Heavy Quarks in Ultra Relativistic Heavy-Ion Collisions - A Summary

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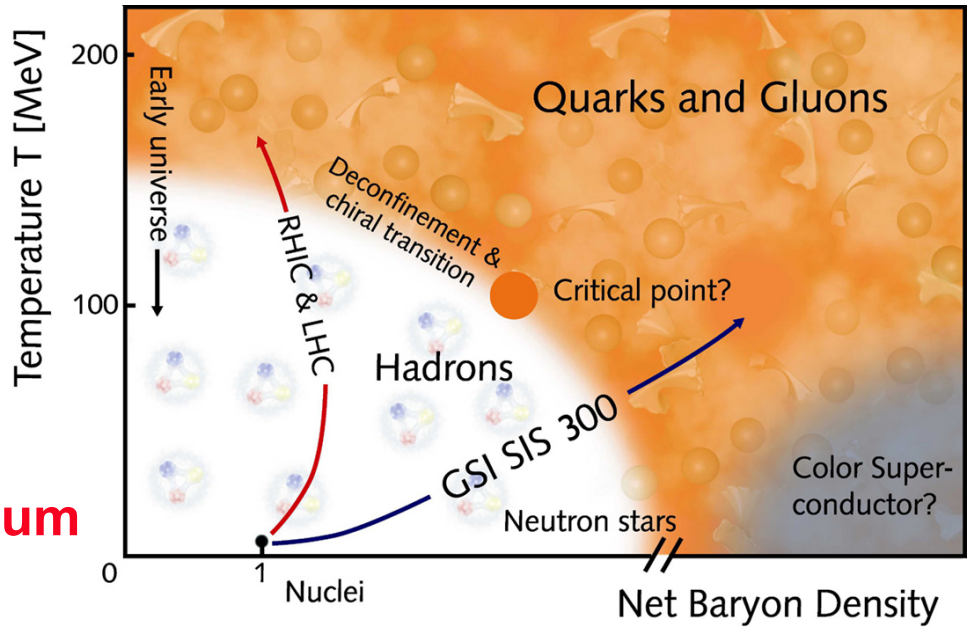
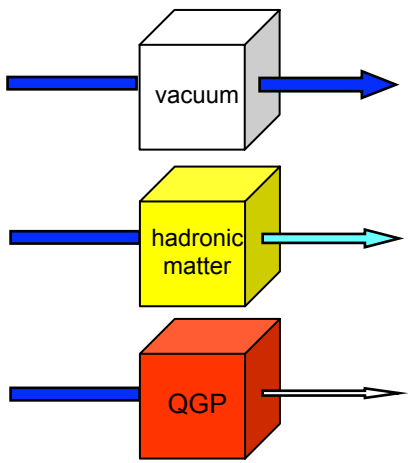
Probing QCD matter

- strongly interacting matter under extreme conditions
  - → heavy-ion (HI) collisions
    - energy √s
    - species (pp, pA, AA)
    - centrality



- hard probe Ansatz
  - study properties of matter produced in HI collisions
  - "shoot" probe through medium and see how it is affected

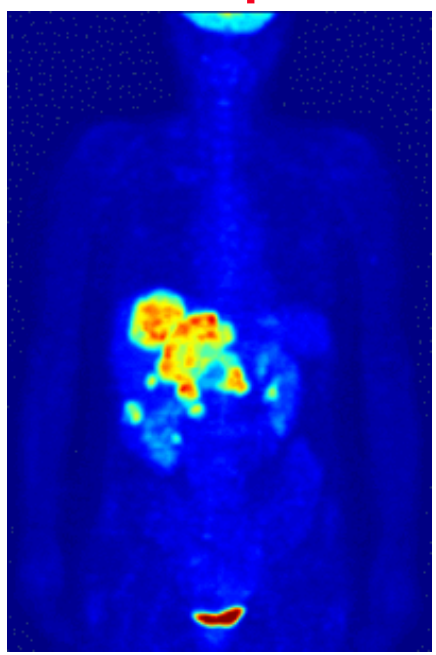
- good probes
  - well calibrated in pp collisions
  - slightly affected and well understood in hadronic matter
  - strongly affected in a partonic medium



Hard probe basics

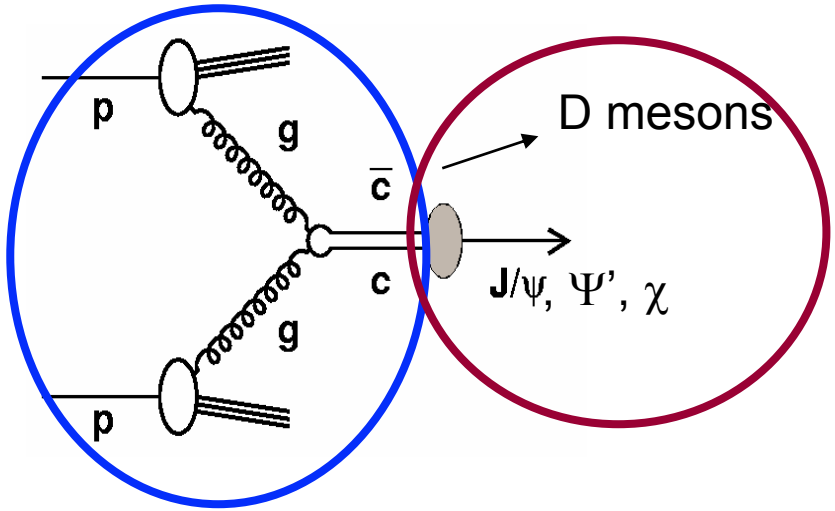
- creation
  - must be produced together with the medium they probe
  - must be present before the medium is formed

  → initial hard parton scattering processes (jets, heavy quarks, ...)
- calibration
  - "trivial" probes providing a baseline for the initial state
    - not affected by the medium → real and virtual photons
  - "trivial" collision systems to calibrate the interaction of the probes with a hadronic medium
    - pp, pA, dA, light AA
- application = "tomography"
  - medical imaging
    - calibrated probe with well understood interaction
    - absorption profile of probe
      → density profile of medium
  - expectation/hope for heavy-ion collisions
    - density profile from jet suppression
    - state of the medium from quarkonia suppression



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 $\sqrt{s}$



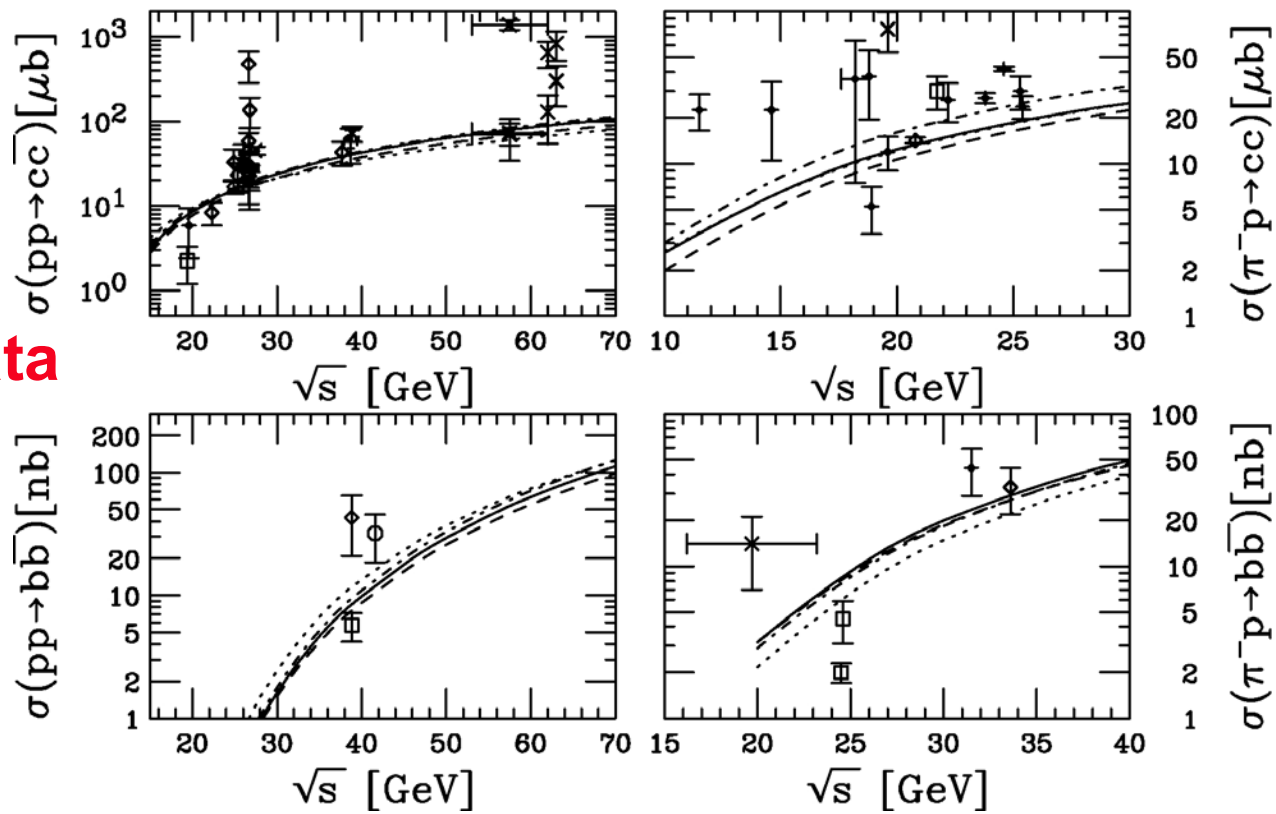
- generic heavy-quark study
  - calibrate heavy flavor production in pp collisions
  - probe the medium
    - initial state: parton density in nuclei
    - interaction with medium ⇨ energy loss, flow?
  - formation of <u>bound</u> states: quarkonia (J/ψ, Υ)

→complementary to other hard probes

→study of yields & spectra in pp, p(d)A, and AA

Open heavy quarks – pre RHIC

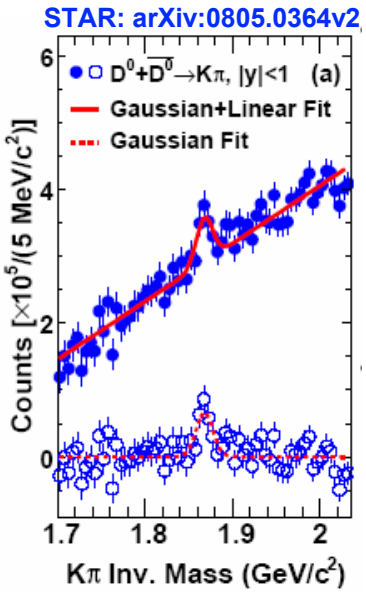
- lower energy ($\sqrt{s} \leq 63$ GeV)
  - SPS, FNAL (fixed target) and ISR (collider) experiments
  - small σ in p/π+A collisions (assume $\sigma_{pA} = \sigma_{pp} A^{\alpha}$, $\alpha = 1$)
  - large discrepancies between some experiments
- higher energy
  - CDF and D0 at FNAL: p+p @ $\sqrt{s} = 1.8$ TeV
  - high p_T b&c data ($p_T \geq 5$ GeV/c)
- recent review
  - C. Lourenco & H.K. Woehri
    - Physics Reports 433(2006)127



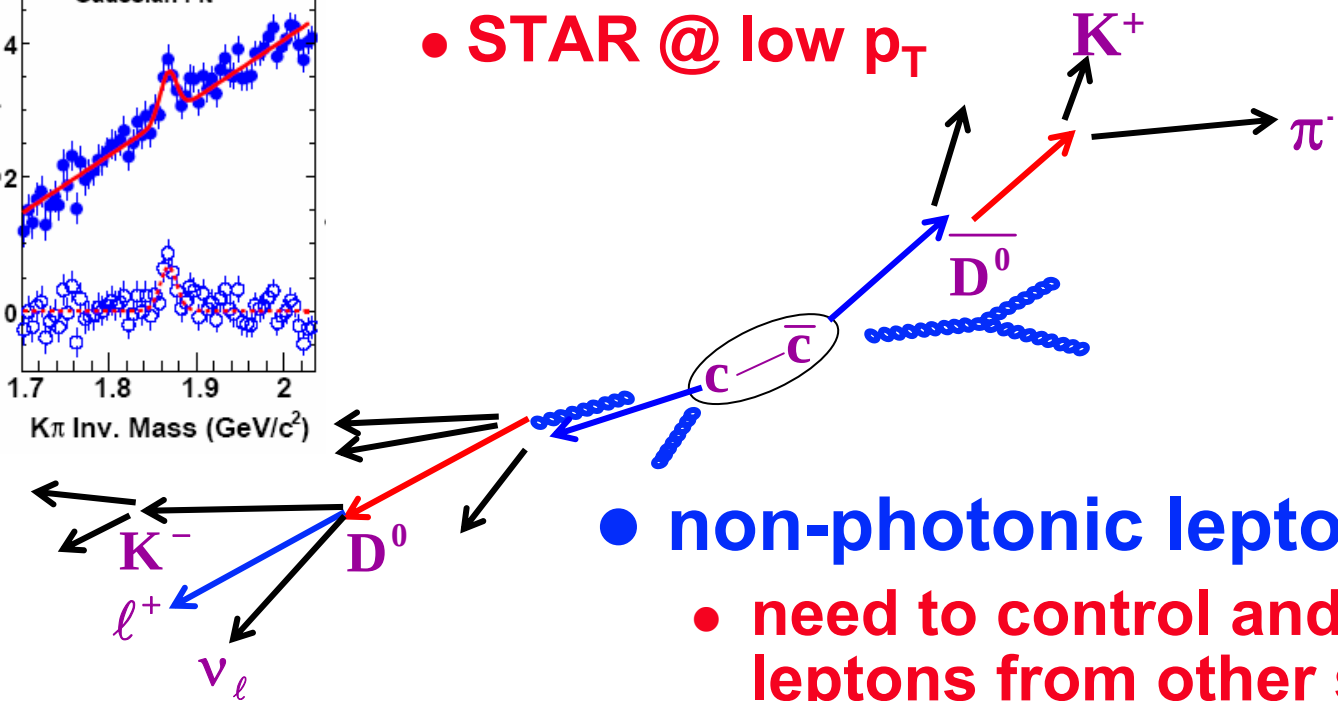
- no systematic "tomographic" study before RHIC

Open charm: techniques

- direct D meson reconstruction



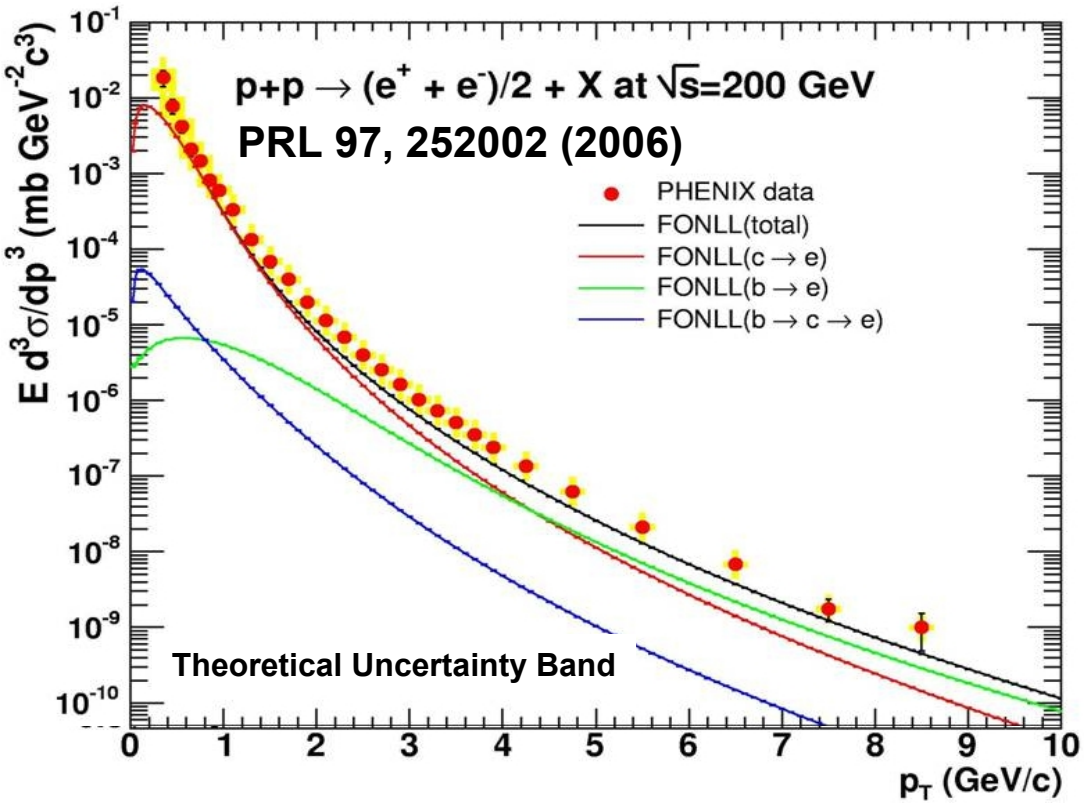
- large combinatoric background when displaced vertex is not measured
- STAR @ low p_T



- non-photonic lepton technique
  - need to control and subtract leptons from other sources
  - loss of kinematic information
  - PHENIX: e, μ, e^+e^-
  - STAR: e, low p_T μ

Proton-proton baseline ($\sqrt{s}$ = 200 GeV)

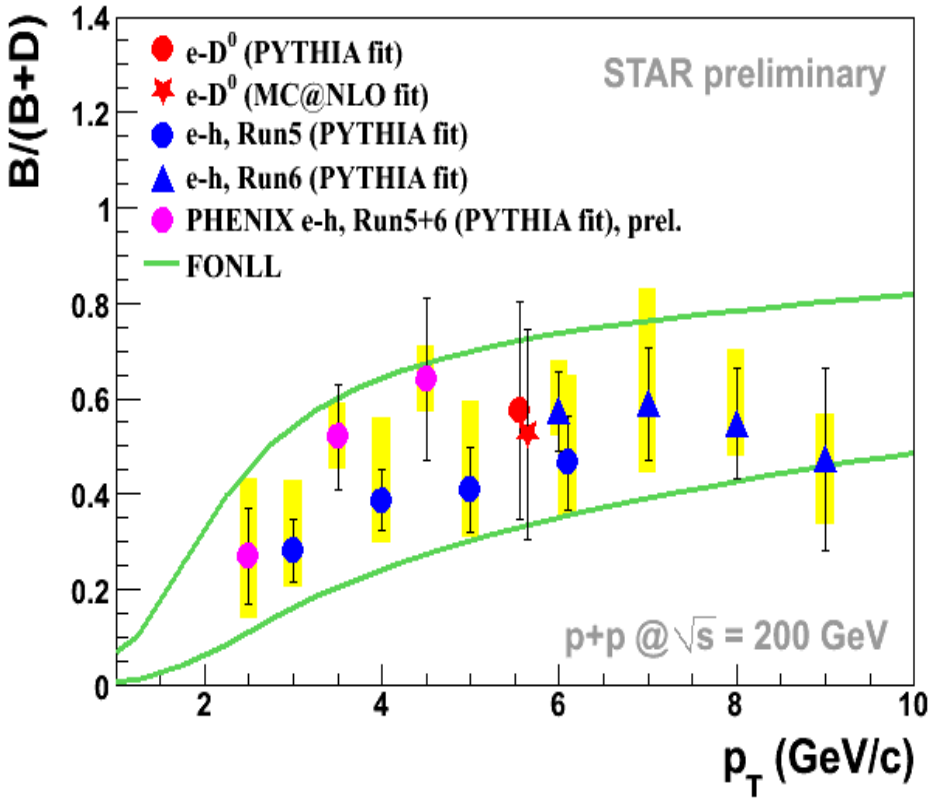
- non-photonic $e^{\pm}$ from c→e and b→e



- comparison with FONLL calculation:
  - Fixed Order Next-to-Leading Log pQCD
    (Cacciari, P. Nason, R. Vogt PRL95,122001 (2005))
- bottom is important at high p_T!

Bottom contribution?

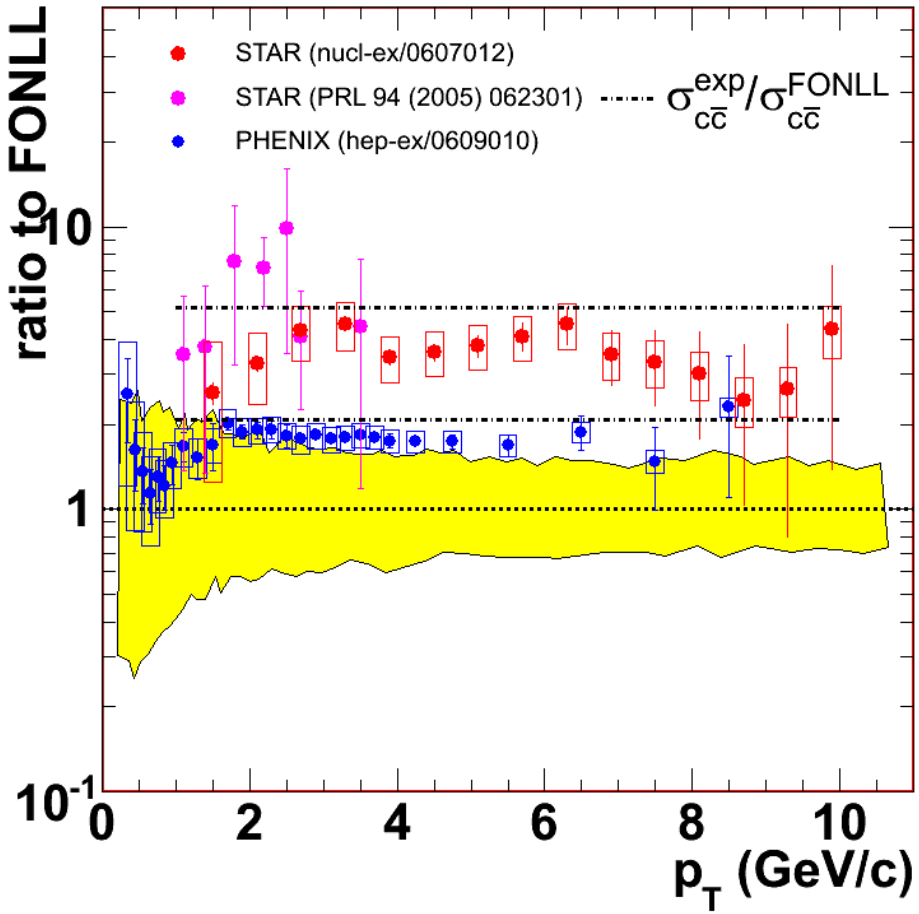
- electron-hadron correlations
  - sensitive to bottom vs. charm due to the different masses of D and B mesons



- PHENIX & STAR are consistent with FONLL

PHENIX vs. STAR vs. FONLL

- ratio of heavy-flavor $e^{\pm}$ spectra to FONLL
  - PHENIX
    - spectral shape of $e^{\pm}$ agrees with FONLL
    - total cross section above FONLL by a factor ~2
  - STAR
    - shape consistent with PHENIX and FONLL
    - total cross section above FONLL by a factor ~4



- systematic uncertainties in pQCD are large, i.e. a factor ~2 (or even ~4: R. Vogt hep-ph/0709.2531)

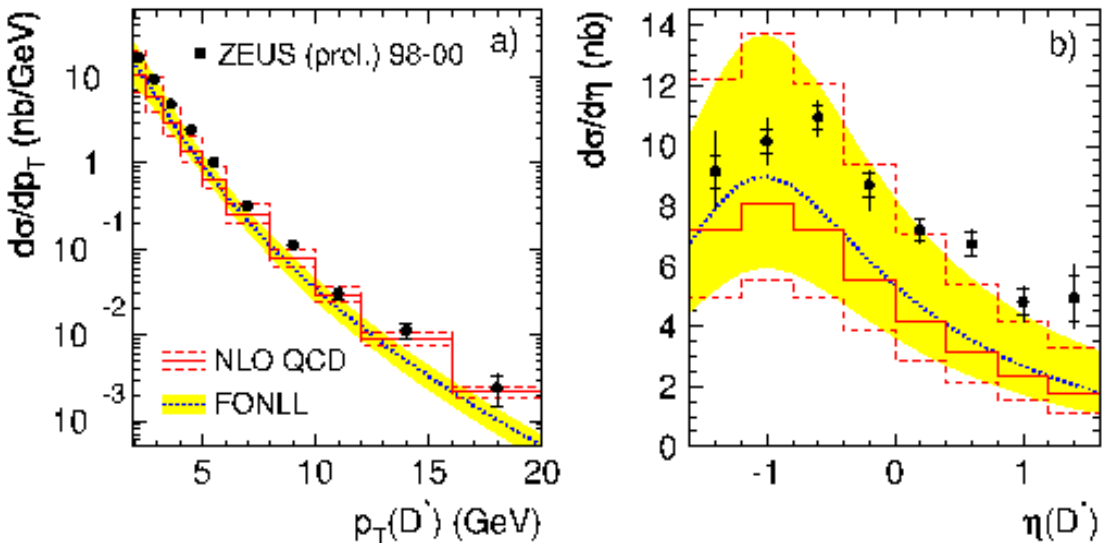
Charm and FONLL elsewhere

- charm data from DESY
  - charm photo production
- charm data from FNAL
  - charm hadro production

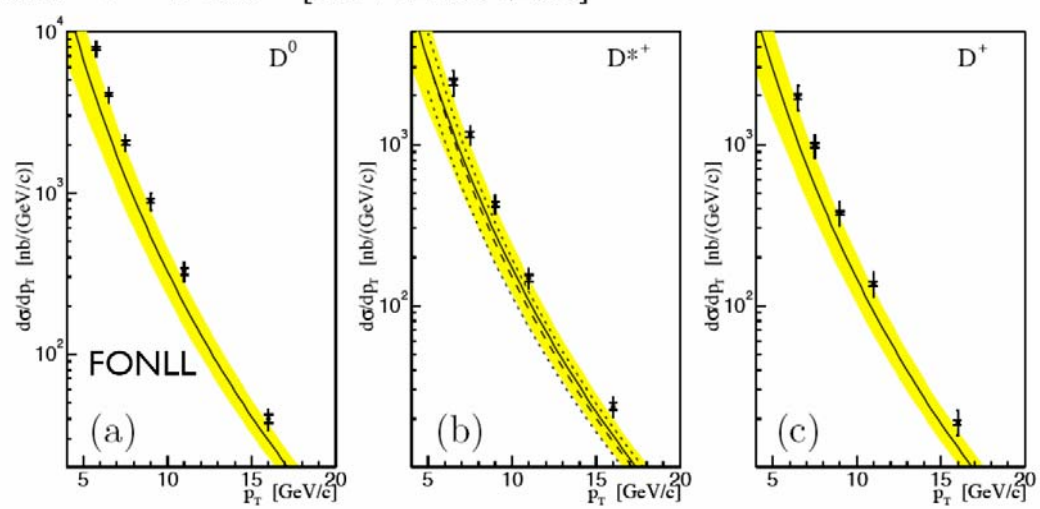
→data ~ 2xFONLL

→significant pQCD uncertainties (scales, quark mass)

ZEUS (Photoproduction)

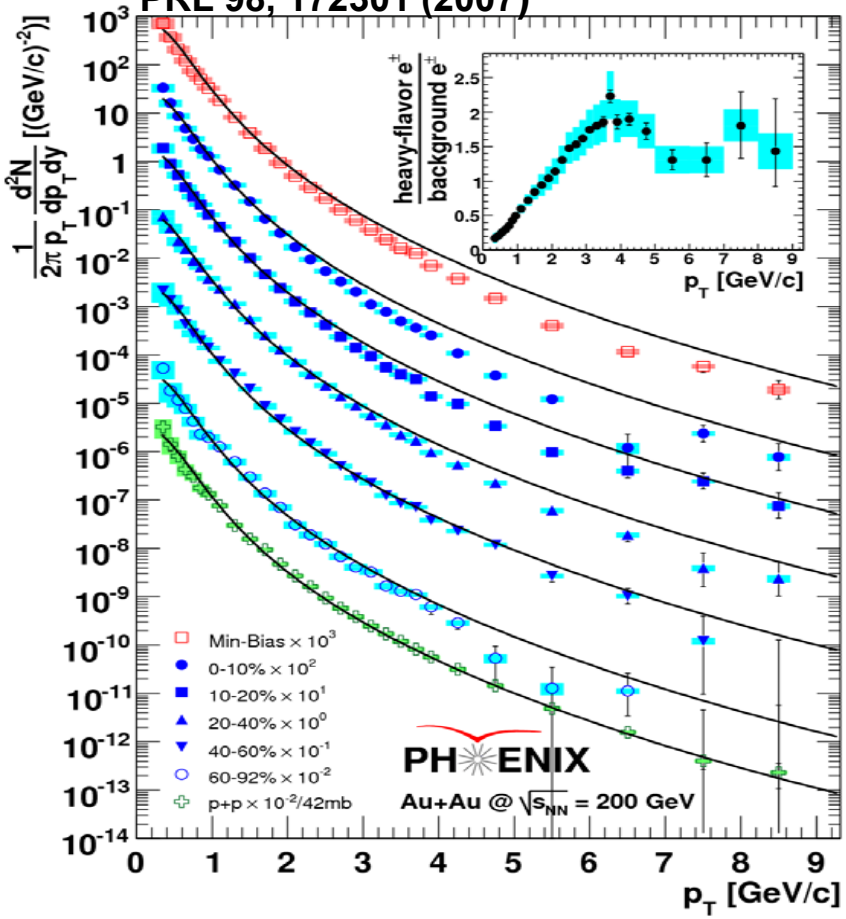


CDF Run II c → D data [PRL 91:241804,2003]

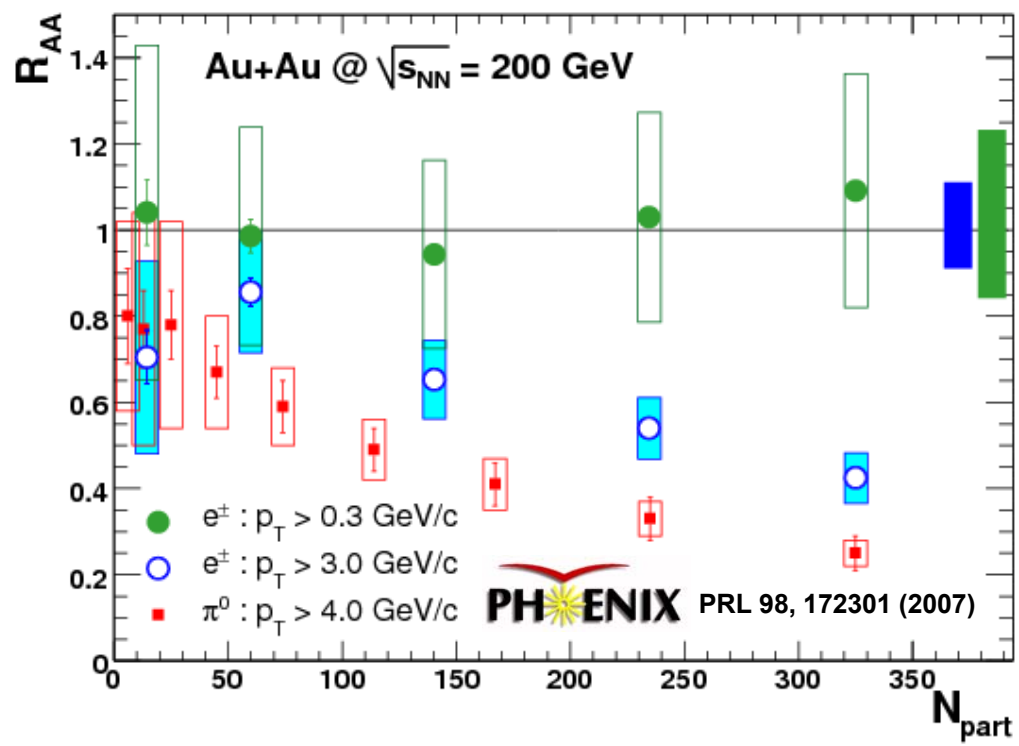


Probing the medium in Au+Au

PRL 98, 172301 (2007)



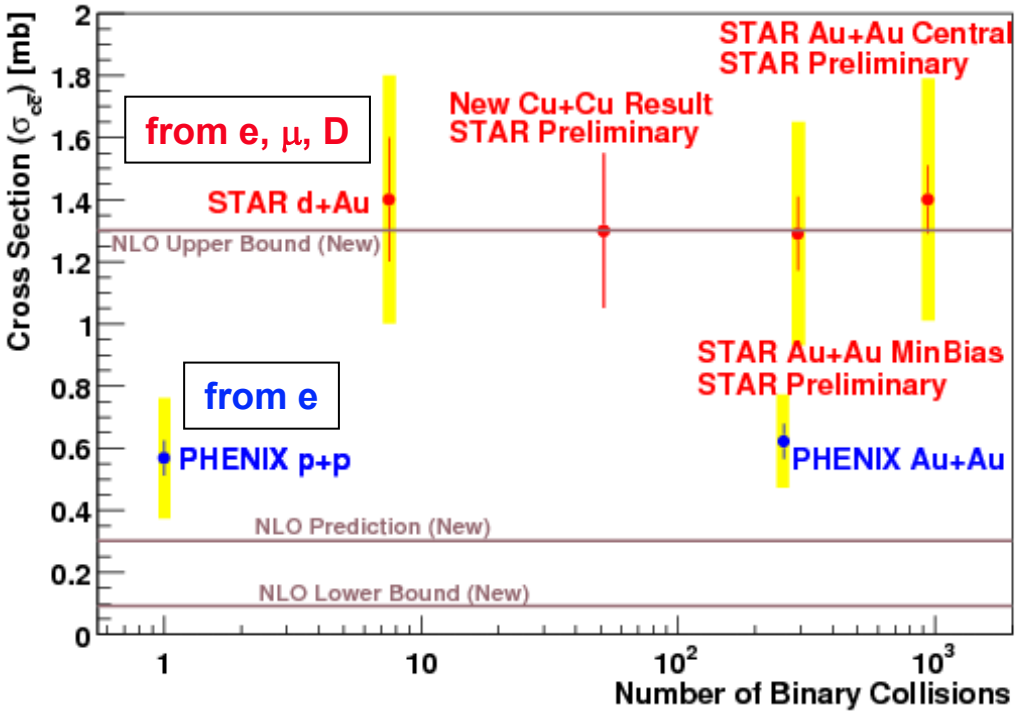
$$R_{AA} = \frac{Yield\ in\ Au + Au}{N_{binary} \times Yield\ in\ p + p}$$



- binary scaling of total $e^{\pm}$ yield from heavy-flavor decays
  - → hard process production and no destruction (as expected)
- high p_T $e^{\pm}$ suppression increasing with centrality
  - similar to π^0 suppression (a big surprise)

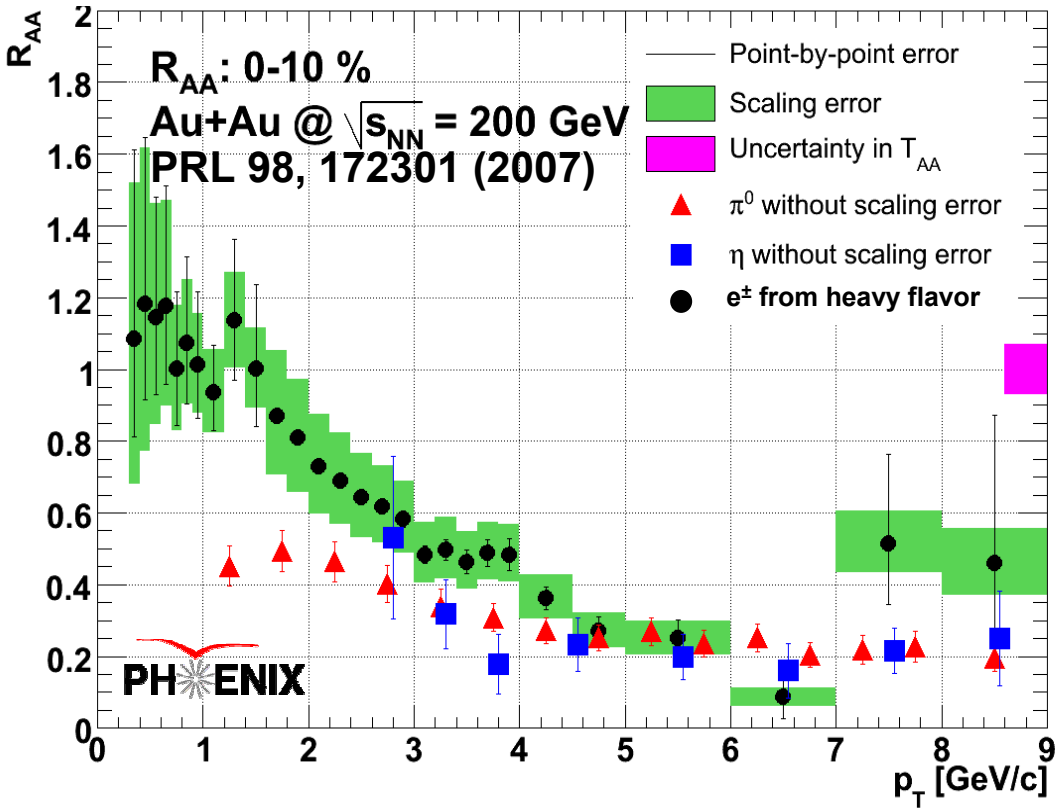
Binary scaling: PHENIX & STAR

- charm cross section / binary collision
  - binary scaling is observed in both experiments
  - but the cross section differs by a factor ~2

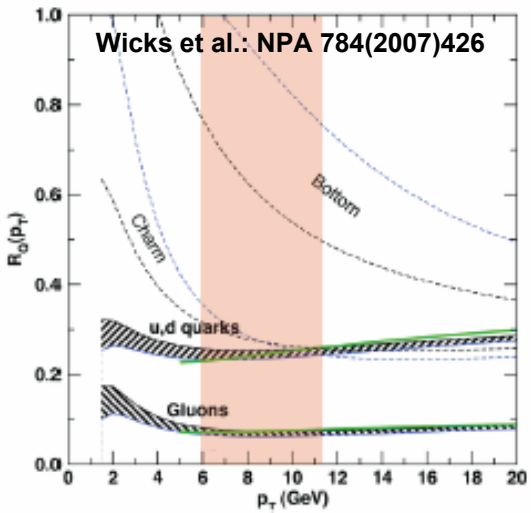


- ongoing efforts to resolve this issue
  - STAR: remove inner tracker → improved $e^{\pm}$ data
  - PHENIX: more systems and D reconstruction
- near future
  - vertex spectrometers for both experiments!!

Nuclear modification factor R_{AA}



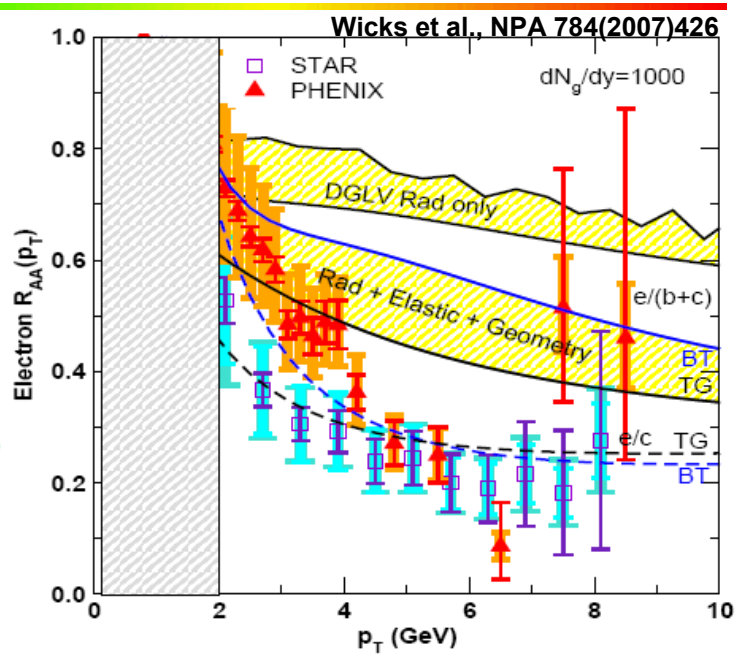
- similar to light hadrons
  - careful:
    - kinematics: $p_T(e^{\pm}) < p_T(D)$
  - intermediate p_T
    - indication for quark mass hierarchy as expected for radiative energy loss (Dokshitzer and Kharzeev, PLB 519(2001)199)
  - highest p_T
    - $R_{AA}(e^{\pm}) \sim R_{AA}(\pi^0) \sim R_{AA}(\eta)$

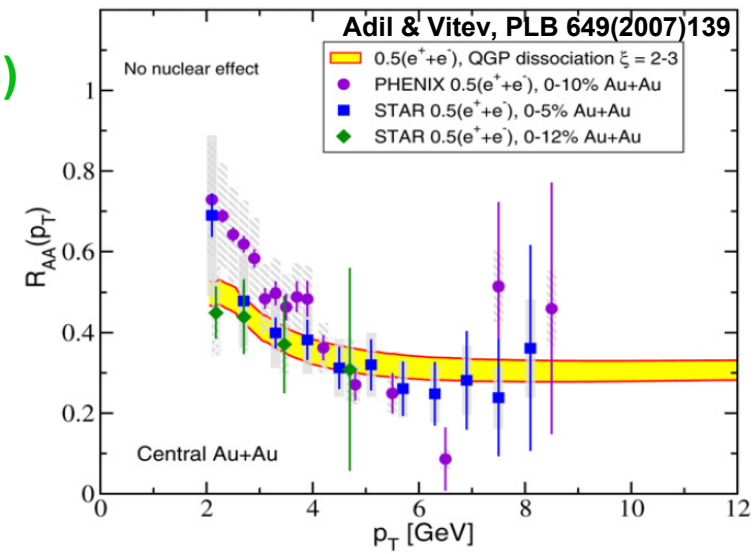


- bottom contribution at high p_T
  - is bottom suppressed?!
- needed: R_{AA} of identified charm and bottom hadrons

$e^{\pm}$ R_{AA}: a challenge for models

- 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 (odd for b)
  - 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 (also for light quarks)
- 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



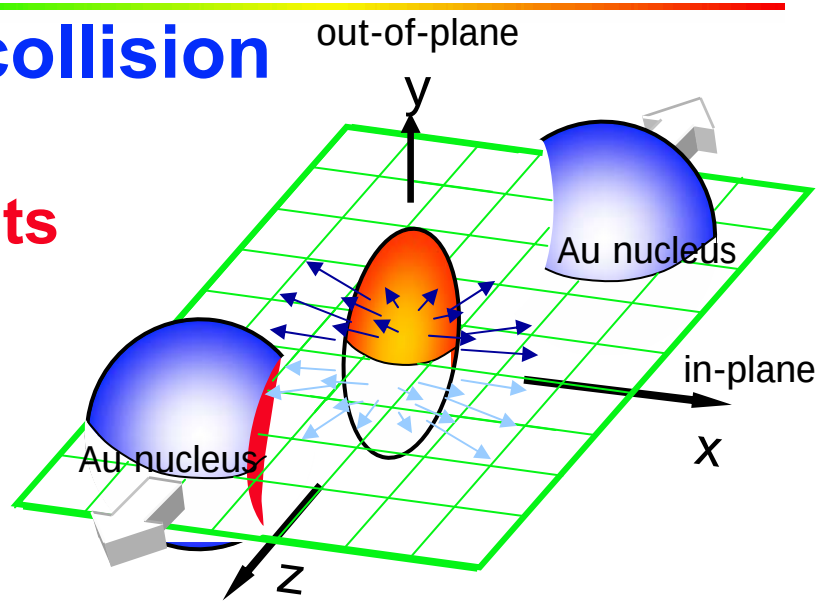


Elliptic flow → early thermalization?

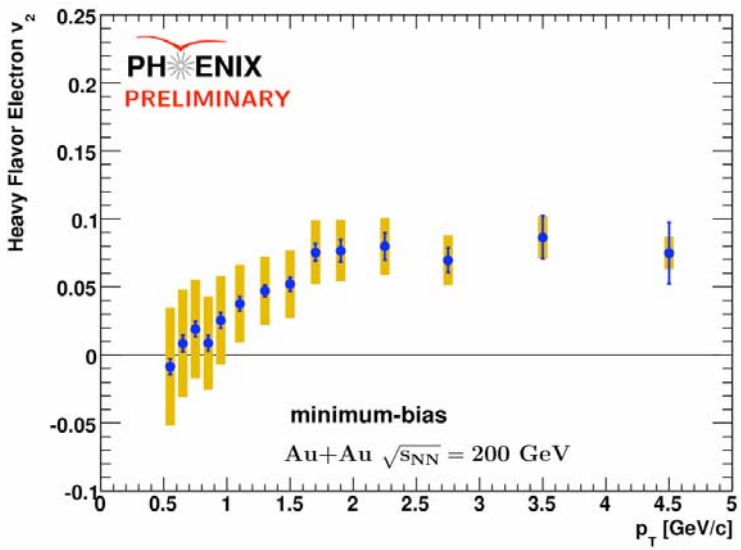
- initial state of non-central collision
  - spatial asymmetry
  - asymmetric pressure gradients
- final state
  - momentum anisotropy
  - Fourier expansion

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

  - elliptic flow strength v_2
- v_2 is "self quenching"
  - reflects early interactions → thermalization?
- $v_2(e)>0$ → $v_2(\text{charm})>0$
  - $v_2(\text{bottom})>0$?!

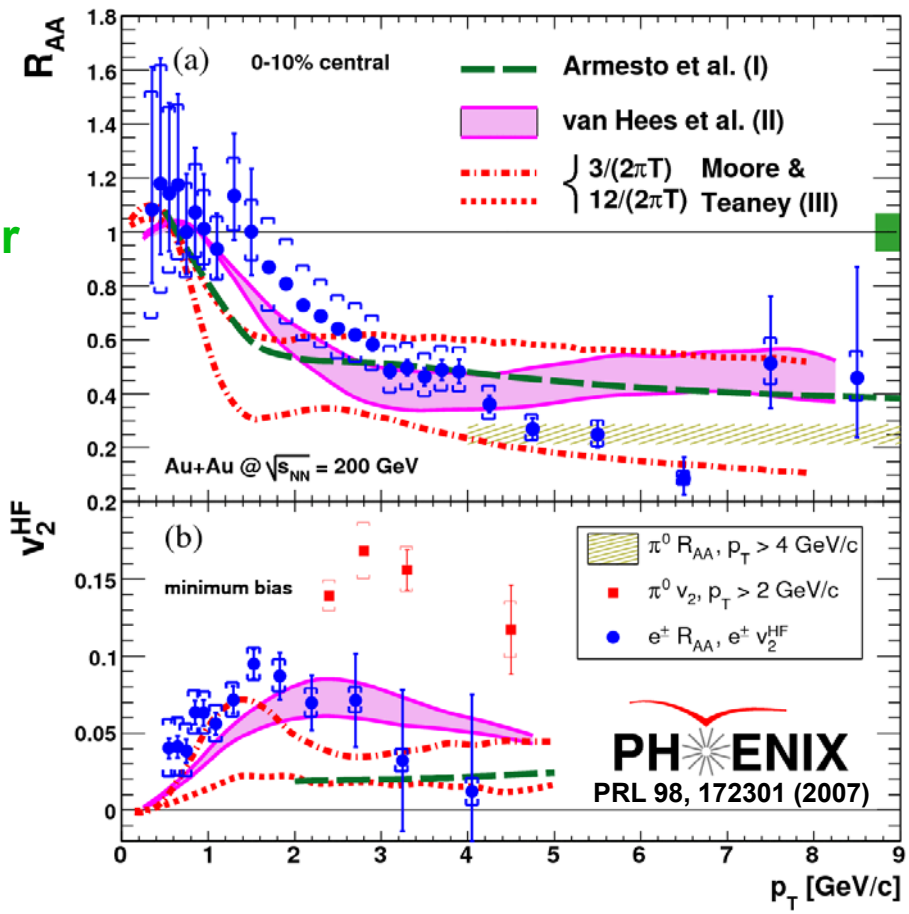


Non-central Collisions



A (near) perfect fluid?!

- transport of heavy quarks in the medium
  - Rapp & van Hees (PRC 71, 034907 (2005))
    - small relaxation time required for simultaneous fit of R_{AA} and v_2
    - → diffusion coefficient D_{HQ}
  - Moore & Teaney (PRC 71, 064904 (2005))
    - difficulties to describe R_{AA} and v_2 simultaneously
    - relate D_{HQ} with viscosity density of the medium
- suggests
  - $\eta/s = (1.3\text{-}2.0)/4\pi$
  - close to a conjectured lower bound ($\eta/s = 1/4\pi$)



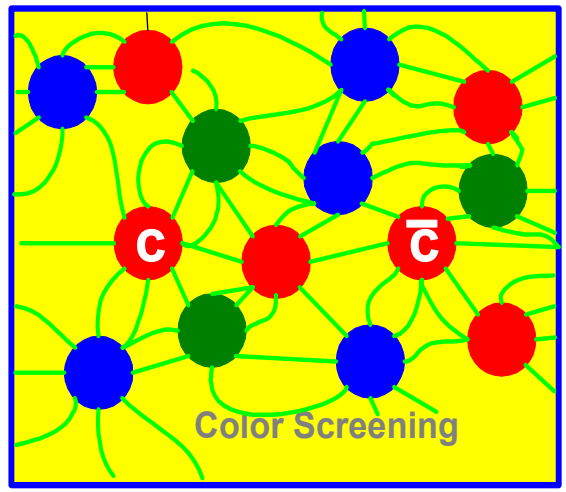
- consistent with other estimates of η/s based on flow and fluctuation measurements for light hadrons

Summary I: open heavy flavor

- hard probe for medium produced in HI collisions
- at RHIC
  - first attempt of a systematic "tomographic" study
    - calibration in p+p collisions
      - experiments are sensitive to charm and bottom production
      - pQCD describes heavy flavor production (but has large uncertainties)
      - PHENIX & STAR disagree in total cross section (by a factor ~2)
    - (cold nuclear matter modifications in d+Au collisions)
      - no large effects observed
      - not enough data (yet)
    - hot medium effects in Au+Au collisions → many surprises
      - substantial high p_T suppression of charm
      - charm "flows"
      - even bottom is affected by the interaction with the medium
  - detector upgrades (vertex trackers) are needed to unambiguously separate open charm from open bottom

Closed heavy flavor (quarkonia)

- a different probe for the medium
- 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



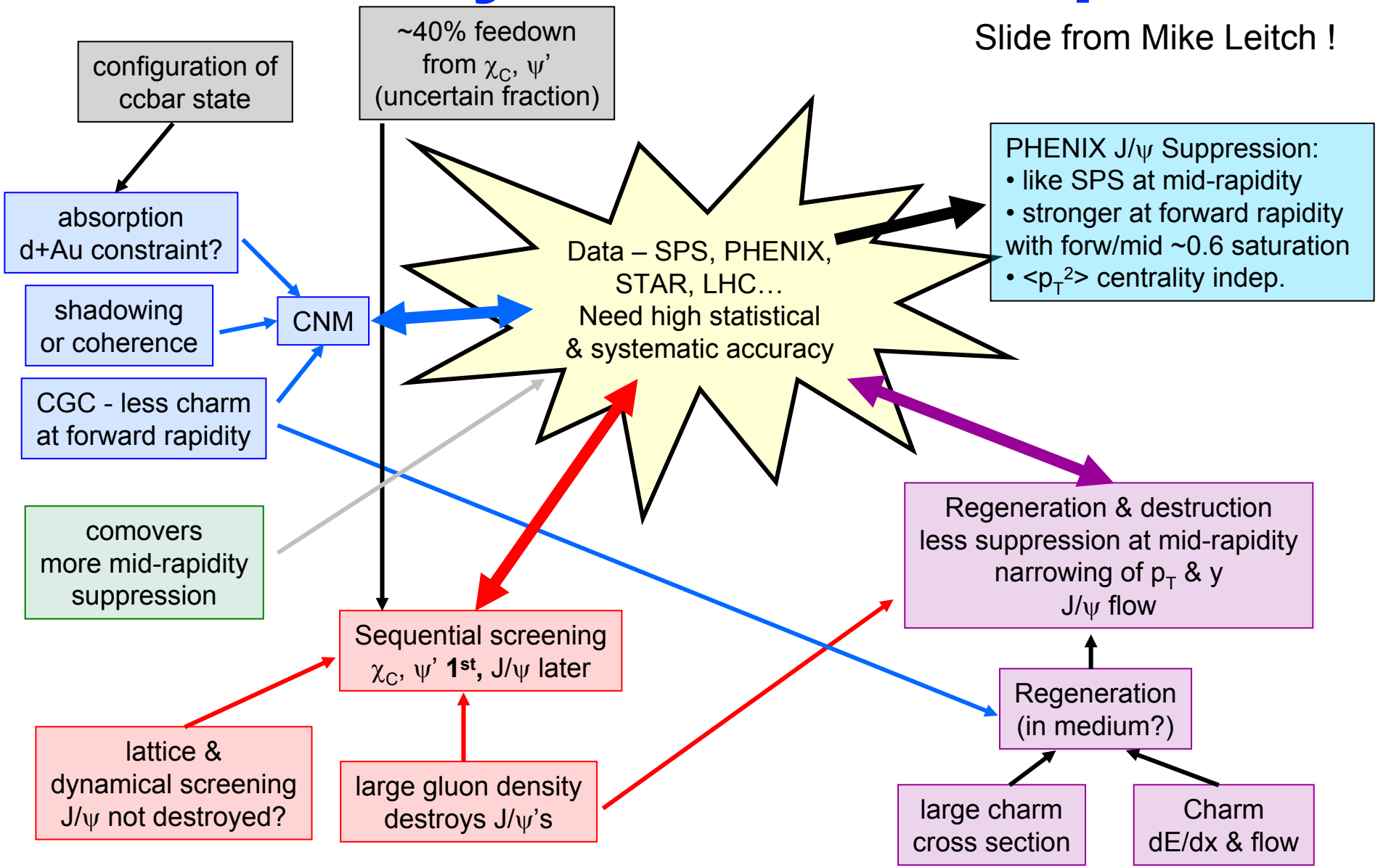
- examples for dissociation temperatures (work in progress)

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
- also from lattice correlators

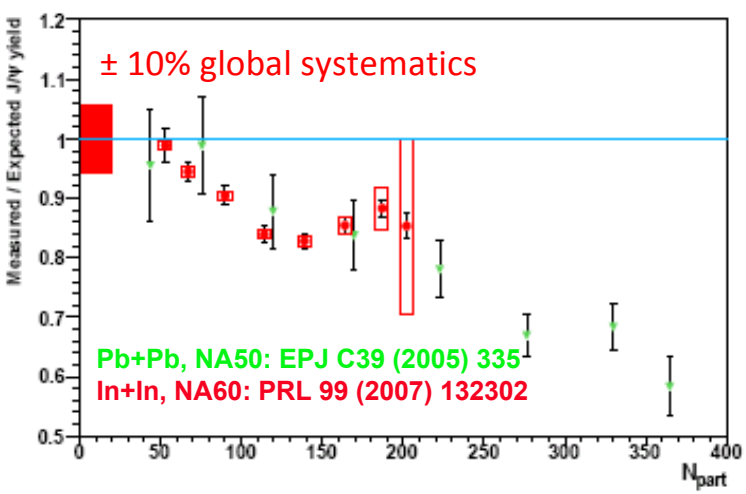
The story is more complex

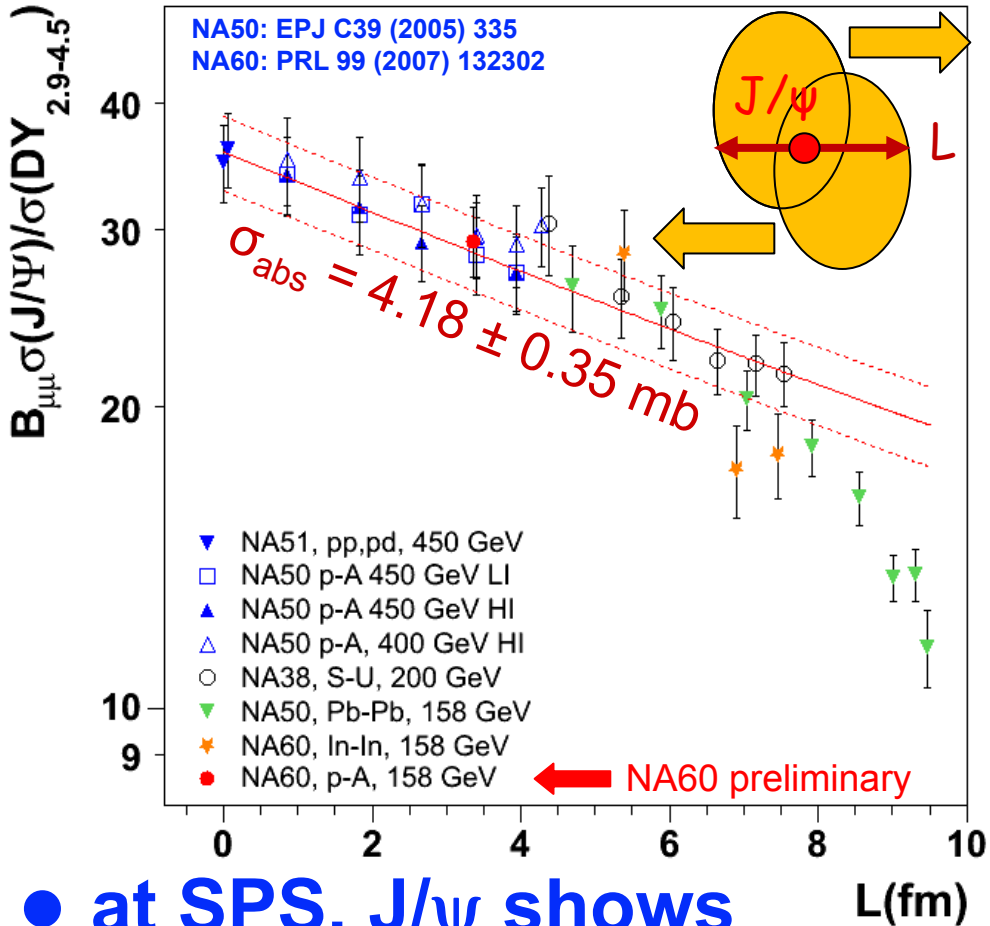
Slide from Mike Leitch !



At a glance: J/ψ at SPS

- absorption in cold nuclear matter ("normal nuclear abs.")
  - good description of p+A, S+U, and peripheral In+In and Pb+Pb collisions
  - σ_{abs} = 4.18 ± 0.35 mb
- additional "anomalous suppression" in more central In+In and Pb+Pb collisions
  - sets in at N_{part} ~ 80

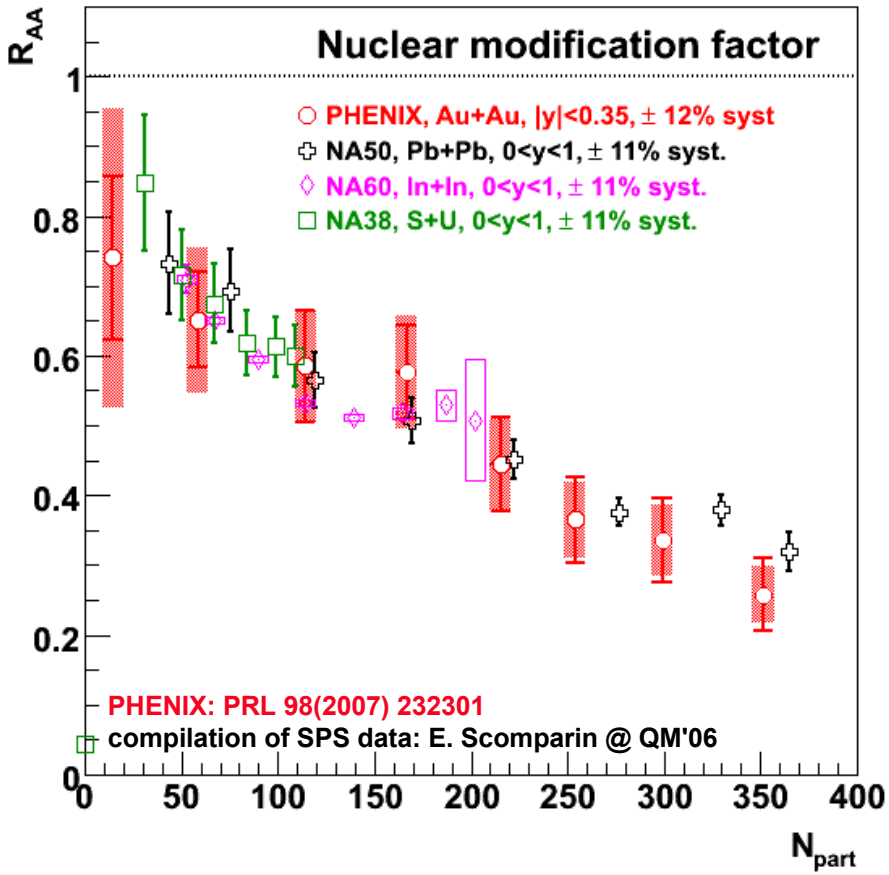




- at SPS, J/ψ shows features expected for the predicted golden QGP signature

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

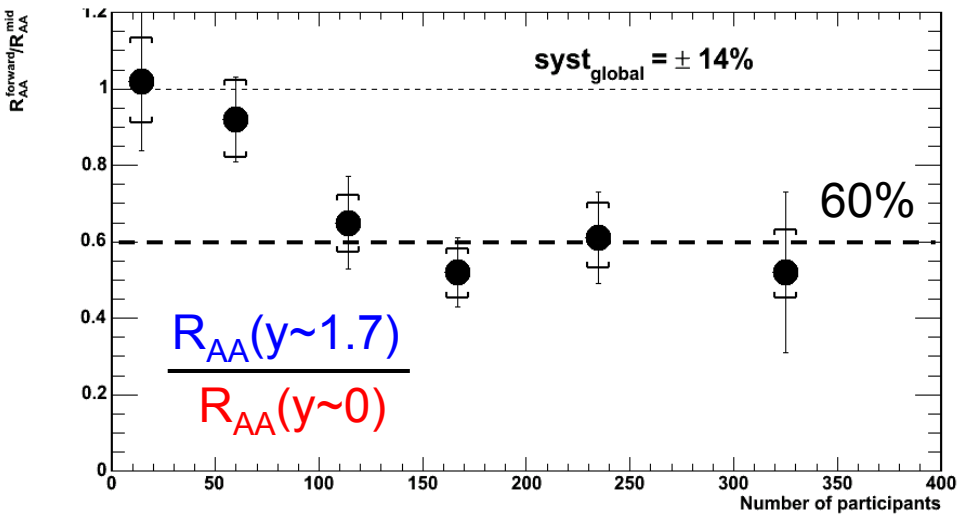
- PHENIX measures J/ψ production at RHIC
  - J/ψ → e^+e^- at |y|<0.35
  - J/ψ → $\mu^+\mu^-$ at 1.2<|y|<2.2
- mid rapidity R_{AuAu} looks surprisingly similar to R_{PbPb} at SPS
- although the systems are very different:
  - different energy densities at a given N_{part}
  - different cold nuclear matter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

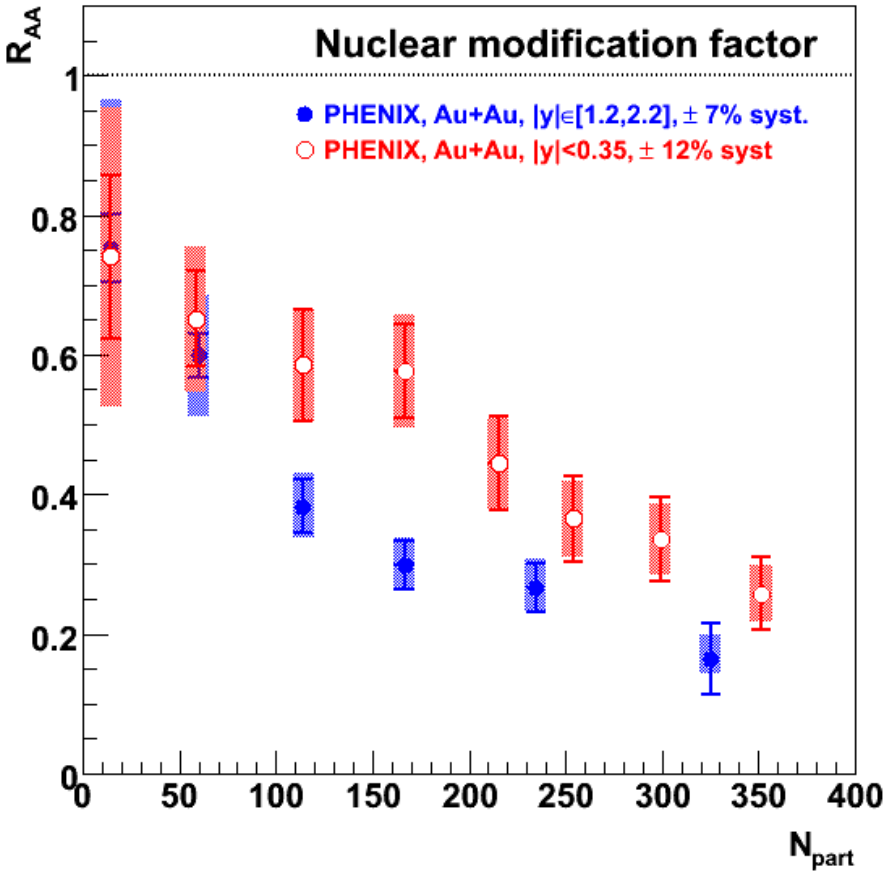


R_{AuAu} (y≈0 @ RHIC) ≈ R_{PbPb} (@ SPS)

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

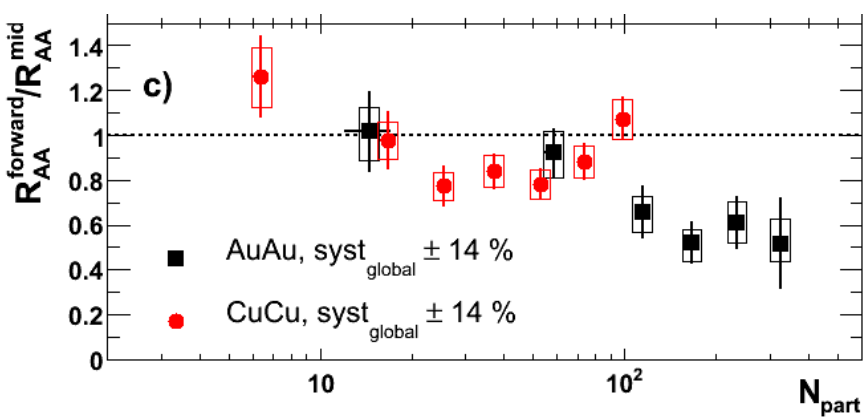


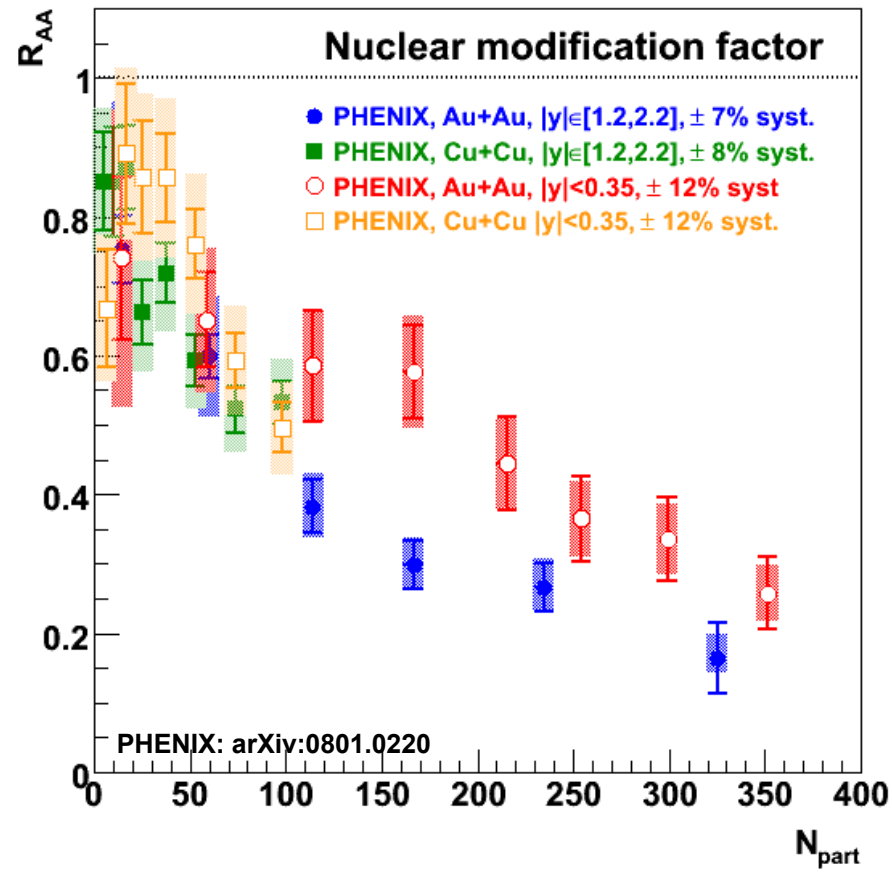


R_{AuAu} (y≈1.7) < R_{AuAu} (y≈0) @ RHIC

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

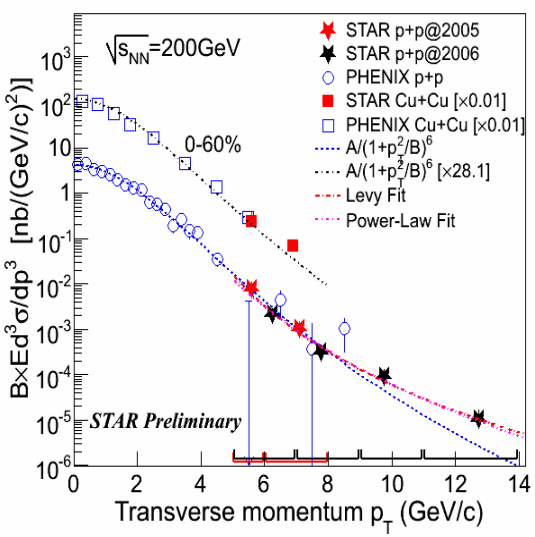
- changing the system size
  - R_{AuAu} versus R_{CuCu}
  - suppression patterns are similar
  - comparison between mid and forward rapidity
    - slightly less suppression at forward rapidity
    - consistent with data from Au+Au collisions

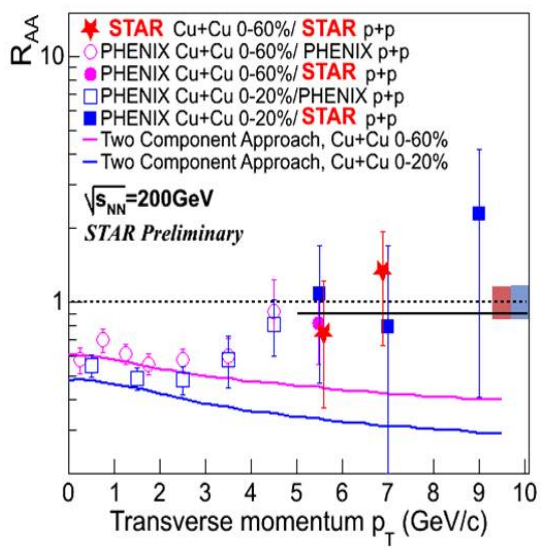


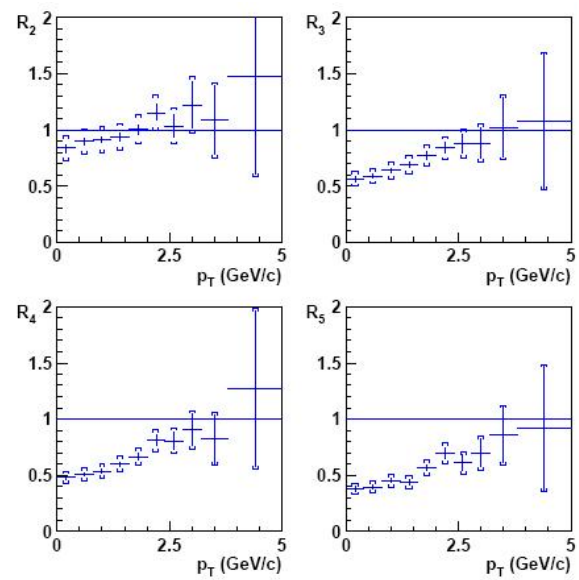


J/ψ R_{AA}: p_T dependence

- observation: J/ψ less suppressed towards high p_T
  - d+Au, Cu+Cu, Au+Au at RHIC/PHENIX (note: J/ψ from STAR in Cu+Cu in agreement with PHENIX data)
  - Pb+Pb (R_{CP}) at SPS/NA60







- potential reasons
  - Cronin effect (initial state scattering)?
  - reduced shadowing for higher x_{BJ} at high p_T?
  - J/ψ "escape", i.e. formation of high p_T J/ψ outside the medium?

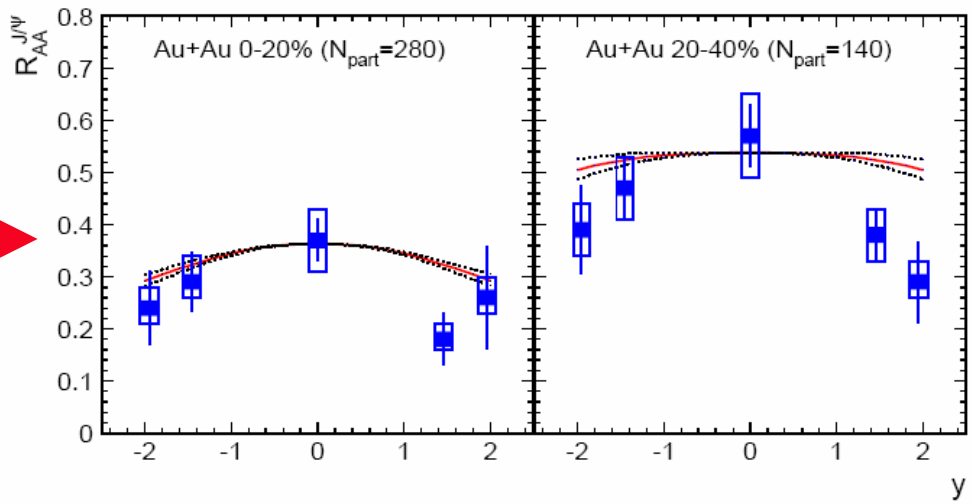
Forward rapidity "puzzle"

at RHIC, more suppression at forward rapidity !

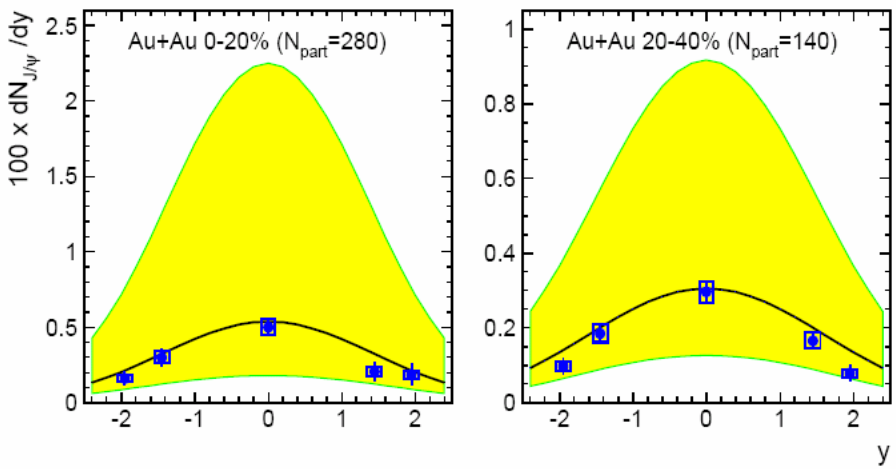
- two possible theoretical explanations
  - hot medium related
    - (re)generation of J/ψ from charm (anti)quarks in a deconfined medium
      - statistical hadronization
      - coalescence
      - regeneration
  - cold matter related
    - modification of initial parton distribution functions in cold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

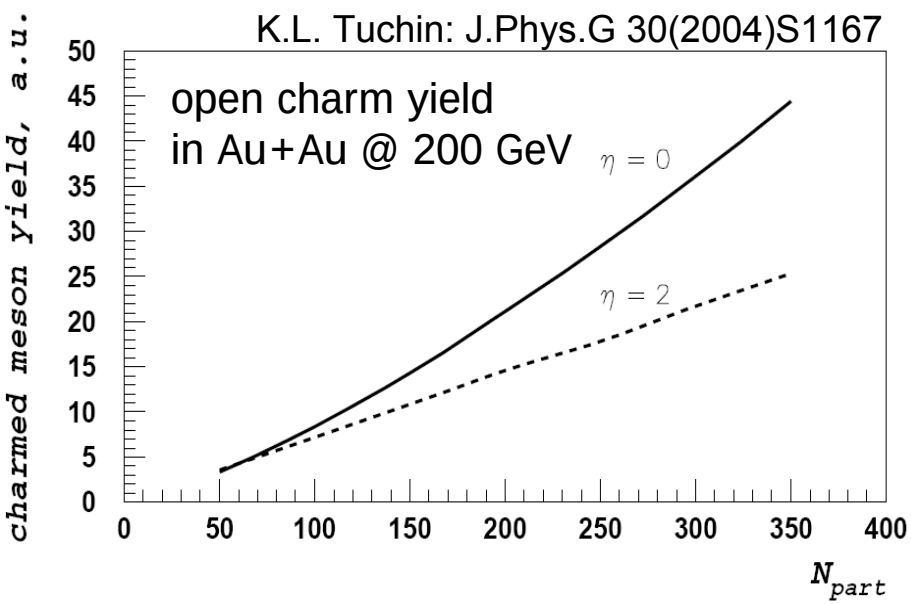


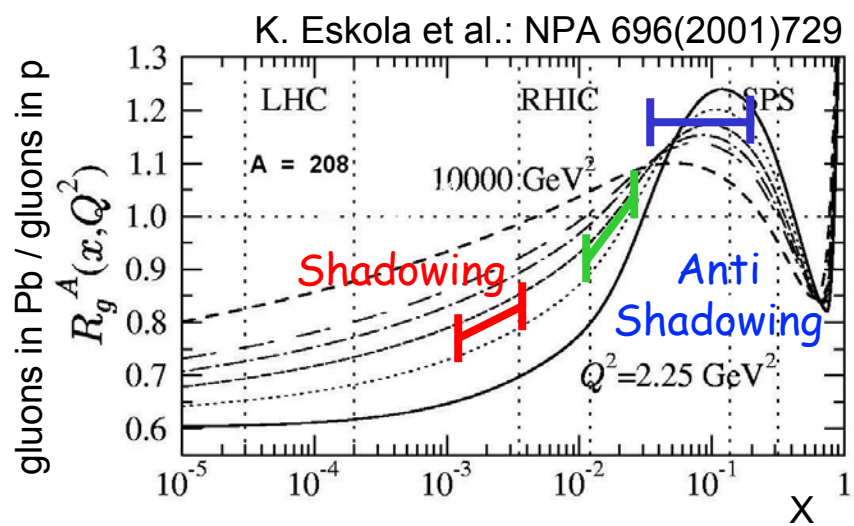
- all explain
  - $R_{AA}(y=0) > R_{AA}(y=1.7)$
  - more c quarks to recombine at y=0
- all need reliable open charm input for quantitative constraints!



Initial PDF in nuclei

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



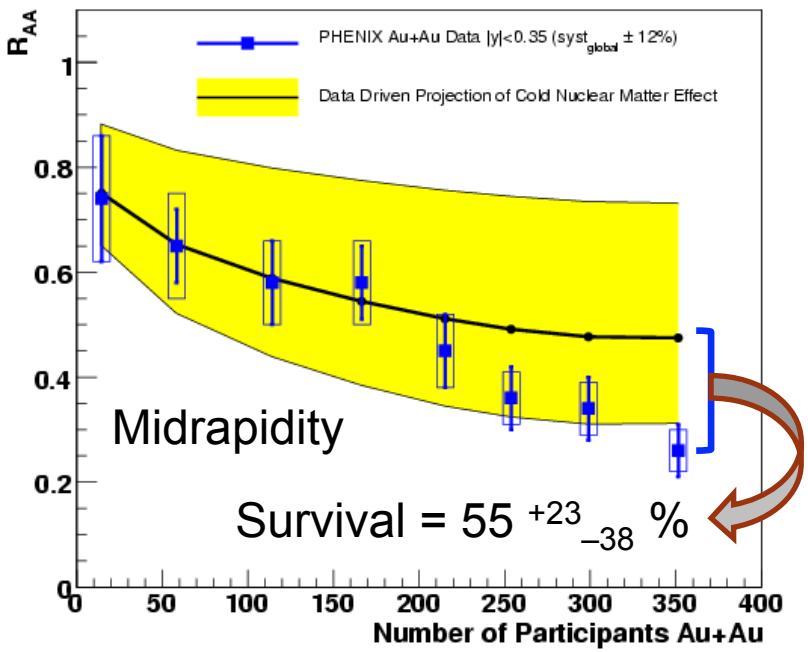


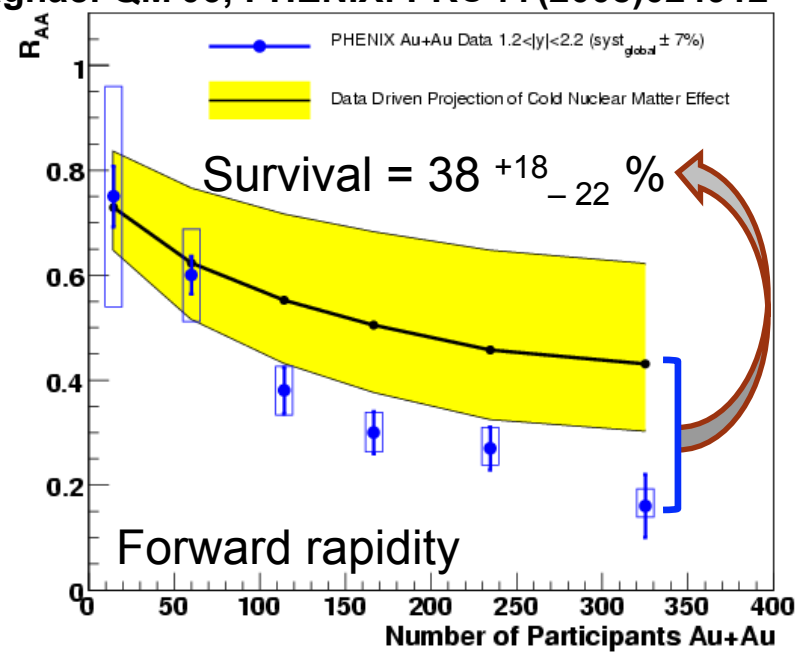
- **precise p(d)+A data are necessary to calibrate cold nuclear matter effects**
  - **are the existing d+Au data from RHIC good enough?**

CNM effects in Au+Au

- **propagate measured R_{dAu} to Au+Au in a Glauber model**
  - **completely data driven**
  - **no dependence on a particular absorption or shadowing scheme**

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

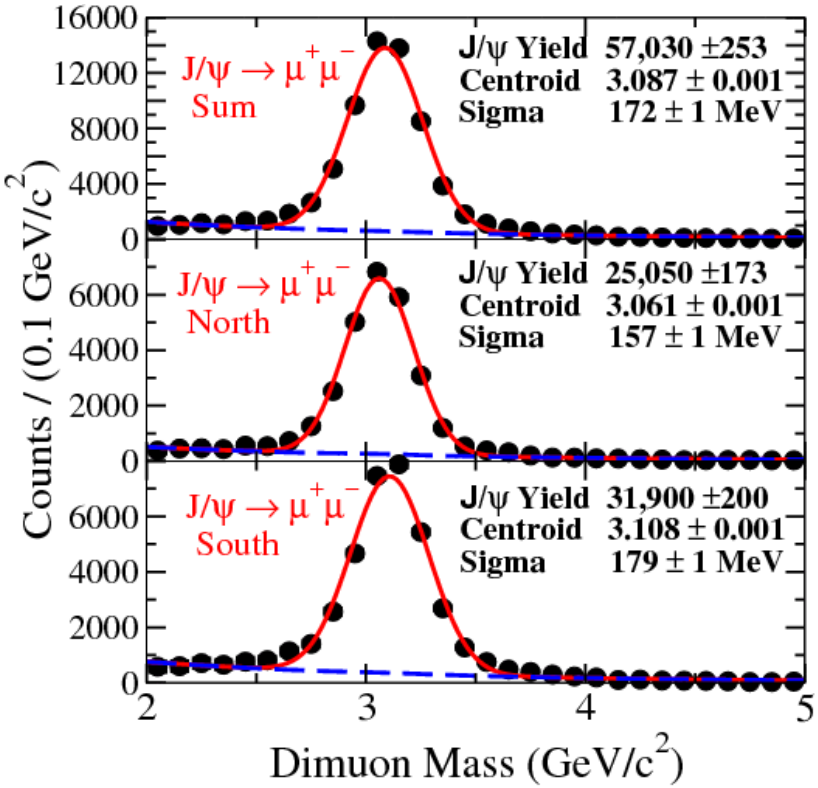


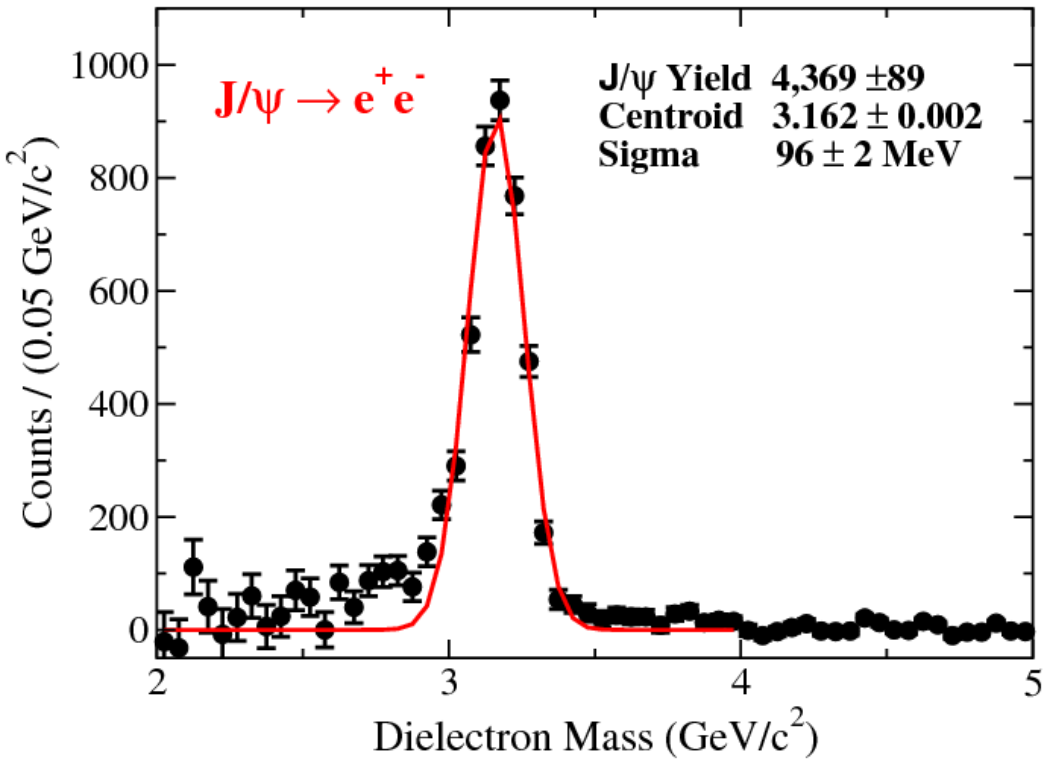


- **uncertainties are huge**
  - **anomalous suppression at least at forward rapidity**
  - **anomalous suppression could be as large at midrapidity, but it could also be negligible**

Help is on the way!

- recent d+Au run at RHIC: ~30 x the old d+Au sample

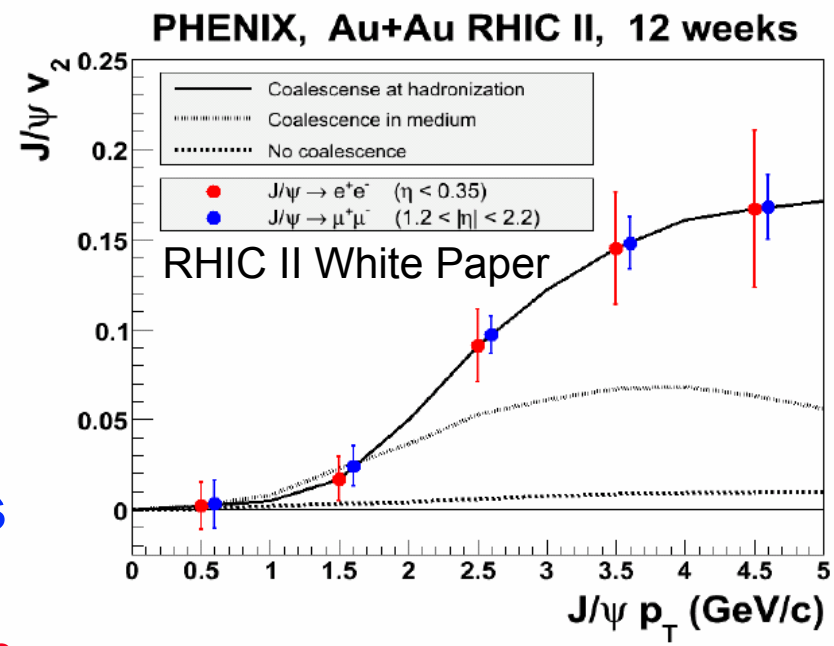


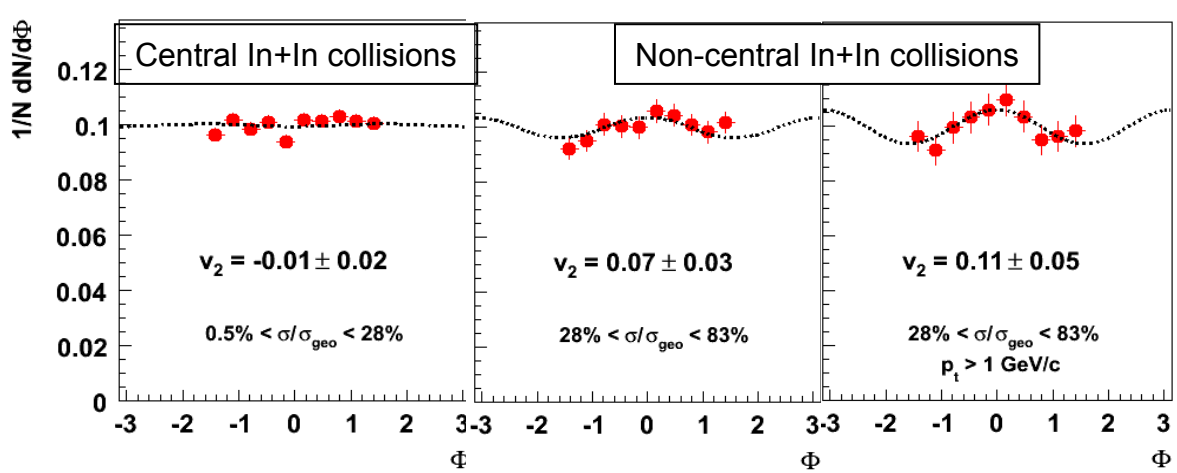


- compared to SPS, this is still low statistics!

J/ψ flow as a new smoking gun?

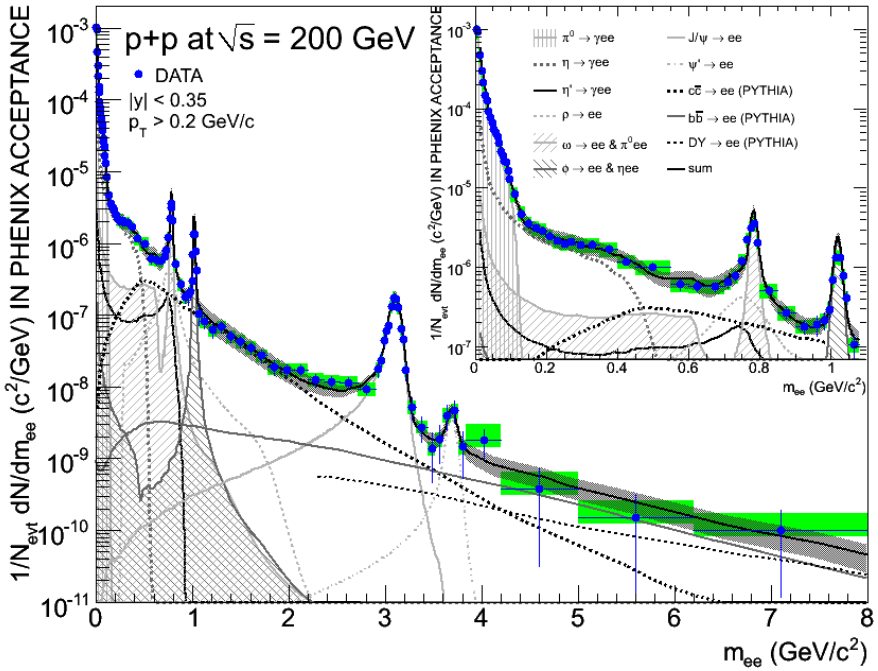
- charm flows!
- J/ψ v_2 measurement could serve as smoking gun for recombination
- no decisive data from RHIC yet
- but surprising measurements come from NA60 @ SPS
  - indication for elliptic flow in In+In
  - recombination is not expected in In+In at SPS



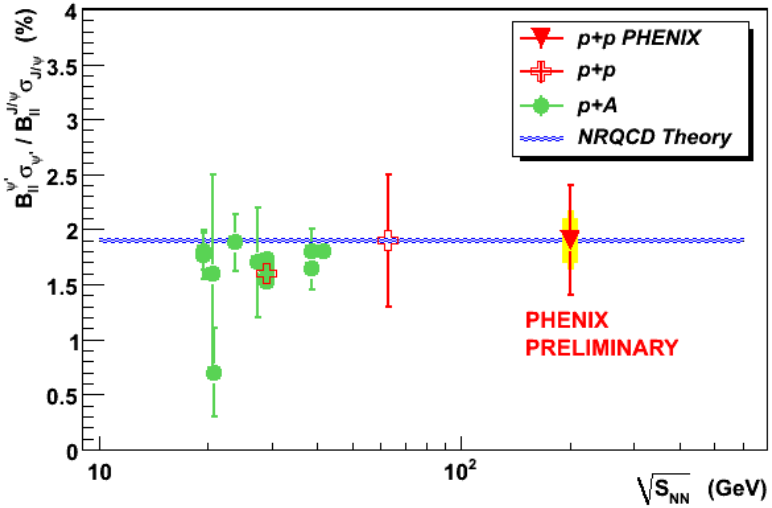


Feed down to J/ψ at RHIC

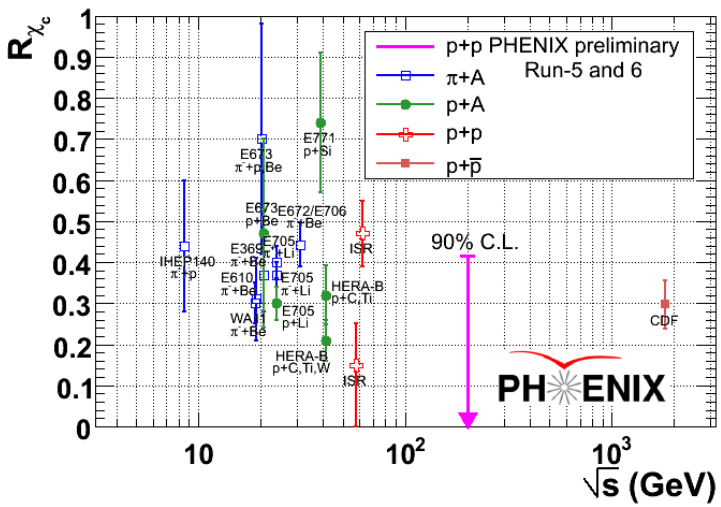
- PHENIX analysis of p+p collisions at 200 GeV



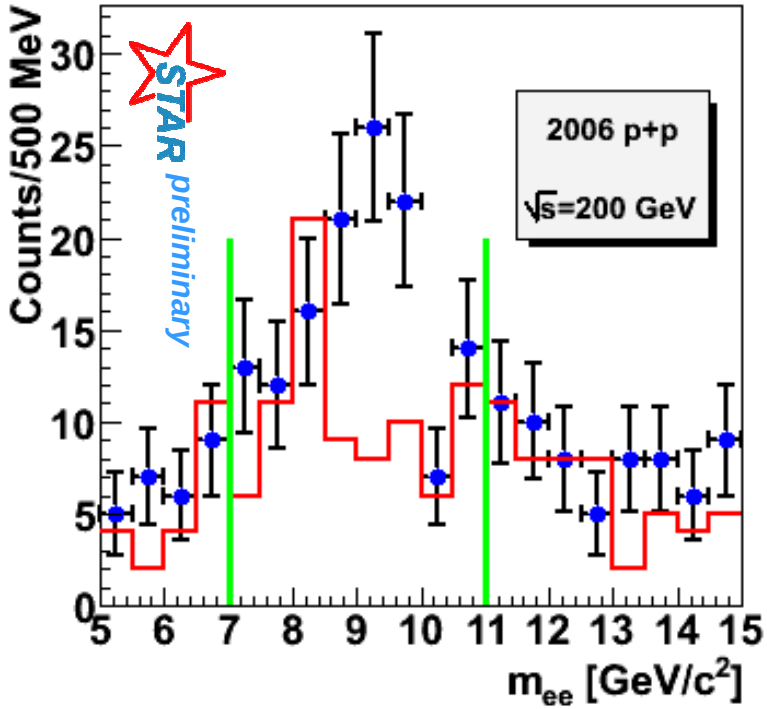
- ψ from ψ': 8.6 ± 2.5 %

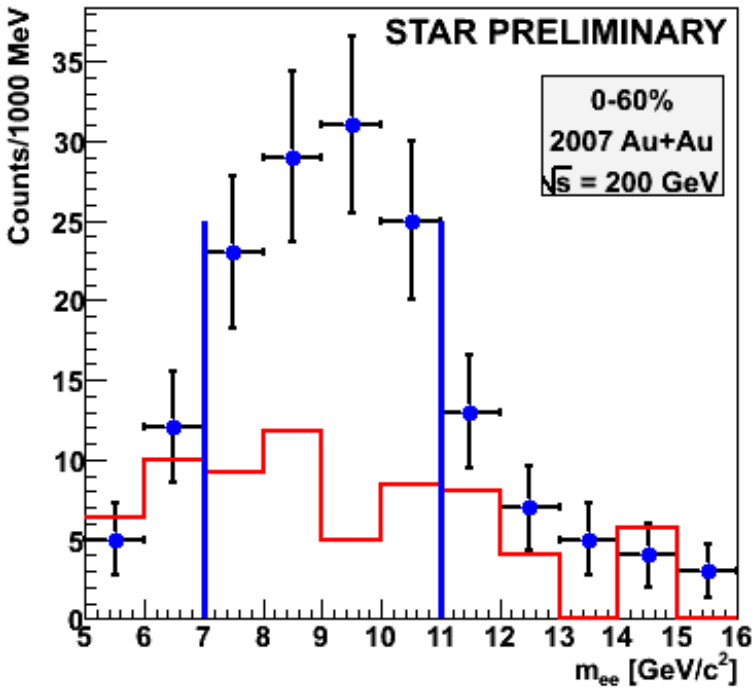


- ψ from B: 4 +3 -2 %
- ψ from χ_c < 42% (90% C.L.)



Bottomonium at RHIC

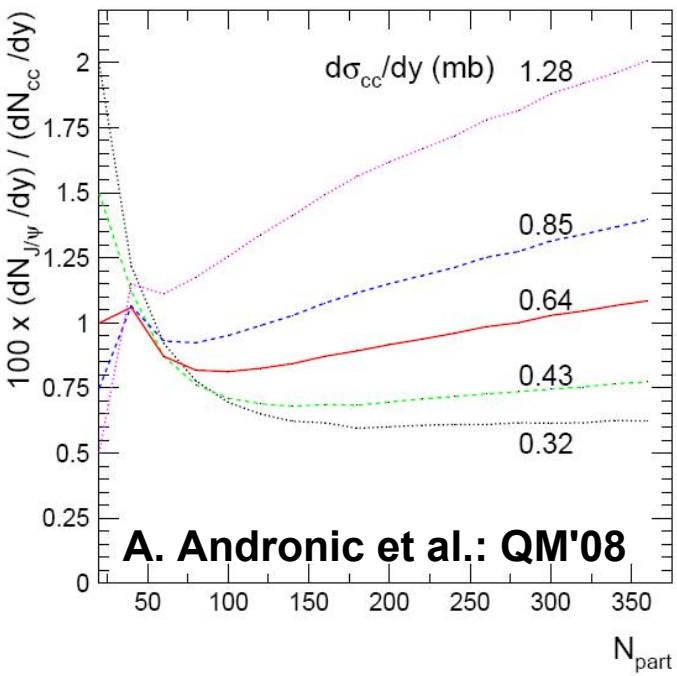




- STAR reconstructs ~50 Υ in p+p and Au+Au collisions
- excited states can not be resolved
- nuclear modification factor could reveal melting of excited states
- more to come

Summary II: quarkonia

- no complete picture yet
- long and successful experimental program at SPS
  - ongoing analysis provides further insight
- new data from RHIC
  - provide important constraints for models
  - not (yet) precise enough (in particular d+Au reference)
  - difference between mid and forward rapidity
    - regeneration vs. saturation vs. ?
- more (and better) data are coming
  - CNM reference
  - feed down
  - bottomonium
- just on the horizon: heavy quarks @ LHC
- a little further down the line: heavy quarks @ FAIR

Outlook: heavy quarks at LHC

- abundant production of heavy quarks
  - central Pb+Pb collision @ 5.5 TeV
    - ~100(5) cc(bb) pairs, i.e. 10(100) times the yield at RHIC
- detectors for clean heavy-flavor measurements
- promise to answer many open questions
- example: J/ψ from regeneration?
  - stronger quarkonia melting
  - larger CNM effects
  - more regeneration (more charm)
  - prediction for regeneration scenario:
    suppression → enhancement
  - a new golden signal?