Study QCD Phase Diagram in High-Energy Nuclear Collisions

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Many Thanks to the Organizers!

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(2) College of Physical Science & Technology, Central China Normal University, China

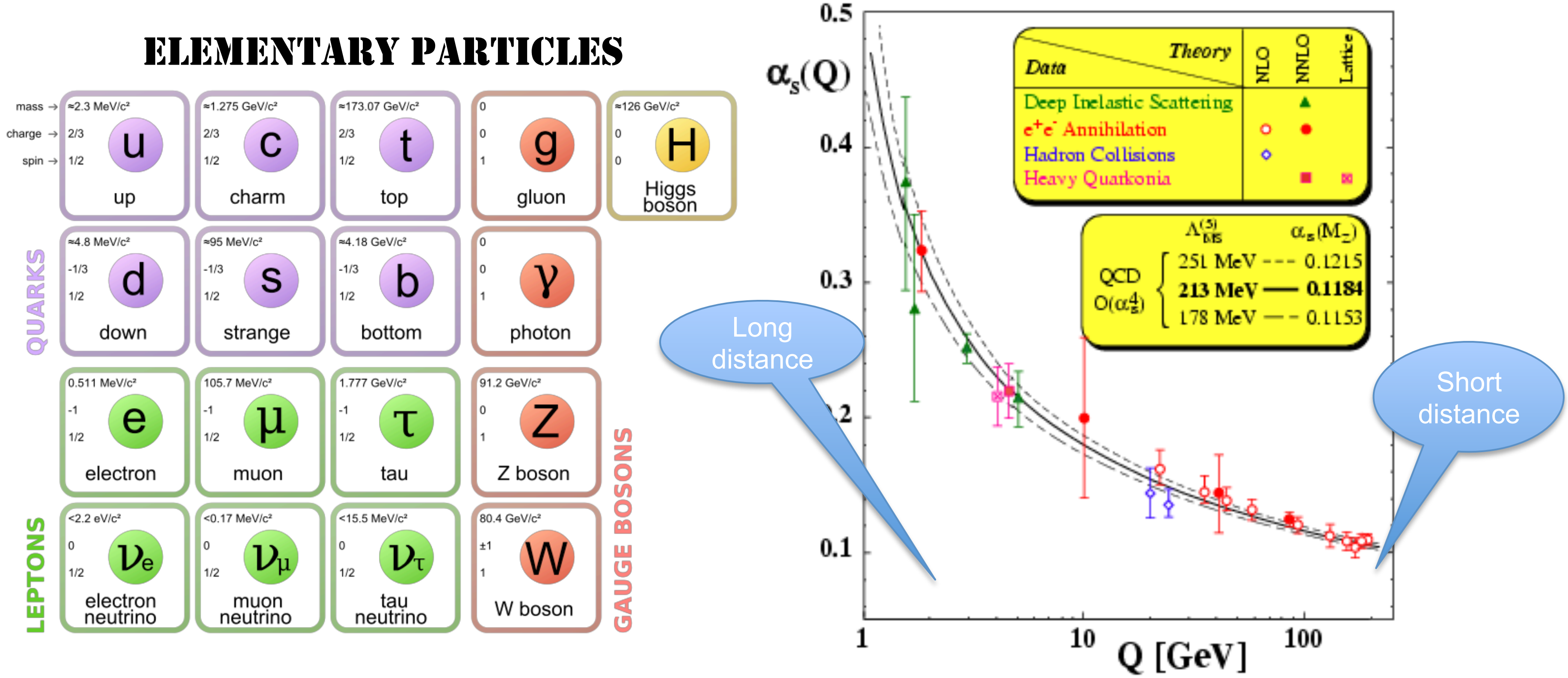
Outline

1) Introduction: QCD Phase Structure

2) Part I: STAR BES-I Results (selected)

3) Part II: Quarkonia in HIC

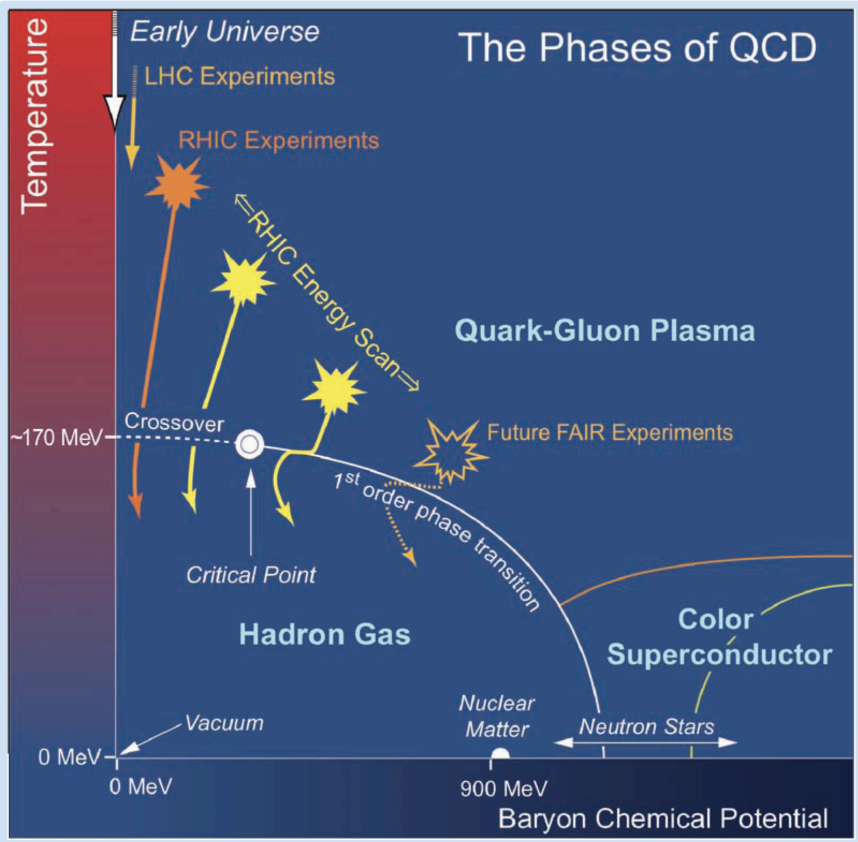
QCD Emergent Properties



1) After the discover of the Higgs boson the QCD degrees of freedom are well defined, at short distance.
2) Study dynamical structures of matter that made from ***q, g***. *E.g. the confinement*, *nucleon spin*, the ***QCD phase structure***... Large $\boldsymbol{\alpha_s}$ and strong coupling – QCD at long distance.

Study QCD Phase Structure at RHIC

QCD Emergent Properties



Study QCD Phase Structure

- Phase boundary?
- Critical point?

Observables:

1st order phase transition

(1) Azimuthally HBT

(2) Directed flow v_1

Partonic vs. hadronic dof

(3) R_{AA}: N.M.F.

(4) Dynamical correlations

(5) v_2 - NCQ scaling*

Critical point, correl. length

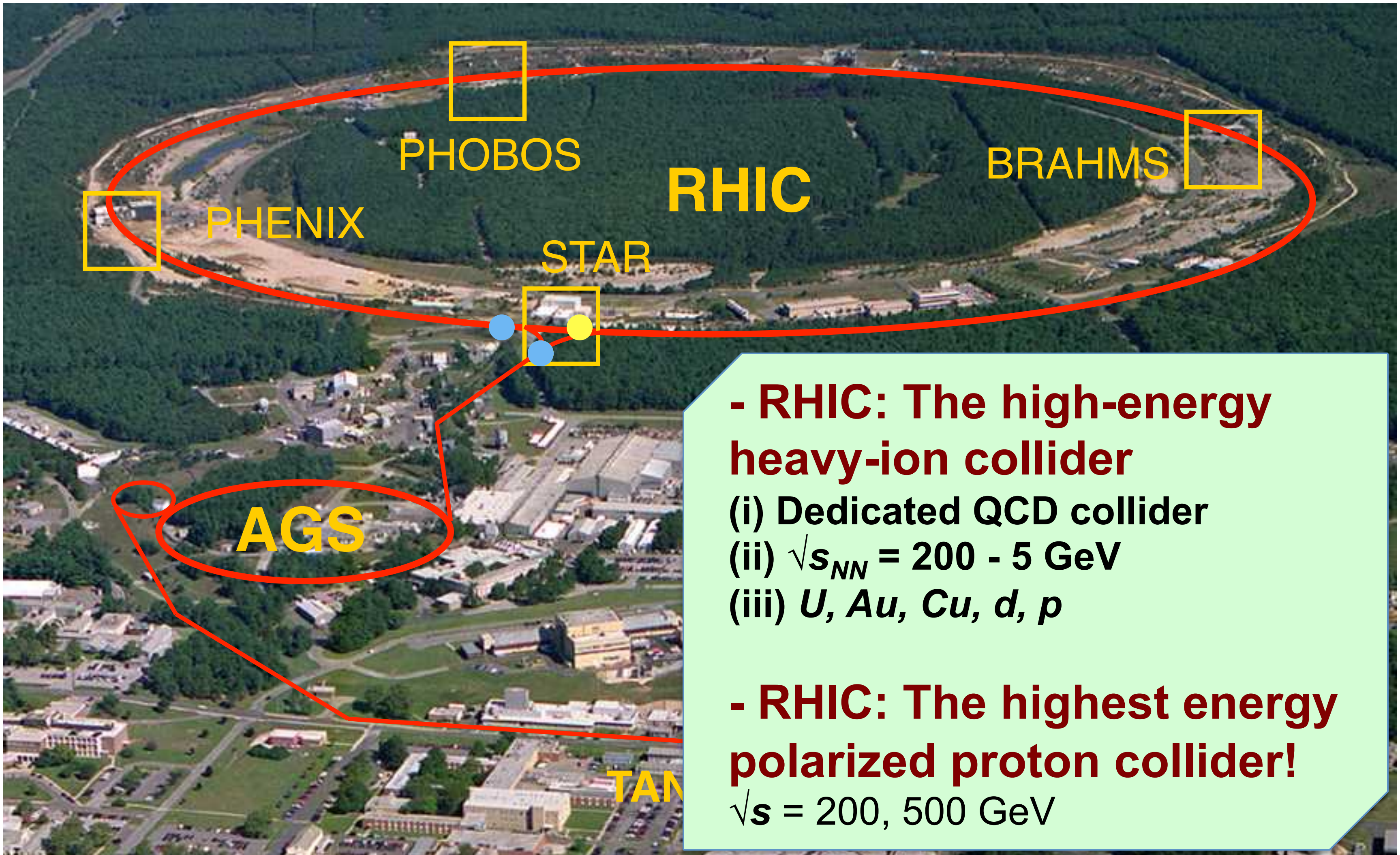
(6) Fluctuations*

(7) Di-lepton production*

BES-I: $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39GeV

Relativistic Heavy Ion Collider

Brookhaven National Laboratory (BNL), Upton, NY



- RHIC: The high-energy heavy-ion collider

(i) Dedicated QCD collider

(ii) $\sqrt{s_{NN}}$ = 200 - 5 GeV

(iii) *U, Au, Cu, d, p*

- RHIC: The highest energy polarized proton collider!

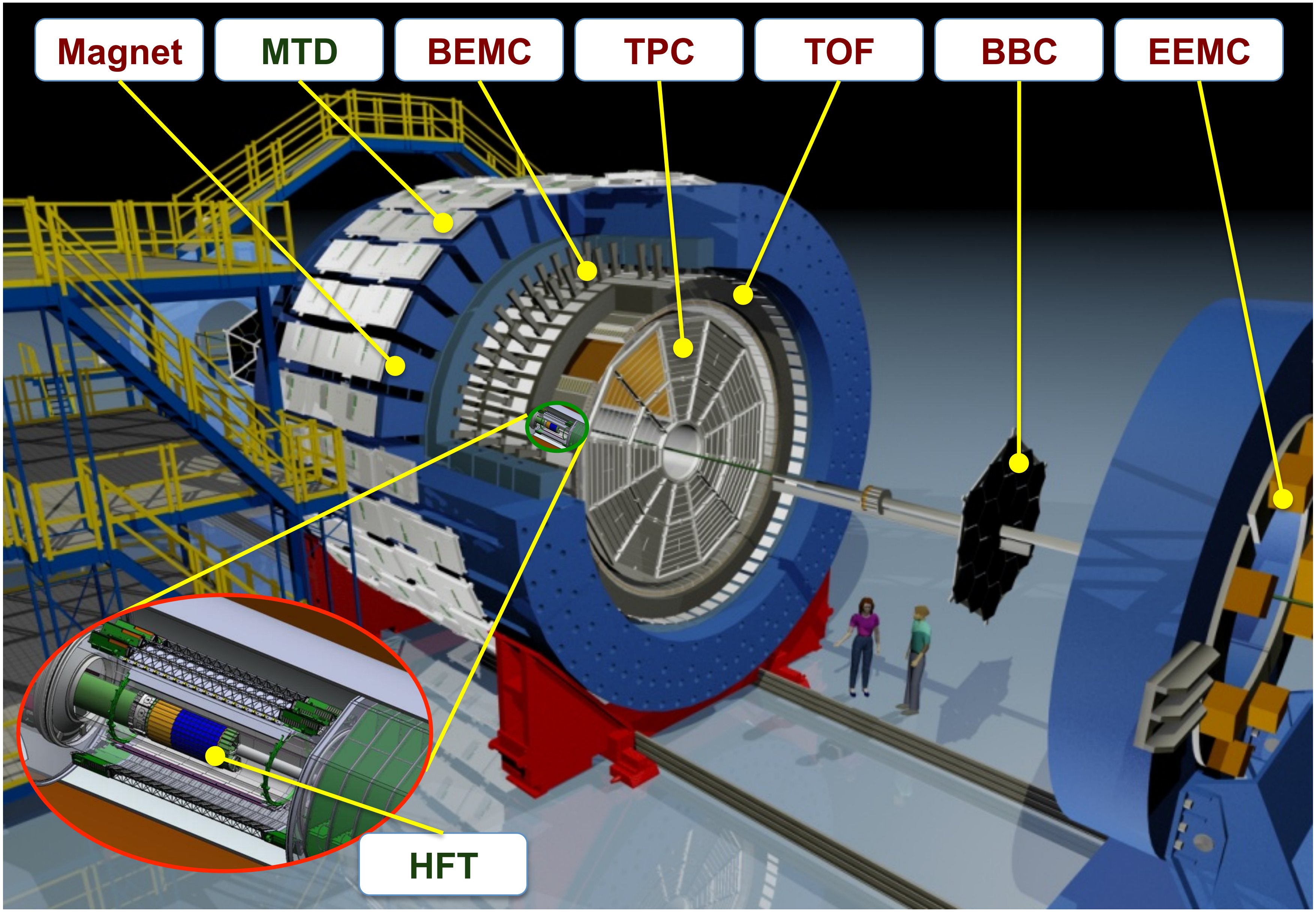
$\sqrt{s}$ = 200, 500 GeV

Animation M. Lisa

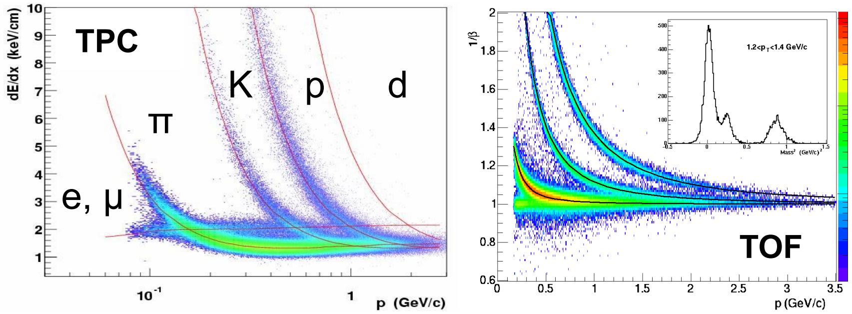
Part I

Recent Results from RHIC BES-I Program

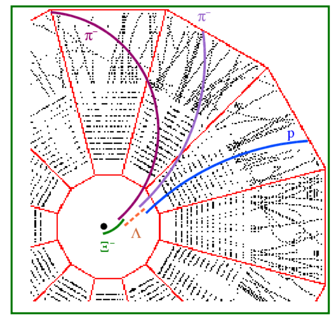
STAR Experiment

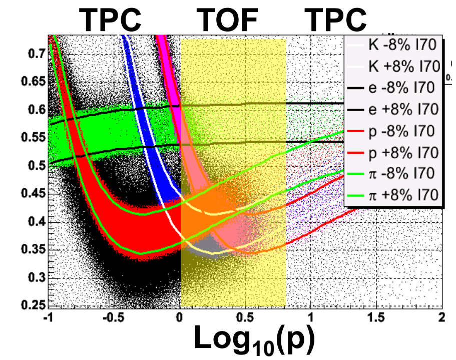


Particle Identification at STAR

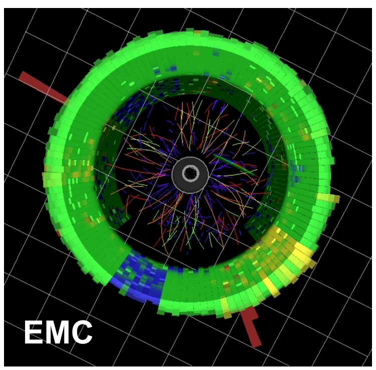


Charged hadrons

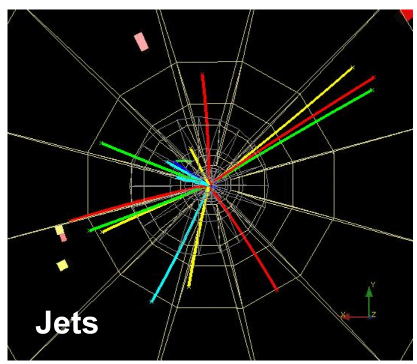




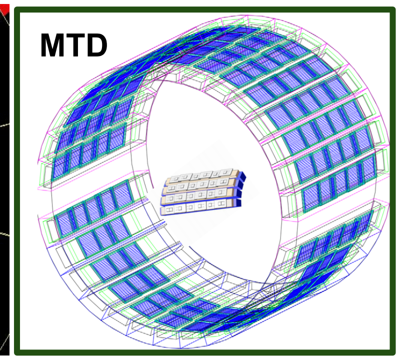
Hyperons & Hyper-nuclei



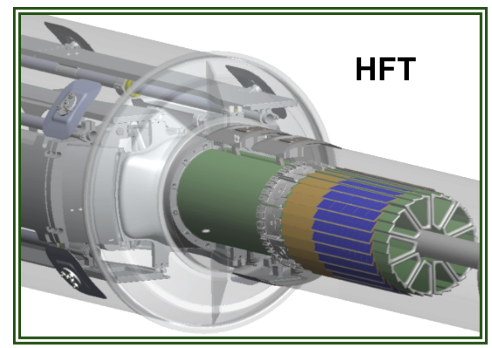
Neutral particles



Jets & Correlations



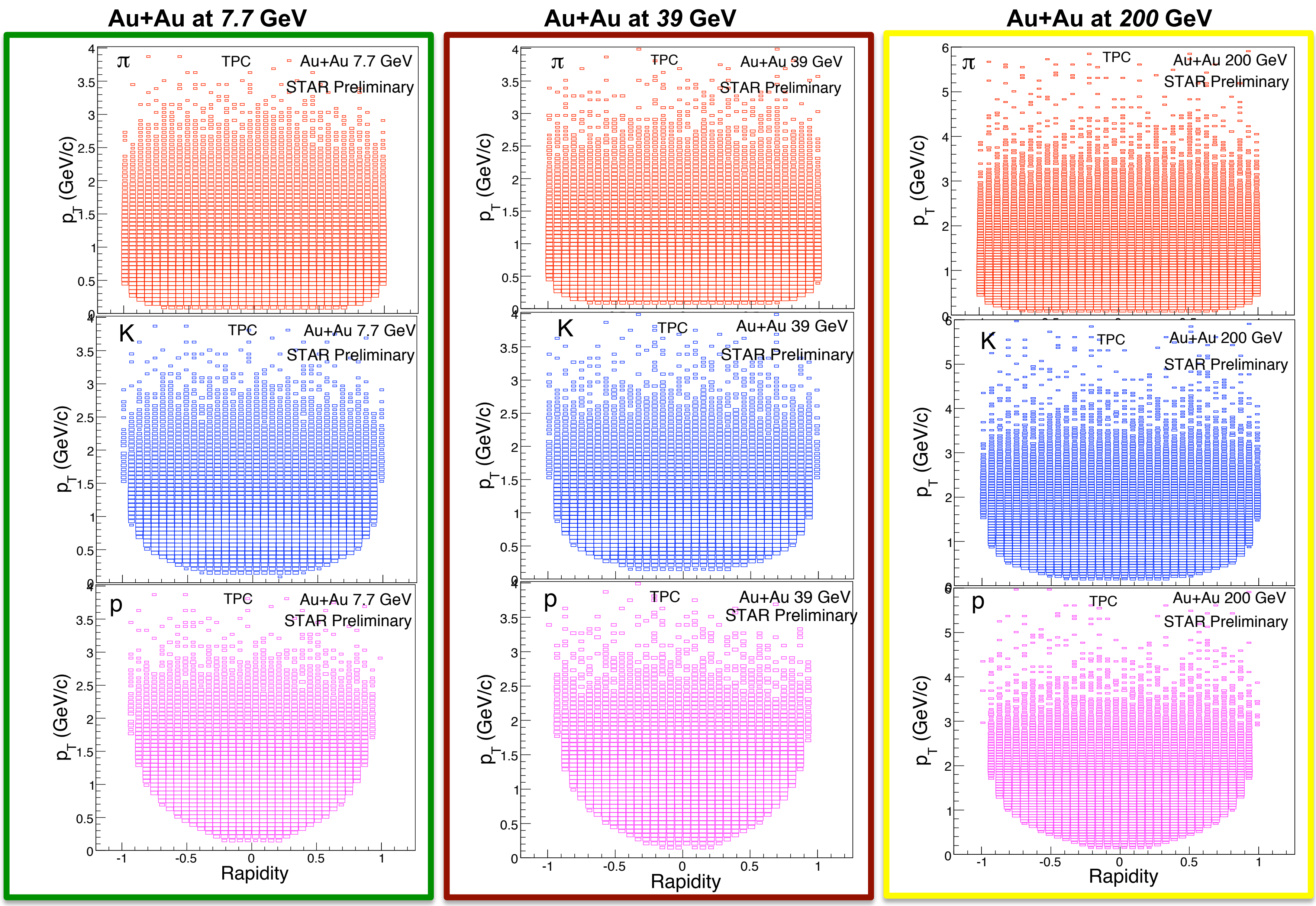
High p_T muons



Heavy-flavor hadrons

Multiple-fold correlations for the identified particles!

STAR PID for (π, K, p)



STAR Detector Configurations

	Period	Detectors	Physics
	2001-2010	**TPC**	*u, d, s*
	2010	TPC + TOF	*u, d, s + dilepton*
	2013	TPC + TOF + MTD	***u, d, s, c, b + dilepton***
	2014	TPC + TOF + MTD **+ HFT**	

➔ **STAR: Large coverage, excellent PID, fast DAQ**

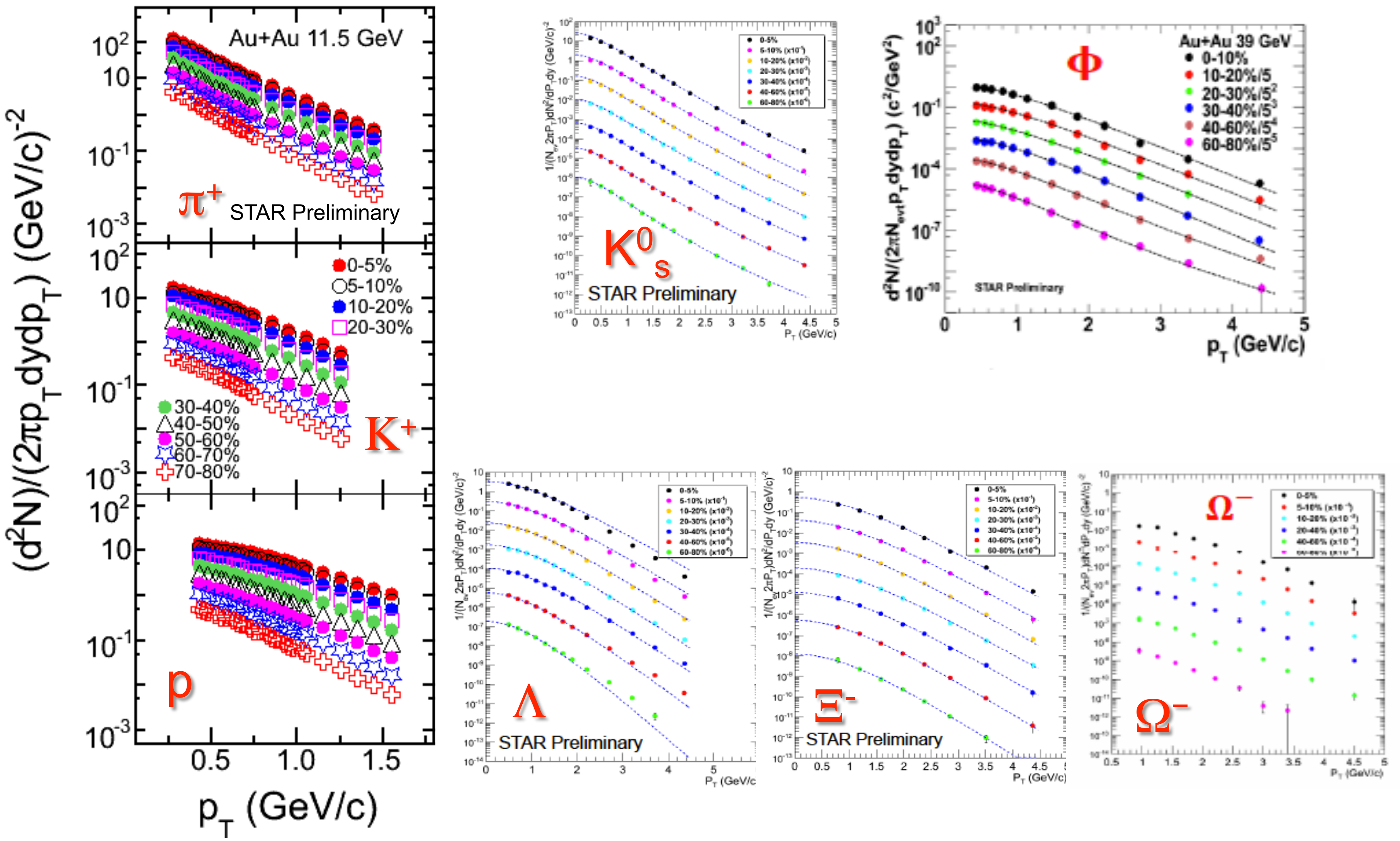
- detects nearly all particles produced at RHIC
- multiple fold correlation measurements
- **Probes: bulk, penetrating, and *bulk-penetrating***

➔ **STAR: Perfect mid-y collider experiment**

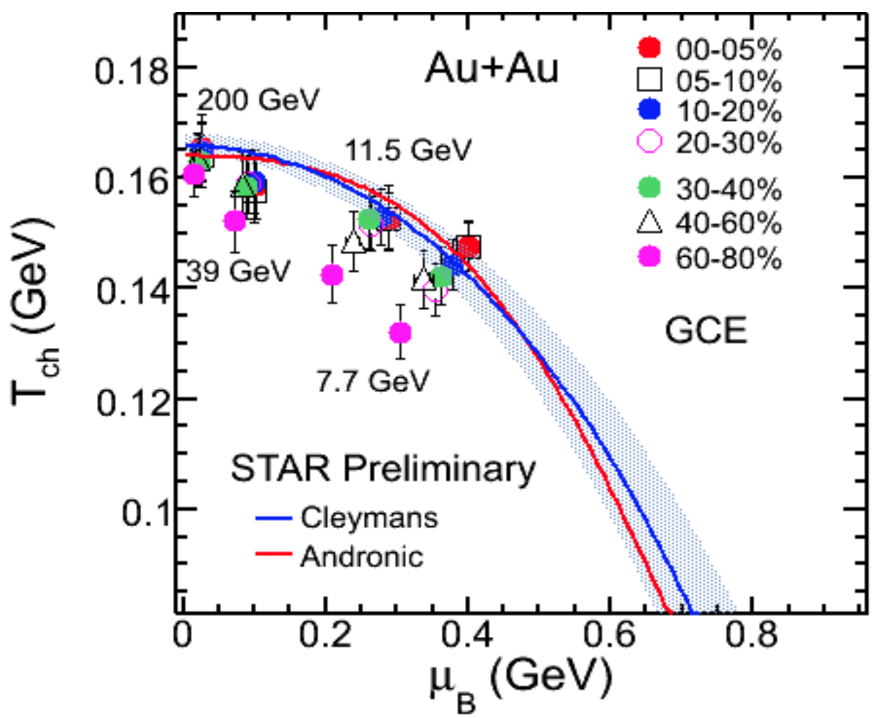
➔ **STAR: Expanding into forward rapidity regions**

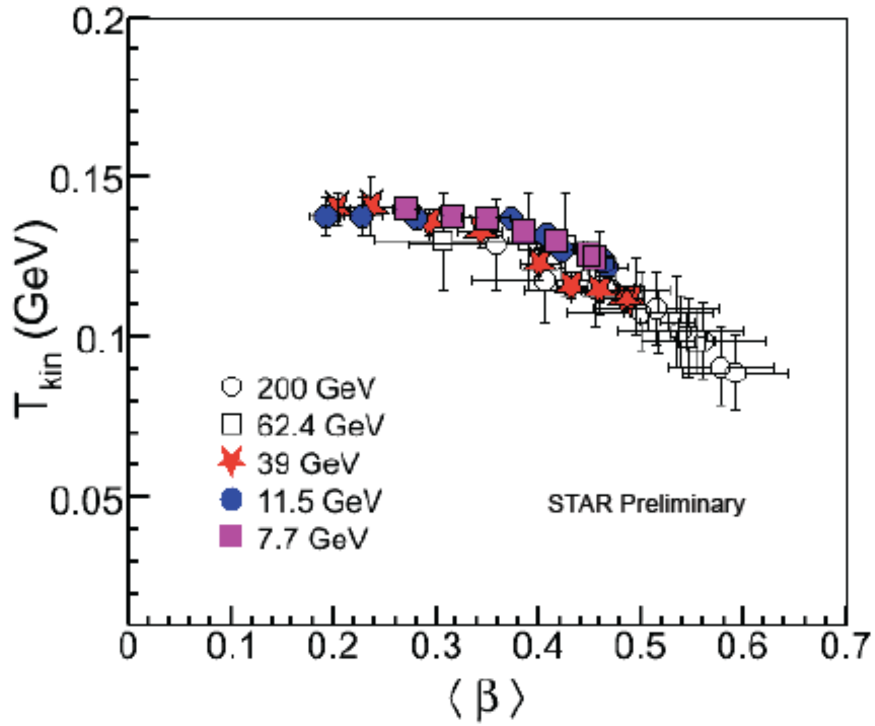
(1) Hadron Spectra

$\sqrt{s_{NN}}$ = *39* GeV Au+Au Collisions



Bulk Properties at Freeze-out





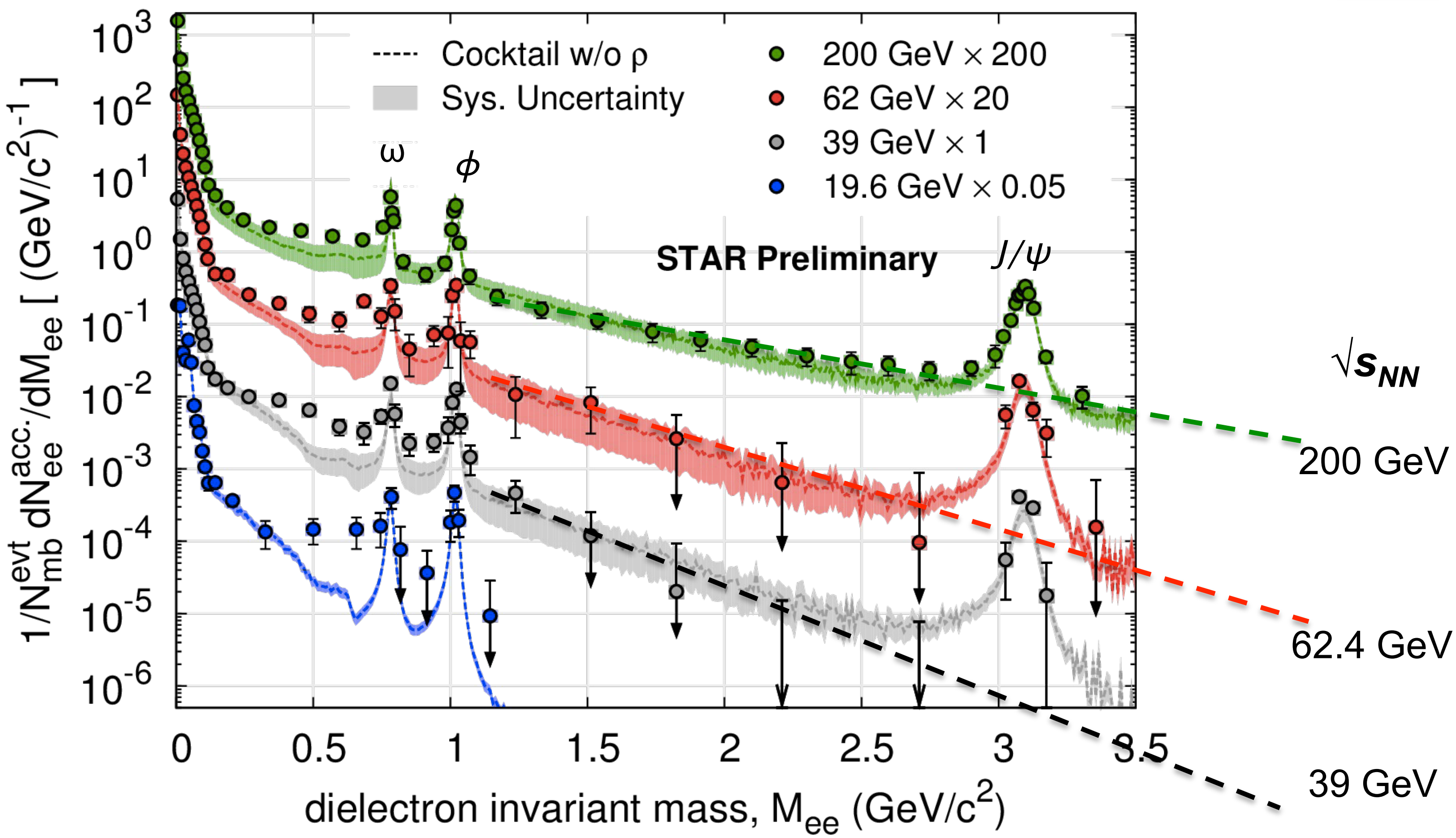
Chemical Freeze-out: (GCE)

- Centrality dependence in T_{ch} and μ_B
- The effect seems stronger at lower energy.

Kinetic Freeze-out:

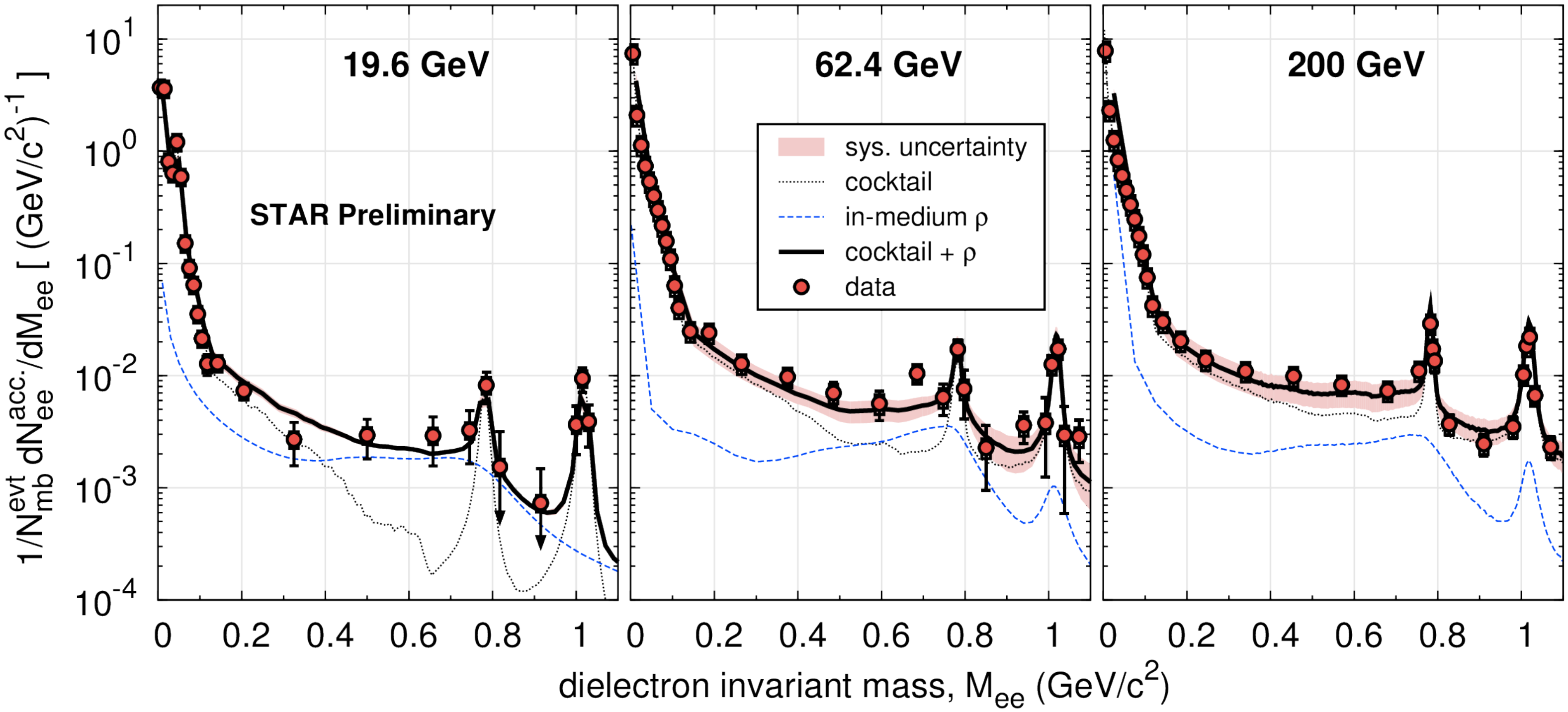
- Central collisions => lower value of T_{kin} and larger collectivity β
- Stronger collectivity at higher energy

(2) BES Dependence Dielectrons



1) Low mass reg. ($M_{ee} \leq$ 1GeV): no obvious energy dependence in the ratio of data/cooktail. At 19.6, the ratio is consistent with SPS results.
2) Intermediate mass reg. (1 ≤ M_{ee} ≤ 3GeV): clear energy dependence, correlated charm? Thermal radiation, ~exp($-M_{ee}/T$)?

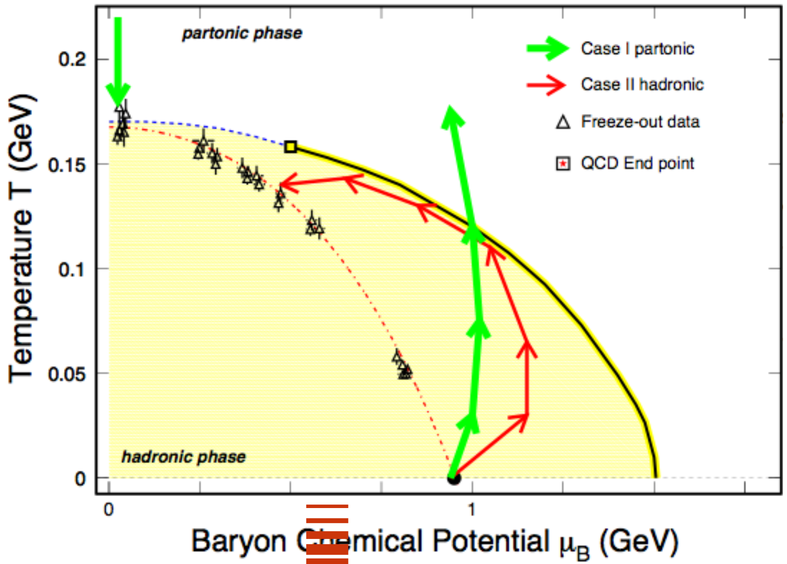
BES Dependence of Di-electrons

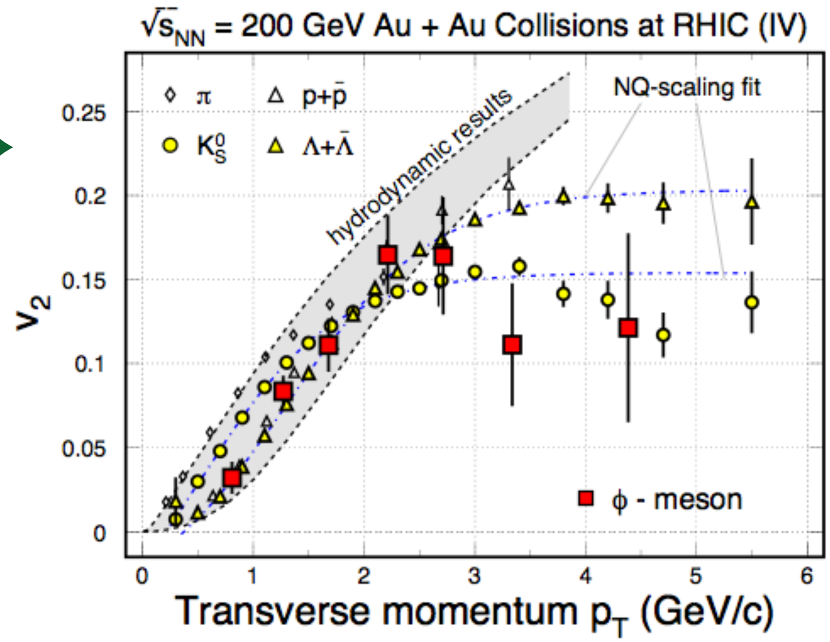


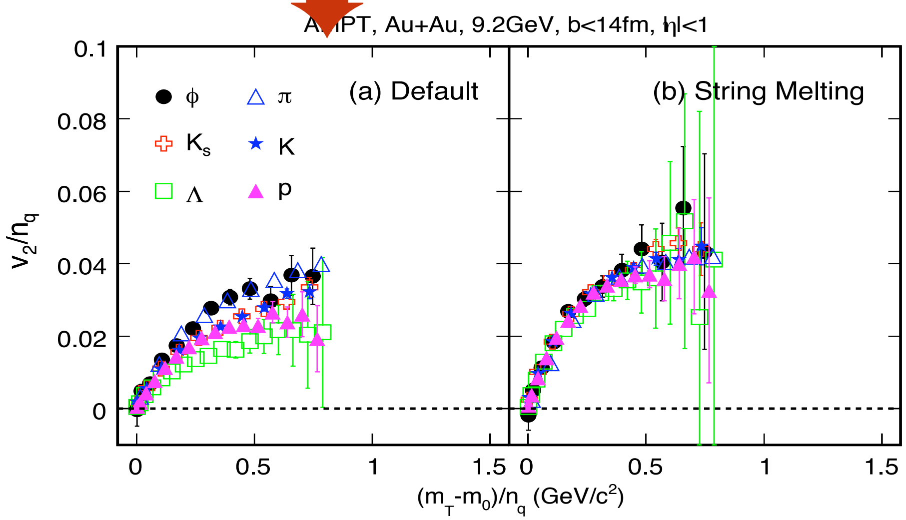
1) With in-medium broadened rho, model results are consistent with experimental data ($m_{ee} \leq 1$ GeV/c^2) at $\sqrt{s_{NN}}$ = 200, 62.4, 39, 27 and 19.6GeV

2) In Au+Au collisions at 200GeV, the centrality and p_T dependence results on data/hadronic cocktails ($m_{ee} \leq 1$ GeV/c^2) understood with current model calculations

(3) NCQ Scaling in v_2







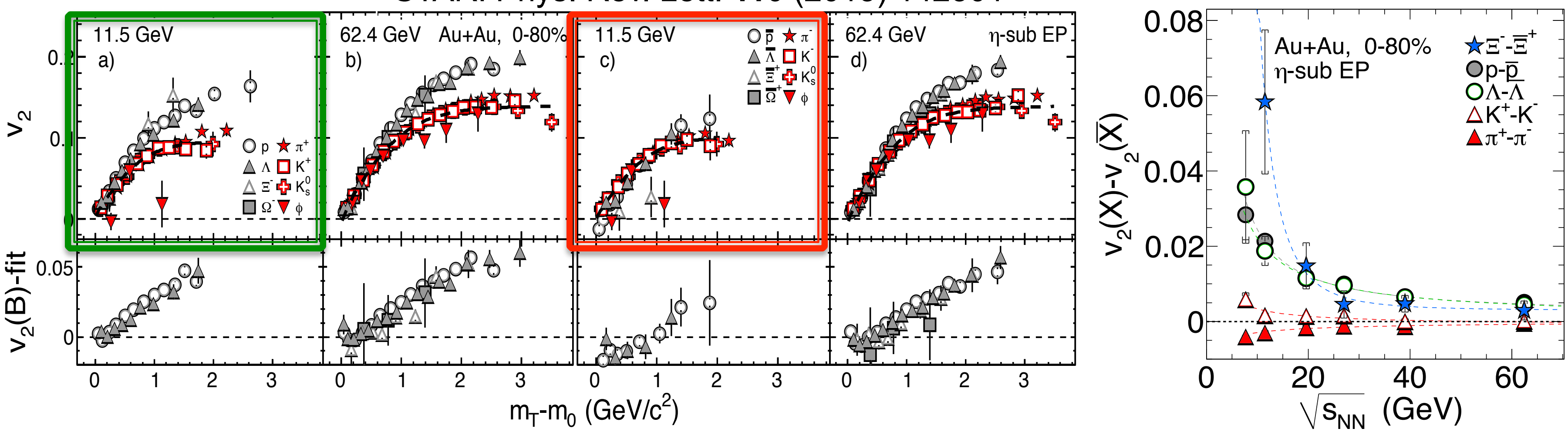
- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi,\, \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of φ will be small.

*** Thermalization is assumed!**

Collectivity v_2 Measurements

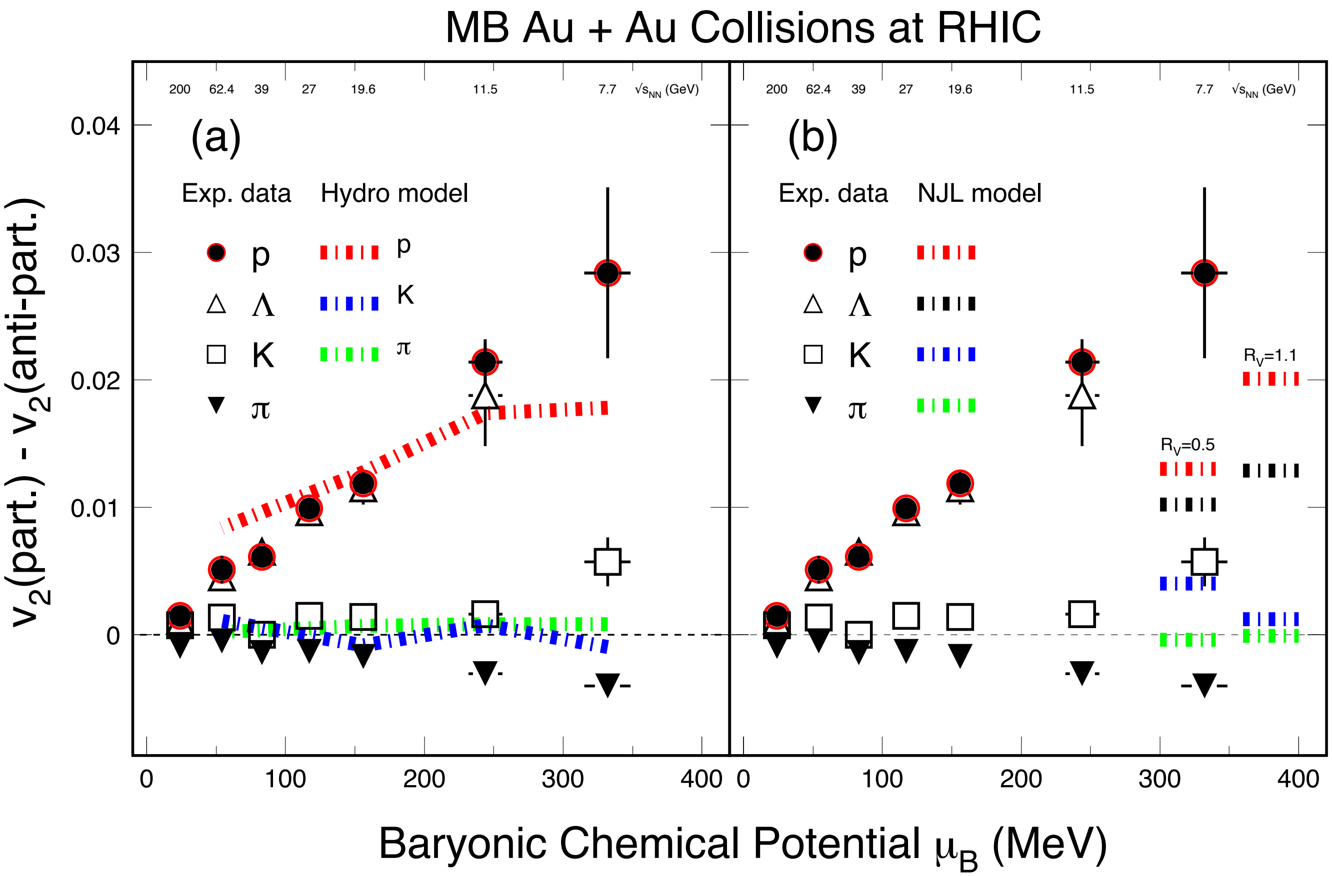
STAR: Phys. Rev. Lett. **110** (2013) 142301



1) Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions

2) At $\sqrt{s_{NN}}$ < 11.5 GeV, the v_2 **NCQ scaling is broken,** indicating hadronic interactions become dominant.

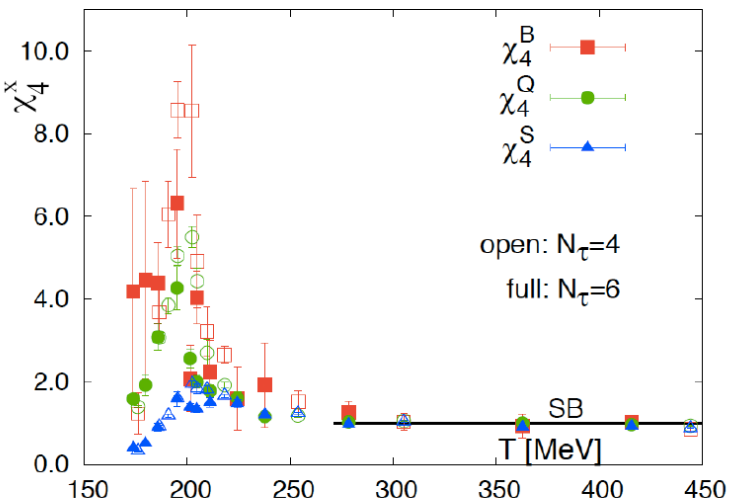
BES v_2 and Model Comparison

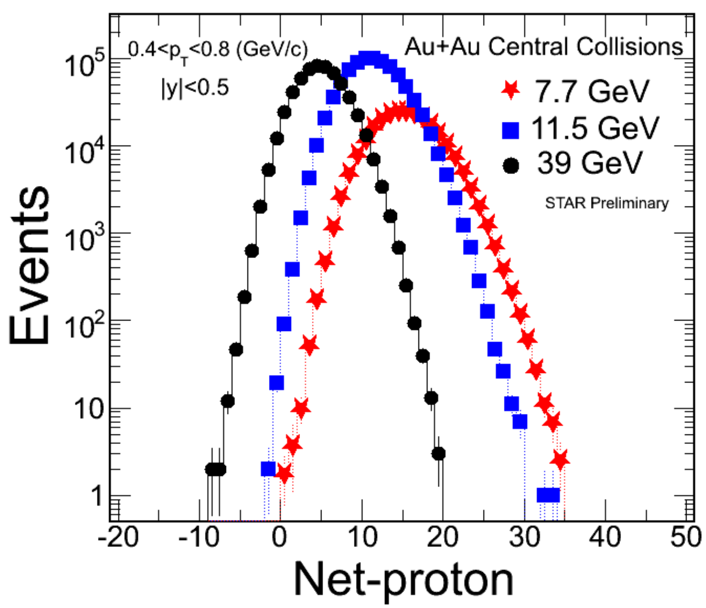


(a) Hydro + Transport: consistent with baryon results.
[J. Steinheimer, V. Koch, and M. Bleicher PRC86, 44902(13).]

(b) NJL model: Hadron splitting consistent. Sensitive to vector-coupling and net-baryon density dependent. [J. Xu, T. Song, C.M. Ko, and F. Li, arXiv:1308.1753]

(4) Higher Moments





1) High moments for conserved quantum numbers: ***Q, S, B***, in high-energy nuclear collisions

2) Sensitive to critical point (ξ correlation length):

$$\langle(\delta N)^2\rangle \approx \xi^2, \quad \langle(\delta N)^3\rangle \approx \xi^{4.5}, \quad \langle(\delta N)^4\rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

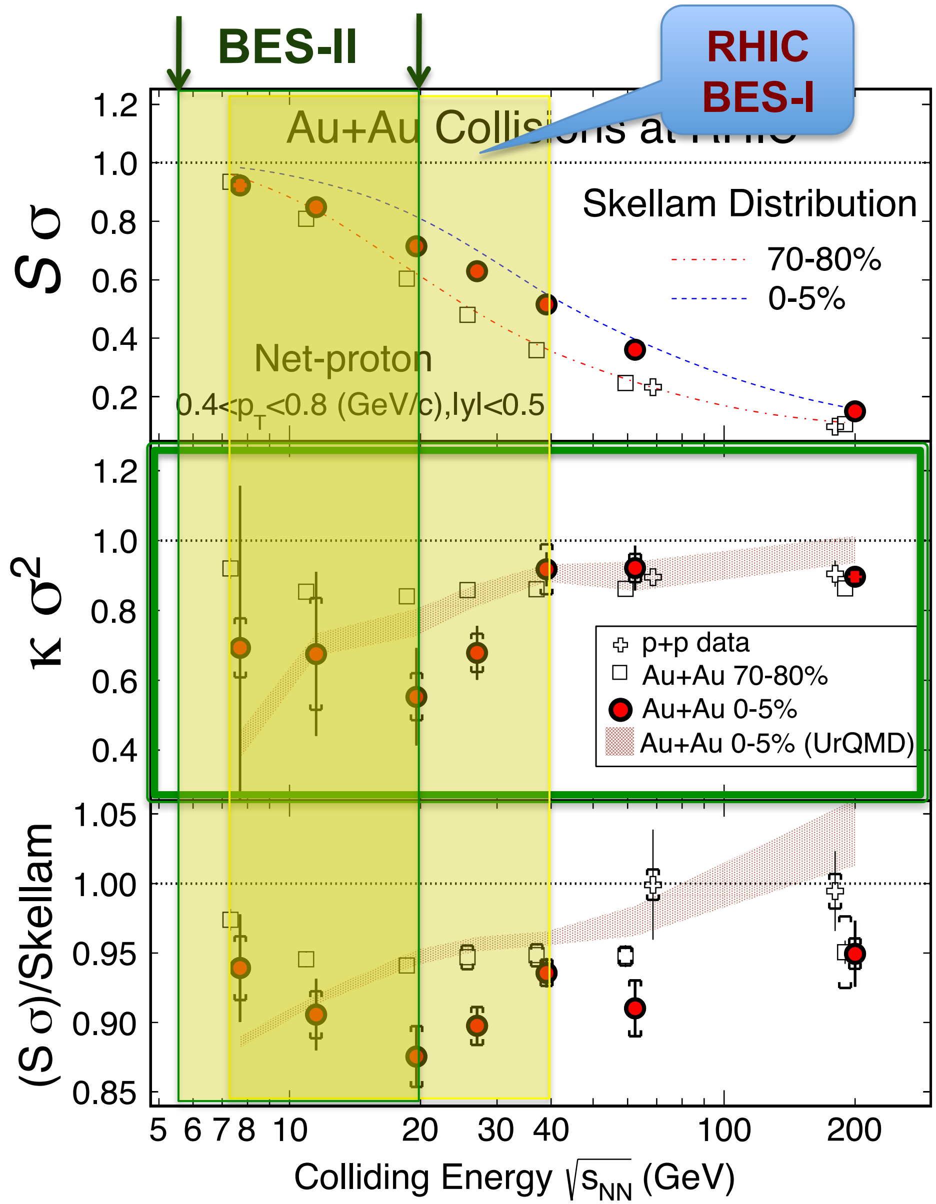
$$S*\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa*\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

4) Extract susceptibilities and freeze-out temperature. An independent/important test on thermal equilibrium in heavy ion collisions.

References:

- A. Bazavov et al. *1208.1220* (NLOTE) // STAR: *PRL*105, 22303(2010) // M. Stephanov: *PRL*102, 032301(2009) // R.V. Gavai and S. Gupta, *PLB696*, 459(2011) // S. Gupta, et al., *Science*, 332, 1525(2011) // F. Karsch et al, *PLB695*, 136(2011) // S.Ejiri etal, PLB633, 275(06) // M. Cheng et al, *PRD79*, 074505(2009) // Y. Hatta, et al, *PRL91*, 102003(2003)

Net-proton Higher Moments



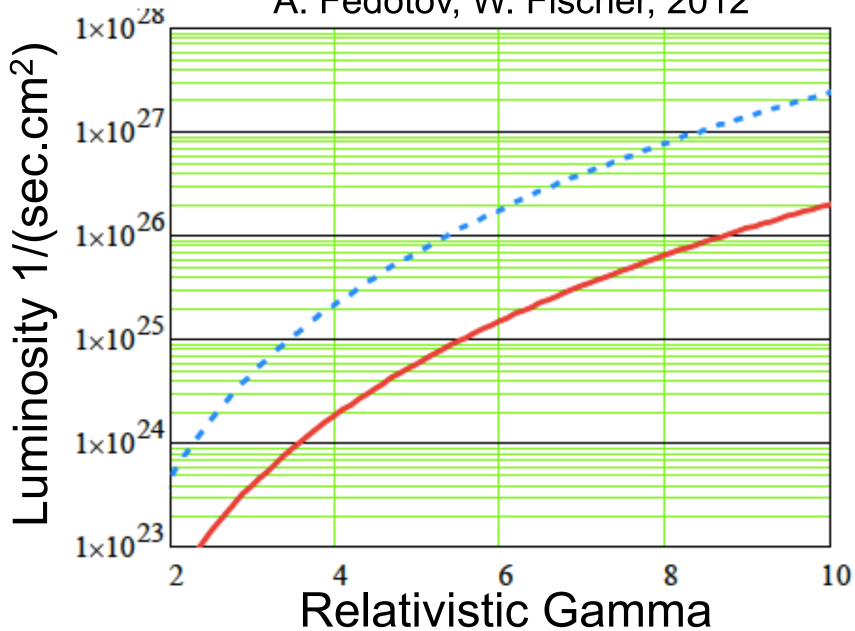
STAR net-proton results:

1) All data show deviations below Poisson beyond statistical and systematic errors in the 0-5% most central collisions for $\kappa\sigma^2$ and $S\sigma$ at all energies. Larger deviation at $\sqrt{s_{NN}}$ ~ 20GeV
2) Independent p and pbar production reproduces the observed energy dependence of $\kappa\sigma^2$ and $S\sigma$
3) UrQMD model show monotonic behavior in the moment products
4) Higher statistics needed for collisions at $\sqrt{s_{NN}}$ < *20 GeV*. **BES-II is needed**.

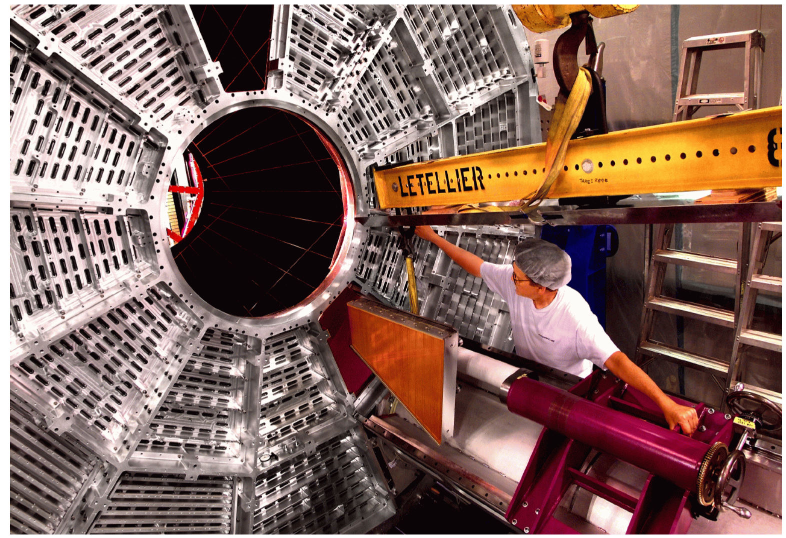
STAR: 1309.5681

BES-II: e-cooling, iTPC Upgrades

A. Fedotov, W. Fischer, 2012



$\sqrt{s_{NN}}$ (GeV)	~ 5	~ 20
Increasing factor	3-5	10



iTPC Upgrade: $|\eta| \leq 1.1$ ➔ **$|\eta| \leq 1.7$**

i) Crucial for BES-II

ii) Important for eSTAR

1) BES-II at $\sqrt{s_{NN}}$ < 20 GeV

2) RHIC e-cooling will provide increased luminosity ~ x3 - 10

3) STAR iTPC upgrade extend mid-rapidity coverage – beneficial to several crucial measurements

Part I: Summary

(1) In high-energy nuclear collisions, $\sqrt{s_{NN}} \geq 200$ GeV, hot and dense ***matter, with partonic degrees of*** **freedom and collectivity, has been formed**

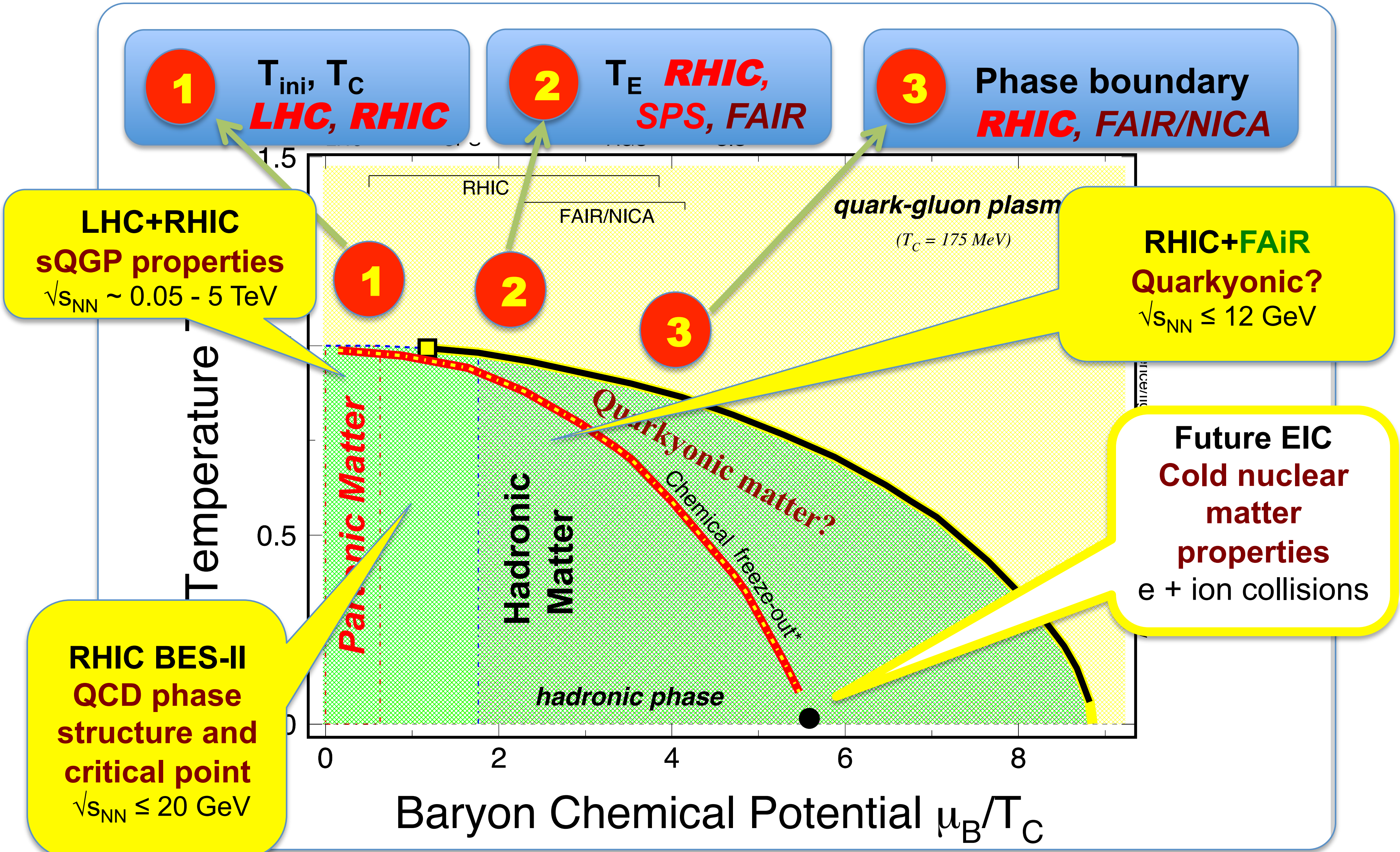
(2) RHIC BES-I:

[partonic] < μ_B ~ *110* (MeV) ($\sqrt{s_{NN}} \geq 39$ GeV)

[hadronic] > μ_B ~ *320* (MeV) ($\sqrt{s_{NN}} \leq 11.5$ GeV)

(3) RHIC BES-II: focus at $\sqrt{s_{NN}} \leq 20$ GeV region with higher luminosity (x10) + detector upgrade iTPC: Run18 (2017)

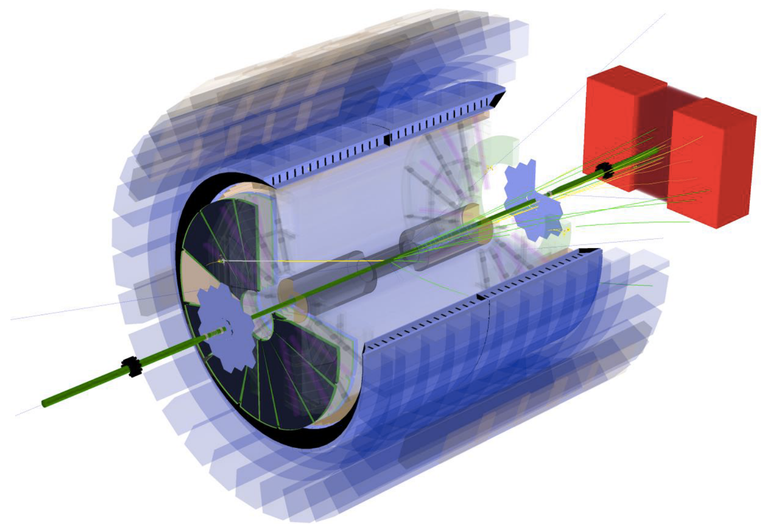
Exploring QCD Phase Structure



eSTAR: The Future of RHIC

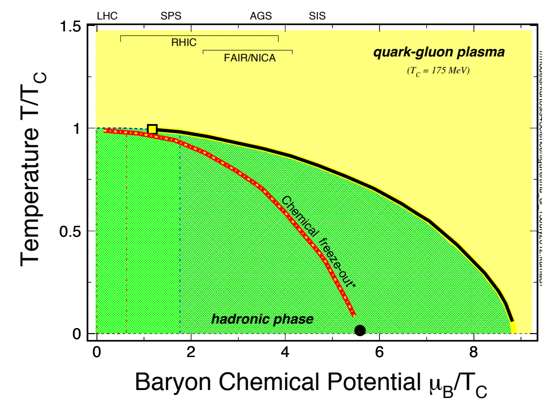
eSTAR: A Letter of Intent

The STAR Collaboration



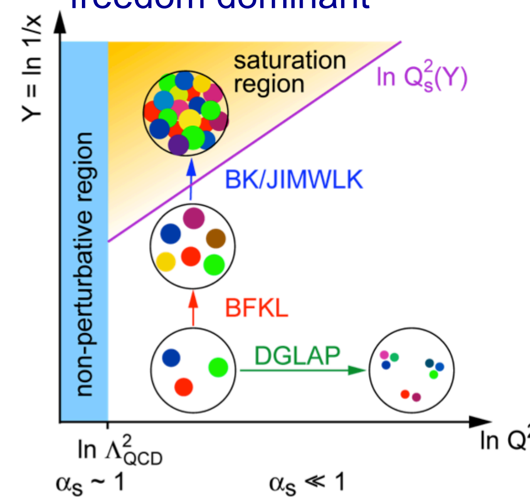
October 1, 2013

Hot QCD Matter



Cold QCD Matter

gluon degrees of freedom dominant



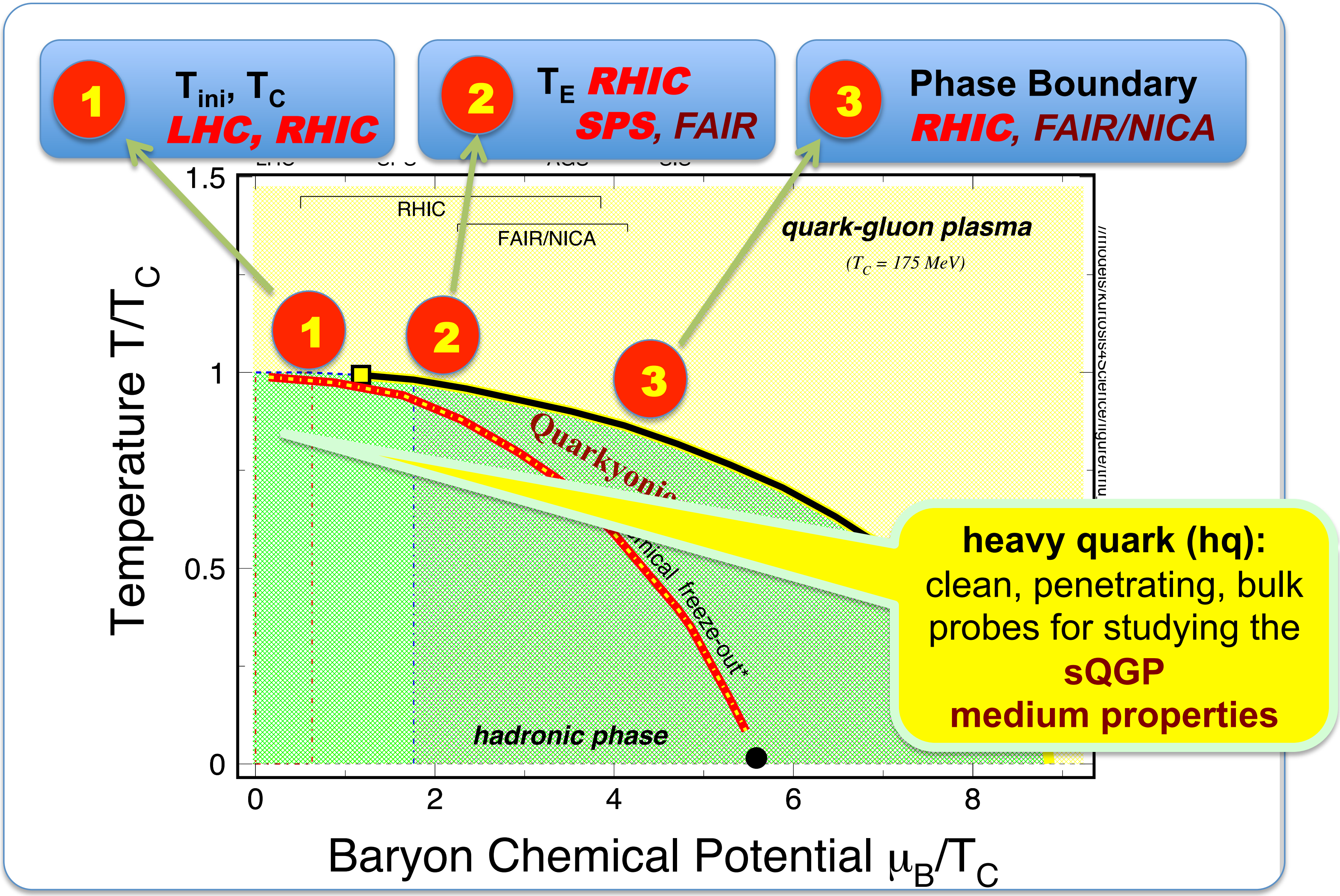
Part II

Study Quarkonia Production at RHIC and LHC

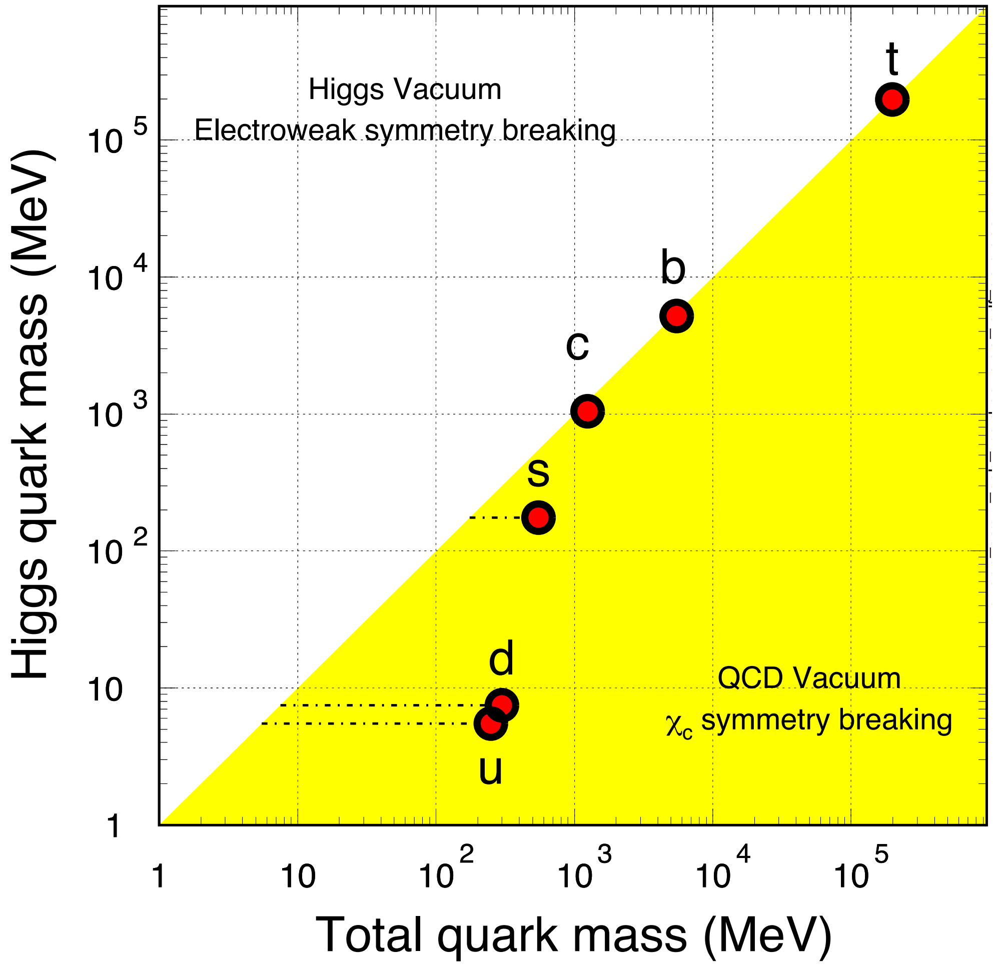
Yunpeng Liu[1], Zebo Tang[2], Kai Zhou[3], NX[4], Pengfei Zhuang[3]

[1]: Texas A&M, USA
[2]: USTC, Hefei, China
[3]: Tsinghua University, Beijing, China
[4]: CCNU and LBNL, China/USA

The QCD Phase Diagram and High-Energy Nuclear Collisions



Why Heavy Quark?



B. Mueller, arXiv: 0404015
X. Zhu, *et al,* PL**B647**, 366(2007)

Mass Matters:

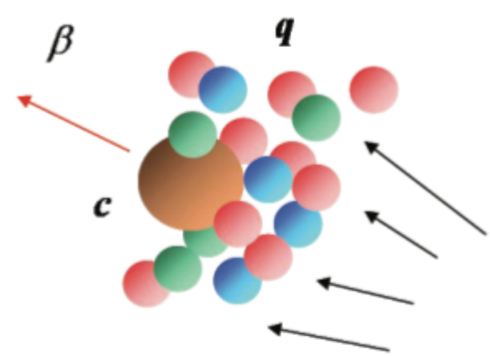
- Heavy quark masses are not altered in QCD medium
- Negligible thermal production in collisions

➢ Tool for studying properties of the hot/dense medium at the early stage of collisions

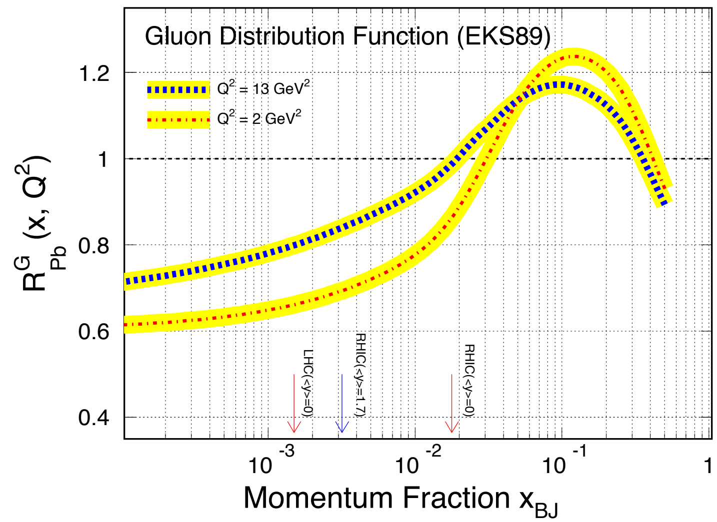
Heavy quark collectivity

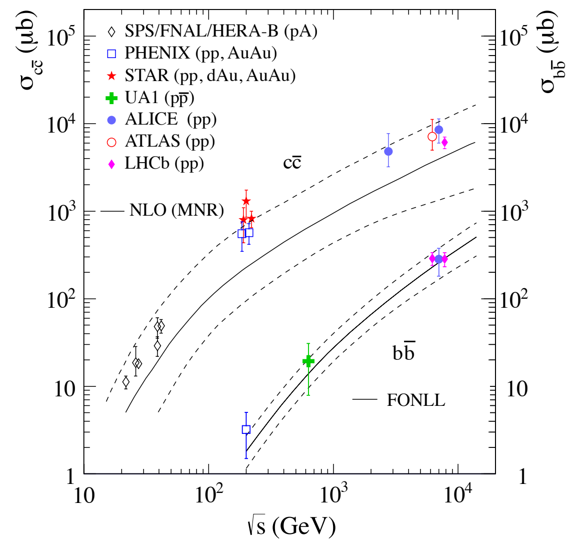
➔ **Thermalization**

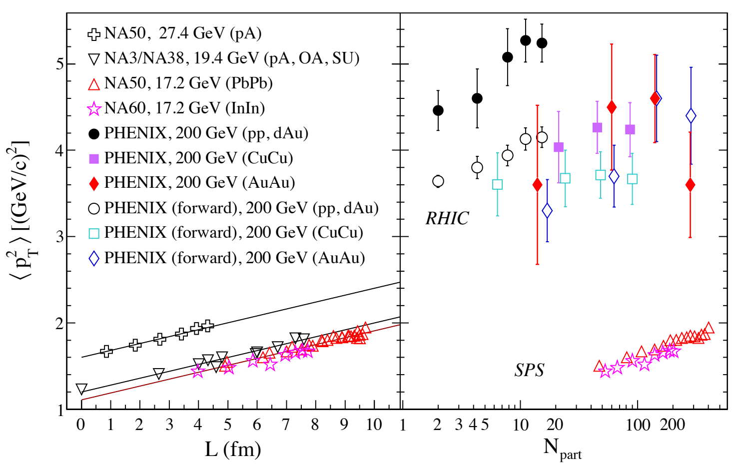
➔ **Deconfinement**



Key Effects







Cold Matter Effects:

1) Npdf: shadowing effect
2) Production cross-sections
3) Cronin effect

Hot Matter Effects:

1) Debye screening
2) Regeneration

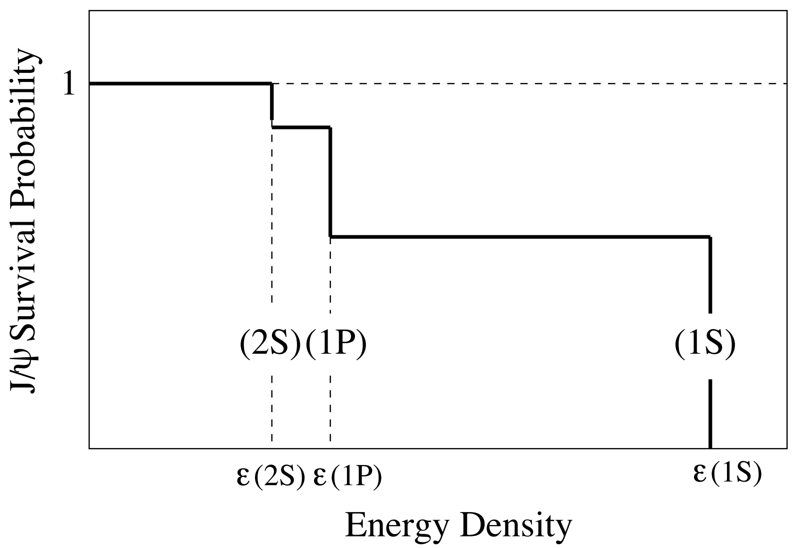
In Nucleus-Nucleus Collisions

Sequential Suppressions

Debye Screening:

$$J/\psi \rightarrow c + \bar{c} \qquad r_{J/\psi} \geq \lambda_D \approx \frac{1}{g(T) \bullet T}$$

1) Total # of J/ψ reduces
2) Sensitive to hot/dense medium



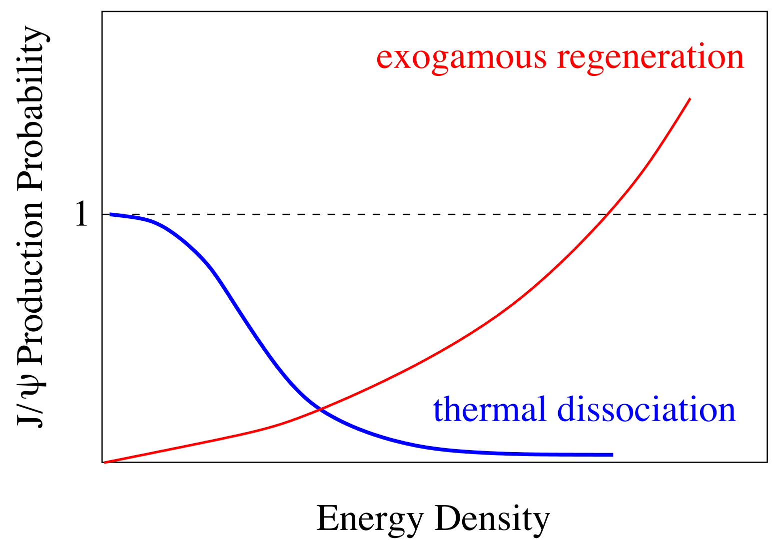
Matsui & Satz, PL**B178**, 178(1986).

Regenerations

At the boundary of hadronizatipn:

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

1) Total # of J/ψ increases
2) Sensitive to hot/dense medium



A. Adronic, *et al*, PL**B652**, 659(2007).

Modification Factors

$$R_{AA} = \frac{\langle \mathbf{N} \rangle^{AA}}{n_{bin}^{AA} \langle \mathbf{N} \rangle^{pp}}$$

1) Traditional R_{AA} depends on the (TMD) p_T integrated yields. Sensitive to *Npdf** and model dependent parameter n_{bin}.

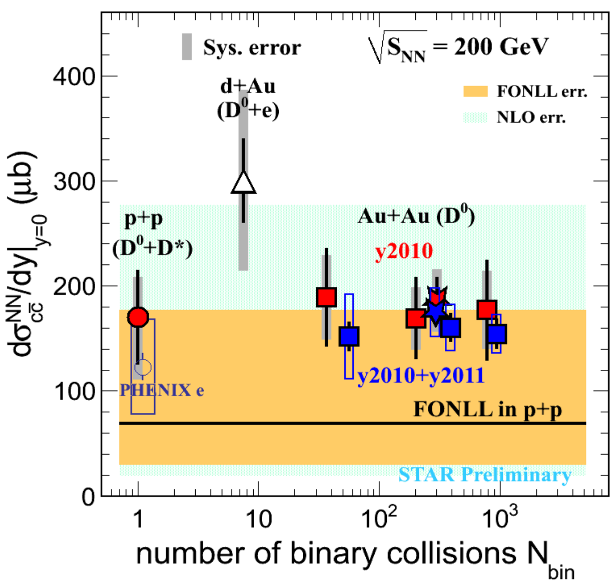
$$r_{AA}(p_T^2) = \frac{\langle p_T^2 \rangle^{AA}}{\langle p_T^2 \rangle^{pp}}$$

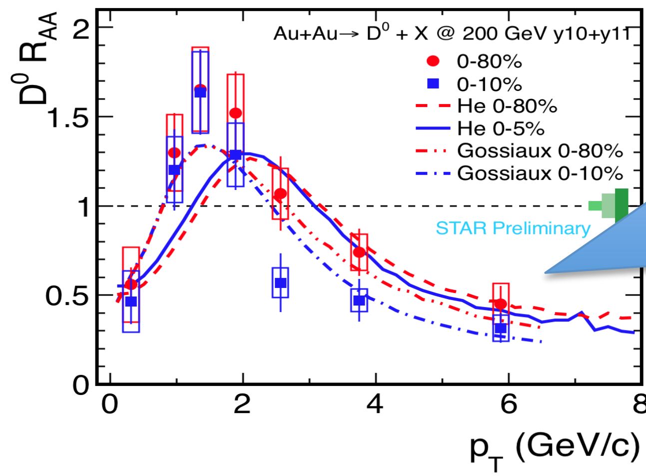
2) The TMD dependent $r_{AA}(p_T{}^2)$ * * more sensitive to ***dynamical medium effects*** including Cronin effect, Debye Screening, and Regeneration.

* H. Satz, arXiv: 1303.3493
* * Kai, Xu, Zhuang, *NP**A834***, 249(2010)

TMD: transverse momentum distribution

Charm Production at RHIC



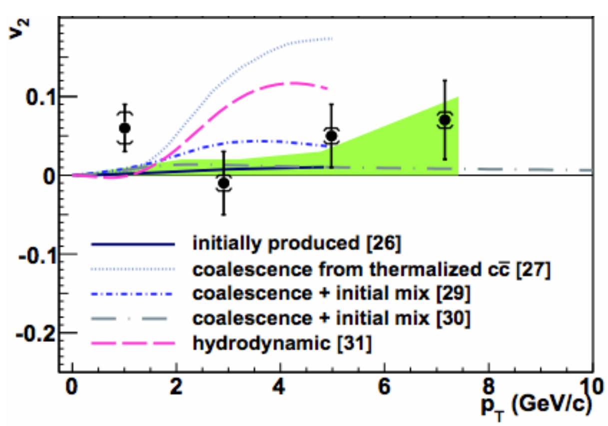


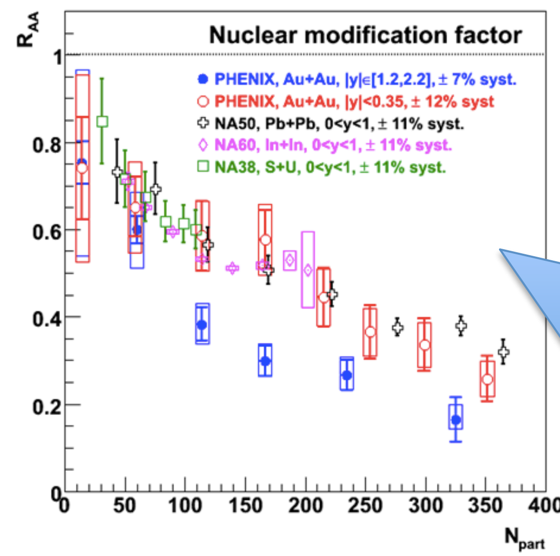
Open Charm:

(1) Initial production follows binary collisions

(2) Suppressed at p_T> 3GeV/c.

QM 2011, QM 2012





J/ψ: (closed Charm)

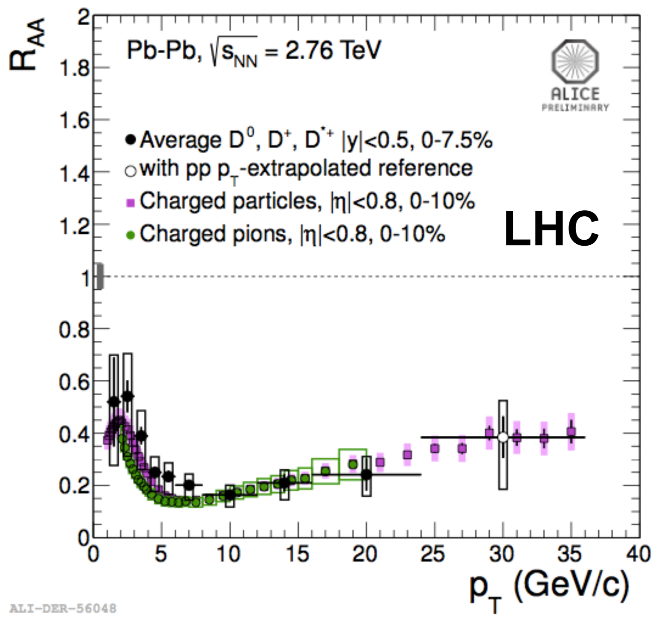
(1) Suppressed in more central collisions. Similar observations at LHC

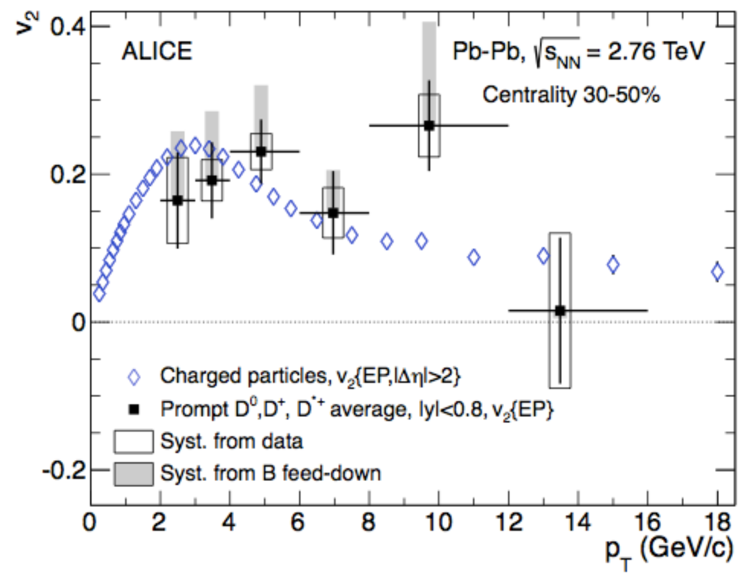
(2) Near zero v_2.

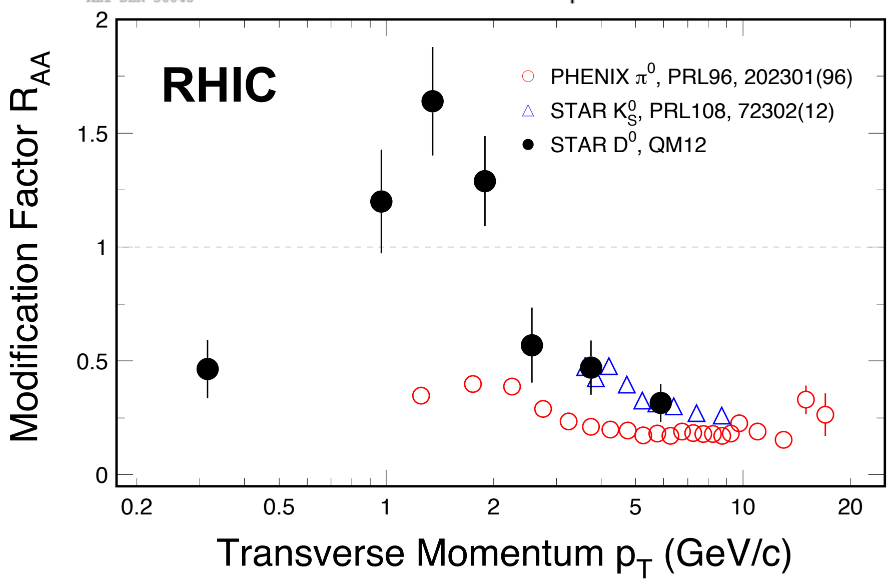
Where is the true QCD medium effect?

He, et al. arXiv: 1204.4442; Gossiaux, et al. arXiv: 1207.5445

Charm Interactions with Medium







1) As for light-quark hadrons, charm-quark hadrons show suppression at intermediate p_T region: energy loss of hq!

2) At LHC, charm-quark hadrons show non-zero collectivity: strong interactions among hq and the hot/dense medium.

Onia Production in HI Collisions

Cold QCD effects
Shadowing, Cronin

Hydro + Transport

Hadronization

Pythia*
heavy-quark

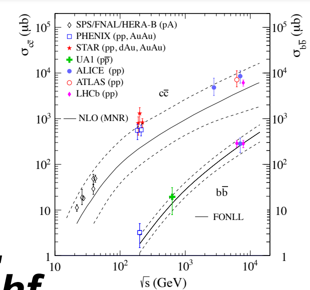
Hot QCD effects
Debye screening
Energy loss

Regeneration

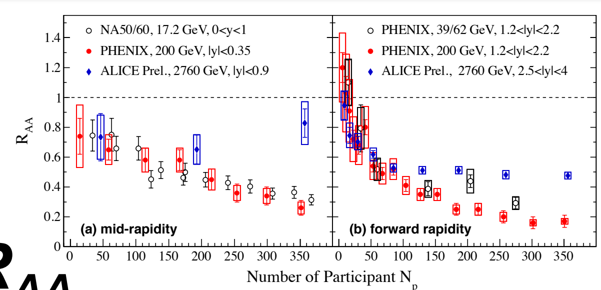
p_T broadening
(for all hadrons)

- p_T decreasing
- thermalization
(hq hadrons)

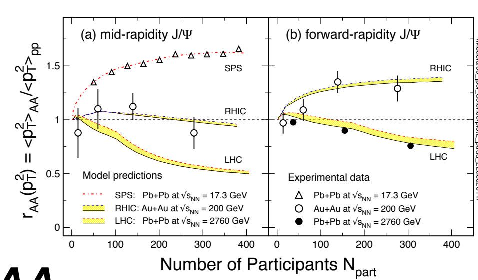
σ_{hf}

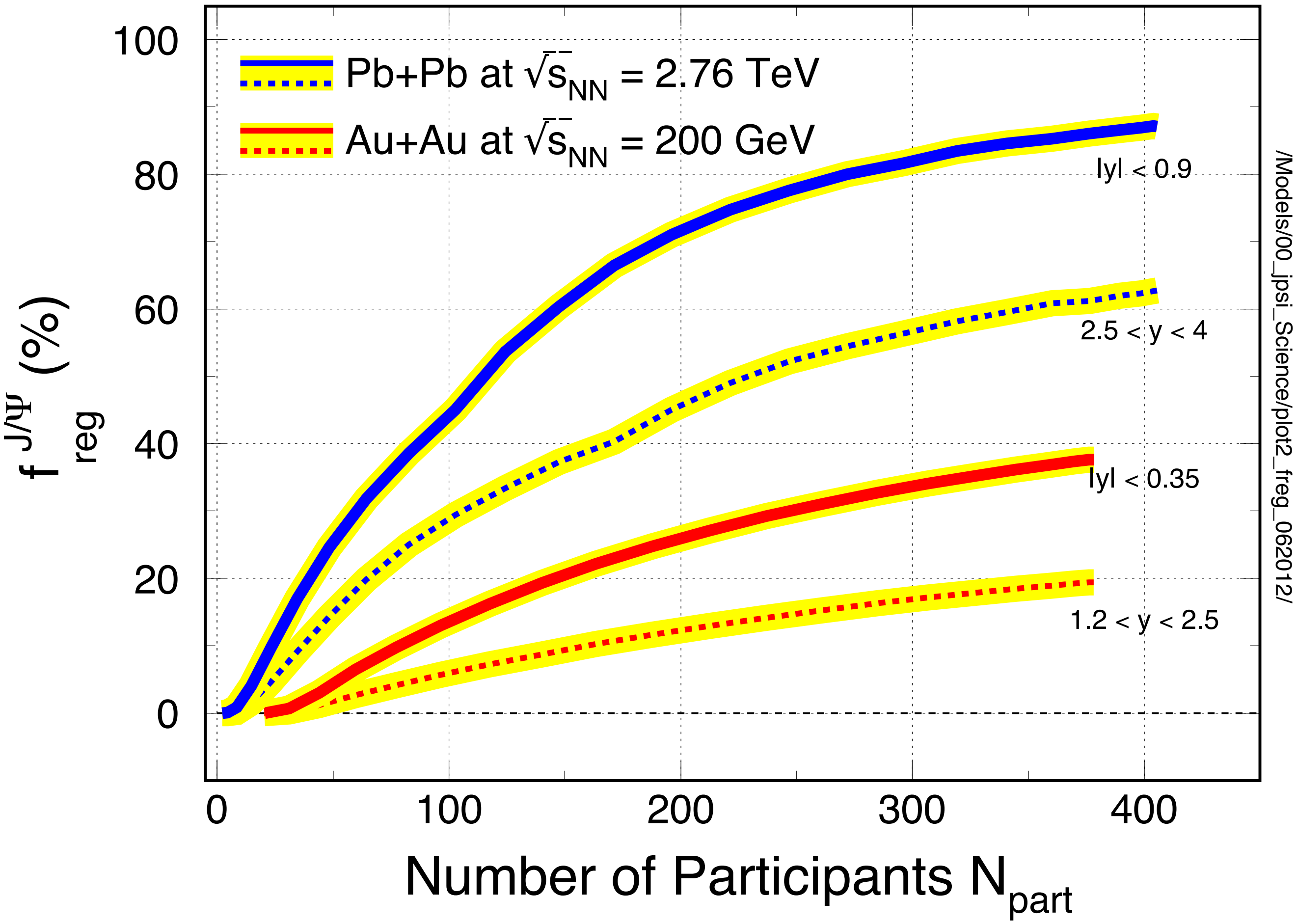


R_{AA}



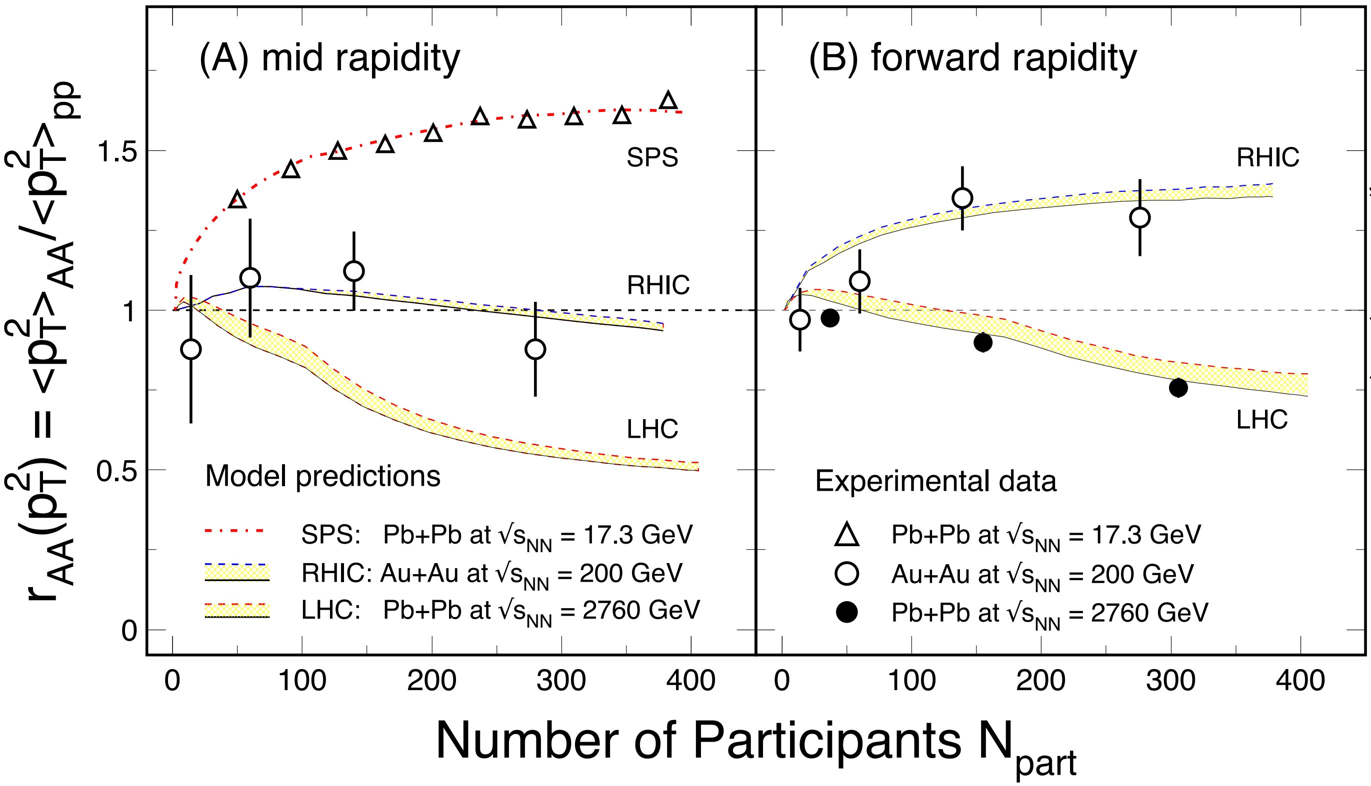
r_{AA}





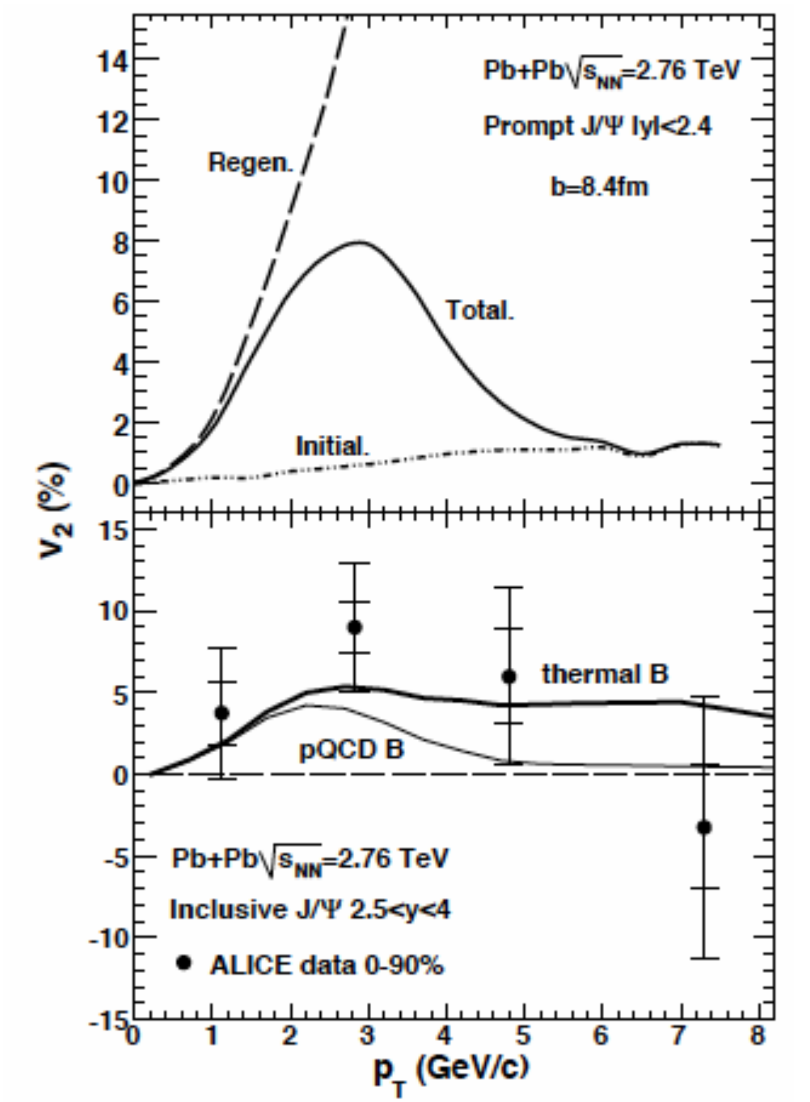
Driven by the initial heavy quark production cross-sections, much larger fraction of J/ψs are formed via regeneration, at hadronization, at LHC than that from RHIC!

T.M.D.: Charmonium Production

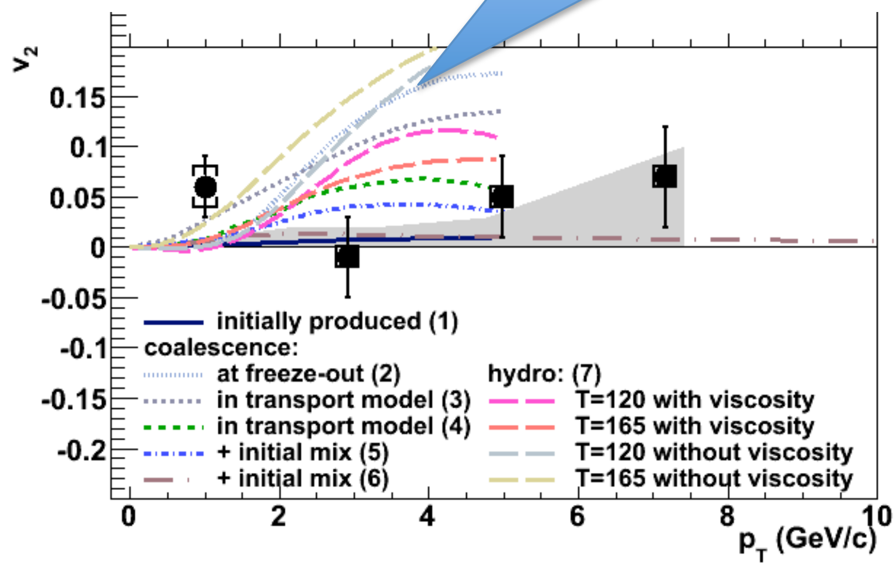


1) **LHC:** large fraction of final *J/ψ*s produced via regeneration leads to lower value of $<p_T>$
2) **SPS:** all final *J/ψ*s are survivors. Increase of $<p_T>$ due to the initial Cronin scatterings
3) **RHIC:** mixture of initial and regenerated *J/ψ*s

J/ψ v_2 Results



Hydro model calculations failed.

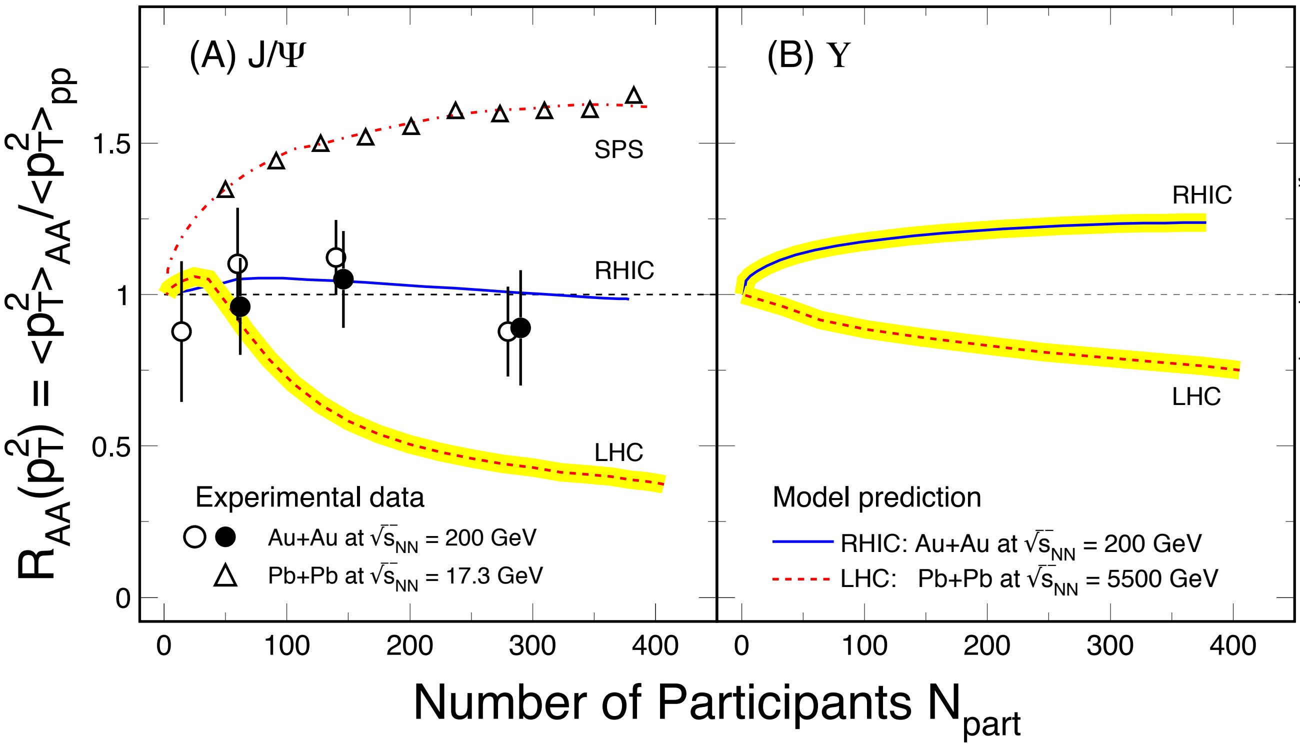


(1) J/ψ v_2 is consistent with zero for MB Au+Au collisions at RHIC.

(2) At LHC energy, finite value of the J/ψ v_2 is seen at the forward-y. Larger v_2 is predicted for mid-y J/ψs.

Stronger regeneration effect at LHC!

T.M.D.: Quarkonia Production

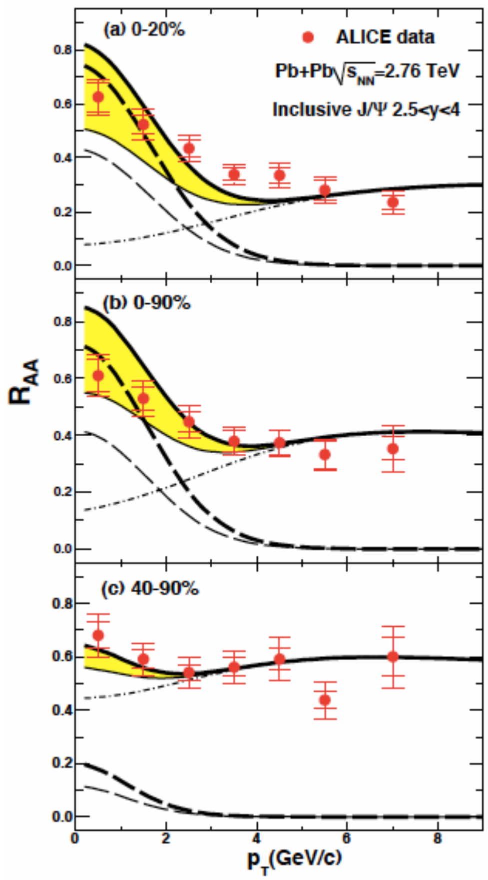


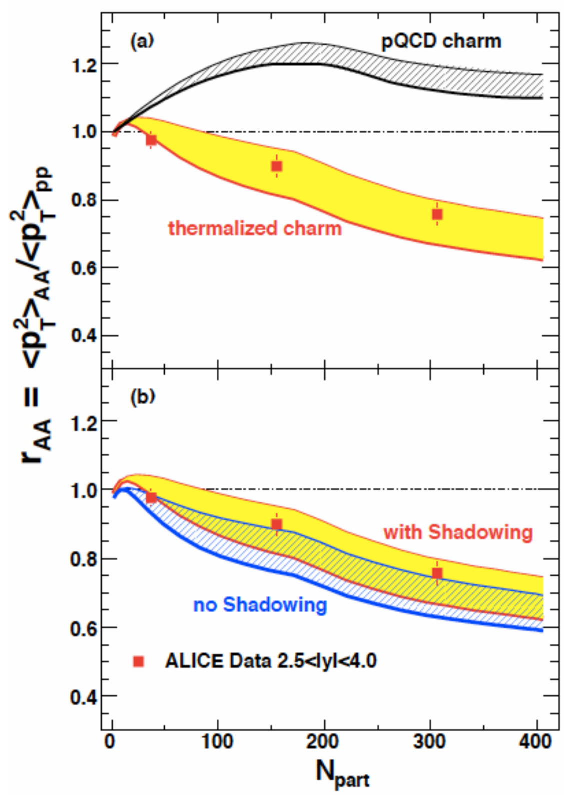
(A) *J/ψ* productions at SPS, RHIC and LHC

(B) *Upsilon* production:

- RHIC: negligible regenerations, Cronin effect dominant.
- LHC: sizable contributions from regenerations.

Regeneration at Low p_T Region





Coalescence J/ψ concentrate at the small transverse momenta: from low p_T charm quarks and lower averaged J/ψ $\langle p_T \rangle$ and $\langle p_T^2 \rangle$. Initial shadowing effect is small on r_{AA}.

At LHC: Deconfinement and Thermalization of charm quarks!

Part II: Summary

(1) In high-energy collisions, transverse momentum distributions (TMD) are important!

(2) The effects of Debye Screening and Regeneration are opposite for quarkonia production. **They are all medium effects.**

(3) J/ψ production showing by $r_{AA}(p_T^2)$, demonstrated the influence of Debye screening and the regeneration, implying the formation of the hot/dense medium, the QGP, at RHIC and LHC.

At LHC: charm quarks are consistent with the scenario of thermalization.

Thank you!