Dilepton & Quarkonium Measurements in STAR

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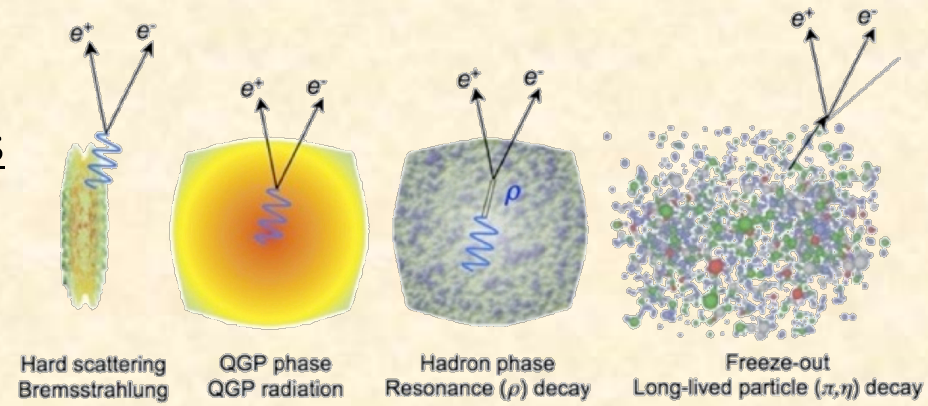
RICE

Outline

- Motivation
- Recent dilepton results
  - dielectron measurement at top RHIC energies
  - dielectron measurements in Beam Energy Scan
- Recent quarkonium results
  - J/ψ and ϒ measurements in various collision systems
- Summary

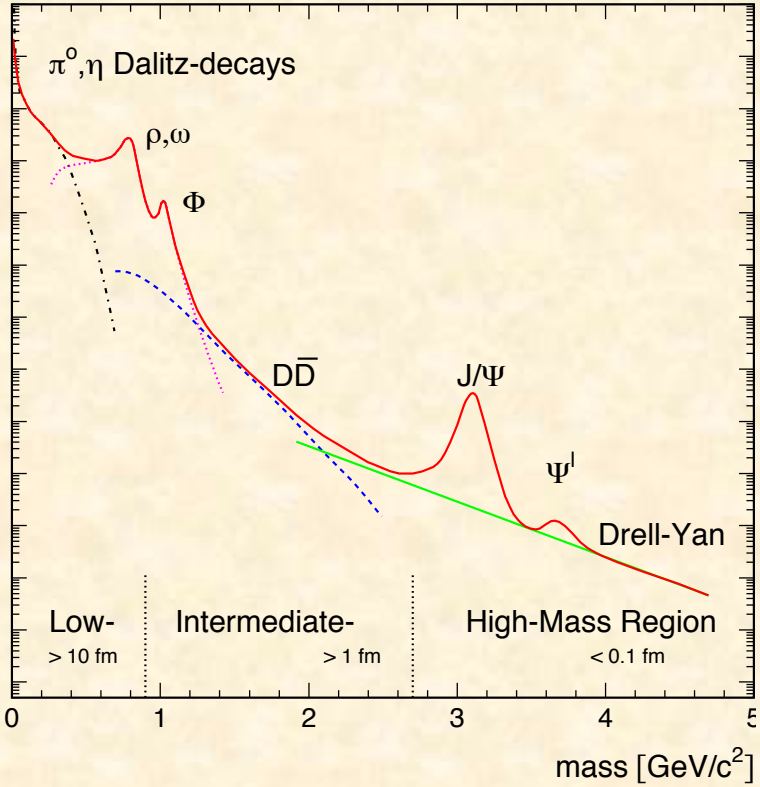
Dilepton Physics



Dileptons are excellent penetrating probes

- very low cross-section with QCD medium
- created throughout evolution of system

Rapp & Wambach, Adv.Nucl.Phys. 25 (2000) 1



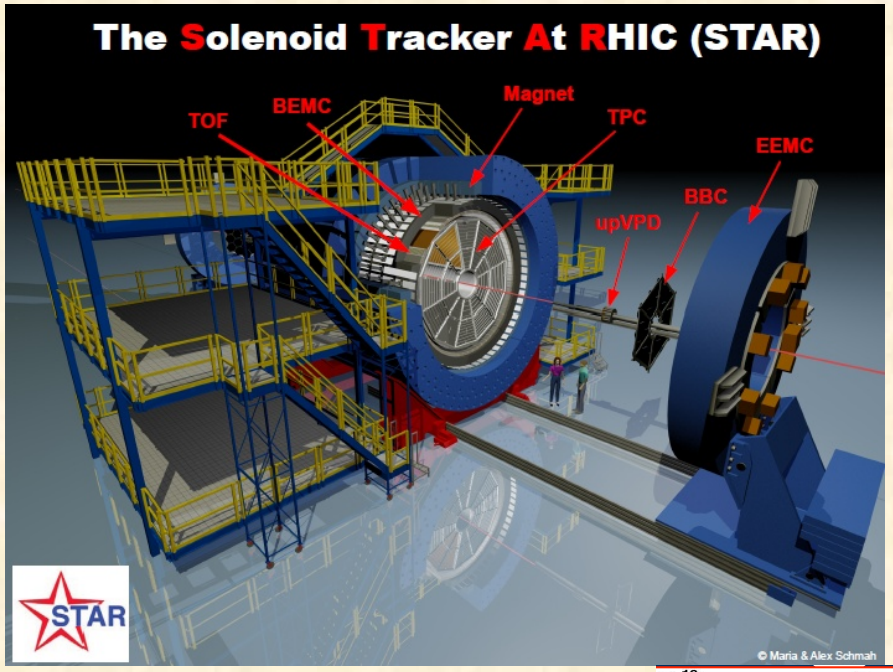
- High Mass Range (HMR)

  $M_{ee} > 3$ GeV/c^2
  - primordial emission, Drell-Yan
  - J/ψ and ϒ suppression
- Intermediate Mass Range (IMR)

  $1.1 < M_{ee} < 3$ GeV/c^2
  - QGP thermal radiation
  - heavy-flavor modification
- Low Mass Range (LMR)

  $M_{ee} < 1.1$ GeV/c^2
  - in-medium modification of vector mesons
  - system lifetime measurement

The STAR Experiment

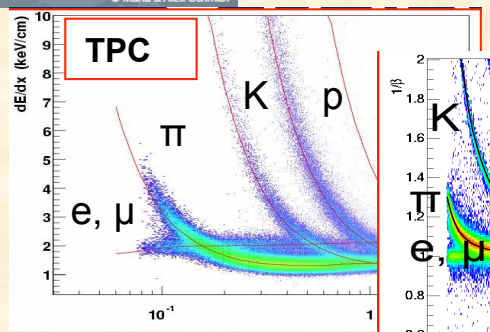


- Large and uniform acceptance at mid-rapidity

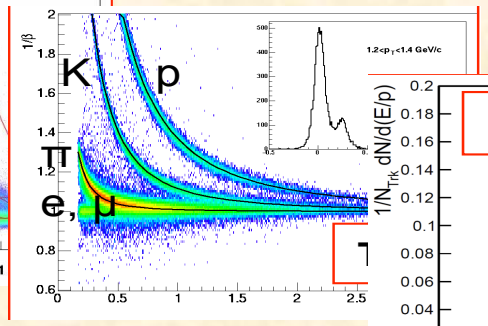
  $|\eta| < 1$ and $0 < \phi < 2\pi$
- Excellent particle identification
- Fast data acquisition
- ➢ Recent upgrades targeted at heavy-flavor measurements
  - improve tracking (Heavy Flavor Tracker)
  - improve muon PID (Muon Telescope Det.)

STAR detectors in these analyses

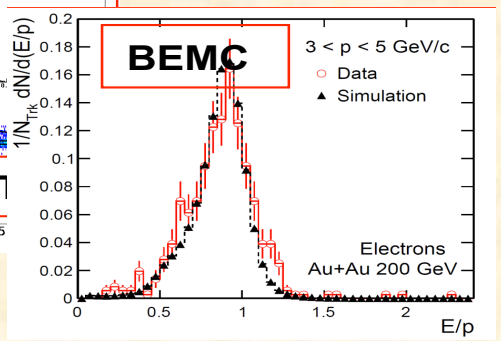
- Time Projection Chamber
- Time-of-Flight detector
- Barrel EM Calorimeter
- Vertex Position Detector



dE/dx



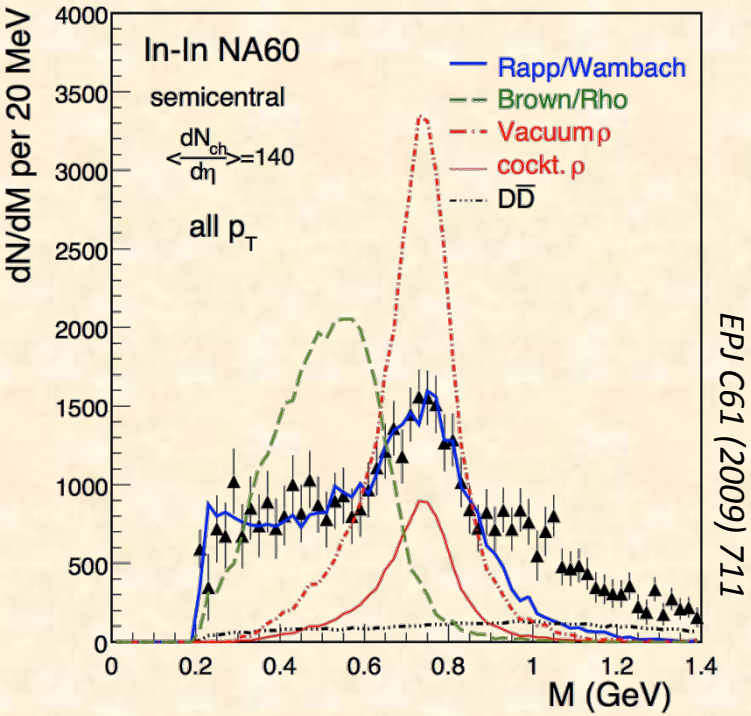
1/β



E/p

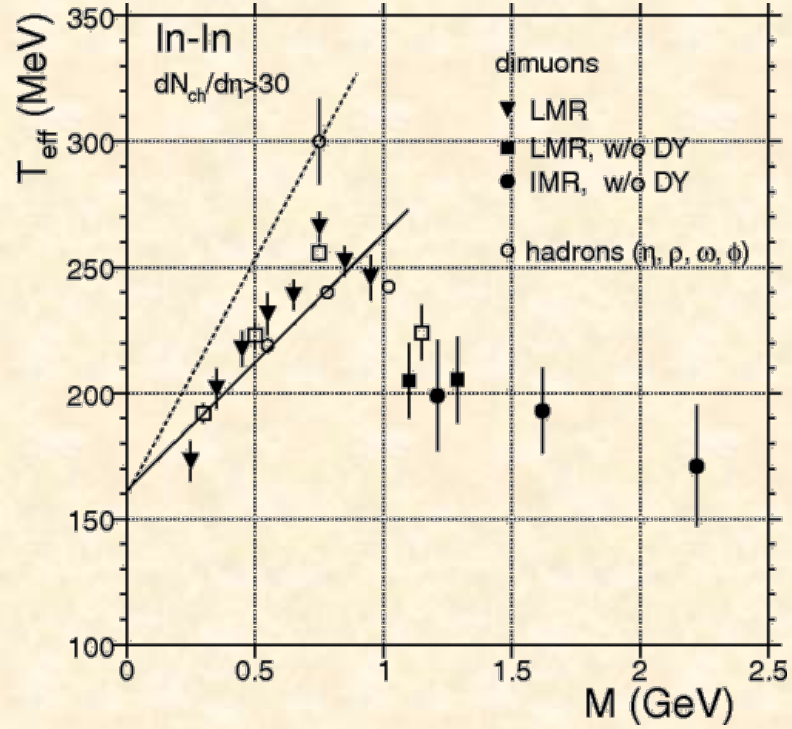
LMR/IMR: What did we learn from SPS?

PRL 96 (2006) 162302



EPJ C61 (2009) 711

PRL 100 (2008) 022302



Precise dimuon mass spectrum

- favors ρ broadening through interactions with hadronic medium

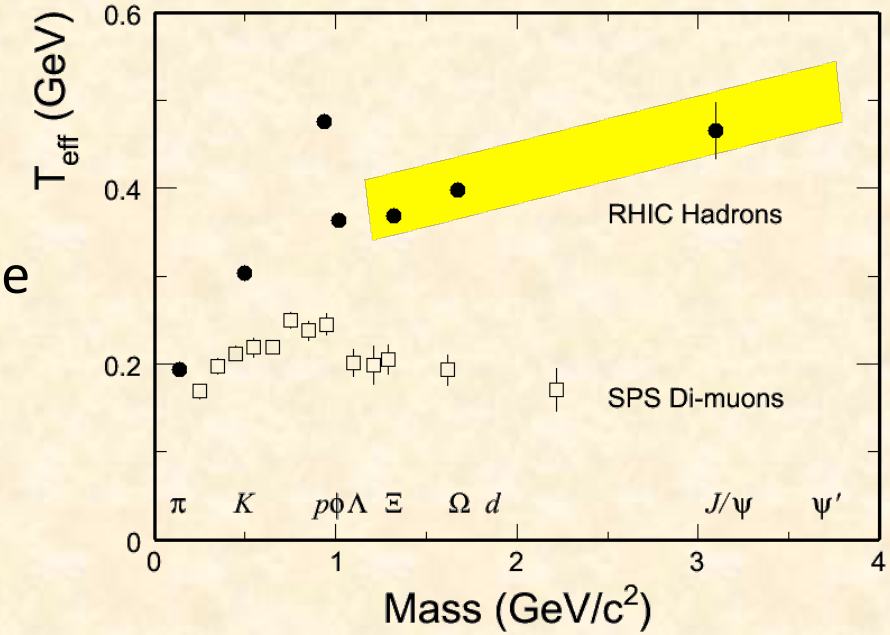
Inverse slope parameter from m_T distributions

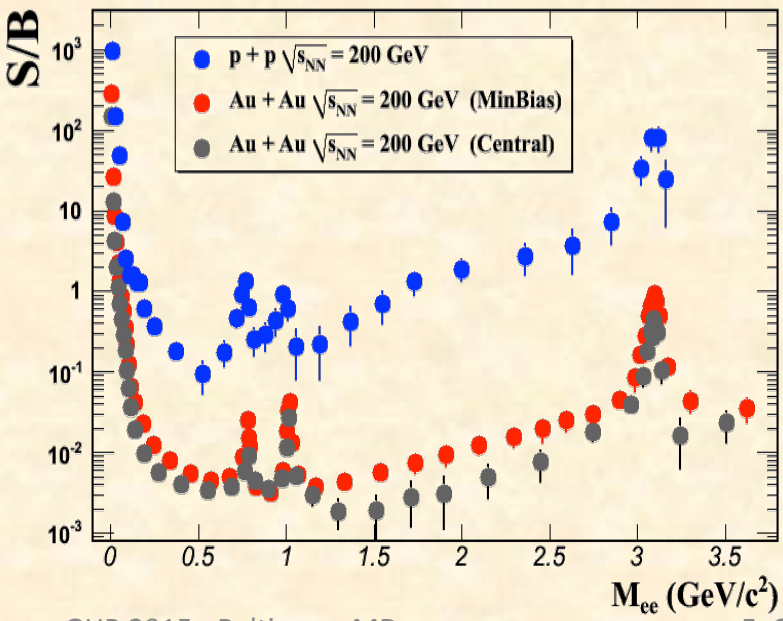
- IMR: no indication of mass dependence
- indicative of thermal radiation from partonic medium, T=205 ± 12 MeV

What to expect at RHIC?

Opportunities:

- expect significant increase of partonic source contribution
- Beam Energy Scan provides unique opportunities to
  - systematically study in-medium ρ broadening
  - on-set of QGP thermal radiation





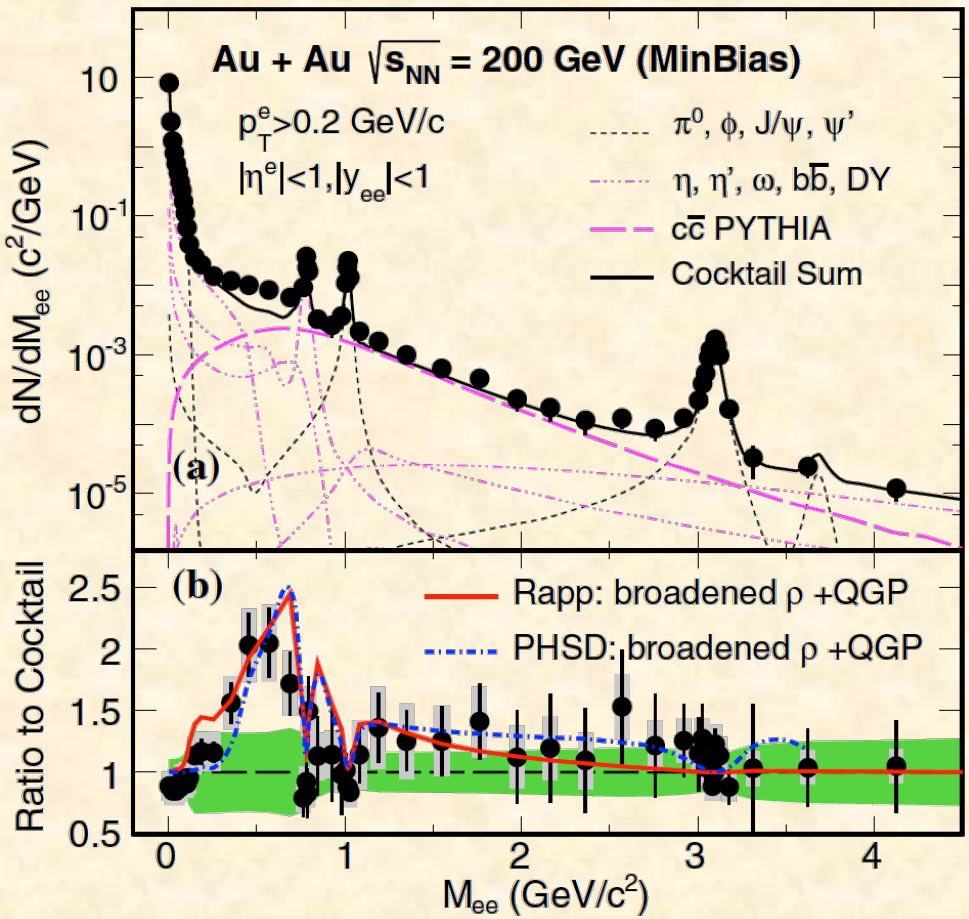
Challenges:

- increased particle multiplicities at higher $\sqrt{s_{NN}}$ lead to significant increase in combinatorial backgrounds
- STAR at 200 GeV for M_{ee}~ 0.5GeV/c^2
  - p+p: S/B ~1/10
  - Au+Au: S/B ~1/250

Production in Au+Au at 200 GeV

STAR Au+Au @ $\sqrt{s_{NN}}$=200GeV

PRL 113 (2014) 022301



R. Rapp, Phys.Rev. C 63 (2001) 054907
O. Linnyk et al., Phys. Rev. C 85 024910 (2012)

Low Mass Range:

- enhancement

  when compared to cocktail (w/o ρ)

  Model calculations with in-medium broadened ρ spectrum function describe LMR excess

Intermediate Mass Range:

within errors consistent with cocktail

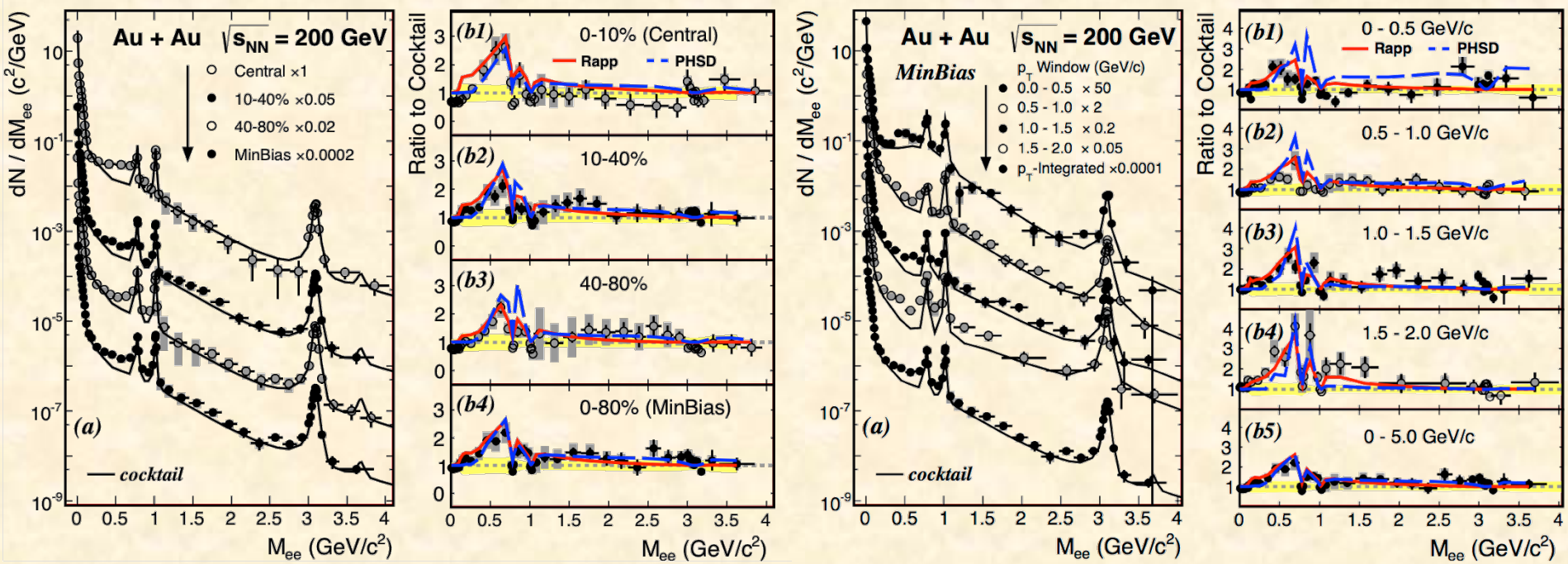
- dominated by correlated charm contributions
- thermal QGP radiation
- modification of charm?

difficult to disentangle

Run-14/16 with new upgrades will address this

Centrality and p_T Dependence

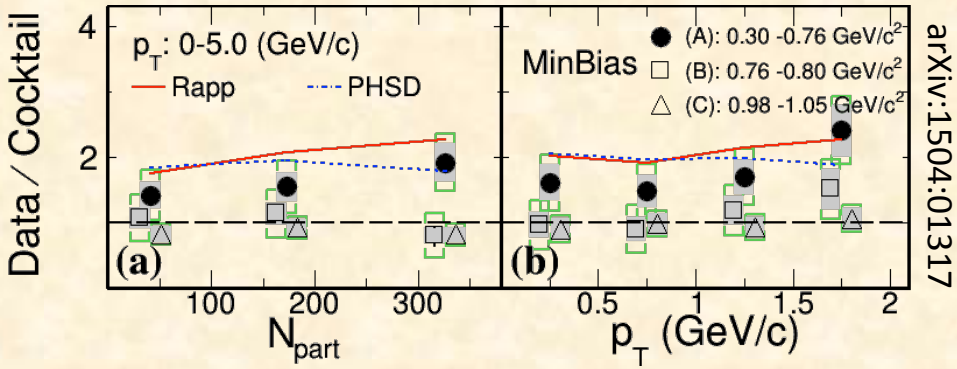
arXiv:1504:01317 (subm. to PRC)



Combined statistics of Run 10 and 11

submitted to PRC (PRL: run-10 only)

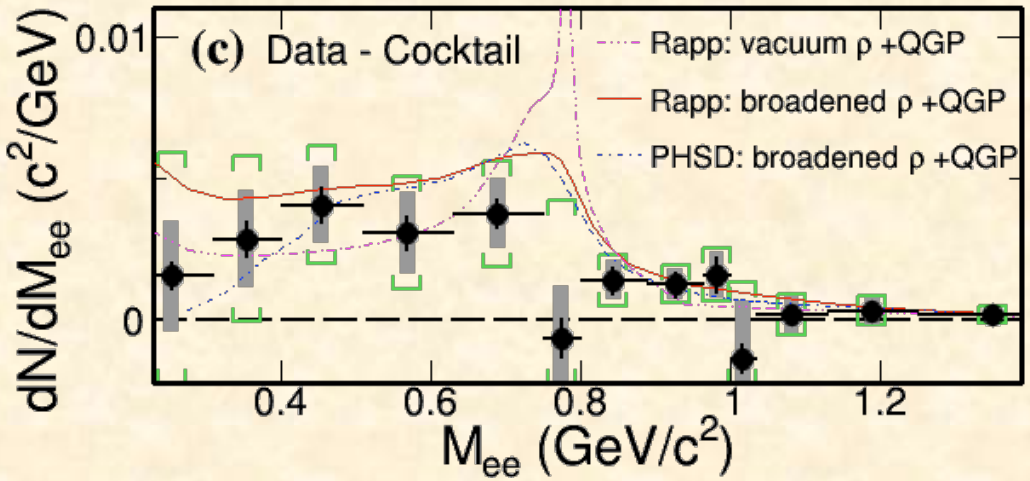
- Data/cocktail: no strong dependence on centrality or p_T
- Model calculations continue to give a reasonable description



Low-Mass Excess: Rapp & PHSD

arXiv:1504:01317 (subm. to PRC)

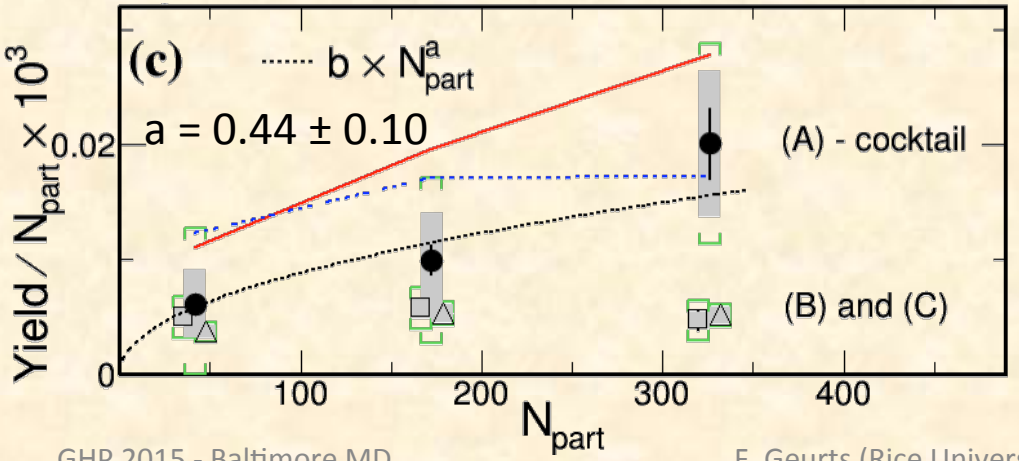
(PRL 113 022301)



A: ρ-like 0.30 - 0.76 GeV/c^2

B: ω-like 0.76 - 0.80 GeV/c^2

C: φ-like 0.98 - 1.05 GeV/c^2



Both models describe NA60 & STAR

- agreement w/in uncertainties
- vacuum ρ disfavored

- low-mass dielectron yield increase ~(N$_{part}$)$^{\alpha}$ with α=1.44±0.10

Ralf Rapp (priv. comm.)

R. Rapp, Phys.Rev. C 63 (2001) 054907

R. Rapp & J. Wambach, EPJ A 6 (1999) 415

Complete evolution (QGP+HG)

PHSD (Linnyk, priv.comm.)

O. Linnyk et al., Phys. Rev. C 85 024910 (2012)

Collisional broadening & radiation from QGP

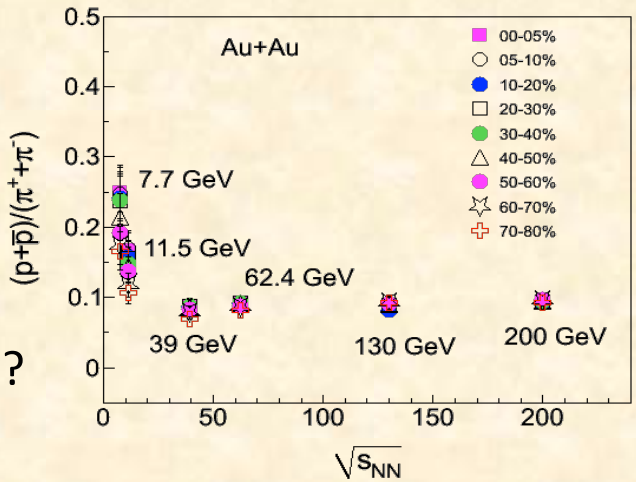
Dielectron Production at lower $\sqrt{s_{NN}}$

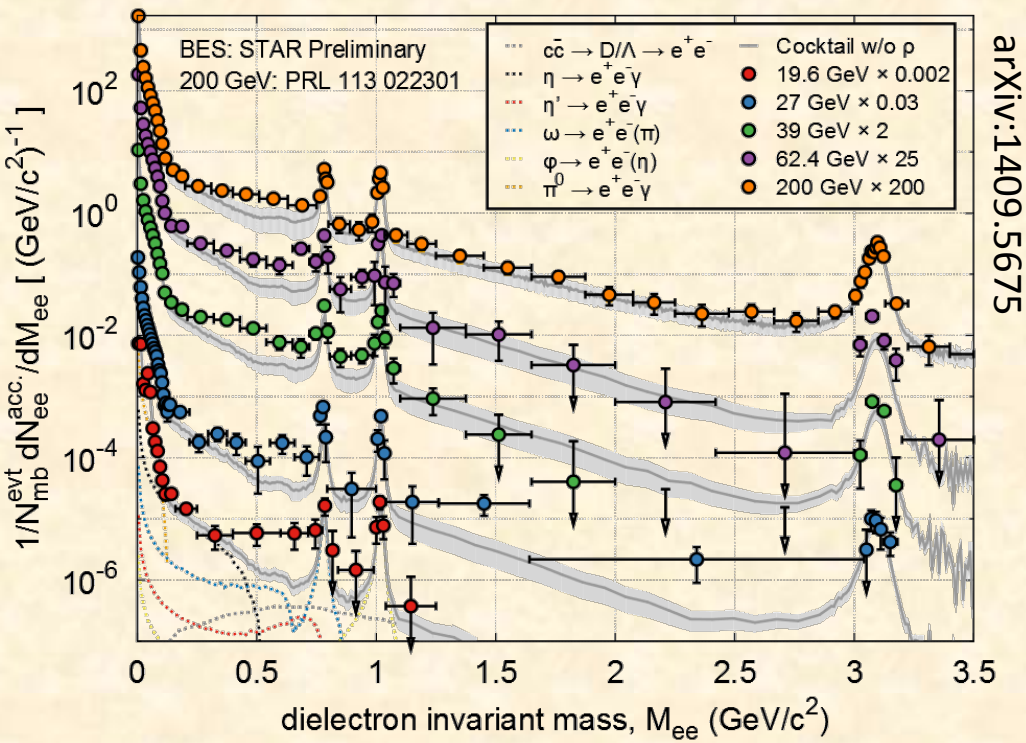
Observed low-mass enhancement at top RHIC energy

- in-medium modification effects?
- indication of chiral symmetry restoration?

Explore low-mass range down to SPS energies

- change initial conditions, net-baryon density
- ~constant total-baryon density
- possible enhancement, consistent model description?





arXiv:1409.5675

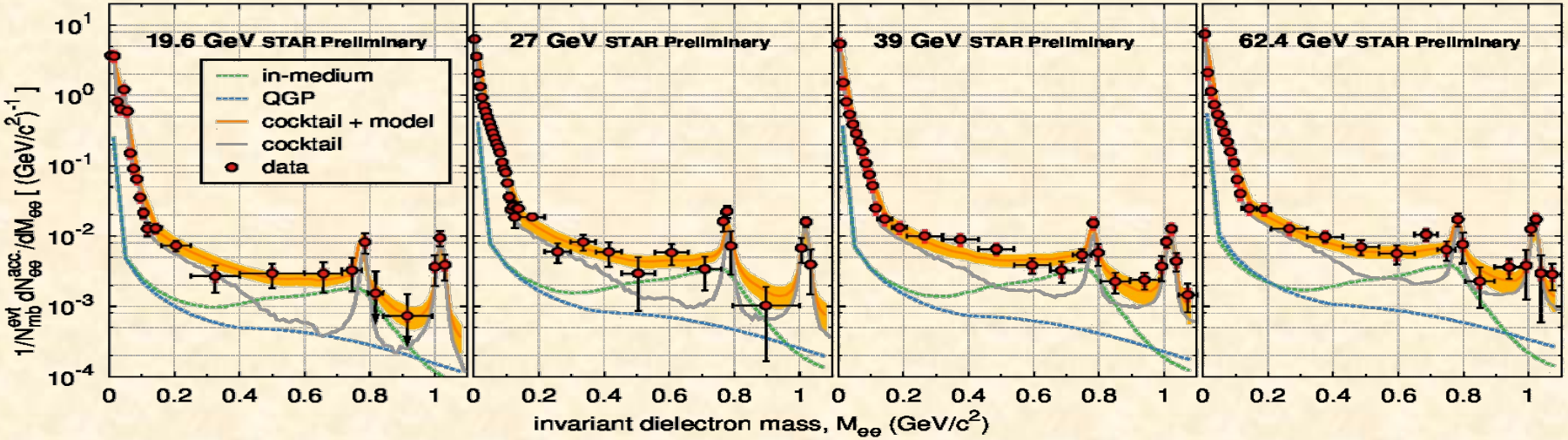
Beam Energy Scan Dielectrons:

2010 – 2011 Au+Au at

62.4, 39,

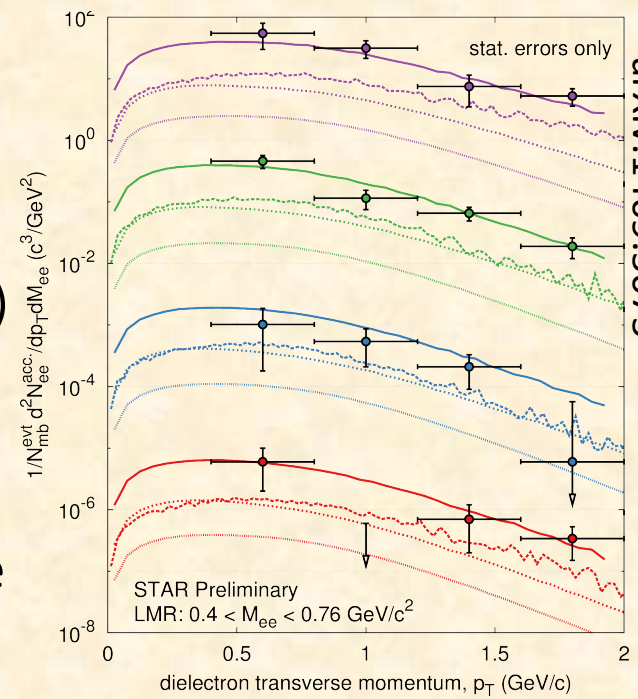
27, and 19.6 GeV

Compare to Theory: In-Medium ρ



Butterworth, TPD'14

- Sustained low-mass excess radiation
  - top RHIC down to SPS energies
- Robust theoretical description
  - black dotted curve: cocktail + in-medium ρ (Rapp)
- Consistent with in-medium ρ broadening
  - expected to depend on total baryon density

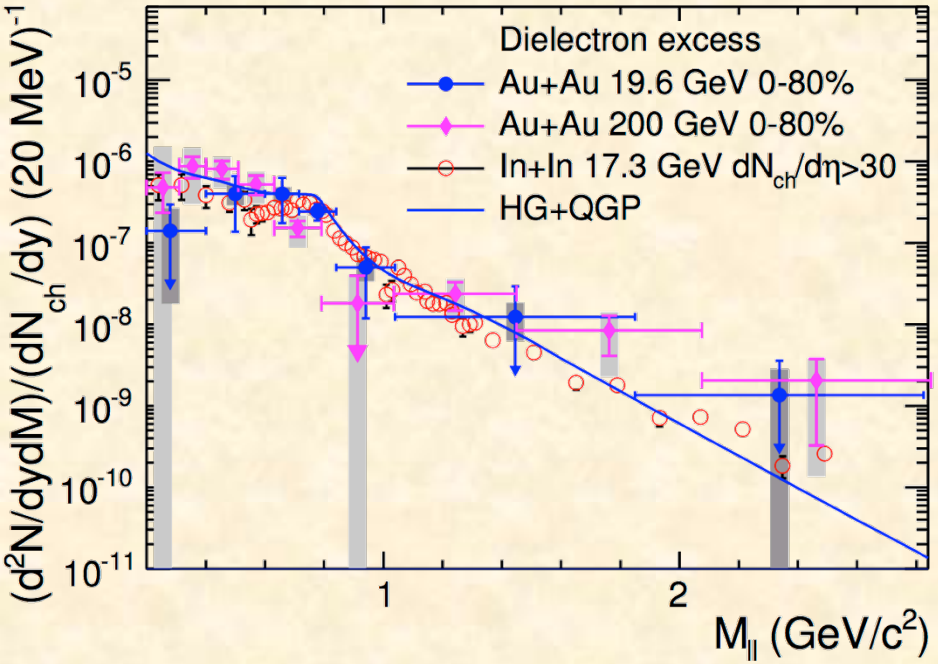


arXiv:1409.5675

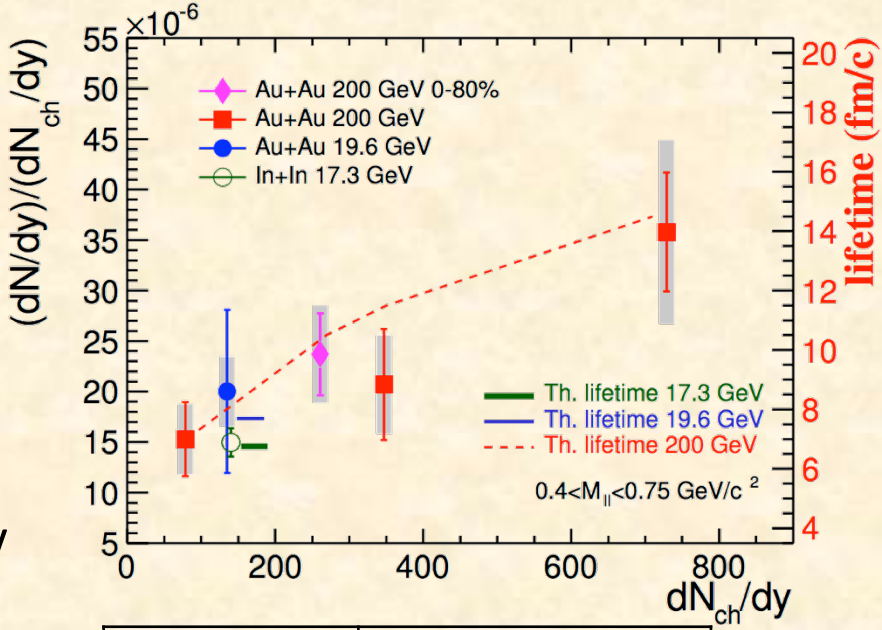
Hohler & Rapp: "Is ρ-meson melting compatible with chiral restoration? " PLB 731 (2014) 103

Excess Yields and Medium Lifetimes

STAR arXiv:1501.05341
subm. to PLB



- Acceptance corrected STAR excess spectra for 200GeV and 19.6GeV
  - normalized to $(dN_{ch}/dy)_{y=0}$
  - compared to NA60 dimuon excess (17.3GeV)

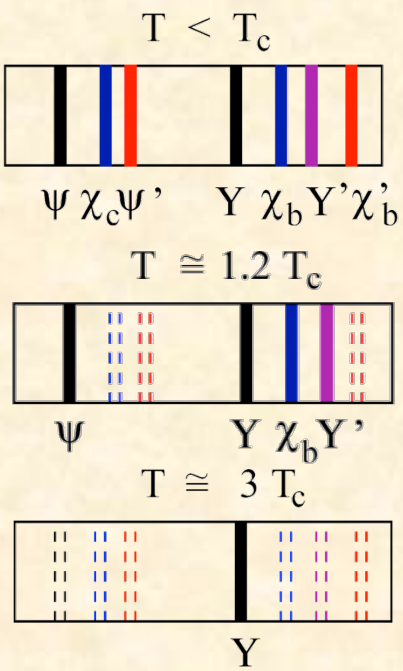


- Integrated LMR excess yields
  - 17.3GeV (NA60) and 19.6GeV consistent
  - 200GeV yields larger than in 19.6GeV
  - centrality dependence in 200GeV
- Lifetime of the emitting medium in 200GeV longer
  - in central compared to peripheral
  - when compared to 17.3GeV

17.3 GeV	6.8 ± 1.0 fm/c
19.6 GeV	7.7 ± 1.5 fm/c
200GeV	10.5 ± 2.1 fm/c

Quarkonia in Strongly Interacting QGP

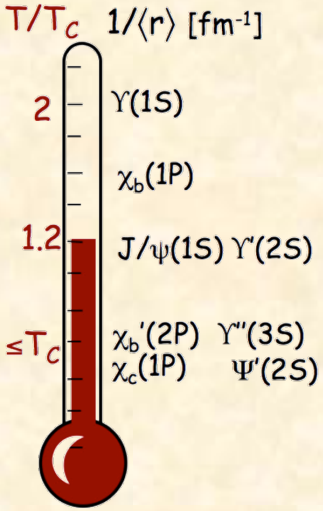
- Sensitive to color Debye screening of quark potential
  - expect to dissociate in sQGP
- Suppression of different states determined by T_{medium} and E_{bind}
  - sequential melting of different states
- ➢ QGP thermometer



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

A more complicated picture …

- Significant feed-down contributions
  - non-prompt J/ψ :: up to 25% (at 12GeV/c) from B-mesons
  - prompt J/ψ :: 40% from ψ' and χ_c
- Cold Nuclear Matter effects
  - initial-state energy loss
  - co-mover absorption
  - nuclear shadowing (modified PDFs)
- Hot Nuclear Matter effects
  - regeneration from coalescence of charm and bottom pairs



Mocsy, EPJ C61 (2009) 705

STAR Quarkonia Measurements

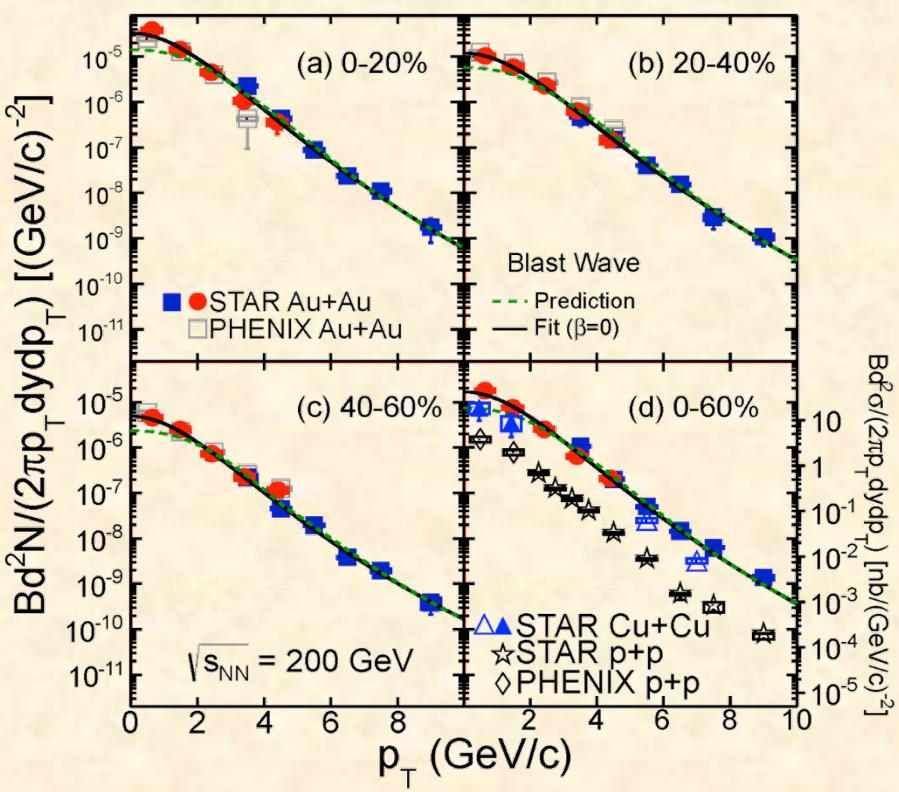
- J/ψ measurements
  - high p_T :: much less affected by CNM and regeneration
  - different colliding systems
    - d+Au :: cold nuclear matter effects
    - Au+Au and U+U :: hot nuclear matter effects, different energy densities
  - beam energy scan
    - change relative production contributions

- ϒ measurements
  - negligible recombination effect
    - RHIC: σ_{cc}(~800μb) >> σ_{bb}(~1-2μb)
  - less co-mover absorption predicted
    - ϒ(1S) tightly bound, thus large kinematic threshold
    - expect σ^{Υ}_{abs} ~0.2mb < $\sigma^{J/\psi}_{abs}$
      - Lin & Ko, PLB 503 (2001) 104
  - low production rate

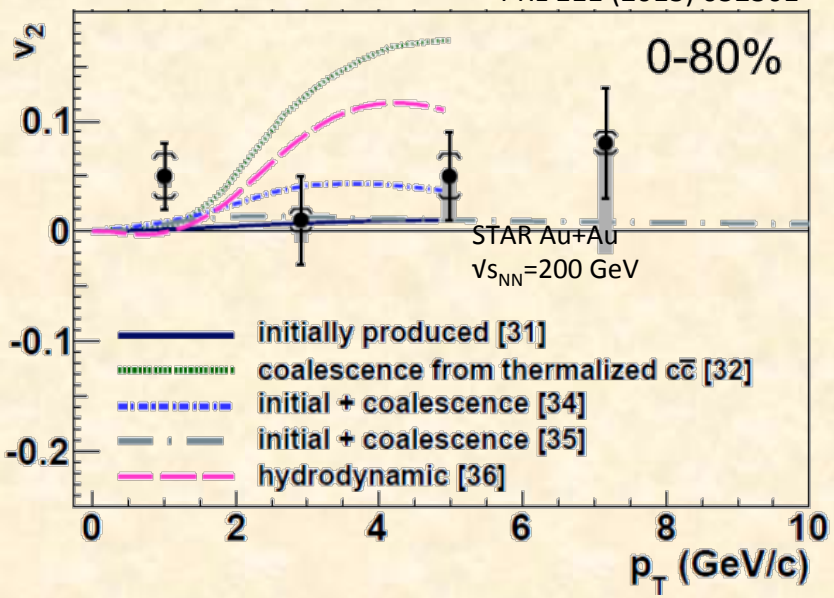
J/ψ Flow in Au+Au at 200 GeV

- elliptic flow v_2 is consistent with 0 for p_T > 2GeV/c
  - disfavors model with J/ψ production via thermalized charm coalescence

PRC 90 (2014) 024906



PRL 111 (2013) 052301



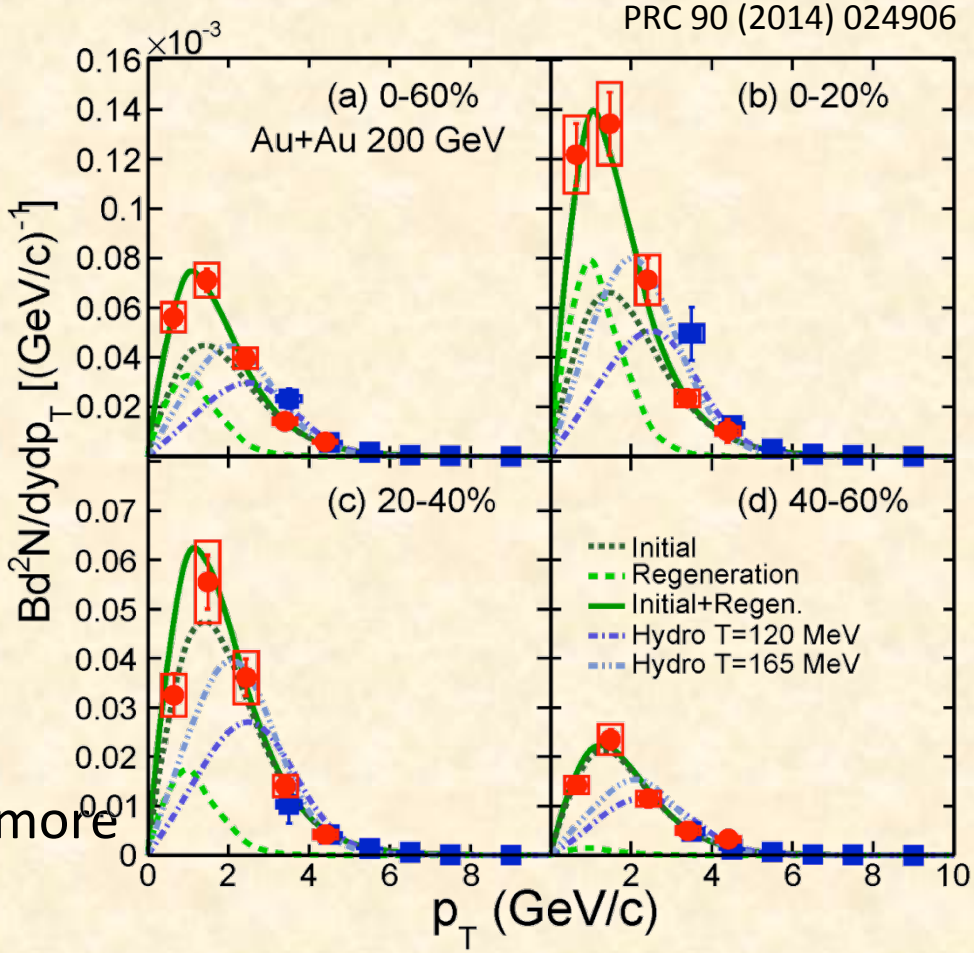
[31] Yan, Zhuang,Xu, PRL97 (2006) 232301
[32] Greco, Ko, Rapp, PLB595 (2004) 202
[34] Zhao, Rapp, PLB 655 (2007) 126
[35] Liu,Xu,Zhuang, NPA834 (2010) 317c
[36] Heinz, Chen (2012)

- J/ψ spectra softer than TBW predictions from lighter hadrons
  - small radial flow?
  - regeneration at low p_T?

J/ψ Spectra in Au+Au at 200 GeV

- J/ψ spectra softer than TBW predictions from lighter hadrons
  - small radial flow?
  - regeneration at low p_T?
- viscous hydrodynamics
  - fails at low p_T
  - decouples at 120 – 160 MeV
- comparison with Liu *et al.*
    - J/ψ suppression from color screening
    - statistical regeneration
  - initial production dominates in peripheral collisions
  - in central collisions: regeneration more significant at low p_T

PRC 90 (2014) 024906

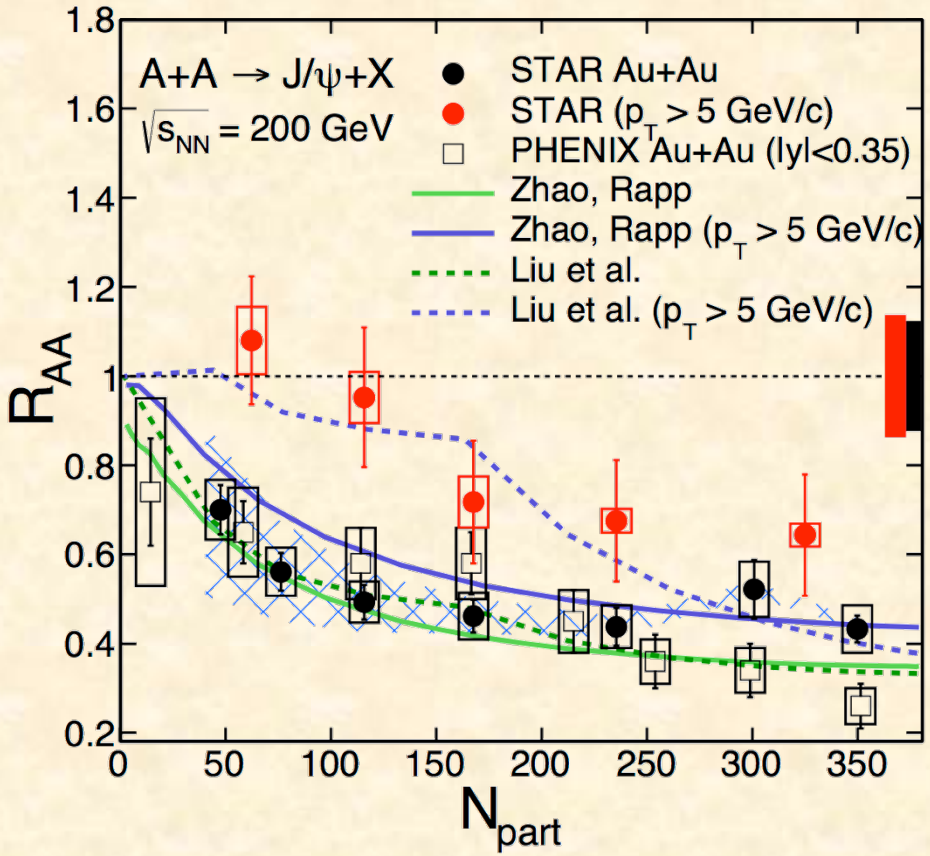


Y. Liu et al., Phys. Lett. B 678, 72 (2009)
U. W. Heinz and C. Shen (2011), priv. comm.

➢ Need coalescence of charm quarks

J/ψ R_{AA} in Au+Au at 200 GeV

nuclear modification factor: $R_{AA} = \frac{1}{\langle Ncoll \rangle} \frac{(dN/dy)^{A+A}}{(dN/dy)^{p+p}}$



- suppression increases with centrality
- high p_T R_{AA} systematically higher

- J/ψ at high p_T almost not affected by CNM effects and recombination
- high-p_T J/ψ suppressed in central collisions
  - may indicate QGP effects

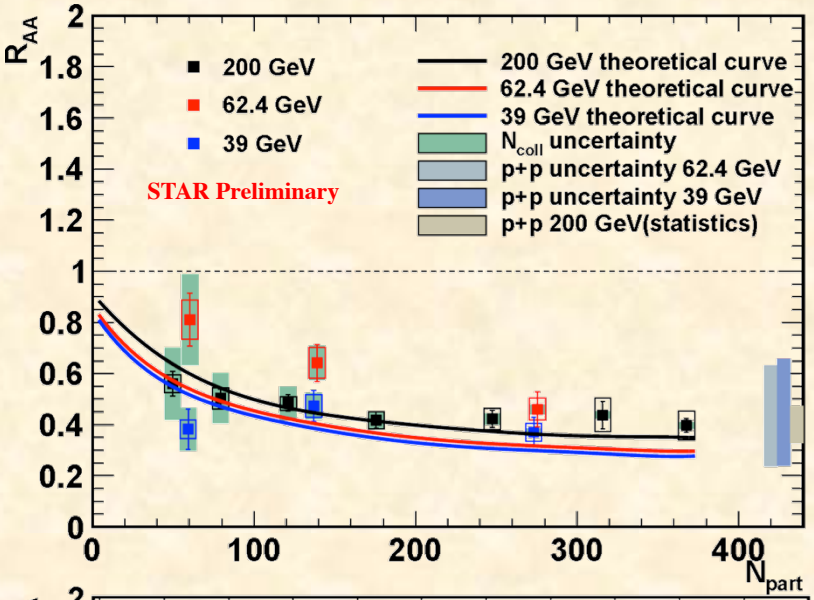
Comparison with models

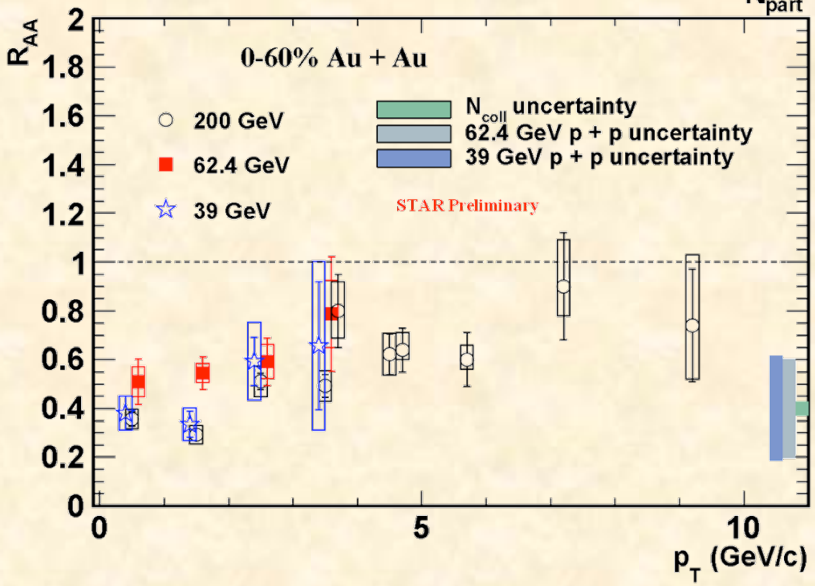
- low p_T: good description by models
- high p_T: underprediction of R_{AA} by Zhao et al

Liu *et al*: direct J/ψ production with color screening and recombination

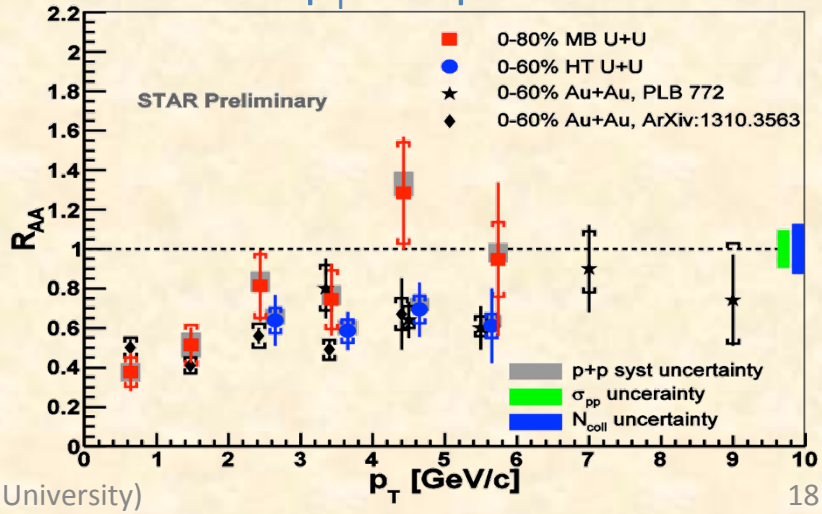
Zhao *et al*: similar plus J/ψ formation time effect and B-meson feed-down

Energy Dependence of J/ψ R_{AA}

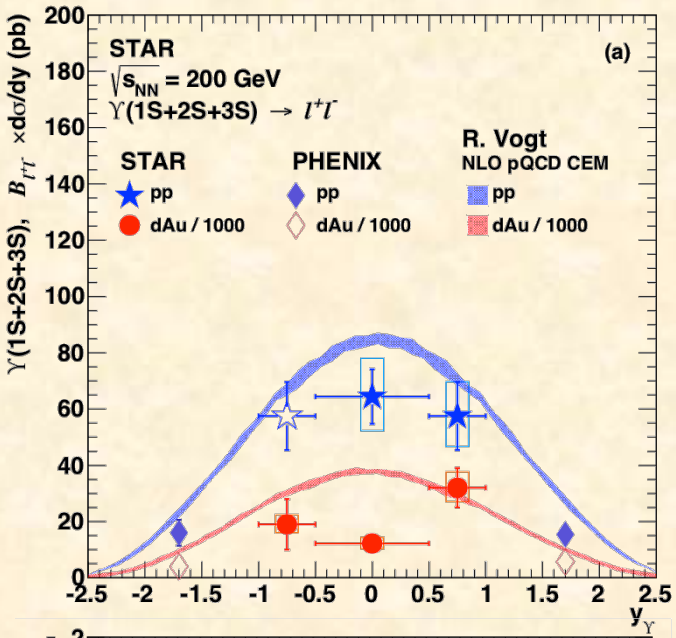


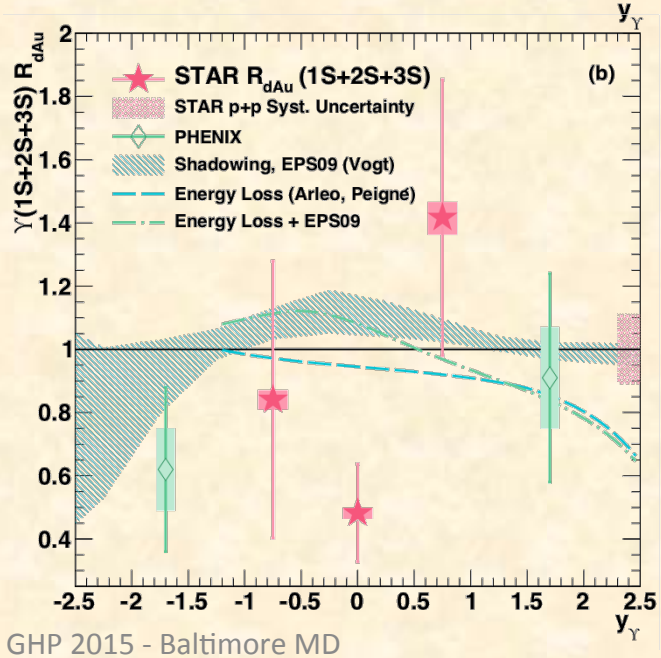


- No strong energy dependence of J/ψ R_{AA} within uncertainties
  - Similar p_T trend in suppression for all energies
  - large uncertainty from CEM-based p+p reference for 39 and 62.4GeV data
- Expect higher energy densities in U+U collisions at similar centralities
  - ➢ J/ψ R_{AA} in U+U at 193GeV
  - p+p reference at 200GeV
  - similar trend in p_T compared to Au+Au



Υ in d+Au at 200GeV :: CNM Effects





Phys. Lett. B735 (2014) 127

R. Vogt Phys. Rep. 462125 (2008)
Arleo et al. EPJ C73 (2013) 2427

- Models include:
  - gluon nPDF (anti)shadowing
  - initial parton energy loss
- Agreement with models
  - for p+p, and backward/forward d+Au
  - except at midrapidity d+Au

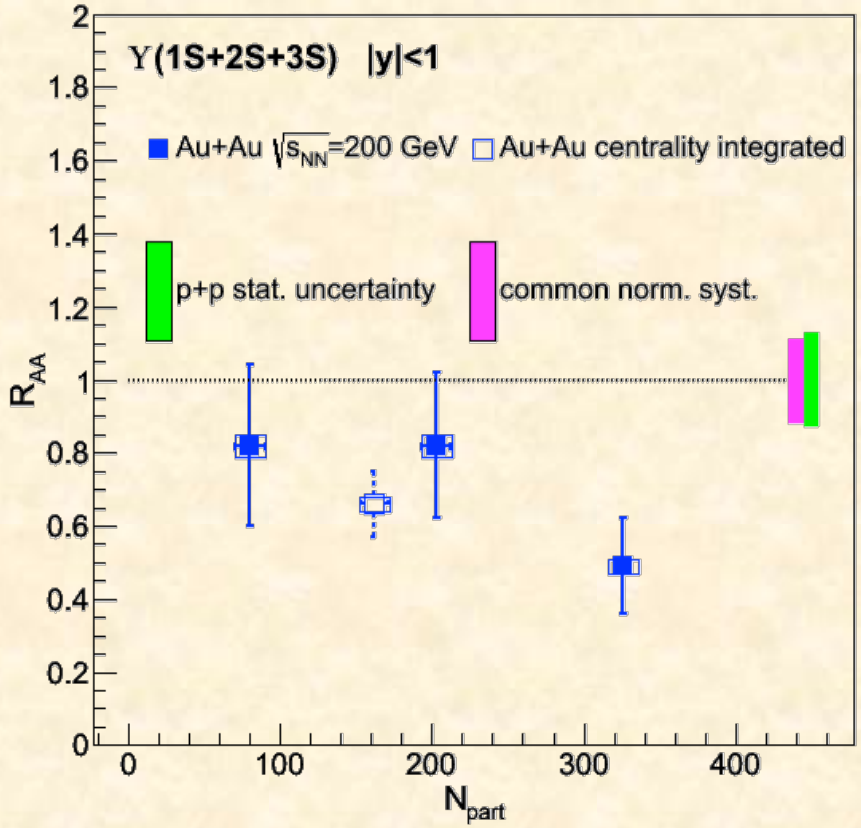
for $|y_\Upsilon|<0.5$

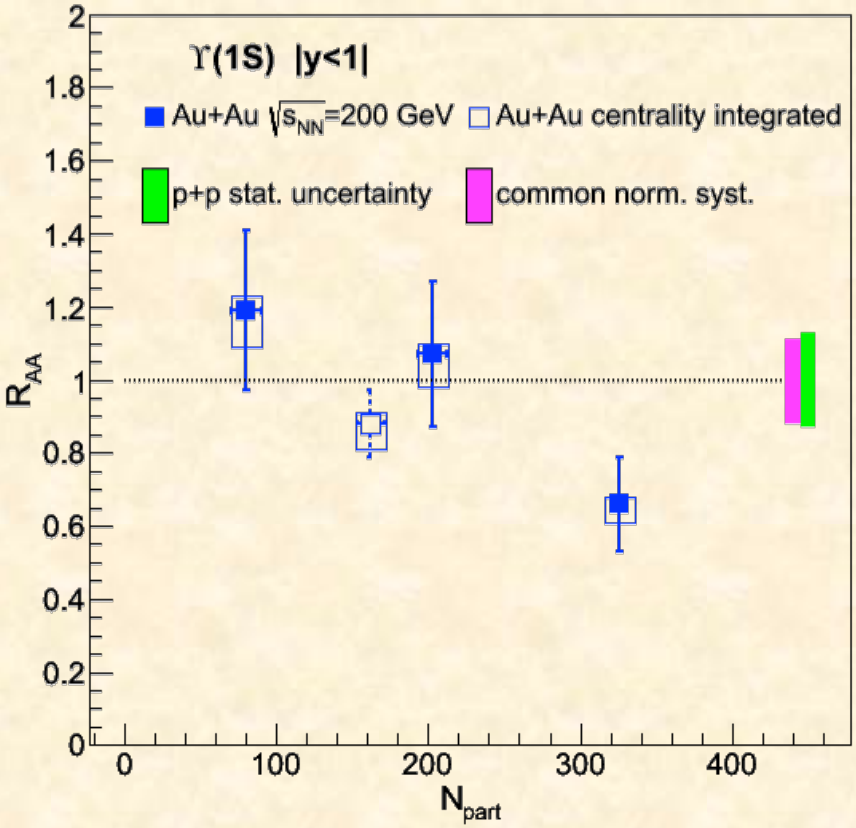
$R_{dAu} = 0.48 \pm 0.14$ (stat) ± 0.07 (pp-stat)
± 0.02 (syst) ± 0.06 (pp-syst)

indication of suppression at mid-rapidity beyond model predictions

(*e.g.* sensitive to co-mover absorption?)

Suppression of ϒ in Au+Au

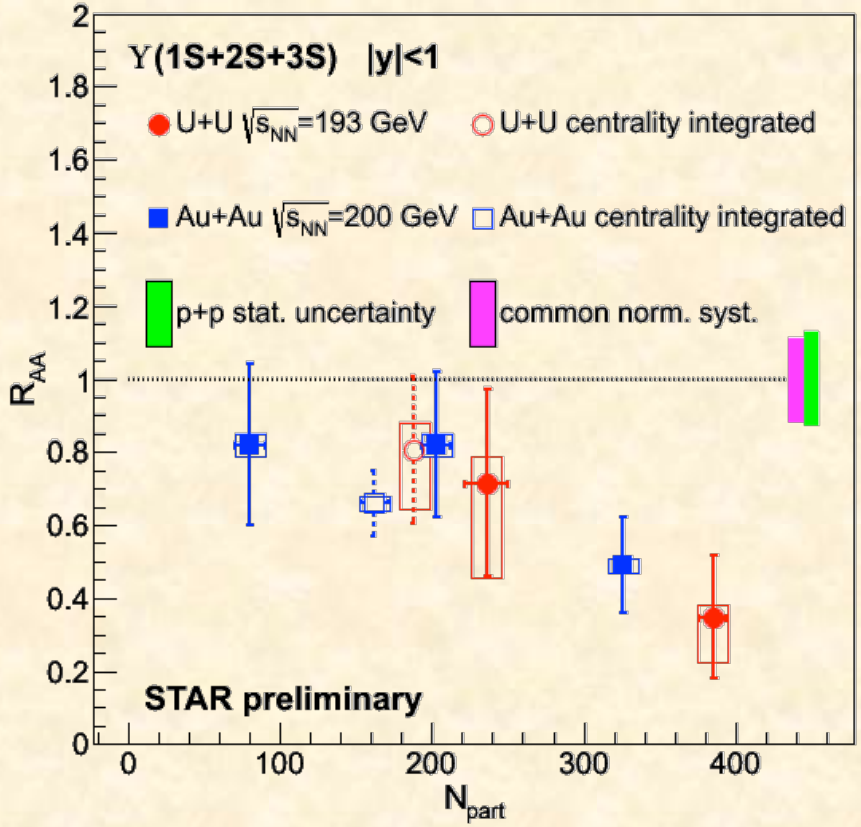


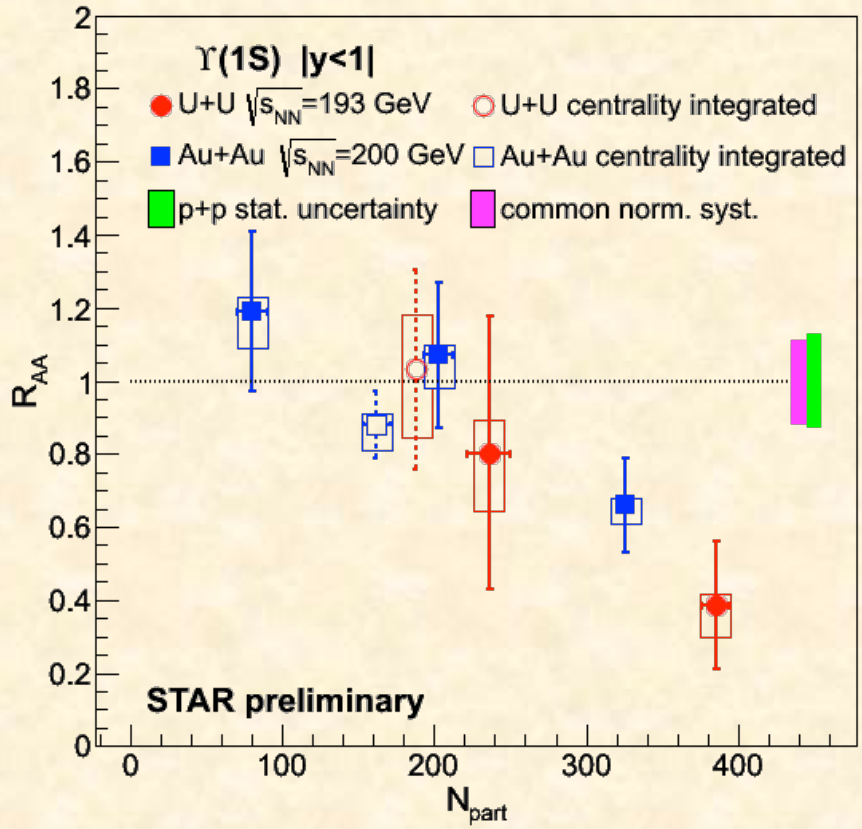


- peripheral ϒ: consistent with no suppression
- central ϒ: significant suppression

- central ϒ(1S): significant suppression

Υ R_{AA} :: Au+Au *vs.* U+U

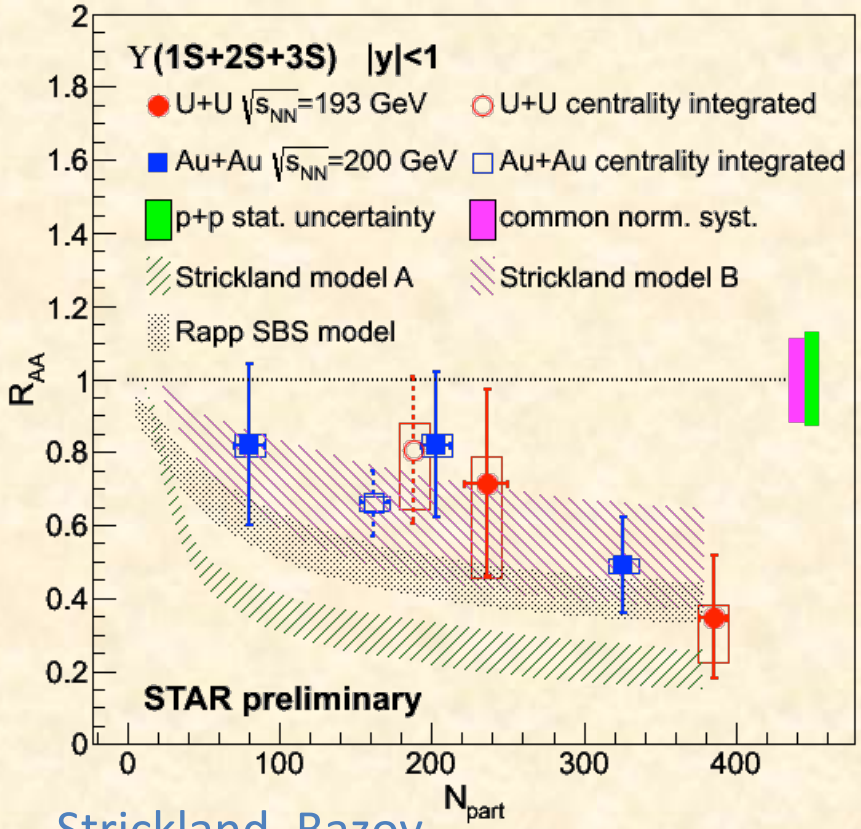


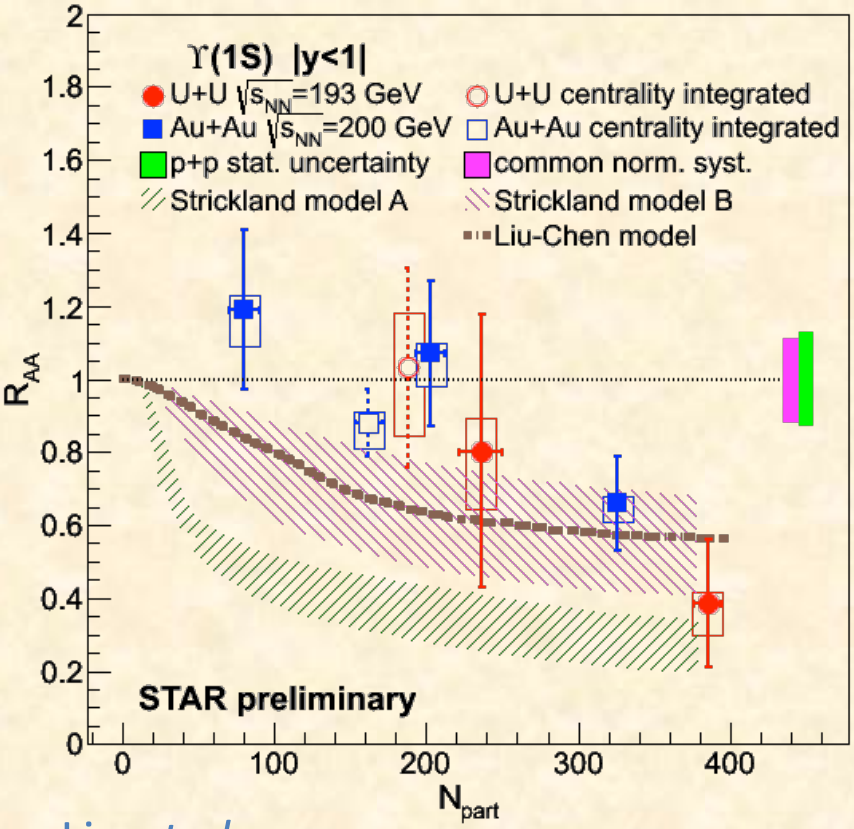


- peripheral Υ: consistent with no suppression
- central Υ: significant suppression

- central Υ(1S): significant suppression
- ➢ new U+U data confirms and extends Au+Au trend

Υ R_{AA} :: data *vs.* models





Strickland, Bazov NPA 879 (2012) 25

- no CNM
- model A disfavored: potential based on heavy quark free energy
- model B: potential based on heavy quark internal energy

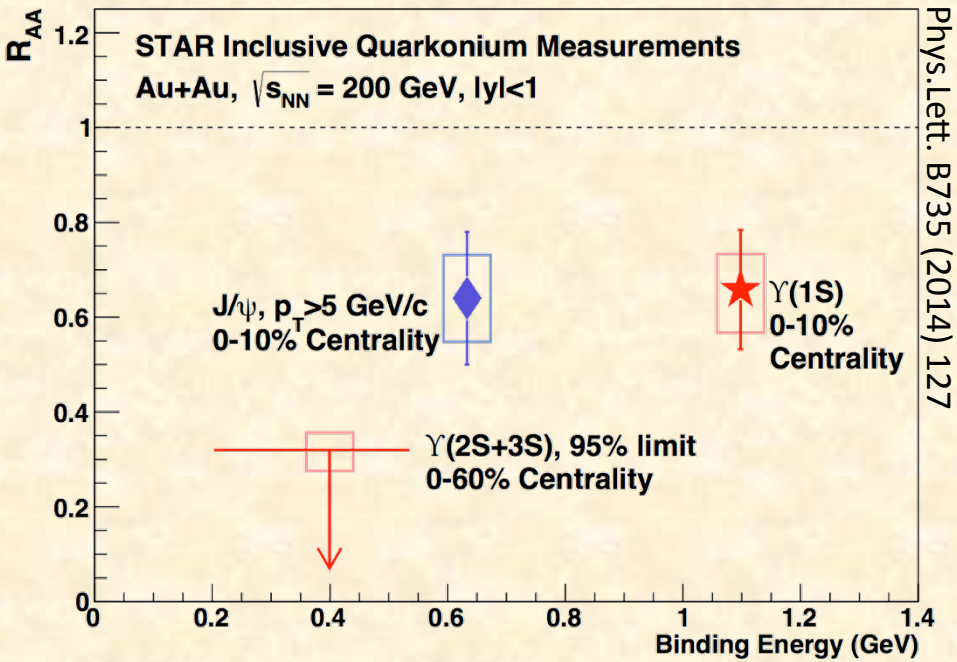
Liu *et al.* PLB 697 (2011) 32

- potential model, no CNM effects
- only excited states disssociate

Rapp *et al.* EPJ A48 (2012) 72

- CNM effects included
- strong binding scenario

Suppression of ϒ states in Au+Au



Central collisions:

- indication of complete ϒ(2S+3S) suppression
- suppression of ϒ(1S) similar to high-p_T J/ψ

➢ ϒ suppression pattern supports sequential melting

Summary & Outlook

- LMR dielectron excess in Au+Au@200GeV consistent with in-medium broadening of ρ meson
  - systematic BES measurements agree with this picture down to 19.7GeV
- LMR excess yields scale with lifetime of the emitting system
  - search for anomalous increases, suggestive of a critical point in the QCD phase diagram
- Quarkonium collectivity: J/ψ no strong v_2 or radial flow
  - thermalized charm coalescence not dominant in production
- Quarkonium hot medium effects: significant suppression of high-pT J/ψ
  - similar to ϒ(1S) suppression in Au+Au
  - ϒ(2S+3S) suppression stronger than ϒ(1S)
- Quarkonium CNM effects: ϒ suppression in d+Au not yet understood

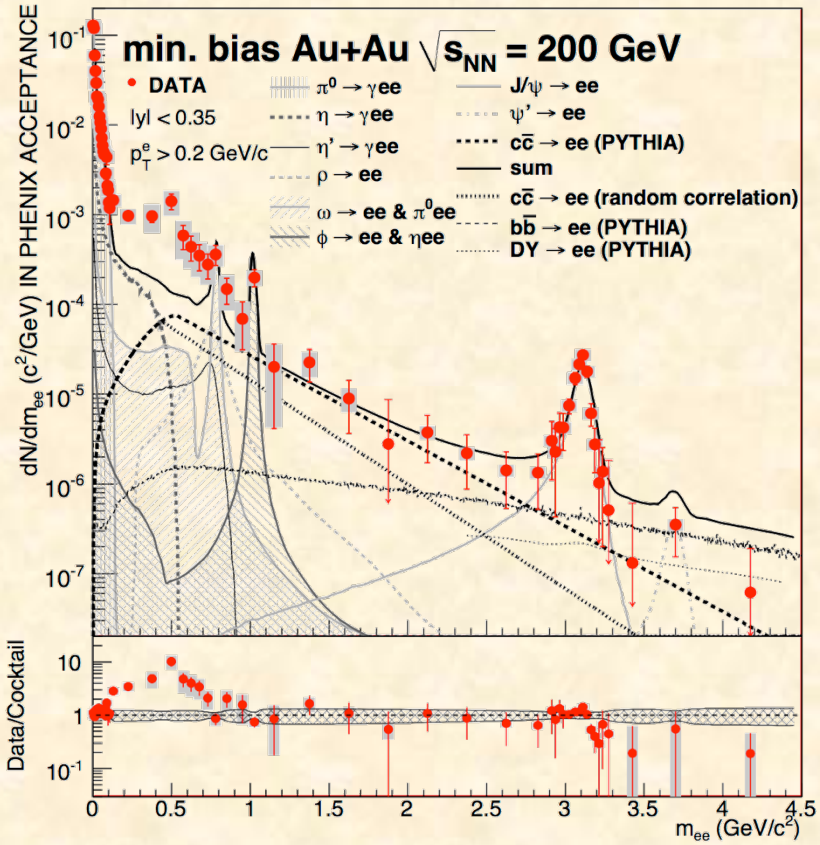
Outlook:

- Two important STAR upgrades: Heavy Flavor Tracker and Muon Detector
- RHIC luminosity has seen a dramatic improvement
- Both have been in effect since 2014
  - first part of a large p+p (2015) and Au+Au@200GeV data set (2014+2016)
  - later this month p+A
- BES phase-2 (2019/2020): improve LMR statistics, increase baryon-density

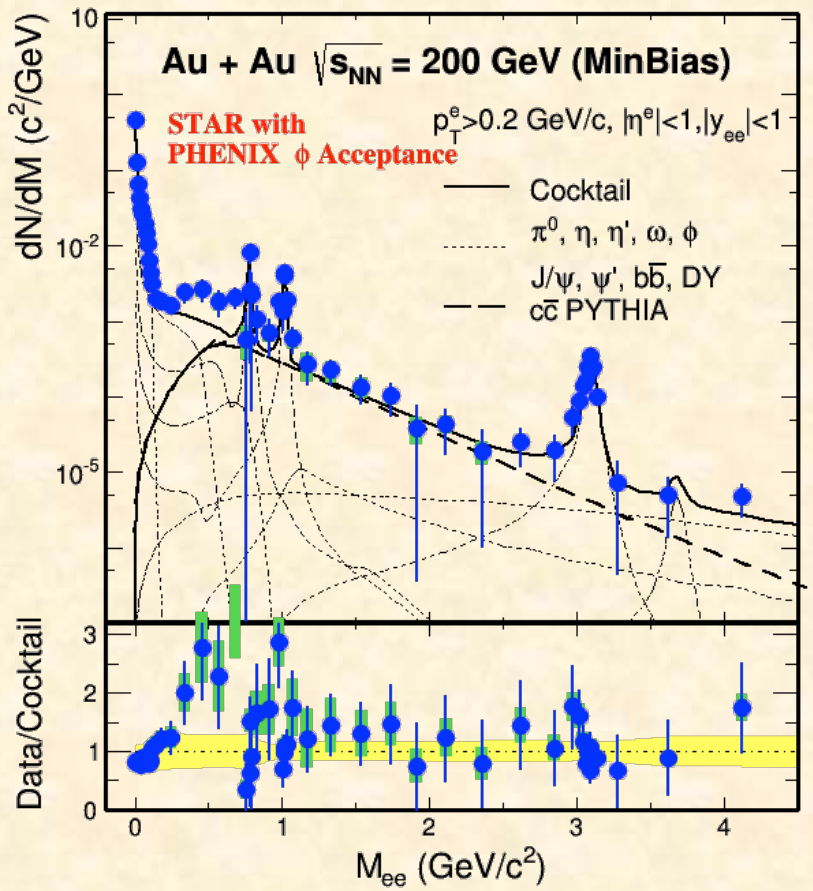
BACKUP

RHIC: PHENIX *vs.* STAR

PHENIX – PRC 81 (2010) 034911



STAR in PHENIX acceptance



Large quantitative differences in the low-mass , low-p_T region remain unresolved

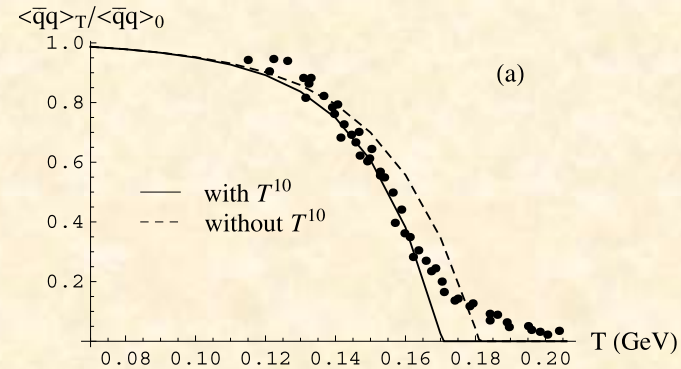
- STAR combined Run 10 and 11 data sets

Work in progress: PHENIX HBD analysis Run-10 data, waiting on top centrality

A Phenomenological Approach

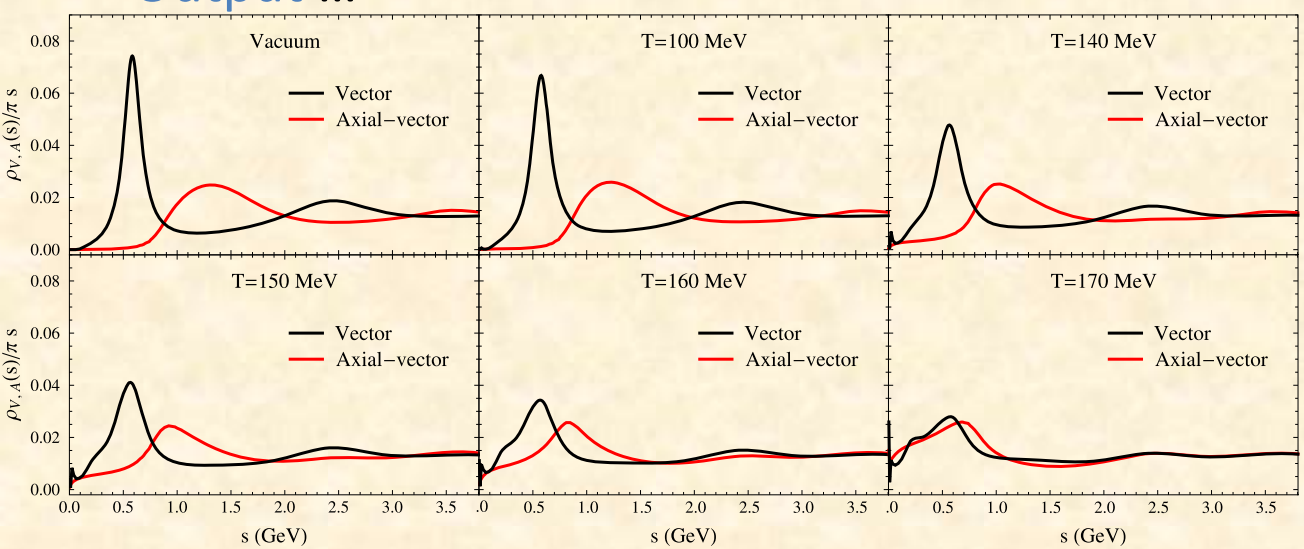
Experiment: Strong evidence ρ meson "melts"

- Input
  - vector SF (ρ meson) from phenomenological model, verified against experimental data
  - T dependence of the condensate: from LQCD
- QCD sum rules
  - constrain vector/axial-vector SFs individually
- Weinberg sum rules
  - difference between vector & axial-vector SFs
- Output …



$$\frac{1}{M^2}\int ds\,\frac{\rho_{V/A}(s)}{s}\,e^{-s/M^2} = \sum_n C_n\langle O_n\rangle$$

$$\int ds(\rho_V - \rho_A)s^n = f_n$$



Hohler, Rapp – PLB 731 (2014) 103

Hohler at TPD'14:

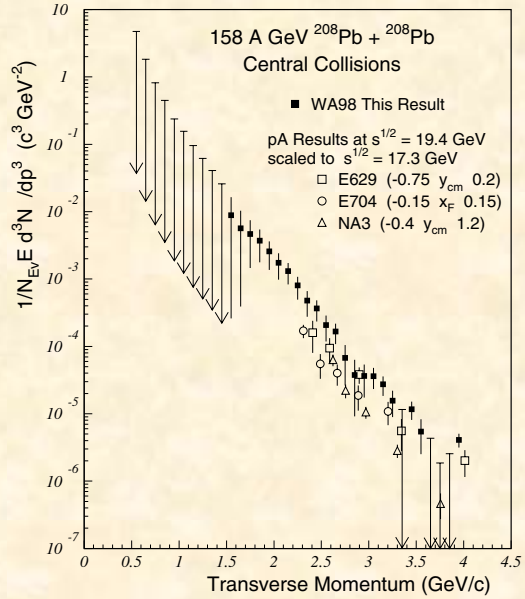
But, still need microscopic calculations of $a_1(1260)$. (Massive Yang-Mills)

Work in progress …

Direct photon measurements

Two methods:

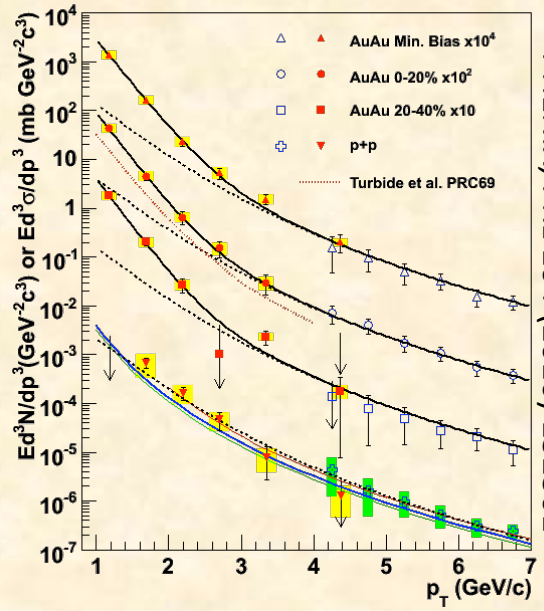
- real photons: measure inclusive spectrum and subtract sources such as from hadron decays
  - e.g WA98
  - establish mostly upper limits
- virtual photons: measure dileptons and use relation between virtual photon and direct photon
  - PHENIX, based on a method proposed by UA1



WA98, PRL 85 (2000) 3595

Virtual photons:

- any process that radiates γ will also radiate γ*
- for M << p_T such a γ* is "almost real"
- extrapolate γ* → e^+e^- to M=0 will give the direct-γ yields

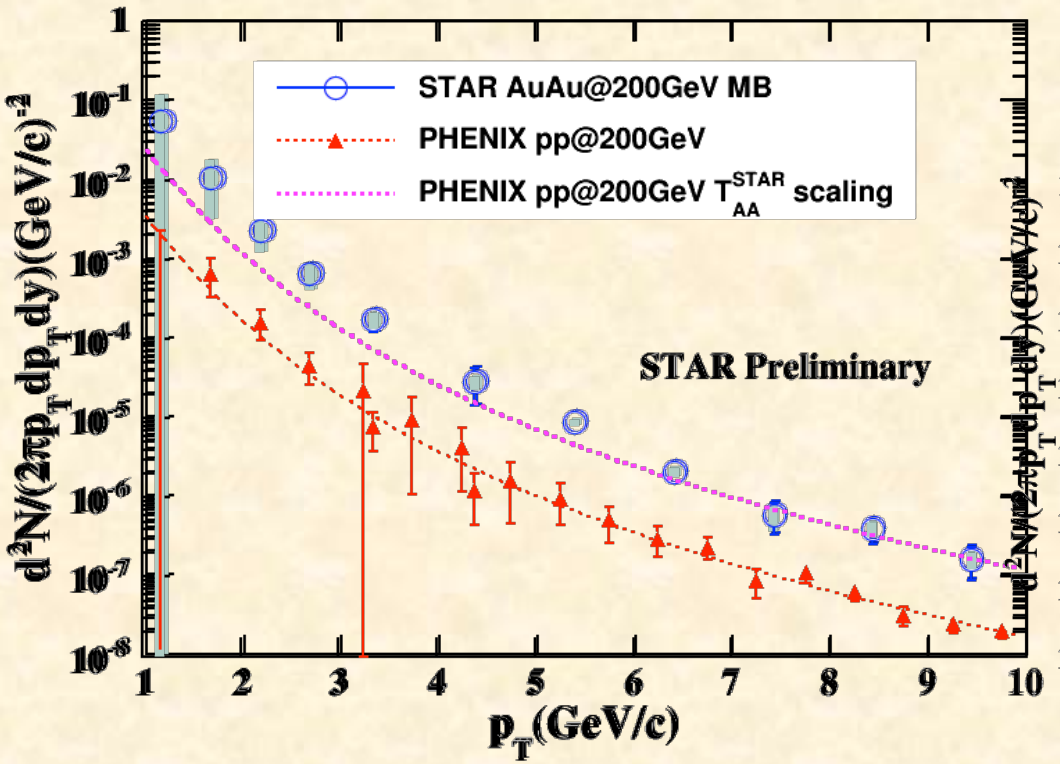


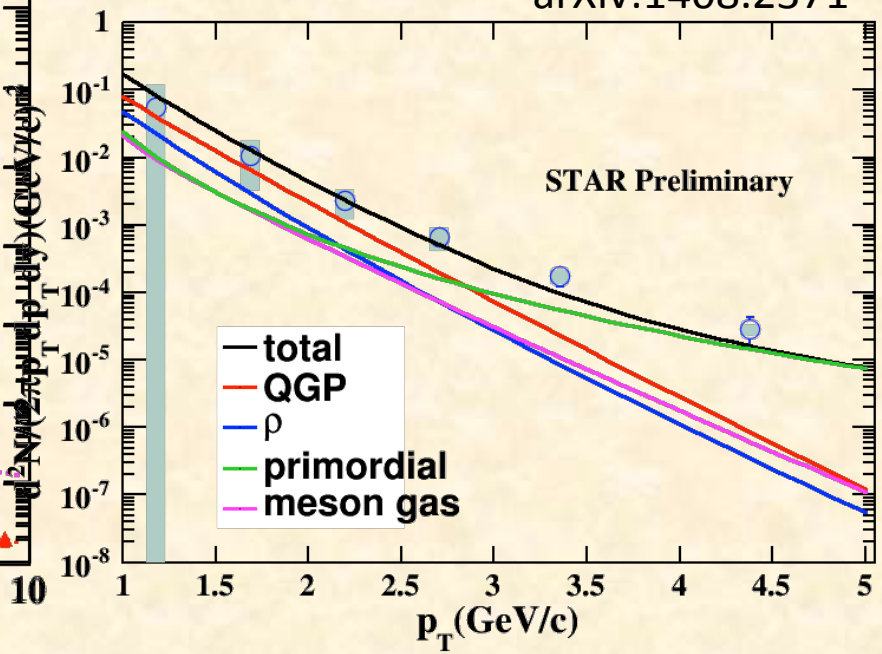
PHENIX, PRL 104 (2010) 132301

Direct Virtual Photon Invariant Yield

B. Huang, TPD'14

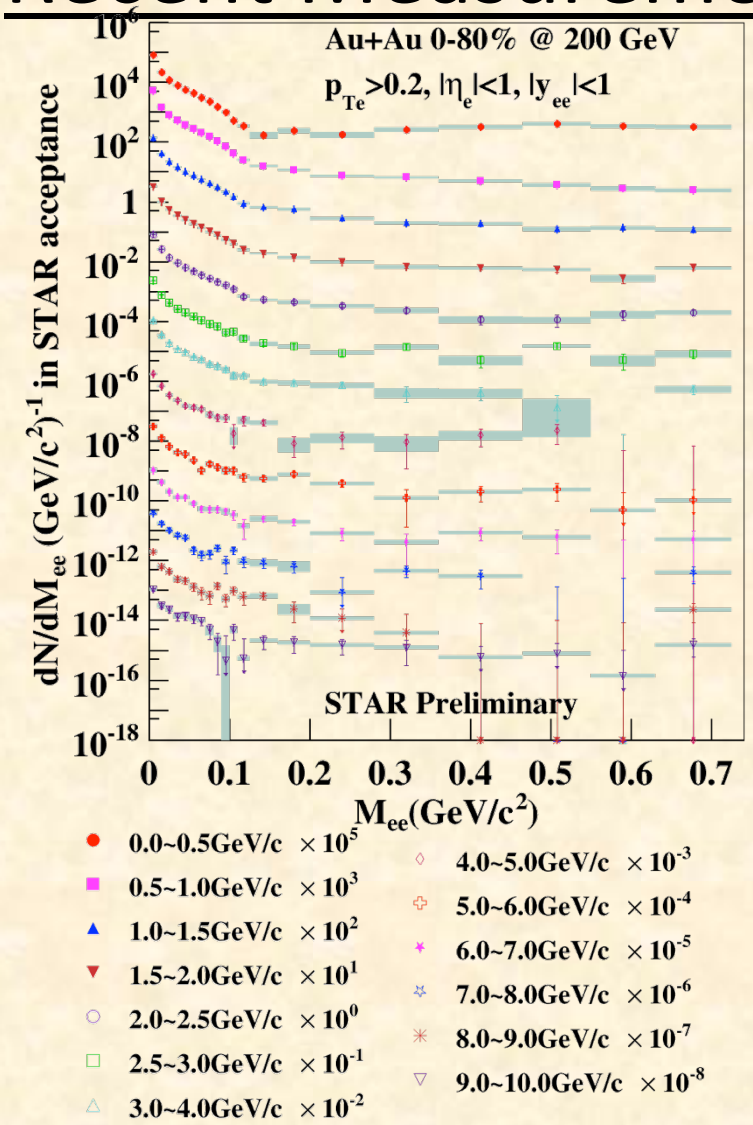
arXiv:1408.2371





- Large uncertainty for $p_T < 2$ GeV/*c* due to lack of η measurements
- Comparison with PHENIX
  - high p_T – consistent with T_{AA}-scaled fit to p+p data
  - for 1-5 GeV/$_c$ observe excess when compared to this p+p reference
- Theory calculations consistent within uncertainty
  - includes contributions from QGP, ρ, meson gas, and primordial production

Recent Measurements from STAR



p_T<5 GeV/c – Run10+11 (MinBias)
5<p_T<10GeV/c – Run11 (EMC trig)

- Using similar method as PHENIX

PRC 81 (1020) 034911

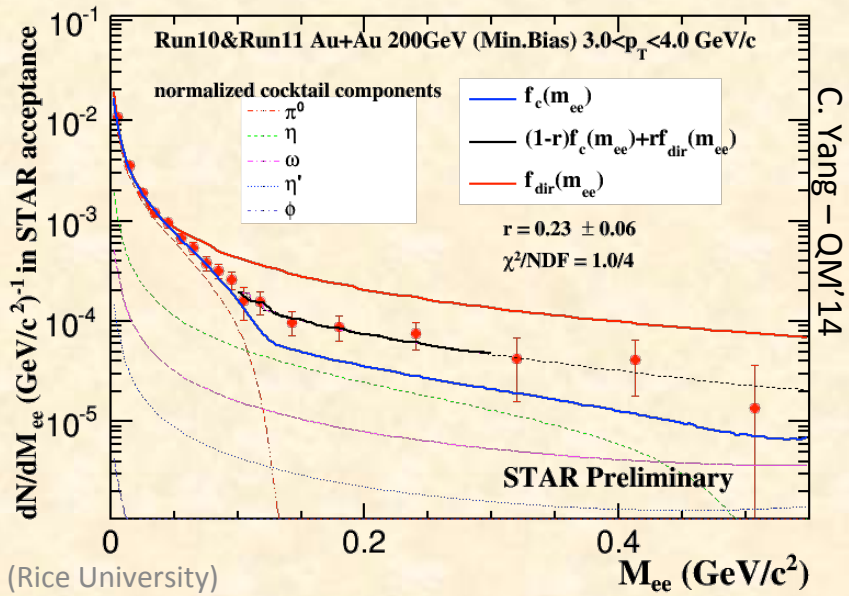
$$\frac{dN_{ee}}{dM} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M^2}}\left(1+\frac{2m_e^2}{M^2}\right)\frac{S(M)}{M}dN_\gamma$$

$$S = dN_{\gamma^*}/dN_\gamma \approx 1 \quad \text{for } p_T >> M \quad \text{and } M >> m_e$$

with $M < 0.3$ GeV/c^2 and $p_T > 1$ GeV/c

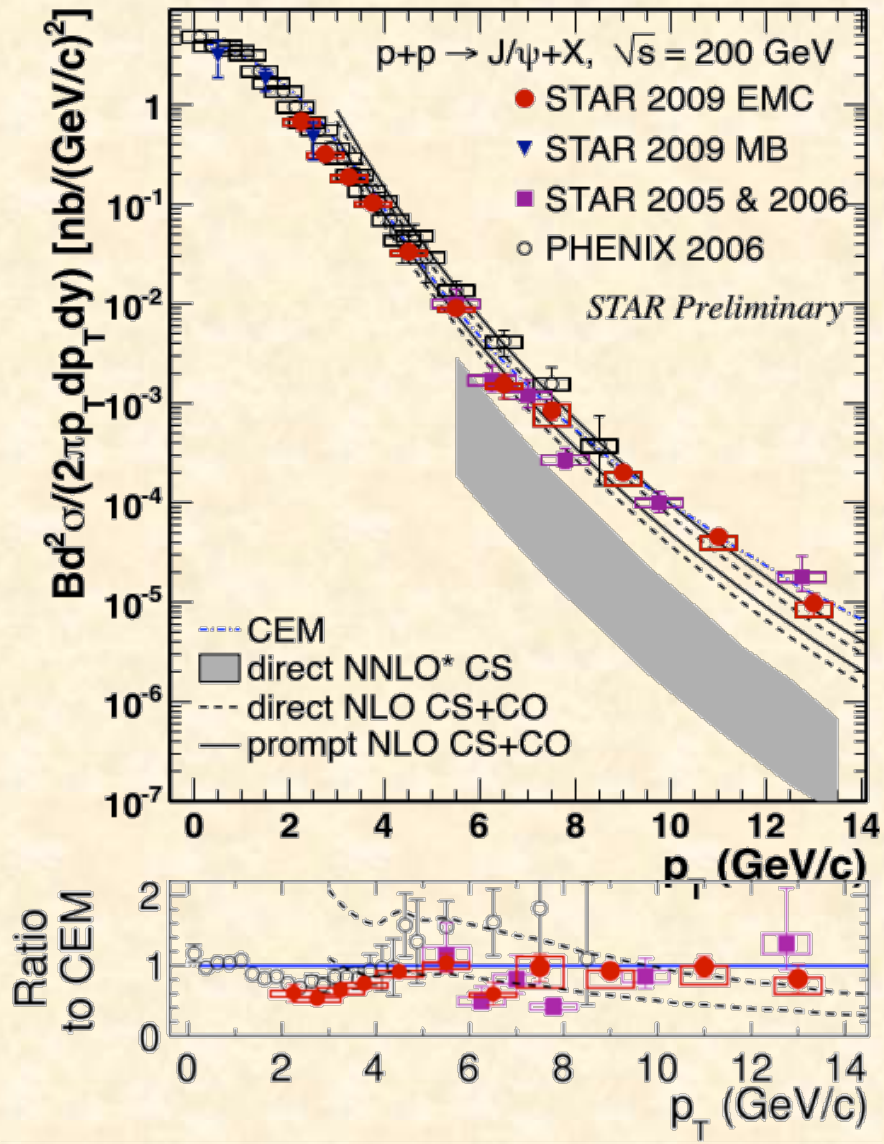
- apply 2-component fit

$$(1-r)f_{\text{cocktail}}(M_{ee}) + rf_{\text{direct}}(M_{ee})$$

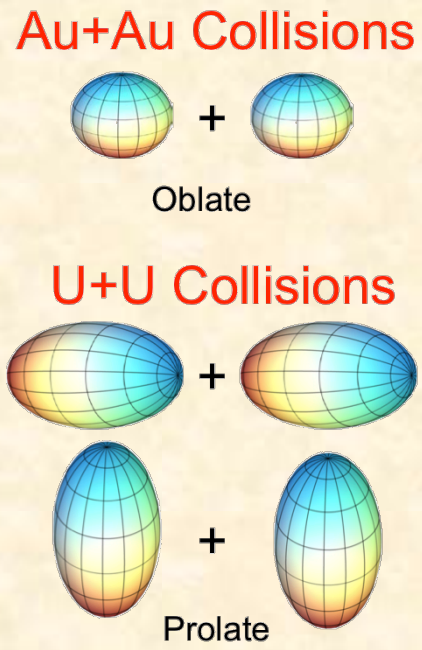
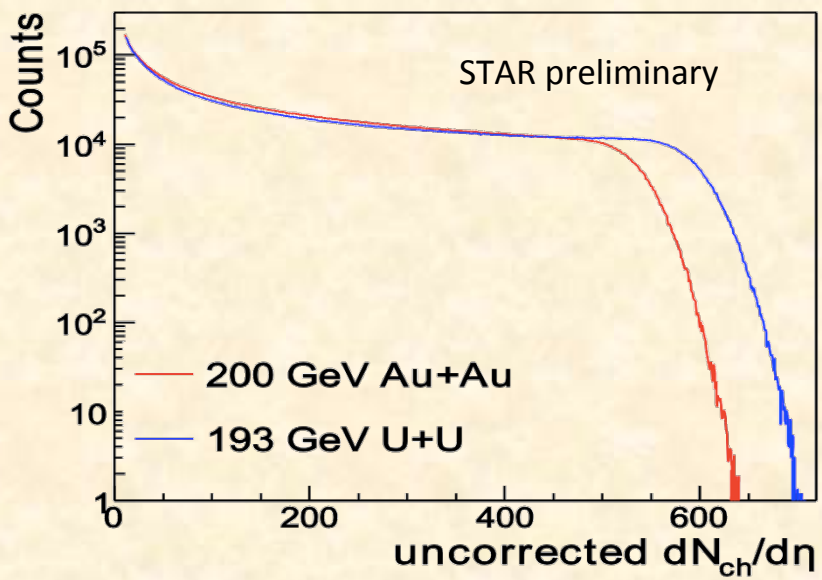
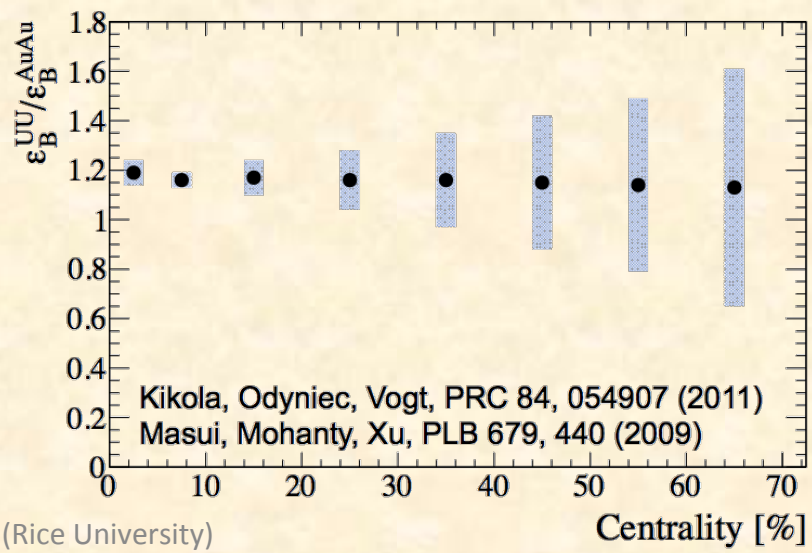


J/ψ Spectra in p+p at 200GeV

- pT range in p+p extended to 14GeV/c
  - Good agreement with PHENIX
- Model Comparison
  - prompt NLO CS+CO describes data pT>4GeV/c
  - direct NNLO*CS misses high-pT



U+U: higher energy densities

RHIC Run-12: $\sqrt{s_{NN}}$=193 GeV U+U data

- Reach higher N_{part} than in Au+Au
- Provide higher energy density at same centralities