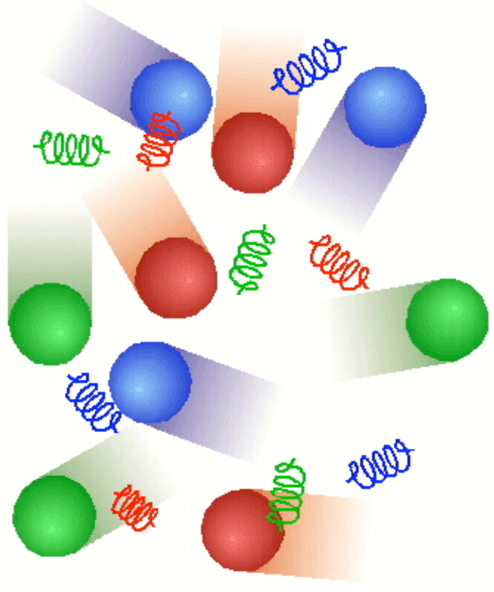
What I have learned at RHIC

Yasuo MIAKE
Univ. of Tsukuba



I think
What I have learned at RHIC

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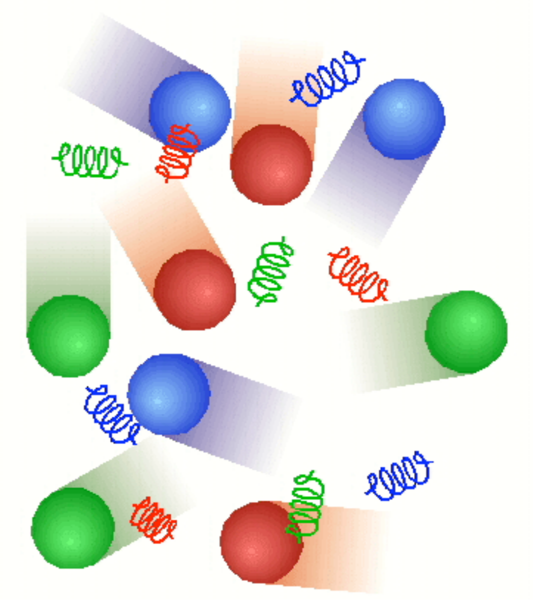

Text book for graduate students

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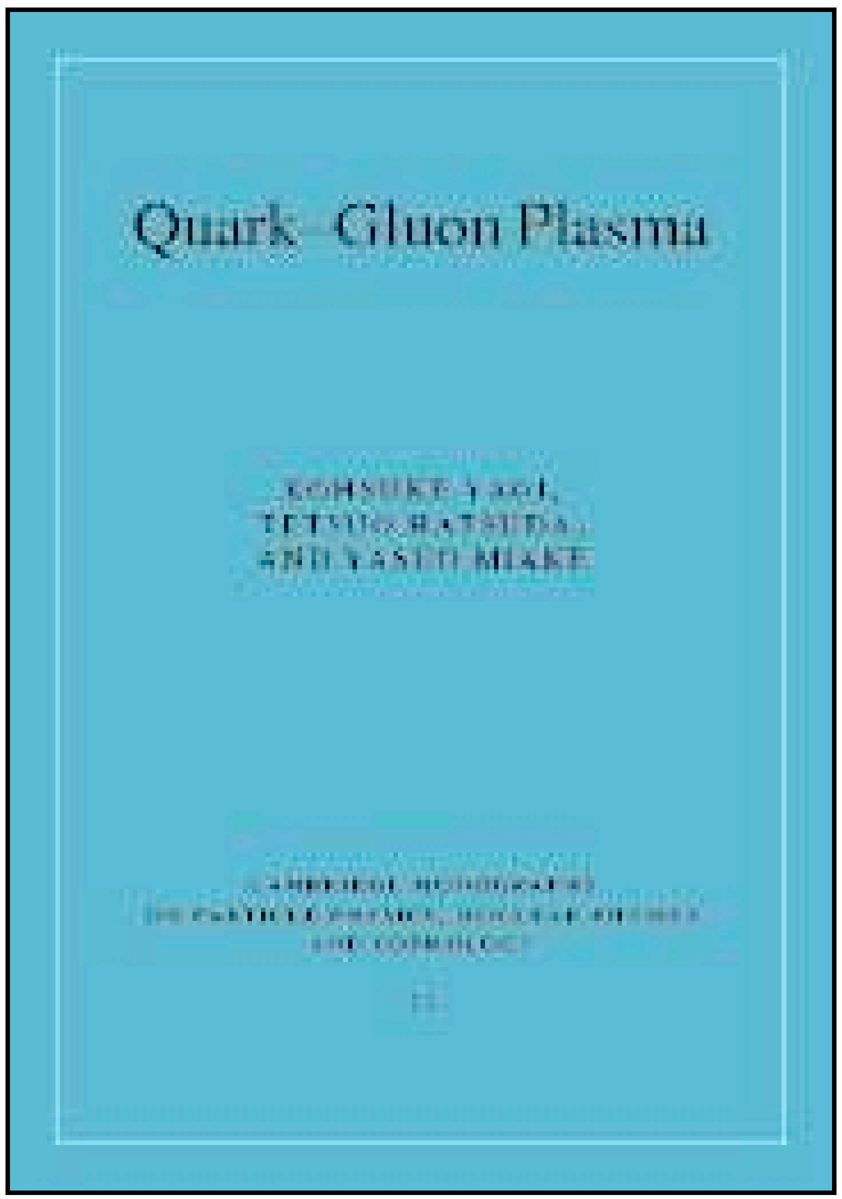

Quark-Gluon Plasma

Series: Cambridge Monographs on Particle Physics, Nucle

Kohsuke Yagi
Urawa University, Japan

Tetsuo Hatsuda
University of Tokyo

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University of Tsukuba, Japan

Hardback (ISBN-10: 0521561086 | ISBN-13: 97805215610

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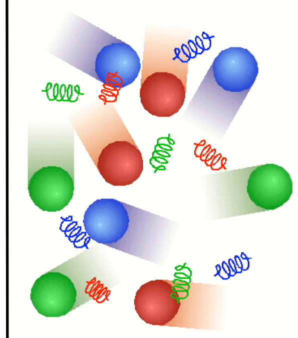
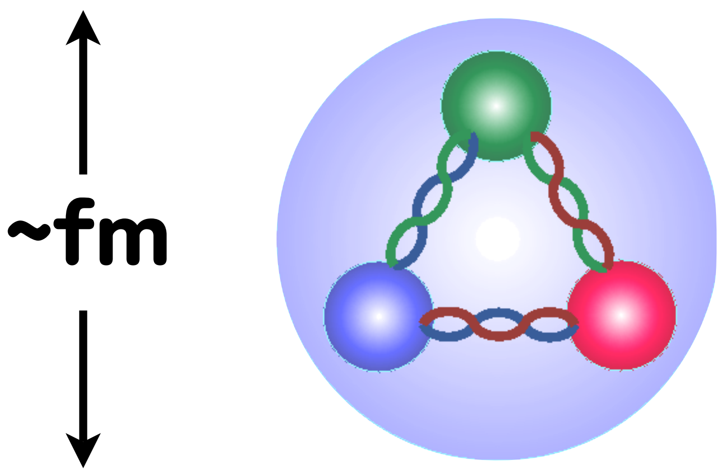
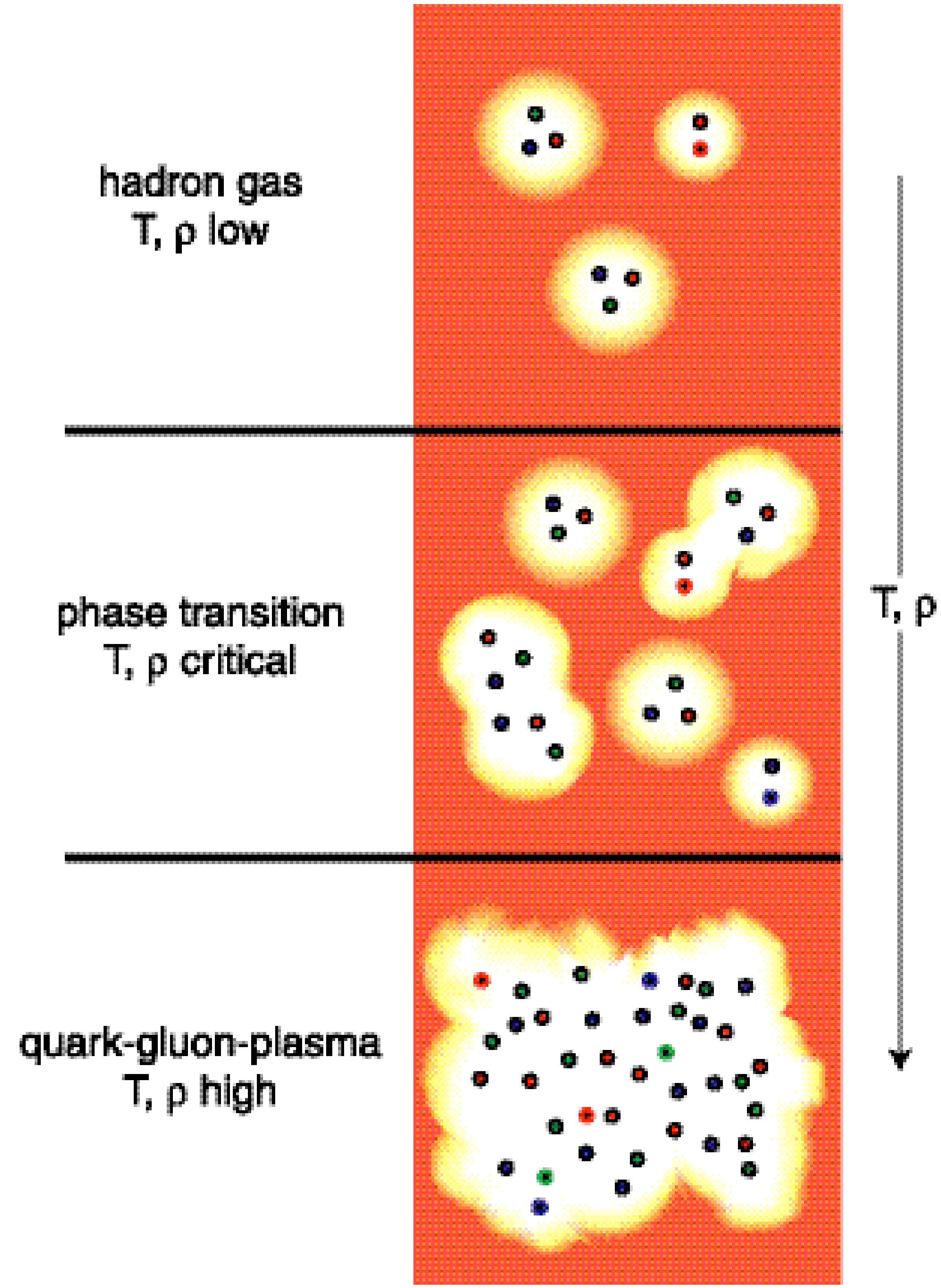
Quark Gluon Plasma



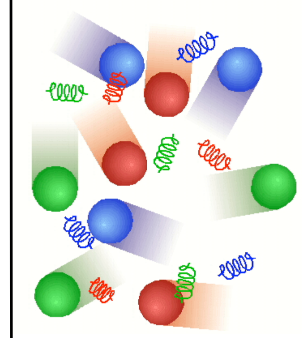


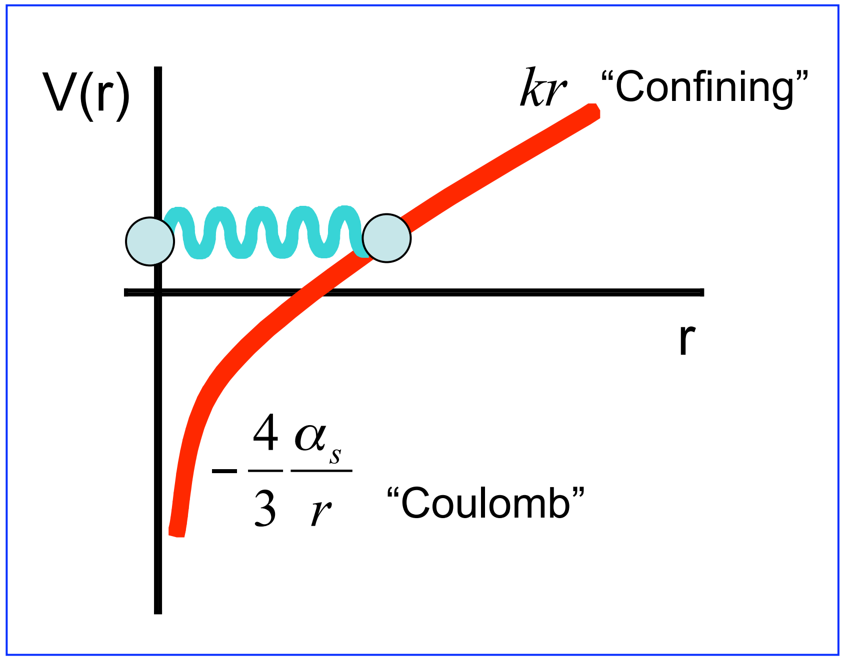
✓Size of hadrons ~ fm

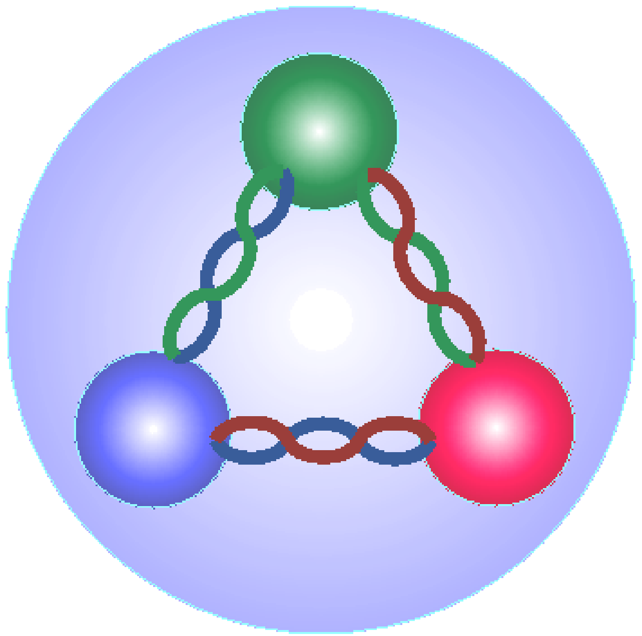
- ✦At high ρ or high T, hadron gas to quark-gluon plasma.
  ➡Phase transition



Is it QGP inside a proton?

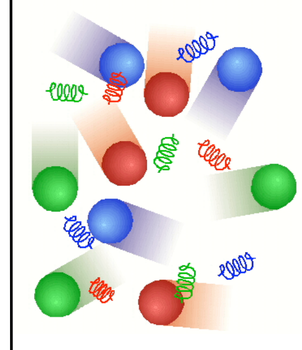






- ✓ Asymptotic freedom means a QGP inside a proton?
  - ➡No!
- ✓ Free moving quarks & gluons for a large volume
- ✓ Applicability of Statistical Physics is essential!

What we expect: Statistical Nature



$$\epsilon_{\mathrm{QGP}} \sim 2\ [\mathrm{GeV/fm^3}]$$ ← **Ex. Lattice QCD**

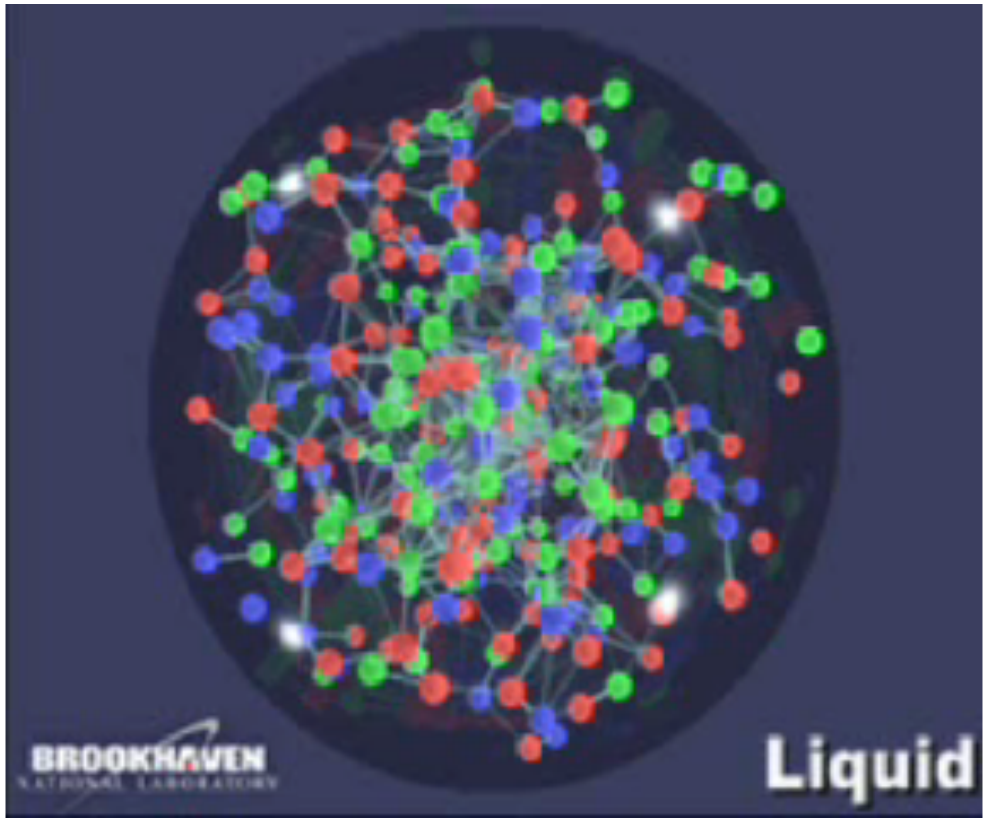
$$< n_{q,\bar{q}} > \sim \frac{\epsilon_{\mathrm{QGP}}}{< m_T >} \sim \frac{2\mathrm{GeV}}{0.4\mathrm{GeV}} \sim 5$$

$$\lambda_q = \frac{1}{n\sigma_{qq}}$$

$$\sim \frac{1}{5 \times 0.4} = 0.5\ [\mathrm{fm}]$$

$$\lambda_q \ll R_{\mathrm{system}}$$

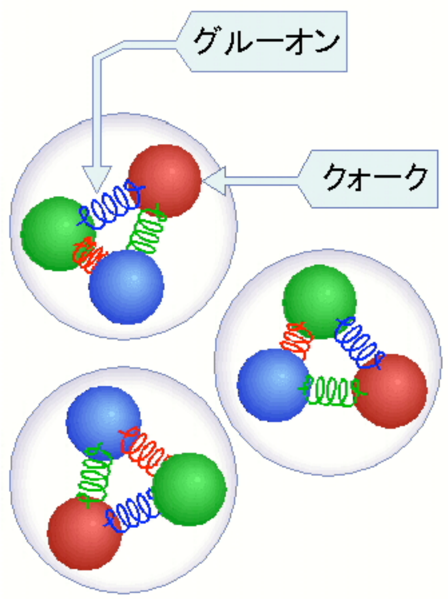
$$\because \sigma_{qq} \sim \frac{\sigma_{NN}}{3 \times 3} \sim \frac{4[\mathrm{fm}^2]}{9} \sim 0.4$$



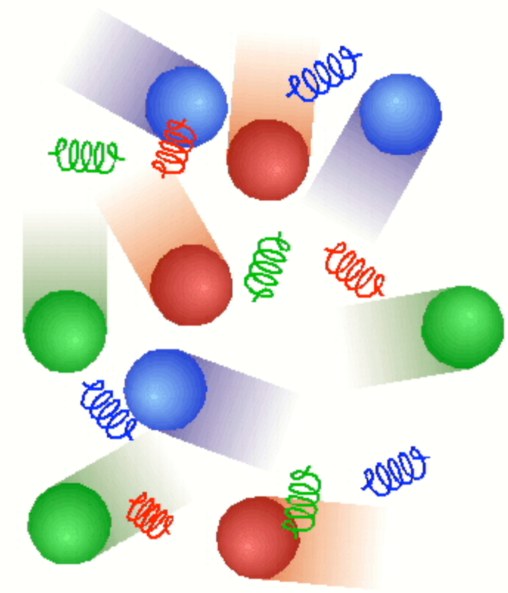
Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration

✓ **What we expect:**

- ✦ **Statistical physics at quark level**
- ✦ **Hydrodynamical behavior at quark level**



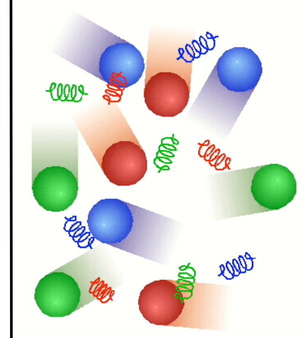
Statistical nature observed



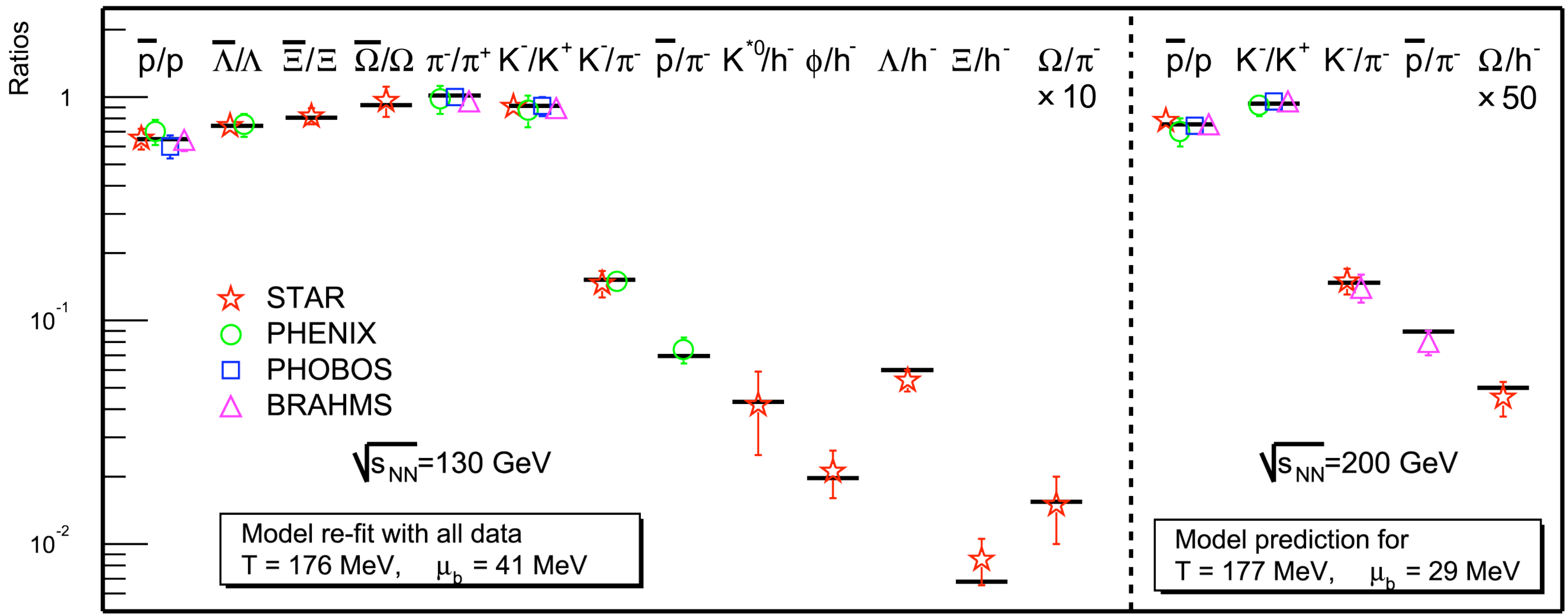
★ Chemical equilibrium from particle yield ratio

★ Kinematical equilibrium from transverse distr.

Chemical Eq. from particle yield ratios



$$n_i = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,dp}{e^{(E_i-\mu_i)/T}\pm 1}$$

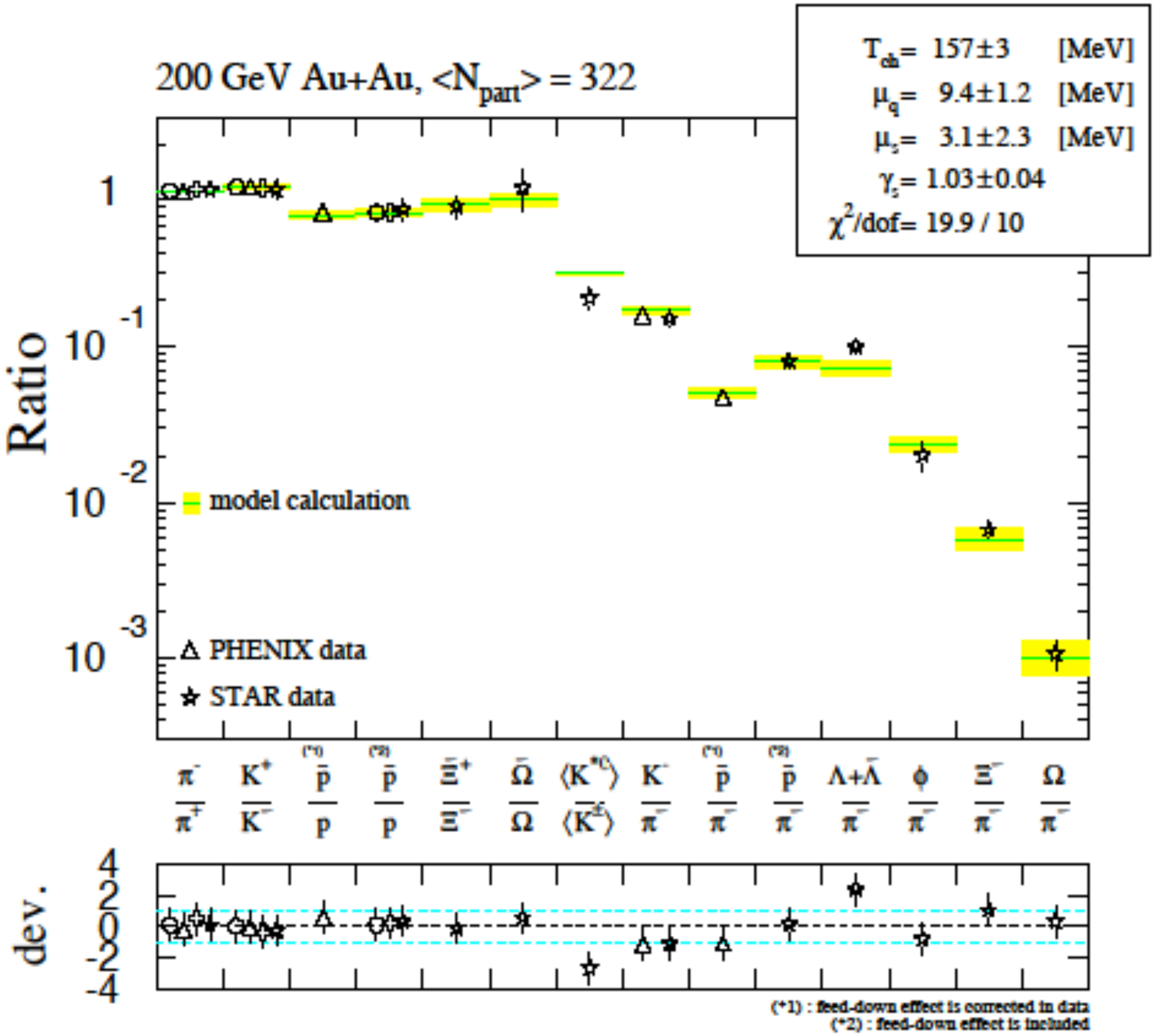


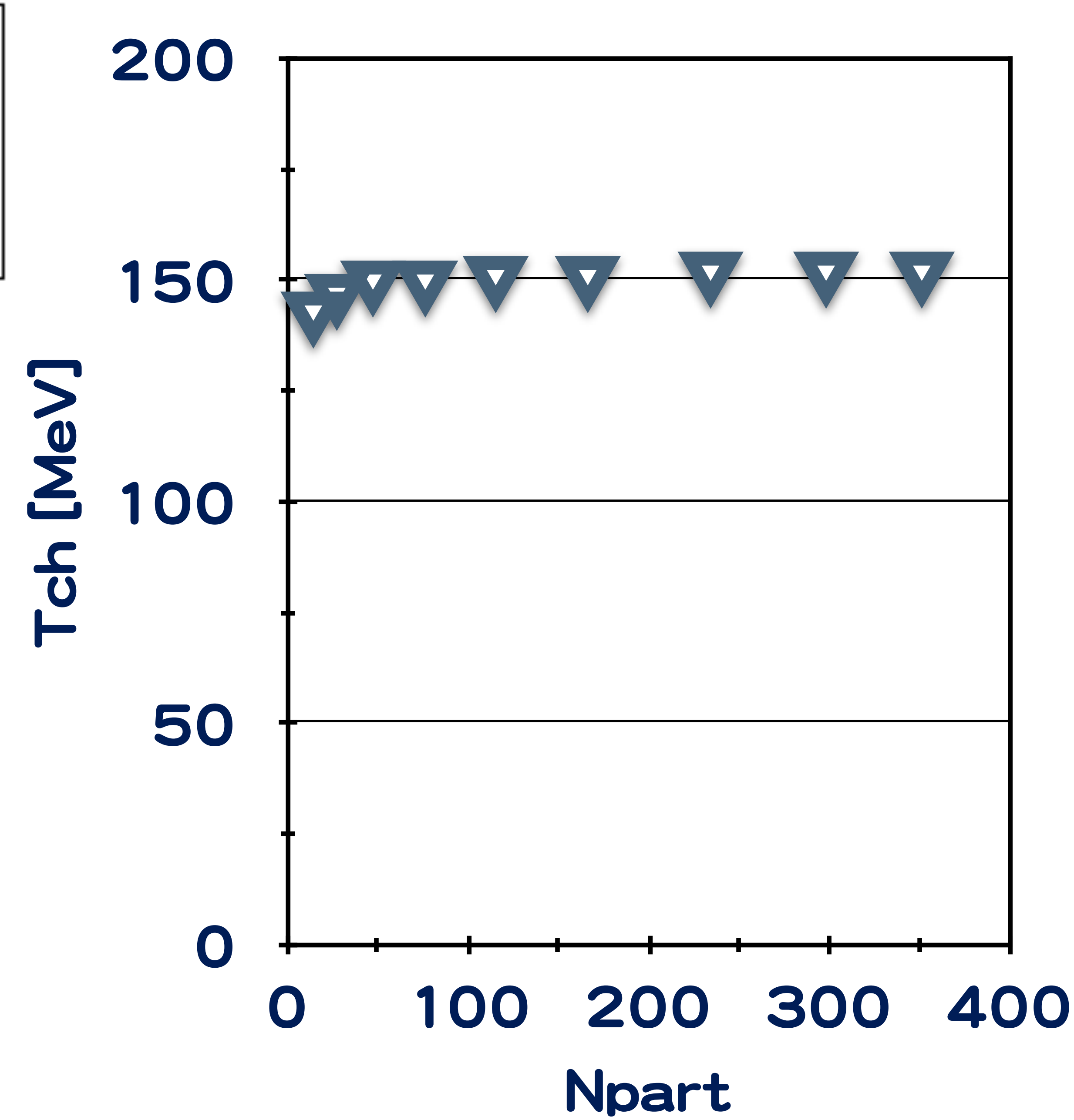
Braun-Munzinger et al., PLB 518 (2001) 41
D. Magestro (updated July 22, 2002)

✓ **Only two parameters fit every ratio very well !**

Centrality dep. of T_{ch}

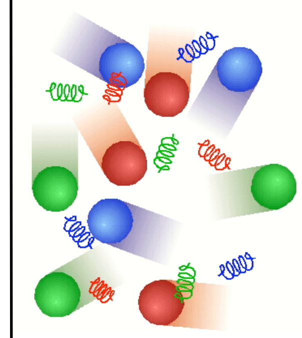
M.Kaneta, N.Xu, nucl-th/0405068





✓ T_{ch} stays amazingly constant from peripheral to central collisions

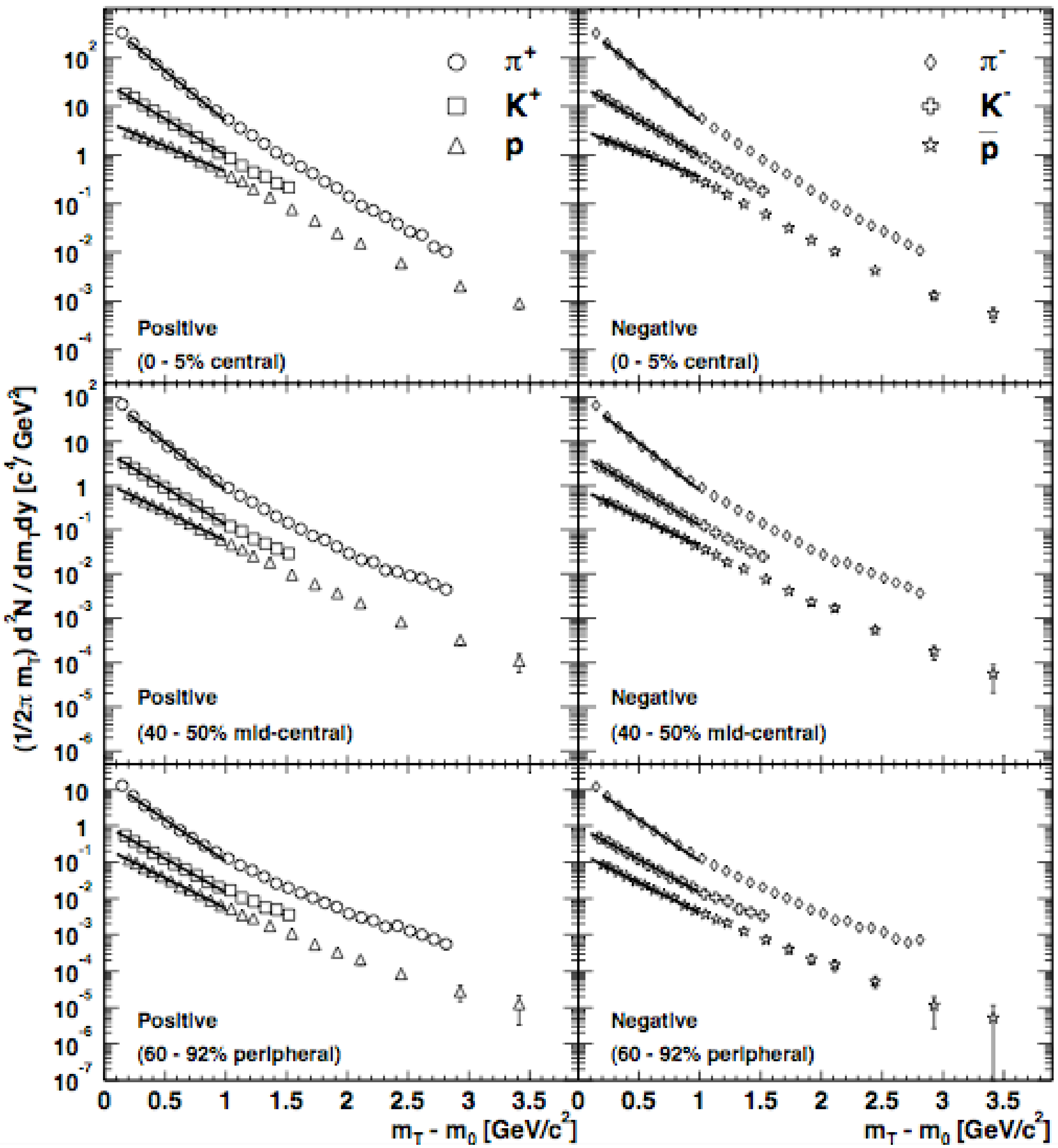
Transverse mass distr.

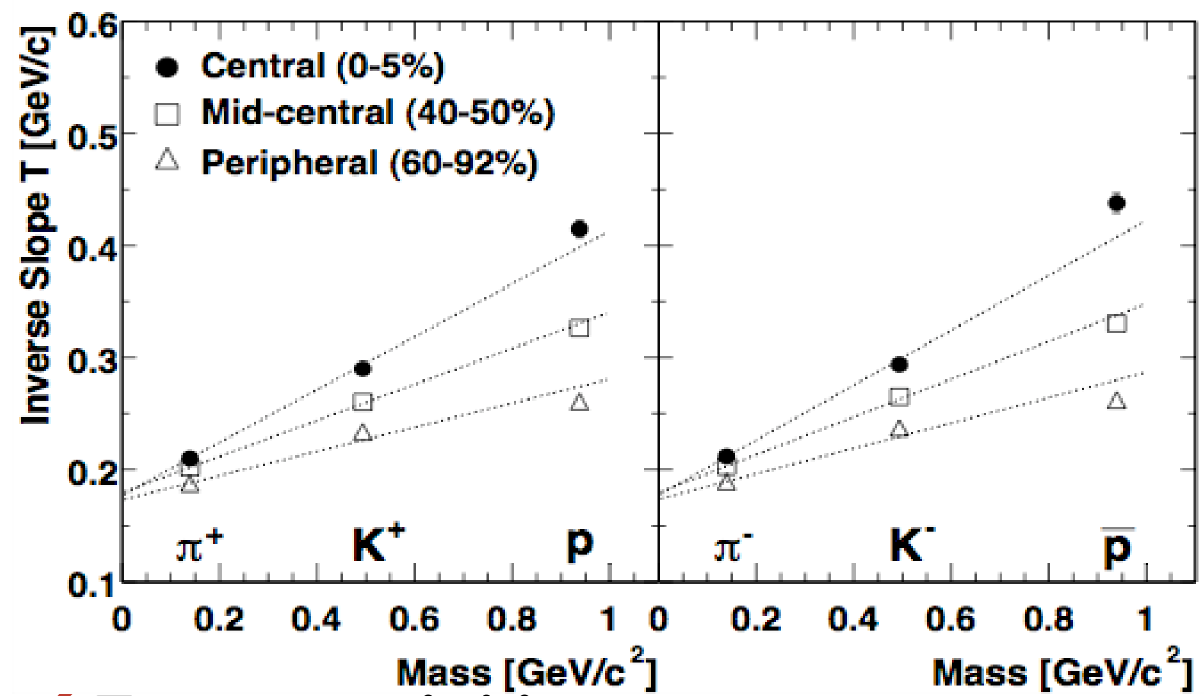


$$m_t = \sqrt{p_t^2 + m^2}$$

$$\frac{d^2N}{2\pi m_T dm_T dy} = \frac{1}{2\pi T(T+m_0)} A \exp\left(-\frac{m_T - m_0}{T}\right)$$

PHENIX, PRC69,034909(2004)



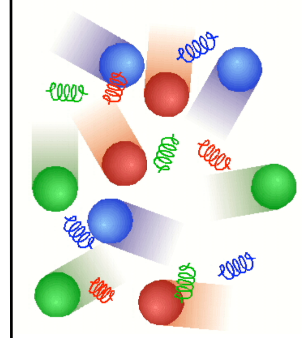


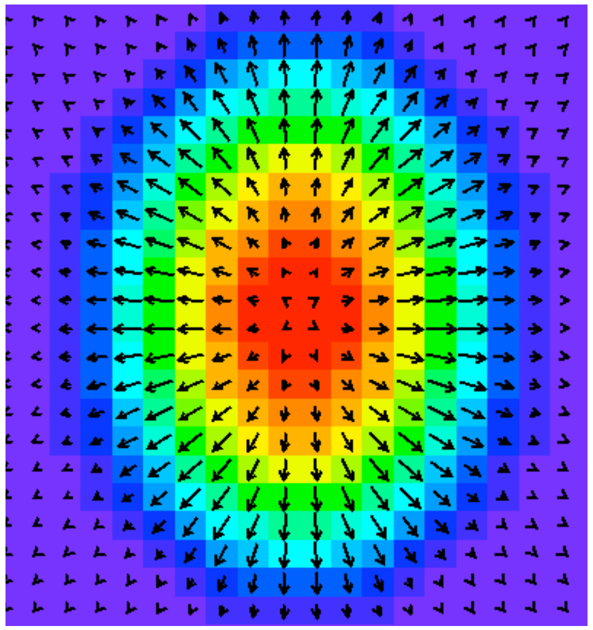
- ✓ Exponential in m_t
  - ✦ Known as m_t scaling
  - ✦ Thermal distr.
- ✓ Flatter m_t distr for heavier particle mass
  - ✦ Mass Ordering of Slope param.
  - ✦ Effect of Collective Flow

$$T \approx T_0 + \frac{1}{2} m \langle v_r \rangle^2$$

Collective Flow

Blast Wave Model





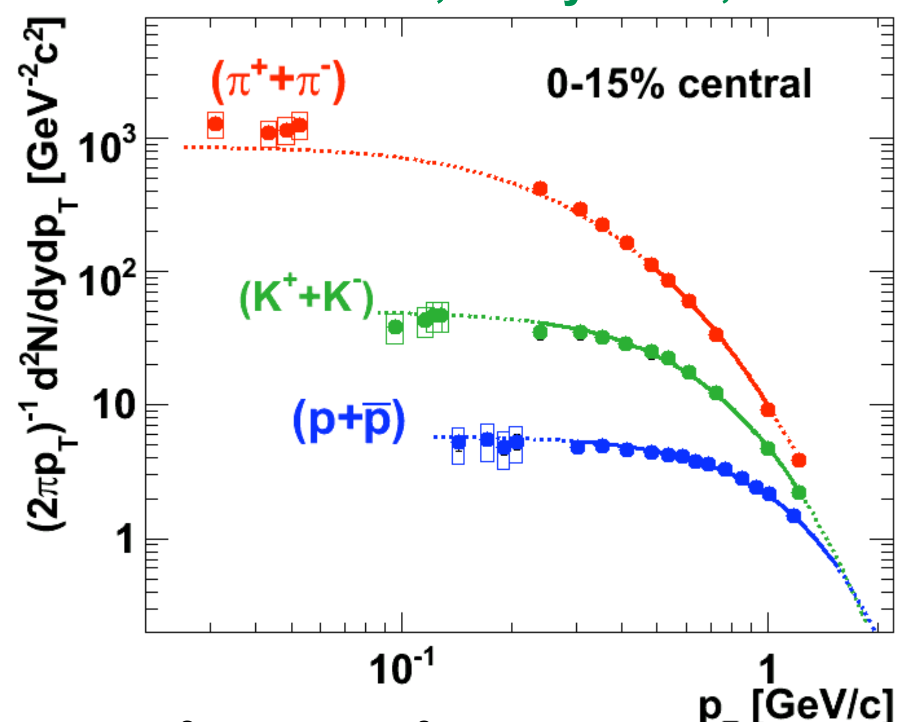
$$\frac{1}{m_T}\frac{dN}{dm_T} = A\int_0^R f(r) r dr m_T \, I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right)$$

PRC48(1993)2462.

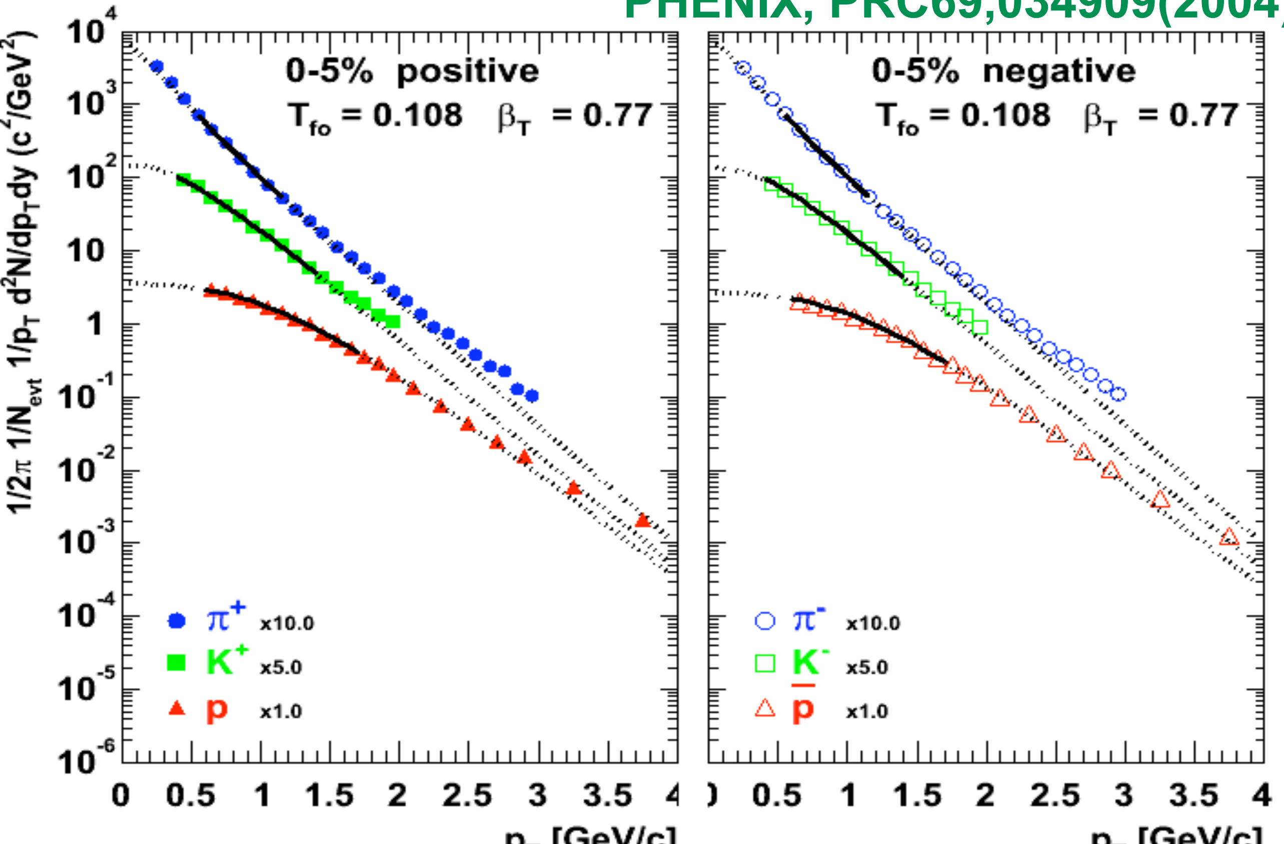
$\mathbf{I_0}$, $\mathbf{K_1}$: modified Bessel function

$$\rho(r) = \tanh^{-1}(\beta_T)\cdot r/R$$

Phobos, J.Phys.G34,S1103-7(2007)

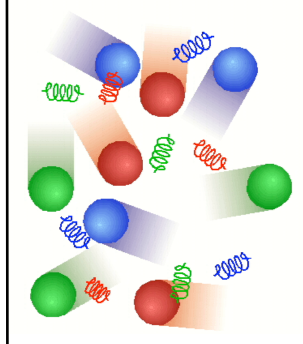


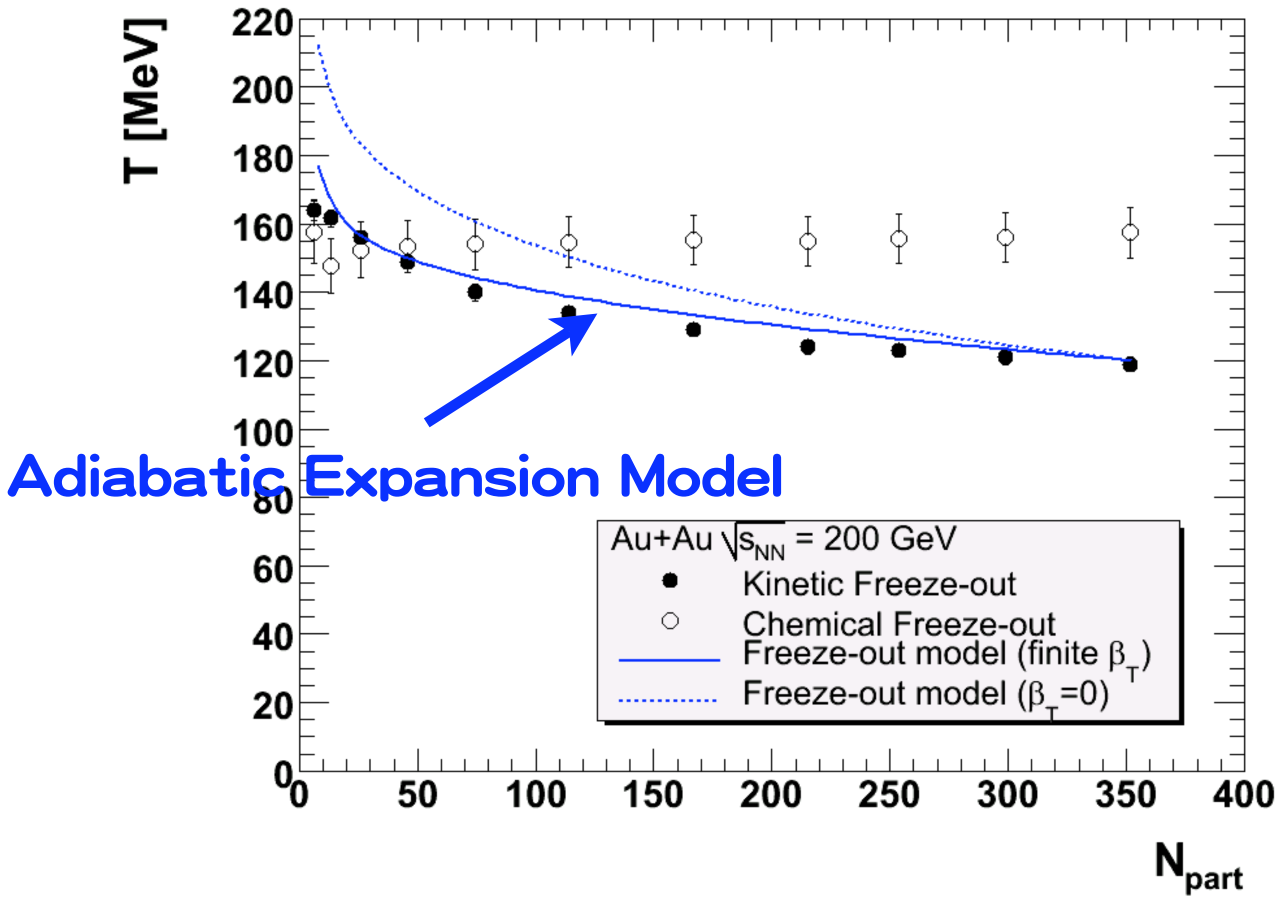
PHENIX, PRC69,034909(2004)

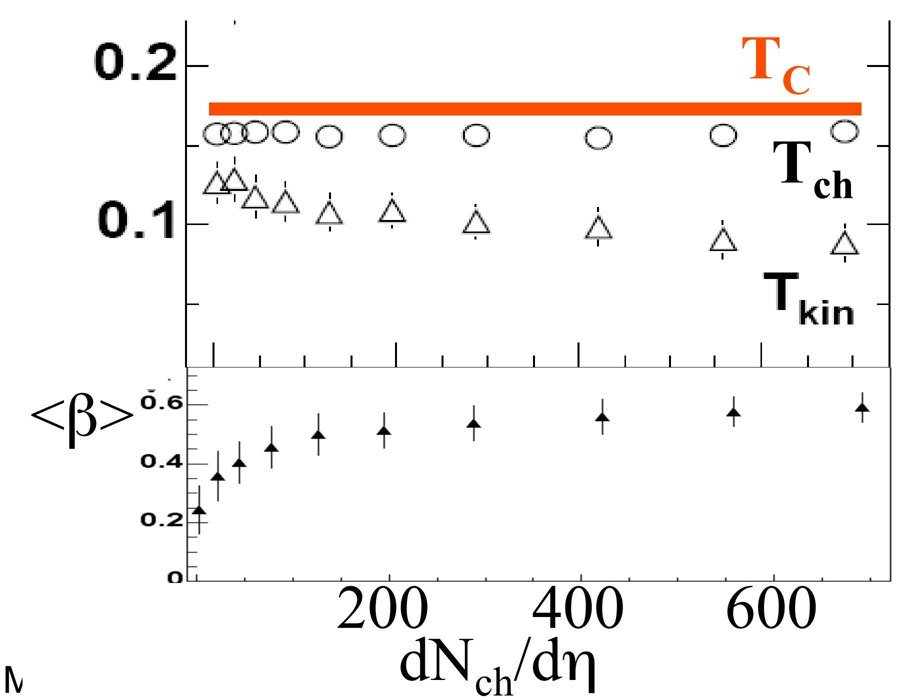


- ✓ Good tool to separate thermal and collective
- ✓ Well describe < 2 GeV/c

Freeze-out Conditions

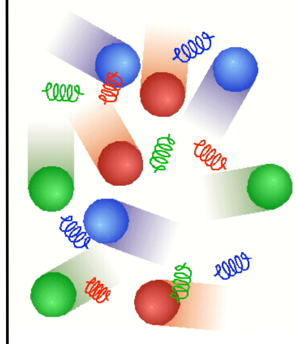


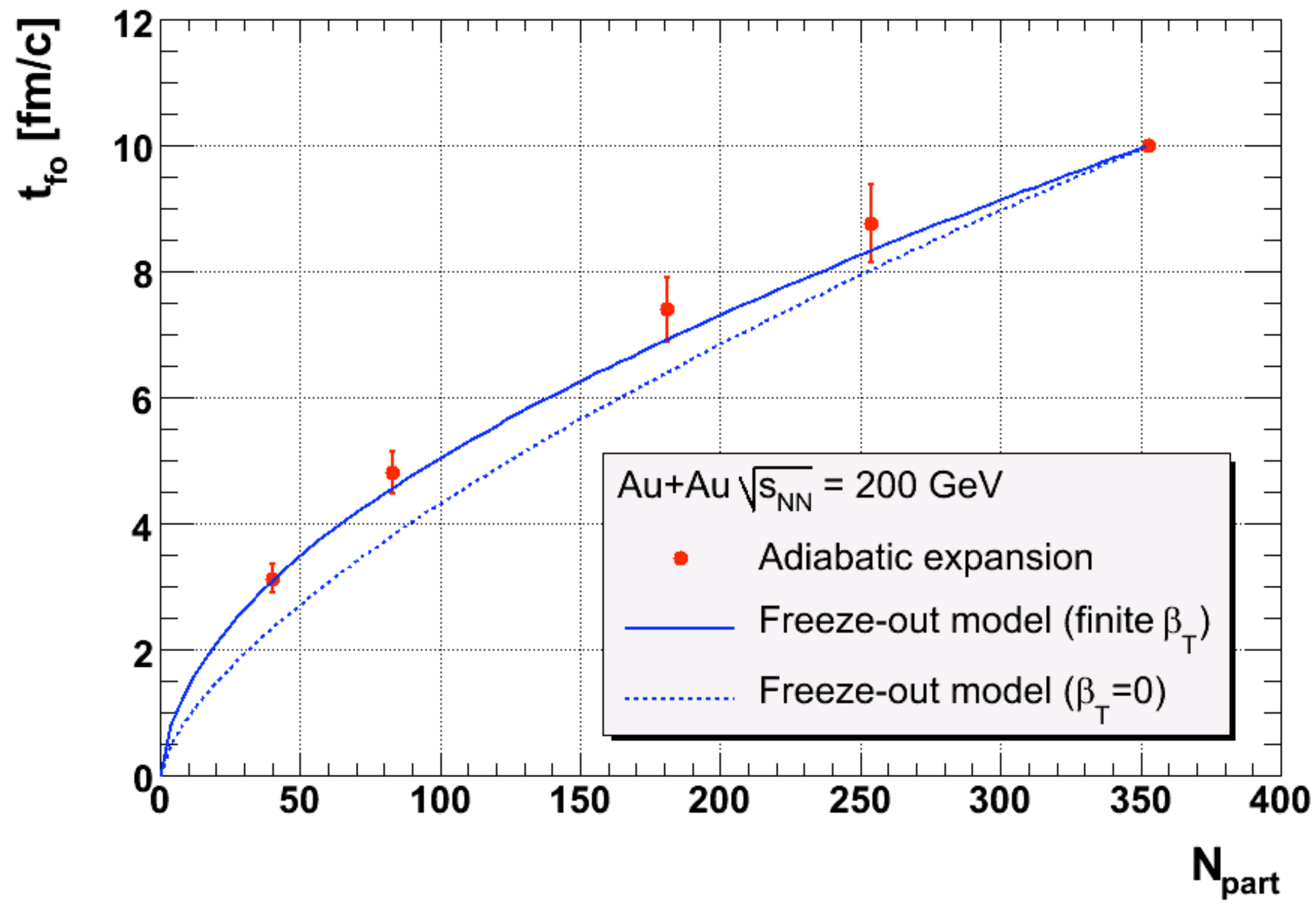




- ✓ Kinematical & Chemical freeze-out show difference in centrality dependence!
  - ✦ Kinematical :
    - ➡ $T_{ch}^{cent.} < T_{ch}^{per.} < T_{ch}$
    - Freeze-out with $\lambda \sim R$
  - ✦ Chemical :
    - ➡ $T_{ch}^{cent.} \sim T_{ch}^{per.} \sim$ 170 MeV
    - Freeze-out with $\varepsilon \sim \varepsilon_{crit}$
- ✓ Nature of Freeze-out
  - ✦ Kinematical freeze-out is collisional, while chemical is not.

Adiabatic Expansion Model

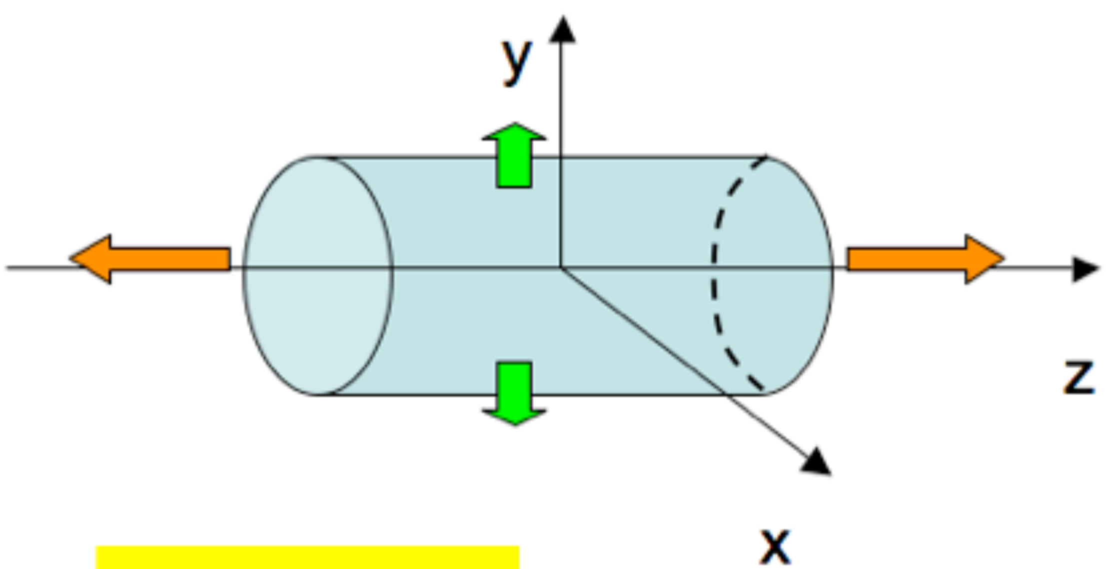




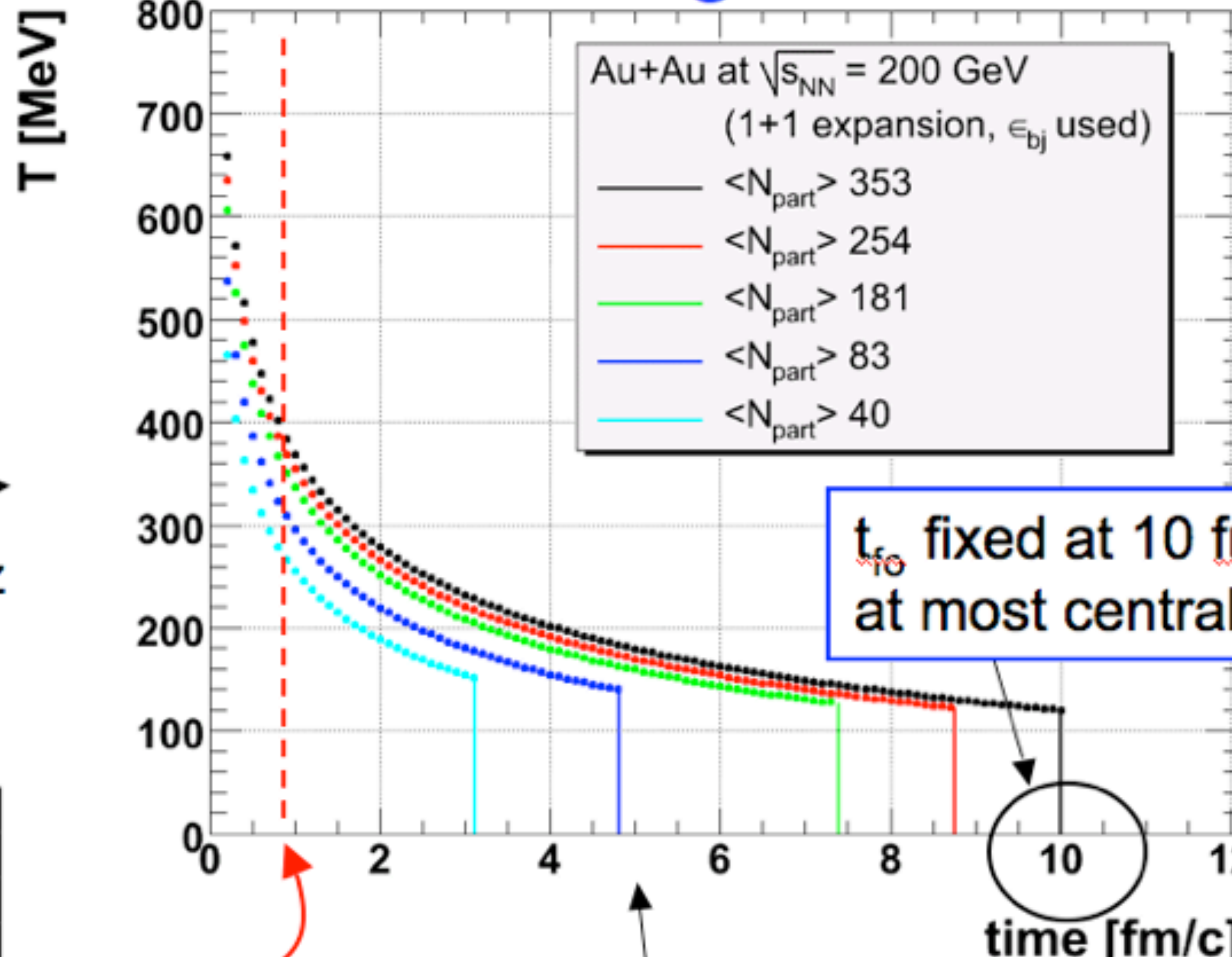
- ✓ Assumptions;
  - ✦ Perfect fluid/Ideal gas
  - ✦ Entropy conservation
  - ✦ Bjorken Formula for ε
  - ✦ Transverse & longitudinal expansion
  - ✦ $\lambda = R$ as freezeout condition
- ✓ Central collisions freeze-out later than

1+1D Adiabatic Expansion

- Ideal gas: P=(1/3)ε
- Entropy conservation
- Longitudinal expansion
  & Transverse expansion



- cooling curves -

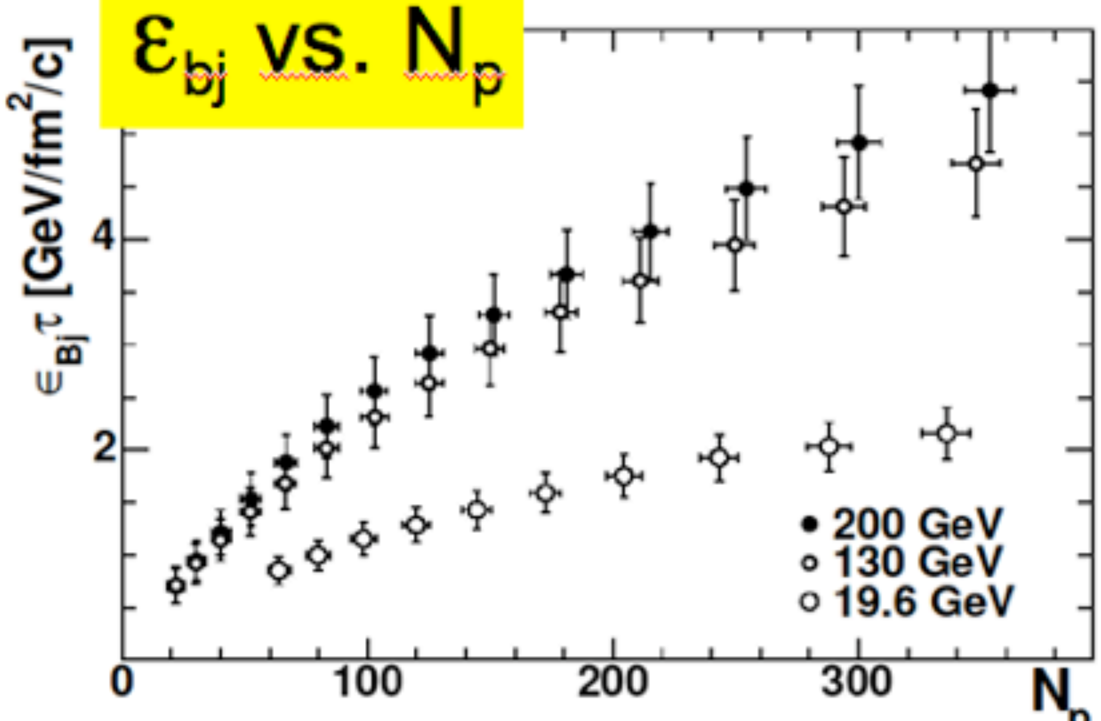


t_{fo} fixed at 10 fm/c
at most central

T scaled with $(\varepsilon_{bj})^{1/4}$
at t = 1 fm/c

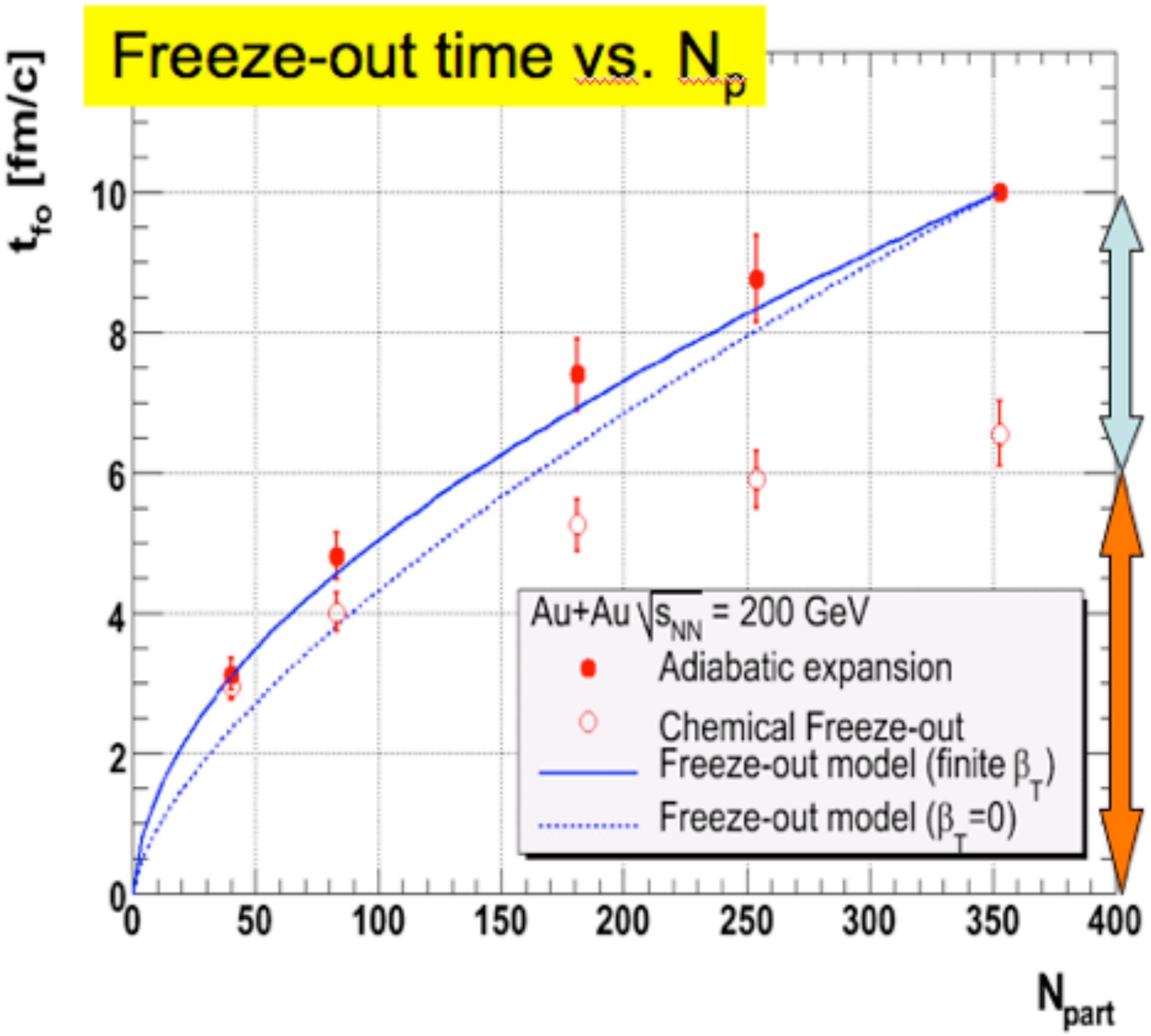
Cooling stopped at T_{fo}

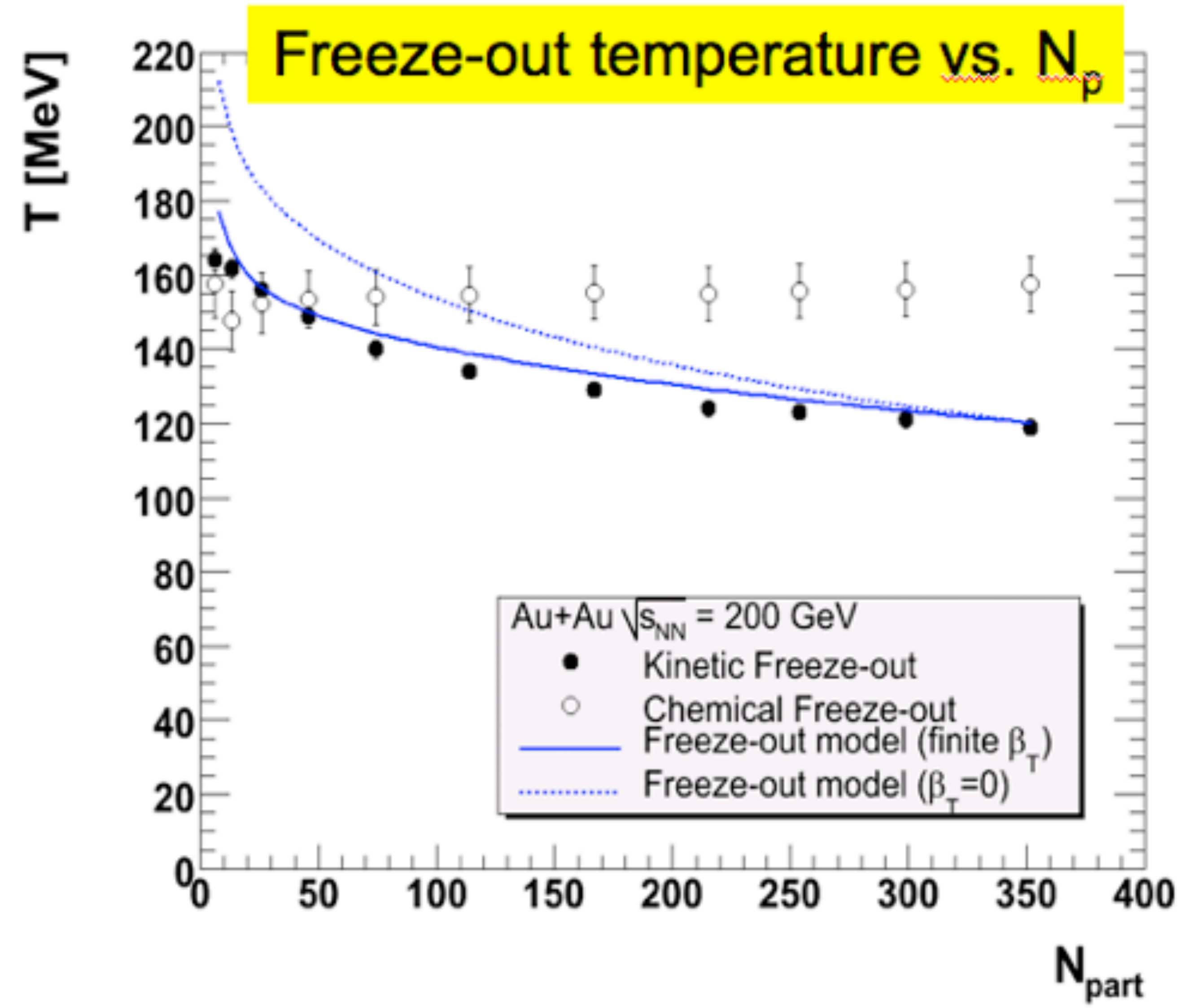
ε_{bj} vs. N_p



M. Konno, Thesis, Tsukuba, 2007

Freeze-out Time & Temperature

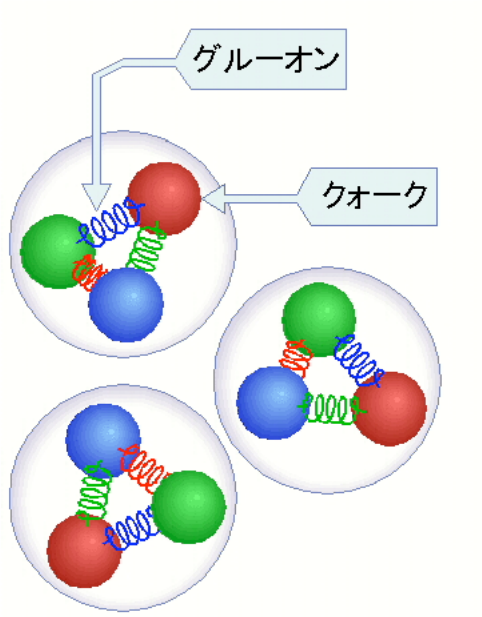




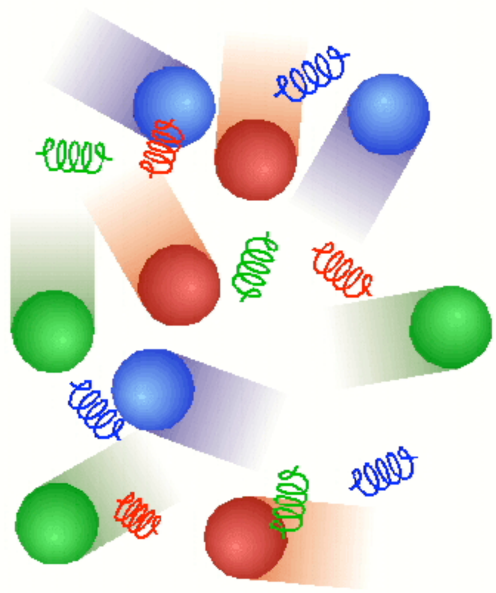
- More central collisions freeze out later at lower temperature.
- Consistent with freeze-out condition: $\lambda(t)=R(t)$
- Even if quark phase is created before hadronization, hadronic scattering should be taken into account.

- As expected, T_{fo} is lower than T_{ch}. Different centrality dependence.
- T_{fo} dropping is consistent with 1+1D adiabatic expansion.
- $T_c \sim T_{ch}$ => the observed chemical eq. not via hadronic scatterings.

M. Konno, Thesis, Tsukuba, 2007



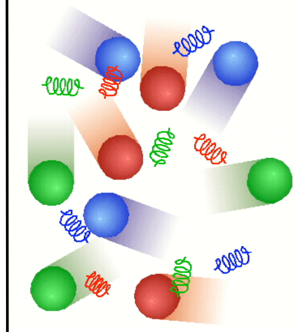
Two Major Discoveries at RHIC

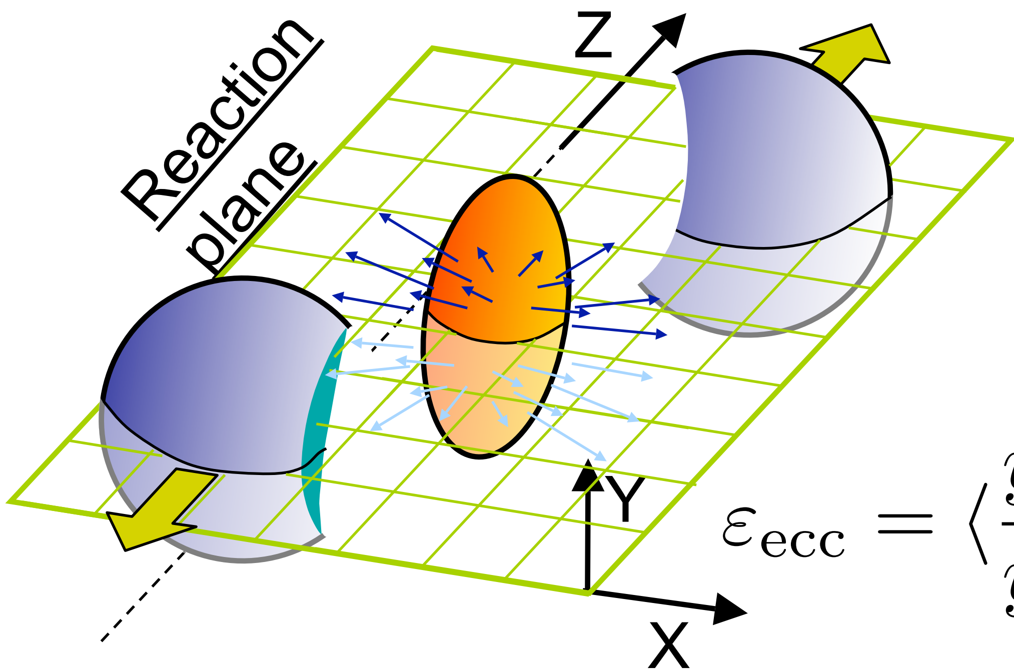


1) Large Elliptic Flow

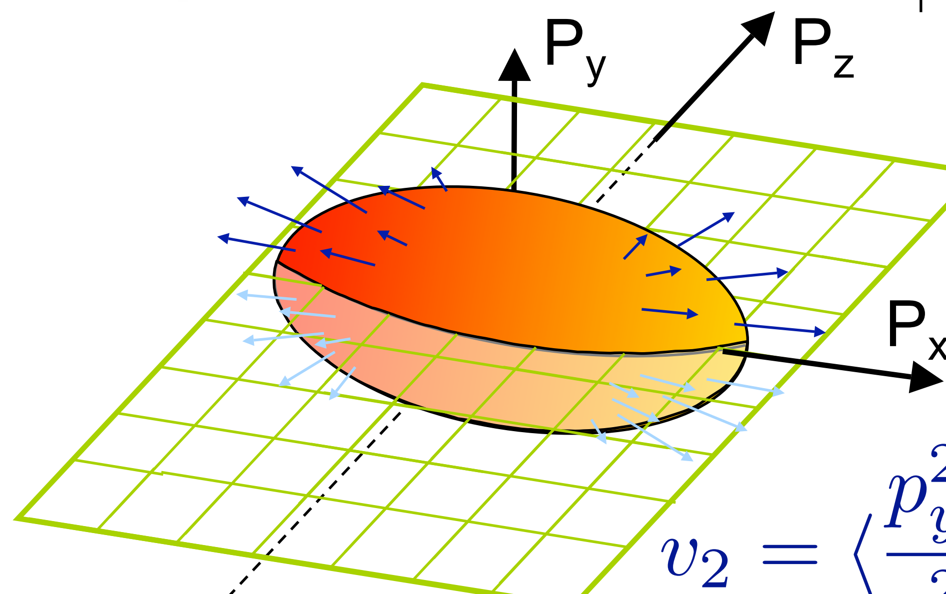
2) Jet Modification

Elliptic Flow, v2 (Azimuthal Anisotropy)





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

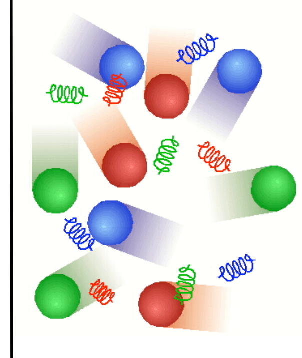


$$v_2 = \langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \rangle$$

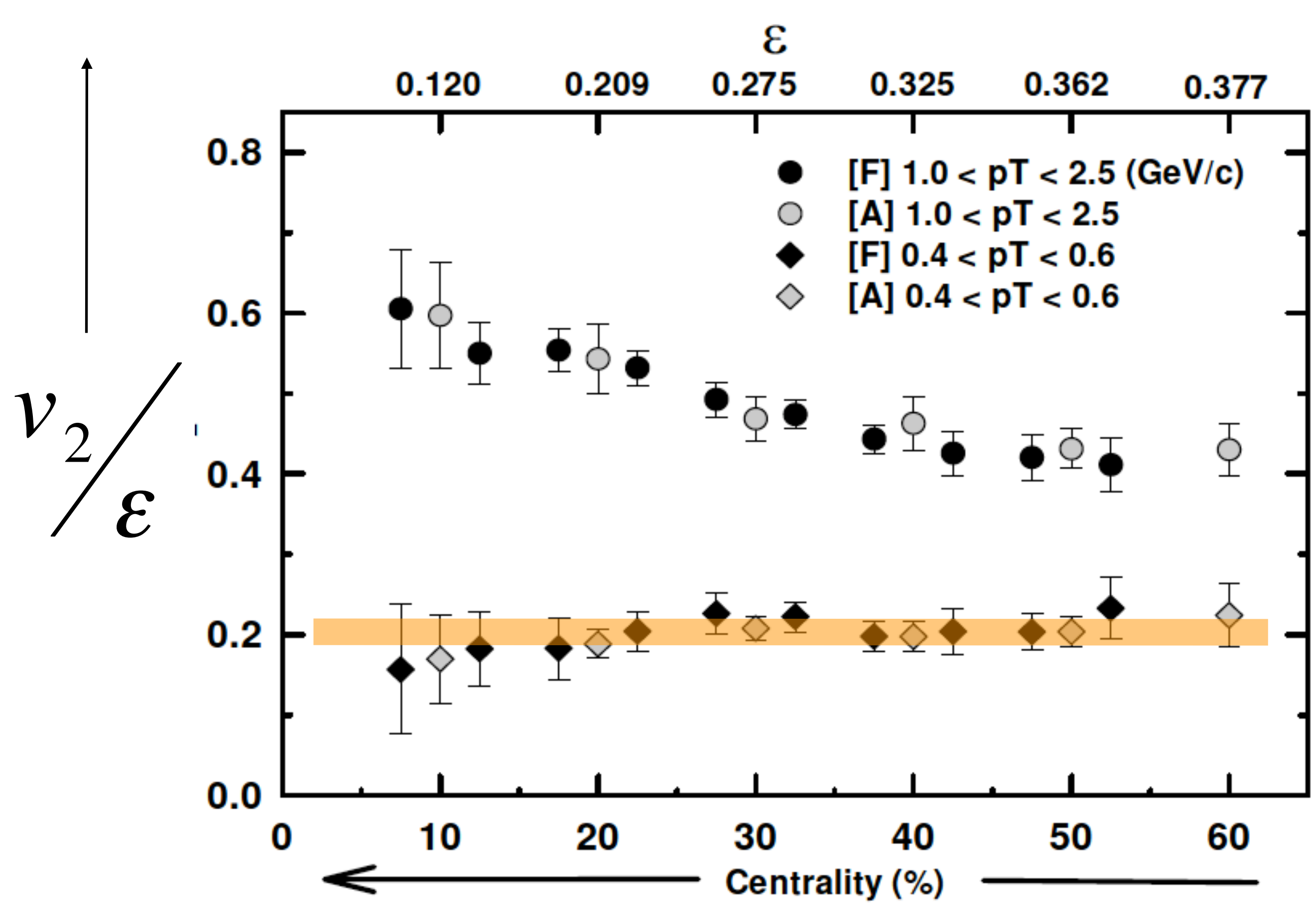
- In non-central collisions, participant region has almond shape.
  - ➡azimuthal anisotropy in coordinate space
- If λ << R, azimuthal anisotropy of the coordinate space is converted to that of the momentum space.
  - ➡v_2 ; second Fourier harmonics of azimuthal distribution
- Goodies :
  - Clear origin of the signal
  - Collision geometry can be determined experimentally

$$N(\phi) = N_0\{1 + 2v_1\cos(\phi - \Psi_0) + 2v_2\cos(2(\phi - \Psi_0))\}$$

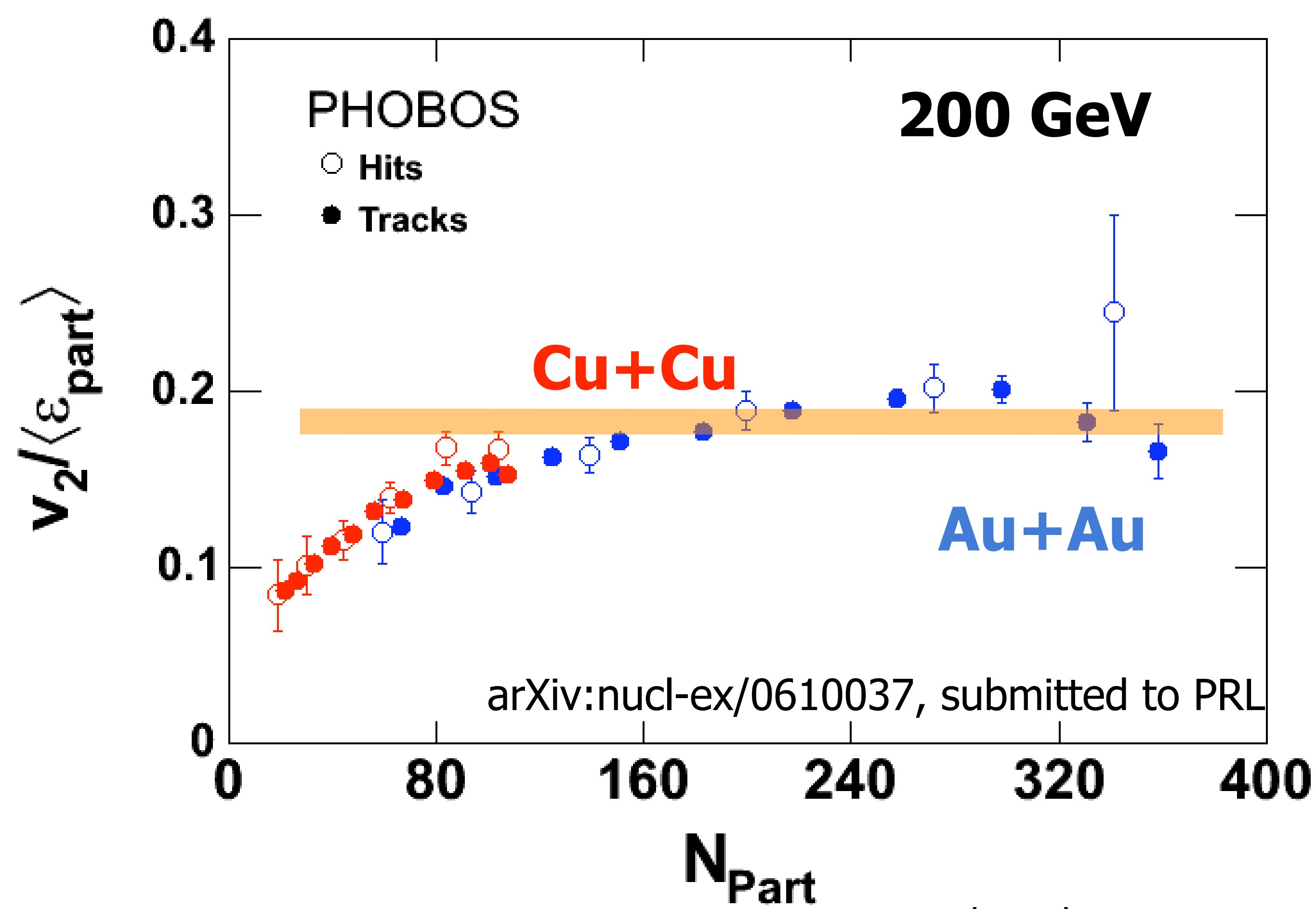
v_2 vs. Eccentricity



Phenix; PRL 89(2002)212301



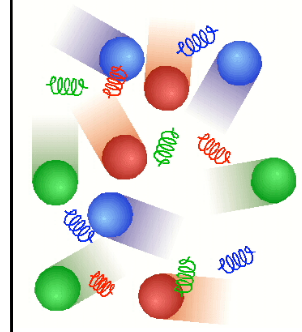
Phobos; nucl-ex/0610037



$\because \langle v_2 \rangle \propto \varepsilon$

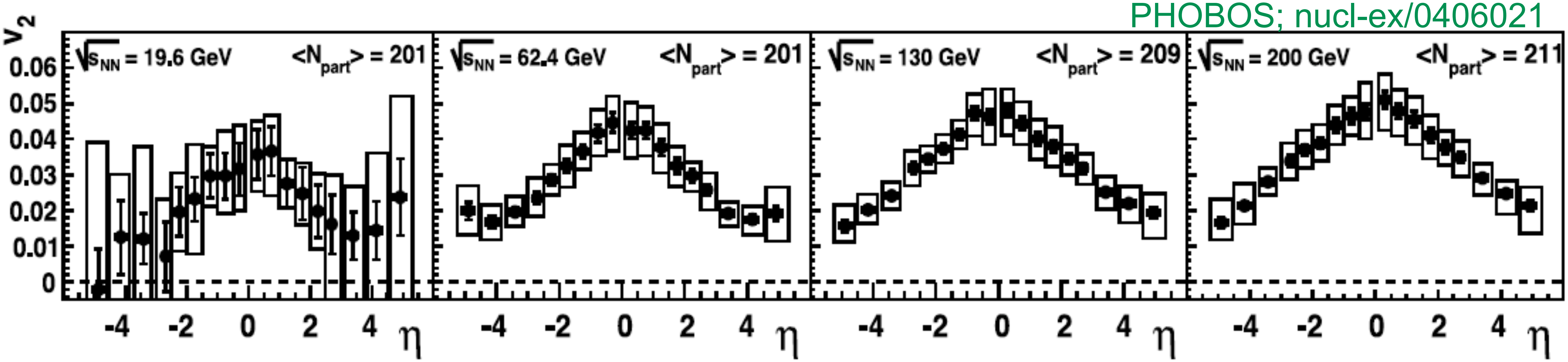
- ✓Eccentricity is evaluated from centrality of collisions
- ✓Ratio stays ~constant
  - ✦Eccentricity scaling observed in comparison of Au+Au, Cu+Cu
    - ➔Scaling with eccentricity shows v_2 builds up at early stage

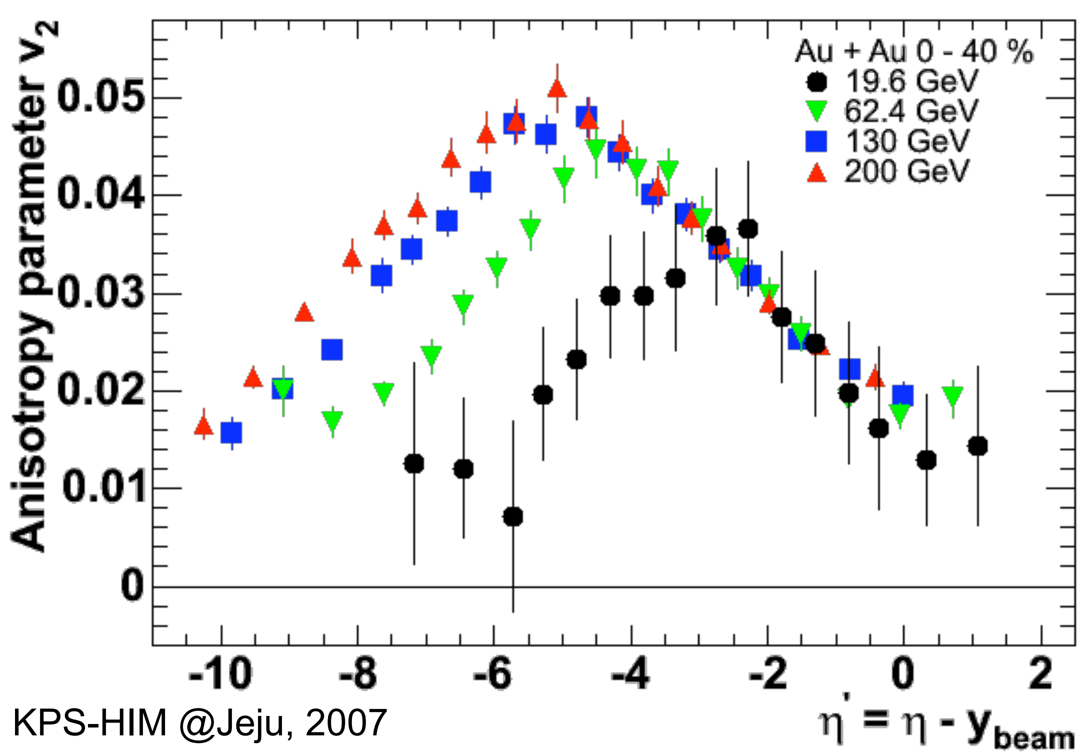
Large azimuthal anisotropy



$$N(\phi) = N_0\{1 + 2v_1\cos(\phi - \Psi_0) + 2v_2\cos(2(\phi - \Psi_0))\}$$

PHOBOS; nucl-ex/0406021

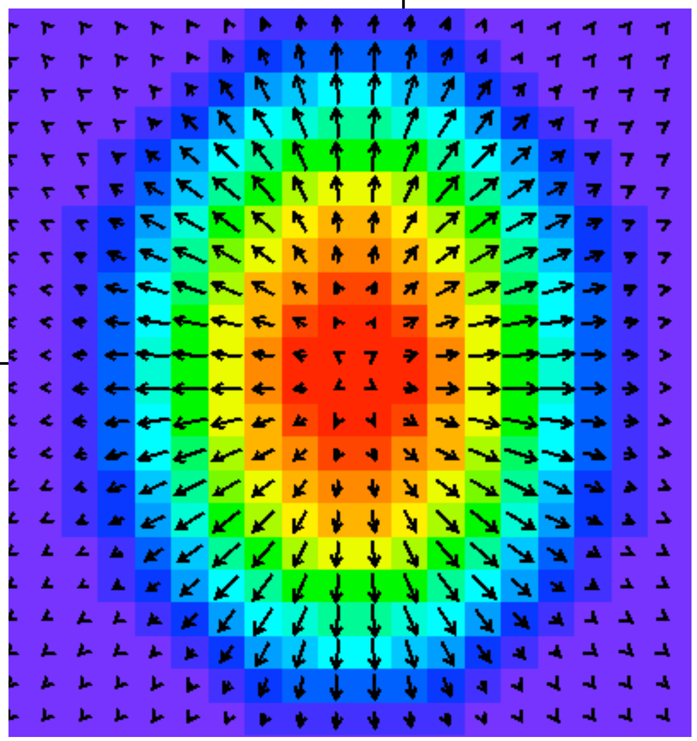




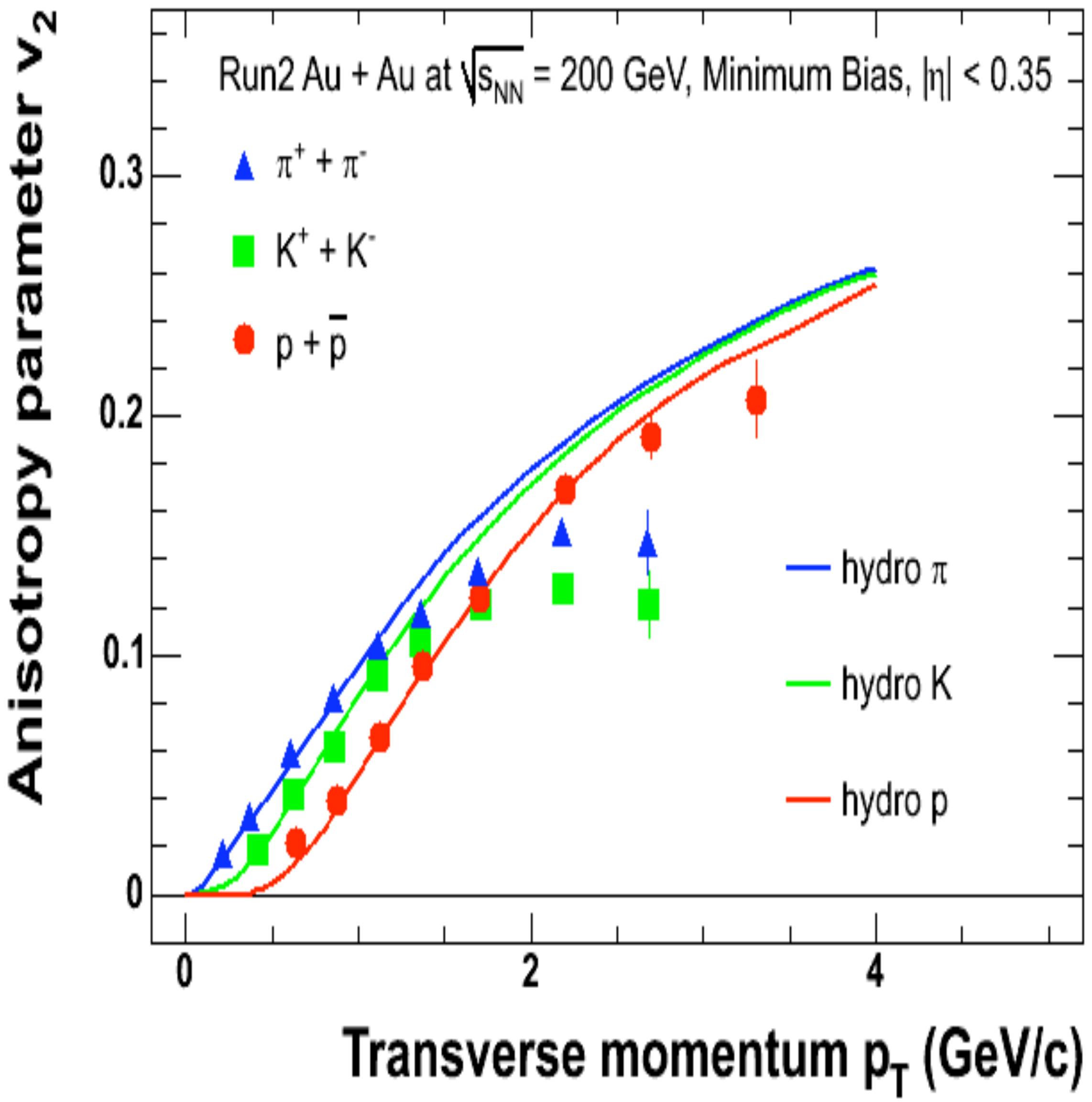
✓ Getting larger & larger in higher energies.

✦ Scaling w. η-y_{beam} !?

Collective Flow



PHENIX : P.R.L. 91, 182301 (2003)



- ✓ Mass Ordering of v_2 at low p_t region:
  - ➡ Existence of collective flow
- ✦ Good agreement with hydrodynamics of perfect fluid
  - Early thermalization (~0.6 fm/c)
  - High energy density (~20 GeV/fm^3)
  - Low viscosity
- ✓ Departure at high pt region (> 1.5 GeV/c);
  - ➡ Other mechanism?

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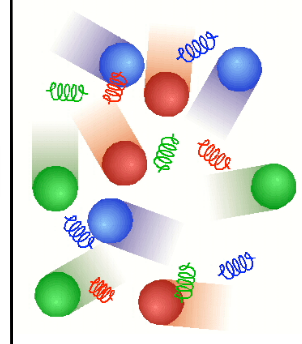
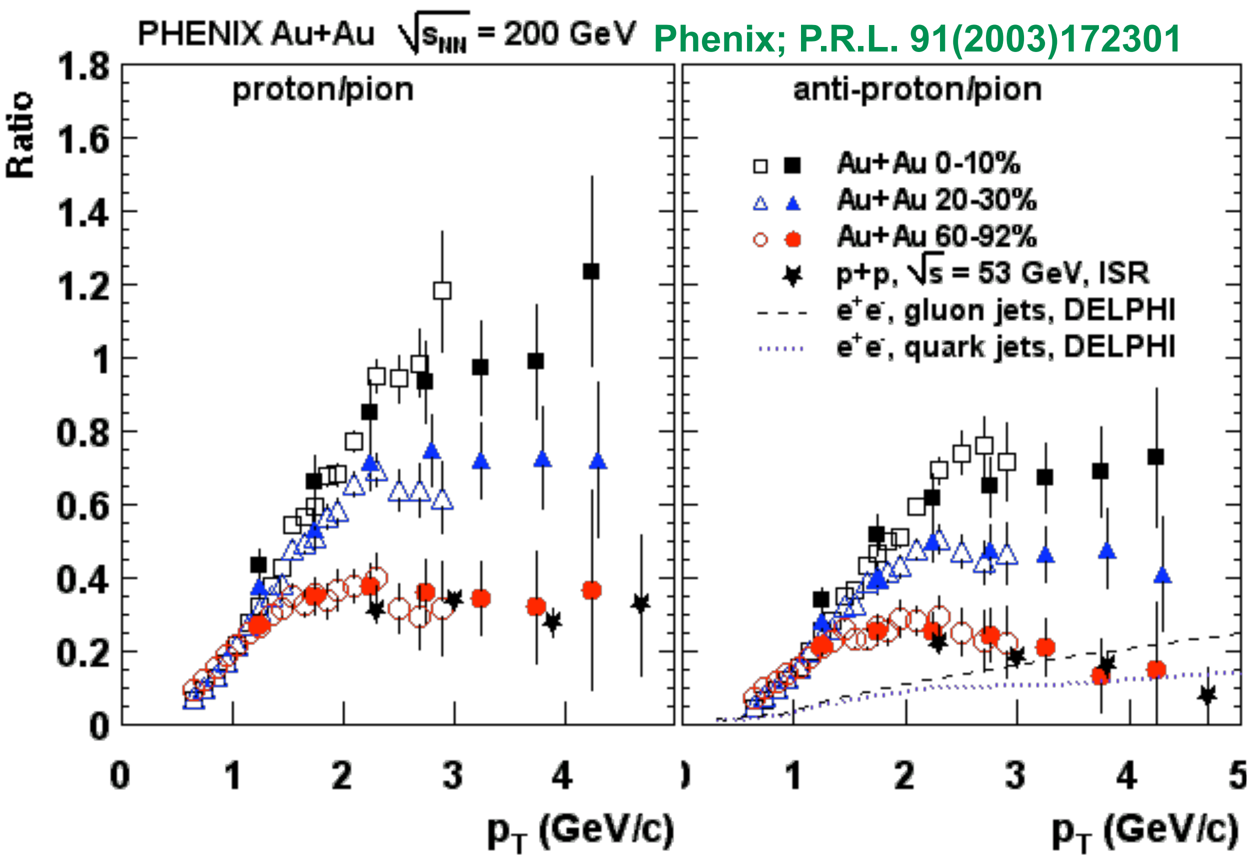
Quark Soup

PHYSICISTS RE-CREATE THE LIQUID STUFF OF **THE EARLIEST UNIVERSE**

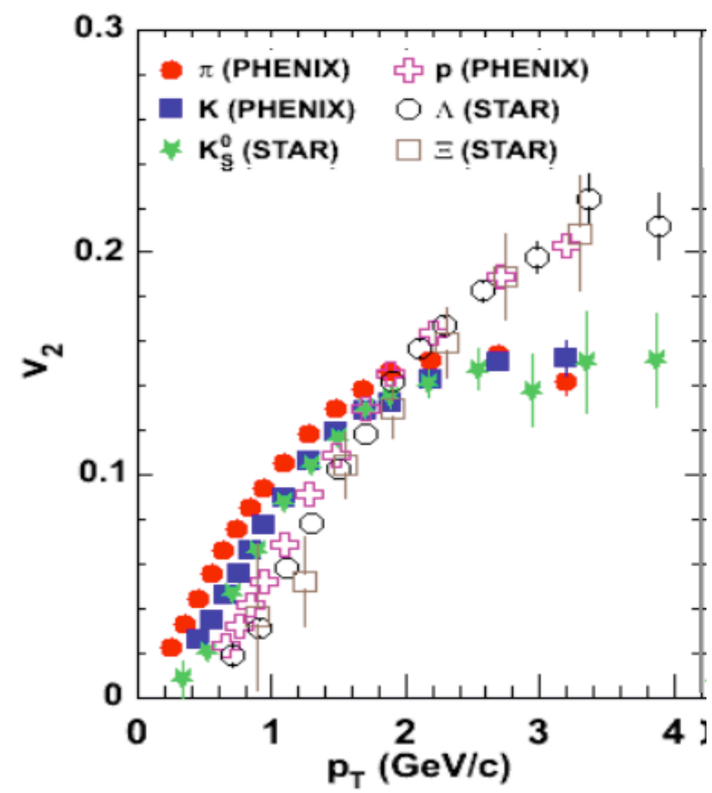
Puzzles in the mid-p_t region



p/π enhances above 1.5 GeV/c



v_2 deviates from the mass ordering above 2 GeV/c

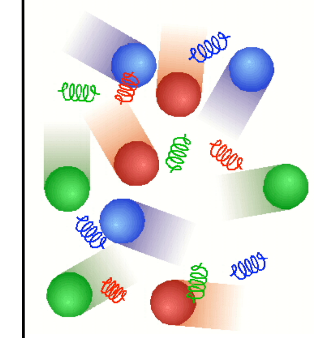


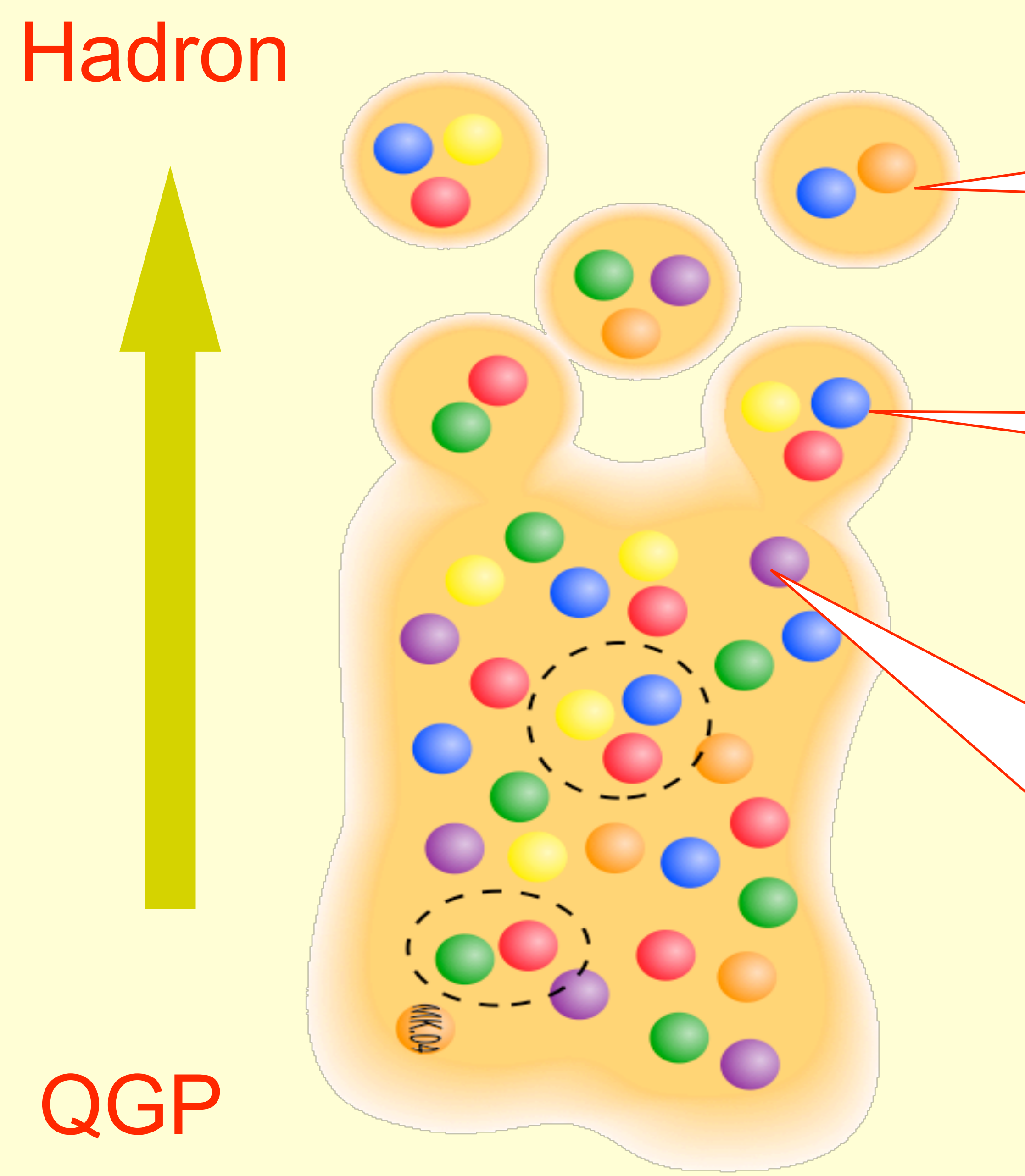
- ✓ In central col., p/π ratio is very large, while in peripheral, p/π ratio similar to those in ee/pp suggesting fragmentaton process.
  - Fragmentation process should show $n_p < n_\pi$ as seen in ee/pp.
- ✓ While mass ordering of v_2 seen at low pt region, clear departure observed.
- ✓ Suggesting other production mechanism.

↓

Quark Recombination Model (Quark Coalescence Model)

Quark recombination model (RECO)





Because of the steep distr. of *w(pt), RECO* wins at high pt even w. small *Cx*.

✓ **Quarks, anti-quarks combine to form mesons and baryons from universal quark distribution, w(pt).**

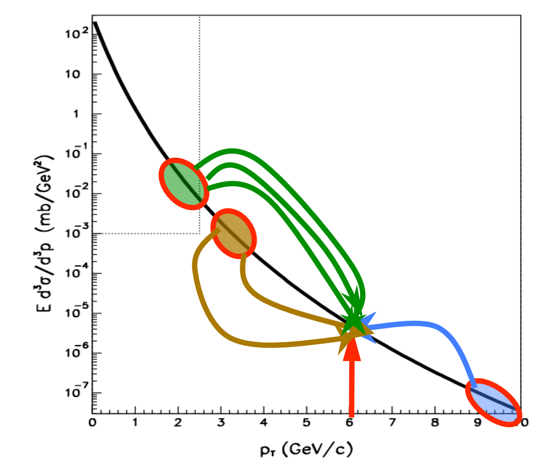
Mom. distr. of meson (2q);

$$W_{\mathrm{M}}(p_t) \approx C_{\mathrm{M}} \cdot w^2(p_t/2)$$

Mom. distr. of baryon (3q);

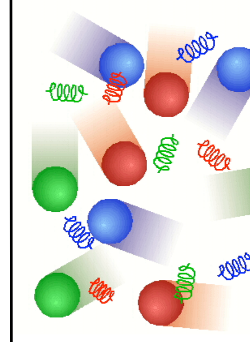
$$W_{\mathrm{B}}(p_t) \approx C_B \cdot w^3(p_t/3)$$

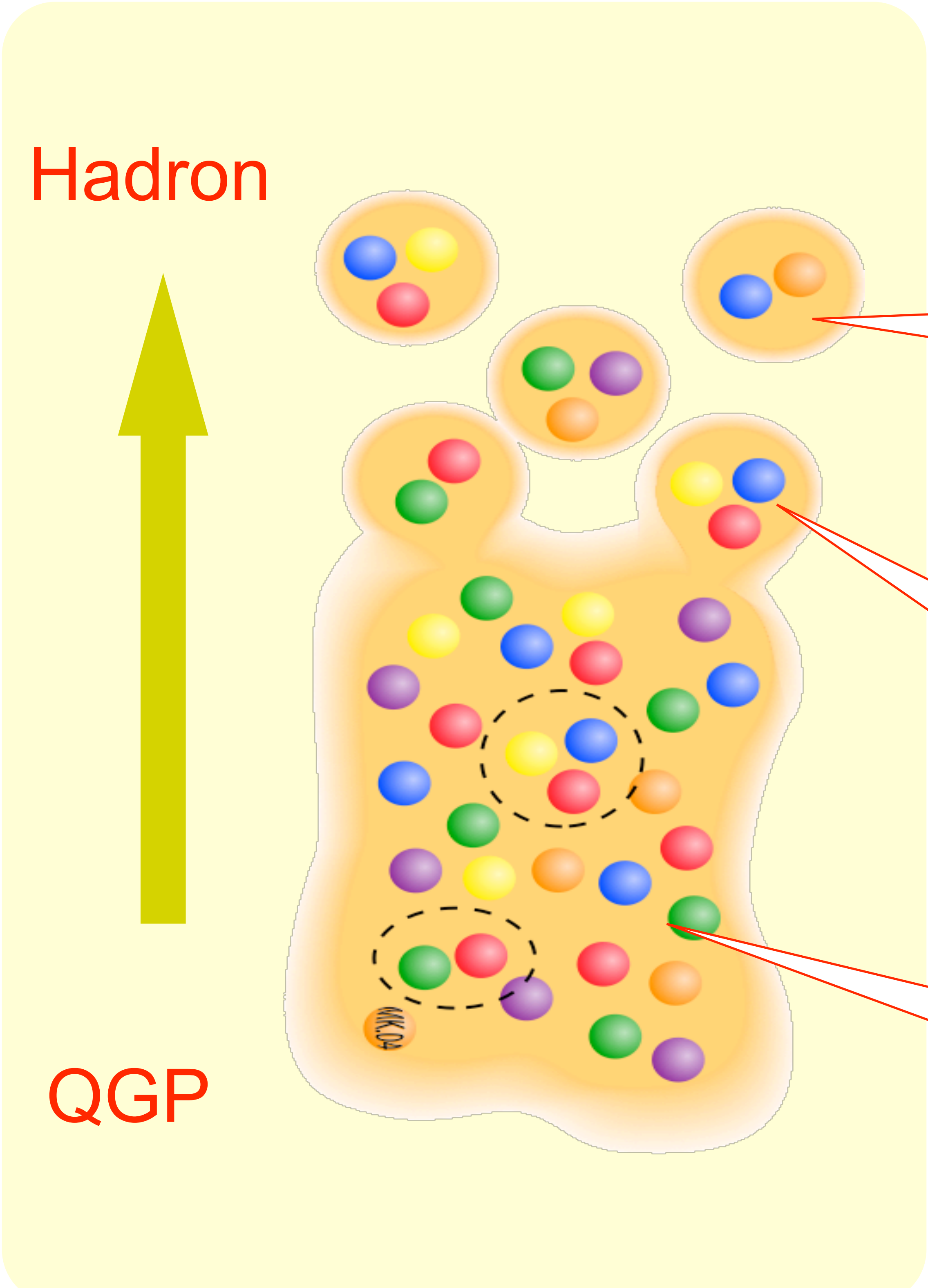
w(pt);
Universal mom. distr. of quarks
{*steep in pt*}



Characteristic scaling features expected.
➔Quark number scaling

V_2 from RECO





√ **Characteristic scaling behavior**

→**Quark Number Scaling**

Azimutal distr. of meson (2q);

$$\frac{dN_M}{d\phi} \propto w^2 = (1 + 2v_{2,q}\cos 2\phi)^2$$

$$\approx (1 + 4v_{2,q}\cos 2\phi)$$

Azimuthal distr. of baryon (3q);

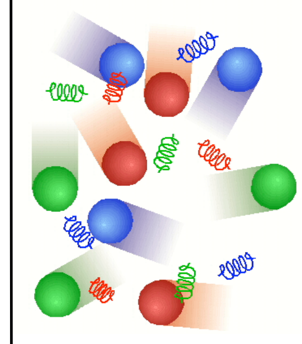
$$\frac{dN_B}{d\phi} \propto w^3 = (1 + 2v_{2,q}\cos 2\phi)^3$$

$$\approx (1 + 6v_{2,q}\cos 2\phi)$$

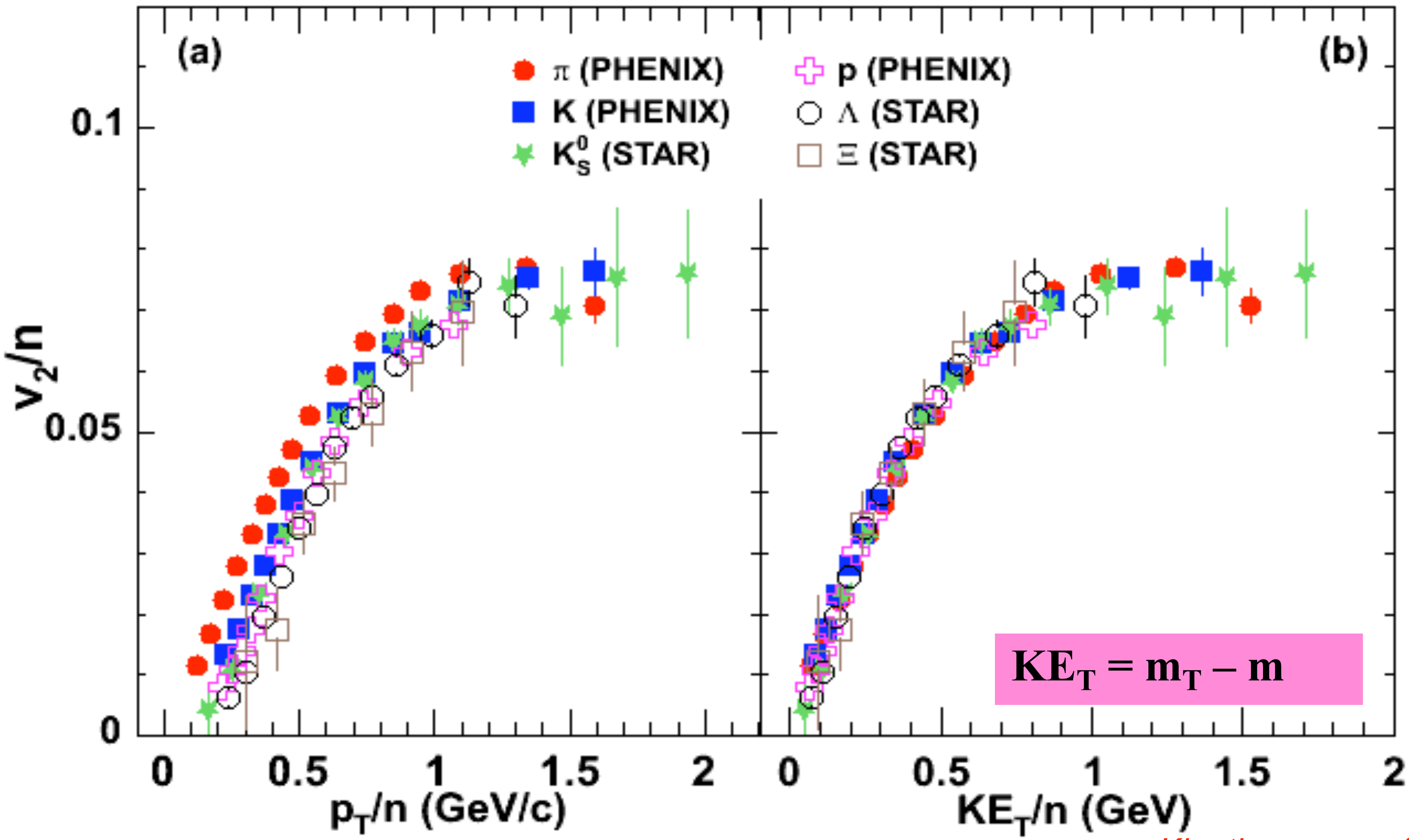
Azimuthal distr of quark; w

$$w \propto (1 + 2v_{2,q}\cos 2\phi)$$

Quark Number Scaling !!



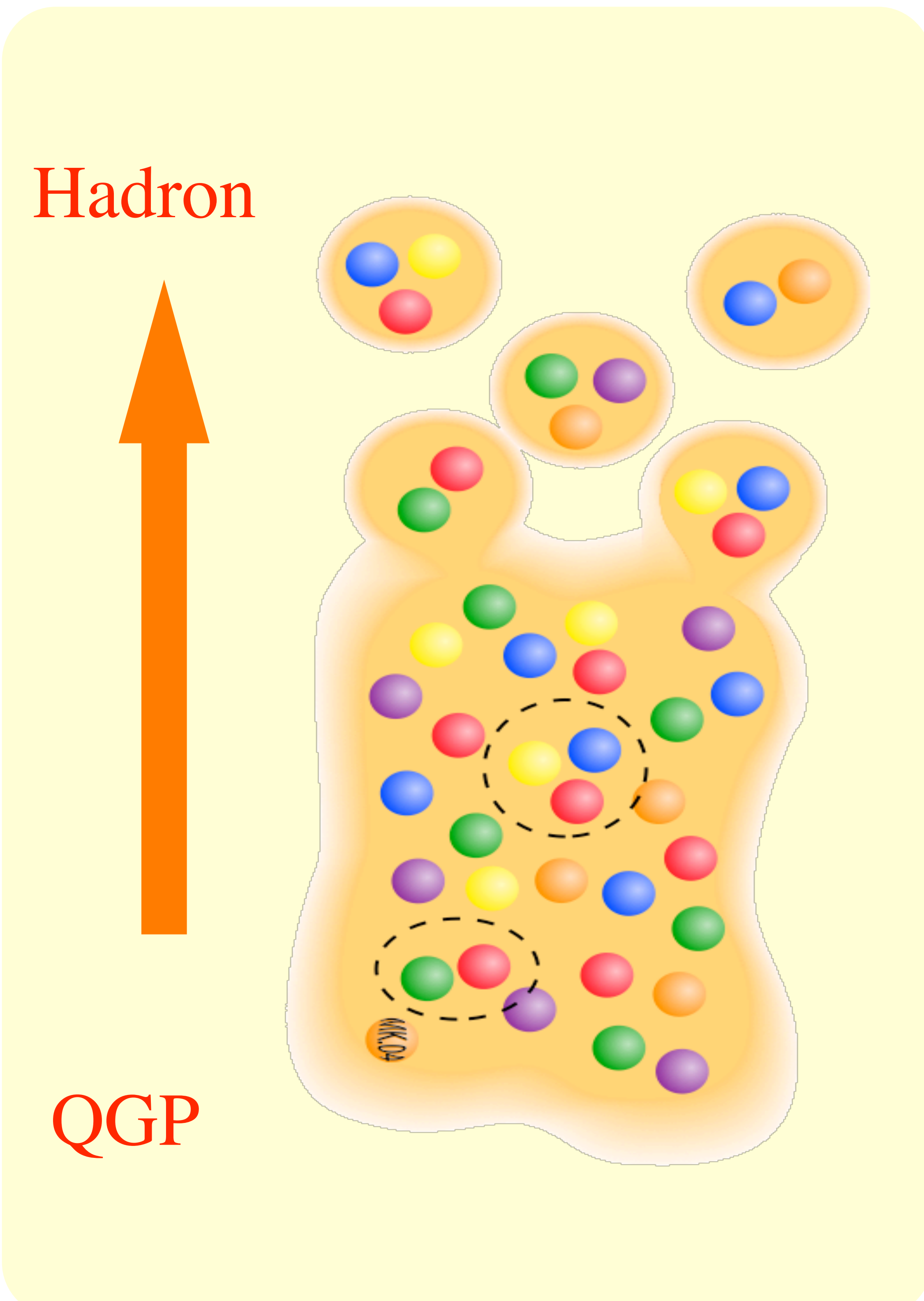
M. Issah, A. Taranenko, nucl-ex/0604011



Kinetic energy of constituent quarks

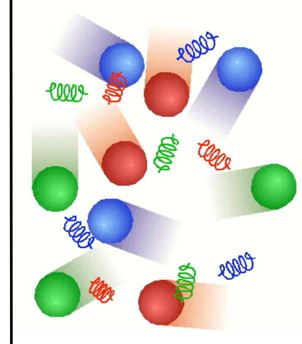
✓ **Mesons and baryons made of light quarks seem to be consistent with the recombination model and there seem to be universal quark distribution, w(pt,Φ).**

Somewhat weird feeling of KE_T scaling



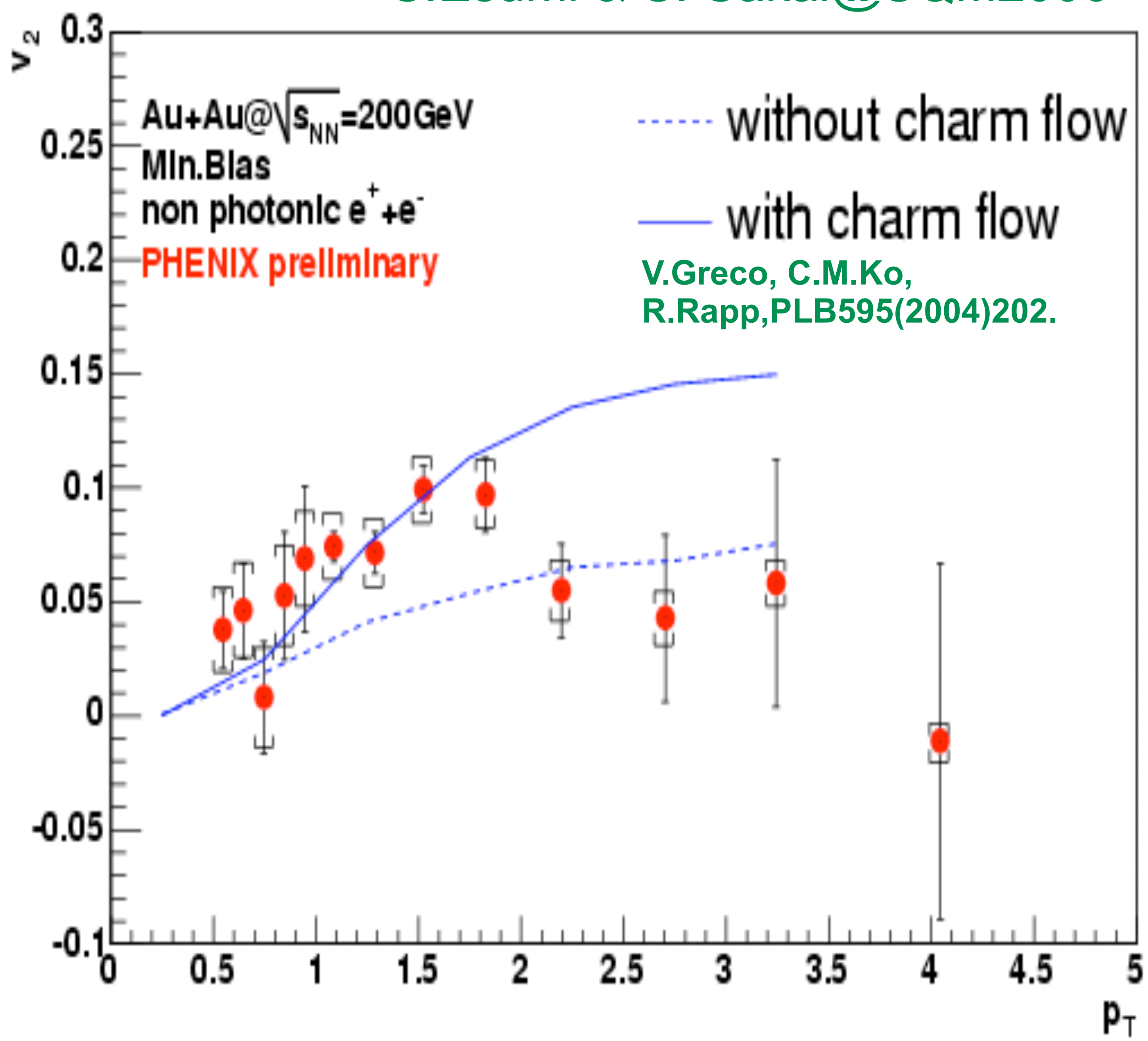
- Where or what is the role of gluons in Reco?
- Universal behavior with kinetic energy of effective mass of quarks ?
  - Quarks wear the gluons first, knowing which hadron they will be.(Effective mass)
  - Then, coalesced and boosted by the pressure behind.

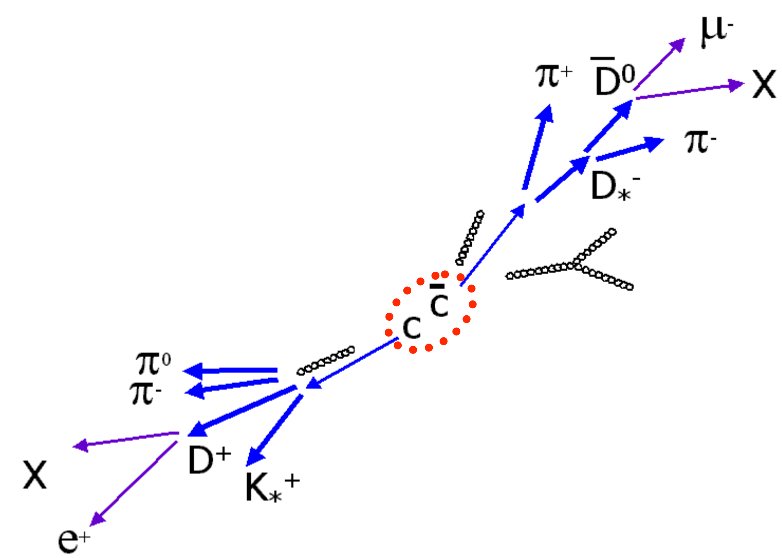
Even charm flows!



v2 of single electrons

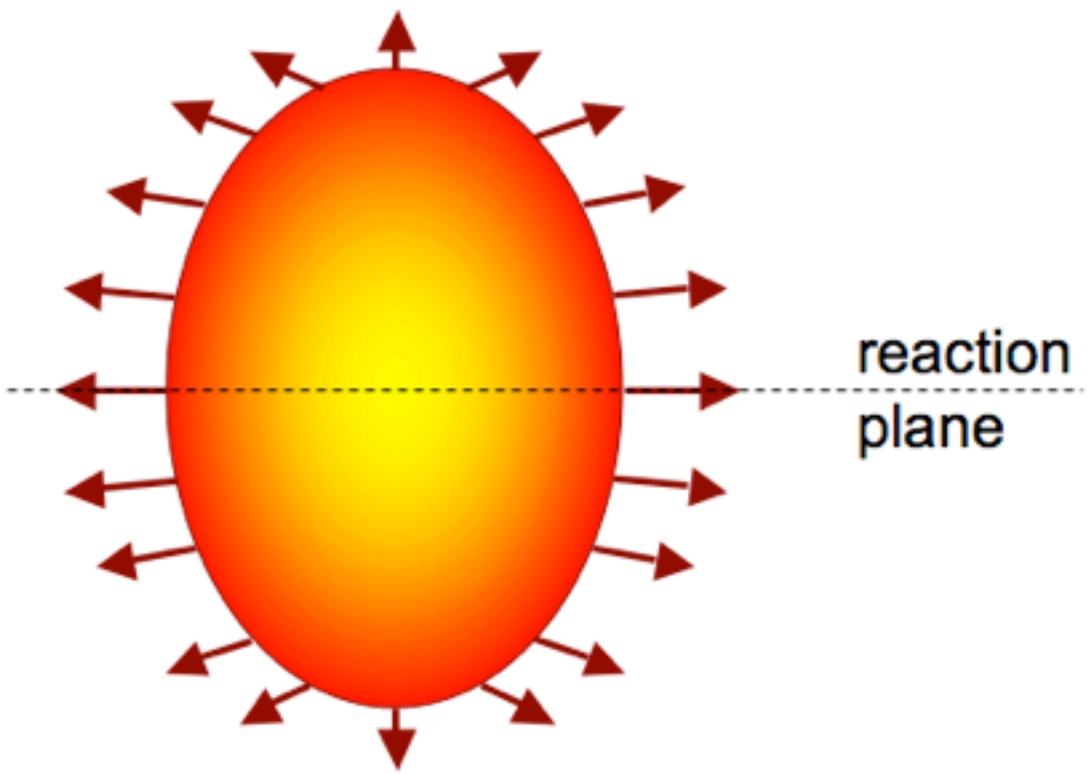
S.Esumi & S. Sakai@SQM2006





- √ Charm decay produces high energy electrons.
- √ v_2 of single electrons are measured.
- √ Observed data favors flow of charm, suggesting thermalization of heavy quarks.
- √ This supports quark-coalescence & formation of QGP.
- √ Best to measure v_2 of J/ψ

Extended Blast-wave model



$$E\frac{d^3N}{dp^3} = \int_{\Sigma_f} f(x,p)\, p^\mu d\Sigma_\mu$$

$$f(x,p) = \frac{1}{(2\pi)^3}\frac{1}{e^{[(p_\mu u^\mu(x)-\mu(x))/T(x)]} \mp 1}$$

$$v_2 = \frac{\int_0^R r dr \int_0^{2\pi} d\phi \ \cos(2\phi) I_2(\alpha) K_1(\beta)}{\int_0^R r dr \int_0^{2\pi} d\phi \ I_0(\alpha) K_1(\beta)}$$

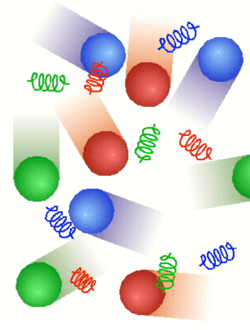
$$\alpha = \left(\frac{p_T}{T}\right)\sinh\rho, \quad \beta = \left(\frac{m_T}{T}\right)\cosh\rho$$

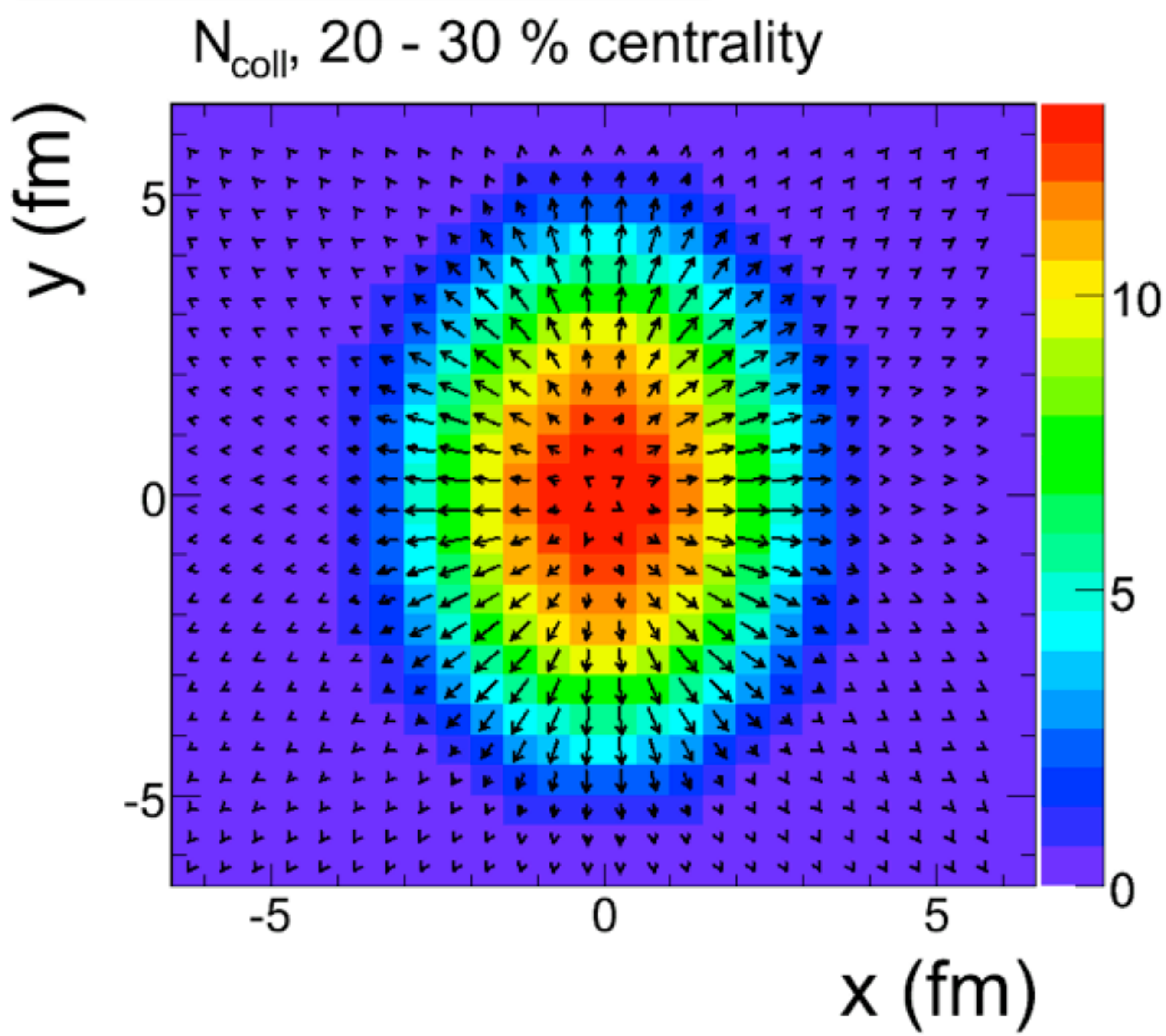
$$\beta_T(r) = \tanh\rho$$

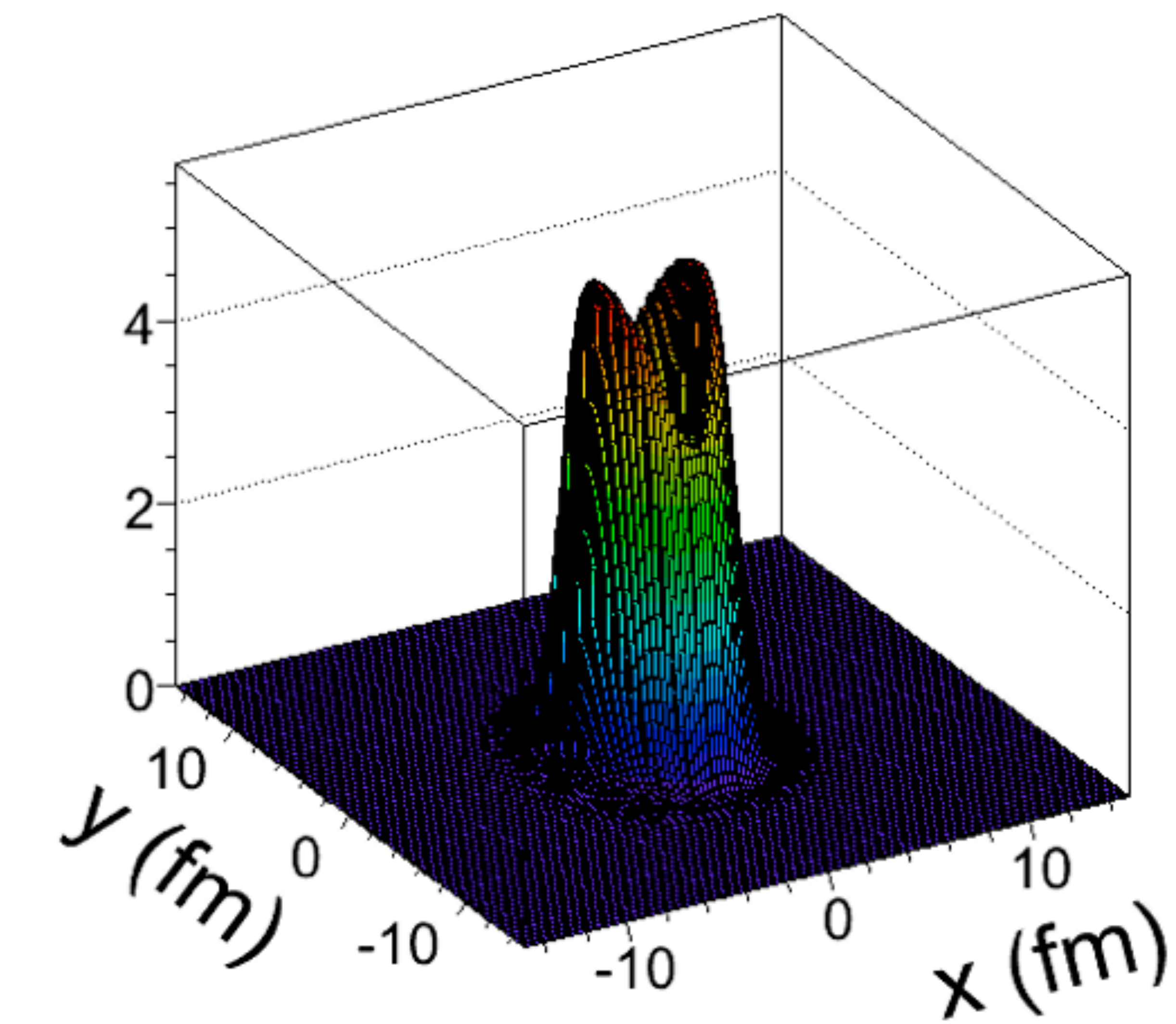
- Extend standard Blast-wave parameterization in order to fit $v_2(p_T)$ in non-central collisions
- Assumptions
  - Use density distributions from initial geometry overlap instead of uniform density
  - Velocity profile
    - Use Density gradient distributions
  - Eccentricity (ε) is fixed by initial overlap density
  - Velocity anisotropy (β_2) is fixed by the velocity profile
- 2 free parameters
  - Temperature: T
  - Magnitude of transverse boost velocity: β_T

H. Masui, Thesis, Tsukuba, 2007

N_{part} profile & N_{coll} profile



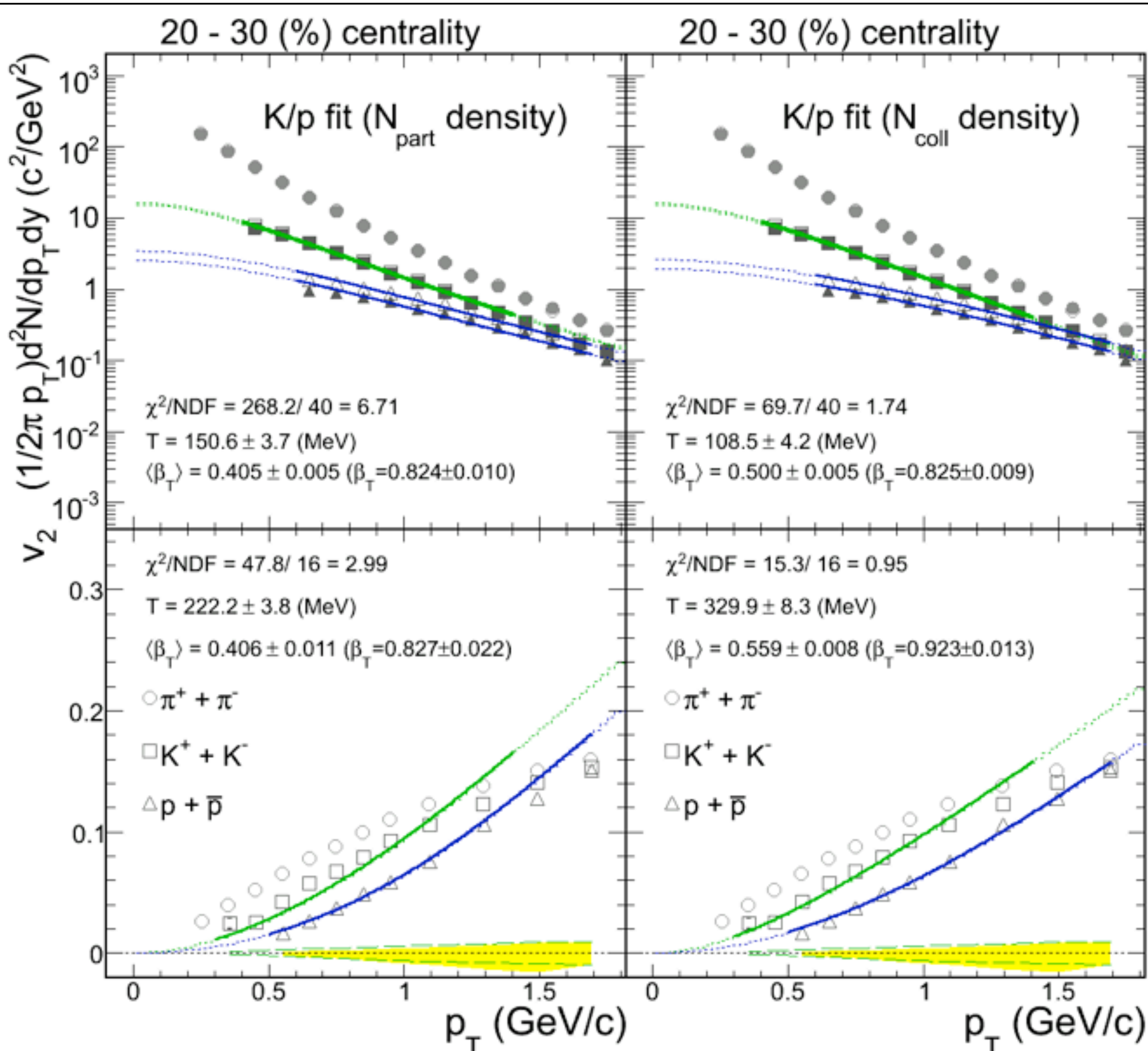




- Calculate $N_{part}(x, y)$ and $N_{coll}(x, y)$ from Woods-saxon density profile
  - Direction of density gradient ⇒ direction of boost
    - Length = magnitude of boost

H. Masui, Thesis, Tsukuba, 2007

N_{part} profile vs N_{coll} profile



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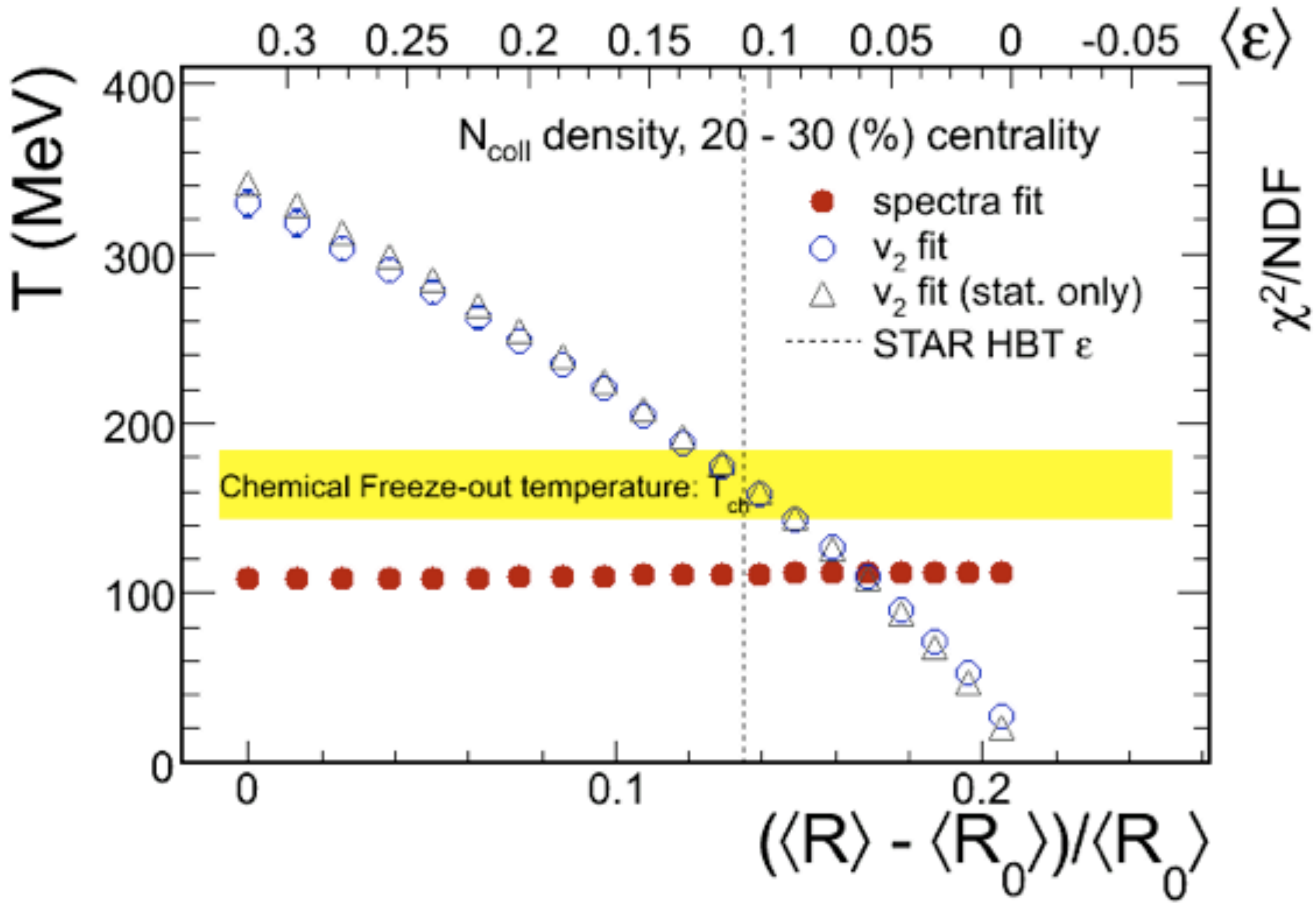
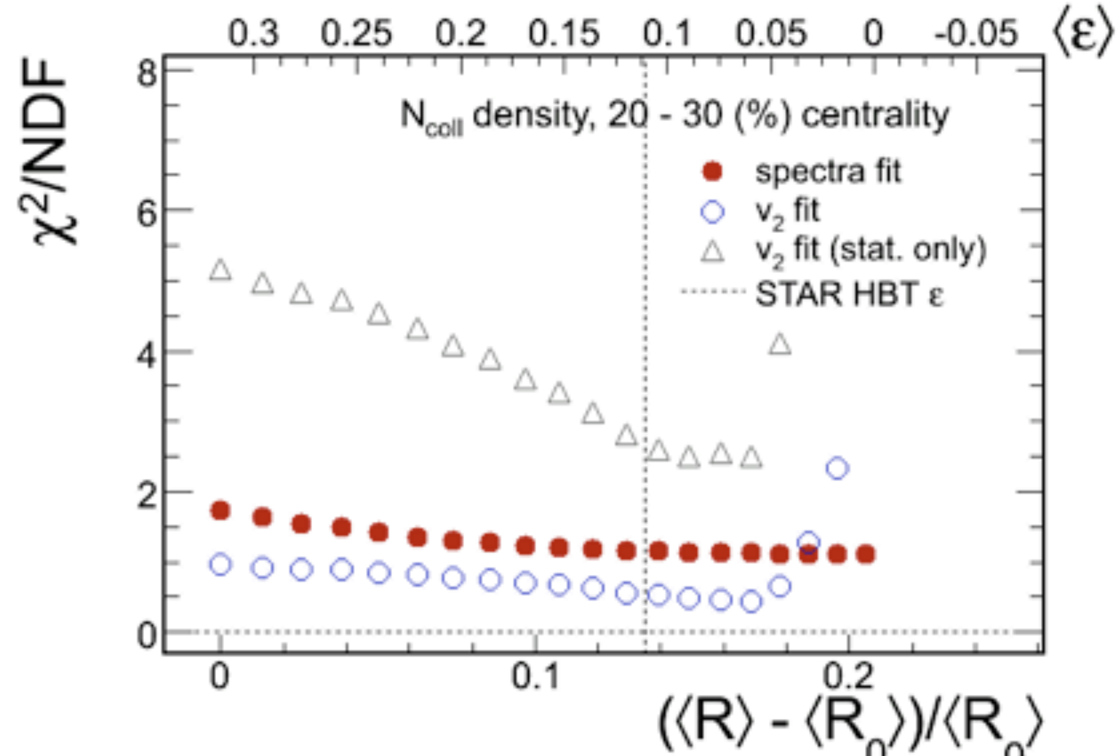
H. Masui, Thesis, Tsukuba, 2007

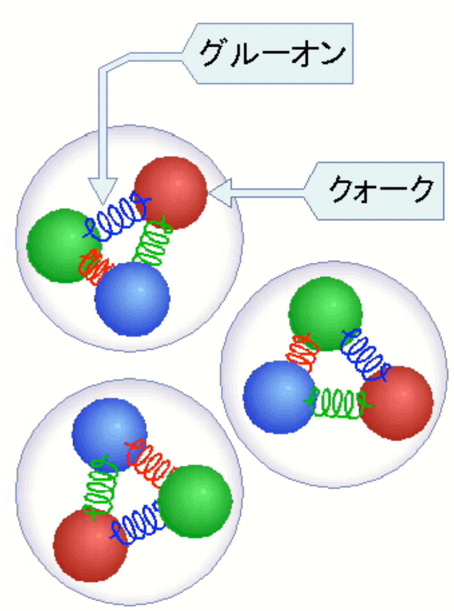
Results



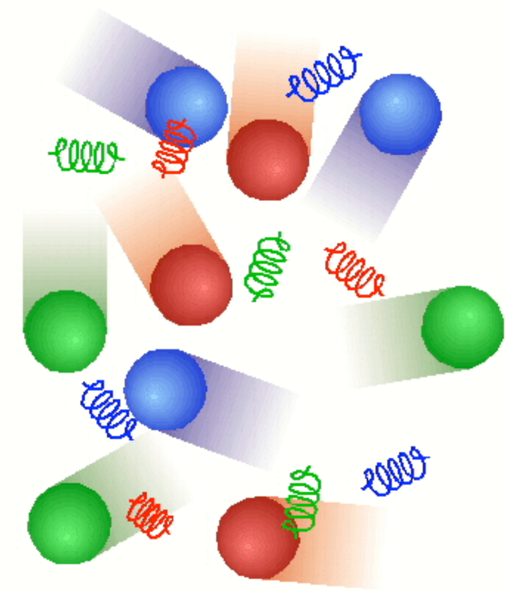


- Radial velocity and T from spectra are not changed with ⟨ε⟩
- Temperature from v_2 fit strongly decrease with ⟨ε⟩
  - χ^2/NDF < 1 up to ε ~ 0.05 with systematic error
- T(v_2) ~ T_{ch} (150 MeV) > T(spectra) at the eccentricity extracted by HBT analysis ⇒ early freeze-out of v_2 ?

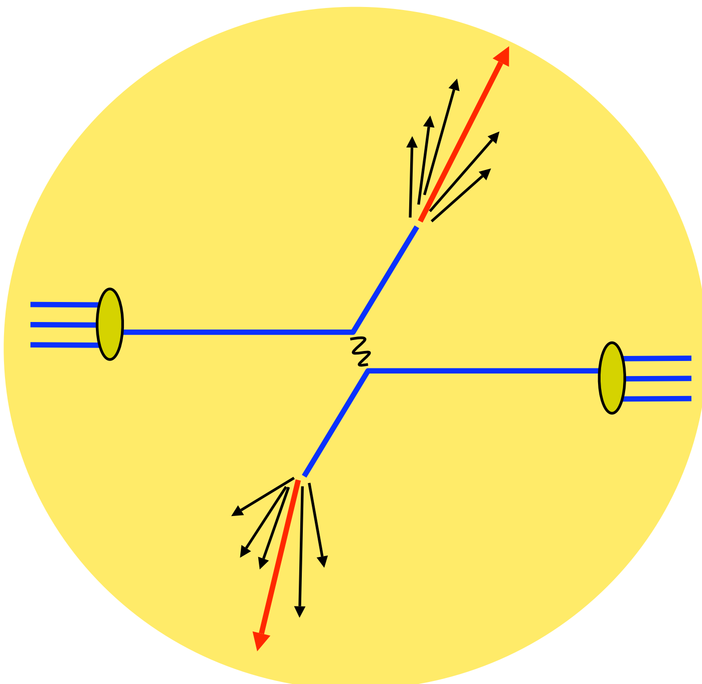
H. Masui, Thesis, Tsukuba, 2007



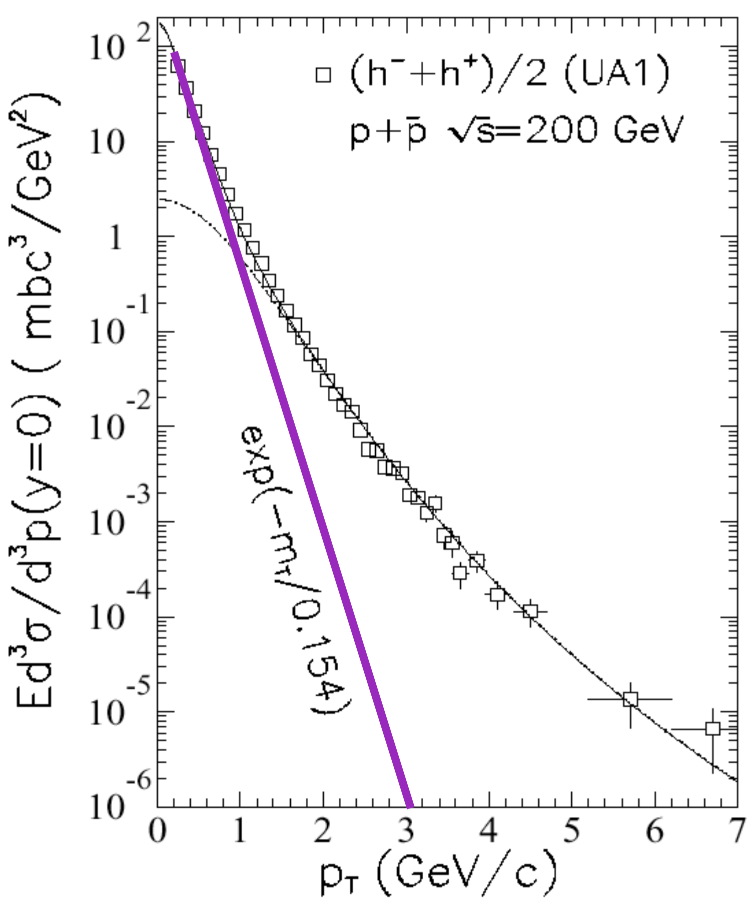
Jet Modification



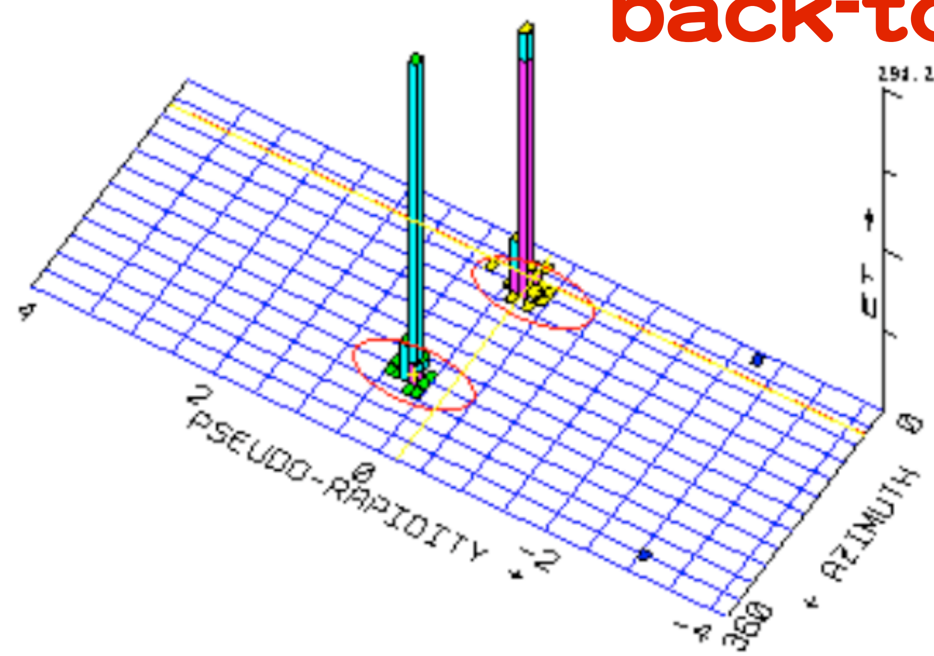
What is Jet ?



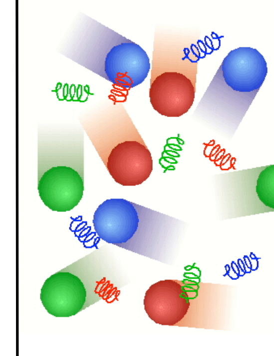
- ✓At ISR in 1972, deviation from the m_t scaling at high p_t region is observed as a first time.
- ✓Binary parton scattering followed by fragmentation produces back-to-back jet.
- ✓Main source of high pt particles.

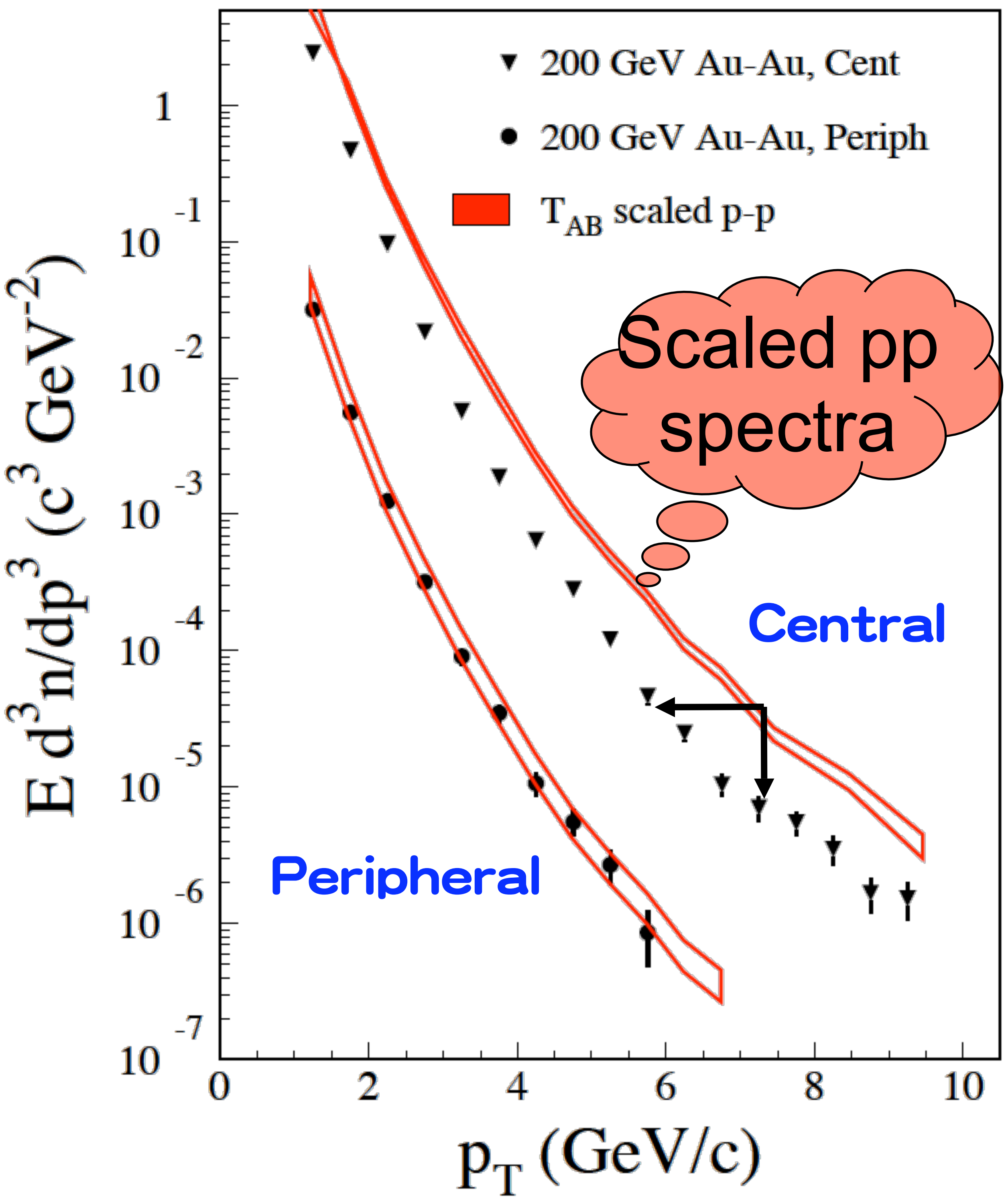


back-to-back



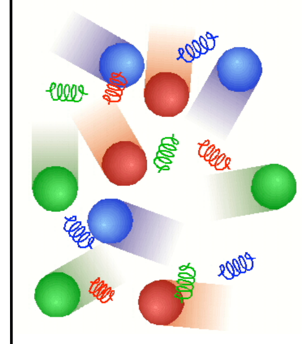
Comparison of Au+Au and pp





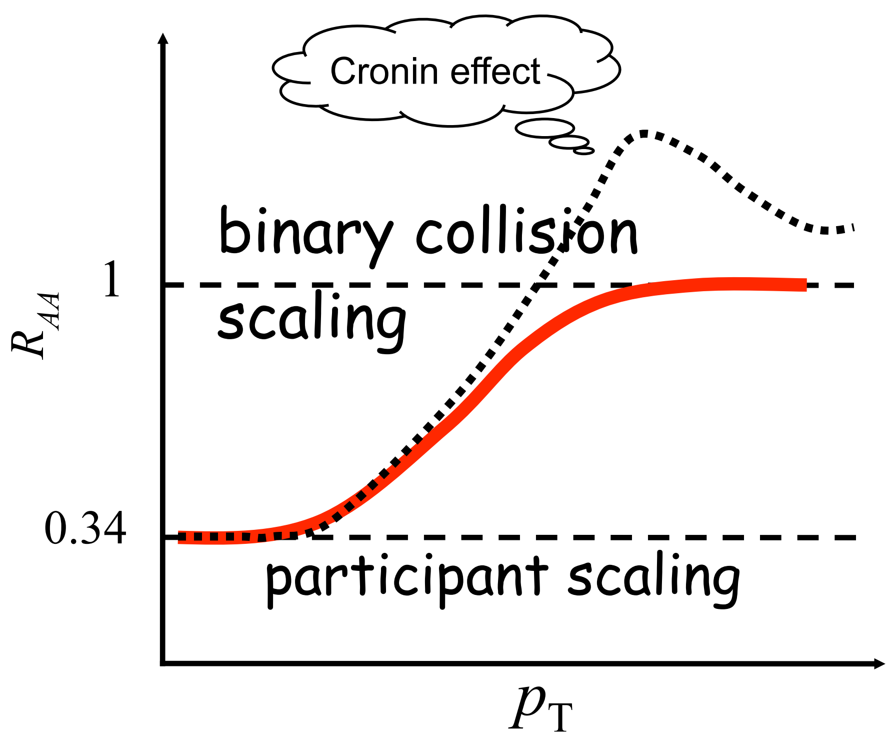
- For comparison, Au+Au & pp spectra scaled by N_{binary}.
- In peripheral collisions, Au+Au ~ pp
- In central collisions, Au+Au < pp
  - Suppression of yield ?
  - Loss of p_T ?
  - Jet Quench?

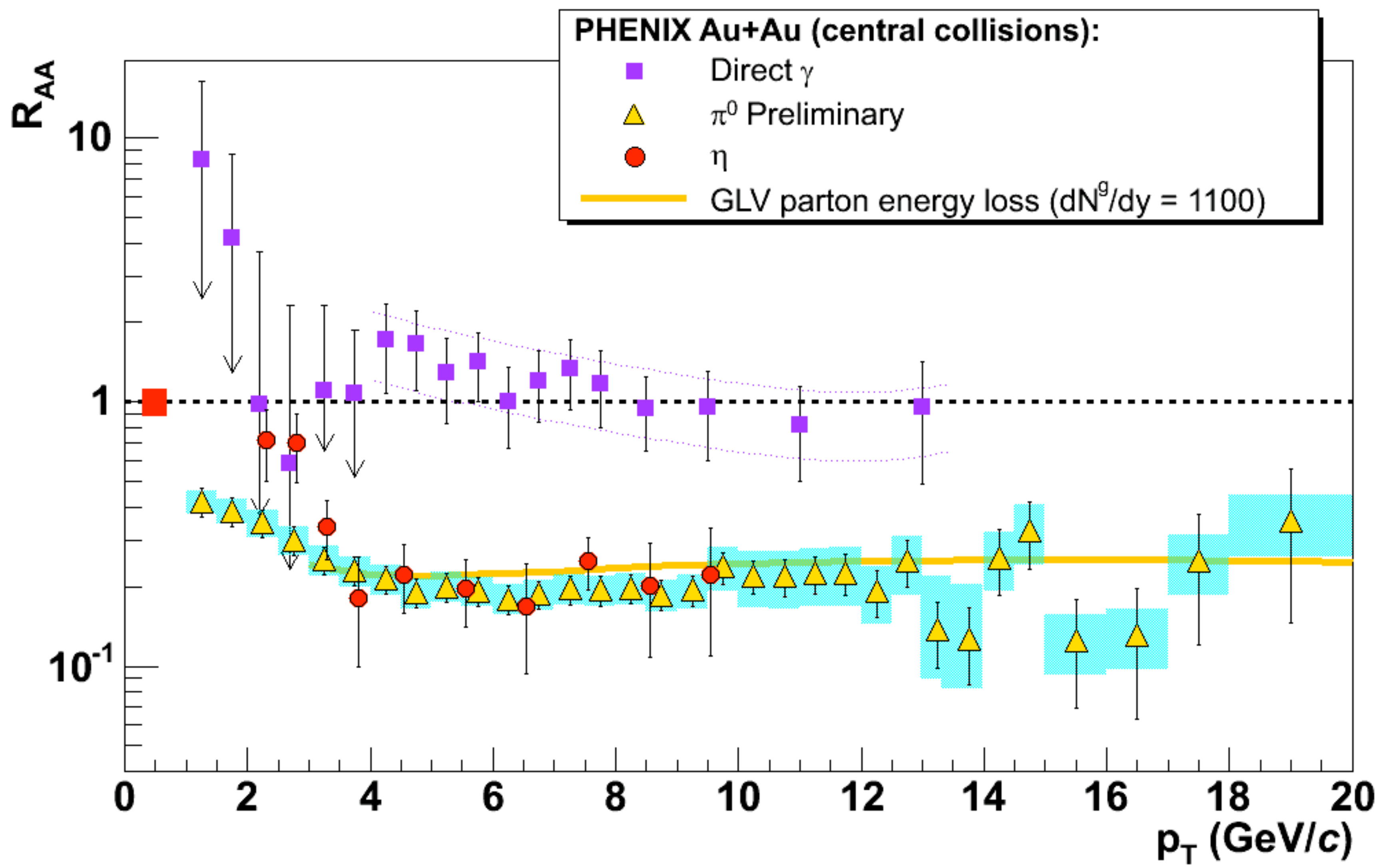
Suppression of high p_t particles



Nuclear Modification Factor

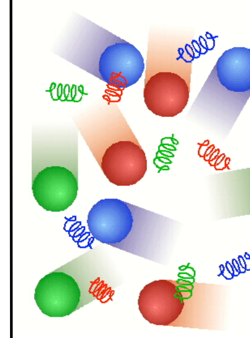
$$R_{Au+Au} = \frac{dn_{Au+Au}/dp_T dy}{\langle N_{binary} \rangle \cdot dn_{pp}/dp_T dy}$$



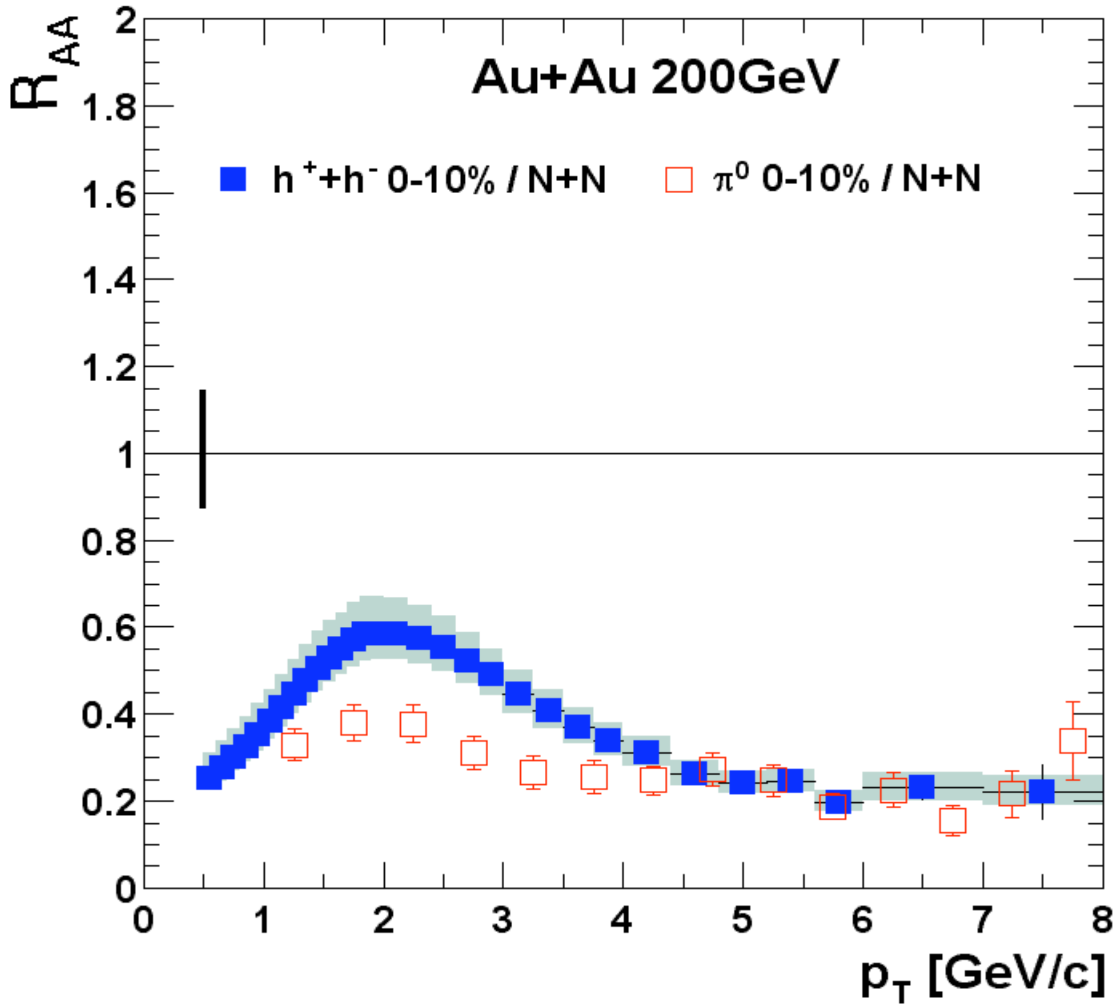


✓ **Pions are suppressed, direct photons are not**

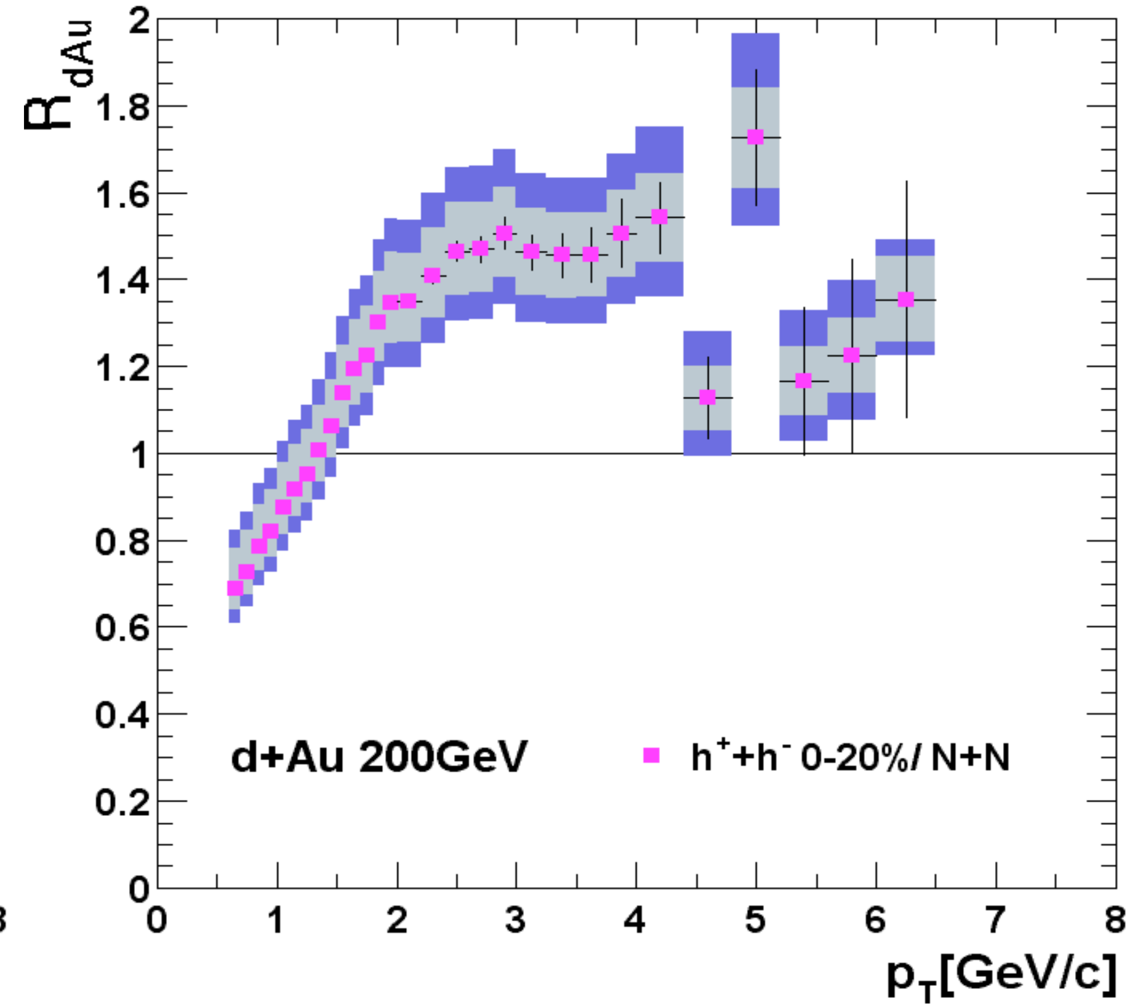
Au+Au vs d+Au



Phenix; P.R.L. 91, 072303 (2003)



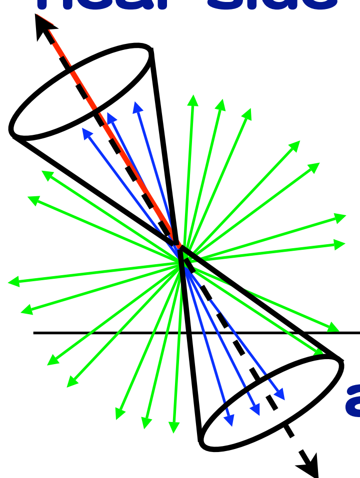
Au+Au at $\sqrt{s_{NN}}$ = 200 GeV



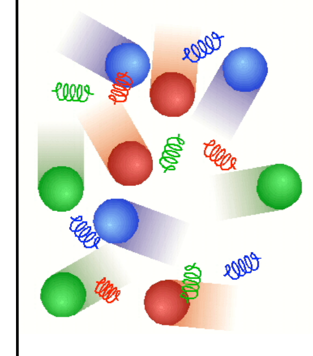
d+Au→$h^{\pm}$+X at $\sqrt{s_{NN}}$ = 200 GeV

✓**High pt suppression in Au+Au, while not observed in d+Au.**

➡**Effect is not due to initial state, but final state.**

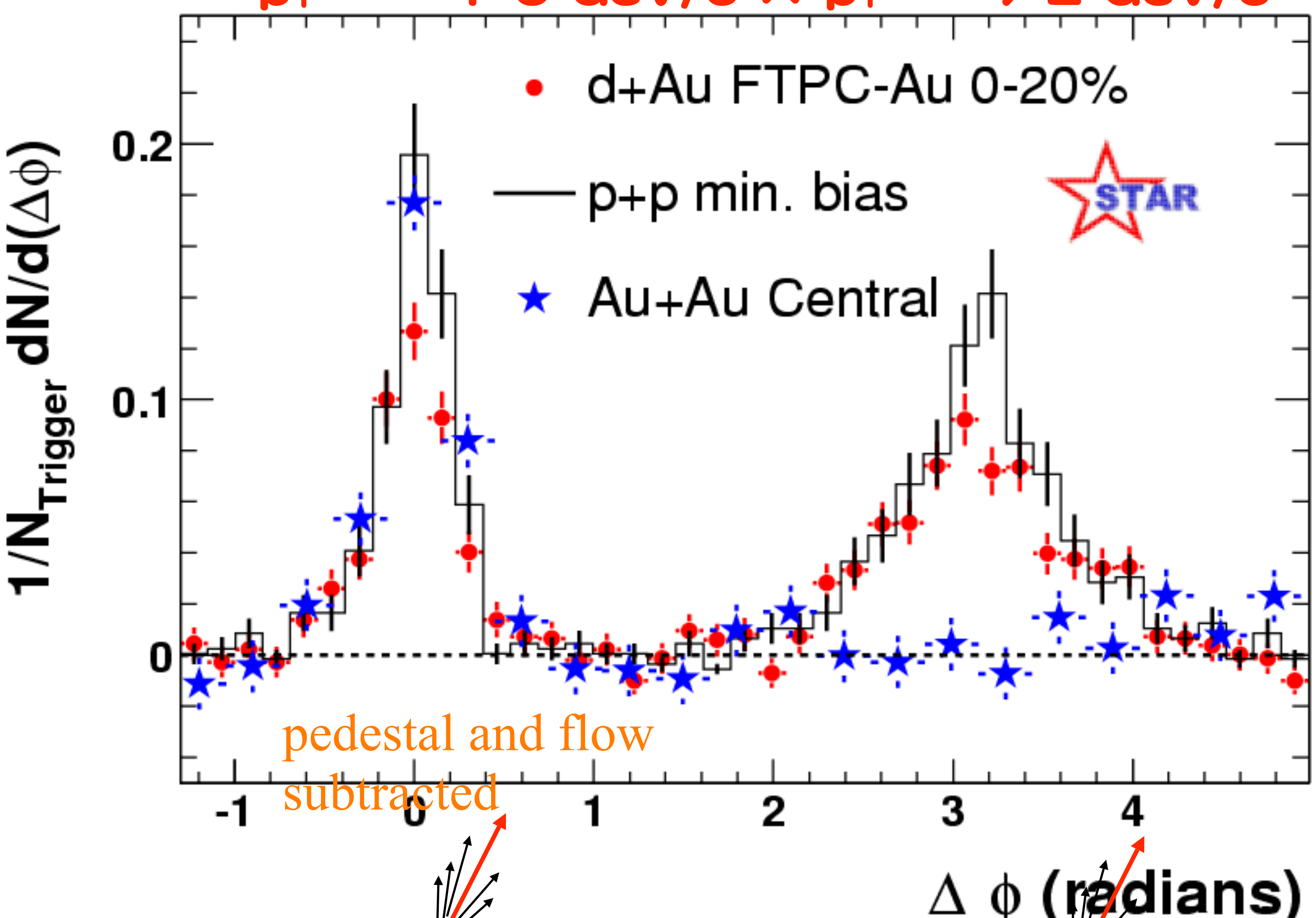


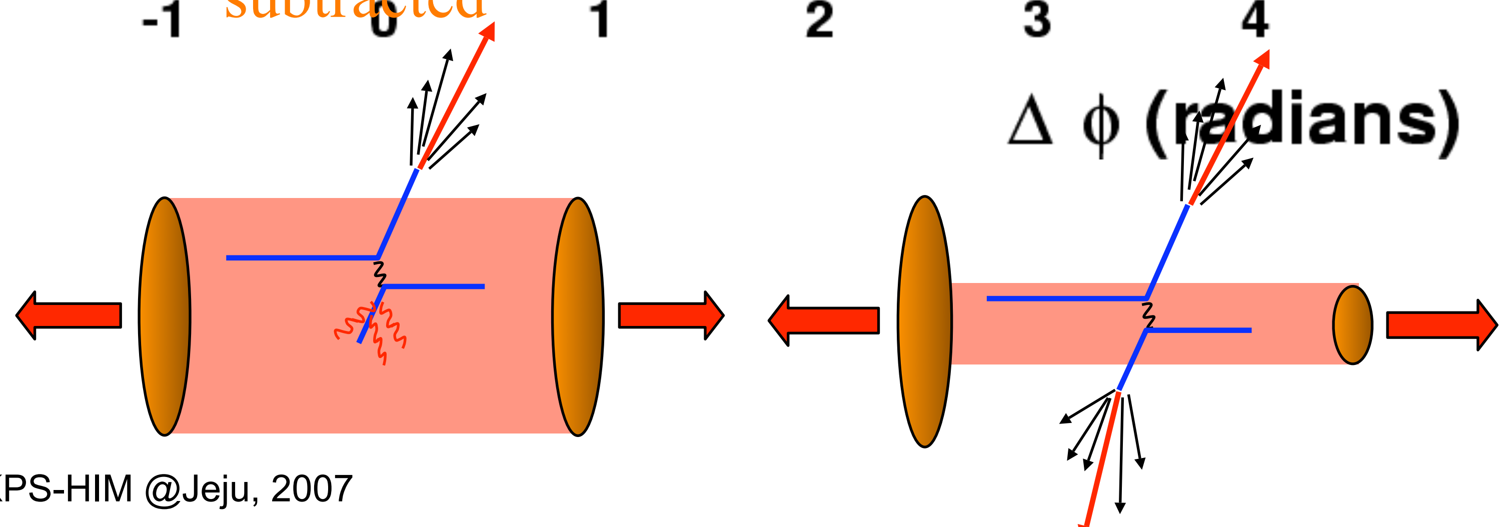
Disappearance of back-to-back corr.



Star; P.R.L. 91, 72304 (2003)

p_T^{trig} = 4~6 GeV/c × p_T^{assoc} > 2 GeV/c

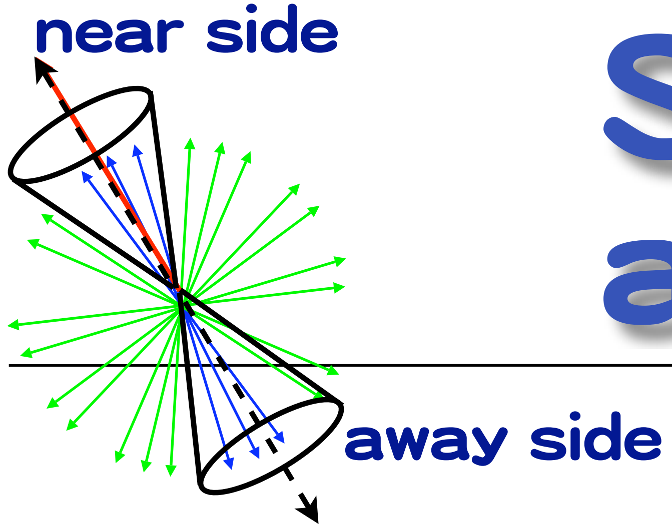




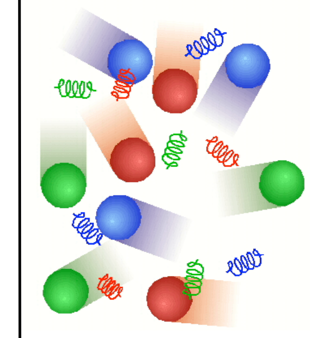
✓ Direct evidence of loss of 'jet'

✓ Azimuthal correlation w.r.t. high pt leading particle (trigger).

- pp ; clean di-jet
- dAu; similar to pp
- Au+Au; Similar on the same side (suggesting jet-like mechanism), but b-to-b disappeared
  - Effect is not in initial but in final stage
  - Energy loss of partons in dense matter created in Au+Au

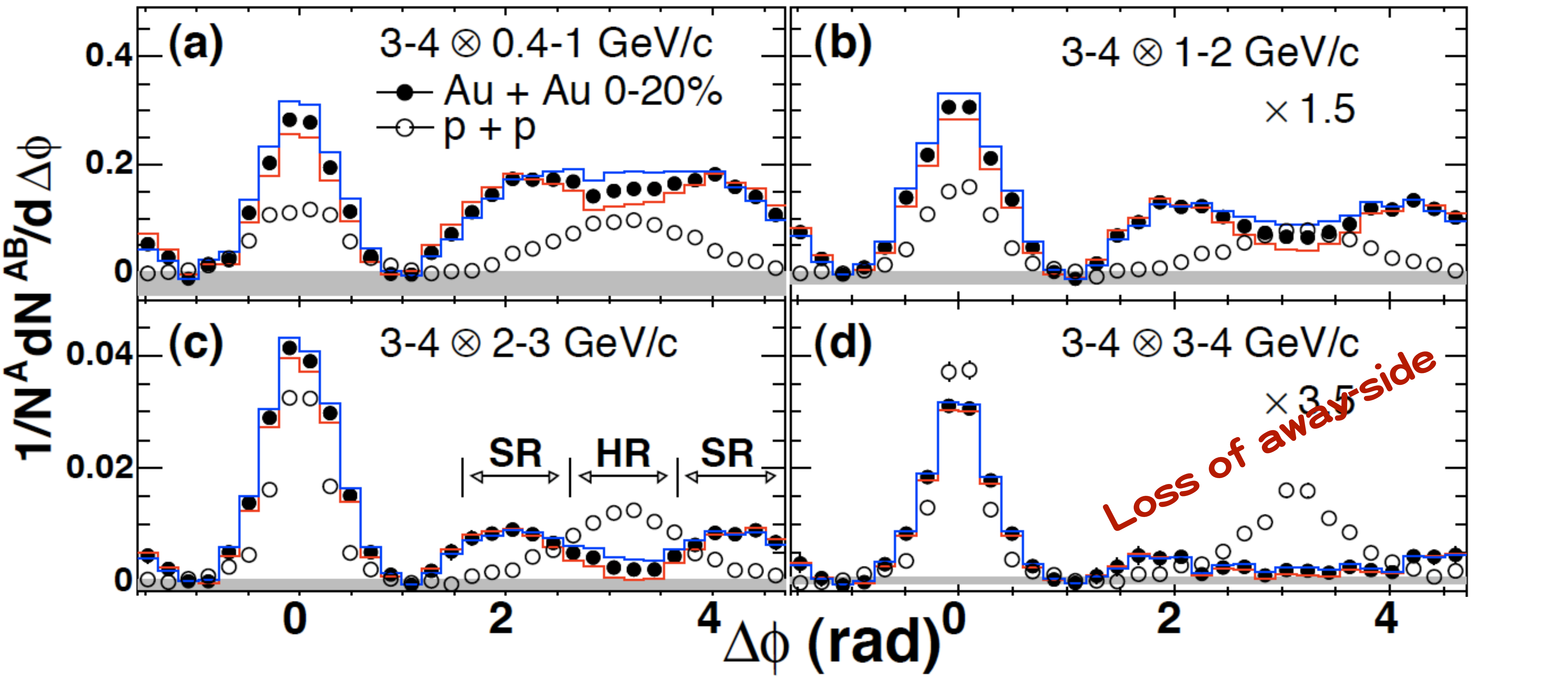


Shape change of away-side



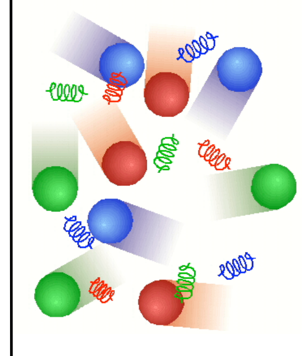
p_T^{trig} = 3~4 GeV/c × p_T^{assoc}

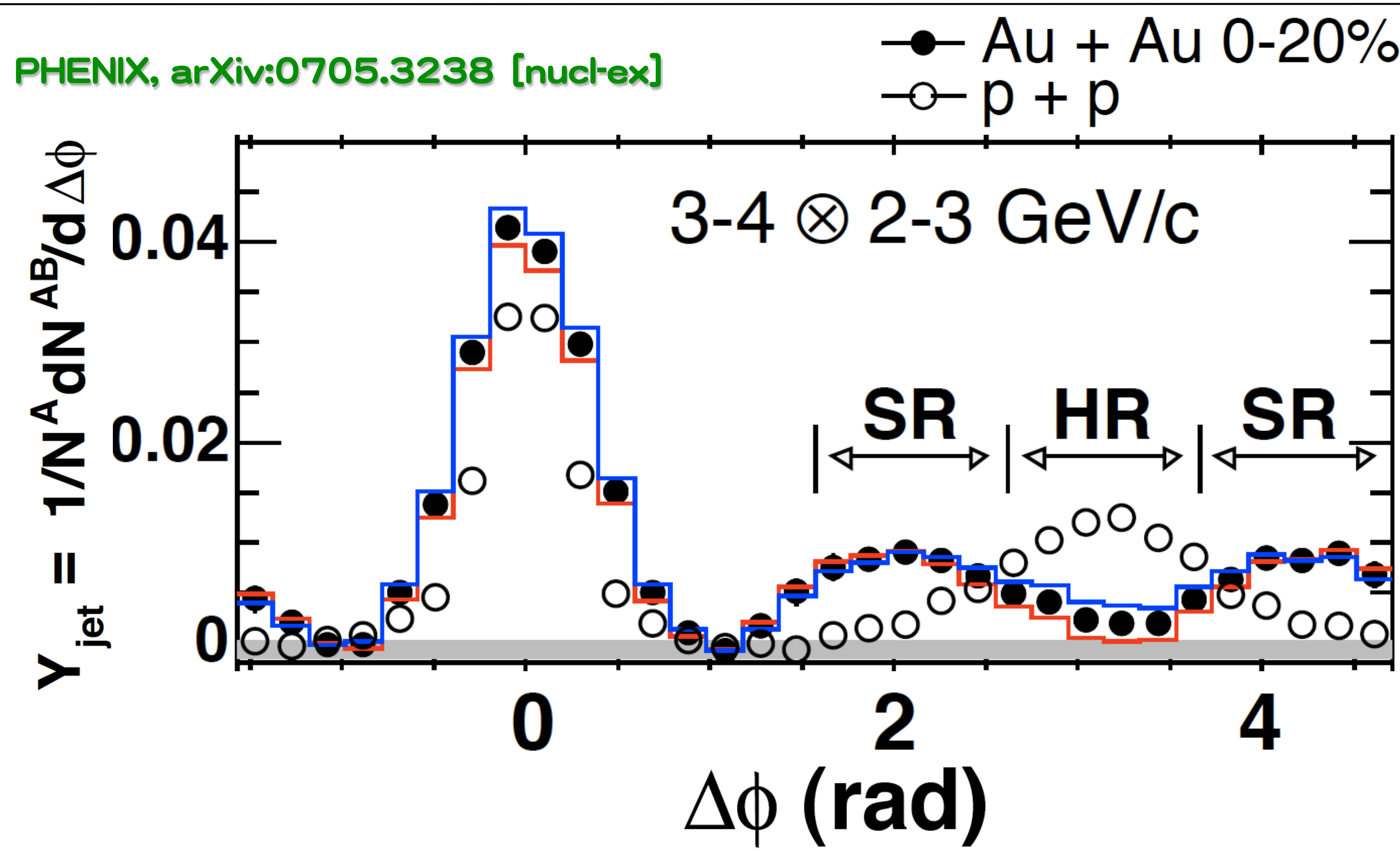
PHENIX, arXiv:0705.3238 [nucl-ex]



✓From broad/none to distinct two shoulders at $\Delta\Phi = \pi \pm 1.1$ with decreasing momentum.

Shoulders at $\Delta\Phi = \pi \pm 1.1$

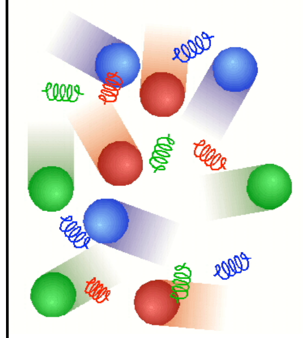




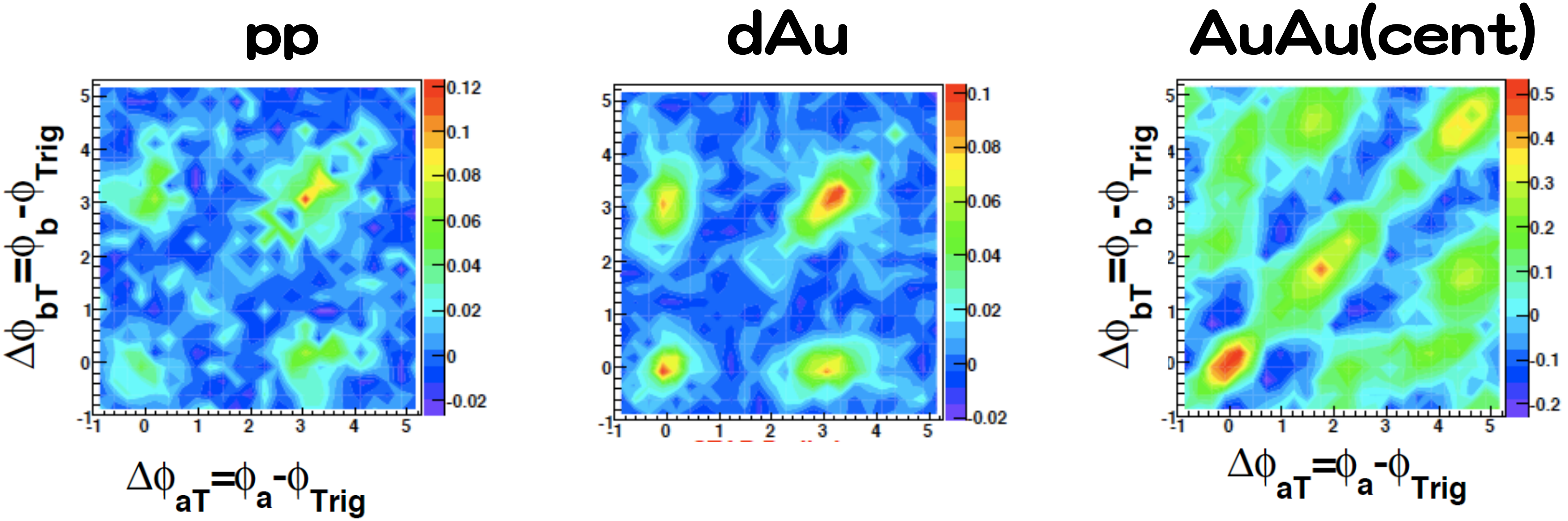
✓Location & <pt> of shoulder seem to be independent of centrality and pt.

- Not cherenkov, not deflection, but, Shock wave !?

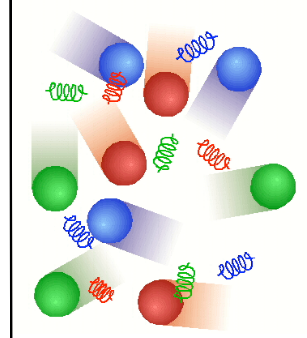
Sophisticated 3-particle correlation analysis



STAR@QM06, nucl-ex/703010

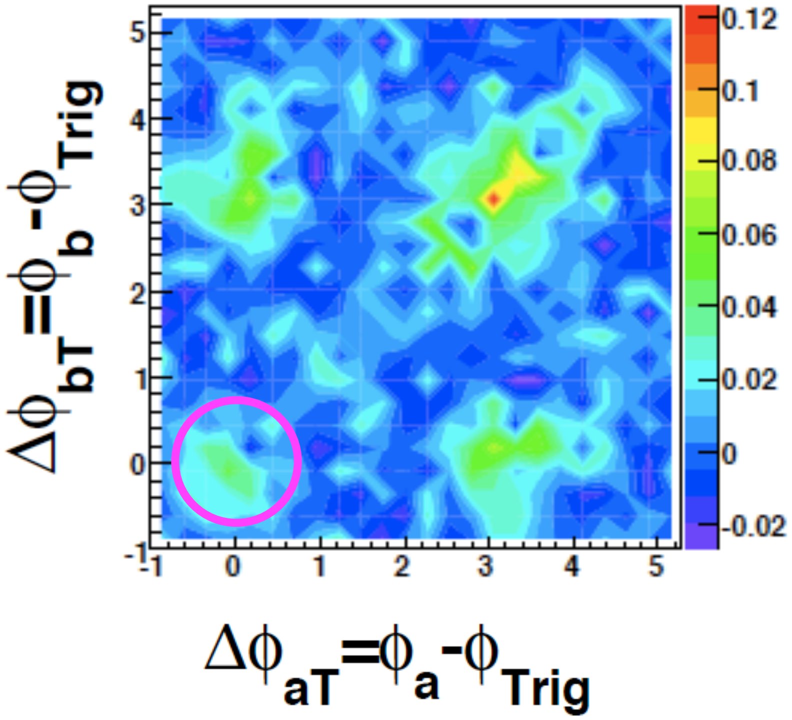


Sophisticated 3-particle correlation analysis

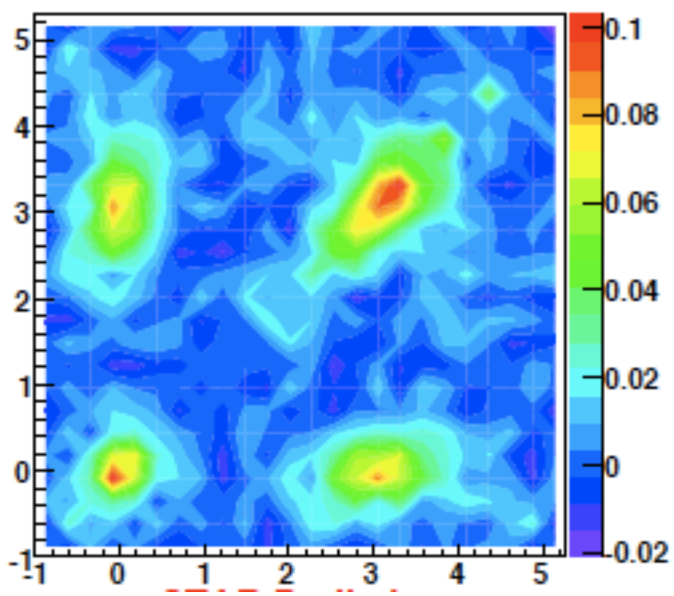


STAR@QM06, nucl-ex/703010

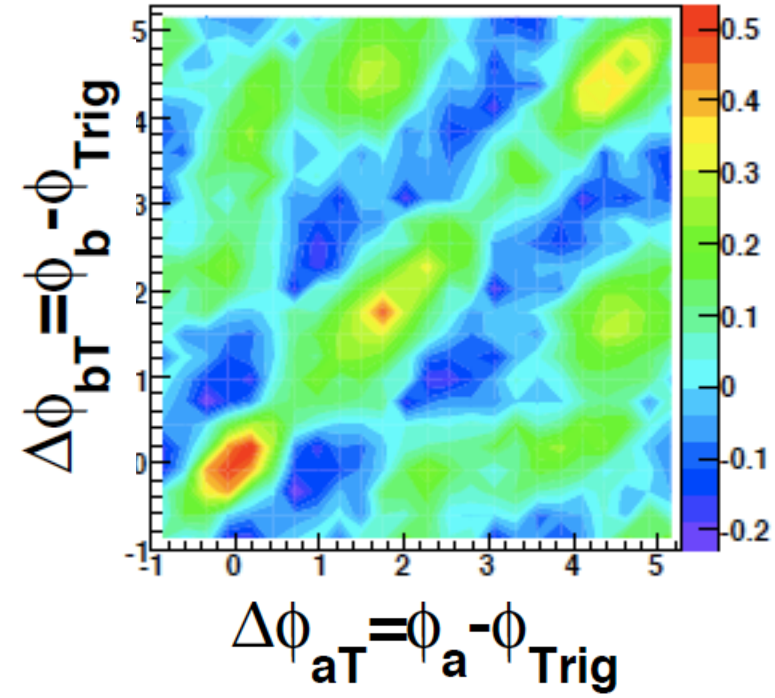
pp

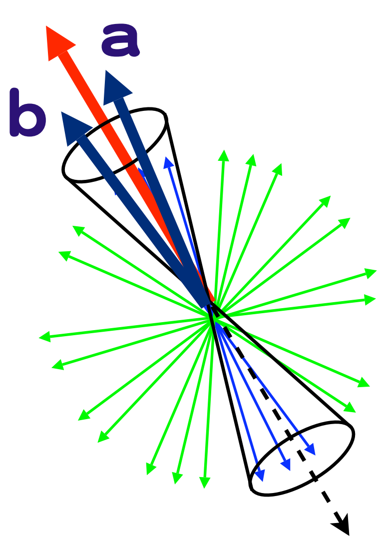


dAu

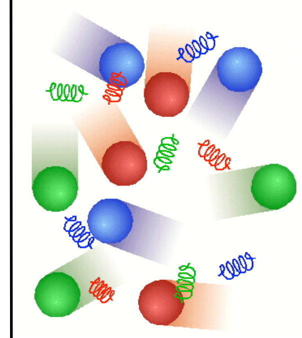


AuAu(cent)





Sophisticated 3-particle correlation analysis



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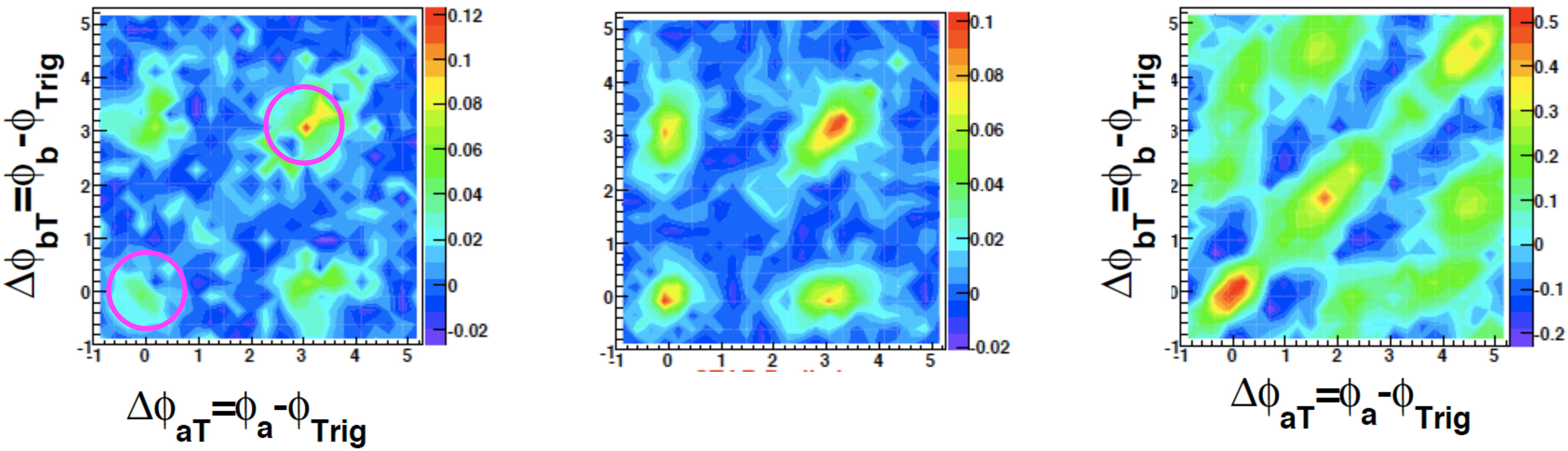
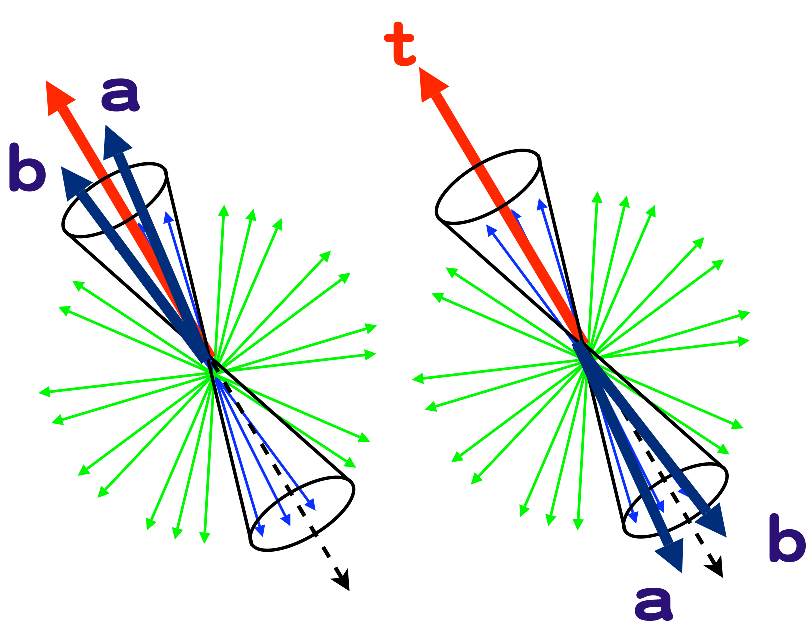
pp dAu AuAu(cent)

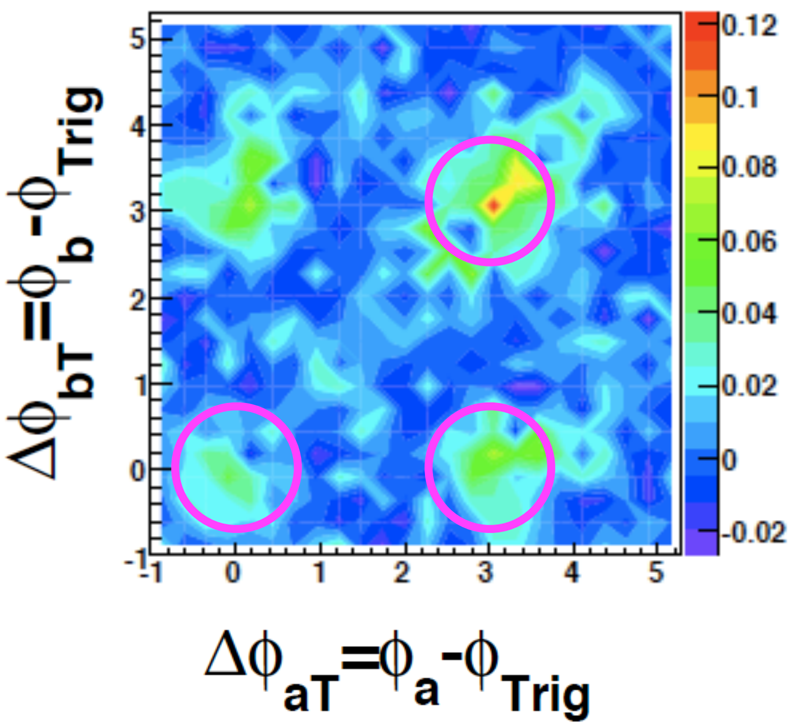




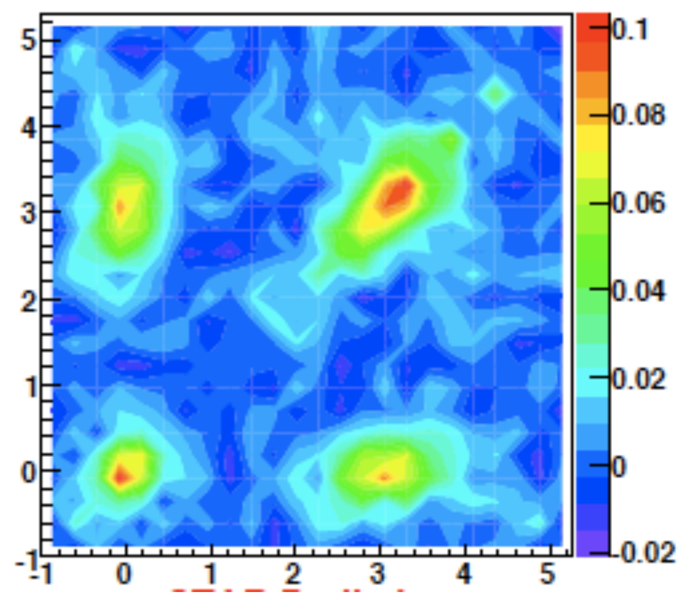
Sophisticated 3-particle correlation analysis

STAR@QM06, nucl-ex/703010

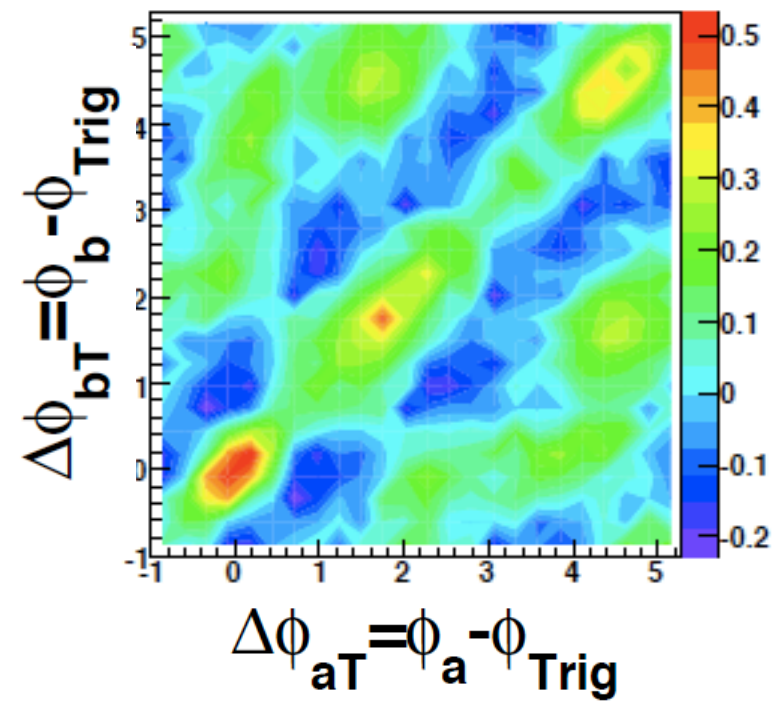
pp

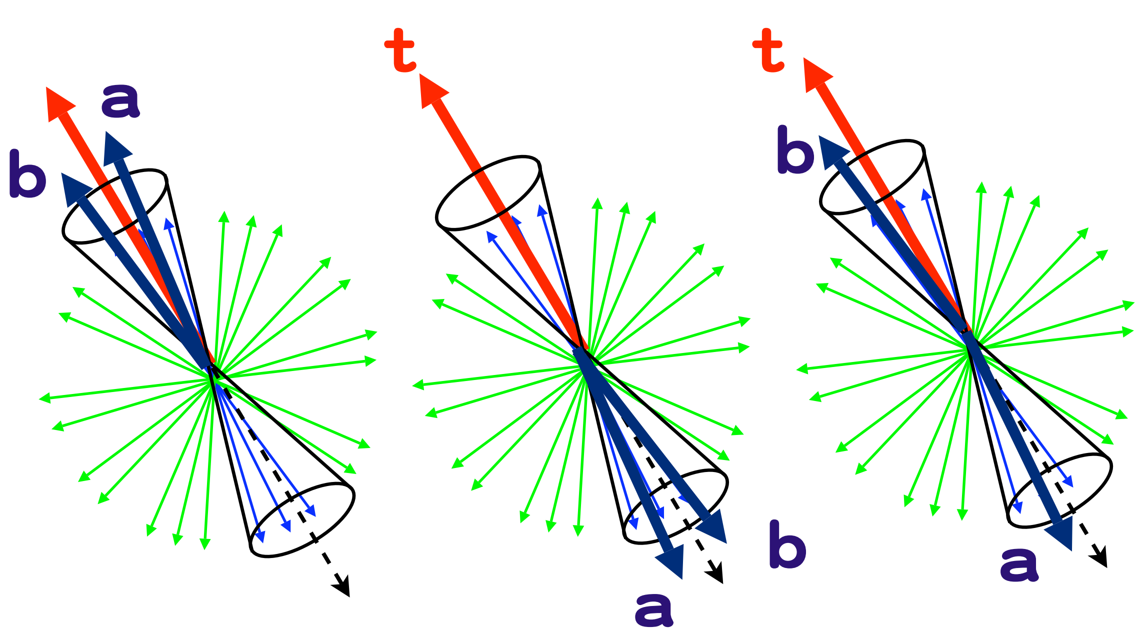


dAu

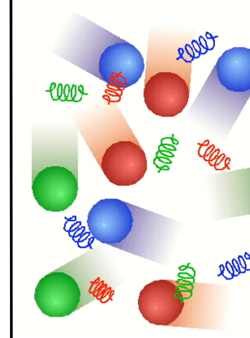


AuAu(cent)





Sophisticated 3-particle correlation analysis



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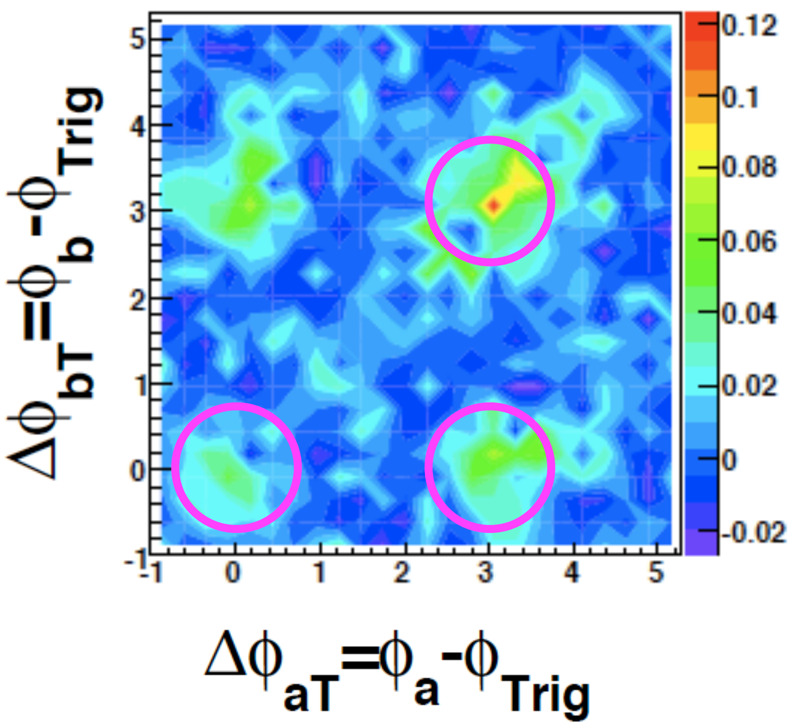
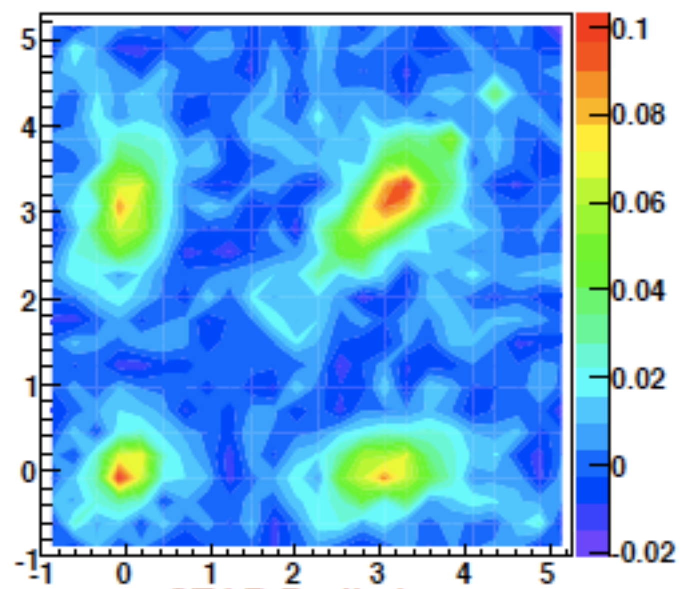
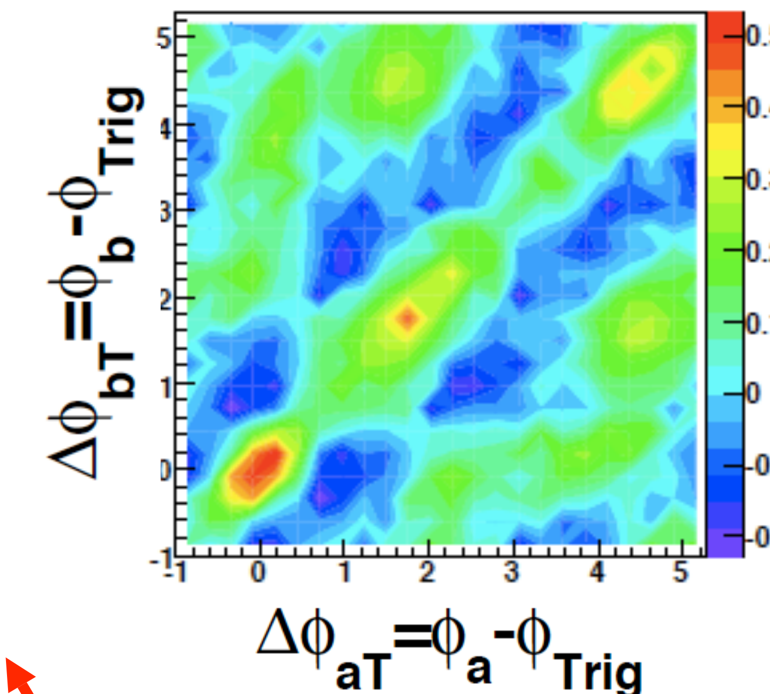
pp

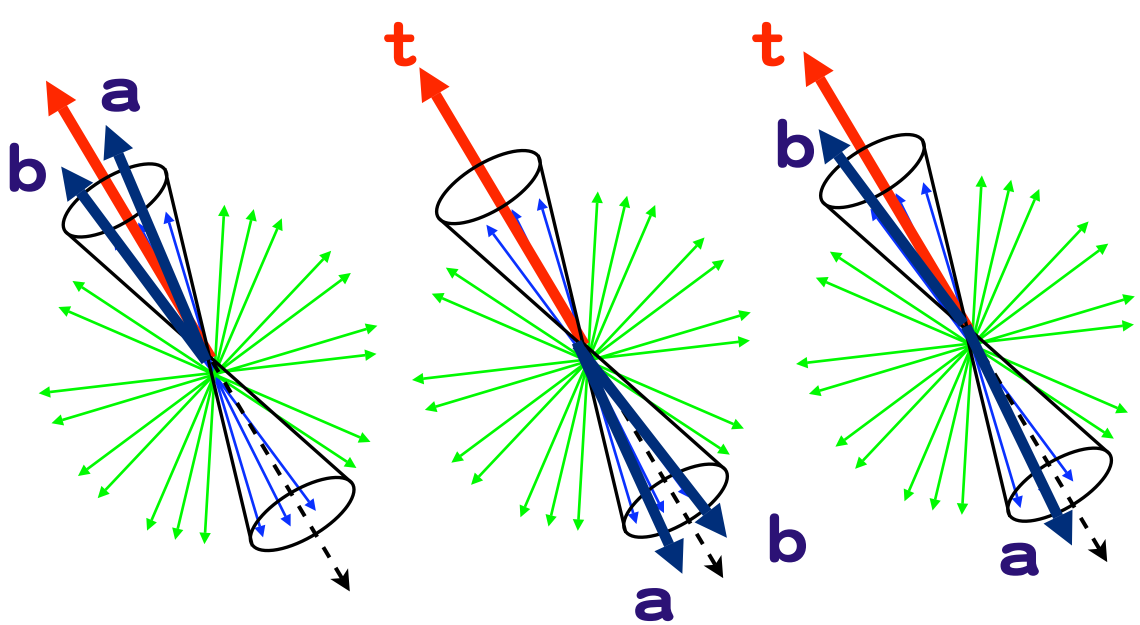


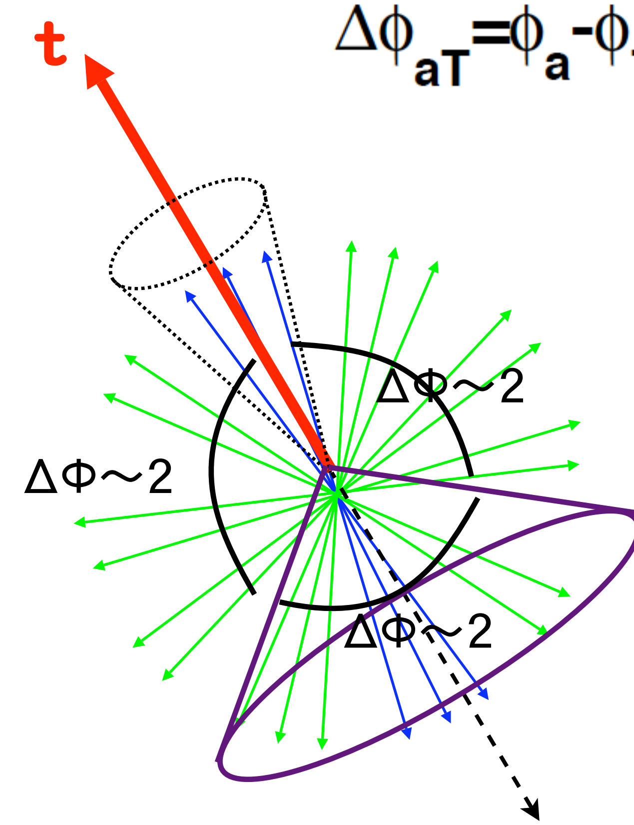
dAu



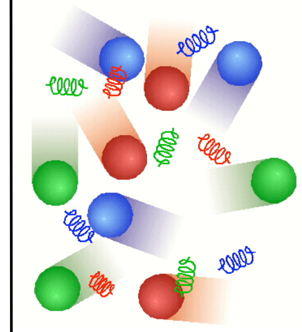
AuAu(cent)







Sophisticated 3-particle correlation analysis



STAR@QM06, nucl-ex/703010

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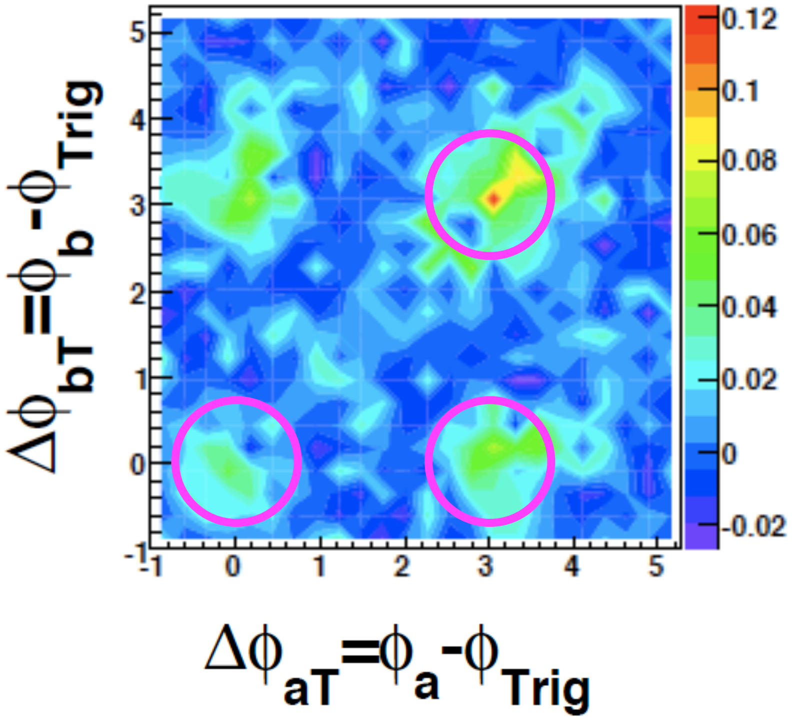

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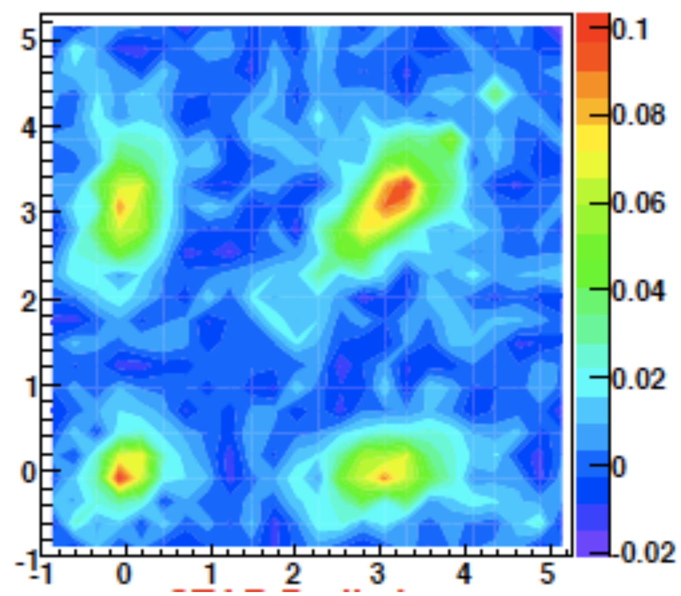
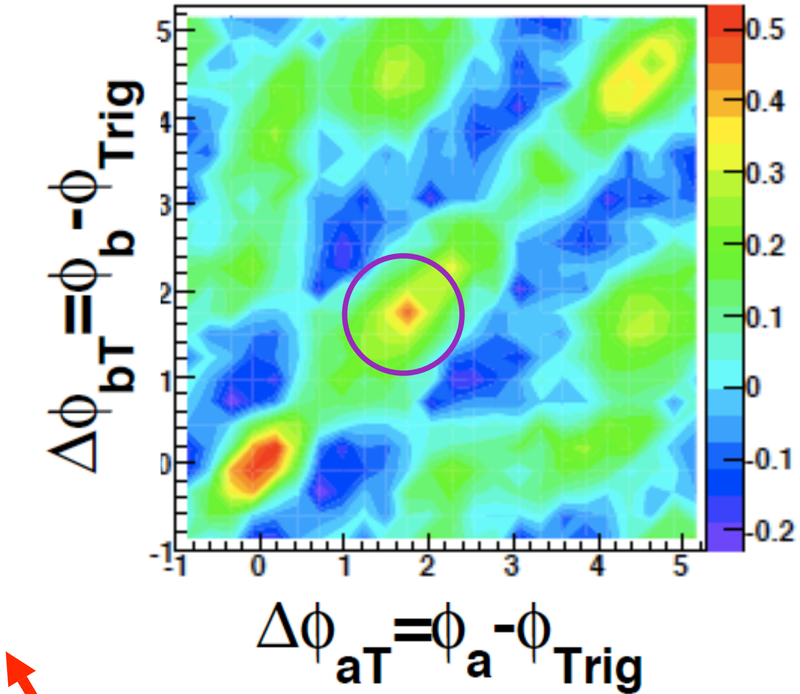
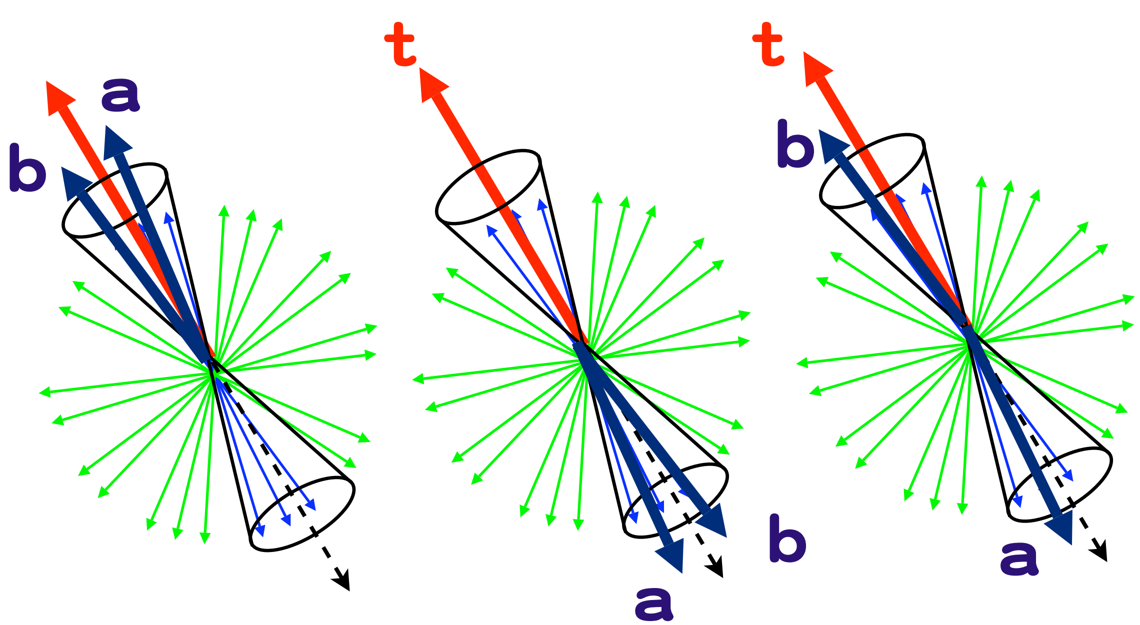
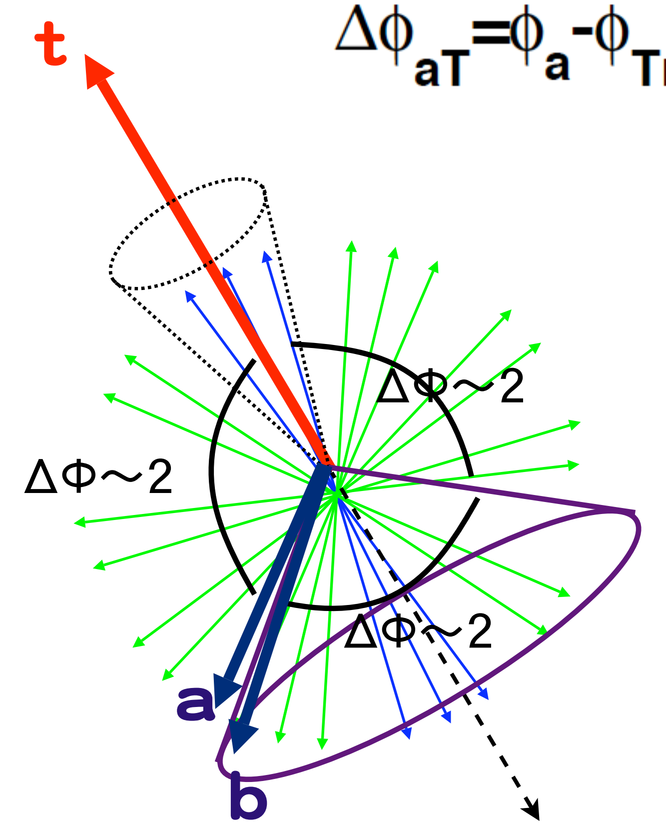


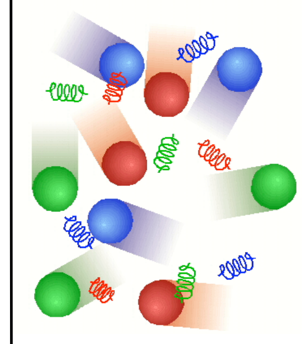
AuAu(cent)







Sophisticated 3-particle correlation analysis



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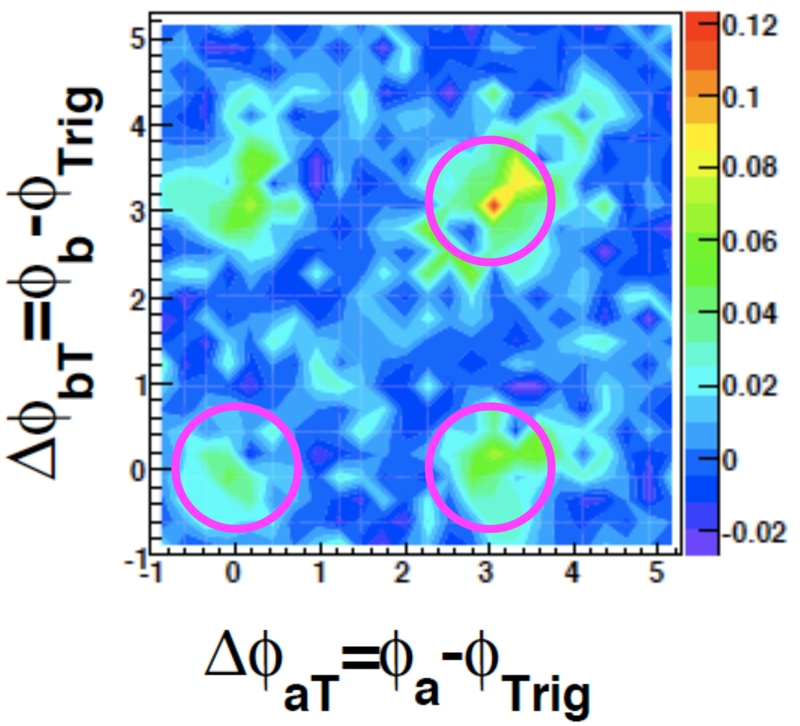

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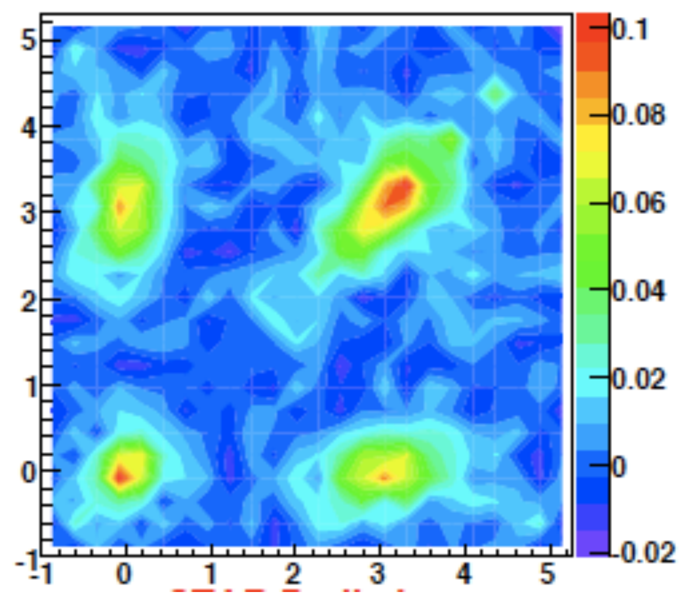

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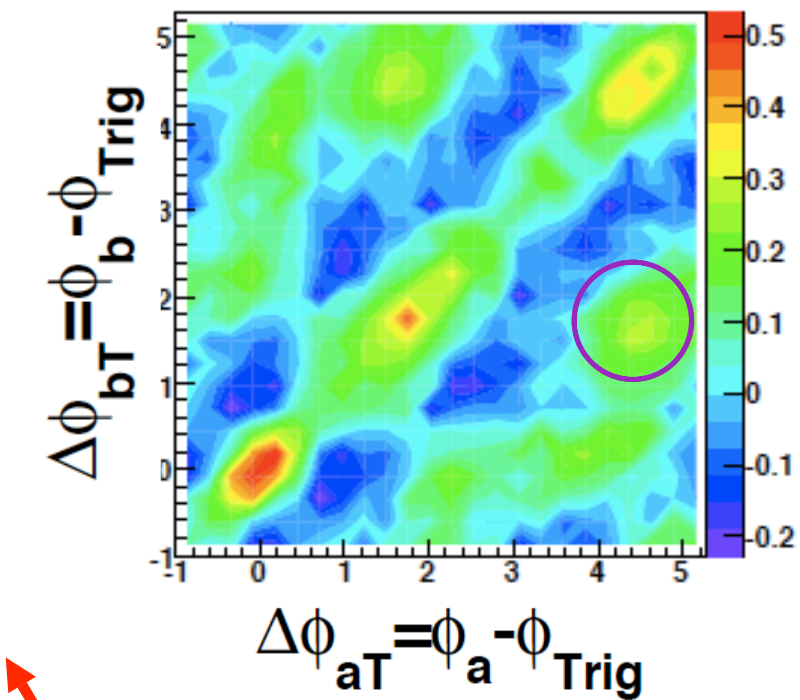

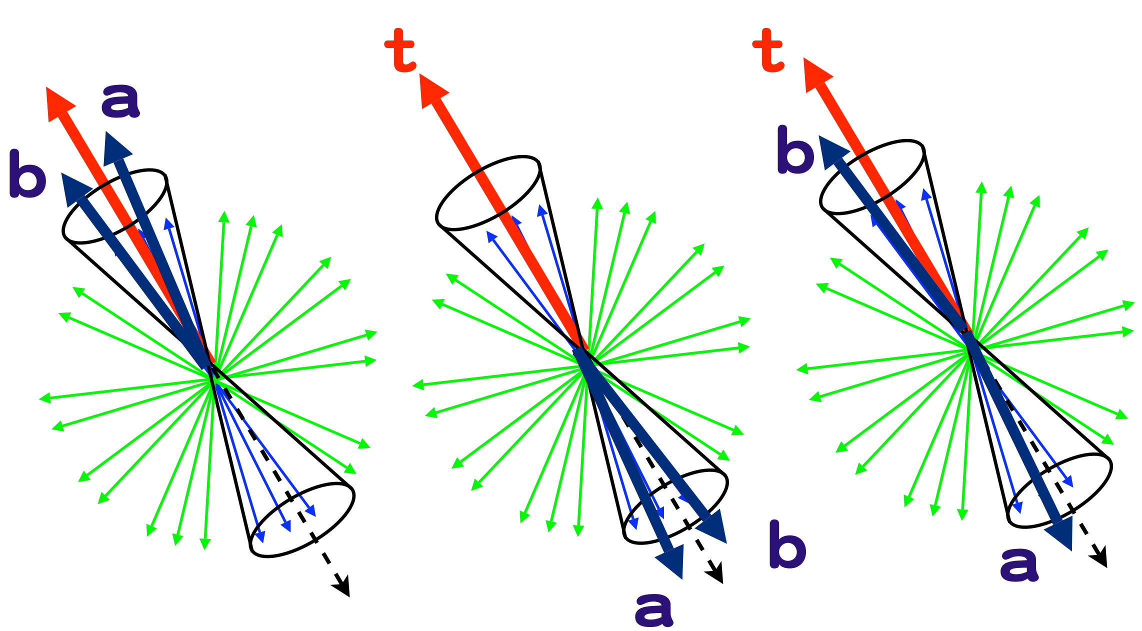

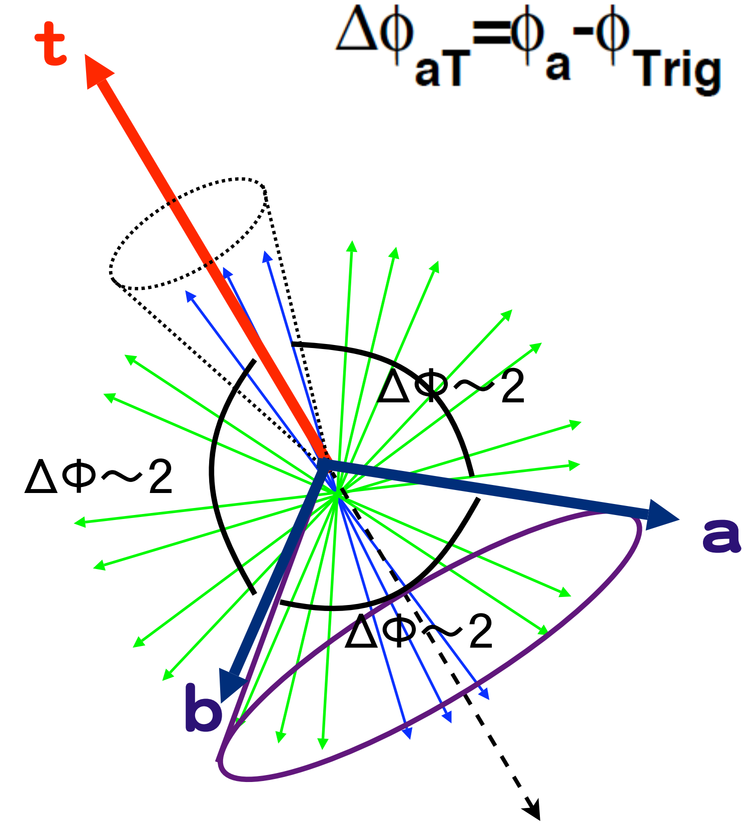

Sophisticated 3-particle correlation analysis

STAR@QM06, nucl-ex/703010

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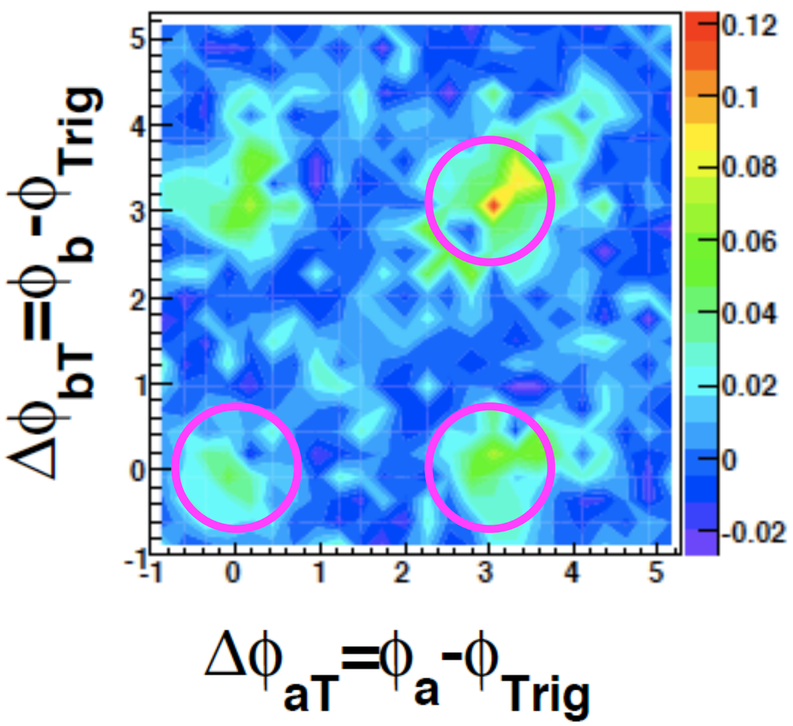

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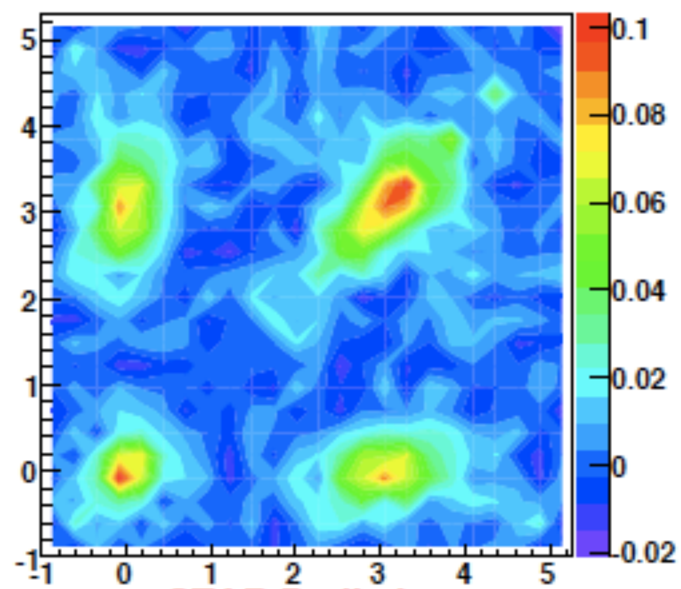

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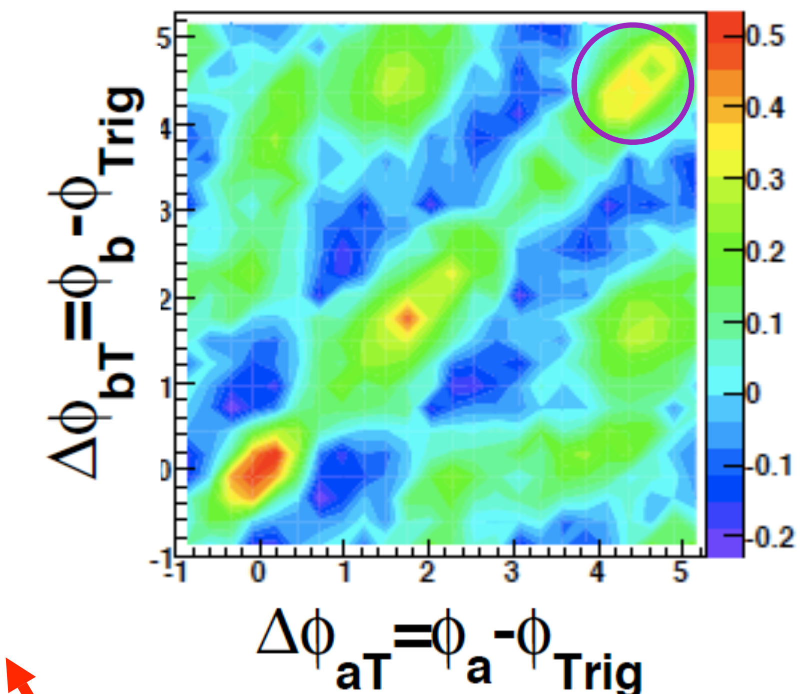

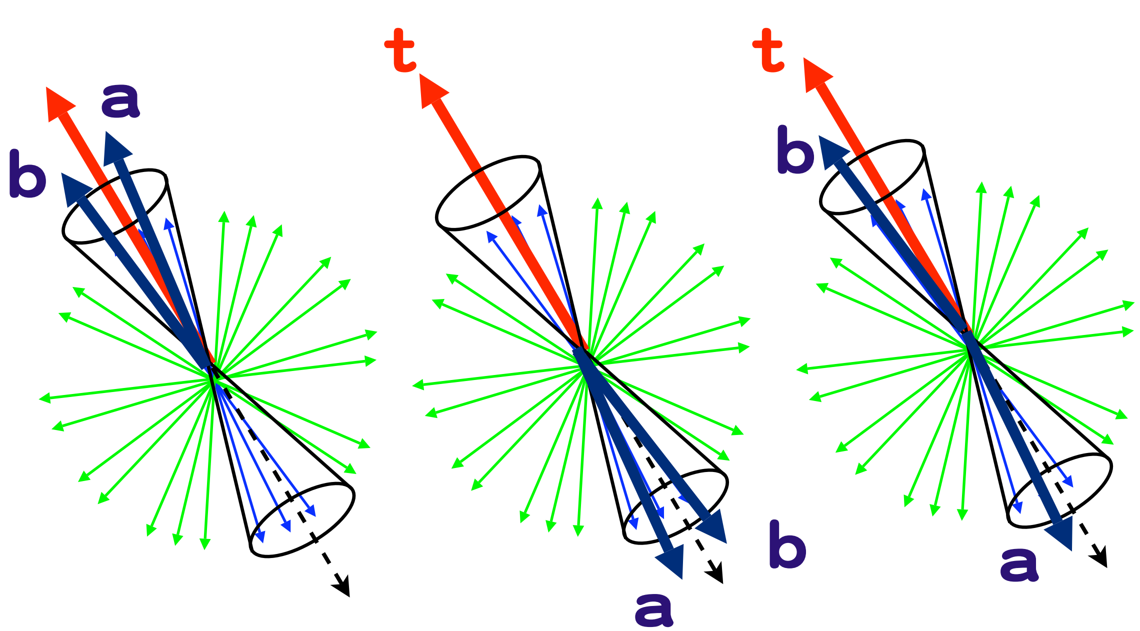

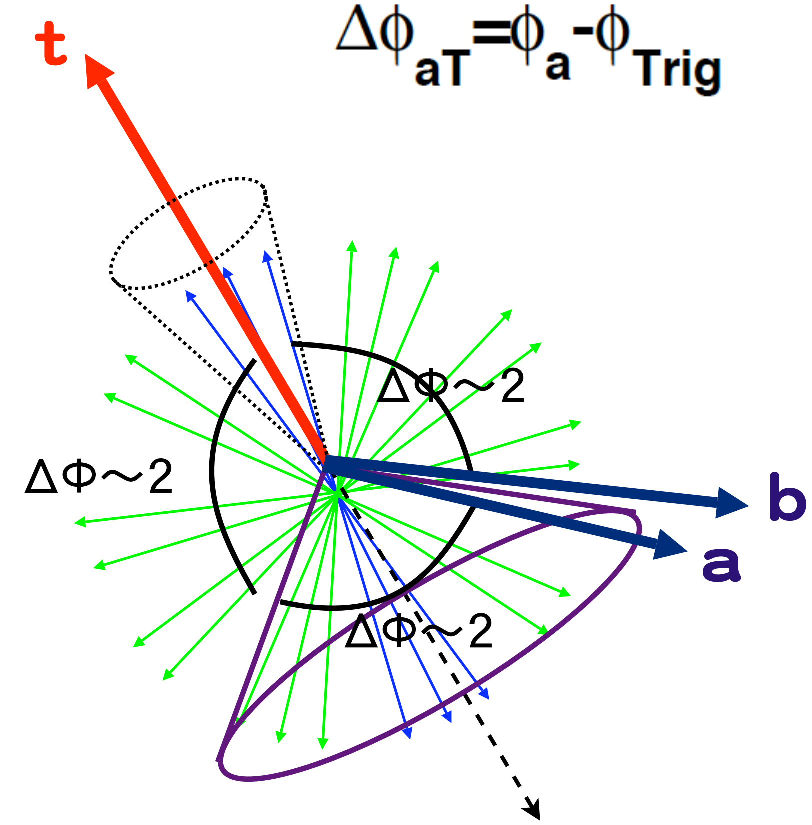

Sophisticated 3-particle correlation analysis

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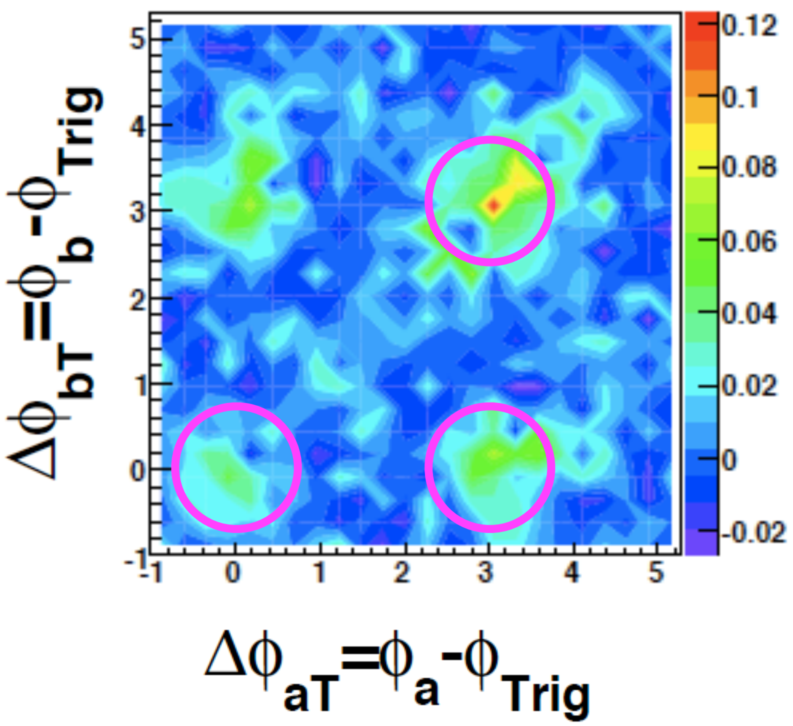

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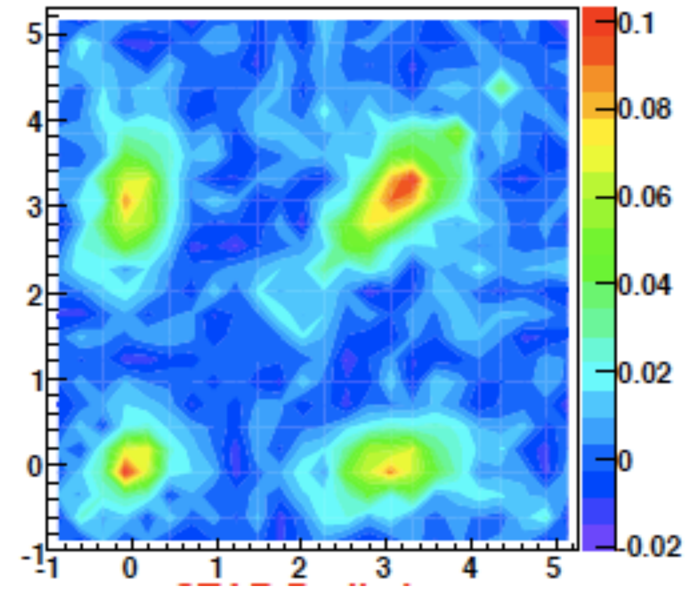

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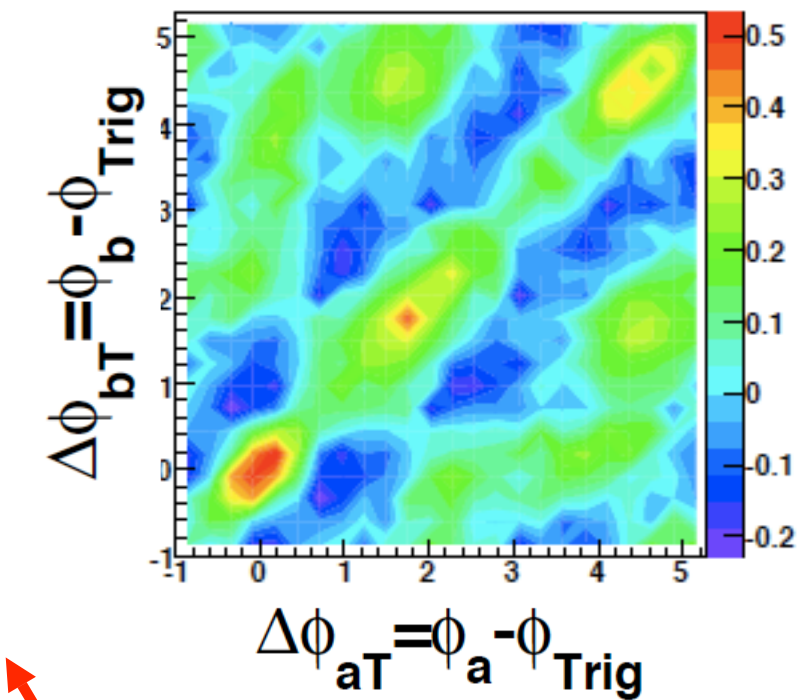
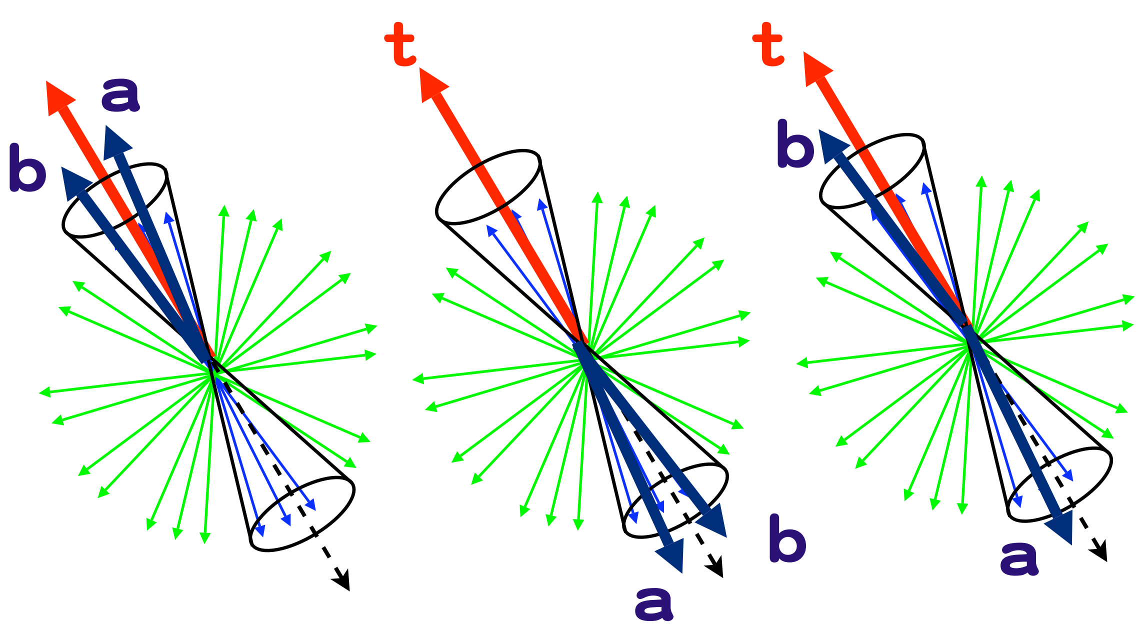
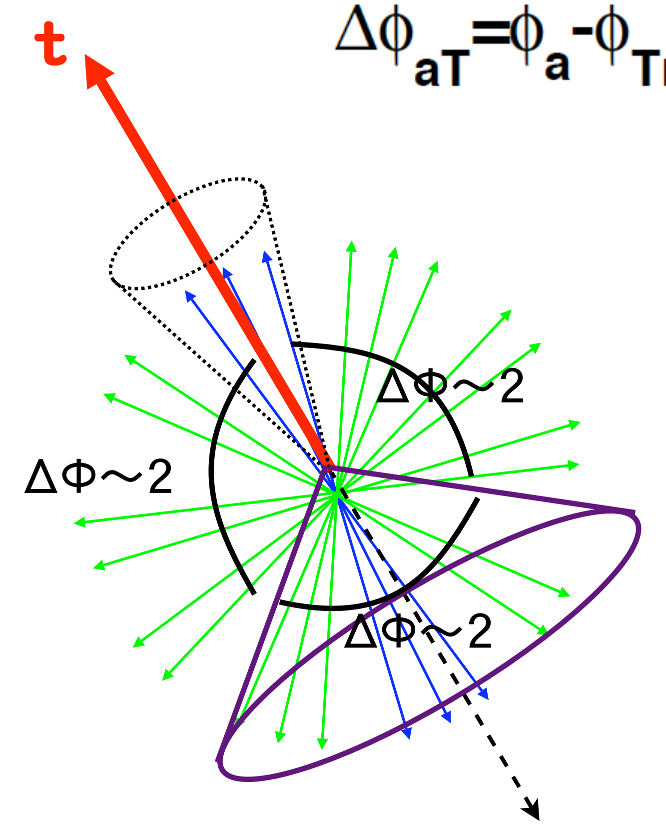
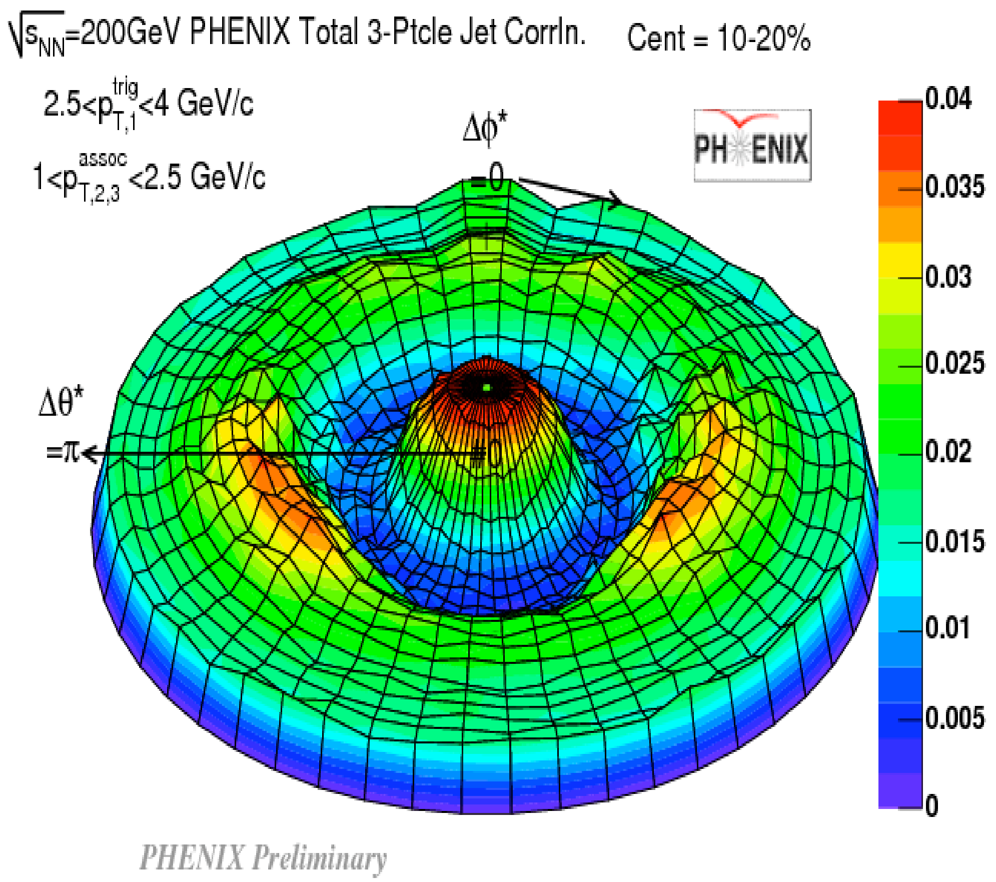




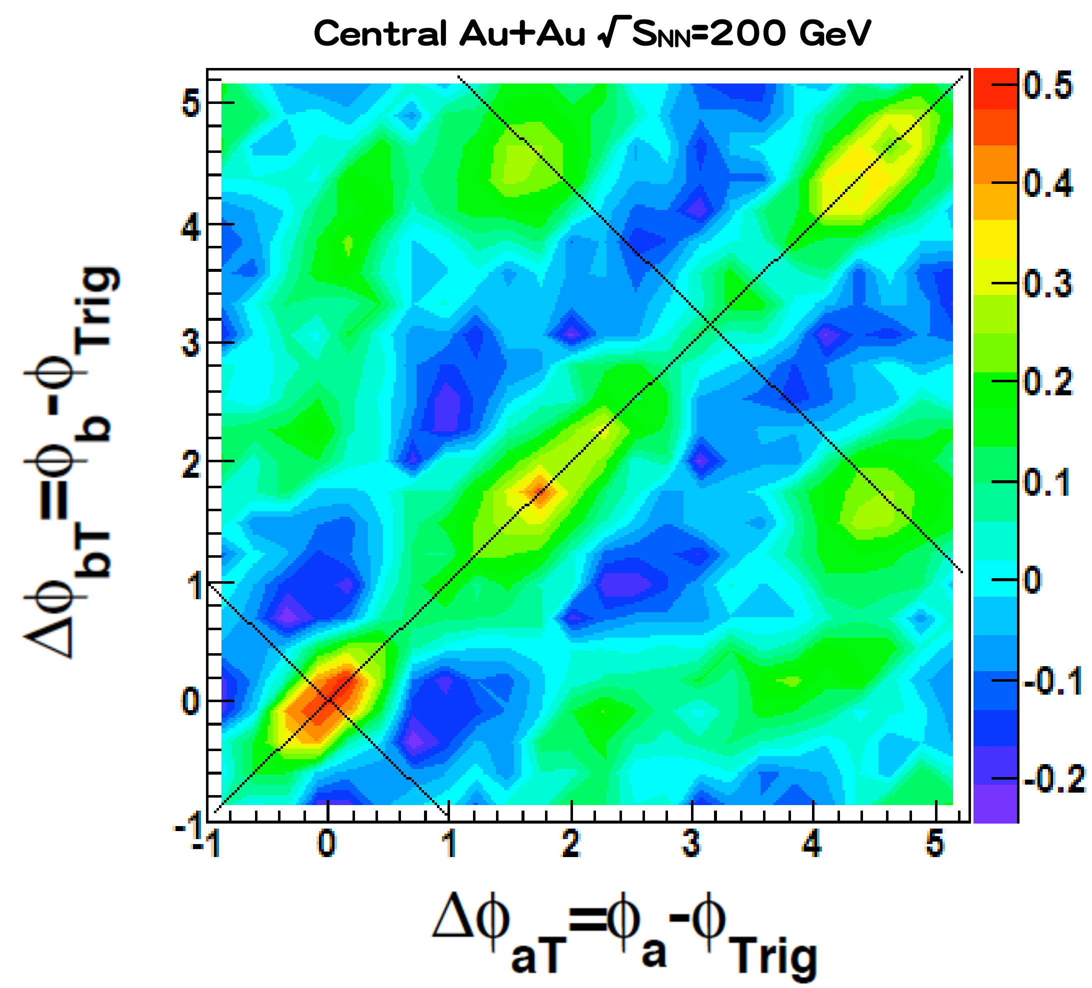


Difficulty of the analysis

Phenix@QM06, J.Phys.G 34(2007)S191

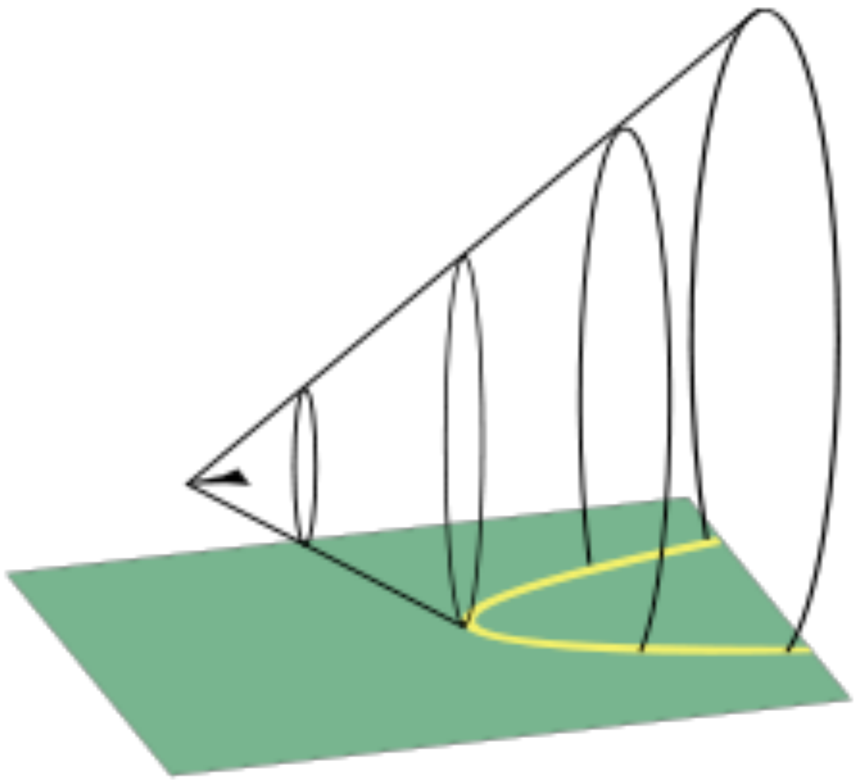


STAR@QM06, nucl-ex/703010



- ✓ **Large azimuthal anisotropy is the major background.**
  - ➡ "Discovery of yesterday is background of today and calibration of tomorrow"
  - ➡ More precise determination of the elliptic flow is important
- ✓ **Both group say it is consistent with Mach Cone.**

Shock Wave !?

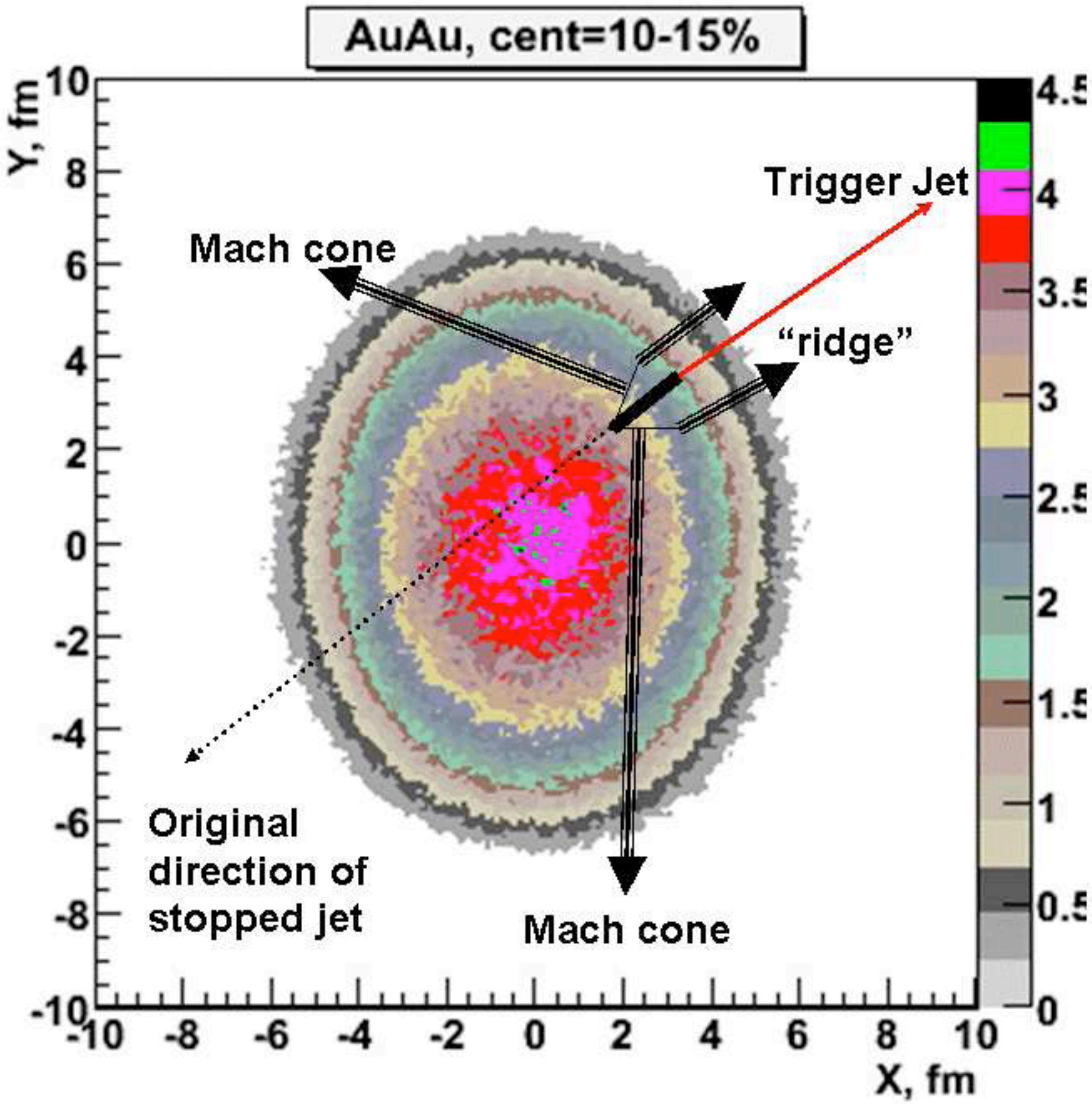


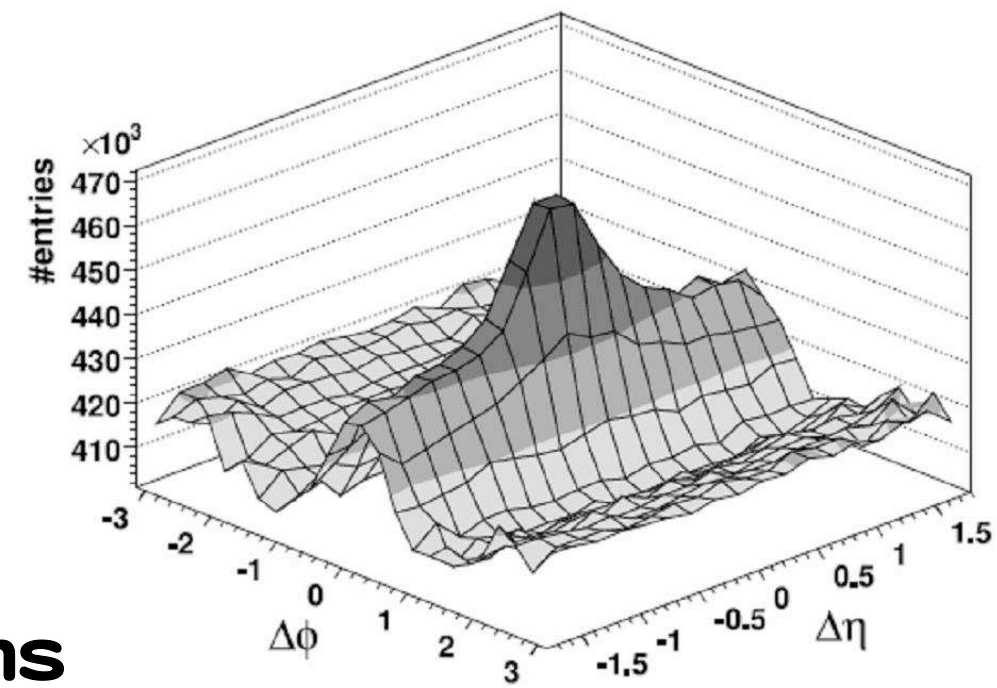
- ✓If confirmed, it is breakthrough from the era of QGP discovery to the study of property, such as sound velocity in the plasma

Near side ridge as splash

V.S. Pantuev, arXiv:hep-ph/0701.1882v1

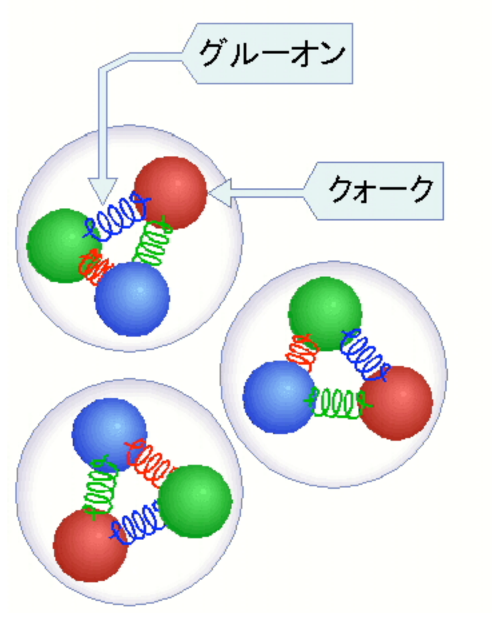
STAR, arXiv:nucl-ex/0701074



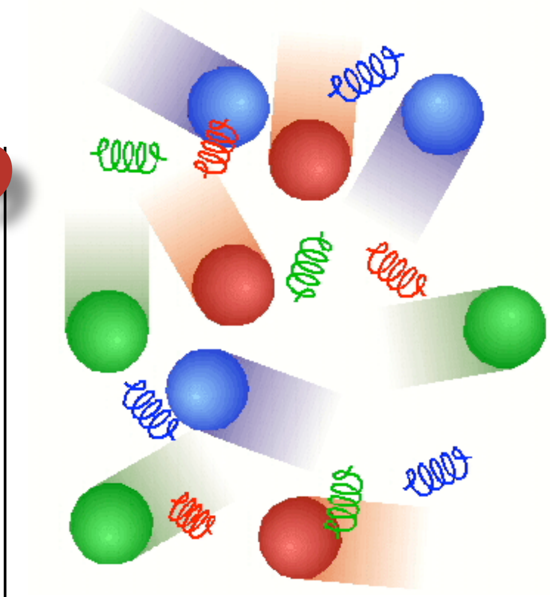


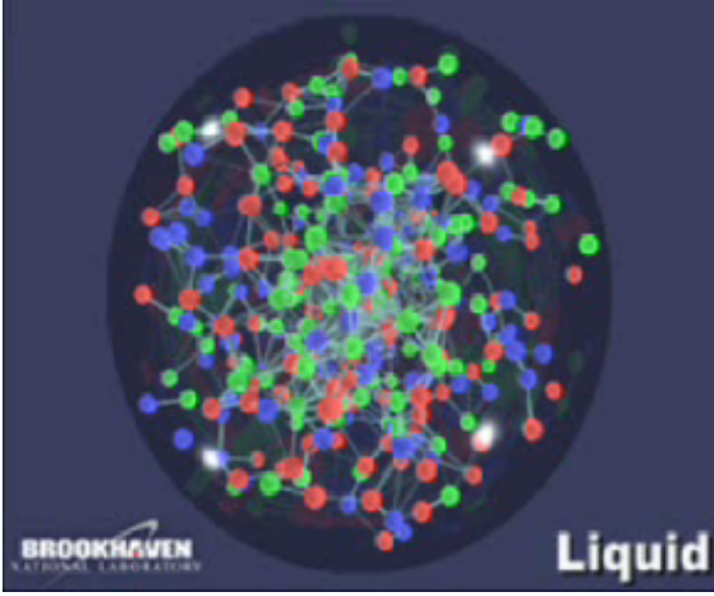
✓ Claims

- Stopped parton is the source of ridge as well as Mach cone.
- This happens only at the surface
- There should be velocity boost at the ridge region (pi,K,p)
- v3 components independent of R.P.

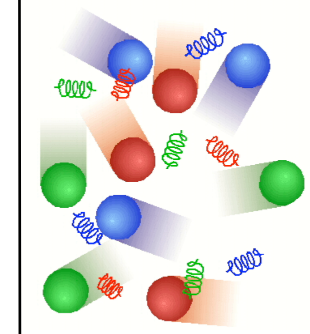


If it is "Liquid", why not a back splash?





Summary



- √ We have seen partonic matter, ie, a QGP!
- √ Successful description of the system in terms of statistical thermo-dynamics;
  - ✦ Particle ratios in Tch, μ, Kinematical distr. in Tth and β
- √ Partonic
  - ✦ Large azimuthal anisotropy cannot be created with hadronic process.
  - ✦ High pt suppression and disappearance of back-to-back is at parton level.
  - ✦ Successful description of quark recombination;
    - ➡ Phenomenological, but universal quark distribution function!
- √ We are in the state of studying property of plasma, like c_s.