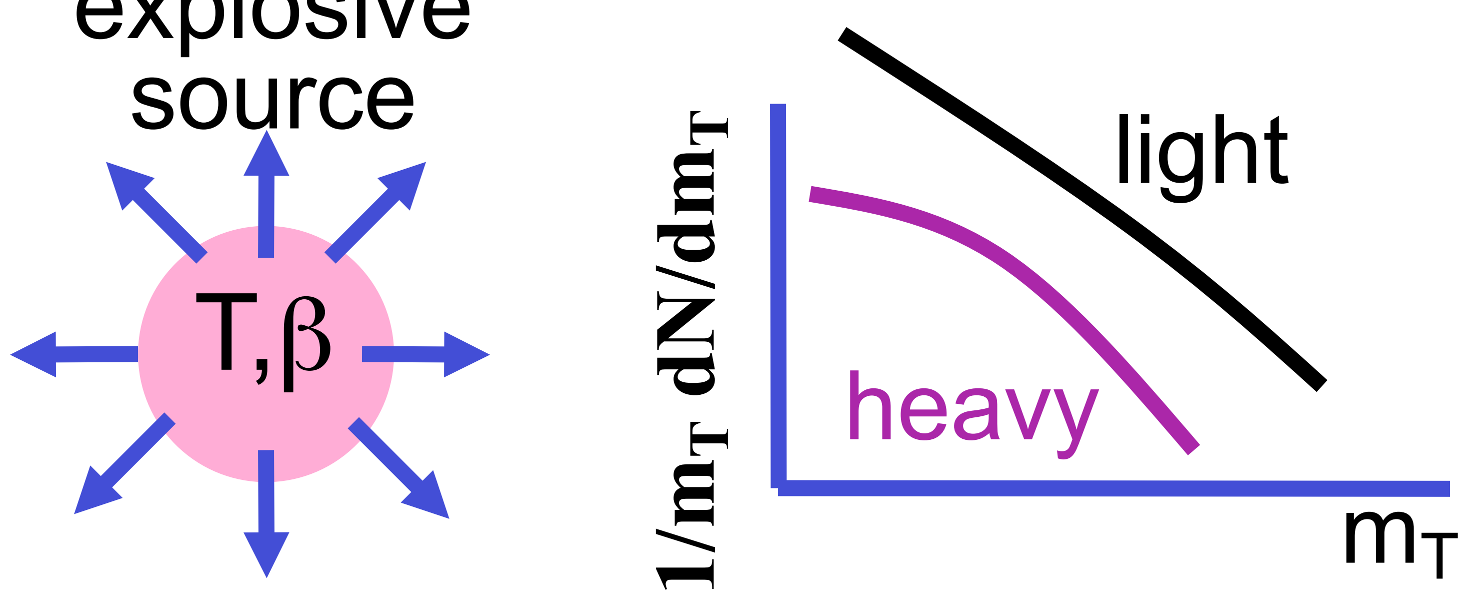

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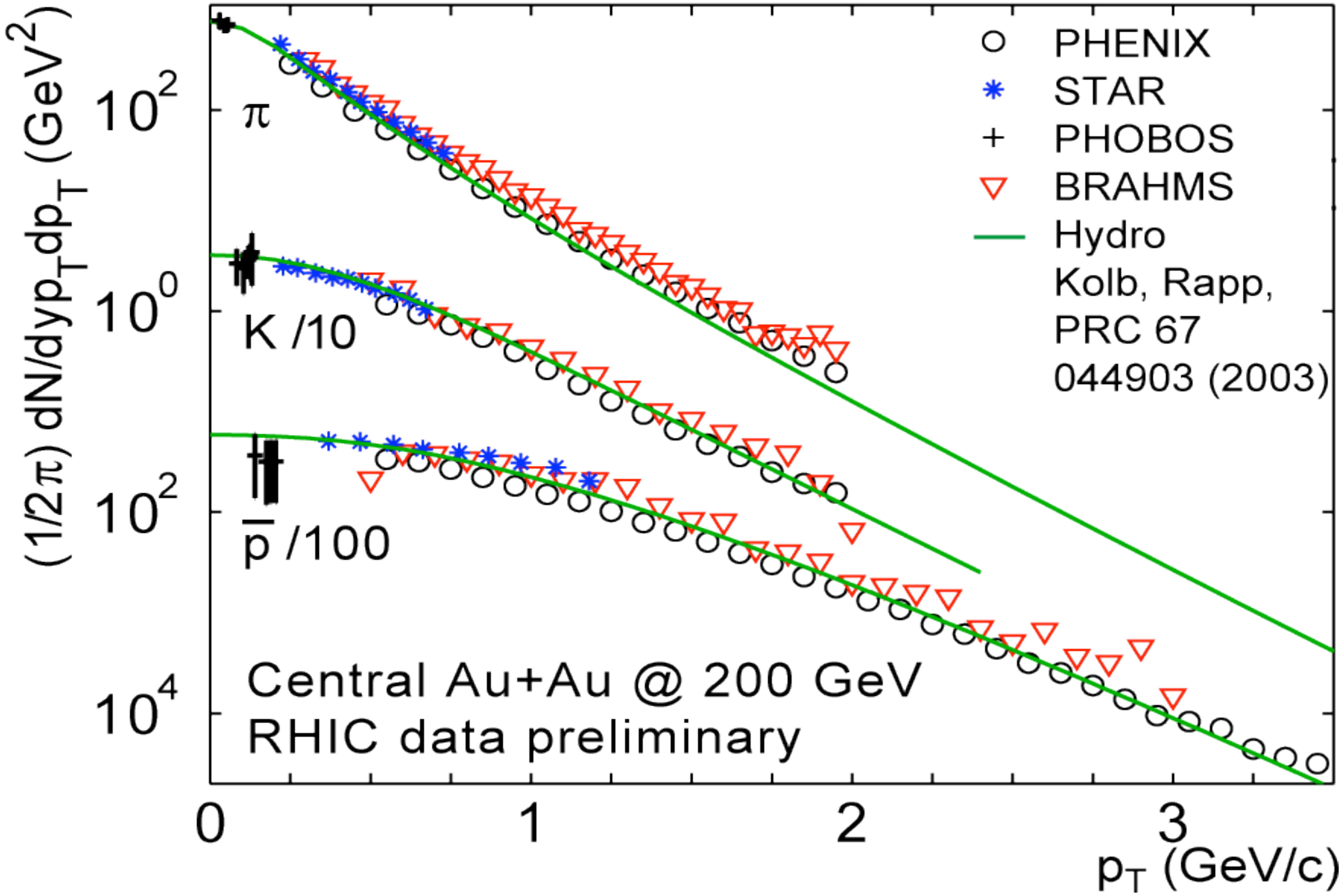
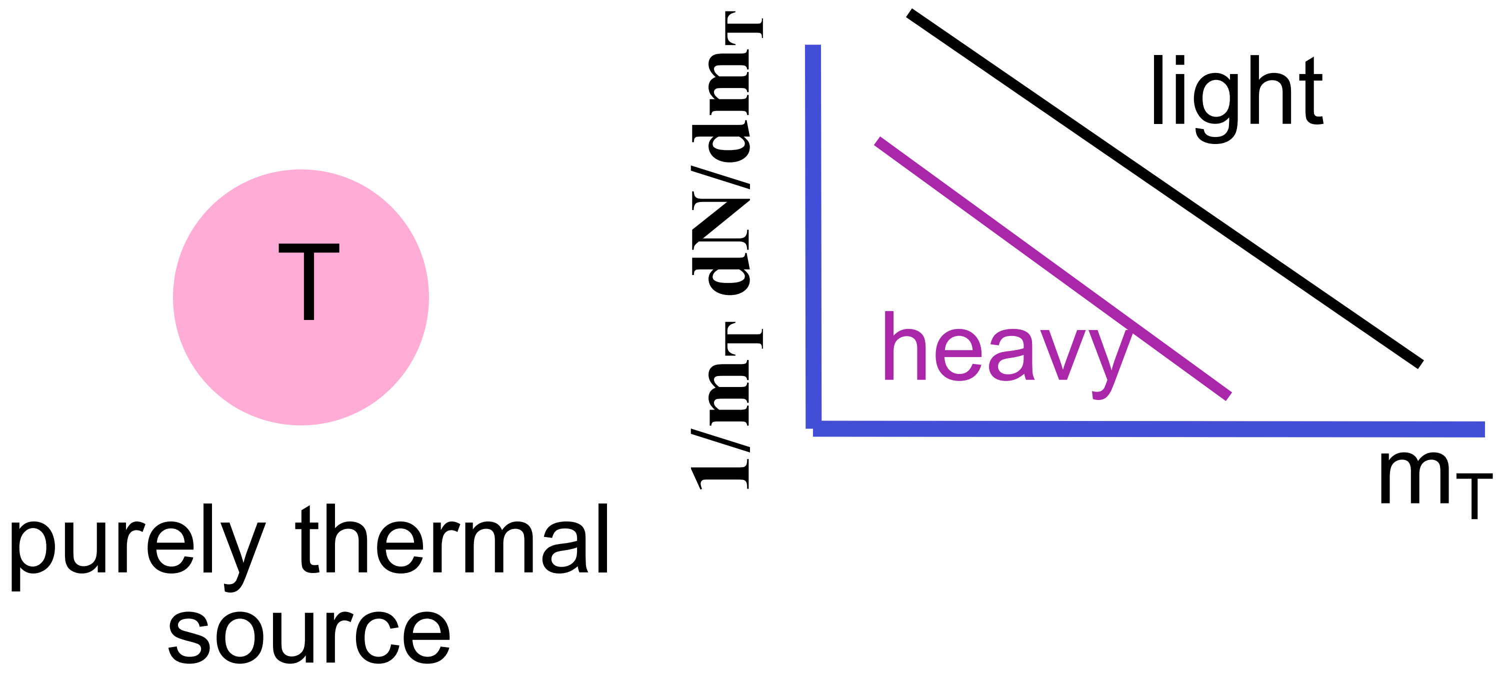
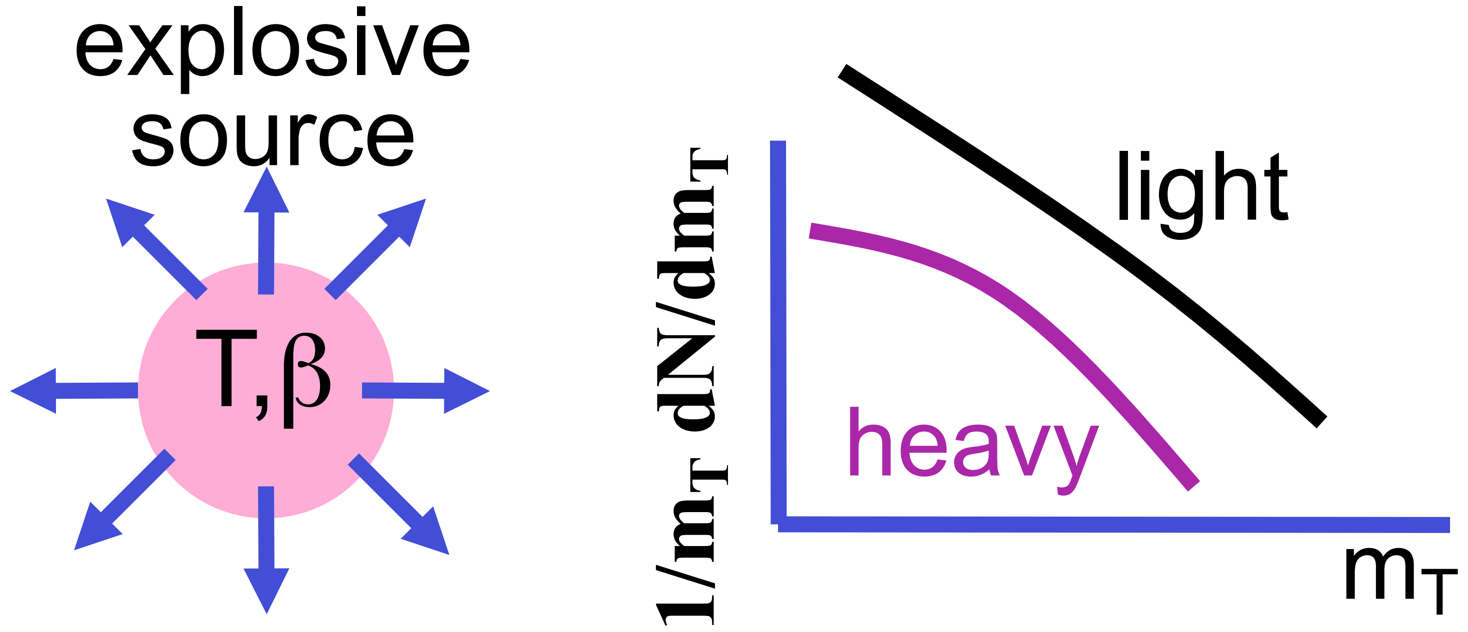


T_{fo}~ 100 MeV
$\langle \beta_T \rangle$ ~ 0.55 c

Good agreement with hydrodynamic explosively expanding source

Kinematics after last scattering





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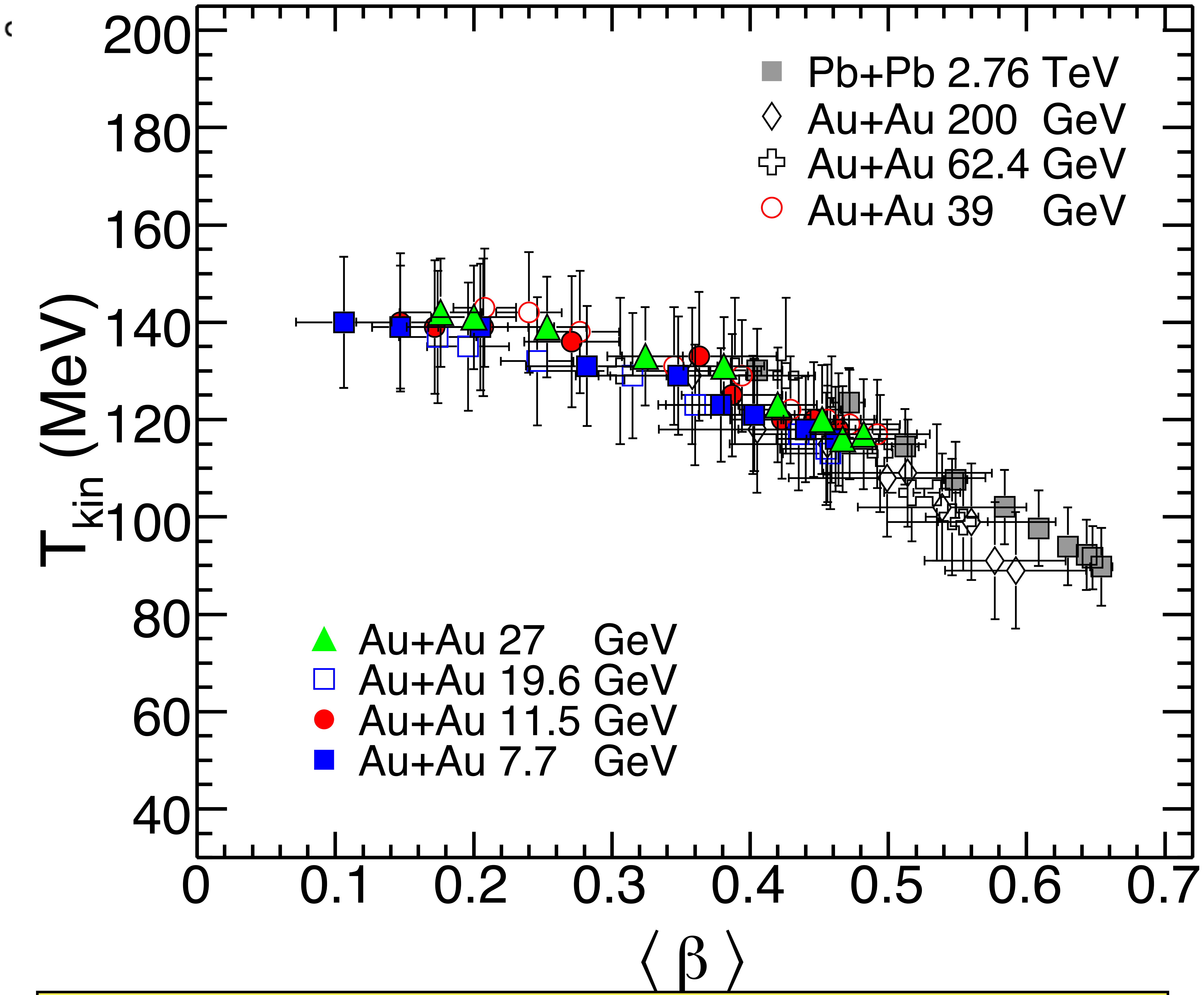

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