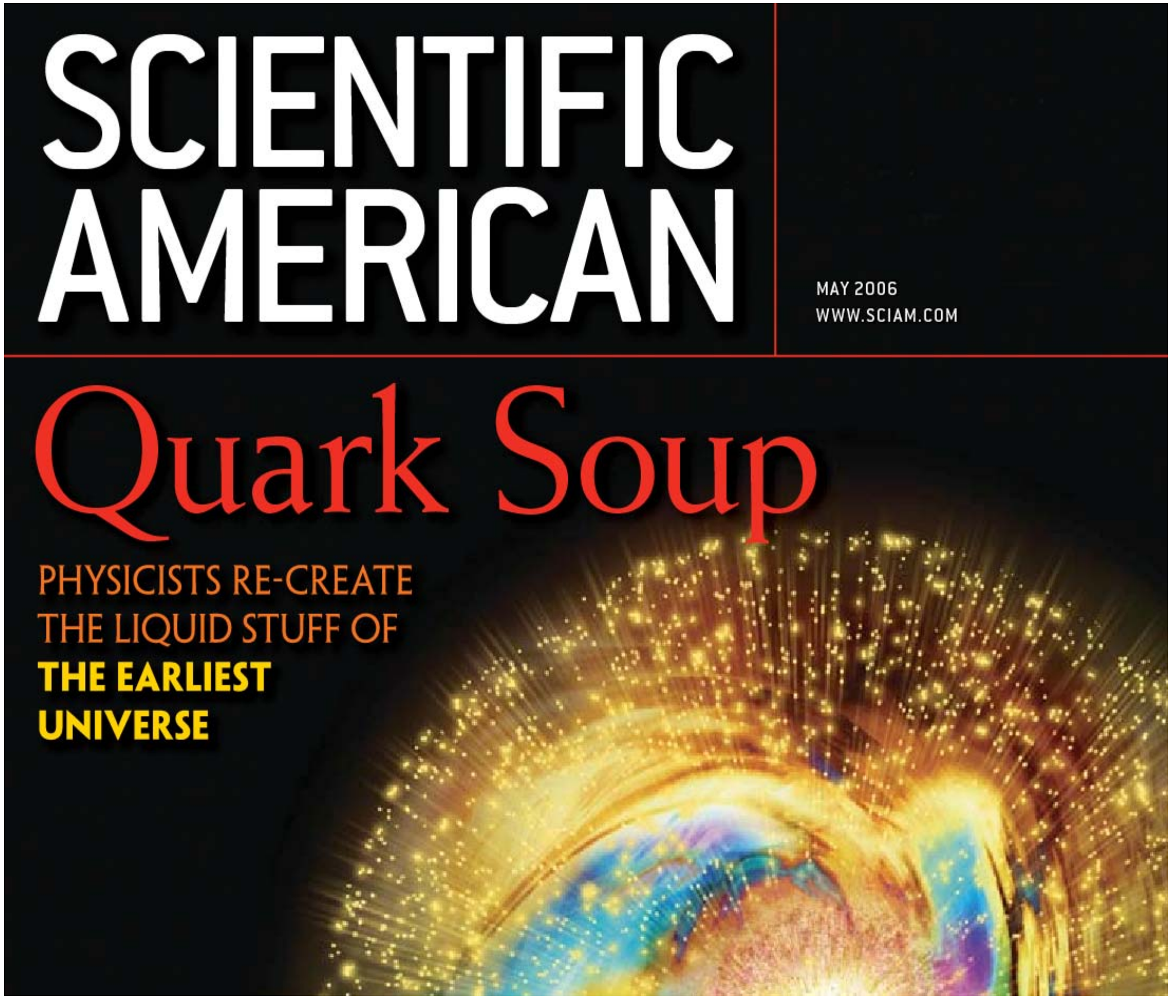
Exploring the Properties of Primordial Matter at RHIC

Ralf Averbeck
GSI Helmholtzzentrum für Schwerionenforschung

Seminar at

Laboratoire de Physique Corpusculaire
Clermont-Ferrand, France, November 28, 2008

Outline

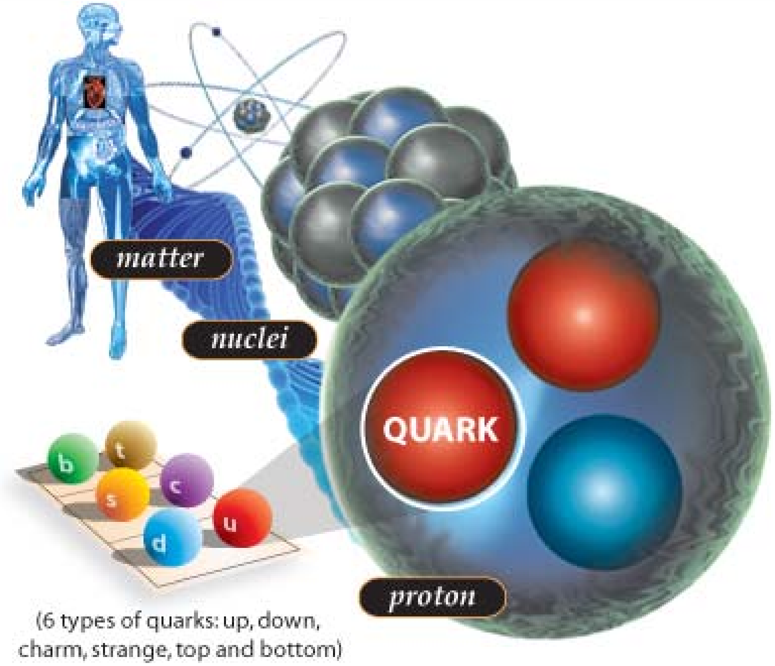


M. Riordan and W. Zajc, Sci. Am., May 2006, 34-41

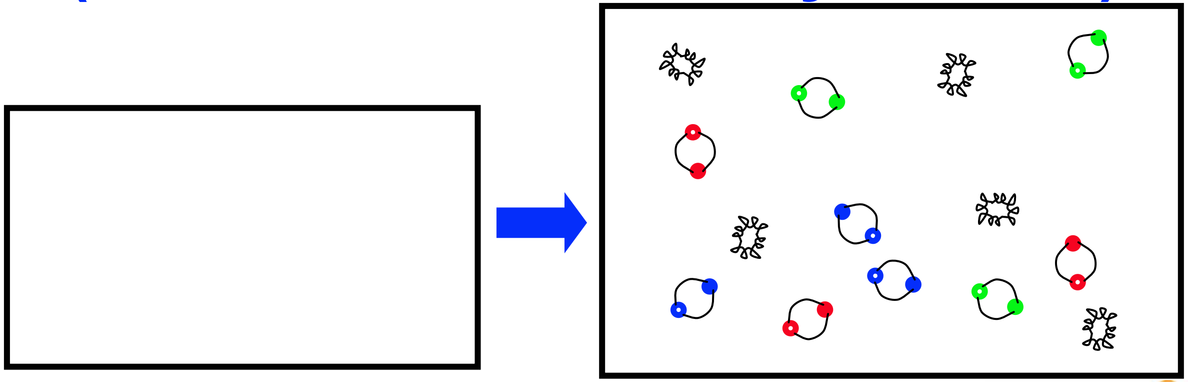
- "quark soup"
  - why should we care?
- probing this medium in nucleus-nucleus collisions
  - final state
  - initial state
  - hot and dense phase
- some (!) highlights from the program at RHIC

Nuclear matter as QCD laboratory

- “ordinary” nuclear matter
  - 3 (light) constituent quarks
  - quarks interact via the exchange of gluons
  - gluons carry color charge!

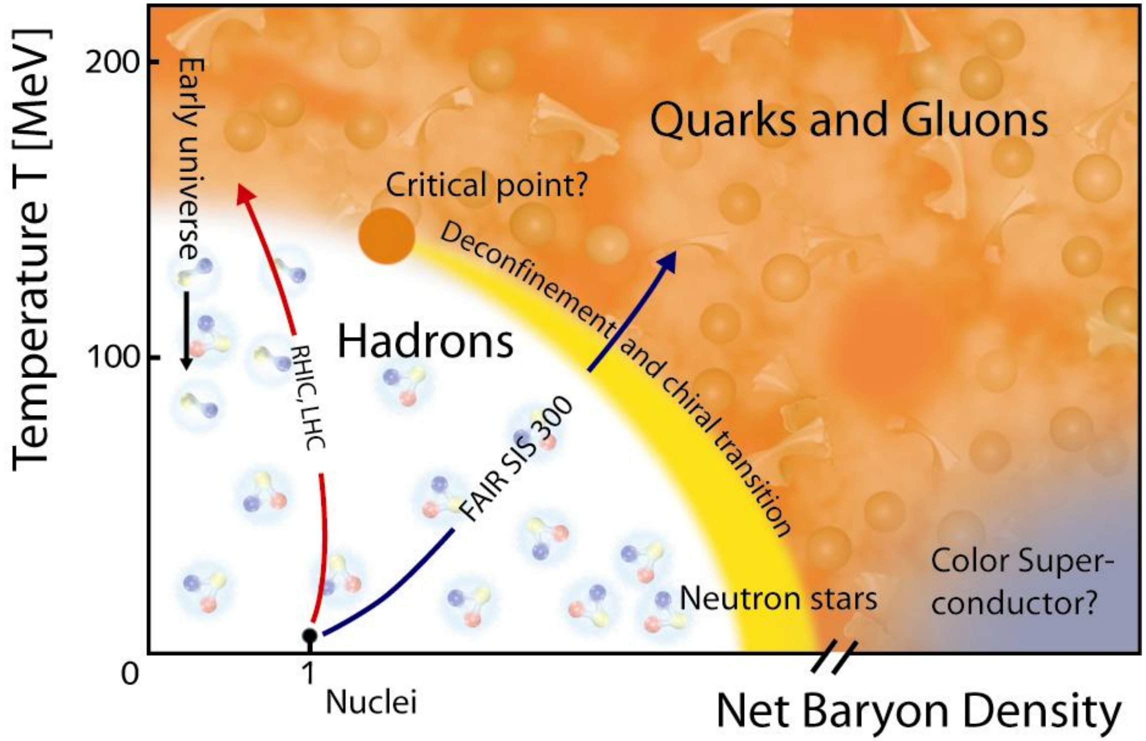


- key observations
  - isolated quarks are NEVER observed (“confinement“)
  - quark masses: ~1% of the nucleon mass
- properties of QCD (Quantum Chromo Dynamics)
  - QCD vacuum
    - NOT empty
    - complicated (more than the QED vacuum)



The QCD phase diagram

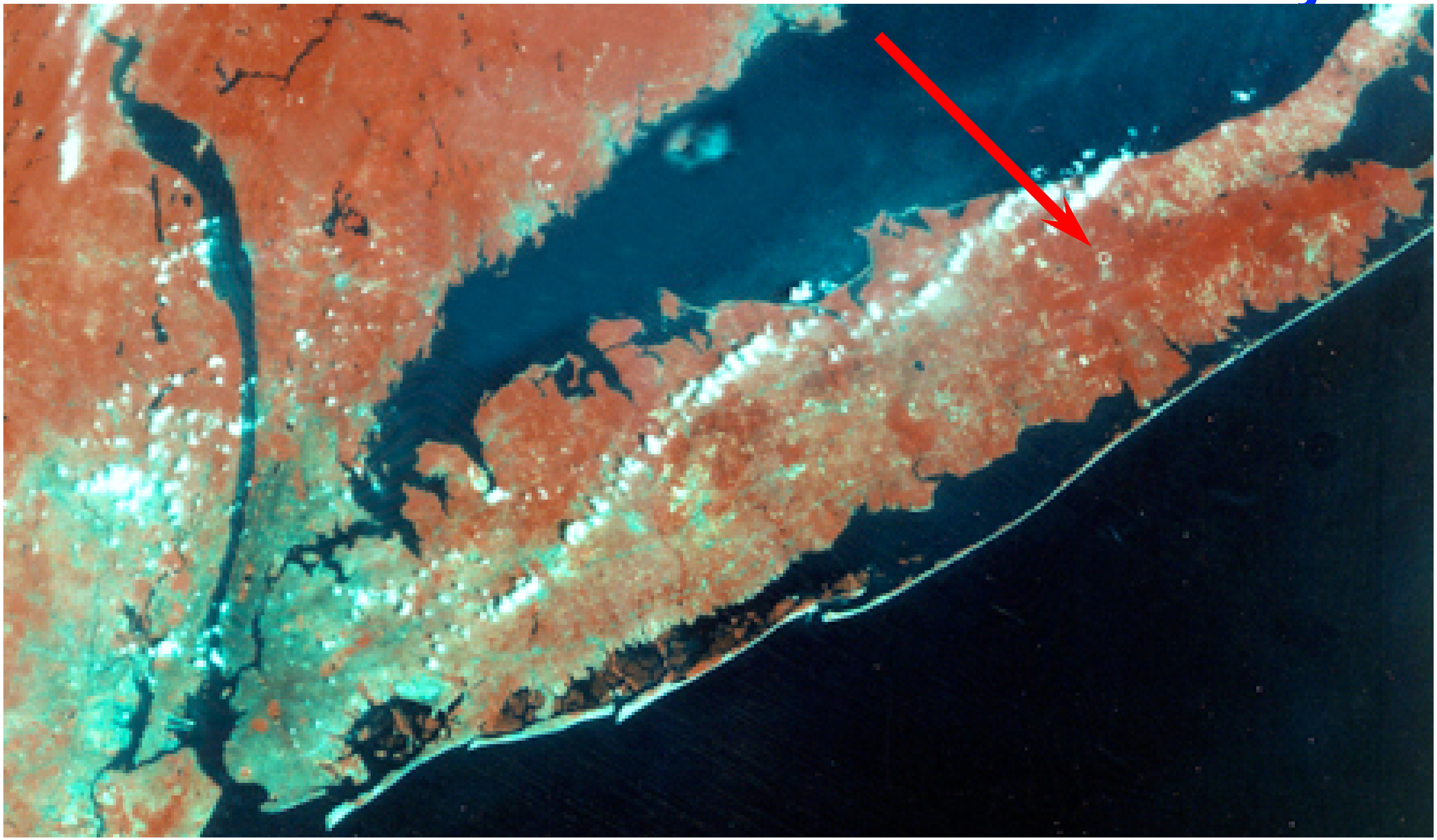
- unique tool to study strongly interacting matter far away from ground state: heavy-ion collisions



- highest temperature at lowest baryon density
  ⇨ colliders: RHIC @ BNL and LHC @ CERN
- moderate temperature at highest baryon density
  ⇨ fixed-target: FAIR @ GSI

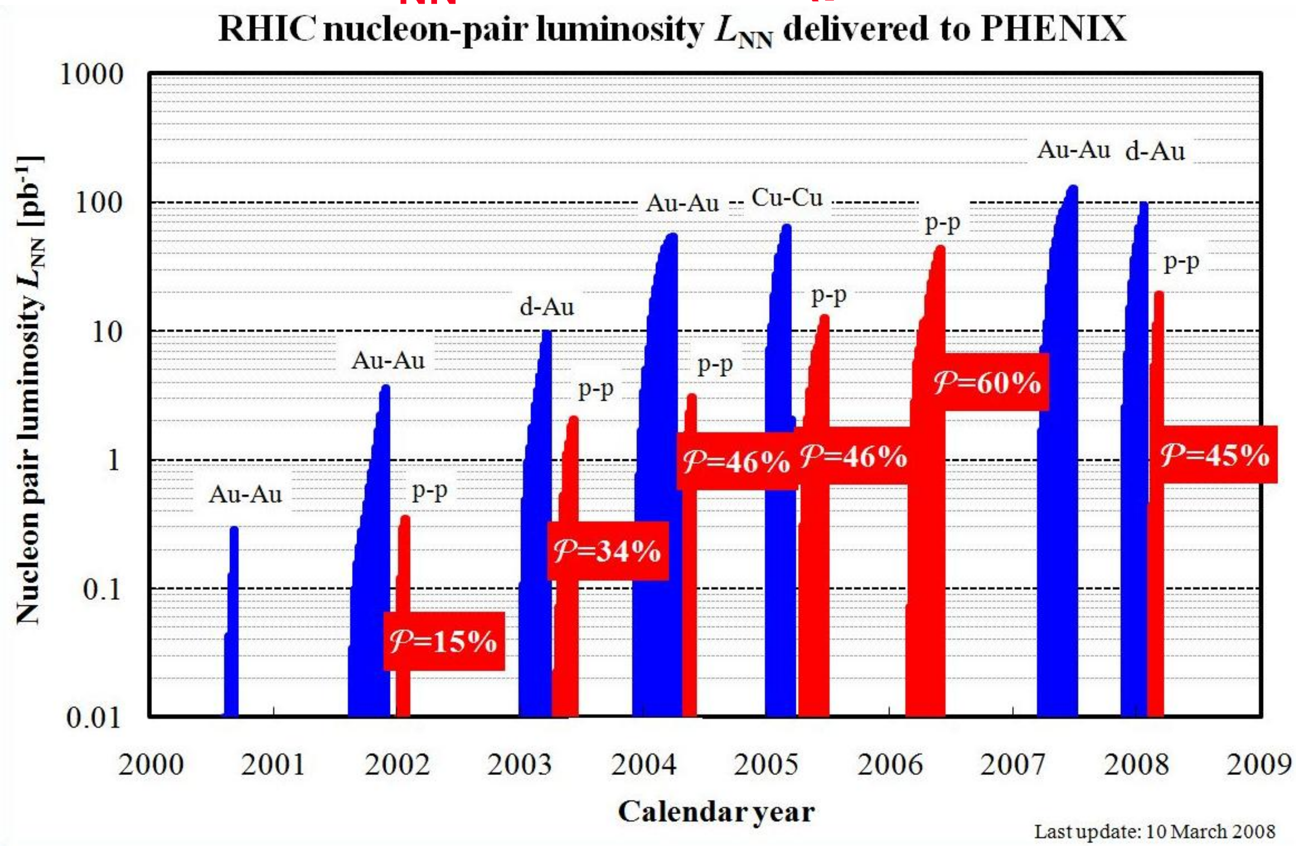
RHIC

- RHIC = Relativistic Heavy Ion Collider
- located at Brookhaven National Laboratory



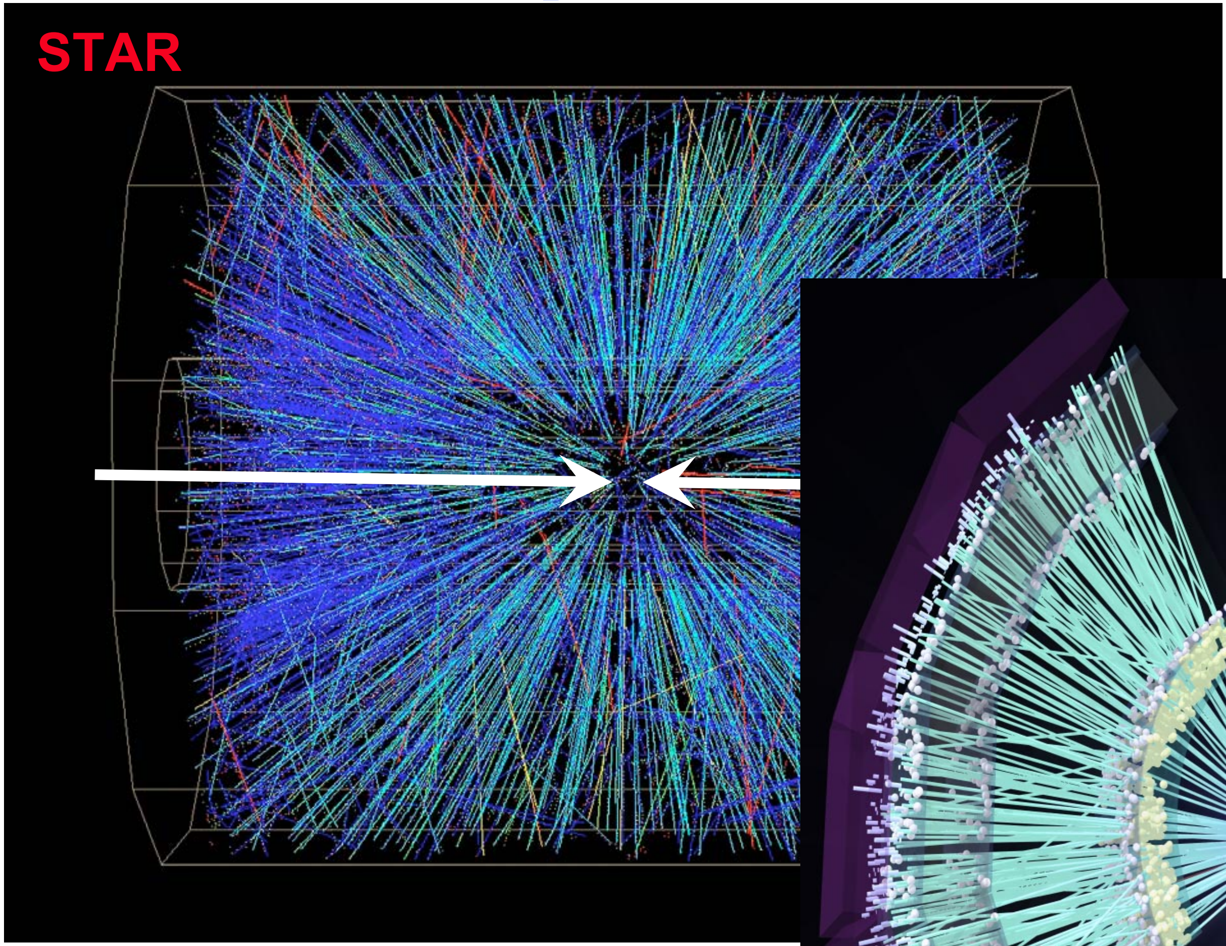
RHIC and its experiments

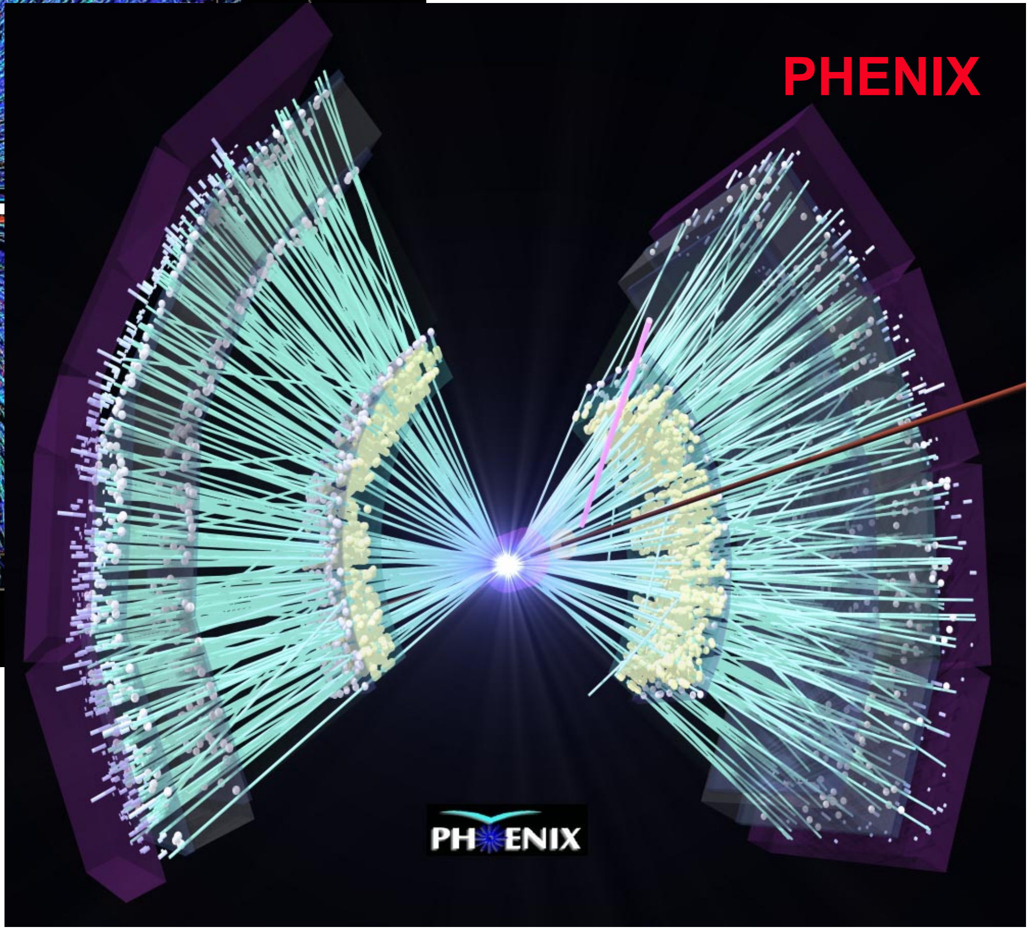
- heating of matter to T ~ 10^{12} K (~180 MeV)
  - RHIC (Relativistic Heavy-Ion Collider) located at Brookhaven National Laboratory
  - p+p: $\sqrt{s} \lesssim 500$ GeV (polarized beams!)
  - A+A: $\sqrt{s_{NN}} \lesssim 200$ GeV (per nucleon-nucleon pair)



- experiments with specific focus
  - BRAHMS (until Run-6)
  - PHOBOS (until Run-5)
- multi purpose experiments
  - PHENIX
  - STAR

The experimental challenge

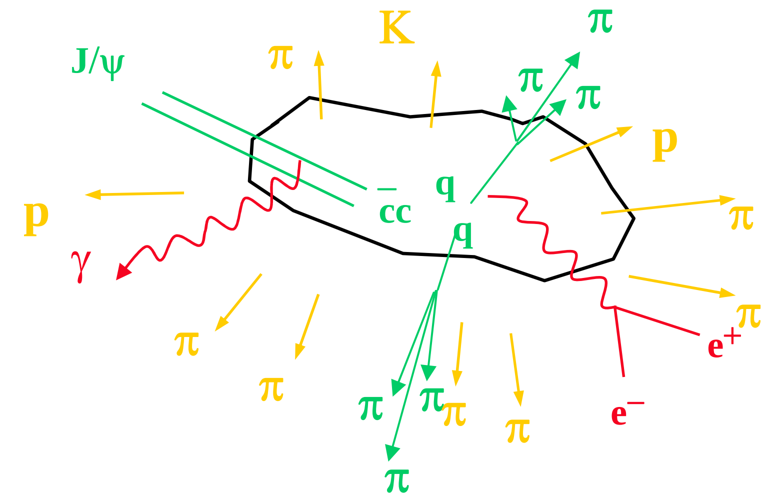




- **<u>ONE</u> central Au+Au collision at max. energy**
- **production of <u>MANY</u> secondary particles**

Different probes tell different stories

- investigate evolution of a system
  - that “lives” for ~10^{-22} s (~100 fm/c)
  - in a volume ~10^{-42} m^3 (~1000 fm^3)
  - with energy ~6 x 10^{-6} J (~40 TeV)



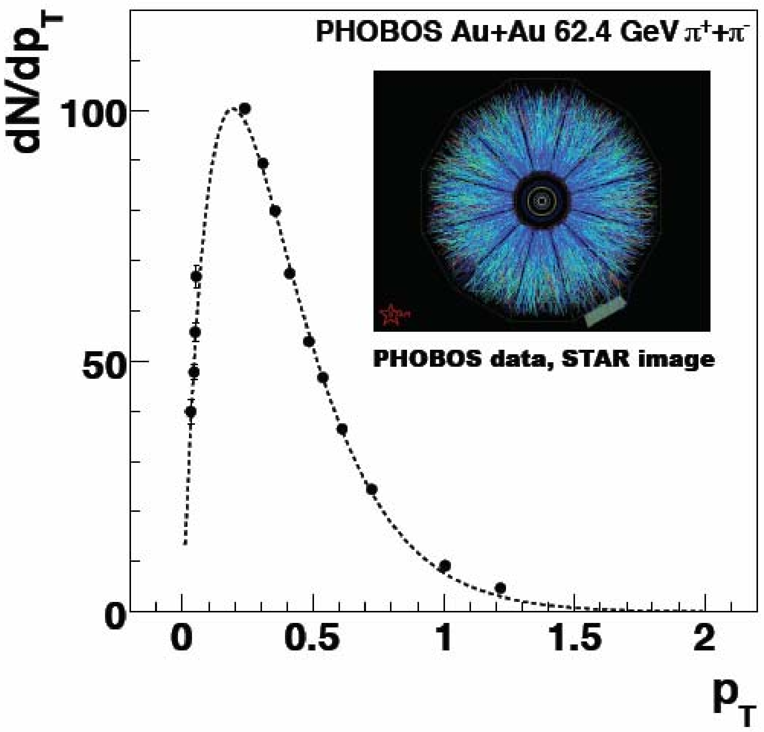
- hadrons: π, K, p, …
  - abundant, (mostly) final state
    - yields, spectra → energy density, thermalization, hadrochemistry
    - correlations, fluctuations, azimuthal asymmetries → collective behavior

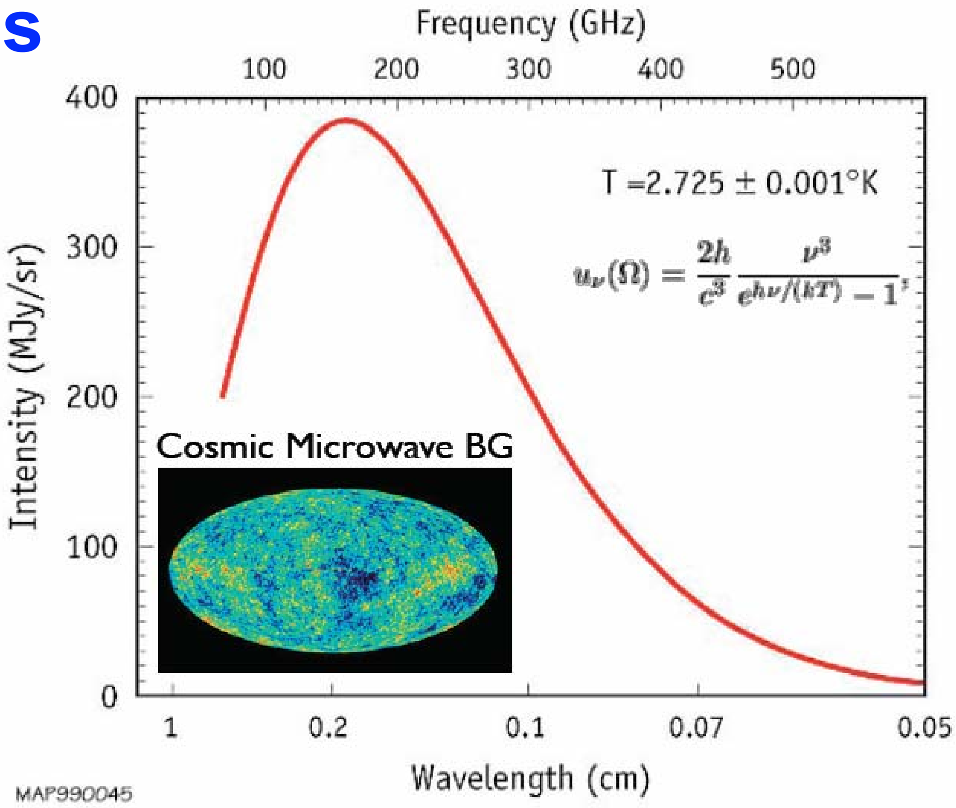
- “hard” probes: jets, heavy quarks, direct γ
  - rare, produced initially (before quark-gluon matter forms!)
    - probe hot and dense matter

- electromagnetic radiation: γ, e^+e^-, $\mu^+\mu^-$
  - rare, no strong interaction
    - probe all time scales
    - initial temperature

Final state blackbody radiation

- do the huge yields of various hadron species in the final state reflect a THERMAL distribution?
- kinematic distributions

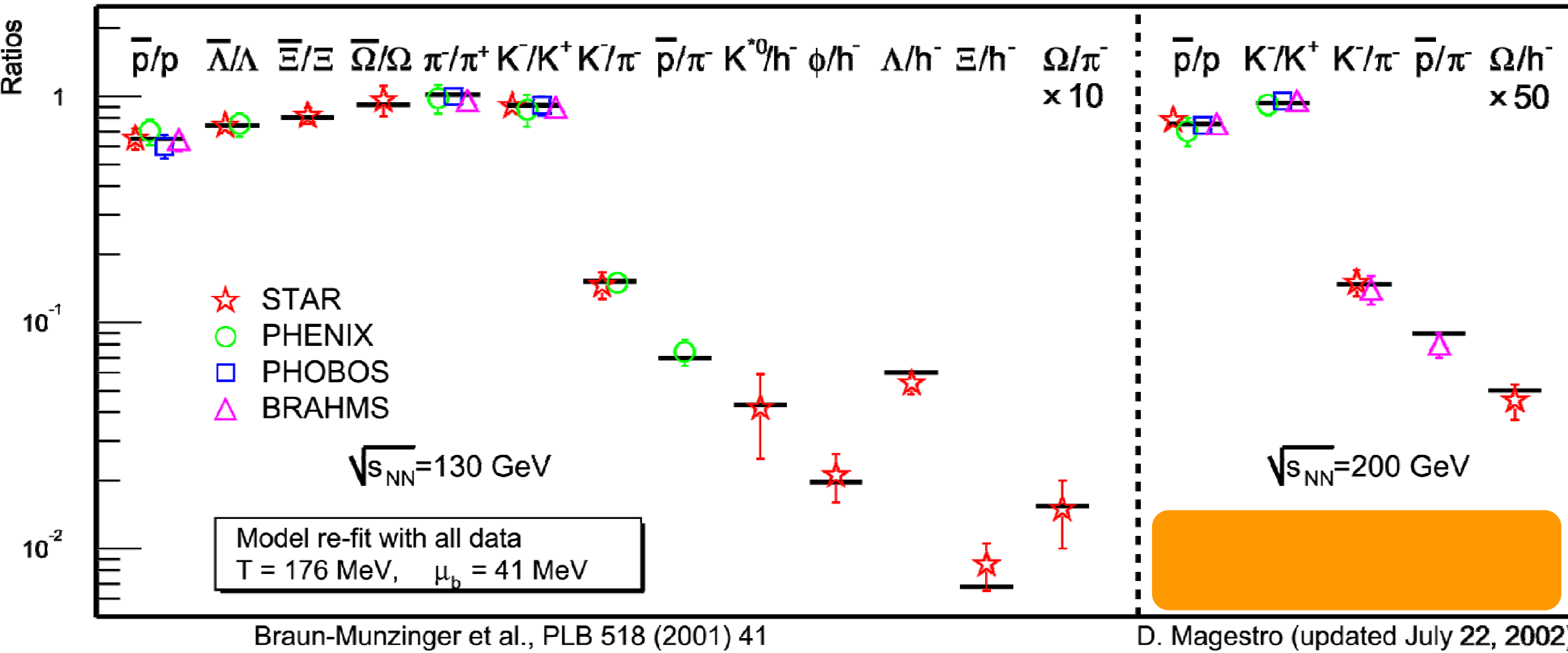




- spectrum of particles emitted from heavy-ion collisions at RHIC: nearly a (hadronic) blackbody!

Final state hadrochemistry

- do the huge yields of various hadron species in the final state reflect a THERMAL distribution?
- abundances in hadrochemical equilibrium



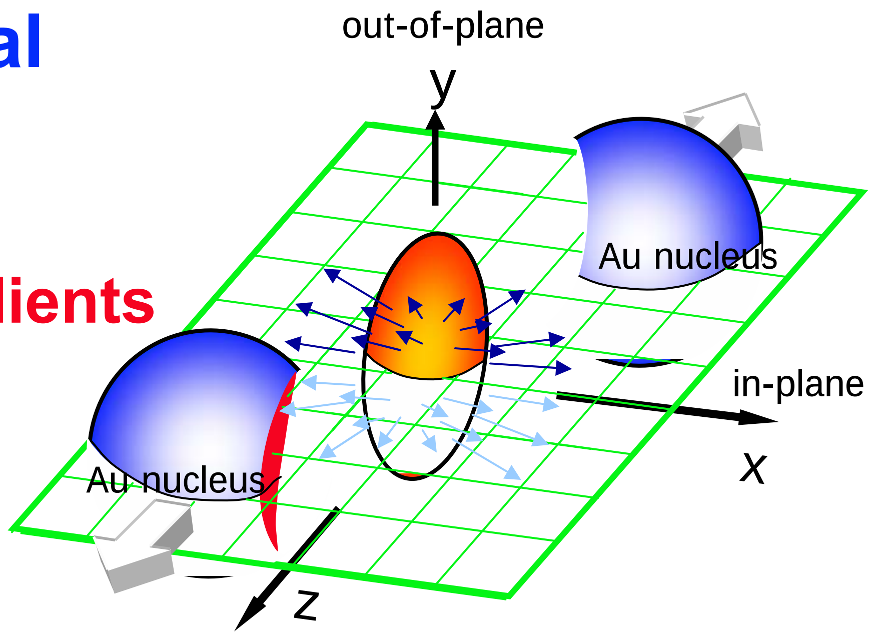
- final state: hadron gas close to phase boundary

Elliptic flow → early thermalization

- initial state of non-central Au+Au collision
  - spatial asymmetry
  - asymmetric pressure gradients
- translates into
  - momentum anisotropy in final state
  - Fourier expansion

$$E\frac{d^3N}{d^3p}=\frac{d^3N}{p_T d\varphi dp_T dy}\sum_{n=0}^{\infty}2v_n\cos\left(n\left(\varphi-\Psi_R\right)\right)$$

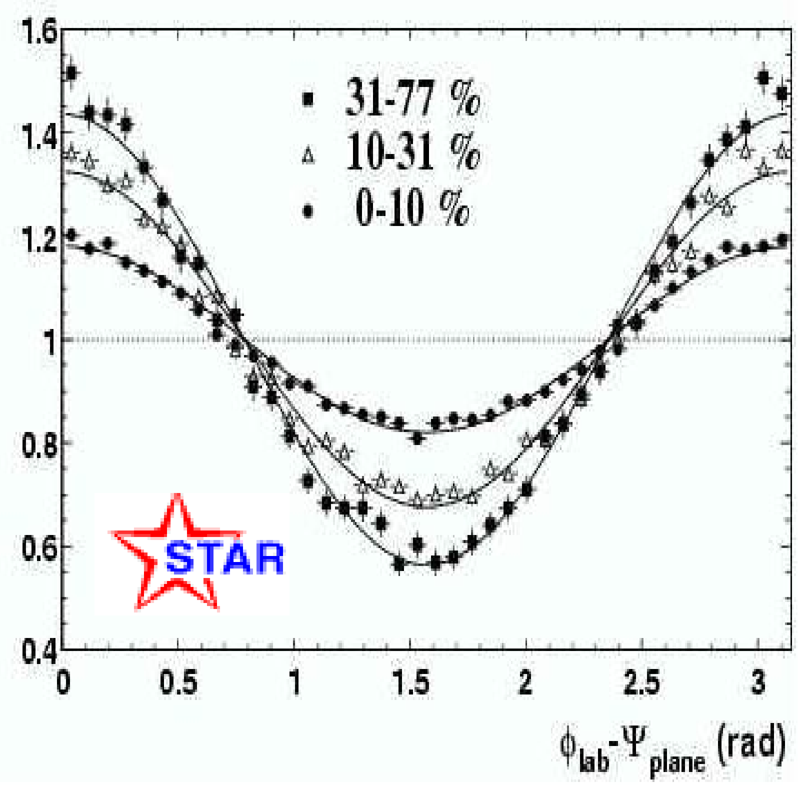
  - elliptic flow strength $v_2=\left\langle\cos 2\left(\varphi-\Psi_R\right)\right\rangle$
- shape "washes out" during expansion, *i.e.* elliptic flow is "self quenching"
  - v_2 reflects early interactions and pressure gradients

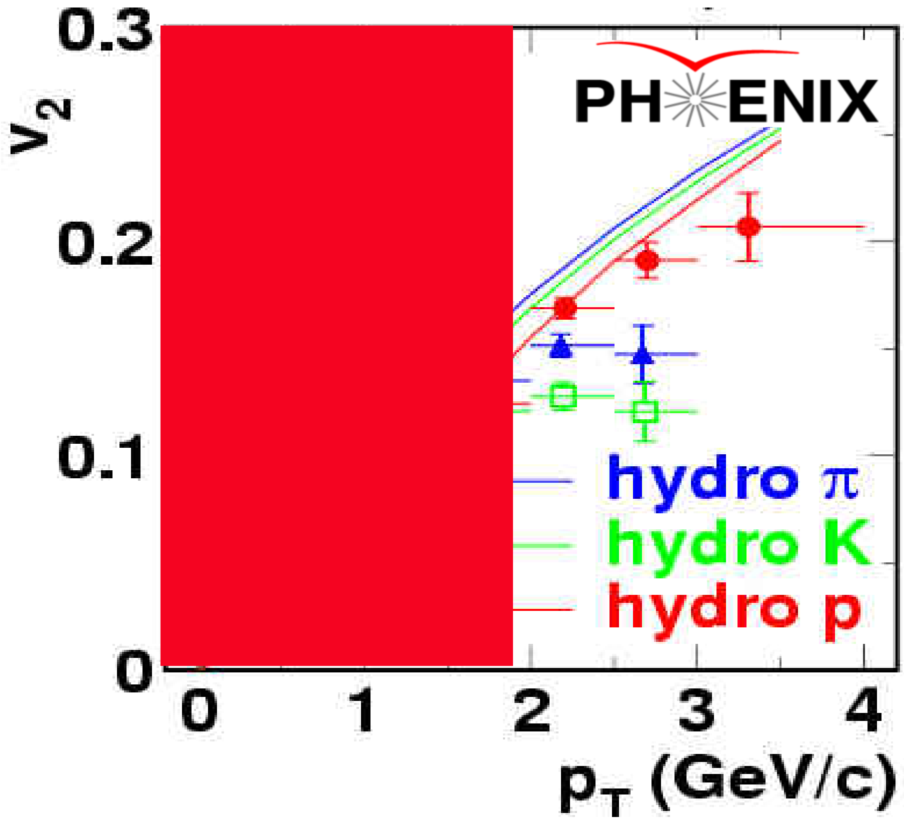


Non-central Collisions

Hadron v_2 and hydrodynamics

- observation at RHIC
  - the asymmetry of the azimuthal distribution of hadrons w.r.t the reaction plane is HUGE



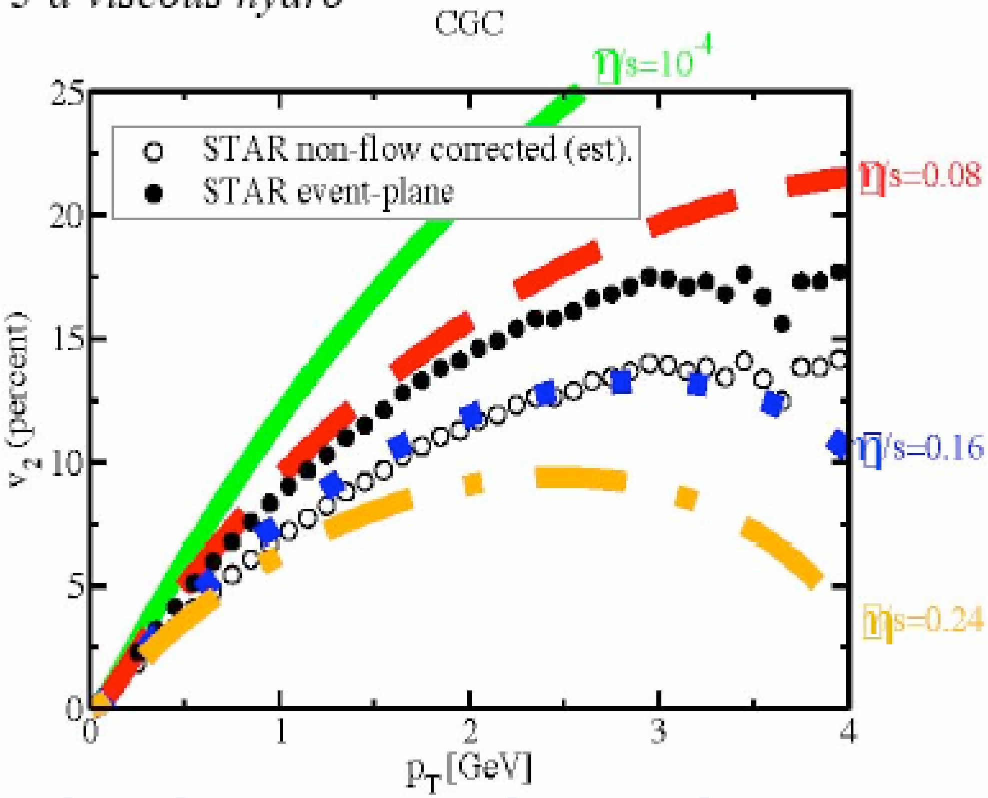


  - the fine structure $v_2(p_T)$ for different mass hadrons is in reasonable agreement with ideal hydrodynamics

(PHENIX: PRL 91(2003)182301, Huovinen et al.: PLB 503(2001)58)

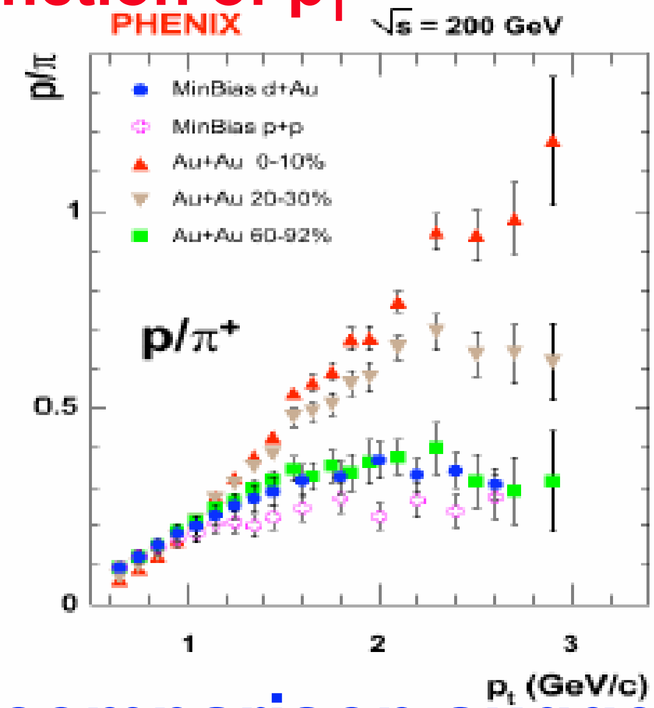
v_2 at RHIC and viscous hydro

Luzum & Romatschke, arXiV:0804.4015
3-d viscous hydro



- hadron species mix calculated for chemical freeze-out

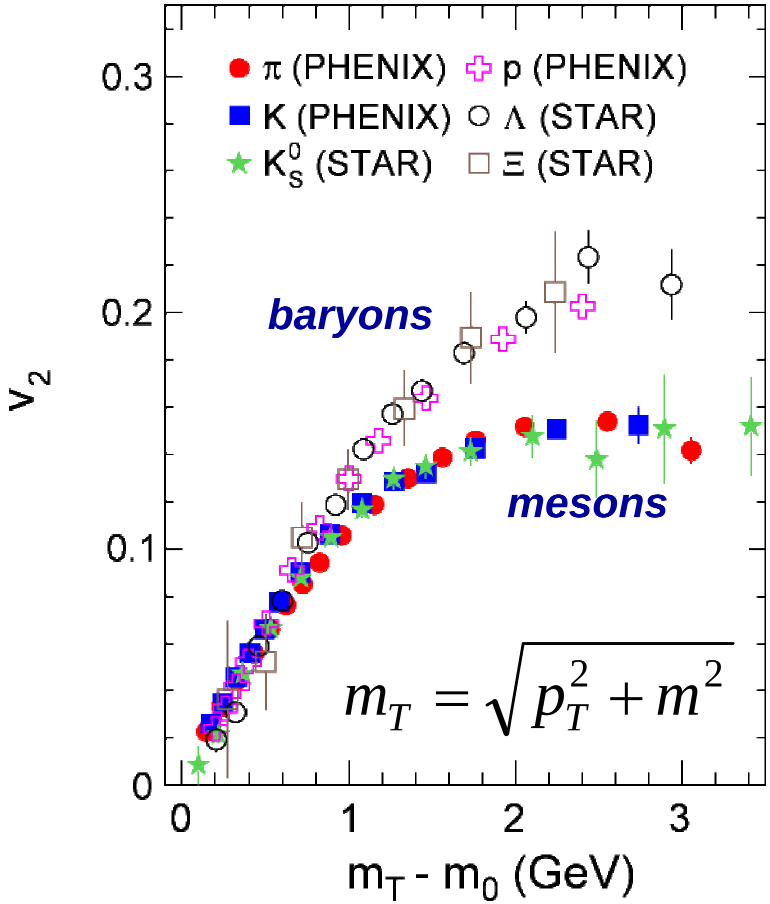
- careful
  - deviations from chemical freeze-out particle mix as function of p_T

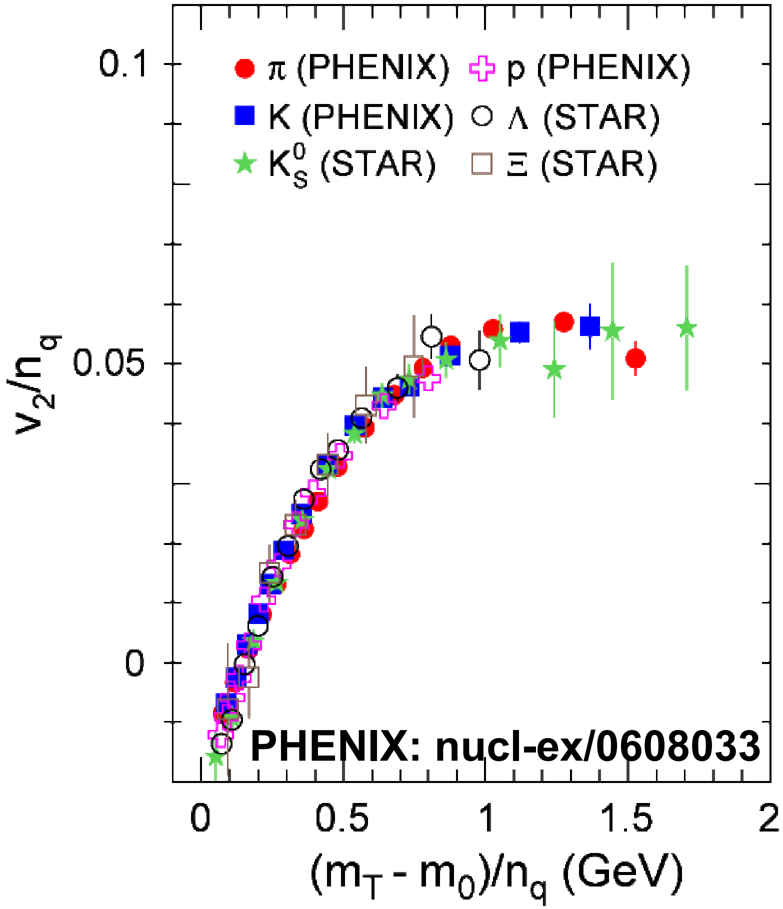


- ALL comparison suggest small viscosity
  → strong coupling!

v_2 scaling: what is flowing?

- scaling flow parameters by quark content

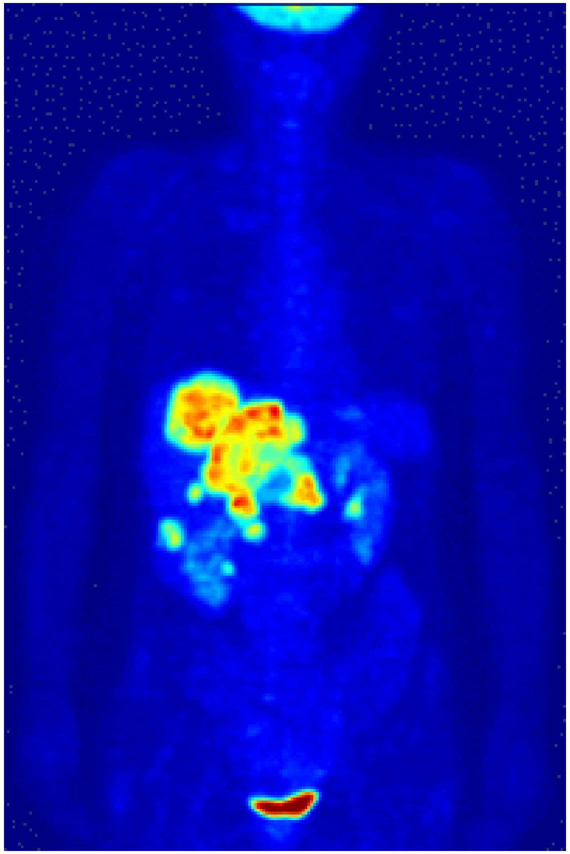




➔ particles flow as if frozen out from a flowing soup of constituent quarks

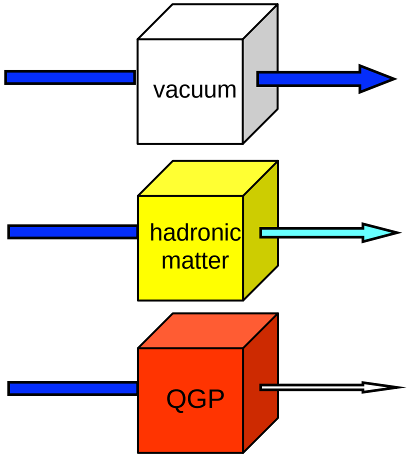
Looking into the medium

- tomography - one way to establish properties of a system
  - calibrated probe ($e^{\pm}$, X-rays with known beam energy & direction)
  - calibrated interaction (known interaction mechanism!)
  - suppression/absorption pattern reveals details about the interior

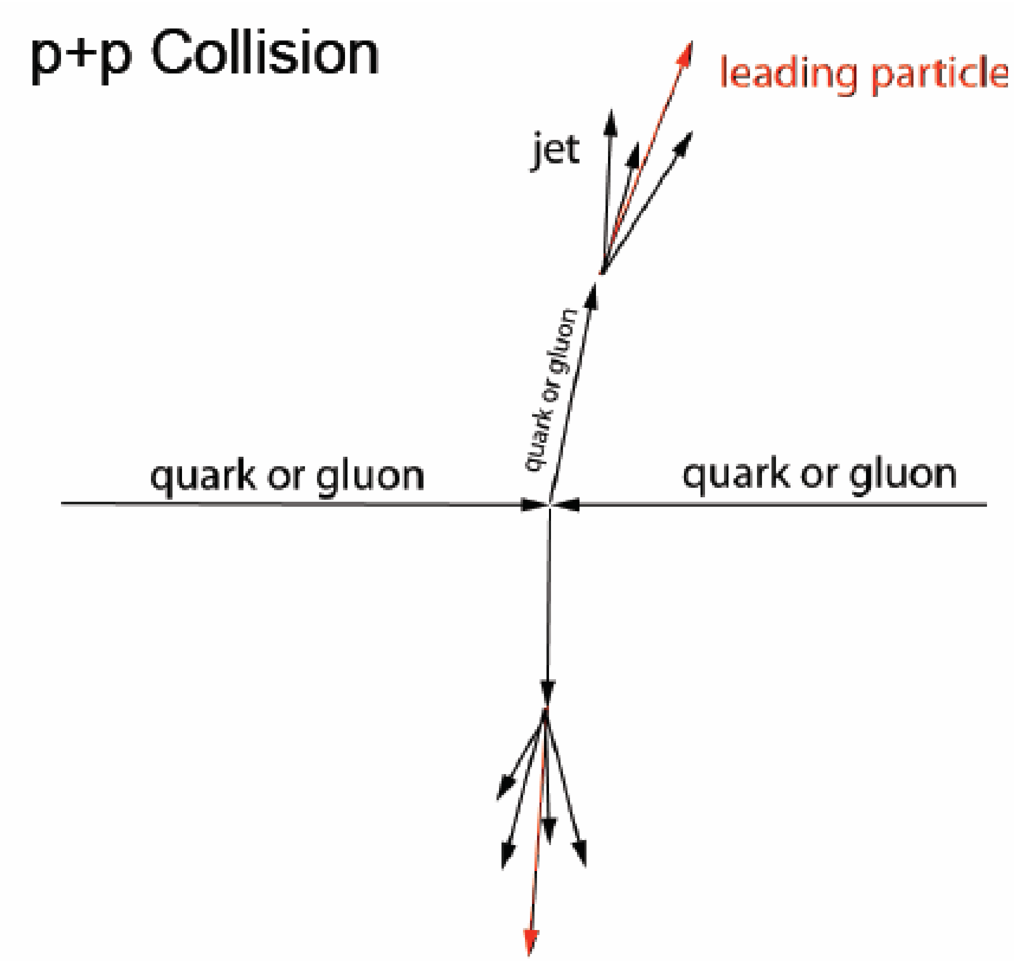


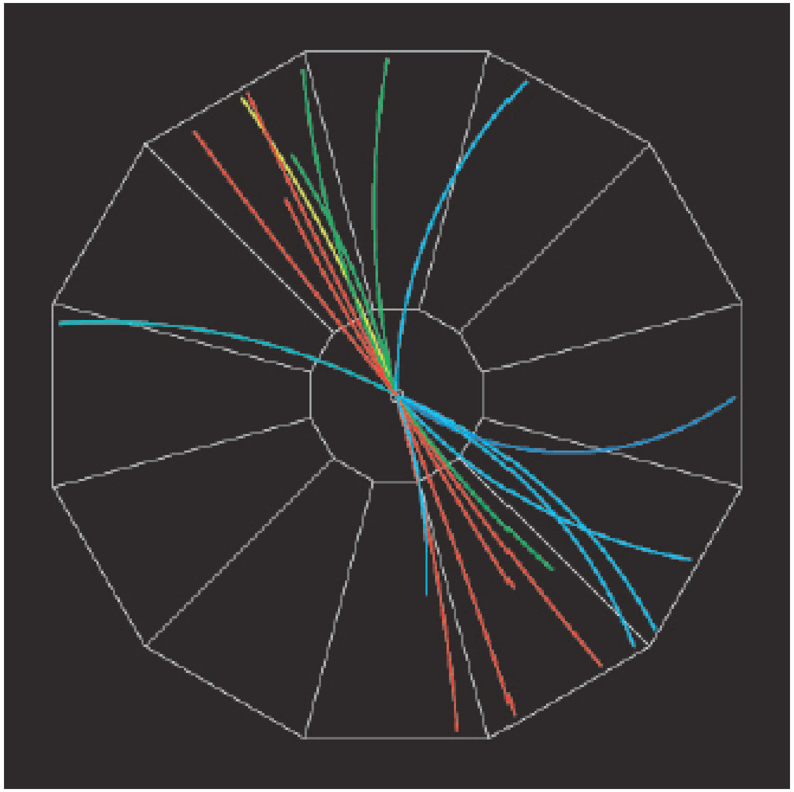
- tomography at RHIC
  - probe has to be "auto generated"
    → initial state hard parton scattering

- good probes
  - well calibrated in pp collisions
  - slightly affected and well understood in hadronic matter
  - strongly affected in a partonic medium

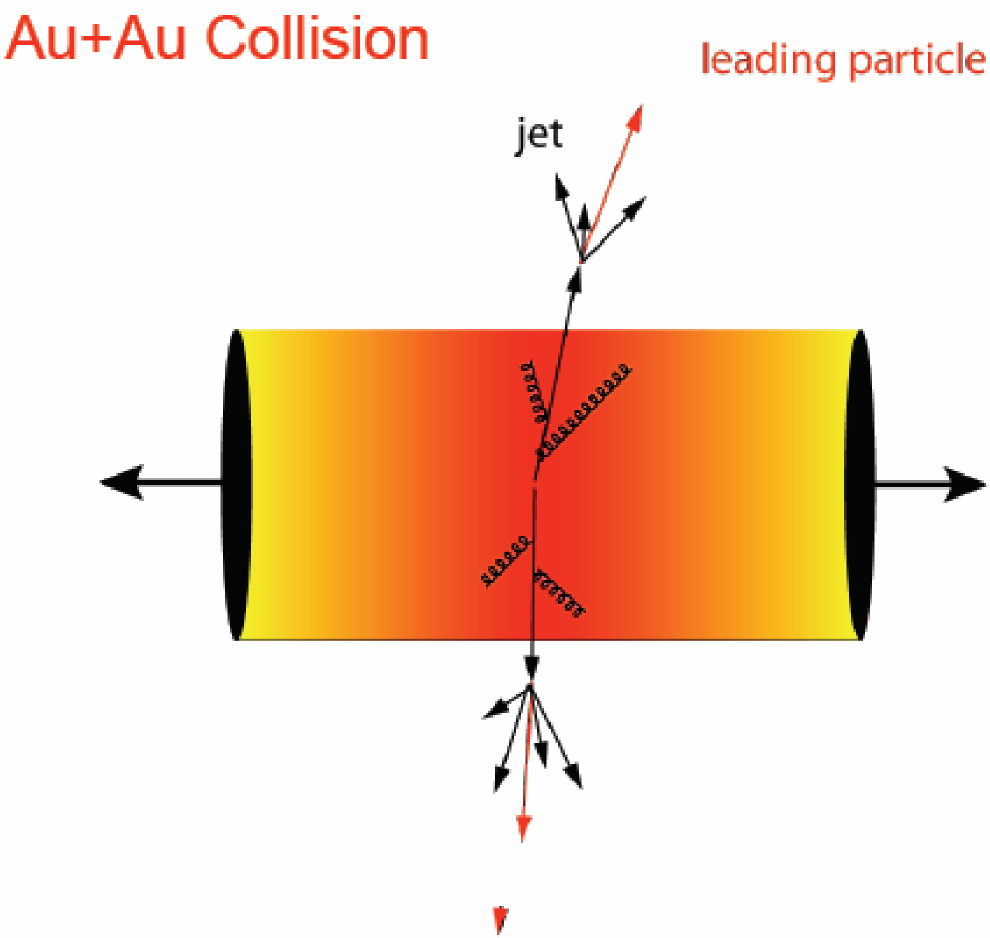


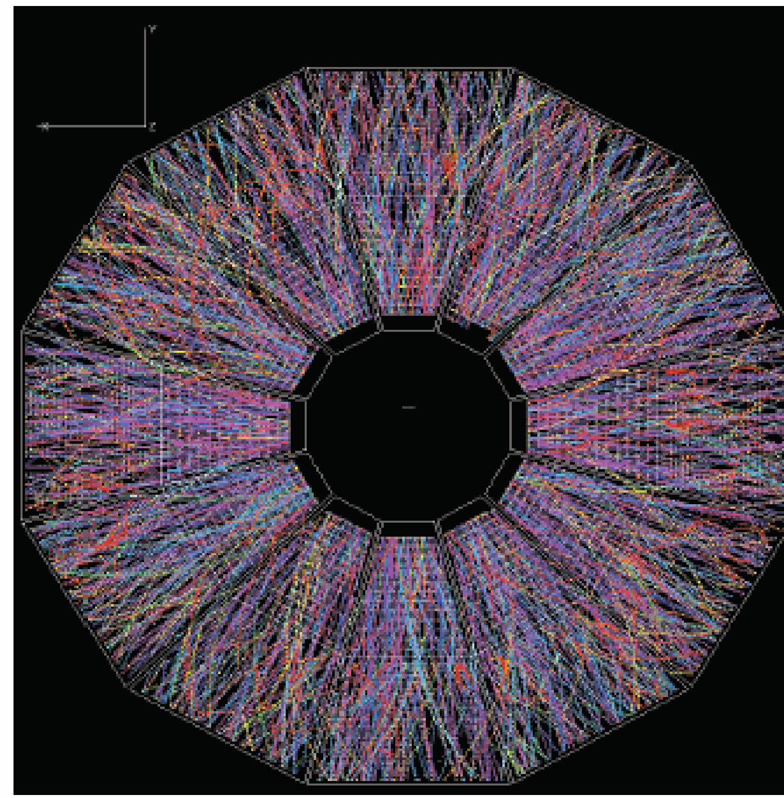
Probing dense matter: calibration





Probing dense matter: tomography

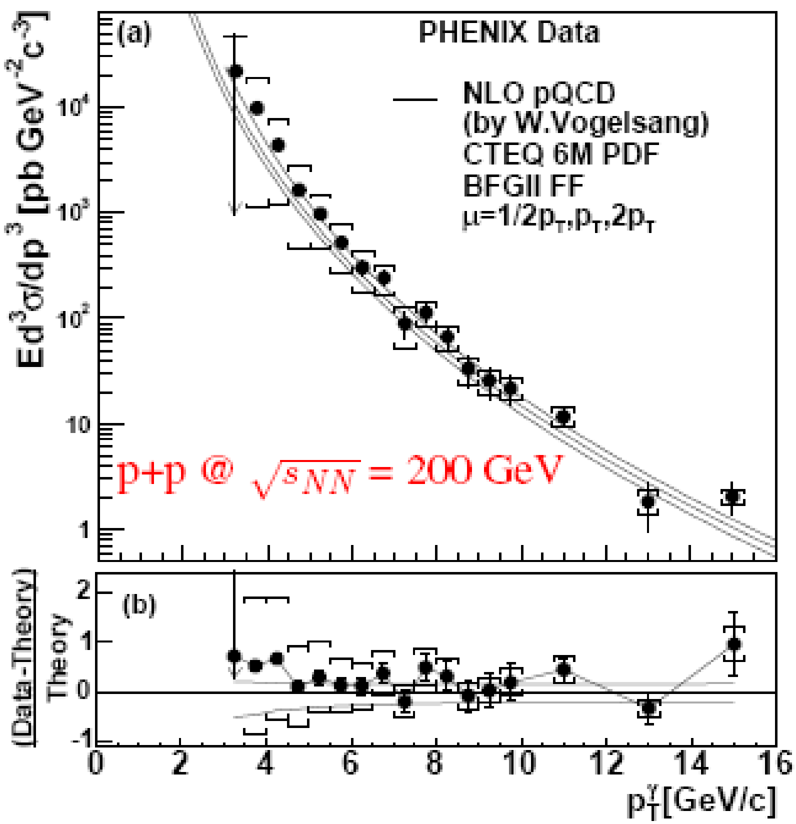


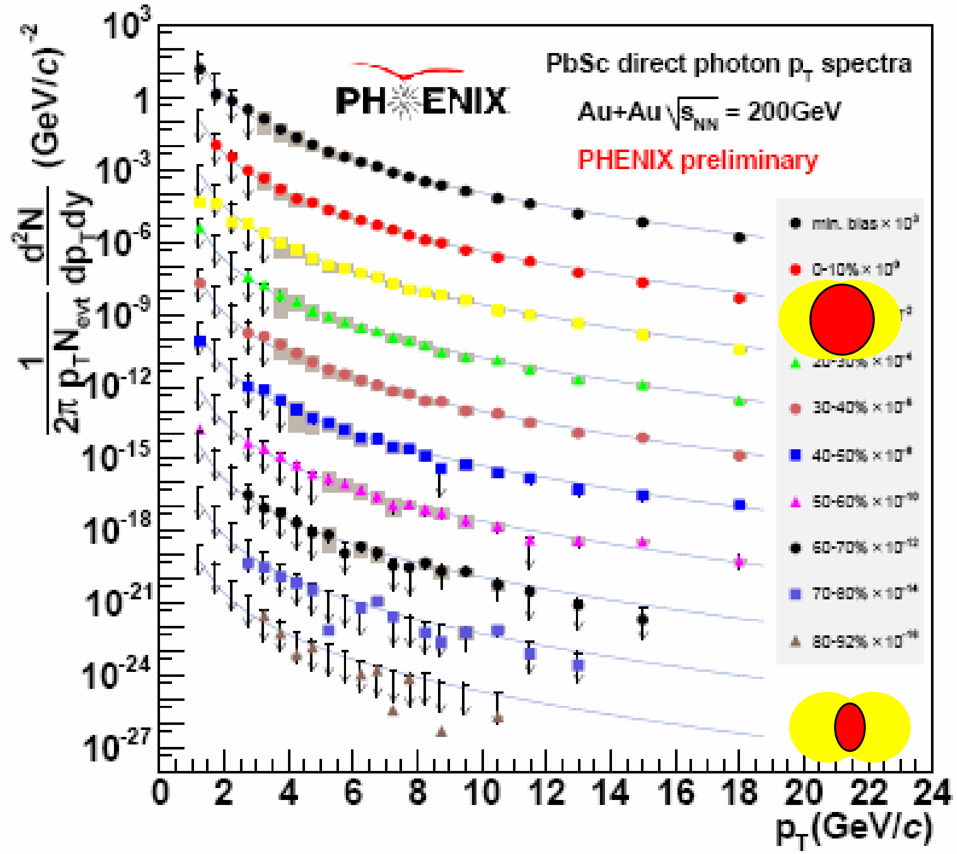


- **how to measure this?**
  - **start with a probe unaffected by the medium!**

Direct photons at $\sqrt{s_{NN}}$ = 200 GeV

- photons from quark-gluon Compton scattering



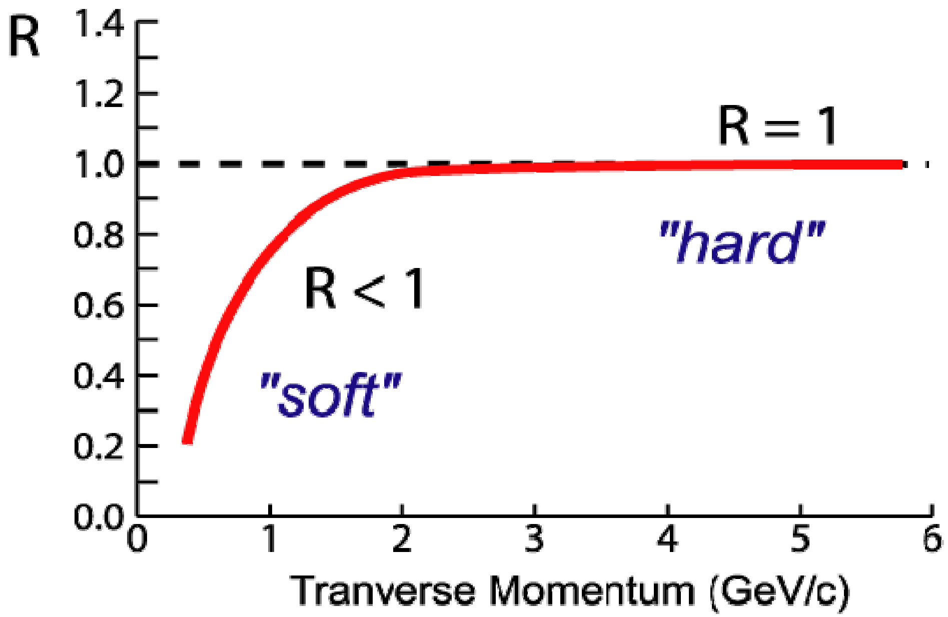


- direct photons are a calibrated probe
- no strong final state interaction: as expected!

Hadrons (π^0) at $\sqrt{s_{NN}}$ = 200 GeV

- pQCD in agreement with data from p+p collisions
- nuclear modification factor:

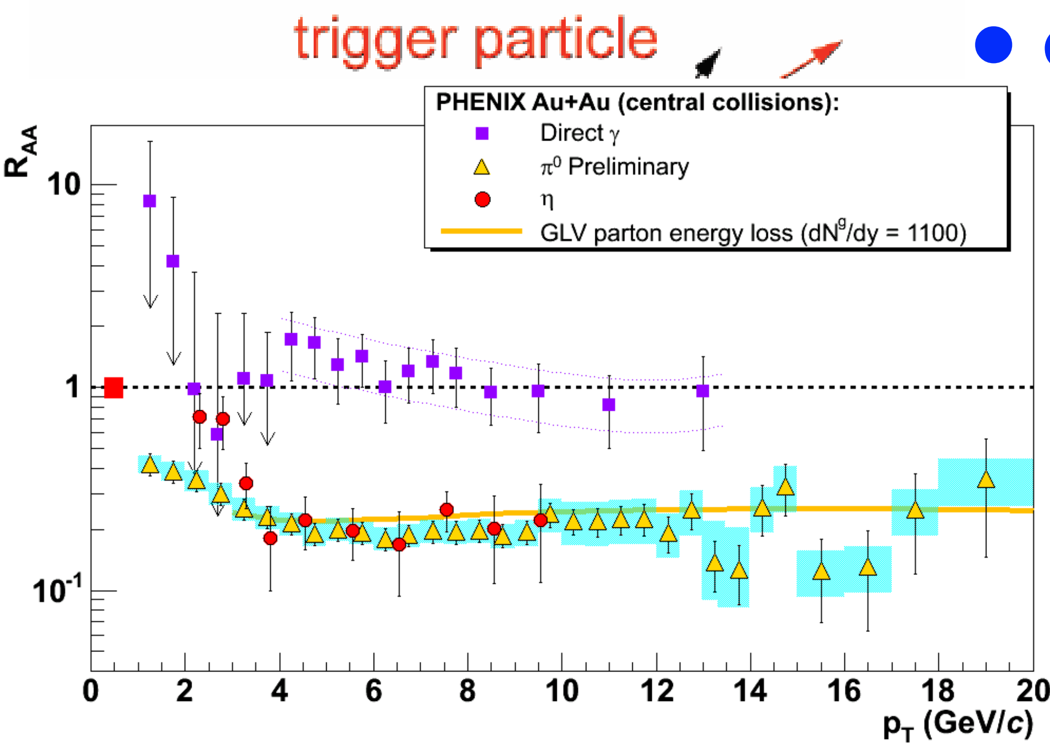
$$R_{AA} = \frac{Yield\ in\ Au+Au}{N_{binary} \times Yield\ in\ p+p}$$

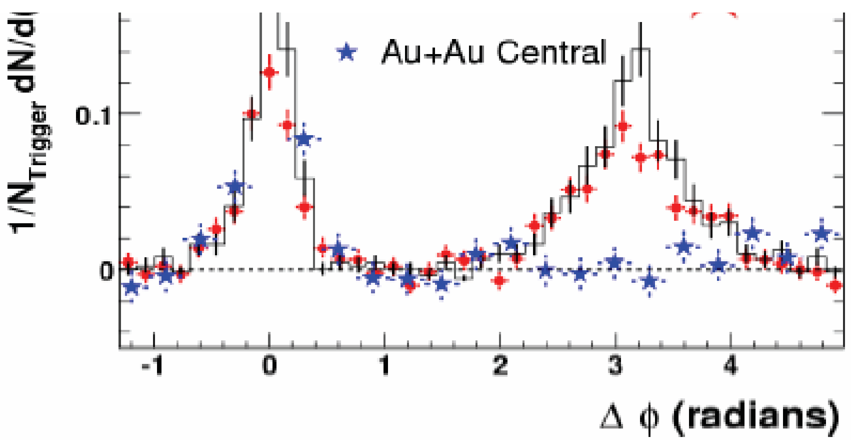


- no medium effect
  - $R_{AA} < 1$ @ low p_T ("soft" region)
  - $R_{AA} = 1$ @ high p_T ("hard" region)
- suppression
  - $R_{AA} < 1$ @ high p_T

- limiting factor for minimum R_{AA}: surface emission

High p_T suppression: opaque matter

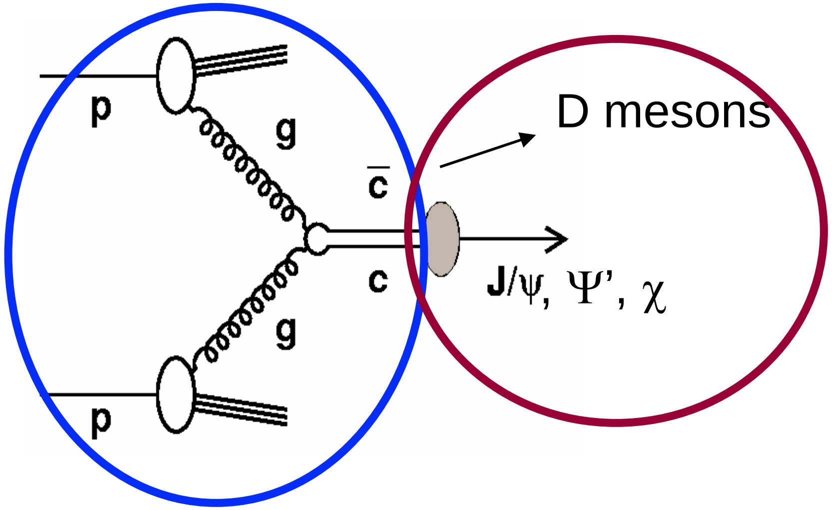




- **observations at RHIC**
  - **photons are not suppressed**
    - no strong interaction
    - binary scaling is OK
  - **hadron suppression**
    - no suppression in peripheral collisions → no dense medium
    - HUGE suppression in central collisions
  - **azimuthal correlation function**
    - complete absence of "away side" jet → absorption in medium
  - **(systematic studies of medium response)**

Heavy-quark production

- heavy quarks ($c\bar{c}$, $b\bar{b}$) from hadronic collisions
  - hard process ($m_q >> \Lambda_{QCD}$)
    - at leading order (LO):
      - quark-antiquark annihilation
      - gluon fusion
    - higher order processes important towards large $\sqrt{s}$

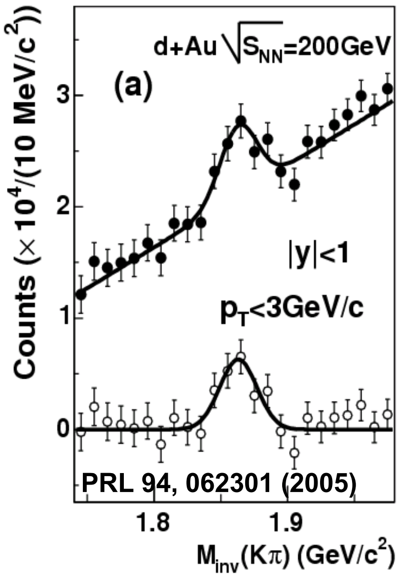


- generic hard-probe study
  - calibrate heavy flavor production in pp collisions
  - probe the medium
    - interaction with medium ⇨ energy loss, flow?
  - formation of <u>bound</u> states: quarkonia (J/ψ, Υ)

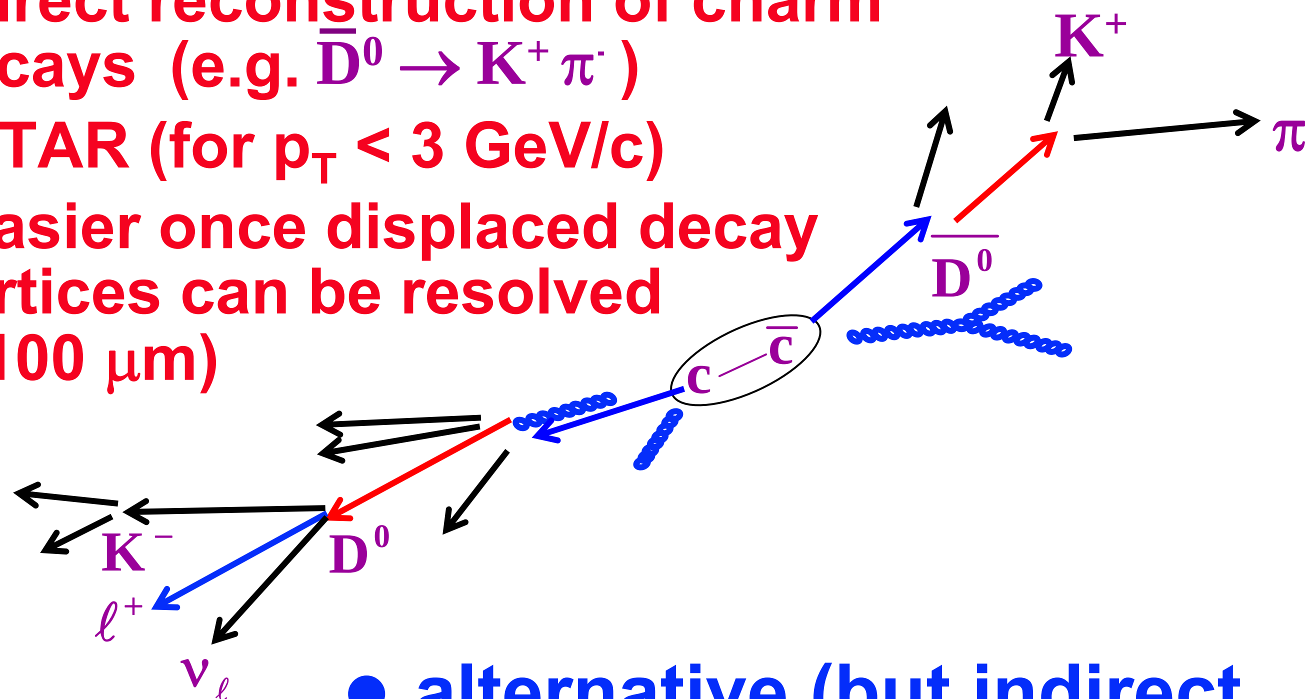
➔ complementary to other hard probes

Charm measurements at RHIC

- ideal (but very challenging in HI environment)



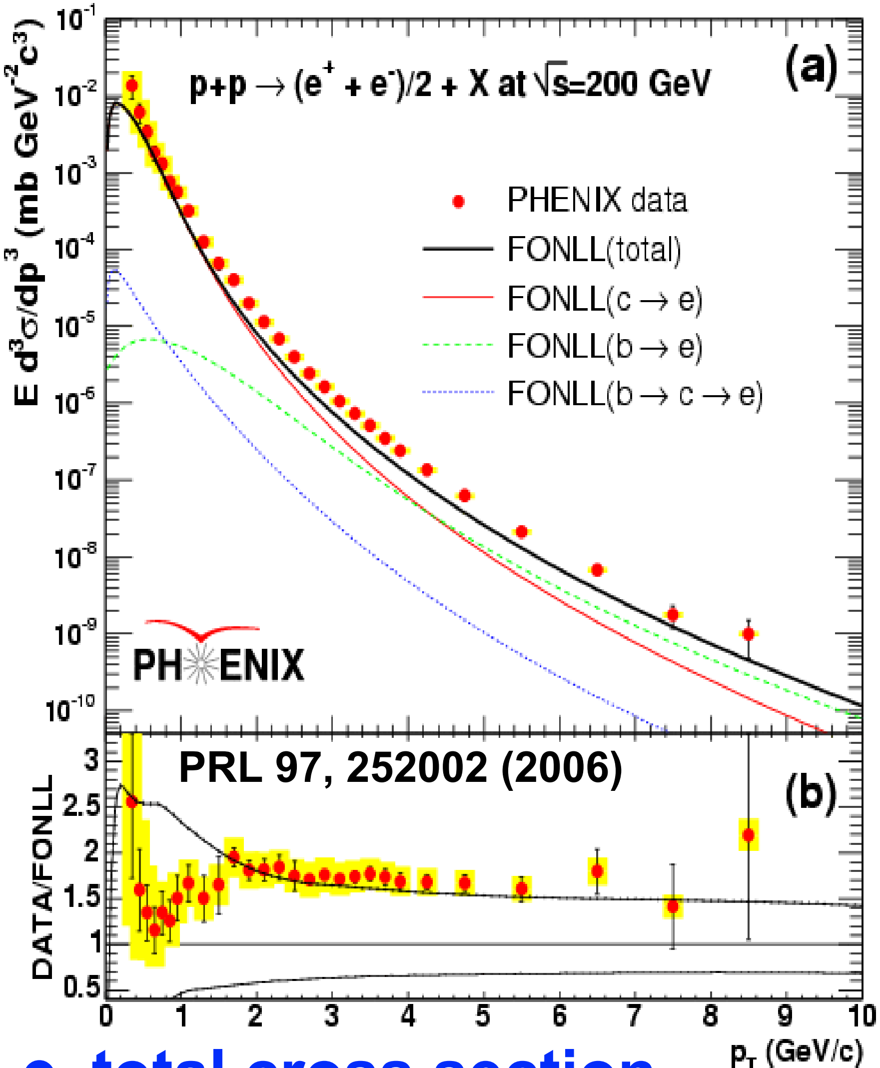
- direct reconstruction of charm decays (e.g. $\bar{D}^0 \rightarrow K^+ \pi^-$)
- STAR (for p_T < 3 GeV/c)
- easier once displaced decay vertices can be resolved (~100 μm)



Meson	$D^\pm$ (D^0)
Mass	1.87 (1.87) GeV
BR D^0 --> $K\pi$	(3.85 ± 0.10) %
BR D --> e +X	17.2 (6.7) %
BR D --> μ +X	17.2 (6.6) %

- alternative (but indirect, and still challenging)
  - contribution of semileptonic decays to lepton spectra
  - PHENIX & STAR

$e^{\pm}$ from heavy flavor in p+p ($\sqrt{s}$=200 GeV)

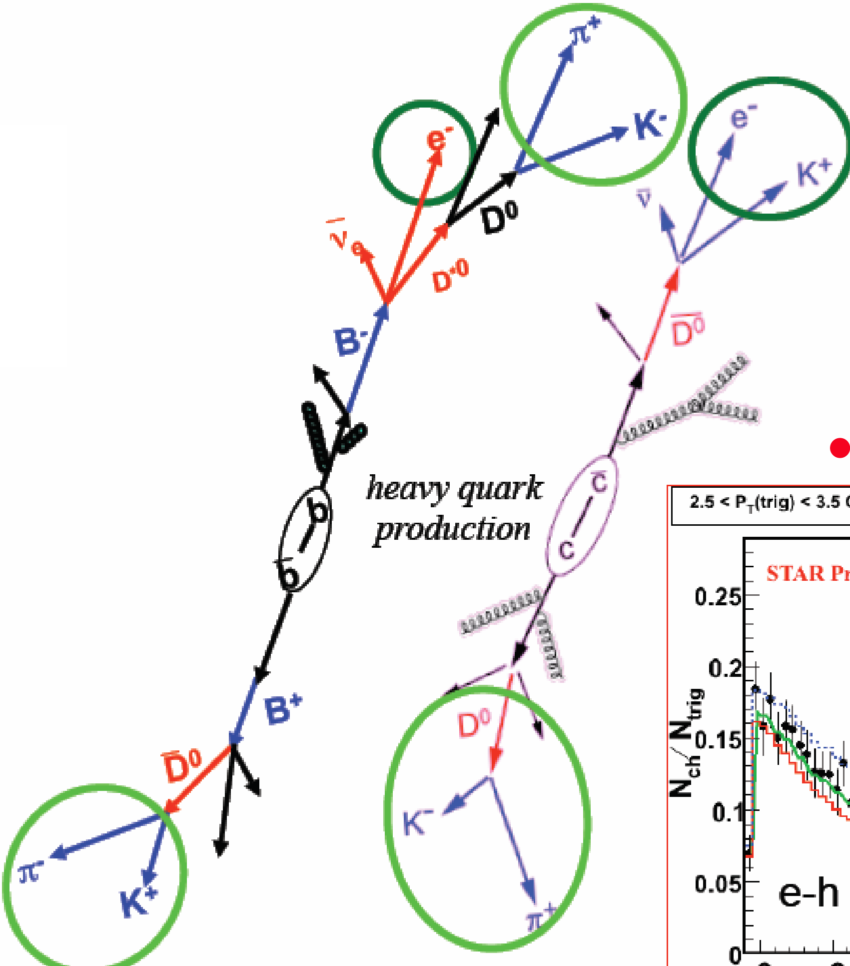


- **non-photonic $e^{\pm}$ from $c \rightarrow e^{\pm}$ and $b \rightarrow e^{\pm}$**
  - **compare with FONLL**
    - **Fixed Order Next-to-Leading Log pQCD**
      (M. Cacciari, P. Nason, R. Vogt PRL95,122001 (2005))
    - **data ~ 2 x FONLL**
      - **seen also in charm yields at**
        - **DESY (photoproduction)**
        - **FNAL (hadroproduction)**
    - **consistent within large uncertainties**
  - **bottom becomes important at high p_T!**

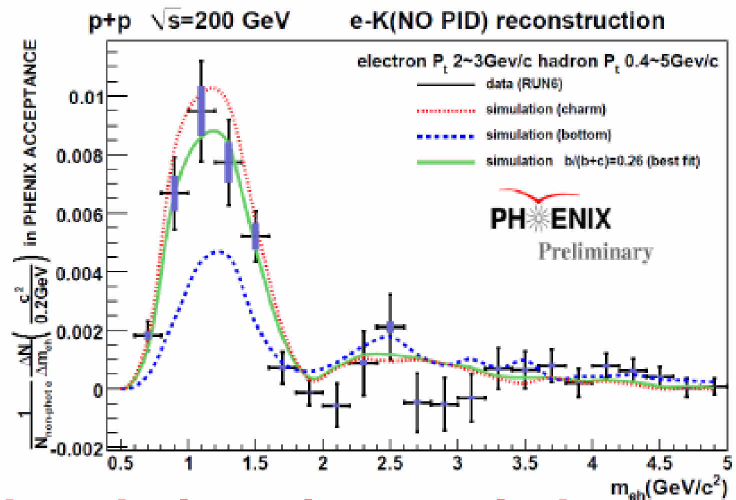
- **total cross section**
  - σ_{cc}= 567 ± 57(stat) ± 224(sys) μb

Separating c→e from b→e

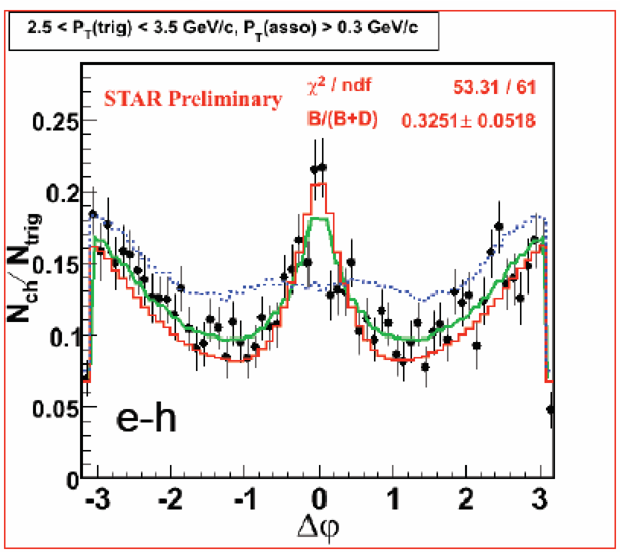
- **electron-hadron correlations**
  - **charm and bottom are different**

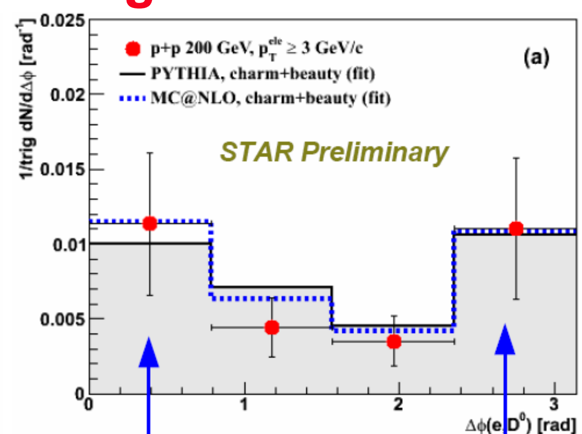


•e-h charge correlation & m_{inv}



•e-h, e-D^0 azimuthal angle correlation





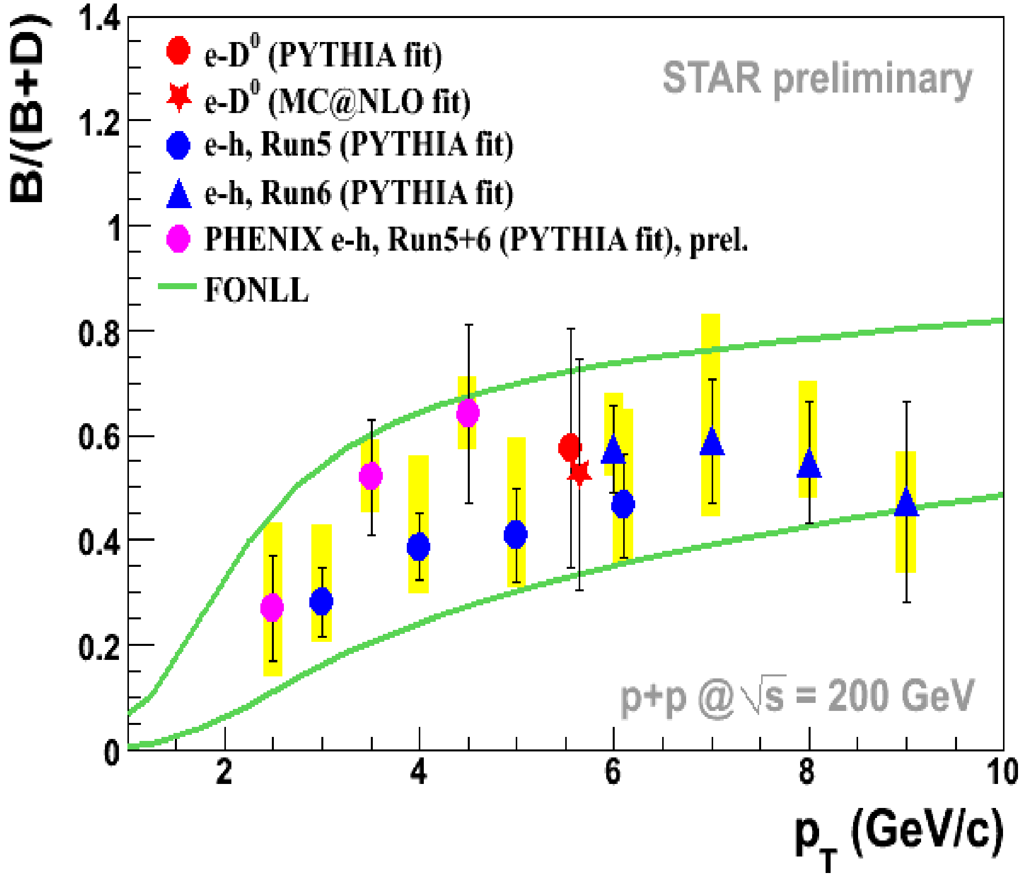
Essentially from B decay

Charm + Bottom decay

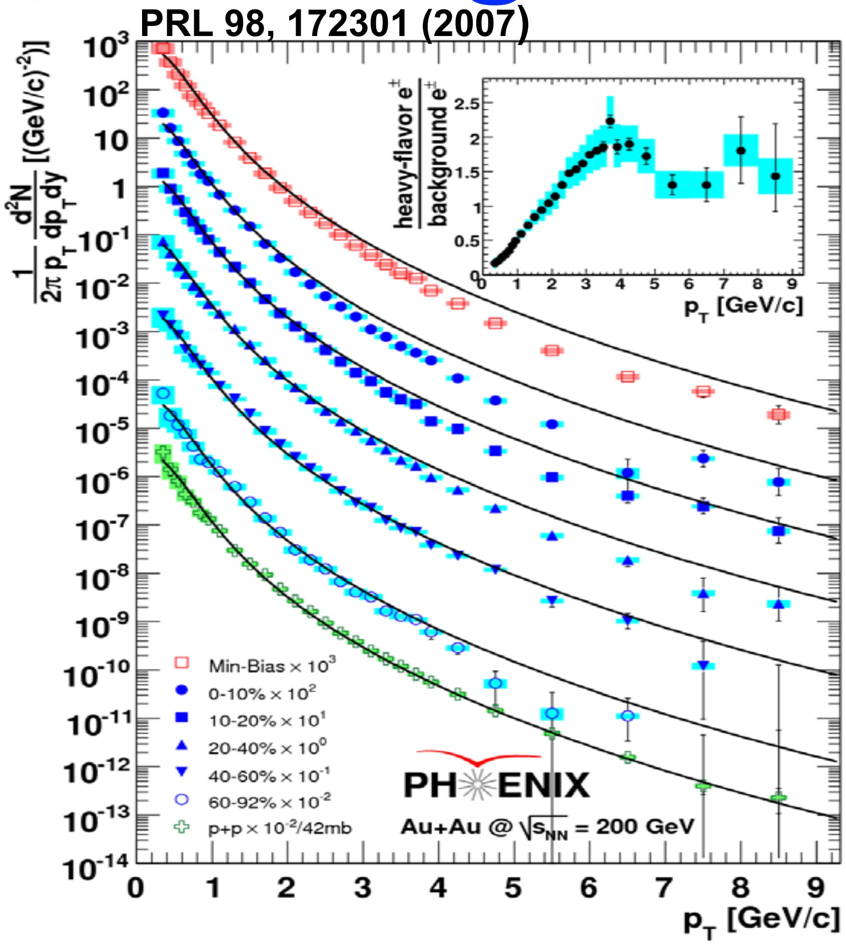
B contribution to e$^{\pm}$ spectra

- consistent with FONLL
- large uncertainties (experiment & theory)

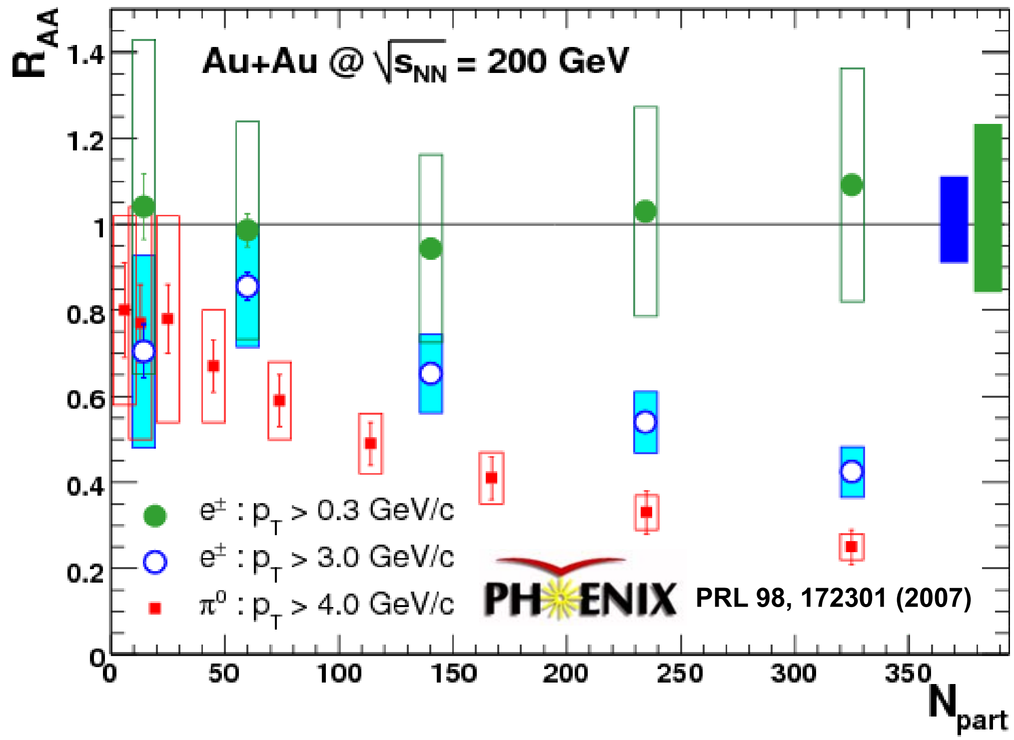
  → need better data to disentangle contributions



Probing the medium in Au+Au



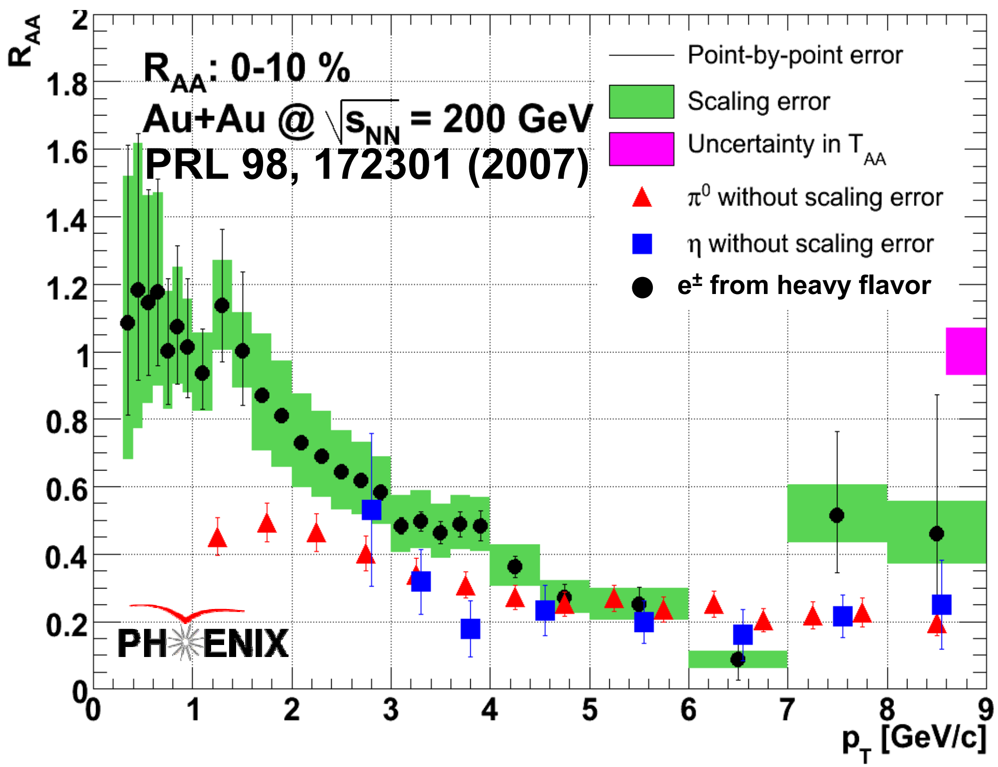
$$R_{AA} = \frac{Yield\ in\ Au+Au}{N_{binary} \times Yield\ in\ p+p}$$

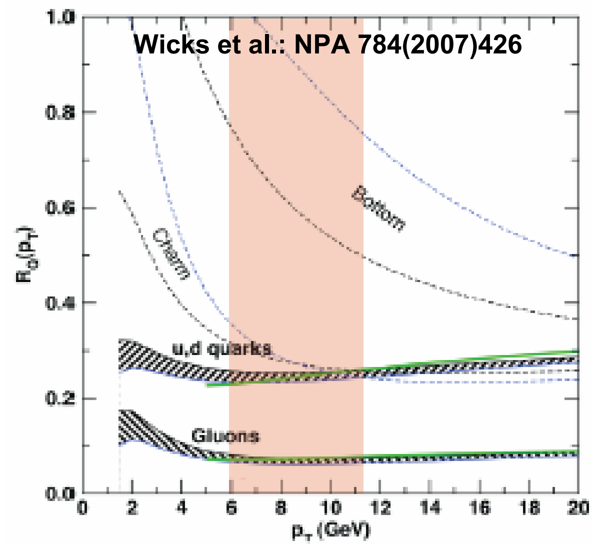


- binary scaling of total $e^{\pm}$ yield from heavy-flavor decays
- high p_T $e^{\pm}$ suppression increasing with centrality
  - footprint of medium effects; similar to π^0 (a big surprise)

Nuclear modification factor R_{AA}

- heavy flavor compared with light hadrons



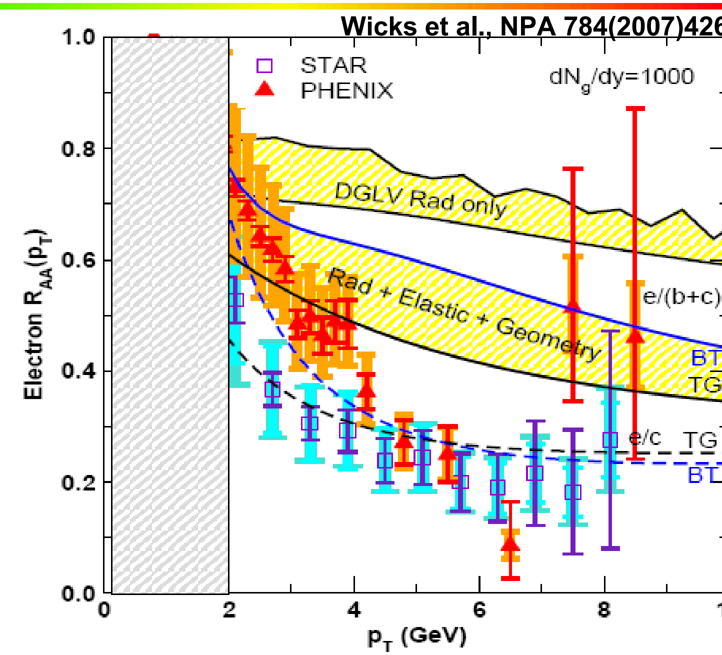


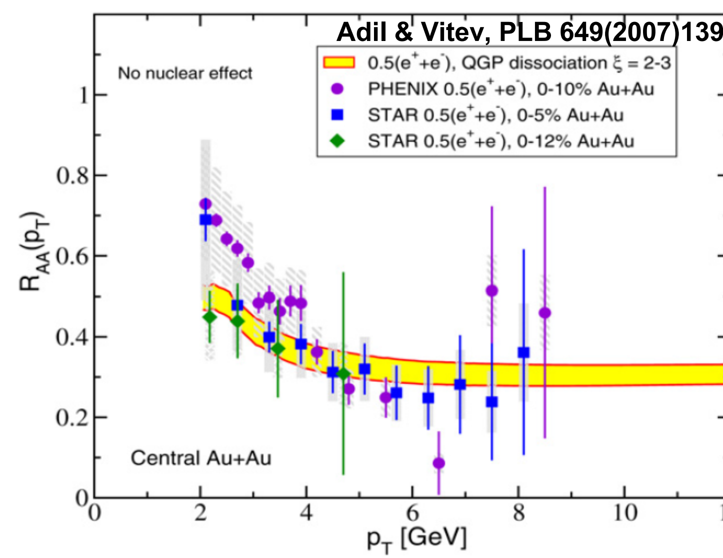
- careful:
  - kinematics: $p_T(e^{\pm}) < p_T(D)$
- intermediate p_T
  - indication for quark mass hierarchy as expected for radiative energy loss (Dokshitzer and Kharzeev, PLB 519(2001)199)
- highest p_T
  - $R_{AA}(e^{\pm}) \sim R_{AA}(\pi^0) \sim R_{AA}(\eta)$

- bottom contribution at high p_T?
  - is bottom suppressed?!
- needed: R_{AA} of identified charm and bottom hadrons

Energy-loss mechanism?

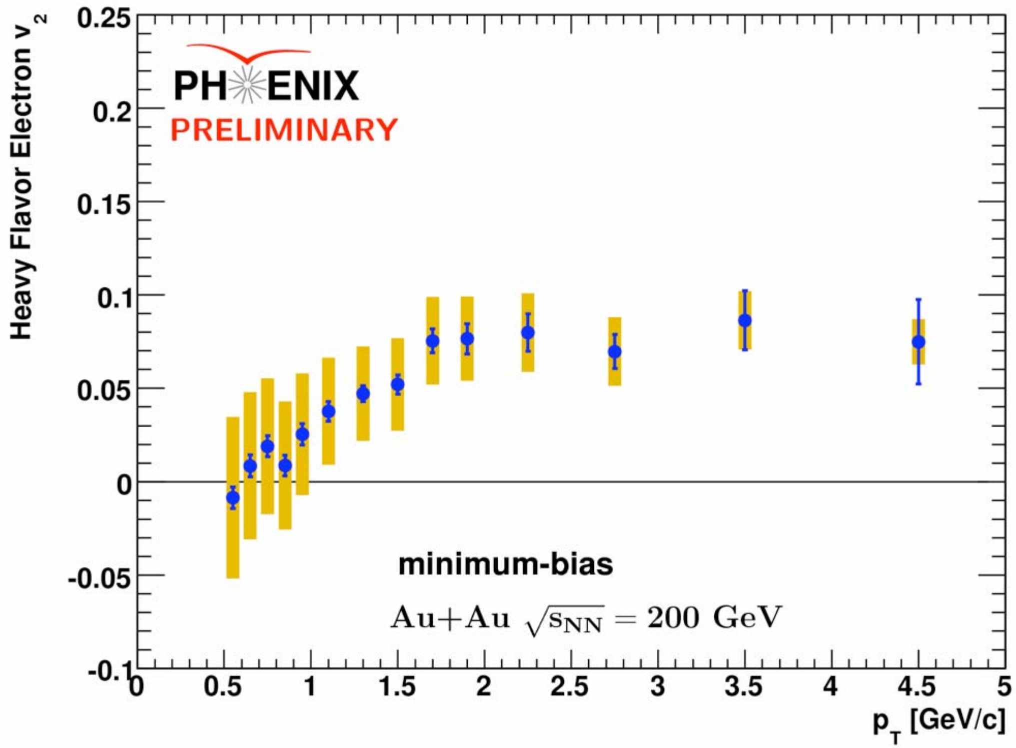
- $e^{\pm}$ R_{AA}: testing ground for various parton energy loss (ΔE) models
  - radiative ΔE only
    - Djordjevic et al., PLB 632(2006)81
    - Armesto et al., PLB 637(2006)362)
    - →would need a very large colour opacity with static scattering centers
  - collisional ΔE included
    - Wicks et al., NPA 784(2007)426
    - van Hees & Rapp, PRC 73(2006)034913
    - →reduces R_{AA} significantly, but the challenge persists
- alternative approaches
  - collisional dissociation of heavy mesons (charm and bottom!)
    - Adil & Vitev, PLB 649(2007)139
  - contribution from baryon enhancement
    - Sorensen & Dong, PRC 74(2006)024902
    - Martinez, Gadrat, Crochet, PLB 663(2008)55





Does charm flow?

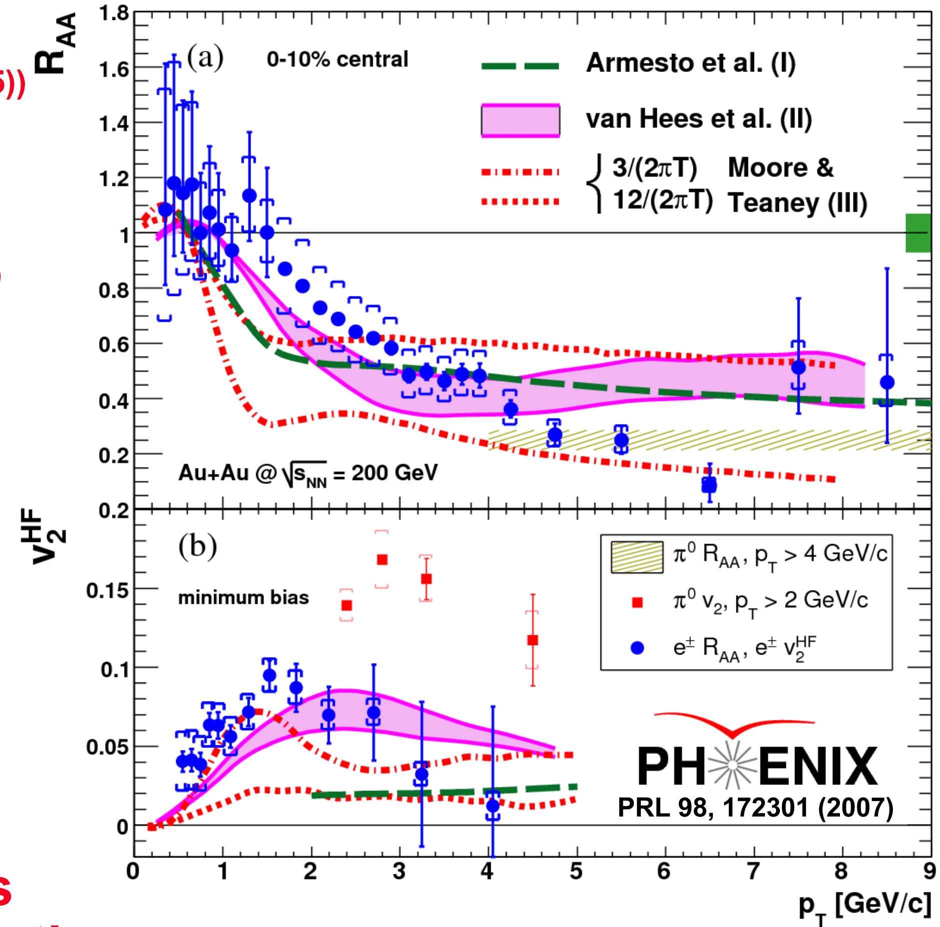
- non-zero elliptic flow strength v_2 of $e^{\pm}$
  → charm flows! (what about bottom?)



- heavy quark propagation through the medium
  → strong coupling!

Viscosity / entropy density: η/s

- transport models
  - Rapp & van Hees (PRC 71, 034907 (2005))
    - diffusion coefficient
      - $D_{HQ} \times 2\pi T \sim 4\text{-}6$
  - Moore & Teaney (PRC 71, 064904 (2005))
    - relation between diffusion coefficient and viscosity
      - $D_{HQ}/(\eta/(\varepsilon+P)) \sim 6$



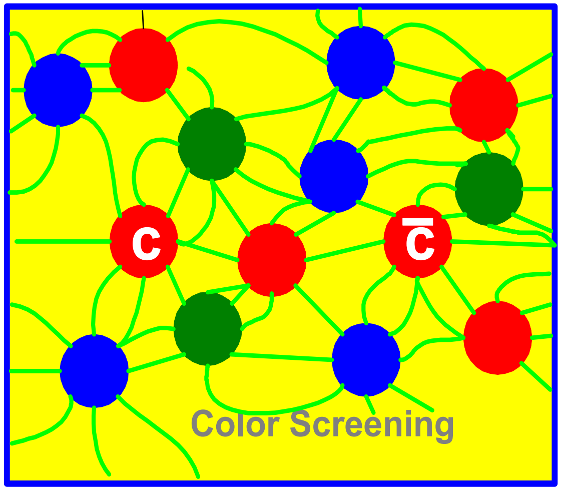
- at $\mu_B = 0$: $\varepsilon + P = Ts$

→ $\eta/s = (1.3\text{-}2.0)/4\pi$
  - close to conjectured lower quantum limit of $1/4\pi$ ($\eta/s = 9/4\pi$ for He at λ point)
  - consistent with other estimates of η/s based on flow and fluctuation measurements for light hadrons

- medium produced at RHIC = nearly perfect fluid

Closed heavy flavor (quarkonia)

- 1986: Matsui & Satz predict an "unambiguous" signature of QGP
  - color screening in the QGP
    → disappearance of quarkonia above certain temperature energy density thresholds
- quarkonia ↔ medium thermometer
- extensive measurements at CERN-SPS
- examples for theoretical dissociation temperatures

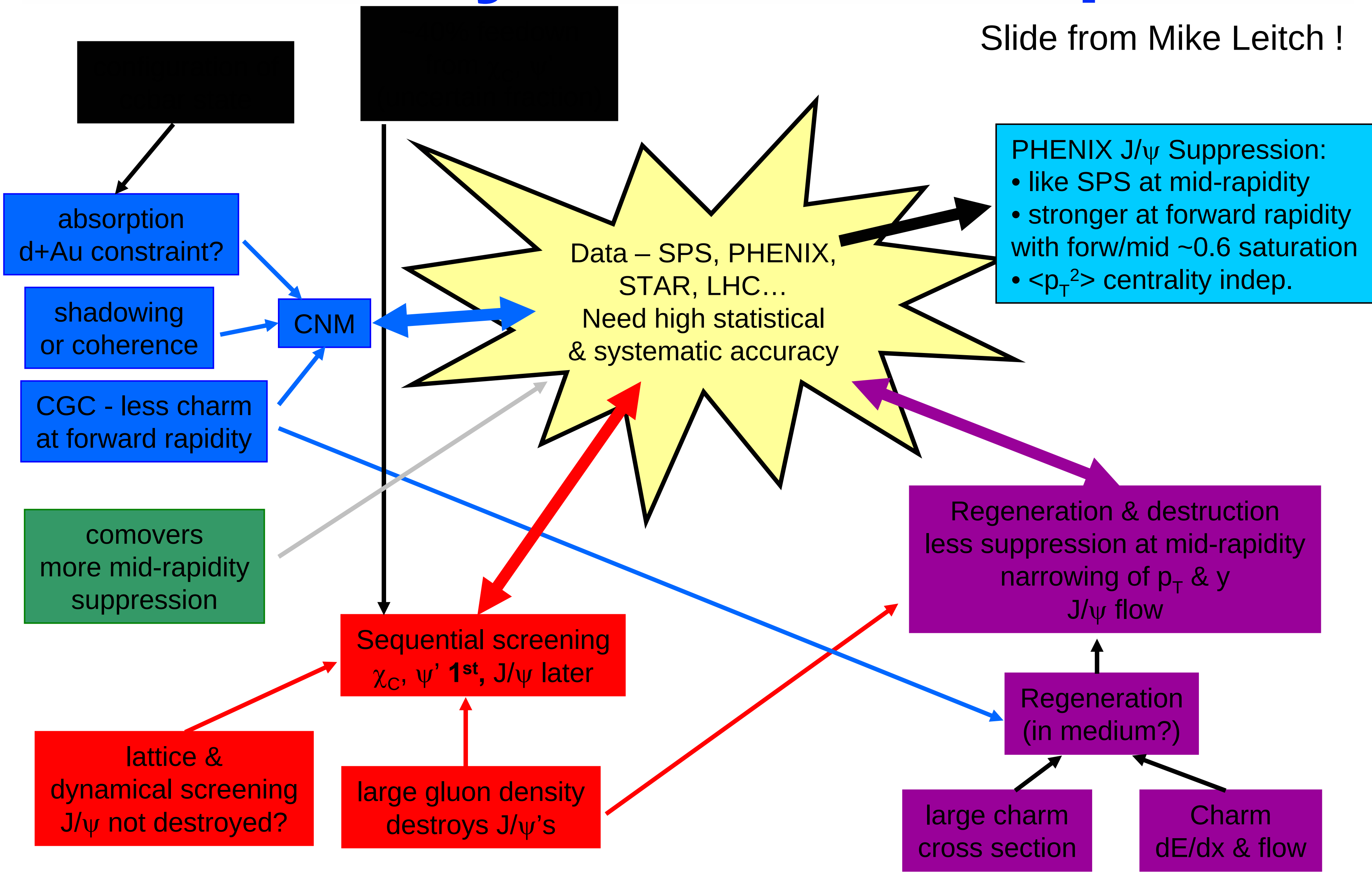


state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
$E_s^i[GeV]$	0.64	0.20	0.005	1.10	0.67	0.54	0.31	0.20
T_d/T_c	1.1	0.74	0.1-0.2	2.31	1.13	1.1	0.83	0.75
T_d/T_c	~ 1.42	~ 1.05	unbound	~ 3.3	~ 1.22	~ 1.18	-	-
T_d/T_c	1.78-1.92	1.14-1.15	1.11-1.12	$\gtrsim 4.4$	1.60-1.65	1.4-1.5	~ 1.2	~ 1.2

- different choices of effective T dependent potentials
  - free energy: S. Digal et al. Phys. Rev. D64 (2001) 094015
  - linear comb. of free energy & internal energy: C.Y. Wong hep-ph/0509088
  - internal energy: W.M. Alberico et al. Phys. Rev. D72 (2005) 114011

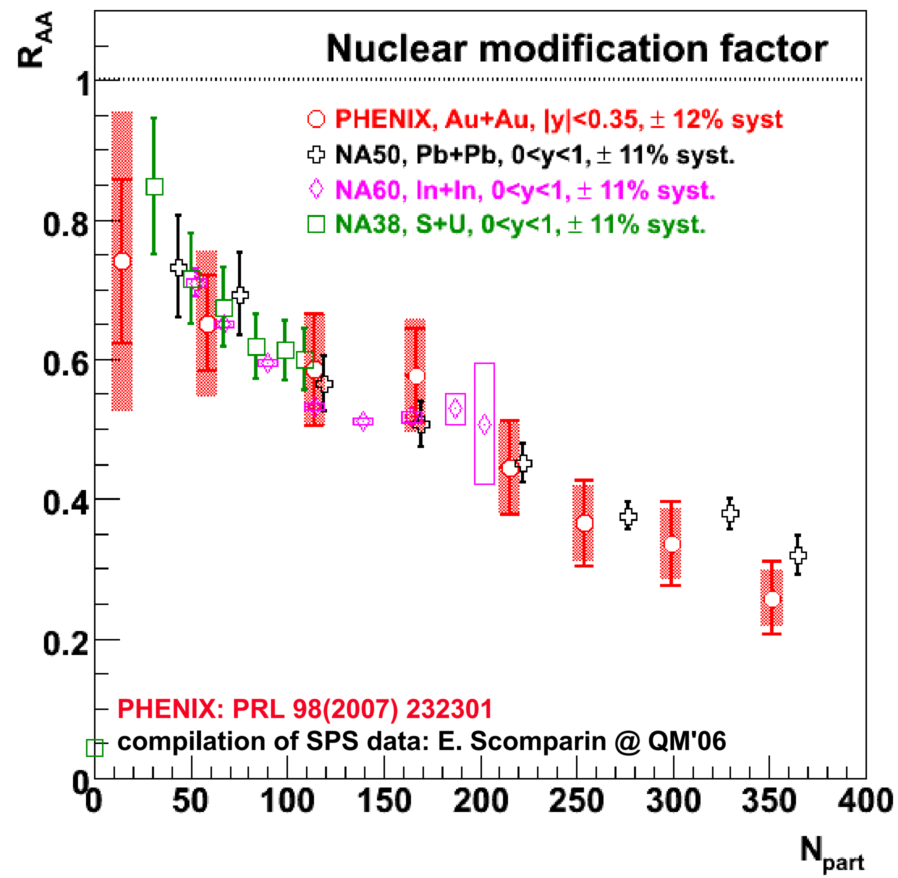
The story is more complex

Slide from Mike Leitch !



J/ψ at RHIC (Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV)

- PHENIX measures J/ψ production at RHIC
  - J/ψ → e^+e^- at |y|<0.35
  - J/ψ → $\mu^+\mu^-$ at 1.2<|y|<2.2
- mid rapidity R_{AuAu} looks surprisingly similar to R_{PbPb} at SPS
- although the systems are very different:
  - different energy densities at a given N_{part}
  - different cold nuclear matter effects ($x_{Bjorken}$, σ_{abs}, …)
  - different overall charm yield

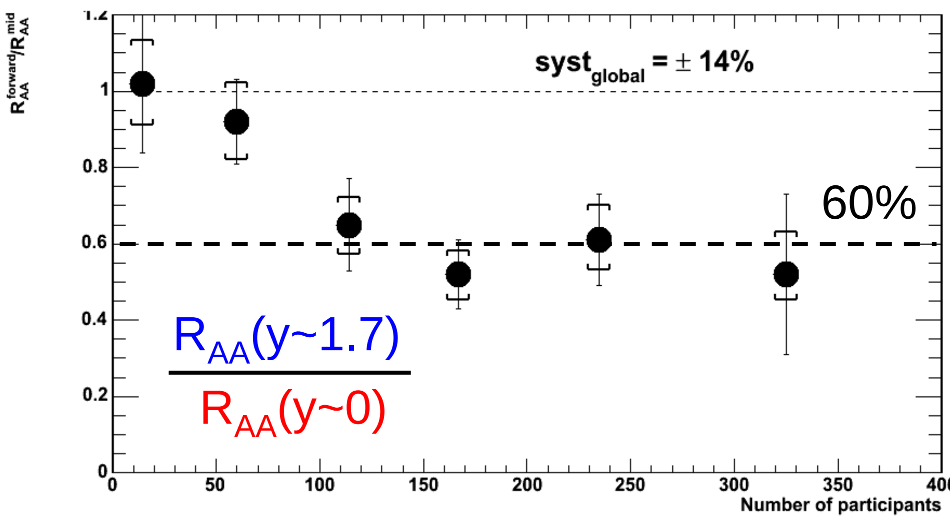


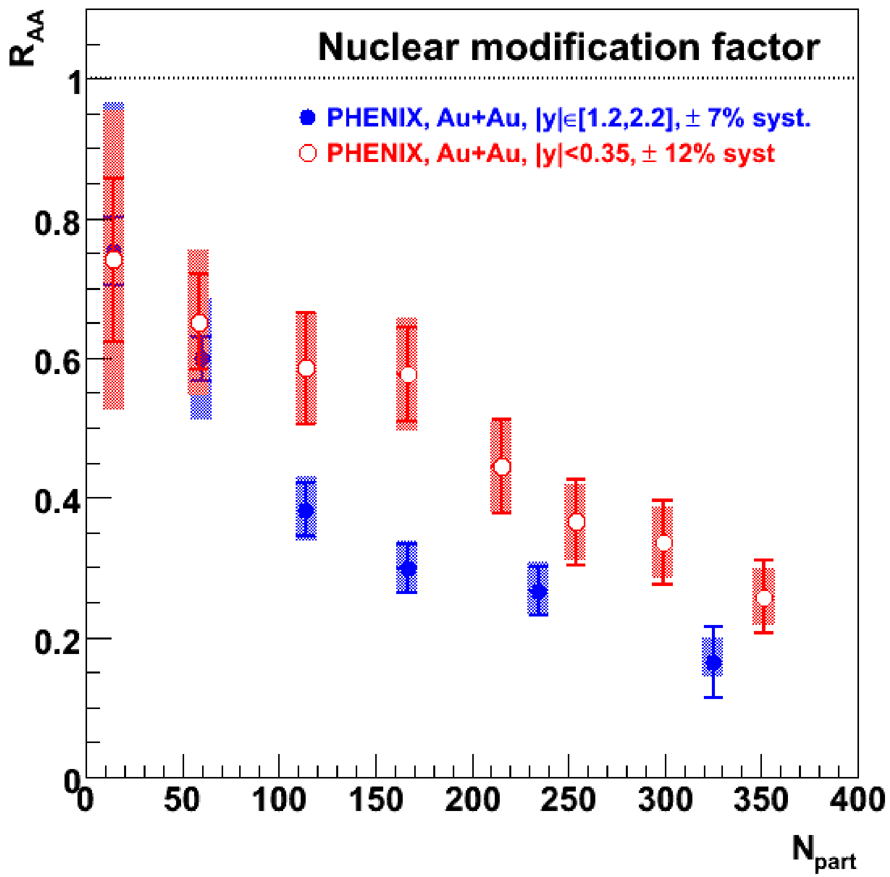
R_{AuAu} (y≈0 @ RHIC) ≈ R_{PbPb} (@ SPS)

J/ψ at RHIC (Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV)

- J/ψ suppression at RHIC
  - mid versus forward rapidity

    → more suppression at forward rapidity!
  - but: energy density should be LOWER at forward rapidity





R_{AuAu} (y≈1.7) < R_{AuAu} (y≈0) @ RHIC

Forward rapidity "puzzle"

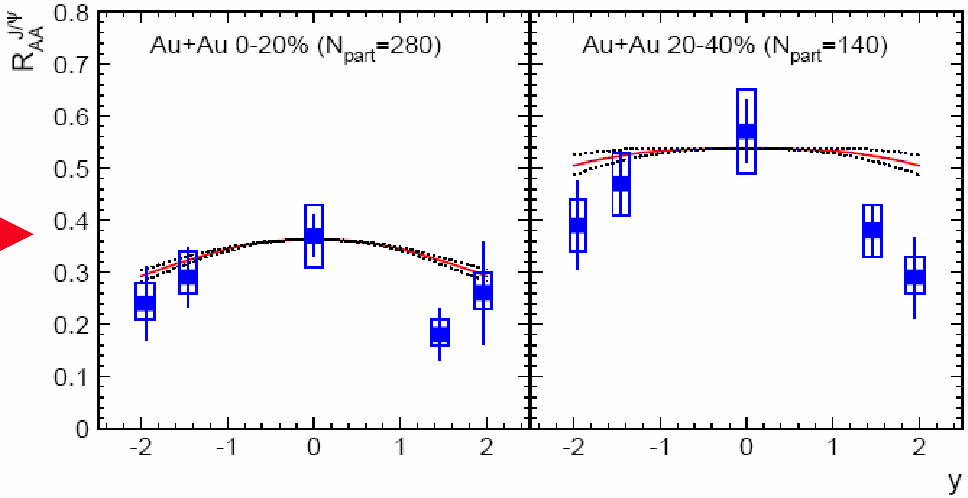
at RHIC, more suppression at forward rapidity !

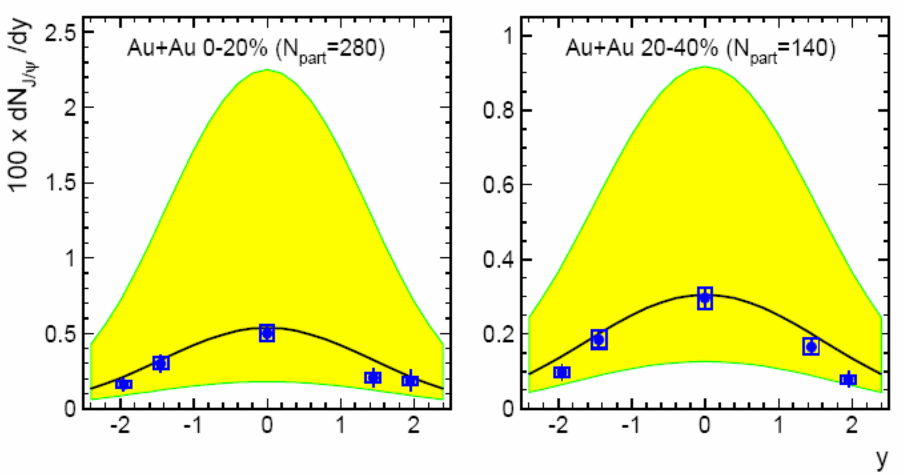
- two possible explanations
  - hot medium related
    - (re)generation of J/ψ from charm (anti)quarks in a deconfined medium
      - statistical hadronization
      - coalescence
      - regeneration
  - cold matter related
    - modification of initial parton distribution functions in cold nuclear matter
      - (anti)shadowing
      - saturation

J/ψ (re)generation

- **many approaches**
  - P. Braun-Munzinger, J. Stachel: PLB 490(2000)196
  - R. Thews et al.: PRC 63(2001)054905
  - L. Grandchamp et al.: PRL 92(2004)212301
  - E. Bratkovskaya et al.: PRC 69(2004)054903
  - L. Yan et al.: PRL 97(2006)232301
  - A. Andronic et al.: NPA 789(2007)334
  - A. Capella et al.: arXiv:0712.4331
  - O. Linnyk et al.: arXiv:0801.4282
  - and many others
- **all explain**
  - $R_{AA}(y=0) > R_{AA}(y=1.7)$
  - more c quarks to recombine at y=0
- **all need reliable open charm input for quantitative constraints!**

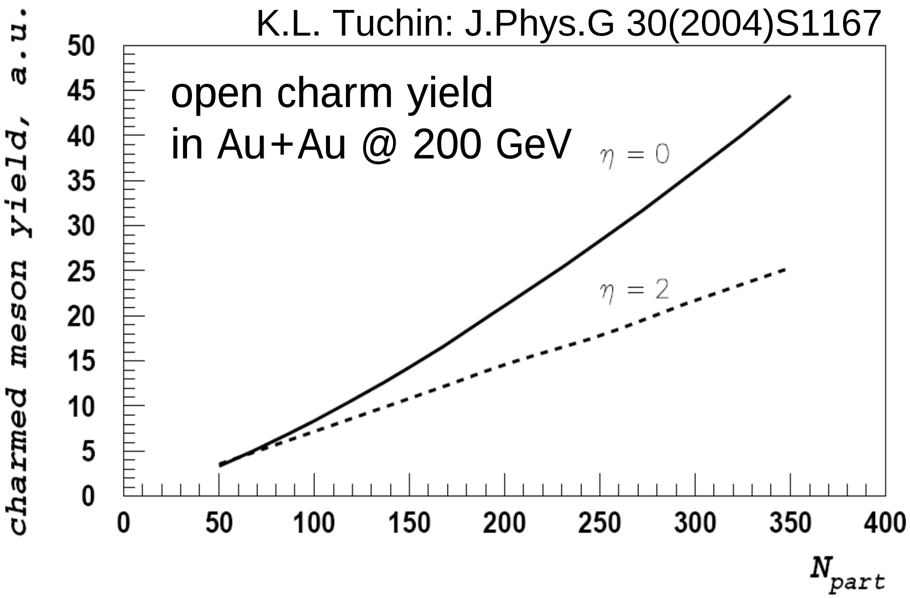
- **one example**

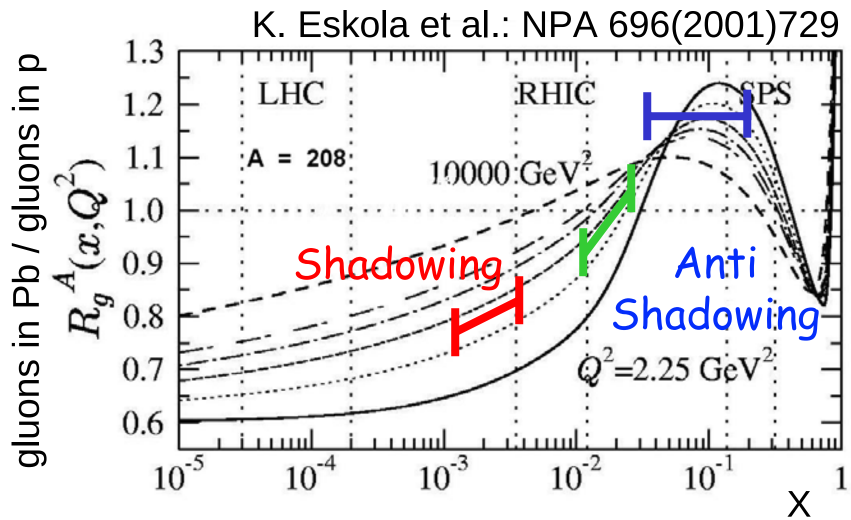




Initial PDF in nuclei

- saturation could suppress forward J/ψ in Au+Au
- gluon shadowing or antishadowing will affect J/ψ R_{AA} , too



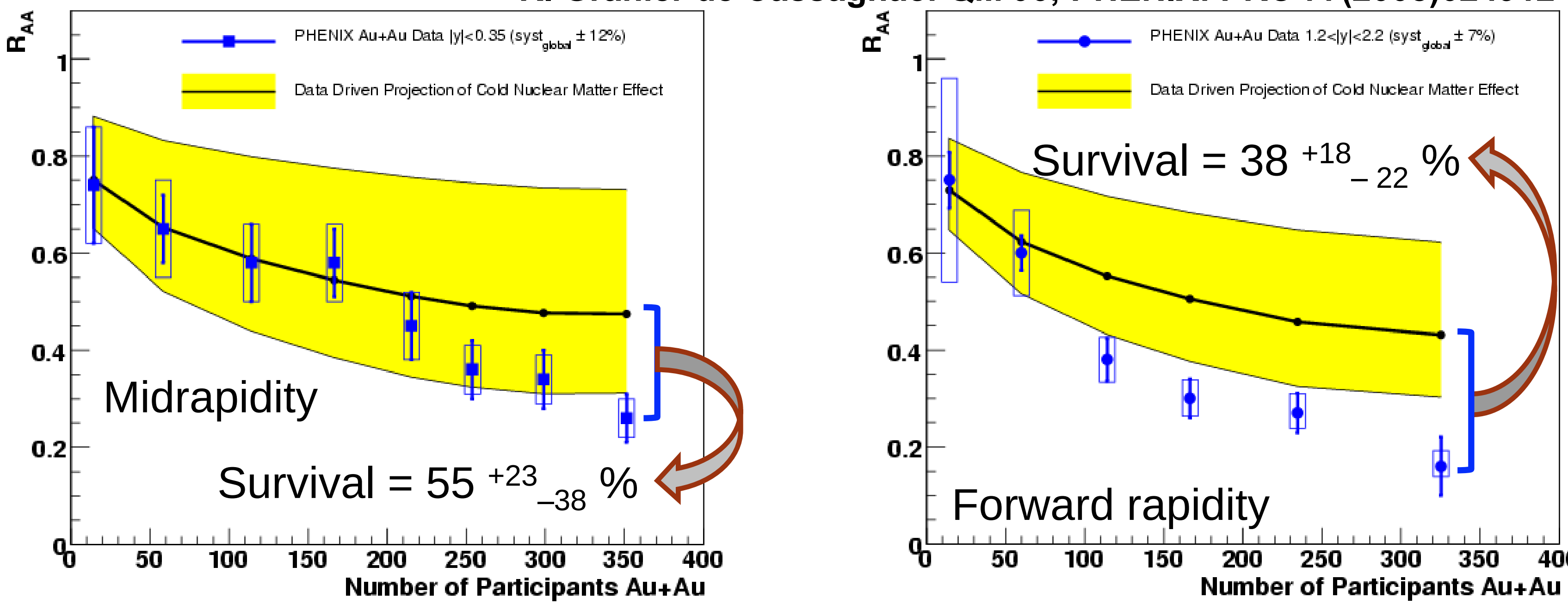


- precise p(d)+A data are necessary to calibrate cold nuclear matter effects
  - are the existing d+Au data from RHIC good enough?

CNM effects in Au+Au

- propagate measured R_{dAu} to Au+Au in a Glauber model
  - completely data driven → no model dependence

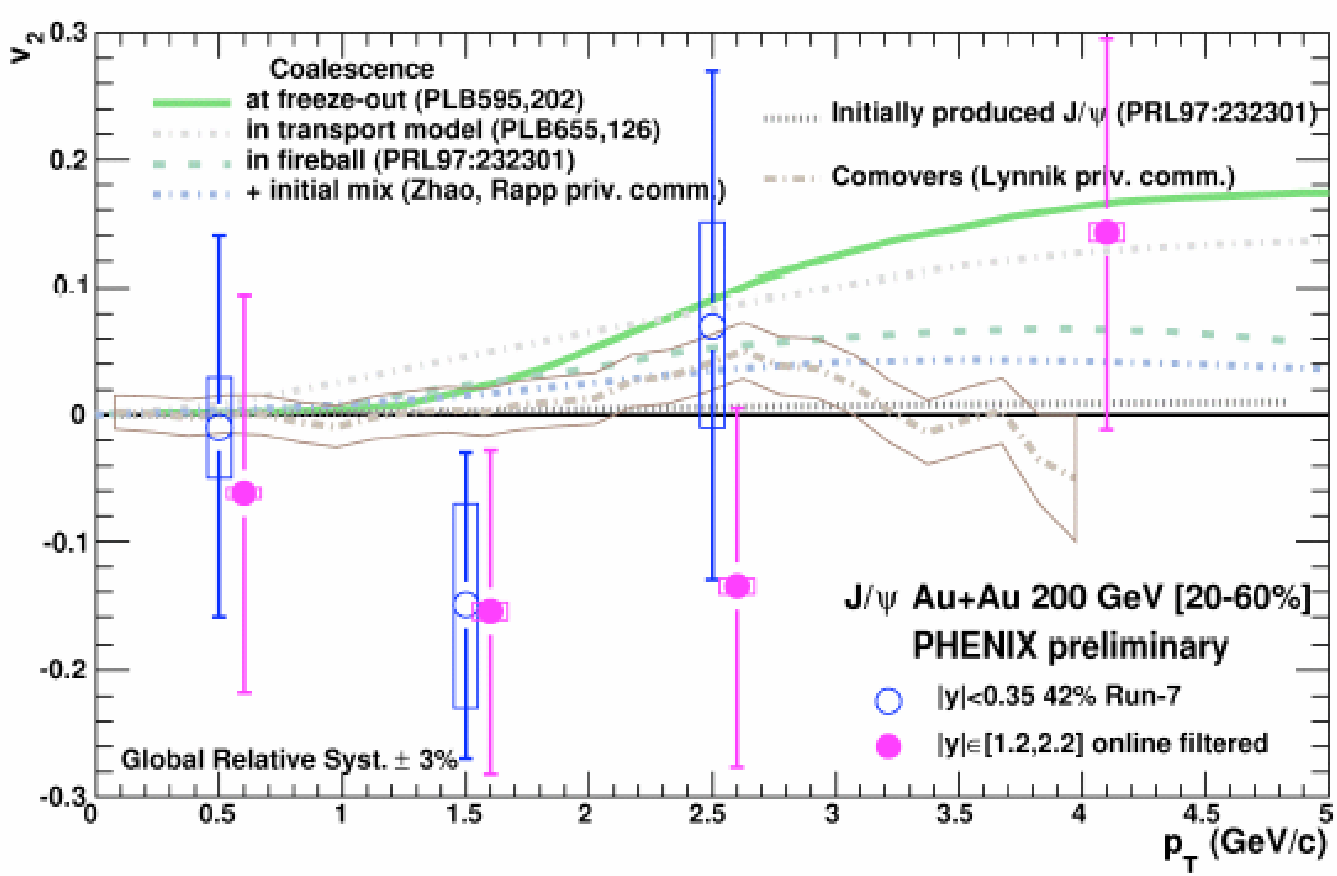
R. Granier de Cassagnac: QM'06; PHENIX: PRC 77(2008)024912



- uncertainties are huge
- RHIC Run-8: increase d+Au statistics by factor ~30

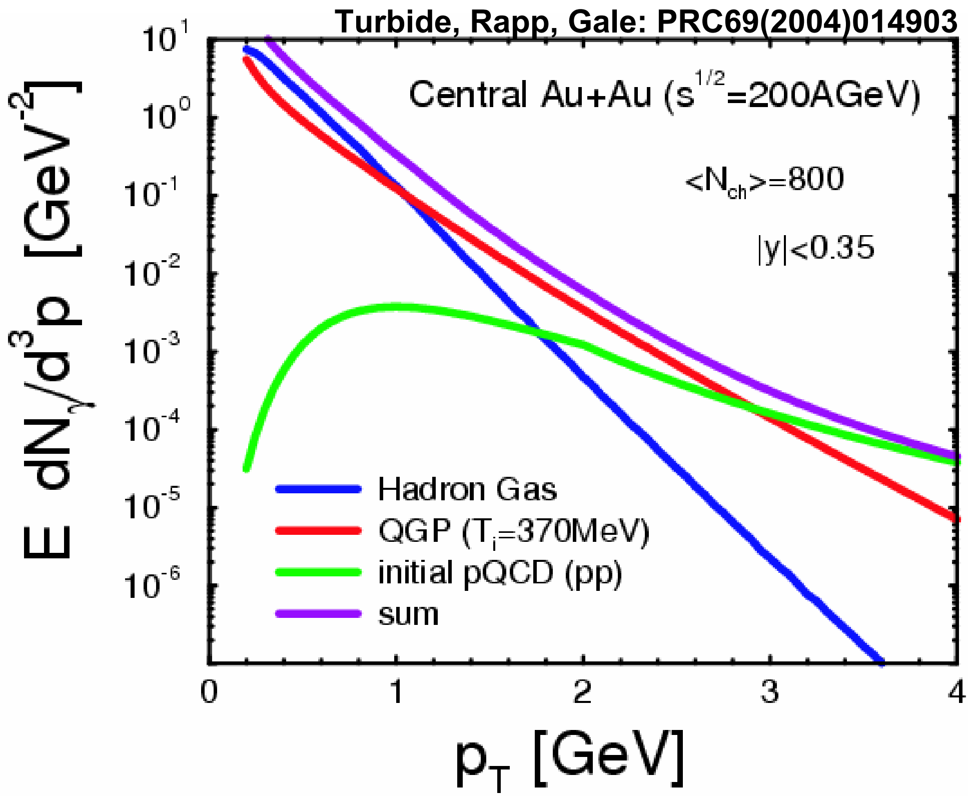
J/ψ flow as a new smoking gun?

- charm flows!
- J/ψ v_2 measurement → a smoking gun for recombination
- no decisive data from RHIC yet



Approaching a “Holy Grail”

- thermal radiation with $T \gg T_C$ would prove beyond any doubt the presence of a "quark-gluon" black body
- competition with photon emission from
  - hadron gas
  - initial pQCD processes (direct γ)

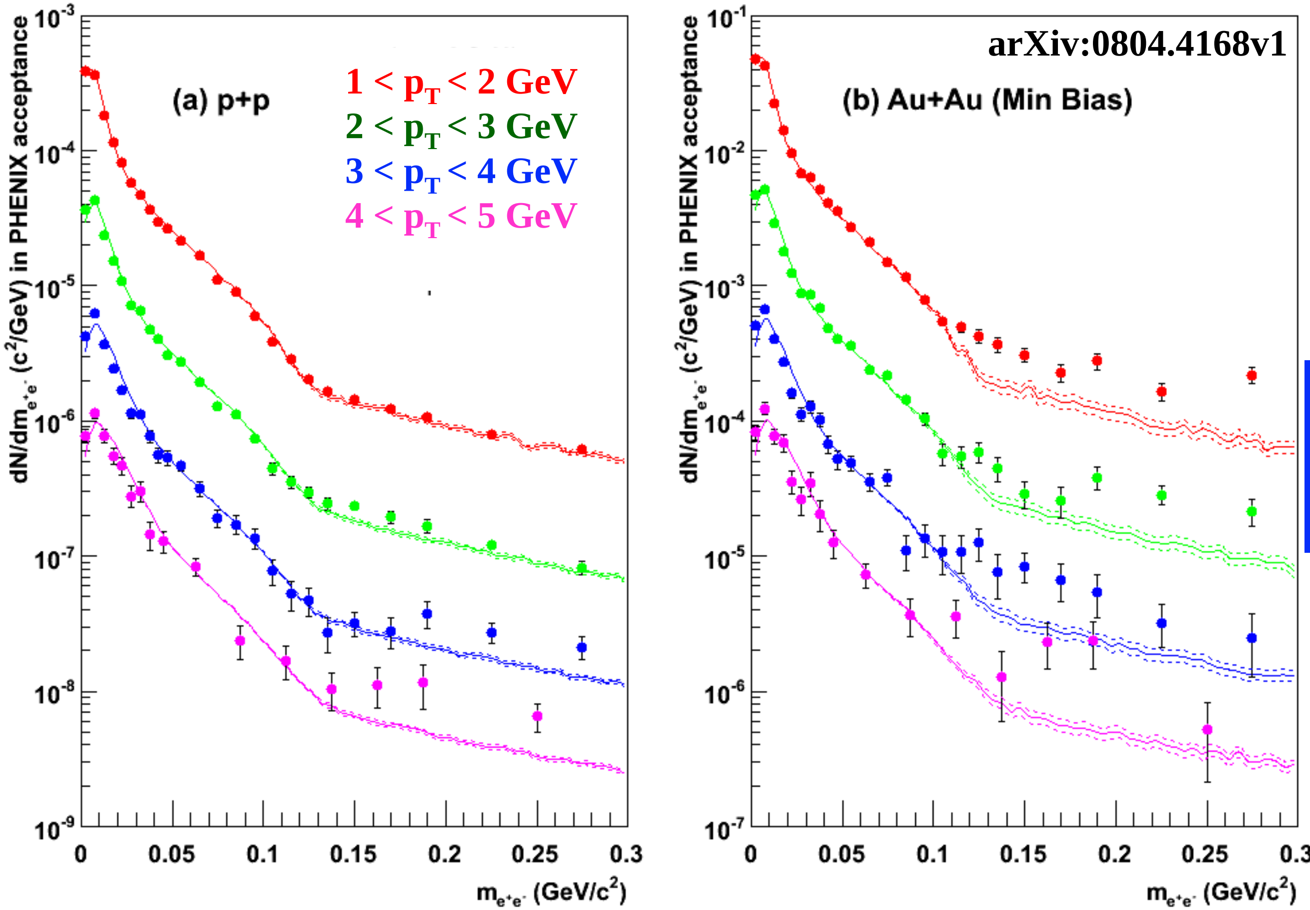


- promising window $1 < p_T < 3$ GeV/c
- “real” photons
  - signal/background currently too small for significant measurement
- “virtual” photons?

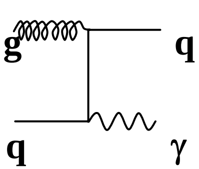
e^+e^- at low mass and high p_T: γ^*

- any process radiating γ will also radiate γ^*
  - $m \ll p_T$: γ^* is "almost real" → line shape given by QED!
  - direct γ in $\gamma^* \to e^+e^-$? then:

$$\frac{\gamma_{direct}}{\gamma_{inclusive}} = \frac{\gamma^*_{direct}}{\gamma^*_{inclusive}} \Leftrightarrow \gamma_{direct} = \frac{\gamma^*_{direct}}{\gamma^*_{inclusive}} \cdot \gamma_{inclusive}$$

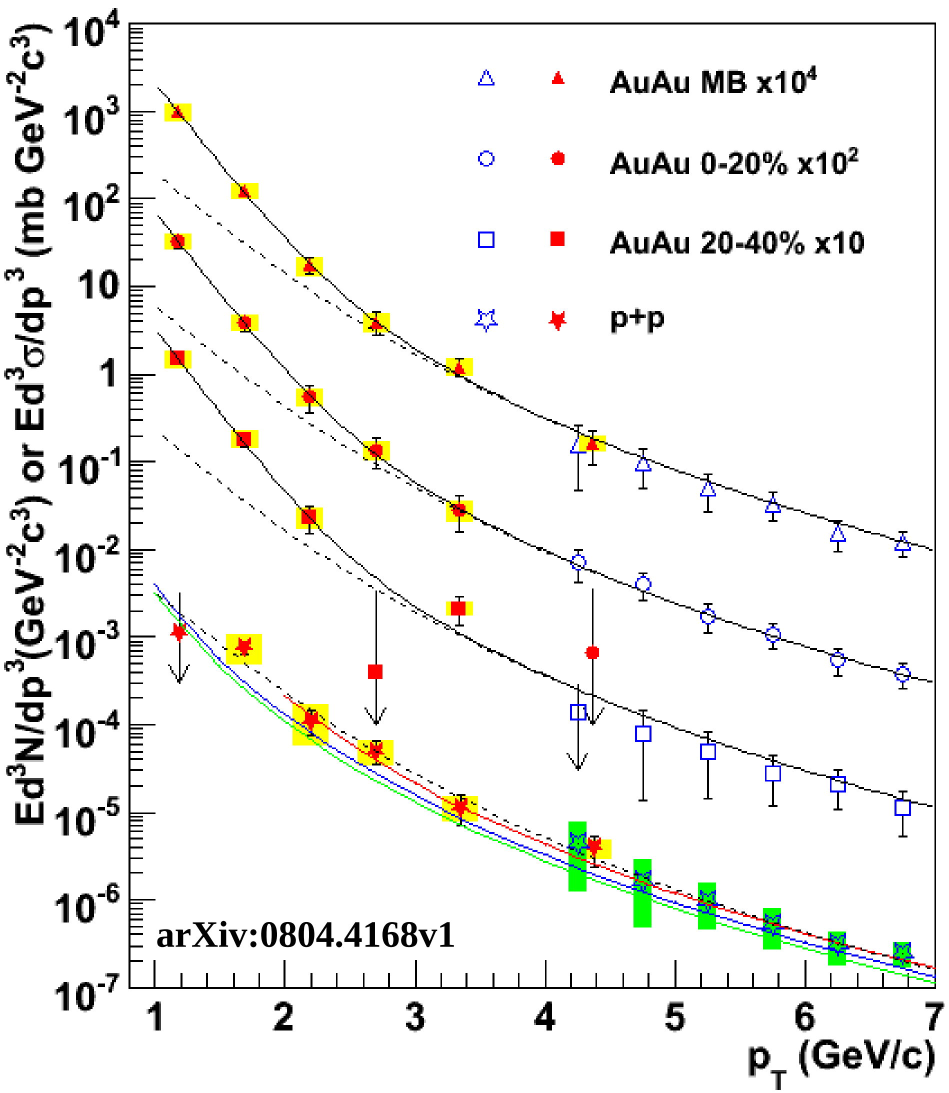


p+p" small excess consistent with pQCD



Au+Au: large excess at all p_T

Thermal radiation at RHIC



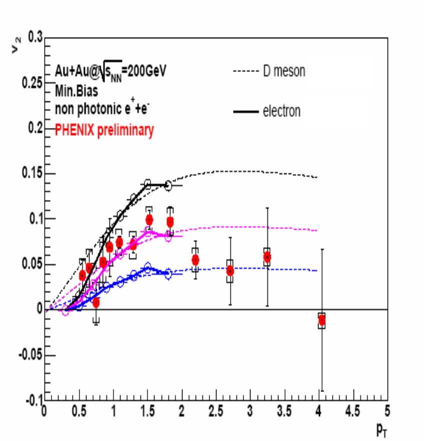
- **slope analysis of data:**
  - **pQCD + exp.**

$$Ae^{-\frac{p_T}{T}} + B \cdot N_{coll}\left(1+\frac{p_T{}^2}{b}\right)^{-n}$$

  - **fix B, b, and n from p+p**
  - **Au+Au (min. bias)**
    - **T = 224±16(stat)±18(sys)**
- **initial temperatures and times from theoretical model fits to data:**
  - **0.15 fm/c, 590 MeV (d'Enterria et al.)**
  - **0.2 fm/c, 450-660MeV (Srivastava et al.)**
  - **0.5 fm/c, 300 MeV (Alam et al.)**
  - **0.17 fm/c, 580 MeV (Rasanen et al.)**
  - **0.33 fm/c, 370 MeV (Turbide et al.)**

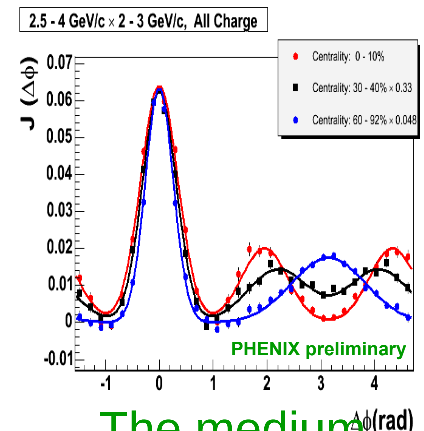
from data: T_{ini} > 220 MeV > T_C
from models: T_{ini} = 300 to 600 MeV
τ_0 = 0.15 to 0.5 fm/c

Summary

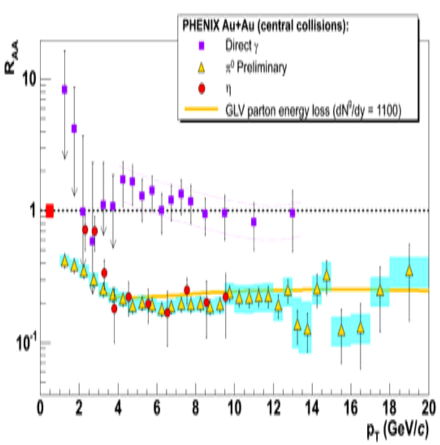


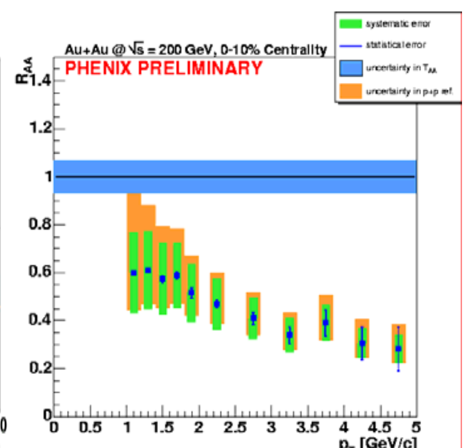
The medium is strongly coupled

HI collisions at RHIC → production of a strongly interacting Quark-Gluon Plasma (sQGP)

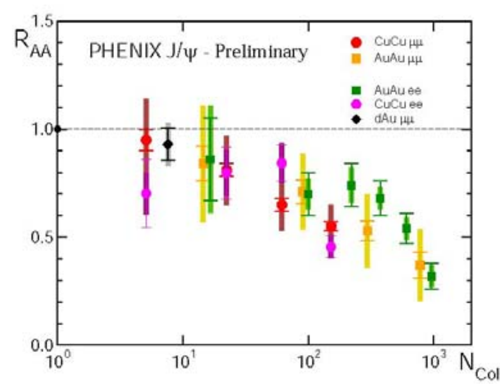


The medium modifies jets

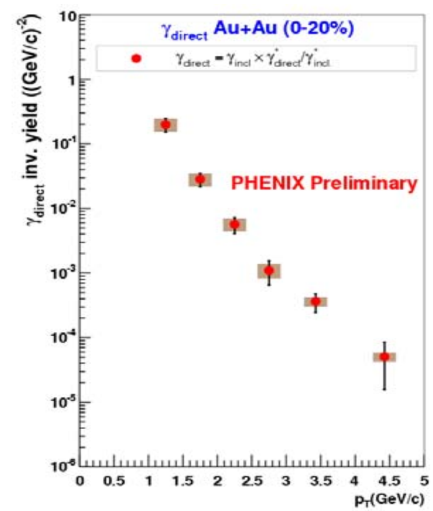




The medium is dense



The medium may melt but regenerate J/ψ's



The medium is hot