Latest Results on the Hot-Dense Partonic Matter at RHIC

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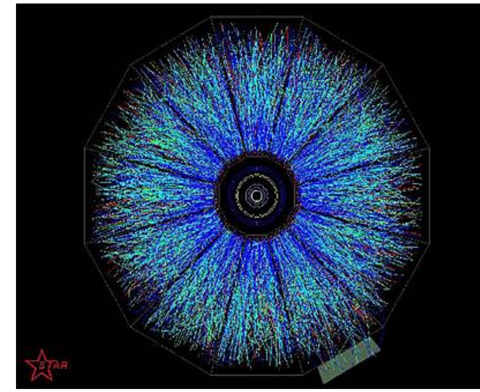
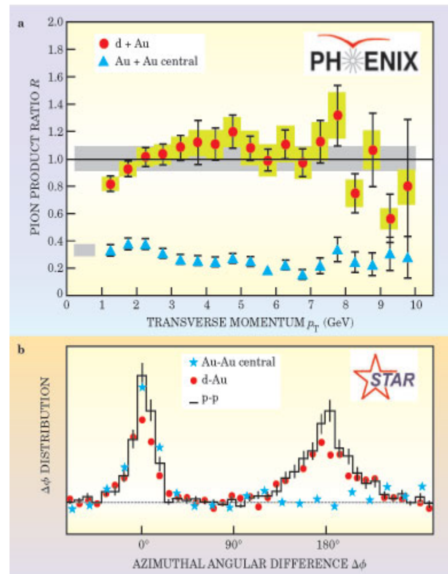
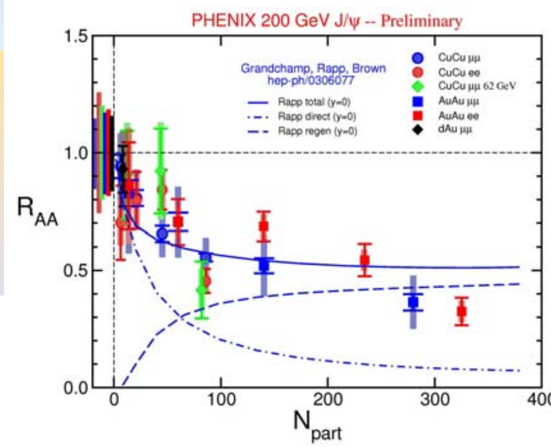
QNP06 - Madrid – 5-10 June 2006

- Deconfined Matter
- RHIC facility & detectors
- Thermalization
- Jets & Correlations
- Direct Photons
- Heavy Quarks
- Cold nuclear matter effects
- Quarkonia
- Future
- Summary



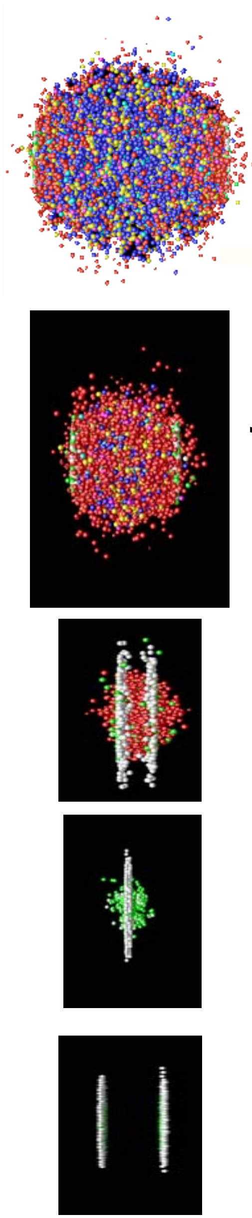




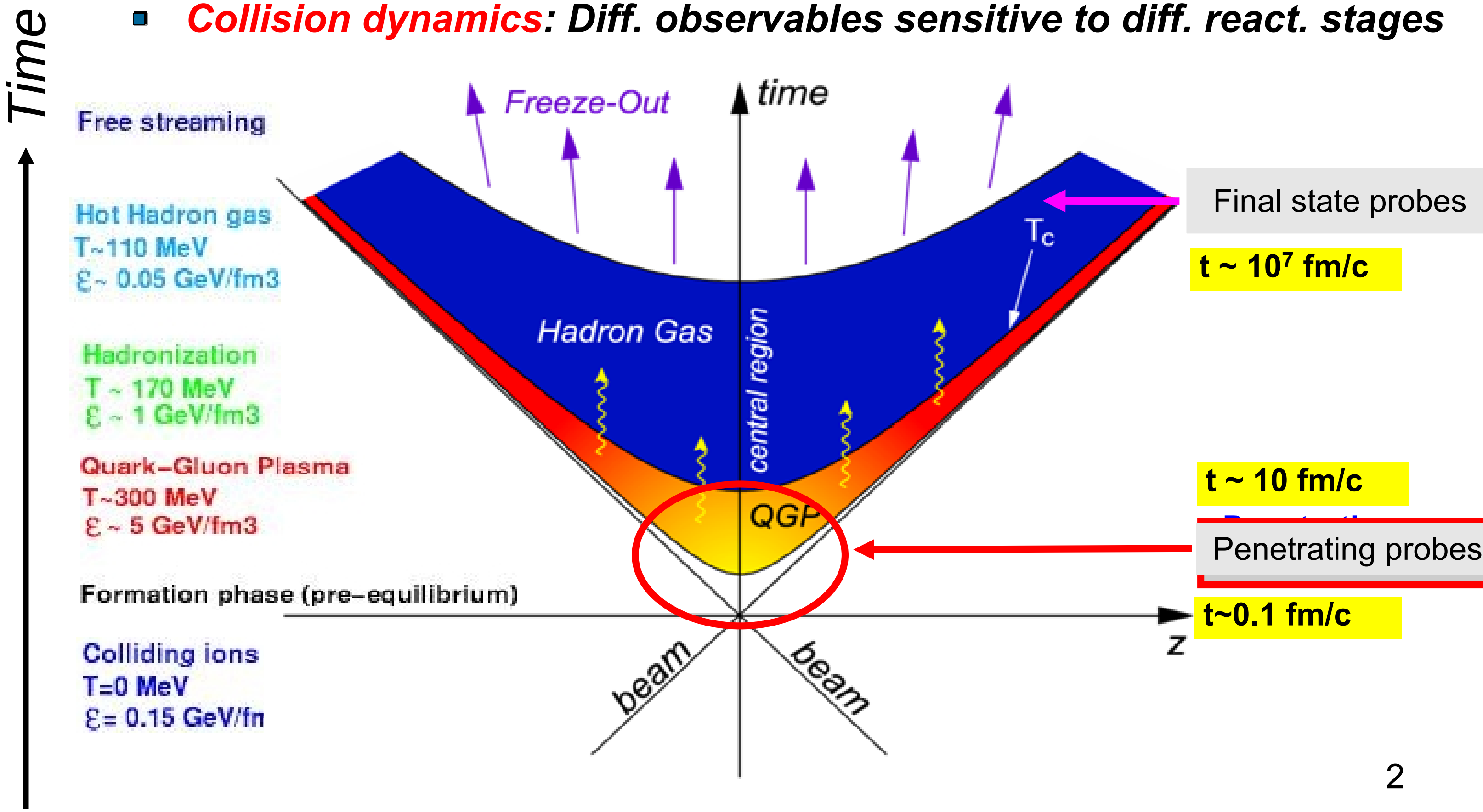
Some other RHIC talks at this conference:
Frantz, Kozlov (Tue); Mitchell, Fleuret (Wed) …
also d'Enteria (Mon), L. McLerran on CGC (Sat) – small-x/CGC

For my talk - thanks to many colleagues, especially:
Akiba, Constatin, d'Enterria, Granier de Cassagnac, Jacak, Nagle, Seto, Zajc …

Deconfined Matter
The "Little Bang" in the lab.

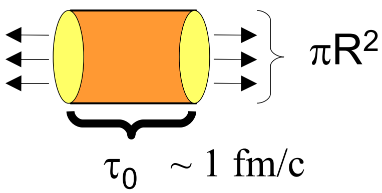


- ***High-energy nucleus-nucleus collisions*: *fixed-target reactions (√s~17 GeV, SPS) or colliders (√s~200 GeV, RHIC, √s~5.5 TeV, LHC)***
  - ***QGP expected to be formed in a tiny region (~10^{-14} m) and to last very short times (~10^{-23} s).***
  - ***Collision dynamics: Diff. observables sensitive to diff. react. stages***



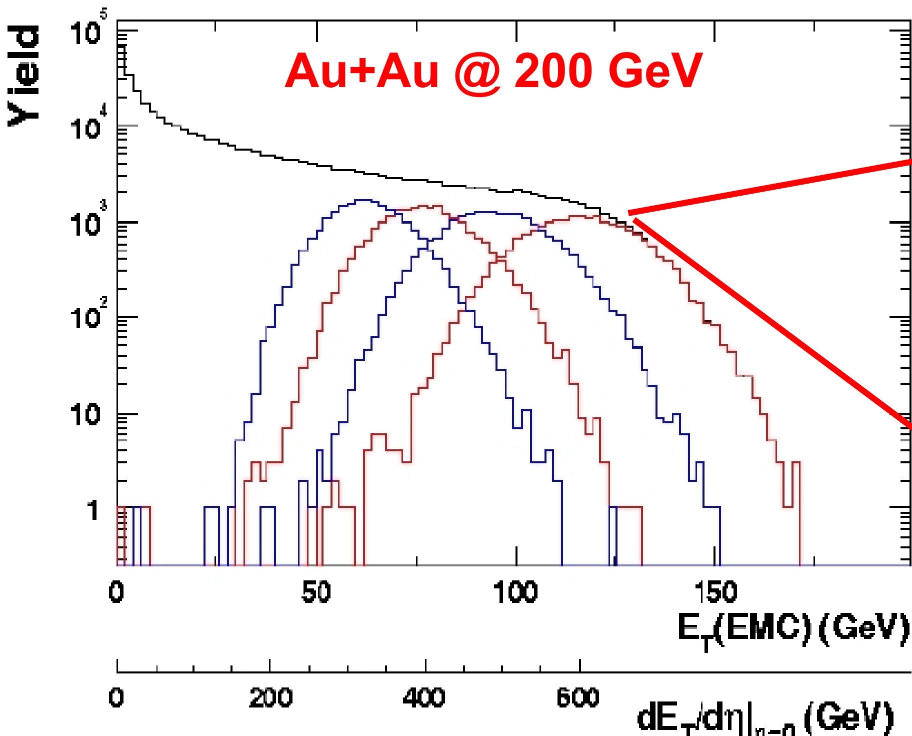
Deconfined Matter
Energy density (Au+Au @ 200 GeV, y=0)

- Bjorken estimate: $\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$



(longitudinally expanding plasma)

- $dE_T/d\eta$ at mid-rapidity measured by calorimetry (e.g. using PHENIX EMCal as *hadronic* calorimeter: $E_T^{had} = (1.17 \pm 0.05)\ E_T^{EMCal}$)



$\langle dE_T/d\eta \rangle \sim 600$ GeV (top 5% central)
(~70% larger than at SPS)

$\varepsilon_{Bjorken} \sim 5.0\ \mathrm{GeV/fm^3}$

> QCD critical density (~1 GeV/fm³)

RHIC & its Detectors

3.83 km circumference

2 independent rings:

- 120 bunches/ring
- 106 ns crossing time

A+A collisions @ $\sqrt{s_{NN}}$ = 200 GeV

Luminosity: $2 \cdot 10^{26}$ cm^{-2} s^{-1} (~1.4 kHz)

p+p collisions @ $\sqrt{s}_{max}$ = 500 GeV

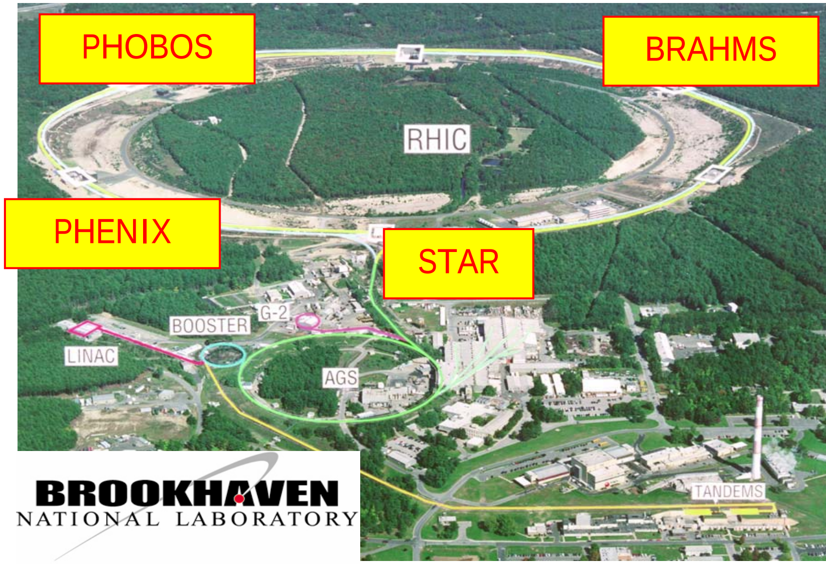
p+A collisions @ $\sqrt{s}_{max}$ = 200 GeV

4 experiments:

BRAHMS, PHENIX, PHOBOS, STAR

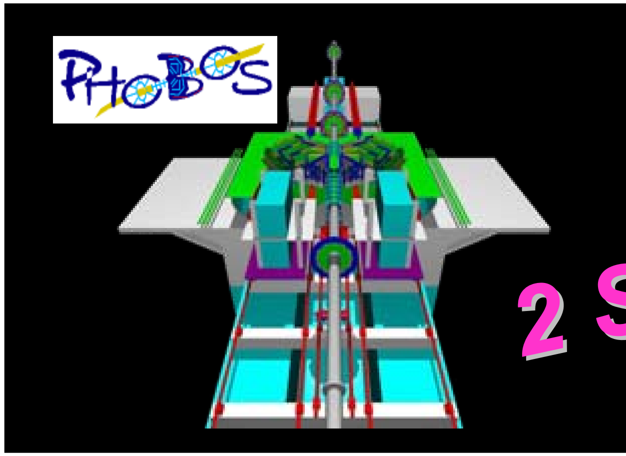
Runs 1 - 6 (2000 – 2006):

Au+Au @ 200, 130, 62, 22 GeV
Cu+Cu @ 200, 62 GeV
d+Au @ 200 GeV (no p+A so far)
p+p @ 200, 62, 22 GeV, … (polarized)

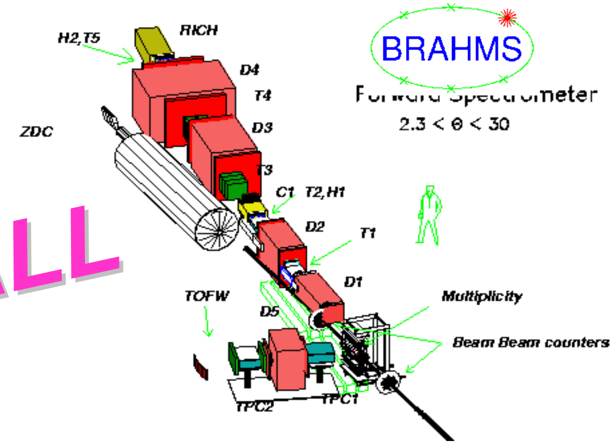


RHIC & its Detectors

RHIC
Relativistic Heavy Ion Collider

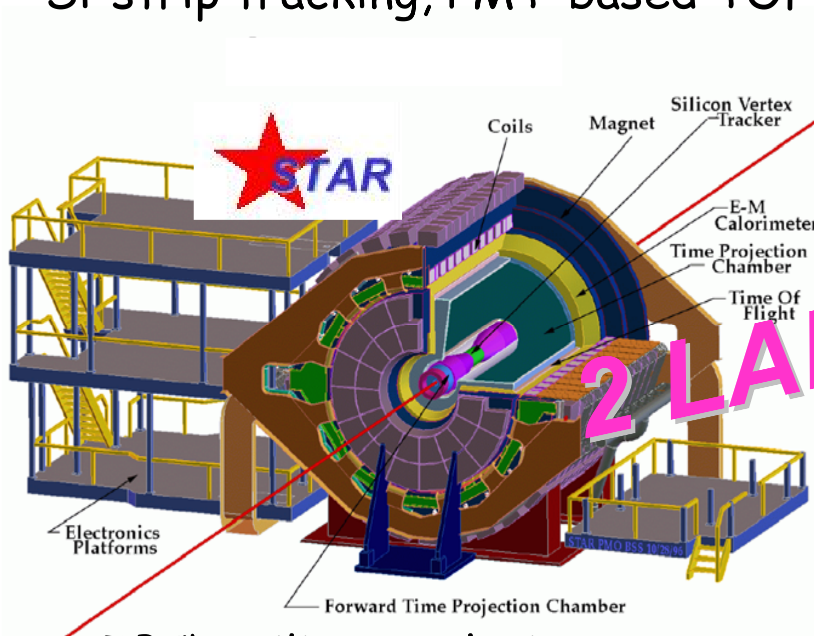


2 SMALL

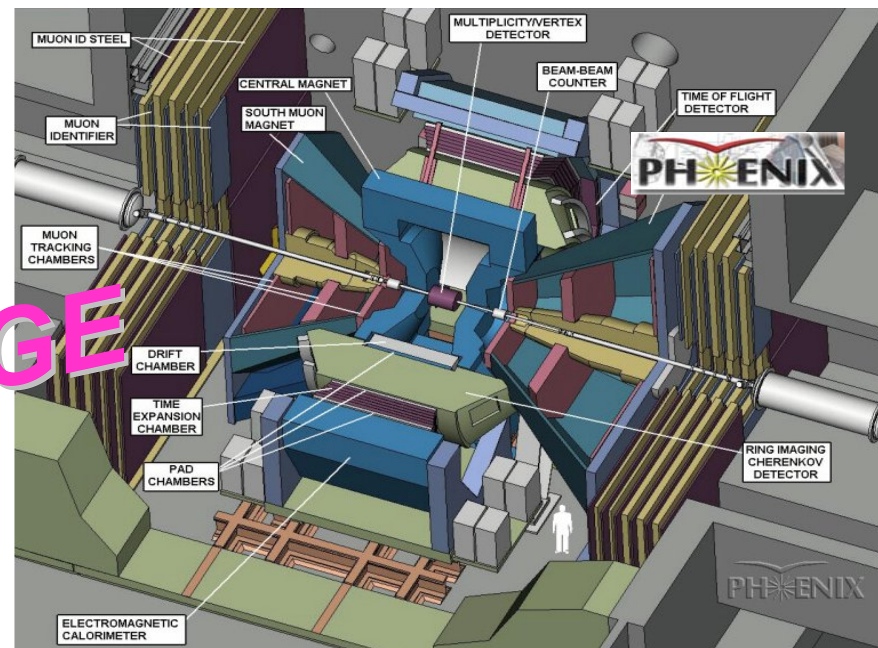


Two magnetic dipole spectrometers in “classic” fixed-target configuration

Si-strip tracking, PMT-based TOF



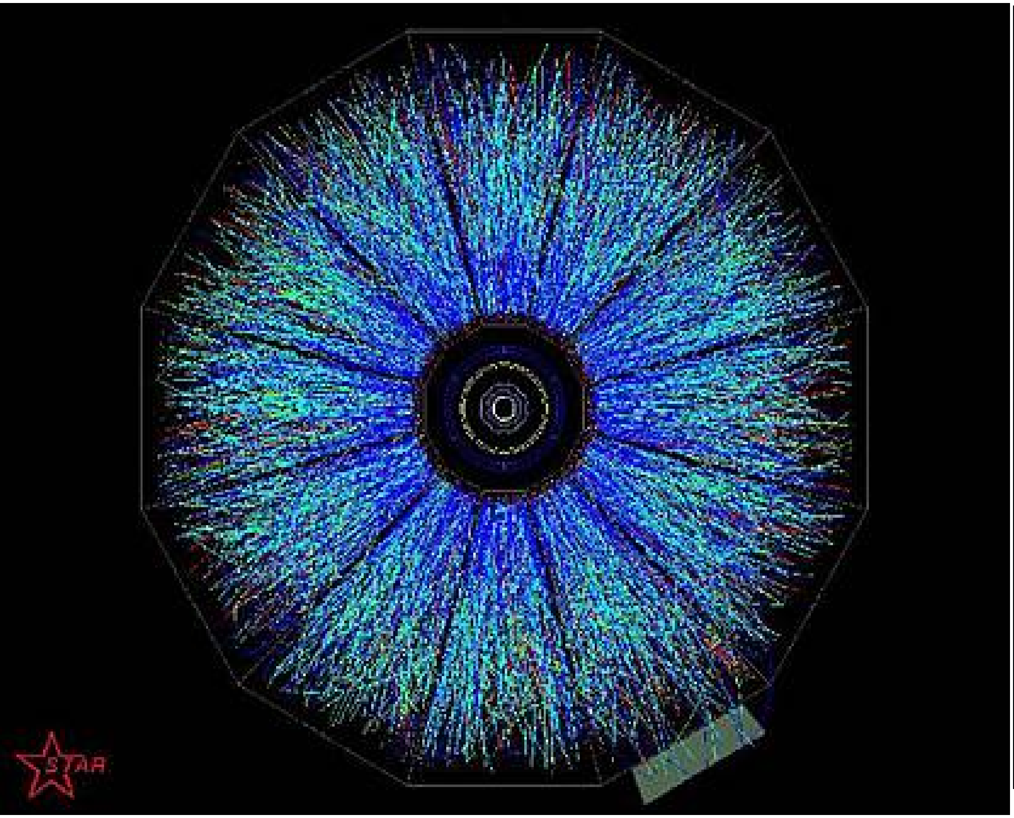
2 LARGE

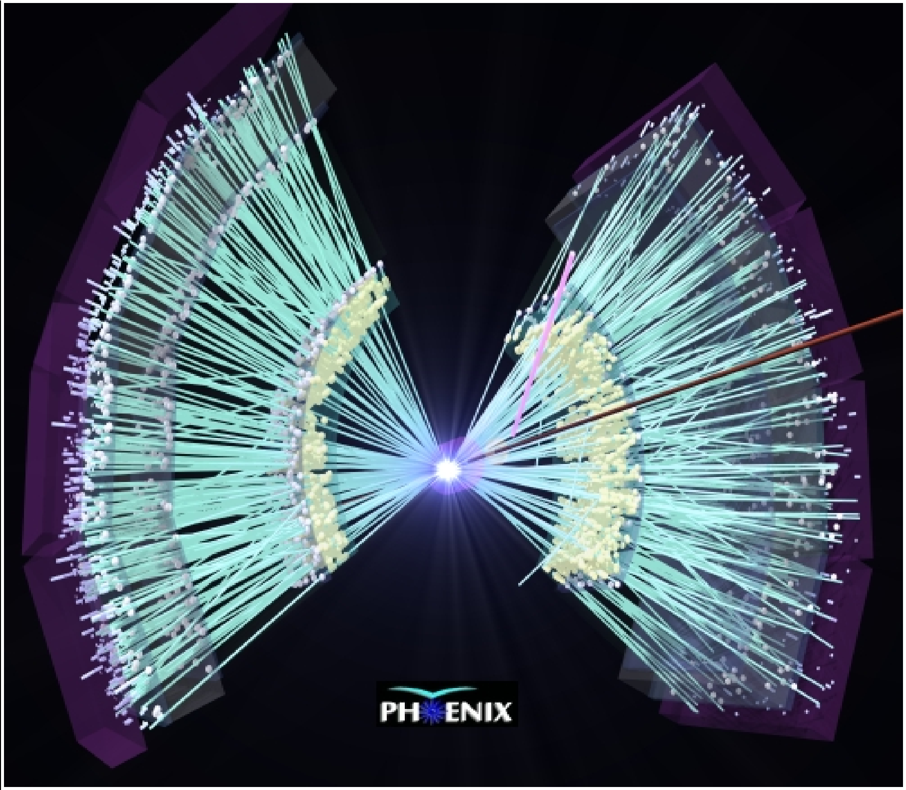


TPC’s, silicon, calorimeters
Large acceptance

Hadrons, electrons, muons, photons
Rare & penetrating probes

RHIC & its Detectors
Au+Au collisions @ 200 GeV





~ 700 charged particles per unit rapidity at midrapidity (top 10% central)

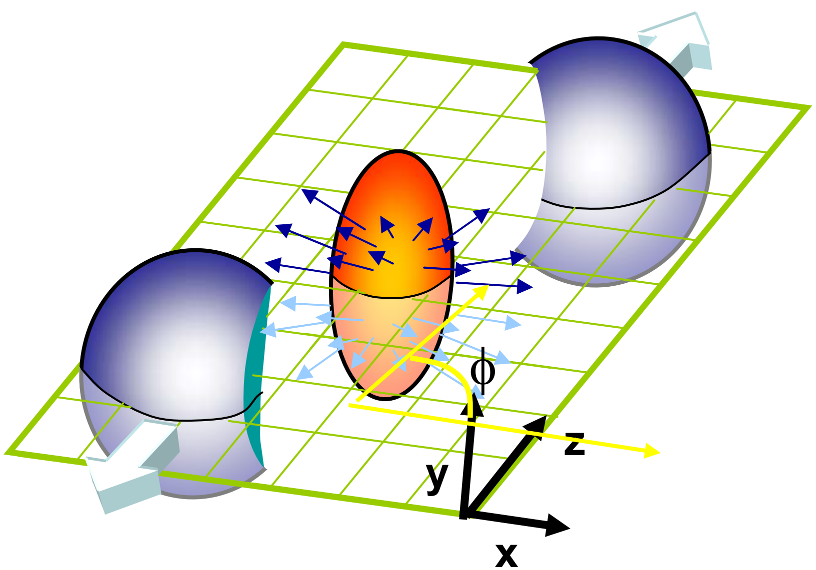
Thermalization
Flow: A collective effect

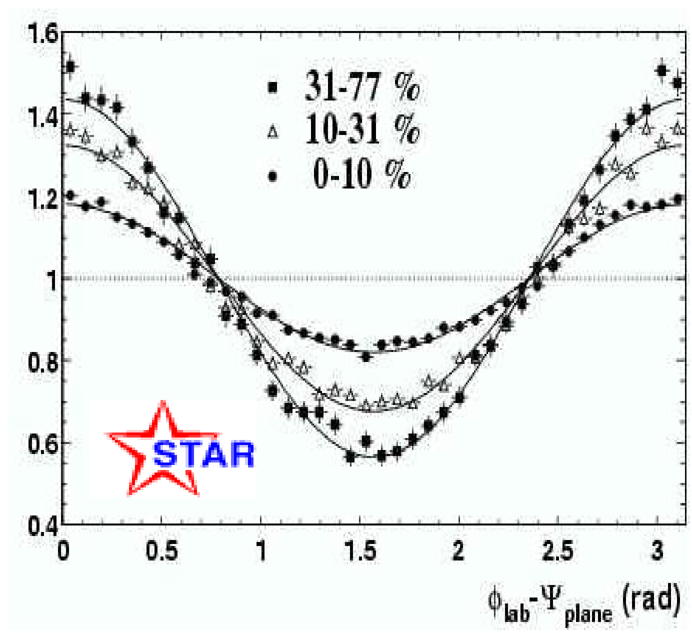
Initial spatial anisotropy converted into momentum anisotropy

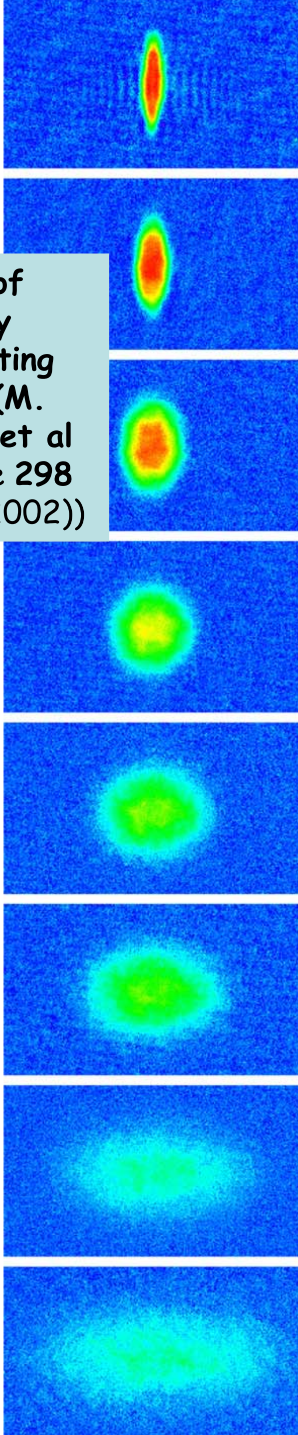
Efficiency of conversion depends on the properties of the medium

Elliptic flow = v_2 = 2nd fourier coefficient of momentum anisotropy

$$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$$



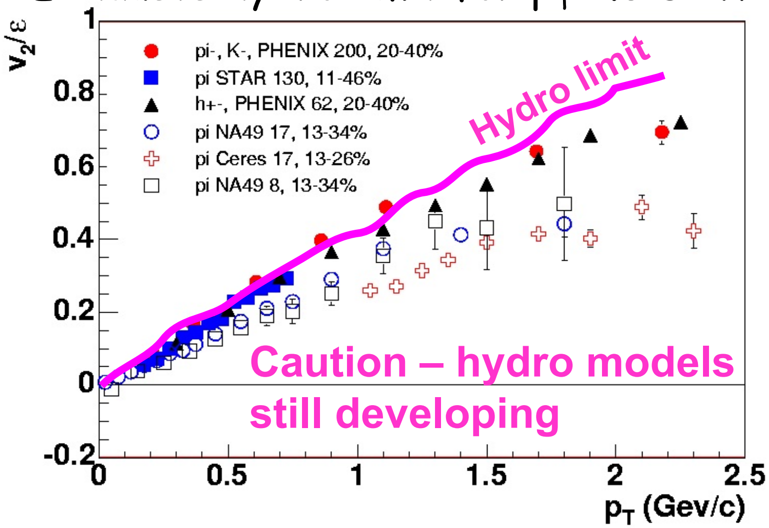




Gases of strongly interacting atoms (M. Gehm, et al Science **298** 2179 (2002))

Thermalization
Early and with zero viscosity - A perfect fluid

Large v_2 signal at RHIC:
Exhausts hydro limit for p_T<1.5 GeV/c

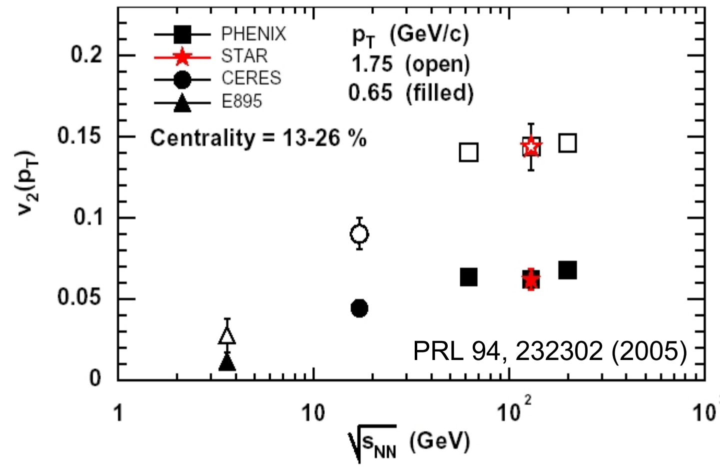


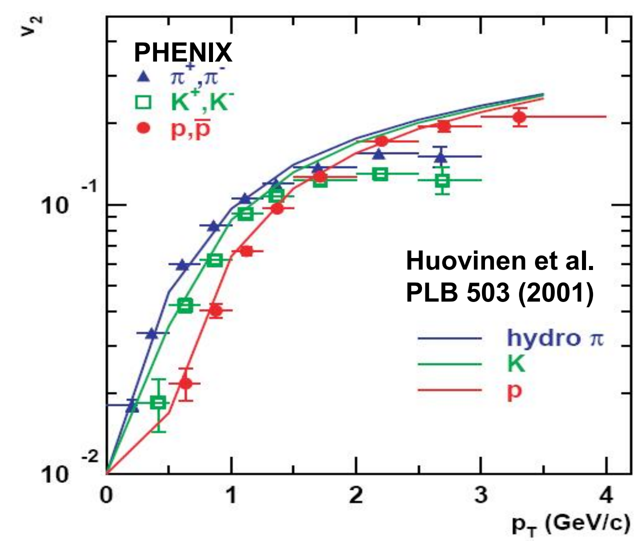
If not thermalized early, spatial anisotropy would be lost

hydro calculations with zero viscosity & early thermalization agree with RHIC data

τ_{therm} ~ 0.6 -1.0 fm/c
ε~15-25 GeV/fm^3
(ref: cold matter 0.16 GeV/fm^3)

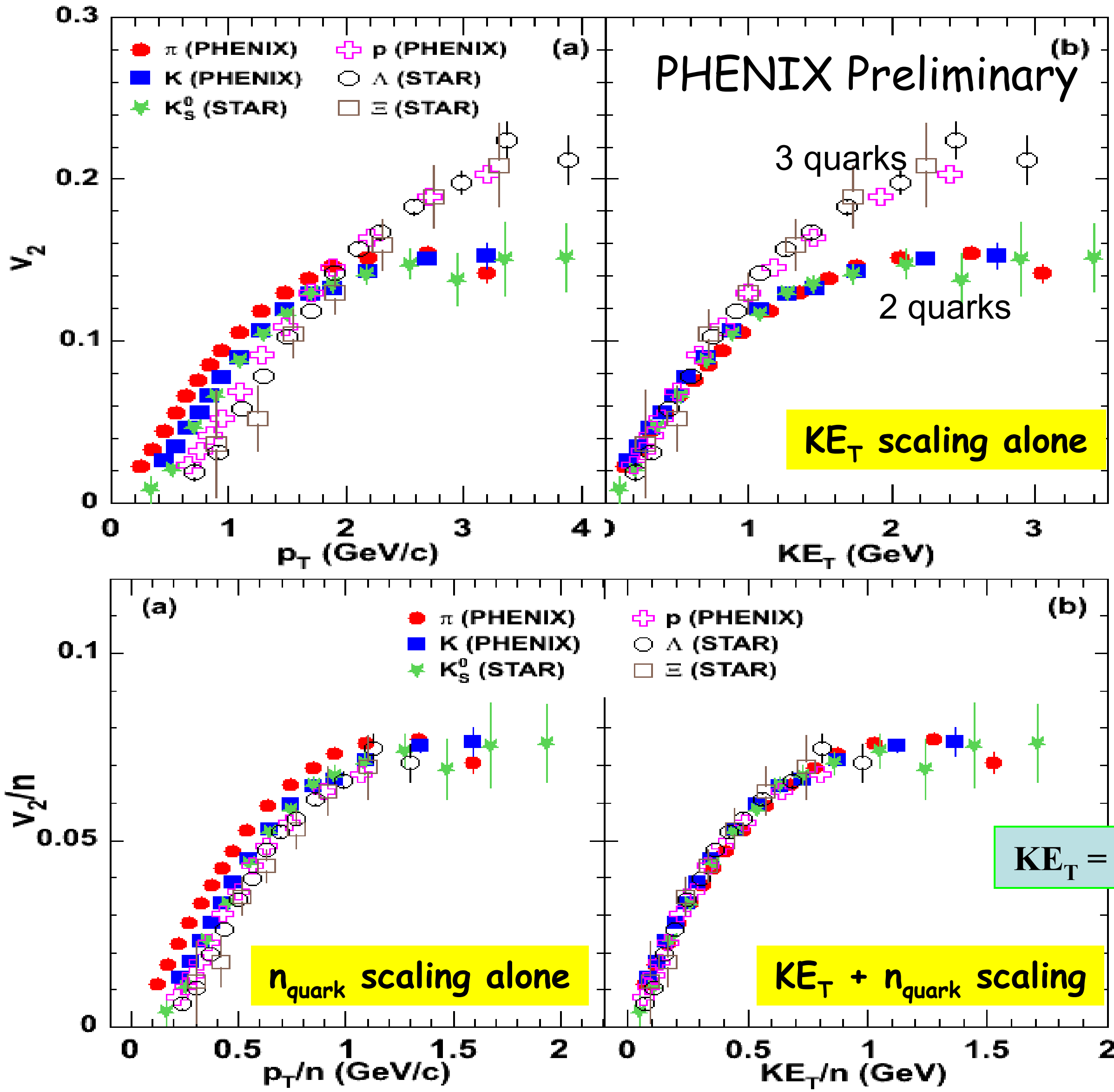
√s-dependence of v_2: ~50% increase from SPS
Apparent saturation within 62-200 GeV





Thermalization - KE_T & n_{quark} scaling of v_2

Effective degree of freedom looks like #quarks



from SQM talk
D. Morrison

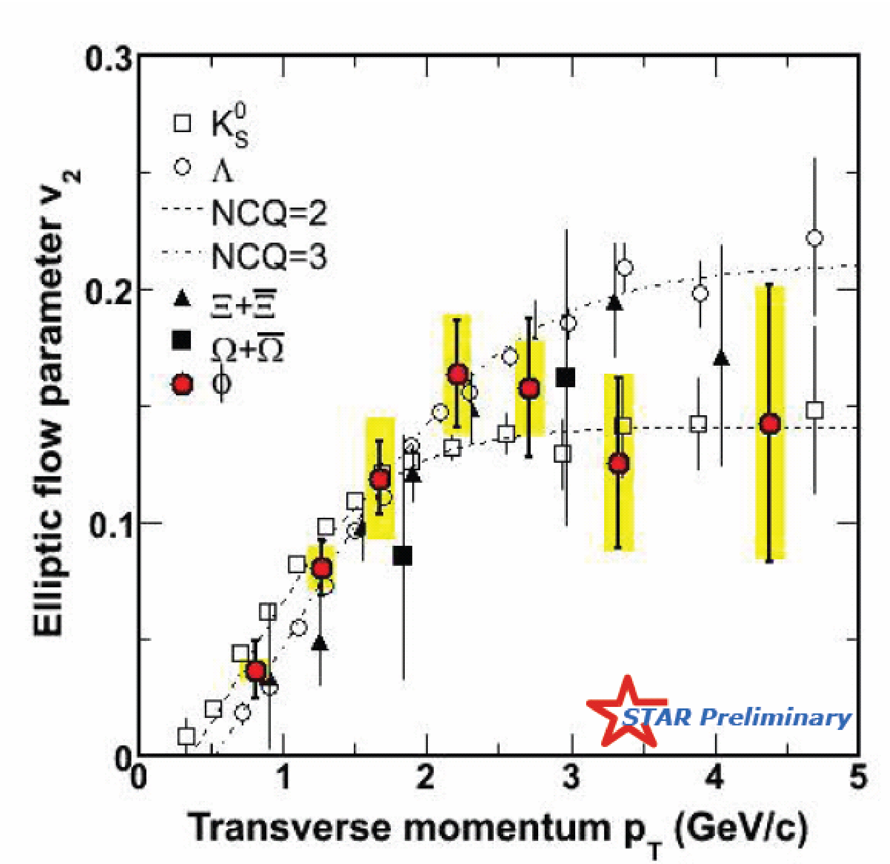
$KE_T = m_T$ – mass (hadron)

Thermalization
Flow of Φ also exhibits quark number scaling

The ϕ has:
- mass ~ proton
- # quarks of meson

V_2 behaves like recombination

ALL hadrons seem to obey quark number scaling!



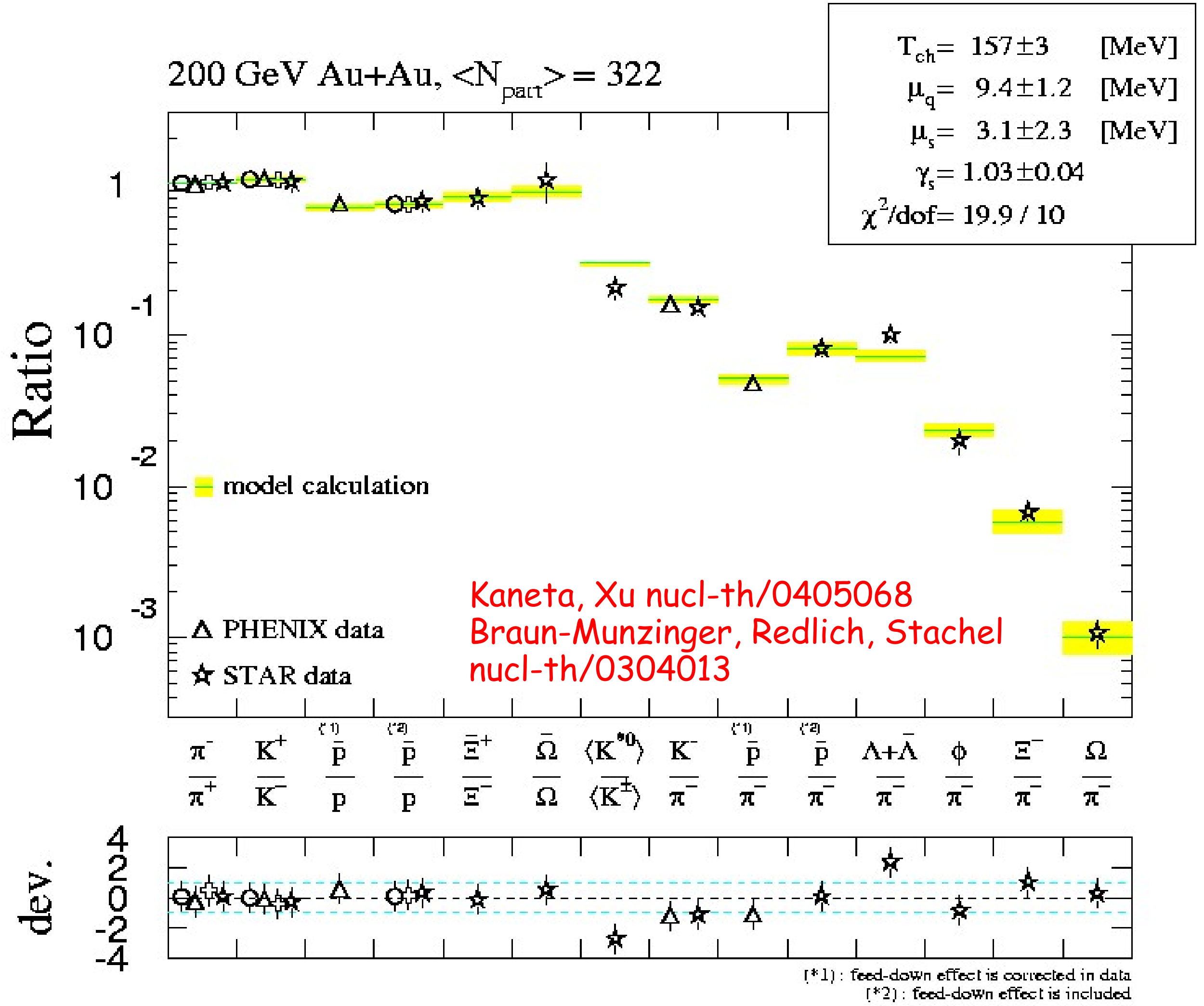
from Sarah Blythe (STAR) - SQM

Thermalization – hadronic abundances

Ratios of hadron yields consistent with system at chemical equilibrium

Global fit to relative particle abundances with 4 parameters:

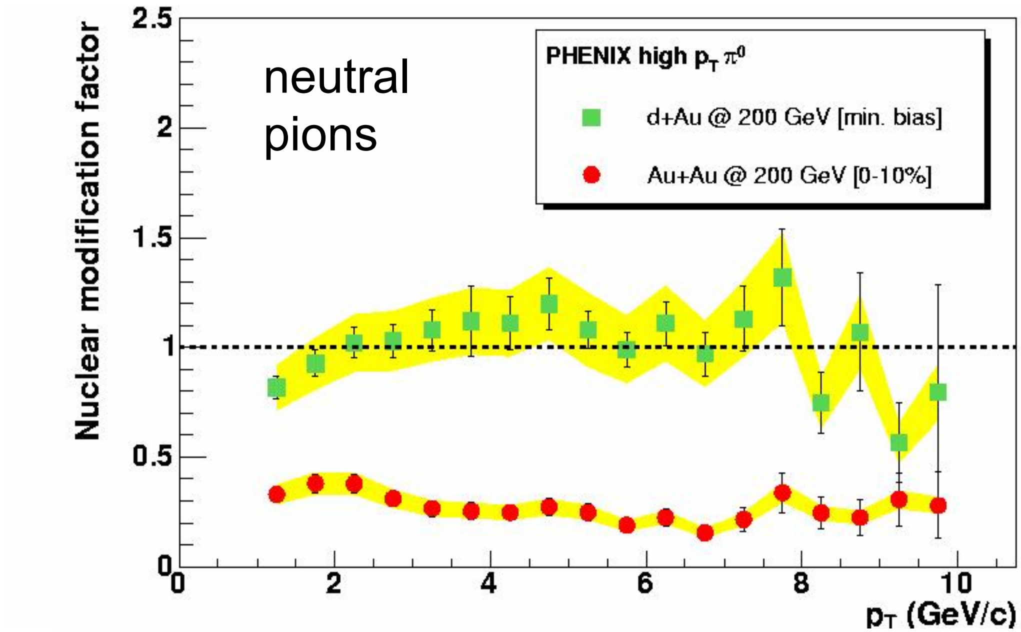
- chemical freezeout temperature (T_{chem} ~ T_{crit}
- baryon chemical potential for light & strange quarks (μ_q, μ_s)
- strangeness saturation factor, γ_S (γ_S =1 is strangeness fully equilibriated)

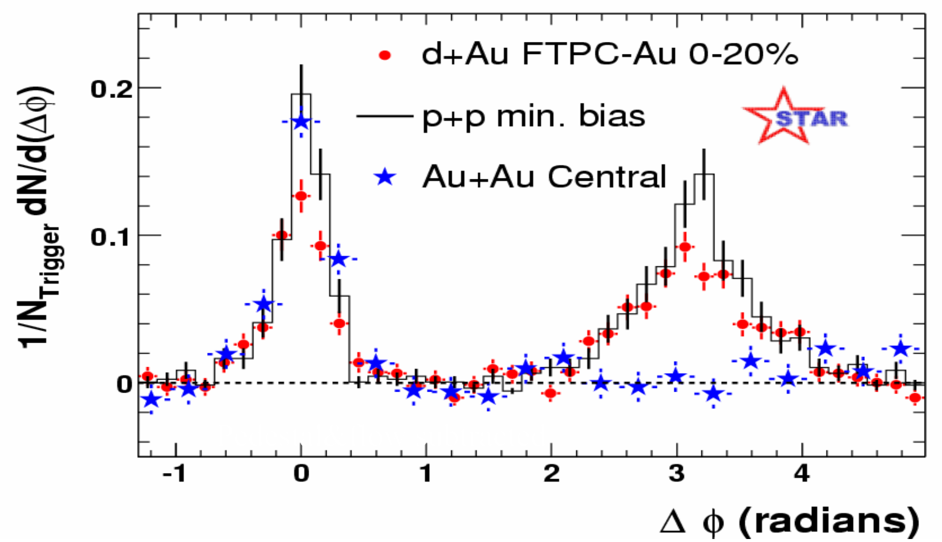


Kaneta, Xu nucl-th/0405068
Braun-Munzinger, Redlich, Stachel nucl-th/0304013

Jets - Quenching & Correlations

PHENIX





- d+Au @ RHIC shows "Cronin" p_T broadening as seen in lower $\sqrt{s}$ p+A
- Suppression in central Au+Au due to final-state effects -> 15x normal nuclear density

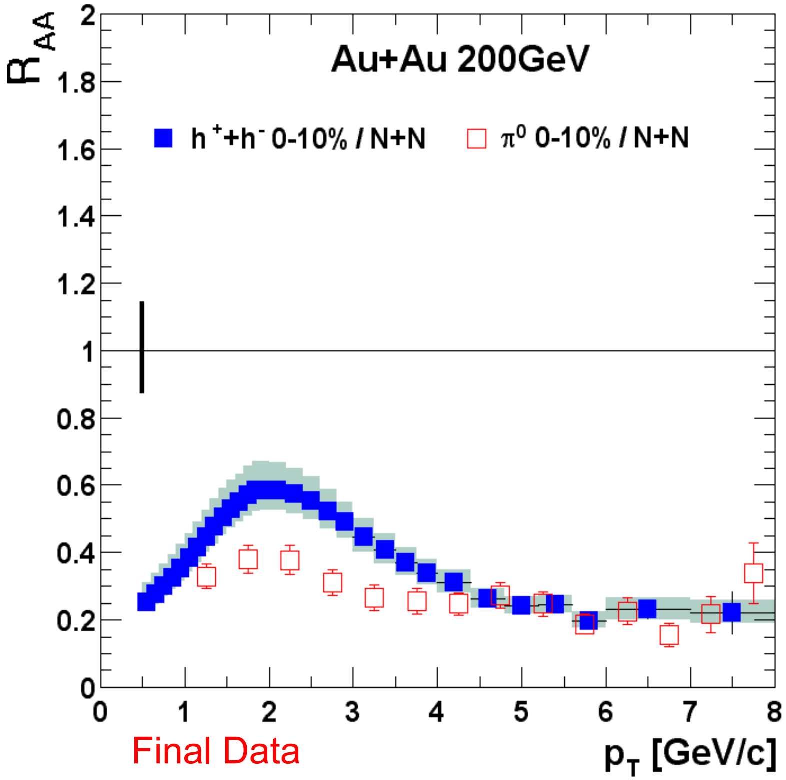
PRL
Aug '03

- back-to-back di-hadron correlations are very similar in p+p and d+Au
- but strongly suppressed in central Au+Au collisions at 200 GeV

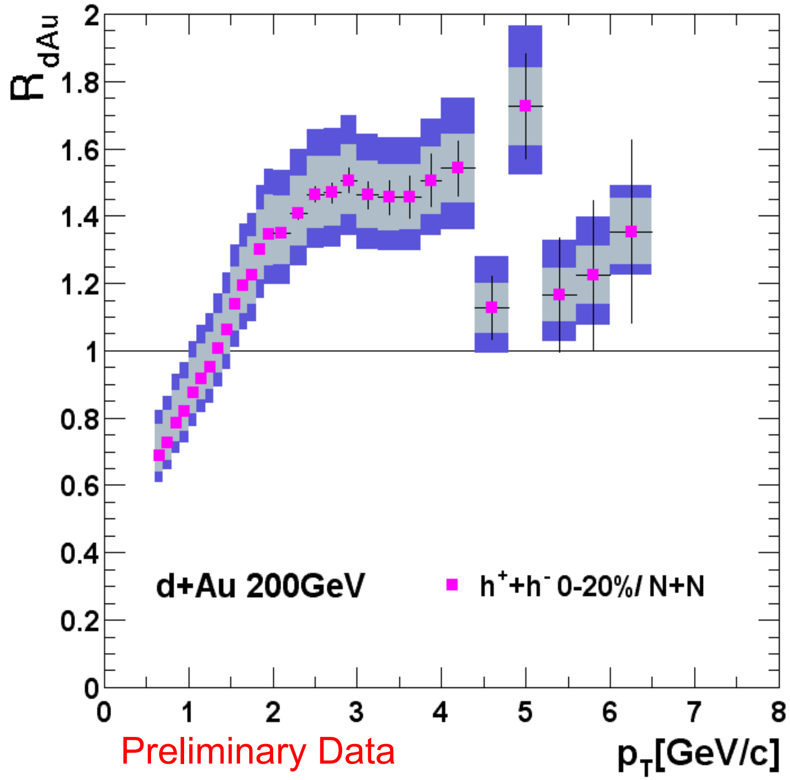
Jets - *AuAu* vs. *dAu* (PHENIX)

PPG028
Phys. Rev. Lett. **91**, 072303 (2003).

Au + Au Experiment

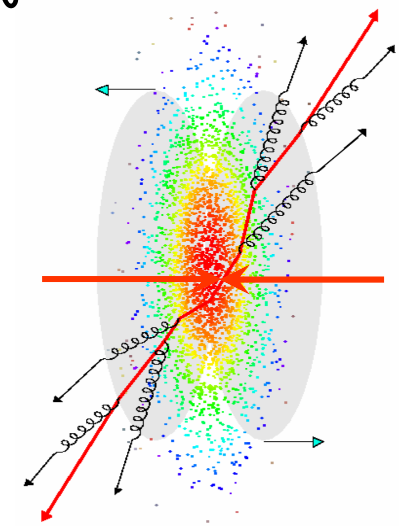


d + Au Control Experiment

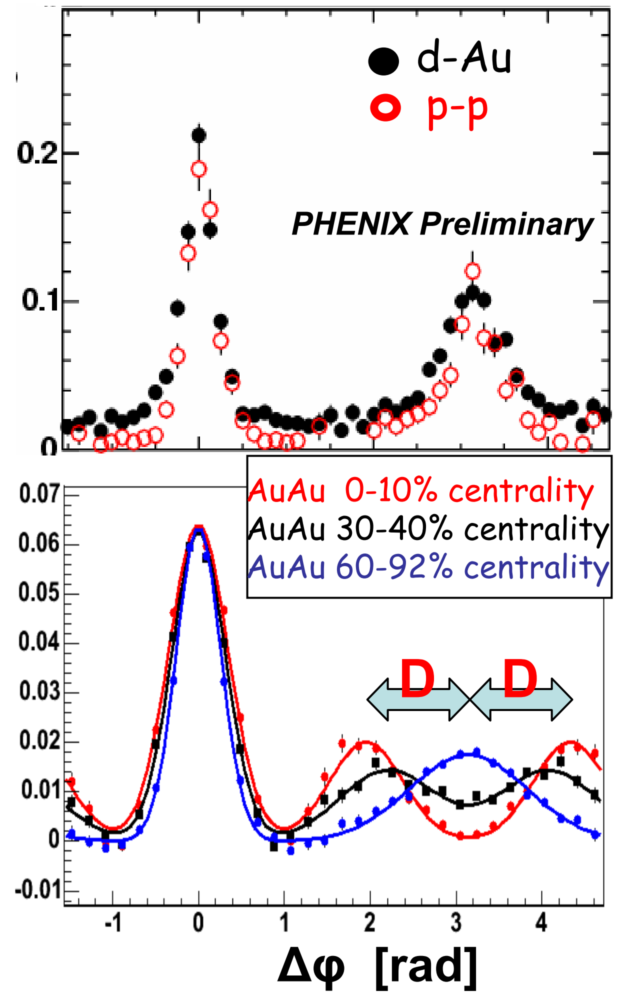


Interaction of Hadronic Dijets with the QGP
Splitting of away-side jets

Dijet event in a hot QCD medium



$p_{Trigger}$ = 2-3 GeV
$p_{Associated}$ = 1-2 GeV



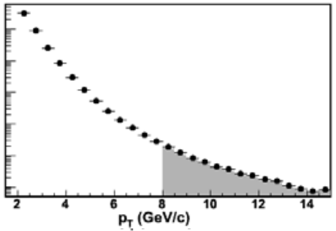
Trigger on one leading hadron, and look for associated particles, "near" and "away"

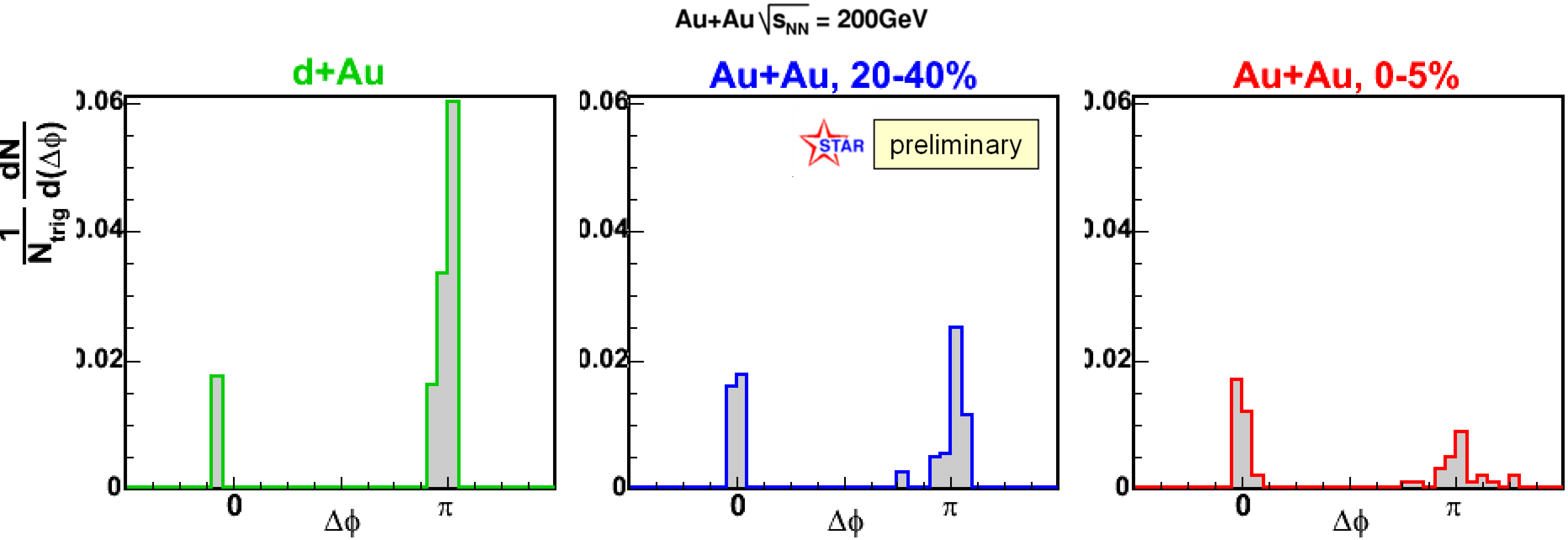
Is jet production modified in medium?

- "away" side jet broadened and split in central and mid-central AuAu (effect vanishes for higher p_T)

Emergence of Dijets w/ increasing p_T(assoc)

$8 < p_T(\text{trig}) < 15$ GeV/c
$p_T(\text{assoc}) > 8$ GeV/c



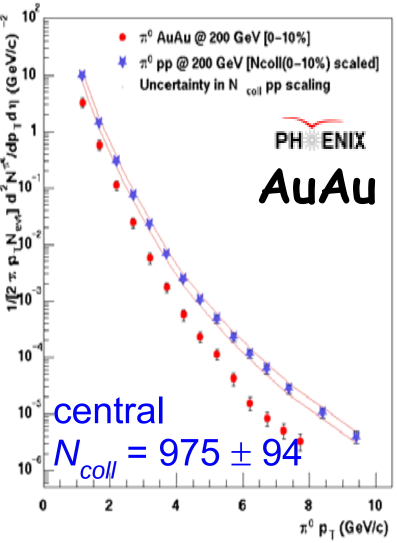


$\Delta\phi$ correlations (not background subtracted)

Narrow peak emerges cleanly above vanishing background

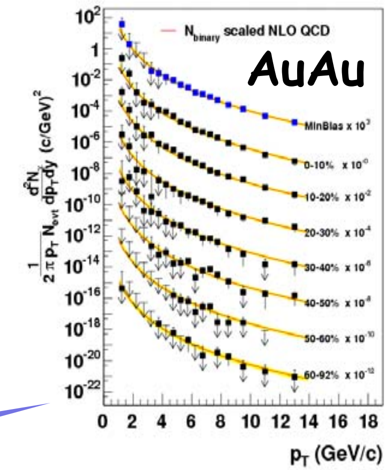
Direct Photons vs hadrons

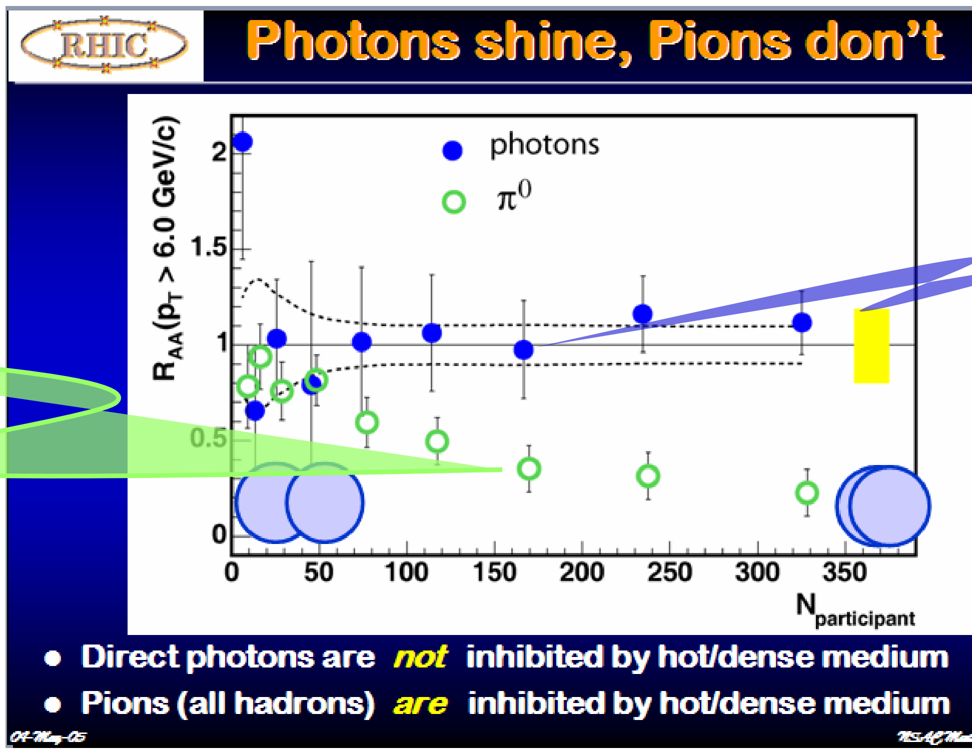
π^0

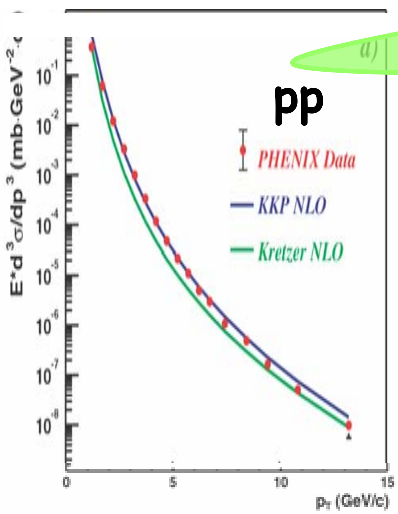


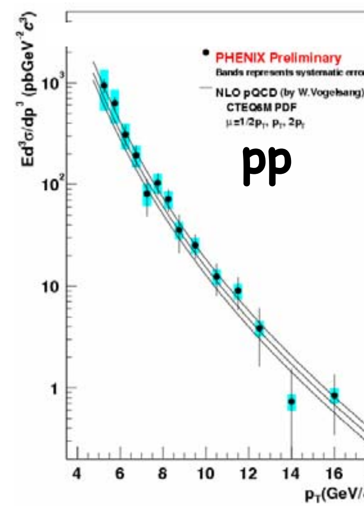
This one figure encodes rigorous control of systematics

direct γ







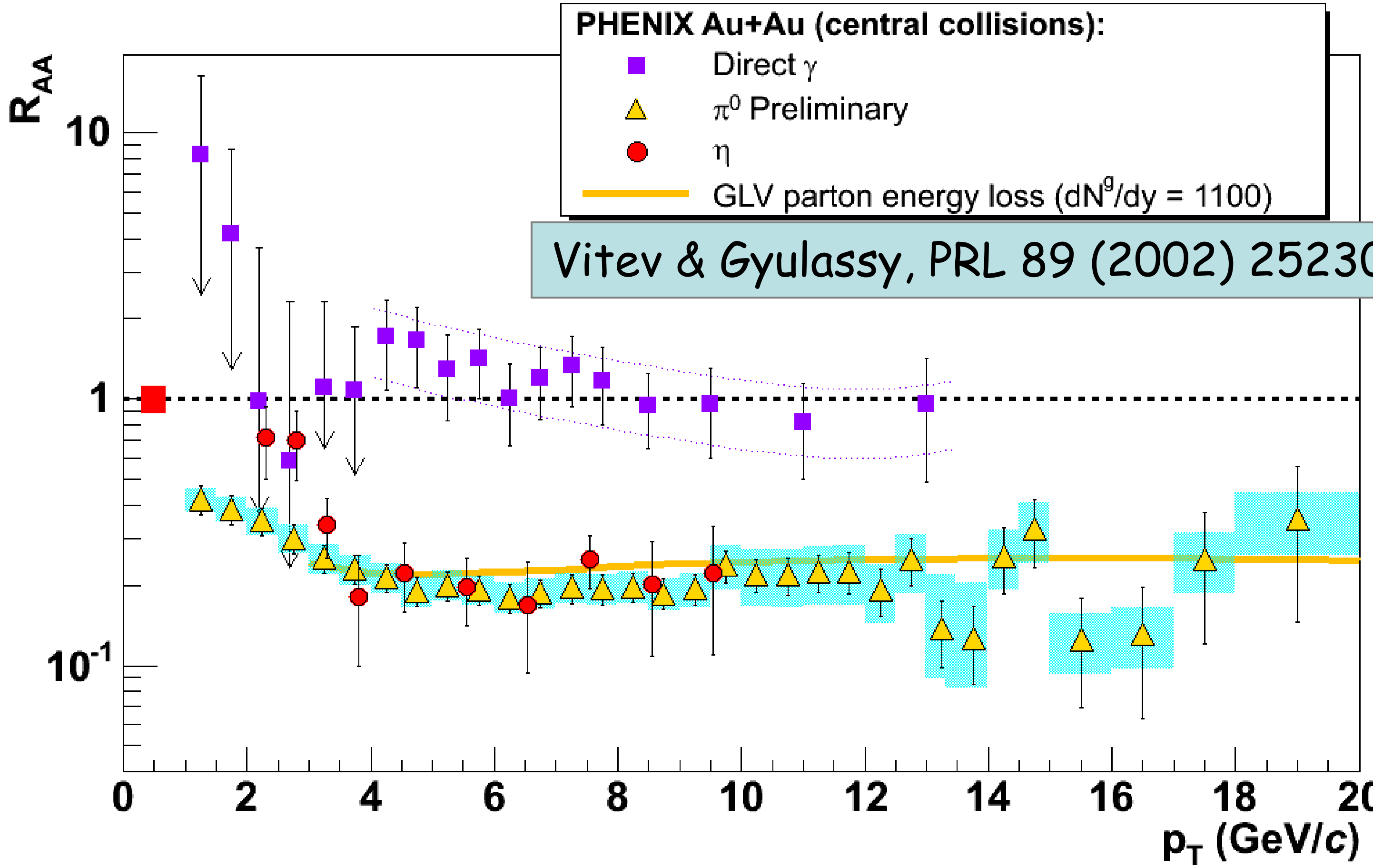


in four different measurements over many orders of magnitude

Direct Photons
Comparison with theory

$dN_{gluon}/dy \sim 1000 \pm 200$ & $\varepsilon \sim 15$ GeV/fm^3

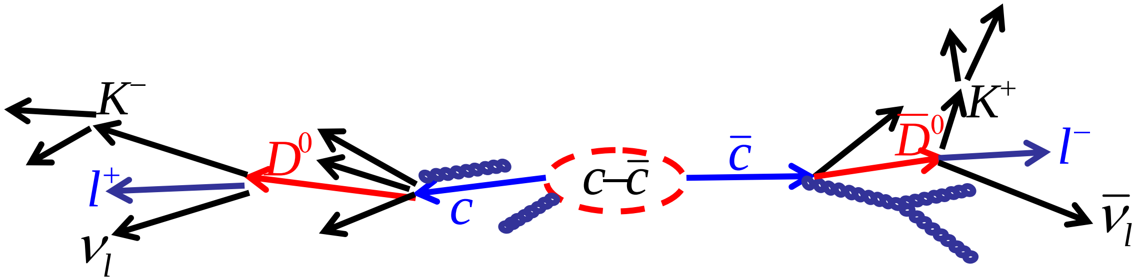
– & consistent with $dN_{ch}/d\eta$

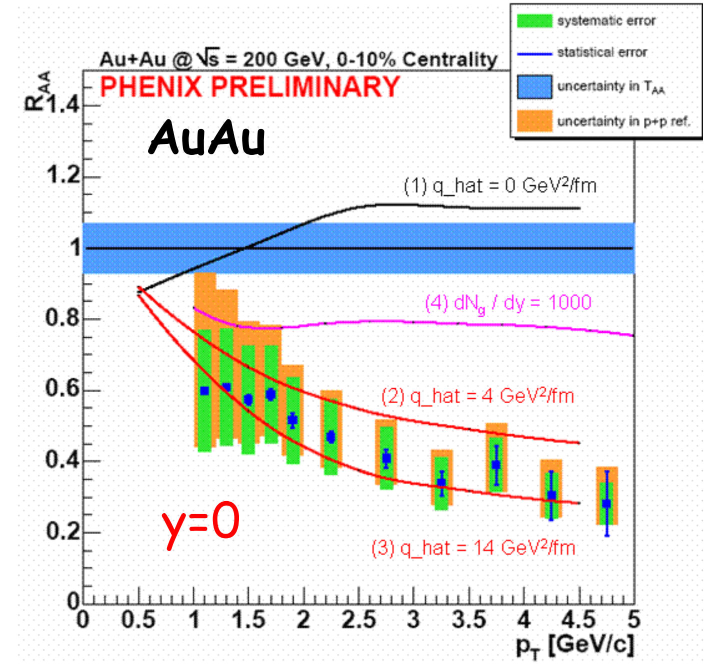


Vitev & Gyulassy, PRL 89 (2002) 252301

Heavy Quark Energy Loss

Heavy-quark energy loss at central rapidity via decay to single leptons (electrons or muons)

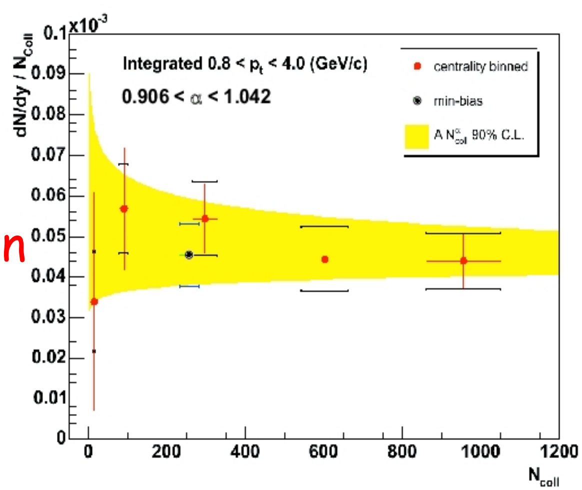




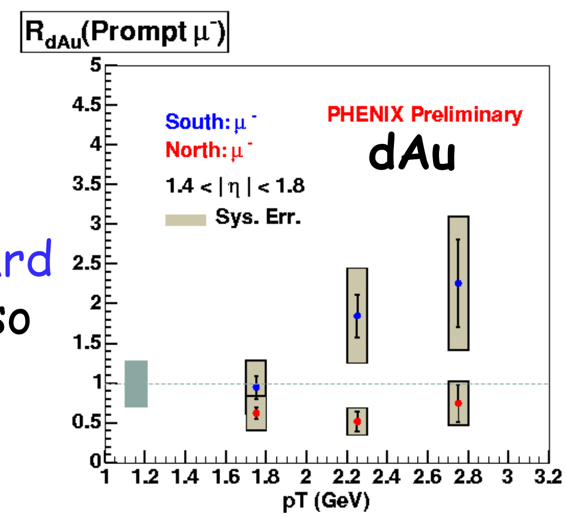
Theory curves at right:
(1-3) from N. Armesto, *et al.*, PRD 71, 054027
(4) from M. Djordjevic, M. Gyullasy, S.Wicks, PRL 94, 112301

The data suggest large c-quark-medium cross section; evidence for strongly coupled QGP?

Meanwhile - total cross-section consistent with Ncoll -scaled p+p charm production

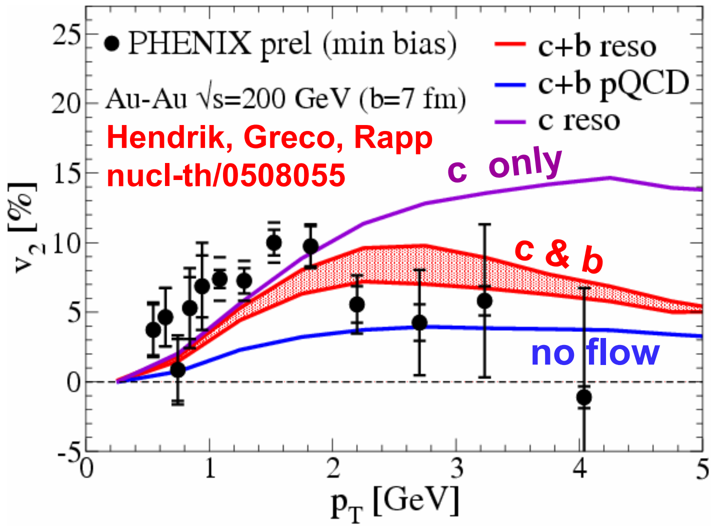


Forward (small-x) & backward muons also (dAu)



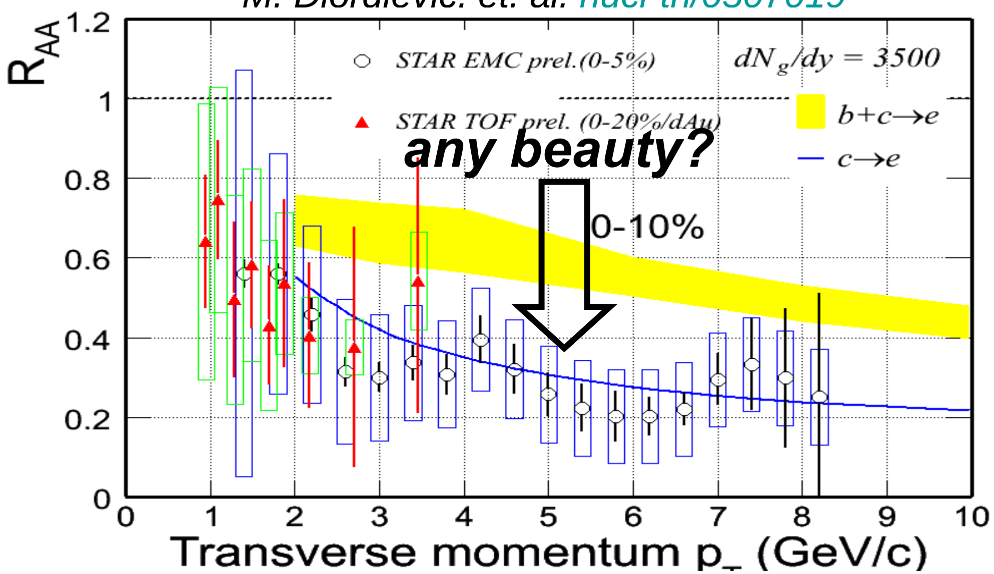
Heavy Quark Flow – but what about Beauty?

Drop of the flow strength at high p_T. Is this due to b-quark contribution?

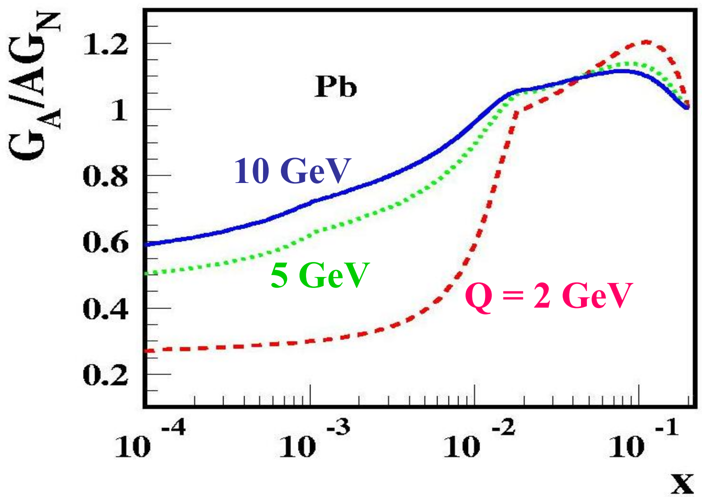


Beauty should become important for larger p_T where it would have a smaller energy loss and less flow

M. Diordievic. et. al. nucl-th/0507019



Cold Nuclear Matter Effects
Gluon Shadowing and Saturation



Leading twist gluon shadowing:

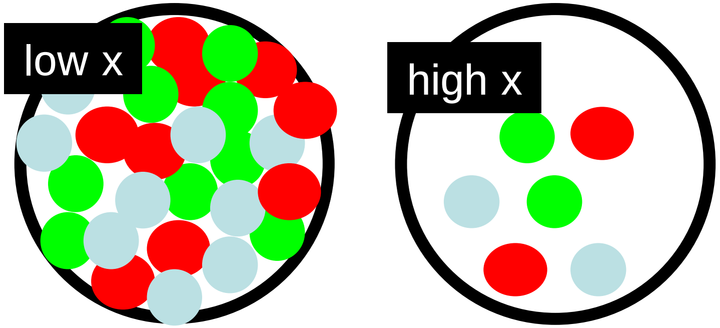
- e.g. "FGS", Eur. Phys. J A5, 293 (1999)

Phenomenological fit to DIS & Drell-Yan data

- e.g. "EKS", Nucl. Phys. A696, 729 (2001).

Coherence approach, and many others

Amount of gluon shadowing differs by up to a factor of three between diff models!



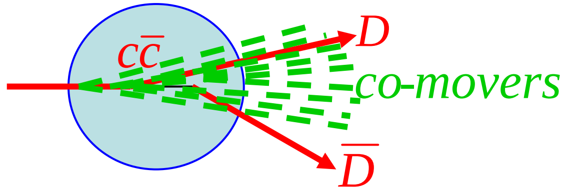
Saturation or Color Glass Condensate (CGC)

- At low-x there are so many gluons that $2 \rightarrow 1$ diagrams become important and deplete low-x region
- Nuclear amplification: $x_A G(x_A) = A^{1/3} x_p G(x_p)$, i.e. gluon density is ~6x higher in Gold than the nucleon

(see talk by Larry McLerran)

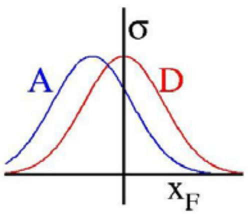
Cold Nuclear Matter Effects
The J/ψ - a Puzzle

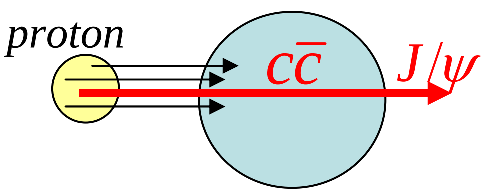
J/ψ suppression is a puzzle with possible contributions from **shadowing** & from:



Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers (the latter most important in AA collisions where co-movers more copious)

Energy loss of incident gluon shifts effective x_F and produces nuclear suppression which increases with x_F

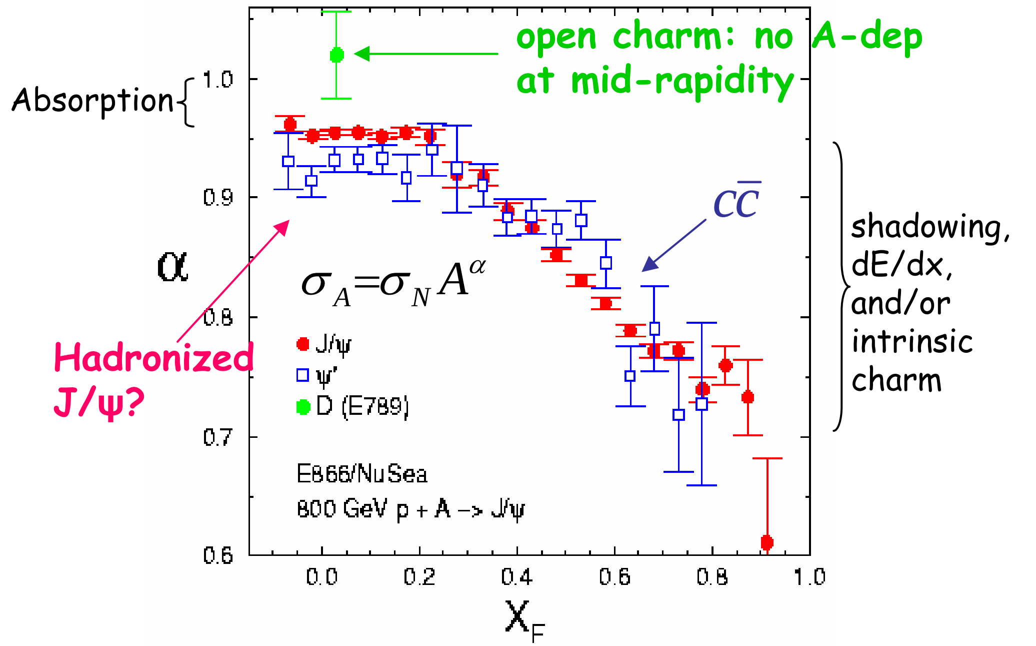




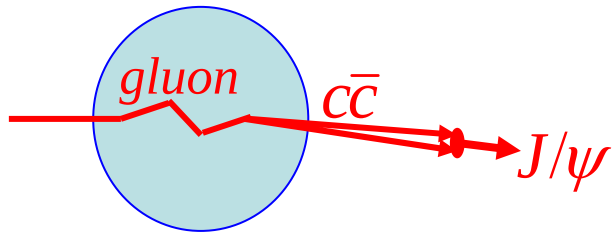
Intrinsic charm components of incident proton produce J/ψ at large x_F. $A^{2/3}$ dependence from surface stripping of proton's light quarks (Brodsky)

800 GeV p-A (FNAL)

PRL 84, 3256 (2000); PRL 72, 2542 (1994)

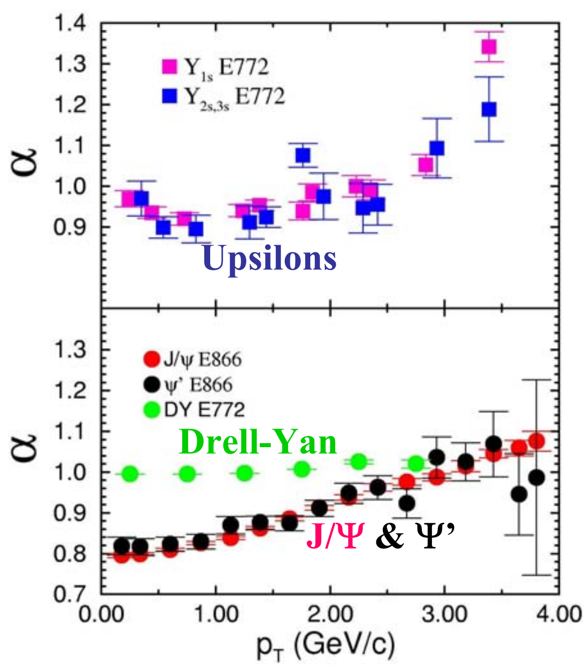


Cold Nuclear Matter Effects
Transverse Momentum Broadening for J/ψ's & ϒ's

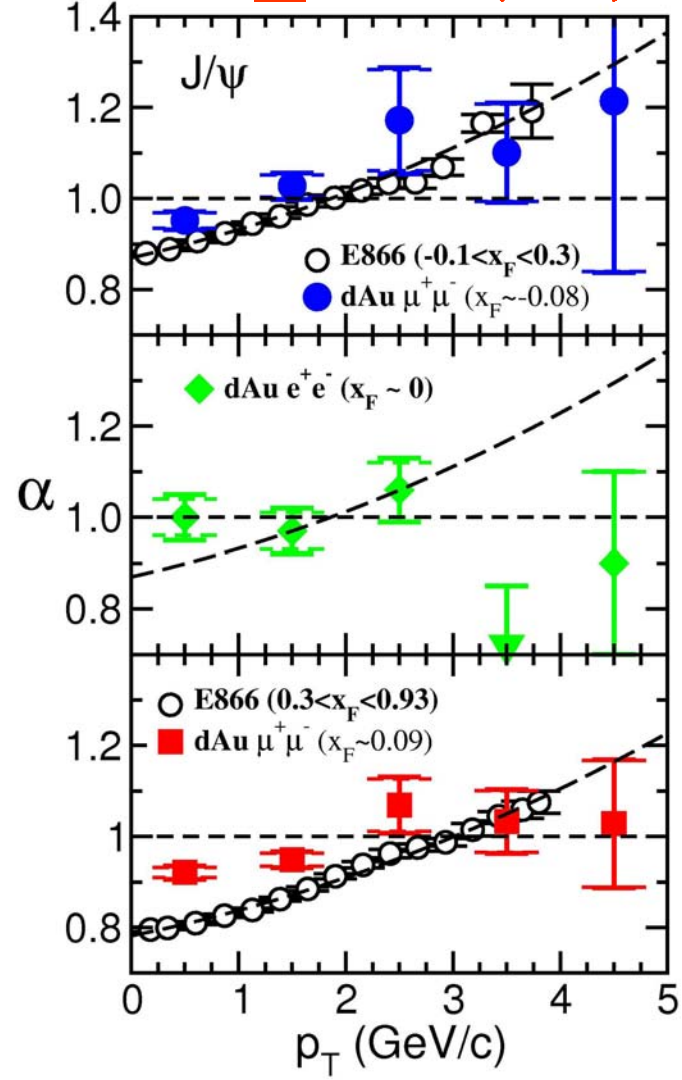


Initial-state gluon multiple scattering causes p_T **broadening** (or Cronin effect)

$$\sigma_A = \sigma_N A^{\alpha}$$



PRL 96, 012304 (2006)



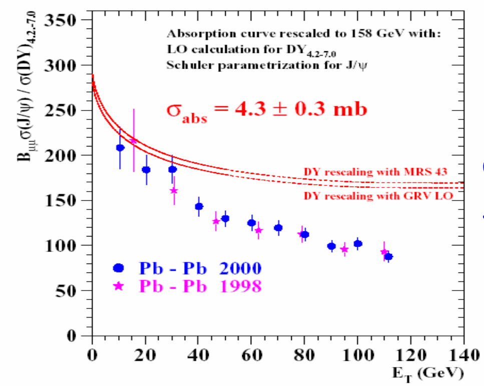
High x_2 ~ 0.09

PHENIX 200 GeV results show p_T broadening comparable to that at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)

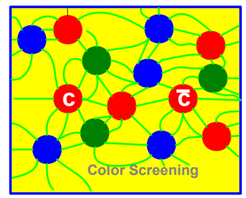
Low x_2 ~ 0.003

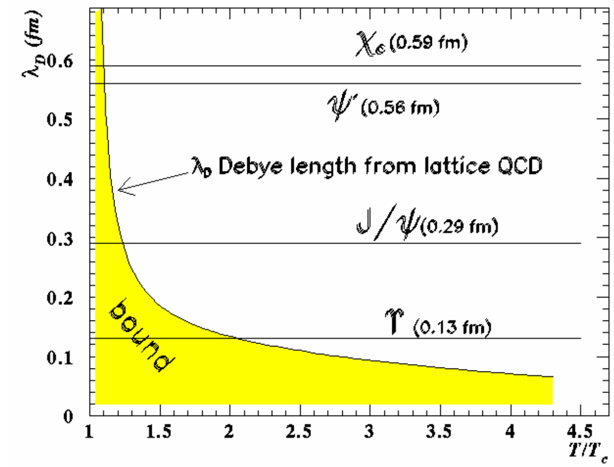
Quarkonia - AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

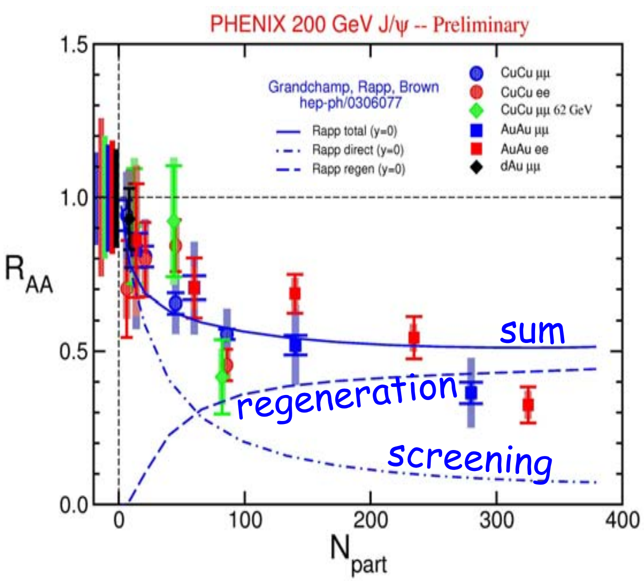
Debye screening predicted to destroy J/ψ's in a QGP with different states "melting" at different temperatures due to different binding energies.



NA50 anomalous suppression

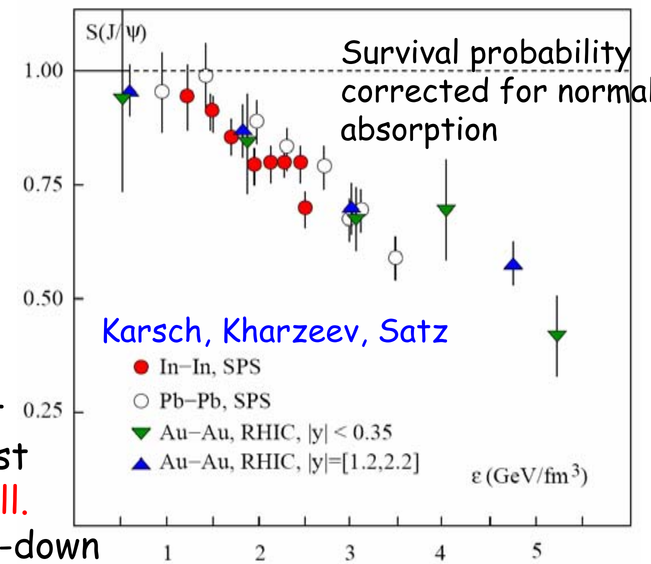






but recent regeneration models might give enhancement that compensates for screening?

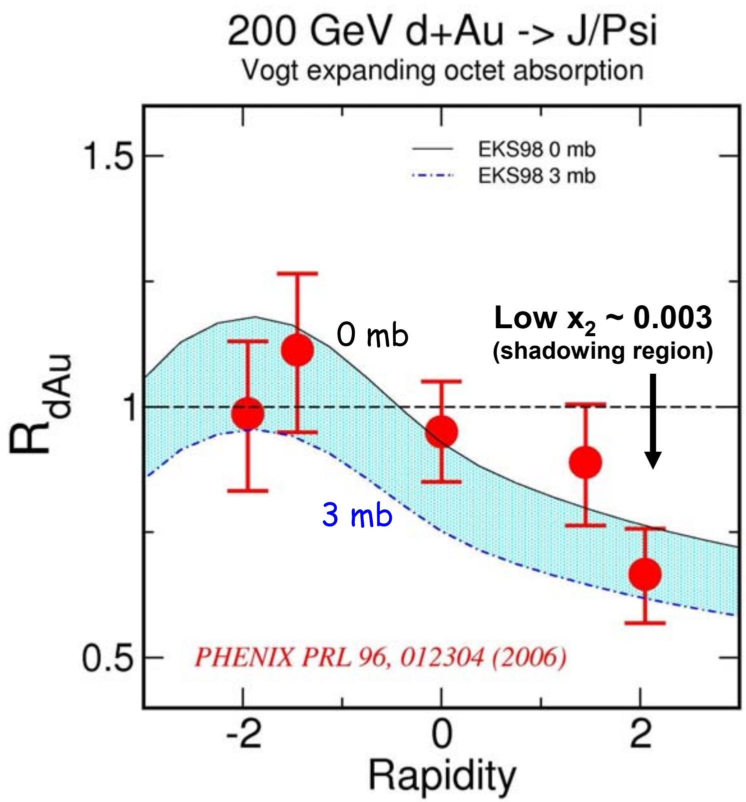
on the other hand, recent lattice calculations suggest J/ψ not screened after all. Suppression only via feed-down from screened χ_C & ψ'

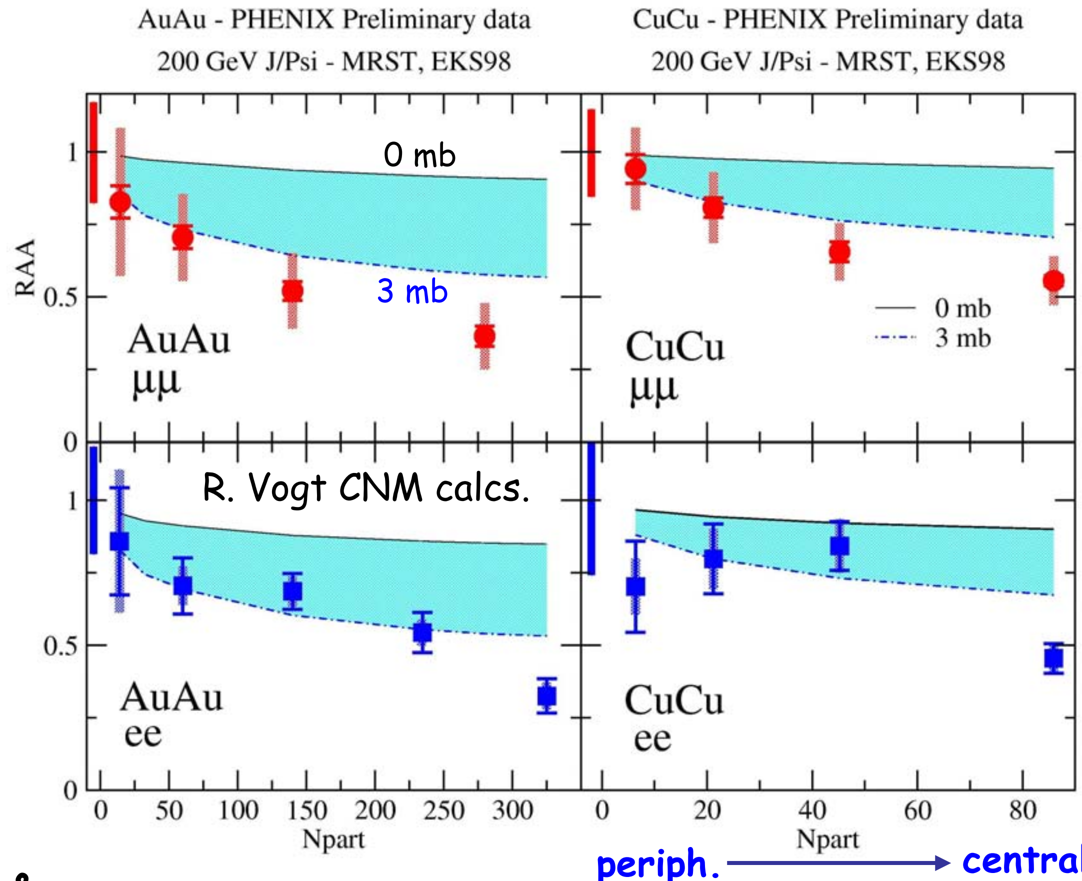


energy density

Quarkonia - J/ψ suppression in AA collisions & CNM baseline

(CNM = Cold Nuclear Matter)

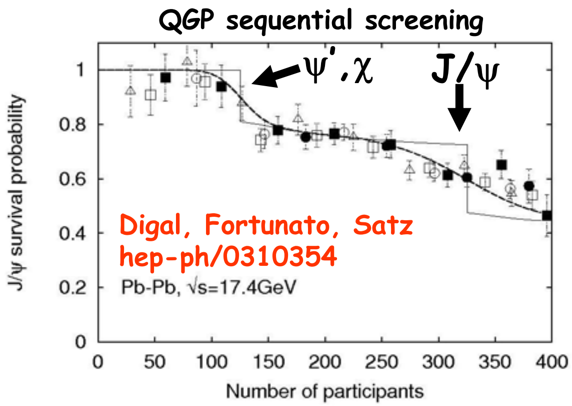


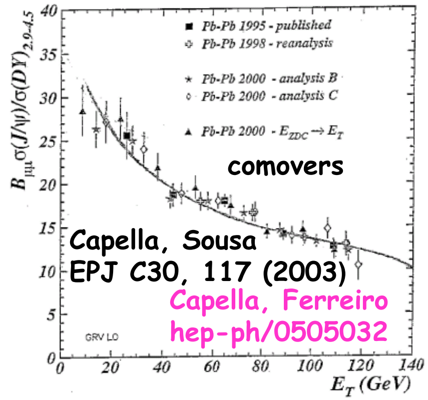


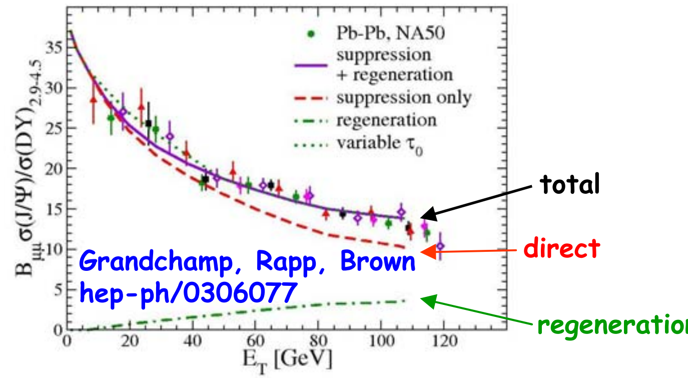
- CNM calculations with shadowing & absorption
- present dAu data probably only constrains absorption to: $\sigma_{ABS} \sim 0\text{-}3$ mb

- AA suppression is somewhat stronger than CNM calculations predict
- but really need more precise dAu constraint!

Quarkonia - Models without regeneration

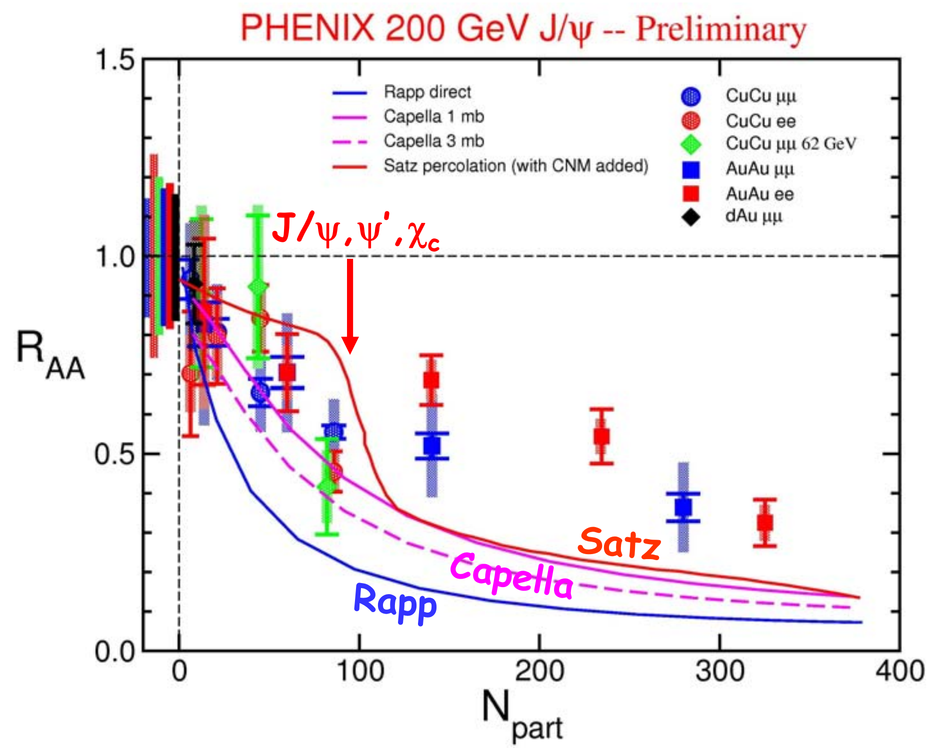






Models that reproduce NA50 results at lower energies predict too much suppression at RHIC!

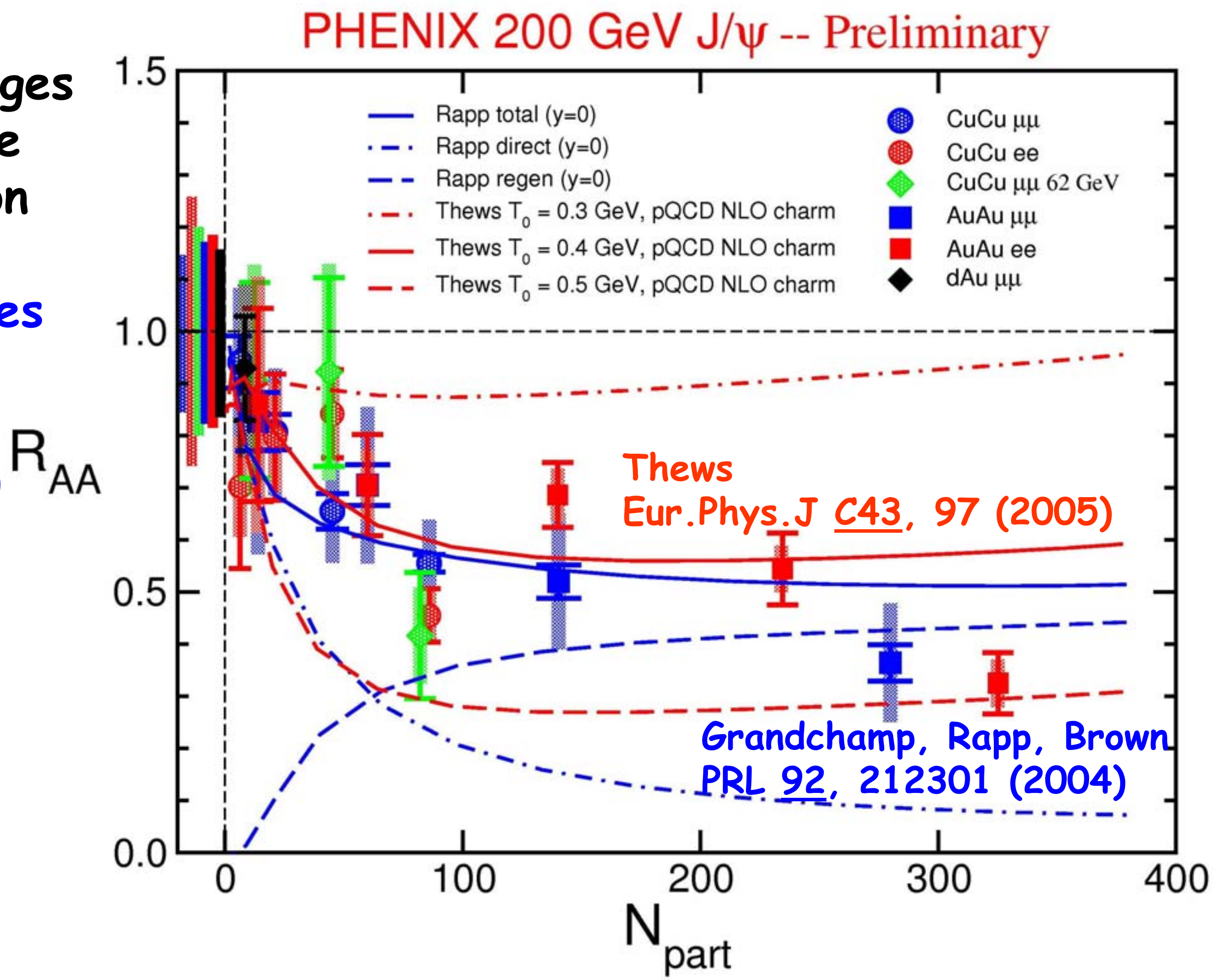
- **Satz - color screening in QGP (percolation model) with CNM added (EKS shadowing + 1 mb)**
- **Capella – comovers with normal absorption and shadowing**
- **Rapp – direct production with CNM effects needs very little regeneration to match NA50 data**

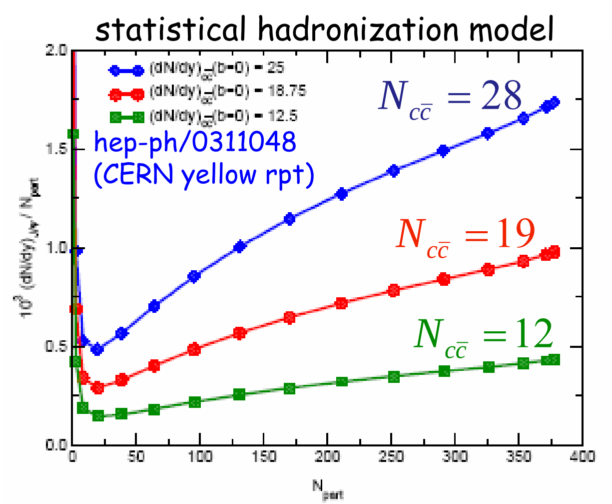


Quarkonia - Models with screening & regeneration

Models with regeneration, i.e. single charm quarks combining in the later stages to form J/ψ's – match the observed RHIC suppression much better!

- **but the regeneration goes as $\sigma_{c\bar{c}}^{\;2}$ - which is still poorly known at RHIC (& that's another story..)**





Quarkonia
Many More Models for RHIC J/ψ suppression in CuCu & AuAu Collisions

All have suppression + various regeneration mechanisms

Rapp – PRL 92, 212301 (2004)
- screening & in-medium production

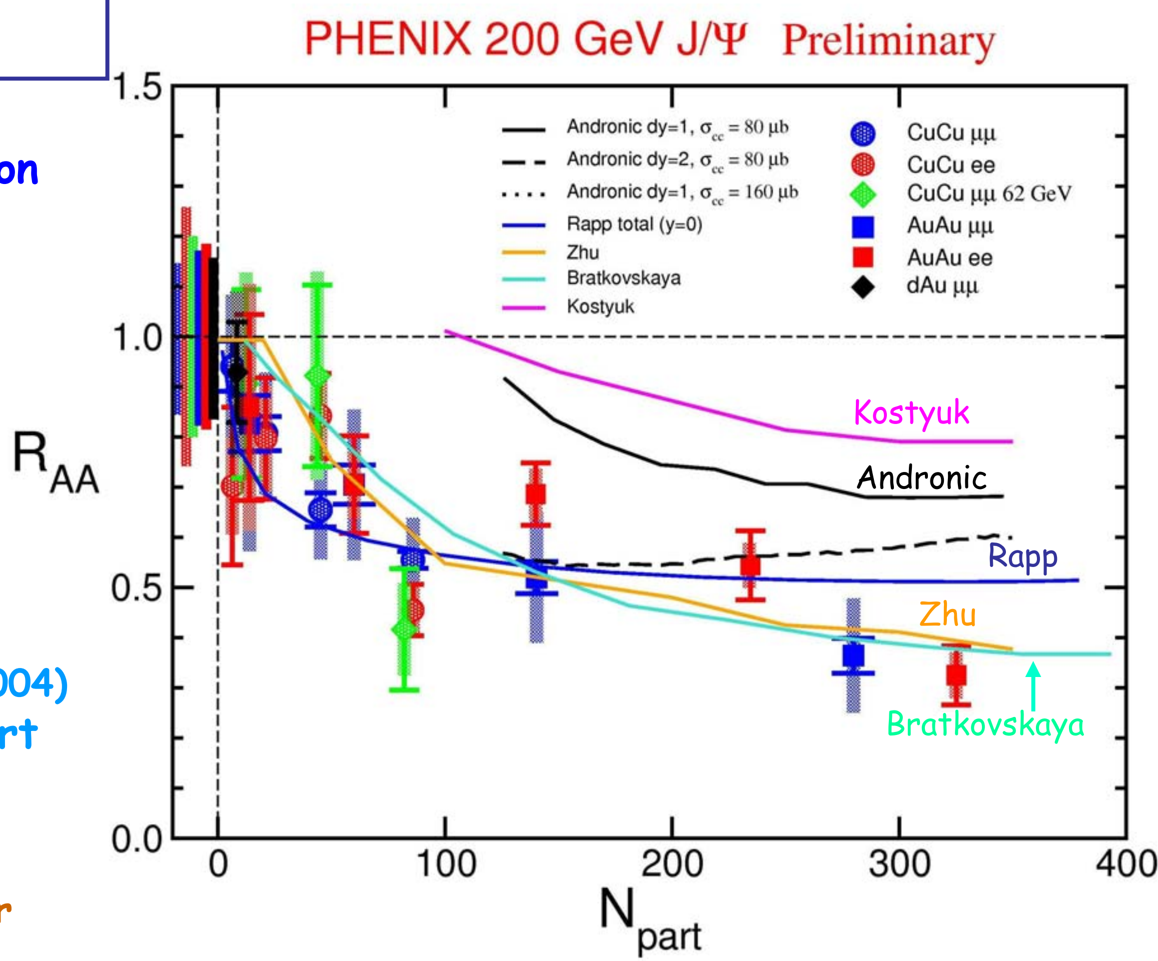
Thews – see previous slide

Andronic – PL B57, 136 (2003)
- statistical hadronization model
- screening of primary J/ψ's
- + statistical recombination of thermalized c-cbar's

Kostyuk – PRC 68, 041902 (2003)
- statistical coalescence
- + comovers or QGP screening

Bratkovskaya – PRC 69, 054903 (2004)
- hadron-string dynamics transport

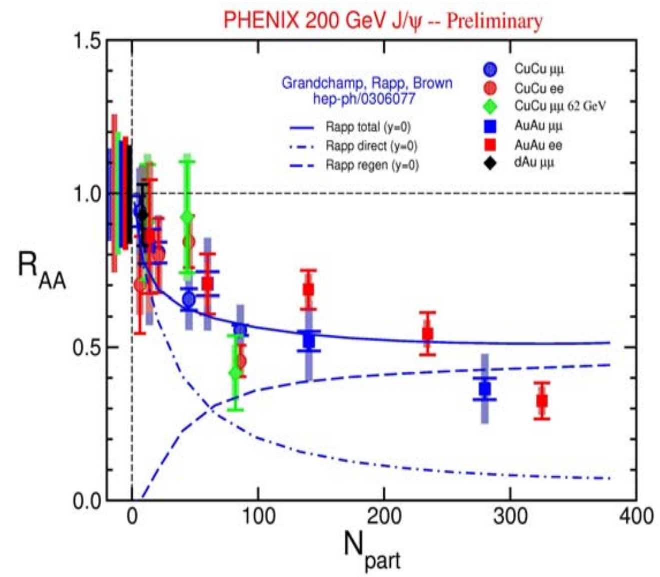
Zhu – PL B607, 107 (2005)
- J/ψ transport in QGP
- co-movers, gluon breakup, hydro for QGP evolution
- no cold nuclear matter, no regeneration



Quarkonia - Regeneration or Sequential Screening?

RHIC suppression looks same as that at NA50

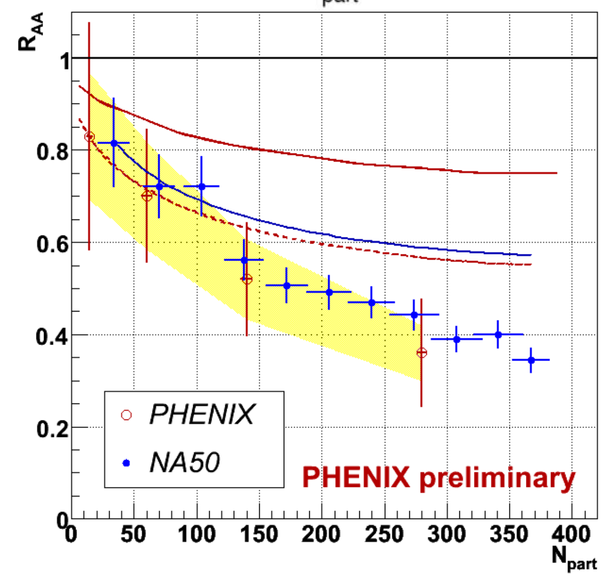
- but ~10x collision energy & ~2-3x gluon energy density at RHIC
- regeneration compensates for stronger QGP suppression?
    - if so, regeneration would be huge at the LHC!



------------- OR ------------------

(Karsch, Kharzeev, Satz, hep-ph/0512239)

- Sequential screening of the higher-mass resonances that feed-down to the J/ψ; with the J/ψ itself still not dissolved?
- supported by recent Lattice calculations that give $T_{J/\psi} > 2\ T_C$



Quarkonium dissociation temperatures – Digal, Karsch, Satz

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60	1.19	1.17

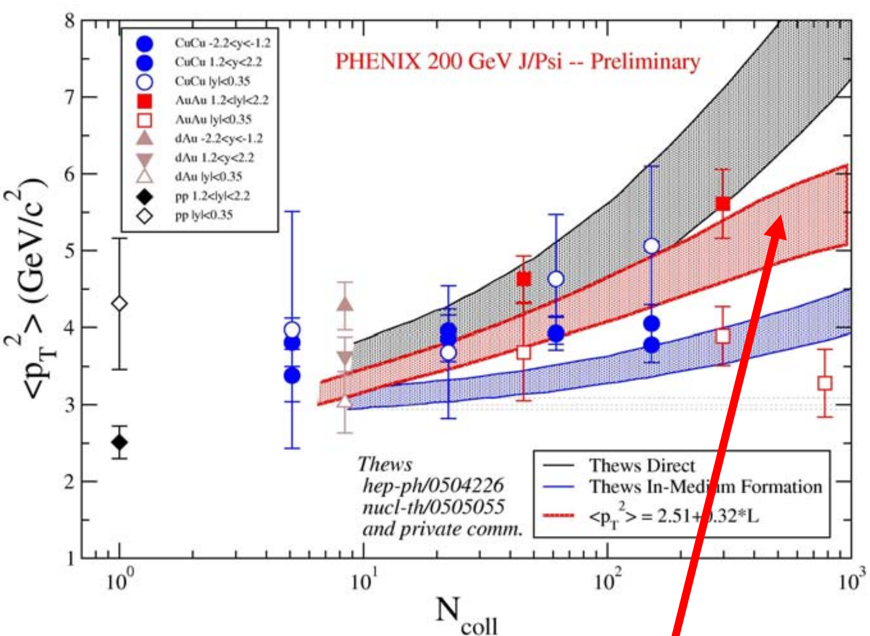
Quarkonia

Regeneration should cause narrowing of p_T and y – does it?

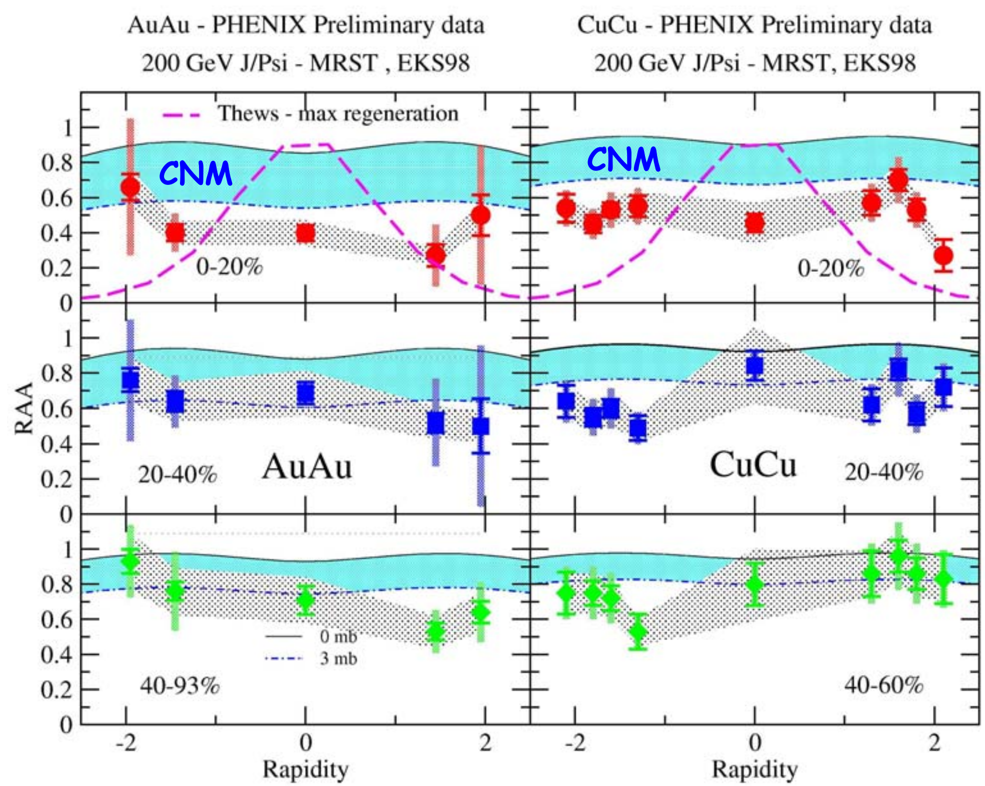
p_T broadening lies in between Thews direct & in-medium formation suggesting some regeneration (but our fit to pp+dAu data vs L also reasonable)

But rapidity dependence of central AA collisions (top panels) shows no narrowing – i.e. peaked ratios as in the Thews (maximal) regeneration, shown below

But careful – is σ_{ccbar} flatter with y than we originally thought?



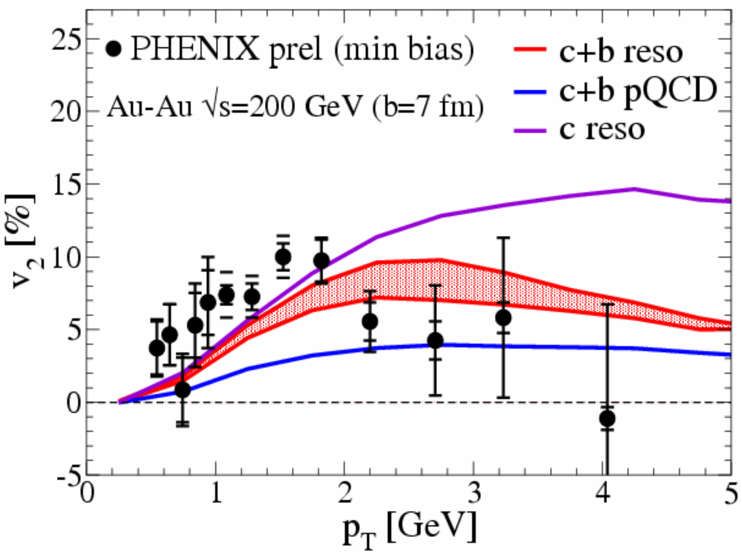
$<p_T^2> = 2.51+0.32*L$ from fit to dAu data vs L



Quarkonia - Flow of J/ψ's?

Need to look for J/ψ flow – if regeneration dominates, the J/ψ's should inherit flow from charm quarks

- open charm has recently been seen to flow (at least at some p_T values)
- but what about geometrical absorption effects, which could also give asymmetry wrt reaction plane?



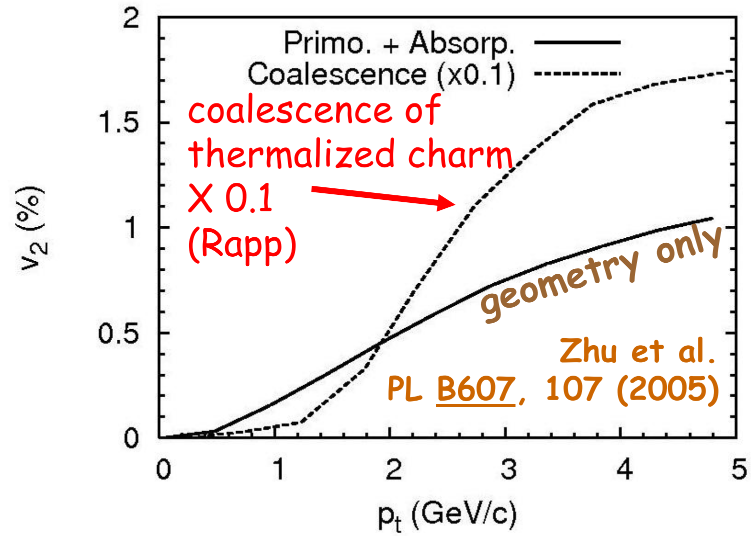
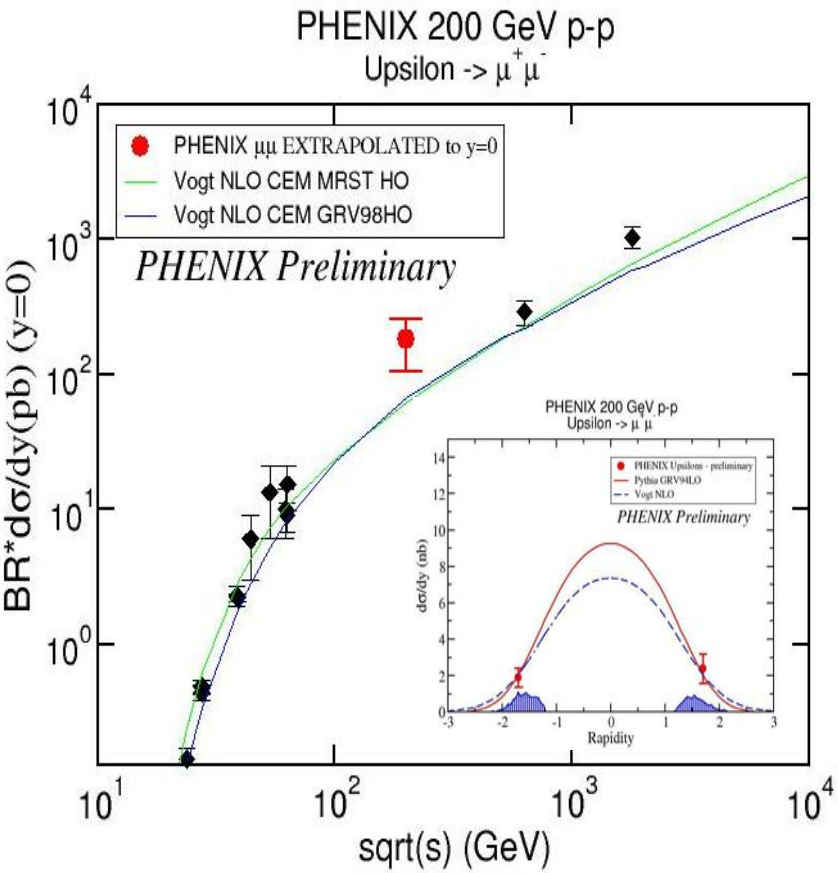


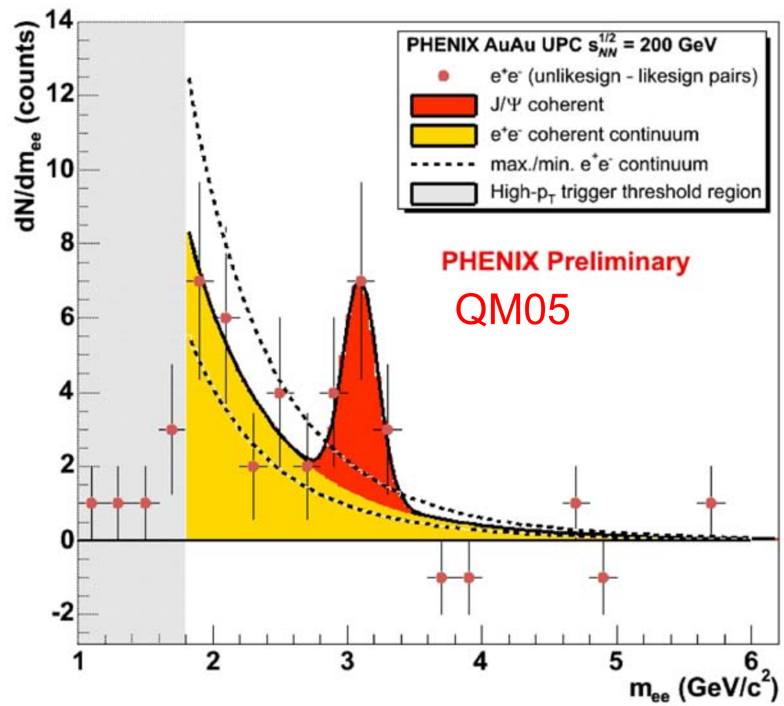
FIG. 4: The elliptical flow of J/ψ as a function of p_t at RHIC energy. The solid line is the maximal v_2 with impact parameter b=7.8 fm calculated in the frame of J/ψ transport, and the dashed line is the minimum-bias v_2 (scaled by a factor of 0.1) of the coalescence model with the assumption of complete charm quark thermalization.

Future
Much More to Come!



1st Upsilons at RHIC from ~3pb^{-1} collected during the 2005 run.

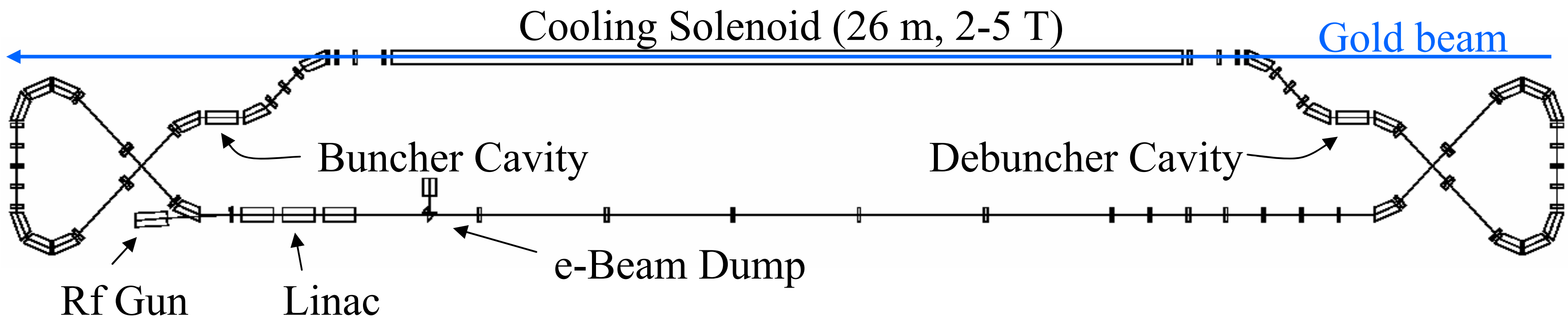
Ultra-peripheral Collisions (UPC's)



UPC's : well calibrated EM probe of small-x gluon saturation

Future
RHIC-II Luminosty Upgrade

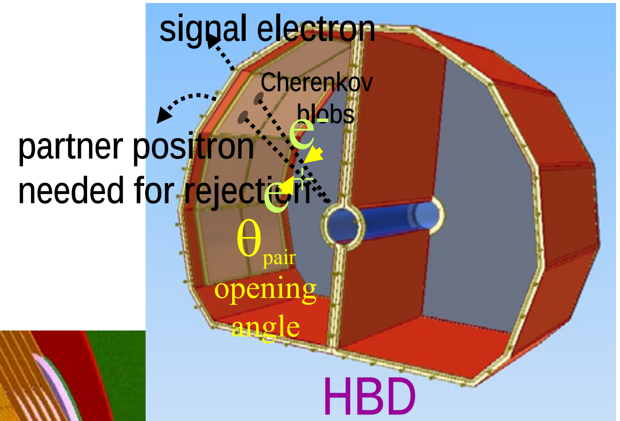
- Luminosity increased by x10 (AuAu), x2-3 (pp) & zvertex size decreased using electron cooling
- Also more reliable source with EBIS



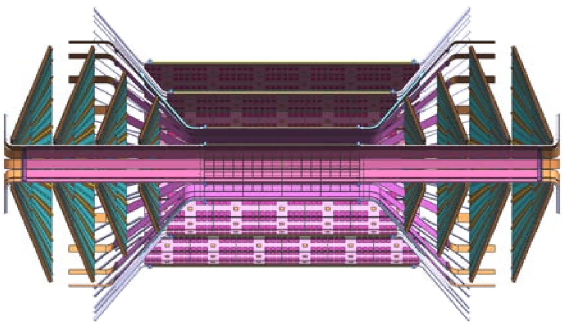
- enabling rare probes: Υ, ψ', $\chi_c \rightarrow J/\psi + \gamma$, $B \rightarrow J/\psi$, J/ψ v_2

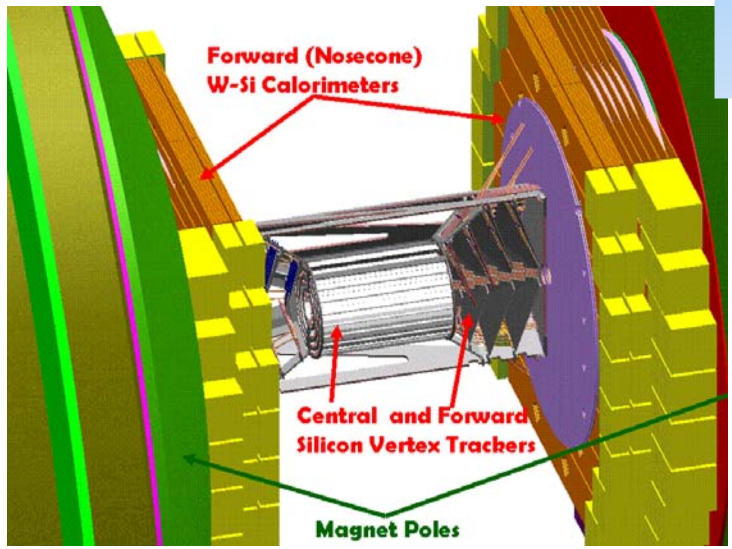
Signal	RHIC Exp. (Au+Au)	RHIC I (>2008)	RHIC II	LHC ALICE$^+$
$J/\psi \rightarrow e^+e^-$	PHENIX	3,300	45,000	9,500
$J/\psi \rightarrow \mu^+\mu^-$		29,000	395,000	740,000
$\Upsilon \rightarrow e^+e^-$	STAR	830	11,200	2,600
$\Upsilon \rightarrow \mu^+\mu^-$	PHENIX	80	1,040	8,400

Future - PHENIX Upgrades

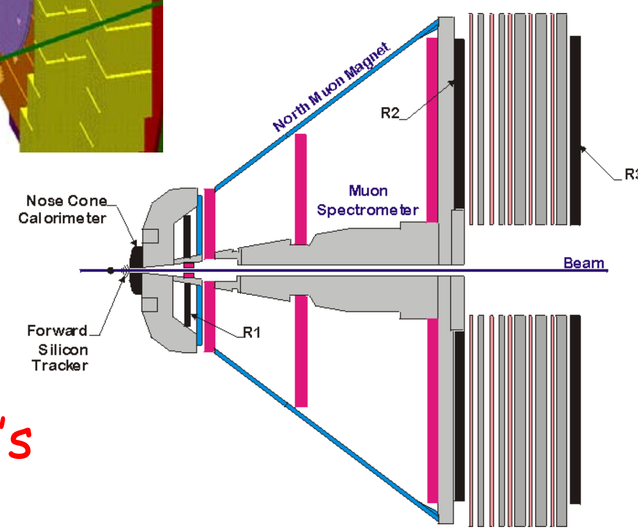


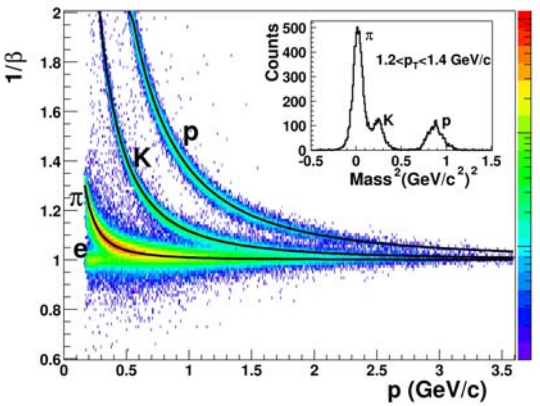
- Hadron blind detector - low-mass e-pairs
- Aerogel & RPC TOF – PID to higher p_T





- Silicon vertex – mid-rapidty & forward heavy-q's, incl. B $\rightarrow$ J/ψ X
- Nose cone calorimeter – forward γ, π^0, χ_c
- Forward muon trigger – high-p_T trigger & W's

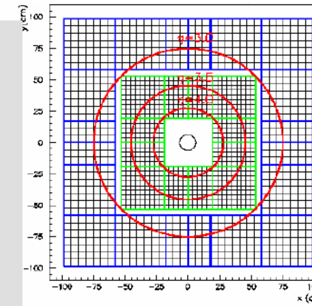


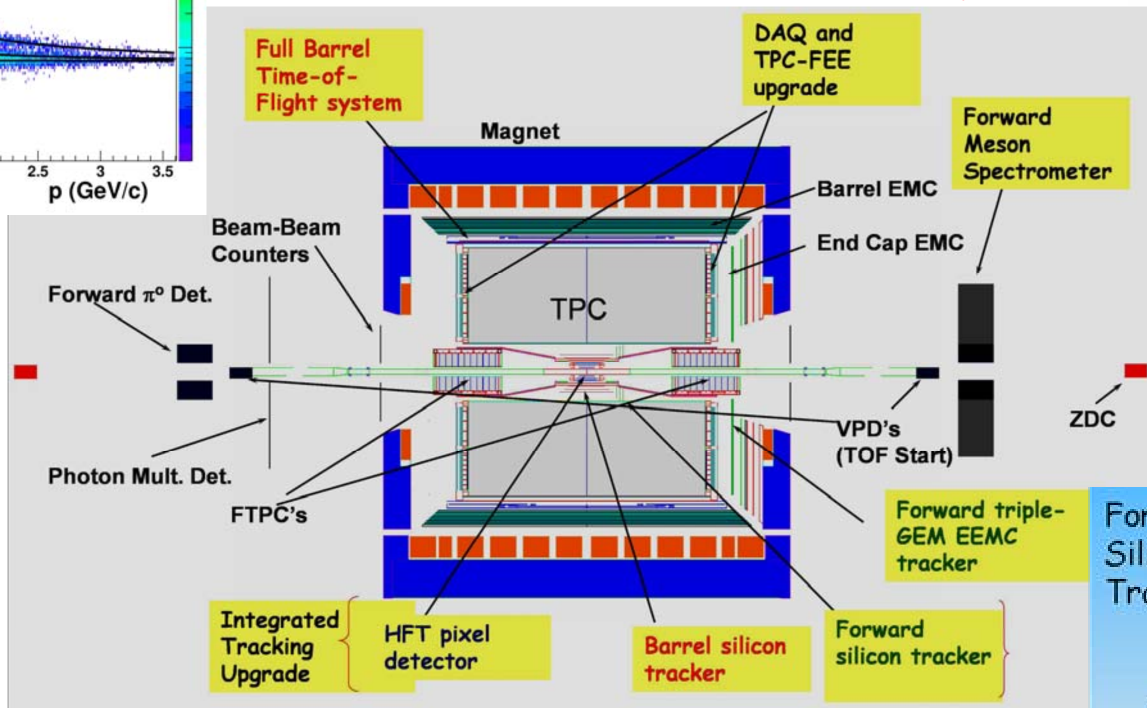


RPC TOF
Flavor tagging at large p_T

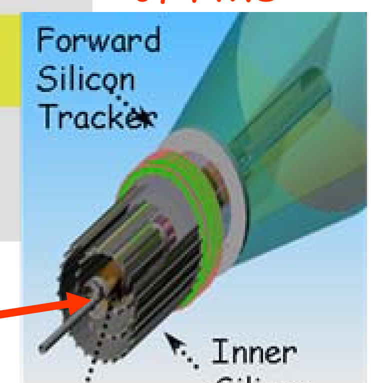
DAQ upgrade
100 → 1000 hz

Forward Meson Spectrometer ($2.5 < \eta < 4$)



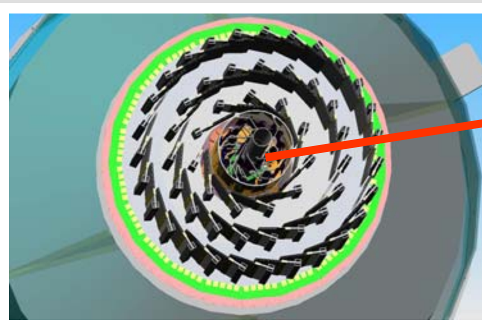


e vs γ in front of FMS



Inner Silicon Tracker

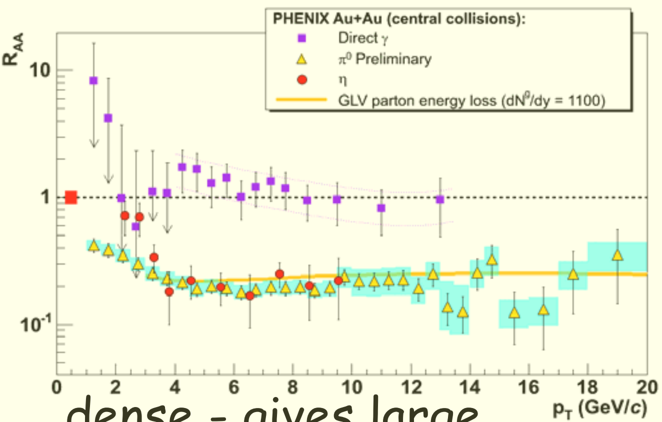
Future STAR Upgrades



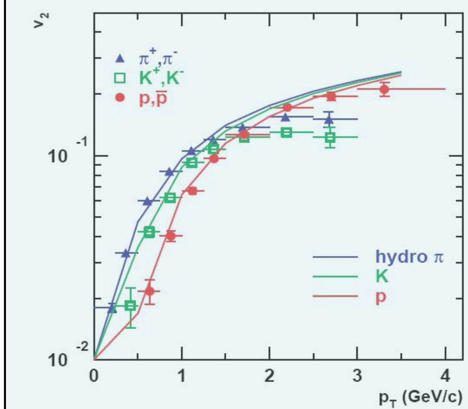
Heavy Flavor Tracker

D → Kπ

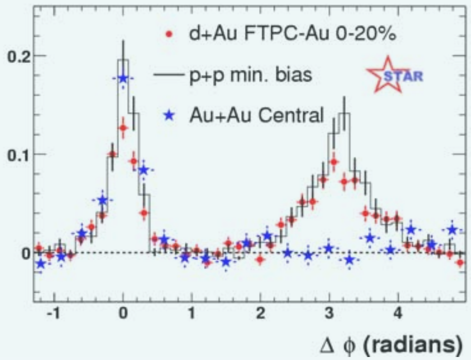
Summary
the matter is



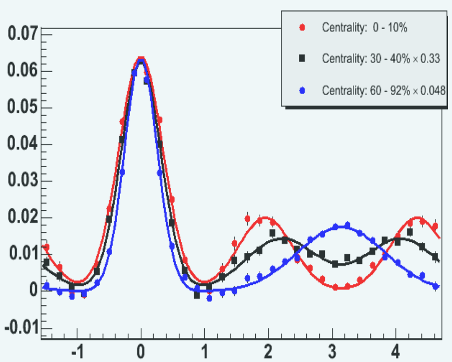
dense - gives large dE/dx for hadrons



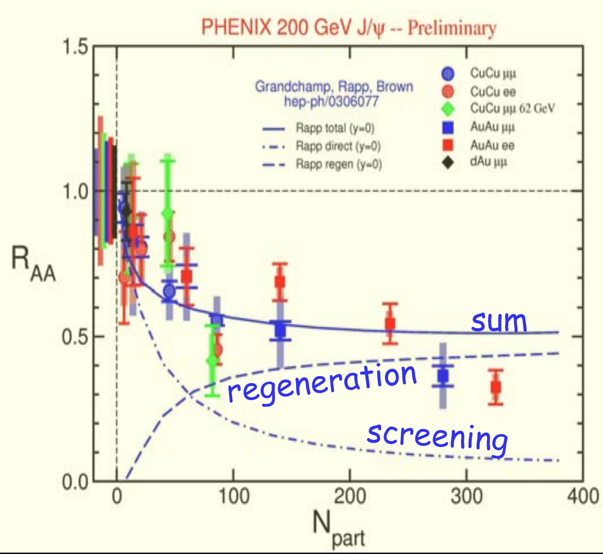
thermalized - maximal flow with quark d.o.f.

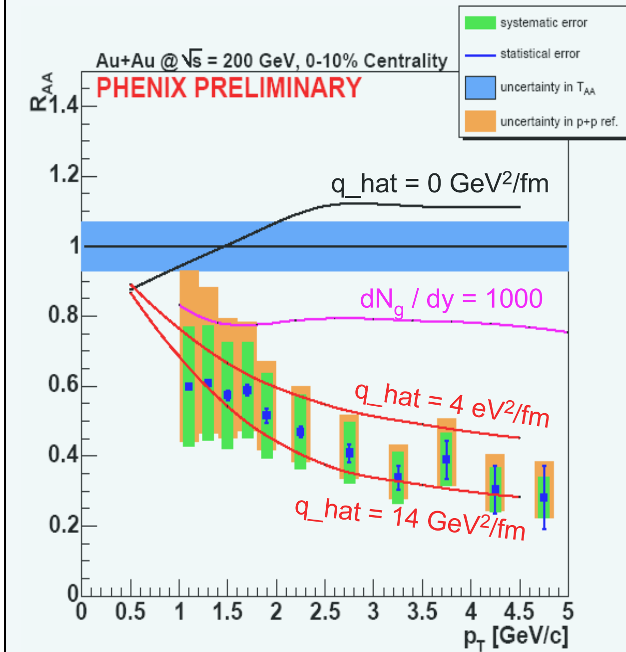


opague - modifies jets

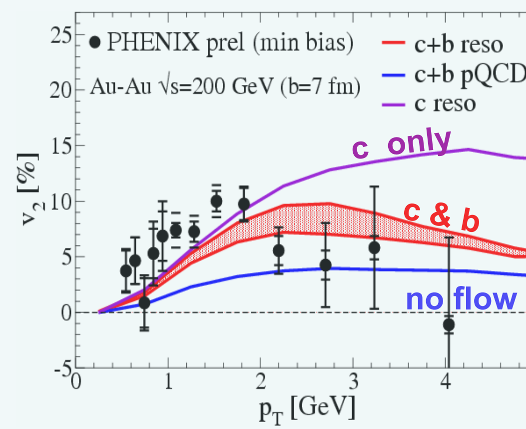


deconfined - screens heavy quark bound states





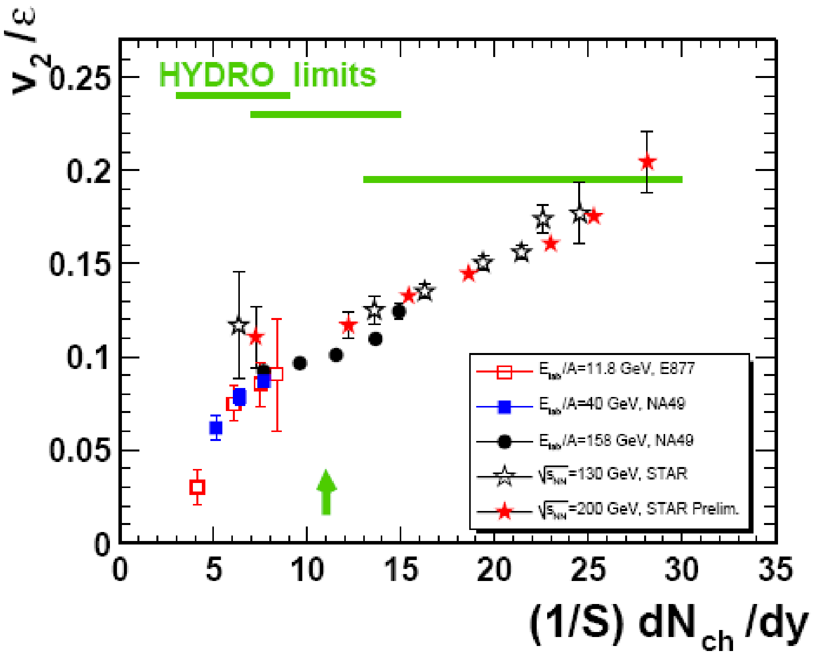
dE/dx and flow for heavy quarks too



Extra Slides

Concerns about Perfect Fluid at RHIC

- "Limits" on this plot are not strict limits
  - literature scan looking for largest calculation at each energy

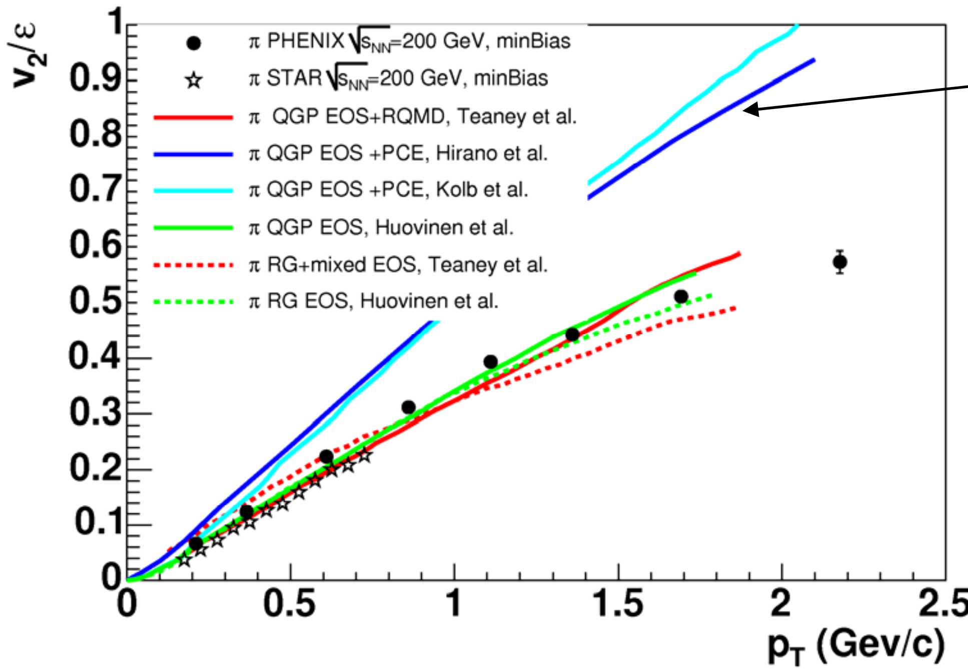


PRC **68**, 034903 (2003)
Private comm. S. Voloshin

- Ollitraut et al (PLB 627, 49 (2005)) argues that hyrdo "limit",
  - is when v_2/ε independent of 1/S dN/dy
  - not reached experimentally => not fully thermalized?

Slide from Craig Ogilvie

Partial-chemical freezeout overpredicts v_2



Partial chemical calculations reproduce spectra

- Hydro models are sensitive to scattering in hadronic final state
  - Spectra change shape, magnitude
  - Redistribution of asymmetry, change v_2(pt)
- Given the failure of these hydro models
  - Not possible (yet) to extract c_s, EoS, low-viscosity,…

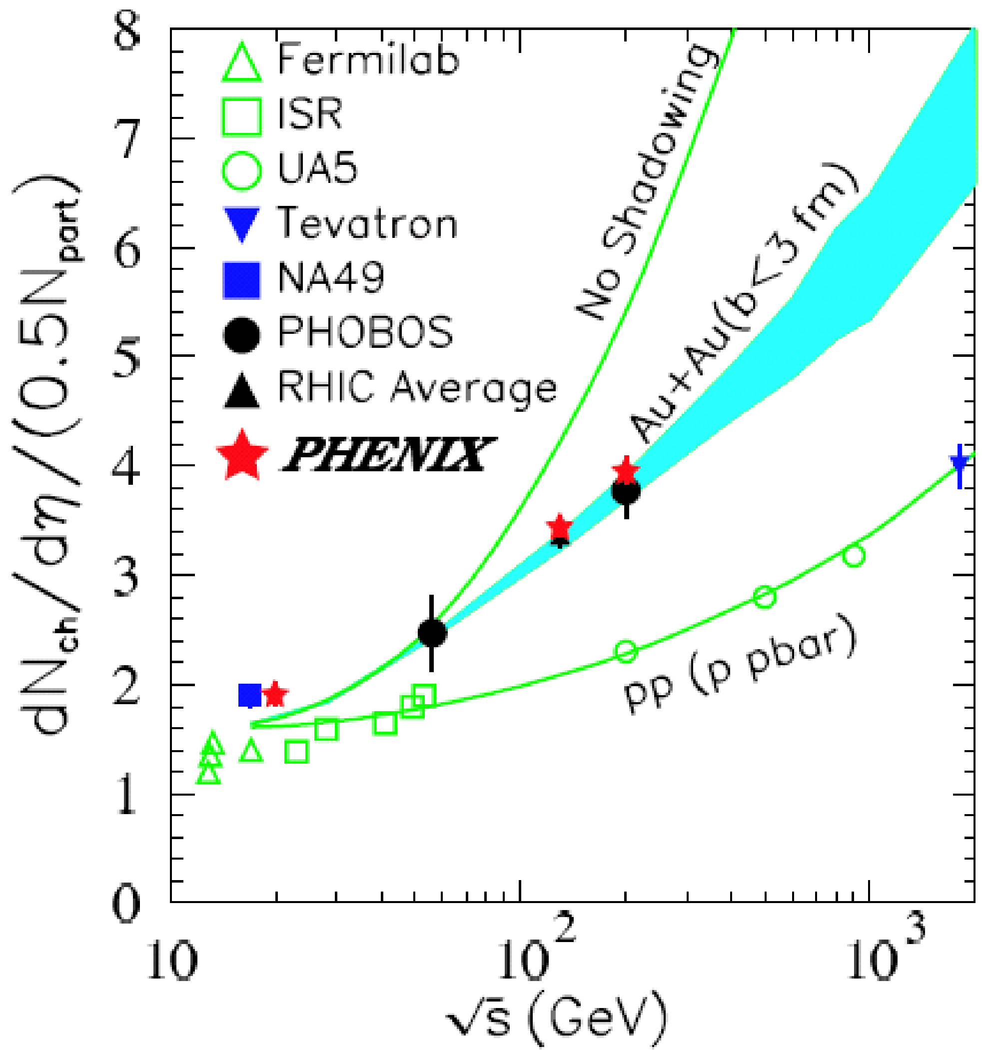
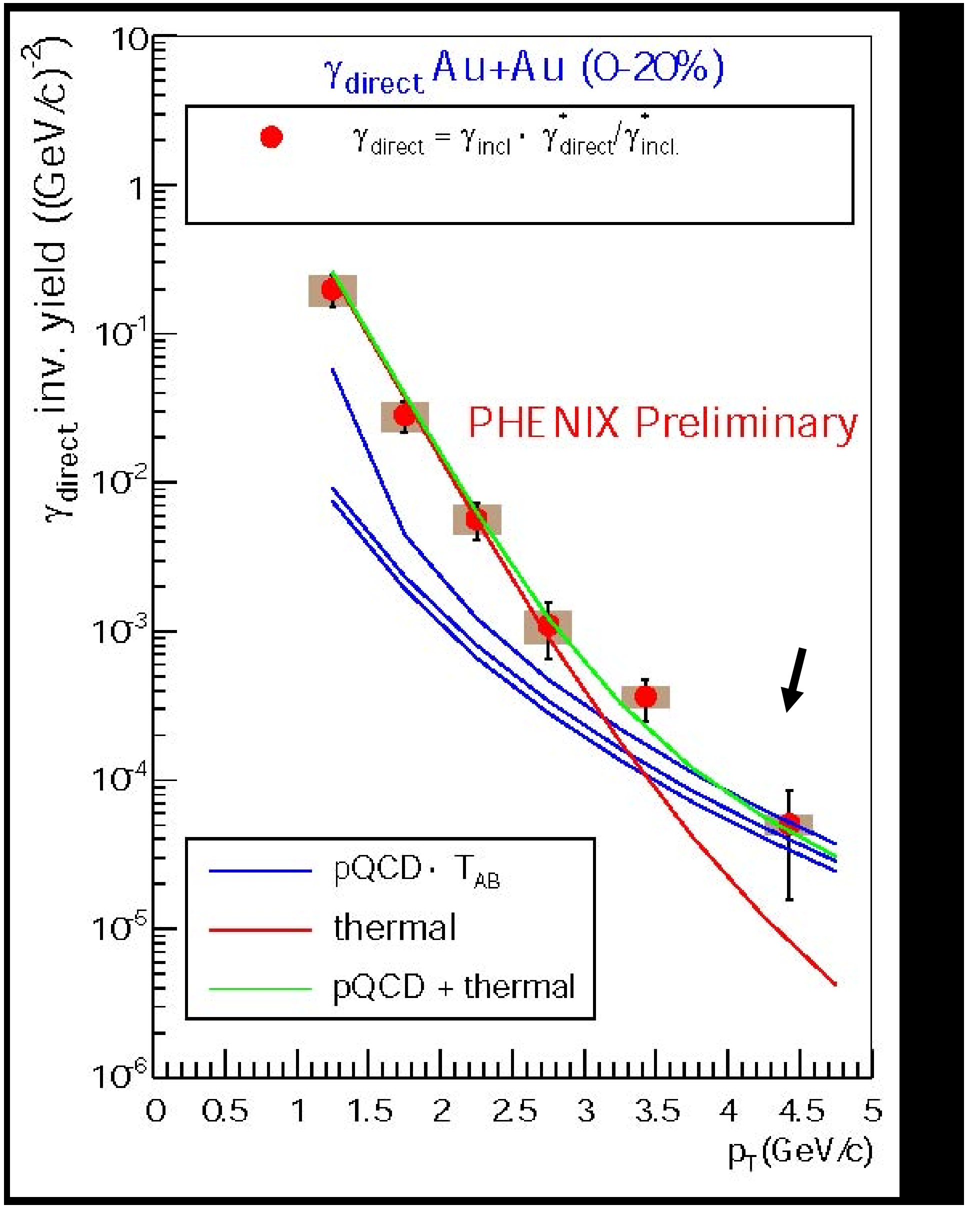


Fig. 7. Figure from Li and Wang [79] showing trends in final-state charged multiplicity per participant pair vs. (nucleon-nucleon) beam energy. (PHENIX data points[59] have been added.) The curves are the result of their two-component "hard/soft" model, which reproduces well the multiplicities from elementary $p(\bar{p})+p$ collisions at RHIC energies. The same model extended to nuclear collisions with no regulating mechanism on hard processes (the "No Shadowing" line) over-predicts the multiplicities in central RHIC collisions, while the data can be matched if substantial nuclear shadowing of gluons is invoked (shaded band).

The Spectrum

Stefan Bathe, QM05



Compare to NLO pQCD

- L.E.Gordon and W. Vogelsang
- Phys. Rev. D48, 3136 (1993)

- excess above pQCD

Compare to thermal model

- D. d'Enterria, D. Perresounko
- nucl-th/0503054

2+1 hydro

T_0^{ave}=360 MeV(T_0^{max}=570 MeV)

τ_0=0.15 fm/c

- data above thermal at high p_T

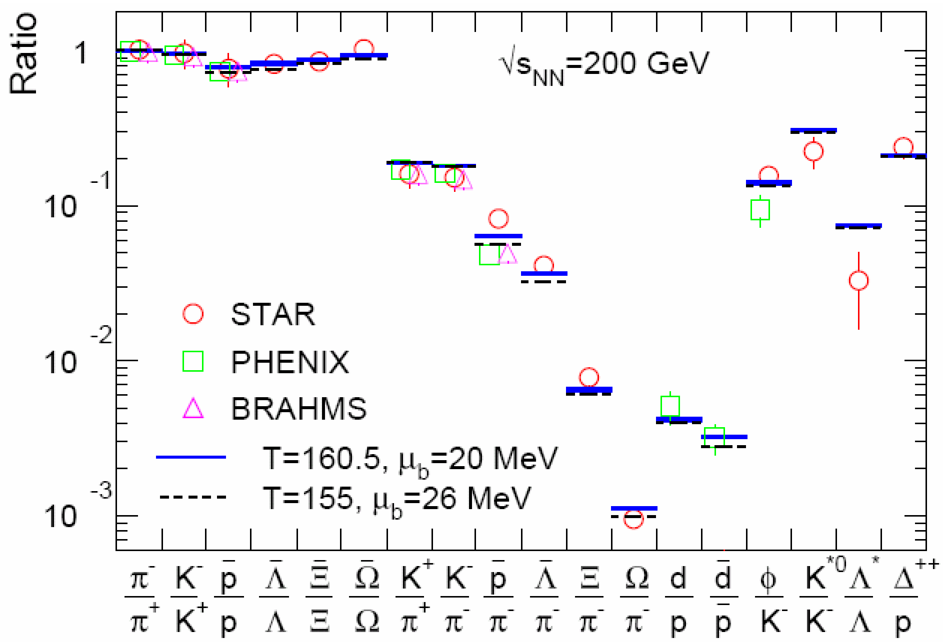
Compare to thermal + pQCD

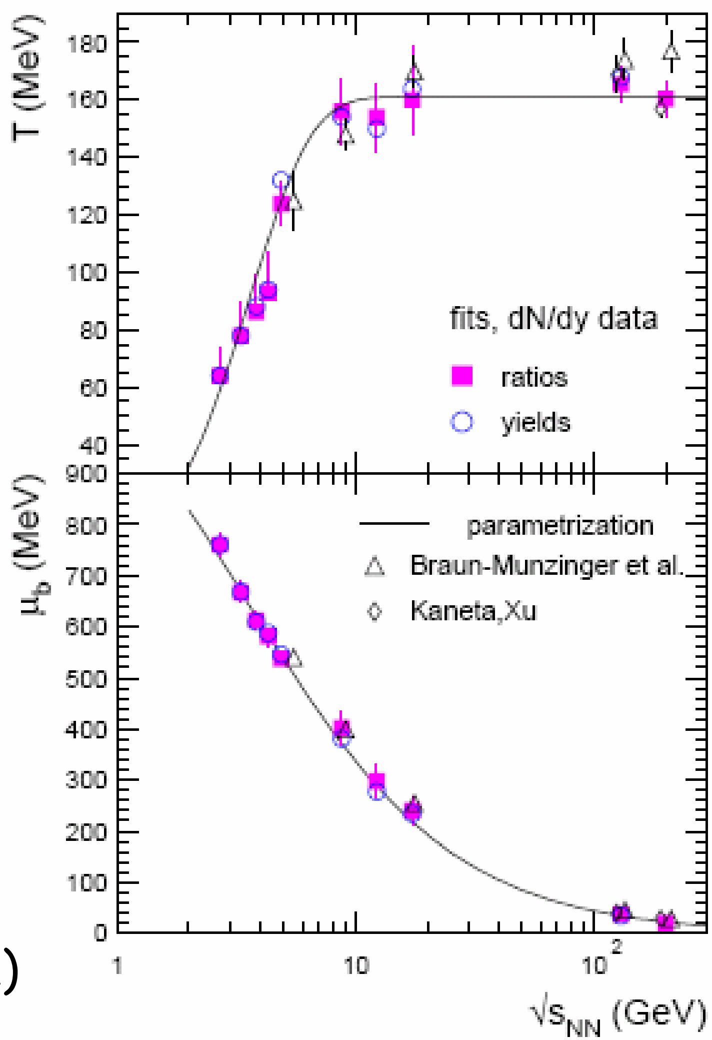
- data consistent with thermal + pQCD

Thermalization - Hadronic Abundances

Ratios of hadron yields consistent with system at chemical equilibrium

e.g. Andronic, Braun-Munzinger, Stachel nucl-th/0511071





Global fit to relative particle abundances with two parameters:

- chemical freezeout temperature ($T_{chem} \sim T_{crit}$)
- baryon chemical potential (μ_b)