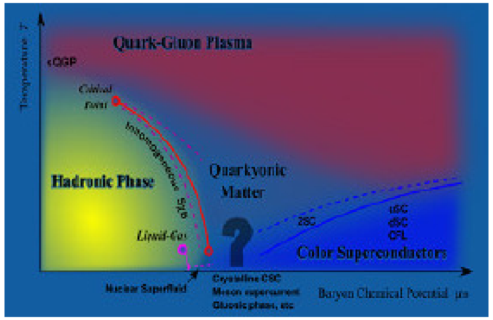
Observables of the deconfinement transition

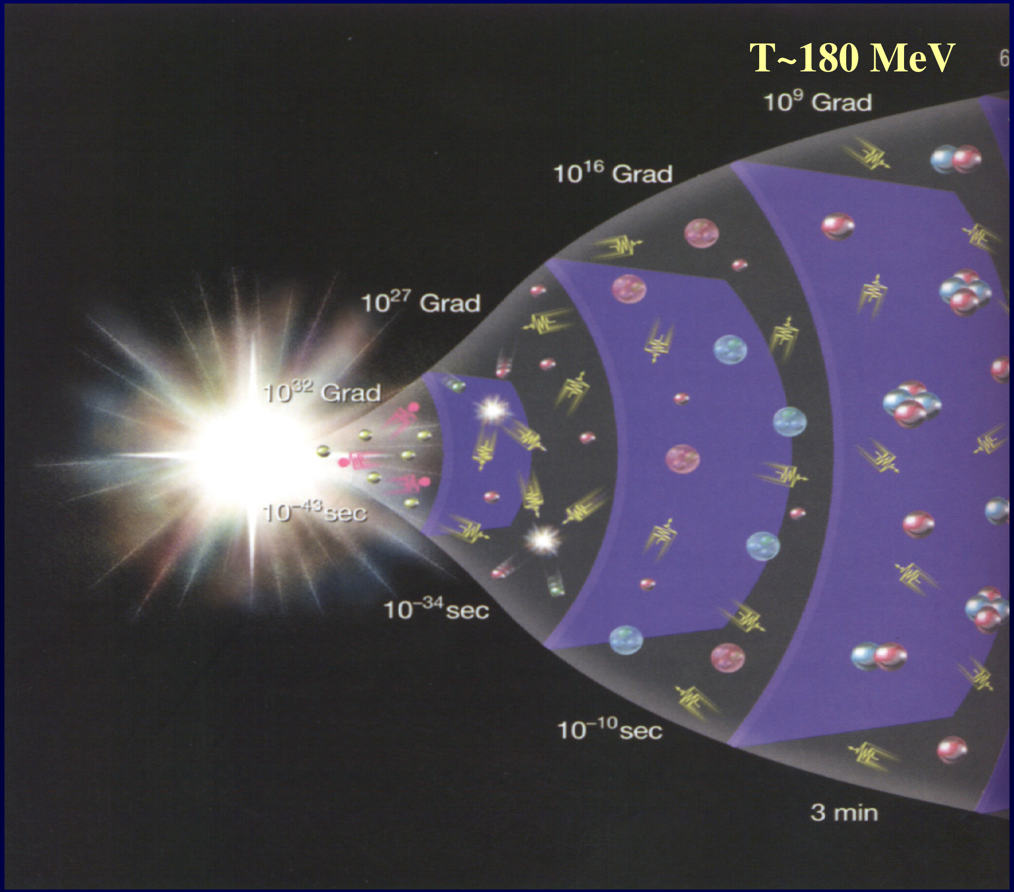
Elena Bratkovskaya

Institut für Theoretische Physik & FIAS, Uni. Frankfurt

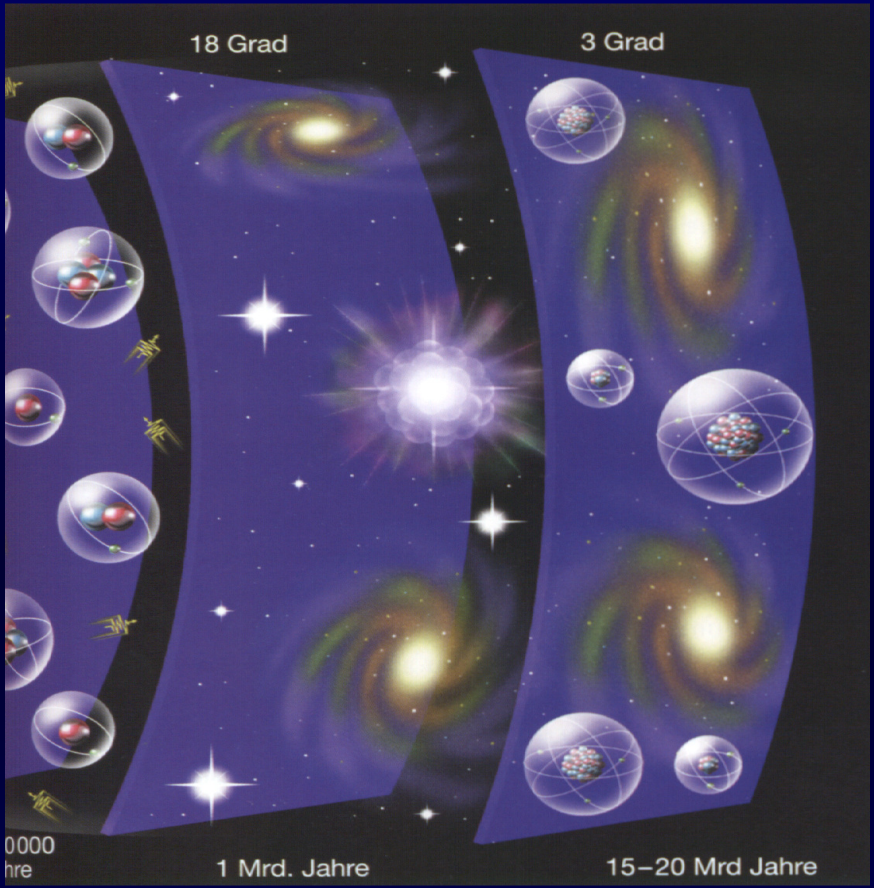
International Advanced School of Theoretical Physics “Dense QCD phases in Heavy-Ion Collisions” (DM2010).
August, 21 – September, 4, 2010, Dubna



From Big Bang to Formation of the Universe

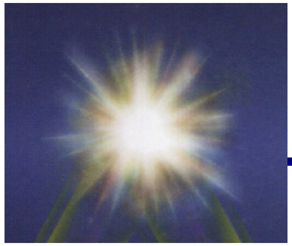


→



time	10^{-3}sec	3 min	300000 years	15 Mrd years
	quarks gluons photons	nucleons deuterons α–particles	atoms	our Universe

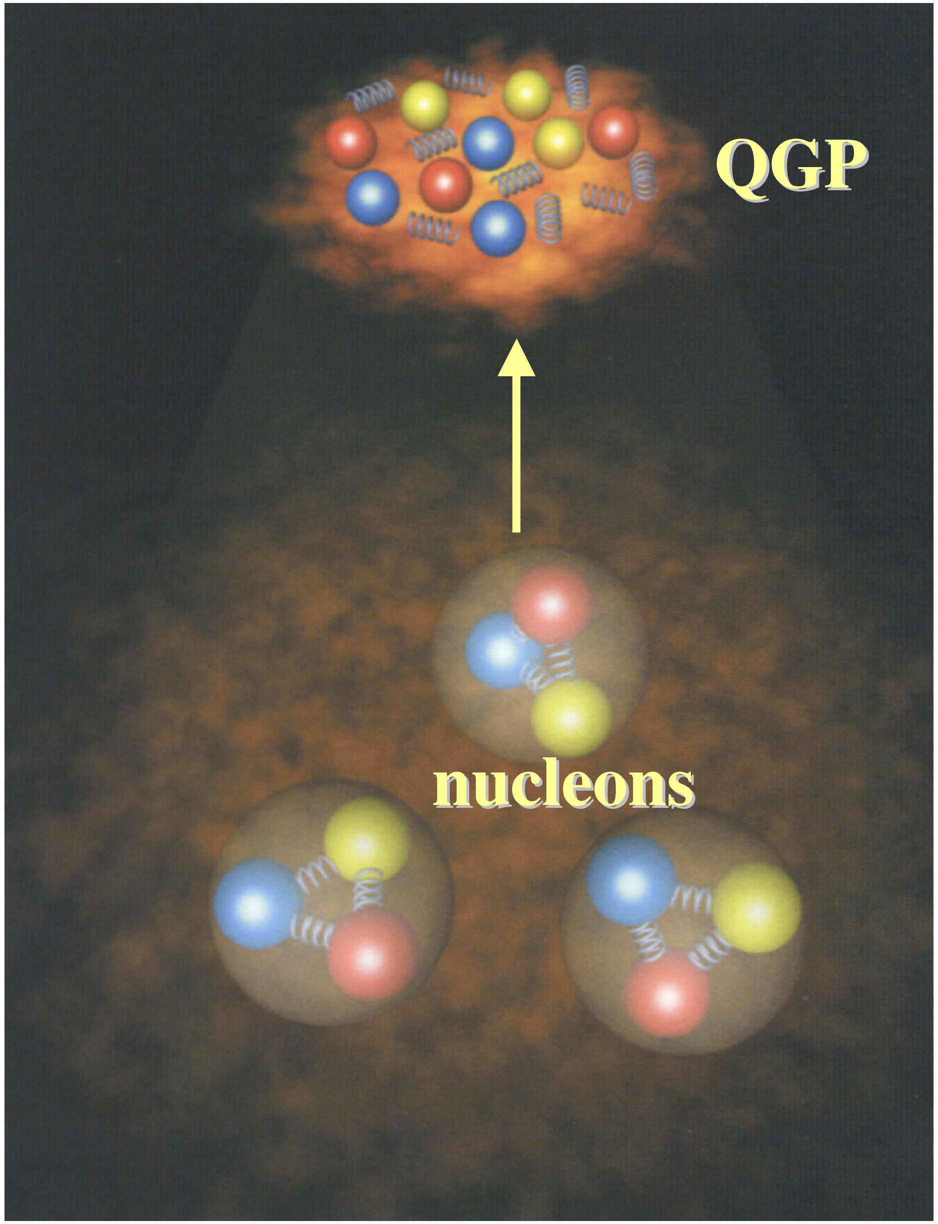
← **Can we go back in time ?**

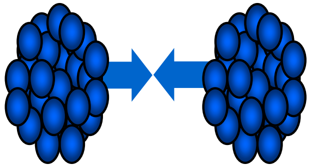


... back in time

‚Re-create‘ the Big Bang conditions:
matter at high temperature and pressure
such that
nucleons/mesons decouple to quarks and gluons --
Quark-Gluon-Plasma

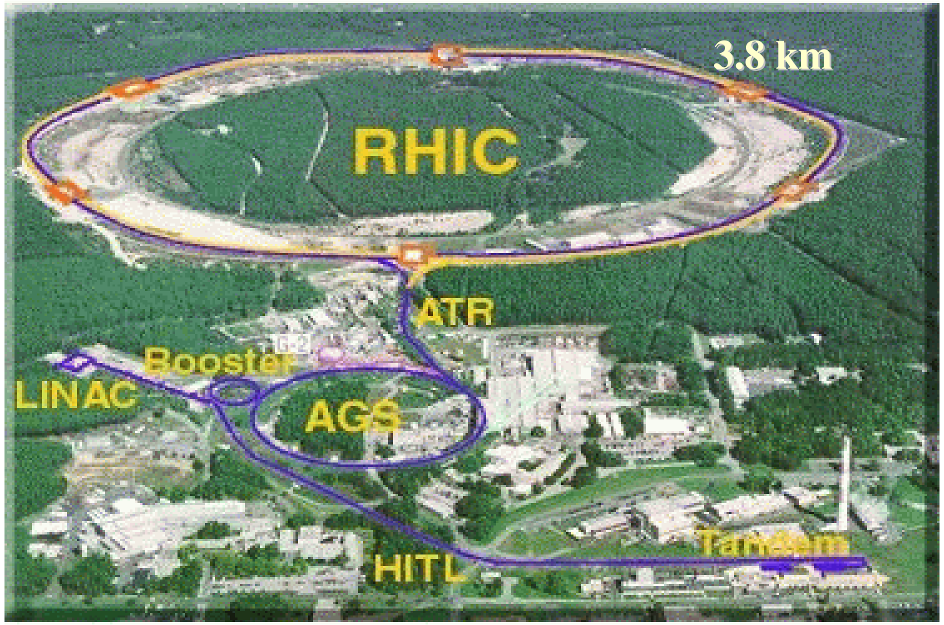
‚Little Bangs‘ in the Laboratory :
Heavy-ion collisions at ultrarelativistic energies





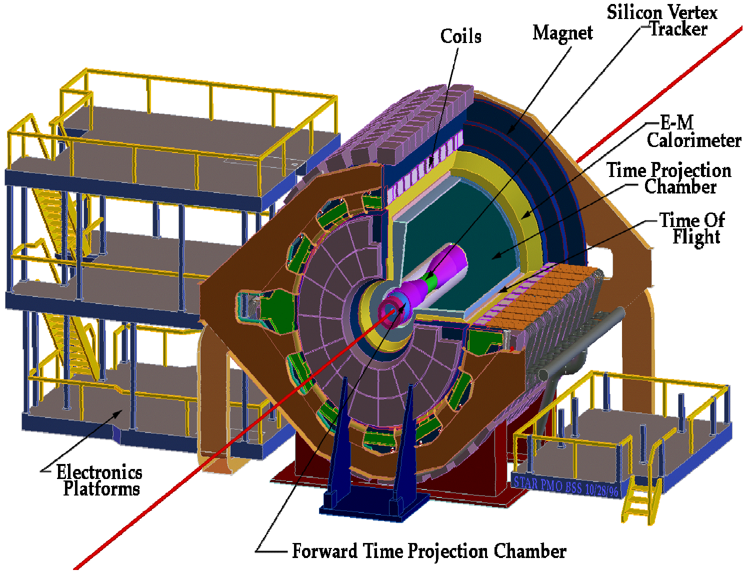
Heavy-ion accelerators

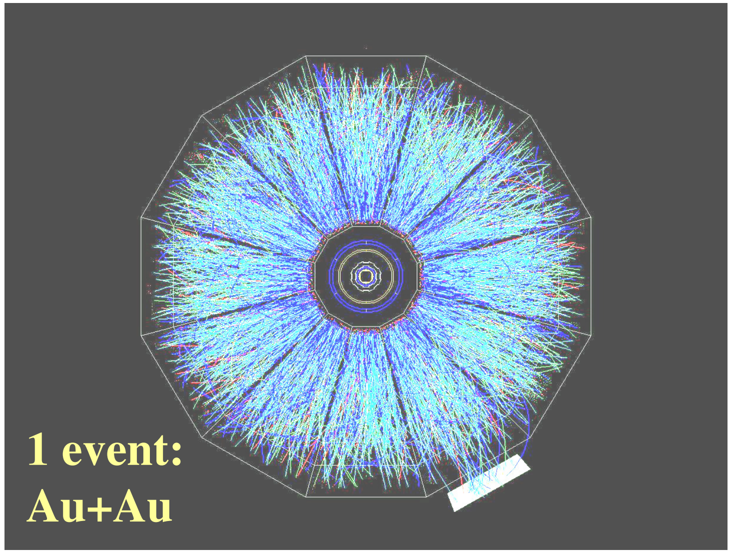
- **Super-Proton-Synchrotron – SPS - (CERN): Pb+Pb at 160 A GeV**
- **Relativistic-Heavy-Ion-Collider - RHIC - (Brookhaven): Au+Au at 21.3 A TeV**



- **Large Hadron Collider – LHC - (CERN): Pb+Pb at 574 A TeV**
- **Future facilities: FAIR (GSI), NICA (Dubna)**

STAR detector at RHIC



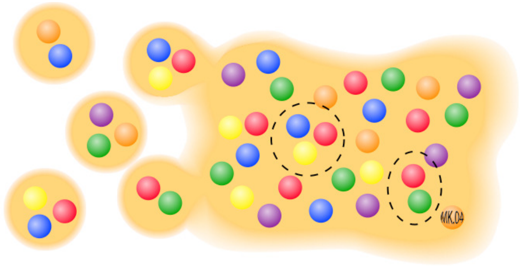


The QGP in Lattice QCD

Quantum Cromo Dynamics :

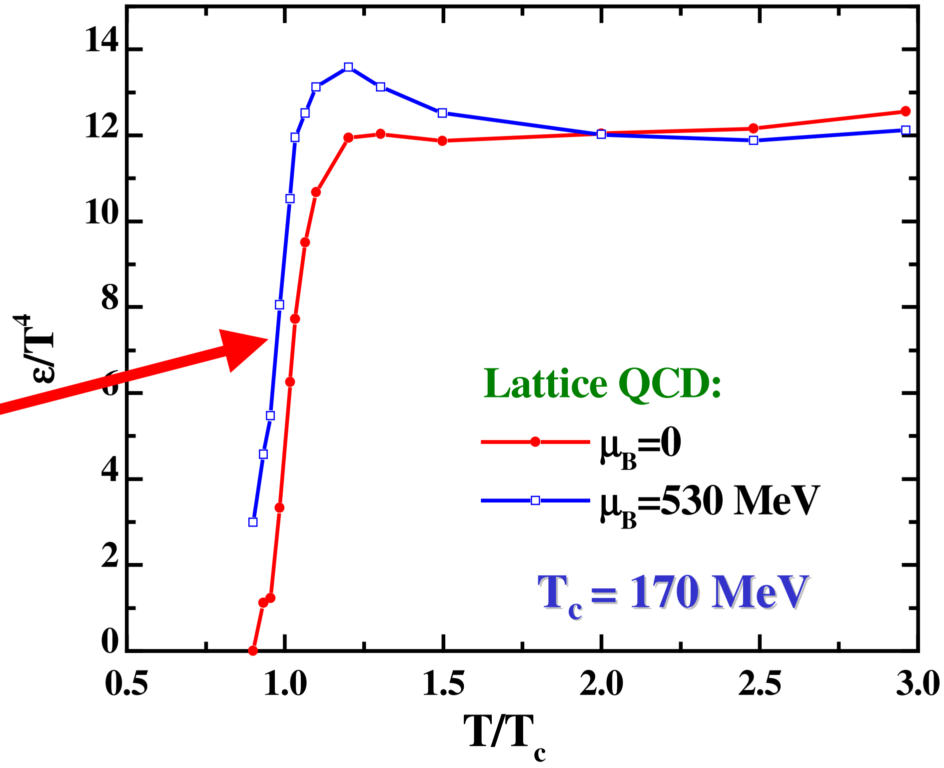
predicts strong increase of the energy density ε at critical temperature T_C ~170 MeV

⇒ Possible phase transition from hadronic to partonic matter (quarks, gluons) at critical energy density ε_C ~1 GeV/fm^3



Lattice QCD:

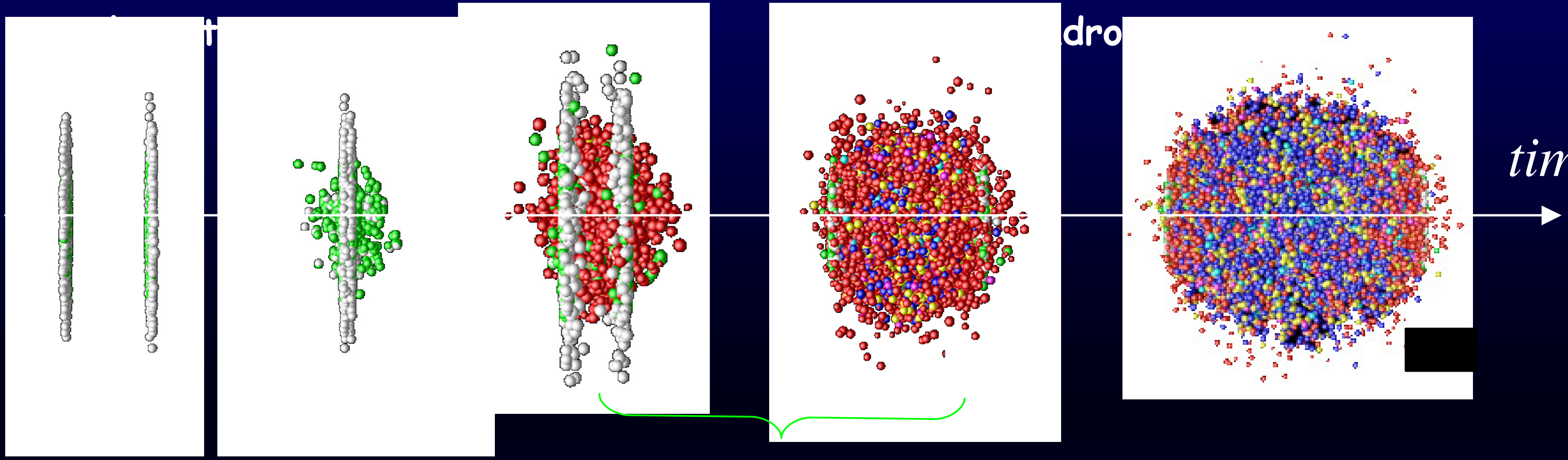
energy density versus temperature



Z. Fodor et al., PLB 568 (2003) 73

Critical conditions - ε_C ~1 GeV/fm^3 , T_C ~170 MeV - can be reached in heavy-ion experiments at bombarding energies > 5 GeV/A

‚Little Bangs‘ in the Laboratory



Quark-Gluon-Plasma ?

hadron
degrees
of freedom → quarks and gluons → hadron
degrees
of freedom

How can we proove that an equilibrium QGP has been created in central Au+Au collisions ?!

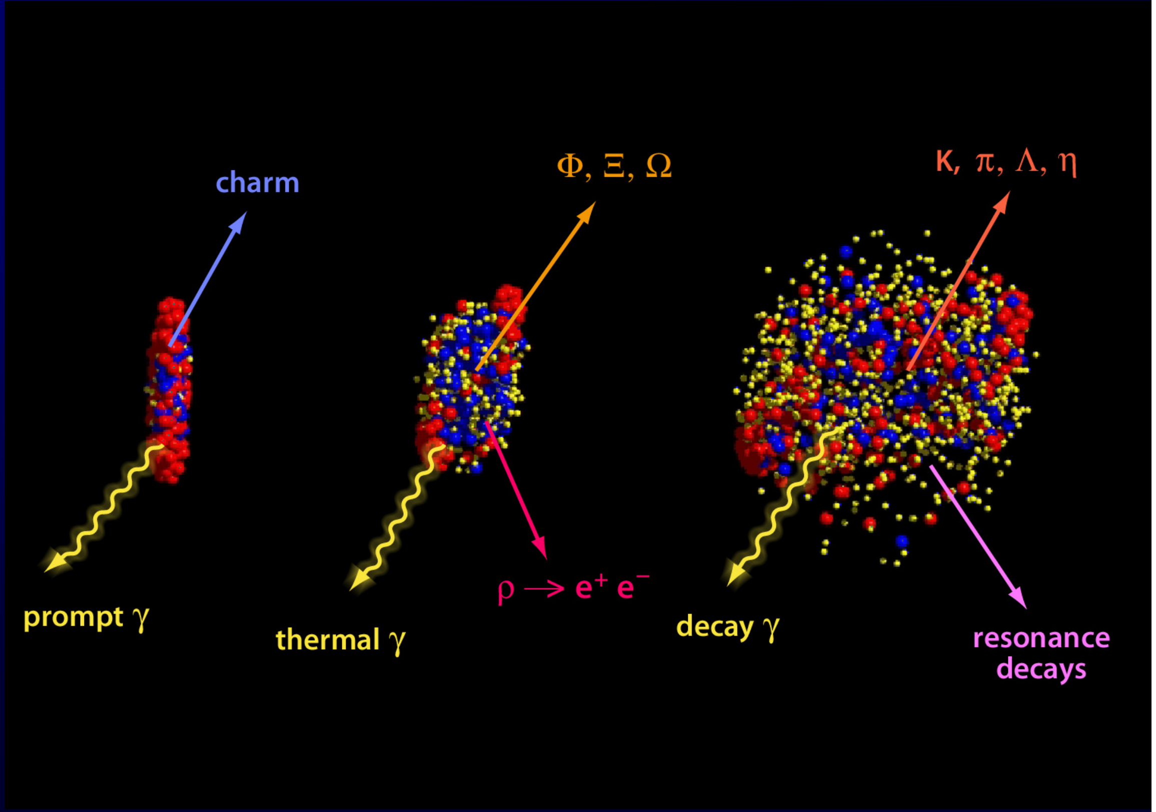
Signals of the phase transition:

- QGP dileptons
- Multi-strange particle enhancement in A+A
- Collective flow (v_1, v_2)
- Charm suppression
- Jet quenching and angular correlations
- High p_T suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- ...

Experiment: measures final hadrons and leptons

How to learn about physics from data?

Compare with theory!



Basic models for heavy-ion collisions

- **Statistical models:**

basic assumption: system is described by a (grand) canonical ensemble of non-interacting fermions and bosons in thermal and chemical equilibrium

[-: no dynamics]

- **Ideal hydrodynamical models:**

basic assumption: conservation laws + equation of state; assumption of local thermal and chemical equilibrium

[-: - simplified dynamics]

- **Transport models:**

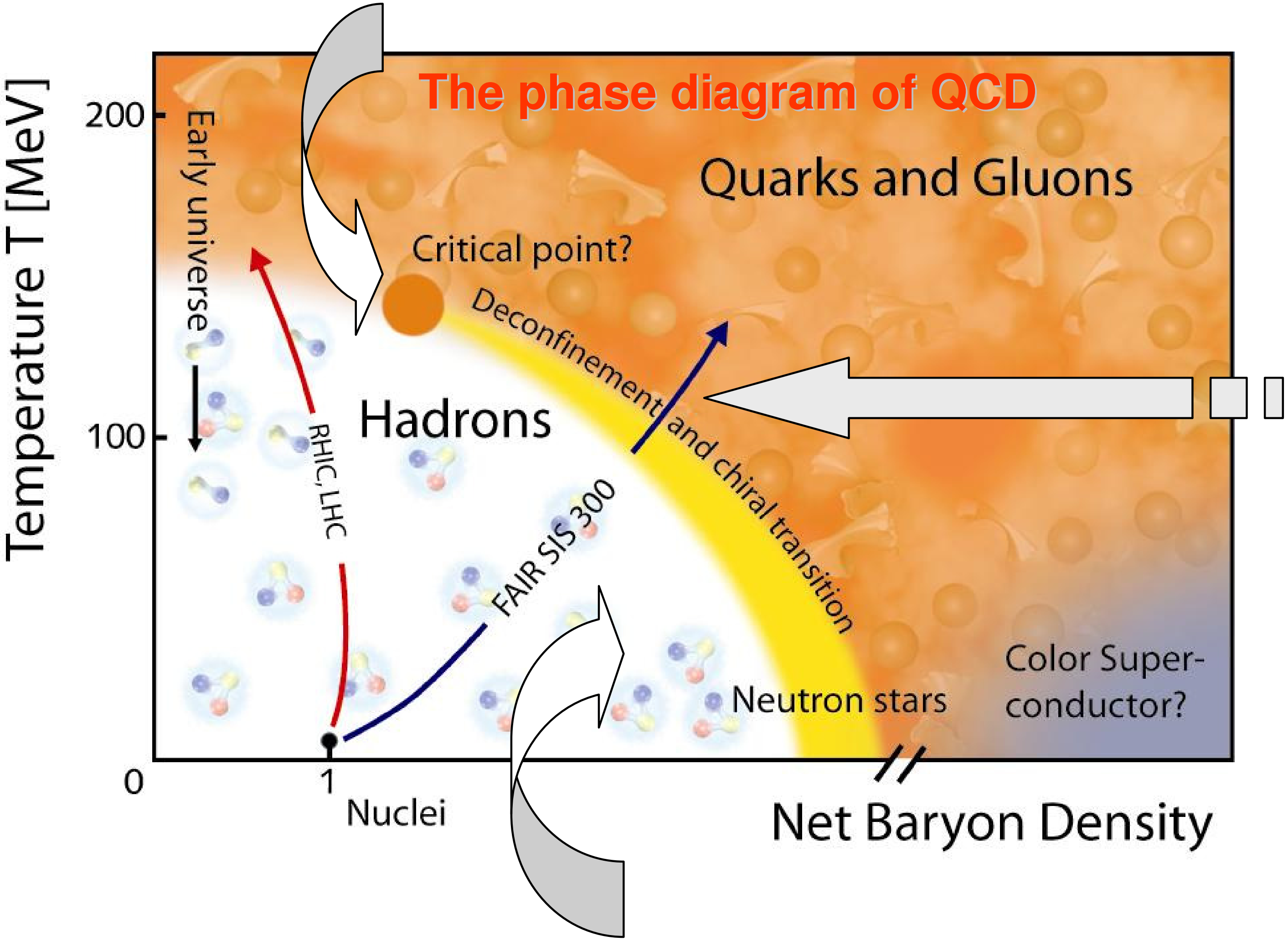
based on transport theory of relativistic quantum many-body systems - off-shell Kadanoff-Baym equations for the Green-functions $S^{<}_{h}(x,p)$ in phase-space representation. Actual solutions: Monte Carlo simulations with a large number of test-particles

[+: full dynamics | -: very complicated]

➔ Microscopic transport models provide a unique dynamical description of nonequilibrium effects in heavy-ion collisions

Our ultimate goals:

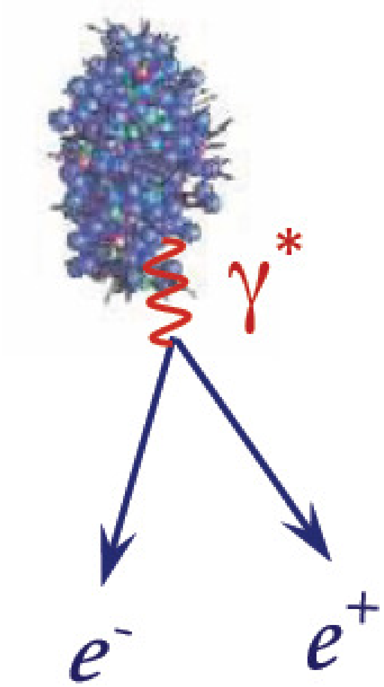
- Search for the critical point

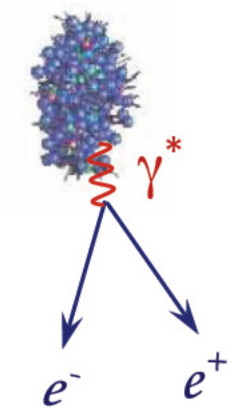


- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma

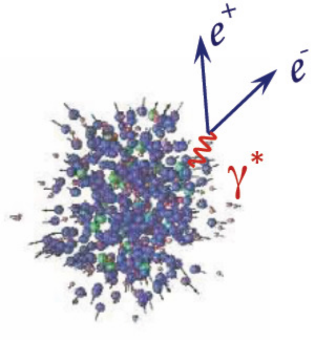
- Study of the in-medium properties of hadrons at high baryon density and temperature

Dileptons





Electromagnetic probes: dileptons and photons



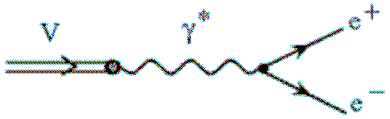
- Dileptons are emitted from different stages of the reaction and not effected by final-state interactions

Dilepton sources:

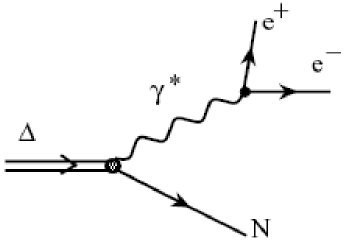
- from the QGP via partonic (q,qbar, g) interactions:

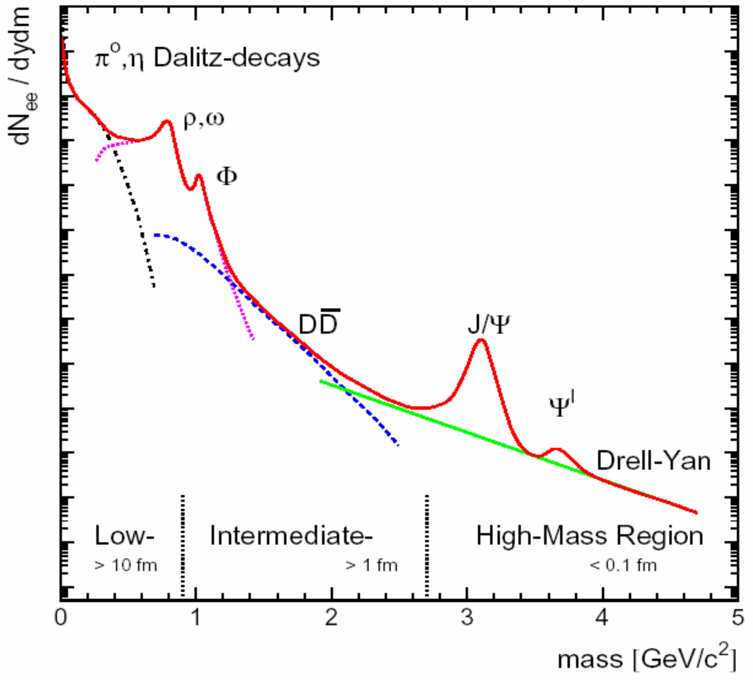
- from hadronic sources:

- direct decay of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ‘)



- Dalitz decay of mesons and baryons (π^0,η, Δ,…)





➔ Dileptons are an ideal probe to study the properties of the hot and dense medium

Dilepton cocktail

- All particles decaying to dileptons are first produced in BB, mB or mm collisions

i	Dilepton channel
1	Dalitz decay of π^0: $\pi^0 \to \gamma e^+ e^-$
2	Dalitz decay of η: $\eta \to \gamma e^+ e^-$ (or $\mu^+\mu^-$)
3	Dalitz decay of ω: $\omega \to \pi^0 e^+ e^-$
4	Dalitz decay of Δ: $\Delta \to N e^+ e^-$
5	direct decay of ω: $\omega \to e^+ e^-$
6	direct decay of ρ: $\rho \to e^+ e^-$
7	direct decay of ϕ: $\phi \to e^+ e^-$
8	direct decay of J/Ψ: $J/\Psi \to e^+ e^-$
9	direct decay of Ψ': $\Psi' \to e^+ e^-$
10	Dalitz decay of η': $\eta' \to \gamma e^+ e^-$
11	pn bremsstrahlung: $pn \to pne^+ e^-$
12	$\pi^\pm N$ bremsstrahlung: $\pi^\pm N \to \pi N e^+ e^-$, where $N = p$ or n

p+p, p+A collisions

π+p, π+A collisions

heavy-ion collisions

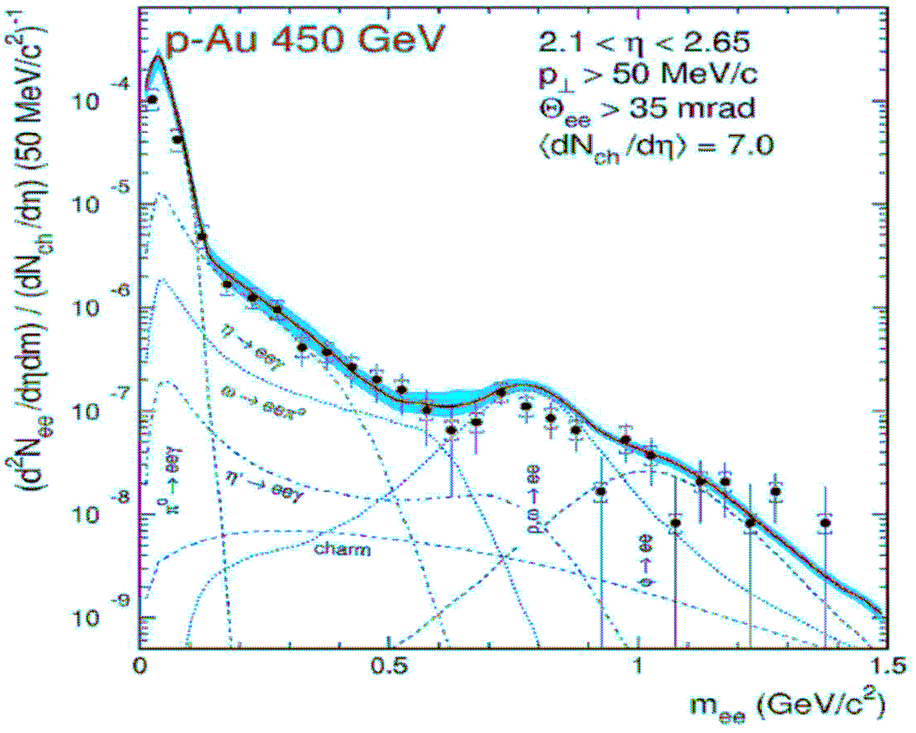
$$\mathbf{BB \to RX}$$

$$\mathbf{mB \to RX}$$

$$\mathbf{R \to e^+e^-X}$$

$$\mathbf{R \to mX,\ m \to e^+e^-X}$$

$$\mathbf{R \to R'X,\ R' \to e^+e^-X}$$



Changes of the particle properties in the hot and dense baryonic medium

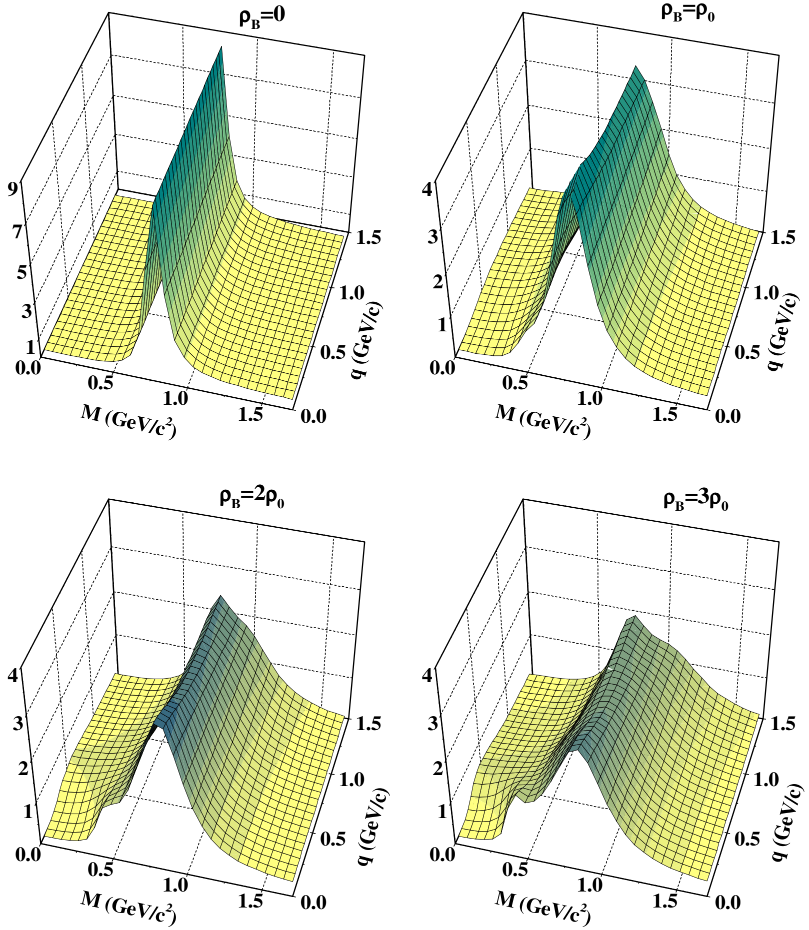
In-medium models:

- chiral perturbation theory
- chiral SU(3) model
- coupled-channel G-matrix approach
- chiral coupled-channel effective field theory

predict changes of the particle properties in the hot and dense medium, e.g. broadening of the spectral function

R. Rapp: ρ meson spectral function

$-\mathrm{Im}\, D_\rho\, (M,q,\rho_B,T)\ (\mathrm{GeV}^{-2})$
T=150 MeV



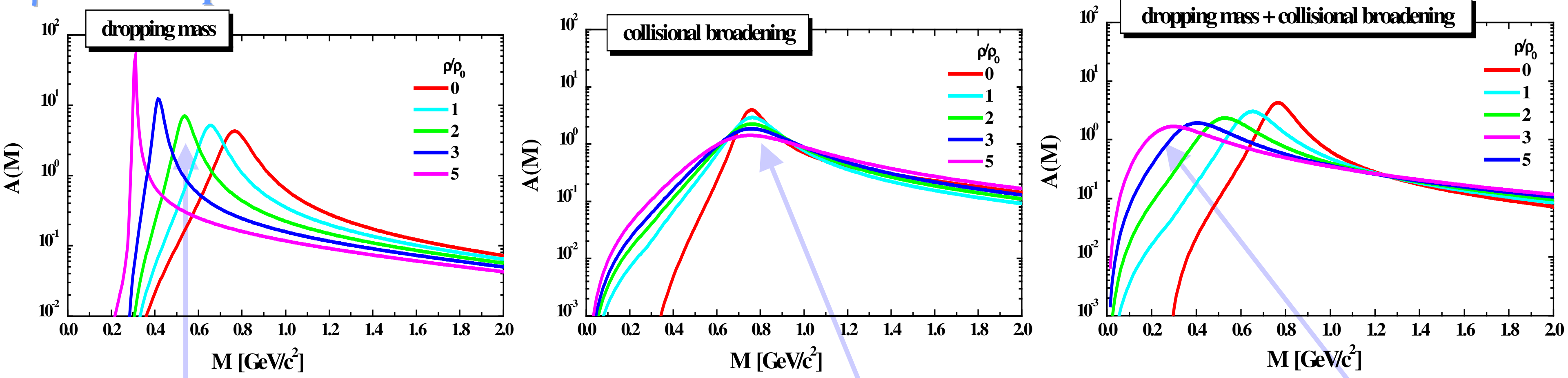
Modelling of in-medium spectral functions for vector mesons

In-medium scenarios:

dropping mass	collisional broadening	dropping mass + coll. broad.
$m^*=m_0(1-\alpha\,\rho/\rho_0)$	$\Gamma(M,\rho)=\Gamma_{vac}(M)+\Gamma_{CB}(M,\rho)$	m^* & $\Gamma_{CB}(M,\rho)$

Collisional width $\Gamma_{CB}(M,\rho) = \gamma\,\rho\,\langle \upsilon\,\sigma_{VN}^{tot}\rangle$

ρ–meson spectral function:



Consequences when increasing the baryon density ρ:

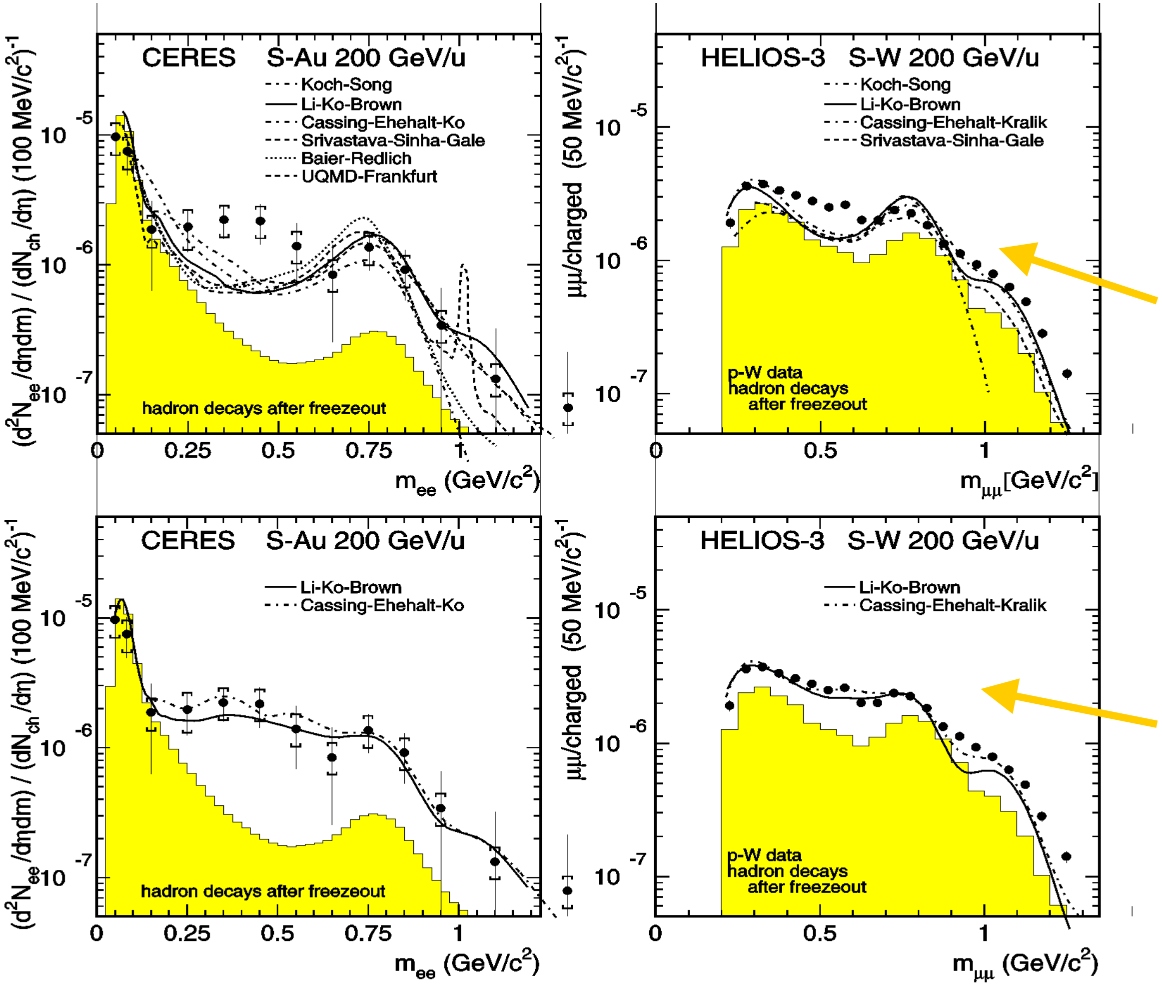
- pole position m_0 : shift to low M
- spectral function : narrowing

- pole position m_0 : unchanged
- spectral function : broadening

- pole position m_0 : shift to low M
- spectral function : broadening

Dilepton spectra from heavy-ion collisions

Dileptons (e+e- or μ+μ- pairs) are an ideal probe for vector meson spectroscopy in the nuclear medium and for the nuclear dynamics !



❑ **CERES, HELIOS-3 data (1995)**

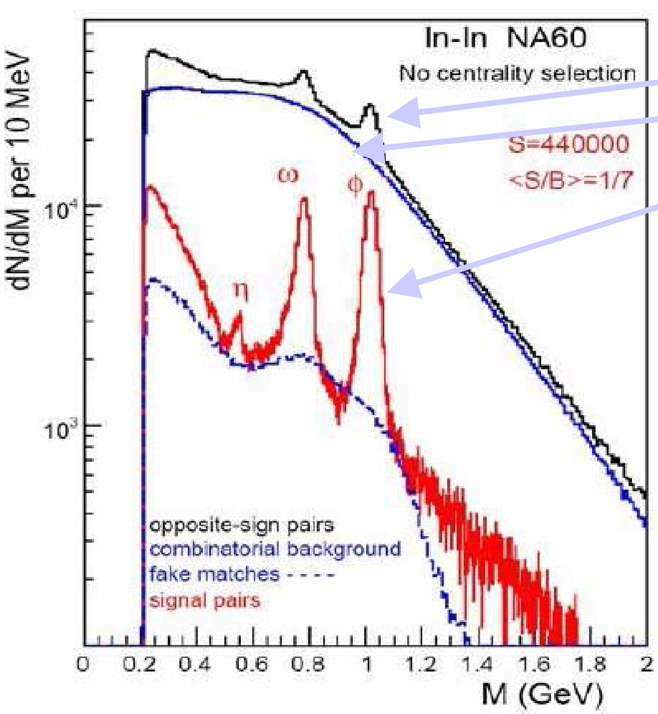
No medium effects:

- **too much yield in the ρ peak**
- **missing yield around M~0.5 GeV**

In-medium spectral function: works rather well

❑ **Dilepton spectra at SIS energies (BEVALAC and HADES) show similar in-medium modification of vector meson spectral functions**

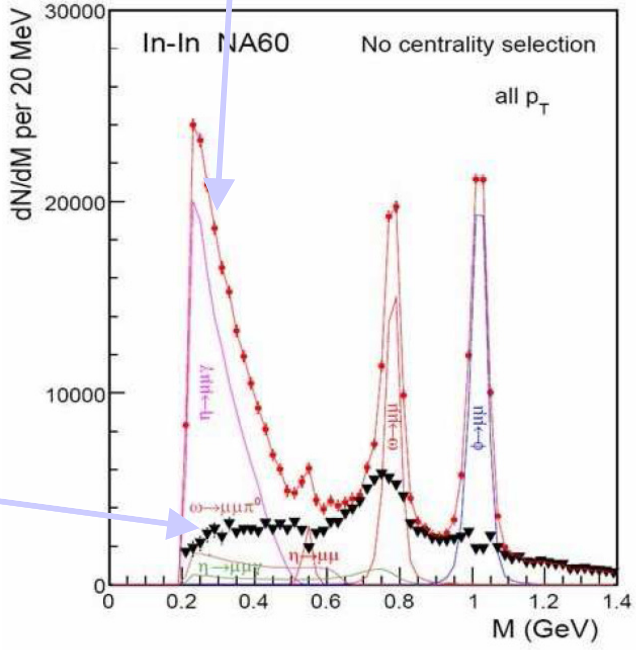
Dileptons: NA60 ($\mu^+\mu^-$ spectra)



opposite-side dimuons

combinatorial background

resulting signal

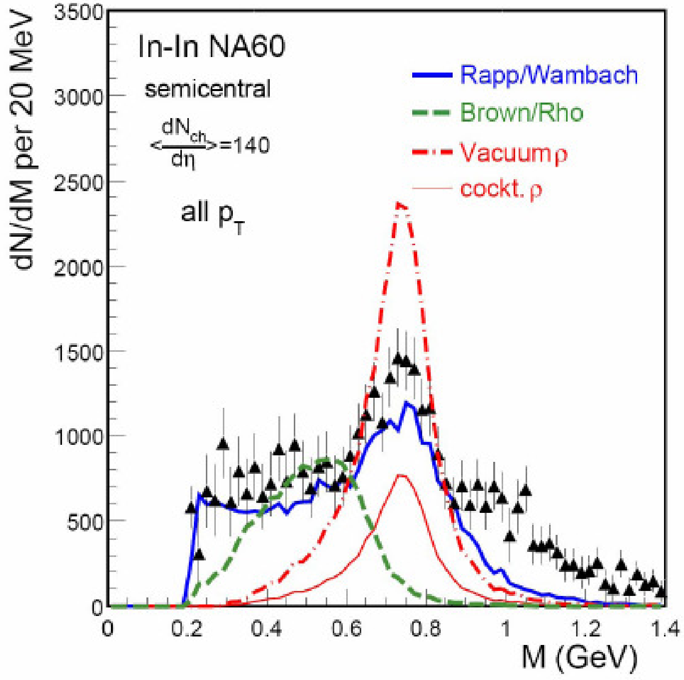


Excess spectrum =
resulting signal –
‚cocktail‘ sources

Exp. data vs theory (Rapp et. al.)

- models for ρ spectral function:

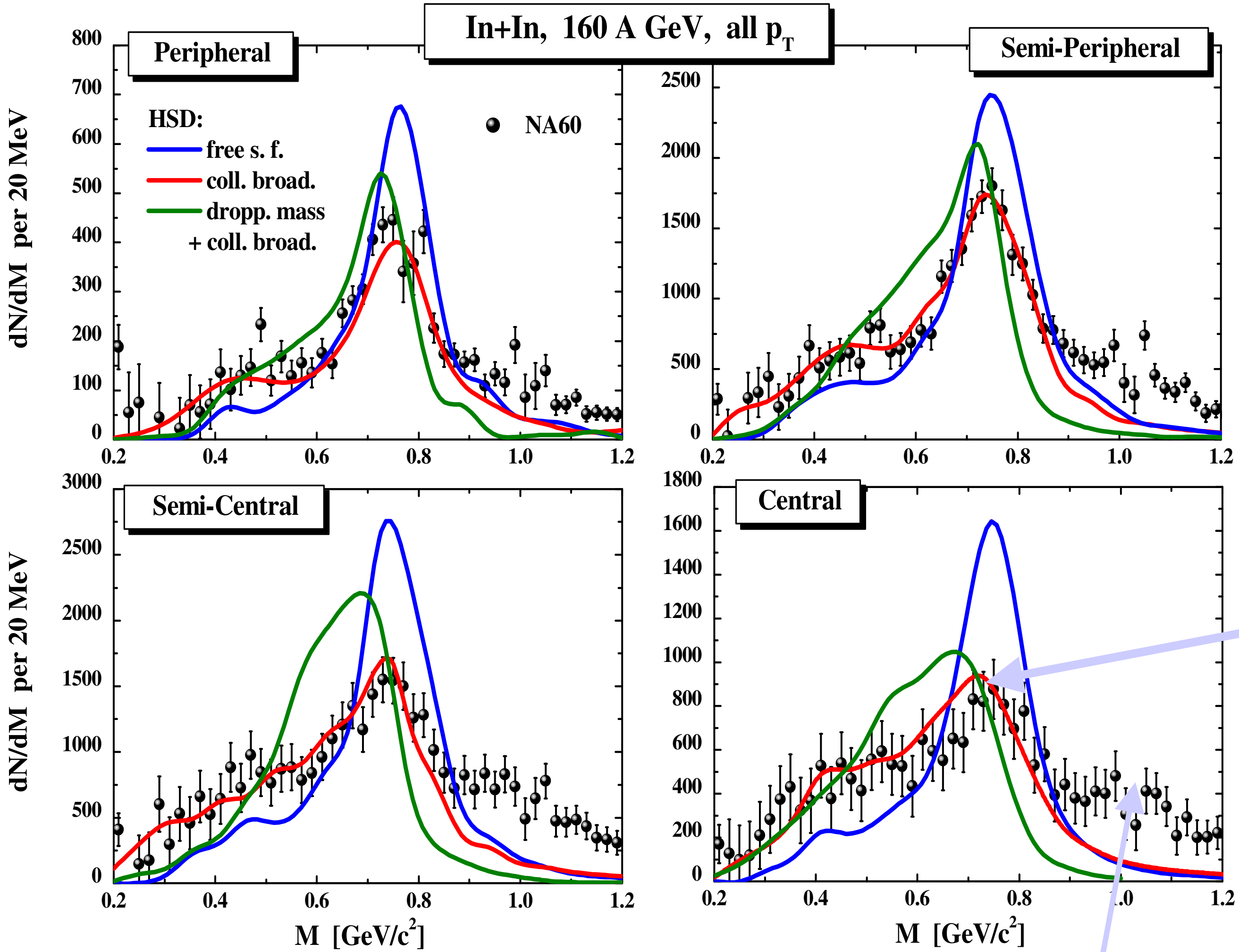
- **vacuum s.f.**
- **dropping mass (Brown/Rho)**
- **coll. broad. (Rapp/Wambach)**



High precision NA60 data allow to distinguish among in-medium models!

Clear evidence for a broadening of the ρ spectral function!

NA60 data vs. HSD transport



HSD – full off-shell propagation of in-medium spectral functions through the hadronic medium

- models for ρ spectral function:

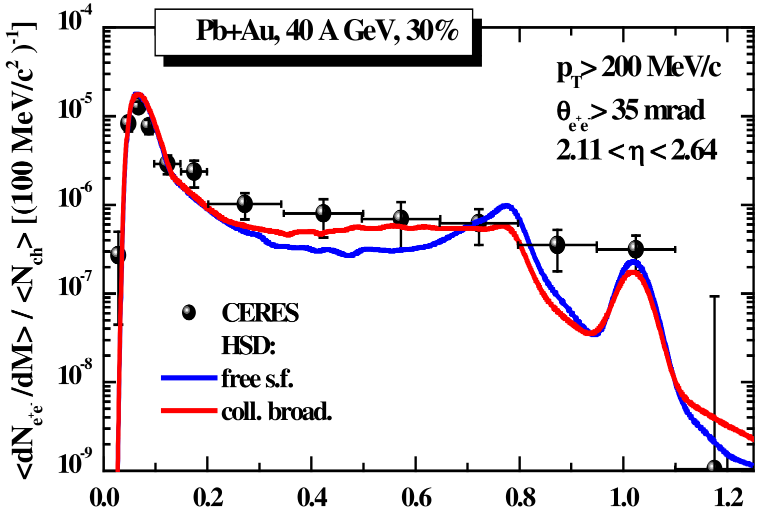
- **vacuum spectral function**
- **dropping mass (Brown/Rho)**
- **coll. broad. (Rapp/Wambach)**

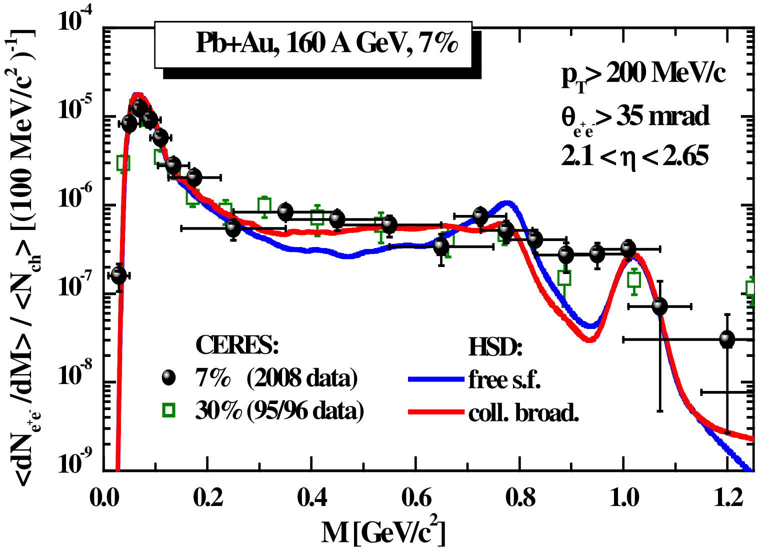
- **NA60 data are better described by in-medium scenario with collisional broadening**

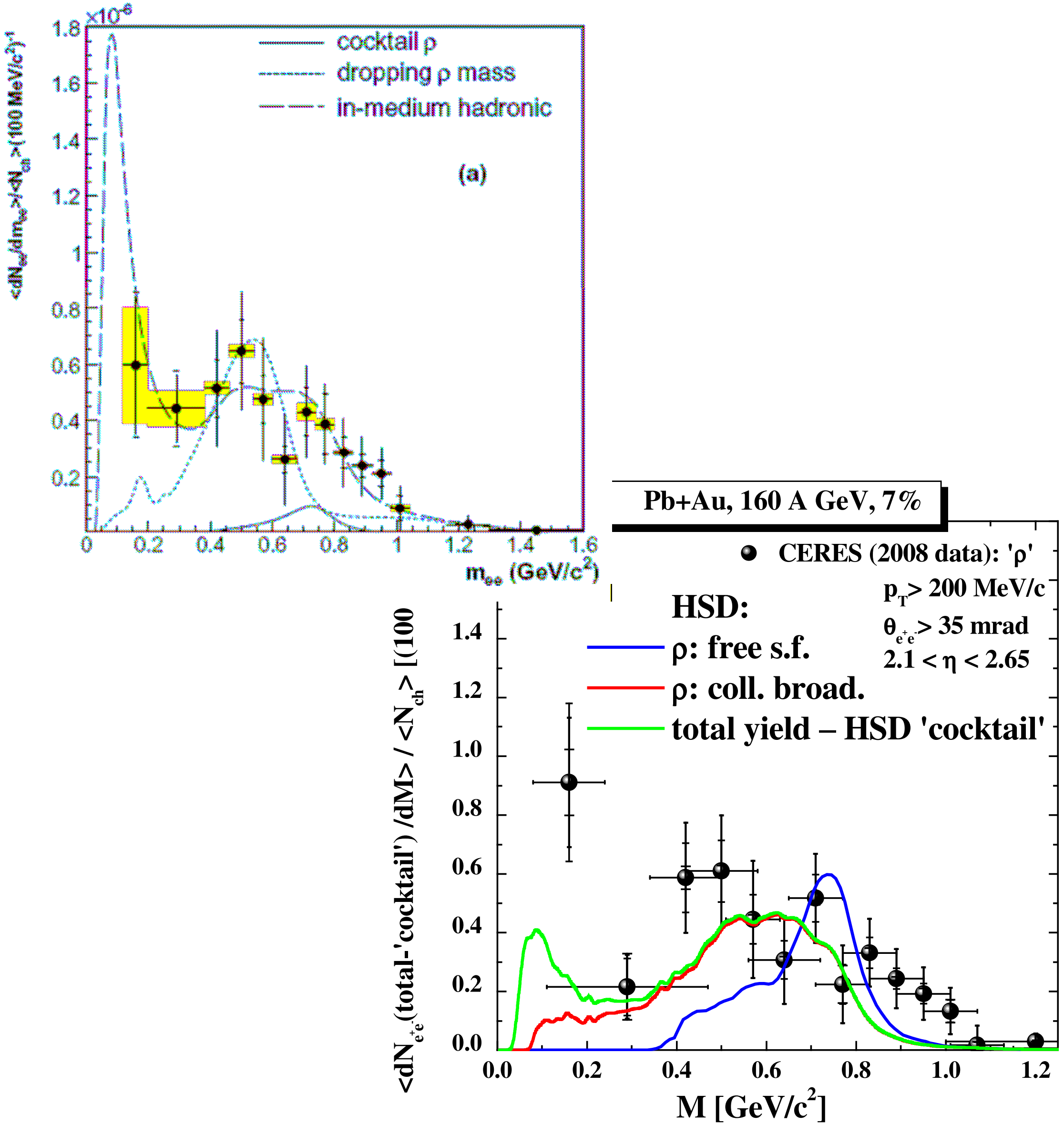
- **High M tail not reproduced in HSD ➔ Non-hadronic origin?**

E. B., W. Cassing, O. Linnyk, PLB 670 (2009) 428

Dileptons at SPS: CERES (e^+e^- spectra)





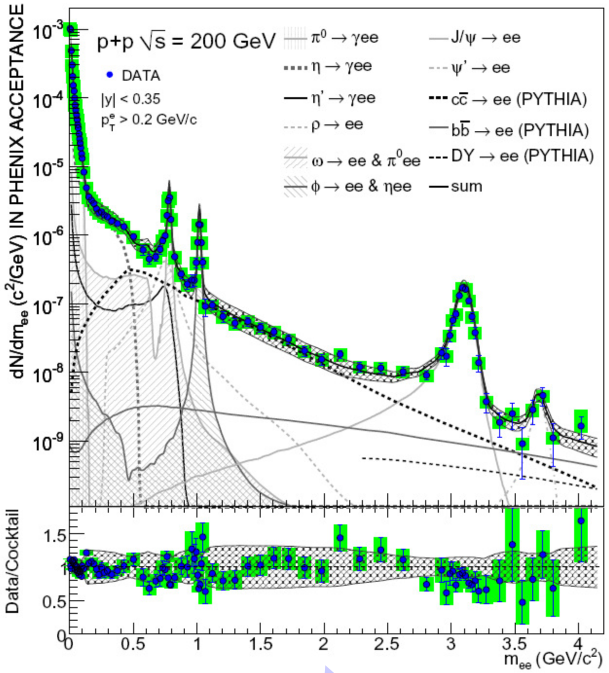


- CERES data are better described by in-medium scenario with collisional broadening

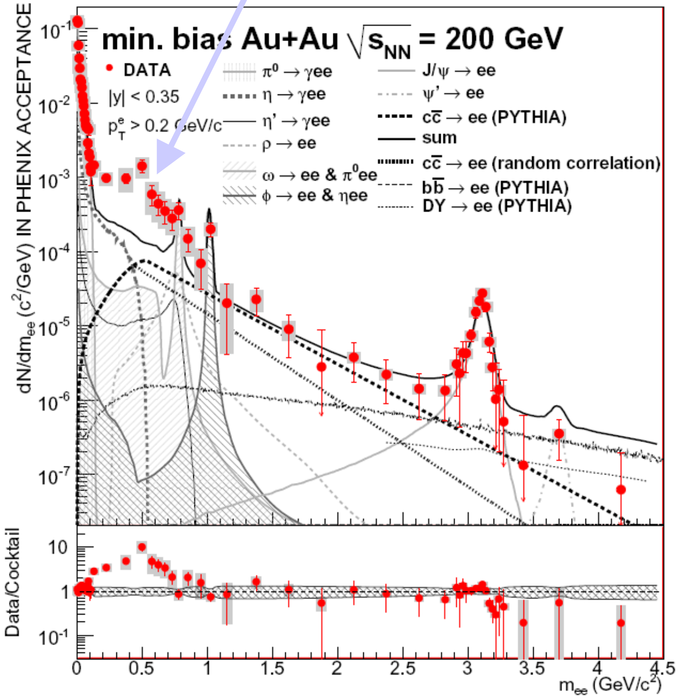
Dileptons at RHIC

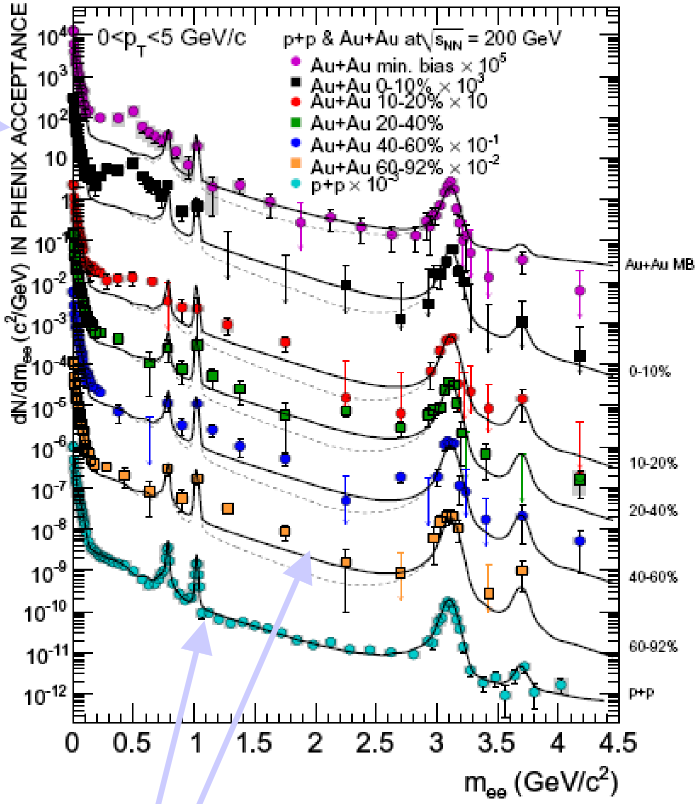
PHENIX: pp

PHENIX: Au+Au



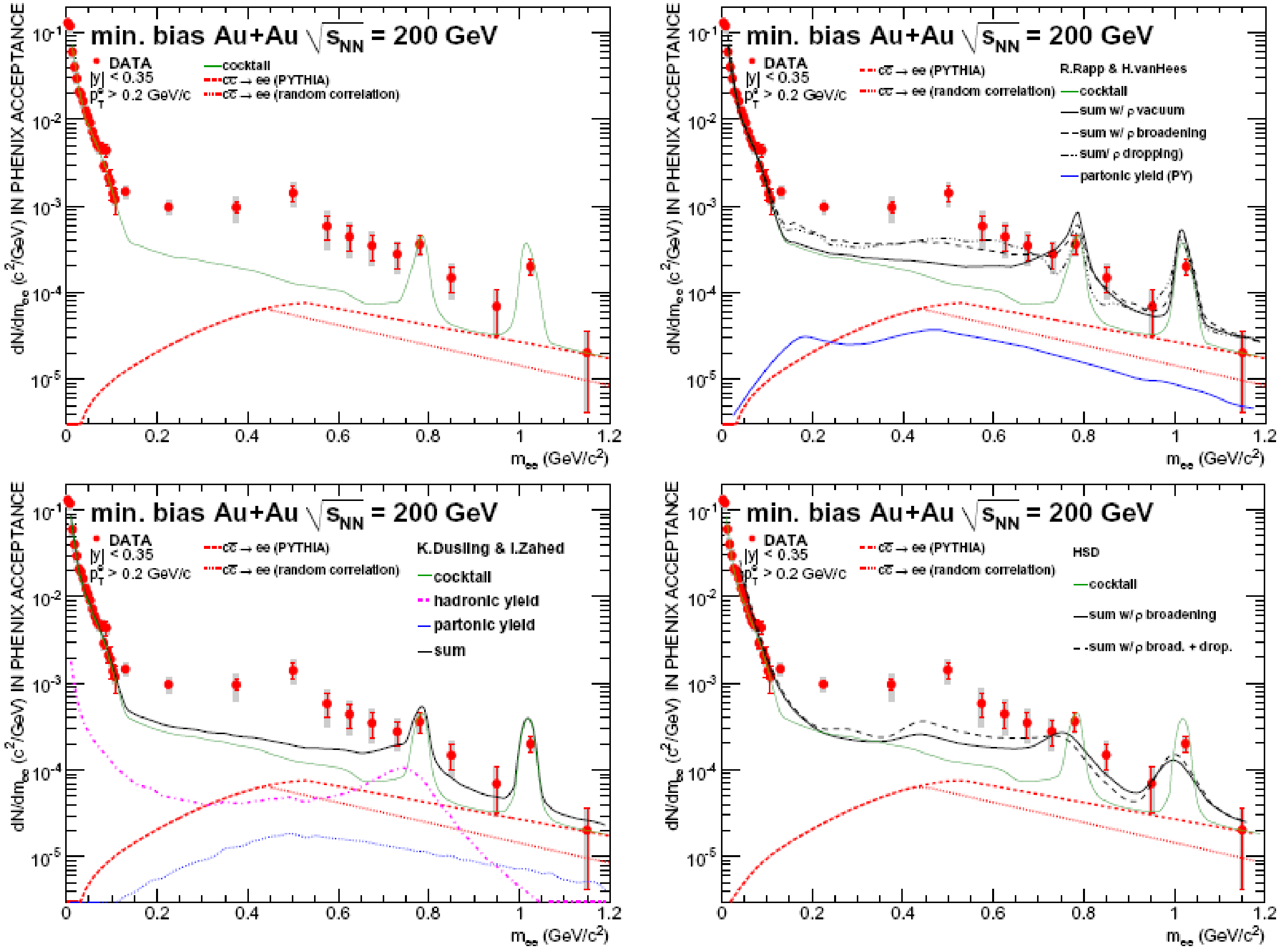
,excess‘





- **Dilepton cocktail** provides a good description of pp data as well as peripheral Au+Au data, however, fails in describing the central bins!

Dileptons at RHIC: data vs. theor. models

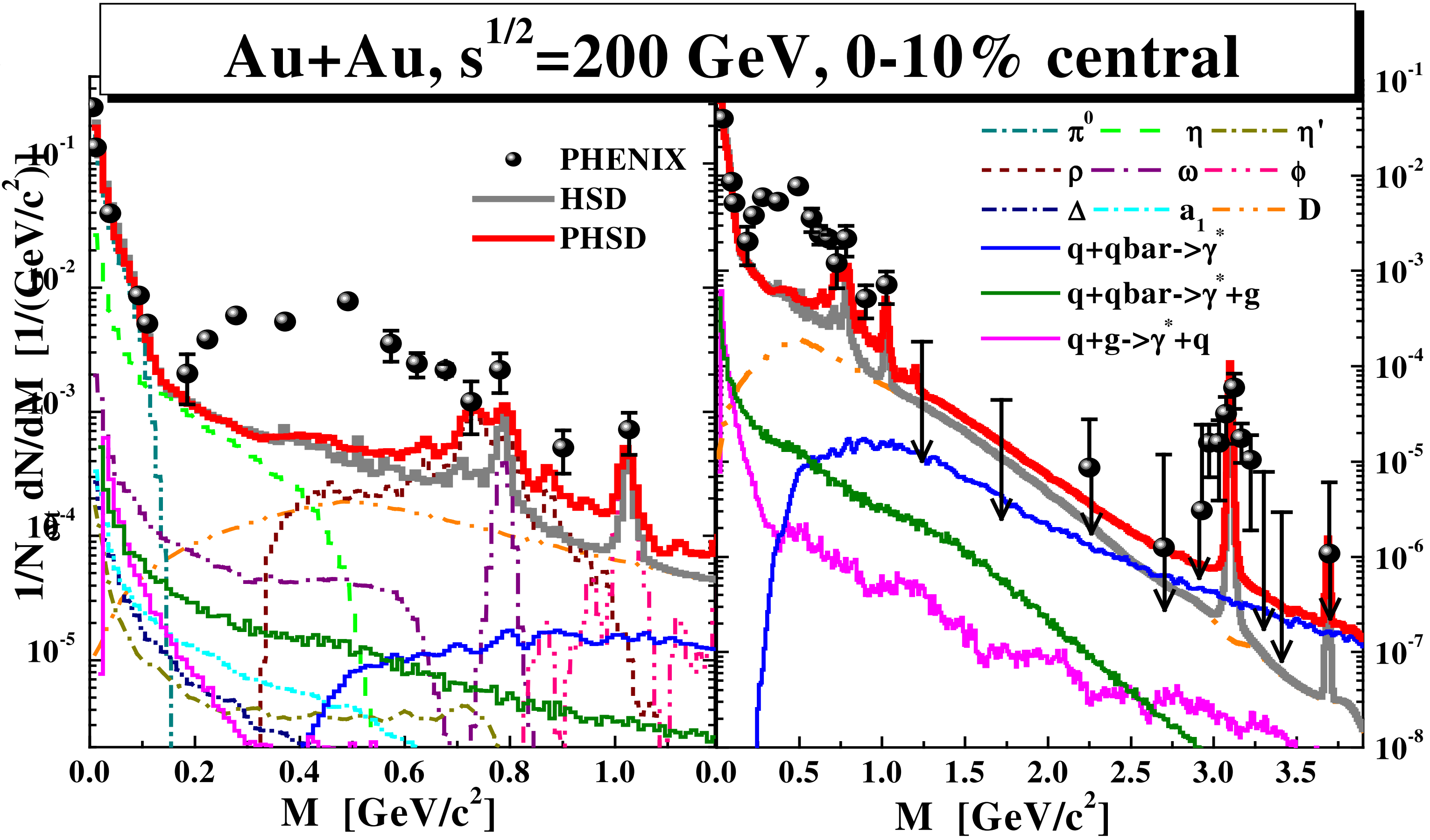


PHENIX:
Au+Au

- Models provide a **good description of pp data**
- Standard in-medium effects of vector mesons -- compatible with the NA60 and CERES data at SPS – **do not explain the large enhancement observed by PHENIX** in the invariant mass from 0.2 to 0.5 GeV in central Au+Au collisions at $s^{1/2}$=200 GeV (relative to pp collisions) ➔ **PHENIX dilepton puzzle ?!**

QGP radiation - PHSD

O. Linnyk

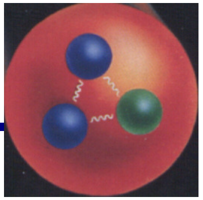


- The contribution of the QGP to the dilepton radiation clearly increases with centrality.
- There is a large discrepancy between the data and PHSD for M=0.15-0.7 GeV.
- However, partonic channels dominate the observed yield at high masses !

➔ PHENIX dilepton puzzle ?

Multi-strange particle enhancement in Au+Au

Strange particles



Mesons:

$K^+(u\bar{s})$ $K^-(\bar{u}s)$

$K^0(d\bar{s})$ $\bar{K}^0(\bar{d}s)$ $m_K = 0.494\ \text{GeV}$

$K^{*+}(u\bar{s})$ $K^{*-}(\bar{u}s)$

$K^{*0}(d\bar{s})$ $\bar{K}^{*0}(\bar{d}s)$ $m_K = 0.892\ \text{GeV}$

Strangeness |S|=1

Baryons:

Strangeness S= -1

$\Lambda^0(uds)$ $m_\Lambda = 1.116\,\text{GeV}$

$\Sigma^0(uds)$ $\Sigma^+(uus)$ $\Sigma^-(dds)$ $m_\Sigma = 1.189\,\text{GeV}$

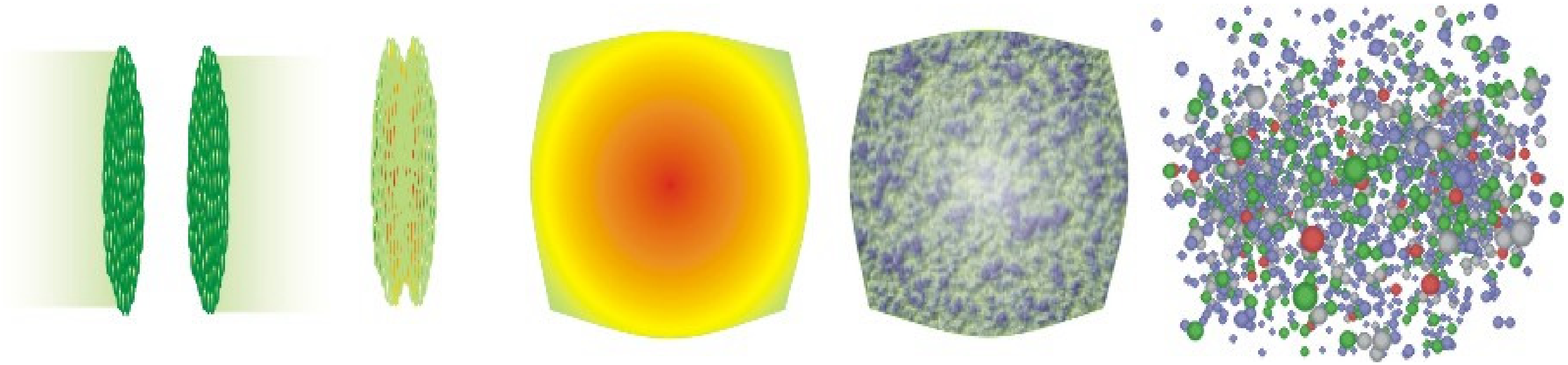
$\Xi^0(uss)$ $\Xi^-(dss)$ $m_\Xi = 1.315\,\text{GeV}$

S= -2

$\Omega^-(sss)$ $m_\Omega = 1.672\,\text{GeV}$

S= -3

Strangeness production in A+A collisions



- **Initially:**

no strangeness

- **Finally:** **$s,\bar{s}$ pairs**

= strange particles

- **How can strangeness be produced?**

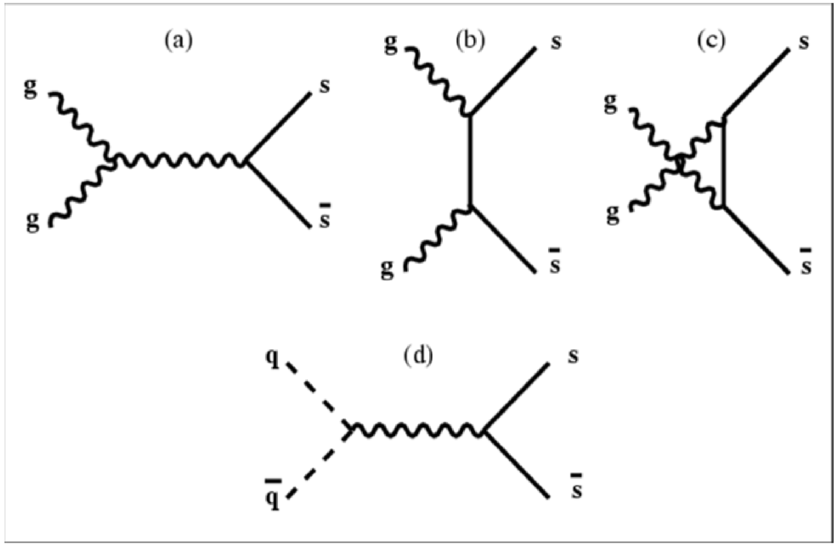
How strangeness can be produced in QGP ?

- **Strangeness production in a hadronic world (at low energy):**

N+N –> N+Λ+K requires $\Delta E = 2M_N-(M_K+M_\Lambda+M_N)$ =670 MeV

π+N –> Λ+K $\Delta E = (M_\pi+M_N)-(M_K+M_\Lambda)$ =535 MeV

- **Strangeness production in a QGP:**



bare mass of strange quark m_S~ 130 MeV

=> s-sbar pair production

by q-qbar annihilation q+qbar –>s+sbar

needs only ΔE=260 MeV

=> s-sbar pair can be also produced by

gluon fusion g+g –>s+sbar

➔**Strong enhancement of strangeness production in a QGP !**

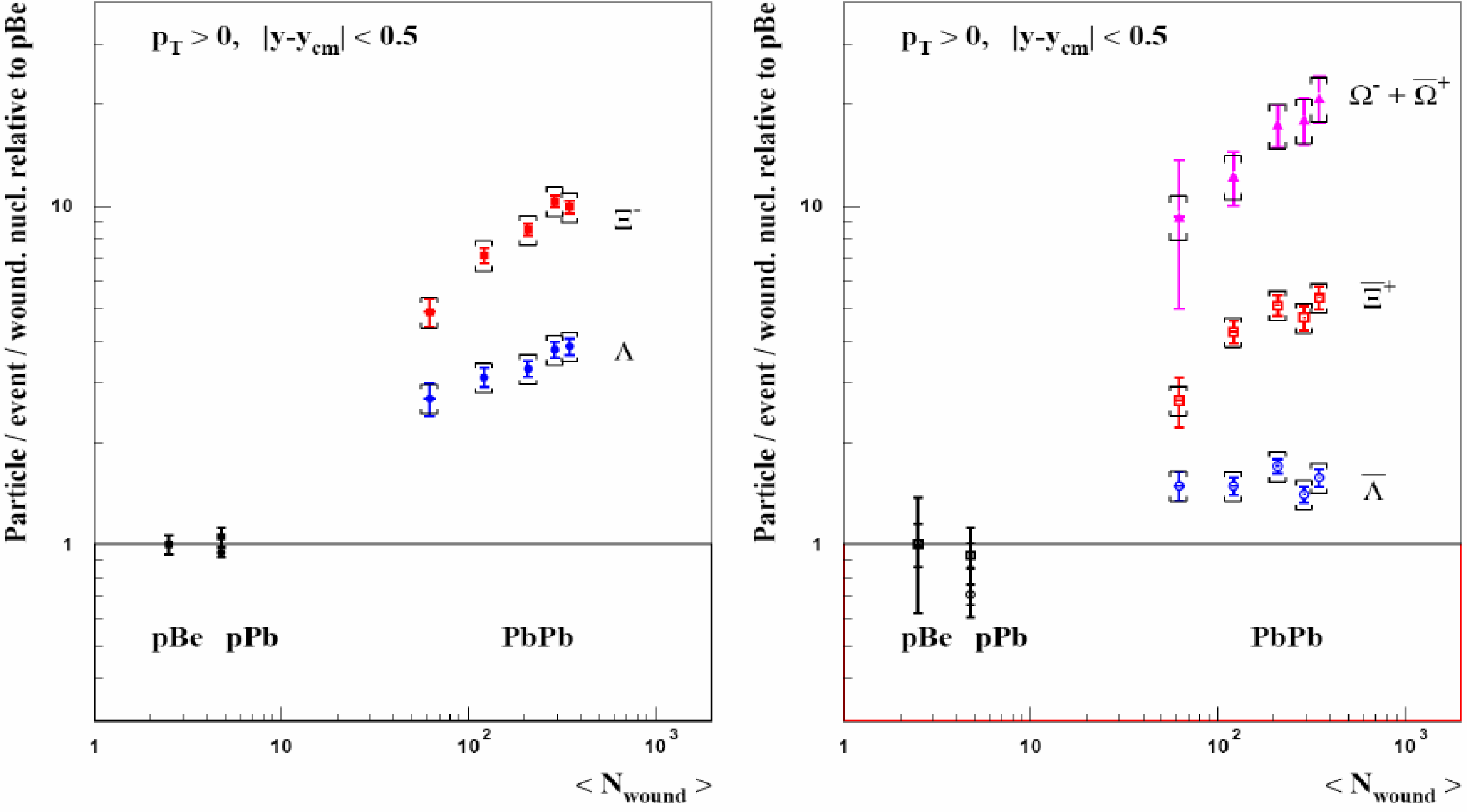
Rafelski-Müller: Phys. Rev. Lett. 48 (1982) 1066

=> strangeness enhancement increases with strangeness content –

stronger effect for multi-strange hadrons Ξ(uss), Ω(sss)

Strangeness enhancement at SPS energies

Experimental observations

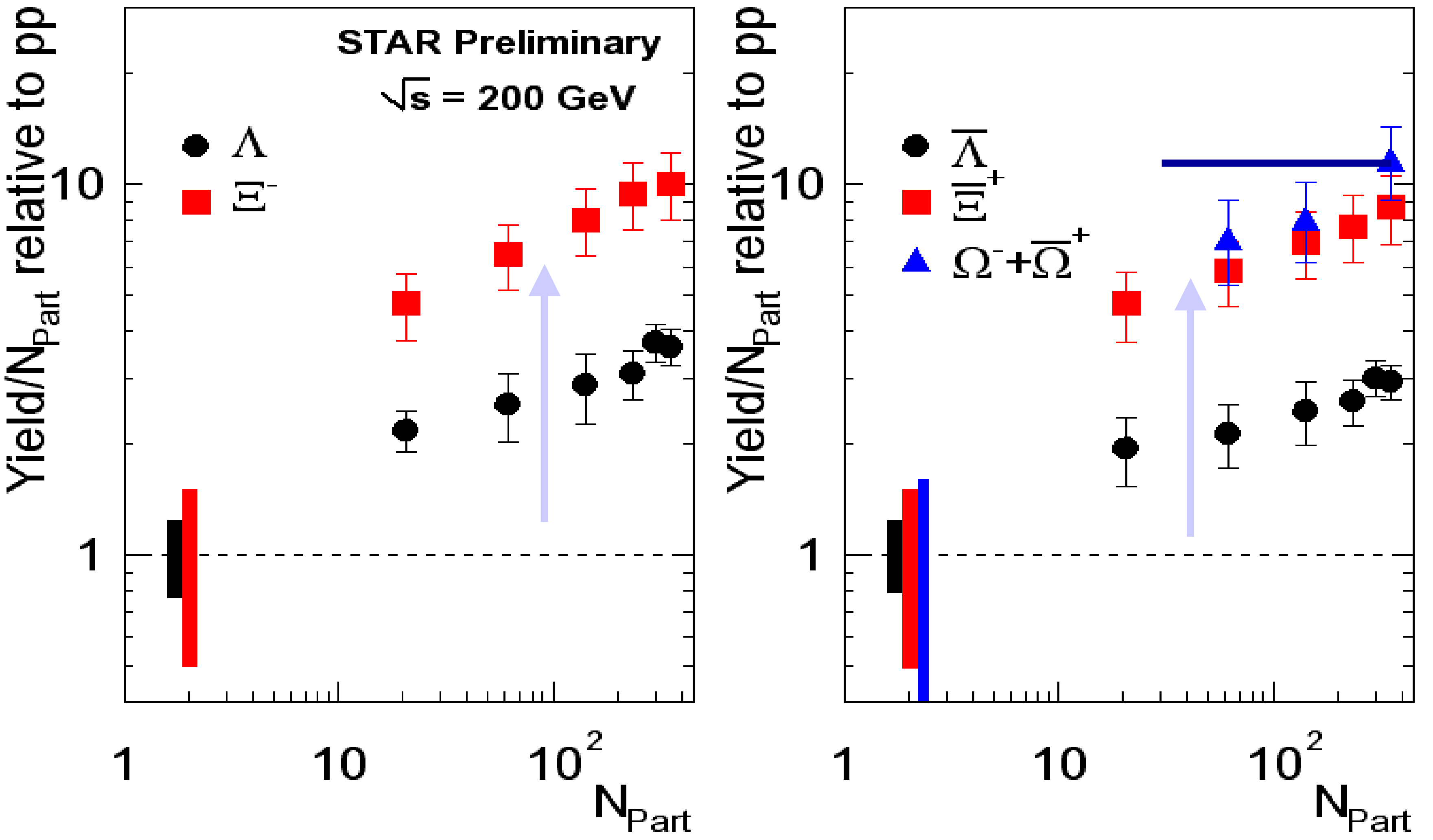


Enhancement grows:

- with the number of wounded nucleons (centrality)
- with the number strange valence quarks: multi-strange particles

Ξ(uss) and Ω(sss) are stronger enhanced for central collisions

Strangeness enhancement at RHIC energies



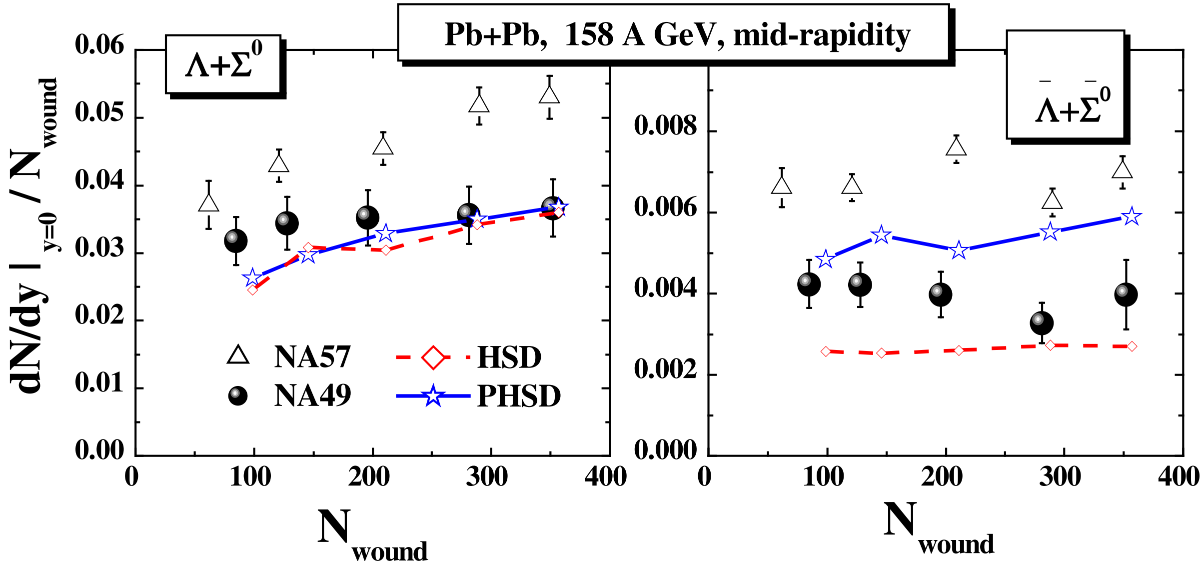
Experiment

➔ Ξ and Ω enhancement for central collisions !

Centrality dependence of (multi-)strange (anti-)baryons

strange baryons

$\Lambda+\Sigma^0$

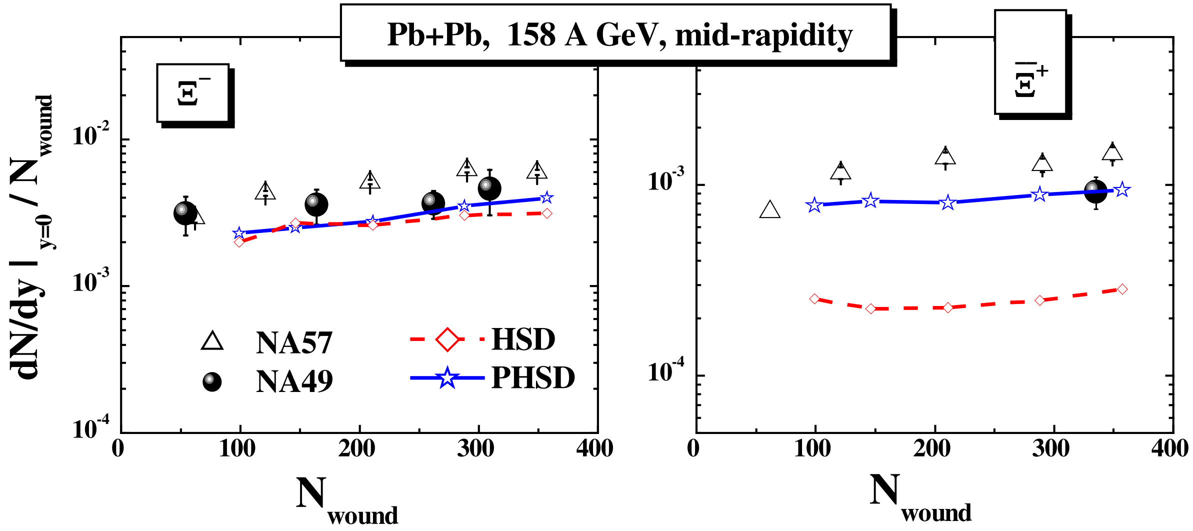


strange antibaryons

$\bar{\Lambda}+\bar{\Sigma}^0$

multi-strange baryon

Ξ^-



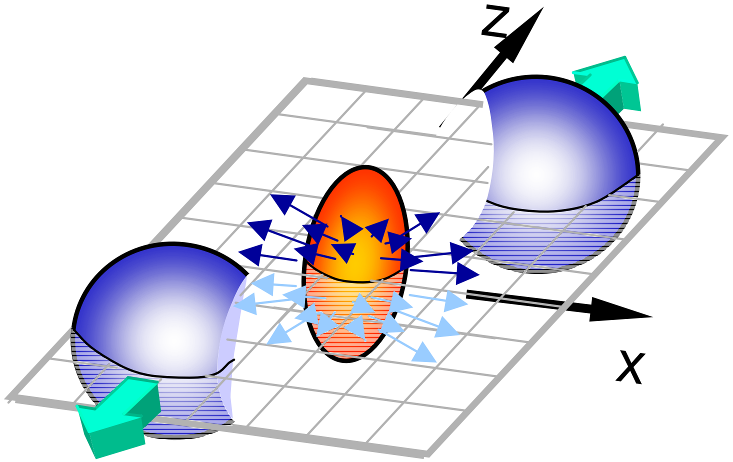
multi-strange antibaryon

$\bar{\Xi}^+$

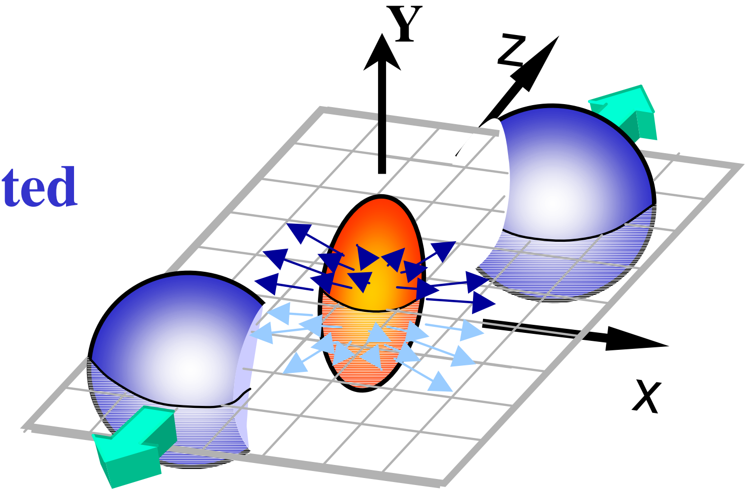
➔ enhanced production of (multi-) strange antibaryons in PHSD compare to HSD

Cassing & Bratkovskaya, NPA 831 (2009) 215

Collective flow (v_1, v_2) in Au+Au



Directed flow v_1 & elliptic flow v_2



Non central Au+Au collisions :

interaction between constituents leads to a pressure gradient => spatial asymmetry is converted to an asymmetry in momentum space => collective flow

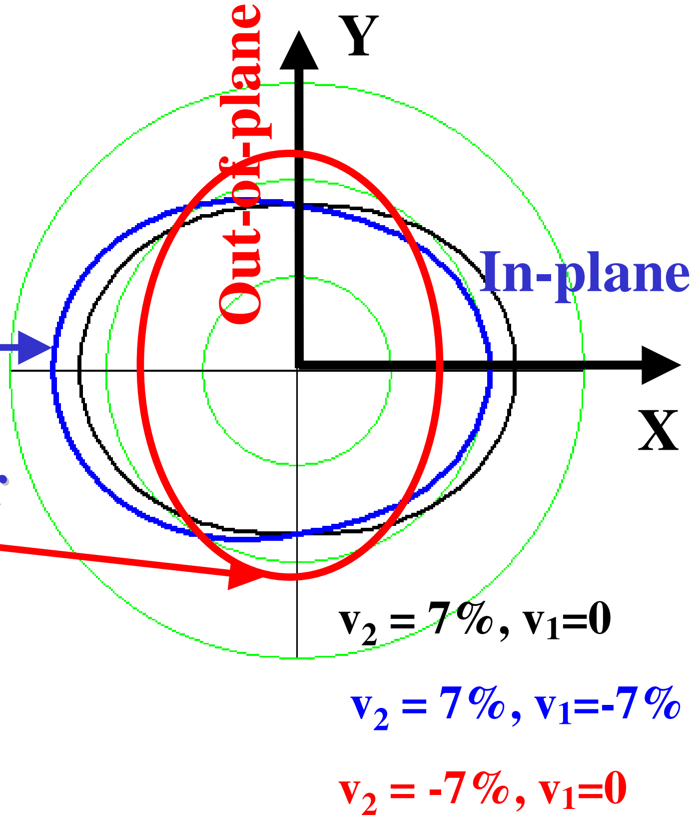
$$\frac{dN}{dyp_T dp_T d\varphi} = \frac{dN}{dyp_T dp_T}\frac{1}{2\pi}\left(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots\right)$$

$$v_1 = <\frac{p_x}{p_T}>$$ - directed flow

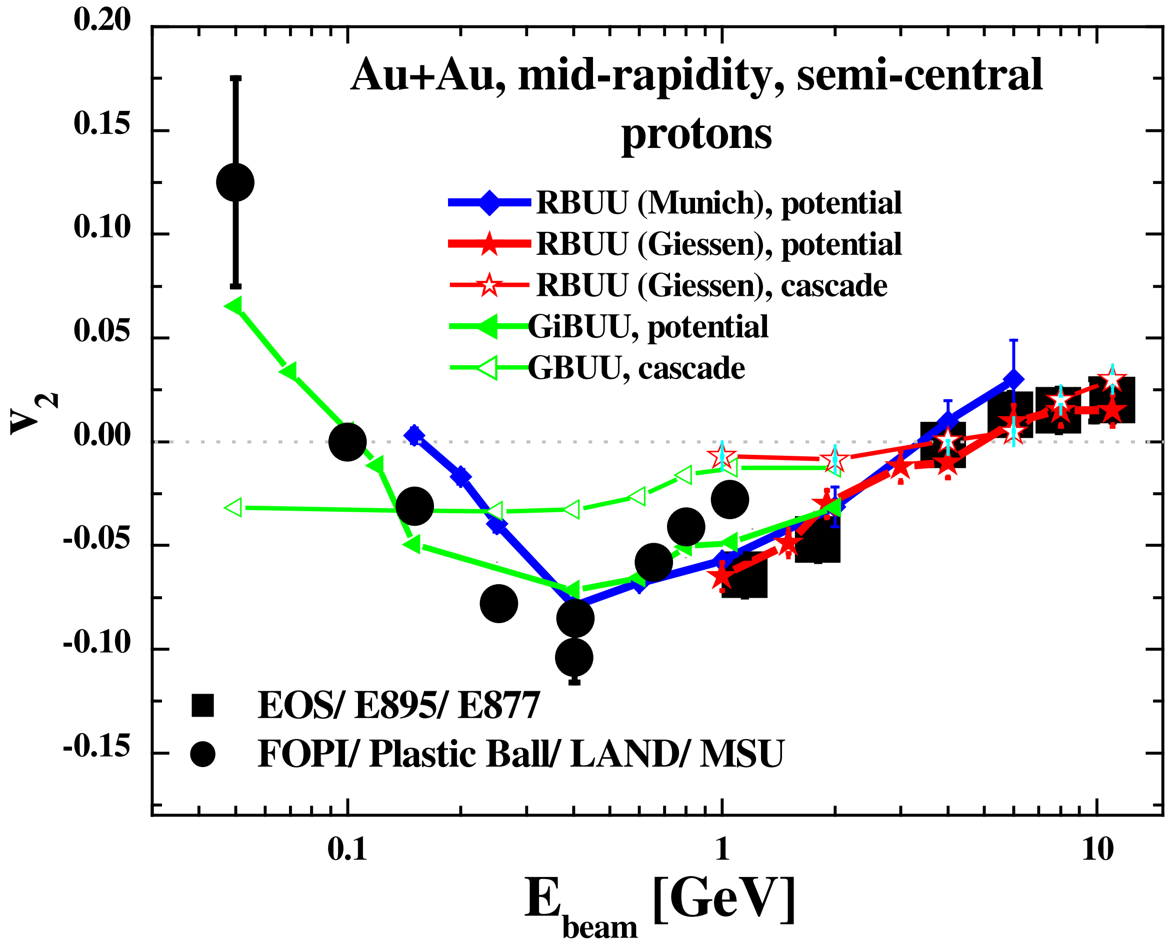
$$v_2 = <\frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}>$$ - elliptic flow

$V_2 > 0$ indicates in-plane emission of particles

$V_2 < 0$ corresponds to a squeeze-out perpendicular to the reaction plane (out-of-plane emission)



Collective flow: v_2 excitation function (SIS-AGS)

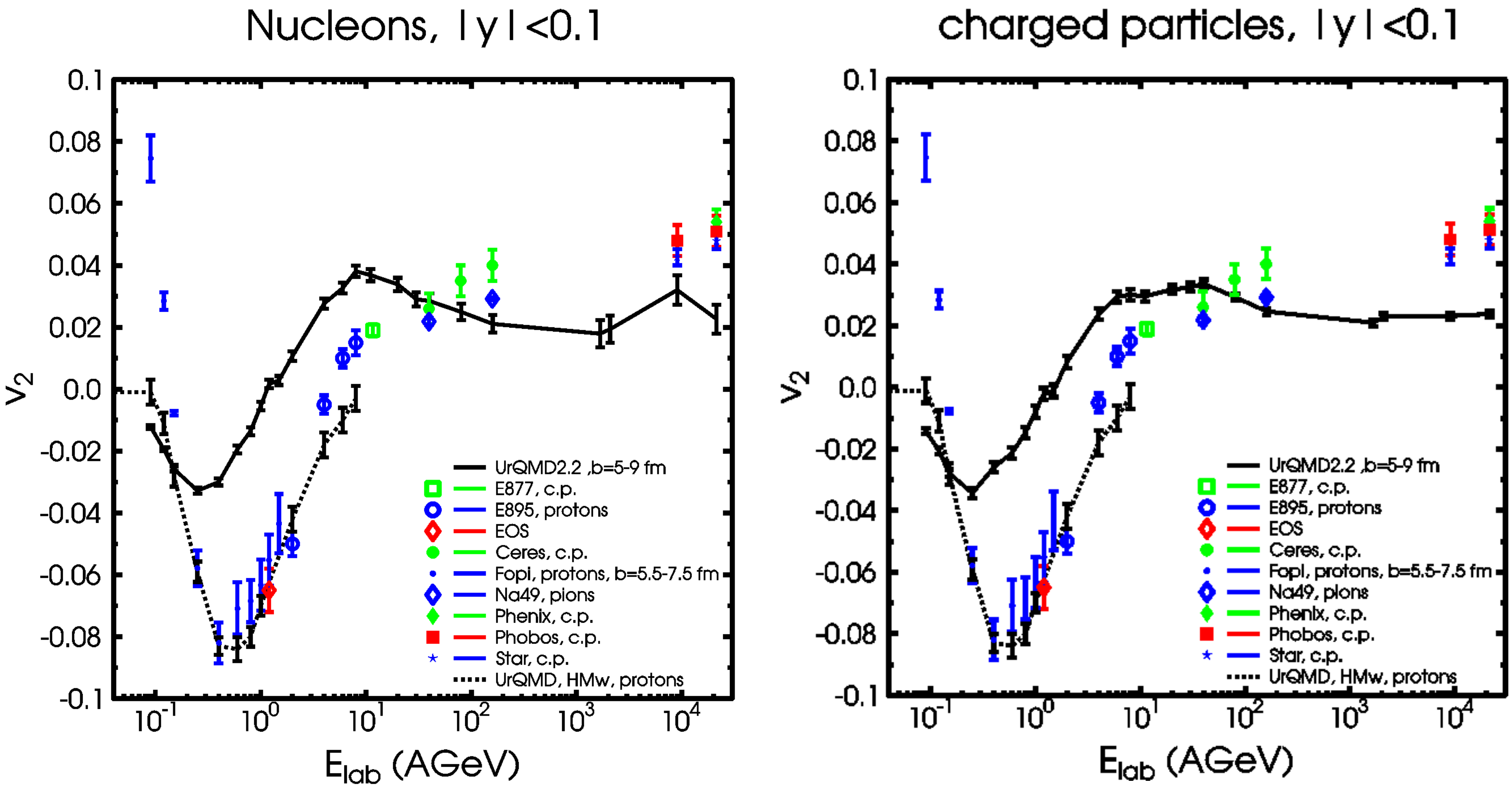


- Proton v_2 at low energy shows sensitivity to the nucleon potential.
- Cascade codes fail to describe the exp. data.
- AGS energies: transition from squeeze-out to in-plane elliptic flow

Collective flow: v_2 excitation function

v_2 excitation functions from the string-hadronic transport model UrQMD:

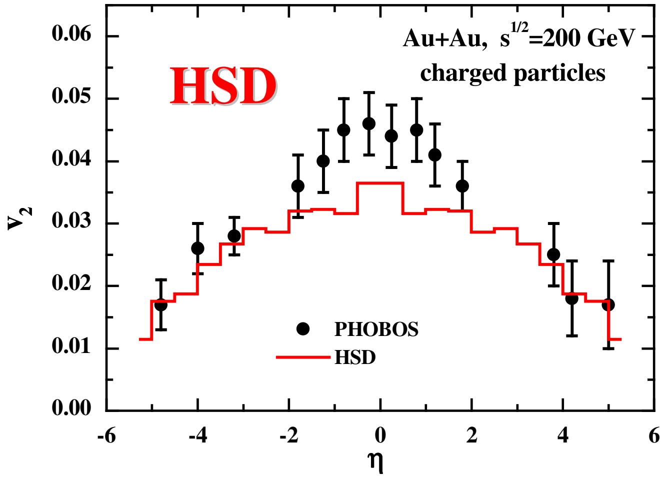
- low energies - sensitivity to the nucleon potential
- high energies - missing v_2 - QGP pressure?!

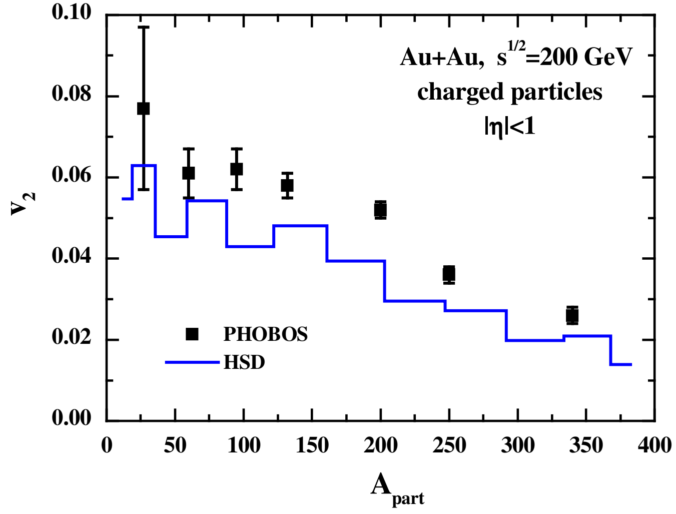


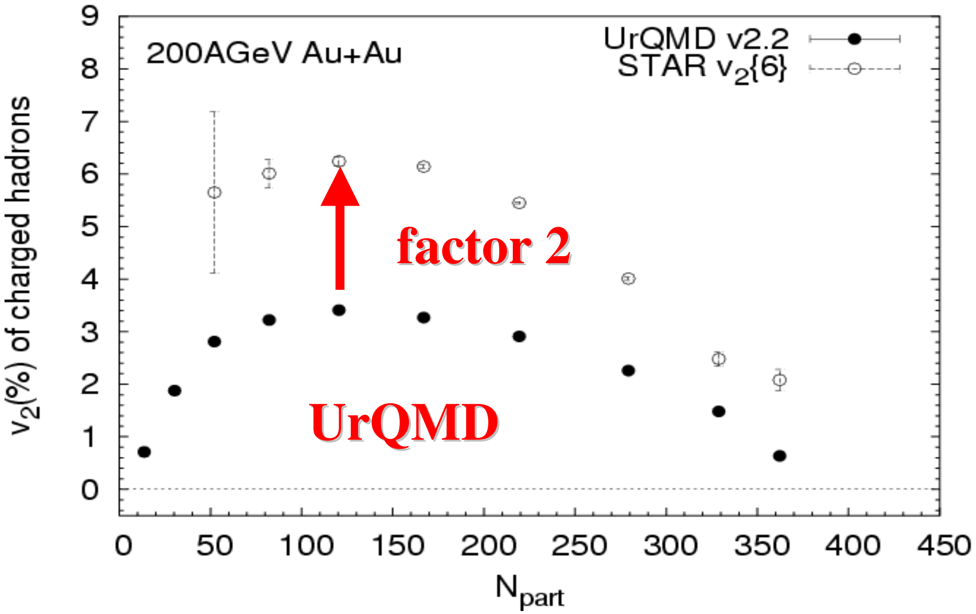
Nucleons, |y|<0.1

charged particles, |y|<0.1

Elliptic flow v_2 in Au+Au at RHIC







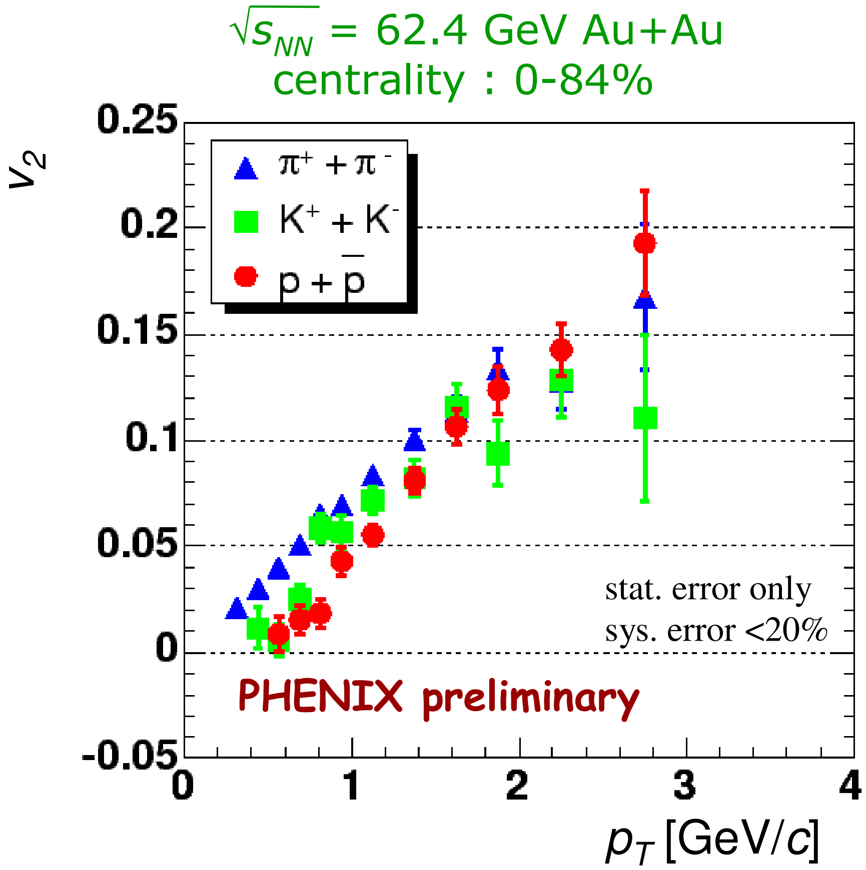
- STAR data on v_2 of charged hadrons are NOT reproduced in the hadron-string picture (UrQMD) =>

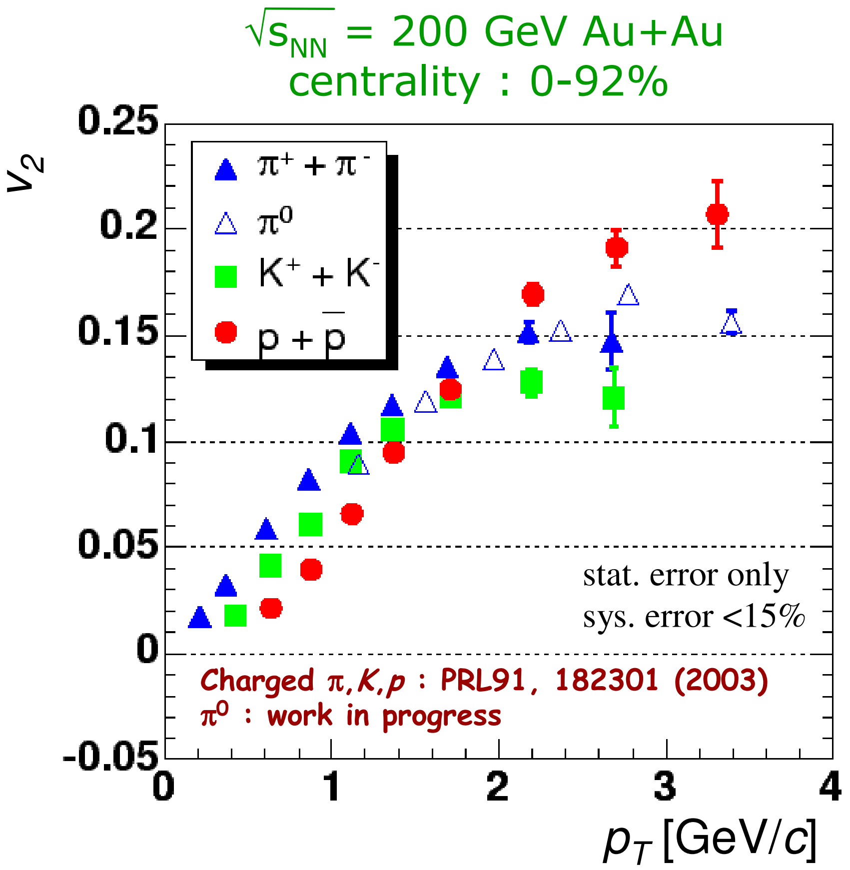
evidence for huge plasma pressure ?!

- PHOBOS data on v_2 for charged hadrons (all p_T) are underestimated in HSD by ~30%

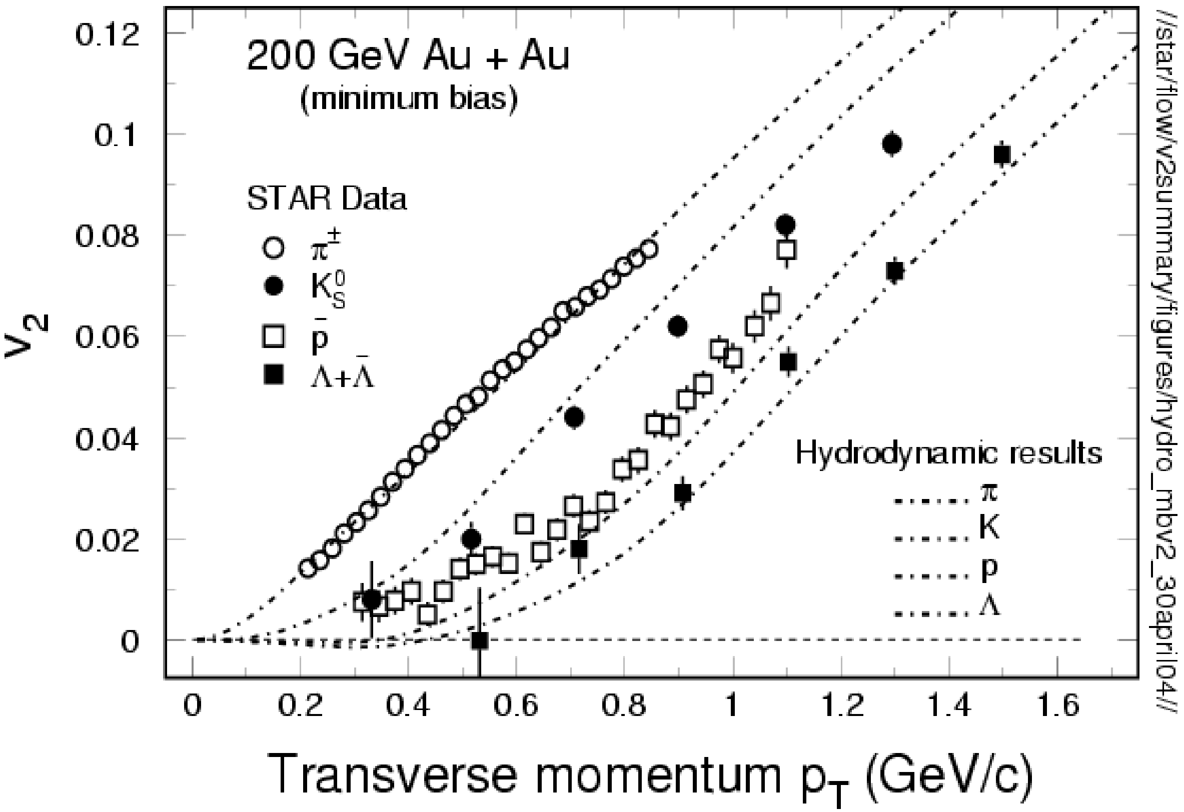
PRC 67 (2003) 054905, Nucl. Phys. A 735 (2004) 277

Elliptic Flow at 62.4 and 200 GeV Au+Au





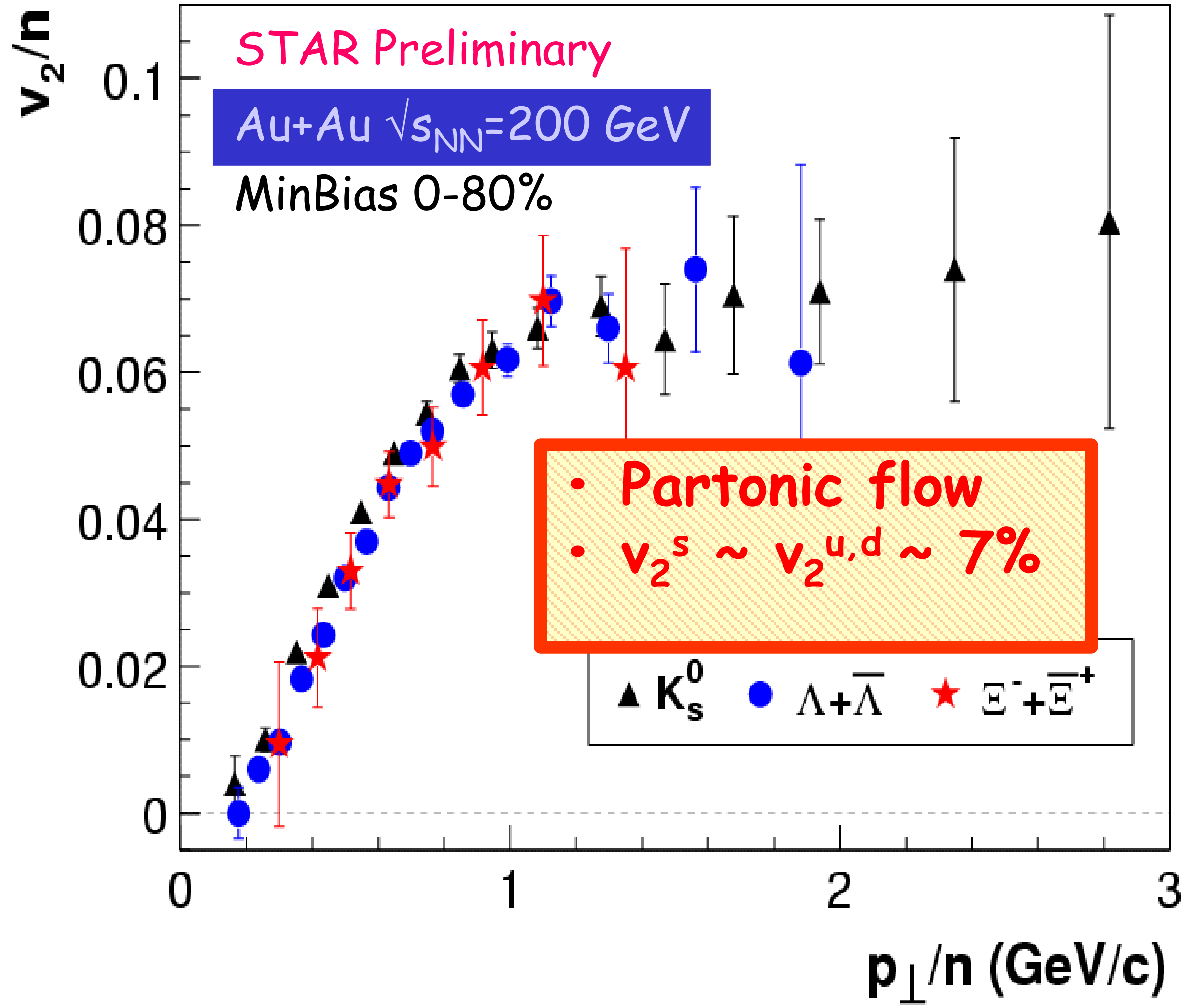
Collective flow - hydrodynamics



In the bulk (low p_T) : hydrodynamics works !
(full hydro or blastwave parametrization) ➔

- ! System behaves like a strongly interacting liquid (of low viscosity) !
- System is likely to be partonic, but not 'plasma-like' (weakly interacting)

Flow at partonic level



- **Partonic flow**
- **$v_2^s \sim v_2^{u,d} \sim 7\%$**

- The complex behaviour of v_2 can be « simply » explained at partonic level

$$v_2^p(p_t) = \frac{v_2^B(3p_t)}{3}$$

$$v_2^p(p_t) = \frac{v_2^M(2p_t)}{2}$$

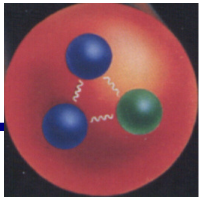
$$v_2^p(p_t) = \frac{v_2^h(np_t)}{n}$$

… at intermediate p_T !

Idea of flow per constituent – Coalescence/Recombination
Elliptic flow developed at partonic level

Open and hidden charm

Charm particles



,Open‘ charm

Mesons:

$D^{+}(c\bar{d})$ $D^{-}(\bar{c}d)$

$D^{0}(c\bar{u})$ $\bar{D}^{0}(\bar{c}u)$

$D^{*+}(c\bar{d})$ $D^{*-}(\bar{c}d)$

$D^{*0}(c\bar{u})$ $\bar{D}^{*0}(\bar{c}u)$

$D_{S}^{+}(c\bar{s})$ $D_{S}^{-}(\bar{c}s)$

$D_{S}^{*+}(c\bar{s})$ $D_{S}^{*-}(\bar{c}s)$

$m_{D} = 1.864$ GeV

Baryons:

$\Lambda_{C}^{+}(udc)$

$\Sigma_{C}^{+}(udc)$

... $m_{\Lambda_C} = 2.284$ GeV

,Hidden‘ charm

$c\bar{c}$ mesons

$\eta_{C}(1S)$	2979.8	MeV
$J/\Psi(1S)$	3096.8	MeV
$\chi_{C0}(1P)$	3415.0	MeV
$\chi_{C1}(1P)$	3510.5	MeV
$\chi_{C2}(1P)$	3556.2	MeV
$\Psi(2S)$	3685.9	MeV
$\Psi(3770)$	$> 2m_{D} = 3729$ MeV	
$\Psi(4040)$		
$\Psi(4160)$		
…		

Decays :

$c\bar{c} \rightarrow$ hadrons

$\rightarrow$ hadrons $+\gamma$

$\chi(\Psi') \rightarrow J/\Psi + \gamma$

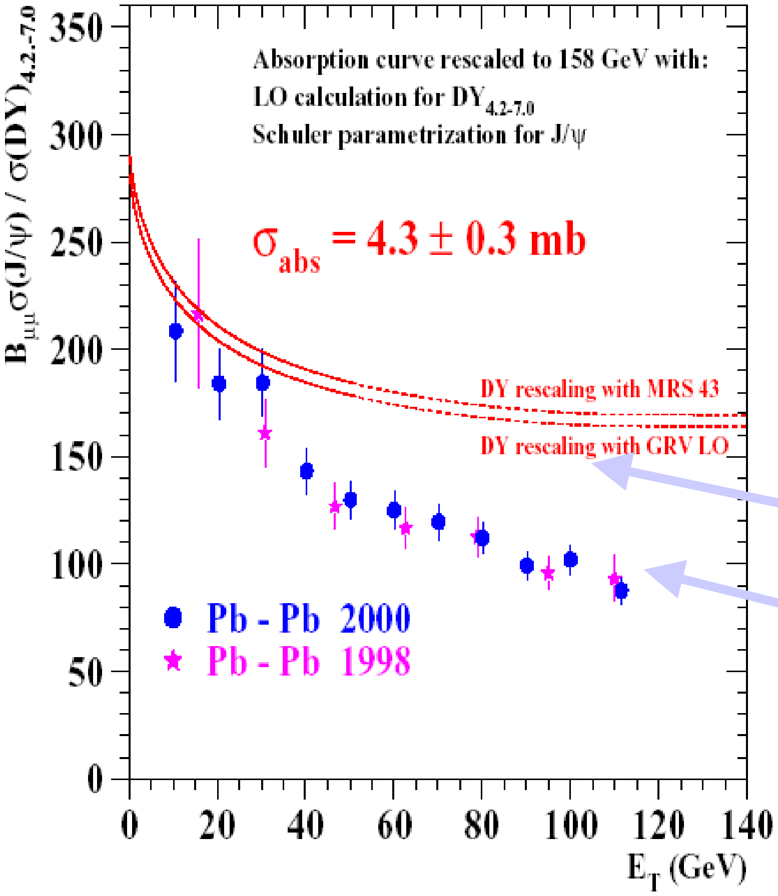
$J/\Psi(\Psi') \rightarrow e^{+}e^{-}$

$\Psi(3770) \rightarrow D\bar{D}$

Anomalous J/Ψ suppression in A+A

Heavy flavor sector reflects the early dynamics since heavy hadrons can only be formed in the very early phase of heavy-ion collisions !

Hidden charm: J/Ψ , Ψ‘: Anomalous J/Ψ suppression in A+A
(NA38/NA50/NA60)



There should be ‚normal‘ nuclear absorption, i.e. dissociation of charmonium by inelastic interactions with nucleons of the target/projectile

Charmonium-N dissociation cross section can be fixed from p+A data

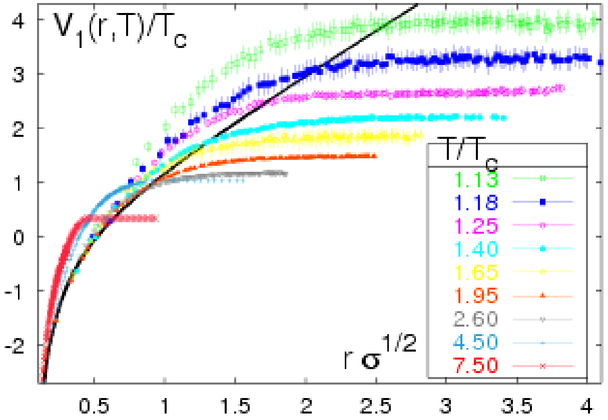
J/Ψ ‚normal‘ absorption by nucleons
(Glauber model)

➔ Experimental observation:
extra suppression in A+A collisions;
increasing with centrality

I. Scenarios for charmonium suppression in A+A

- **QGP color screening:**

[Matsui and Satz '86]: **dissociation of charmonia in the deconfined medium: c-cbar cannot form a bound state (J/Ψ) due to color screening in QGP**



- **However, lattice QCD predicts (2004): J/Ψ can exist up to ~2 T_C !**

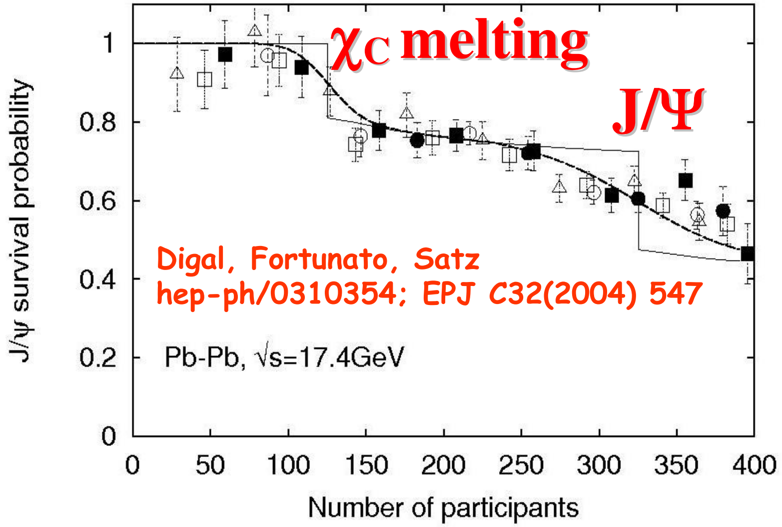
Quarkonium dissociation temperatures:

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	2.10	1.16	1.12

- **I. QGP threshold melting**

[Satz et al'03]:

Charmonia suppression sets in abruptly at threshold energy densities, where χ_C and J/Ψ are melting



Digal, Fortunato, Satz hep-ph/0310354; EPJ C32(2004) 547

- **Regeneration of J/Ψ in QGP at T_C:**

[Braun-Munzinger, Thews, Ko et al. `01]

J/Ψ+g <–> c+cbar+g

II. Scenarios for charmonium suppression in A+A

II. Comover absorption

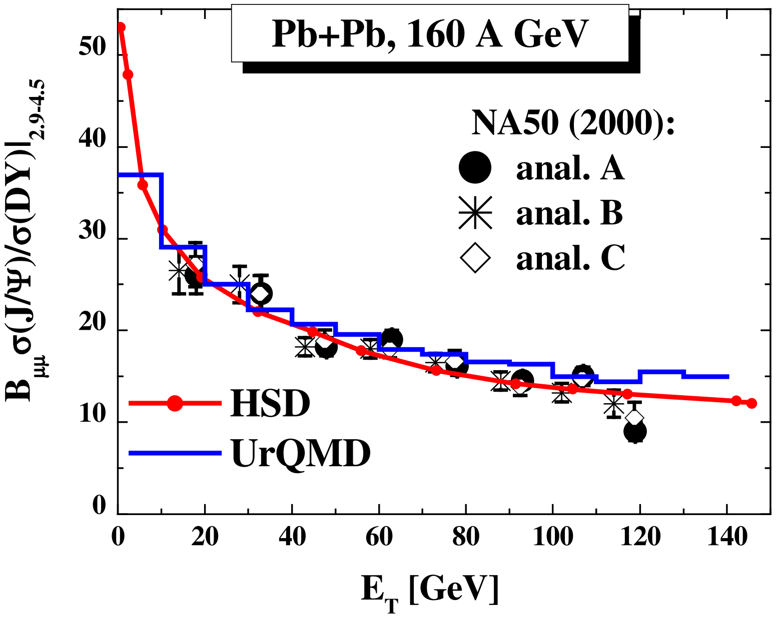
[Gavin & Vogt, Capella et al.`97]:

charmonium absorption by low energy inelastic scattering with ‚comoving‘ mesons (m=π,η,ρ,...):

J/Ψ+m <–> D+Dbar

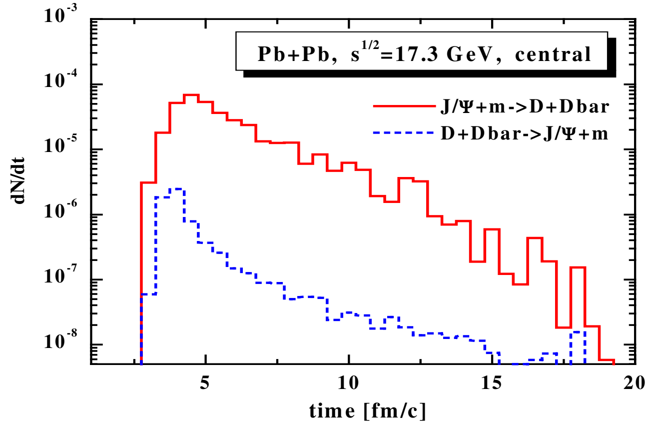
Ψ‘+m <–> D+Dbar

χ_C+m <–> D+Dbar

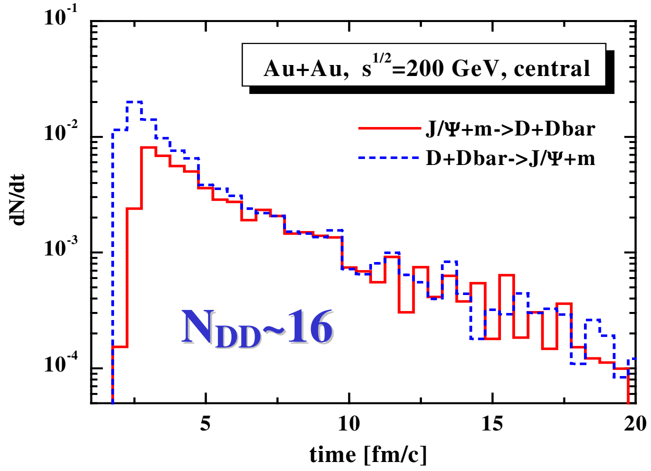


+ Charmonium recombination by D-Dbar annihilation:

At SPS recreation of J/Ψ by D+Dbar annihilation is negligible

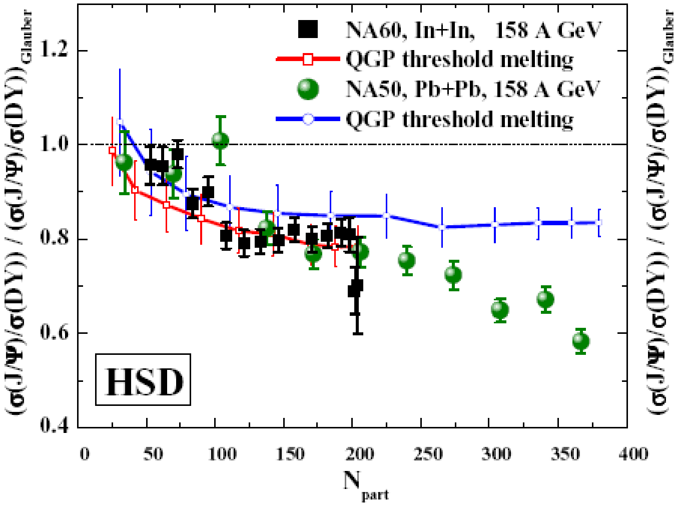


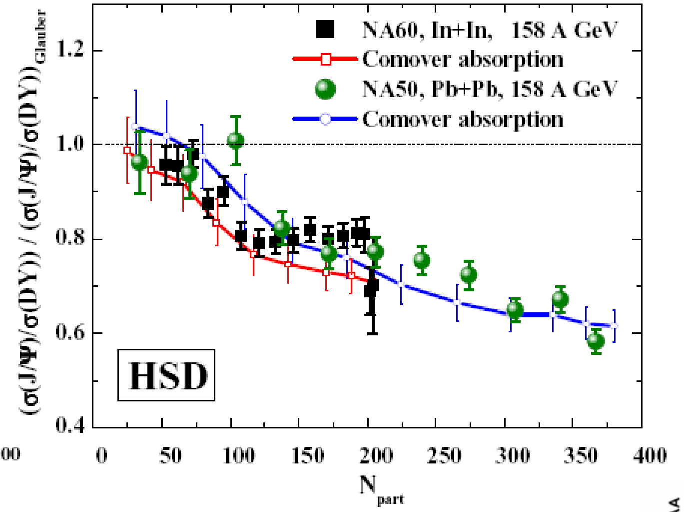
but at RHIC recreation of J/Ψ by D+Dbar annihilation is strong!



I,II. Scenarios for charmonium suppression in A+A

- QGP threshold melting as well as a comover absorption scenario are qualitatively consistent with exp. data (for In+In and Pb+Pb) at SPS energies

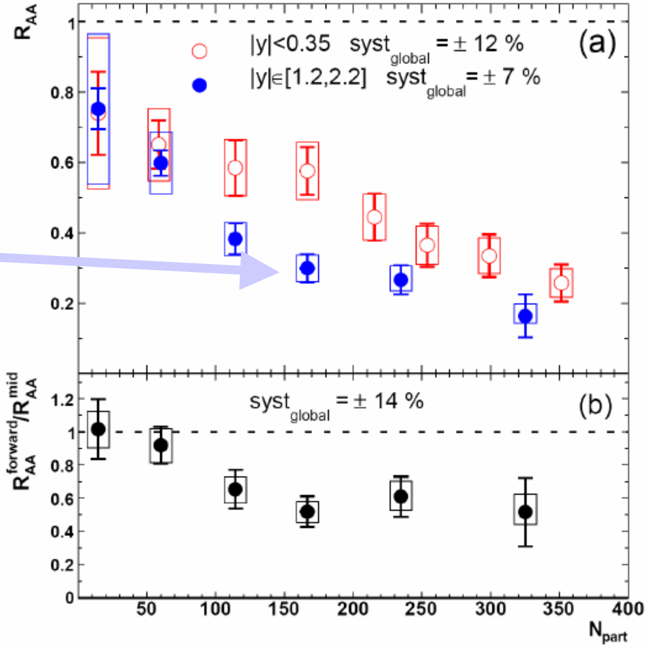




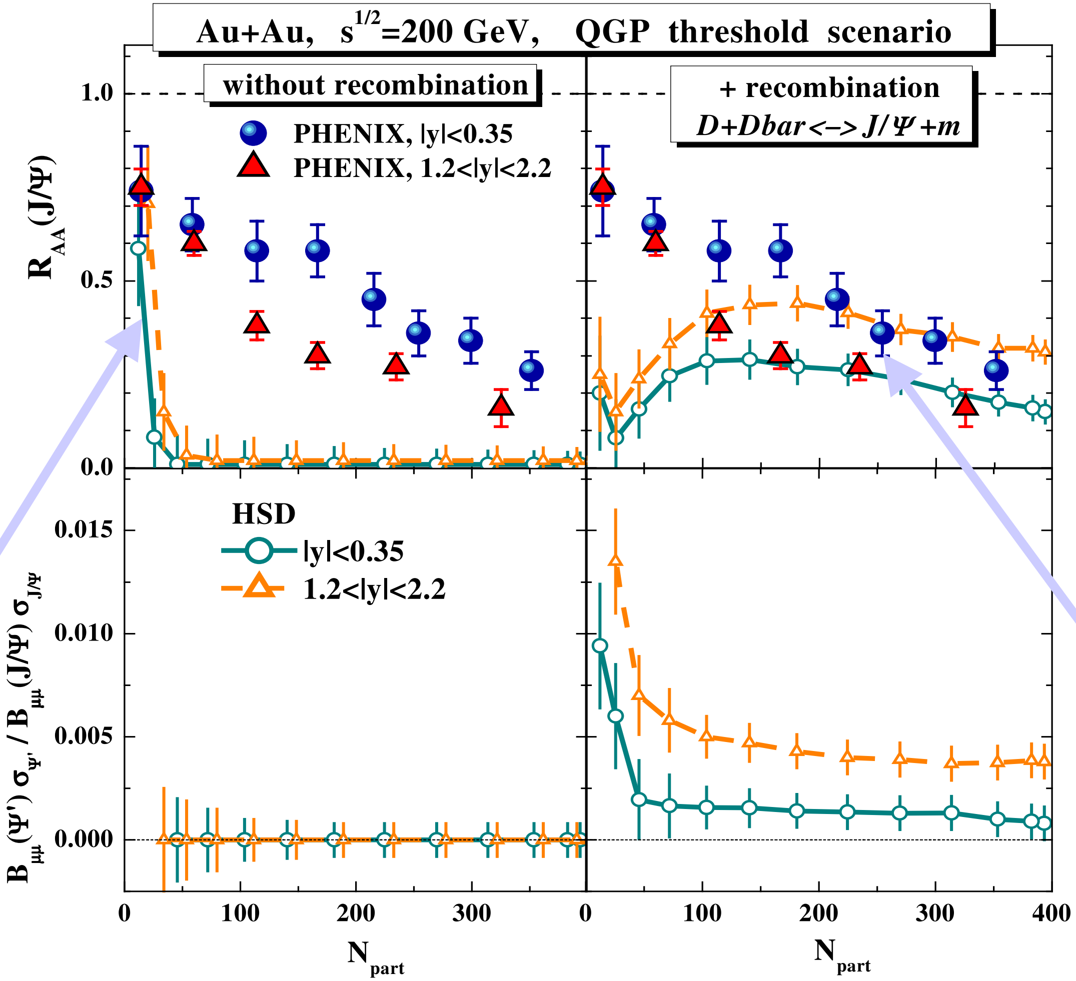
- Increase the energy: new RHIC data at $s^{1/2}$=200 GeV for Au+Au:
suppression at forward-rapidity is larger then at mid-rapidities !

Nuclear modification factor:

$$R_{AA} = \frac{N_{AA}^{J/\psi}}{N_{pp}^{J/\psi} N_{coll}}$$



J/Ψ and Ψ´ suppression in Au+Au at RHIC:
(I.) QGP threshold melting scenario



[Olena Linnyk et al., arXiv:0705.4443, PRC 76 (2007) 041901]

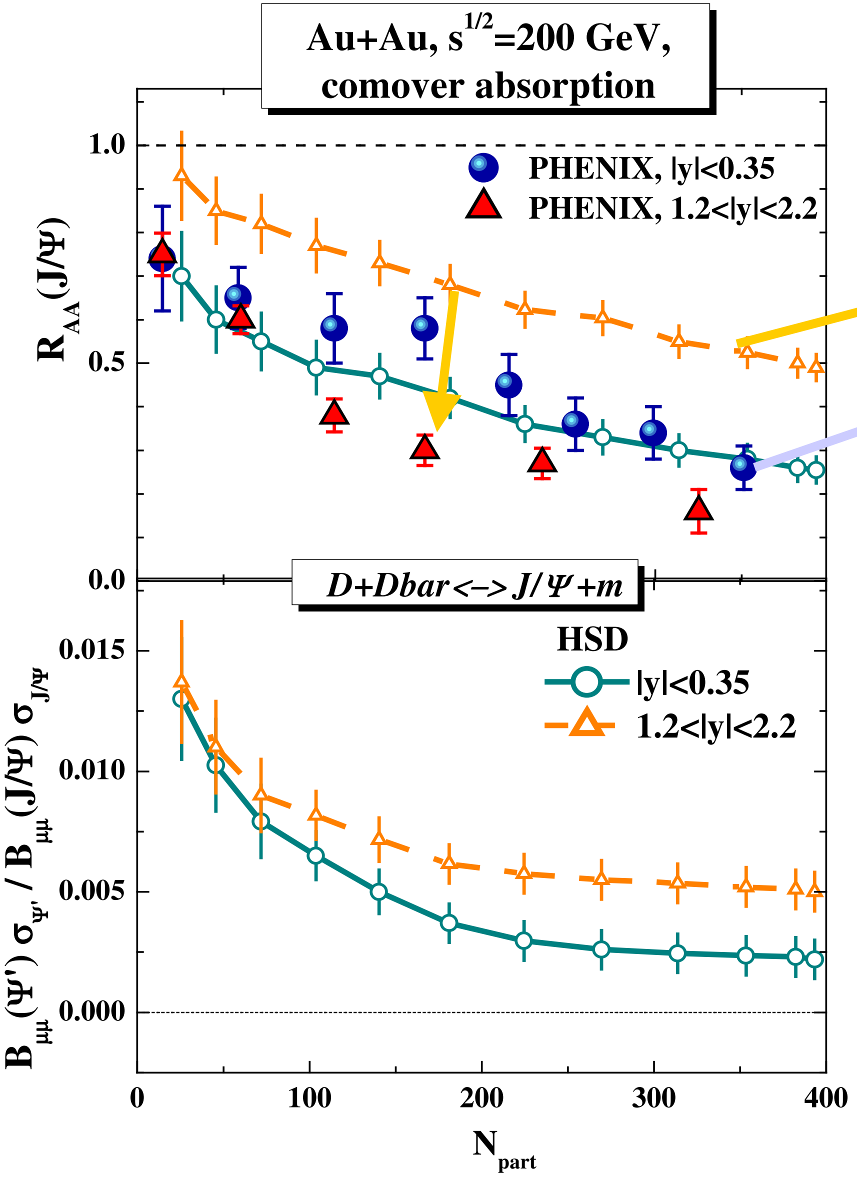
Satz's model: complete dissociation of initial J/Ψ and Ψ´ due to the huge local energy densities !

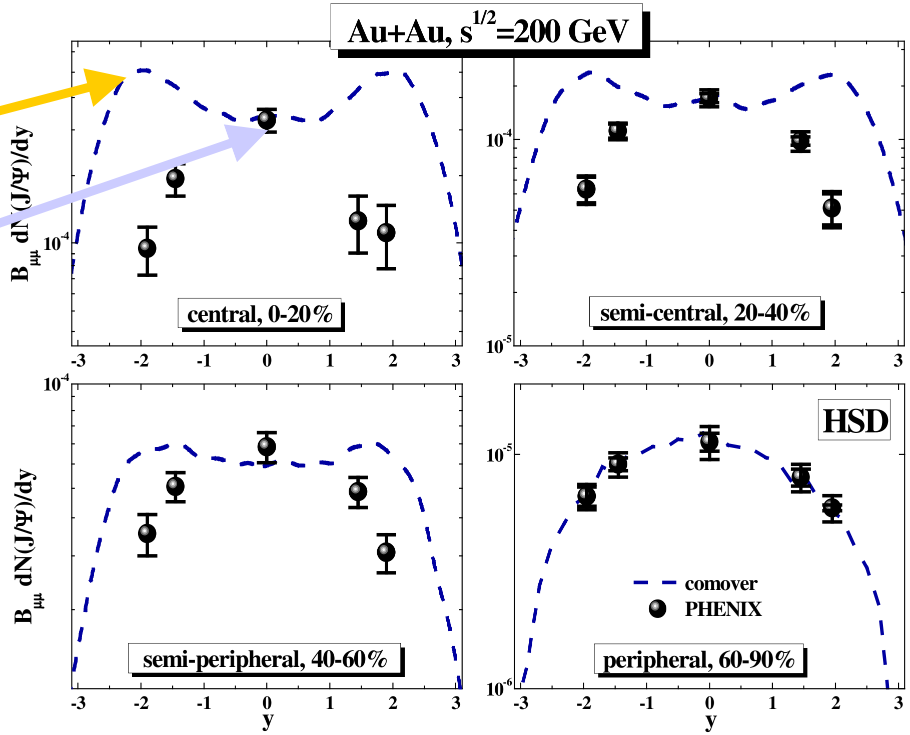
Charmonia recombination by D-Dbar annihilation is important, however, it can not generate enough charmonia, especially for peripheral collisions!

QGP threshold melting scenario is ruled out by PHENIX data!

J/Ψ and Ψ´ suppression in Au+Au at RHIC:
(II.) Comover absorption (+ recombination by D-Dbar annihilation)

Olena Linnyk et al.,
nucl-th/0612049, NPA 786 (2007) 183;
arXiv:0801.4282, NPA 807 (2008) 79



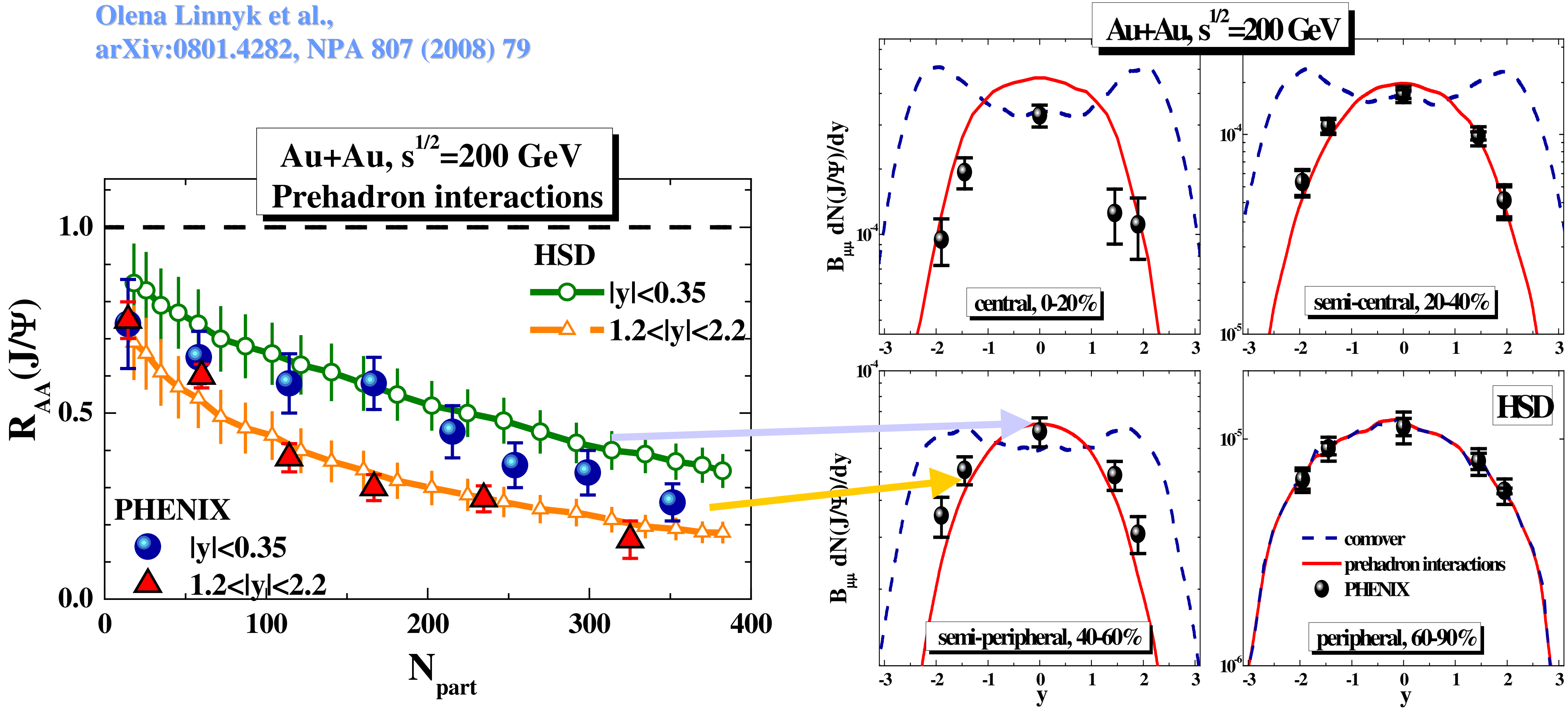


In the comover scenario the J/Ψ suppression at mid-rapidity is stronger than at forward rapidity, unlike the data!

Pure comover scenario is ruled out by PHENIX data!

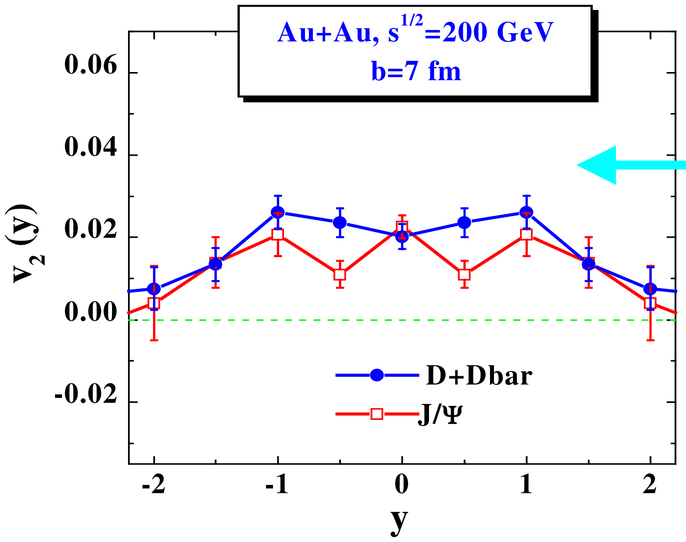
J/Ψ and Ψ´ suppression in Au+Au at RHIC:
(III.) Pre-hadronic interaction scenario

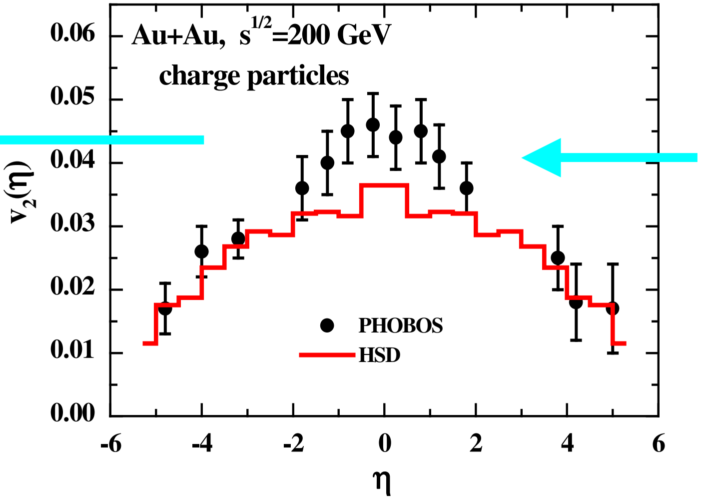
Olena Linnyk et al.,
arXiv:0801.4282, NPA 807 (2008) 79



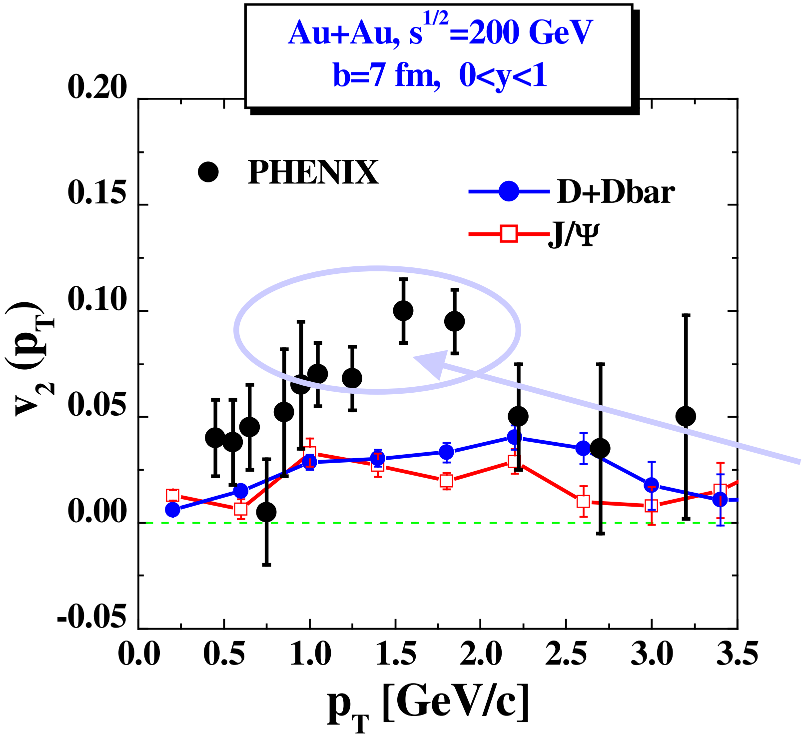
In the prehadronic interaction scenario the J/Ψ rapidity distribution has the right shape like the PHENIX data! => can describe the RHIC data at $s^{1/2}$=200 GeV for Au+Au at mid- and forward-rapidities simultaneously.

HSD: v_2 of D+Dbar and J/Ψ from Au+Au versus p_T and y at RHIC





Collective flow from hadronic interactions is too low at midrapidity !



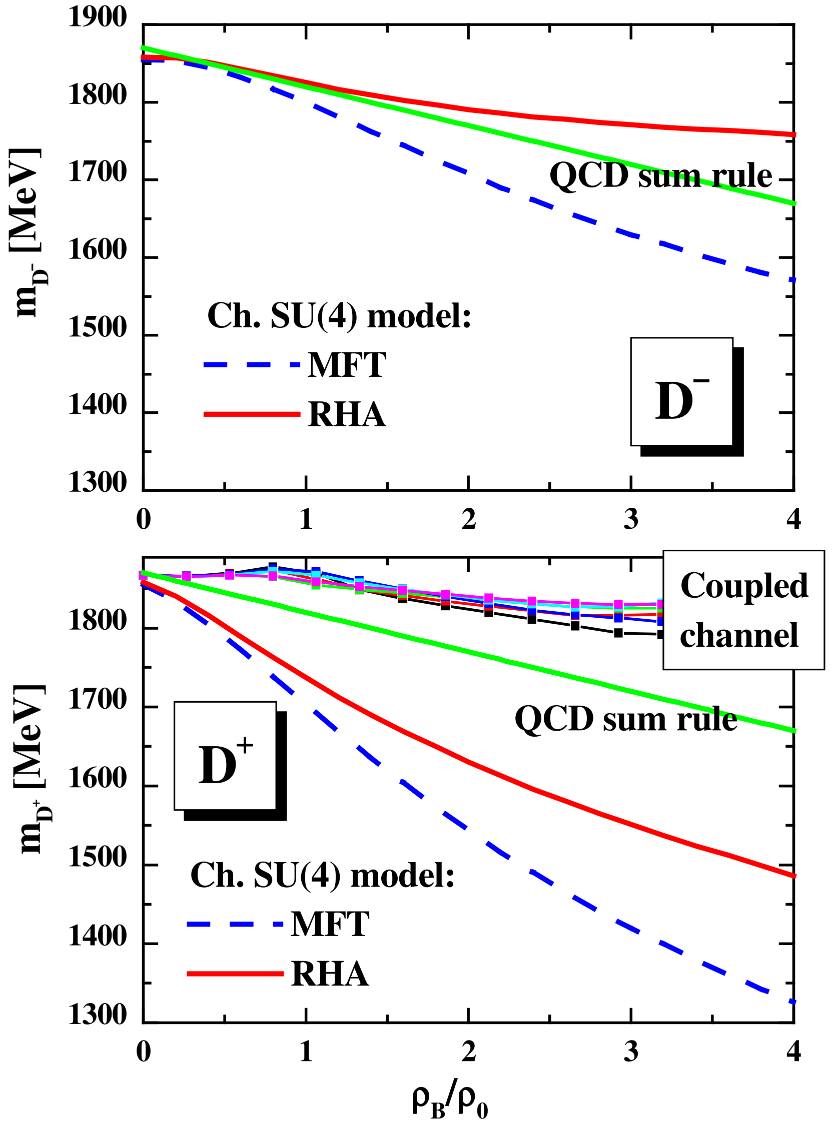
- **HSD: D-mesons and J/Ψ follow the charged particle flow => small v_2 < 3%**

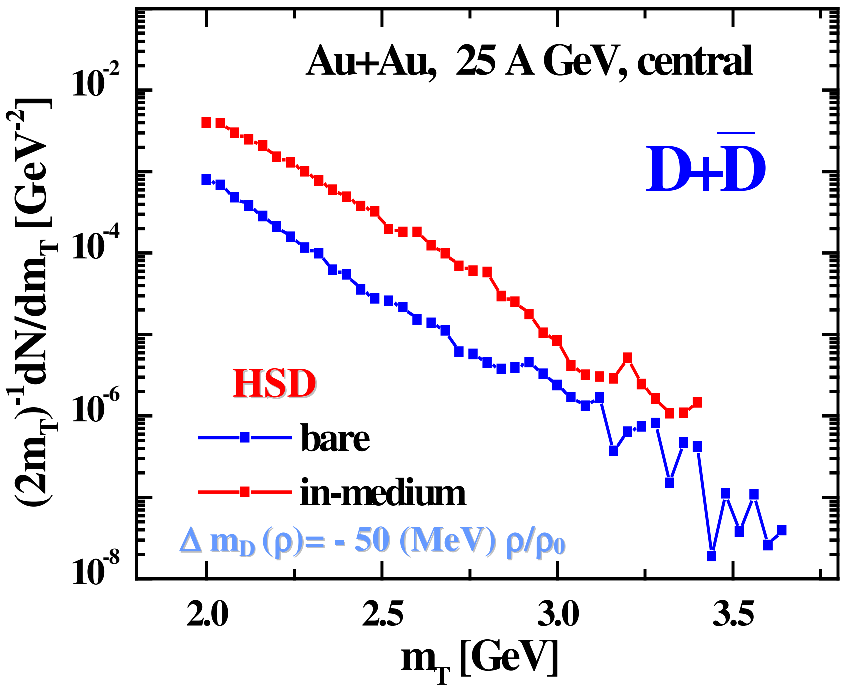
- **STAR data show very large collective flow of D-mesons v_2~15%!**

=> strong initial flow of non-hadronic nature!

PRC 71 (2005) 044901

D/Dbar-mesons: in-medium effects





- **Dropping D-meson masses with increasing light quark density might give a large enhancement of the open charm yield at 25 A GeV !**

FAIR (CBM)

- **Charmonium suppression increases for dropping D-meson masses!**

HSD: NPA691 (2001) 761

Ch. SU(4): A. Mishra et al., PRC69 (2004) 015202
QCD sum rule: Hayashigaki, PLB487 (2000) 96
Coupled channel: Tolos et al., EPJ C43 (2005) 761

Jet quenching and angular correlations in A+A

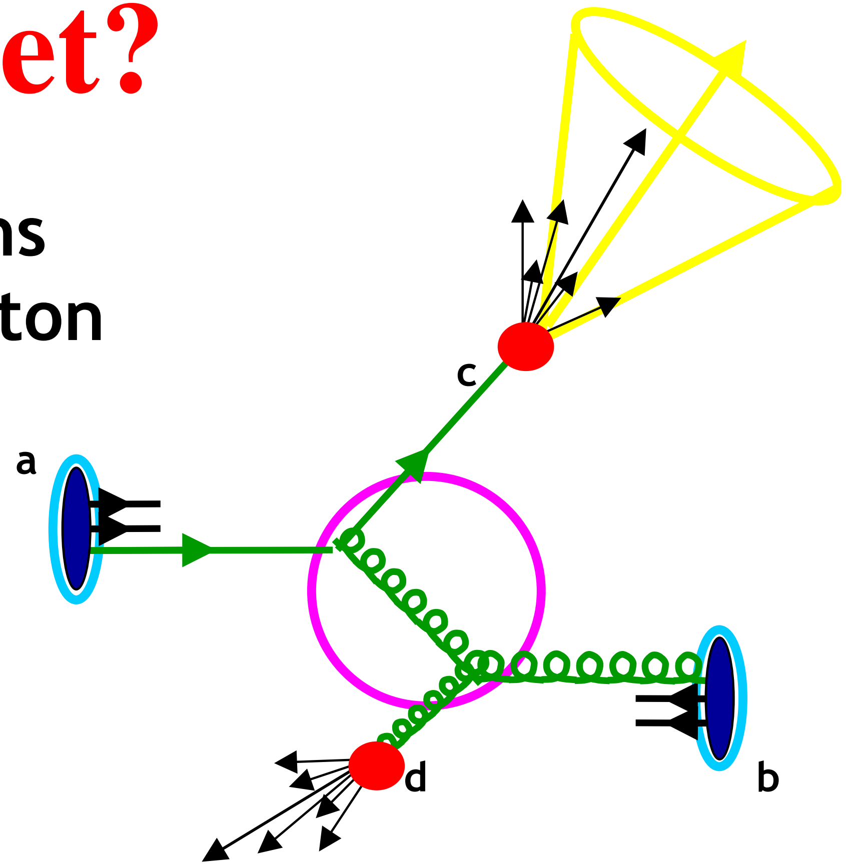
What is a jet?

Jet: A localized collection of hadrons which come from a fragmenting parton

Parton distribution Functions

Hard-scattering cross-section

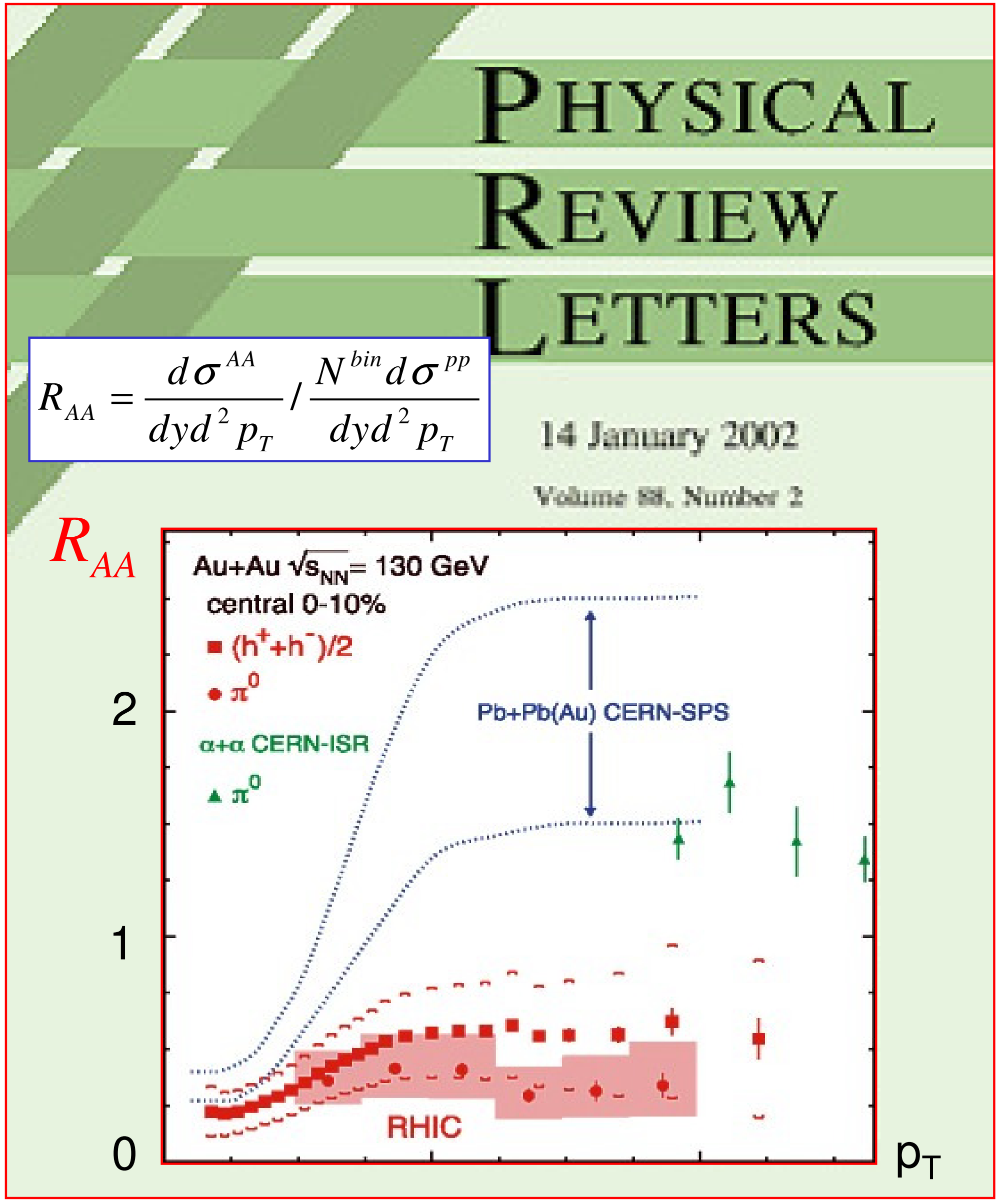
Fragmentation Function



High p_T (> ~2.0 GeV/c) hadron production in pp collisions:

$$\frac{d\sigma^{h}_{pp}}{dy\,d^2p_T} = K\sum_{abcd}\int dx_a\,dx_b\,f_a(x_a,Q^2)\,f_b(x_b,Q^2)\,\frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)\,\frac{D^0_{h/c}}{\pi z_c}$$

Discovery of “Jet Quenching”

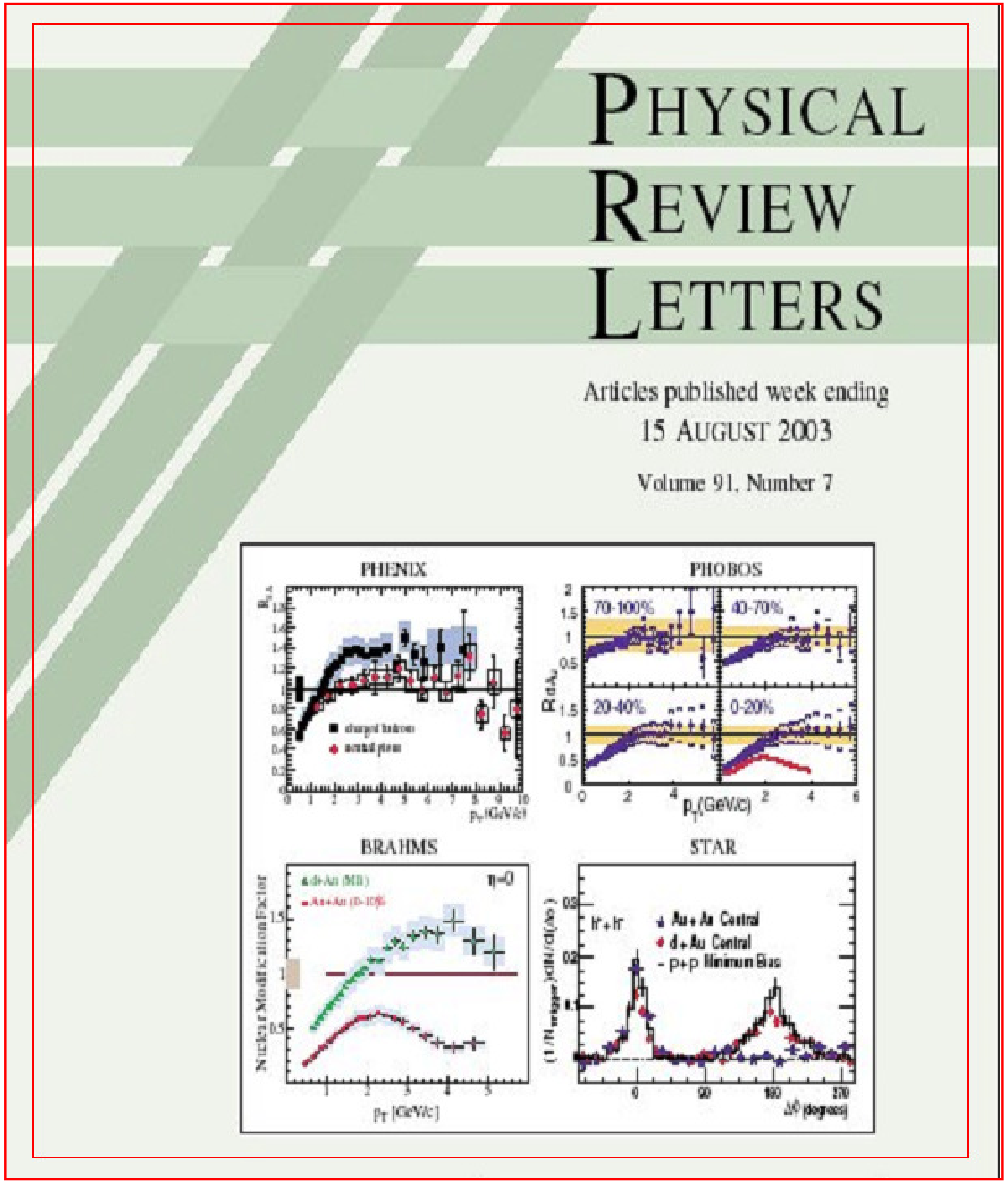


PHYSICAL REVIEW LETTERS

14 January 2002

Volume 88, Number 2

$$R_{AA} = \frac{d\sigma^{AA}}{dyd^2p_T} / \frac{N^{bin}d\sigma^{pp}}{dyd^2p_T}$$

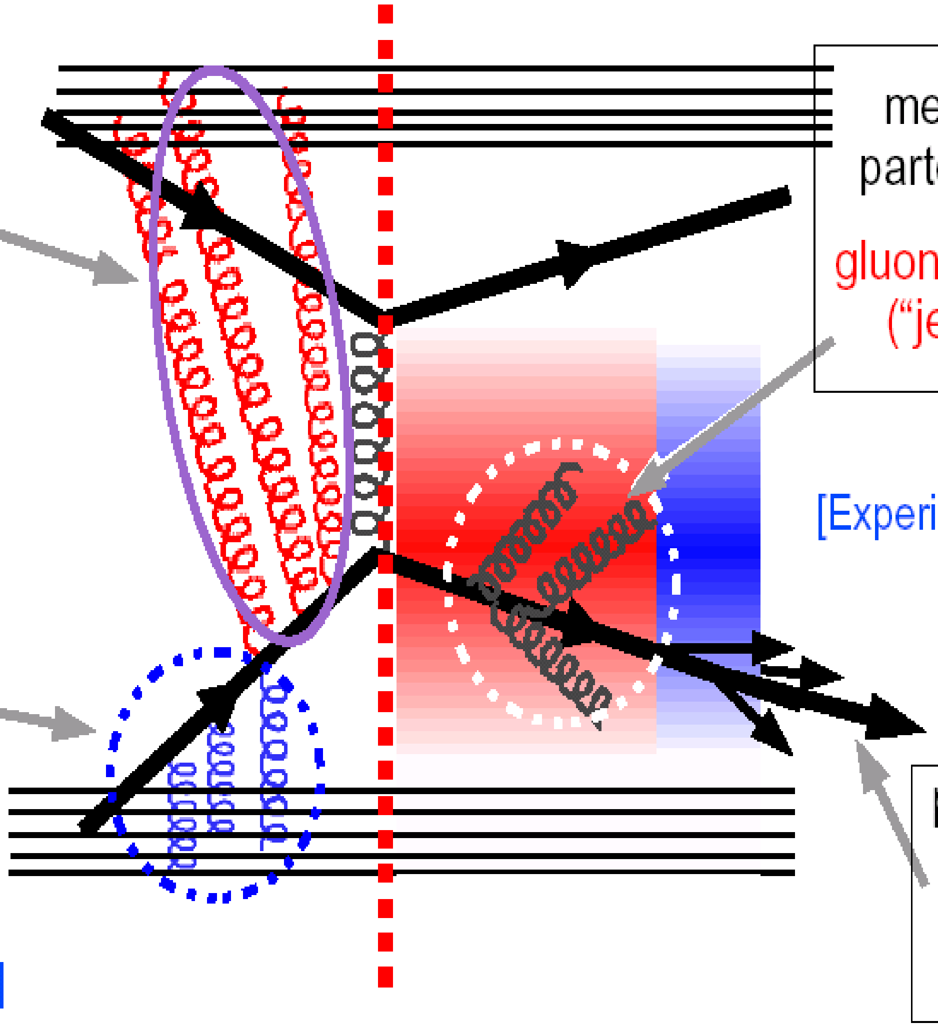


PHYSICAL REVIEW LETTERS

Articles published week ending
15 AUGUST 2003

Volume 91, Number 7

Behavior of hard probes



Initial-state effects:

p_T broadening:
("Cronin enhancement")
Soft & semi-hard extra k_T

[Experimental handle: p,d+A]

Leading-twist shadowing
(modified nuclear PDF)
OR
Gluon saturation in the
highly non-linear regime
of small-x

[Experimental handle: e+A, p,d+A]

Final-state effects:

medium-induced
parton energy loss:

gluon bremsstrahlung
("jet quenching")

[Experimental handle: A+A]

possible hadronic
rescattering
(after/before
hadronization ?)

'jet quenching' – inelastic and elastic scattering of the partons in the medium (partonic and hadronic)

Dynamics and hadronization mechanisms

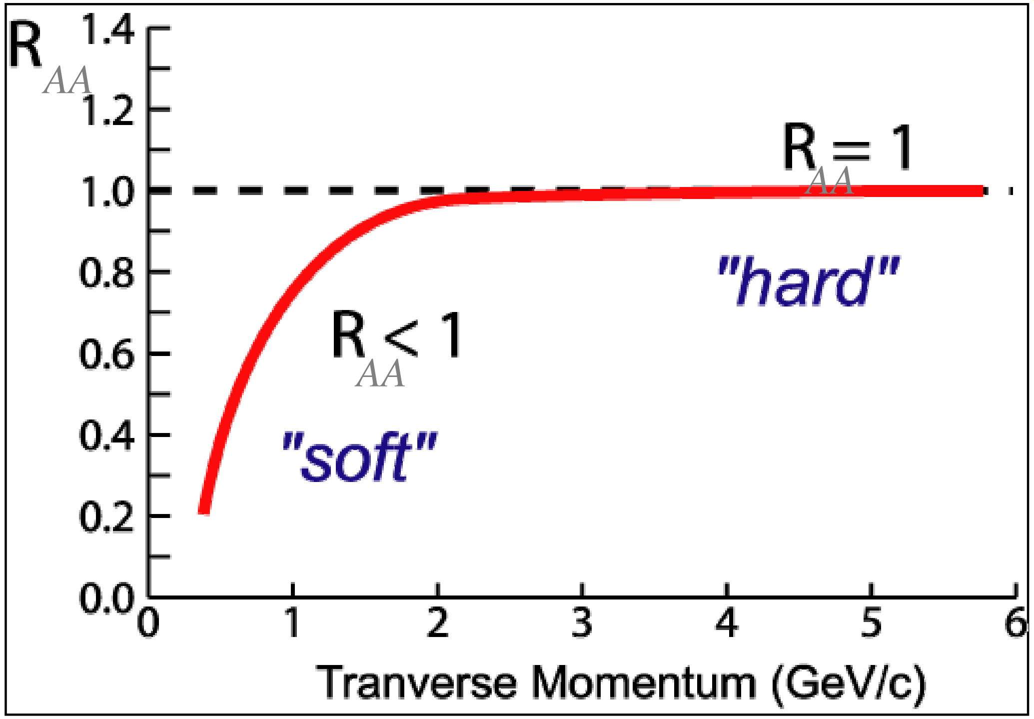
1. Compare Au+Au to nucleon-nucleon cross sections
2. Compare Au+Au central/peripheral

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

$<N_{binary}>/\sigma_{inel}^{p+p}$



If no "effects":

$R_{AA} < 1$ in regime of soft physics (since soft physics scales with N_{part} which is smaller then N_{binary})

$R_{AA} = 1$ at high-p_T where hard scattering dominates

Suppression:

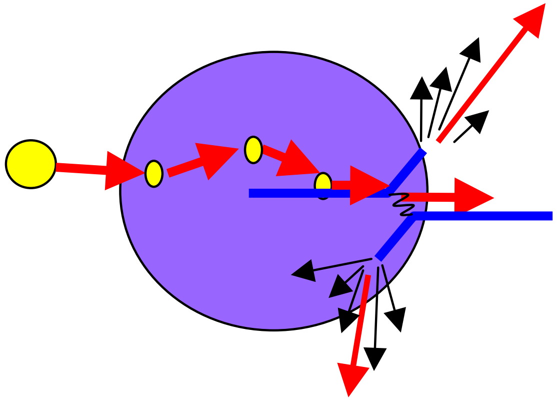
$R_{AA} < 1$ at high-p_T "jet quenching"

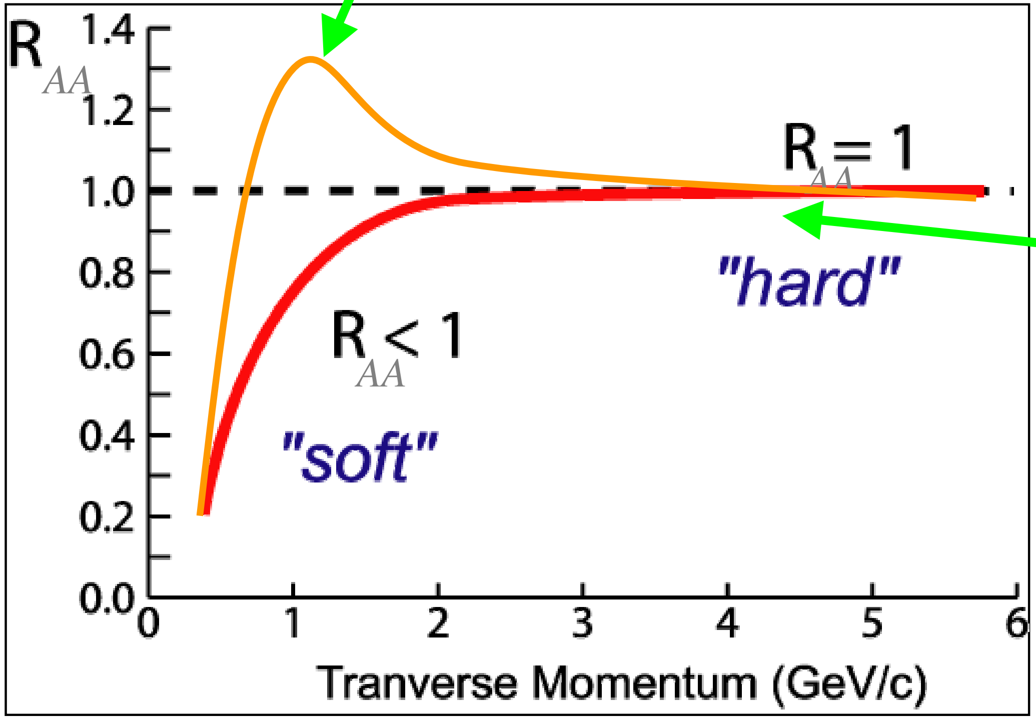
Also: $R_{AA} > 1$: Cronin Effect

Nuclear Modification Factor

“Cronin effect”

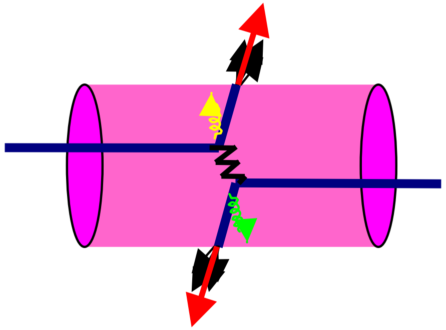
Initial state multiple scattering leading to Cronin enhancement (R_{AA}>1)



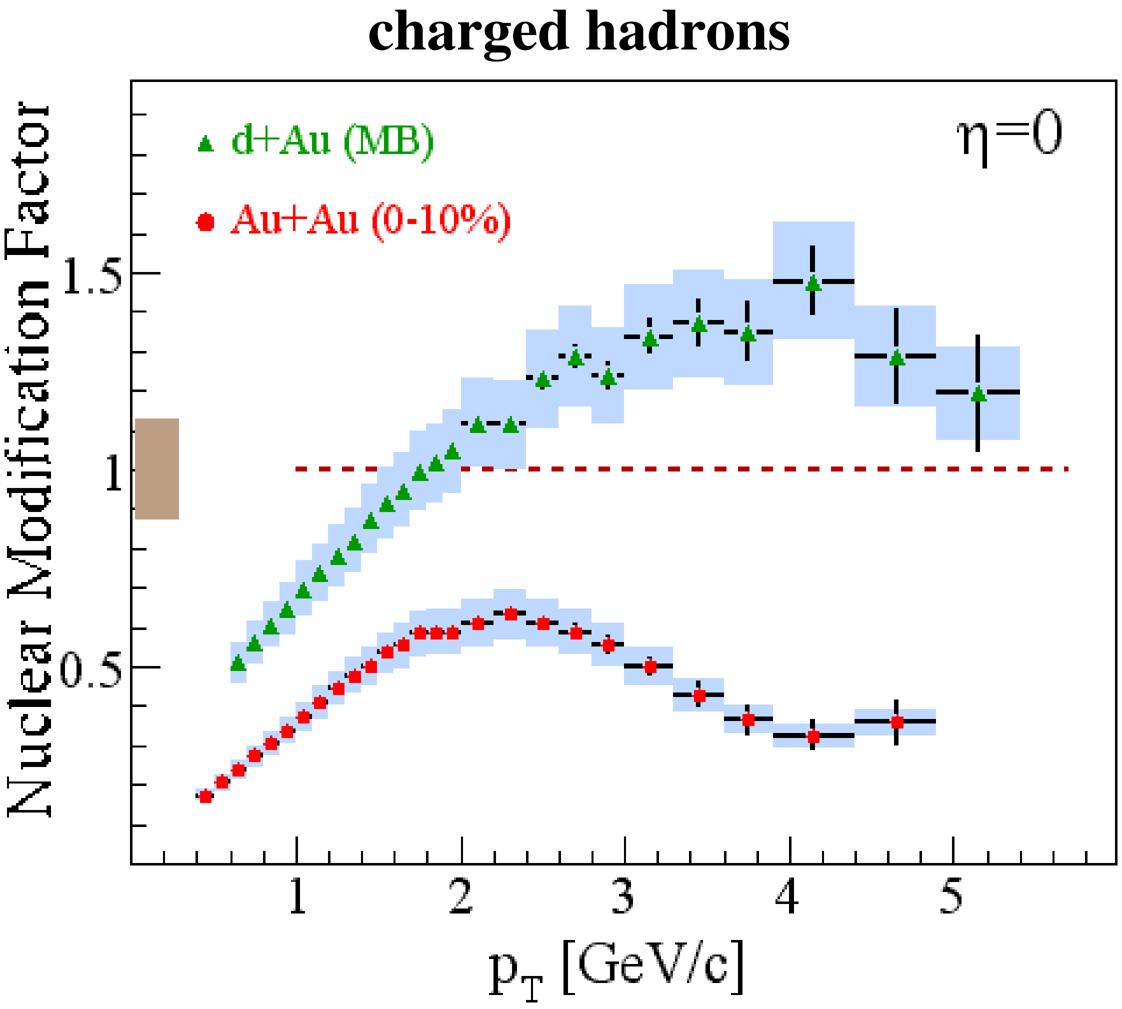


Jet-quenching

(R_{AA}<1)



Nuclear Modification Factor



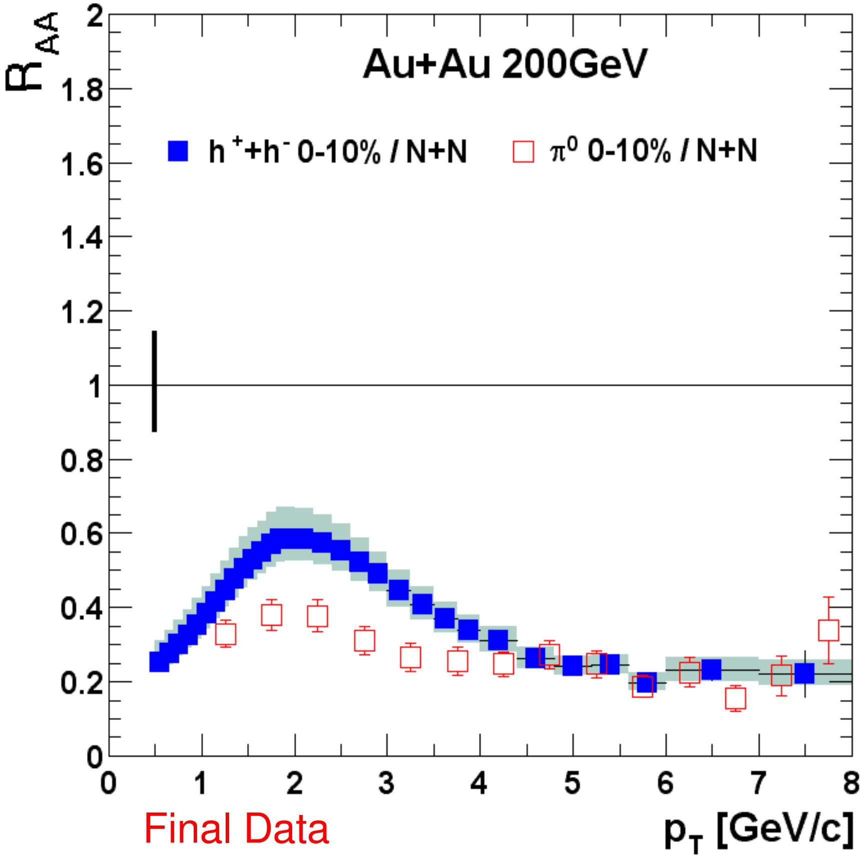
- High p_T enhancement in d+Au collisions at $\sqrt{s_{NN}}$=200 GeV
- Comparing Au+Au to d+Au at midrapidity

  ⇒ Strong effect of dense medium

  ⇒ Partonic energy loss?

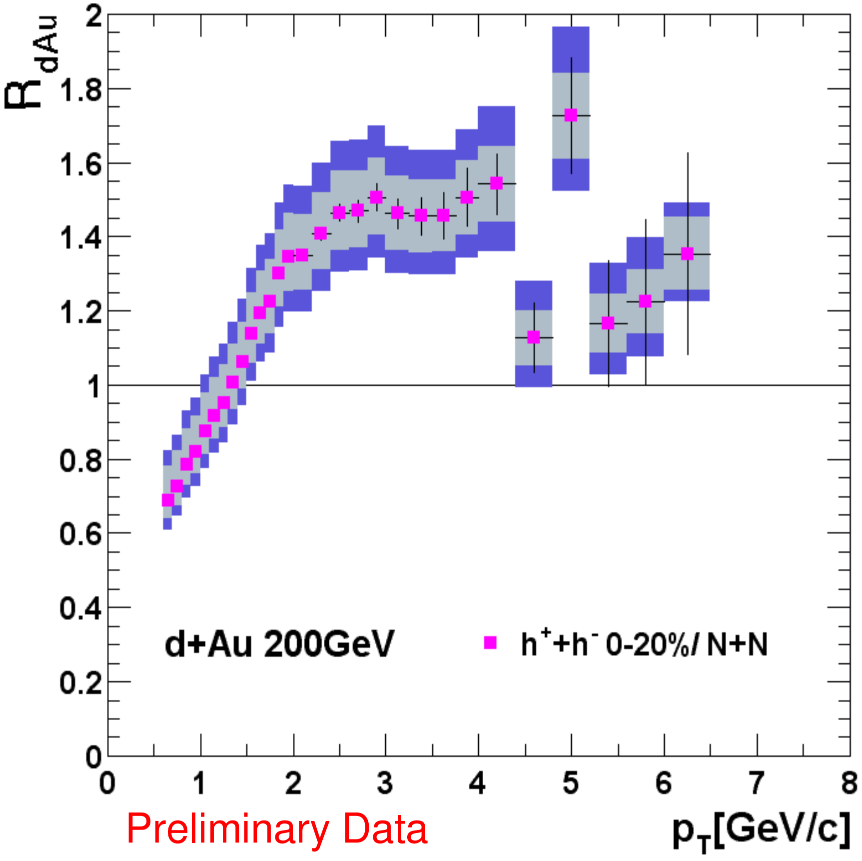
Centrality Dependence

Au + Au Experiment



Final Data

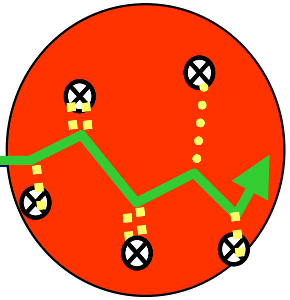
d + Au Control Experiment



Preliminary Data

- **Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control experiment.**
- **Jet suppression is clearly a final state effect of the dense medium!**

Cronin effect at RHIC (HSD)



Cronin effect: initial state semi-hard gluon radiation increases p_T spectra already in p+A or d+A

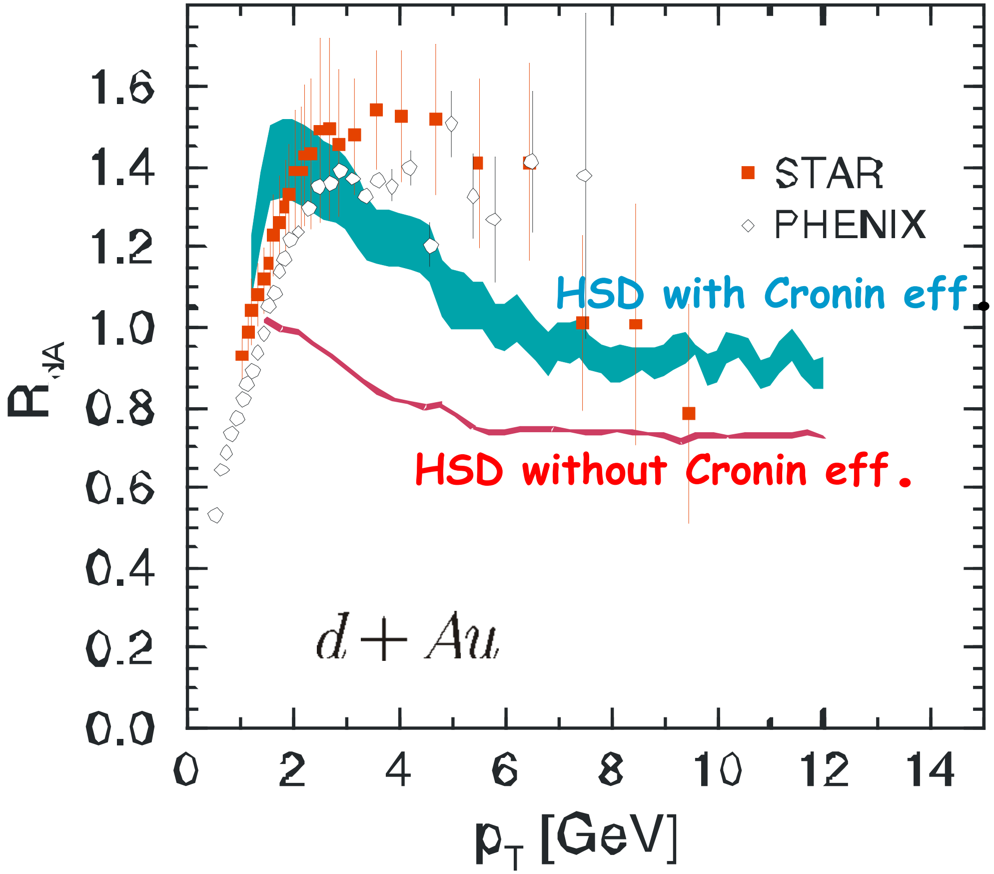
$$R_{dA}(p_T) = \frac{1/N_{dA}^{event} \cdot d^2N_{dA}/dydp_T}{<N_{coll}>/\sigma_{pp}^{inelas} \cdot d\sigma_{pp}/dydp_T}$$

Modelling of the Cronin effect in HSD:

$$<k_T^2>_{AA} = <k_T^2>_{PP} (1+a\, N_{Prev})$$

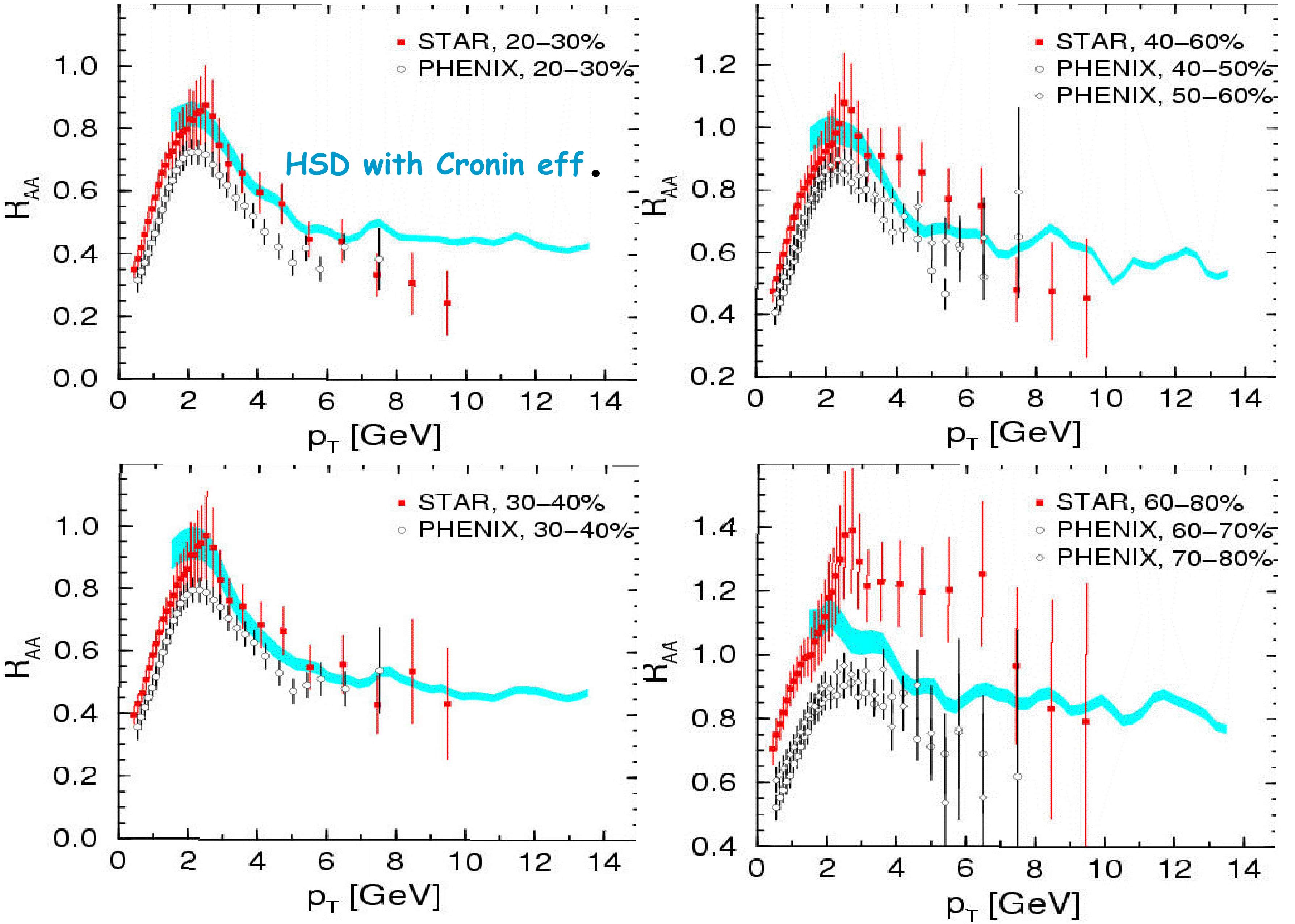
N_{Prev}= number of previous collisions

parameter a = 0.25 – 0.4



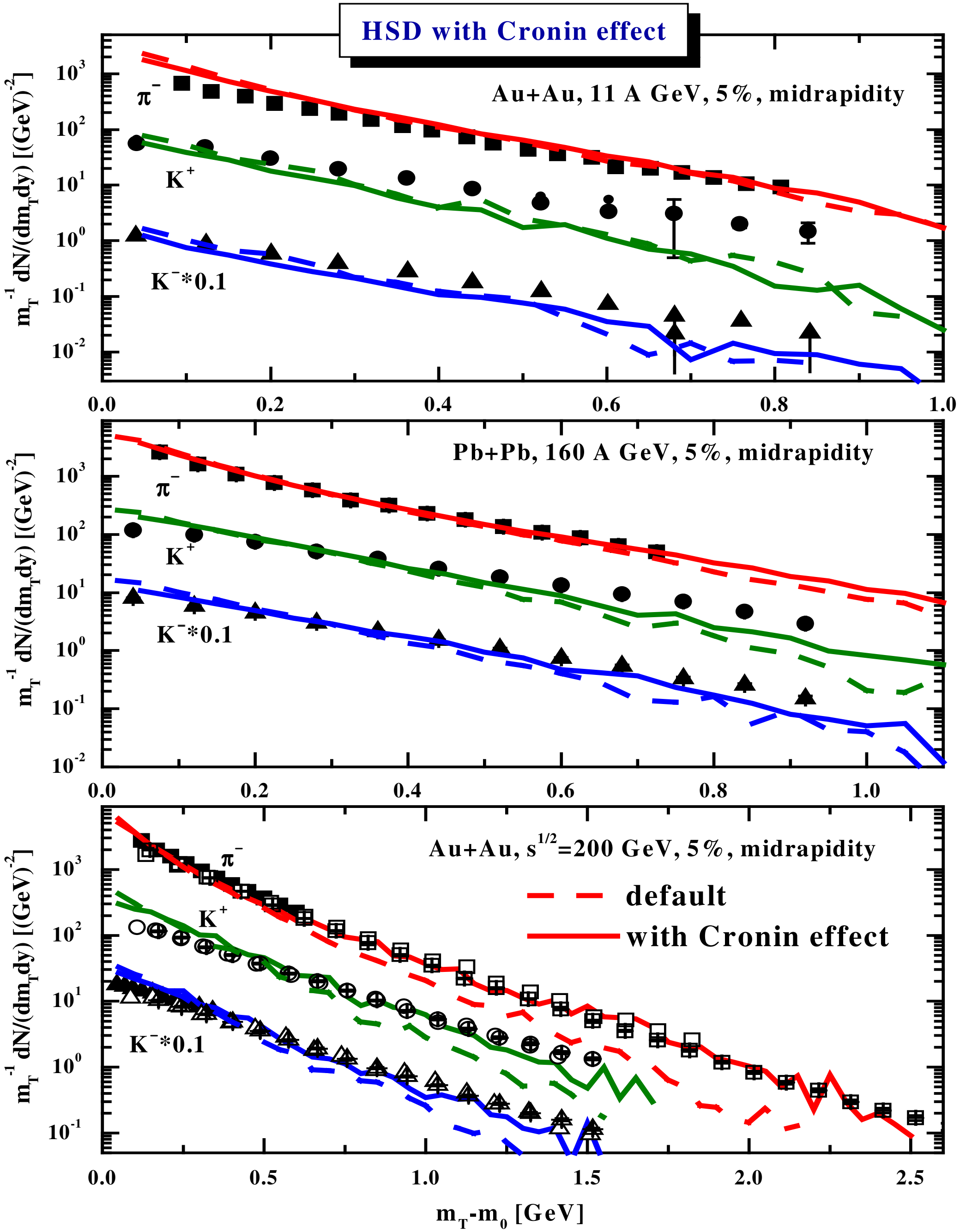
W. Cassing, K. Gallmeister and C. Greiner, Nucl. Phys. A 735 (2004) 277

High p_T suppression in non-central Au+Au (HSD)



HSD with Cronin eff.

Cronin effect on π, K± m_T-spectra in A+A (HSD)



- Very small effect at AGS
- Hardening of the m_T spectra at top SPS
- Substantial hardening of the m_T spectra at RHIC –> large improvement !
- Consistent with other observables !

PRC 69 (2004) 015202

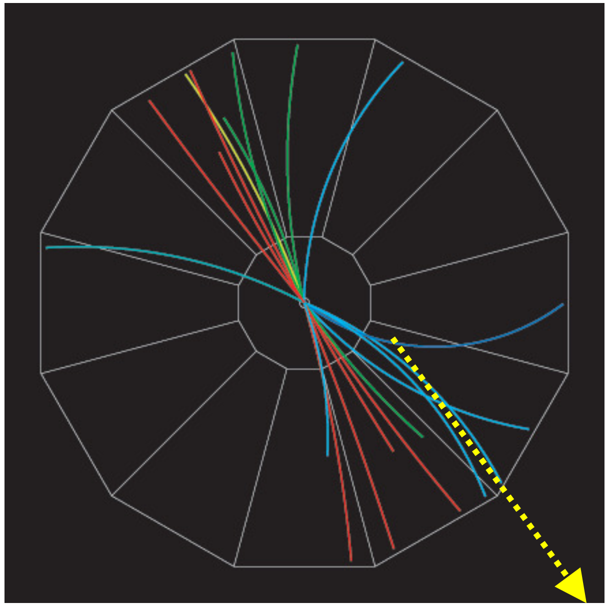
Different Ways to “Skin a Jet”

1) Integral Distributions:
$<p_T>, <N_{ch}>$

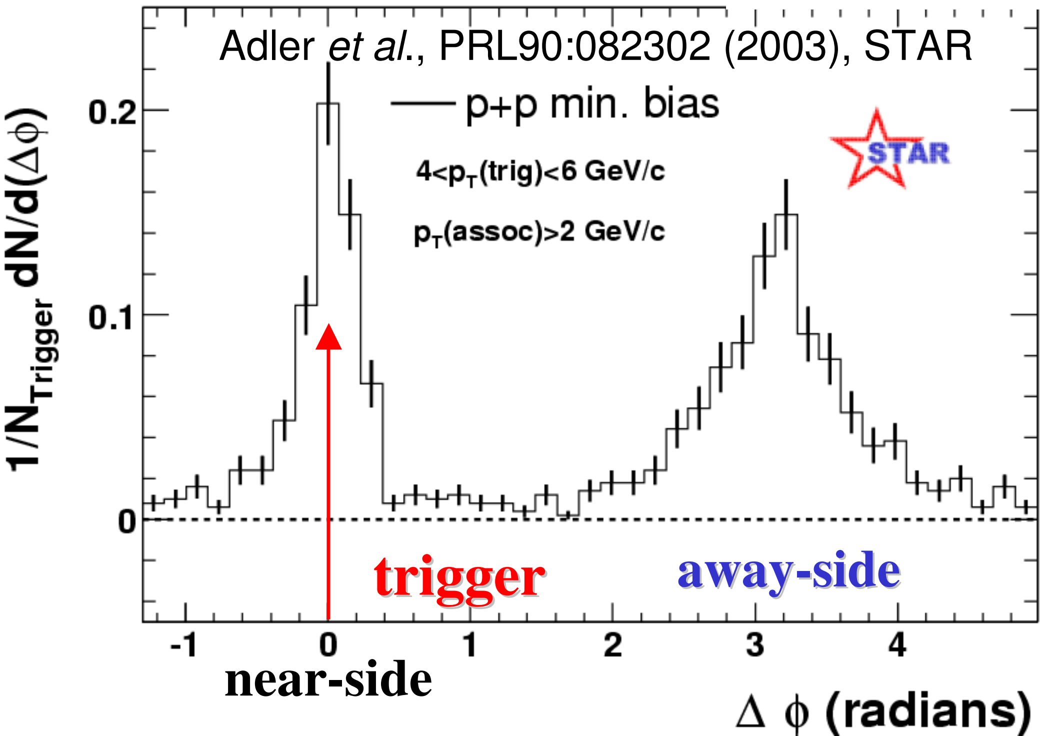
2) Single Particle Spectra:
$d\sigma/dp_T \Rightarrow R_{AA}, R_{dA}$

3) 2-Particle Correlations:
$dN/d(\Delta\phi)$

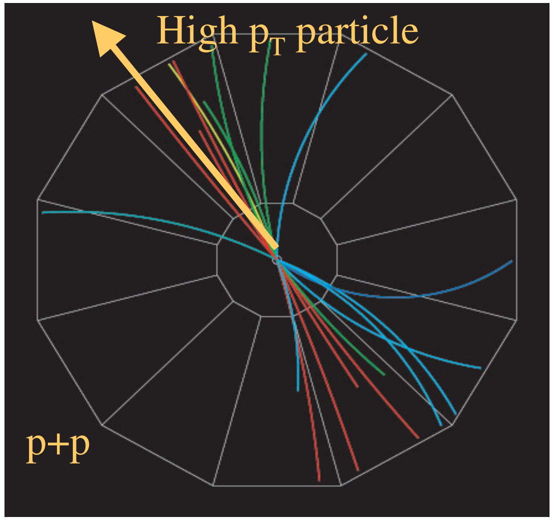
4) Jet Reconstruction:
$d\sigma/dE_T$, *Frag. Func.*

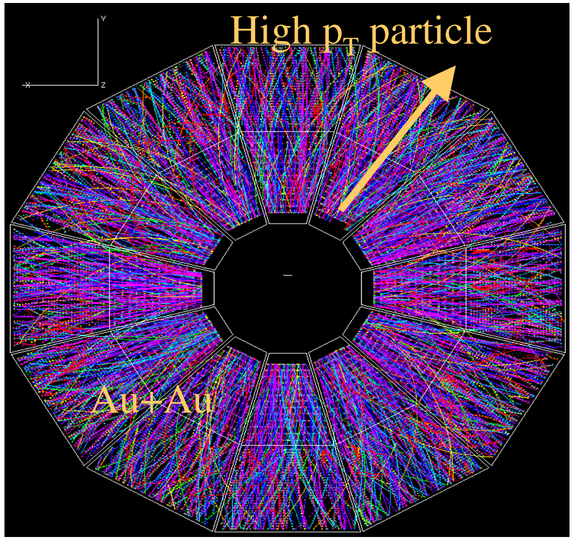


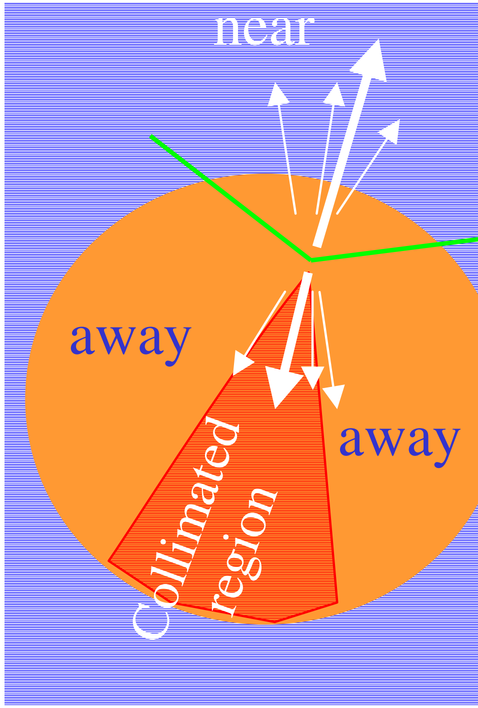
“Trigger”
$\phi = 0$

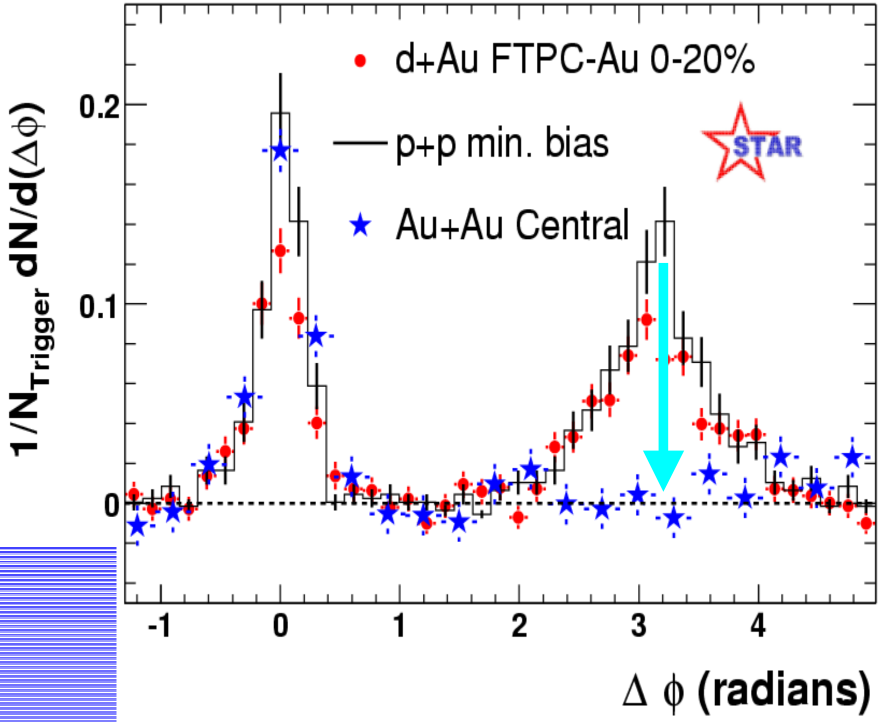


Jet Energy Loss



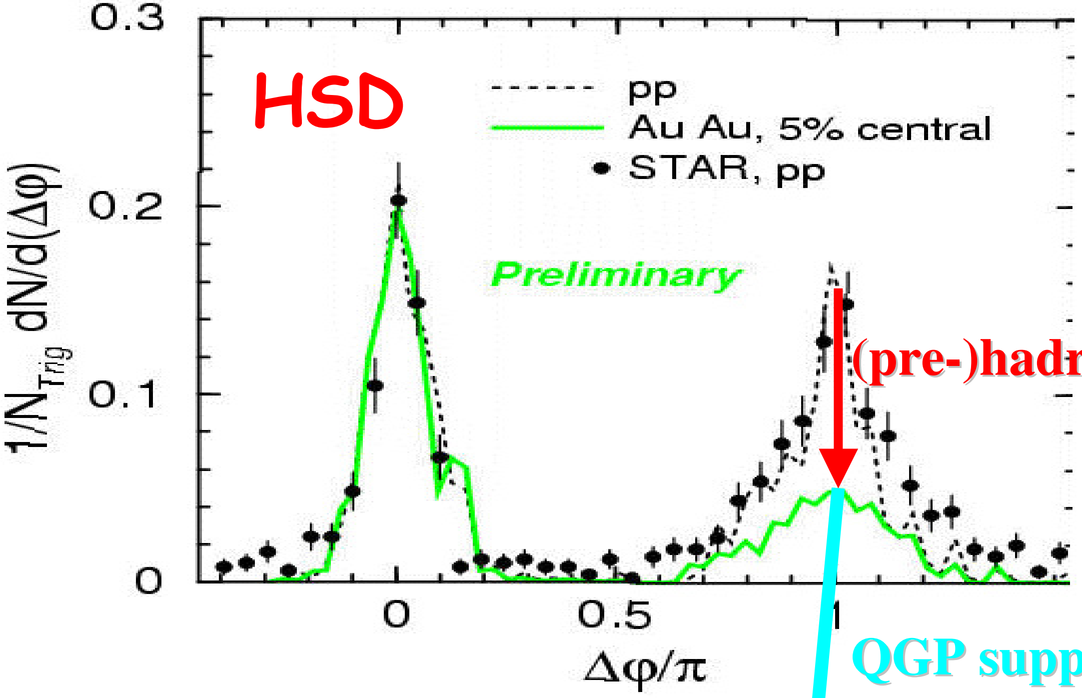






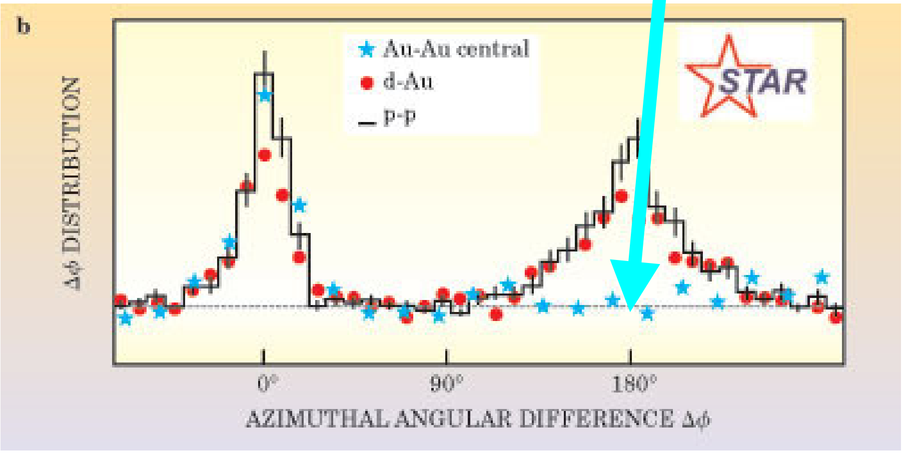
QGP suppression ?!

Jet suppression: dN/dφ (HSD)



(pre-)hadronic FSI

QGP suppression

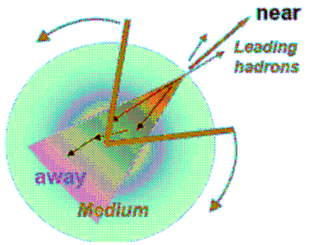


Δ ϕ (radians)

- The jet angular correlations for pp are fine !
- The near-side jet angular correlation for central Au+Au is well described, but the suppression of the far-side jet is too low !

W. Cassing, K. Gallmeister, C. Greiner,
J.Phys.G30 (2004) S801; NPA 748 (2005) 41

New exp. data: ϕ–η angular correlations

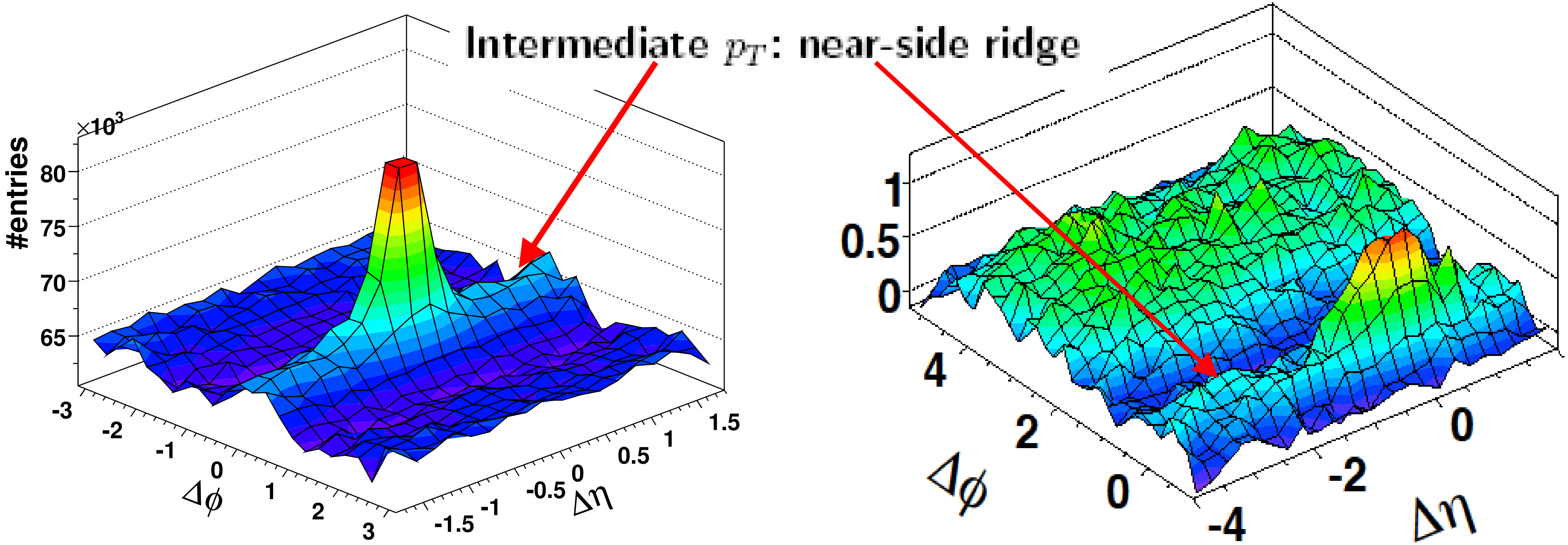


STAR

Eur.Phys.J.C61 (2009) 569-574

PHOBOS

Phys.Rev.Lett.104 (2010) 062301



Intermediate p_T: near-side ridge

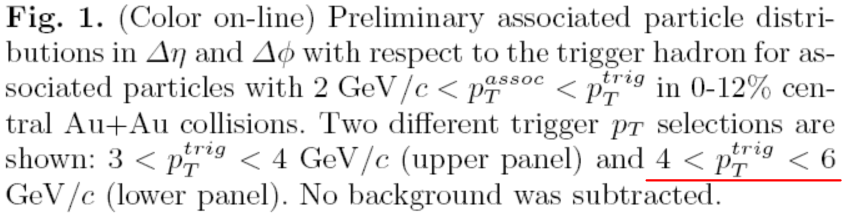


Fig. 1. (Color on-line) Preliminary associated particle distributions in $\Delta\eta$ and $\Delta\phi$ with respect to the trigger hadron for associated particles with 2 GeV/$c < p_T^{assoc} < p_T^{trig}$ in 0-12% central Au+Au collisions. Two different trigger p_T selections are shown: $3 < p_T^{trig} < 4$ GeV/c (upper panel) and $4 < p_T^{trig} < 6$ GeV/c (lower panel). No background was subtracted.

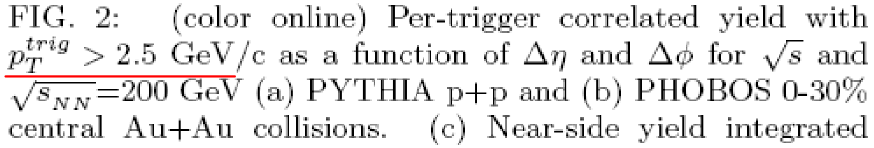
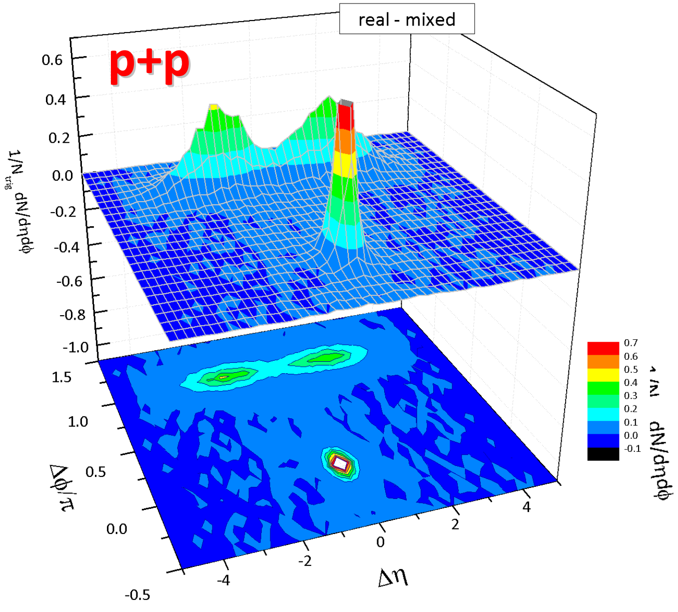


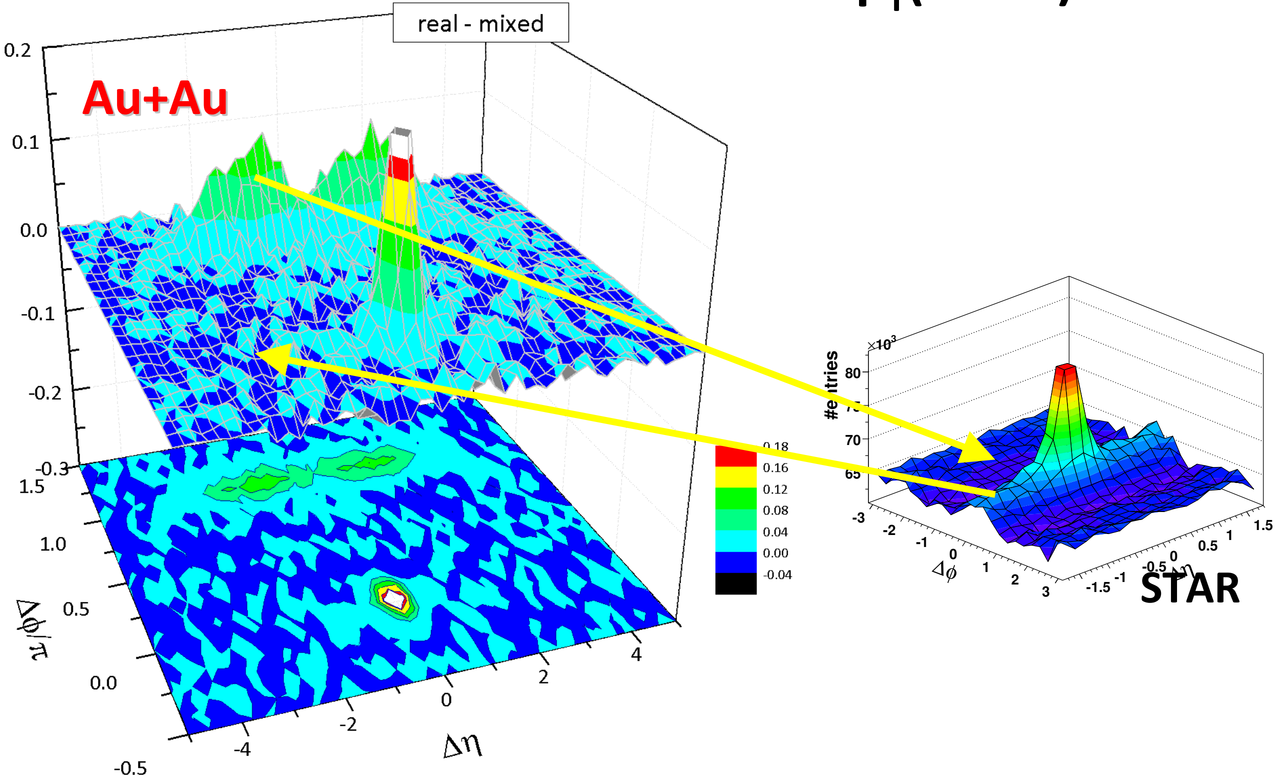
FIG. 2: (color online) Per-trigger correlated yield with $p_T^{trig} > 2.5$ GeV/c as a function of $\Delta\eta$ and $\Delta\phi$ for $\sqrt{s}$ and $\sqrt{s_{NN}}$=200 GeV (a) PYTHIA p+p and (b) PHOBOS 0-30% central Au+Au collisions. (c) Near-side yield integrated

I: High p_T particle correlations in HSD vs. STAR data



Real-Mixed distribution

STAR: **High p_T:**
p_T(trig) > 4 GeV/c
2 < p_T(assoc) < 4 GeV

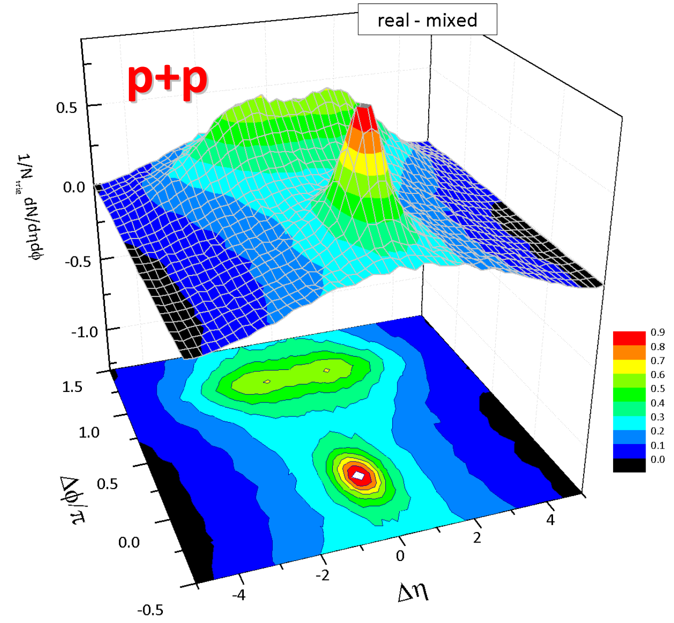


HSD vs. STAR:

- **away side structure is suppressed in Au+Au collisions in comparison to p+p, however, HSD doesn‘t provide enough high p_T suppression to reproduce the STAR Au+Au data**
- **near-side ridge structure is NOT seen in HSD!**

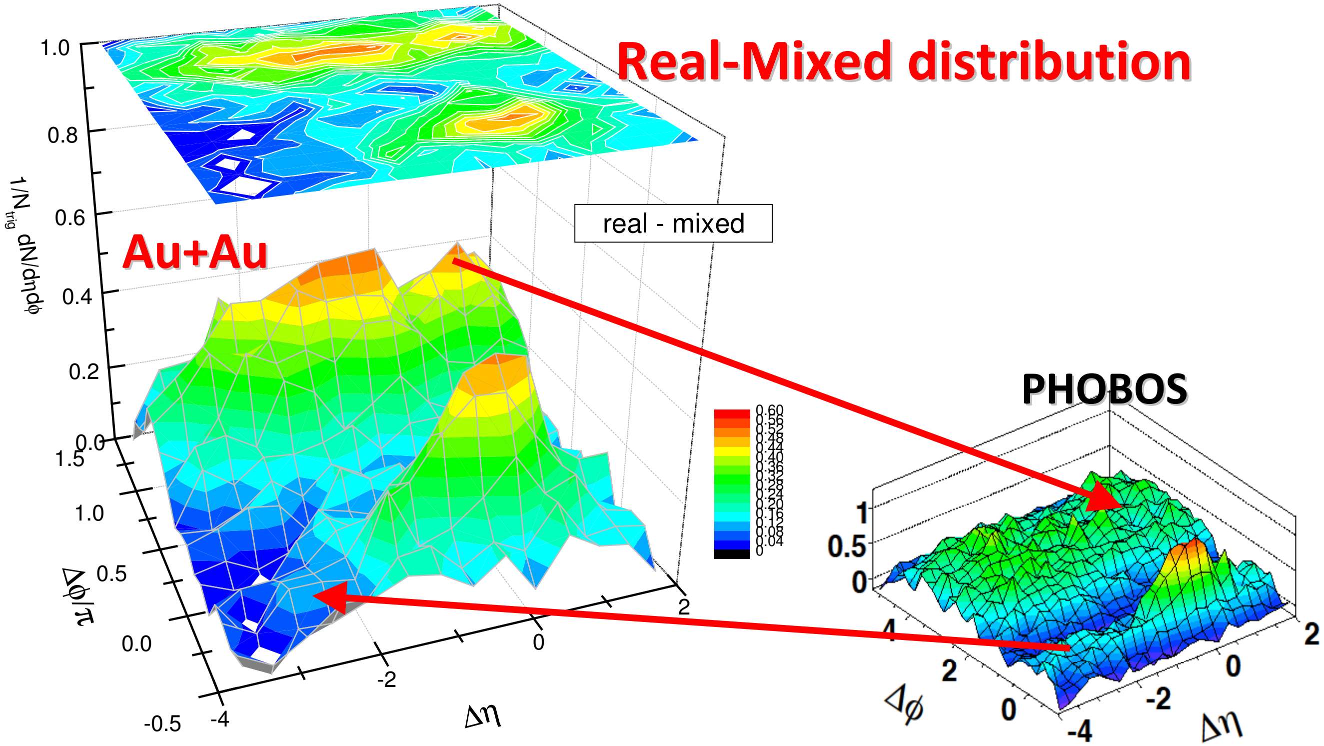
V. Konchakovski

II: Intermediate p_T particle correlations in HSD vs. PHOBOS data



PHOBOS: Intermediate p_T:

p_T(trig) > 2.5 GeV/c; 0.02 < p_T(assoc) < 2.5 GeV



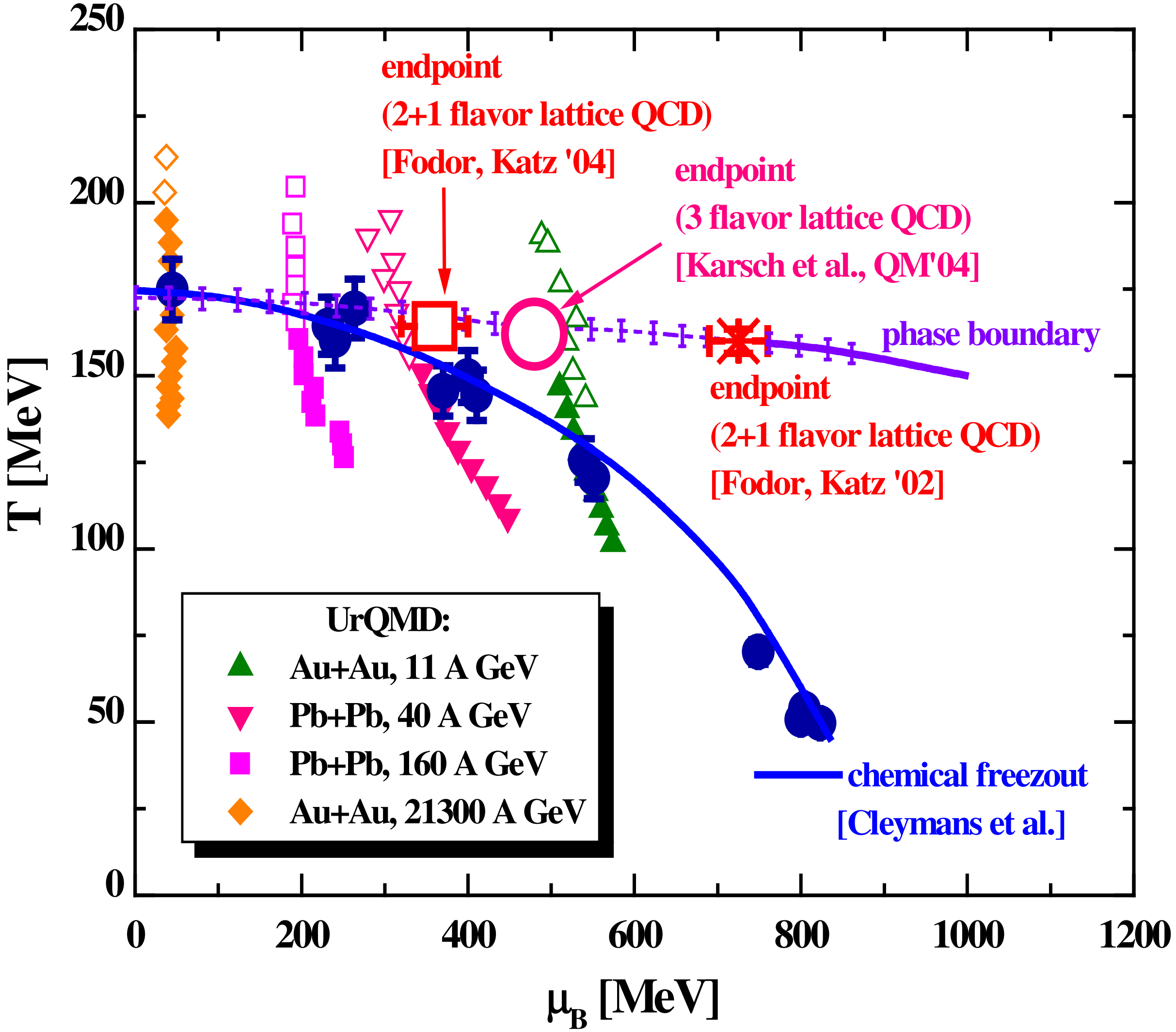
HSD vs. PHOBOS:

- away side structure is suppressed in Au+Au collision in comparison to p+p, however, HSD doesn‘t provide enough high p_T suppression to reproduce the PHOBOS Au+Au data
- near-side ridge structure is NOT seen in HSD!

V. Konchakovski

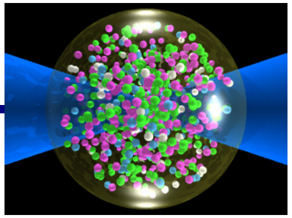
The QGP is observed at RHIC !

The phase diagram of QCD



- UrQMD initial energy density is higher than the boundary from LQCD
- Tri-critical point reached somewhere between 20 and 30 A GeV
- ➔ we are probing a new phase of matter already at AGS!

Outlook

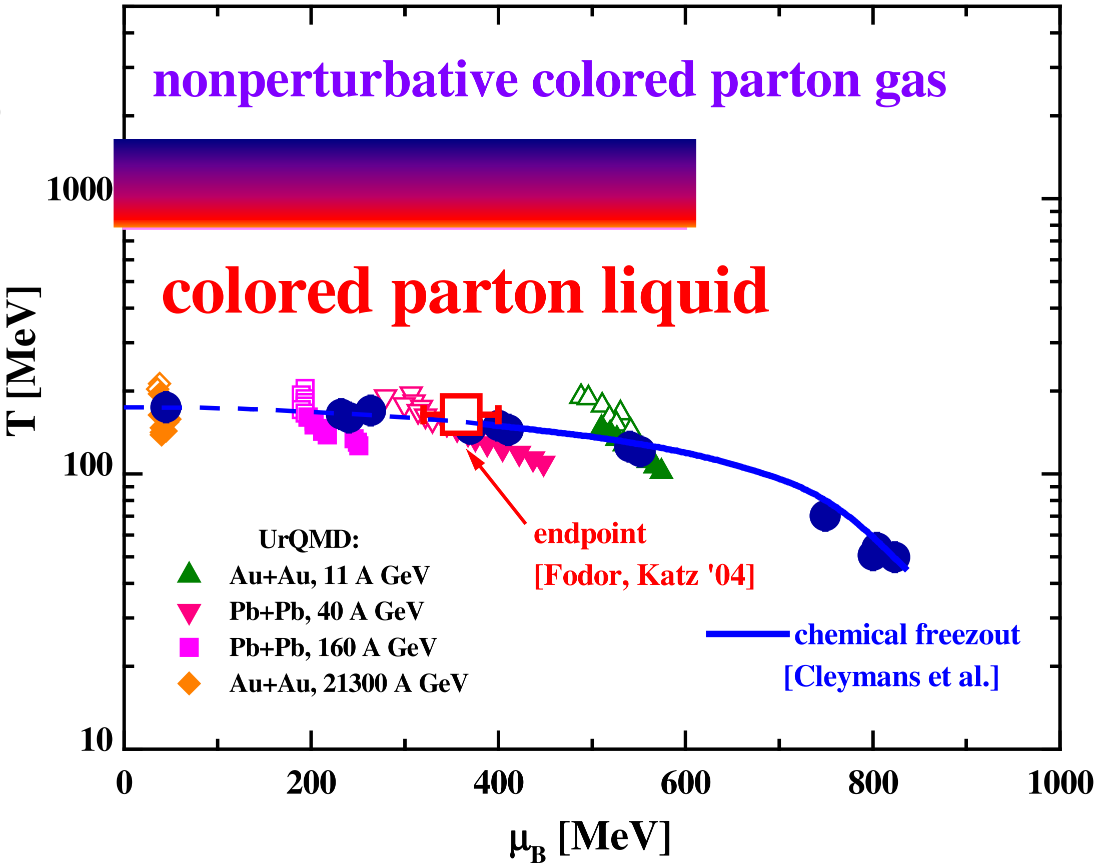


The Quark-Gluon-Plasma is there!
But what are the properties of this phase ?!

Initial idea (1970 – 2003):
QGP is a weakly interacting gas of colored but almost massless quarks and gluons

State of the art 2010:
QGP is a strongly interacting and almost ideal „color liquid“ !

New phase diagram of QCD



A. Peshier, W. Cassing, PRL (2005)