Understanding of the QCD phase structure at RHIC

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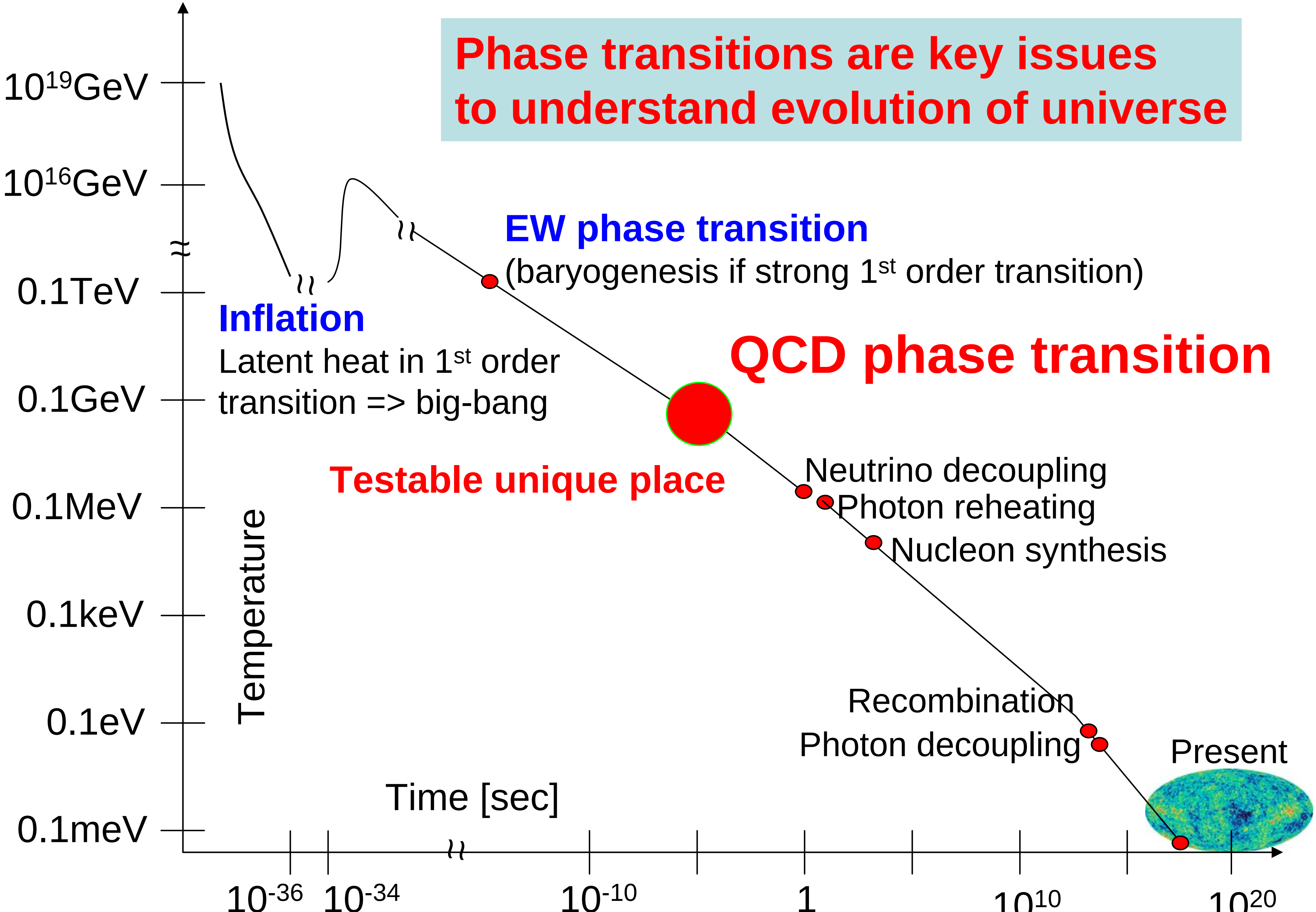
1. Phase transitions and QCD phase diagrams
2. RHIC landmarks
3. Experimental approaches to critical phenomena
4. Plan for RHIC low energy runs (PHENIX)

LINC-2008

18 June, 2008 in IHEP, Protvino, Russian Federation

Phase transitions in the early universe



Understanding of QCD phase structure

RHIC achieved:

- **High temperature & opacity**
- **Strongly coupled matter with quark d.o.f**

T

Conjectured chiral p.t.

Tc

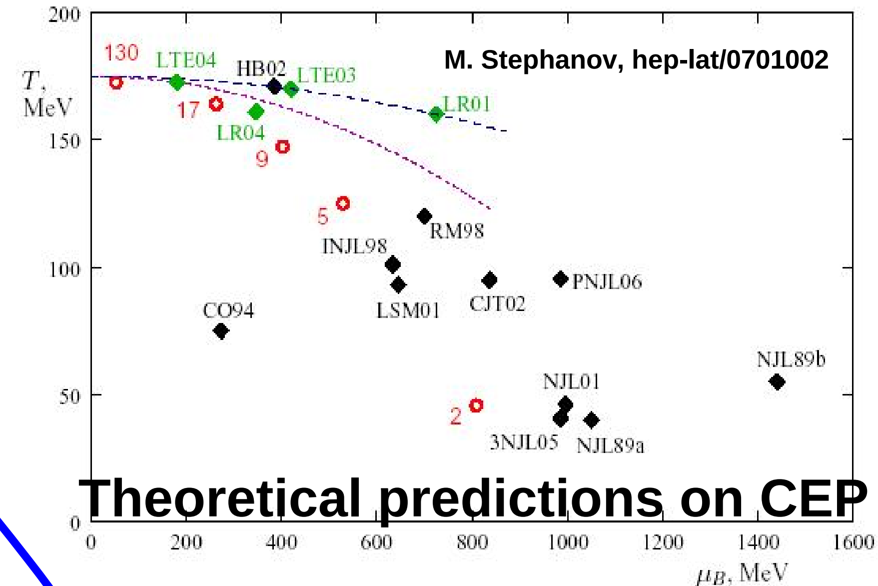
Crossover m_q!=0

CEP ?

Black = model prediction

Green = lattice predictions

Red = freezeout points from data



Theoretical predictions on CEP

Is accessible region by RHIC really crossover?

Relation with deconfinement p.t.?

Crossover for any kinds of order parameters?

1^{st} order ?

μ_B

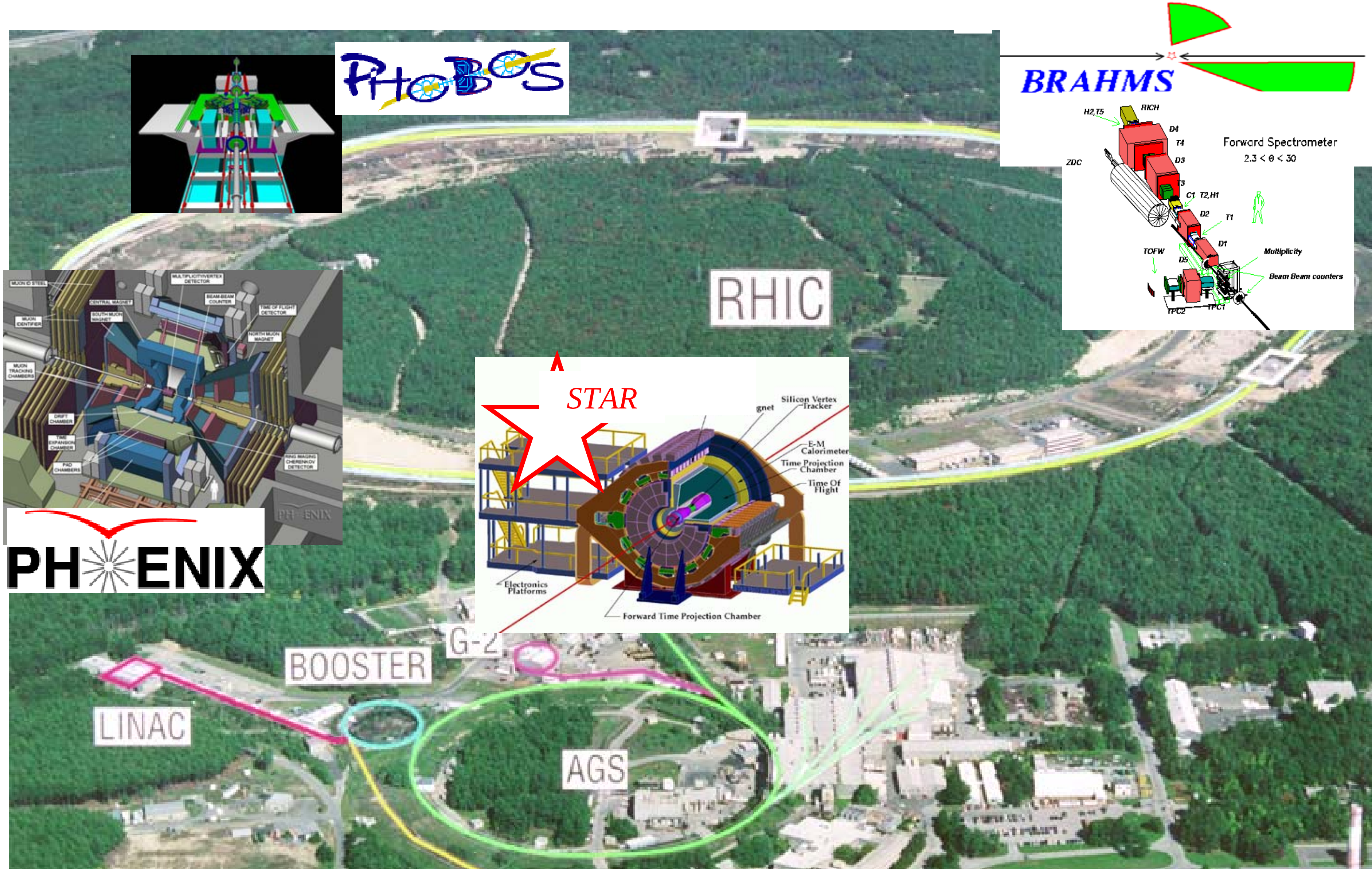
Landmarks at RHIC

RHIC Specifications

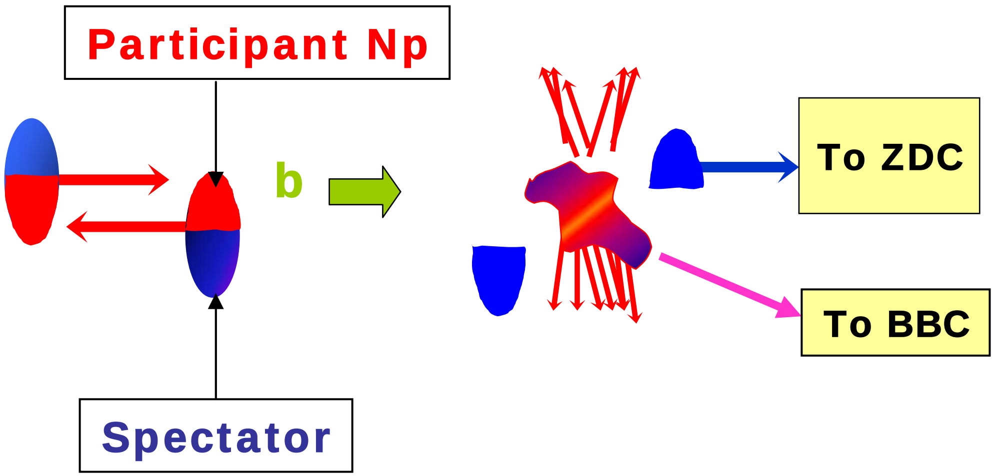
- 3.83 km circumference
- Two *independent* rings
  - 120 bunches/ring
  - 106 ns bunch crossing time
- **Can collide**
  ~any nuclear species
  on
  ~any other species

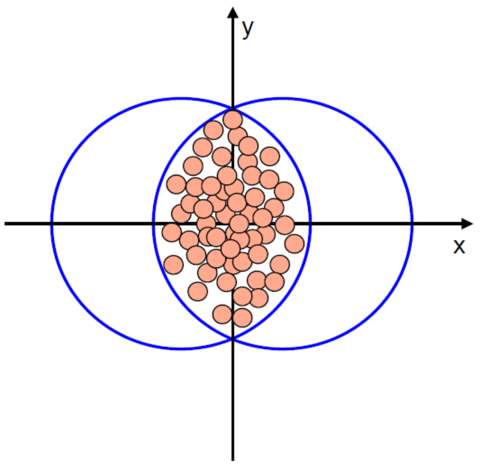
- **Top Energy:** $\sqrt{s_{NN}} \approx \frac{Z}{A}(500\,\mathrm{GeV})$
  - ➔ **500 GeV for p-p**
  - ➔ **200 GeV for Au-Au**
- Luminosity
  - Au-Au: 2 x 10^{26} cm^{-2} s^{-1}
  - p-p : 2 x 10^{32} cm^{-2} s^{-1} (*polarized*)

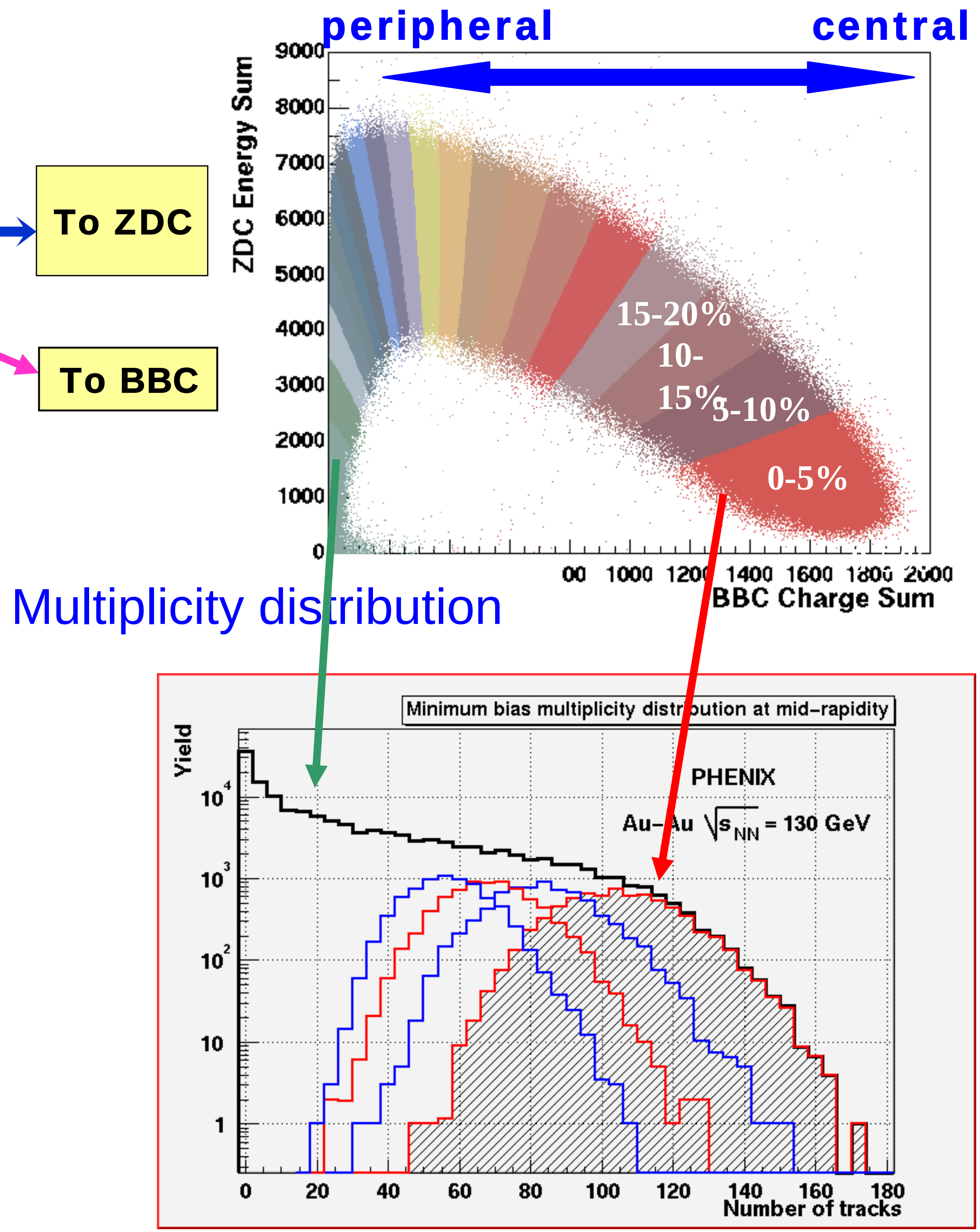
RHIC's Experiments



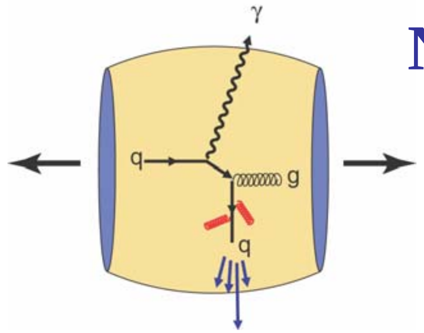
Number of participants, Np and Centrality







Is medium dense enough?

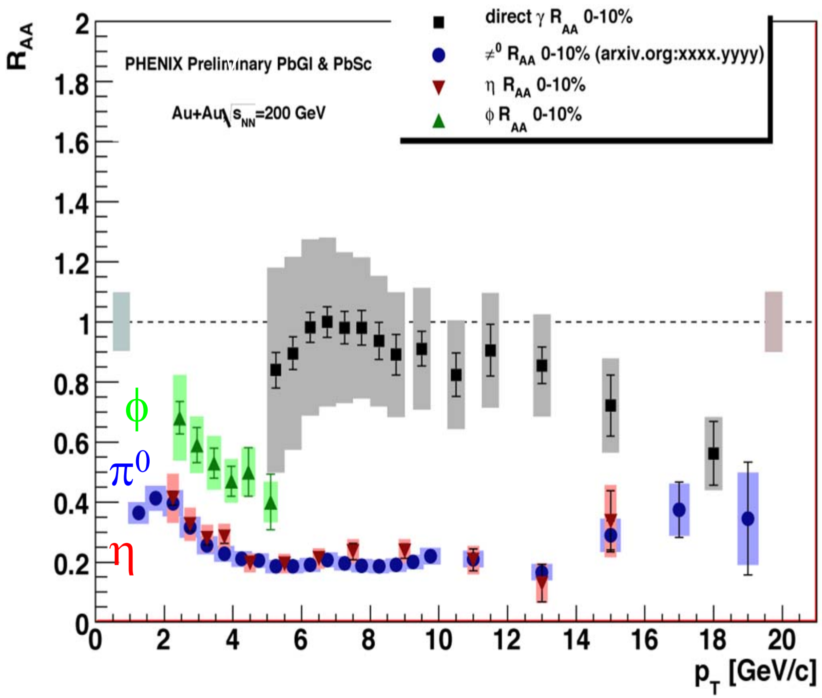


Nuclear Modification Factor

$$R_{AA} \equiv \frac{d^2N^{AA}/dydp_T}{d^2N^{pp}/dydp_T \cdot \langle N_{coll}^{AA} \rangle}$$

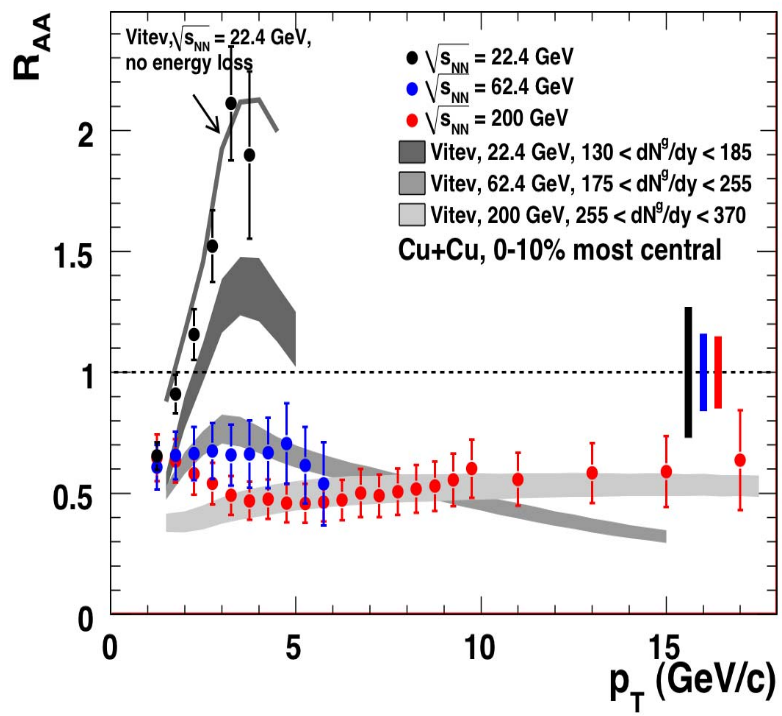
Particle Species

π^0 Au+Au 200 GeV (Run 4)



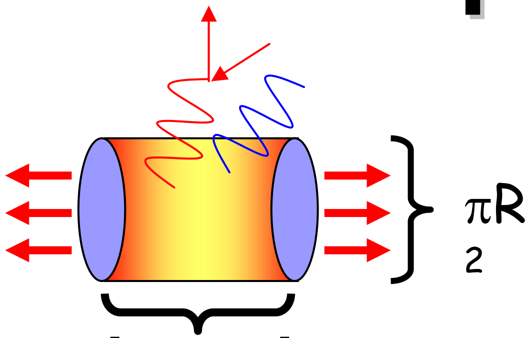
Energy

π^0 Cu+Cu 22,62,200 GeV (Run 5)



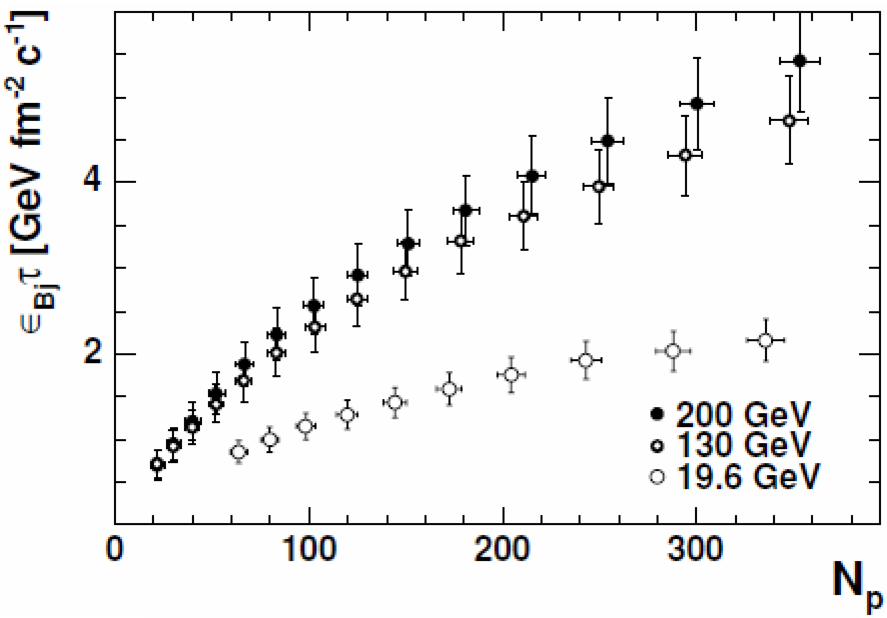
arXiv:0801.4555

Is initial temperature high enough?



$$dz = \tau_0 dy$$

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

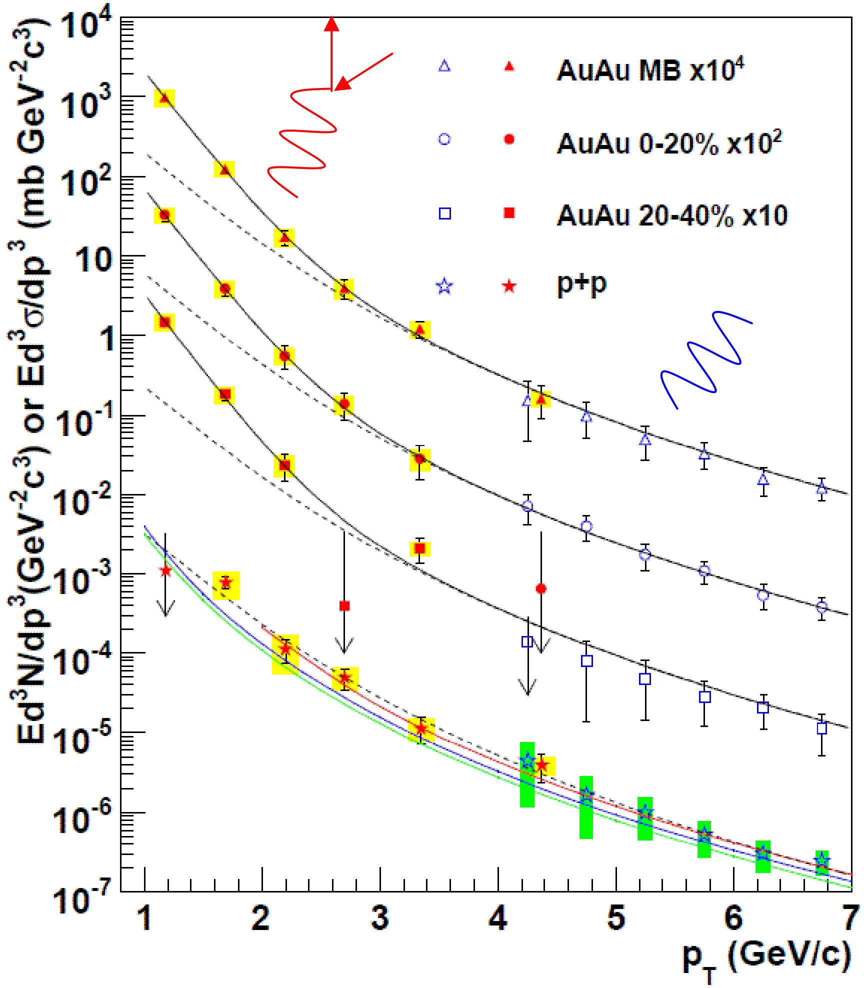


PHYSICAL REVIEW C 71, 034908 (2005)

In central Au+Au collision

T=221±23(stat)±18(sys

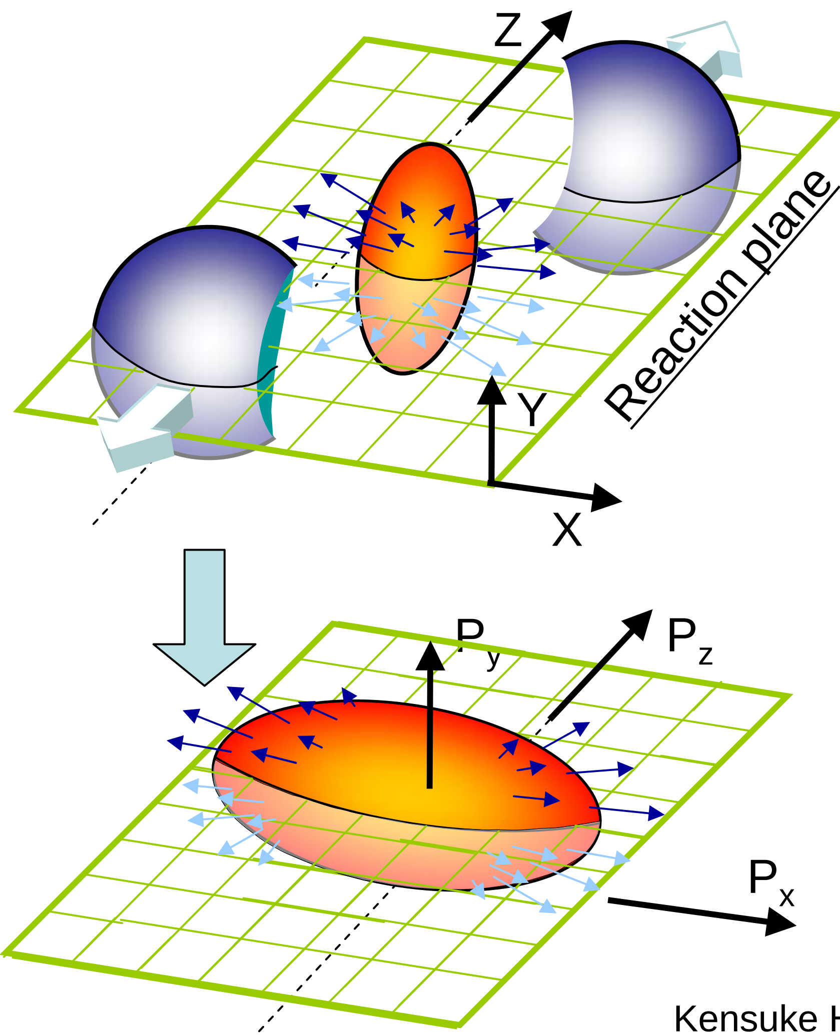
Lattice result T_c~170MeV



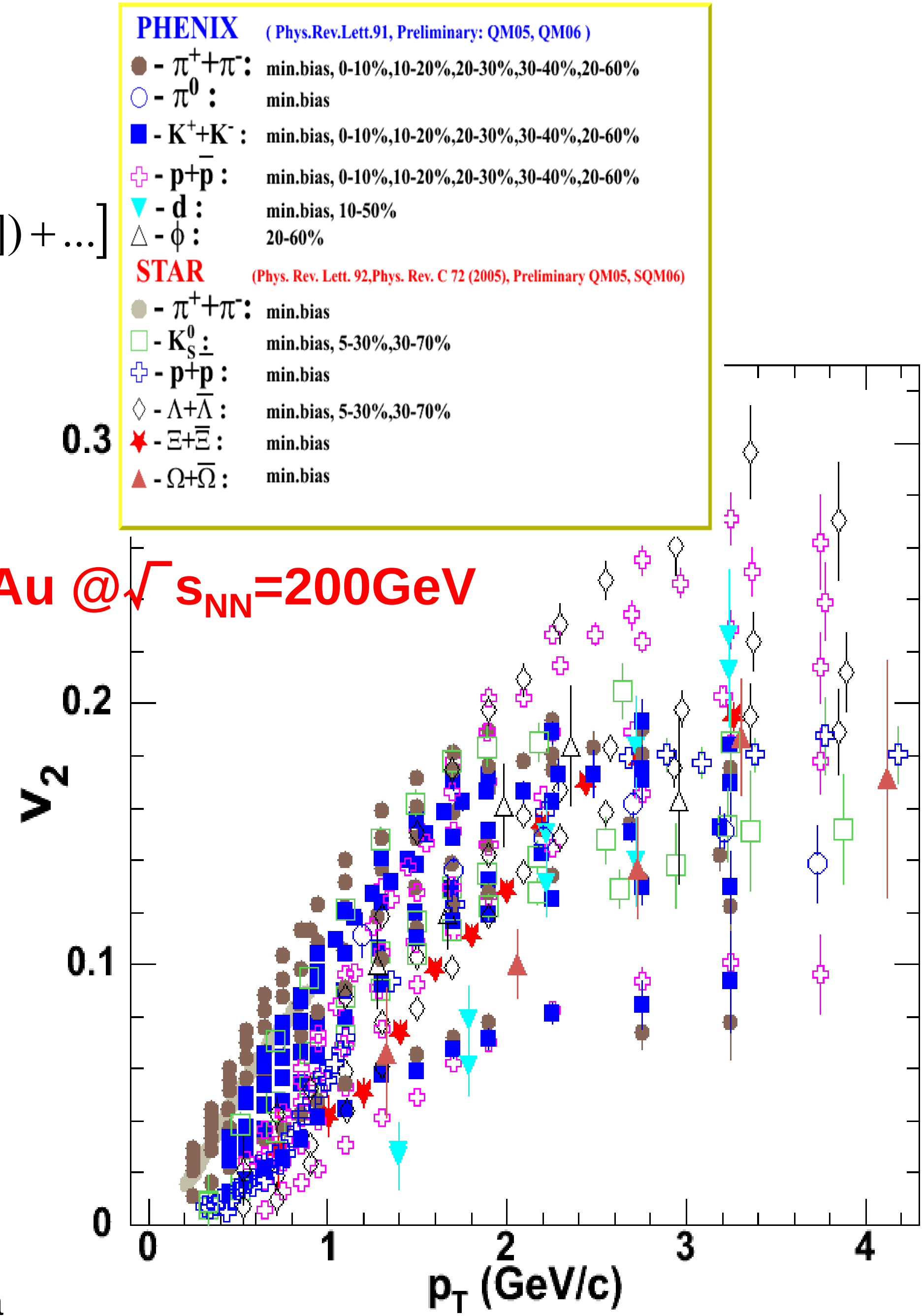
arXiv:0804.4168v1 [nucl-ex] 25 Apr 2008

Is bulk collective motion seen?

$$E\frac{d^3N}{d^3p}=$$
$$\frac{1}{\pi}d^2\frac{N}{dp_T^2dy}\left[1+2v_1\cos(\varphi-\Psi_R)+2v_2\cos(2[\varphi-\Psi_R])+\ldots\right]$$



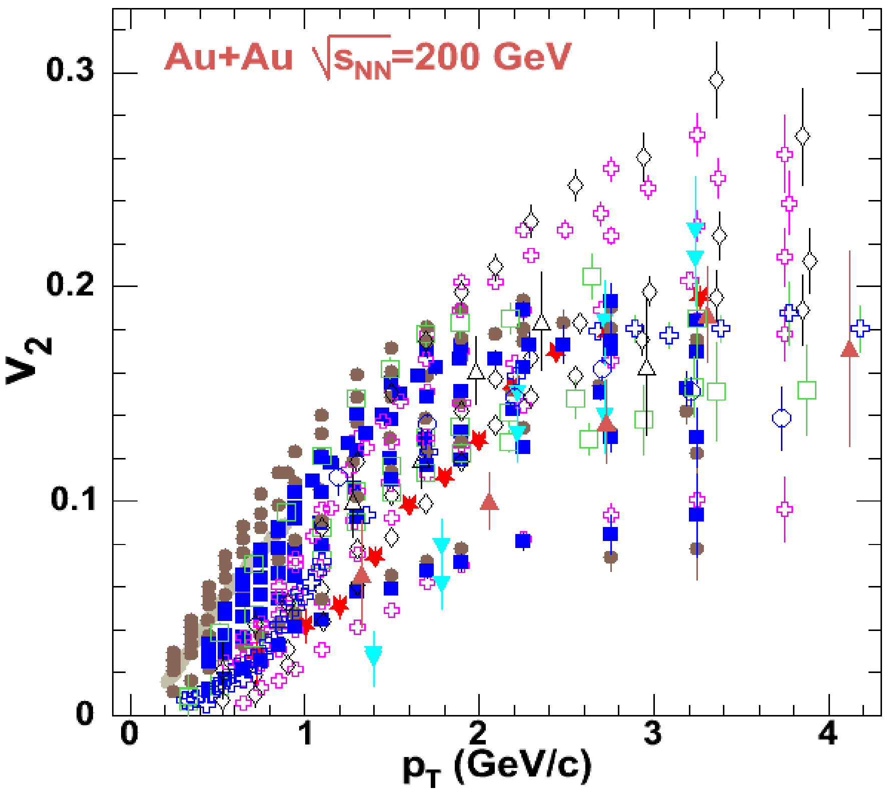
Au+Au @$\sqrt{s_{NN}}$=200GeV

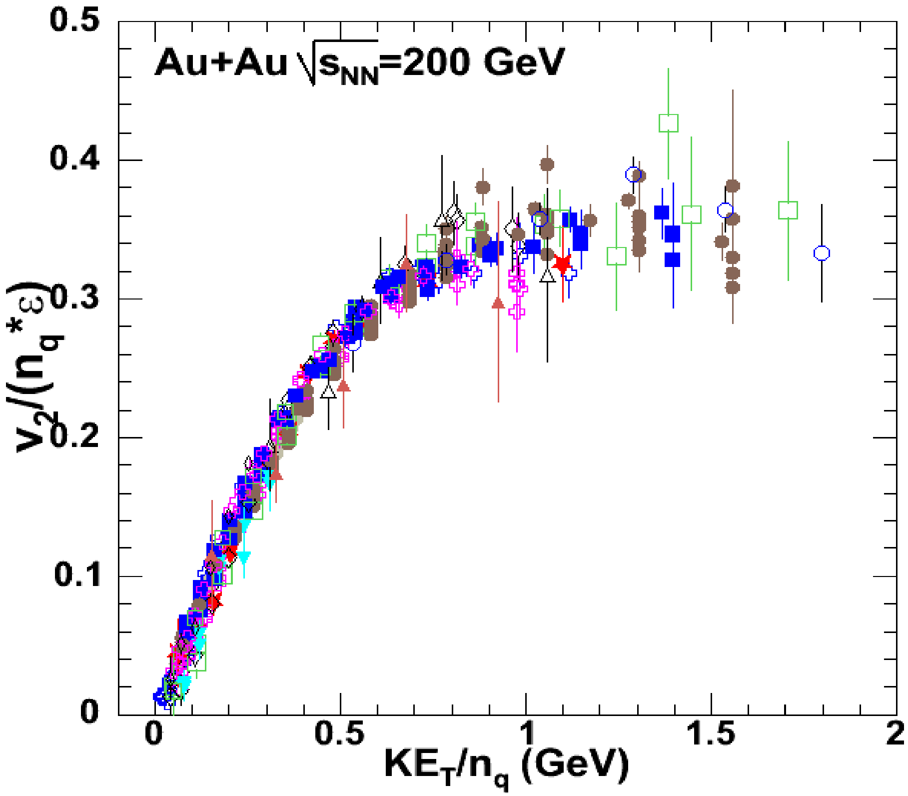


Kensuke Homma

Any partonic degree of freedom?

Constituent quark number, n_q scaling





$KE_T=m(\gamma_T-1)=m_T-m$

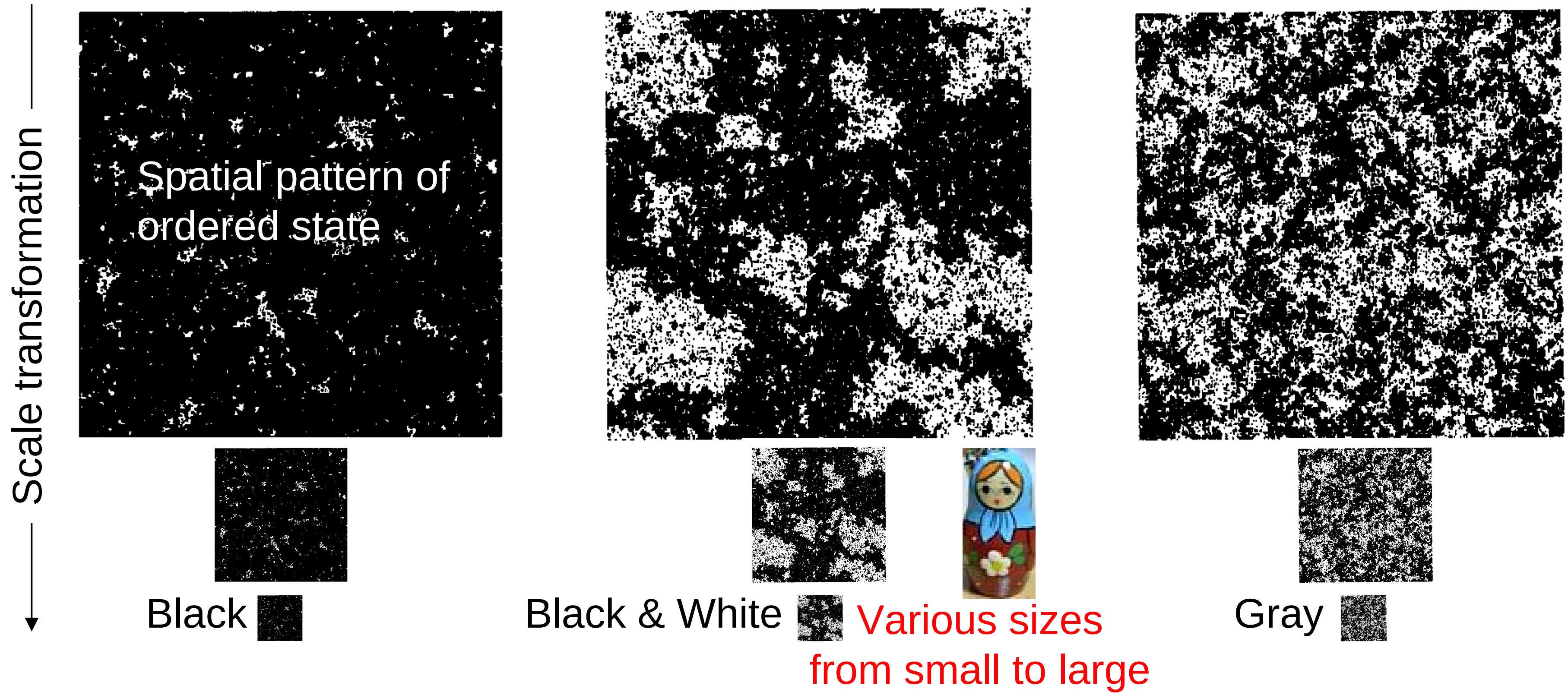
Experimental approaches to critical phenomena

- **<qq-bar>:**
- **J/ψ suppression (deconfinment)**
- **low mass vector mesons and dilepton continum (chiral)**

- **Bulk collective observables:**
- **Density-density correlation in longitudinal space (critical temperature for any order)**
- **Isothermal compressibility (2nd order)**
- **Heat capacity (2nd order)**
- **Sound velocity via eccentricity scaling of v2 (1st order)**
- **Viscosity to entropy ratio with v2 and R_{AA} (CEP?)**

What is the critical behavior ?

Ordered $T=0.995T_c$ | Critical $T=T_c$ | Disordered $T=1.05T_c$



- Large fluctuations of correlation sizes on order parameters:
  - **critical temperature (focus of this talk)**
- Universality (power law behavior) around Tc reflecting basic symmetries and dimensions of the underlying system:
  - **critical exponent (future study after finding Tc)**

A simulation based on two dimensional Ising model from ISBN4-563-02435-X C3342l

Density-density correlation in longitudinal space

Longitudinal space coordinate z can be transformed into rapidity coordinate in each proper frame of sub element characterized by a formation time τ where dominant density fluctuations are embedded.

$$z = \tau \sinh(y)$$

$$t = \tau \cosh(y)$$

$$dz = \tau \cosh(y) dy$$

Due to relatively rapid expansion in y, analysis in y would have an advantage to extract initial fluctuations compared to analysis in transverse plane in high energy collision.

$$g(T,\phi,h) - g_0 = \int_{\delta y} dy \cancel{\int_{S\perp} d^2 x_\perp}$$

$$\left[\frac{1}{2\tau^2 \cosh(y)} \left(\frac{\partial \phi}{\partial y} \right)^2 + \cosh(y) \left(\cancel{\frac{1}{2} (\nabla_\perp \phi)^2} + U(\phi) \right) \right]$$

In narrow midrapidity region like PHENIX, cosh(y)~1 and y~η.

Longitudinal multiplicity density fluctuation from the mean density can be an order parameter:

$$\phi(\eta) = \rho(\eta) - \langle \rho \rangle$$

Direct observable for Tc determination

GL free energy density *g* with ϕ ~ 0 from high temperature side is insensitive to transition order, but it can be sensitive to Tc

$$g(T,\phi,h) = g_0 - \underbrace{\frac{1}{2}A(T)(\nabla\phi)^2}_{\text{spatial correlation}} + \underbrace{\frac{1}{2}a(T)\phi^2}_{\phi\text{ disappears at Tc}} + \cancel{\frac{1}{4}b\phi^4 + \frac{1}{6}c\phi^6} \cdots - h\phi$$

spatial correlation

ϕ disappears at Tc → $a(T) = a_0(T - T_c)$

Fourier analysis on

$G_2(y) = \langle\phi(0)\phi(y)\rangle$

$$\left\langle |\phi_k|^2 \right\rangle = Y\int G_2(y)e^{-ik(y)}dy$$

$$\left\langle |\phi_k|^2 \right\rangle = \frac{NT}{Y}\frac{1}{a(T)+A(T)k^2}$$

1-D two point correlation function

$$G_2(y) = \frac{NT}{2Y^2A(T)}\xi(T)e^{-|y|/\xi(T)}$$

Correlation length

$$\xi(T)^2 \equiv \frac{A(T)}{a_0(T-T_c)}$$

Susceptibility

$$\chi_k = \frac{\partial\phi_k}{\partial h} \propto \left(\frac{\partial^2(g-g_0)}{\partial\phi^2{}_k}\right)^{-1} = \frac{1}{a_0(T-T_c)(1+k^2\xi^2)}$$

Susceptibility in long wavelength limit

$$\chi_{k=0} = \frac{1}{a_0(T-T_c)} \propto \frac{\xi}{T}G_2(0)$$

Product between correlation length and amplitude can also be a good indicator for T~Tc

Intuitive observable: blob intensity α x blob size ξ

At RHIC

Order parameter

$\phi(\eta)=\rho(\eta)-<\rho(\eta)>$

ϕ<<1 in T>>Tc,

Ginzburg-Landau(GL) free energy up to 2nd order term

Two point correlation $<\phi(\eta_1)\phi(\eta_2)>$ in 1-D longitudinal space

$$C_2 \propto \alpha \exp(-|\eta_1-\eta_2|/\xi)$$

$$\alpha\xi \propto \chi_{k=0} T <\rho>^{-2} \propto <\rho>^{-2} \frac{1}{1-T_c/T}$$

T=Tc

Many length scales appear (a typical ϕ_k disappears)

Non monotonic increase of $\alpha\xi$ indicates T~Tc w.r.t. monotonically decreasing baseline as mean density $<\rho>$ increases.

T<Tc

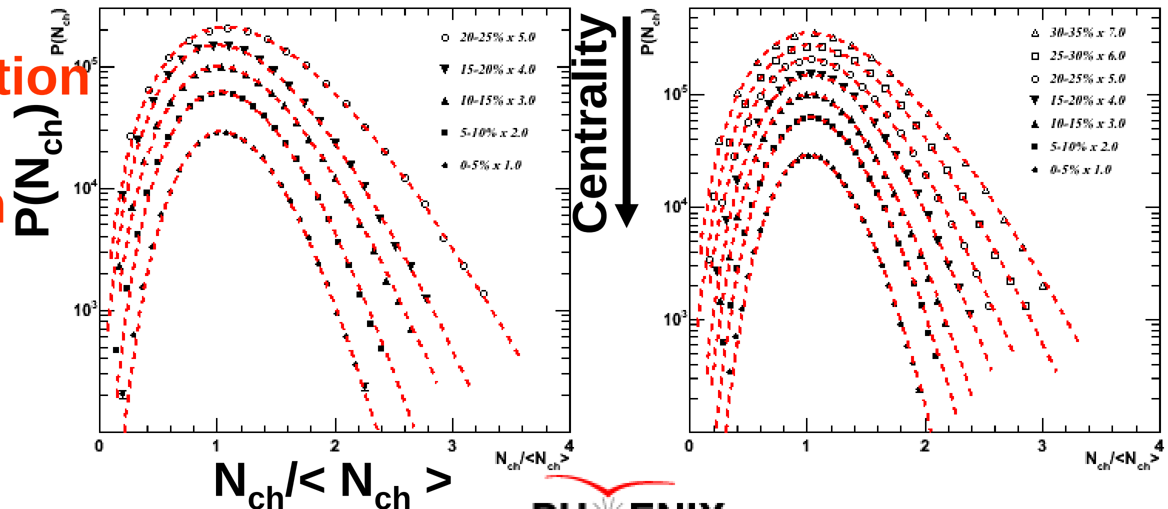
GL with higher order terms

Density measurement: inclusive $dN_{ch}/d\eta$

Negative Binomial Distribution (NBD) perfectly describes multiplicities in all collision systems and centralities at RHIC.

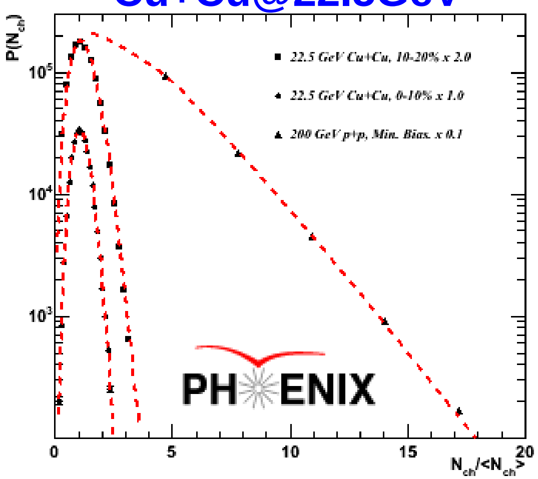
Cu+Cu@62.4GeV

Cu+Cu@200GeV

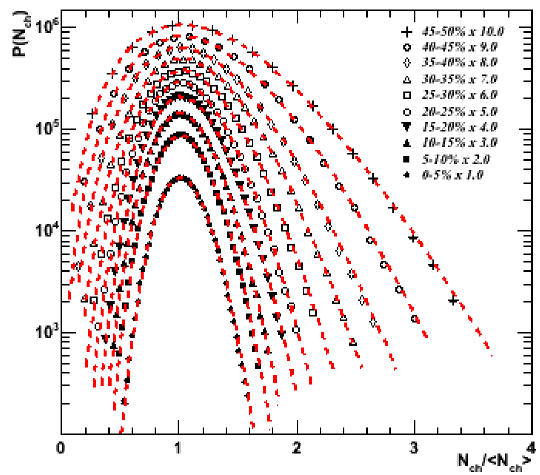


p+p@200GeV

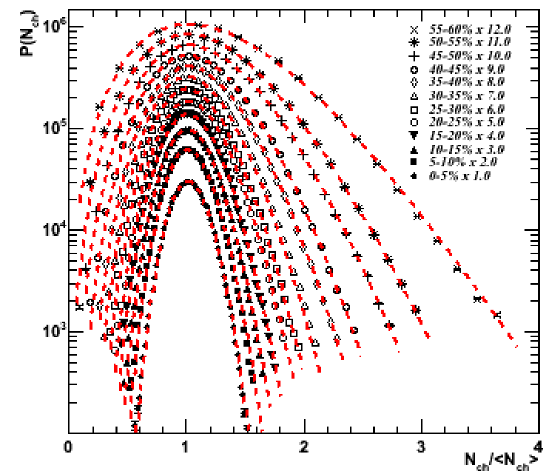
Cu+Cu@22.5GeV



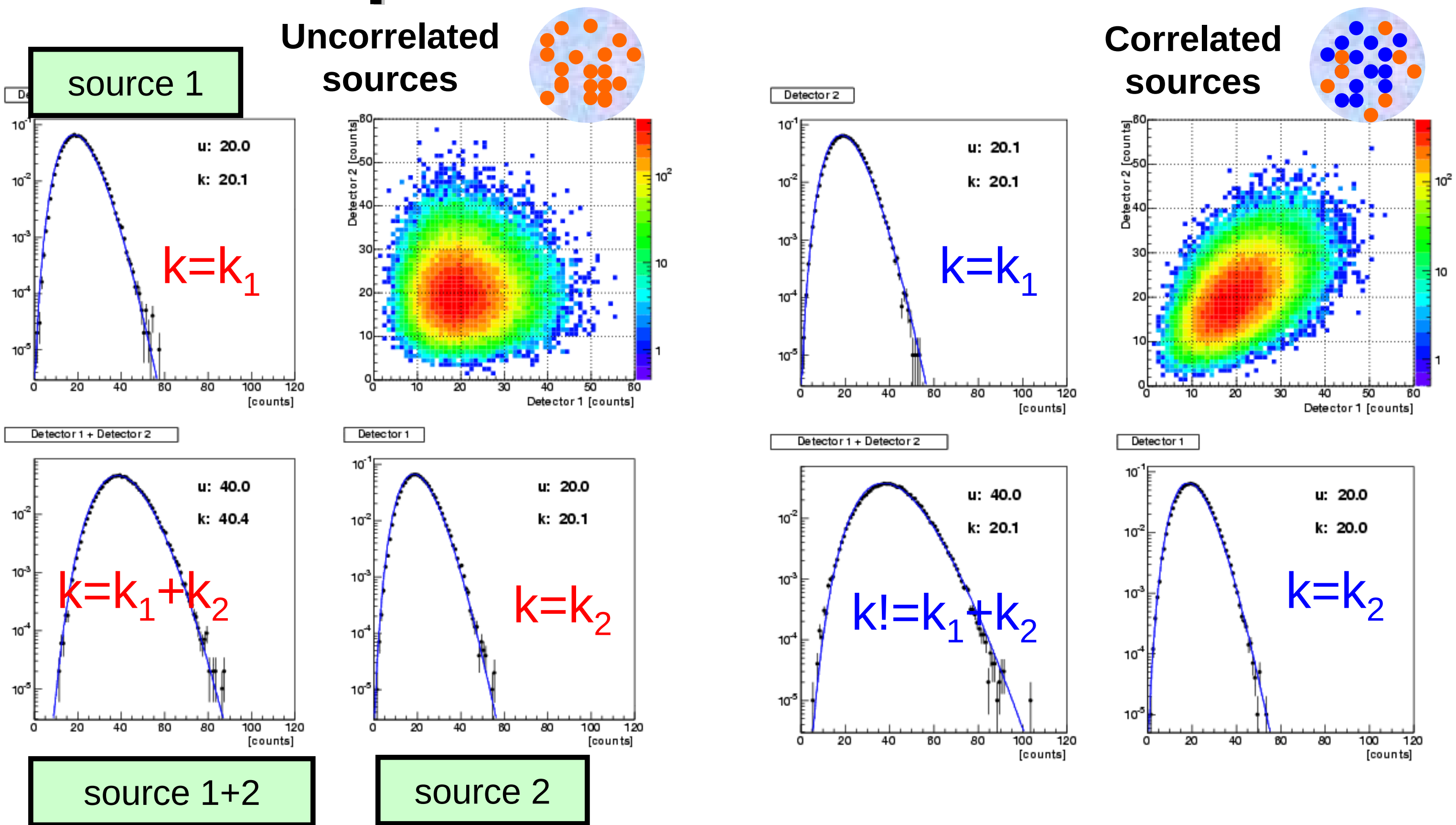
Au+Au@62.4GeV



Au+Au@200GeV



Two point correlation via NBD



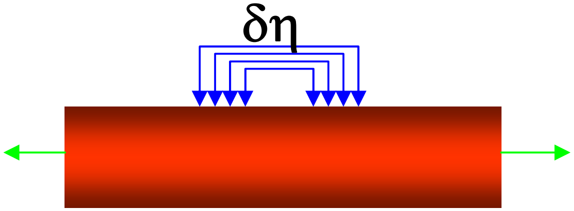
NBD $$P_n^{(k)} = \frac{\Gamma(n+k)}{\Gamma(n-1)\Gamma(k)}\left(\frac{\mu/k}{1+\mu/k}\right)^n \frac{1}{(1+\mu/k)^k}$$

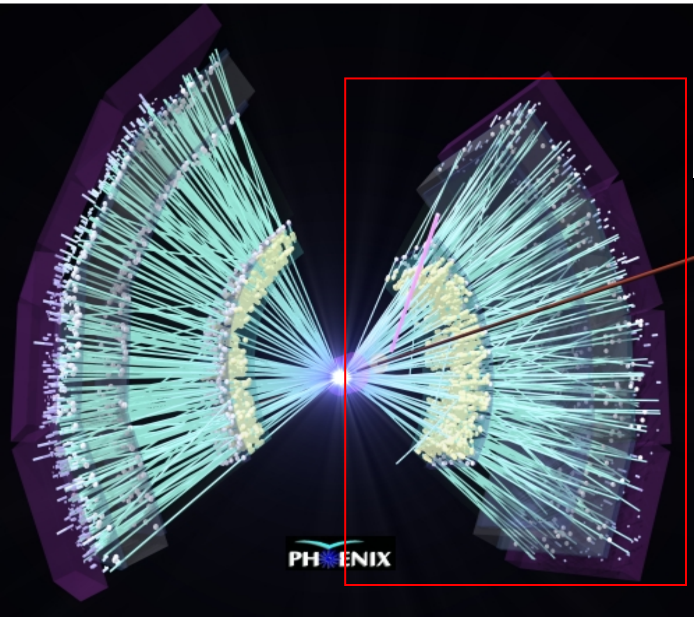
k=1 Bose-Einstein
k=∞ Poisson

$$\frac{\sigma^2}{\mu^2} = \frac{1}{\mu} + \boxed{\frac{1}{k}} \qquad \mu \equiv < n >$$

1/k corresponds to integral of two point correlation

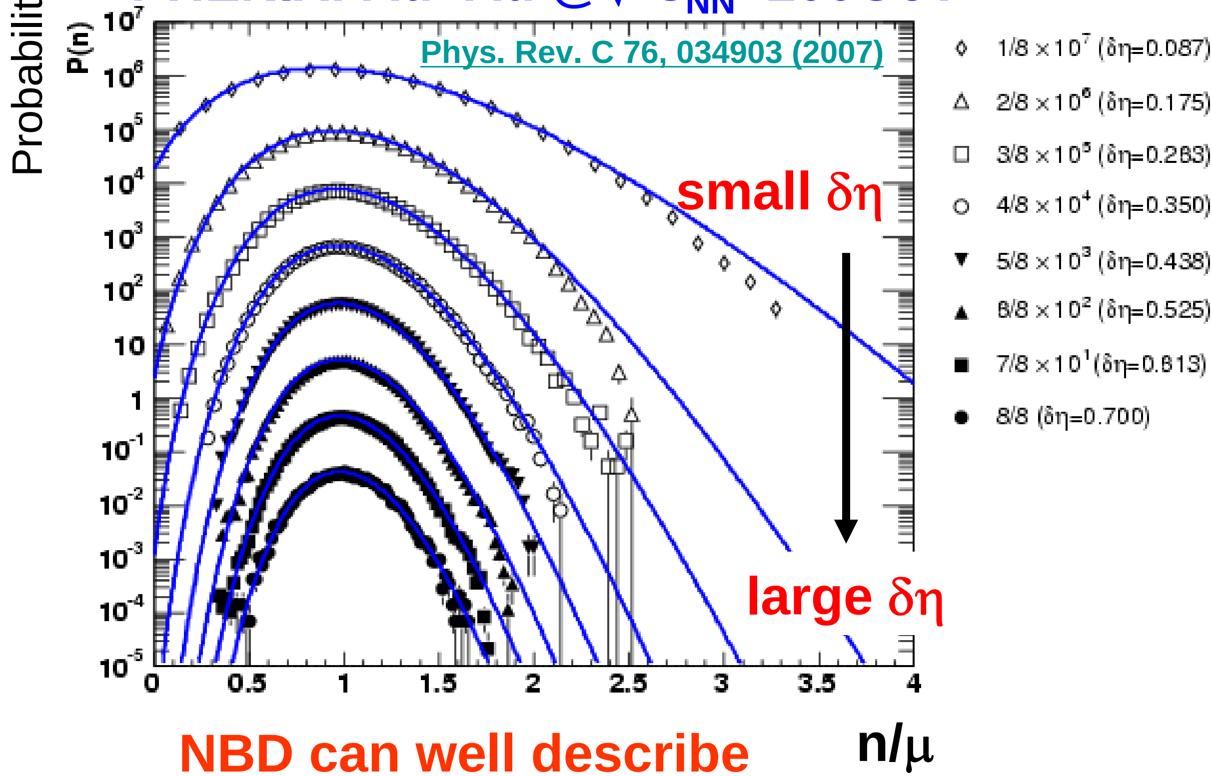
Differential multiplicity measurements





$\Delta\eta<0.7$ integrated over $\Delta\phi<\pi/2$

PHENIX: Au+Au @$\sqrt{s_{NN}}$=200GeV

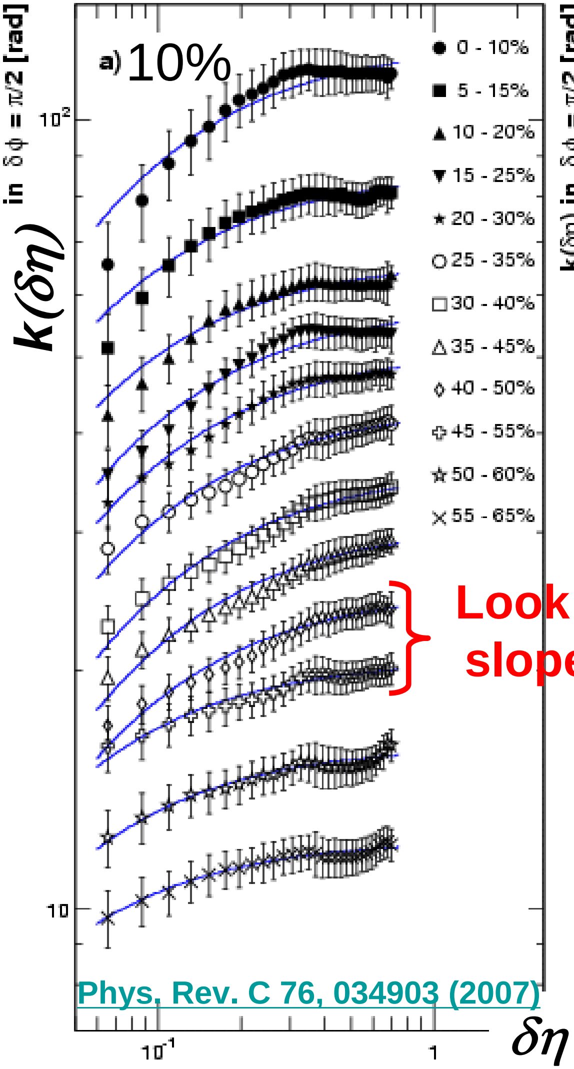


Zero magnetic field to enhance low pt statistics per collision event.

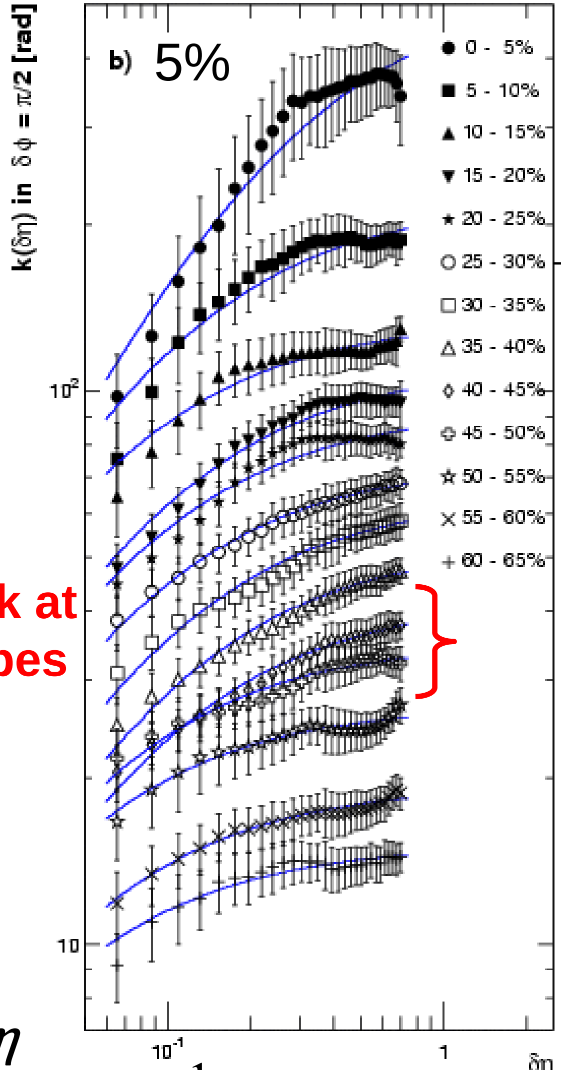
NBD can well describe differential distribution too.

Extraction of αξ product

Fit with approximated functional form



Look at slopes



Parametrization of two particle correlation

$$C_2(\eta_1,\eta_2) \equiv \rho_2(\eta_1,\eta_2) - \rho_1(\eta_1)\rho_1(\eta_2)$$

$$\frac{C_2(\eta_1,\eta_2)}{\bar{\rho}_1^2} = \alpha e^{-\delta\eta/\xi} + \beta$$

β absorbs rapidity independent bias such as centrality bin width

Exact relation with NBD *k*

$$k^{-1}(\delta\eta) = \frac{\langle n(n-1)\rangle}{\langle n\rangle^2} - 1$$

$$= \frac{\int_0^{\delta\eta}\int_0^{\delta\eta} C_2(\eta_1,\eta_2)\,d\eta_1 d\eta_2}{\delta\eta^2\bar{\rho}_1^2}$$

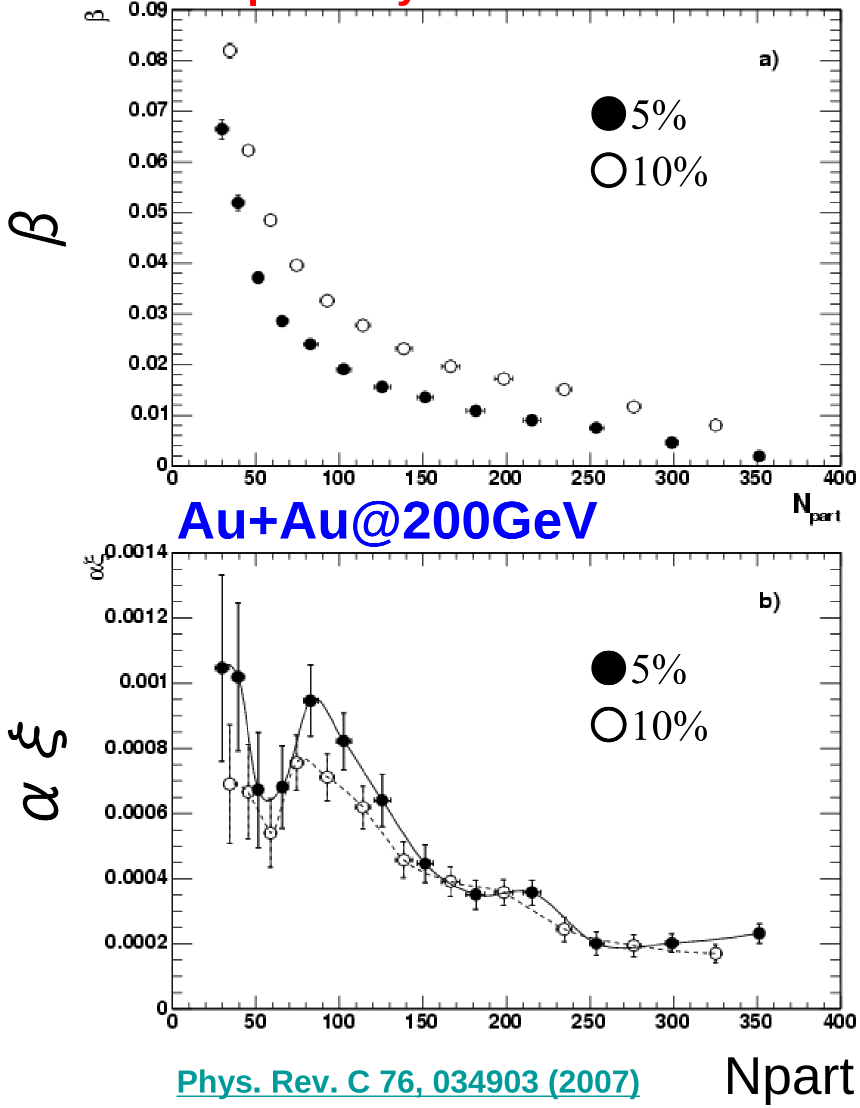
$$= \frac{2\alpha\xi^2(\delta\eta/\xi - 1 + e^{-\delta\eta/\xi})}{\delta\eta^2} + \beta$$

Approximated functional form

$$k(\delta\eta) = \frac{1}{2\alpha\xi/\delta\eta + \beta} \quad (\xi << \delta\eta)$$

$\alpha\ \xi$, β vs. Npart

Dominantly Npart fluctuations
and possibly correlation in azimuth



Phys. Rev. C 76, 034903 (2007)

β is systematically shift to lower values as the centrality bin width becomes smaller from 10% to 5%. This is understood as fluctuations of Npart for given bin widths

$\alpha\ \xi$ product, which is monotonically related with $\chi_{k=0}$ indicates the non-monotonic behavior around Npart ~ 90.

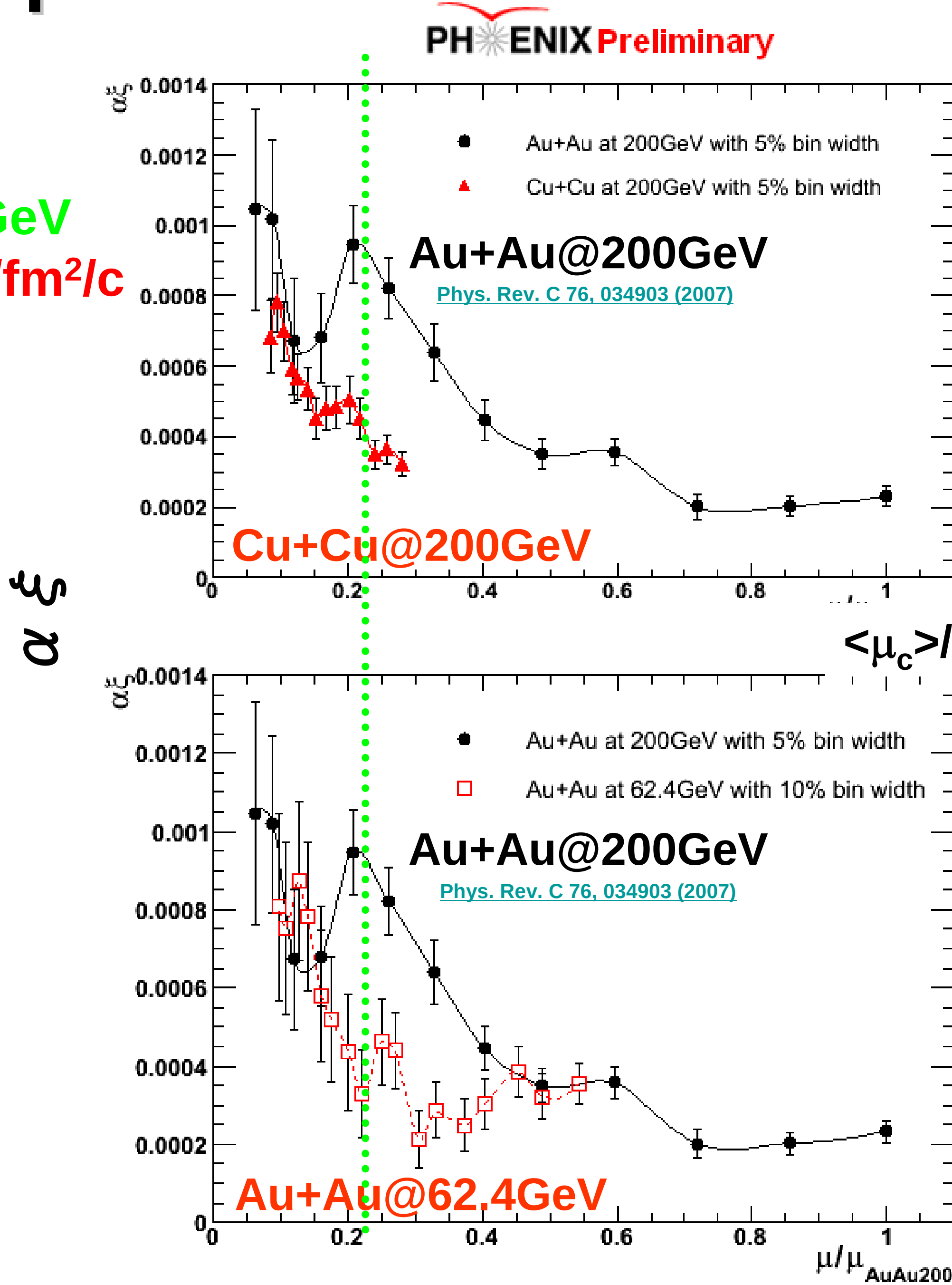
$$\alpha\xi = \chi_{k=0} T / \bar{\rho}_1^{\,2} \propto \bar{\rho}_1^{\,-2} \frac{T}{|T - T_C|}$$

Significance with Power + Gaussian:
3.98 σ (5%), 3.21 σ (10%)
Significance with Line + Gaussian:
1.24 σ (5%), 1.69 σ (10%)

Comparison of three collision systems

Npart~90 in AuAu@200GeV

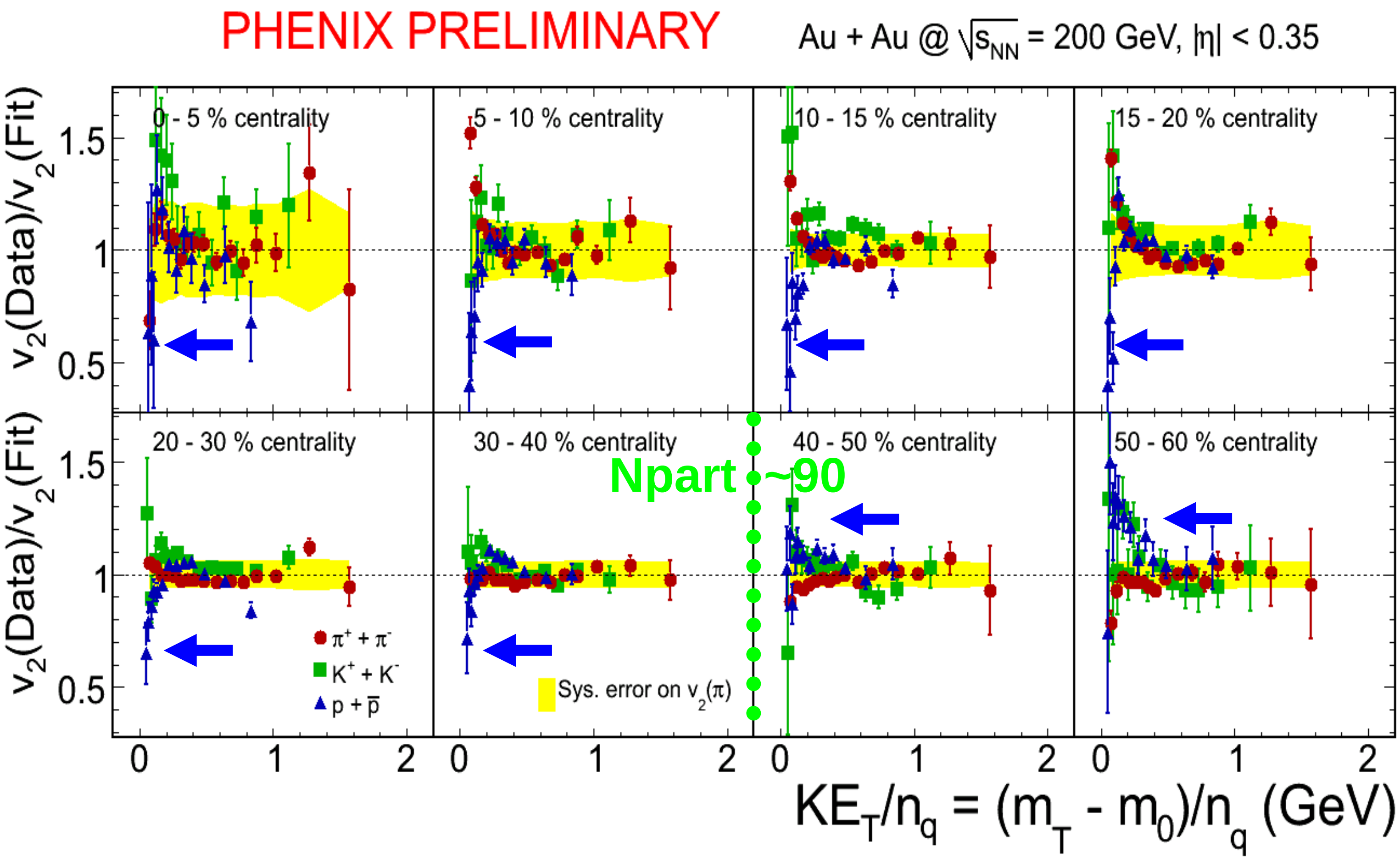
$\varepsilon_{BJ}\tau$~2.4GeV/fm^2/c



Normalized mean multiplicity to that of top 5% in Au+Au@200GeV

Are there symptoms in other observables at around the same Npart?

Deviation from scaling at low KE_T region ?

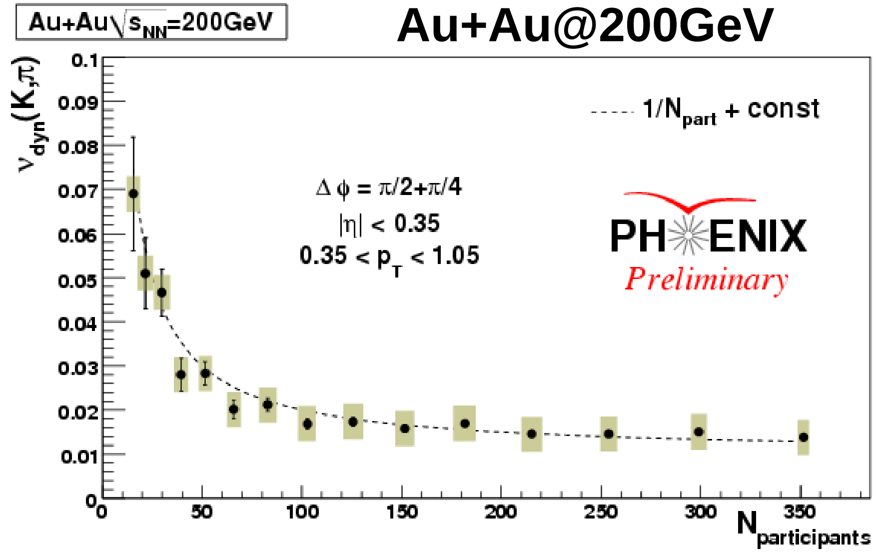


In lower KE_T, there seems to be different behaviors between baryon and mesons. The transition is at Npart~90.

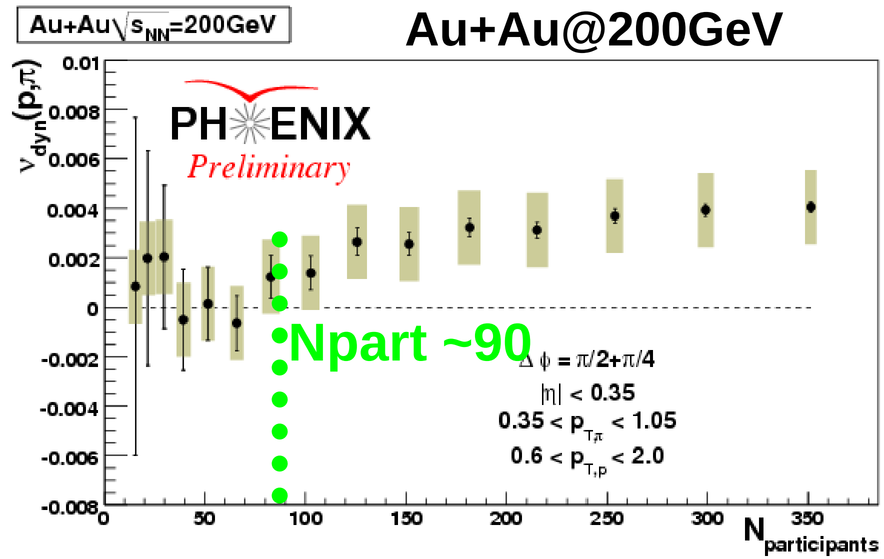
Low mass sigma field may repulse pion and attract proton?

Meson-meson and baryon-meson fluctuations

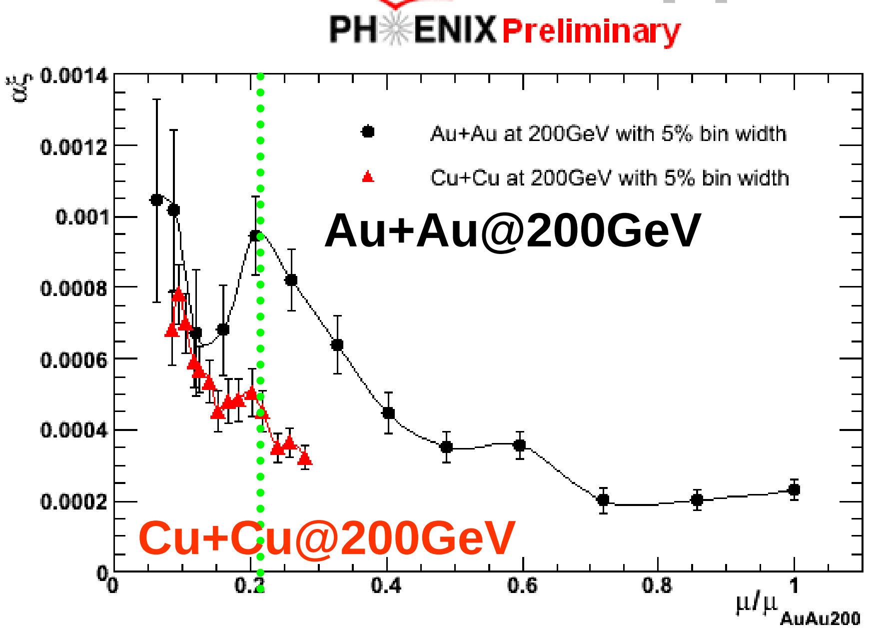
$$\nu_{dyn}(K,\pi) = \frac{\langle \pi(\pi-1) \rangle}{\langle \pi \rangle^2} + \frac{\langle K(K-1) \rangle}{\langle K \rangle^2} - 2\frac{\langle \pi\, K \rangle}{\langle \pi \rangle \langle K \rangle}$$



$$\nu_{dyn}(p,\pi) = \frac{\langle \pi(\pi-1) \rangle}{\langle \pi \rangle^2} + \frac{\langle p(p-1) \rangle}{\langle p \rangle^2} - 2\frac{\langle \pi\, p \rangle}{\langle \pi \rangle \langle p \rangle}$$

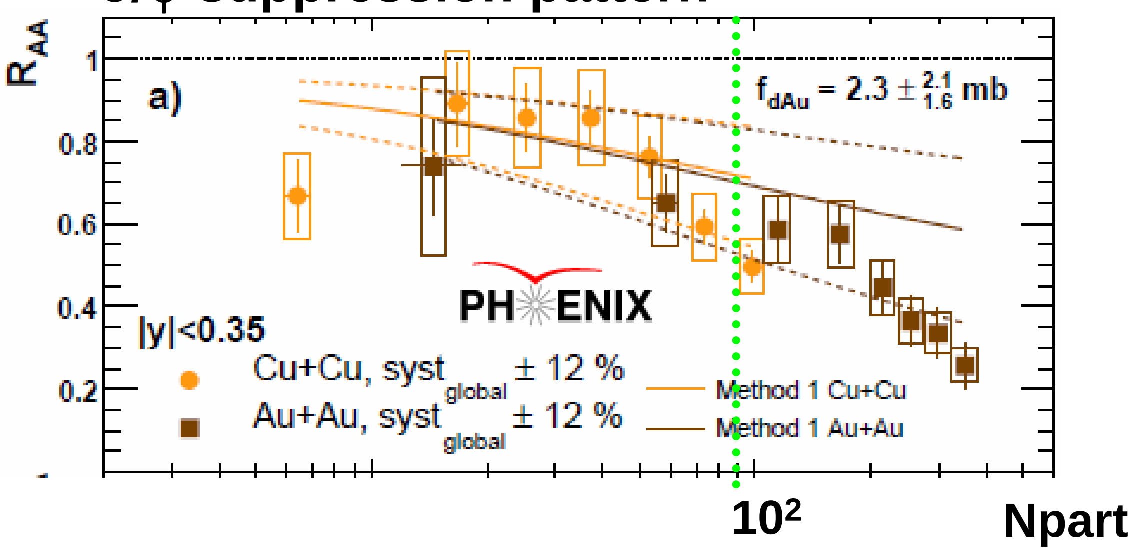


How about <c$\bar{c}$> suppression?



Npart~90 in AuAu@200GeV
$\varepsilon_{BJ}\tau$~2.4GeV/fm2/c

J/ψ suppression pattern

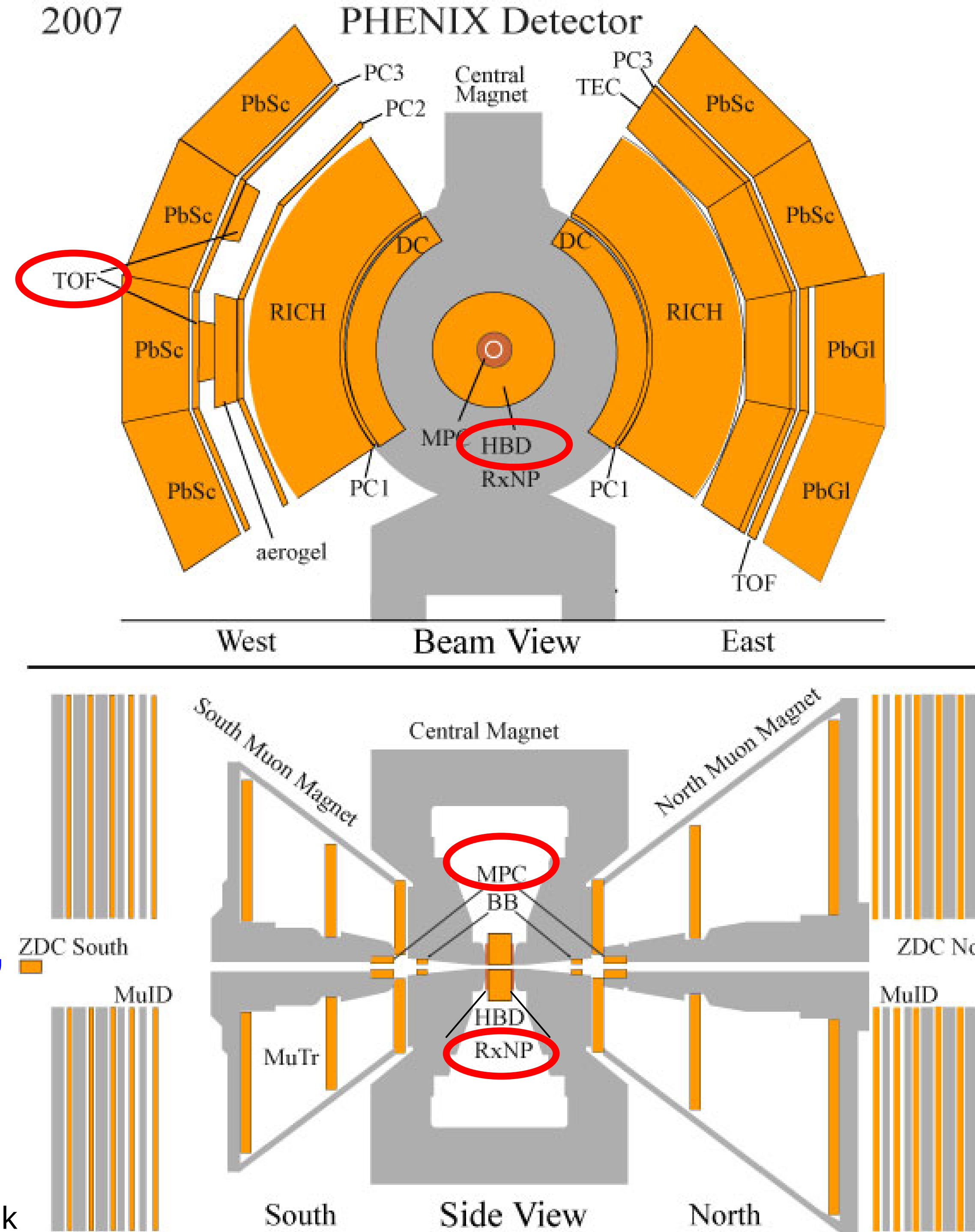


arXiv:0801.0220v1 [nucl-ex]

Plan for lower energy runs (readiness of PHENIX)

PHENIX 2007

- **Increase statistical & systematic precision of rare signals in AuAu, e.g. J/ψ, jet correlations, etc**
- **Increase reach in p_T, especially with PID from new TOF-West detector (p_T > 8 GeV/c)**
  - **Identified particle spectra**
  - **Identified leading particles in jets**
- **Factor of three or more improvement in Reaction Plane resolution - valuable to many signals**
  - **v_2 for J/ψ, γ , electrons, hadrons will be extended**
- **Low-mass lepton pairs with the Hadron Blind Detector**

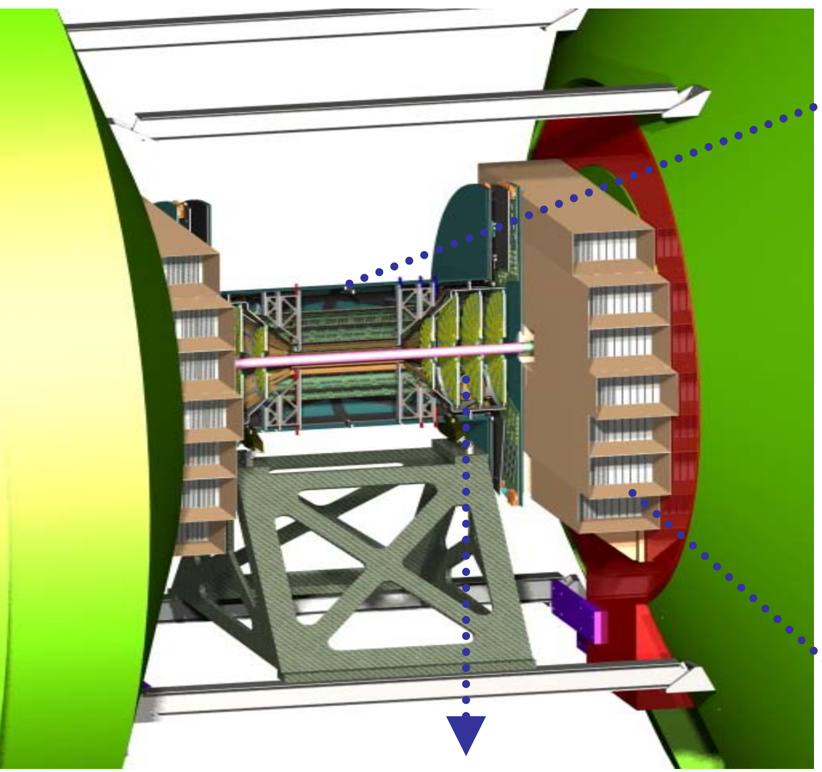


Kensuk

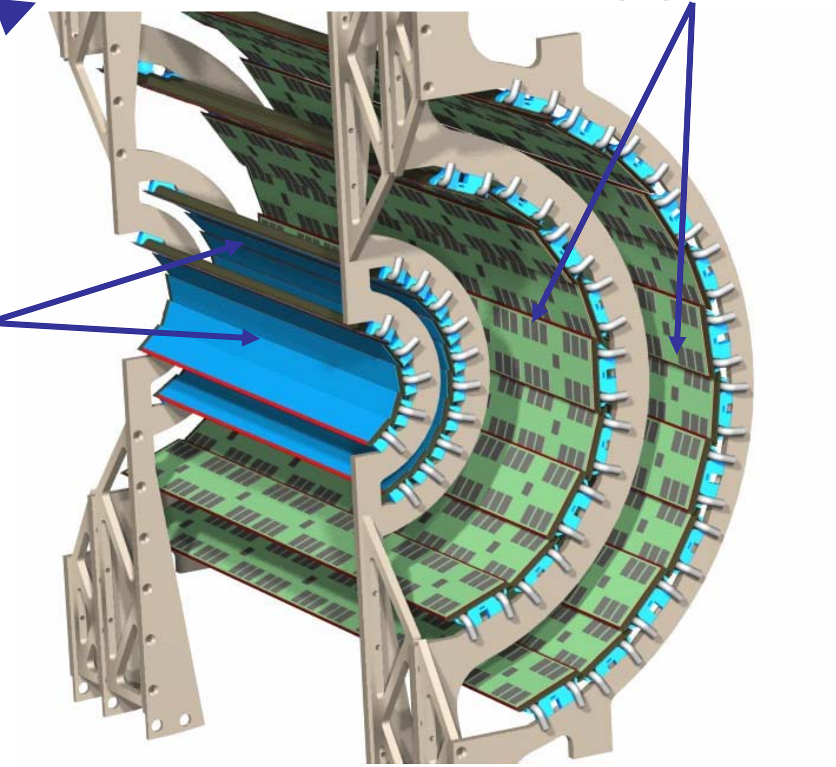
VTX, FVTX, and NCC for future runs

Central Vertex detector (VTX)

Strip pixel



Pixel

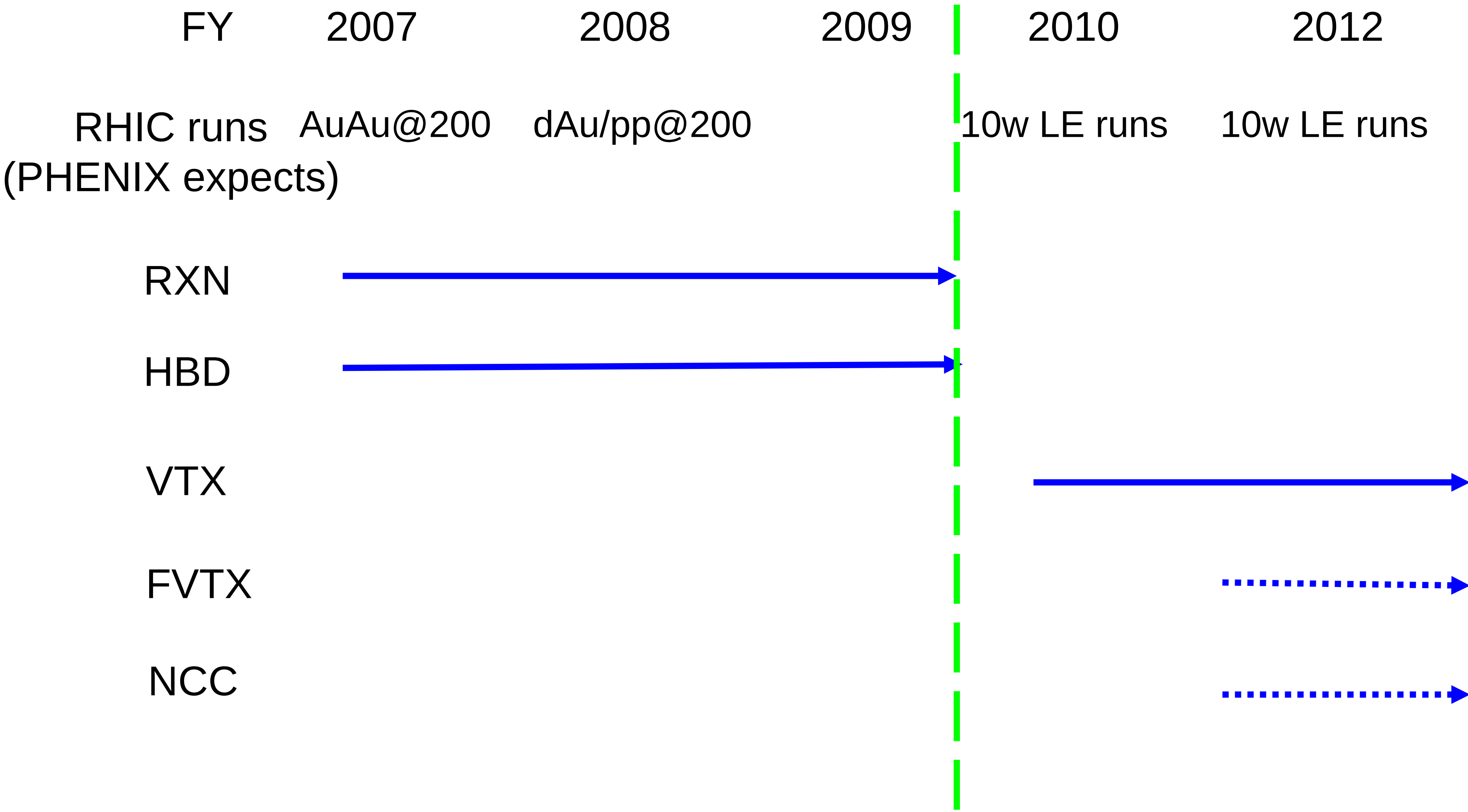


Nose Cone Calorimeter

Forward VTX (FVTX) **(NCC)**

PHENIX can extend both rapidity and azimuthal coverage

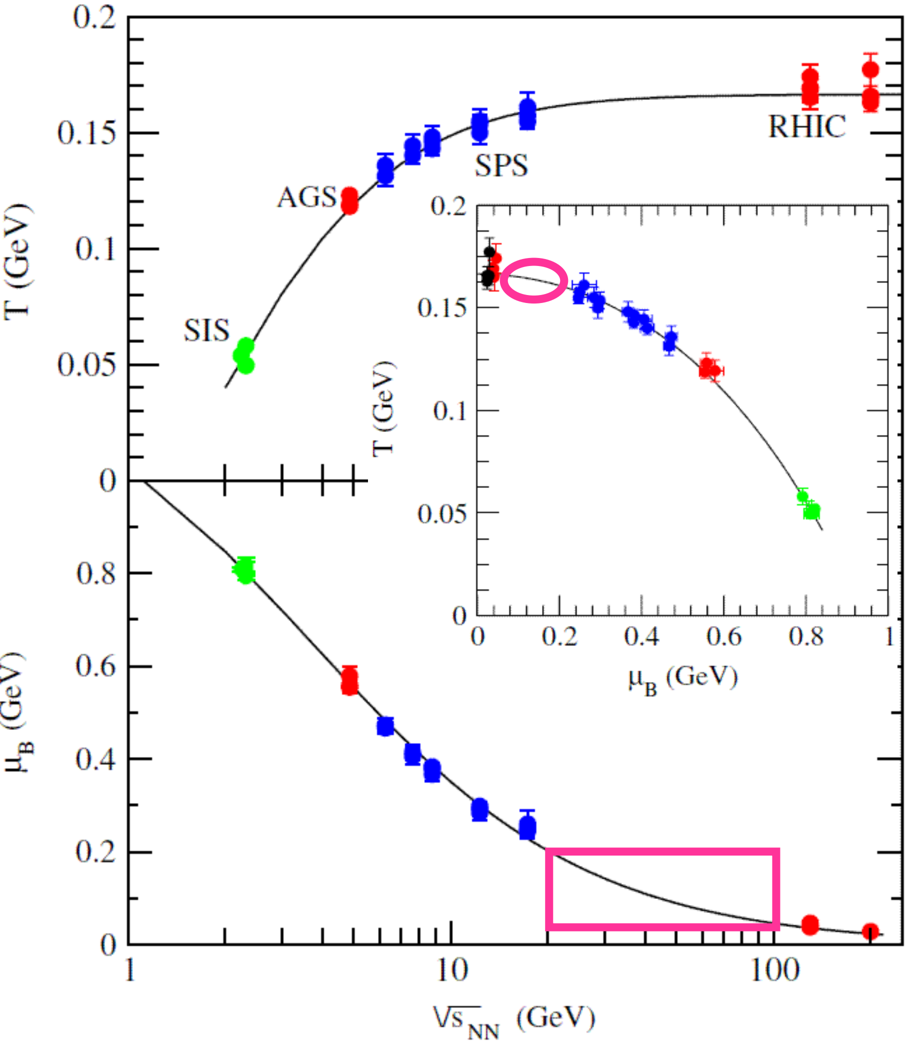
In/out of relevant detectors



Accessible observables in PHENIX

Signature	Required # of events	Note
Differential <N_{ch}> fluctuations	100 M	B = 0
Integral <N_{ch}> fluctuations	1 M	
<p_T> fluctuations	1 M	
<k/π> fluctuations	1 B	
Minimum bias PID spectra	0.5 M	$p_T < 2$ GeV/c, EMCAL (would like more at higher collision energies)
Centrality binned PID spectra	5 M	$p_T < 2$ GeV/c, EMCAL (would like more at higher collision energies)
Minimum bias v_2	5 M	$p_T < 2$ GeV/c, EMCAL (would like more at higher collision energies)
Centrality binned v_2	50 M	$p_T < 2$ GeV/c, EMCAL (would like more at higher collision energies)
R_{AA} π^0	100 M	Full centrality dependence
R_{AA} e	2 B	Full centrality dependence
Di-hadrons	100 M	
HBT (“Basic”)	100 M	
HBT (“Advanced”)	2B	
Di-electrons	50 M	

Choice of collision energies



PRC73,034905 (2006)

Weeks to collect AuAu sample in 2010

Energy	300M	100M	50M	5M	1M
5	870	290	145	14	3
6.3	547	182	91	9	2
7.6	375	125	63	6	1
8.8	273	91	45	5	1
12.3	143	48	24	2	0
17.2	73	24	12	1	0
27.4	9	3	2	0	0
38.8	5	2	1	0	0
62.4	2	1	0	0	0
100	1	0	0	0	0

PHENIX preference

Weeks to collect AuAu sample in 2012

Energy	300M	100M	50M	5M	1M
5	1596	532	266	27	5
6.3	1003	334	167	17	3
7.6	690	230	115	11	2
8.8	515	172	86	9	2
12.3	263	88	44	4	1
17.2	135	45	22	2	0
27.4	9	3	1	0	0
38.8	4	1	1	0	0
62.4	2	1	0	0	0
100	1	0	0	0	0

PHENIX preference

Summary

1. **RHIC created strongly coupled high temperature & opaque state with partonic d.o.f. This is the very beginning of the scientific program on quantitative understanding of the QCD phase structure.**
2. **Correlation function derived from GL free energy density up to 2nd order term in the high temperature limit is consistent with what was observed in NBD k vs $\delta\eta$ in three collision systems. This provides a way to directly determine transition points without tunable model parameters with relatively fewer event statistics.**
3. **The product of susceptibility and temperature, $\alpha\xi$ as a function of Npart indicates a possible non monotonic increase at Npart~90. The corresponding Bjorken energy density is 2.4GeV/fm^3 with τ=1.0 fm/c and the transverse area=60fm^2 The trends of $\alpha\xi$ in smaller system in the same collision energy and in the same system size in lower collision energy as a function of mean multiplicity are similar to that of Au+Au at 200GeV except the region where the possible non monotonicity is seen.**
4. **Combining other symptoms in the same multiplicity region, we hope to understand possibly interesting behaviors.**
5. **Lower energy runs will surely take place at RHIC. However, actual colliding energies are still under discussion between collaborations.**