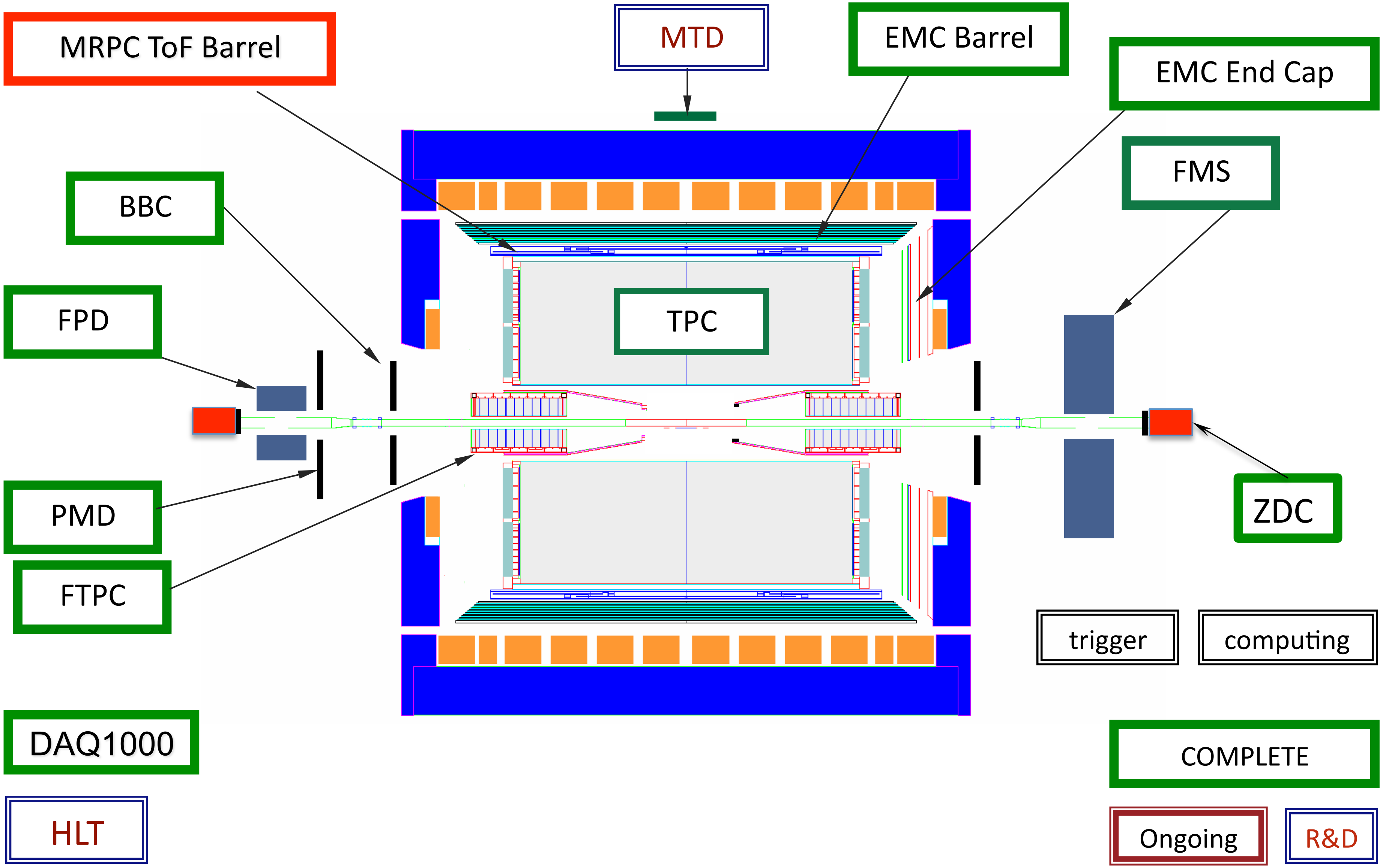
Recent Results from STAR

Rashmi Raniwala for
STAR Collaboration

High Energy Physics Symposium
Dec. 13-18, 2010, Jaipur

THE STAR DETECTOR



OUTLINE

- First evidence of Anti-Matter-Hyper-Nucleus at STAR
- Measurement of photons at forward rapidity using PMD

Flow at STAR

- Elliptic flow and Degree of Thermalization at RHIC energies
- Results on Flow of Multi-Strange particles
- What we learn from elliptic flow of ρ^0 vector meson
- Charge correlations wrt to reaction plane: Do we see local Parity violation in Strong interactions?

- Locating QCD Critical Point: Data from AuAu $\sqrt{s_{NN}}$ = 9.2 GeV
- Higher Moments of Net protons distribution : Do we see critical behaviour?

Exotic phenomenon at STAR: First observation of ANTI-MATTER HYPER-NUCLEUS

Ref: Science 328 **(2010) 58**

Normal
Nucleon N
qqq
q -> u or d

Normal Nucleus
Proton
+
Neutrons

Anti-Hyper-
Triton
Contains
$\bar{p} + \bar{n} + \bar{\Lambda}$

Hyperon Y
qqs
q -> u or d
or s

Hyper-Nucleus
Contains
p,n + atleast
one hyperon

Anti-Matter Hyper-Nucleus at STAR

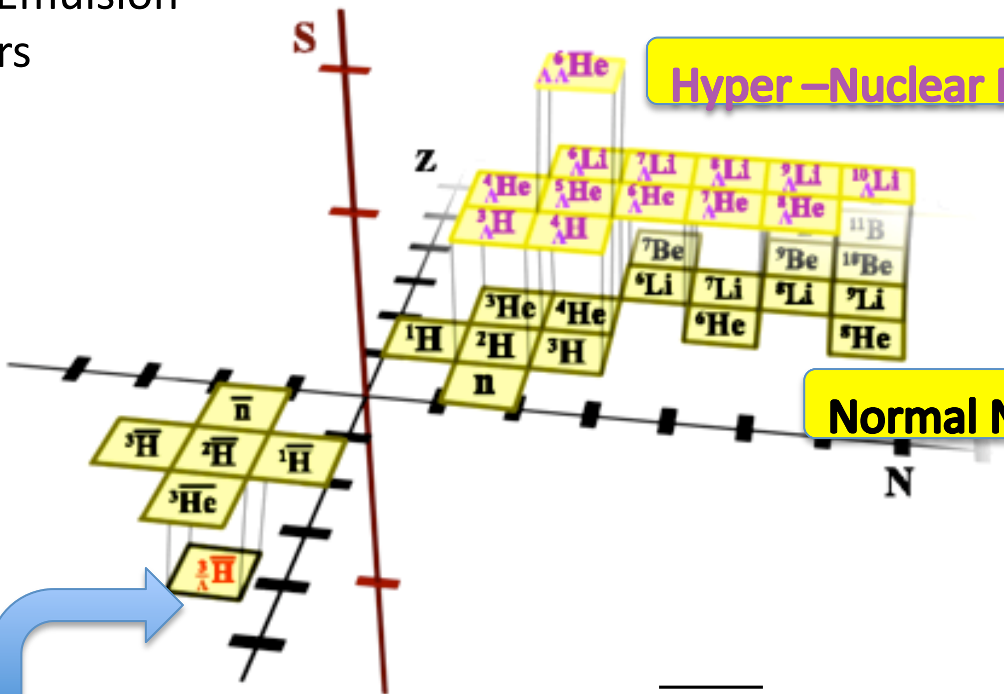
Hyper-Nuclei discovered in 1952 using Nuclear Emulsion Cosmic Ray Detectors

p,n,
Λ

Hyper –Nuclear Matter

$\bar{p}$,$\bar{n}$

Normal Anti-Nuclear Matter



Normal Nuclear Matter

p,n

Anti-Hyper-Triton composed of antiproton, anti-neutron and anti-lambda-hyperon

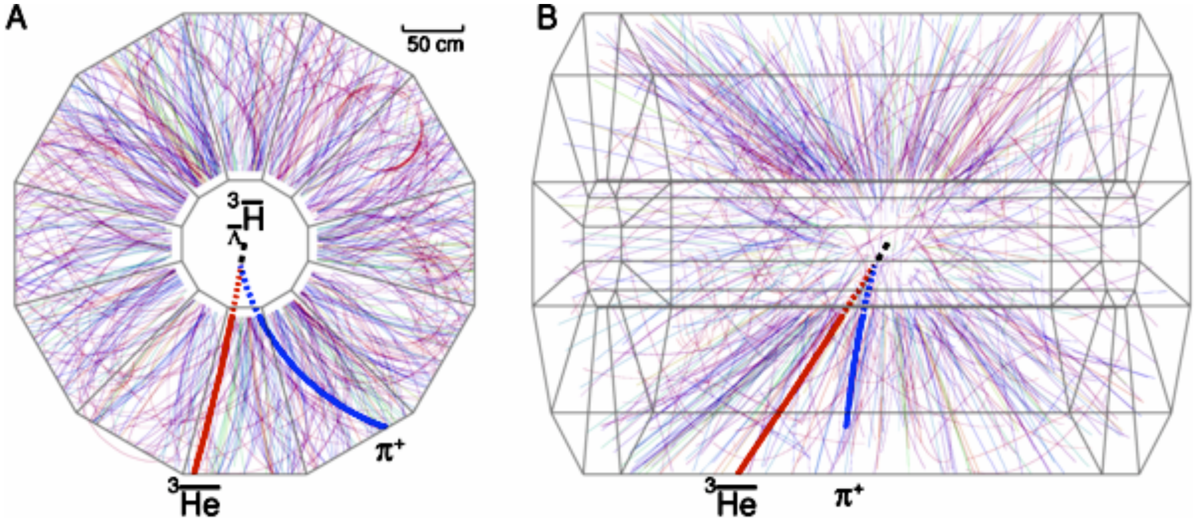
$\bar{p}$,$\bar{n}$
$\bar{\Lambda}$

Lifetime of $\overline{{}^{3}_{\Lambda}H}(\bar{p}+\bar{n}+\bar{\Lambda})$
Related to strength of Y-N interaction
-> Interesting in Nuclear Physics, Nuclear Astrophysics……….

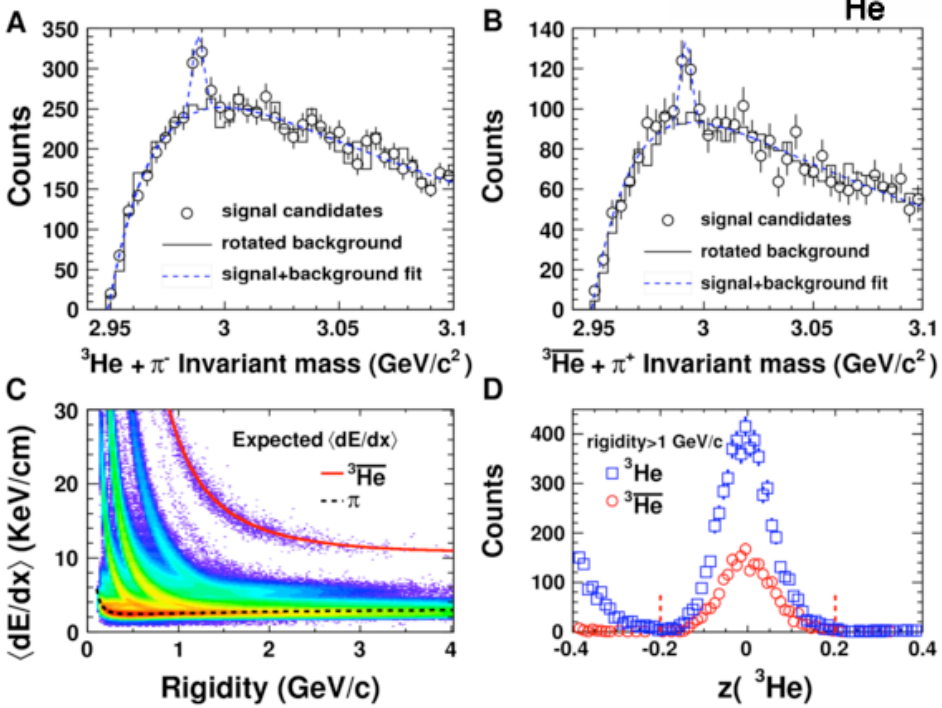
Detecting Anti-Hyper-Triton

Decay Mode used

$${}^{3}_{\Lambda}\overline{H} \Rightarrow {}^{3}\overline{He} + \pi^{+}$$



${}^{3}_{\bar{\Lambda}}\overline{H}$ peak visible in Invariant Mass Distribution



- Background obtained by rotating (Anti)He track & Subtracted to get:

${}^{3}_{\Lambda}H$ -> 157 ± 30 ${}^{3}_{\bar{\Lambda}}\overline{H}$ -> 70 ± 17

Mass of ${}^{3}_{\bar{\Lambda}}\overline{H}$

2.991 ± 0.001 ± 0.002 GeV/c

Lifetime : ${}^{3}_{\bar{\Lambda}}\overline{H}$ + ${}^{3}_{\Lambda}H$

$\tau = 182^{+18}_{-27} \pm 27$ pico sec.

(Anti) Hyper-Nuclei Yield Ratios

Coalescence model : To form a hyper-Nucleus the nucleons & hyperons have to be in close proximity

So Hyper-Nuclei Yield -> Sensitive to phase-space distbn. of p n Λ

P. Braun-Munzinger, J. Stachel, Nature 448(2007)302 , M. Danysz, J. Pniewski, Phil. Mag. 44(1953) 348

e.g.

$$\overline{{}^{3}_{\Lambda}He}/{}^{3}_{\Lambda}He = \frac{\overline{\Lambda}}{\Lambda} * \frac{\overline{p}}{p} * \frac{\overline{n}}{n}$$

Ratios of Hyperons and Nucleons available from particle spectra.

Measured Ratios of Hyper-Nuclei : consistent with Coalescence Model

Particle Type	Measured Ratio
${}^{3}_{\Lambda}\overline{H}/{}^{3}_{\Lambda}H$	0.49 ± 0.18 ± 0.07
${}^{3}\overline{He}/{}^{3}He$	0.45 ± 0.02 ± 0.04
${}^{3}_{\Lambda}\overline{H}/{}^{3}\overline{He}$	0.89 ± 0.28 ± 0.13
${}^{3}_{\Lambda}H/{}^{3}He$	0.82 ± 0.16 ± 0.12

Strangeness phase space population is similar to that of light quarks

Particle Production at Forward Rapidity

Collective knowledge by RHIC experiments have shown that

• Process of particle production different in different phase space regions.

Ref: PHOBOS Coll: PRL 87(2001)102303; PRL 91(2003) 052303)

• Different particle species might show different behaviour of production in the same phase space.

Ref: STAR Coll. J. Adams et al., Phys. Rev. Lett. 95 (2005)062301 ;

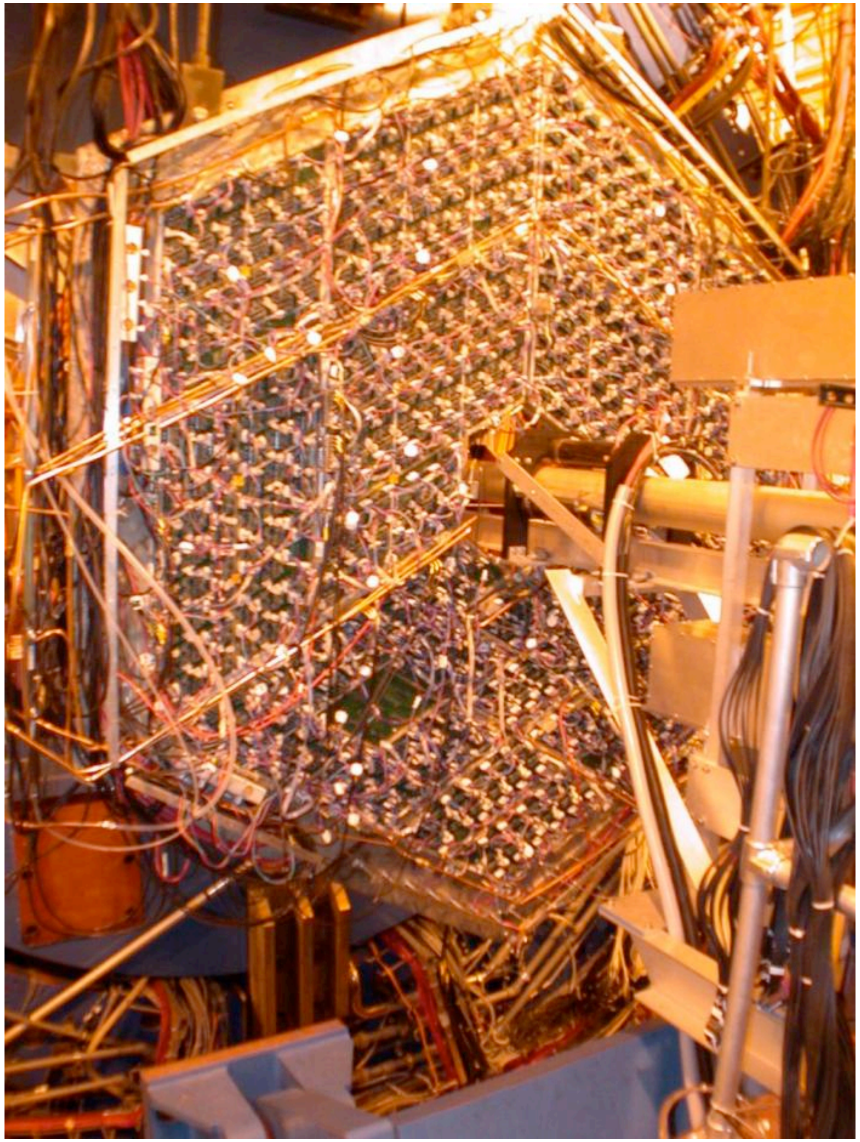
HIJING: Total produced particle has contributions from:
Soft processes (N_{part} scaling) + Hard processes ($N_{collisions}$ scaling)

• Varying event centrality -> Relative contribution of soft and hard processes. Ref: PHENIX Coll. PRL 86 (2001) 3500

• PMD at STAR studies photons production (different species) at forward rapidity $-3.7 < \eta < -2.3$ (different phase space) : Compares with charge particle production at RHIC ! Phys. Rev. C 73 (2006) 34906; Phys. Rev. Lett. 95 (2005) 62301

The Photon Multiplicity Detector at STAR

Nucl. Instrum. Meth. A 499 (2003) 751



Photon Multiplicity Detector measures N_γ and $dN_\gamma/d\eta$ at forward rapidity ($-3.7 < \eta < -2.3$)

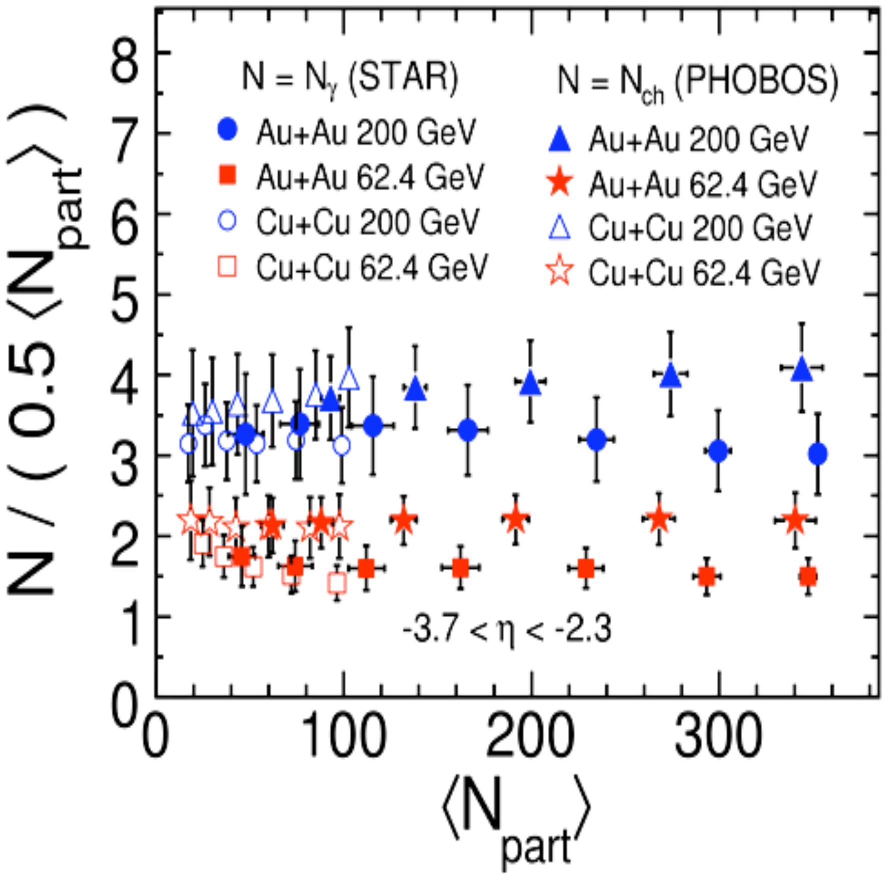
Designed, Fabricated, Installed & Maintained by 3 Indian Univ. & 3 Institutes.

Photon Production studied as a function of:

- Event centrality
- System size : AuAu and CuCu collisions
- Center of mass Energy ($\sqrt{s_{NN}}$): 200 GeV & 62.4 GeV

Photon Production: Scaling with N_{part}

Nucl.Phys.A 832: 134-147, 2010



Ref: PHOBOS data : PRL 87 (2001) 102303 ; PRL 91(2001) 052303

- N_{γ} measured in $-3.7 \leq \eta \leq -2.3$ have been scaled with $N_{part}/2$
- Increasing coll. energy increases N_{γ}
- CuCu and AuAu collisions at same N_{part} have same N_{γ}
- $N_{\gamma}/0.5*N_{part}$ constant with N_{part}: Photon production at forward rapidity is due to Soft processes
- HIJING results match well with data
- N_{ch} also scales with N_{part}
- $N_{ch}/N_{\gamma} = 1.4 \pm 0.1$ for $\sqrt{s_{NN}} = 62.4$GeV
  $= 1.2 \pm 0.1$ for $\sqrt{s_{NN}} = 200$ GeV

Longitudinal Scaling of Photon Production

- $dN_{ch}/d\eta/0.5*N_{part}$ v/s (η -y_{beam}) : independent of beam energy:
Limiting Fragmentation Phys. Rev. 188 (1969) 2159

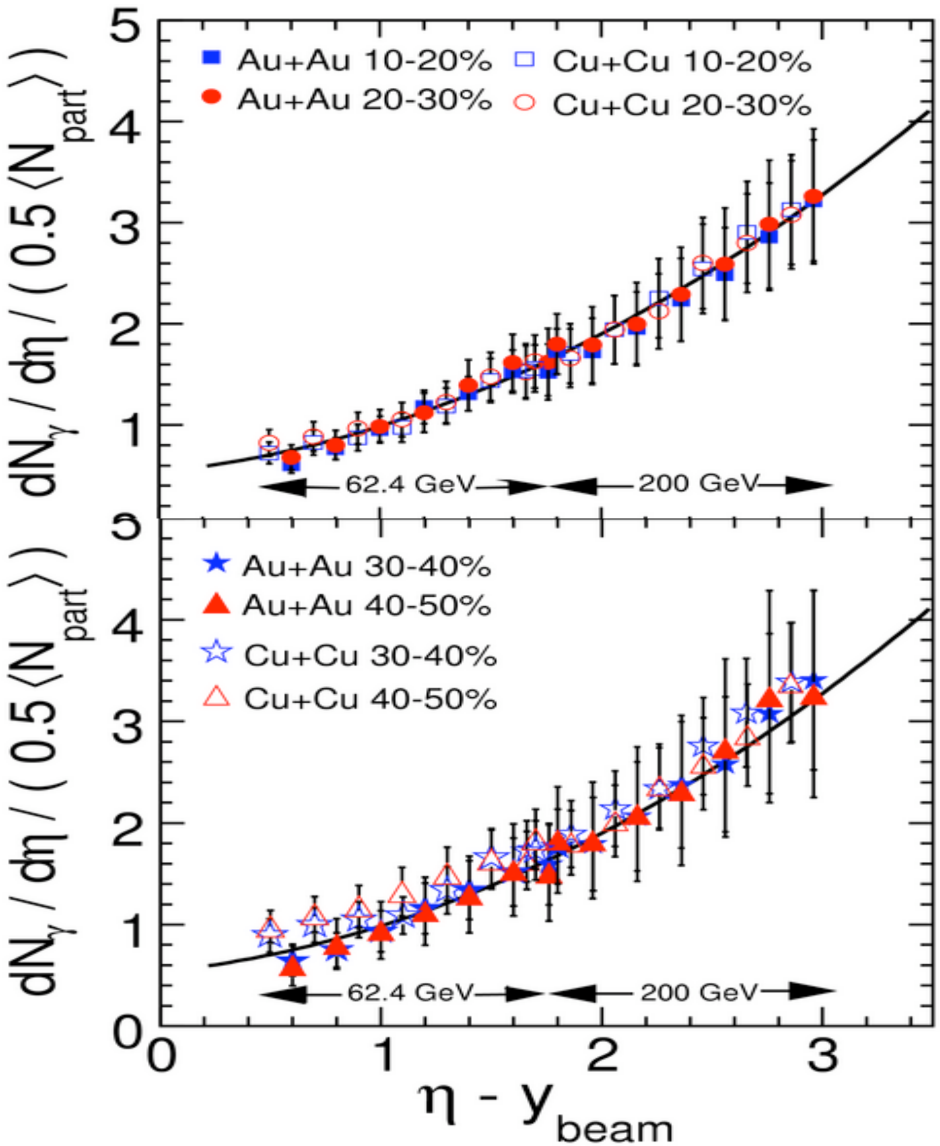
- Longitudinal scaling observed for Photons at forward rapidity independent of Beam Energy, Event Centrality

STAR Coll. PRL 95(2005) 062301

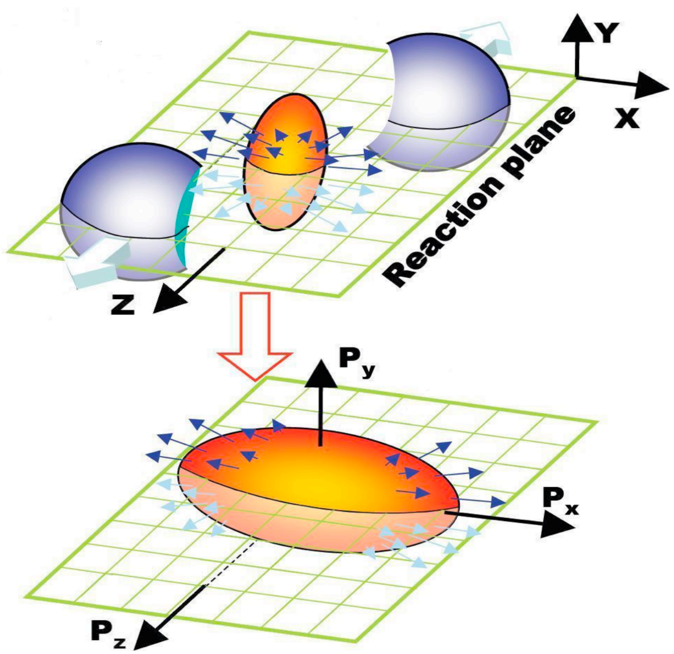
- Now also seen to be true for different Colliding Systems

- Longitudinal scaling in Charge Particles centrality dependent at $\eta - y_{beam}$ = 0.25 to 1.25

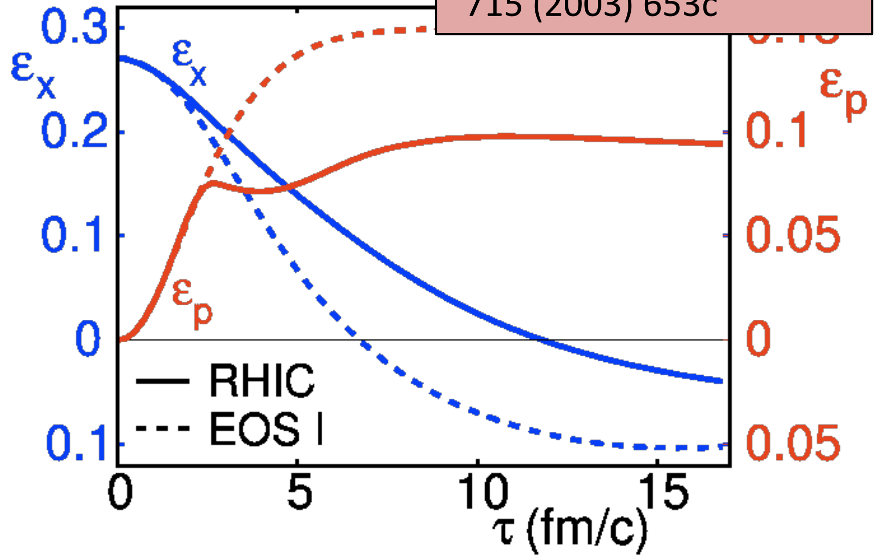
STAR Coll. Phys. Rev. C 73 (2006) 034906.



WHY IS ANISOTROPIC FLOW IMPORTANT?



P.F. Kolb & U. Heinz, NP A 715 (2003) 653c



- Anisotropic Geometry + strongly interacting medium -> Momentum anisotropy -> More particles emitted in Reaction Plane : FLOW
- Reaction zone expansion -> decreases spatial eccentricity : Self Quenching
- Flow develops before ε_X vanishes -> Sensitive to early stages of evolution.

$$\left[(1/N)dN/d(\Phi-\Psi_R)\right] \sim 1+2v_1\cos(\Phi-\Psi_R)+2v_2\cos 2(\Phi-\Psi_R)$$

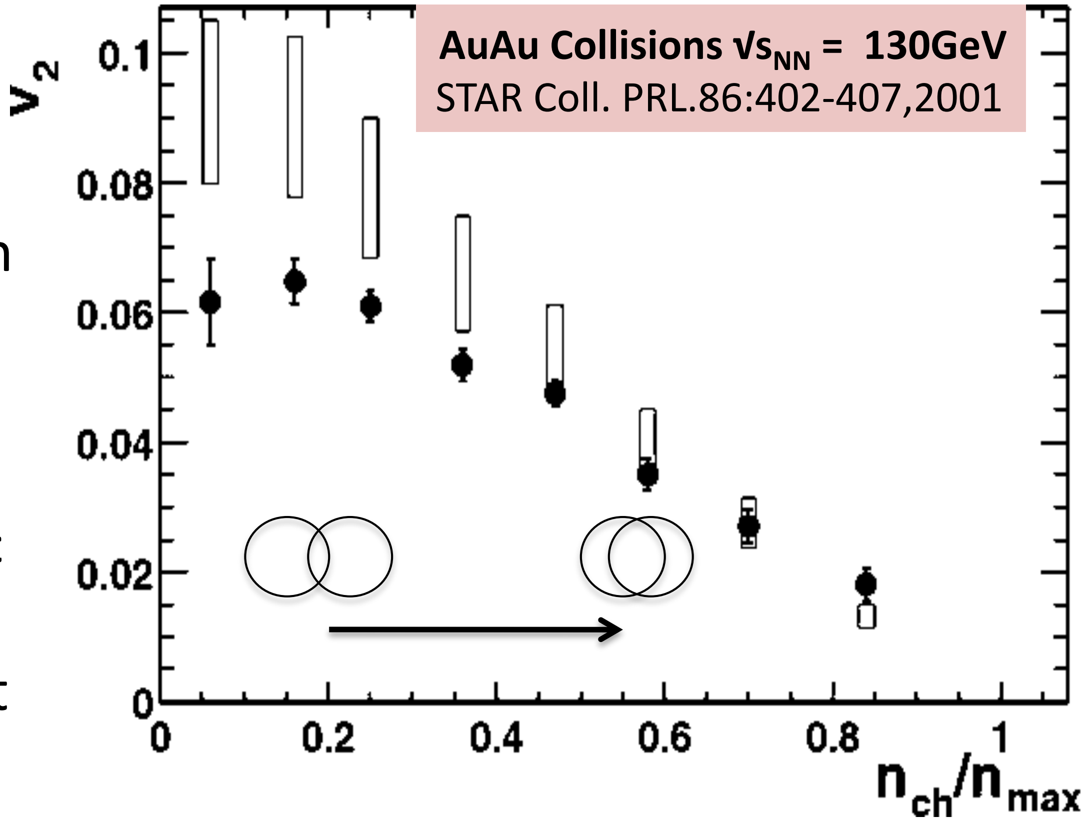
S,Voloshin & A.Poskanzer Phys. Rev. C 58: 1671-1678, 1998

FLOW AT RHIC : Hydrodynamics works!

• Initial results of v_2 by STAR :
Large values, close to the ideal hydrodynamic model with complete thermalization

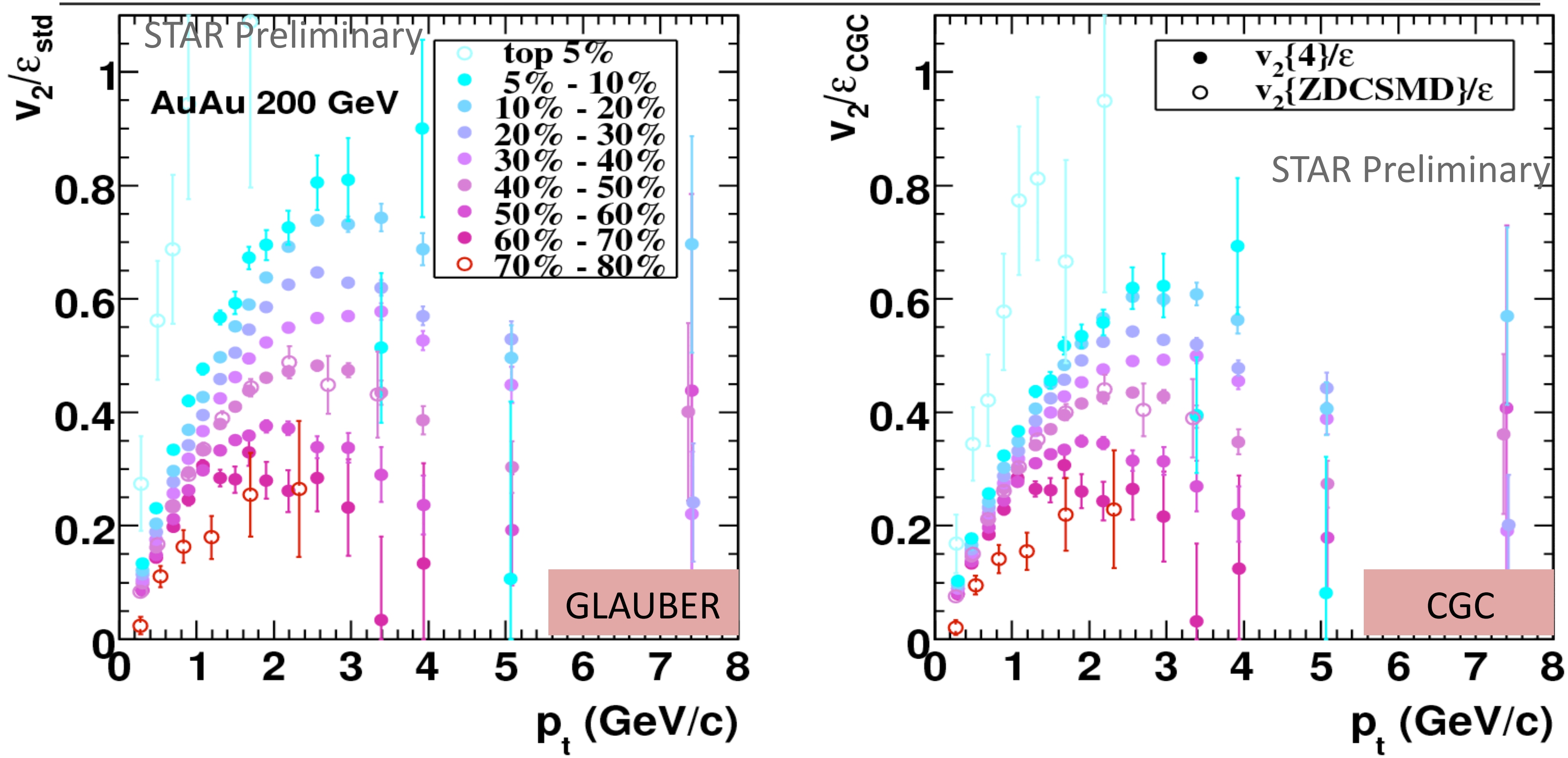
• v_2 depends on
✓ Equation of state of the system
✓ Initial Spatial Eccentricity ε

• v_2/ε : filters out trivial effect of geometry
• Calculate ε using models :
Glauber And Color Glass Condensate



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

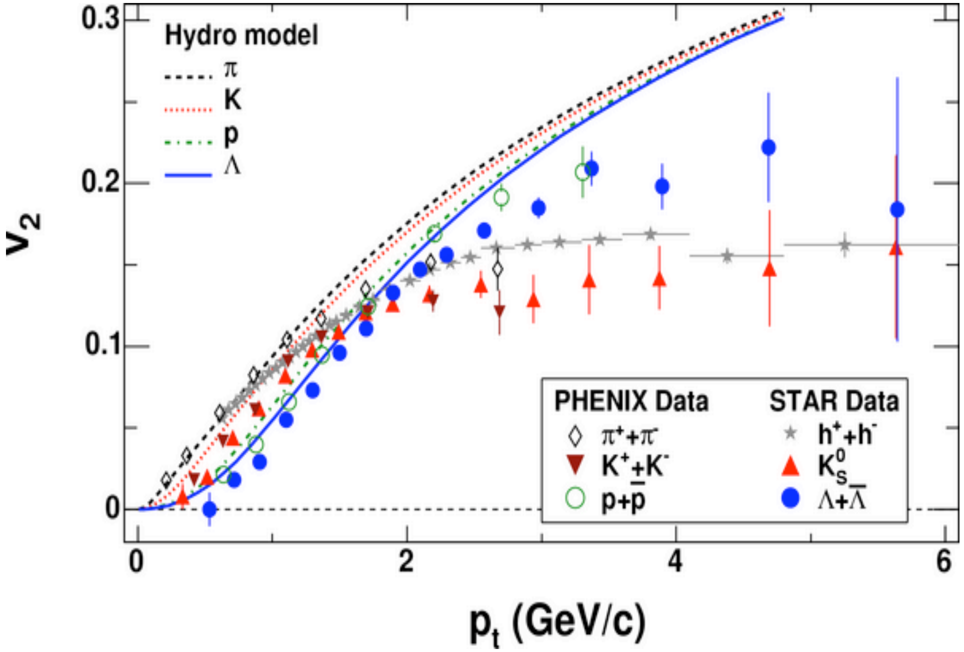
A Closer look at p_T dependence of v_2/ε

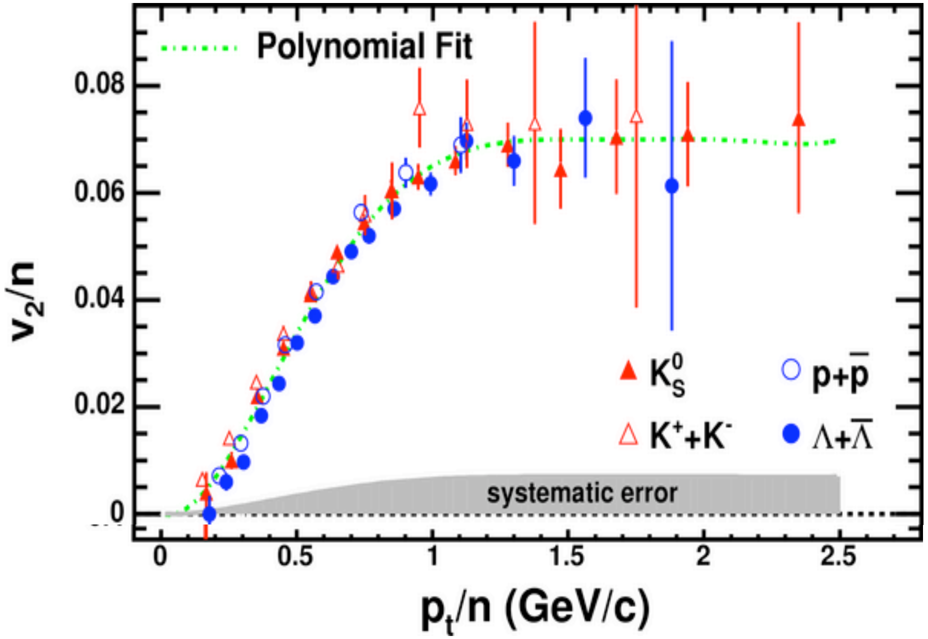


- v_2/ε increases with centrality for both Glauber & CGC initial conditions
  - ✓Better conversion of initial ε to final v_2
- CGC eccentricity is larger and hence gives smaller v_2/ε values
- Both models indicate higher thermalization in more central collisions

Number of Constituent Quark Scaling

STAR Coll. Phys. Rev. C 72 (2005) 1490

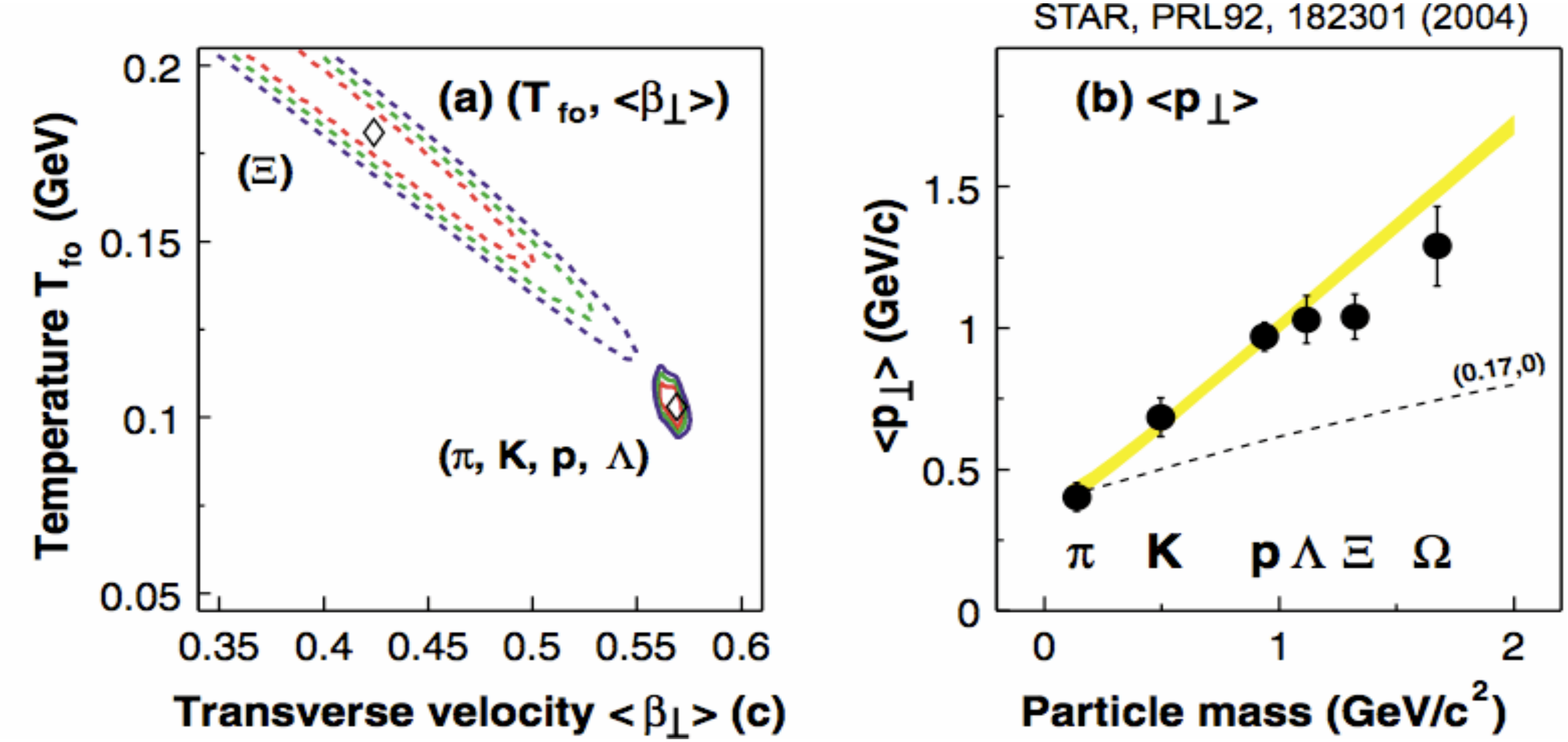




- v_2 shows a rise with p_T at low p_T : matches with Hydrodynamic model
- At intermediate p_T : v_2 saturates
- Saturation value different for Mesons and Baryons->Depends on Number of Quarks?

- v_2 Scaled by Number of Constituent Quarks: Mesons and Baryon scale at intermediate p_T : NCQ Scaling
- Suggests partonic degrees of freedom during early stages of event evolution

Why v_2 of Multi-strange hadrons?



✓Smaller $<\beta_T>$ Larger $T_{freeze\text{-}out}$ obtained from spectra.

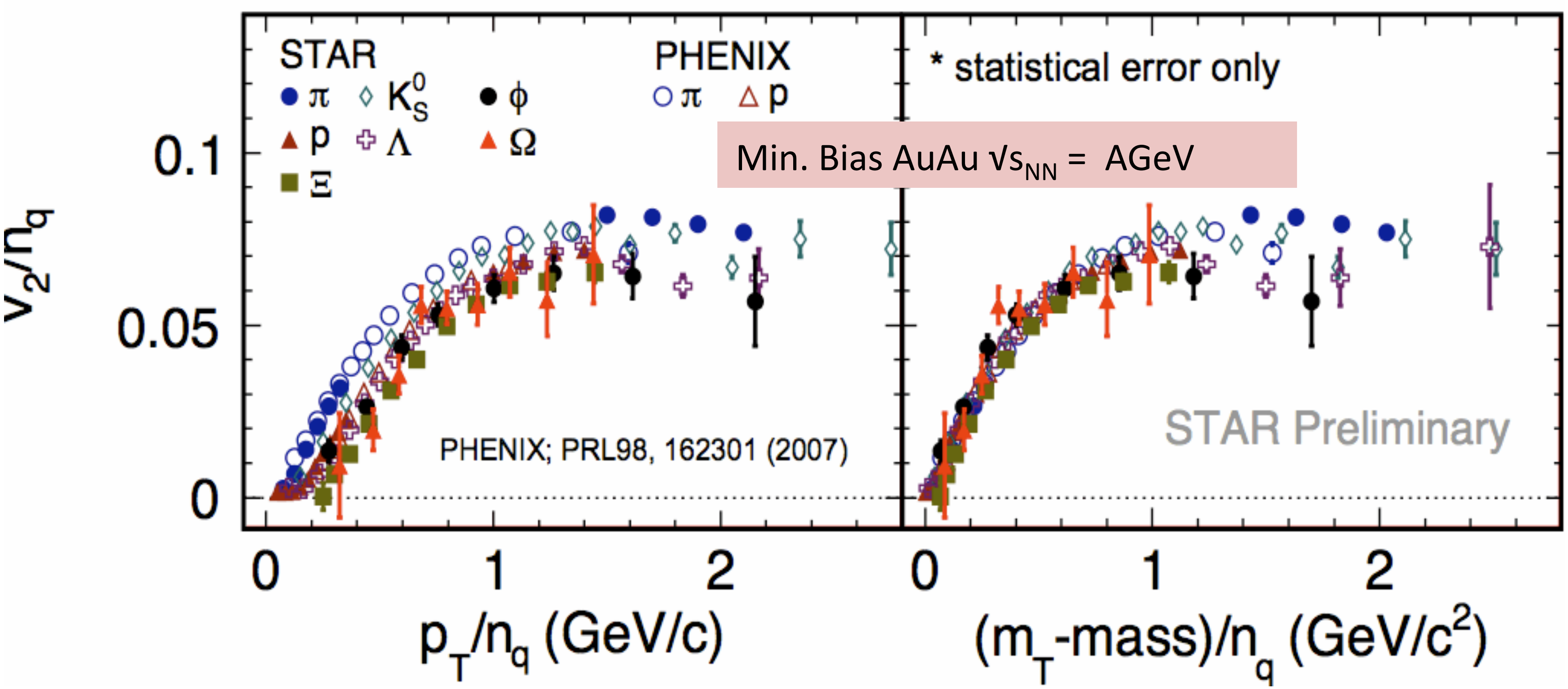
✓$<p_T>$ deviates from expected relation

→ Freeze out earlier than lighter hadrons

Does Multi-strange hadron v_2 show same features as lighter hadrons?

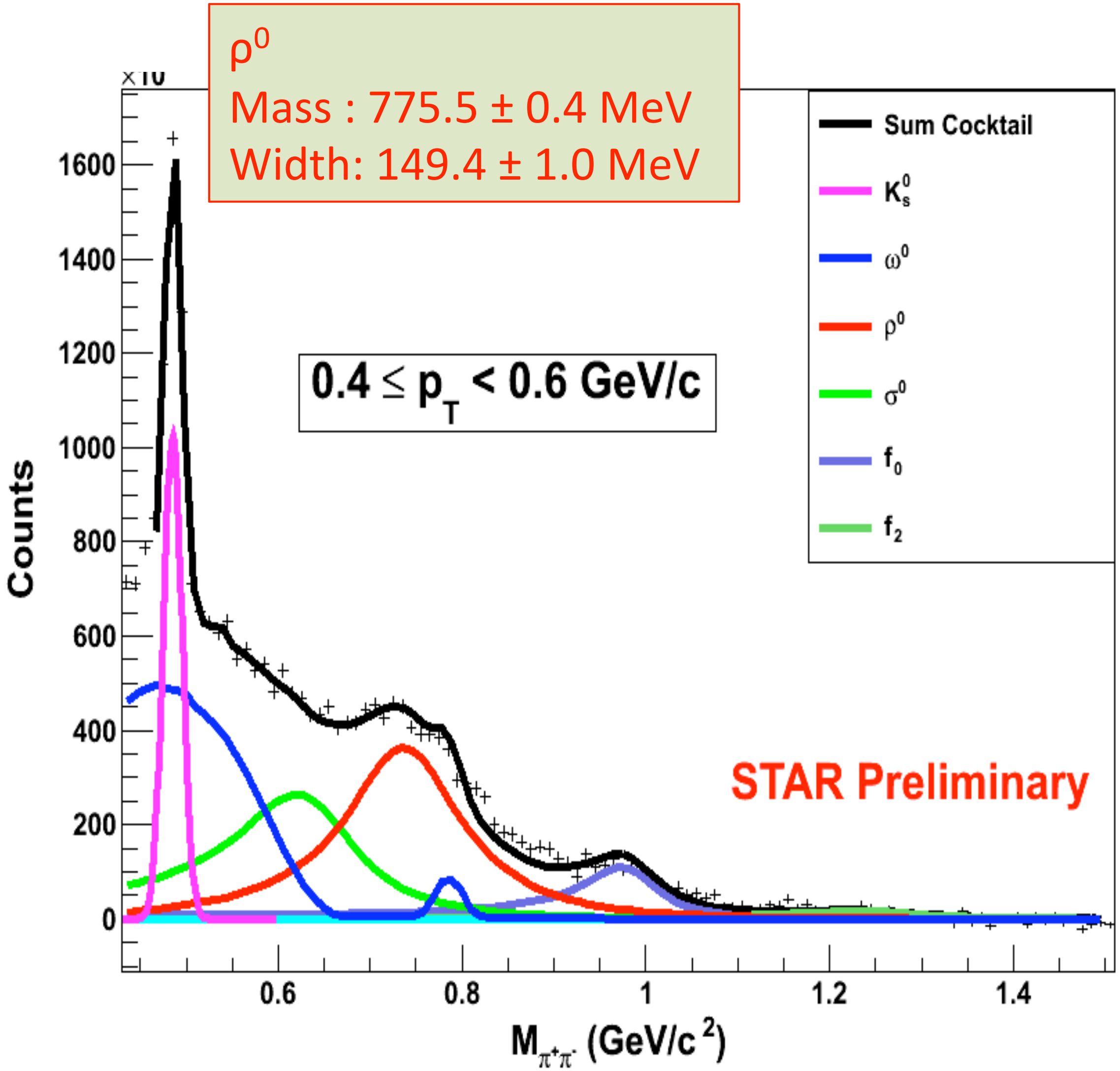
Elliptic Flow of Multi-strange hadrons: Φ, Ξ, Ω

NPA 830 (2009) 187



- v_2 is of the same order as for lighter hadrons
- NCQ scaling works well upto p_T/n_q ~ 1.5 GeV/c
- validates coalescence model -> Partonic degrees of freedom

ρ^0 Meson Production and NCQ Scaling



- Decay Mode $\rho^0 \rightarrow \pi^+ \pi^-$
- Invariant mass -> Fit to Hadronic cocktail (ω^0 K^* ρ^0 K_S….)
- Hadronic decay products sensitive to medium
- Production Mechanism probed using NCQ Scaling of v_2

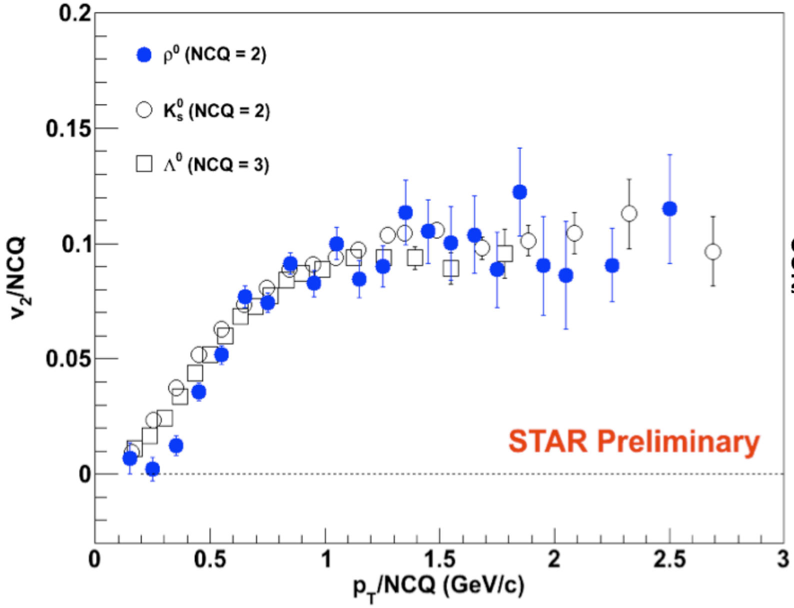
  $\pi^+ \pi^- \rightarrow \rho^0$ $n_q = 4$

  $q\bar{q} \rightarrow \rho^0$ $n_q = 2$

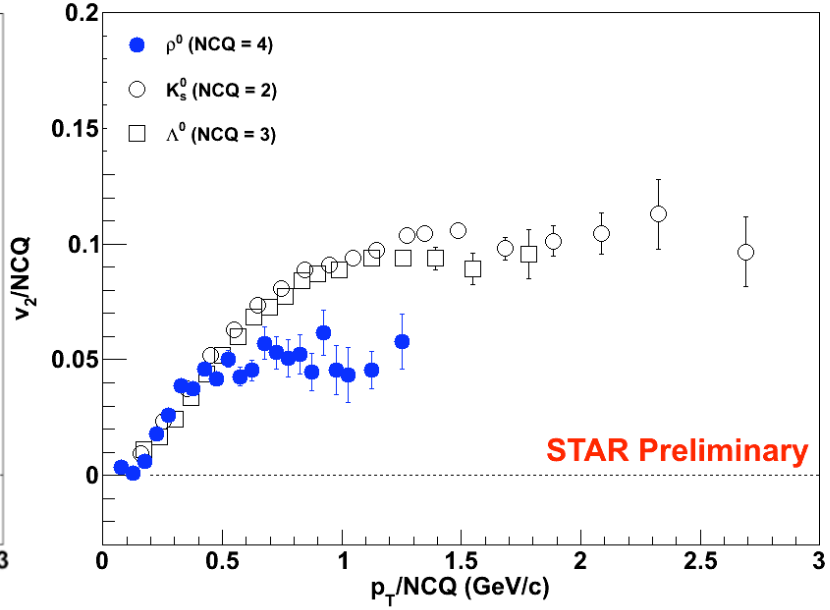
- Prabhat Pujahari's talk in QMRHIC parallel session

ρ^0 Production : n=2 or n=4?

$q\bar{q}$ -> ρ^0 n_q= 2



$\pi^+ \pi^-$ ->ρ^0 n_q= 4



- **ρ^0** v_2 at intermediate p_T (1.5 to 4.0 GeV) shows n_q = 2 scaling
- Production mode by quark and anti-quark pair dominant!

Is Local Parity Violation in Strong Interactions Observable?

P/CP globally invariant in strong interactions as evident from Zero Electric Dipole Moment of Neutrons

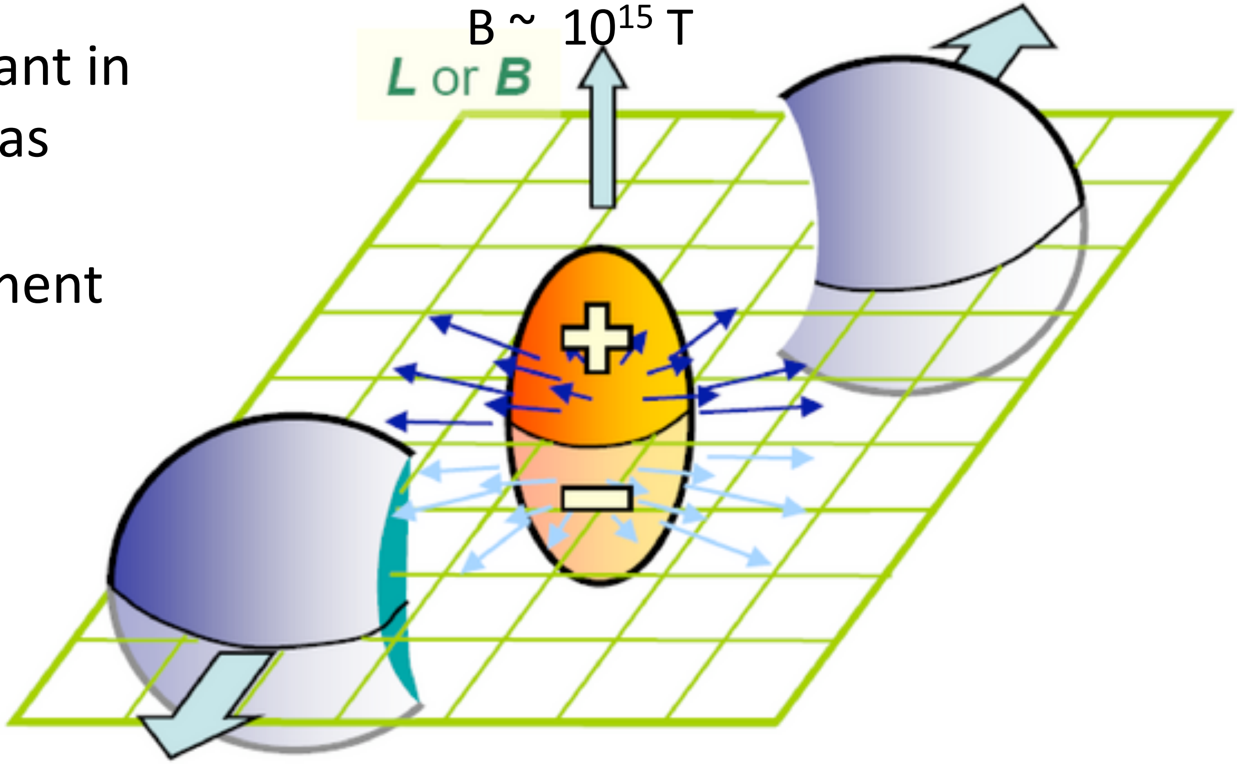
BUT

Local meta-stable P-odd domains are not forbidden

Kharzeev, Kraanitz, Venugopalan PL B545 (2002)298 and references therein

$L \sim 10^5$

$B \sim 10^{15}$ T



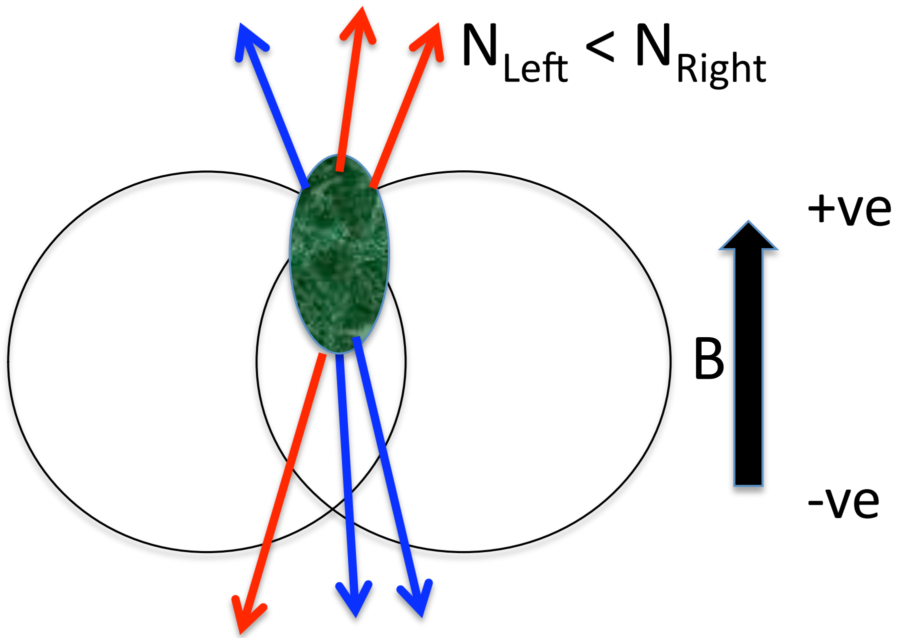
Local P-Odd domains result in charge separation along the large Magnetic field of the medium.

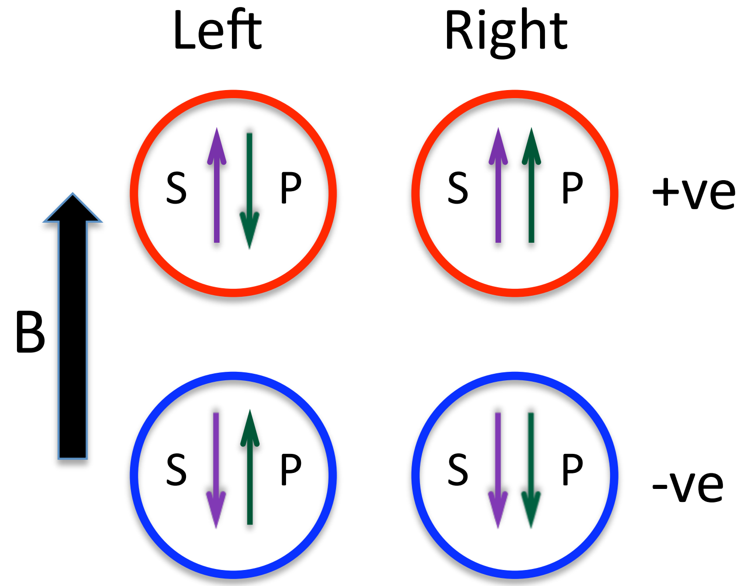
T.D.Lee,PRD 8,1226(1973), T.D.Lee & G.C.Wick, PRD 9,2291(1974)

Charge Separation in a Heavy Ion Collision

Magnetic Field aligns

- Spin of +ve charged quarks along itself
- Spin of -ve charged quarks opposite to itself





Kharzeev, PLB 81(1998)512 Kharzeev, Zhitnitsky, NPA 797 (2007)67 , Kharzeev, McLerran, Warringa, NPA 803(2008) 67, Voloshin PRC 62(2000)044901, Liang, Wang, PRL 94(2005)102301

Observing Charge separation w.r.t. Reaction Plane

Azimuthally Anisotropic Distribution : was charge independent earlier.

: Now has a charge dependent term

$$\frac{dN_{\pm}}{d\phi} \sim 1 + 2\sum_{n=1} v_n \cos(n\Delta\phi) + 2a_{\pm}\sin\Delta\phi + ...$$

Predicted charged particle asymmetry $a_{\pm}$ ~ 1% for mid-central collisions

BUT averaged over all events -> $\langle a_{\pm} \rangle =$ ☹

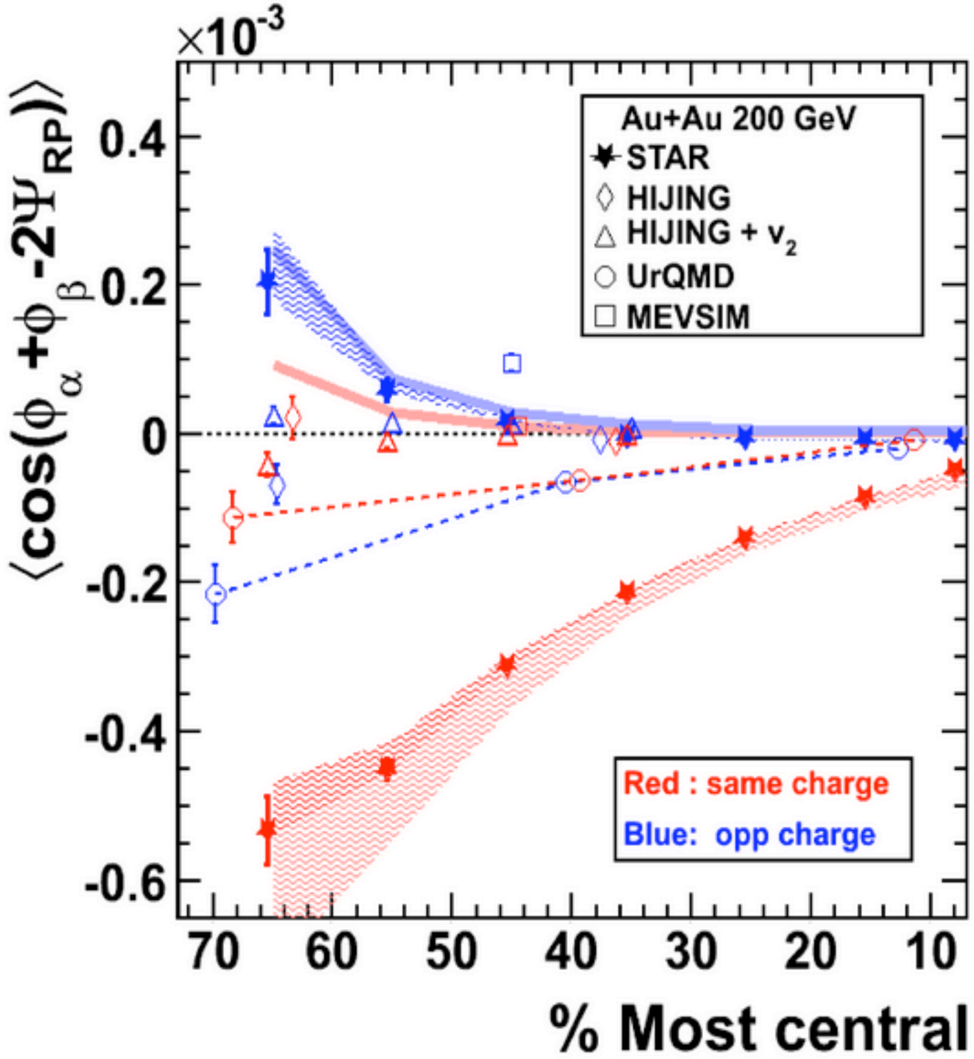
If we measure charge particle correlations $\langle a_{\alpha} a_{\beta} \rangle$ …. Does not vanish ☺

$\langle a_{\alpha} a_{\beta} \rangle \sim 10^{-4}$: Can be measured using correlation with Reaction Plane OR using a three particle correlator $\left\langle \cos\left(\phi_{\alpha} + \phi_{\beta} - 2\phi_{c}\right)\right\rangle$

$$\left\langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP})\right\rangle = \left[\left\langle v_{1,\alpha} v_{1,\beta}\right\rangle + Bg^{(in)}\right] - \left[\left\langle a_{\alpha} a_{\beta}\right\rangle + Bg^{(out)}\right]$$

$$\left\langle \cos\left(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP}\right)\right\rangle = \left\langle \cos\left(\phi_{\alpha} + \phi_{\beta} - 2\phi_{c}\right)\right\rangle / v_{2,c}$$

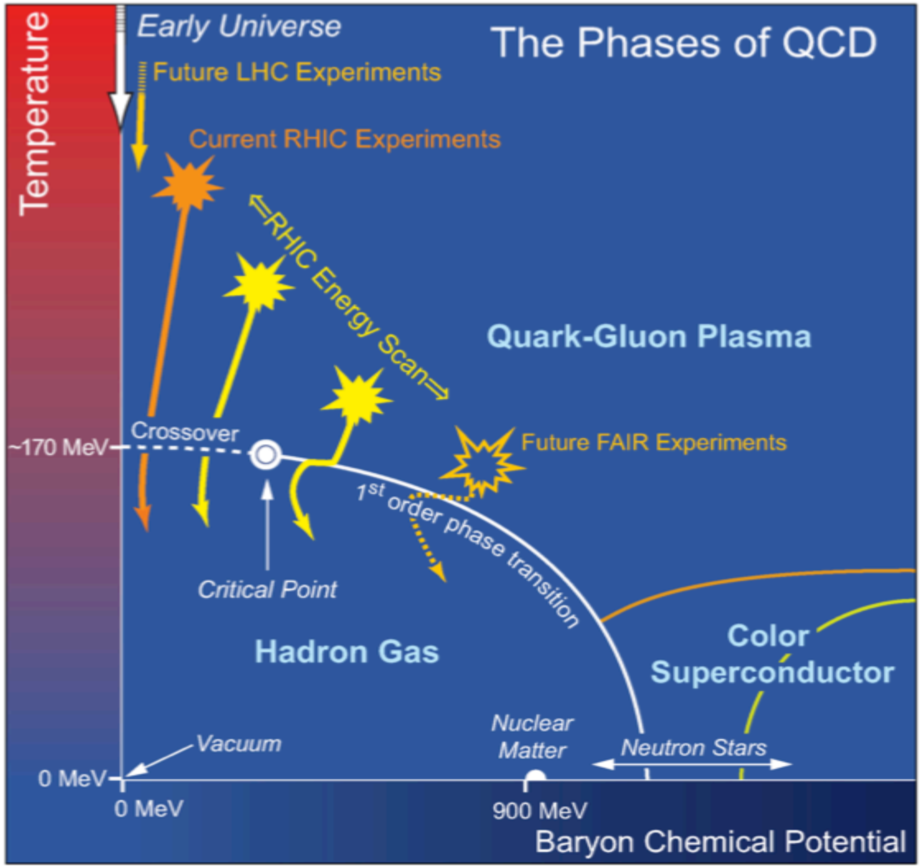
Observation from Data and Simulations



- Same Charge signal <a₊a₊>, <a₋a₋> is strong
- Opposite charge signal <a₊a₋> is small : suppression by medium !
- Opposite Charge signal dominated by background according to models
- Reaction Plane dependent and independent background effects built into various models do not explain Same Charge Signal

Local Strong Parity Violation:
A possible explanation of the observed phenomenon

QCD Phase Diagram : Locating Critical Point



- Lattice QCD Y. Aoki et al. Nature 443 (2006) 675 , PLB 643 (2006) 46

At μ_B=0; phase transition is a cross-over at T ~170 MeV

- QCD based Model Calculations: C.Athanasiou, M. Stephanov, K. Rajagopal PRL 102(2009)032301, R. Gavai S.Gupta PRD 78 (2008) 114503

At large μ_B : 1st order phase transition

- 1st order transition ends at CP

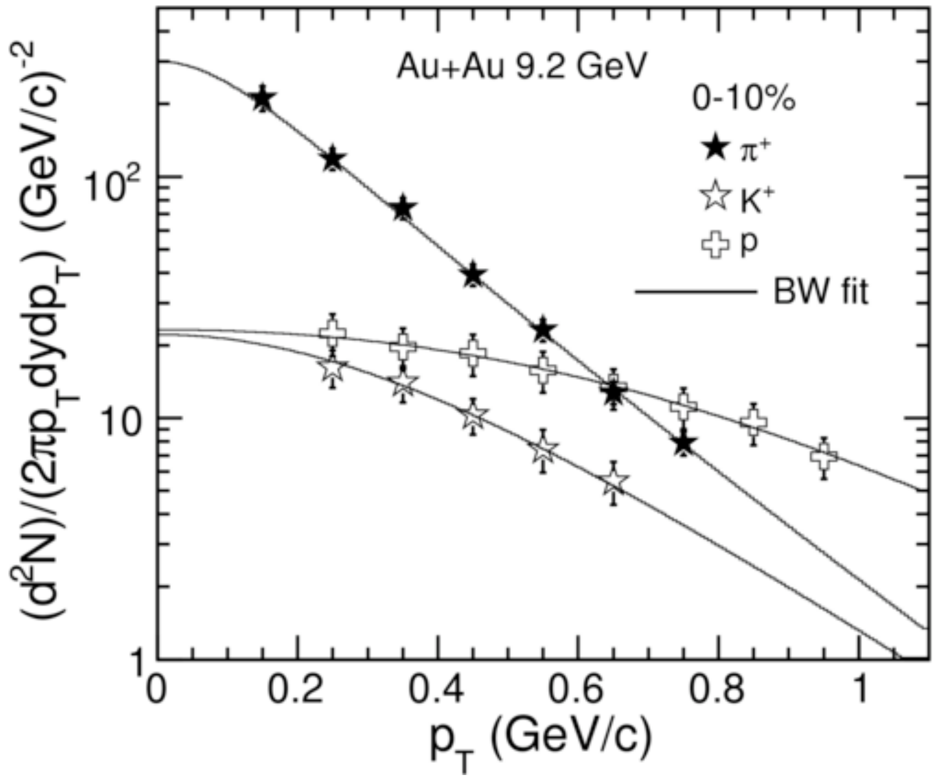
QCD Phase space mapped exptly. by varying $\sqrt{s_{NN}}$ in HI Collisions
PR D78(2008) 074597; PR D74(2006)054507 ; PRC 79(2009) 0152202 ; Prog.Th.Phy.Supp 153(2004)139

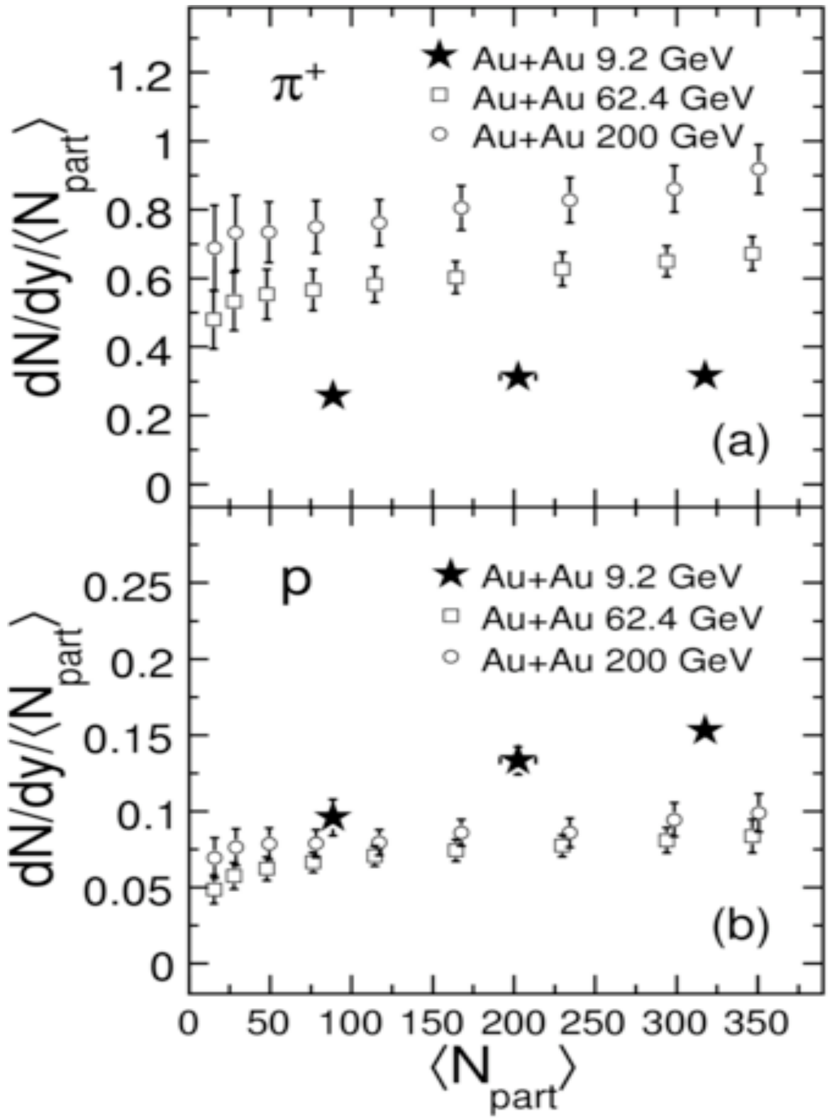
- ➢RHIC Beam Energy Scan $\sqrt{s_{NN}}$ = 5-39 GeV -> μ_B = 550 - 100MeV
- ➢STAR known to work very well at top RHIC energies !
- Check it work as well at low energy : AuAu collisions $\sqrt{s_{NN}}$ = 9.2 GeV
- Need tools to detect CP : Higher Moments of Net Proton Multiplicity

AuAu collisions at $\sqrt{s_{NN}}$= 9.2 AGeV

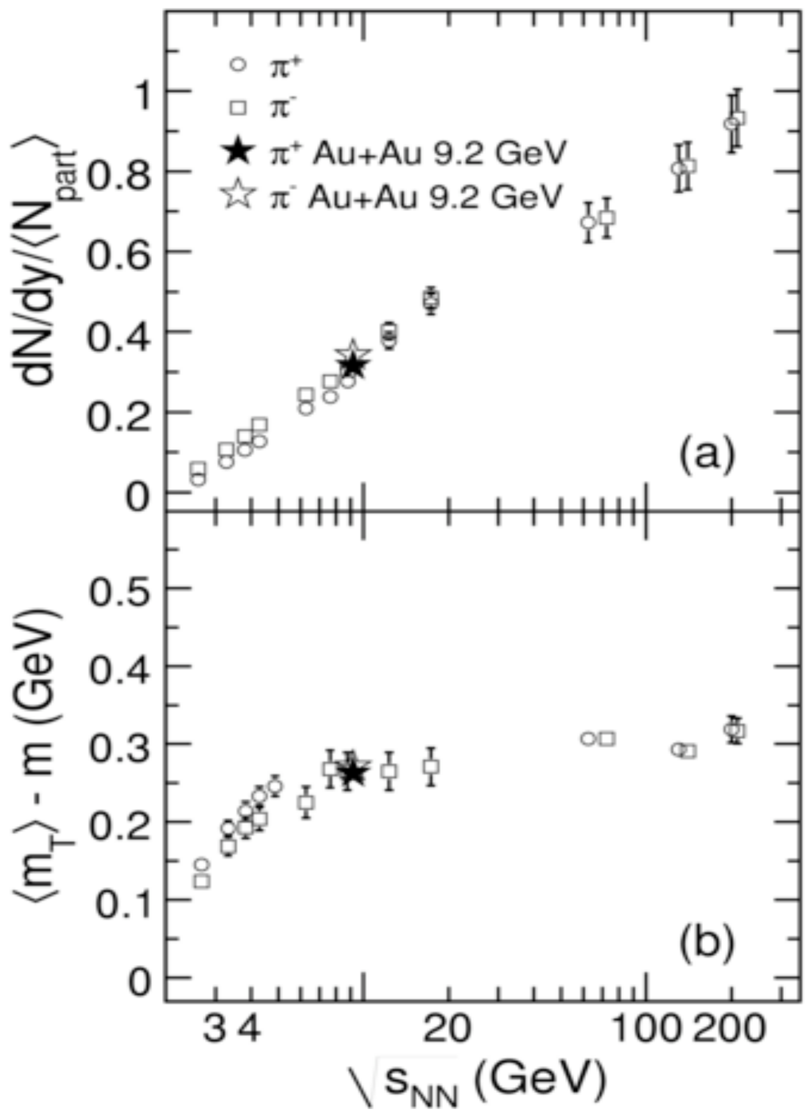
Ref: Phys. Rev. C 81(2010) 24911

Spectra of π^+, π^-, p, pbar, K^+, K^- was obtained using TPC ;
Centrality dependence of Multiplicity, <pT> was studied





Comparison of 9.2 GeV results with SPS data



STAR AuAu at 9.2 GeV : consistent with SPS results.
List of references for AGS and SPS data are listed in:
STAR Coll. Phys.Rev. C 81 (2010) 24911

STAR Advantages:

- Similar Acceptance at all energies
- All detectors are tested and known to work very well
- Addition of Time of Flight makes Particle ID better
- DAQ1000 makes data taking faster

STAR capable of making best use of Beam Energy Scan Runs

How to recognize Critical Behaviour?

- Correlation length ξ related to various moments of distributions of conserved quantities like Net Baryon, Net Charge, Net Strangeness number : Higher moments are more sensitive

M. A. Stephanov, Phys. Rev. Lett. 102 (2009)032301 ; M. Asakawa et al., Phys. Rev. Lett. 103 (2009) 262301

$$\Delta N = N - \langle N \rangle$$

$$\sigma^2 = \langle (\Delta N)^2 \rangle \propto \xi^2$$

$$\kappa = \left[\langle (\Delta N)^4 \rangle / \sigma^4 \right] - 3 \propto \xi^7$$

$$S = \langle (\Delta N)^3 \rangle / \sigma^3 \propto \xi^{4.5}$$

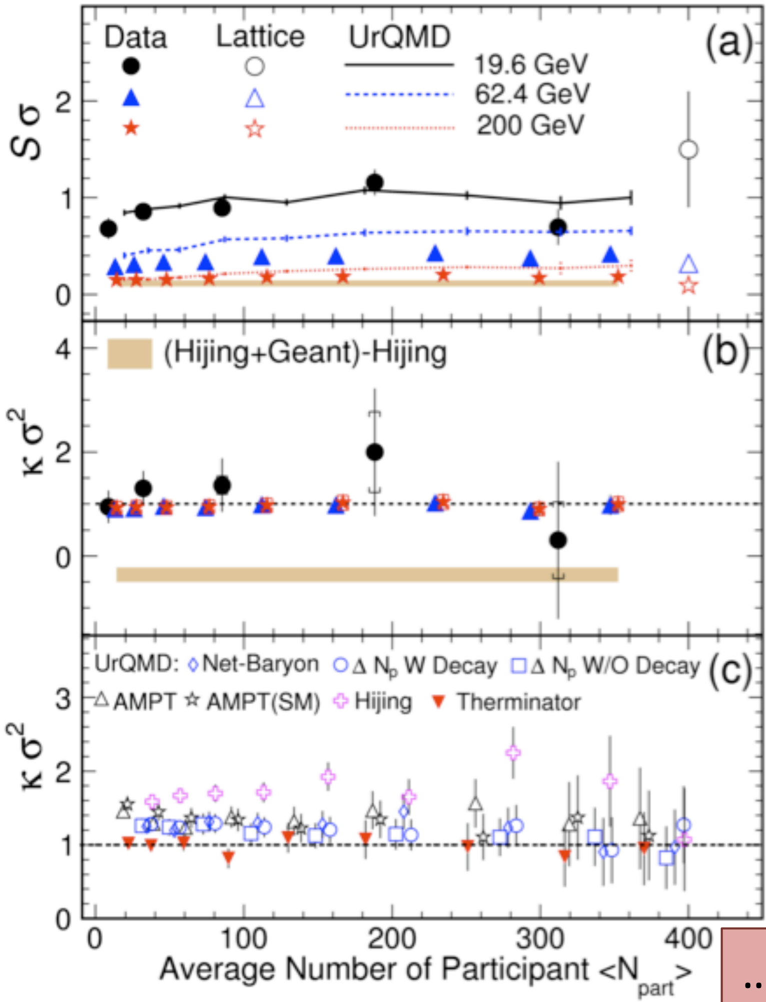
$$\kappa\sigma^2 \sim \chi_B^{(4)} / \chi_B^{(2)}$$

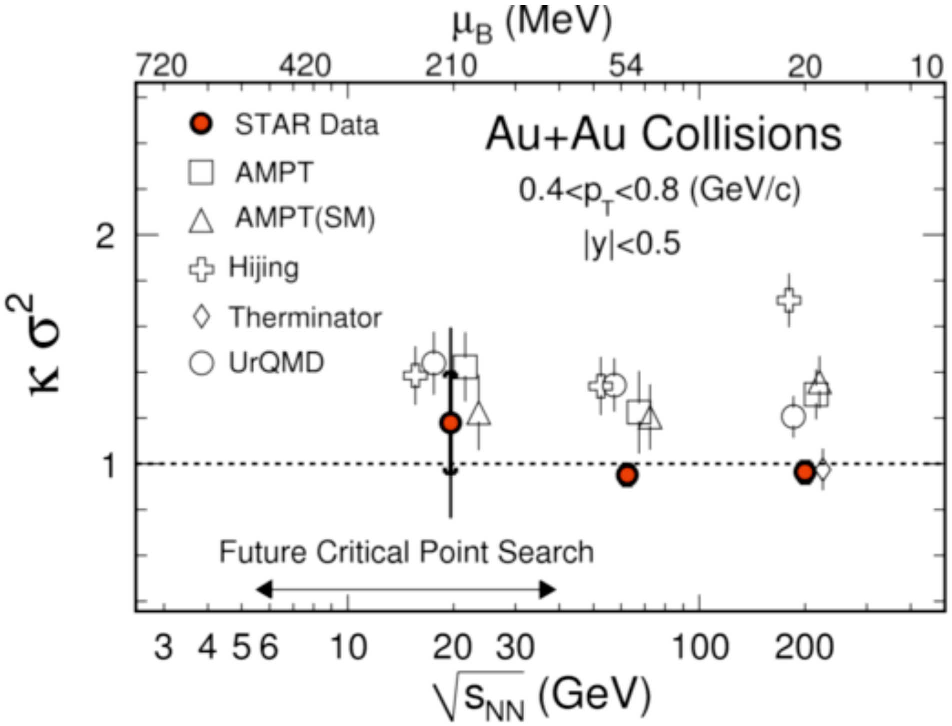
- According to QCD based model calculations:
  At Critical Point : ξ diverges -> Non-Gaussian Fluctuations
  -> $\kappa\sigma^2$ and $S\sigma$ diverge
  Away from CP : according to Central Limit Th. : $\kappa\sigma^2 = 1$; $S\sigma$=const.
- Models show that fluctuations in Net Proton number reflect the fluctuations in Net Baryon Number Y. Hatta et al. PRL 91(2003) 102003
- Study of Higher Moments of Net Proton Multiplicity as a function of centrality and beam energy as a probe for Critical Point

Experimental search for Critical Point

STAR Coll. Phys. Rev. Lett. 105 (2010) 22302

Study of $\kappa\sigma^2$ & $S\sigma$ with event centrality and Collision Energy





No-divergences observed till μ_B< 200 MeV

No indication of CP yet.

…………………………………..BES data is being analyzed!

New results in Nihar Sahoo's talk in Parallel Session

Summary

- First Observation of Anti-Hyper-Triton with a statistical significance of 4.2 σ.
- Photon multiplicity and rapidity distribution at forward rapidity is a measured for different centrality, colliding energy and systems. Centrality independent Limiting fragmentation behaviour confirmed.
- Matter at RHIC more thermalized in central collisions as compared to peripheral collisions as shown by both CGC and Glauber Model.
- NCQ Scaling observed for Multi-strange quarks and ρ^0 vector meson.
- Local Parity Violation in Strong Interactions : Results for same and opposite charge correlation presented : Models rule out detector effects for same charge correlations.
- Results from AuAu collision at 9.2 GeV presented -> STAR has taken good data in phase I of BES in 2010. Watch out for interesting results.
- Critical behaviour ruled out by Higher Moments upto $\mu_B < 200$ MeV.

Thank you from All of us

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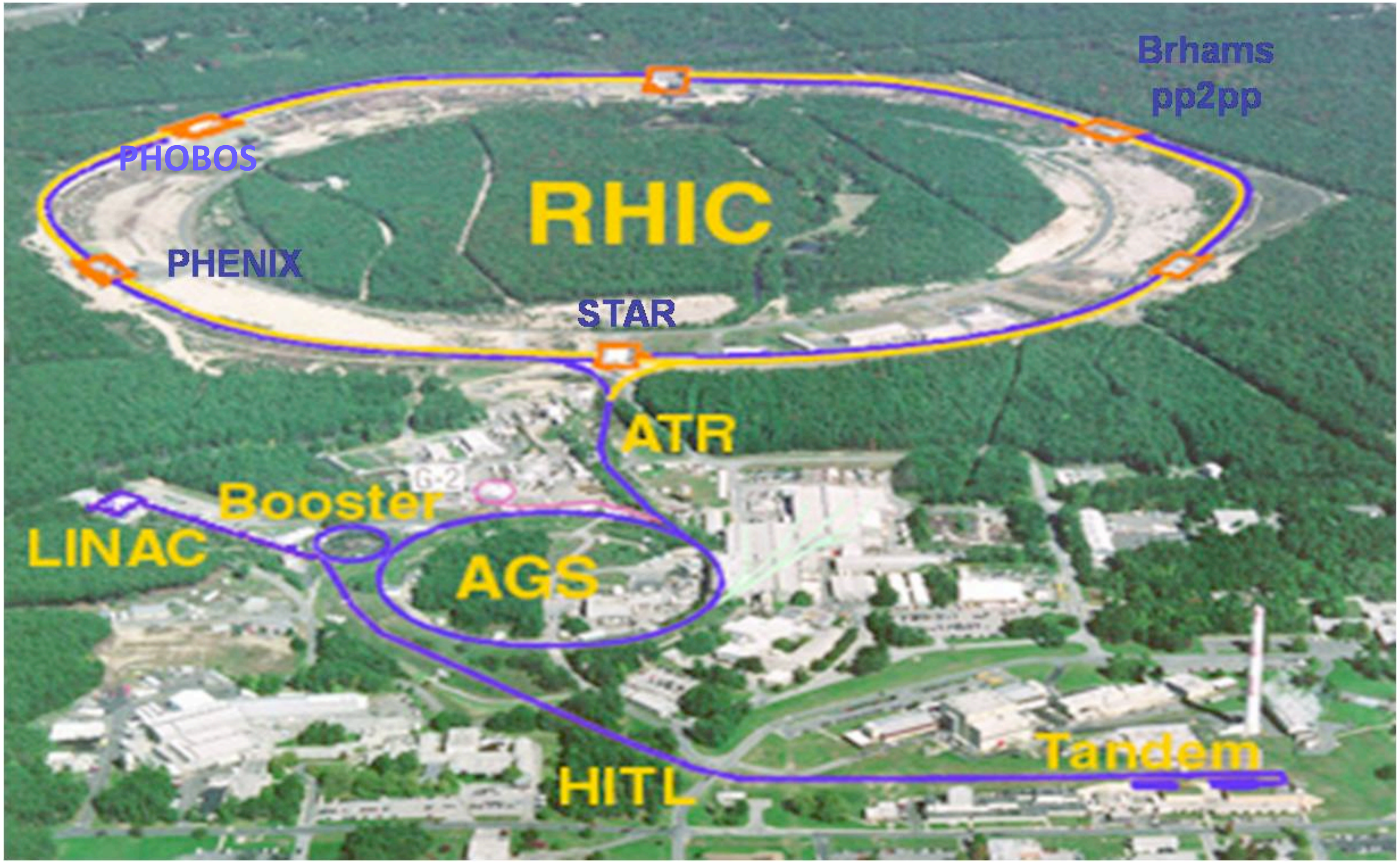
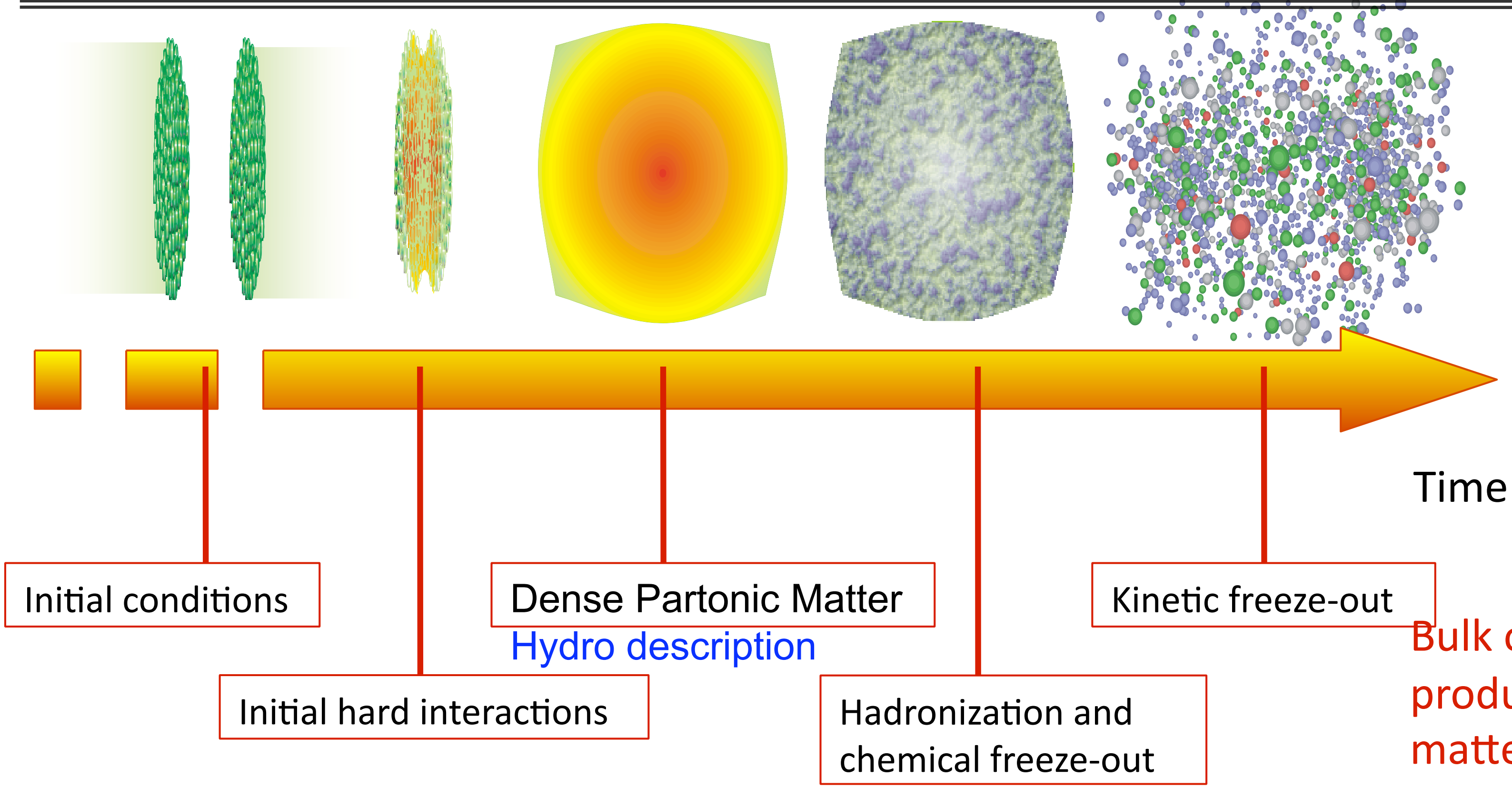
Relativistic Heavy Ion Collider



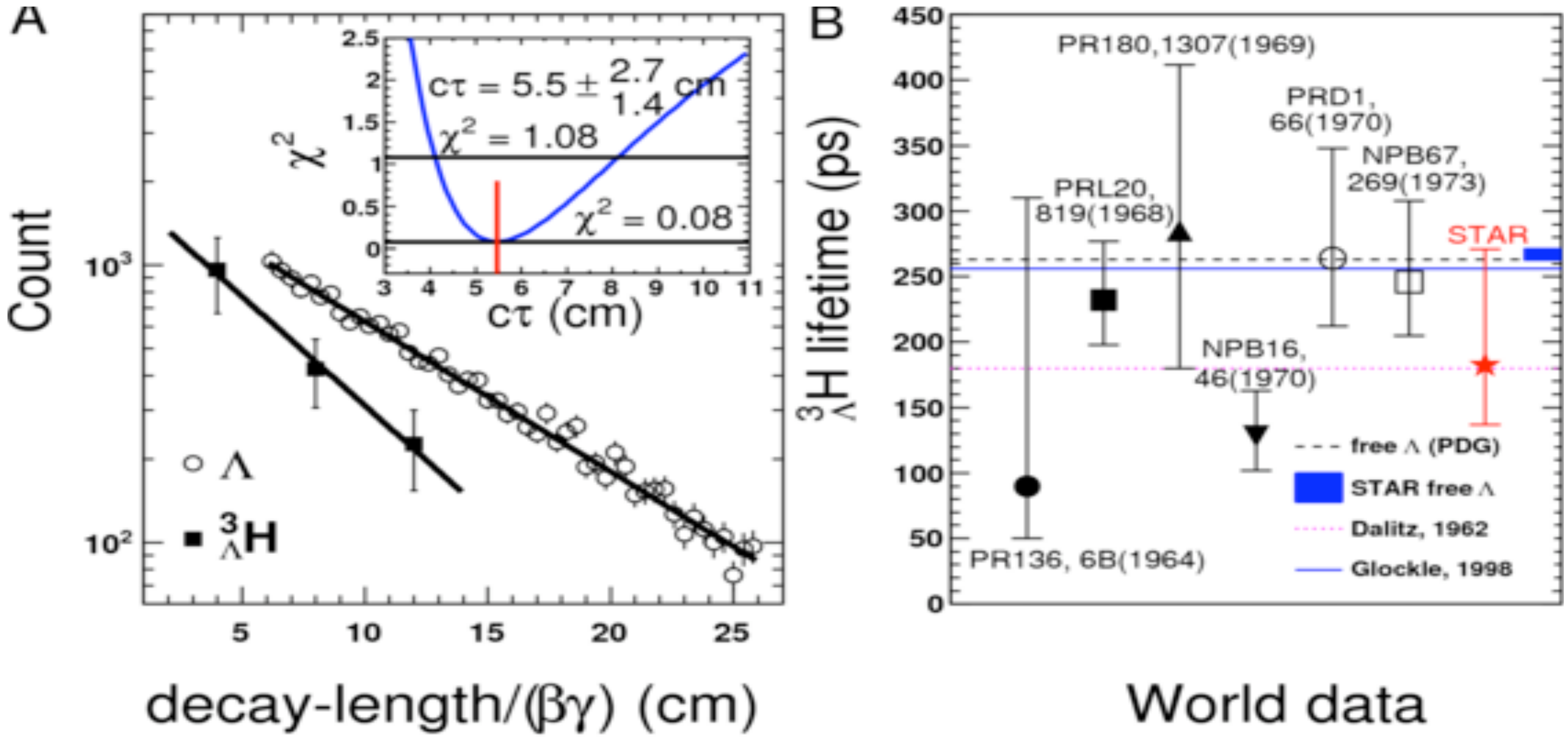
EVOLUTION OF A HEAVY ION COLLISION AT RHIC



Bulk of this produced matter is soft

- Anisotropic flow : early expansion stage (v, v, Knudsen fitting to the identified particles)
- Particle Spectra : Properties at Chemical & Kinetic Freeze-out
- Multiplicity, Rapidity density of various species in various phase space regions and its variation with centrality, beam energy and system size : Particle Production Mechanism

Lifetime of Anti-Hyper-Triton



Lifetime measurement of
Anti-Hyper-Triton + Hyper-Triton
τ = ± $^{+18}_{-45}$ pico sec
Consistent with other measurements of Hyper-Triton lifetime

$$N(t) = N(0)e^{-t/\tau}$$

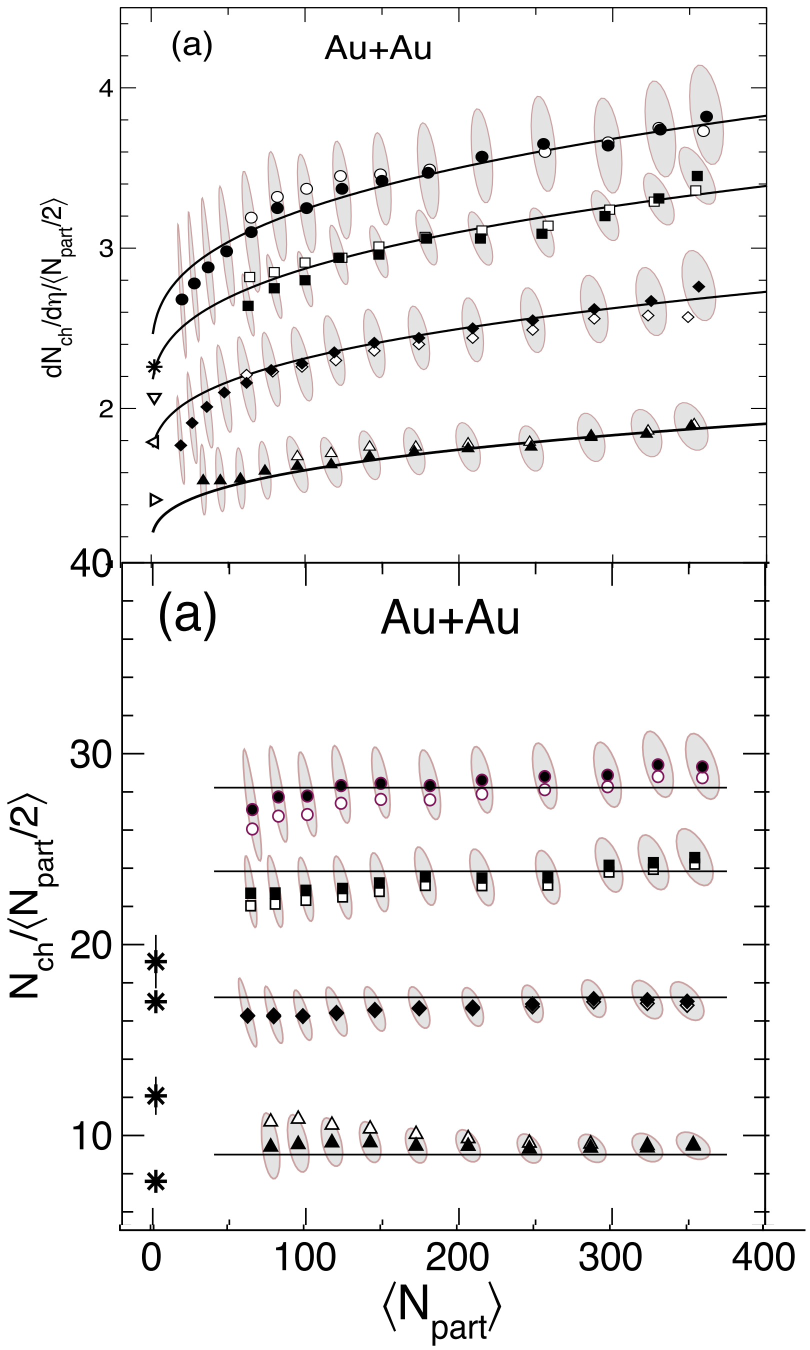
$$t = l/\beta\gamma c$$

Particle production in Different phase space

Ref: PHOBOS Collaboration
PRL () ; PRL ()

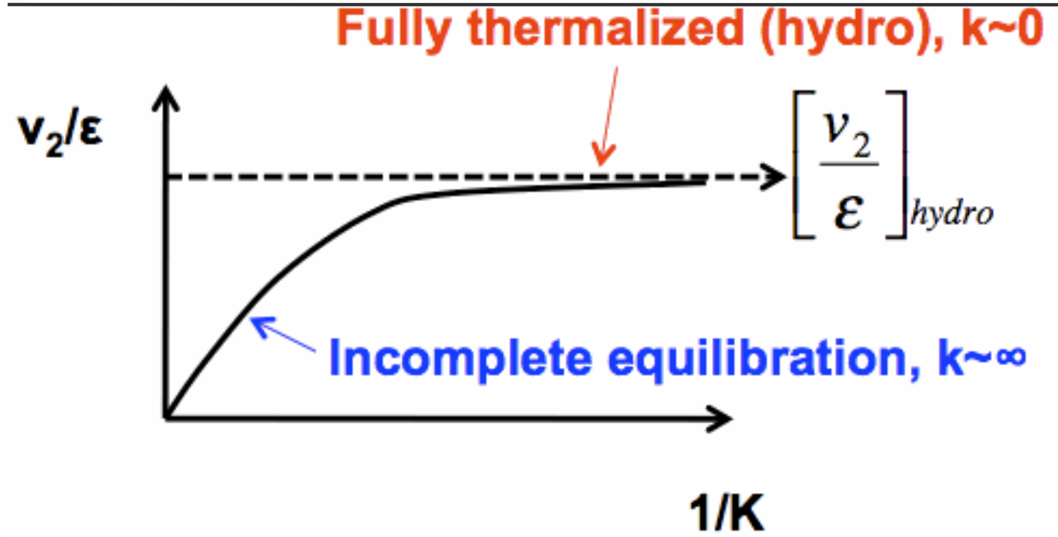
- With increasing energy and increasing event centrality the total particle multiplicity increases: due to increase in the num. of participants / binary collisions and increase in the energy per participant / binary coll.
- Total N_{charge}/N_{part} increases with N_{part}
- $(dN/dy)/N_{part}$ increases with N_{part} at midrapidity; constant at forward η.
- N_{part} scaling is different in different phase space regions ->

  Important to study it in each pseudo-rapidity region



Degree of thermalization: Knudsen No.

Ref: J-Y Ollitrault et. al. , PLB 627 (2005) 49, PRC 76 (2007) 024905



$$\frac{[v_2/\varepsilon]}{[v_2/\varepsilon]_{hydro}} = \frac{1}{1+K/K_0} = \frac{1}{1+\left(\sigma c_s \frac{1}{S}\frac{dN}{dy}\right)^{-1}\frac{1}{K_0}}$$

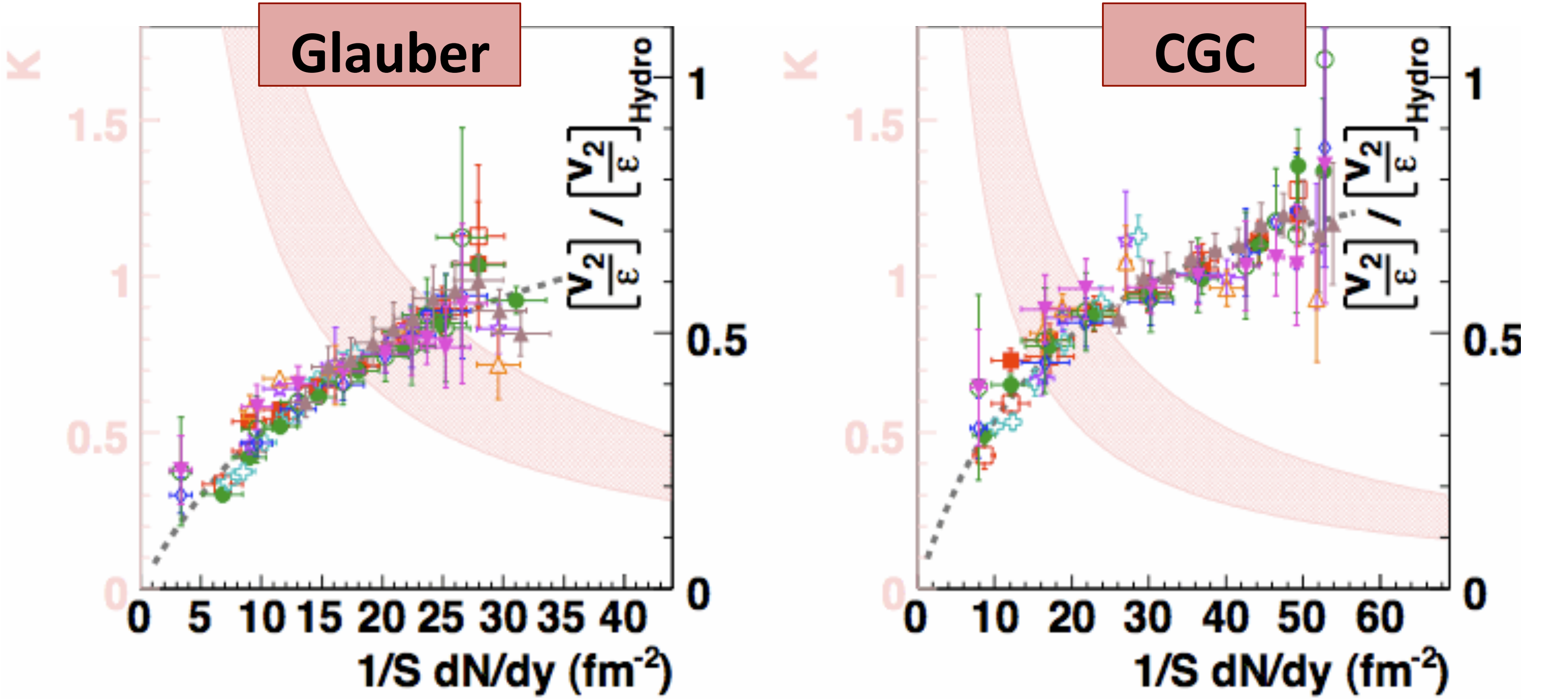
- Transport model ->Hydro for small λ interaction length (Ref: above)
- K ~ λ/R is ratio of mean free path and system size
- Hydrodynamic limit can only be approached asymptotically (K->0)
- In low density limit v_2/ε is proportional to system size and hence to 1/K

K = 0.7 from model calculations and

S = 4π √ (⟨x²⟩ ⟨y²⟩) and ε are calculated using initial conditions: we use Glauber or CGC model initial conditions

Fitting the plot of v_2/ε with 1/S*dN/dy gives σc_s

Obtaining Knudsen Number from Data

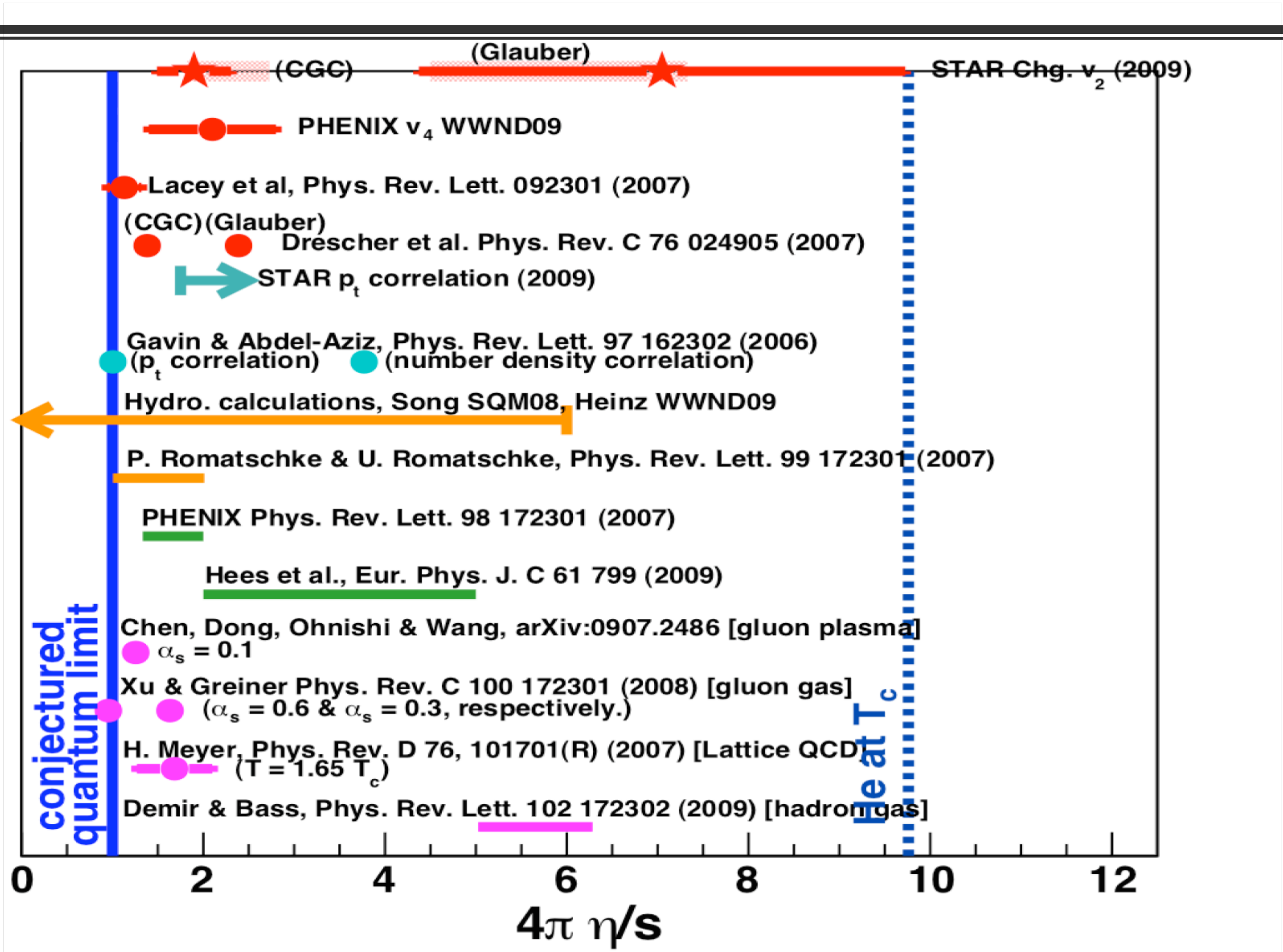


✓All p_T integrated v_2/ε plotted for Glauber and CGC initial conditions: fits nicely to transport model Relation

✓CGC gives steeper curve as compared to Glauber : Estimates the system is Closer to hydro limit!

✓Fit parameters $\sigma^* c_s$ related to η/s under model assumptions

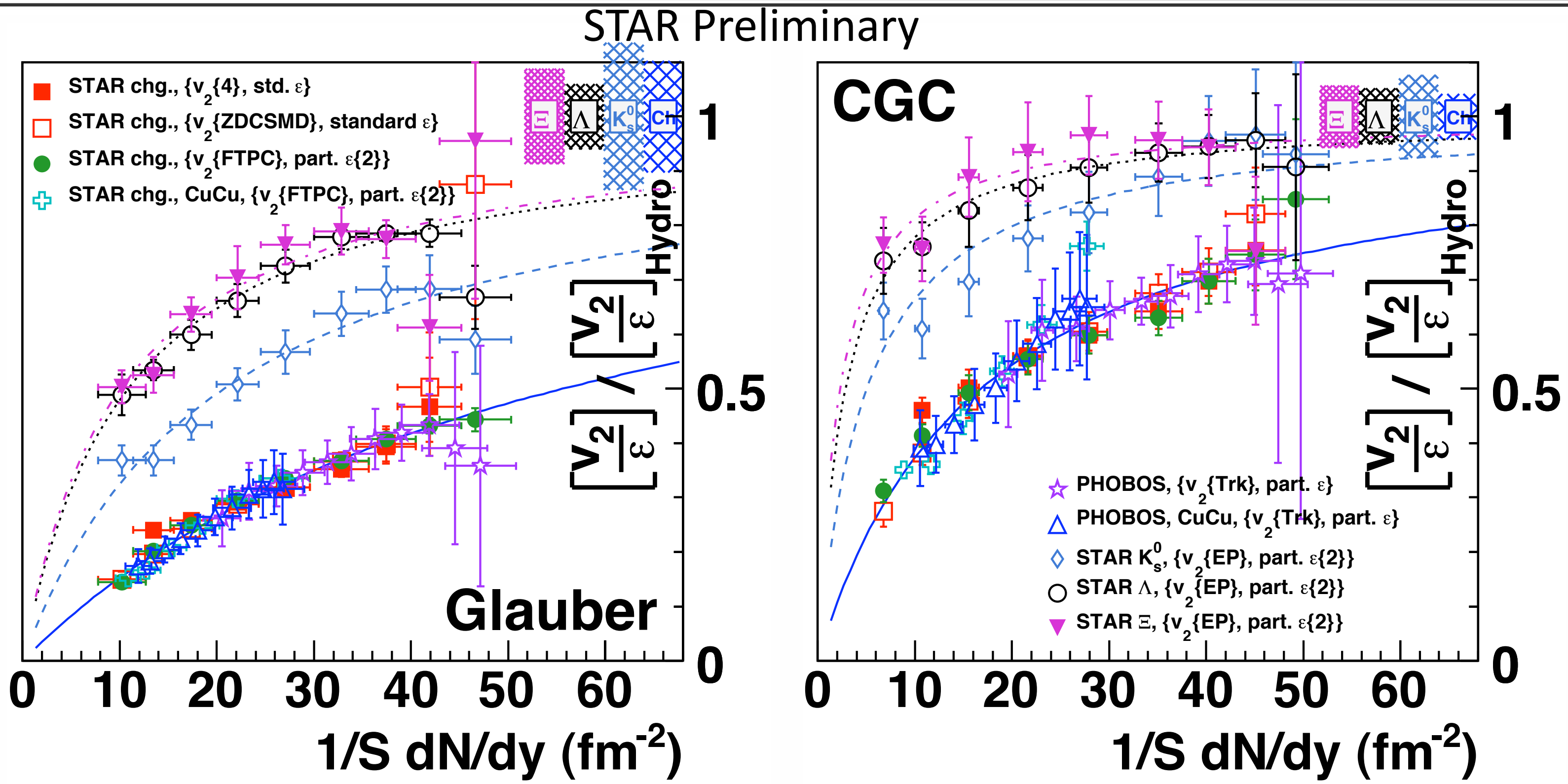
Estimates of η/s (Viscosity/Entropy)



η/s estimated by various Experiments & Models

η/s is small and close to the Conjectured Quantum Limit of 1/4π

Knudsen Fit to Charge Particle v_2/ε



✓p_T integrated v_2/ε plotted for Glauber and CGC initial conditions: fits nicely to transport model Relation

✓CGC gives steeper curve as compared to Glauber : Estimates the system is Closer to hydro limit!

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