夸克胶子等离子体实验进展

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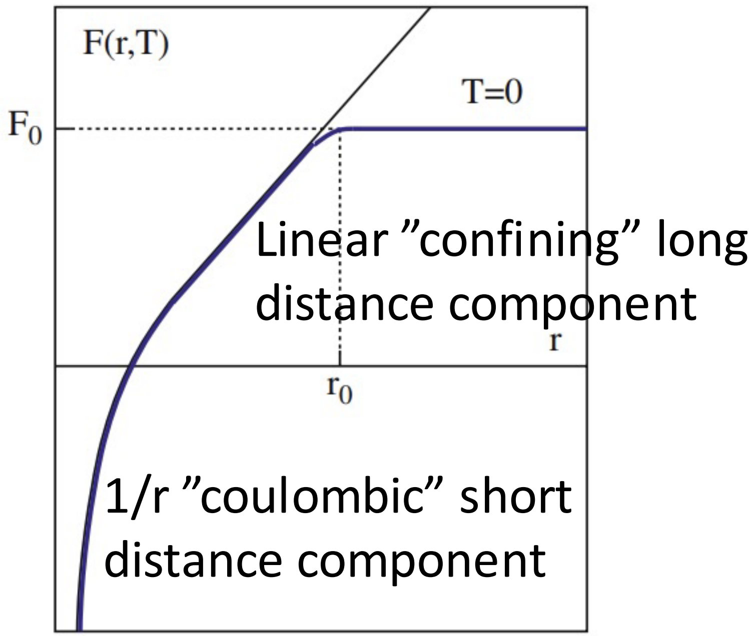
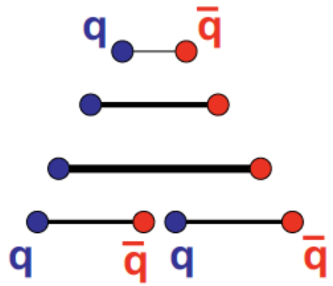
2025年8月12-13日

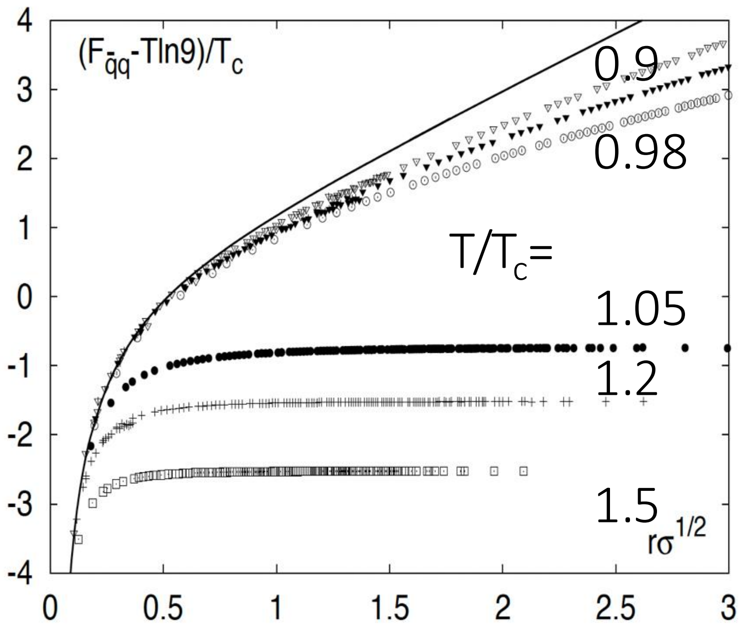
QED vs. QCD

	Electromagnetic interaction	Strong interaction
Theory	Quantum Electrodynamics (QED)	Quantum Chromodynamics (QCD)
Carrier	photon Charge neutral No self interaction	Gluon Carries color Self interaction
Coupling constant	$\alpha \sim 10^{-2}$ Increase with distance Perturbative	$\alpha_s \sim 1$ Decrease with distance Perturbative only at short distance

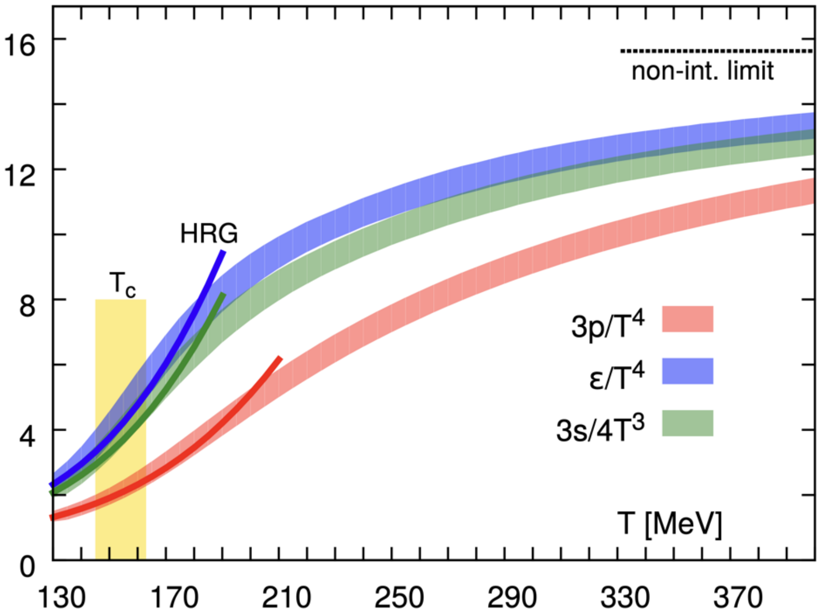
Confinement and Deconfinement







F. Karch, JPG30, S887 (2004)

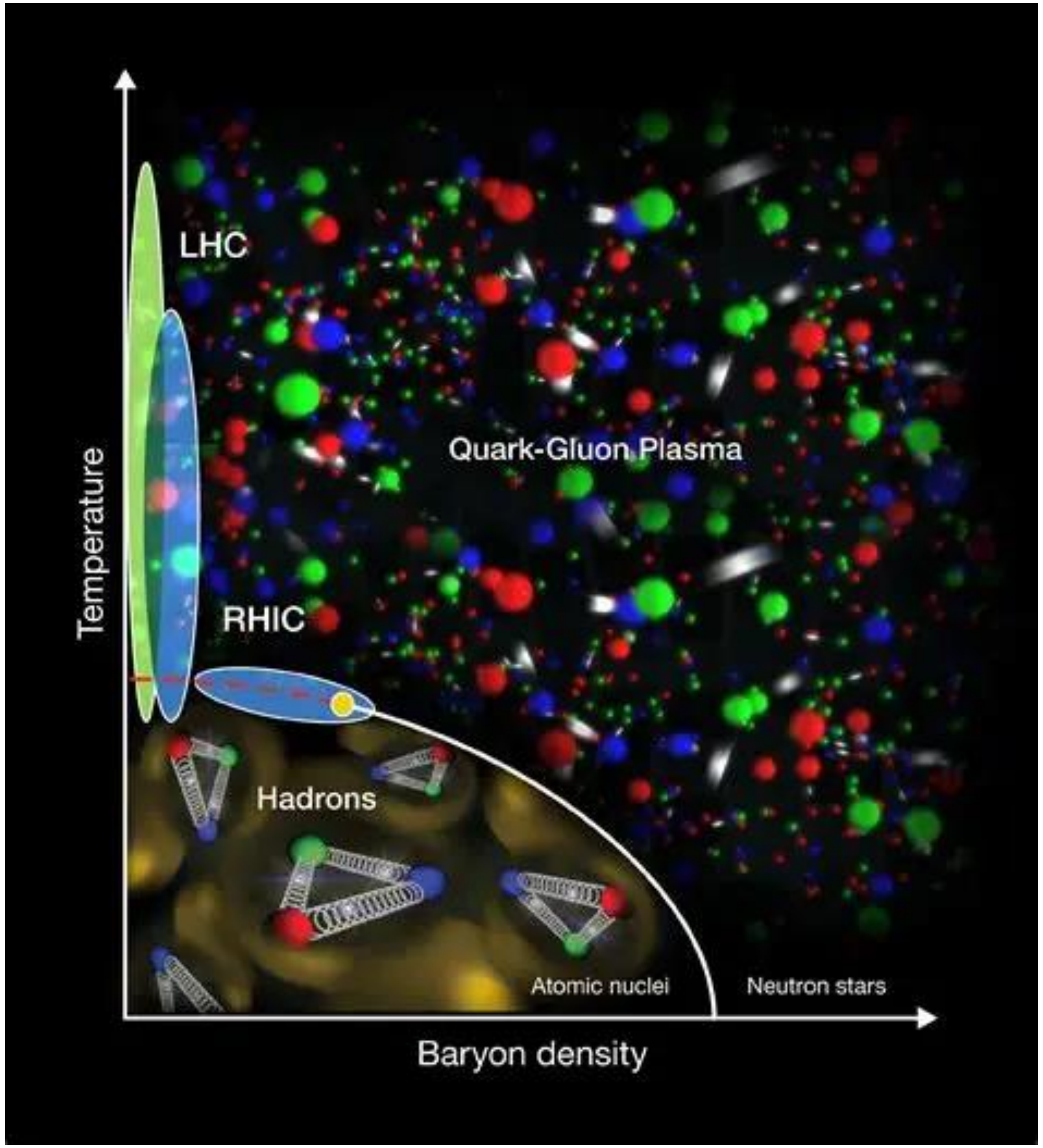


A. Bazavova et al., PLB795, 12 (2019)

Quarks are confined in hadrons
No free quarks

Lattice QCD predicts a phase transition at extremely high temperature T~155 MeV

Quark Gluon Plasma



Quarks are freed from nuclei/hadrons and Can move freely in relatively large volume

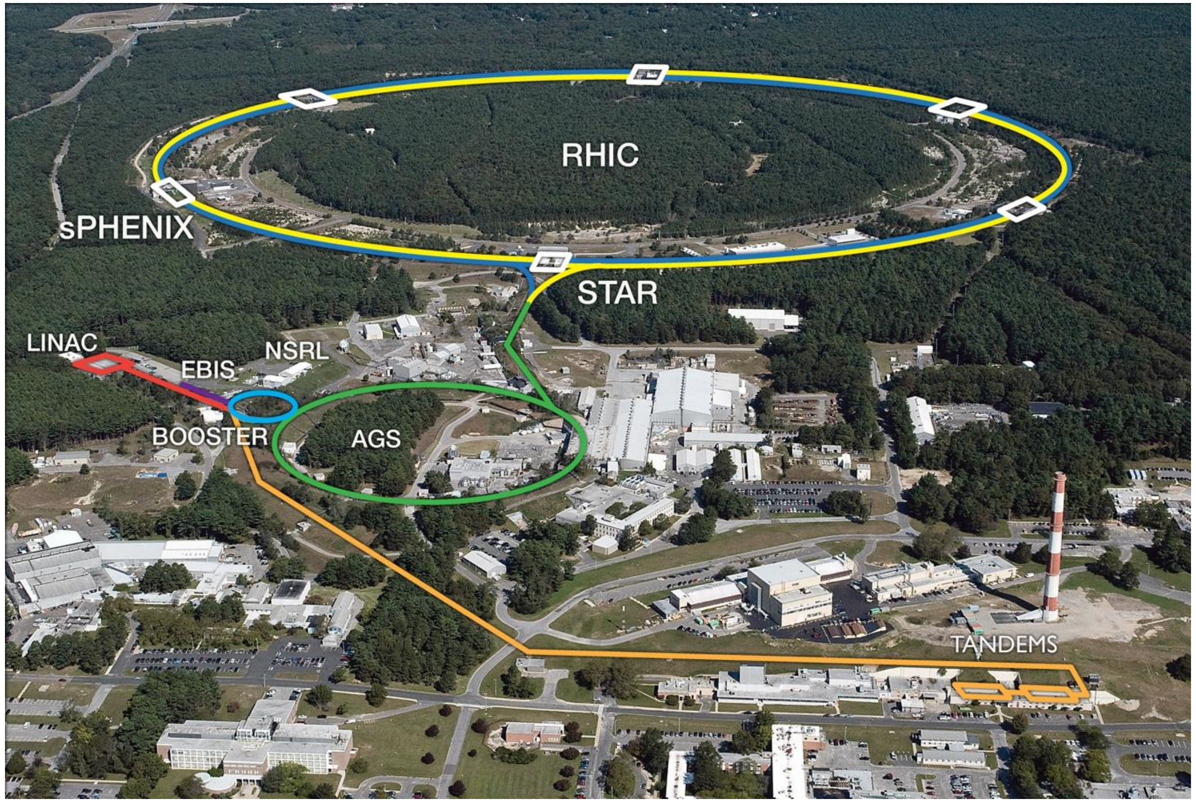
New form of matter
with partonic degree of freedom

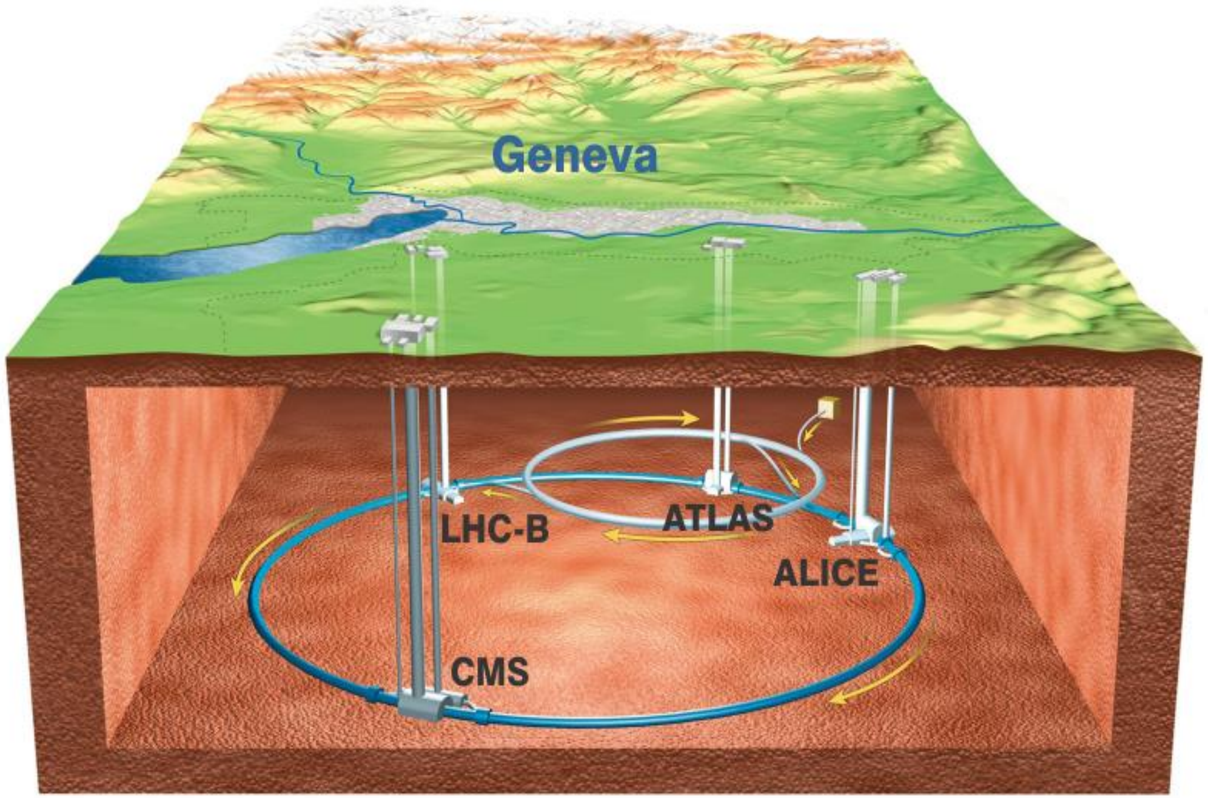
A test ground of QCD at non-perturbative region and its emergent property

It is believed that our Universe was in the form of QGP ~μs after the Big Bang

It is proposed to search for and study its properties in laboratory via heavy ion collisions at high energy

Running Large Experiments





Relativistic Heavy Ion Collider (RHIC)

@Brookhaven National Laboratory, New York

From p+p to Au+Au, $\sqrt{s_{NN}}$ upto 200 GeV

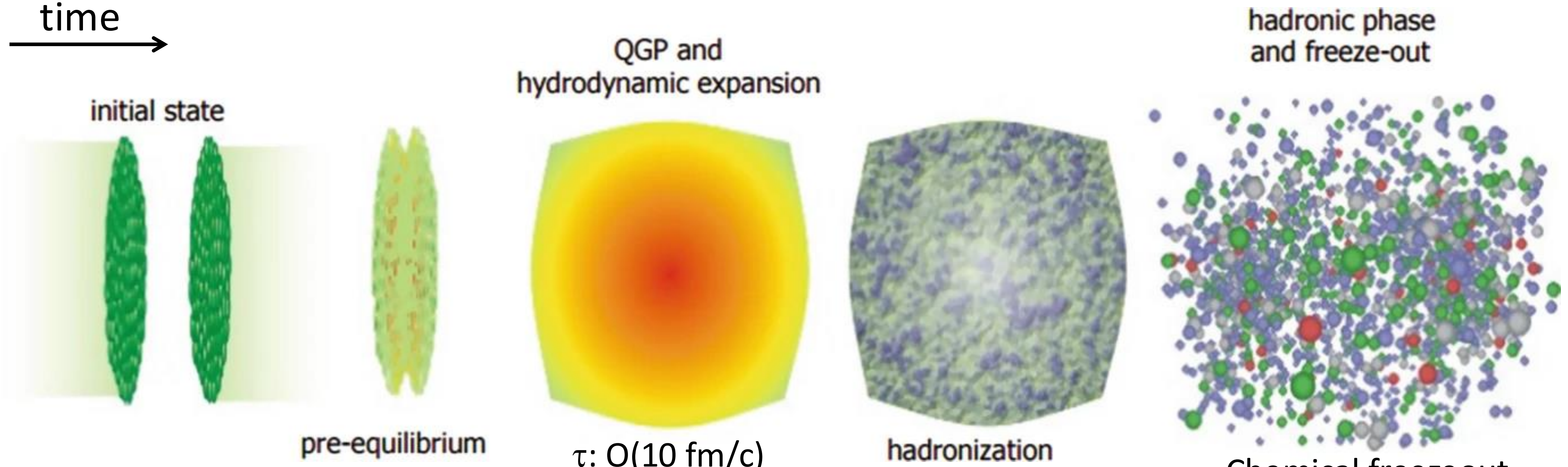
Large Hadron Collider (LHC)

@CERN, Geneva

From p+p to Pb+Pb, $\sqrt{s_{NN}}$ upto 5360 GeV

Evolution of Heavy Ion Collision

time →

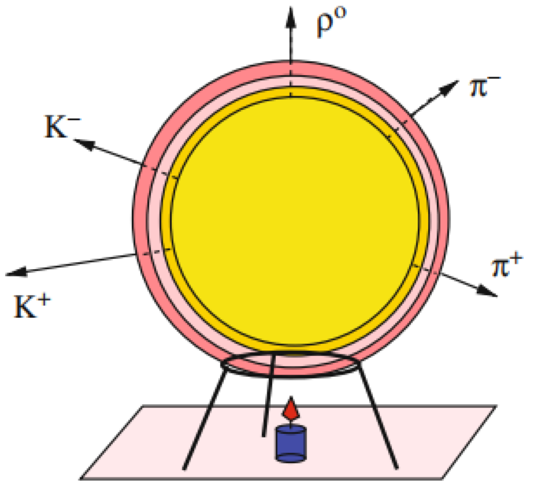


τ: O(10 fm/c)

Chemical freezeout
Kinetic freezeout

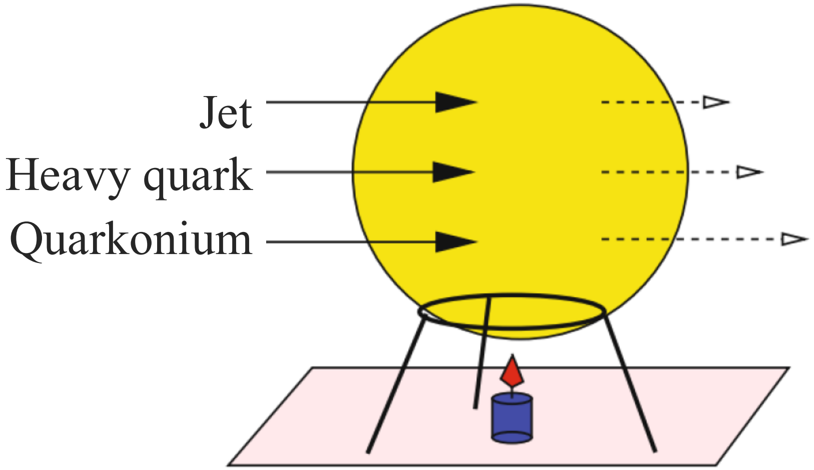
What we can control → What we want to study ← What we can measure

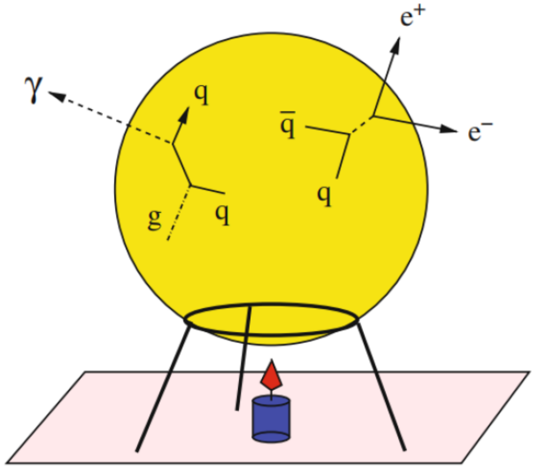
Probes



Hadron radiation:

- Chemistry
- Thermodynamics
- Collective motion





Electromagnetic radiation:

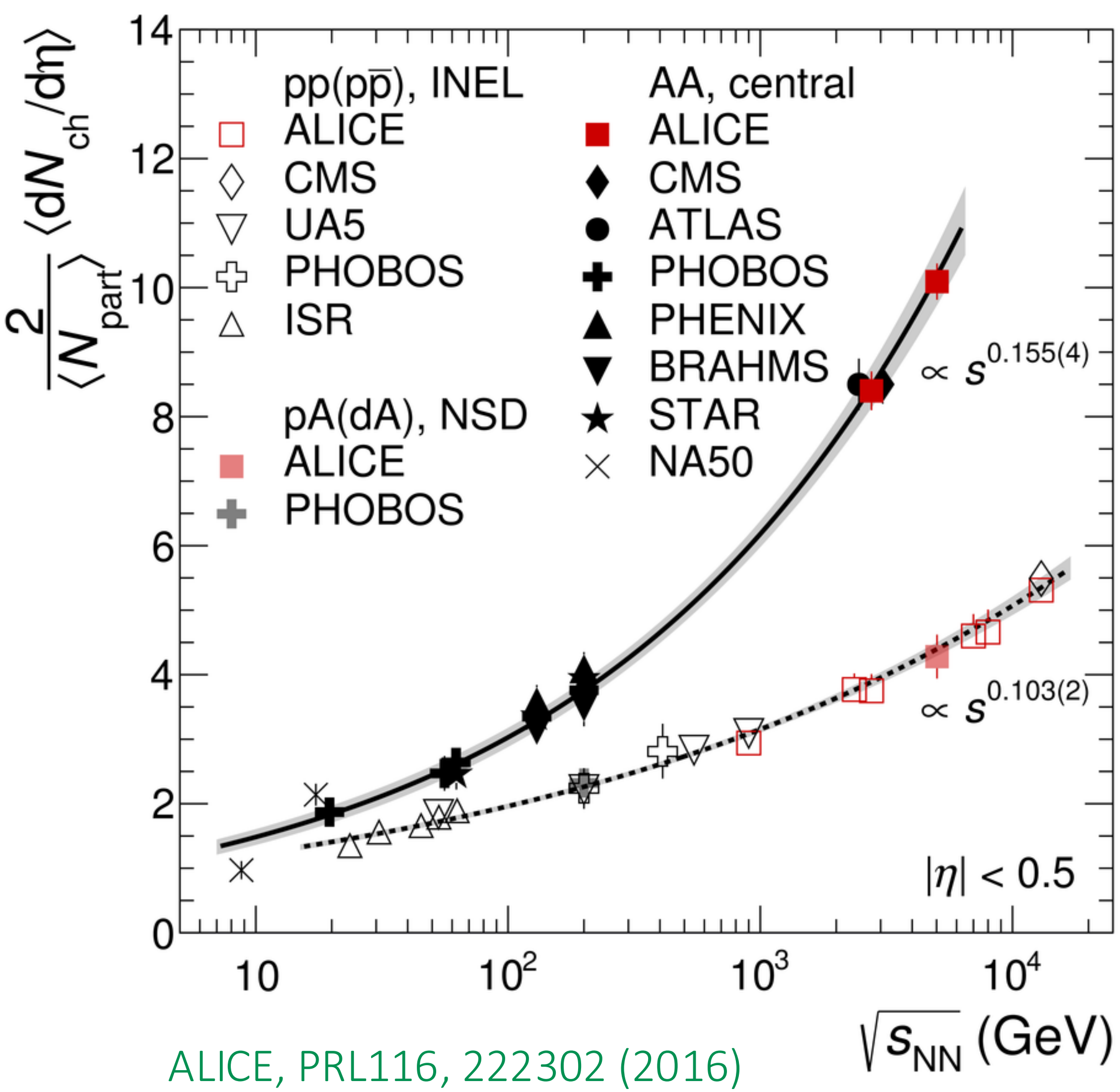
- “PET” scan of QGP
- QGP thermal radiation
- Chiral symmetry restoration

Hard probe transport:

- “CT” scan of QGP
- Transport properties
- Hadronization mechanism

Temperature

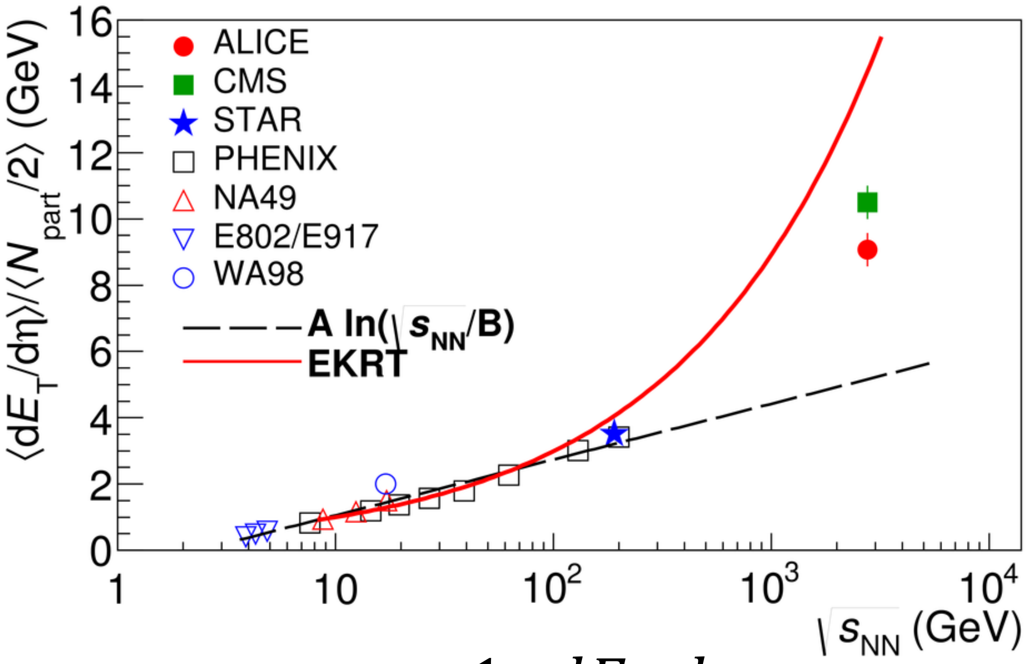
Charged-Particle Multiplicity

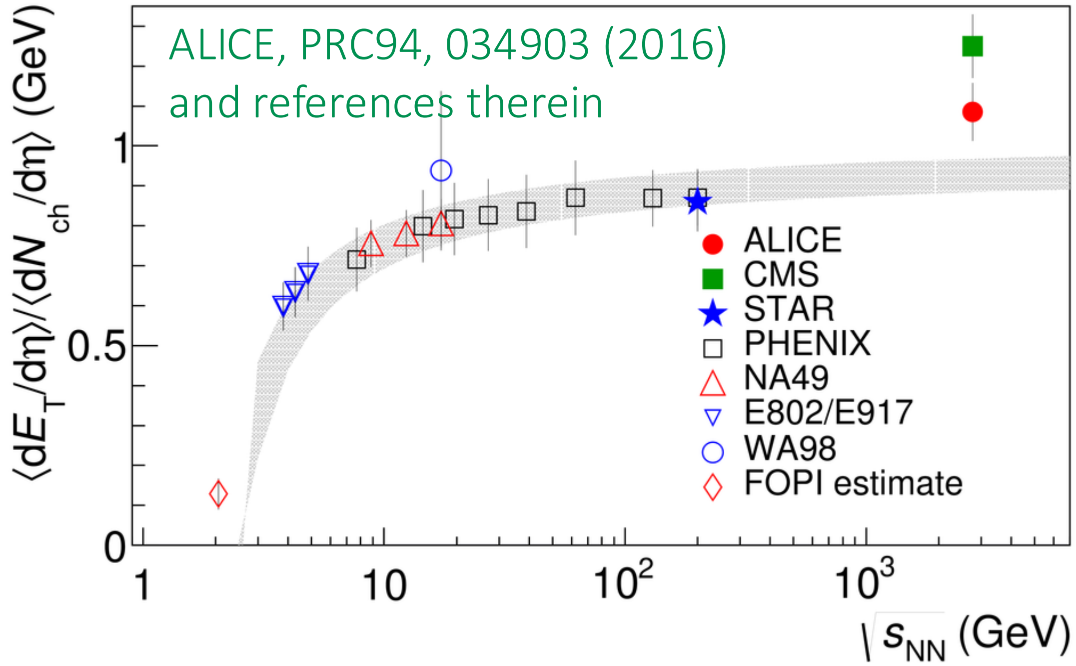


ALICE, PRL116, 222302 (2016)

Charged particle produced per participating nucleons are significantly higher in heavy ion collisions than in p+p and p+A collisions

Transverse Energy Density





$$\epsilon_{BJ} = \frac{1}{A\tau_0}\frac{dE_T}{d\eta}\frac{d\eta}{dy}$$

$$\epsilon_{BJ}(\mathrm{PbPb@2.76\ TeV}) \sim 14.5\ \mathrm{GeV/fm^3}$$

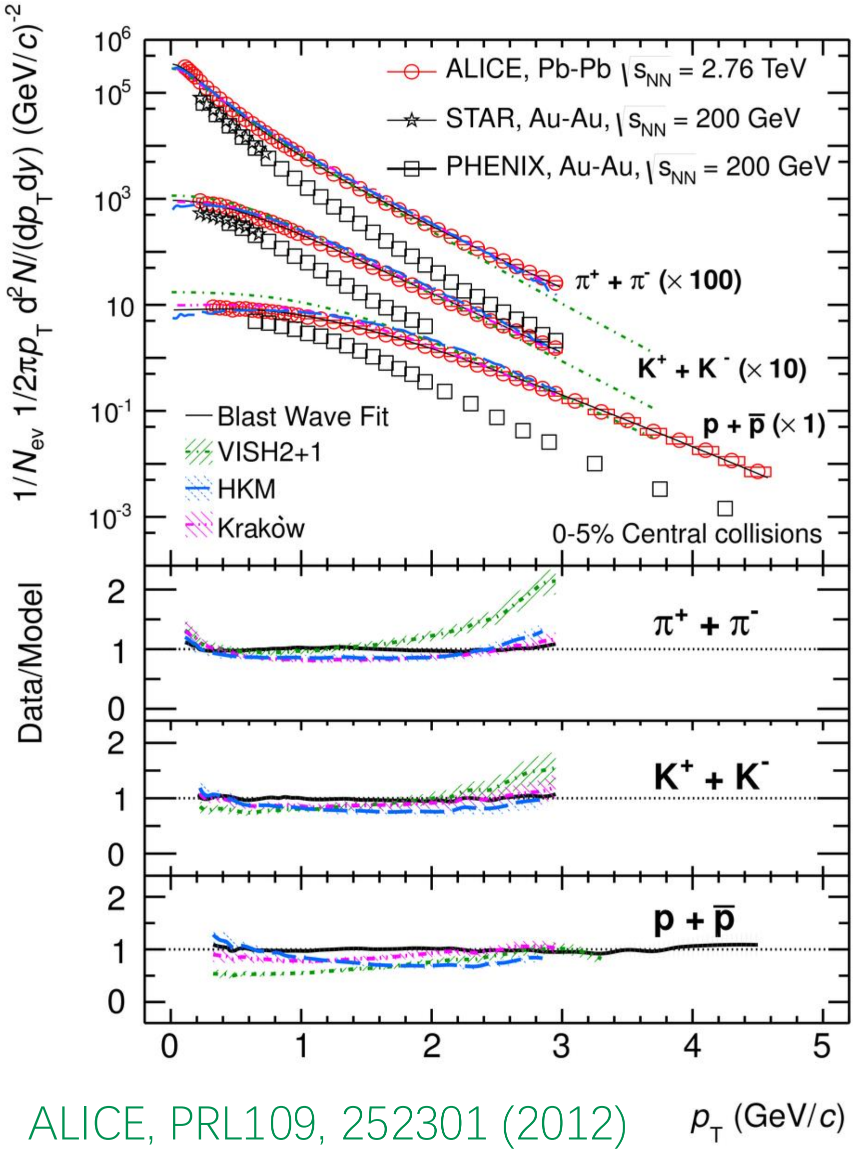
$\gg \epsilon_c$

$$\epsilon = 37\frac{\pi^2}{30}T^4 \rightarrow T \sim 300\ MeV$$

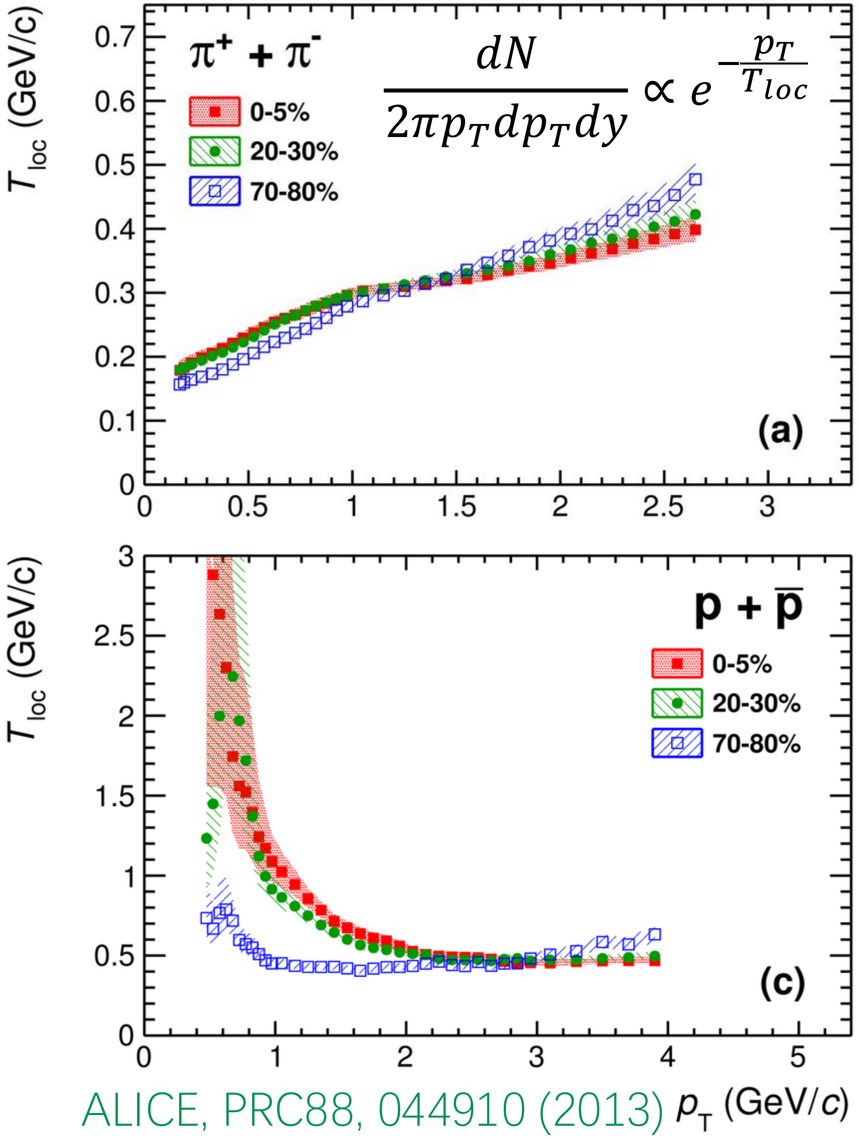
$\sim 2 \times\ T_c$

P. Braun-Munzinger, K. Redlich, and J. Stachel, arXiv:2506.04733

Transverse Momentum Distribution for Hadrons

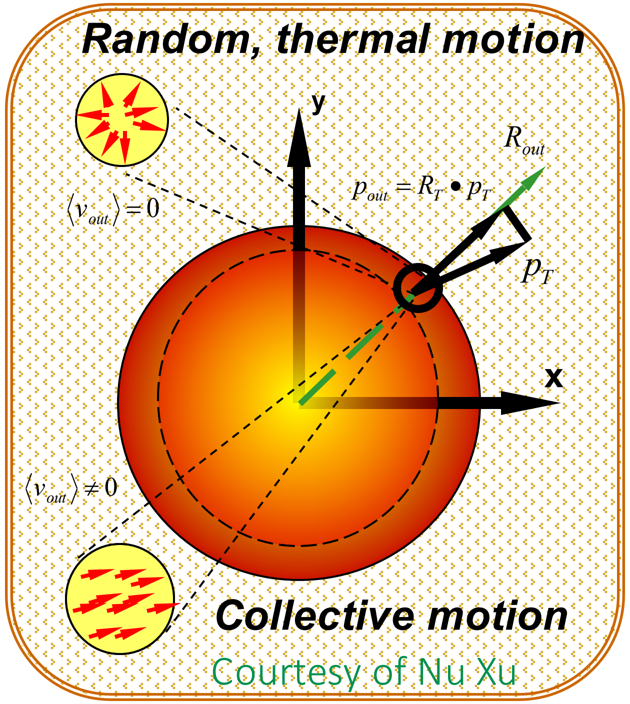


ALICE, PRL109, 252301 (2012)



ALICE, PRC88, 044910 (2013)

Kinetic Freezeout Temperature

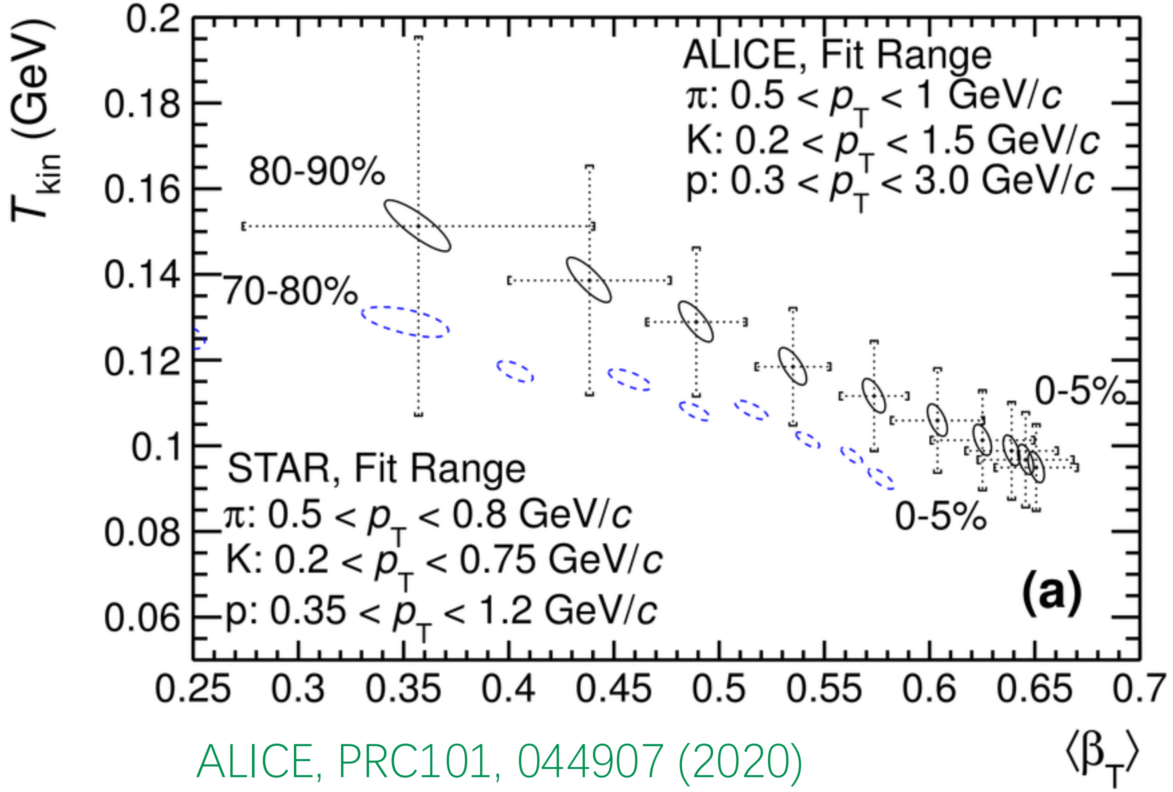


$$E\frac{d^3N}{dp^3} \propto \int_\sigma e^{-(u^\mu p_\mu)/T_{fo}}\, p\, d\sigma_\mu \Rightarrow$$ Blast Wave Model

$$\frac{dN}{m_T dm_T} \propto \int_0^R r\,dr\,m_T K_1\left(\frac{m_T\cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T\sinh\rho}{T_{fo}}\right)$$

$$\rho = \tanh^{-1}\beta_r \qquad \beta_r = \beta_S\left(\frac{r}{R}\right)^\alpha \qquad \alpha = 0.5, 1, 2$$

E. Schnedermann, J. Sollfrank and U. Heinz, PRC48, 2462 (1993)

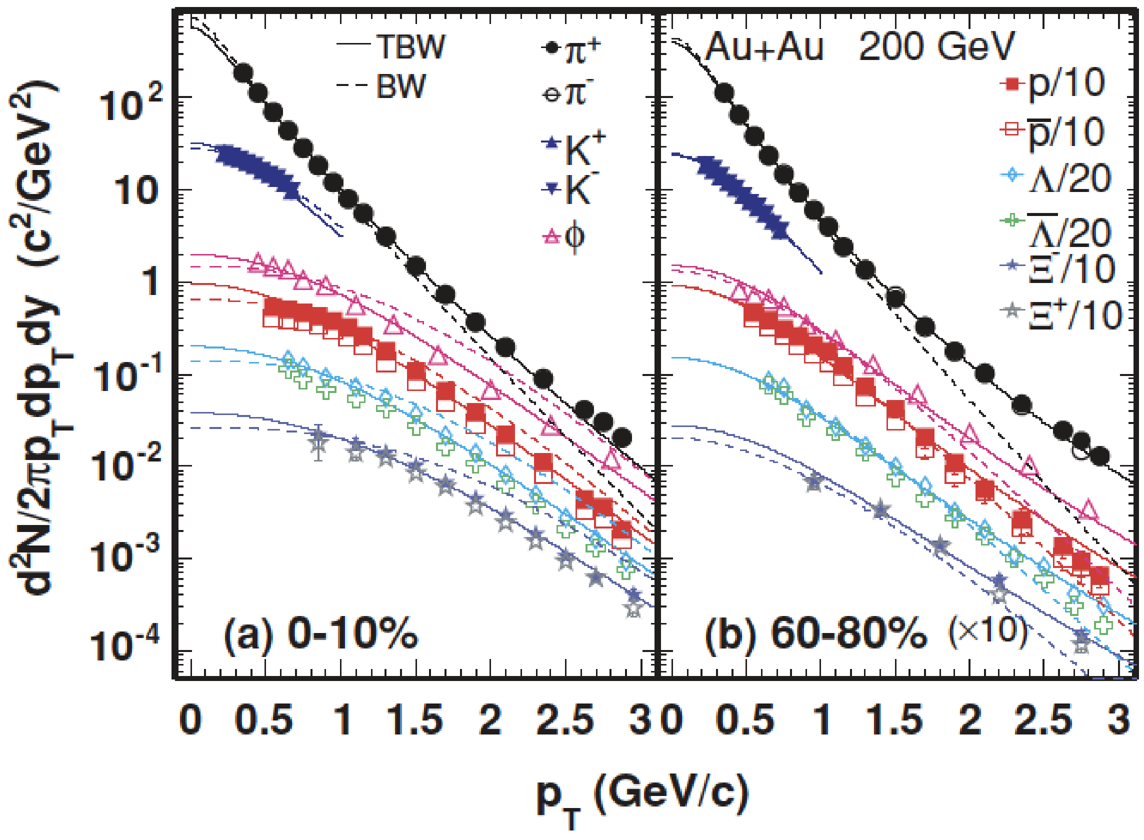


ALICE, PRC101, 044907 (2020)

- Collective expansion with velocity up to 0.65c
- Cools to kinetic (thermal) freezeout temperature of ~100 MeV
- Higher energy, larger velocity and higher T_{kin}

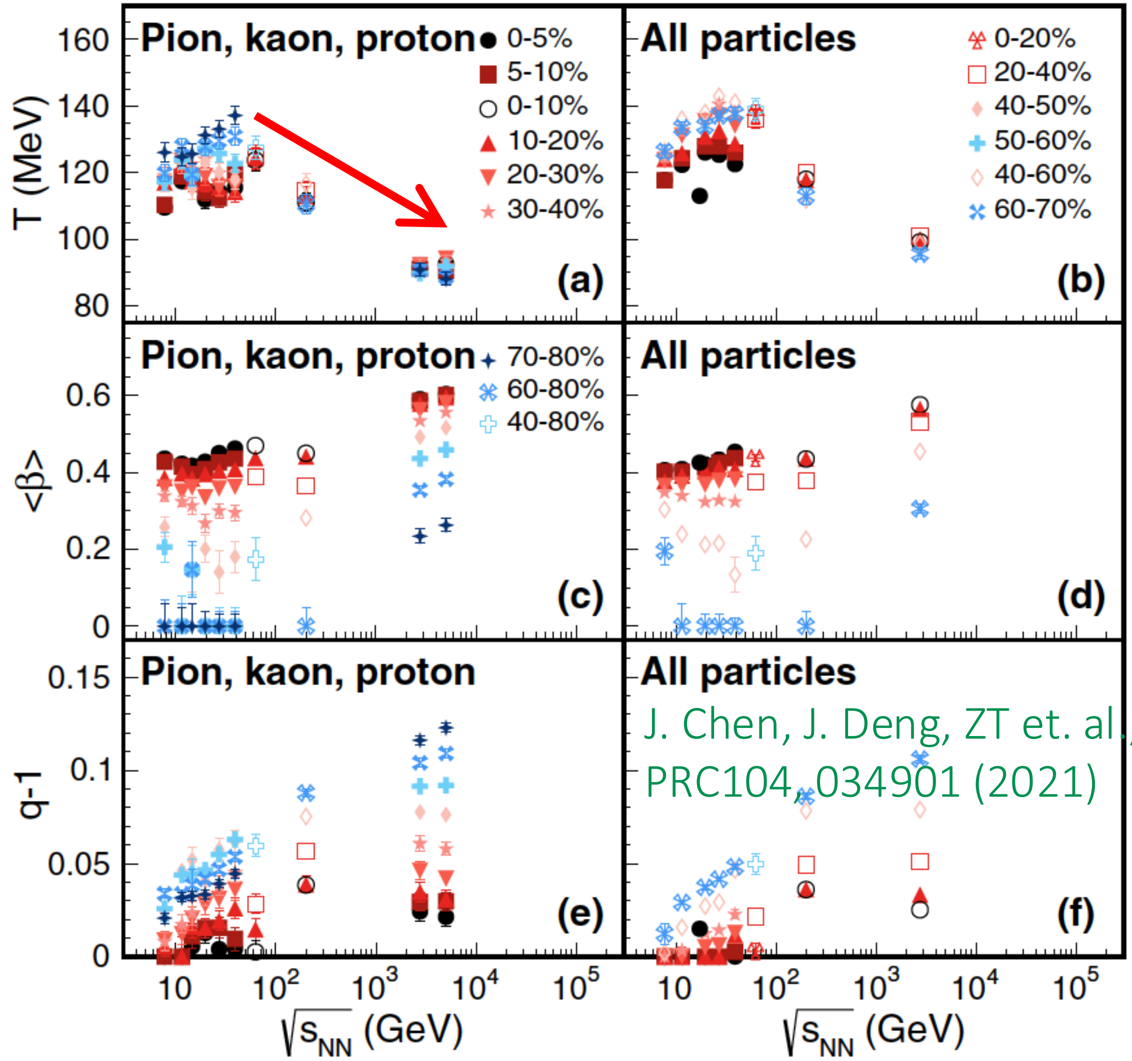
Tsallis Blast Wave Model

Introduce non-extensive Tsallis statistics to account for fluctuation/non-equilibrium



ZT, Y. Xu, L. Ruan et. al., PRC79, 051901(R) (2009)

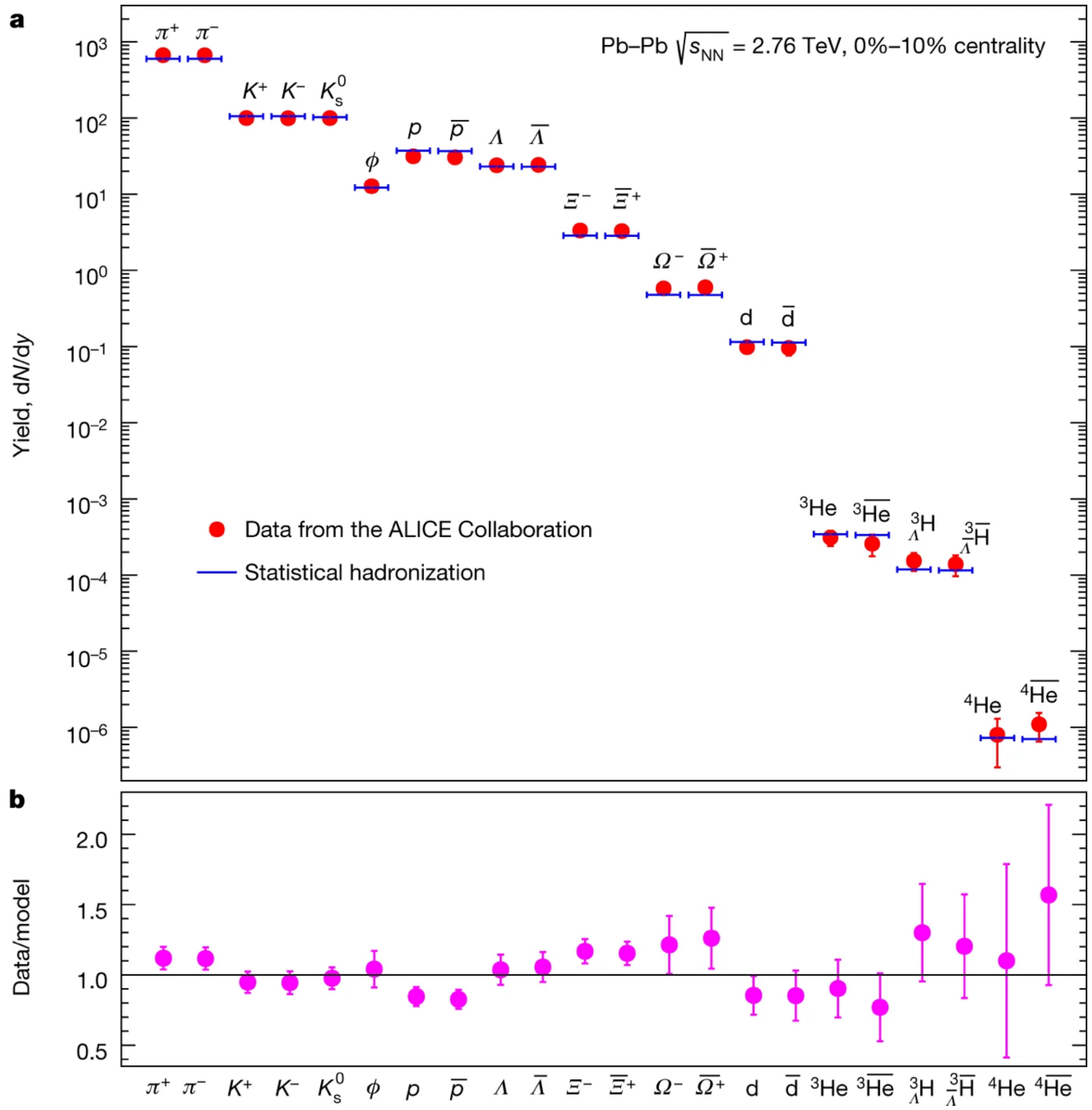
Cited by 228 times



J. Chen, J. Deng, ZT et. al., PRC104, 034901 (2021)

Decrease with increasing energy at RHIC and LHC

Chemical Freezeout Temperature



Thermal model:

$$N_i = V\frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{(E_i-\mu_B B_i-\mu_S S_i-\mu_3 I_{3i})/T} \pm 1}$$

Describe yield with 3 free parameters for

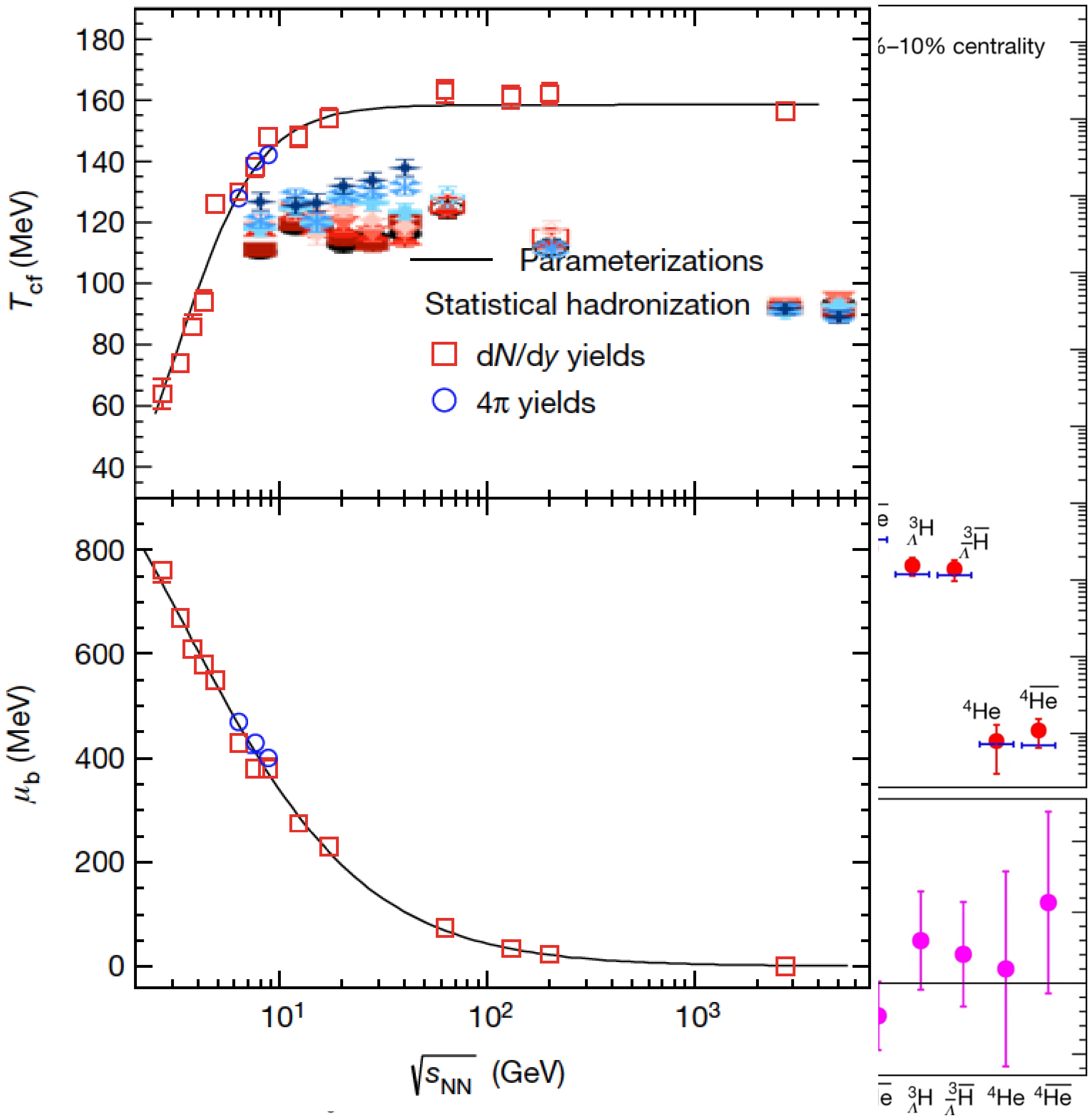
- 22 particle species
- 9 orders of magnitude difference

T_{cf} = 156.5 ± 1.5 MeV

μ_B = 0.7 ± 3.8 MeV

V = 5280 ± 410 fm^3

Chemical Freezeout Temperature



Thermal model:

$$N_i = V\frac{g_i}{2\pi^2}\int\frac{p^2dp}{e^{(E_i-\mu_B B_i-\mu_S S_i-\mu_3 I_{3i})/T}\pm 1}$$

Describe yield with 3 free parameters for

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- 9 orders of magnitude difference

T_{cf} = 156.5 ± 1.5 MeV

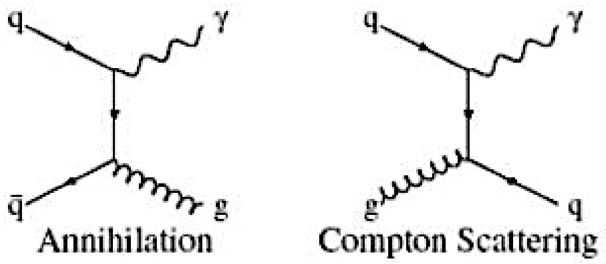
μ_b = 0.7 ± 3.8 MeV

V = 5280 ± 410 fm

Direct Photon

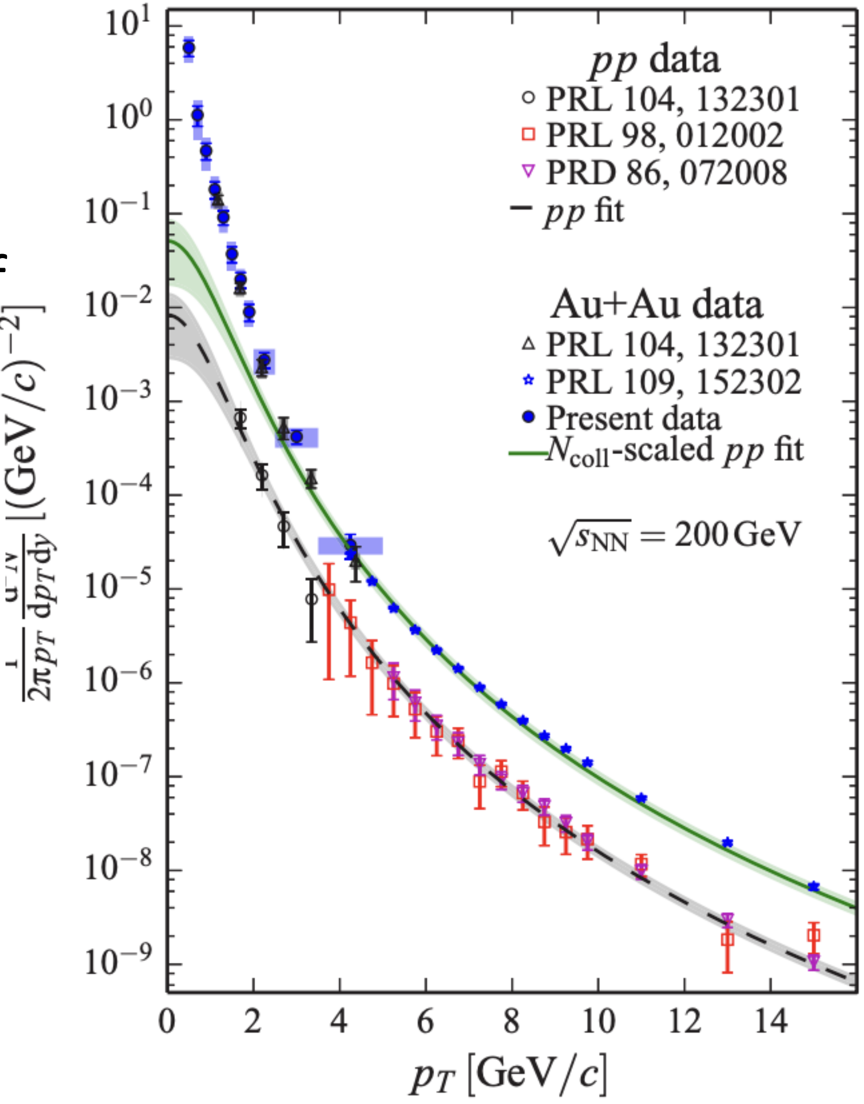
Photons do not interact with the system

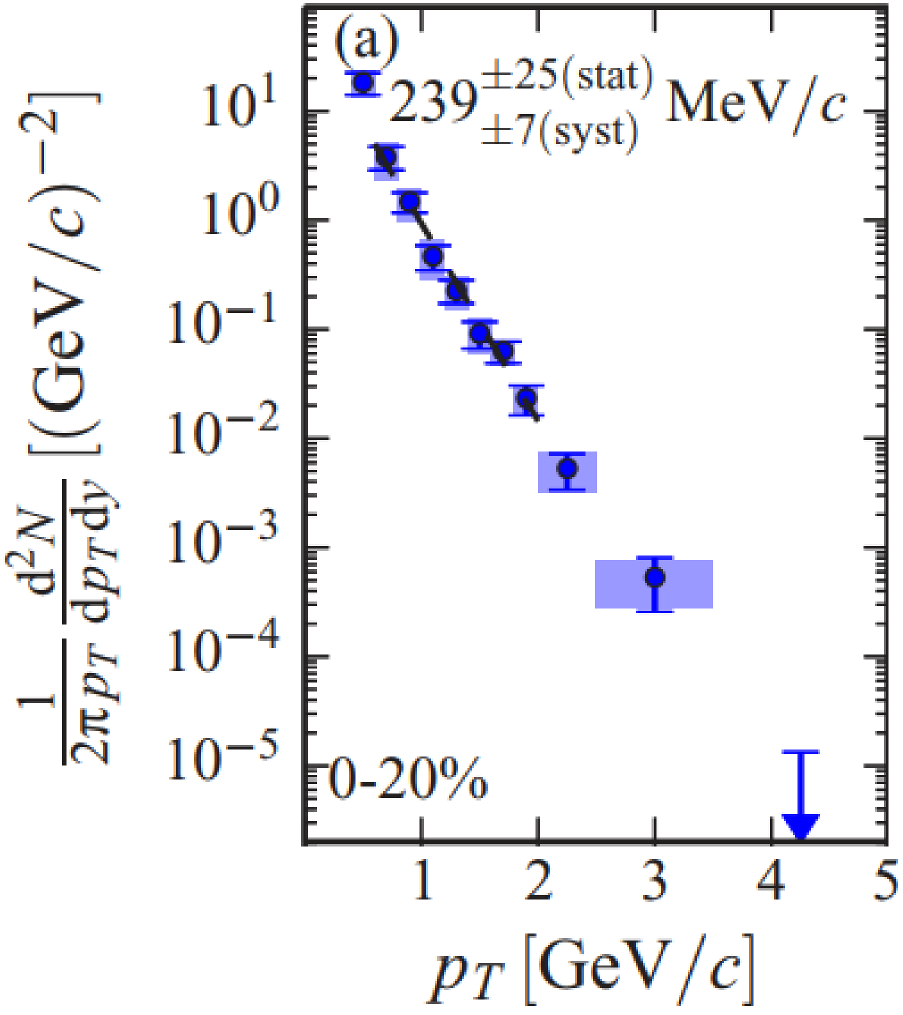
Carry the information of the system when it is produced (early)



T_{eff} ~ 240 MeV

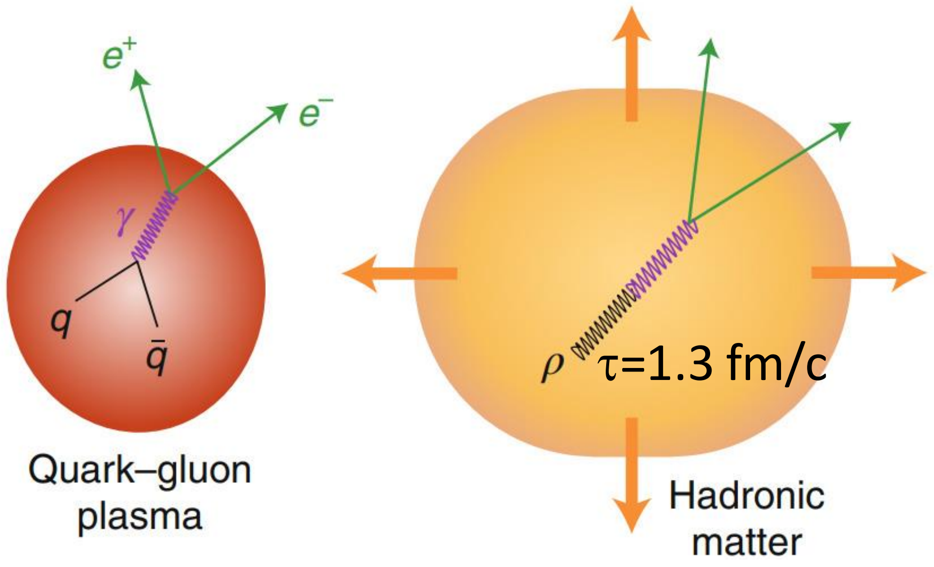
But has bule-shift effect





PHENIX: Phys. Rev. C 91, 064904 (2015)

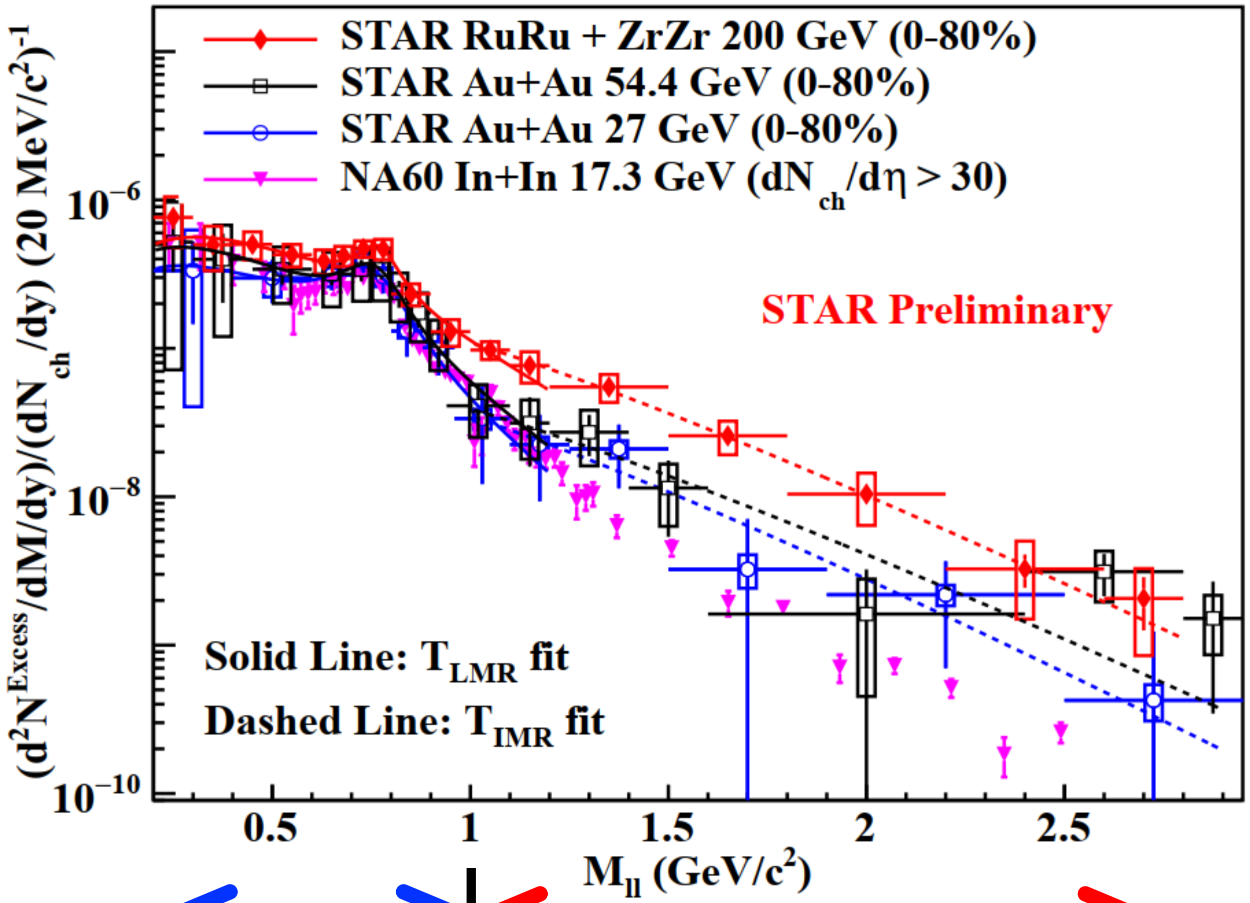
Thermal Di-lepton



Di-lepton can be produced from QGP thermal radiation and resonance decay

The invariant mass distribution reflect temperature without blue-shift effect

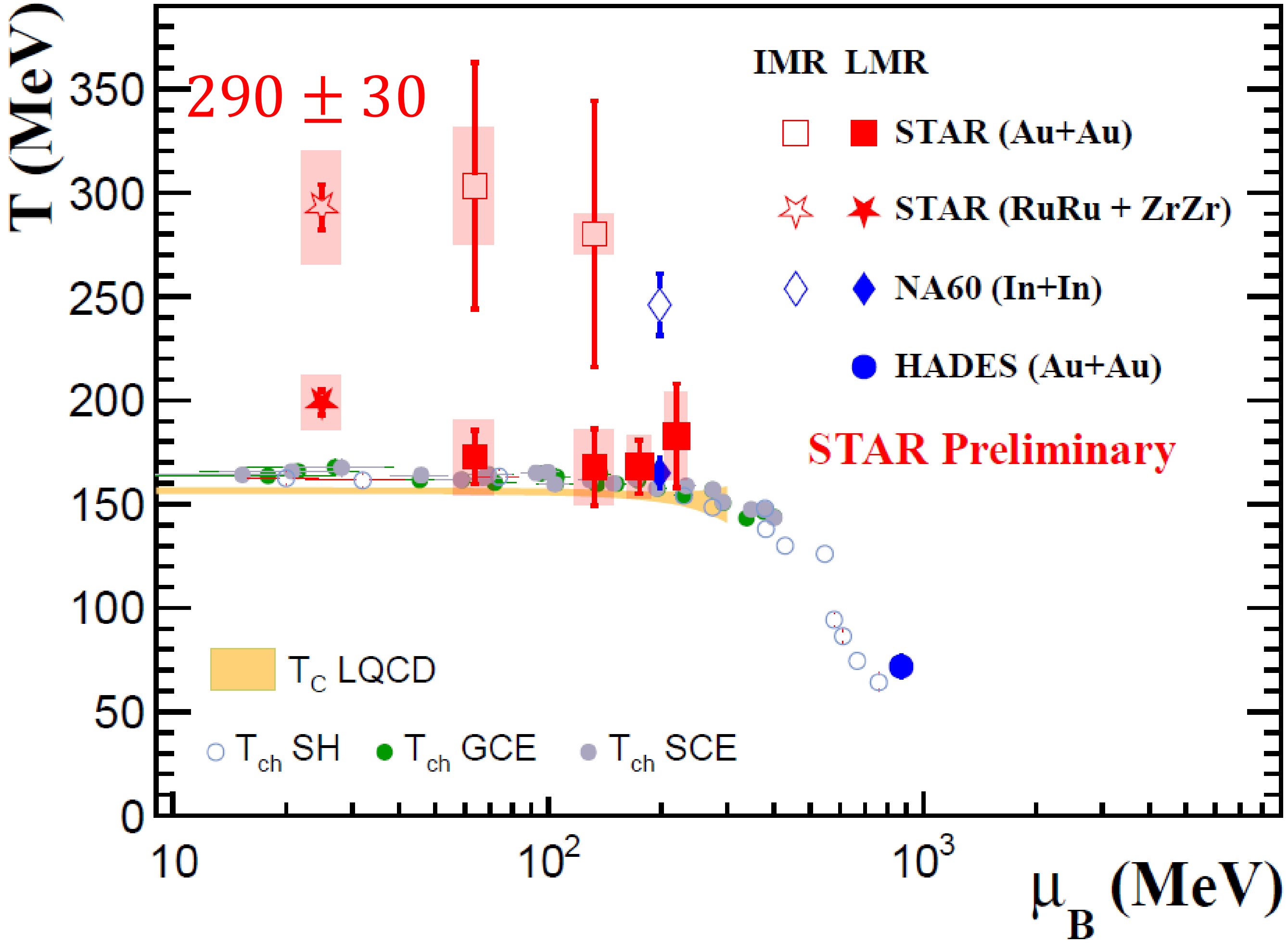
Hadronic (except ρ) contribution subtracted



Low mass region
ρ dominant

Intermediate mass region
QGP radiation dominant

Temperature Extracted from Di-lepton



Low mass region:

- Close to chemical freezeout temperature and phase transition temperature from Lattice QCD
- Dominantedly produced around phase boundary

Intermediate mass region:

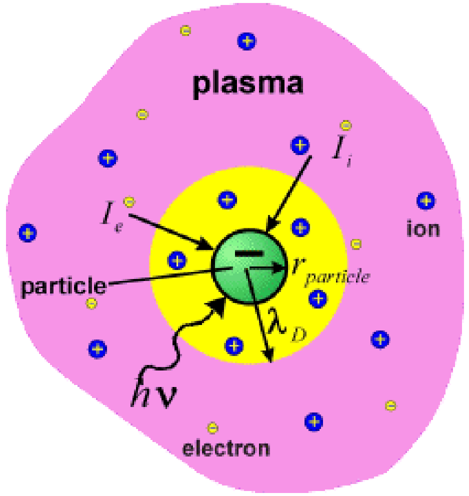
- T ~ 290 MeV (blue-shift free)
- Stronge evidence of thermal radiation from early QGP

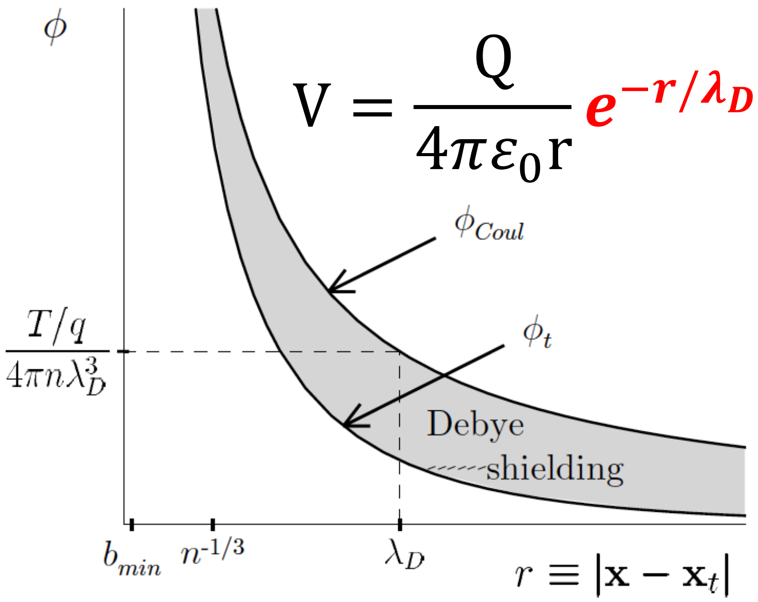
NA60: EPJC59,607 (2009)
STAR: arXiv:2402.01998
HADES:Nat. Phys.15, 1040 (2019)

HotQCD: PLBB795,15 (2019)
T_{SH}: P. Braun-Munzinger et al. Nat.561, 321 (2018)
$T_{GCE/SCE}$: STAR, PRC96, 044904(2017)

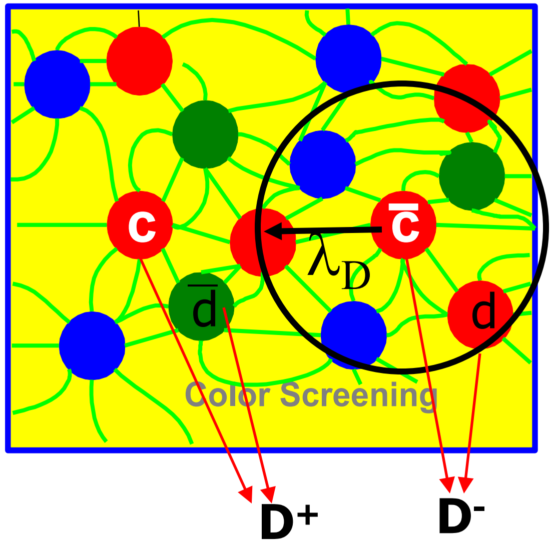
Deconfinement

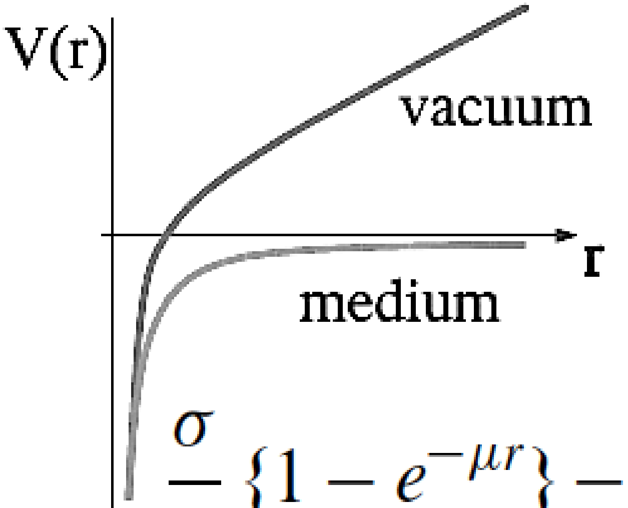
Debye Screening in Plasma and QGP





$$V = \frac{Q}{4\pi\varepsilon_0 r} e^{-r/\lambda_D}$$





$$\frac{\sigma}{\mu}\{1 - e^{-\mu r}\} - \frac{\alpha}{r} e^{-\mu r}$$

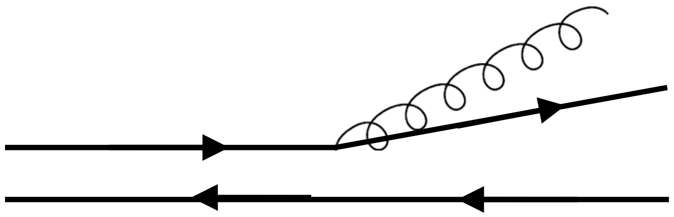
$$\mu = 1/\lambda_D$$

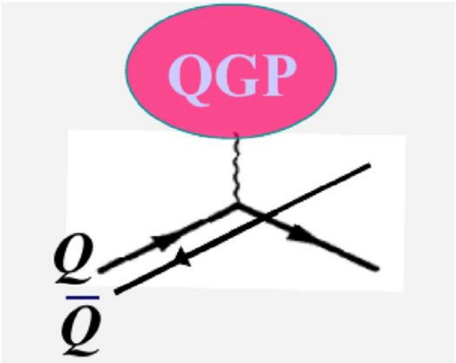
Suppression of quarkonium in heavy ion collision should provide a "smoking-gun" signature of QGP formation

Dissociation rate depends on quarkonium size and Debye length

T. Matsui, H. Satz, PLB174, 416 (1986)

Dynamic Dissociation in QGP



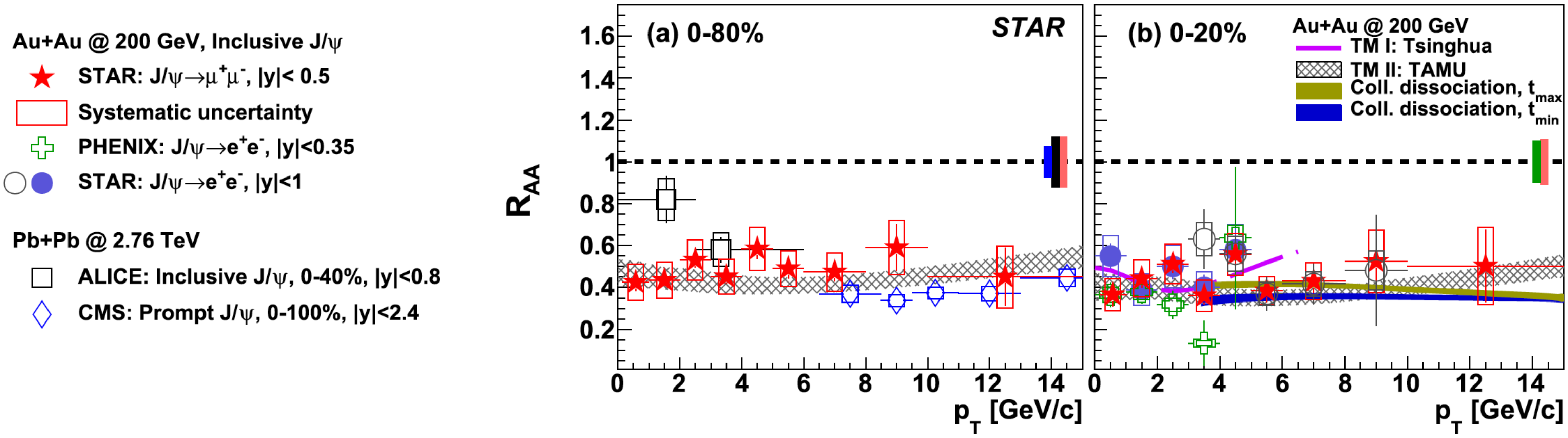


M. He, H. van Hees and R. Rapp, PPNP130, 104020 (2023)

Quarkonium may absorb a gluon or interact with partons in QGP and be dissociated

Dissociation rate depends also on quarkonium size and QGP temperature etc

J/ψ Yield Suppression in Heavy Ion Collisions



STAR, PLB797, 134917 (2019)

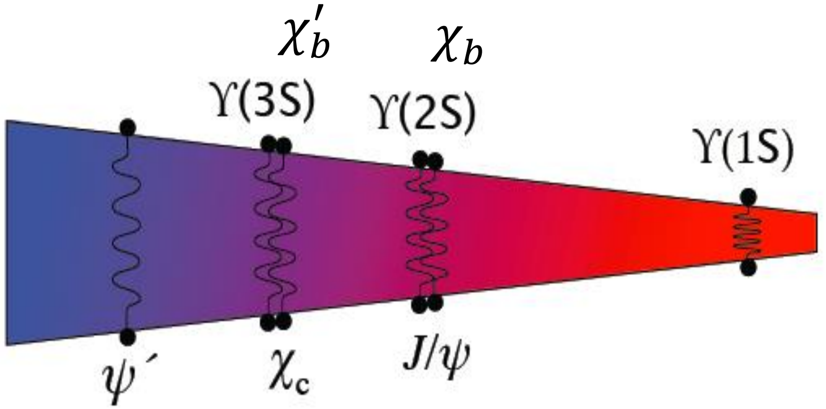
- Yield suppression quantified with nuclear modification factor R_{AA}

R_{AA}<1 means suppression compared to p+p collisions at the same energy

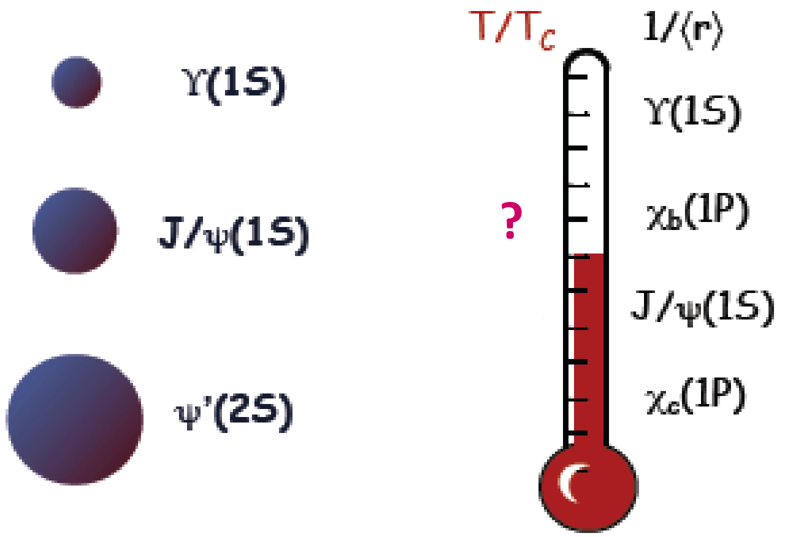
- Significant suppression observed at high p_T

“Providing strong evidence for the color-screening in the deconfined medium”

Sequential Suppression



Plasma thermometer

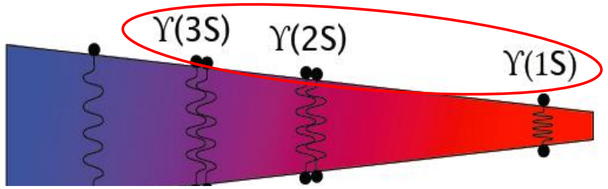


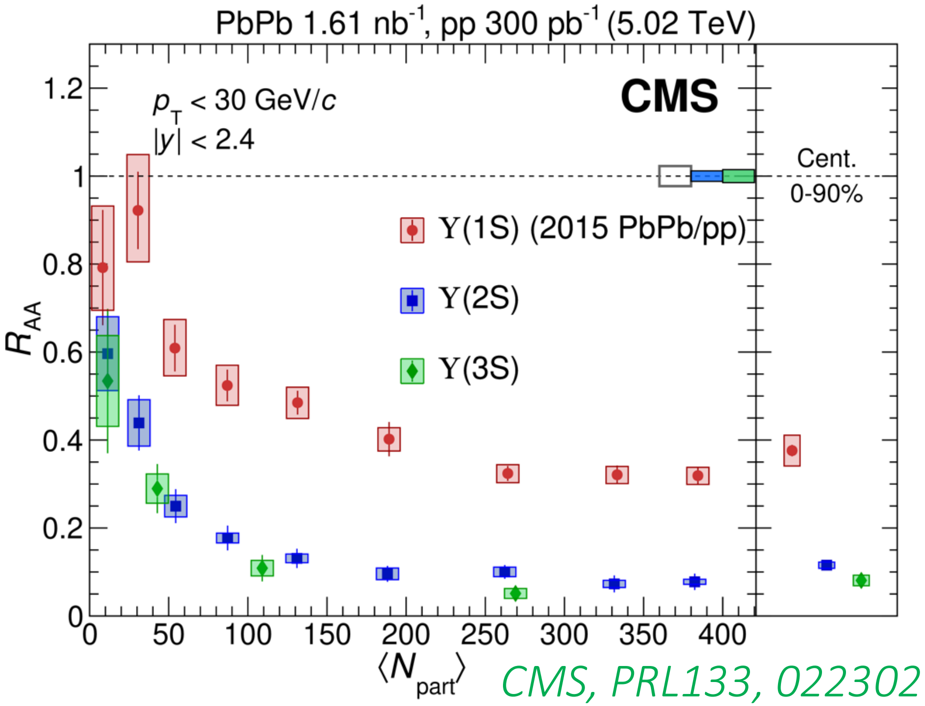
Debye radius is inversely proportional to the temperature of QGP

Different quarkonium states dissociate at different temperatures
→ Sequential melting

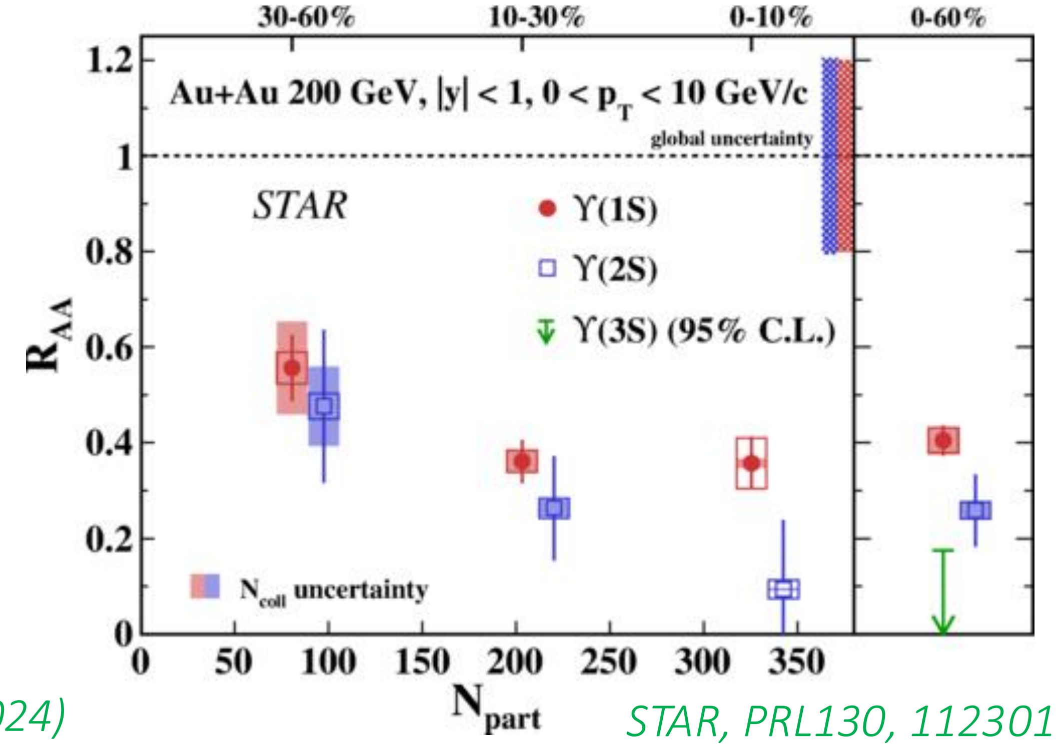
Sequential melting confirms deconfiment and provides more information about T_{QGP}

Sequential Melting in Bottom Sector





CMS, PRL133, 022302 (2024)

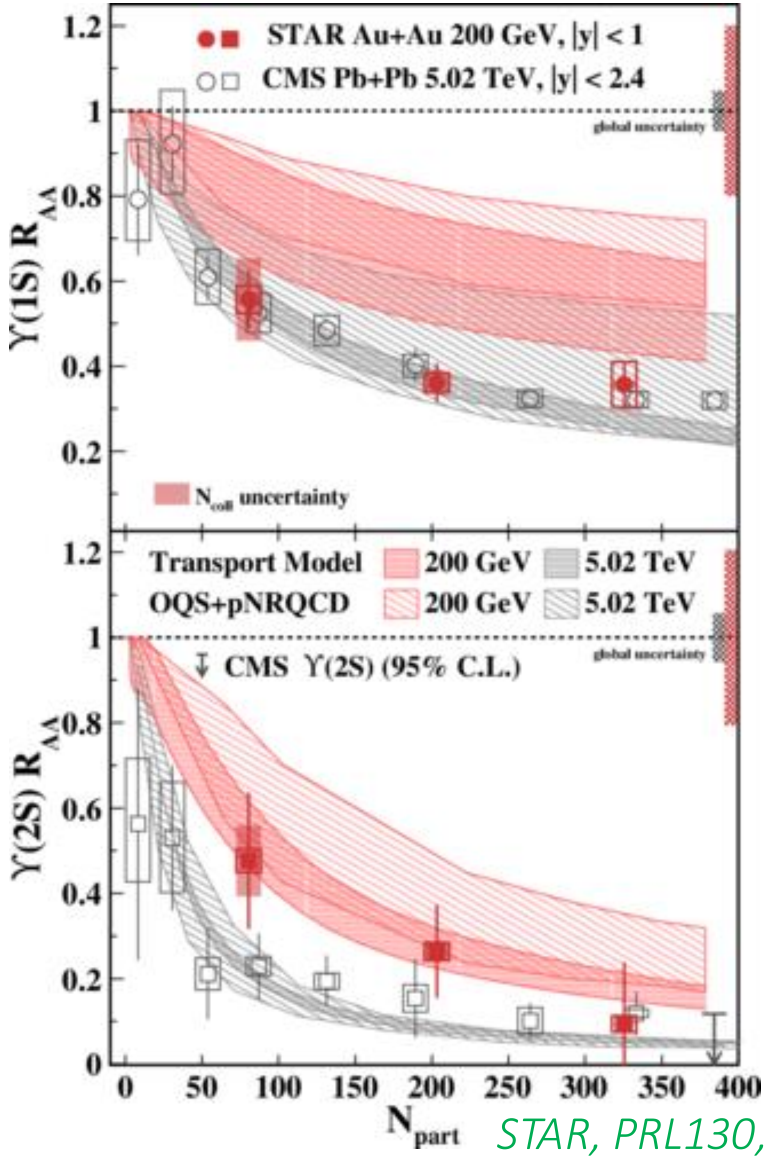


STAR, PRL130, 112301 (2023)

Precise measurement of "sequential melting" at the LHC

First observation of "sequential melting" at RHIC

Sequential Melting in Bottom Sector



STAR, PRL130, 112301 (2023)

Upsilon(1S):

- Strong suppression, and similar at RHIC and LHC

→ Arises mainly from the suppression of excited states feed down to Upsilon(1S) and CNM effects

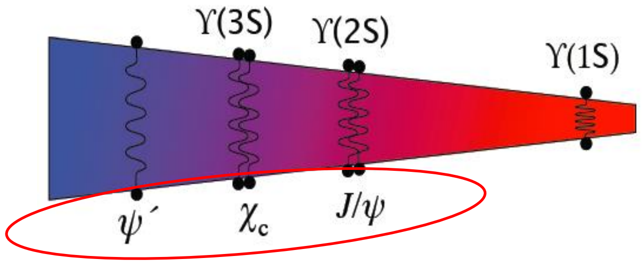
→ Primordial Upsilon(1S) not significantly suppressed

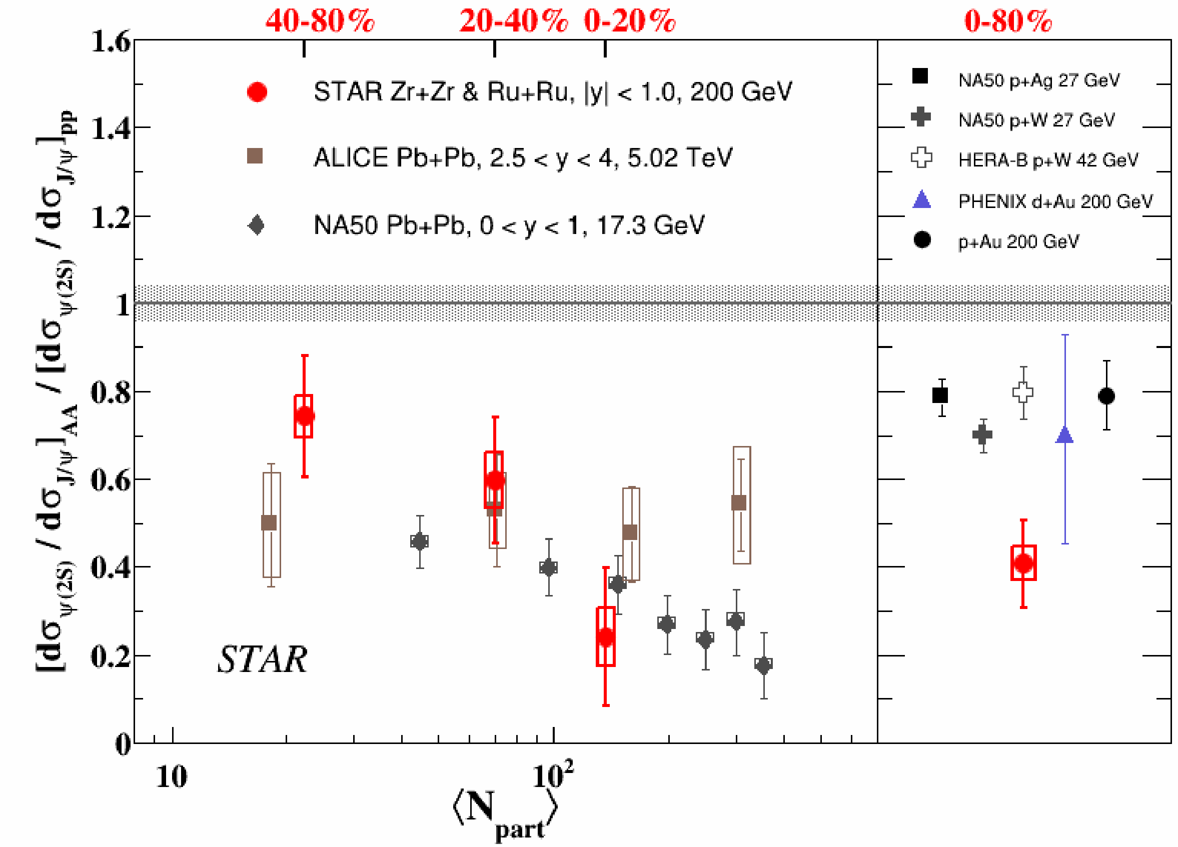
Upsilon(2S):

- Hints of less suppression at RHIC in peripheral collisions

QGP is formed, and its temperature is high enough to melt excited bottomonium states!!!

Sequential Melting in Charm Sector

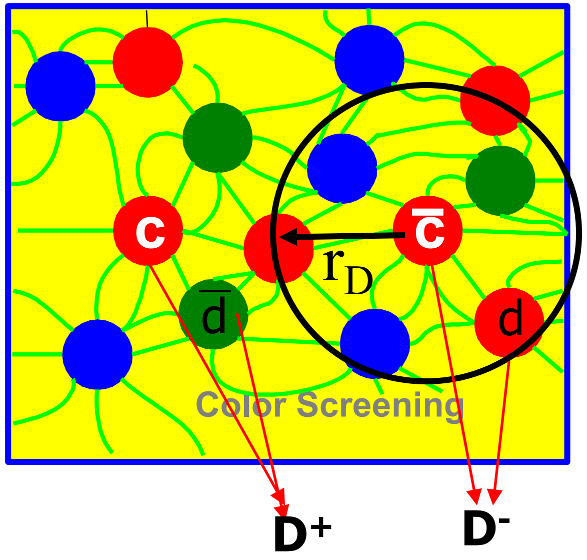


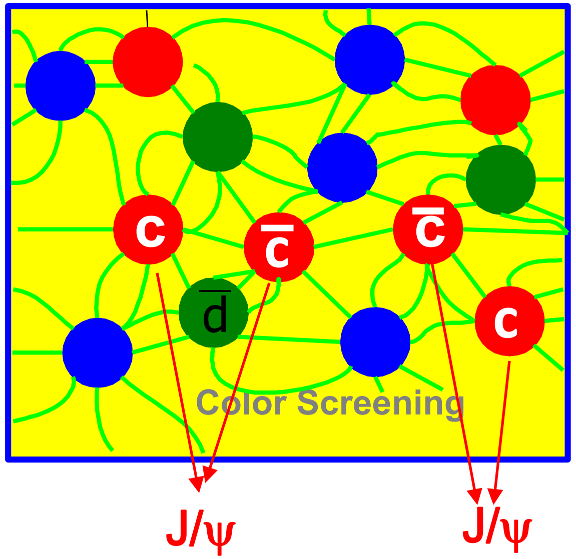


Yan Wang,
Quark Matter 2023
paper in STAR review

- Clearly stronger suppression for ψ(2S) than J/ψ from SPS to LHC
- “Sequential melting” in charm sector
- Indication of different behavior at different energy

Melting vs. Regeneration



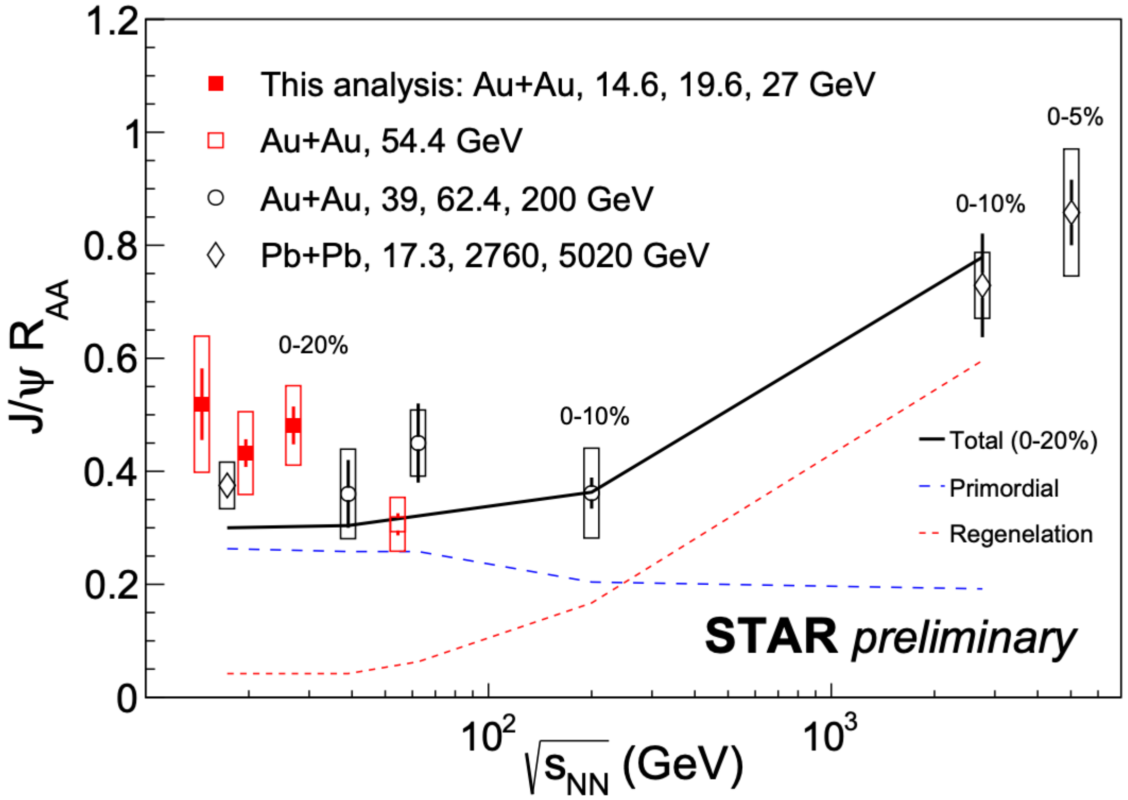


Quarkonium melting in QGP

Quarkonium regeneration in QGP

QGP formation is the prerequisite of both effects

Energy Dependence of J/ψ Suppression



NA50, PLB 477, 28 (2000)

Wei Zhang, QM 2023

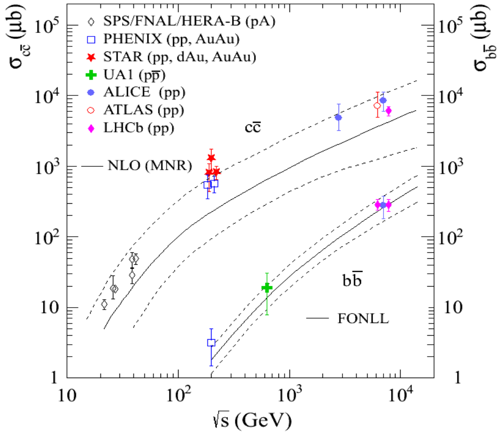
STAR, PLB 722, 55 (2013)

STAR, PLB 771, 13 (2017)

STAR, arXiv:2506.20962, submitted to PLB

ALICE, PLB 734, 314 (2014)

ALICE, PLB 849, 138451 (2024)



SPS → RHIC → LHC

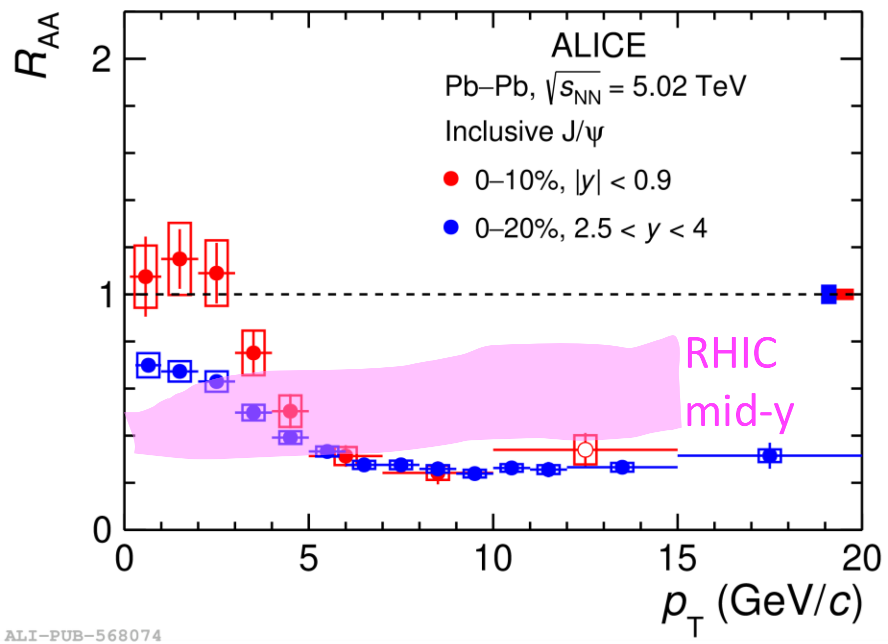
CNM + screening

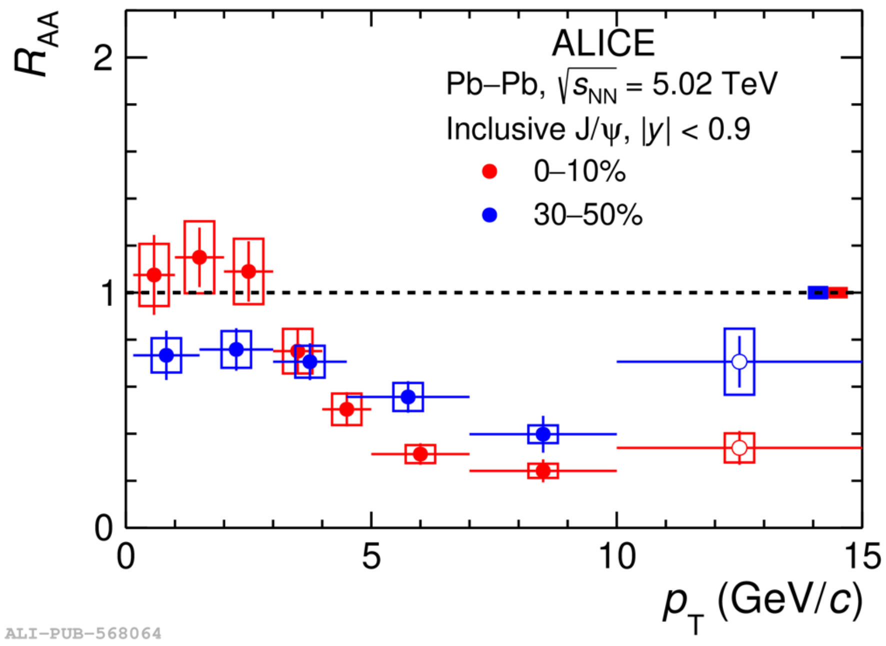
CNM + screening + regeneration

Regeneration domain

Differential Measurements at ALICE

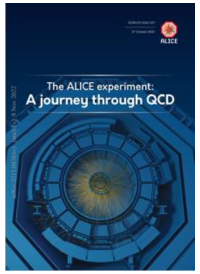
ALICE, PLB 849, 138451 (2024)





- Strong p_T dependence, unlike at RHIC
- Clear rapidity dependence at low p_T

- Clear centrality dependence
- Opposite at low and high p_T region

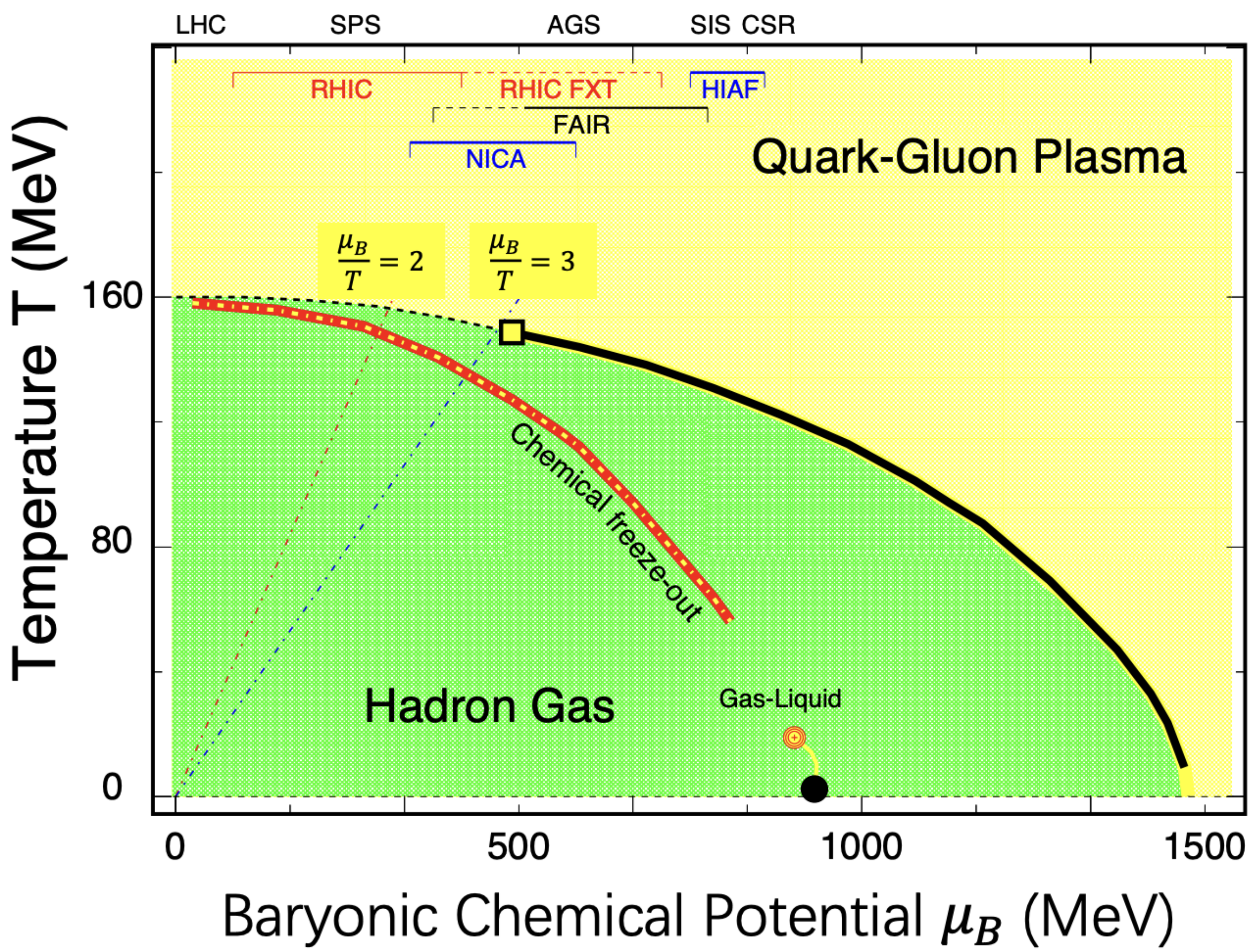


2.5.1 Study of the charmonium ground state: evidence for the (re)generation and demonstration of deconfinement at LHC energies

*Jet quenching might play an import role at high p_T

Onset of Phase Transition

QCD Phase Diagram

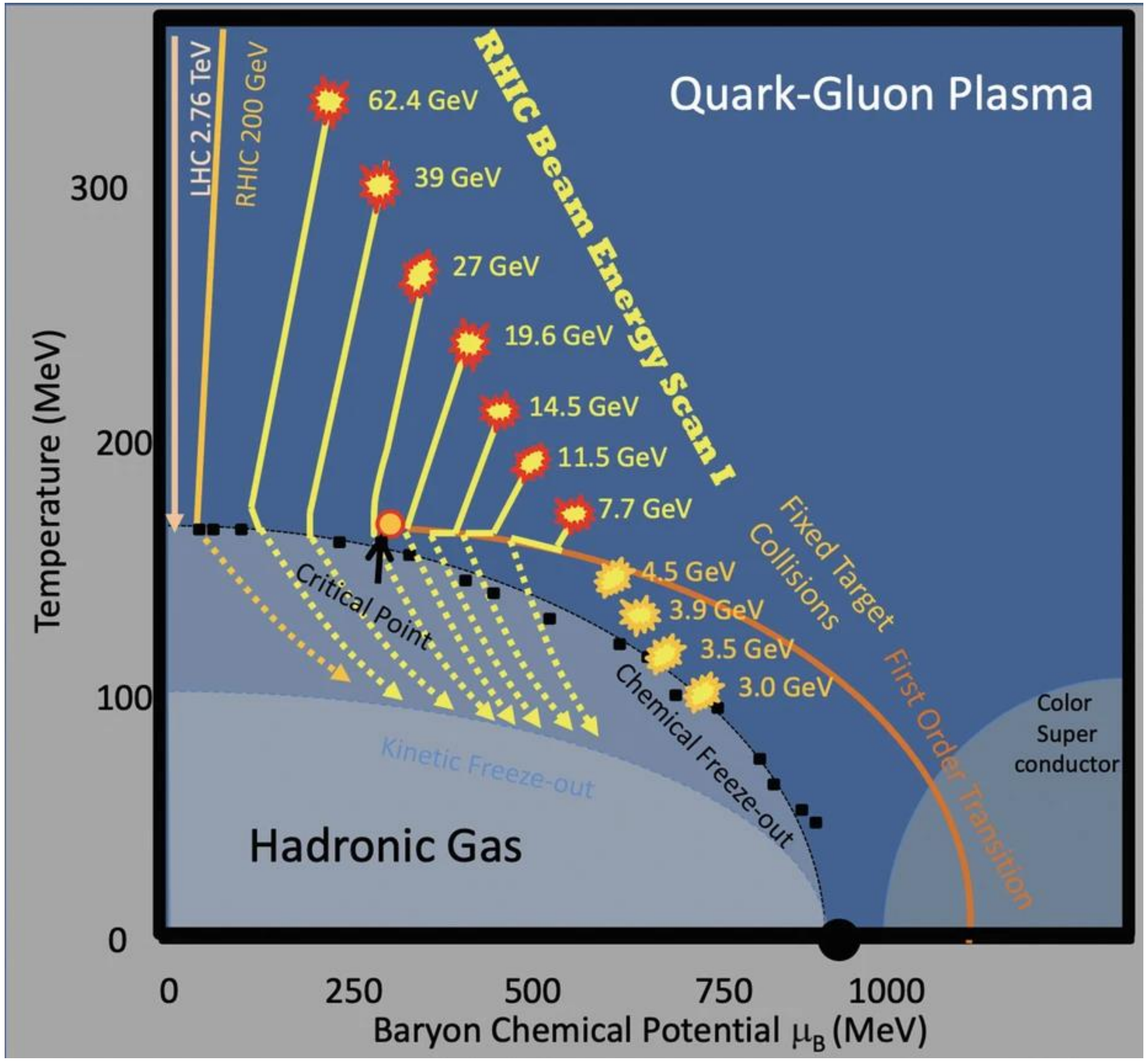


Lattice QCD: at μ_B=0, smooth crossover

Large μ_B: 1st order phase transition and QCD critical end point?

Y. Aoki et al., Nature 443, 675 (2006)
A. Bazavov et al (HotQCD), PRD 85, 054503 (2012)
K. Fukushima and C. Sasaki, PPNP, 72, 99 (2013)
A. Bzdak et al., Phys. Rep. 853, 1 (2020)

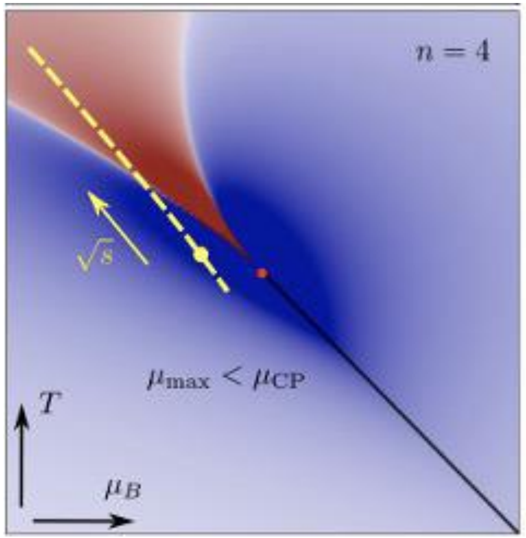
Beam Energy Scan: Explore QCD Phase Diagram



At Critical end point with an infinite system

- Correlation length should diverge
- Susceptibilities should diverge

$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T\wedge 4)}{\partial(\mu_q)^n}, q = B, Q, S$$



Measured multiplicity N, $\langle \delta N \rangle = \mathbf{N} - \langle N \rangle$

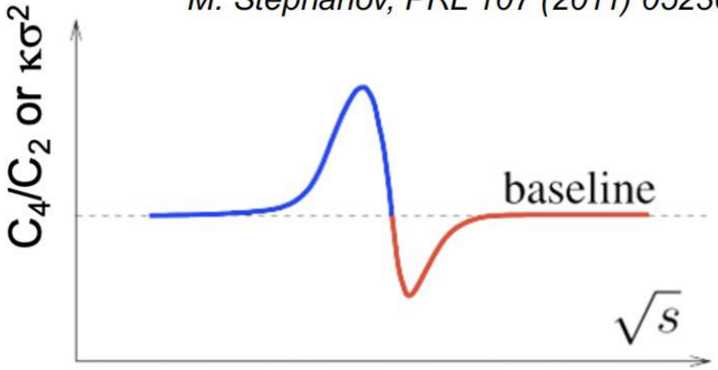
mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3 / C_2^{3/2}$

kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4 / C_2^2$

M. Stephanov, PRL 107 (2011) 052301



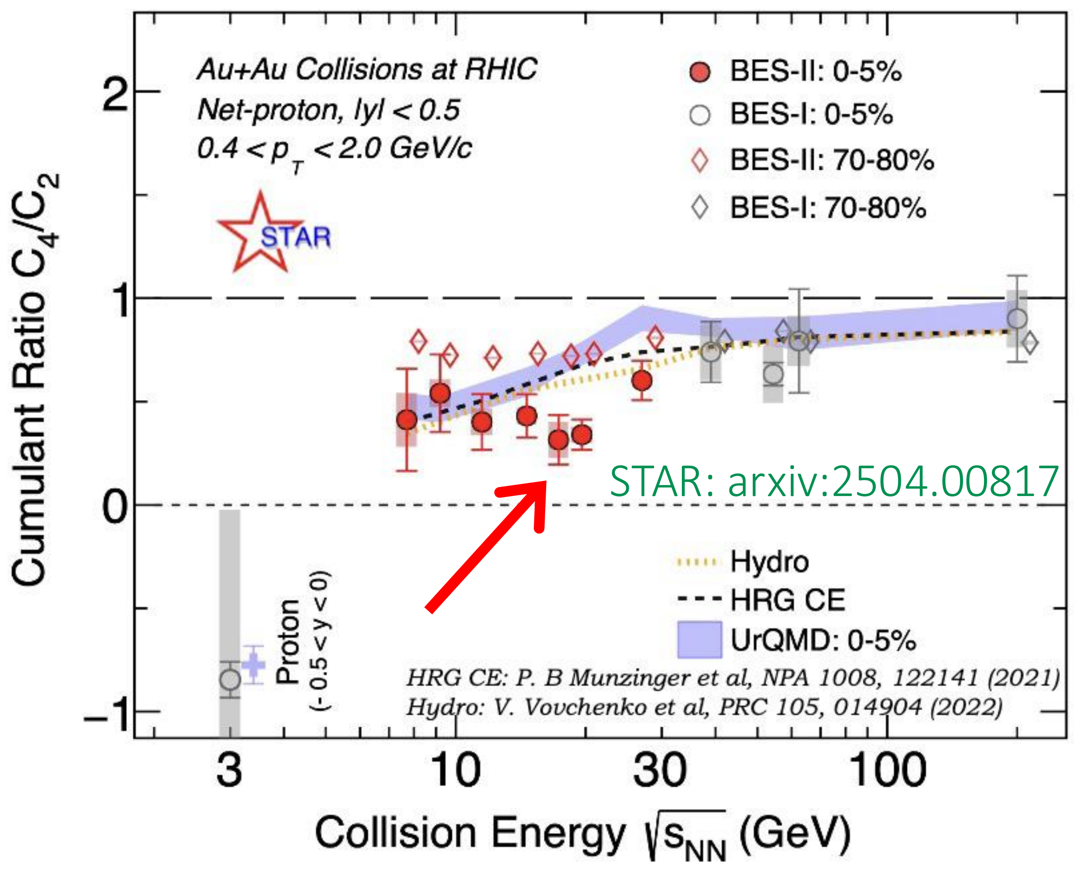
Moments, cumulants and susceptibilities:

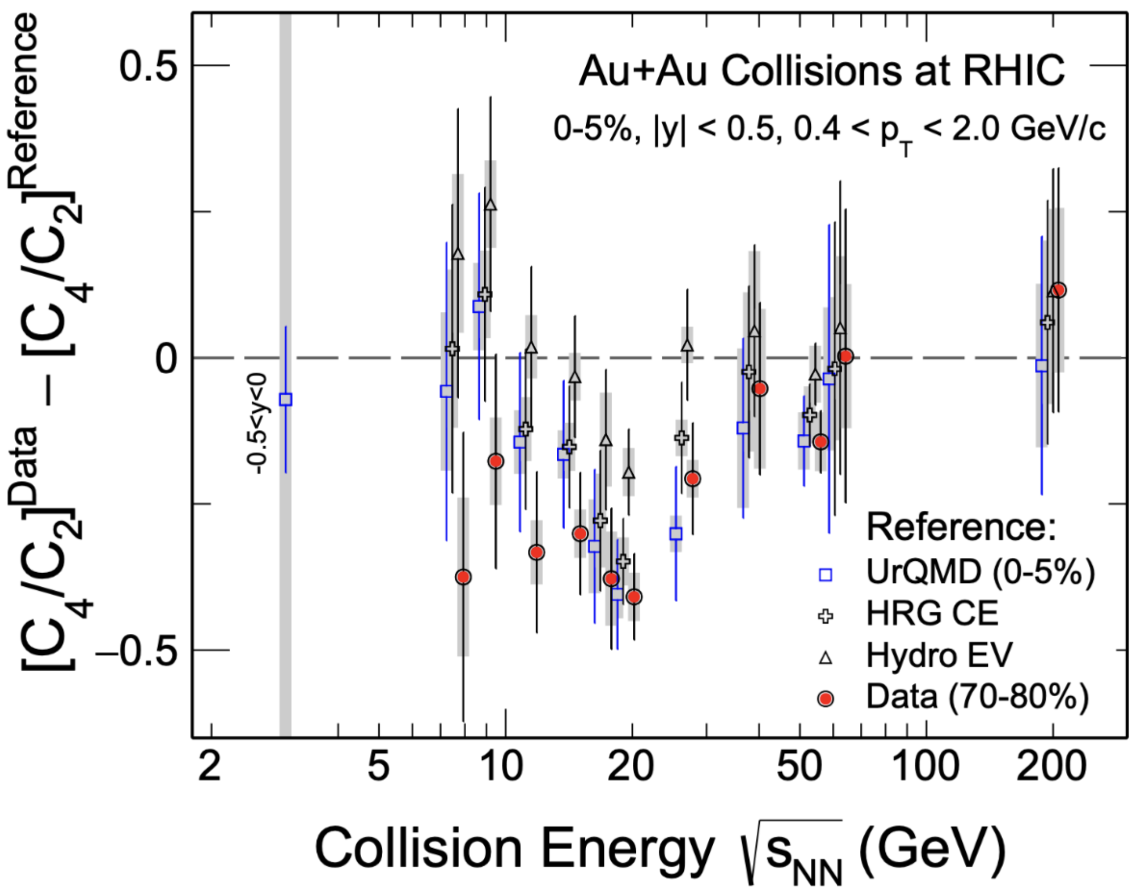
2nd order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

3rd order: $S\sigma \equiv C_3/C_2 = \chi_3/\chi_2$

4th order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$

C4/C2 vs. Collision Energy

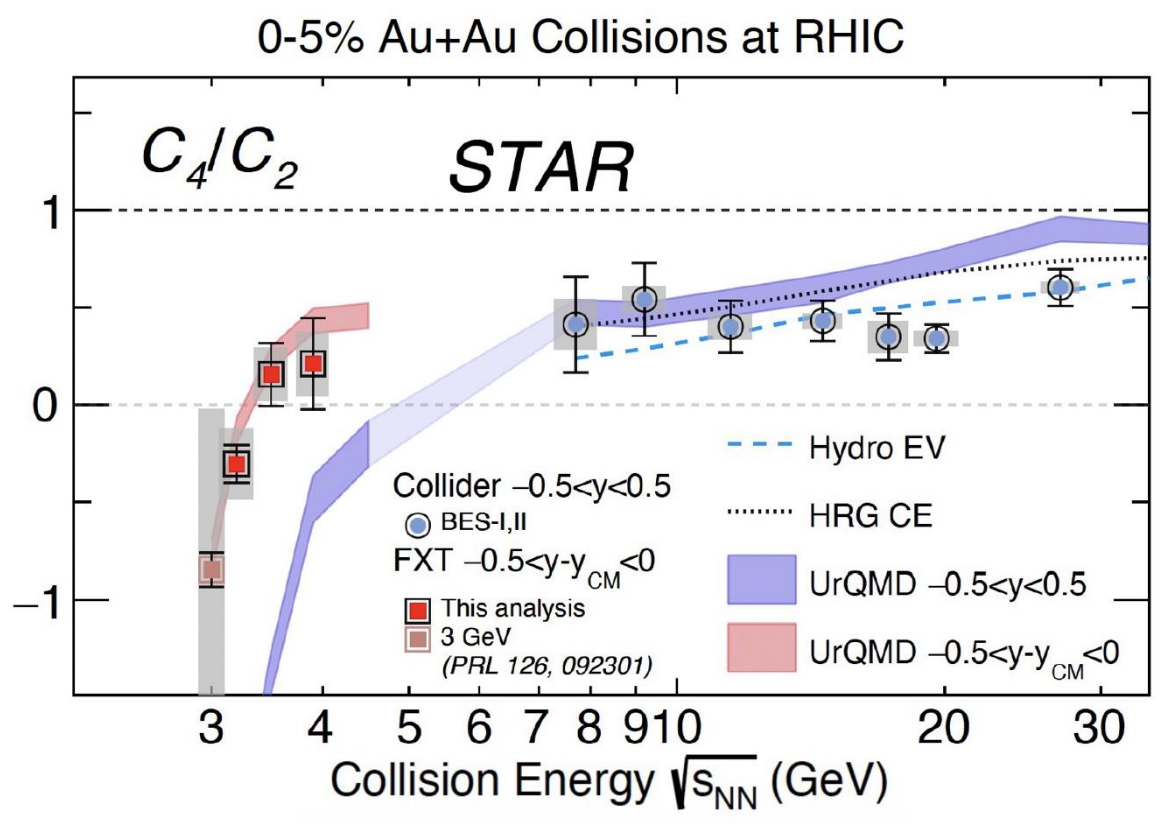


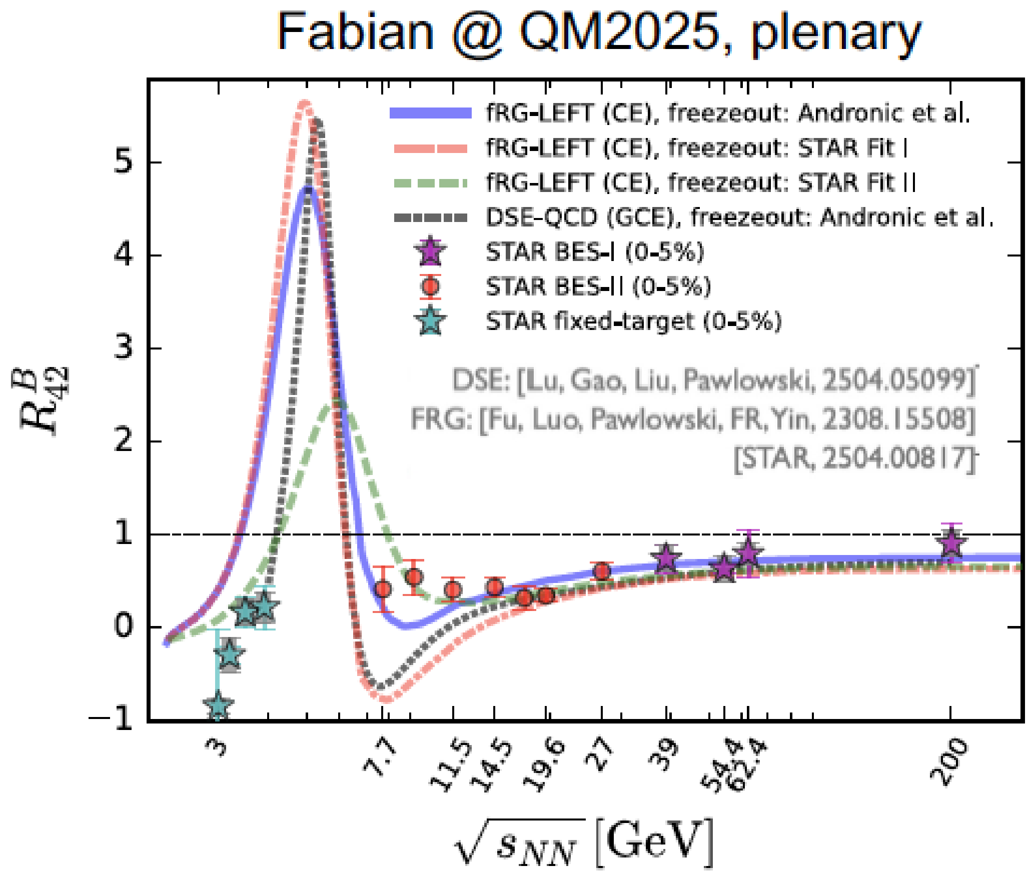


STAR: PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

- 2-5σ deviations to non-CEP baselines at 19.6 GeV
- Data from low energies are needed to establish the oscillation pattern of CEP signal

C4/C2 at Lower Energy

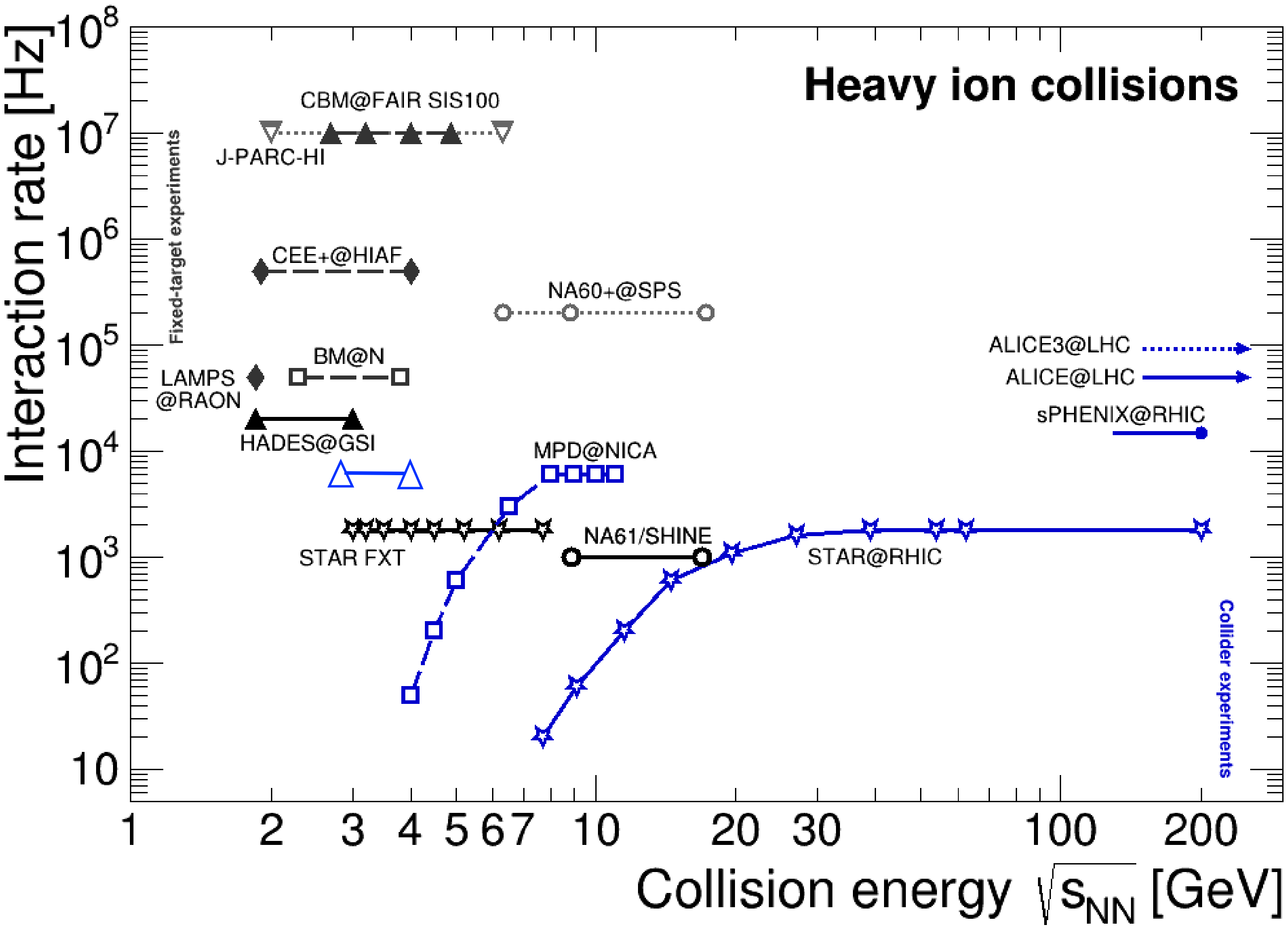




Data from STAR Fixed-target data consistent with non-CEP baseline

Experimental results between 4 and 8 GeV are crucial

Future Experiments



Collider experiment:

MPD @ NICA @ JINR @ Russia

Fixed-target experiments:

CBM @ FAIR @ GSI @ Germany

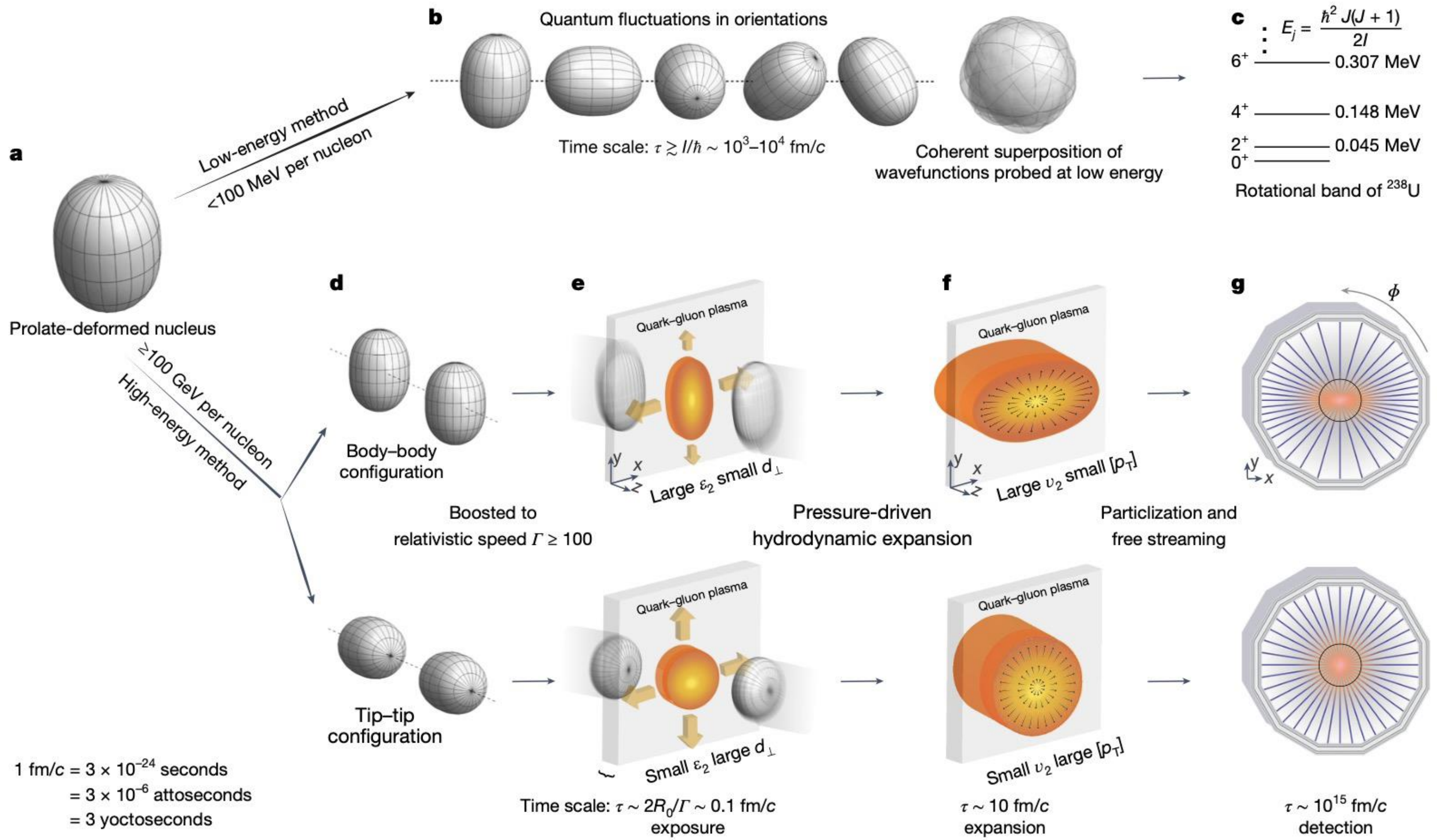
CEE+ @ HIAF @ IMP @ China

J-PARC-HI @ JAEA @ Japan

NA60+/NA61 @ SPS @ CERN

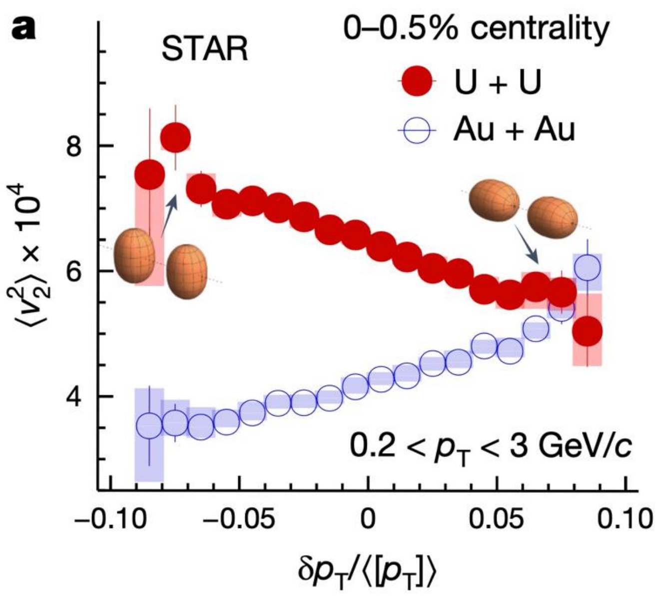
Other Unique Opportunities

Nuclear Imaging with Heavy Ion Collisions



Very short time scale compared to low-energy experiments

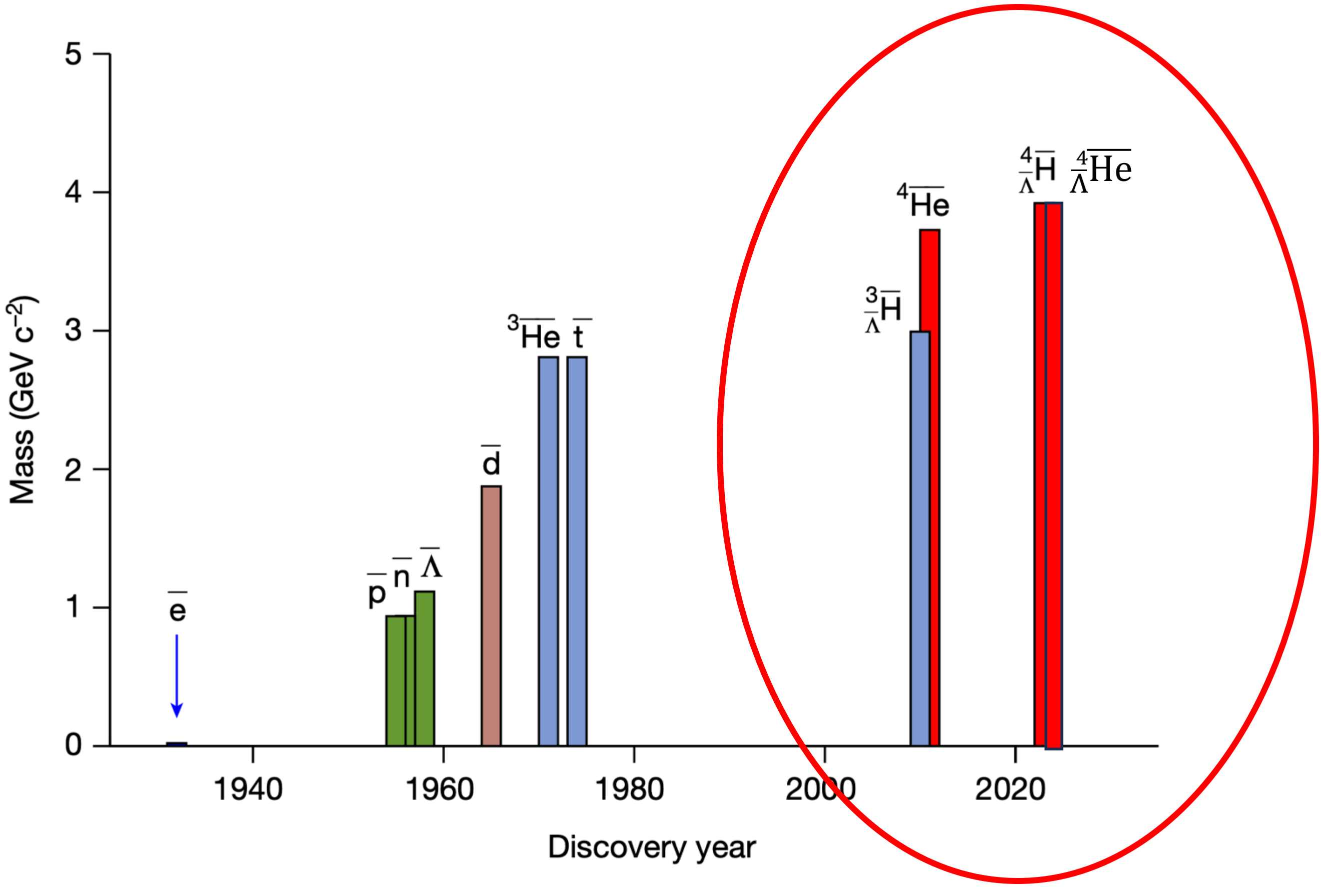
➔ Snapshot of nuclear shape



STAR, Nature 635, 67 (2024)

Antimatter Factory

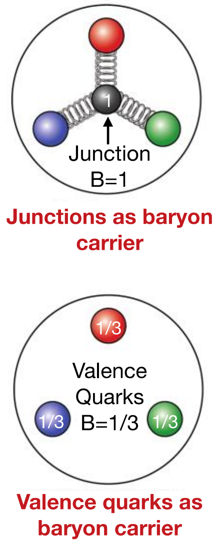
- Large number of anti-baryon produced in relativistic heavy ion collisions
- Antimatter nucleus can be formed via coalescence
- Ideal place for antimatter production

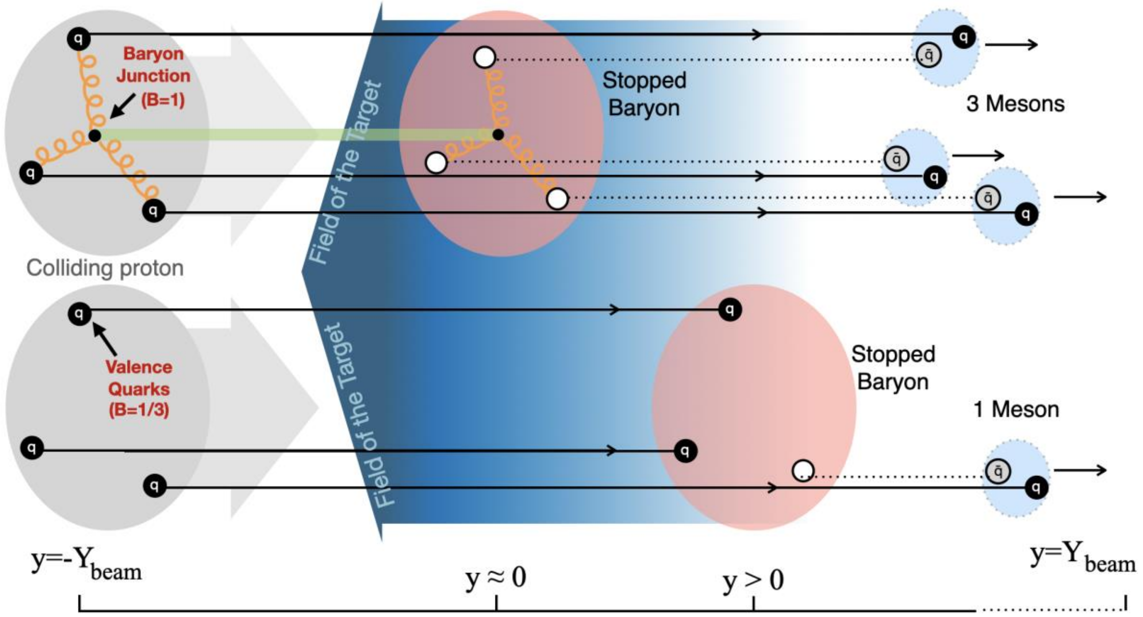


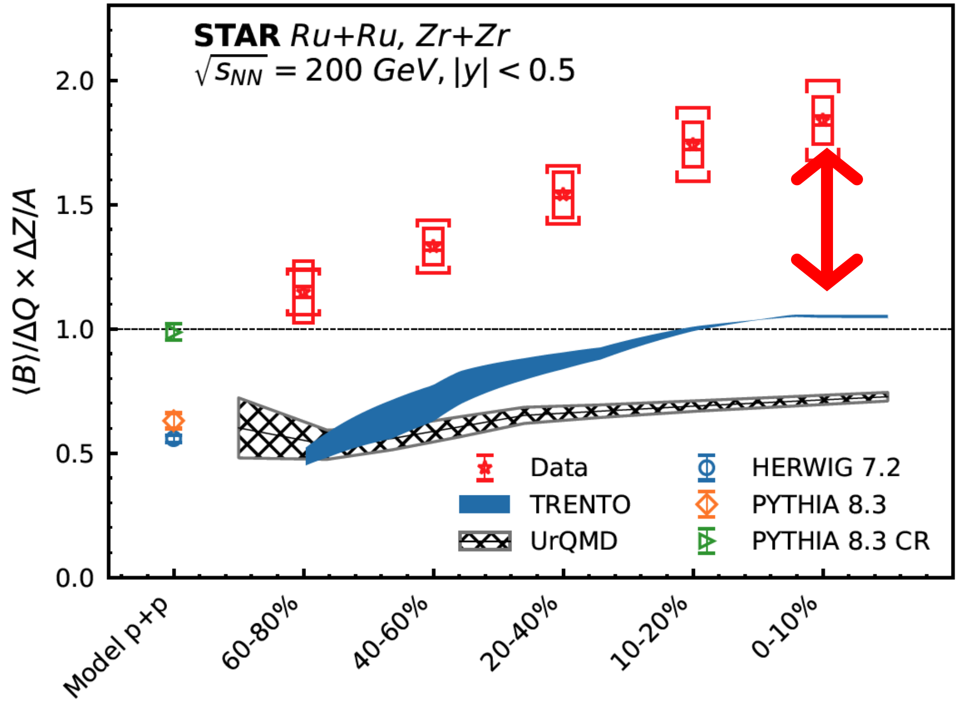
Discovered by heavy ion collision experiments

Baryon Junction Search

- Textbooks say baryon number is carried by valence quarks, but no experimental evidence
- Alternative theory proposed that the baryon number carried by gluon junction in 1970s
- Baryon and charge transport in heavy ion collisions provides an novel probes







STAR, arXiv:2408.15441, submitted to Science
Y. Li, PhD thesis, USTC (2023)
W. Lv et al., CPC48, 044001 (2024)

Data disfavor baryon number carried by valence quark

Extreme Electromagnetic Field

- Fast moving charge generates strong EM filed, especially for heavy ions

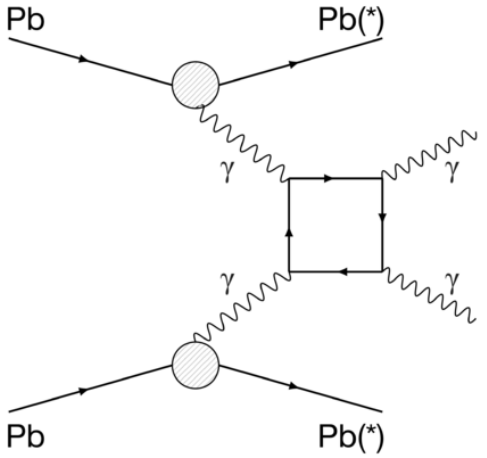
$$B\sim\frac{1}{4\pi}\frac{\gamma Ze\beta r}{[\gamma^2(z-\beta t)^2+r^2]^{3/2}}\sim O(10^{14-16}\,T)$$

- The Lorentz contracted EM field can be expressed in terms of equivalent photon flux

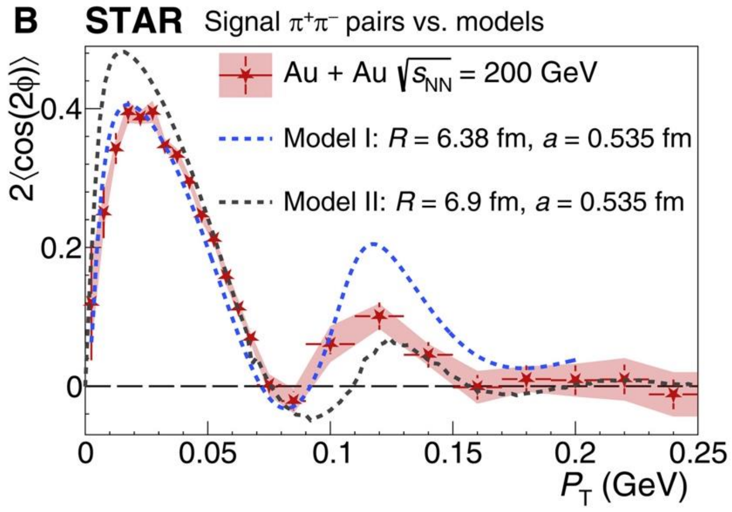
$$E\perp B\perp z, E=B$$

$$\omega_{max}\sim\ 3\ \mathrm{GeV}\ @\ \mathrm{RHIC}, \sim 80\ \mathrm{GeV}\ @\ \mathrm{LHC}$$

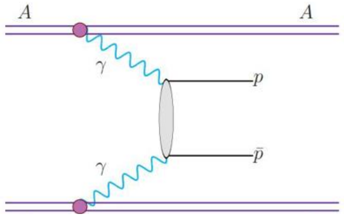
E. Fermi, Z. Phys. 29, 315 (1924)



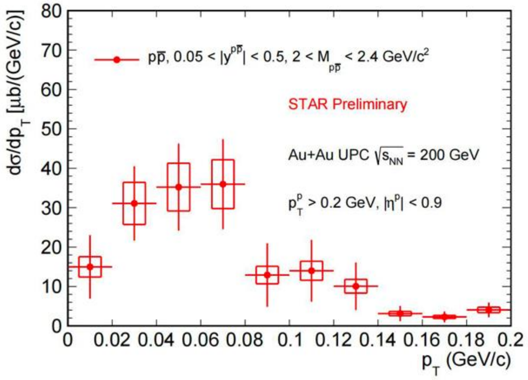
ATLAS, Nat. Phys. 13, 852 (2017)



STAR, Sci. Adv. 9, 3903 (2023)



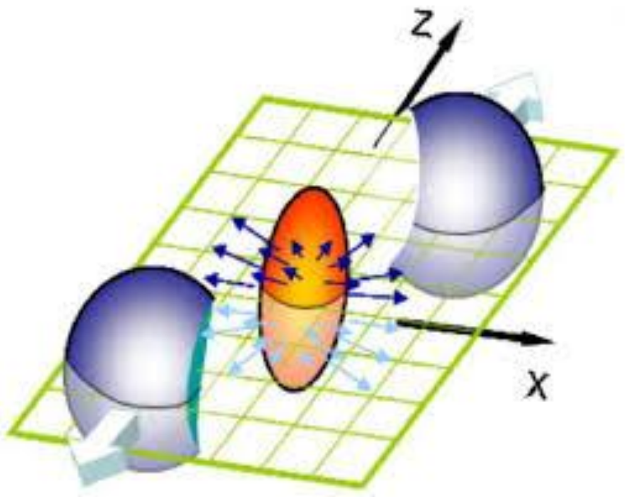
ppbar from QED vacuum

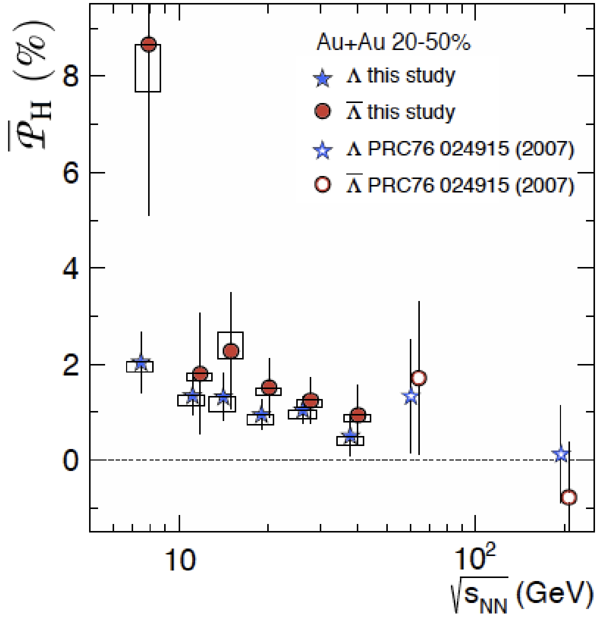


X. Wu, SQM2024 (flash talk)

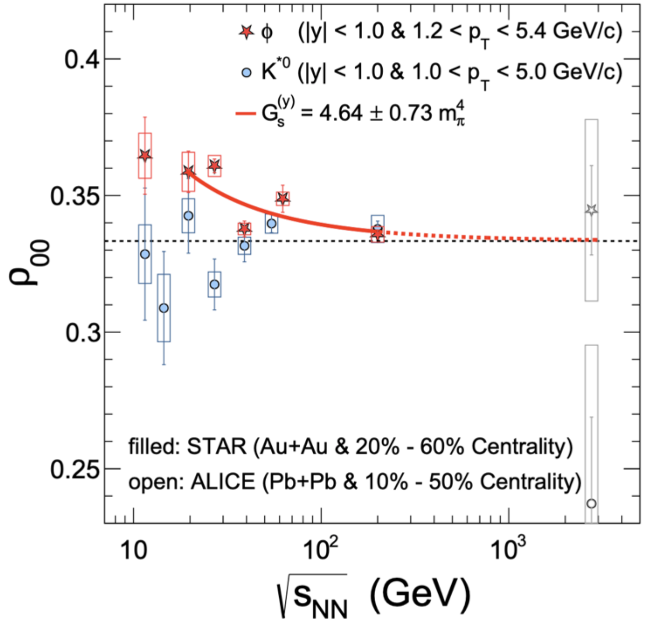
Extreme Vorticity

- Non-central heavy ion collisions produced huge orbital angular momentum
- Largest vorticity fluid in nature
- Can transfer to quark spin polarization and thus hadron spin polarization





STAR, Nature 548, 62(2017)



STAR, Nature 614, 244 (2023)

Summary

Nuclear matter undergoes phase transition to quark gluon plasma at extremely high energy density (~GeV/fm^3)

Medium produced in high energy heavy ion collisions consistent with QGP phenomenon

- Chemical freezeout temperature ~ T_c from Lattice QCD calculations
- Temperature from IMR dilepton ~ 290 MeV, significantly higher than T_c
- Quarkonium suppression and regeneration observed → Deconfinement

QGP properties (inner working) being studied via various probes
(many progresses are not covered in this talk, apology…)

QCD phase diagram under exploration via scanning collision energy
Several large facilities are under construction, stay tuned

Thanks!