What ~~we~~ I have learned at RHIC

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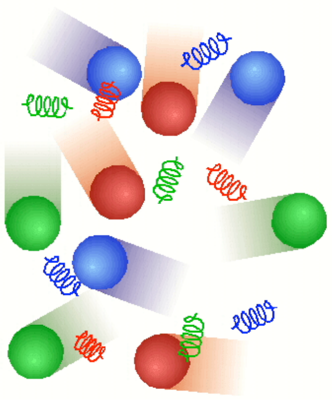
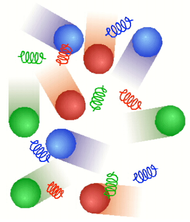
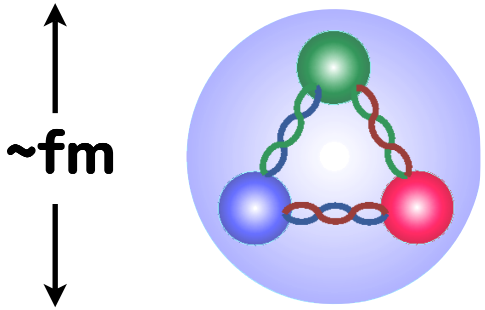
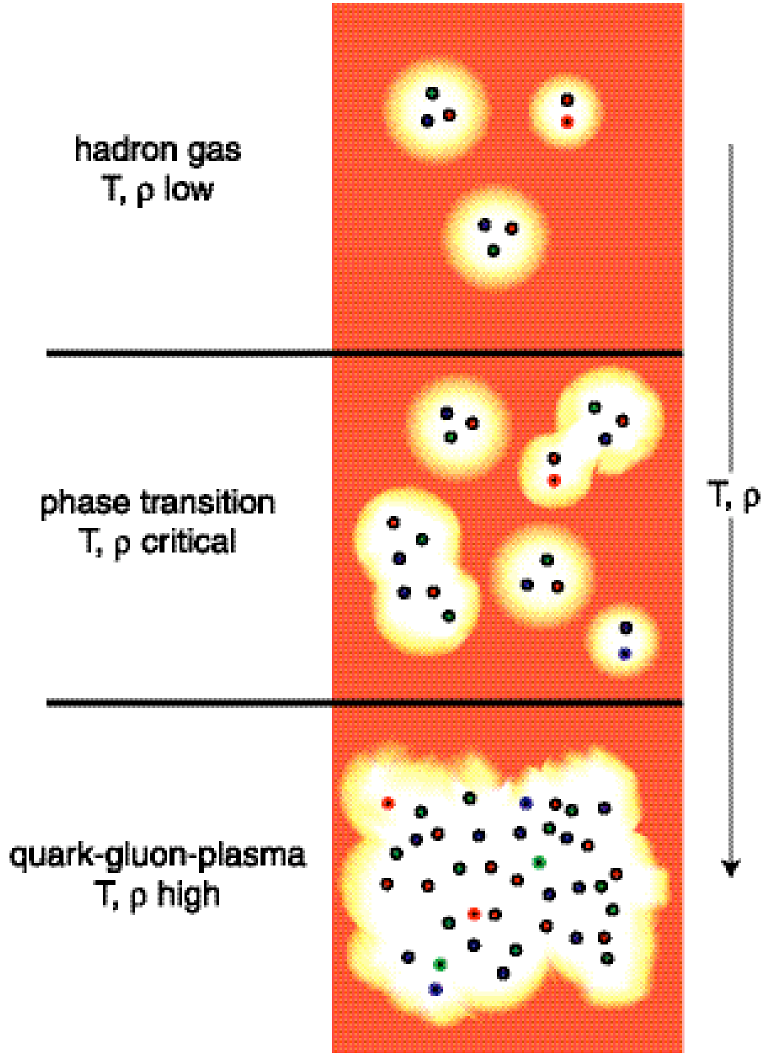


Quark Gluon Plasma

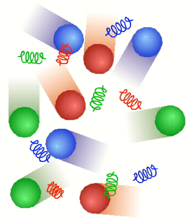


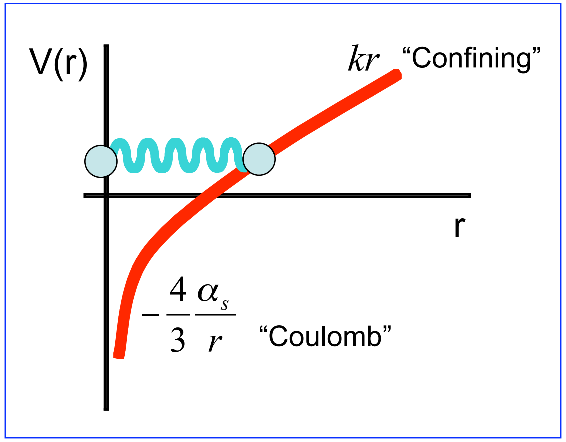


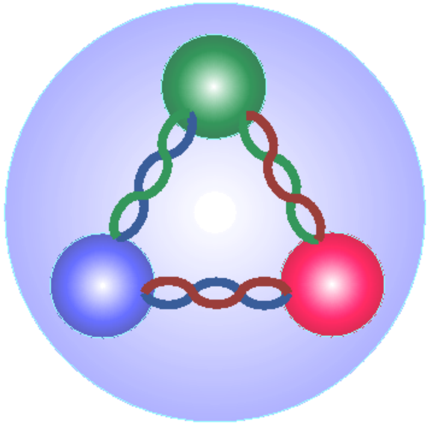
- Size of hadrons ~ fm
- At high ρ or high T, they overlap each other.
  - Not confined to each hadron.
    - ➡New state of matter: quark-gluon plasma.
    - ➡Phase transition



FAQ: is it the QGP inside proton?

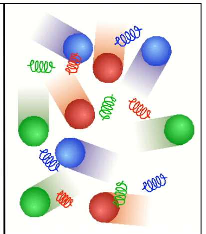






- ✓Asymptotic freedom means a QGP inside a proton?
  - ➡No!
- ✓We want many free quarks and gluons over a large volume as a matter.
- ✓Applicability of Statistical Physics is essential!

What we expect: Statistical Nature



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

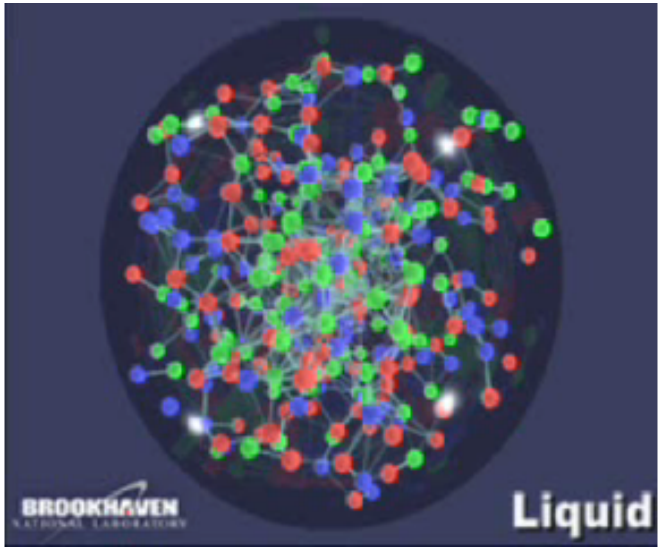
$$< n_{q,\bar{q}} > \sim \frac{\epsilon_{\rm QGP}}{< m_T >} \sim \frac{2{\rm GeV}}{0.4{\rm GeV}} \sim 5$$

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

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

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

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

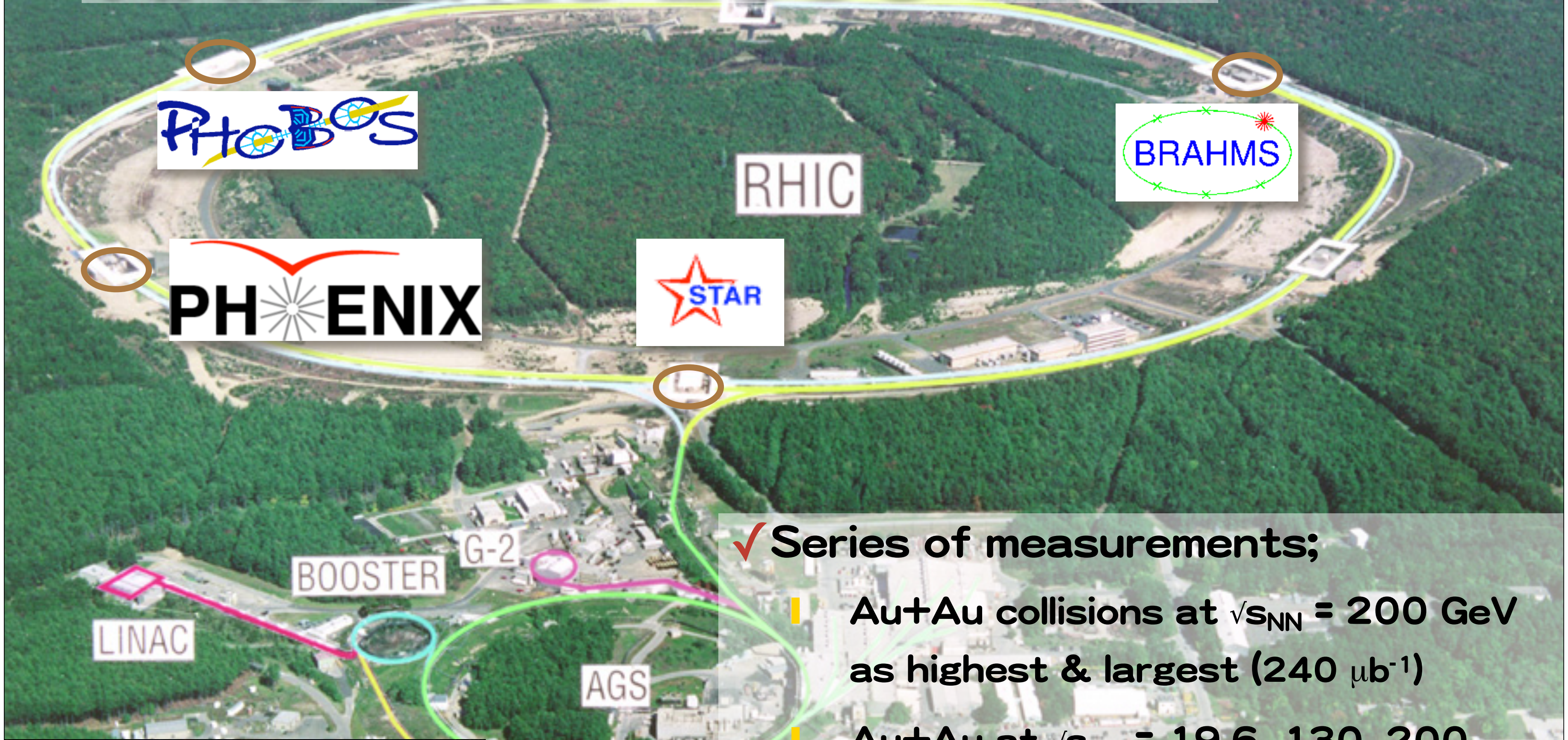


Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration

✓ **What we can expect:**

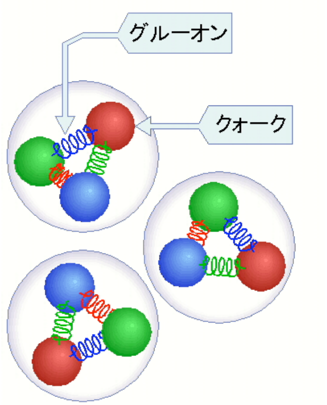
- ✦ **Statistical physics at quark level**
- ✦ **Hydrodynamical behavior at quark level**

RHIC since 2000

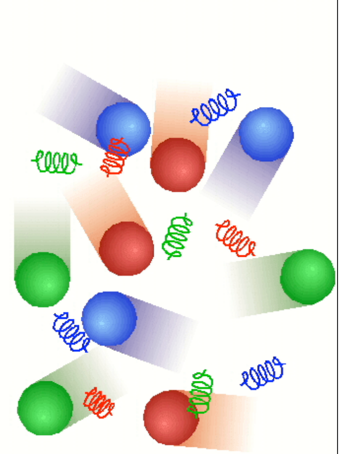


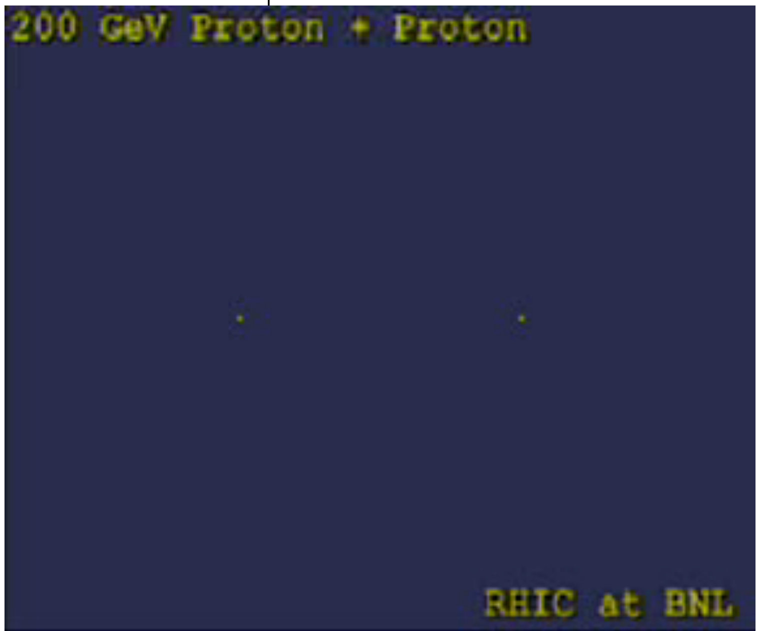
✓ Series of measurements;

- Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV as highest & largest (240 μb^{-1})
- Au+Au at $\sqrt{s_{NN}}$ = 19.6, 130, 200 GeV as Energy Scan
- p+p at $\sqrt{s_{NN}}$ = 200 GeV as Comparison data
- d+Au $\sqrt{s_{NN}}$ = 200 GeV as Controlled Comparison



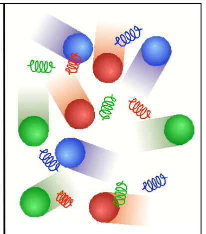
How the collisions look like

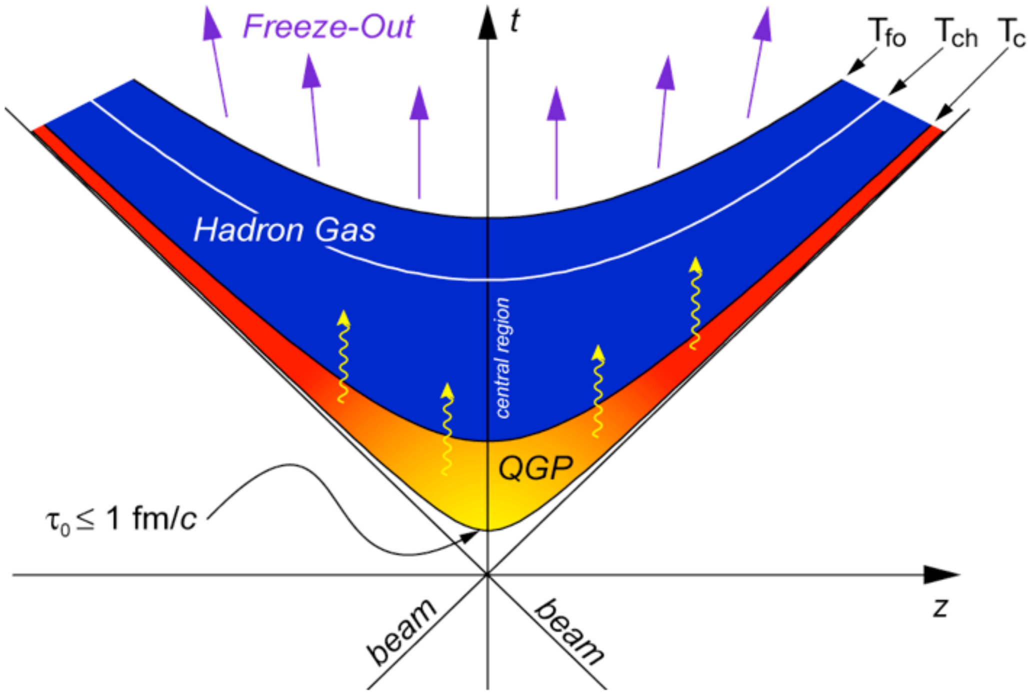




Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration

Time Evolution of collision

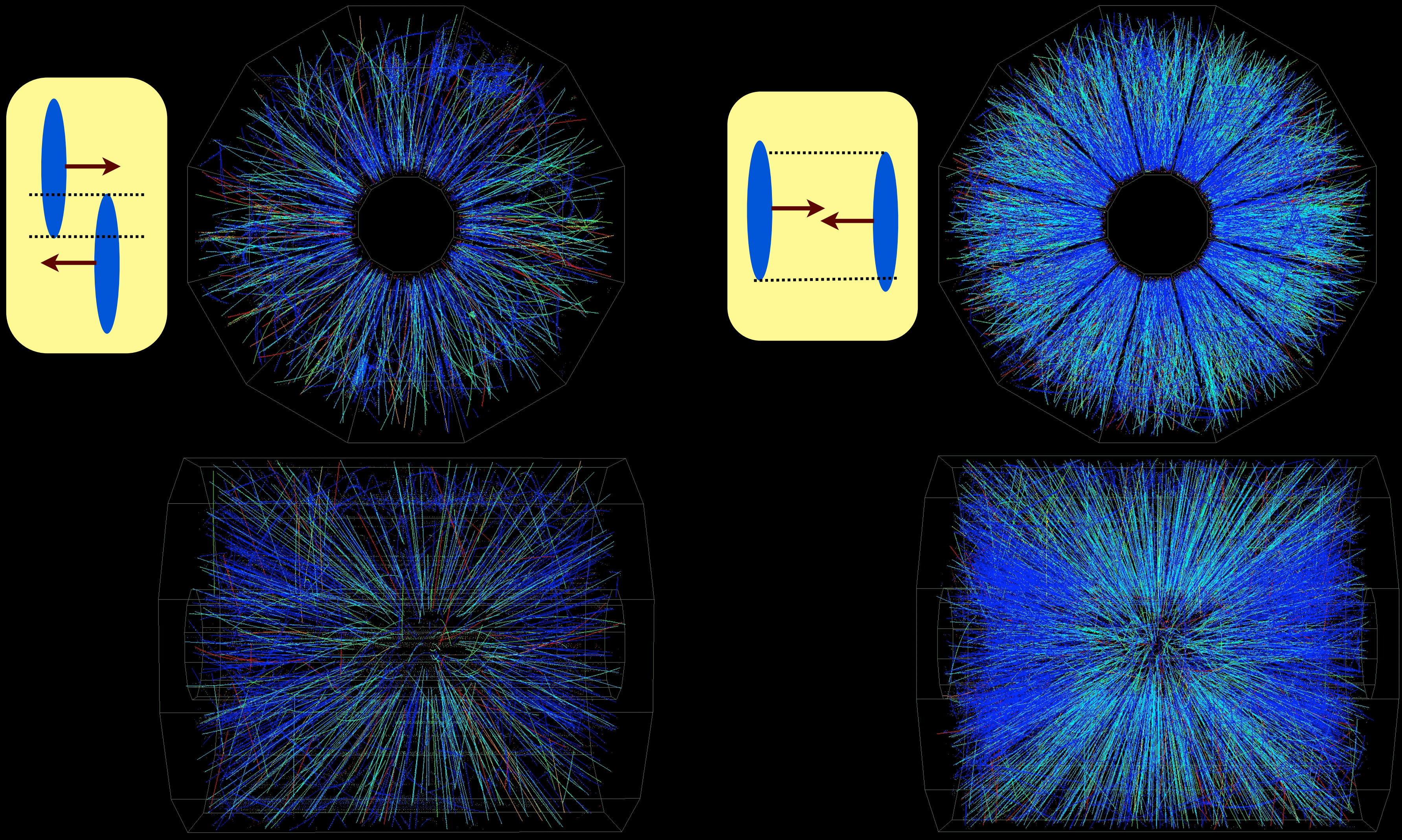




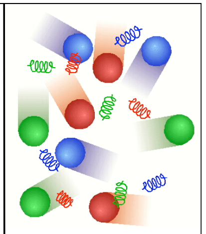
✓ Time evolution which we expect.

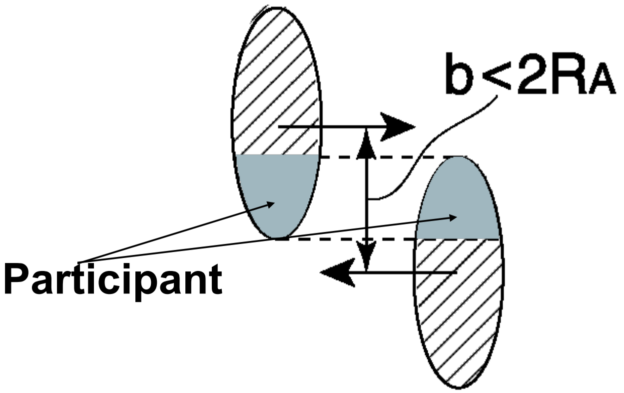
- Parton cascade
- Quark Gluon Plasma
- Chemical freeze-out
  - ➡ no more hadron produced
- Kinematical freeze-out
  - ➡ no more scattering
- If the beam energy is high enough, we think observable to be Lorentz invariant.

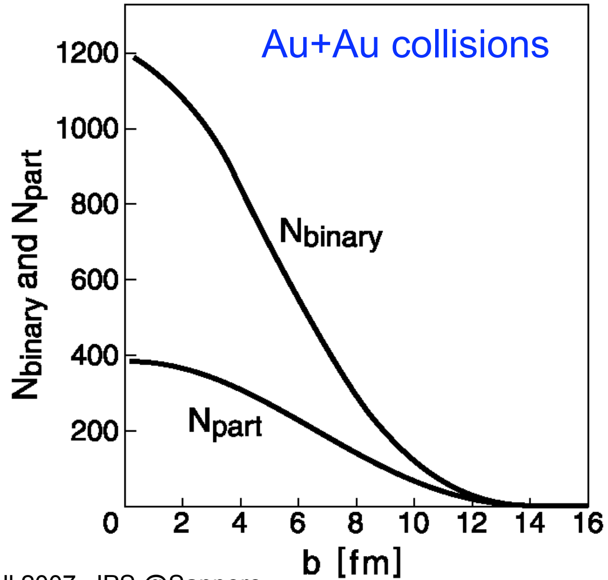
Peripheral ~ Central coll.



N_{part} vs N_{binary}

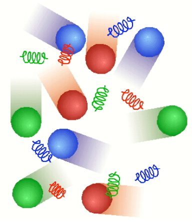




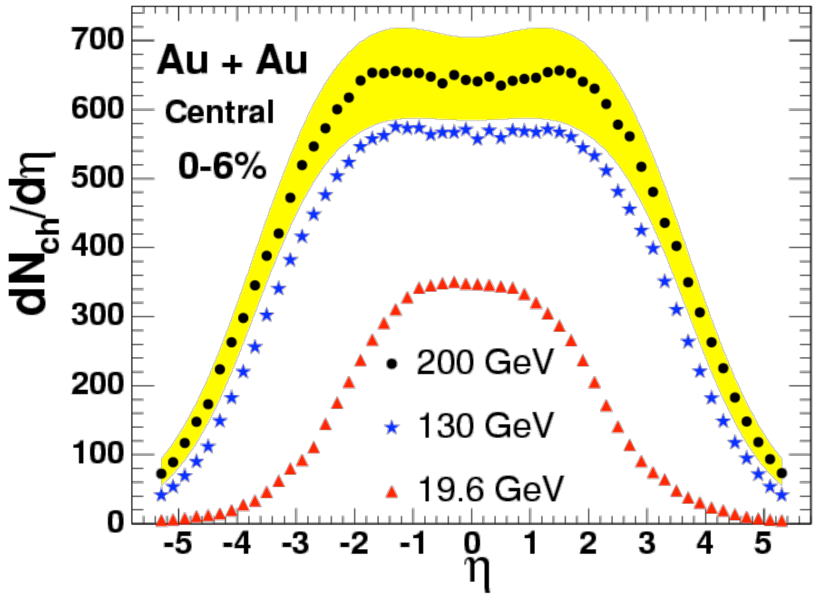


- For comparison with pp or dAu also for centrality study, we need scaling variables.
- N_{part};
  - # of participant nucleons
  - Particle production in hA is known to be proportional to N_{part}. (Wounded-Nucleon Model)
- N_{binary};
  - # of binary nucleon-nucleon collisions
  - Pass through at high energy.
- Evaluation of N_{part} & N_{binary} by **Glauber Model**.

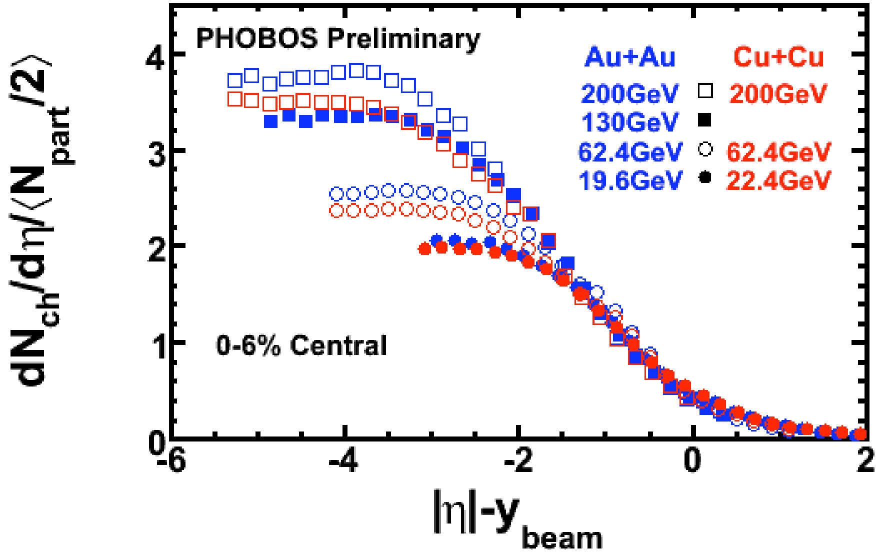
Particle production (η distr.)



Phobos; P.R.L. 91, 052303(2003)

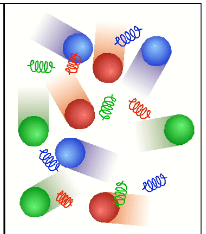


Phobos; J.Phys.G:Nucl.34,S217(2007)



- ✓ All the data taken at RHIC-Phobos.
- ✓ dn/dη ; wider & larger in higher energies.
- ✓ Not very flat even at 200 GeV despite our naive expectation
  - Note that it is plotted in η.
- ✓ Features of 'limiting fragmentation' seen
  - No 'Lorentz Invariance' yet!

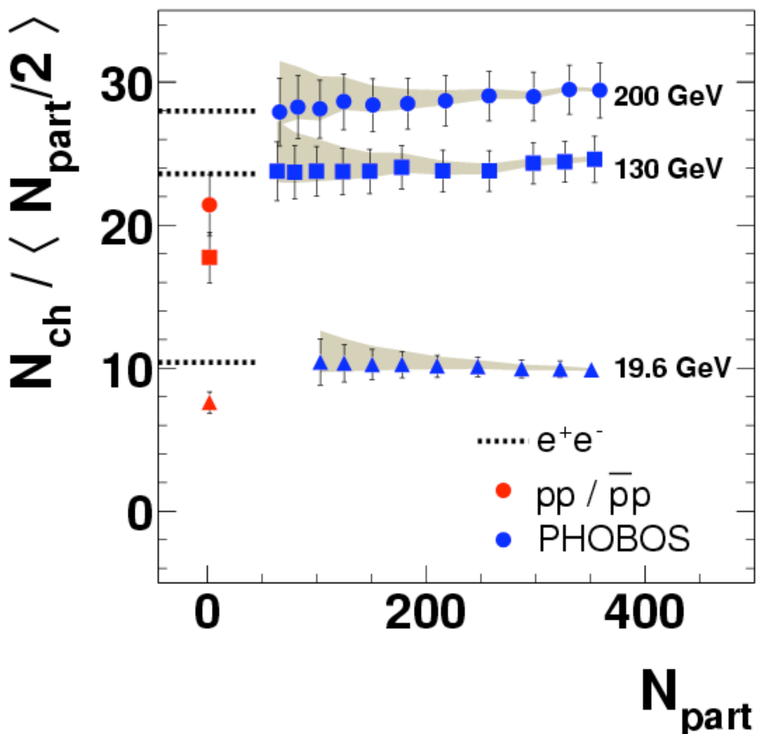
Particle production (total mult.)

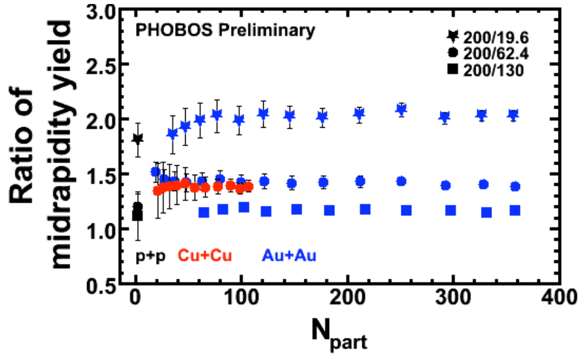


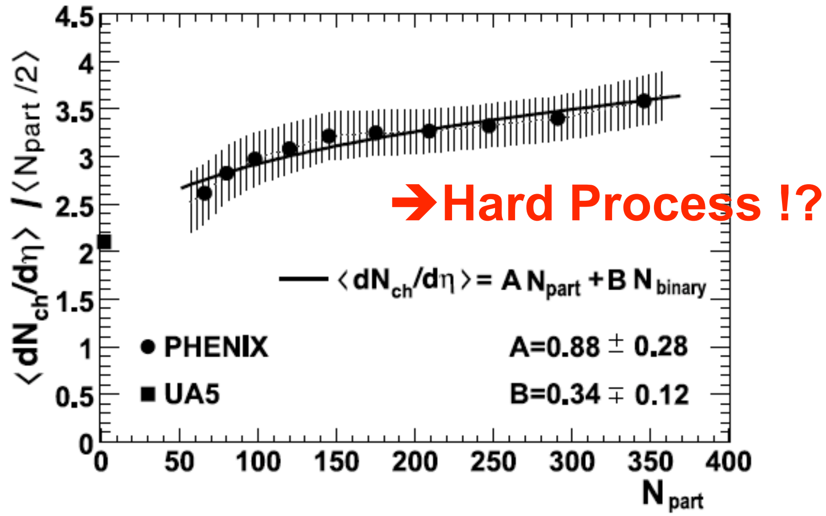
√ Total multiplicity per N_{part} stays constant.

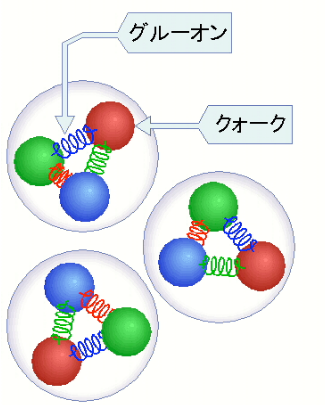
- WNM holds even at RHIC.
- Slight deviation at higher collision energies.

√ Deviation from N_{part} scaling more visible at mid-rapidity.

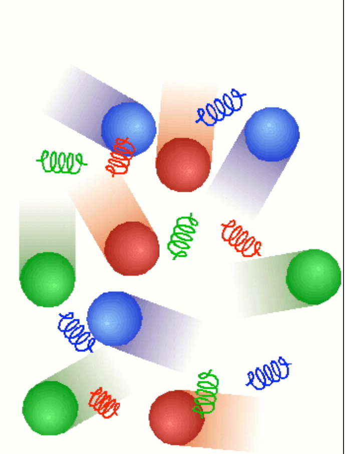






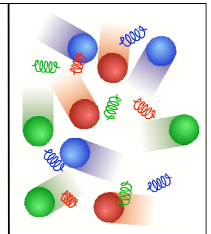


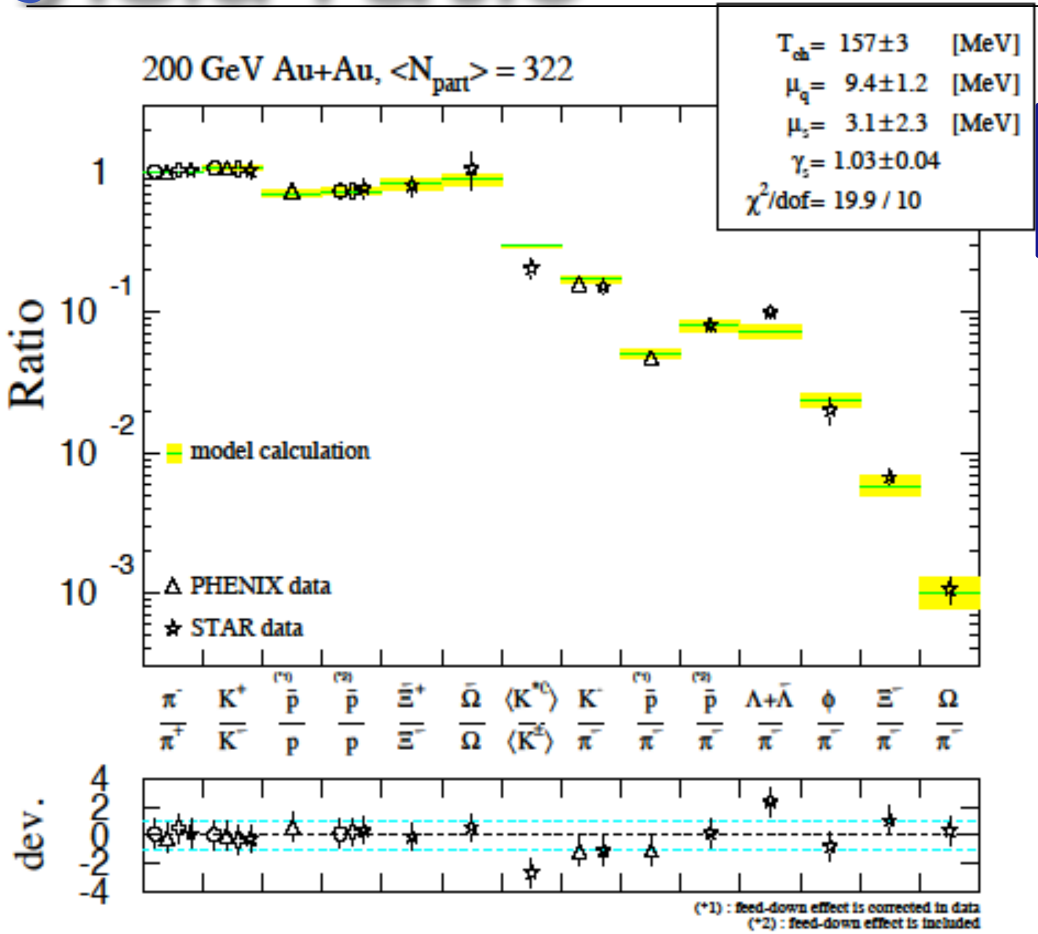
Thermal Equilibrium



- ★ Chemical Eq. from particle yield ratio
- ★ Kinematical Eq. from transverse mom. distr.

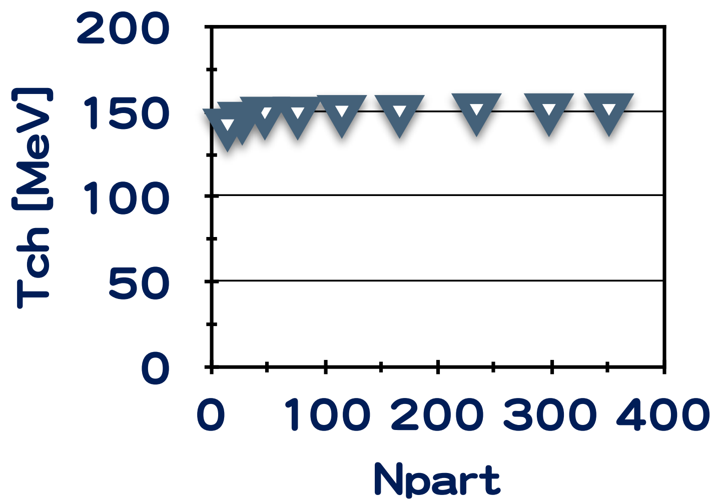
Chemical Eq. from particle yield ratio





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

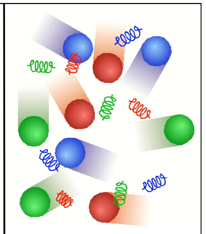
$$n_i = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i-\mu_i)/T} \pm 1}$$



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

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

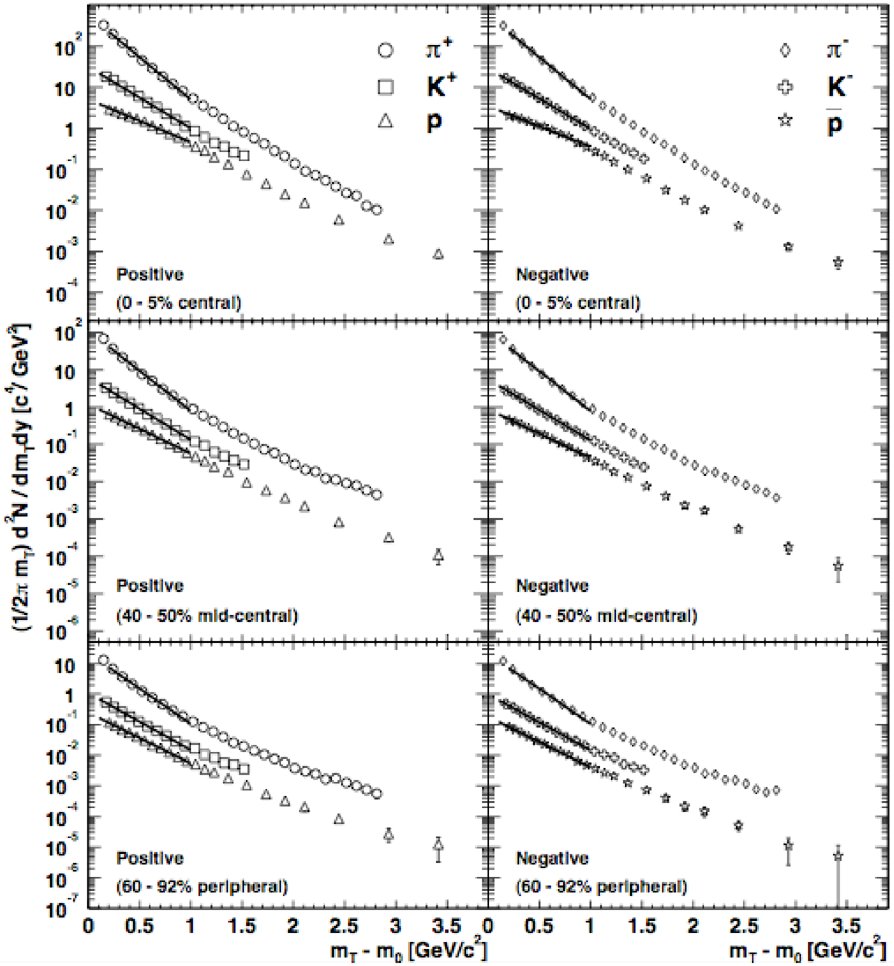
Kinematical Distr.: Transverse mass distr.

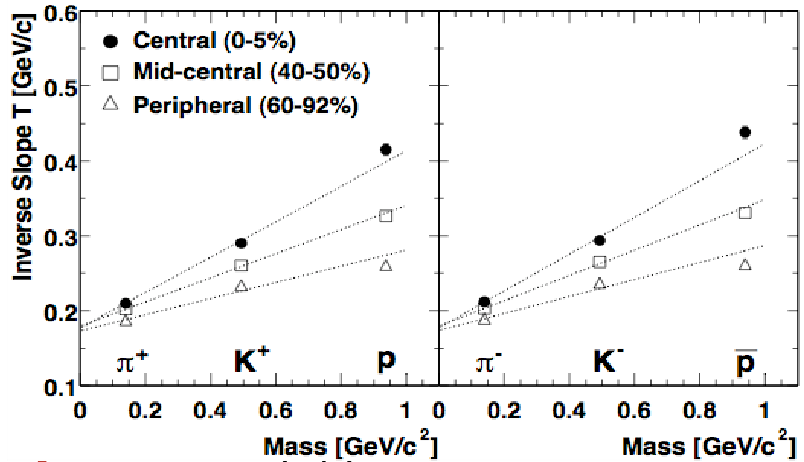


$$m_t = \sqrt{p_t^2 + m^2}$$

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

PHENIX, PRC69,034909(2004)



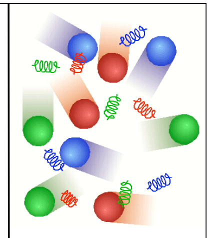


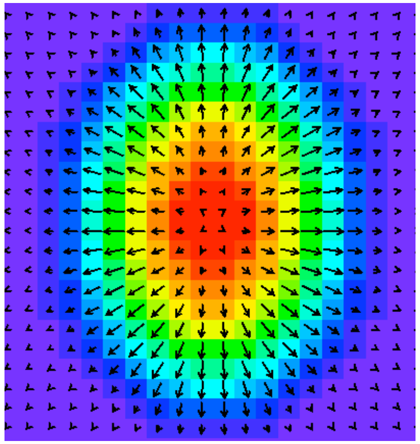
- ✓ Exponential in m_t
  - ✦ Known as m_t scaling
  - ✦ Thermal distr.
- ✓ Flatter m_t distr for heavier particle mass
  - ✦ Mass Ordering of Slope param.
  - ✦ Effect of Collective Flow

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

Collective Flow

Blast Wave Model





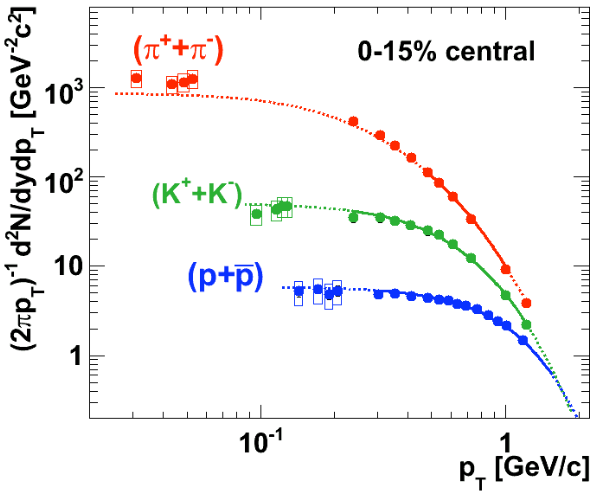
$$\frac{1}{m_T}\frac{dN}{dm_T} = A\int_0^R f(r)rdrm_T \, I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right)$$

PRC48(1993)2462.

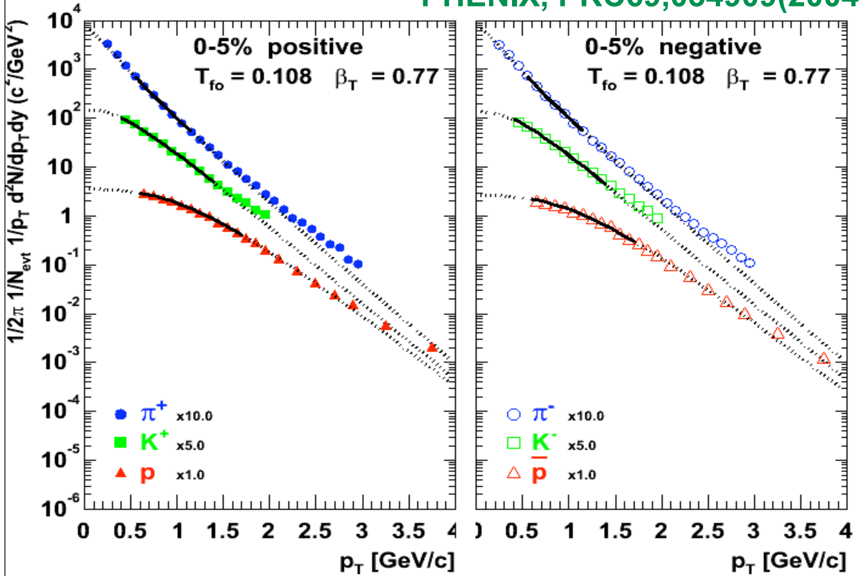
$$\rho(r) = \tanh^{-1}(\beta_T)\cdot r/R$$

I_0 , K_1: modified Bessel function

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



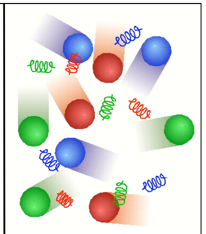
PHENIX, PRC69,034909(2004)

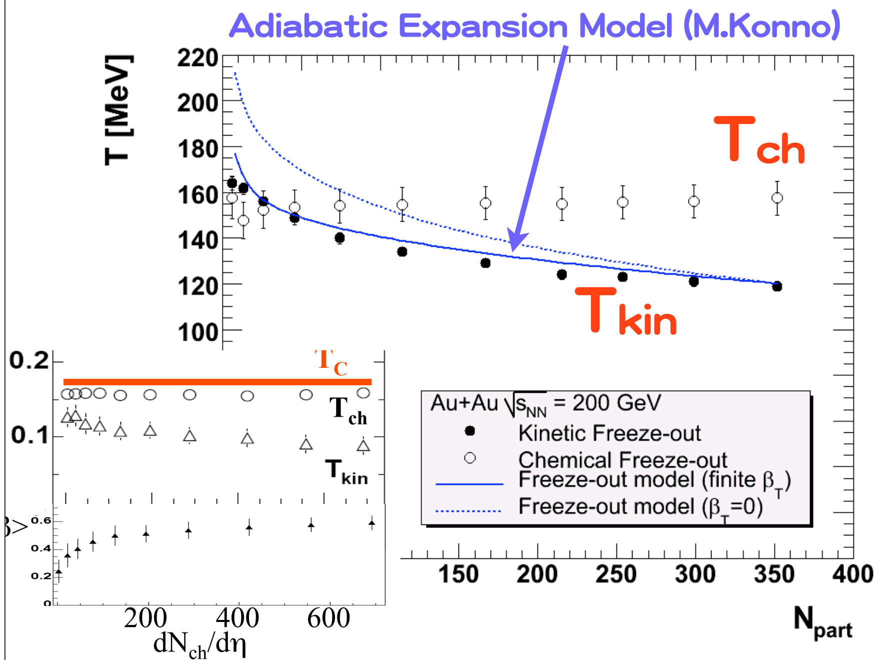


✓Good tool to separate thermal and collective

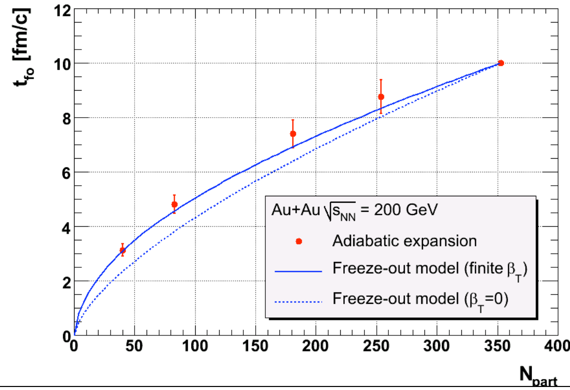
✓Well describe < 2 GeV/c

Distinct feature of freeze-out conditions

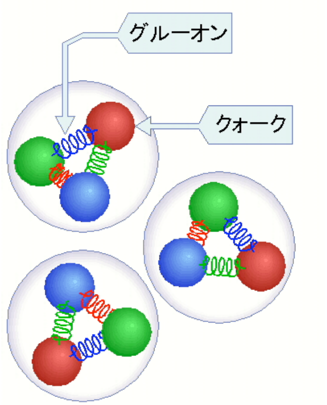




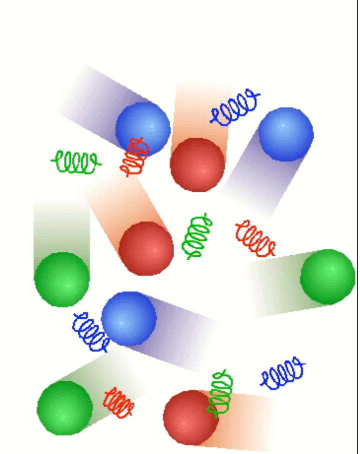
Central collisions freeze-out late.



- ✓Kinematical & Chemical freeze-out show difference in centrality dependence!
  - ✦Kinematical :
    - ➡$T_{kin}^{cent.} < T_{kin}^{per.} < T_{ch}$
    - Freeze-out with $\lambda \sim R$
  - ✦Chemical :
    - ➡$T_{ch}^{cent.} \sim T_{ch}^{per.} \sim$ 160 MeV
    - Freeze-out with $T \sim T_{crit}$
- ✓Nature of Freeze-out
  - ✦Kinematical freeze-out is collisional, while chemical is not.



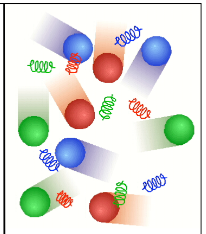
Two Major Discoveries at RHIC

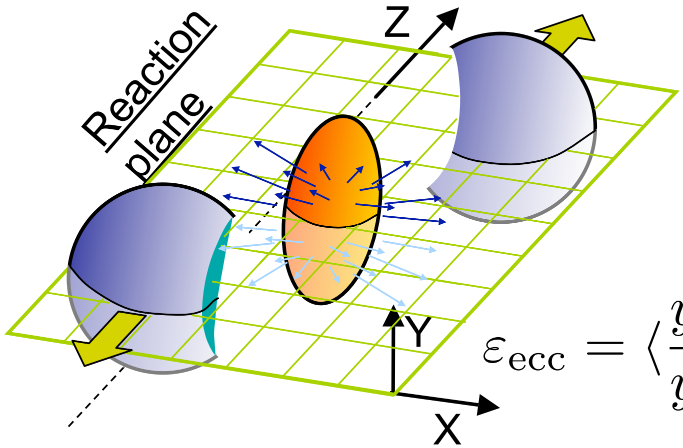


1) Large Elliptic Flow

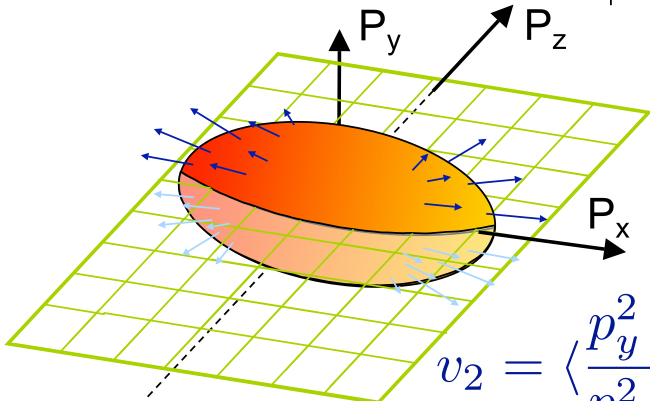
2) Jet Modification

Elliptic Flow, v2 (Azimuthal Anisotropy)





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

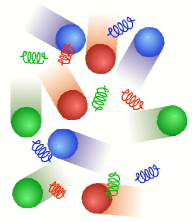


$$v_2 = \langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \rangle$$

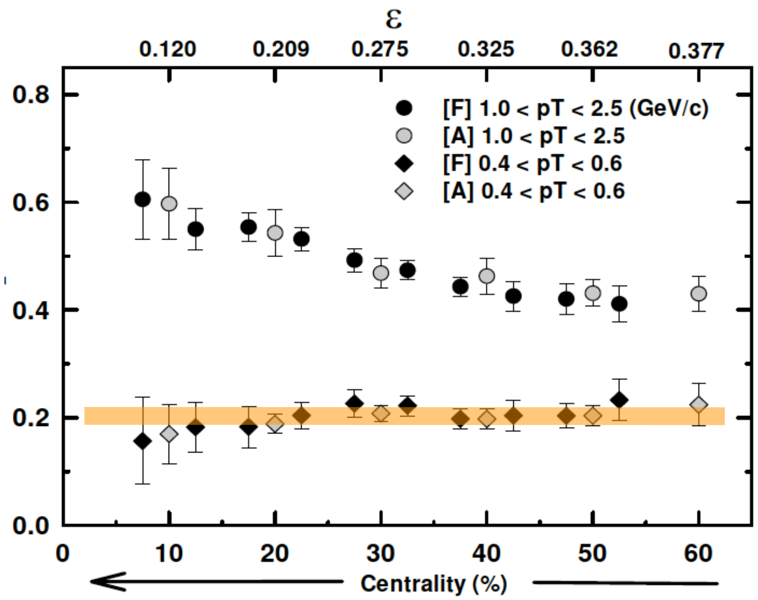
- √ In non-central collisions, participant region has almond shape.
  - ➡azimuthal anisotropy in coordinate space
- √ If λ≪ R, azimuthal anisotropy of the coordinate space is converted to that of the momentum space.
  - ➡v_2 ; second Fourier harmonics of azimuthal distribution
- √ Goodies :
  - ✦Clear 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

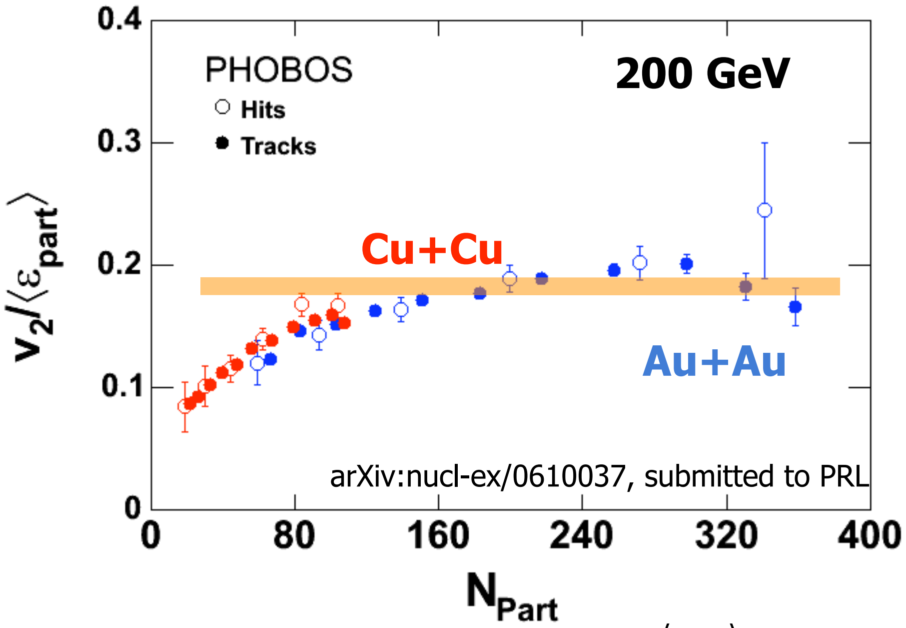


Phenix; PRL 89(2002)212301



v_2/ε

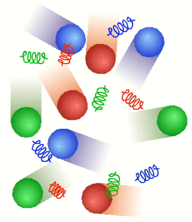
Phobos; nucl-ex/0610037



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

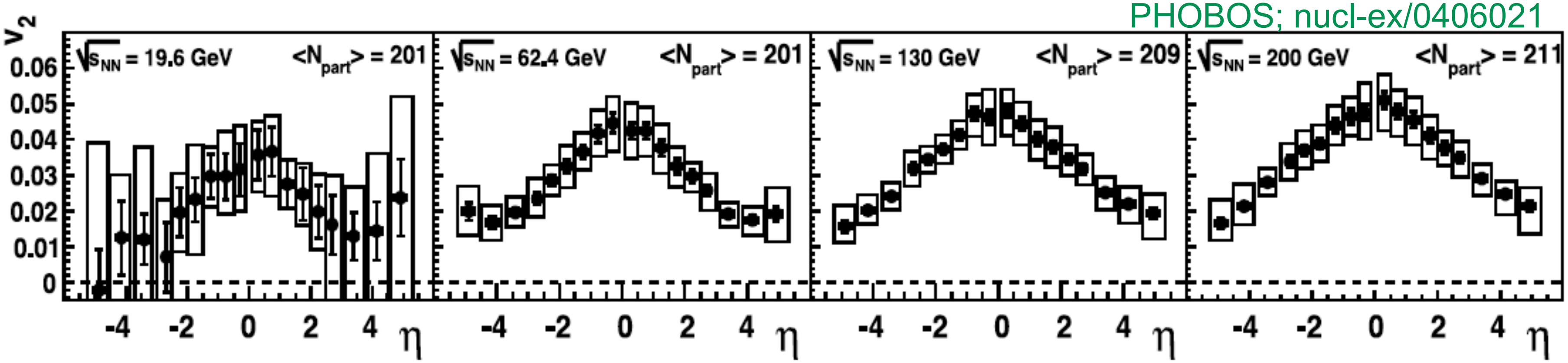
- √Eccentricity is evaluated from centrality of collisions
- √Ratio stays ~constant
  - ✦Eccentricity scaling observed in comparison of Au+Au, Cu+Cu
    - ➔Scaling with eccentricity shows v_2 builds up at early stage

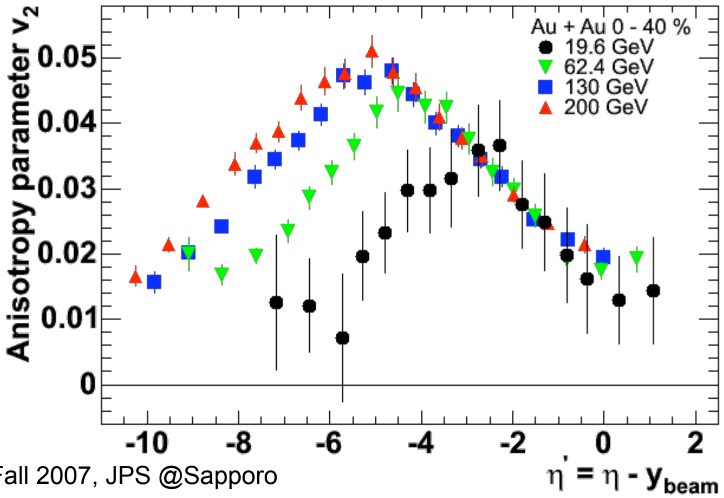
Large azimuthal anisotropy



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

PHOBOS; nucl-ex/0406021

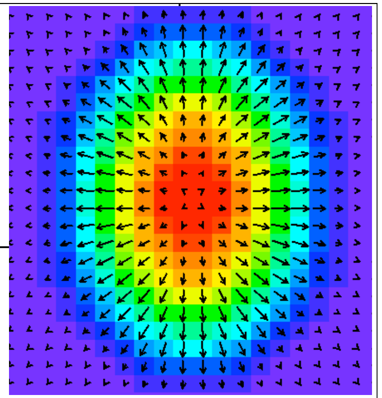




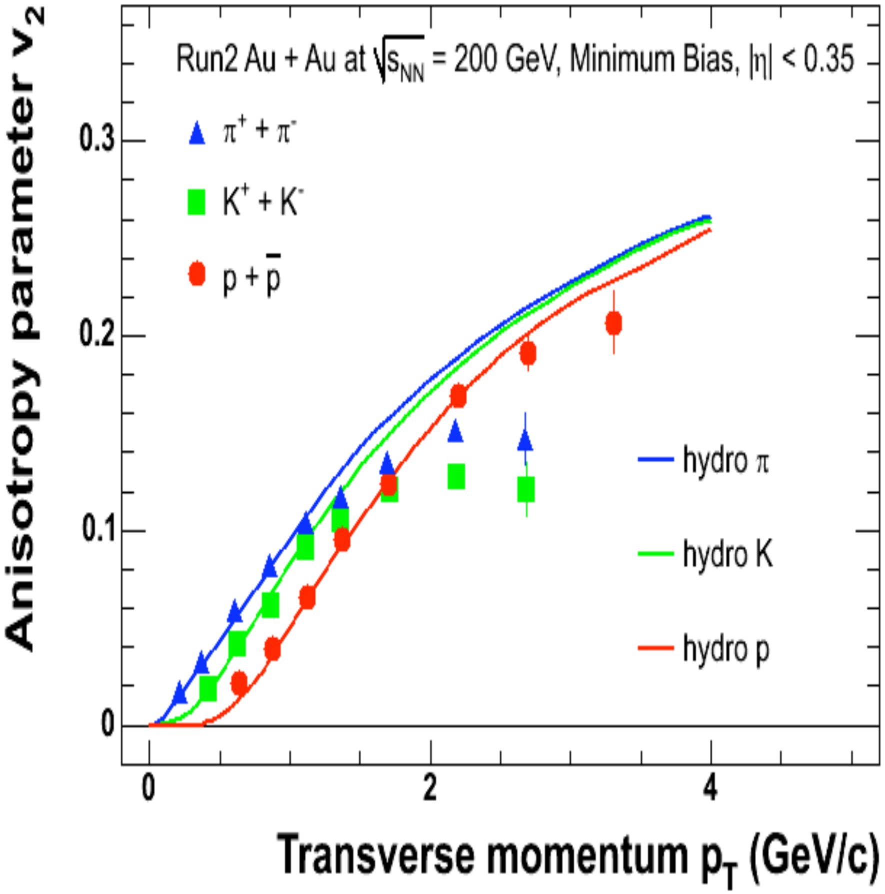
✓ Getting larger & larger in higher energies.

- ✦ Hadronic scenario fails
- ✦ Scaling w. $\eta - y_{beam}$!?

v_2 of identified particle



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)
  - ➡ Very low viscosity
- √ Departure at high pt region (> 1.5 GeV/c);
  - ➡ Other mechanism?

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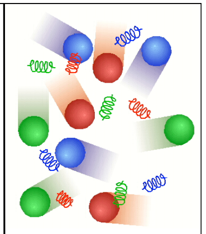
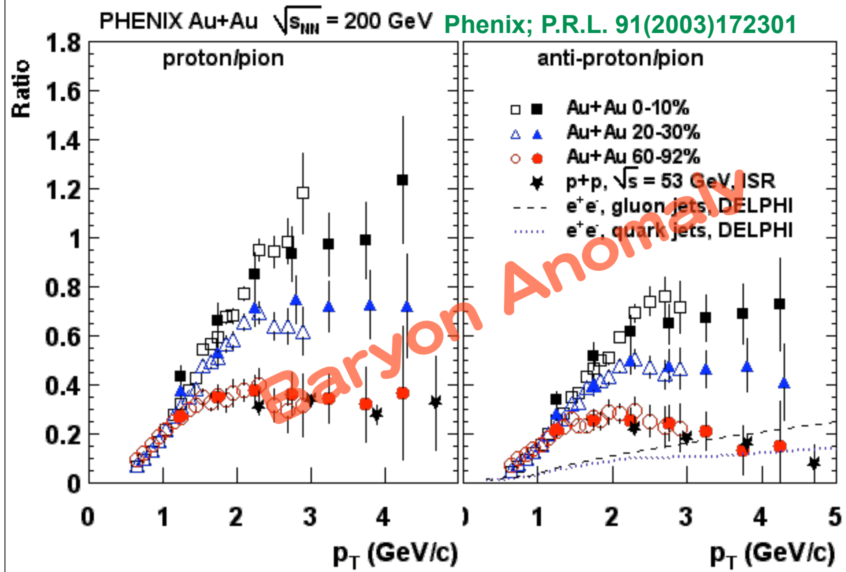
Quark Soup

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

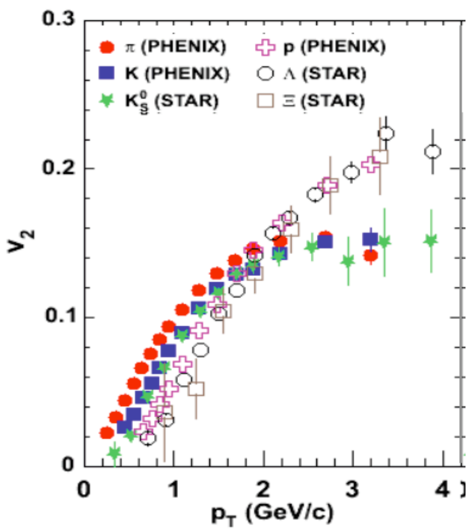
Puzzles in the mid-p_t region



p/π enhances above 1.5 GeV/c



v_2 deviates from the mass ordering above 2 GeV/c

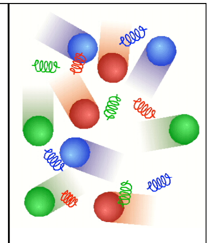


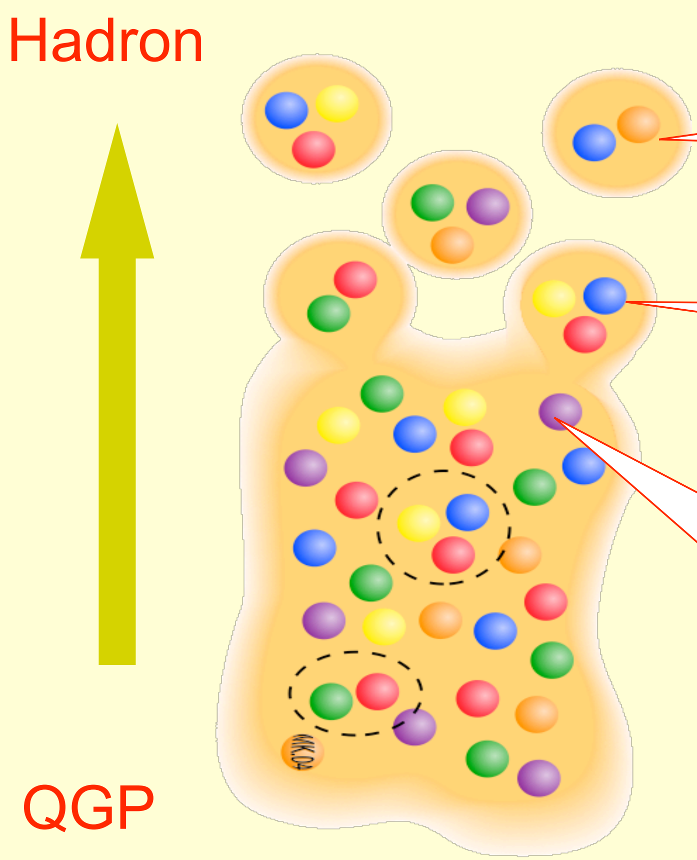
- ✓ In central col., p/π ratio is very large, while in peripheral, p/π ratio similar to those in ee/pp suggesting fragmentaton process.
  - Fragmentation process should show $n_p < n_\pi$ as seen in ee/pp.
- ✓ While mass ordering of v_2 seen at low pt region, clear departure observed.
- ✓ Suggesting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

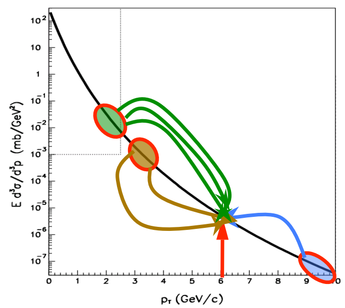
Mom. distr. of meson (2q);

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

Mom. distr. of baryon (3q);

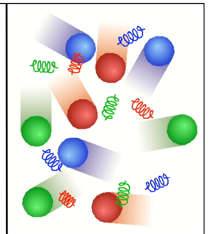
$$W_{\mathrm{B}}(p_t) \approx C_B \cdot w^3(p_t/3)$$

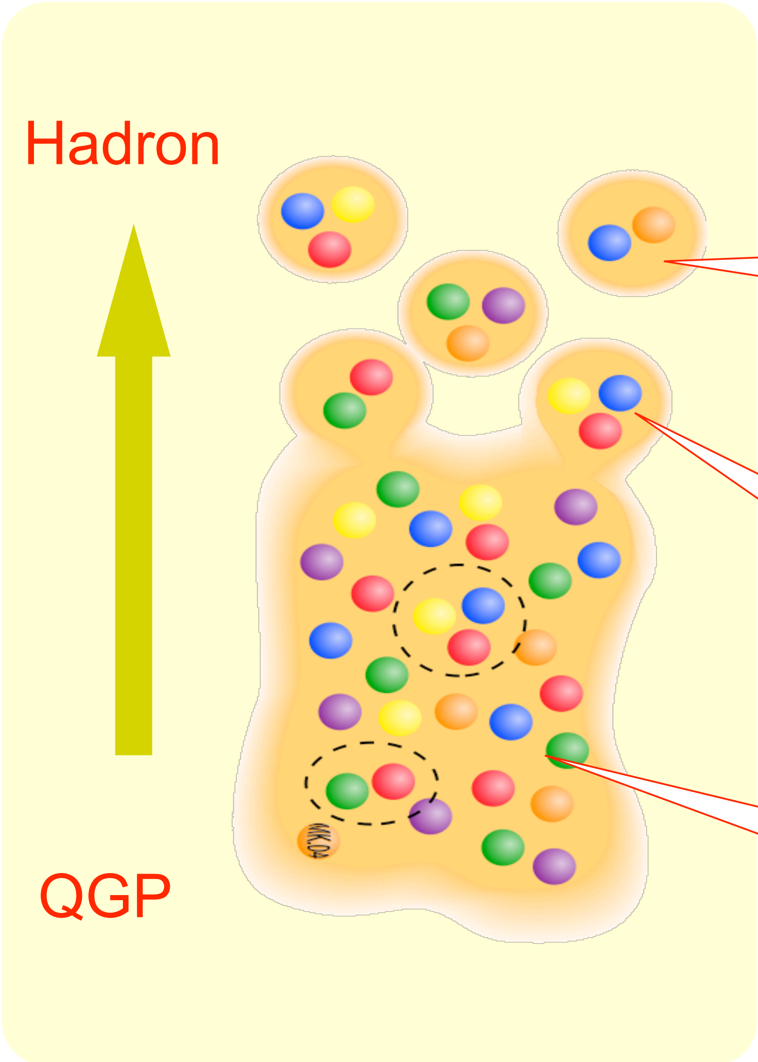
w(pt);
Universal mom. distr. of quarks
{*steep in pt*}



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);

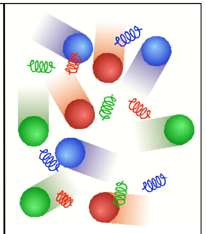
$$\frac{dN_B}{d\phi} \propto w^3 = (1 + 2v_{2,q}\cos 2\phi)^3$$

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

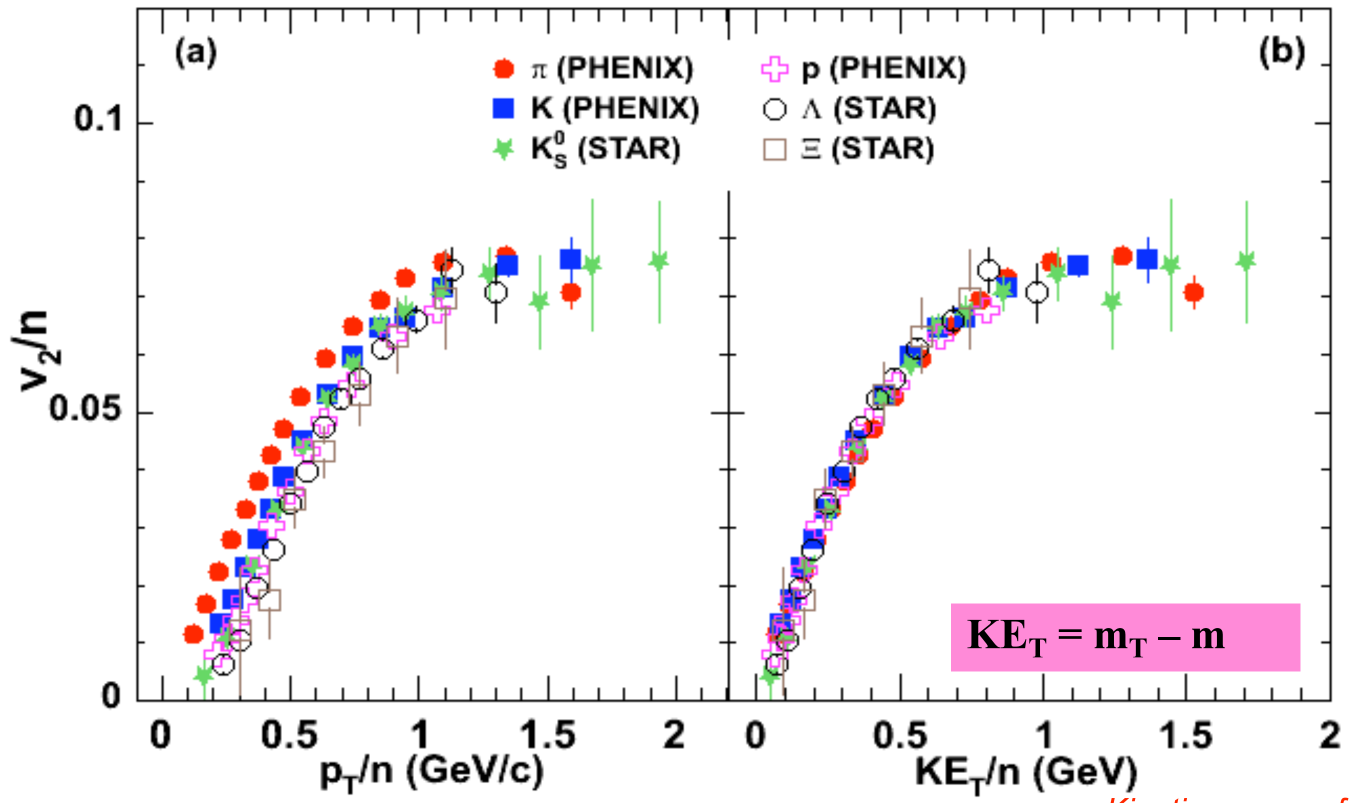
Azimuthal distr of quark; w

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

Quark Number Scaling !!



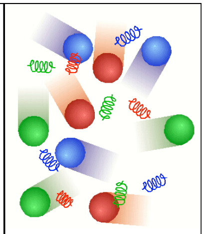
M. Issah, A. Taranenko, nucl-ex/0604011



Kinetic energy of constituent quarks

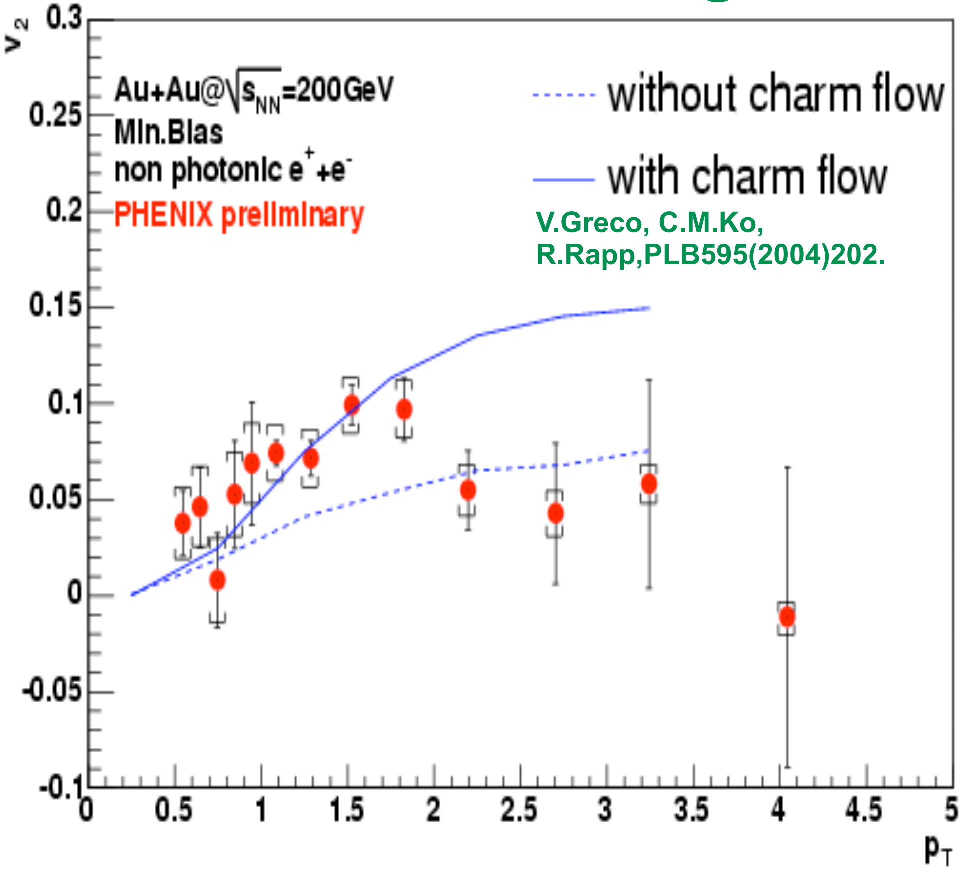
- ✓ **Mesons and baryons made of light quarks seem to be consistent with the recombination model and there seem to be universal quark distribution, w(pt,Φ).**

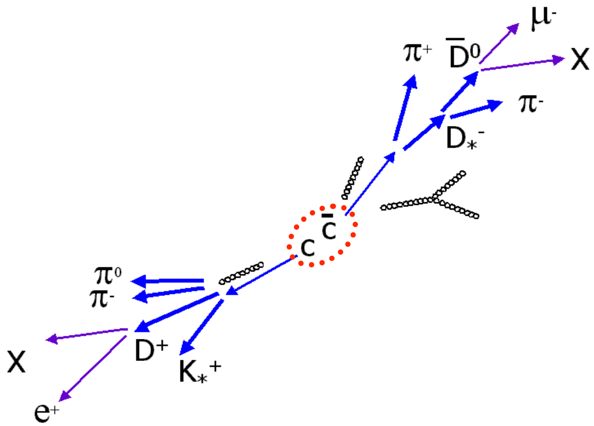
Even charm flows!



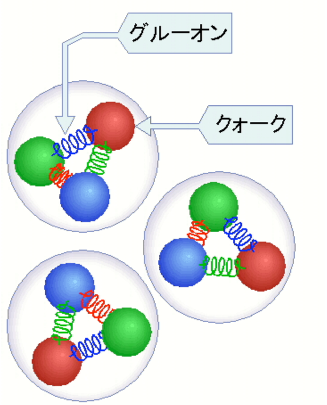
v2 of single electrons

S.Esumi & S. Sakai@SQM2006

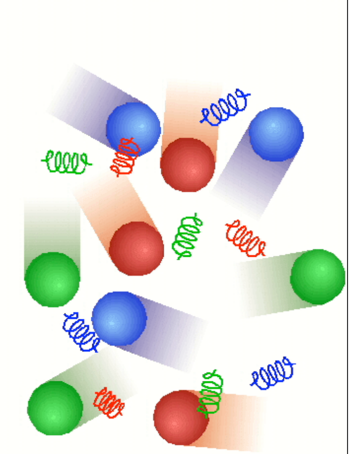




- √ Charm decay produces high energy electrons.
- √ v2 of single electrons are measured.
- √ Observed data favors flow of charm, suggesting thermalization of heavy quarks.
- √ This supports quark-coalescence & formation of QGP.

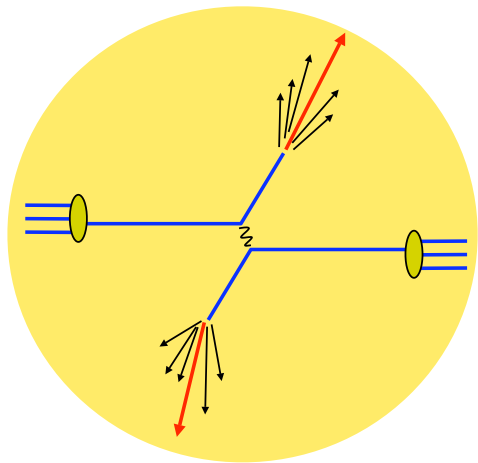


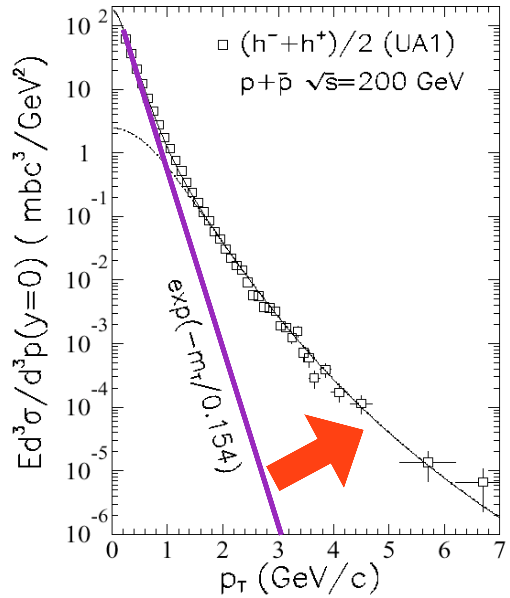
Jet Modification

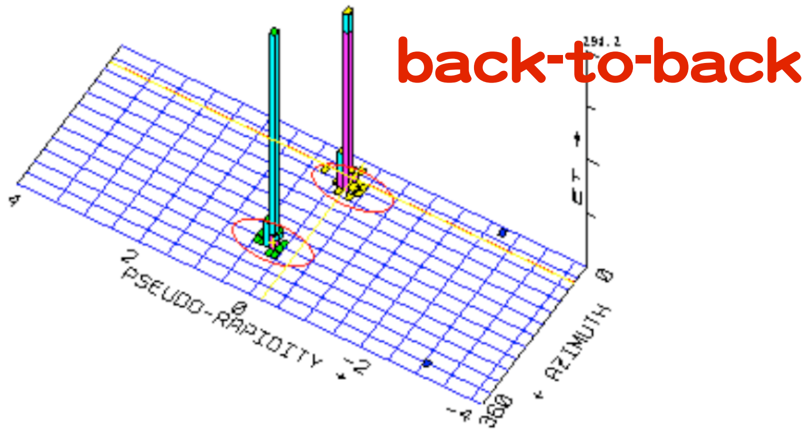


What is Jet ?

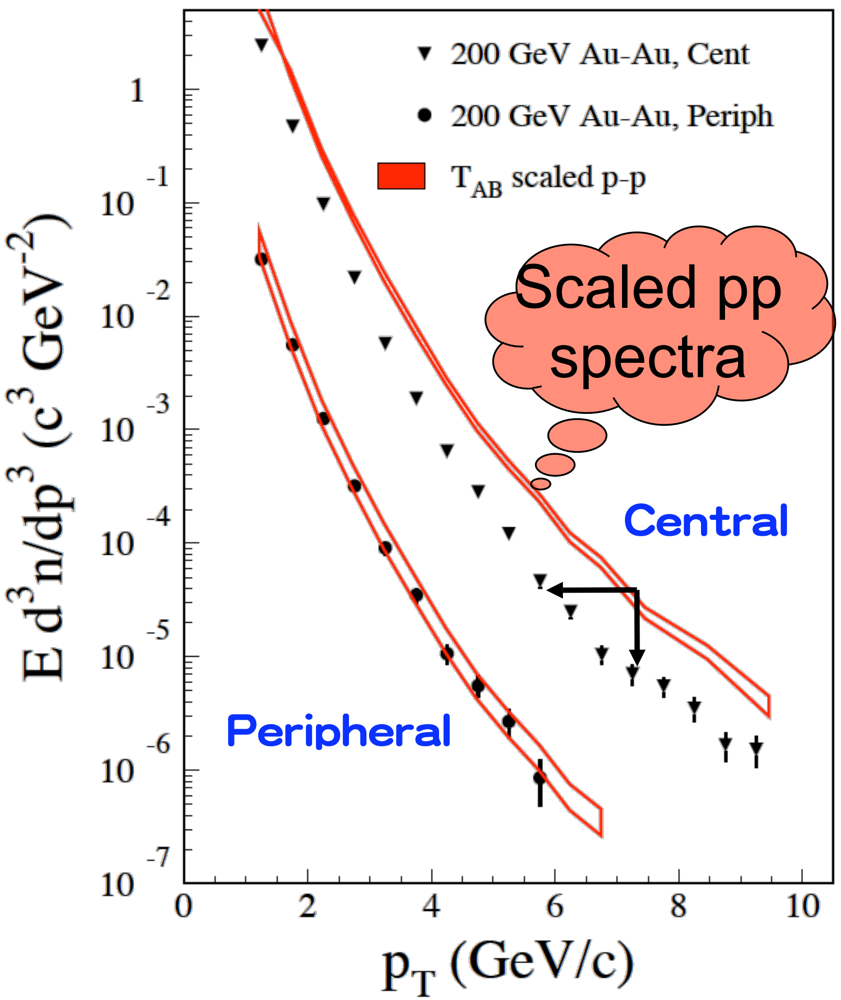
- At ISR in 1972, deviation from the m_t scaling at high p_t region is observed as a first time.
- Binary parton scattering followed by fragmentation produces back-to-back jet.
- Origin of high pt particles in elementary particle collisions.





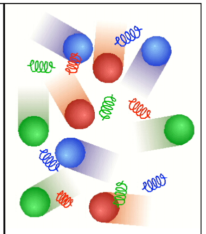


Comparison of Au+Au and pp



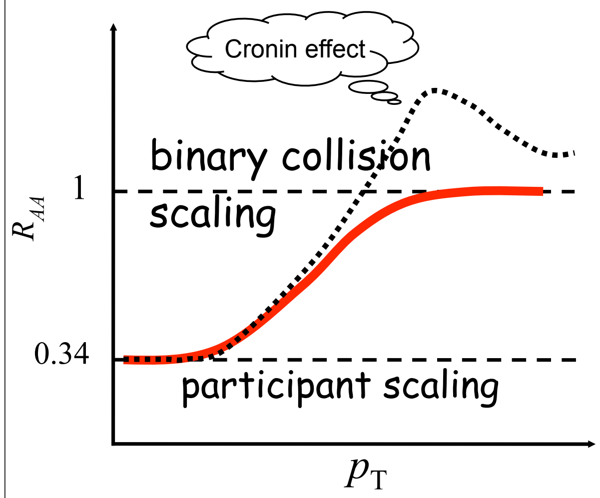
- ✓For comparison, Au+Au & pp spectra scaled by N_{binary}.
- ✓In peripheral collisions, Au+Au ~ pp
- ✓In central collisions, Au+Au < pp
  - Suppression of yield ?
  - Loss of p_T ?
  - Jet Quench?

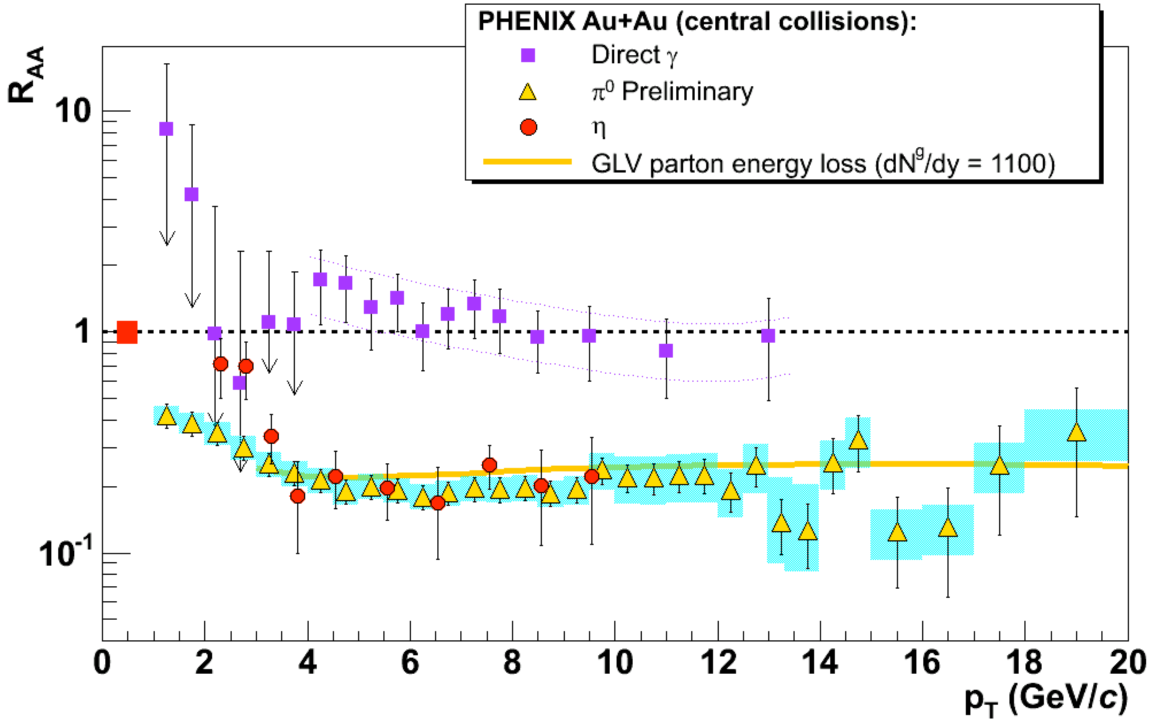
Suppression of high p_t particles



Nuclear Modification Factor

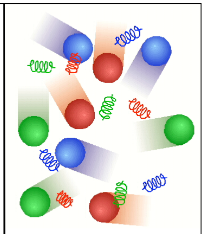
$$R_{Au+Au} = \frac{dn_{Au+Au}/dp_T dy}{\langle N_{binary} \rangle \cdot dn_{pp}/dp_T dy}$$



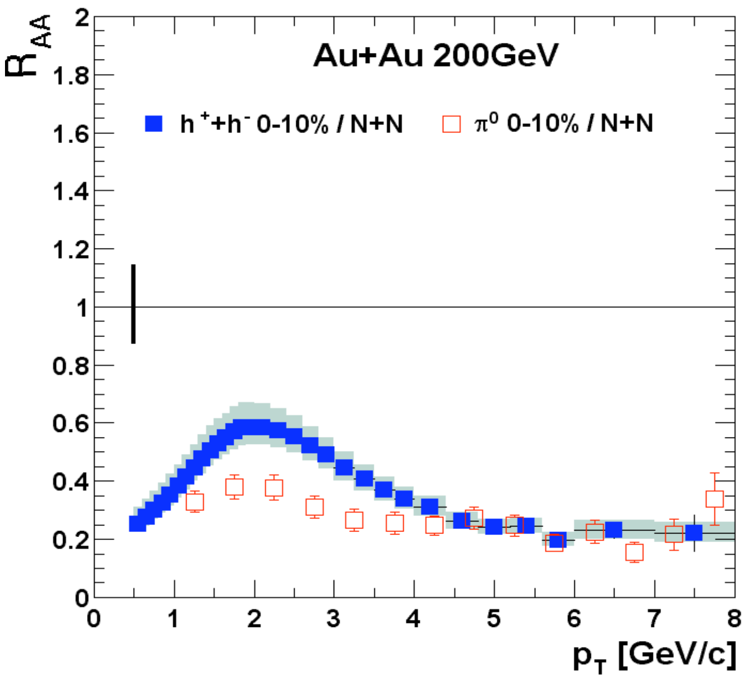


✓ **Pions are suppressed, direct photons are not**

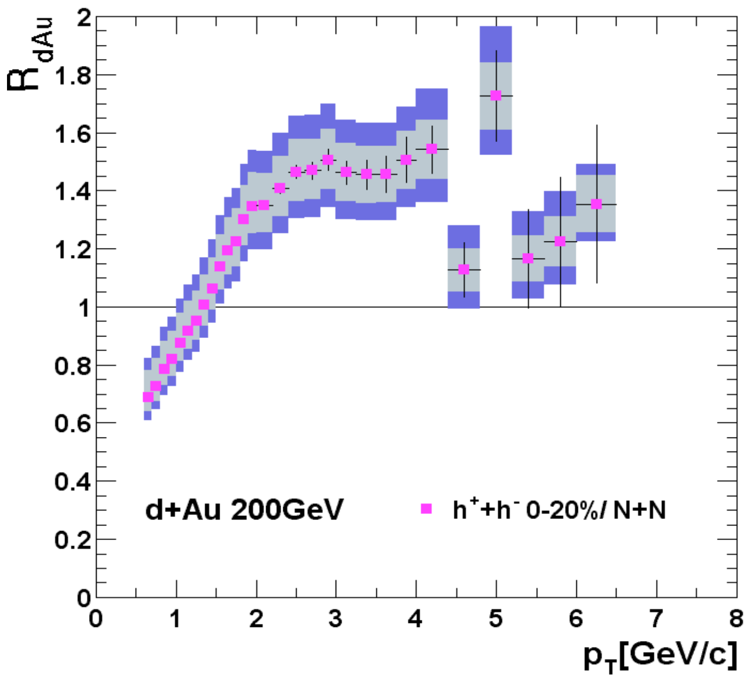
Au+Au vs d+Au



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



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

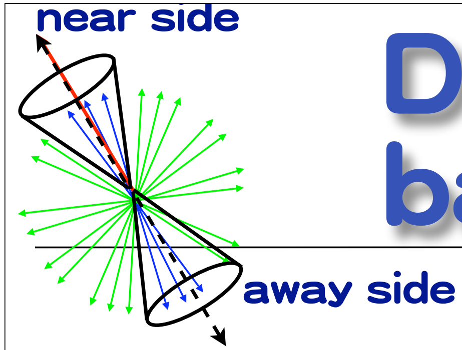


d+Au→h±+X at $\sqrt{s_{NN}}$ = 200 GeV

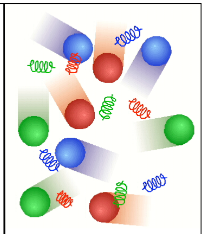
poro

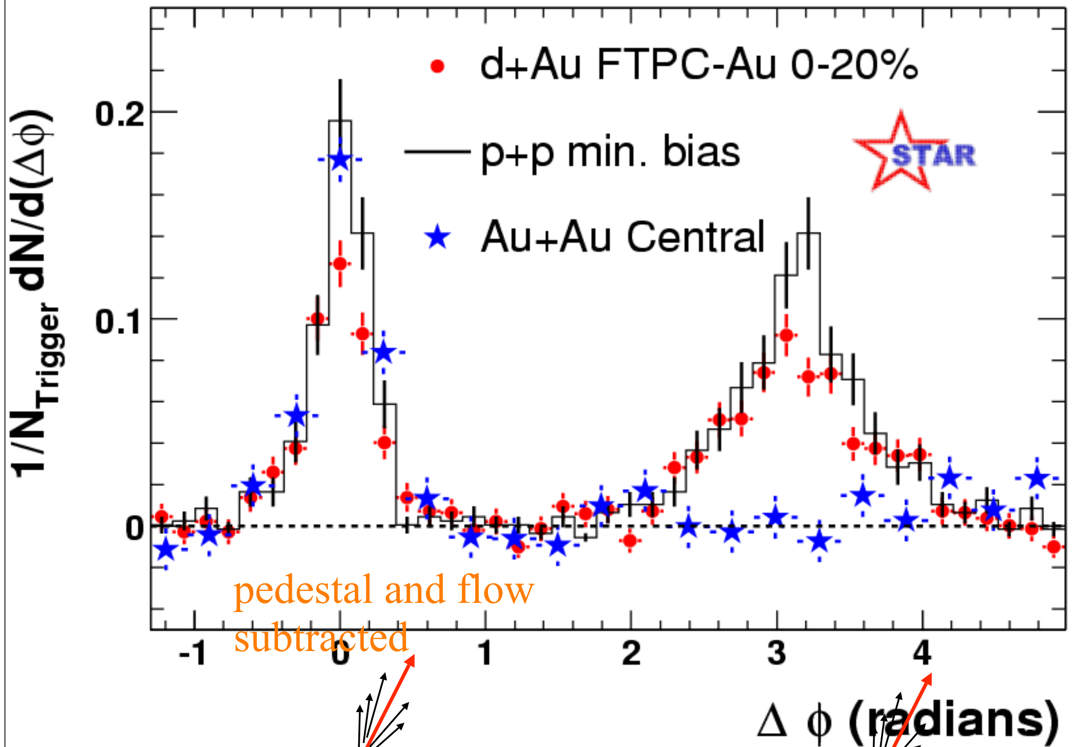
✓**High pt suppression in Au+Au, while not observed in d+Au.**

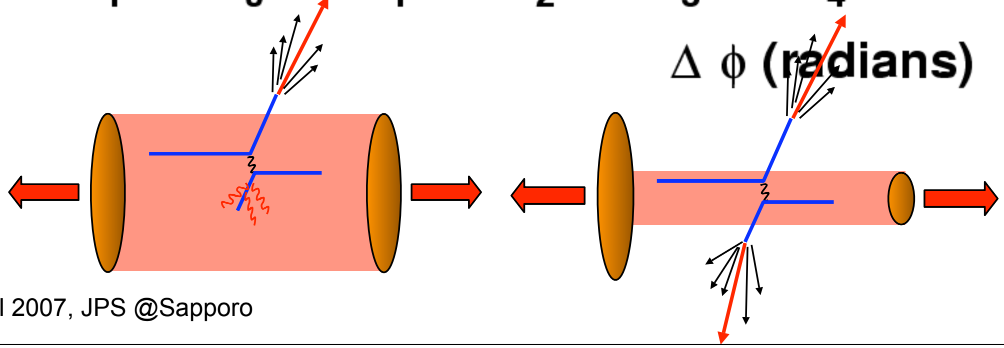
➡**Effect is not due to initial state, but final state.**



Disappearance of back-to-back corr.

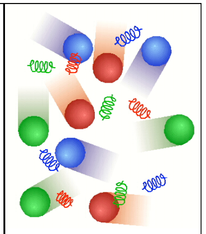


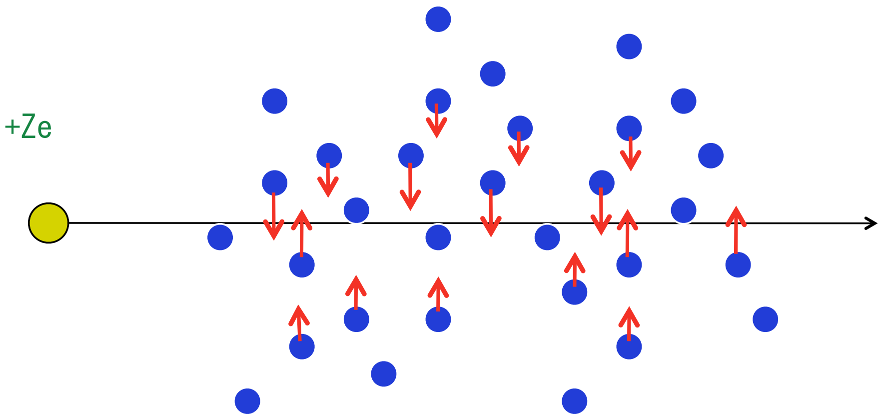


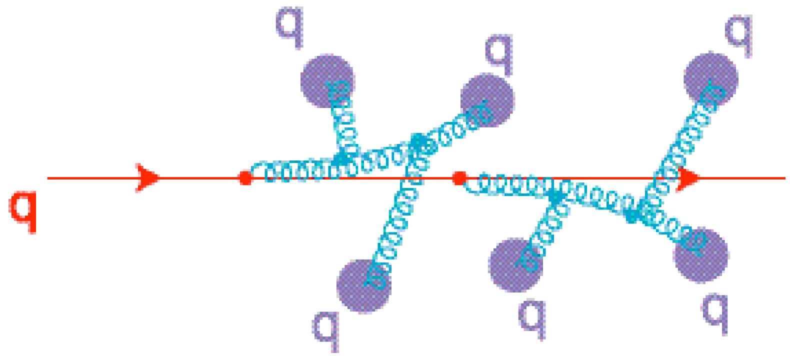


- ✓ Direct evidence of loss of 'jet'
- ✓ Azimuthal correlation w.r.t. high pt leading particle (trigger).
  - pp ; clean di-jet
  - dAu; similar to pp
  - Au+Au; Similar on the same side (suggesting jet-like mechanism), but b-to-b disappeared
    - Effect is not in initial but in final stage
    - Energy loss of partons in dense matter

Energy Loss of Parton ?



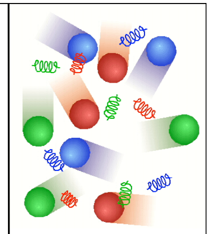




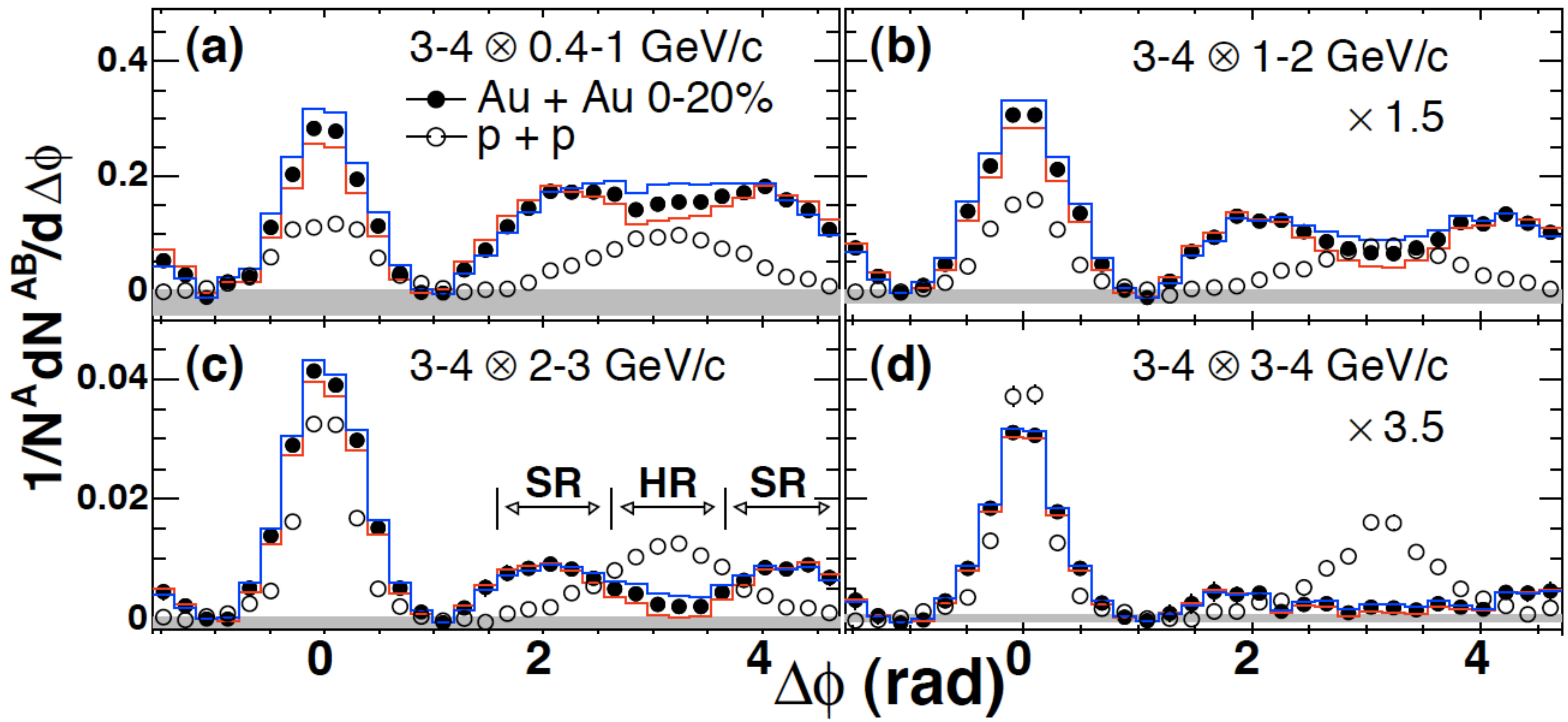
$$-\frac{dE_{\mathrm{Bethe}}}{dx} \propto \frac{N_e}{\beta^2} \ln(\beta^2 \cdots) \qquad -\frac{dE_{\mathrm{GLV}}}{dx} \propto \frac{N_g}{f(E)} \ln\left(\frac{E}{\mu}\right)$$

- √ **Energy loss of charged particle in matter;**
  - Collisions with atomic electrons, proportional to the electron density
  - Radiative energy loss.
    - ➔Bethe-Heitler Formula
- √ **In QCD, major loss will be radiative**
  - Energy loss of parton should be proportional to the gluon density

Shape change of away-side



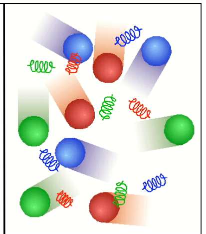
p_T^{trig} = 3~4 GeV/c   PHENIX, arXiv:0705.3238 [nucl-ex]



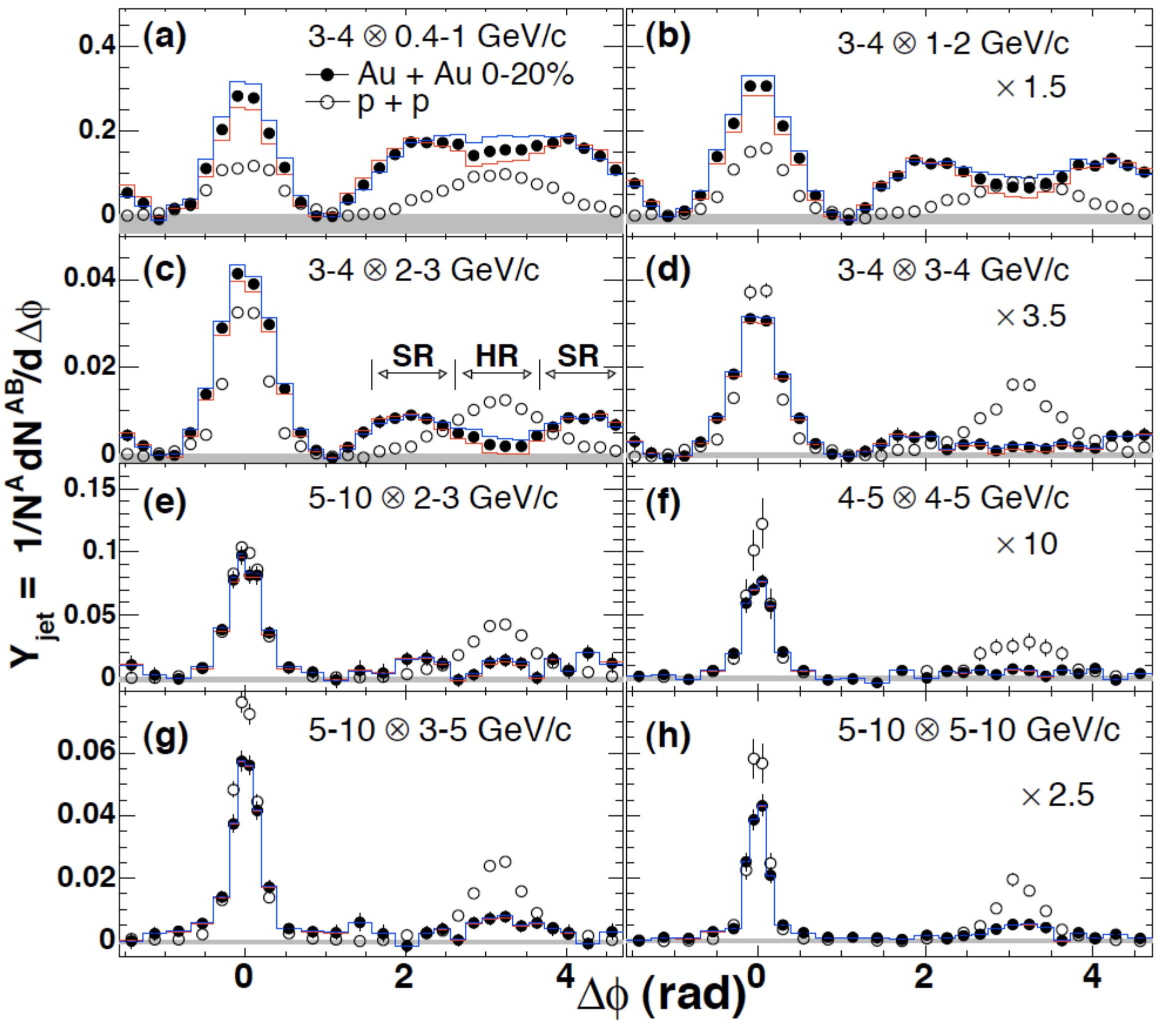
✓From broad to distinct two shoulders at $\Delta\Phi = \pi \pm 1.1$ with decreasing momentum

➡Location of shoulders independent of centrality

Separate contributions at $\Delta\Phi = \pi \pm 1.1$ & $\Delta\Phi = \pi$

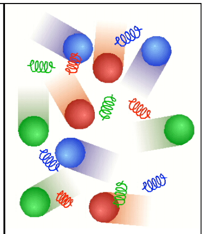


PHENIX, arXiv:0705.3238 [nucl-ex]

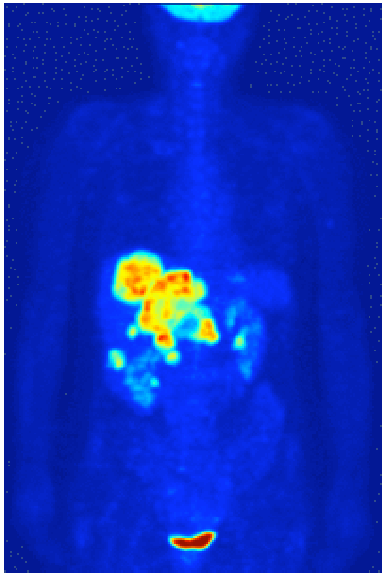


- ✓ Shoulders appear at lower momentum.
- ✓ Location & <pt> of shoulder seem to be independent of centrality and pt.
  - ✦ Not cherenkov
  - ✦ Not deflection
  - ✦ But, Mach Cone !?

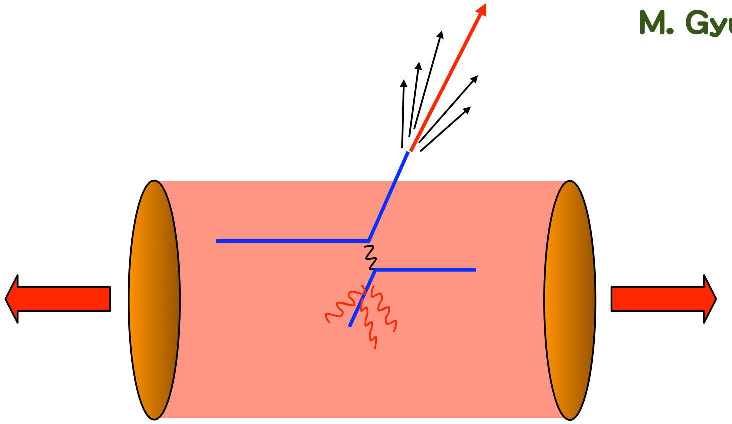
Jet Tomography



Positron EmissionTomography



Jet Tomography

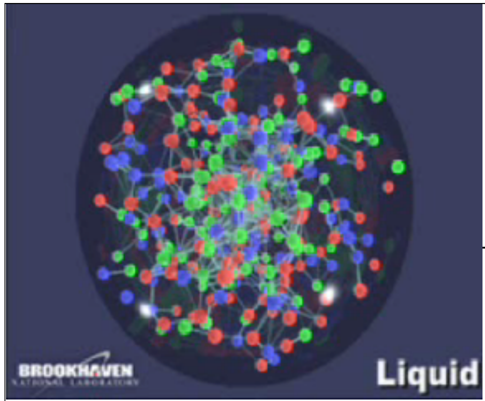


M. Gyulassy ?

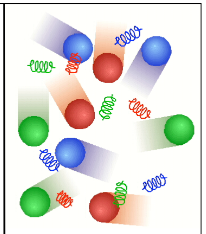
√Tool to prove structure of the dense matter

√Large azimuthal anisotropy is major background now.

➡ "Discovery of yesterday is background of today and calibration of tomorrow"



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.