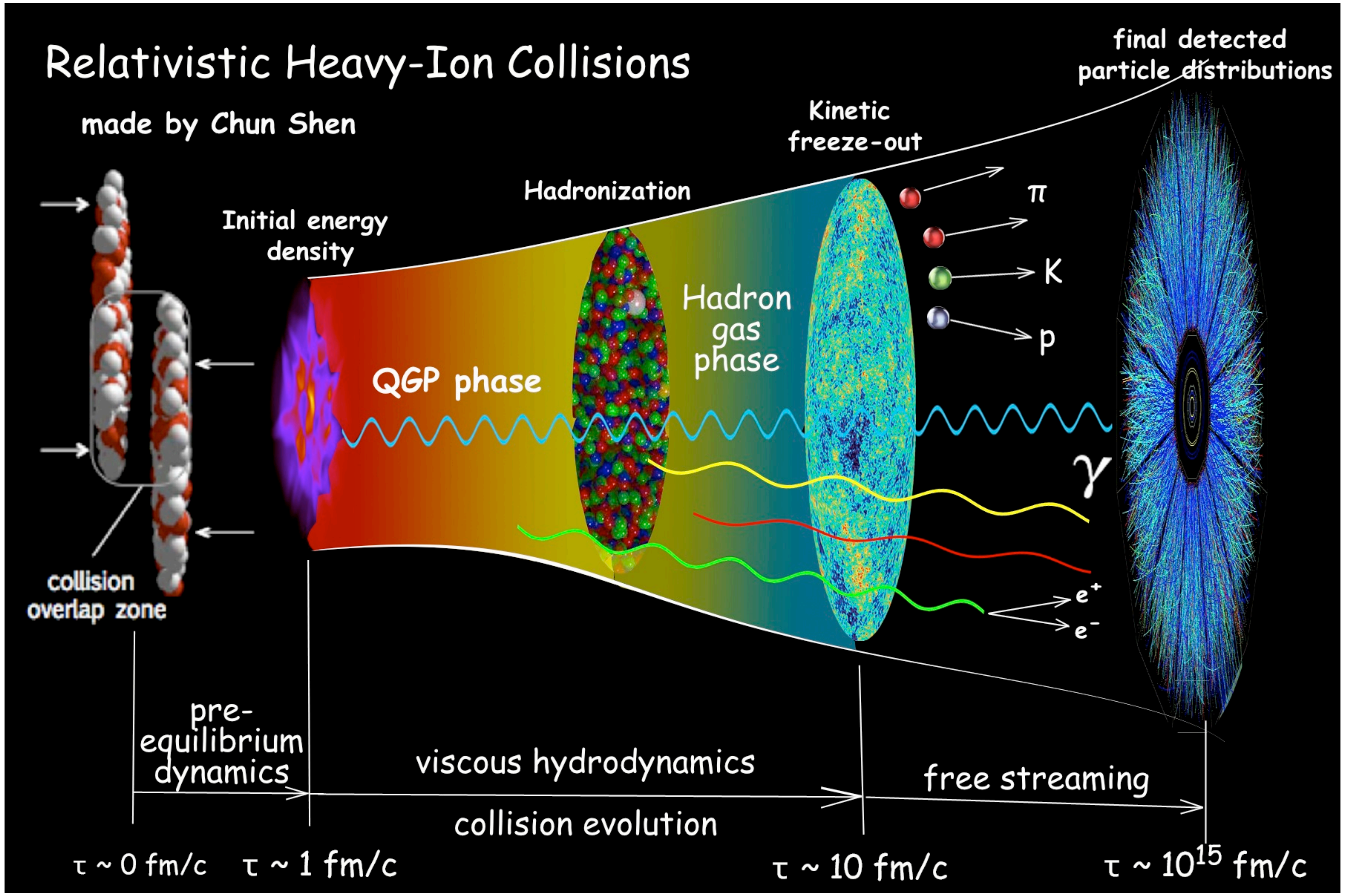
Hot QCD:
Recent discoveries and Open Questions

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



Center for Frontiers in Nuclear Science

CFNS Postdoc Meeting, Stony Brook, Oct 2023

U.S. DEPARTMENT OF ENERGY Office of Science

Wright Laboratory

LUX ET VERITAS

A time to celebrate in hot QCD

50 years since QCD conceived

40 years since NSAC recommended RHIC be constructed - whole report only 5-6 pages long

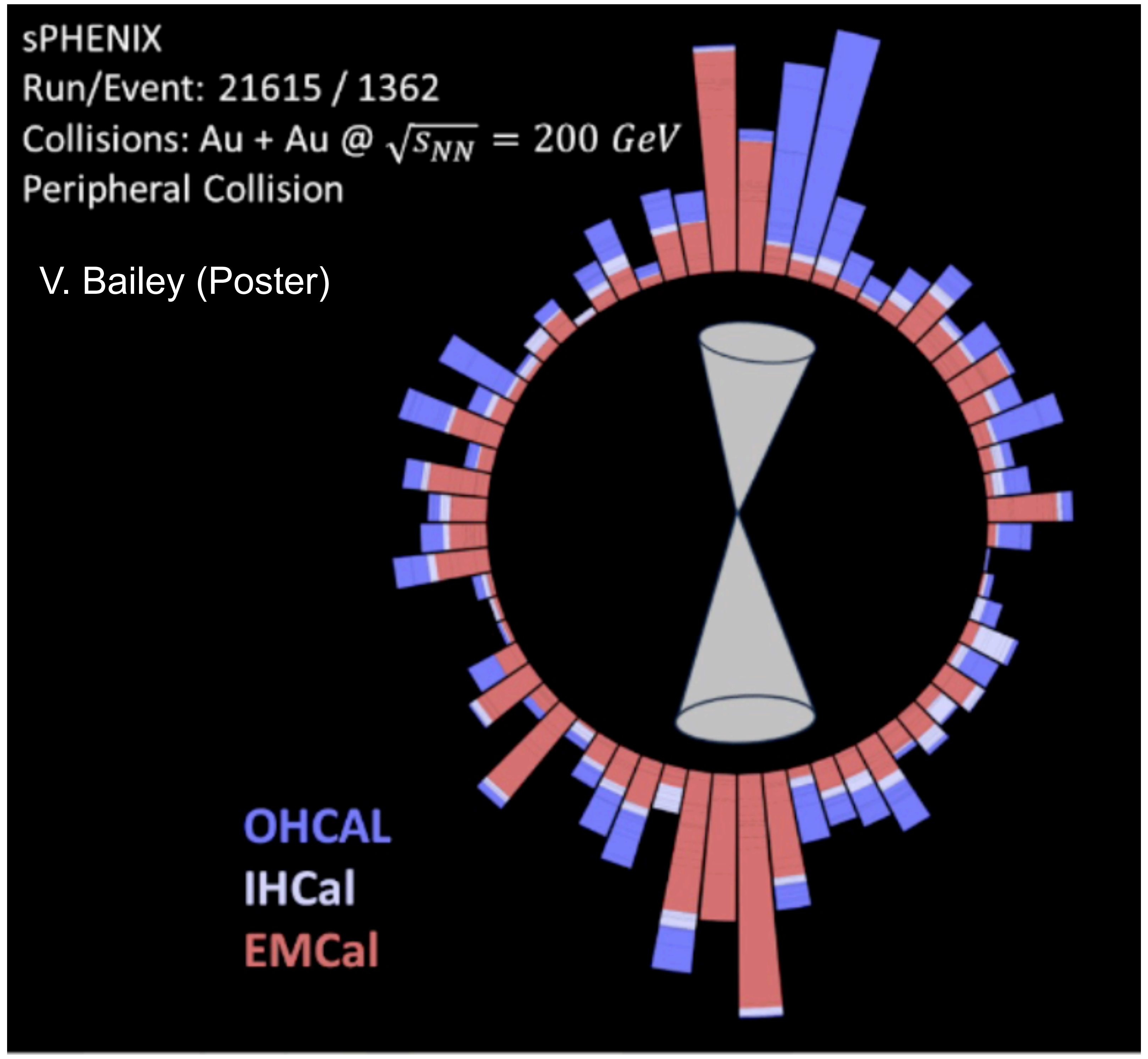
30 years LoI for ALICE submitted to CERN

20 years since FAIR CDR was approved

10 years since Electron-Ion Collider white paper - strictly speaking appeared arXiv in Dec 2012

0 years since sPHENIX ran for first time

First jets in sPHENX



From the NSAC LRP 2023 - released Oct 4

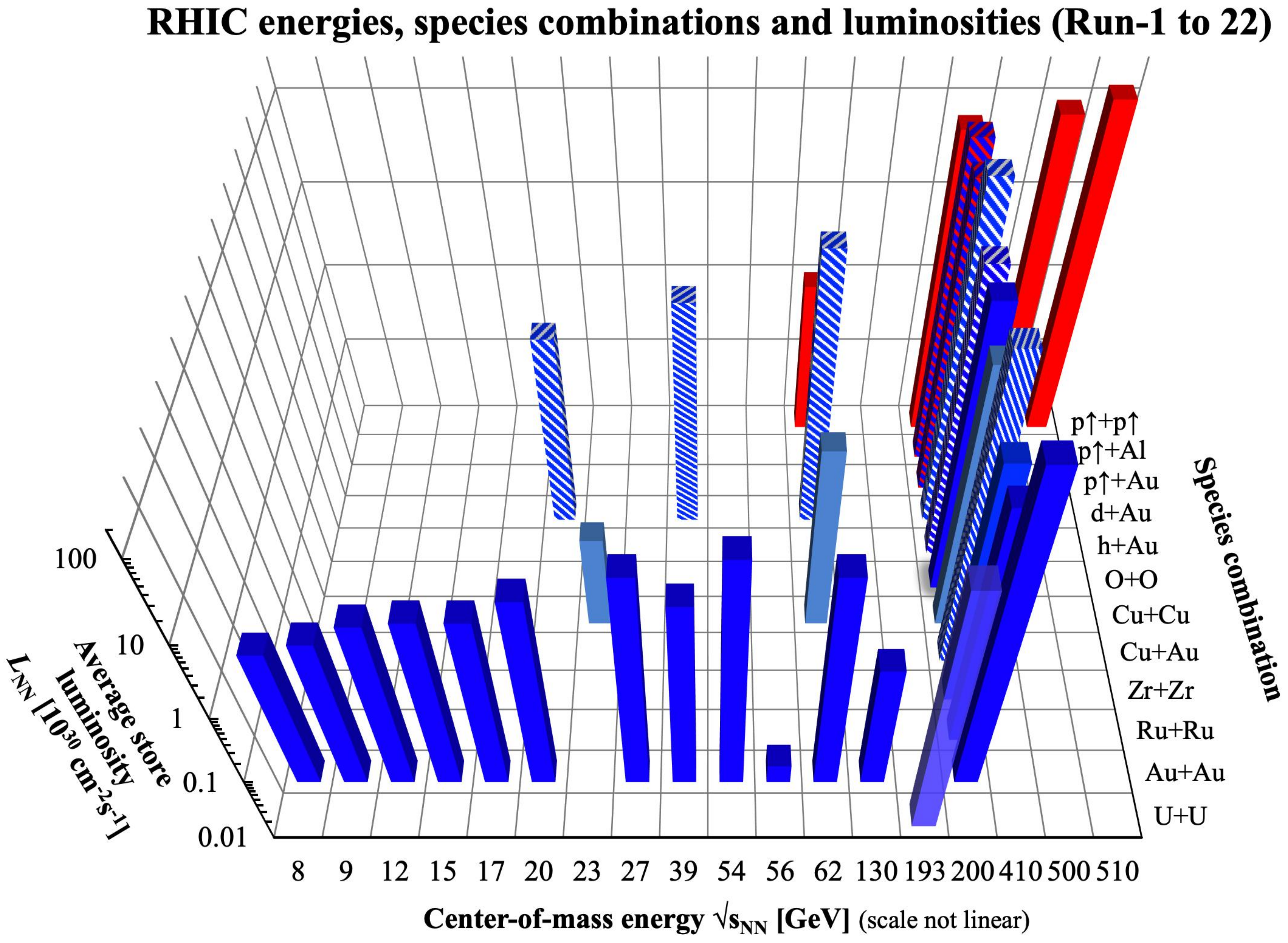
Recommendation 1: The highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments of the United States. We must draw on the talents of all in the nation to achieve this goal.

This recommendation requires….completing the RHIC science program, pushing the frontiers of human knowledge.

Recommendation 3: We recommend the expeditious completion of the EIC as the highest priority for facility construction.

Strategic opportunities exist to realize a range of projects that lay the foundation for the discovery science of tomorrow. These projects include … targeted upgrades for the LHC heavy ion program,…

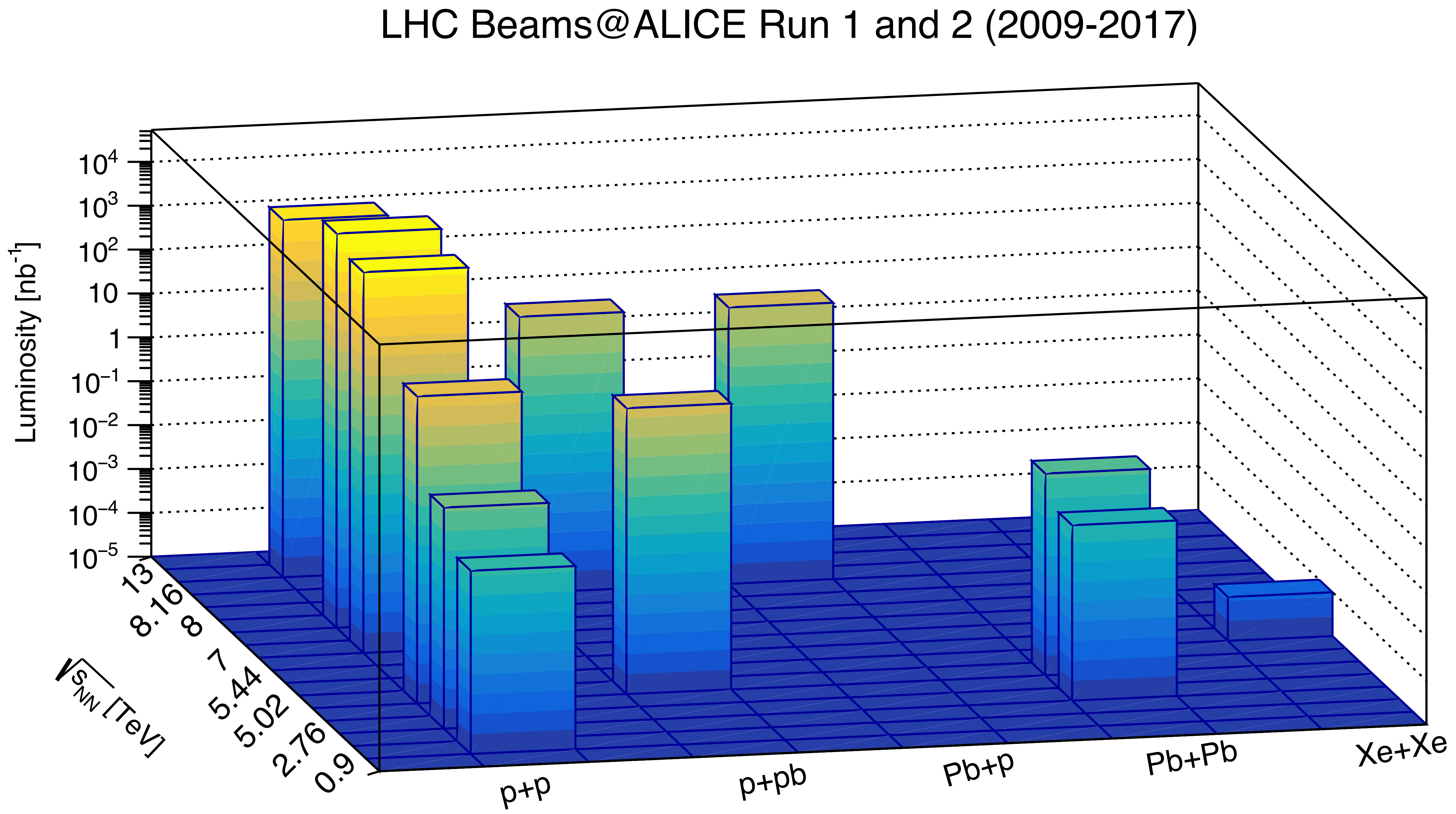
Wealth of datasets available



RHIC:

U+U, Au-Au, Ru+Ru, Zr+Zr, Cu+Cu, O+O, Cu+Au, He3+Au, d+Au, p+Au, p+Al, p+p

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



LHC:

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

For Pb+Pb mostly at 5.02 TeV

HUGE datasets

(significantly bigger at ATLAS and CMS)

Much of this data is not yet completely mined

Hot QCD: 6 Opportunities

1) Can We Understand the Phase Transition to QGP and EOS?

2) Can We Detect the Initial Conditions (EM Field and Temperature)?

3) Can We Understand the Nature of Parton Energy Loss to QGP?

4) Can We Understand Small Systems?

5) Can We Understand Nuclear/Hadron Structure?

6) Can We Detect New Physics Via UPC?

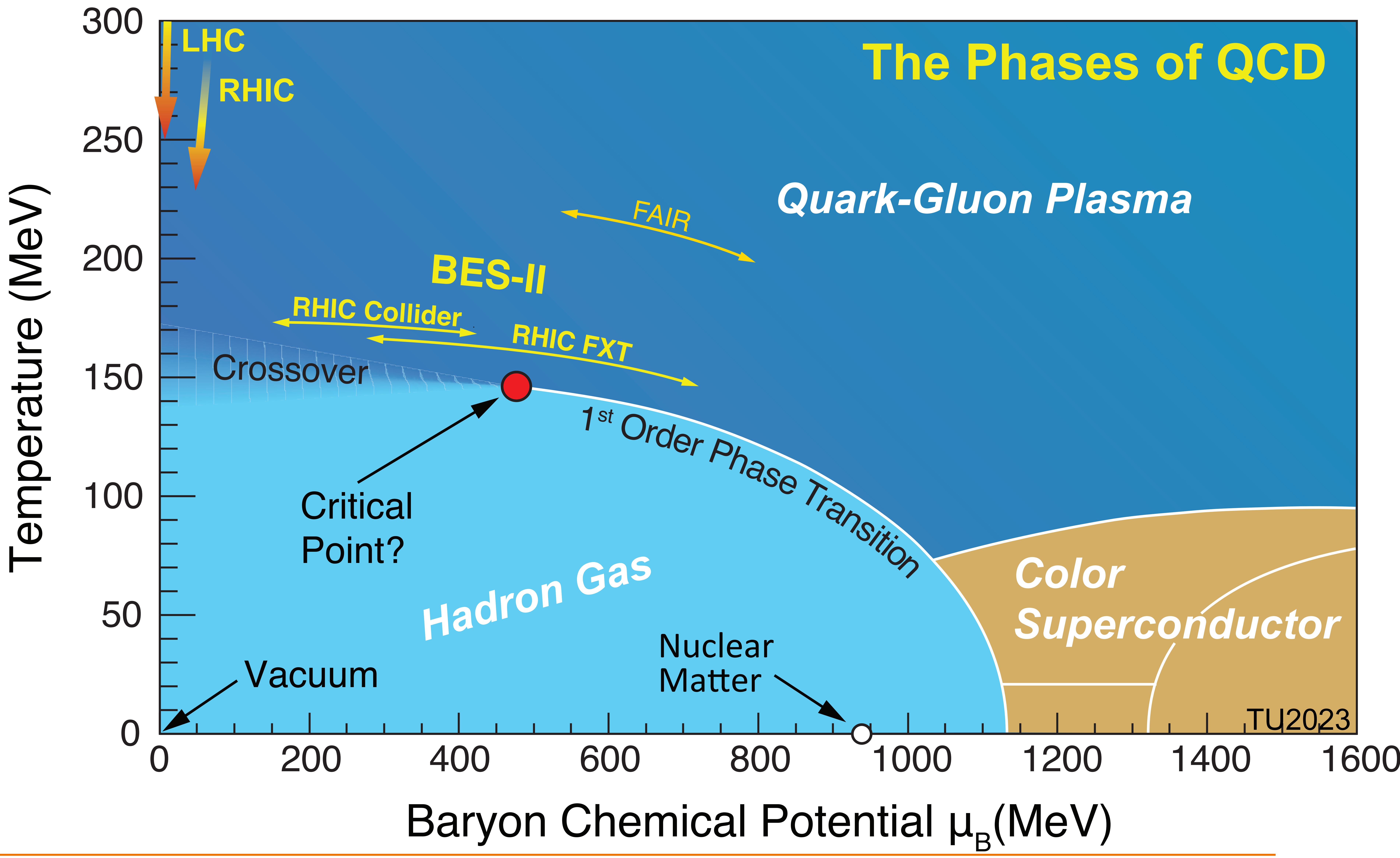
Names in footer indicate a presenter at QM23.
Review their presentations for more information

Can We Understand the Phase Transition to QGP and EOS?

The phase diagram - Theory input

Cross-over at low μ_B

Significant progress in extrapolating off $\mu_B = 0$ axis



A. Pasztor, V. Vovchenko

The phase diagram - Theory input

Cross-over at low μ_B

Significant progress in extrapolating off $\mu_B = 0$ axis

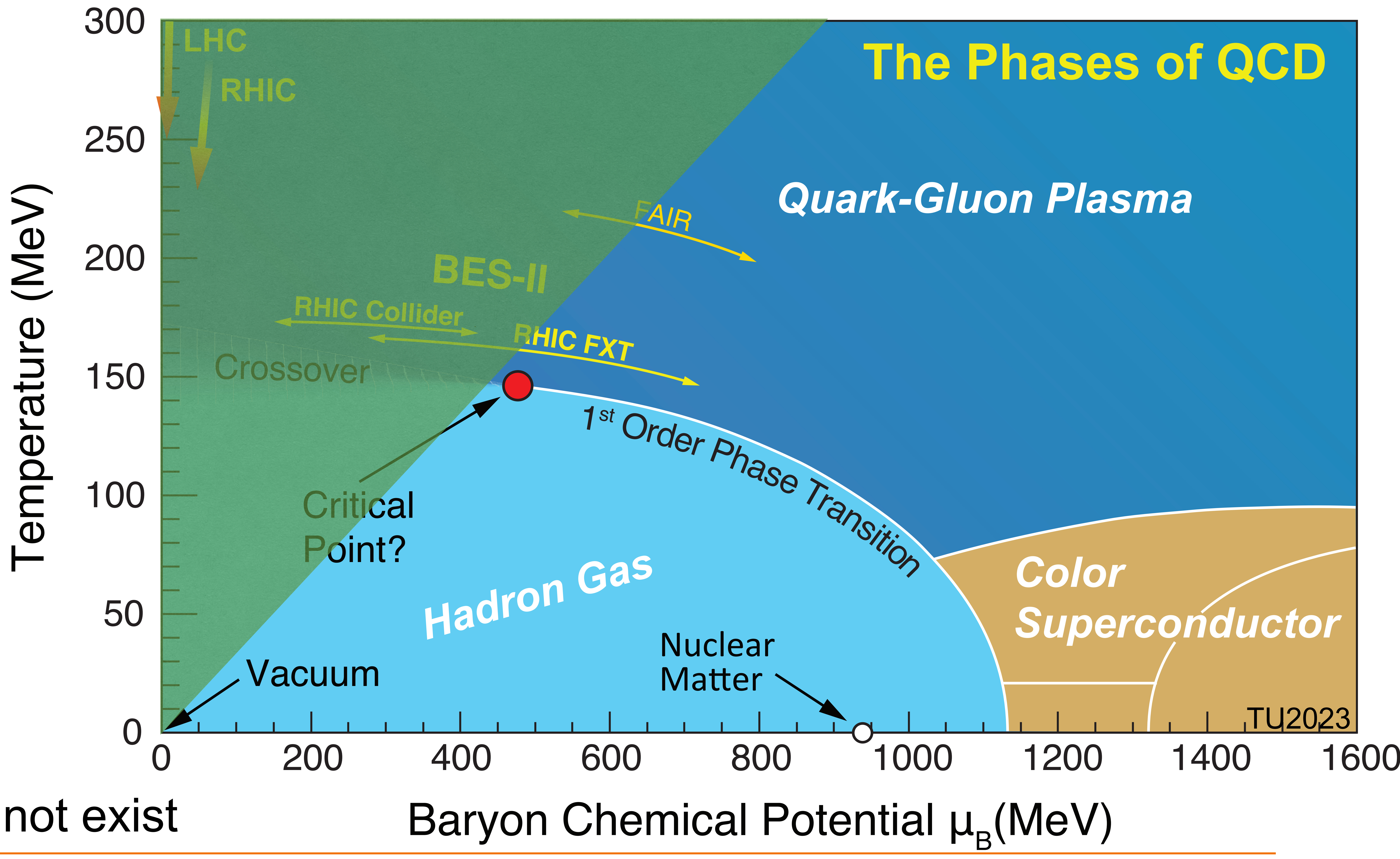
Disfavor QCD critical point at $\mu_B/T < 3$

Several calculations settling on CP at

T~90-100 MeV
μ_B~500-600 MeV

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

But still CP might also not exist



A. Pasztor, V. Vovchenko

Moving around the phase diagram

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 / 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

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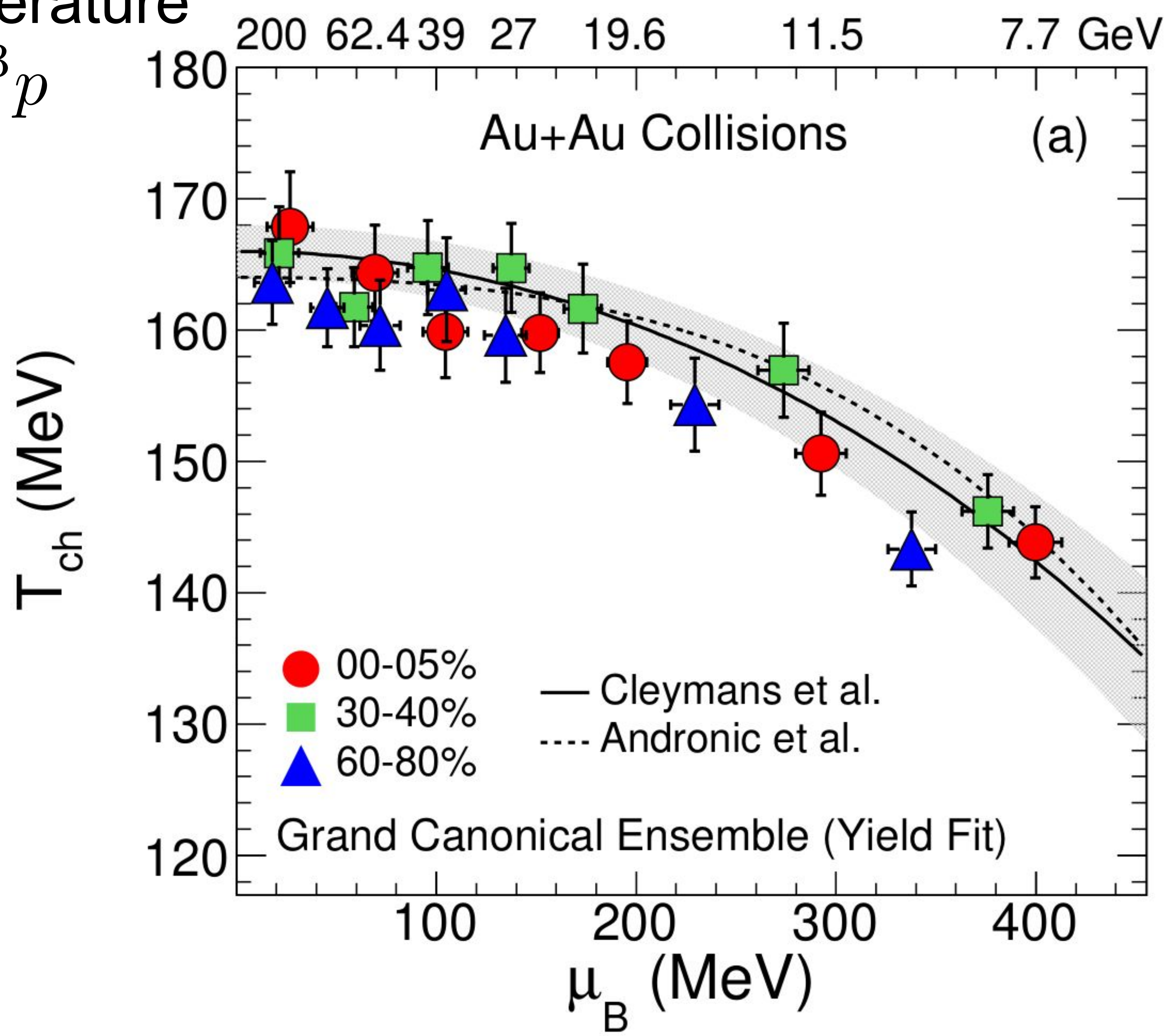
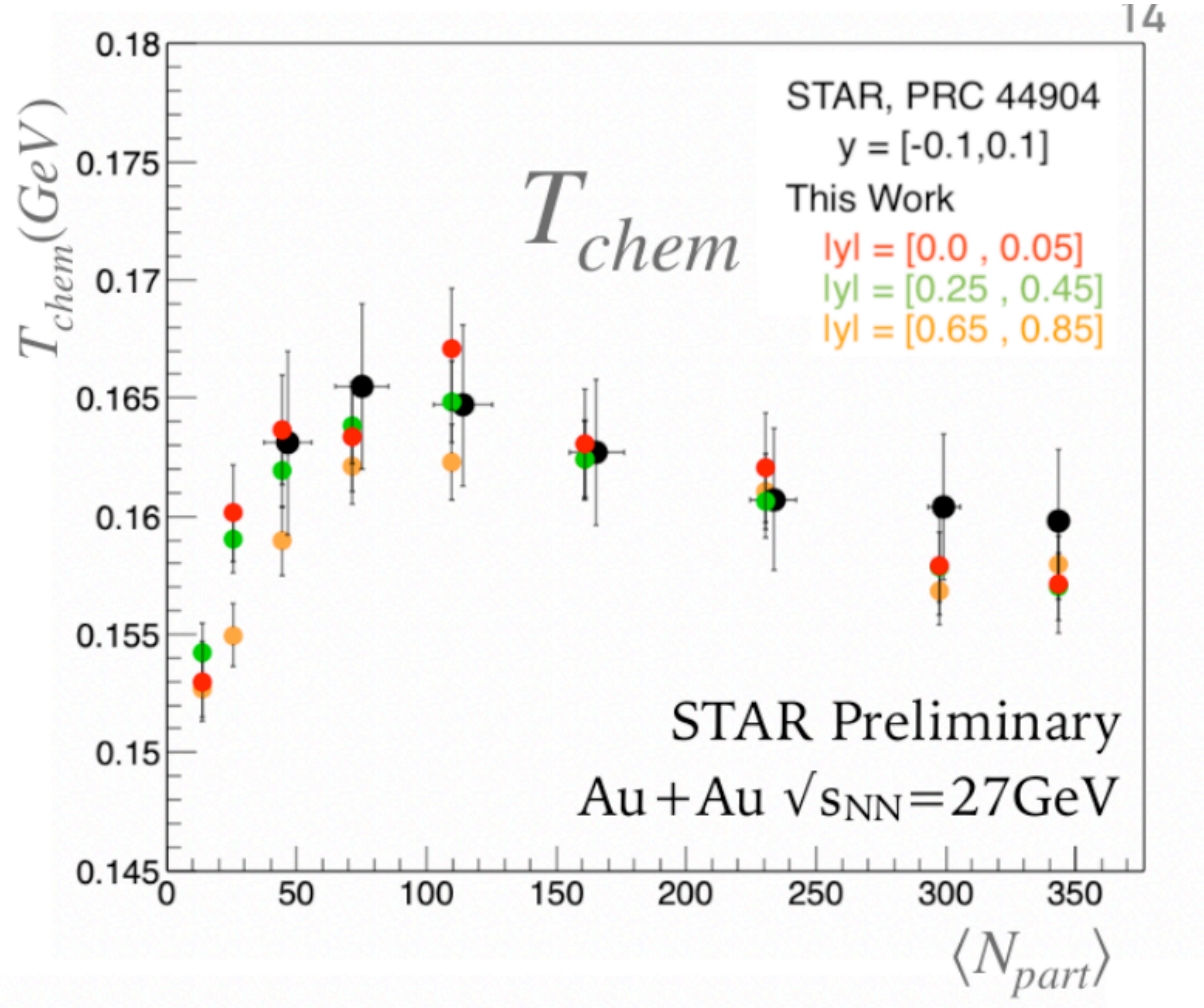
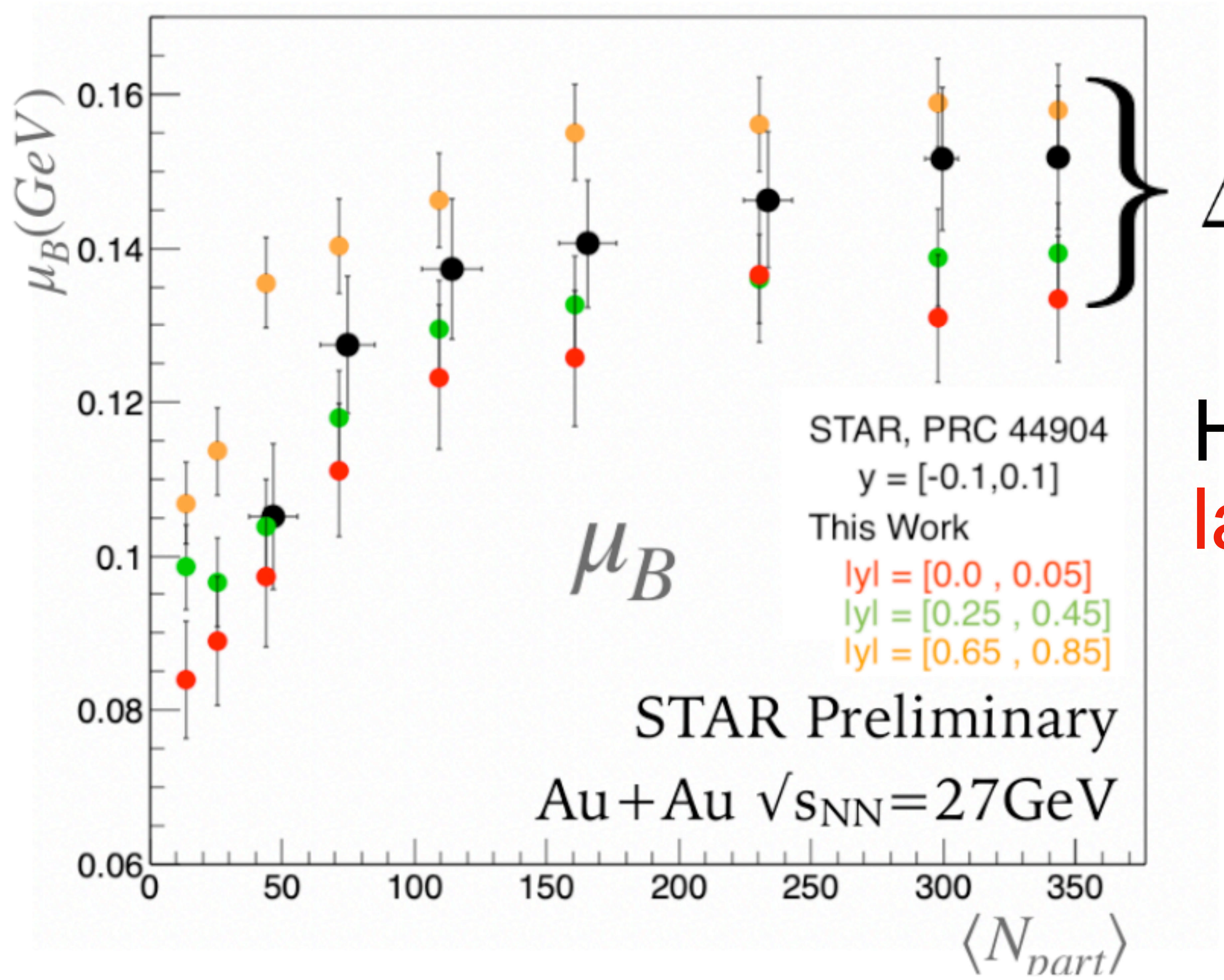


Chemical Freeze-out temperature T_{ch} close to that of T_{pc} at top energies

Varying trajectory through the phase diagram?

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





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?

Searching for CP

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

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

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

δN = N - ⟨N⟩

Experiment measure event-by-event distribution of conserved quantities

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

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

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

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

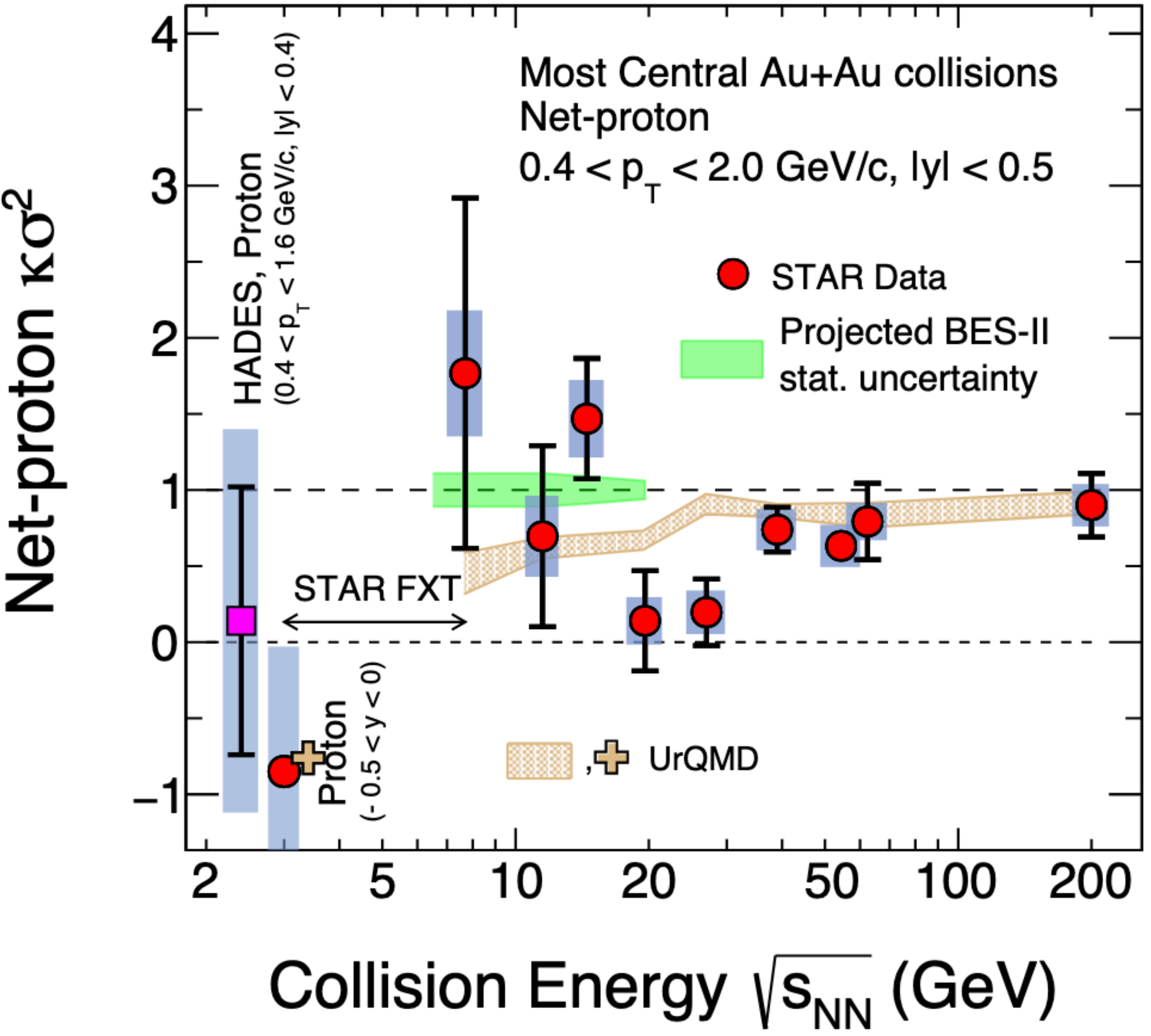
Focus on net-proton as proxy for net-baryon

Take ratios to remove volume and T dependence

$\kappa\sigma^2 = \chi4/\chi2$

M. Stephanov. PRL 107:052301(2011)

Hints of critical fluctuations



$\kappa\sigma^2$

Scan from BES-I, 3 GeV from BES-II

Strong suppression at $\sqrt{s_{NN}}$ = 3 GeV

consistent with UrQMD which has no CP

consistent baryon number conservation and volume fluctuations

Suggestive of predicted signature of CP

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

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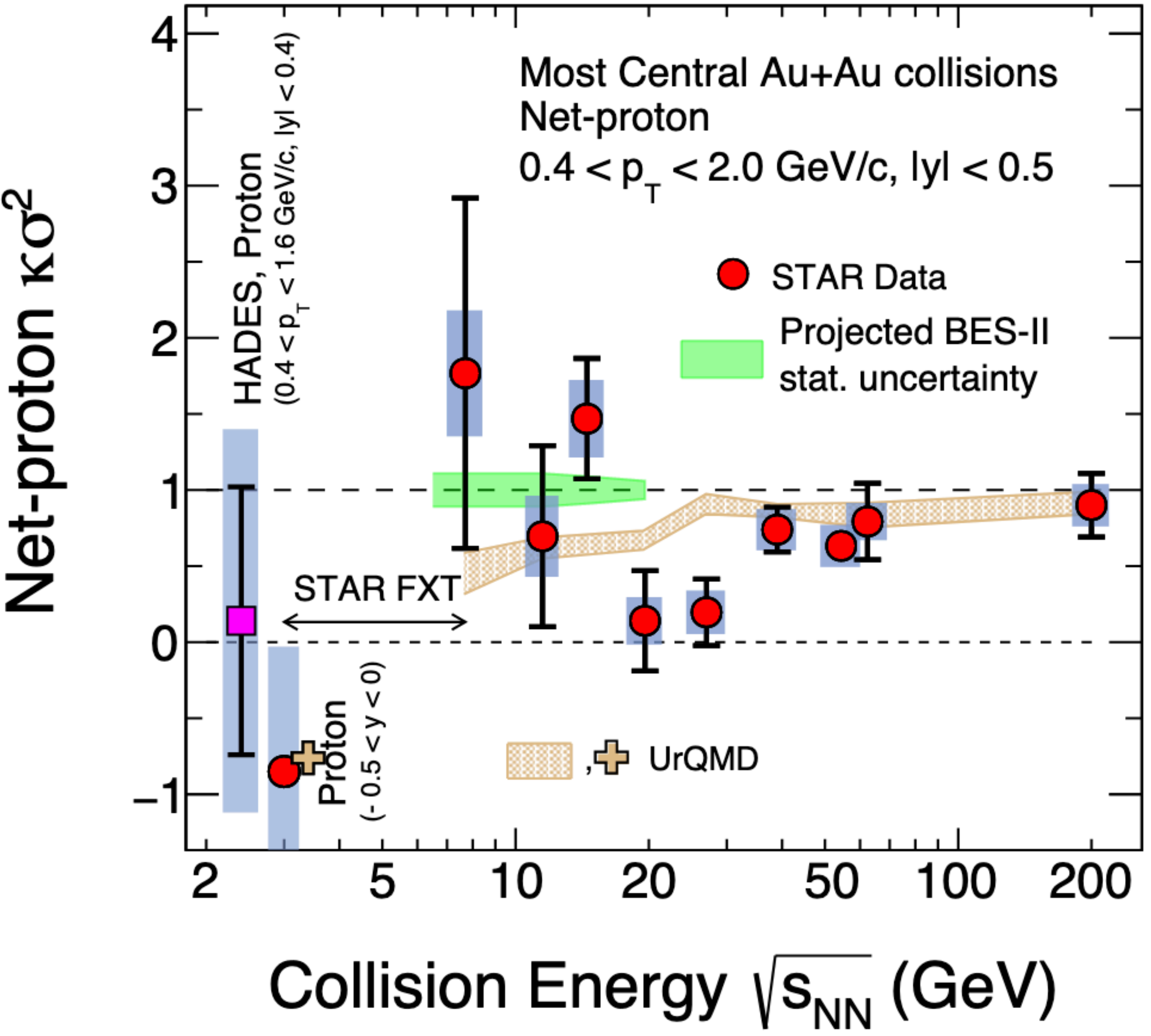

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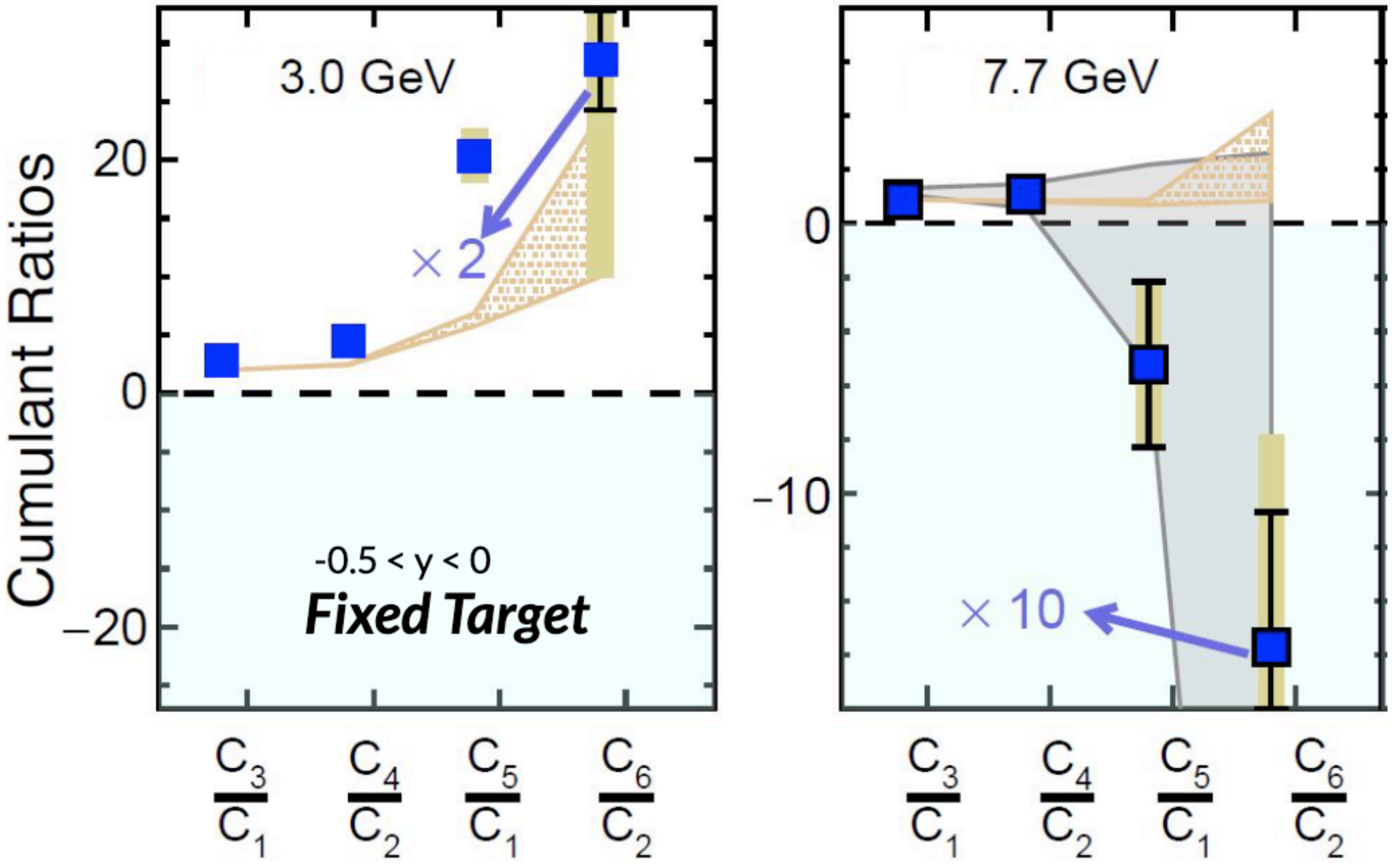

Cumulant ratios sensitive to nature of phase transition

$\sqrt{s_{NN}}$ =7.7-200 GeV: falling trend with rising order

- trend in agreement with Lattice with PT

$\sqrt{s_{NN}}$ = 3 GeV (FXT): rising trend with rising order

- trend in agreement with UrQMD no PT

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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

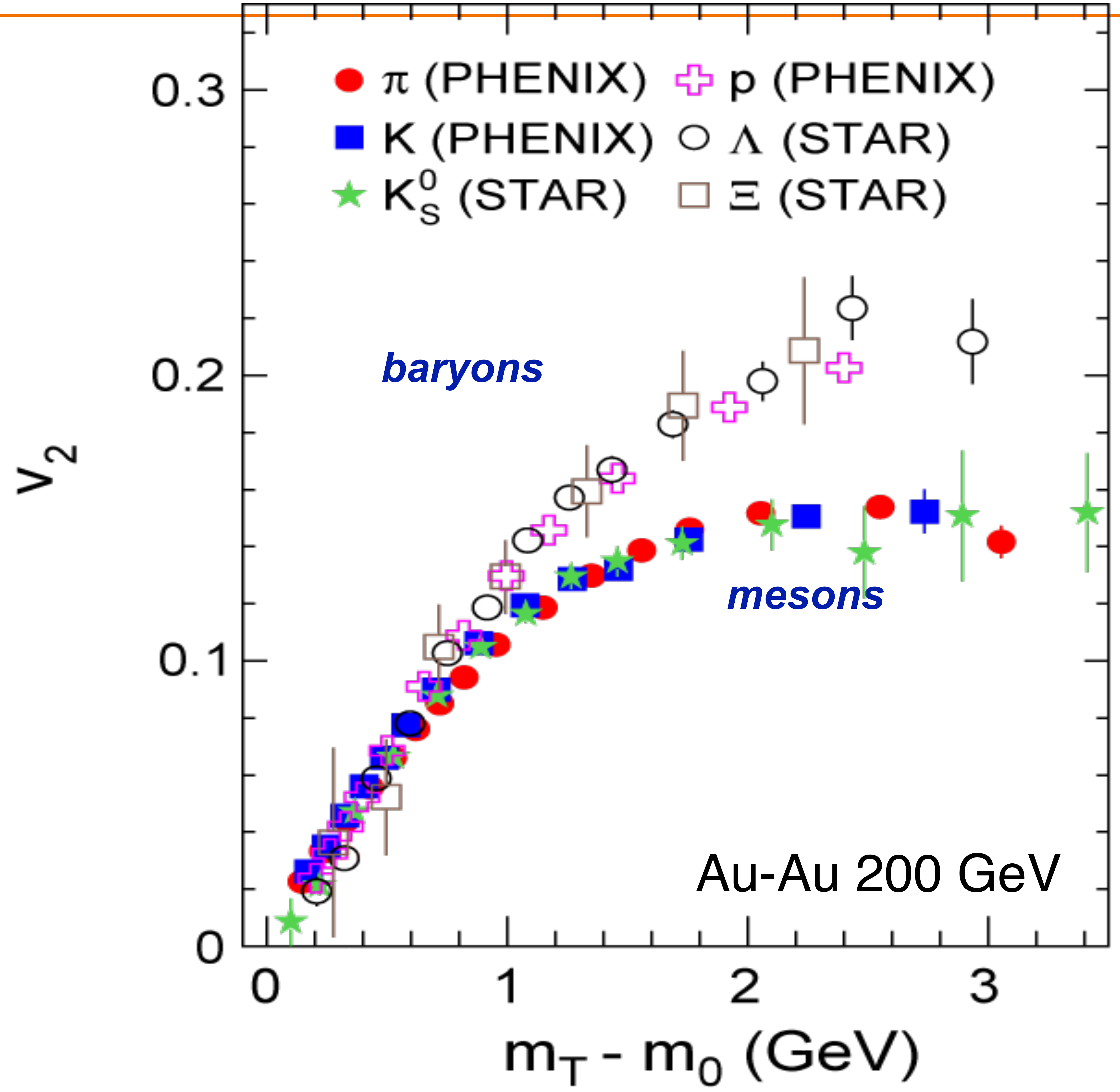
$$\frac{d^2N}{dp_T d\phi} \propto 1 + 2 v_2(p_T)\cos(2\phi)$$

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)



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

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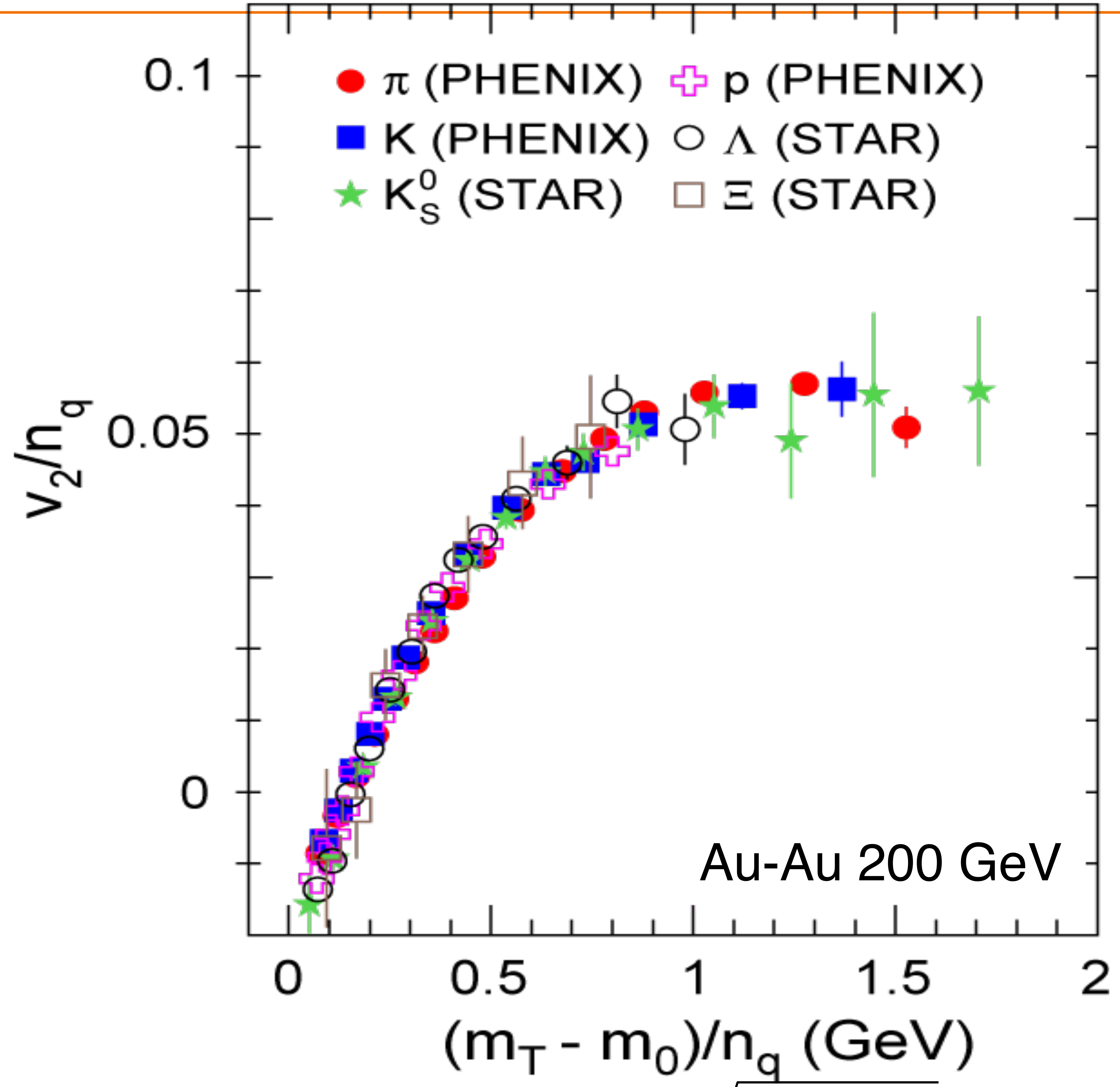


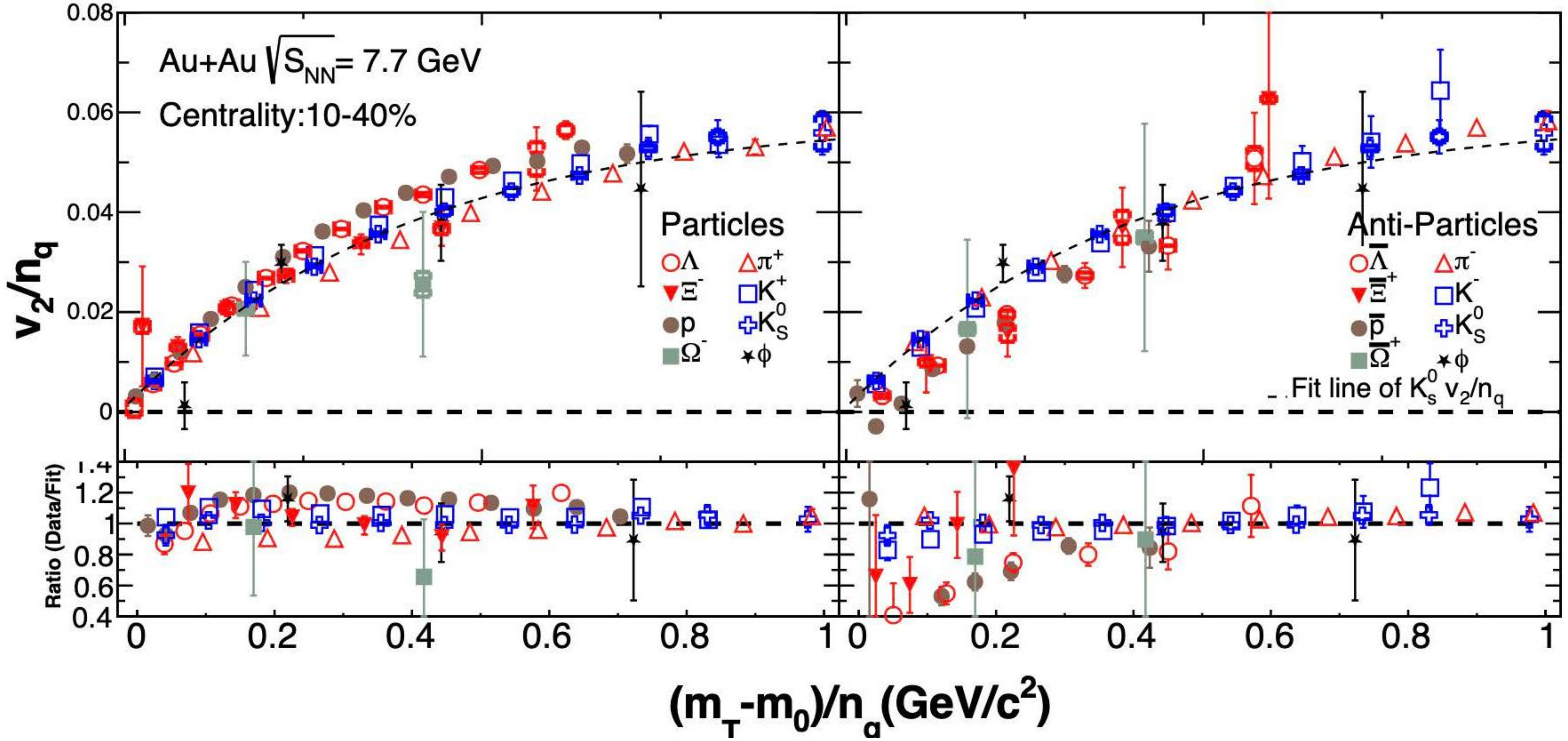
Works for p, π, K^0_s, Λ, Ξ..

$v_2^s \sim v_2^{u,d} \sim 7\%$

Constituents of QGP are partons

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

NCQ of elliptic flow



Using BES-II data high precision now available for multi-strange

NCQ scaling holds at $\sqrt{s_{NN}}$ = 7.7 GeV and above
Better for anti-particles (~10%) than particles (~20%)
Similar trends observations for v_3

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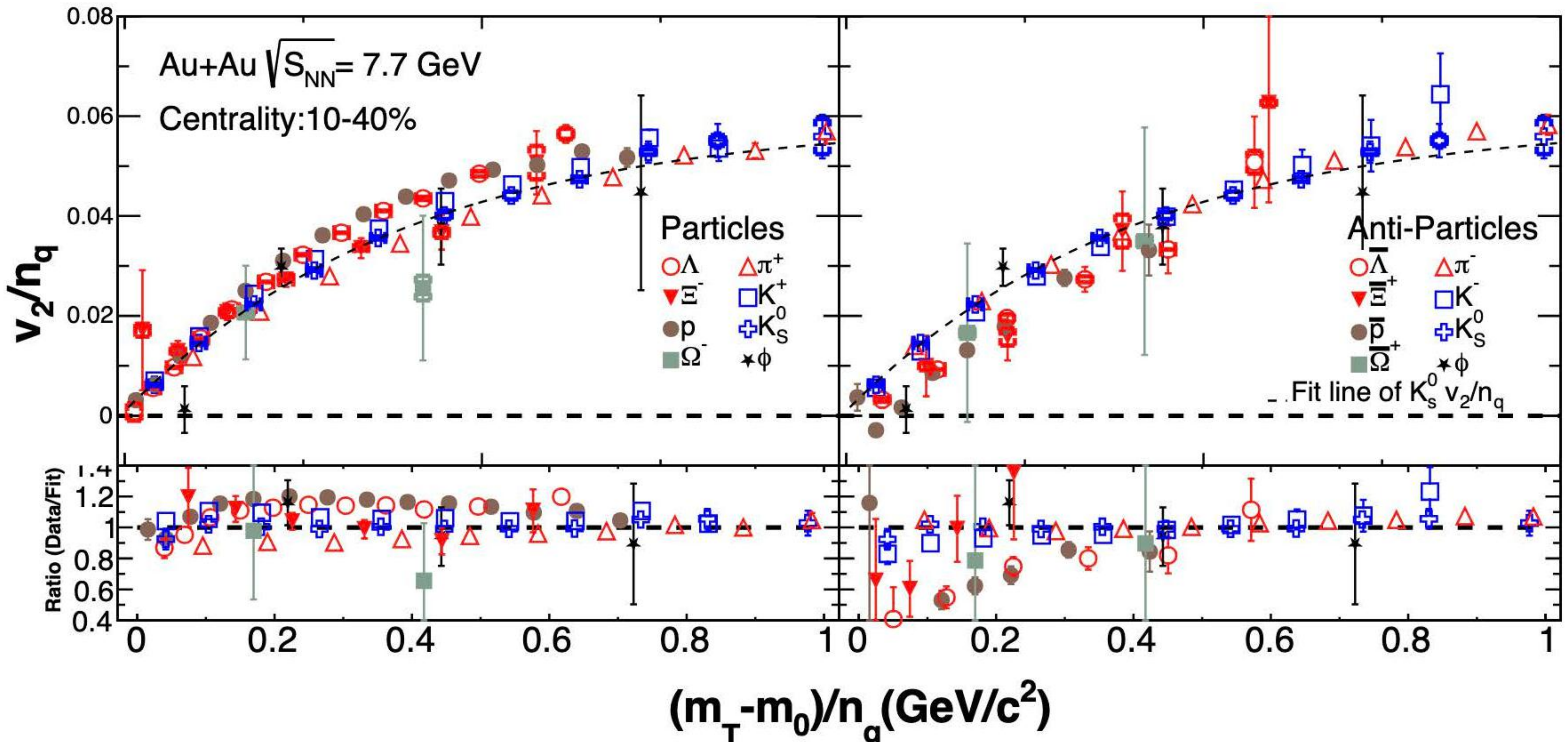

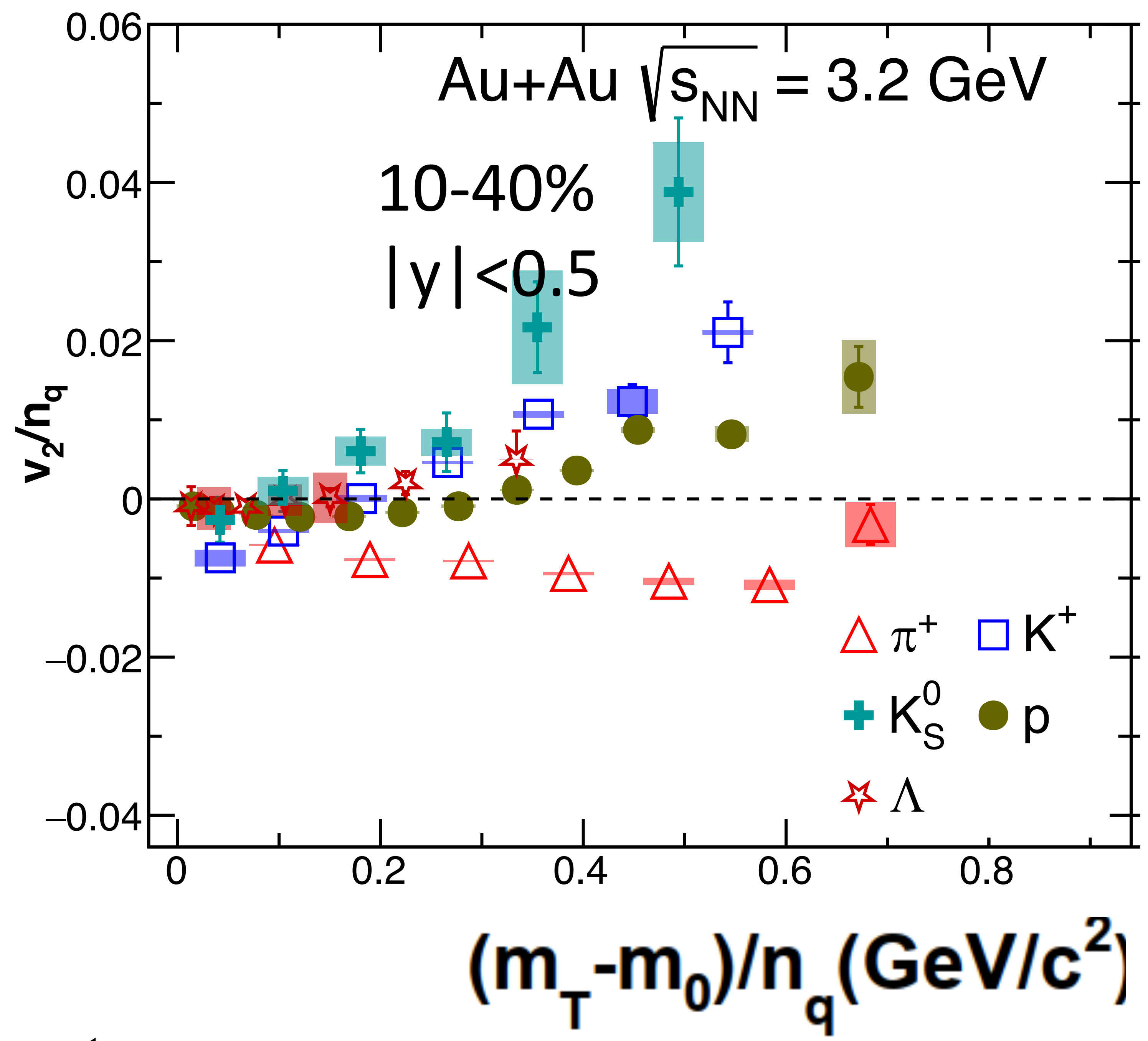

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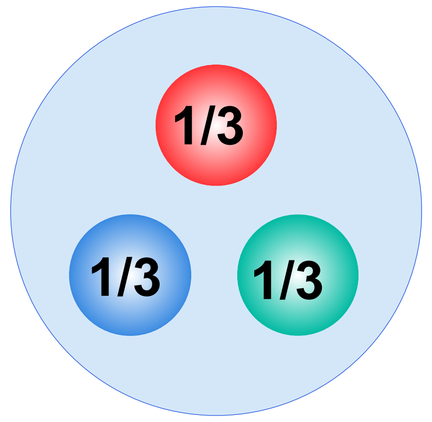
NCQ scaling fails at $\sqrt{s_{NN}}$ = 3.2 GeV and lower

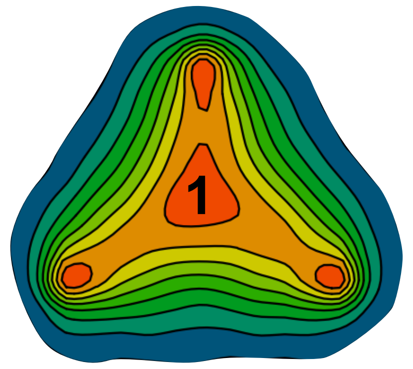
Partonic for $\sqrt{s_{NN}}$ = 7.7 and above

Hadron dominated below $\sqrt{s_{NN}}$ = 3.2

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

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

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

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

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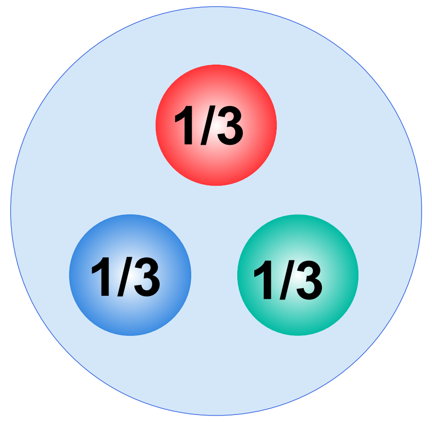

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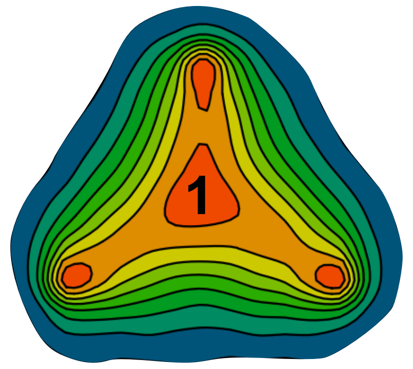

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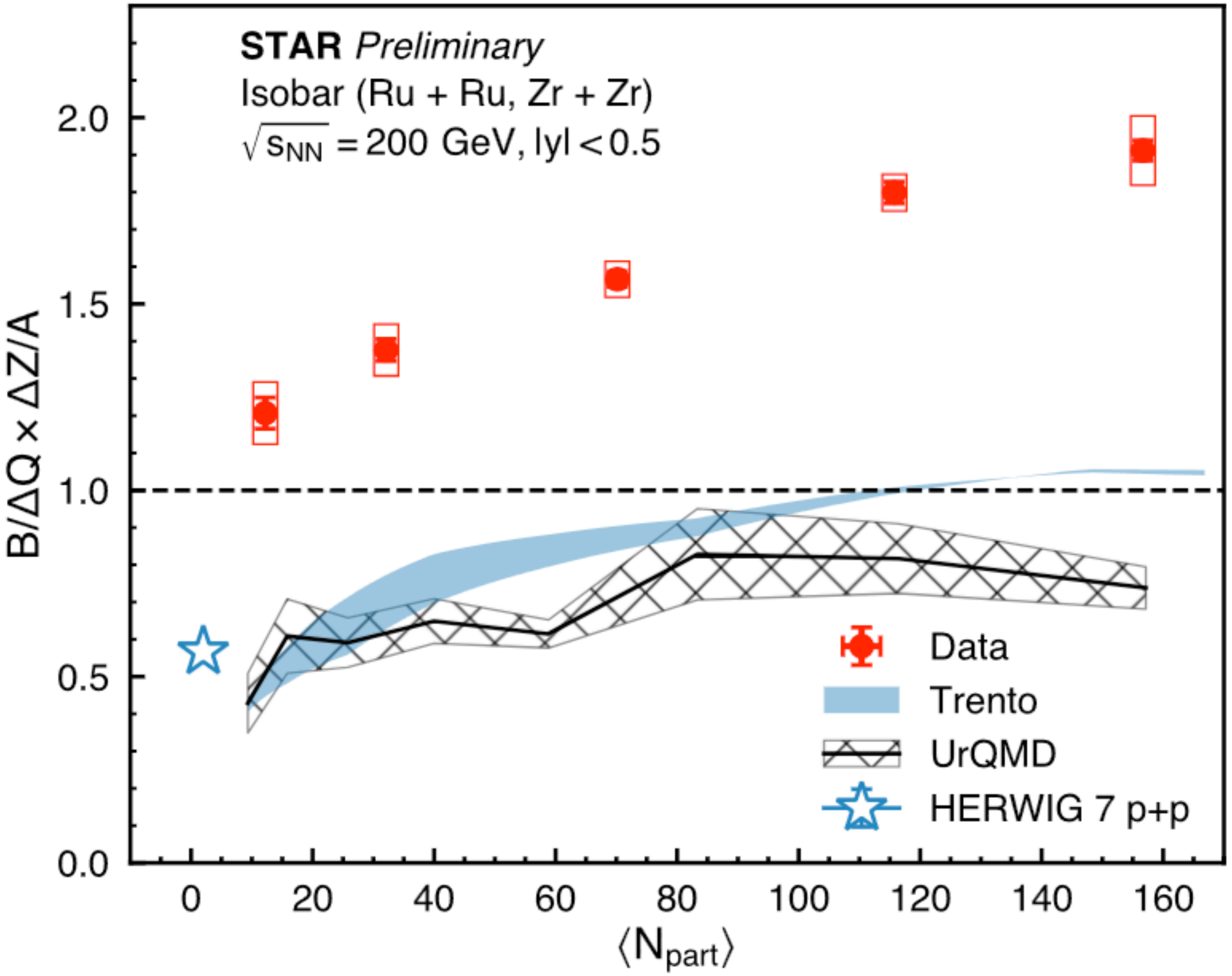


Data currently favor baryon junctions

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

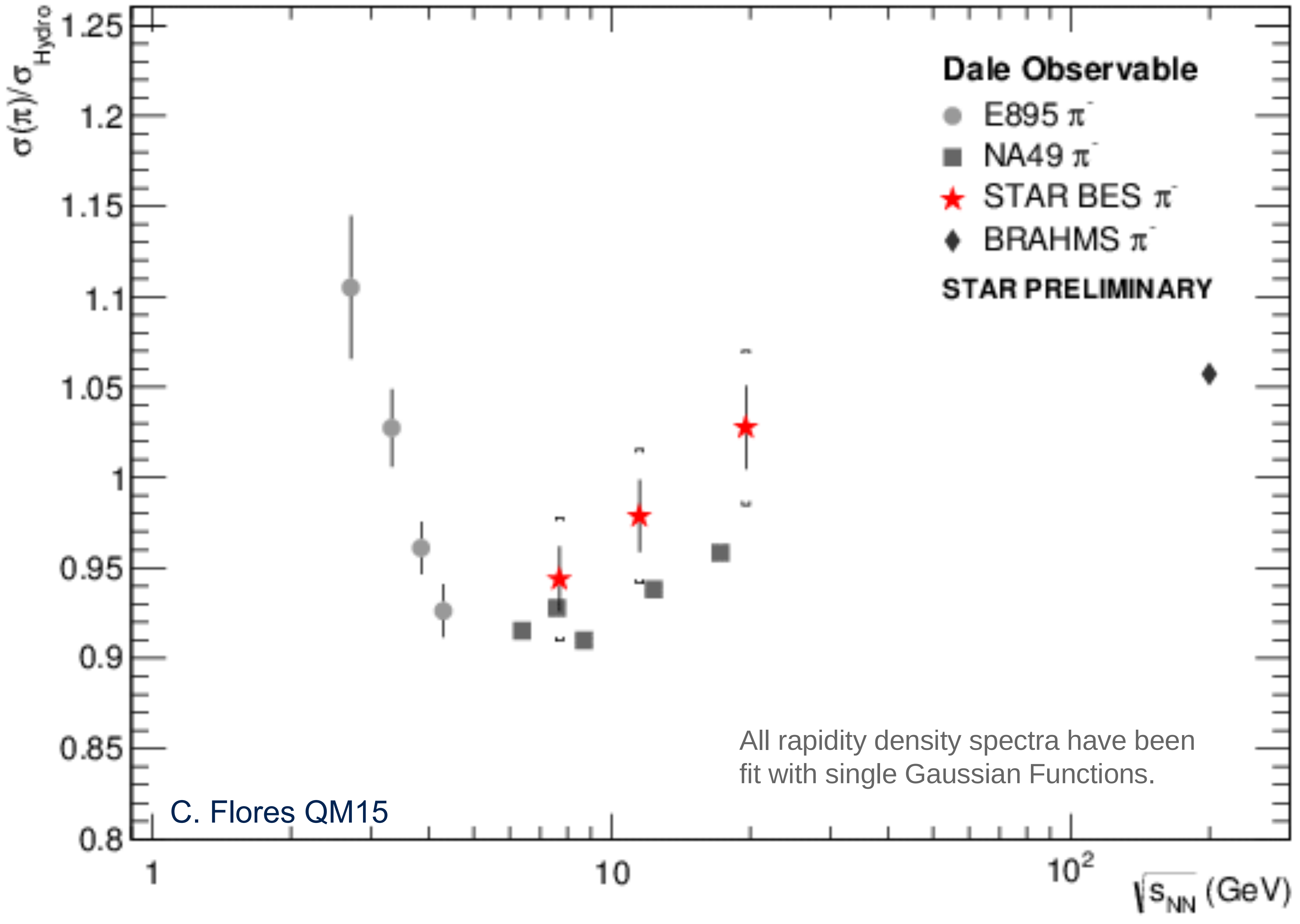
$$\frac{dn}{dy} = \frac{K s_{NN}^{1/4}}{\sqrt{2\pi\sigma_y^2}} e^{-\frac{y^2}{2\sigma_y^2}} \qquad \sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln\left(\frac{\sqrt{s}}{2m_N}\right)$$

Minimum observed at √s = ~7 GeV

Minimum in the speed of sound?

$c_s^2 \sim 0.26$

Indication of softening of EoS?



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

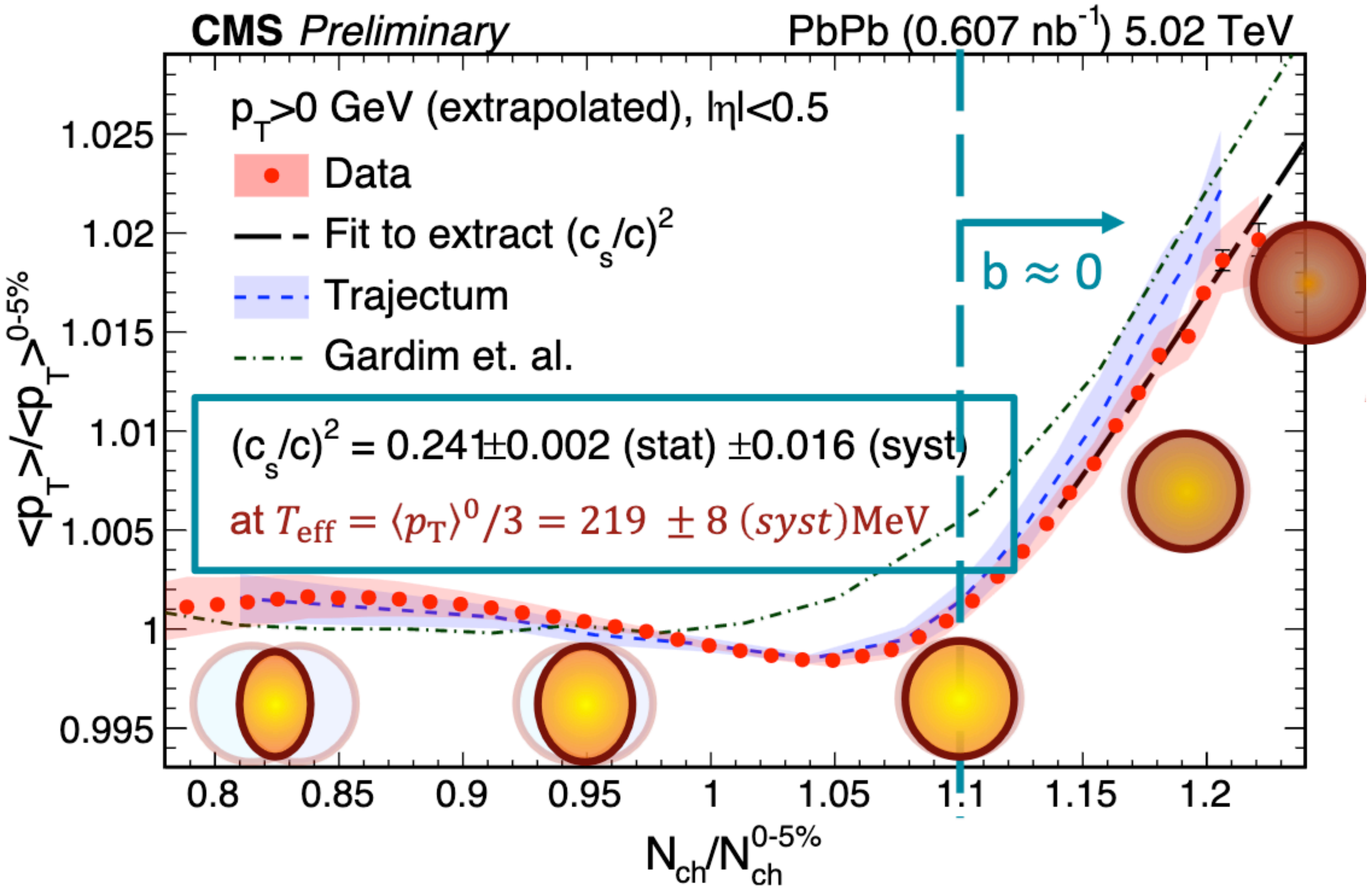
Confirm c_s in other ways?

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



C. Bernardes

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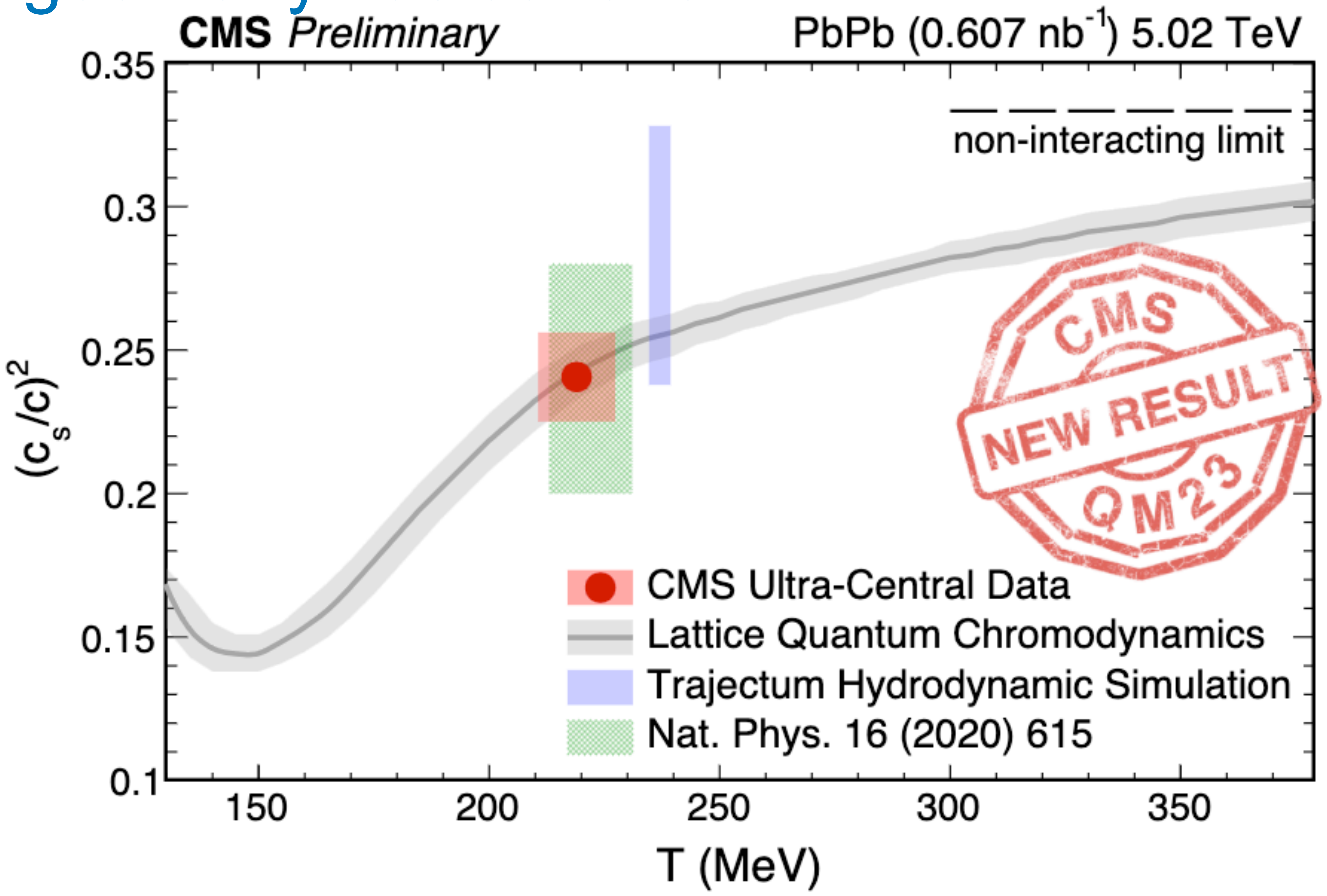
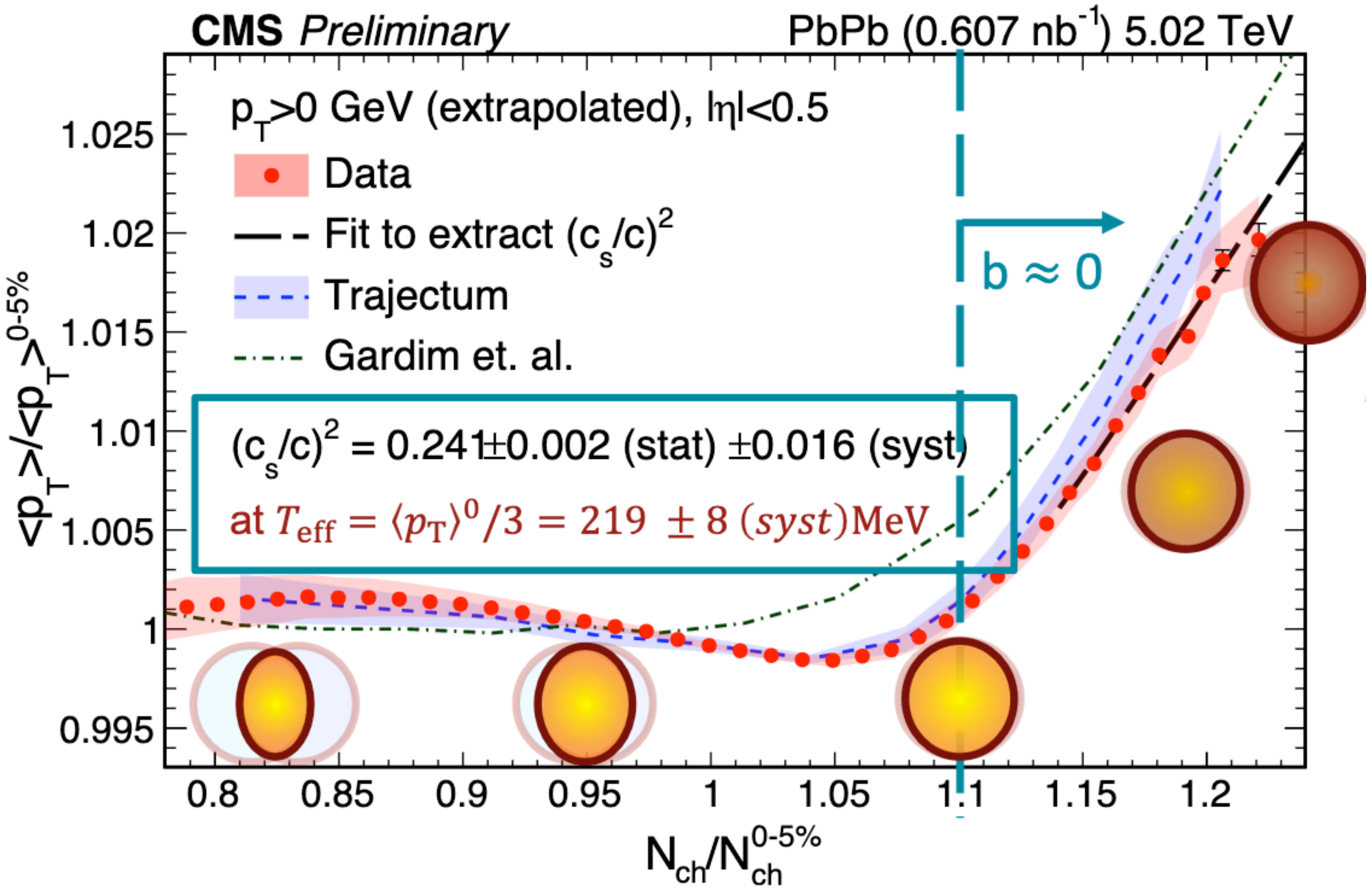




Too good to be true?

Up to the field to run with this

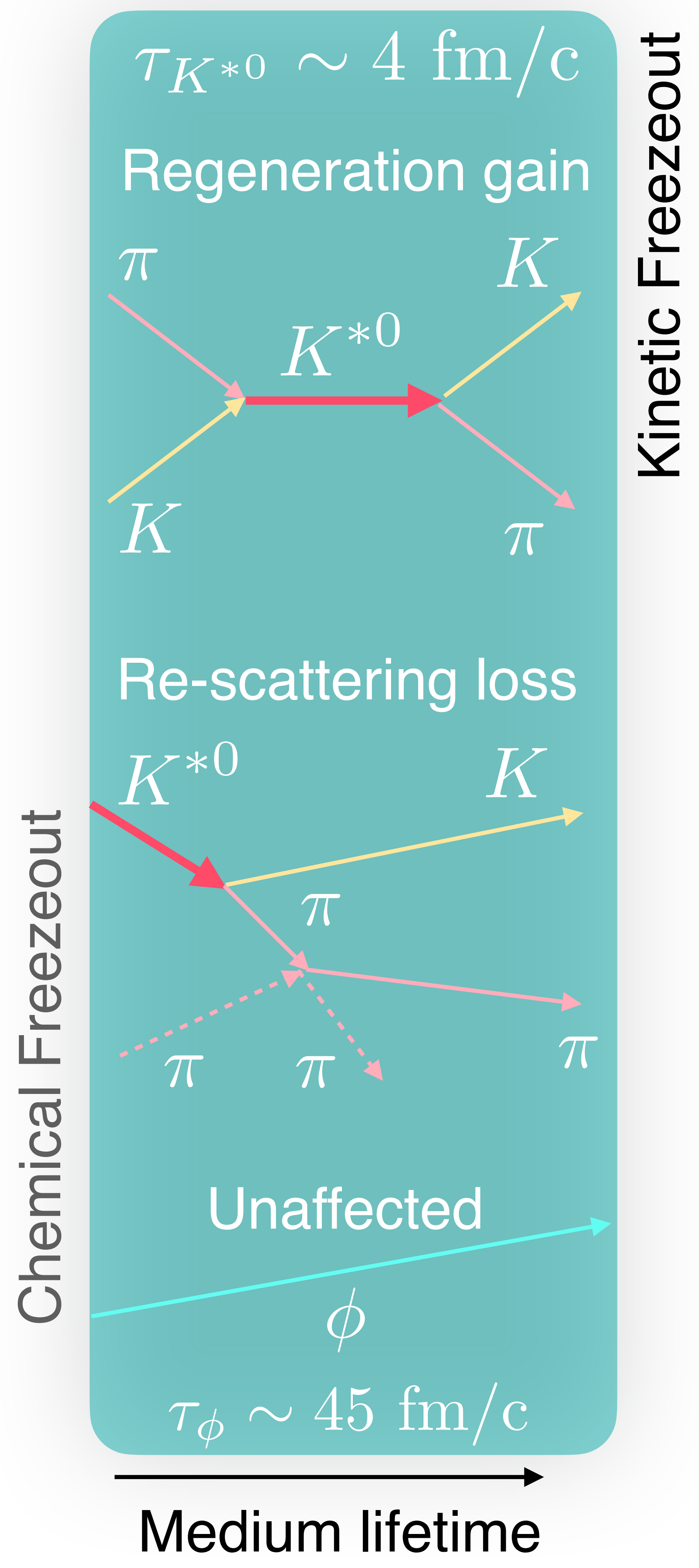
ALICE: Less p_T extrapolation

Does particle species matter?

What about other systems?

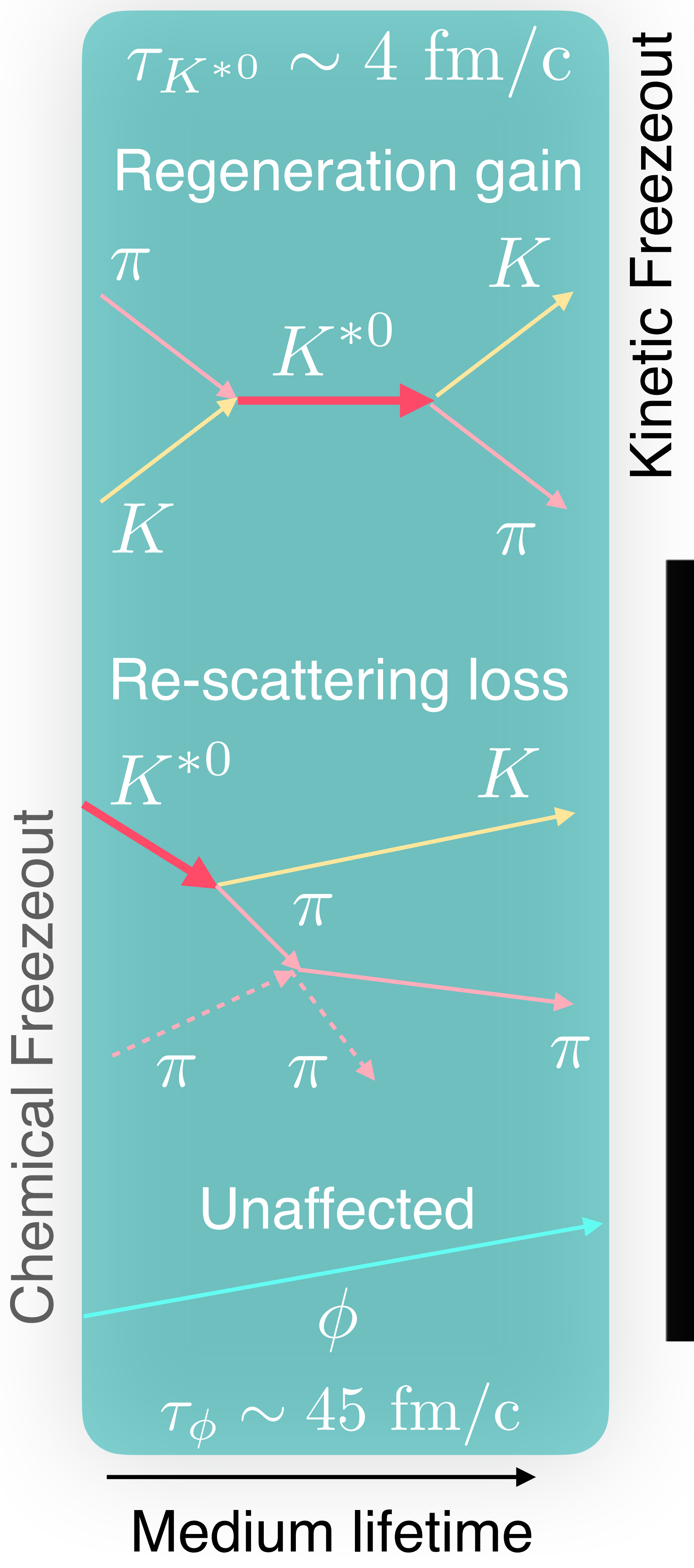
C. Bernardes

Strange resonance production



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

Strange resonance production



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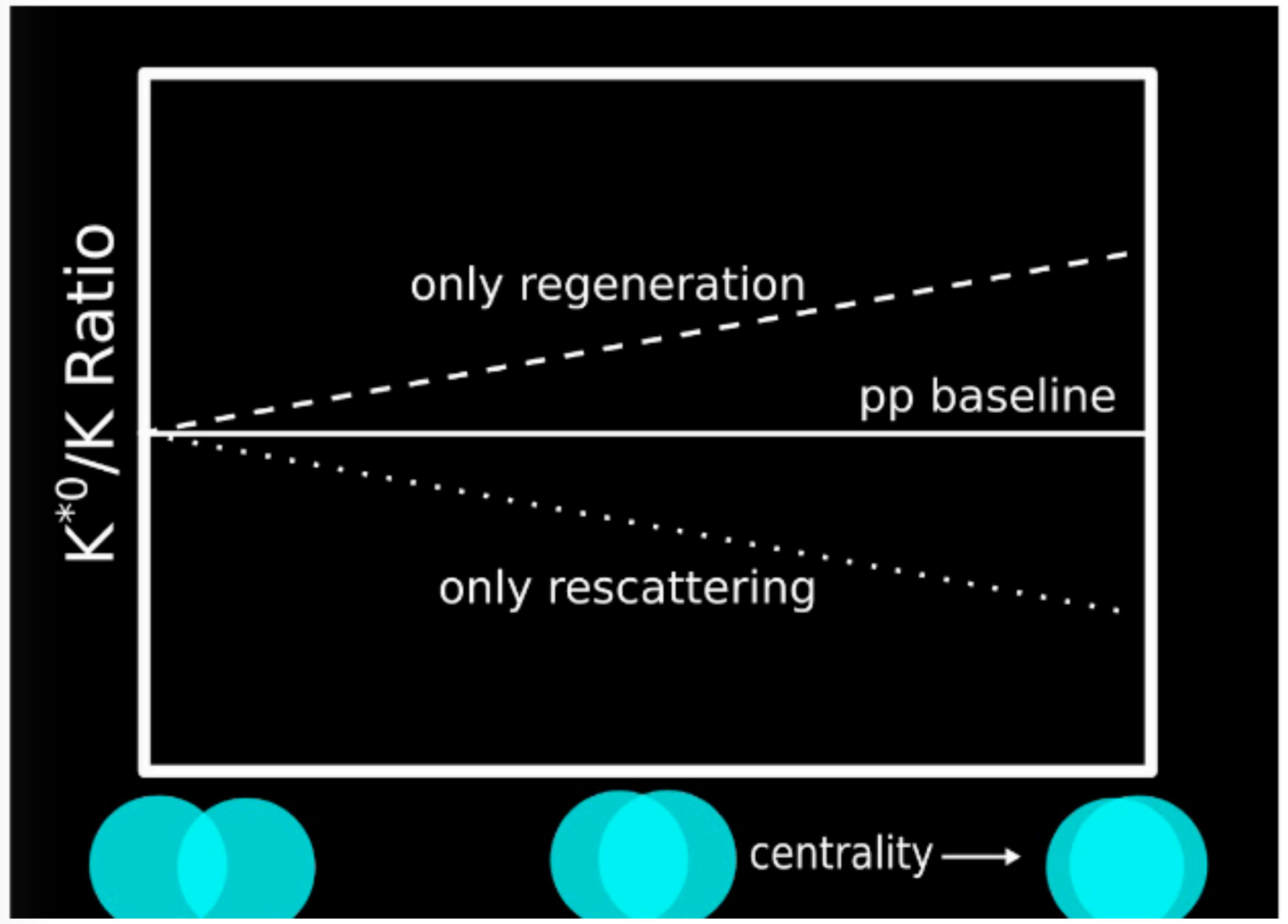

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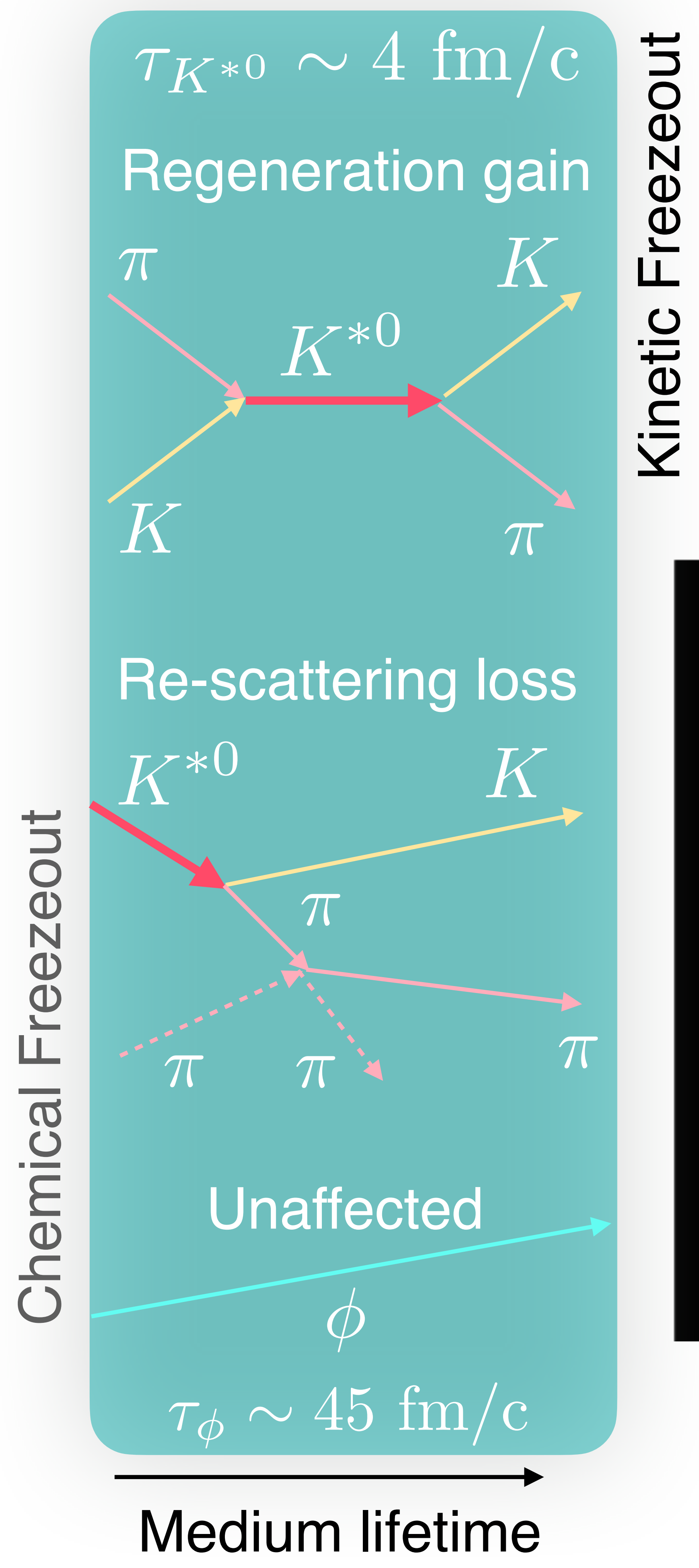

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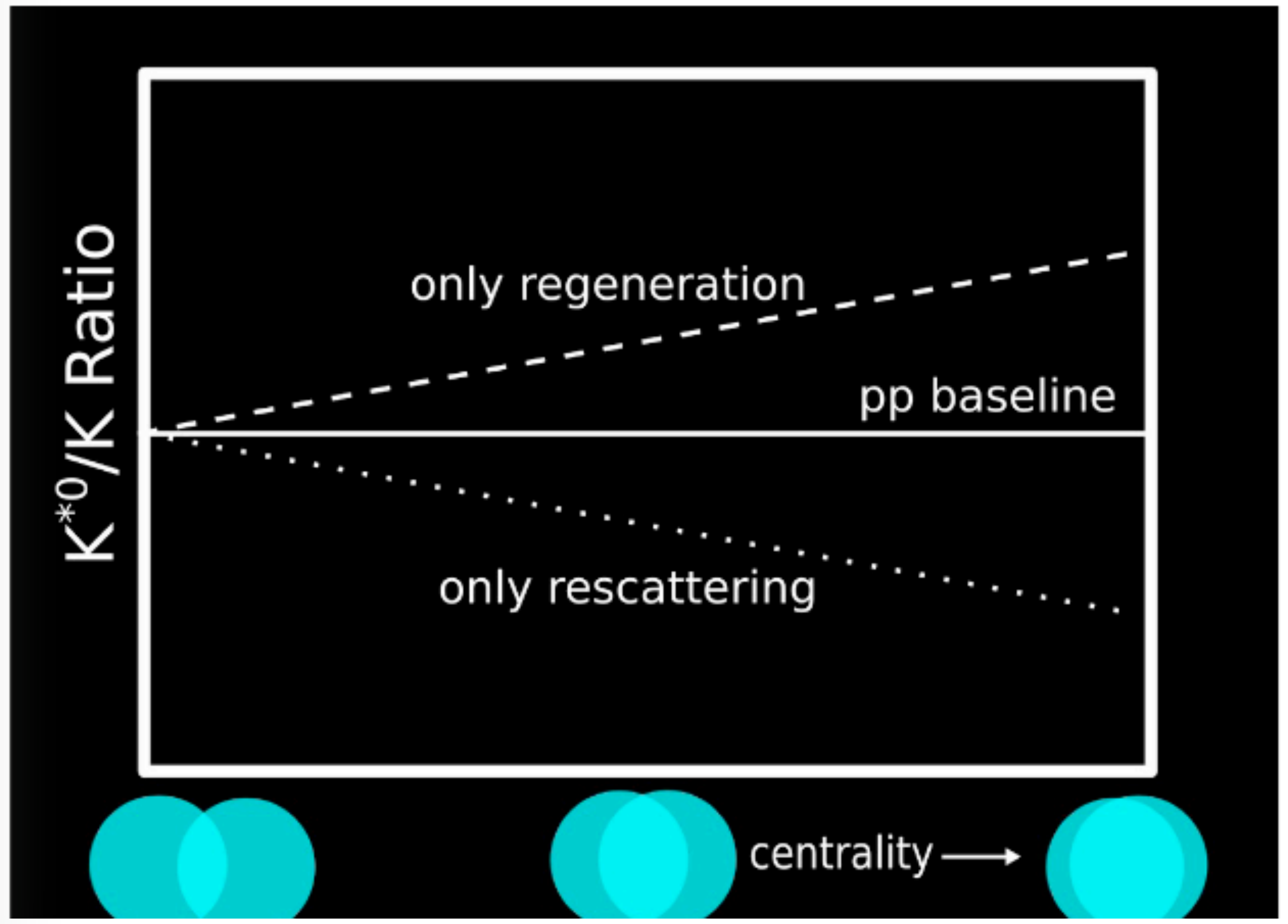

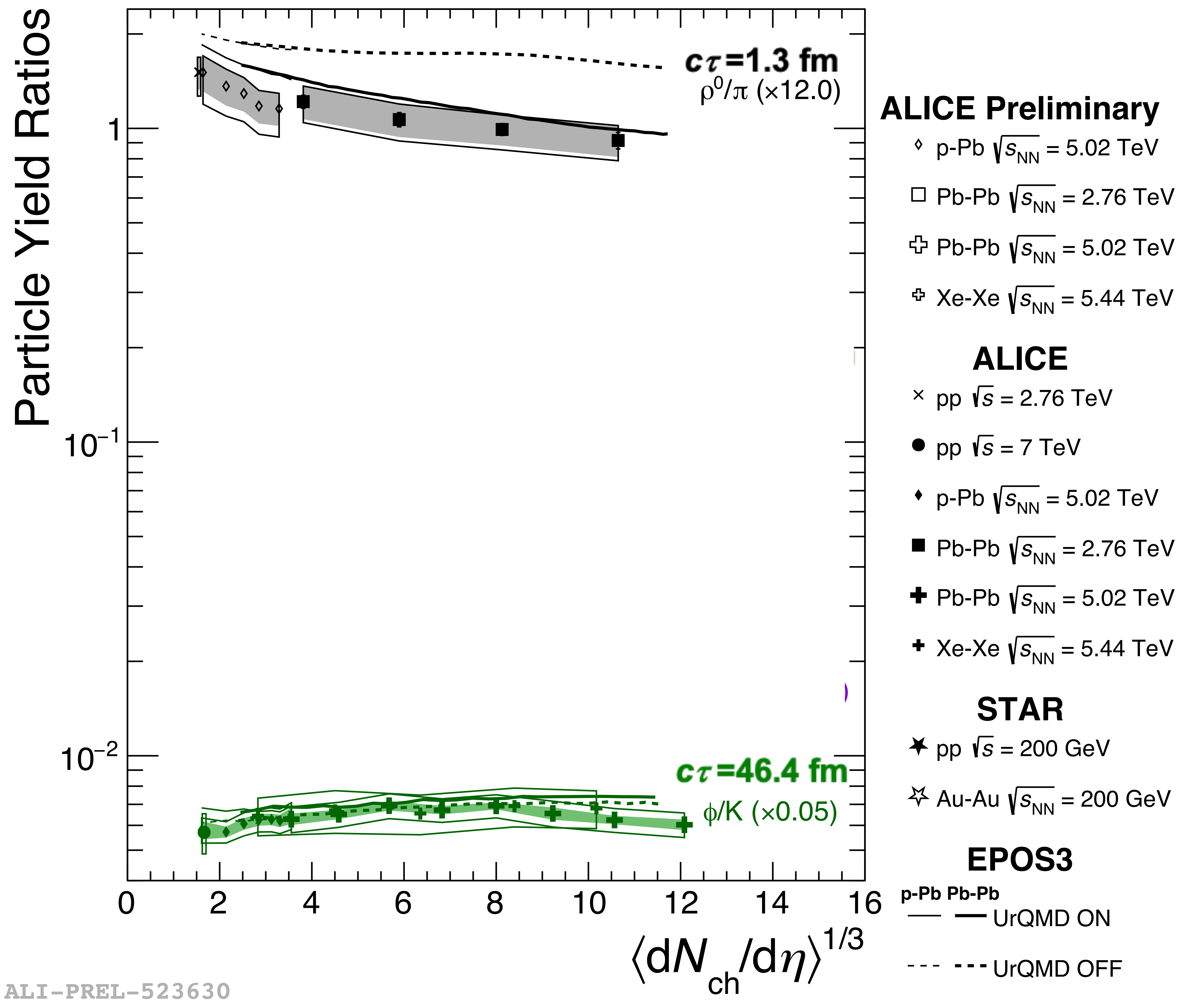

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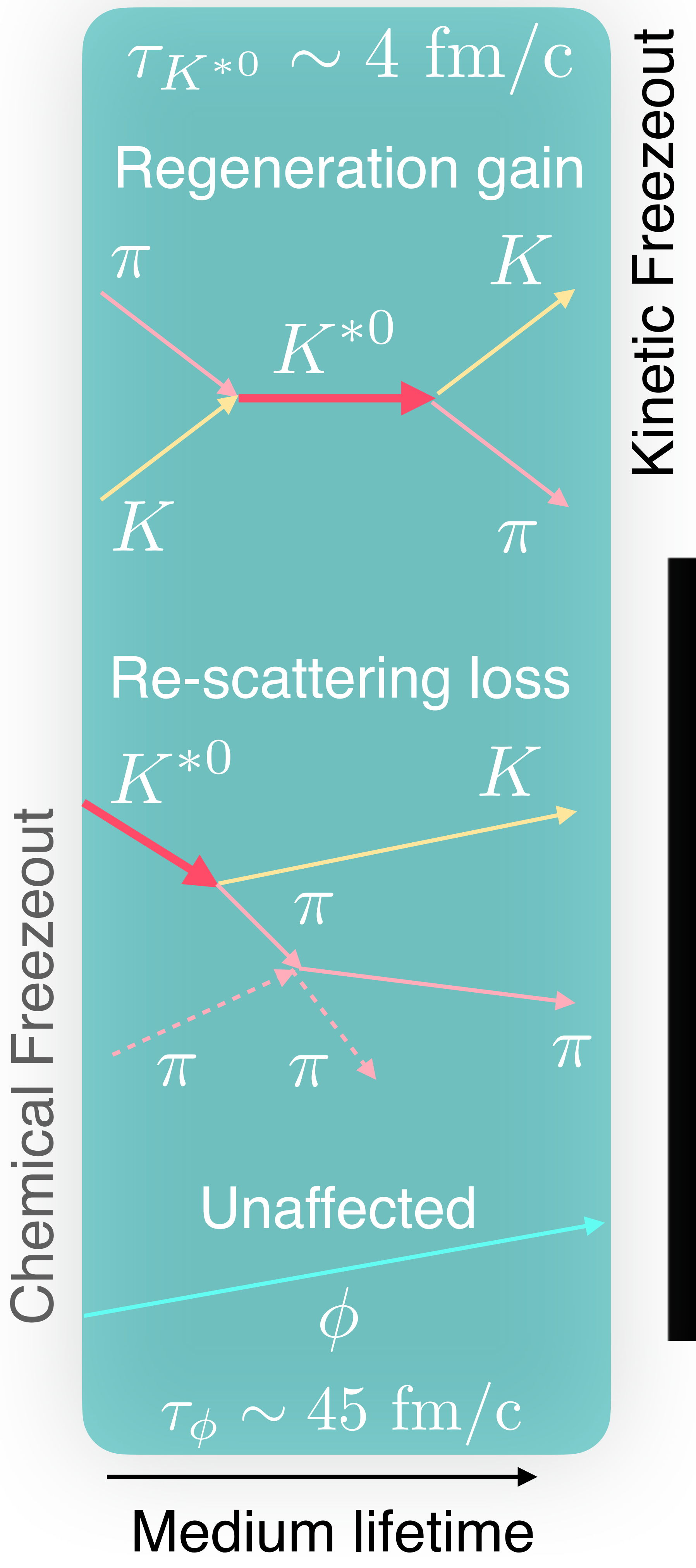

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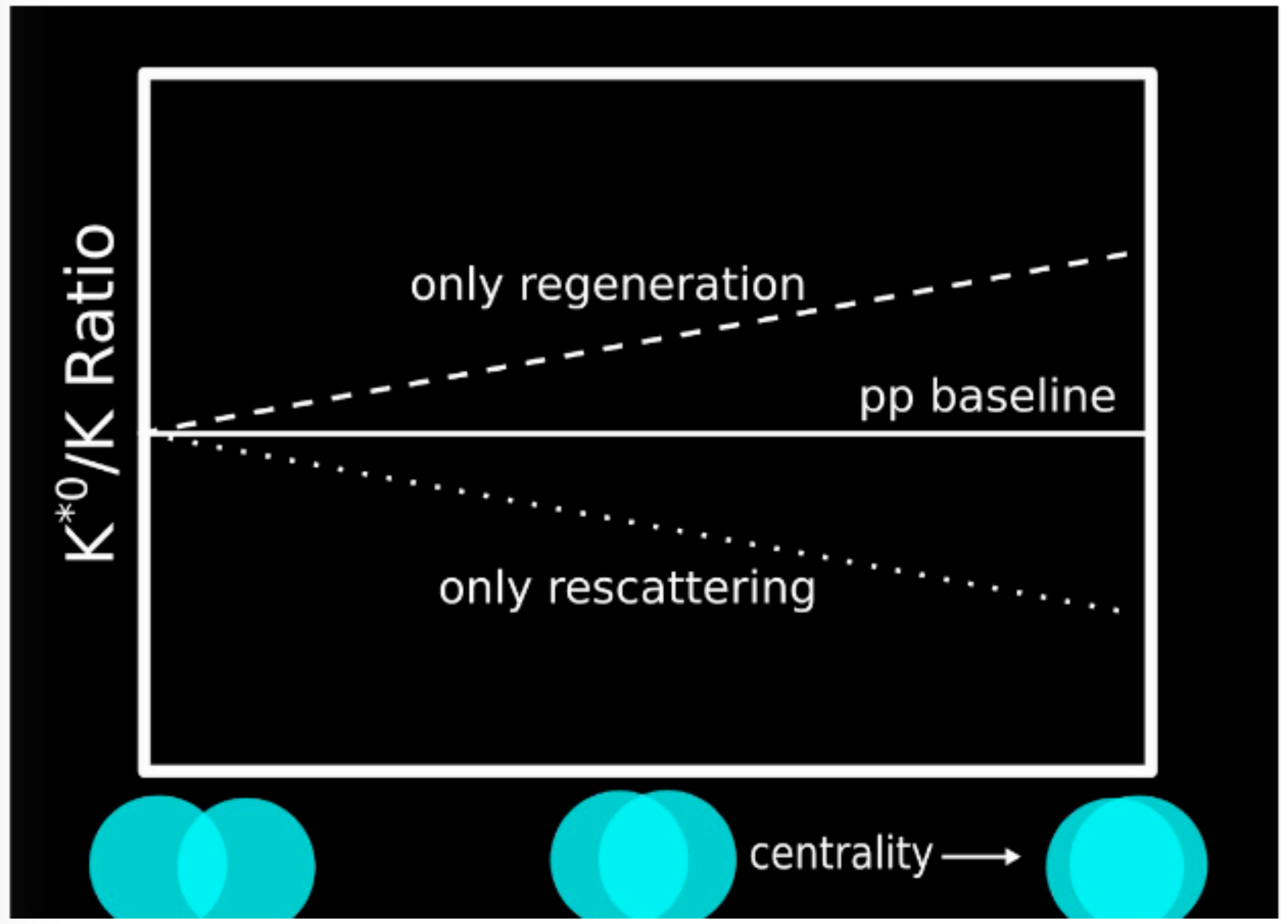
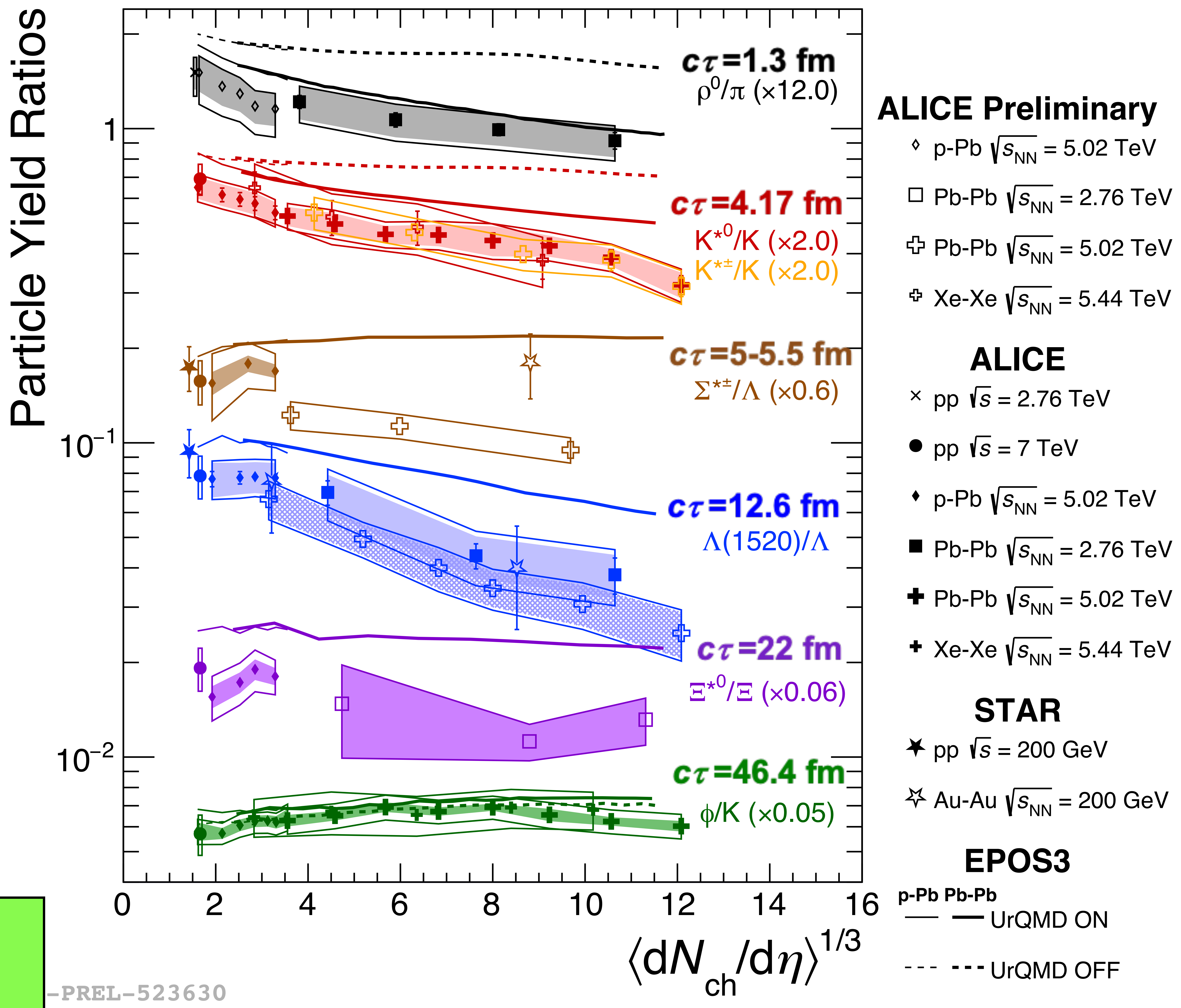




Ratios suggest hadronic phase is long, rescattering cross-section also important

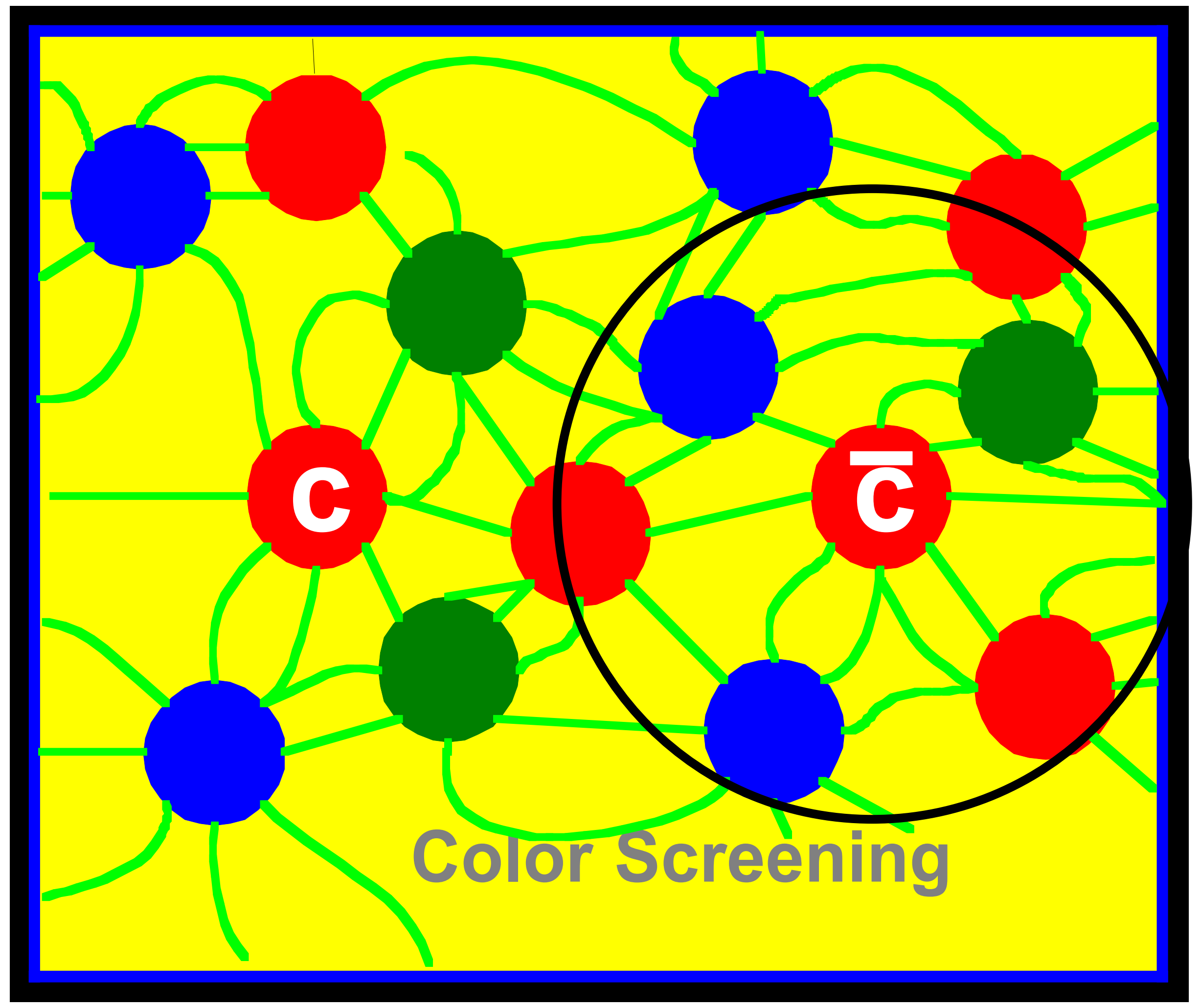
Can We Detect the Initial Conditions (EM Field and Temperature)?

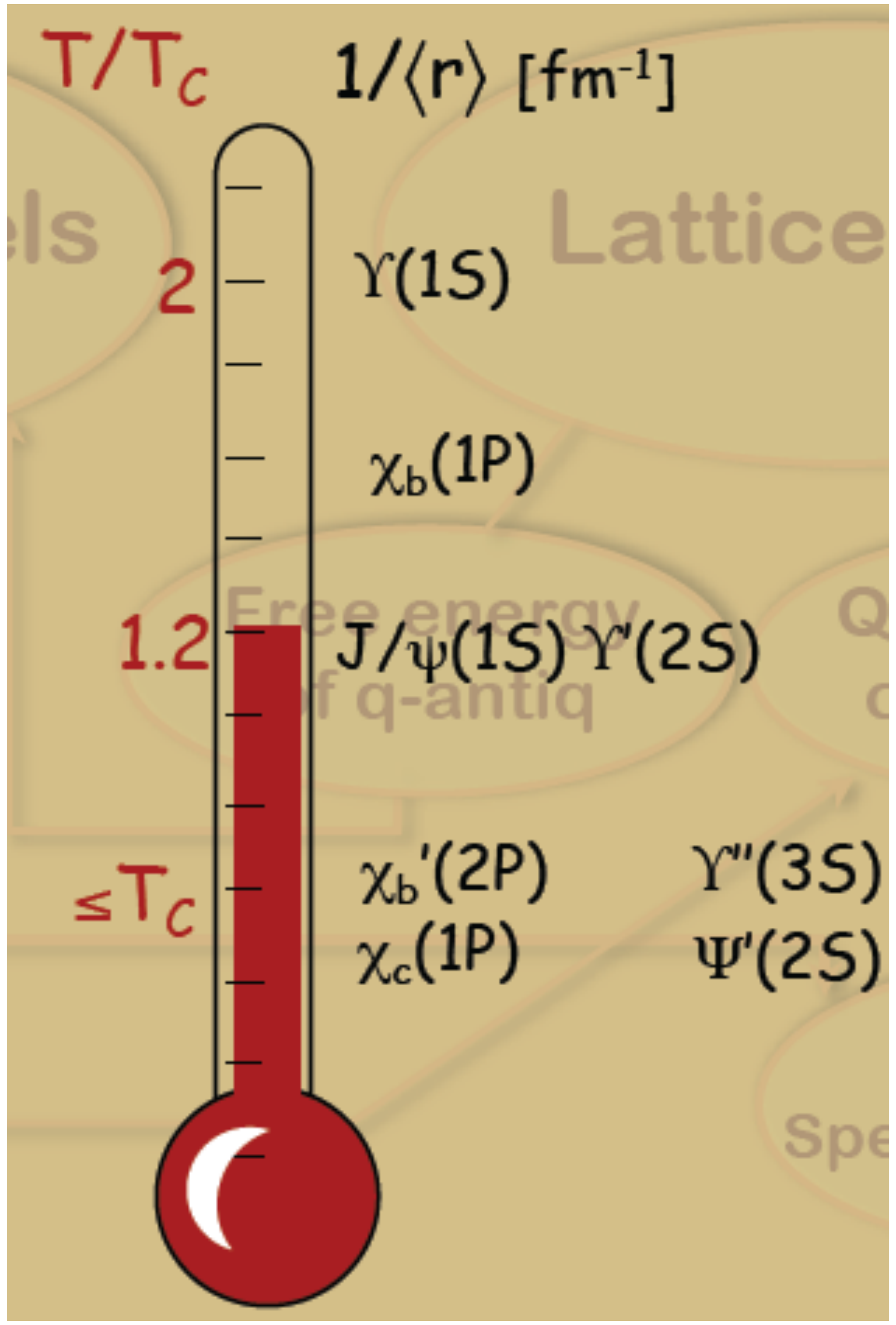
Quarkonia - QGP thermometers

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)





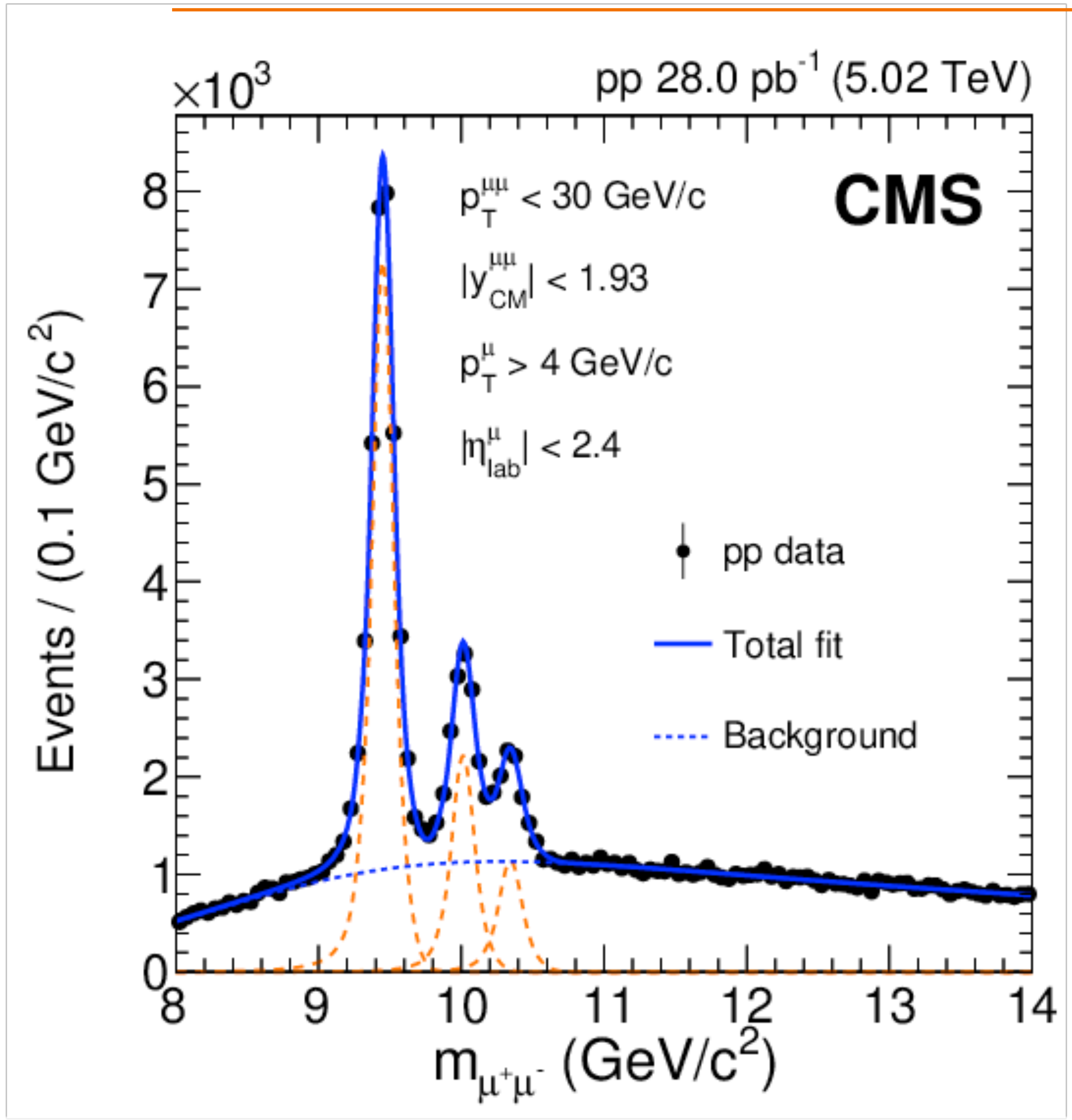
Charmonia: J/ψ, Ψ', χc

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) 112301, O. Kukral, C. Da Silva

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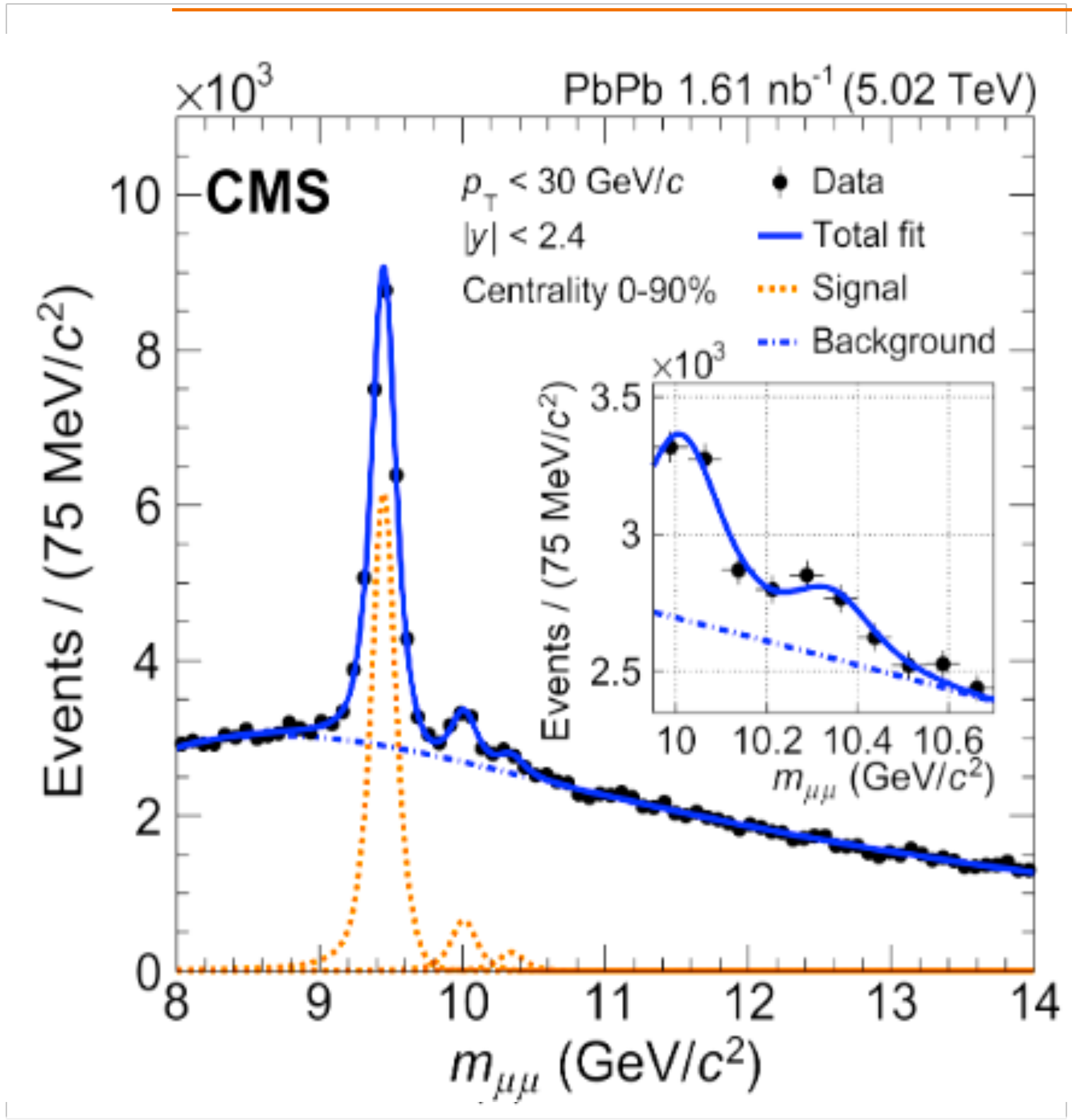
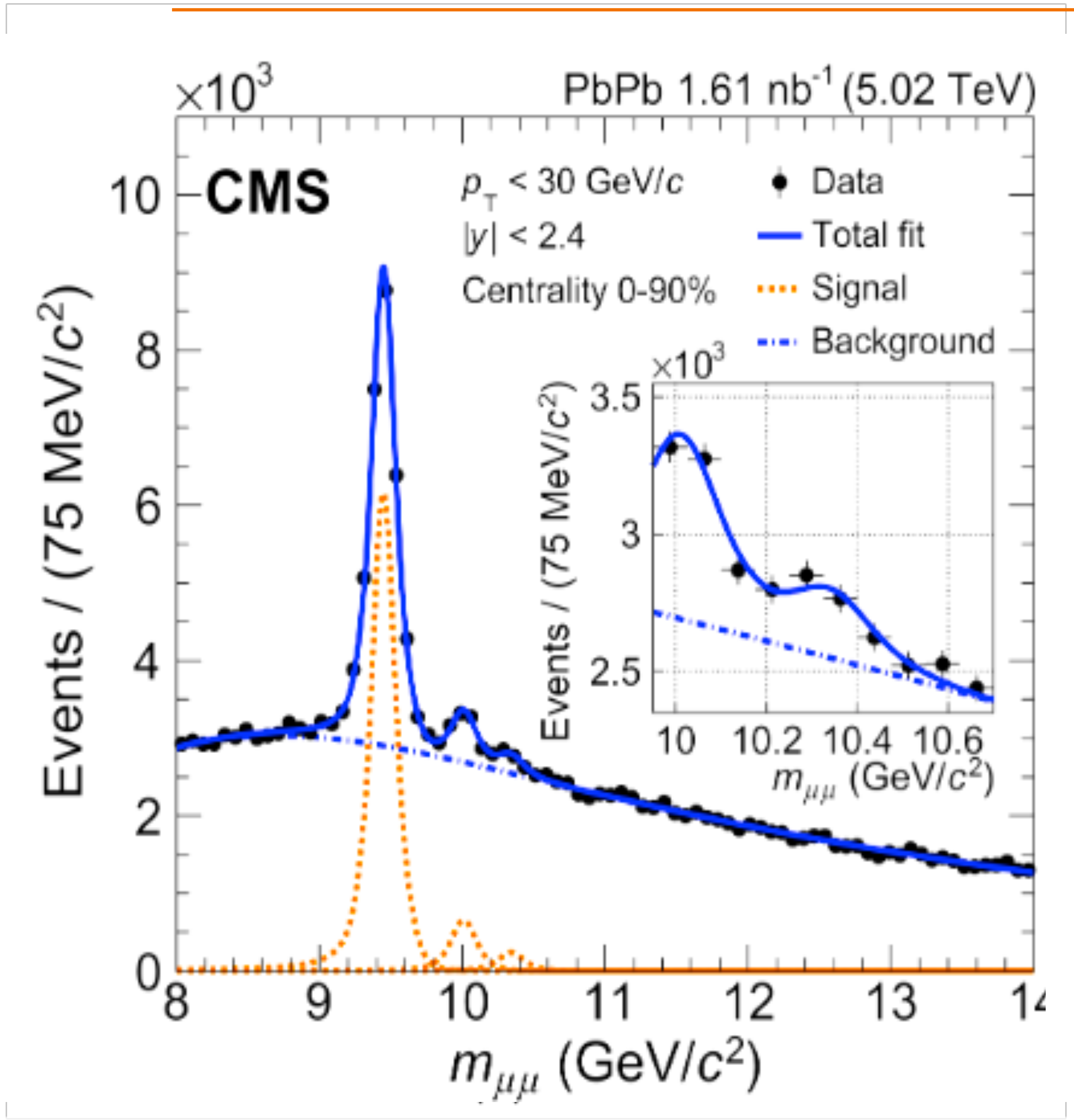


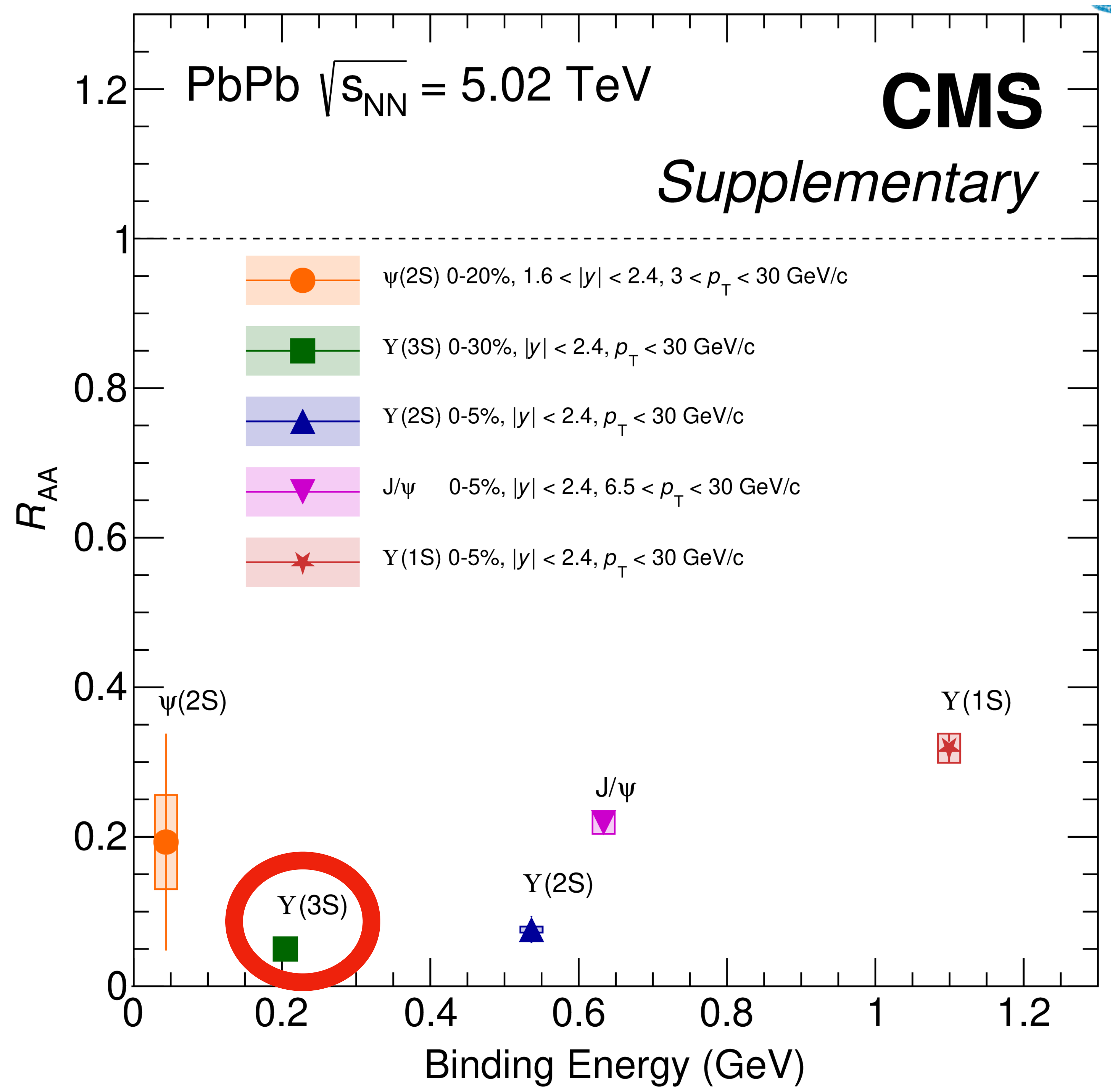
Most lightly bound states have melted at LHC and top RHIC

$T > 1.5\ T_c \sim 300$ MeV

CMS:PRL 109 (2012) 222301, PLB 835 (2022) 137397
STAR:PRL 130 (2023) 112301, O. Kukral, C. Da Silva

Sequential melting of quarkonia





Most lightly bound states have melted at LHC and top RHIC

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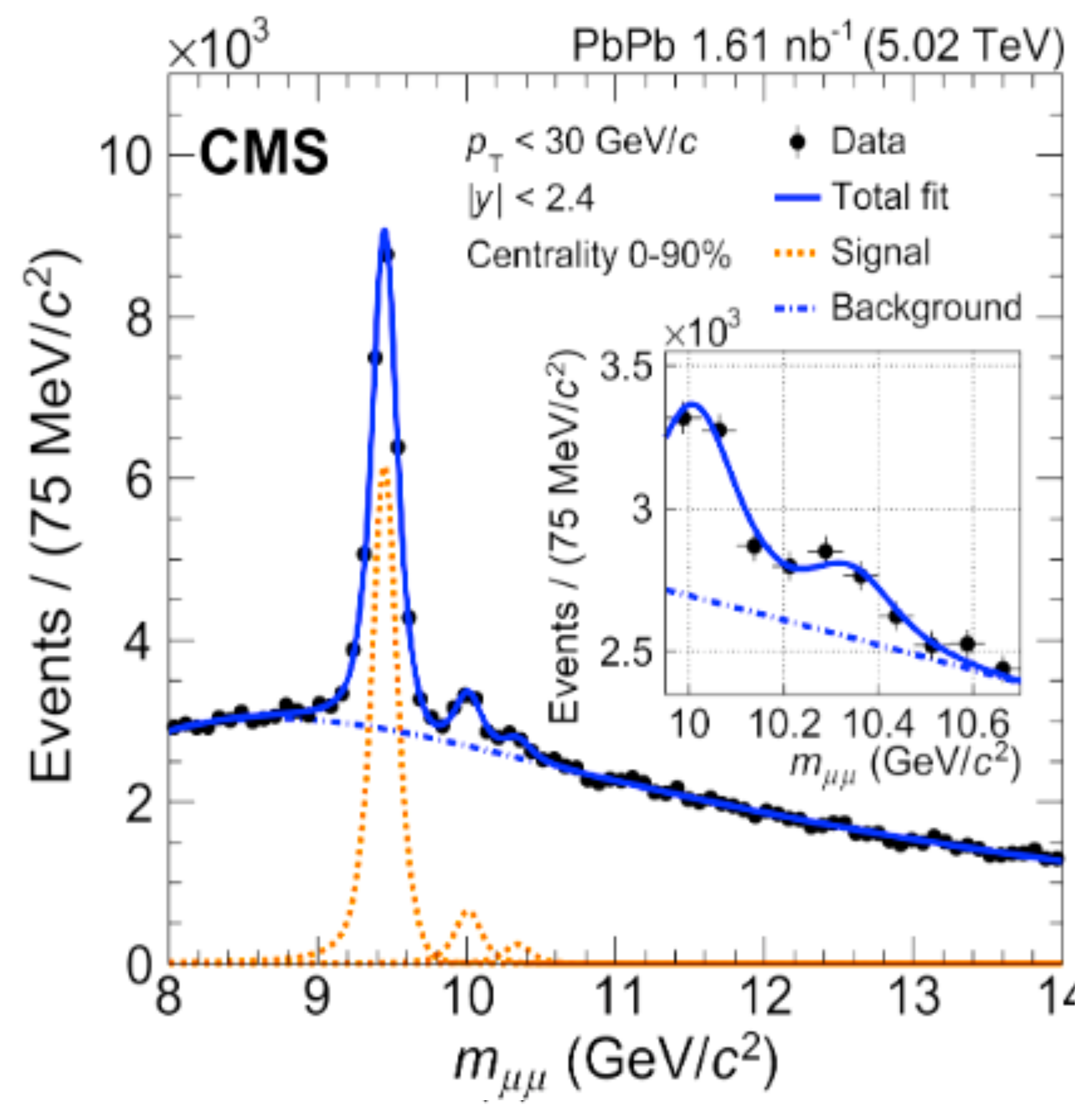
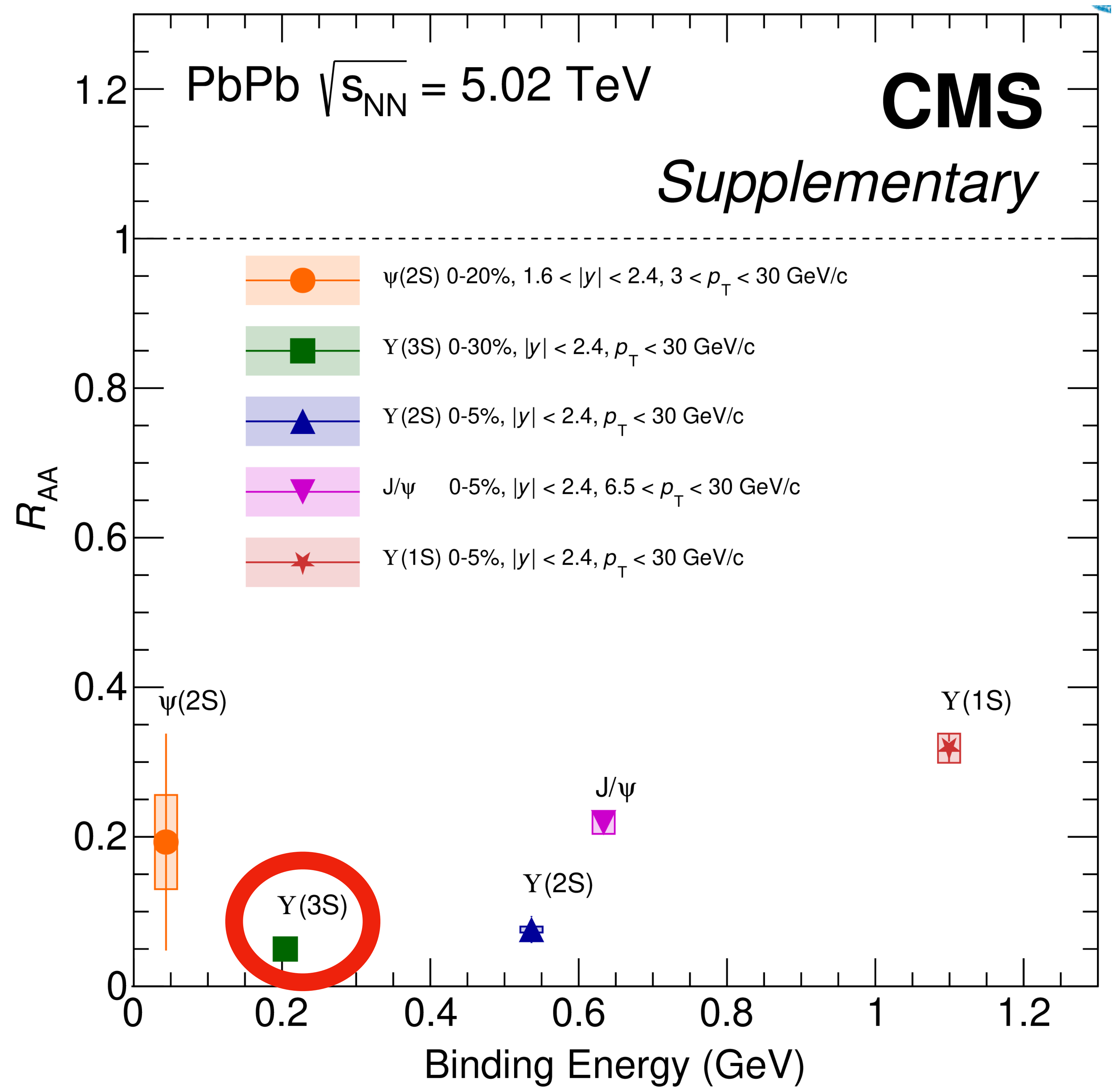
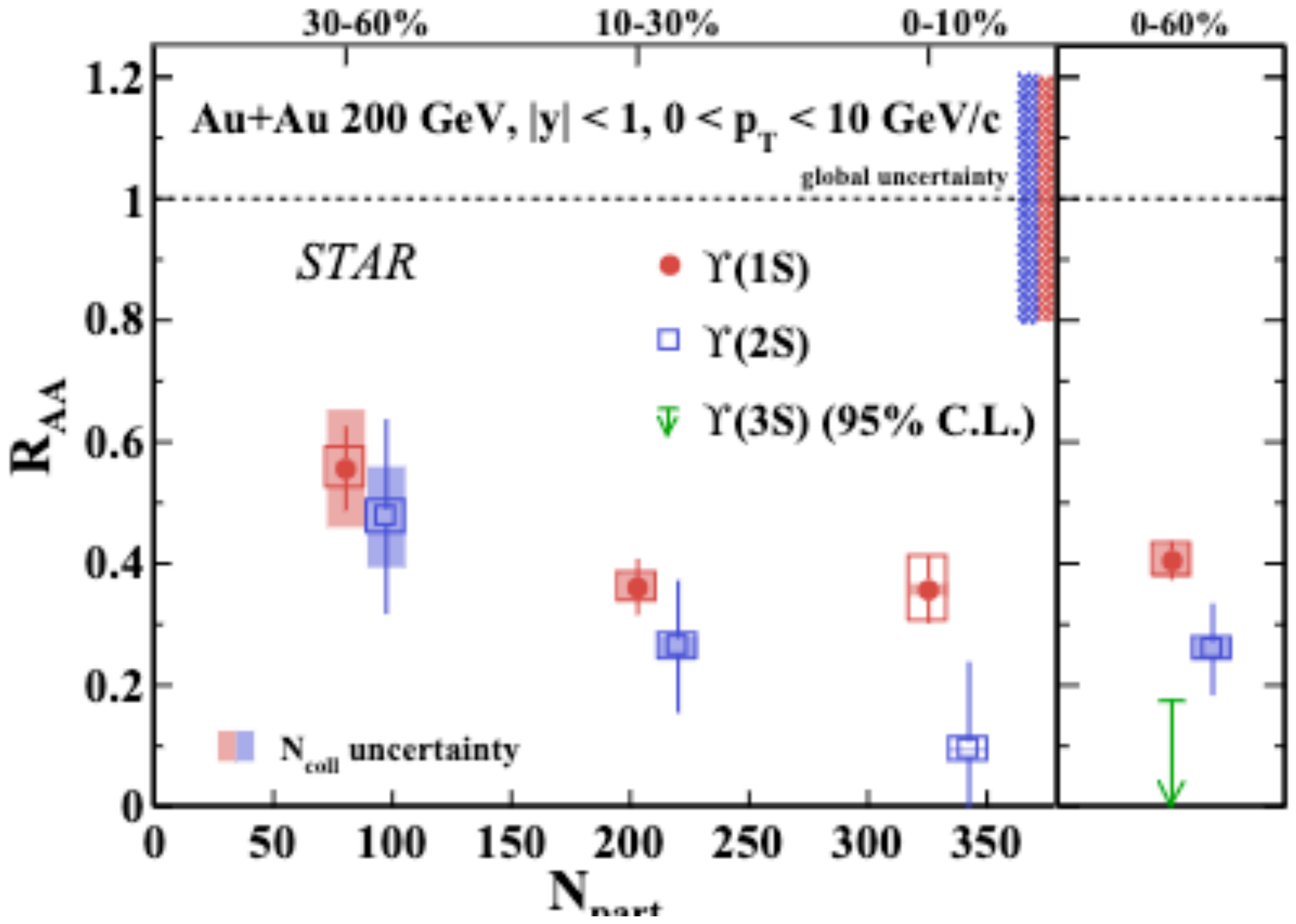






Most lightly bound states have melted at LHC and top RHIC

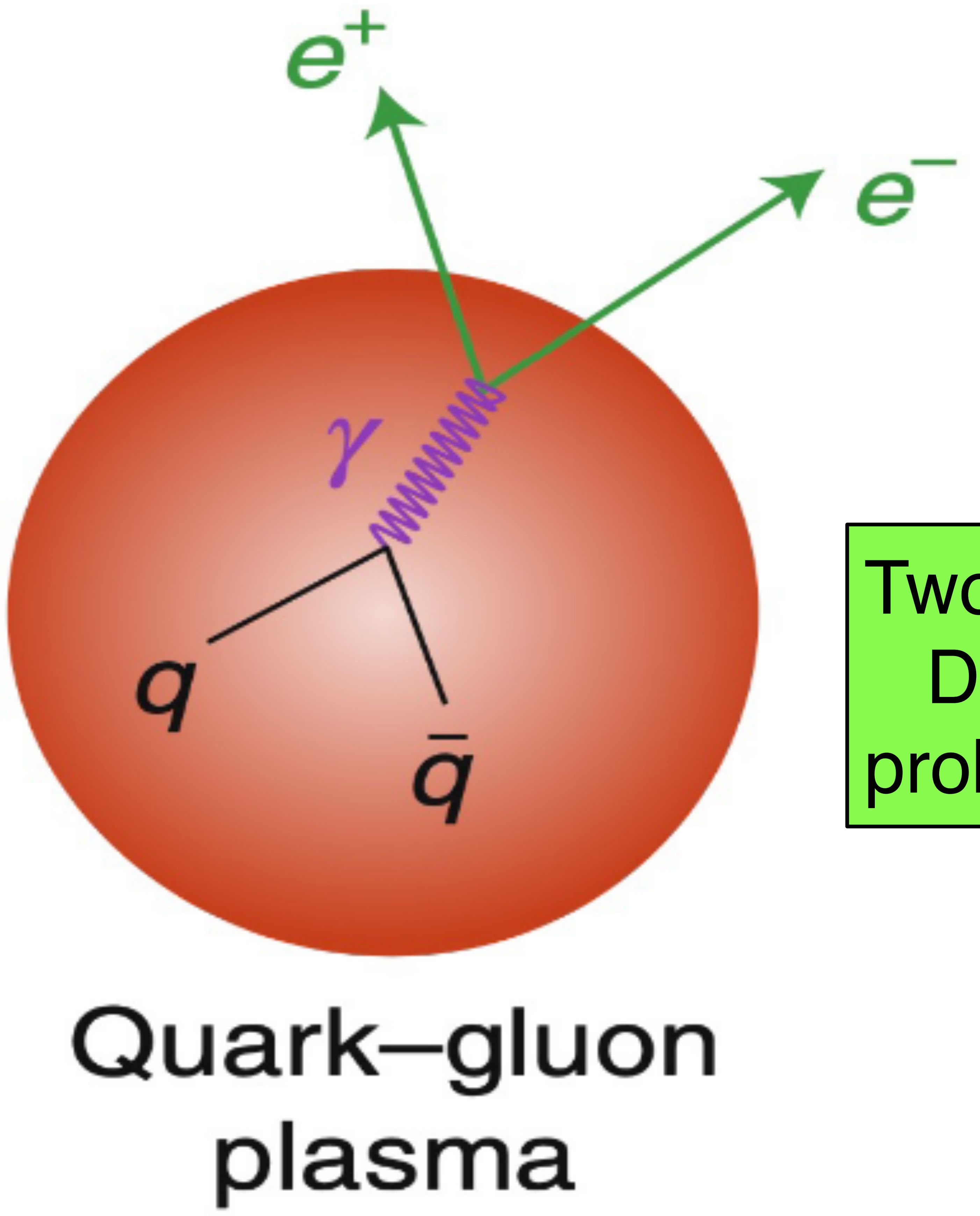
$T > 1.5\ T_c \sim 300$ MeV

Eagerly awaiting statistics for sPHENIX to report on Υ(3S)

CMS:PRL 109 (2012) 222301, PLB 835 (2022) 137397
STAR:PRL 130 (2023) 112301, O. Kukral, C. Da Silva

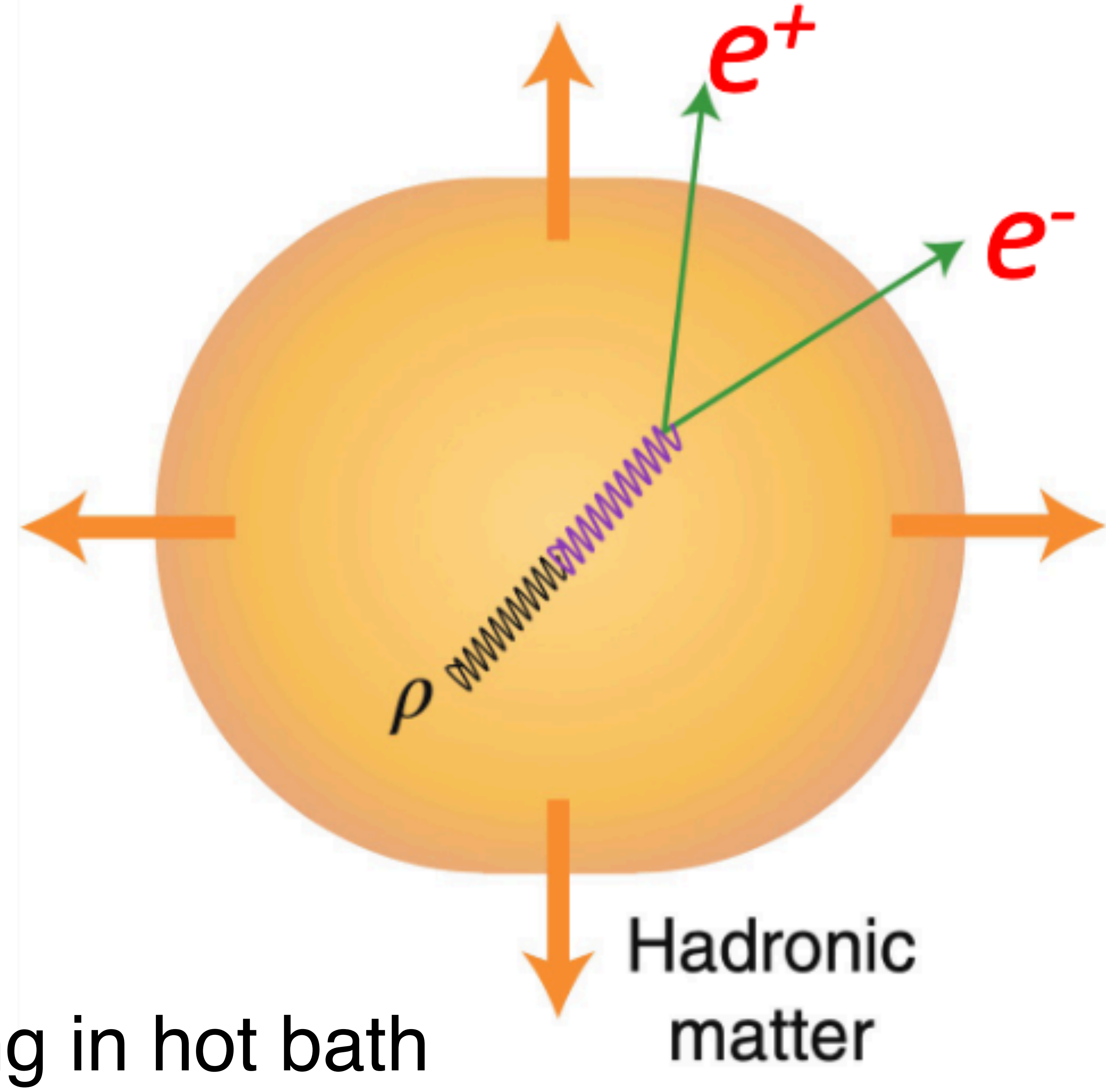
What about the initial temperature?

Di-leptons probe medium over its whole evolution. Escape medium without interacting (no color charge)



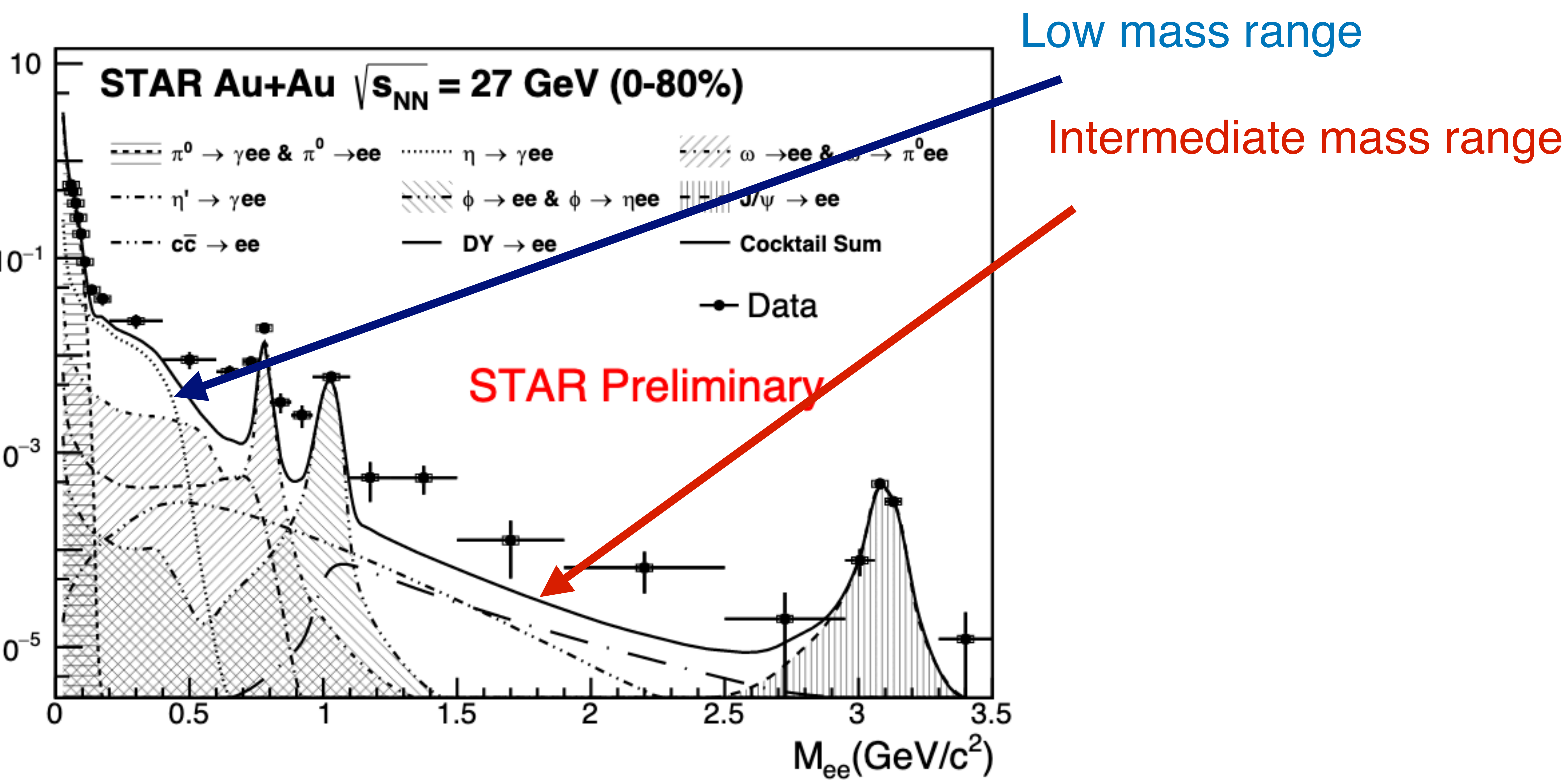
Production rate proportional to QGP temperature
: Early time measurement

Two for the price of one:
Different di-lepton invariant mass ranges probe different times



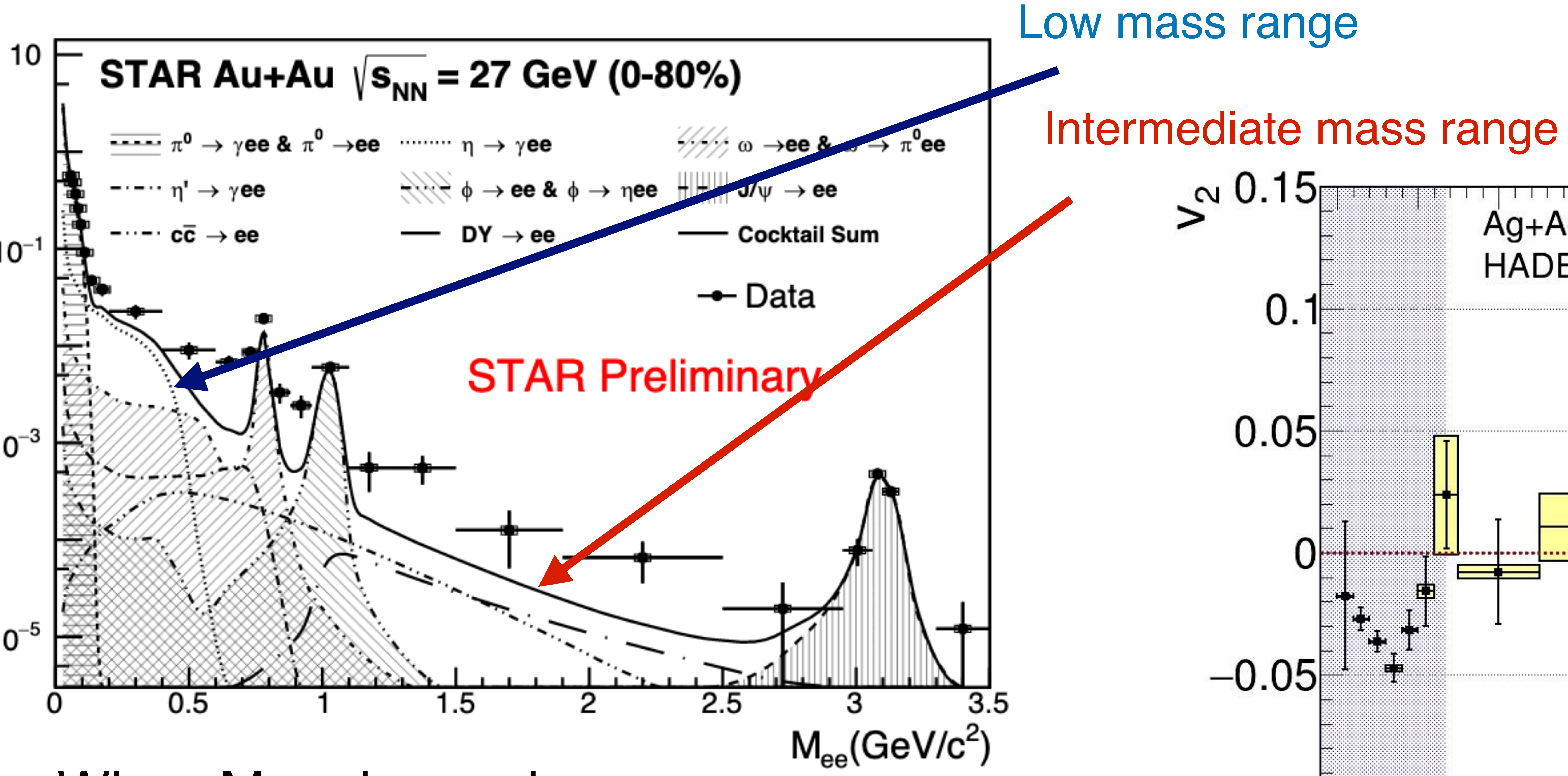
ρ spectral function broadens when sitting in hot bath
: Later time measurement

Significant enhancement above cocktail

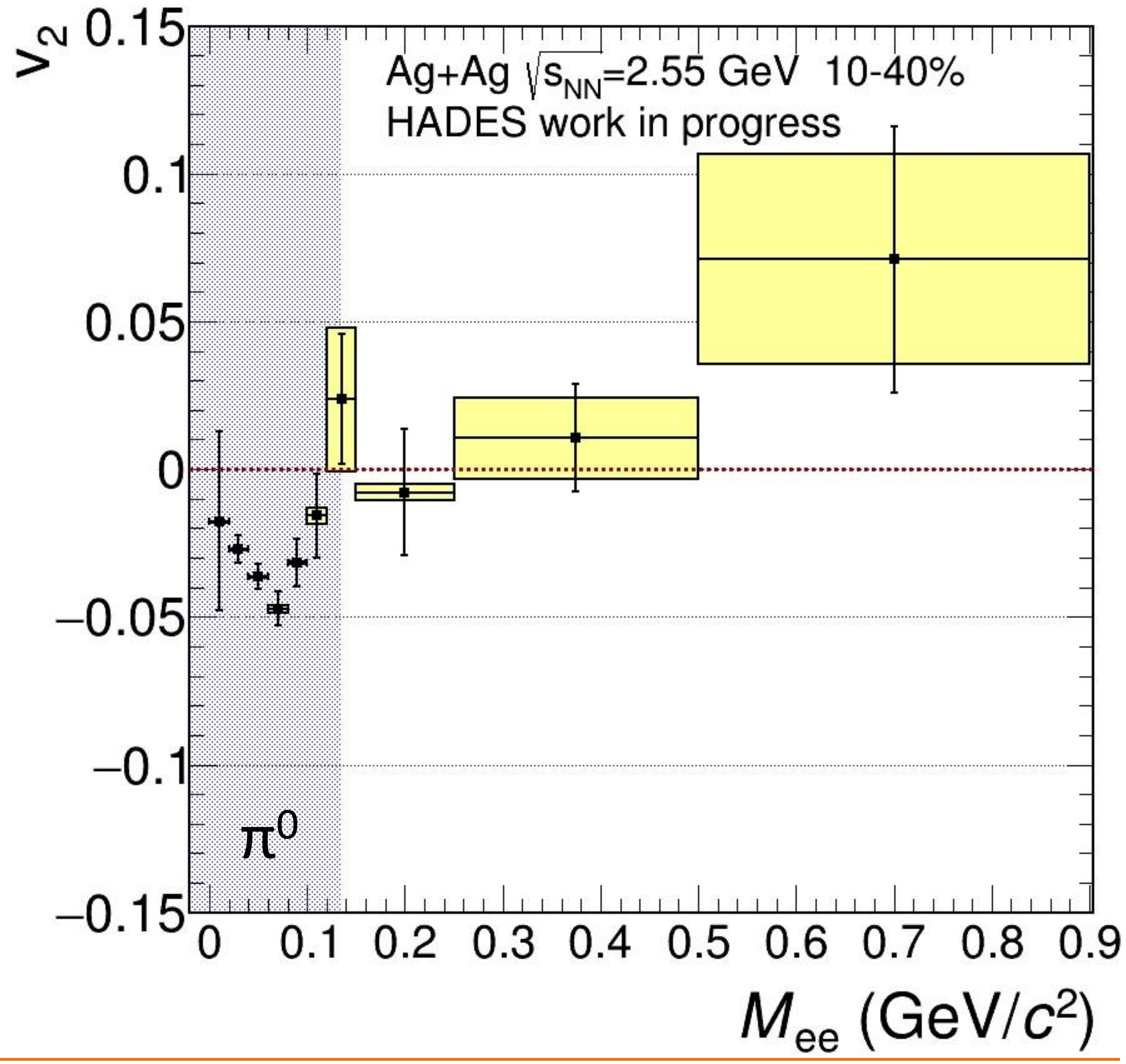


Clear enhancement for LMR and IMR

Significant enhancement above cocktail



Clear enhancement for LMR and IMR

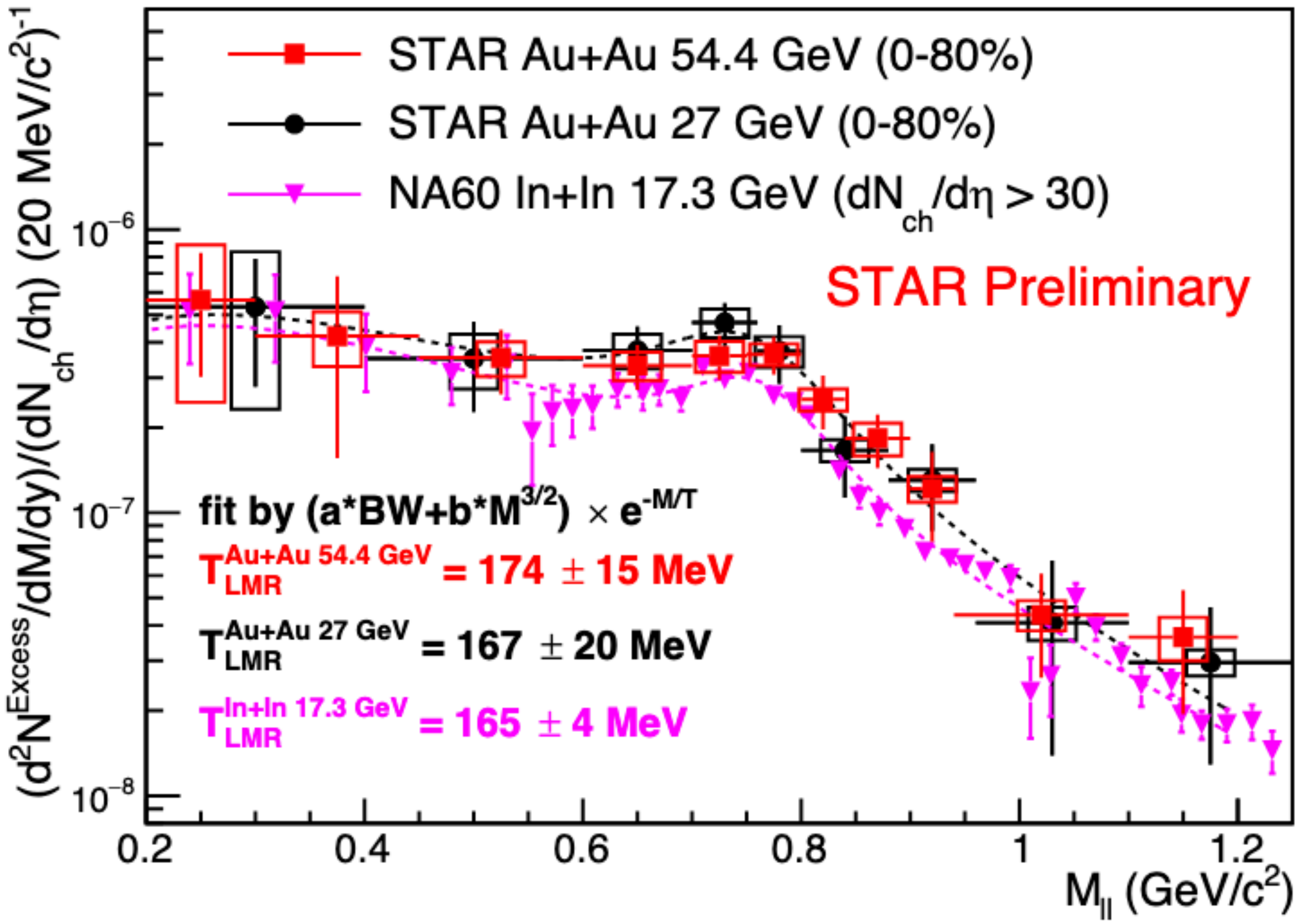


When M_{ee} above pion mass:
no collectivity exhibited

We've identified a penetrating probe with no boost

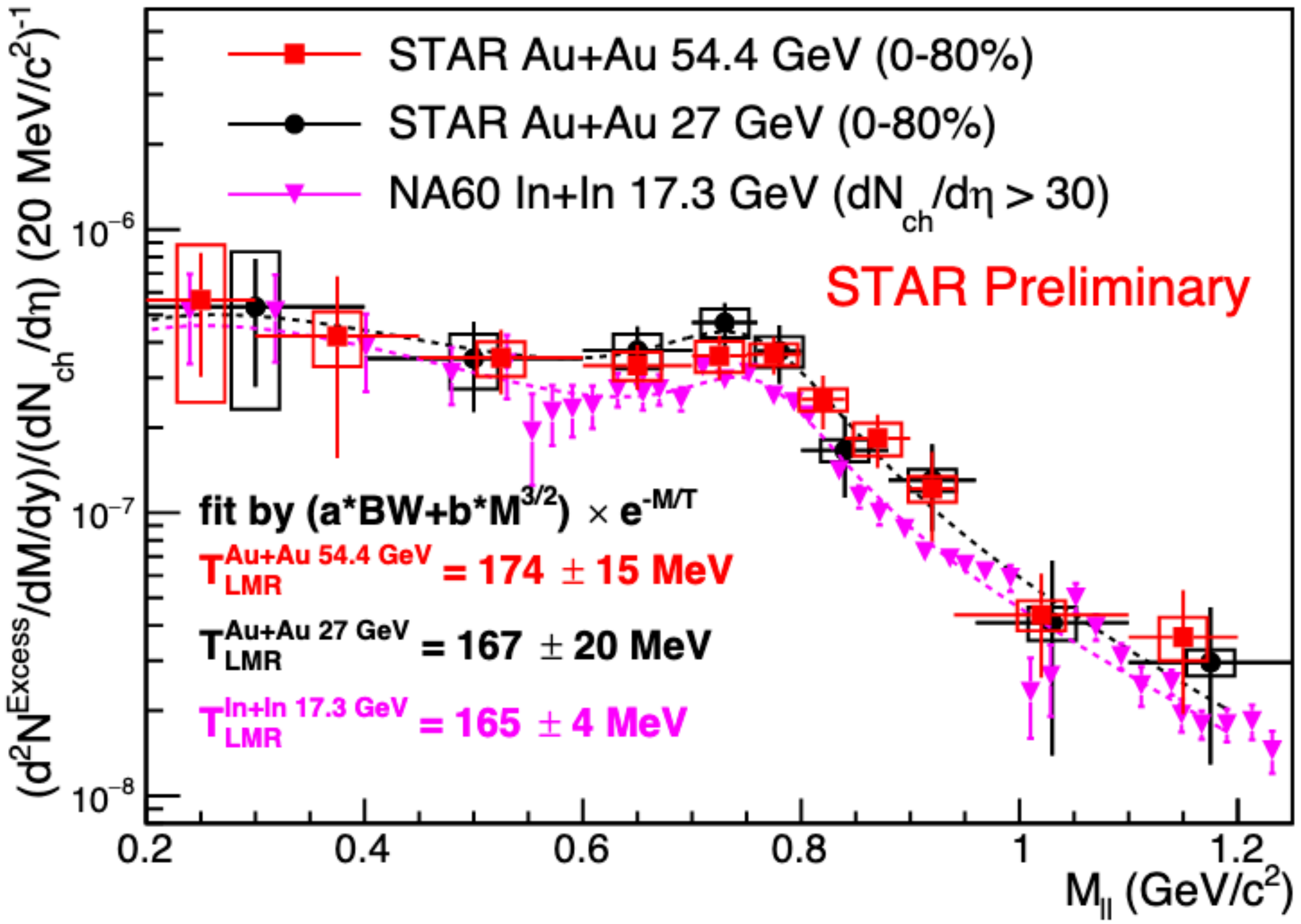
N. Schild

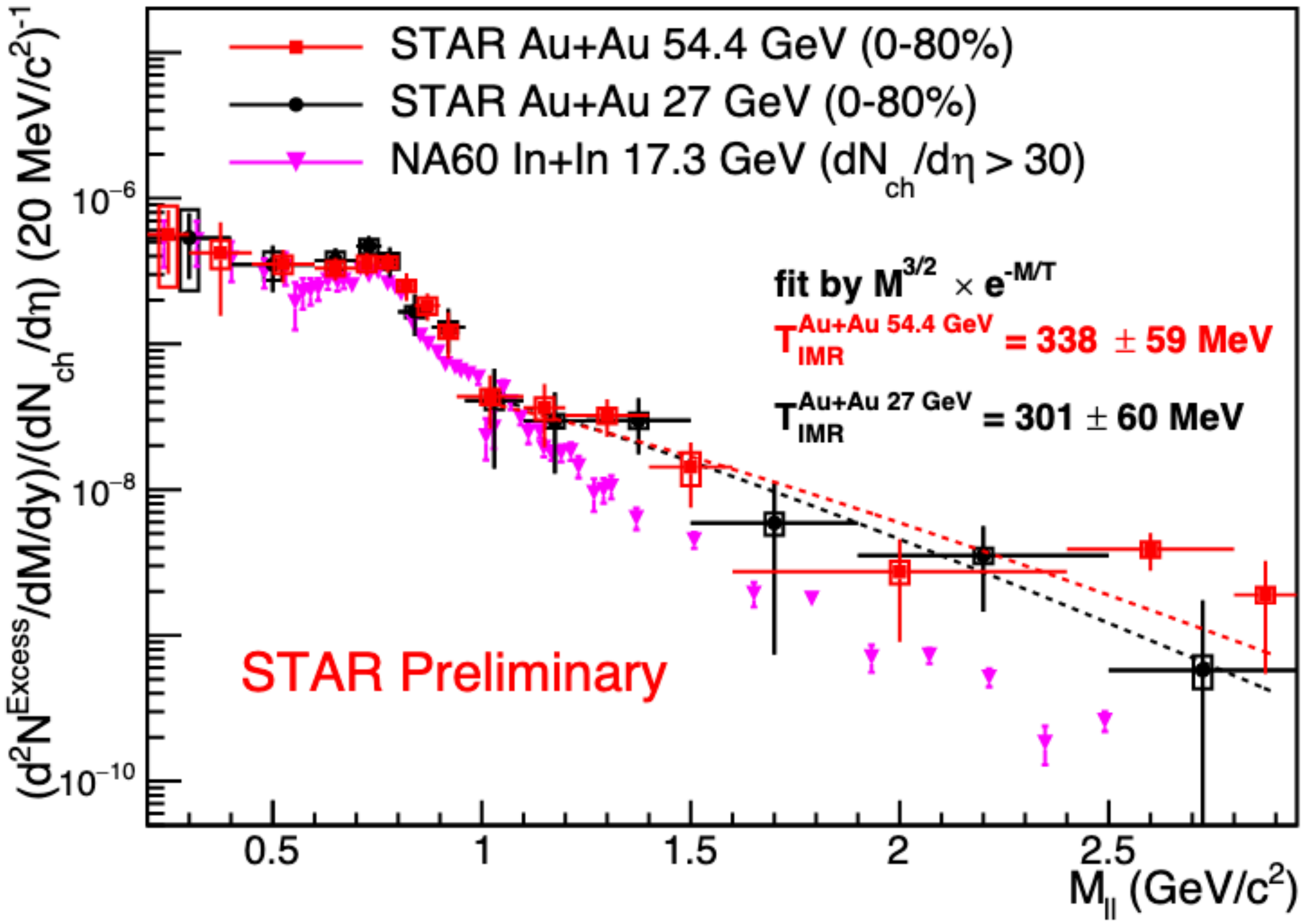
Extracting the temperatures



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

Extracting the temperatures



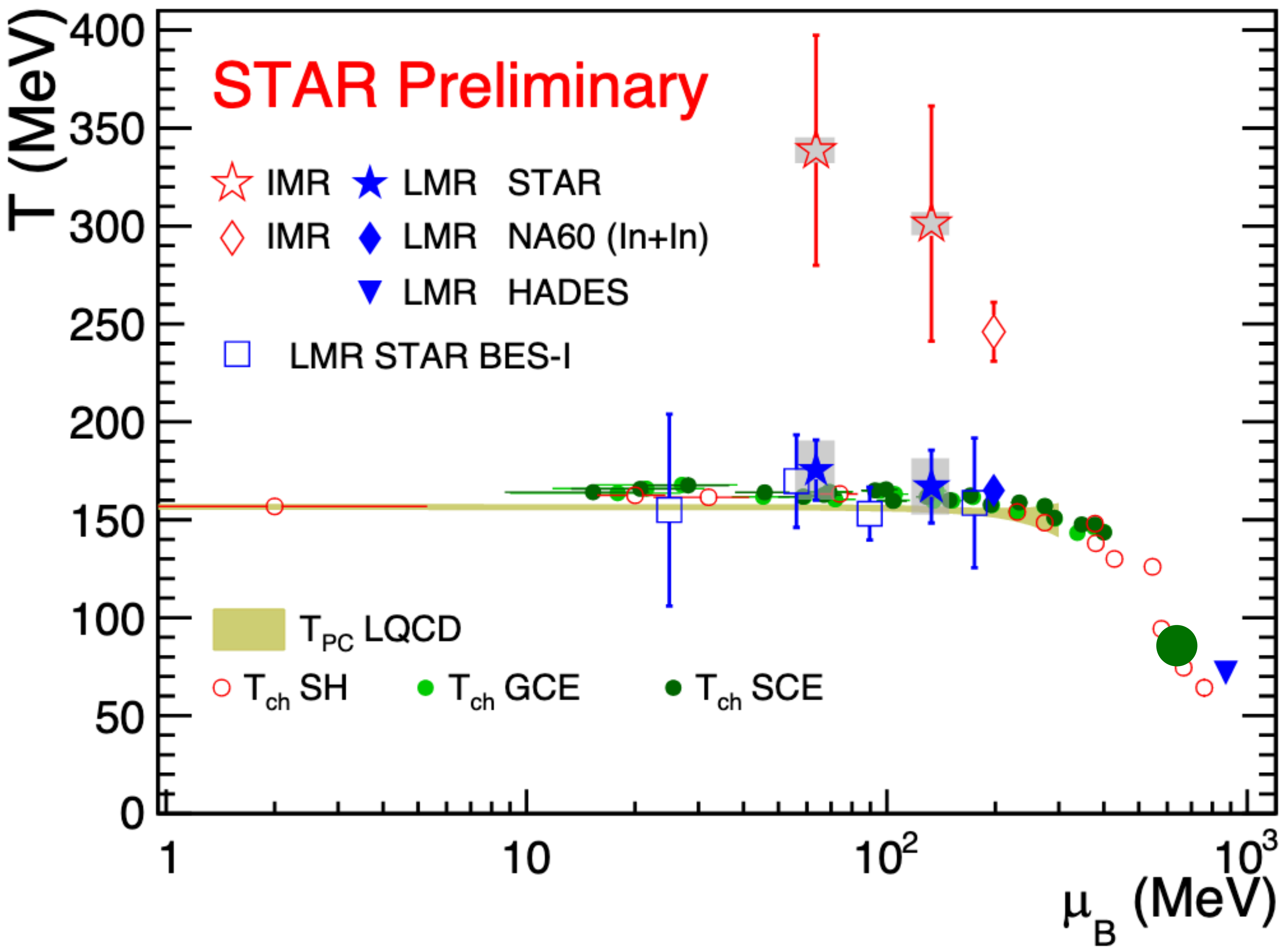


Low mass range: Similar mass spectrum, similar T,
in-medium ρ produced and broadened in similar heat bath from $\sqrt{s_{NN}}$ =17-56 GeV

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

Something different starts to happens below 20 GeV

Initial vs Freeze-out temperature



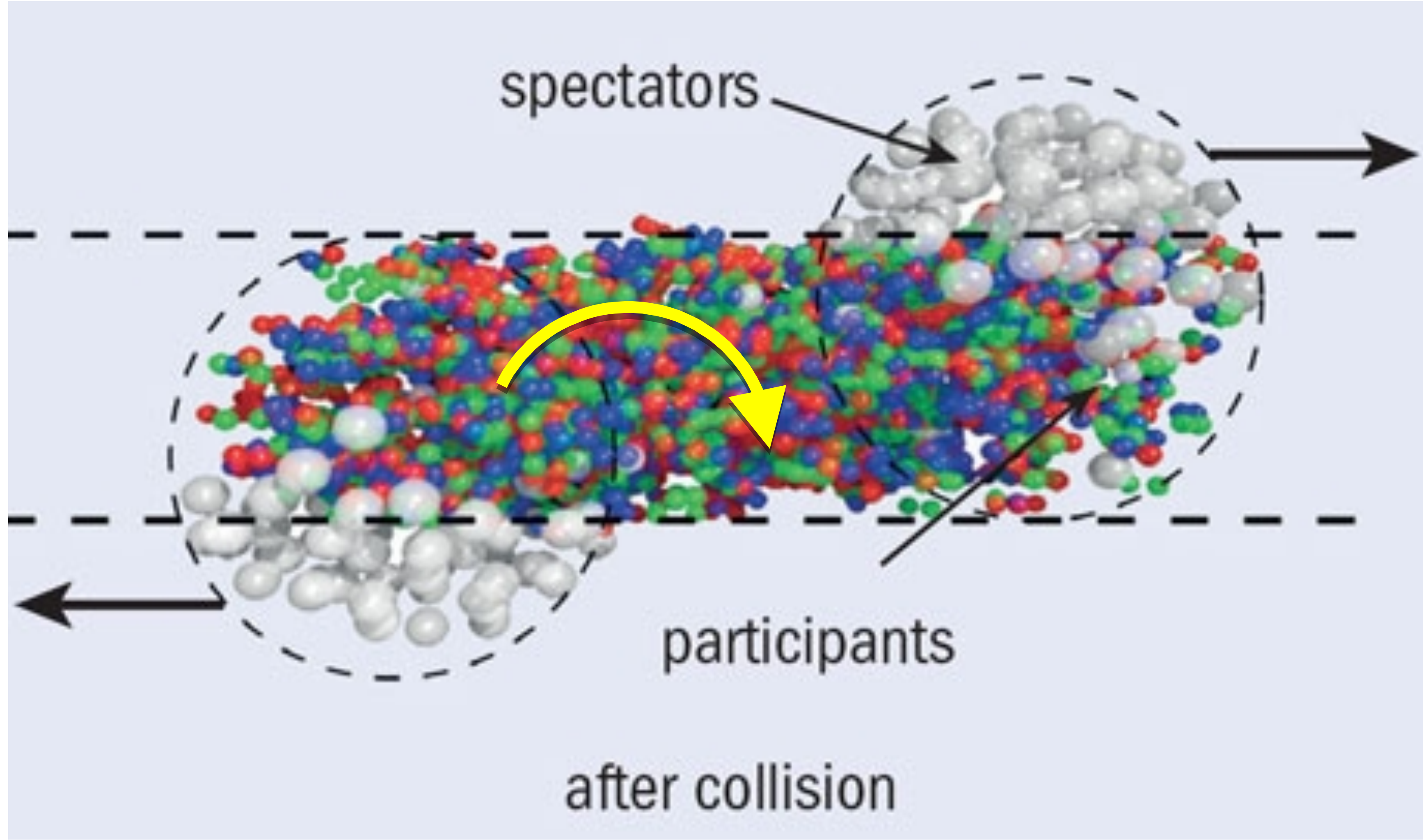
LMR : Extracted T in agreement with statistical model fits

HMR : Closer to initial T

Alternative ways to access early T?

Especially at low $\sqrt{s_{NN}}$

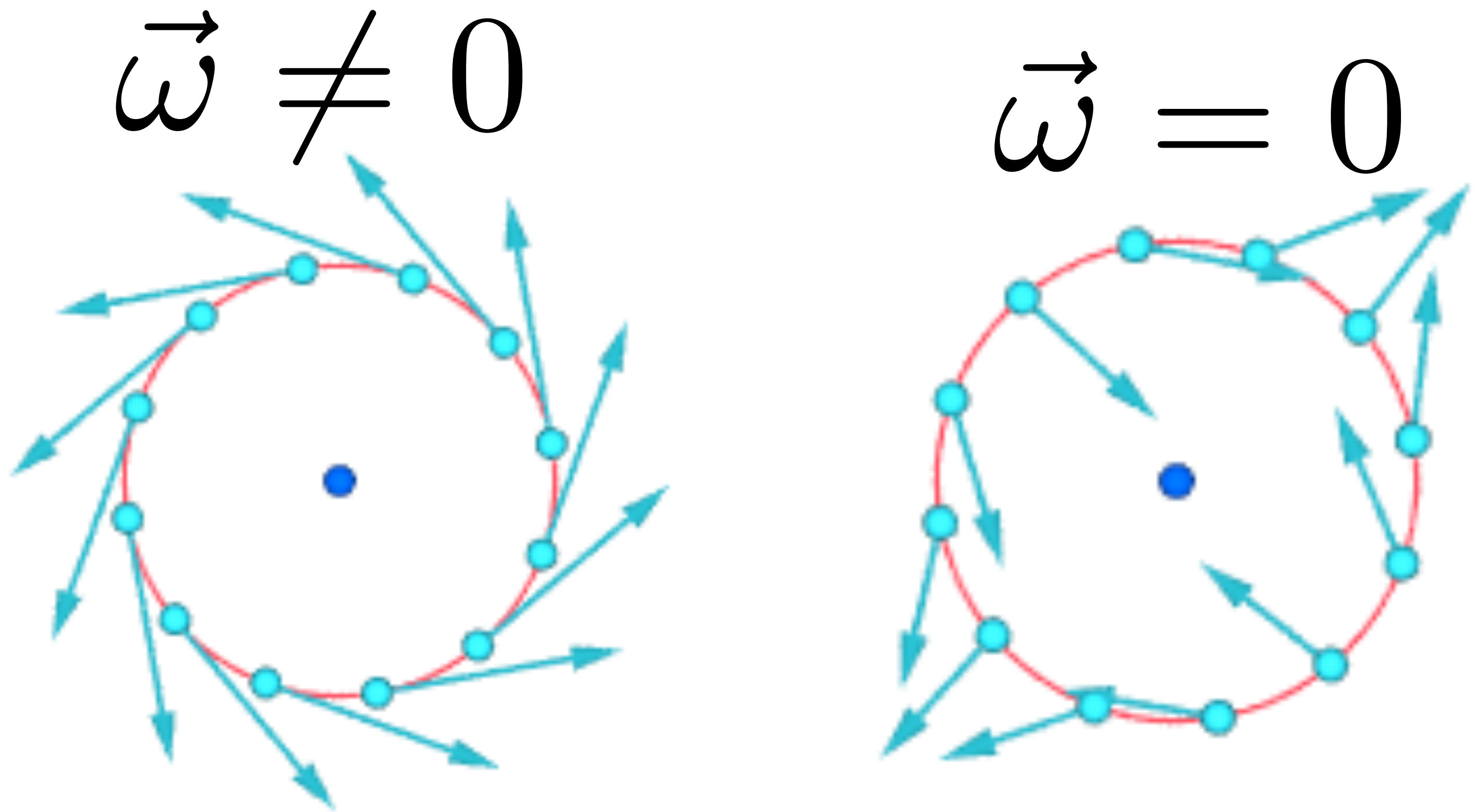
The spinning QGP



$|L| \sim 10^5$ in peripheral collisions

We generate a "spinning" QGP?

Spectators create a large magnetic field



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

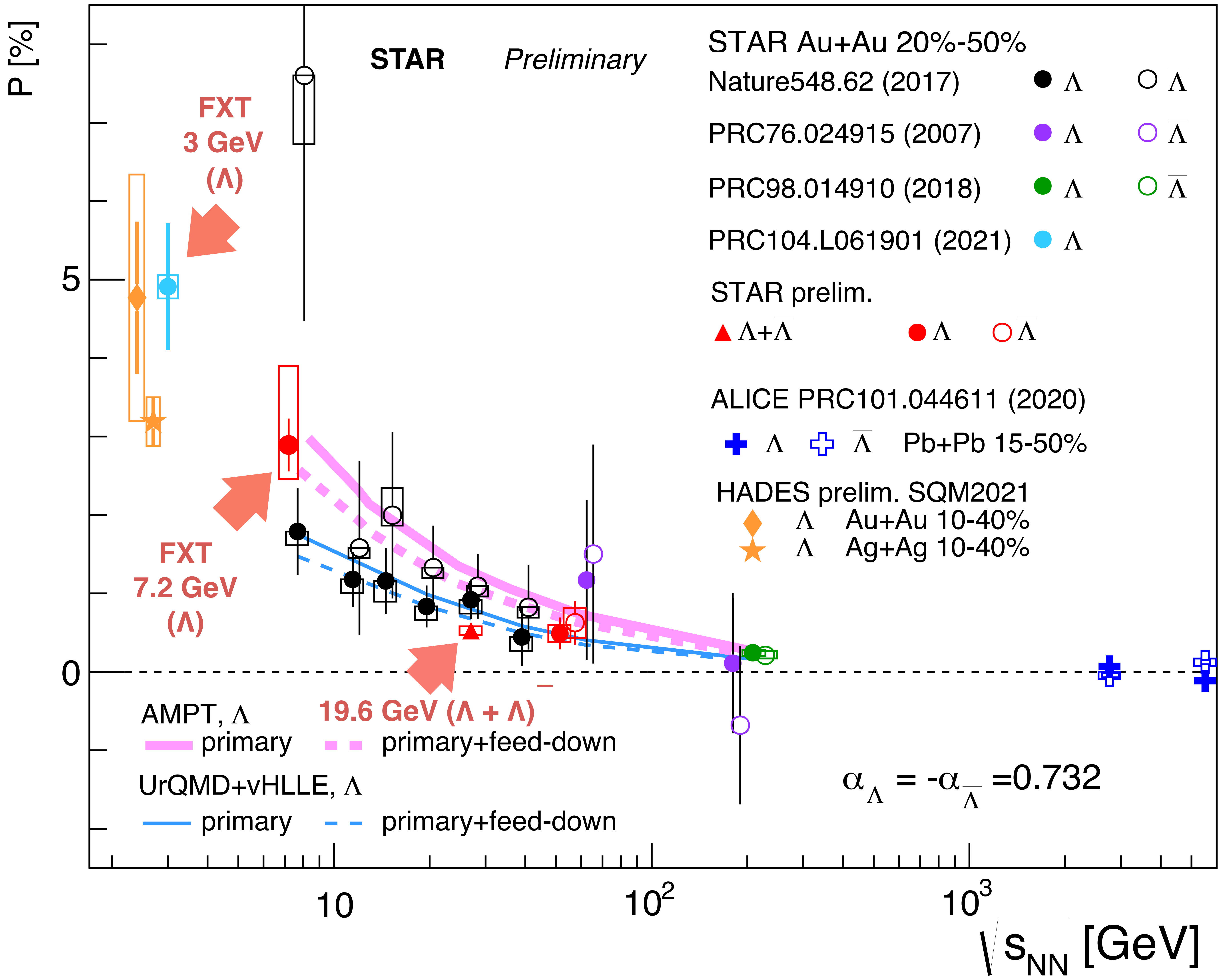
$$\vec{\omega} = \vec{\nabla} \times \vec{v}$$

Viscosity dissipates vorticity to fluid at larger scales

Can we see any manifestation of this in the data?

Global Λ polarization

Precision measurements from 3-5000 GeV: Global trend emerges



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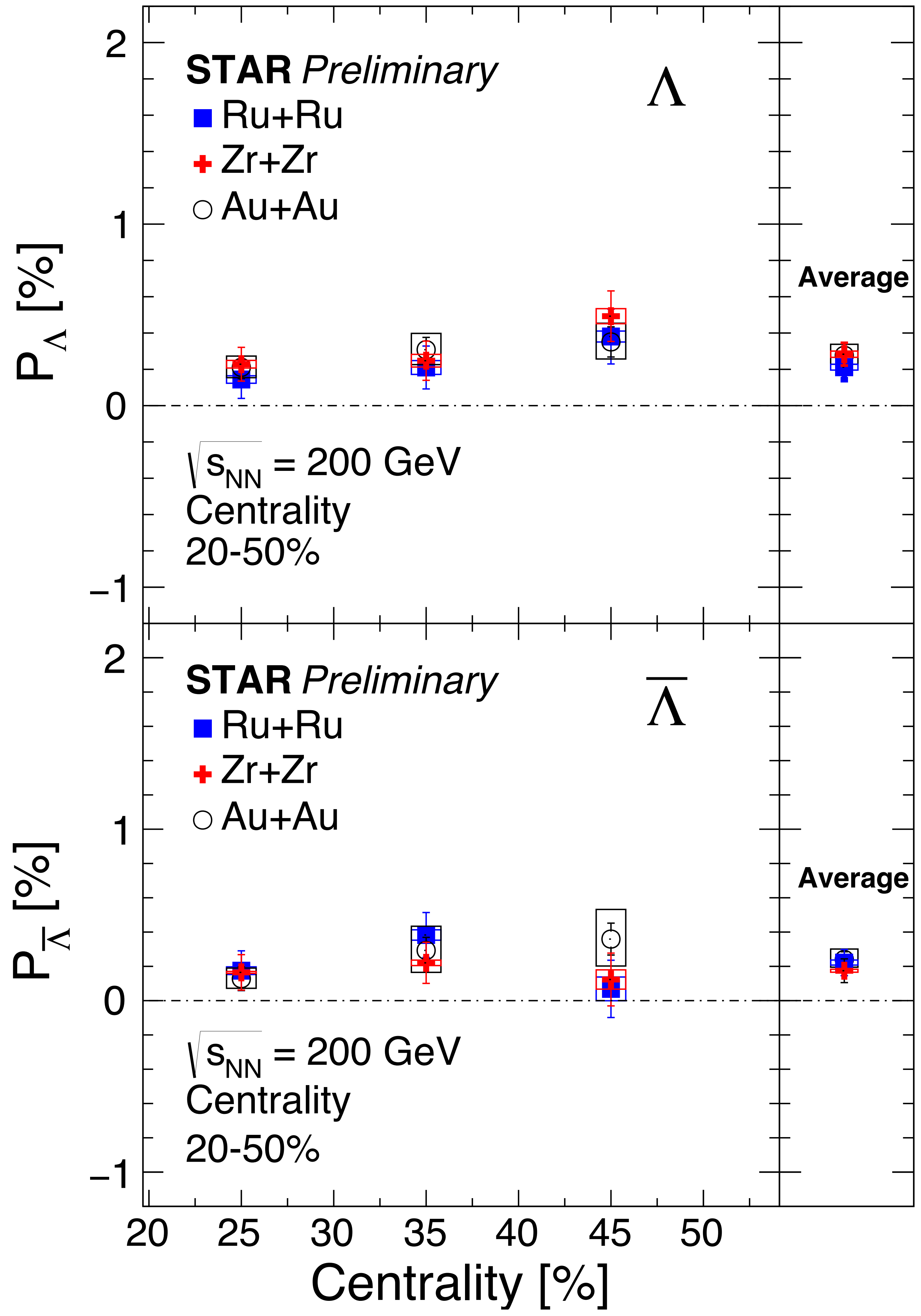
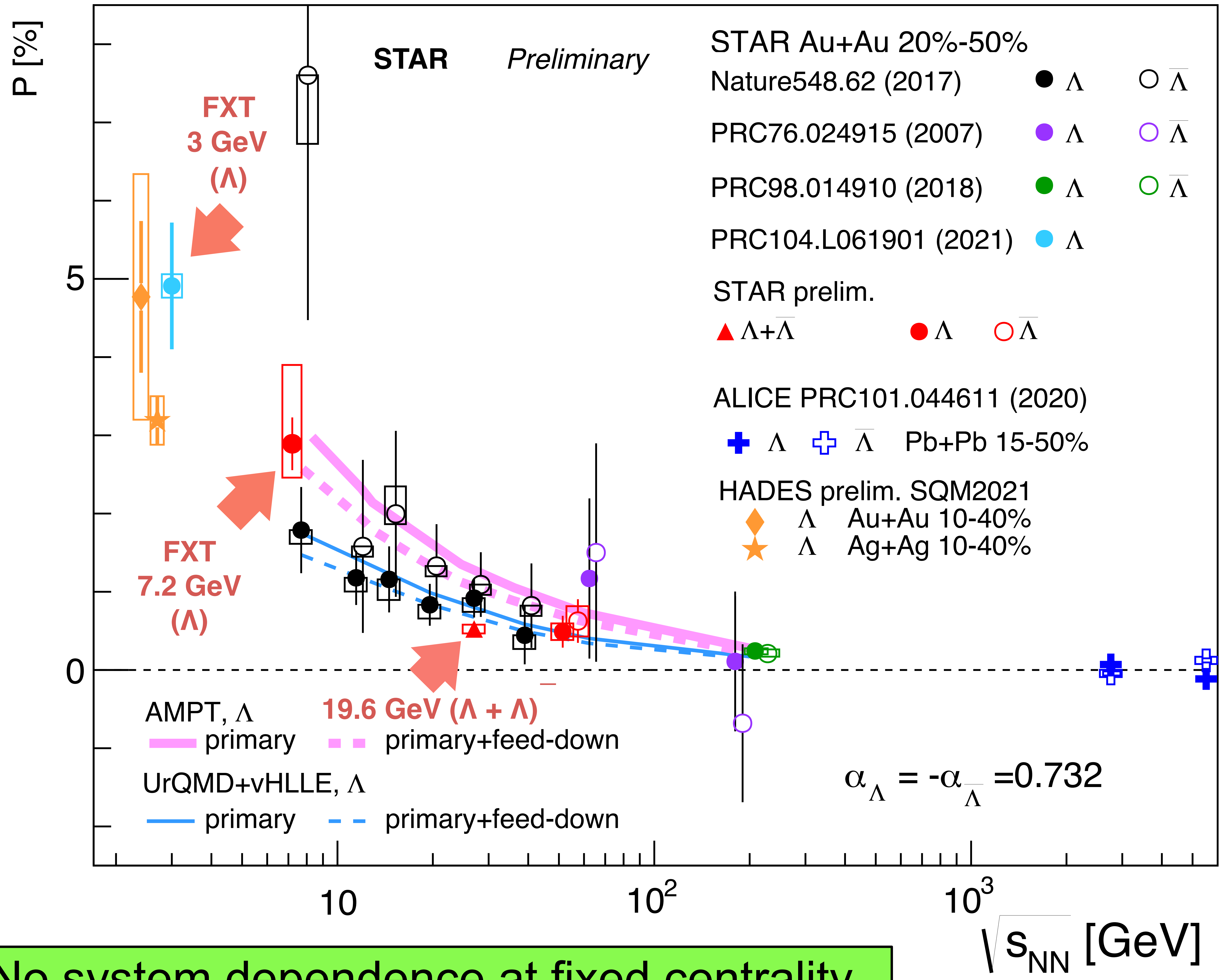
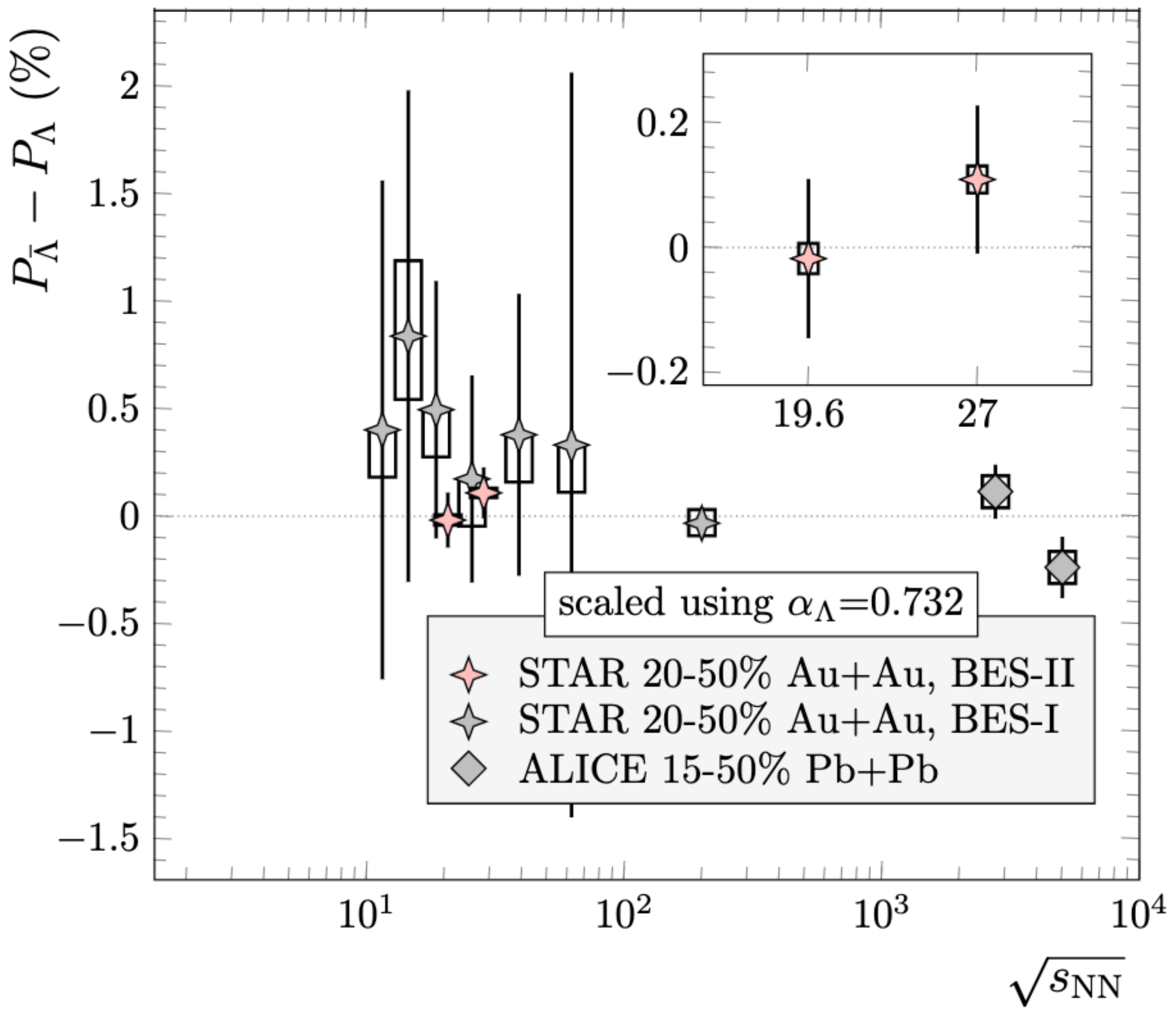




No system dependence at fixed centrality

Splitting of hyperon polarization



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

No splitting observed over wide range of beam energies

None in Isobar data either

At 95% confidence level late stage magnetic field (Initial field 10^{14}-10^{16} T)

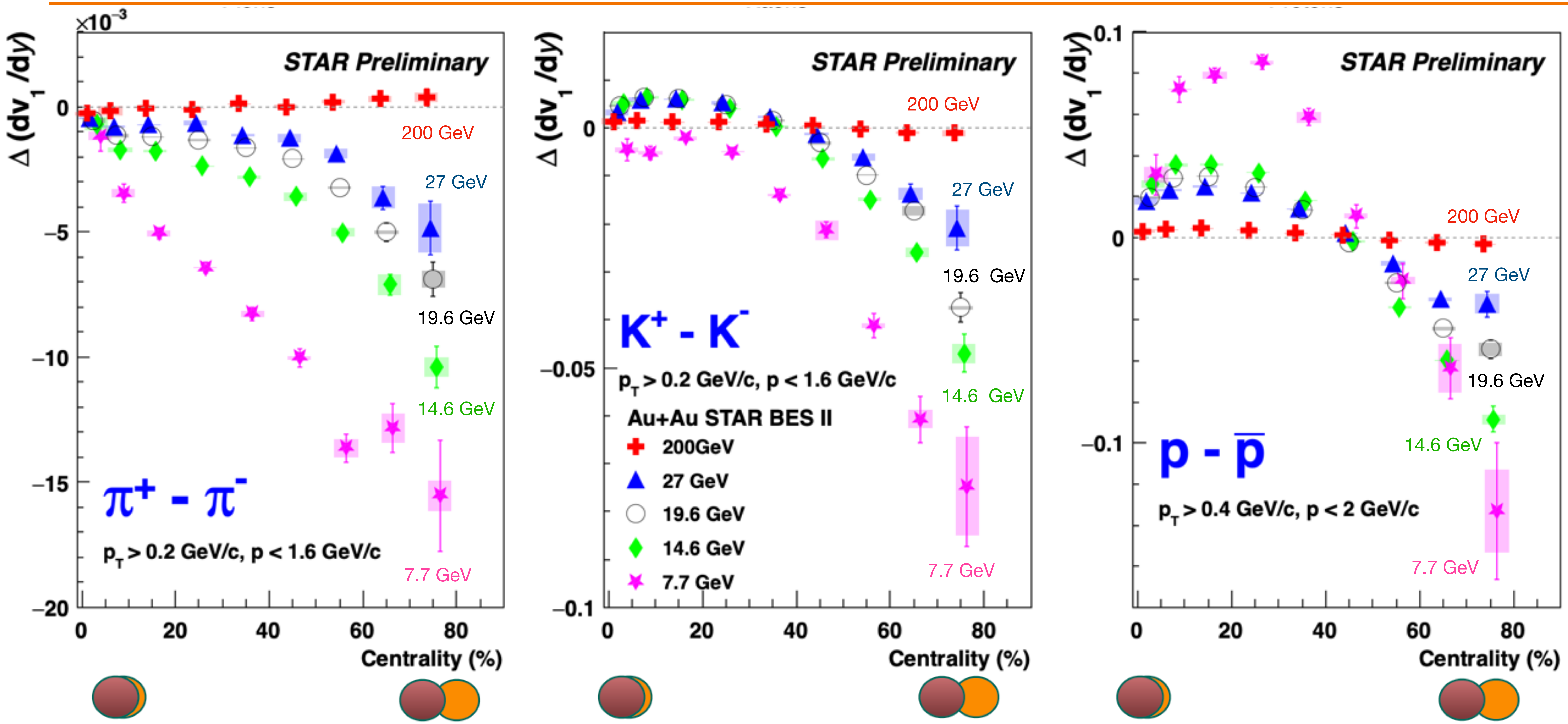
B(19.6 GeV) < 9.4×10^{12} T

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

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

X. Gou

Directed flow difference



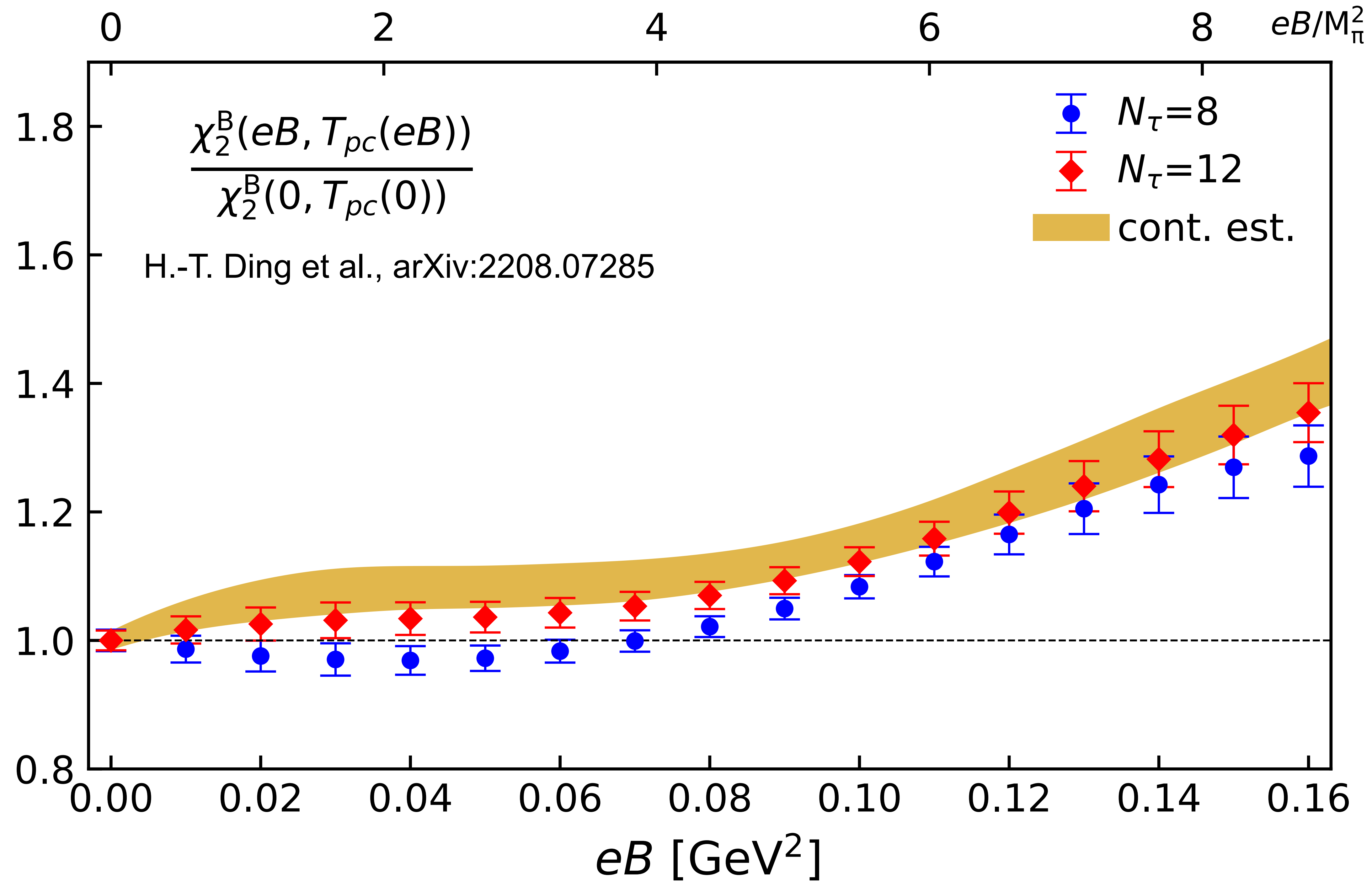
Different effects can/do dominate in different regimes - Have precision to hopefully disentangle

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

Net-proton cummulants at LHC

Lattice calculations suggest susceptibilities sensitive to initial EM field



I. Fokin

Net-proton cummulants at LHC

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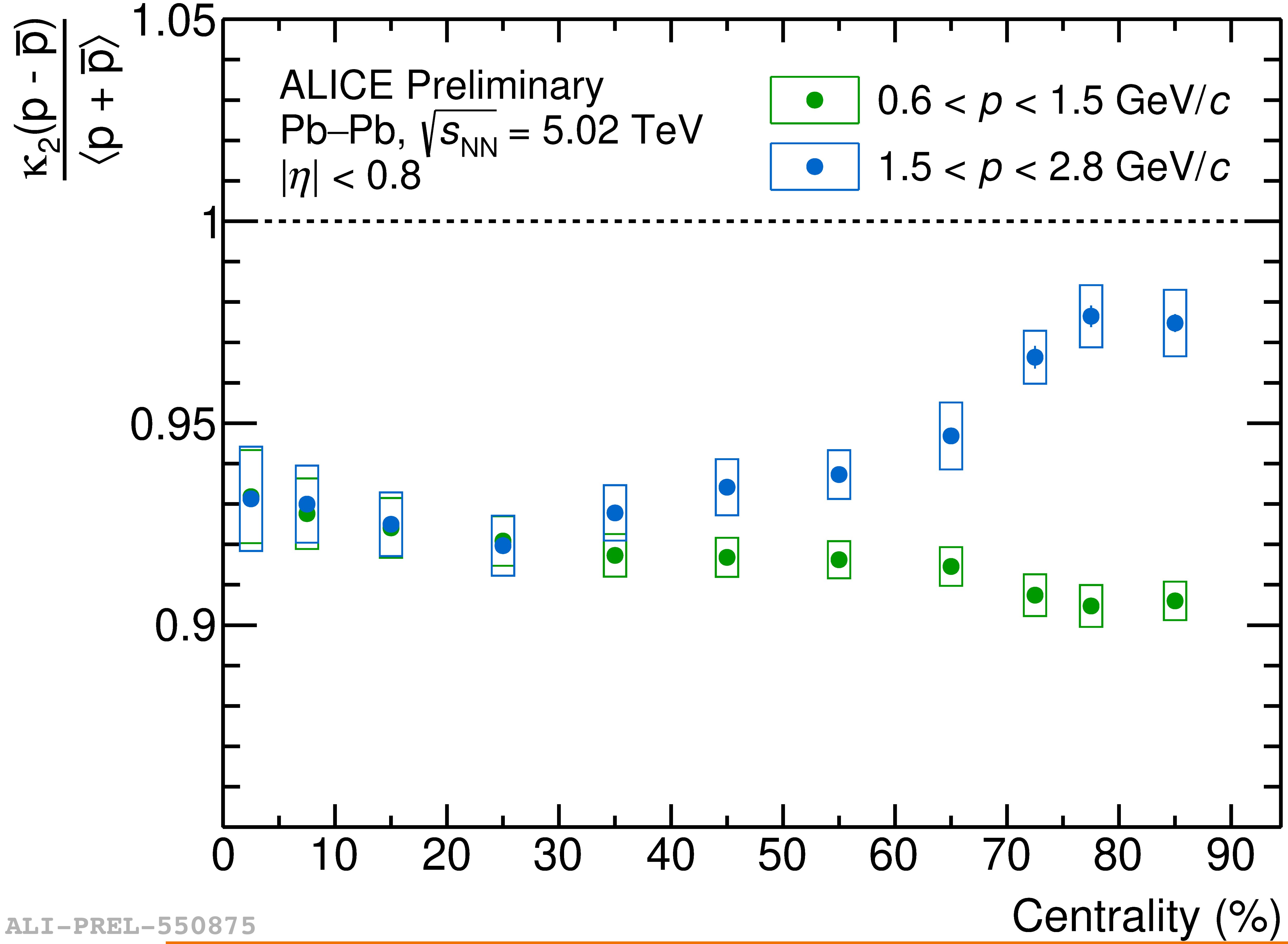
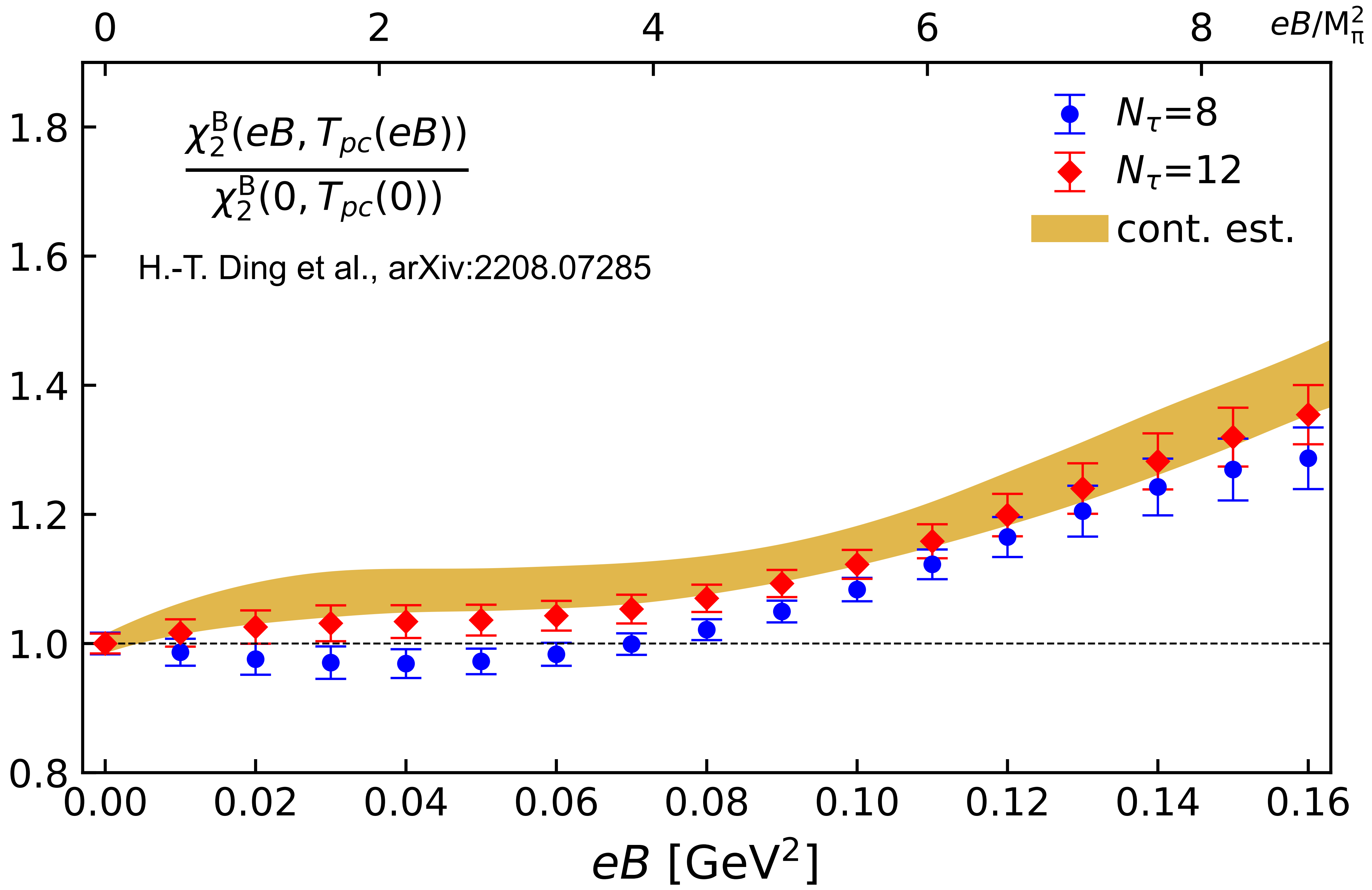




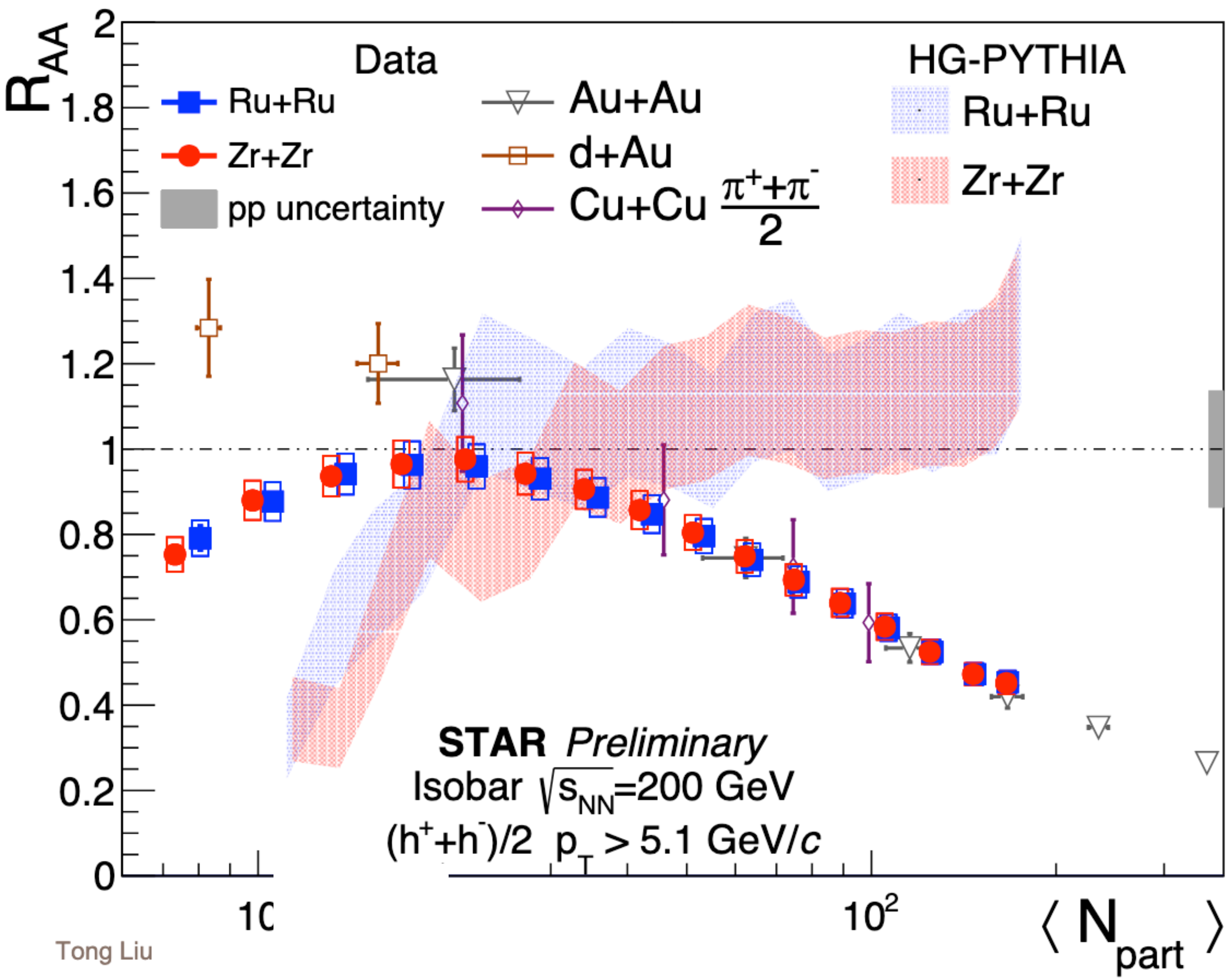
First measurement above 2 GeV/c

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

More discussion with theory and measurement in pp needed

Can We Understand the Nature of Parton Energy Loss to QGP?

Precision quenching measurements



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

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 $N_{part} \lesssim 20$

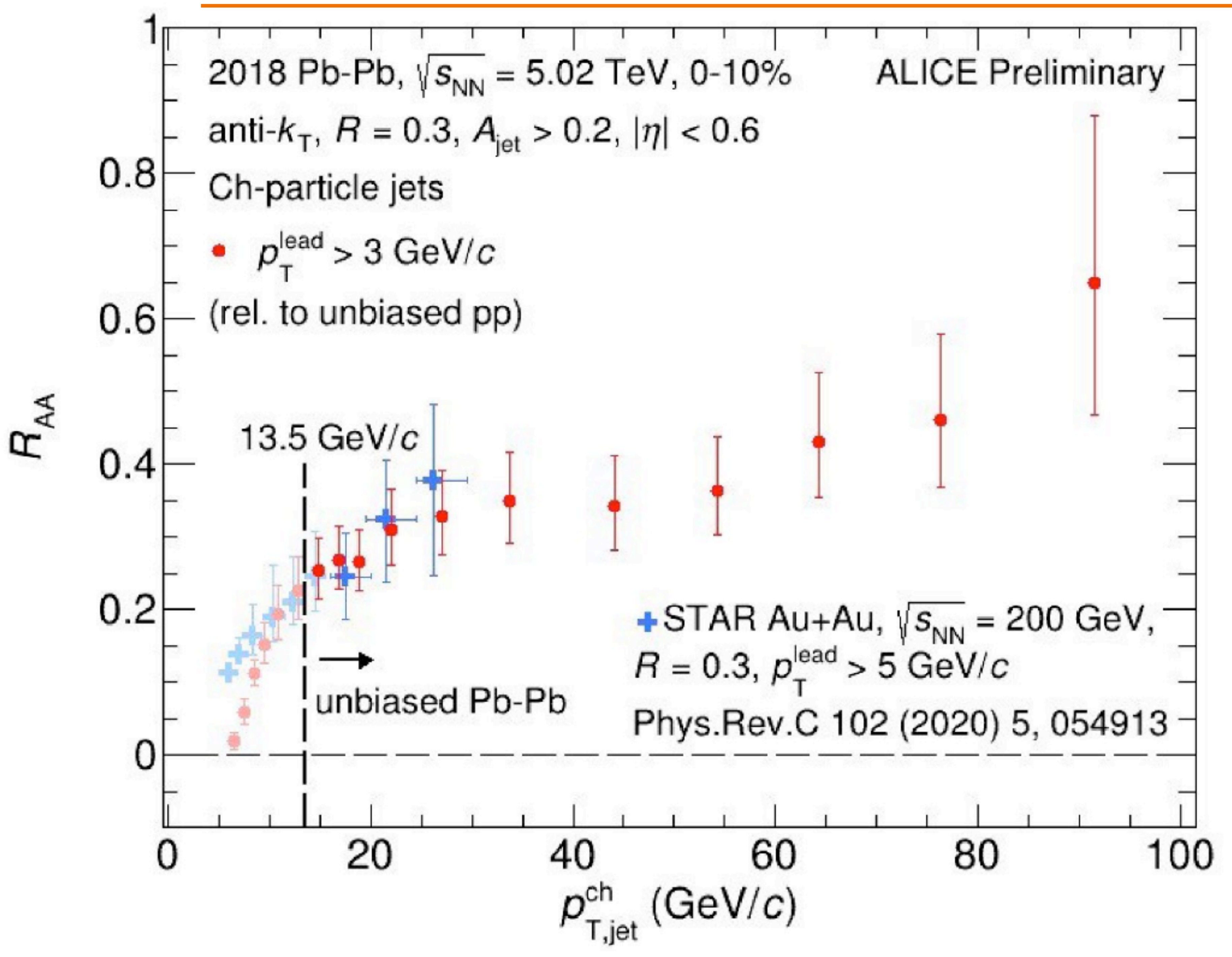
Event selection bias in peripheral events causes artificial suppression?

- 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

Nuclear modification of jets

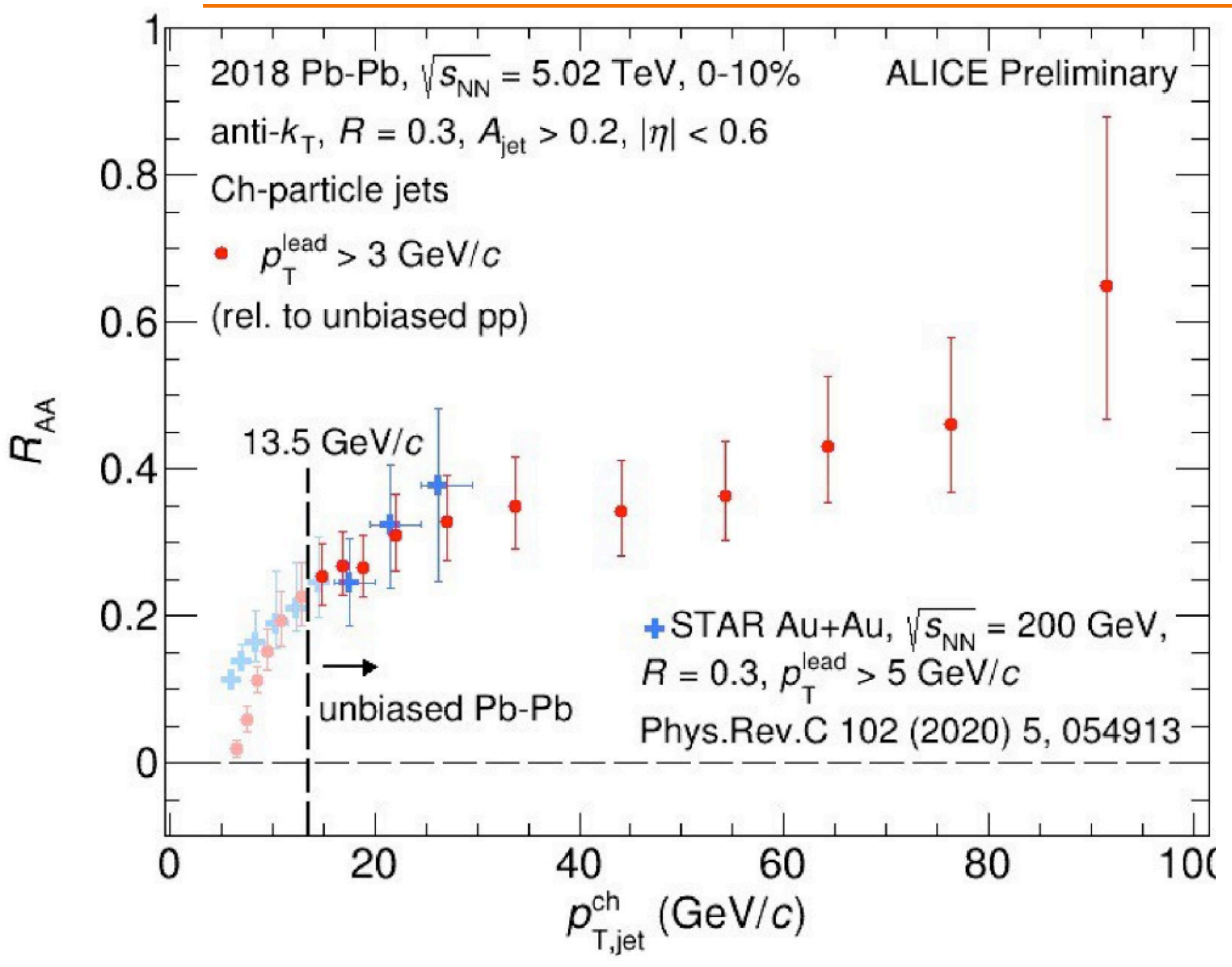


Charged jet results at same p_T for RHIC and LHC (N.B. scale by ~1.5 to get to full jet equivalent p_T)

Similar R_{AA} for both collision energies

N. Grünwald, C. McGinn

Nuclear modification of jets



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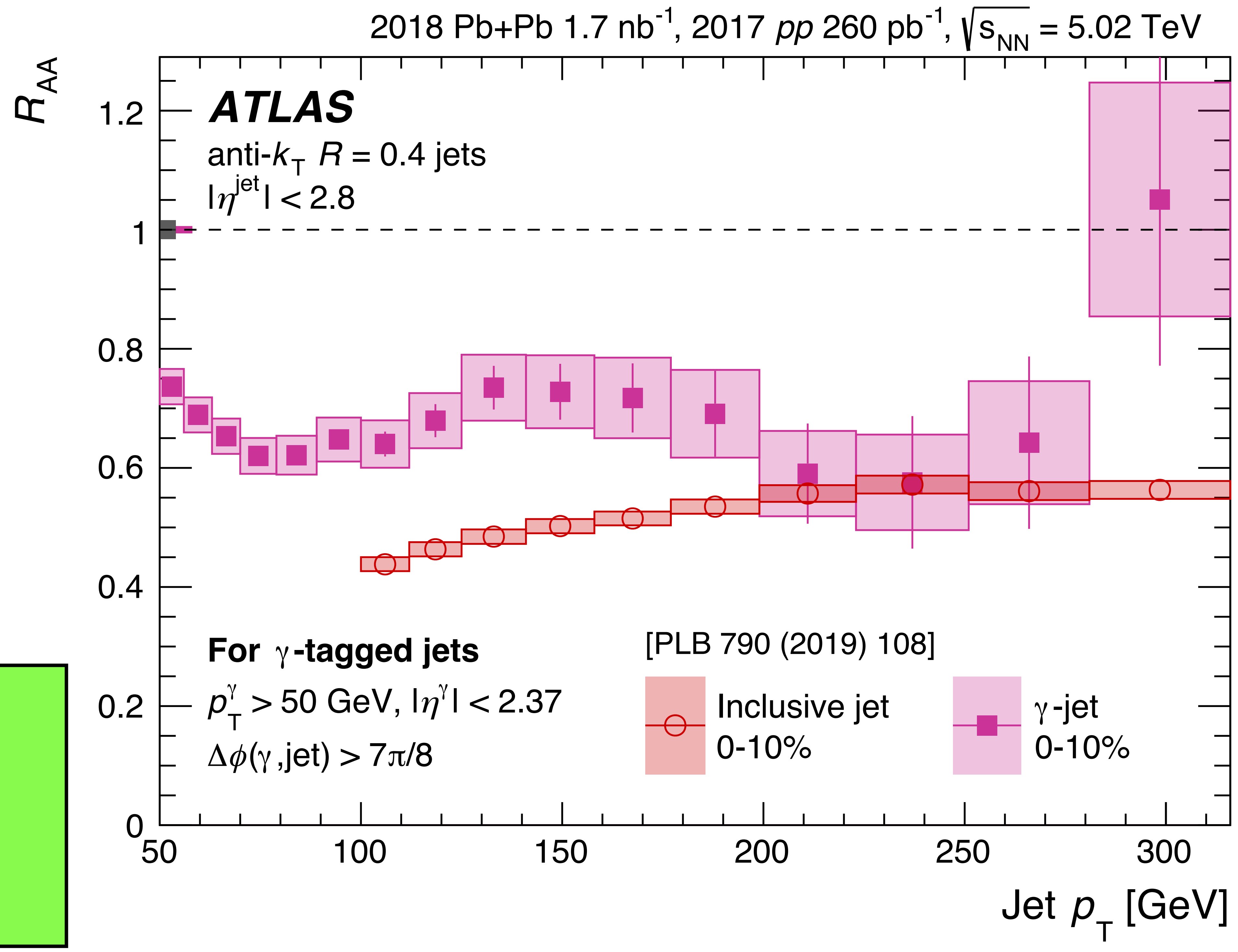


~ 80% quark jets

~ 40—50 % quark jets

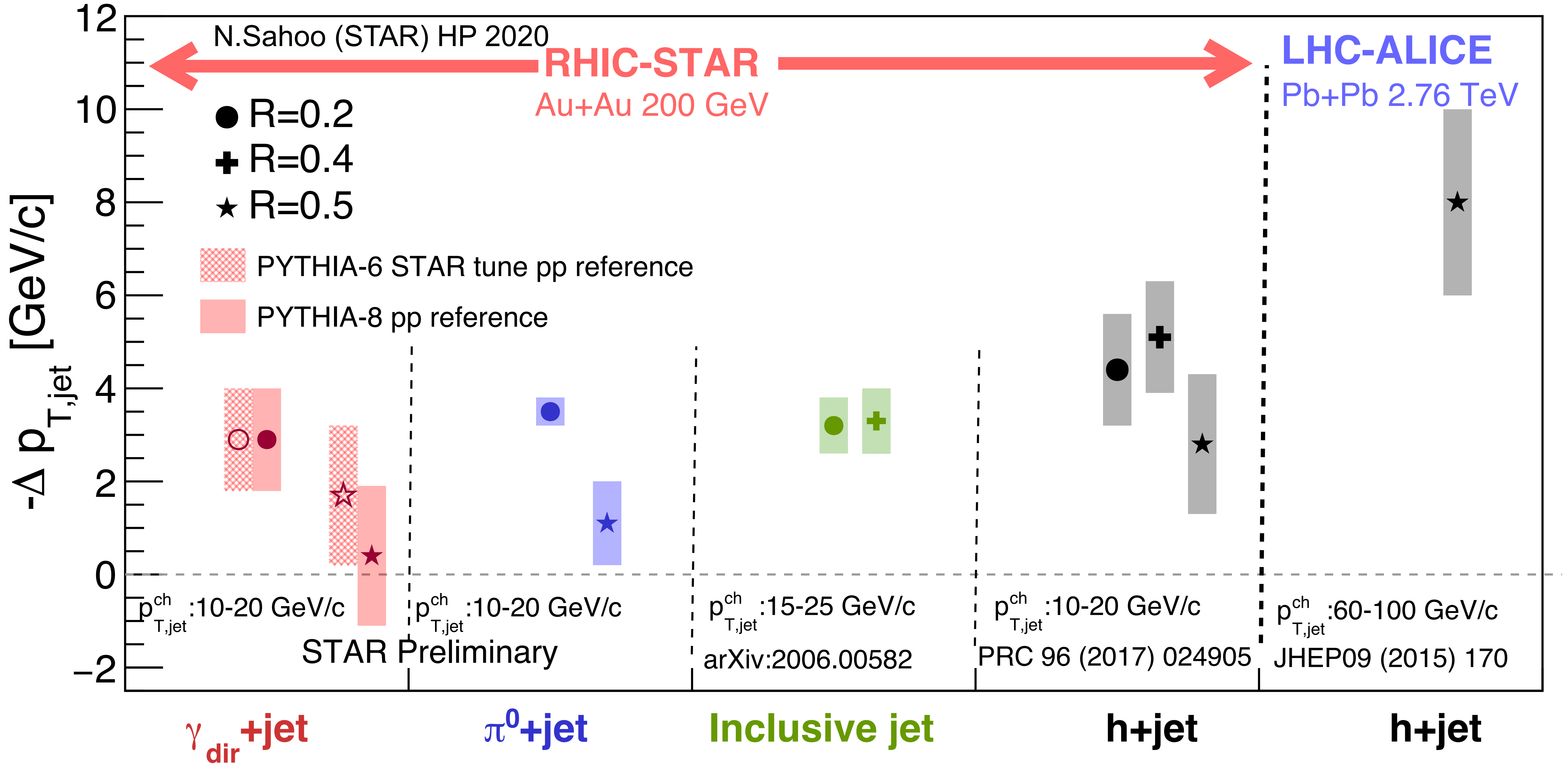
Clear difference in R_{AA} for inclusive and γ-tagged jets

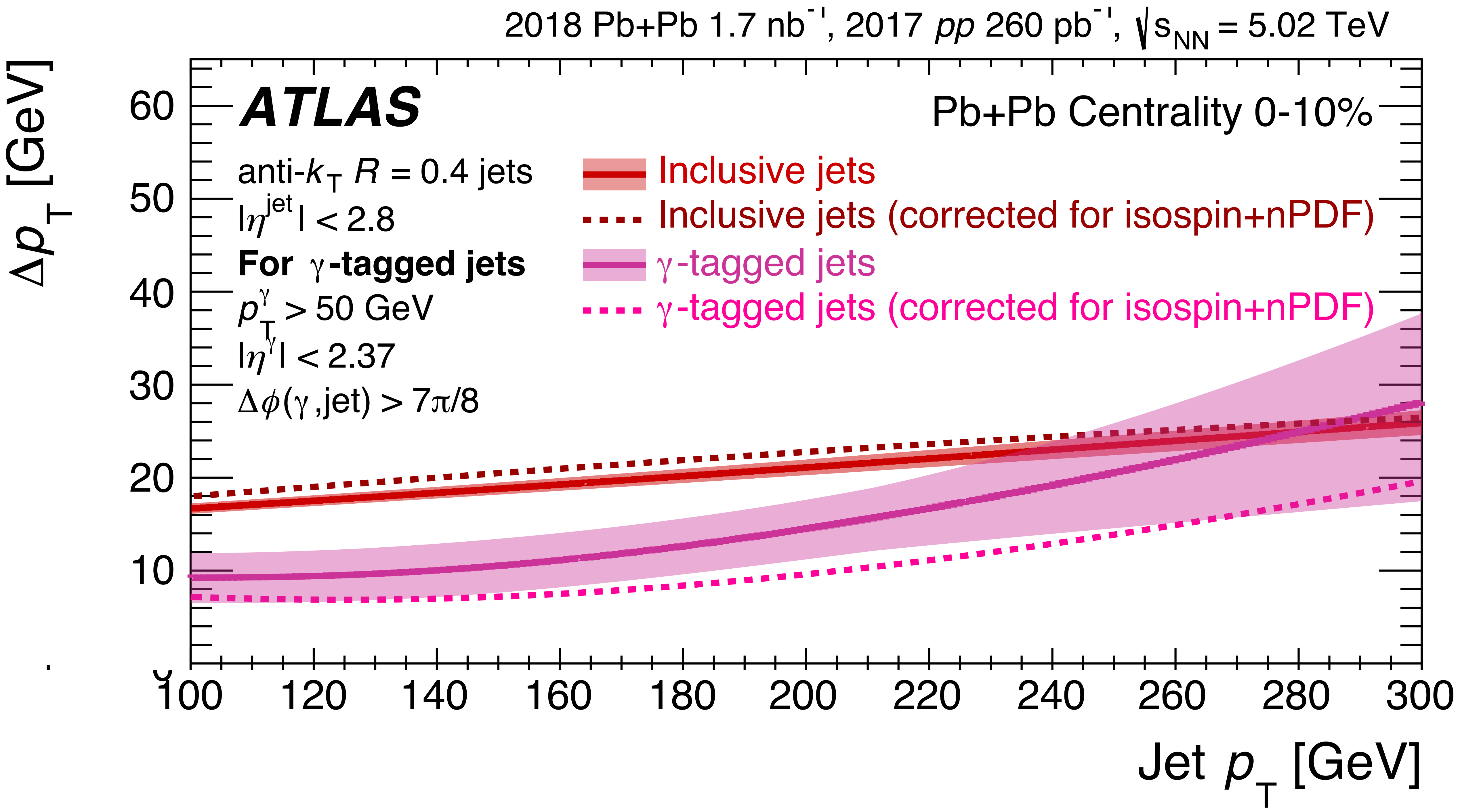
In both cases interpretation complicated due to differing slopes of pp baselines

N. Grünwald, C. McGinn

Energy loss of jets to QGP

Δp_T removes effect of changing pp spectra - first performed by PHENIX





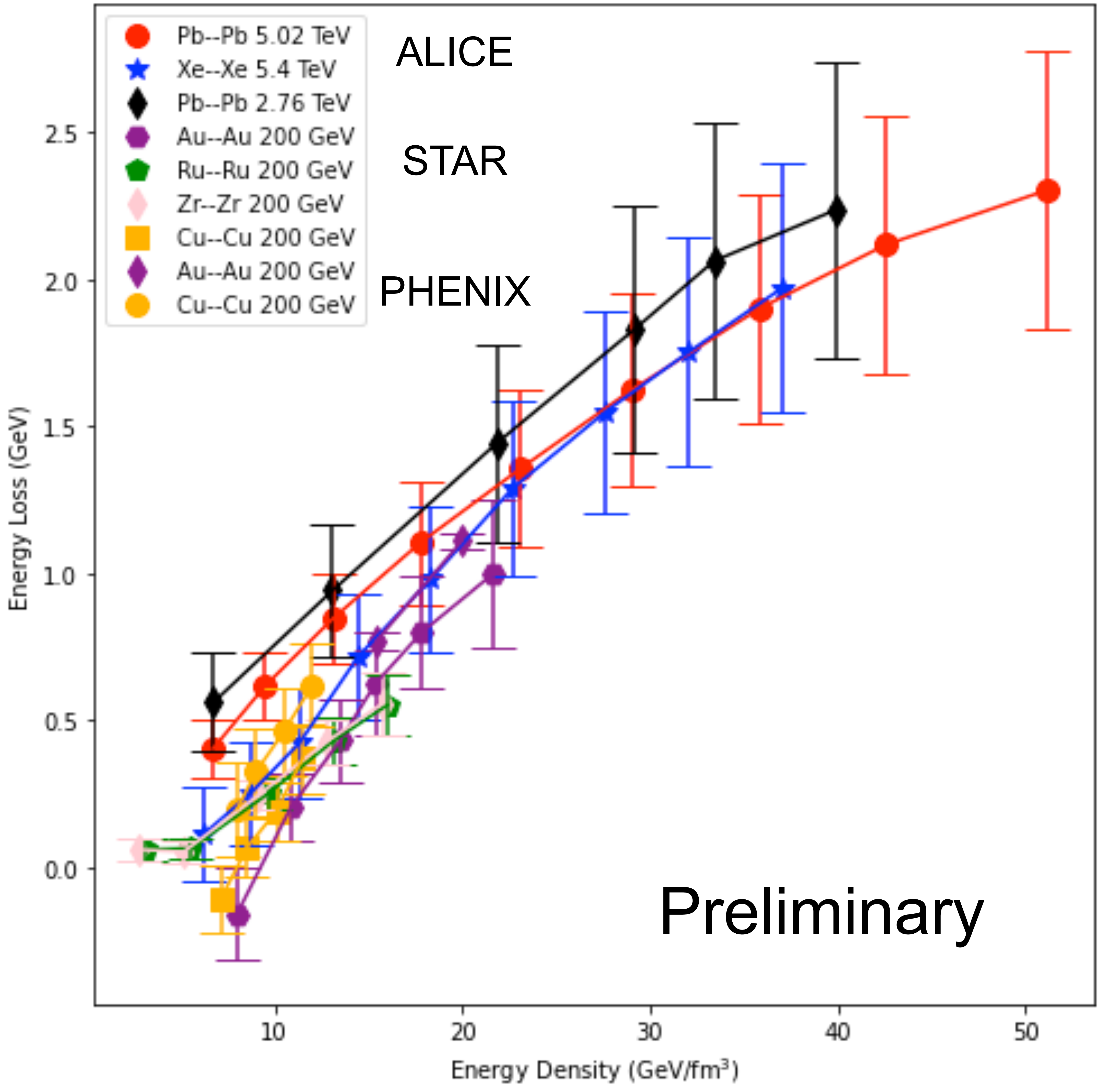
Δp_T (RHIC) < Δp_T (LHC)

Δp_T (quark) < Δp_T (g)

- Interesting to go in an unfold to "true" Δp_T of q and g

Need to also understand variation in E_{Loss} per jet from theory and experimental side

Energy loss vs energy density



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

E_{Loss} from: shift of p_T spectra

Approximate energy density from:

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

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

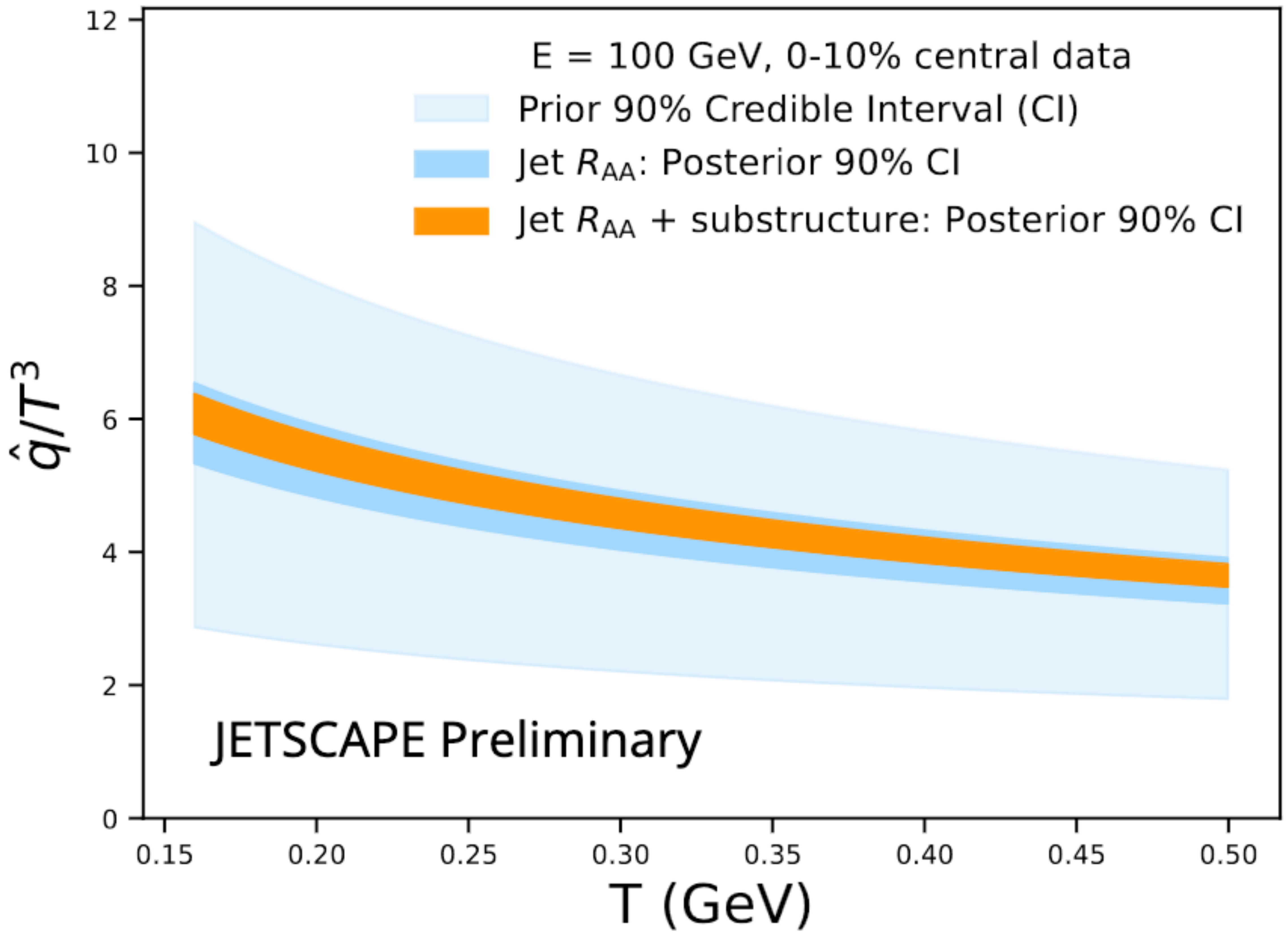
Given number of approximations reasonably reasonable correlation between E_{Loss} and ε_{init} over different species and collision energies

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

Maybe worth more careful calculation?

T. Hachiya, S. Schlichting

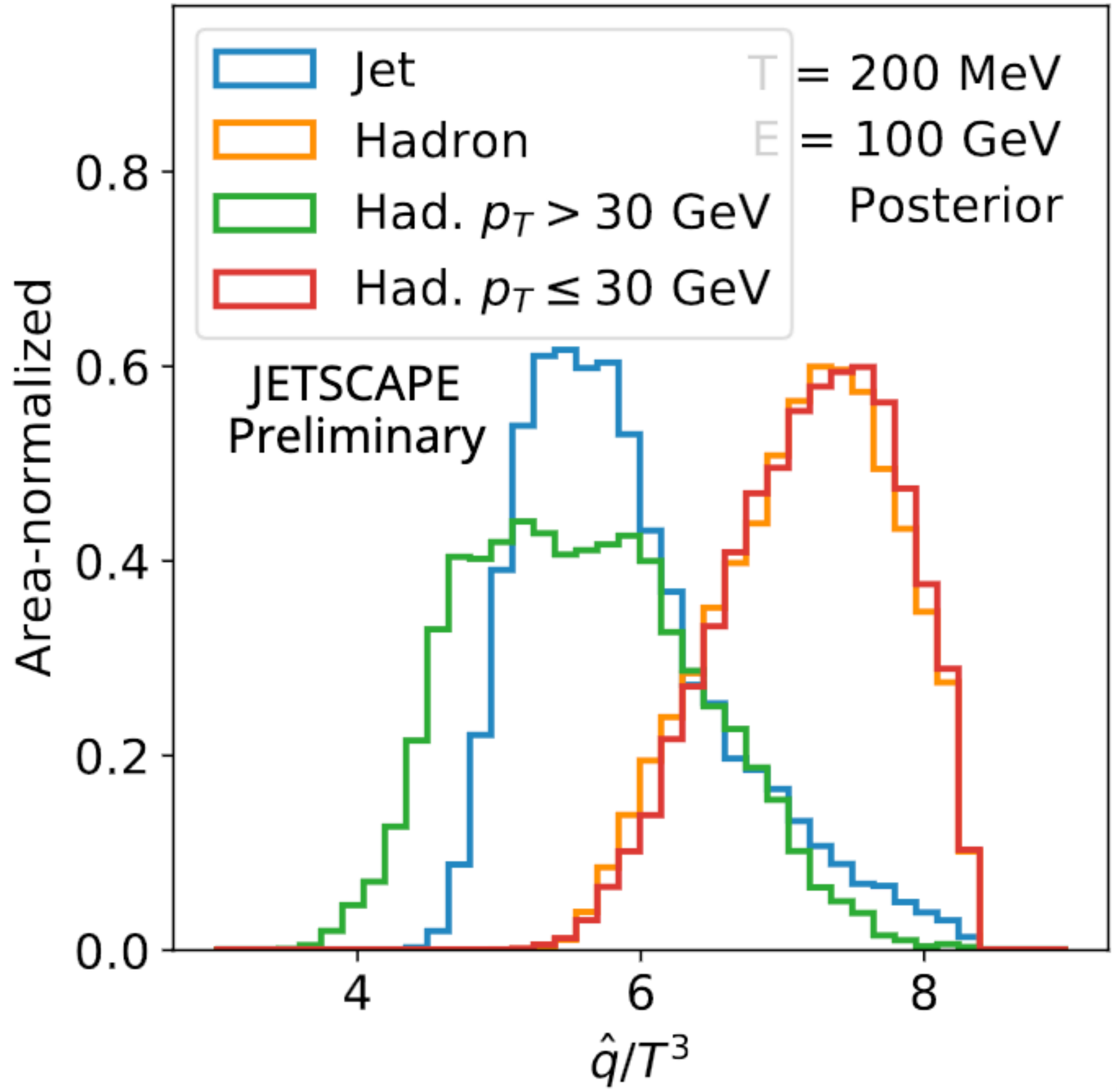
Exploiting bayesian inference



Advances continue - especially via JETSCAPE (but not only)

Now includes jet R_{AA} and substructure measurements

Some tension when include hadron R_{AA}



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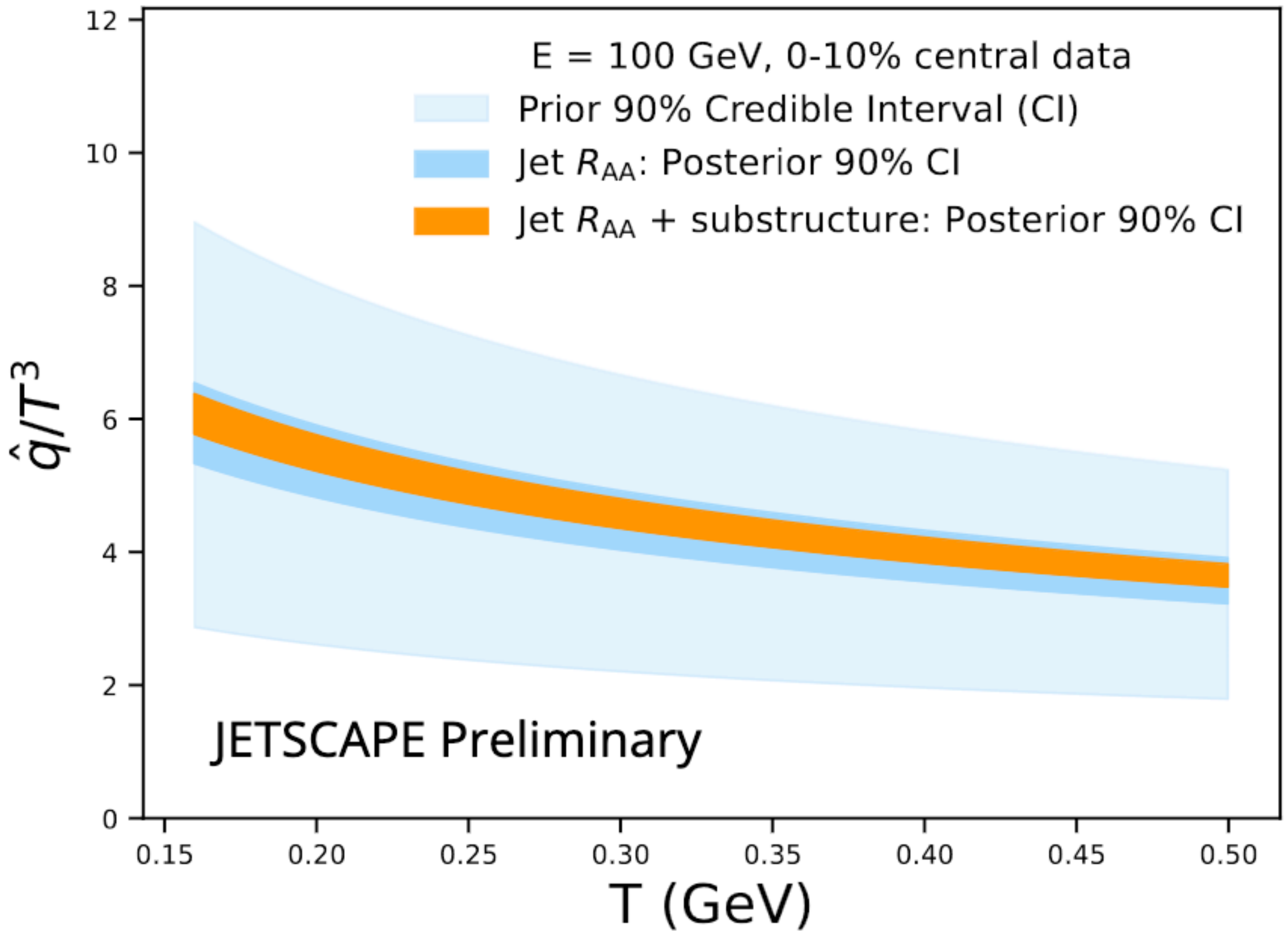

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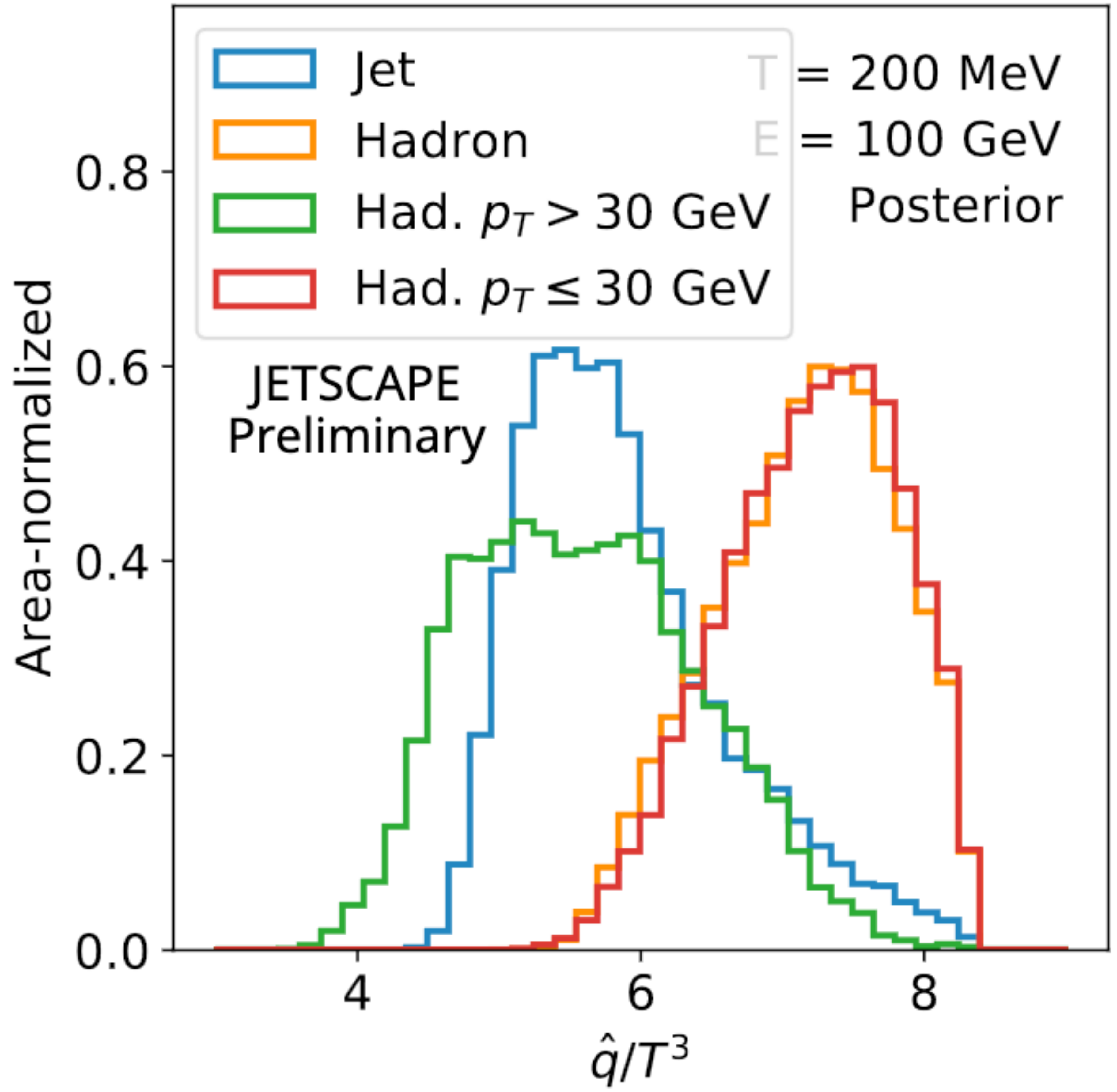


Some tension when include hadron R_{AA}

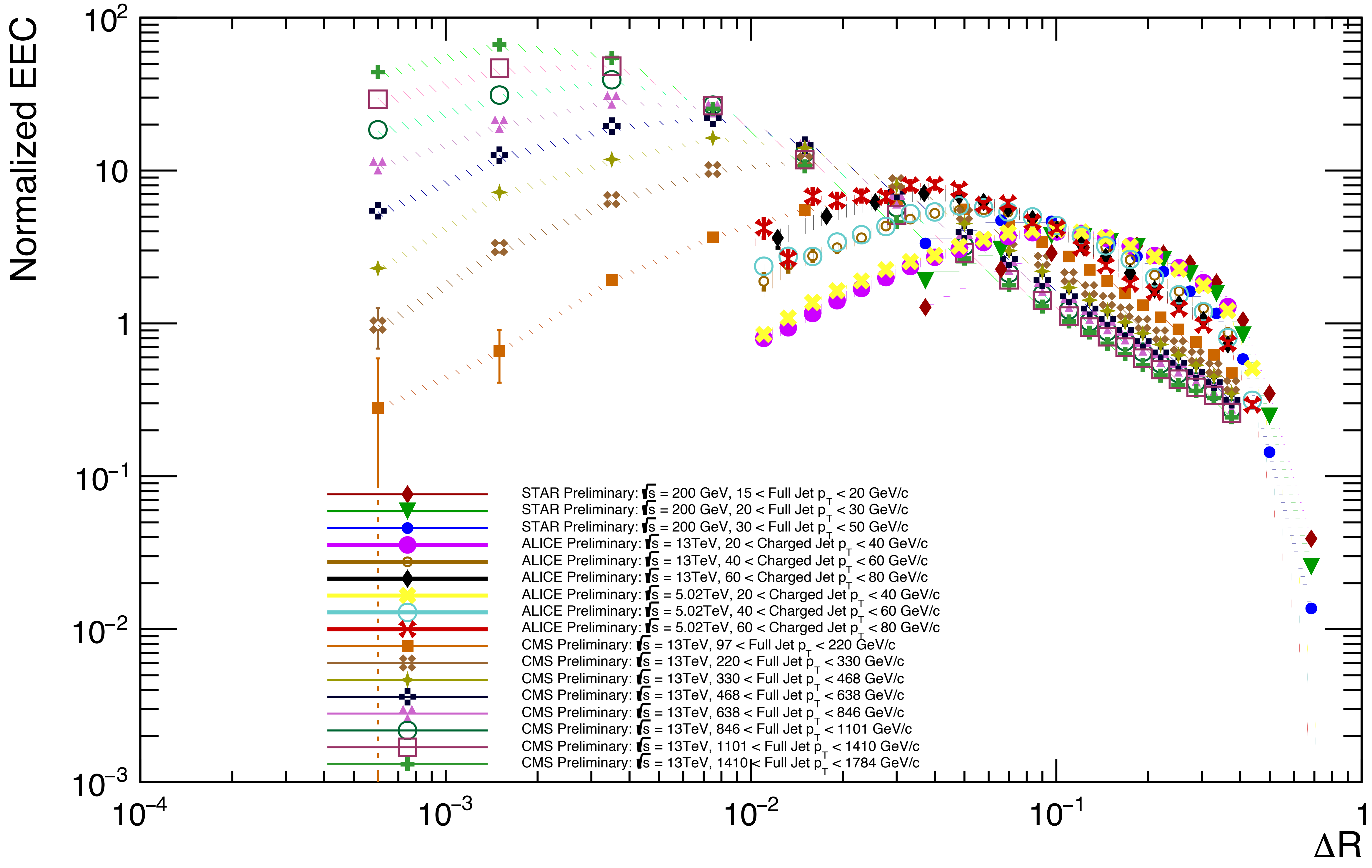
Some physics missing?
Uncertainties incorrect?
Theory uncertainty critical?
All of the above?

R.Ehlers

Probing energy flow in jets

N-point Energy Correlators

Perturbative region grows as jet p_T increases



B. Liang-Gilman, W Fang, I. Moult, A. Rai, A. Tamis

Probing energy flow in jets

N-point Energy Correlators

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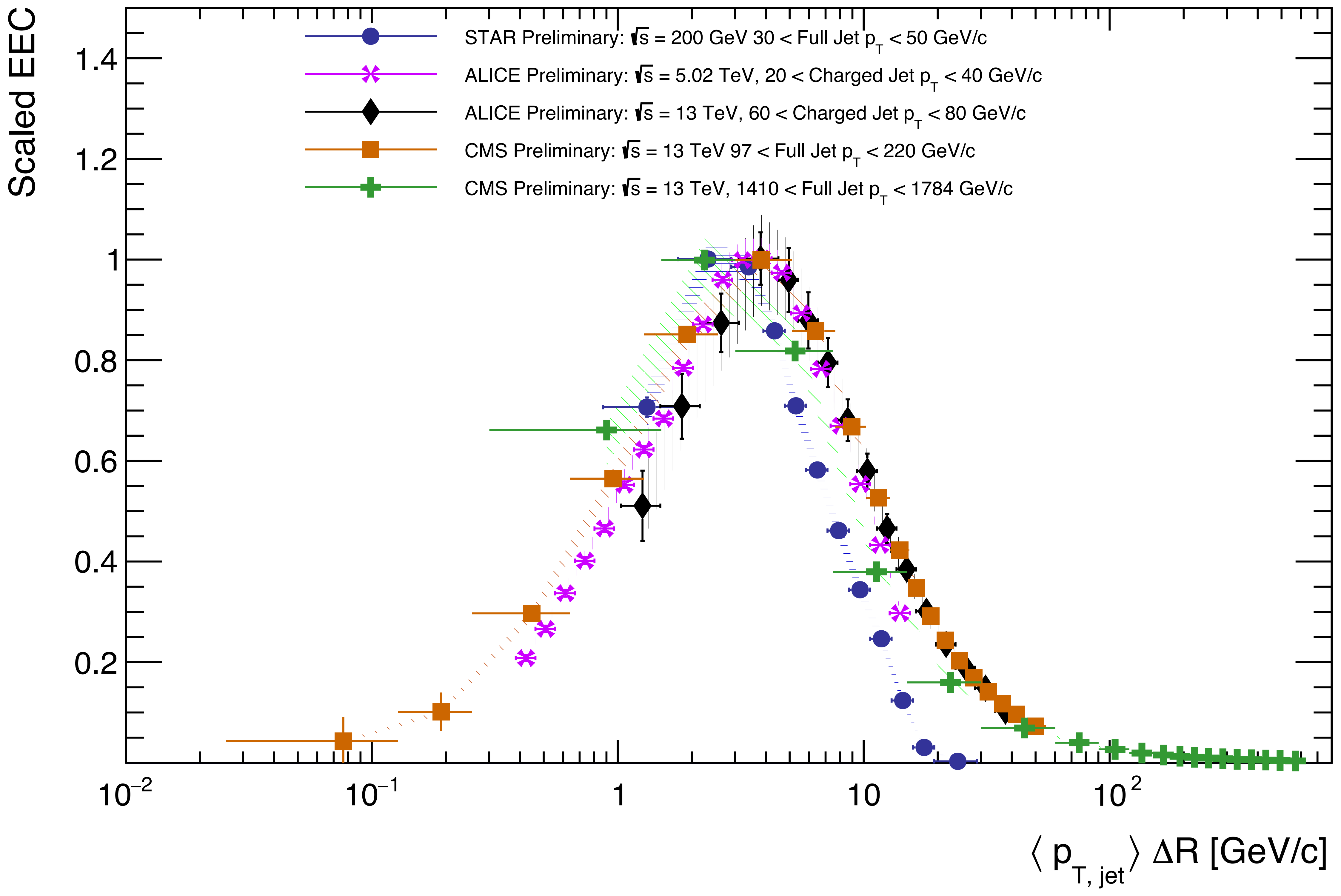
Scaling by jet p_T: universal transition point
- HF jets' transition point affected deadcone



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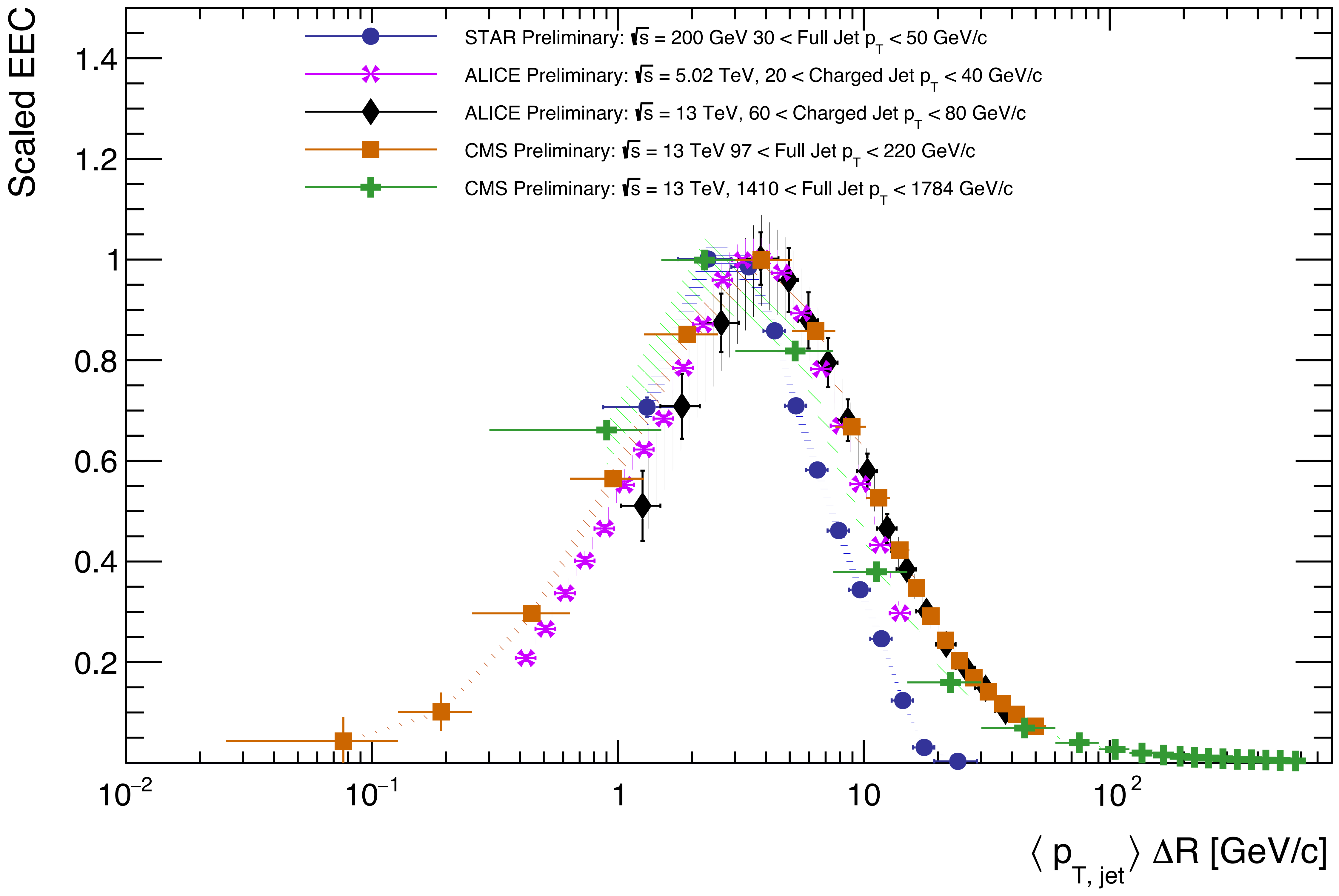
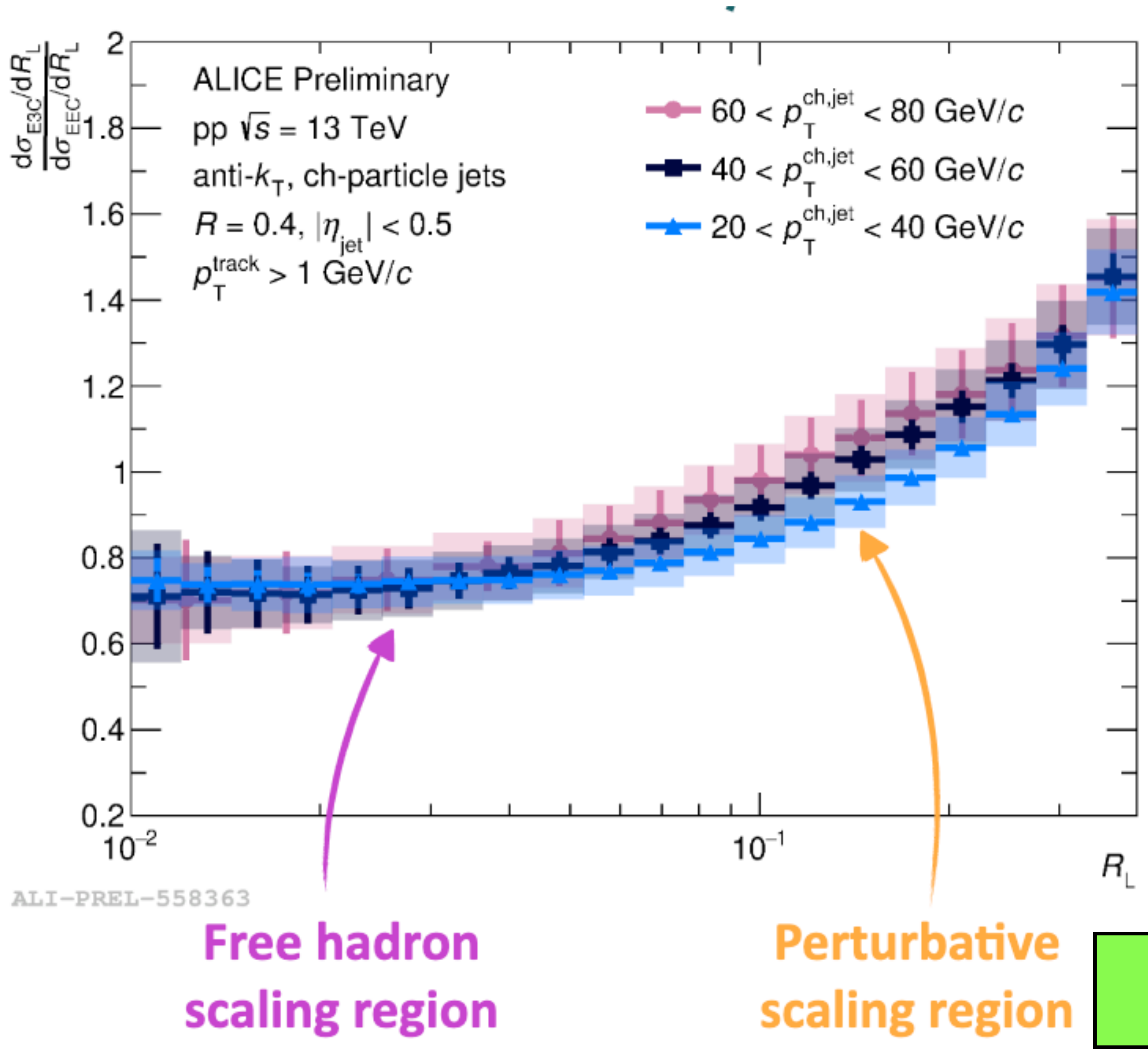




Ratio of 3-point/2-point correlators:

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

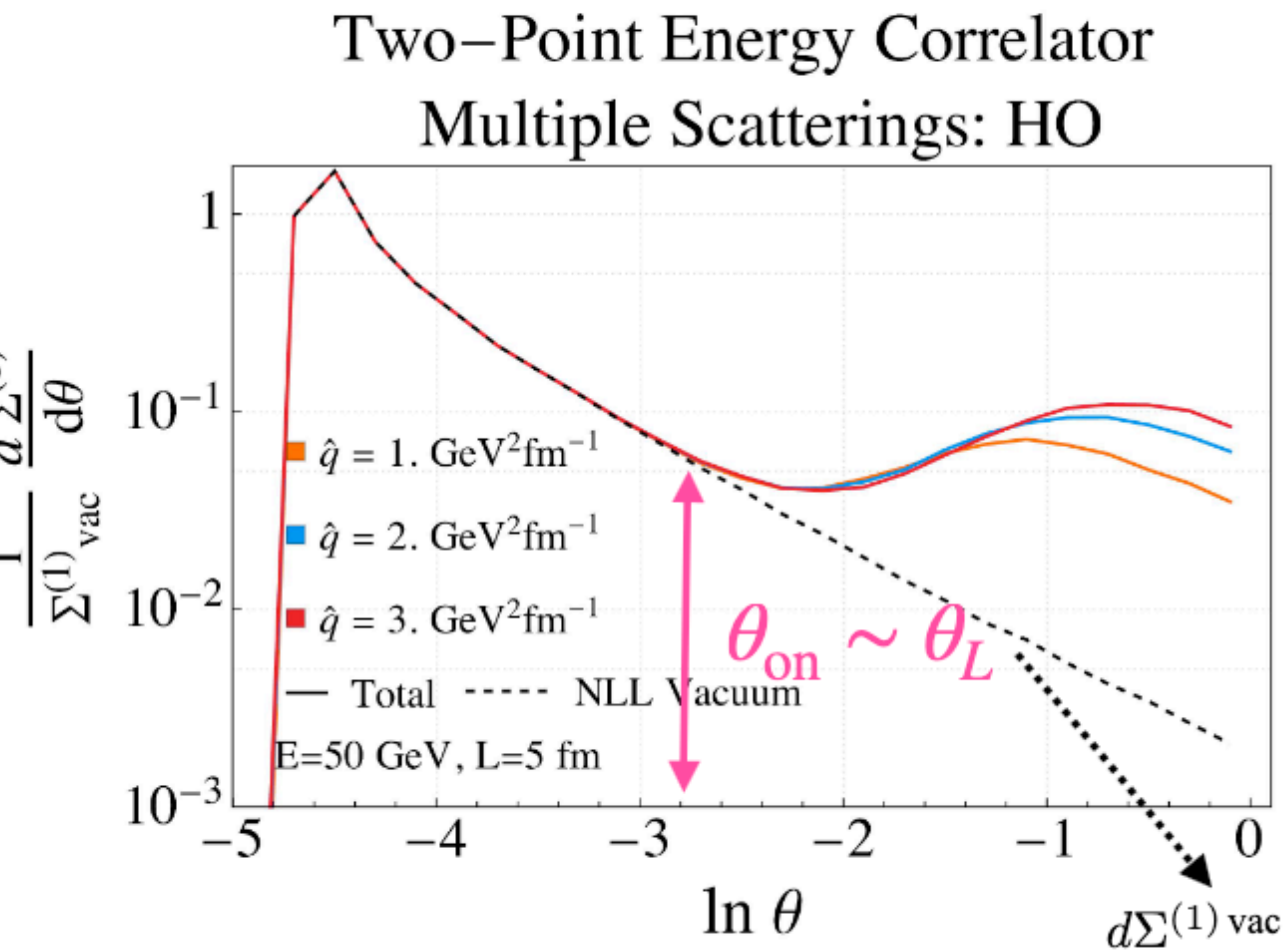
B. Liang-Gilman, W Fang, I. Moult, A. Rai, A. Tamis

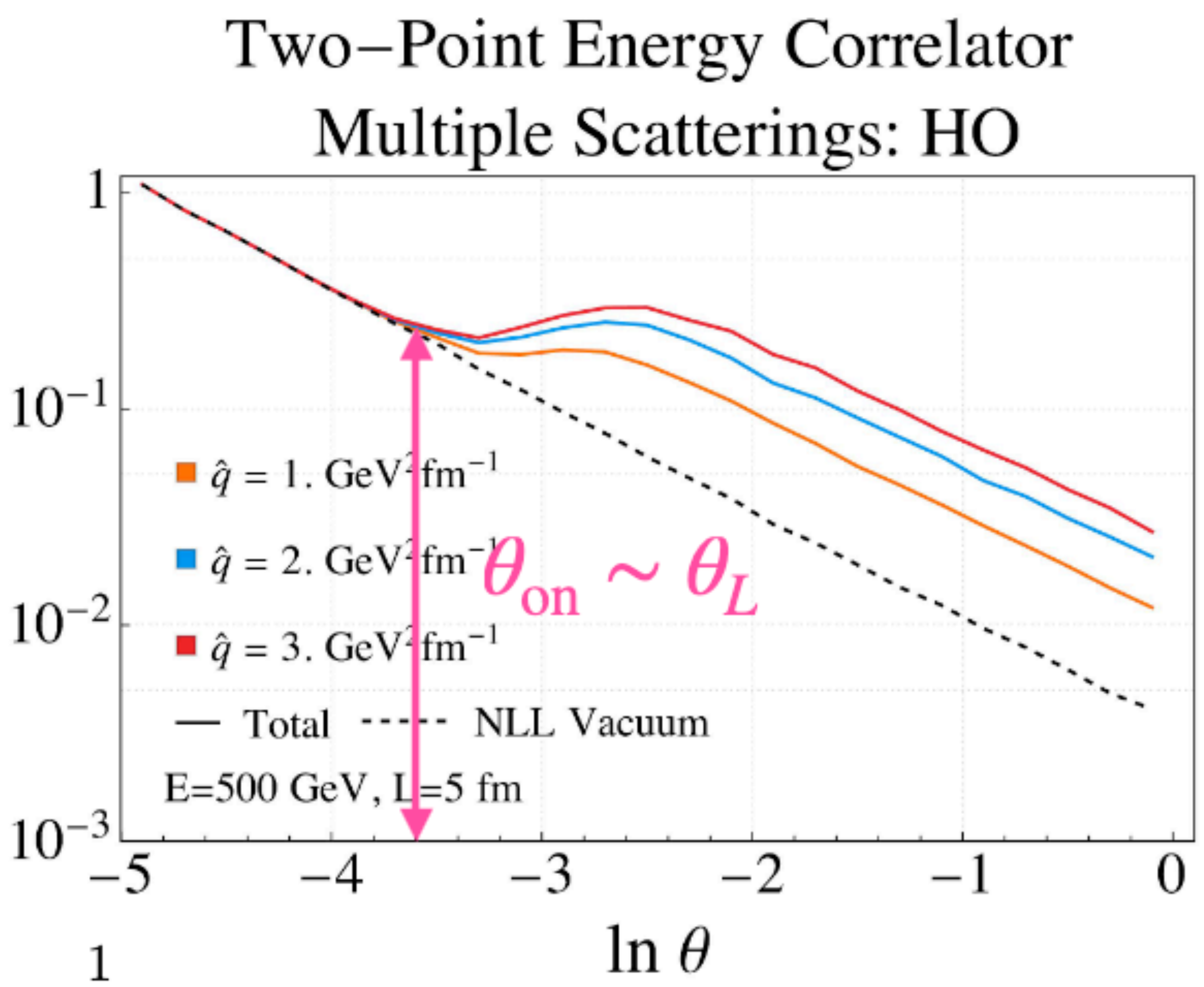
Sensitivity to medium effects

First study using static toy model and no background

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

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





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

Medium-induced radiation effects only at small angles

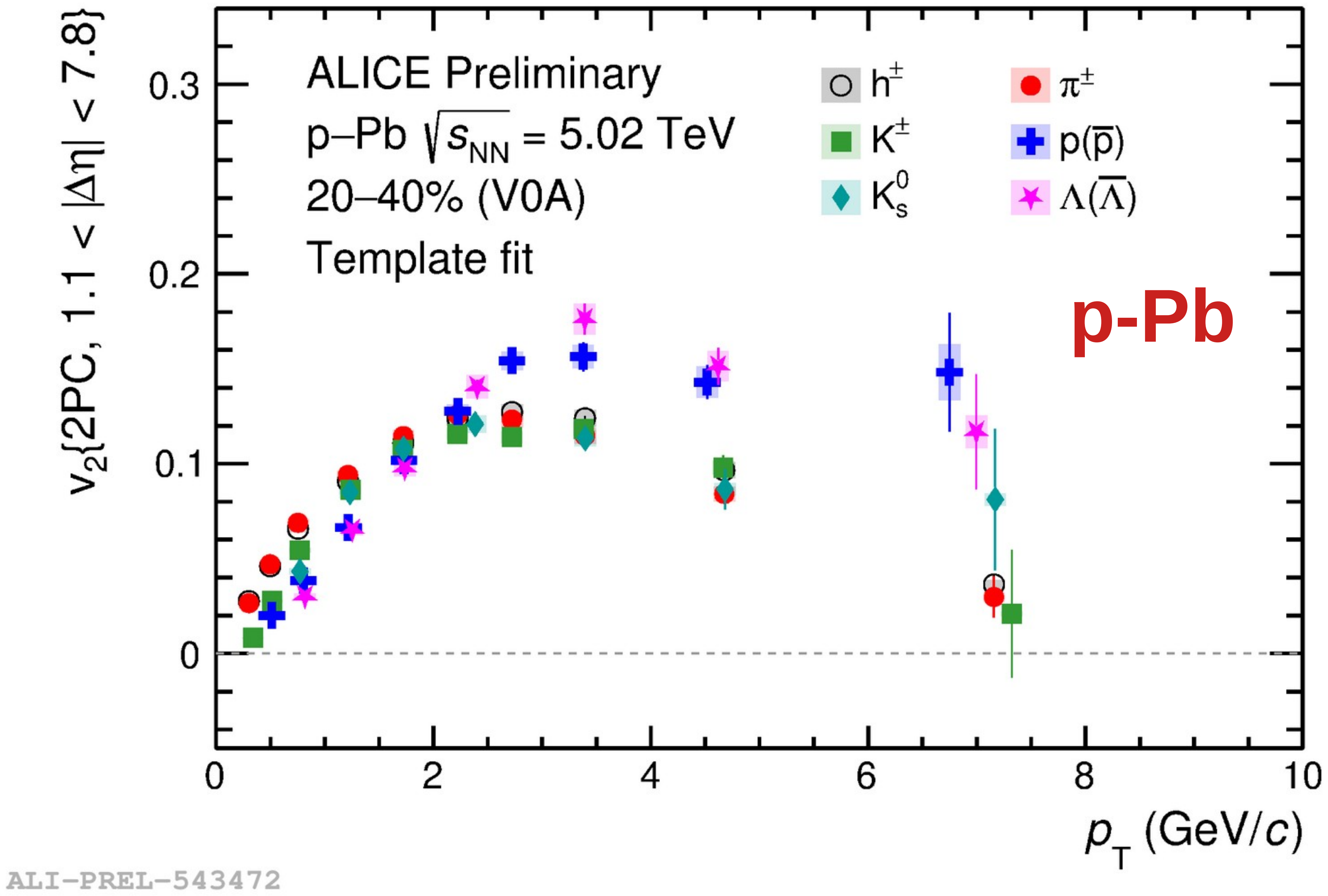
θ_{onset} independent of $\hat{q}$

How does more realistic simulation look?

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

Can We Understand Small Systems?

Small system flow

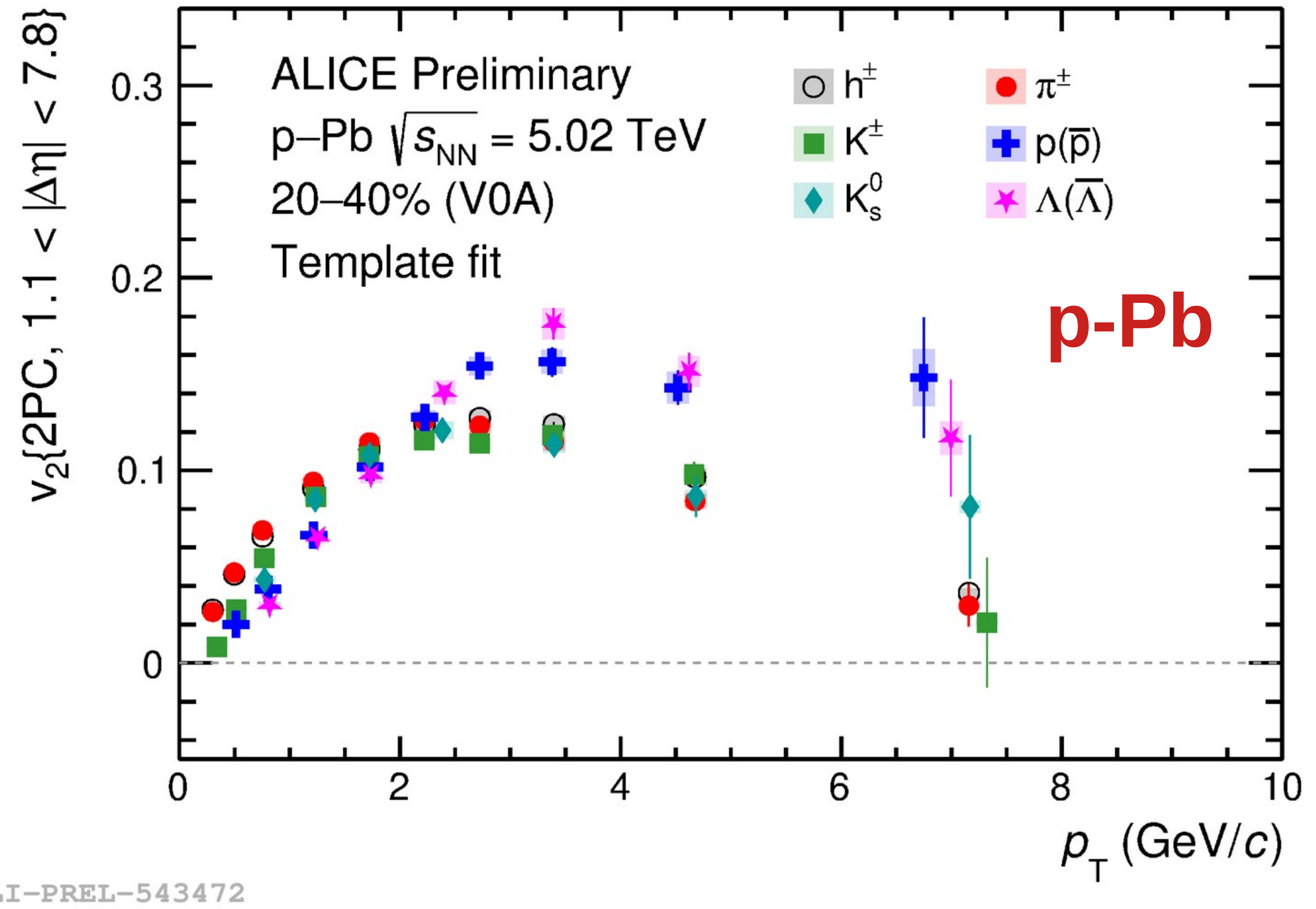


Low p_T - mass ordering

Intermediate p_T - NCQ scaling

B. Schenke, M.Zhao

Small system flow



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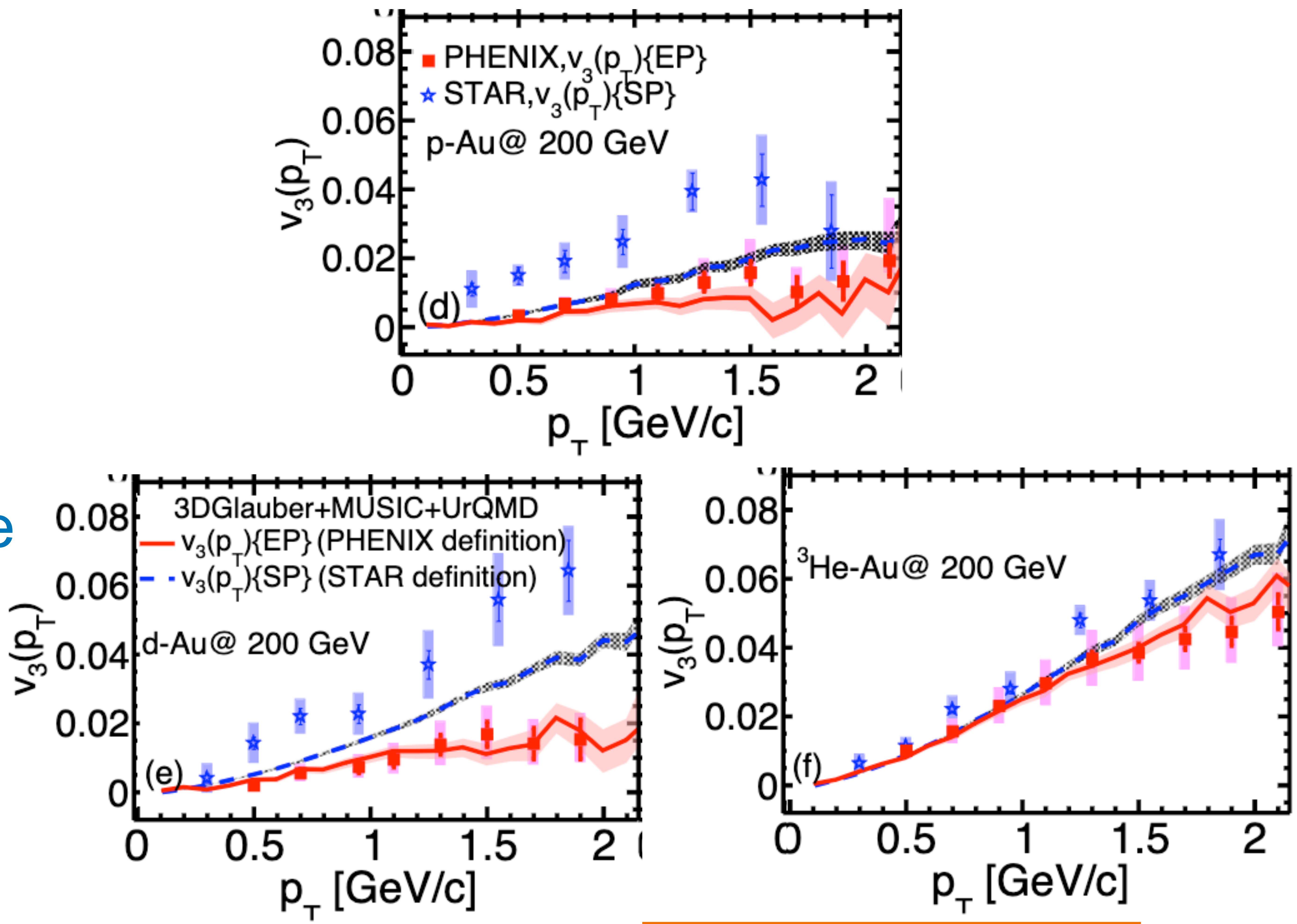
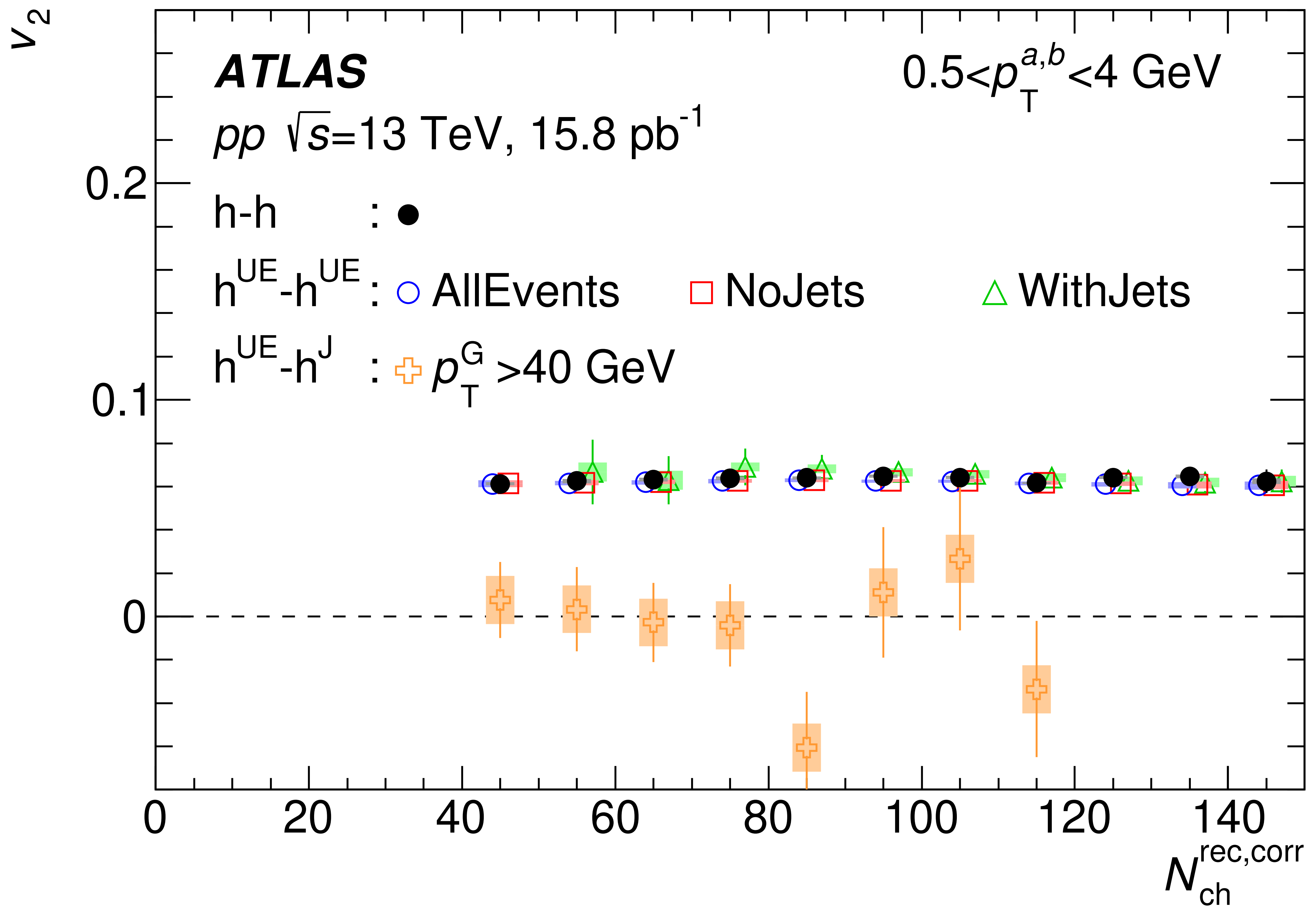


v_2 and v_3 differences at RHIC largely due to use of different rapidity ranges

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

B. Schenke, M.Zhao

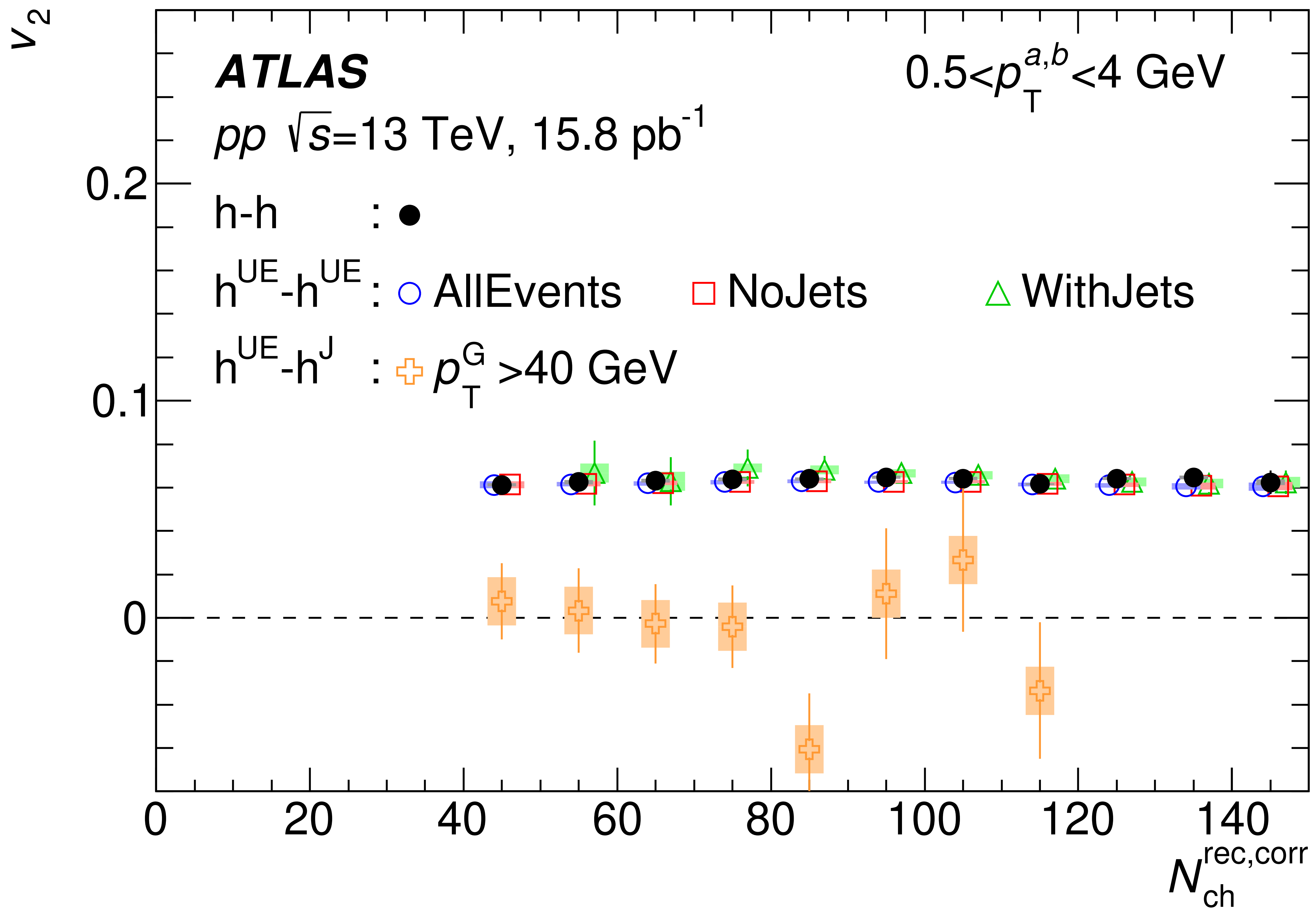
Small system jet v_2



UE in both pp and pPb : strong v_2

jet constituent - UE in pPb: $v_2 = 0$

Small system jet v_2



But…

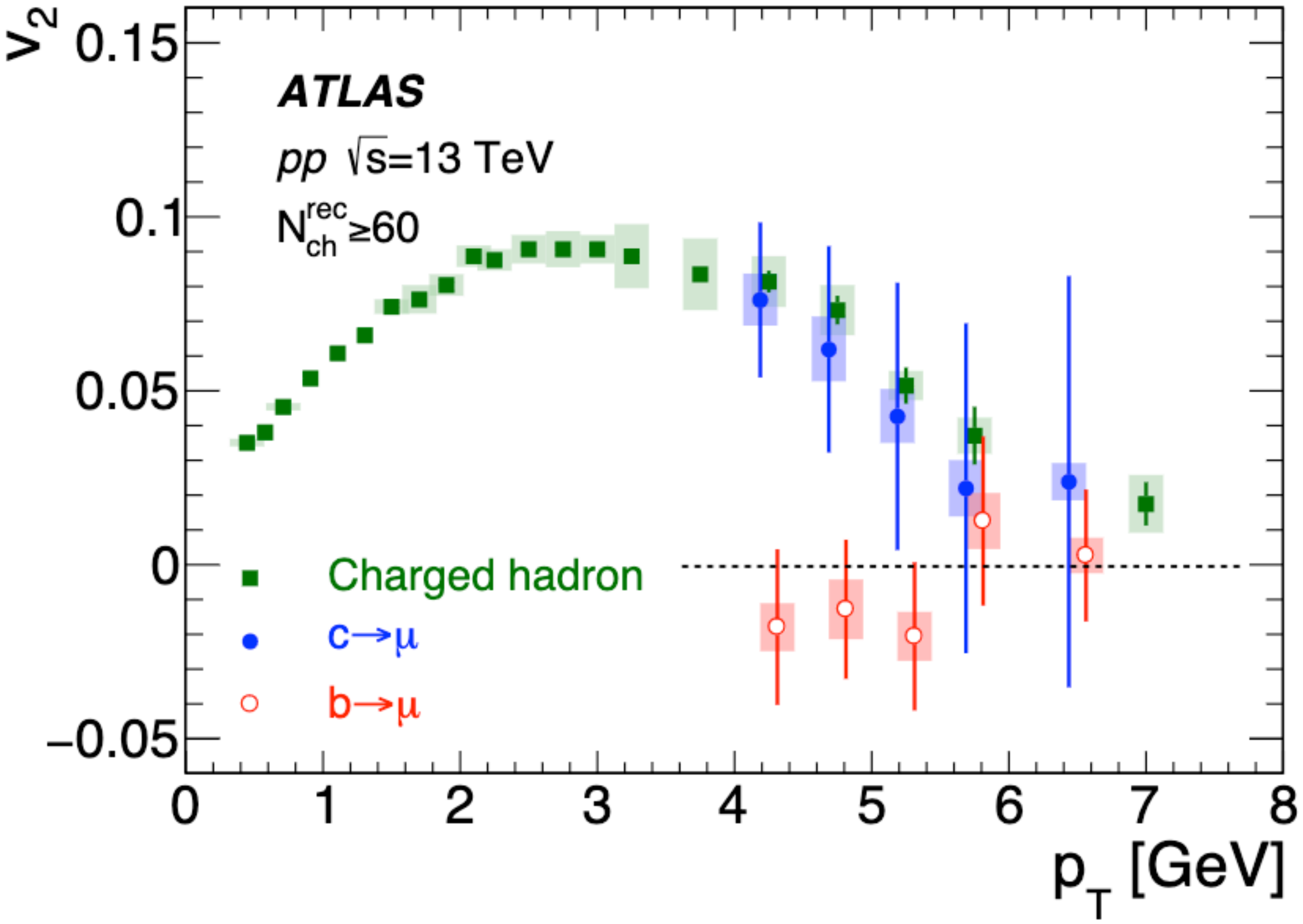
We've also observed v_2 of high p_T charged hadrons

So what is high p_T v_2? mini-jets? Different analysis sensitivities?

UE in both pp and pPb : strong v_2

jet constituent - UE in pPb: $v_2 = 0$

ATLAS, PRL 124 (2020) 082301



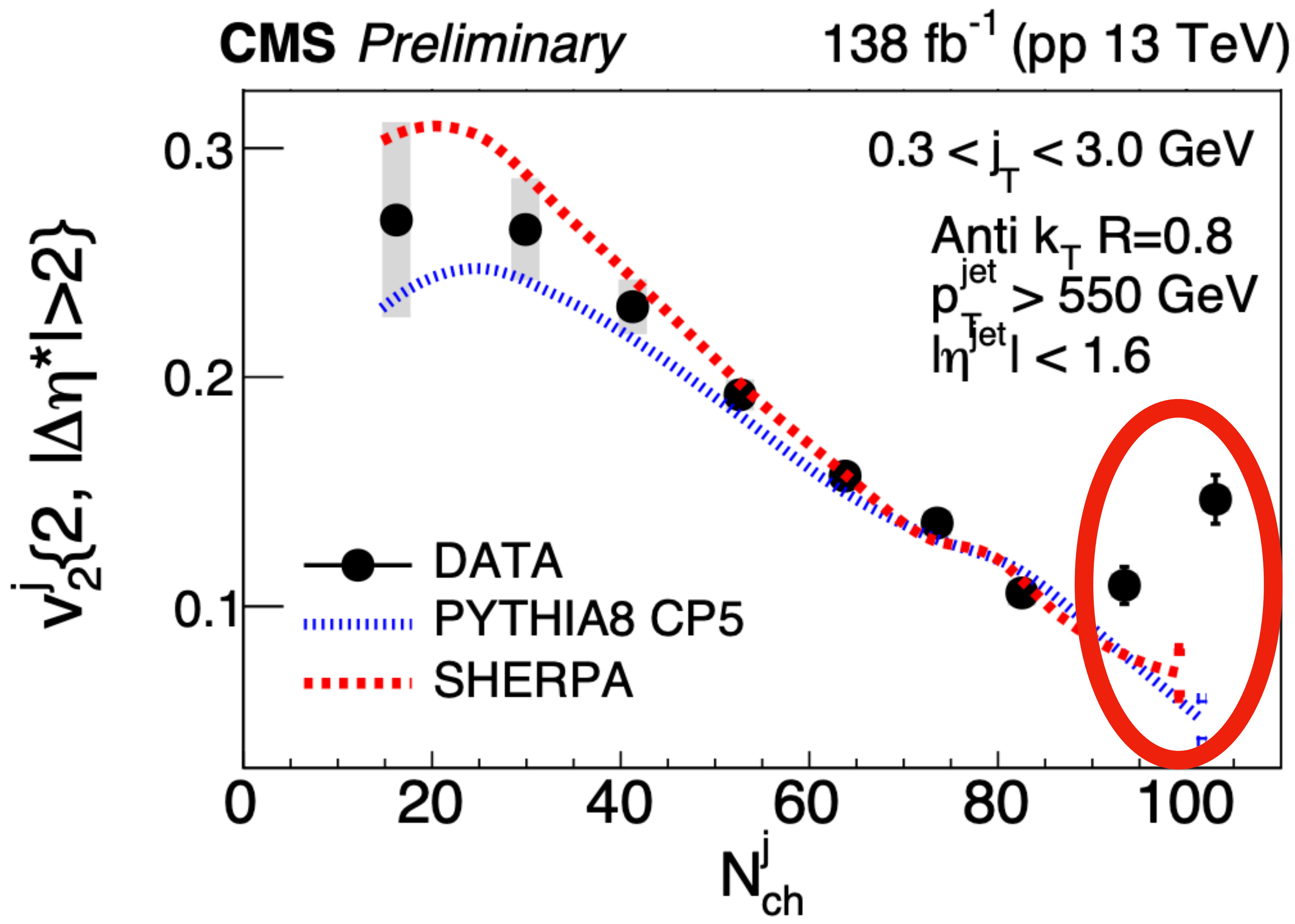
Collectivity within a jet?

v_2 also reported between constituents within jet

Well described by theory for $N_{const} < 80$

Dramatic uptick for $N_{const} > 80$

Density high enough in jet cone that partonic scatterings occurring during fragmentation?



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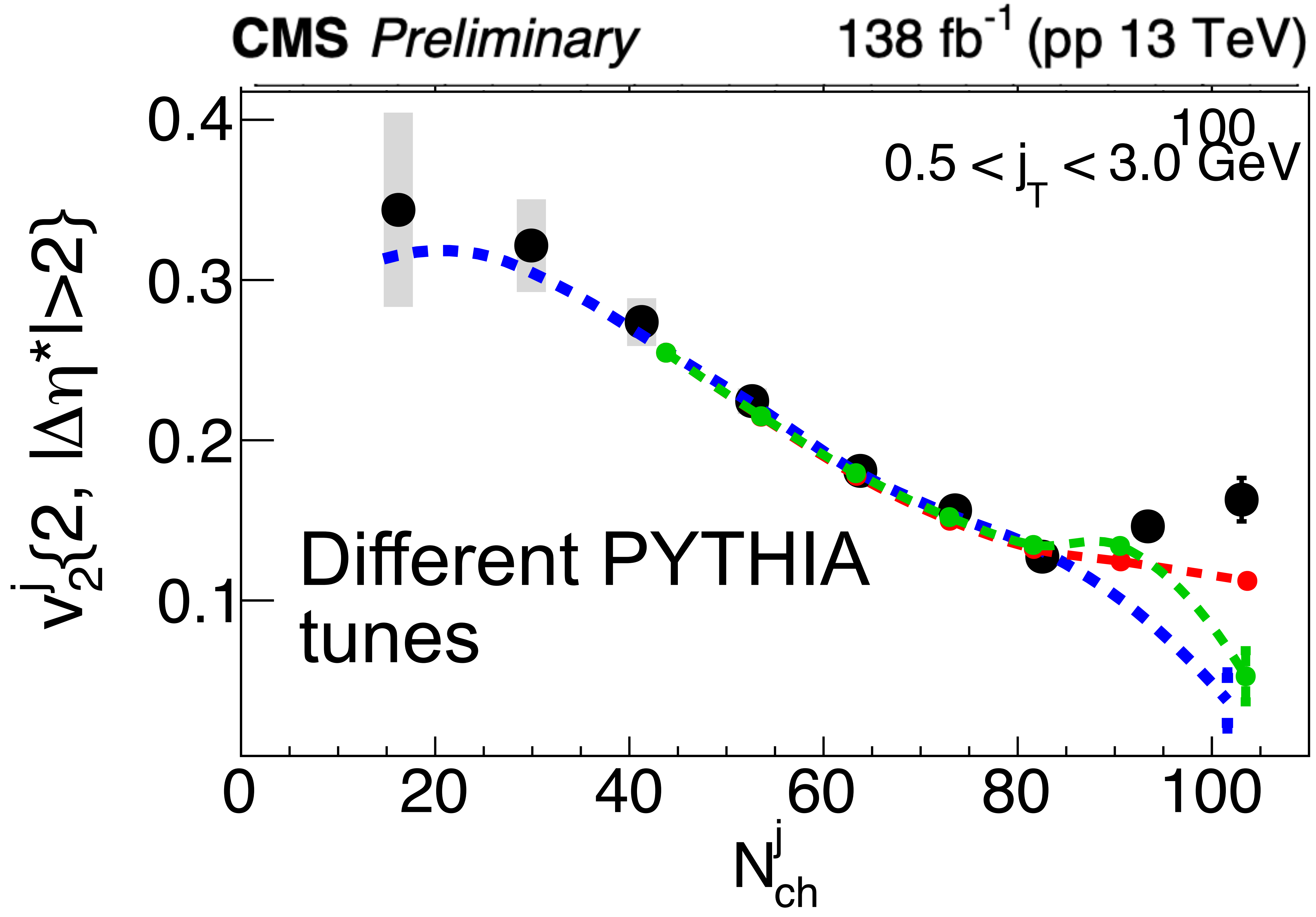
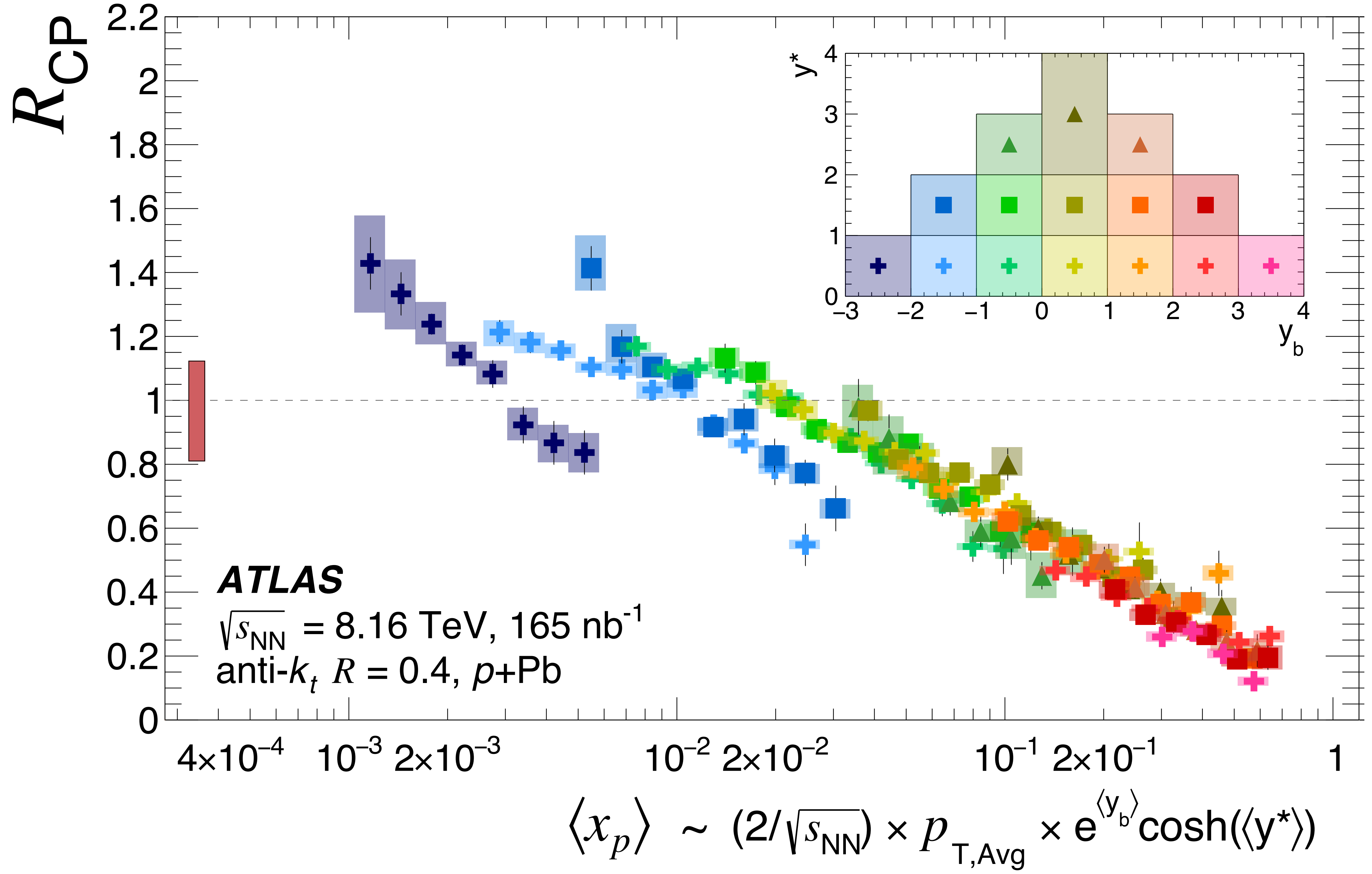


or small corner of fragmentation not quite modeled?

Can change the v_2 in PYTHIA in this region via different parameters

- While these parameters don't reproduce other variables, maybe others can do both

Energy loss to p(d)-Au medium?

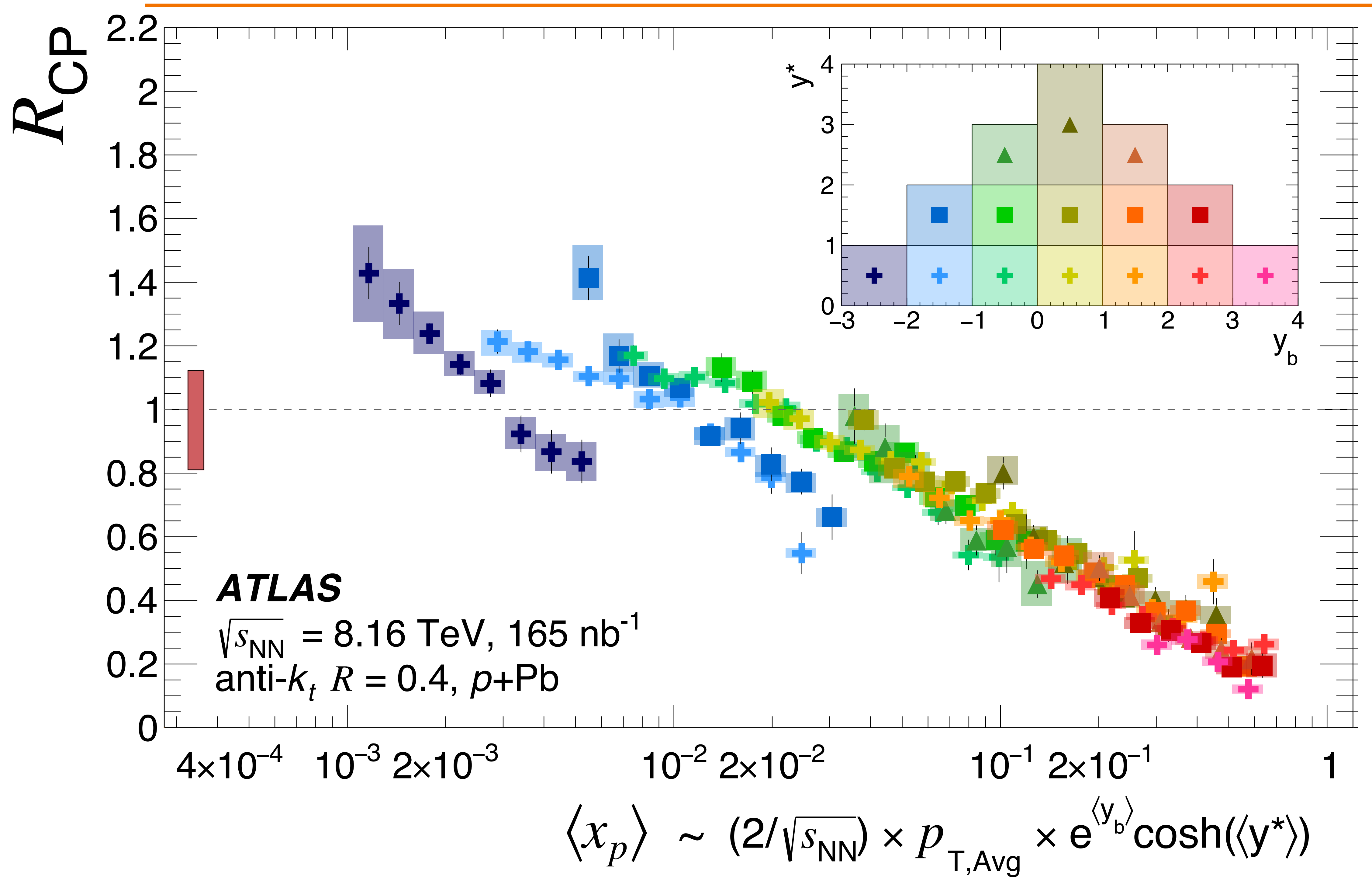


ATLAS di-jet studies: centrality dependence of jet yield initial (x_p), not final, state effect!

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

D. De Souza Lemos, D. Firak, B. Gilbert, R. Longo, P. Potepa

Energy loss to p(d)-Au medium?



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

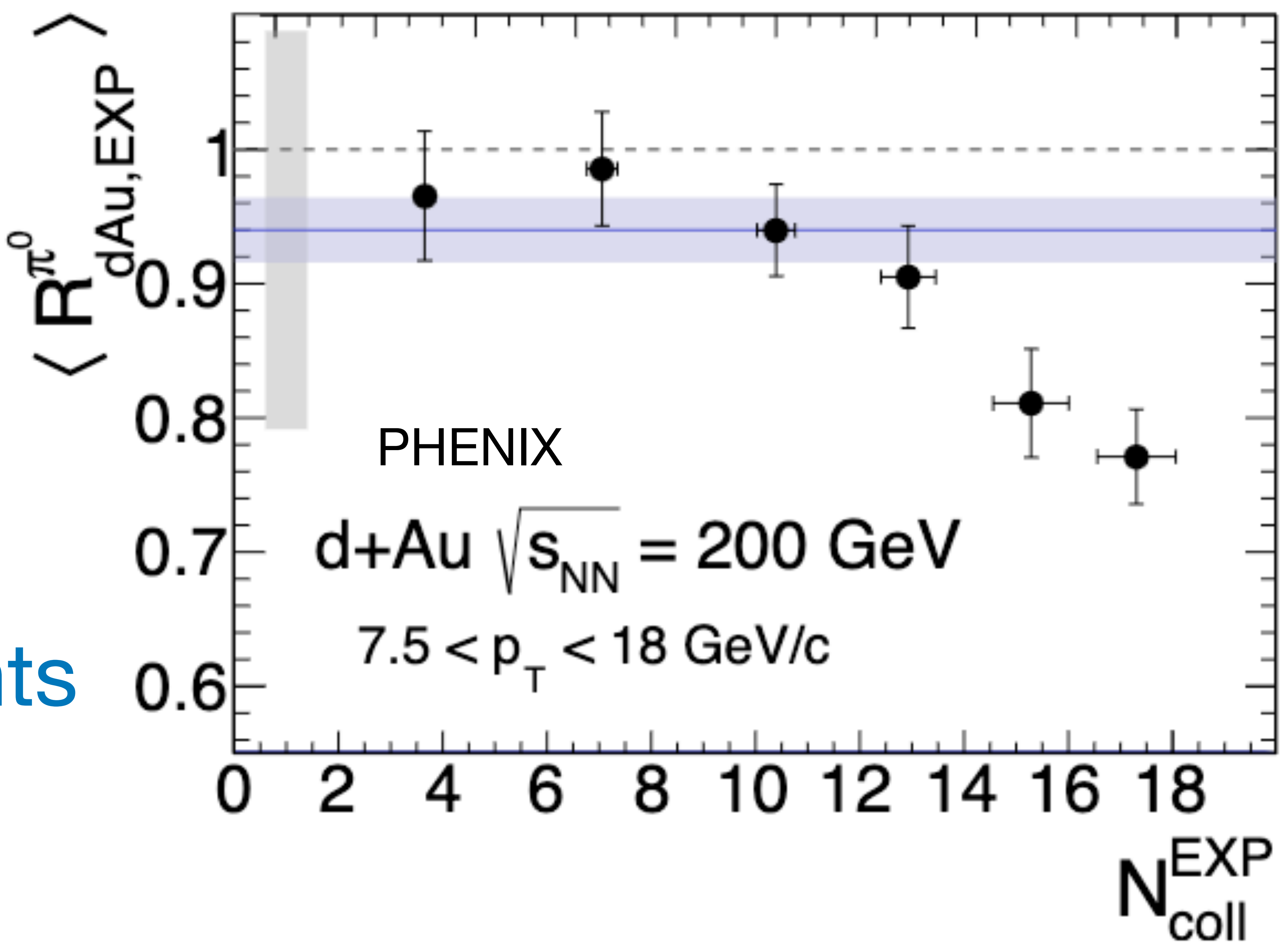
CMS: no di-jet imbalance, no E_{Loss}

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

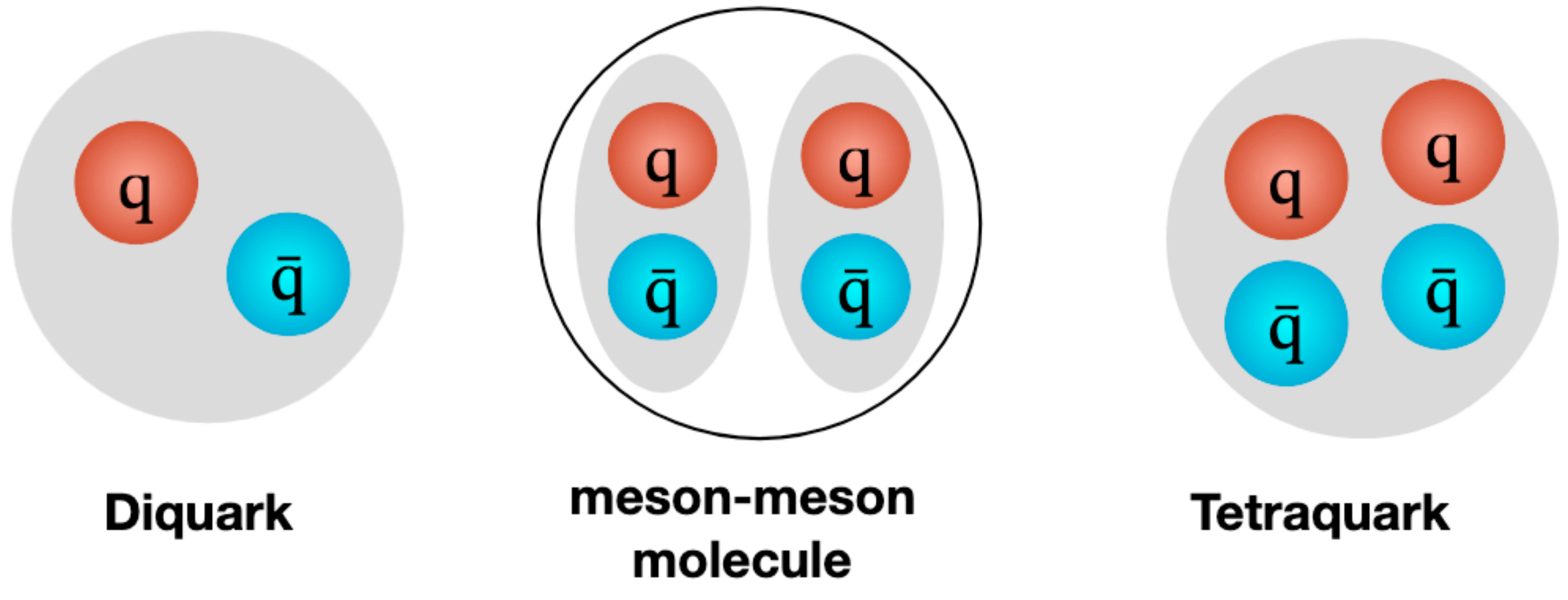
D. De Souza Lemos, D. Firak, B. Gilbert, R. Longo, P. Potepa

Can We Understand Nuclear/ Hadron Structure?

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



A. Gu, S. Padhan

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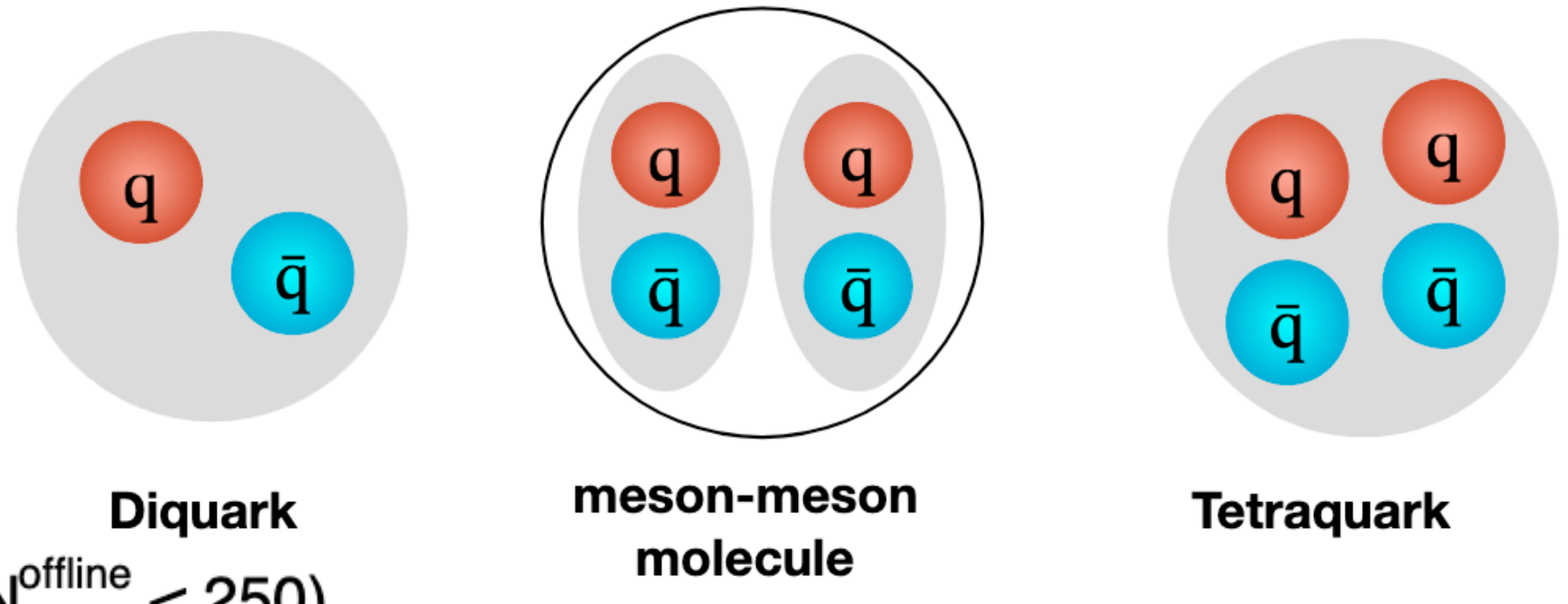
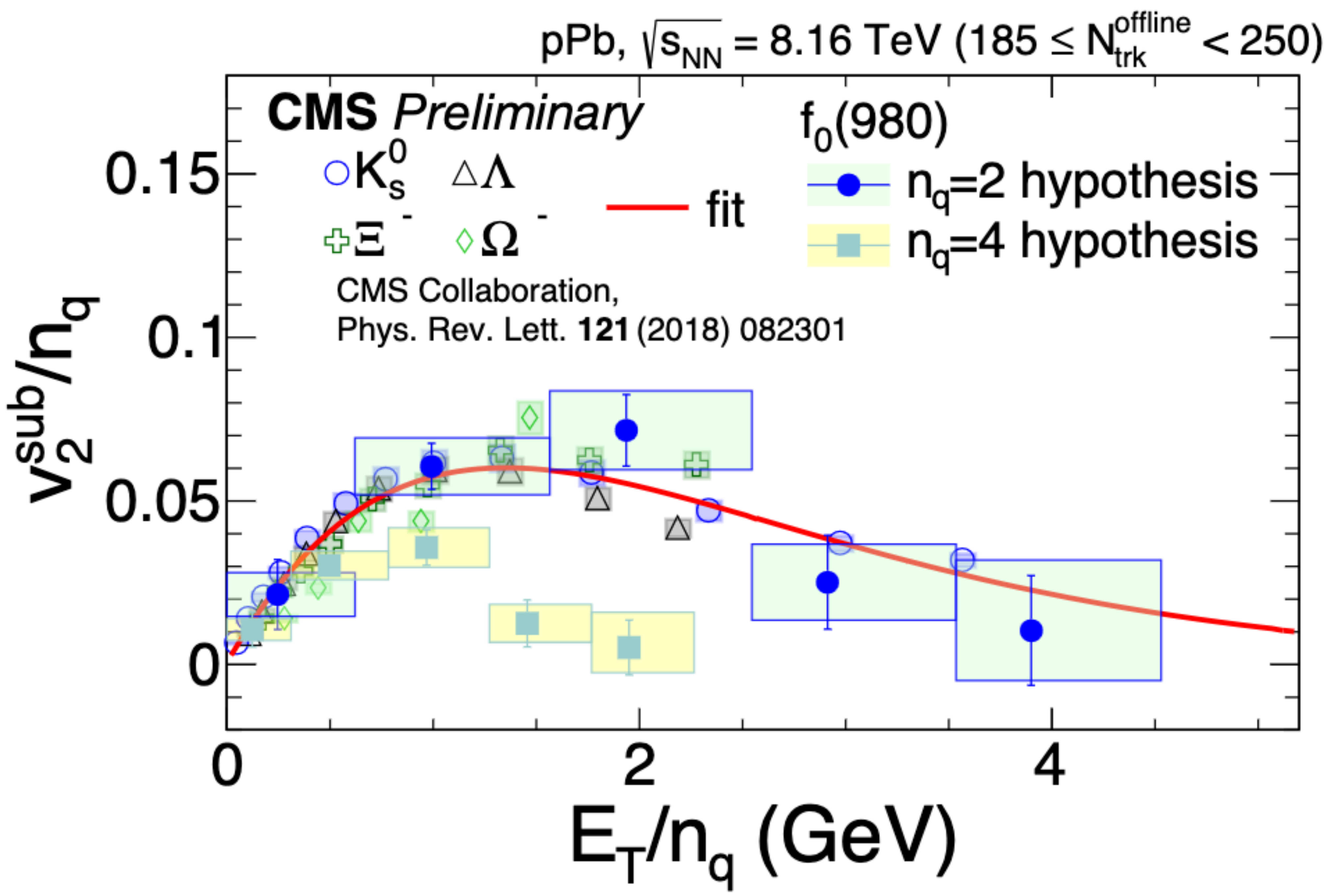


In p-Pb

Elliptic flow:

Scales when $n_q = 2$



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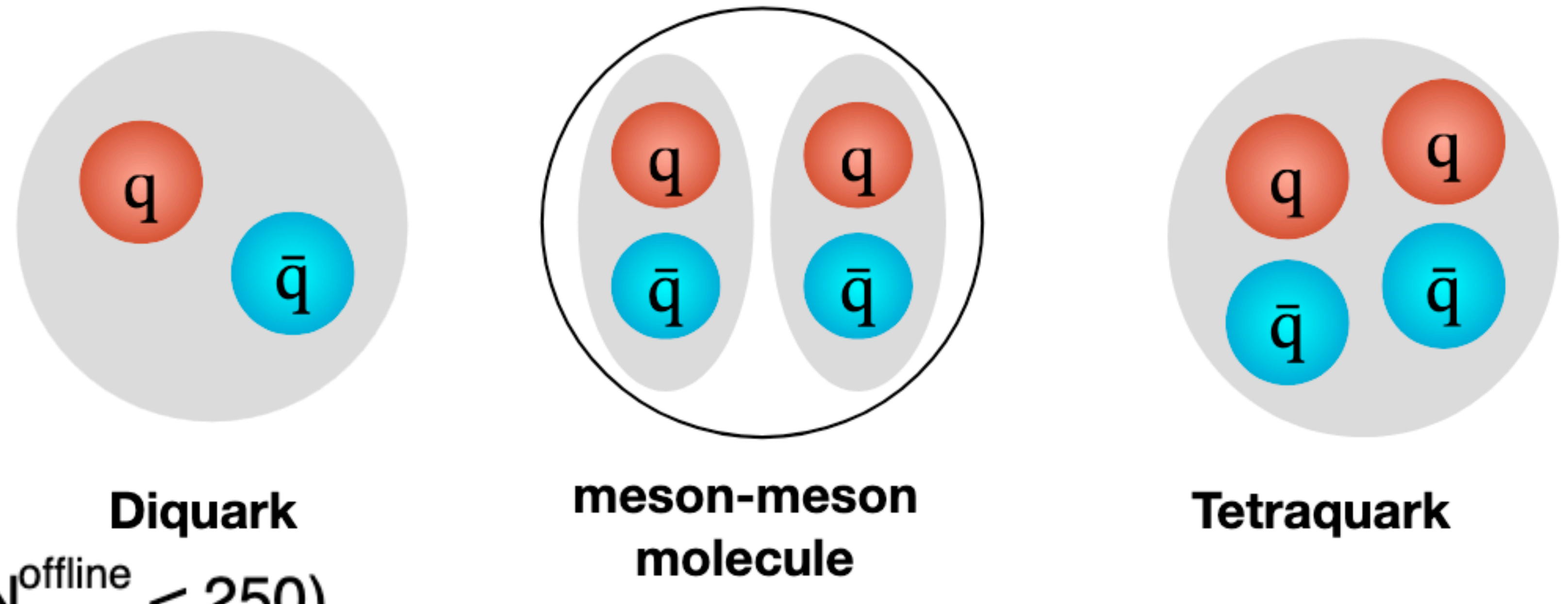
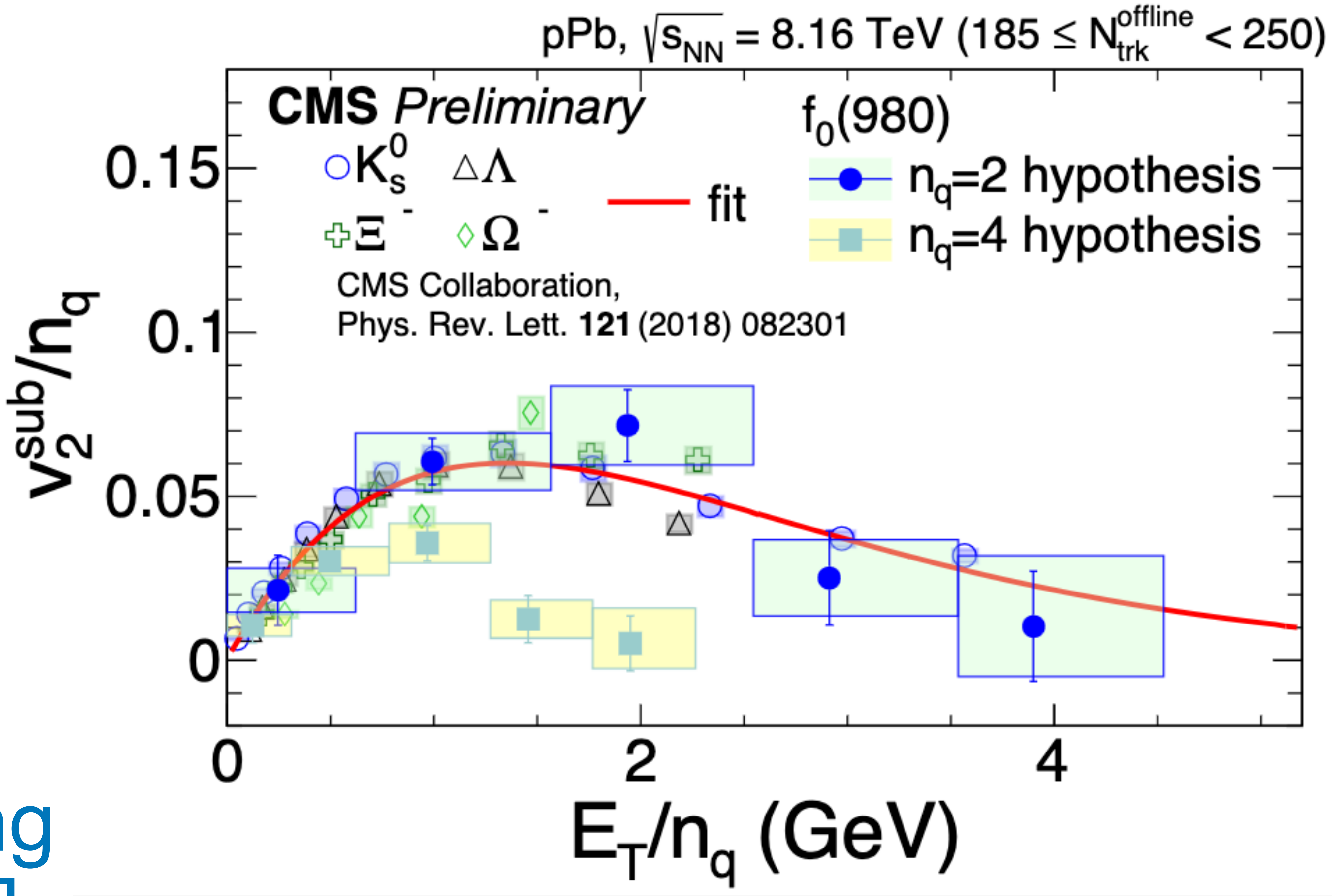
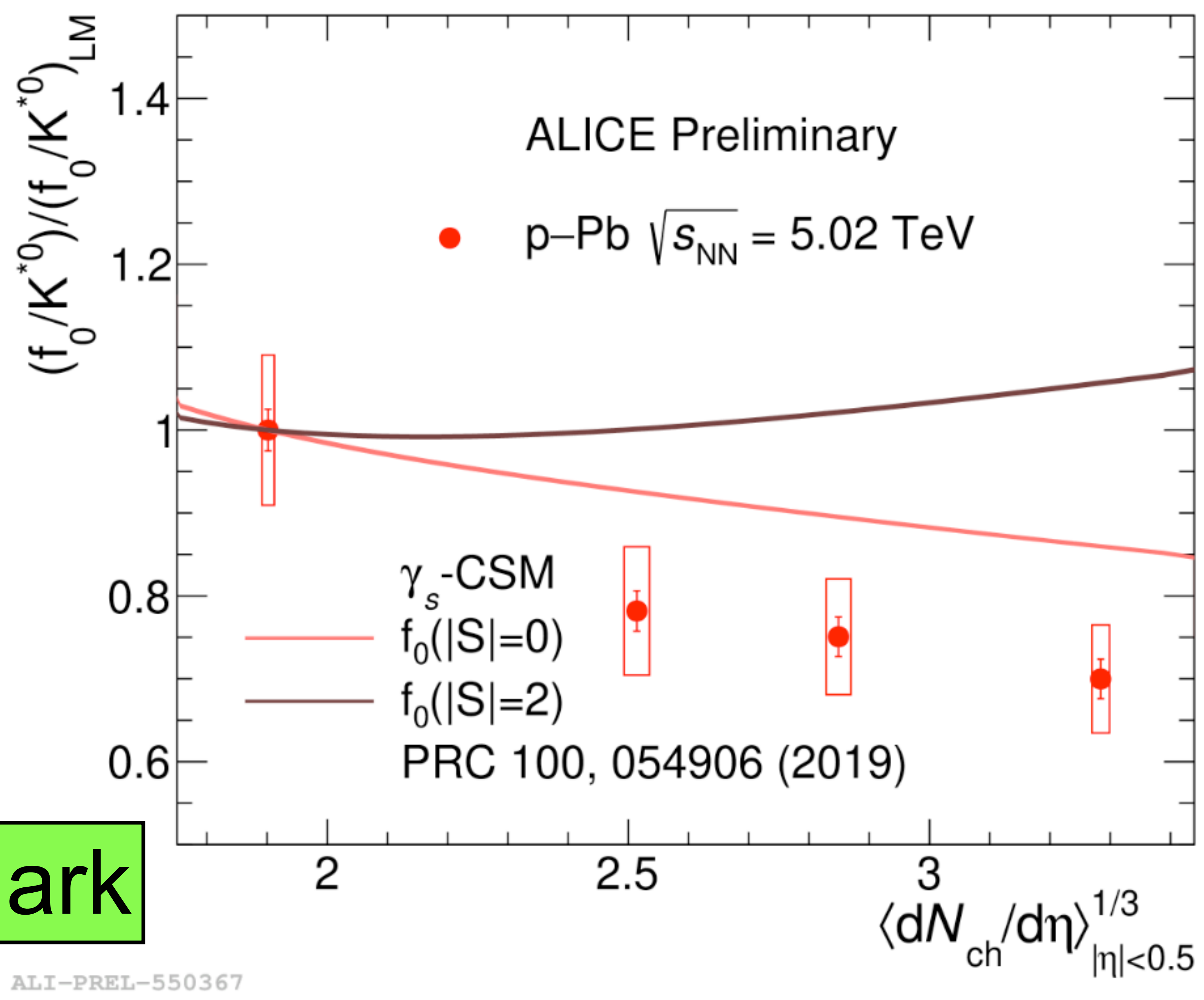


In p-Pb

Elliptic flow:
Scales when $n_q = 2$

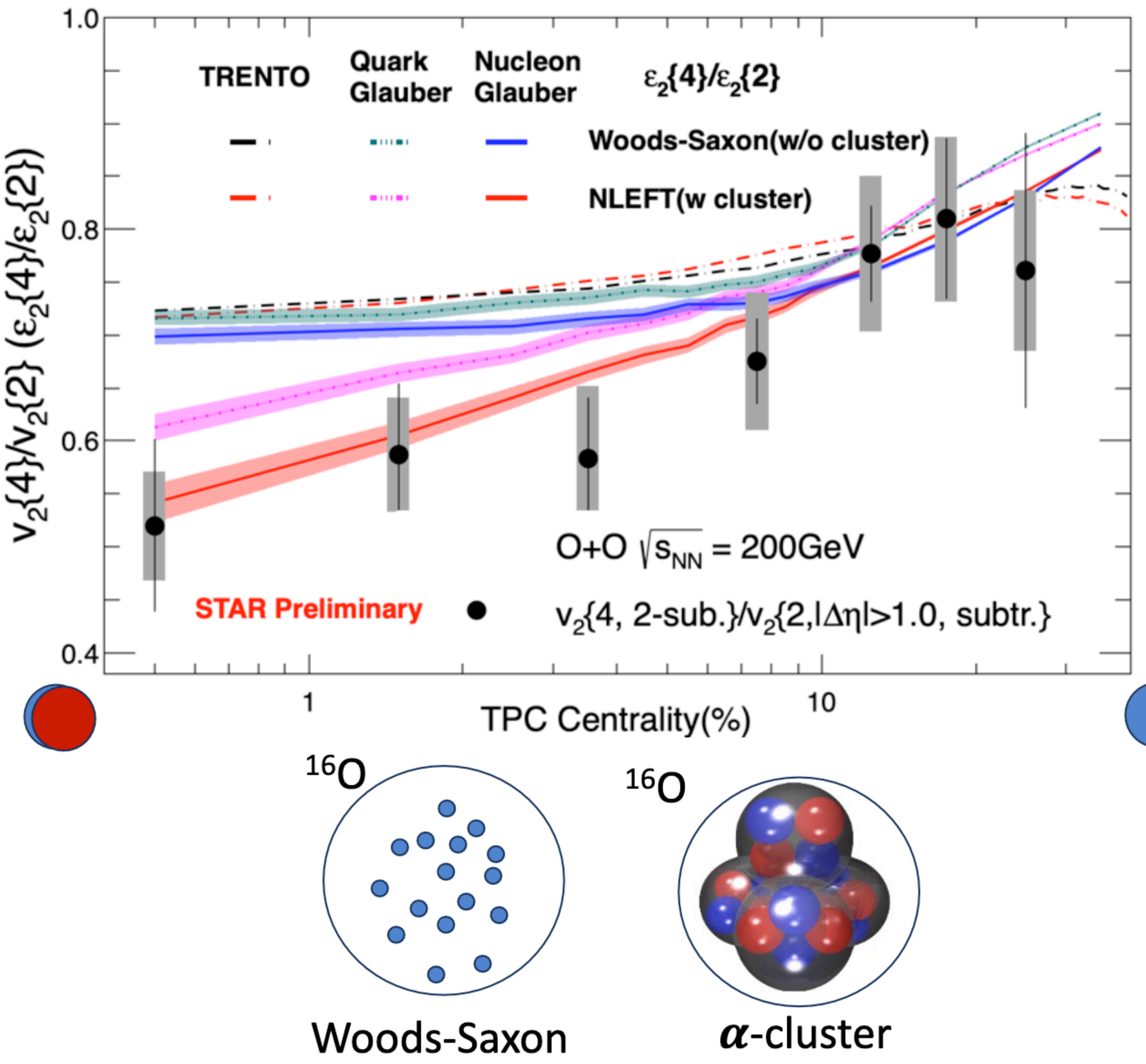


f_0/K^{*0} ratio :
consistent with calculation assuming $|S| = 0$ $[(u\bar{u} + d\bar{d})/2]$



Both results suggest f_0 is a di-quark

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

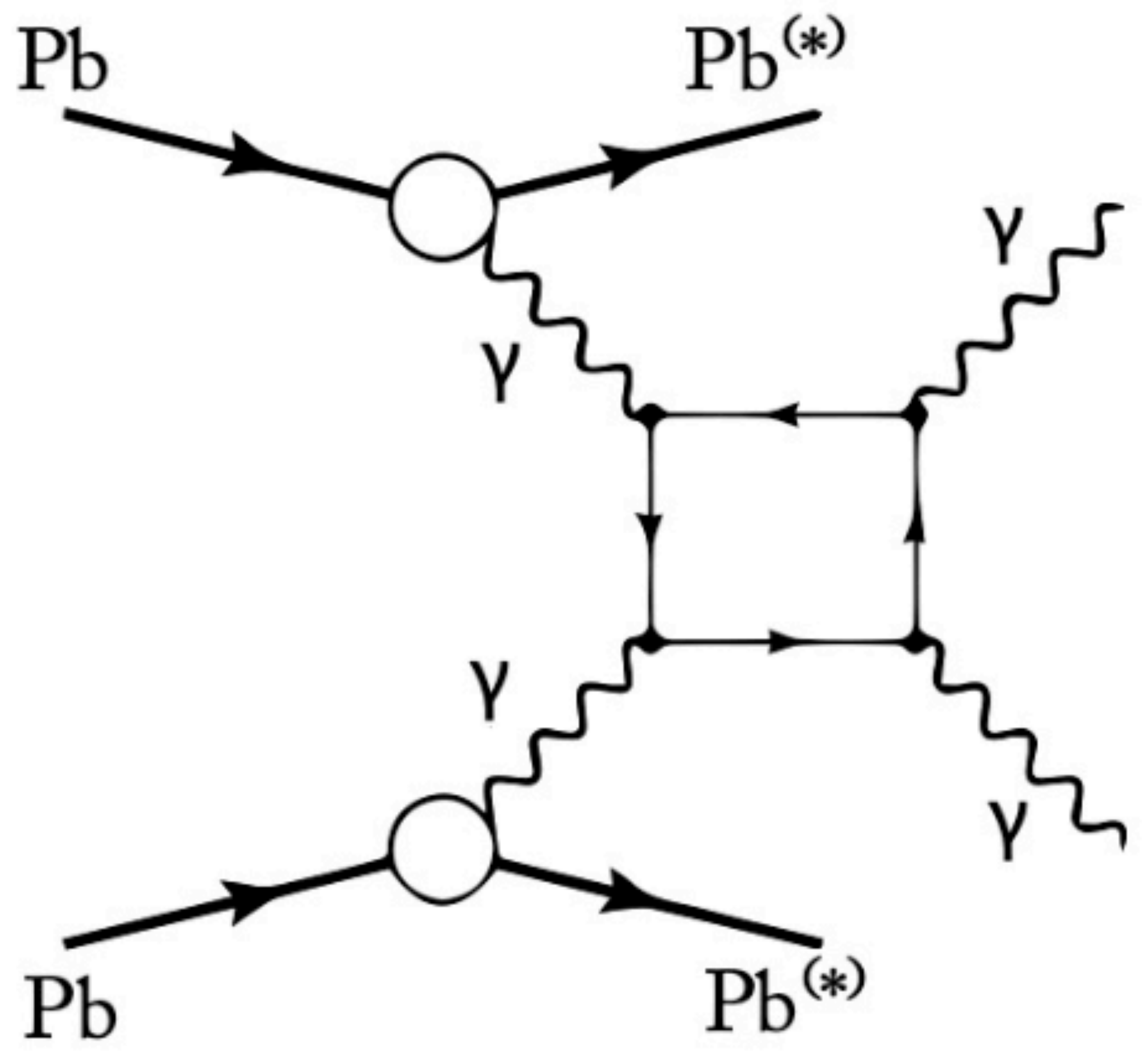
Data strongly favor alpha-clustering

S. Huang

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

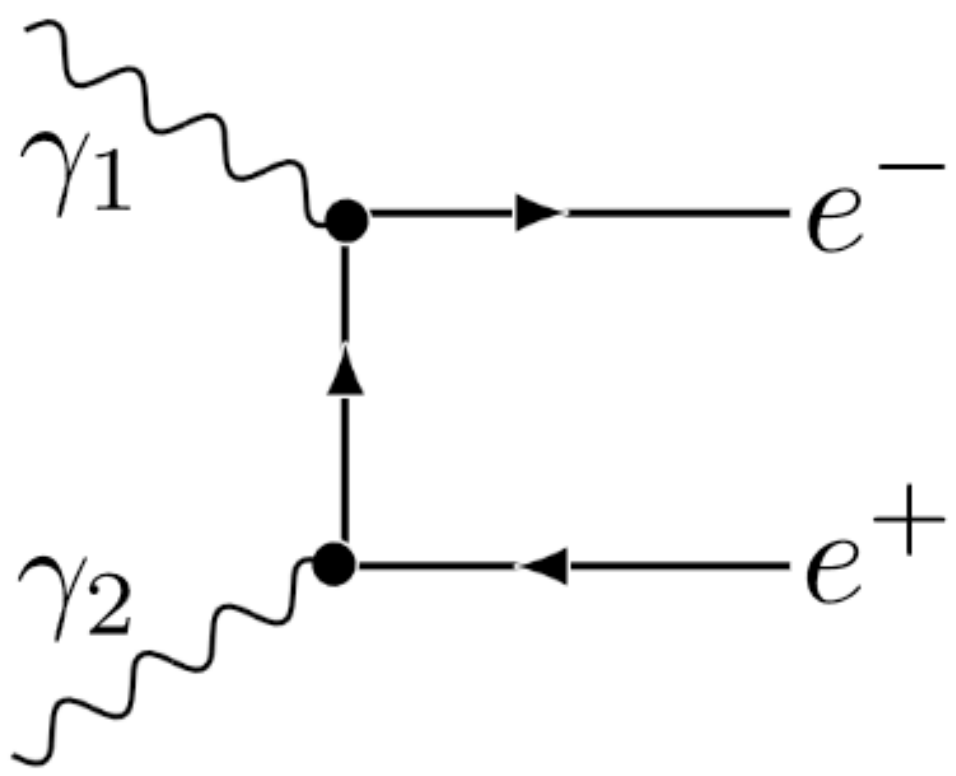
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

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

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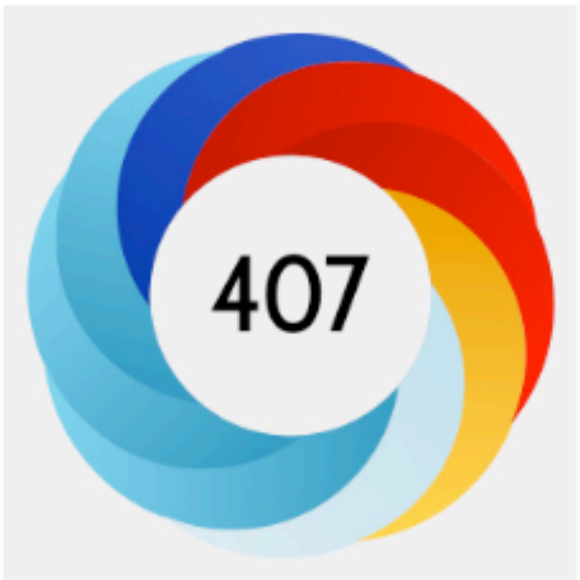
Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

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

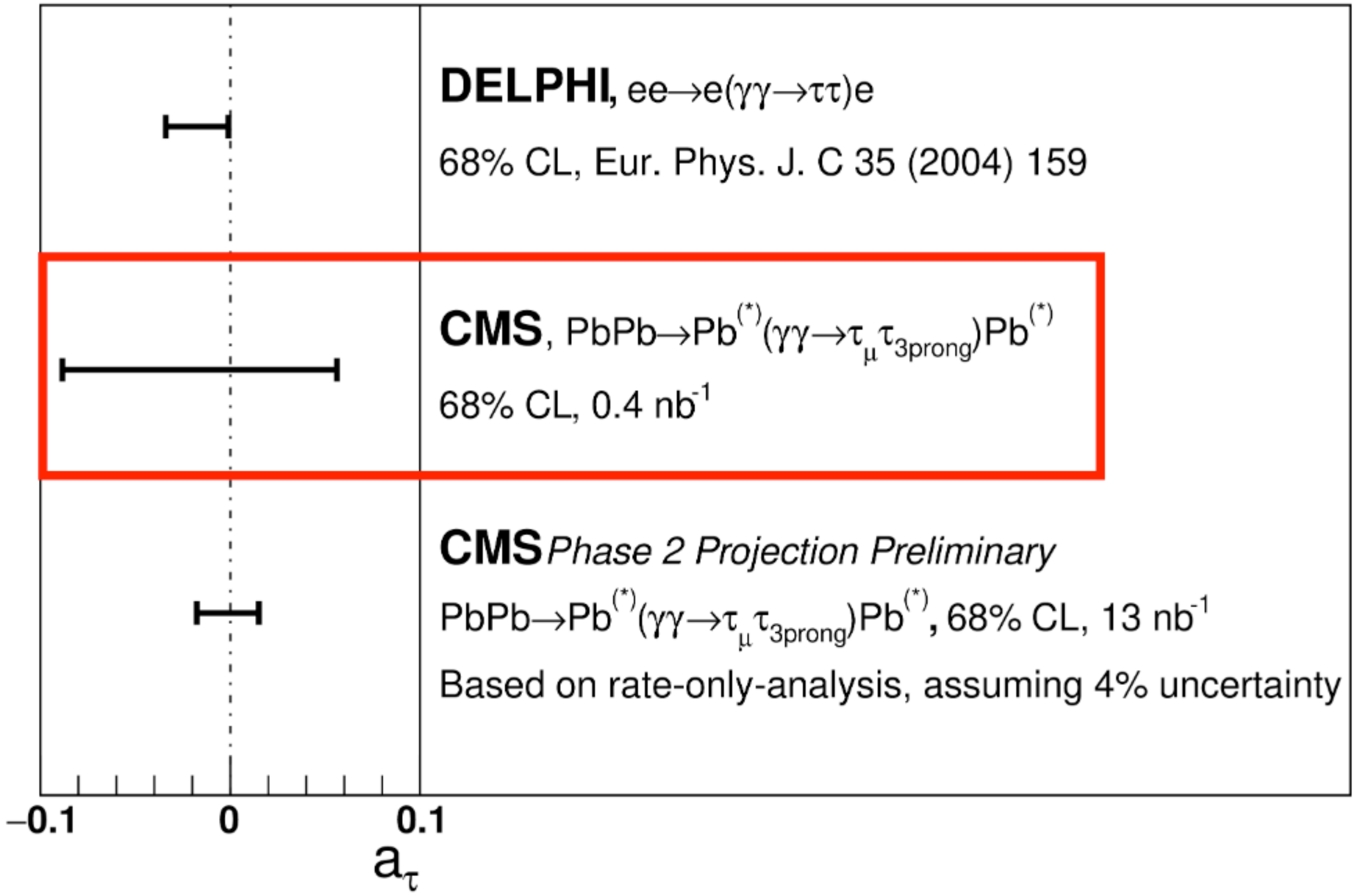


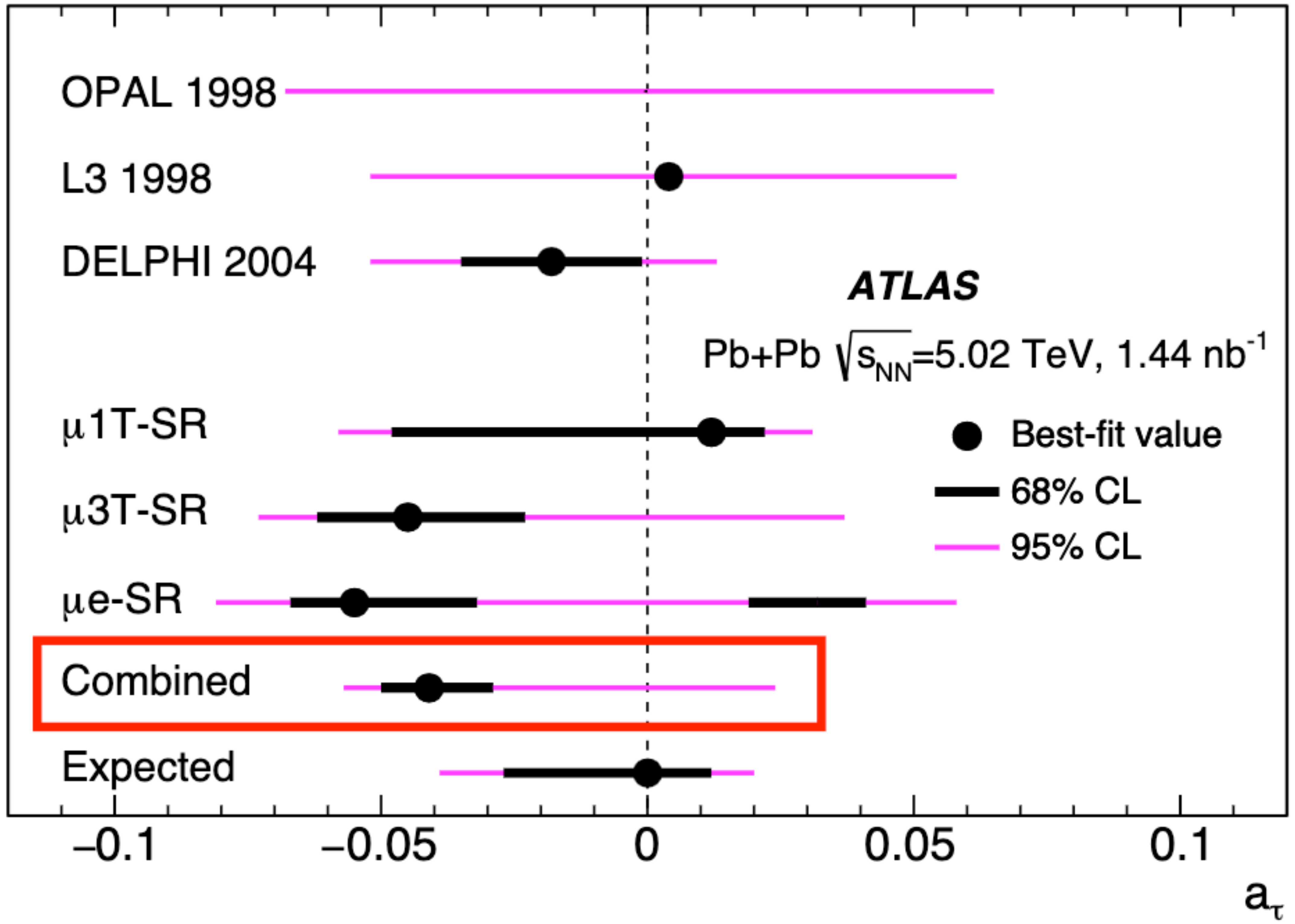
Exploiting both γγ and γ-A collisions

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



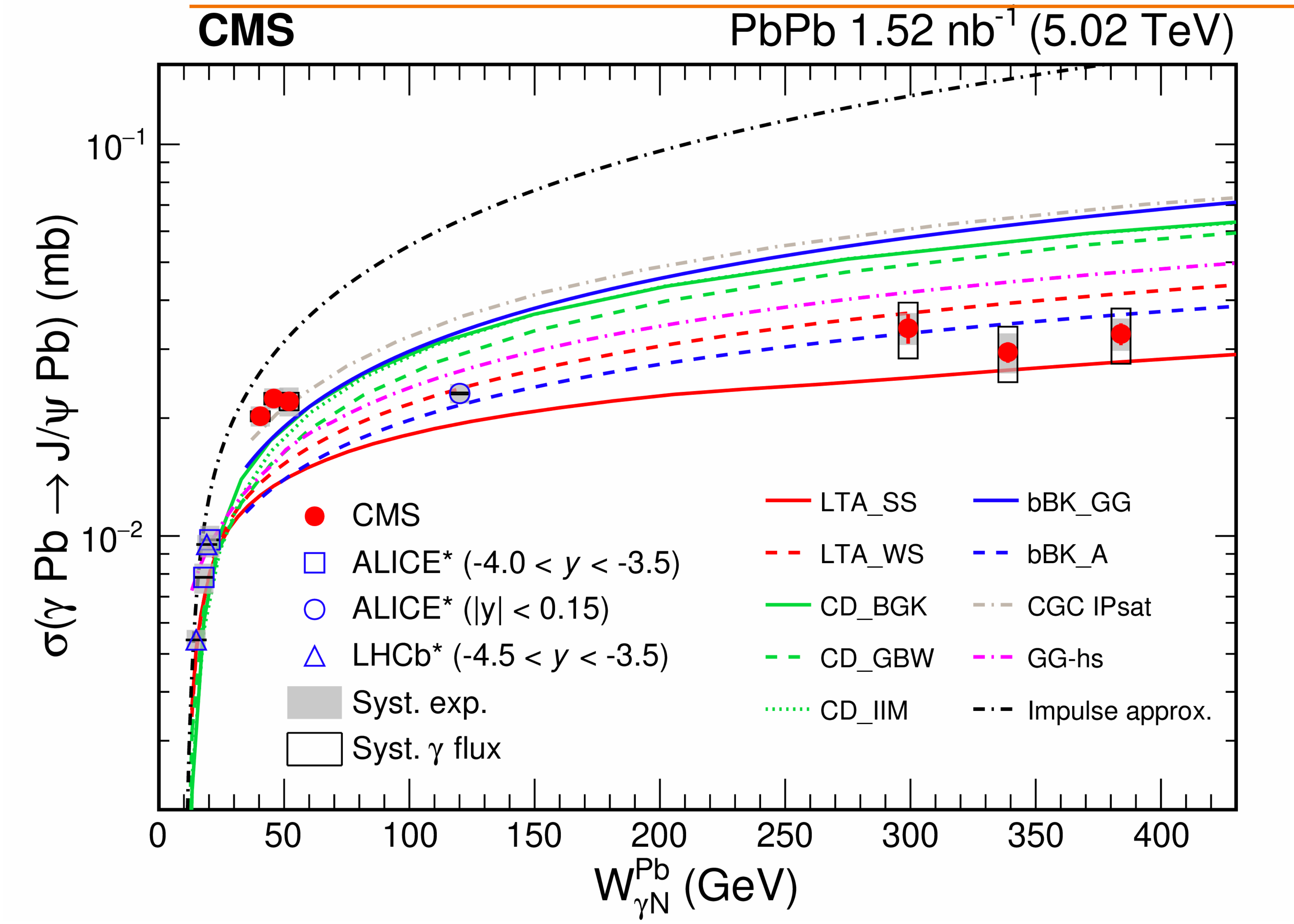


$a_\tau = 0.001 - 0.089 + 0.055$ at 68% CL

95% CL $-0.057 < a_\tau < 0.024$

First uses of hadron-collider data to test EM properties of τ
Results are competitive with existing lepton-collider constraints

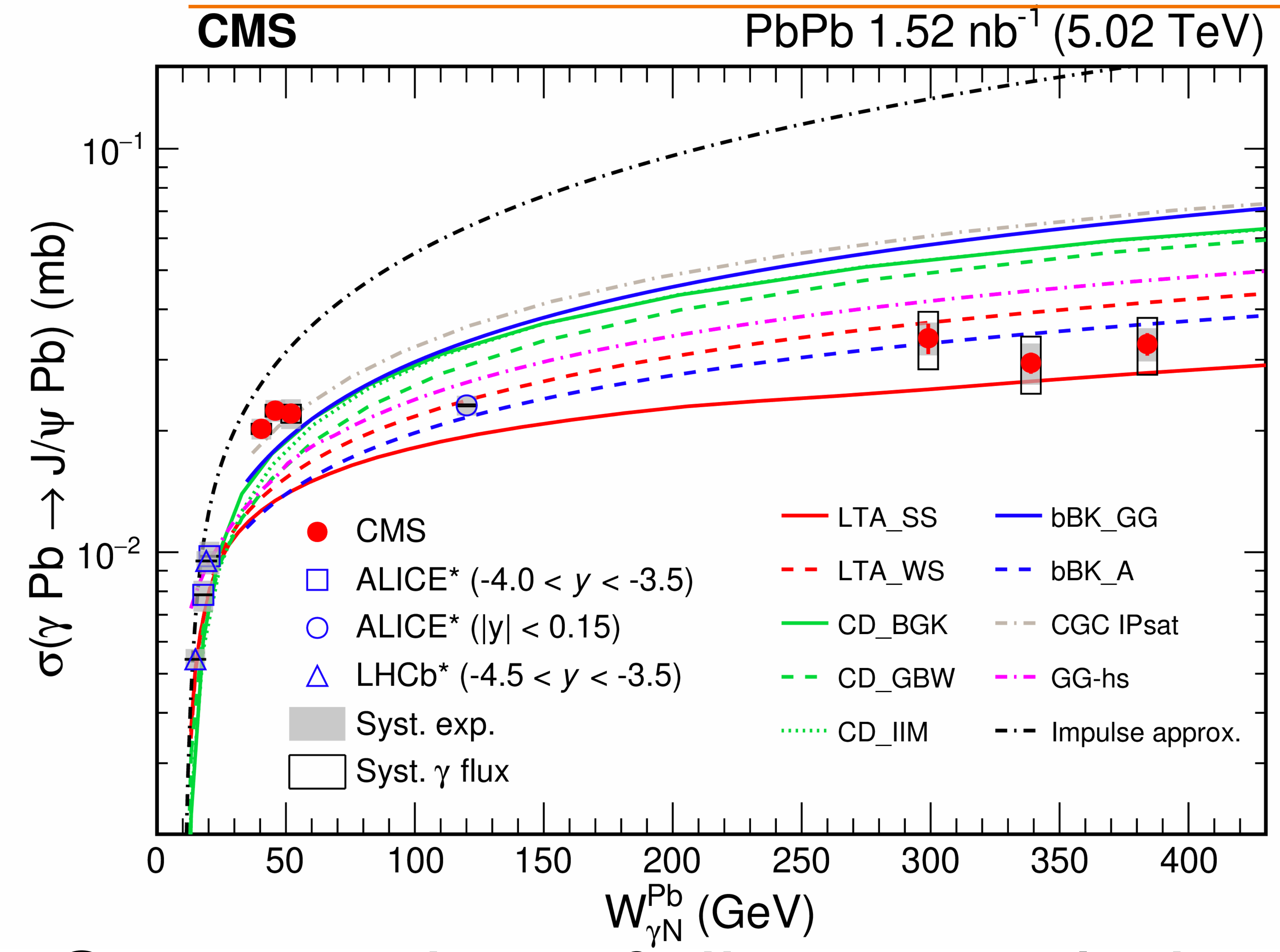
Evidence for gluon saturation



J/ψ photo-production:

- CMS access to new W range
- Shape of coherent $\sigma_{\gamma A \to J/\psi A'}(W)$ not predicted by models
- Gluon saturation? black disk limit?

Evidence for gluon saturation

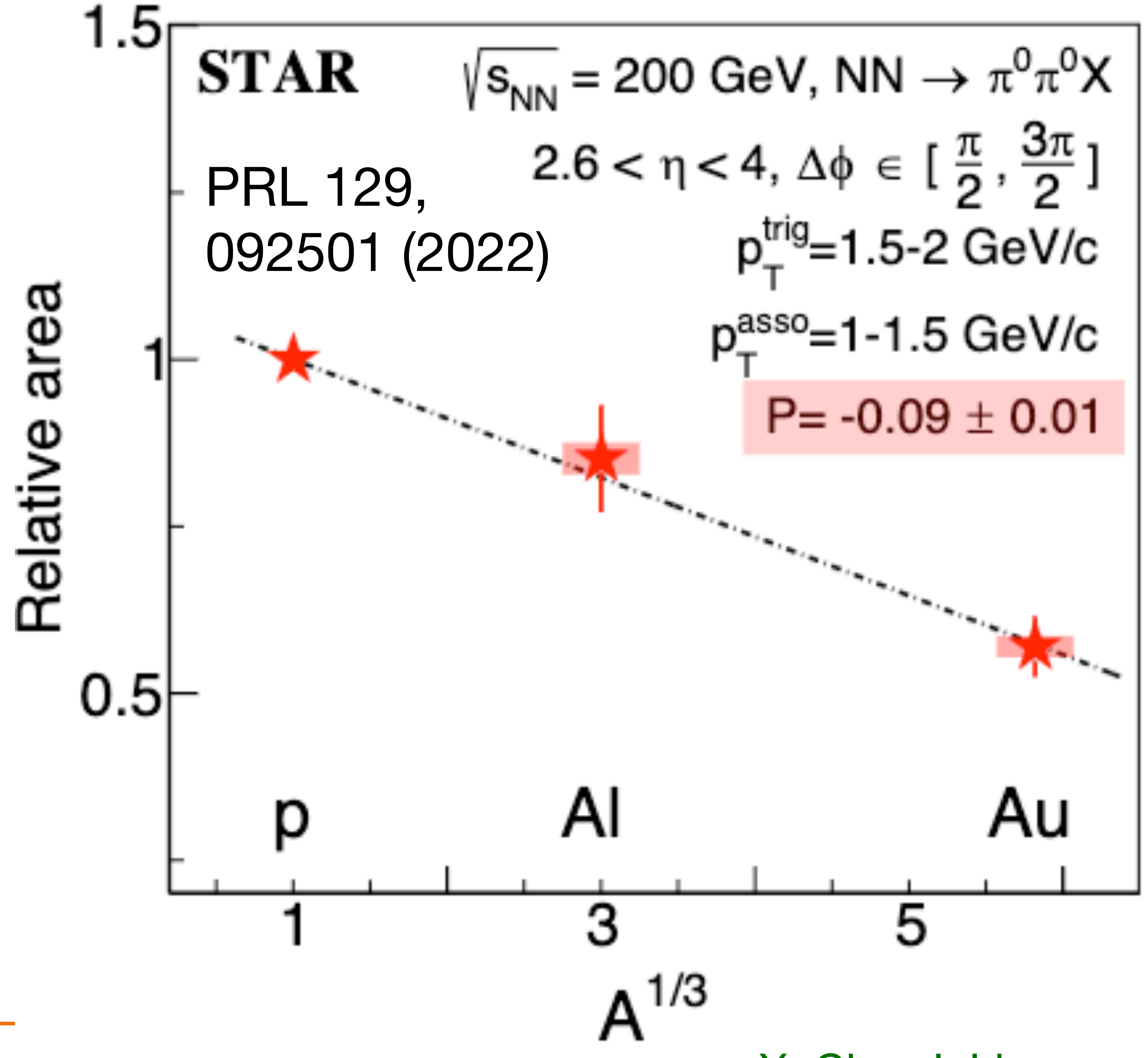


J/ψ photo-production:

- CMS access to new W 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 pA

- Dependence on A as predicted
- No broadening, not as predicted



Hints saturation RHIC and LHC
- unique opportunity with STAR forward upgrades prior to EIC. Important to have pA before RHIC stops

X. Chu, J. Lin

Summary

Precision era has been reached

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

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

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

Yale group past and present are excited to be involved - hope you are CFNS are too

Much is understood, but lots left to discover!