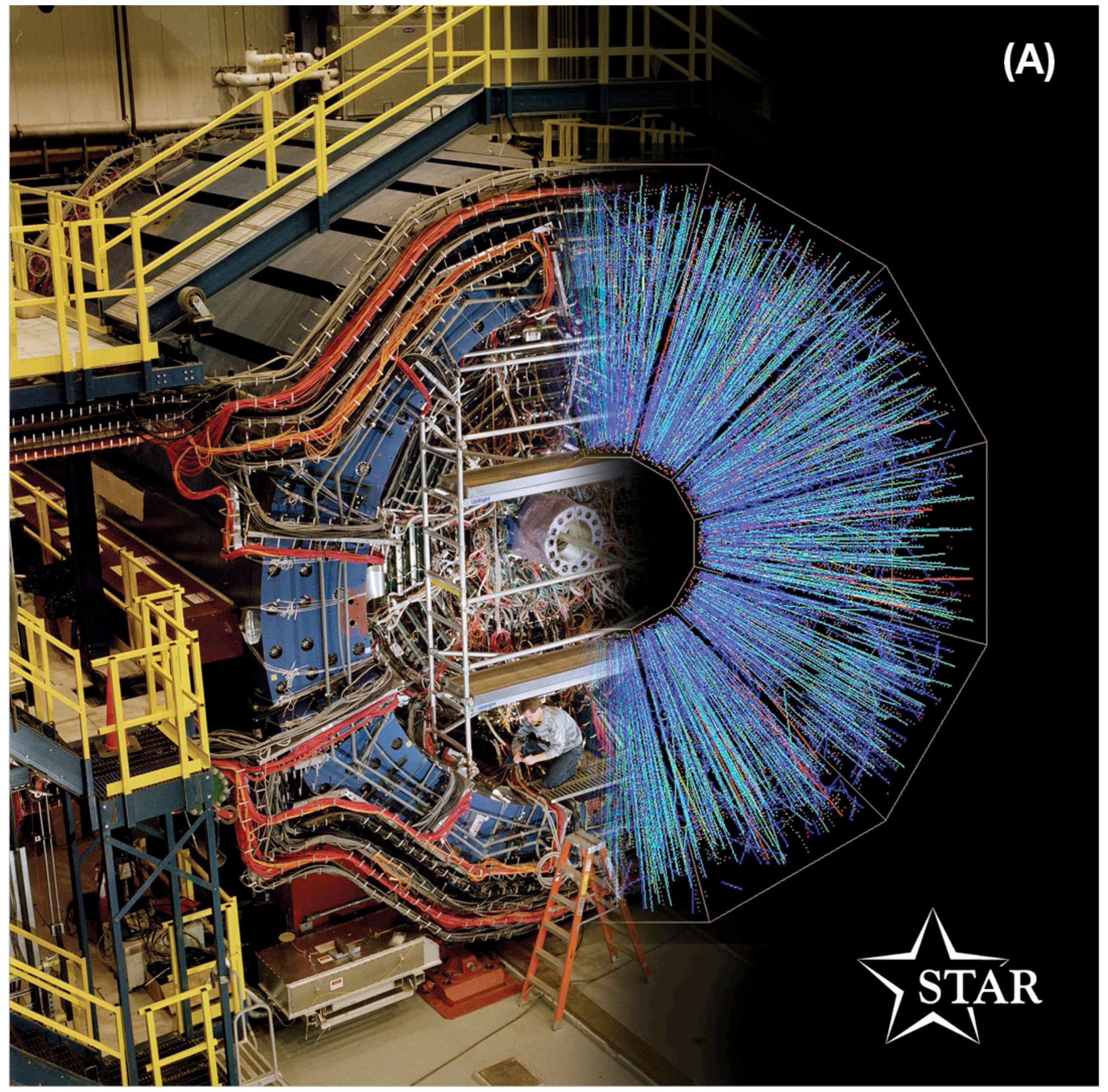
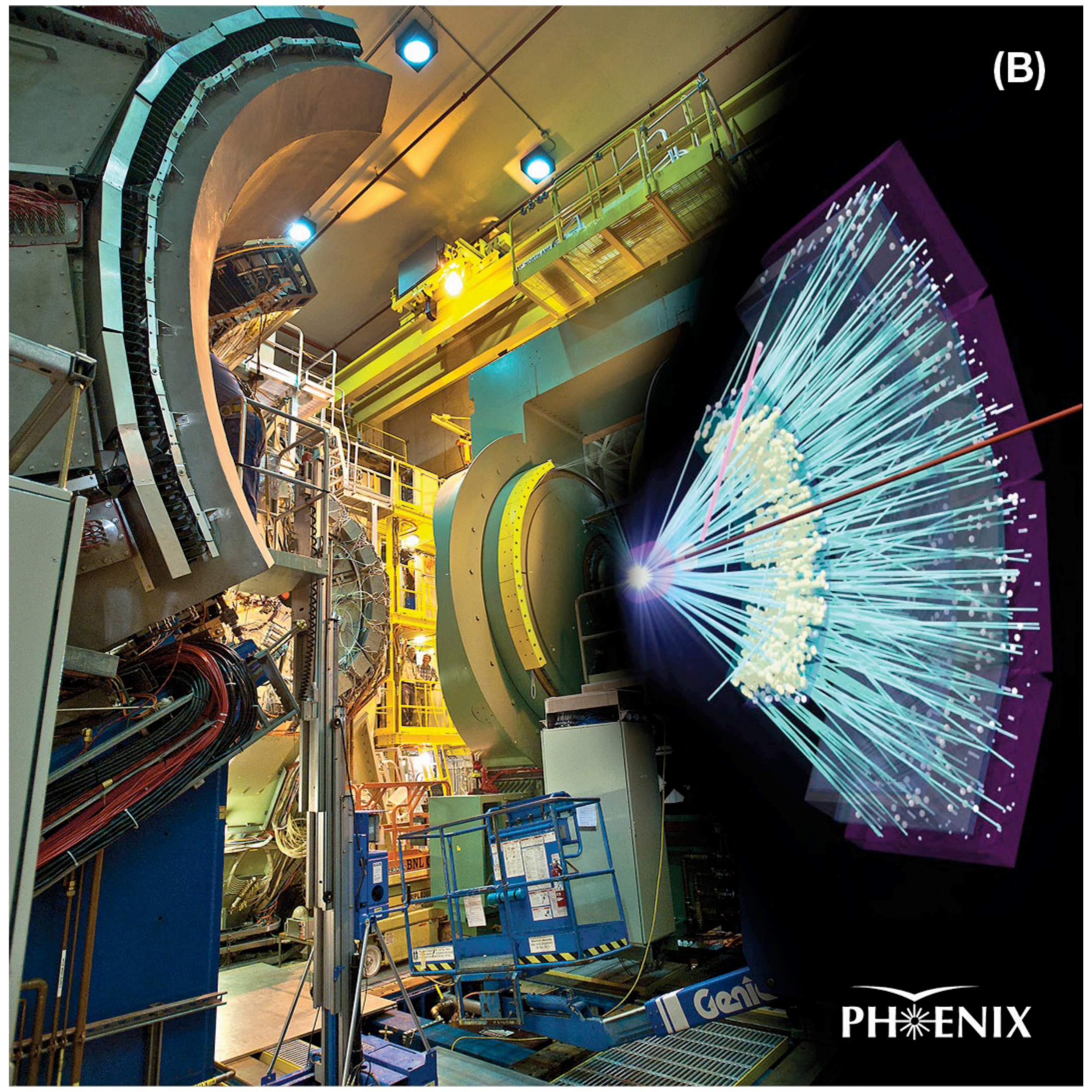
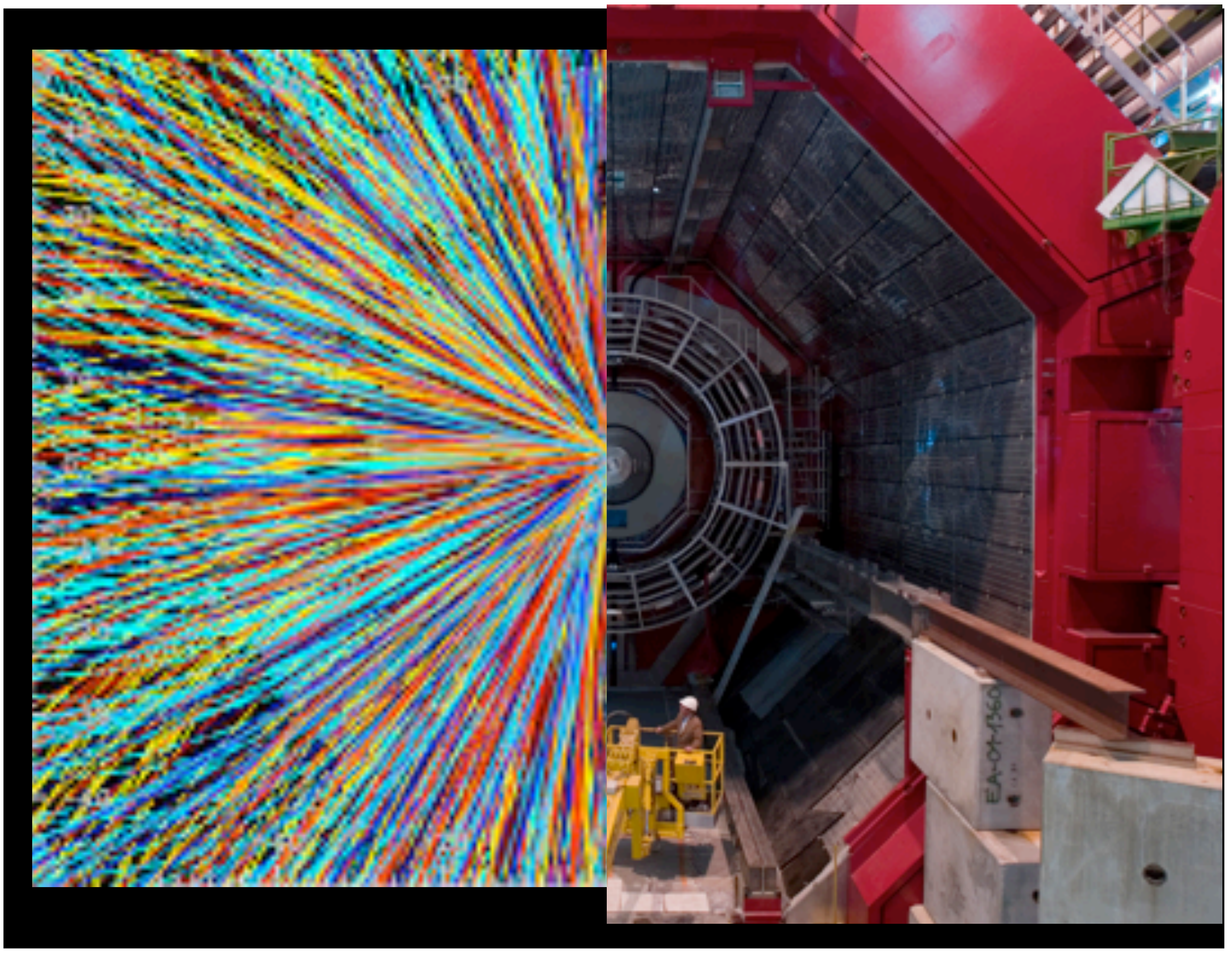


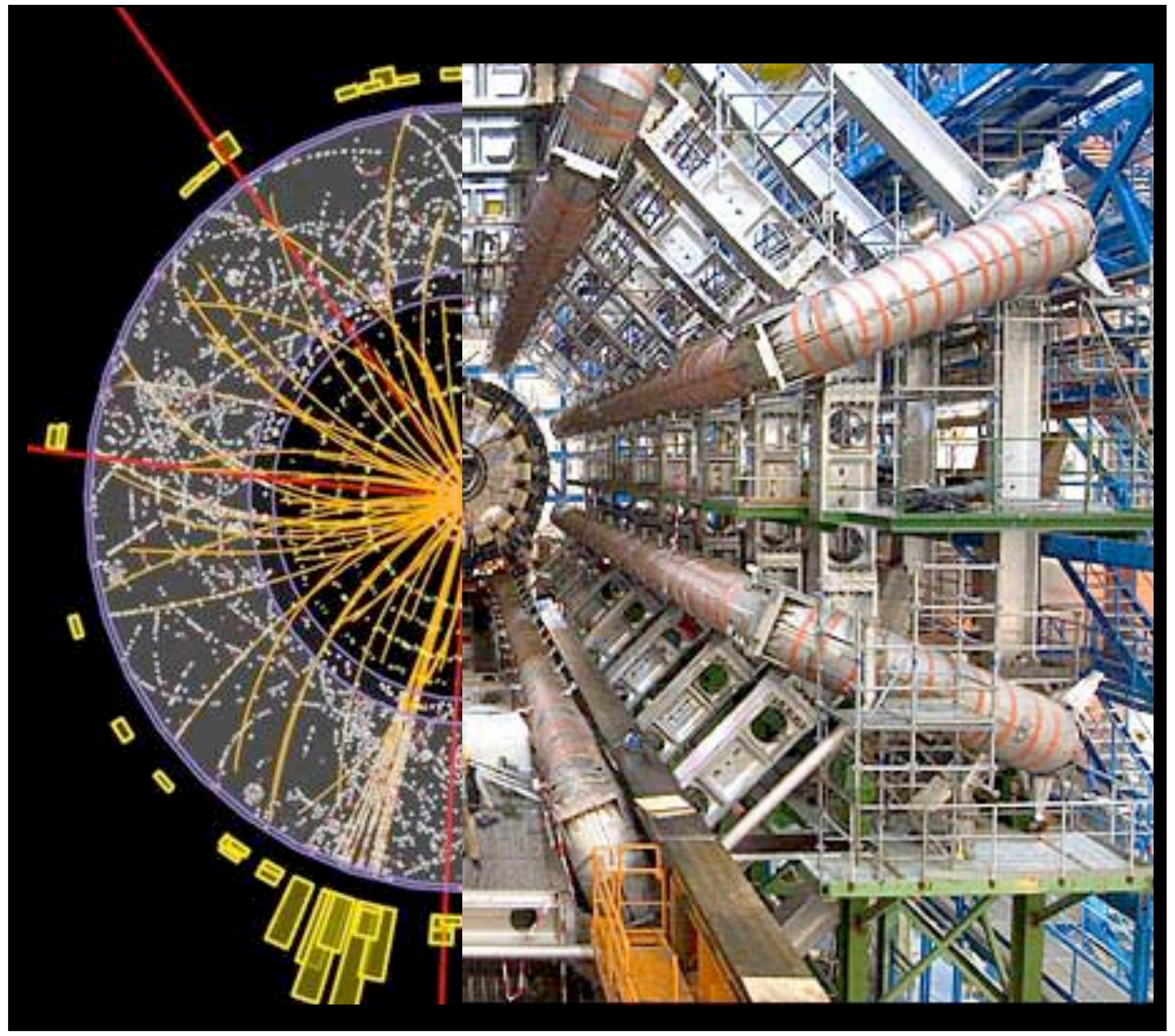
Relativistic Heavy Ions

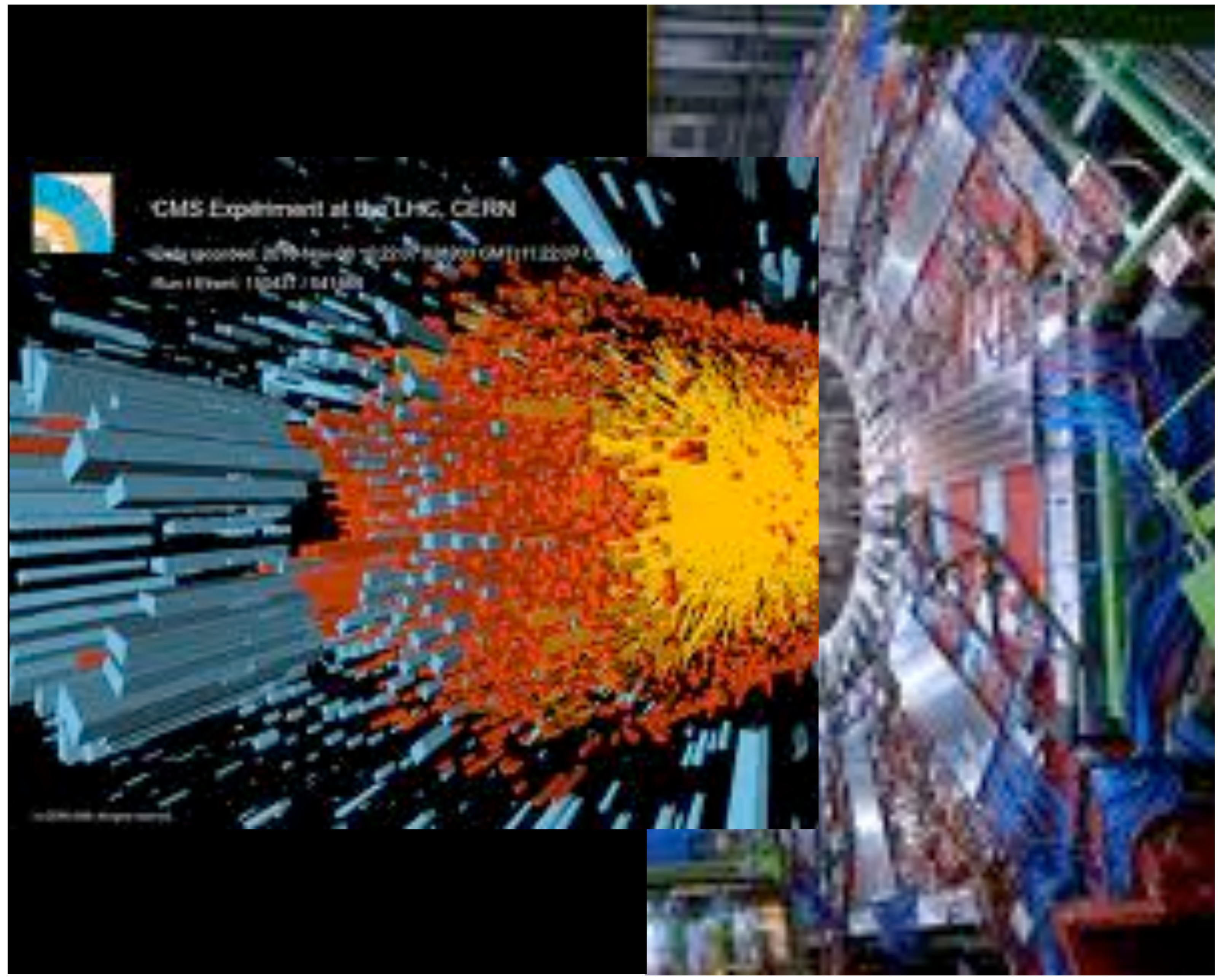
Helen Caines (she/her), Wright Lab, Yale University

Lecture 1: Creating the QGP
Lecture 2: Using Hard Probes
Lecture 3: Unexpected Physics & the Future









NNPSS - Indiana University, July 2024

Relativistic Heavy Ions I - The What, Why, Where, and How of It All

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

The Basics of QCD, Asymptotic Freedom, and the QGP
The Necessary Conditions to Make the QGP
Evidence for QGP Creation in Heavy-Ion Collisions
Our Current Understanding of the QGP's Evolution
Critical Points and How to Search for Them

Color confinement - QCD

Quarks seem to be confined within colorless hadrons

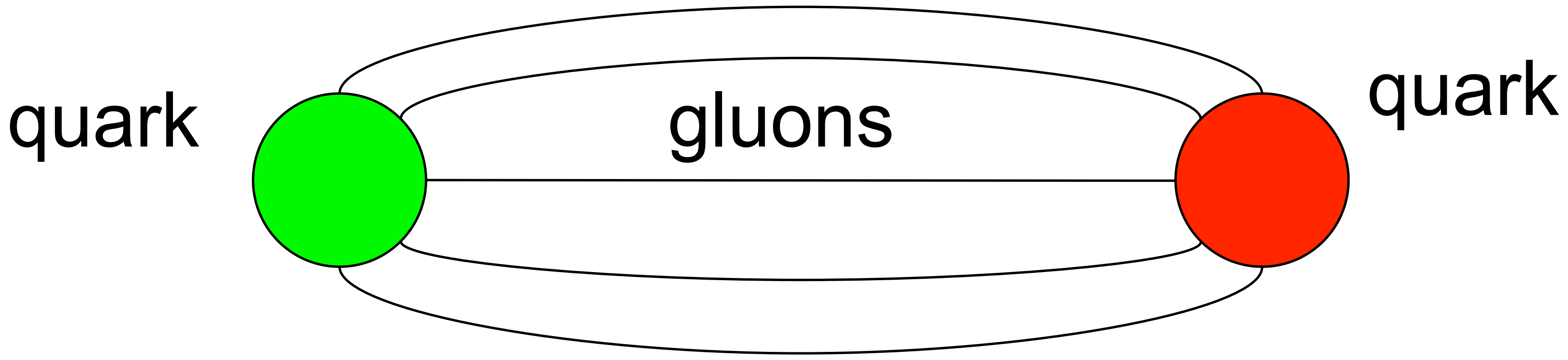
Nobody ever succeeded in detecting an isolated quark or gluon

One half of the fundamental fermions are not directly observable.

Why? The strong force

To understand the strong force and confinement:
Create and study a system of deconfined
colored quarks and gluons

We don't see free quarks



Strong force becomes ~constant at ~size of a hadron which is ~1 fm (10^{-15} m)

$$1\frac{GeV}{fm} = \frac{10^9 eV}{10^{-15} m} \times \frac{1.6 \times 10^{-19} J}{eV} = 1.6 \times 10^5 N$$

Compare to gravitational force at Earth's surface

$$F = 1.6 \times 10^5 N = M \times g = M \times 9.8 m/s^2$$

$$\Rightarrow \quad M = 16,300 kg$$

Quarks exert 16 metric tons of force on each other!

Asymptotic freedom

Coupling constant is not a “constant”

Runs with Q^2 (mtm transfer) accounts for vacuum polarisation

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{[1+(\alpha_s(\mu^2)\frac{(33-2n_f)}{12\pi})ln(Q^2/\mu^2)]}$$

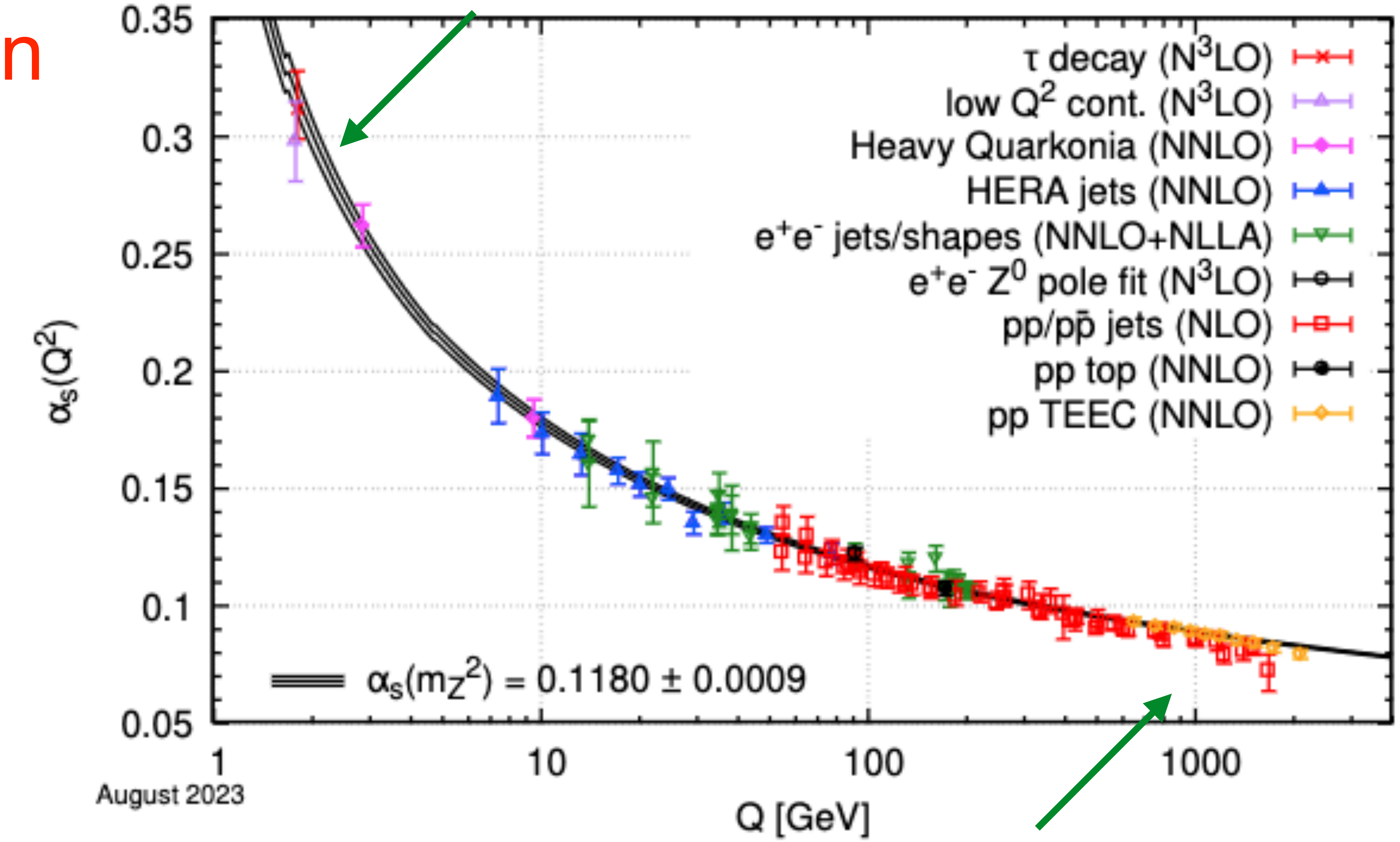
$\alpha_s(\mu^2) \sim 1$!!
μ^2 : renormalization scale
33 : 11 * # colors
n_f : # quark flavors = (3-6)

$(33-(2*6))/(12\pi)$ is positive
$\alpha_s(Q^2) \rightarrow 0$, as $Q \rightarrow \infty$, $r \rightarrow 0$
Coupling very weak
→ partons are essentially free

Asymptotic Freedom

Measured experimentally

Small E/large r scales - coupling constant large - perturbative corrections are large - confinement/hadrons



Large E/small r scales - coupling constant small - perturbative calculations valid - deconfinement/asymptotic freedom

PDG2024

Asymptotic freedom

Measured experimentally

Coupling

Runs with

accounts

$\alpha_s(Q^2) =$

α_s

μ^2

33

n_f

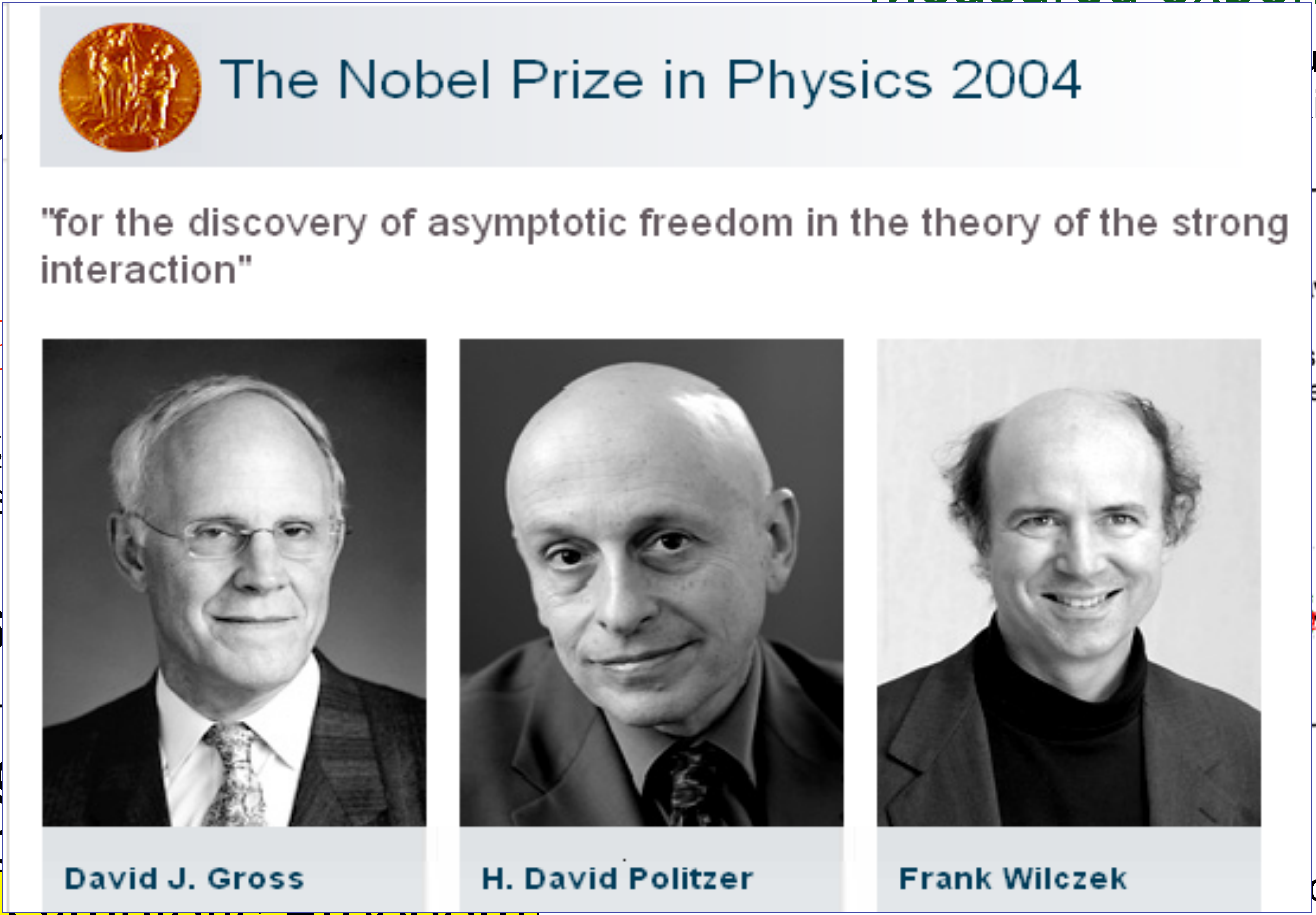
(33-(2*6

$\alpha_s(Q^2)$ –

Couplin

→ partc

Asymptotic Freedom



The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

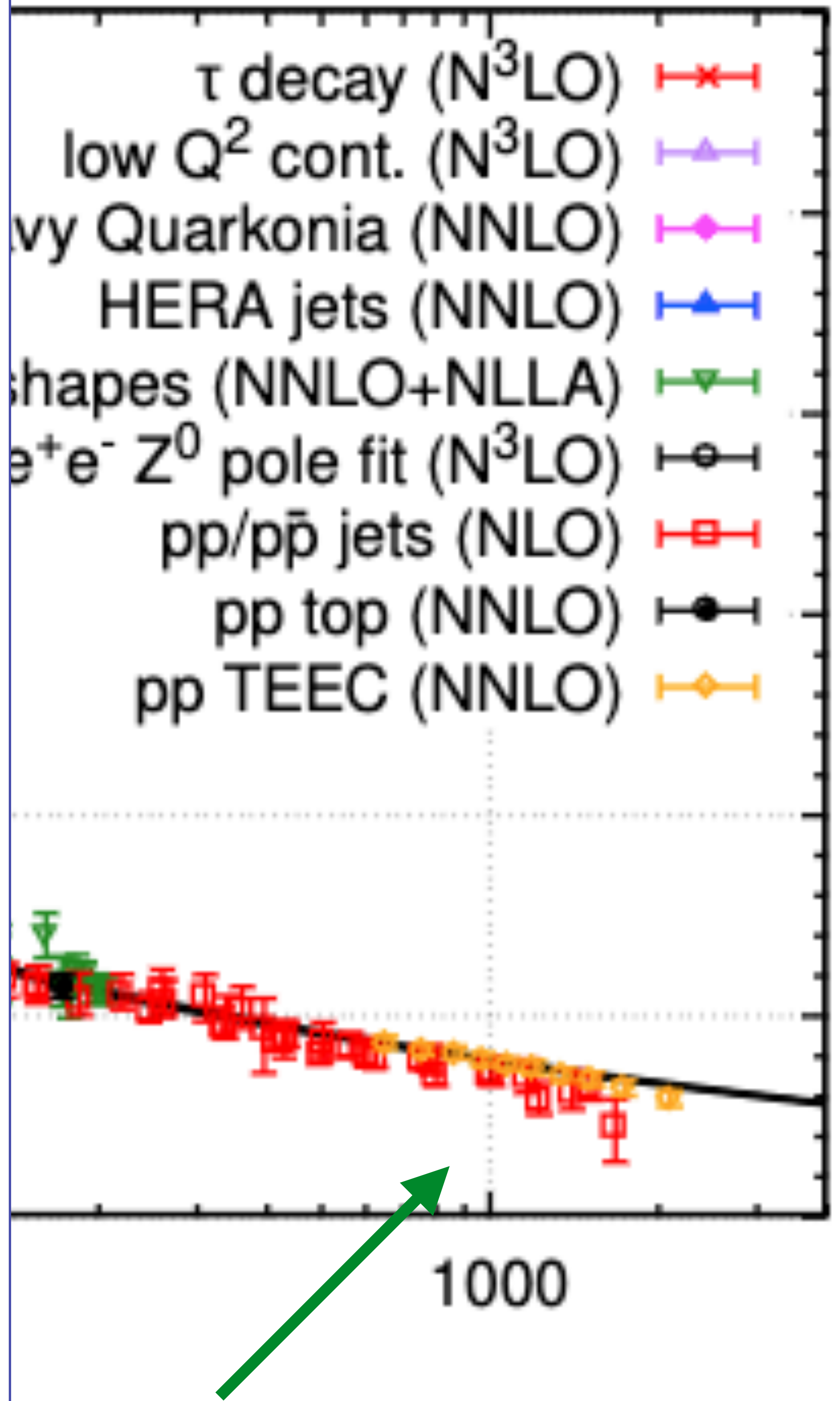
David J. Gross

H. David Politzer

Frank Wilczek

upling constant

ions are large -



coupling constant

culations valid -

deconfinement/asymptotic freedom

PDG2024

Asymptotic freedom vs Debye screening

Asymptotic freedom occurs at very high Q^2

Problem: Q^2 much higher than available in the lab.

So how to create and study this new phase of matter?

Solution: Use effects of Debye screening

In the presence of many color charges (charge density n), the short range term of the strong potential is modified:

$$V_s(r) \propto \frac{1}{r} \Longrightarrow \frac{1}{r} exp[\frac{-r}{r_D}]$$

where $r_D = \frac{1}{\sqrt[3]{n}}$ is the Debye radius

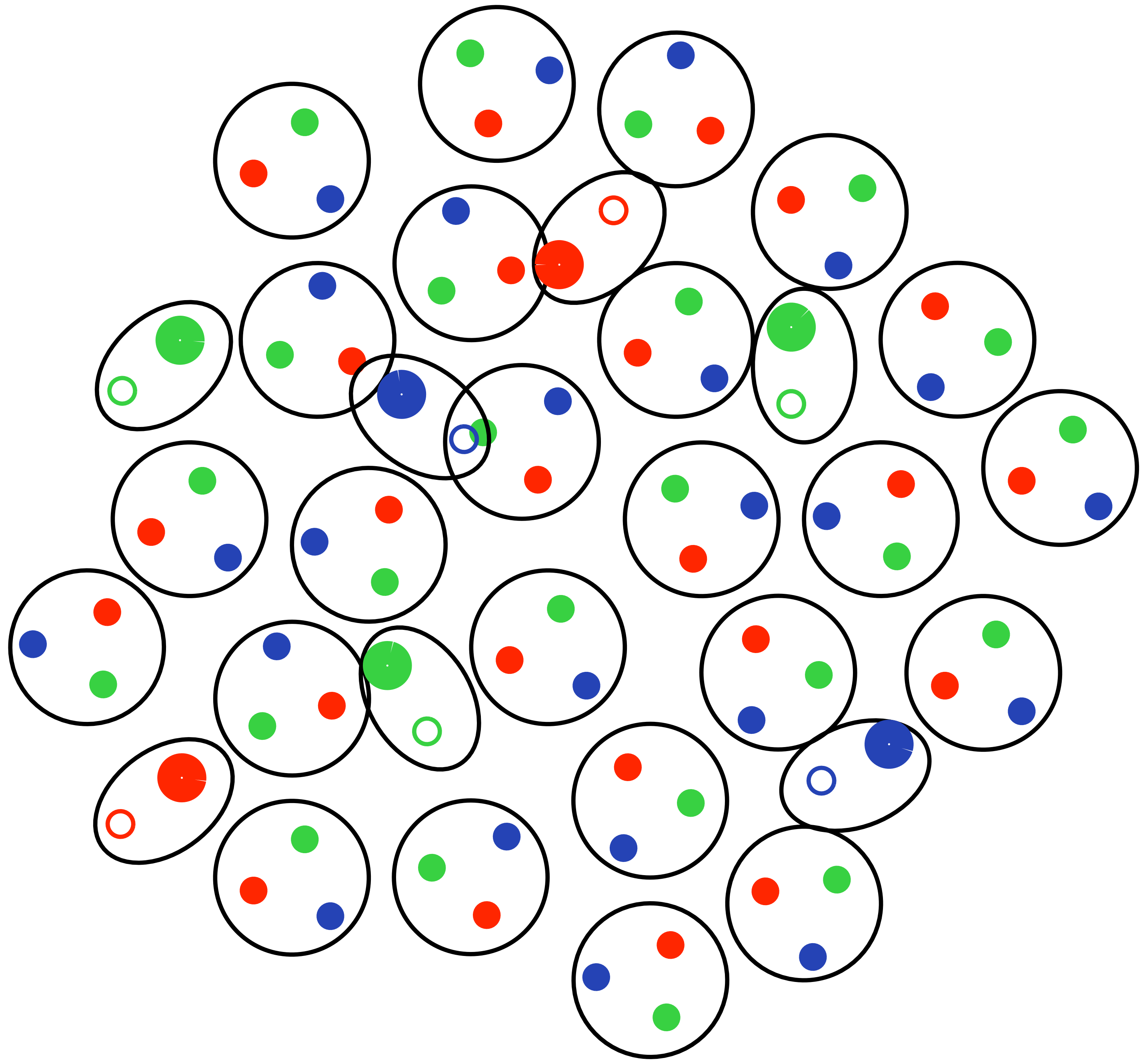
Charges at long range ($r > r_D$) are screened

QCD and Debye screening

At low color densities:

quarks and gluons confined into color singlets

→ hadrons (baryons and mesons)



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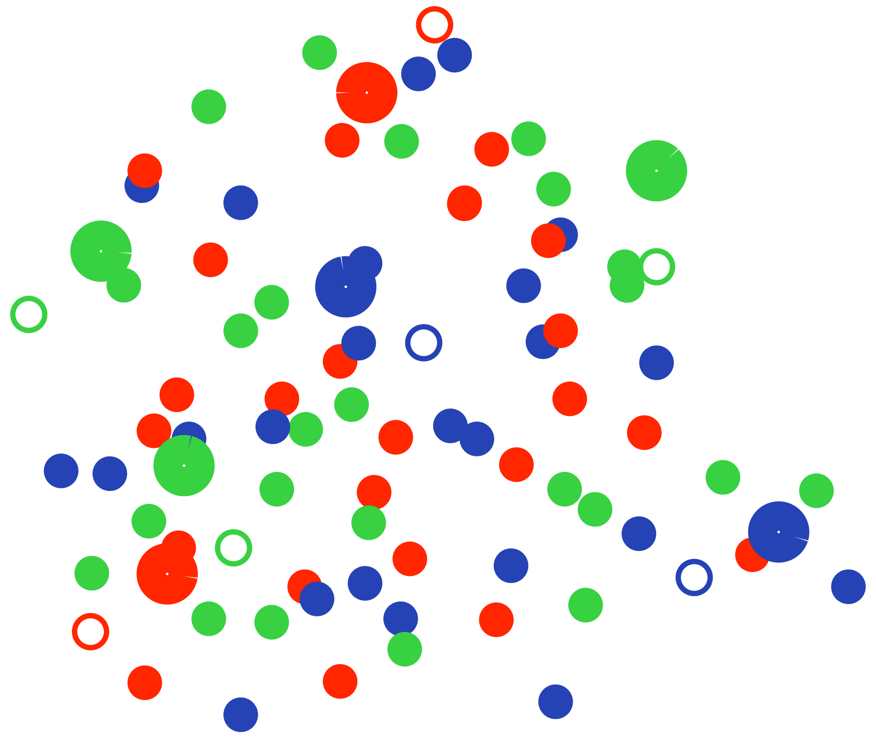


At high color densities:

quarks and gluons unbound

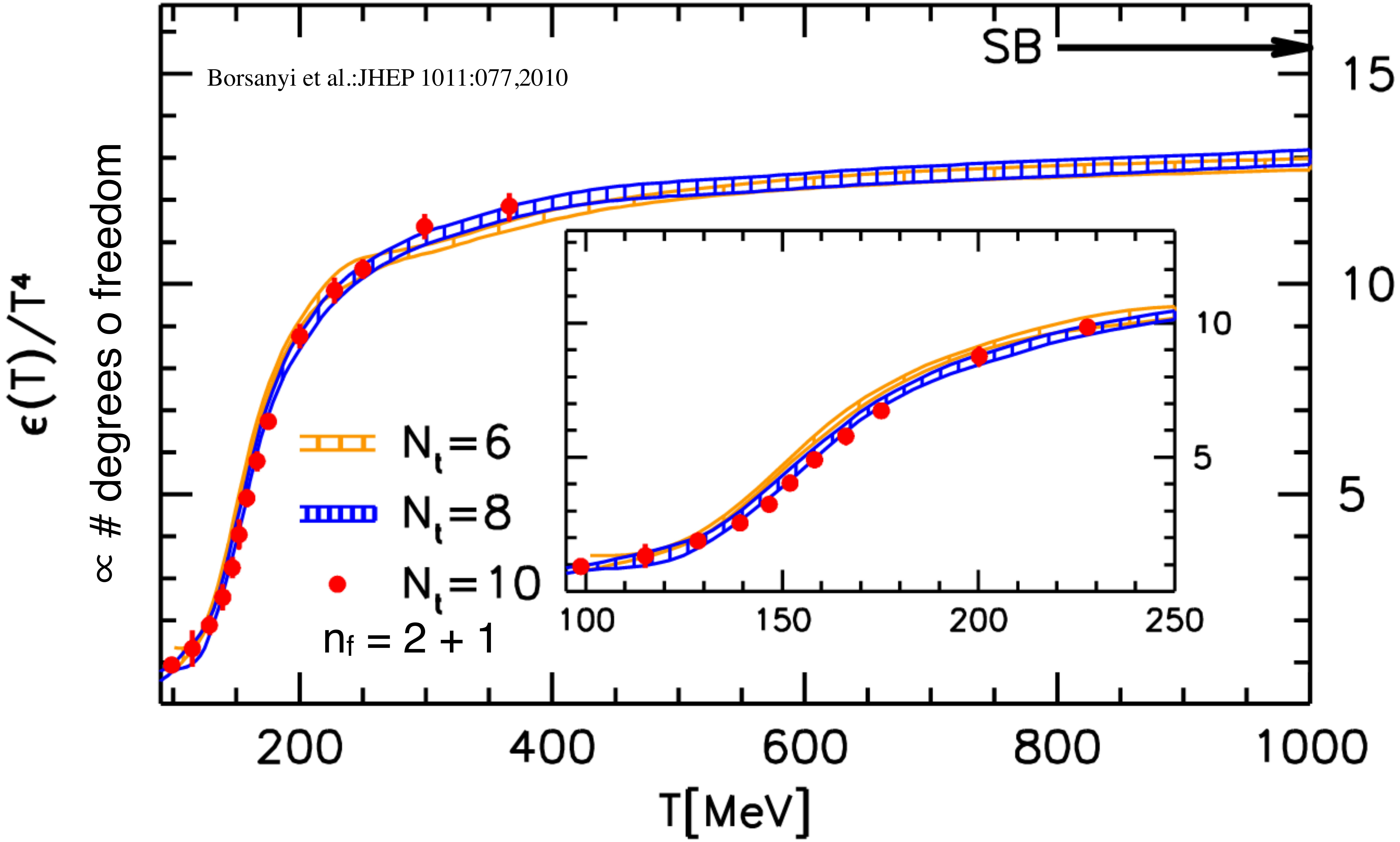
Debye screening of color charge

→ QGP - color conductor

Can create high color density by heating or compressing

→ QGP creation via accelerators or in neutron stars

Goal of Hot QCD in a nutshell



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

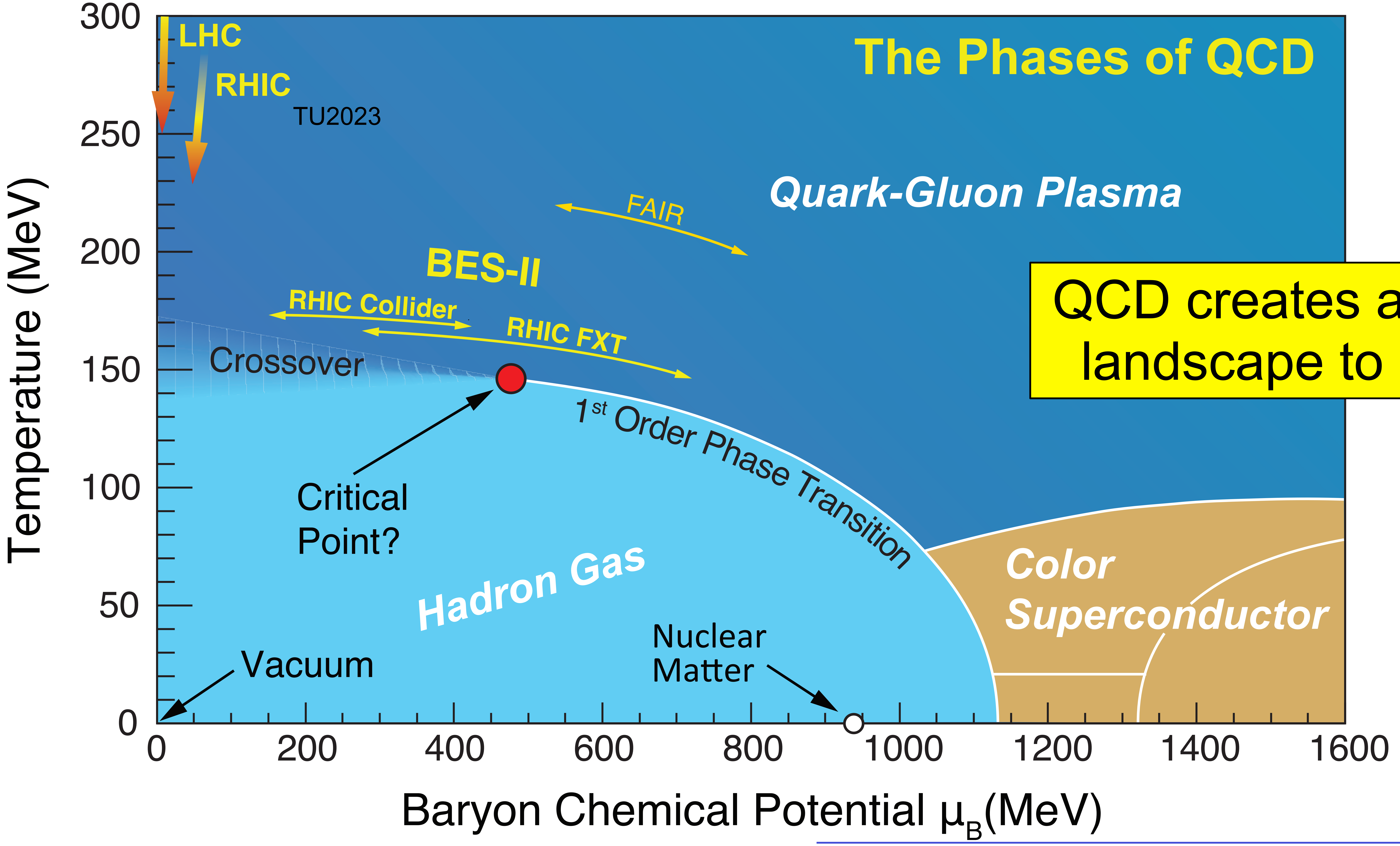
Lattice calculations: rapid smooth cross-over at μ_B ~0

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

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

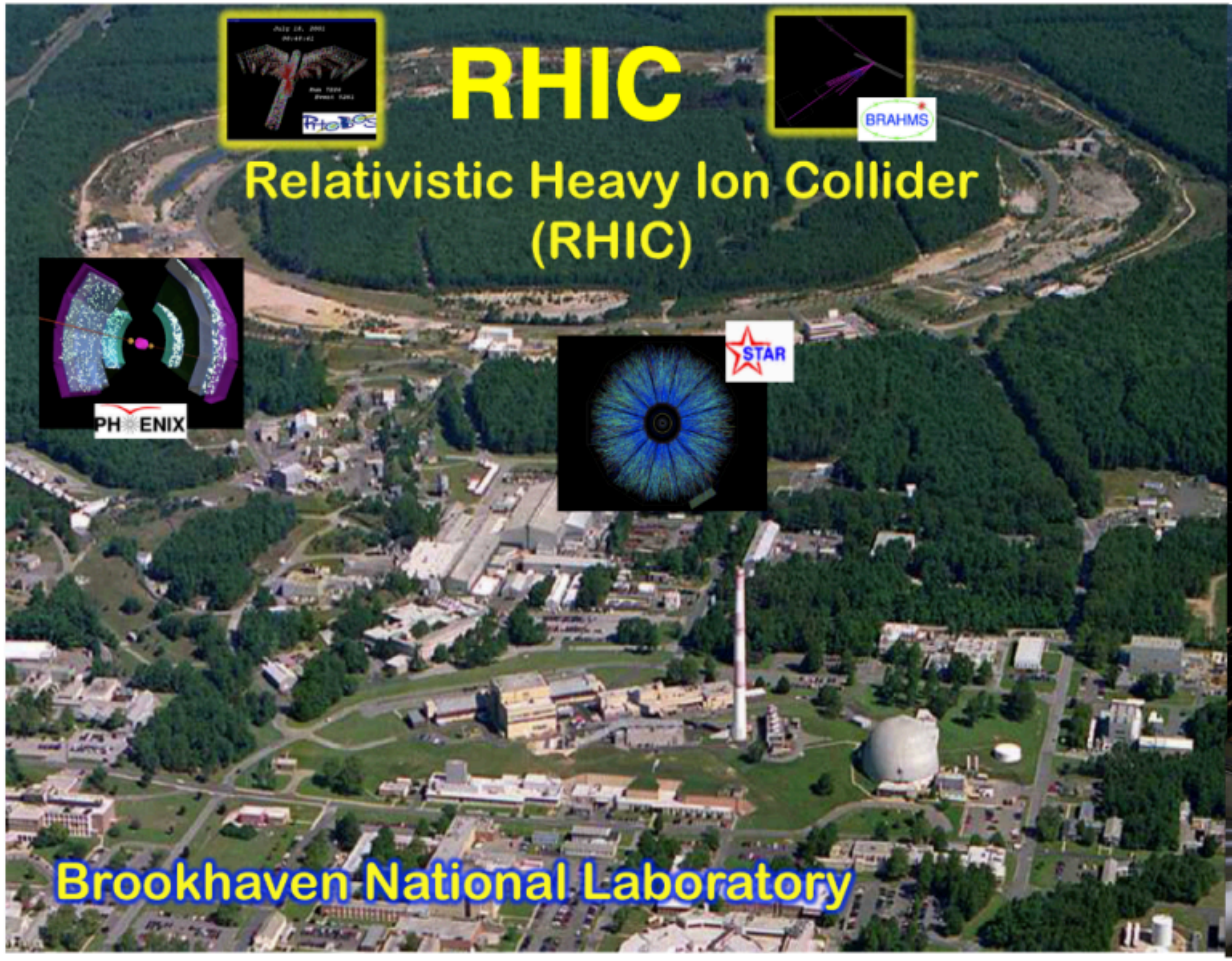
Such conditions can be created via HI collisions at RHIC and LHC

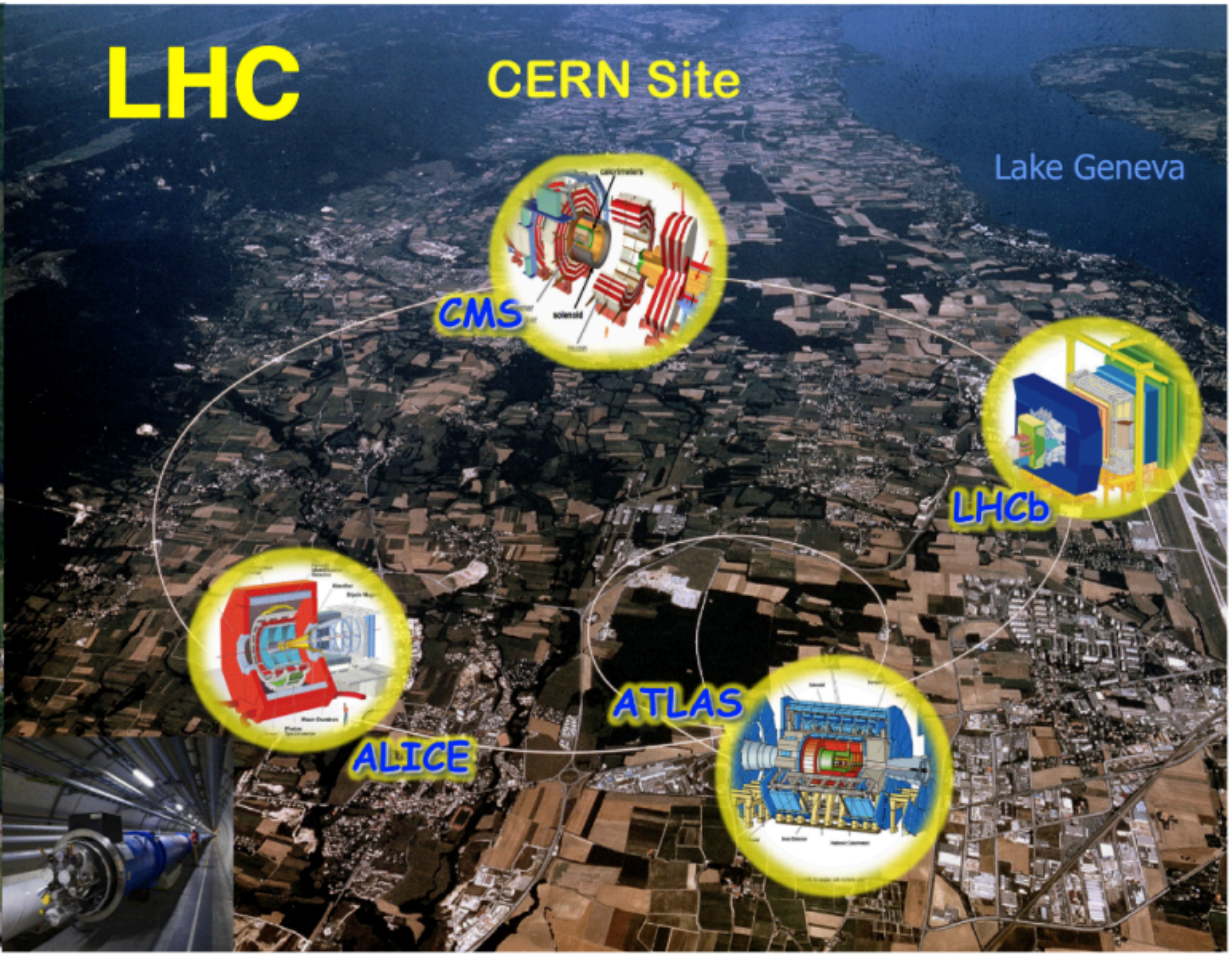
The phase diagram of QCD



QCD creates a rich landscape to explore

Recreating in the lab



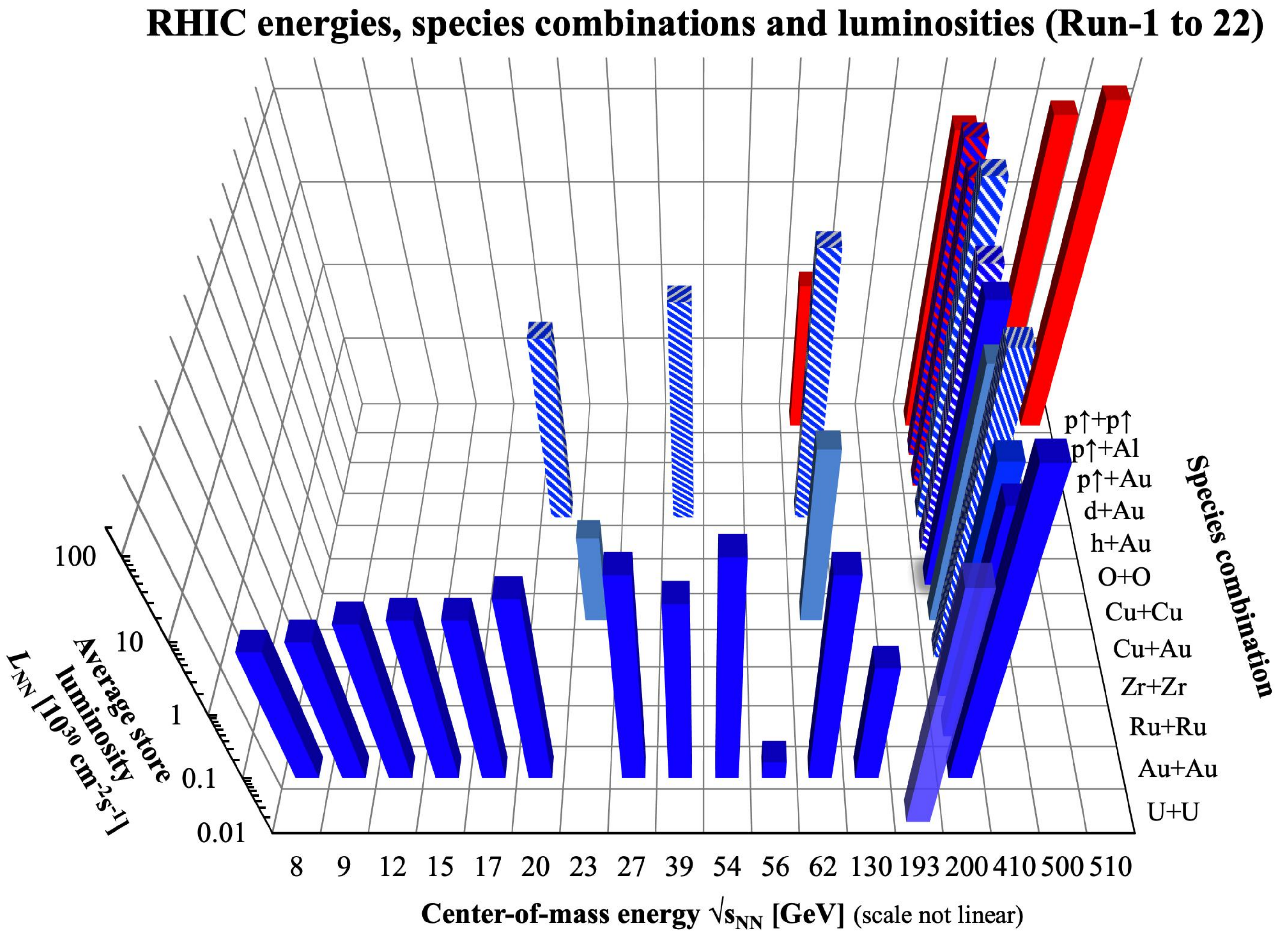


RHIC Start date: 2001

LHC Start date: 2010

sPHENIX taking first data at RHIC now

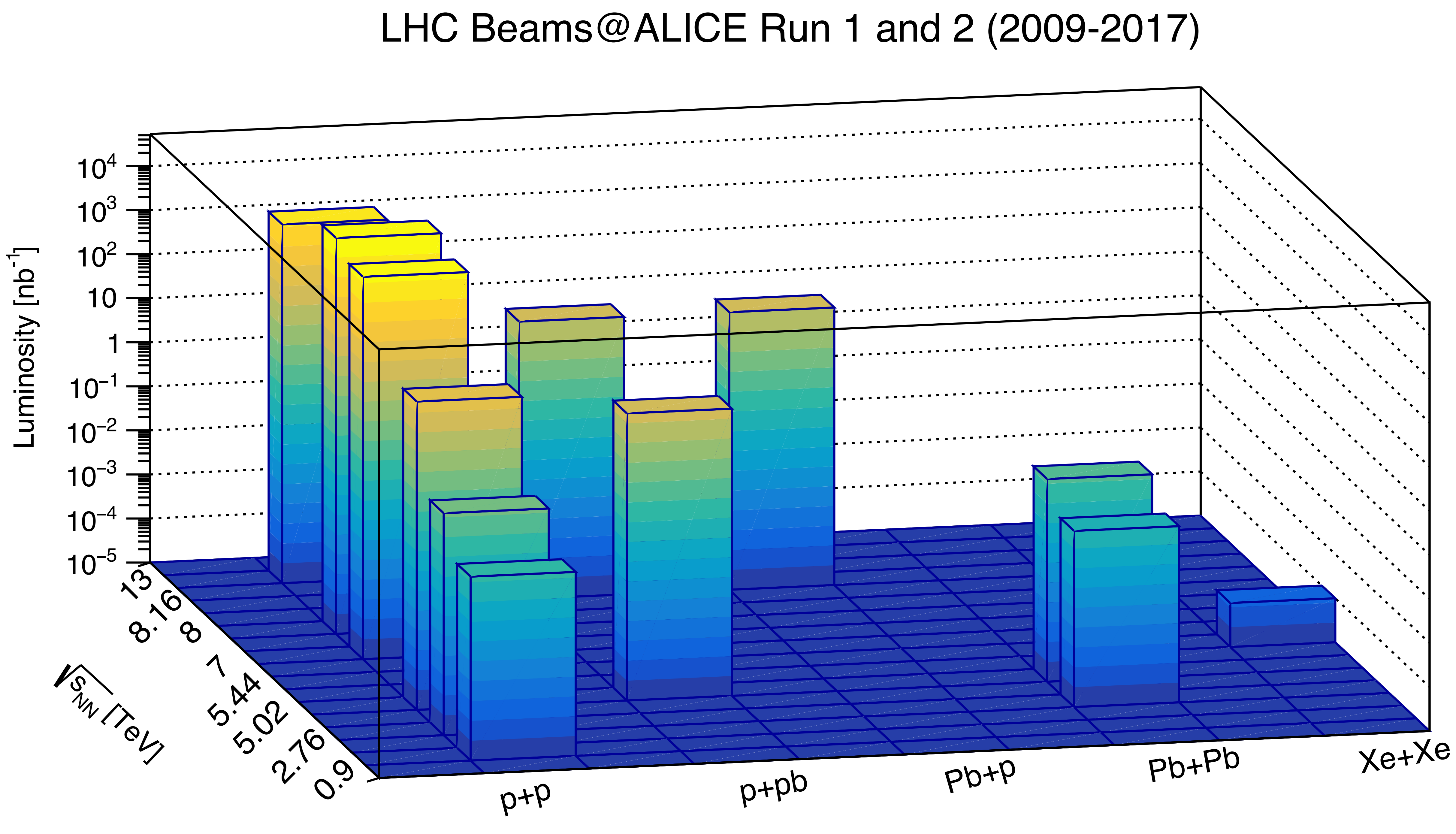
Wealth of data available



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

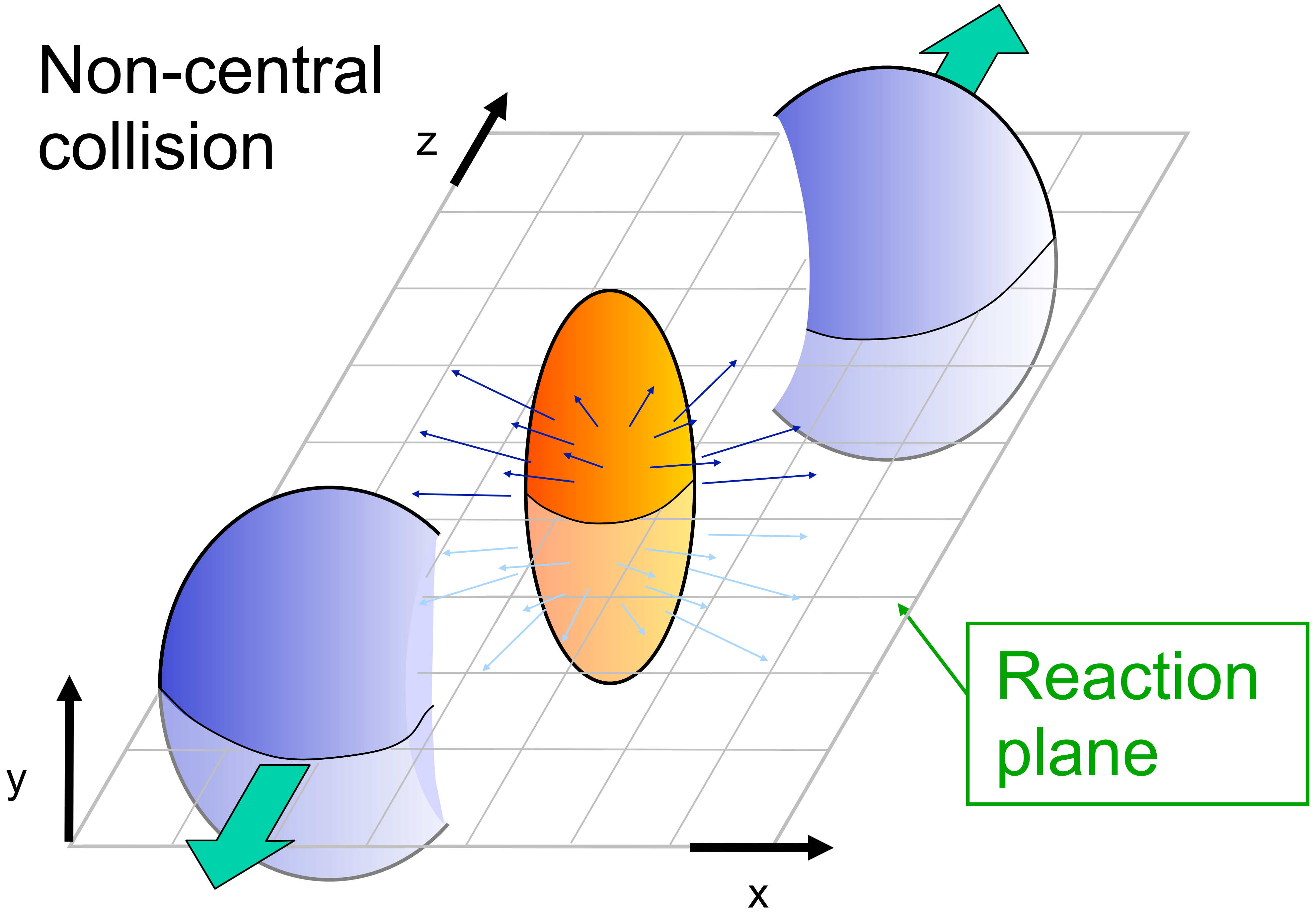
For Pb+Pb mostly at 5.02 TeV

HUGE datasets

(significantly bigger at ATLAS and CMS)

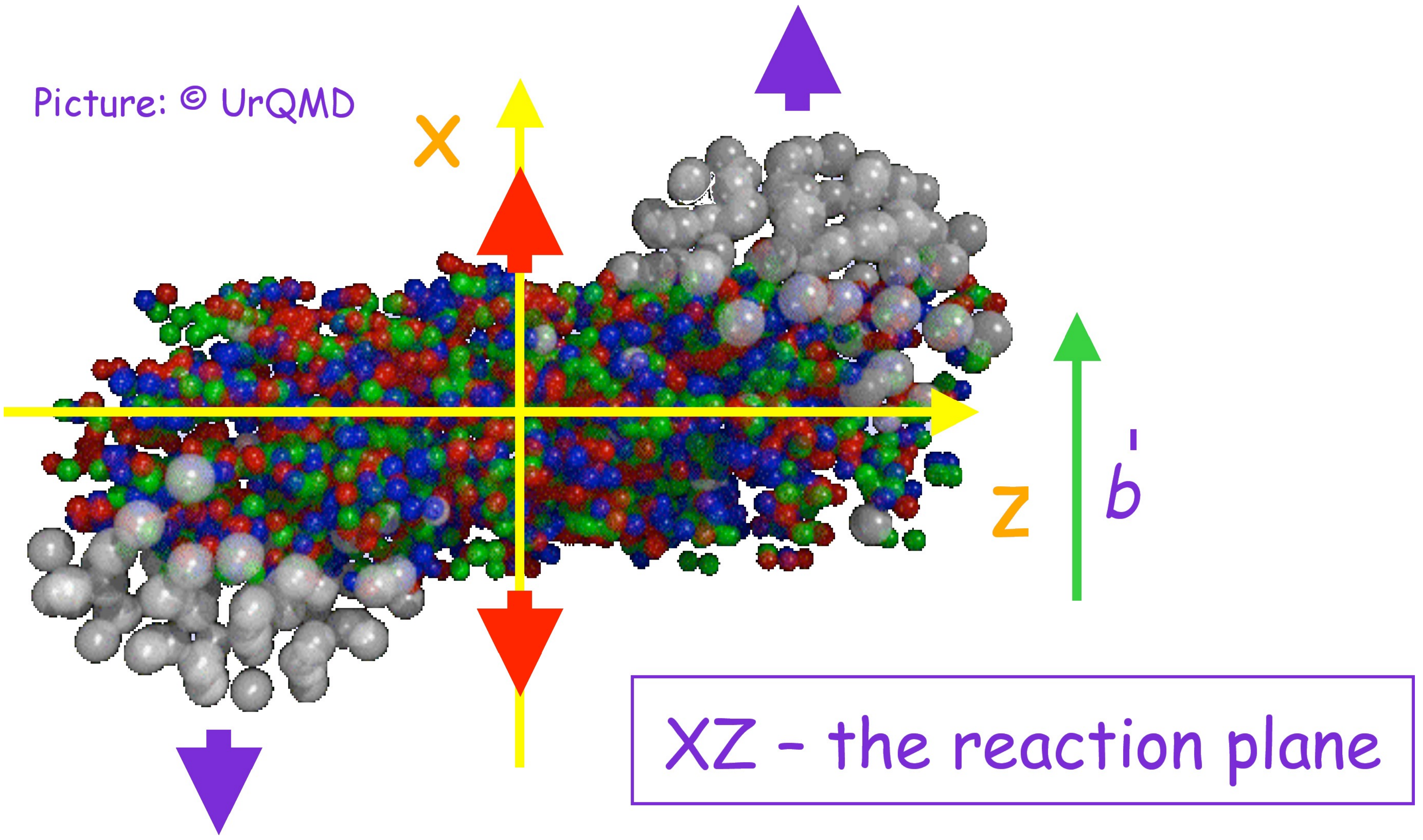
Complimentary datasets

Geometry of a heavy-ion collision



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

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



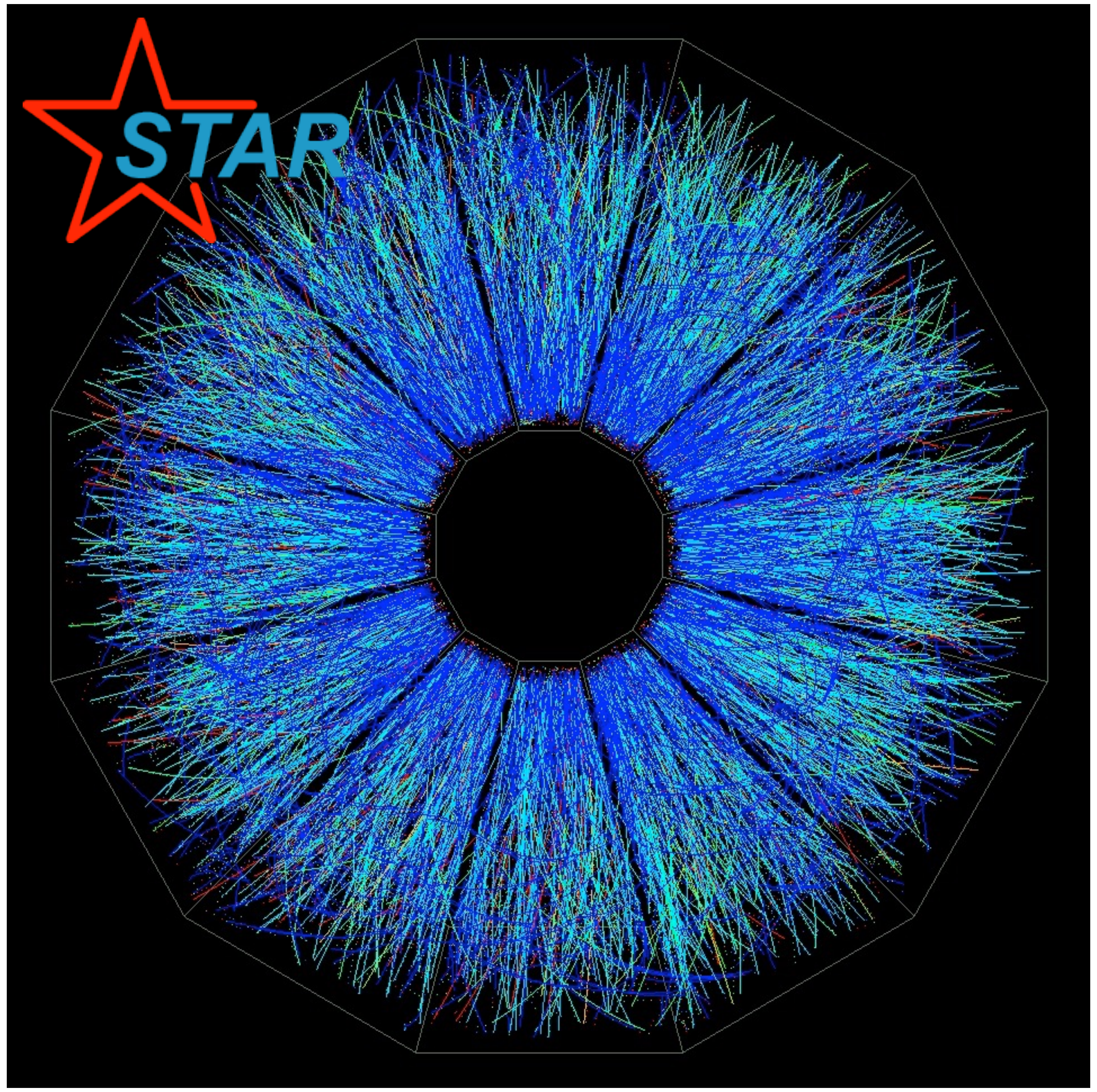
Number of participants (N_{part}): number of incoming nucleons (participants) in overlap region

Number of binary collisions (N_{bin}): number of equivalent inelastic nucleon-nucleon collisions

$$N_{bin} \geq N_{part}/2$$

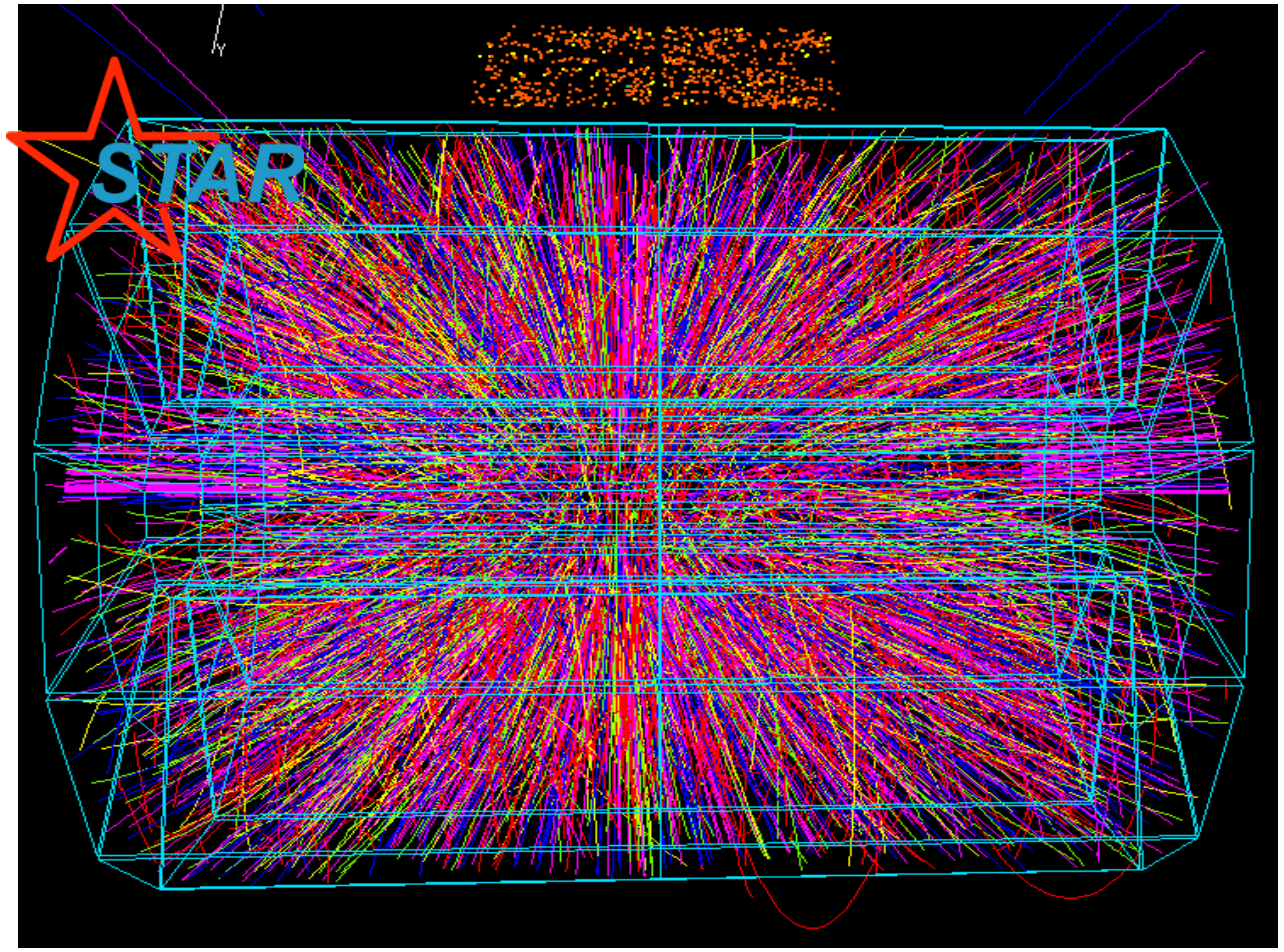
More central collisions produce more particles

39.4 TeV in central Au-Au collision



Only charged particles shown

Neutrals don't ionize the TPC's gas so are not "seen" by this detector.

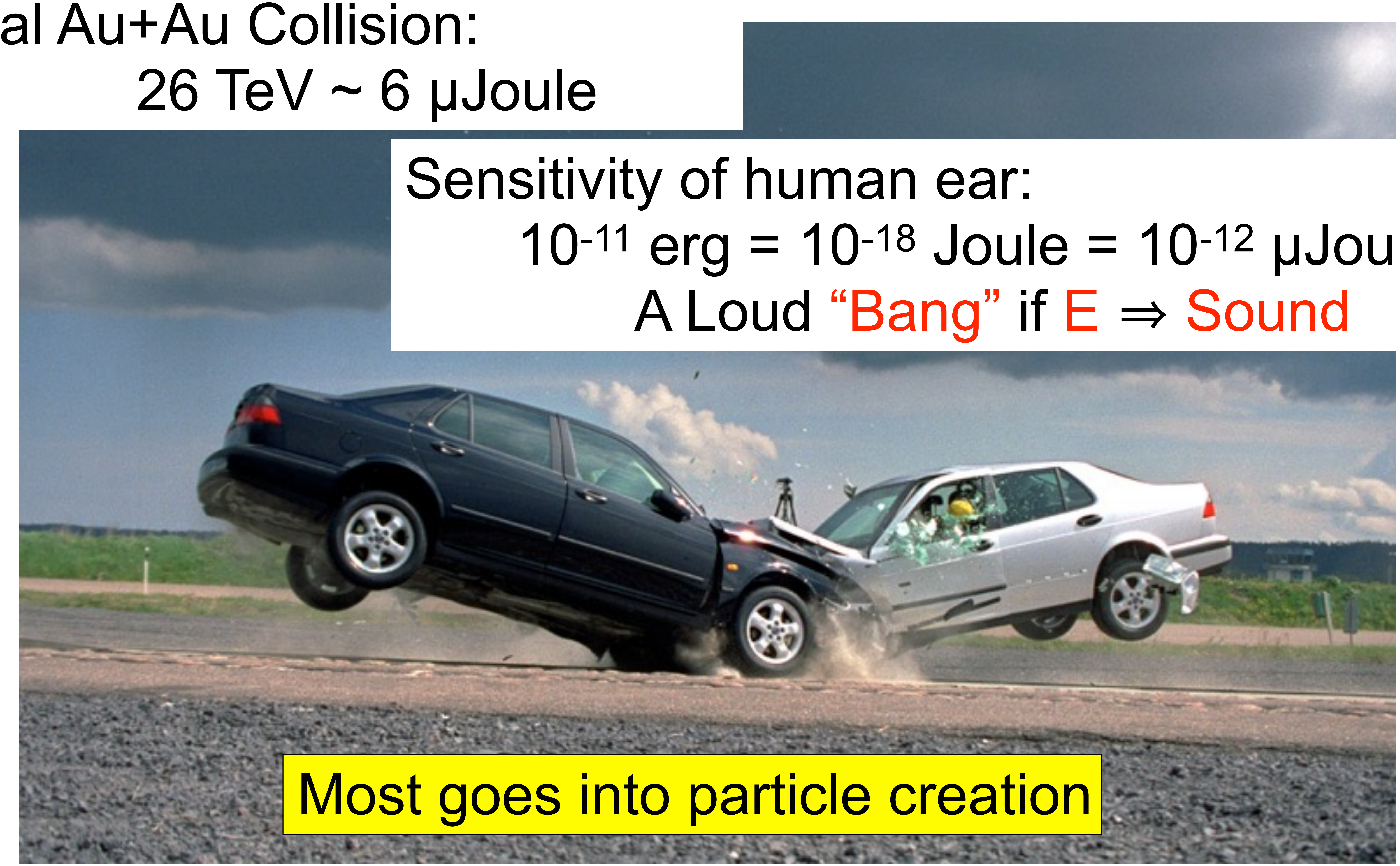


>5000 hadrons and leptons

26 TeV is removed from colliding beams.

The energy contained in one collision

Central Au+Au Collision:
26 TeV ~ 6 μJoule



Sensitivity of human ear:
10^{-11} erg = 10^{-18} Joule = 10^{-12} μJoule
A Loud "Bang" if E ⇒ Sound

Most goes into particle creation

Quantifying the collision

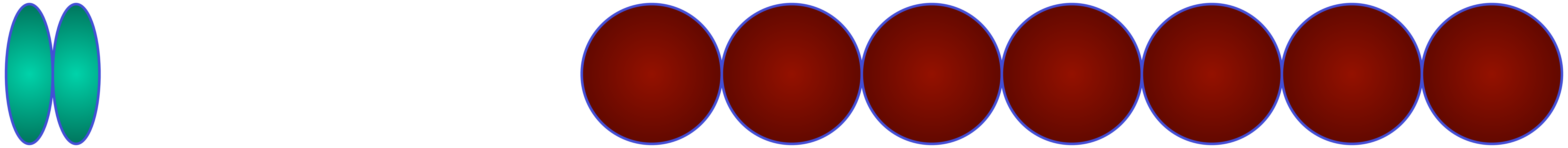
p+p: 2 Participants, 1 Binary Collision

Participants: those nucleons that have interacted at least once

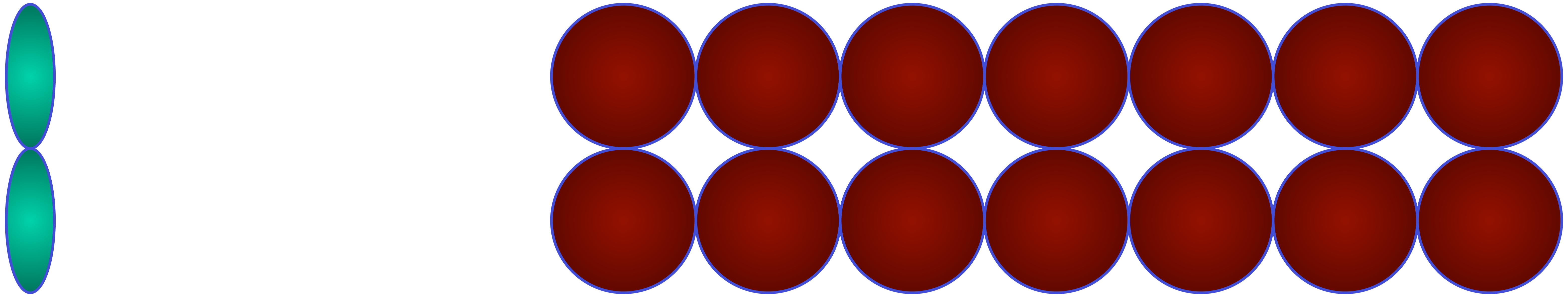
Binary collisions: the number of 1+1 collisions

Quantifying the collision

A+A:



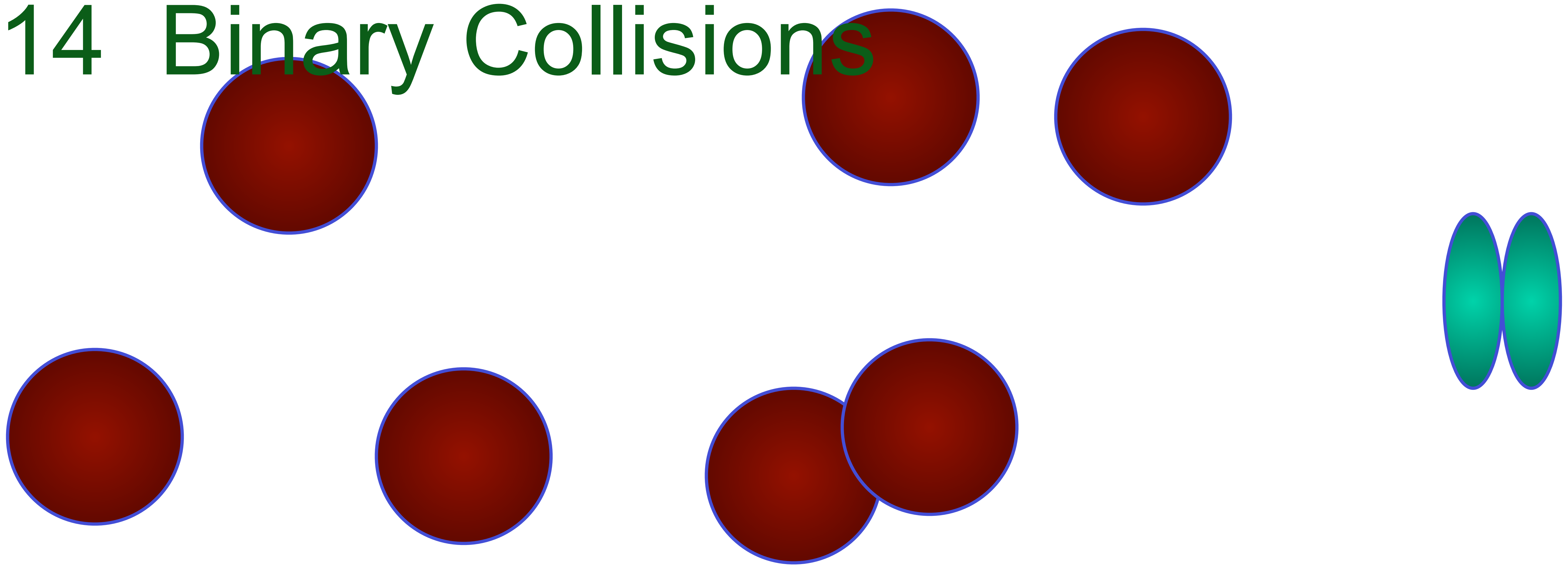
A+A:



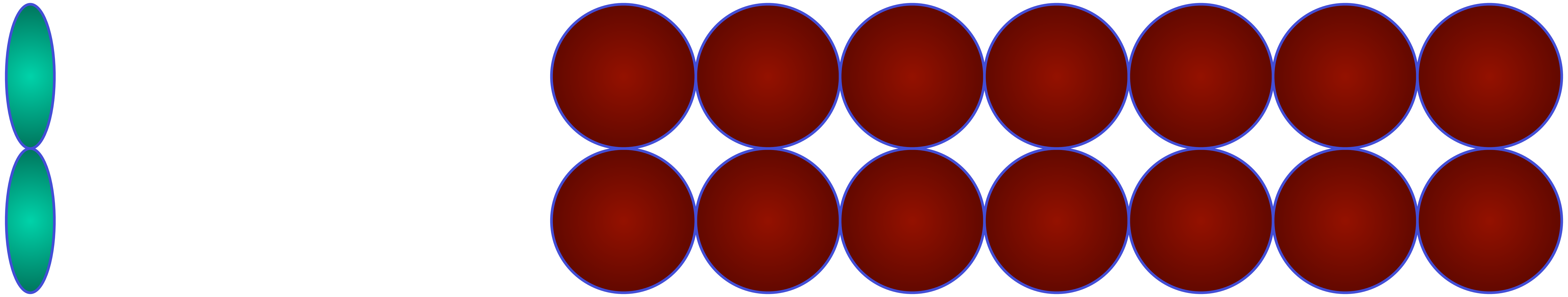
Multiplicity of event and N_{part} correlated

Quantifying the collision

A+A: 9 Participants, 14 Binary Collisions



A+A:



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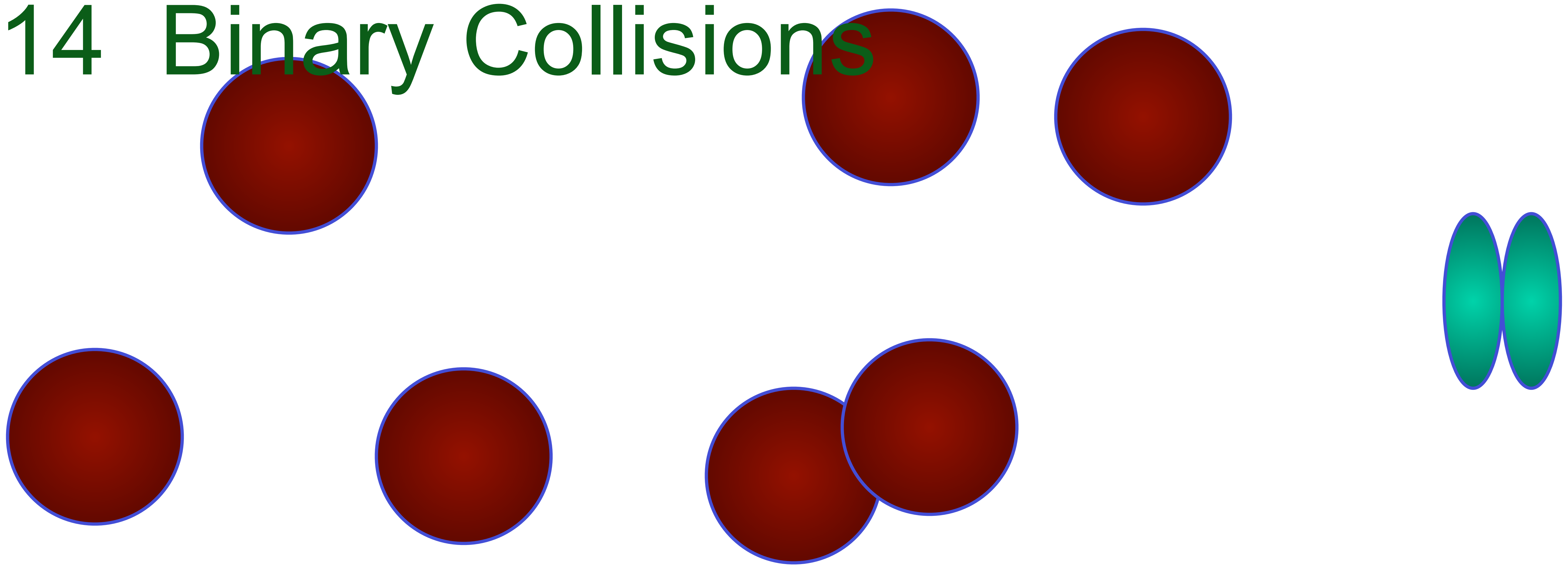
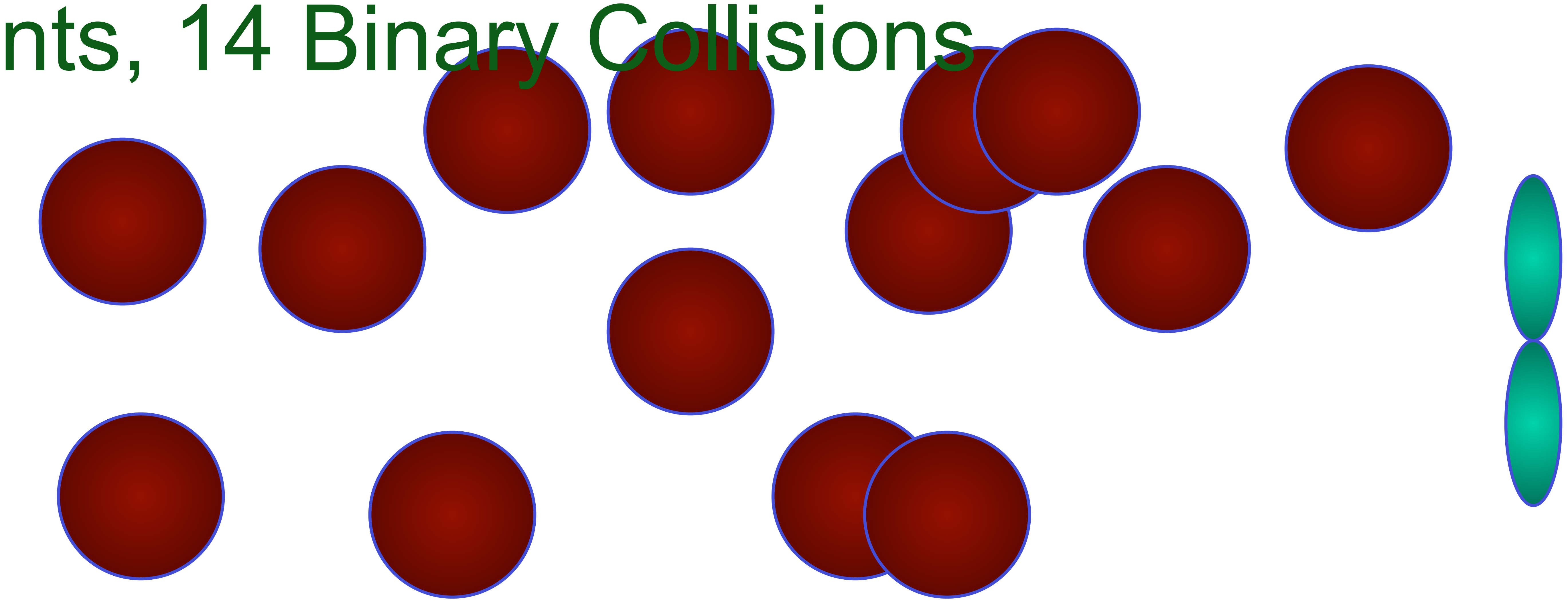


A+A: 16 Participants, 14 Binary Collisions



Multiplicity of event and N_{part} correlated

Glauber to the rescue

Use a Glauber calculation to estimate N_{bin} and N_{part}

Roy Glauber: 2005 Nobel prize for “his contribution to the quantum theory of optical coherence”

Application of Glauber theory to heavy ion collisions does not use the full sophistication of these methods.

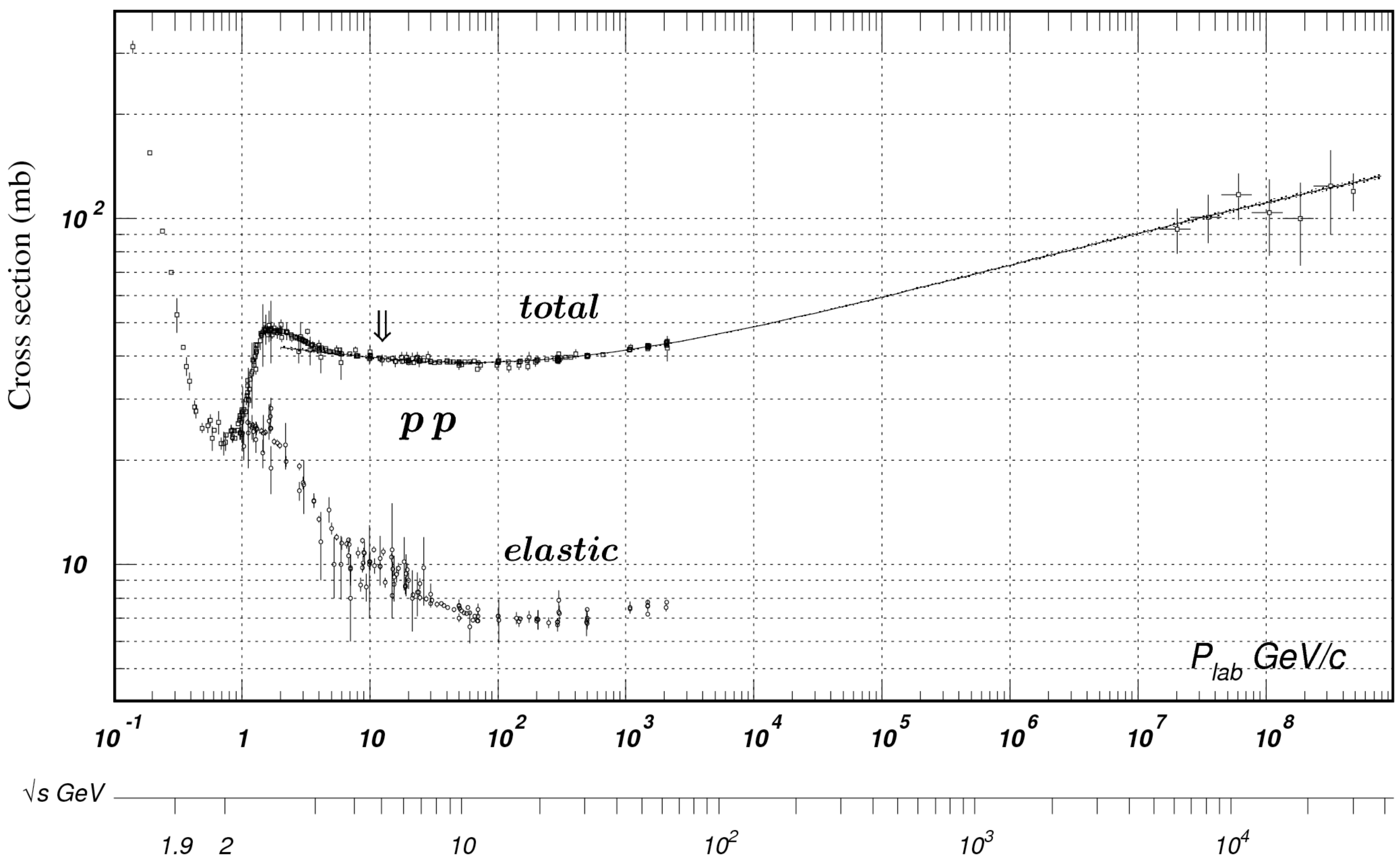
Two simple assumptions:

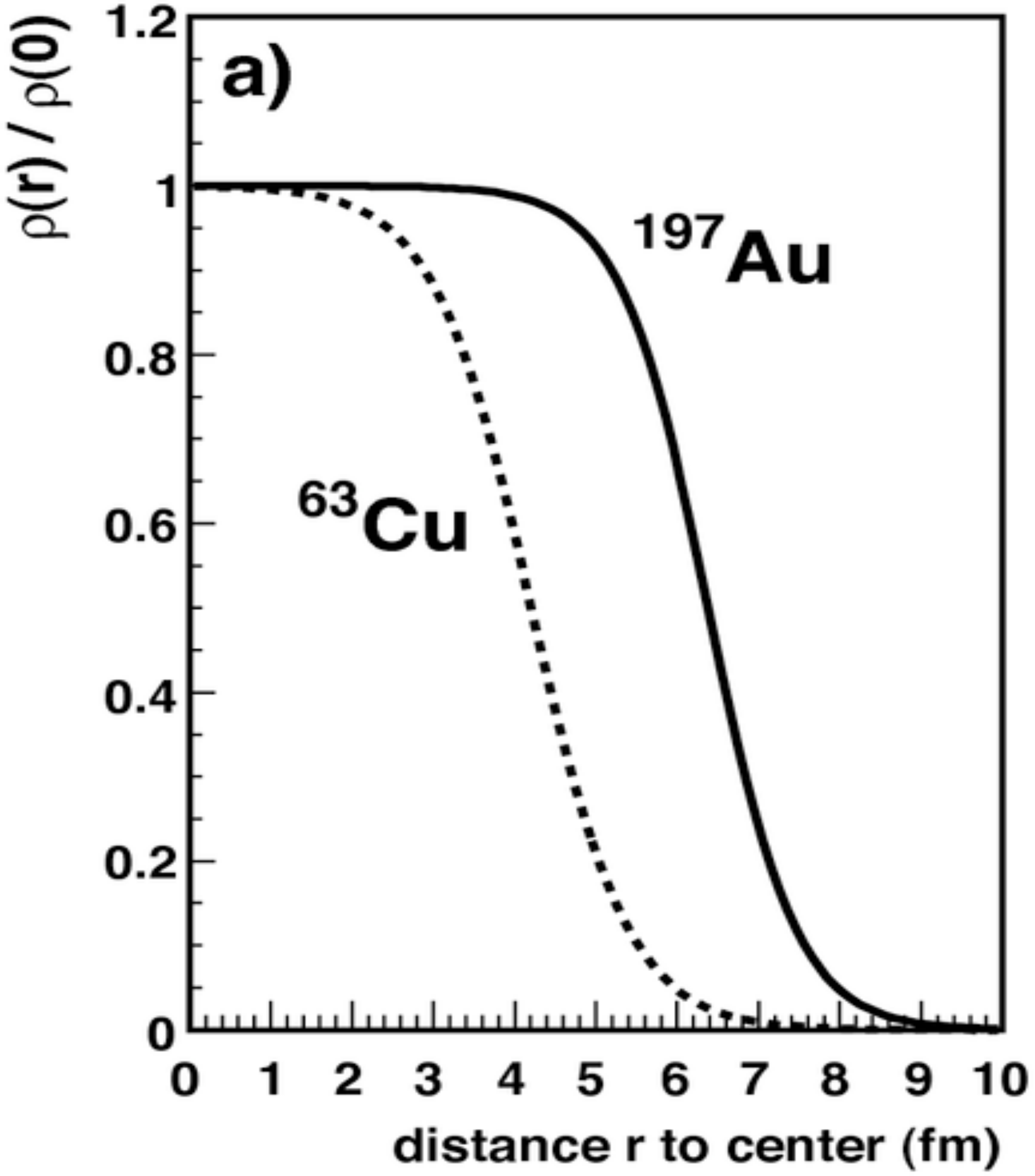
1) Eikonal - constituents of nuclei proceed in straight-line trajectories

2) Interactions determined by initial-state shape of overlapping nuclei

Ingredients for Glauber calculations

Particle Data Book: W.-M. Yao et al., J. Phys. G 33,1 (2006) Fig 40.11





Nucleon-nucleon interaction cross section

Most use inelastic: 42 mb at √s=200 GeV

Probability density distribution for nucleons:

\`Wood-Saxon’ from electron scattering experiments

M. Miller et al, Ann.Rev.Nucl.Part.Sci.57:205,2007

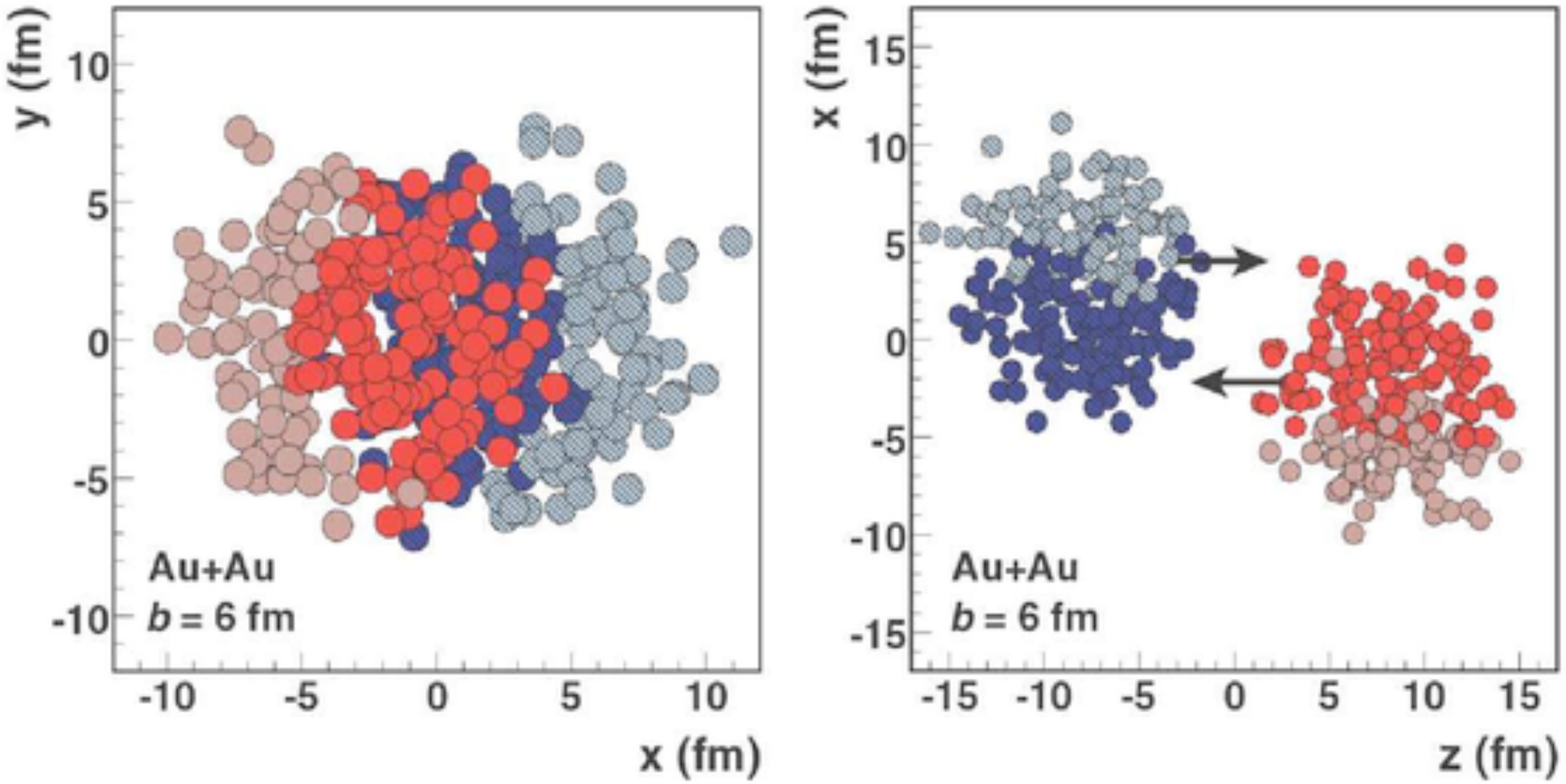
Monte-carlo Glauber modeling

Randomly initialize nucleons

Randomly select impact parameter

Randomly sample probability of nucleons to interact from interaction cross-section if separated by

$$d < \sqrt{\sigma_{int}/\pi}$$



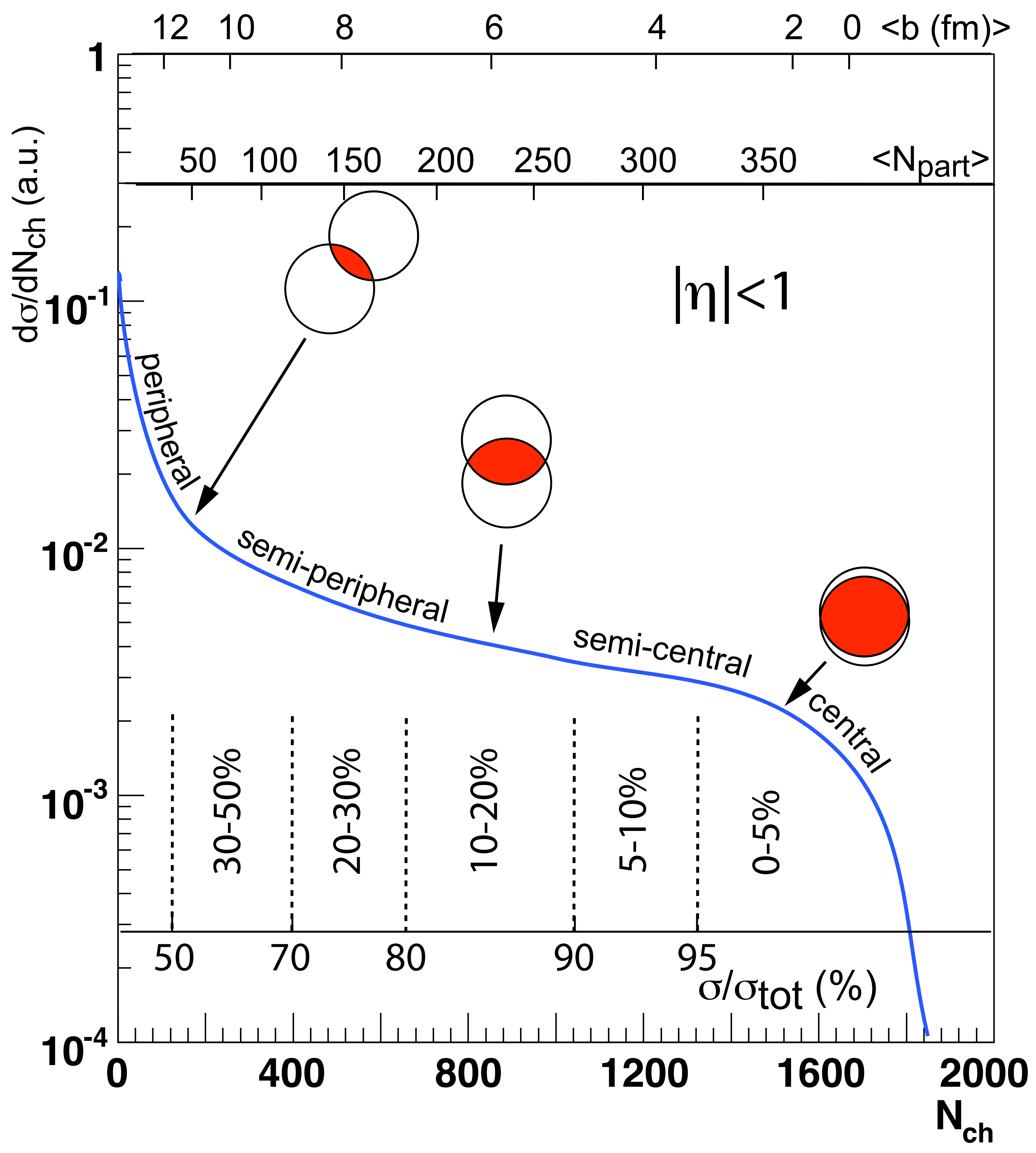
Calculate probability that N_{part} or N_{bin} occurs per event

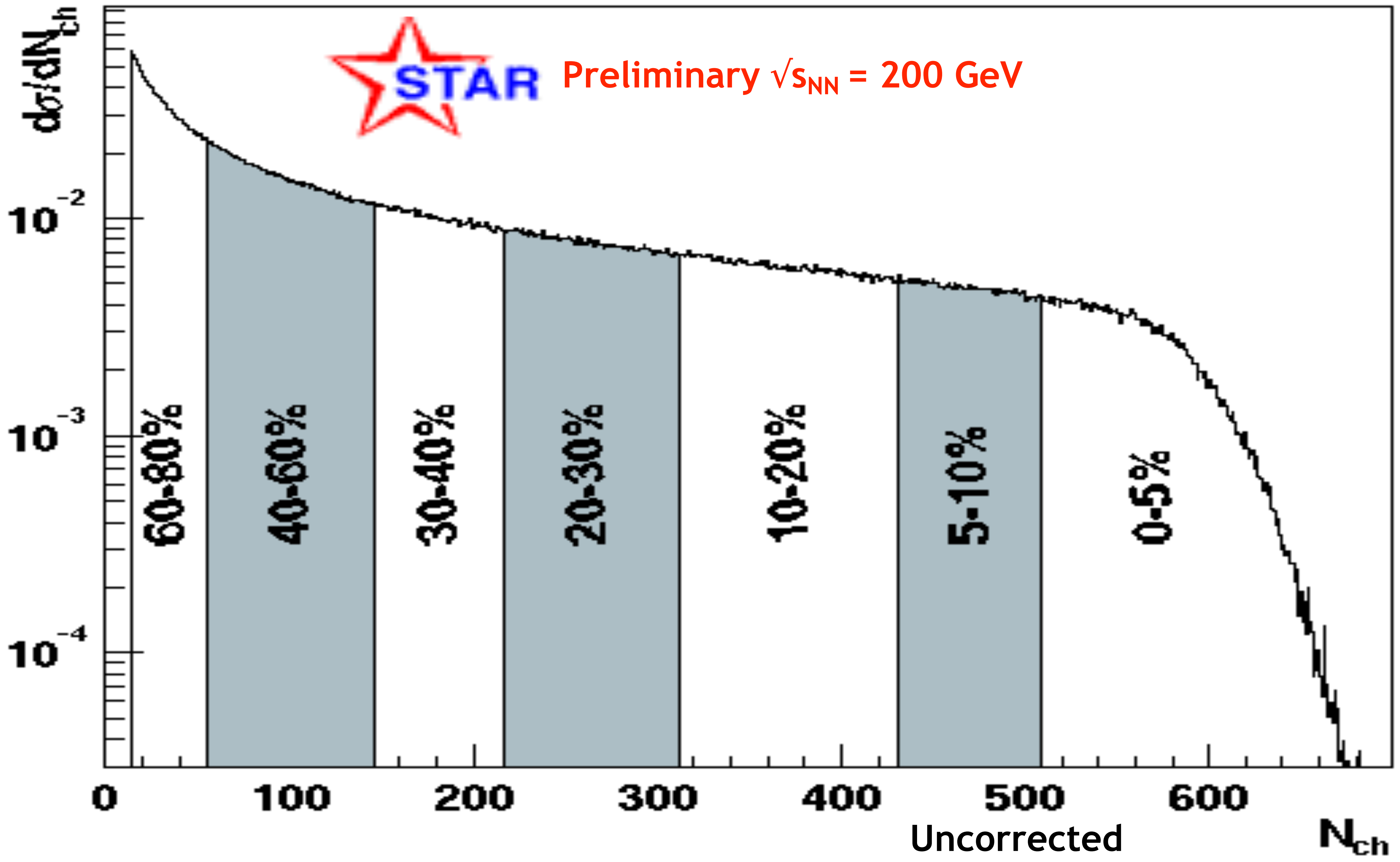
Map onto an experimentally measurable variable expected to scale with centrality

i.e. particle multiplicity

M. Miller et al, Ann.Rev.Nucl.Part.Sci.57:205,(2007)

Comparing to data



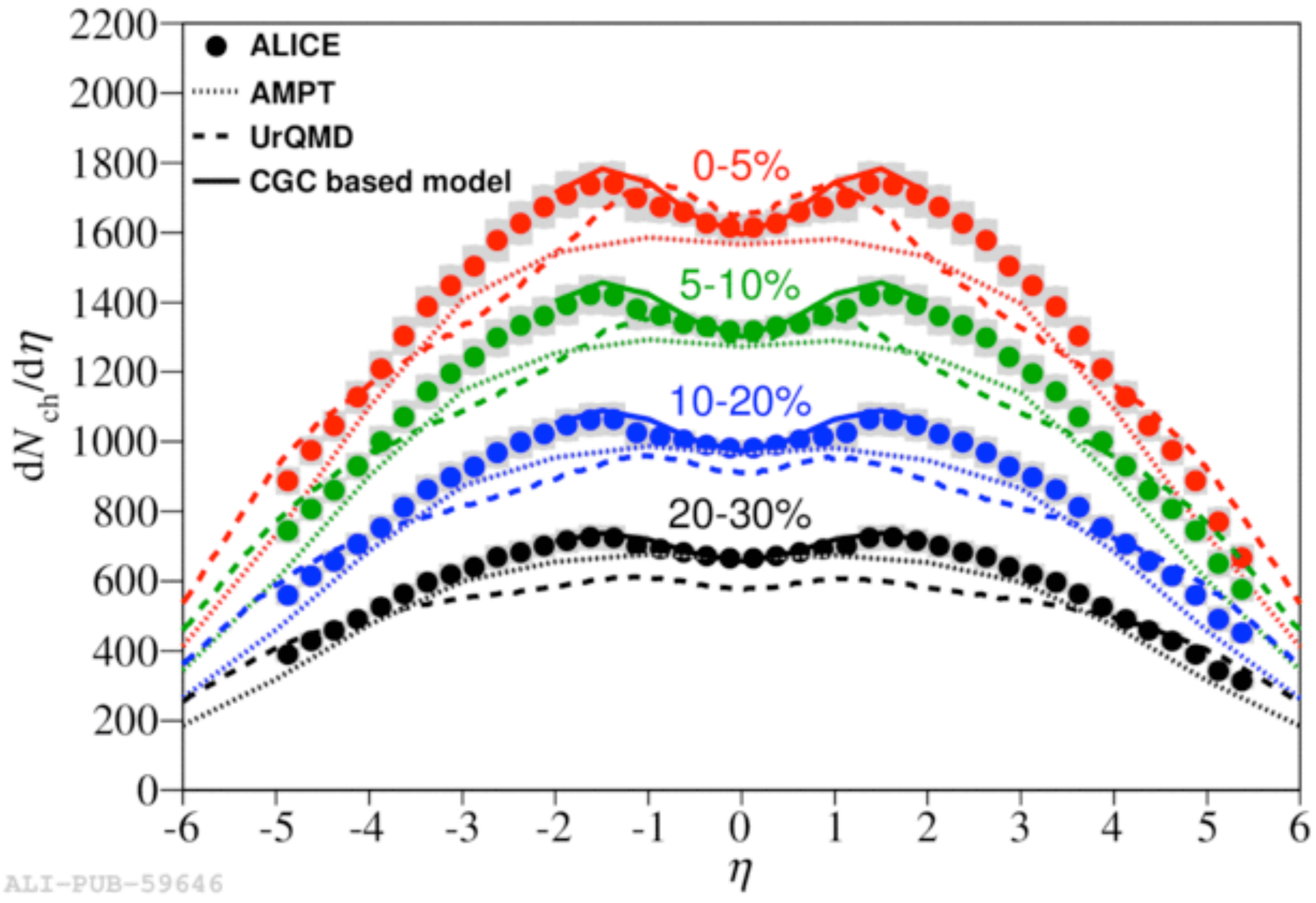


Good agreement between data and calculation

Measured mid-rapidity particle yield can be related to size of overlap region

Do we create the necessary initial conditions?

Energy density of a central collision

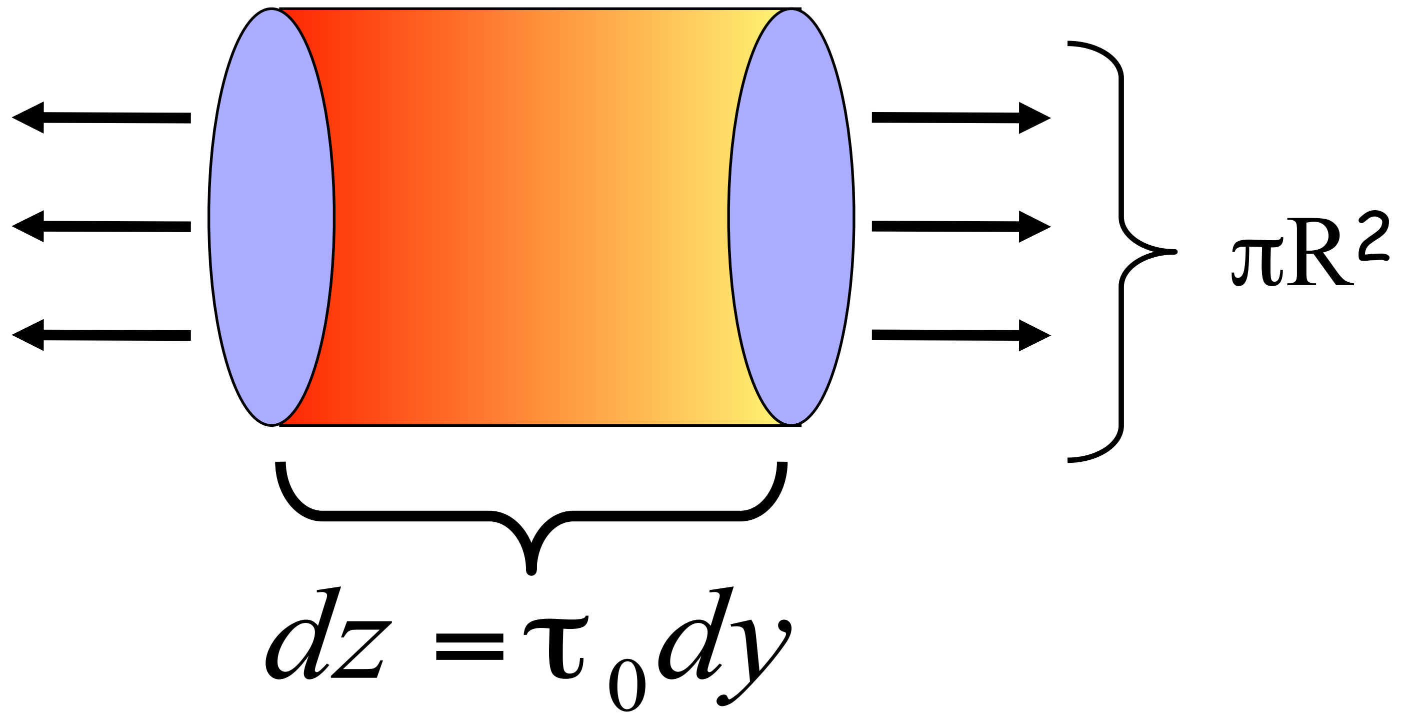


Bjorken-Formula for Energy Density:

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

Radius of medium ~7fm

Time to thermalize system



In central Pb-Pb events:

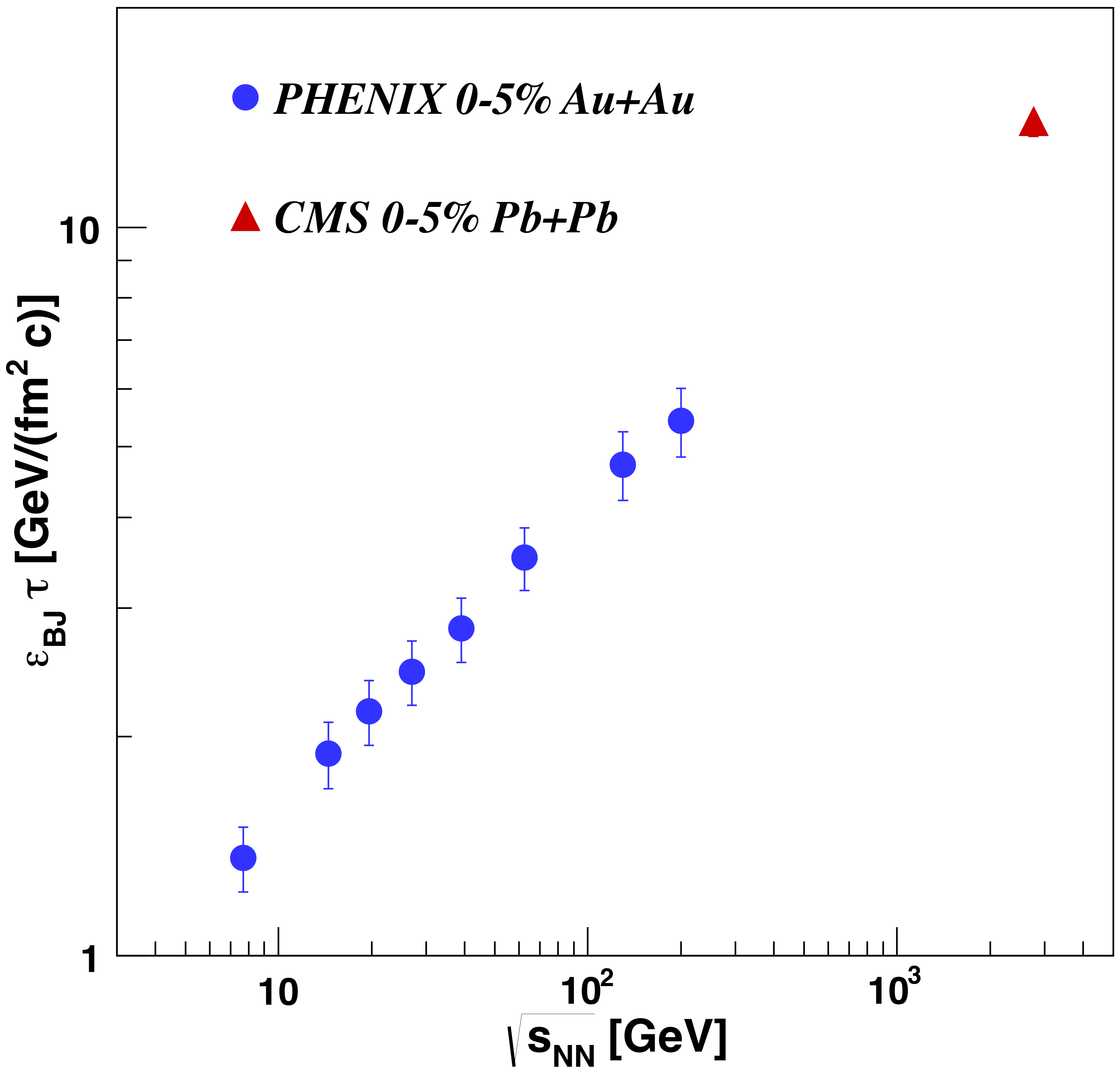
$dN_{ch}/d\eta$ ~ 1600

$\langle p_T\rangle$ ~ 650 MeV

τ_0 ~ 1fm

ALICE: PLB 726, 610 (2013),

Energy density of a central collision



In central Pb-Pb events:

$dN_{ch}/d\eta \sim 1600$

$\langle p_T \rangle \sim 650$ MeV

$\tau_0 \sim 1$fm

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 ~7fm

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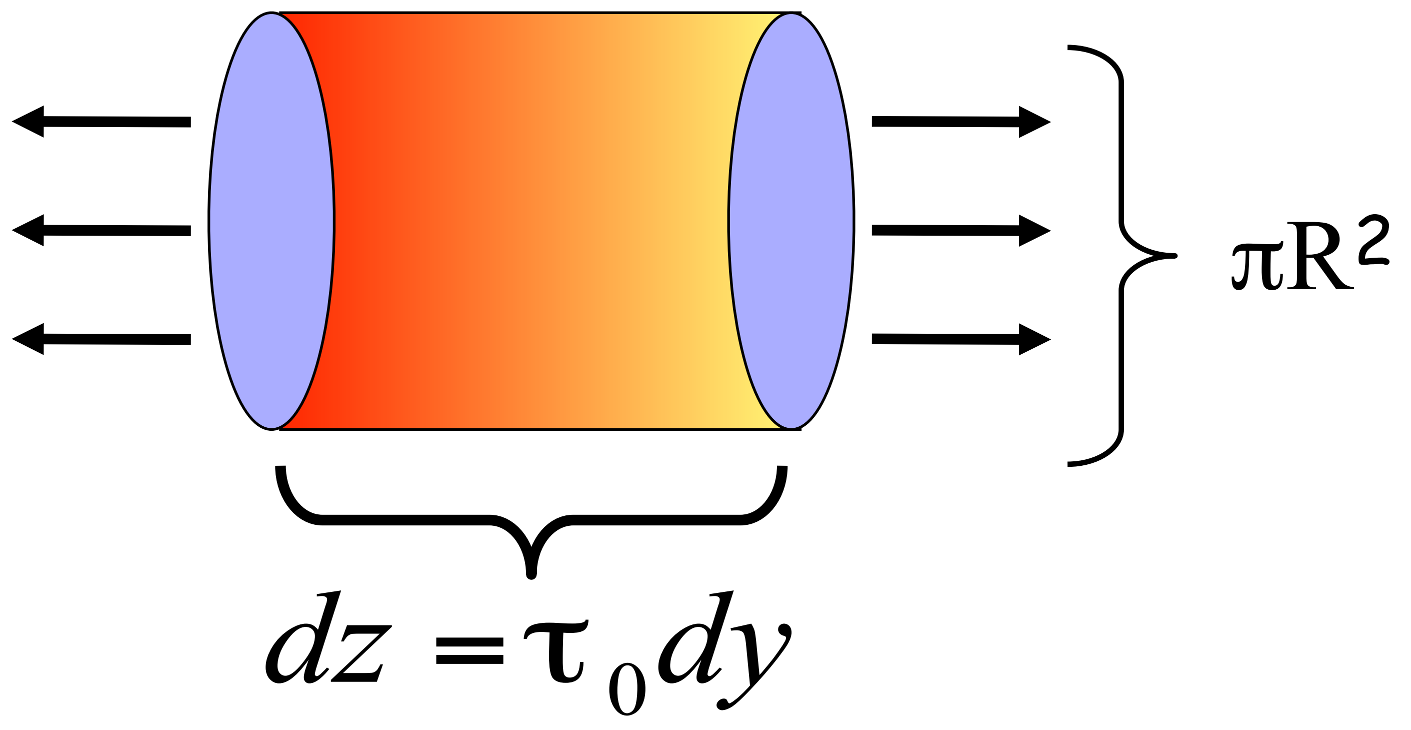

ε_{BJ} (LHC) ≈ 10 GeV/fm^3
~75 times normal nuclear density
~ 15 times > $\varepsilon_{critical}$ (lattice QCD)

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

10 GeV/fm³. 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 woul you need to pack this energy into to produce equivalent energy density?

A. A cube ~5 μm x ~5 μm x ~5 μm (approximate size of red blood cell)

B. A cube ~10 mm x ~10 mm x ~5 mm (approximate size of corn kernel)

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

D. A cube ~1 m high by 94,326 km^2 (approximately the area of Indiana)?

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 woul you need to pack this energy into to produce equivalent energy density?

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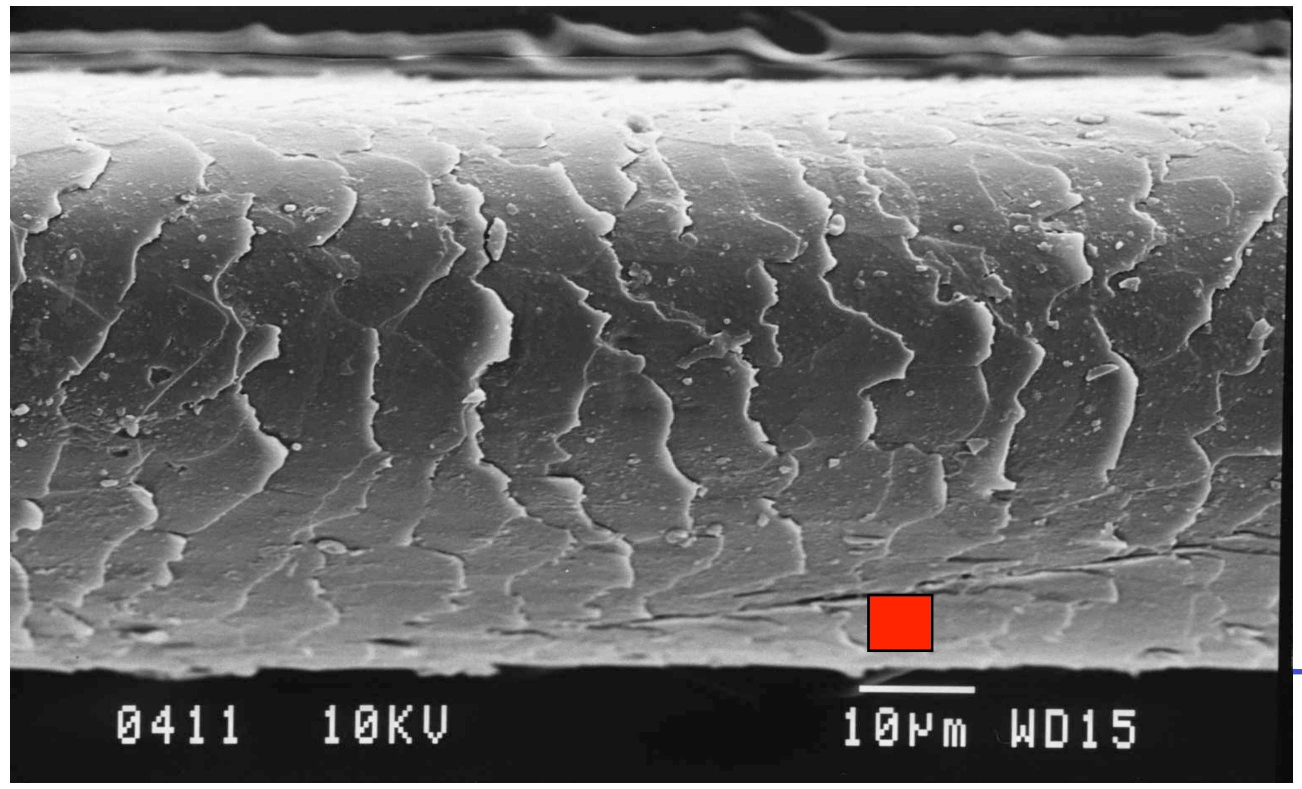
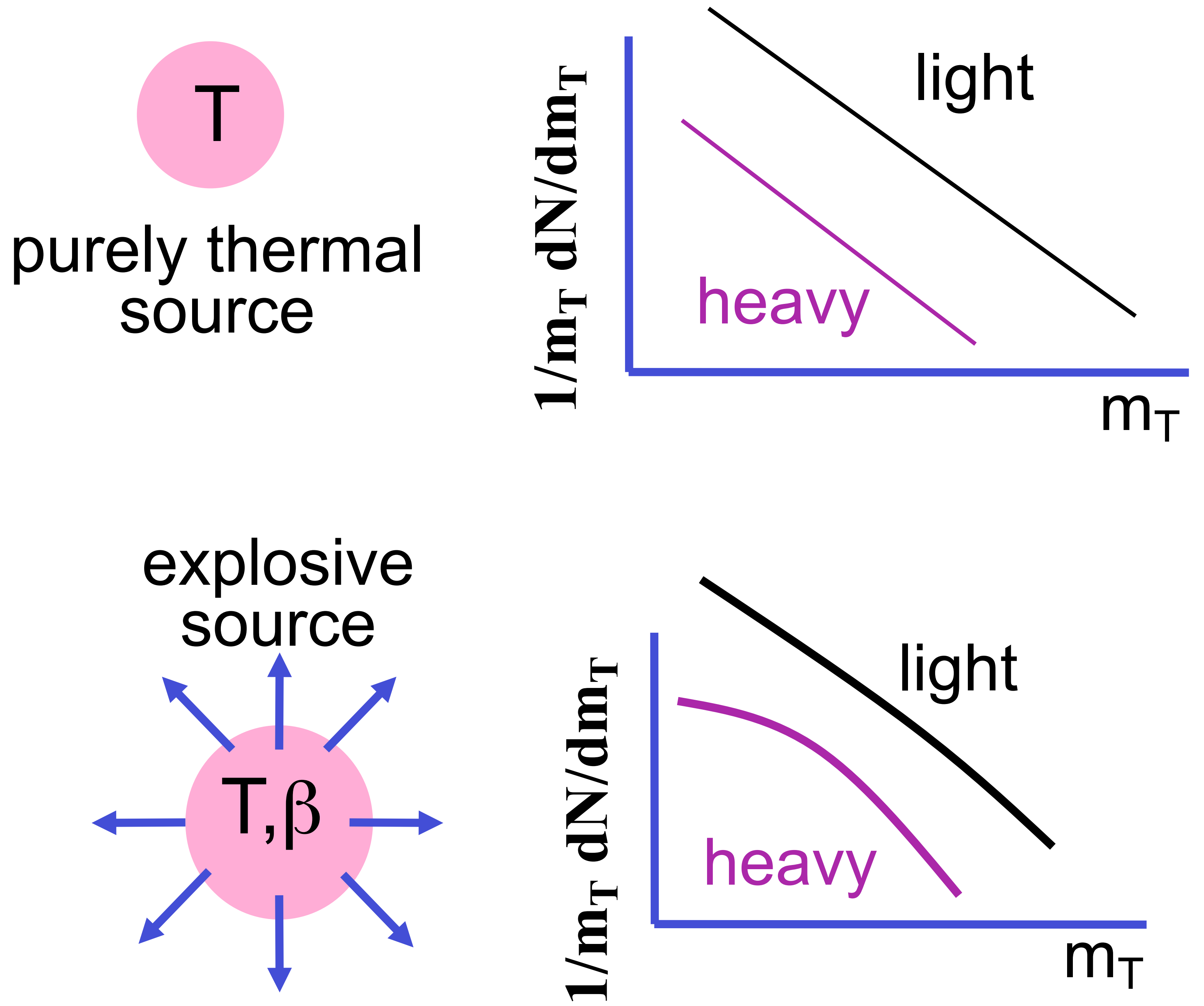
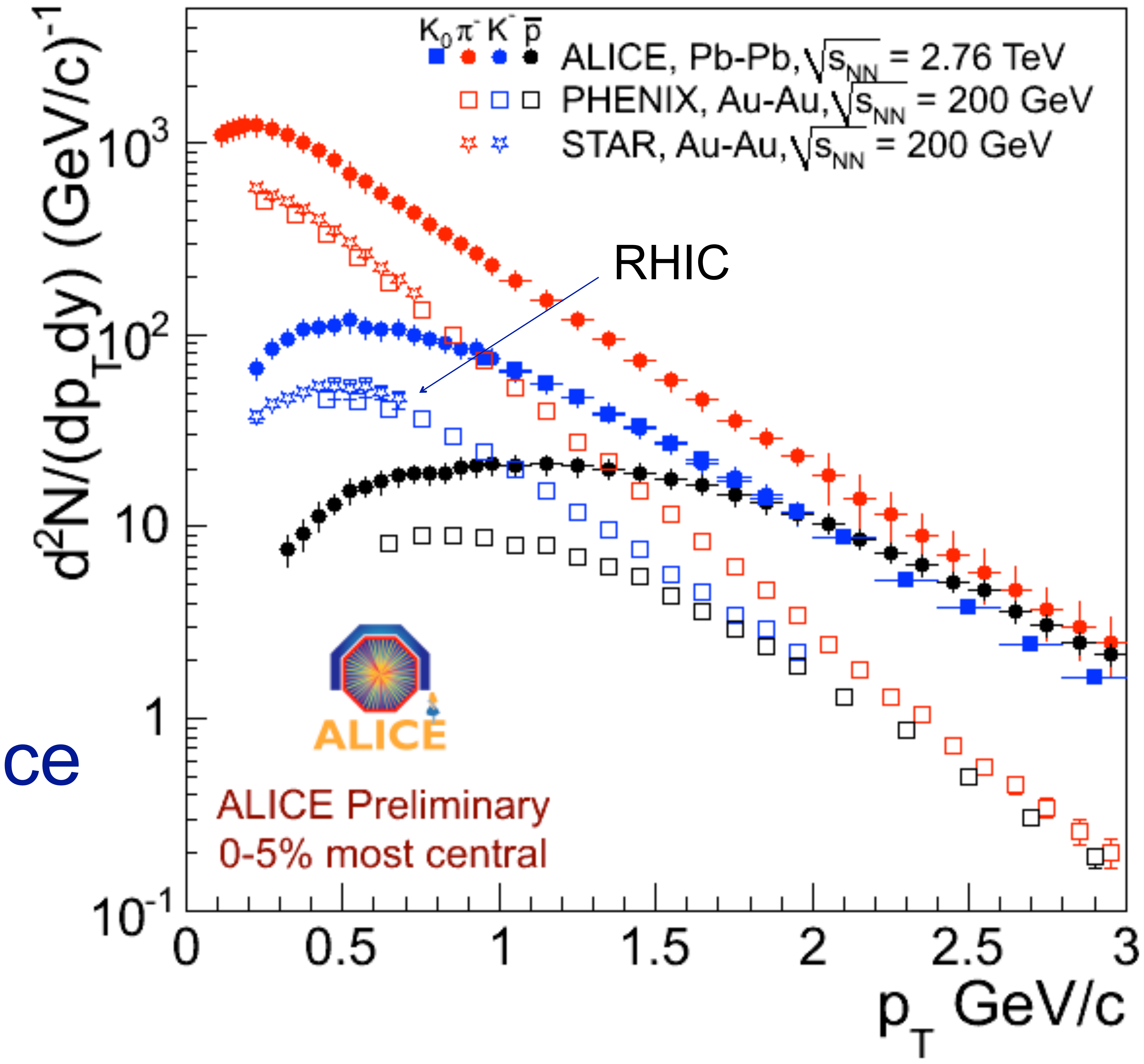


Kinematics after last scattering



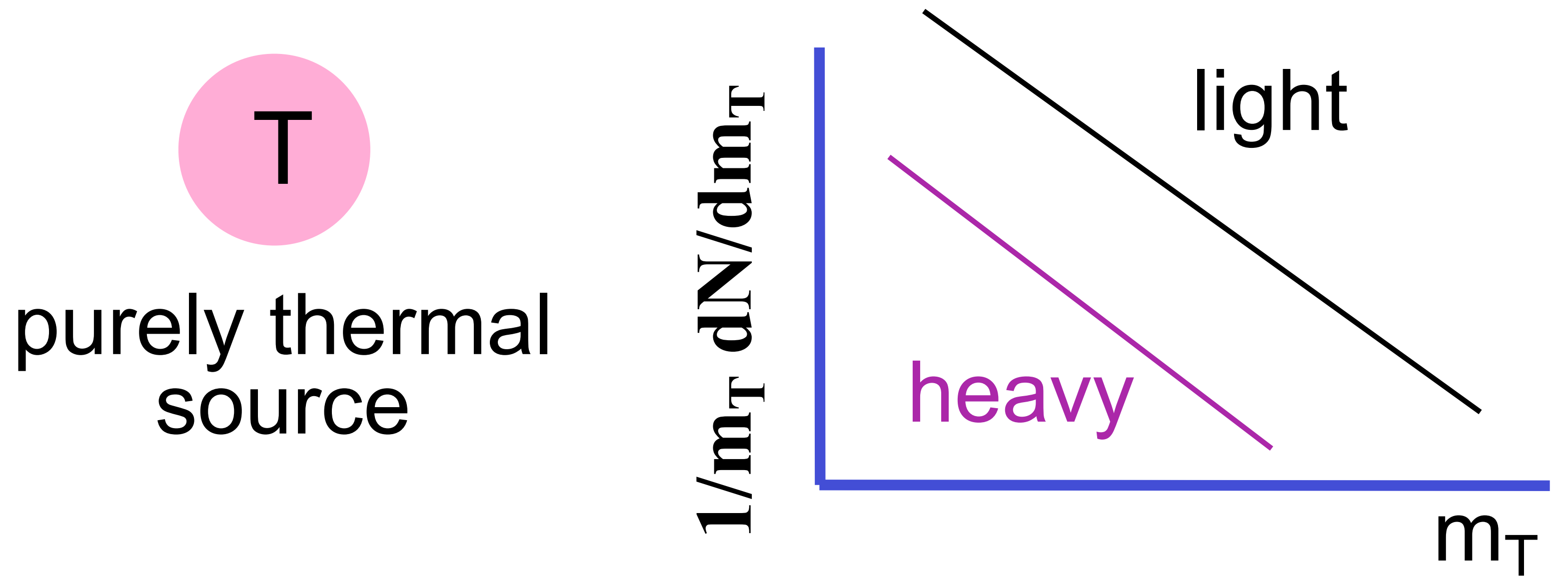
$m_T = (p_T^2 + m^2)^{1/2}$

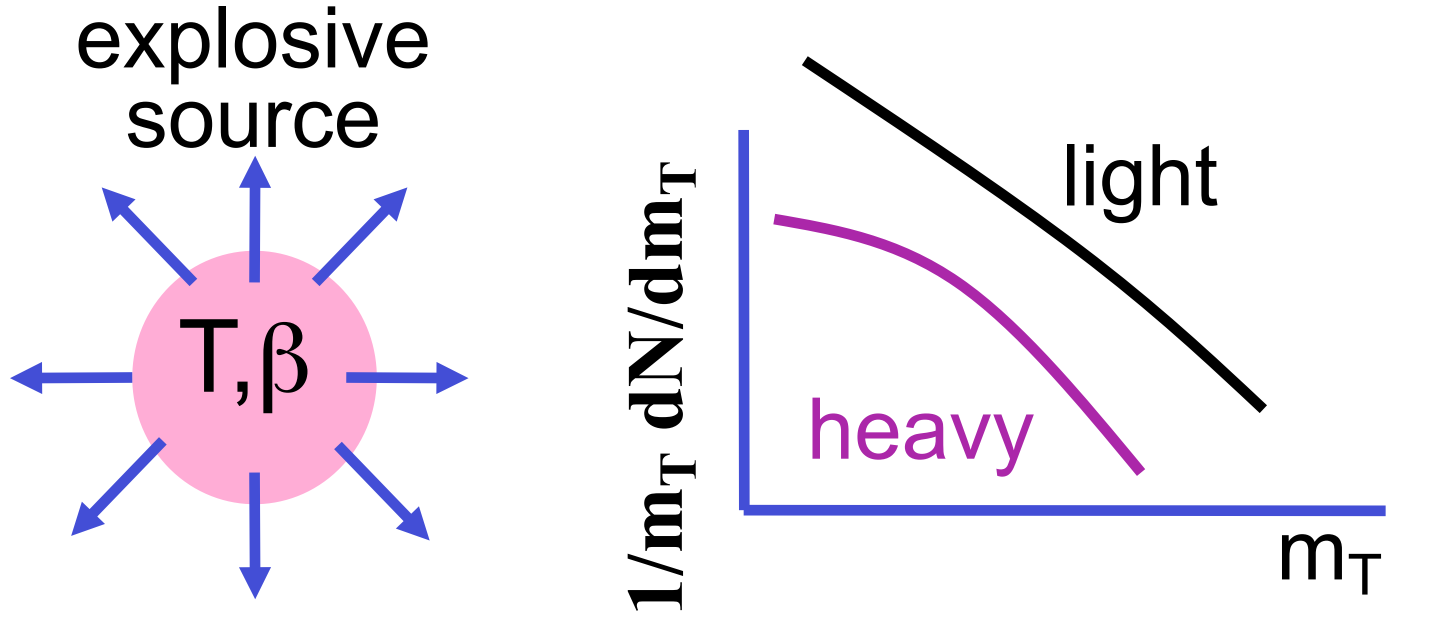


See expected mass dependence

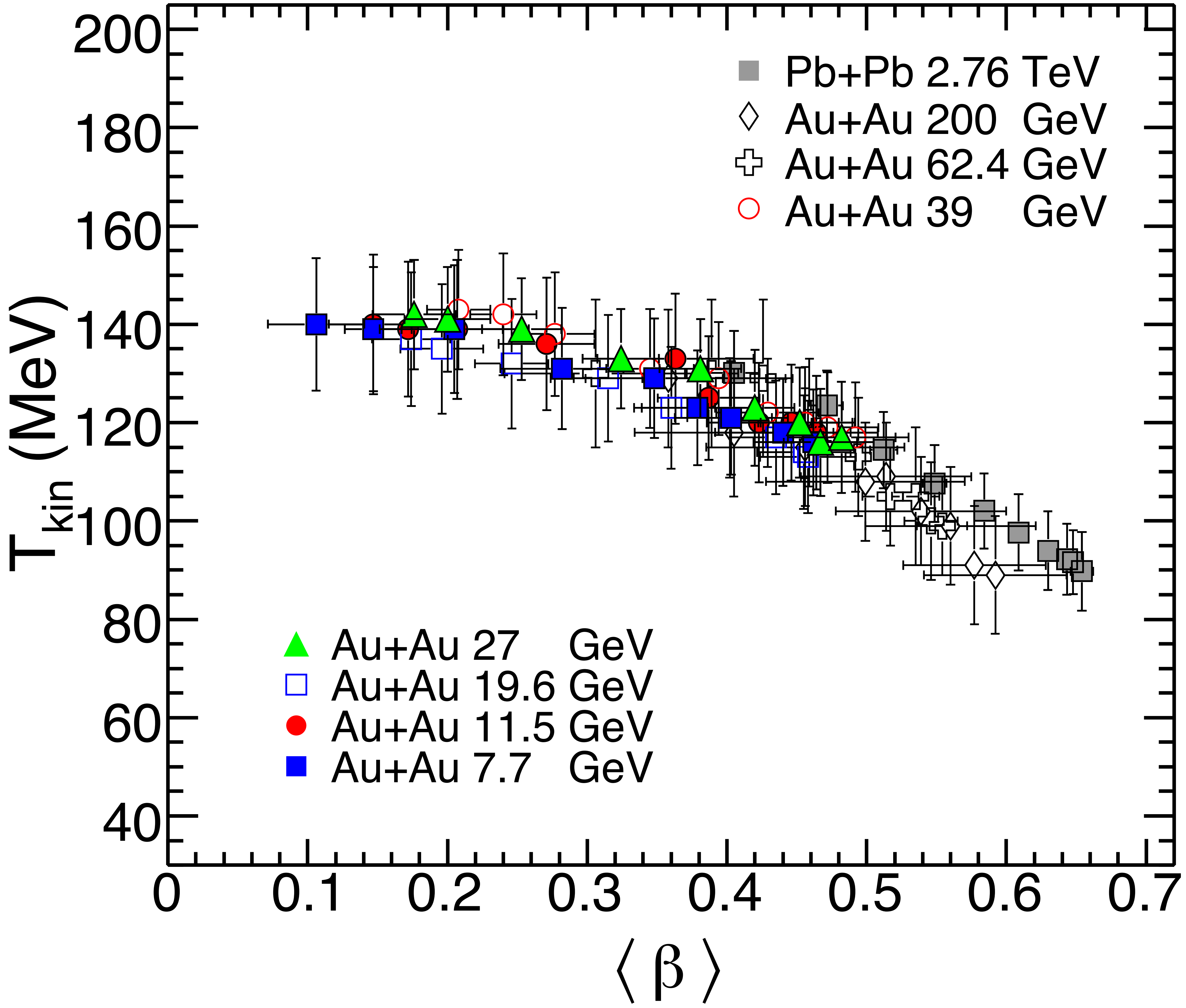
Spectra much harder and yield higher at LHC than RHIC

Kinematics after last scattering





$m_T = (p_T^2 + m^2)^{½}$



See expected mass dependence

Spectra much harder and yield higher at LHC than RHIC

QGP expands explosively

Only gives access to temp at kinetic freeze-out

ALICE: PRC 93(3) (2016), STAR: PRC 96, (2017) 044904

Temperature of chemical freeze-out

Number of particles of a given species related to T

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

Assume all particles described by same T and μ_B

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

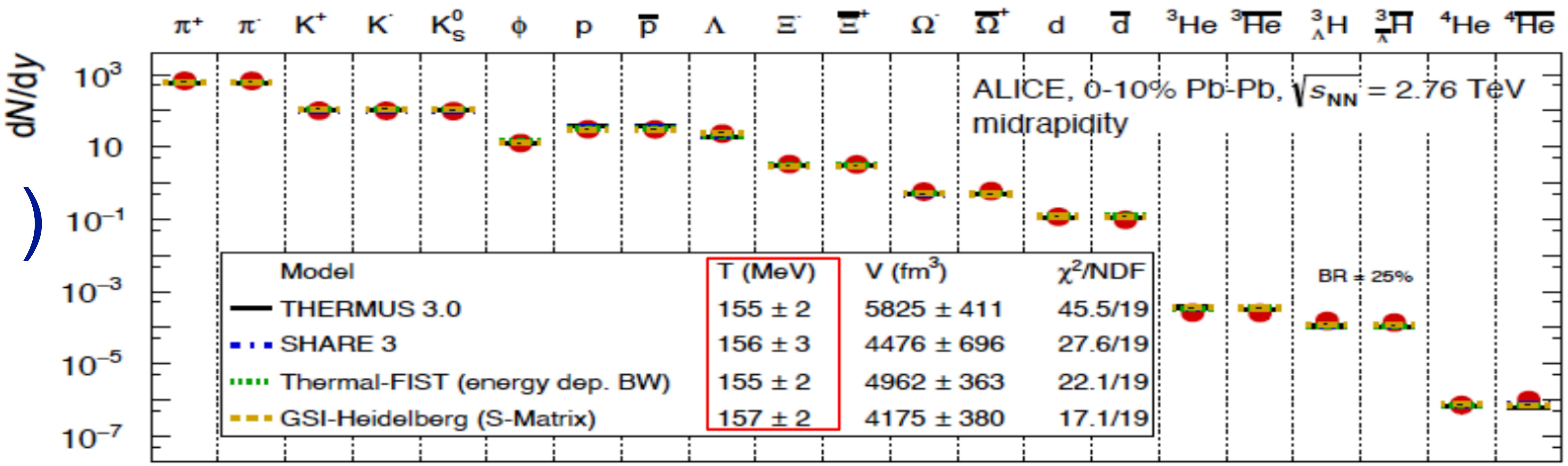
One ratio (e.g., $\bar{p}$ / p) determines μ_B /T :

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

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

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

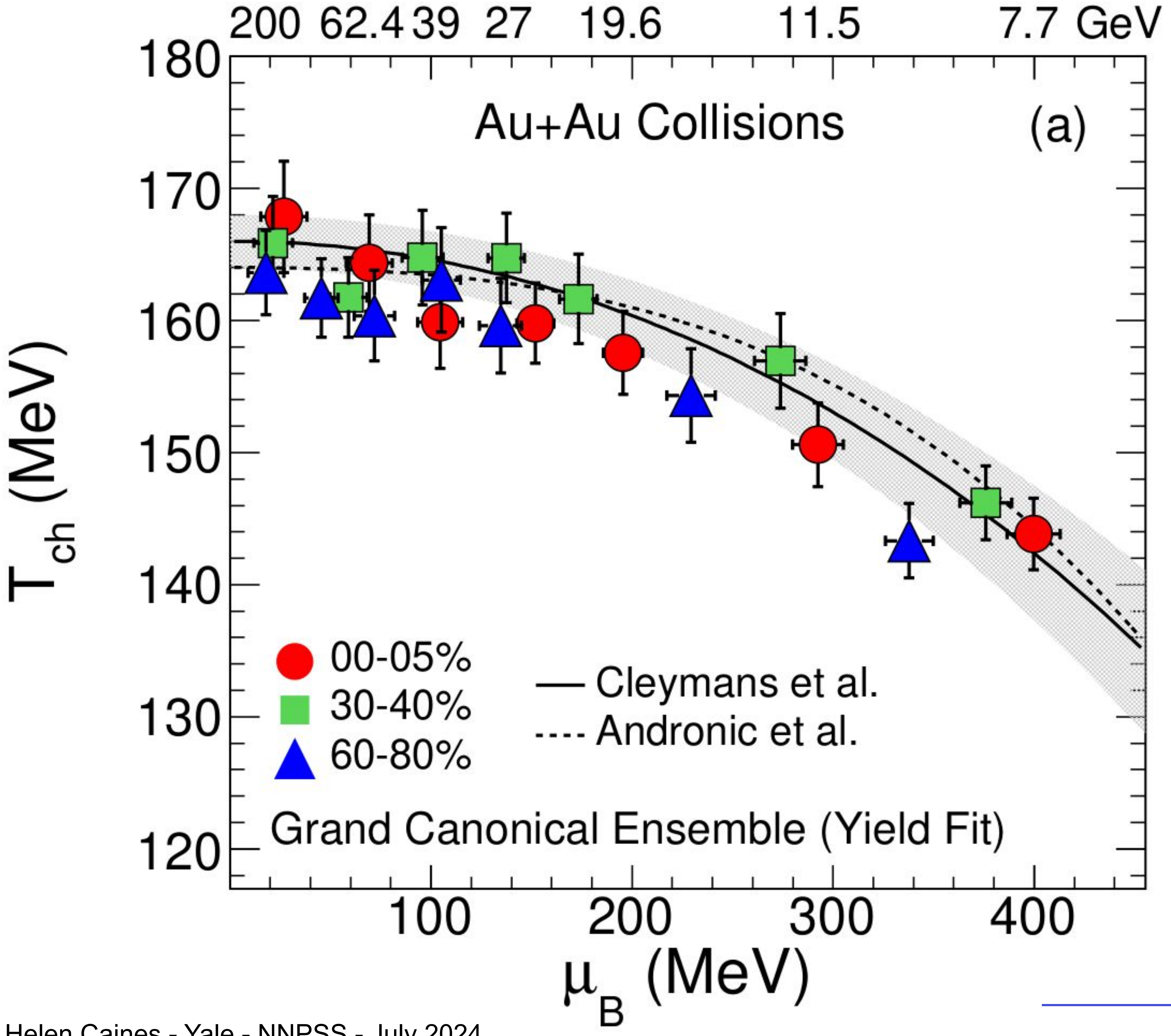
Then all other hadronic ratios (and yields) defined



Model	T (MeV)	V (fm³)	χ²/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

ALICE: arXiv:2211.04384

Temperature of chemical freeze-out



Below 200 GeV:

Baryon chemical potential becomes significant

T_{ch} reduces

But this is T at which hadronic ratios are fixed.

Still not the initial T

STAR: PRC 96 (2017) 44904

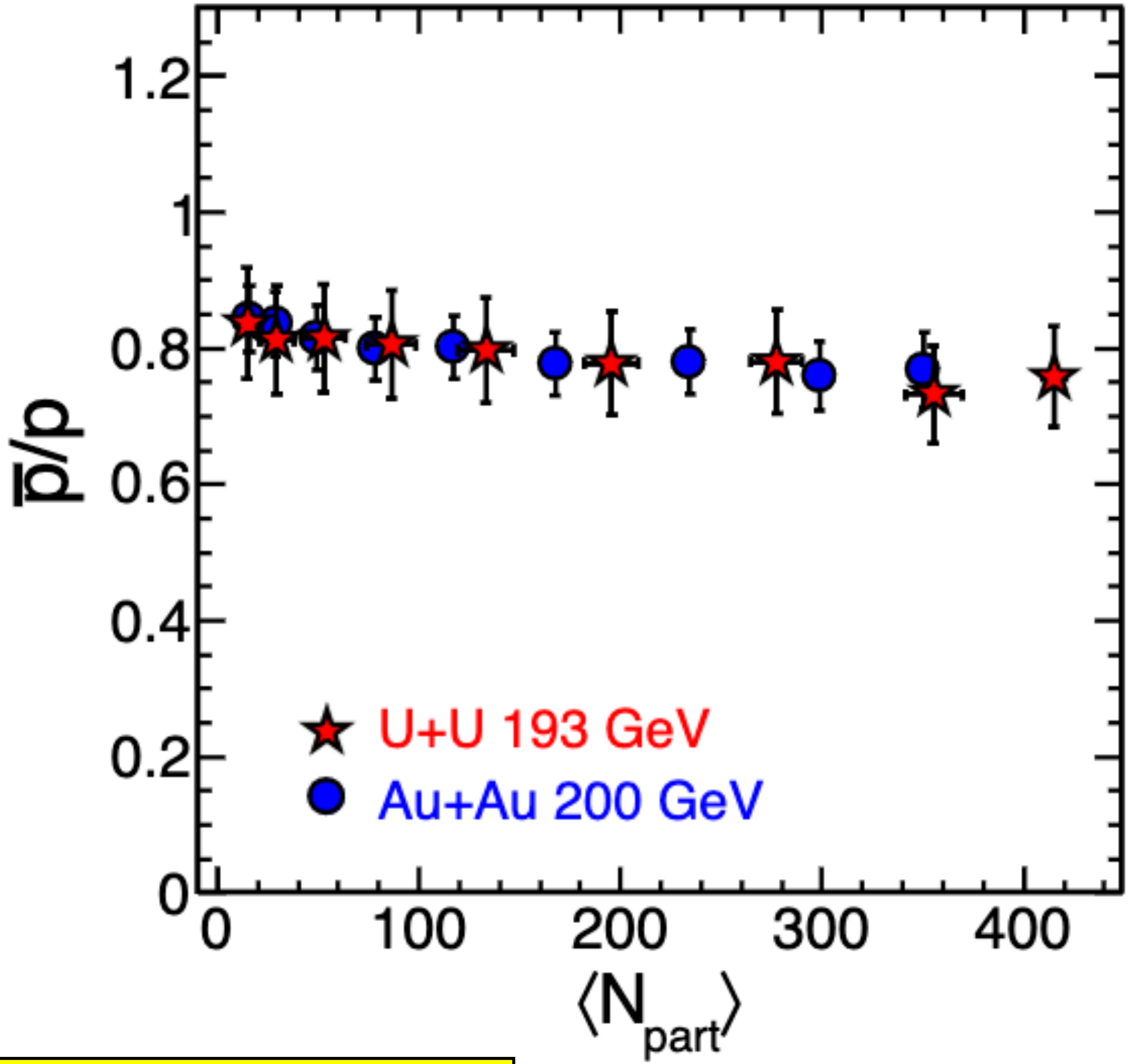
By the way!

Take a second look at the anti-proton/proton ratio

$\bar{p}/p \sim 0.8$

There is a net baryon number at mid-rapidity!!

Baryons number is being transported over 6 units of rapidity from the incoming beams to the collision zone!



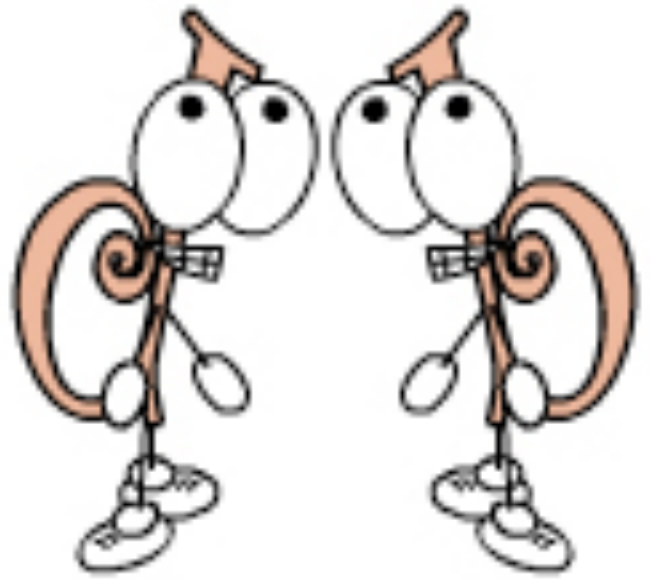
Where does baryon number reside?

STAR: PRC **107** (2023) 24901

Melting quarkonia

Quarkonia - bound states of heavy quark-anti-quark pairs

$c + \bar{c} = J/\psi$

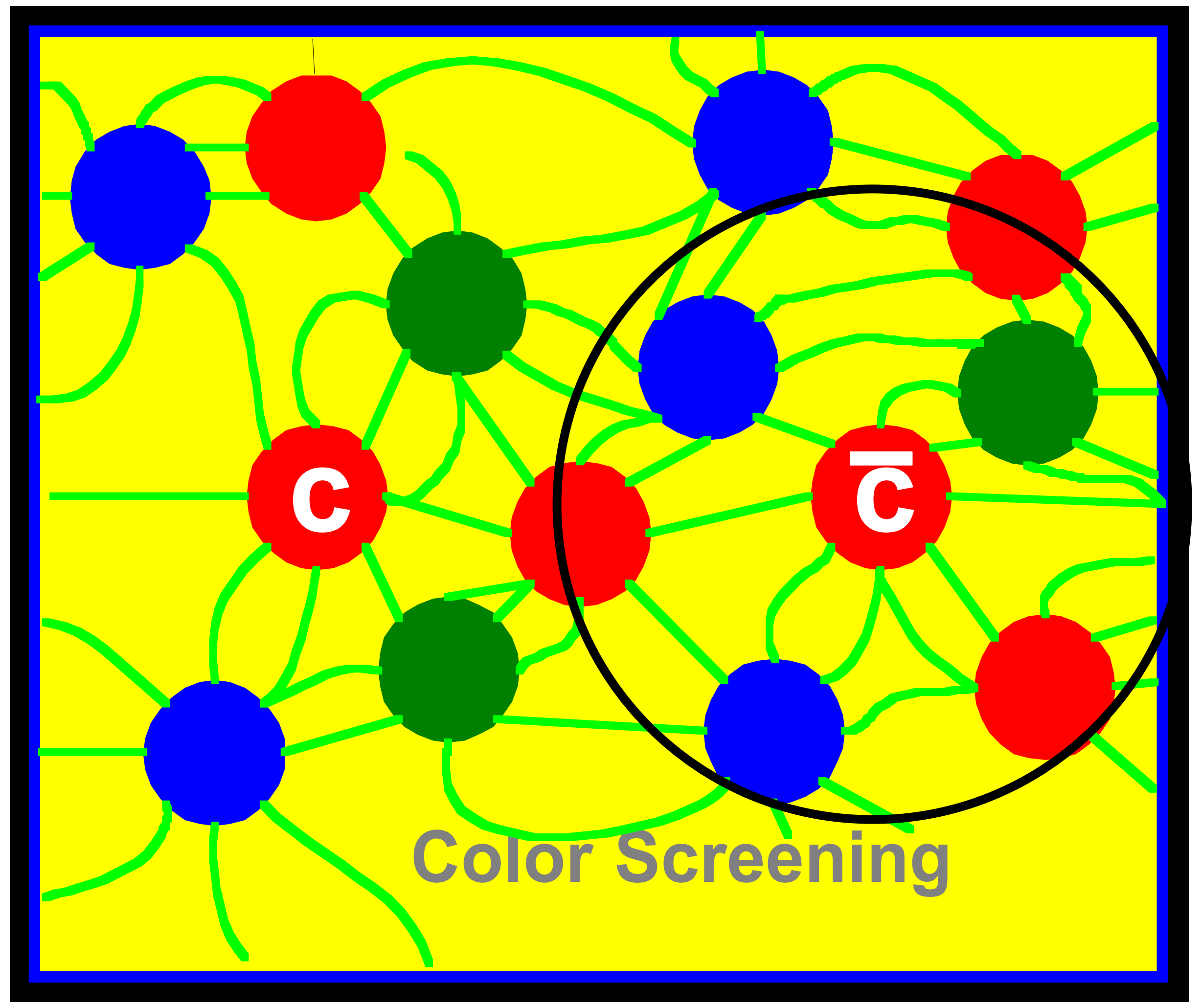


$b + \bar{b} = \Upsilon$

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

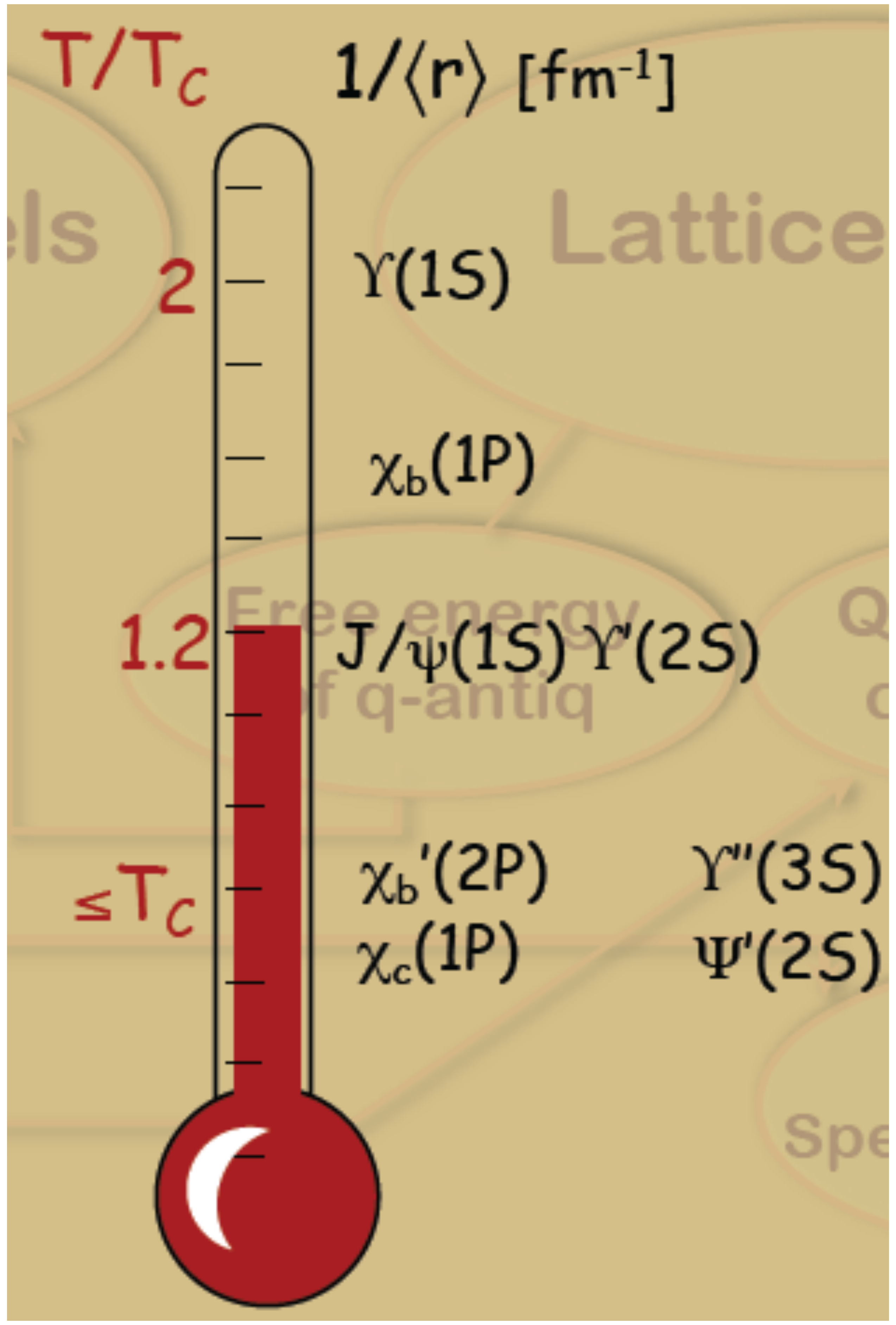
Only loosely bound

Melt in the QGP



Quarkonia - QGP thermometers

Color screening of static potential between heavy quarks



Charmonia: J/ψ, Ψ', χ_c

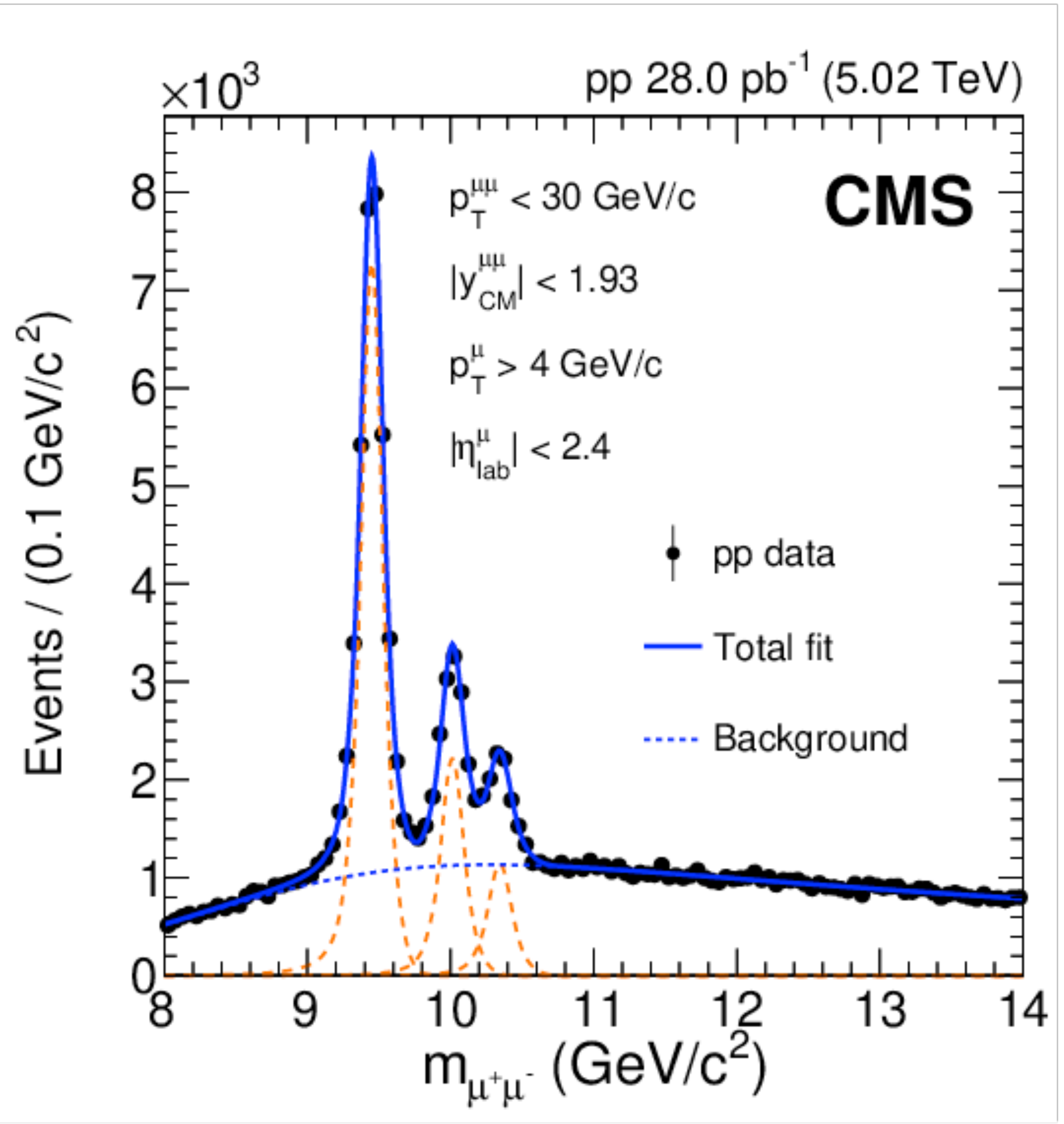
Bottomonia: Υ(1S), Υ(2S), Υ(3S)

	$E_{binding}$ (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

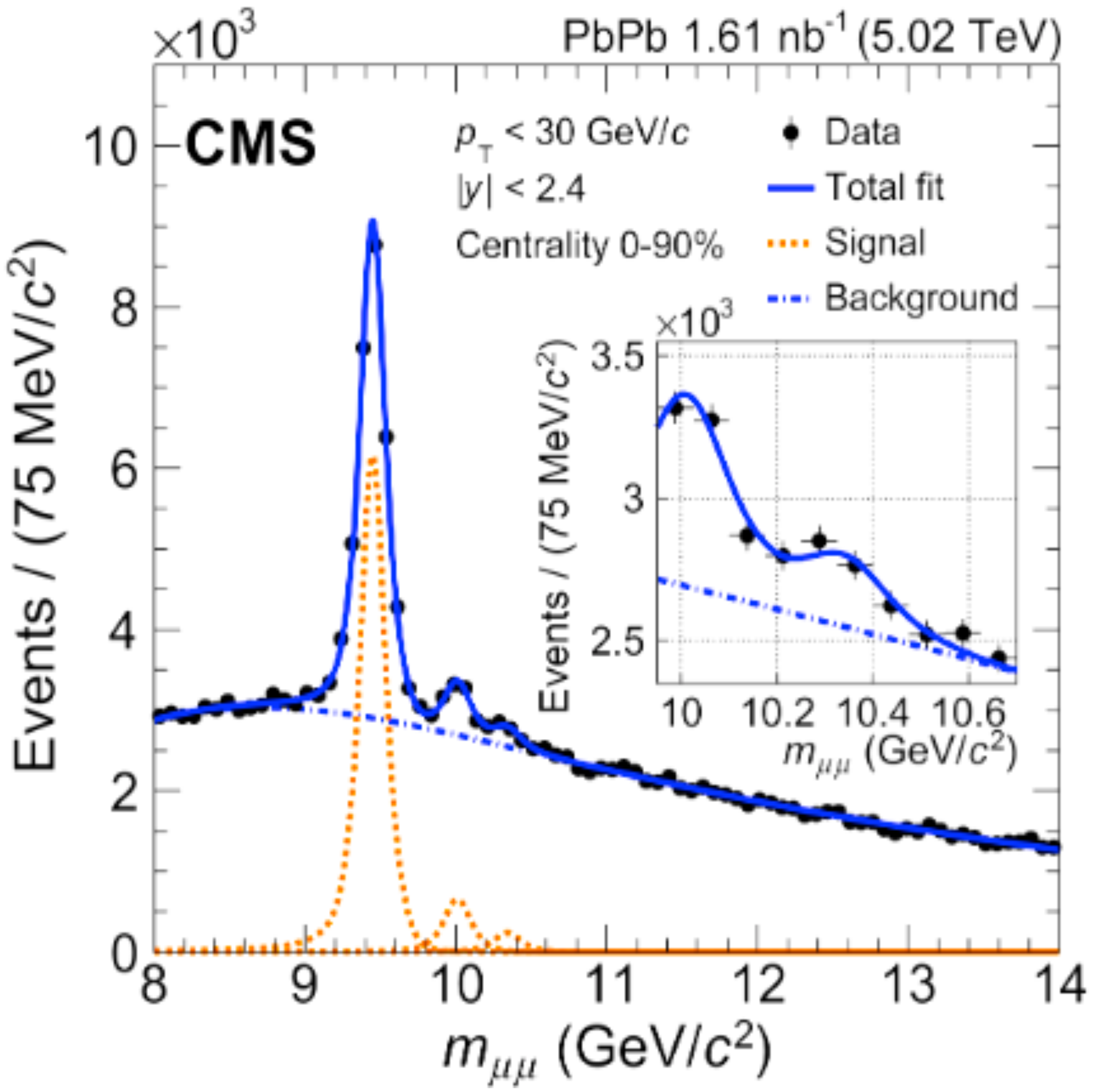
Matsui and Satz, *PLB* **178** (1986) 416

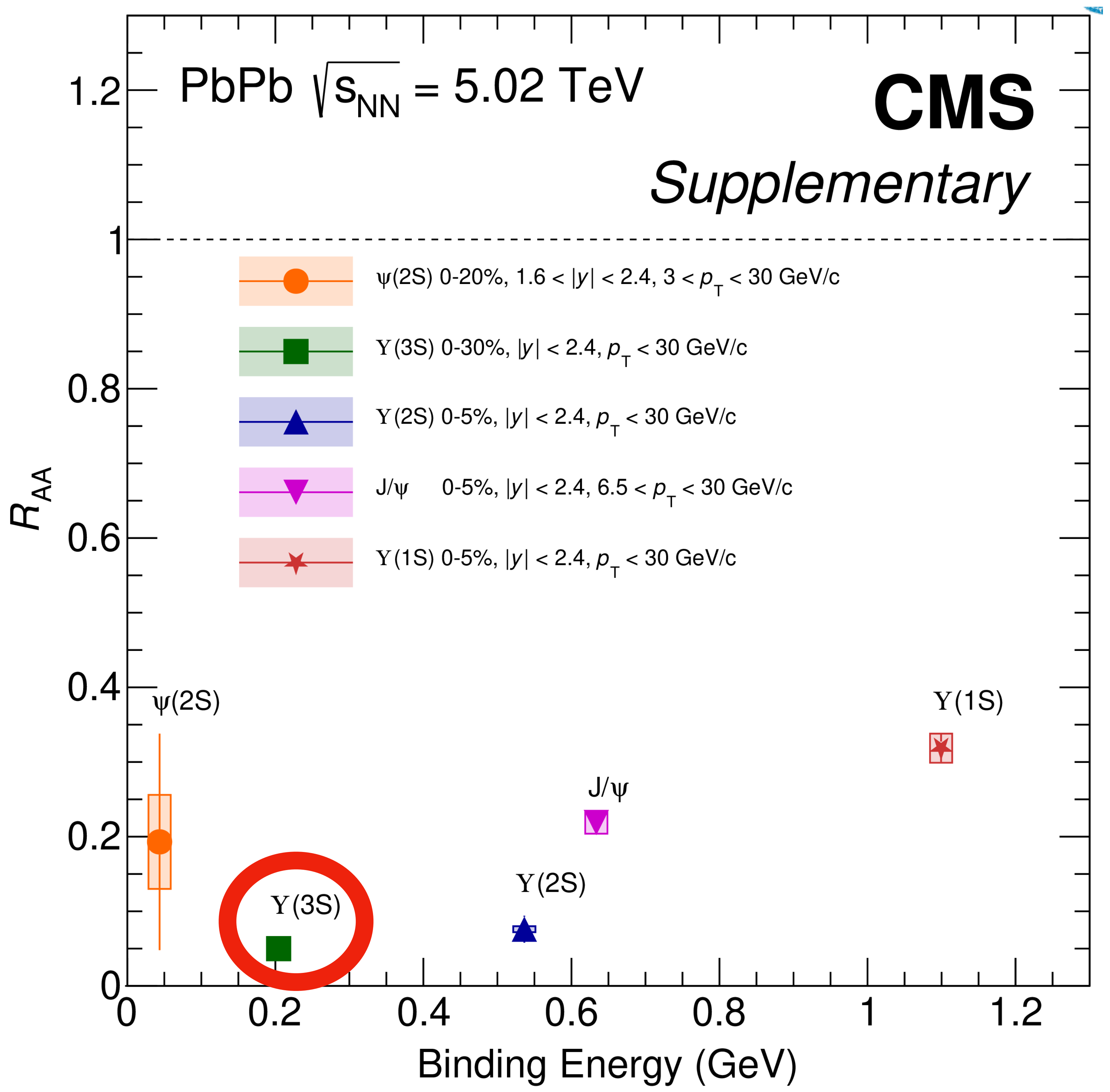
Sequential melting of quarkonia

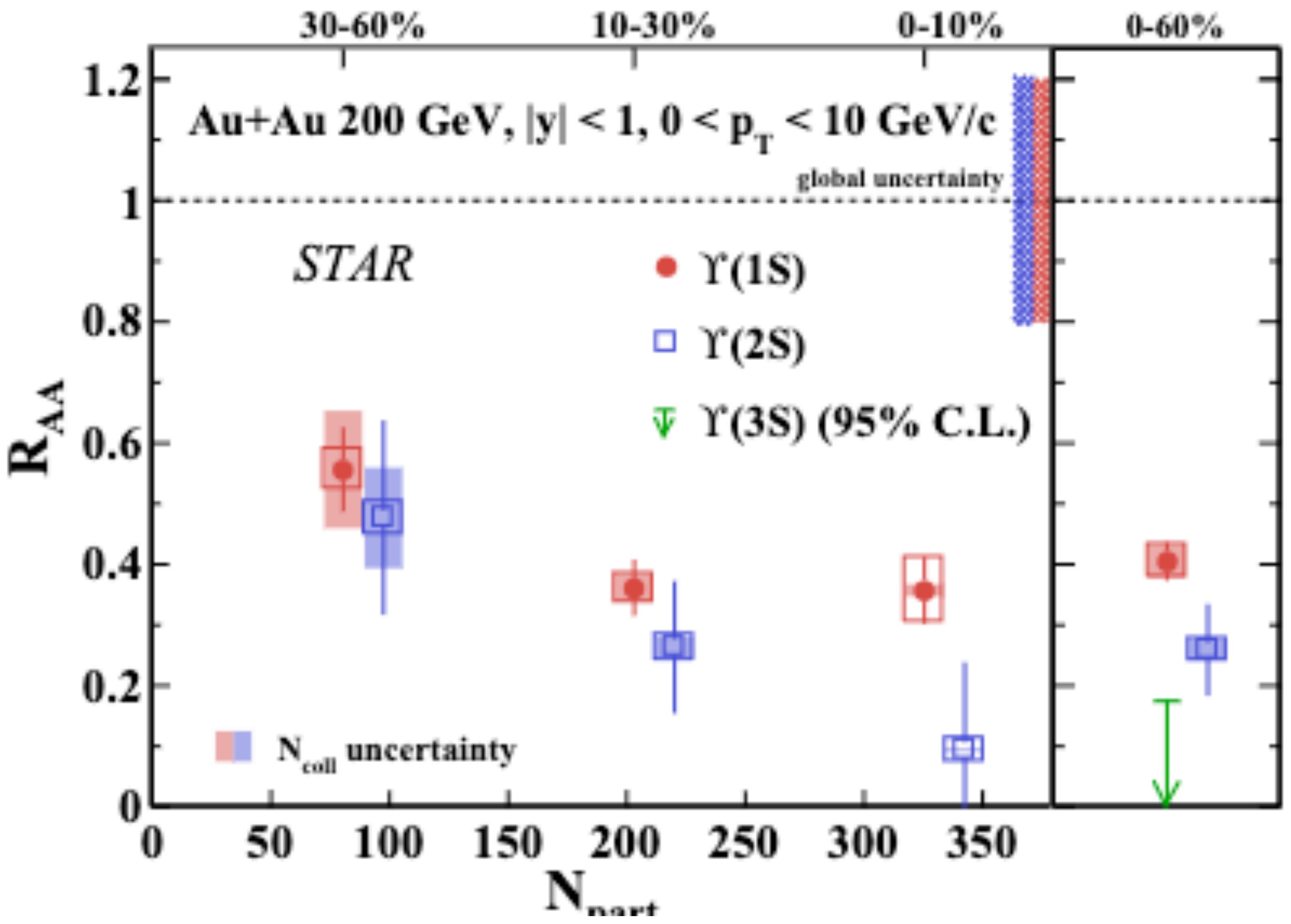


CMS: PRL 109 (2012) 222301, PLB 835 (2022) 137397, STAR: PRL 130 (2023) 11230

Sequential melting of quarkonia







Lightly bound states:

almost completely gone

Tightly bound states:

mostly melted at LHC energies

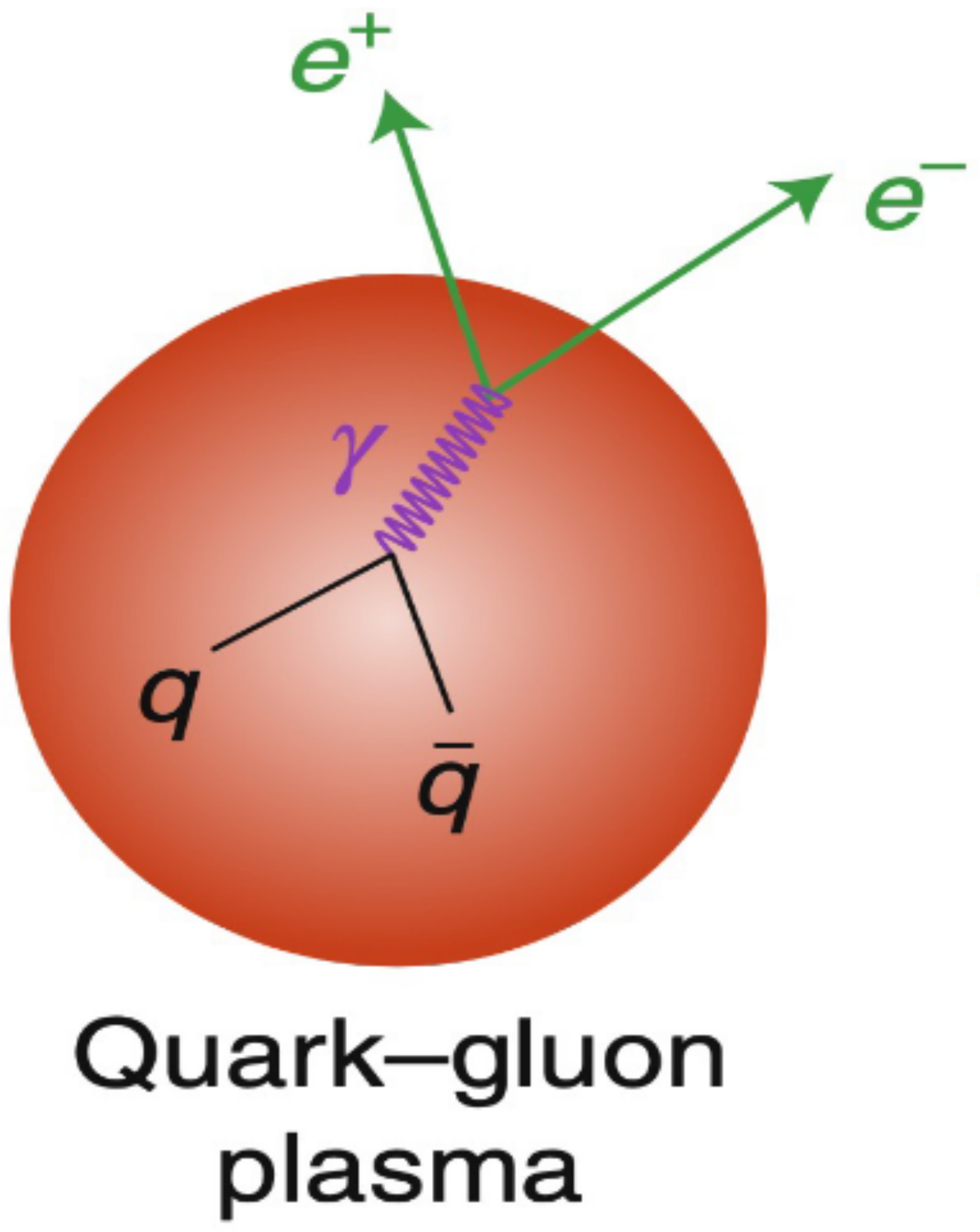
and top RHIC

$T > 1.5\ T_C \sim 300$ MeV

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

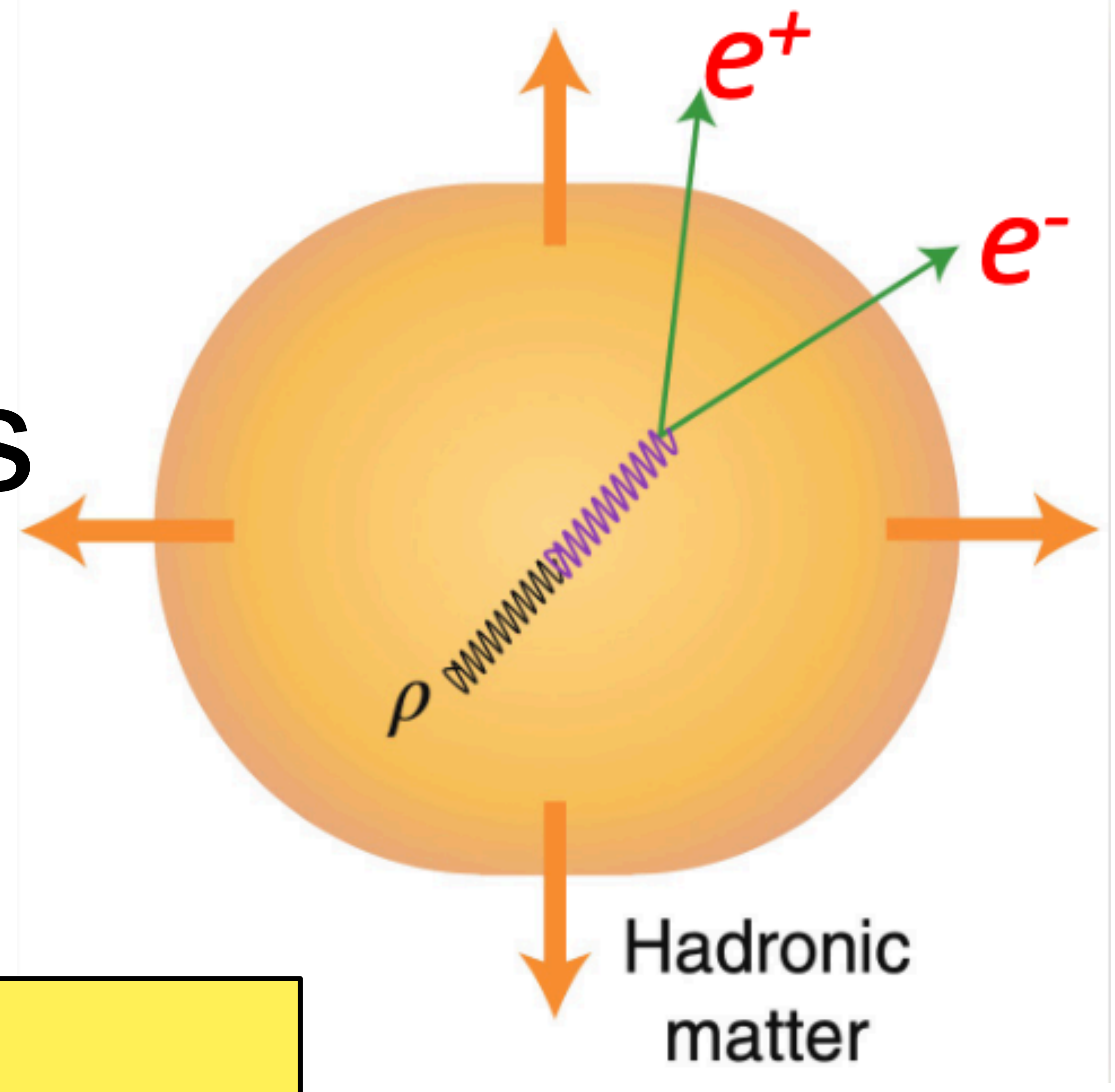
Extracting the initial T: non-interacting probe

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



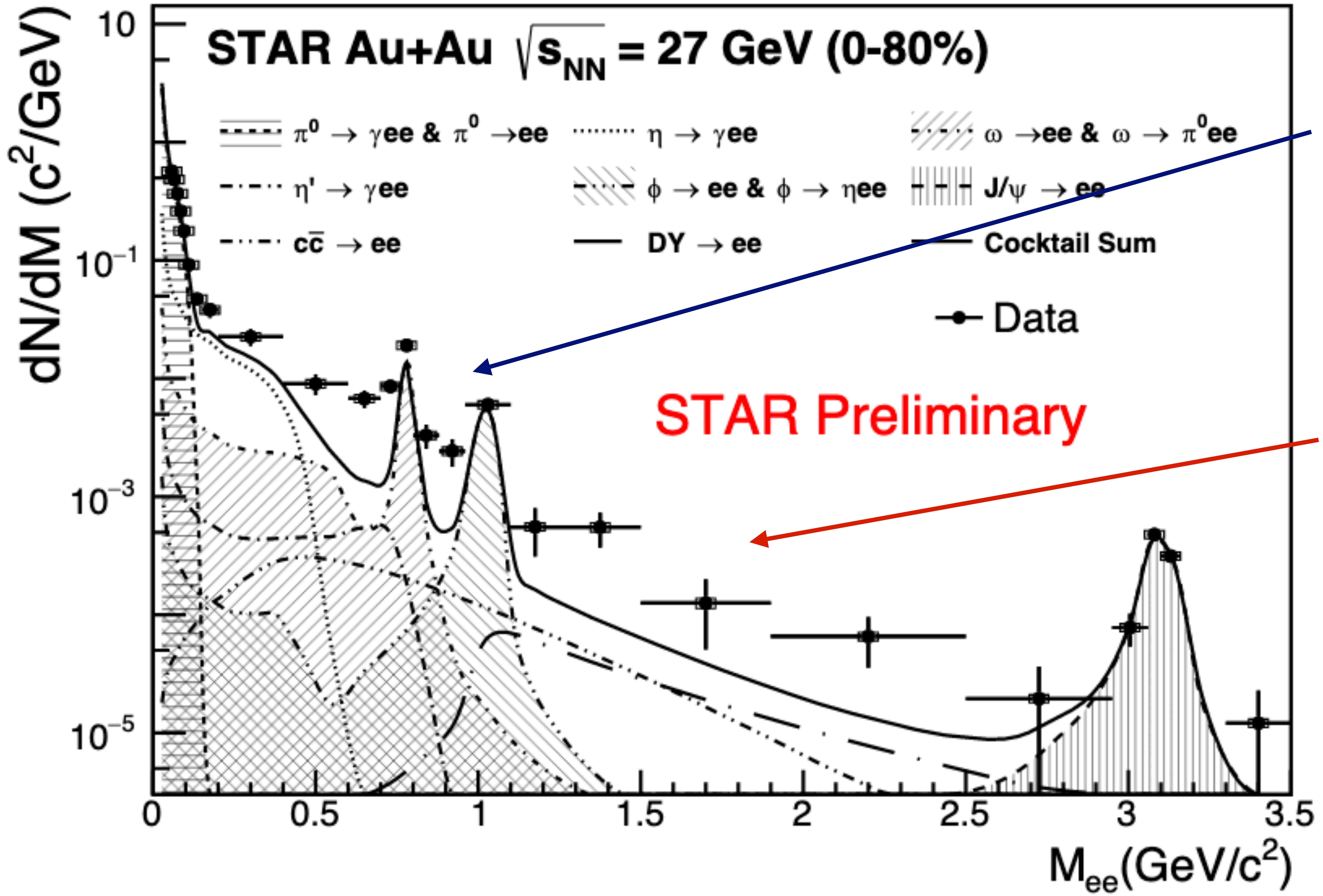
Production rate proportional to QGP temperature
: Early time measurement

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



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

Extracting the signal

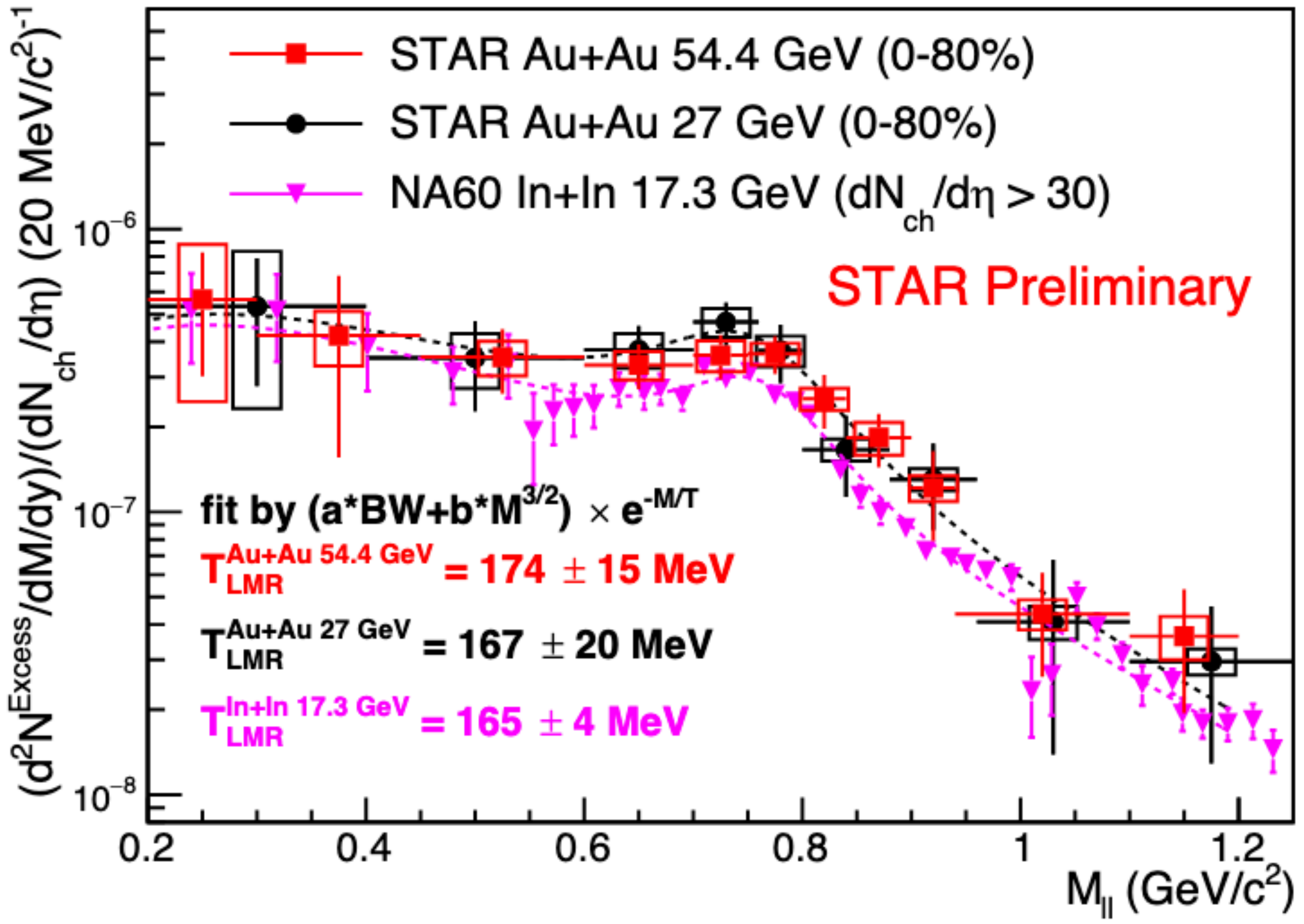


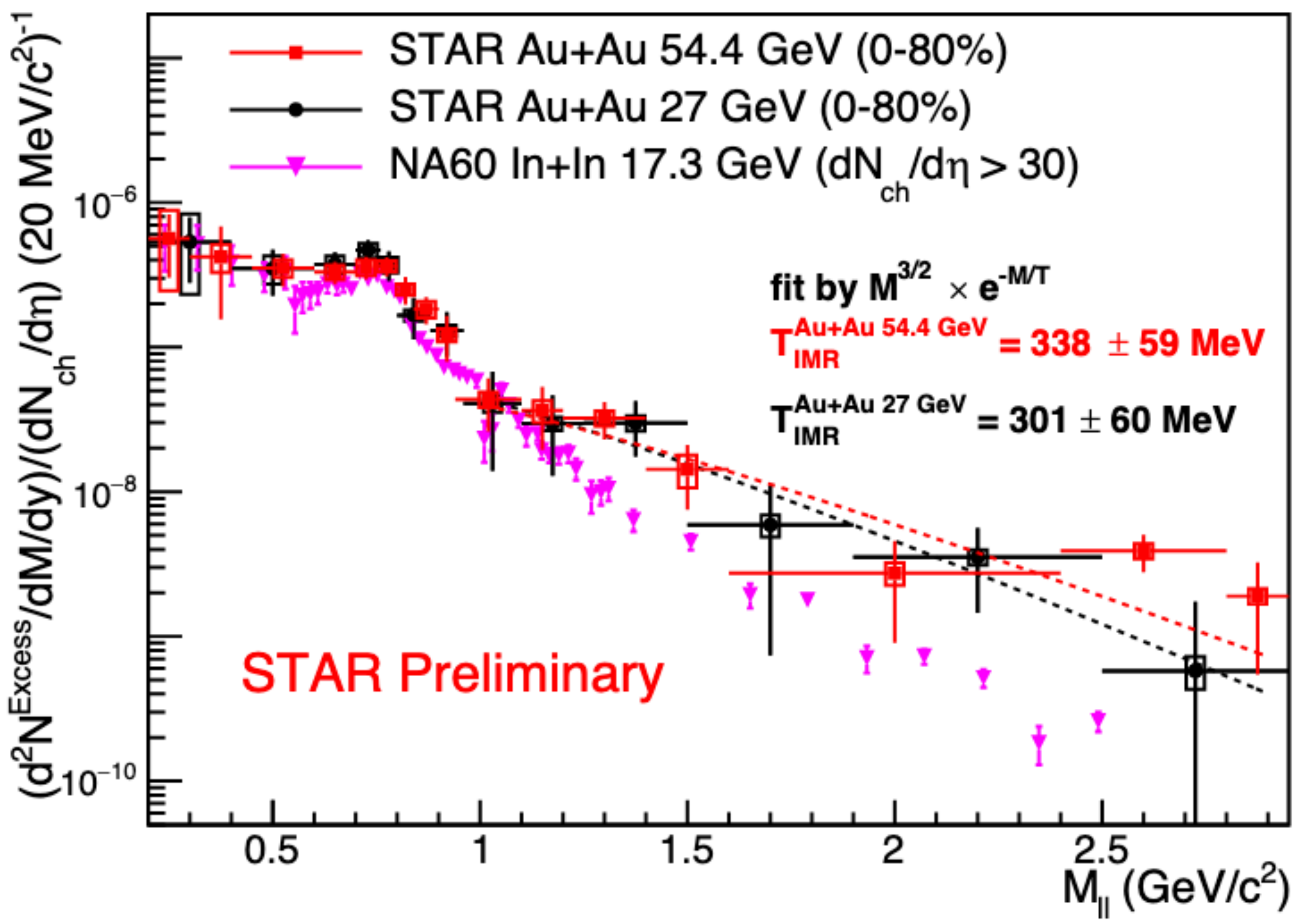
Low mass range

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

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

How hot is ~200 MeV ?

A. Approximately the same as the hottest recorded T in Indiana (~46.7 °C/116 °F, Collegeville, 1936)

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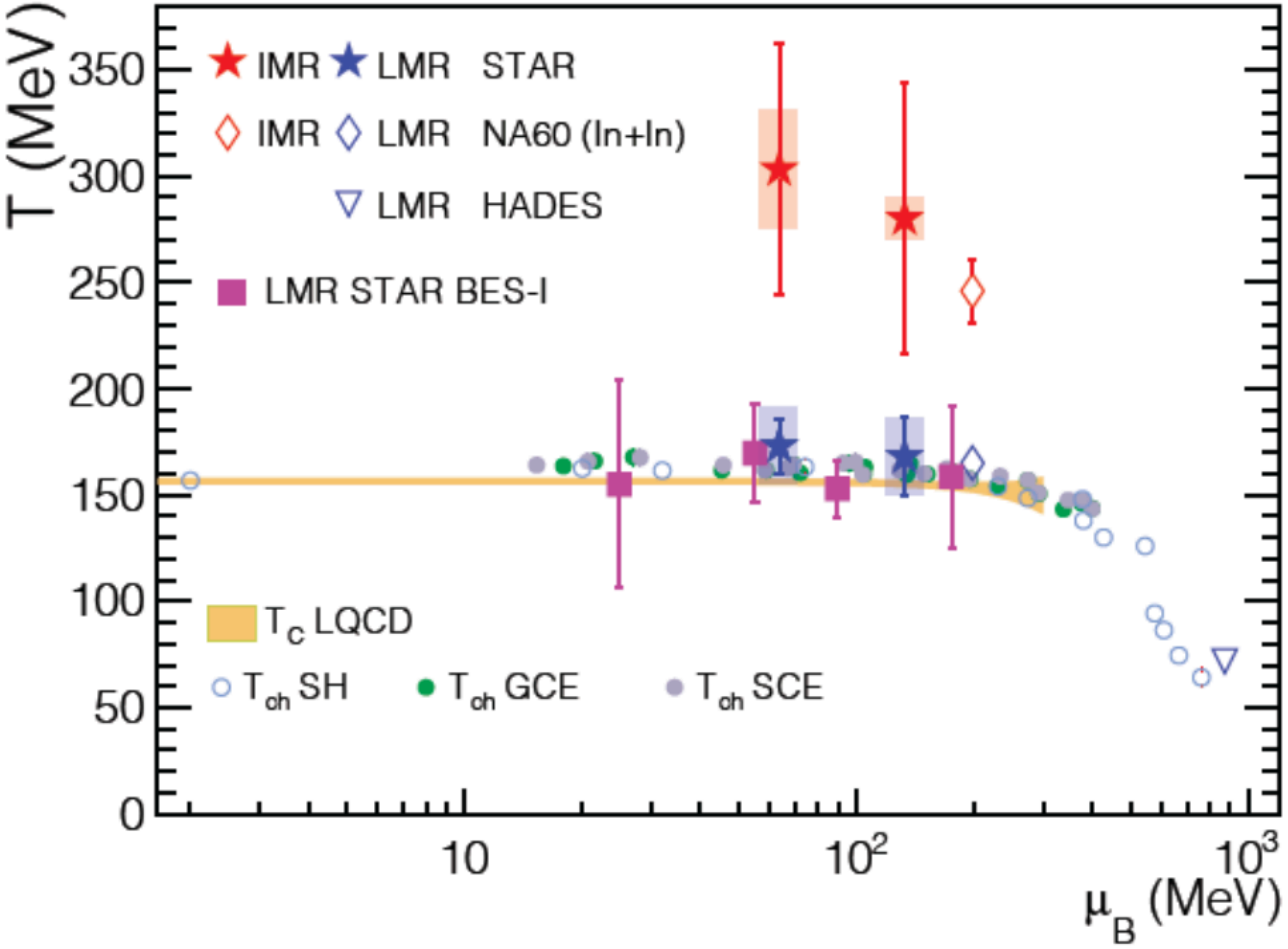
C. Approximately that of the center of the sun (~15 million °C)

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

E. Even hotter ~0.1 trillion °C

Initial T summary



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

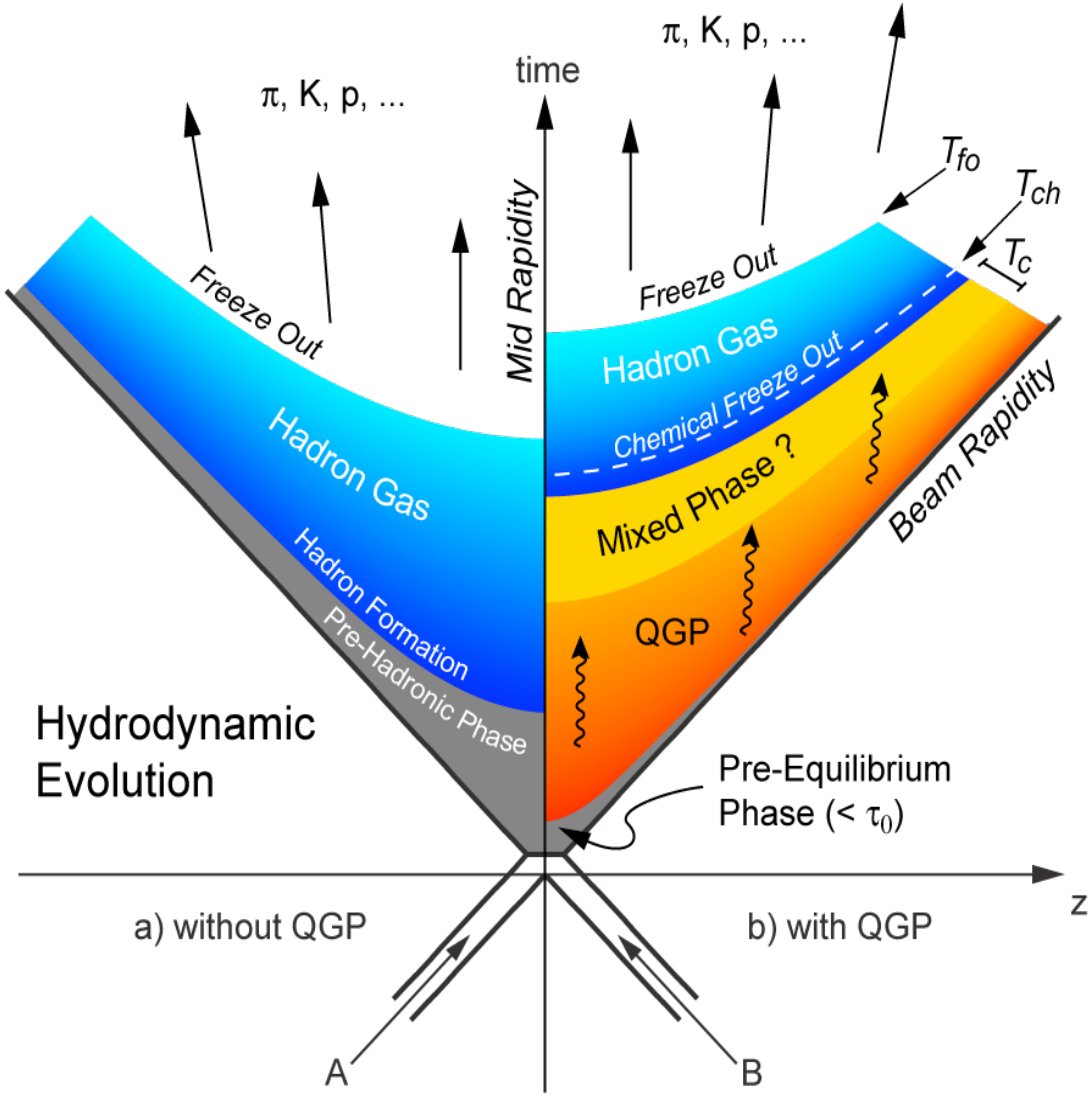
Potentially dropping below 20 GeV

(dileptons)

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

STAR: arXiv: 2402.01998

Summary of the collision's evolution



Lattice (2-flavor):

$T_C \approx 173 \pm 8$ MeV

$\varepsilon_C \approx (6 \pm 2)\ T^4 \approx 0.70$ GeV/fm^3

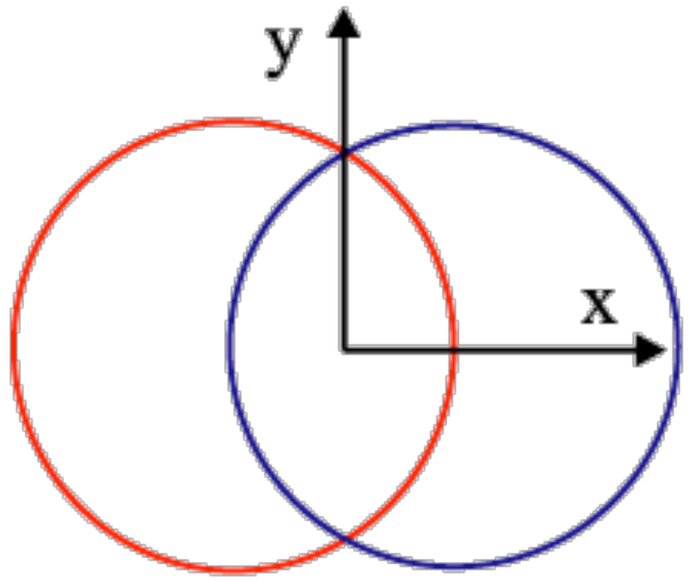
Chemical freeze-out:
($T_{ch} \leq T_c$): inelastic scattering ceases

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

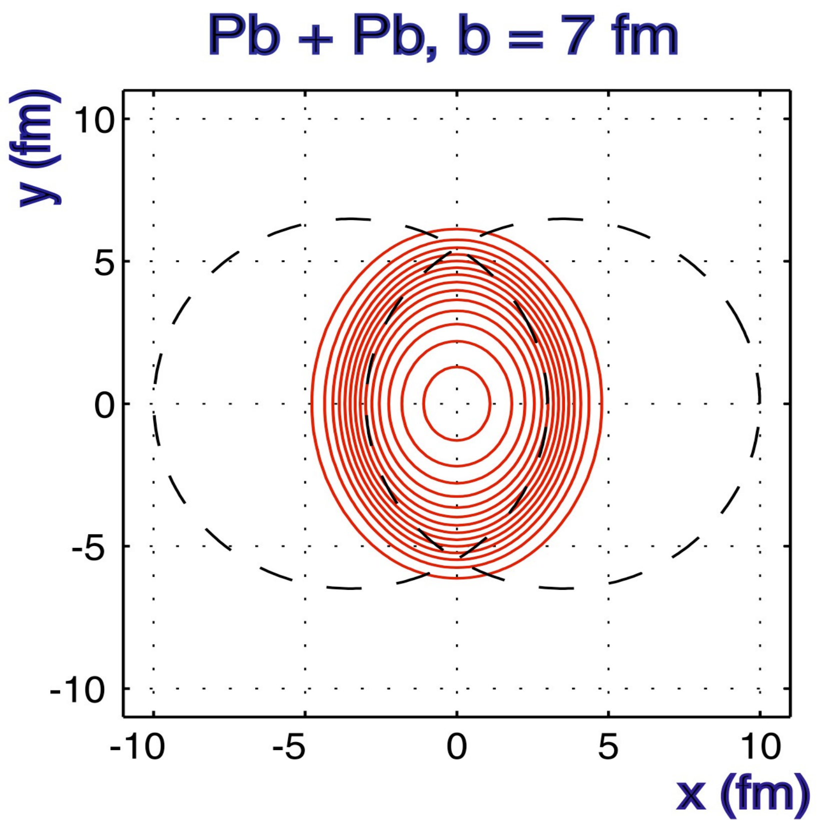
Many constituents ⇒

Thermal Equilibrium?

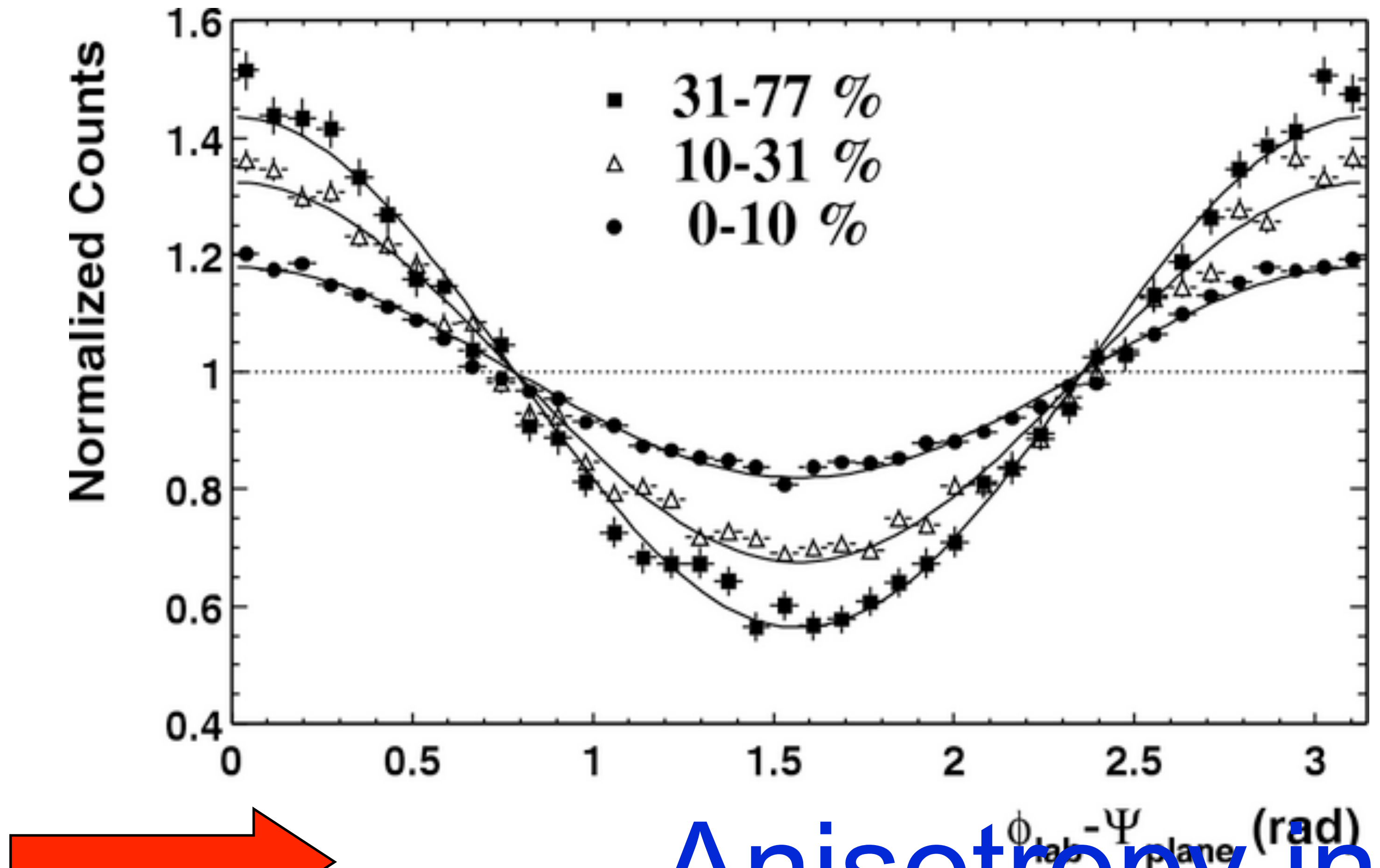
Initial conditions: Thermalization



Almond shape overlap region in coordinate space



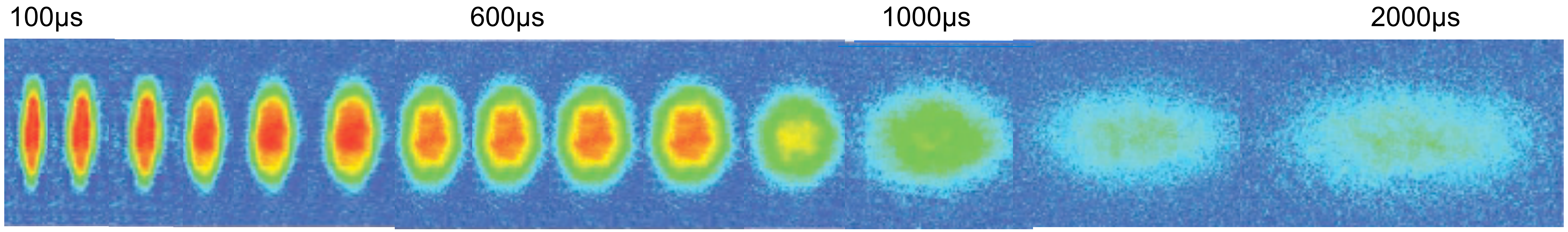
Interactions/ Rescattering



Anisotropy in momentum space

$dN/d\phi \sim 1+2\, v_2(p_T)\cos(2\phi) + \ldots.$ $\phi = \mathrm{atan}(p_y/p_x)$ $v_2 = \langle \cos 2\phi \rangle$

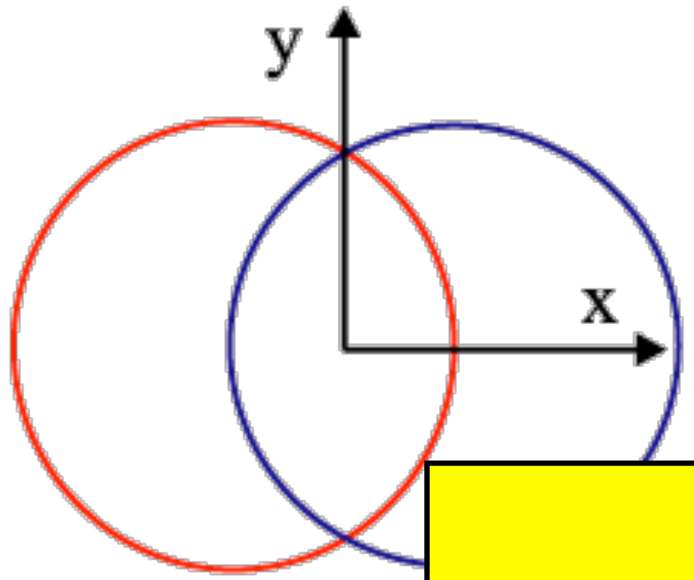
v_2: 2nd harmonic Fourier coefficient in $dN/d\phi$ relative to reaction plane

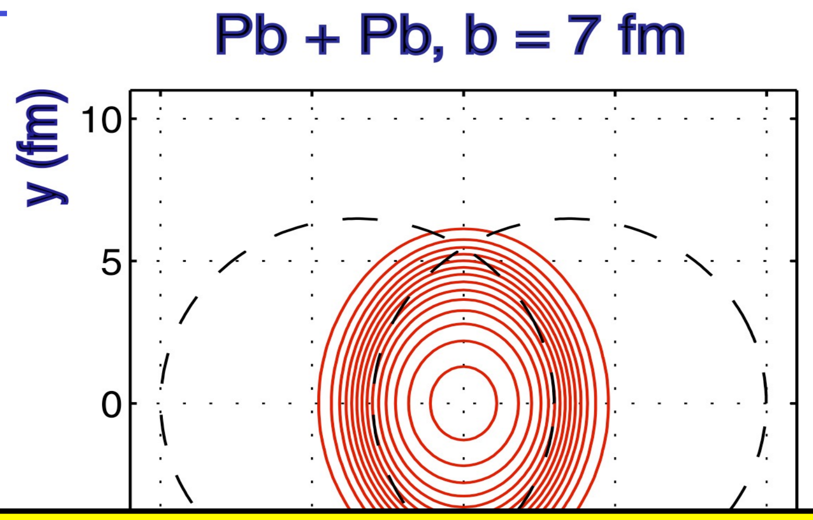


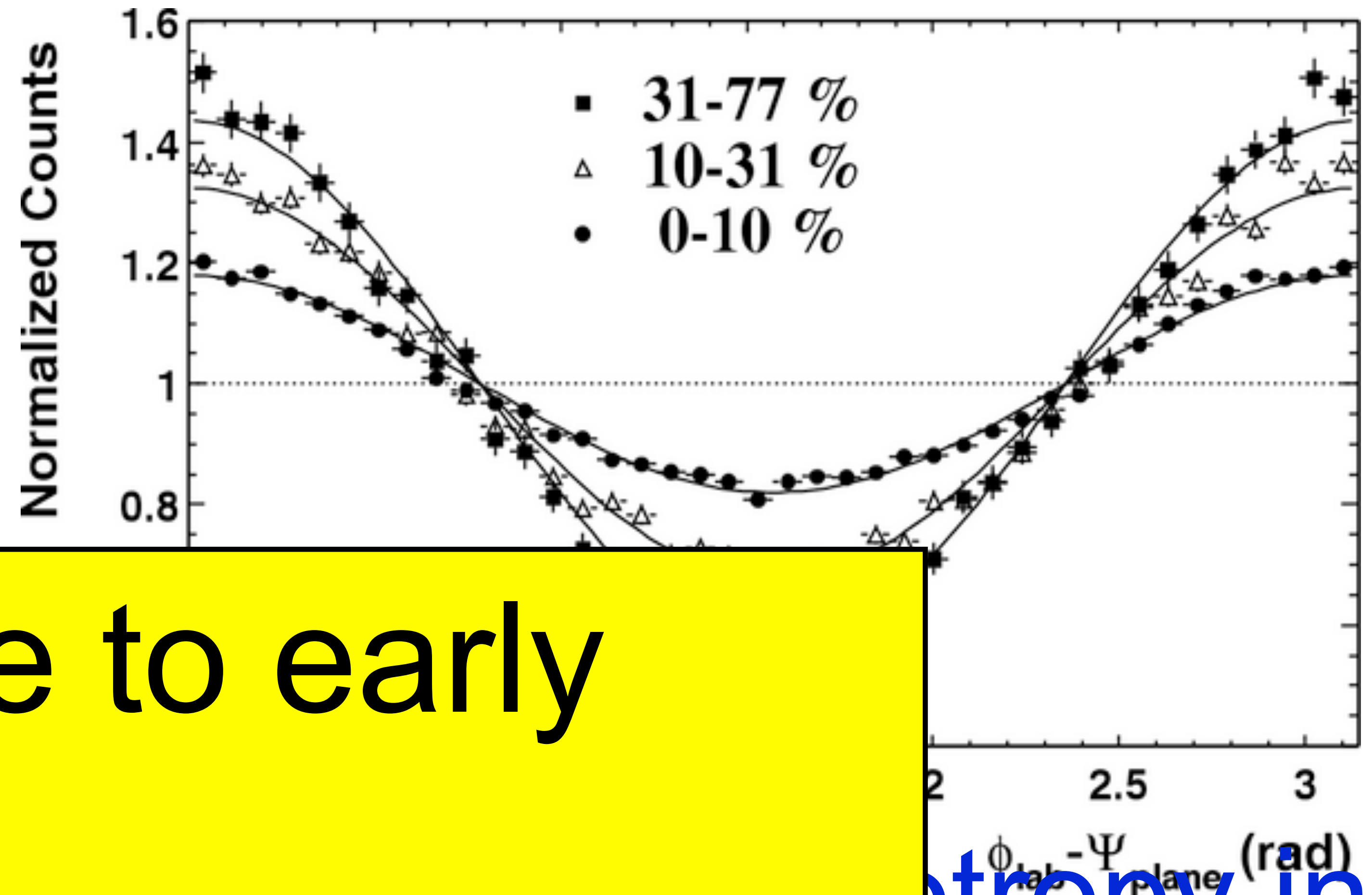
Time

M. Gehm, et al. Science 298 2179 (2002)

Initial conditions: Thermalization







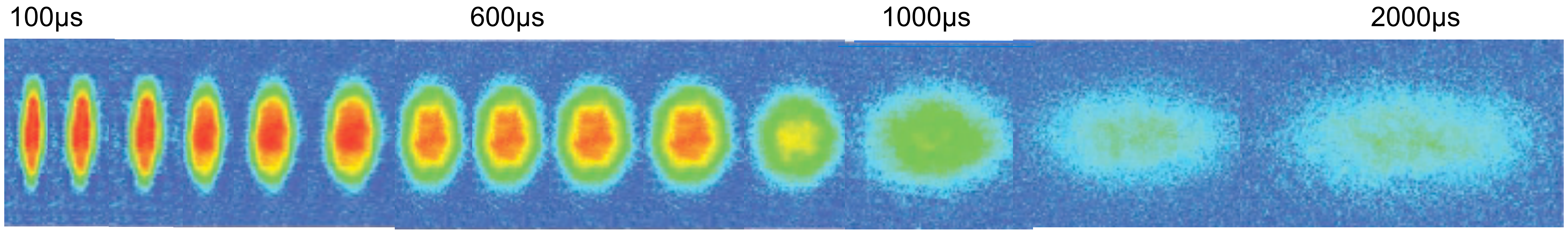
Almond s
region in
space

Elliptic flow observable sensitive to early evolution of system

Mechanism is self-quenching

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

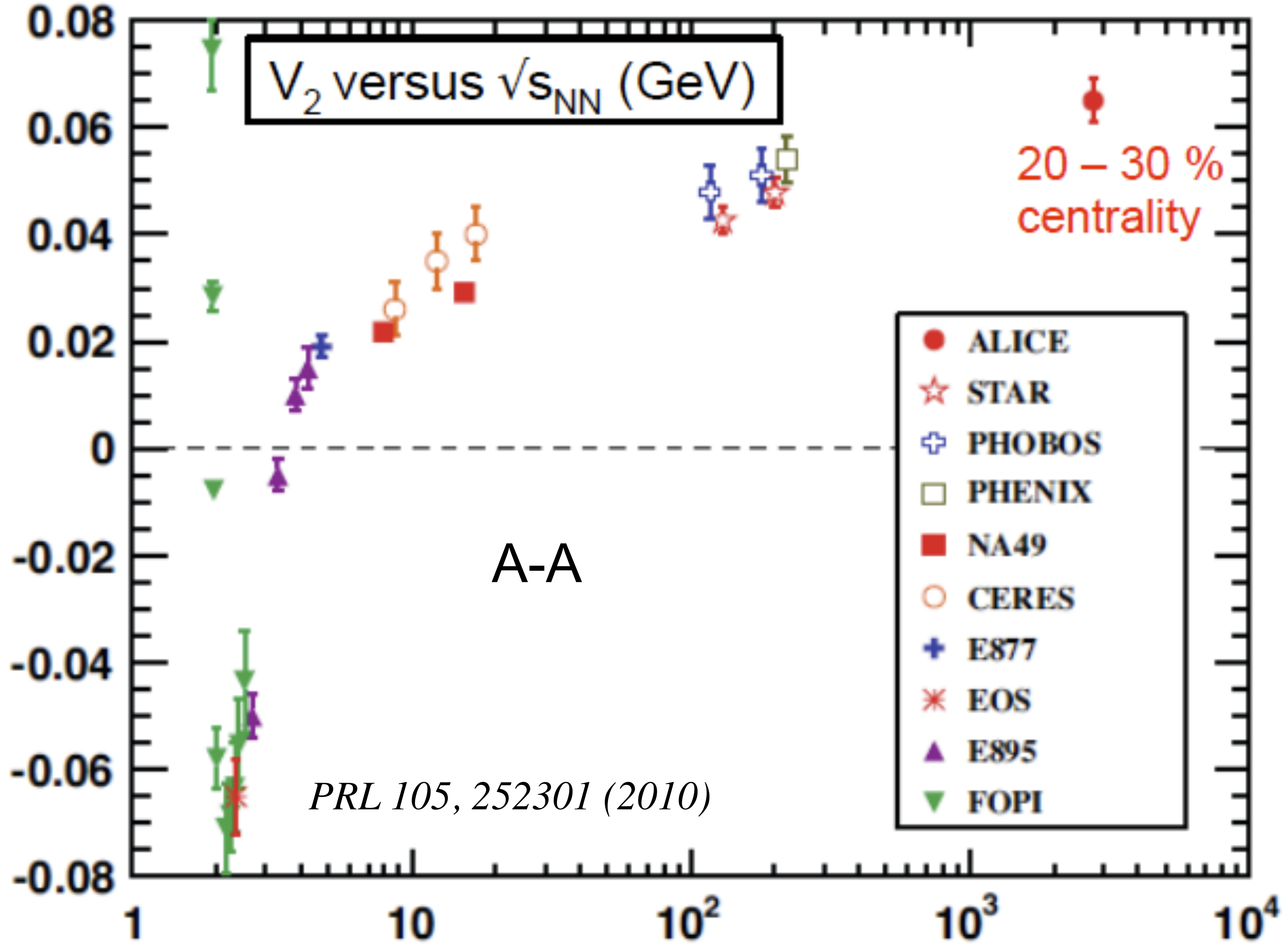
tropy in
entum space

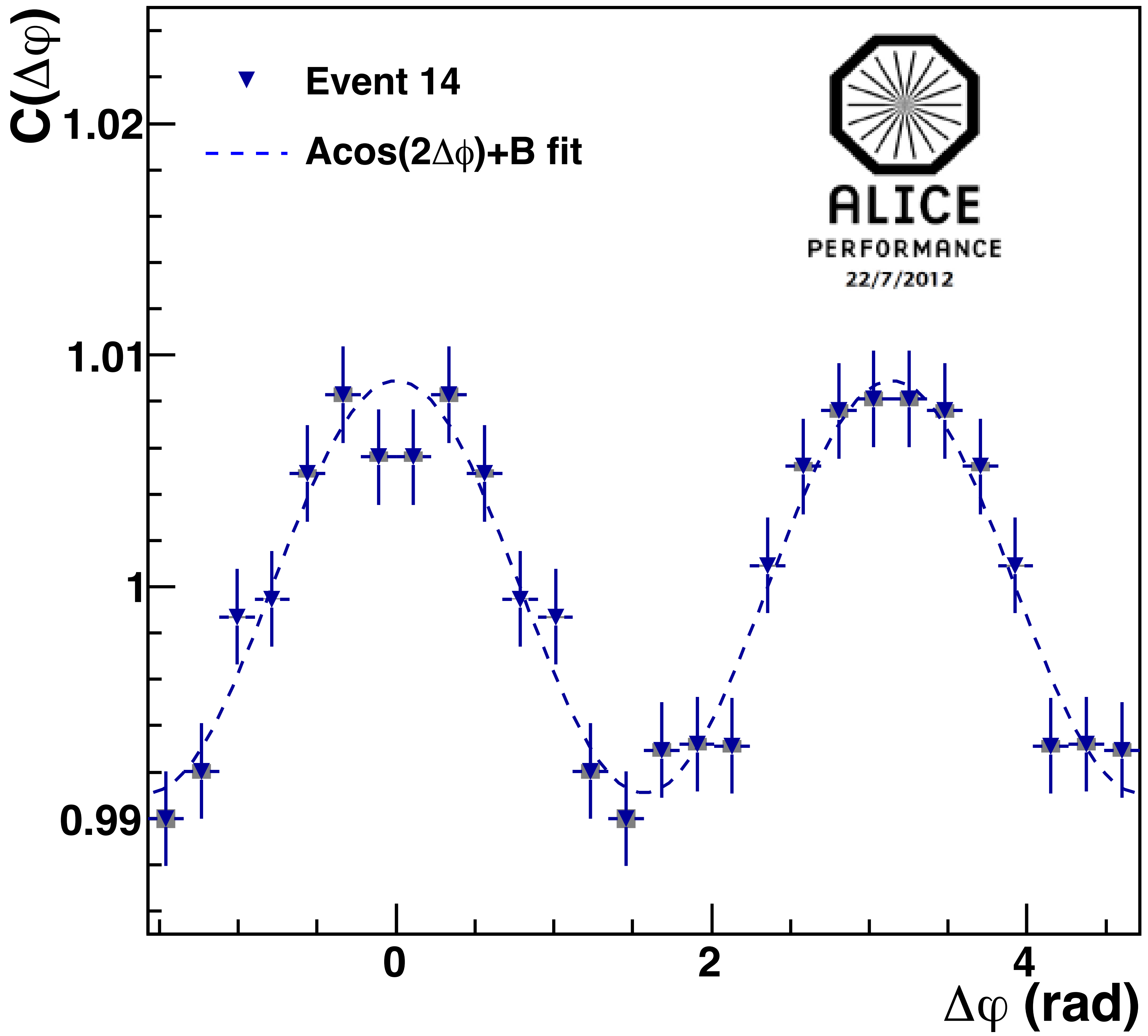


Time

M. Gehm, et al. Science 298 2179 (2002)

Early thermalization - elliptic flow





v_2 (p_T int.) LHC ~1.3x (p_T int.) RHIC

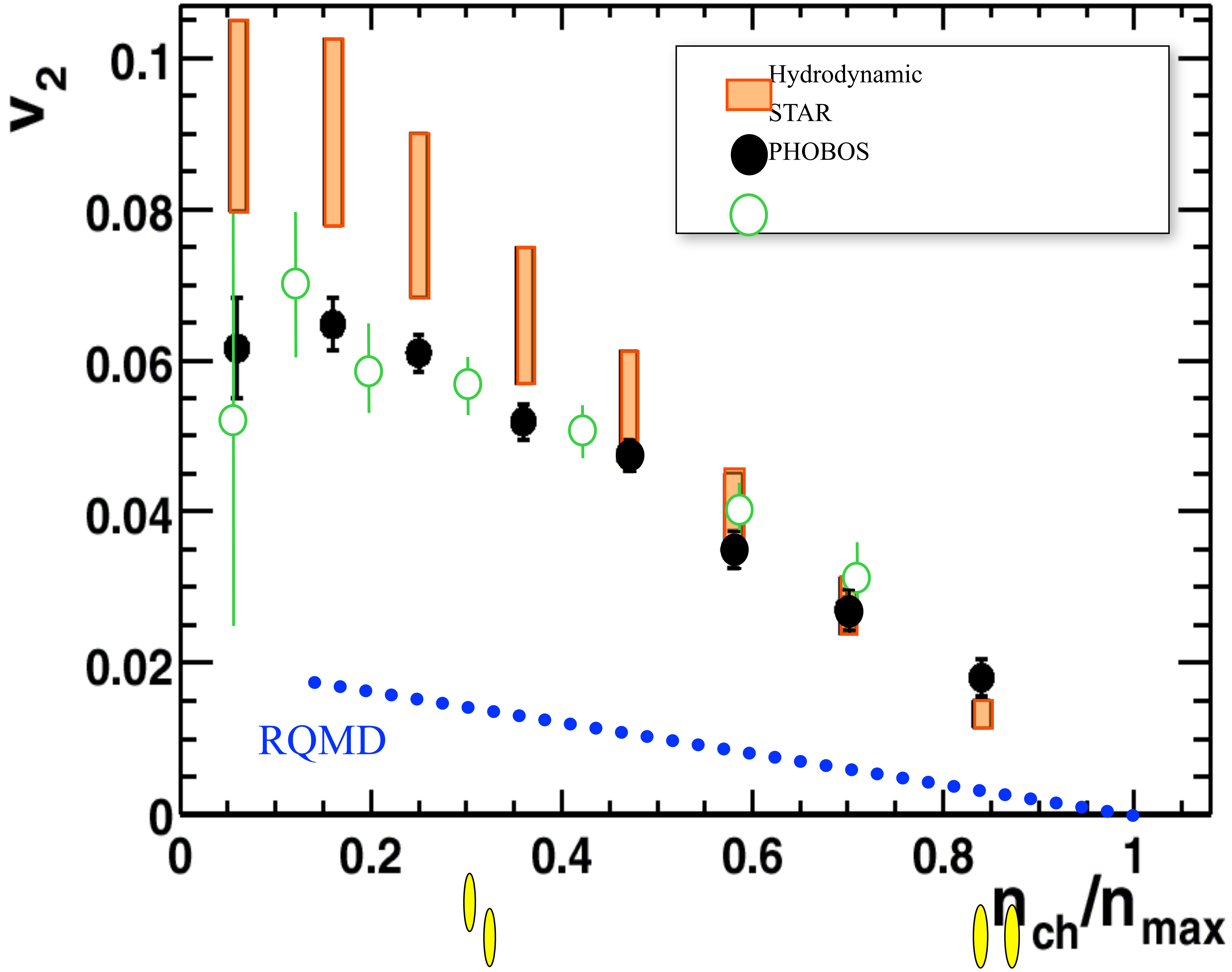
Overall increase is consistent with increased radial expansion leading to a higher mean p_T

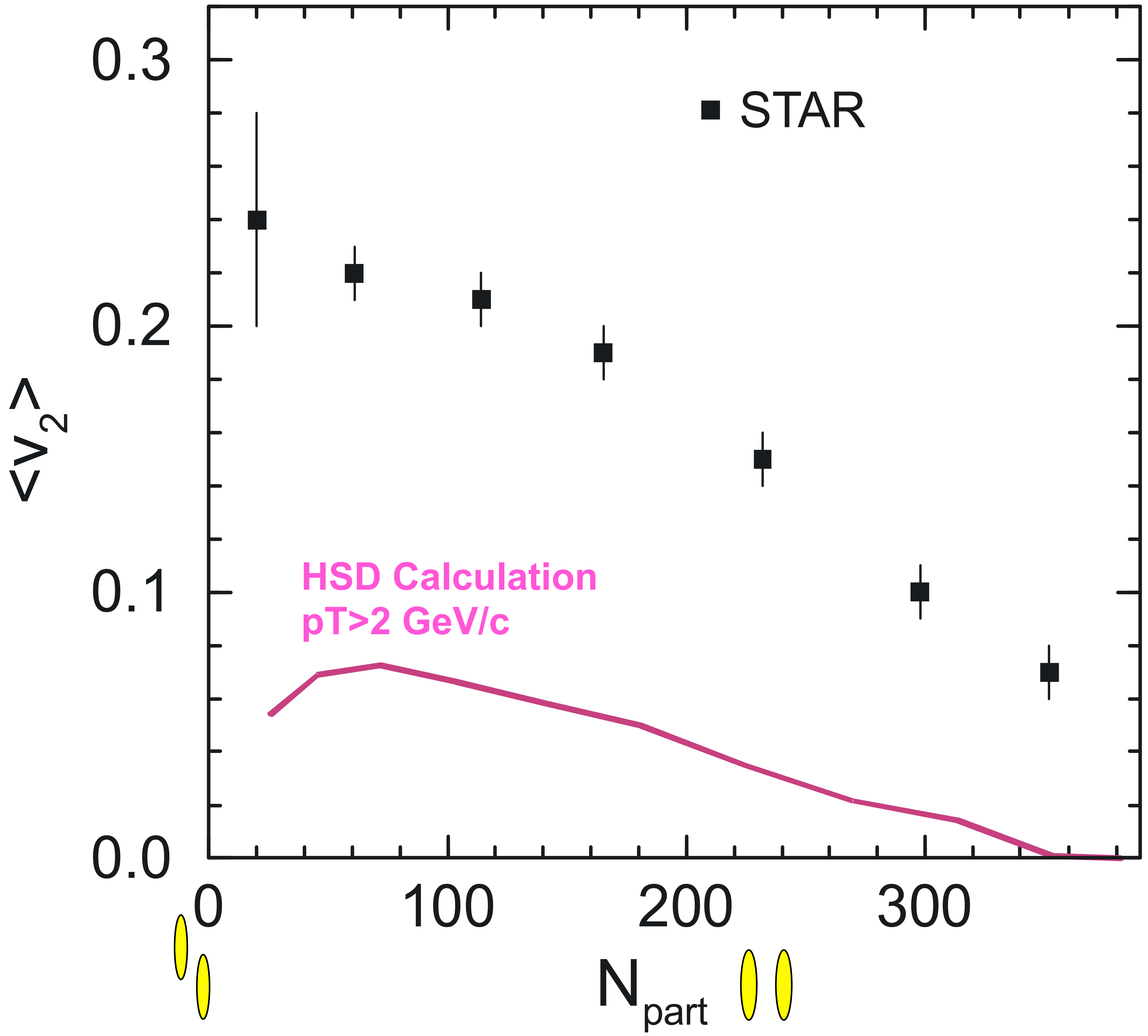
Such high event multiplicity flow measured event-by-event

Strong evidence for thermalization

Just a gas of hadrons?

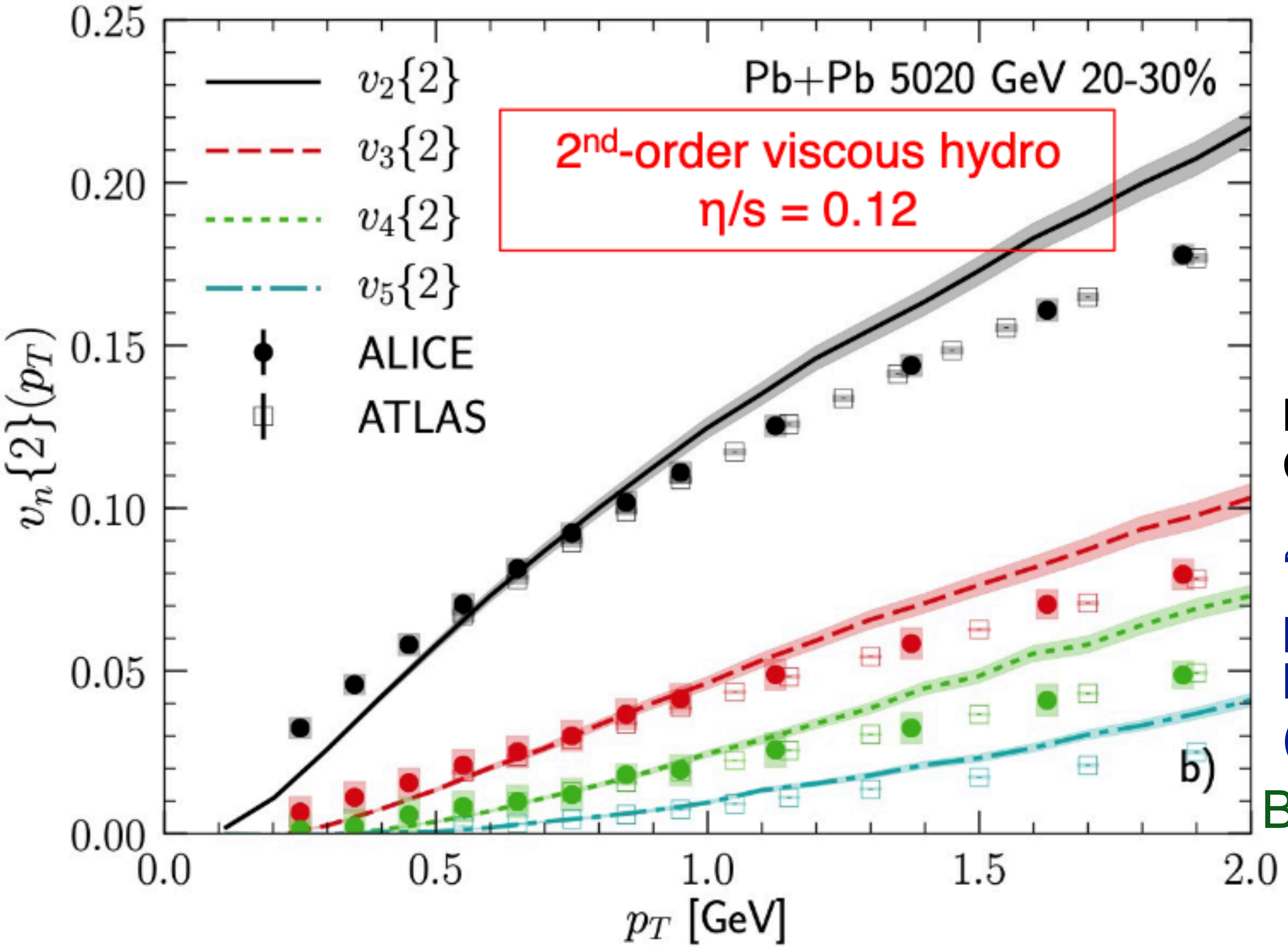
Hadronic transport models (e.g. RQMD, HSD, ...) with hadron formation times ~1 fm/c, fail to describe





Not a gas of weakly interacting hadrons

Its a fluid



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

A near-perfect fluid!

BNL Press release in 2005
CERN Press release 2010

‘confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)...’

Better description with
non-zero η/s
+ realistic initial conditions
+ hadronic rescattering afterburner

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

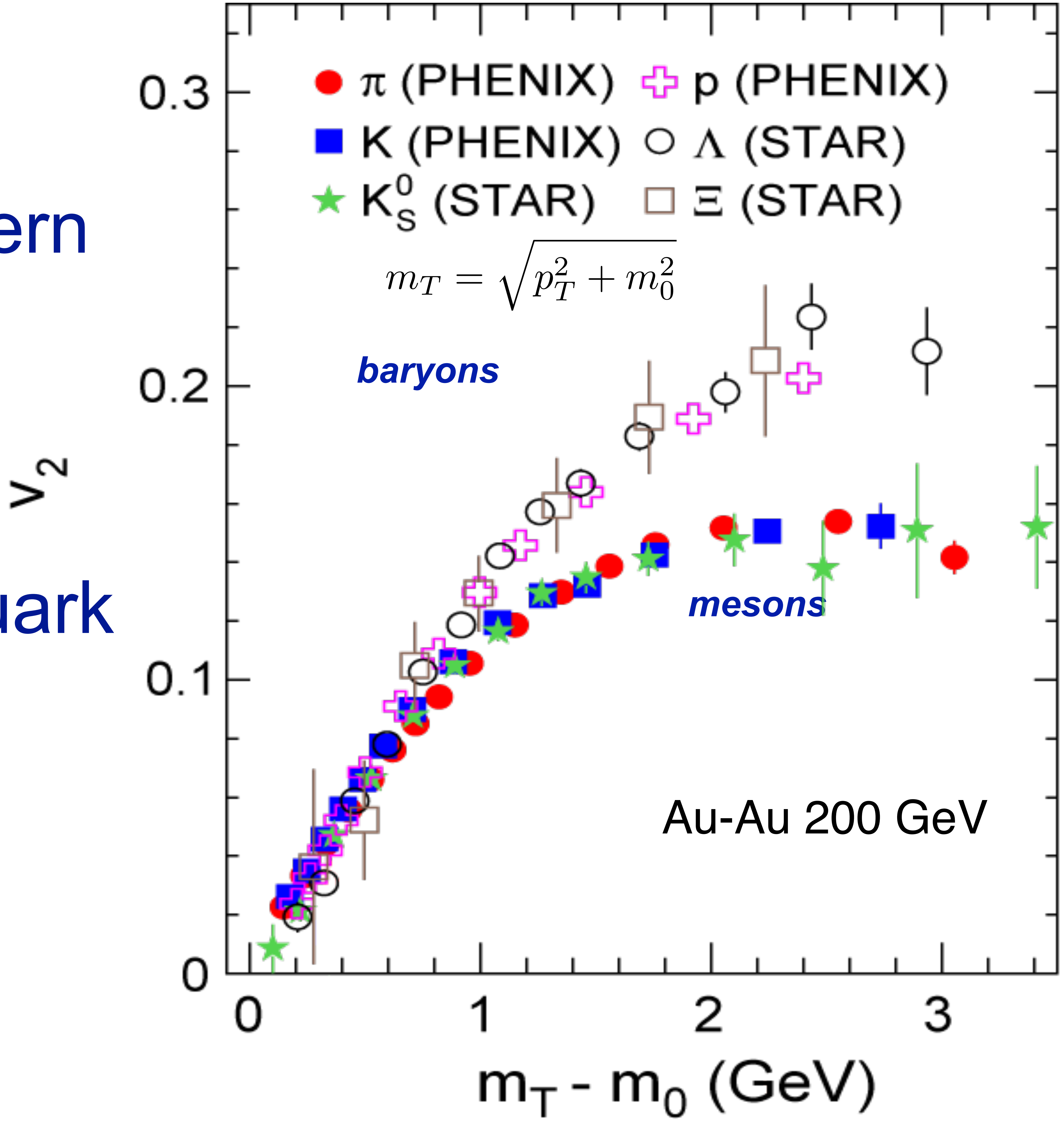
$$\frac{d^2N}{dp_T d\phi} \propto 1 + 2v_2(p_T)\cos(2\phi)$$

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)



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

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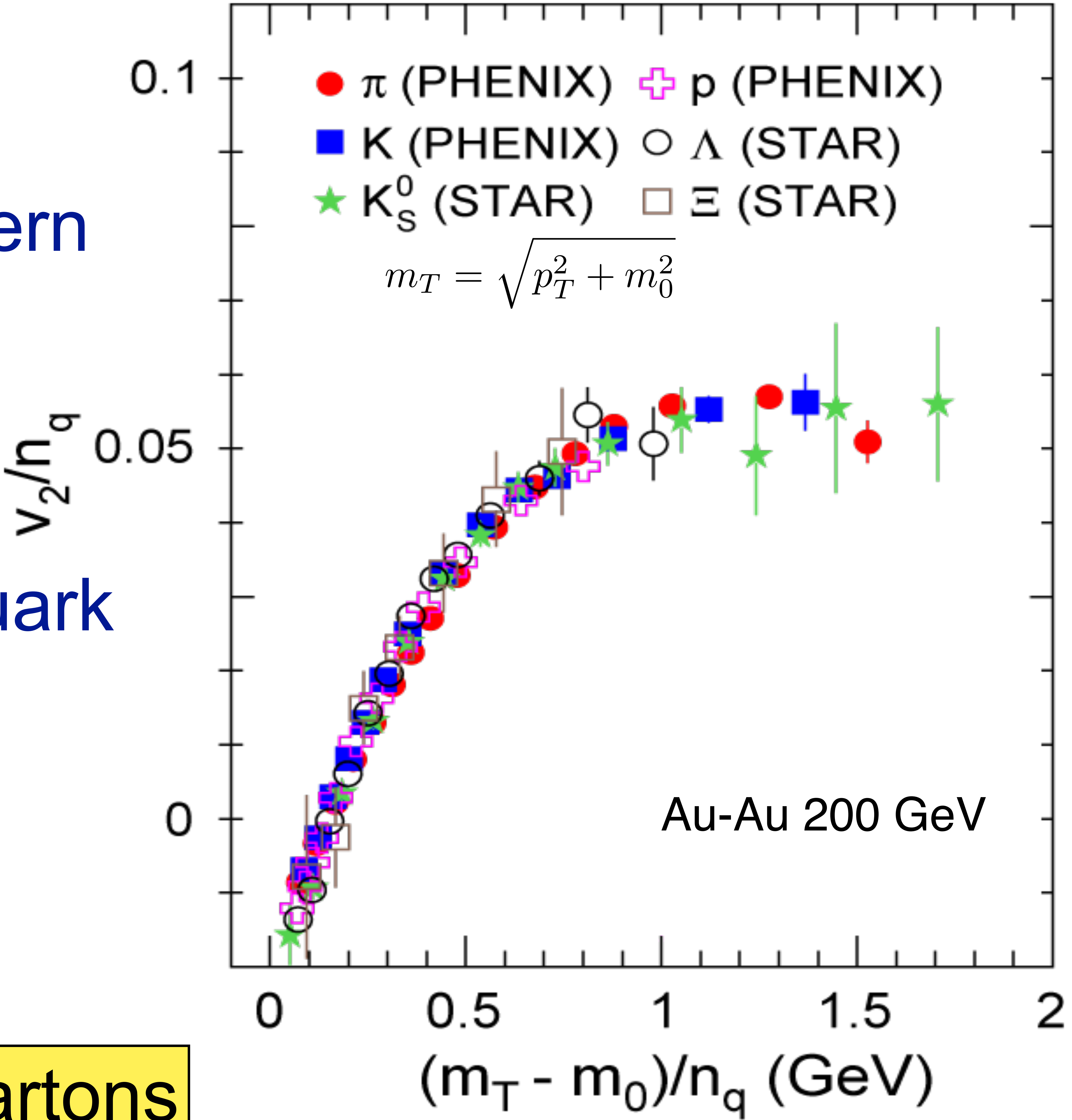
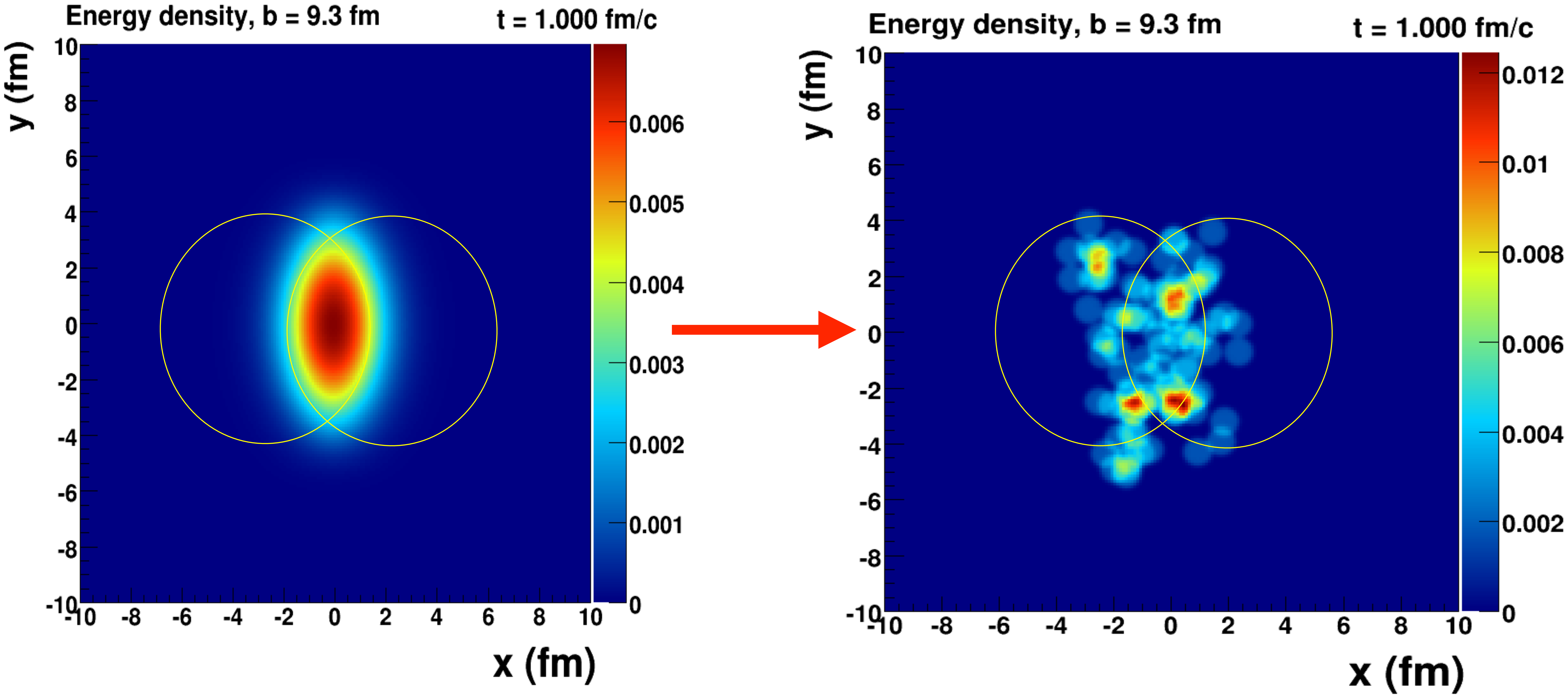
Constituents of QGP are partons



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

Initial conditions are complex

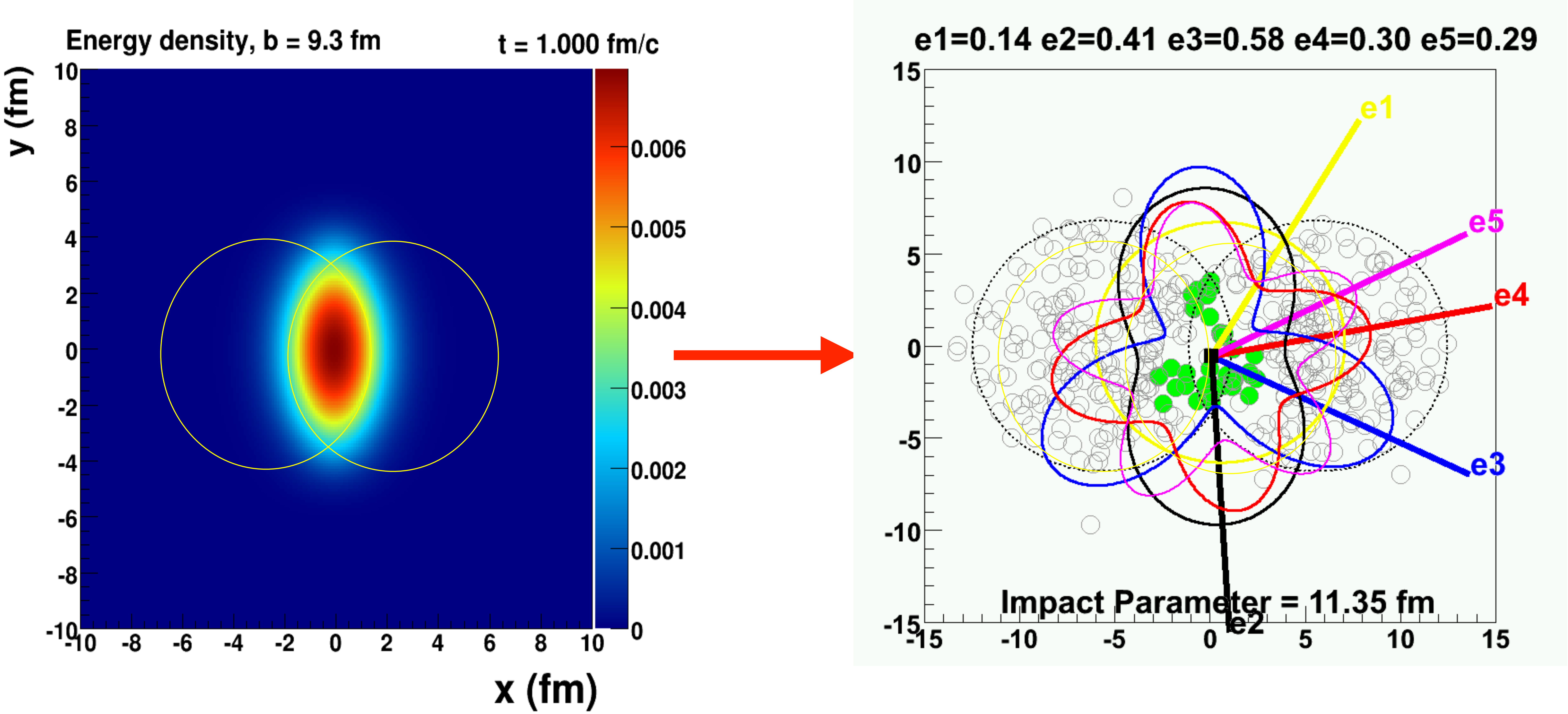


Event-by-event fluctuations in initial conditions are important

- induce angular correlations

Pressure gradients convert all spatial anisotropies into momentum anisotropies

Initial conditions are complex



More than just elliptic flow

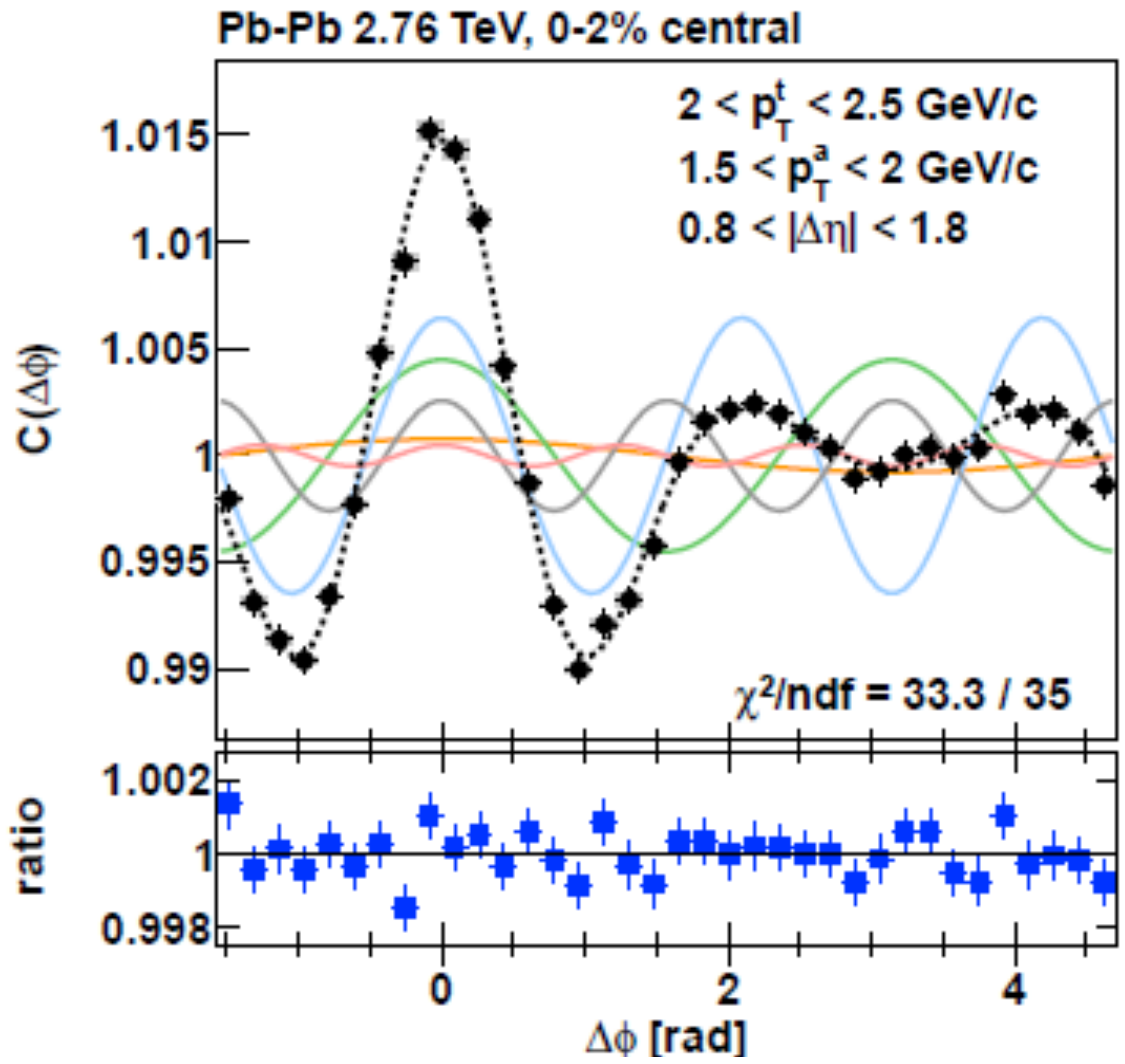
v_n - magnitude of the flow w.r.t nth plane

Event-by-event fluctuations in initial conditions are important

- induce angular correlations

Pressure gradients convert all spatial anisotropies into momentum anisotropies

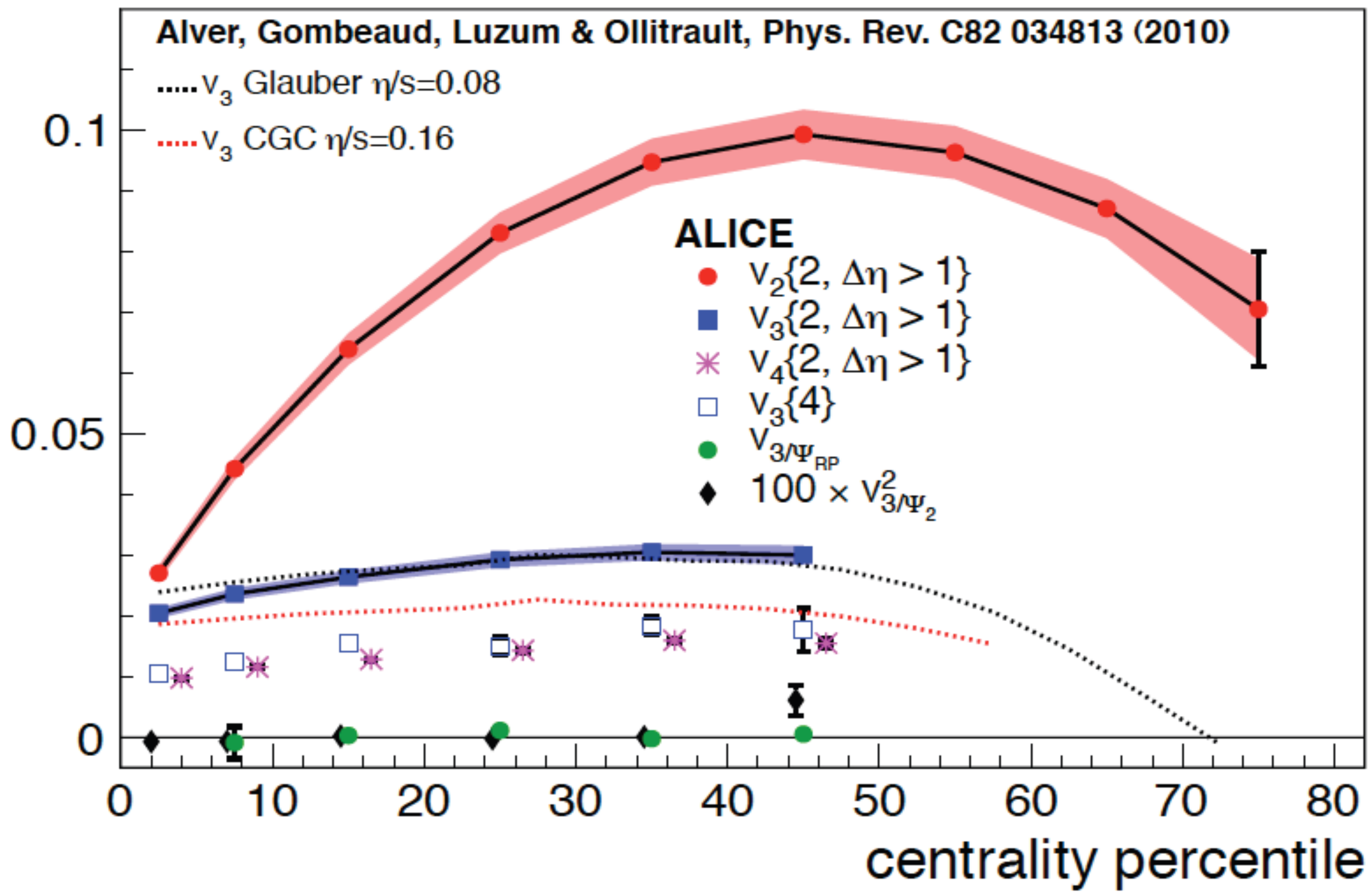
Higher harmonics



Data indicate fluctuating initial conditions

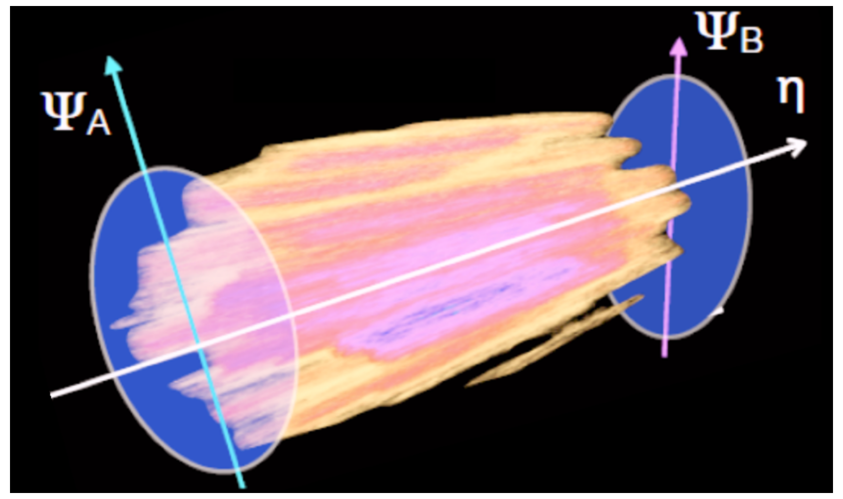
First 5 v_n components describe majority of correlations

But higher orders have been extracted

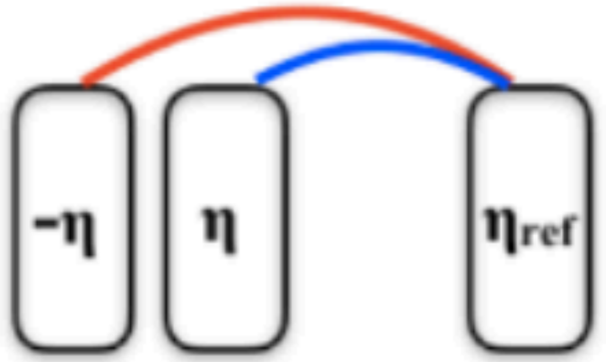


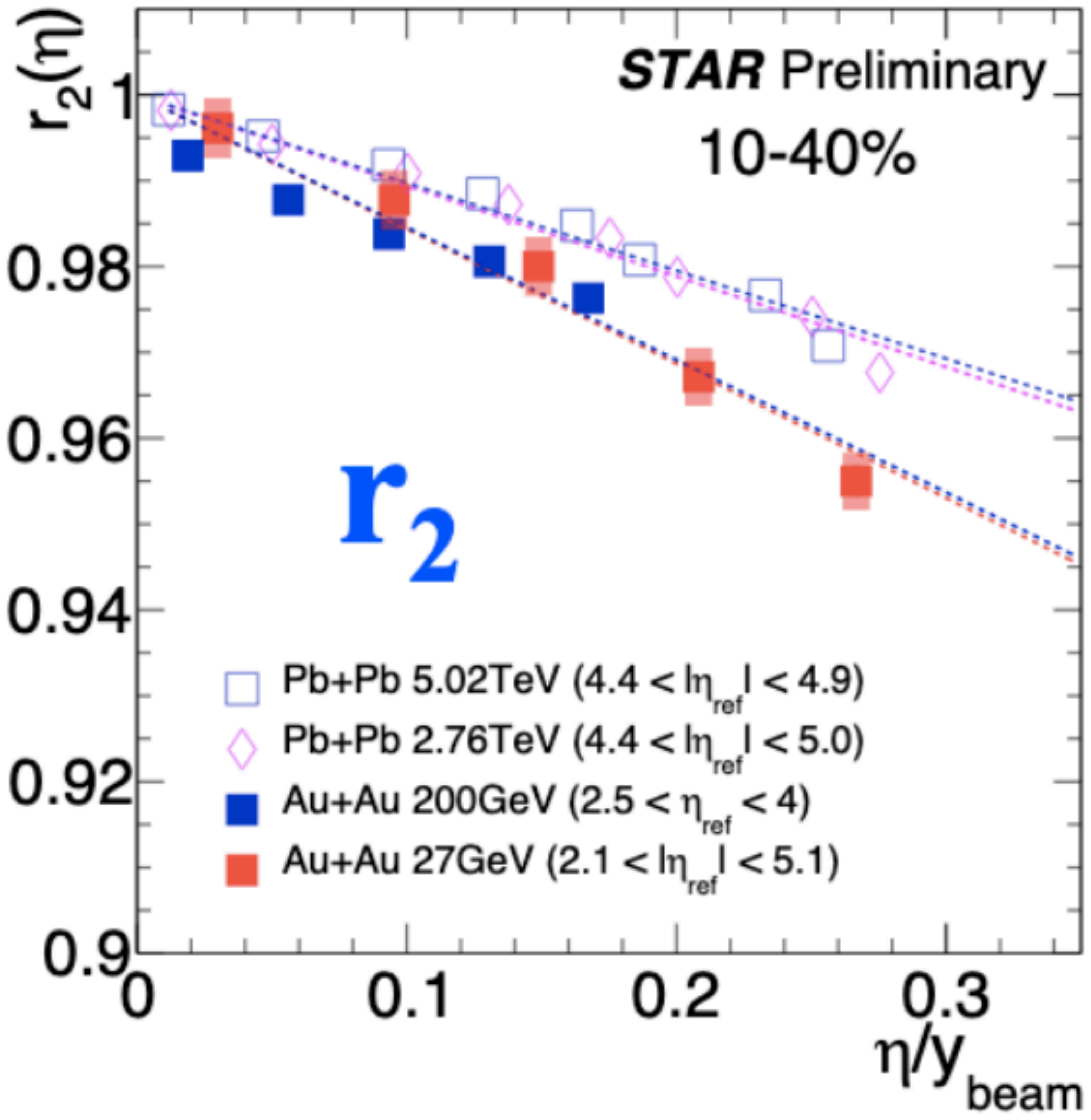
ALICE: PRL 107:032301 (2011)

What about the longitudinal dimension?

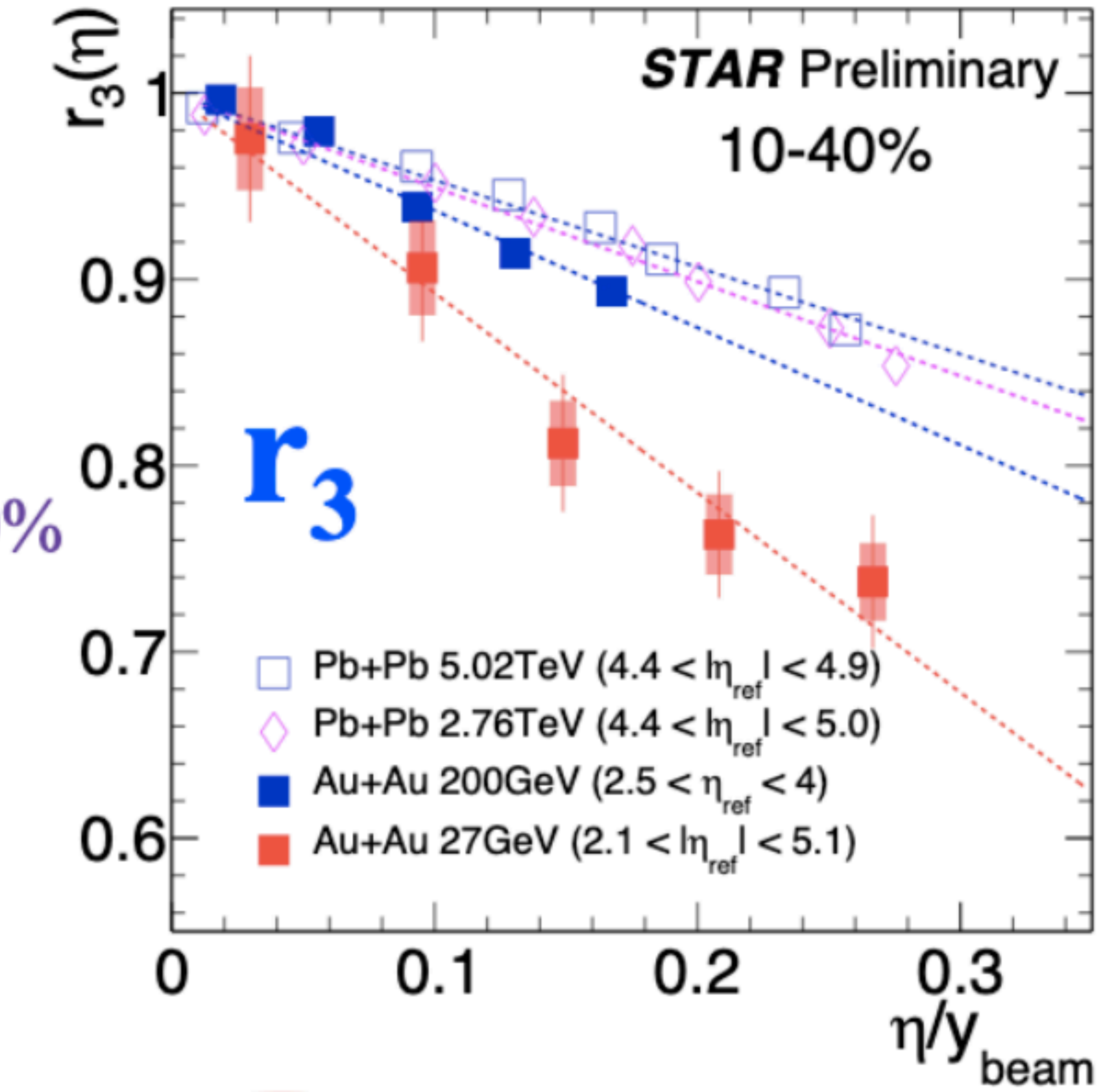


$$r_n(\eta) = \frac{\langle V_n(-\eta)V_n^*(\eta_{\rm ref})\rangle}{\langle V_n(\ \eta)V_n^*(\eta_{\rm ref})\rangle}$$





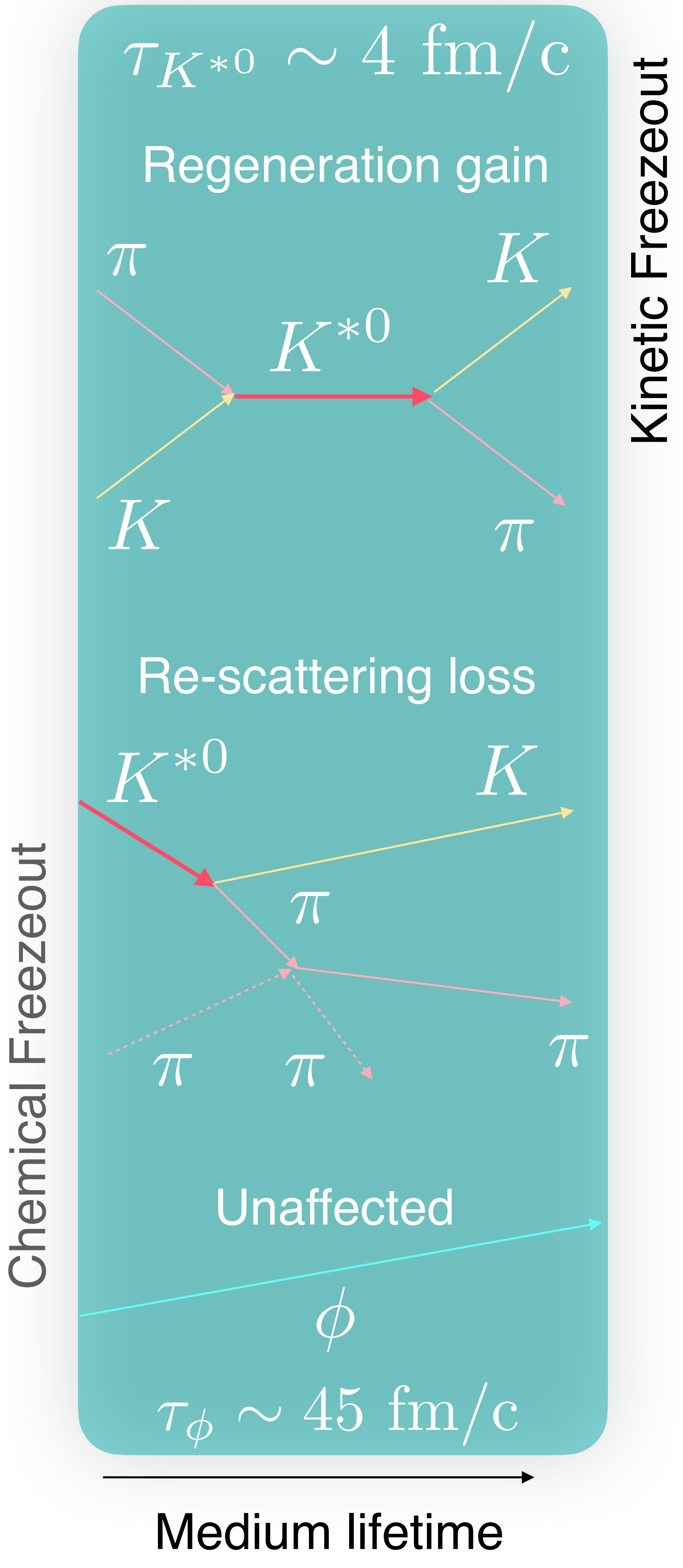
r_3 shows up to 30% decorrelation



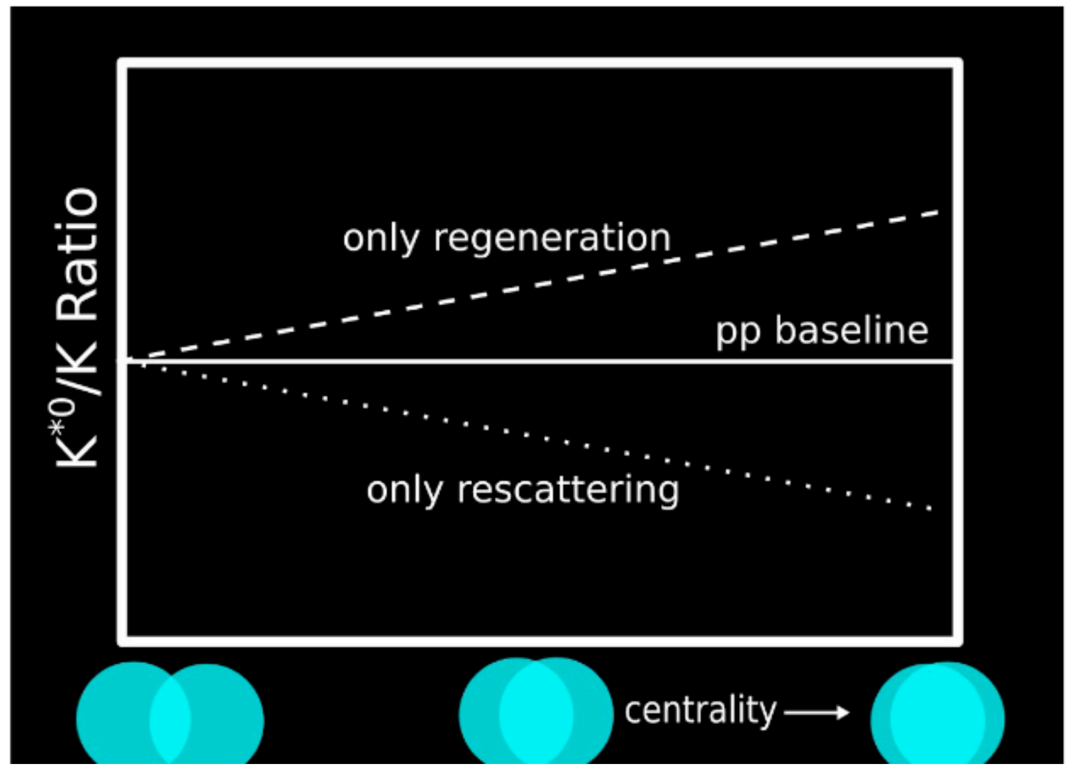
Lower energies stronger flow de-correlation
- less boost invariant

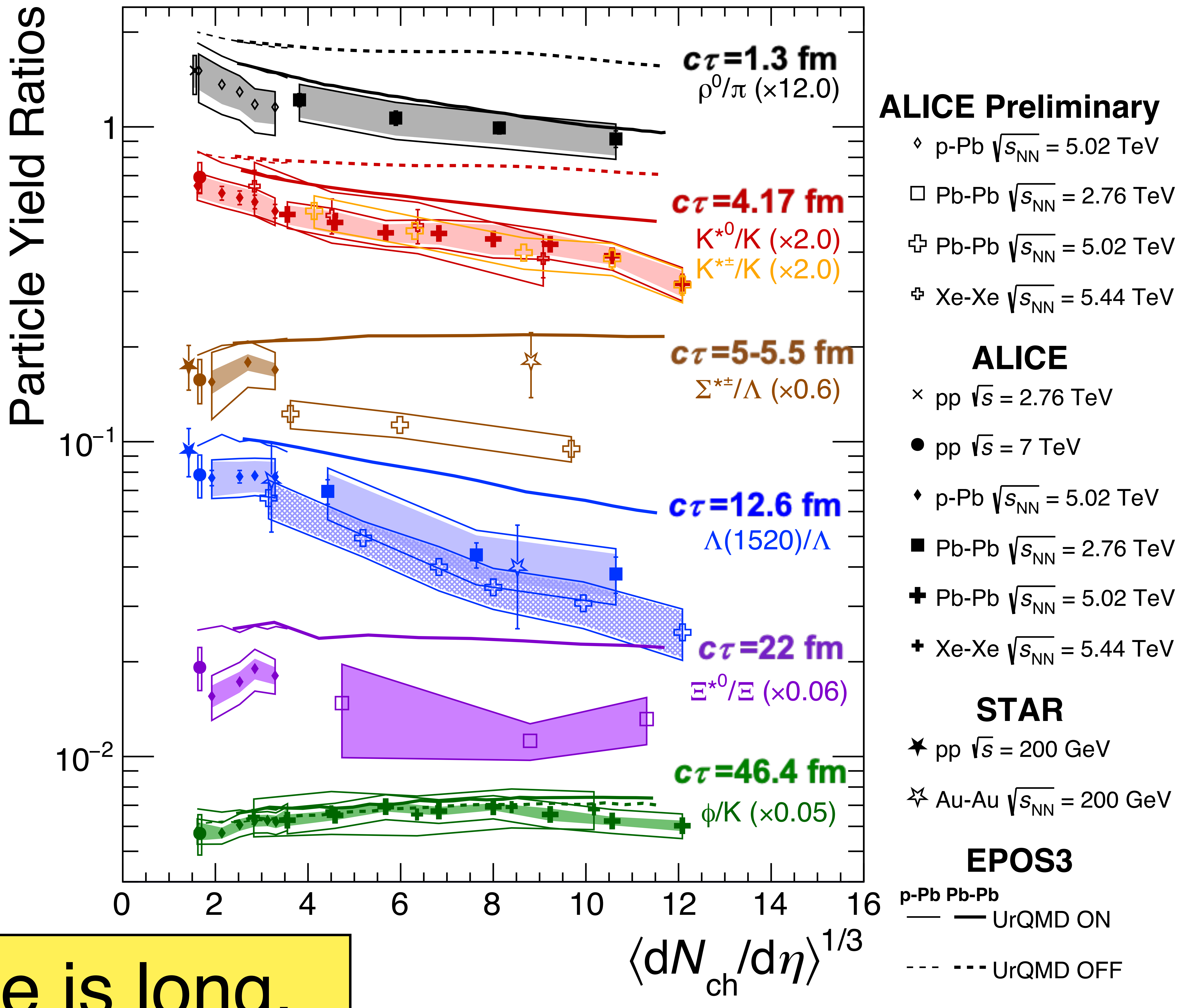
QGP medium has a twist

What about the hadronic phase?



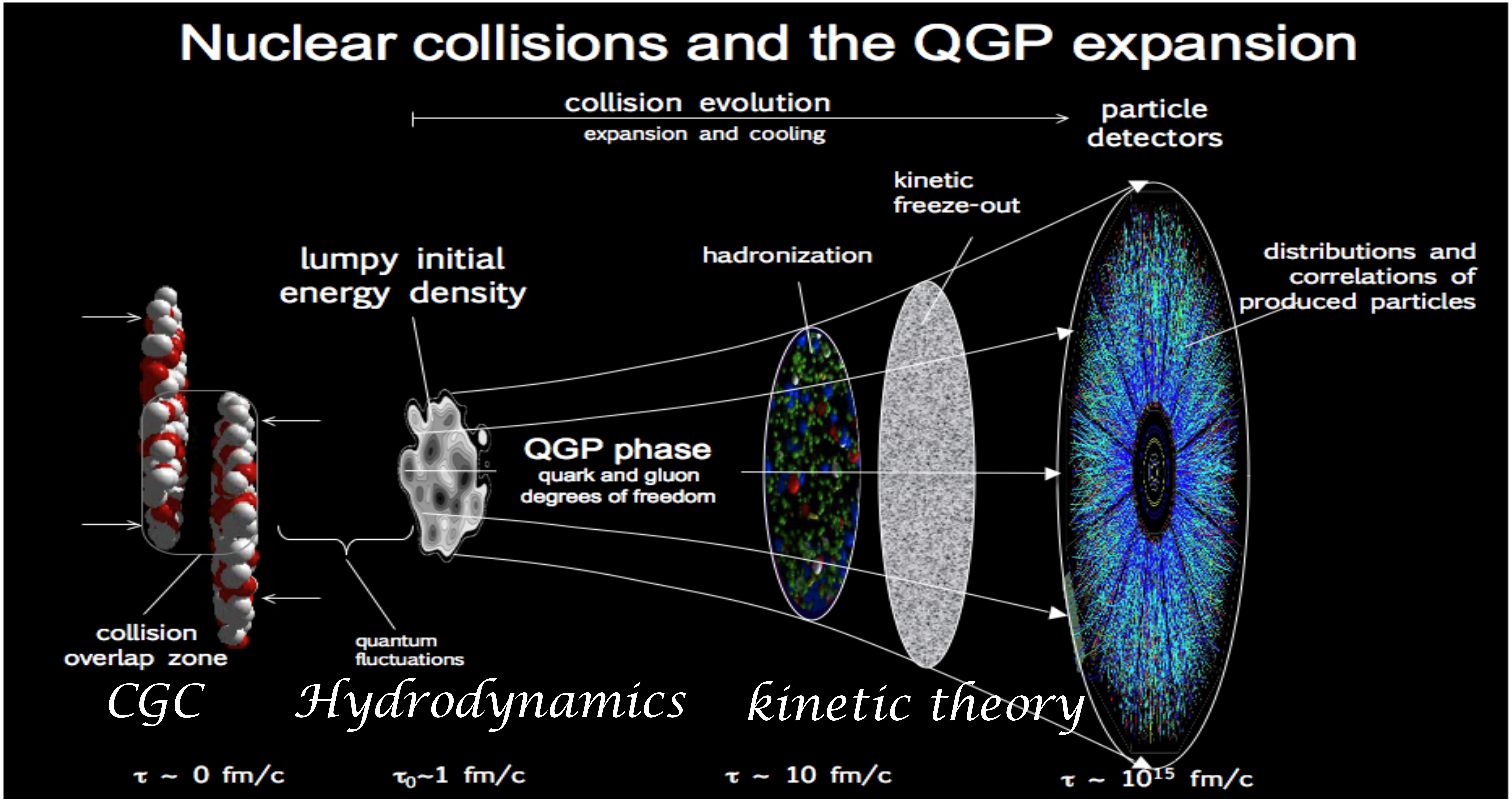
Resonance/non-resonance probes hadronic phase between chemical and kinetic freeze-out



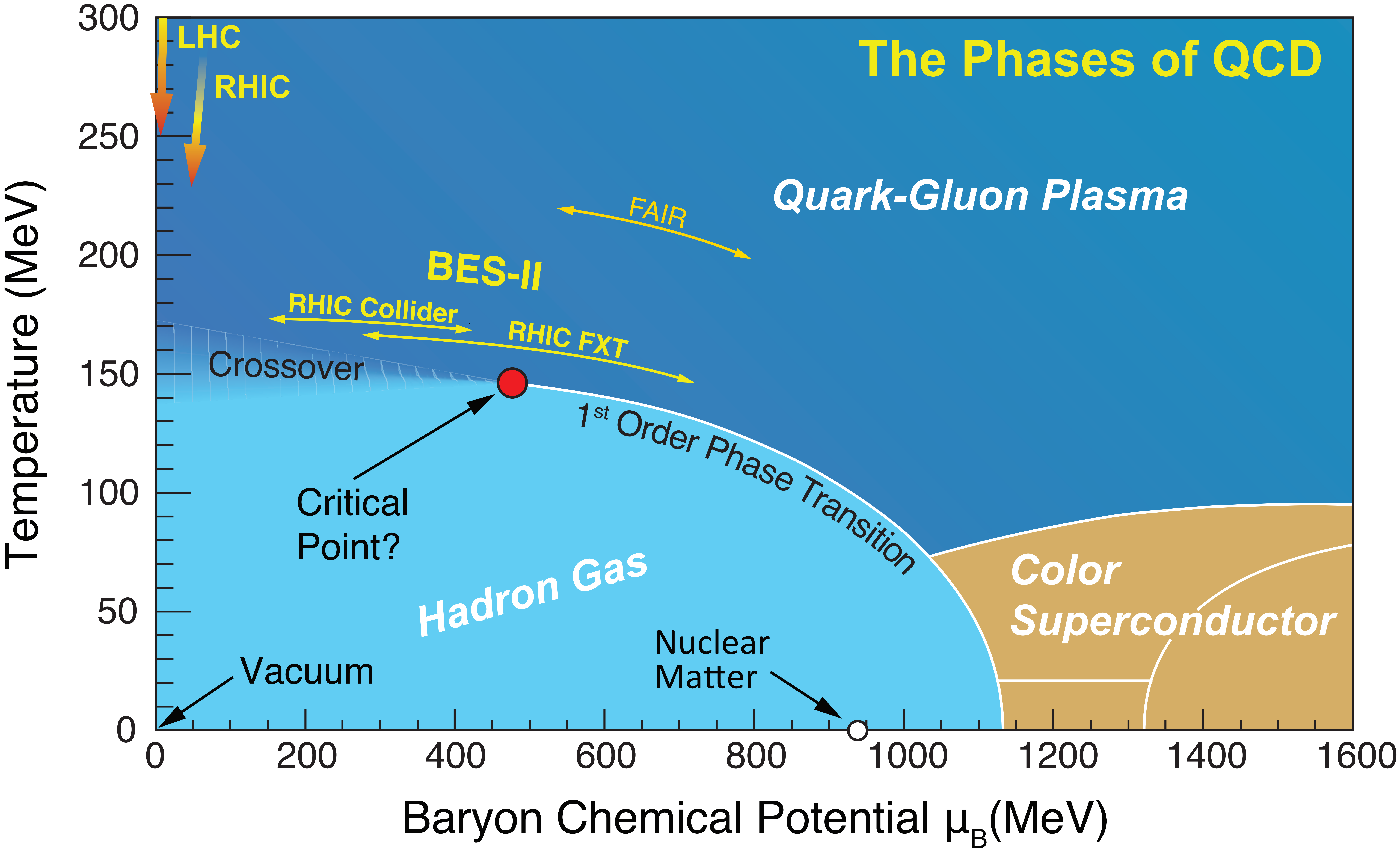


Ratios suggest hadronic phase is long, rescattering cross-section also important

More detailed summary of the collision's evolution



Back to the phase diagram

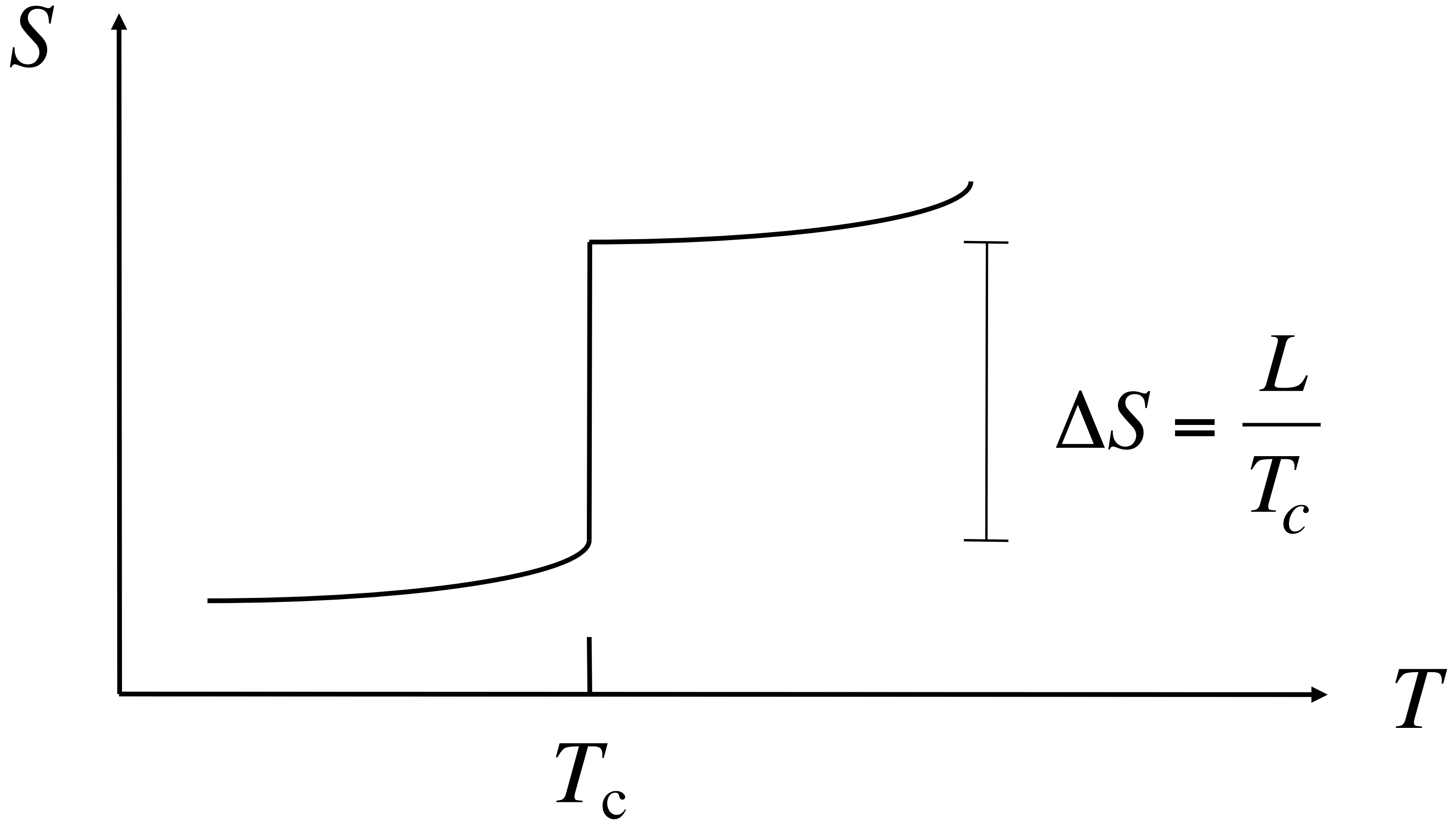


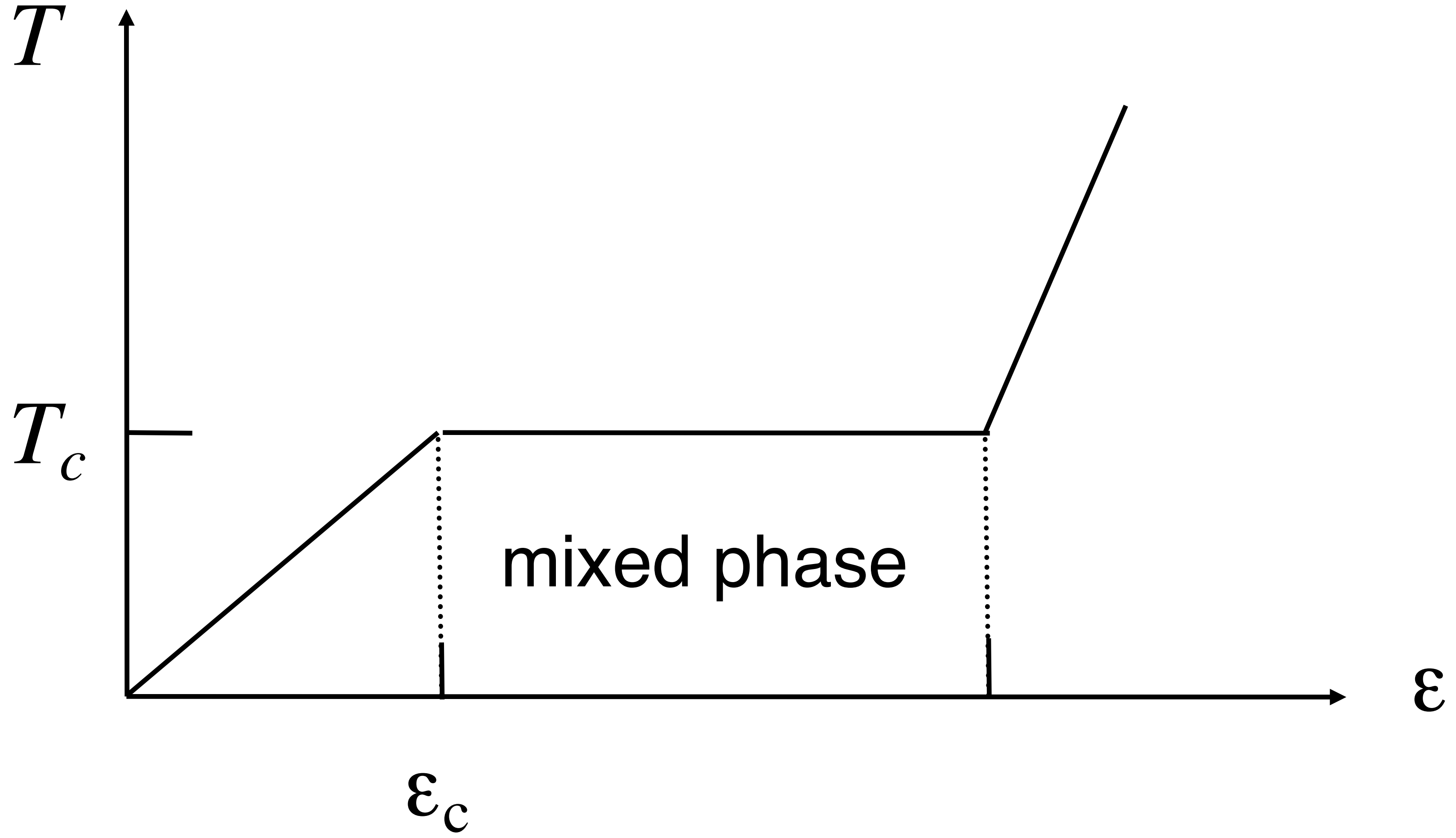
Thermodynamics - phase transitions

Phase transition or a crossover?

Signs of a phase transition:

1st order: discontinuous in entropy at T_c → Latent heat, a mixed phase





Higher order: discontinuous in higher derivatives of $\delta^n S/\delta T^n$ → no mixed phase - system passed smoothly and uniformly into new state (ferromagnet)

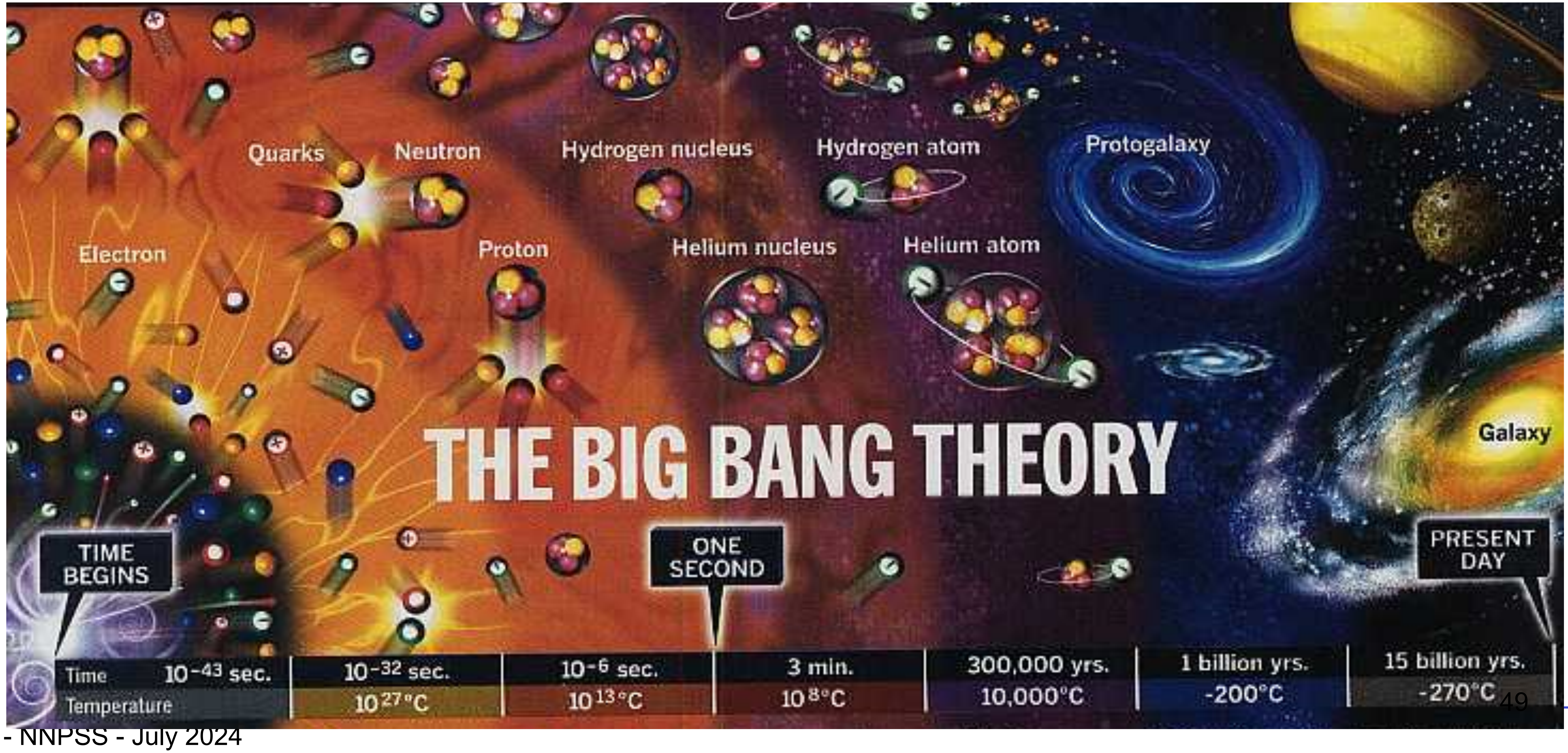
Temperature ⇔ transverse momentum

Energy density ⇔ transverse energy

Entropy ⇔ multiplicity

The order of the phase transition

"A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario." Ed Witten, Phys. Rev. D (1984)



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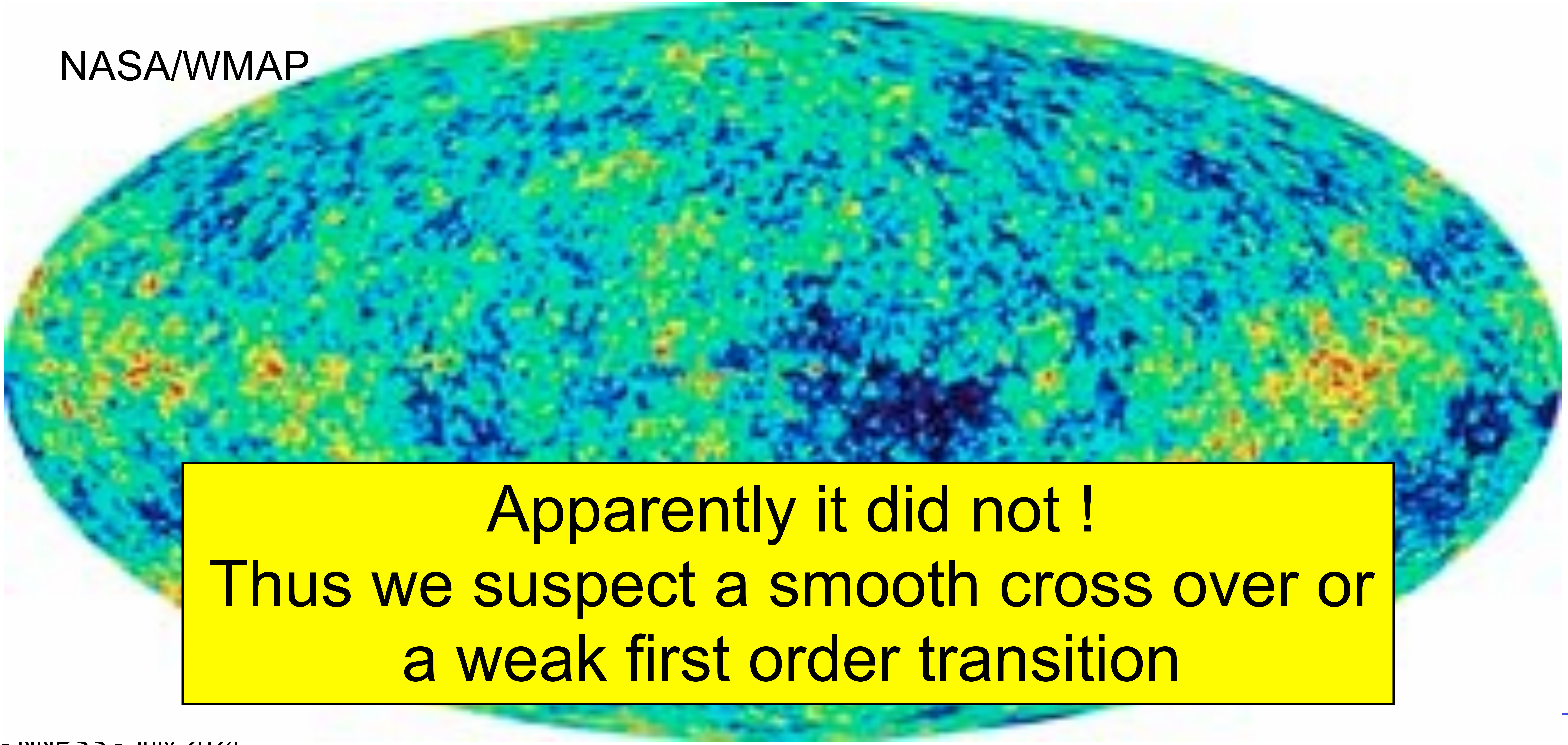

NASA/WMAP

Apparently it did not !
Thus we suspect a smooth cross over or a weak first order transition

Is there a Critical Point or evidence of an ordered transition?

The phase diagram of QCD - theoretical input

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

Cross-over at low μ_B

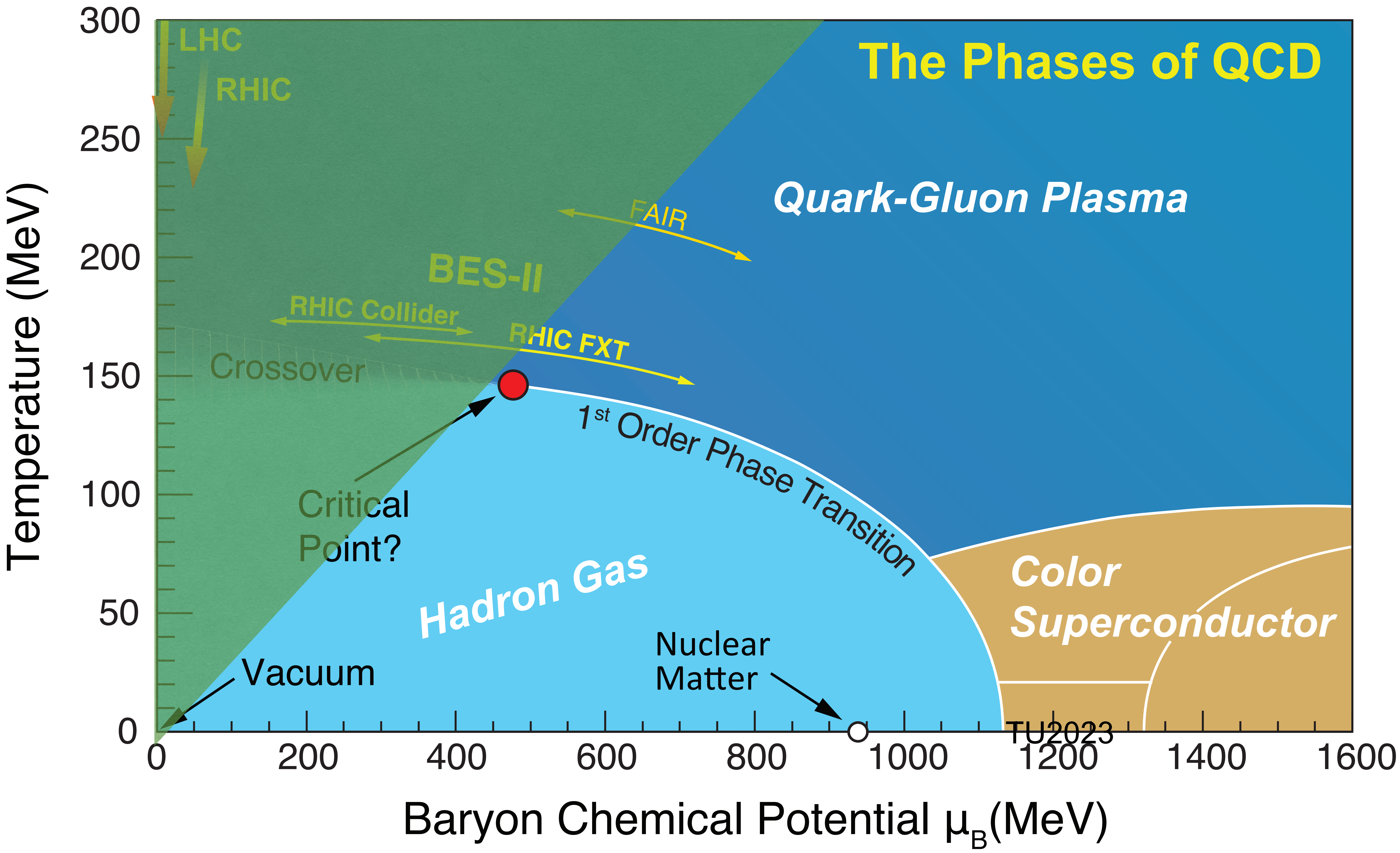
Disfavor QCD critical point at $\mu_B/T < 3$

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



QCD creates a rich landscape to explore

Critical fluctuations

Critical Points:

divergence of susceptibilities

e.g. magnetism transitions

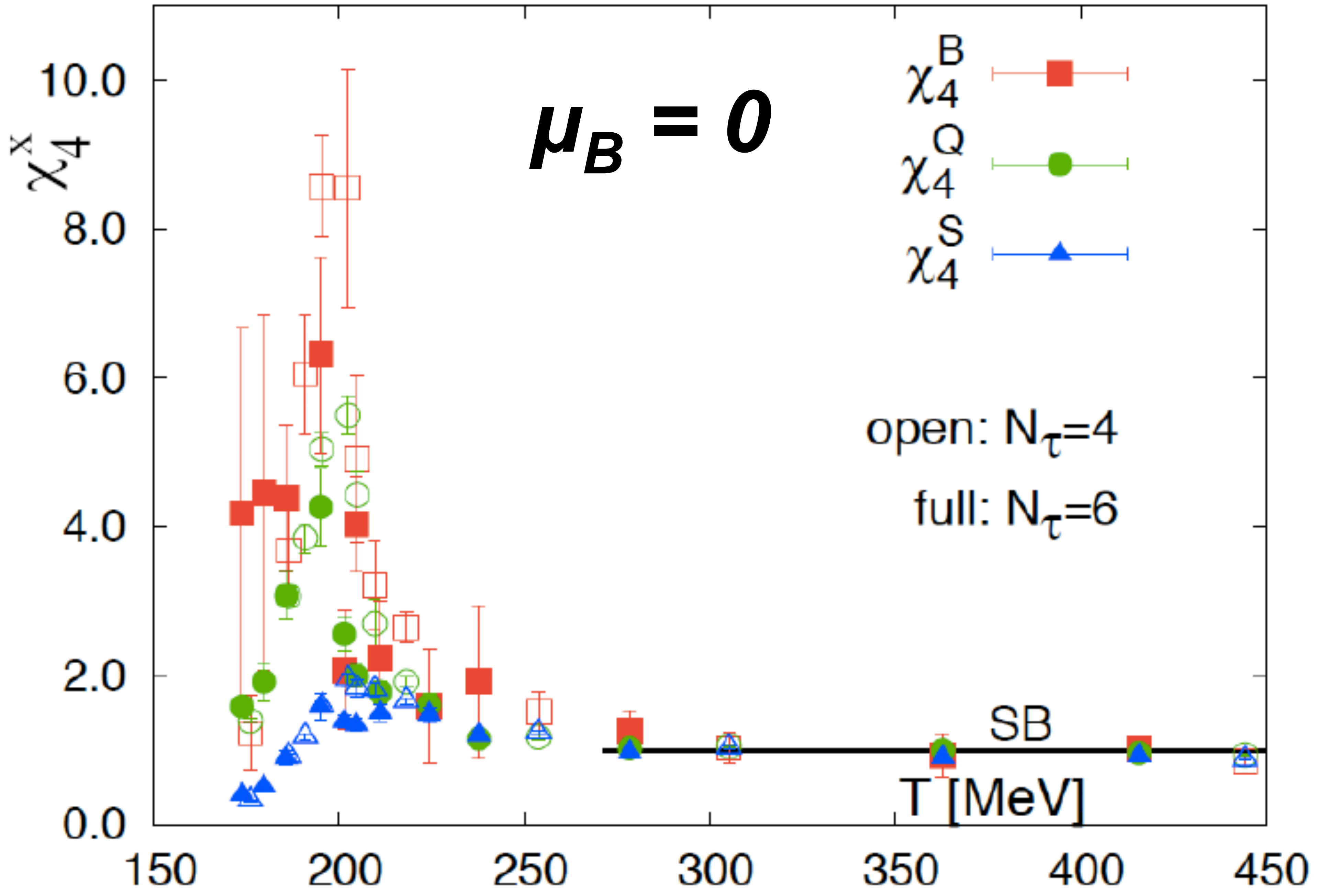
divergence of correlation lengths

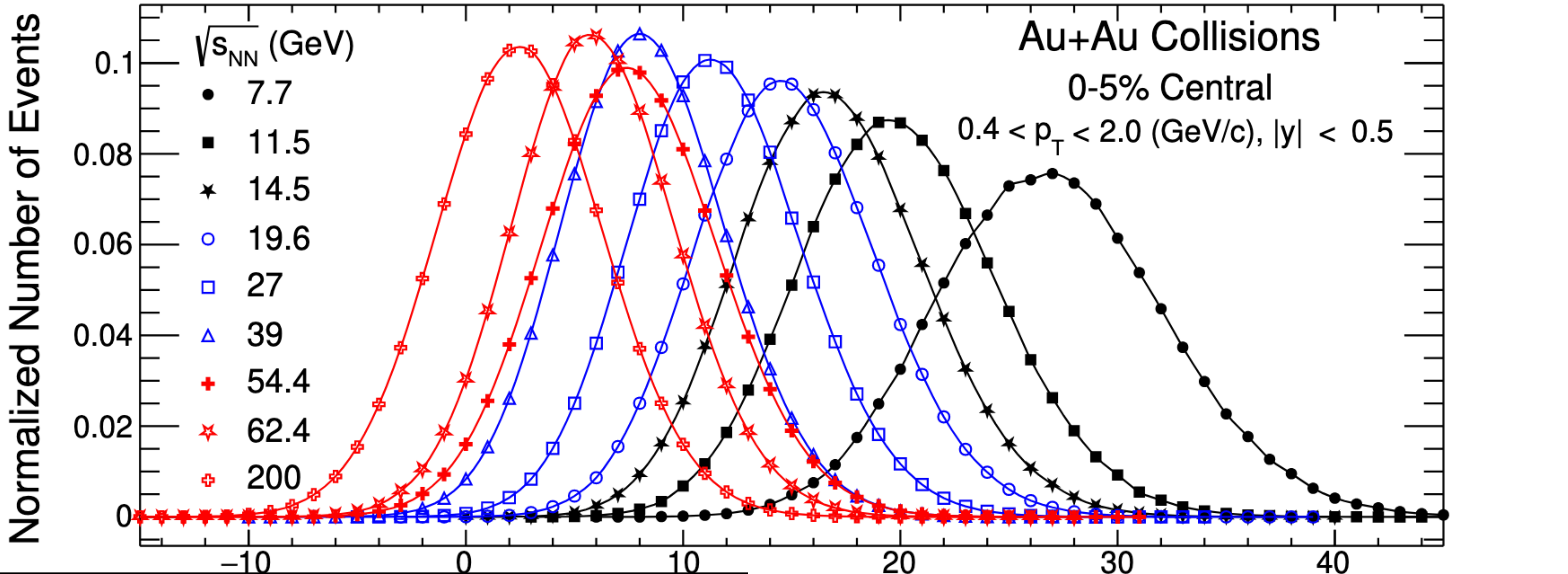
e.g. critical opalescence

Lattice QCD:

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

Divergences of conserved quantities may survive in the final state





STAR: PRL 126, 092301 (2021)

Non-gaussian fluctuations of net-baryon density

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

Conserved quantities are the key

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 :

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

$\delta N = N - \langle N \rangle$

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

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

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

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

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

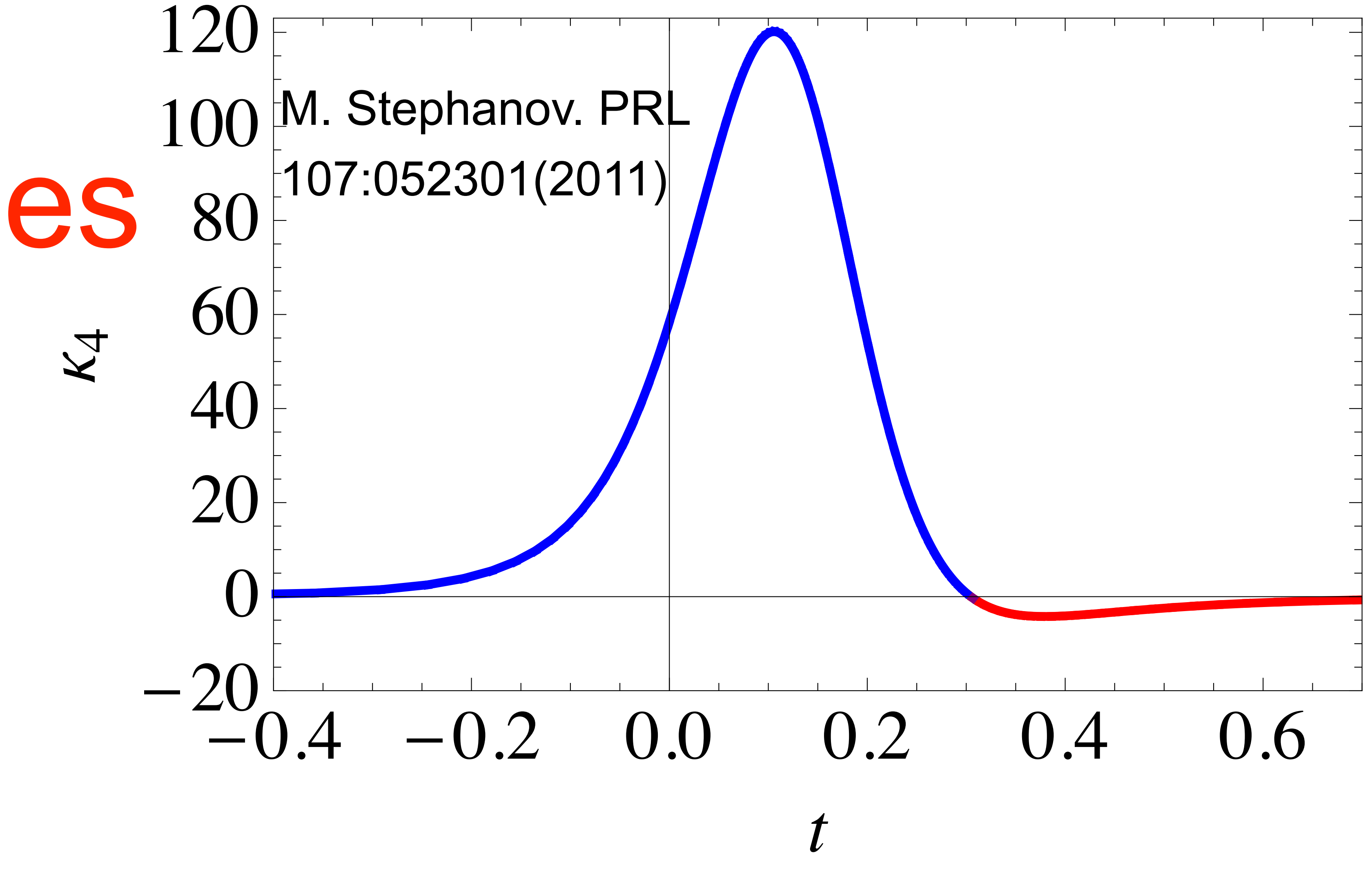
(Kurtosis - 4th moment - "tailiness" of distribution)

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

M. Stephanov. PRL 107:052301(2011)

Presence of Critical Point?

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



Top 5% central collisions:

Non-monotonic behavior

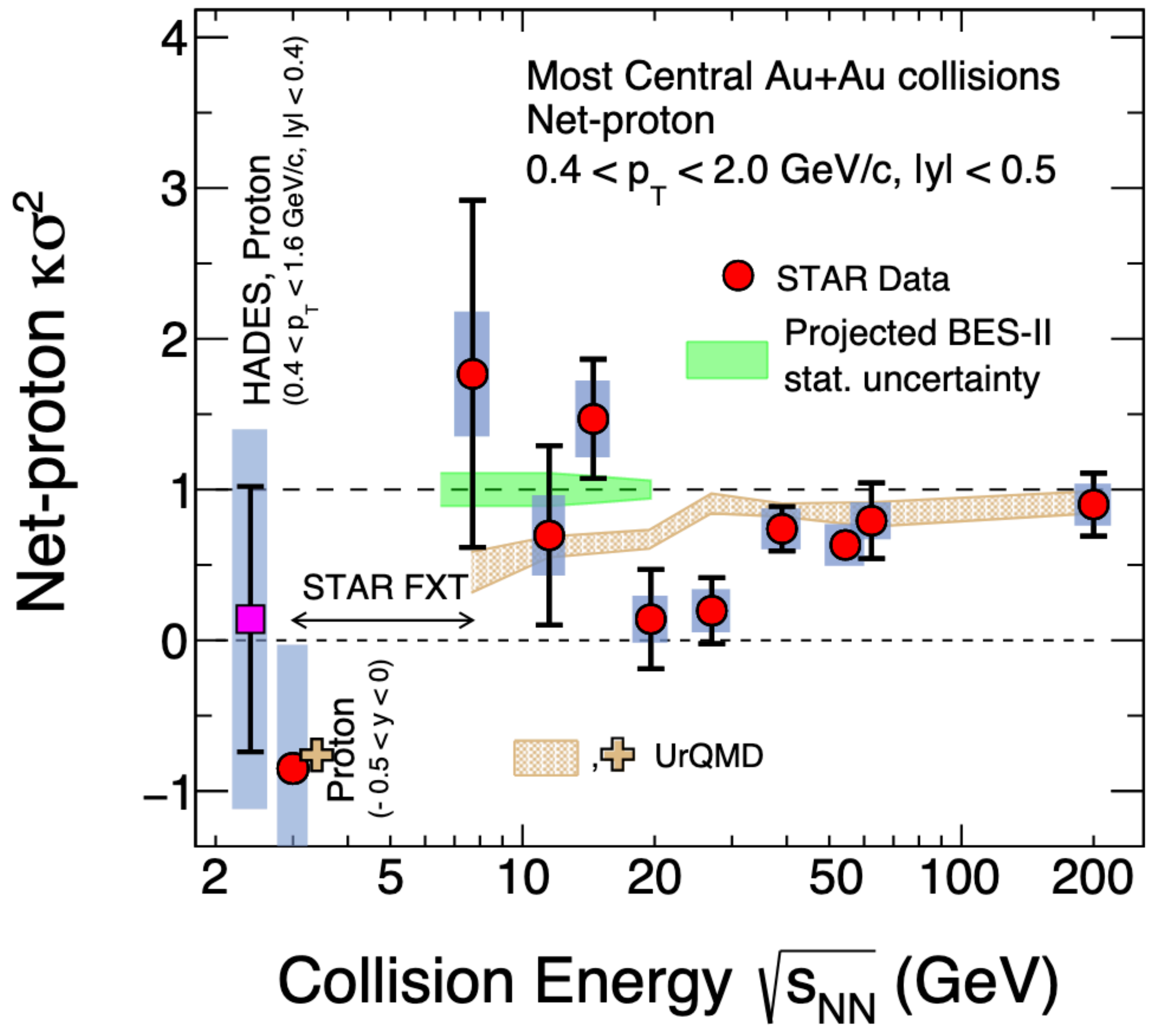
Enhanced p_T range → enhanced signal

Not seen in peripheral data

UrQMD (no Critical Point):

shows suppression at lower energies

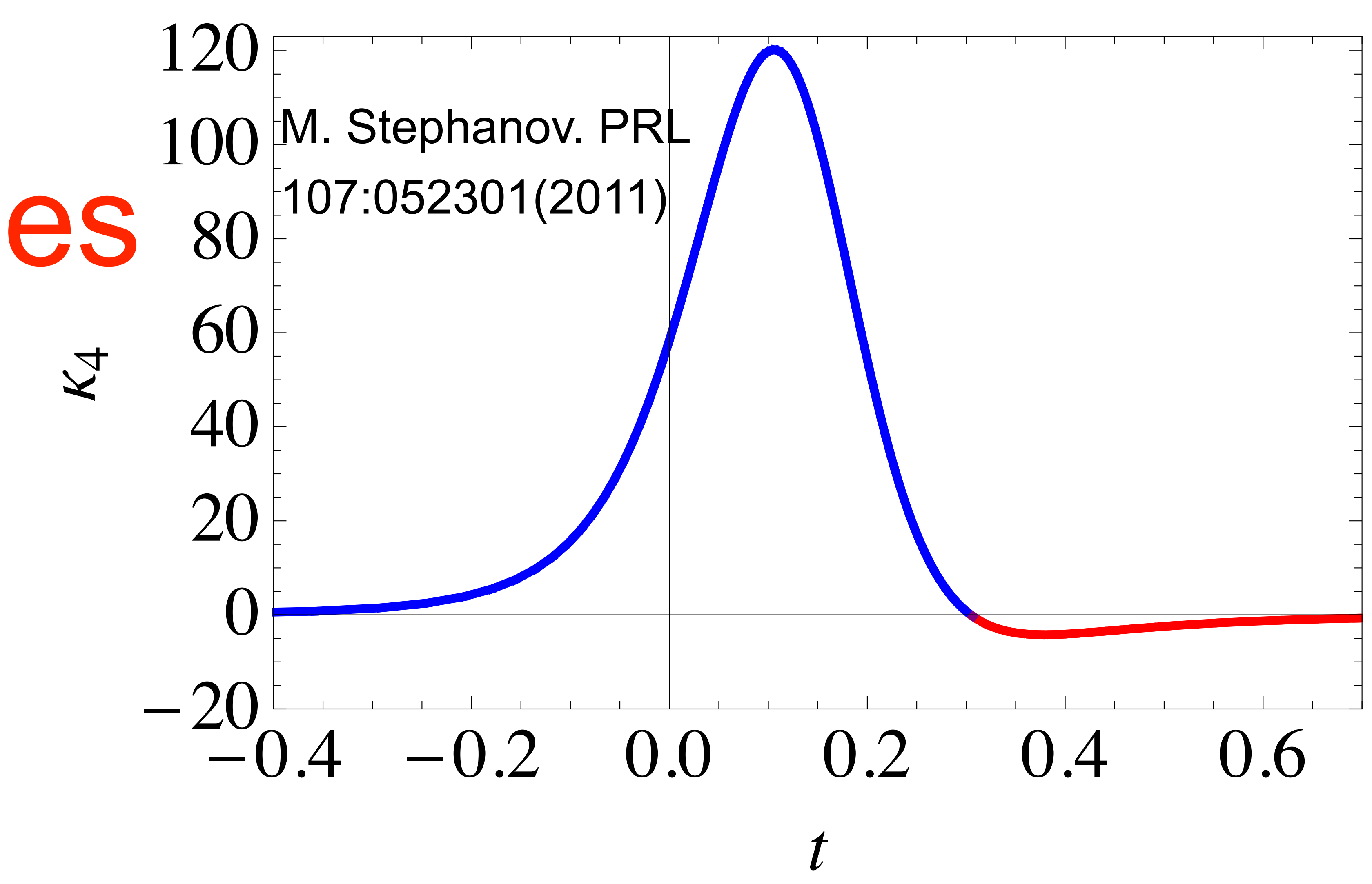
- due to baryon number conservation



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

Presence of Critical Point?

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



Top 5% central collisions:

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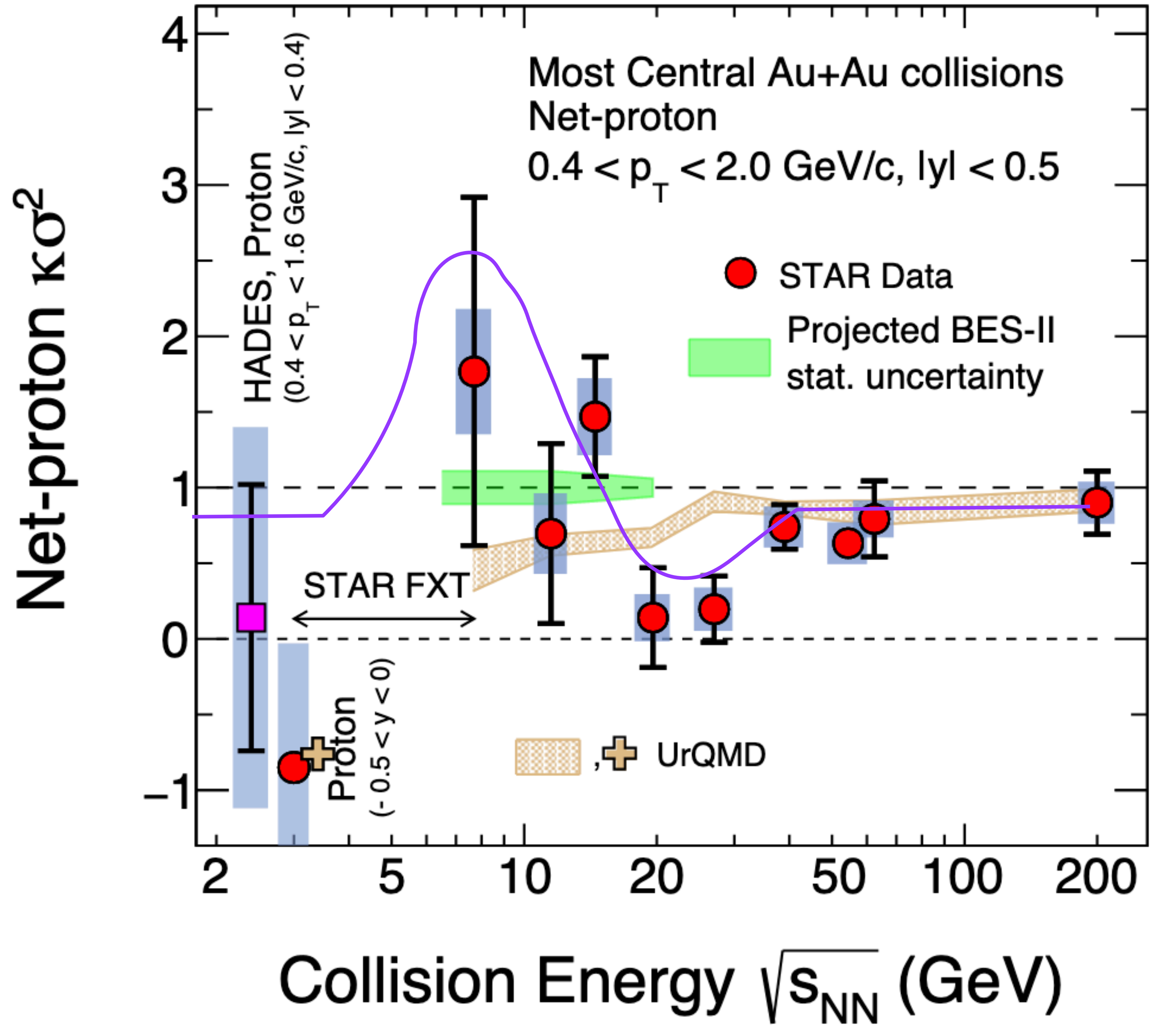
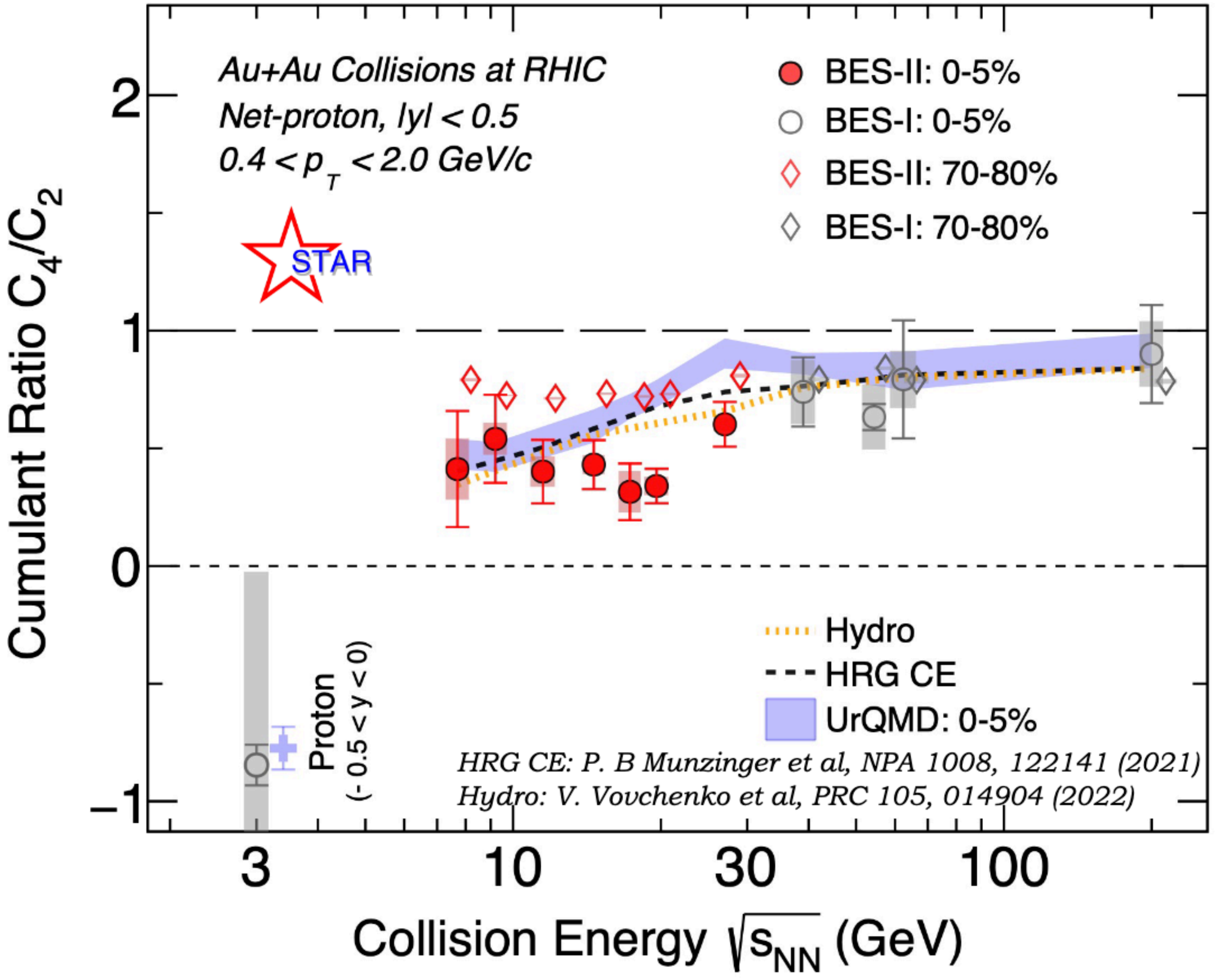
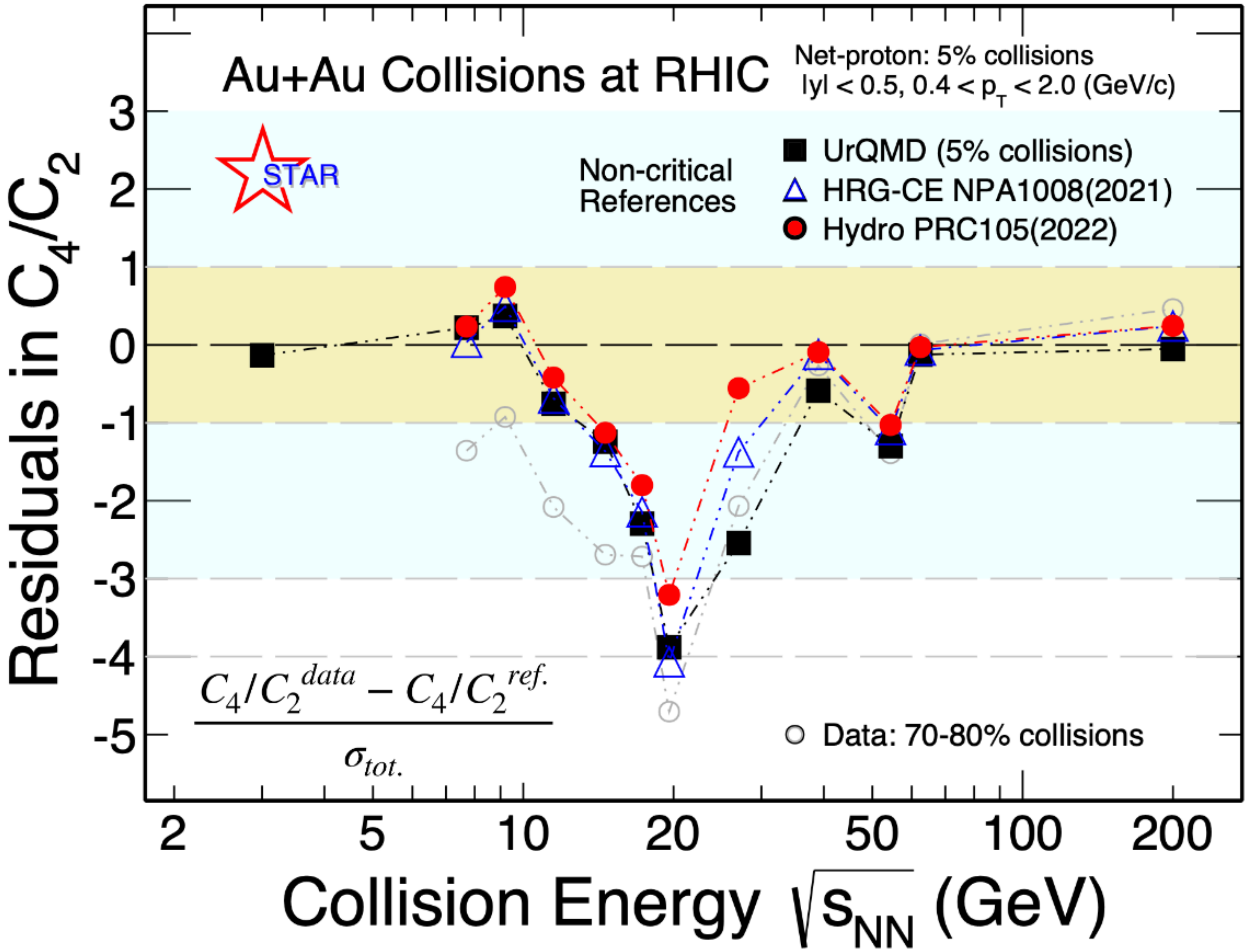
Hints of Critical fluctuations
More data needed



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

BES-II data released this month



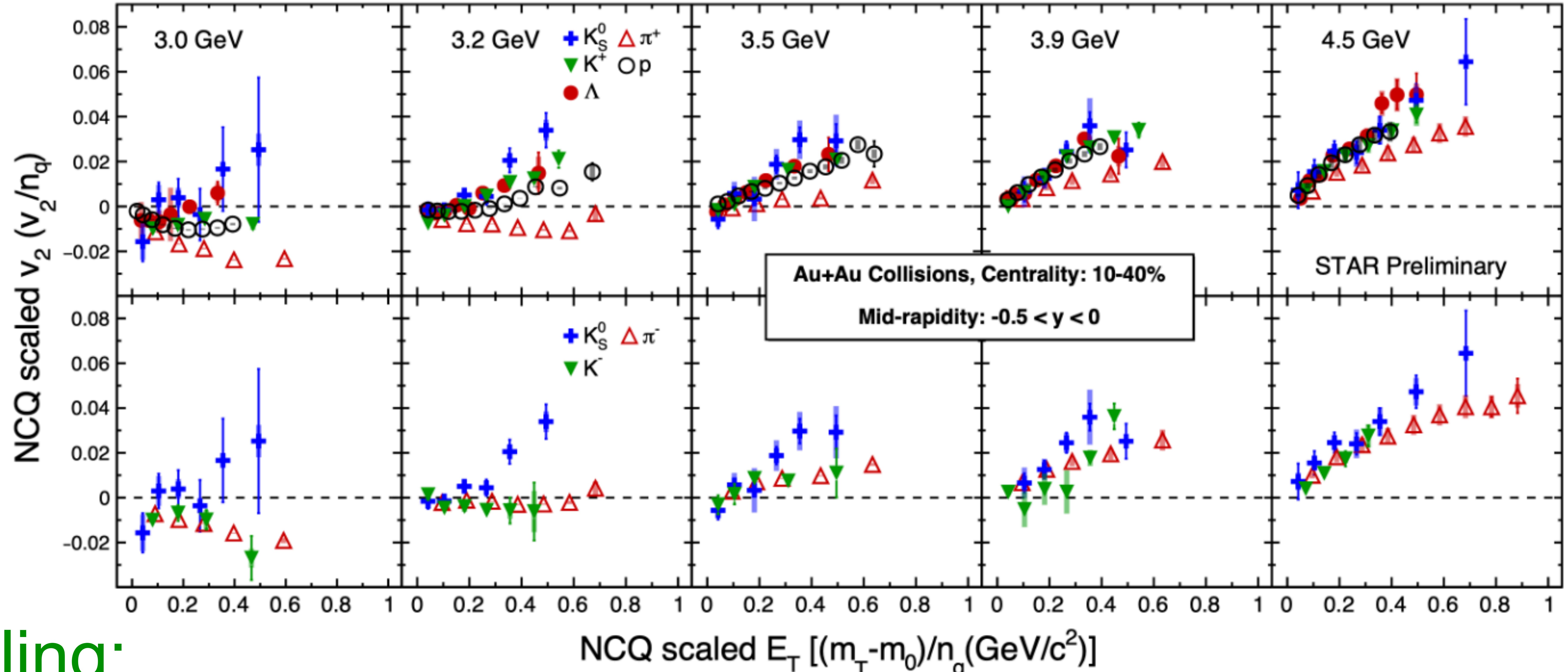


$\kappa\sigma^2$ (C_4/C_2) minimum around ~20 GeV comparing to non-CEP models and 70-80% data

Maximum deviation: $3.2 - 4.7\sigma$ at ~ 20 GeV

Disappearance of partonic collectivity

Hadronic interaction



Partonic collectivity

NCQ scaling:

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

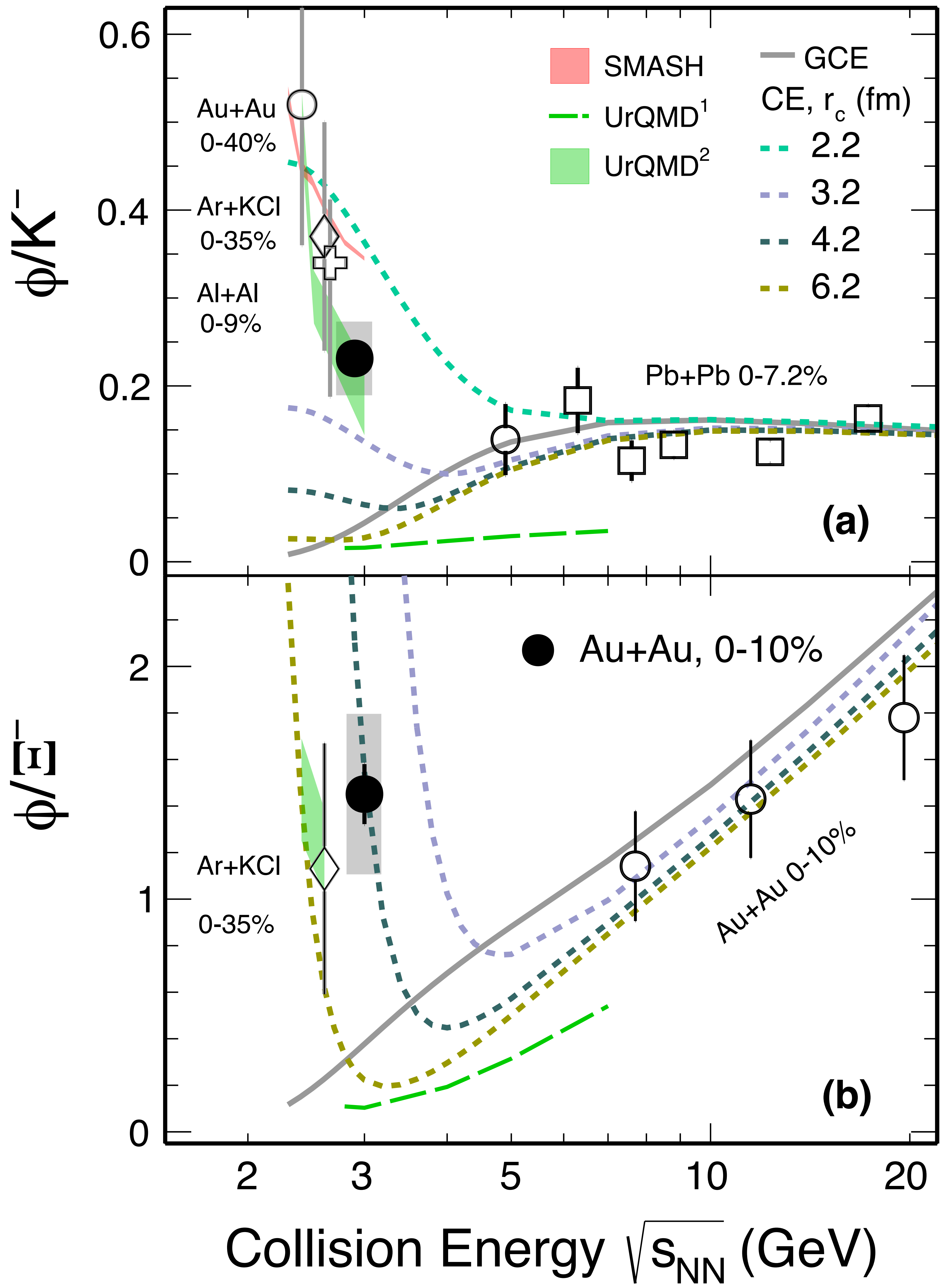
Gradually restores up to $\sqrt{s_{NN}}$ = 4.5 GeV

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

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

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

Probing (grand)canonical production



Things change at low $\sqrt{s_{NN}}$

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

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

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

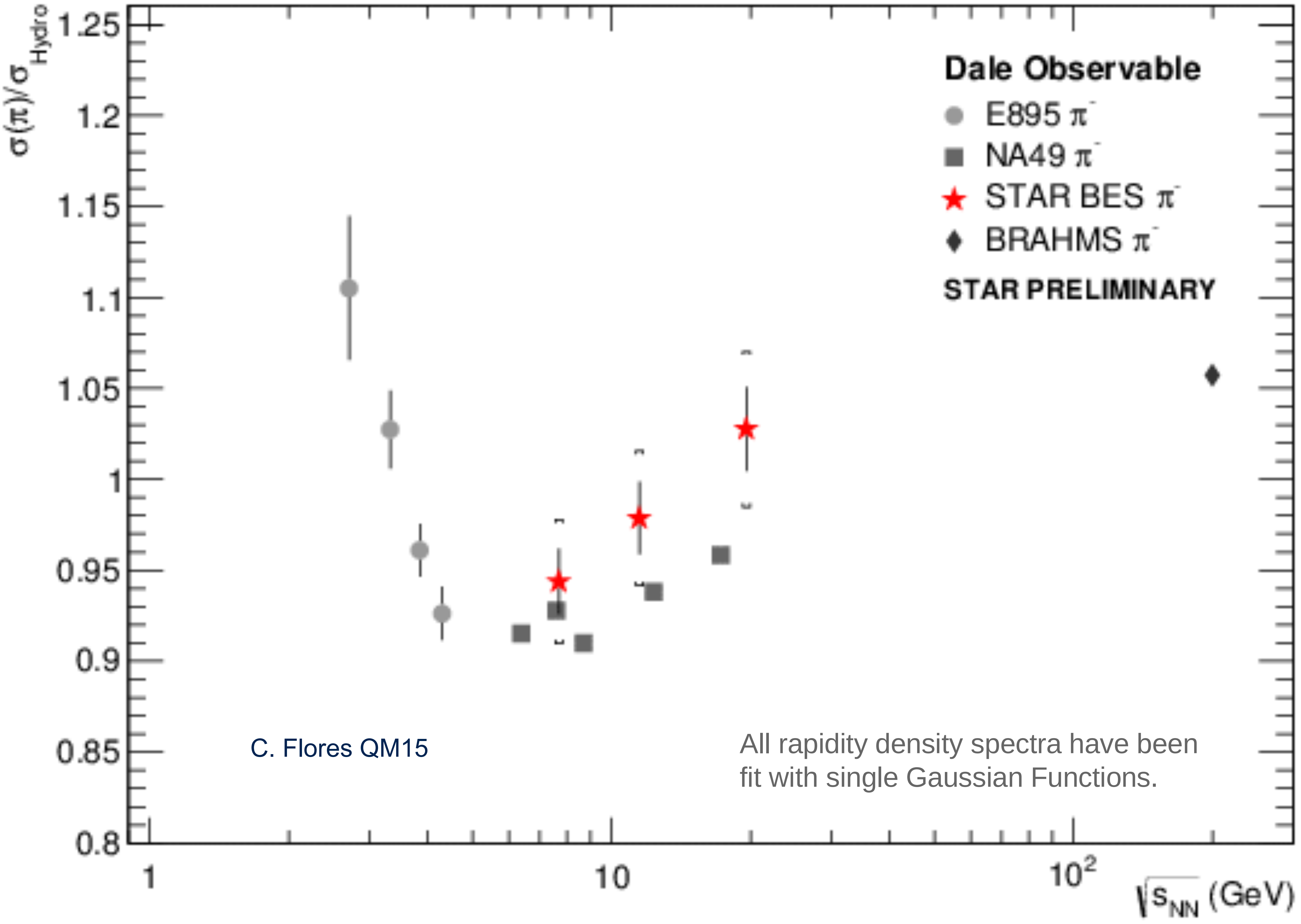
Minimum observed at √s = ~7 GeV

Minimum in the speed of sound?

$c_s^2 \sim 0.26$

Indication of softening of EoS?

Confirm c_s in other ways?



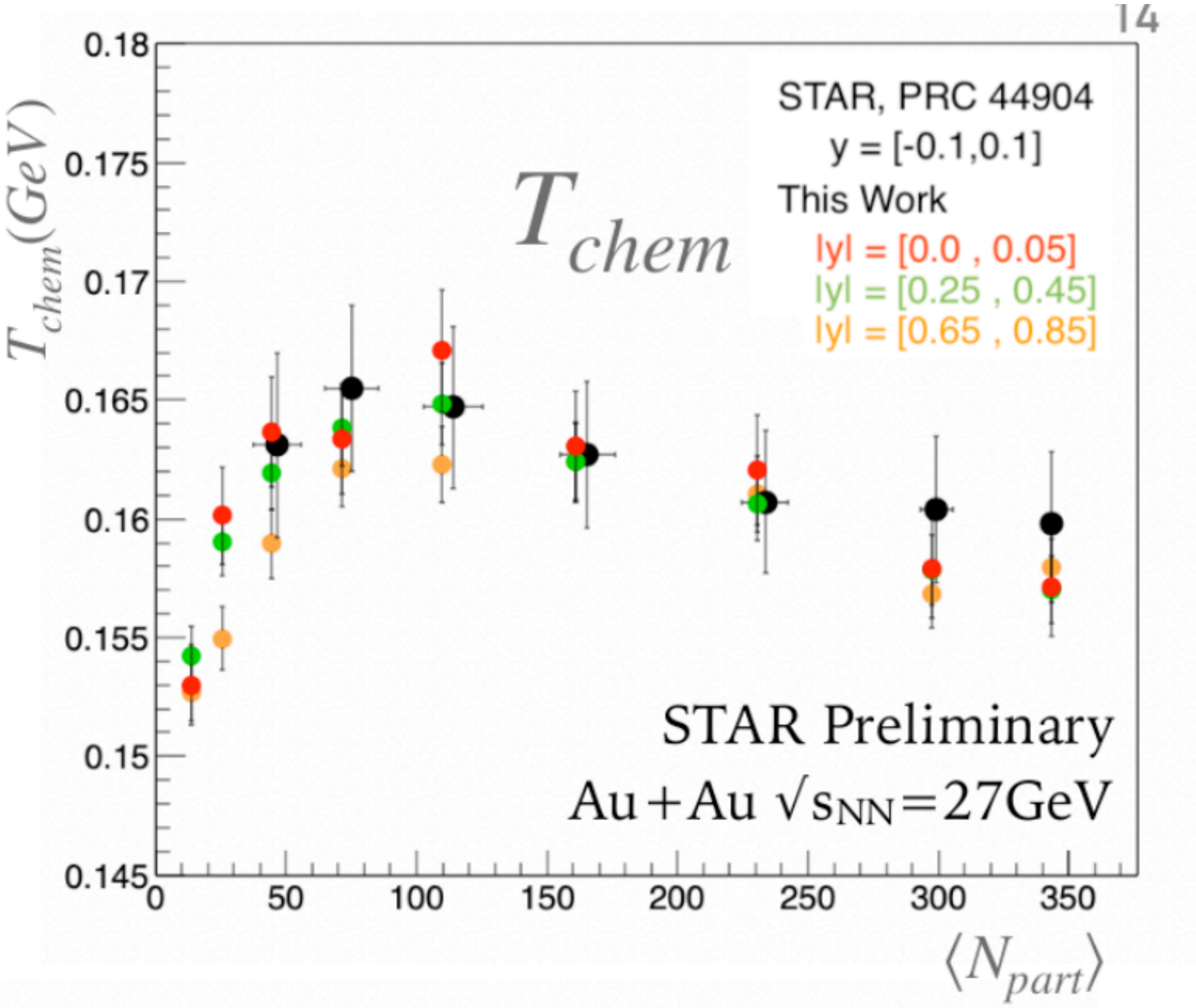
C. Flores QM15

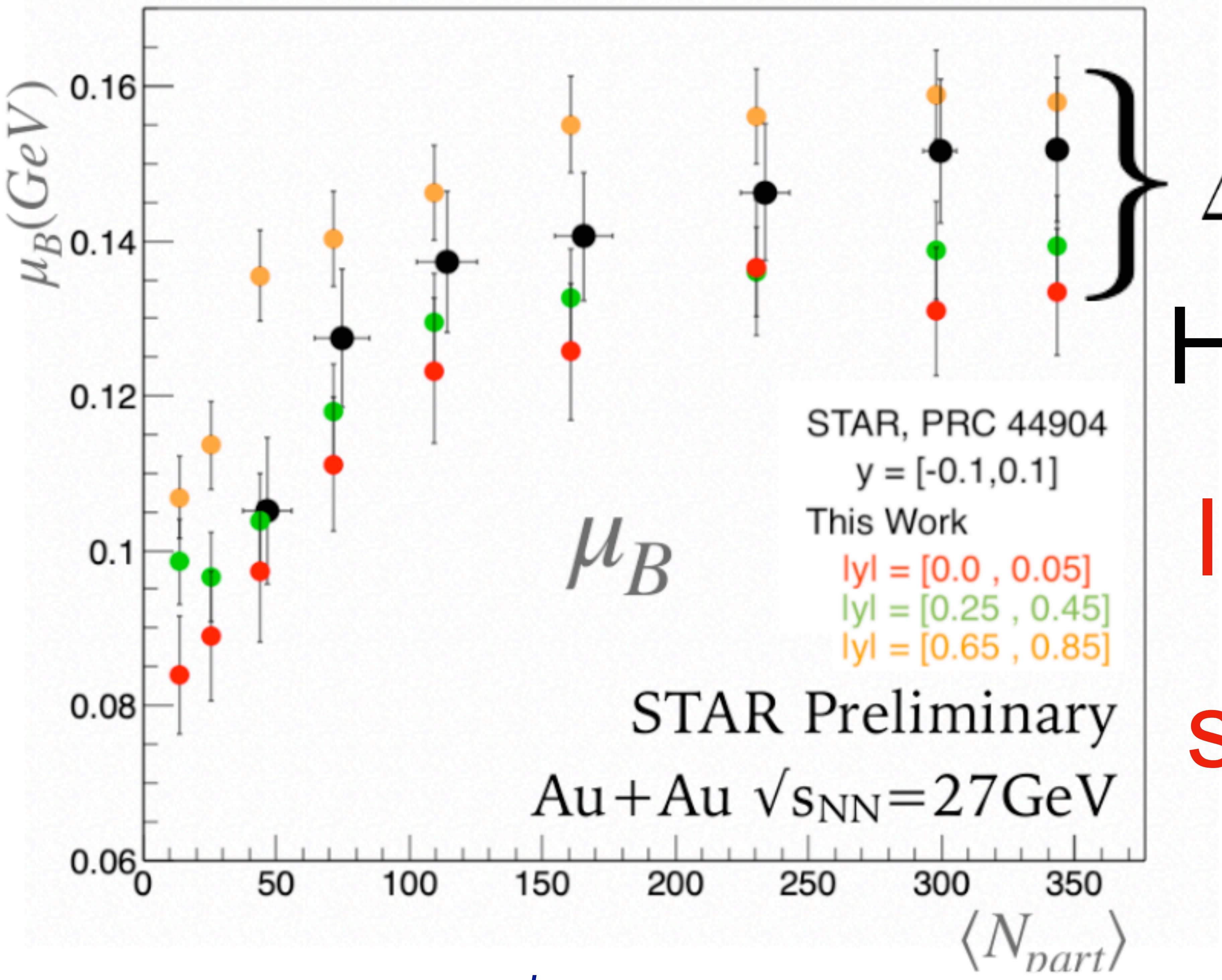
All rapidity density spectra have been fit with single Gaussian Functions.

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

Varying trajectory through the phase diagram?

With RHIC BES-II statistics and larger STAR 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?

Executive summary of bulk studies

Energy density of fireball way above that where hadrons can exist

Initial temperature of fireball way above that where hadrons can exist

We create a new state of matter in HI collisions - the QGP. Smooth transition from RHIC to LHC

QGP has quark and gluon degrees of freedom and flows like an almost "perfect" liquid, but there are significant hadronic final state interactions

No clear evidence yet for a Critical Point, but strong evidence that hadronic state dominates at low energies

Come back tomorrow to discuss more on how we are learning about the QGP from studying how partons interact with it?