EW PROBES AND HEAVY QUARKS: LOTS OF NEW CALCULATIONS AND NEW DATA!

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EW Probes Quarkonium and Heavy Flavors

- EW: Penetrating probes, biased towards high T, probe the entire history of the space-time dynamics, sensitive to transport coefficients
- Heavy quarks: test of pQCD and of in-medium modification, initial state effects, energy loss (final state effect)

Lattice studies

P. Petreczky: Quarkonium state potential

- Correlation function of the Polyakov loop related to the free energy of a static quark-antiquark pair:

$$G(r,T) = \frac{1}{N^2}\left\langle \mathrm{Tr}\, L(r)\, \mathrm{Tr}\, L^{\dagger}(0) \right\rangle = e^{-F(r,T)/T}$$

$$= \frac{1}{N^2} e^{-F_1(r,T)/T} + \frac{N^2-1}{N^2} e^{-F_8(r,T)/T}$$

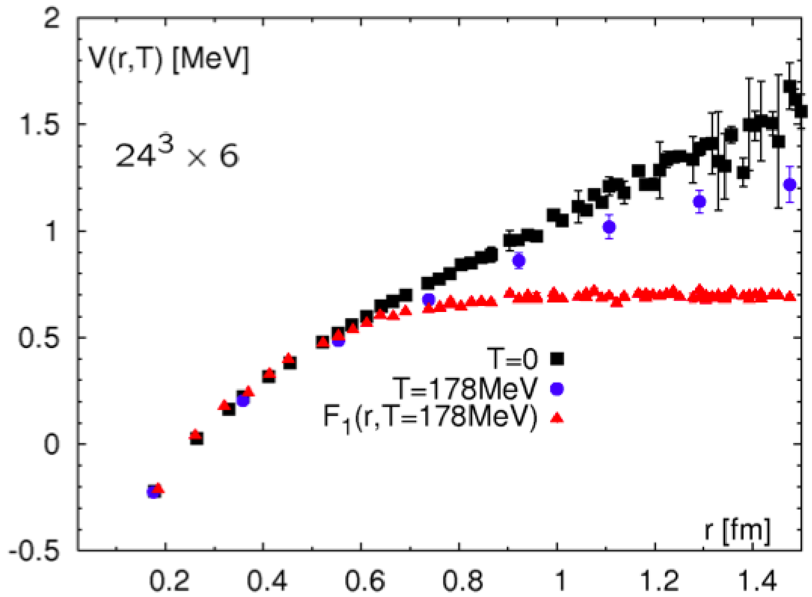
- New: the use of Wilson loop spectral functions allows for an extraction of the quark-antiquark potential

$$W(r,\tau) = \int_{-\infty}^{\infty} d\omega \sigma(\omega,T) e^{-\omega\tau}, \tau < 1/T$$

$$\sigma(\omega,T) \sim \delta(\omega - V(r,T))$$

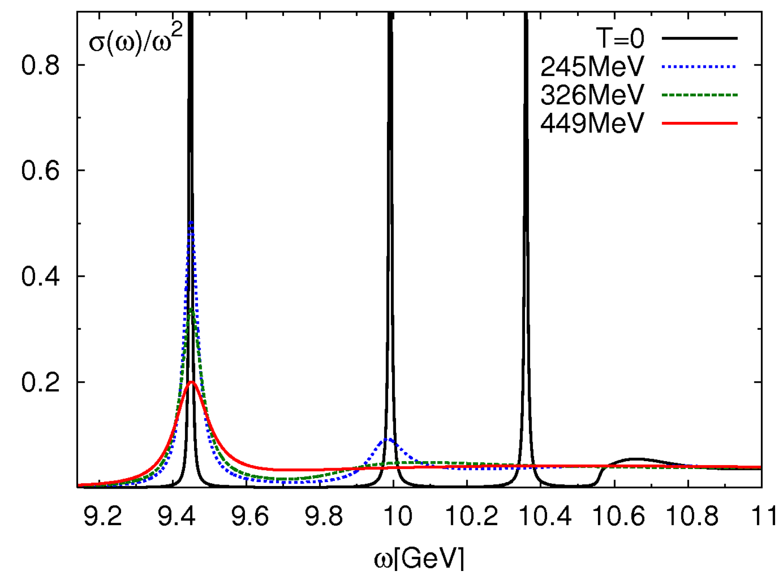
Assume single-state dominance

$$V_{eff}(r,\tau) = \ln(W(r,\tau)/W(r,\tau+1))$$



- Potential systematically larger than F but approaches as T increases
- Implications for potential model studies:

- Real and Imaginary part will be calculated consistently
- Single-state dominance

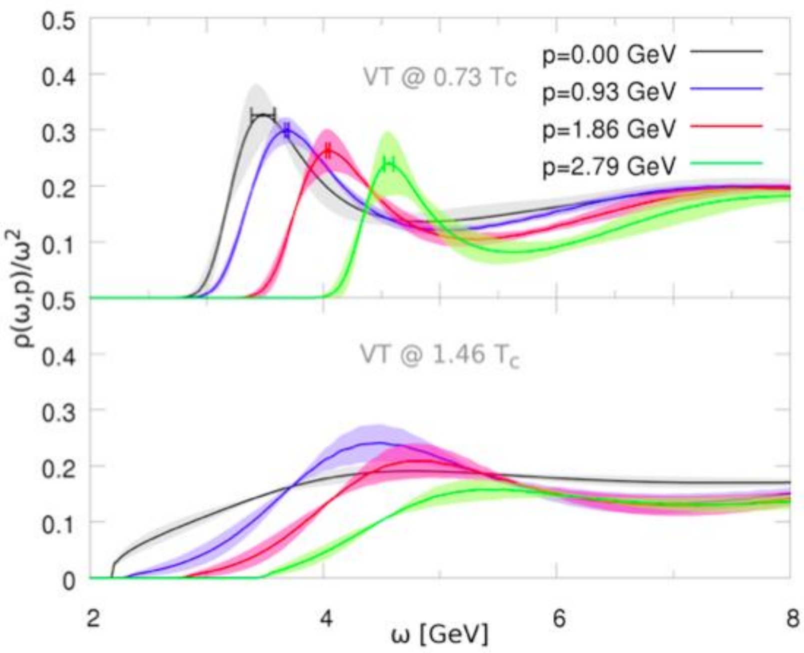


charmonium and *2S* bottomonium states dissolves for *T>245* MeV,
1S bottomonium states dissolves for *T>450* MeV

H. Ding: Dispersion relations

$$G(\tau,T)=\int_0^{\infty}\frac{d\omega}{2\pi}K(\tau,\omega,T)\rho(\omega,T)$$

J/ψT



- Relies on MEM to invert the mapping of the spectral function
- Prediction of and   dissociate at 1.46 T_c : new feature
- Evaluation of the dispersion relation
- Similar message for other channels
- Effect on pheno models
- Need to do studies over a range of temperatures

In-medium Quarkonium

R. Rapp: Transport theory

$$\frac{dN_\psi}{dt} = -\Gamma_\psi (N_\psi - N_\psi^{eq})$$

Loss & gain terms

$$T_\alpha(E;q,q') = V_\alpha(q,q') + \int k^2 dk\, V_\alpha(q,k)\, G^0_{Q\bar{Q}}(E,k)\, T_\alpha(E;k,q')$$

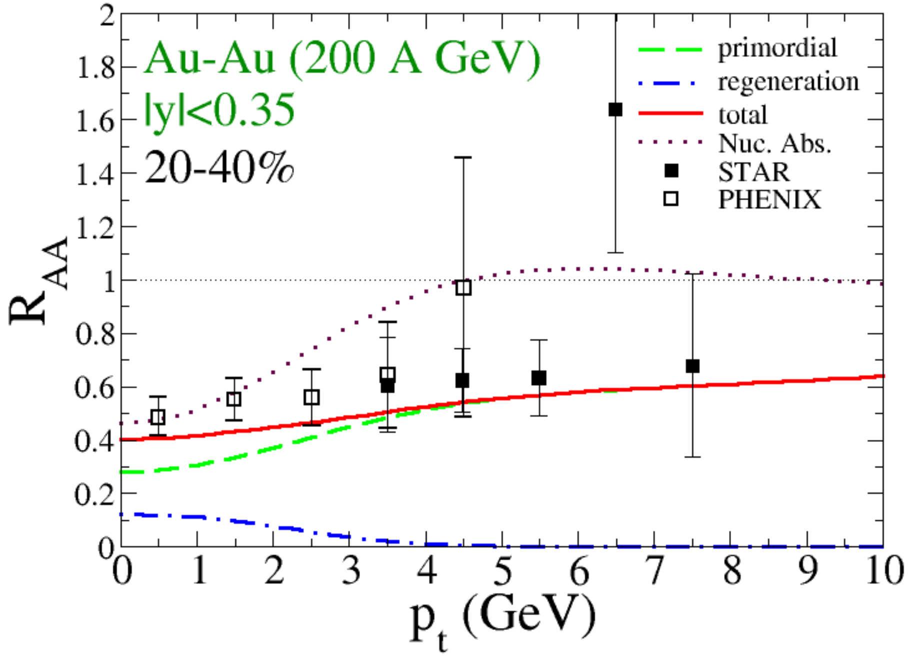
Input & ingredients:

- Primordial production cross-sections
- CNM effects: Cronin, shadowing, absorption
- Thermal fireball evolution
- Includes gluon dissociation channel

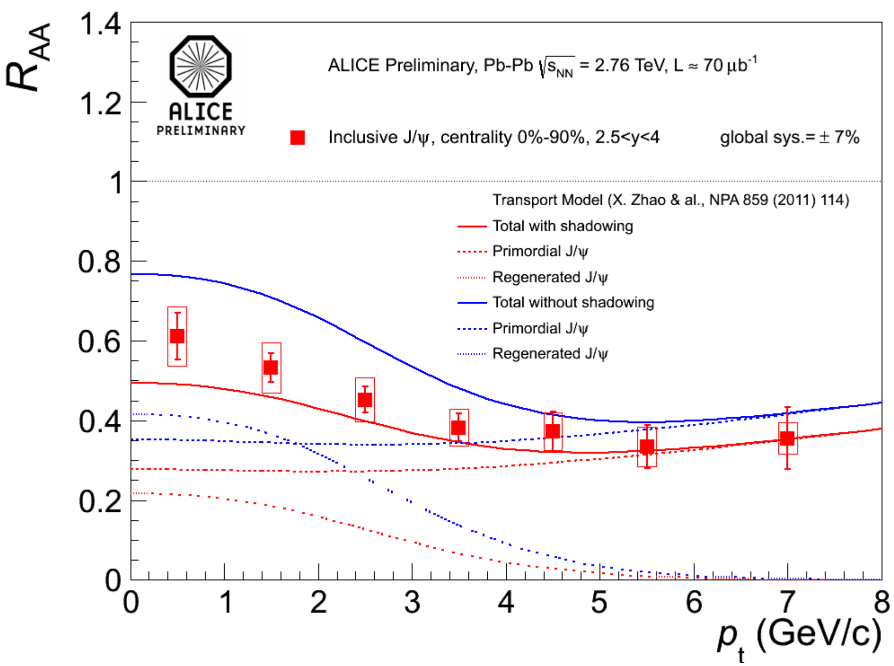
$$g + J/\psi \rightarrow c + \bar{c}$$

- Quarkonia binding energy determined from a screened potential (WBS), or from a T=0 potential (SBS)

Allows for a survey of results from SPS, RHIC, and LHC

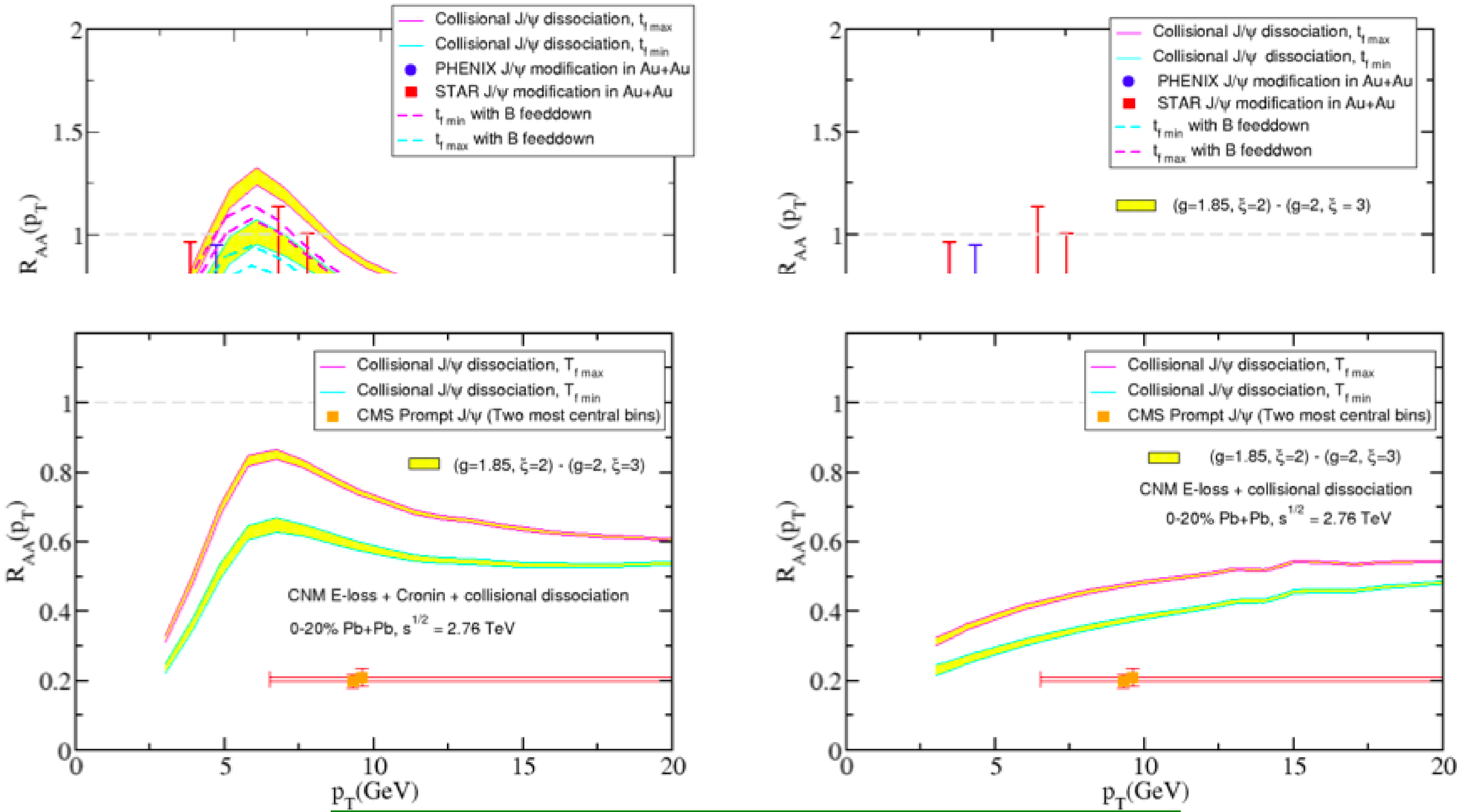


J / y P_T spectrum at RHIC: contributions from supression, regen., and CNM absorption



- P_T spectrum at LHC: contributions from supression, regen., and CNM absorption.
- Regeneration causes the low momentum bump
- Consistency between new lattice results and SBS

R. Sharma: High P_T quarkonia and heavy flavors

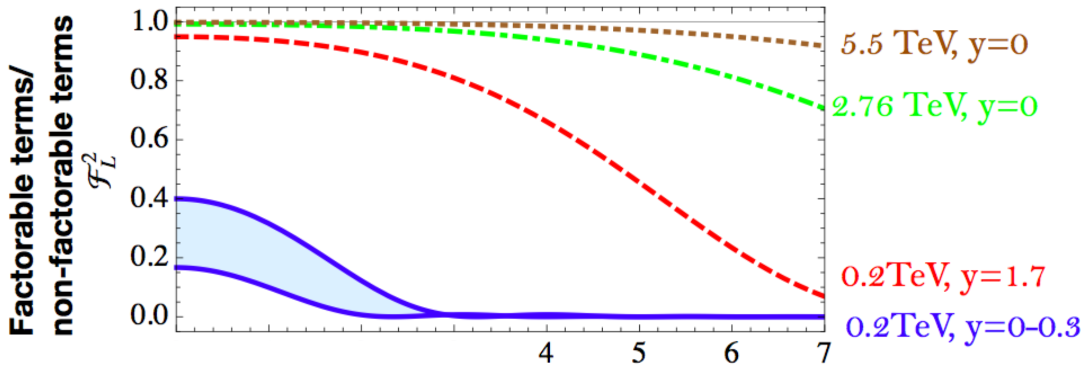


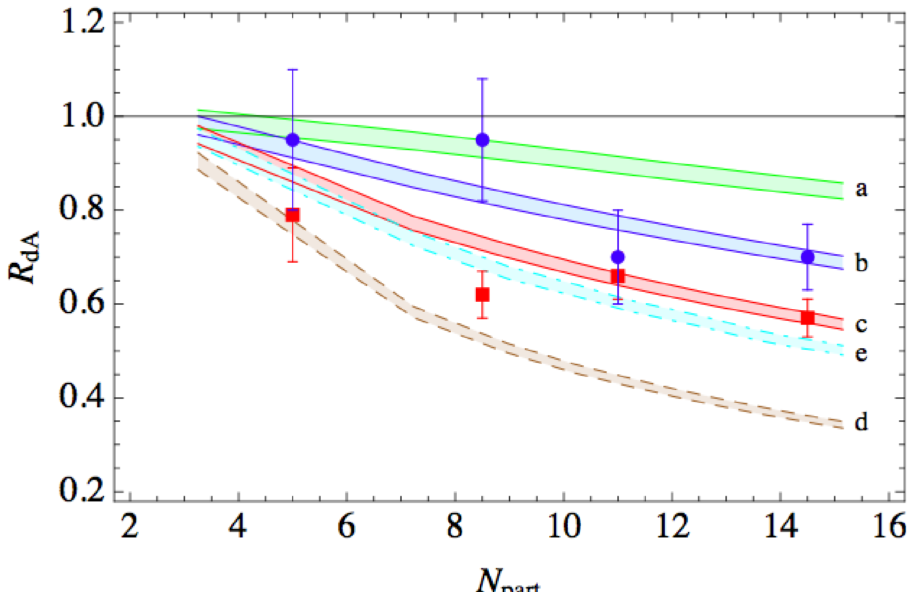
No Cronin

Physics is largely in the formation/dissociation times

K. Tuchin: Gluon saturation effects on Charmonium in dA and AA

- Multiple scattering effects in the nuclear medium (formation time) will make the production mechanism *coherent.*





p_T

th the nucleus (dA): enhancement

rings $a_s^2 A^{1/3}$

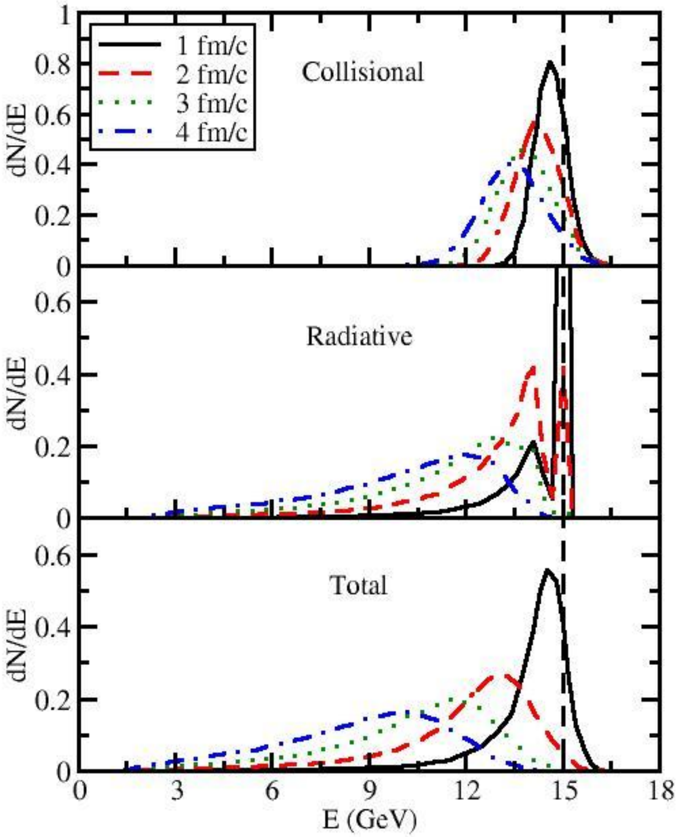
ie dipole (cc)-nucleon cross-section

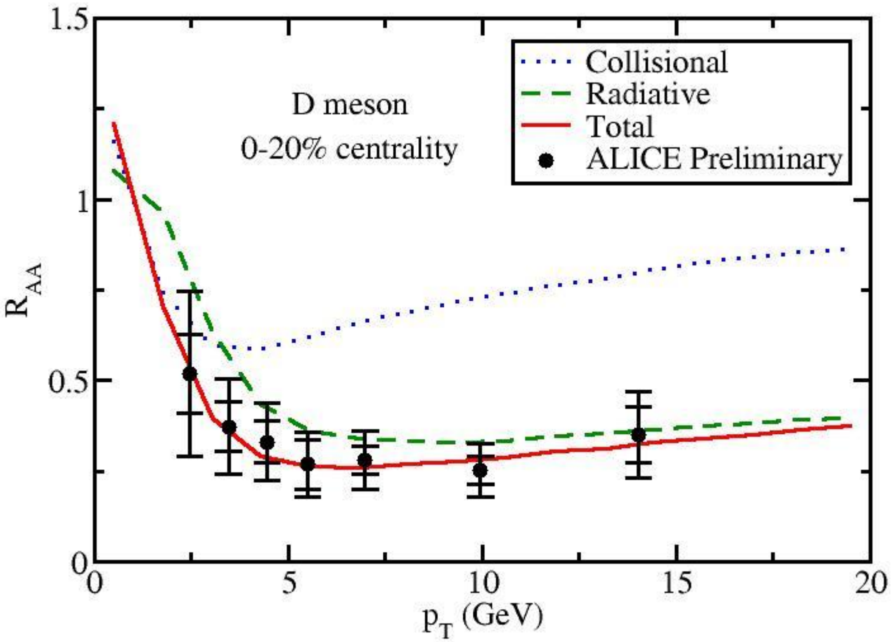
RHIC, LHC; different y's

CNM from first principles. LHC prediction
No qualitative agreement for AA

S. Cao: Heavy quark evolution & flow

- Include radiative E loss of heavy quark by extending the Langevin equation $\frac{d\vec{p}}{dt} = -h_D(p)\vec{p} + \vec{\xi} + \vec{f}_g$



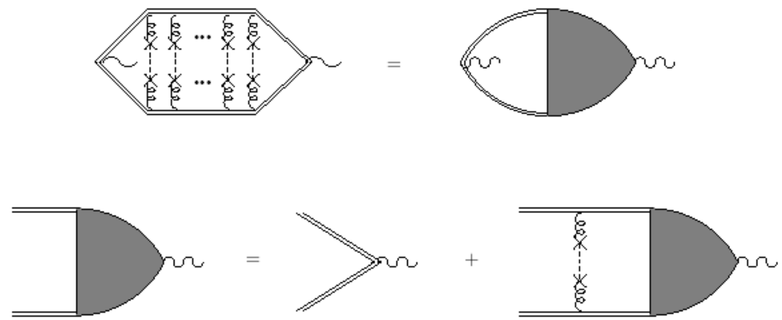


Respective effects of radiative & collisional E loss
Check effect on light flavors

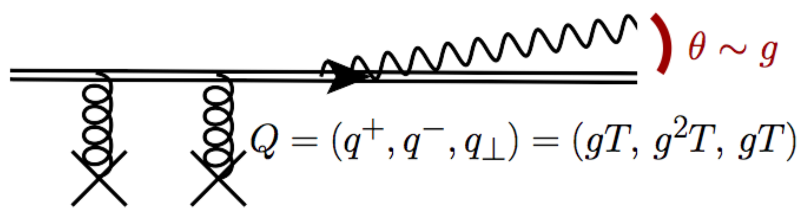
Thermal Photons & Dileptons

D. Teaney: Photons @ NLO

- Photon yield=Photon-emission rates Ä hydro
- LO rates in QGP phase = AMY (2001)



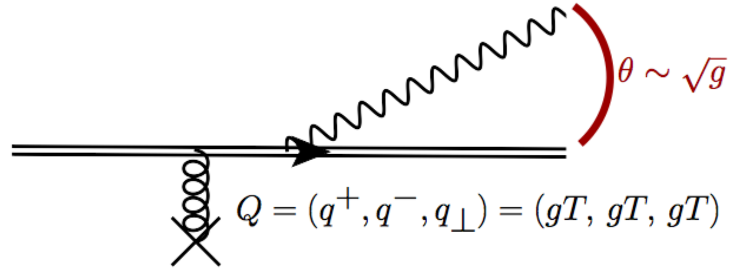
NLO:



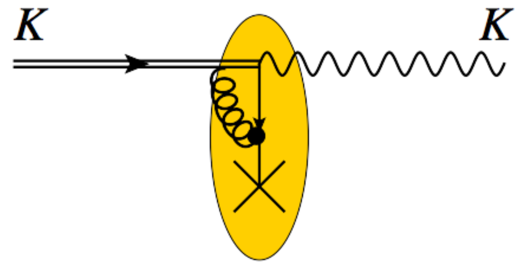
$$C(q_T)_{\mathrm{LO}} = \frac{Tg^2 m_D}{q_T(q_T + m_D)} \text{ Þ NLO}$$

S. Caron-Huot (2010)

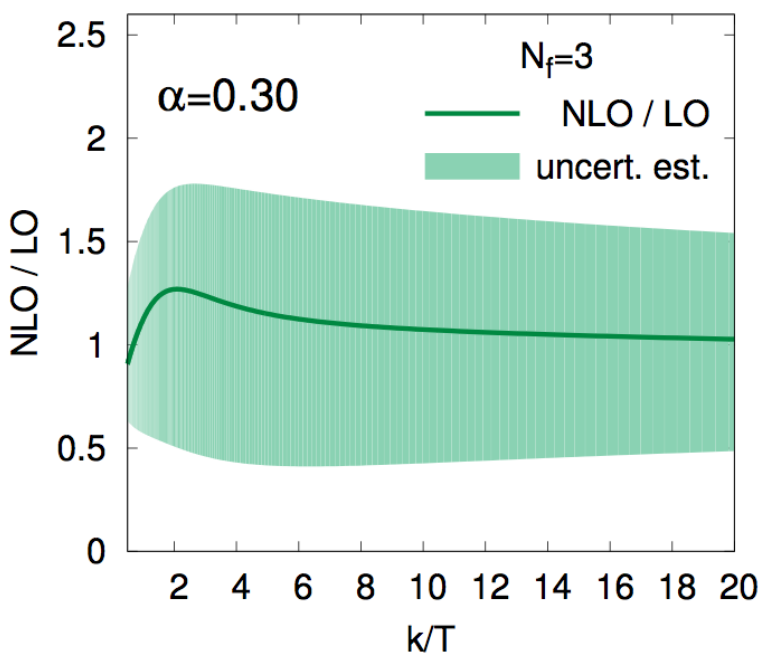
Larger angle emission



Conversion photons

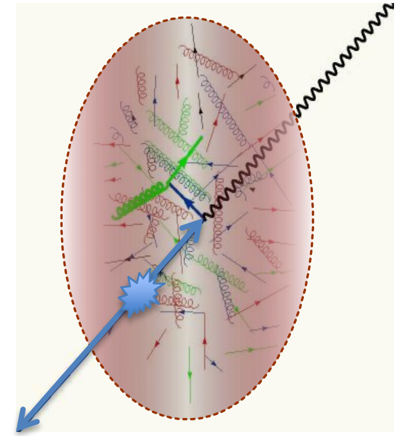


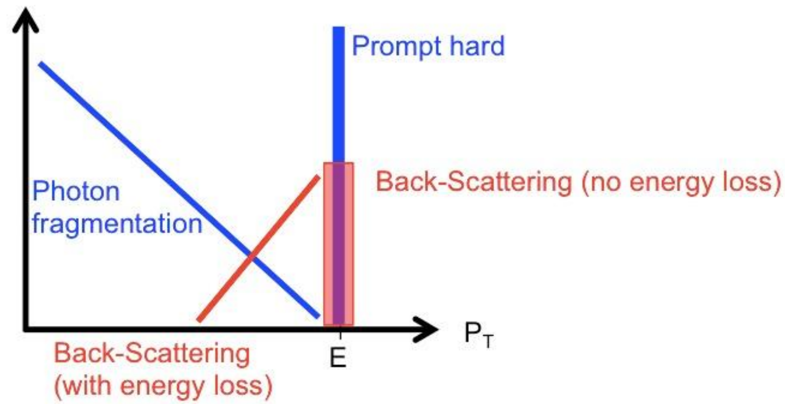
$$R_{\mathrm{NLO}} \sim g^3 \ln(1/g) + g^3$$



- Net correction to emission rate not numerically important in region up to k/T ~10
- Techniques developed here will have other applications in FTFT

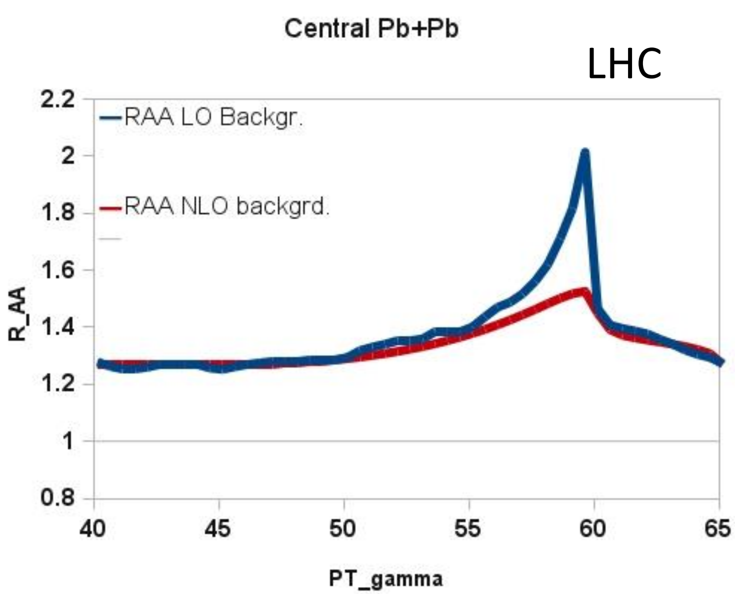
R. Fries: Jet-Photon conversions





Hard to observe, trigger on jet first

60-65 GeV Jet Trigger

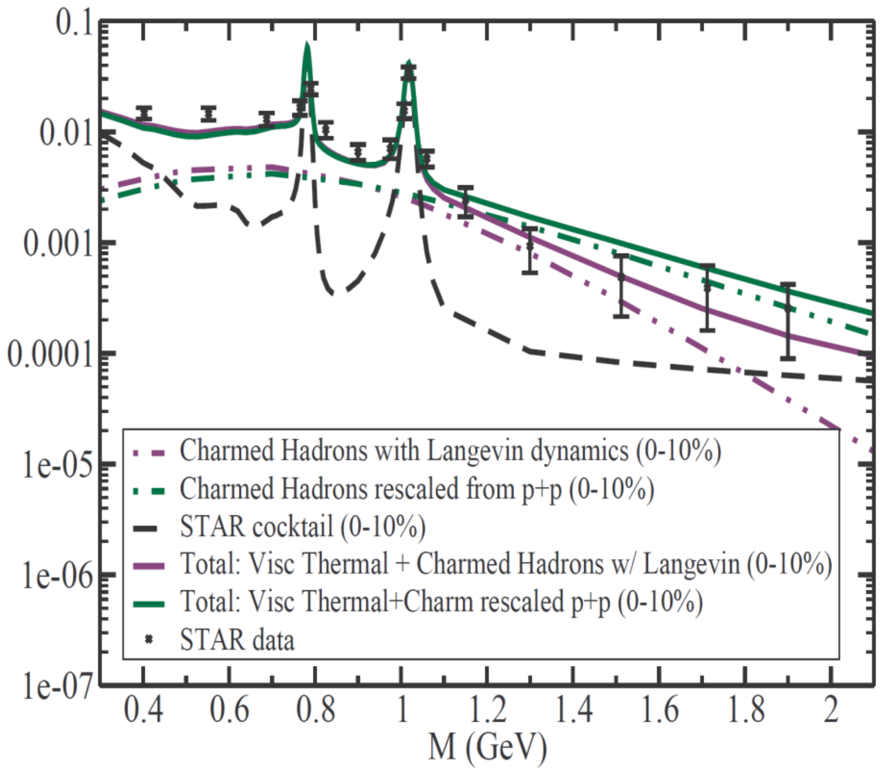


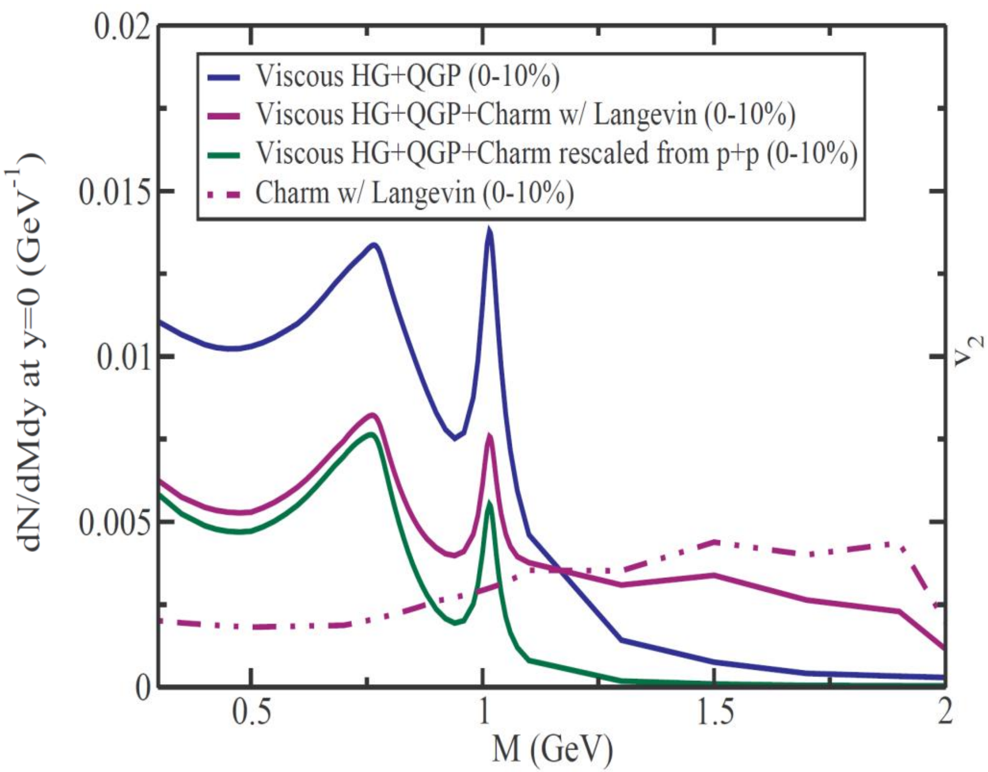
- NLO effects wash out signal, but it still shines
- Background evaluations

Low and Intermediate Mass Dileptons

G. Vujanovic: Thermal dileptons with 3D viscous hydro

- Use vector meson spectral densities consistent with analysis of NA60 data
- Use viscous 3D hydro consistent with analysis of hadronic data
- Investigated effect of viscous corrections to dilepton spectra and v_2, including c E-loss





v2: sensitive to viscosity corrections
IMR spectrum and v2: sensitive to charm energy-loss

The experimental results

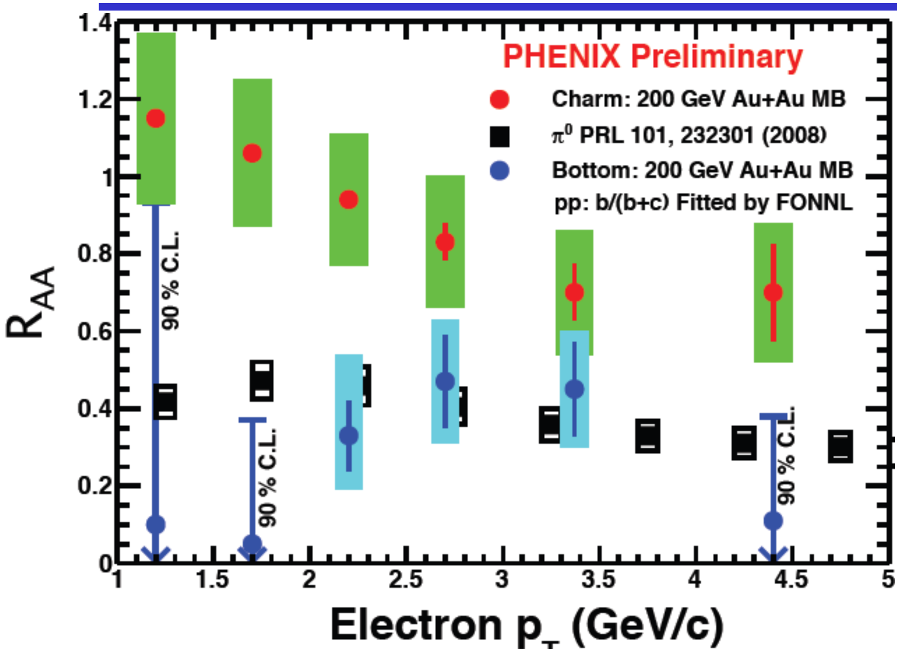
Outline:

- **Heavy flavor: D, B, and their decayed e and μ**
- **Quarkonia: J/ψ, Υ and their excited states**
- **Controlled Probes: W, Z, and γ**
- **Thermal di-leptons and photons: γ, e^+e^-, and $\mu^+\mu^-$**

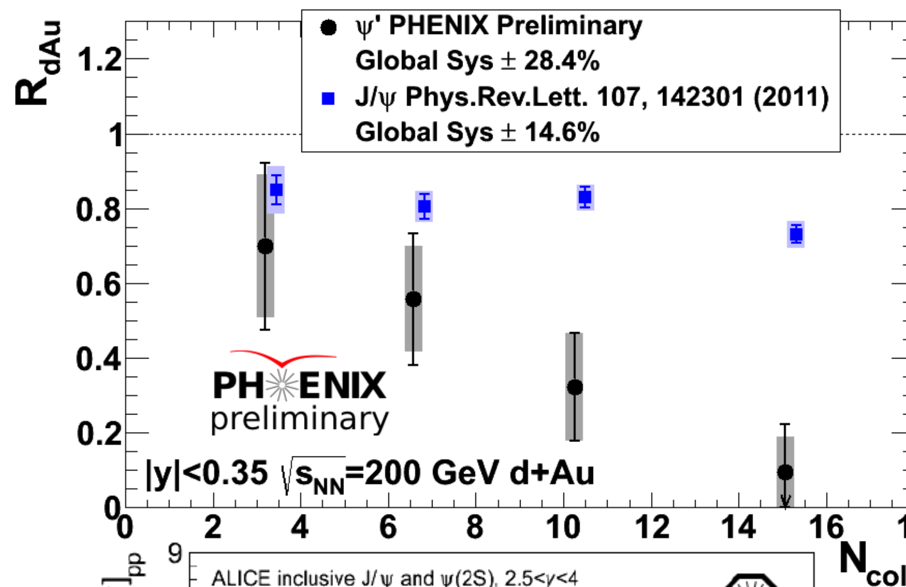
The measurements presented at QM2012

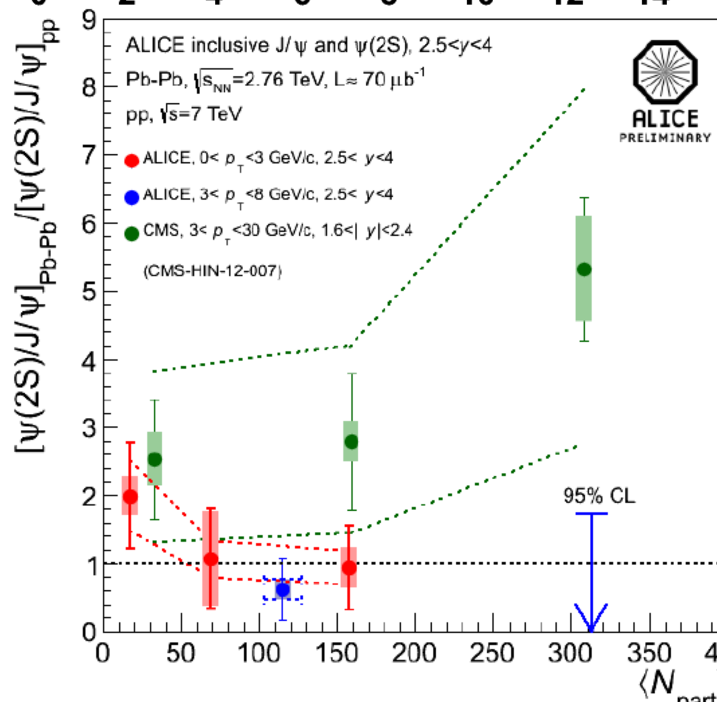
Experiment	Heavy flavor	Quarkonia	Electroweak
PHENIX	μ: 1.2<|y|<2.2 e: |y|<0.35	J/ψ, $\Upsilon\rightarrow\mu\mu$ J/ψ, $\Upsilon\rightarrow$ee	γ, di-electron
STAR	e, D: |y|<1	J/ψ, $\Upsilon\rightarrow$ee	di-electron
ALICE	μ: 2.5<|y|<4 e,D: |y|<0.9 B$\rightarrow$J/ψX$\rightarrow$eeX	J/$\psi\rightarrow$ $\mu\mu$ J/$\psi\rightarrow$ ee	γ
ATLAS	μ: |y|<1.05, p_T>4 GeV/c		γ: |y|<1.3, E_T (45-200 GeV) W$\rightarrow\mu\nu$: |η^{μ}|<2.7,$p_T(\mu)$>7 GeV/c Z$\rightarrow\mu\mu$ (ee): |y|<2.7 (|y|<2.5)
CMS	B$\rightarrow$J/ψX$\rightarrow\mu\mu$X	J/$\psi\rightarrow\mu\mu$: |y|<2.4, p_T>6.5 GeV/c $\Upsilon\rightarrow\mu\mu$ |y|<2.4	γ: |y|<1.44, E_T (20-80 GeV) W$\rightarrow\mu\nu$: |η^{μ}|<2.1,$p_T(\mu)$>25 GeV/c Z$\rightarrow\mu\mu$: |y|<2.1

Surprising results at QM2012



PHENIX: McGlinchey, Nouicer, Rosati, Sakaguchi, Wysocki

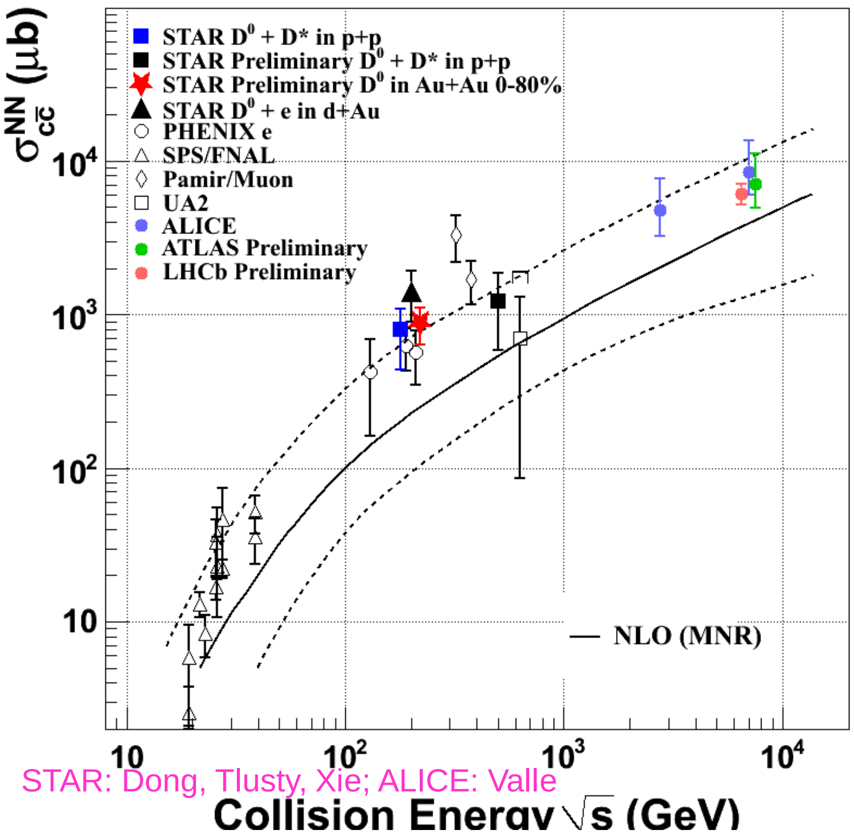




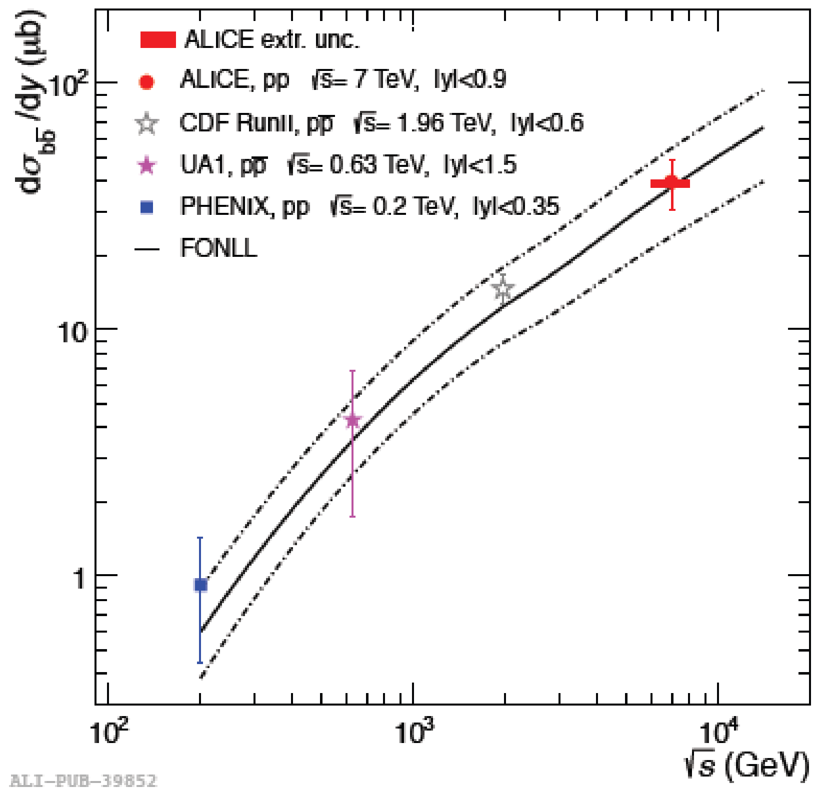
- **PHENIX: R_{AA}(b→e) < R_{AA} (c→e)** at p_T=1-5 GeV/c in 200 GeV Au+Au
- **PHENIX: R_{dAu}(ψ') < R_{dAu}(J/ψ) by a factor of 5** in most central d+Au
- **CMS: At 1.6<|y|<2.4, 3<p_T<30 GeV, ψ(2S) less suppressed than J/ψ in central Pb+Pb**, not confirmed by ALICE with 2.5<|y|<4, 3<p_T<8 GeV.

CMS: Mironov, Moon, Roland; ALICE: Arnaldi, Safarik, Scomparin

Open heavy flavor measurements in p+p collisions



STAR: Dong, Tlusty, Xie; ALICE: Valle



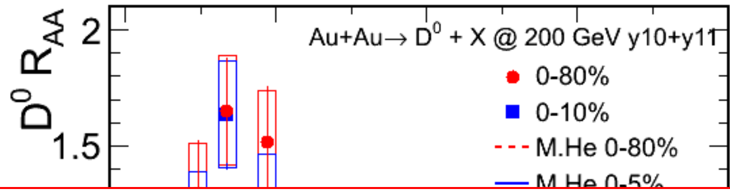
Charm cross section follows N_{bin} scaling from p+p to Au+Au collisions

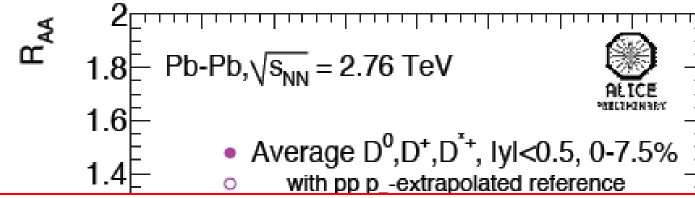
Expect to get 60 ccbar and 2 bbbar pairs in central Pb+Pb collisions at 2.76 TeV

Expect to get 15 ccbar and 0.1 bbbar pairs in central Au+Au collisions at 200 GeV

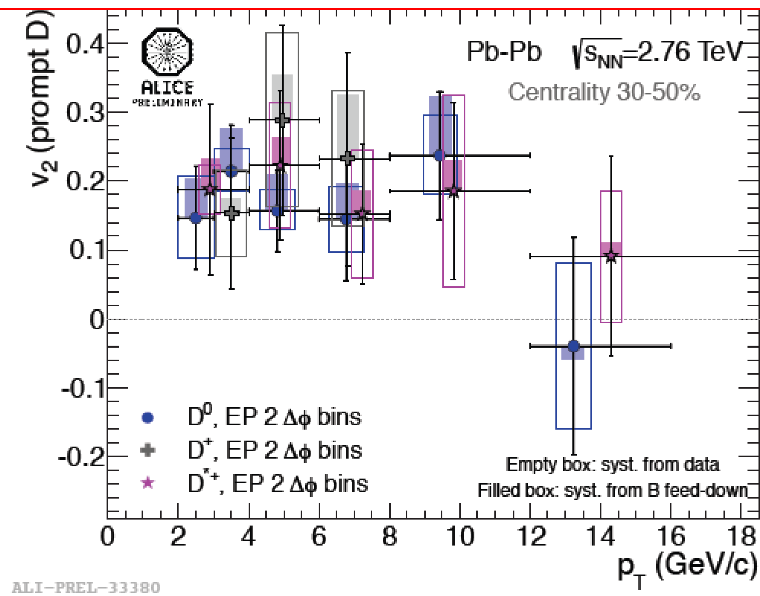
Coalescence from bbbar to Υ is negligible at RHIC.

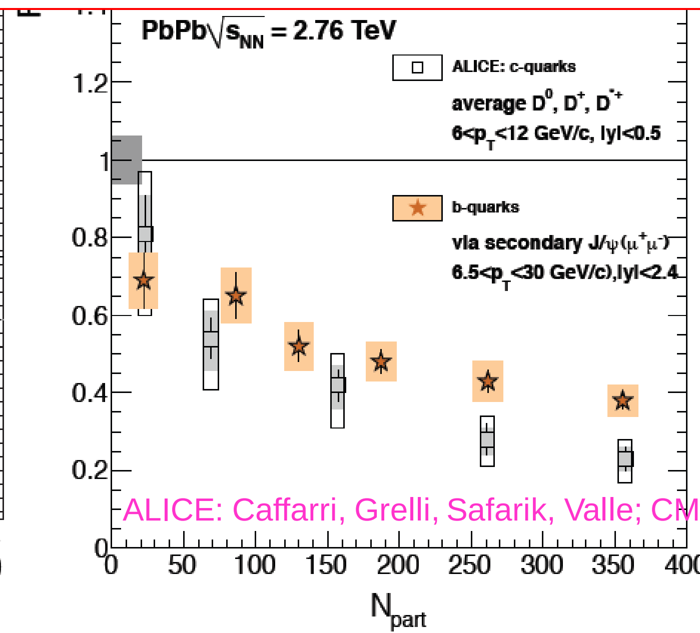
Open heavy flavor results in A+A





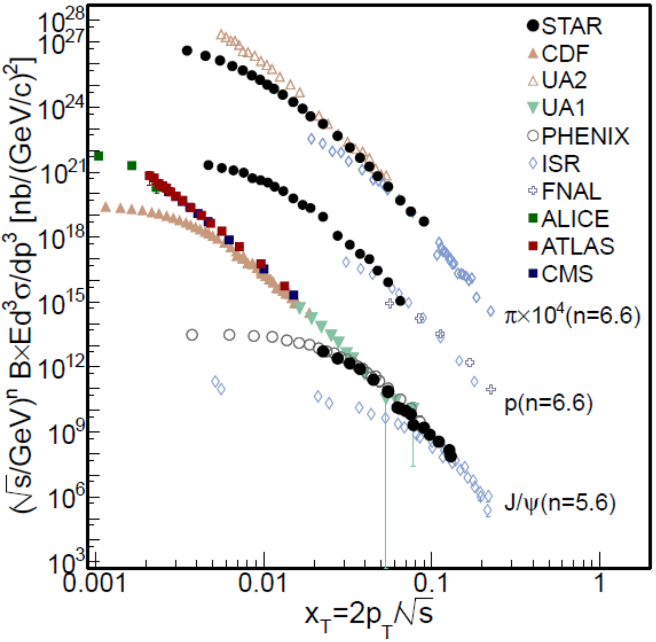
- **Significant charmed hadron, B hadron suppression observed. $R_{AA}(D)$~$R_{AA}(\pi)$ ≤$R_{AA}(B\rightarrow J/\psi)$**
- **D meson flows** (High precision measurements of electron, muon R_{AA} and v_2 also reported by ALICE, ATLAS, and STAR)
- **Need more precise measurements to study color charge and/or flavor dependence of energy loss**



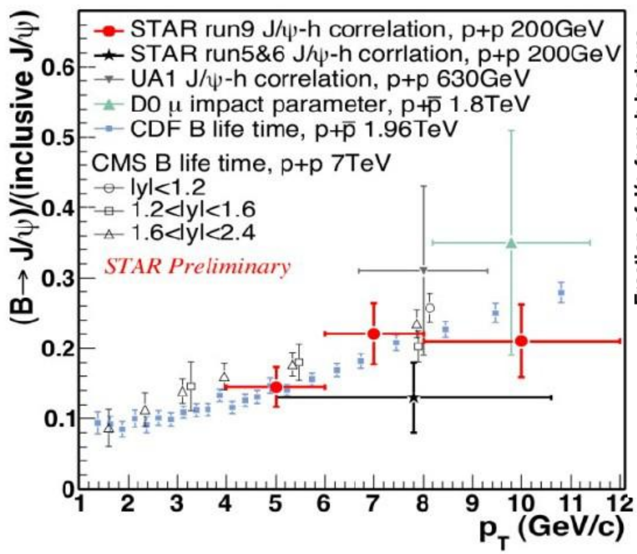


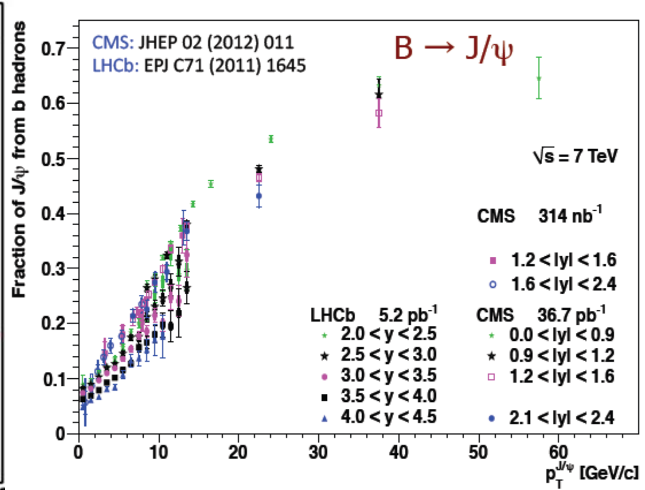
ALICE: Caffarri, Grelli, Safarik, Valle; CMS: Mironov, Jo

J/ψ results in p+p



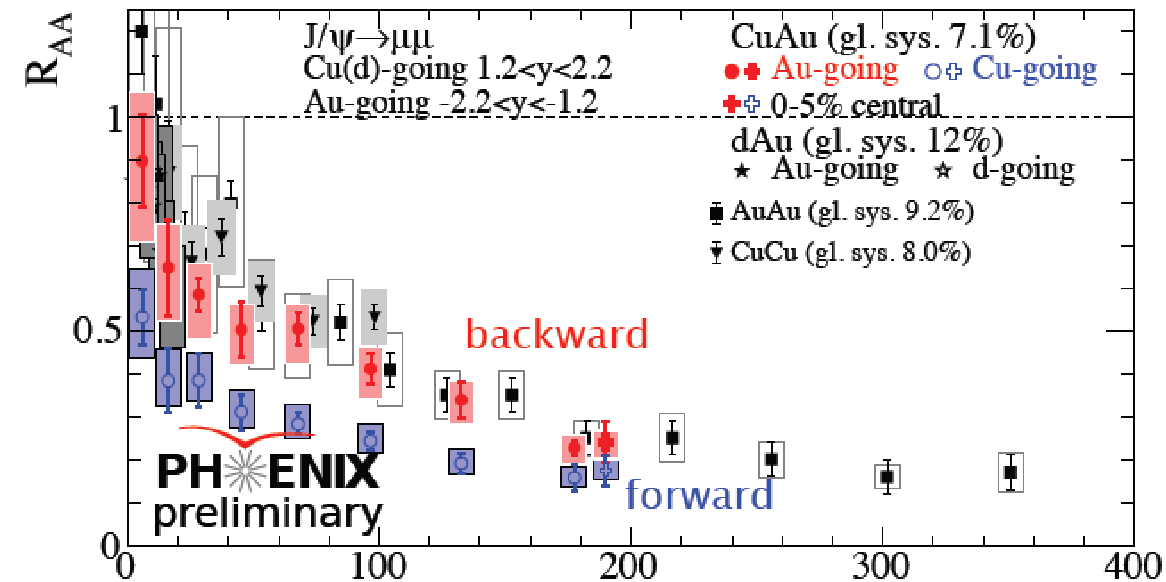
STAR: arXiv: 1208.2736, Trzeciak, Xie

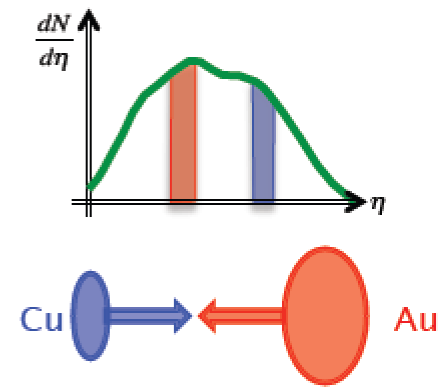




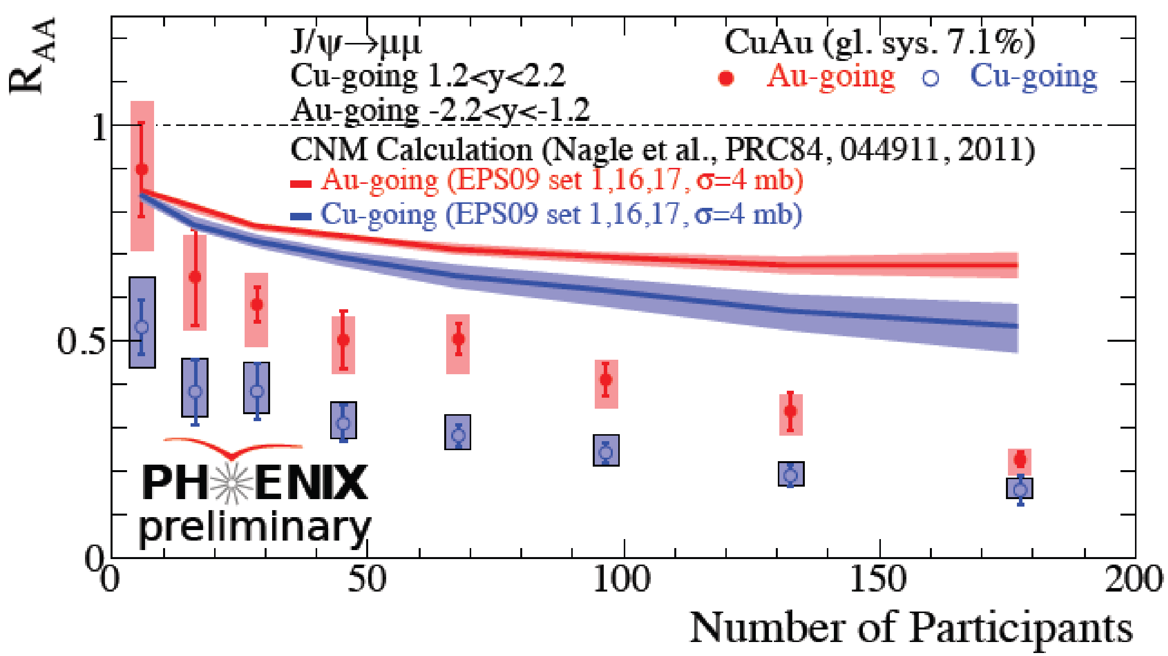
- **The J/ψ production at p_T>3 GeV/c, follows x_T scaling in p+p collisions.**
- **B feed-down contribution:<20% at p_T<10 GeV/c, more significant at higher p_T**

J/ψ results in 200 GeV Cu+Au



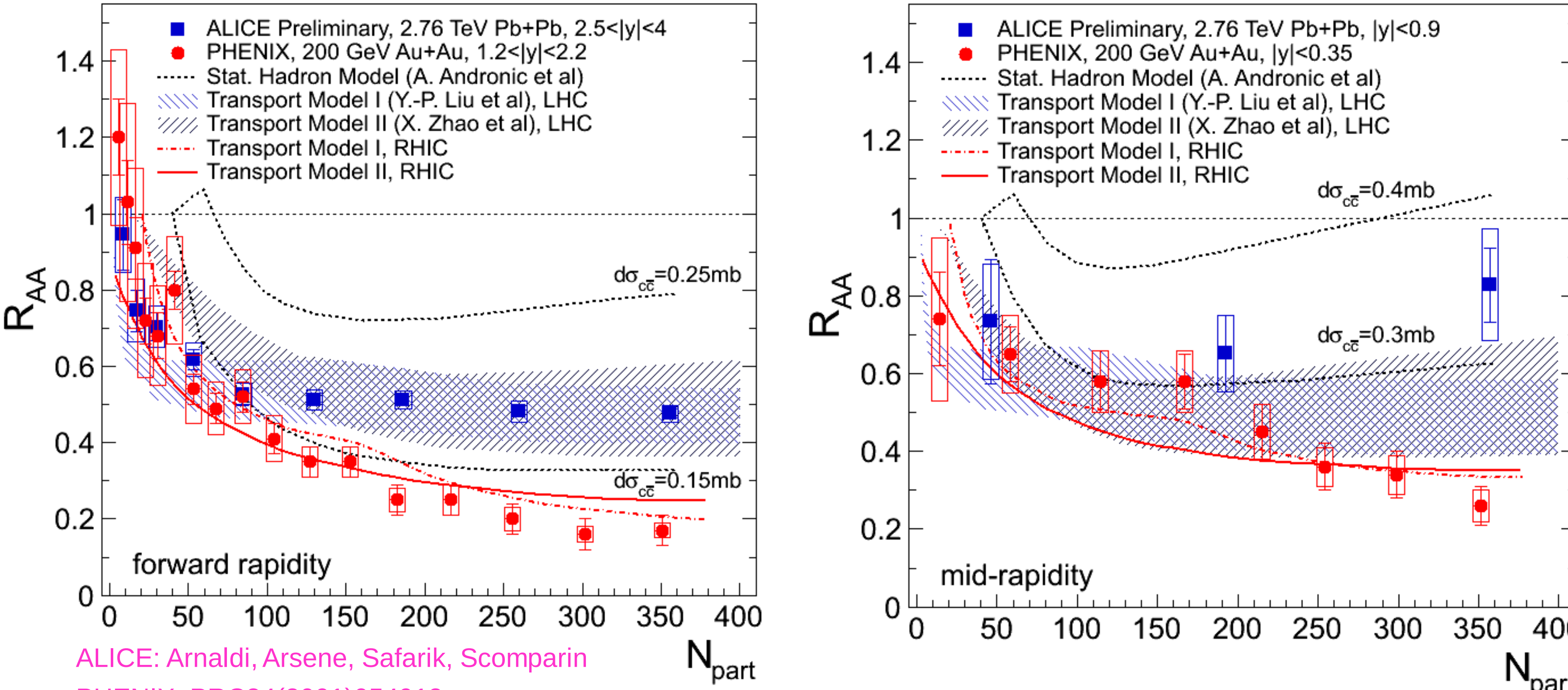


PHENIX: Hollis, Rosati, Sakaguchi



In Cu+Au collisions, R_{AA}(Au-going) > R_{AA}(Cu-going), qualitatively described by CNM but not quantitatively. Additional suppression suggests hot, dense medium effect

J/ψ results in A+A: centrality dependence



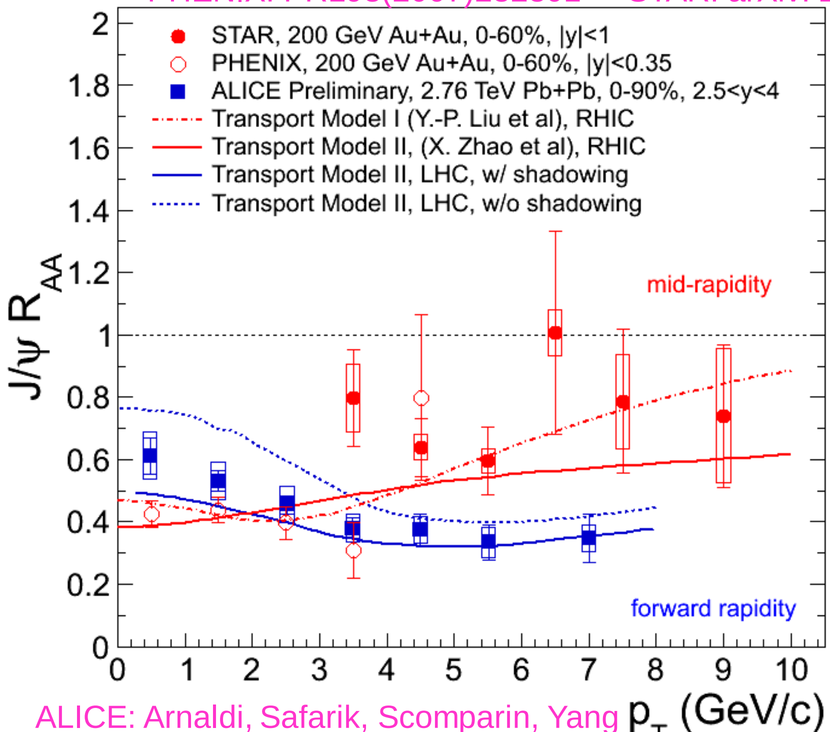
ALICE: Arnaldi, Arsene, Safarik, Scomparin

PHENIX: PRC84(2001)054912

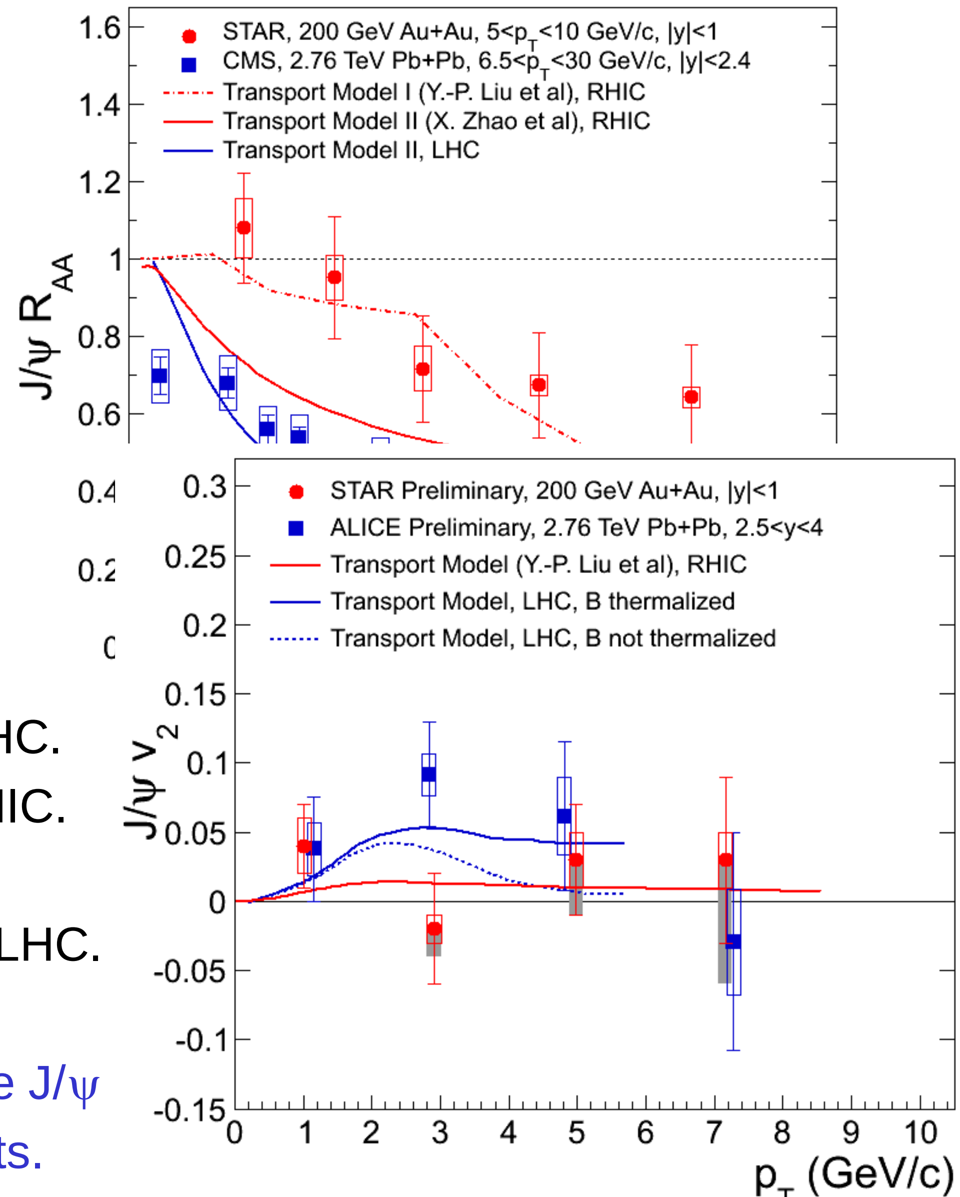
- N_{part} dependence of J/ψ R_{AA}: less suppression at LHC compared to at RHIC in central collisions
- interplay between CNM, color screening and ccbar recombination
- consistent with more significant contribution from ccbar recombination at LHC energies

J/ψ results in A+A: p_T dependence

PHENIX: PRL98(2007)232301 STAR: arXiv: 1208.2736, Trzeciak, Xie CMS: Mironov, Moon, Roland



ALICE: Arnaldi, Safarik, Scomparin, Yang



J/ψ R_{AA} decreases from low to high p_T at LHC.

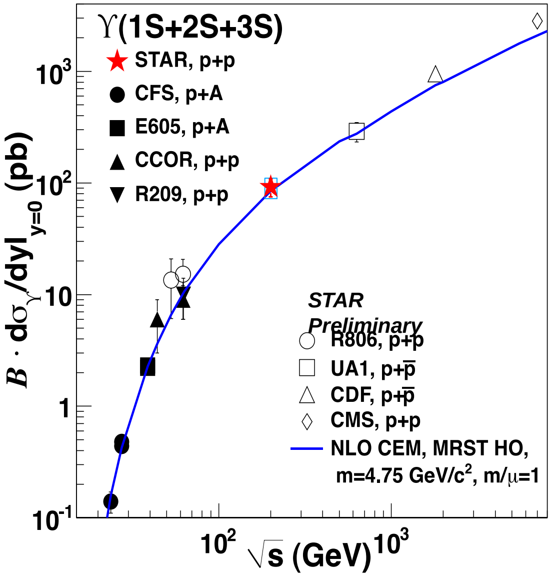
J/ψ R_{AA} increases from low to high p_T at RHIC.

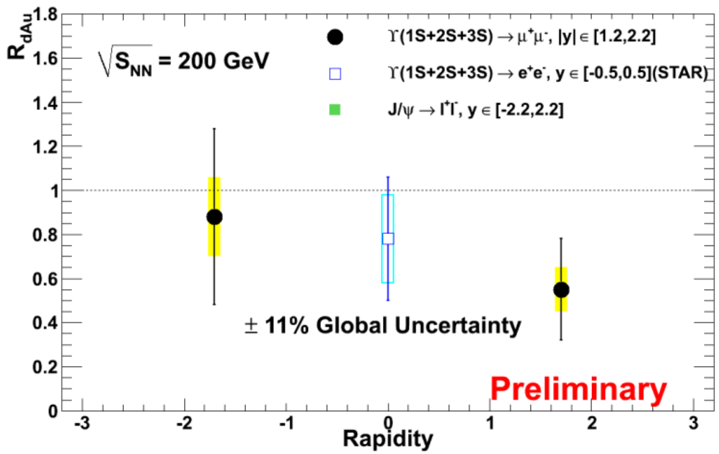
At high p_T, J/ψ more suppressed at LHC.

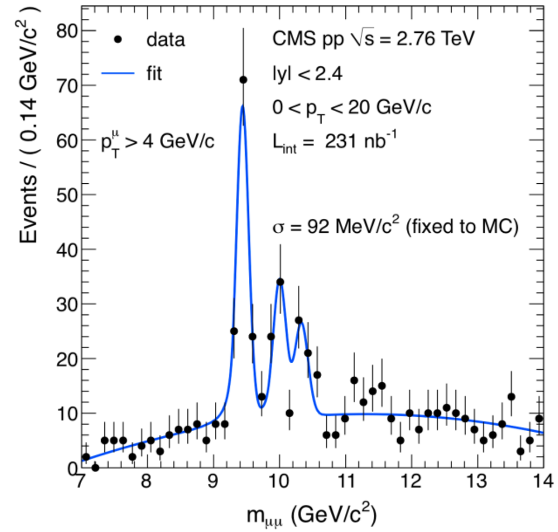
Hint for possible J/ψ flow at p_T=3 GeV/c at LHC.

Models incorporating color screening and recombination can consistently describe the J/ψ suppression pattern and flow measurements.

ϒ result in p+p, dAu collisions

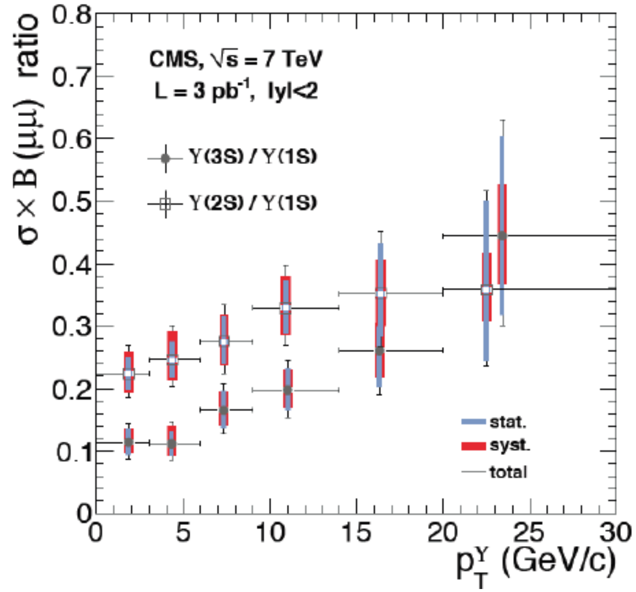




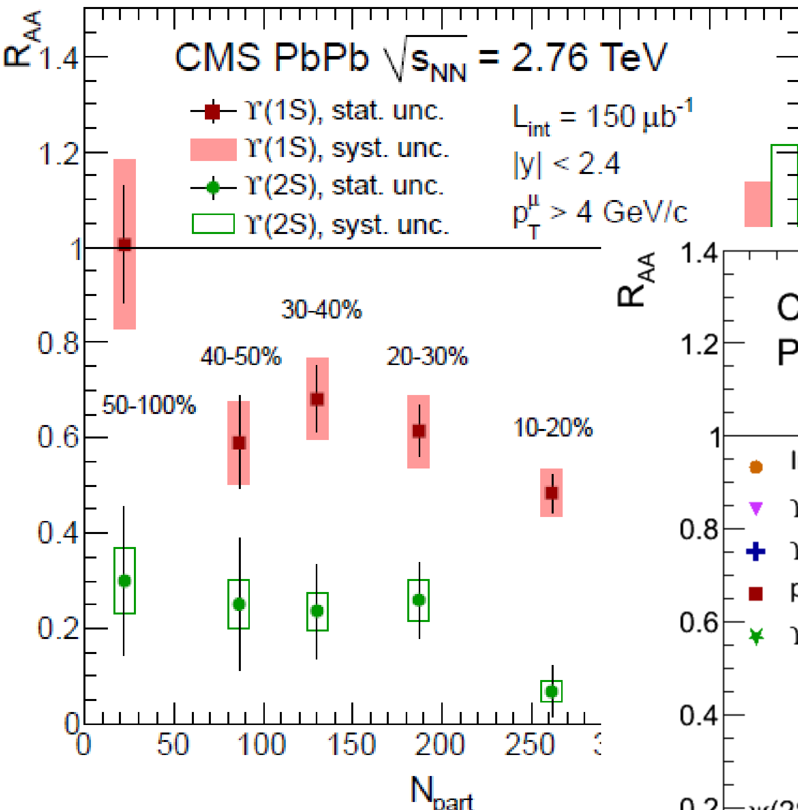


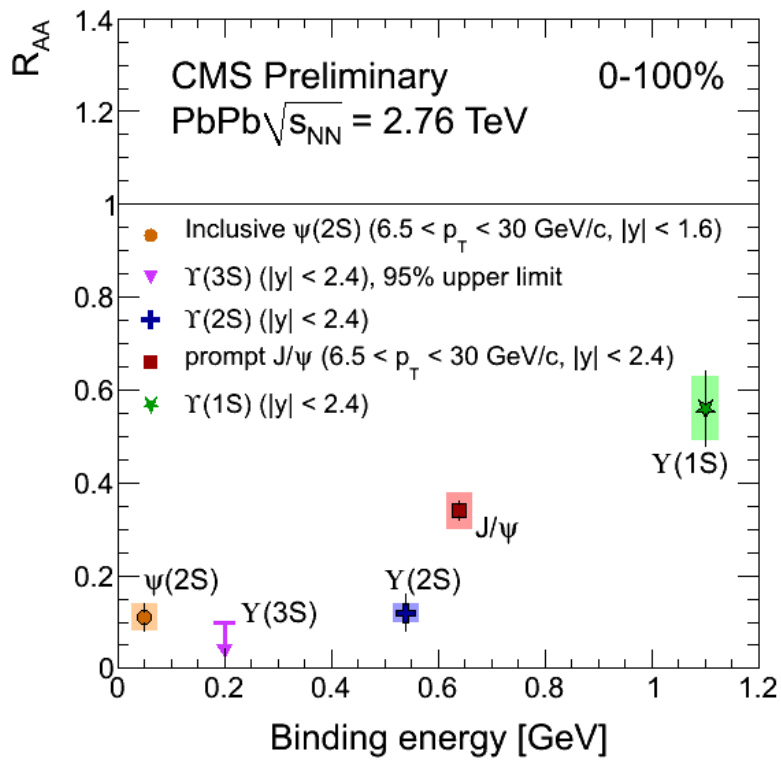
STAR: Trzeciak, Xie ; PHENIX: HP2012;
CMS: PRD83(2011)112004

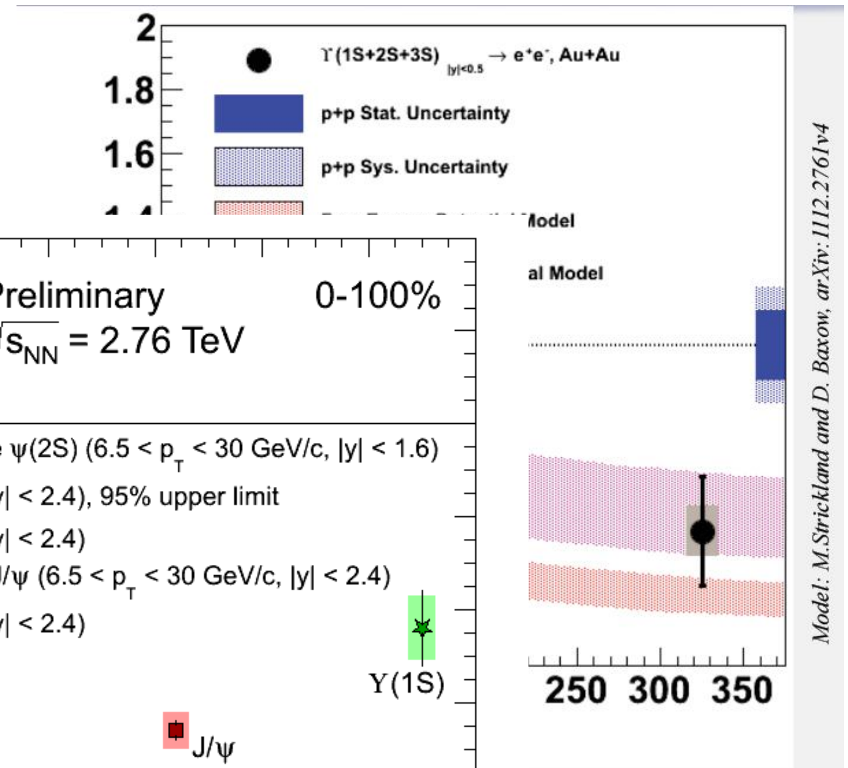
- ϒ cross section consistent with NLO calculations.
- Rapidity dependence of ϒ nuclear modification in d+Au observed.
- Different ϒ state measured in CMS.



ϒ results in A+A







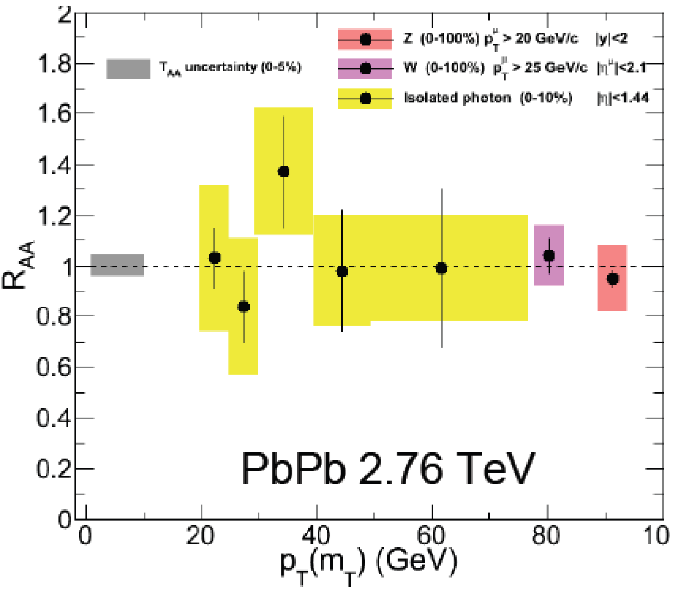
STAR: Dong, Trzeciak, Xie
CMS: arXiv: 1208.2826, Mironov

ϒ(1s) suppression magr … **suppression.**

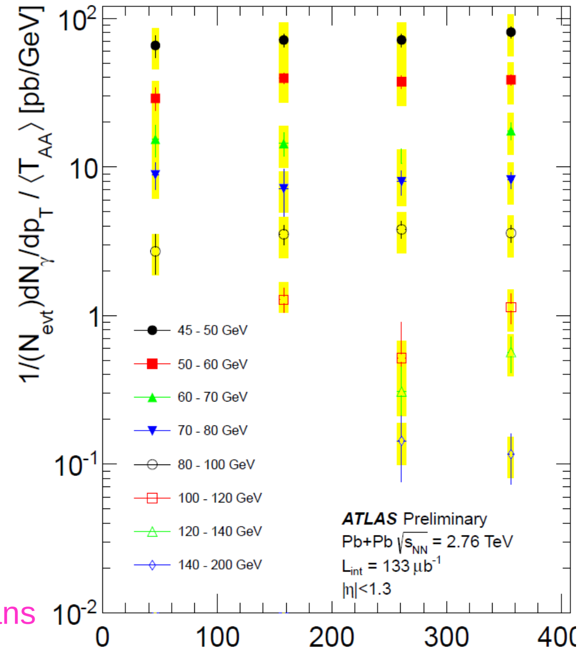
ϒ(2S) strongly suppress

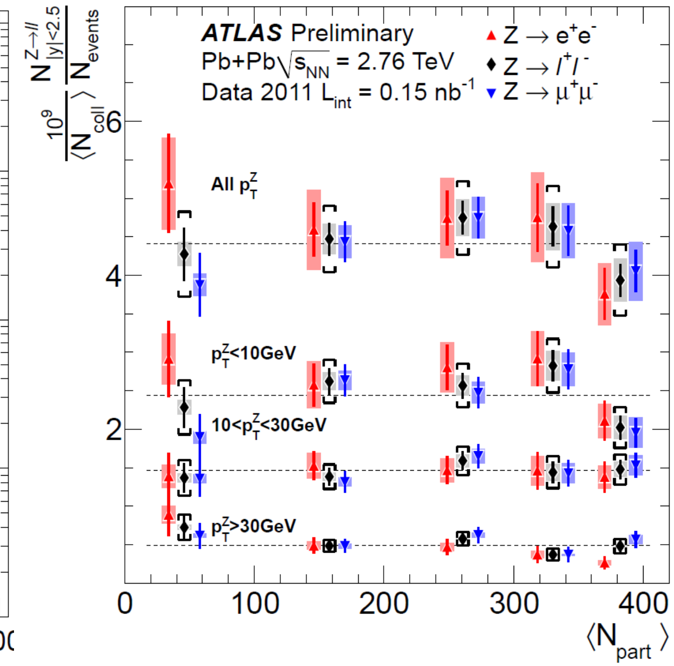
Now is the perfect time to study color screening features of hot, dense medium in light of RHIC and LHC precise quarkonium measurements.

Electro-weak probes



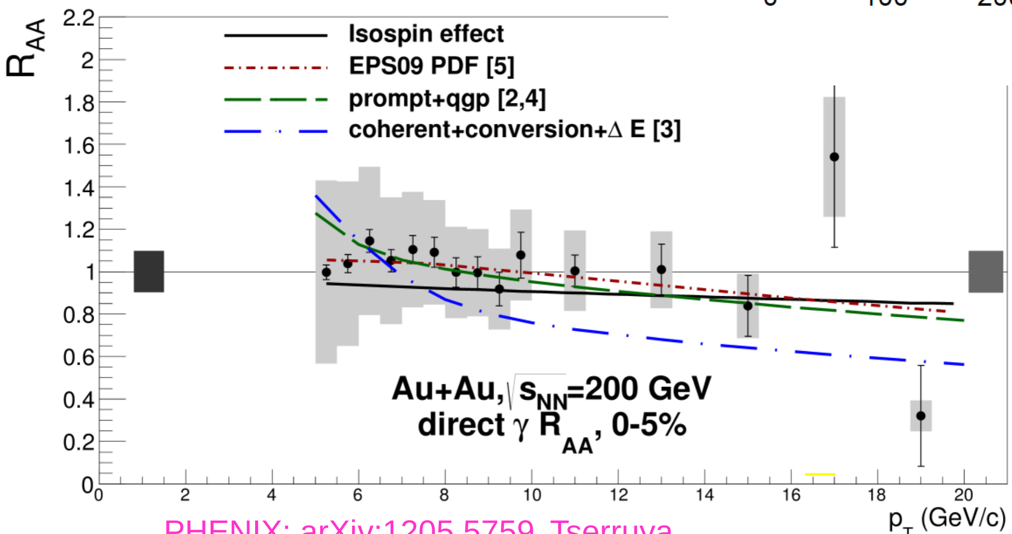
CMS: Benhabib, Cassagnac, Roland, Stephans





$\langle N_{part} \rangle$

ATLAS: Dolejsi, Grabowska-Bold, Steinberg, Wosiek



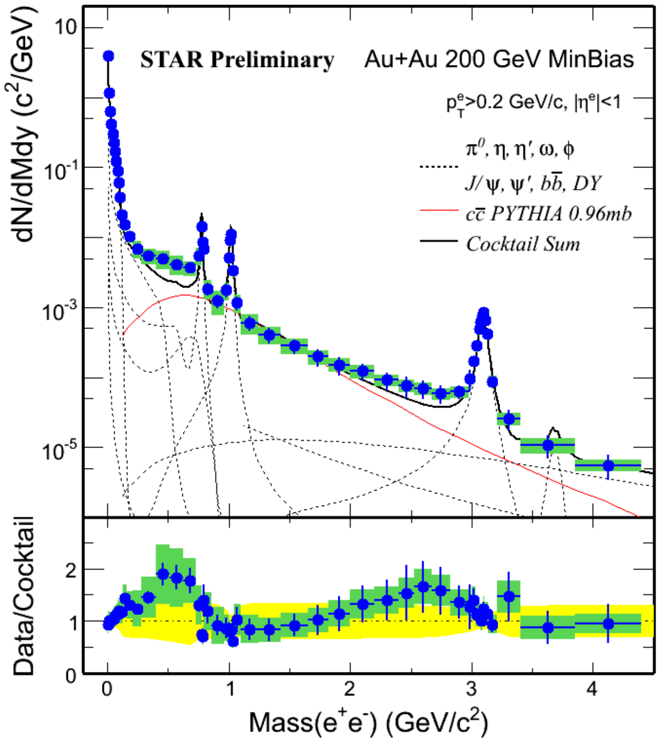
PHENIX: arXiv:1205.5759, Tserruya

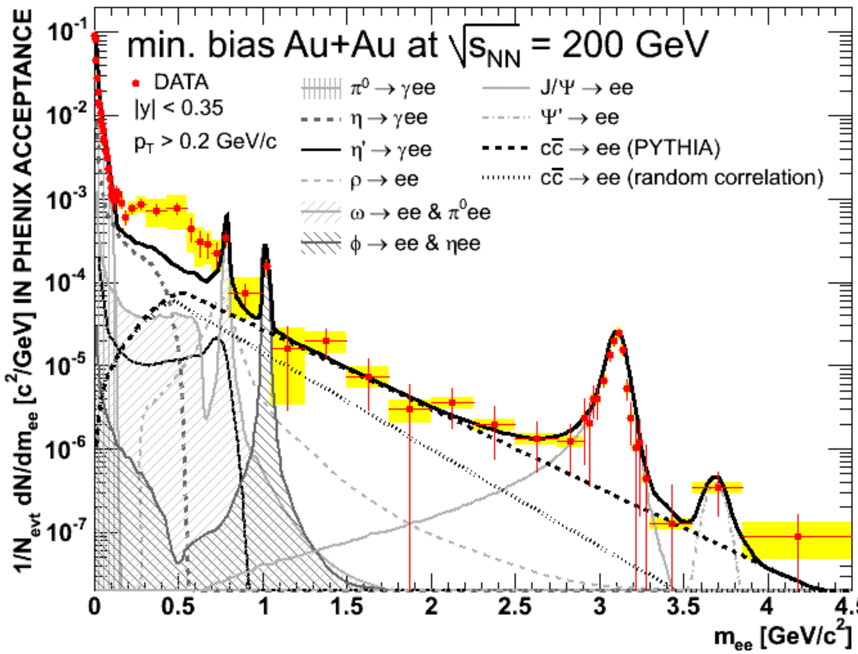
W, Z and high energy γ production in heavy ion collisions:

consistent with number of binary scaling.

Initial nuclear wave function effect is not significant wrt. uncertainties

RHIC di-lepton results at last QM





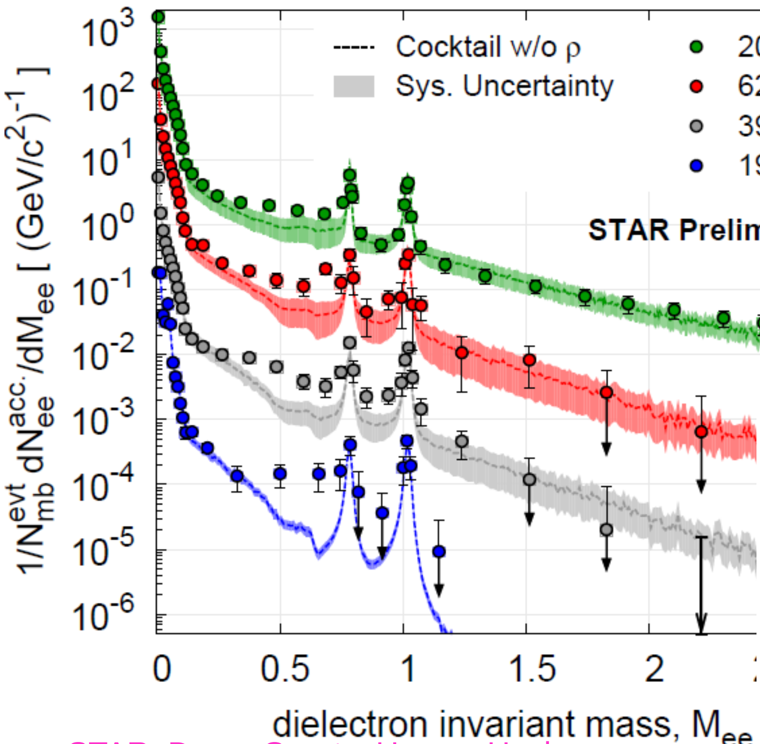
PHENIX PRC 81 (2010) 034911

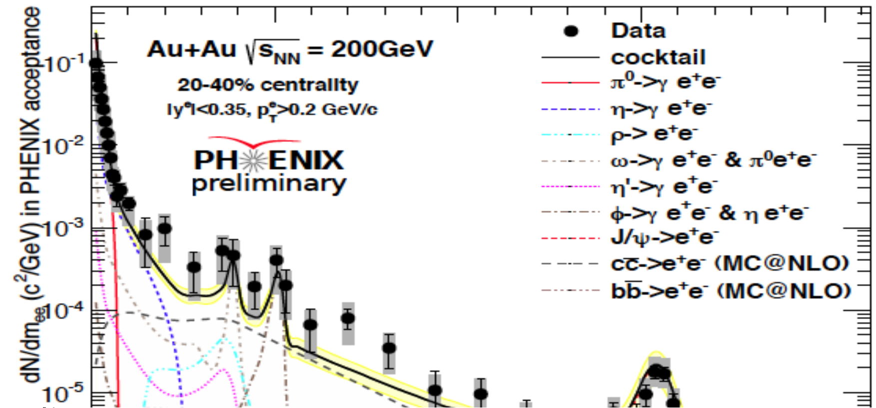
Enhancement factor in $0.15<M_{ee}<0.75$ Gev/c2

	Minbias (value ± stat ± sys)	Central (value ± stat ± sys)
STAR	**1.53 ± 0.07 ± 0.41 (w/o ρ)** **1.40 ± 0.06 ± 0.38 (w/ ρ)**	**1.72 ± 0.10 ± 0.50 (w/o ρ)** **1.54 ± 0.09 ± 0.45 (w/ ρ)**
PHENIX	**4.7 ± 0.4 ± 1.5**	**7.6 ± 0.5 ± 1.3**
Difference	**2.0 σ**	**4.2 σ**

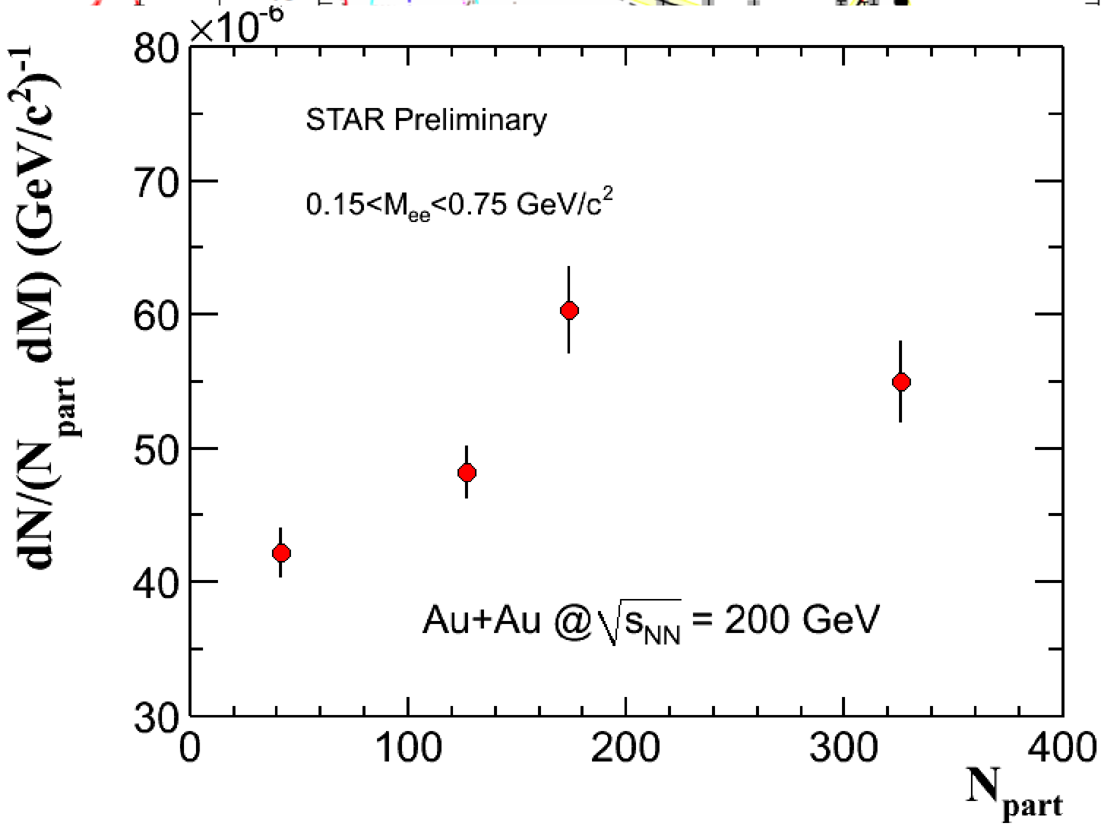
The discrepancy is in 0-20% central Au+Au collisions. The 0-20% HBD results will be important to clarify the discrepancy experimentally.

Energy dependence of di-electron spectra





STAR: Dong, Geurts, Huang, Huck



PHENIX HBD results at 200 GeV : co

STAR results: systematically study t

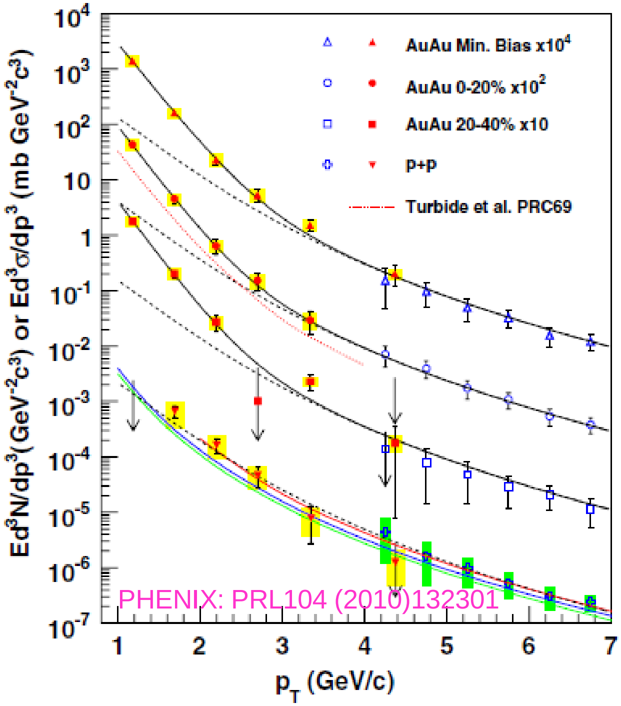
GeV. **Note:** **enhancement factor (EF**

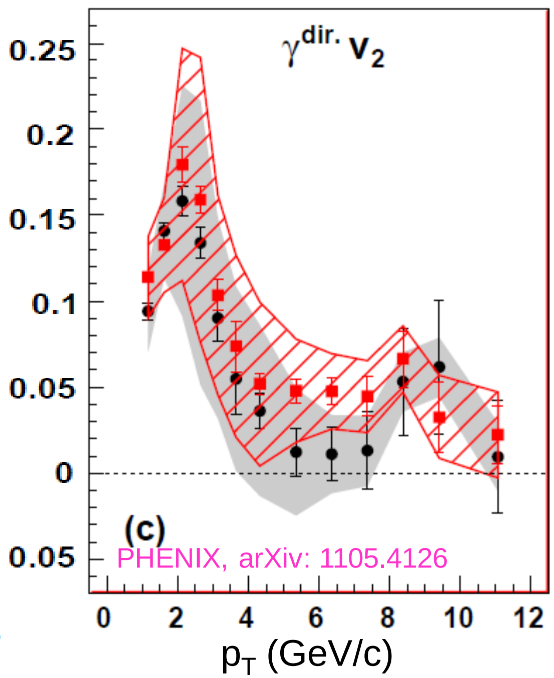
using cocktail as a reference, which

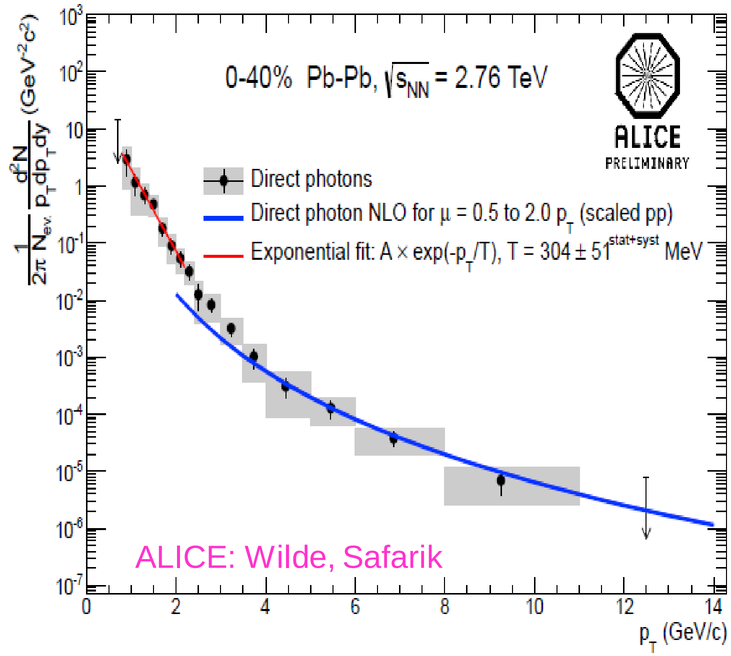
centrality dependence from STAR ex

using N_{part} as a reference, there is ce

Direct photon spectra and elliptic flow v_2

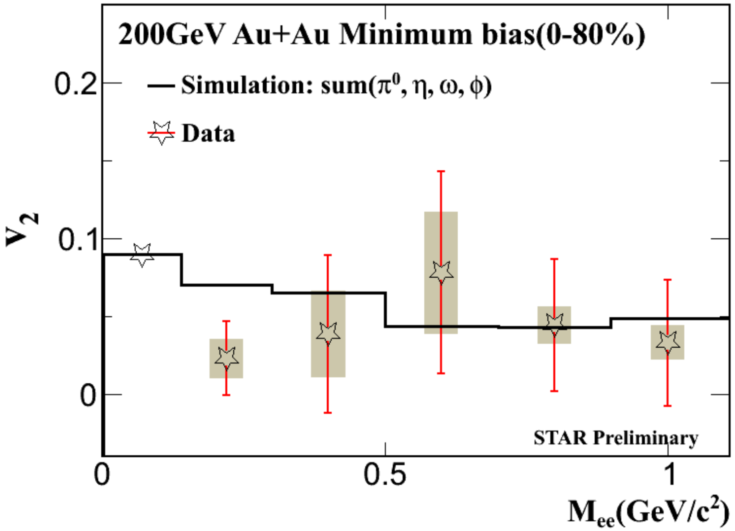


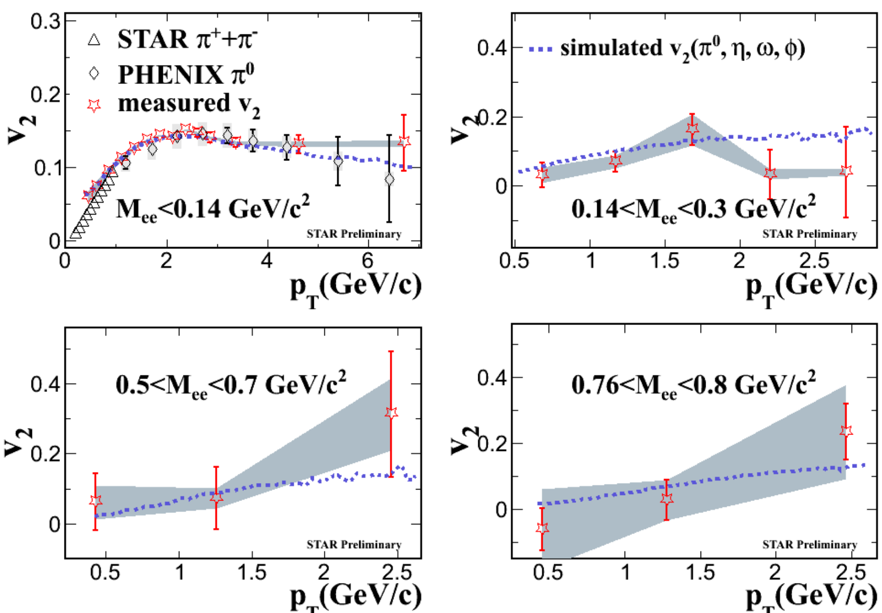




- Low p_T direct photon elliptic flow measurement could provide direct constraints on QGP dynamics (η/s, T, t_0…).
- Excess of direct photon yield over p+p: T_{eff}=221 ± 19 ± 19 MeV in 0-20% Au+Au; substantial positive v_2 observed at p_T<4 GeV/c.
- Excess of direct photon yield over p+p at p_T<4 GeV/c: T_{eff}=304 ± 51 MeV in 0-40% Pb+Pb.
- Di-lepton v_2 versus p_T & M_{ll}: probe the properties of the medium from hadron-gas dominated to QGP dominated. (R. Chatterjee, D. K. Srivastava, U. Heinz, C. Gale, PRC75(2007)054909)

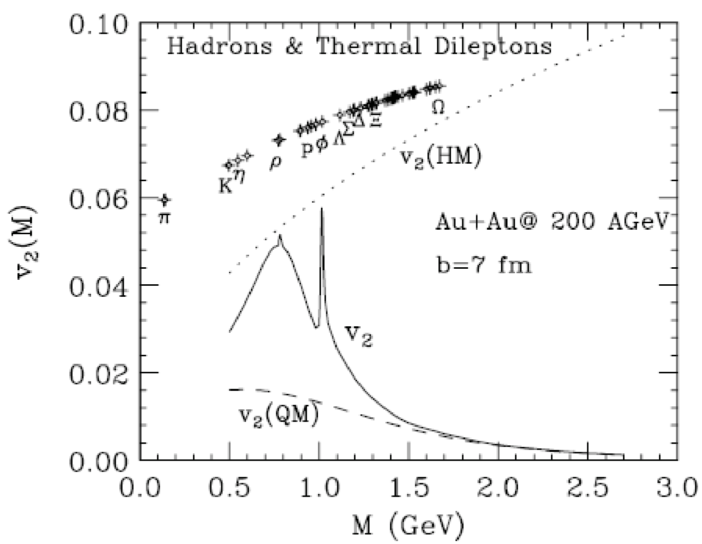
Di-electron v_2 at 200 GeV Au+Au





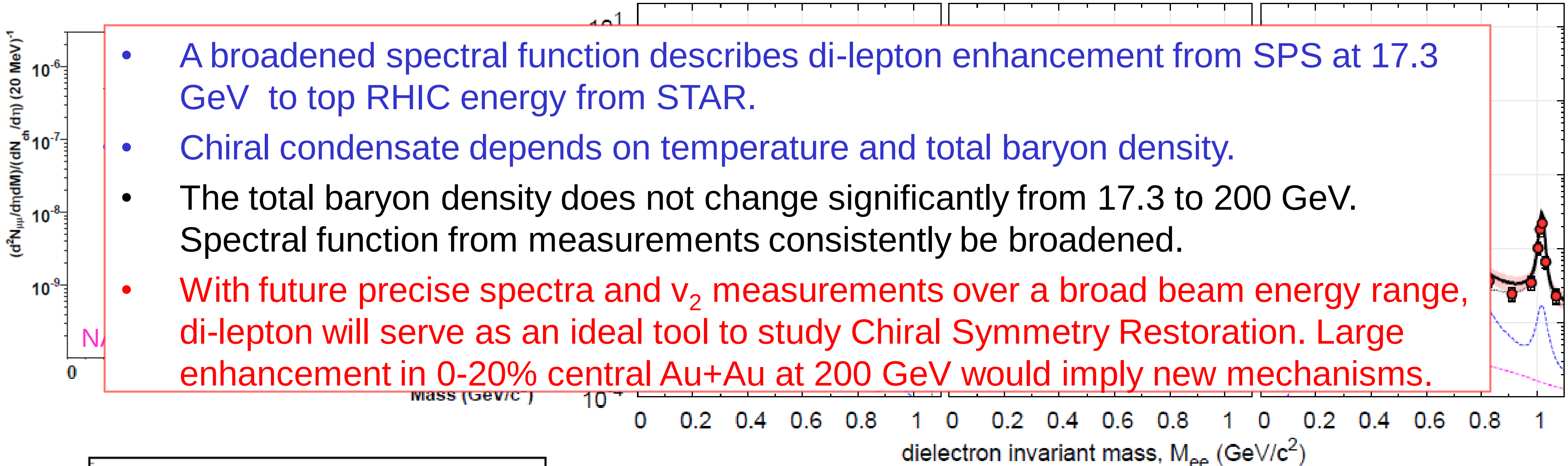
STAR: Cui, Geurts, Huang

- Cocktail simulation is consistent with the measured di-electron v_2 at M_{ee}<1.1 GeV/c^2.
- Need a factor of two more data to be sensitive to hardon gas and QGP contribution, in addition to independent measurements to disentangle ccbar correlation contribution



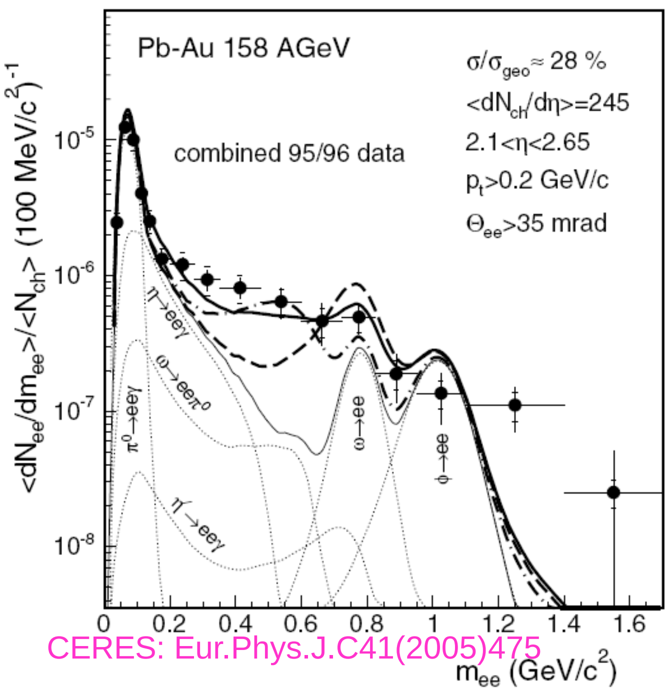
R. Chatterjee, D. K. Srivastava, U. Heinz, C. Gale, PRC75(2007)054909)

A tool to study Chiral Symmetry Restoration

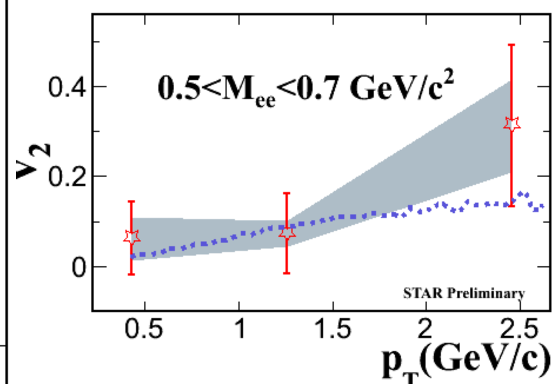


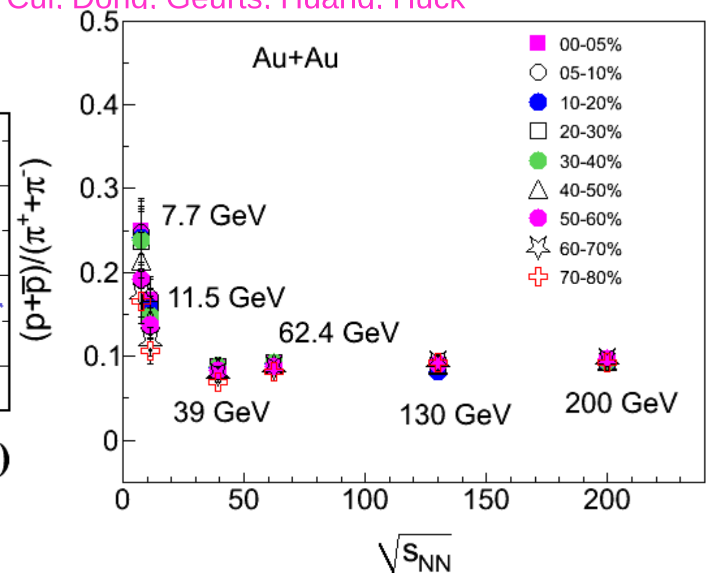
- A broadened spectral function describes di-lepton enhancement from SPS at 17.3 GeV to top RHIC energy from STAR.
- Chiral condensate depends on temperature and total baryon density.
- The total baryon density does not change significantly from 17.3 to 200 GeV. Spectral function from measurements consistently be broadened.
- With future precise spectra and v_2 measurements over a broad beam energy range, di-lepton will serve as an ideal tool to study Chiral Symmetry Restoration. Large enhancement in 0-20% central Au+Au at 200 GeV would imply new mechanisms.

STAR: Cui, Dong, Geurts, Huang, Huck



CERES: Eur.Phys.J.C41(2005)475





Summary

At RHIC and LHC, strongly interacting Quark-Gluon Plasma created:

Heavy flavor: charmed hadrons and B-meson strongly suppressed in A+A Collisions; charmed hadrons flow.

Quarkonia: the centrality and p_T dependence of J/ψ suppression pattern at RHIC and LHC can be interpreted as the interplay of two key ingredients: recombination and color screening; Υ(2S) strongly suppressed, Υ(3S) completely melted. We are in the era to study color screening features of hot, dense medium in light of RHIC and LHC precise quarkonium measurements.

Electro-weak probes: a broadened spectra function describes STAR's 19.6, 62, and 200 GeV data and SPS data consistently. Precise di-lepton measurements over a broad beam energy scan at RHIC, LHC and FAIR provides a unique opportunity to study Chiral Symmetry Restoration.