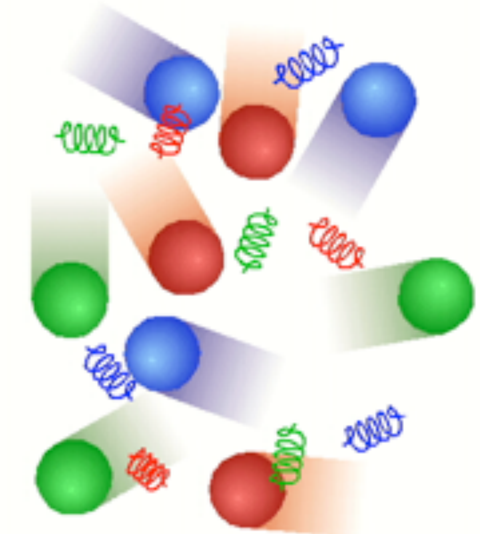
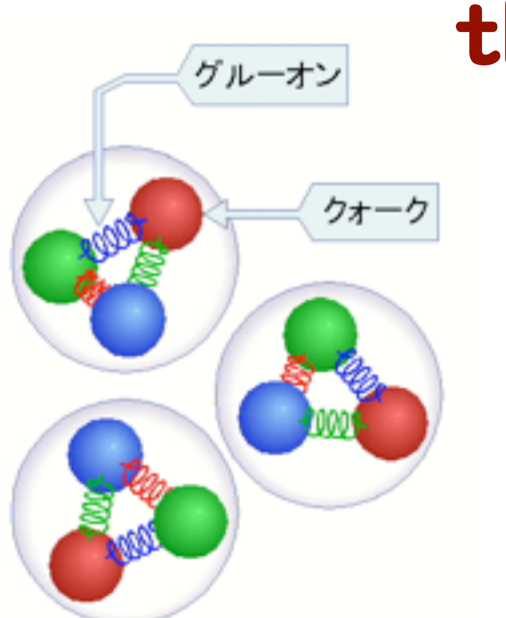
Experimental Seminar: Quark-Gluon Plasma

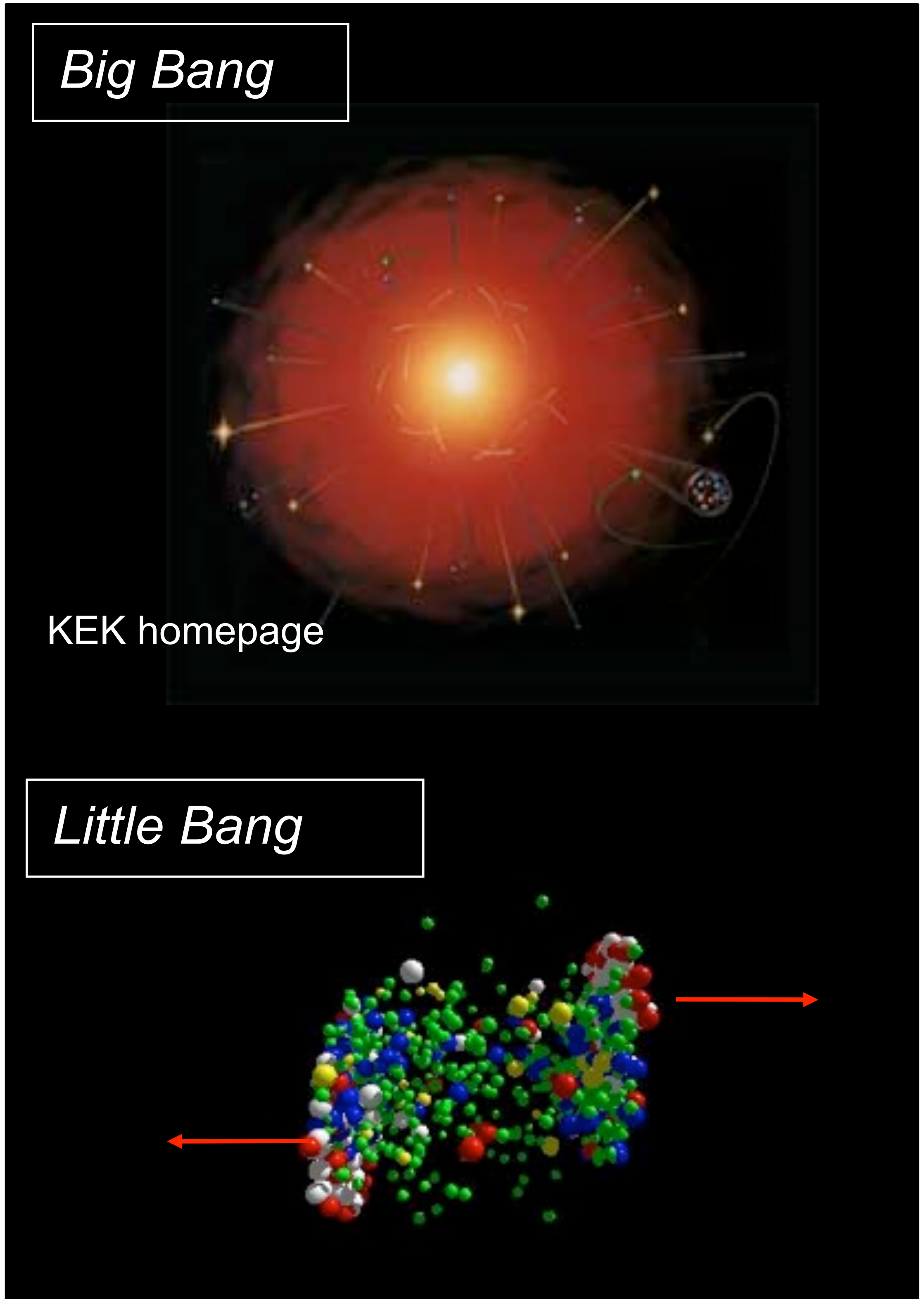


QGP:
Form of the Universe, right after the Big bang, ~a few μs, just before the nucleon synthesis



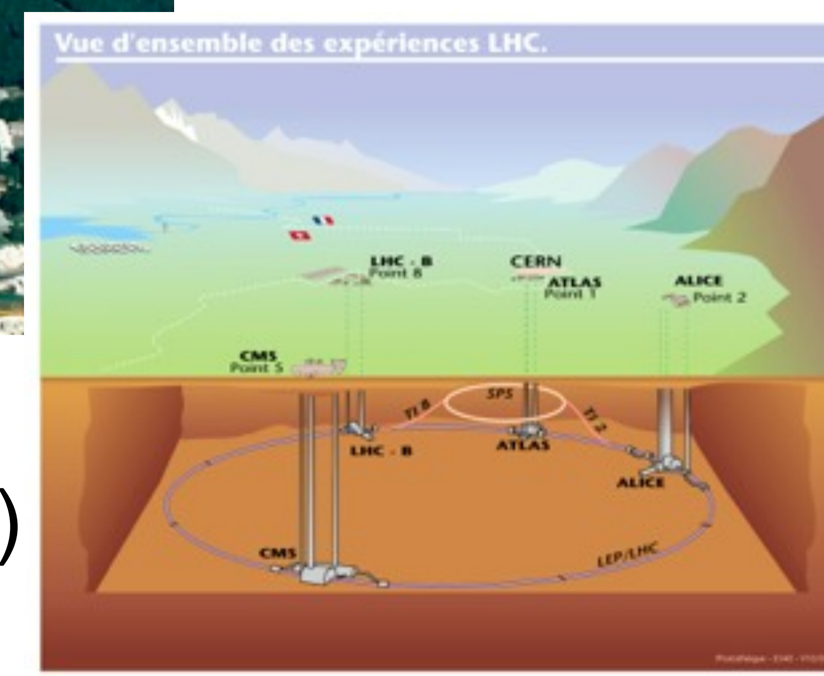
Yasuo MIAKE
Univ. of Tsukuba

Experimental study using Relativistic Heavy Ion Collisions



Accelerator Facilities

RHIC(200GeV)
since 2000



LHC(5.6TeV)
2009

- ✓ **Instead of Big Bang, create QGP in an experiment using relativistic nucleus-nucleus collisions, i.e. Little Bang**
- ✓ **How & what we prove/study the QGP, emerging connection with string theory, black hole thermodynamics....**

First things first !

CAMBRIDGE | Catalogue

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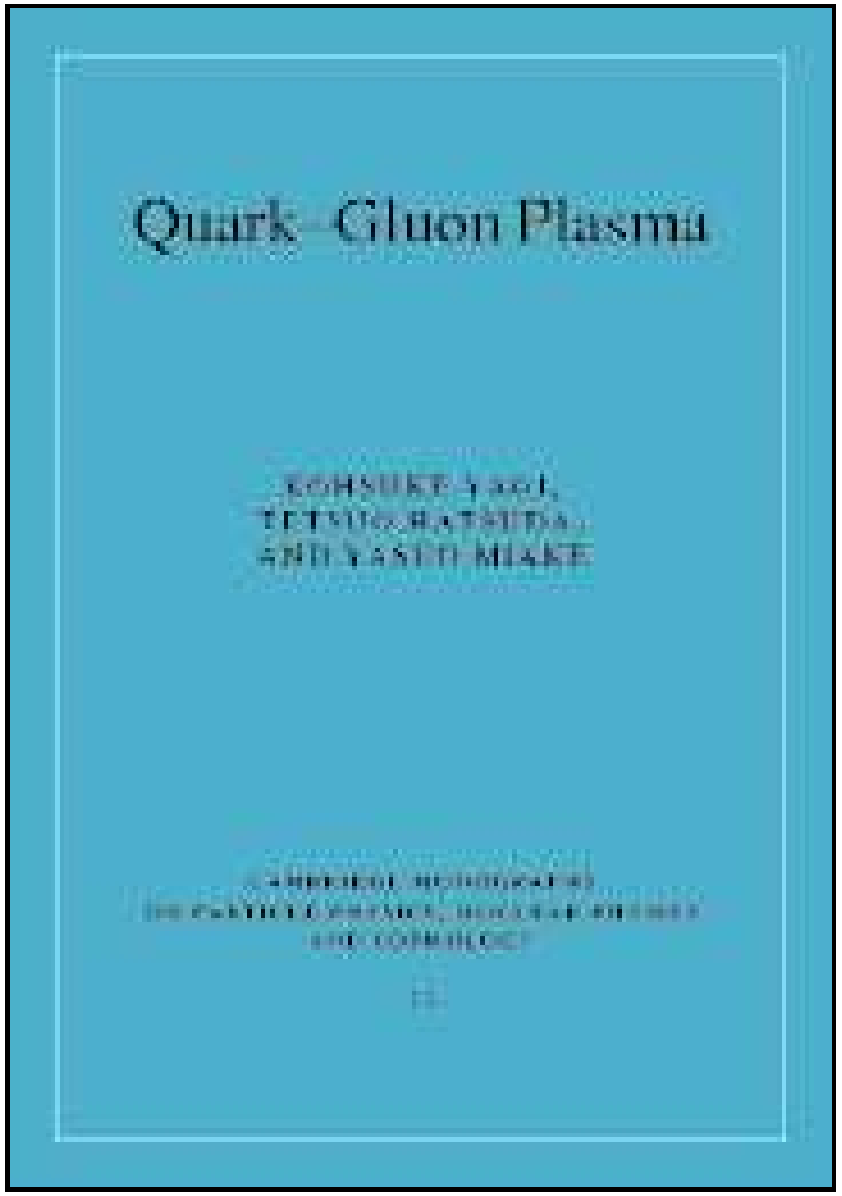

Quark-Gluon Plasma

Series: Cambridge Monographs on Particle Physics, Nucle

Buy at Amazon

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Urawa University, Japan

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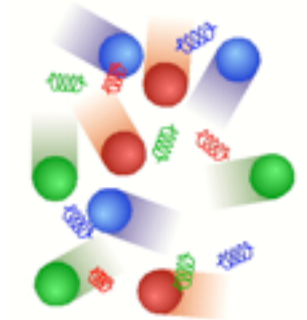
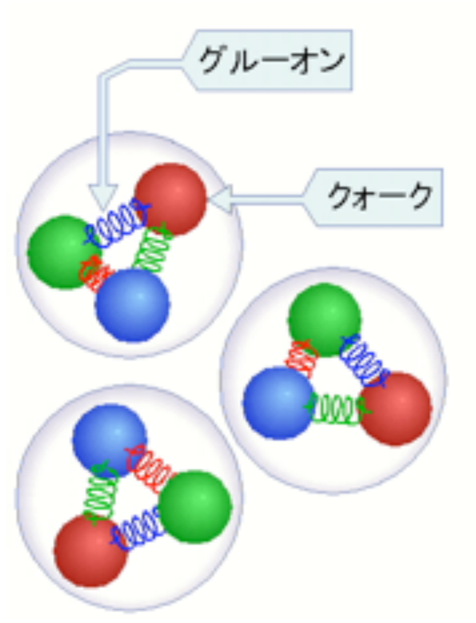
Outline

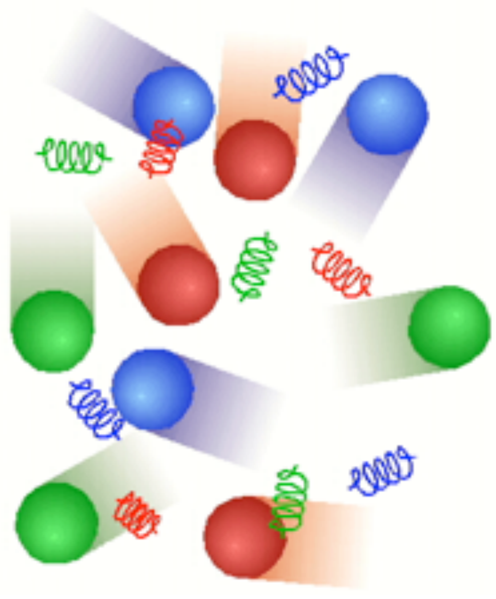


- ✓Chapt. 1 What is Quark Gluon Plasma?
- ✓Chapt. 2 How to create QGP?
- ✓Chapt. 3 What we learned at RHIC
  - Properties of Bulk matter
  - Azimuthal Anisotropy
  - Jet quench
- ✓Chapt. 4 Results from LHC
- ✓Summary Remarks

Many other topics !
Refer to the text book

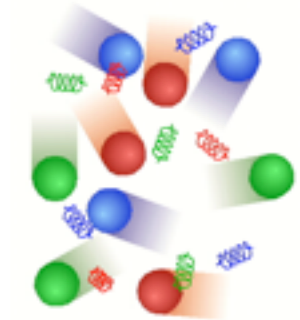


Chapter 1

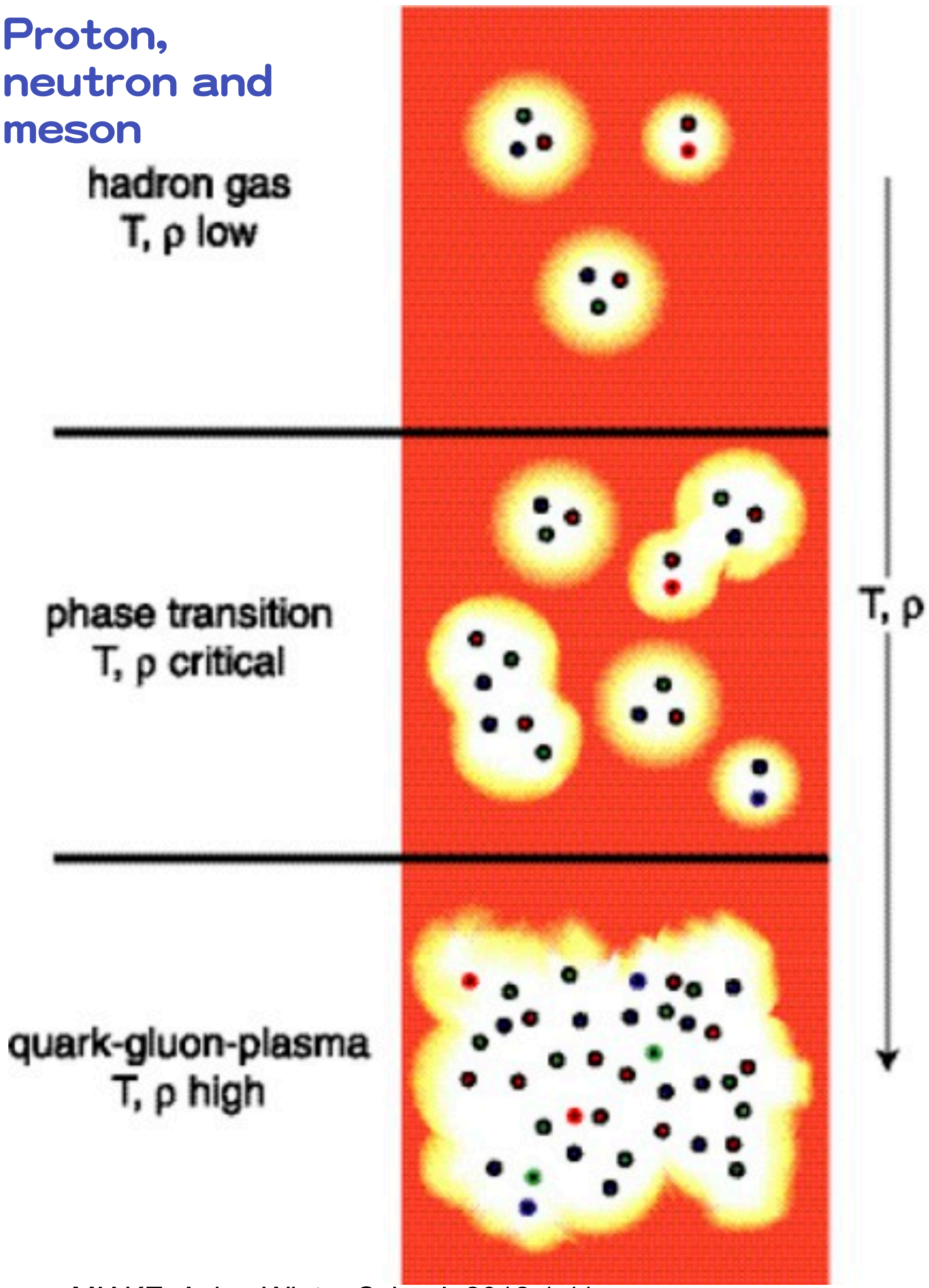


What is Quark Gluon Plasma?

Primordial state of the matter; Quark Gluon Plasma



Proton, neutron and meson

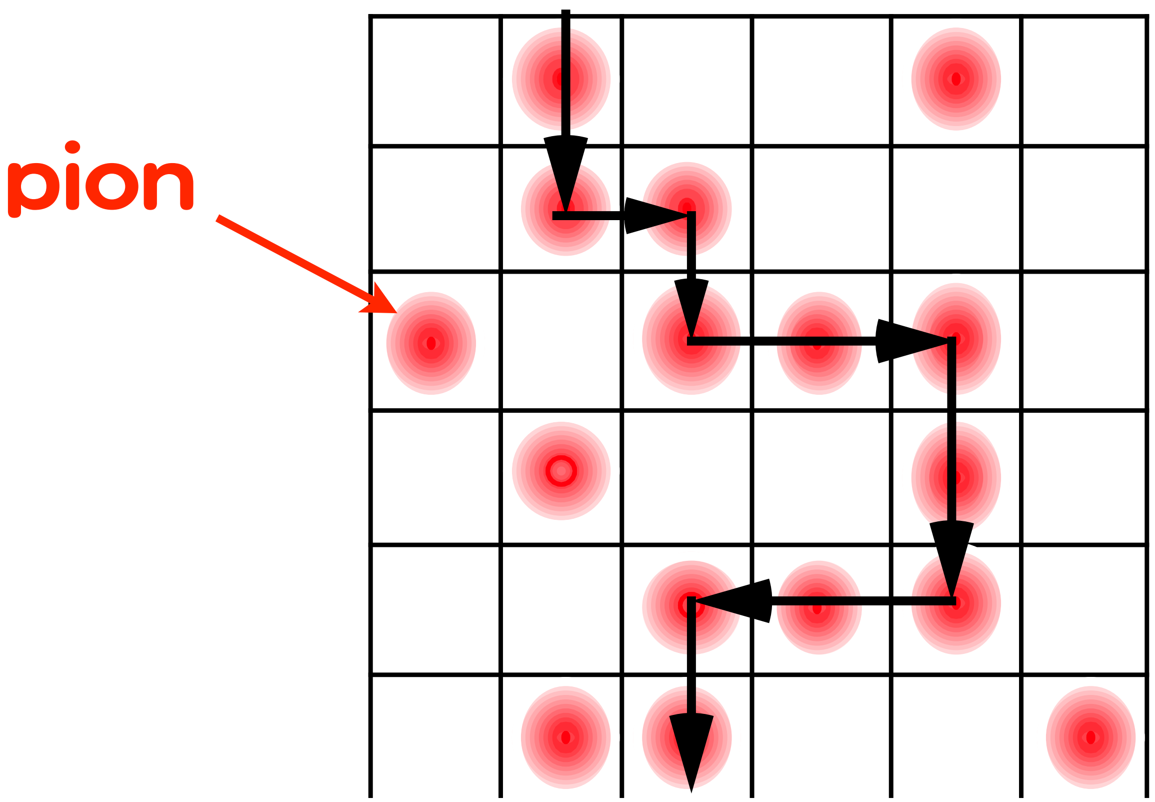


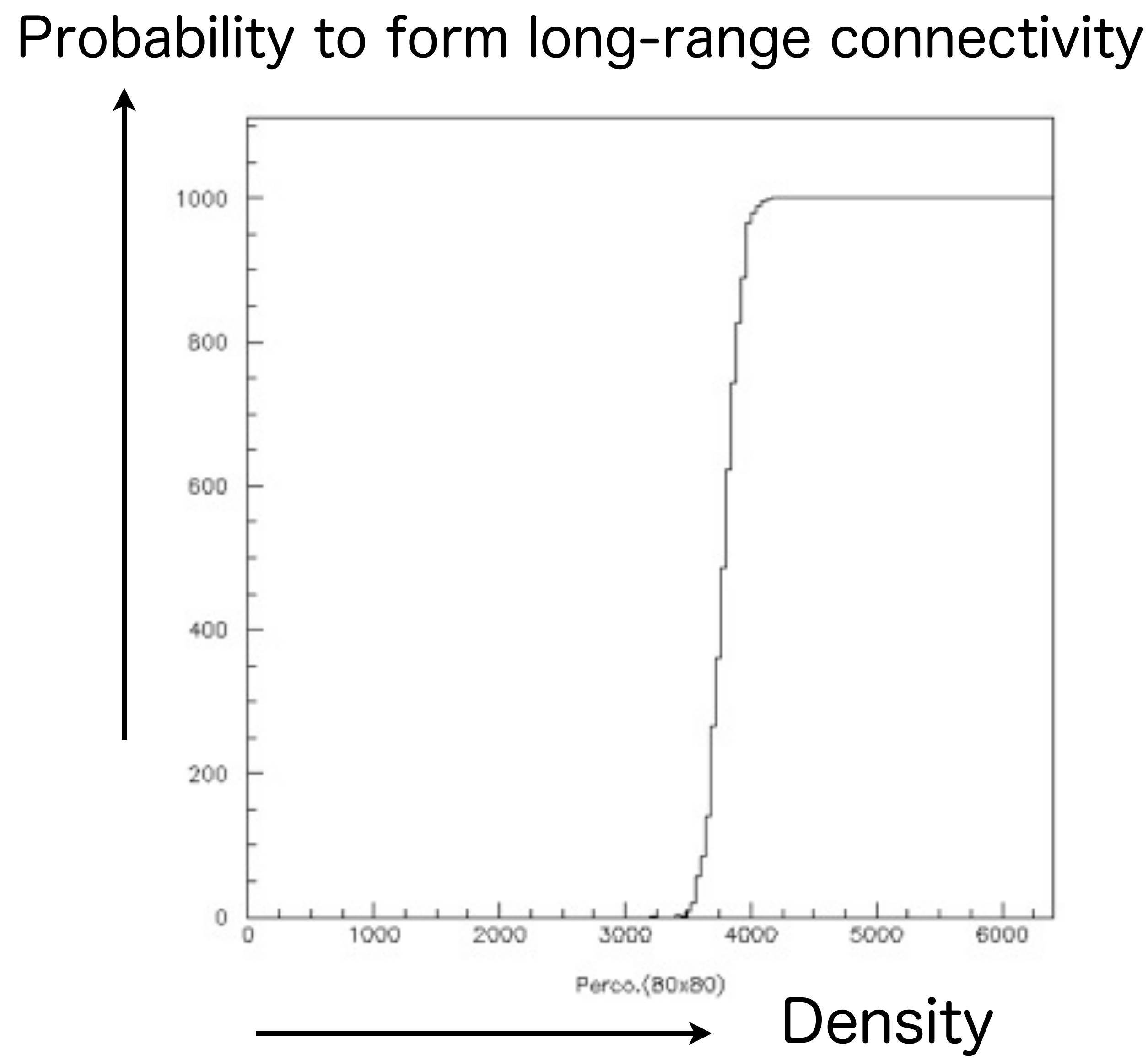
- ✓ Hadrons such as proton, neutron and mesons have a size of ~1 fm and are composed of quarks and gluons
  - Proton/Neutron ; 3 quarks
  - Meson ; quark and anti-quark
  - Described by Quantum ChromoDynamics
    - ➡Confinement of quarks and gluons in hadrons
    - ➡Asymptotic freedom
- ✓ What happen if we heat or compress the hadron gas?
  - ➡Hadrons are overlapped each other and quarks and gluons start to move around in relatively large volume.

! Quark Gluon Plasma !

QGP phase transition with percolation theory

Toy Model



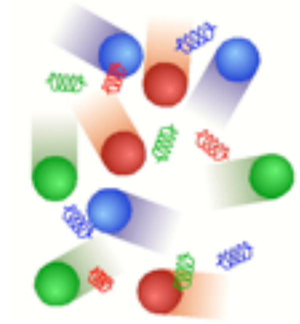


✓ **Formation of long-range connectivity in random system**

- **populate pions in 80x80 cells randomly**
- **evaluate probability to form long-range connectivity (from top to bottom in this case)**

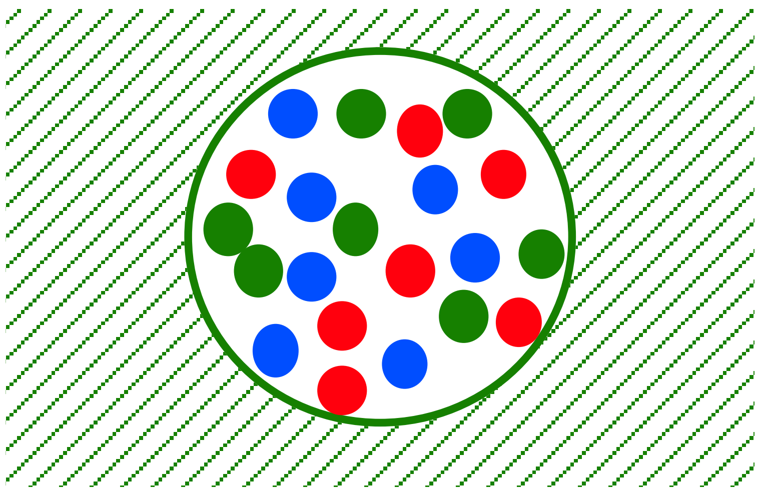
1st order phase transition ?!

QGP phase transition with Ideal Gas Model



Toy Model

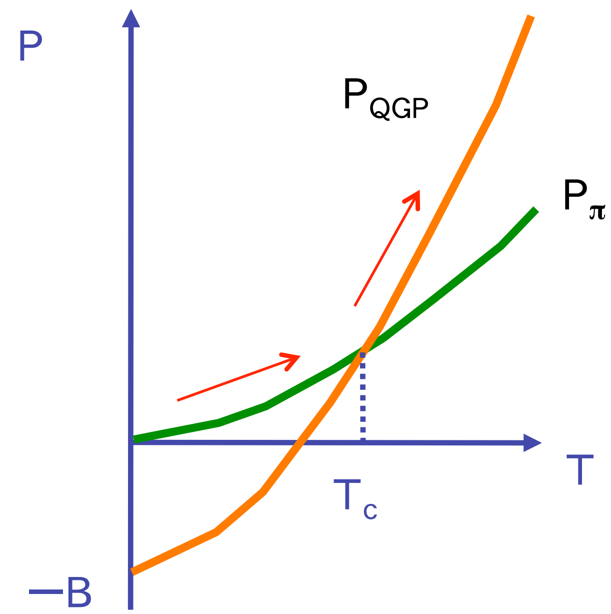
QGP

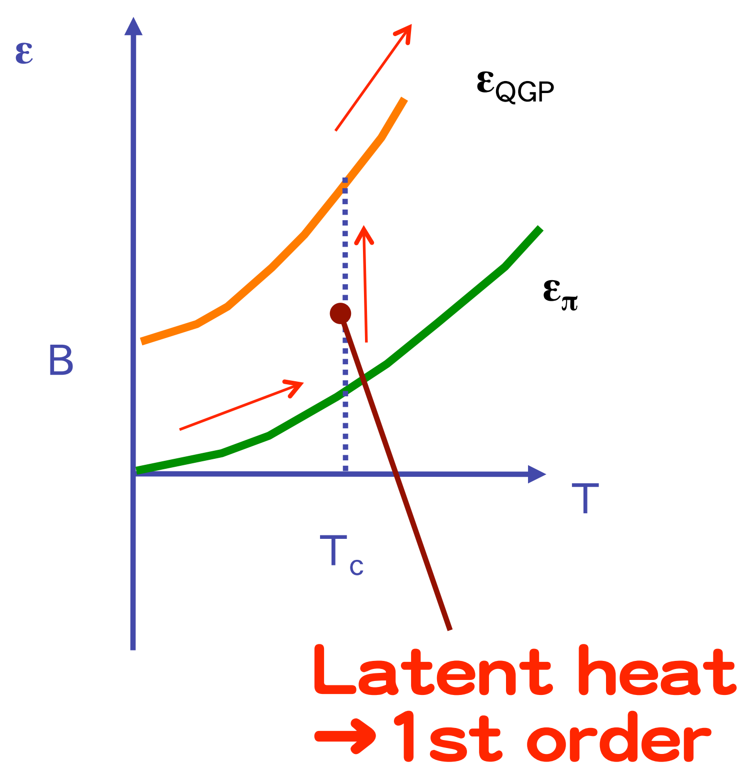


$$\varepsilon_{QGP} = f_{gluon} \cdot \varepsilon_{boson} + f_{quark} \cdot \varepsilon_{fermi}$$

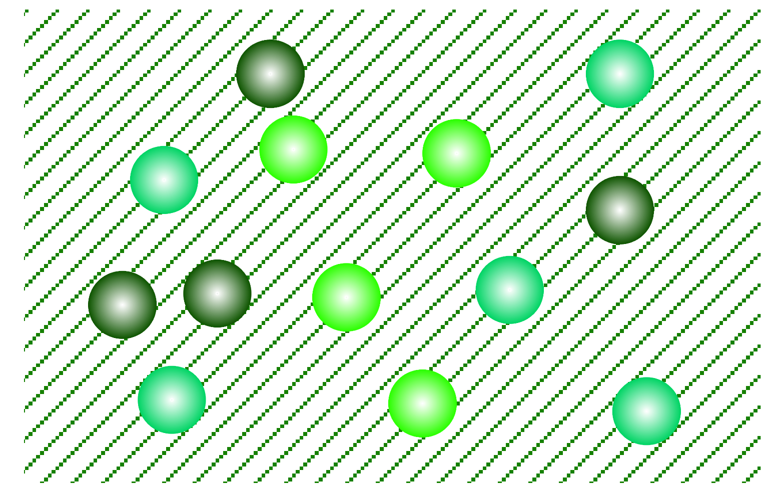
$$\therefore \varepsilon_{QGP} = \frac{37\pi^2}{30} T^4 + B$$

$$\begin{cases} \varepsilon_{QGP} = \dfrac{37\pi^2}{30} T^4 + B \\ p_{QGP} = \dfrac{37\pi^2}{90} T^4 - B \end{cases}$$





Pion Gas



$$\varepsilon_\pi = f_\pi \cdot \varepsilon_{boson}$$

$$\therefore \varepsilon_\pi = \frac{\pi^2}{10} T^4$$

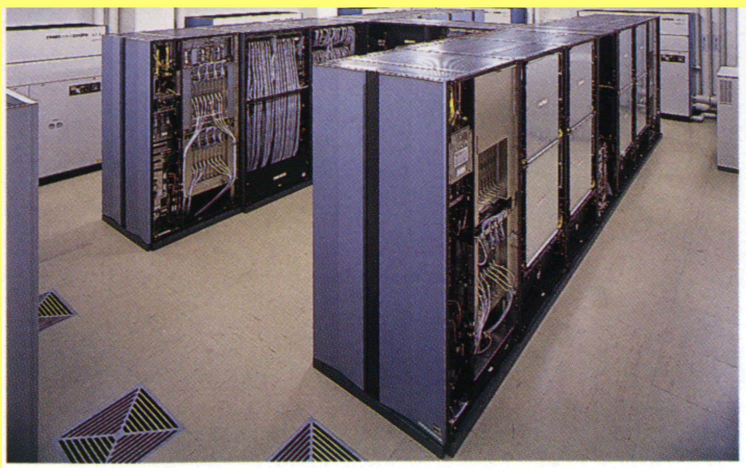
$$\begin{cases} \varepsilon_\pi = \dfrac{\pi^2}{10} T^4 \\ p_\pi = \dfrac{\pi^2}{30} T^4 \end{cases}$$

Stefan-Boltzman's $\varepsilon = \sigma T^4$

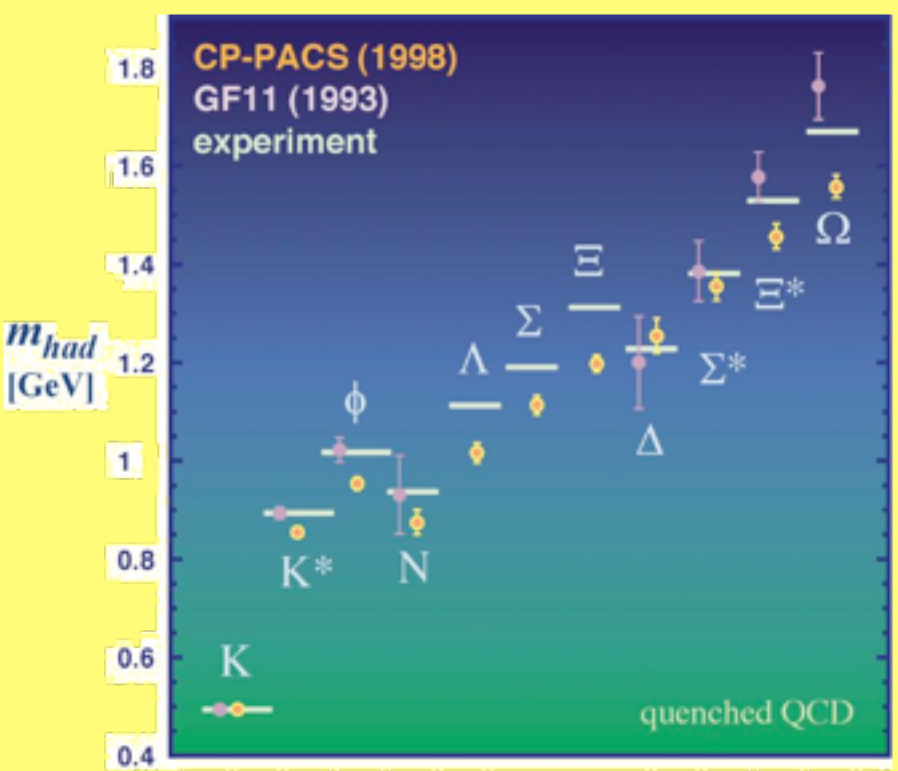
QGP phase transition with Lattice QCD

Center for Computational Sciences, Univ. of Tsukuba

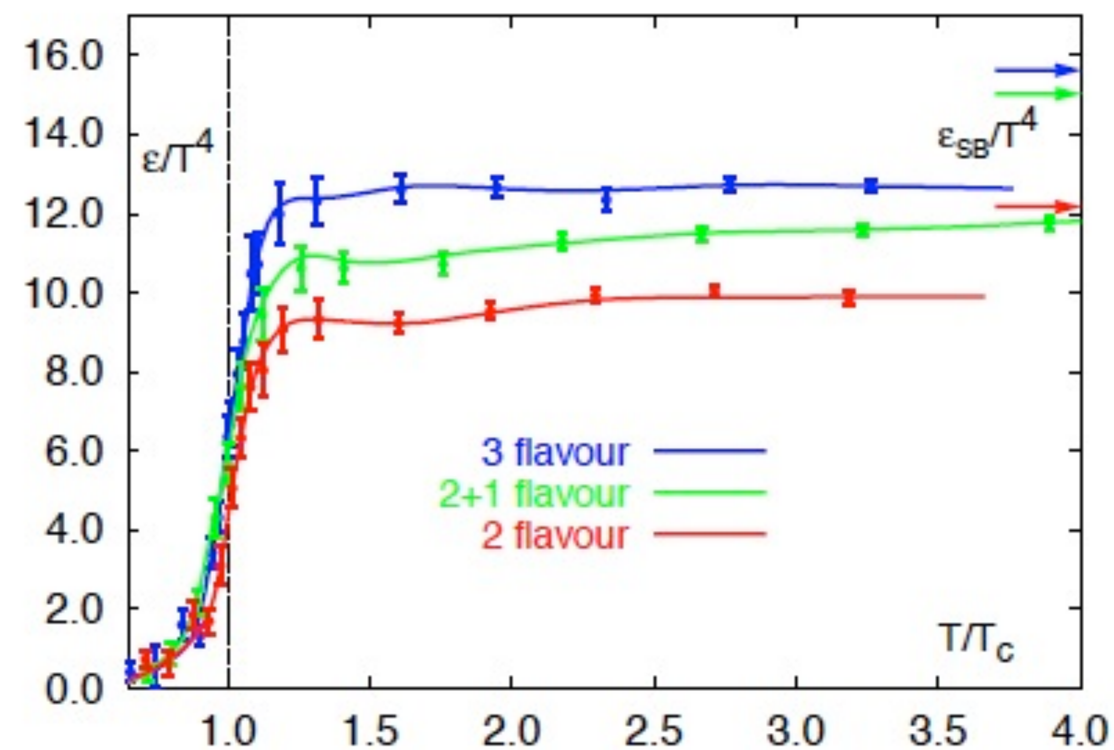
CP-PACS



Hadron Mass

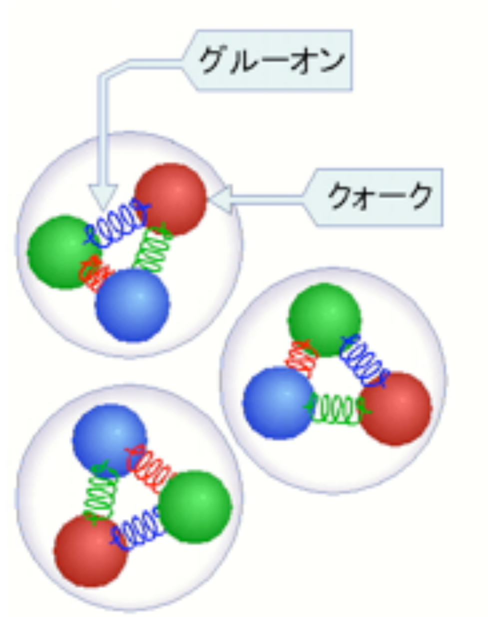


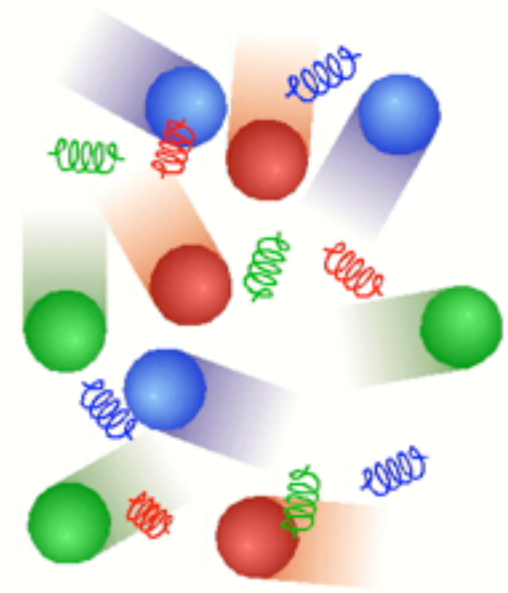
F. Karsch, Lect. Notes Phys. 583 (2002) 209.



✓It can be 1st order phase transitions

$\varepsilon_c \sim 0.6 - 1.2\ \mathrm{GeV/fm^3}$



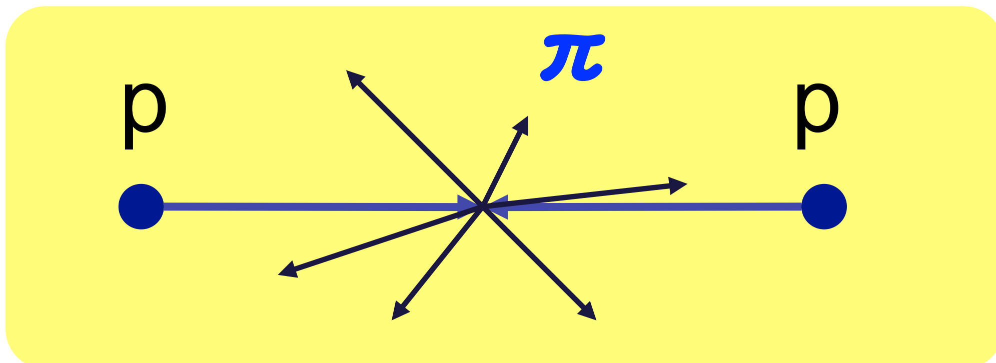


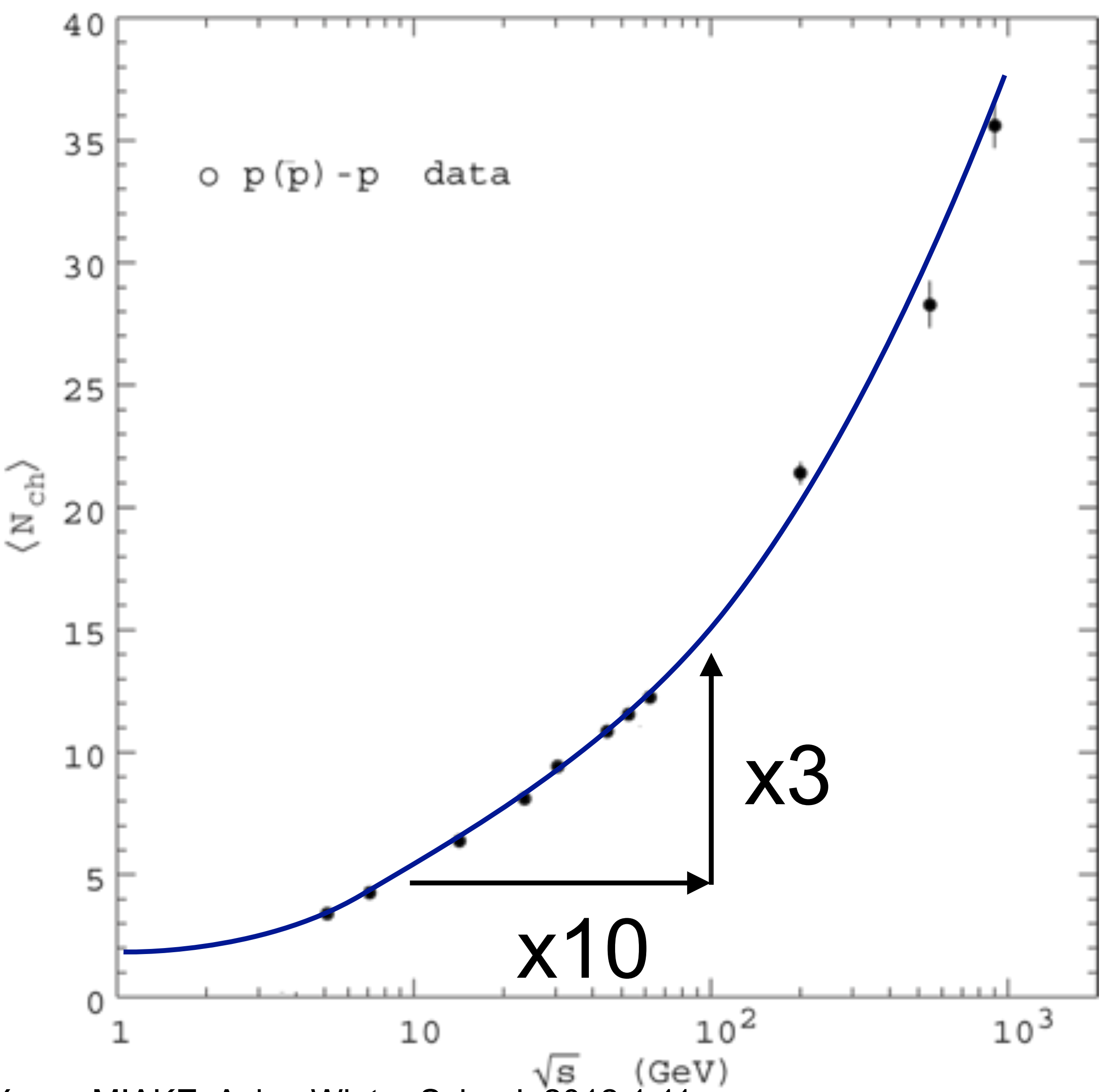
Chapter 2

How to create QGP

How to produce particles?
How to obtain dense particle production?

Produce particles in pp collisions





- ✓ Particle (mostly pions) produced above the threshold
- ✓ At higher energy, more particle produced

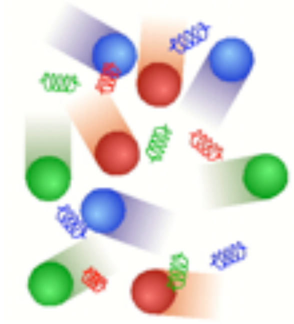
$$s \equiv (\tilde{p}_{\rm A} + \tilde{p}_{\rm B})^2, \quad \tilde{p} \equiv (E, \vec{p})$$

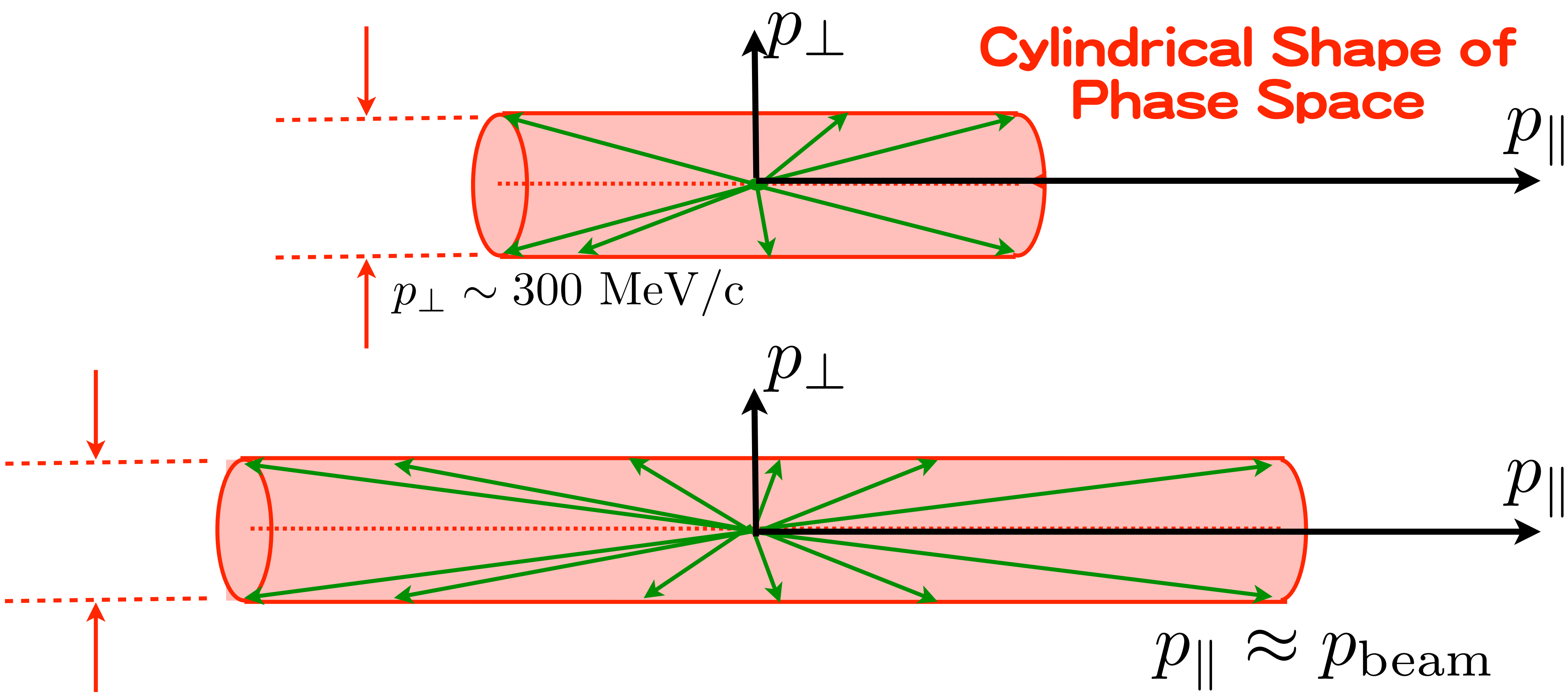
$$\tilde{p}_{\rm A} = (\sqrt{p^2 + m^2}, 0, 0, +p)$$

$$\tilde{p}_{\rm B} = (\sqrt{p^2 + m^2}, 0, 0, -p)$$

$$s = (2\sqrt{p^2 + m^2})^2 = (E_{\rm cm})^2$$

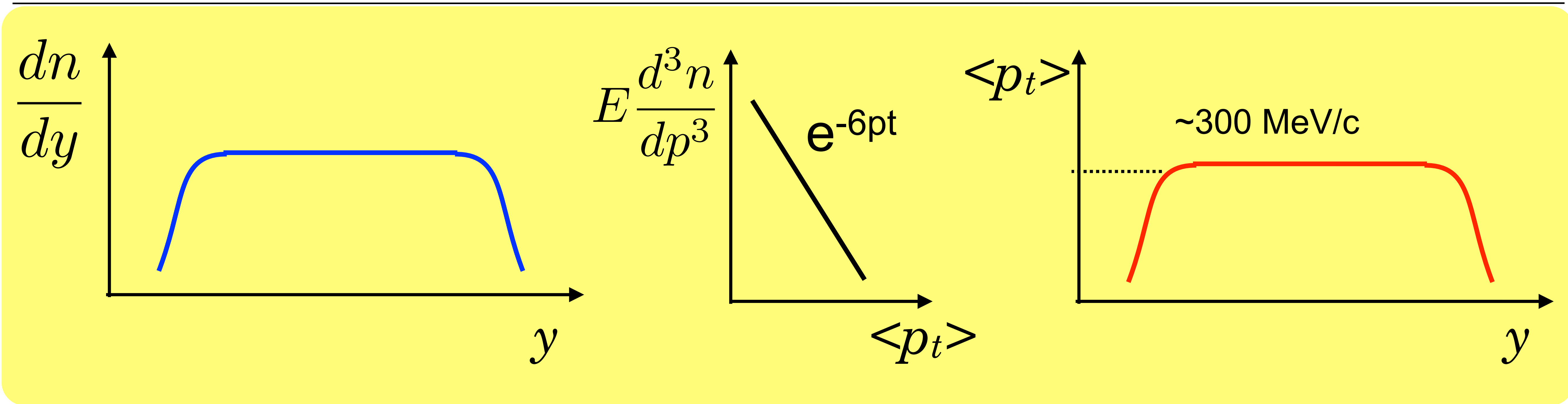
Produced particles populated in cylindrical momentum space





- ✓Produced particles populated in momentum phase space, which is cylindrical with pt~300 MeV/c
  - ➡Spaghetti
- ✓Higher the energy of collision, longer the cylinder, with almost the same radius

Particle production



$$E\frac{d^3n}{dp^3} \simeq \frac{dn}{dy} \times \frac{1}{p_{\mathrm{T}}}\frac{d^2n}{dp_{\mathrm{T}}d\phi}$$

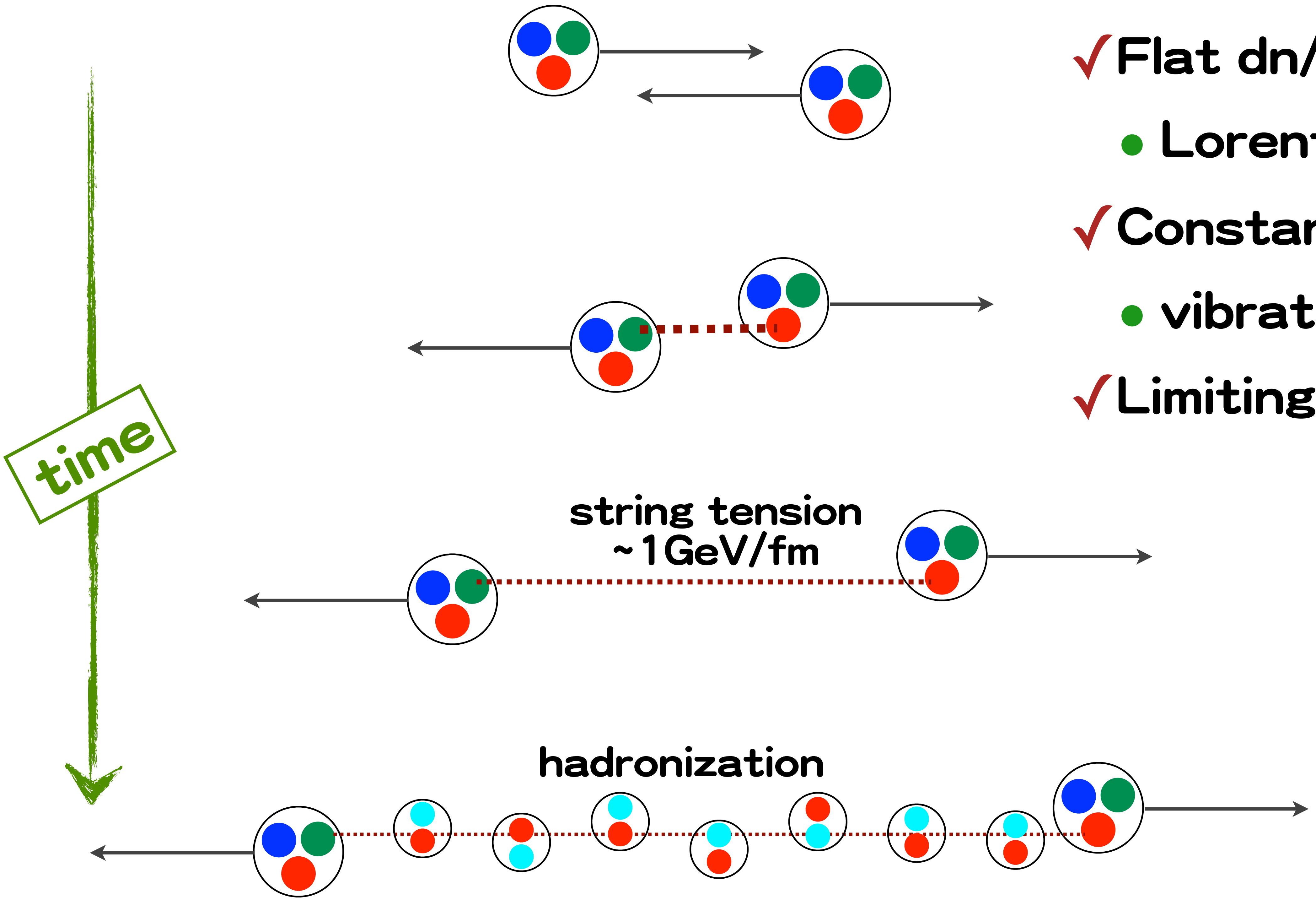
Rapidity y

$$y \equiv \frac{1}{2}\ln\frac{E+p_{\parallel}}{E-p_{\parallel}} \approx \frac{1}{2}\ln\frac{1+\beta}{1-\beta} \longrightarrow \beta$$

dy ; Lorentz inv.

✓ **<n> & <pt> increase very slowly with $\sqrt{s}$**

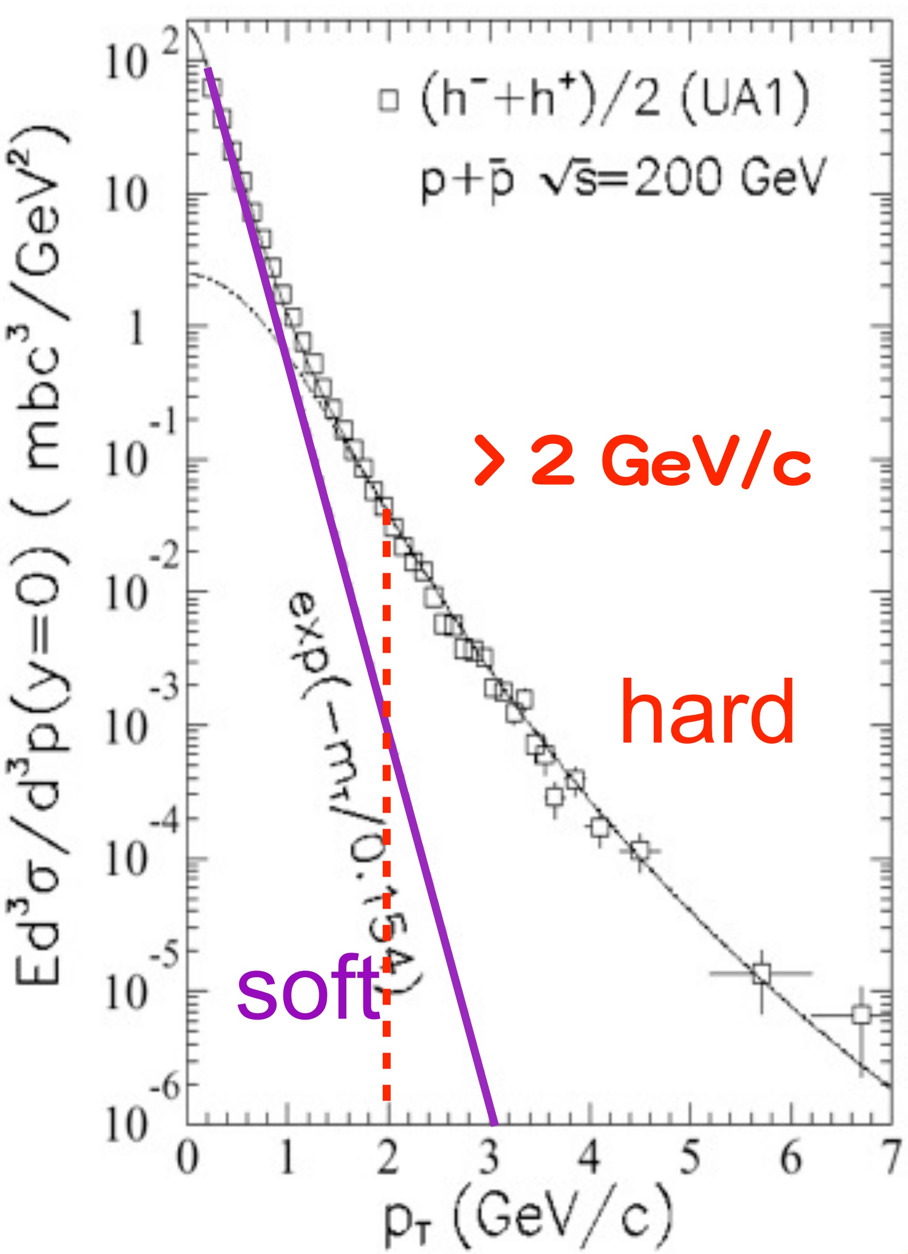
Interpretation w. string picture



- √ Flat dn/dy
  - Lorentz invariant
- √ Constant <pt>
  - vibration of string
- √ Limiting Frag.

√ Often called as **soft** component

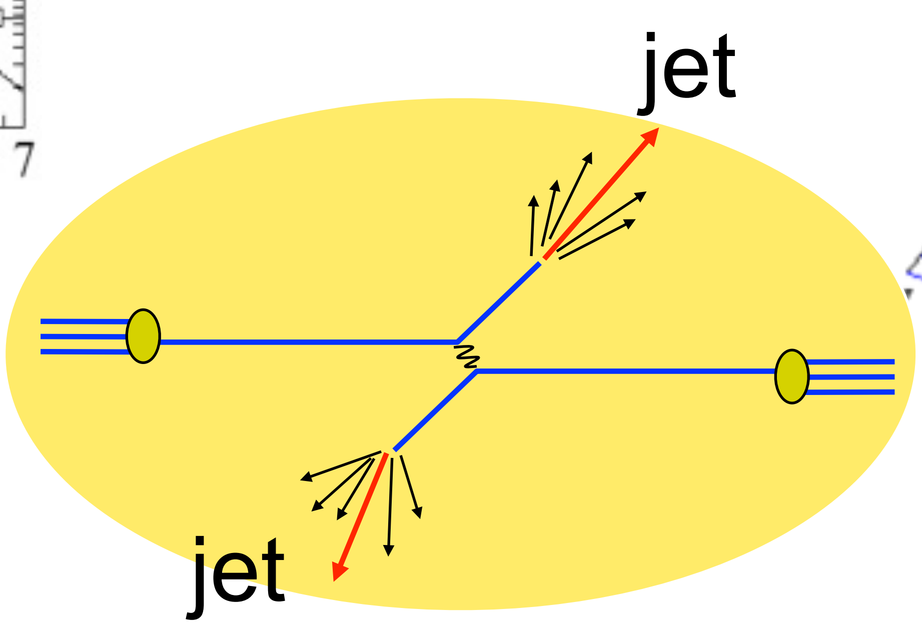
Hard component, another type of particle production

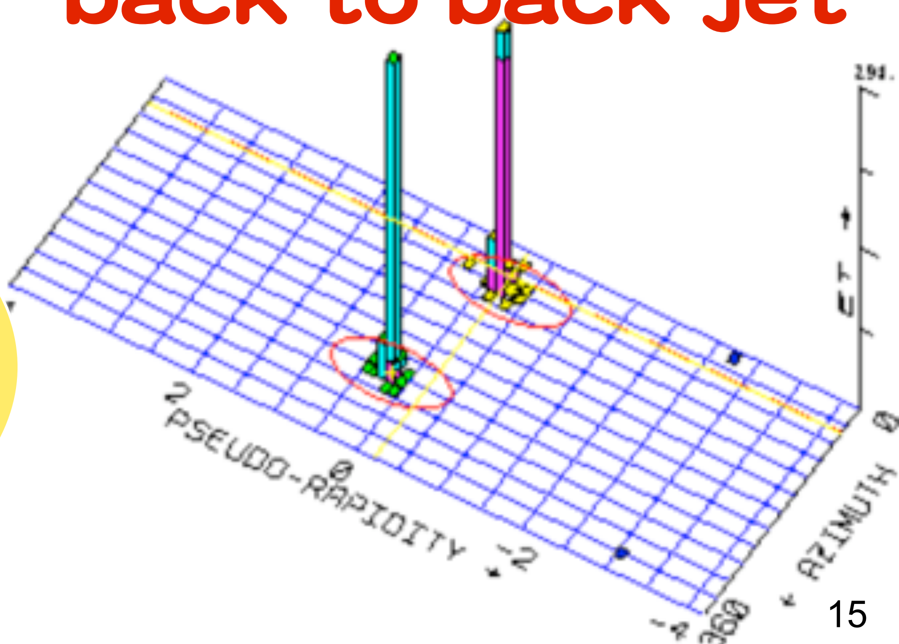


$$E\frac{d^3\sigma}{dp^3} = C_0 \exp(-\frac{m_t}{T_0}) + \frac{C_1}{(p_t + p_0)^n}$$

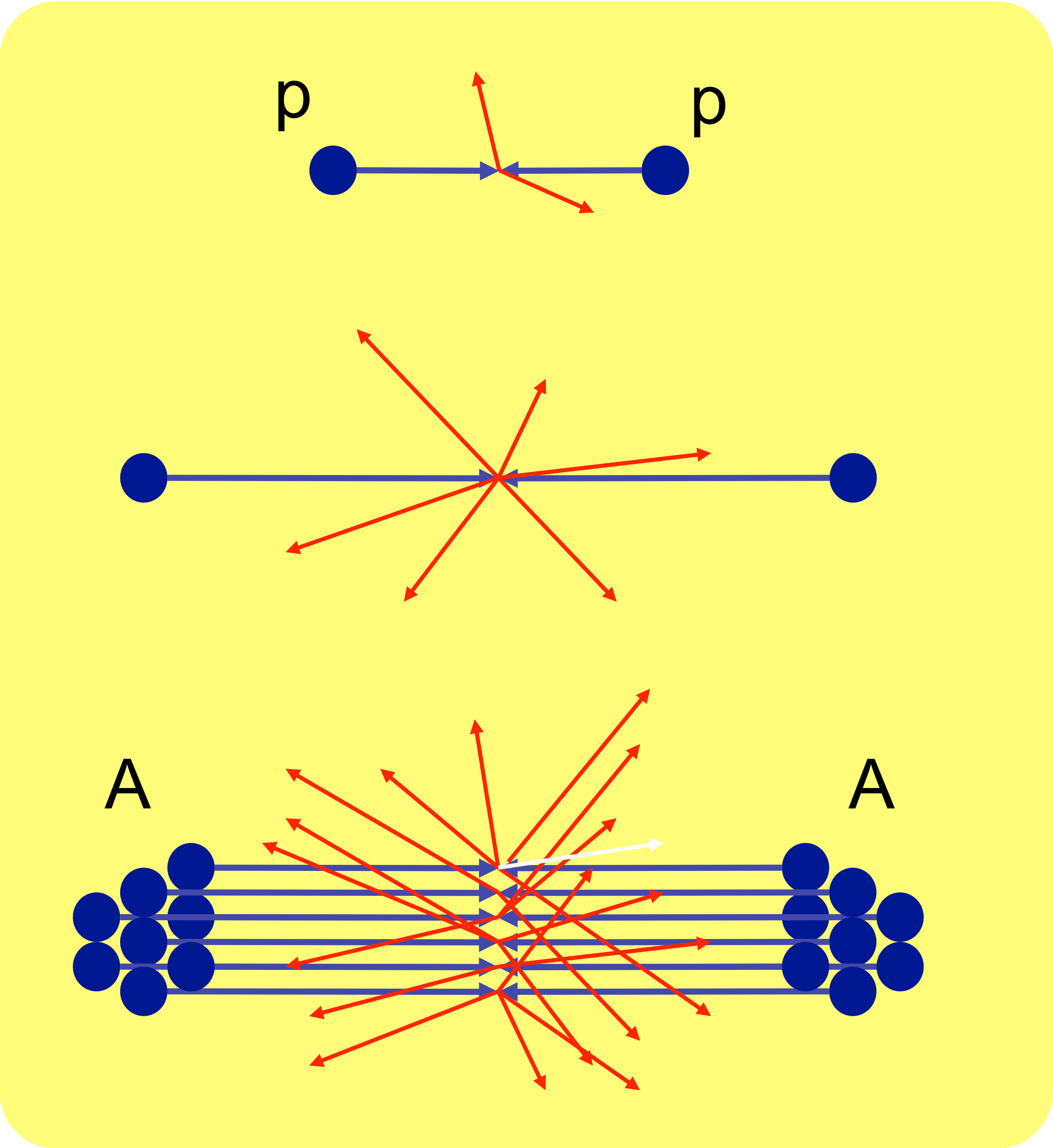
- √ At ISR in 1972, deviation from the m_t scaling at high p_t region is observed as a first time.
- √ Binary parton scattering followed by fragmentation produces back-to-back jet.
- √ Main source of high pt particles.
  - ➡Please note very different mechanism

back-to-back jet



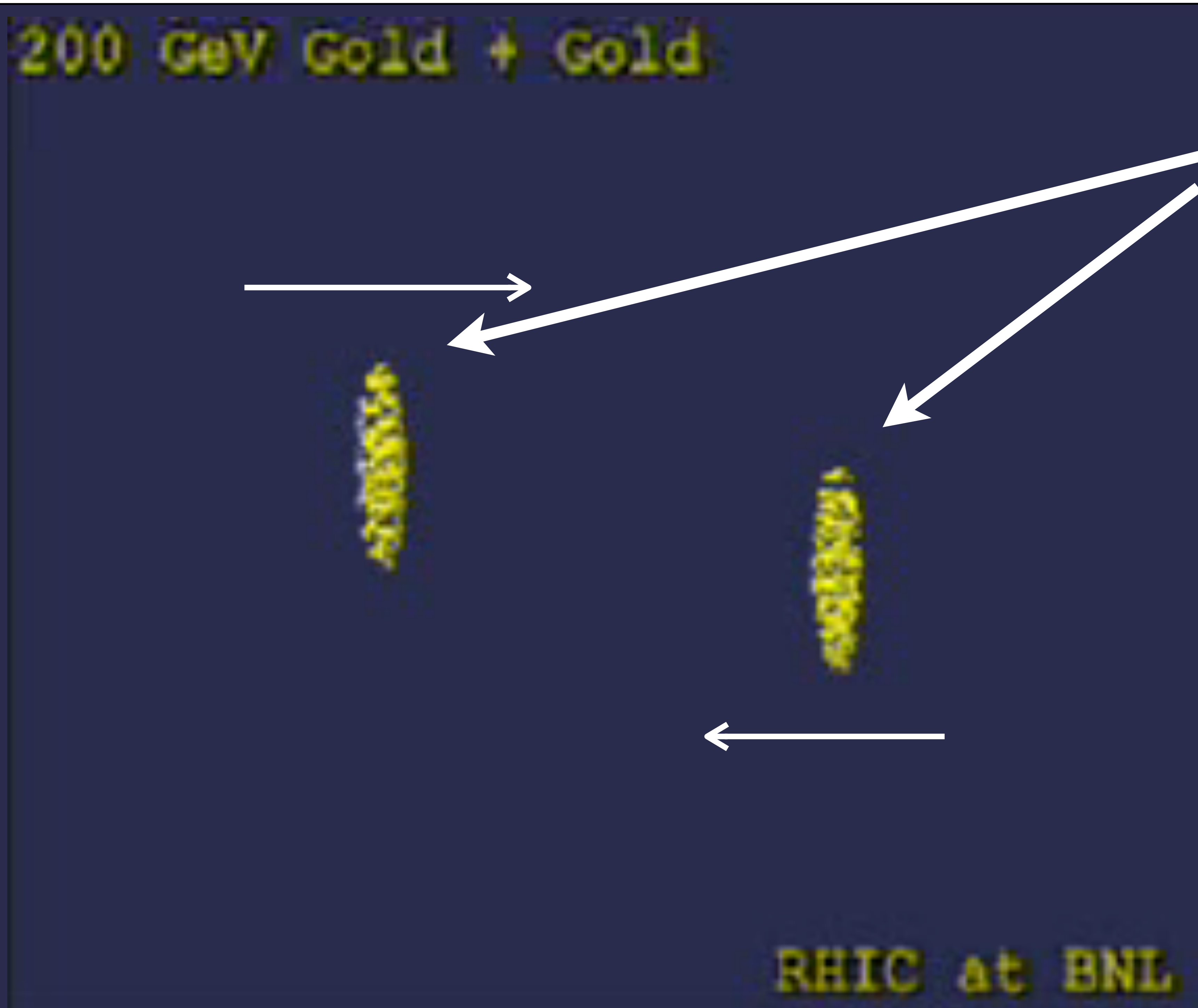


How to achieve dense particle production



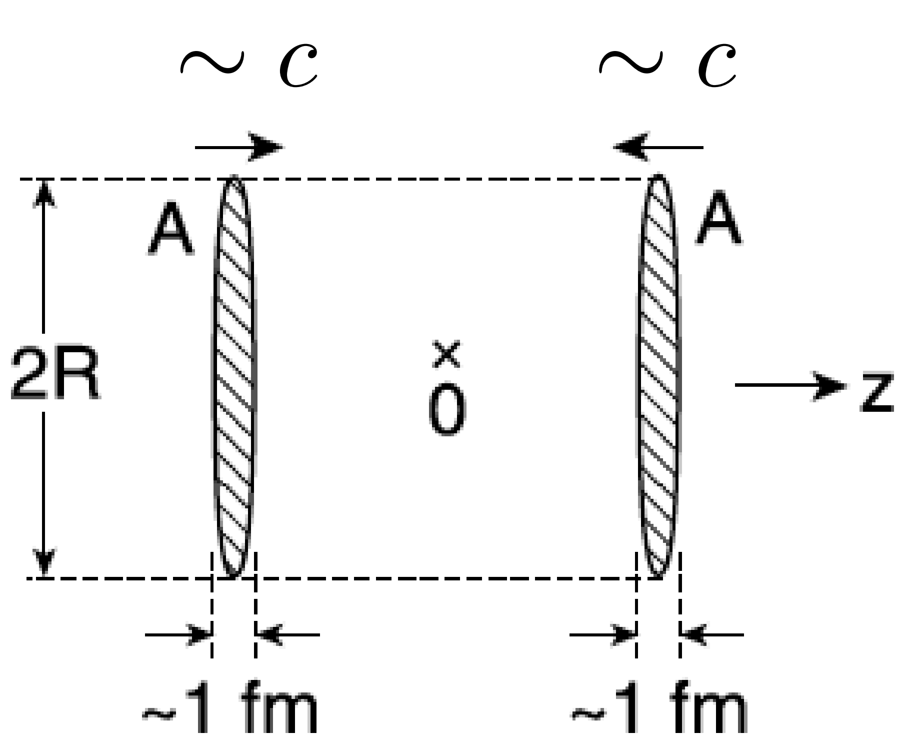
- ✓Higher the energy, more particle produced in pp
  - ➡Relativistic
- ✓Nucleus cluster of many nucleons in a small volume
- ✓Relativistic AA collisions achieve dense particle production

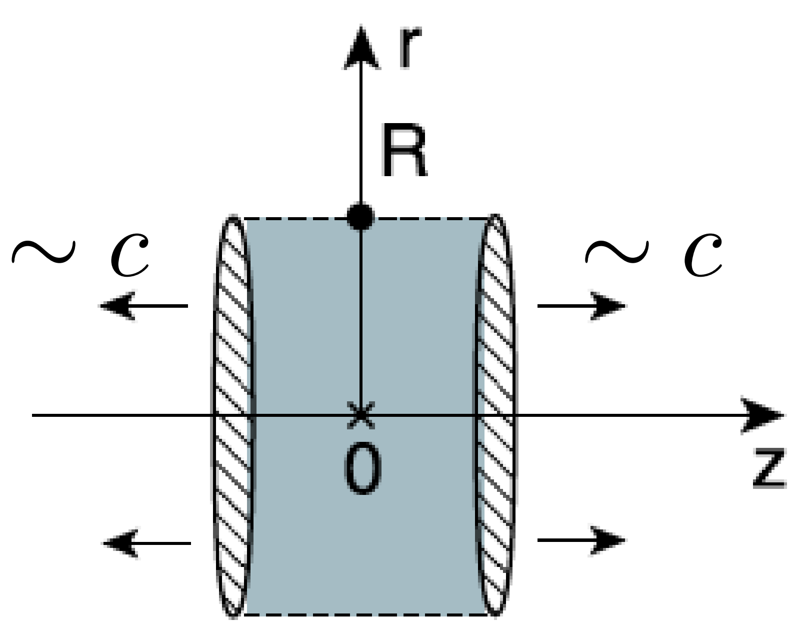
Simulation at 100 GeV Au+Au collision



In-coming Lorentz contracted nucleus

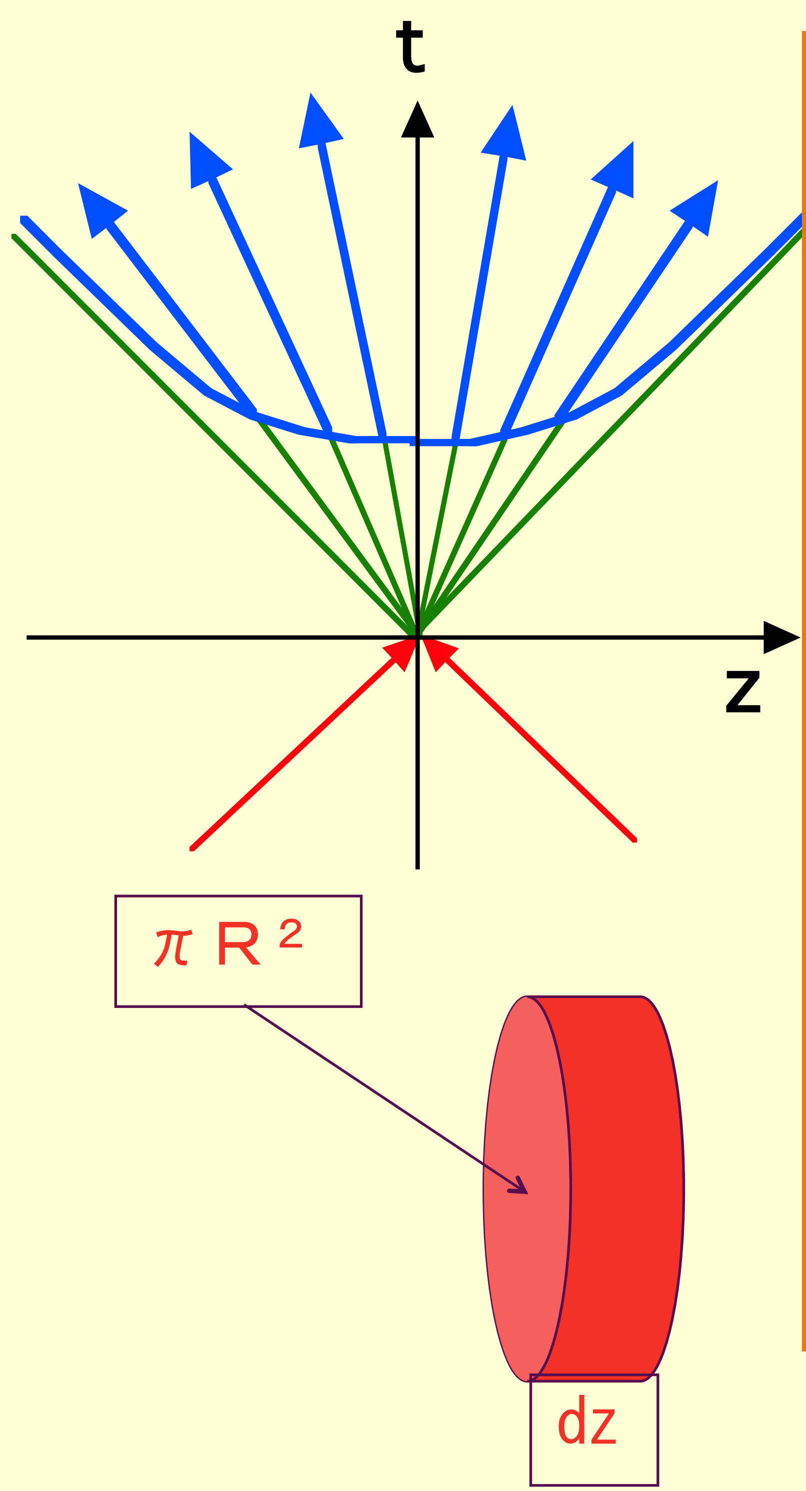
Bjorken Picture





- ✓At very high energy, nucleus penetrate each other, leaving ~particles behind
- ✓If the density is high enough, QGP is there!
- ✓QGP pulled apart at ~c
  - ➡1dimensional expansion unlike the 3 dim. expansion of the Big Bang

Evaluation of Energy Density



$$y=\frac{1}{2}\ln\left(\frac{E+p_l}{E-p_l}\right)$$

$$\begin{cases} E = m_t\cdot\cosh y \\ p_l = m_t\cdot\sinh y \end{cases}$$

$$y=\frac{1}{2}\ln\left(\frac{1+\beta_l}{1-\beta_l}\right) \quad \because \beta_l=\frac{p_l}{E}$$

$$y=\frac{1}{2}\ln\left(\frac{t+z}{t-z}\right) \quad \left(\because \beta_l=\frac{z}{t}\right)$$

$$\begin{cases} t = \tau\cdot\cosh y \\ z = \tau\cdot\sinh y \end{cases}$$

$$dtdz = \tau d\tau dy$$

$$dz = \tau d\tau \quad (\because t\approx\tau \;@\; y\approx 0)$$

✓ **Bjorkenの描像**

- ローレンツ収縮のために原子核衝突は短時間の間に起こり、その短時間にハドロンの多重発生が起こるが、固有時 **τ** 以後、それらは自由粒子として飛び出す。

free streaming
各粒子は原点から一定の速度で放出（大きな仮定）

✓ Energy density

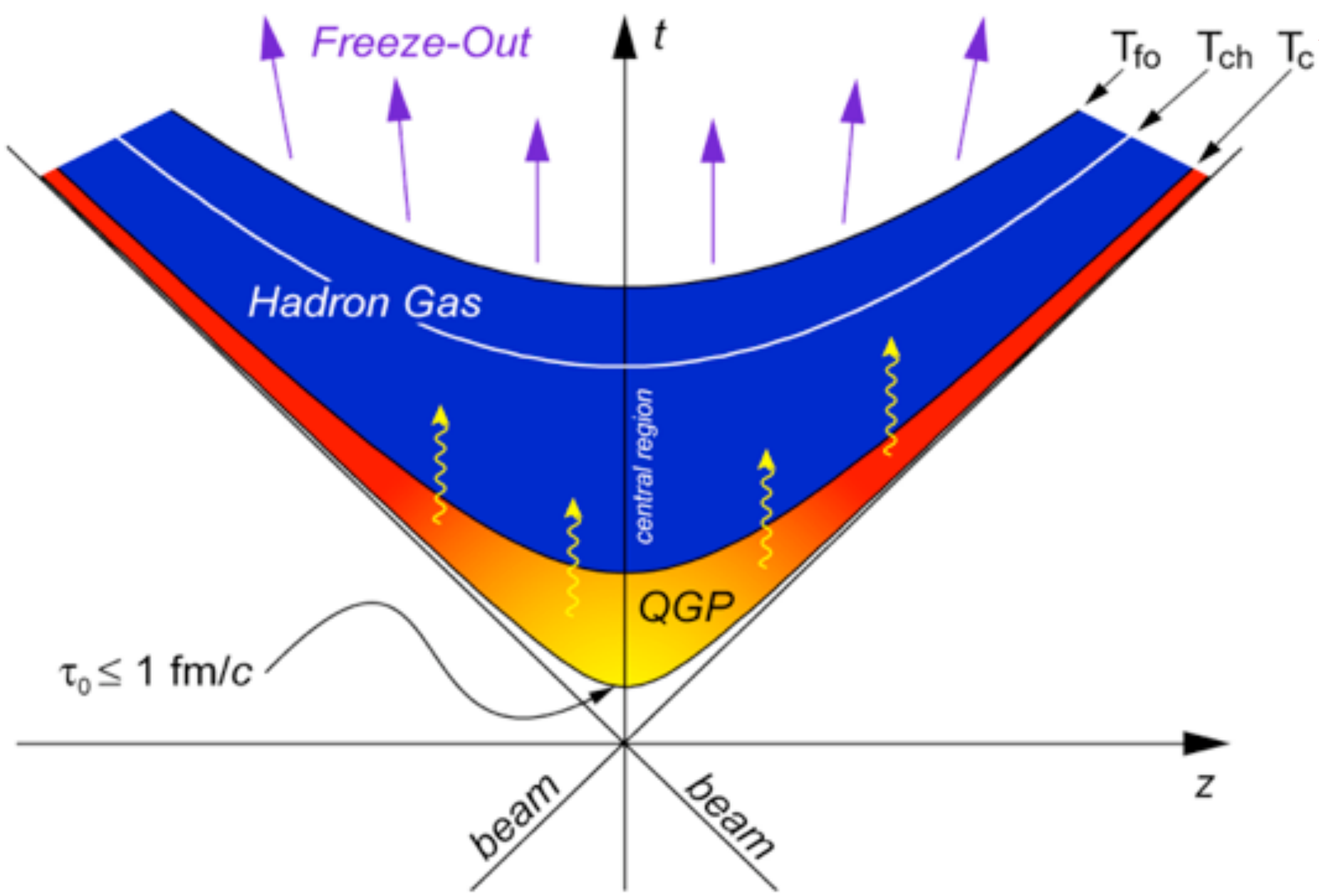
$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{c\tau_0}\frac{dE_T}{dy}$$

$$\approx 4.6\mathrm{GeV/fm}^3 \quad \text{RHIC}$$

$$> \varepsilon_c \approx 0.6-1.2\mathrm{GeV/fm}^3$$

Key 1; Time Evolution

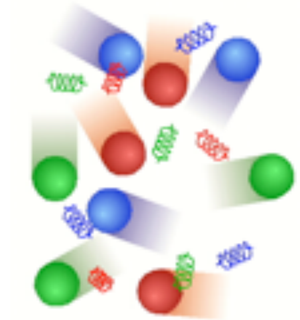
Minkowski



- ✓ It is like Big Bang.
- ✓ Time evolution in statistical nature
  - Parton cascade? followed by partonic thermalization (QGP)
  - Hadron production
  - Freezeout of v_2 ?
  - Chemical freeze-out
  - Kinematical freeze-out

Need consistent understanding of these epocs, in particular, aspects of statistical nature.

Key2 ; Statistical Nature



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

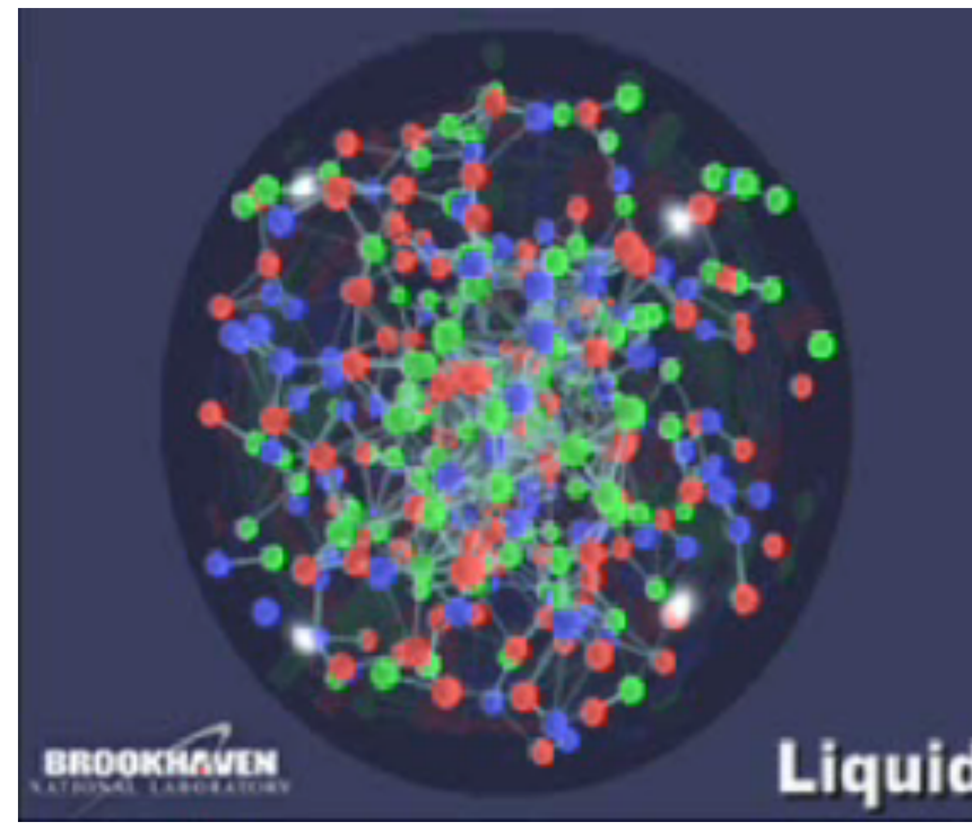
$$< n_{q,\bar{q}} > \sim \frac{\epsilon_{\rm QGP}}{< m_T >} \sim \frac{2{\rm GeV}}{1{\rm GeV}} \sim 5$$

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

$$\sim \frac{1}{5 \times 0.4} = 0.2\ [{\rm fm}]$$

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

$$\because \sigma_{qq} \sim \frac{\sigma_{NN}}{n_{\rm q}} \sim \frac{4[{\rm fm}^2]}{3} \sim 1$$

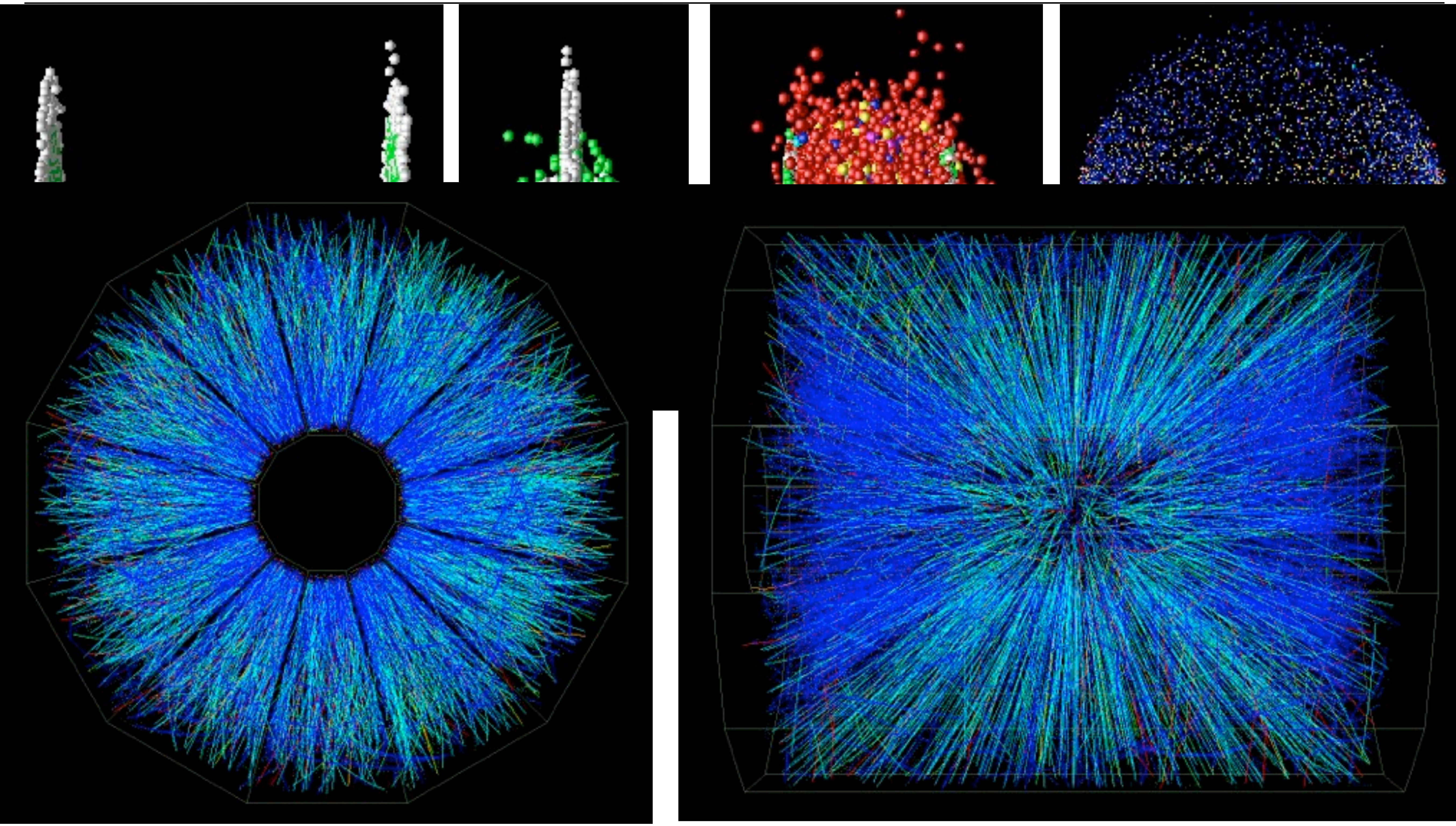


Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration

✓**What we expect,**

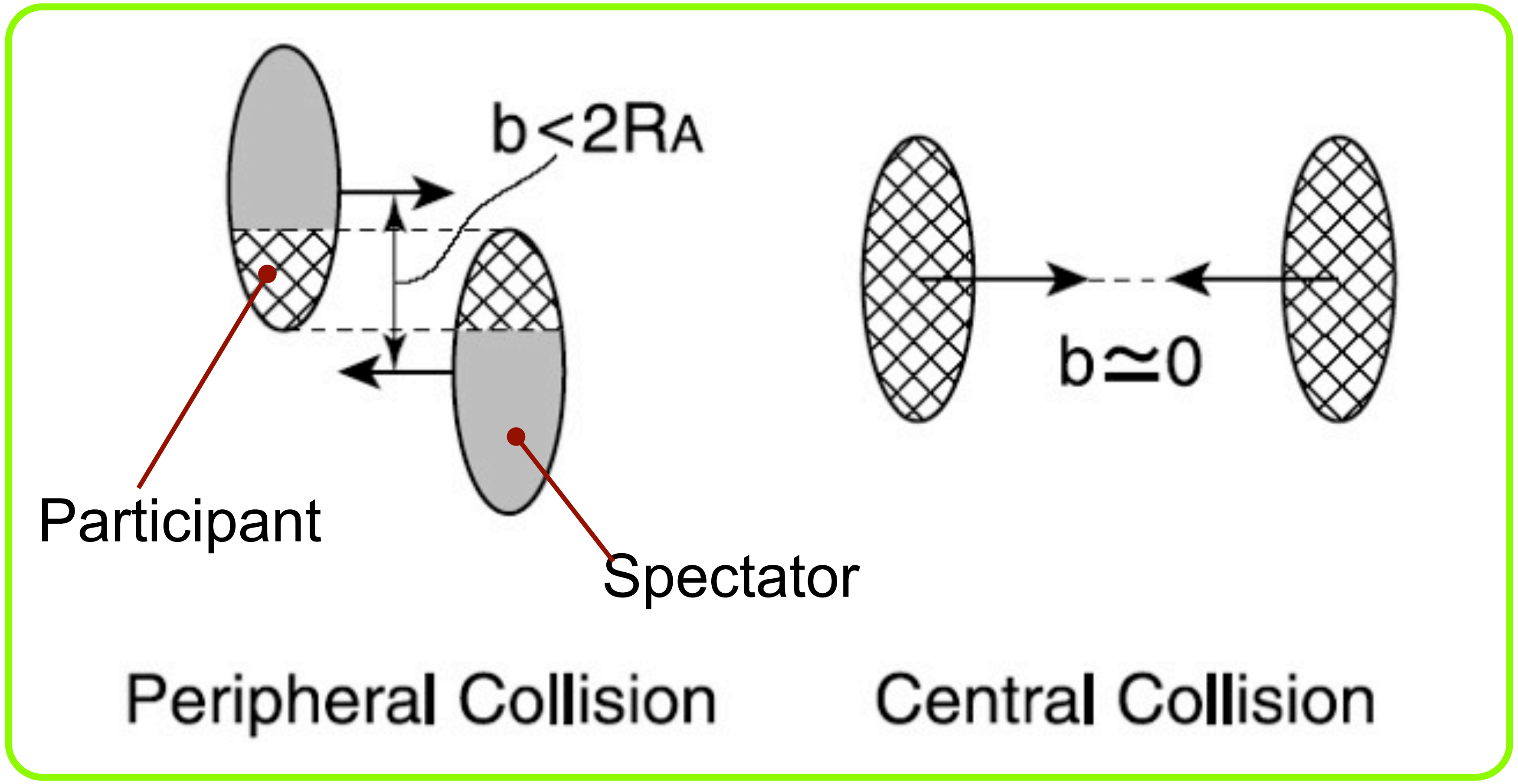
- **Statistical physics at quark level**
- **Hydrodynamical behavior at quark level**

Relativistic Heavy Ion Collision



Identify track, measure momentum, identify particle species, distributions.....

Important Feature of AA



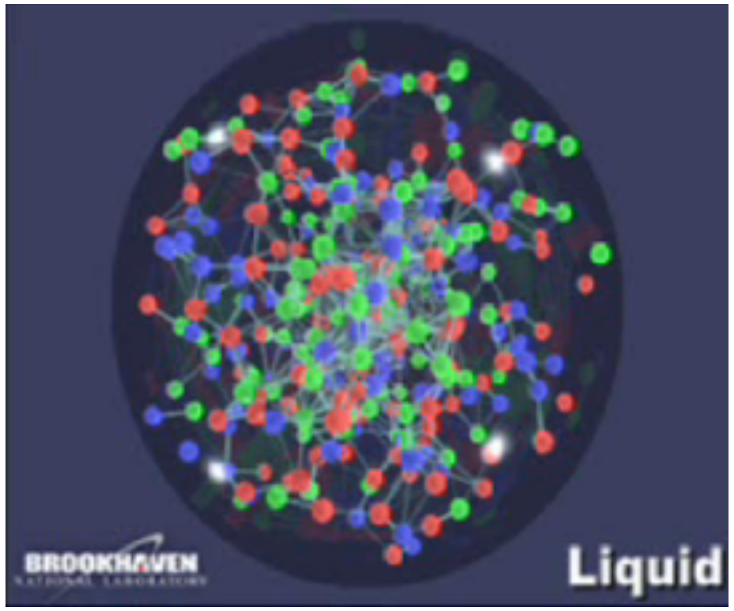
$$\tau_{\rm col} \equiv \frac{R_{\rm A}}{c\gamma_{\rm beam}} \ll \tau_{\rm int} \equiv \frac{R_{\rm A}}{c\beta_{\rm Fermi}}$$

$$\text{centrality} \equiv \frac{\sigma_b}{\sigma_{\rm geom}} = \frac{\pi b^2}{4\pi R_{\rm A}^2}$$

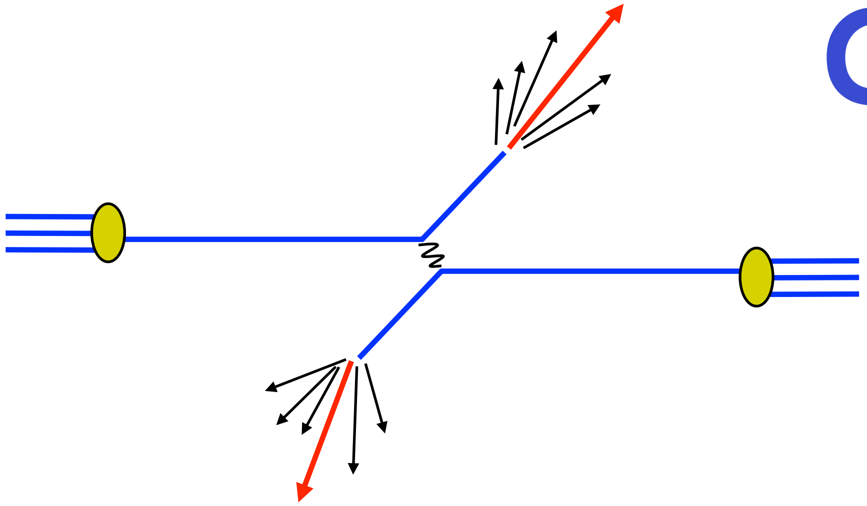
$$R_A \sim 10 \text{ fm}$$

- ✓ **Nucleus is extended object**
- ✓ **Collision time << intrinsic time of nucleus**
  - ➡ **Clear separation of participant and spectator**
- ✓ **Size of participants determines the initial geometry (eccentricity later), the size of QGP and development of the system, it is very important to sort the data accordingly**

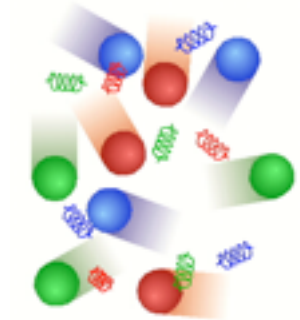
Chapter. 3
Bulk matter



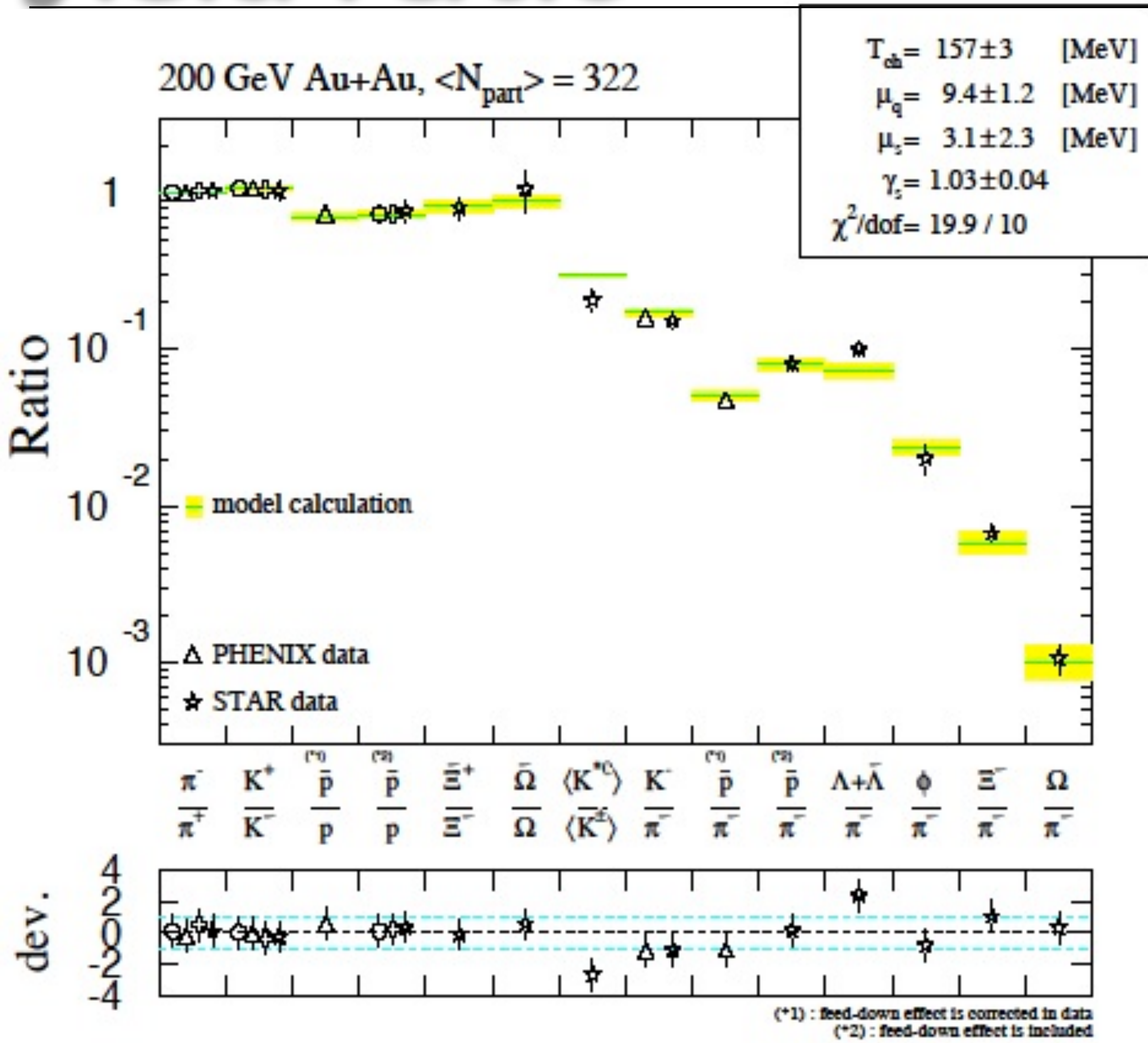
Chemical Eq.
&
Collective flow



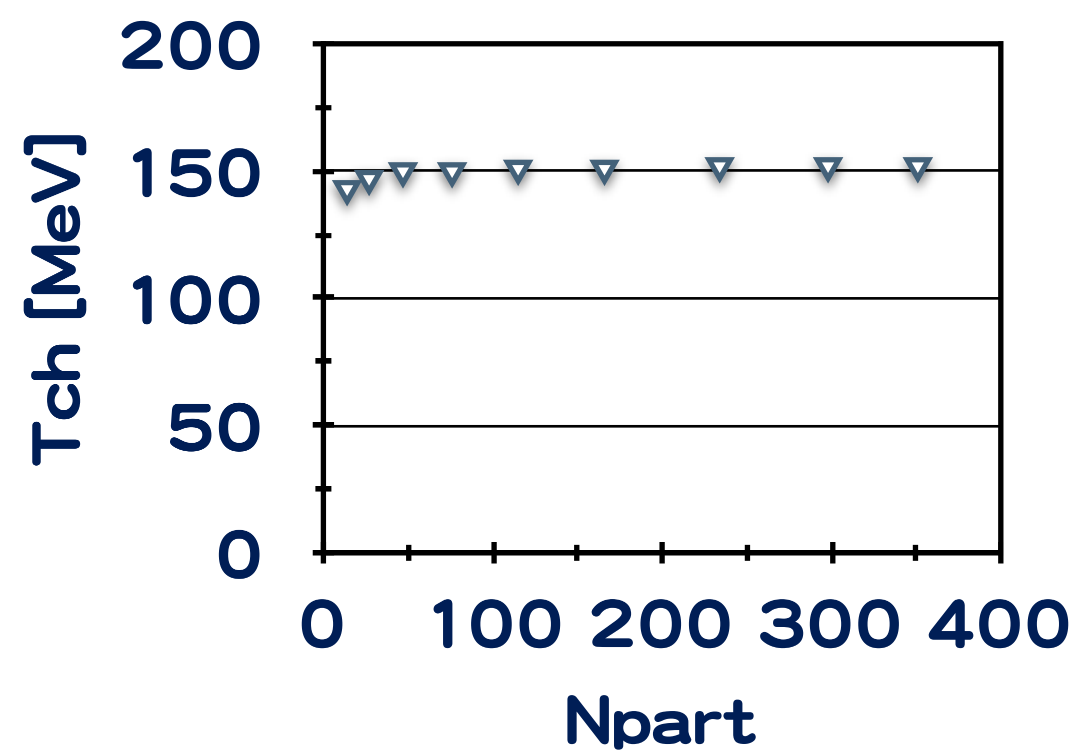
Chemical Eq. from particle yield ratio



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

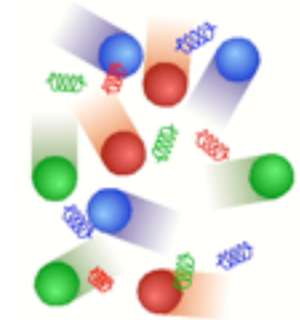


$$n_i = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i-\mu_i)/T} \pm 1}$$



- √ Only **few** parameters fit every ratio very well !
- √ T_{ch} stays constant from peripheral to central collisions

Kinematical Distr.: Transverse mass distr.



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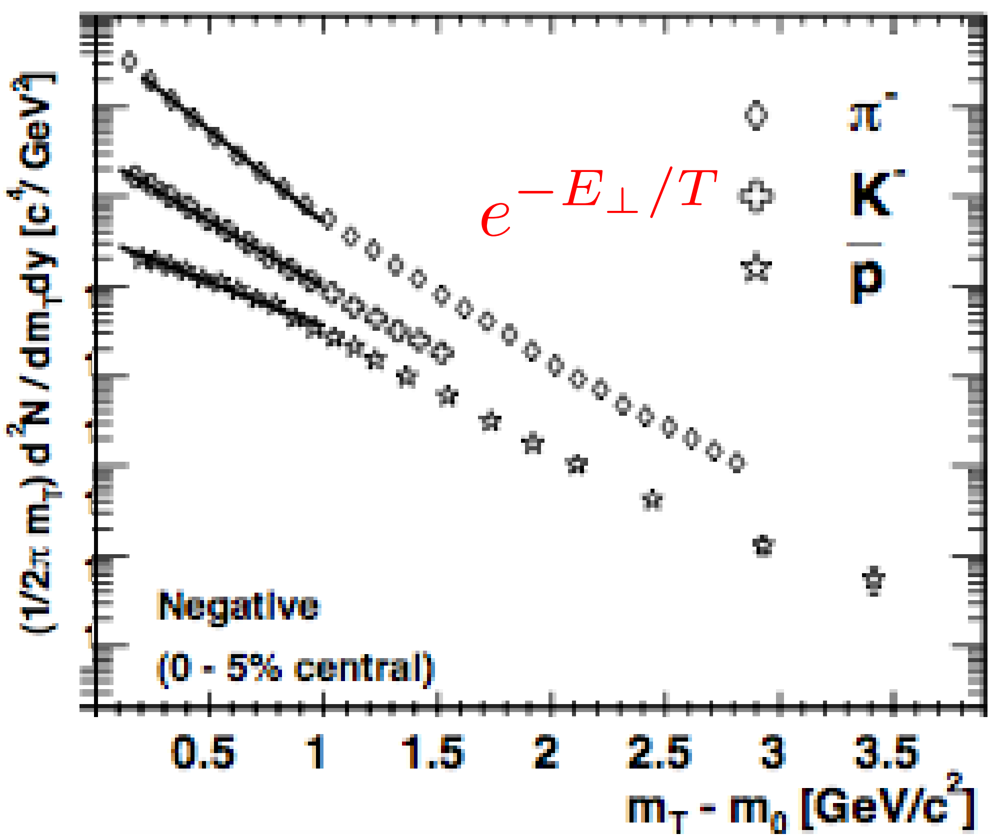
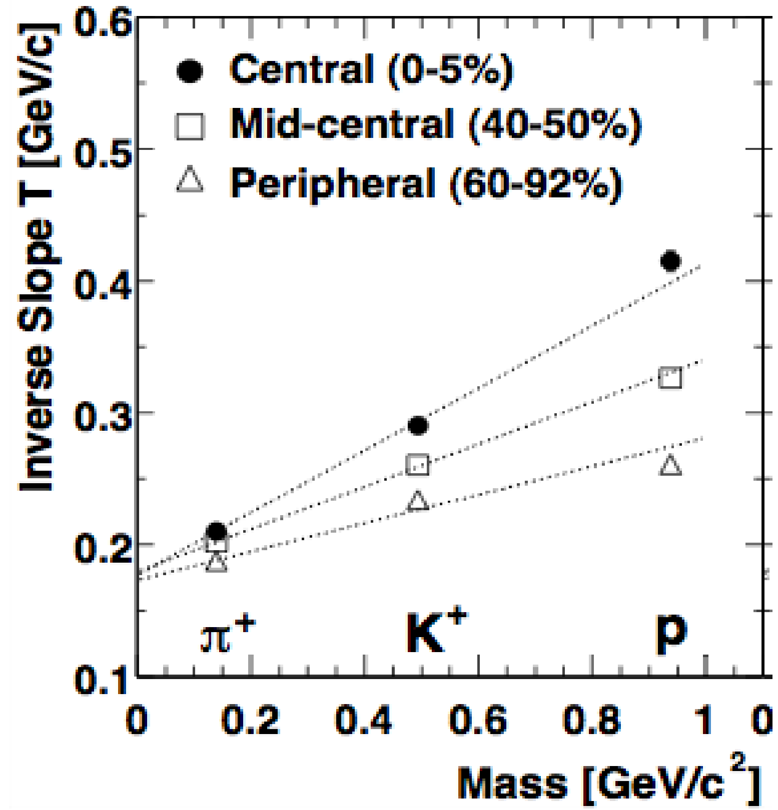
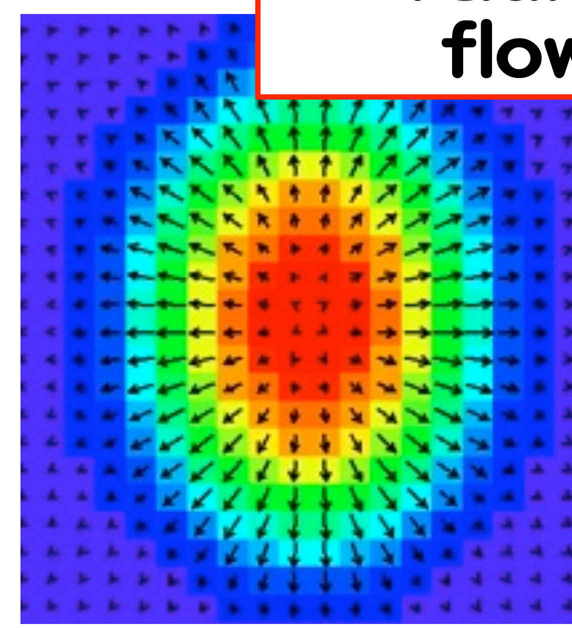




collective radial flow



collective flow

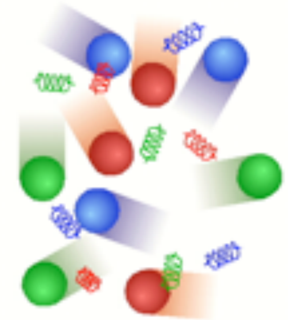
$$T \approx T_0 + \frac{1}{2} m v_r^2$$

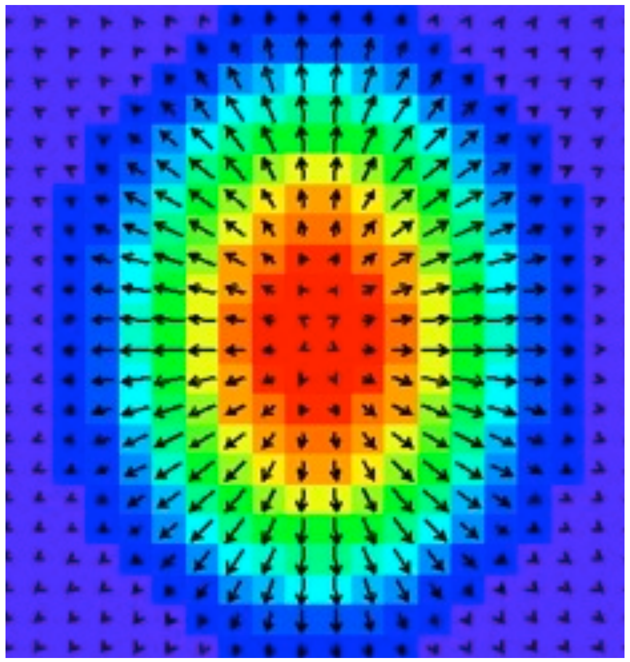
✓ Flatter m_t distr for heavier particle mass

- Mass Ordering of Slope parameter T.

✓ Collective flow boosts pt distr. according to its mass

Blast Wave Model





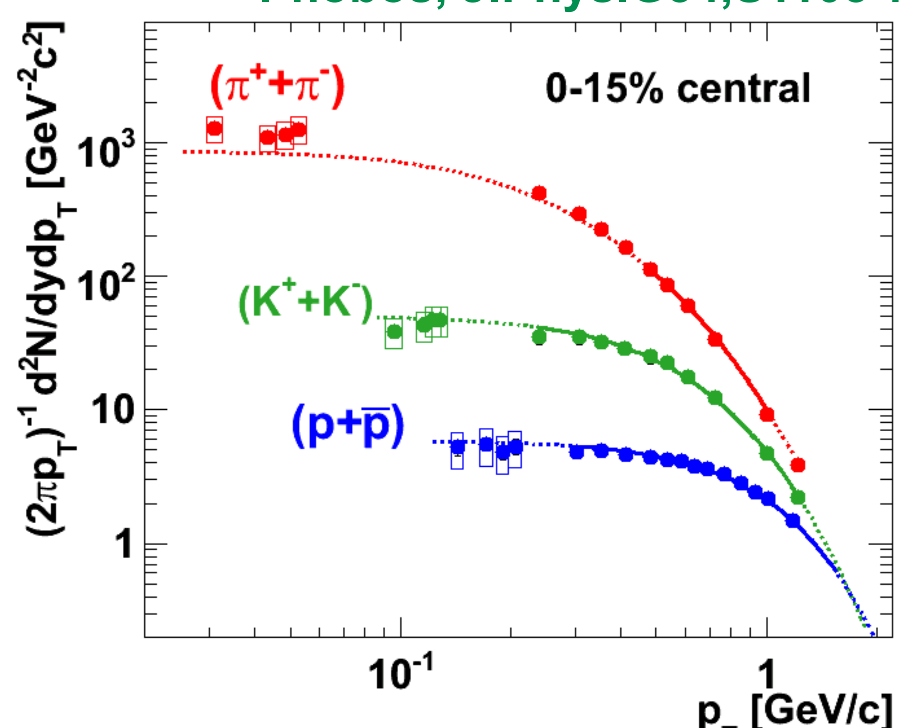
$$\frac{1}{m_T}\frac{dN}{dm_T} = A\int_0^R f(r)\,r\,dr\,m_T\,\mathrm{I}_0\left(\frac{p_T\sinh\rho}{T_{fo}}\right)\mathrm{K}_1\left(\frac{m_T\cosh\rho}{T_{fo}}\right)$$

PRC48(1993)2462.

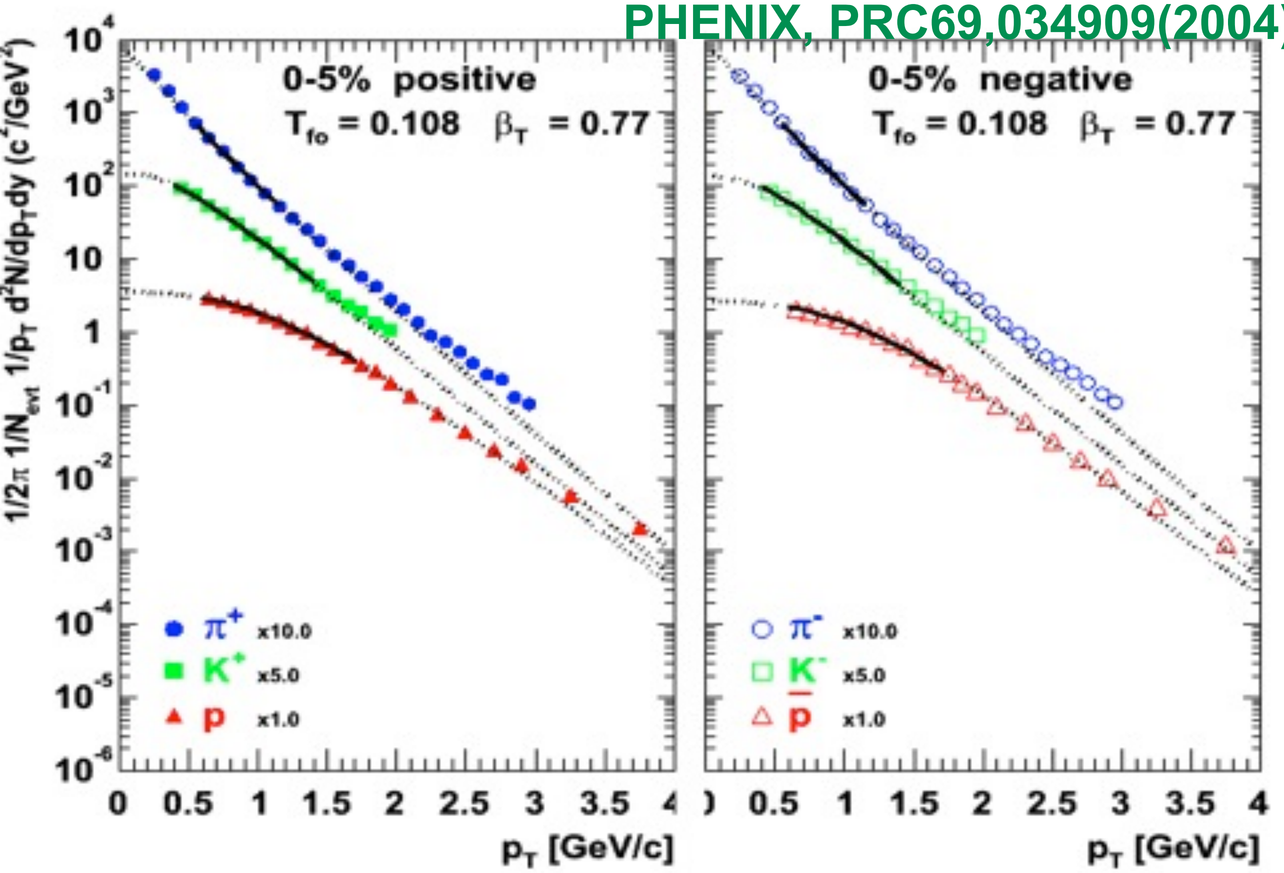
$$\rho(r) = \tanh^{-1}(\beta_T)\cdot r/R$$

I_0 , K_1: modified Bessel function

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



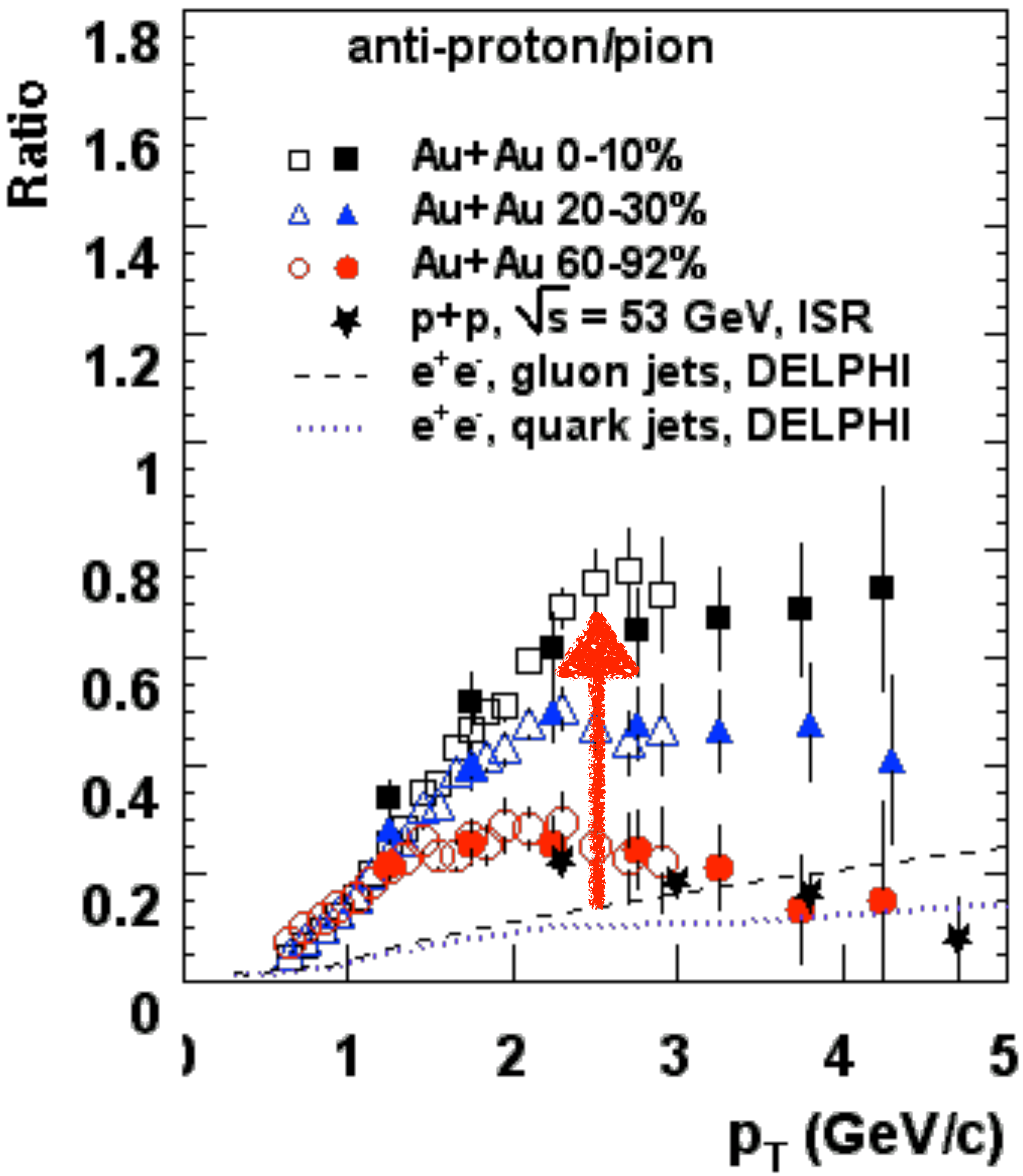
PHENIX, PRC69,034909(2004)



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

Baryon Anomaly

Phenix; P.R.L. 91(2003)172301

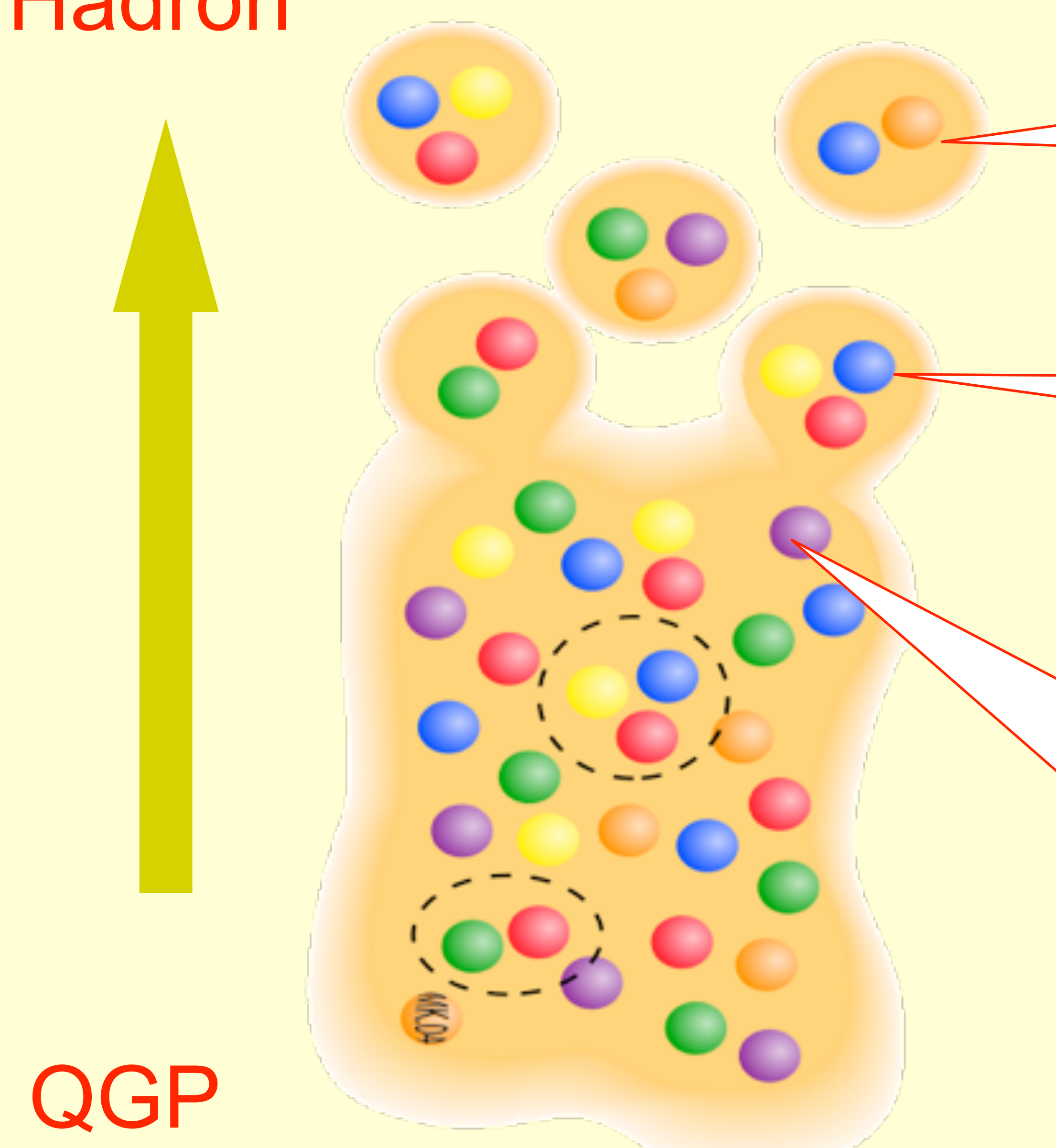


- In peripheral, p/π ratio at high pt similar to those in ee/pp suggesting fragmentaton process
- In central col., p/π ratio is very large, while.
  - Fragmentation process should show $n_p < n_\pi$ as seen in ee/pp.
- Suggesting other production mechanism.

↓

Quark Recombination Model
(Quark Coalescence Model)

Quark Coalescence explains Baryon Anomaly



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).**

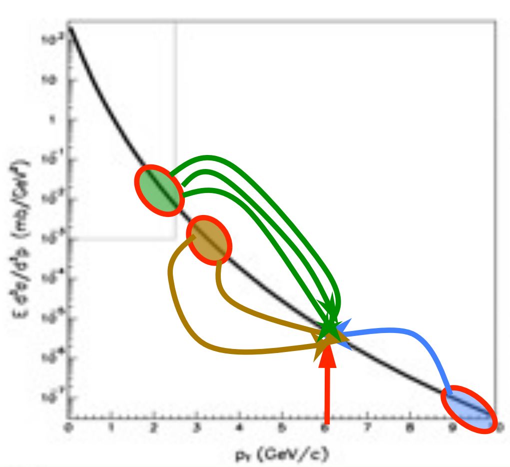
Mom. distr. of meson (2q);

$$W_M(p_t) \approx C_M \cdot w^2(p_t/2)$$

Mom. distr. of baryon (3q);

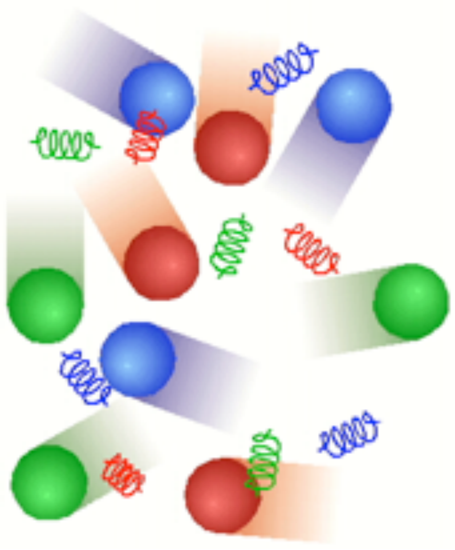
$$W_B(p_t) \approx C_B \cdot w^3(p_t/3)$$

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

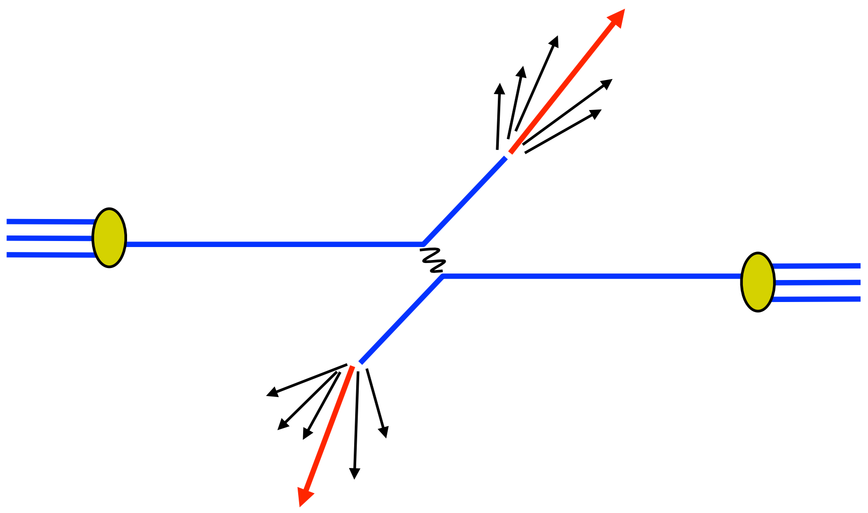


Characteristic scaling features expected.

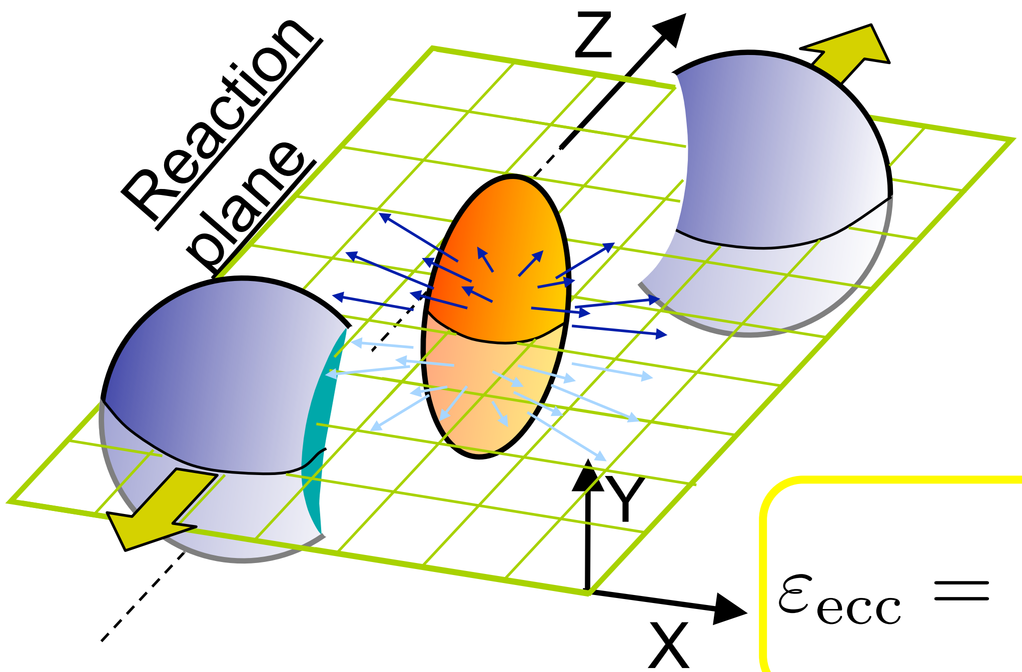
➔Quark Number Scaling (QNS)



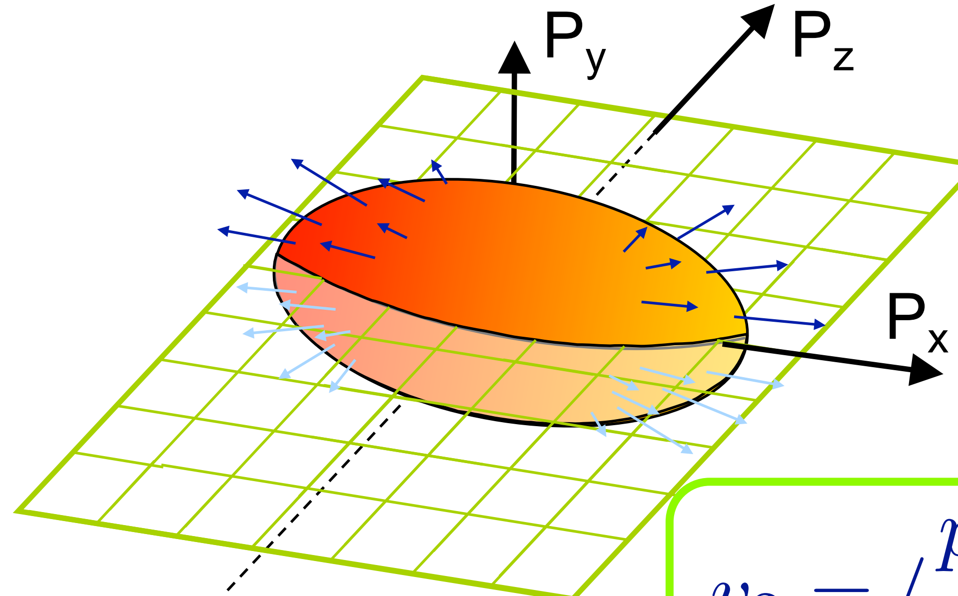
Azimuthal Anisotropy



Conversion of anisotropy in coordinate space to momentum space



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



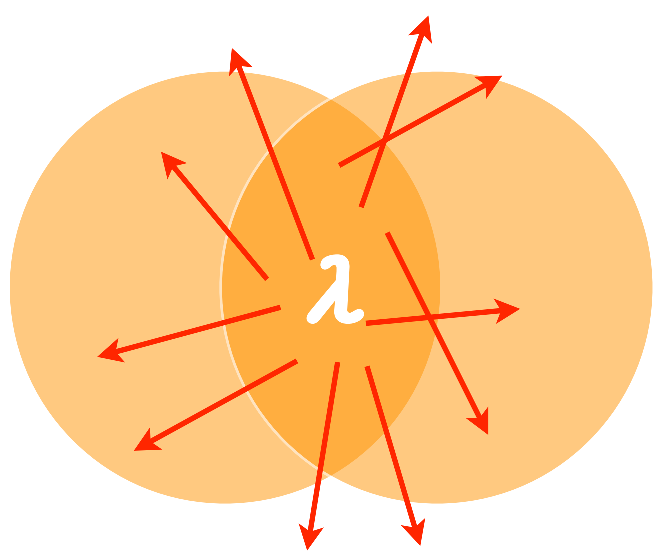
$$v_2 = \langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \rangle$$

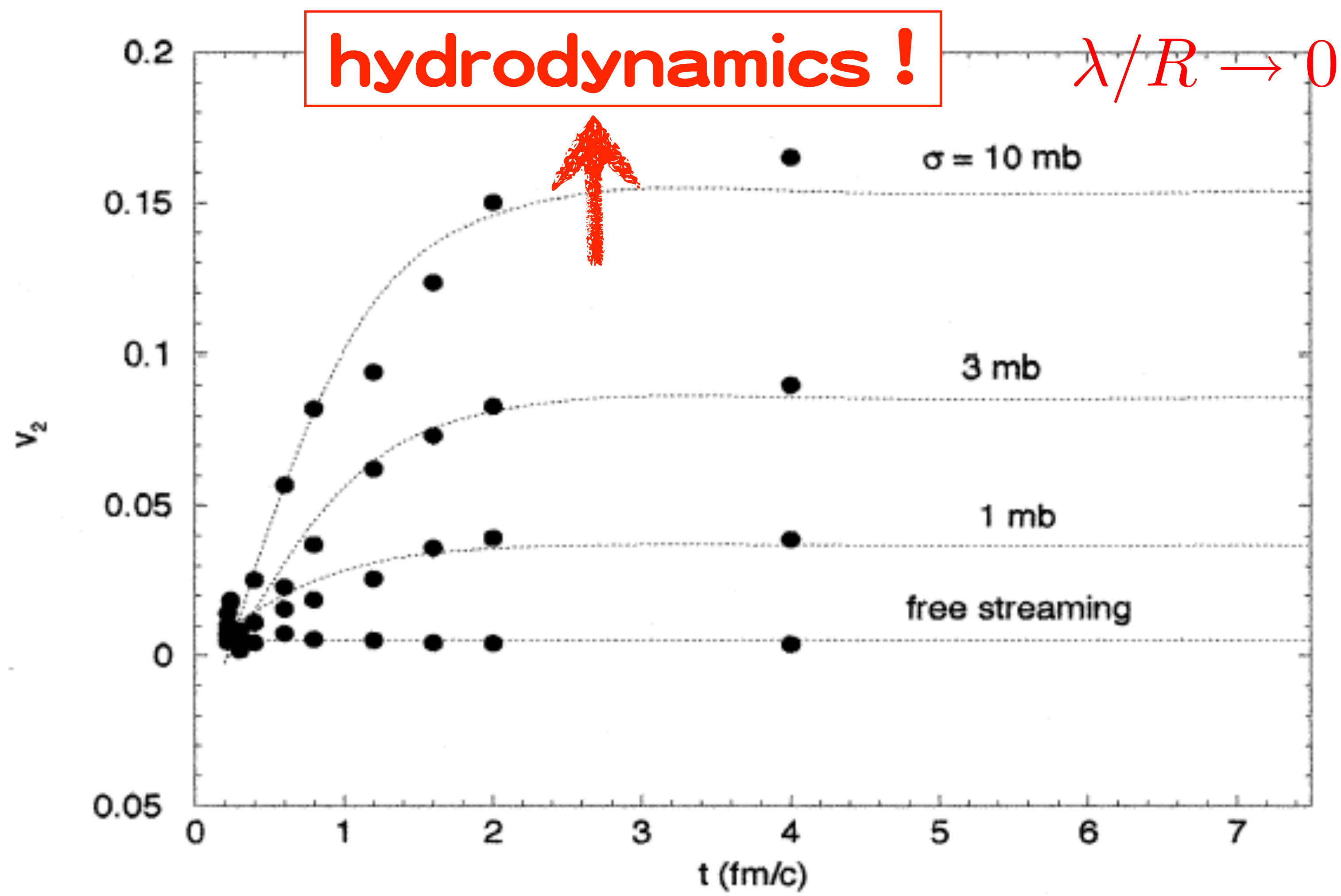
- ✓ In non-central collisions, participant region has almond shape.
  - ➡azimuthal anisotropy in coordinate space
- ✓ If $\lambda \ll$ R, azimuthal anisotropy of the coordinate space is converted to that of the momentum space.
  - ➡v_2 ; second Fourier harmonics of azimuthal distribution
- ✓ Goodies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

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

Conversion from ecc to v_2

$$\varepsilon_{\rm ecc} = \langle \frac{y^2 - x^2}{y^2 + x^2} \rangle \qquad \lambda = \frac{1}{n\sigma} \qquad v_2 = \langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \rangle$$





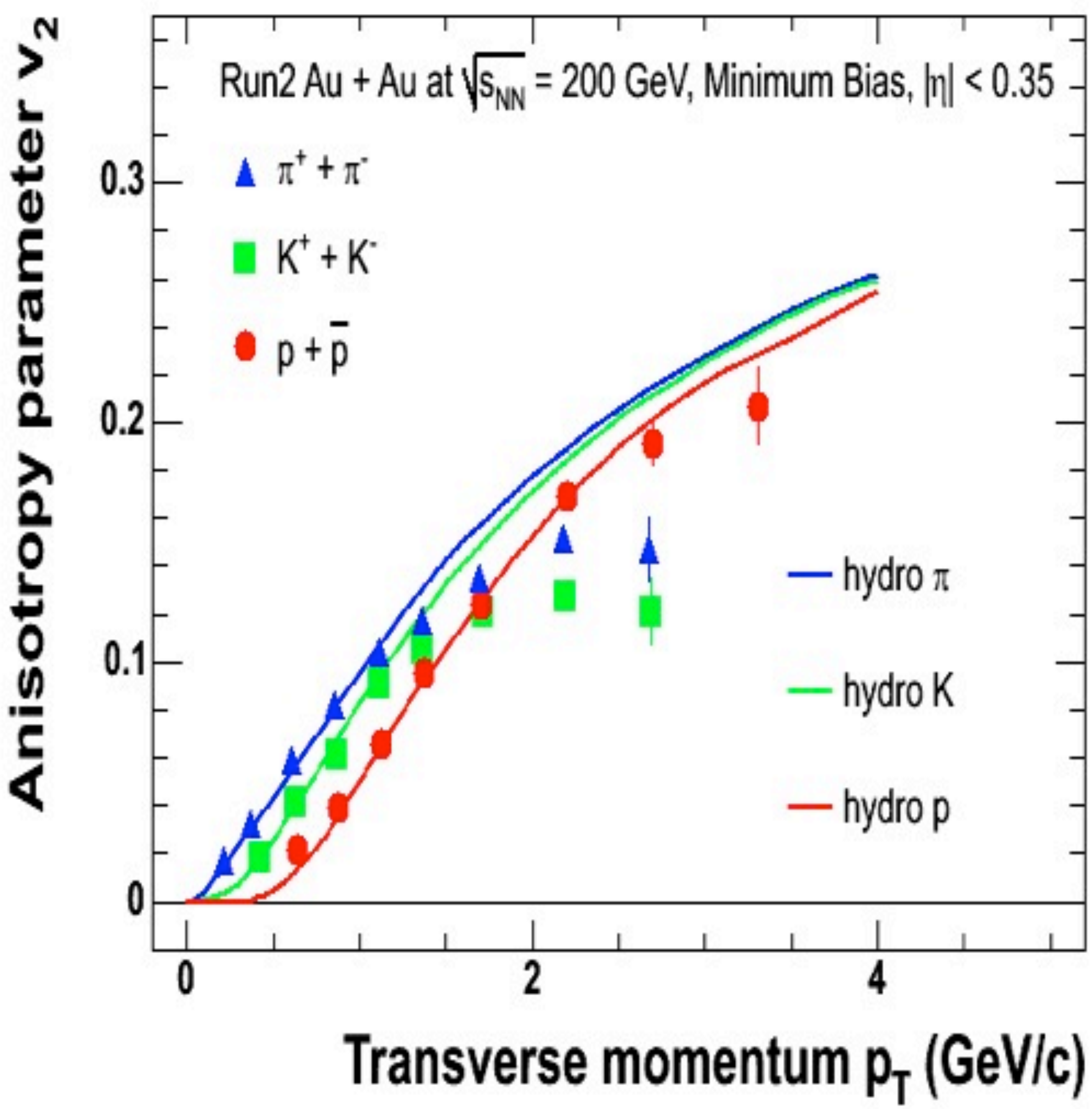
✓ v_2 saturates in the early stage

- Geometrical eccentricity disappears quickly

➡ v_2 is sensitive to the early stage of the collisions

v_2 of identified particle

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



✓Characteristic behavior

➡ Mass Ordering of v_2 at low pt region, collective flow

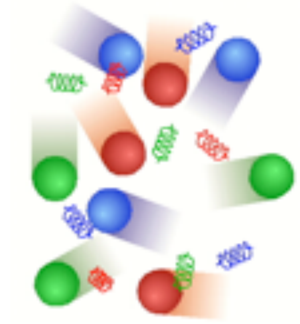
- (1) Departure at high pt region (> 1.5 GeV/c);

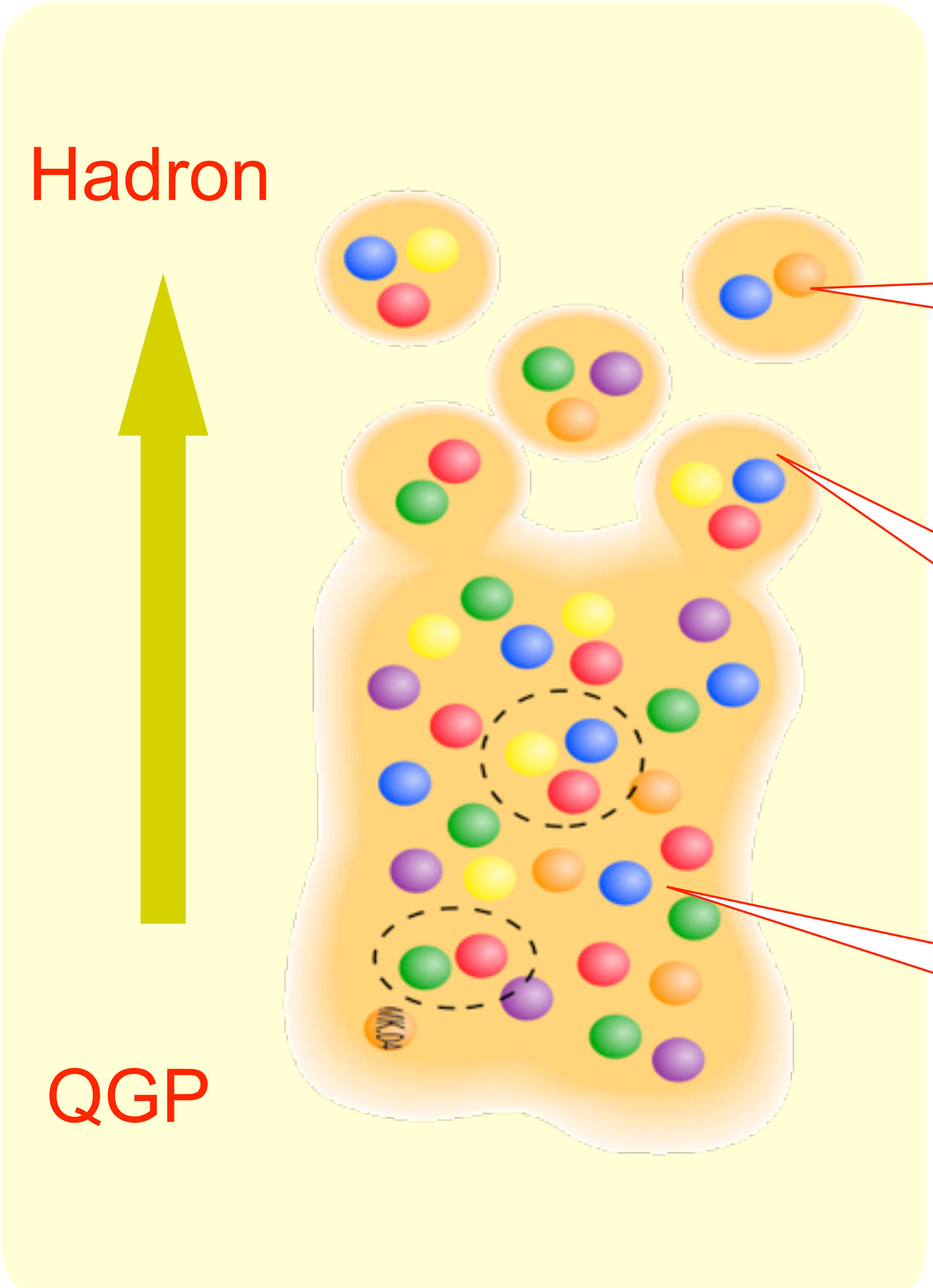
  Other mechanism ; quark coalescence

- (2) Good agreement with hydrodynamics, in which

  early thermalization ~0.6 fm/c
  perfect fluid

Quark Coalescence also explains v2 behavior





✓ **Universal azimuthal distribution of quarks**

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);

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

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

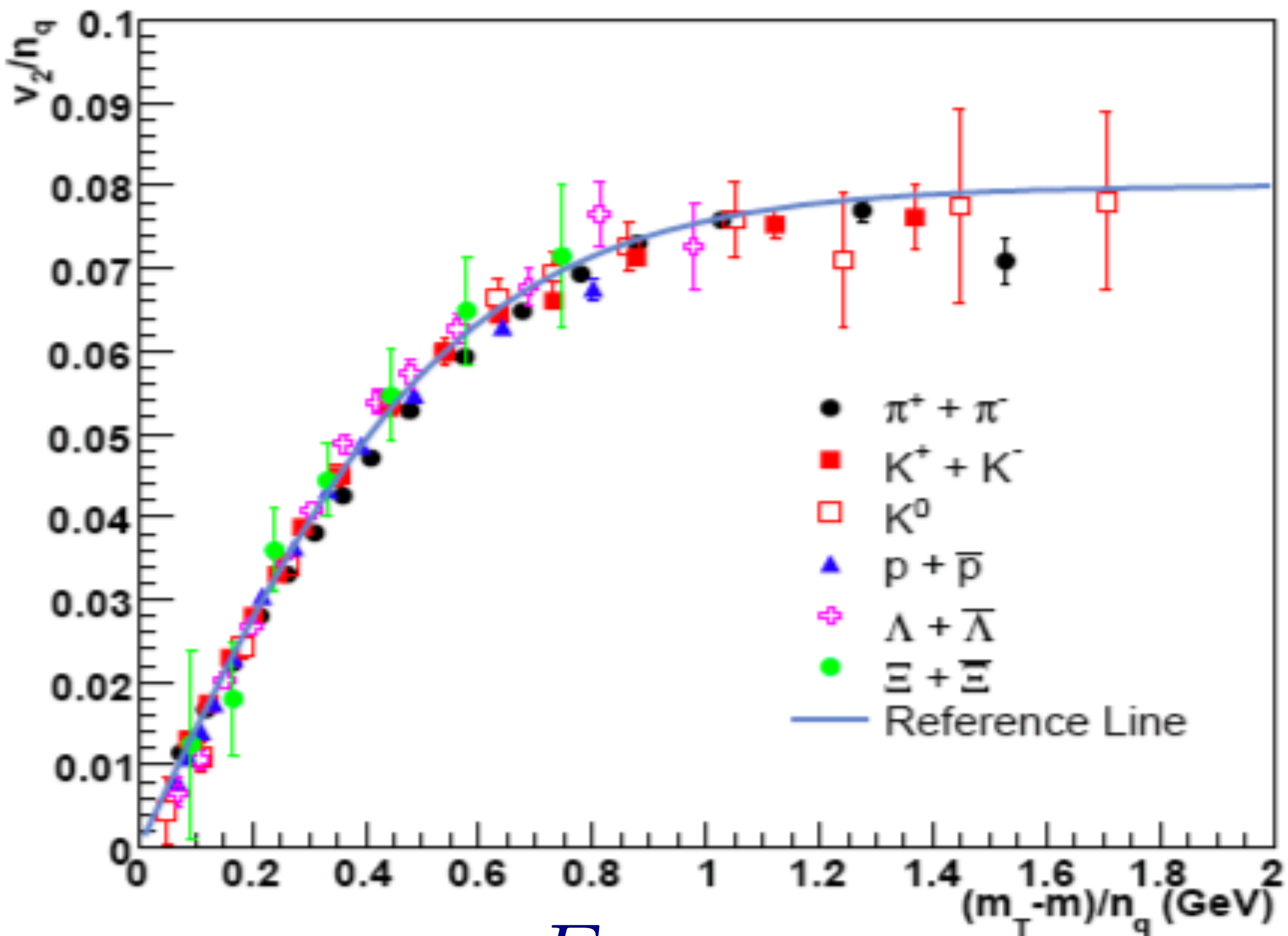
Azimuthal distr of quark; w

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

→ Quark Number Scaling in v2 !!

Beautiful scalings of v_2

Au+Au 200 GeV　PHENIX PRL 98(2007)162301



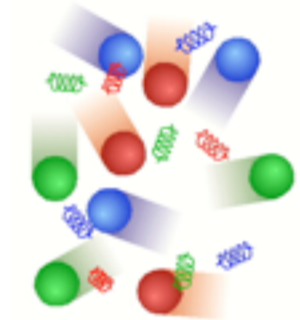
$$\frac{v_2}{n_q}$$

$$\frac{E_T}{n_q}$$

✓ **Quark coalescence works !**

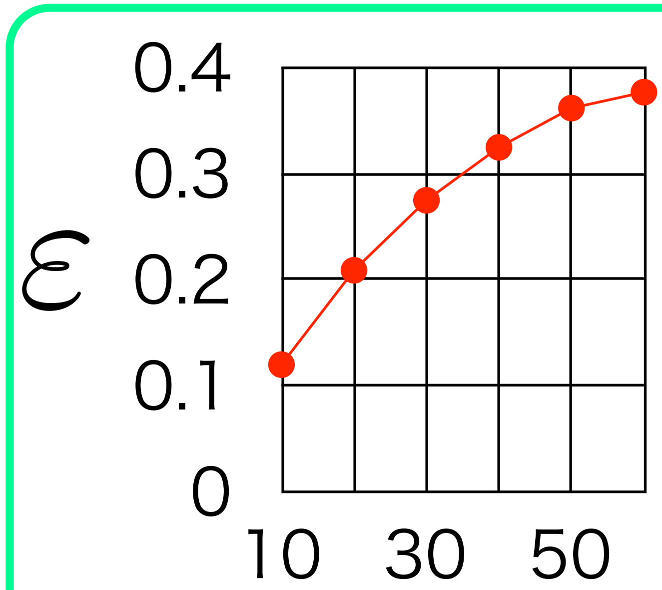
➡ **Universal/Statistical distribution at quark level**

"Nearly perfect Quark-Gluon Liquid"

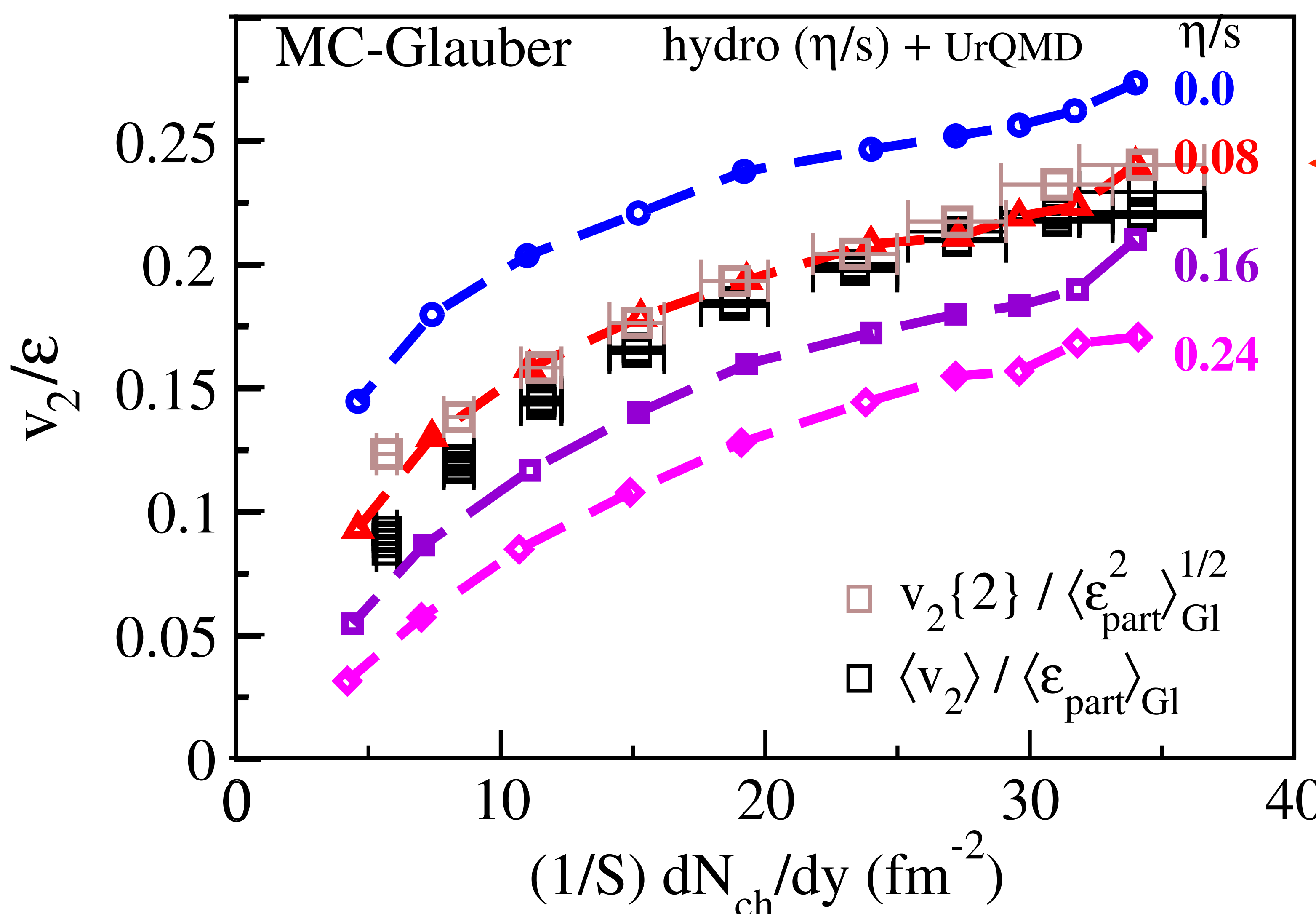


PRL, 106, 192301(2011)

central ⟷ peripheral



central ⟷ peripheral



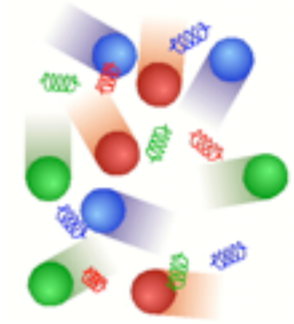
peripheral ⟷ central

✓ **Systematic study with hydrodynamics**

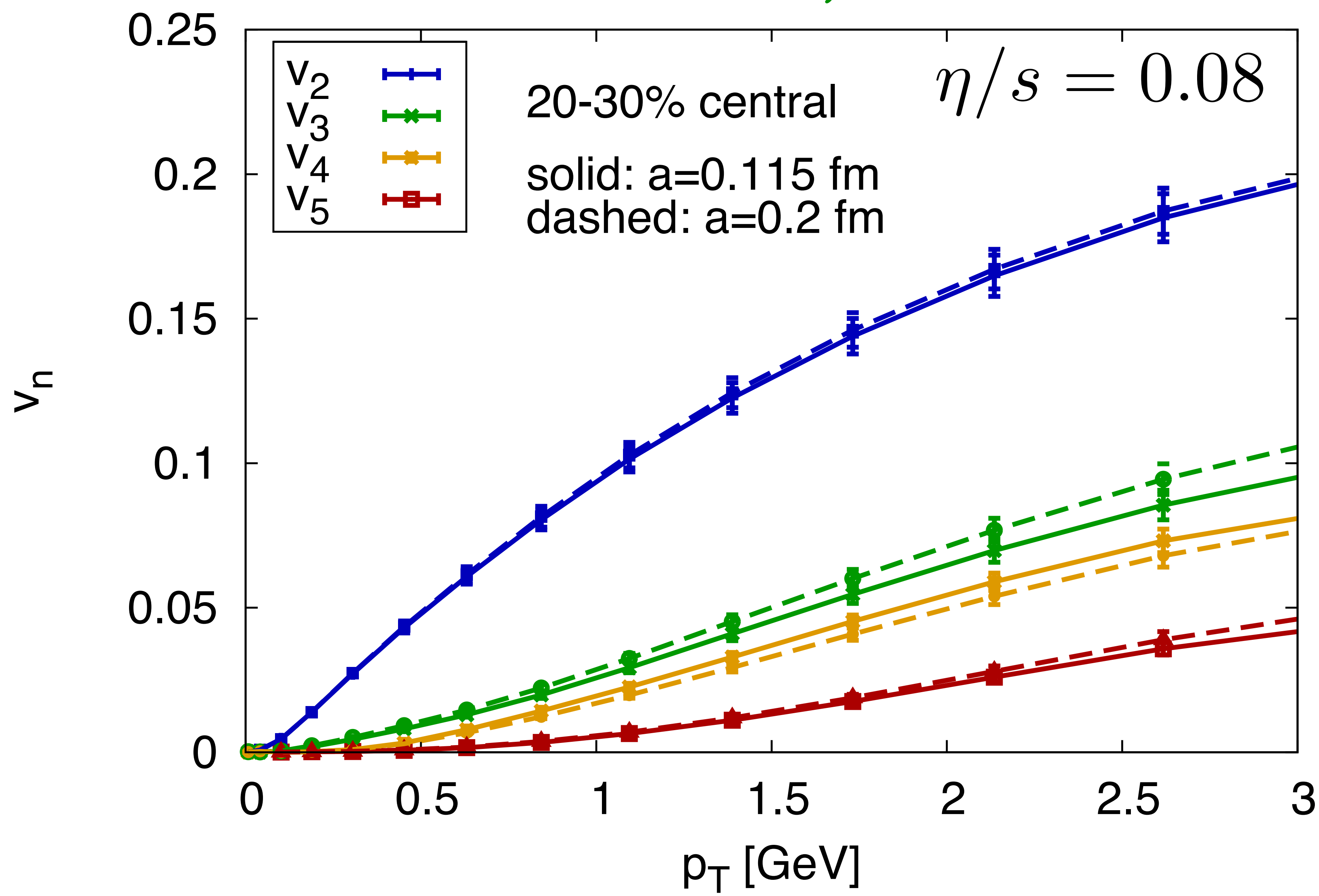
- **for various centralities, η/s & initial conditions**

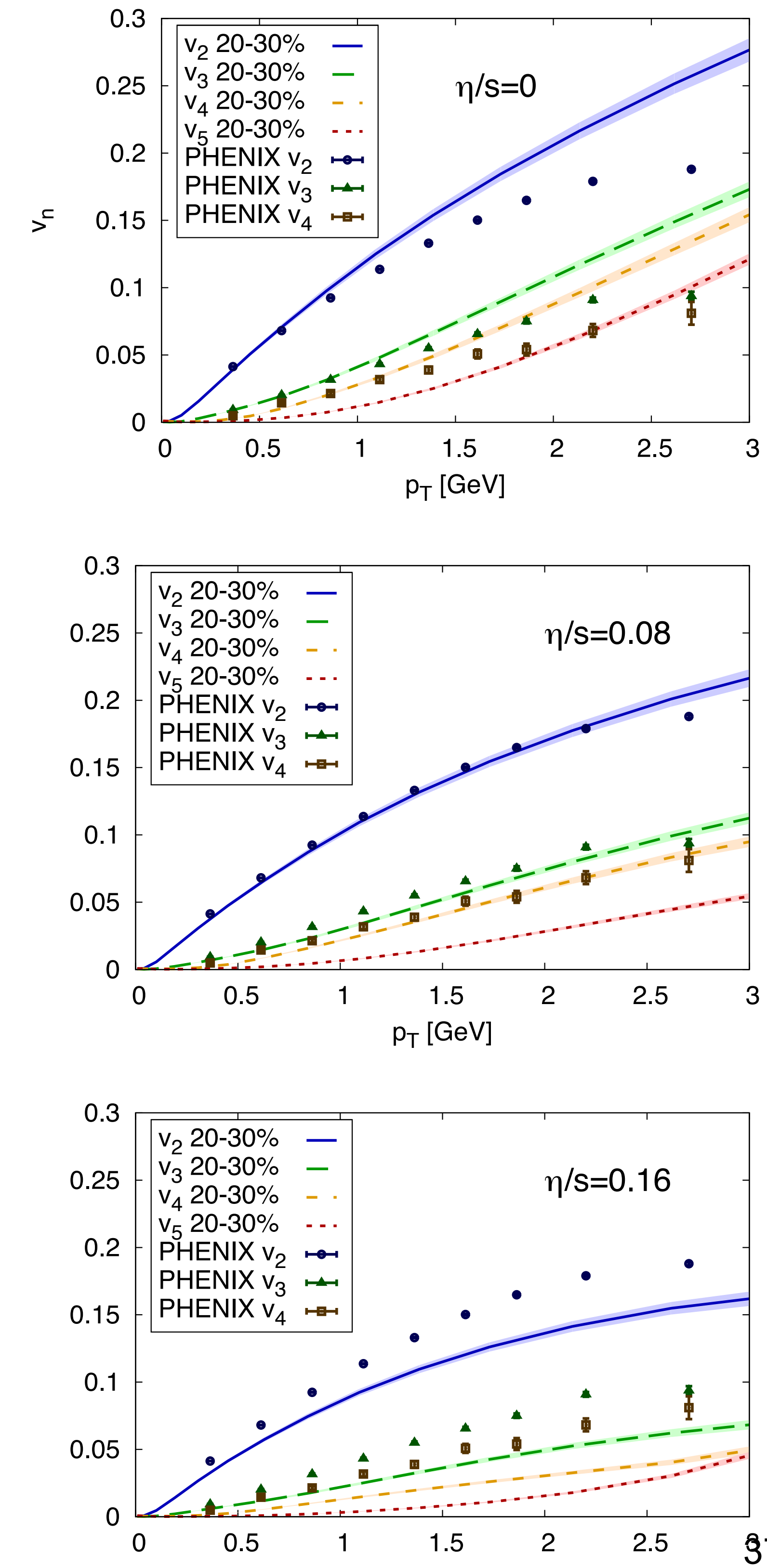
$$\Rightarrow \frac{1}{4\pi} < (\eta/s) < \frac{2.5}{4\pi}$$

Further analysis of higher harmonics



B.Schenke, arXiv:1109.6289





✓ **Viscosity as low as the quantum bound**

➡Perfect Fluid !

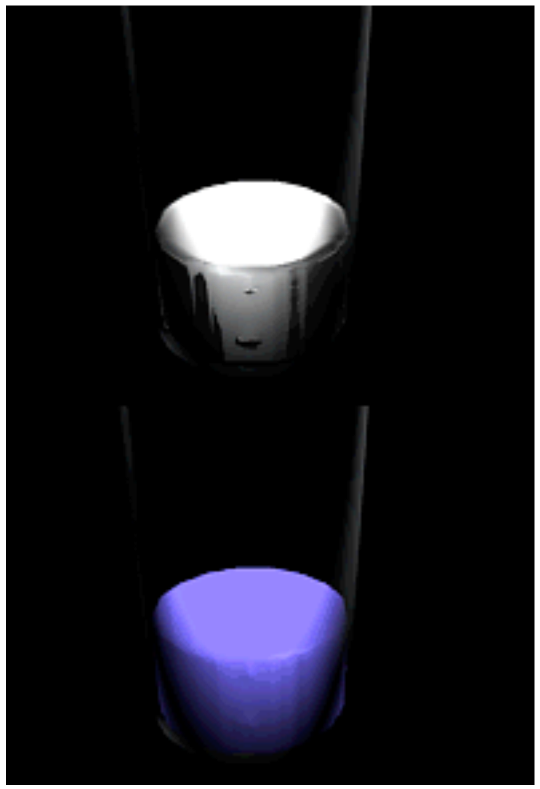
$$\eta/s \geq \frac{1}{4\pi} \sim 0.08$$

Shear viscosity

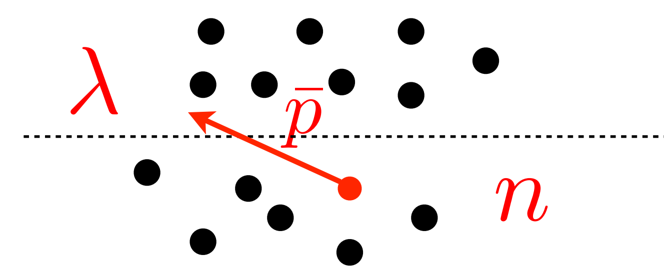
internal resistance to flow

Low η

High η



From view point of Kinetic theory,

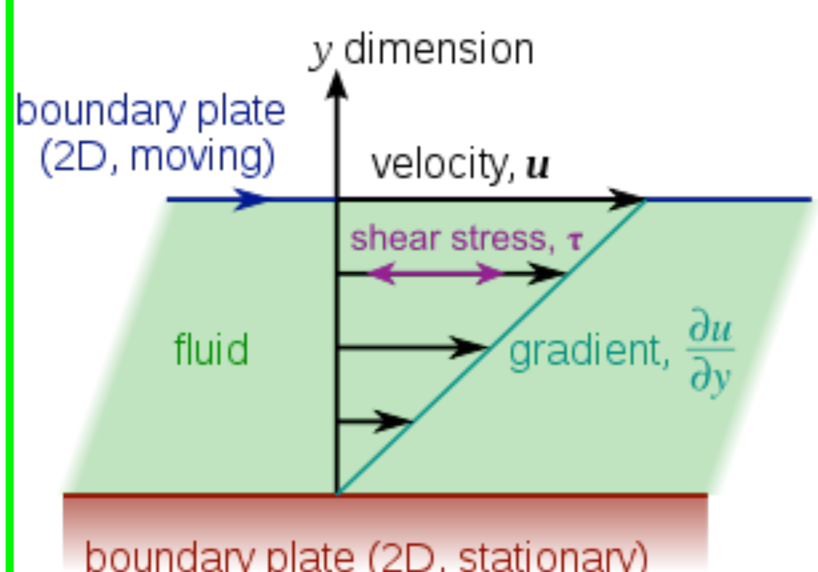


$$\begin{cases} \eta \approx \frac{1}{3} n \bar{p} \lambda \\ s \approx n \end{cases}$$

$$\therefore (\eta/s) \sim \bar{p}\lambda \overset{(\lambda\to 0)}{\searrow} 0$$

(uncertainty principle)

dimension less in natural unit

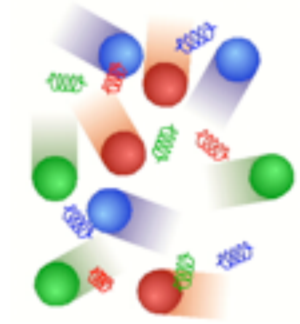


$$\tau (= \frac{F}{S}) \equiv \eta \frac{\partial u}{\partial y}$$

Wikipedia

✓Strong coupling

First η/s from AdS/CFT correspondence calc.



VOLUME 87, NUMBER 8 PHYSICAL REVIEW LETTERS 20 AUGUST 2001

Shear Viscosity of Strongly Coupled $\mathcal{N} = 4$ Supersymmetric Yang-Mills Plasma

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(Received 14 April 2001; published 2 August 2001)

Using the anti–de Sitter/conformal field theory correspondence, we relate the shear viscosity η of the finite-temperature $\mathcal{N} = 4$ supersymmetric Yang-Mills theory in the large N, strong-coupling regime with the absorption cross section of low-energy gravitons by a near-extremal black three-brane. We show that in the limit of zero frequency this cross section coincides with the area of the horizon. From this result we find $\eta = \frac{\pi}{8}N^2T^3$. We conjecture that for finite 't Hooft coupling $g_{YM}^2 N$ the shear viscosity is $\eta = f(g_{YM}^2 N)N^2T^3$, where $f(x)$ is a monotonic function that decreases from $\mathcal{O}(x^{-2}\ln^{-1}(1/x))$ at small x to $\pi/8$ when $x \to \infty$.

DOI: 10.1103/PhysRevLett.87.081601 PACS numbers: 11.25.Hf, 11.10.Wx

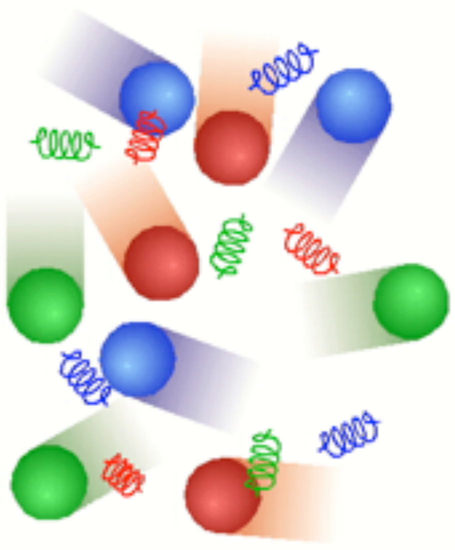
Introduction.—At finite temperatures, the large distance, long time behavior of gauge theories is described, as in any other fluid, by a hydrodynamic theory [1]. To write down the hydrodynamic equations one has to know the thermodynamics (i.e., the equation of state) of the medium, as well as the transport coefficients: the shear and the bulk viscosities, the electrical conductivity [in the presence of a U(1) gauge group], and the diffusion constants (in the presence of conserved global charges).

In this Letter, we compute the shear viscosity η of the strongly coupled finite-temperature $\mathcal{N} = 4$ SYM theory (the bulk viscosity of this theory vanishes due to scale invariance). We first relate, using previously known results from the AdS/CFT correspondence, the shear viscosity with the absorption cross section of low-energy gravitons falling perpendicularly onto near-extremal black three-branes. We further show that this cross section is equal to the area of the horizon, in a way very similar to the case of

$$(\eta/s)_{\mathrm{AdS/CFT}} = \frac{1}{4\pi}$$

✓ no question here, please, since no answer

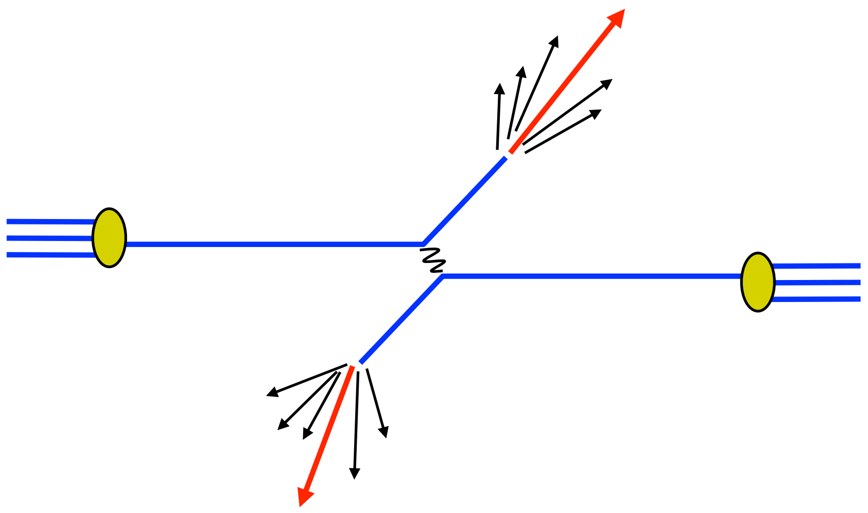
Hard comp.



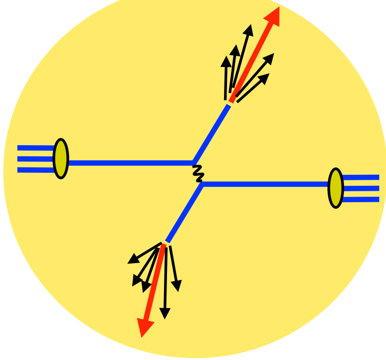
Partonic energy loss

Medium response

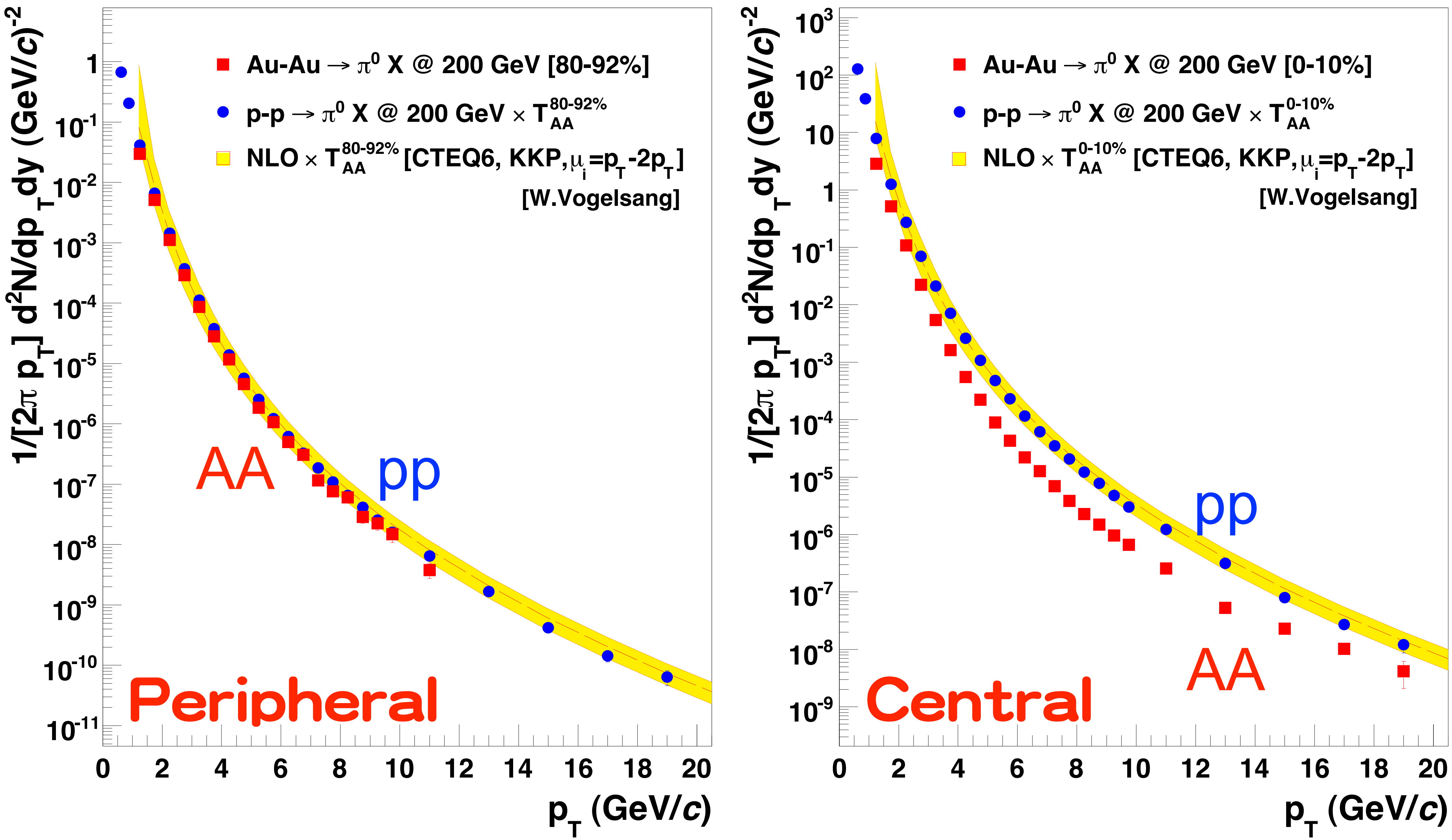
Tomography



Compare pp & AA

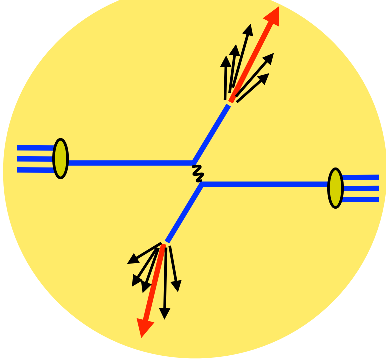


Phenix; P.R.L. 91, 232301 (2008), PRD76,051106(2007)



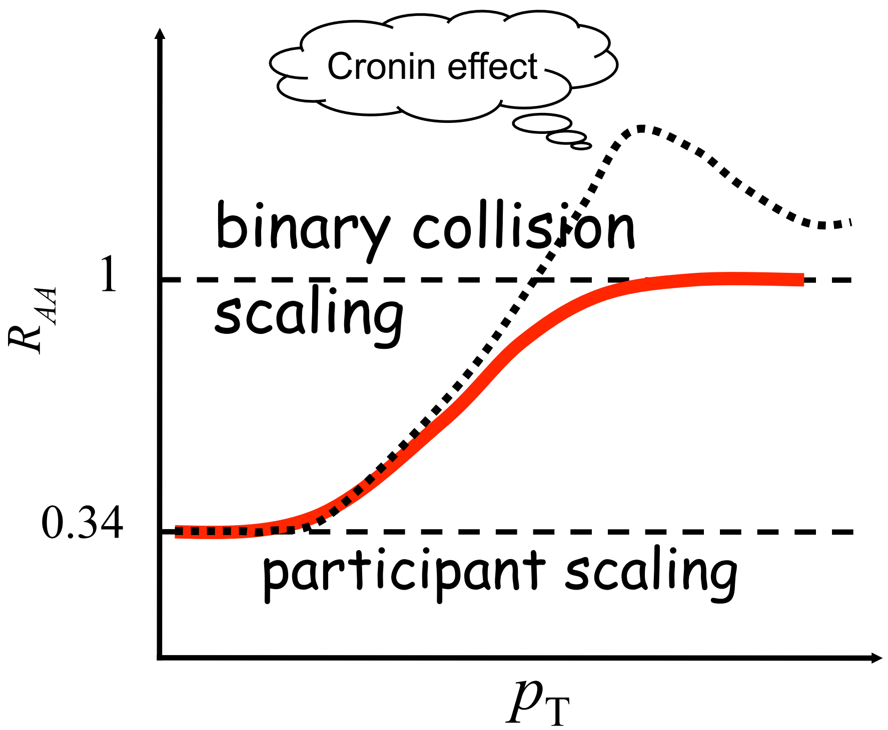
- ✓ Peripheral ; AA=superposition of AA
- ✓ Central ; suppression of high pt

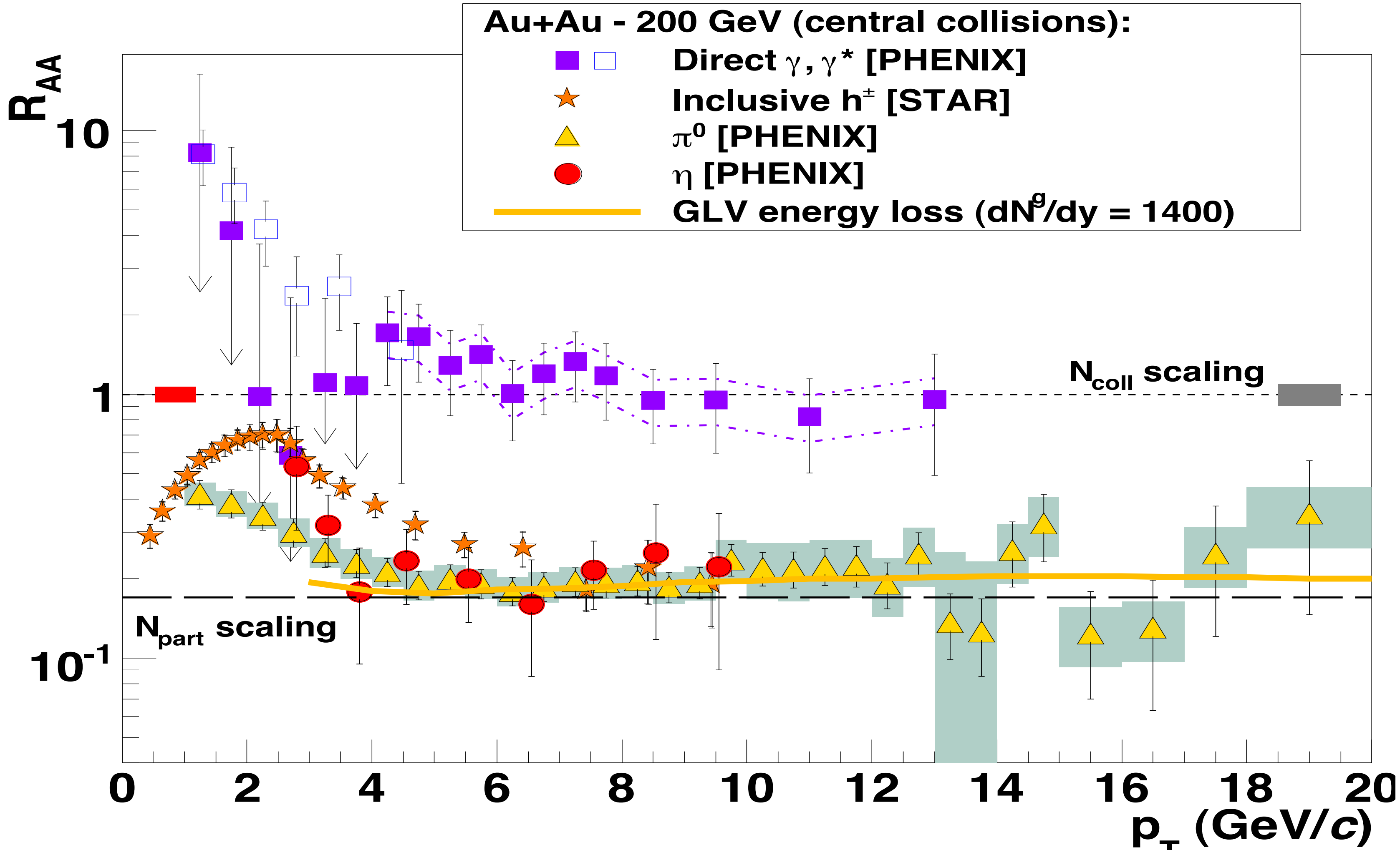
Suppression of high p_t particles



Nuclear Modification Factor

$$R_{AA} = \frac{\text{"hot/dense QCDmedium"}}{\text{"QCD vacuum"}} = \frac{dn_{AA}/dp_T dy}{\langle N_{binary} \rangle \cdot dn_{pp}/dp_T dy}$$

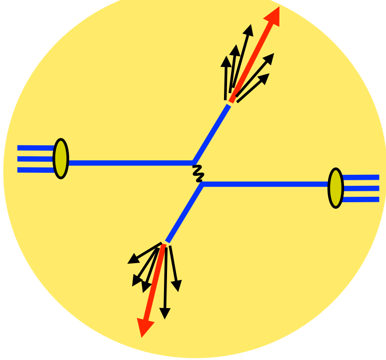




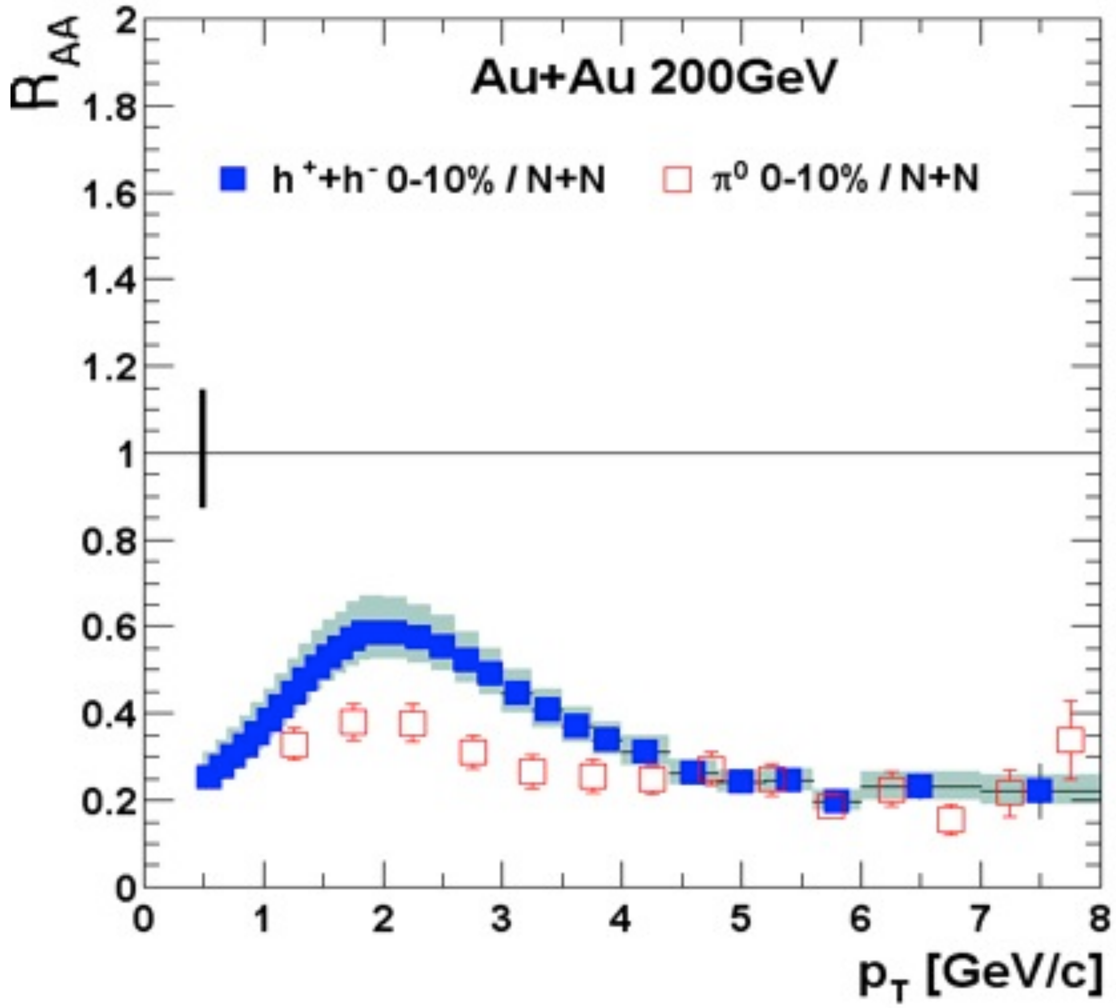
✓ **Pions are suppressed, direct photons are not**

- **Accidental with N_{part} scaling !?**

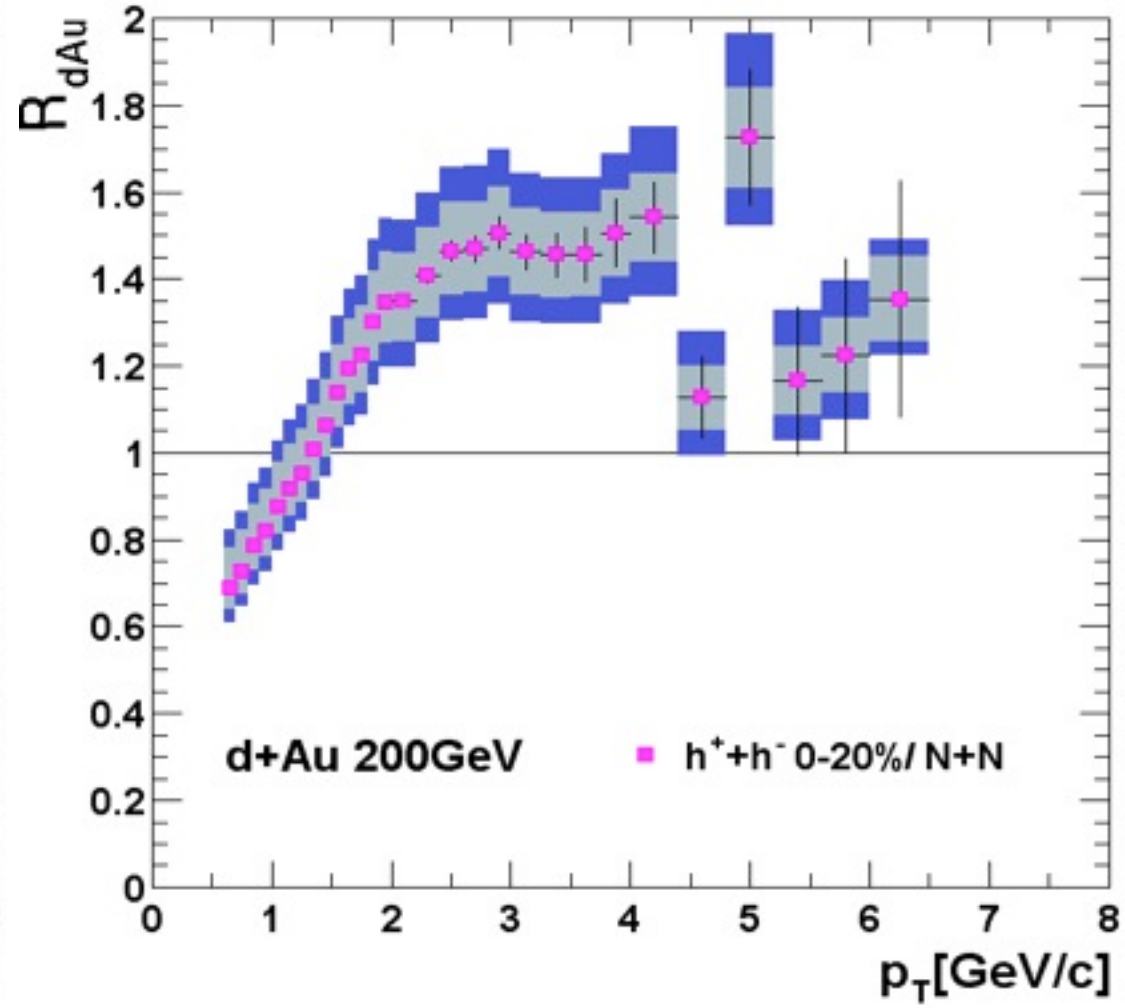
Au+Au vs d+Au



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



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

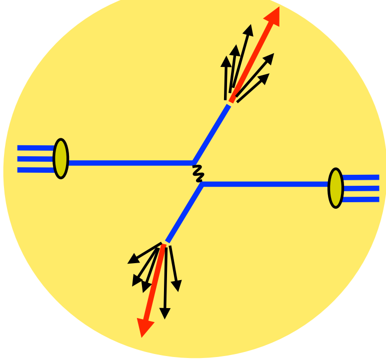


d+Au→$h^{\pm}$+X at $\sqrt{s_{NN}}$ = 200 GeV

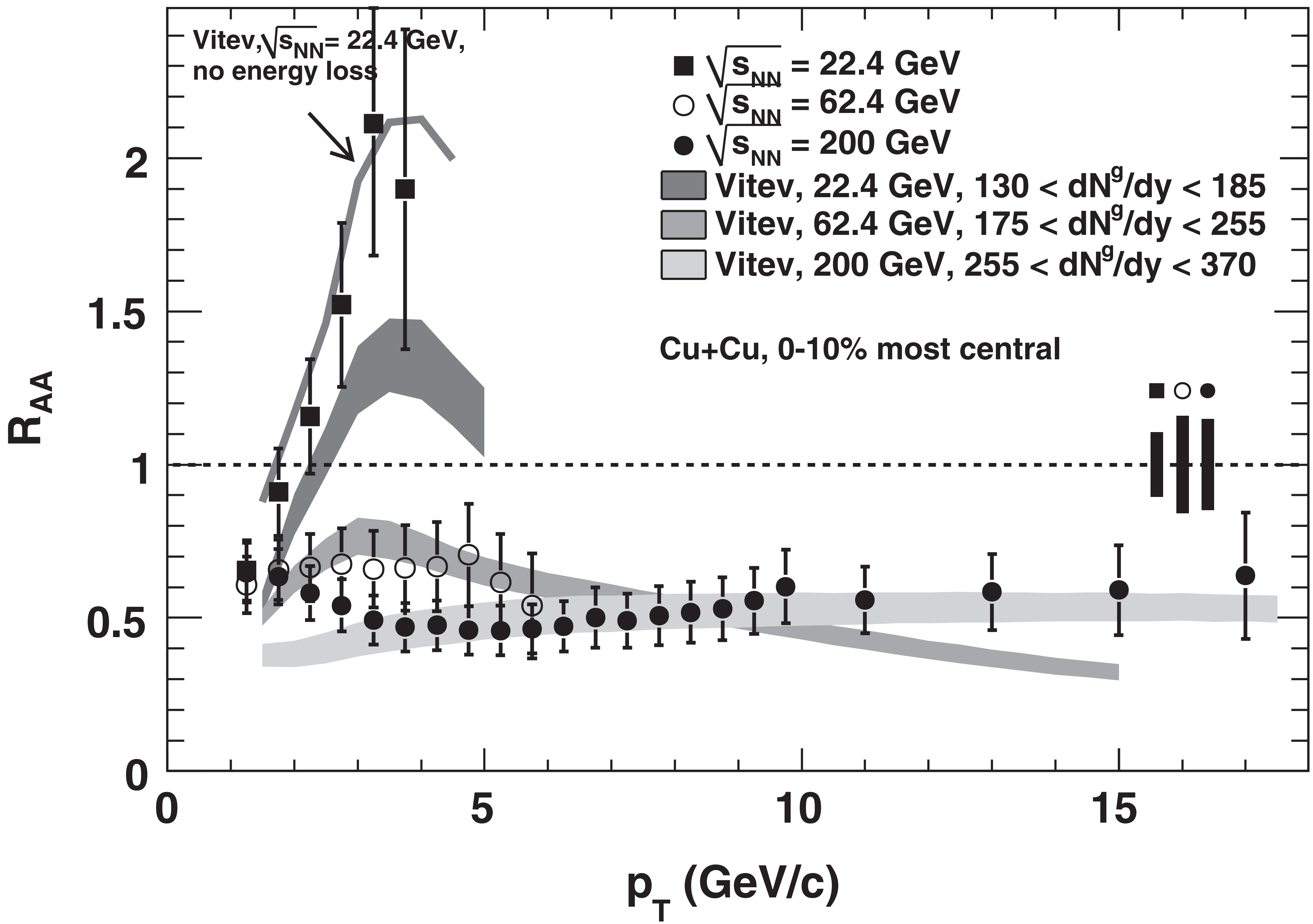
✓**High pt suppression in Au+Au, while not observed in d+Au.**

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

Onset of suppression between 22 and 39 GeV

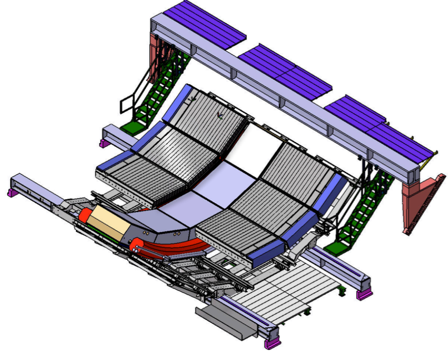


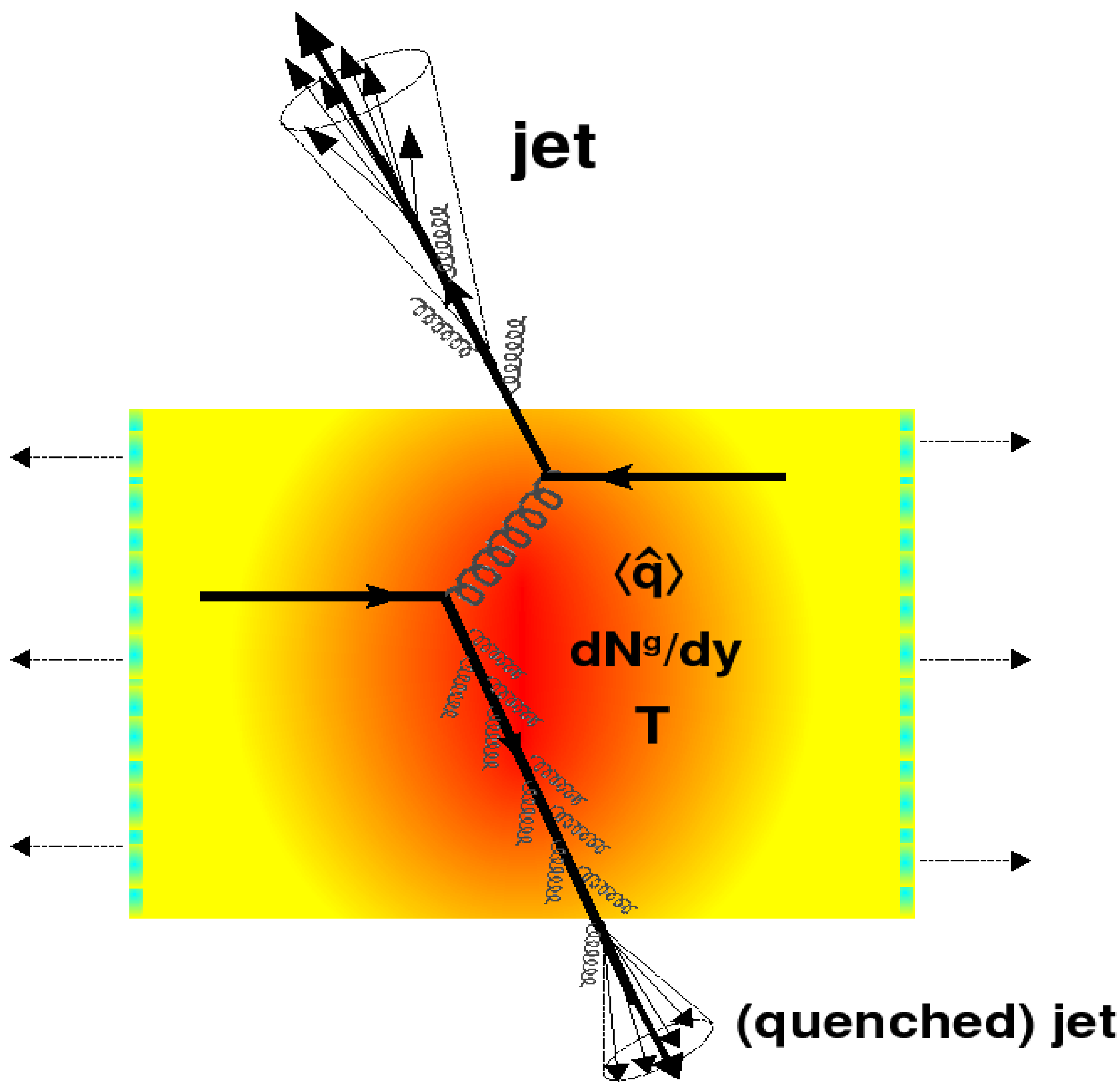
PHENIX, PRL 101,162301



✓Suppression not seen < 39 GeV

"Jet Quench"

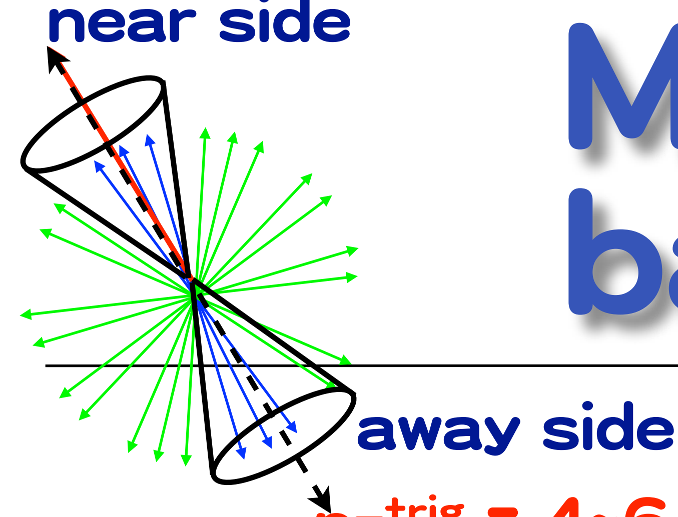




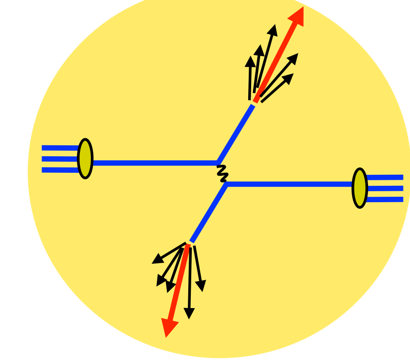
"Jet quenching" in nucleus-nucleus collision.

✓ Two quarks suffer a hard scattering in AA collision
- One goes out to vacuum creating jet,
- but the other goes through the QGP suffering energy loss due to gluon

✓ Manifestation:
- attenuation/ disappearance of jet
- suppression of high pt hadrons
- modification of jet frag.

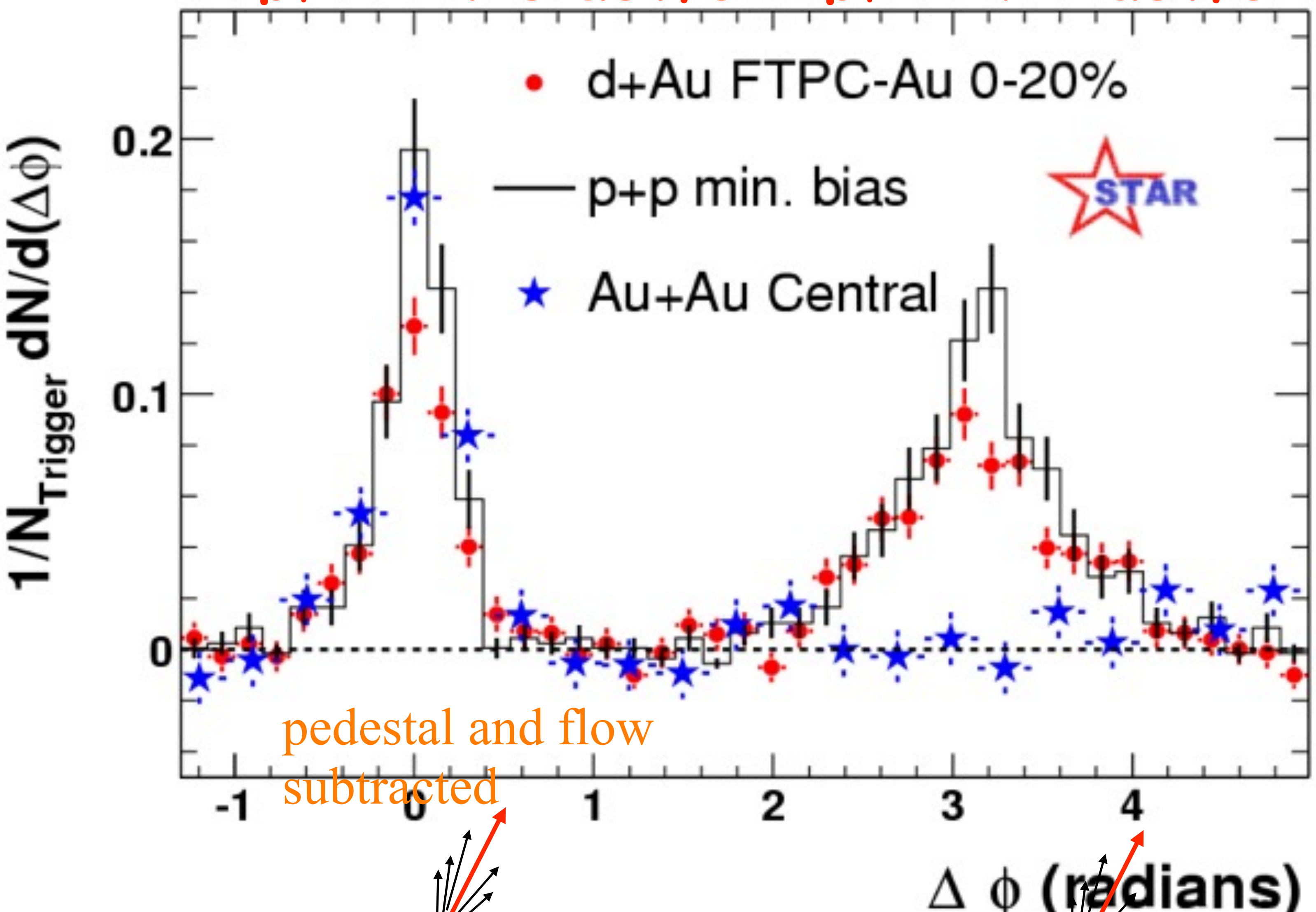


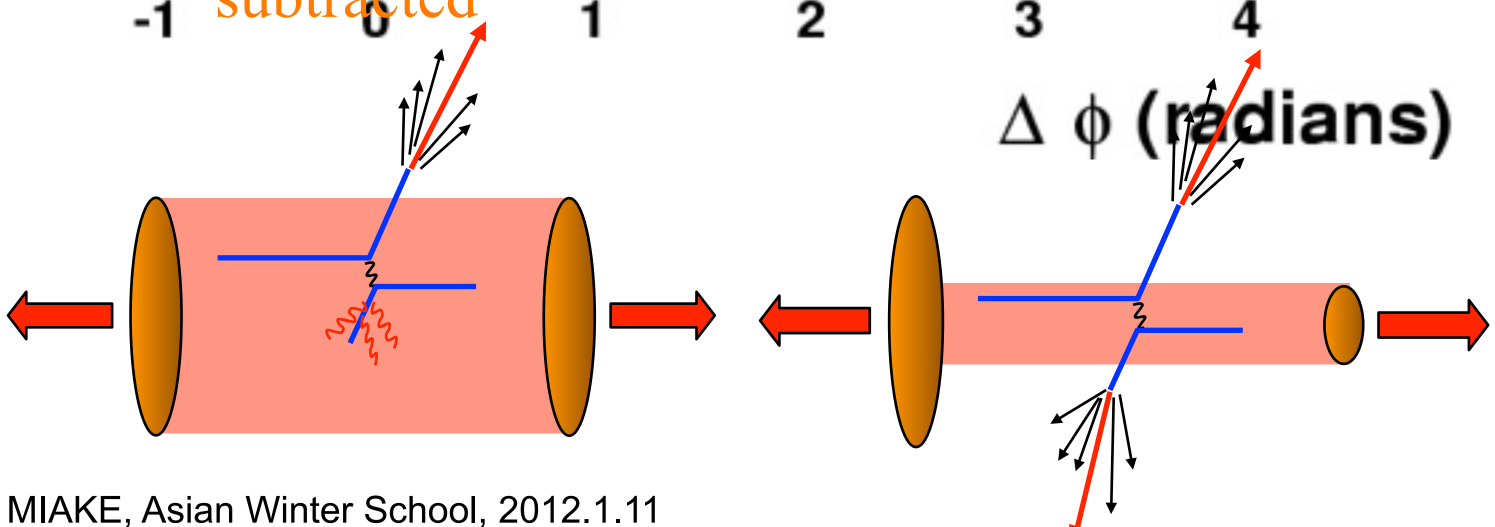
Modification of back-to-back corr.



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

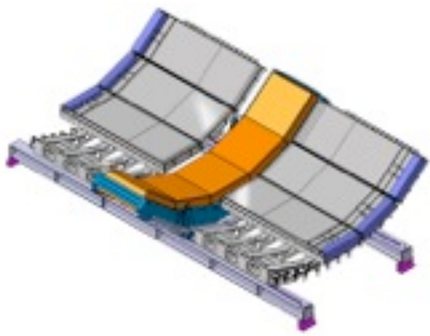
p_T^{trig} = 4~6 GeV/c × p_T^{assoc} > 2 GeV/c



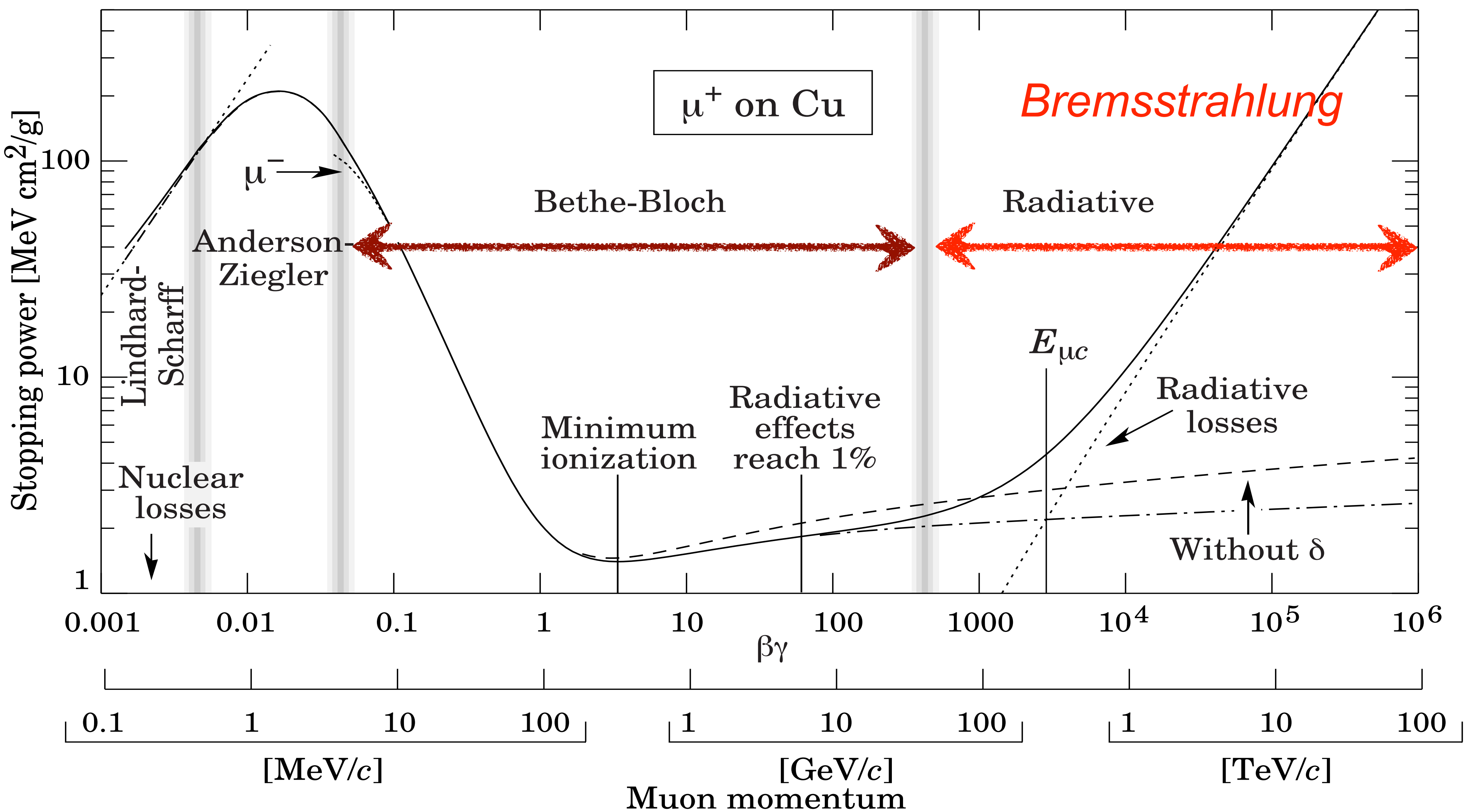


- ✓ Direct evidence of loss of 'jet'
- ✓ Azimuthal correlation w.r.t. high pt leading particle (trigger).
  - pp ; clean di-jet
  - dAu; similar to pp
  - Au+Au; Similar on the same side (suggesting jet-like mechanism), but b-to-b disappeared
    - Effect is not in initial but in final stage
    - Energy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

Energy loss in QED



Energy loss of charged particle in a matter



Collisional

- √Bethe-Bloch

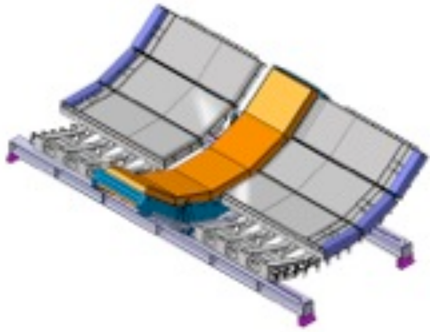
Radiative

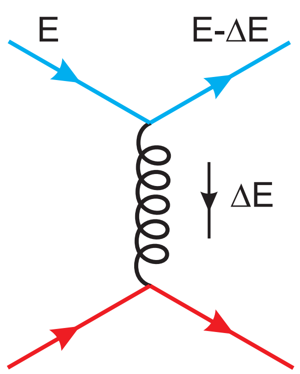
- √Bethe-Heitler (thin; L<<λ)
- √Landau-Pomeranchuk-Migdal (thick; L>>λ)

√**Measurements of dE/dx gives prop. of matter**

- **Energy loss in QED plasma gives T & m_D info.**

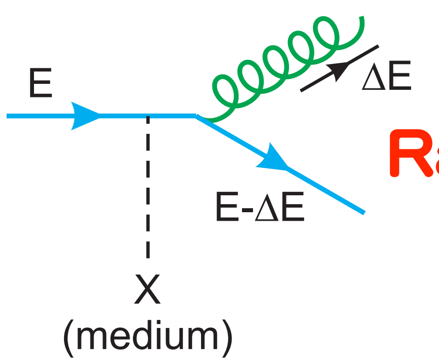
Energy Loss in QCD





Collisional

$\Delta E \propto \ell^1$

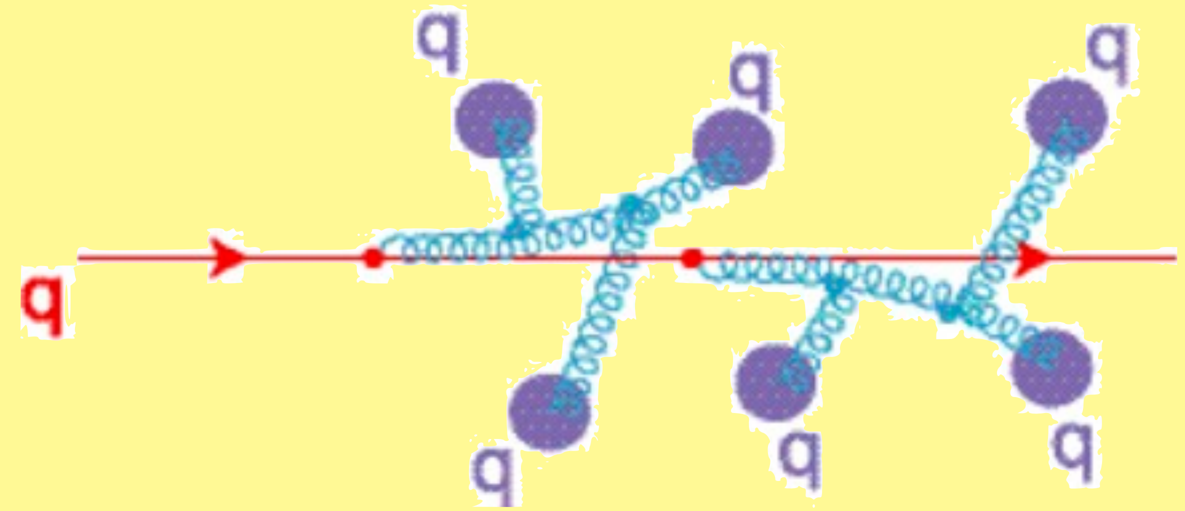


Radiative

$\Delta E \propto \ell^2$

✓ **Many theories on**

- **Collisional loss**
- **Radiative loss**
  - ➡ Bethe-Heitler regime
  - ➡ LPM regime
  - ➡ "dead-cone" effect



$$\Delta E \propto \alpha_S C_R \langle \hat{q} \rangle L^2$$

pQCD

(Executive) Summary

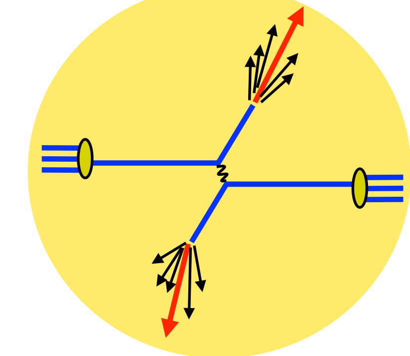
Radiative loss is dominant

Effects are;

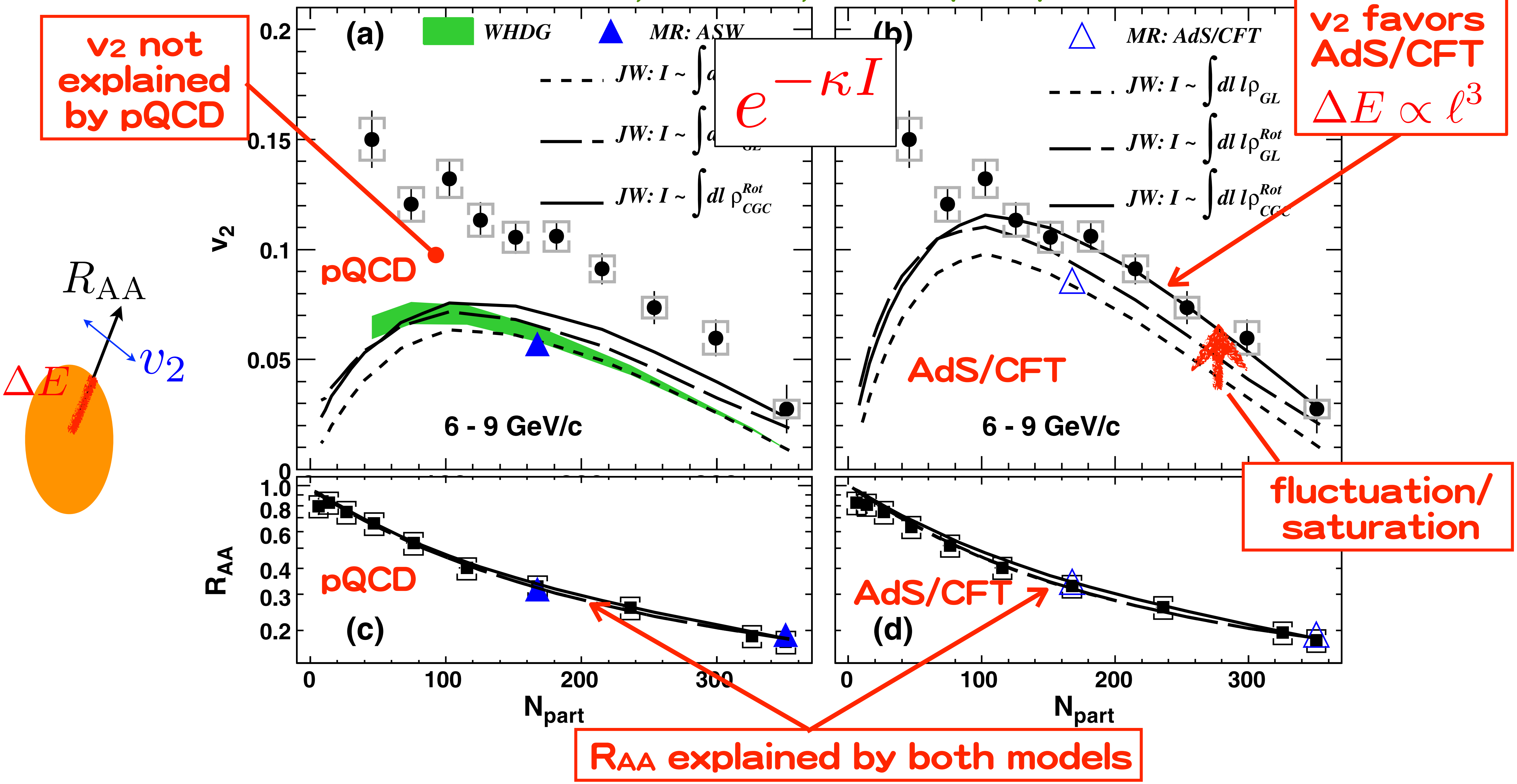
- suppression of high pt hadron
- unbalanced back-to back
- modification of jet fragmentation
  softer, larger multiplicity,
  angular broadening

$$\Delta E_{\mathrm{gluon}} > \Delta E_{\mathrm{quark}} > \Delta E_{\mathrm{charm}} > \Delta E_{\mathrm{bottom}}$$

Sophisticated Analysis on both R_{AA} & v_2



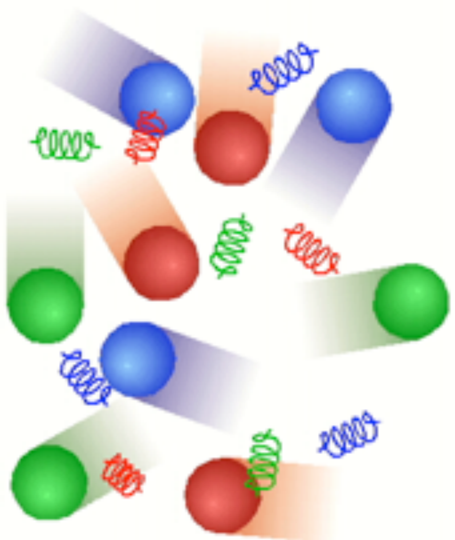
PHENIX; P.R.L. 105, 142301 (2010)

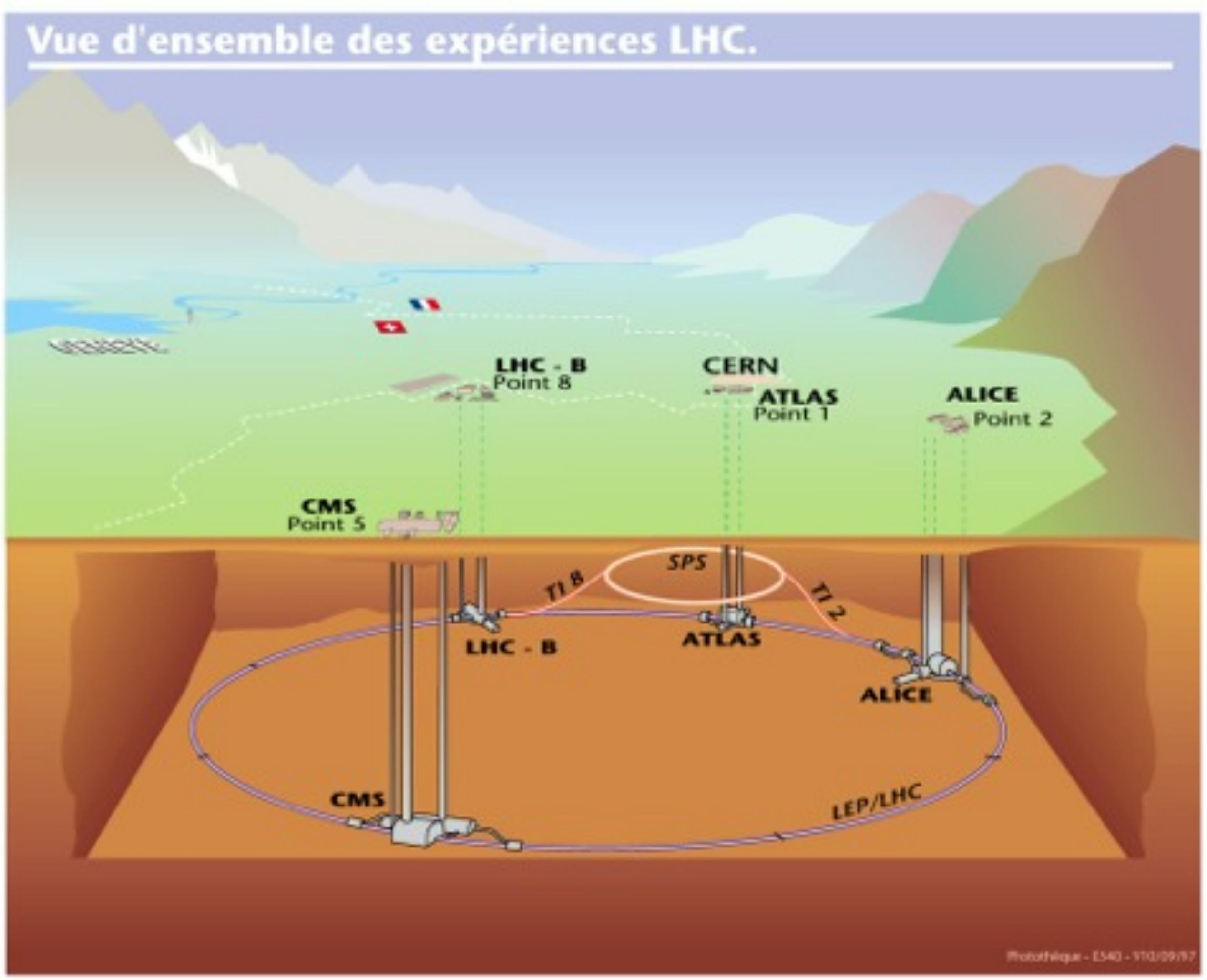


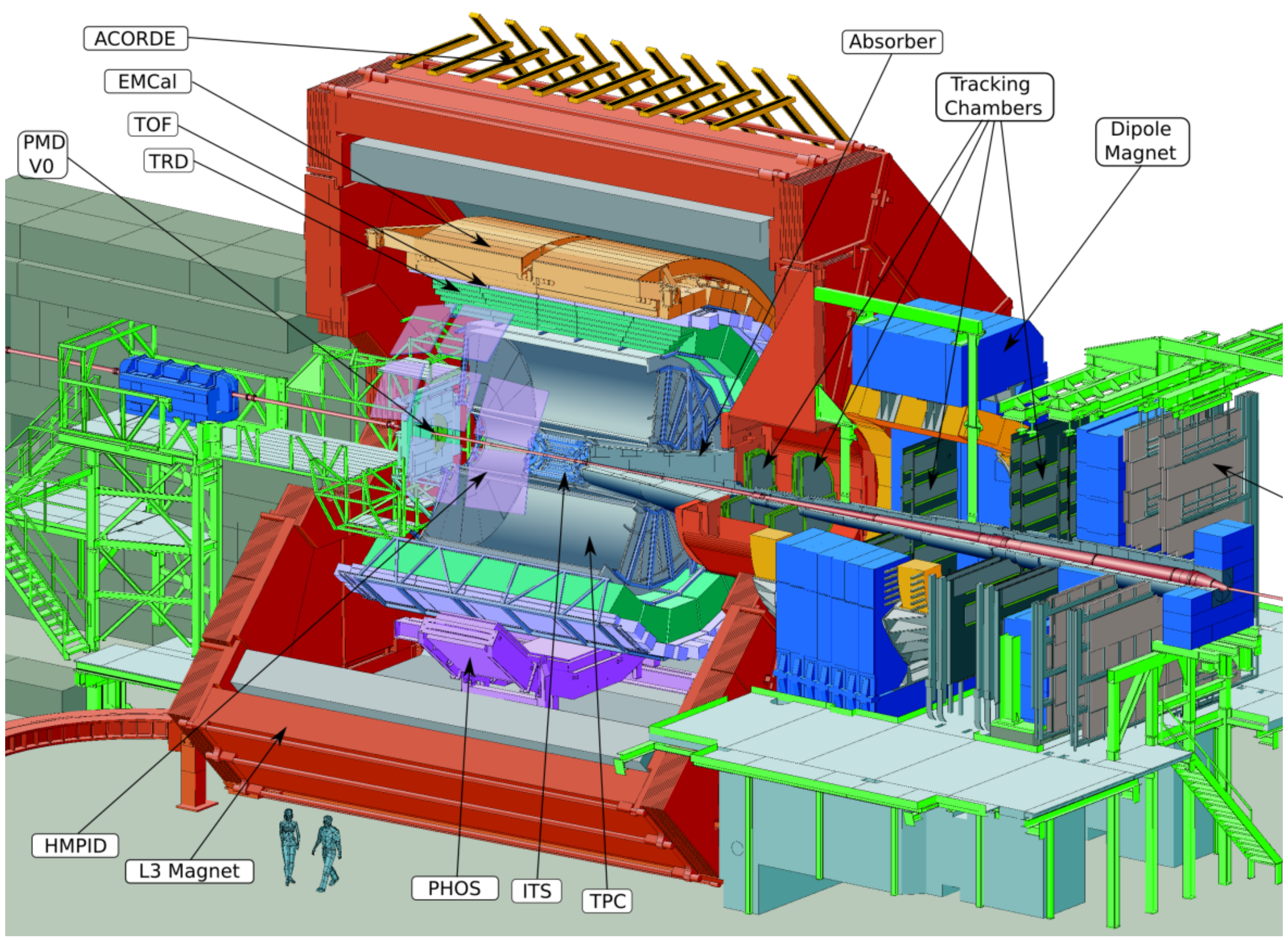
✓ Analyze both v_2 and R_{AA} together

- Large v_2 favors stronger path length dependence

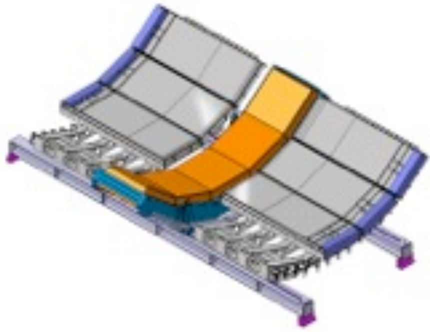
Now, LHC




Vue d'ensemble des expériences LHC.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC


ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking
Chambers
Dipole
Magnet
HMPID
L3 Magnet
PHOS
ITS
TPC

View from RHICians



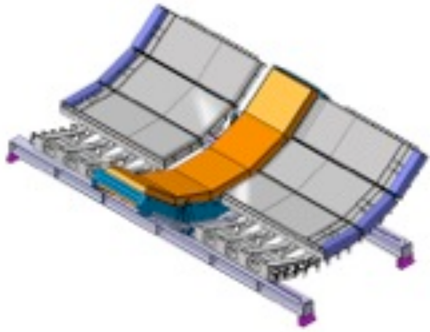
	RHIC	LHC
$\sqrt{s_{NN}}$ (GeV)	200	5500
T/T_c	1.9	3.0-4.2
ε (GeV/fm^3)	5	15-60
τ_{QGP} (fm/c)	2-4	>10

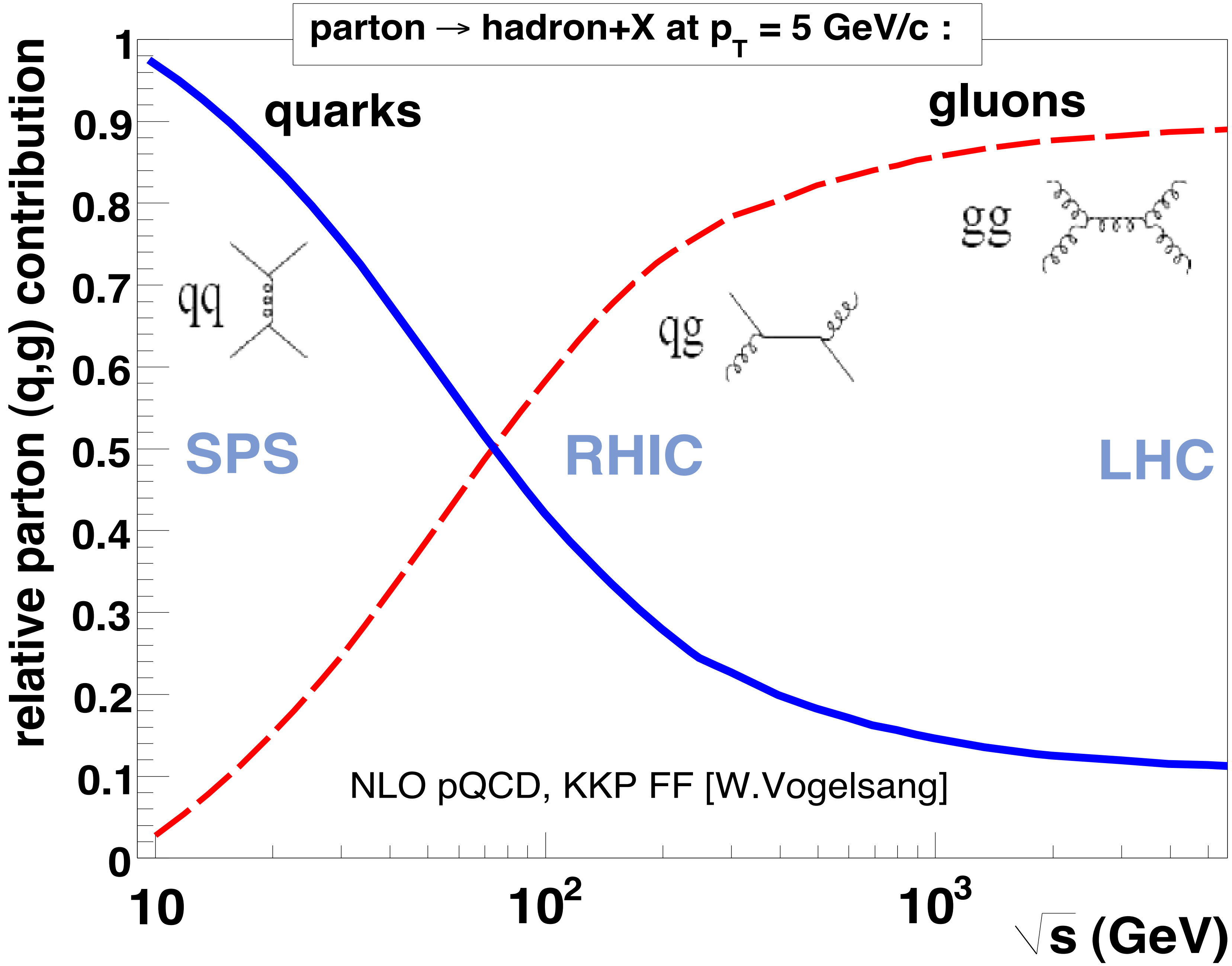
✓ Nothing much changes from RHIC to LHC.

- Nevertheless,
  - ➡Larger/longer QGP
  - ➡Nice to confirm RHIC results

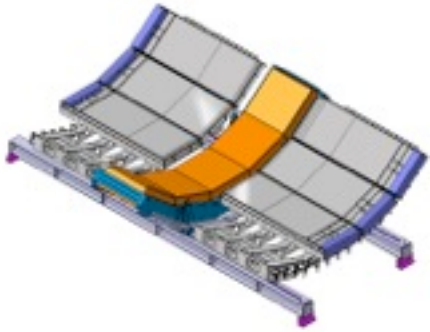
✓ Moreover, higher energy jets become available!

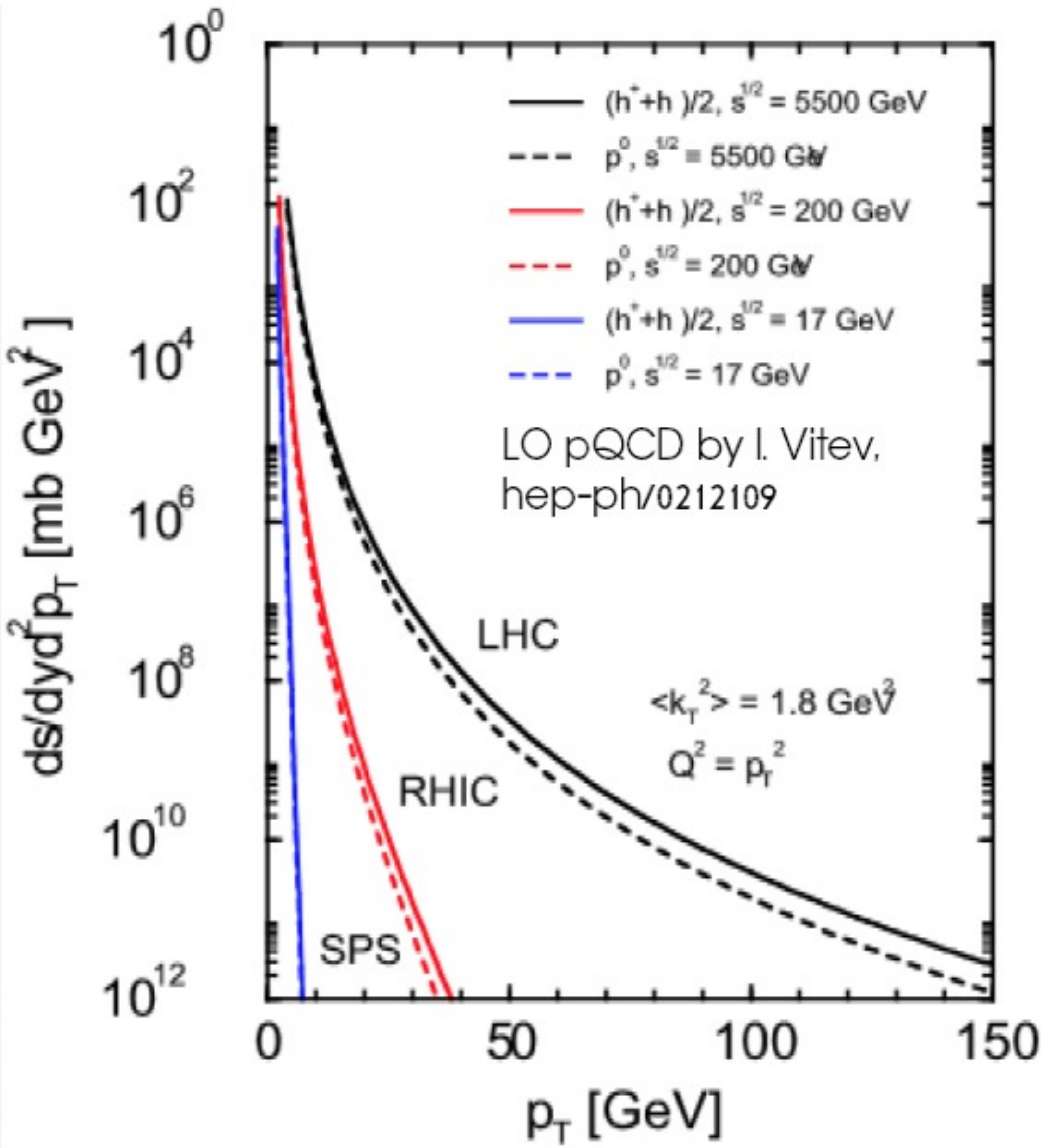
More gluons !!



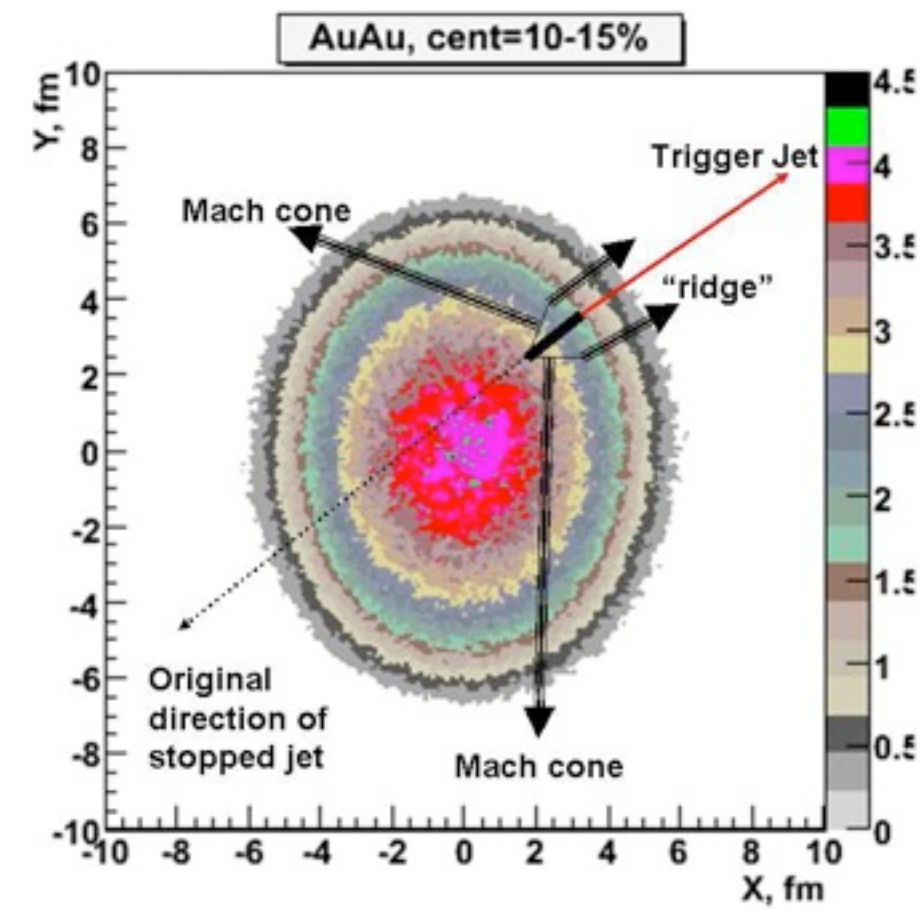

parton → hadron+X at p_T = 5 GeV/c :
quarks
gluons
qq
qg
gg
SPS
RHIC
LHC
NLO pQCD, KKP FF [W.Vogelsang]
relative parton (q,g) contribution
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
10^2
10^3
$\sqrt{s}$ (GeV)

Chances at LHC



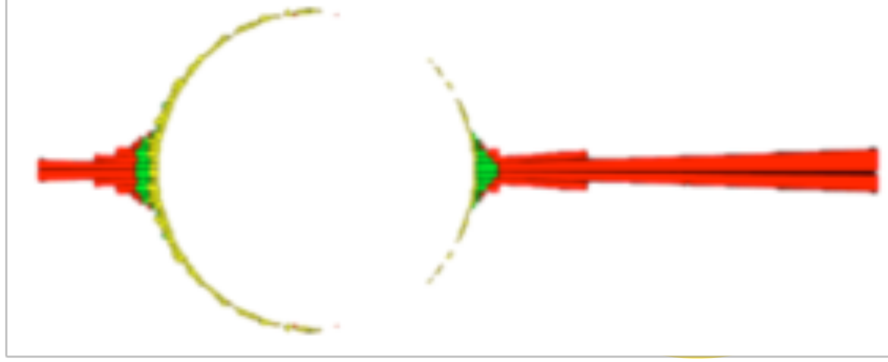


V.S. Pantuev, arXiv:hep-ph/0701.1882v1



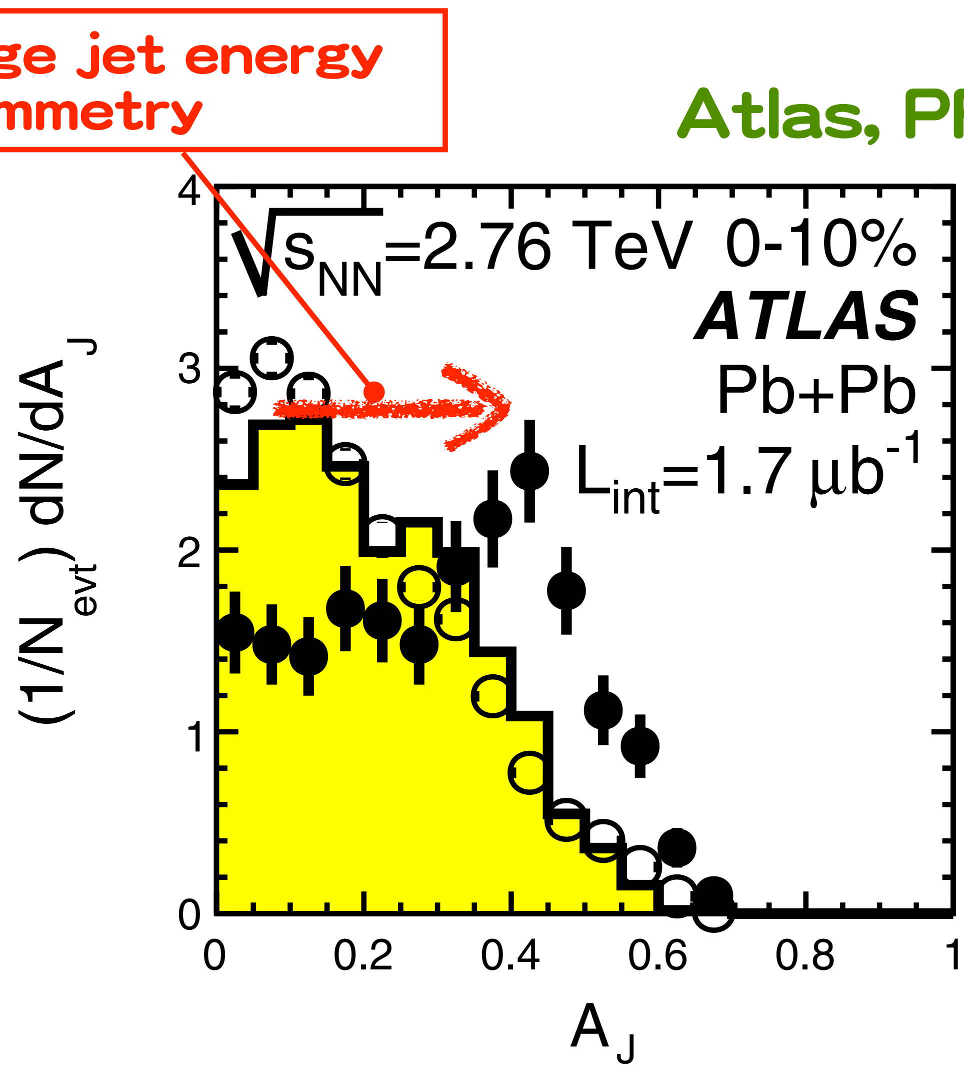
- ✓ Many orders of magnitude higher!
- ✓ Detail analysis of the energy loss

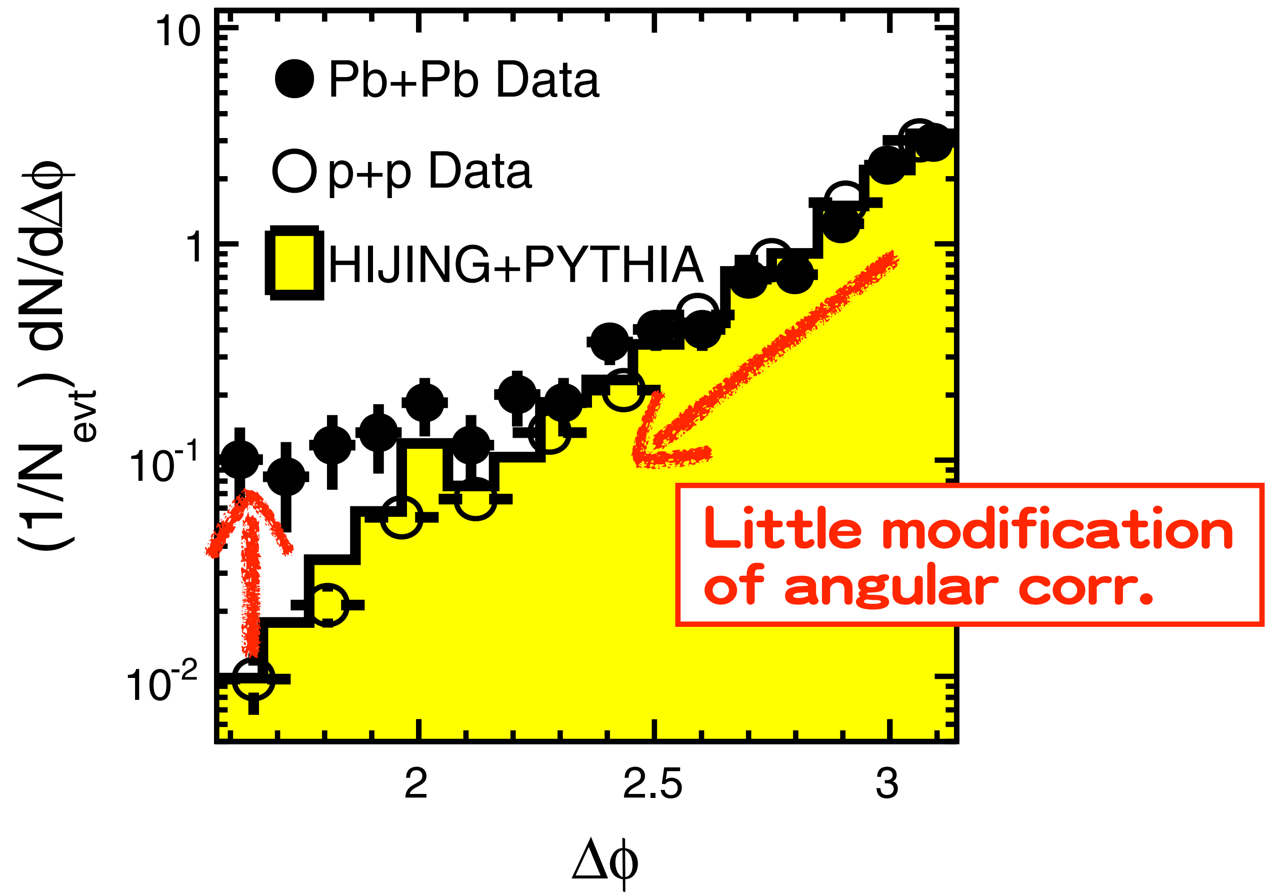
Hot/Jet Results from LHC



$E_{T1} > 100$ GeV

Atlas, PRL 105,252303(2010)





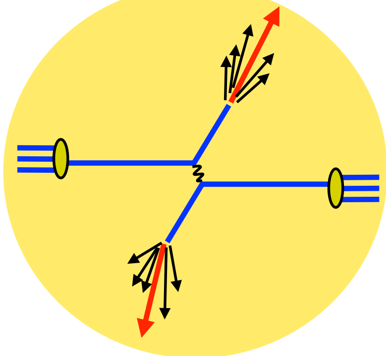
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

$$\Delta\phi = |\phi_1 - \phi_2|$$

- **Detail study of dijet asymmetry**
  - **pp vs Pb+Pb**

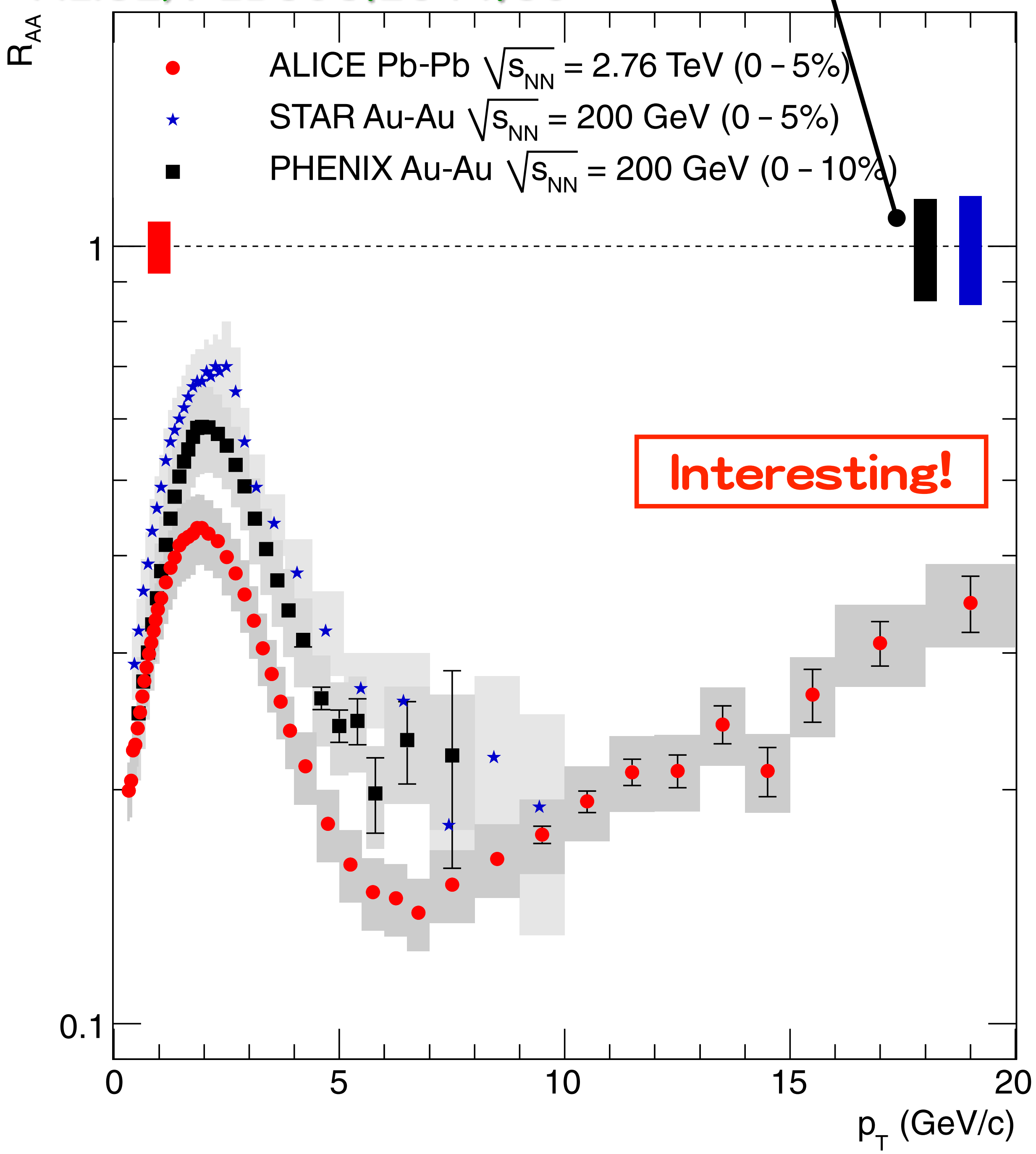
Challenge to theorists!

RAA & v2 at LHC & RHIC

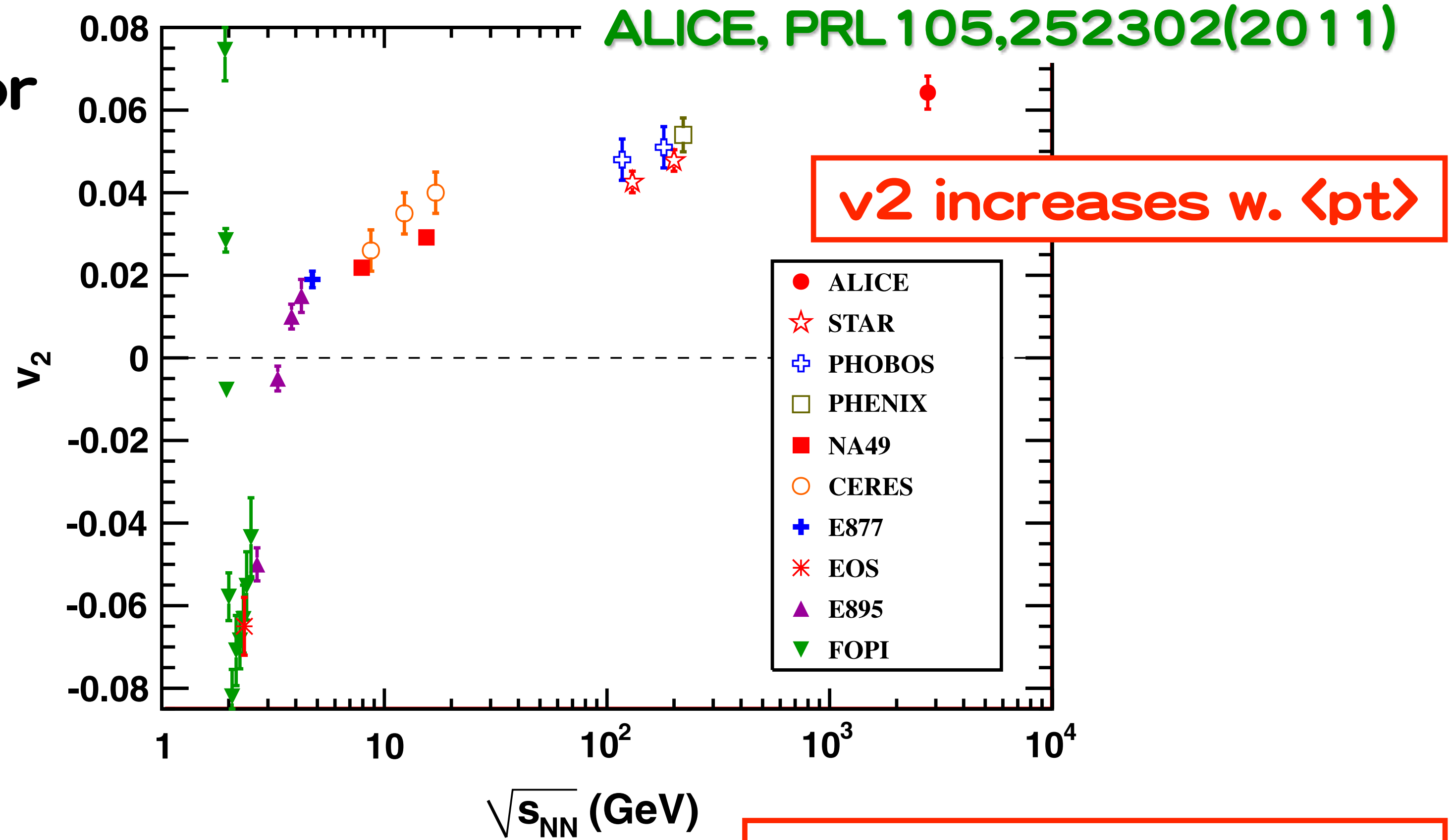


Note the systematic error

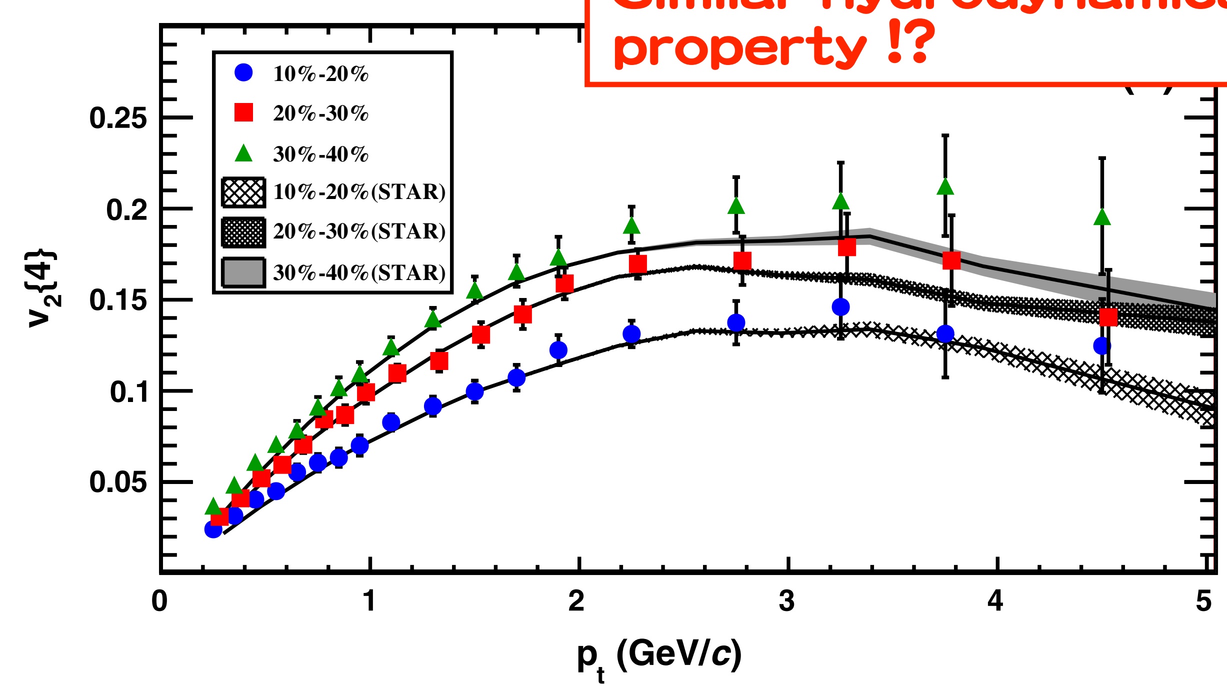
ALICE, PLB696(2011)30



ALICE, PRL105,252302(2011)



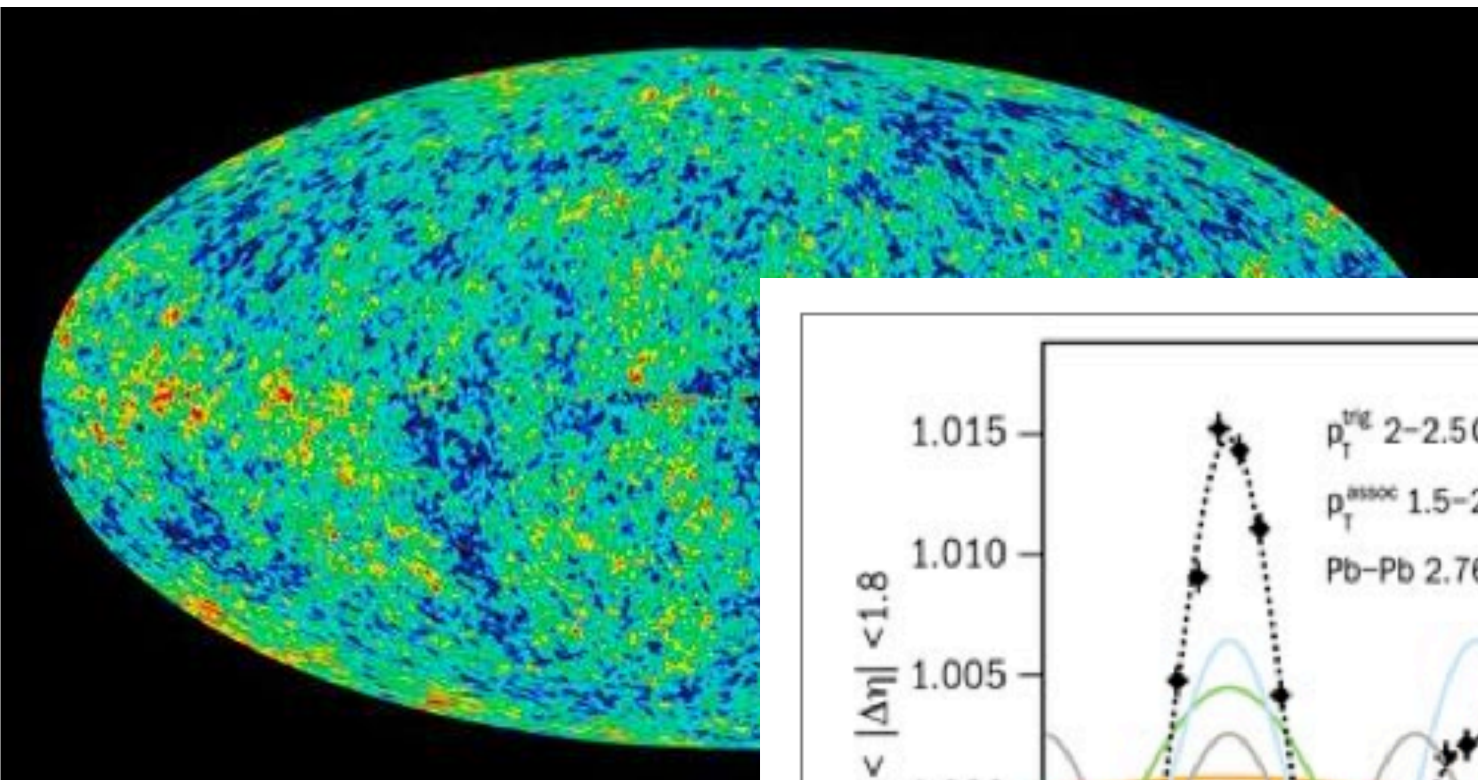
Similar hydrodynamical property !?



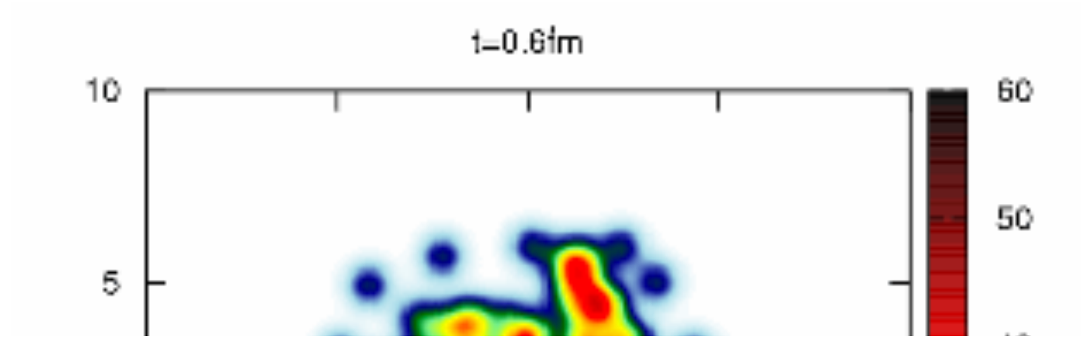
Future: fluctuations

Fluctuations of the Universe

WMAP



Fluctuations of Little bang



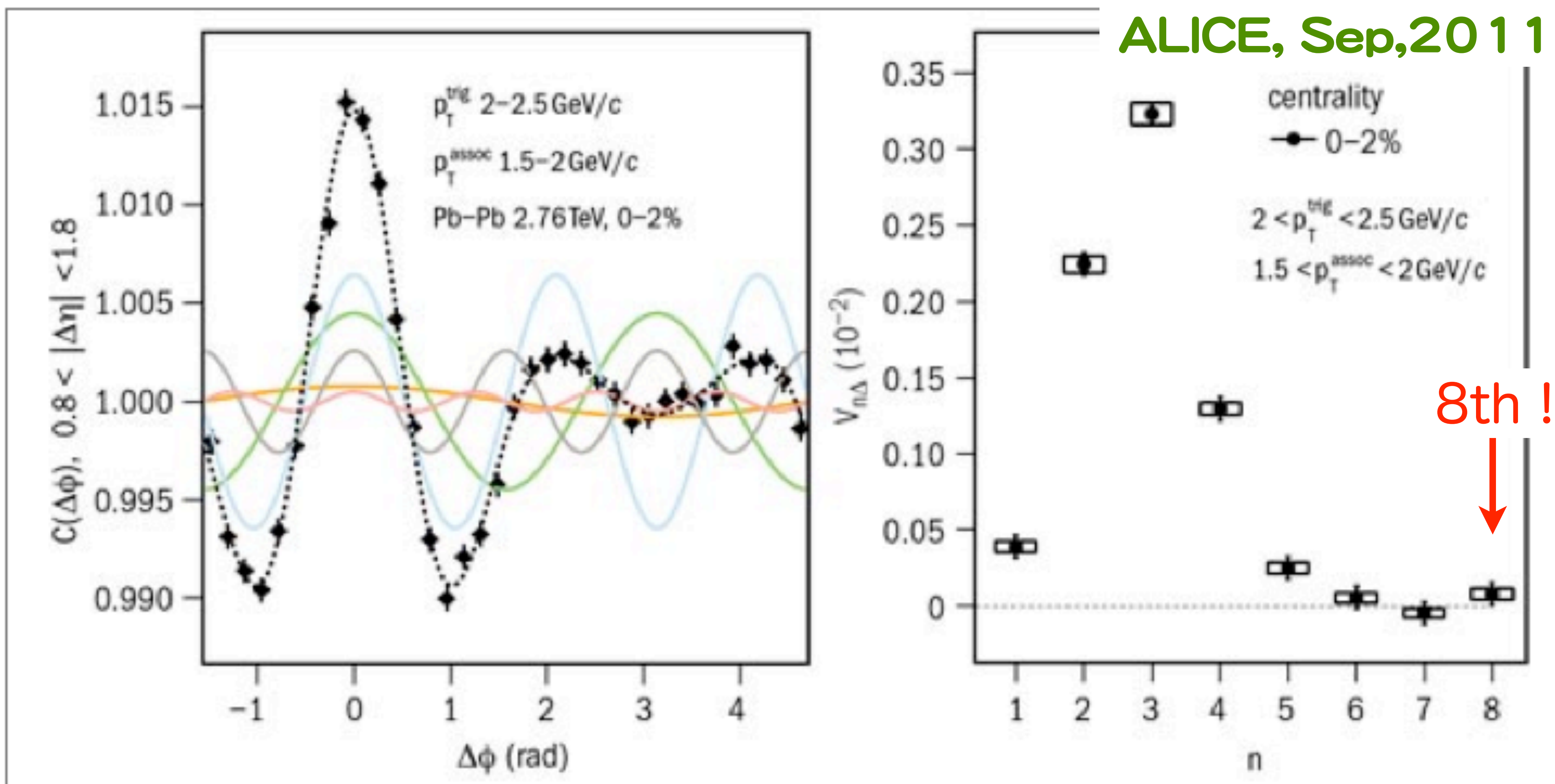


Fig. 1. Left: correlation function for charged hadron pairs from head-on Pb–Pb collisions. Right: corresponding spectrum of Fourier harmonic amplitudes vs n.

- ✓ Clue to th
  - MC Glaube

Summary Remarks

✓Relativistic Heavy Ion Collisions have provided very interesting play ground for theorists

✓New players have joined and they are amazingly successful

- String theory, Black hole dynamics, AdS/CFT

✓Now challenges are,

- jet quench,
- rapid thermalization,
  - ➡parton cascades too slow
- initial conditions
  - ➡chiral glass condensate

"Holography and colliding gravitational shock waves in asymptotically AdS_5"

PRL 106,021601(2011)