STAR Heavy Ion Physics Program and Future Perspective

Huan Zhong Huang
黄焕中
Department of Physics and Astronomy
University of California at Los Angeles

The 6th Workshop on Hadron Physics
July 21-24, 2014 @Lanzhou, China

Selected QCD Results from RHIC AA Program

sQGP Properties – QFT @ Strong Coupling Limit

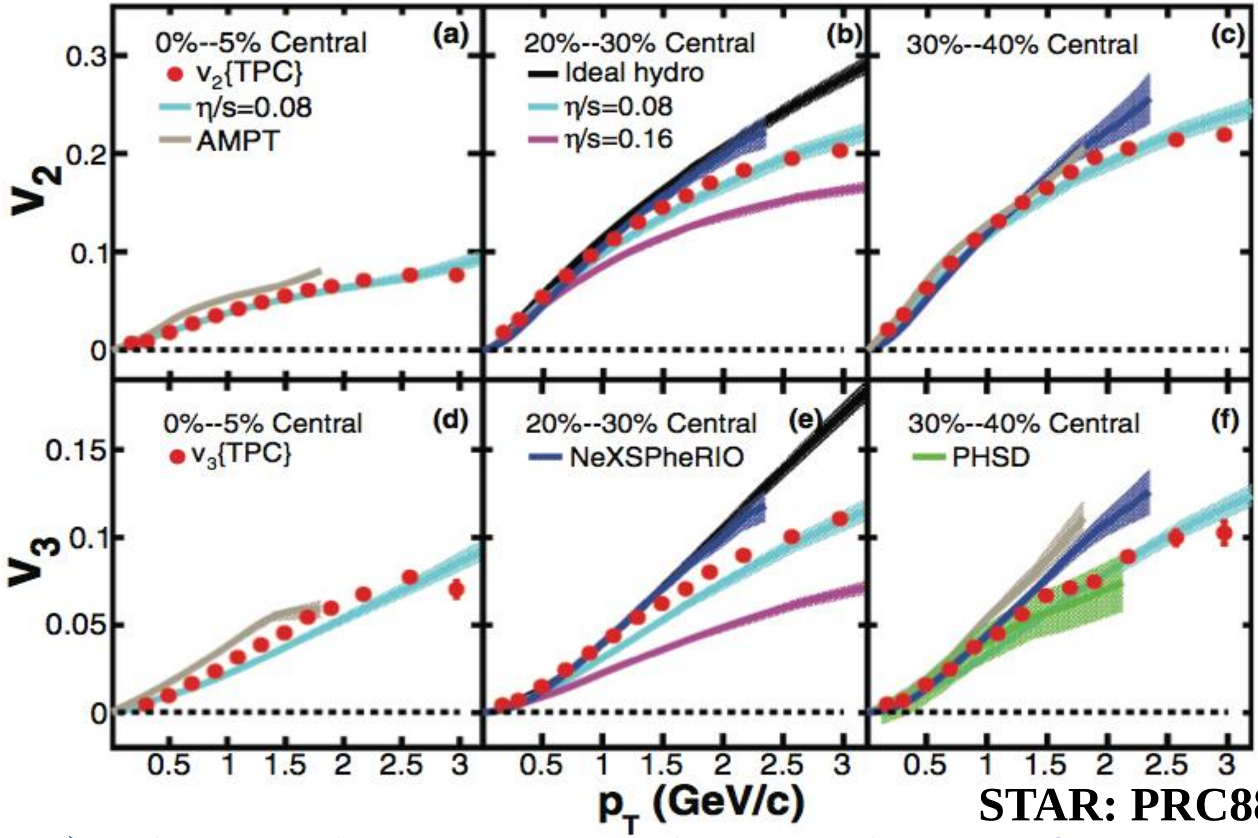
QCD Phase Diagram

QCD Exotics

Towards Future QCD Studies @RHIC & Beyond

sQGP Created at RHIC – η/s

$$\frac{dN}{p_t dp_t dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_t dp_t dy}\left[1+\sum_{i=1} 2v_i \cos(i(\varphi-\psi_R))\right]$$



Au+Au @200 GeV

STAR: PRC88, 014904(2013)

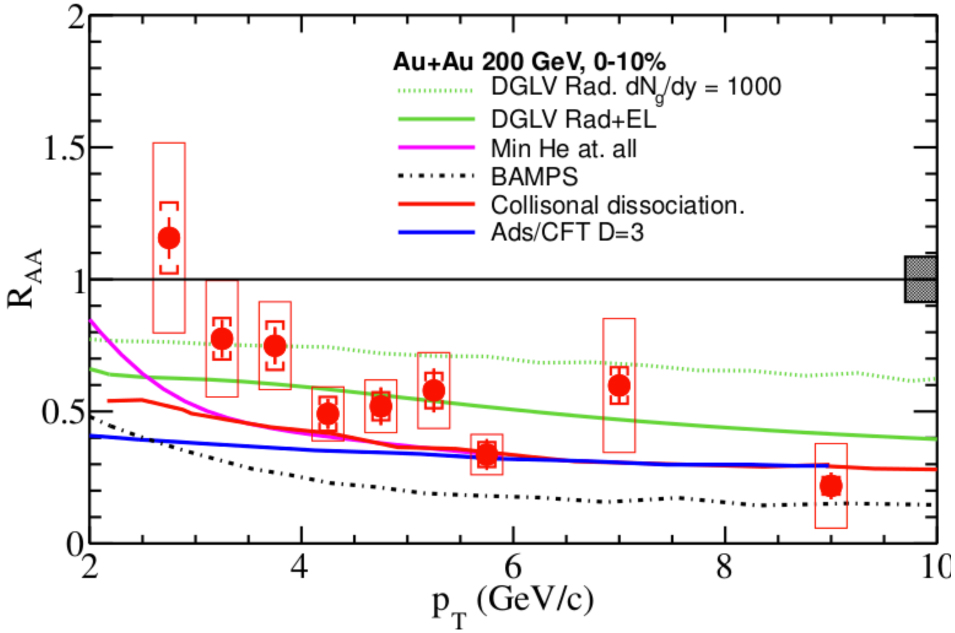
- The initial conditions in the models come from MC-Glauber
- NeXSPheRIO model reproduce the data well for 20-30% and 30-40% at pT < 1 GeV/c
- Both v_2 and v_3 are better described by η/s ~ 0.08

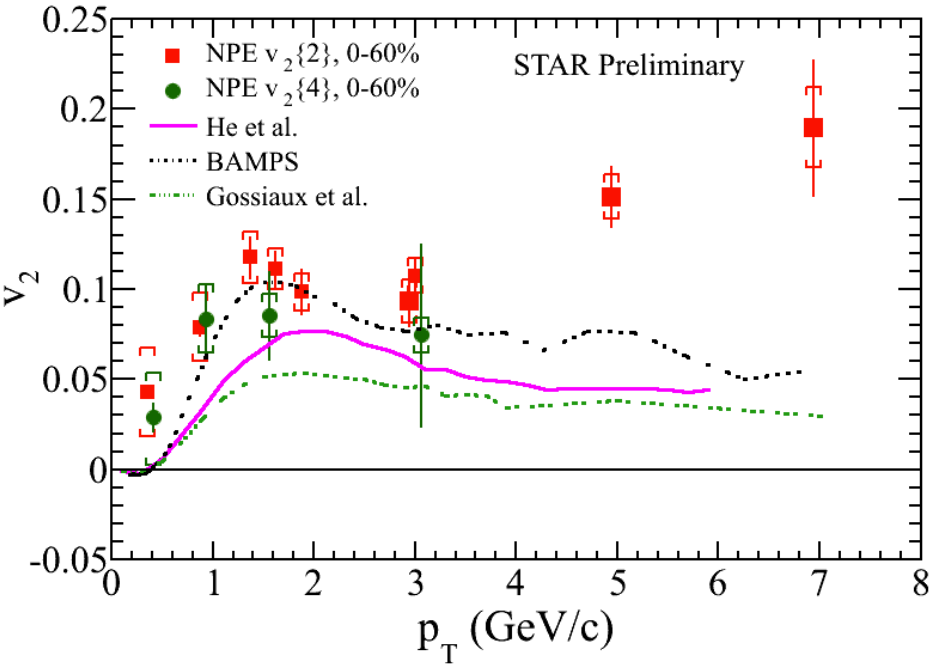
Heavy Quark Probe of sQGP properties

Heavy Quark – trace the evolution of collision

Simultaneous Measurements of R_{AA} and v_2

Electrons from heavy quark semi-leptonic decays



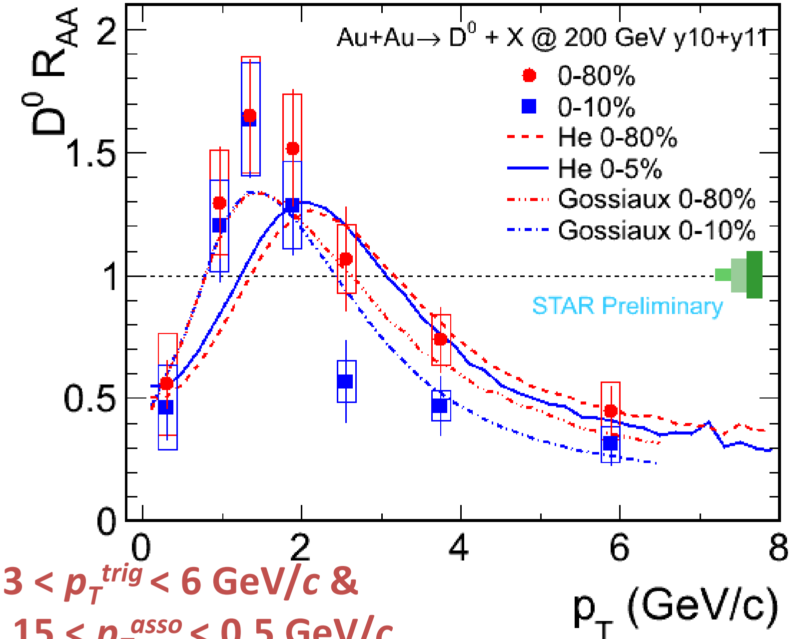


Better p+p reference data

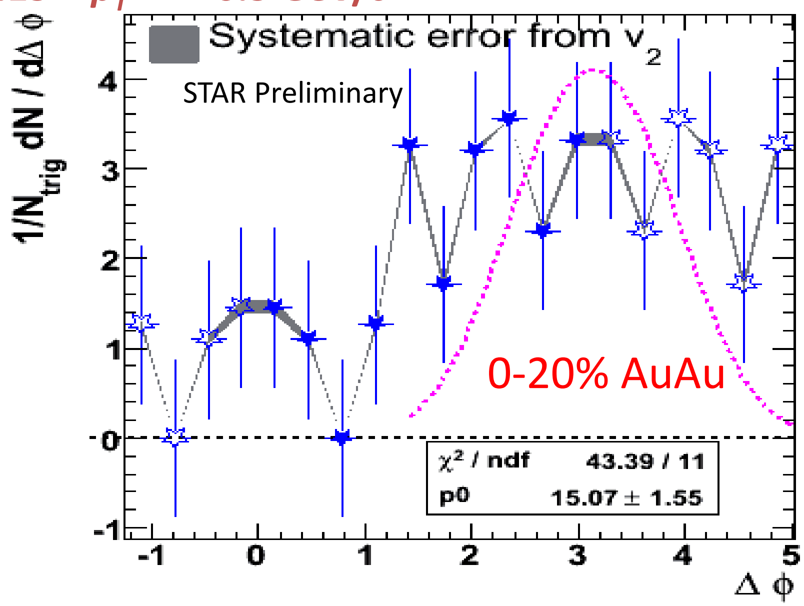
Nature of the measured v_2 value at high pT

Separation of B and D decay electrons !

Heavy Quark Collectivity – Next 2 years !



$3 < p_T^{trig} < 6$ GeV/c &
$0.15 < p_T^{asso} < 0.5$ GeV/c



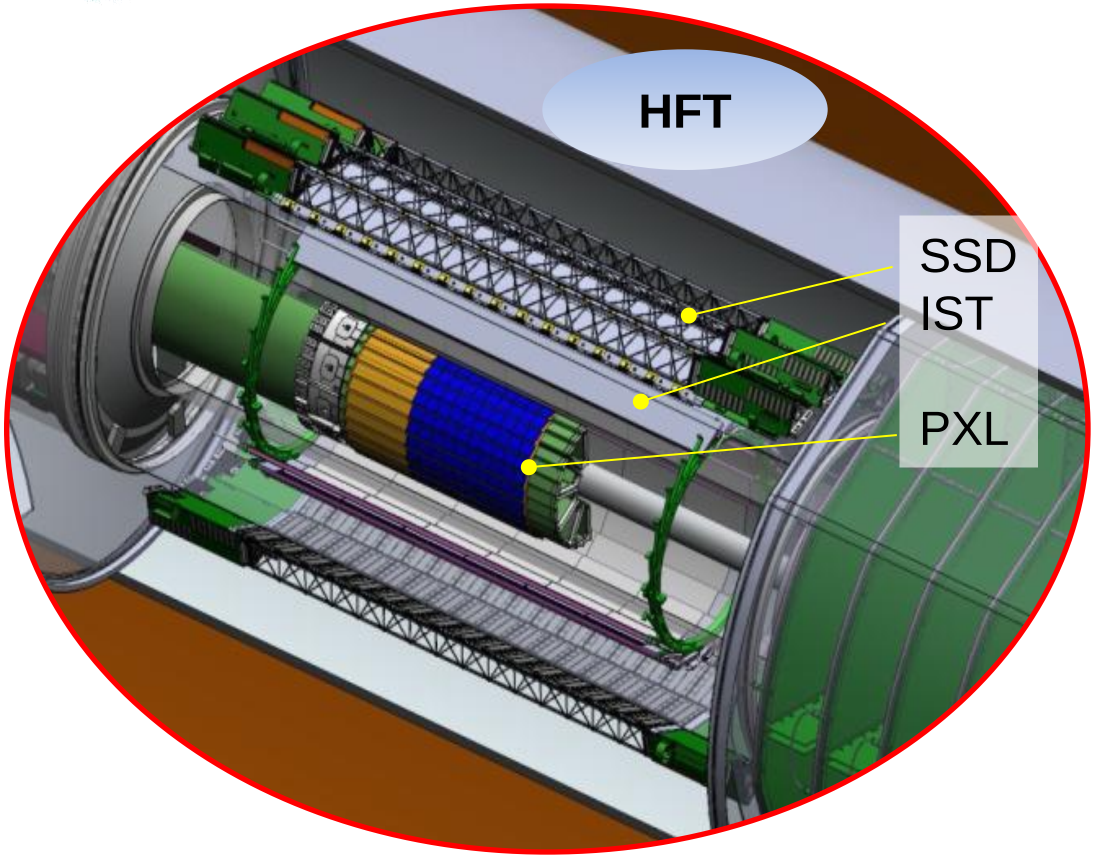
Elliptic Flow v_2 of D at low pT

NPE – Separation of B and D decays in Au+Au collisions

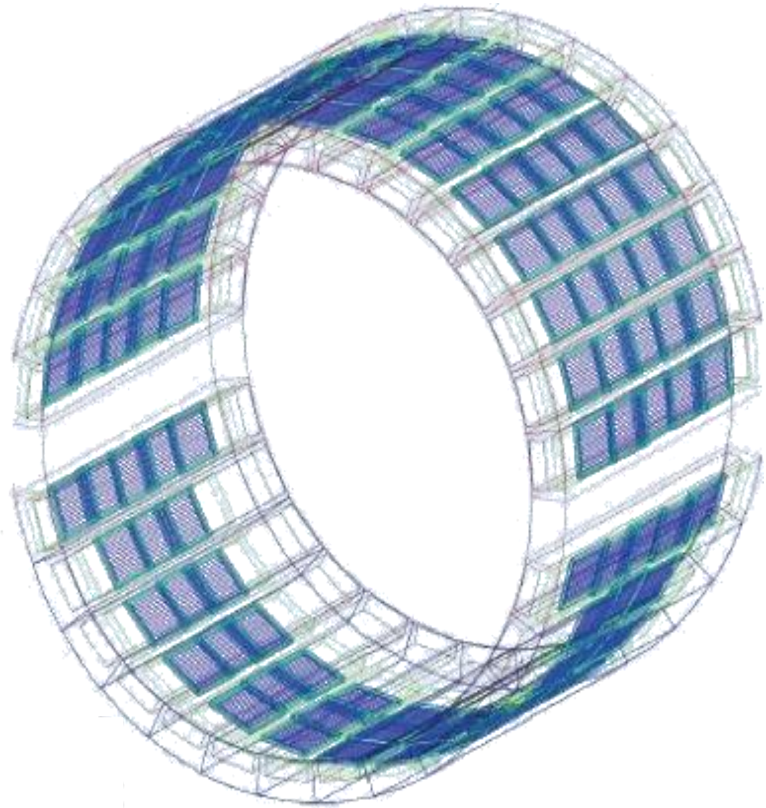
----Needs HFT Upgrade

Heavy Quark Tagged Jet-Medium Interaction and Medium Response !

Status of HFT and MTD Upgrades



Heavy Flavor Tracker



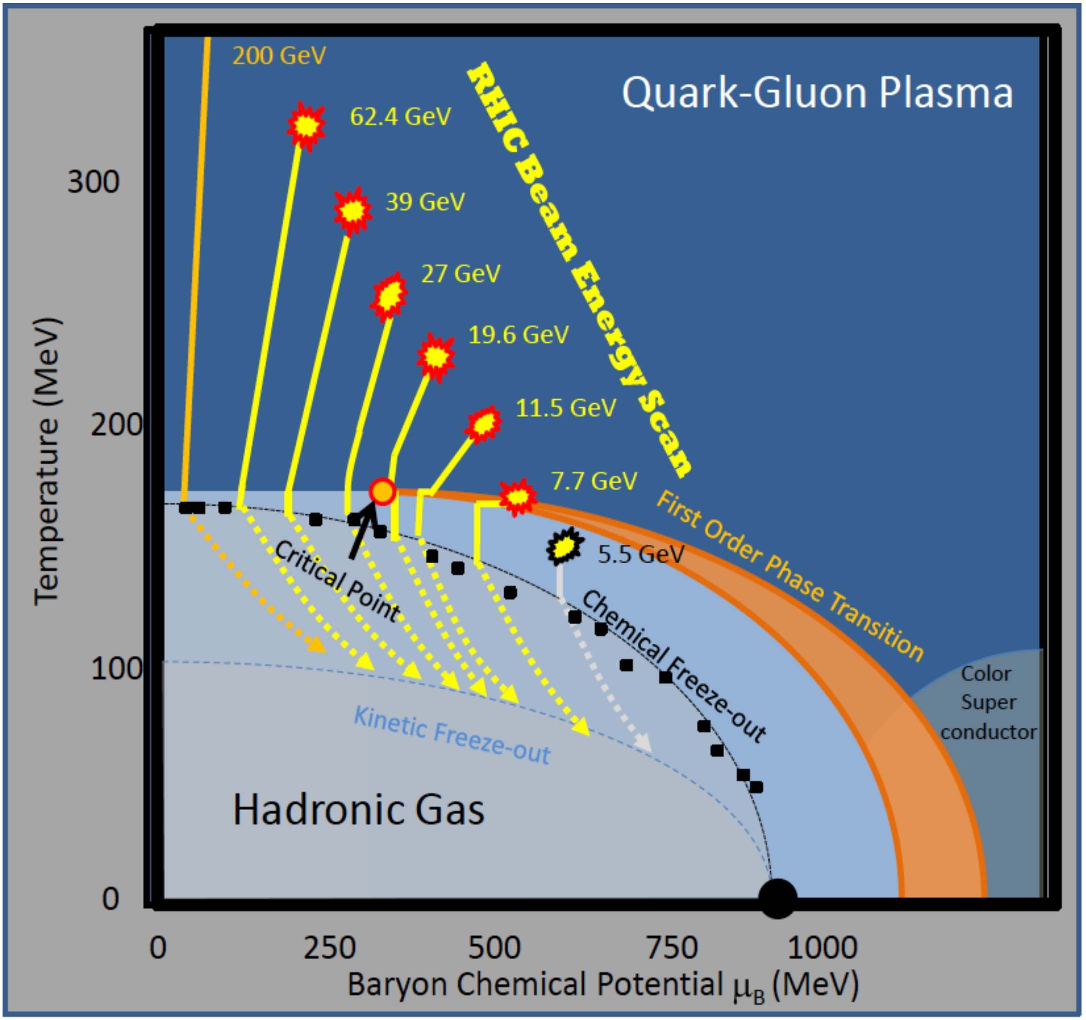
Muon Telescope Detector

Full Detector Commissioning and Physics Running in 2014

> 1 billion Au+Au Minimum Bias events !

Heavy Quark Collectivity, NPE B and D separation, Upsilon

QCD Phase Diagram and RHIC BES-I



Year	En (GeV)	# Event (10^6)
2010	39	130
2010	11.5	12
2010	7.7	5
2011	27	70
2011	19.6	36
2014	14.6	150

RHIC can deliver low energy beams !

STAR: First glimpse of QCD bulk matter over a broad range of chemical potentials !

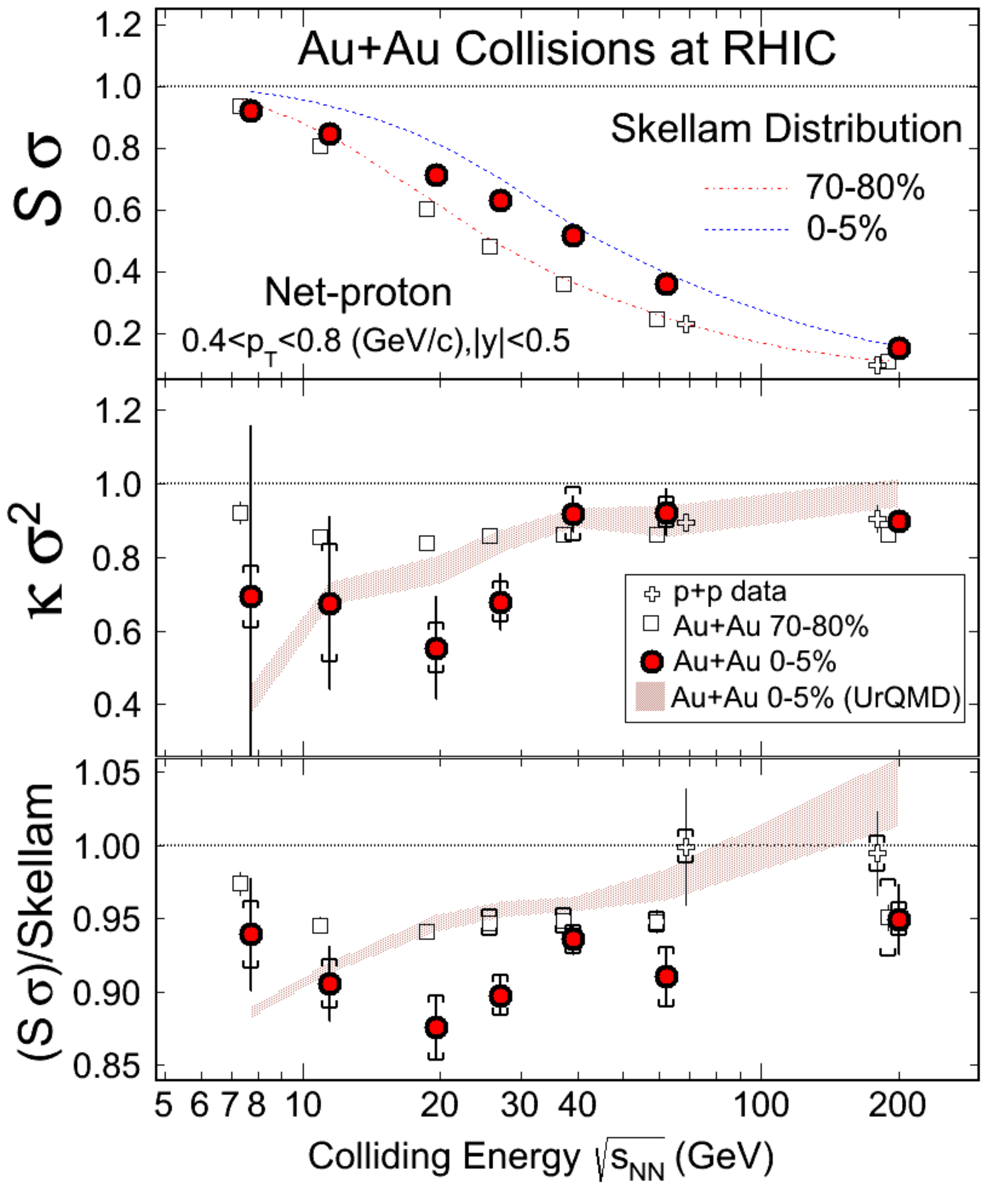
Searches for QCD Critical Point

$$S = \frac{<(\delta N)^3>}{\sigma^3}$$

$$\kappa = \frac{<(\delta N)^4>}{\sigma^4} - 3$$

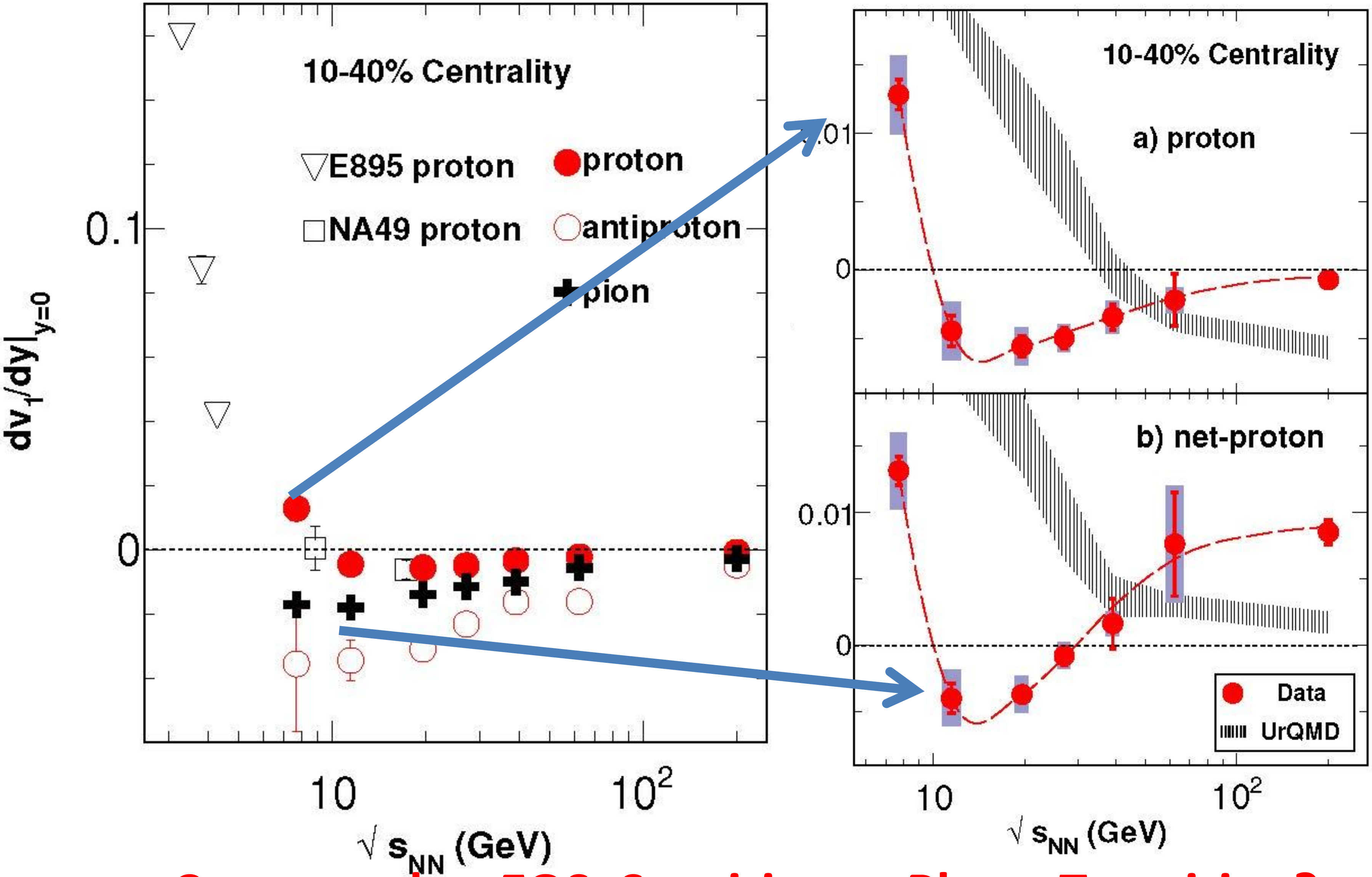
What is the width in sqrt(s) or chemical potential for the QCD critical point ?

What is the most appropriate reference distribution for high moments?



arXiv: 1309.5681

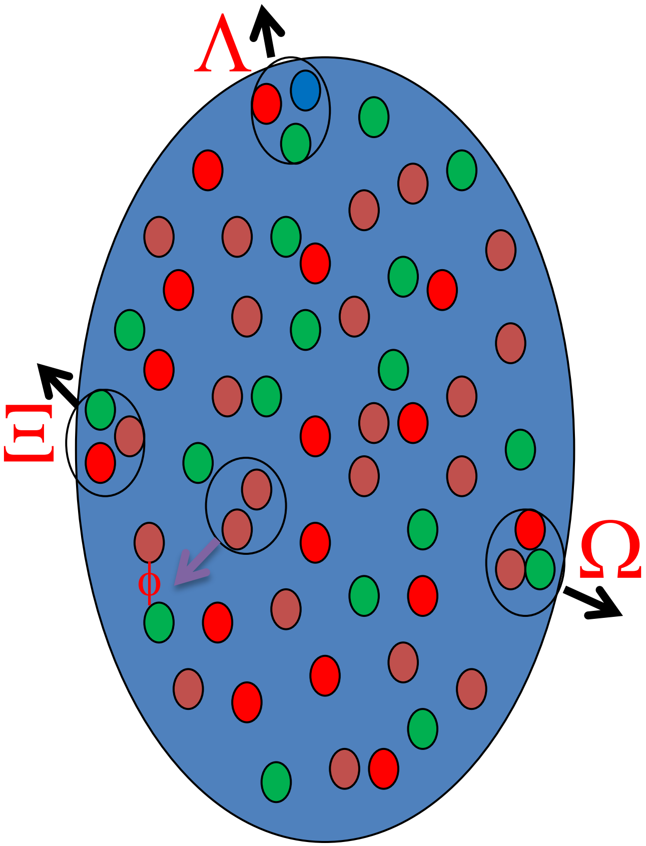
Direct Flow v_1 Slope from BES



Connected to EOS, Sensitive to Phase Transition?

J. Brachmann et al., PRC 61, 024909 (2000)

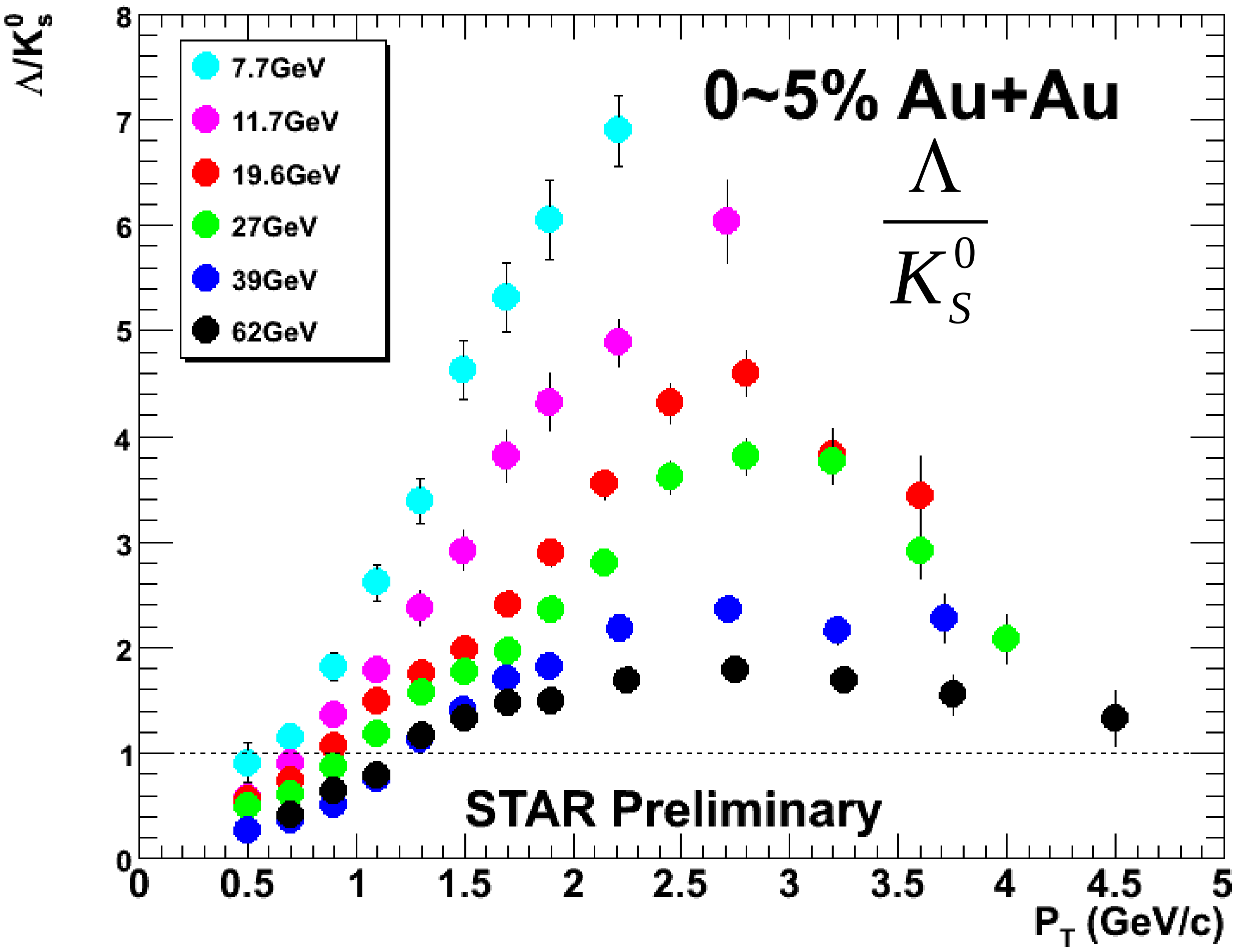
Coalescence and Cluster Formation



Hadron kinematics from sum of constituent partons instead of fragmentation of leading partons !

Increased Hyperon over Ks ratios

The formation probabilities of baryons and mesons depend on the environment – local parton density



B/m ratios
- -- measure of local parton density at hadronization !

Au+Au at 7.7 GeV
- -- higher net baryon density !

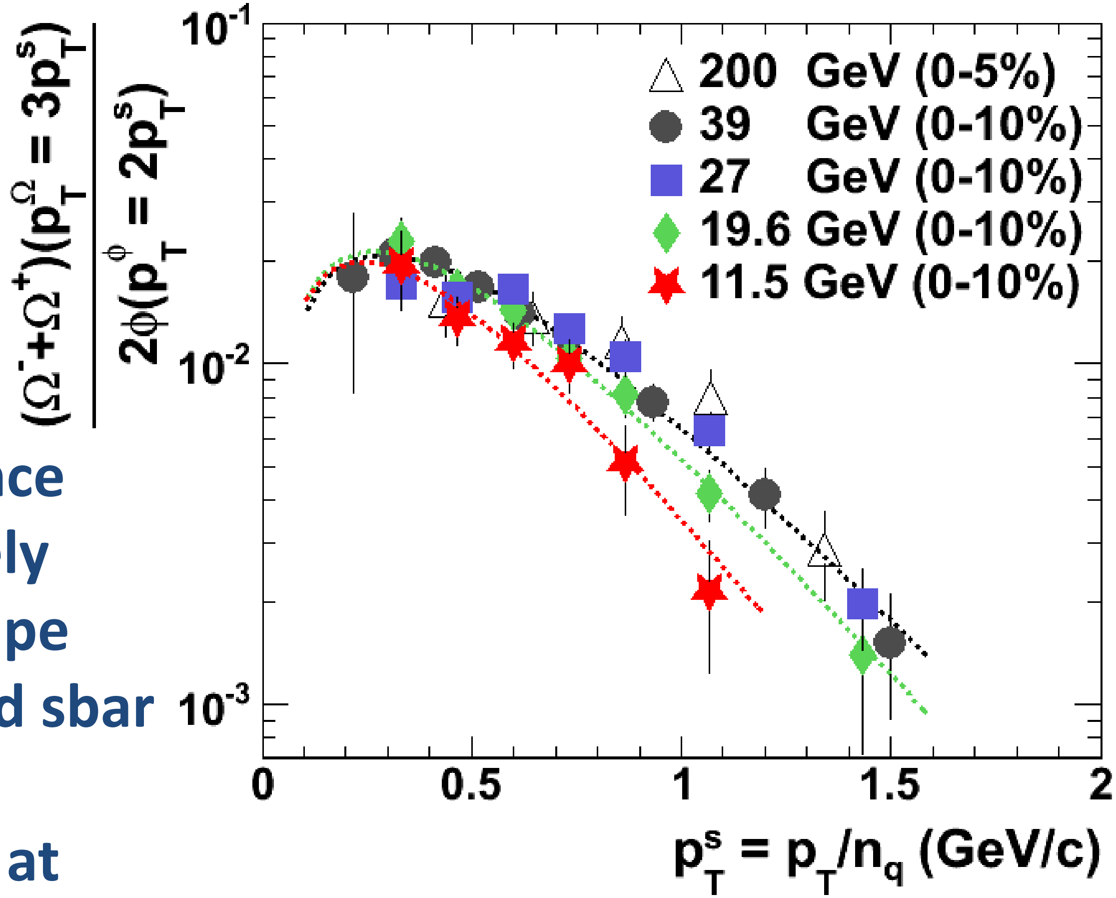
In a broad pT region [1-4] GeV/c, much more hyperons than mesons produced !!
- -- Coalescence

Strange quark analysis from Ω and ϕ using Coalescence Framework

Ω(sss) and ϕ(s$\bar{s}$) formed at chemical freezeout from coalescence of 3 s quarks and s-sbar pairs.

Assuming sudden coalescence of s quarks of approximately equal pT and the same shape of pT distributions for s and sbar quarks

The s quark pT distribution at freeze-out ~ $\Omega(3p_T)/\phi(2p_T)$



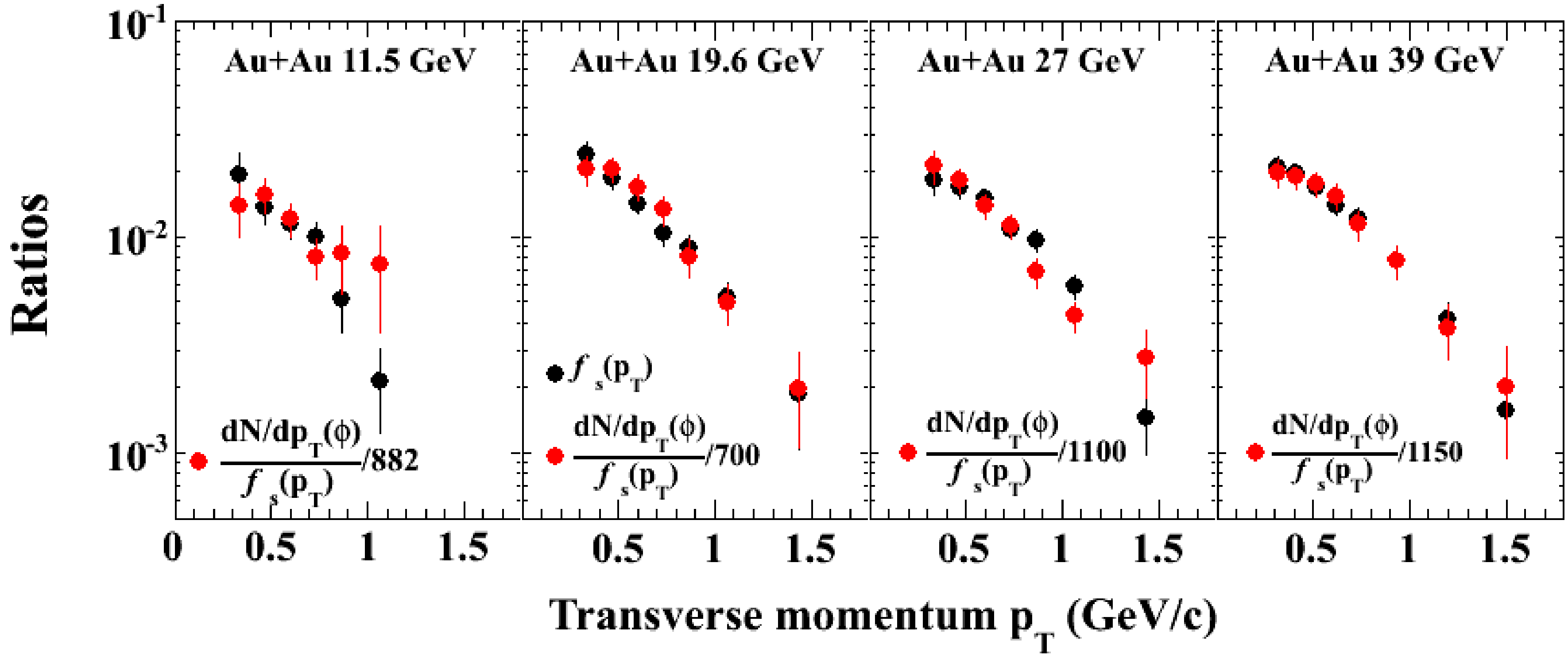
IS there a difference in partonic dynamics between 11 and 20 GeV?
NEED more statistics (BES II) and a 15 GeV run !!

Coalescence Picture !

Independent Empirical Check on Coalescence –

if $s(p_T) \sim \Omega(3p_T)/\phi(2p_T)$, then $\phi(2p_T)/s(p_T)$ is also $s(p_T)$

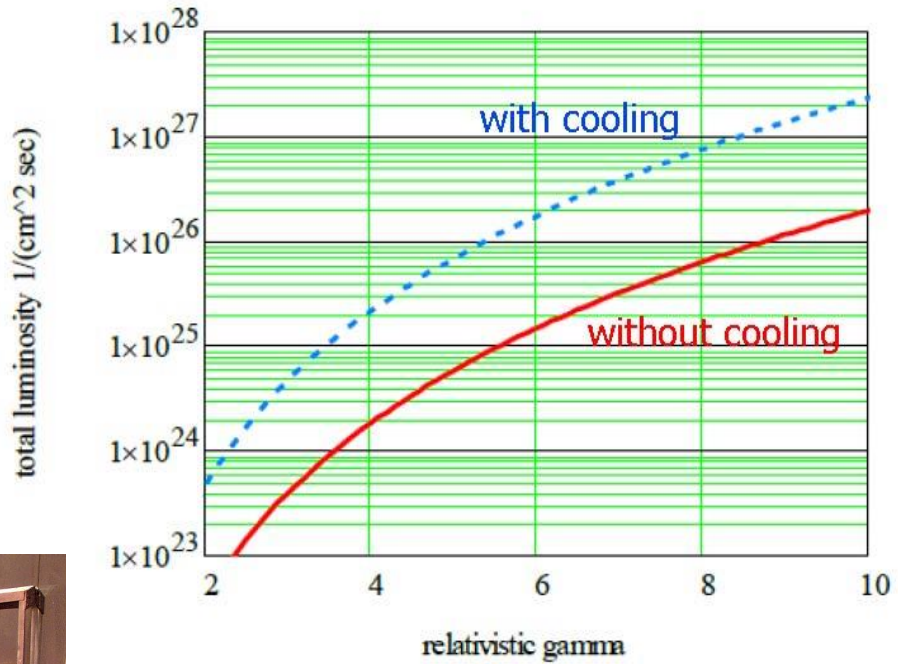
are these functions of similar shape?

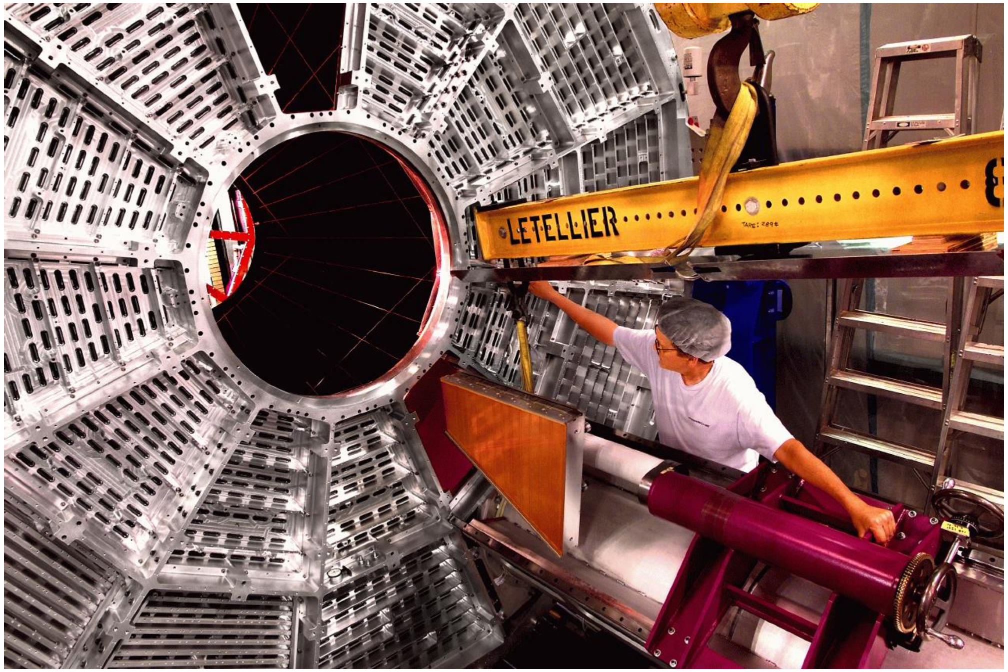


Probe Parton Distributions in QCD Drops at Hadronization !

Road to Beam Energy Scan II

1) Need electron cooling to be more efficient !





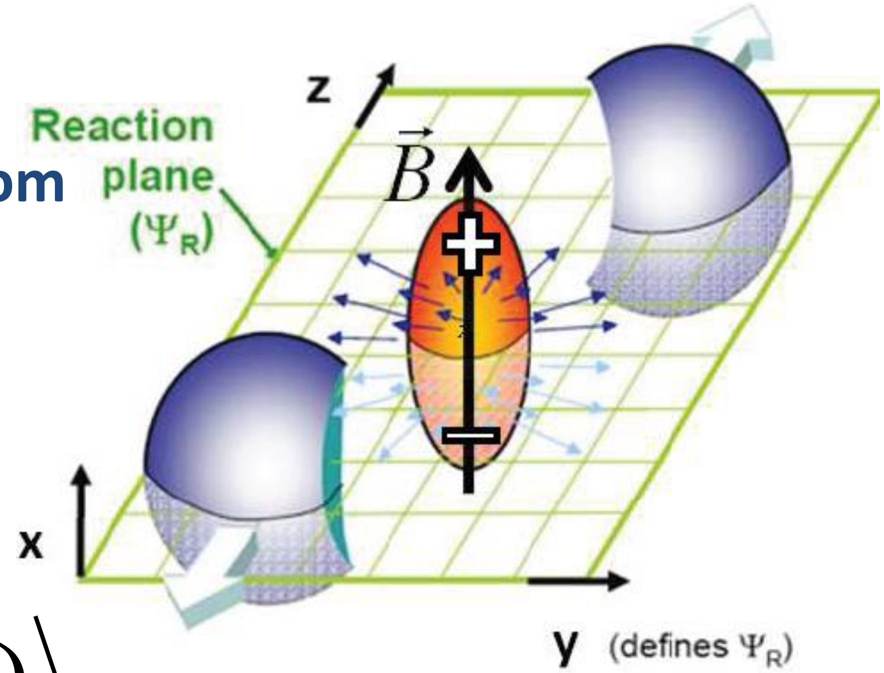
2) STAR TPC Inner Sector readout upgrade
-- enhance tracking and PID in η 1-1.7 region

BES II Starting 2018+

QCD Chiral Magnetic Effect

QCD Vacuum Sphaleron excitation
coupled to strong magnetic field from
spectator protons
-- charge separation across the
reaction plane
parity violating in strong interaction

Kharzeev et al NP A803, 227 (2008)



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

Voloshin, PRC70, 057901 (2004)

charge dependent – same sign (++,--) and opposite sign(+-, -+)
sensitive to charge separation

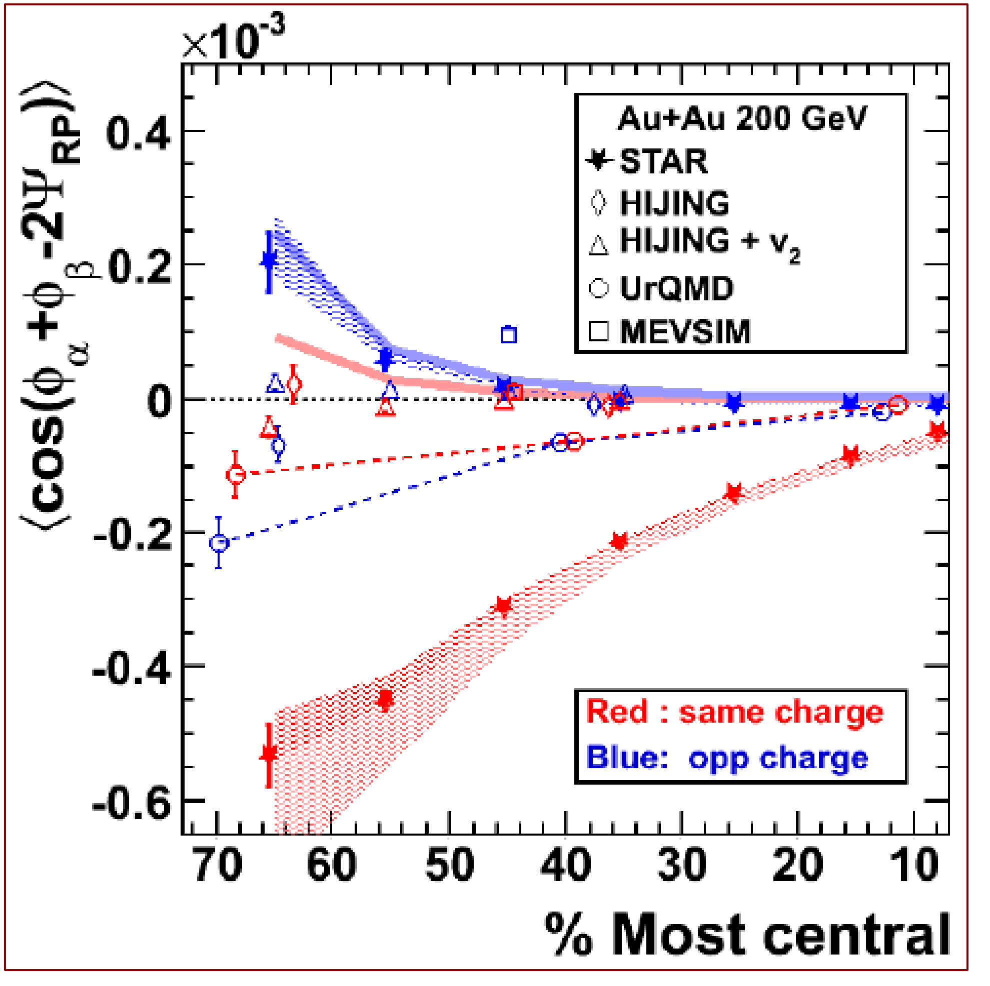
First measurements

B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **103**, 251601 (2009).
B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **81**, 054908 (2010).

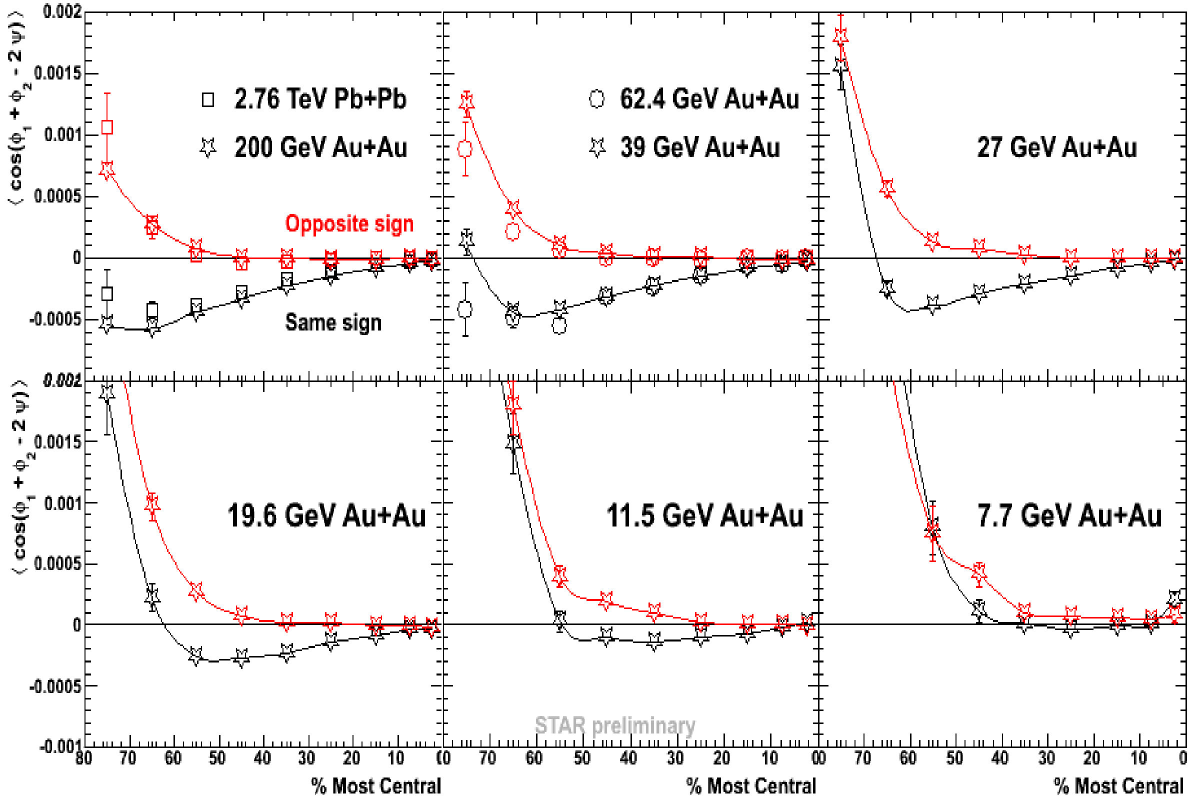
Strong charge sign dependent –
  Same-Sign (SS)
  Opposite-Sign (OS)
  correlation – very different feature and magnitude !

Existing models cannot reproduce the data !

How to separate LPV signal and background?



Recent STAR Results on the Charge Separation Measurement



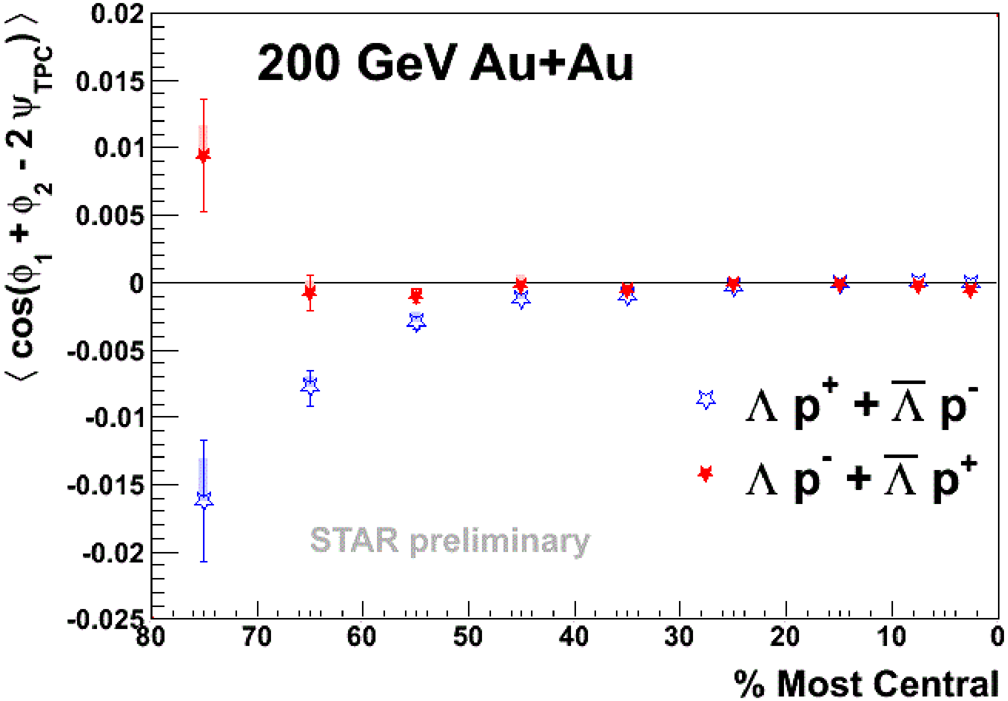
Charge separation
-- disappears at low energy where QGP presumably cannot be formed and/or cannot live long enough!

No QGP → No Local Parity Violation !

Is this the unique explanation ?

Chiral Vortical Effect

QCD – Gauge Fields → Topological Domain/Charge Formation (Parity Odd Bubbles) → Angular Momentum (Fluid Vorticity) → Chirl Vortical Effect (Baryon Number Correlations)



1) **The opposite baryon number (Λ-pbar or Λbar-p) correlations (OB) are similar**
2) **The same baryon number (Λ-p or Λbar-pbar) correlations (SB) are lower than that of the OB, *as expected from the CVE.***

D. Kharzeev, D.T. Son, PRL106, 062301(11)
D. Kharzeev. PLB633, 260 (06)
D. Kharzeev, et al. NPA803, 227(08)

What other sources could contribute to the correlations in baryon #s? CME and CVE – quantitative relations?

Intriguing, yet inconclusive !

Experimental measurements

-- consistent with some aspects of expectations from
Chiral Magnetic Effect,
Chiral Magnetic Wave and
Chiral Vortical Effect

-- But we do not know for sure the magnitude of the background

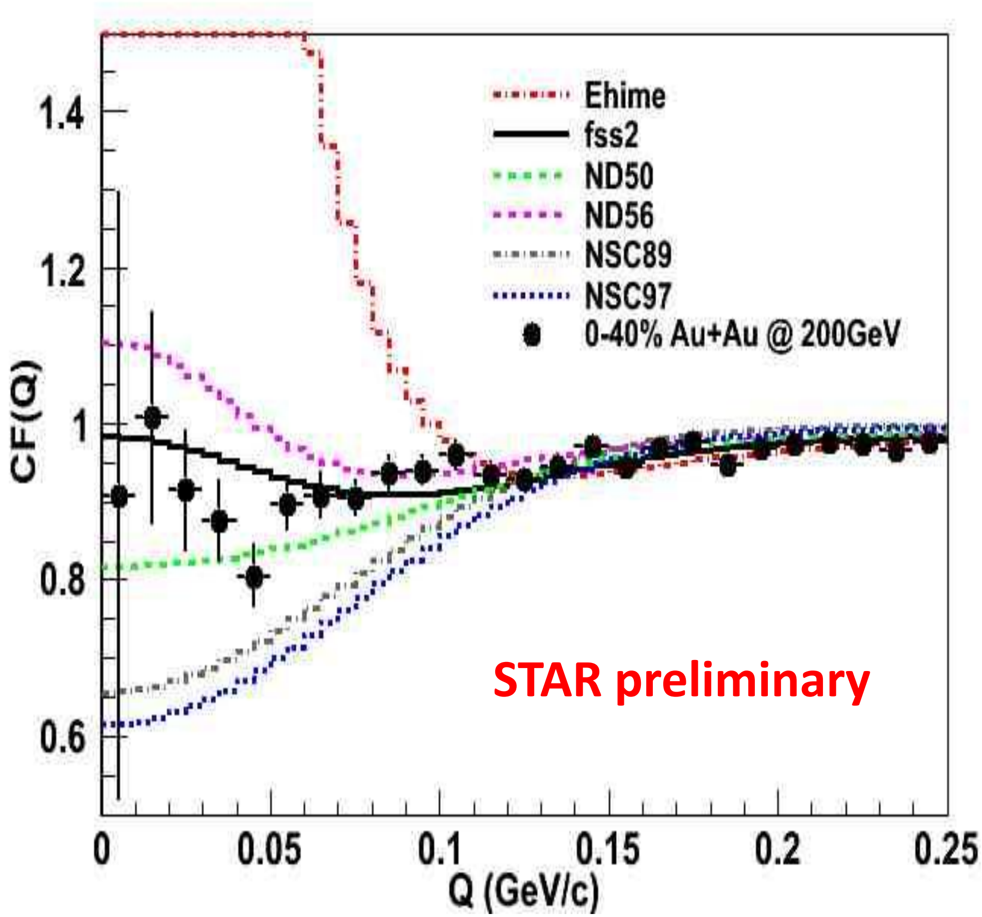
-- we are not sure of the nature of background for CMW, CVE.

We need more ideas and explorations !

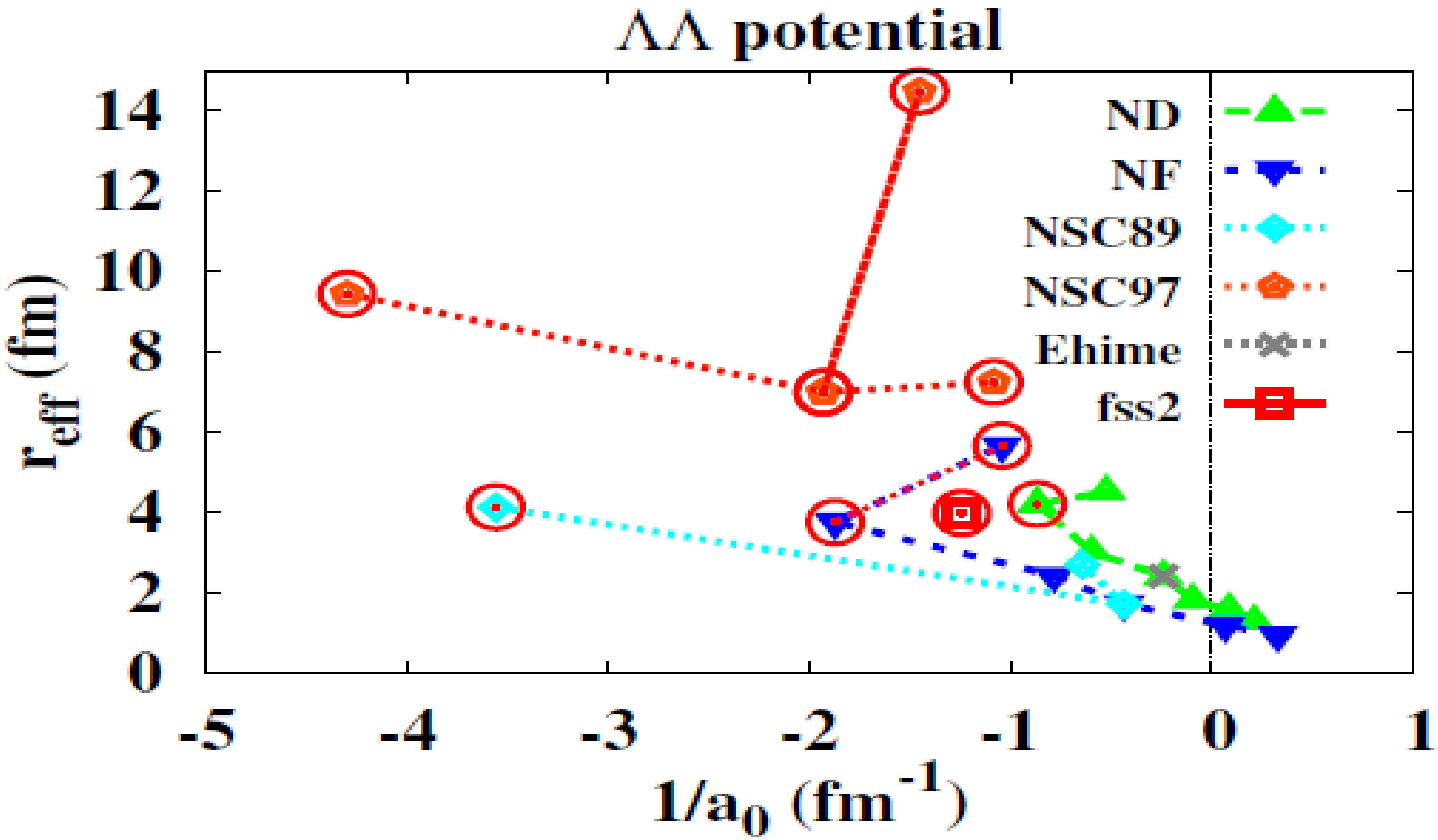
Searches for Exotic Particles

Λ-Λ Correlation
-- sensitive to ΛΛ interaction
H (uuddss) bound state
-- depletion of ΛΛ pairs

Theoretical models fit to
STAR preliminary data:
ΛΛ – attractive interaction
no bound state !



Λ-Λ Correlation Function

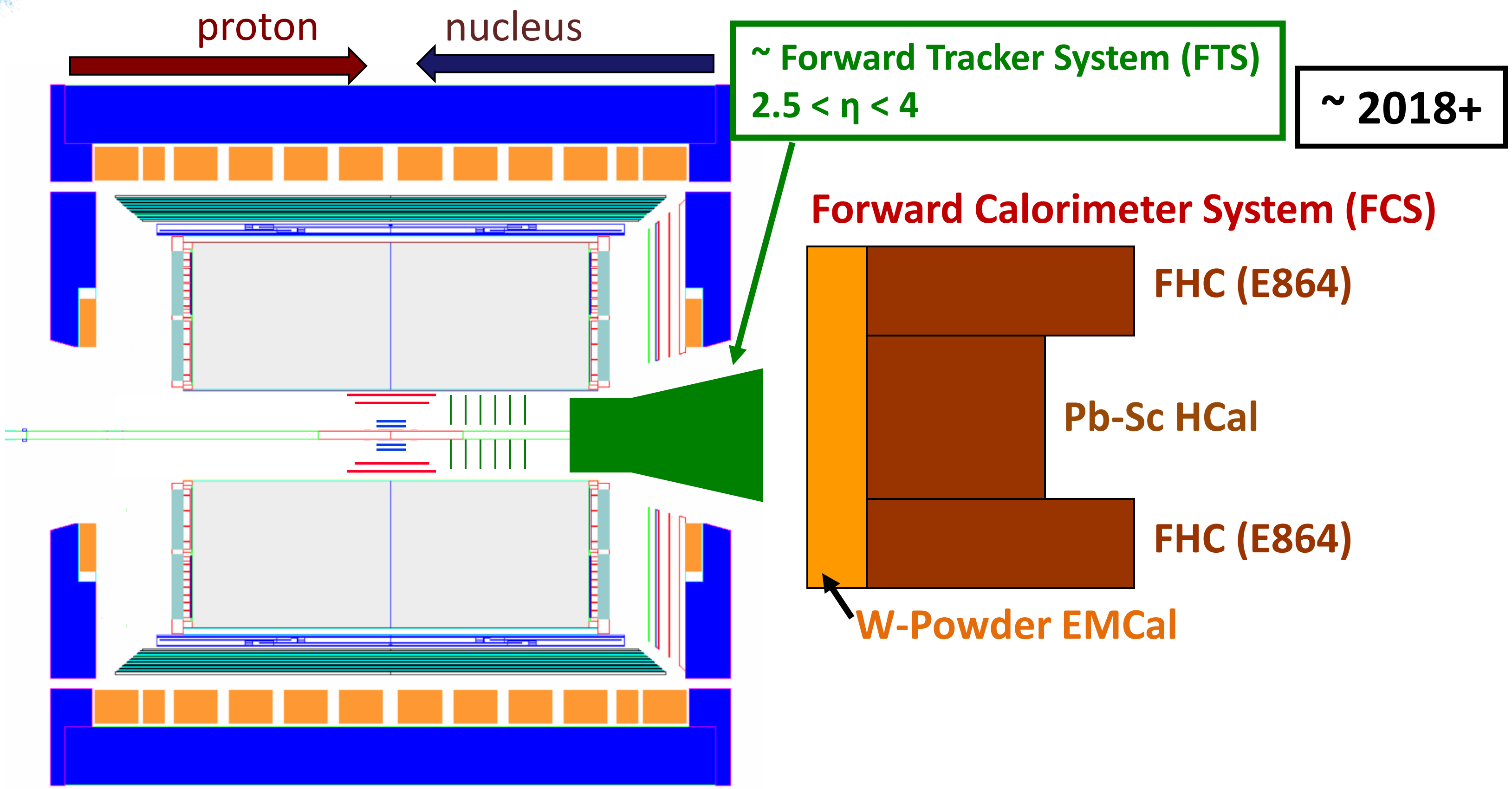


A. Ohnishi, HHI workshop proceedings 2012

- Scattering length (a_0) is negative in most fits
- Current fit from different potential models to data gives indication towards non-existence of bound H-dibaryon

Other exotic particles? ΞΞ, ΩΩ, NΩ, J/ψp, (bcs) …..

STAR Forward Upgrades: QCD at X and x



- Forward instrumentation optimized for pp/pA and AA
  - Charged-particle tracking
  - *e*/*h* and γ/π^0 discrimination
  - Jet reconstruction

RHIC – a Dedicated QCD Facility

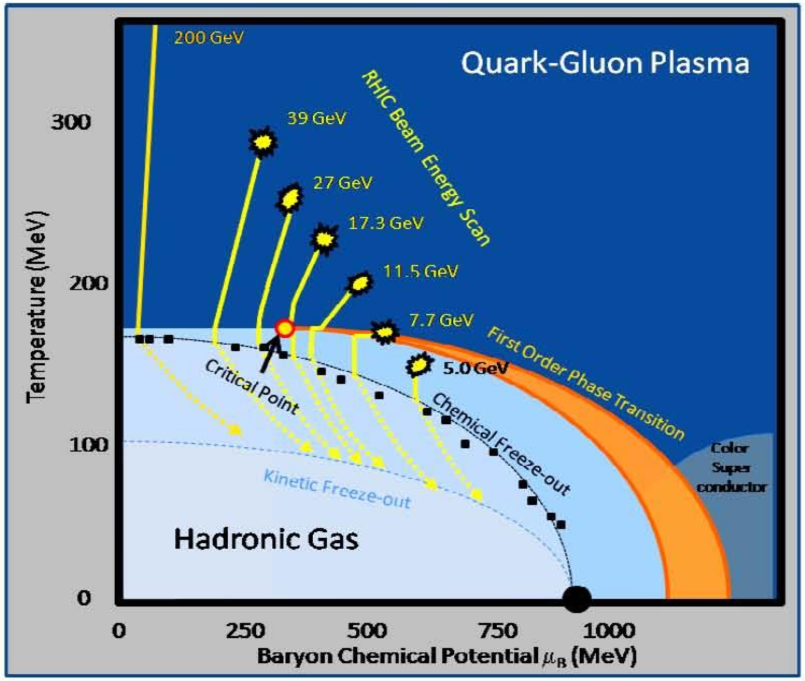
QCD – Fundamental Corner Stone of the Standard Model !!
-Dynamics of QCD in bulk matter, vacuum structure and hadrons?
Condensed Matter Physics with Underlying QCD Interactions !

We are beyond the QGP discovery phase already !
LHC -- Energy/Temperature Frontier
RHIC – New Horizons in QCD Phase Structure, Vacuum Excitation, Initial State Color Charge Dynamics, Hadron Structure and Exotics

The Best of STAR is yet to Come
Heavy Flavor Physics – HFT/MTD: 2014-16
QCD Phase Diagram – BES Phase II: 2018-19+
Spin, Gluon Color Dynamics and AA – Towards eRHIC

Outstanding Scientific Questions at RHIC in Coming Decade

Hot QCD Matter



1: Properties of the sQGP

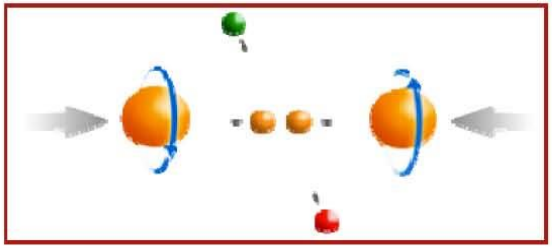
2: Mechanism of energy loss:
weak or strong coupling?

3: Is there a critical point, and if so, where?

4: Novel symmetry properties

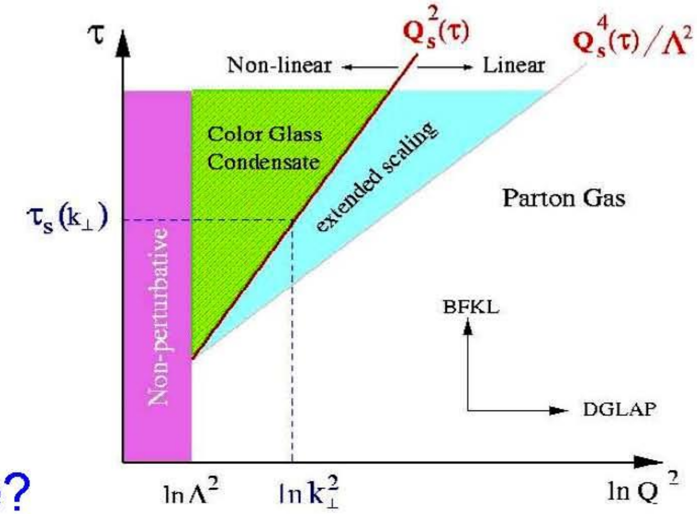
5: Exotic particles

Partonic structure



6: Spin structure of the nucleon

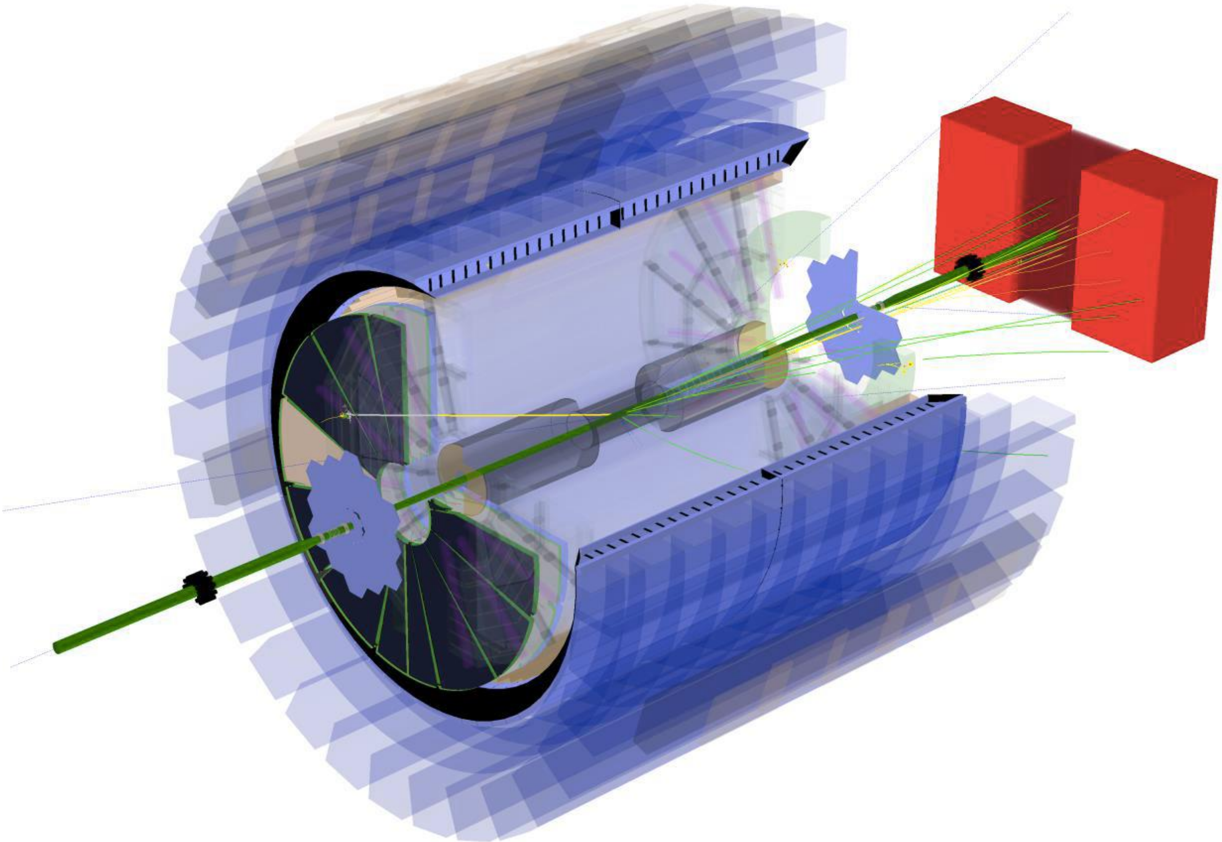
7: How to go beyond leading twist and collinear factorization?



8: What are the properties of cold nuclear matter?

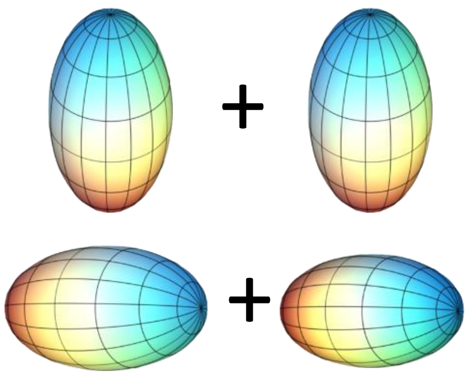
The End

eSTAR – STAR in the eRHIC Era

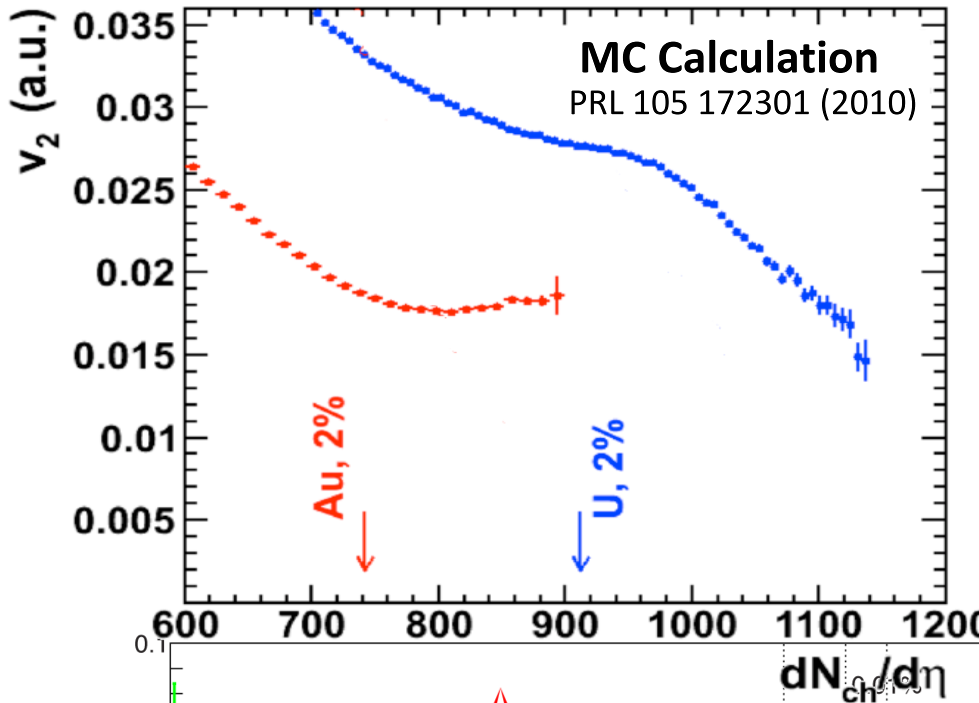


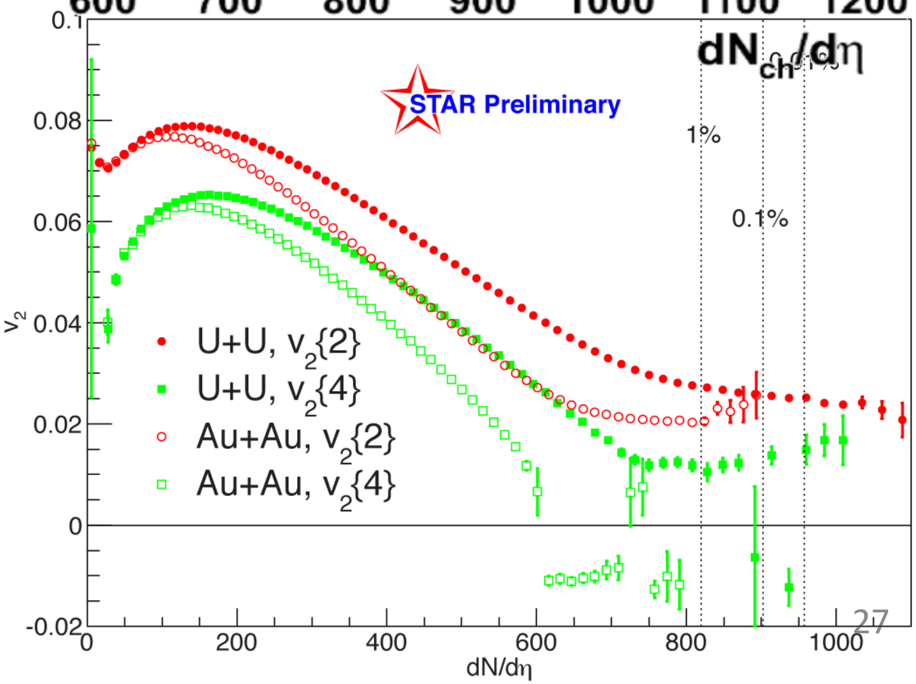
We Do not Truly Understand the Geometry Yet

U+U Collisions



Prolate

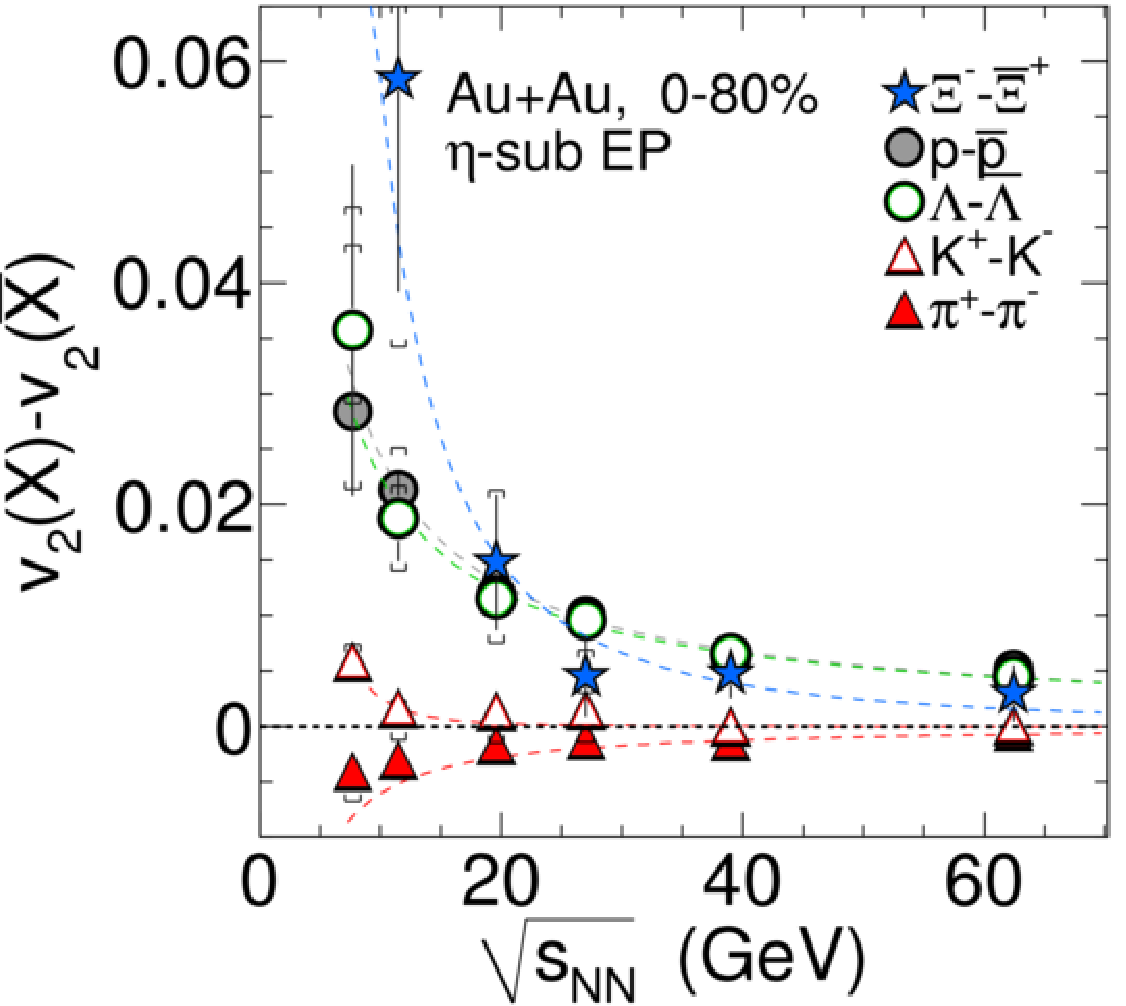




We do not understand detailed features from U+U data based on known collision geometry dependence of v_2 !

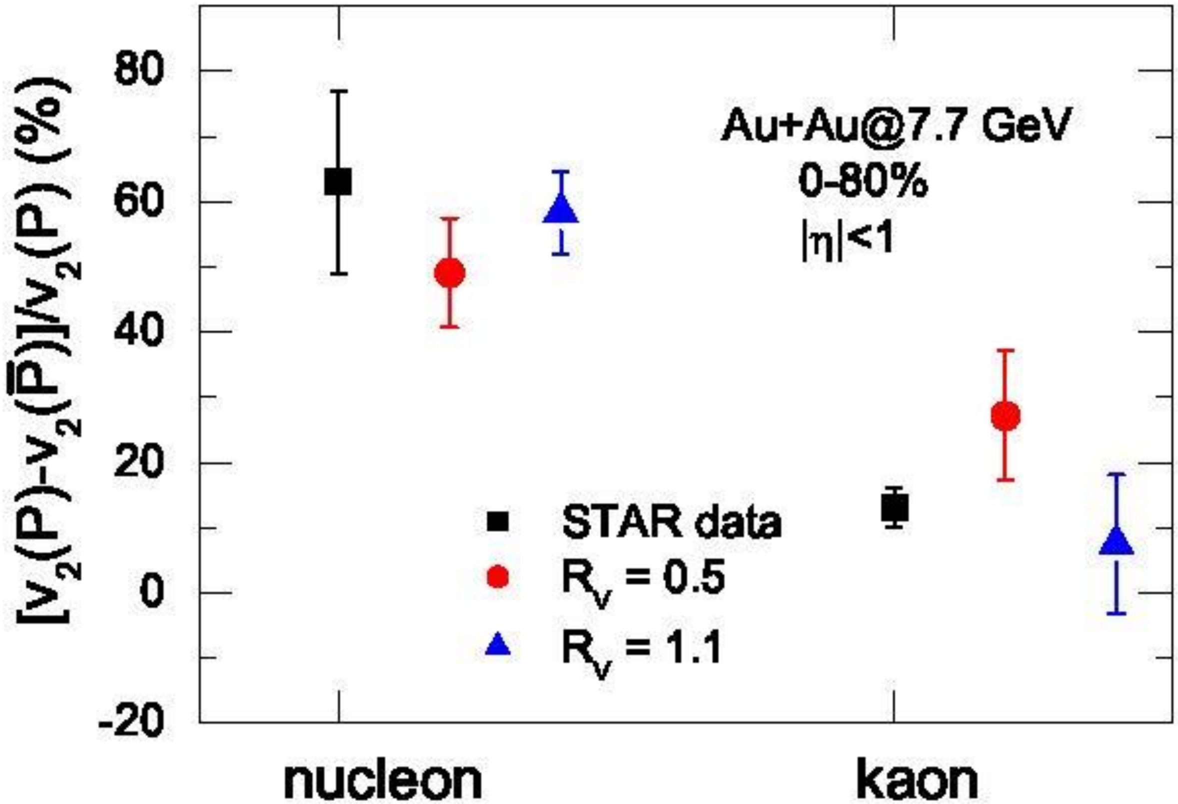
Incomplete understanding of geometrical and dynamical fluctuations !!

Systematic v_2 Differences between particle and anti-particles



Mass and Flavor Dependence !!

Implication for large Rv = G_V/G ?



Theoretical models predicted that large R_V →
no critical point or first-order PT in physical region !
What other measurements to access R_V ?

Jun Xu, Taesoo Song, Che Ming Ko and Feng Li, arXiv 1308.1753
M. Asakawa et al., NP A504, 668 (1989);
N.M. Bratovic, T. Hatsuda and W. Weise, PLB 719 (2013) 131.

Conventional Explanation ?

Blast Wave Parameterization = Charge Correlation + Radial + Elliptic Flow

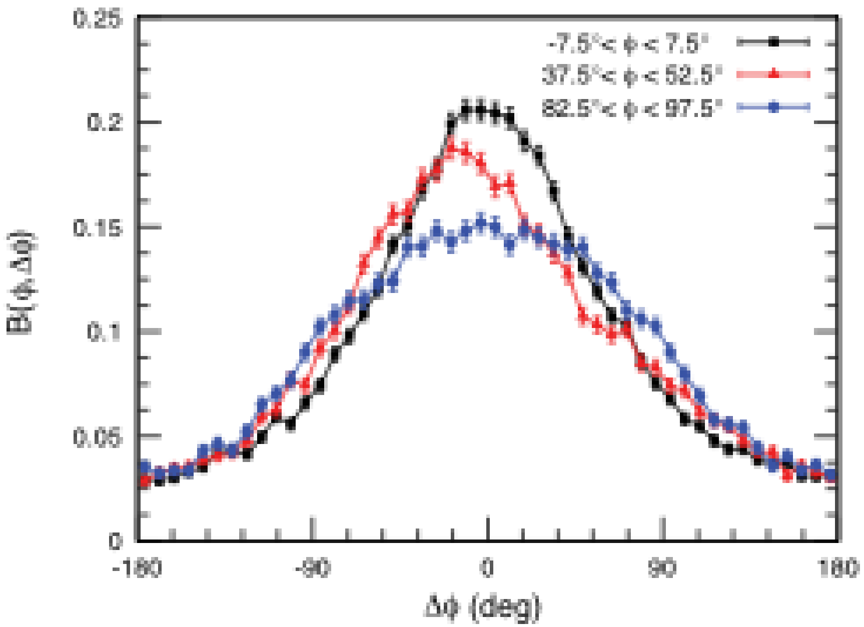
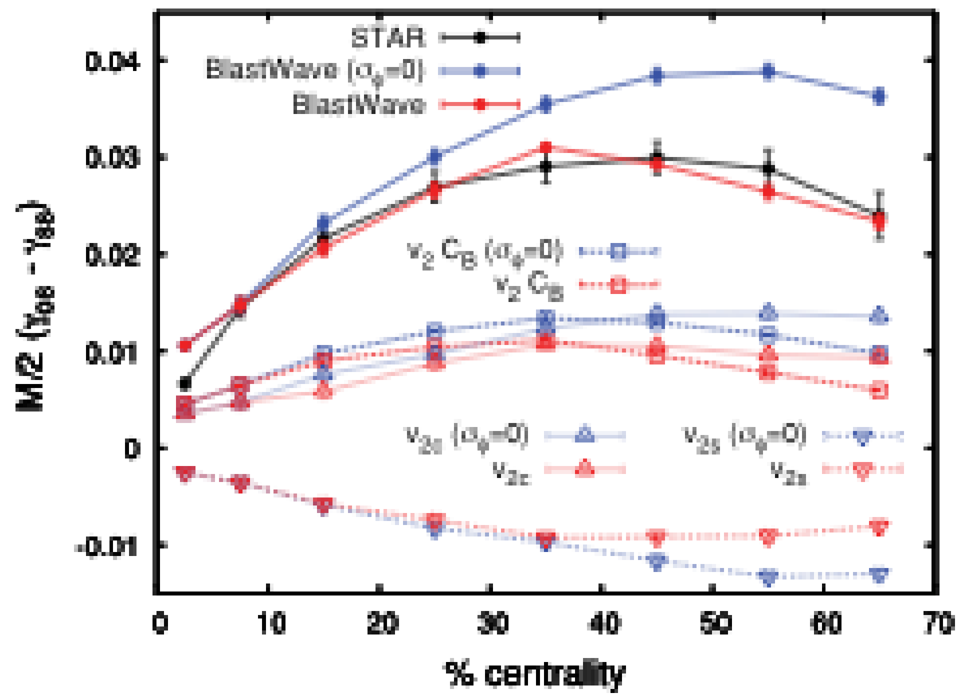


FIG. 7. (Color online) Balance function $B(\phi, \Delta\phi)$ for 40–50% centrality as function of the relative angle included by balancing partners for $\phi = 0°$ (black squares), 45° (red triangles), and 90° (blue circles). The balance function is narrower for in-plane pairs than for out-of-plane pairs. For intermediate angles, the balance function is biased toward negative angles.

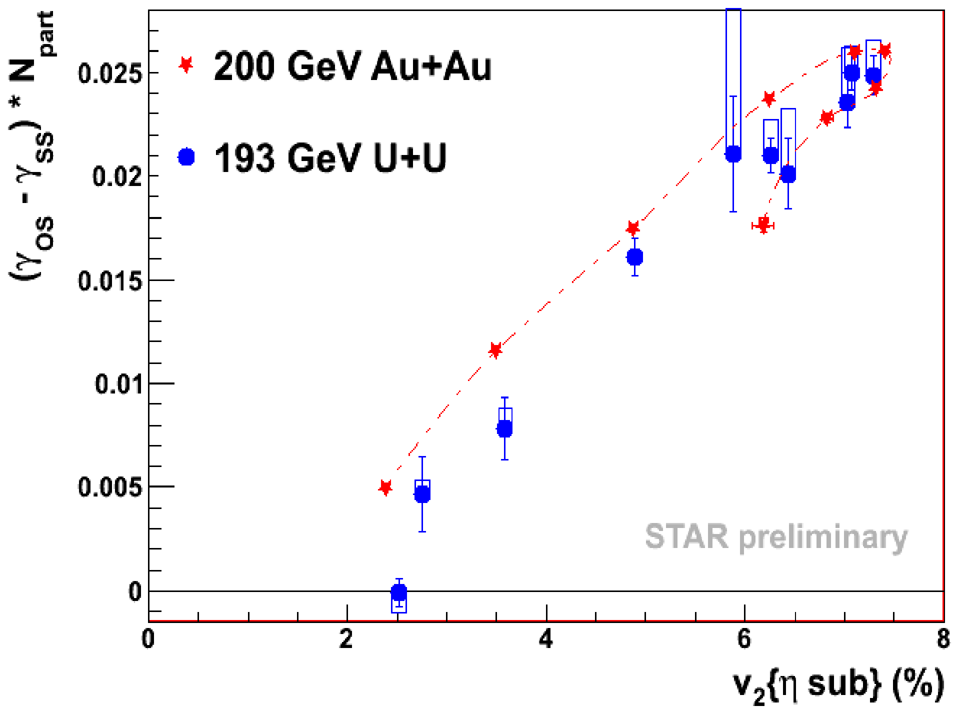


$$\frac{\langle M^2 \gamma_P \rangle}{\langle M \rangle} = \frac{2}{\langle M \rangle} \int d\phi \, d\Delta\phi \langle \frac{dM}{d\phi} \rangle \; B(\phi, \Delta\phi) \times [\cos(2\phi)\cos(\Delta\phi) - \sin(2\phi)\sin(\Delta\phi)],$$

- With some “adjustments” can describe the data (diff “opp” - “same”).
- Note that the correlator is inversely proportional to multiplicity

Schlichting and Pratt, PRC83 014913 (2011)

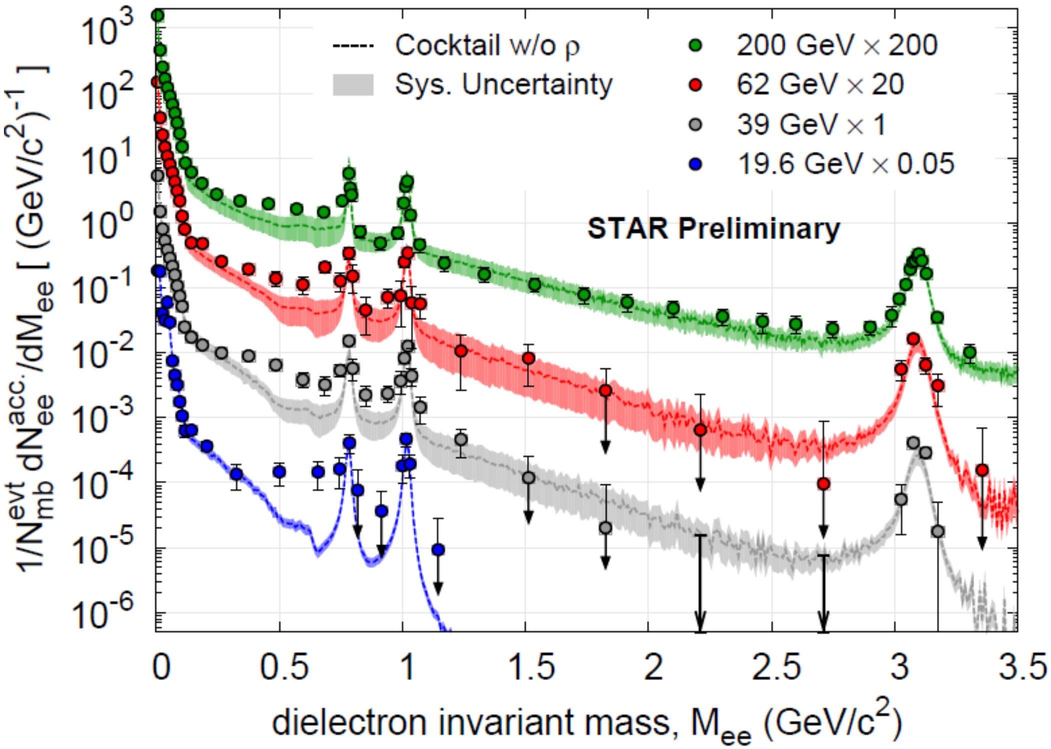
Recent STAR Results on the Charge Separation Measurement

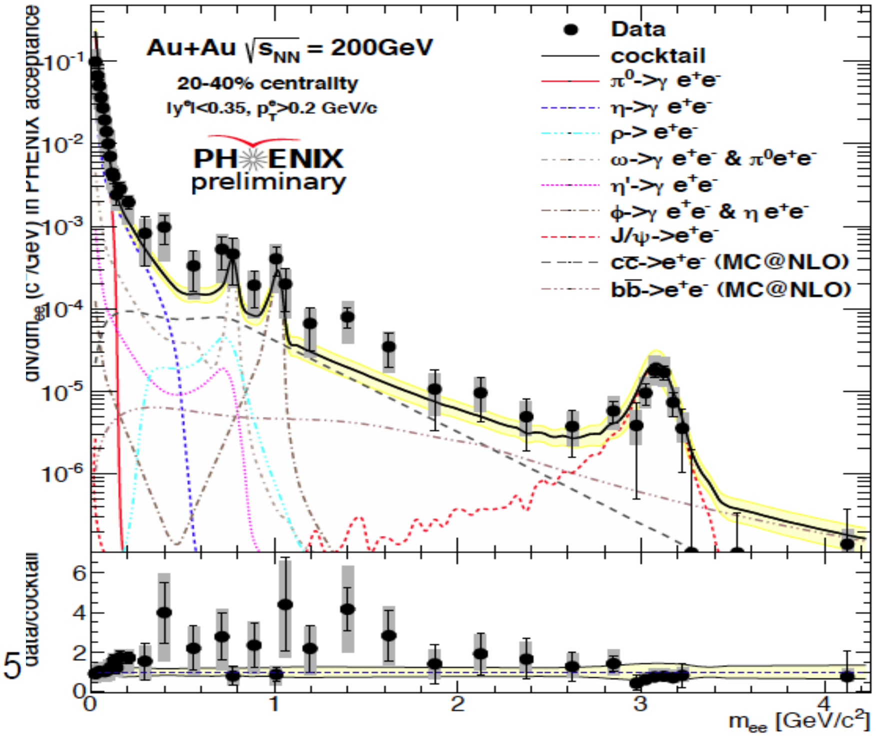


Charge separation
-- disappears in very central collisions when magnetic field approaches zero, but elliptic flow is finite !

Background has to be coupled to v_2 –
no reason for background to disappear when v_2 is finite !
Measured correlator unlikely be entirely due to background !

Chiral Symmetry and Di-electrons





Low mass region (<1.0 GeV) – vector meson properties in the QCD medium

Intermediate mass region (1-3 GeV) – QGP radiation and heavy quark decays

(depends on heavy quark evolution in the QCD medium)

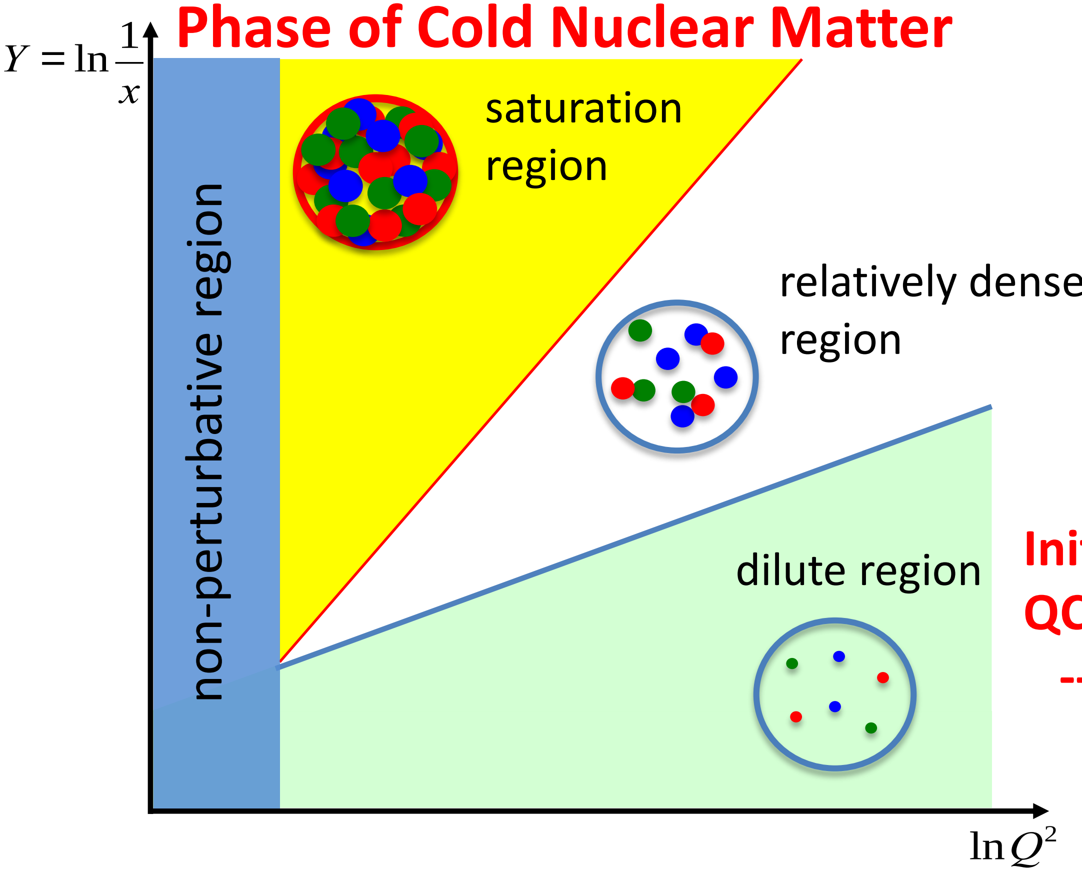
Very difficulty experimental measurements!

lessons from SPS – need 5-10 years to understand the signal and background!

Gluon Saturation in Nuclei

pA dynamics in the forward proton semi-sphere sensitive to details of the gluons in the nuclei

Phase of Cold Nuclear Matter

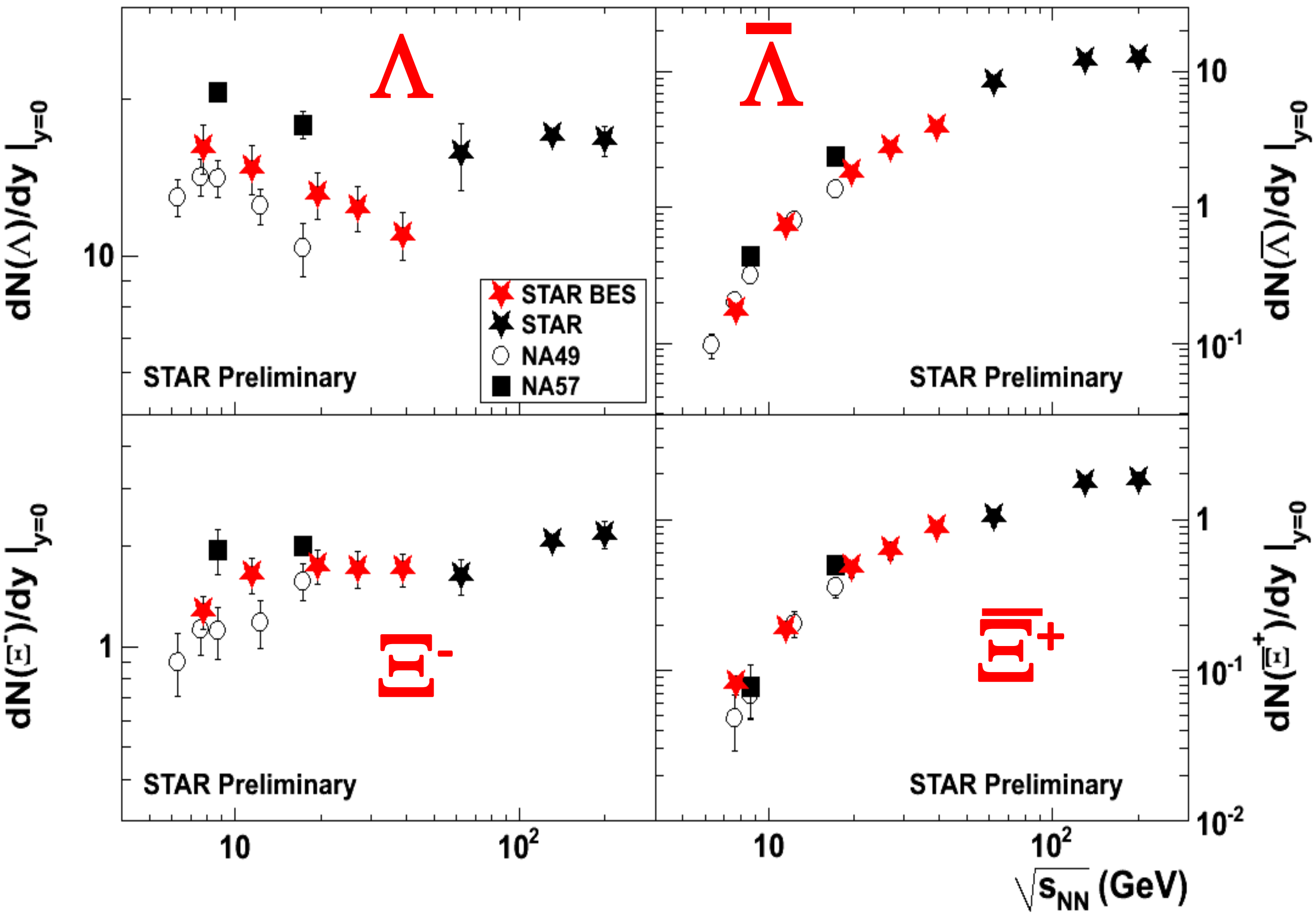


Forward direction kinematics favors parton scatterings of large x partons from p off small x partons from A !

Initial conditions for AA
QCD in high density non-linear regime
-- Color Glass Condensate

The quantum nature of the partons must manifest through saturations ! At what Q_S and x scales and to what extent?

Mid-Rapidity Hyperon Yield



Mechanism:
Pair Production
Associated Prod.

-- quark or hadron level

-- difference in hyperon vs. anti-hyperons

-- sensitive to chemical potential