Probing QGP at RHIC with leptonic and quarkonia probes.

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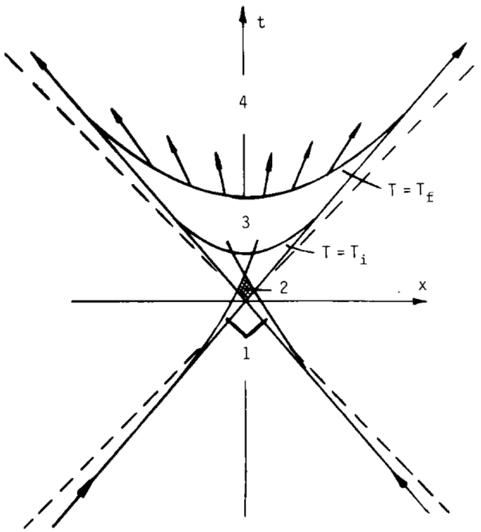

Fig. 1. The space–time picture of hadronic collisions, proceeding through the following stages: (1) structure function formation; (2) hard collisions; (3) final state interaction; (4) free secondaries.

QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, USSR

Received 16 March 1978

I should like to argue in this paper, that a very important intermediate region exists, namely reactions taking place far from the collision point and not obeying the parton model, but at the same time treatable by perturbative QCD methods.

We are interested in the final state interaction region, limited by two lines: T(x, t) = Ti, the initial temperature at which the thermodynamical description becomes reasonable, and T(x, t) = Tf ~ m~, where the system breaks into secondaries [4,7].

The medium is assumed to be the quark-gluon plasma discussed in ref. [5] ,

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New Energy and Intensity Frontiers

- **RHIC → RHIC II**

- **First collisions 2000**
- **p+p, d+Au, Cu+Cu, Cu+Au, Au+Au, U+U**
- **$\sqrt{s_{NN}}$ ~ 7 – 200 GeV**
- **Polarized protons**

LHC

- **First collisions 2010**
- **p+p, Pb+Pb, p+Pb**
- **$\sqrt{s_{NN}}$ =2.76 TeV**
- **(5.5 TeV in 2015-16)**

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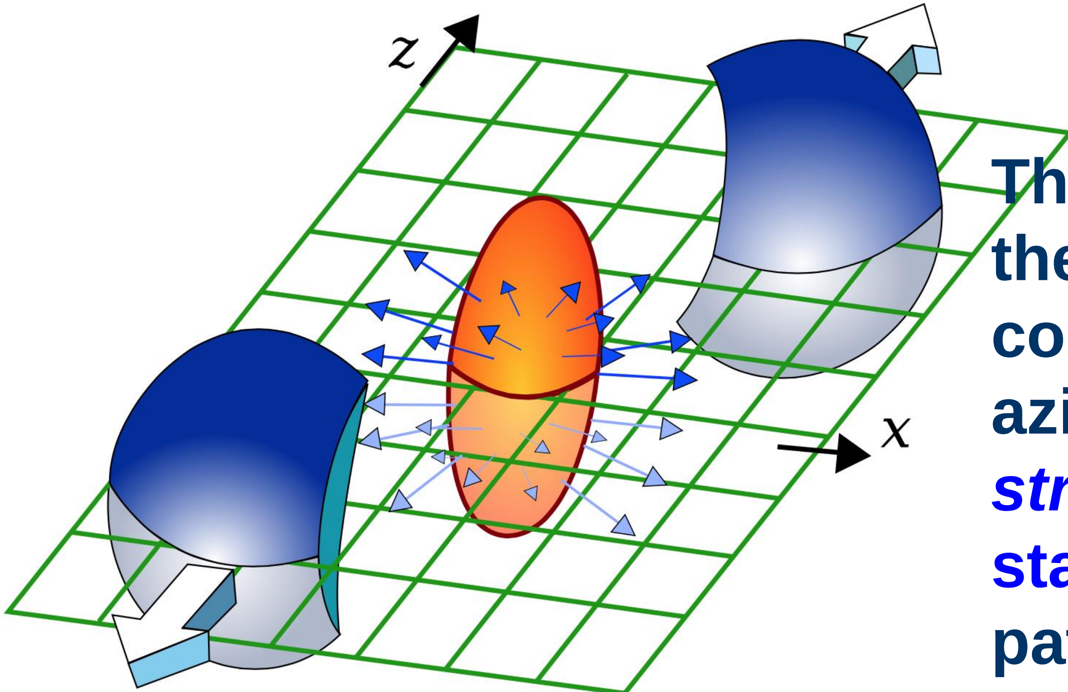
An experimentalist view of Heavy Ion Collisions



The collective nature of the the collision created medium converts initial state azimuthal asymmetry into a *strong* signal in the final state particle emission pattern

$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi)$

$$\frac{dN}{d(\phi - \Phi_n)} = N_0 \left[1 + 2 \sum v_n \cos\{n(\phi - \Phi_n)\}\right]$$

$$v_n = \langle \cos\{n(\phi - \Phi_n)\}\rangle$$

V3 and higher tells of fluctuations

Space-Time Evolution in Heavy Ion Collisions

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Collision

Initial state?

CGC?

Rapid equilibration

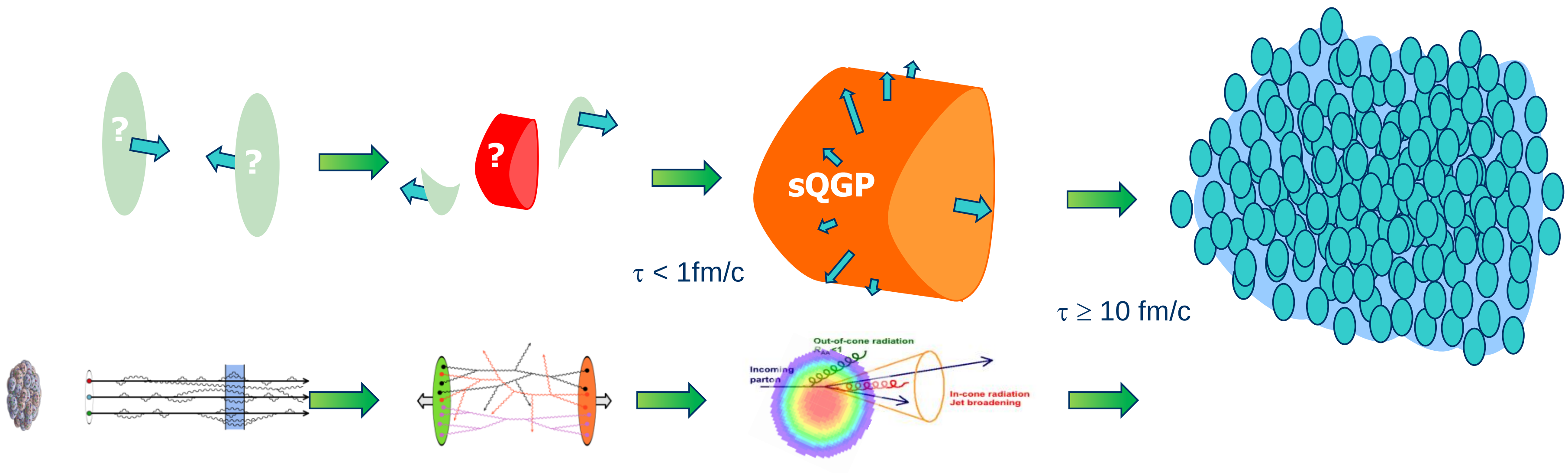
How?
Glasma?
Role of B-field?

Anisotropicaly expanding sQGG

Properties?
T, η/s, q, D, … ?
Quasiparticles ?

Hadronization to freeze-out

Coalescence? Chiral symmetry?



Observables:

Photon emission
Di-leptons and quarkonia
Heavy flavors
Jets

Measurable:

Yields
Spectra
Suppression (with respect to scaled reference)
Energy loss and pattern

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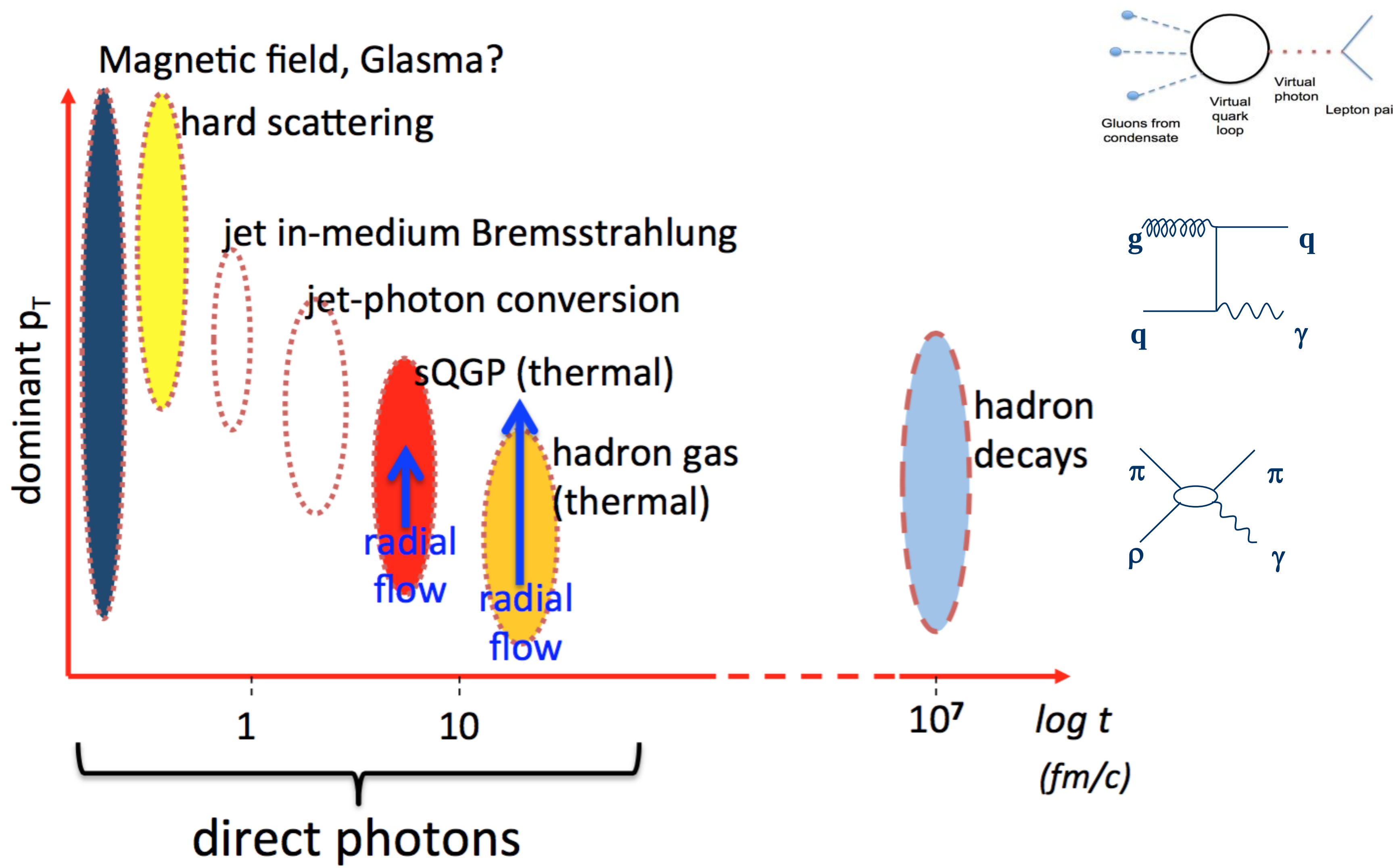
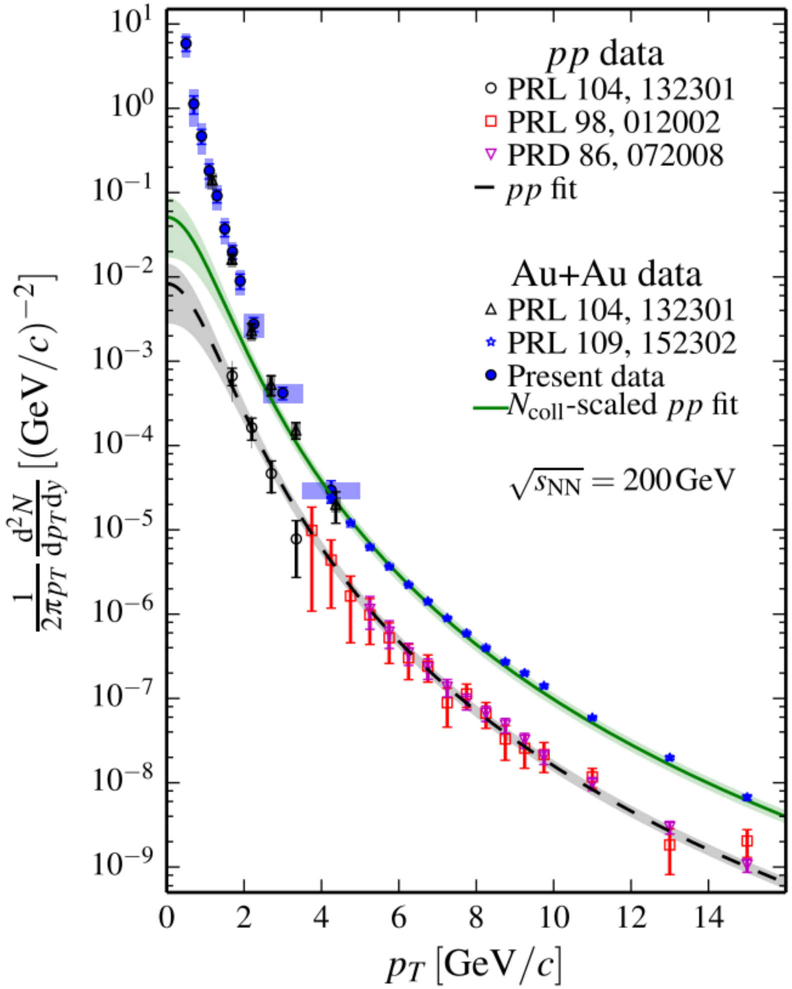
Photons Sources in Heavy Ion Collisions



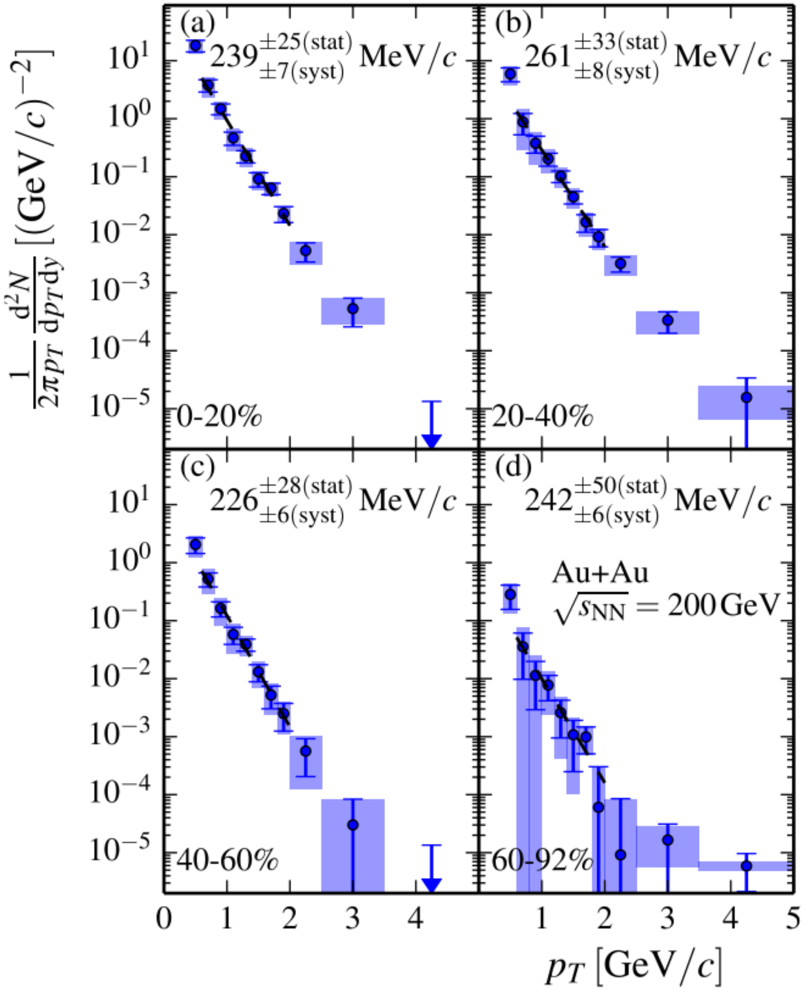
Early emission →High yield → high T
Late emission → Long in-medium time → Large Doppler shift

Direct Photon Emission from 200 GeV Au+Au

PHENIX: Phys. Rev. C 91 064904 (2015)



Prompt component subtracted



Large direct photon excess yield with inv. slope T ~ 240 MeV

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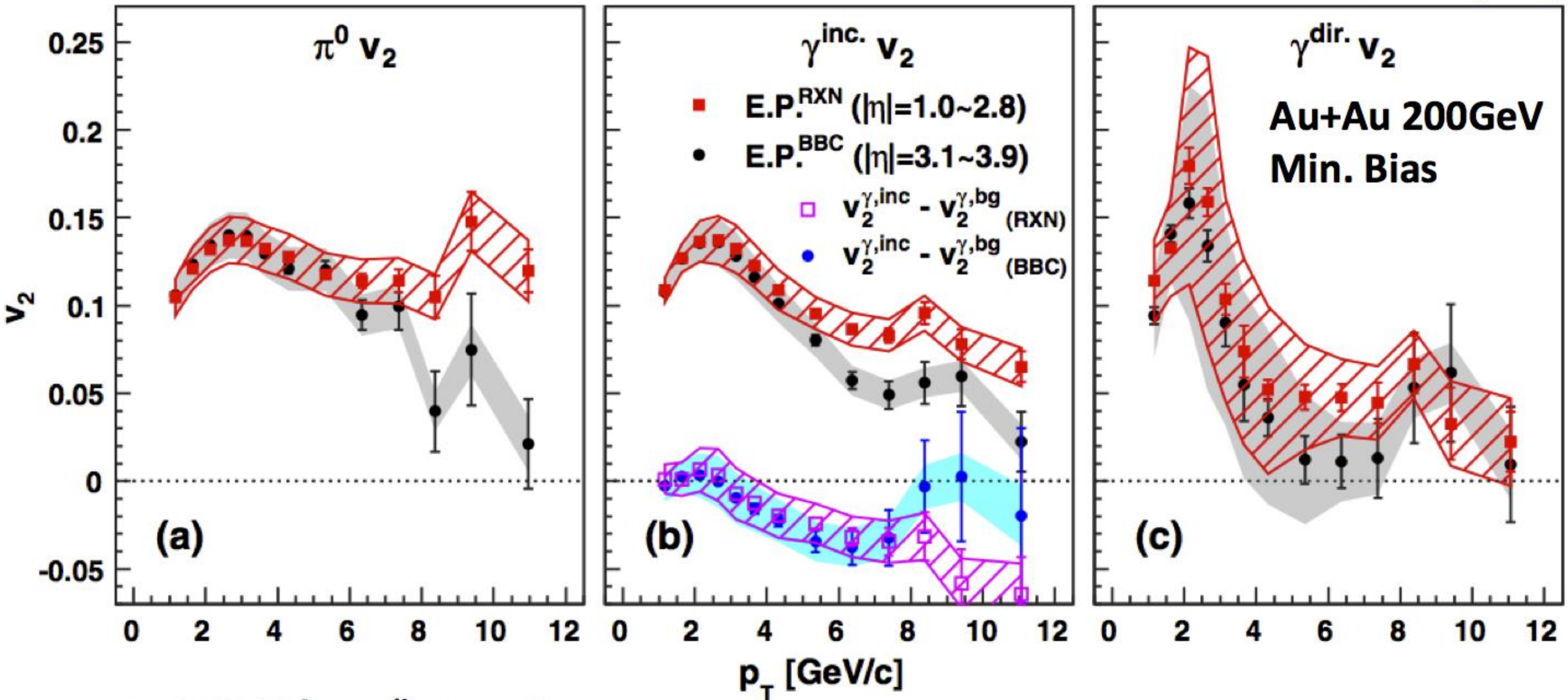
Large Direct Photon Elliptic Flow (v_2)

P.R.L. 109, 122302(2012)



p_T > 4 GeV/c : $\gamma^{dir.}$ $v_2 \approx 0$

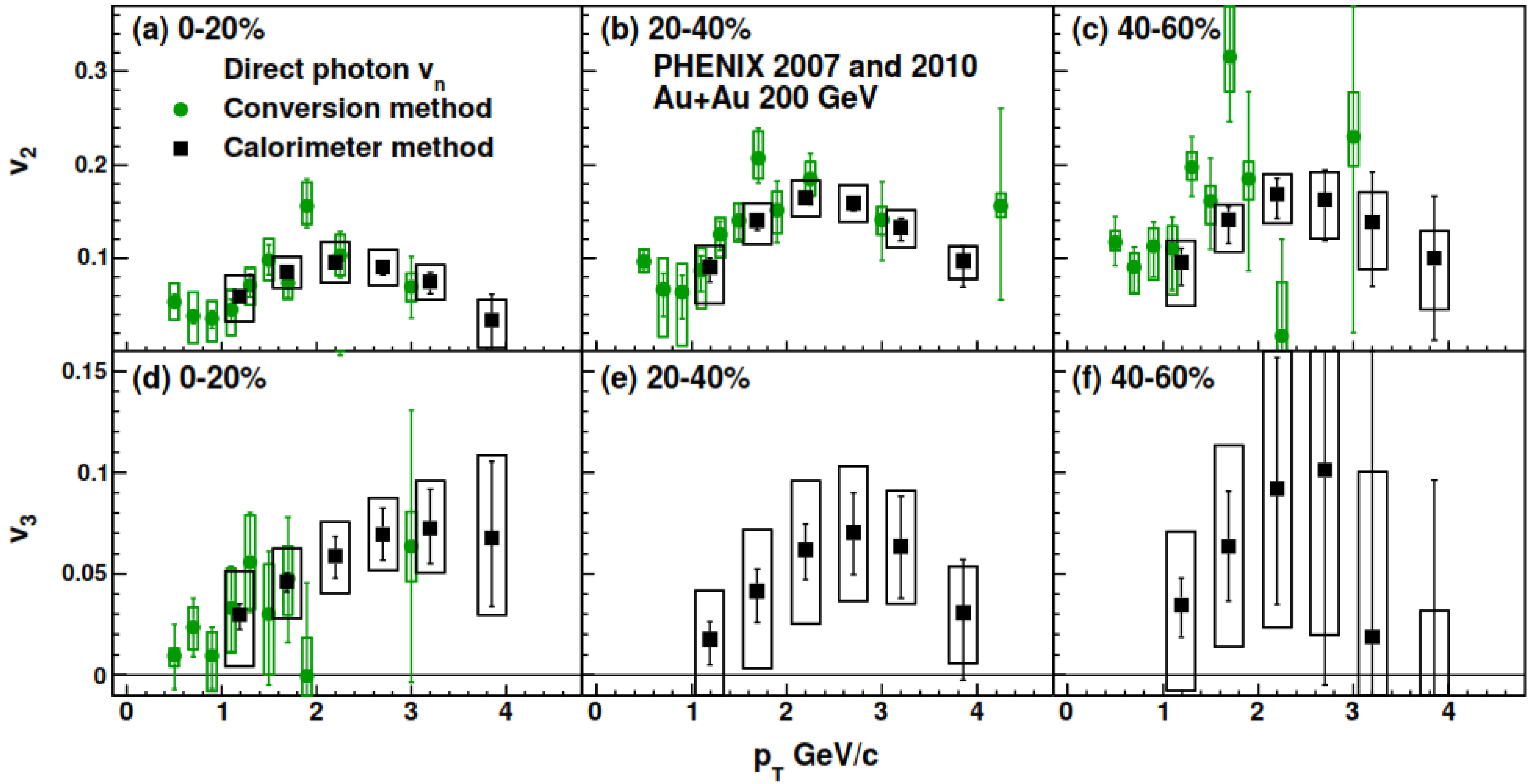
p_T < 4 GeV/c ($p_T \approx$ 2 GeV/c) : hadron $v_2 \approx \gamma^{dir.}$ $v_2 > 0$

Conventional wisdom : p_T < 4 GeV/c

Photons are emitted at late stage of collisions, temperature is low.

Direct Photons Flow confirmed

PHENIX: arXiv:1509.07758 (2015)



Large v_2 and v_3

Consistent with that measured for charged and π^o's

but not interpreted ….

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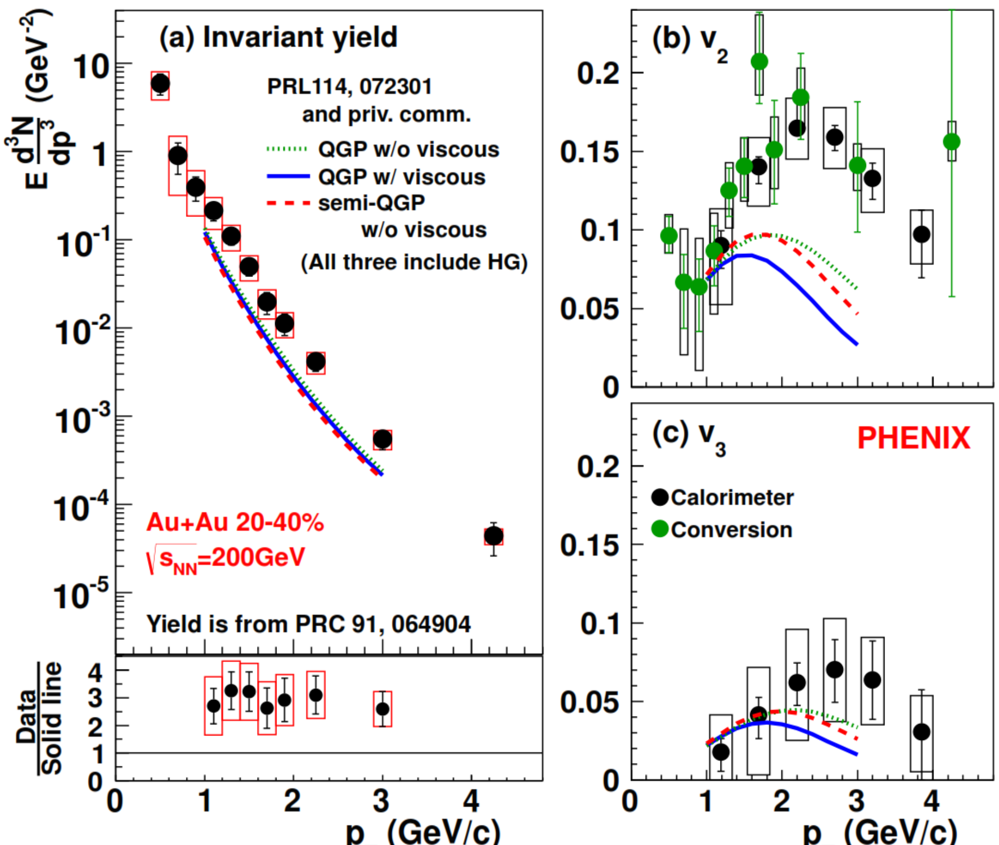
Many model calculations and consideration*:

- More traditional, large contribution from hadron gas
  - Thermal rate in QGP & HG, with hydro (viscous/non viscous) or blastwave evolution
  - Microscopic transport (PHSD)
- New early contributions
  - Non-equilibrium effects (glasma, etc.)
  - Enhanced thermal emission in large B-fields
  - Modified formation time and initial conditions
- New effects at phase boundary
  - Extended emission
  - Emission at and after hadronization

**list not complete*

PHENIX: Phys. Rev. C 91 064904 (2015)

Example: viscous hydro + thermal emission



Large yield and v_n challenge understanding of sources, emission rates and space-time evolution

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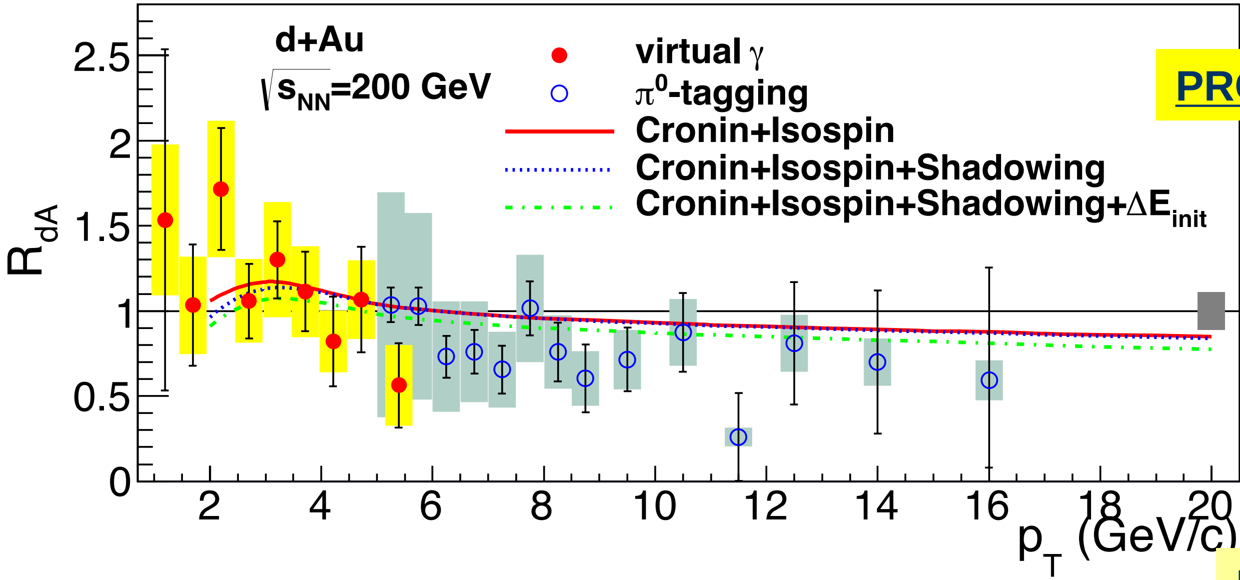
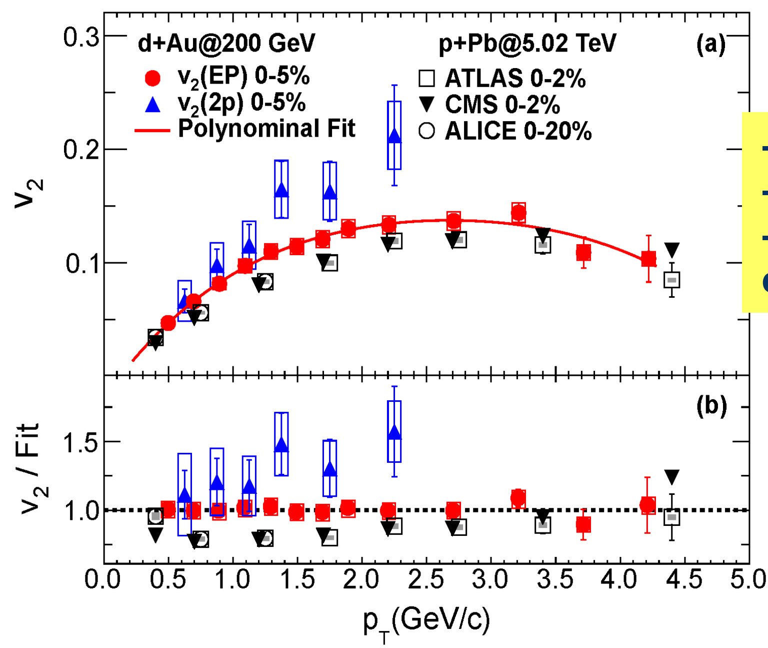
Expected and unexpected …



PRC87, 054907 (2013)

PHENIX, PRL114, 192301 (2015)

- No modification in initial hard scattering and PDF compared to p+p at mid-rapidity but …
- We didn't anticipate "flow" in a small system like d+Au



-all charged
-EP – event plane
-2p – Au direction only

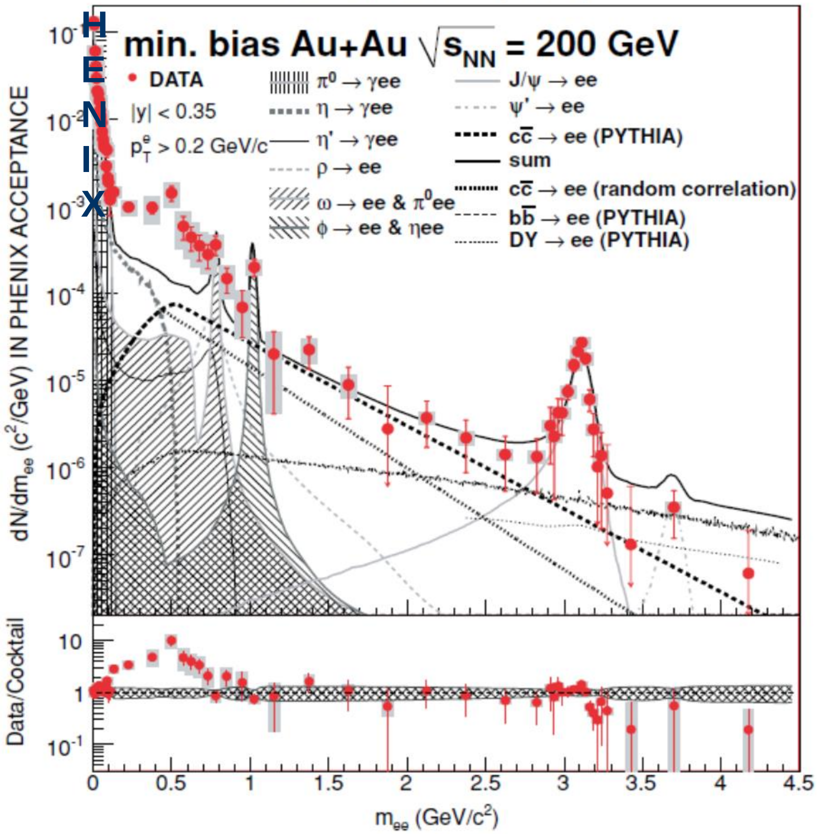
Single Photon's summary:

- ✓ **An excess of yield above the Ncoll scaled p+p yield is observed at all centralities up to about 4GeV/c photon pT;**
- ✓ **Prompt photon subtracted pT slope of the excess photons is close to ~240Mev and independent of centrality;**
- ✓ **Excess yield scales as $N^{1.4}$**
- ✓ **Photons from affected pT range flow with measured v2 and v3 close to that of π^0's;**
- ✓ **Theoretical picture is incomplete at best. Large excess points to early emission, large flow points to late emission.**

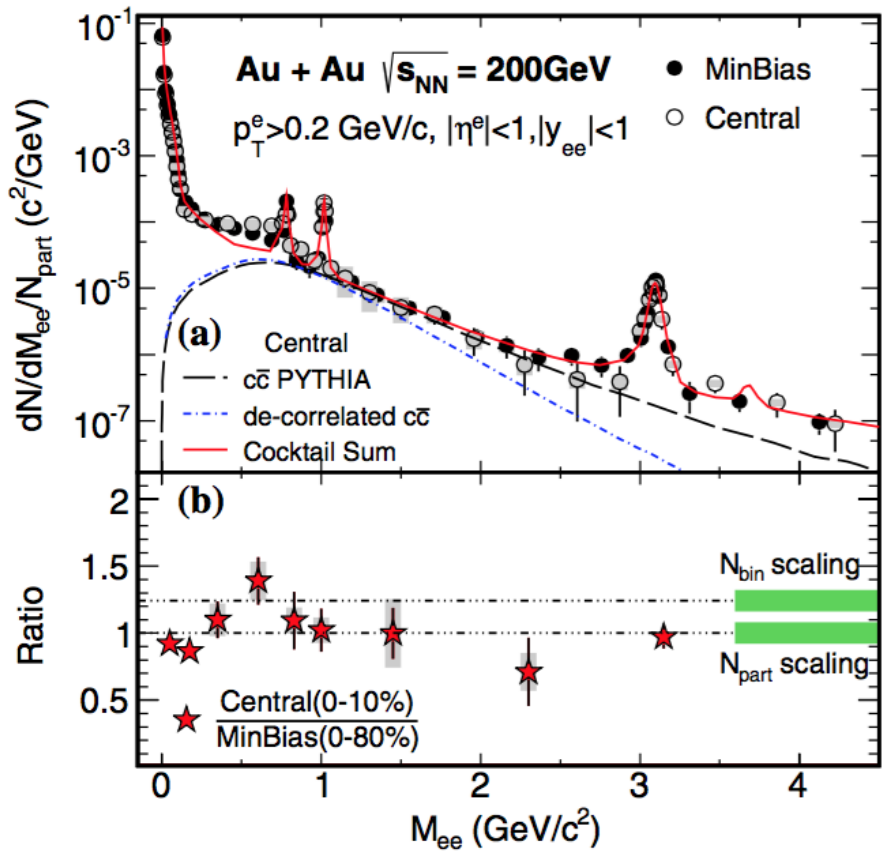
Low Mass e⁺e⁻ Pair Emission

P
H
E
N
I
X

PRC 81, 034911(2010)

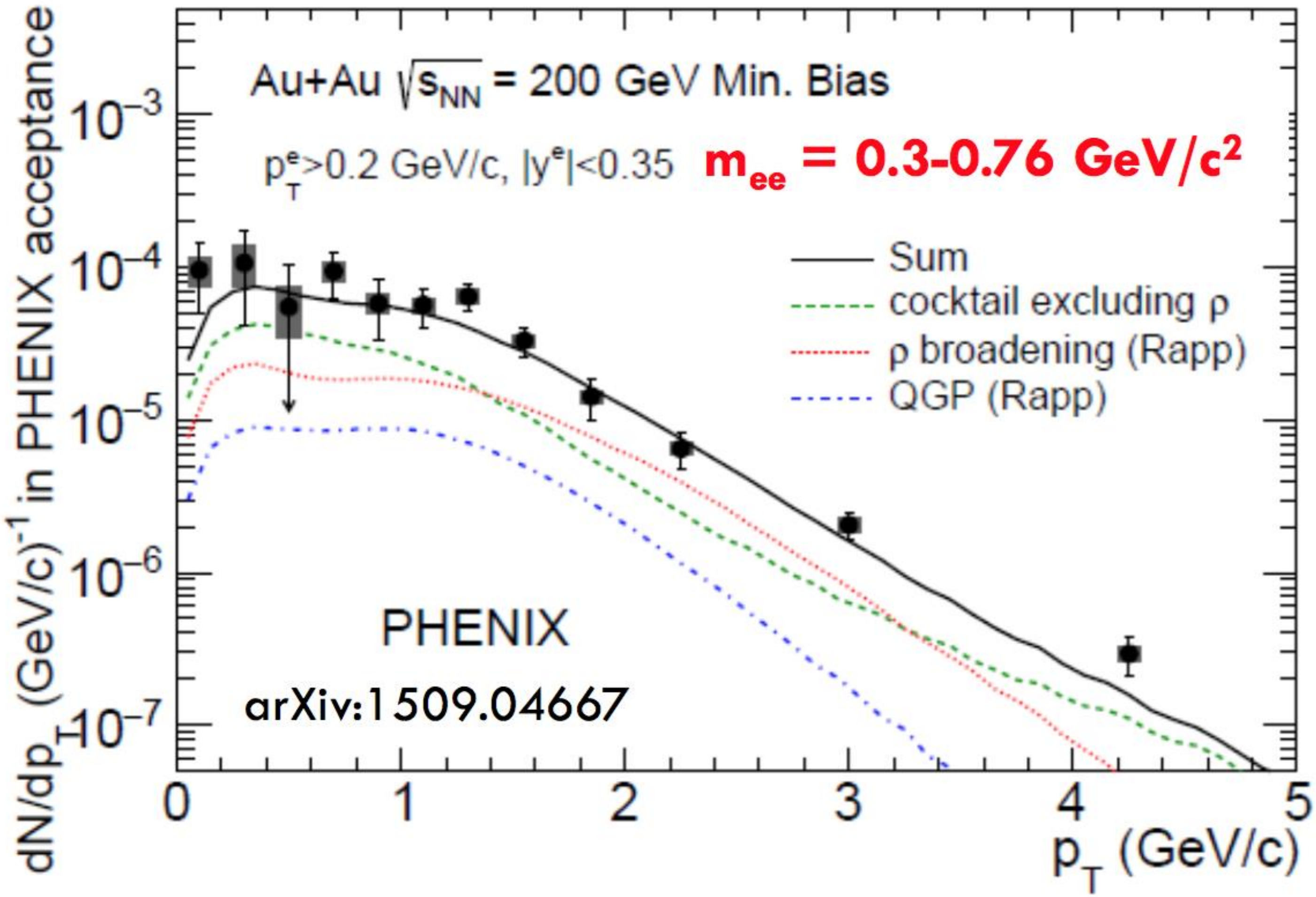


STAR, PRL 113 022301 (2014)

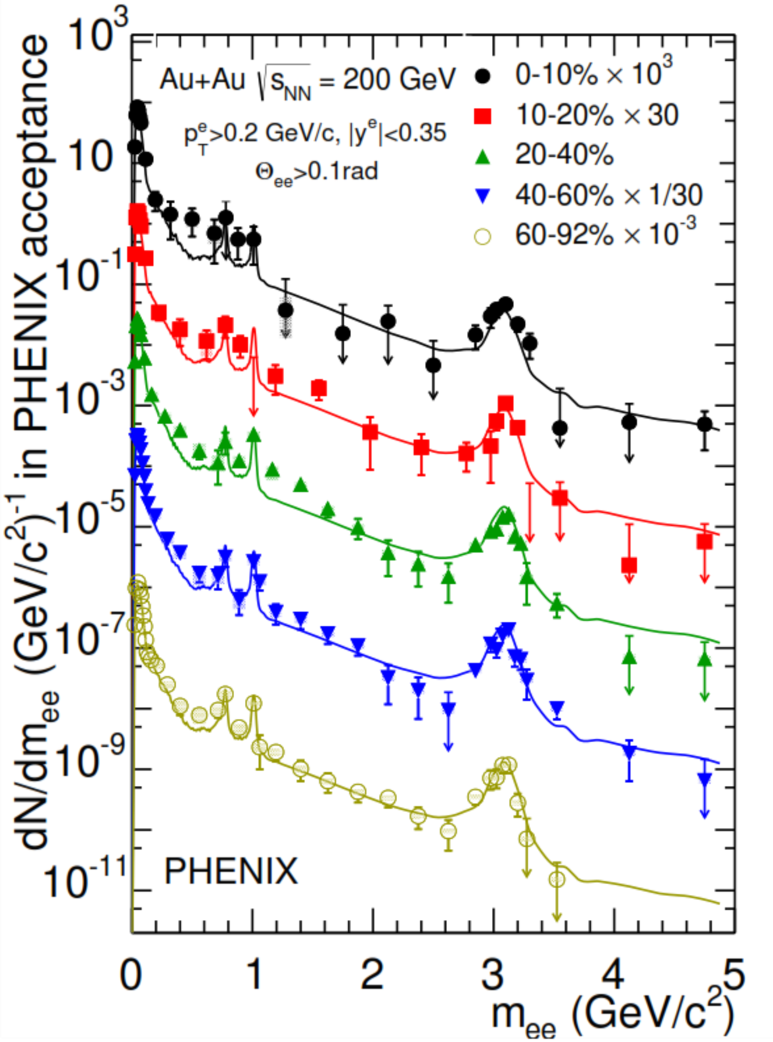


Resolution: PHENIX+HBD Data from 2010

- Active rejection of conversion and Dalitz pairs;
- Improved hadron rejection;
- Improved analysis technique.

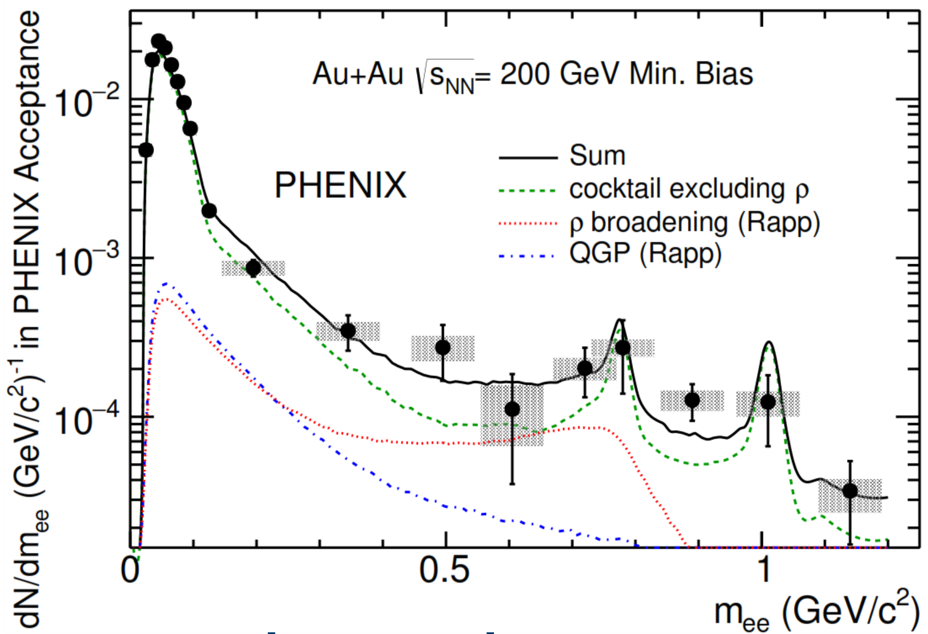


Moderate Enhancement in 200 GeV Au+Au



Moderate enhancement consistent with ρ broadening

PHENIX: arXiv 1509.04667 (2015)



- **Moderate enhancement**
  - for $300 < m < 750$ MeV factor*
    min.bias $2.3 \pm 0.4 \pm 0.4 \pm 0.2$
    central $3.2 \pm 1.0 \pm 0.7 \pm 0.2$
- **Smaller than previous result**
- **Consistent with STAR data**
- **Consistent with ρ broadening**

**binary scaled PYTHIA for c/b*

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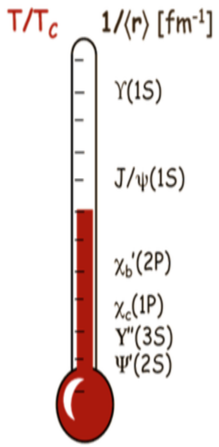
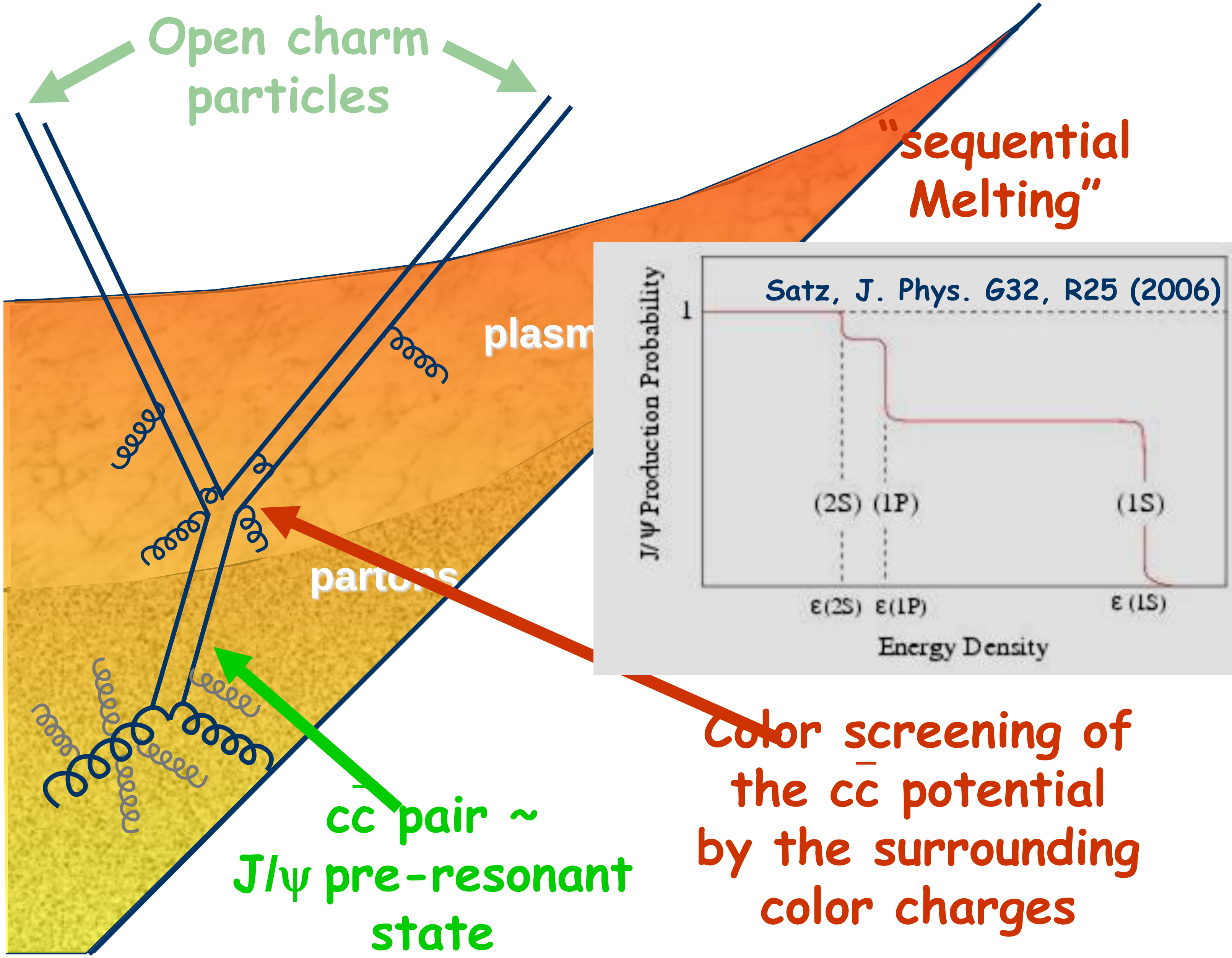
Di-electron summary

- Small excess in di-electron pair production is a good news;
- It is naturally explained by ρ-broadening in the matter which is now kind of “experimentally” proven;
- It points towards “clustered” objects in “produced” matter ;
- Could those objects be “quasiparticles” of Edward Shuryak ????

J/ψ production and differential suppression



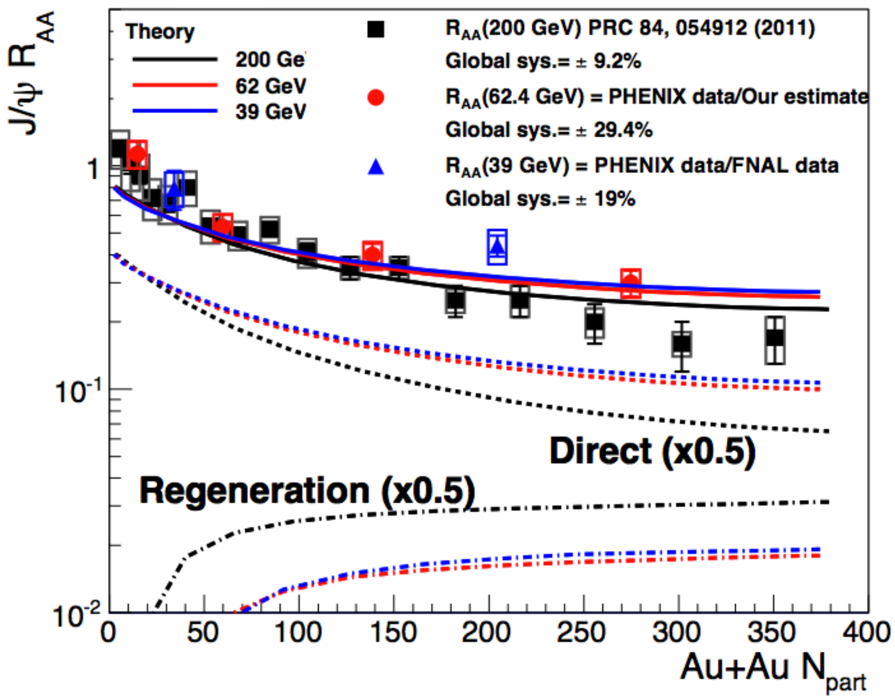
QGP thermometer based on sequential suppression of quarkonia. courtesy: A. Mocsy



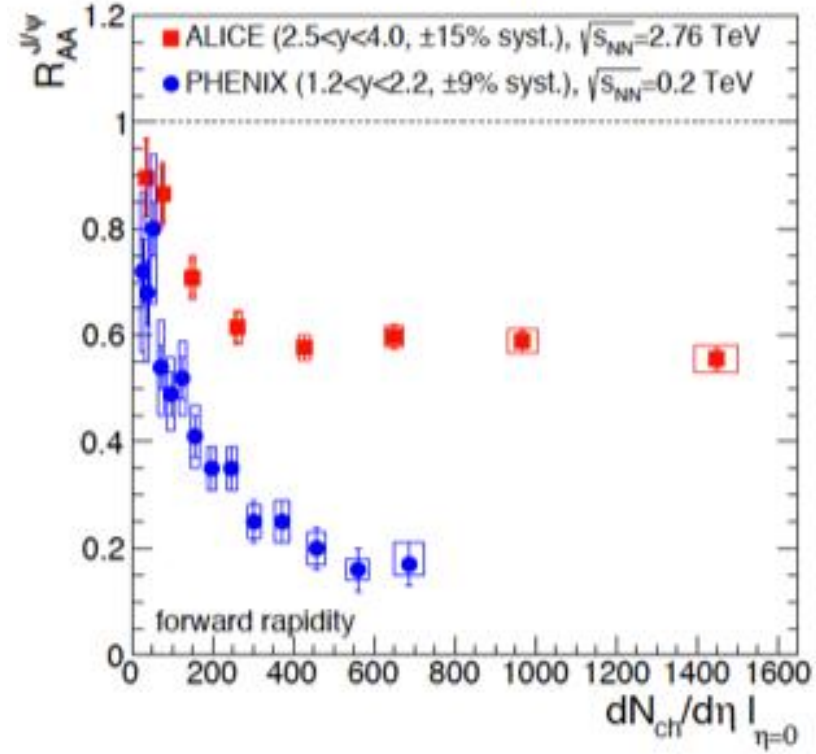
LHC and strong charm coalescence

At RHIC 39 GeV, 62 GeV, 200 GeV all show similar suppression

- perhaps strongest at 200 GeV

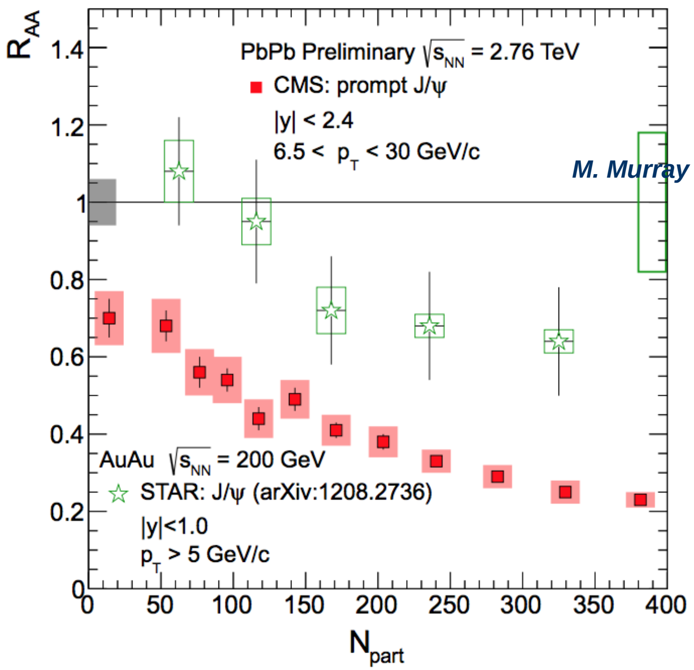


J/ψ suppression much stronger at 200 GeV than 2.76 TeV for similar energy density - strong coalescence

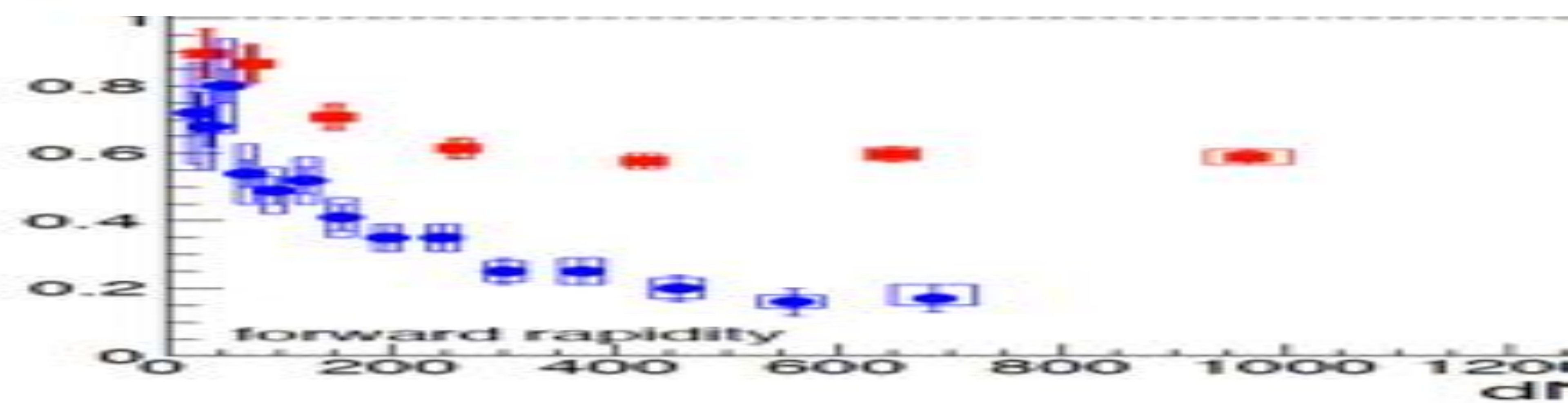


In the model (PRC82, (2010) 064905) this similarity is due to a balance between color screening and coalescence

Questioning the RHIC-LHC differences



M. Murray / Nuclear Physics B (Proc. Suppl.) 233 (2012) 212–216



Can coalescence be proven experimentally

U+U measurements

U+U collisions allow us to go to higher energy density at RHIC
Central U+U collisions should have:

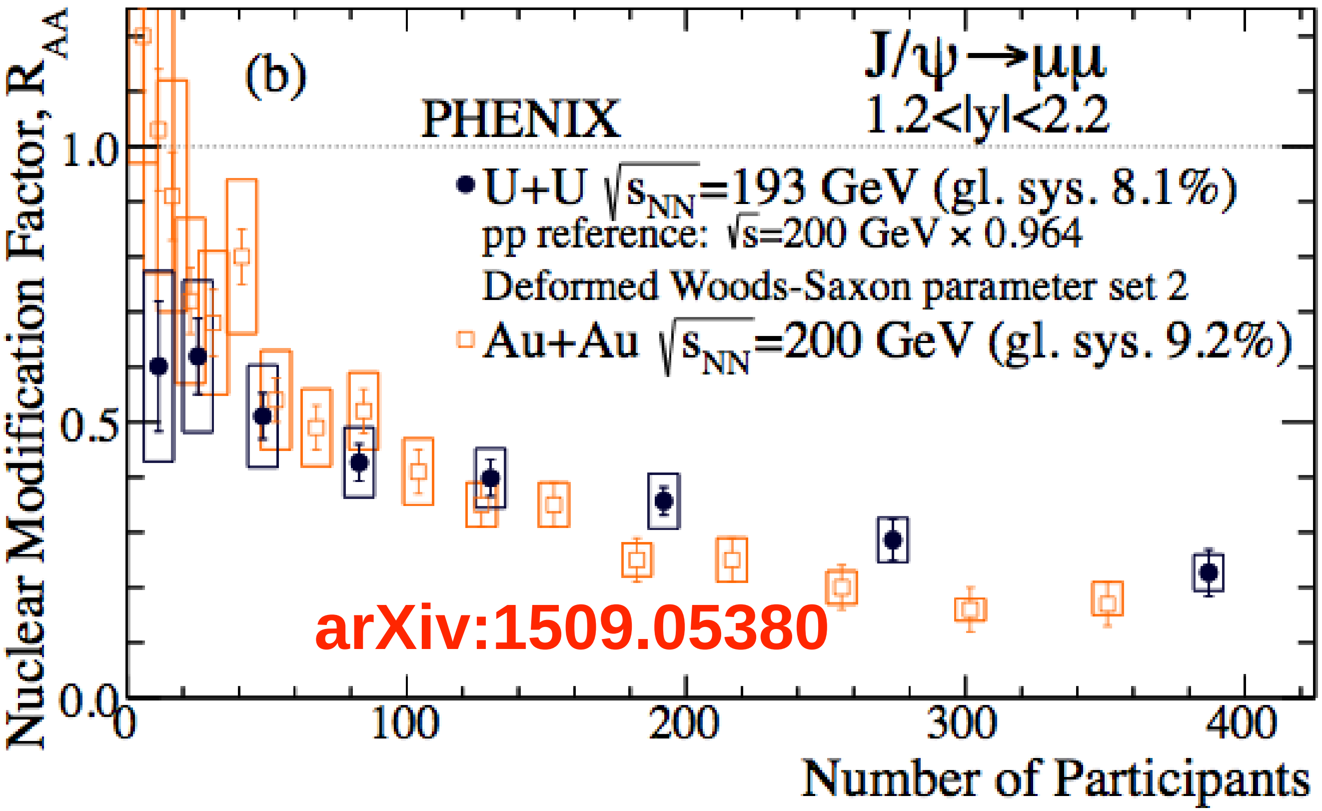
- **15-20% higher energy density than Au+Au collisions**
  - **stronger color screening**
- **Increased charm production from ~ 25% larger N_{coll} values**
  - **stronger coalescence**

J/ψ production in U+U collisions allows us to explore how the trade-off between color screening and coalescence evolves as we increase energy density and charm production

In RHIC Run 12 PHENIX recorded
1.08 B minbias $\sqrt{s_{NN}}$ = 193 GeV U+U events

The U+U R_{AA}

Start with the latest parameter set (2) to calculate R_{AA}

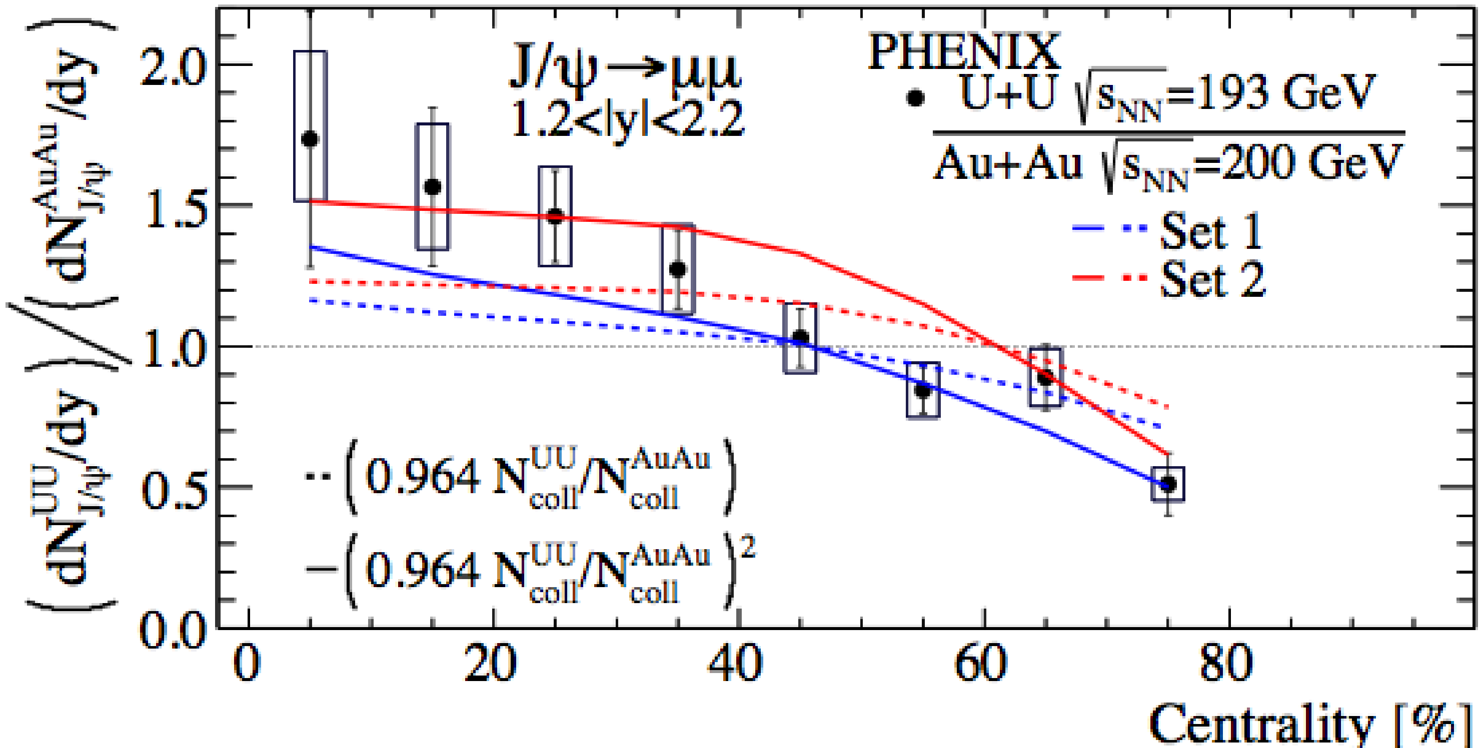


The U+U R_{AA} is somewhat larger than that for Au+Au at low centralities

Make the experimental ratio of dN/dy values.

- Has the advantage that it does not rely on N_{coll}
- However our expectation for its behavior is determined by N_{coll}

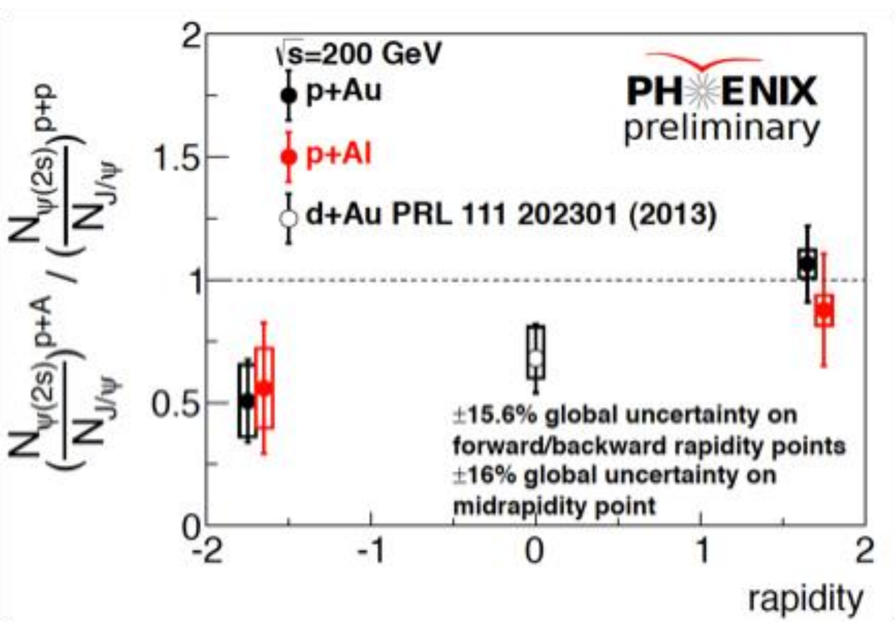
arXiv:1509.05380



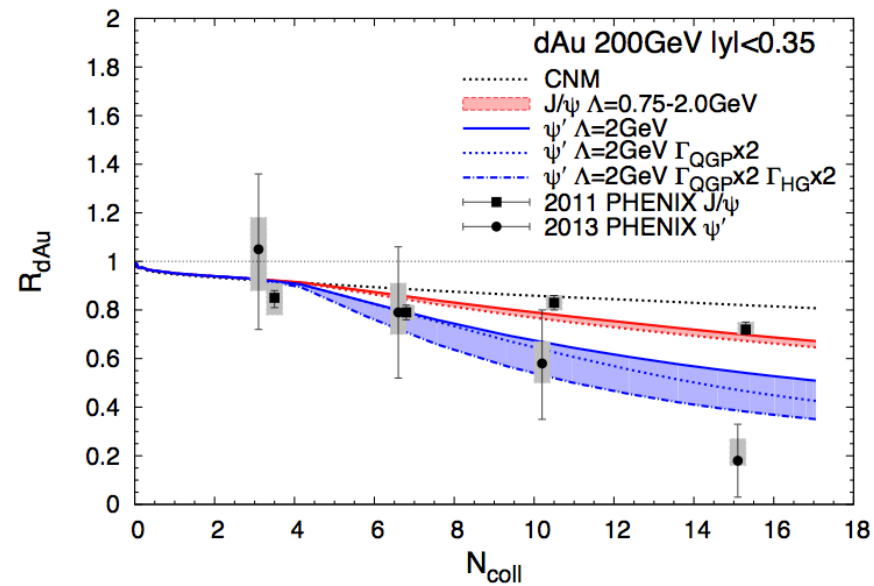
Consistent with a picture in which the increase in charm coalescence becomes more important than the increased color screening when going from Au+Au to U+U

May small systems hold the key to answers

- ✓ In pA/dA the breakup effects could be ignored (formation time arguments);
- ✓ Data shows suppression at forward rapidity, no suppression at backward rapidity
- ✓ Suppression is caused by interactions with produced particles and occurs after the charmonium leaves the target



Du & Rapp arXiv:1504.00670



Quarkonia summary

In AuAu and PbPb collisions over the whole RHIC-LHC energy range prompt J/Y follow common pattern of suppression when plotted against participant multiplicities;

Little or almost no suppression is visible in RHIC and LHC High pT J/Y data;

The suppression of comparable magnitude is also observed in forward direction in small systems (pAu, dAu, pAl) essentially excluding large breakup effects in nuclear matter;

What is left are color screening resulting in quarkonia melt in produced media and recombination which follows.

Global summary

After many years of theoretical and experimental efforts the Hot & Dense matter probing is still a challenge:

- ✓ We may reliably extract and decompose signals of prompt and “thermal” photons produced at a different stages of collisions but can’t reconcile the total yield and flow attributed to those photons;
- ✓ From the onset of the field our understanding of QGP strongly relied on explanation of disproportionally low yield of quarkonia (J/Y) in central HI collisions (compared to scaled pp-collisions. Today we have related data covering the energy range from SPS to RHIC to LHC. That data shows amazing consistency and energy independent behavior currently impossible to explain without assuming an almost miraculous balancing between quarkonia melting (or break-up by comoves) and regeneration in QGP.

The final consistentcy between data on di-leptons between experiments and theory is certainly a very good news. What is even better – rho broadening due to in the matter scattering is sufficient to explain observed excess over expectations.

Can it be a sign of “*… particles with M, pt as large as 4-5 GeV are mainly produced not via hard collisions, but at the plasma stage …*.. “ (Edward Shuryak, 1978)