Highlights from the Relativistic Heavy Ion Collider

BROOKHAVEN NATIONAL LABORATORY

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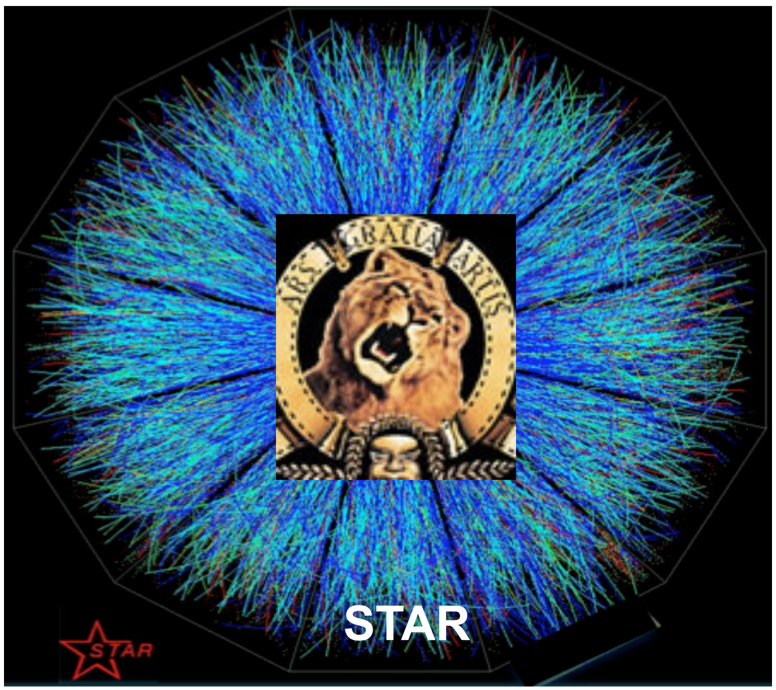
International Workshop on New Discoveries at the LHC, Kruger Park, South Africa, 3-7 Dec 2012



Outline

Introduction – physics goals and experimental set up

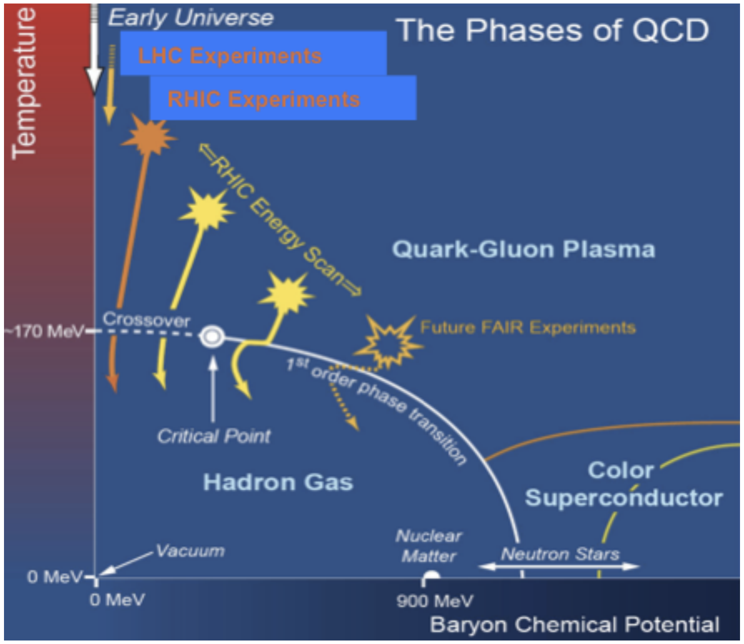
Results on:

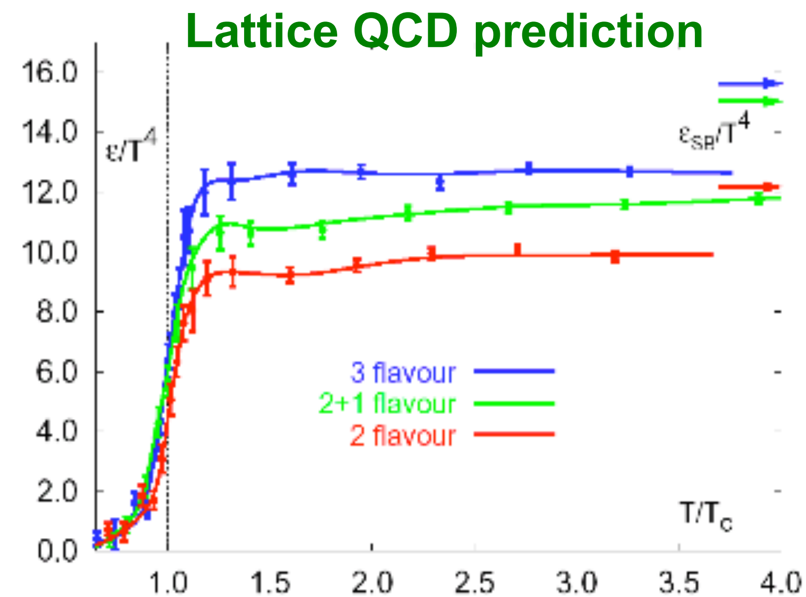
1 Direct photons
2 Jet quenching
3 Open heavy flavour
4 Quarkonia
5 Dileptons
6 Beam Energy Scan and flow
7 Beam Energy Scan and search for the critical point

Conclusions
Outlook

Introduction – physics goals and experimental set up

Heavy Ion program at RHIC:
Map out the QCD phase diagram





Study QCD matter under extreme conditions of densities and Temperatures with Cu+Cu, Au+Au and U+U (2012) collisions up to √s_NN=200 GeV

RHIC HI program:

- **study sQGP properties at high energy up to 200 GeV**
- **scan the phase diagram with Beam Energy Scan**

Beam Energy scan at RHIC

Talk of G. Odyniec, this conference

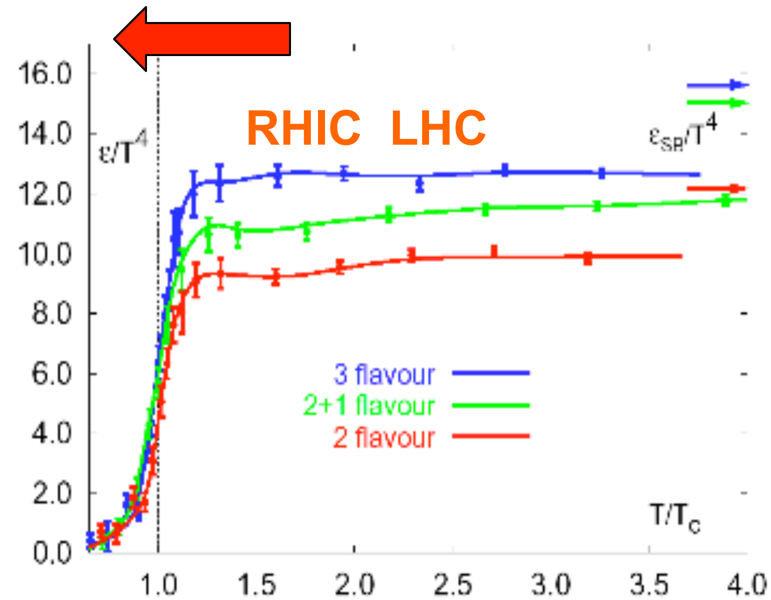
Beam Energy Scan (BES): $\sqrt{s_{NN}}$=7.7, 11.5, 19.6, 27, 39 GeV Au+Au collisions, to

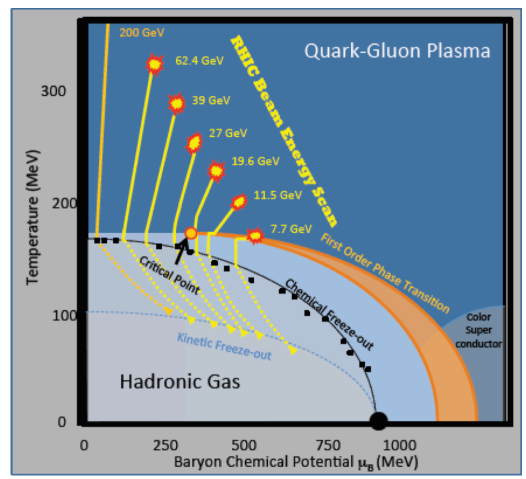
- **Discover a possible critical point,**
- **Search the √s at which QGP signals switch off,**
- **Study the nature of the phase boundary**

BES I - STAR

Year	$\sqrt{s_{NN}}$ (GeV)	Events (10^6)
2010	39	130
2011	27	70
2011	19.6	36
2010	11.5	12
2010	7.7	5
2012*	**5**	Test Run

RHIC BES





Relativistic Heavy Ion Collider

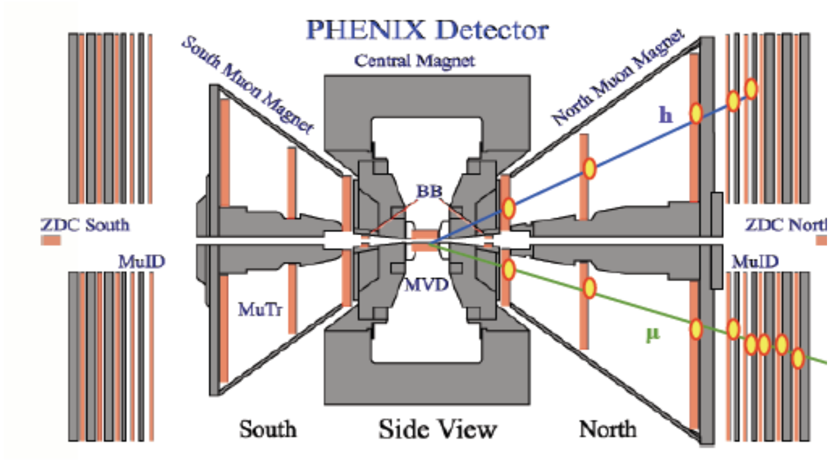
at the Brookhaven Lab, Long Island, New York, USA

RHIC has been exploring nuclear matter at extreme conditions over the last decade 2000-2011

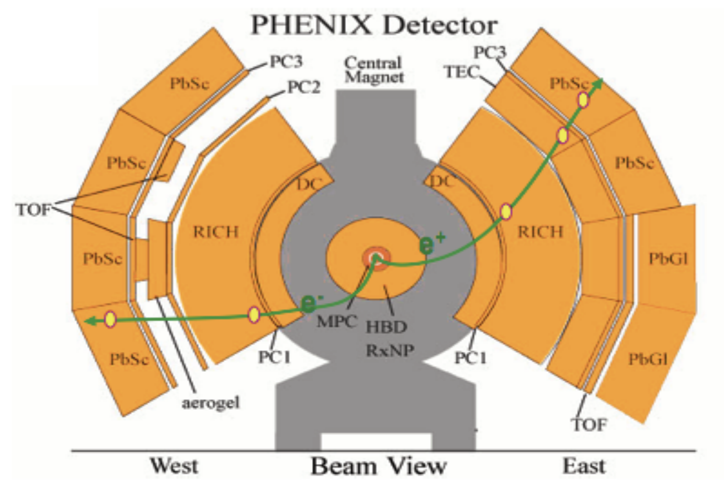
4 experiments:
STAR PHENIX
BRAHMS PHOBOS

Colliding systems:
p↑+p↑, d+Au, Cu+Cu, Au+Au
Cu+Au, U+U
Energies A+A :
$\sqrt{s_{NN}}$ = 62, 130, 200 GeV
and low energy scan
7.7, 11.5, 19.6, 22.4, 27, 39 GeV

STAR and PHENIX detectors at RHIC

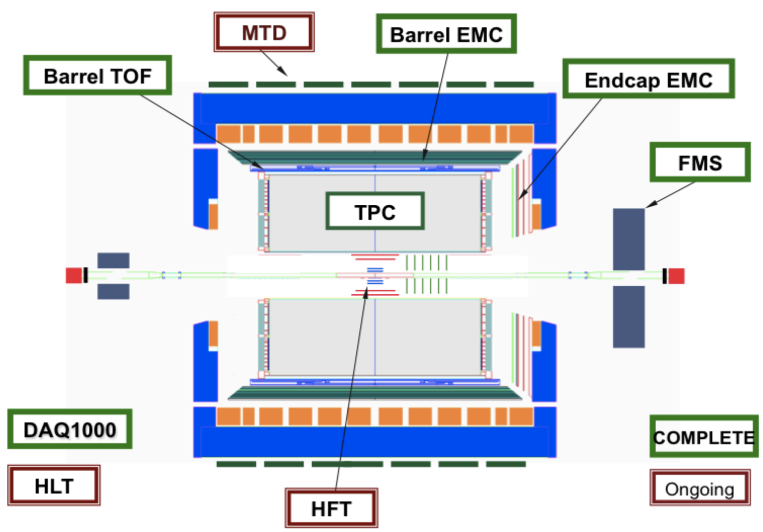


1.2<|y|<2.2 ΔΦ=2π



|y|<0.35 ΔΦ=2xπ/2

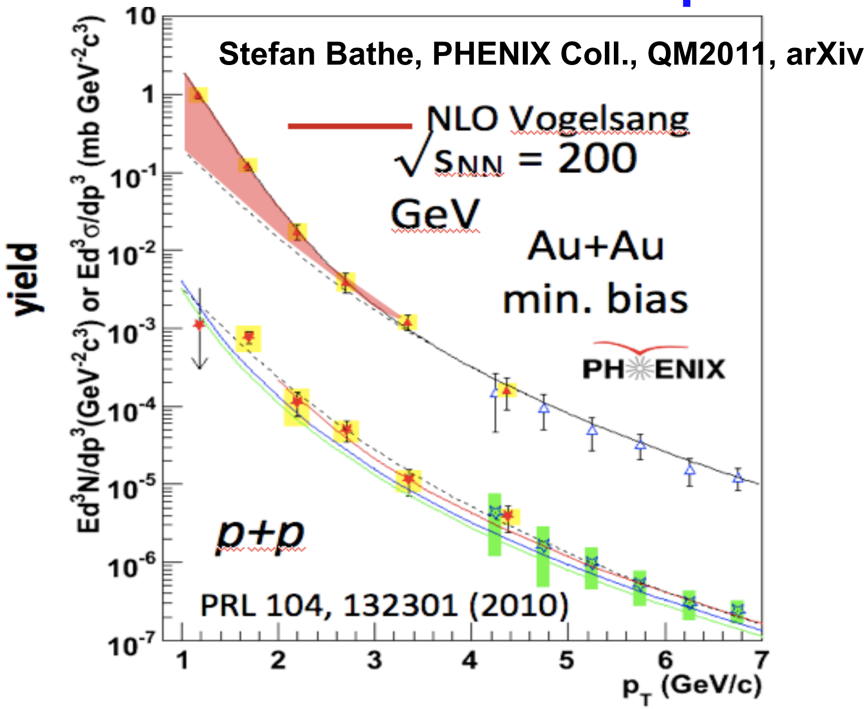
PHENIX: two central arms cover midrapidity: Drift Chamber, multiwire proportional pad chamber, ring-imaging Cherenkov counter (RICH) and electr. Cal. and forward muon measurement.

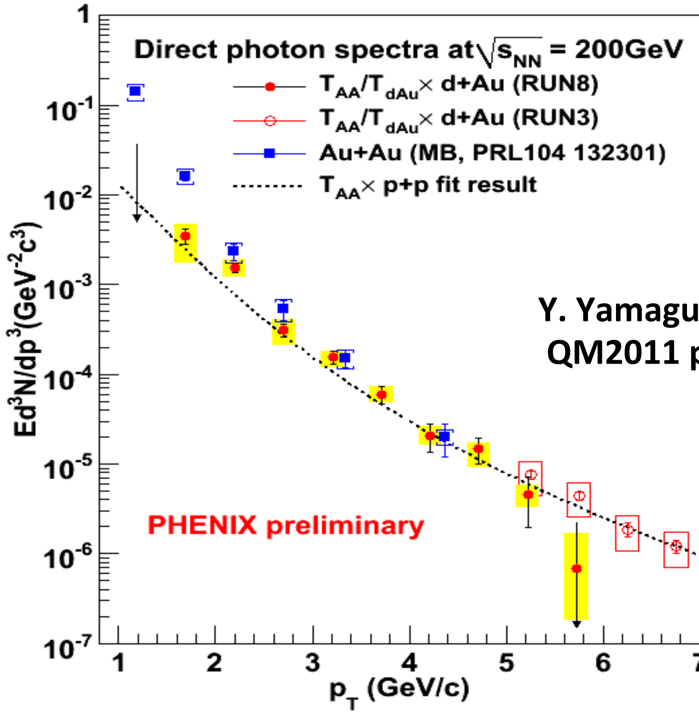


STAR : TPC, Em cal , TOF cover midrapidity, full azimuthal angle coverage

Direct photons

Previous results: Direct photon excess in min bias Au+Au at 200 GeV





Y. Yamaguchi, PHENIX Coll., QM2011 poster

Direct photons in p+p described by NLO

Direct photon excess in min. bias Au+Au at 200 GeV over p+p at 200 GeV below pT ~2.5 GeV

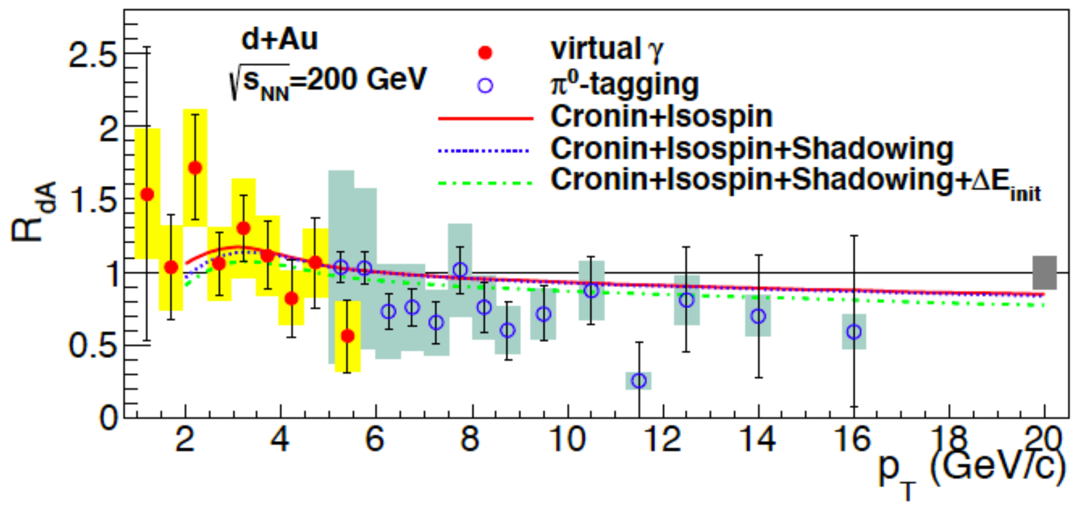
Exponential spectrum in Au+Au - consistent with thermal below pT ~2.5 GeV with inverse slope 220 ± 20 MeV --> T (init) from hydrodynamic models : 300-600 MeV, depending on thermalization time

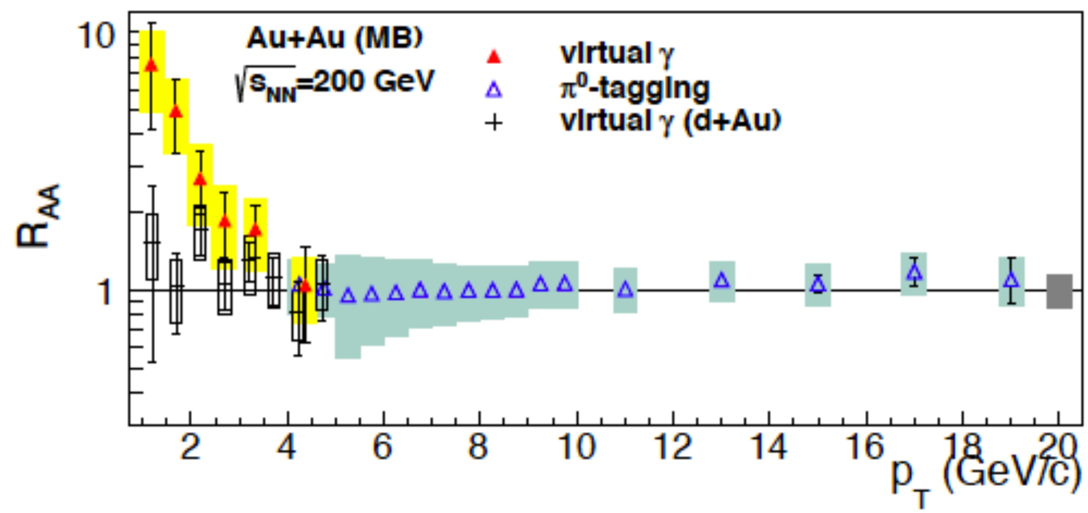
Critical d+Au check : No exponential excess in d+Au

Direct thermal photons firmly established for the first time !

BNL press release, 15 Feb 2010 : 'Perfect' Liquid Hot Enough to be Quark Soup

Direct photons in d+Au from PHENIX





data from PRL104, 132301, 2010

PHENIX 1208.1234

- RdAu direct photons pT=1-16 GeV consistent with unity

- Standard cold-nuclear-matter effects describe the RdAu data at all pts

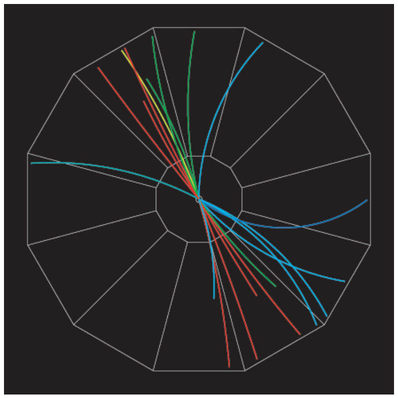
- RAuAu consistent with unity at high pt, while it shows large enhancement below pt=2 GeV compared to d+Au

- dAu data indicate that the RAuAu enhancement is due to a source other than the initial state nuclear effects.

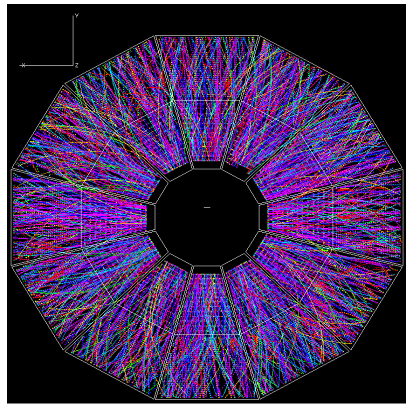
Jet quenching

Jet quenching

p+p Collision



Au+Au Collision

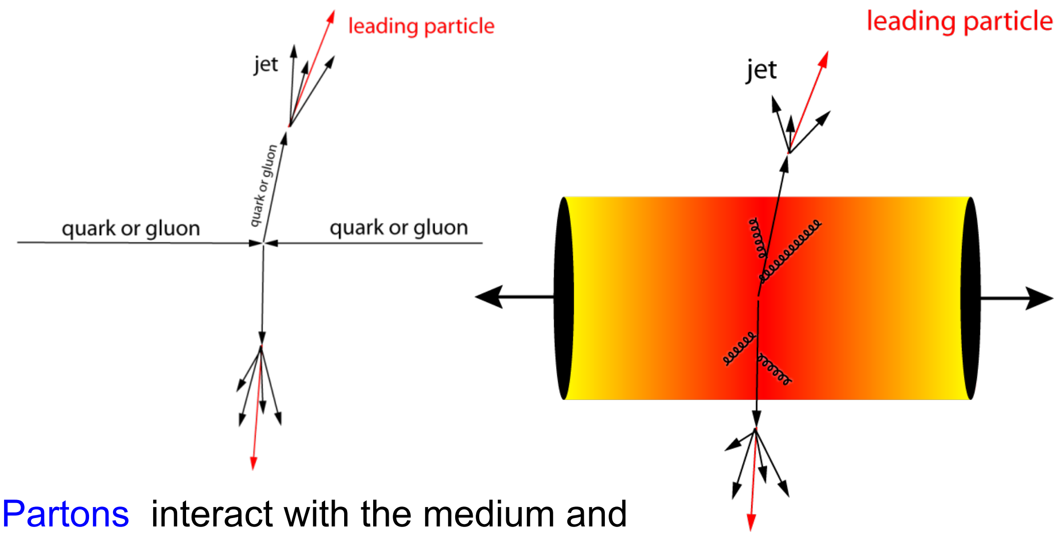


We compare A+A to expectations from p+p, using the "nuclear modification factor" R_{AA} defined as:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

N coll : Average number of NN collisions in AA collision

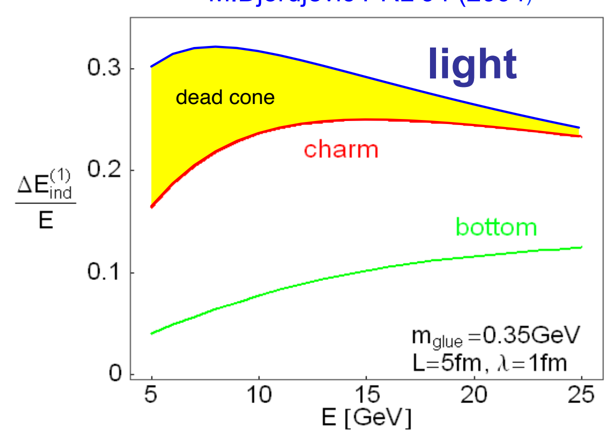
Suppression of jets in AuAu: $R_{AA} < 1$



Partons interact with the medium and loose energy through eg gluon radiation

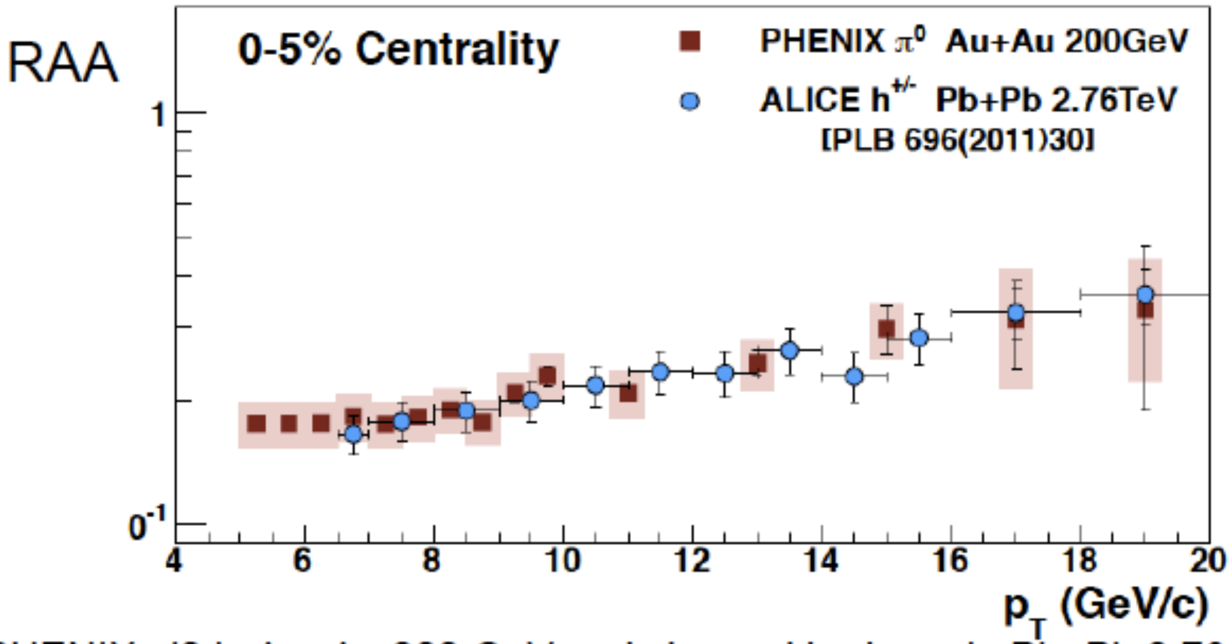
Quarks are expected to exhibit different radiative energy loss depending on their mass (**D.Kharzeev et al. Phys Letter B. 519:1999**)

M.Djordjevic PRL 94 (2004)



R_{AA} of pi^0 in Au+Au 200 GeV PHENIX compared to ALICE

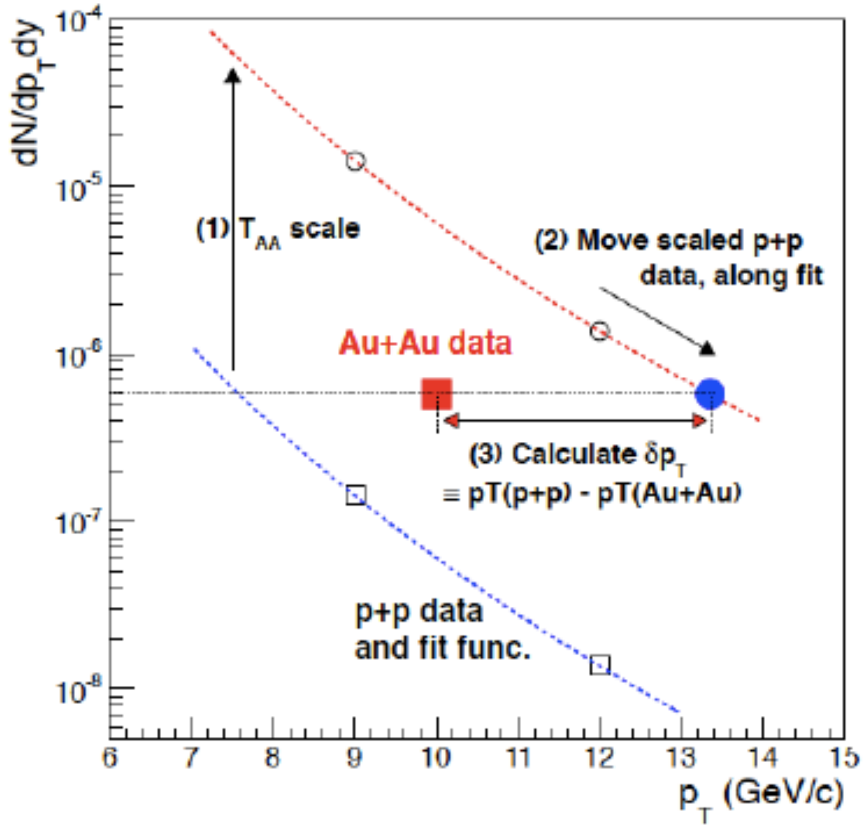
Sakaguchi, PHENIX, QM2012



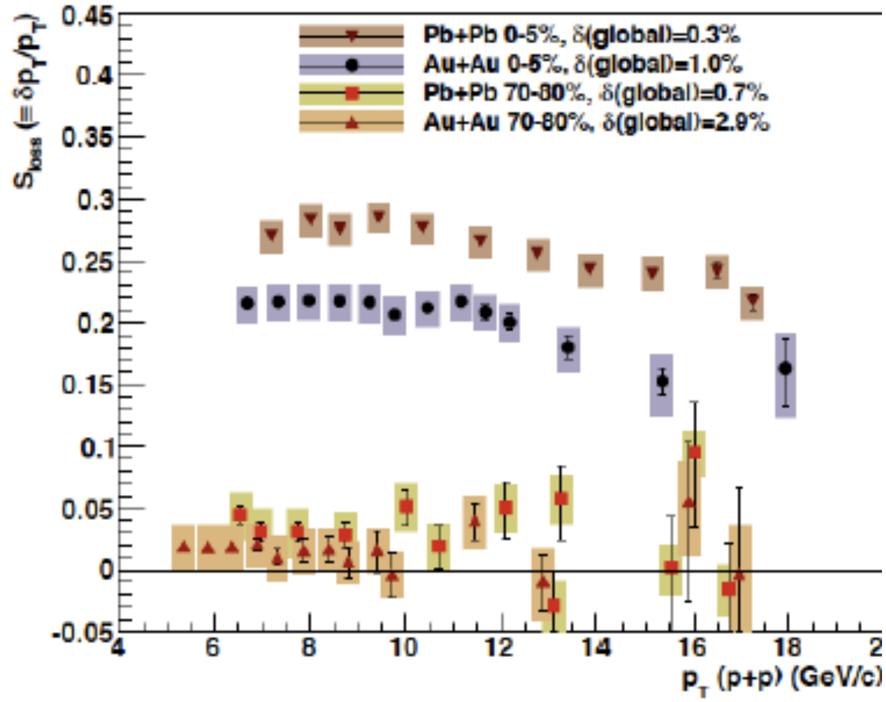
PHENIX pi0 in Au+Au 200 GeV and charged hadrons in Pb+Pb 2.76 TeV 0-5% look very similar

Fractional momentum loss from PHENIX

arXiv:1208.2254

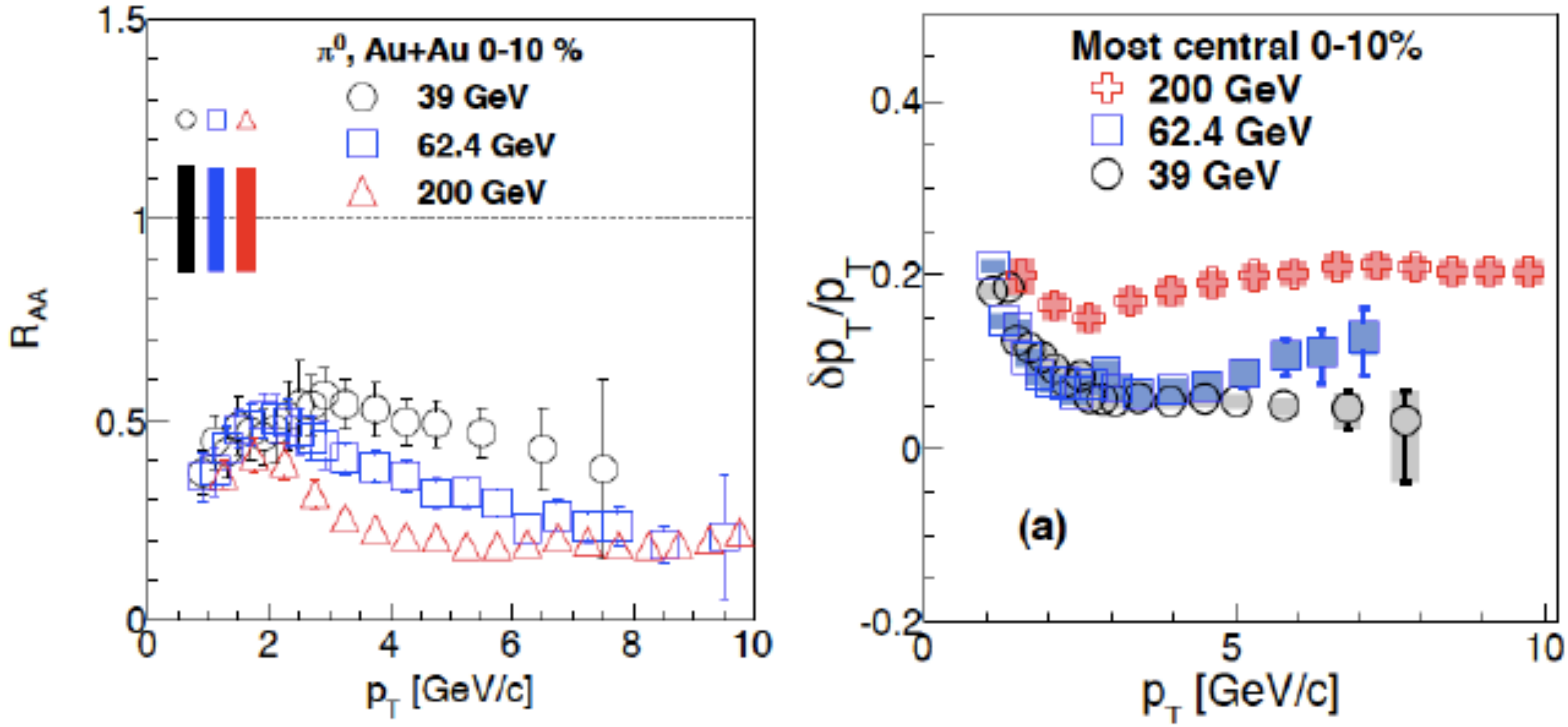


Measure fractional momentum loss instead of RAA



- Different dpT/pt for RHIC and LHC, for same RAA
- dpt/pt is 25% higher for ALICE
- dpt/pt decreases slightly with increasing pt (where rise of RAA occurs)

RHIC BES: Energy dependence of dpt/pt from PHENIX

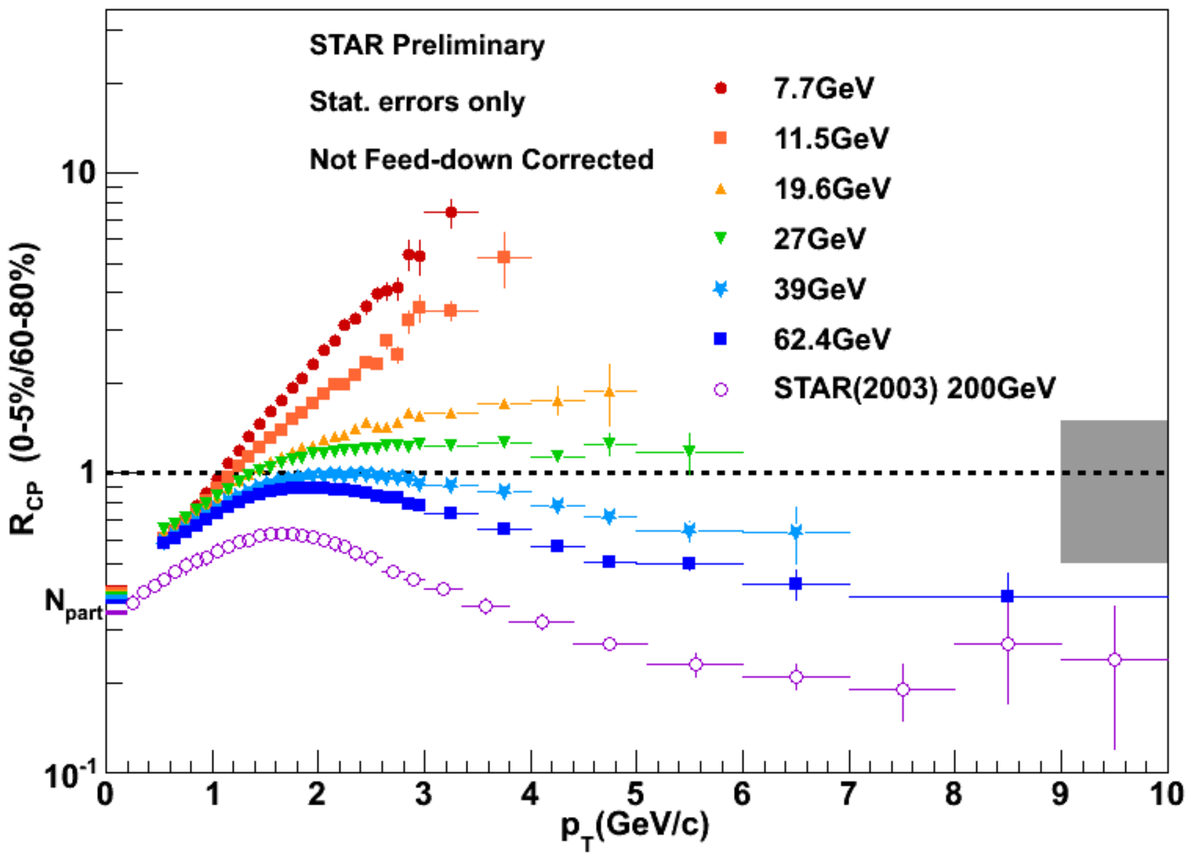


PHENIX 1204.1526, O'Brien, PHENIX QM2012

dpt/pt decreases significantly from 200 GeV to 62.4 and 39 GeV

At what collision energy does jet quenching dissapear ?

STAR Coll., QM2012



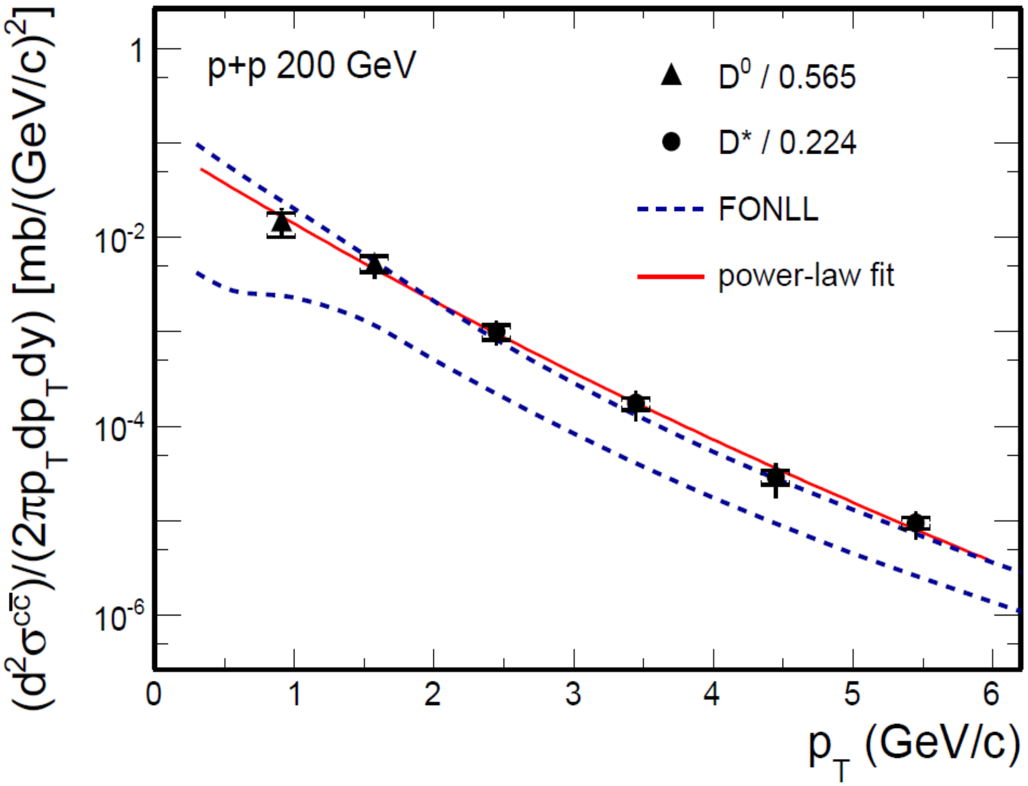
Dissappearance of R_{cp} suppression at lower energies below 39 GeV

Open Charm and Beauty

D^0 and D* p_T spectra in p+p 200 GeV

Phys. Rev. D 86 (2012) 072013.

STAR Coll.,Utrecht2012



FONLL: Fixed-Order Next-to-Leading Logarithm: M. Cacciari, PRL 95 (2005) 122001

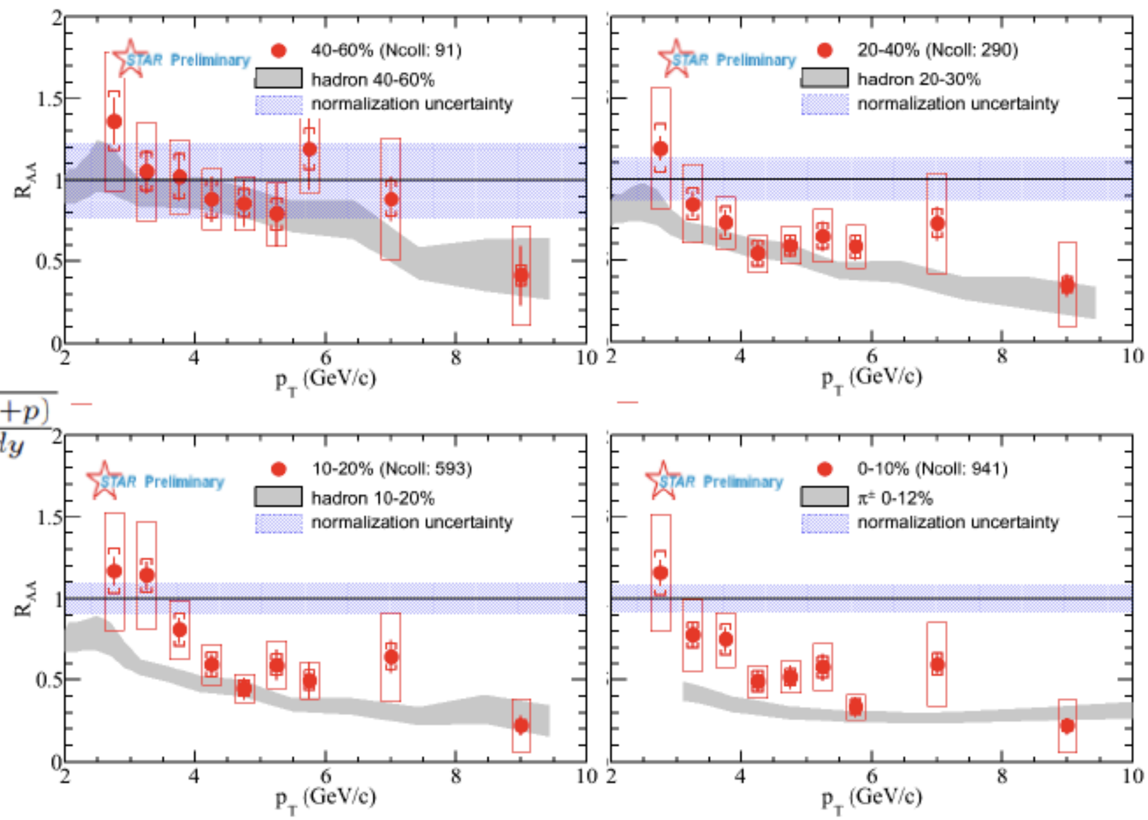
Consistent with FONLL upper limit.

Charm cross at midrapidity in p+p collisions at √s=200 GeV :

$$\left.\frac{d\sigma}{dy}\right|_{y=0}^{pp} = 170 \pm 45^{+38}_{-59}\ \mu b$$

Is there a mass dependence of jet quenching ?

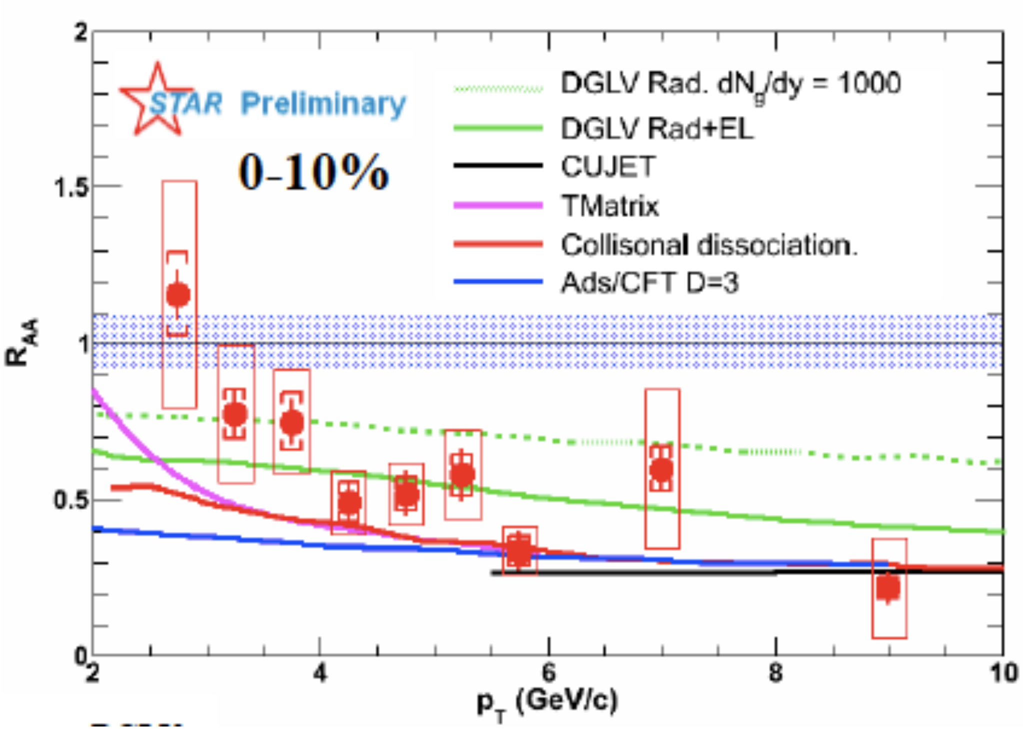
$$R_{AA} \equiv \frac{\frac{d^2N(A+A)}{dp_T dy}}{\langle N_{binary}\rangle \frac{d^2N(p+p)}{dp_T dy}}$$



STAR Coll., Utrecht 2012

R_{AA} suppression at high p_T with new Non Photonic Electron (NPE) measurement of STAR is consistent with R_{AA}(pion)

Comparison of R_{AA} NPE to models



DGLV:
Djordjevic, PLB632, 81 (2006) and references within.

CUJET:
Buzzatti, arXiv:1207.6020

T-Matrix:
Van Hees et al., PRL100,192301(2008).

Coll. Dissoc.
R. Sharma et al., PRC 80, 054902(2009).

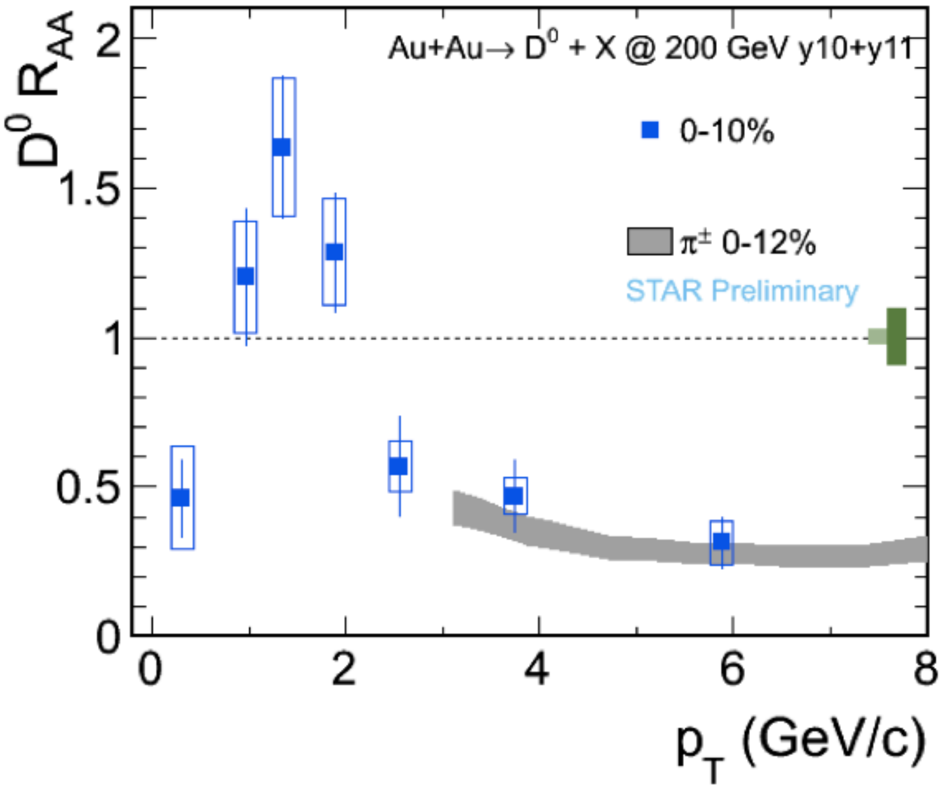
Ads/CFT:
W. Horowitz Ph.D thesis.

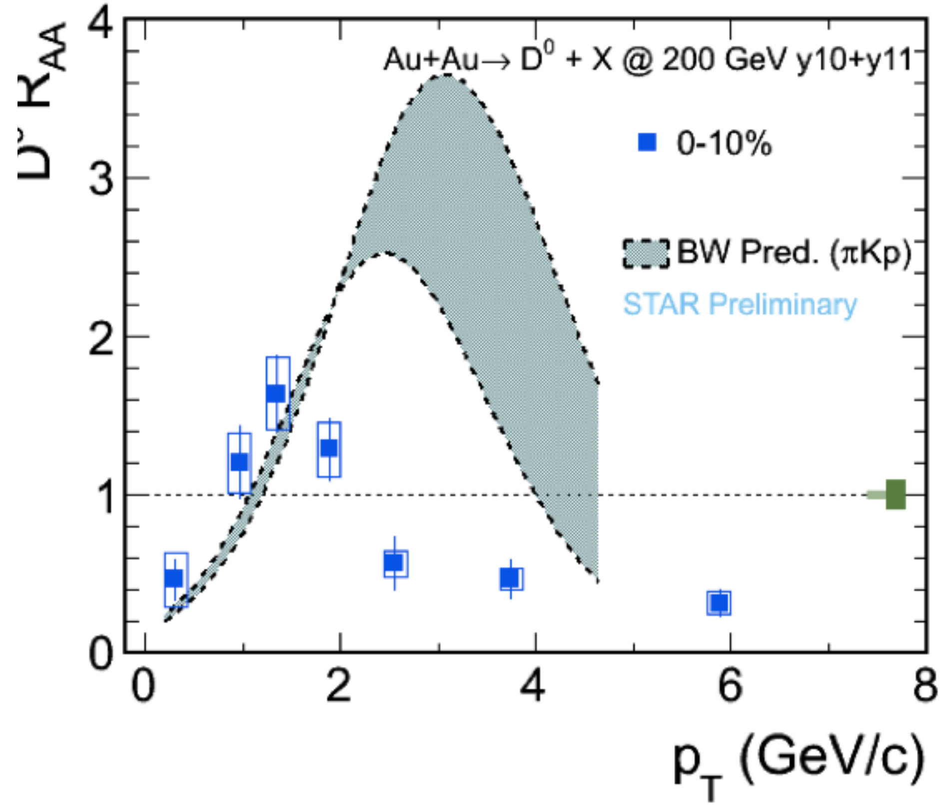
STAR Coll., Utrecht 2012

High p_T R_{AA} disfavours radiative energy loss as the only mechanism
All other ploted energy loss mechanisms agree with data at high p_T

-> more measurements are needed to differentiate the scenaria
eg beauty/charm separation, simultaneous prediction of R_{AA} and v_2, collision, p_T and centrality dependence

R_{AA} of D^0 in Au+Au at 200 GeV



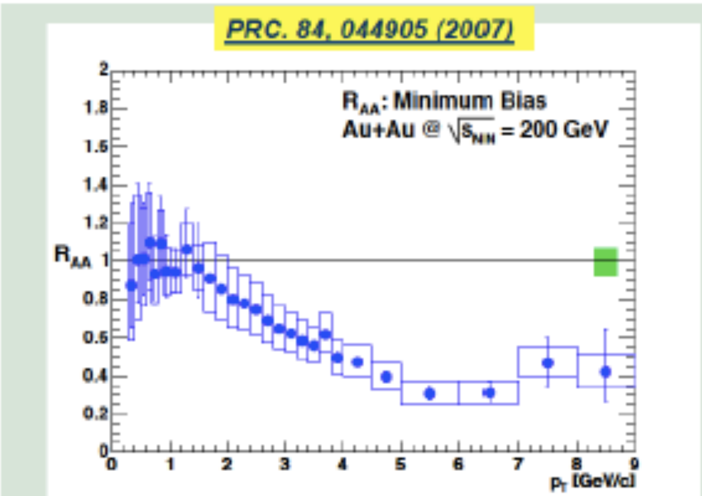


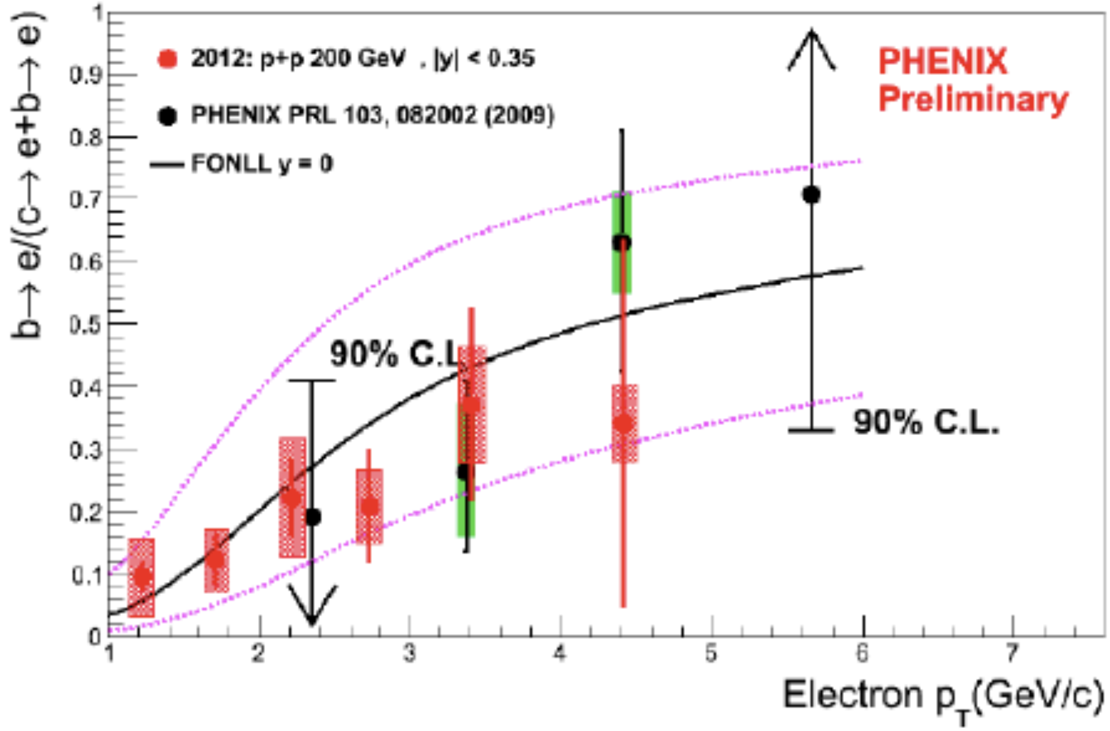
Suppression of R_{AA} in central Au+Au collisions at high p_T ~2-6 GeV/c, consistent with pions R_{AA}

Deviation of D^0 RAA from Blast Wave fit prediction from pions, kaons and protons indicates that D mesons may freeze out earlier than light hadrons

STAR Coll., Utrecht 2012

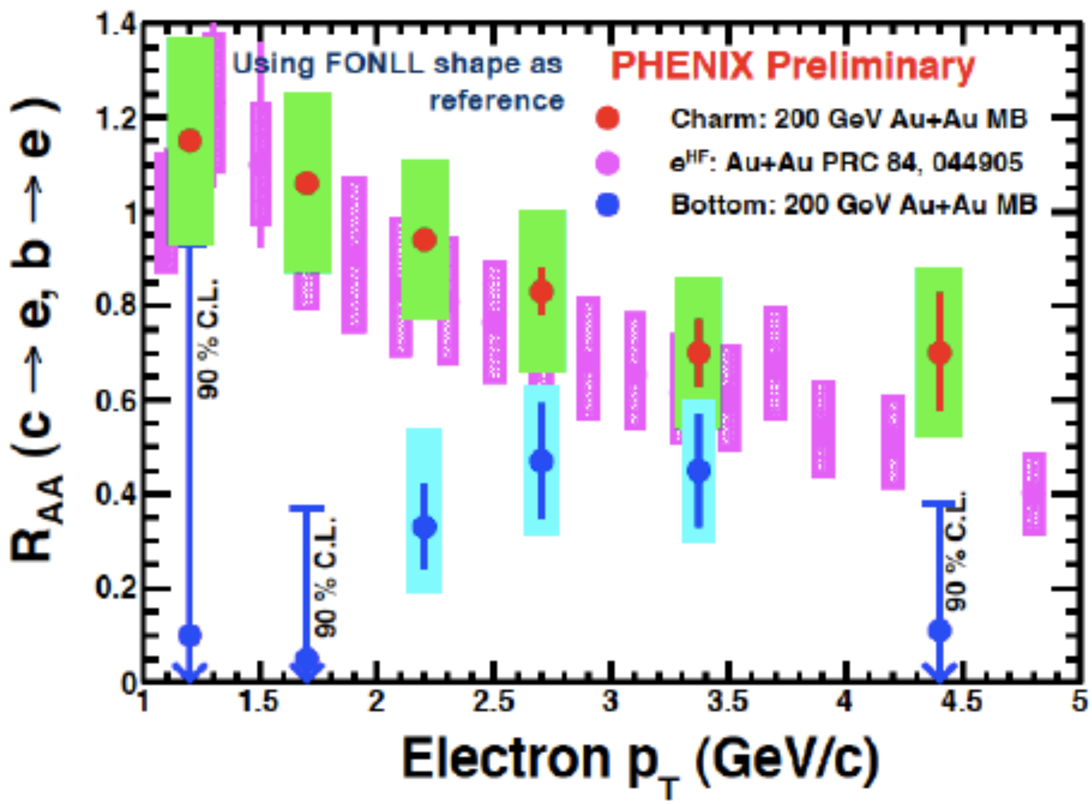
Open Heavy Flavour in PHENIX





- First direct c/b decomposition in p+p 200 GeV using the new vertex detector
- New direct measurement of beauty fraction agrees with FONLL (M Rosati, R Nouicer QM2012)

First RAA for charm and beauty measured in MinBias Au+Au from PHENIX



M Rosati,R Nouicer, QM2012

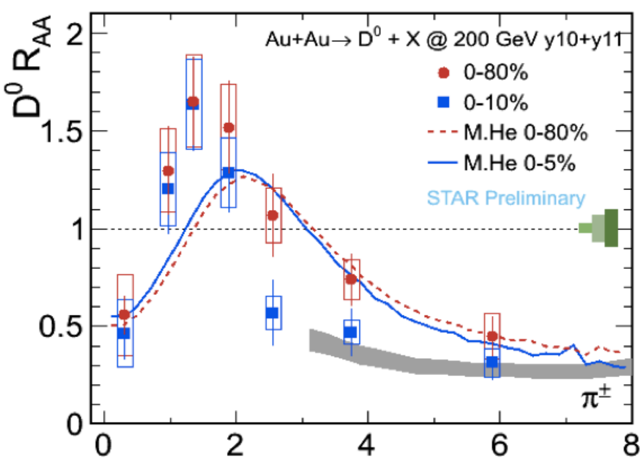
Beauty->e is strongly suppressed

Charm->e is less suppressed

RAA for c->e is consistent with RAA for heavy flavour -> e

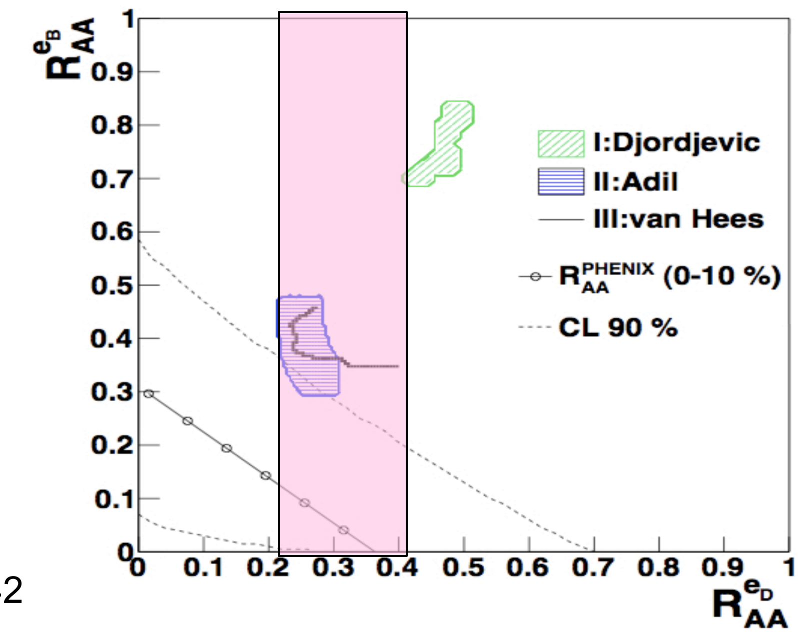
R_{AA}(b) in central Au+Au at 200 GeV

Implications of $R_{AA}(D^0)$ in Au+Au, assuming $R_{AA}(D^0) \sim R_{AA}$(c->e)



He, Fries, Rapp, PRC86, 014903, arXiV:1204.4442

M Aggarwal et al, STAR, arXiv:1007.1200



$R_{AA}(D^0)$ of ~ 0.3+-0.1 in 0-10% central Au+Au collisions at p_T~6 GeV/c and the 90% CL R_{AA} (b->e) vs R_{AA}(c->e) correlation in 0-5% Au+Au and p_T>5 GeV suggest:

R_{AA}(b->e) < 0.4

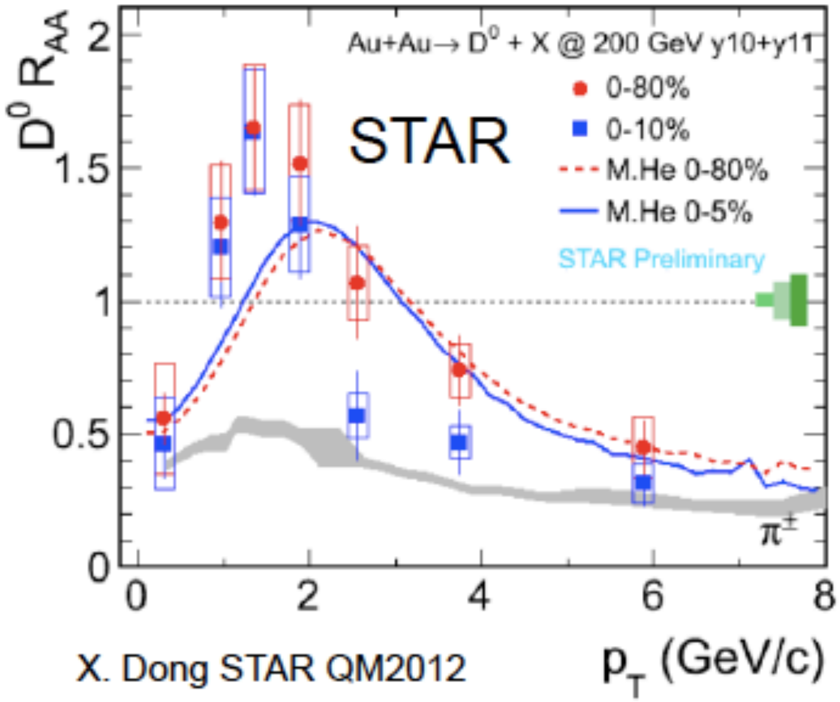
in central Au+Au at p_T~6 GeV/c (90% CL).

Consistent with PHENIX R_{AA}(b->e) < 0.4 at 90% CL in p_T~4.5 GeV/c, in min. bias Au+Au 200 GeV (M Rosati, PHENIX Coll., QM2012).

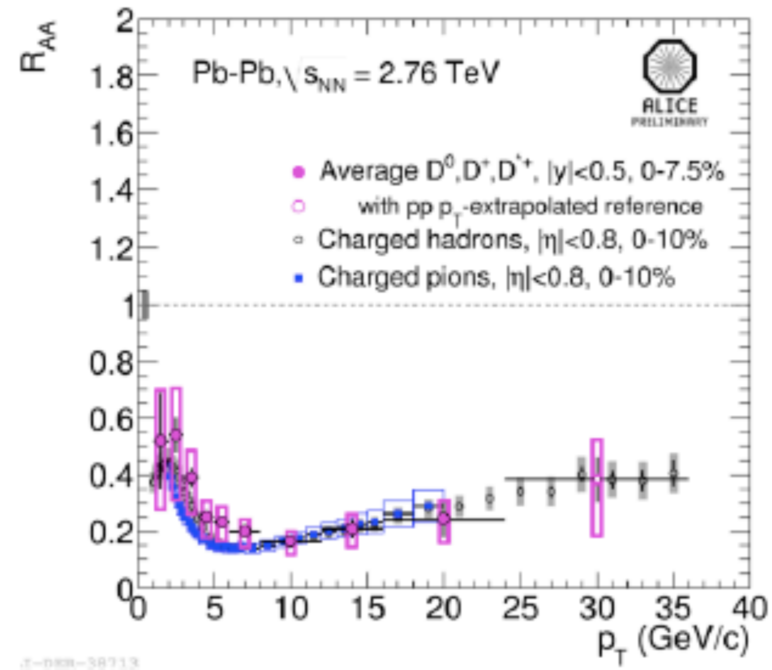
→ Heavy Flavour Tracker upgrade of STAR (2014) for precise R_{AA}(b)

RHIC vs LHC: Quenching of open charm

The RAA of Charm and Beauty are both suppressed at RHIC and LHC.



X. Dong STAR QM2012

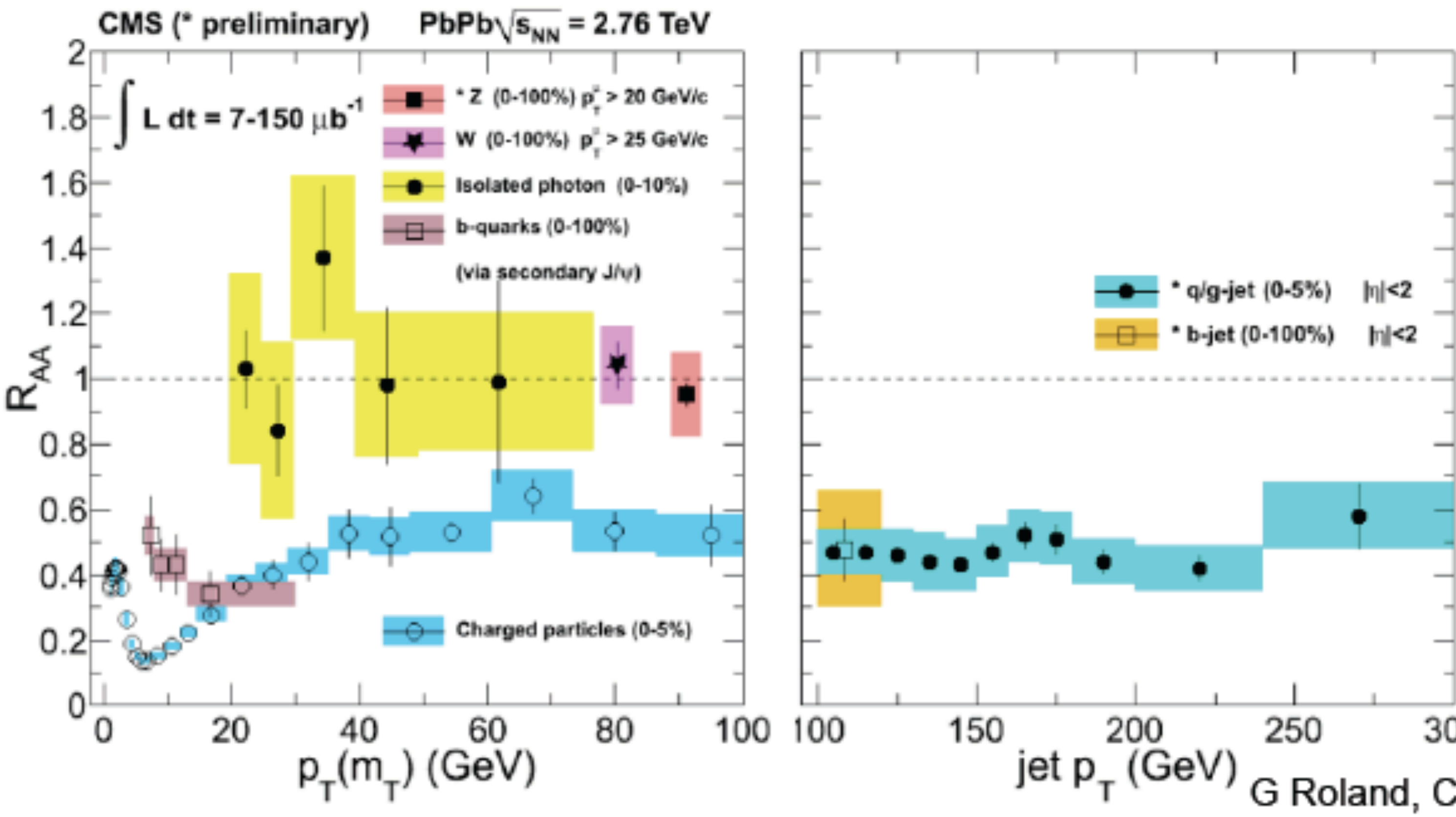


K Safarik, ALICE, QM2012

*** The RAA of D0 at RHIC (STAR) is suppressed after pT=3 GeV, and is similar to the RAA of charged hadrons at pT~6 GeV.**

*** The RAA of D0 at LHC (ALICE) is suppressed and is similar to the RAA of charged hadrons at high pT.**

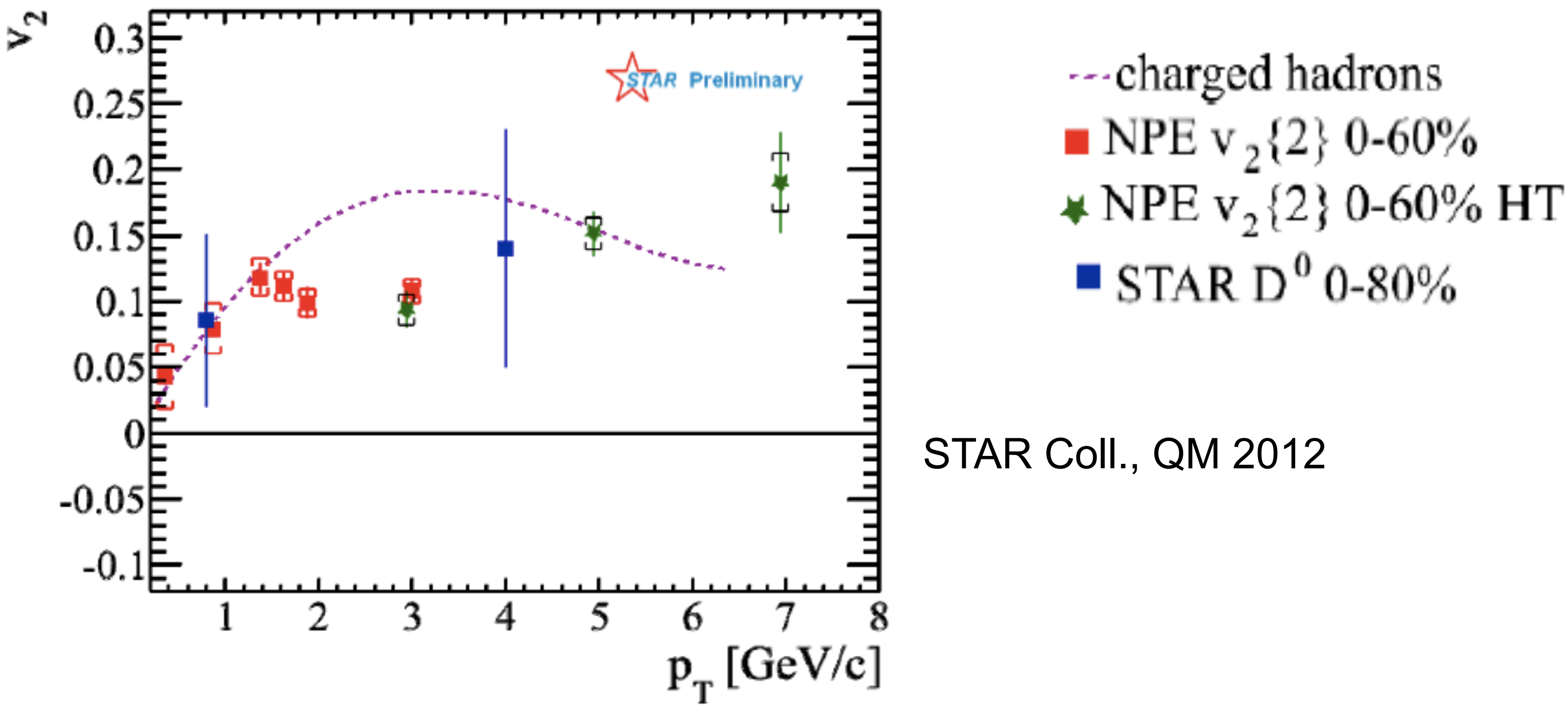
Beauty suppression :at the LHC



G Roland, CMS, QM2012

b-quark suppression in Pb+Pb

Does charm exhibit flow at RHIC?
v_2 from charm in Au+Au at 200 GeV



STAR Coll., QM 2012

* Large v_2 of Non-Photonic-Electrons in 0-60% centrality Au+Au at 200 GeV

* Large v_2 of D^0 in 0-80% centrality Au+Au at 200 GeV

Conclusions 1st part

Direct gammas in d+Au 200 GeV consistent with Cold Nuclear Matter effects -> confirms results for T(init) Au+Au > Tc

RAA pi0 (5-20 GeV) agrees with LHC, while fractional energy loss shows collision energy dependence (RHIC+BES, LHC)

Jet quenching dissappears at energies ≤ $\sqrt{s}$=27 GeV

$R_{AA}(D^0)$ and R_{AA}(b,c->e) suppression, similar to R_{AA}(pion) : no mass dependence observed

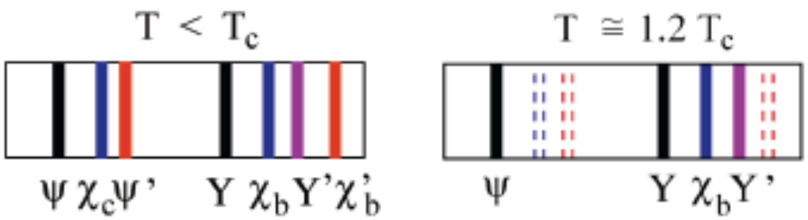
First RAA(b->e) measurement at RHIC (PHENIX) in min. bias Au +Au beauty is more suppressed than charm.

Charm exhibits large v_2

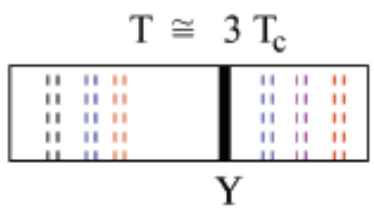
Quarkonia

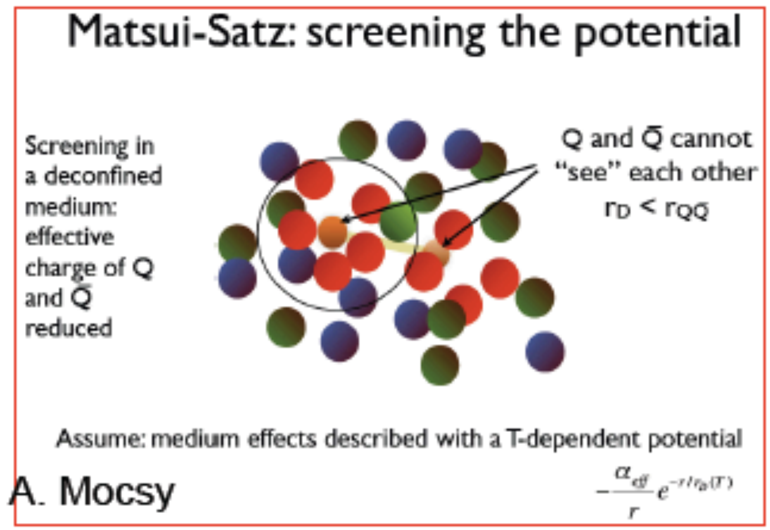
Quarkonia

Ch. Powel, STAR Coll., talk in this conference.



H. Satz, Nucl. Phys. A (783): 249–260(2007)





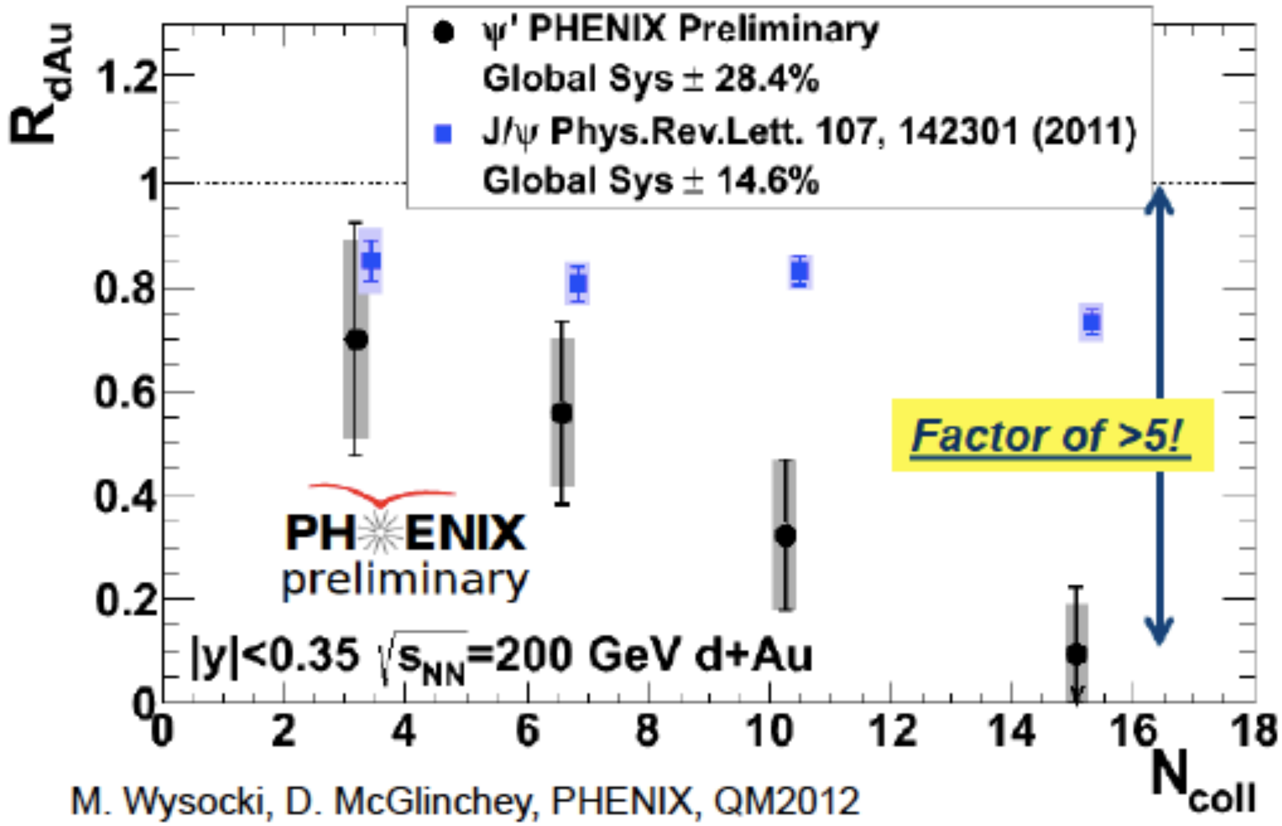
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

Quarkonia: Thermometer of QGP through hierarchy of T(dissociation)

Many effects can play a role, like color screening, cold nuclear matter absorption, recombination from c and cbar, feeding

Hidden charm

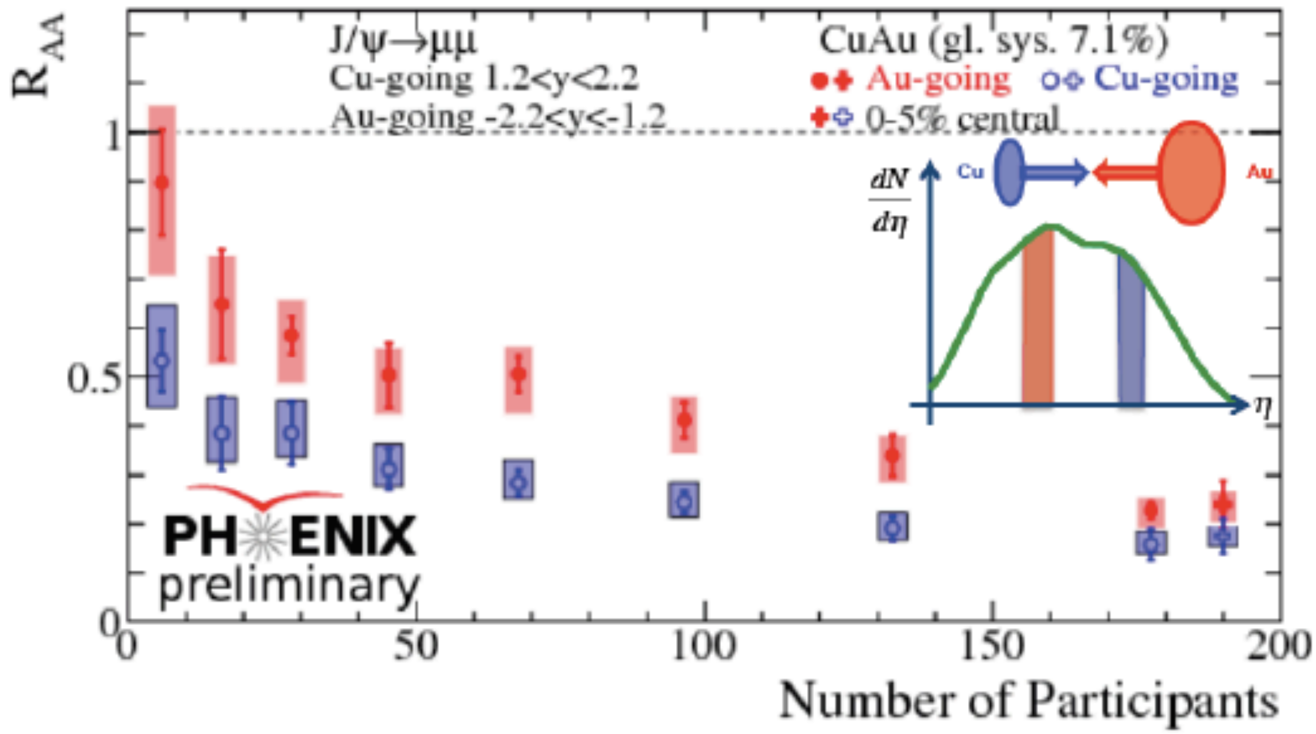
First measurement of Psi prime in d+Au from PHENIX



M. Wysocki, D. McGlinchey, PHENIX, QM2012

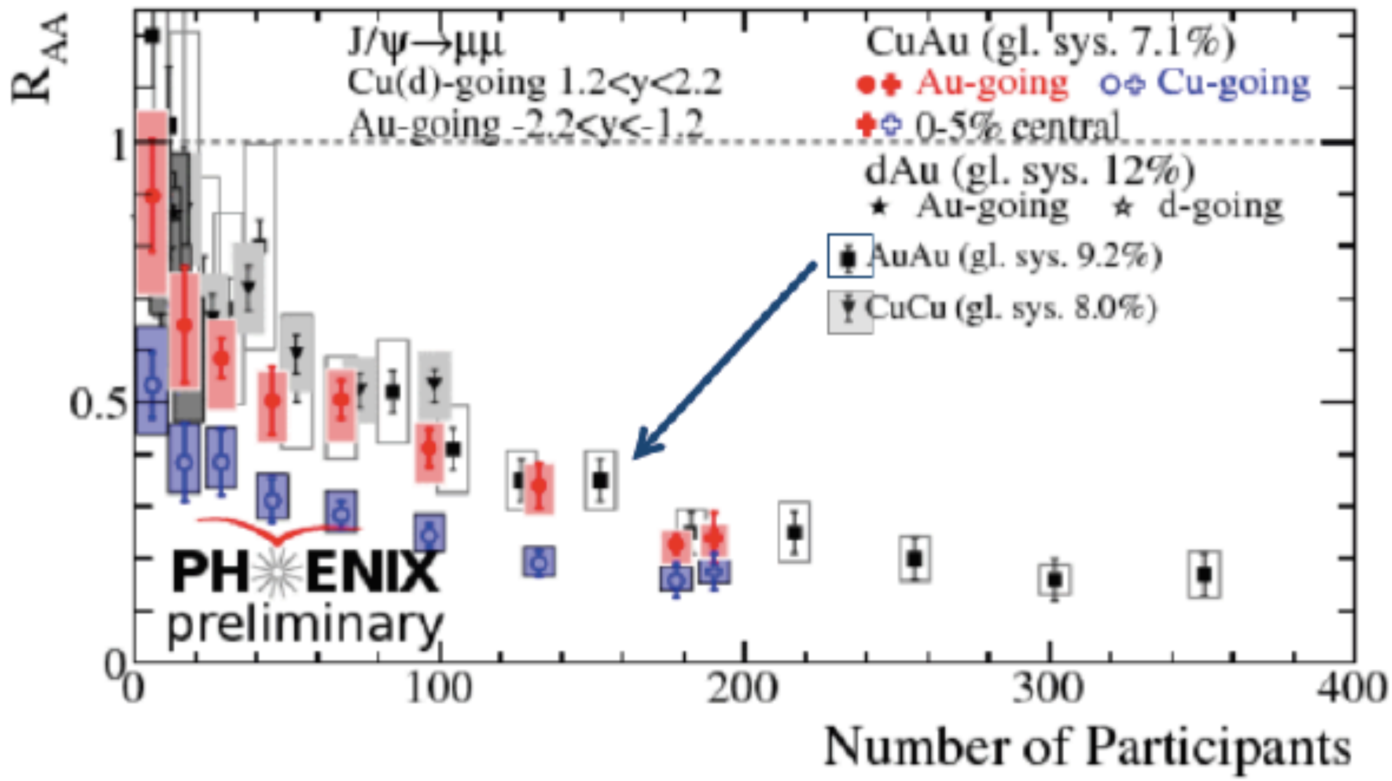
Psi prime is strongly suppressed in d+Au

J/Psi in Cu+Au 200 GeV from PHENIX



J/Psi in Cu+Au is more suppressed in the Cu going direction as compared to Au going direction

J/Psi in Cu+Au and Au+Au from PHENIX

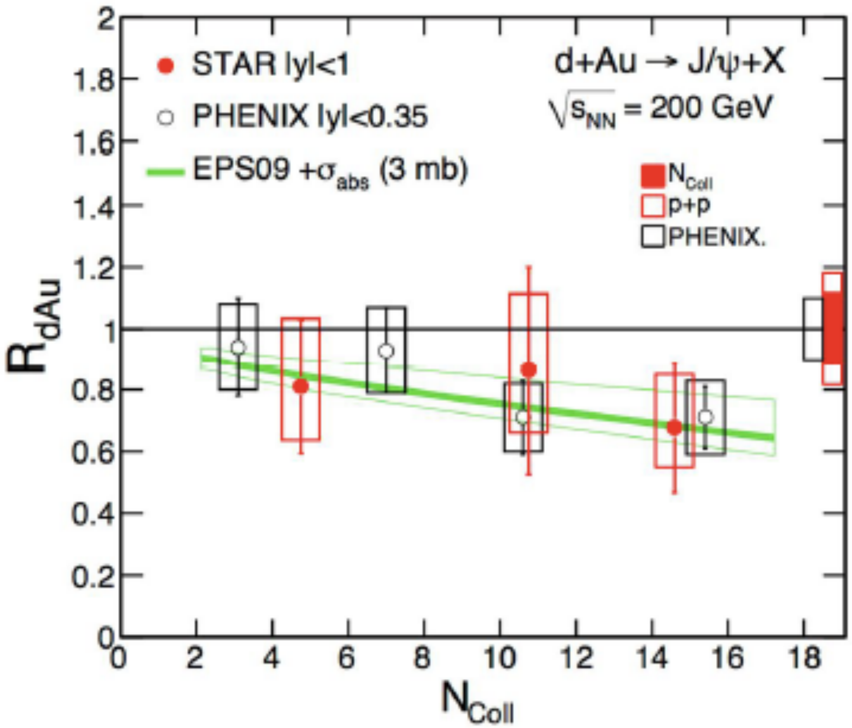


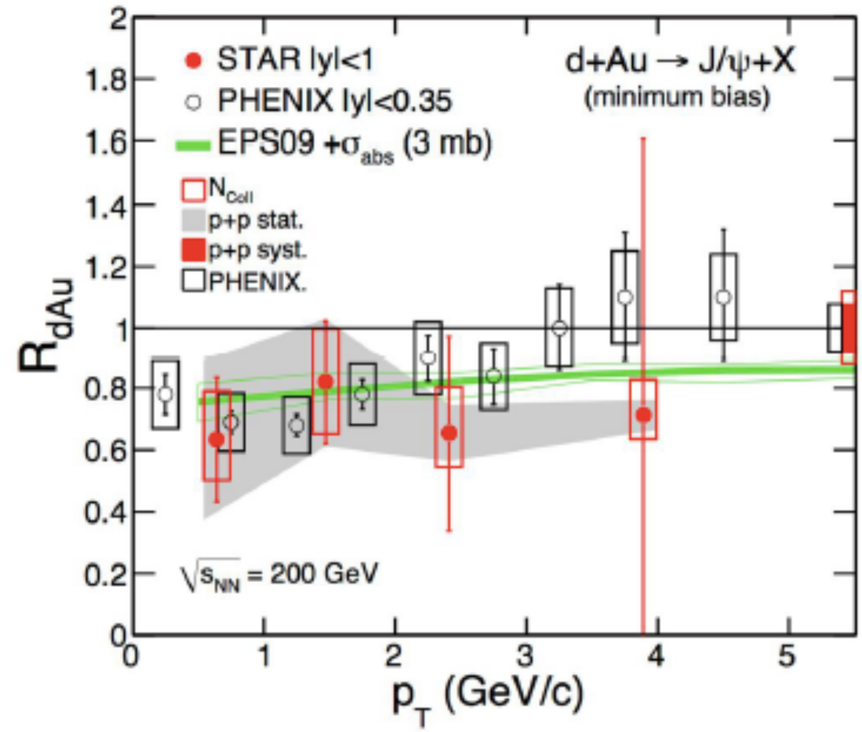
M Rosati, R Hollis, PHENIX, QM2012

J/Psi suppression in Au-going direction is the same as Au+Au

Cu-going direction shows stronger suppression than in Au+Au

J/Ψ in d+Au collisions at 200 GeV from STAR





Absorption cross section estimated : Ch. Powell, STAR Coll., this conference

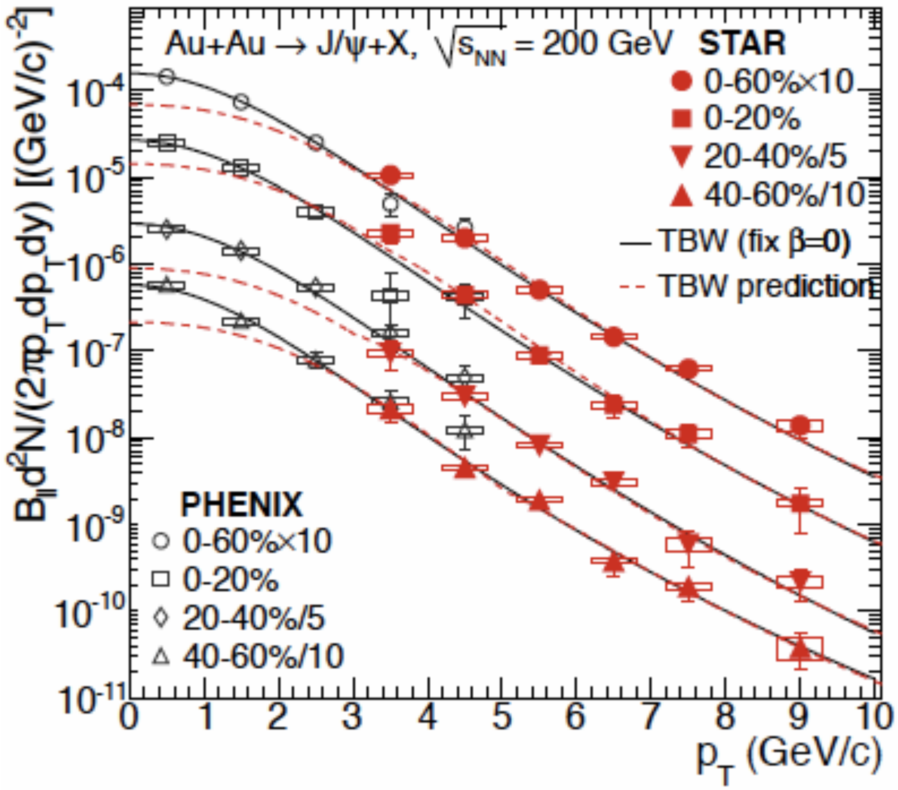
$$\sigma_{abs} = 2.8\ ^{+3.5}_{-2.6}\,(\text{stat.})\ ^{+4.0}_{-2.8}\,(\text{syst.})\ ^{+1.8}_{-1.1}\,(\text{EPS09})$$

EPS09, Nucl. Phys. A 830, 599 (2009) R. Vogt, Phys. Rev. C 81, 044903 (2010)

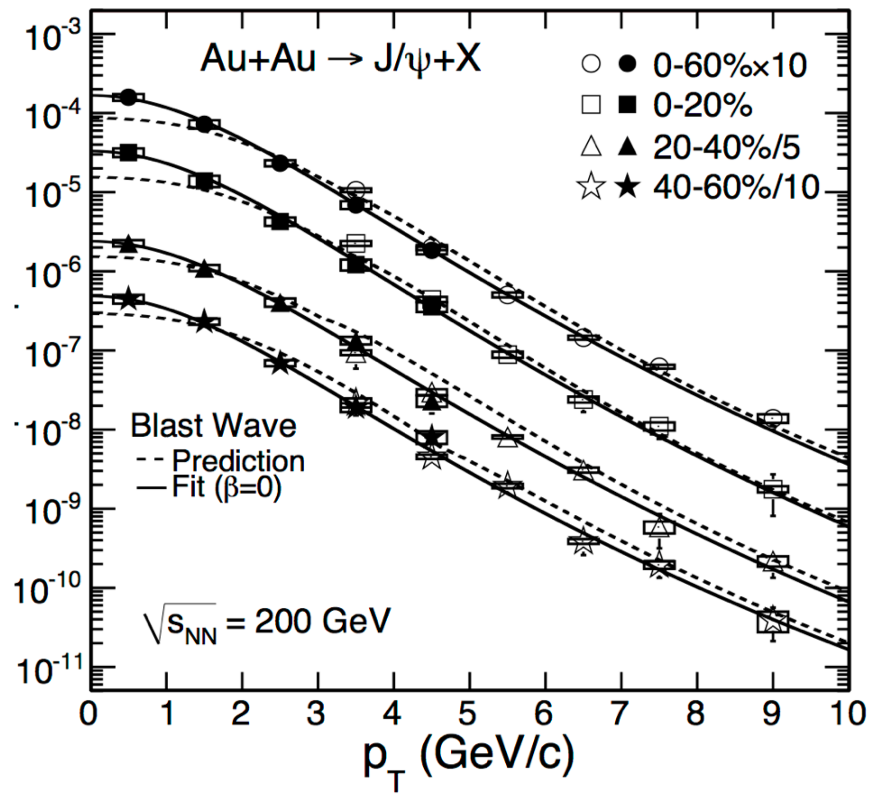
STAR and PHENIX results are consistent with eachother

J/Ψ p_T distribution in Au+Au collisions at 200 GeV

STAR, arXiv:1208.2736

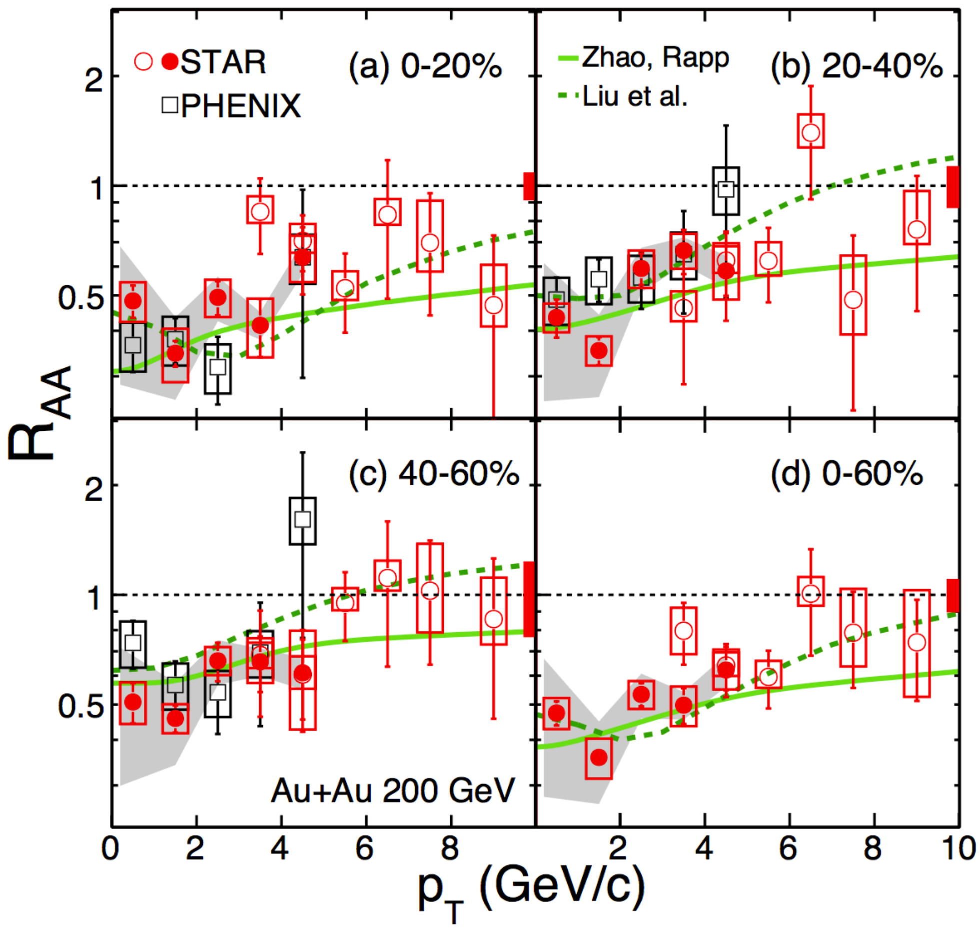


STAR preliminary



STAR Coll. QM2012

J/Ψ R_{AA} in Au+Au collisions at 200 GeV



J/Ψ is supressed at low p_T

R_{AA} of J/Ψ increases with increasing p_T

STAR: Arxiv:1208.2736, Arxiv:1111.6944v2
PHENIX: Phs.Rev.Lett.98:232301,2007
Zhao, Rapp: Phys. Rev. C 82, 064905 (2010)
Liu et. al: Phys. Lett B. 678, 72 (2009).

Ch. Powell, STAR Coll., this conference

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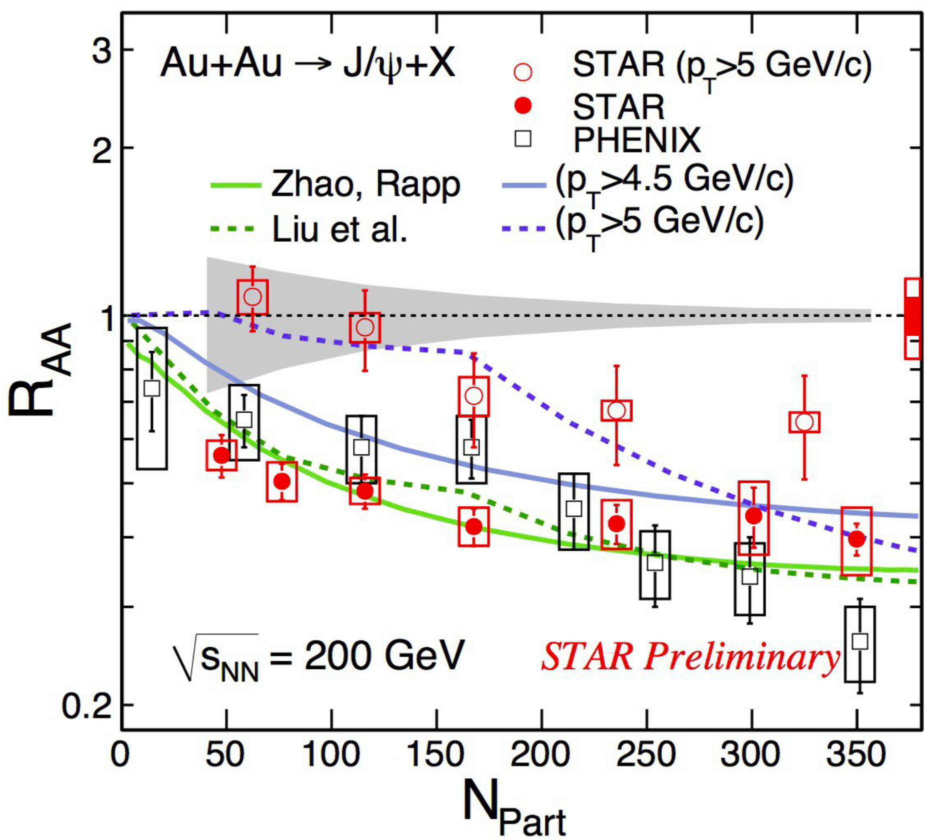

- **J/Ψ suppression increases with collision centrality**
- **J/Ψ suppression decreases with increasing p_T at all centralities**
- **At low p_T data agree with two models including color screening and regeneration effects**
- **At high p_T Liu et al model describes the data reasonably well**

STAR: Arxiv:1208.2736, Arxiv:1111.6944v2
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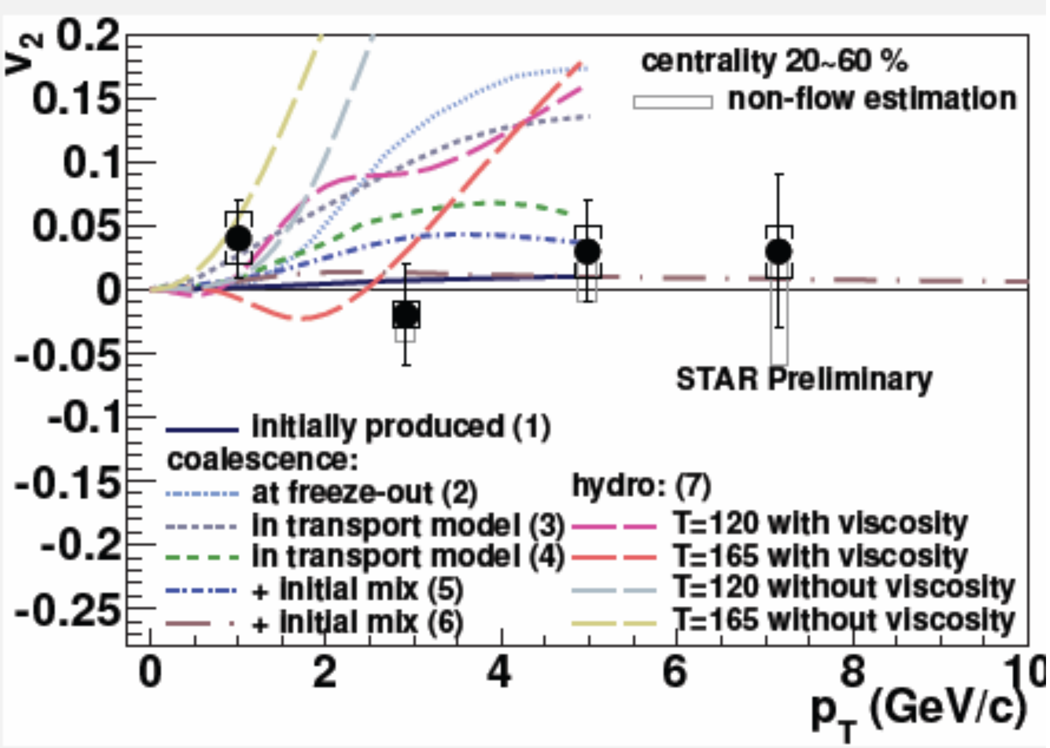
Liu et. al: Phys. Lett B. 678, 72 (2009).

Does the J/Ψ exhibit elliptic flow in Au+Au collisions at 200 GeV ?



(1) (4) Phys. Rev. Lett. 97, 232301 (2006)
(2) Phys. Lett. B595, 202 (2004)
(3) Phys. Lett. B655, 126 (2008)
(5) X.Zhao, R.Rapp, 24th WWND (2008)
(6) Nucl. Phys. A834, 317 (2010)
(7) U.Heinz, C. Shen, private communication

STAR Coll., QM2012

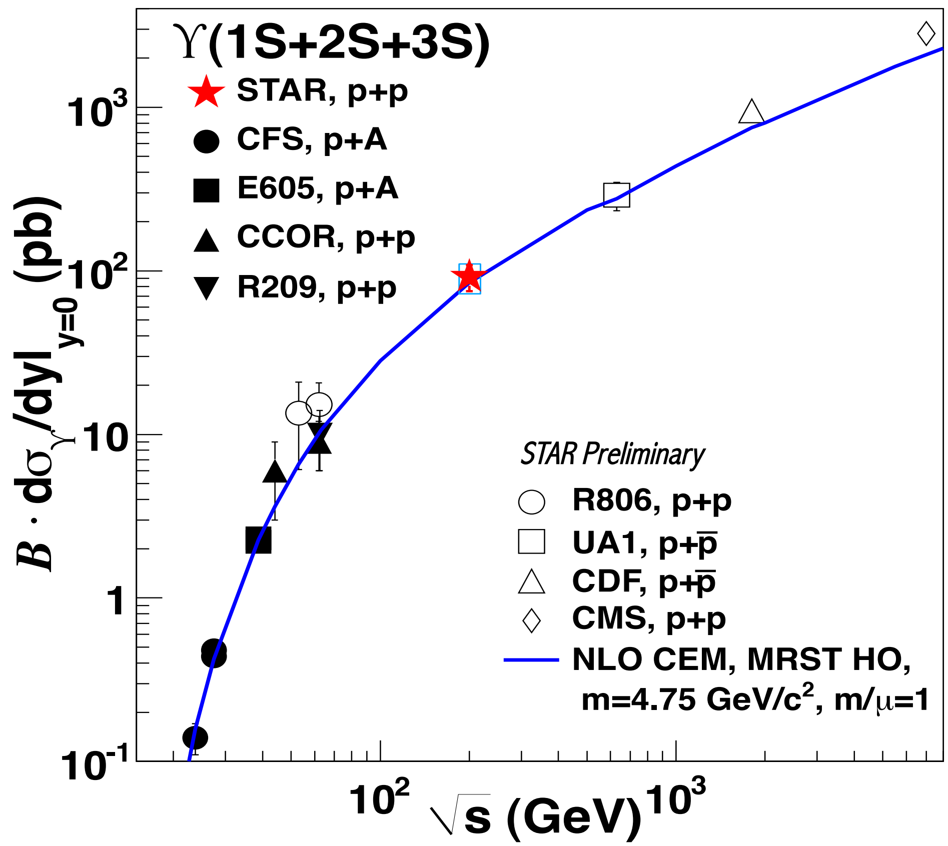
J/Ψ v_2 consistent with zero for p_T>2 GeV

Disfavours J/Ψ production dominantly through coalescence from thermalized charm, anti-charm quarks.

Best fit is for :
- **Initially produced J/Ψ (1)**
- **Coalescence + initial J/Ψ (mix) (5),(6)**

Hidden beauty

Υ in p+p 200 GeV vs world data



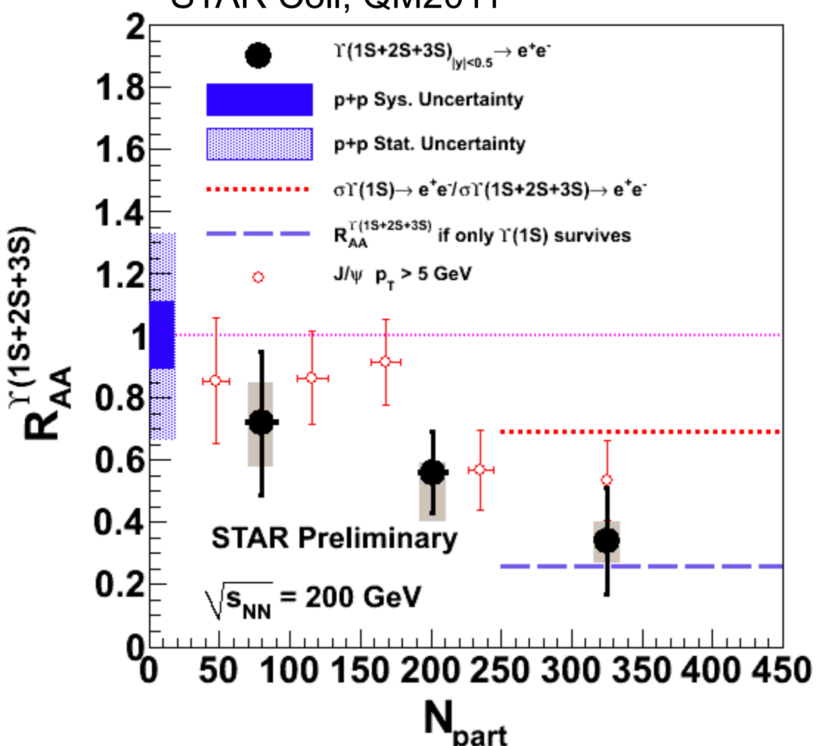
STAR Coll., Utrecht2012

STAR's Y+Y'+Y"->e+e- cross section in p+p collisions at 200 GeV consistent with world data trend and pQCD

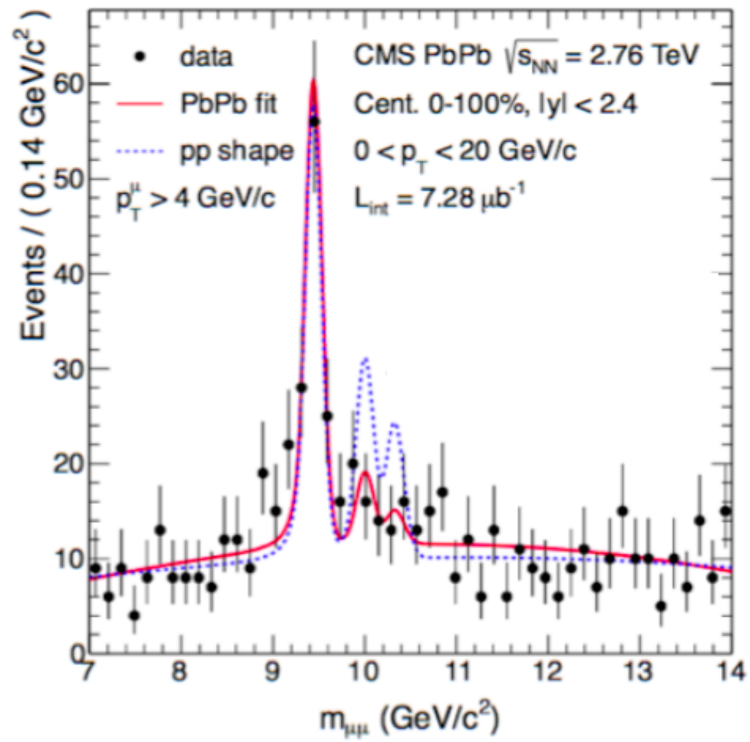
Y suppression in A+A collisions discovered at RHIC (STAR) and LHC

First results from 2011

STAR Coll, QM2011



PRL 107 (2011) 052302



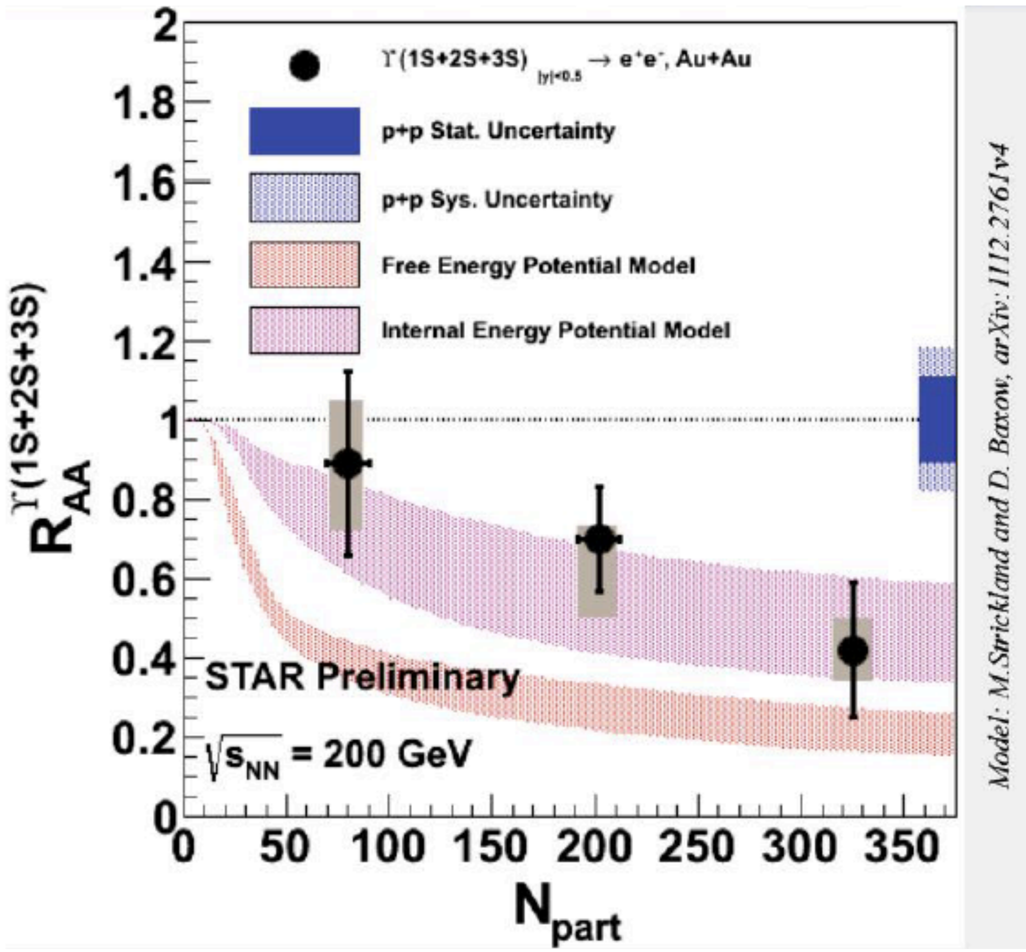
* First measurement of Y(1S+2S+3S) suppression at RHIC
* R_{AA} of most central point in agreement with only Y(1S) surviving

* Suppression of Y(2S+3S) with respect to Y(1S)

Y in Au+Au at 200 GeV

Ch. Powel, STAR Coll., talk in this conference.

M. Strickland, PRL 107, 132301 (2011).



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

Y more clean probe than ccbar's :

- **Y recombination can be neglected at RHIC**

*** Final state comover absorbtion small**

*** STAR observes a significant suppression of Y(1S+2S+3S) in central Au+Au at 200 GeV.**

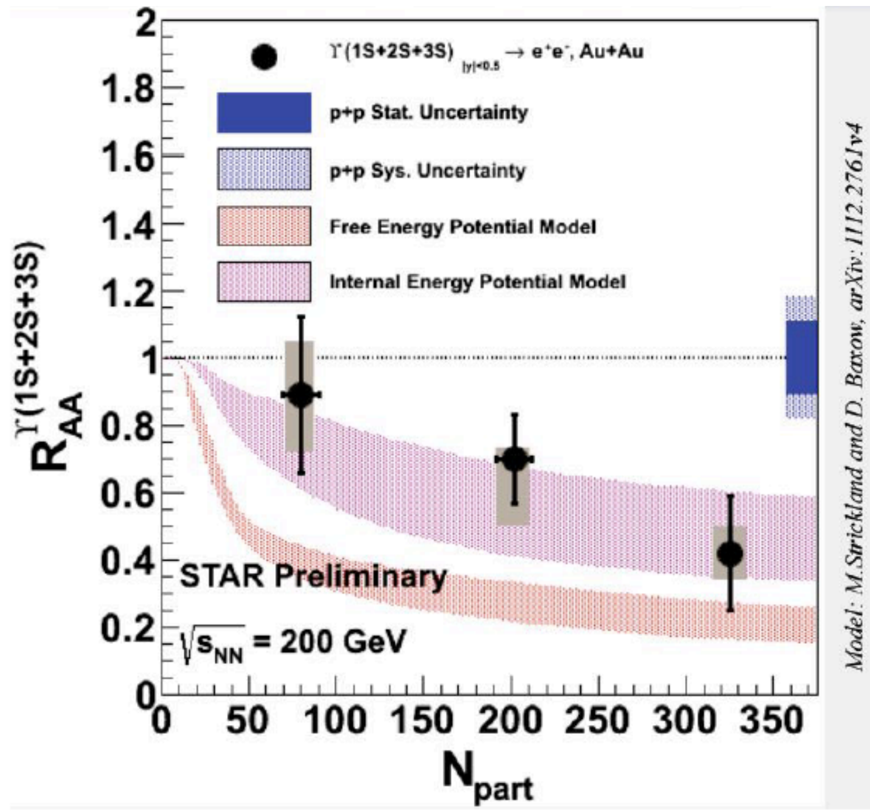
The data are consistent with a model requiring strong Y(2S) and complete Y(3S) suppression

In agreement with LHC results on Y(2S)+Y(3S)/Y(1S) suppression in Au+Au

Temperature estimate from Υ

Model includes sequential melting and feed-down contributions
~50% feed-down from χ_b.

Dynamical expansion, variations in initial conditions (T_0, η/S)
Data indicate:
$428 < T_0 < 442$ MeV at RHIC
for $3 > 4\pi\eta/S > 1$



M. Strickland, PRL 107, 132301 (2011).

STAR Coll., Utrecht 2012

Conclusions part 2

First measurement of Psi' : strongly suppressed in d+Au 200 GeV.

J/Ψ measurement in d+Au -> allows CNM effect estimate

R_{AA} of J/Ψ suppressed in central Au+Au collisions and in Cu+Au 200 GeV. The J/Ψ suppression in Au+Au increases with centrality, and decreases with increasing pT at all centralities.

J/Ψ v_2 is zero above p_T> 2 GeV/c -> regeneration not dominant

Y+Y'+Y" measured in p+p and d+Au in agreement with worlds data trend and pQCD

Y+Y'+Y" suppressed in central Au+Au, consistent with complete Y" suppression, strong Y' suppression and Y surviving -> in agreement with sequentiel dissociation of quarkonia and the LHC.

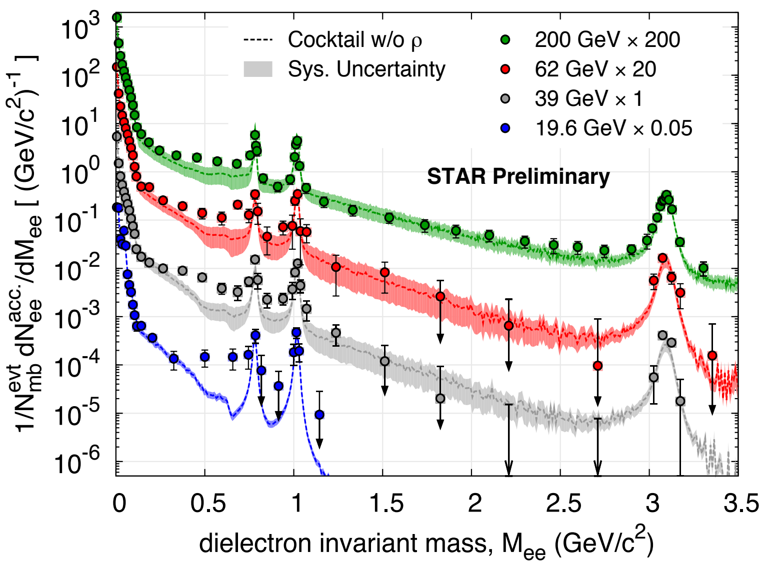
-> T(init) ~ 428-442 MeV ~ 2.7 Tc

and 3 > 4π η/S > 1

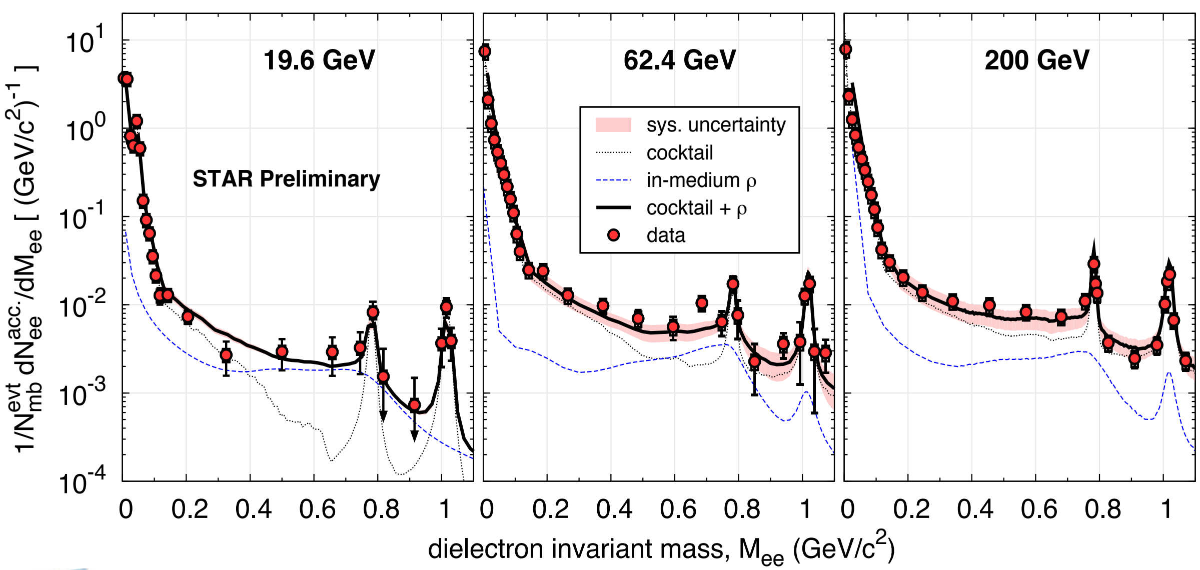
Dileptons

Dielectron invariant mass vs collision energy

STAR Coll., QM2012



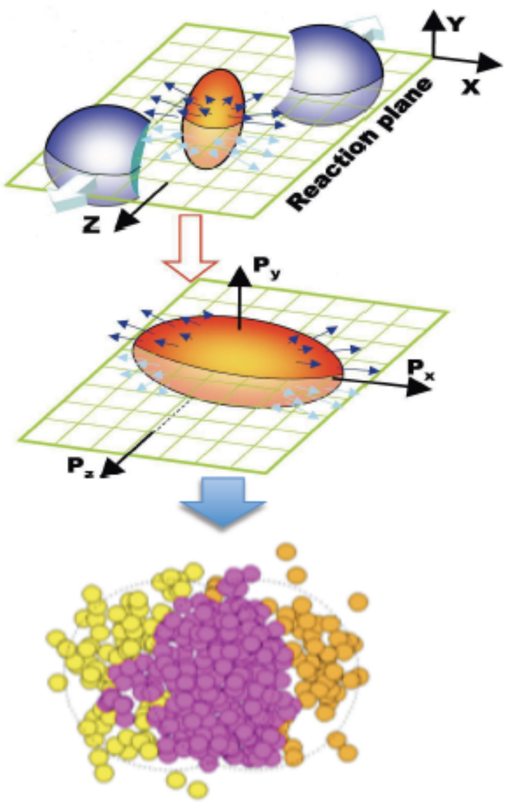
Enhancement in Low Mass Range (LMR) observed from 200 GeV down to 19.6 GeV



Model assuming In-medium broadening of ρ reproduce the LMR excess at 19.6-200 GeV

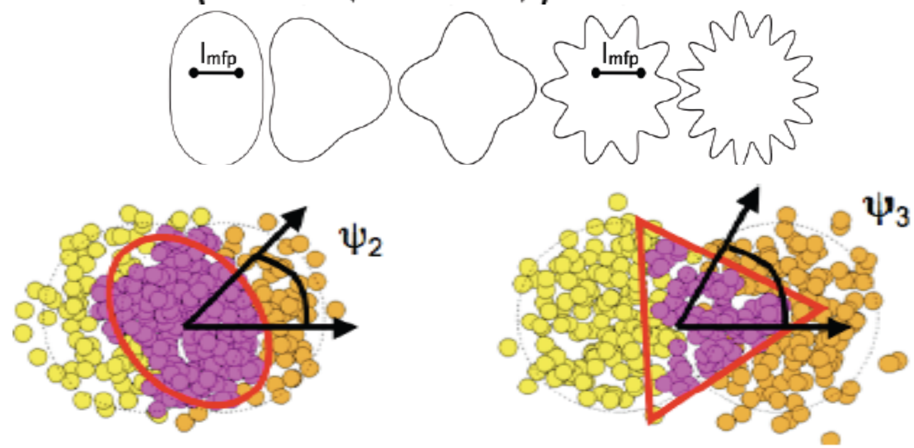
Beam Energy Scan

Flow and Beam Energy Scan



$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

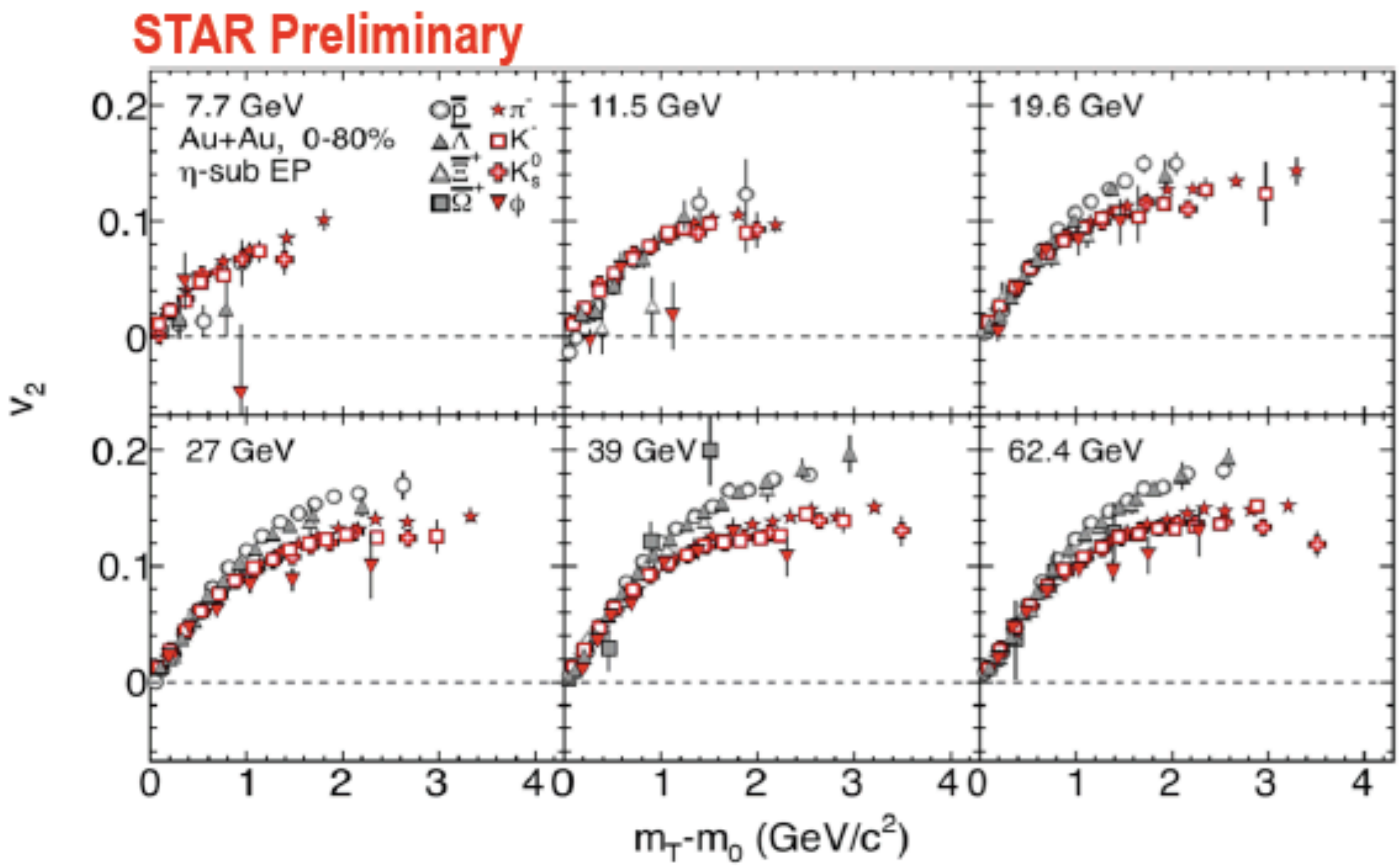
$$v_n = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$



v_1= directed flow, v_2= elliptic flow, v_3=triangular flow, …

Initial anisotropy in position space becomes final anisotropy in momentum space

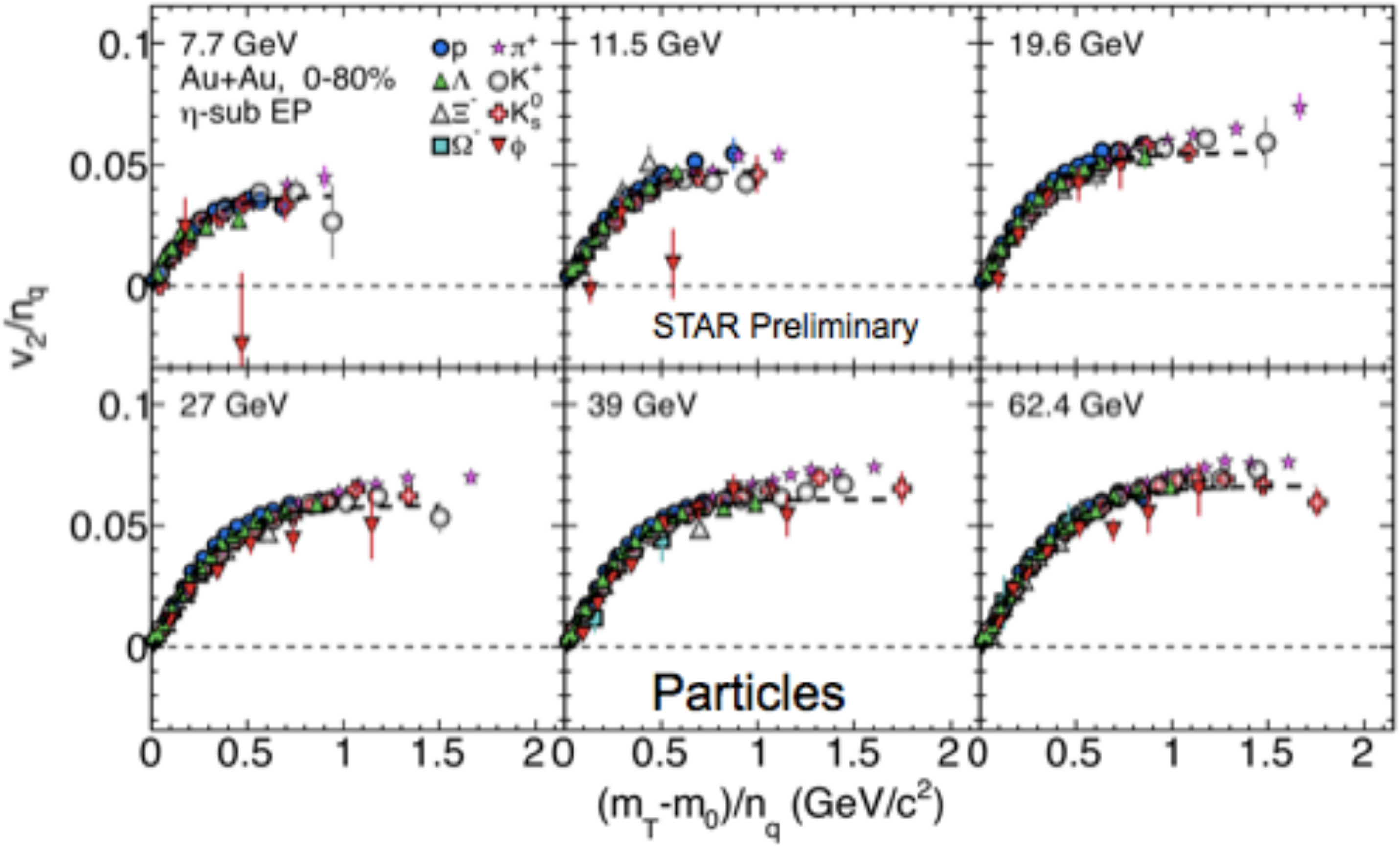
Antiparticles v_2 vs. m_T-m_0



For antiparticles the baryon–meson splitting is almost gone within errors at 11.5 GeV.

G Odyniec, this conference

NCQ Scaling and deviations



STAR Coll.
QM2012

*** Universal trend for most of particles and the corresponding anti-particles**

*** ϕ meson v_2 deviates from other particles ~ 2σ at the highest p_T data in 7.7 and 11.5 GeV collisions**

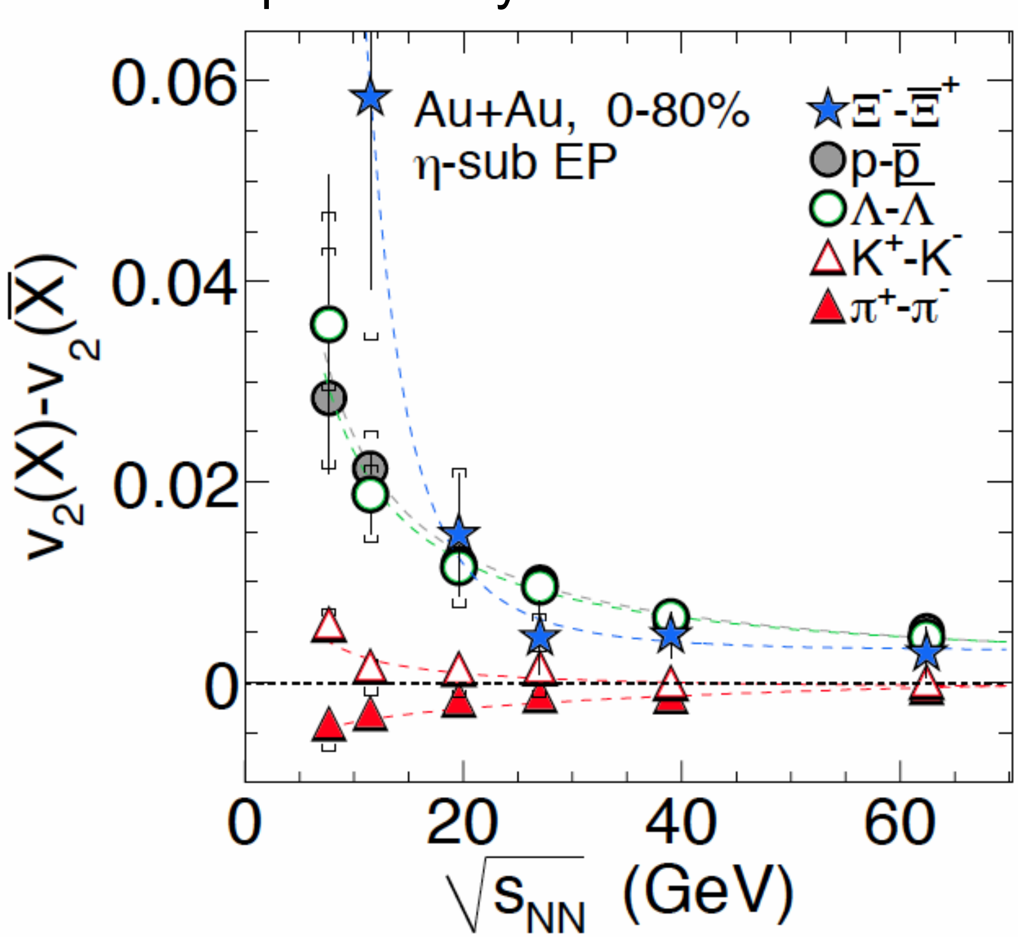
Hadronic interactions are more important at lower energies

More data for 7.7 and 11.5 GeV are needed

v_2: difference of particles and anti-particles

STAR preliminary

STAR Coll. QM2012



- **Beam energy ≥ 39 GeV**
  - Δv_2 for baryon and anti-baryon within 10%
  - Almost no difference for mesons

- **Beam energy < 39 GeV**
  - The difference of baryon and anti-baryon v_2

  Increasing with decrease of beam energy

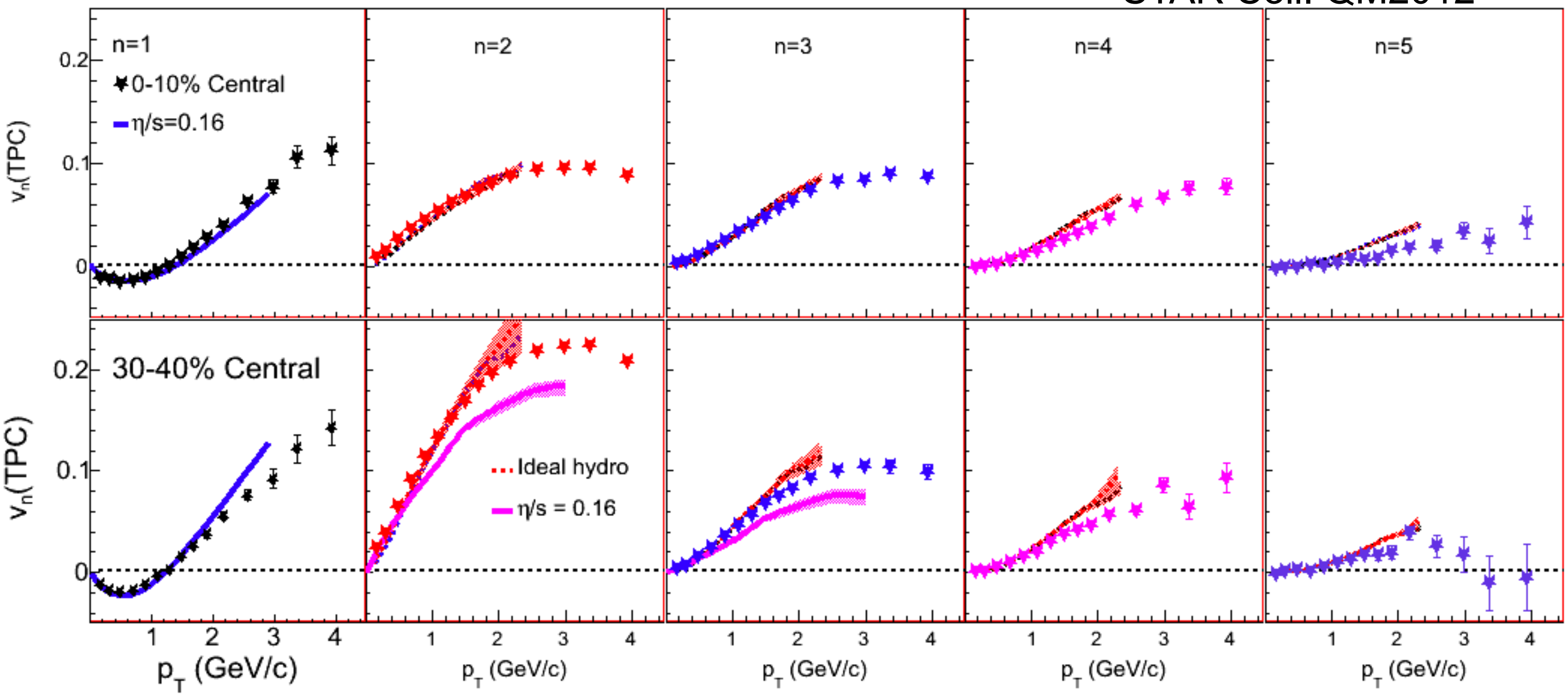
- $v_2(K^+)>v_2(K^-)$ at 7.7-19.6 GeV
- $v_2(\pi^-)>v_2(\pi^+)$ at 7.7-19.6 GeV

NCQ scaling is broken between particles and anti-particles at low energies

Flow harmonics n=1-5 in 0-10% Au+Au at 200 GeV vs p_T and shear viscosity estimates

STAR preliminary

STAR Coll. QM2012

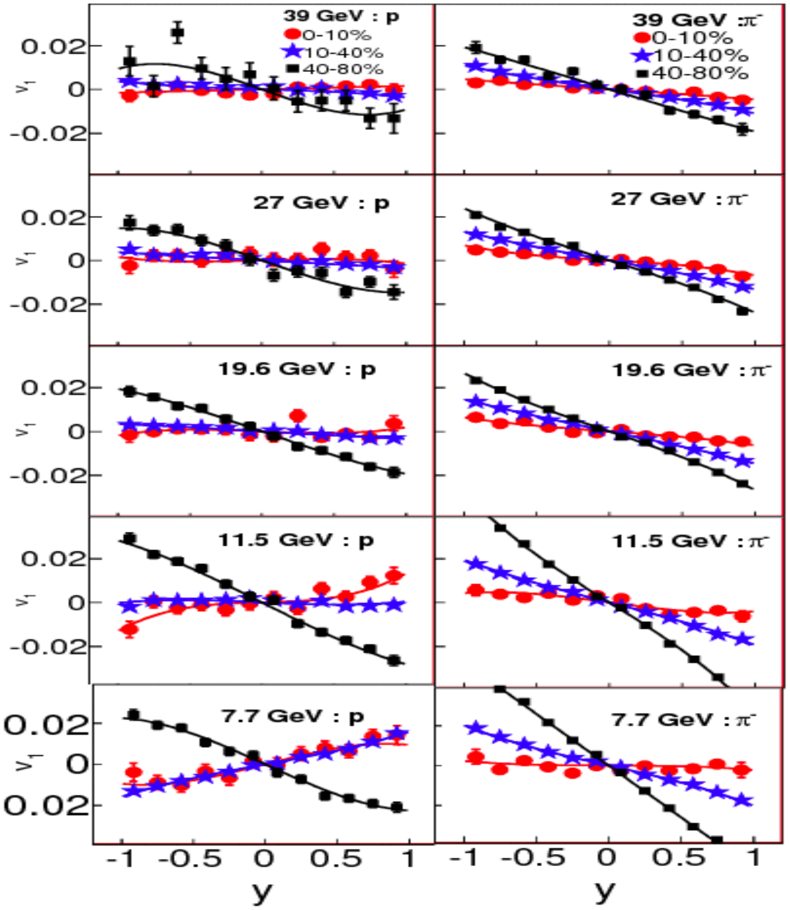


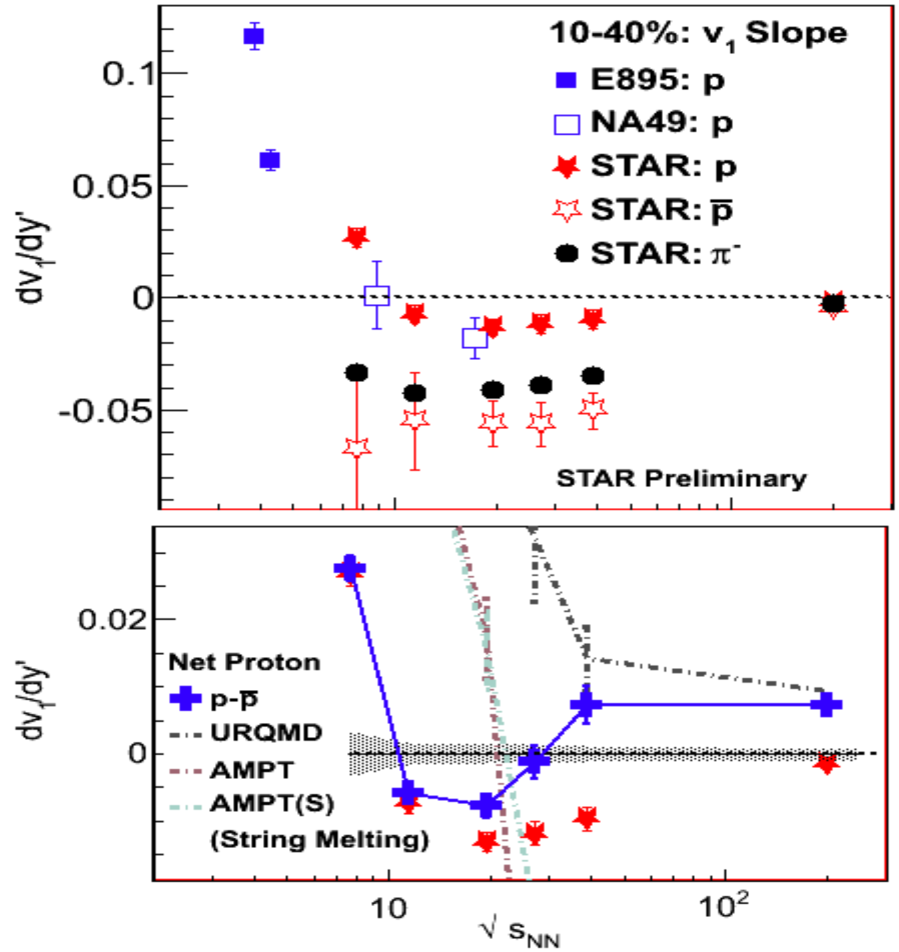
- Model curves for *n*=1 are from Retinskaya, Luzum & Ollitrault, PRL **108**, 252302 (2012) (η/s=0.16); higher *n* curves are from Gardim *et al.*, arXiv:1203.2882 (ideal hydro) and for n=2 and n=3 with η/s= 0.16 are from B. Schenke *et al.*, PRL **106**, 042301 (2011).
- The models do a good job describing the general features of the data. These comparisons suggest that low or zero viscosity is favored.

STAR, QM2012

Proton and pion v_1

STAR preliminary



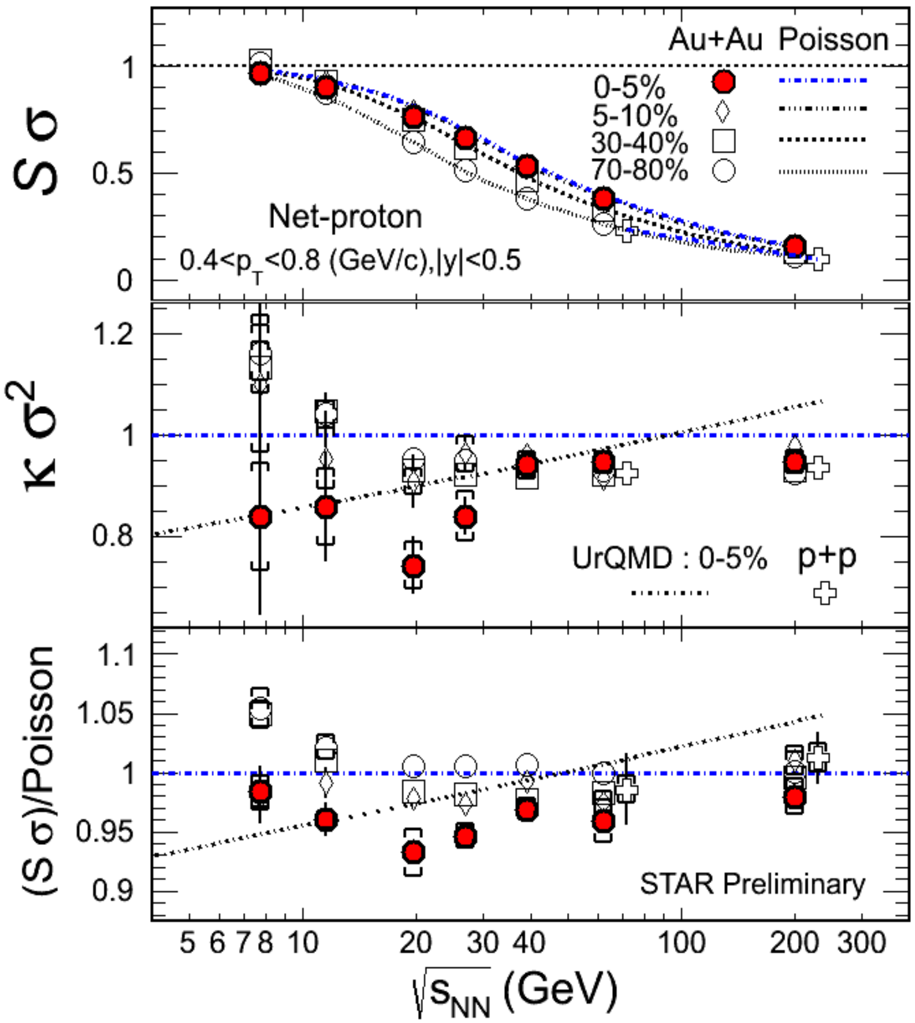


* Non-monotonic behaviour of v1 slope of net protons (p-antip) observed as a function of collision energy
* UrQMD and AMPT models do not describe the data on net-protons

Search for the critical point

Higher moments of net-protons

STAR Coll. QM2012



$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$$
$$S = \langle (N - \langle N \rangle)^3 \rangle / \sigma^3$$
$$\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3$$

Higher moments are sensitive to critical point induced fluctuations

Deviation from Poisson baseline in 0-5% Au+Au collisions (red points) at $\sqrt{s}$ > 7.7 GeV

UrQMD shows monotonic behaviour

-> More data needed at low energies

Conclusions part 3

Dileptons: deviations in Low Mass Range observed at several energies can be explained as due to rho mass broadening.

Flow harmonics up to n=5 provide constraints on initial conditions and transport coefficients

Observed « turn off » of several sQGP signatures e.g. : baryon-meson splitting for antiparticles, v_2(part-antipart), jet quenching - RCP suppression

Search for sign of a 1st order phase transition: v_1 slope changes with energy. More theoretical input is needed to understand these data.

Search for a possible critical point:, deviations observed in higher moments of net-protons need more data to be explored

Conclusions

STAR and PHENIX at RHIC entered **a new era** of high statistics precision measurements thanks to major recent upgrades.

At top energy, above Tc, STAR and PHENIX have measured signatures and characteristics of sQGP, among which J/Ψ suppression and the discovery of Y suppression in Au+Au collisions at RHIC, consistent with sequential suppression of quarkonia (J/Ψ, Y', Y")

In **the low Beam Energy Scan towards and below Tc**, STAR and PHENIX observed several key signatures of sQGP dissapear at low $\sqrt{s}$.

Outlook

Near future (2014-2018) **upgrades** (run of 2014) will allow high precision quarkonia, open heavy flavour and dilepton measurements in STAR.

BES II (2016-2019): electron cooling for Lumi x 10 (Au+Au: 7.7, 11.5, 15, 19.6 and U+U 20 GeV) and fixed target program

pA/eA (2017-)

Outlook

2013 2014 2015 2016 2107 2018 2019 2020

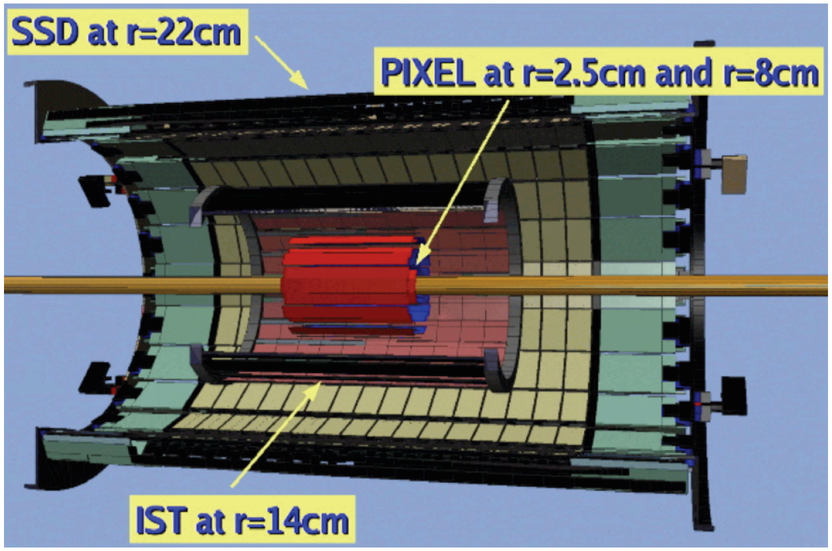
BES II (2016-2019)

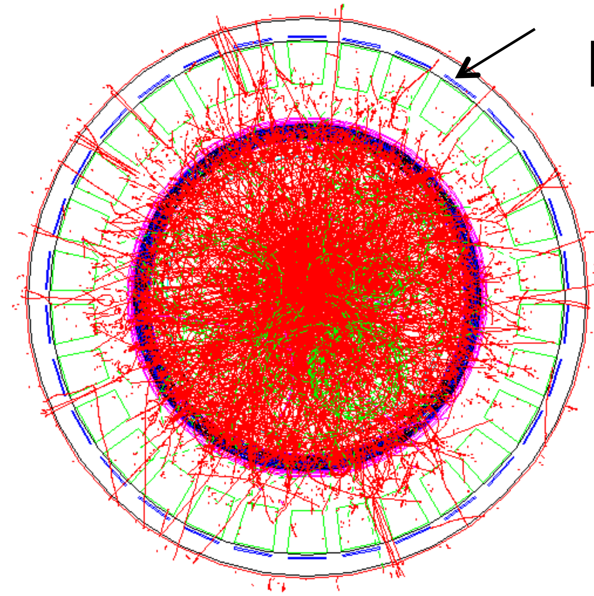
HFT/MTD STAR (2014-2018)

pA/eA (2017-)

Outlook

Heavy Flavour Tracker





Short term upgrades of STAR which are underway:

Heavy Flavour Tracker: Open Heavy Flavour precision studies, (eg D reconstruction at low and high p_T)

Muon Detector (MTD): B -> J/Ψ -> μμ, Y/Y'/Y" separation, QGP thermal dilepton radiation, understand background via e-μ correlations