1) Please silent your cell phone

2) Please ask questions:

“There is no stupid question”

“学而不问，非礼也”

nxu@lbl.gov

October 17, 2016

Study emergent properties of matter with QCD degrees of freedom

Introduction to the Physics of High-Energy Nuclear Collisions (Heavy Ion Physics II)

Nu Xu (1,2)

Many Thanks to Organizers!

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Outline

I. **Introductions**

II. **Status of the Relativistic Heavy Ion Collider**
- Accelerator complex and Detectors
- **Definitions**
- Future planes

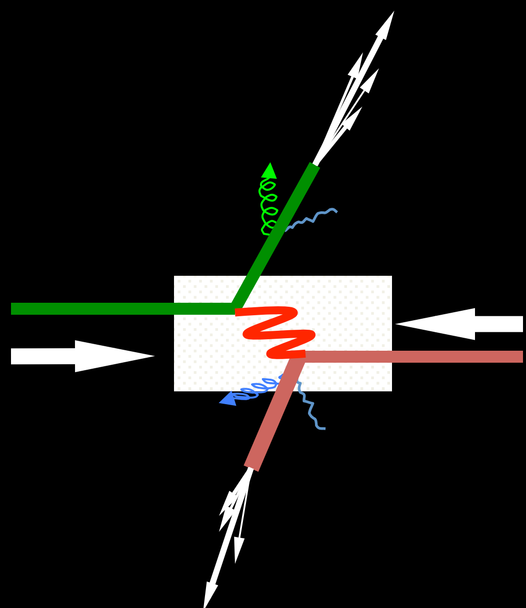
III. **Selected topics in High-energy Nuclear Collisions**
i. Parton Energy Loss
ii. Collectivity
iii. Criticality
iv. Chirality
v. Heavy quark production

IV. **Summary**

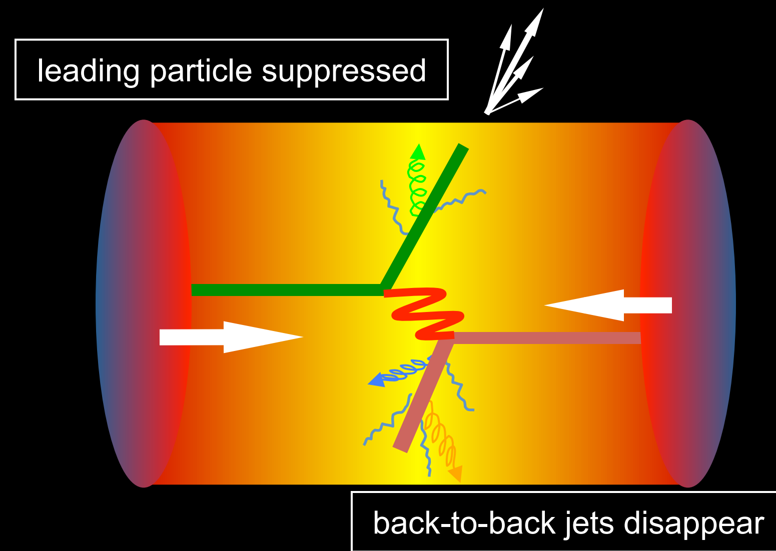
i Parton Energy Loss

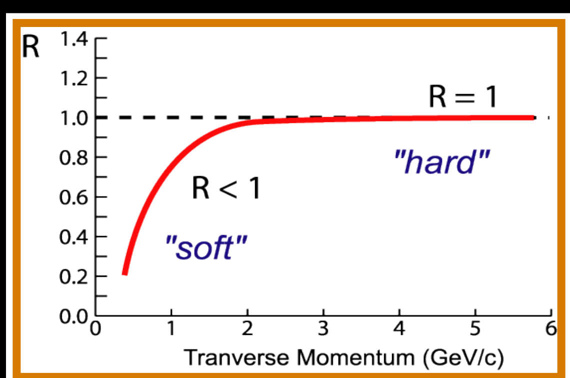
Jet Quenching at RHIC

p + p



Au + Au

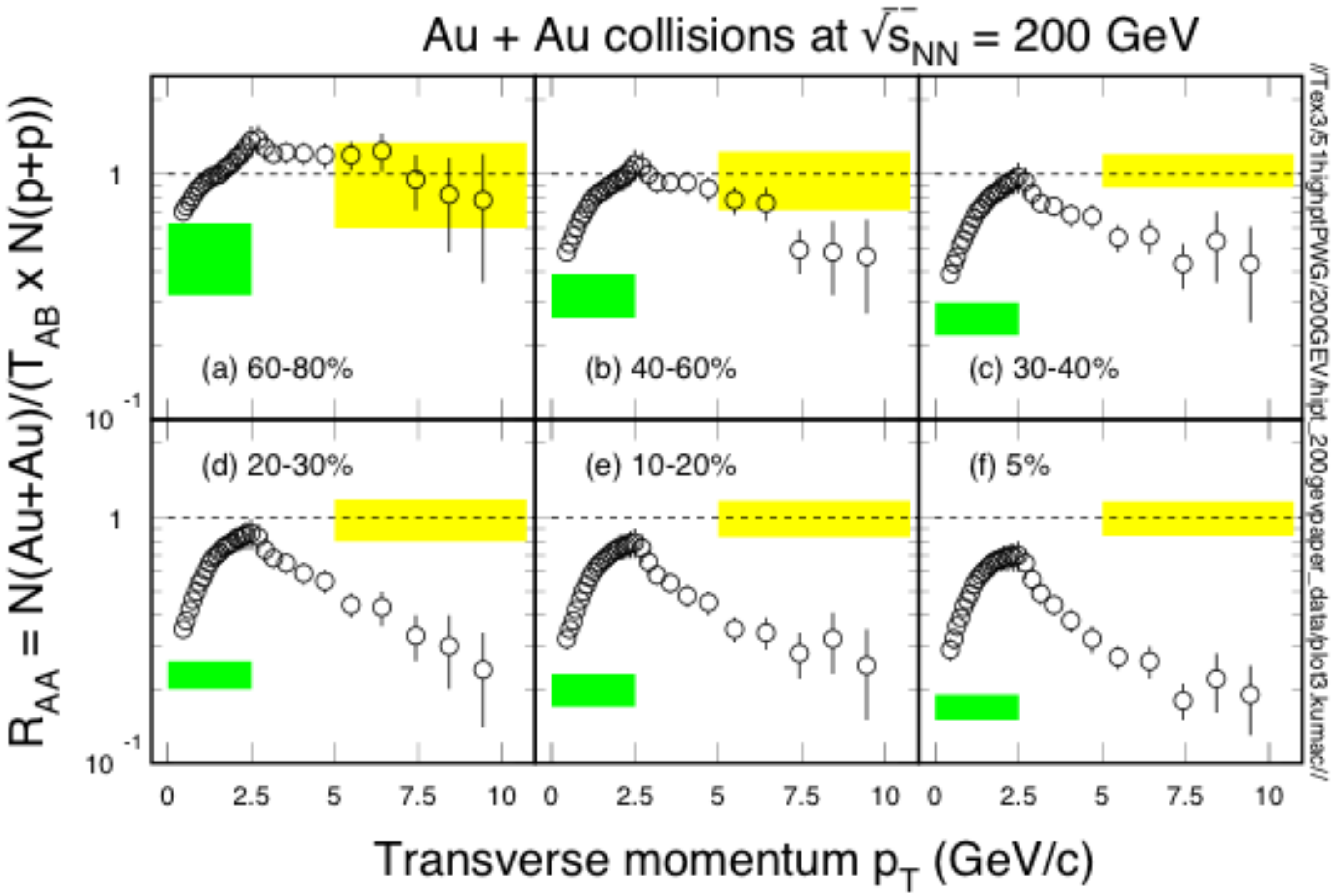




Nuclear Modification Factor:

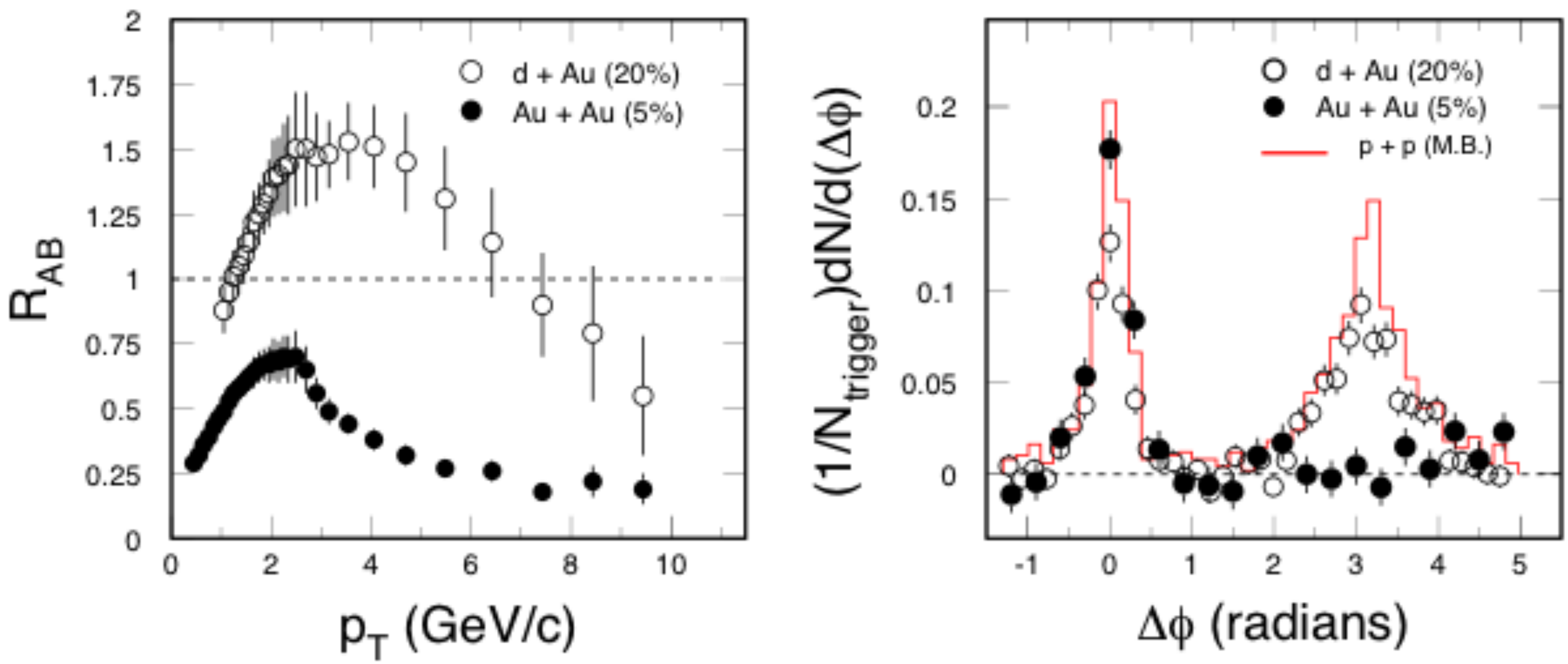
$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

Hadron Suppression at RHIC



Hadron suppression in more central Au+Au collisions!

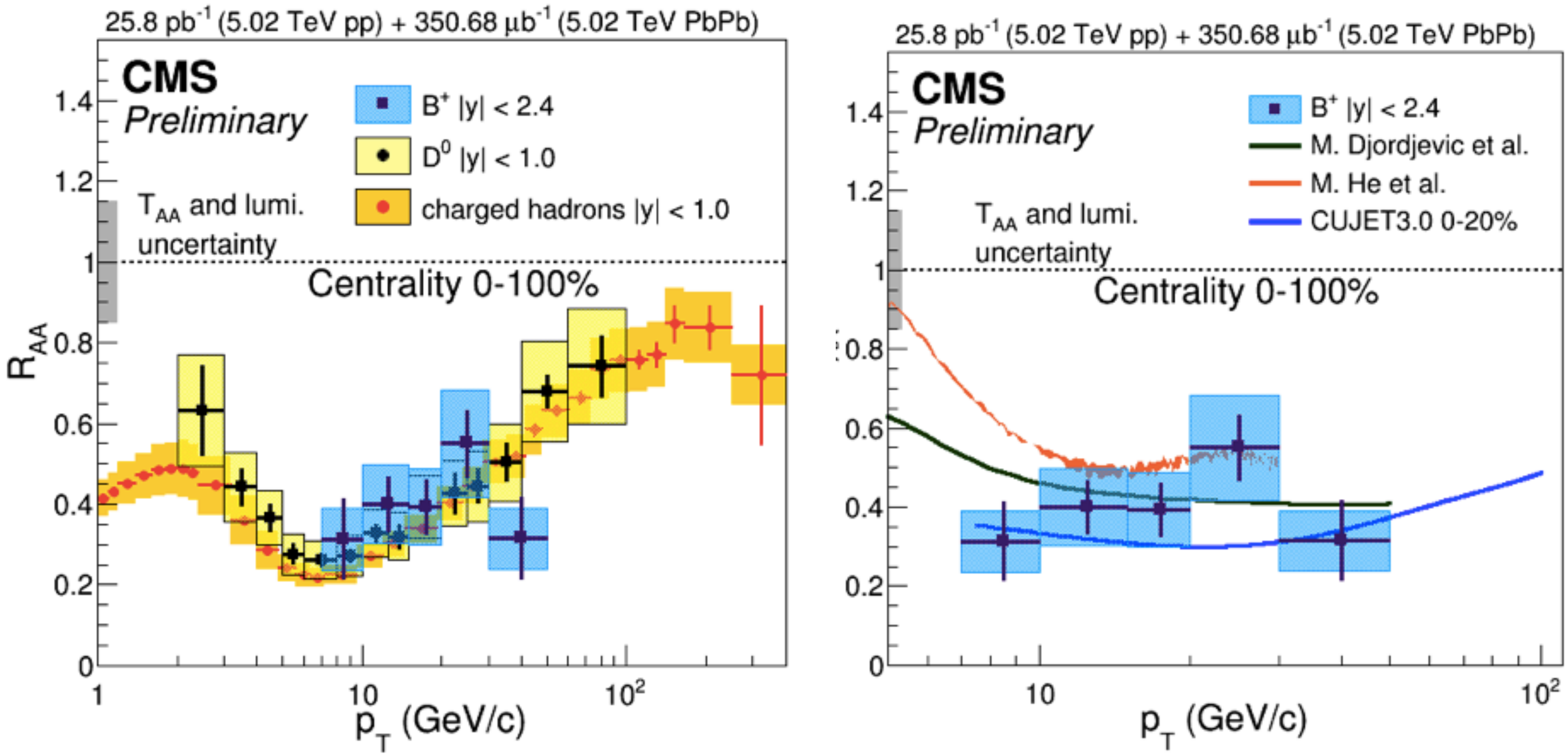
Suppression and Correlation



In central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV: light quark hadrons and away-side jets are suppressed.

Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε_0

First Results on Bottom Hadron R_{AA}

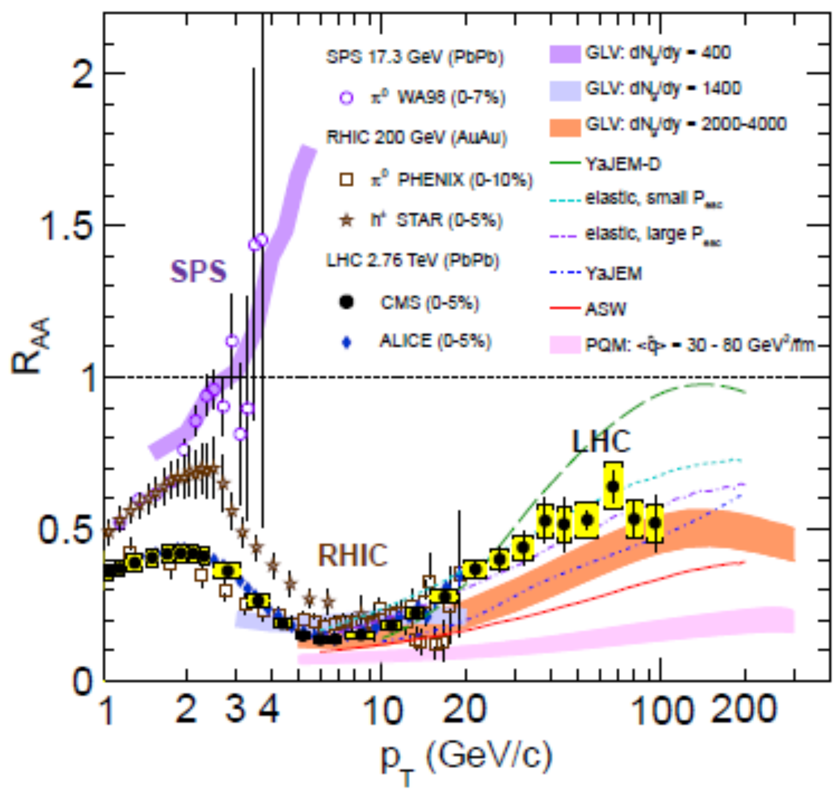


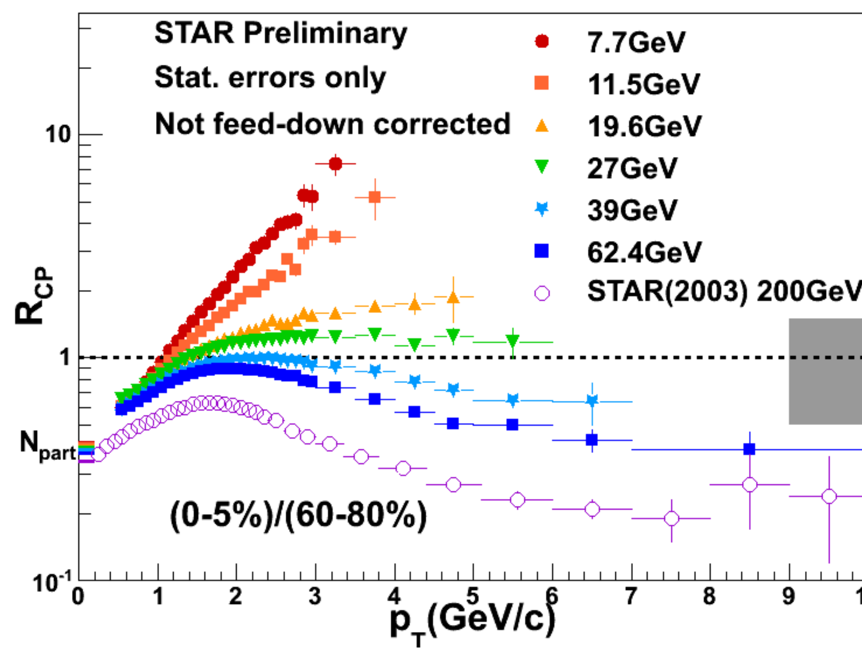
1) Bottom hadron R_{AA} similar to that of (*u*,*d*,*s*,*c*). Errors are still large!
2) Model results different as large as error bars.

CMS: HP2016 Overview talk, Sept. 2016

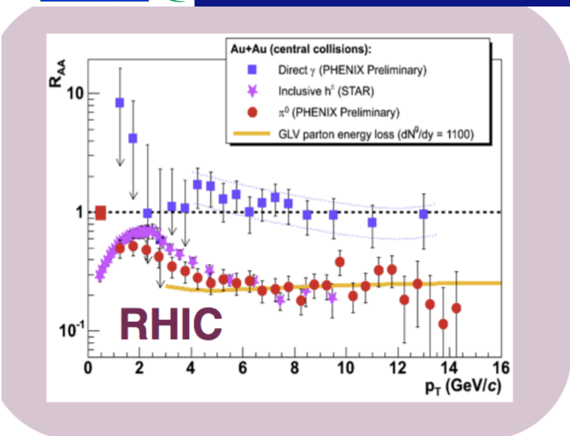
Beam Energy Dependence of R_{AA}

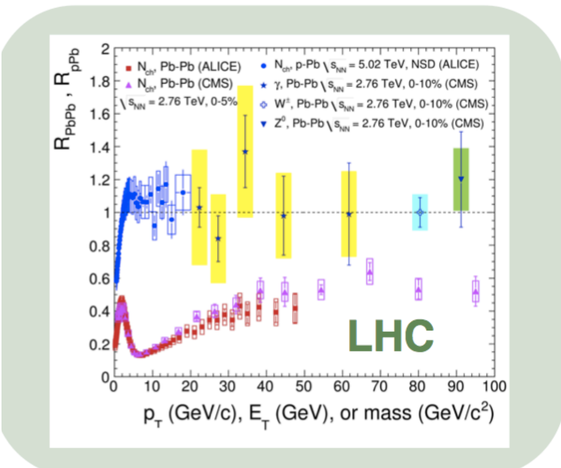
1) Suppression of high p_T hadrons is one of the key signatures for the formation of strongly interaction Quark-Gluon Plasma in high-energy nuclear collisions
2) The **suppression was not observed** in low energy Au+Au collisions, especially for $\sqrt{s_{NN}} \le 11.5$GeV

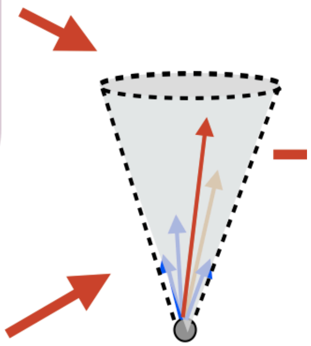


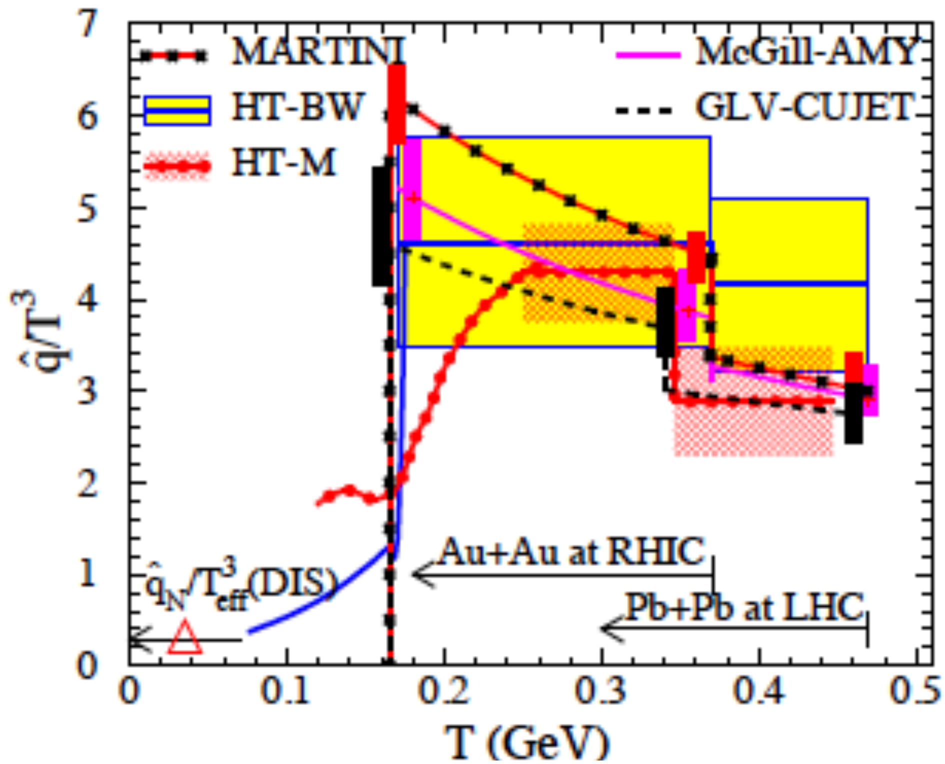


Jet Transport Coefficient *q^*









HotQCD Whitepaper: 1502.02730
Jet Collaboration: PRC90, 014909(2014)

1) Leading transport parameter q^ and its temperature dependence. Only leading hadron results used in the pQCD fitting.
2) The q^ reflects the properties of the medium. The (weak) temperature dependence might be due to the weak coupling limit in higher energy.

Parton Energy Loss: Summary

1) At high energy, strong parton energy loss occur in the strongly coupled plasma
2) The energy loss seems disappear below $\sqrt{s_{NN}}$ = 20 GeV
3) Heavy quark hadrons show similar R_{AA} at p_T > 10 GeV/c. Not fully understood

ii. Collectivity

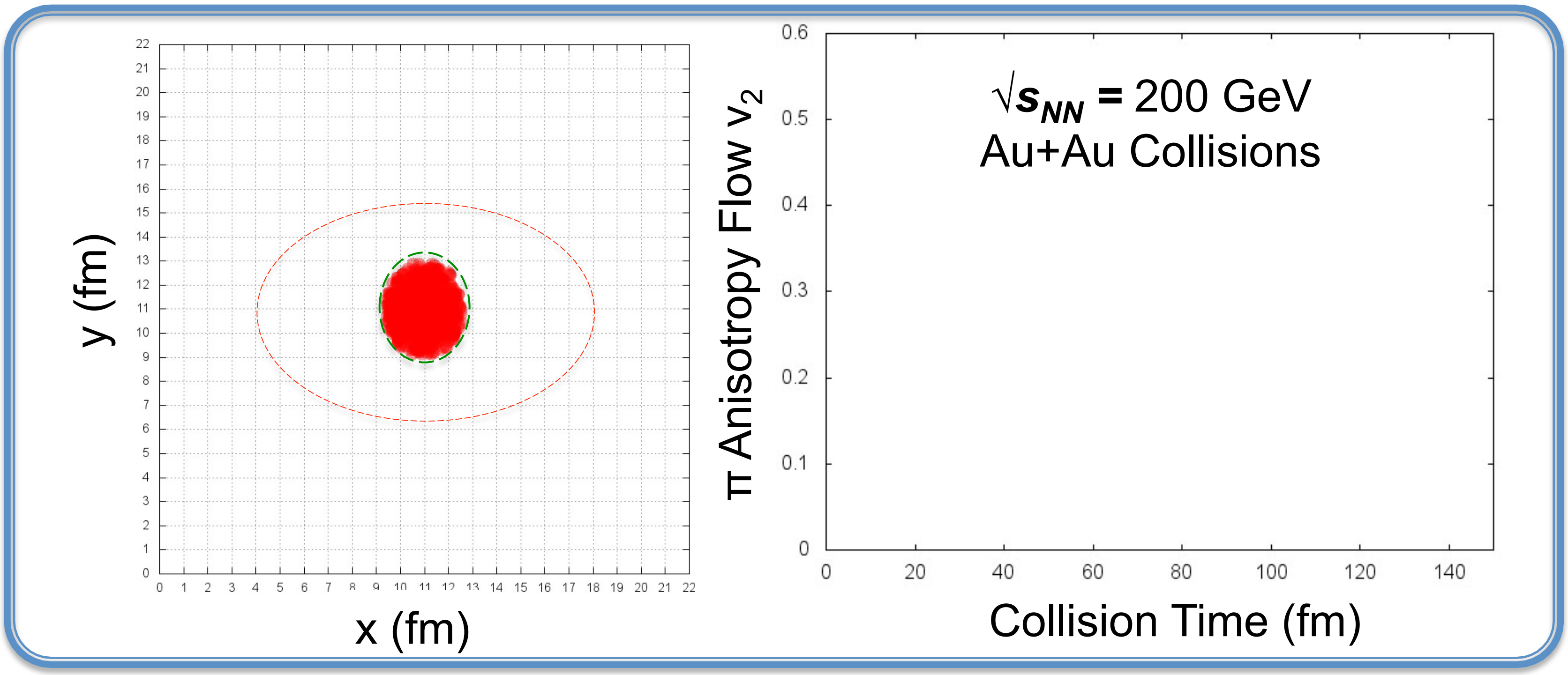
$$\partial_\mu [(\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu}] = 0$$
$$\partial_\mu [s\, u^\mu] = 0$$

Observables for Collectivity

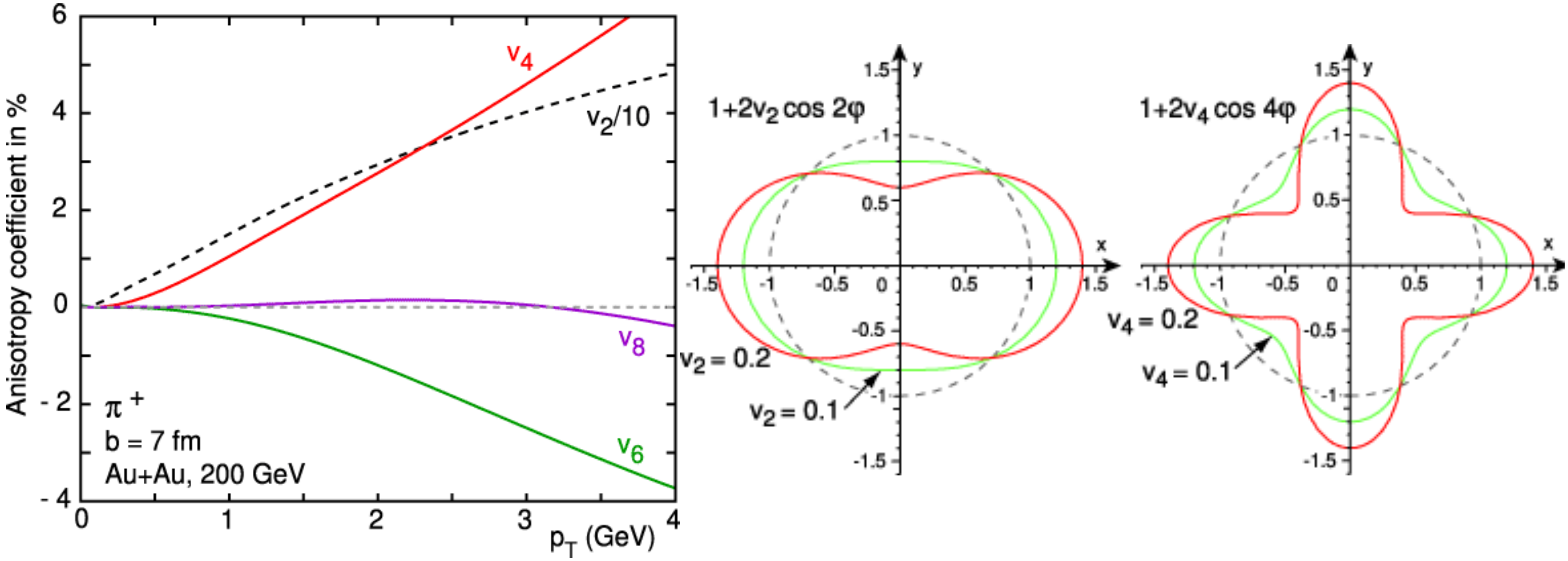
$$\frac{d\sigma}{d\Omega} = \frac{d^3\sigma}{dp_x dp_y dp_z} = \frac{dN}{p_t dp_t dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_t dp_t dy}\left[1 + \sum_i 2v_i \cos(i\varphi)\right]$$

$$p_t = \sqrt{p_x^2 + p_y^2}, \qquad m_t = \sqrt{p_t^2 + m^2}$$

$$v_i = \langle \cos(i\varphi) \rangle_{event}, \qquad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$



Higher Harmonics

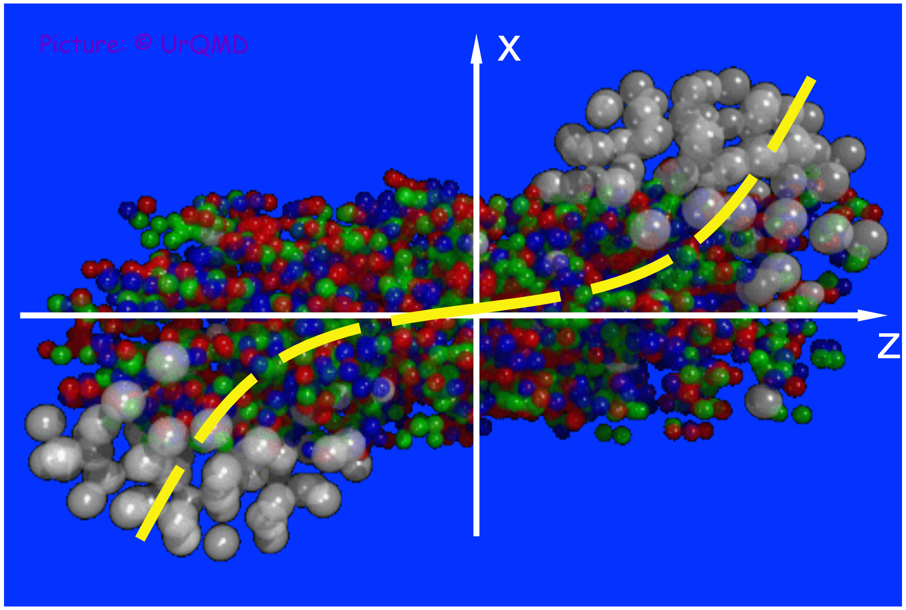


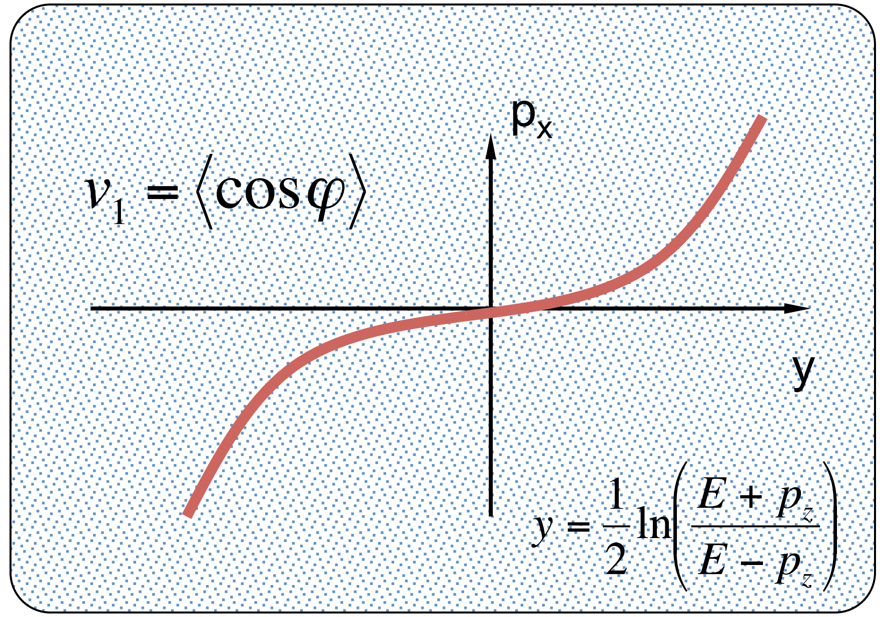
Higher harmonics are expected to be present. For smooth azimuthal distributions the higher harmonics will be small $v_n \sim v_2^{n/2}$

- v_4 - a small, but sensitive observable for heavy ion collisions.

*P. Kolb, PR **C68**, 031902(04); Borghini and Ollitrault, nucl-th/0506045*

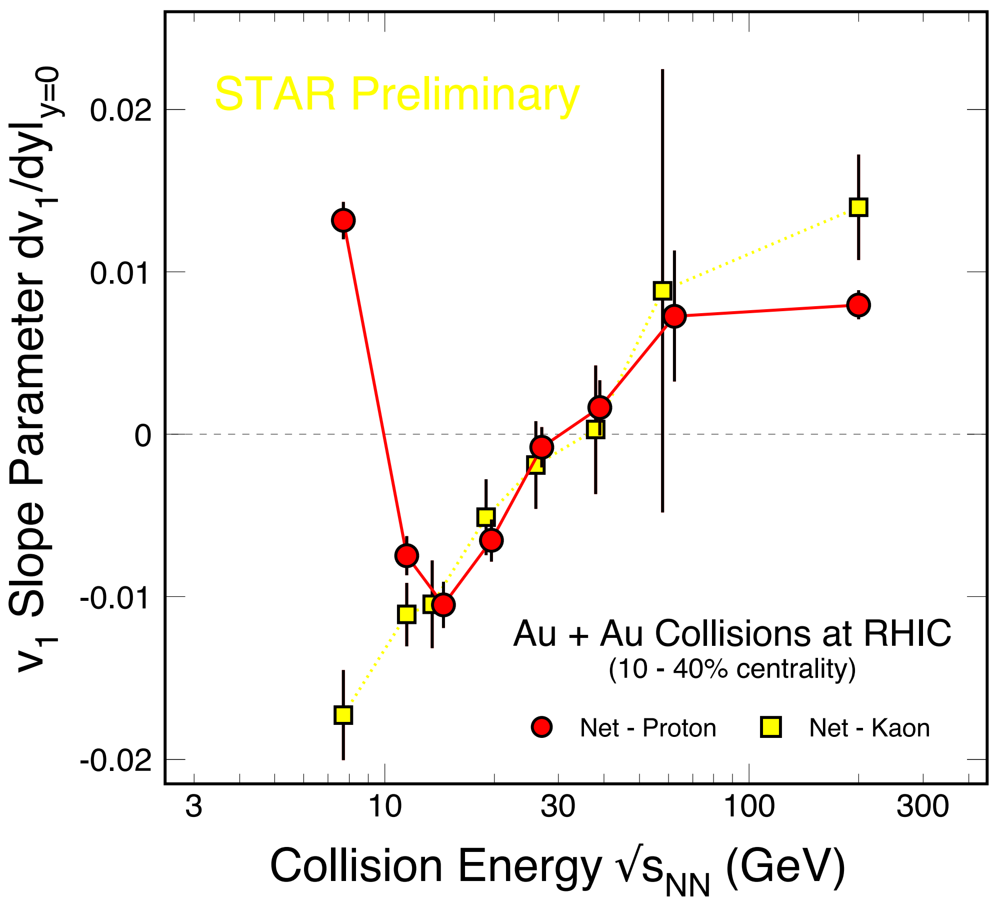
Directed Flow v_1





Initial spatial anisotropy ➠ **Anisotropy in momentum space**

Directed Flow v_1 Results



1) Mid-rapidity net-proton dv_1/dy published in 2014 by STAR, except the point at 14.5 GeV

2) Minimum at $\sqrt{s_{NN}}$ = 14.5 GeV for net-proton. Soft point!

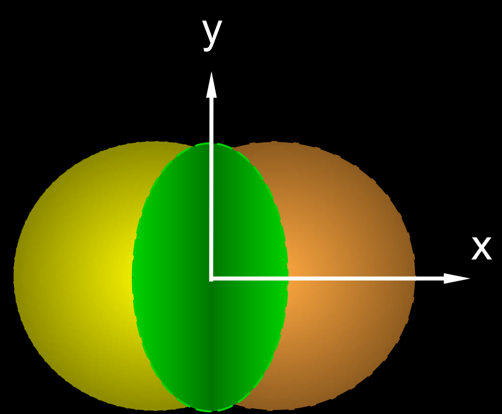
3) At low energy, or in the region where the net-baryon density is large, repulsive force is expected, v_1 slope is large and positive!

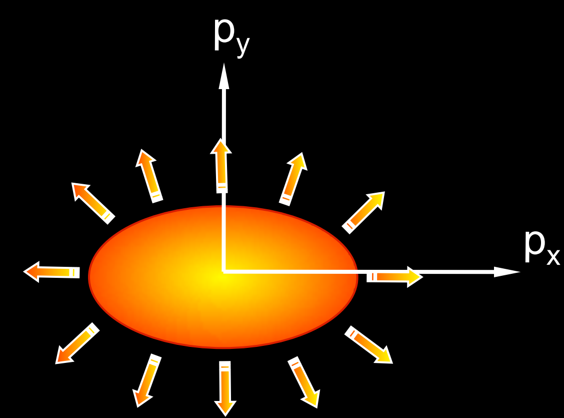
M. Isse, A. Onishi et al, PRC72, 064908(05)

STAR Protons, pion: PRL**112**, 162301(2014)
STAR Lambda, Kaon: Preliminary

Anisotropy Parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy

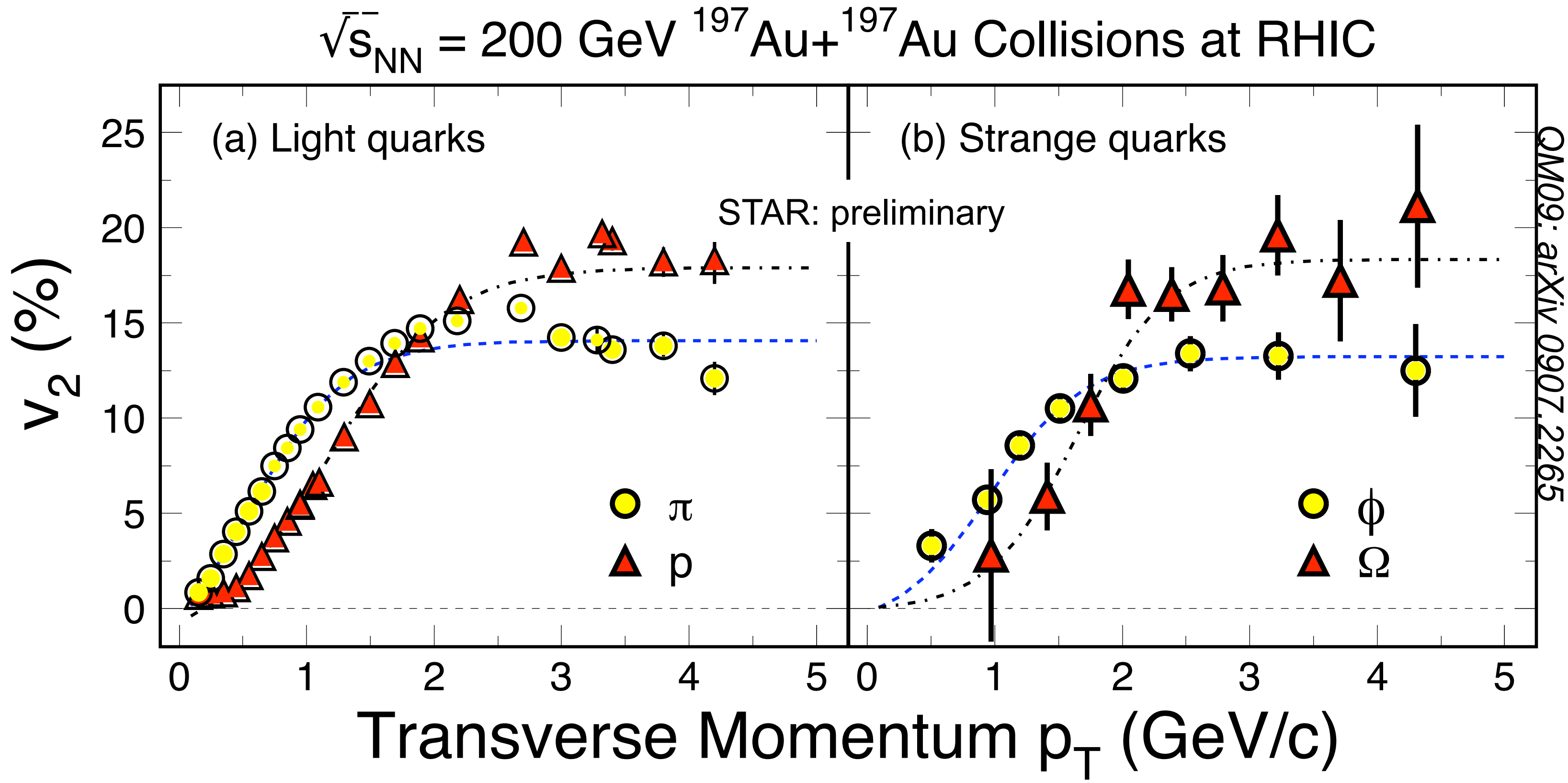




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \;\; \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

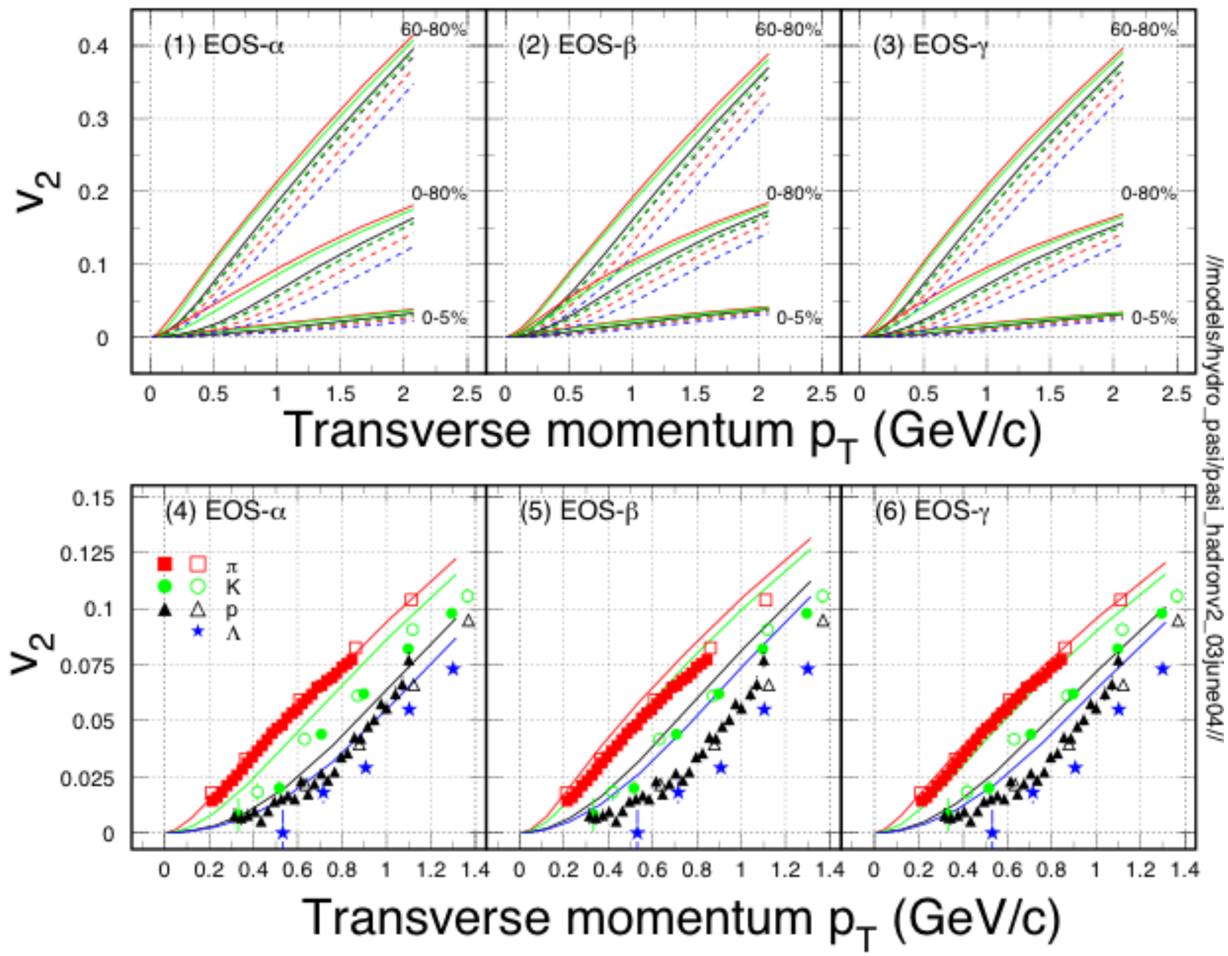
Partonic Collectivity at RHIC



Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks scaling***

➔ ***Partonic Collectivity, necessary for QGP!***
➔ ***De-confinement in Au+Au collisions at RHIC!***

Compare with data: (0-80%)

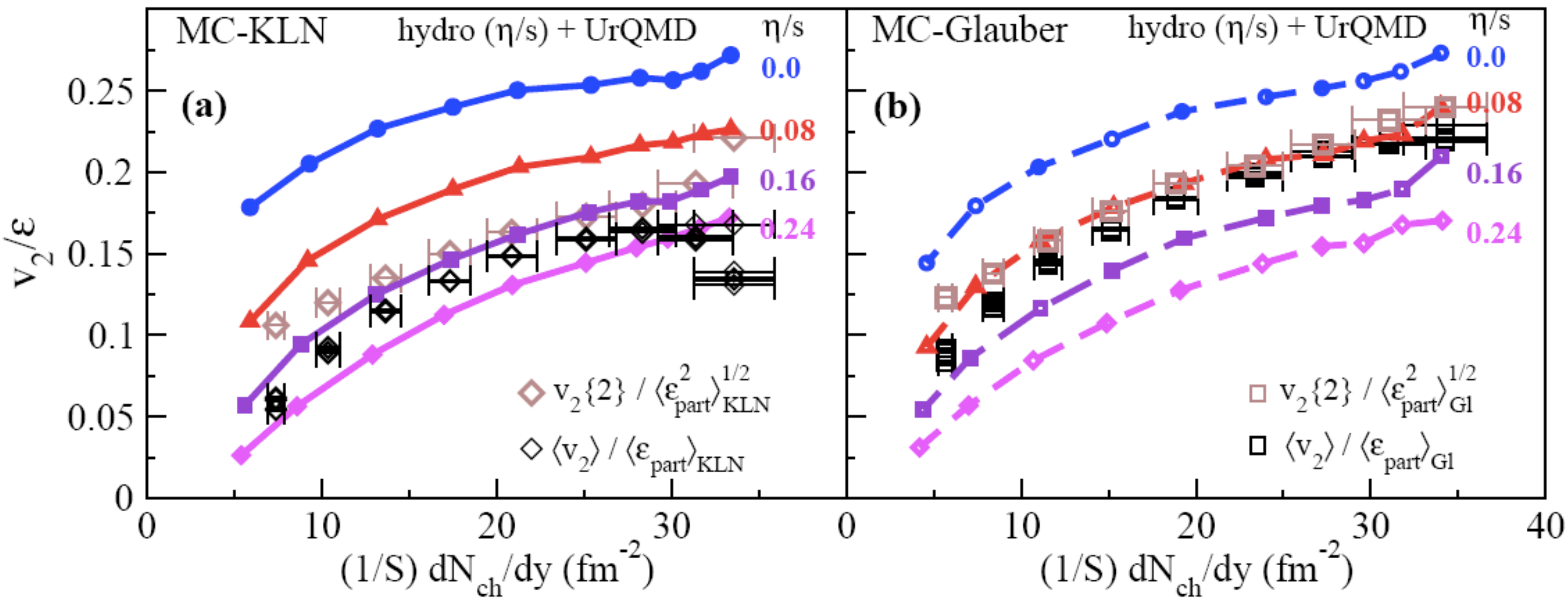


200 GeV Au+Au *P. Huovinen, June 4, 2004*

STAR: filled symbols; PHENIX: open symbols

⇒ ***EOS-α provides a reasonable fit to data***

v_2: Hydrodynamic Model vs. Data

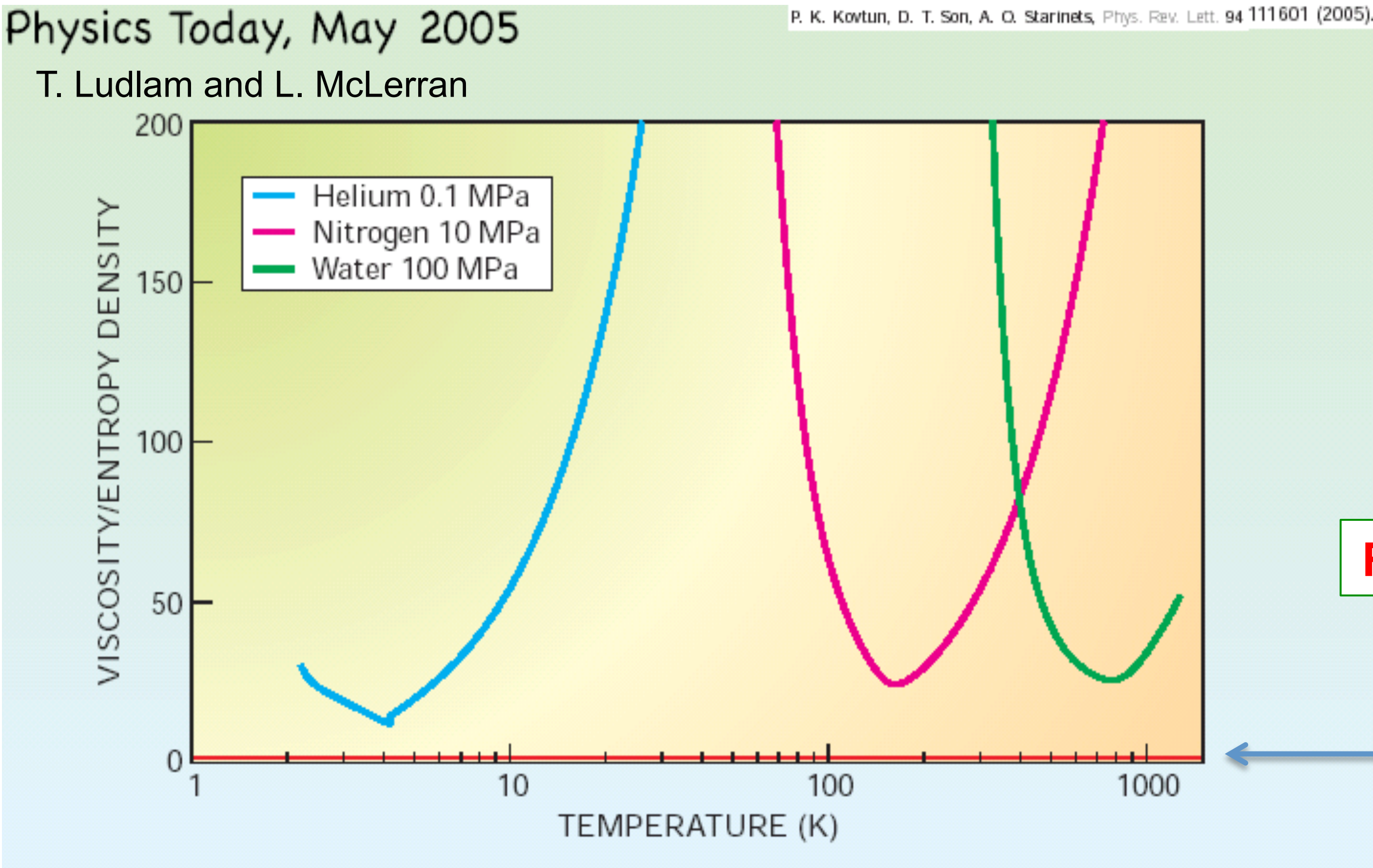


➔ Small value of specific viscosity over entropy ***η/s***

➔ Model uncertainty dominated by initial eccentricity ε. EIC needed in order to understand the npdf and the initial eccentricity ε.

Model: Song *et al.* ***PRL106****, 192301(2011), arXiv:1011.2783*

Low *η/s* for QCD Matter at RHIC

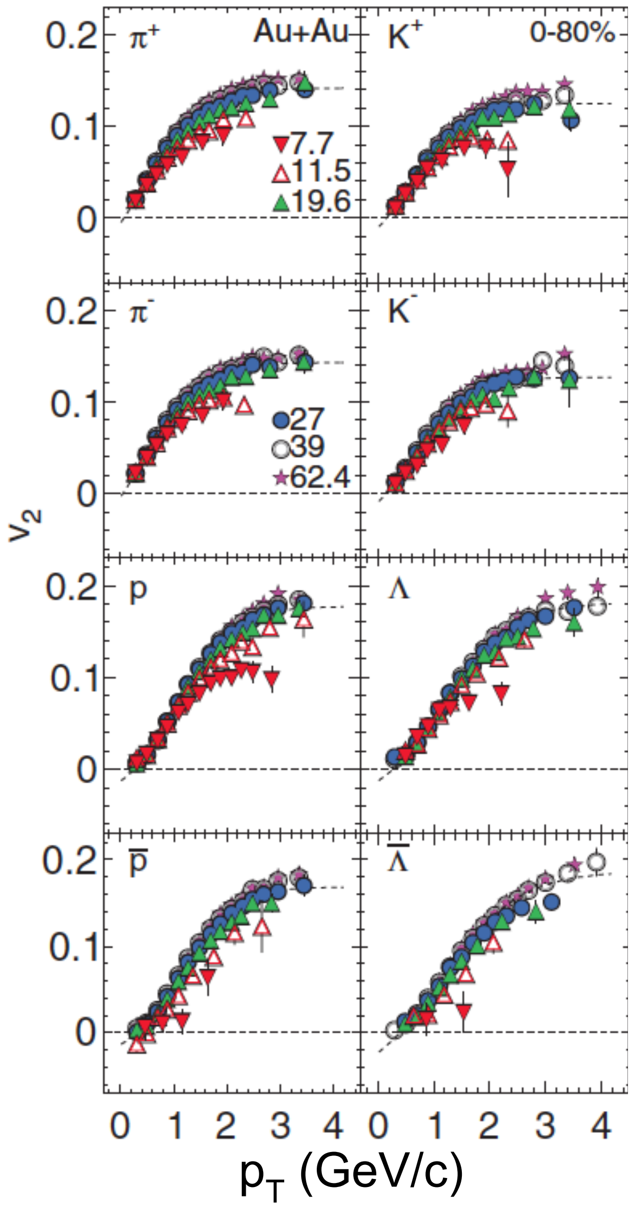


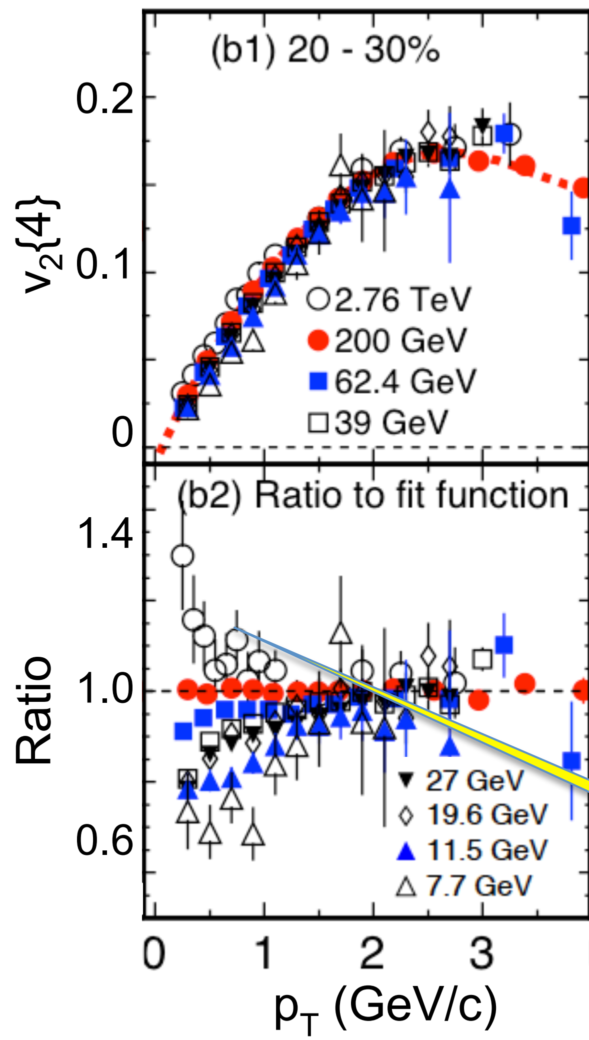
RHIC results

1) $\eta/s \geq 1/4\pi$, **'perfect liquid'**

2) η/s(QCD matter) << η/s(QED matter)

PID Hadron v_2 Results





1) Normalized to 200 GeV results

2) Stronger collectivity at higher collision energy

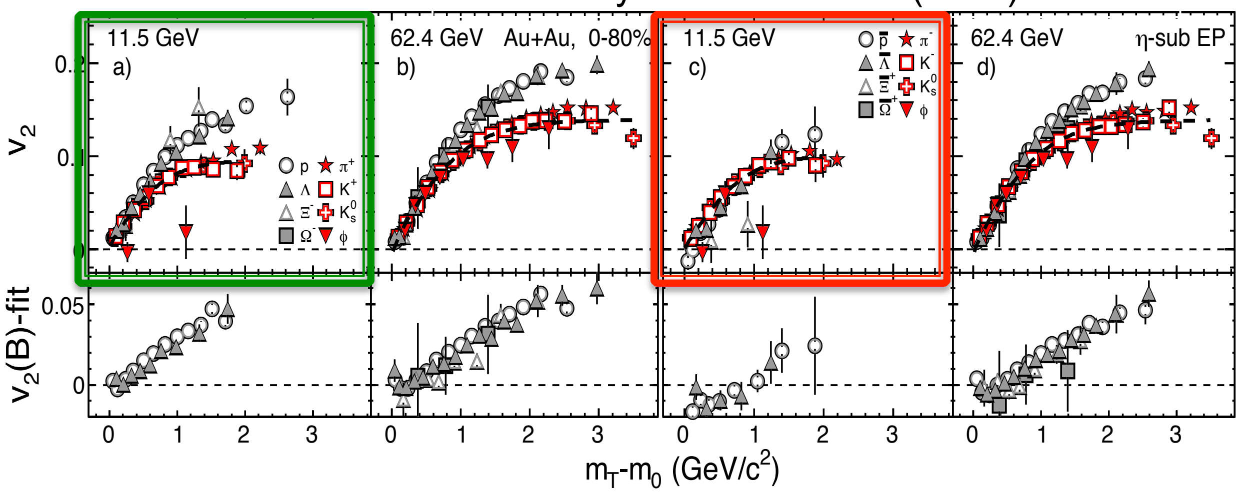
3) Particle and anti-particle display different behavior as a function of collision energy

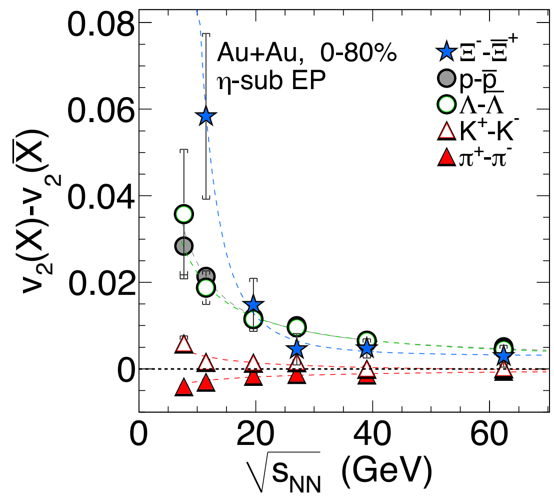
ALICE!

STAR: **PRC86**, 054908 (2012); **PRC88**, 014902 (2013)
ALICE: **PRL105**, 252302 (2010)

Collectivity v_2 Measurements

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

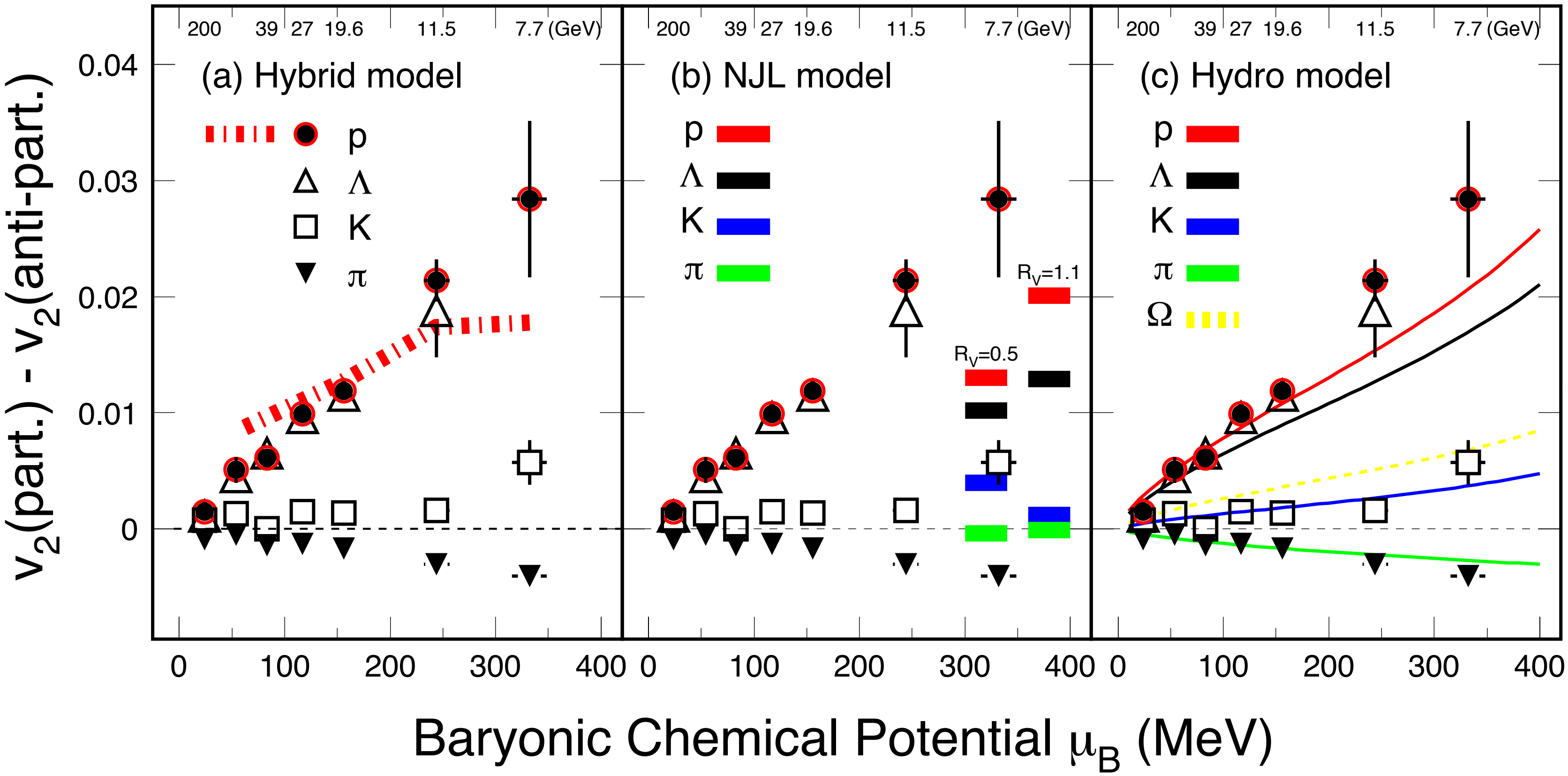




1) Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions

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

BES v_2 and Model Comparison



(a) Hydro + Transport: Baryon results fit [J. Steinheimer, et al. PR **C86**, 44902(13)]

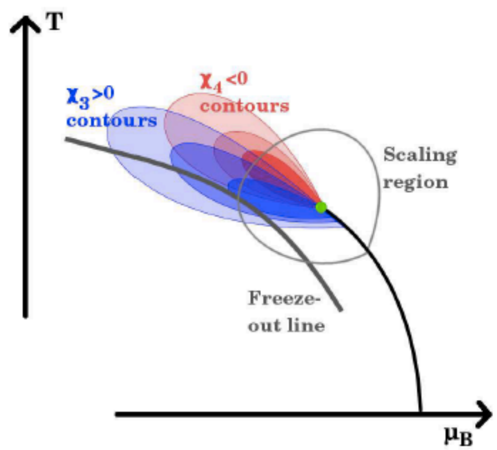
(b) NJL model: Sensitive to vector-coupling, **CME, μ_B** driven. [J. Xu, et al., PRL**112**.012301(14)]

(c) Hydro solution: **Chemical potential μ_B** and **viscosity η/s** driven! [Hatta et al. PR **D91**, 085024(15); **D92**, 114010(15) //NP **A947**, 155(16)]

Collectivity: Summary

1) At high energy, strong collectivity and vanishing ratio of η/s => Perfect liquid of the strongly coupled plasma
2) Hadron formation via coalescence at T_C
3) At beam energy $\sqrt{s_{NN}} < 20$ GeV, net-proton v_1 shows a dip and the break down of the number of quark scaling in v_2

iii Criticality



Susceptibilities and Moments

Thermodynamic function:

$$\frac{p}{T^4} = \frac{1}{\pi^2}\sum_i d_i (m_i/T)^2 K_2(m_i/T)\cosh[(B_i\mu_B + S_i\mu_S + Q_i\mu_Q)/T]$$

The susceptibility: $T^{n-4}\chi_q^{(n)} = \frac{1}{T^4}\frac{\partial^n}{\partial(\mu_q/T)^n} P\left(\frac{T}{T_C},\frac{\mu_q}{T}\right)\Big|_{T/T_C}$, $\quad q = B, Q, S$

Conserved Quantum Numbers

$$\chi_q^{(1)} = \frac{1}{VT^3}\langle \delta N_q \rangle$$

$$\chi_q^{(2)} = \frac{1}{VT^3}\langle (\delta N_q)^2 \rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3}\langle (\delta N_q)^3 \rangle$$

$$\chi_q^{(4)} = \frac{1}{VT^3}\left(\langle (\delta N_q)^4 \rangle - 3\langle (\delta N_q)^2 \rangle^2\right)$$

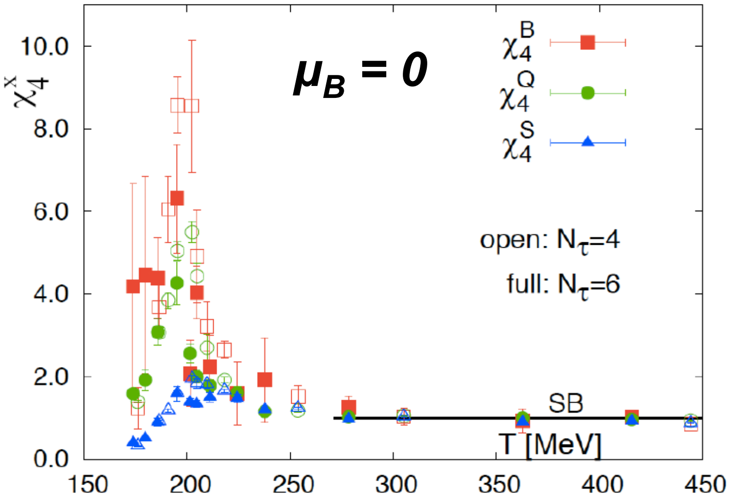
$$\frac{T^2\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2$$

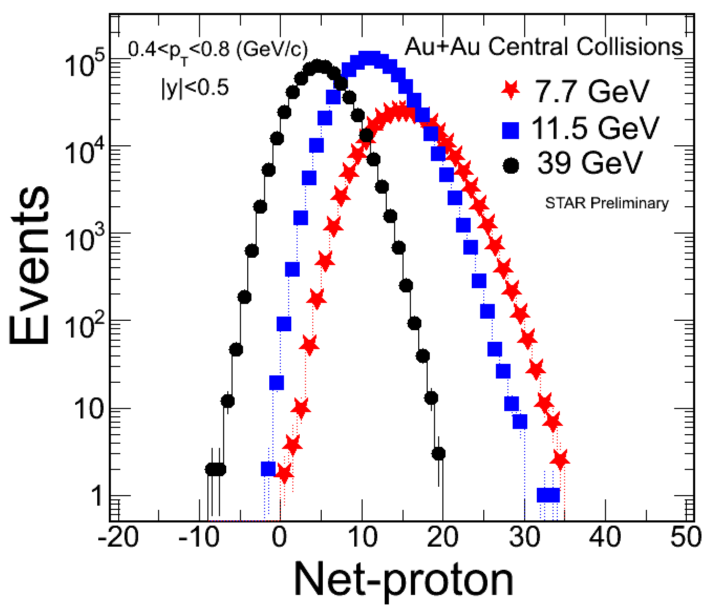
$$\frac{T\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma$$

Thermodynamic function ⇔ Susceptibility ⇔ Moments

Model calculations, *e.g.* LGT, HRG ⇔ Measurements

Higher Moments and Criticality





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

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

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

3) Direct comparison with calculations at any order:

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

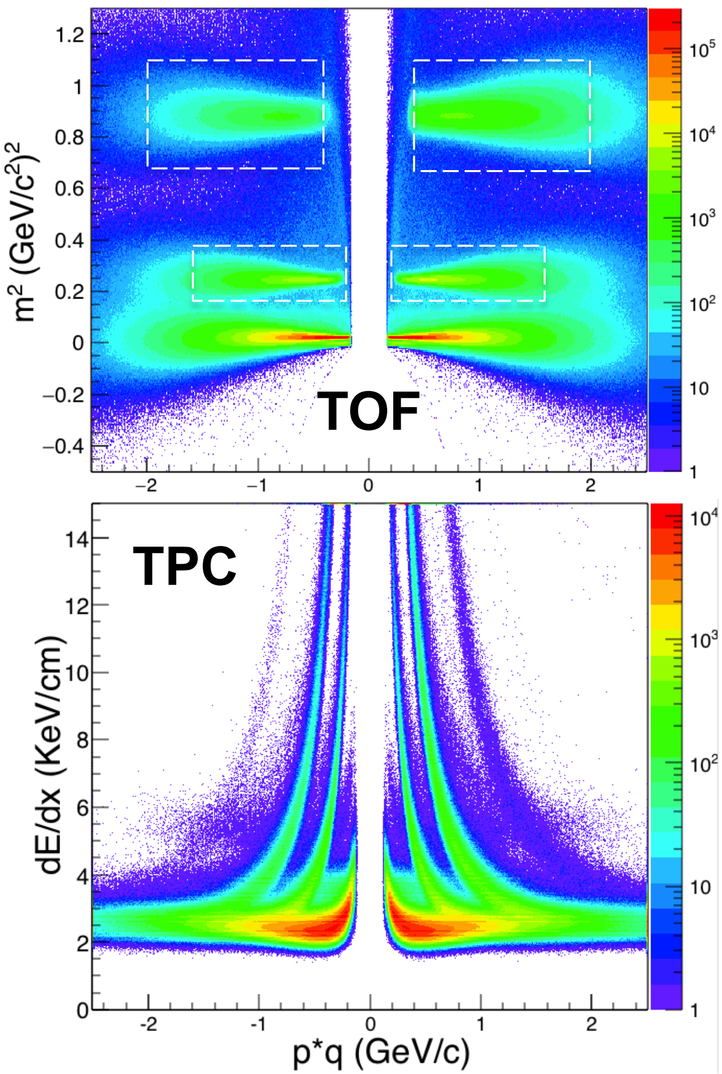
4) **Extract susceptibilities and freeze-out temperature**. An independent/important test of thermal equilibrium in heavy ion collisions.

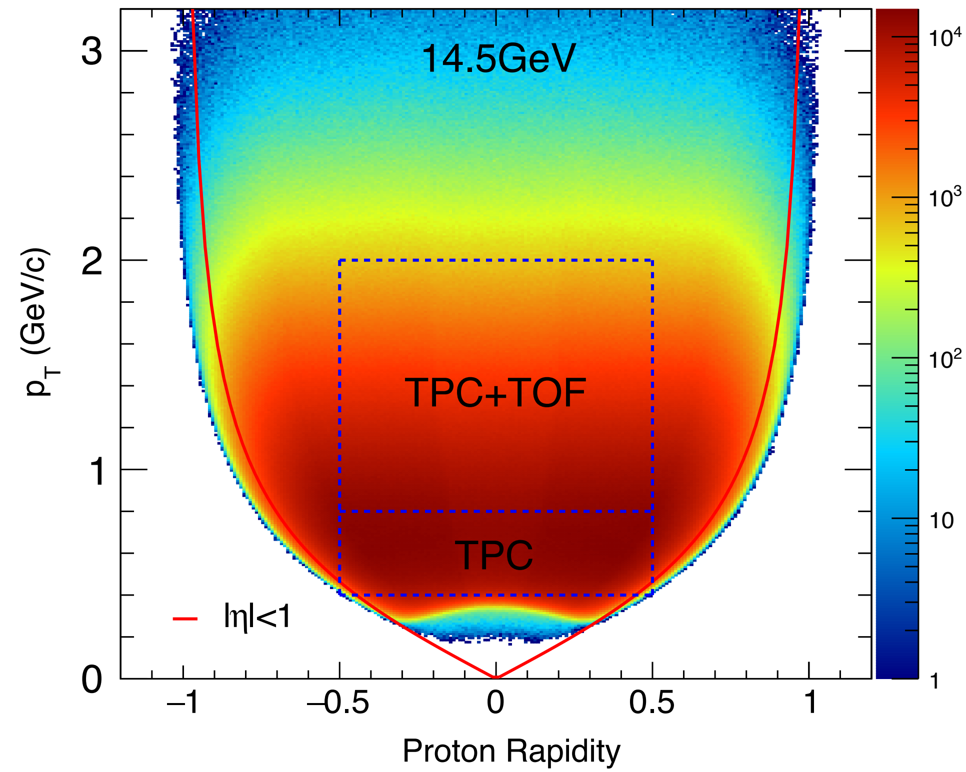
References:

- STAR: *PRL* **105**, 22303(10); *ibid*, **112**, 032302(14)
- S. Ejiri, F. Karsch, K. Redlich, *PLB633*, 275(06) // M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB696*, 459(11) // F. Karsch et al, *PLB695*, 136(11),
- A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // V. Skokov et al., PRC88, 034901(13)

Proton Identification with TOF

Published net-proton results: Only TPC used for proton/anti-proton PID. TOF PID extends the phase space coverage.





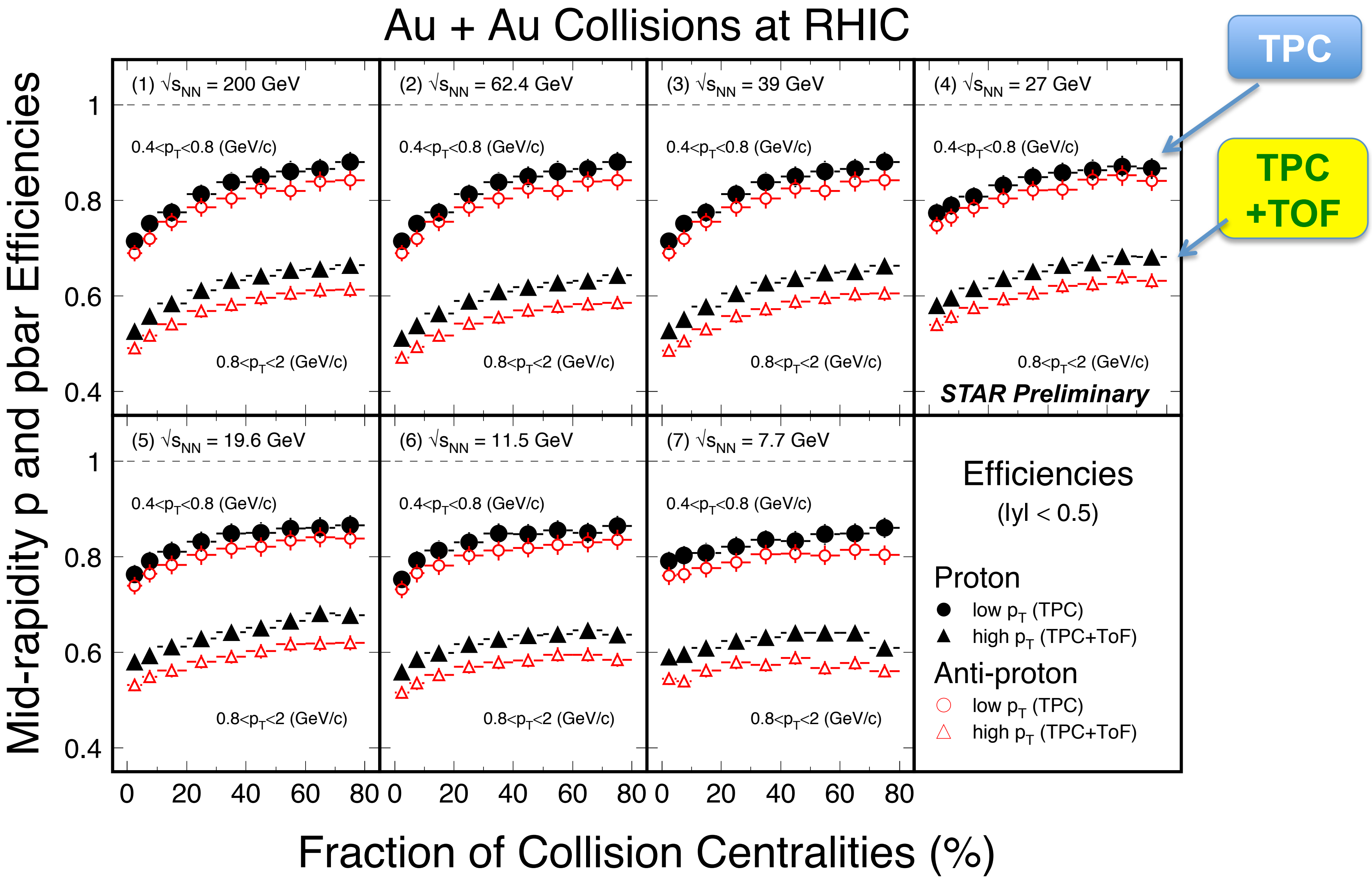
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

Efficiency corrections:

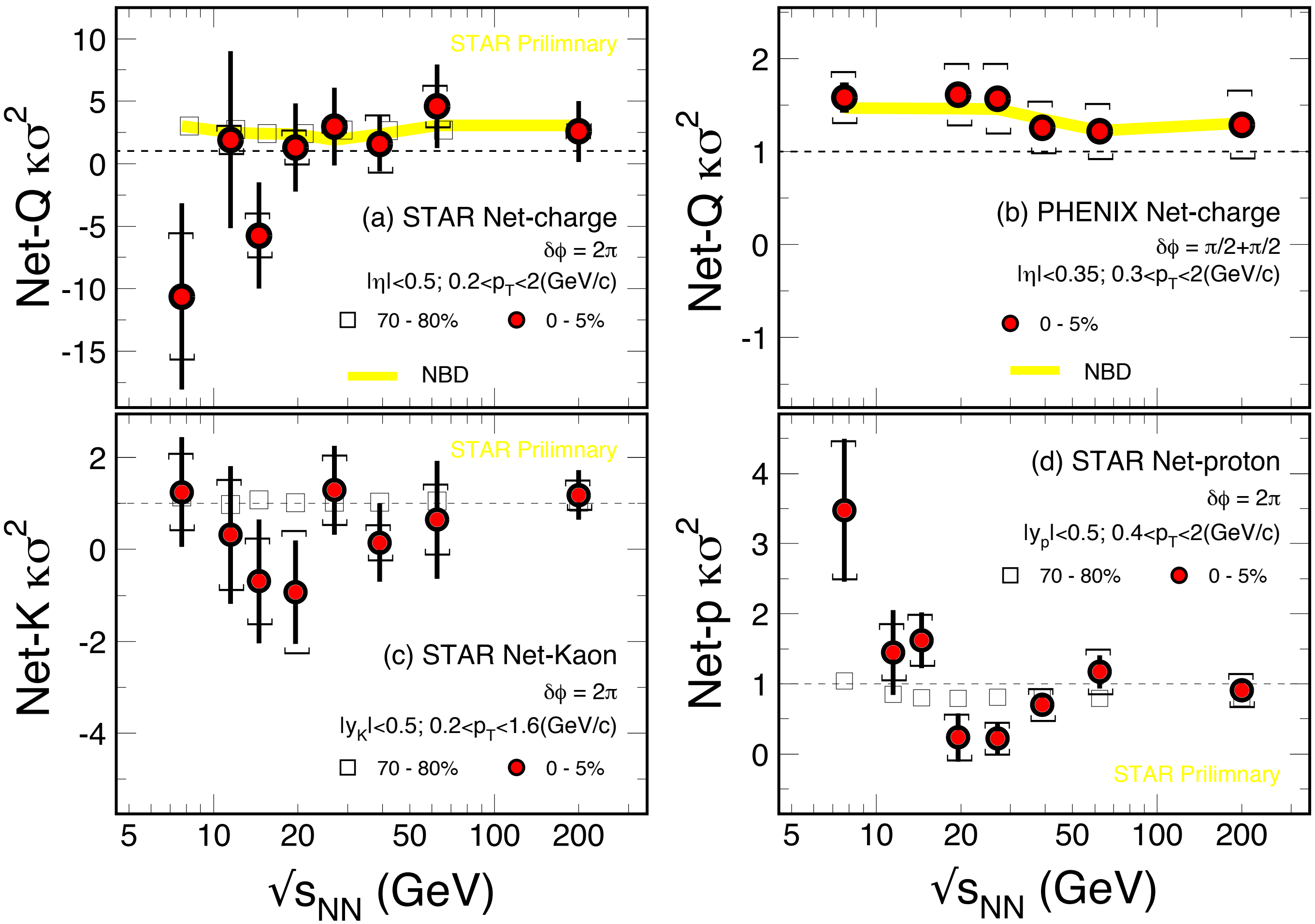
TPC ($0.4 \leq p_T \leq 0.8$ GeV/c): **$\varepsilon_{TPC} \sim 0.8$**

TPC+TOF ($0.8 \leq p_T \leq 2$ GeV/c): **$\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$**

Efficiencies for (anti-)Protons



Higher Moments of Net-Q, -K, -p



$$error(\kappa * \sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

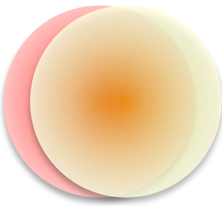
In STAR:

σ(Q) > σ(K) > σ(p)

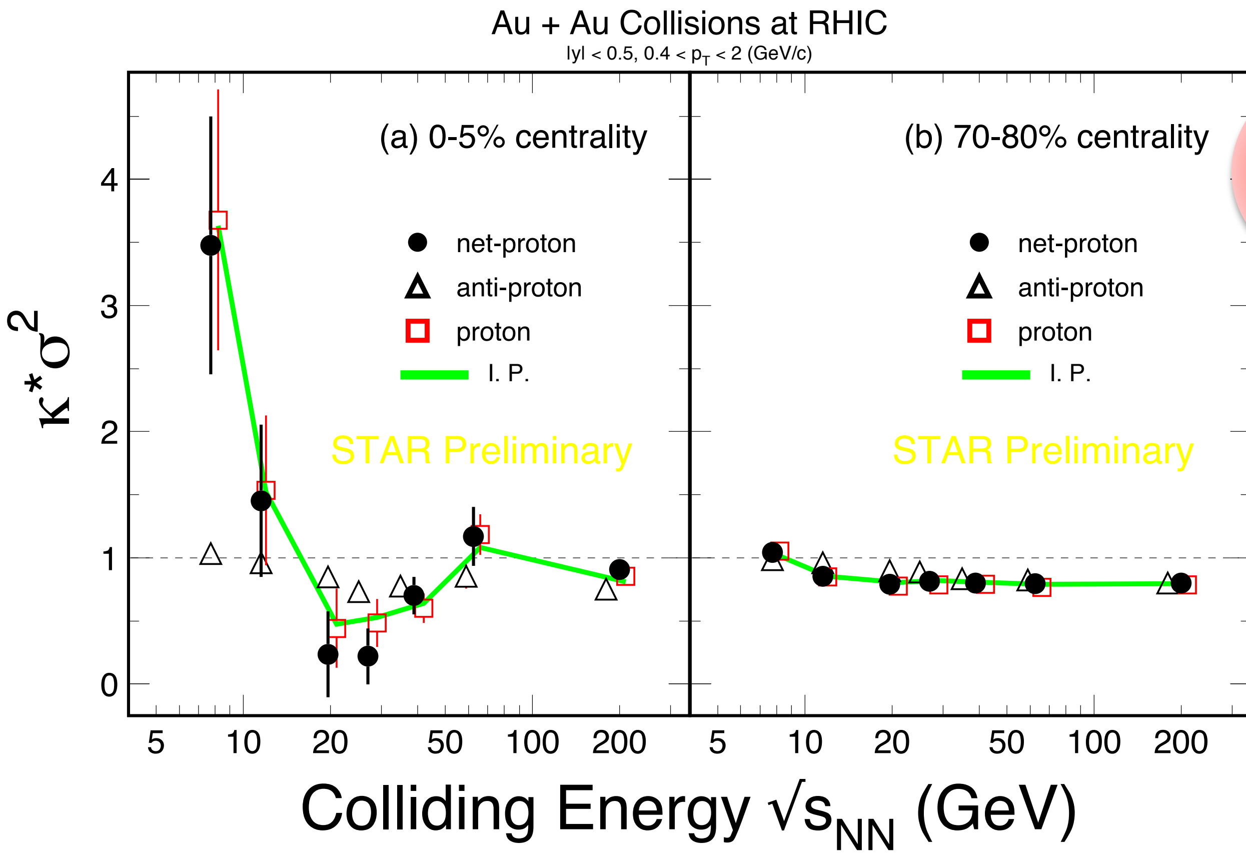
1) The results of net-Q and net-Kaon show flat energy dependence.
2) Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions starting at $\sqrt{s_{NN}}$ < 27 GeV!

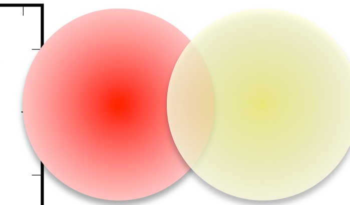
PHENIX: talk by P. Garg at QM2015;   STAR: talk by J. Thäder and poster by J. Xu at QM2015

Net-proton Higher Moment



central





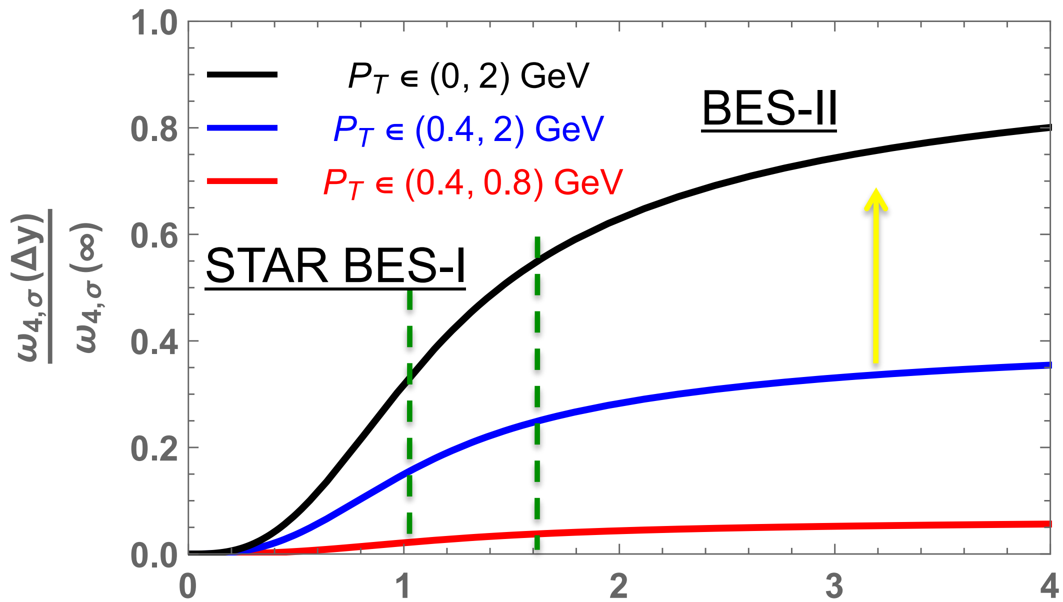
peripheral

1) Flat energy dependence for 70-80% peripheral collisions
2) Non-monotonic behavior in the most central 0-5%, and 5-10% collisions. Net-p follow protons, especially at lower collision energies

X.F. Luo, CPOD2014, QM2015

Acceptance Matters

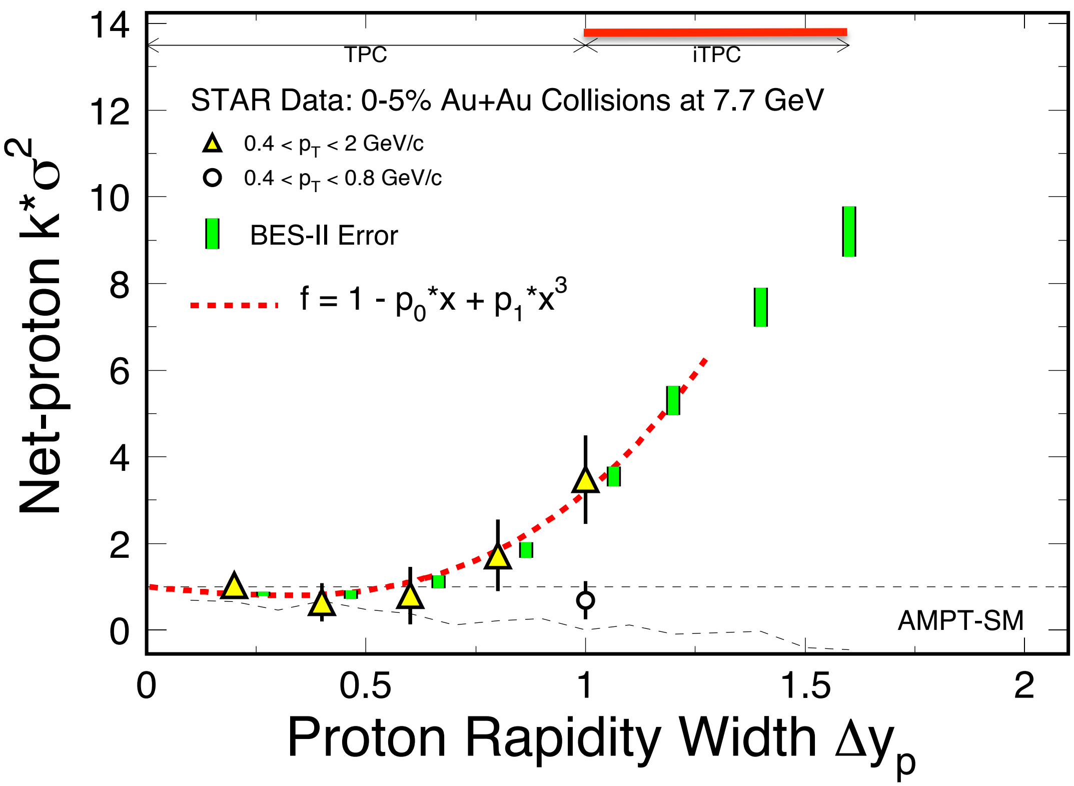
B. Ling, M. Stephanov, 1512.09125, Phys. Rev. **C93**, 034915(2016)



$$\kappa_4[M] = \underbrace{\langle M \rangle}_{\text{Poisson}} + \kappa_4[\sigma_V] \times g^4 \underbrace{\left(\bigcirc \right)^4}_{\sim M^4} + \ldots \propto \begin{cases} M^4 & \textbf{Critical} \\ \langle M \rangle & \text{Non-critical} \end{cases}$$

1) Acceptance is important!
2) Low p_T of protons is more important than wider rapidity. Fixed-target experiment is more advantageous

Power-law Behavior vs. Rapidity

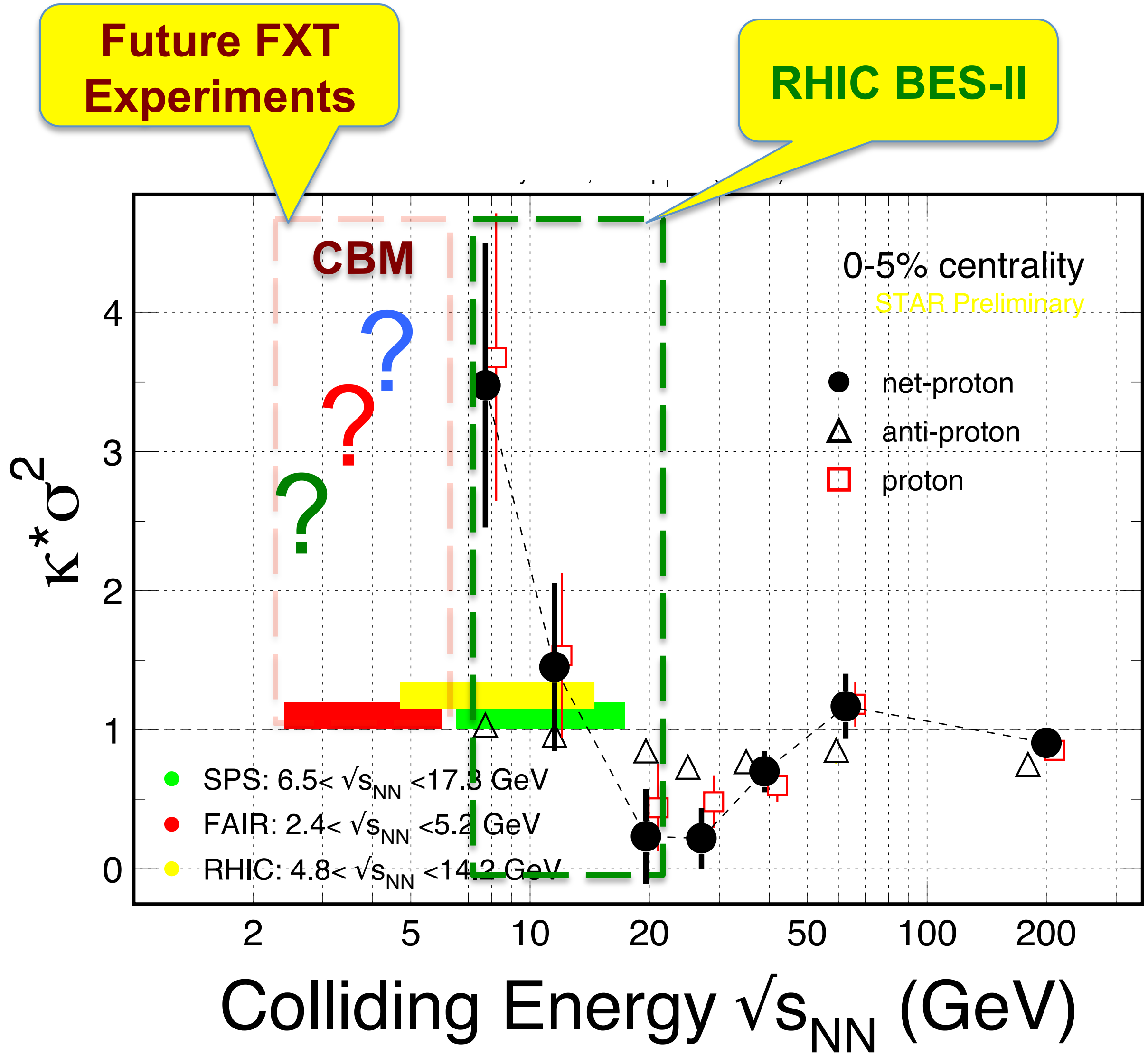


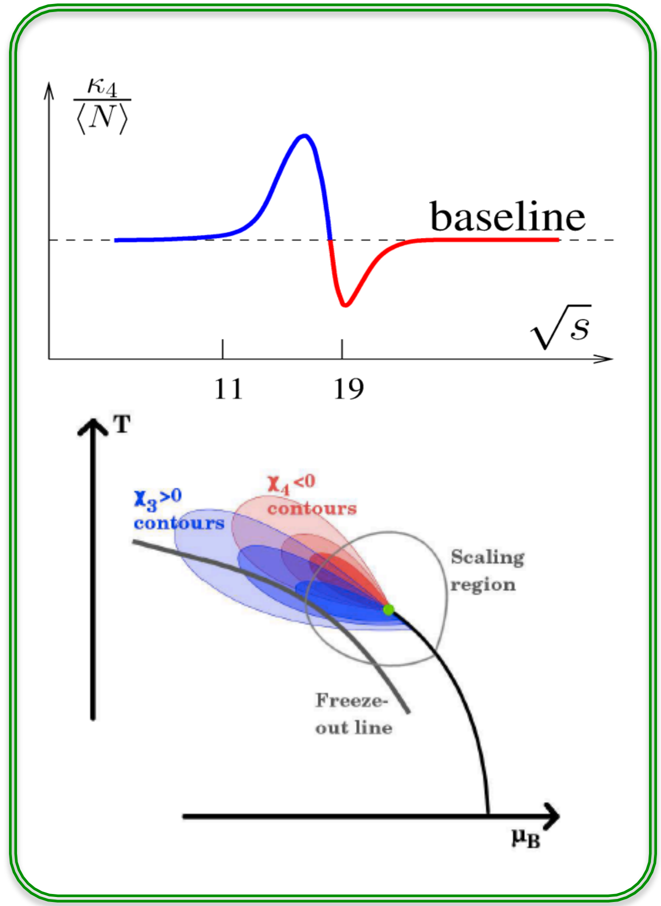
STAR BES-II Whitepaper:
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

1) BES-I results: Poisson + Baryon conservation + v^3. Power-law-like at $\sqrt{s_{NN}} \leq 11.5$ GeV only.

2) RHIC BES-II: iTPC extend the rapidity coverage to Δy = 1.6, allowing to study kinematic dependence and precision measurement of higher moments

Search for the QCD Critical Point





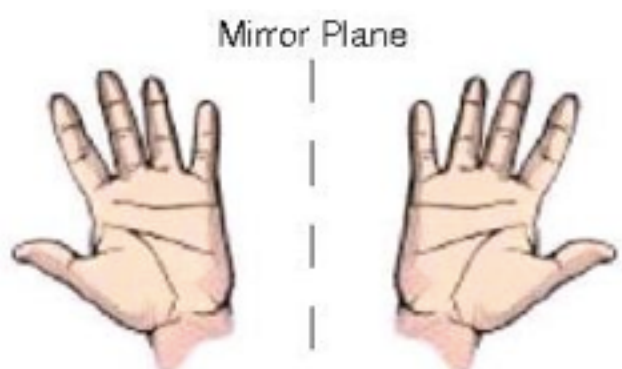
RHIC BES-II + FXT Experiments in the future!

STAR Data: X.F. Luo et al, PRL**112** (2014) 32302; X.F. Luo, PoS(CPOD14)019; QM plenary (15)

Criticality: Summary

1) Non-monotonic trend in the energy dependence of the net-proton $\kappa*\sigma^2$, from the top 5% Au+Au collision. Within error bars, flat dependence in net-Q and net-K
2) Collisions below $\sqrt{s_{NN}} \leq 5$ GeV needed for the **search of the QCD critical point**

iv Chirality

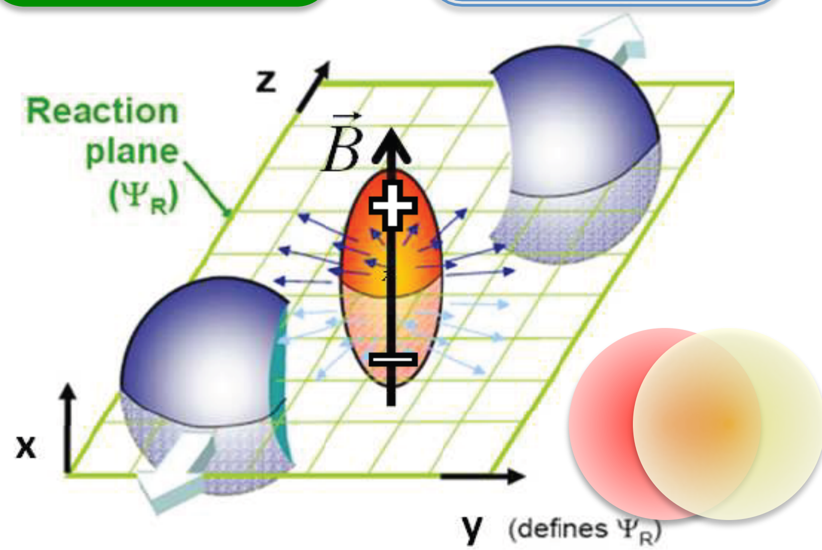


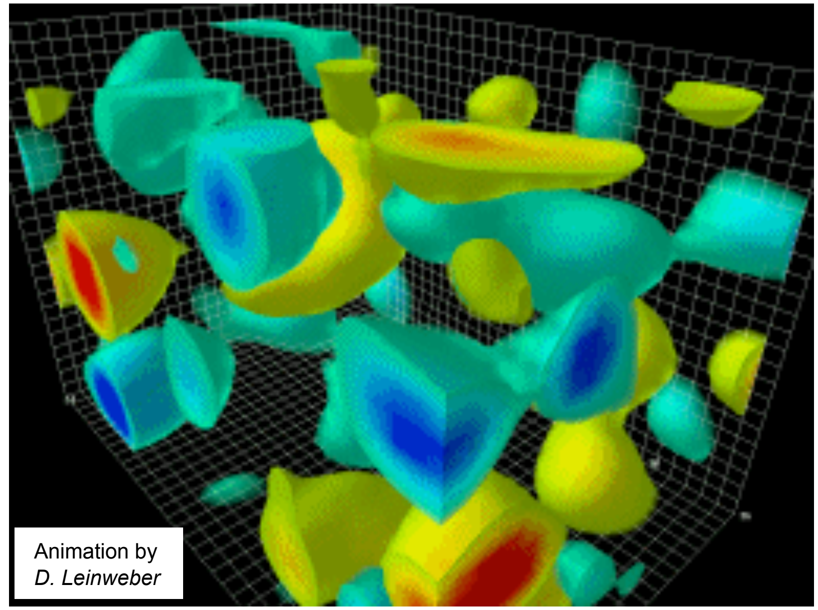
Study QCD Topological Structure

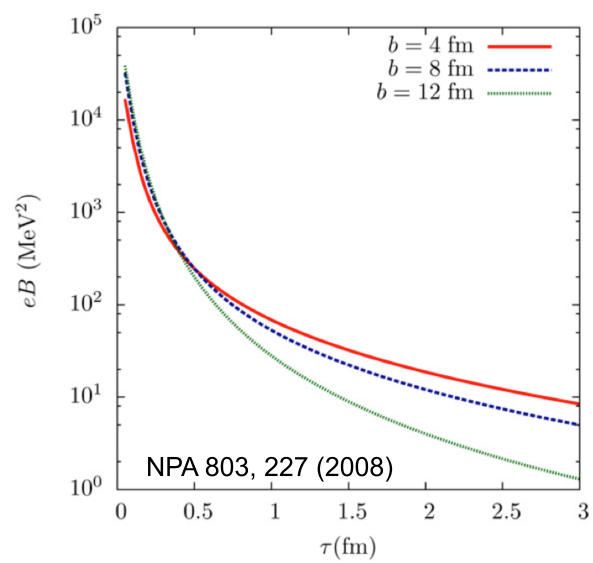
Hot/dense QCD Medium
Parity odd domains form

External Magnetic Field → Chiral magnetic effect (**CME**) (electric charge)

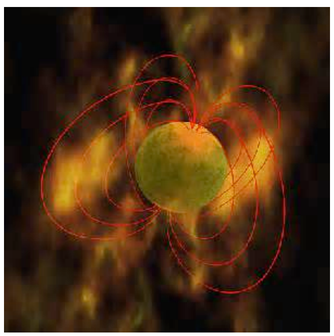
External Angular Momentum → Fluid Vorticity → Chiral vortical effect (**CVE**) (baryonic charge)

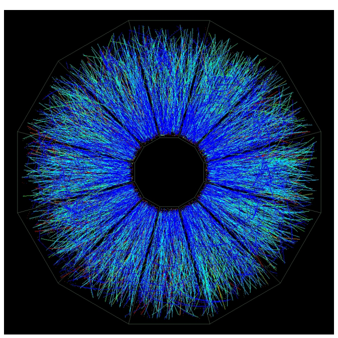






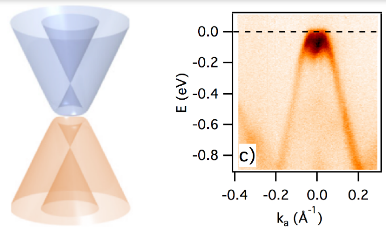
Strength of Magnetic Field





The Earth's magnetic field	0.6 Gauss
A common hand-held magnet	100 Gauss
The stable and strongest magnetic fields achieved in the laboratory	4.5×10^5 Gauss
The strongest man-made magnetic field, only briefly existed	10^7 Gauss
Ratio pulsars: typical surface, polar magnetic field	~ 10^{13} Gauss
Magnetar's surface field http://solomon.as.utexas.edu/magnetar.html	~ 10^{15} Gauss
The strongest magnetic field in high-energy nuclear collisions: in non-central $\sqrt{s_{NN}}$ = 100GeV Au+Au: **eB ~ 10^3-10^4 MeV^2**	~ **10^{17}** Gauss

Chiral Symmetry is Life



"Observation of the chiral magnetic effect in $ZrTe_5$"

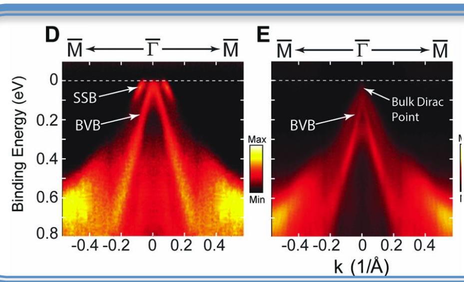
Q. Li et al., arXiv: 1412.6543 [cond-mat.str-el]

"Force of nature gave life its asymmetry"

'Left-handed' electrons destroy certain organic molecules faster than their mirror versions.

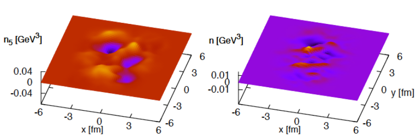
E. Gibney, ***Nature***, 25 September 2014

J.M. Dreiling and T.J. Gay, ***PRL113***, 118103(2014)



"Discovery of a Three-Dimensional Topological Dirac Semimetal, Na_3Bi"

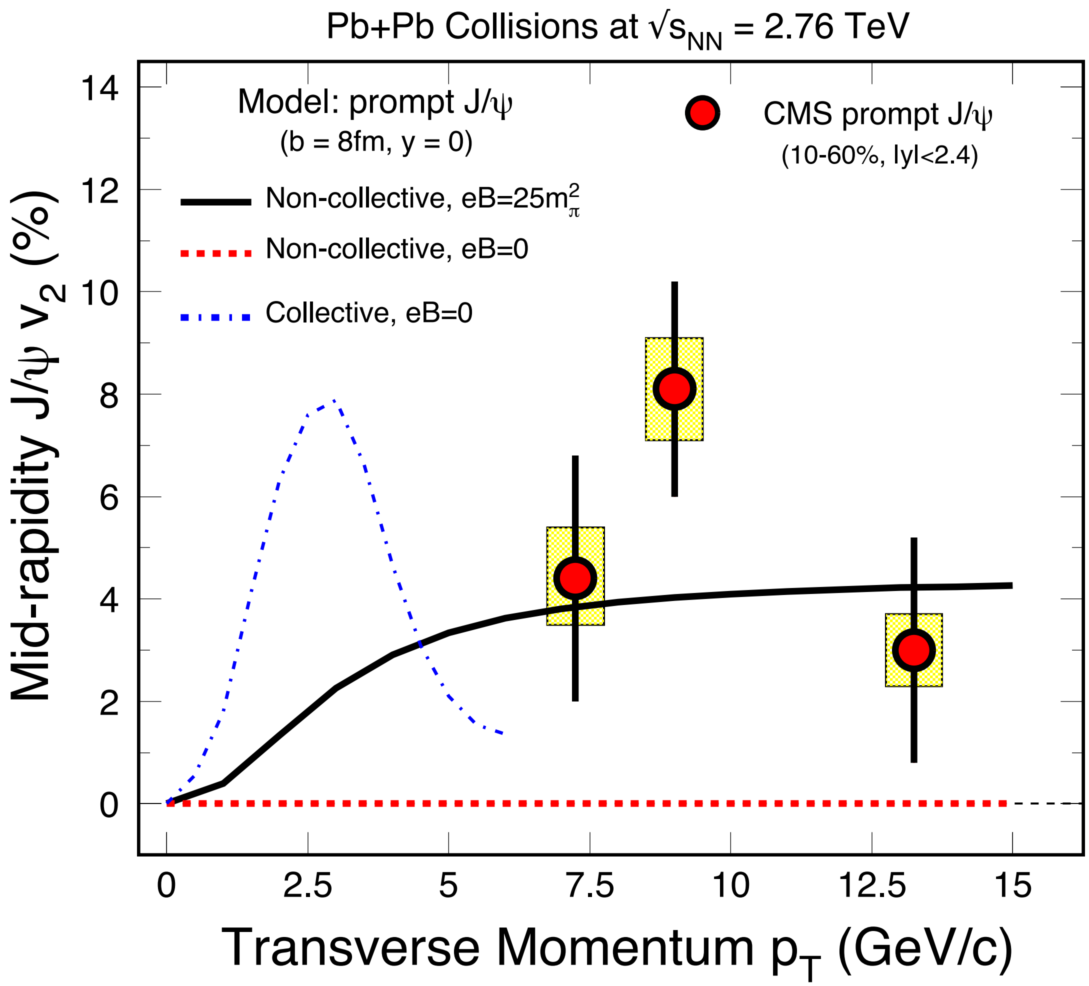
Z.K. Liu et al., ***Science***, 343, 864(2014)



"The Chiral magnetic effect in heavy-ion collisions from event-by-event anomalous hydrodynamics"

Y. Hirono et al., arXiv: 1412.0311 [hep-ph]

Initial B-Field



1) Very strong external magnetic filed at the beginning of the heavy-ion collisions

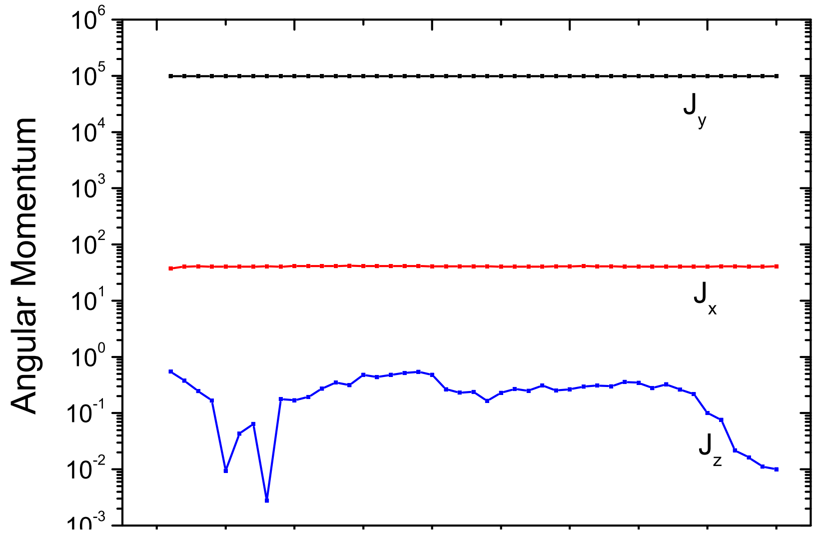
2) Early production of the high p_T quarkonia are sensitive to the initial field

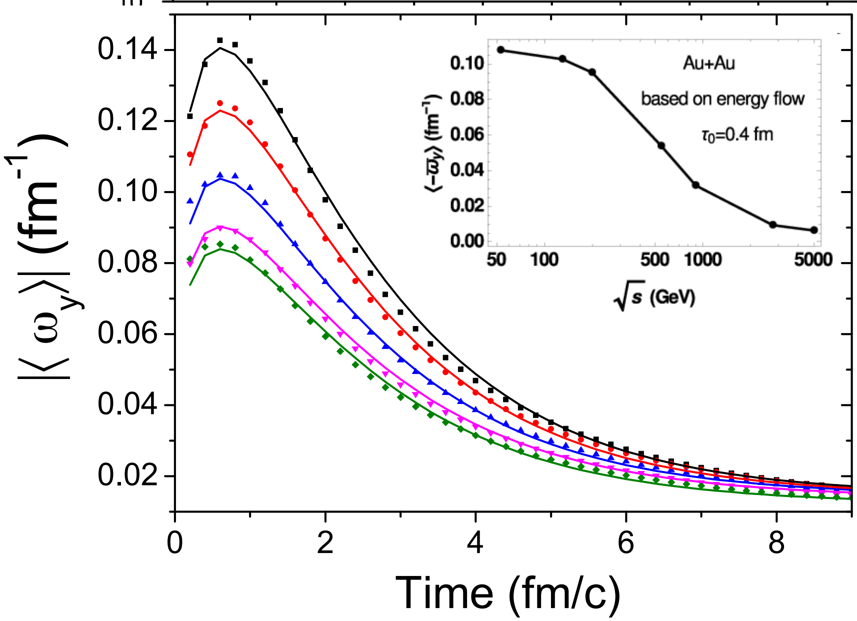
3) Measurements of the large p_{T}, non-collective v_2 of J/ψ, from Pb+ Pb collisions at LHC, seems consistent

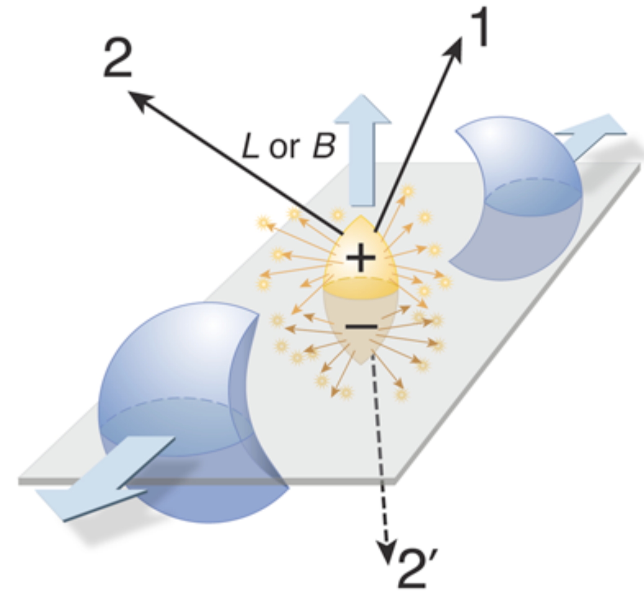
4) Future tests:
   - Upsilon v_2 from LHC
   - Collectivity of J/ψ
   - J/ψ v_2 from RHIC

Evidence of the external magnetic field!

Angular Momentum at RHIC







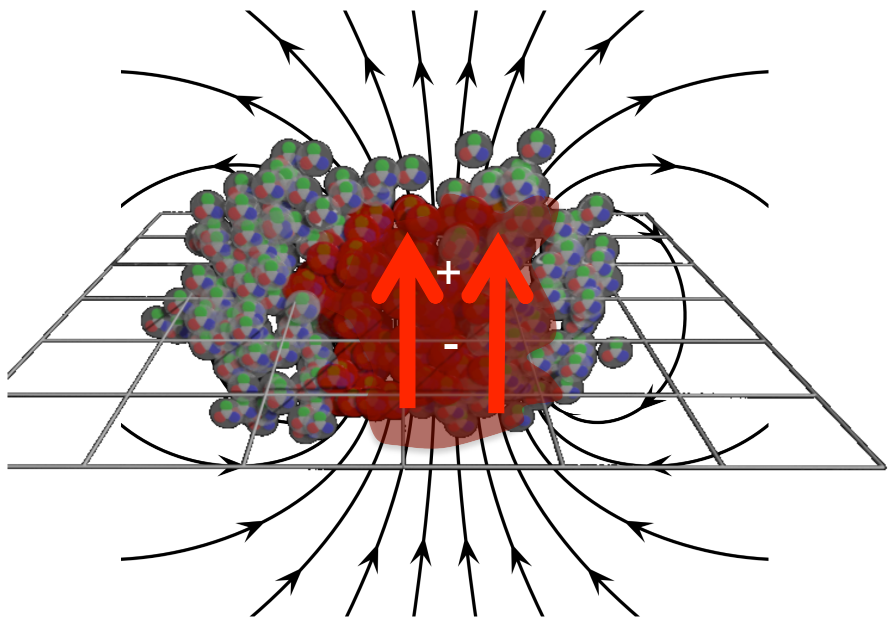
1) AMPT, Au+Au collisions, b = 7fm
2) Angular momenta conserved, no change as a function of time
3) Larger vorticity at lower collision energy
4) Mean lifetime:

$$tau_{\omega} > tau_{Hydro} >> tau_{B}$$

Y. Jiang, Z.W. Lin, J.F. Liao, 1602.06580
W. Deng and X. Huang, 2016

Observable: The γ - Correlator

$$\gamma = \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\psi_{EP}\right)\right\rangle = \left[\left\langle v_{1,\alpha} v_{1,\beta}\right\rangle + b_{in}\right] - \left[\left\langle a_\alpha a_\beta \right\rangle + b_{out}\right]$$



Same for SS and OS pairs. Removed in Δγ

Sensitive to the separation signal

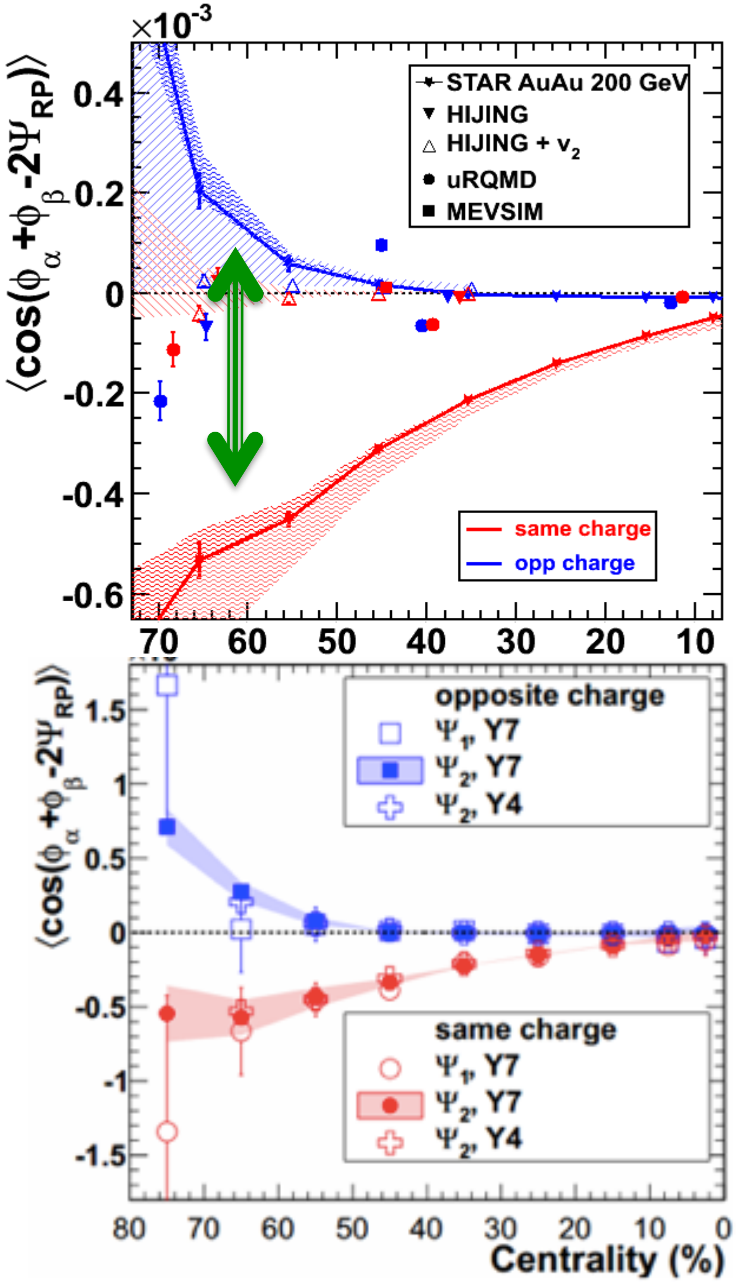
$$\gamma_{SS} = \left\langle \cos\left(\phi_\pm + \phi_\pm - 2\psi_{EP}\right)\right\rangle$$

$$\gamma_{OS} = \left\langle \cos\left(\phi_\pm + \phi_\mp - 2\psi_{EP}\right)\right\rangle$$

$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

S. Voloshin, Physical Review **C70** (2004) 057901

Charge Separation (**CME**)



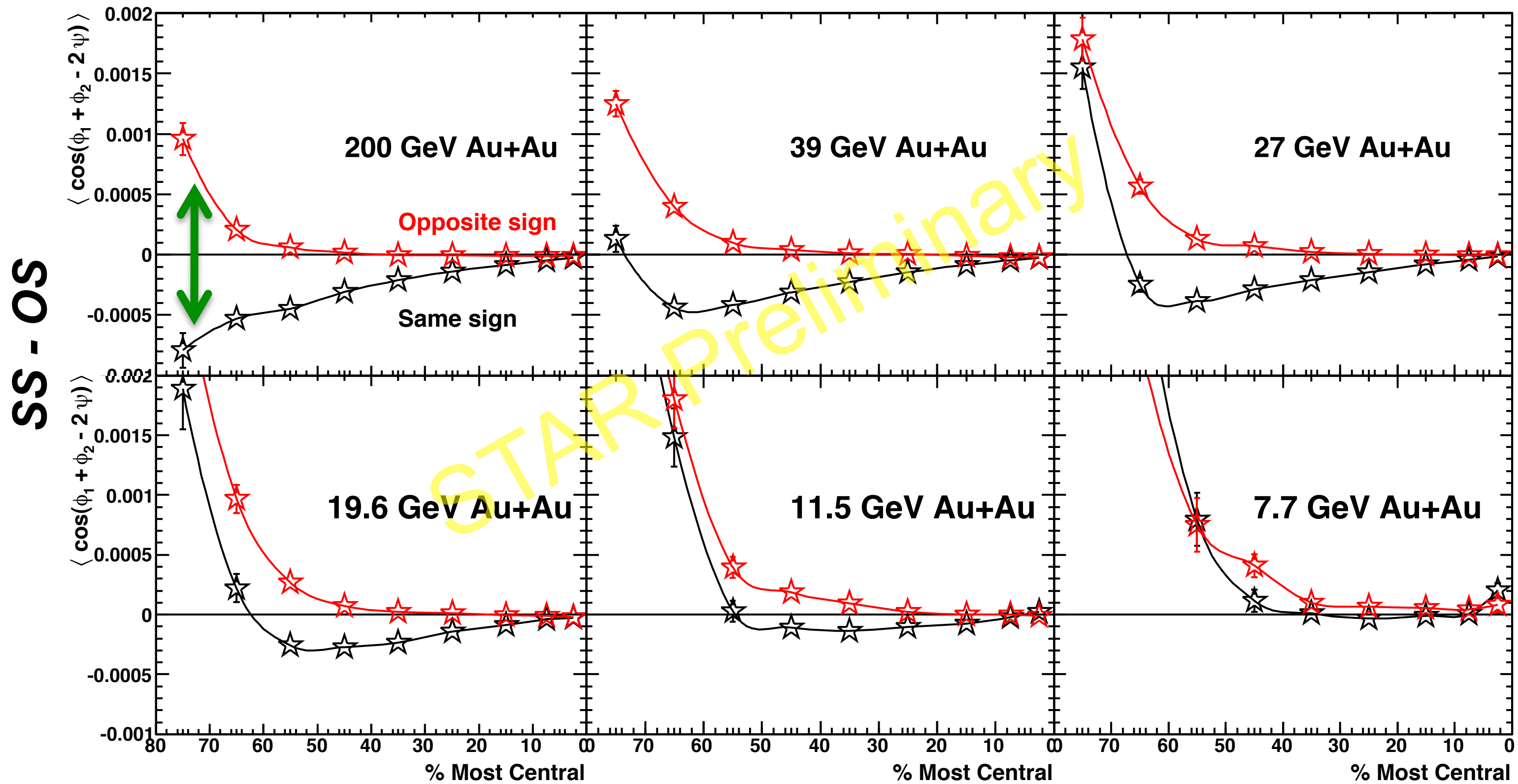
1) At 200 GeV, OS&SS charged-hadron-pairs separation at non-central collisions

2) At peripheral collisions, OS pairs larger than 0: effects of flow, energy loss,…

3) Model calculations: HIJING(v_2) and UrQMD do not show the observed separation. Note: no event-plane reconstruction, as in data, in the model analysis.

STAR: ***PRL103**, 251601(09); PRC**88**, 64911(13)*
D. Kharzeev, **PLB633**, 260 (06)
D. Kharzeev, et al. **NPA803**, 227(08)
D. E. Kharzeev, J. Liao, S. A. Voloshin and G. Wang, Prog. Part. Nucl. Phys. 88, 1(2016)

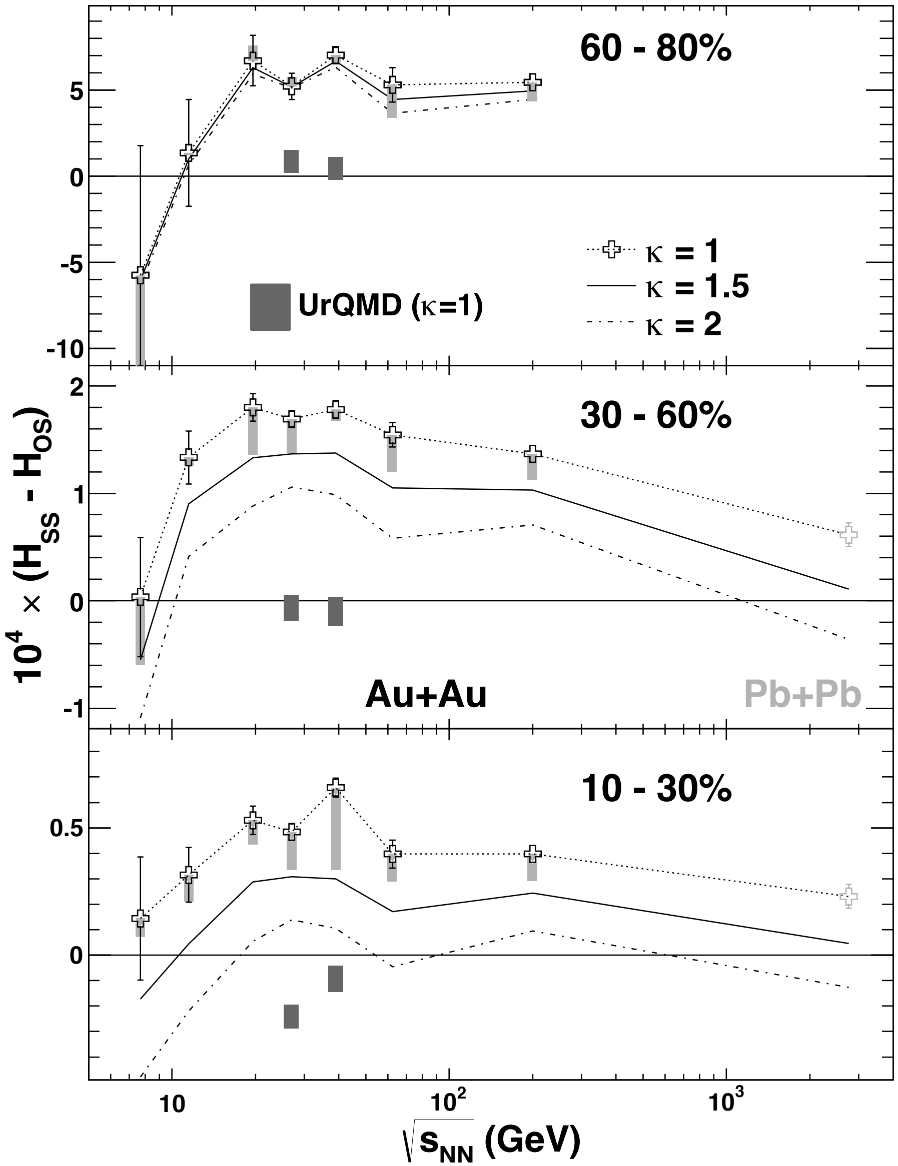
Dynamical Correlations



(1) Below $\sqrt{s_{NN}}$ = 11.5 GeV, the splitting between the same- and opposite-sign charge pairs (SS-OS) disappear

(2) If QGP is the source for the observed splitting at high-energy nuclear collisions ➔ hadronic interactions become dominant at $\sqrt{s_{NN}} \leq$ 11.5 GeV

Case I: Background Subtraction



Energy Dependence:

1) H-function removes the flow contributions:

$$H^{\kappa} = \frac{\kappa v_2 \delta - \gamma}{1 + \kappa v_2}$$

κ model dependent

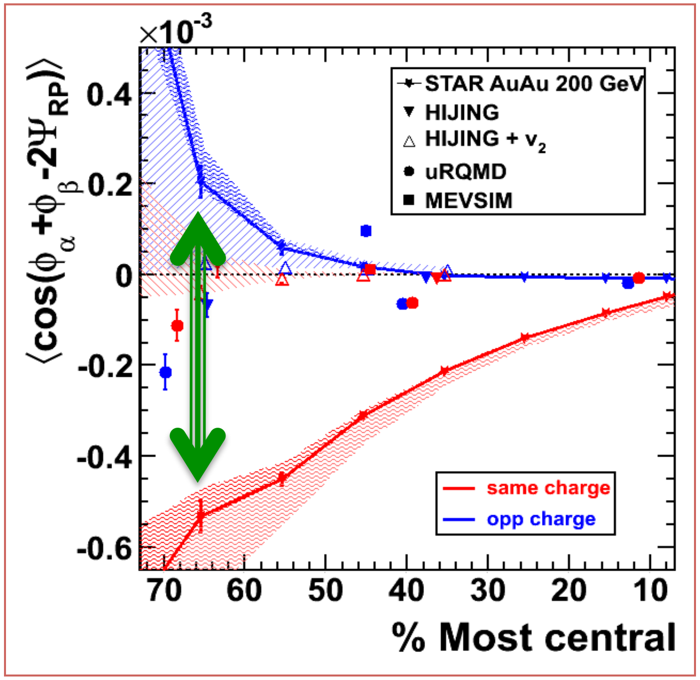
2) UrQMD model does not show the observed separation

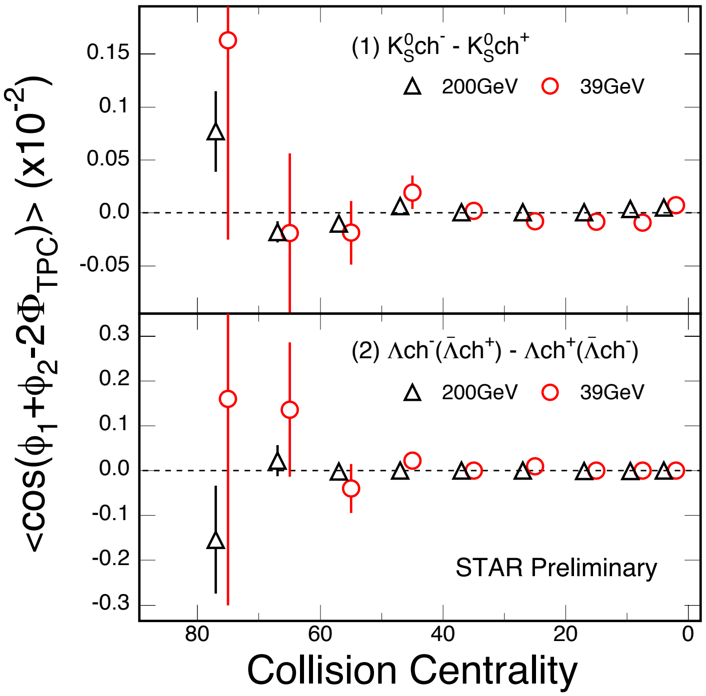
3) At low energy, no chiral symmetry restoration so any CME effect would vanish.

➔ hadronic interactions become dominant at $\sqrt{s_{NN}} \leq 11.5$ GeV

STAR: ***PRL103***, *251601(09)*; ***PRL113***, *052302(14)*
ALICE: ***PRL110***, *012301(13)*
A. Bzdak, V. Koch and J.F. Liao, Lect. Notes Phys. ***871***, 503(13)

Charge Separation (CME)

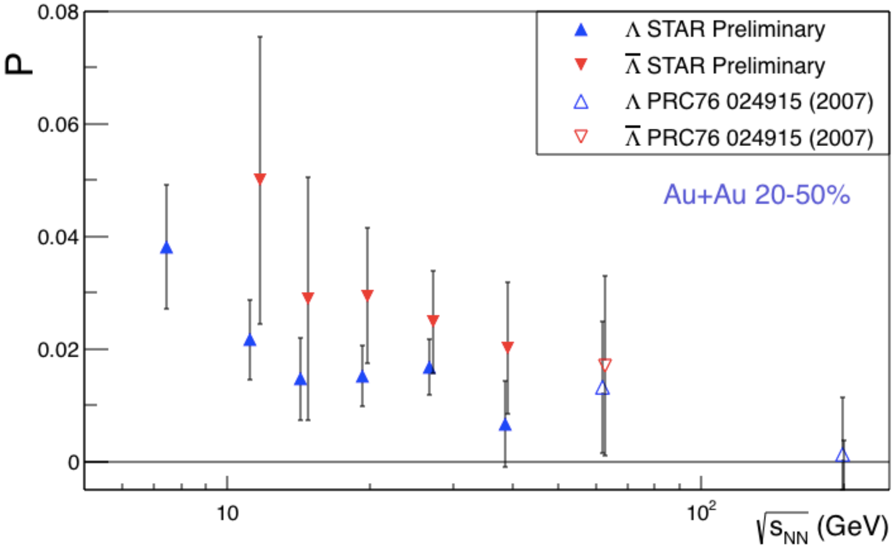




1) CME should disappear with neutral hadrons. Data of Ks-h and Λ-h show no effects.
2) Flow related background under study

STAR: ***PRL103***, *251601(09);* ***PRL113***, *052302(14); Q.Y. Shou, talk at QM2014*
D. Kharzeev, **PLB633**, 260 (06)
D. Kharzeev, et al. **NPA803**, 227(08)

Global Alignment in AA Collisions at RHIC



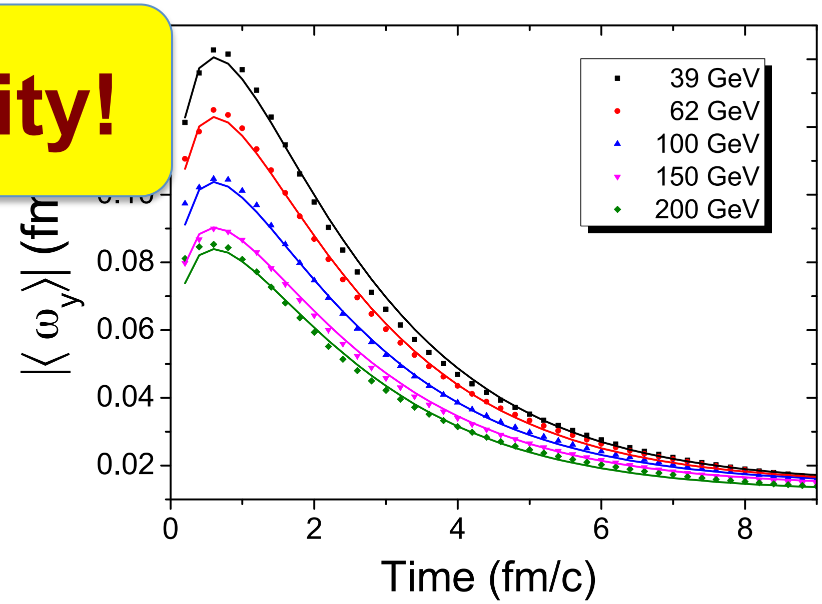
1) Finite positive alignment with total angular momentum/ **Isaac Upsal's talk**
2) At lower energy, the effect is stronger ➔ larger vorticity at lower collision energy
3) New observable for studying underlying dynamics. Important for the search of CVE in high-energy nuclear collisions

Evidence of the vorticity!

Y. Jiang, Z.W. Lin, J.F. Liao, 1602.06580

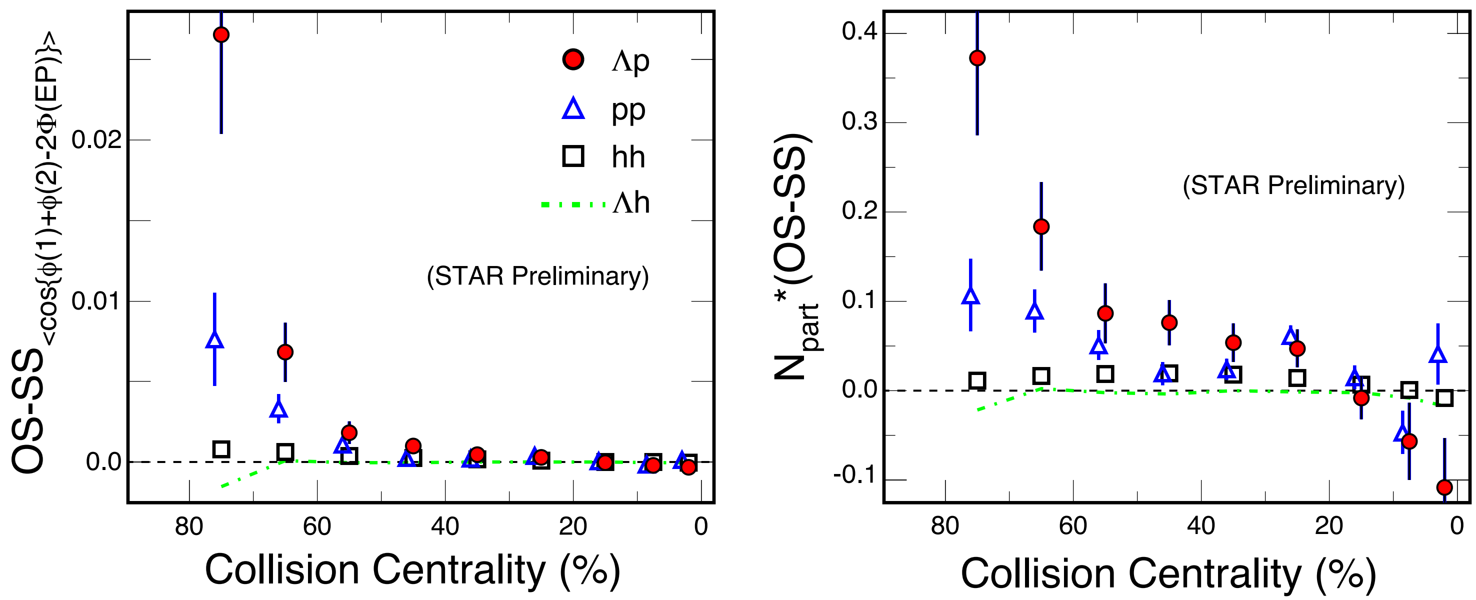
1) AMPT, Au+Au collisions, b = 7fm
2) Larger vorticity at lower collision energy
3) Mean lifetime:

$\boldsymbol{tau_\omega > tau_{Hydro} >> tau_B}$



Baryon-Charge Separation (CVE)

$\sqrt{s_{NN}}$ = 200GeV Au+Au Collisions



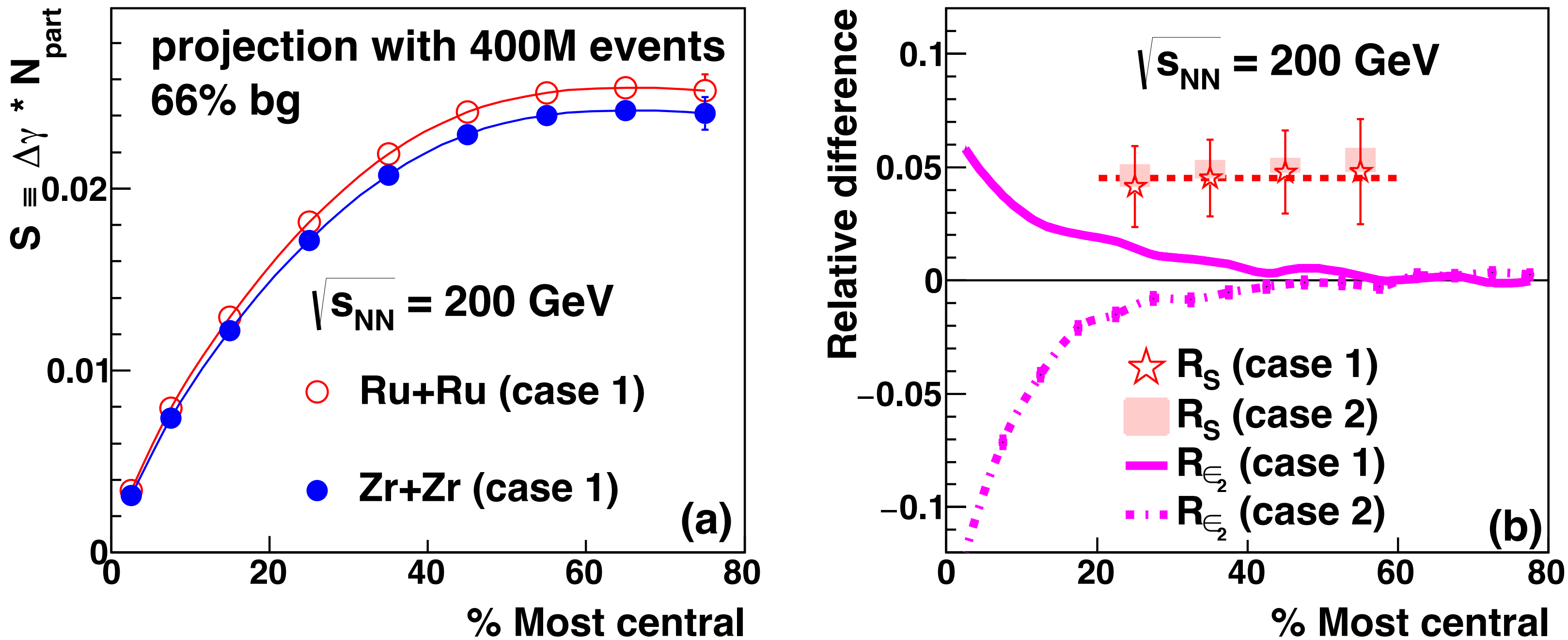
1) The values of Δγ, in pp and Λp, are non-zero, ***baryon charge separation***, as expected from the CVE

2) The Λh does not show any separation effect, consistent with CVE

3) Note: pp pairs have both CME+CVE!

STAR: F. Zhao, QM2014 Proceedings **NPA931**, 746(14) ; L.W. Wen, “Chiral Workshop”, UCLA, 2016
Kharzeev, Son, **PRL106**, 062301(11); Kharzeev. **PLB633**, 260 (06); Kharzeev, et al. **NPA803**, 227(08)

2018: 200 GeV Isobaric Collisions



A=96	$_{44}$Ru + $_{44}$Ru vs. $_{40}$Zr + $_{40}$Zr
CME	>
CMW	>
CVE	= $\mu_e << \mu_B$
Flow	=

RHIC Run18 Plan: 200 GeV Collisions

- $_{44}$Ru+$_{44}$Ru, MB, 1.2B events
- $_{40}$Zr + $_{40}$Zr, MB, 1.2B events

ΔH(Ru)/ΔH(Zr) > 5σ (30-60%)

V. Sokokov et al., 1608.00982

Chirality: Summary

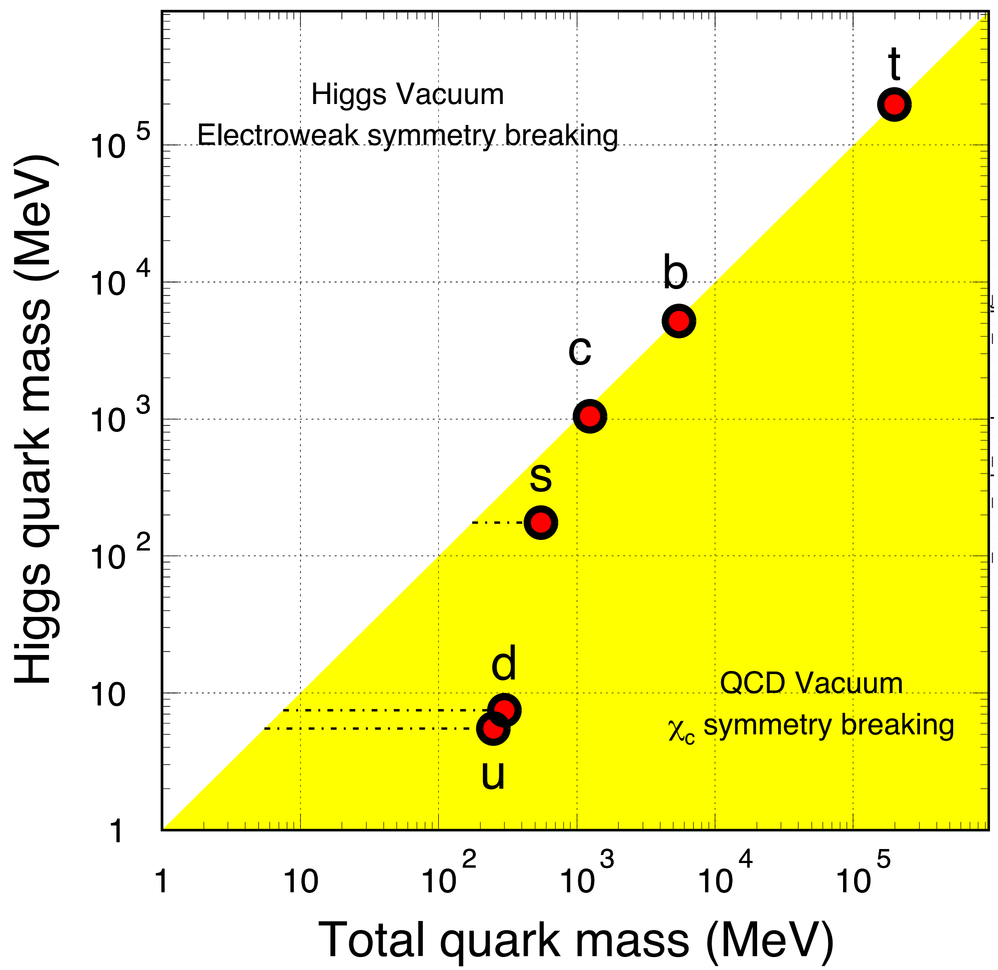
1) Evidences for both charge-separation and baryon-charge-separation along the event plan direction in high-energy nuclear collisions

2) Sevier physics background under study

3) Future isobaric nuclear collisions will clarify the irreducible background

v Heavy Quark Productions

Why Heavy Quark?

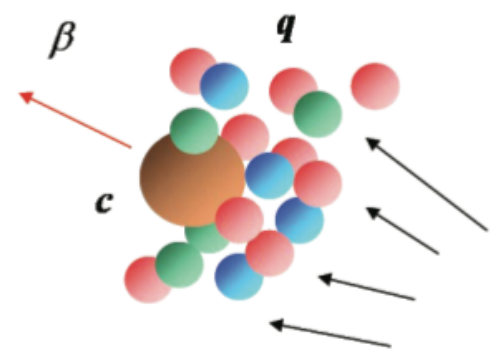


X. Zhu, *et al*, PL**B647**, 366(2007)

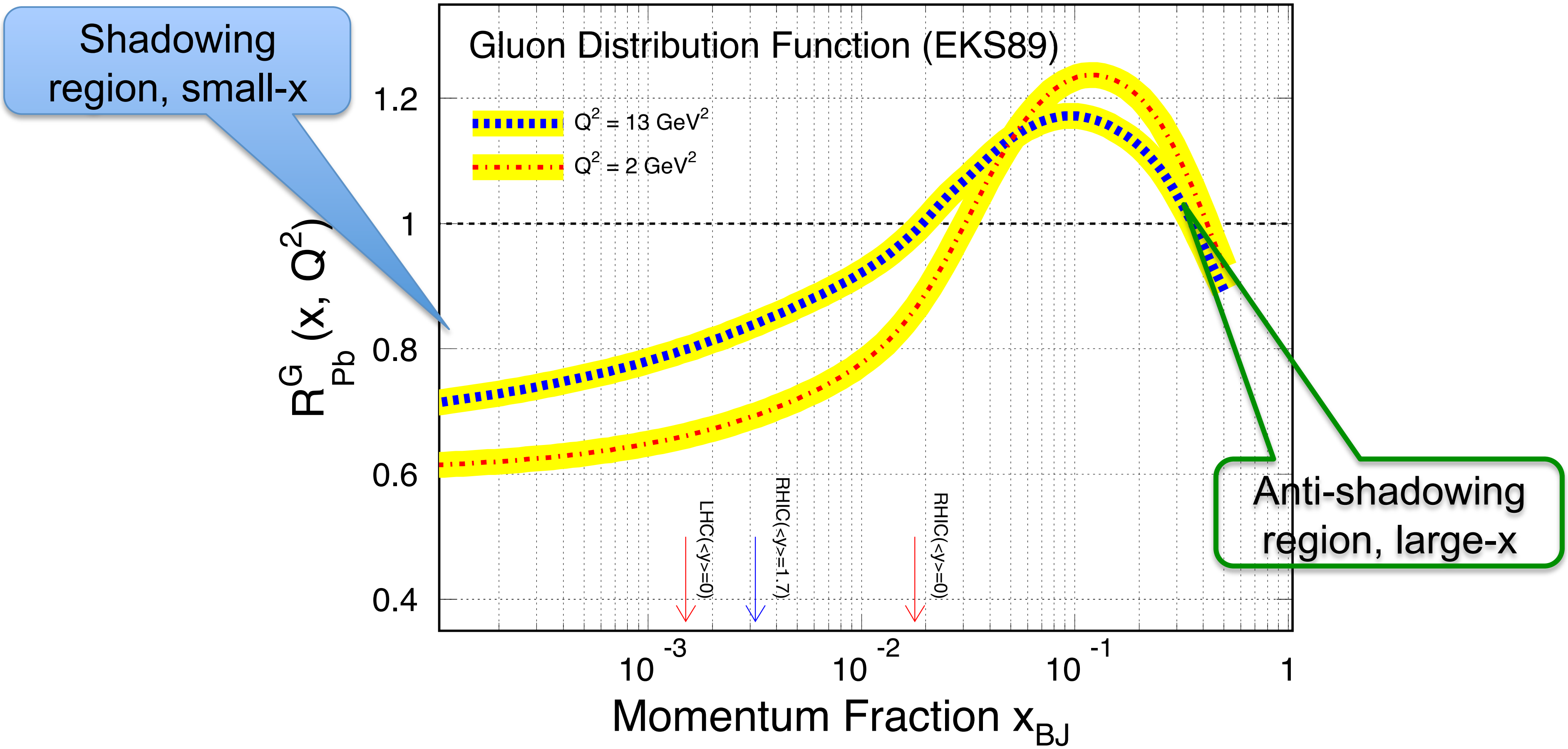
- Heavy quark masses are not altered in QCD medium
- Negligible thermal production in collisions due to their heaviness

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

Heavy quark collectivity => Light flavor thermalization

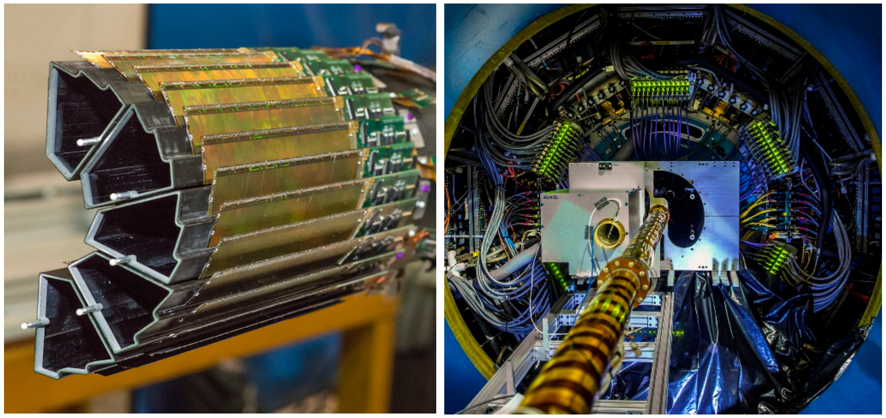


Parton Distribution Function

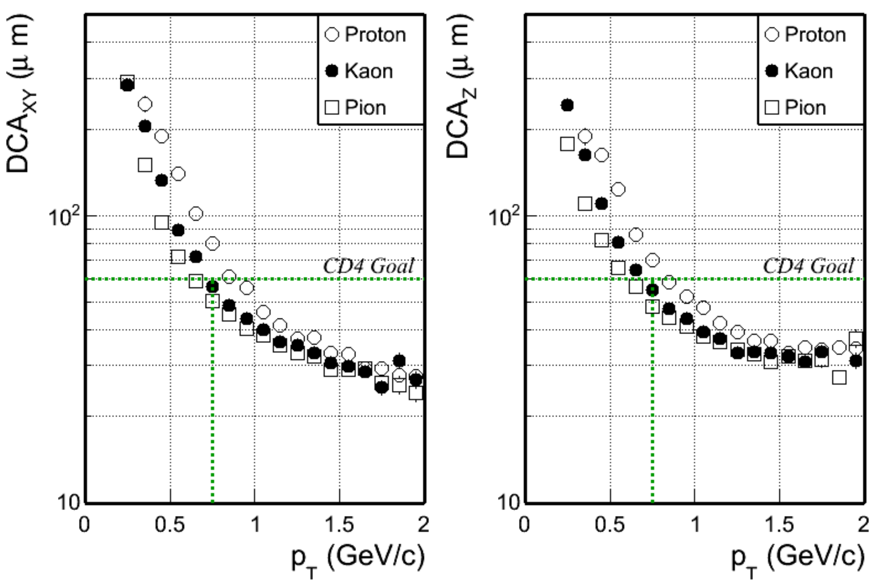


1) Nucleon parton distribution function. Due the non-linear dynamic at small-x, the nuclear parton distribution is different.
2) Different x means different initial parton flux

Heavy Flavor Tracker at RHIC



$\sqrt{s_{NN}}$ = 200GeV Au+Au Collisions



Heavy Flavor Tracker (HFT)

Physics goal: **Precision measurement of heavy quark hadron production in heavy ion collisions**

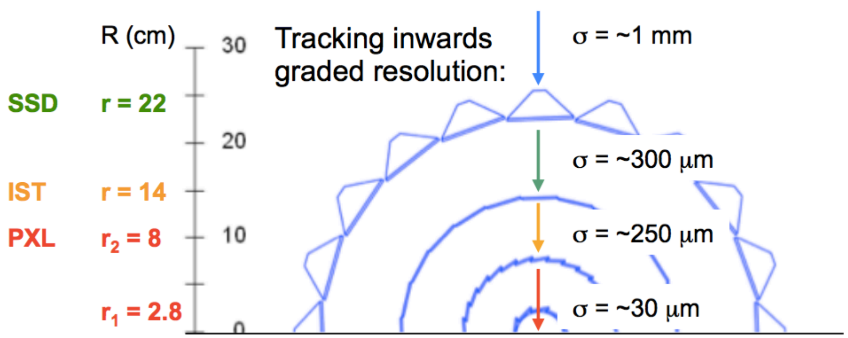
All 3 sub-detectors (PXL, IST, SSD) were completed, installed prior to Run14

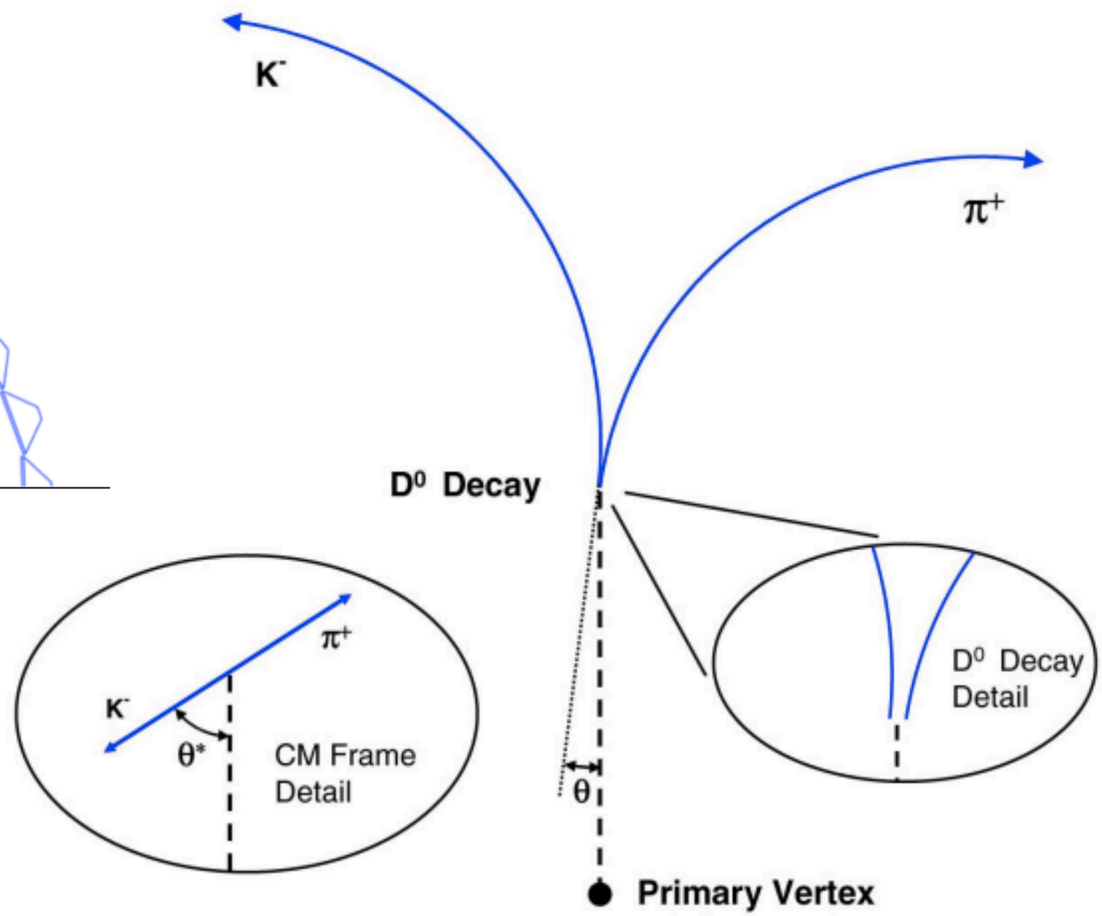
PXL – heart of the HFT: state-of-art detector, MAPS technology, first time used at a collider experiment.
Integration time ~ 190μs

Taking data with STAR detector system, on track towards the physics goal

With survey and preliminary alignment,
Kaons at 750 MeV/c: DCA < 60μm

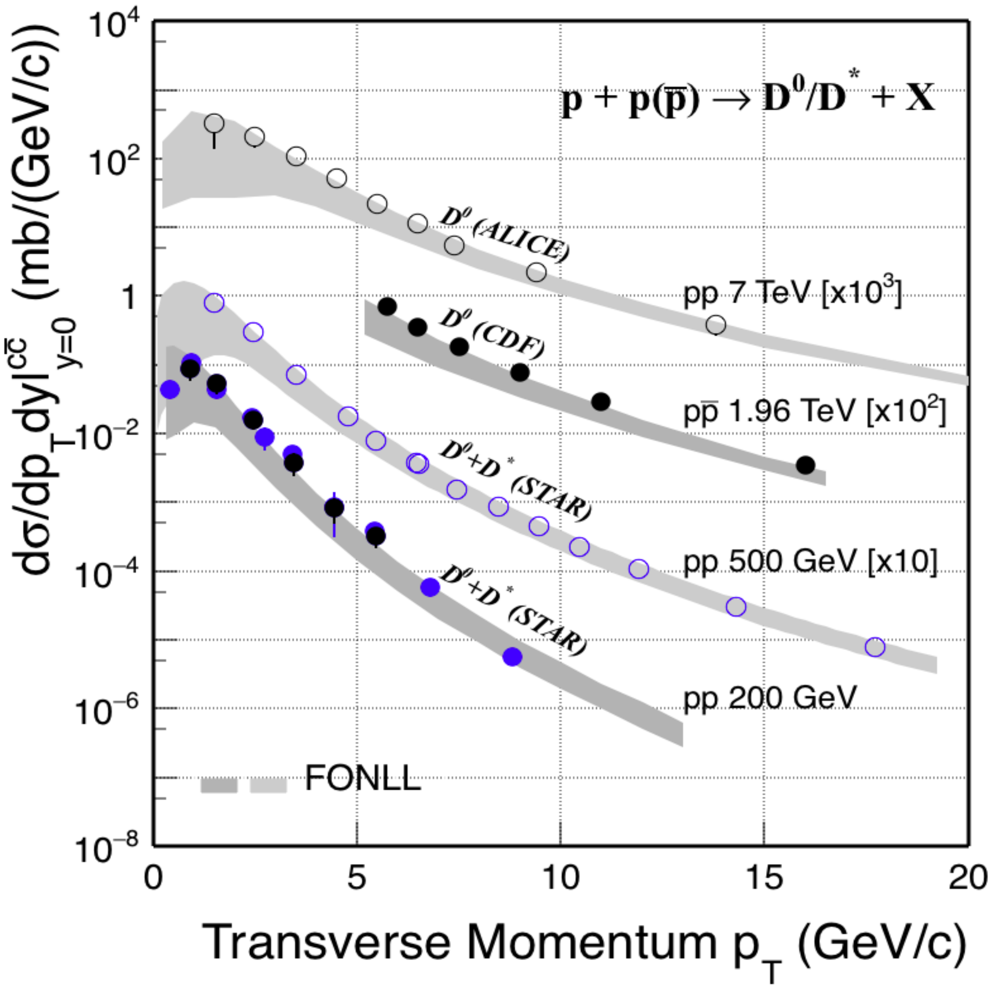
Topological Reconstruction of Secondary Vertices





Hadron	Abundance	cτ (μm)
D^0	56%	123
D^+	24%	312
D_s	10%	150
Λ_c	10%	60
B^+	40%	491
B^0	40%	456

Charm Quark Production

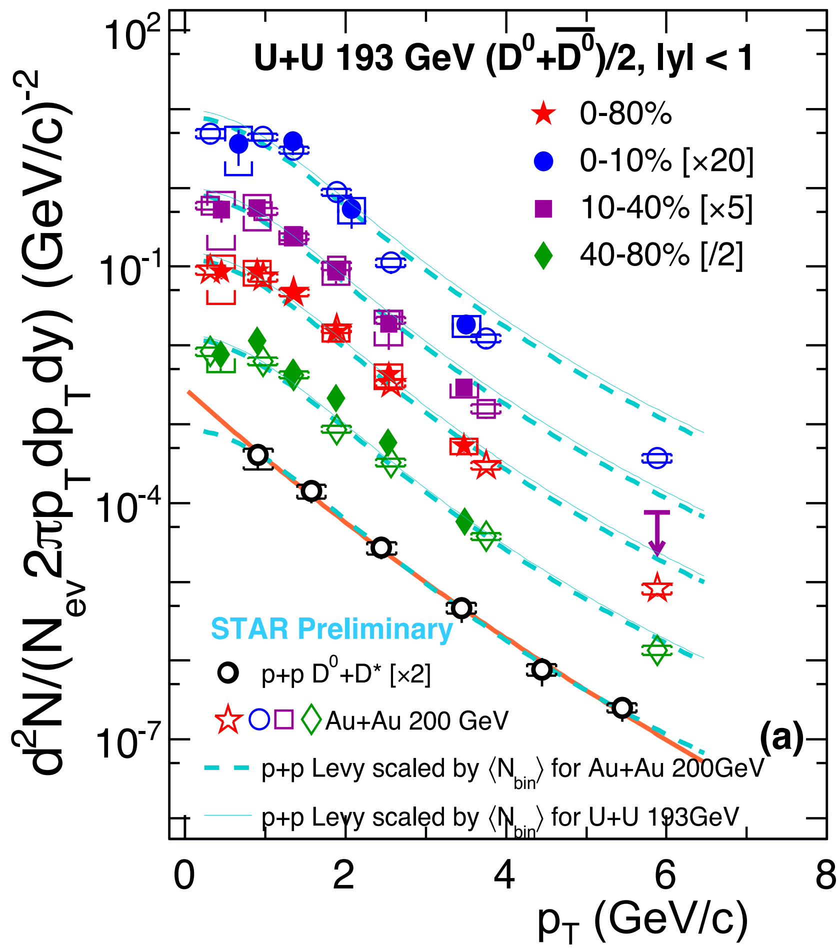


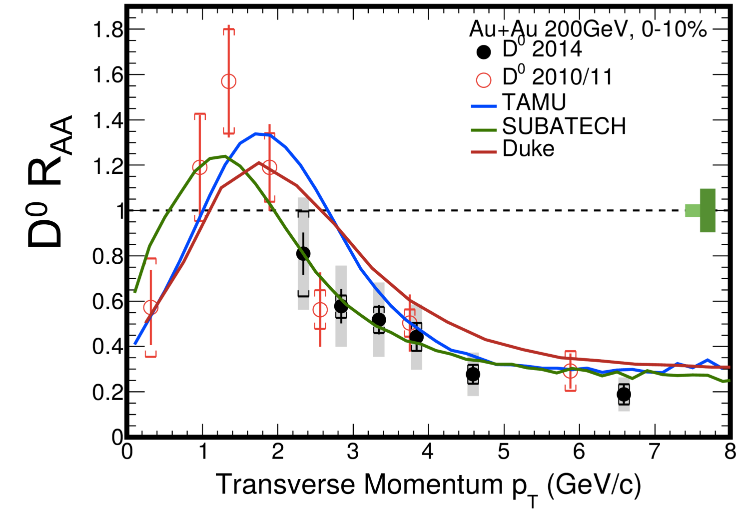
Charm quark, $m_c >> T_{QGP}$ & Λ_{QCD}, sensitive tool for probing medium:

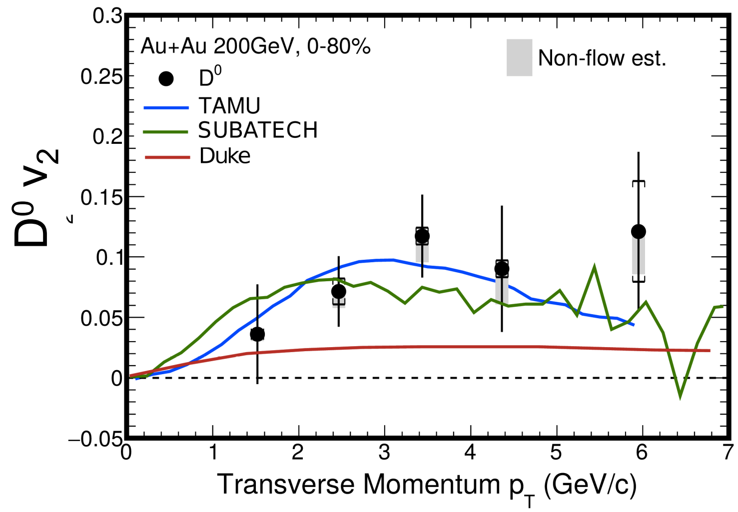
1) Produced in the hard scatterings at the early stage of nuclear collisions. Its production rate is described by pQCD in elementary collisions
2) Charm cross section scales with N_{coll} in Au+Au collisions
3) QCD model predictions are consistent to data

STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520
CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128
FONLL: PRL 95 (2005) 122001
**PRL 113 (2014) 142301*

D-mesons in 200GeV Au+Au Collisions

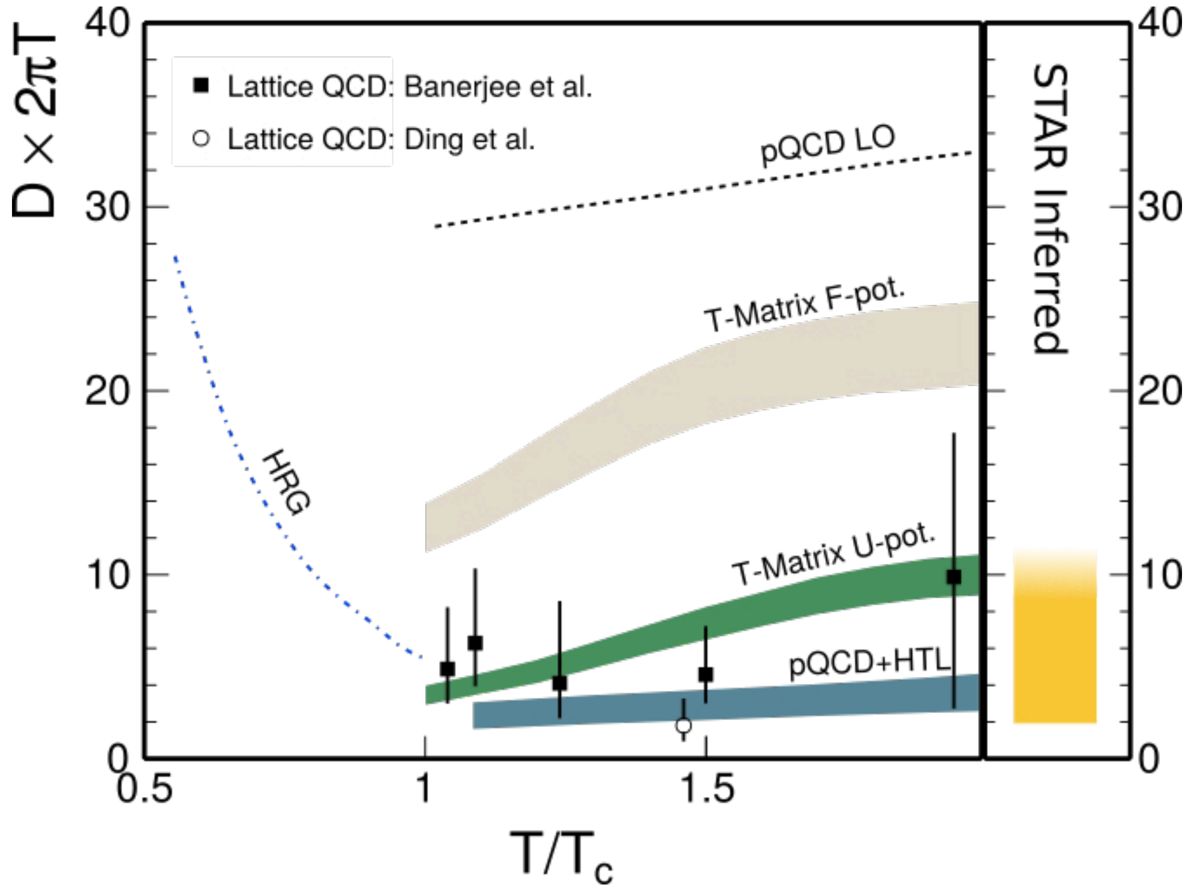






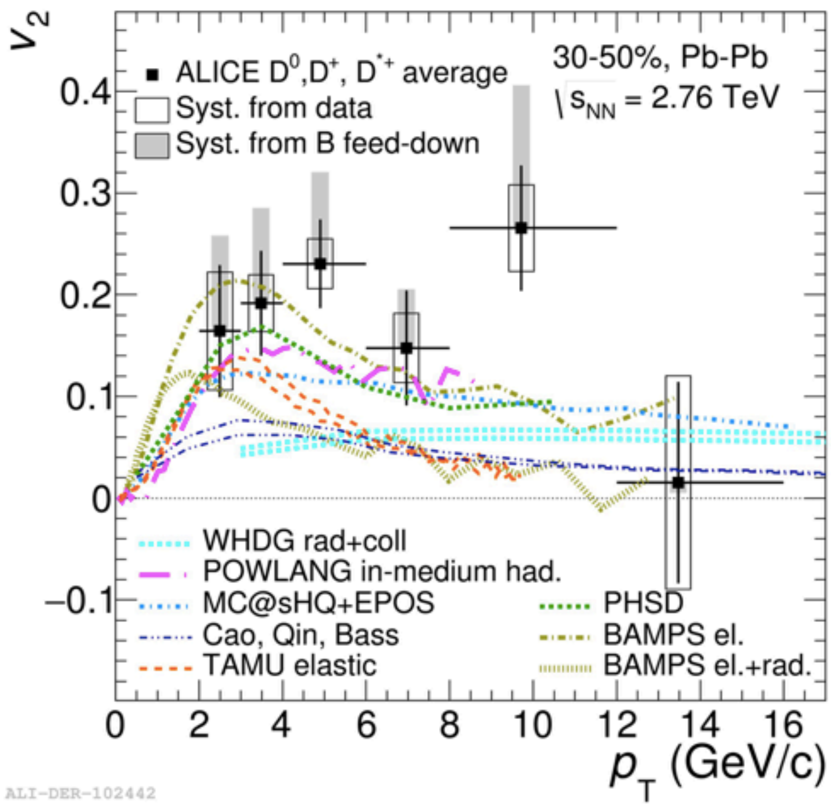
1) As seen in light-flavor hadrons, large suppression in R_{AA} observed at high p_T
2) Model results show that ***Coalescence is necessary*** for hadronization in high-energy nuclear collisions

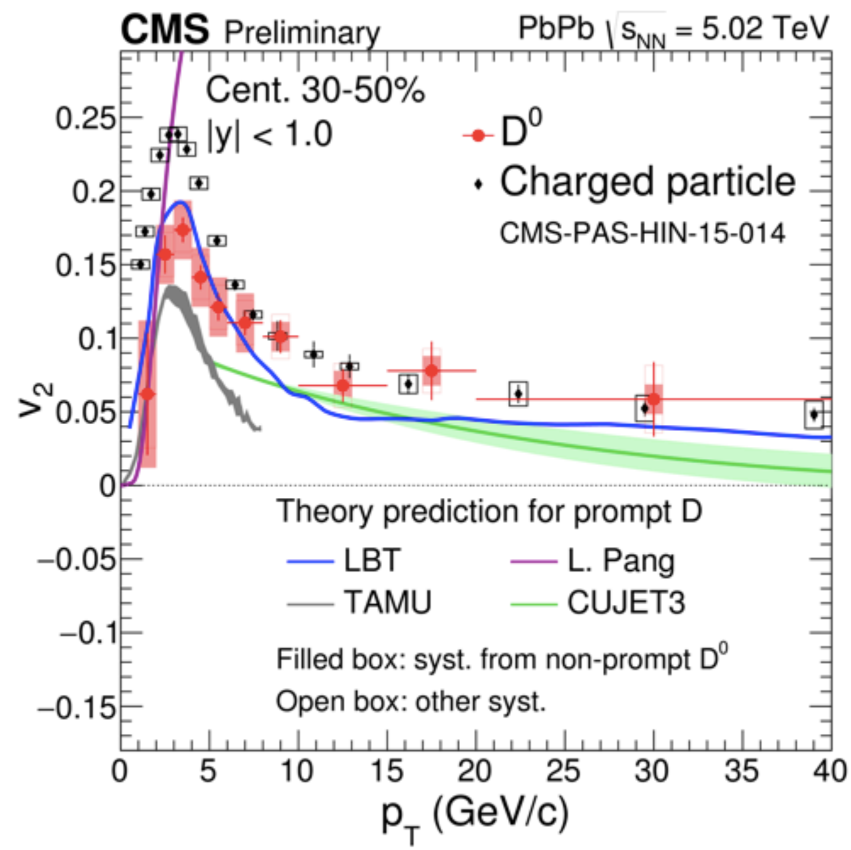
sQGP Thermal Properties at RHIC



1) Charm Diffusion Coefficient: D = 2 – 10/(2πT) from RHIC data
2) Lattice calculations are consistent with values inferred from data

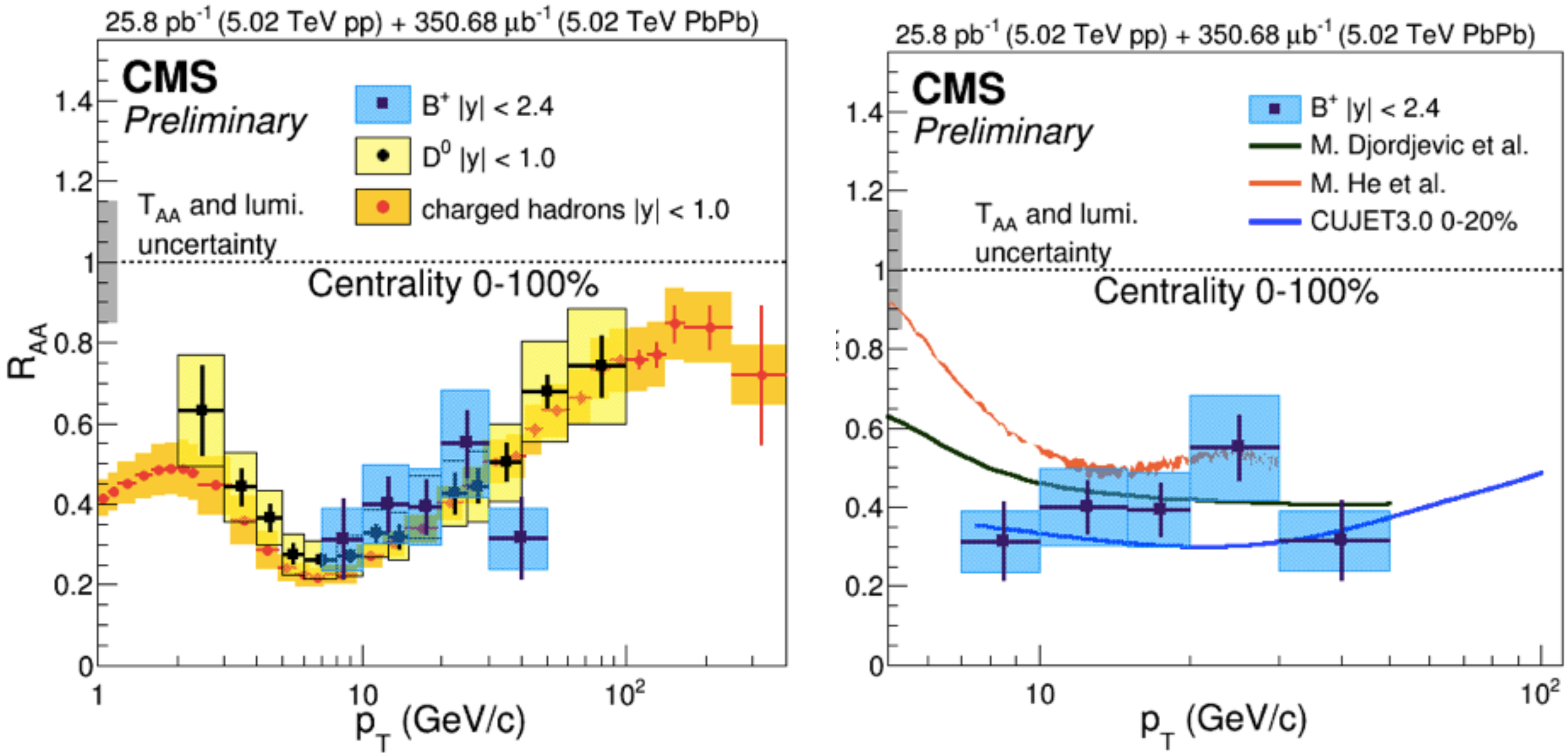
Heavy Quark Collectivity





1) Finite diffusion needed to describe the data =>
Charm quarks flow at in collisions at LHC
2) More data with finer centrality bins needed

First Results on Bottom Hadron R_{AA}

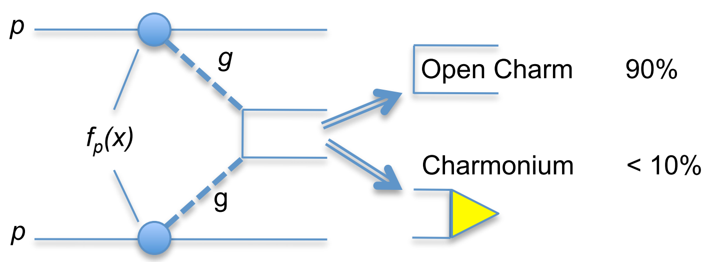


1) **Bottom hadron R_{AA} similar to that of (*u,d,s,c*)**. Errors are still large!
2) Model results different as large as error bars.

CMS: HP2016 Overview talk, Sept. 2016

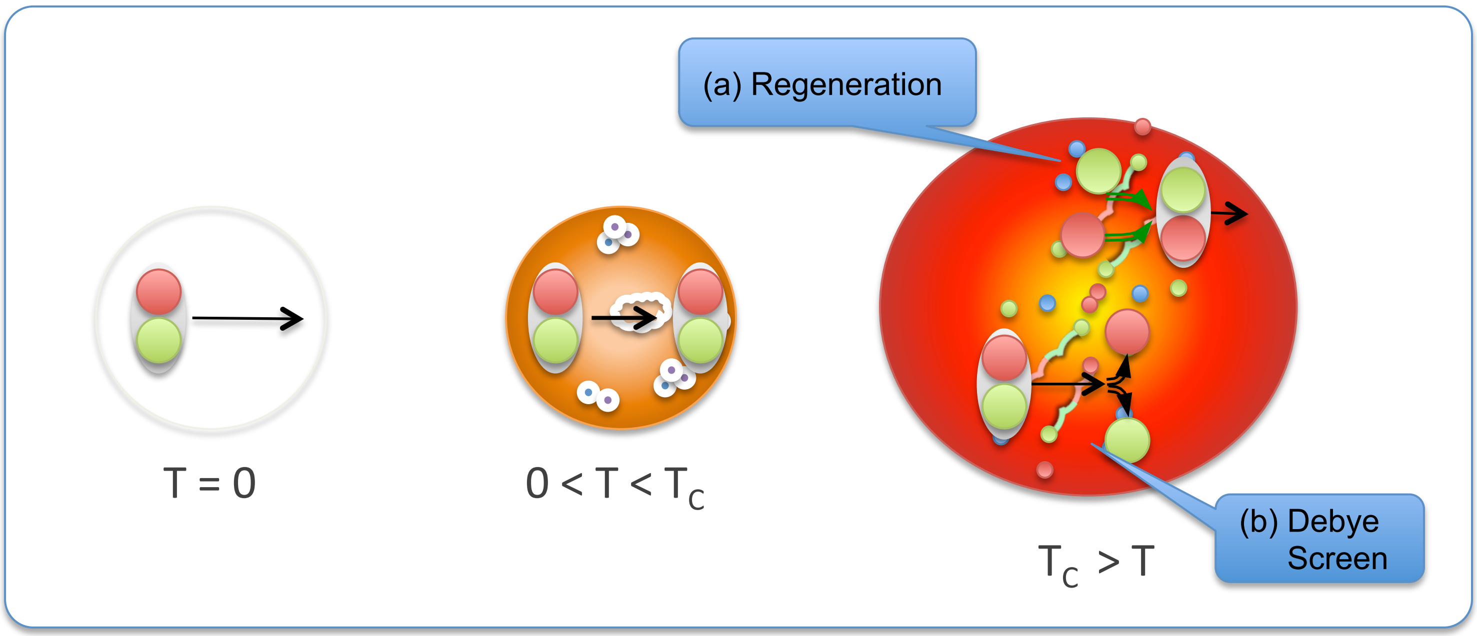
Quarkonium Production

p + *p* Collisions



Heavy Ion Collisions

1) *Npdf:* Initial condition
2) *Cronin effect:* Cold nuclear matter
3) *Debye Screen:* Hot/dense
4) *Regeneration:* Hot/dense



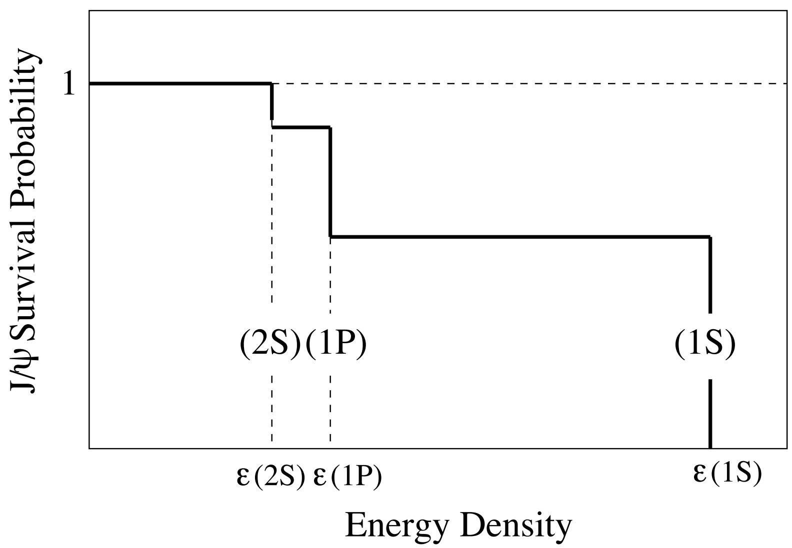
In Nucleus-Nucleus Collisions

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 initial scattering



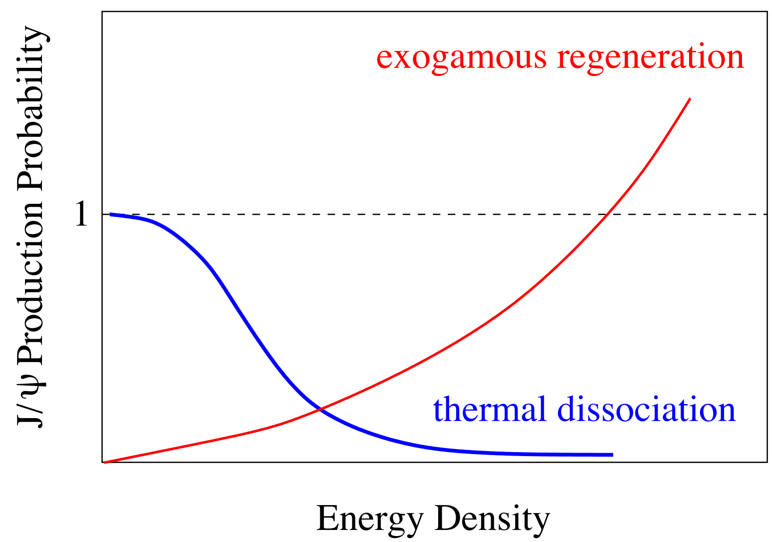
Matsui & Satz, PL**B178**, 178(1986).

Regenerations

At the boundary of hadronizatipn:

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

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



Modification Factors

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

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

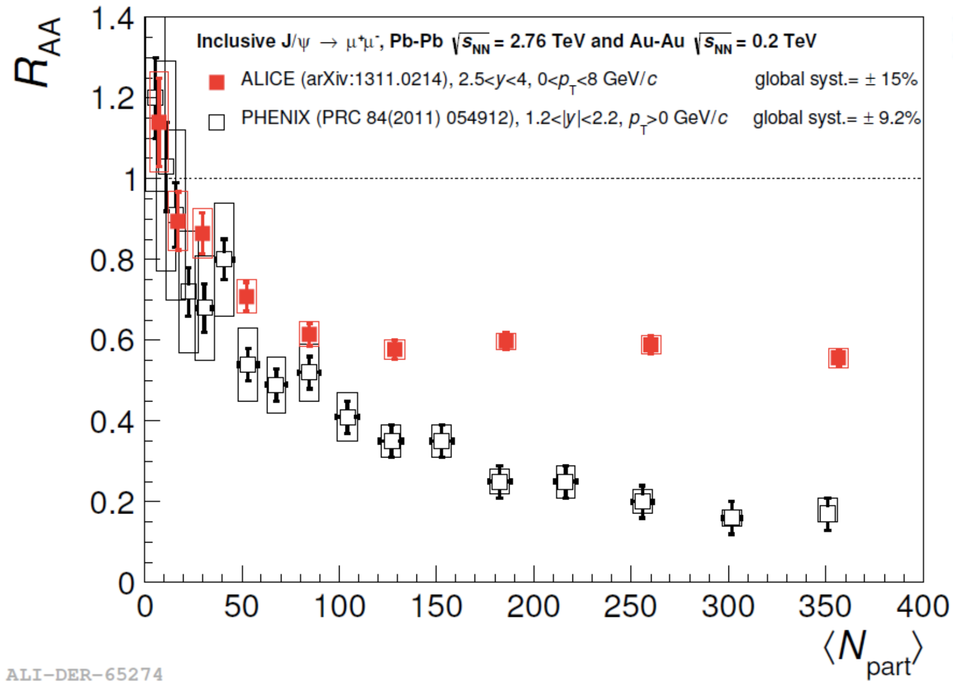
$$r_{AA}(p_T^2) = \frac{\langle p_T^2 \rangle^{AA}}{\langle p_T^2 \rangle^{pp}}$$

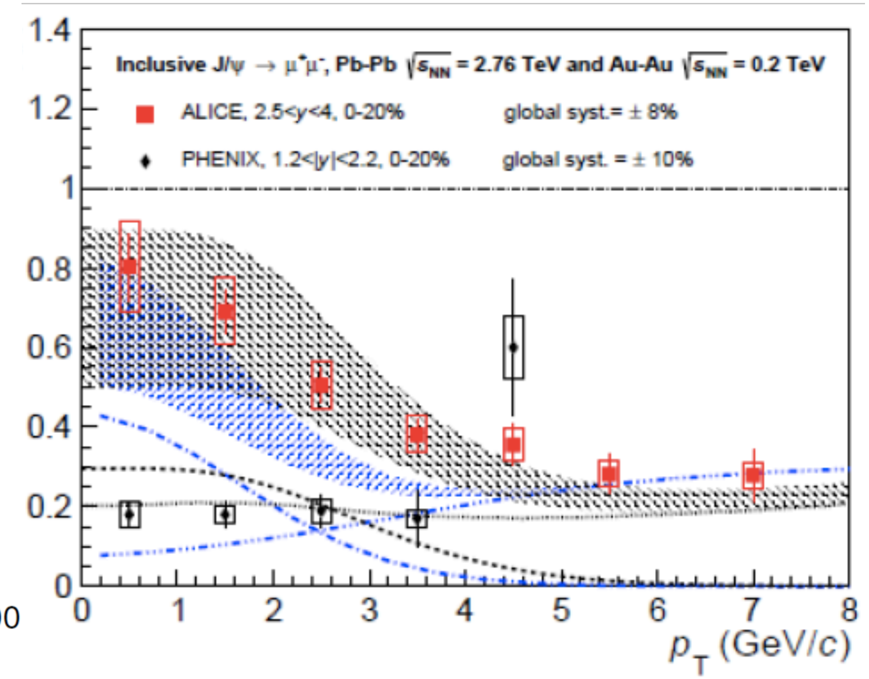
2) The p_T dependent $r_{AA}(p_T)$ sensitive to medium effect including Cronin scattering, Debye Screening, and regeneration * *.

* H. Satz arXiv: 1303.3493

* * Pengfei Zhuang et al, 2010

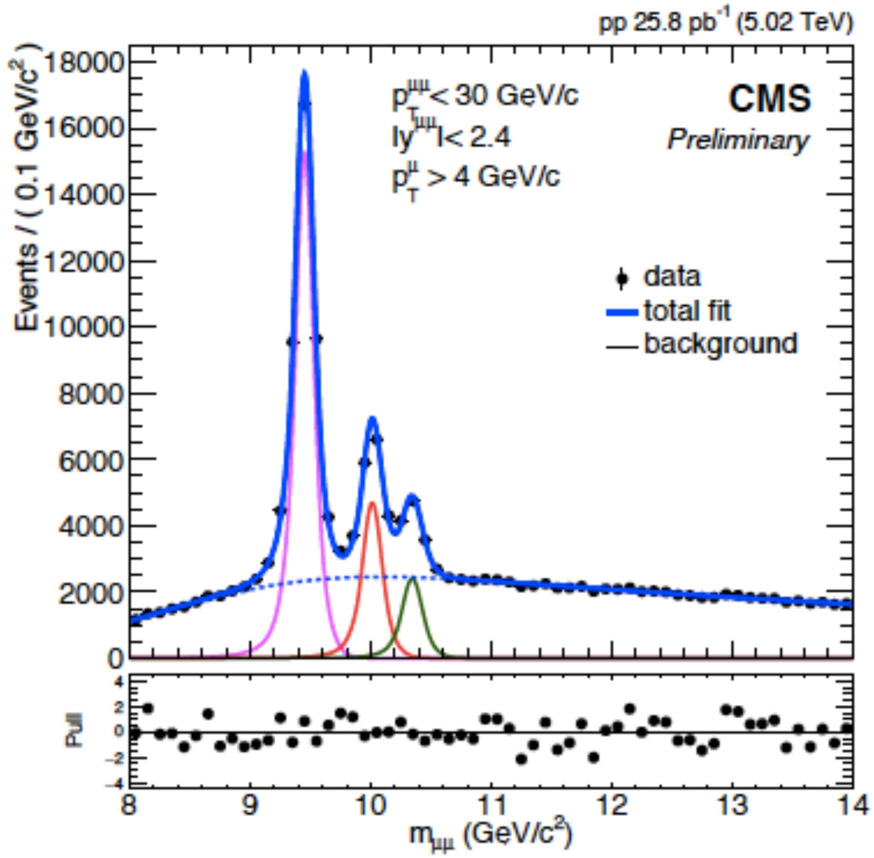
J/Ψ R_{AA}

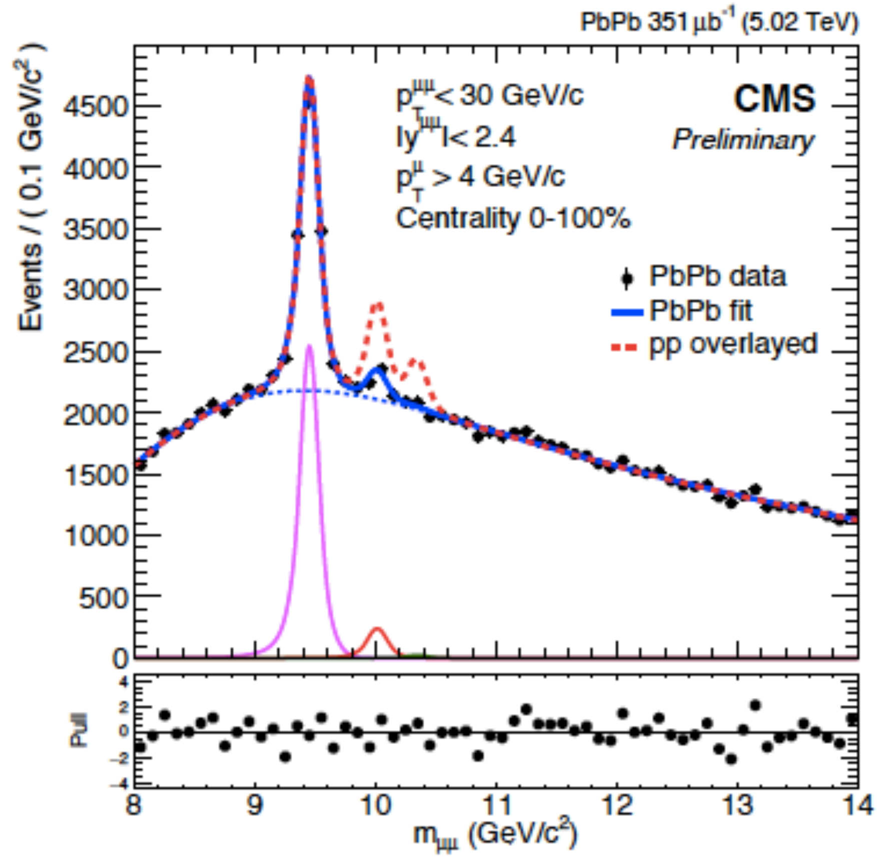




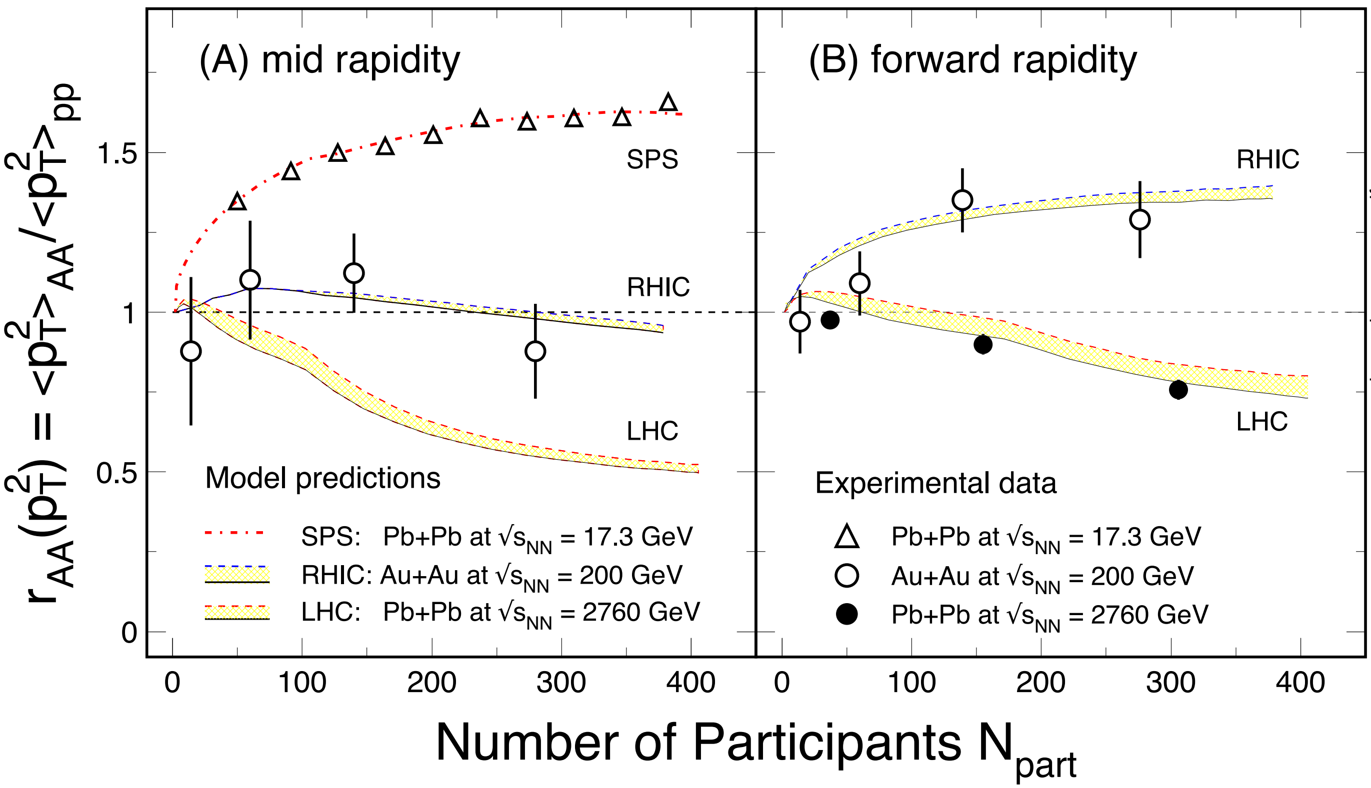
1) R_{AA}(LHC) > R_{AA}(RHIC), especially at low p_T region => Evidence for regeneration
2) RHIC: suppression dominant
3) Model results: only 20-40% J/Ψ from regeneration at RHIC. At LHC: >85%

ϒ Suppression in Heavy Ion Collisions



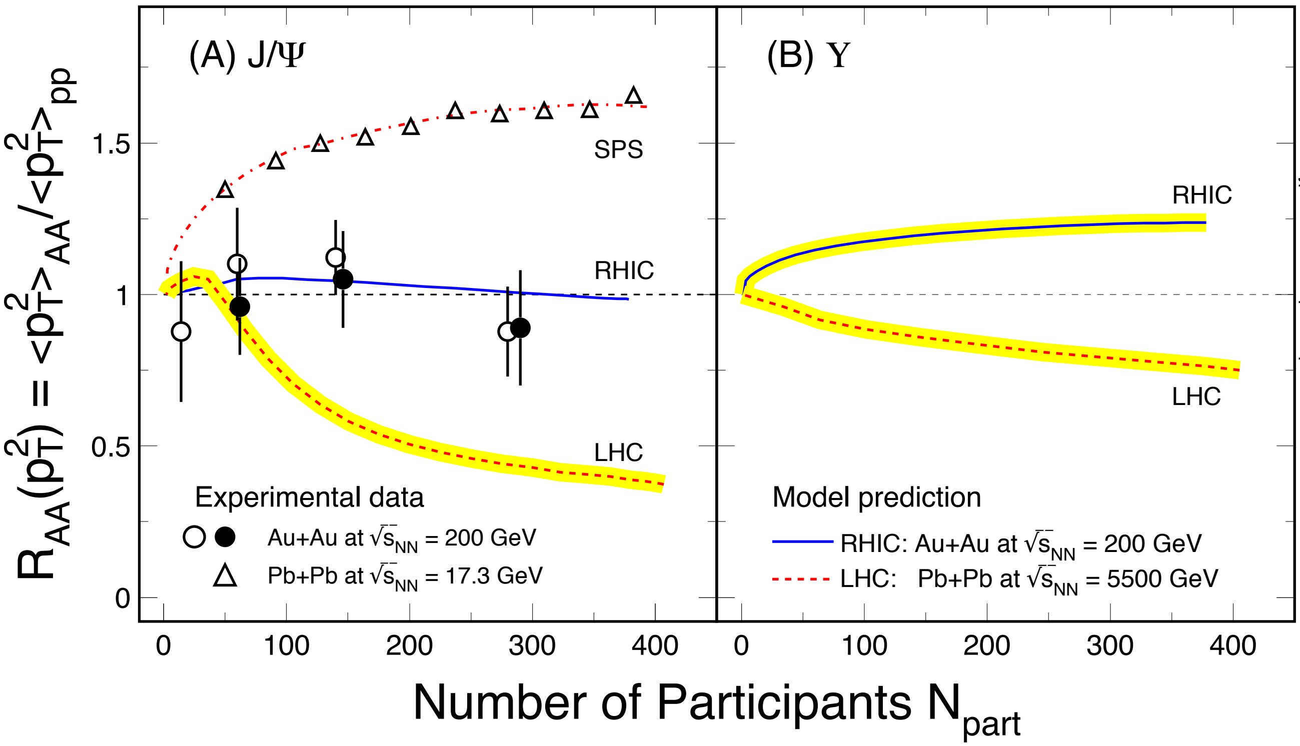


Charmonium Production



1) **LHC:** more final *J/ψ*s produced via regeneration leads to lower value of $<p_T>$
2) **SPS:** all final *J/ψ*s are survival ones. The increase of $<p_T>$ is due to the initial Cronin scatterings
3) **RHIC:** mixture of initial and regenerated *J/ψ*s

Quarkonia Production



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

(B) Prediction of *Upsilon* production: Due to small bottom cross section at RHIC, negligible regenerations, Cronin effect is dominant. At LHC, sizable contributions from regenerations. A prediction!

Heavy Quark: Summary

(1) The effects of Debye Screening and Regeneration: **are all medium effects.**

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

(3) Upsilon: Predictions for both RHIC and LHC.

Outline

I. Introductions

II. Status of the Relativistic Heavy Ion Collider

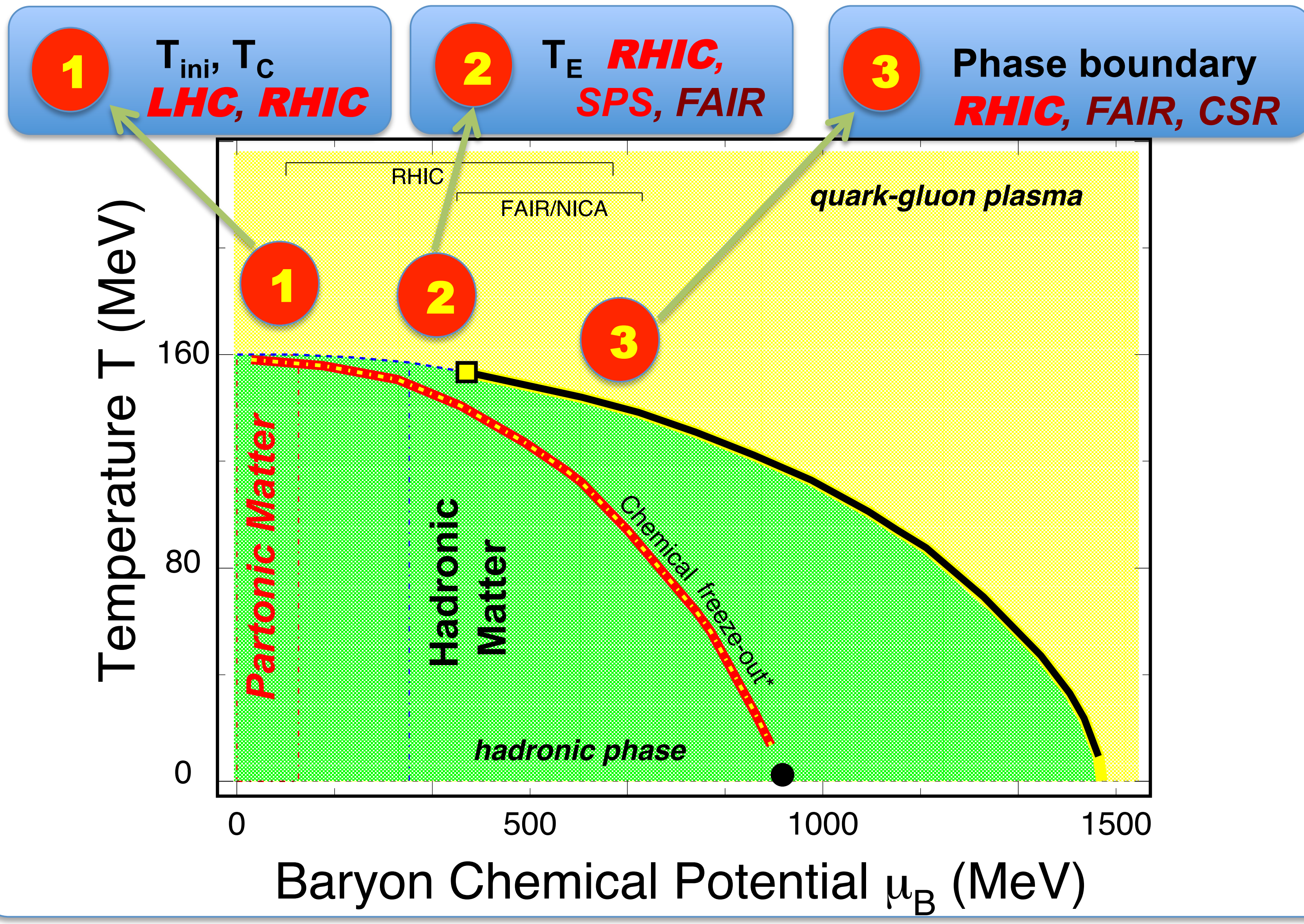
- Accelerator complex and Detectors
- Definitions
- Future planes

III. Selected topics in High-energy Nuclear Collisions

i. Parton Energy Loss
ii. Collectivity
iii. Criticality
iv. Chirality
v. Heavy quark production

IV. Summary

Exploring QCD Phase Structure



S. Gupta, et al, ***Science***, 332, 1525(2011)

Please ask questions: nxu@lbl.gov

"There is no stupid question"

"学而不问，非礼也"

Thank you for your attention!