2011 CERN – Latin-American School of
High Energy Physics
Natal – 23/03 to 05/04 2011

Heavy Ion Physics

Lecture 2: April 1st, 2011

Jun Takahashi

QGP Signatures

Original QGP Signatures: observed at SPS, confirmed at RHIC and new results coming in from the LHC.

- Strangeness Enhancement
- J/Ψ Suppression
- Direct photons, excess in the di-lepton spectra.

New observables, what have we learn at RHIC, can we confirm the results at the LHC?

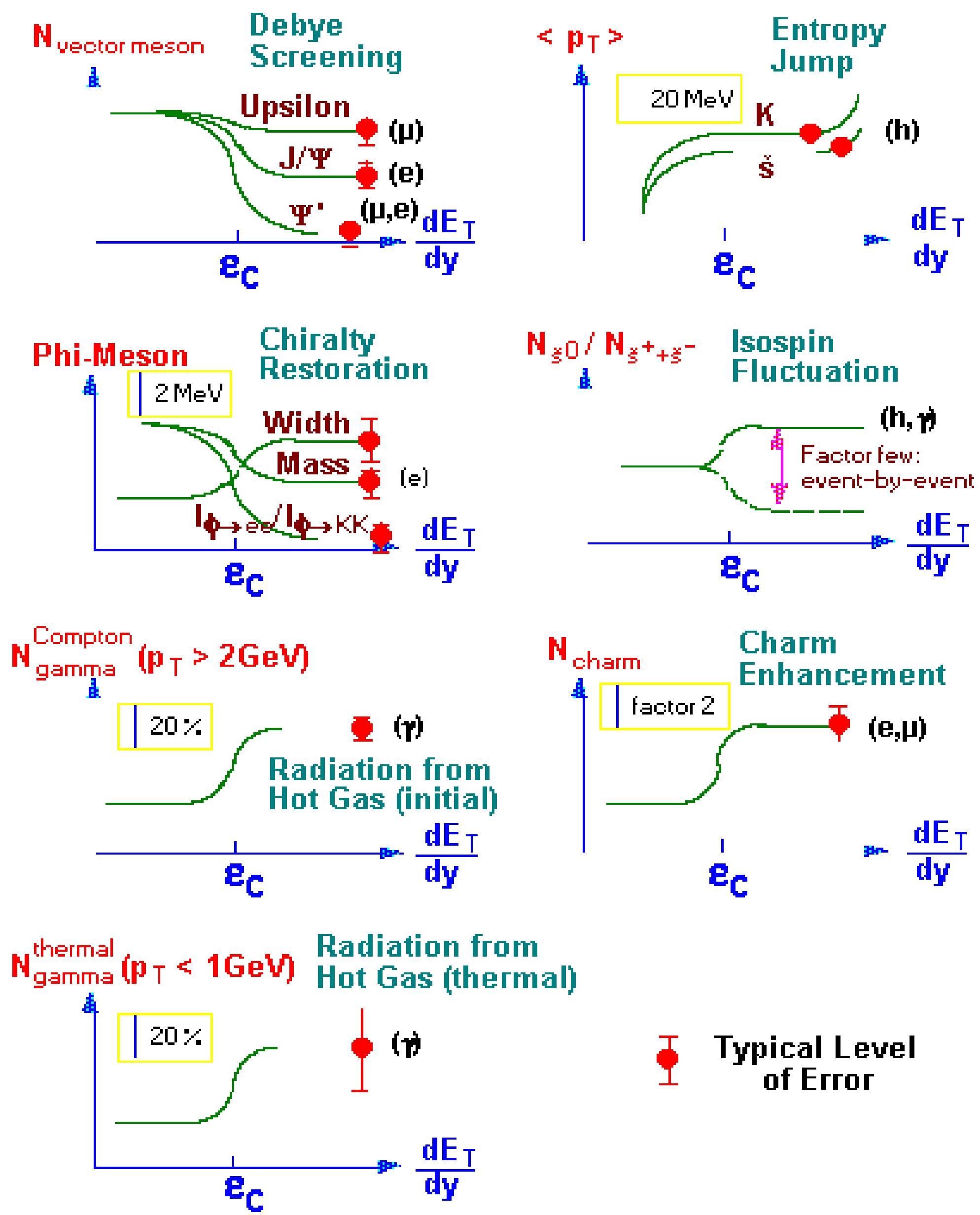
Soft Sector:

- System formed consistent with thermalization.
- Collective behavior observed
- Hints of partonic degree of freedom

Hard Sector:

- Matter formed is strongly interacting: Jet suppression

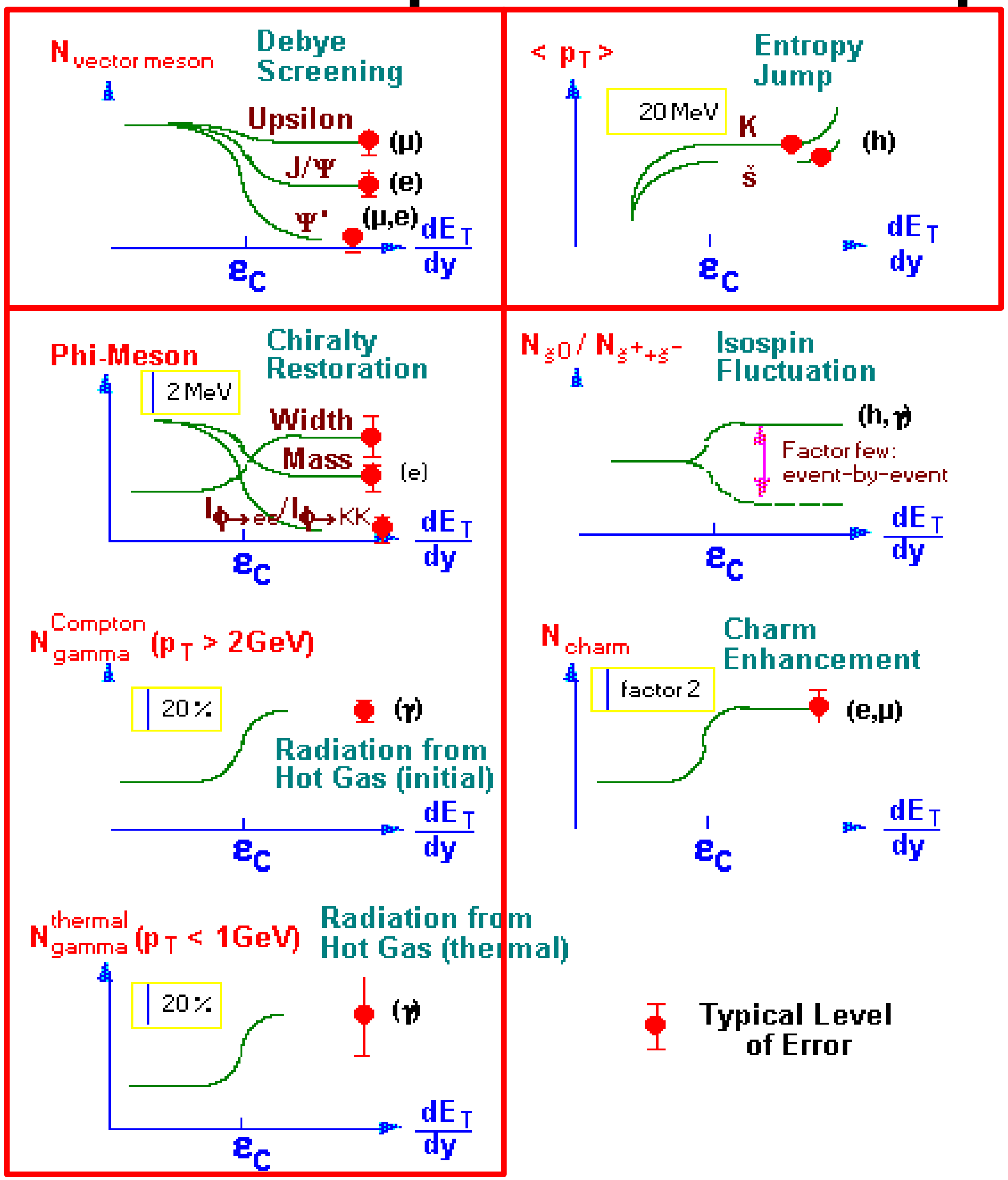
Search for the QGP



What was expected to be the main signatures of the QGP ?

The increase in the entropy going through the phase transition should cause the rapid variation of several experimental observables.

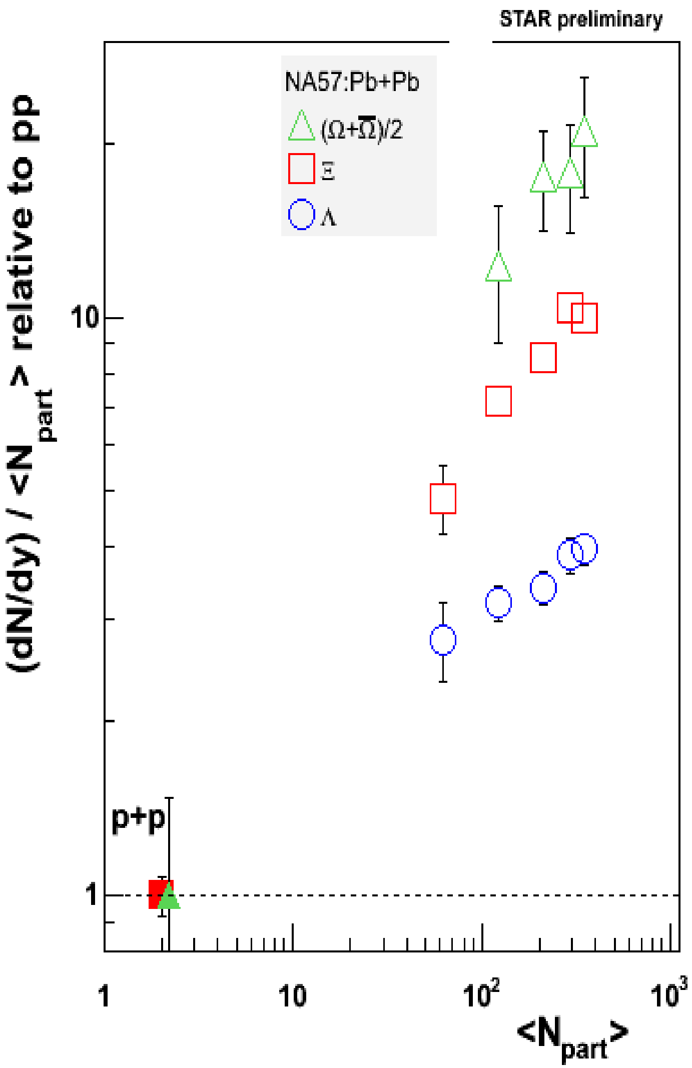
What did we find in the early experiments up to the SPS ?



- J/Ψ suppression, cc-bar screening due to high density and confinement.
- Strangeness Enhancement, one of the original signatures of the QGP formation.
- Di-lepton excess in low mass region, that could be interpreted as medium modifications thus, studies confinement and symmetry restoration.

Strangeness Enhancement: SPS

F.Antinori et al. (NA57 Collab.)
Jorn. Phys. G, 32 (2006) 427-441

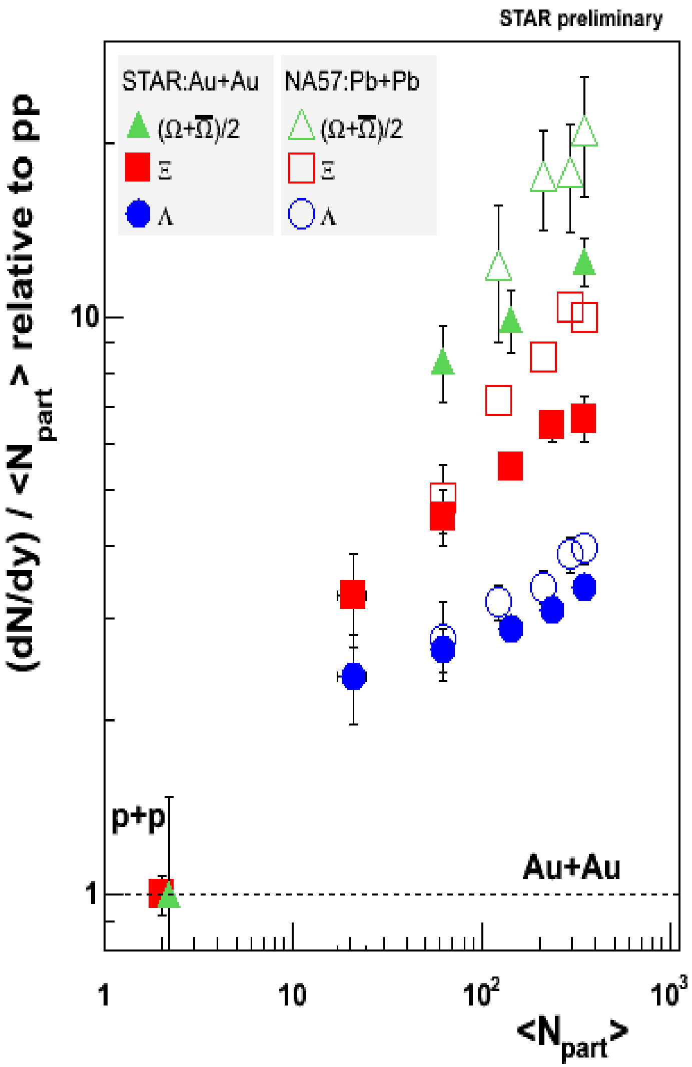


Strangeness enhancement was proposed as one of the signatures of the QGP, due to chiral symmetry restoration that would cause a reduction in the dynamical mass of the strange quark pair and also due to statistical saturation of strange quarks.

Enhancement was observed in AA collisions relative to pp, even after being normalized by the number of participants.

Strangeness Enhancement: SPS and RHIC

F.Antinori et al. (NA57 Collab.)
Jorn. Phys. G, 32 (2006) 427-441



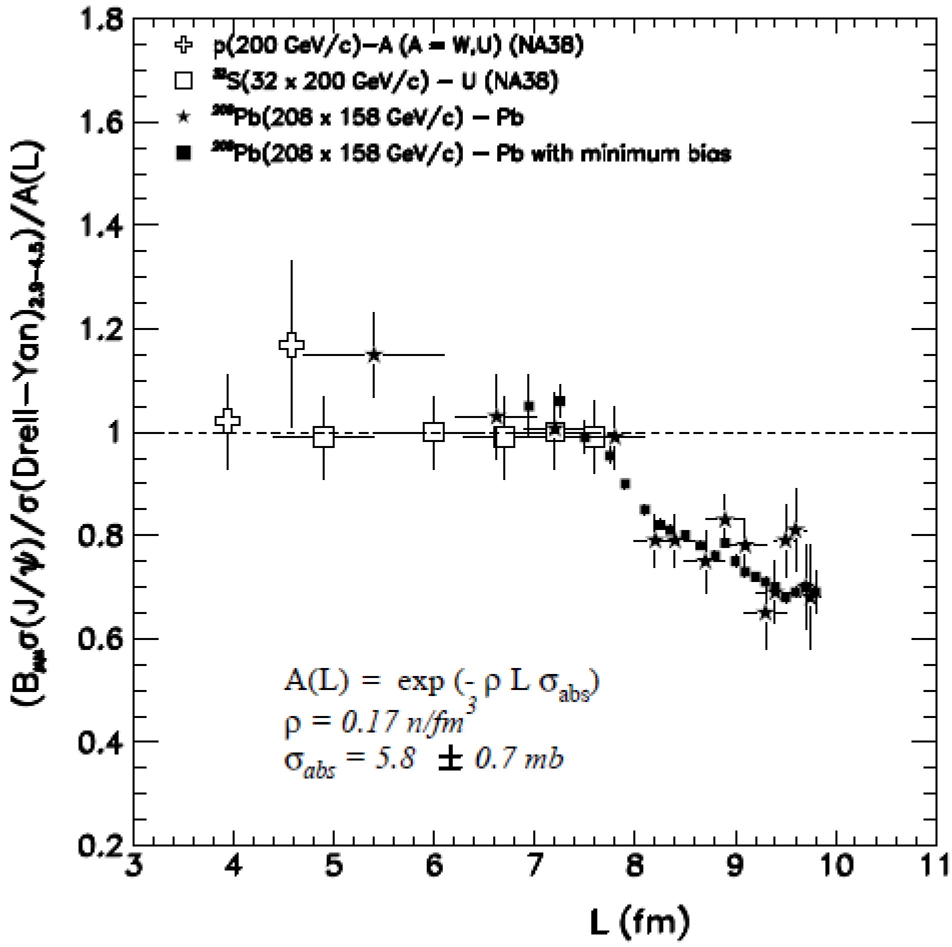
Data from RHIC confirmed the strangeness enhancement observed at SPS.

But, event in a HG scenario:

If the interacting gas lives long enough, inelastic collisions will drive chemical equilibration, and strangeness can be produced via several re-interactions. Once produced, the probability of the strange baryons to be destroyed is very low.

So, strangeness enhancement alone cannot be a proof of the QGP formation.

J/Ψ suppression @ SPS



J. Schukraft, Proceedings of the 2001 CERN L.A. School of H.E.P, Brazil

In a QGP scenario, J/Ψ production would be suppressed due to Debye screening mechanism.

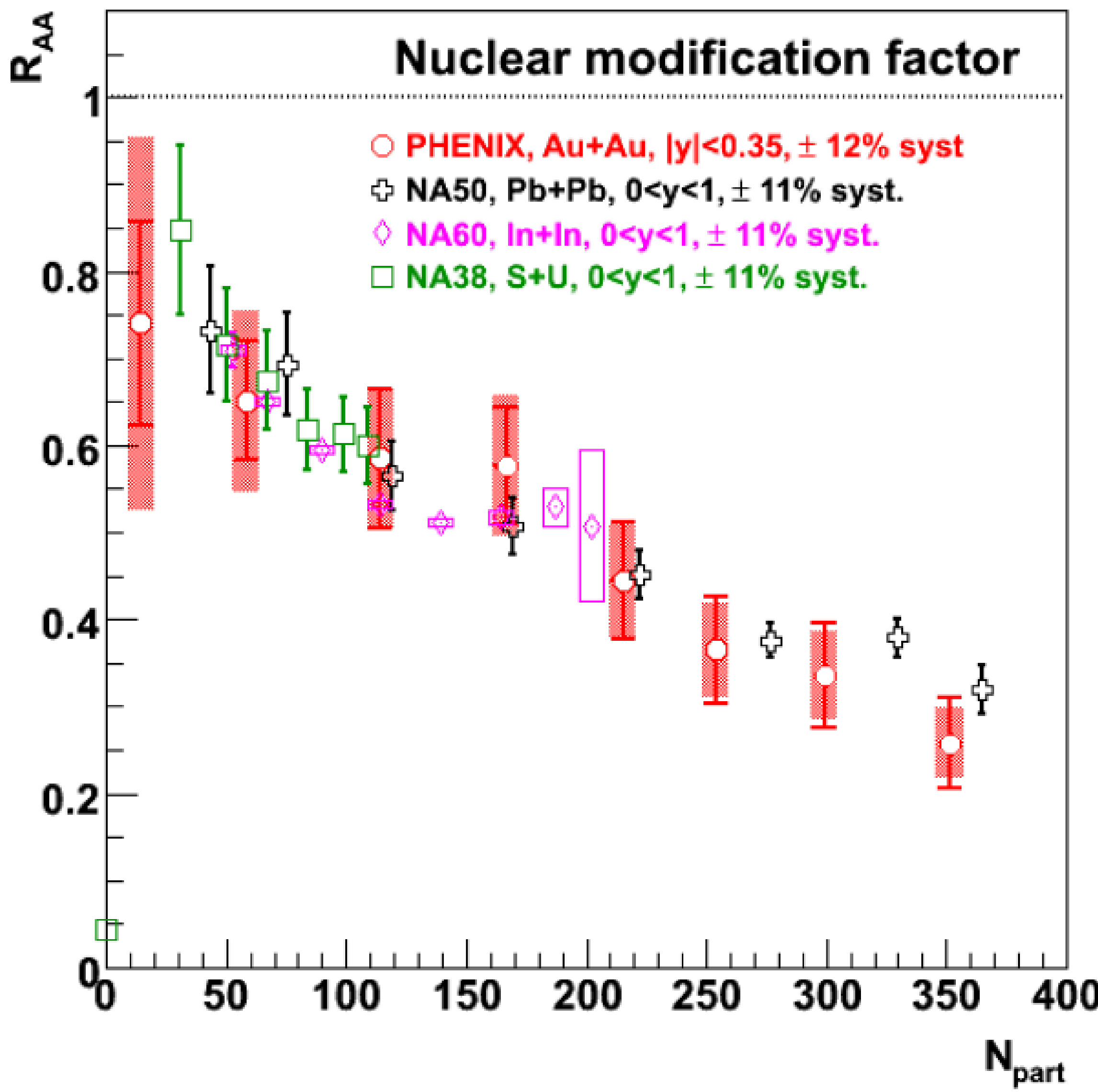
Left plot show a compilation of results from Heavy Ion reactions normalized by the expected J/Ψ due to hadronic absorption models.

Could be due to deconfinement …

But could also be due to:
Enhancement on the hadronic re-scattering.
Changes in the gluon distribution function.

J/Ψ suppression : @ RHIC

PRL, 101, 122301 (2008), PHENIX Collab.

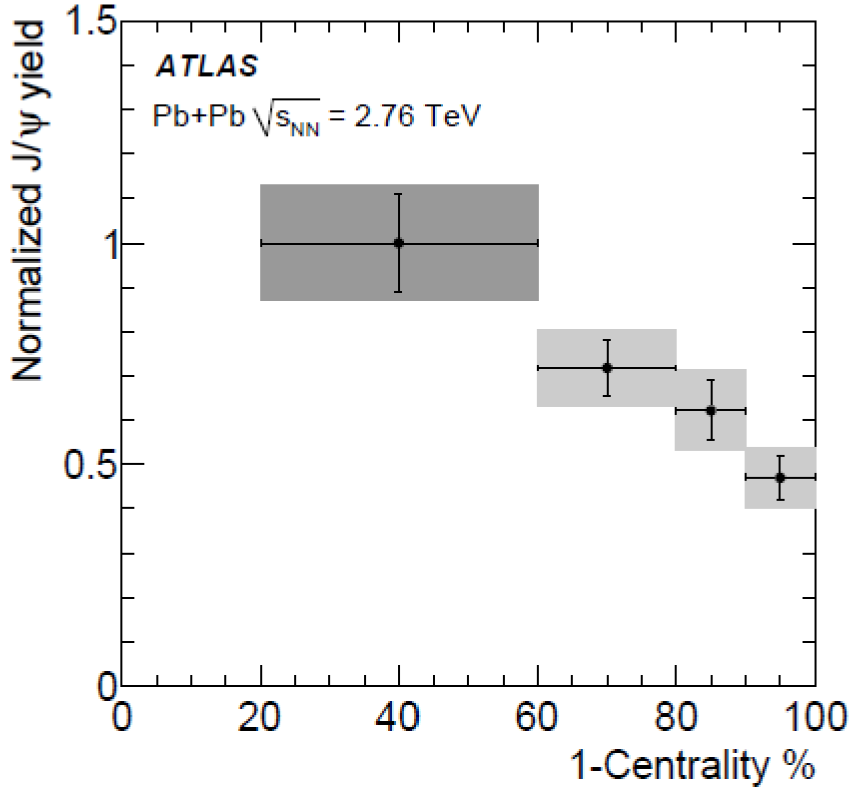


Suppression of J/Ψ observed at RHIC is similar to observed at SPS.

Feed-down from higher states and dynamic competition between suppression and recombination can be affecting the observed result.

J/Ψ suppression : @ LHC

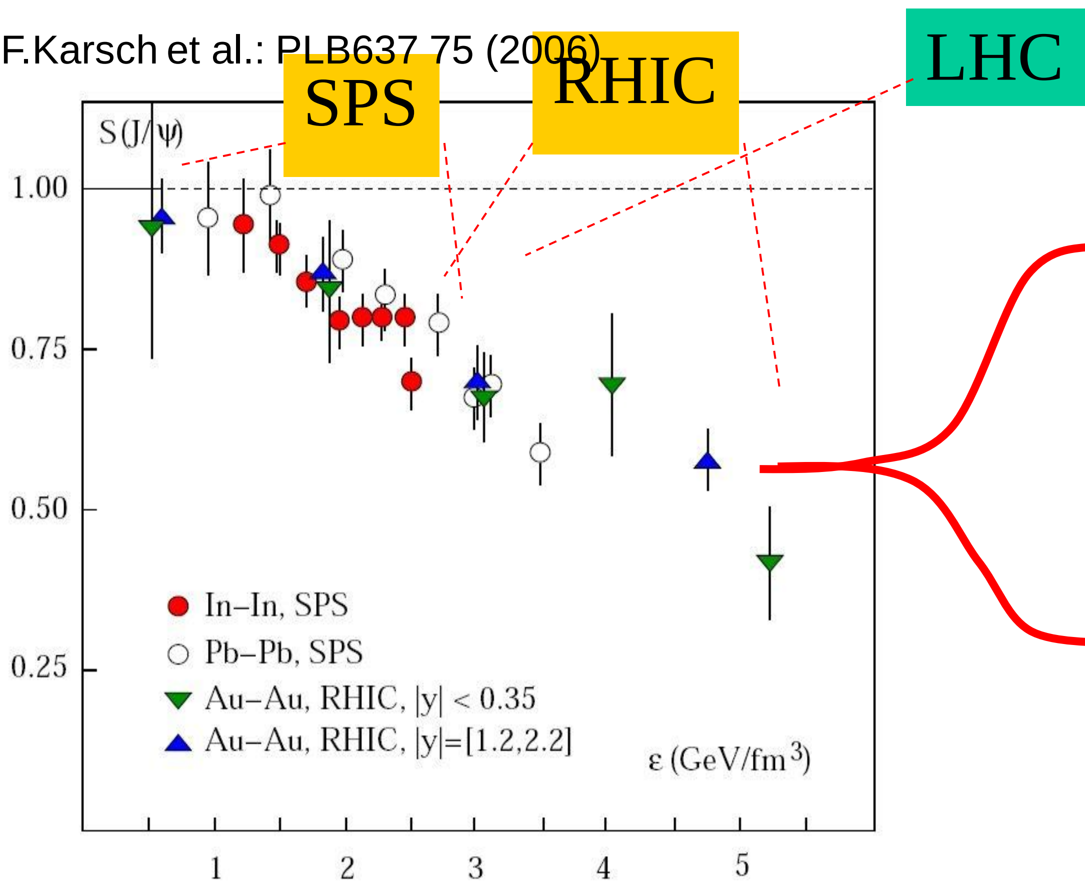
arXiv:1012.5419 [hep-ex] (2010), ATLAS Collab.



J/Ψ measured through the $\mu^+\mu^-$ decay channel.
Ratio of (Pb-Pb)/(Pb-Pb)$_{Peripheral}$ normalized by the number of binary collisions.

J/Ψ suppression @ LHC

F.Karsch et al.: PLB637 75 (2006)



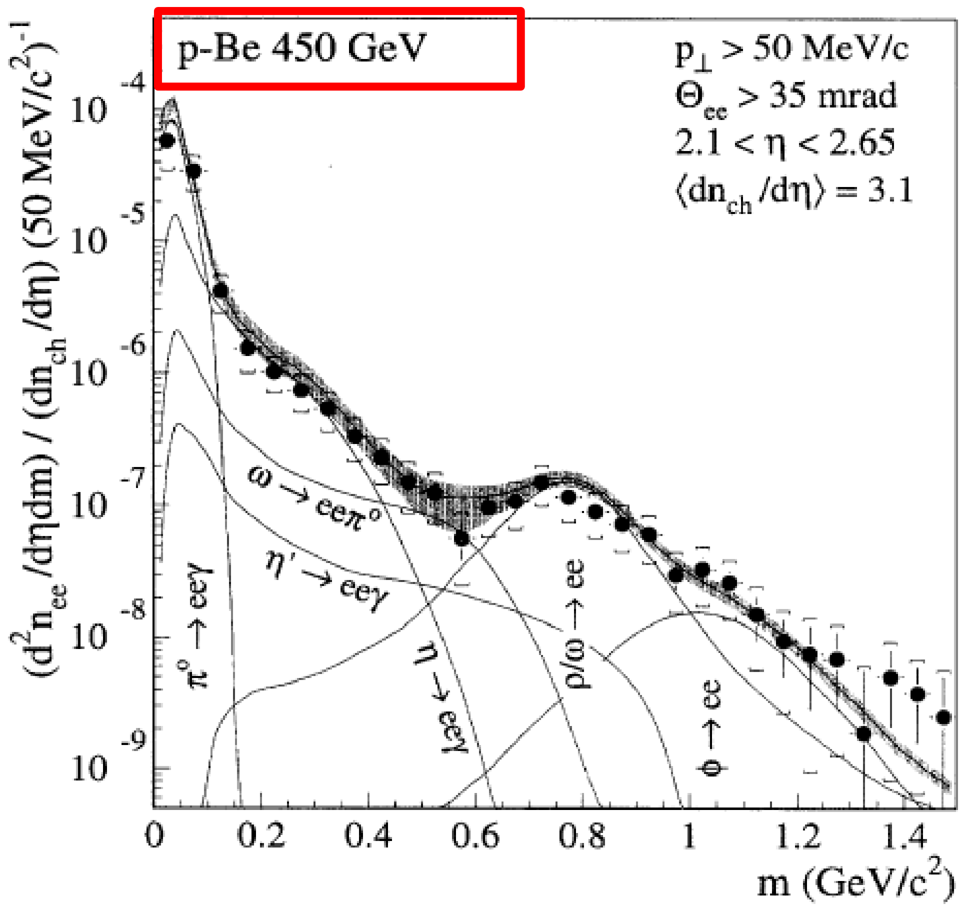
more ccbar → reco dominates?

larger ε → J/ψ finally melts?

- J/Ψ suppression similar to observed at RHIC and SPS.
- But quarkonia melting could be competing with recombination.
- Need to measure open charm enhancement and also consider higher mass states that can decay into J/Ψ.

Di-lepton excess

Di-lepton invariant mass spectra is used to measure several short lived resonances that decay into e^+e^- pairs.

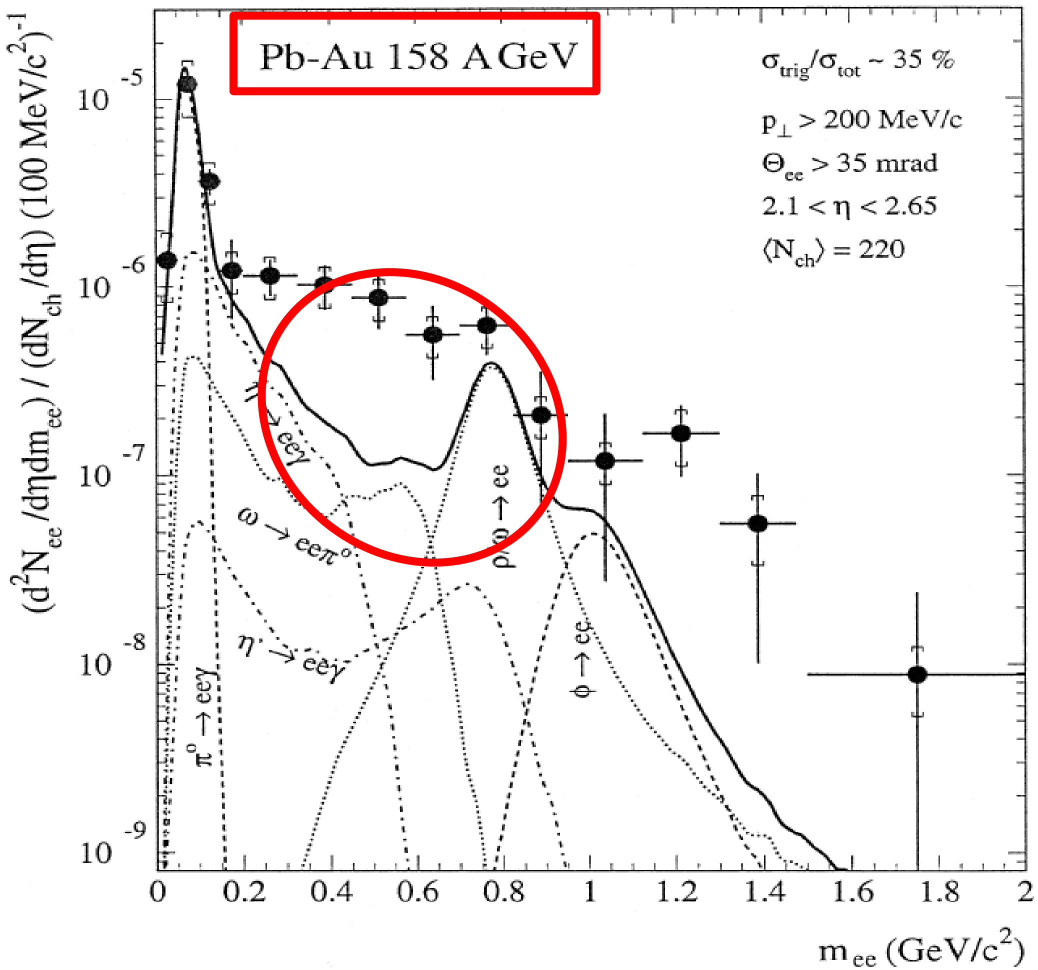


In heavy ion collisions leptons are a good probe because they can leave the medium undisturbed by the final state interactions.

PRL 75 (1995) 1272, CERES /NA45

Di-lepton excess @ SPS

An excess of di-lepton was observed in the mass region between 200 MeV and 750 MeV in Heavy Ions Collisions, that could not be explained with the known resonances.

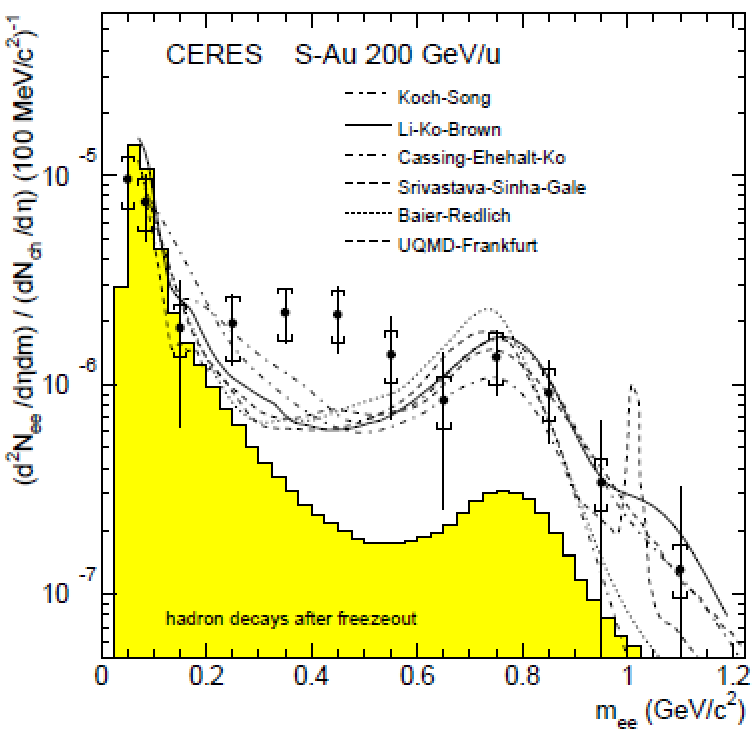


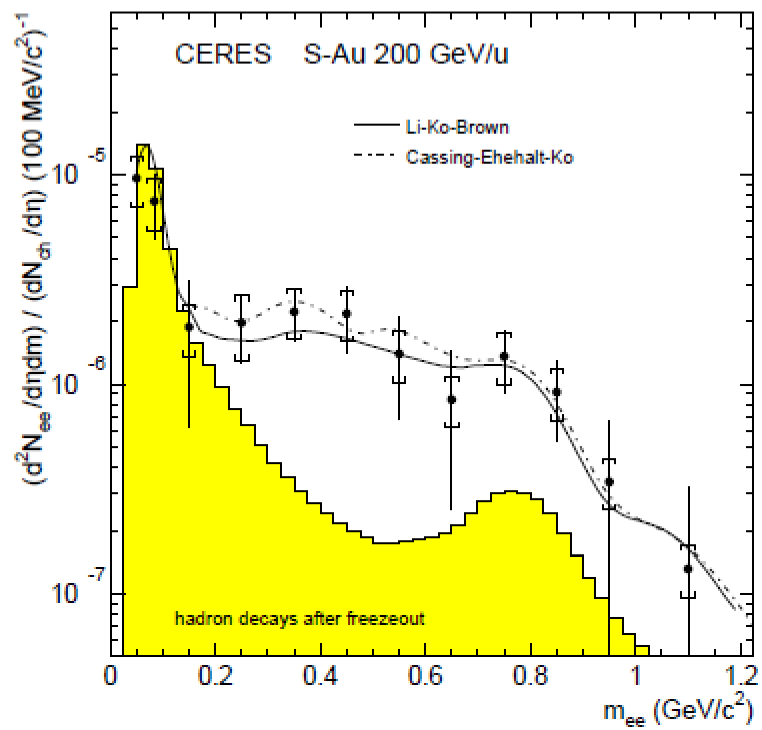
Remember that in p-Be, the known sources of the di-lepton spectra described very well the measured spectra.

PLB 422 (1998) 405, CERES /NA45

Di-lepton excess @SPS

- Could be from direct photons from thermal radiation of the QGP ?
- In medium modification of vector mesons due to chiral symmetry restoration?

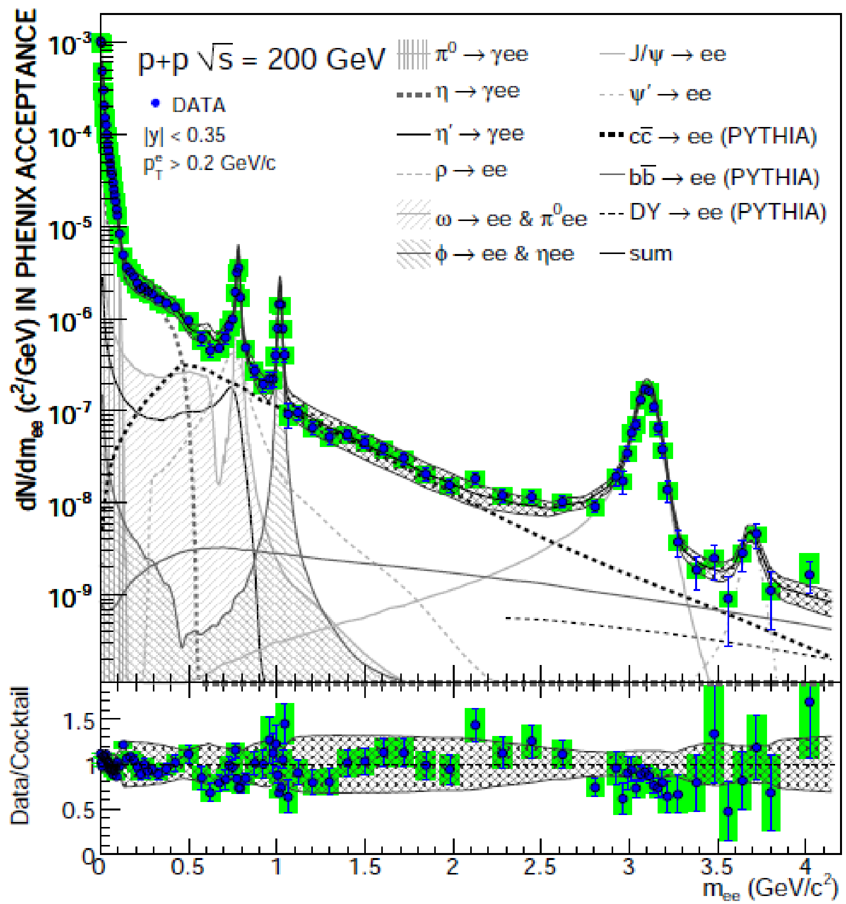


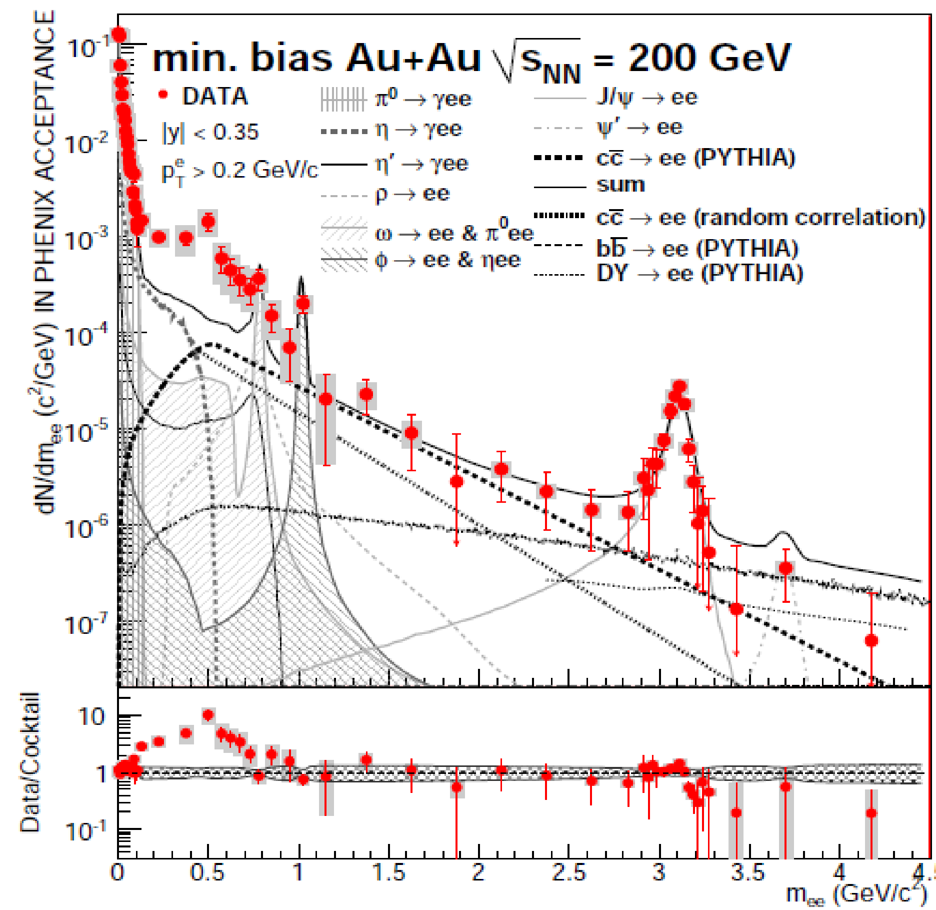


J. Schukraft, Proceedings of the CERN L.A.School of H.E.P, Brazil 2001

Di-lepton excess @ RHIC

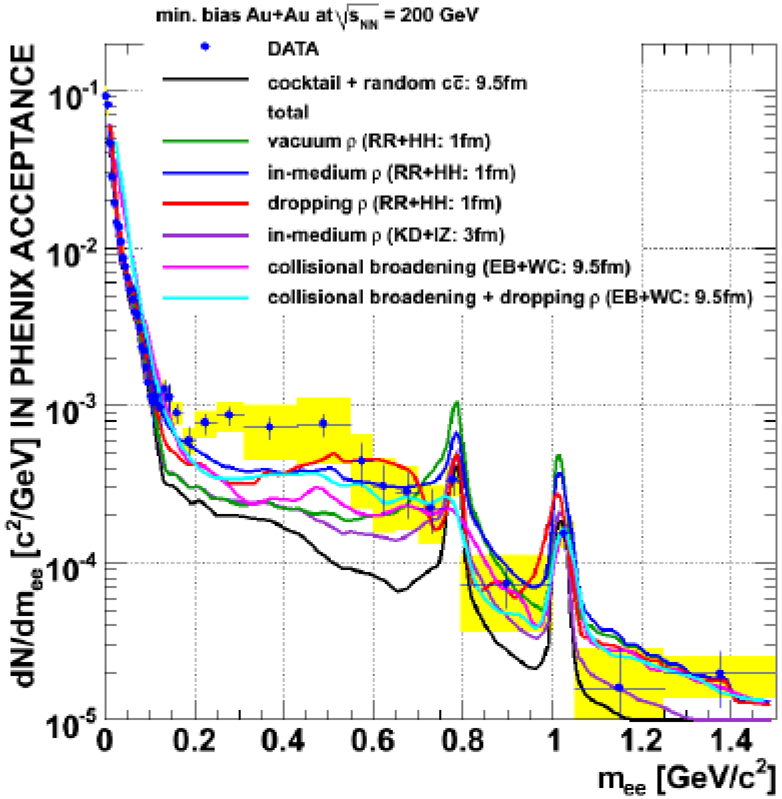
Phys.Rev.C81:034911 (2010)





In RHIC, we also observe an excess in the same mass region as observed at SPS and higher than the expected hadronic contribution.

Di-lepton excess @ RHIC



All models and groups that considered in-medium modification and successfully described the SPS data of the dilepton excess fail to describe the RHIC results.
So the jury is still out there!!!!

What have we learn at RHIC about the SPS results?

Originally observed QGP signatures at SPS were also observed at SPS, indicating that system formed are consistent with a QGP scenario.

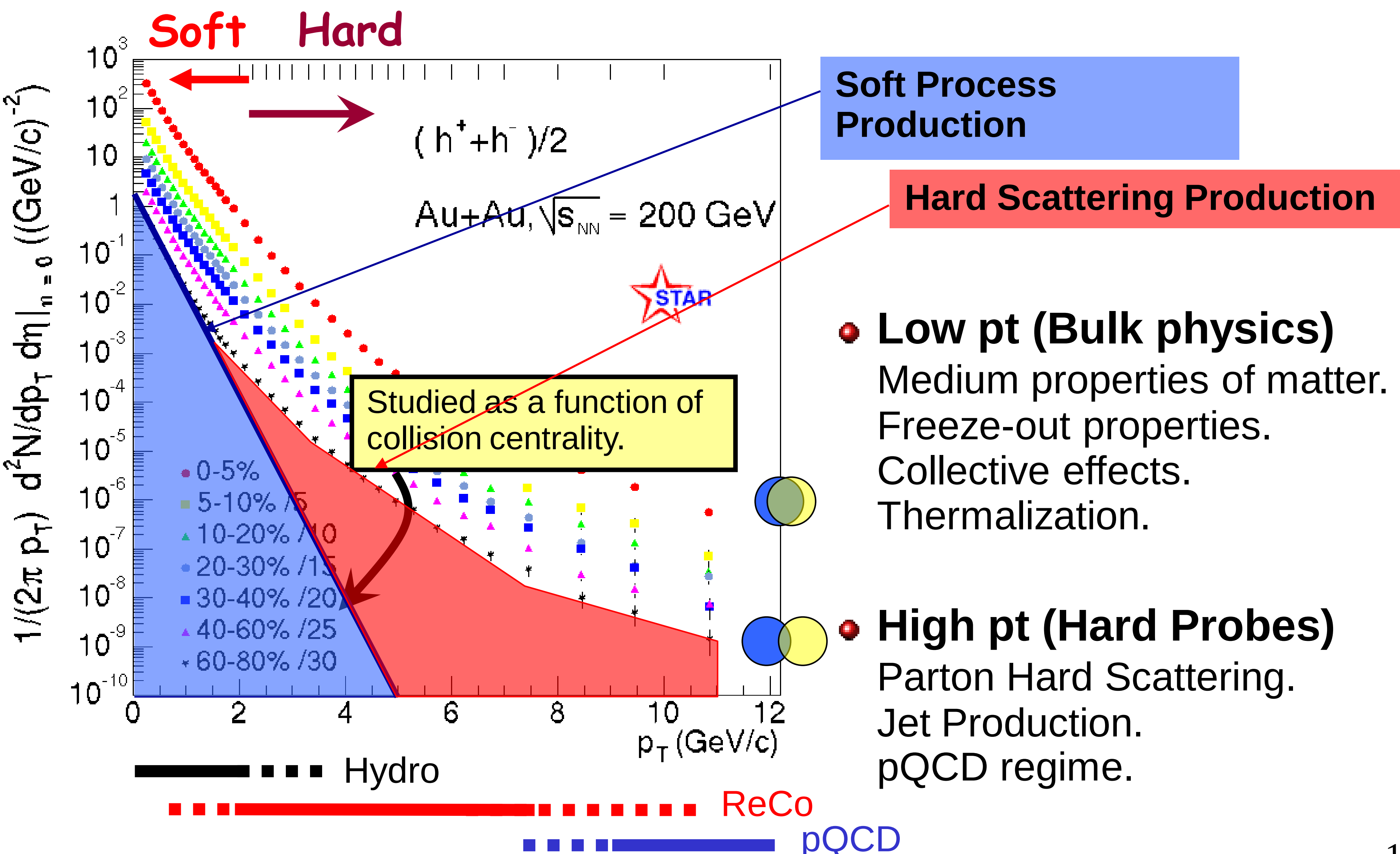
But …

All the observed phenomena also have alternative explanations that does not require the phase transition and can be explained in a HG model.

Did we learn anything new at RHIC ????

Yes !!!!!

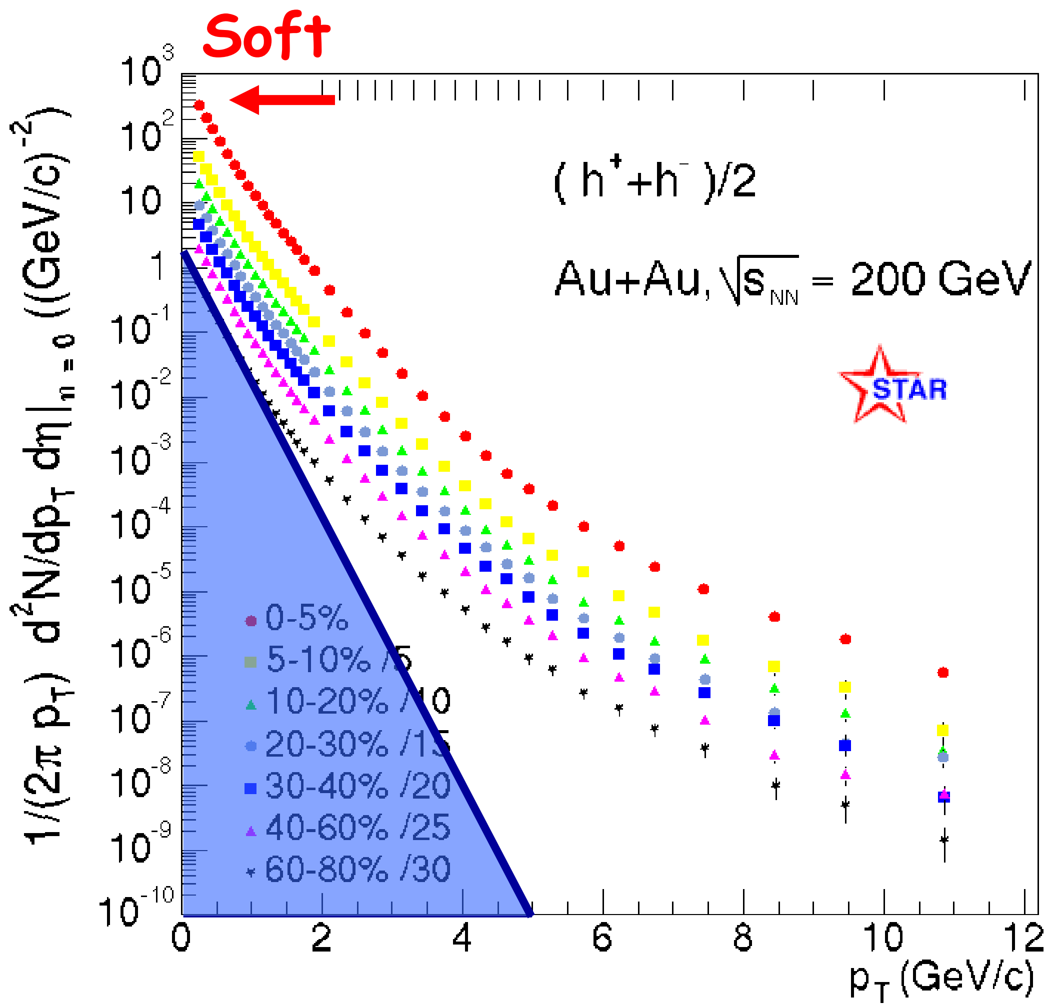
What about the momentum distribution of particles ?



- **Low pt (Bulk physics)**
  Medium properties of matter.
  Freeze-out properties.
  Collective effects.
  Thermalization.

- **High pt (Hard Probes)**
  Parton Hard Scattering.
  Jet Production.
  pQCD regime.

Let's look first at the soft sector?



Most of the particles are in this sector.
We can start assuming a simple model do describe the particle spectra: an expanding thermal source.

The particle spectra can be described by:

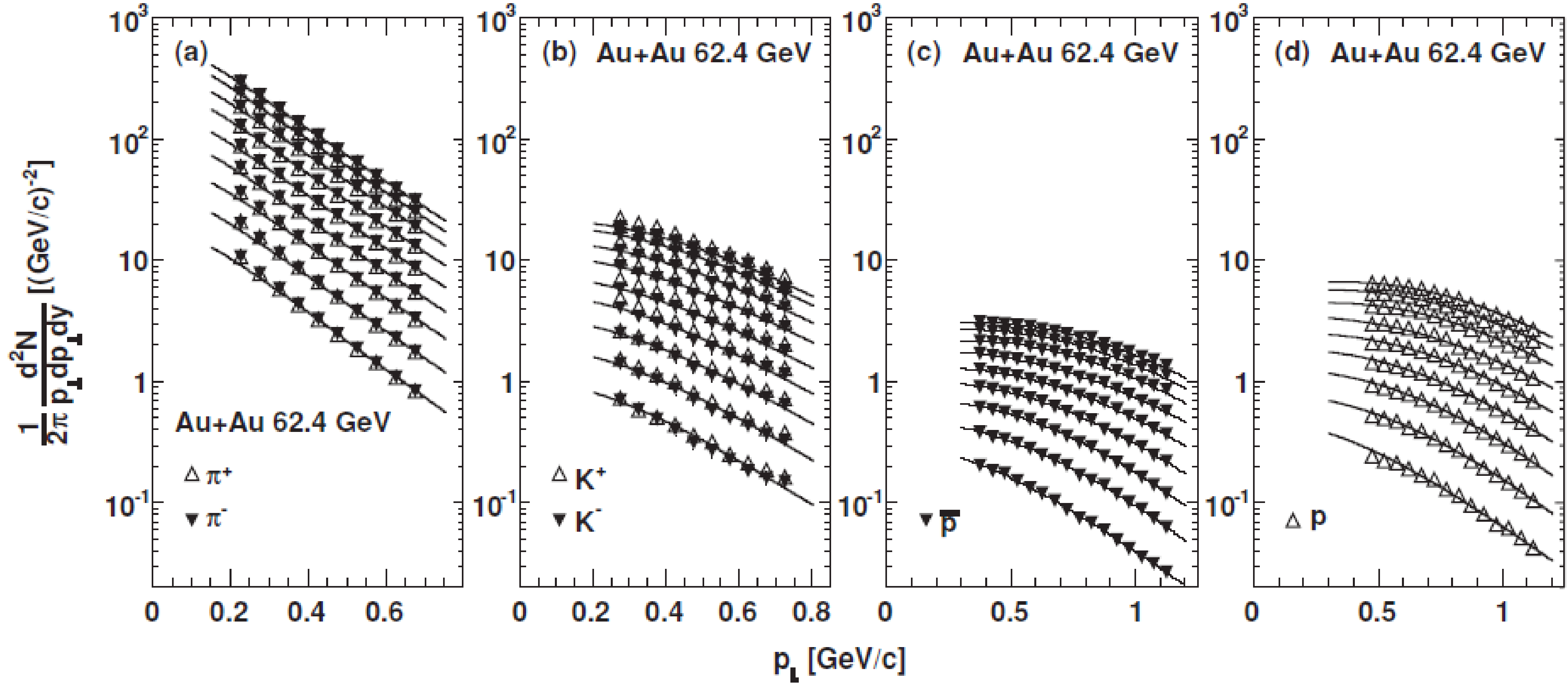
$$\frac{1}{m_t}\frac{dN}{dm_t} = A \cdot m_t \cdot e^{-\frac{m_t}{T}}$$

Where the slope parameter T has a thermal part and the expansion velocity part.

$$T = T_0 + \langle \beta^{\alpha} \rangle \cdot m$$

Thermal spectra and flow

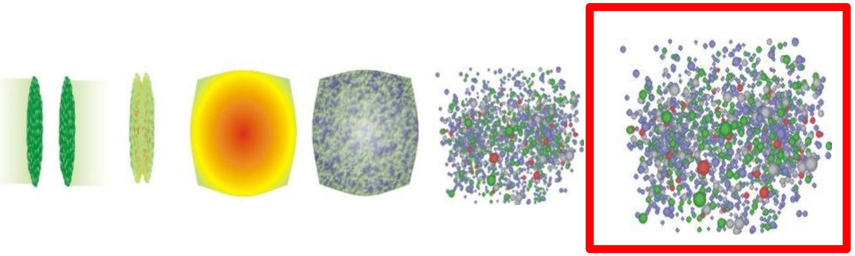
PRC 79, 034909 (2009) STAR Collab.



Different spectral shapes for particles of differing mass:

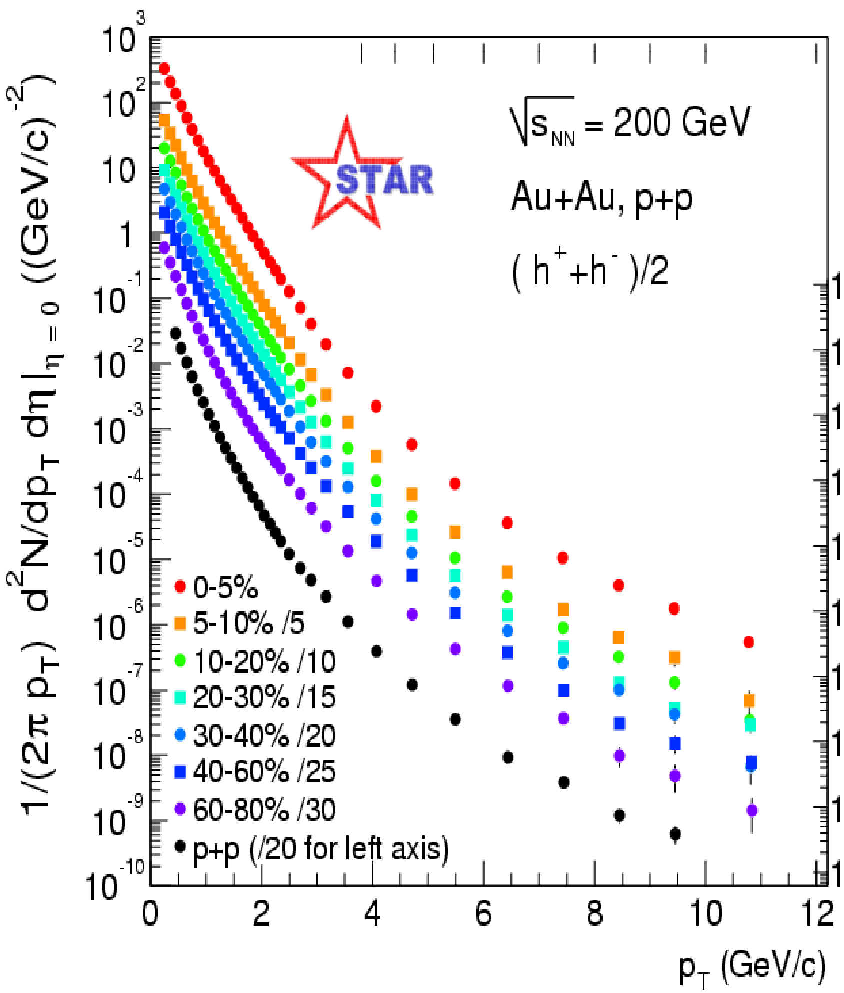
indication of Strong Collective Radial flow

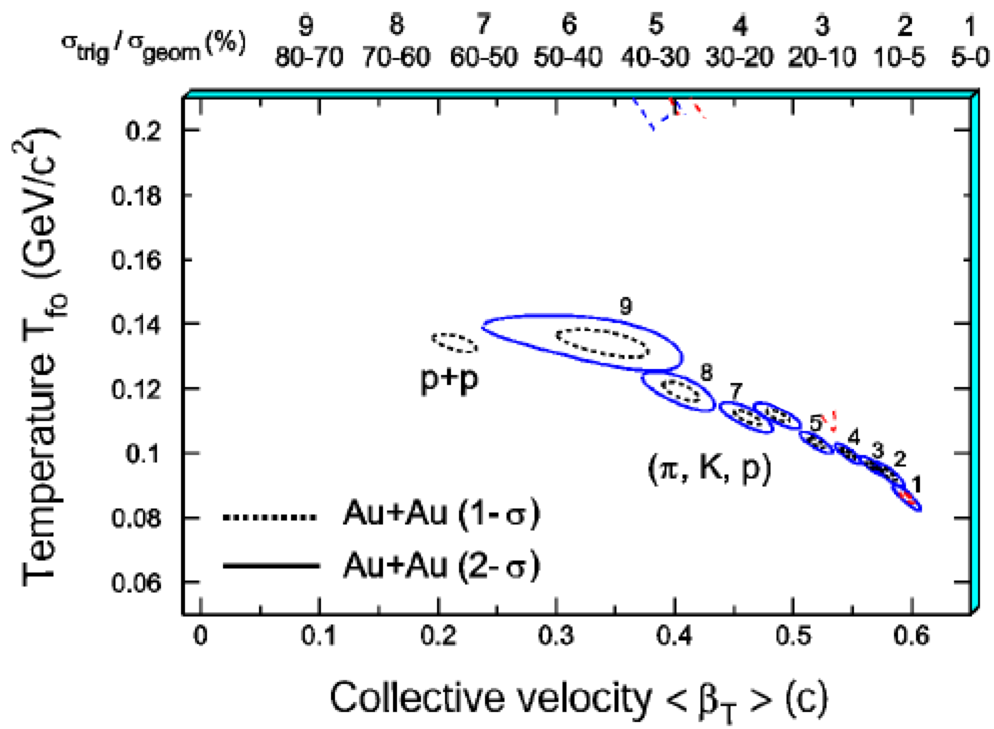
Thermal freeze-out characteristics



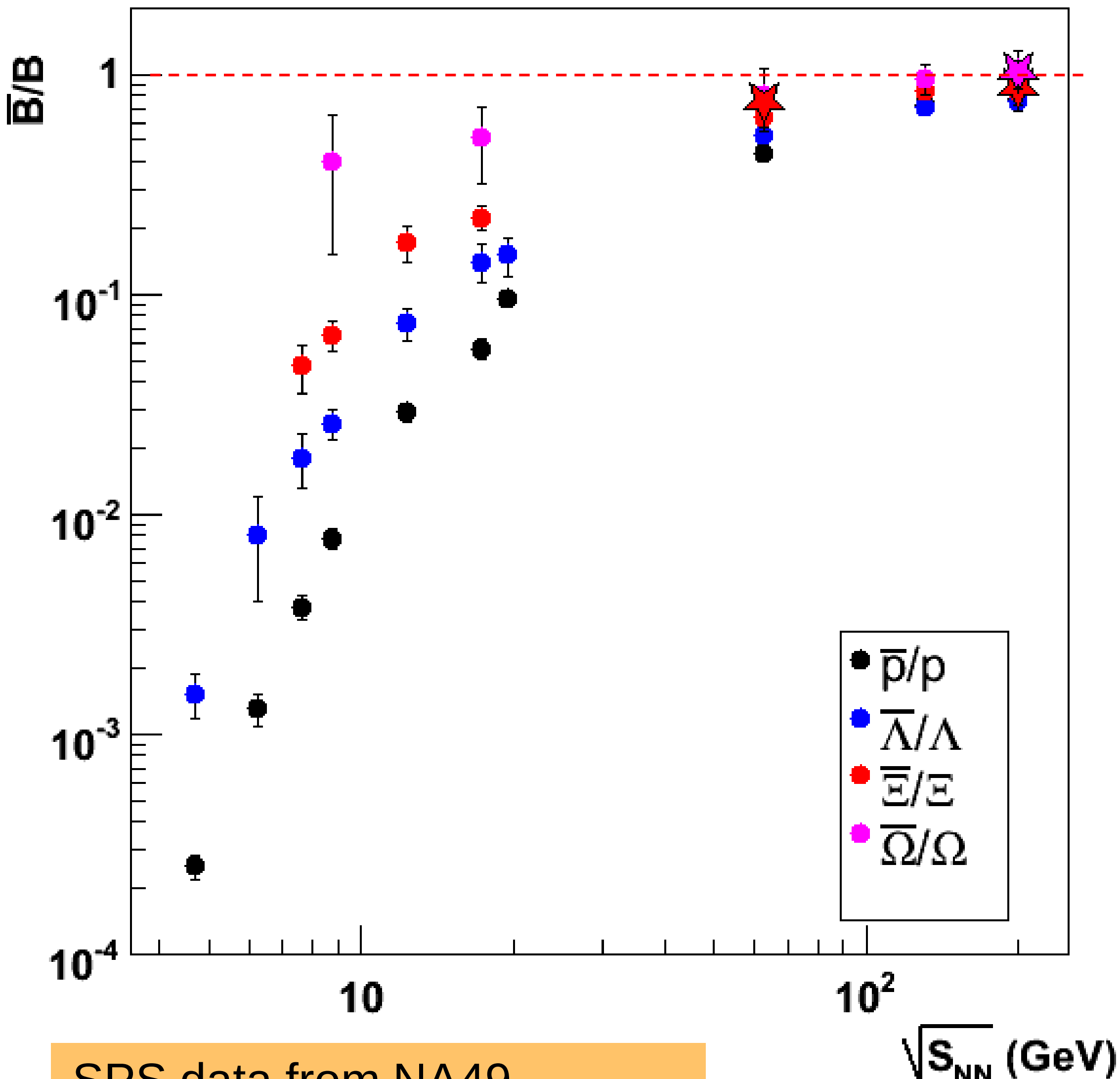
Results from a simple "Blast wave" model:

- Temperature is around 90-130 MeV.
- Expansion velocity increase from 0.2c to 0.6c, from peripheral to central collisions !!!!





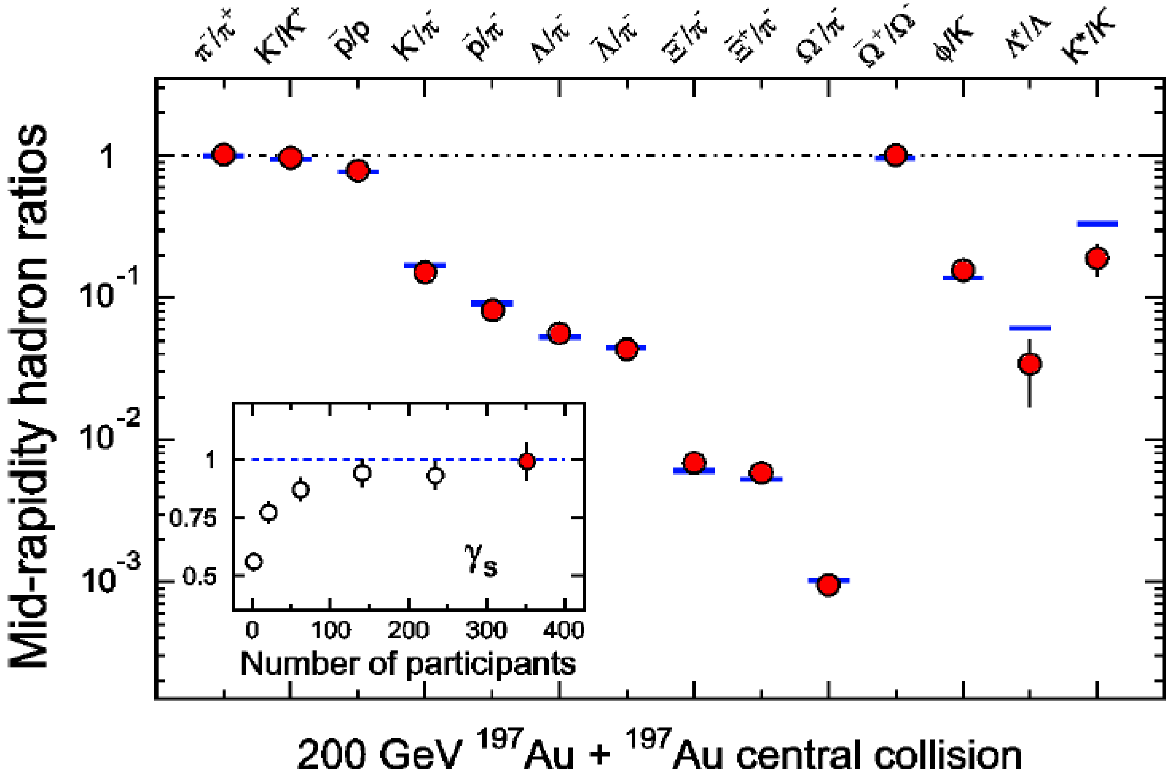
Study of Identified particles



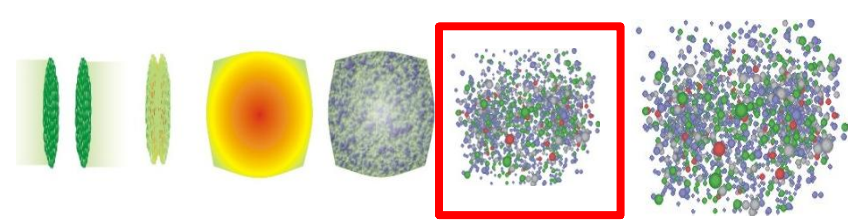
SPS data from NA49
AGS data from E896 & E802
RHIC data from STAR

- Different techniques can be used for particle identification. (W. Riegler lectures).
- Ratio approaching baryon free environment at RHIC and LHC energies.
- Suggests that most particles in this region are produced through pair production.

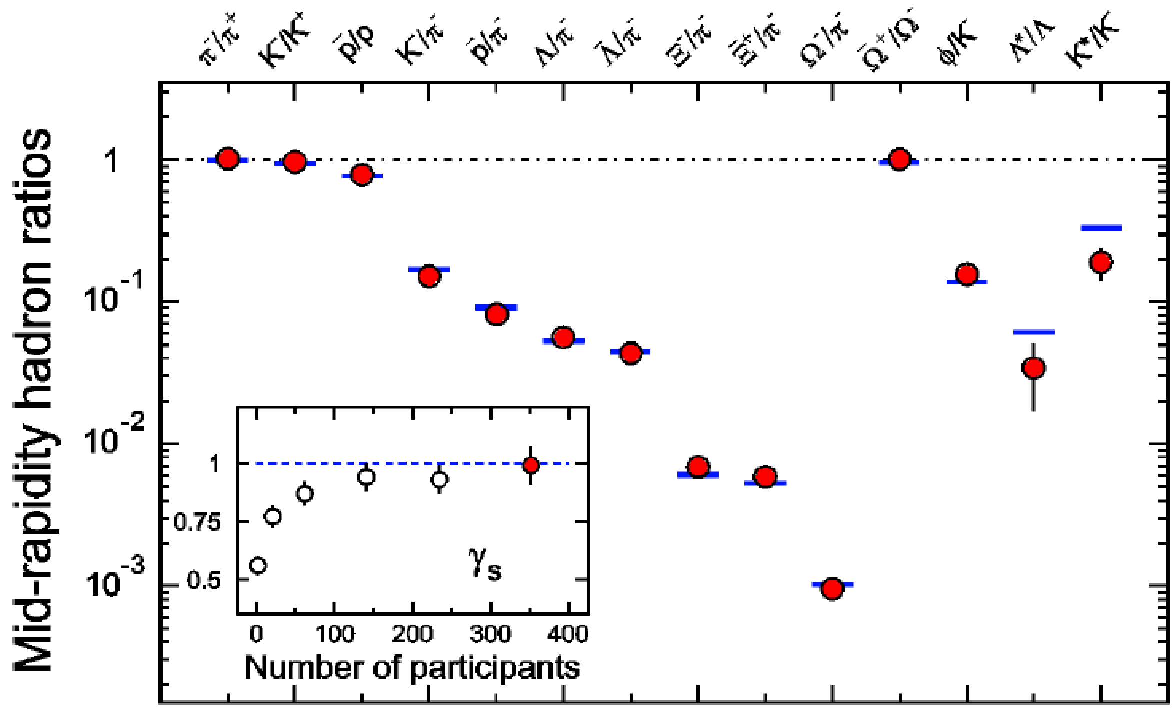
Study of Identified particles



Now, we can make different ratios using the integrated identified particle yields.
These ratios are defined in the chemical freeze-out stage of the collision evolution.



Can we get more detailed information from the chemical freeze-out?

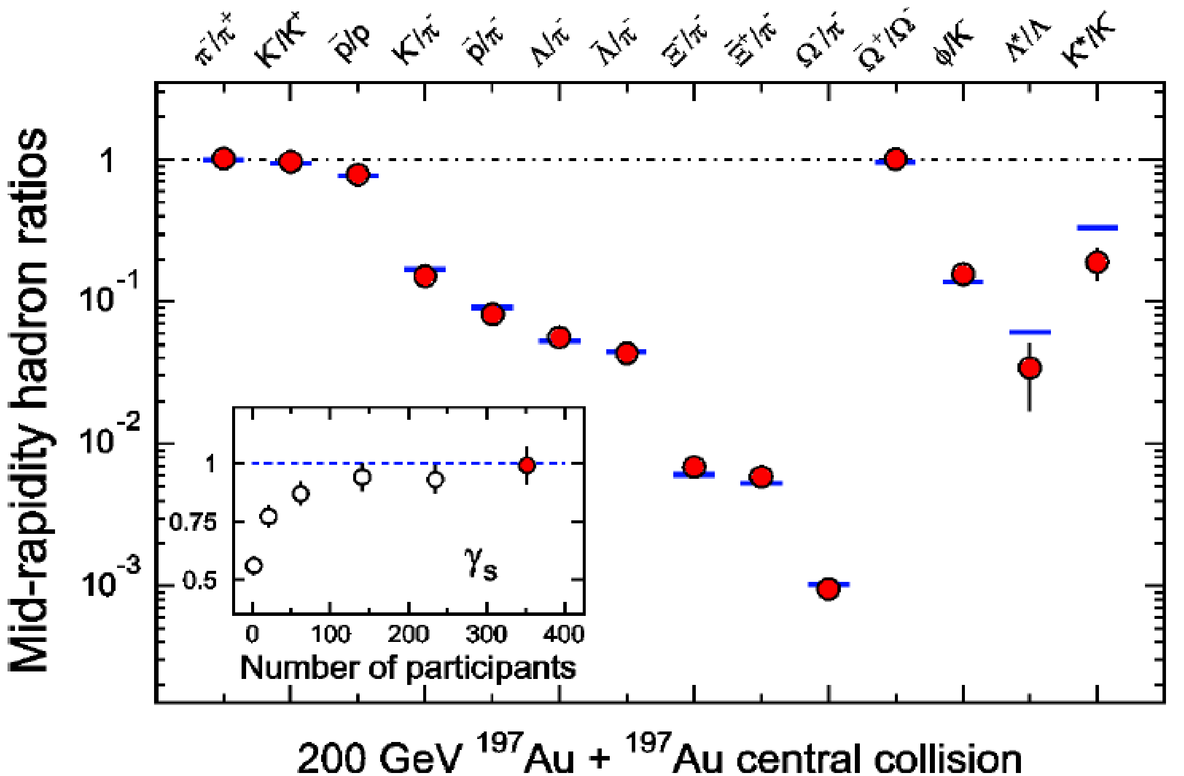


200 GeV ^{197}Au + ^{197}Au central collision

Assume: Ideal hadron resonance gas thermally and chemically equilibrated fireball at hadro-chemical (T_{ch}, μ_B) freeze-out.

Recipe: Grand canonical ensemble to describe partition function $\Rightarrow$ density of particles of species ρ_I

Can we get more detailed information from the chemical freeze-out?



Thermal model works well for SPS to RHIC energies.

=> Thermal equilibrium achieved

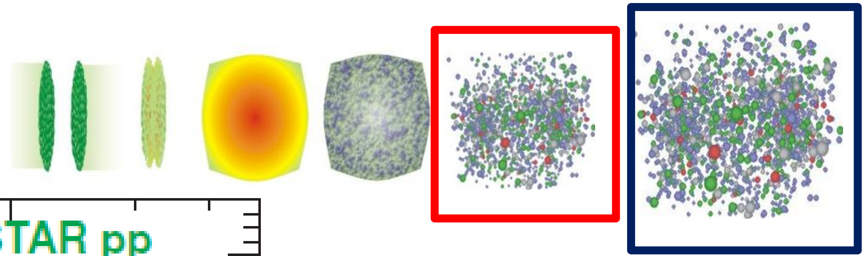
Even heavier strangeness seems to be in complete equilibrium.

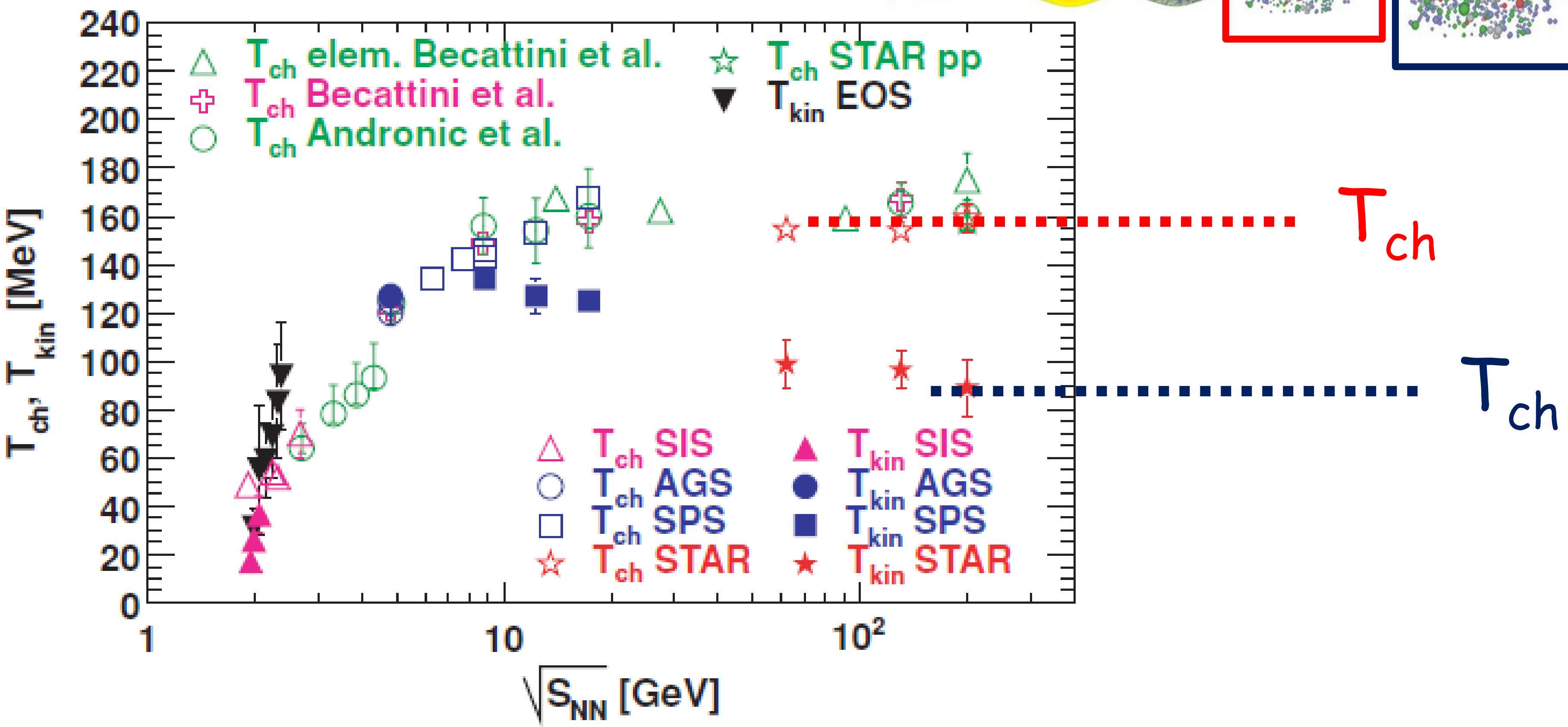
At RHIC, $T_{ch} \approx T_{Critical} \approx 175 \pm 10$ MeV

=> Fast equilibration after hadronization

Chemical and thermal freeze-out

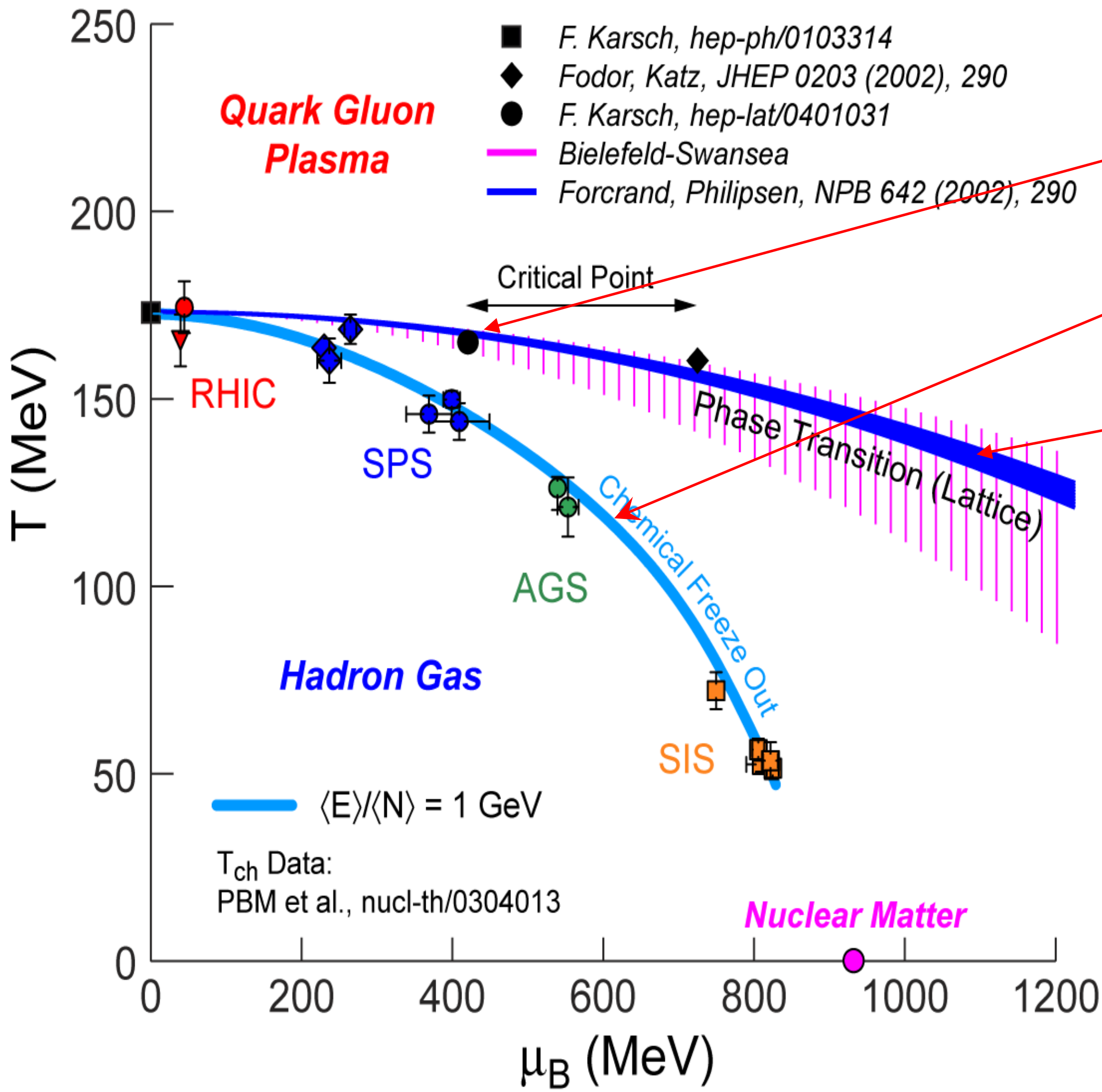
PRC 79, 034909 (2009) STAR Collab.





T_{ch} constant for collision energy above 10 GeV indicating that regardless of the different conditions in AA collisions, system always evolve to the same chemical freeze-out.
Thus, we loose the information of the IC.

Chemical Equilibration, T_{ch} close to $T_{critical}$



Endpoint of cross-over

Unified freeze-out condition at fixed ε=1 GeV

QCD phase boundary (LGT)

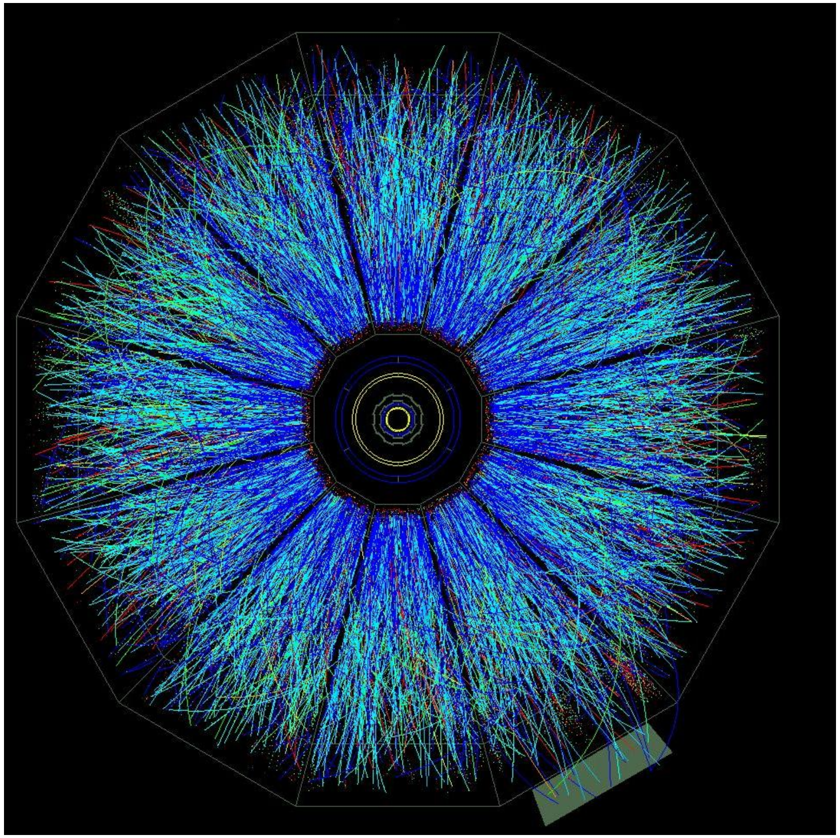
QCD on Lattice

T_c = 173±8 MeV, N_f=2

T_c = 154±8 MeV, N_f=3

Seems that chemical equilibration was reached.
If Tch = Tc, it means that hadrons were born in an equilibrated system

What about the angular distribution of particles?



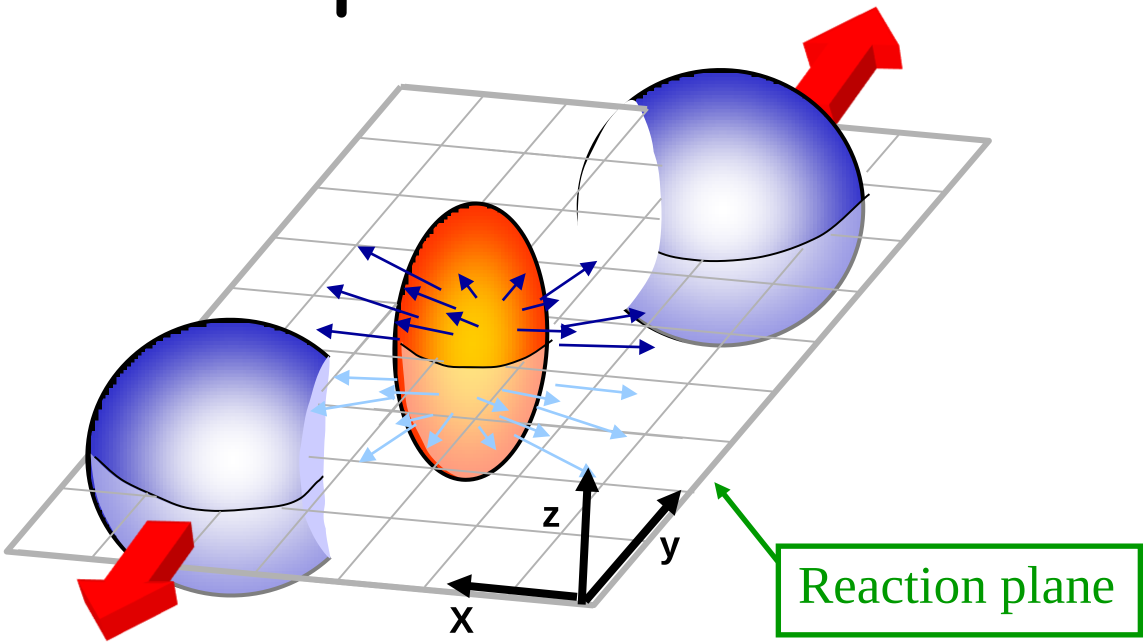
What can we learn from the angular distribution of particles?

Should there be any angular dependence ?

In the longitudinal direction, we can look at the rapidity distribution of particles.

In the azimuthal direction, we can look at the angular distribution with respect to the reaction plane.

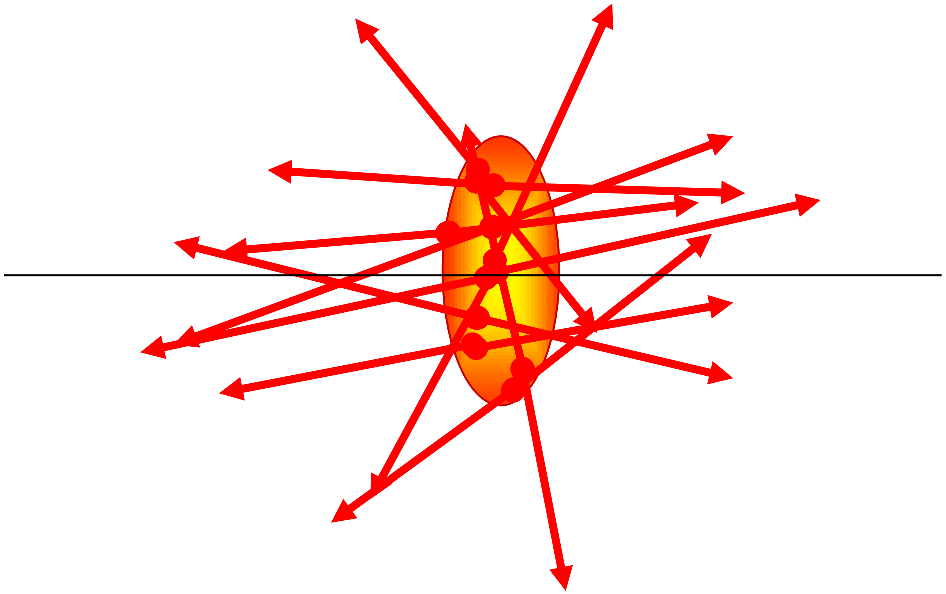
What about the angular distribution of particles?



When collision is not completely central, there is a finite impact parameter “b” and thus we can define a reaction plane using the directions of b and the beam.

The overlap region between the two colliding nuclei will have a initial spatial anisotropy.

Should there be an azimuthal angular dependence with respect to RP?



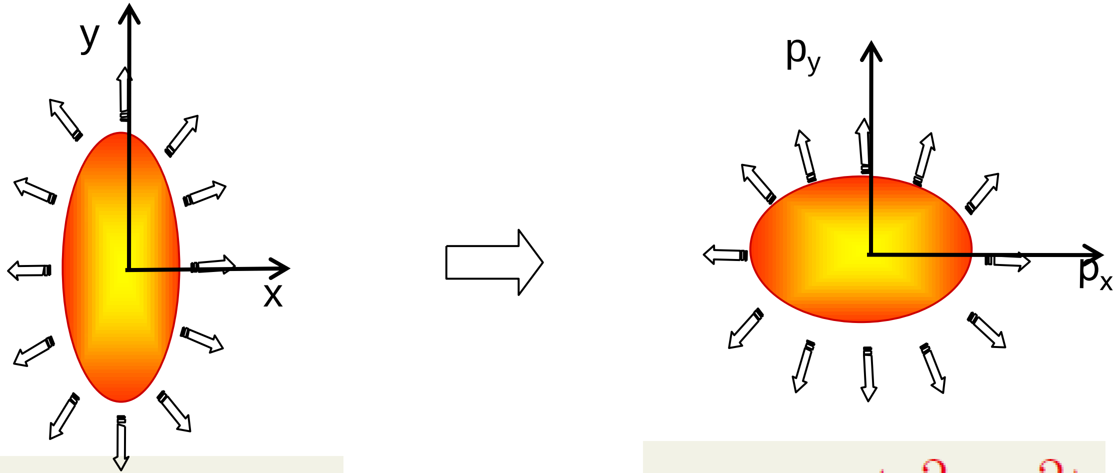
Almond shape
overlap region in
coordinate space

Incoherent processes like di-Jet production should not have any angular dependence with the reaction plane. But they will generate a large angular anisotropy within the event.

But, if we look at several events, added together, the azimuthal angular distribution of particles from Jets should not have any preferential direction.

Should there be an angular dependence with respect to the reaction plane?

Almond shape overlap region in coordinate space



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

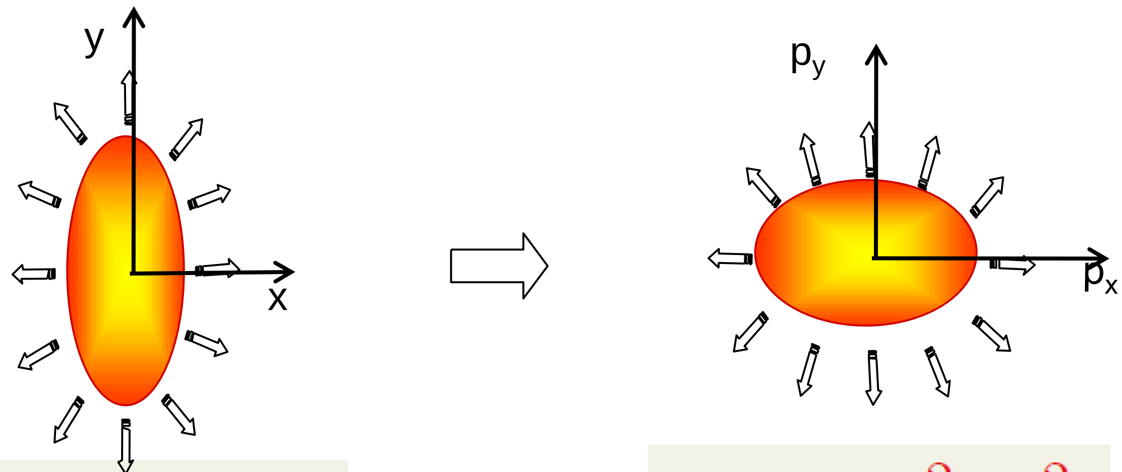
$$v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

Now, if we consider the particles that come from the final state interactions, a collective property of the system could affect the azimuthal angular distribution of the particles.

The initial anisotropy in the coordinate space (ε) will be transferred to an anisotropy in the momentum space, during the evolution of the system by the large amount of interactions between particles.

Should there be an angular dependence with respect to the reaction plane?

Almond shape overlap region in coordinate space



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

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

spatial anisotropy → momentum anisotropy → $d^2N/dp_t d\varphi$

Directed Flow

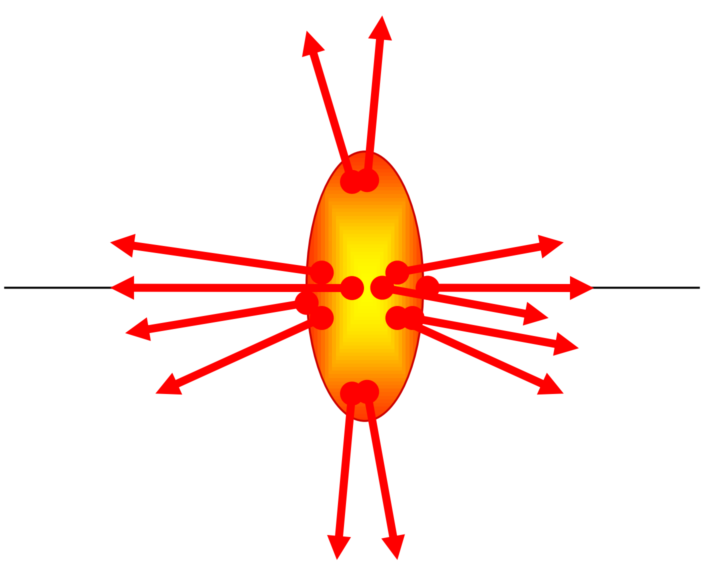
Elliptic Flow

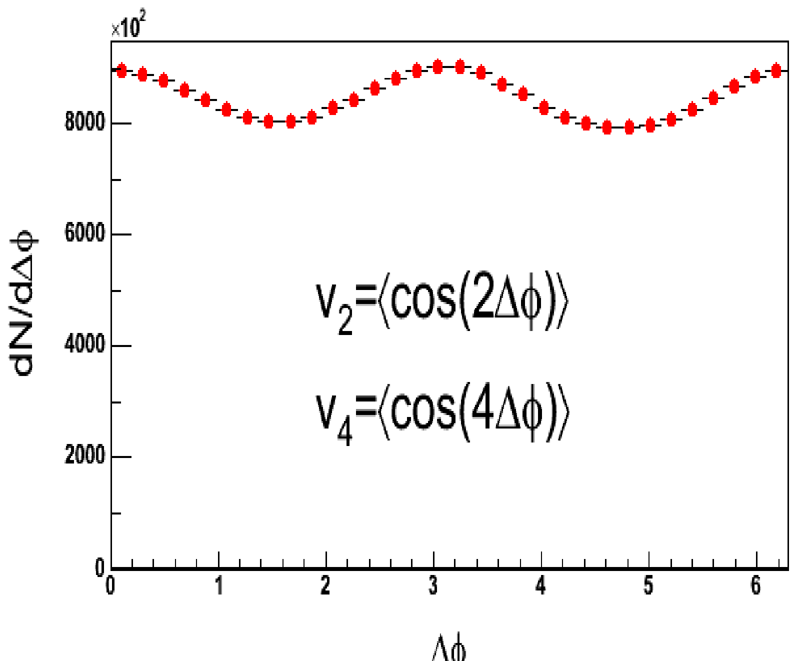
$$\frac{d^3N}{d\phi dp_T dy} \propto \left[1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots\right]$$

But, experimentally we do not know what is the direction of the RP.

Different methods can be used to determine the RP.
For a certain momentum interval, due to the transfer of the anisotropy, there will be more particles in the direction of the RP.

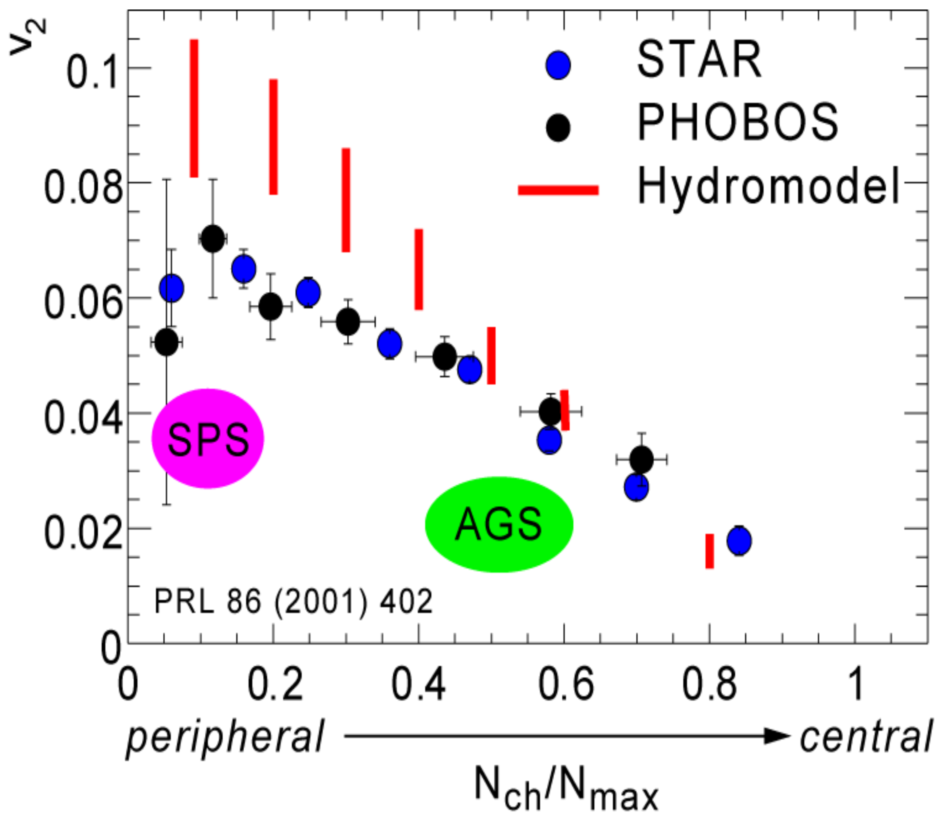
So, if we look at the distribution of angular difference between two particles Δφ we should observe an excess in the direction of the RP, so at Δφ=0 and Δφ=π.





Collective behavior observed at RHIC

Large values of v2 have been observed at RHIC.



Large ***v_2*** suggests very strong internal pressure and **early thermalization**.

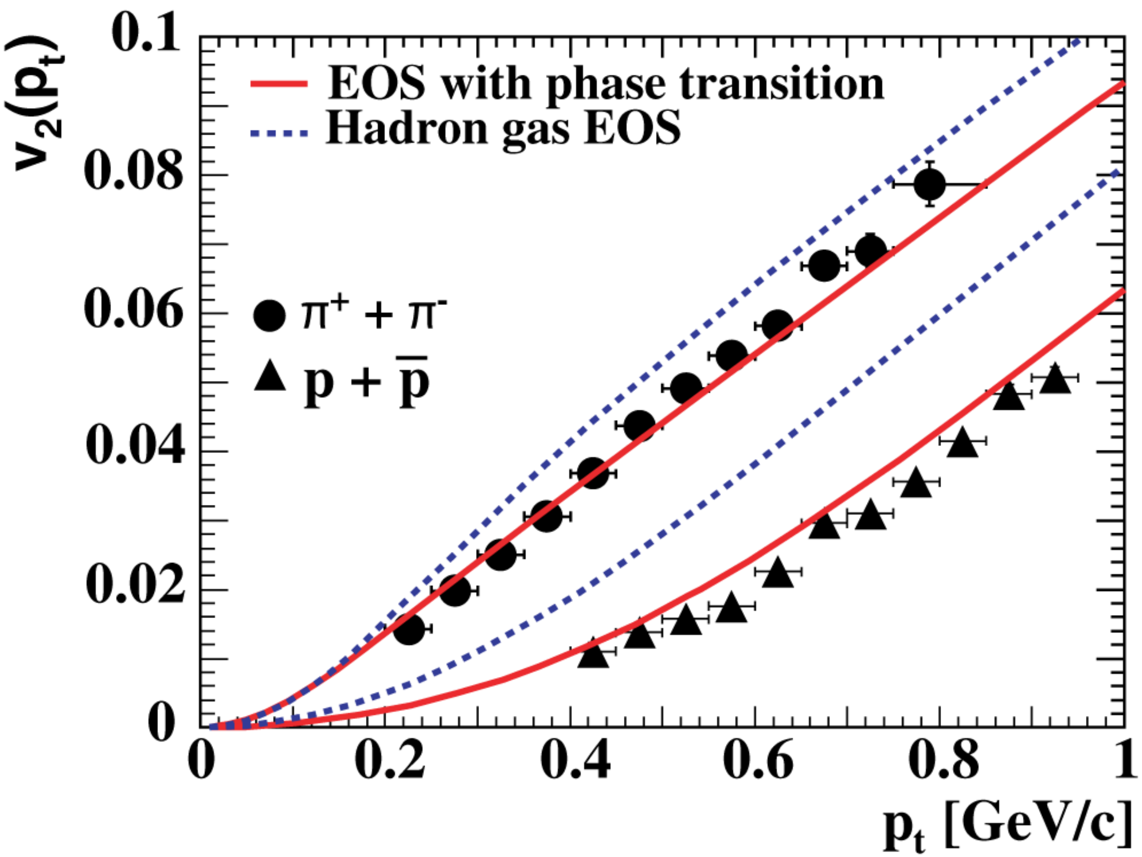
⇒ contrast to lower energy data SPS and AGS that had lower v2 values.

⇒ Observed values very close to what is expected from hydrodynamical models.

Elliptic flow establishes there is strongly interacting <u>matter</u>

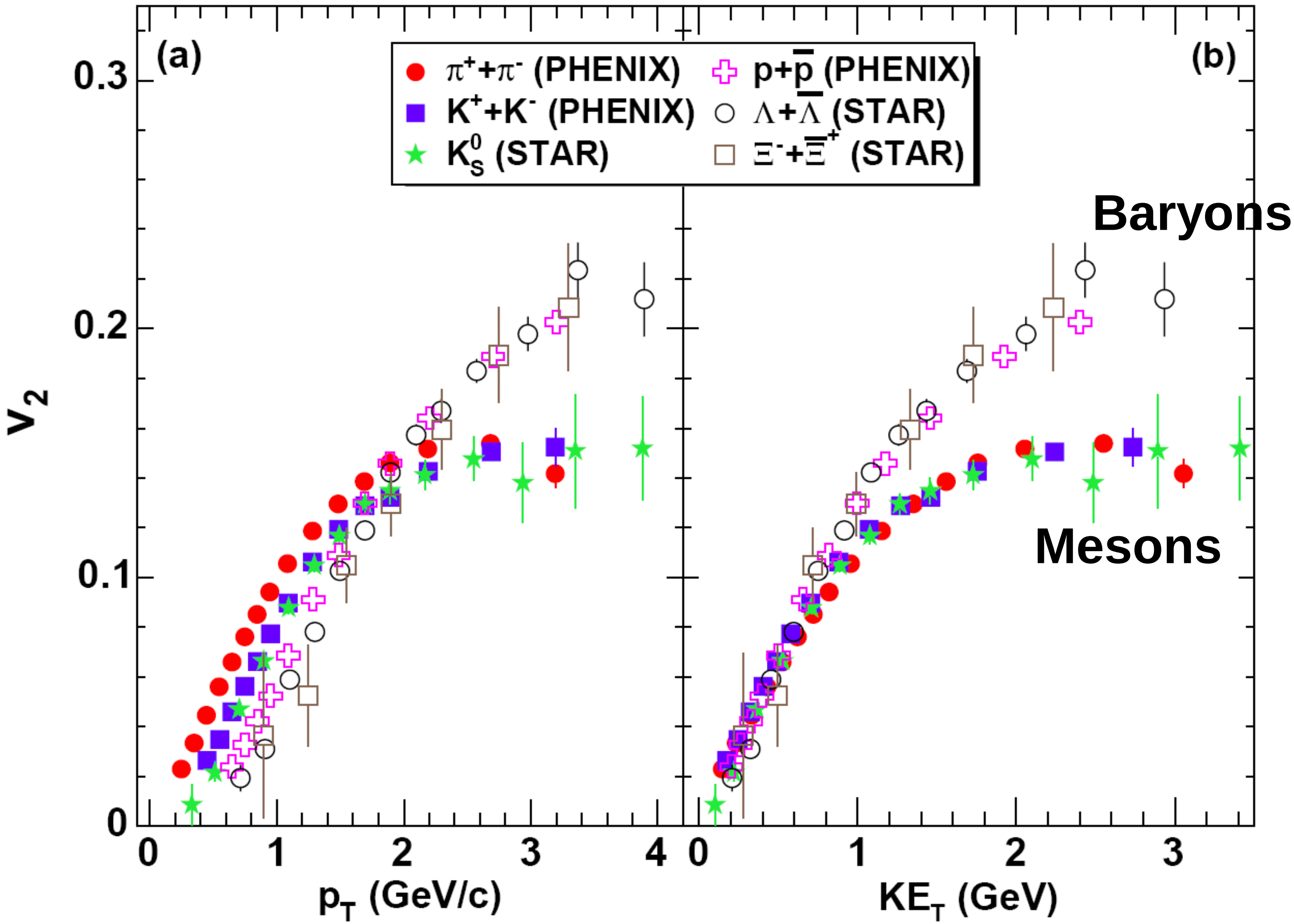
V2 for different particles

Kolb et al, nucl-th/0305084

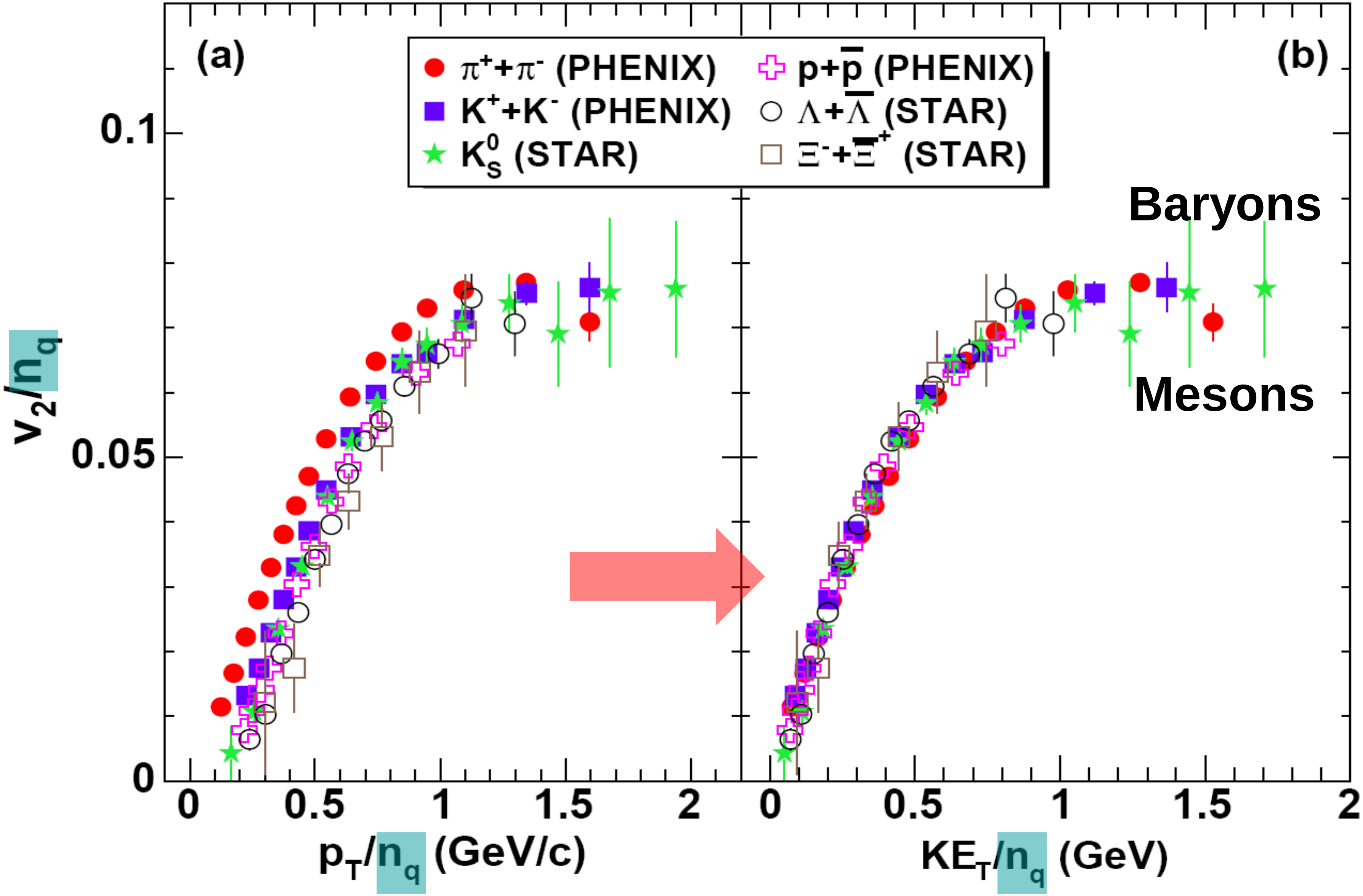


The hydro-models which include both **hadronic and QGP phases** in the EOS, a **common transverse velocity** and **zero viscosity** reproduce well the qualitative features of the measured $v_2(p_t)$ of pions, kaons, and protons.

Signs of partonic degree of freedom



Signs of partonic degree of freedom



RHIC announces Perfect Liquid !

THE QGP DISCOVERED AT RHIC

M. Gyulassy
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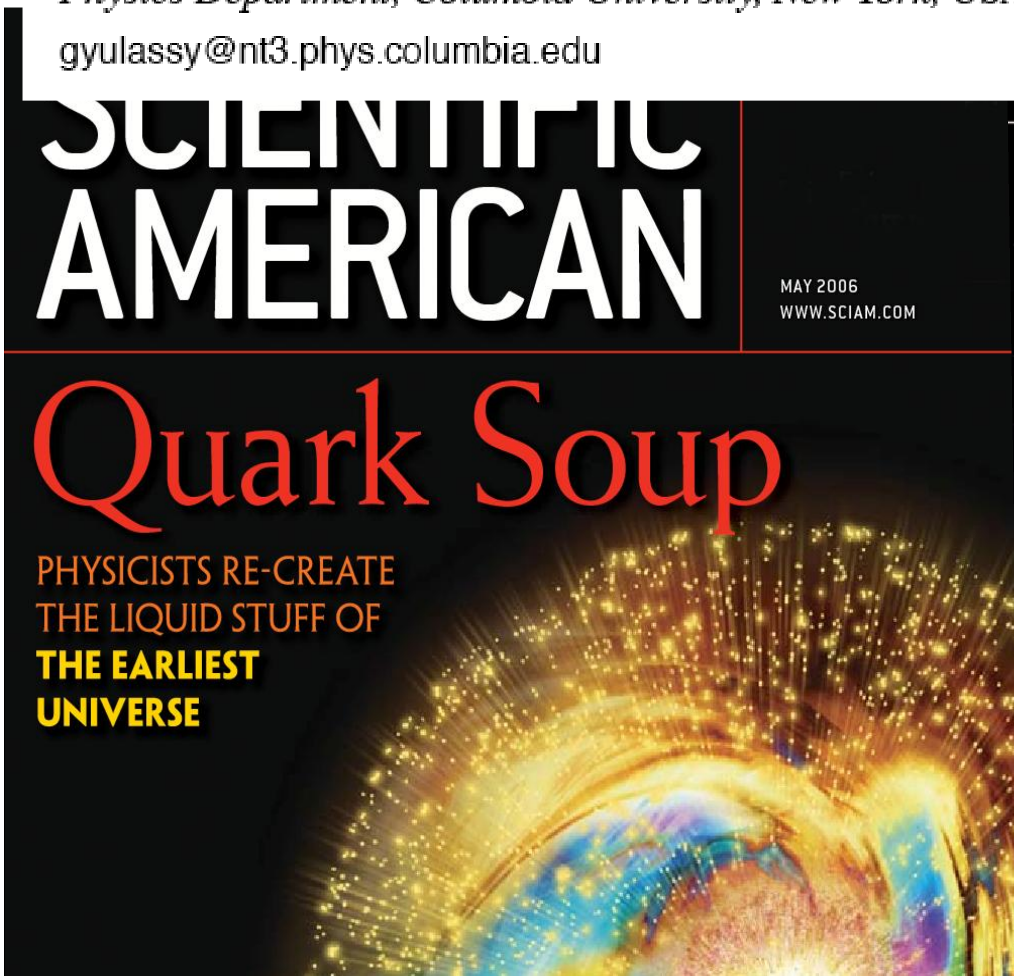
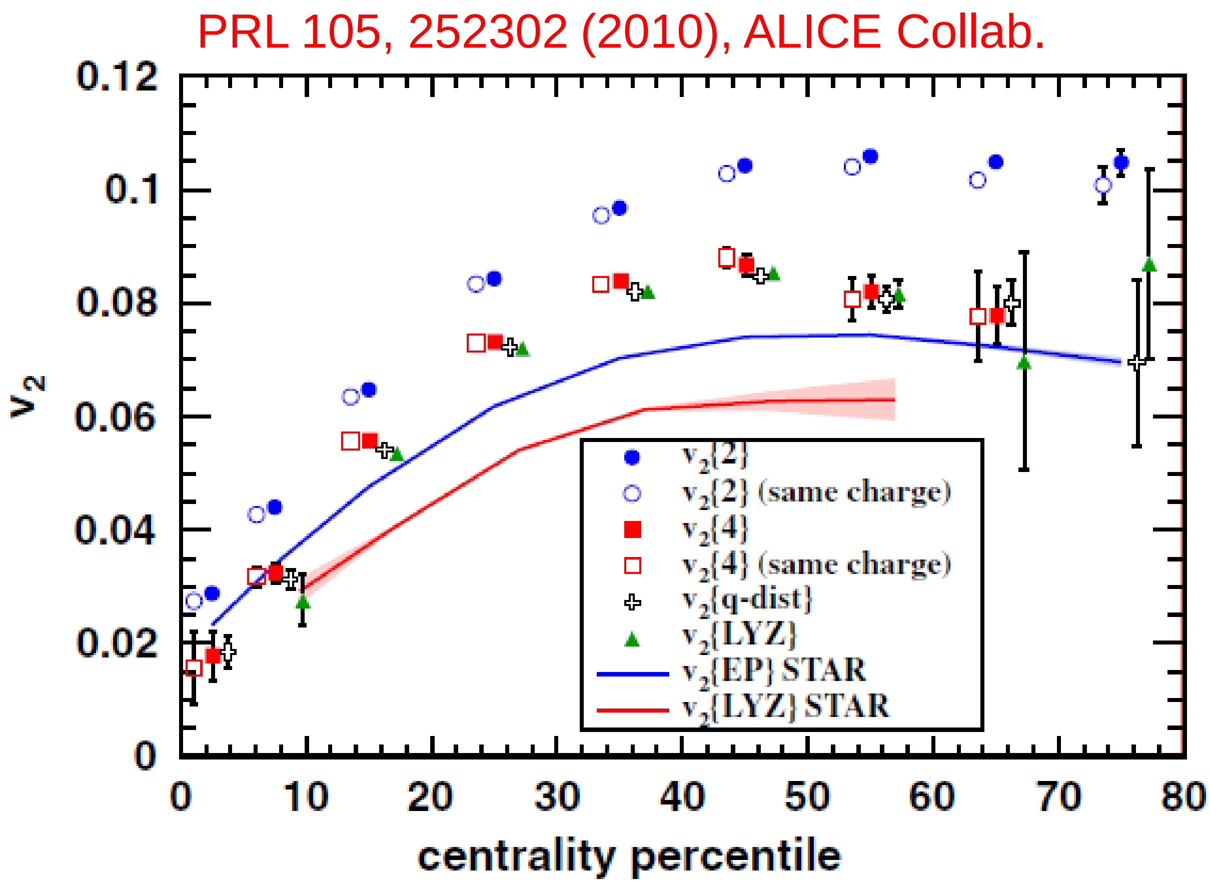


V2 measured at LHC

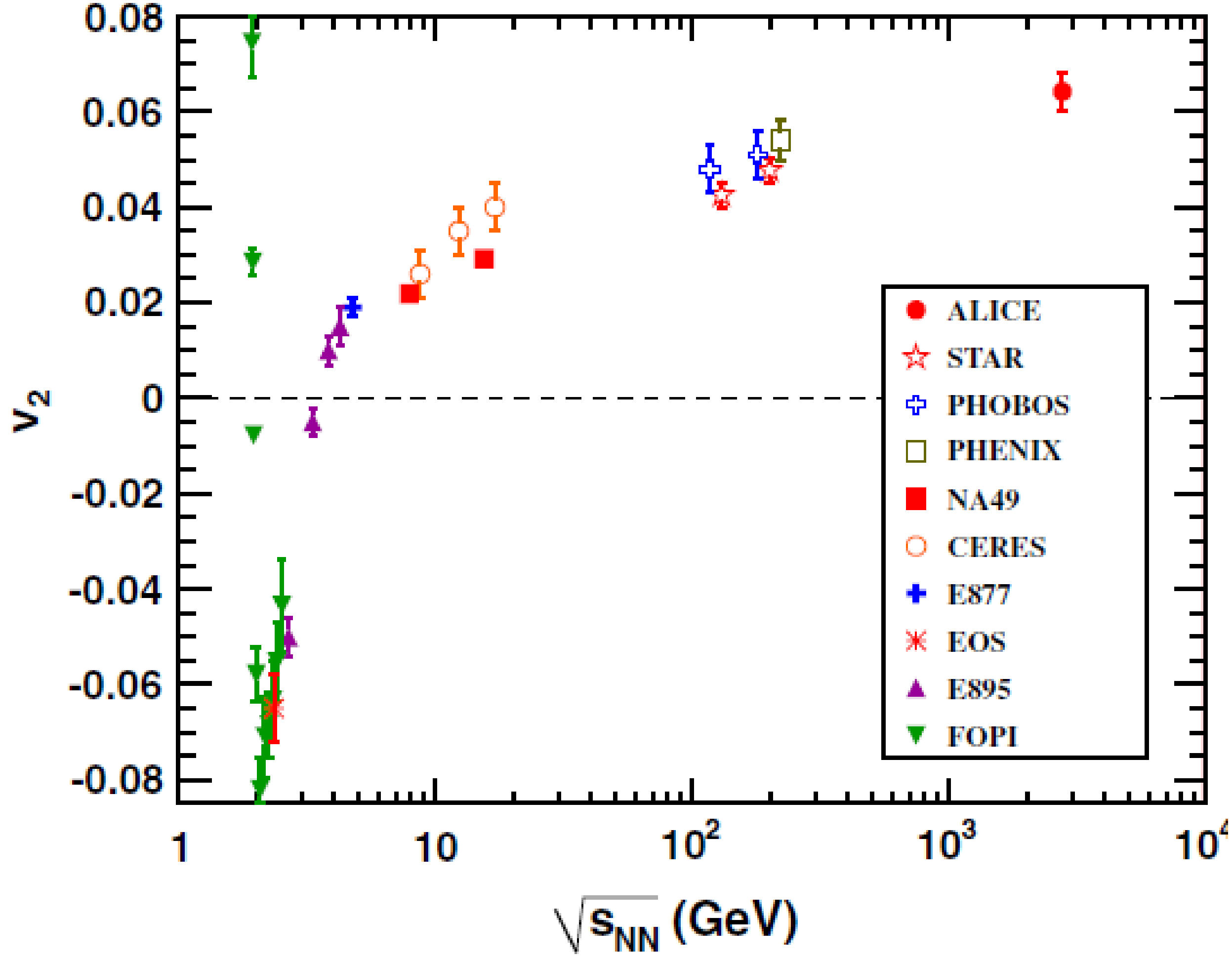


Elliptic flow measured at 2.76 TeV also increase with collision centrality, with similar behavior as observed at RHIC.

Shape of the p_T dependence of v2 is also consistent hydrodynamical model predictions.

V2 measured at LHC

PRL 105, 252302 (2010), ALICE Collab.

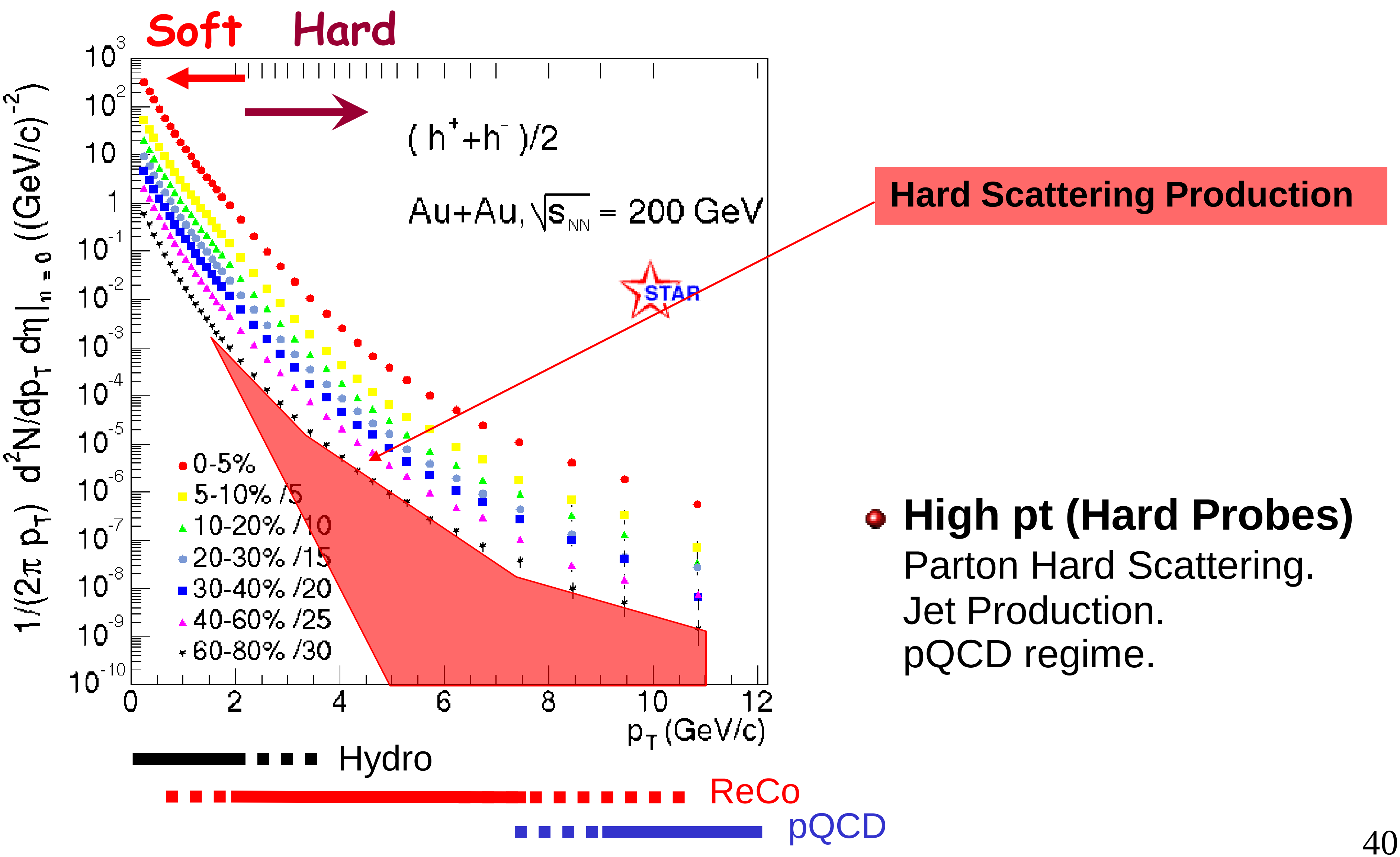


Elliptic flow measured at 2.76 TeV is approximately 30% higher than measured at RHIC.

Why?

Could be due to increase in the average transv. momentum $\langle p_T \rangle$.
Continuous increase in the magnitude of v2 with collisions energy.
The increase is higher than predicted by ideal hydro model, but agrees with some viscous hydro-models.

Now, lets look a the hard sector.



- **High pt (Hard Probes)**
  Parton Hard Scattering.
  Jet Production.
  pQCD regime.

Lets compare Au+Au to p+p

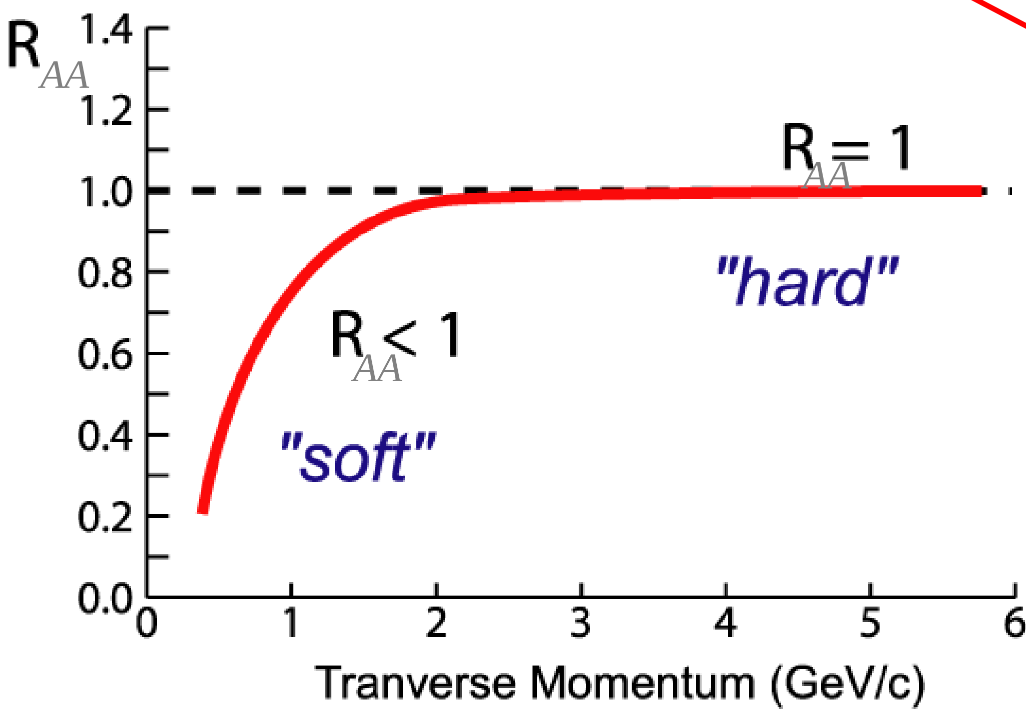
1. Compare Au+Au to nucleon-nucleon cross sections
2. Compare Au+Au central/peripheral

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

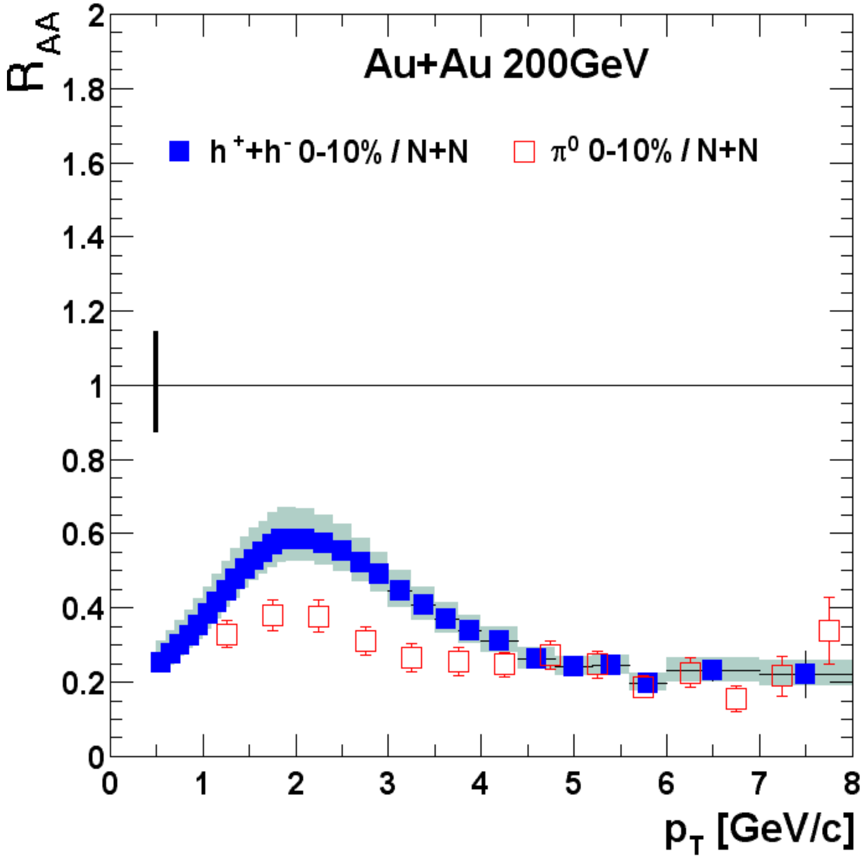
nucleon-nucleon cross section

$\langle N_{binary}\rangle / \sigma_{inel}^{p+p}$

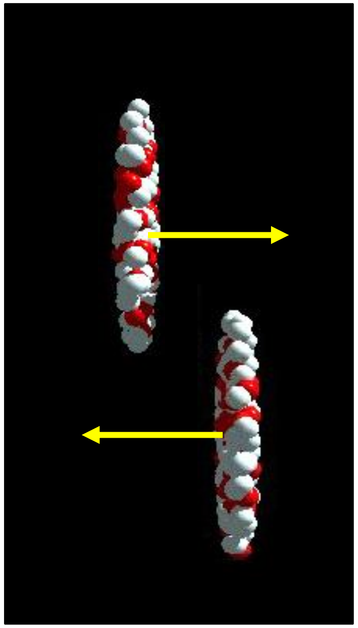


Centrality Dependence

Au + Au Experiment



PRL91, 072301(2003)

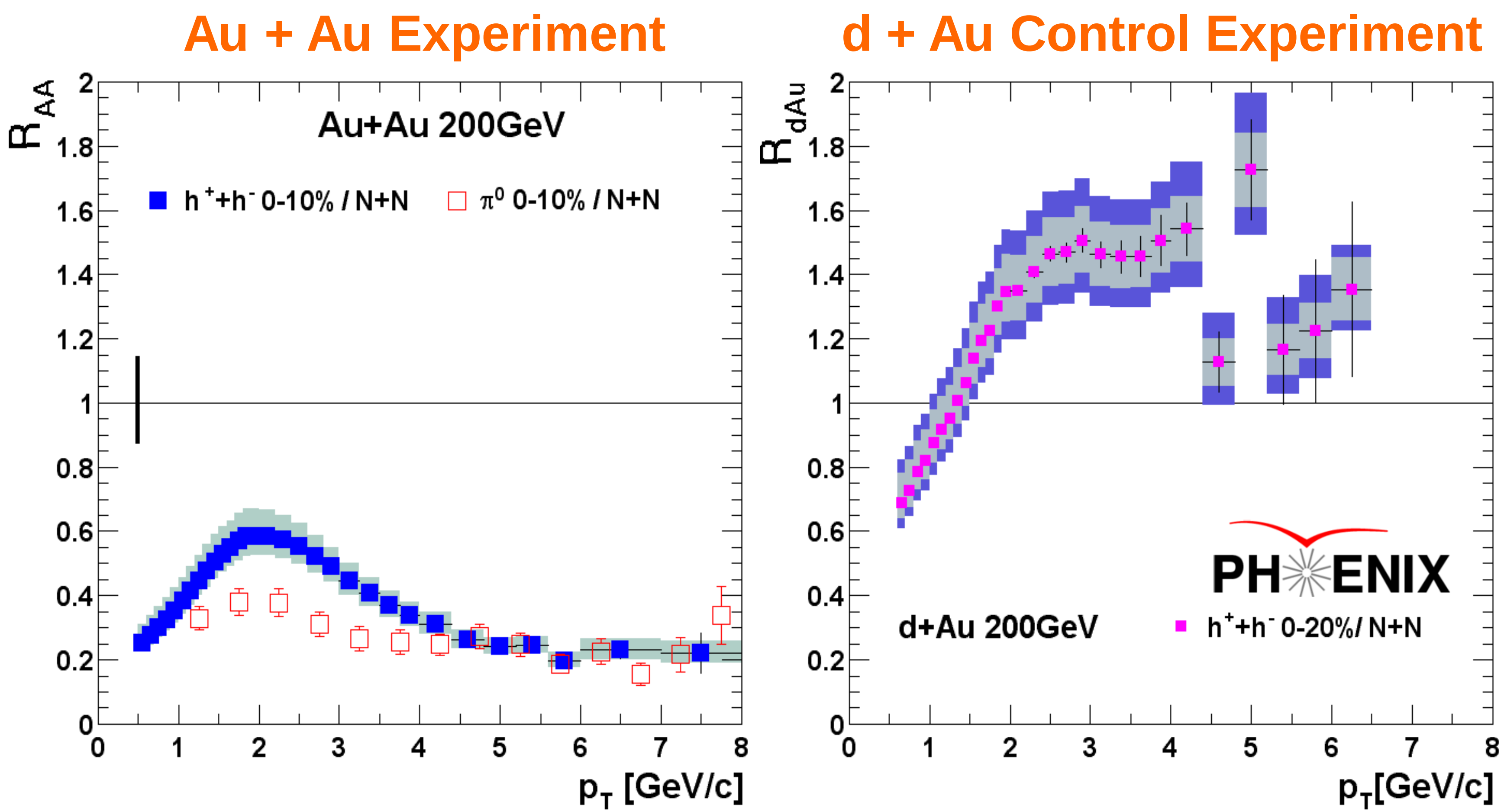


Suppression of high momentum particles !!

Is this an effect of jet suppression, due to final state interaction?

Can we determine the density of the medium from the energy loss?

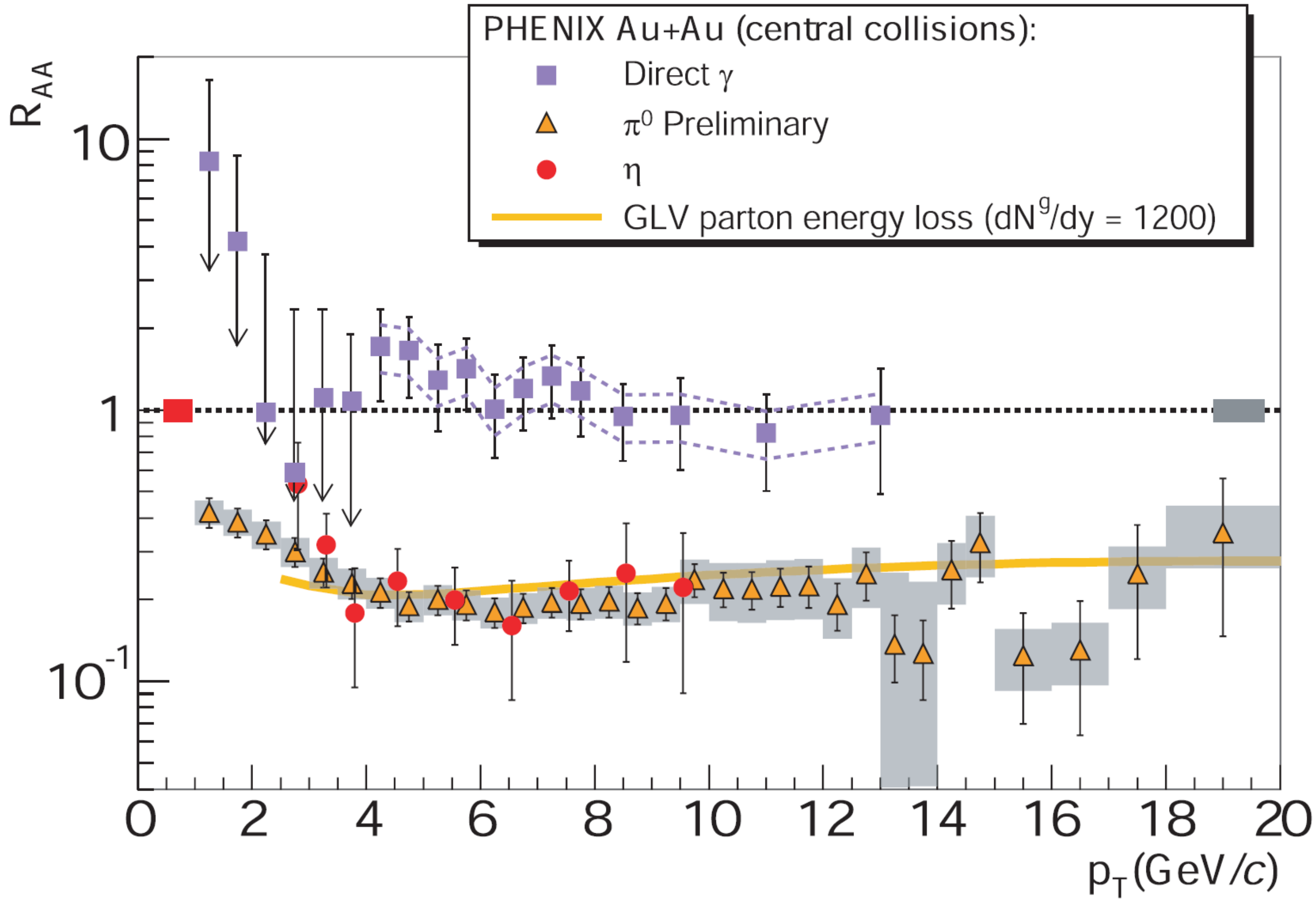
Comparison to control experiment d+Au



Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.

Suppression of inclusive spectra of Au+Au is clearly a final state effect.

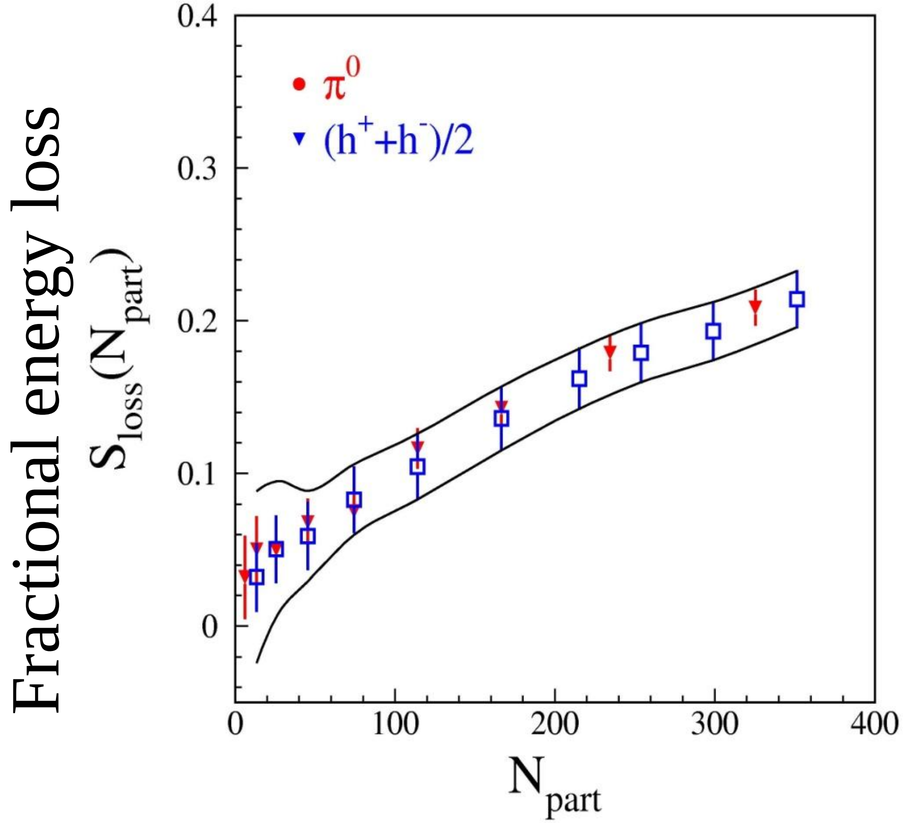
Hadrons are suppressed but Photons are not !!



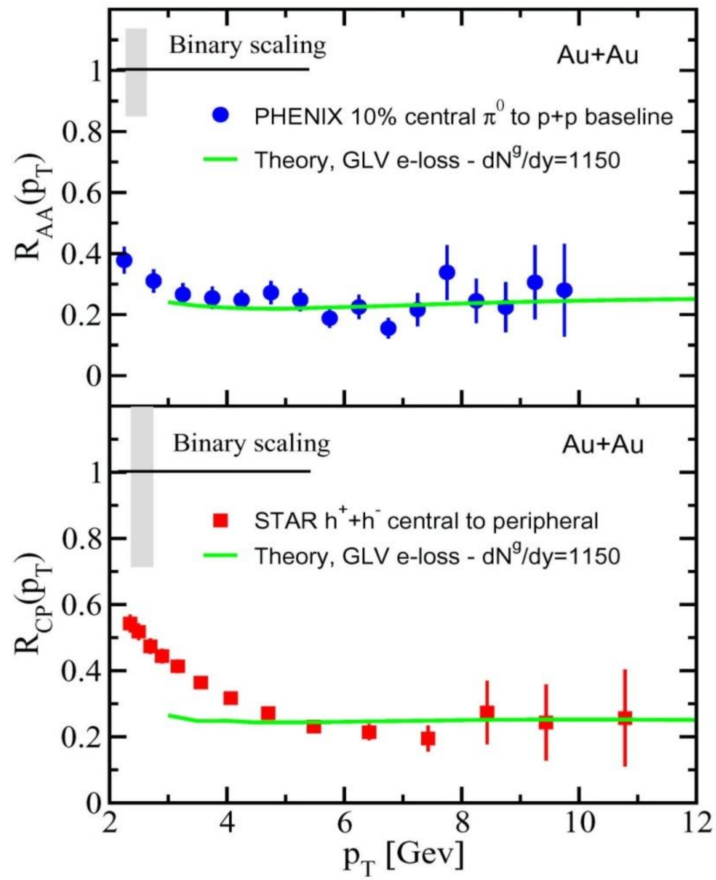
Photons do not interact strongly, so direct photons created inside the medium should not suffer any suppression. This is observed at RHIC, measured by the PHENIX experiment.

Quantify the Energy Loss

Empirical energy loss from data

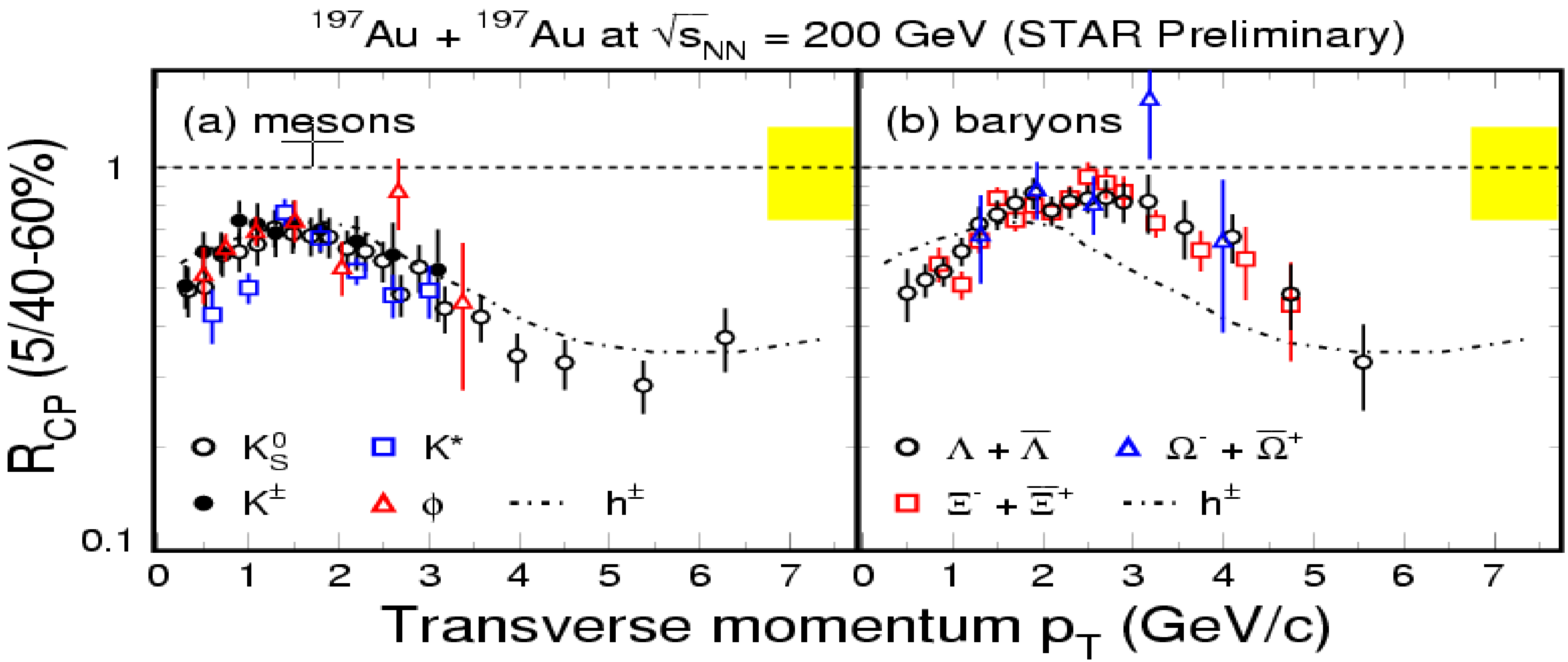


R_{AA} data vs GLV model



- Medium induced energy loss is the only currently known physical mechanism that can consistently explain the high p_T suppression.
- Radiative energy loss in a medium 50-100 times normal nuclear matter density.

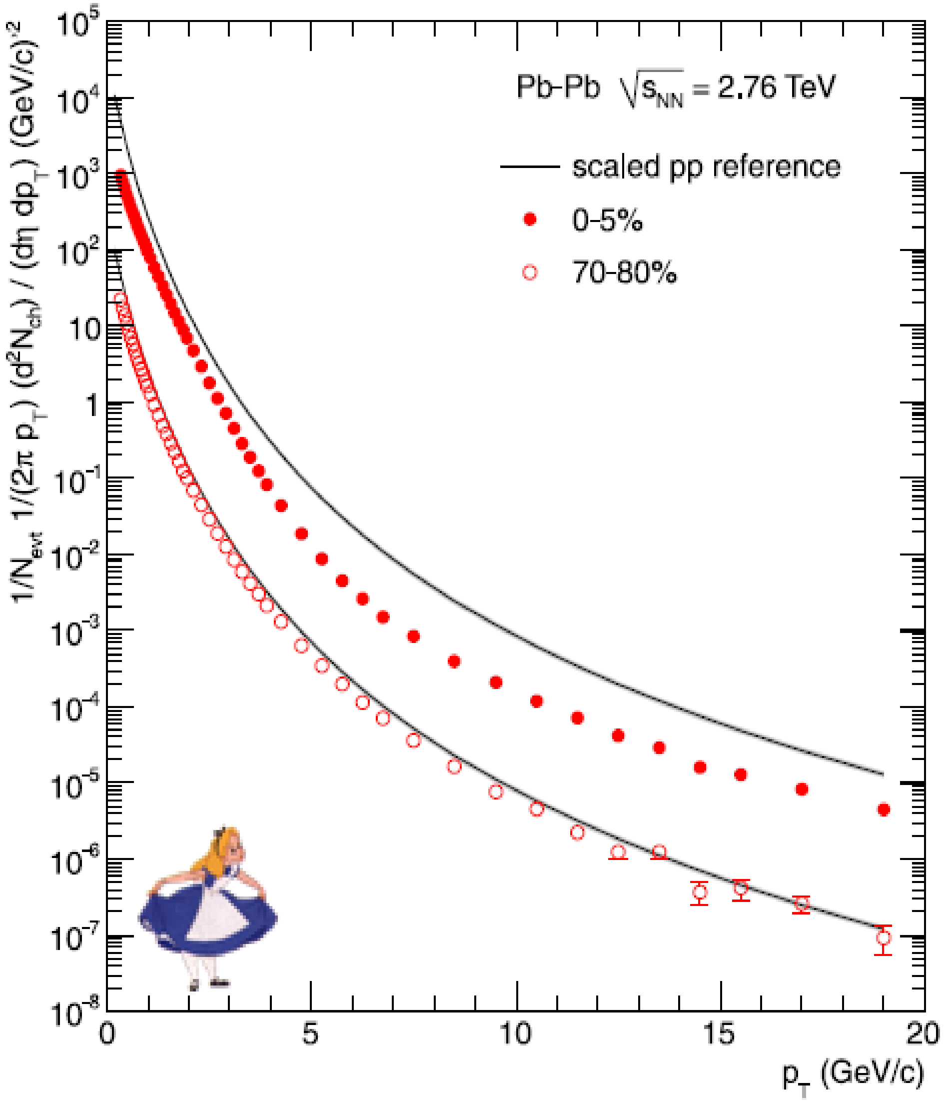
Indication of partonic degrees of freedom in spectra suppression



- Baryon/Meson diff. suggests recombination at intermediate pt.
- Coalescence/Recombination model describes data well from 1.5-5 GeV
- Recombination models requires the assumption of a **thermalized parton phase.**

Pb-Pb p_T spectra at 2.76 TeV

PLB 696 (2011) 30, ALICE Collab.



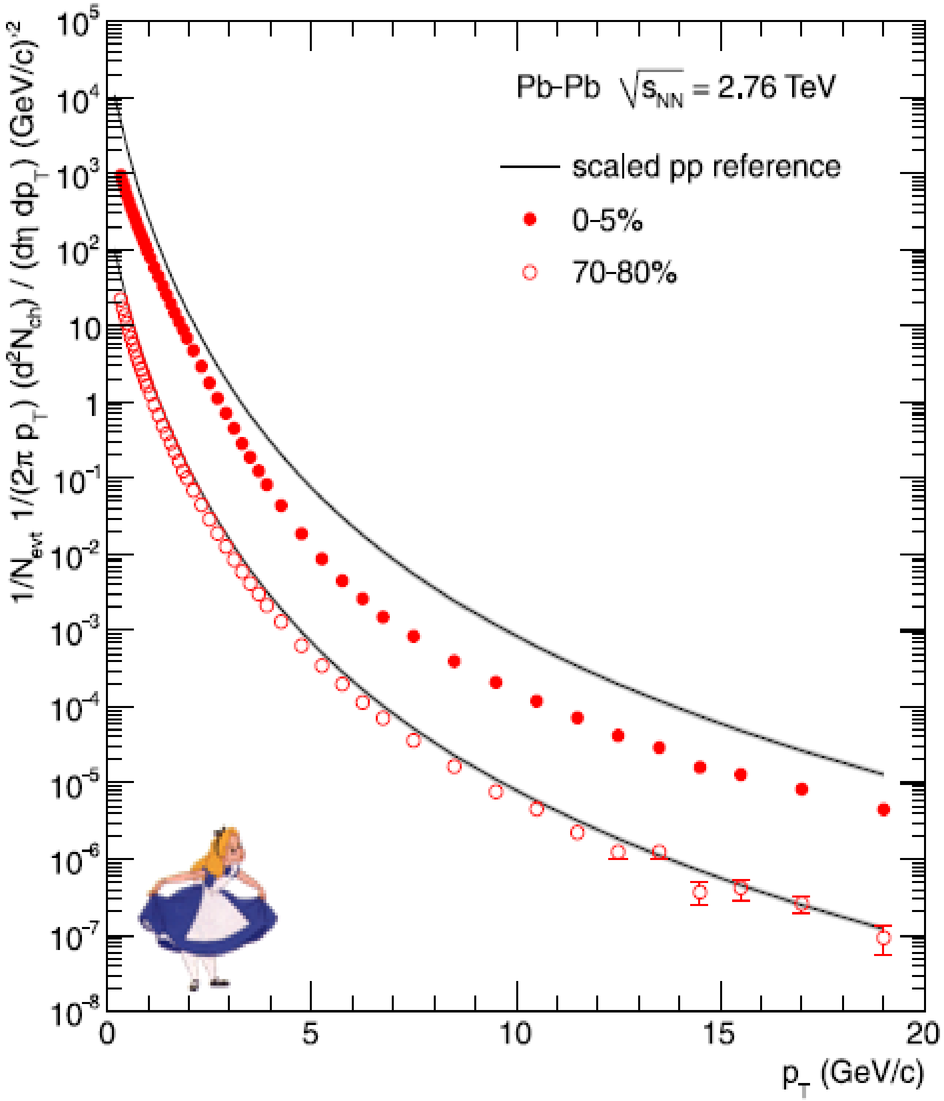
Inclusive transverse momentum spectra was measured for collisions of Pb-Pb at 2.76 TeV with the ALICE detector.

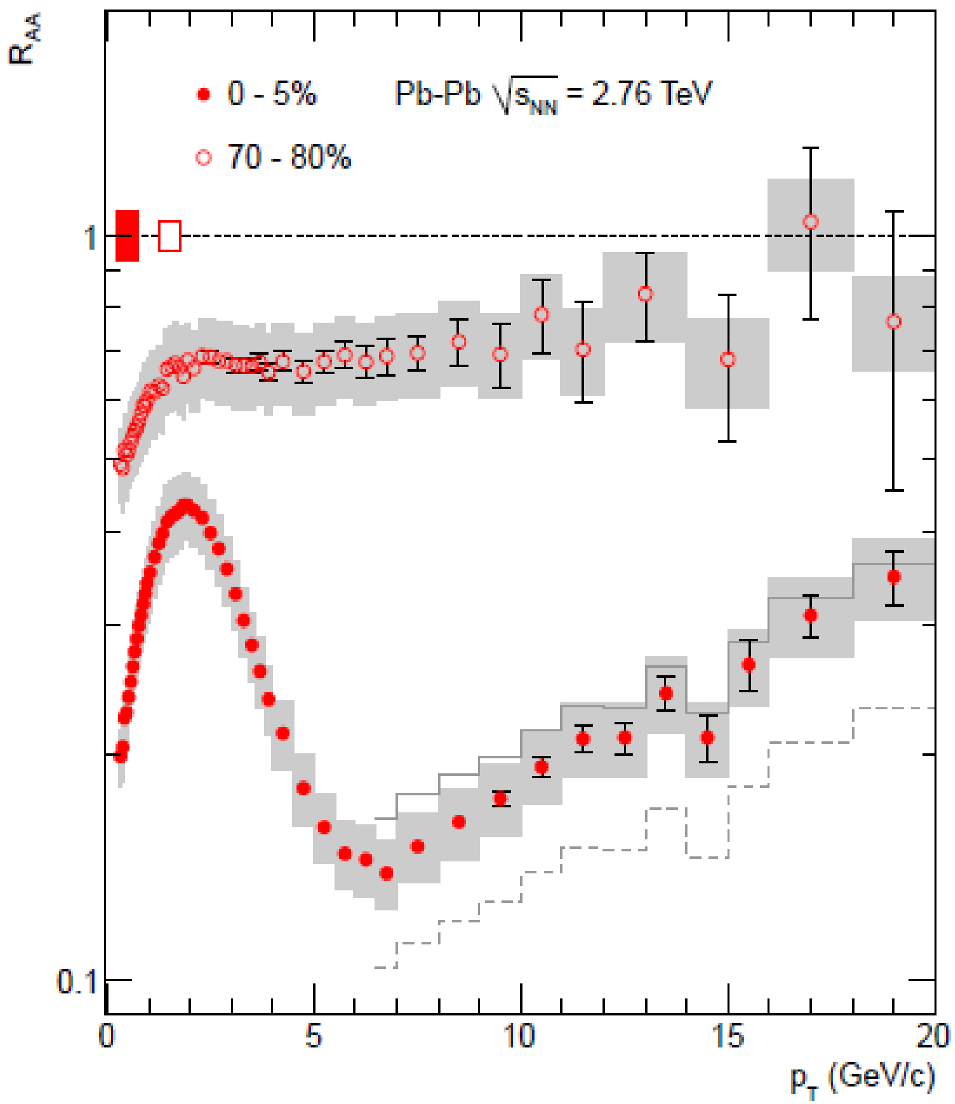
Events were separated into different collision centrality classes.

Spectra shape of Pb-Pb collision is compared to pp reference data, normalized by the number of binary collisions.

Suppressions also observed in LHC

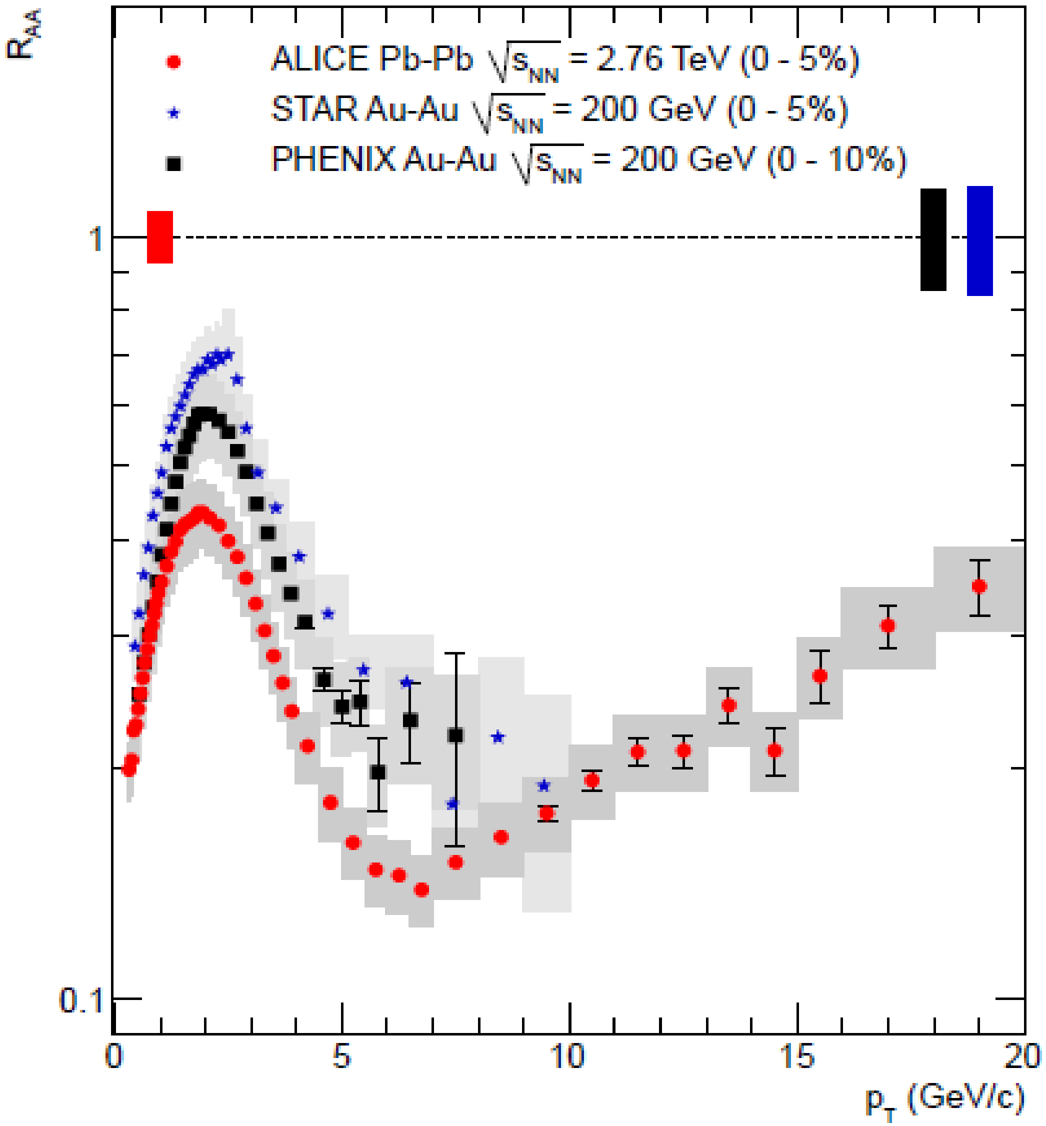
PLB 696 (2011) 30, ALICE Collab.





Suppressions also observed in LHC

PLB 696 (2011) 30, ALICE Collab.

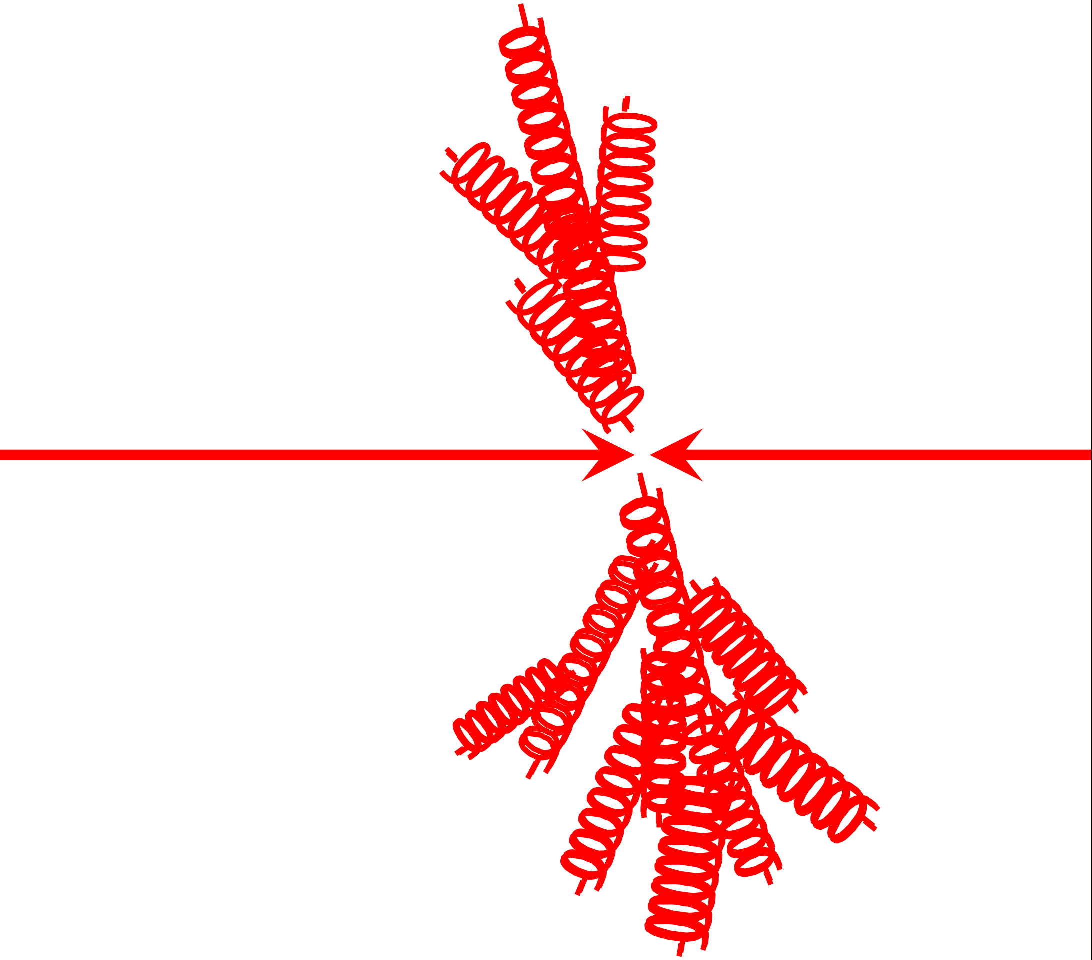


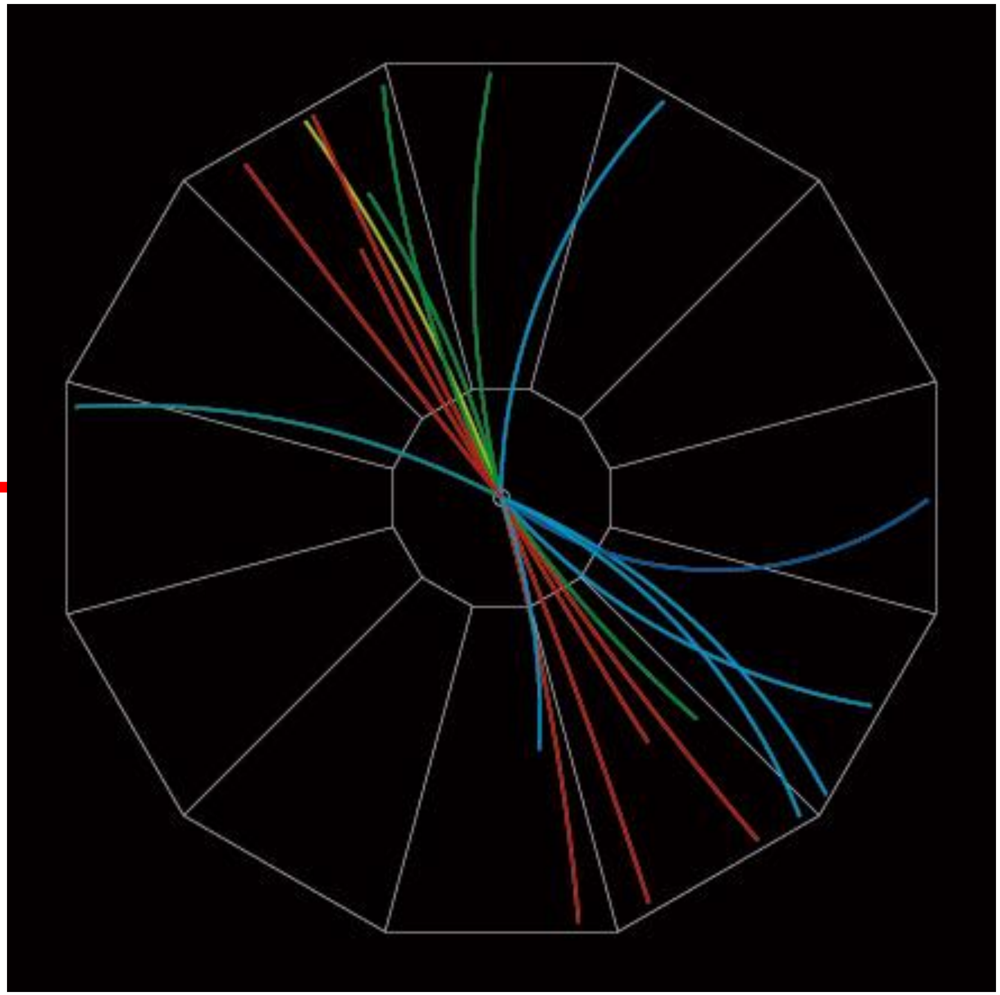
Enhanced energy loss at LHC
→ denser medium

R_{AA} increases significantly for pT>7 GeV/c
→ Could indicate "punch through"

Hard Scattering

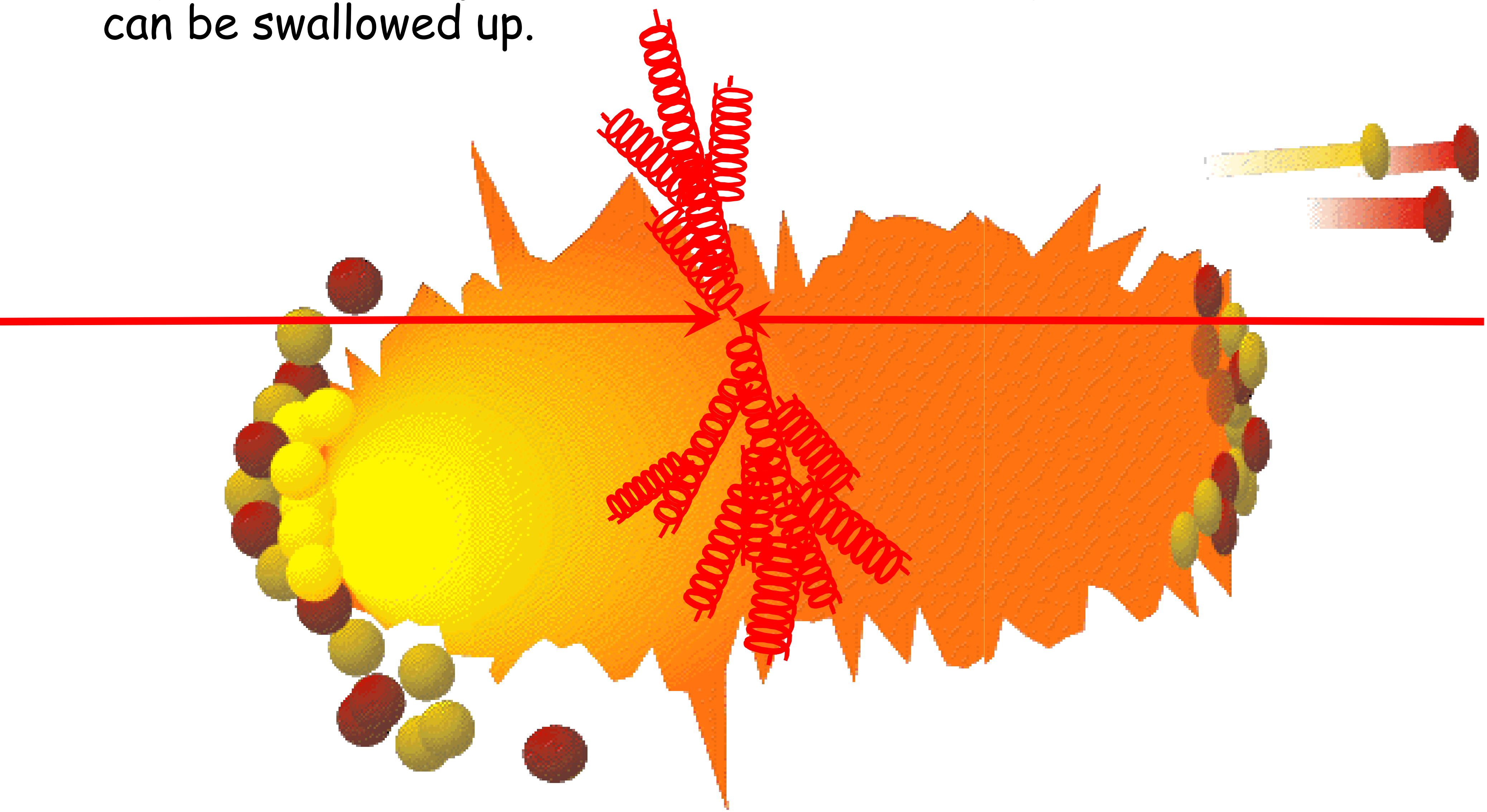
Parton-Parton scattering with high Q^2 produces back to back particle jets, with high transverse momentum particles.



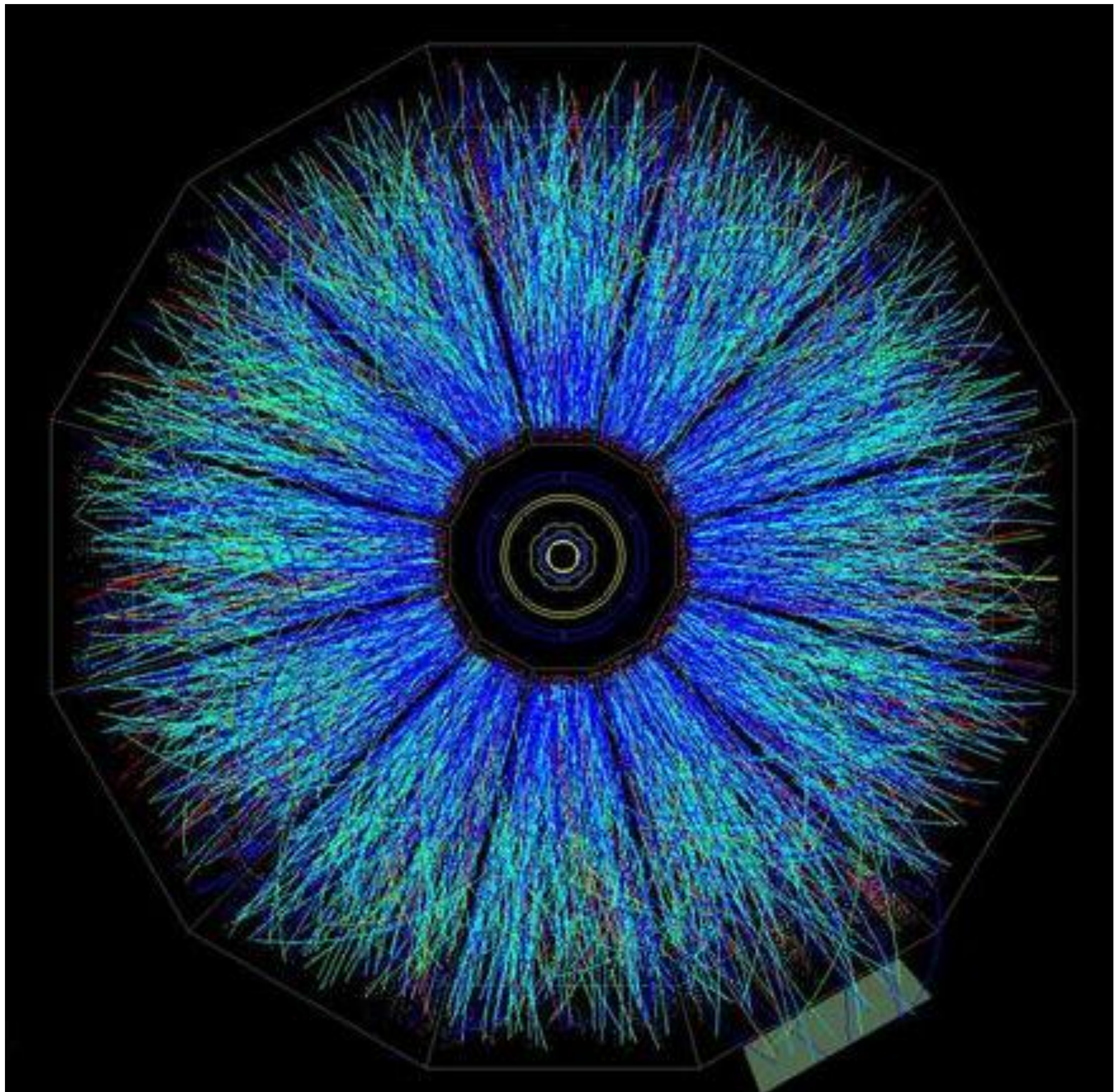


Color Probes of the Medium

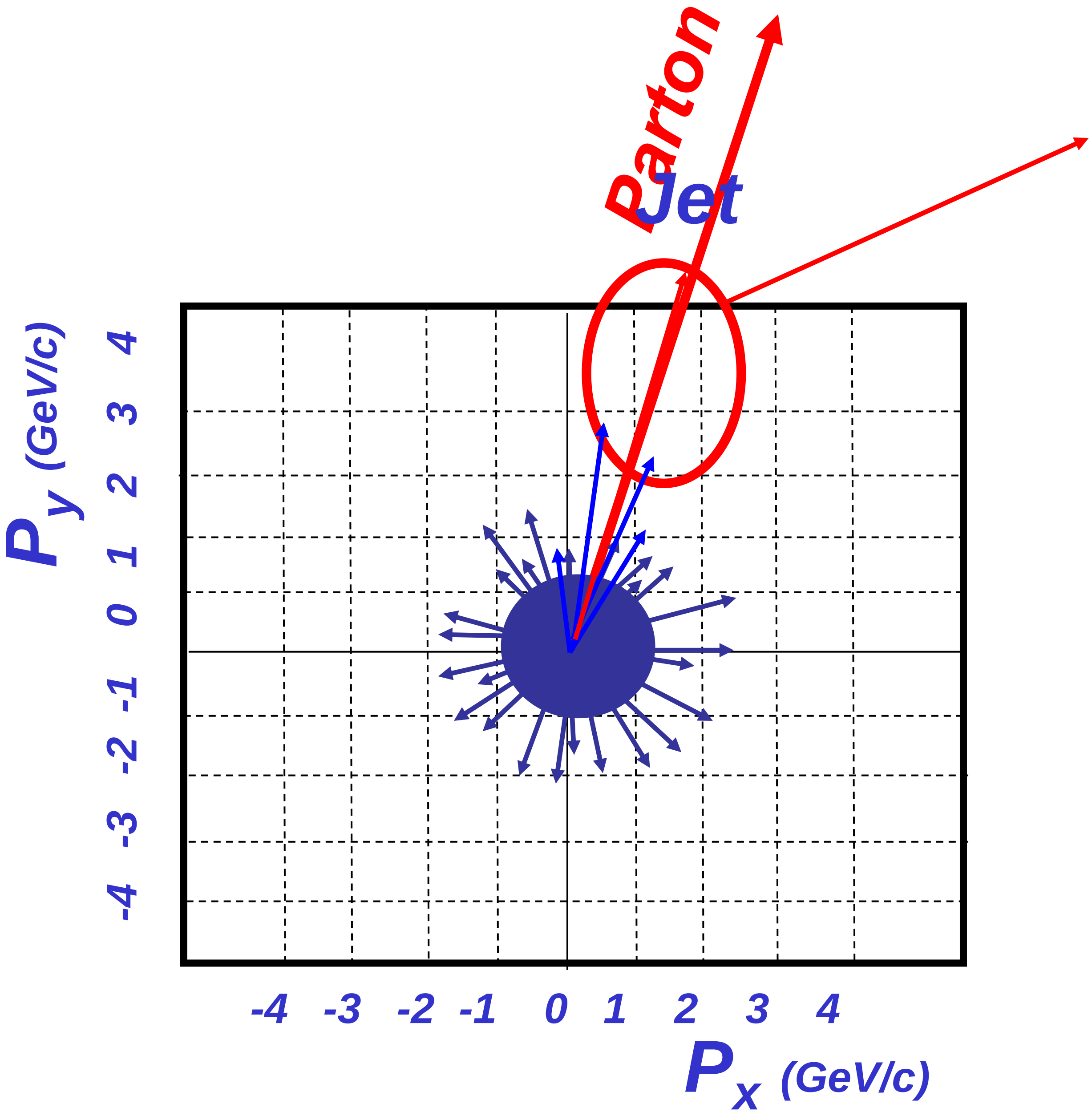
If the jet pair is produced inside a plasma dense enough, we expect that the jet quark or gluon will dissipate energy and can be swallowed up.



But, can we do jet reconstruction in a HI environment?



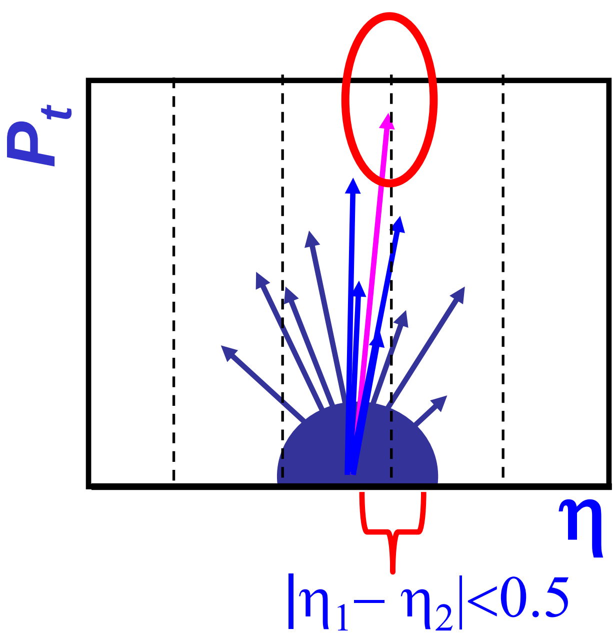
How do we find Jet in HI environment ?



Find the leading particle in the event, highest pt.

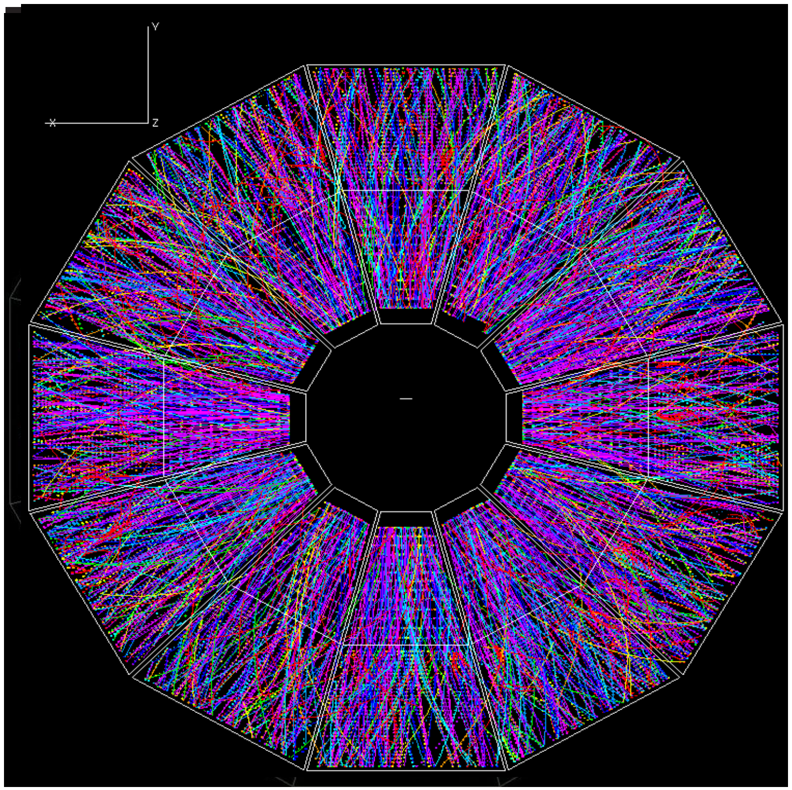
Calculate the angular distribution of all particle with respect to the leading particle.

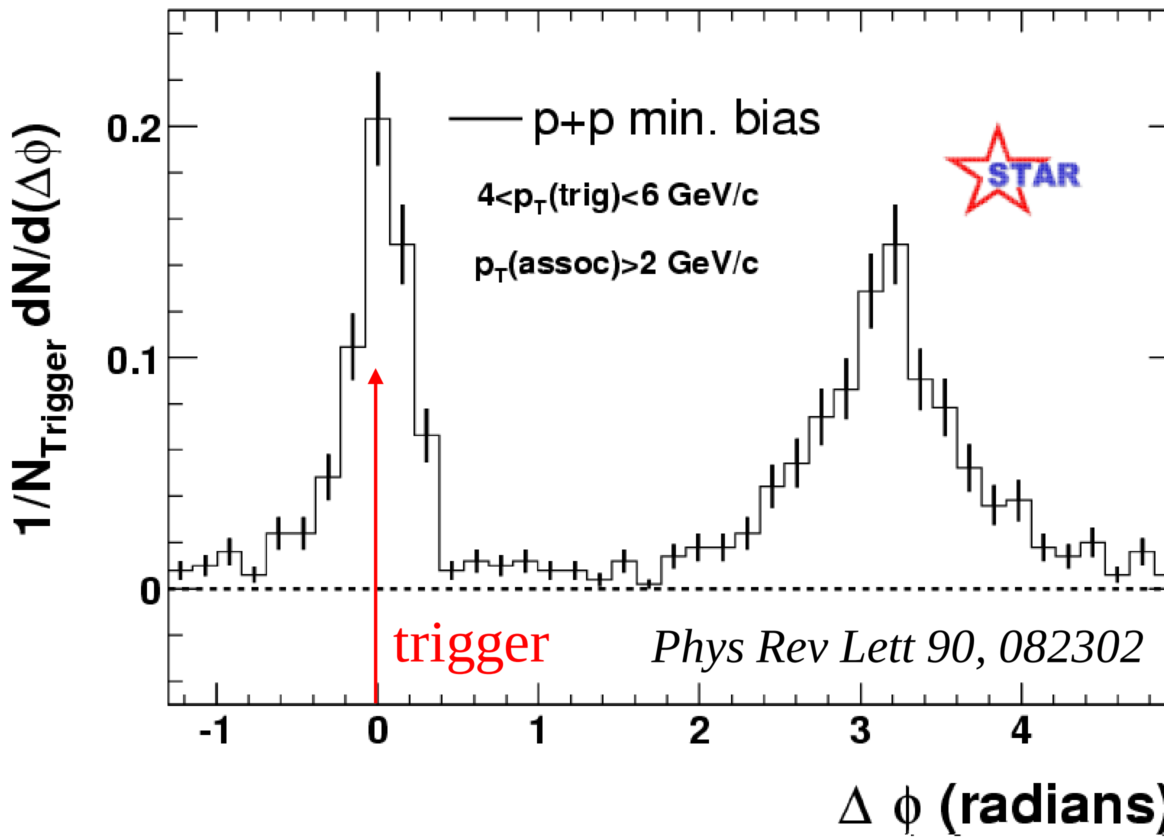
To reduce the background, we use a pt threshold, p_t>2 GeV/c



Azimuthal correlation of Jets

p+p → dijet

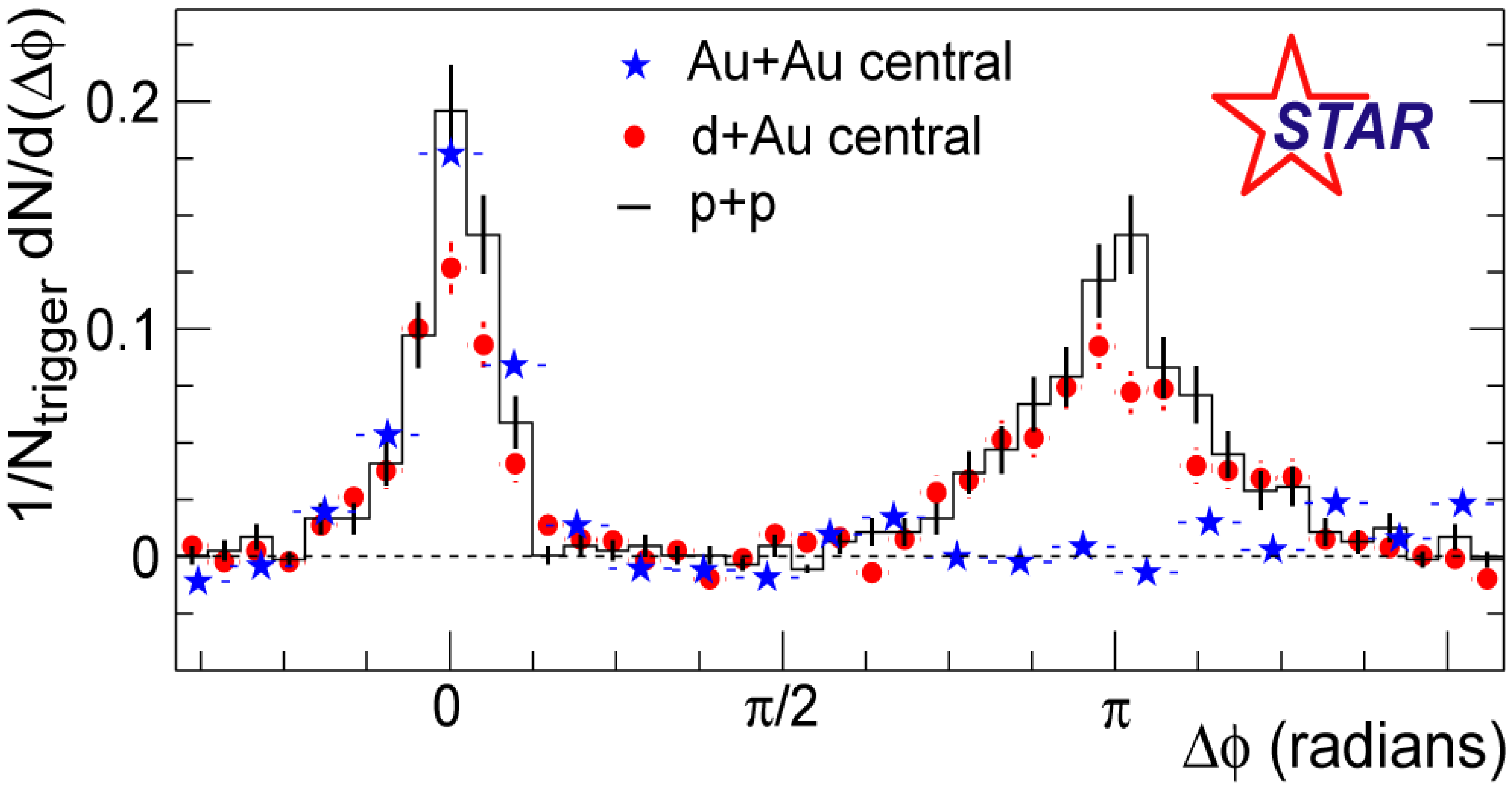




$\Delta\phi \approx 0$: Au+Au peripheral collision similar a p+p
$\Delta\phi \approx \pi$: Strong suppression of back-to back jets in central Au+Au collisions.

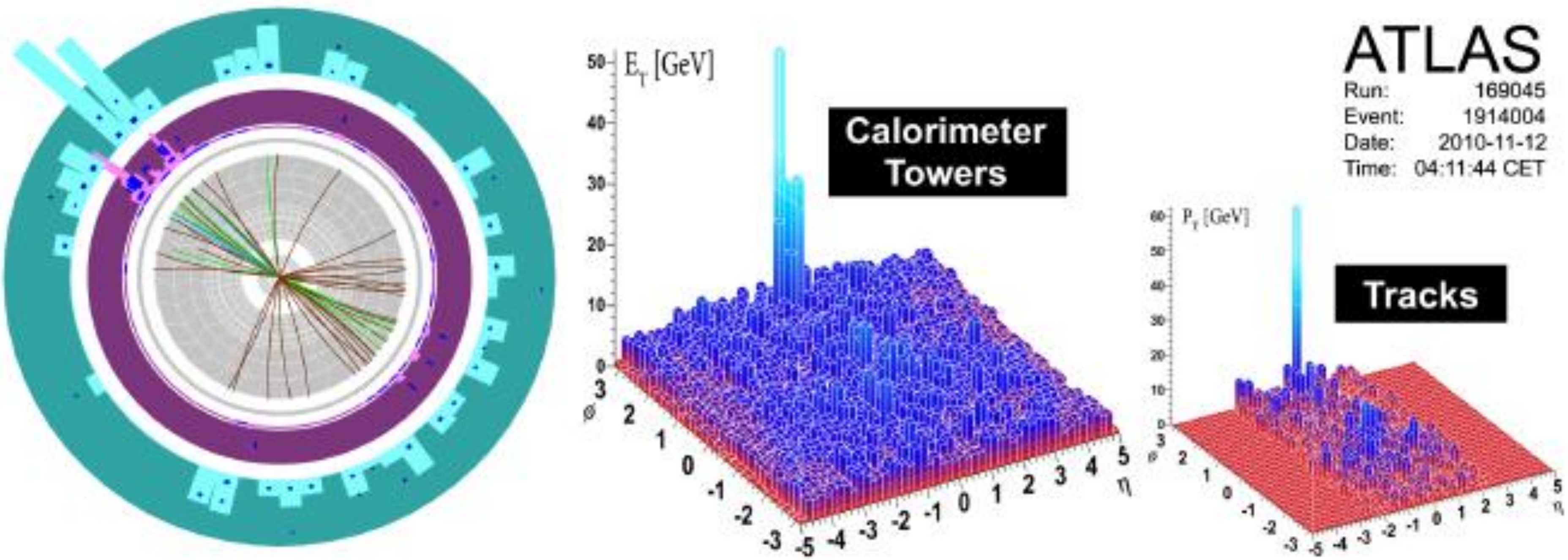
Comparison to control experiment d+Au

Can the Jet suppression observed at Au+Au collisions be an effect of the initial state (CGC) condition instead of a absorption in the final state interaction?



Jet suppression at LHC

arXiv: 1011.6182 (2010) [hep-ex] ATLAS Collab.



Jet suppression also observed at LHC in Pb-Pb collisions at 2.76 TeV.
"Transverse energy of dijets in opposite hemispheres is observed to become systematically more unbalanced with increasing event centrality"

What we know from RHIC

From the Soft part of the data:

At RHIC most particles are generated through pair production.

System has high pressure, with rapid expansion and fast equilibration.

Thermal and chemical freeze-out temperatures consistent with phase transition.

Collective behavior with high v2, indicating low viscosity.

From the hard part of the data:

It is strongly interacting and causes Jet Quenching.

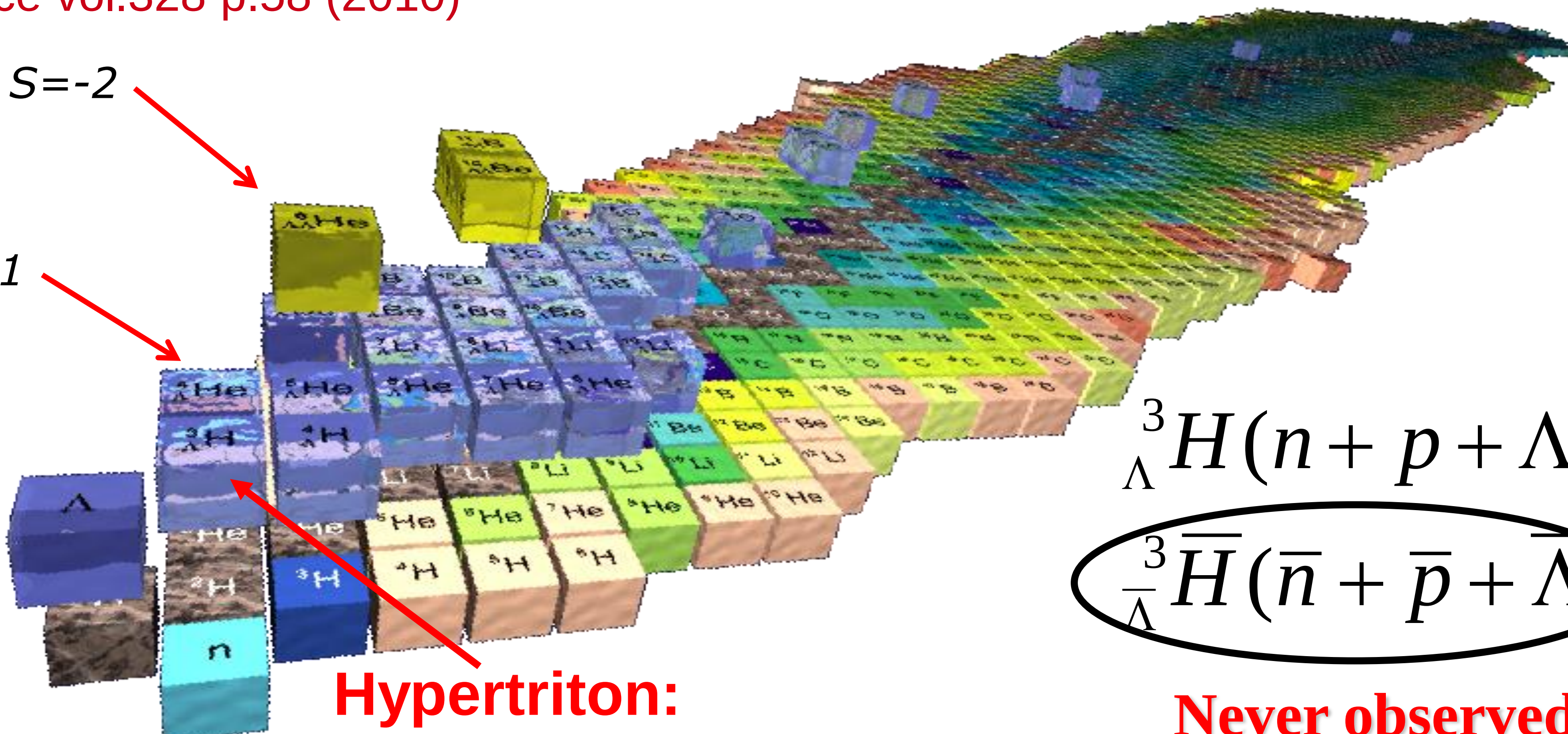
We have successfully created a Quark-Gluon Plasma, the same phase from the early universe, with a strongly interacting deconfined quarks and gluons, but, surprisingly it behaves like a Perfect Liquid !!!!

Observation of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ @RHIC

Science vol.328 p.58 (2010)

S=-2

S=-1



S=-0

$${}^{3}_{\Lambda}H(n+p+\Lambda)$$

$${}^{3}_{\bar{\Lambda}}\overline{H}(\bar{n}+\bar{p}+\overline{\Lambda})$$

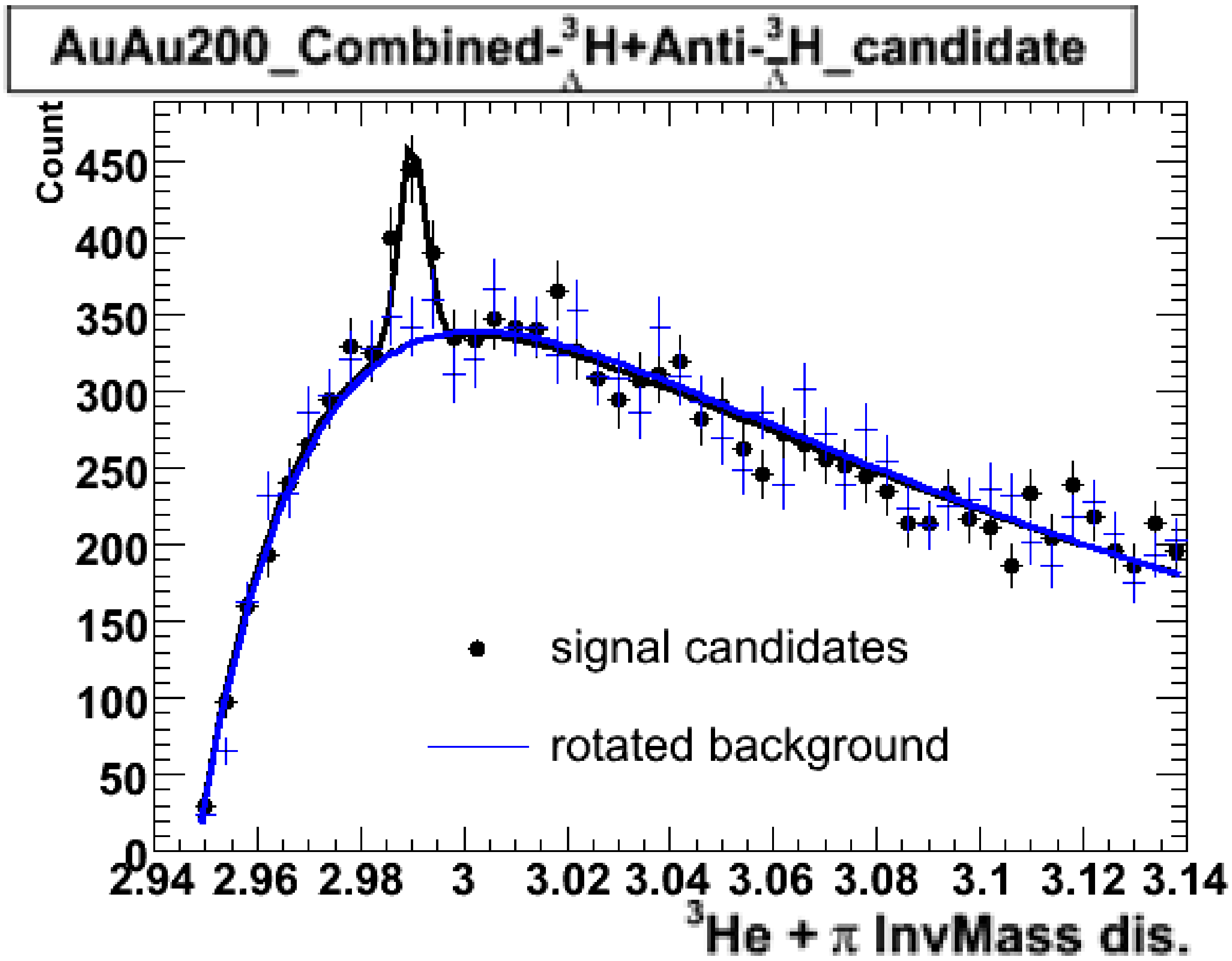
Hypertriton:

hypernucleus with lowest A

Never observed before !!!

- Y-N interaction: a good window to understand the baryon potential
- **Study the strange sector of baryon-baryon interaction**
- **Interesting for astrophysics objects, like neutron star**

Observation of ${}^{3}_{\Lambda}H$ and ${}^{3}_{\bar{\Lambda}}\overline{H}$ @RHIC

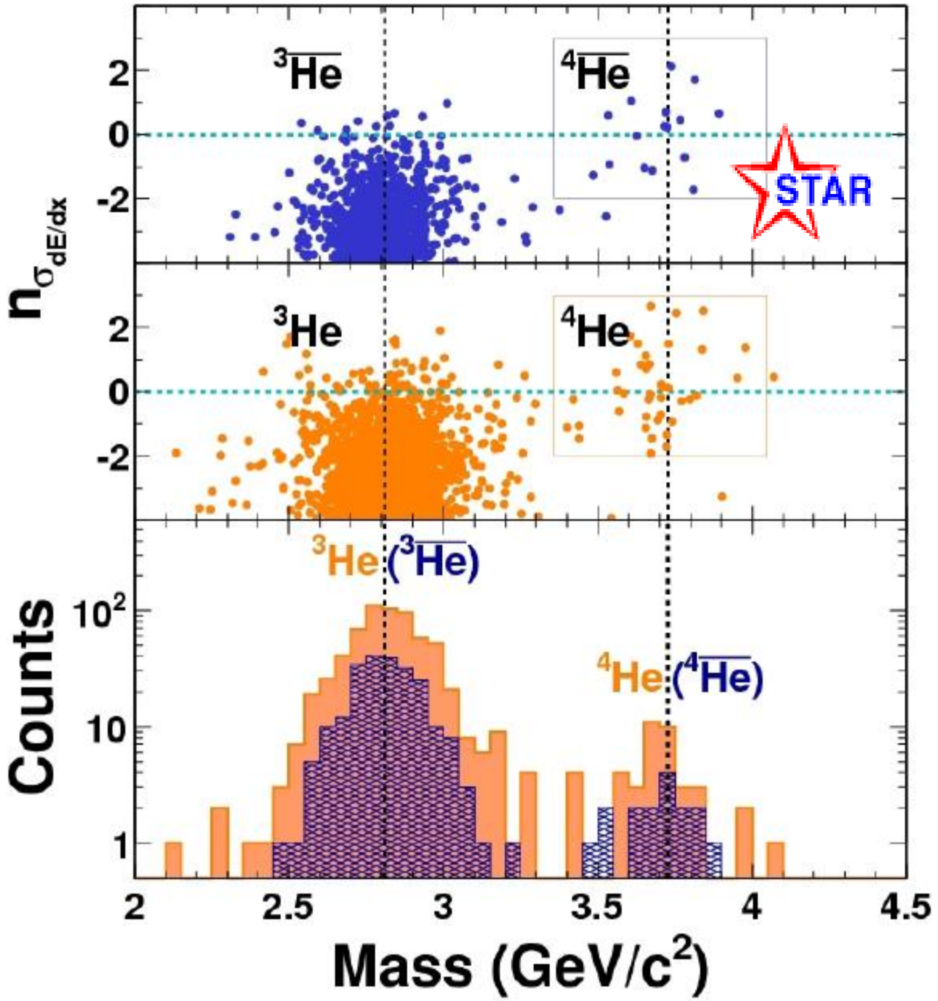


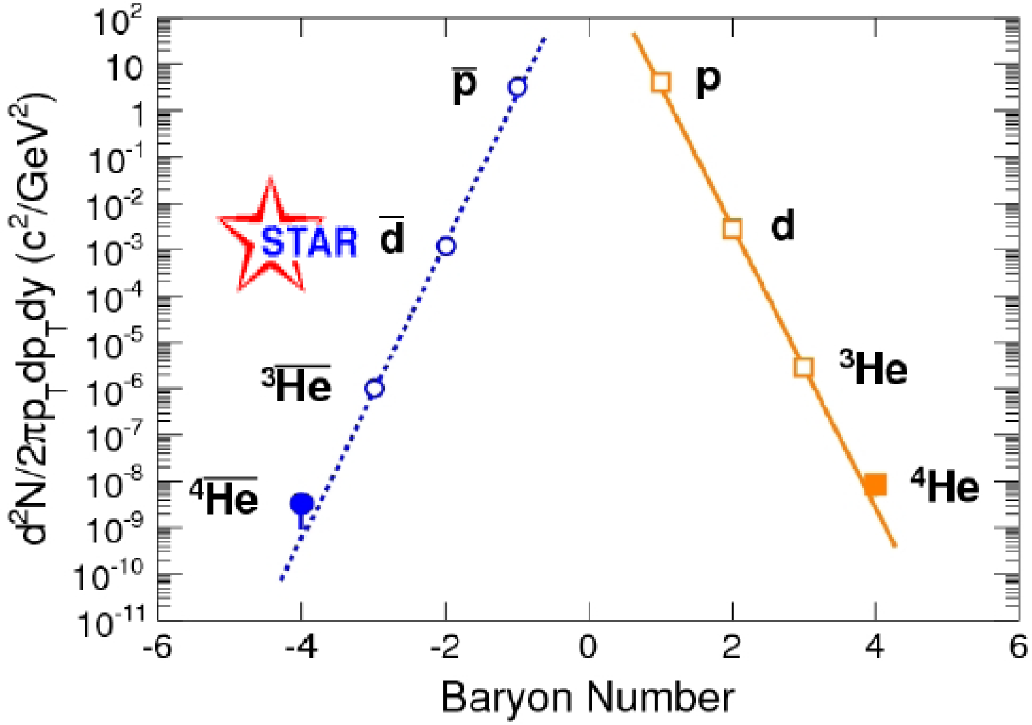
Science vol.328 p.58 (2010)

- First ever observation of an **anti-hypernucleus**.
- The hypertriton and anti-hypertriton lifetime: $\tau = 153 \pm^{43}_{30}\ ps$

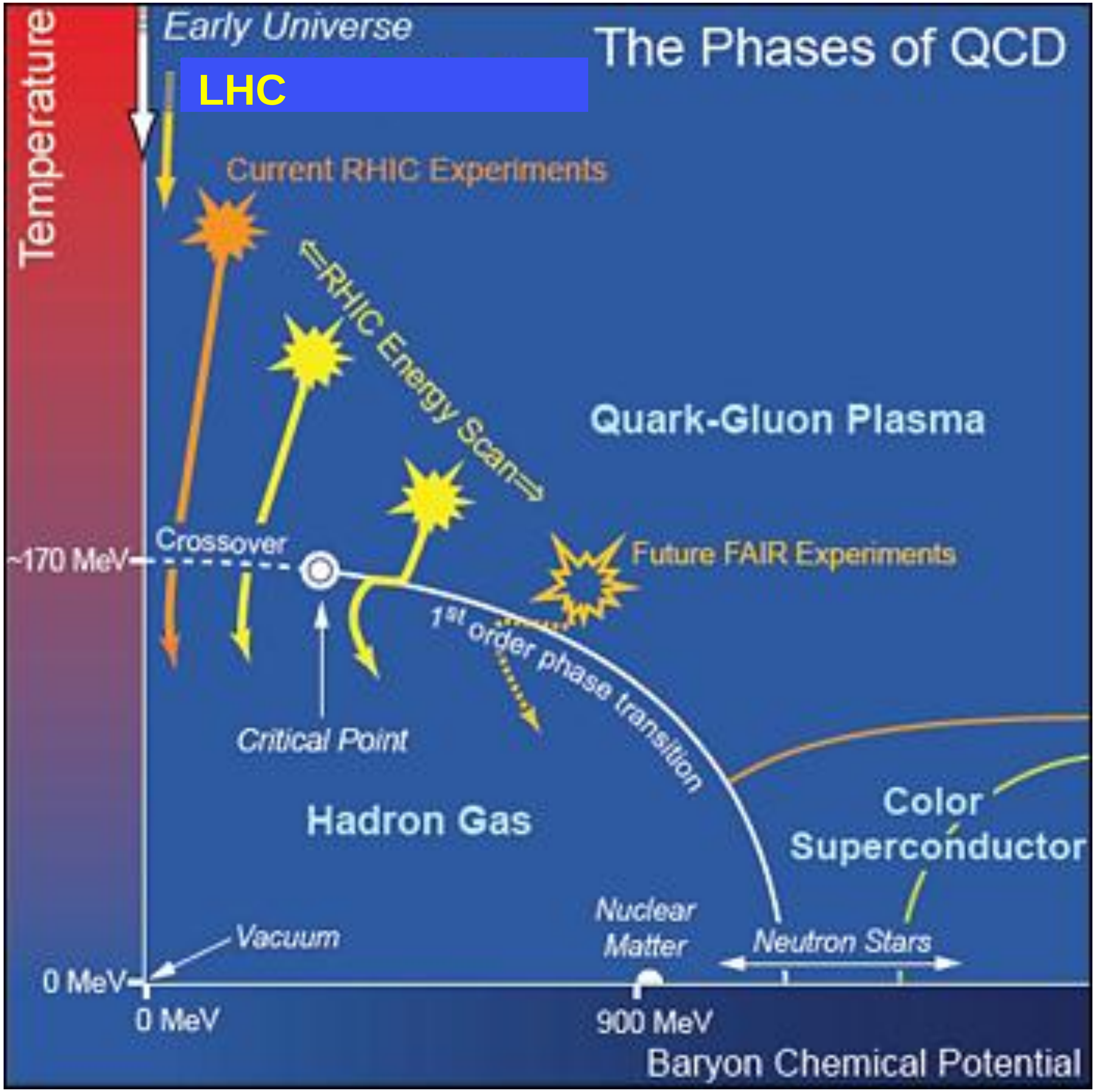
Observation of antimatter helium-4 nucleus

arXiv: 1103.3312v2 [nucl-ex]

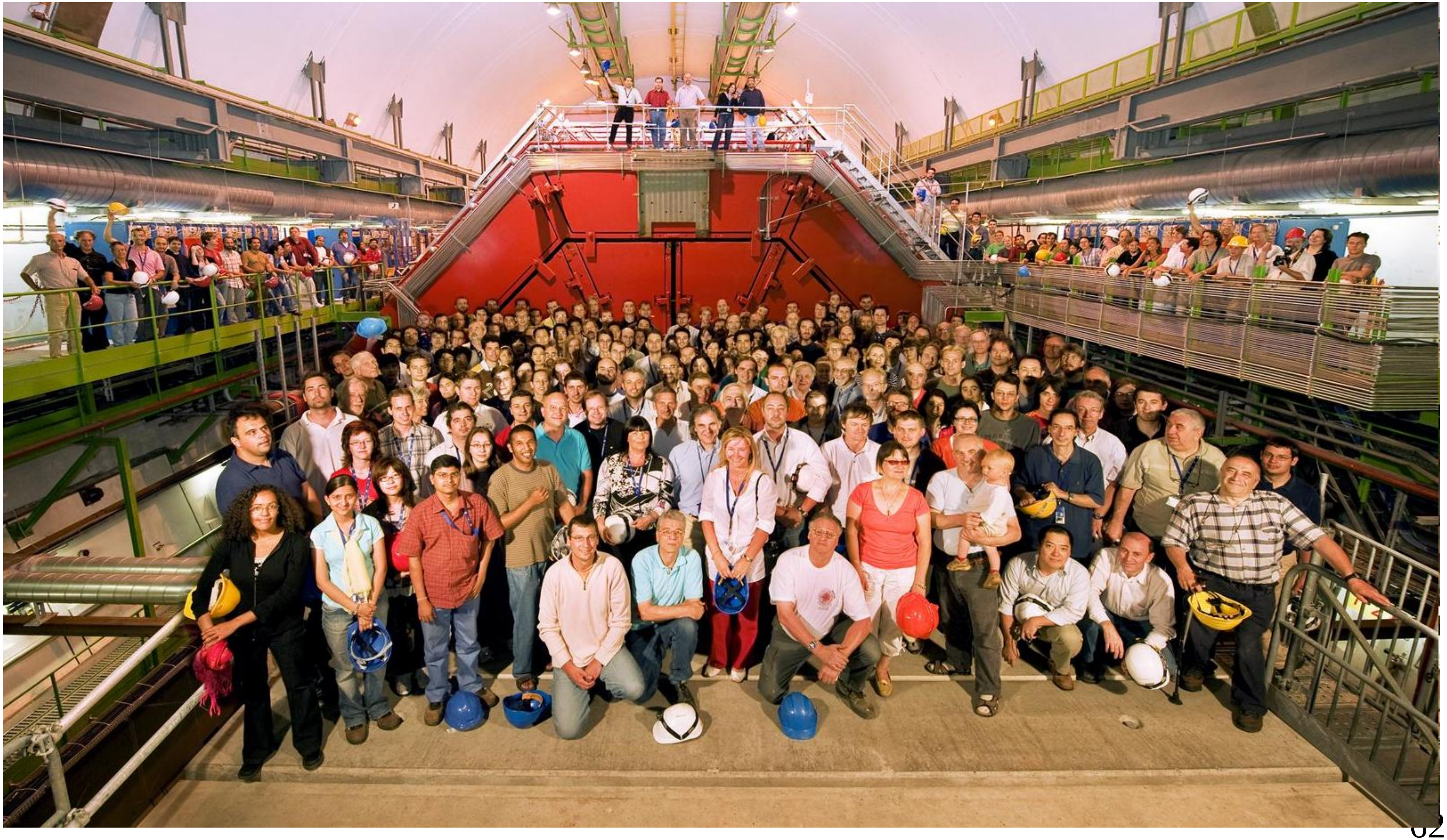




The QCD phase diagram, today and tomorrow



Many new results expected from PbPb data at the LHC



Thank you !!!