Summary and perspective

Denes Molnar, Purdue University

Heavy Flavor Workshop

January 4-6, 2011, Purdue University, IN

3 days

$\mathcal{O}(50)$ **participants**

$\mathcal{O}(30)$ **speakers**

$\mathcal{O}(1000 + 100)$ **slides**

Life is hard/easy, depending:

- good theory control

- open-heavy flavor in elementary collisions

- marginal control (or little)

- dense nuclear medium, especially for quarkonia in heavy-ion collisions

theory still evolving

Braaten on Tue

Summary

Heavy hadron production

Rigorous factorization formula at large p_T
involves nonperturbative fragmentation functions
parton cross sections should soon be available at NNLO

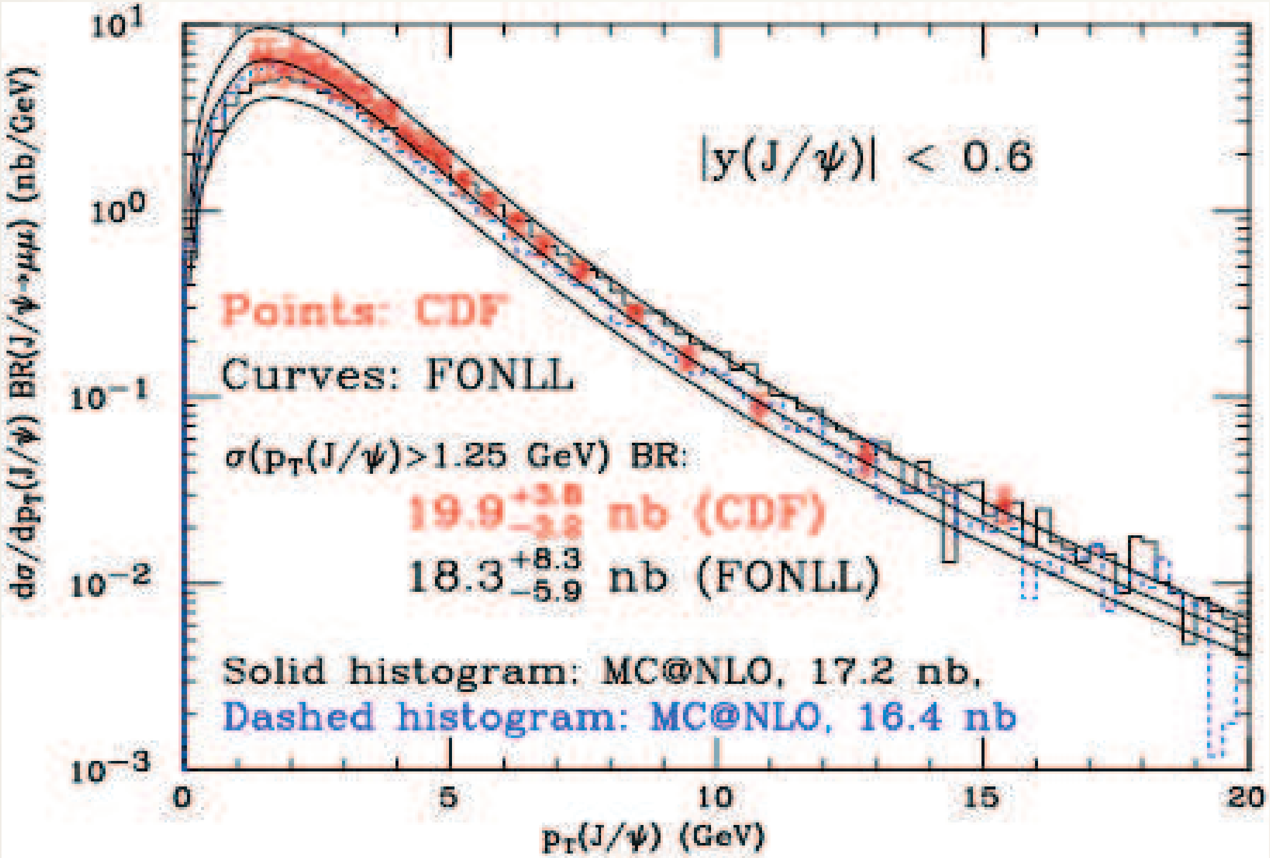
Quarkonium production

Rigorous factorization formula at large p_T
involves nonperturbative fragmentation functions
NRQCD factorization could reduce them to constants
parton cross sections at NLO available for moderate p_T
NLO calculations of fragmentation functions also needed

Albert Einstein:
"Make everything as simple as possible, but not simpler."

J/ψ from *b* hadron decays at the Tevatron

- Cacciari, Frixione, Mangano, Nason, Ridolfi 2004

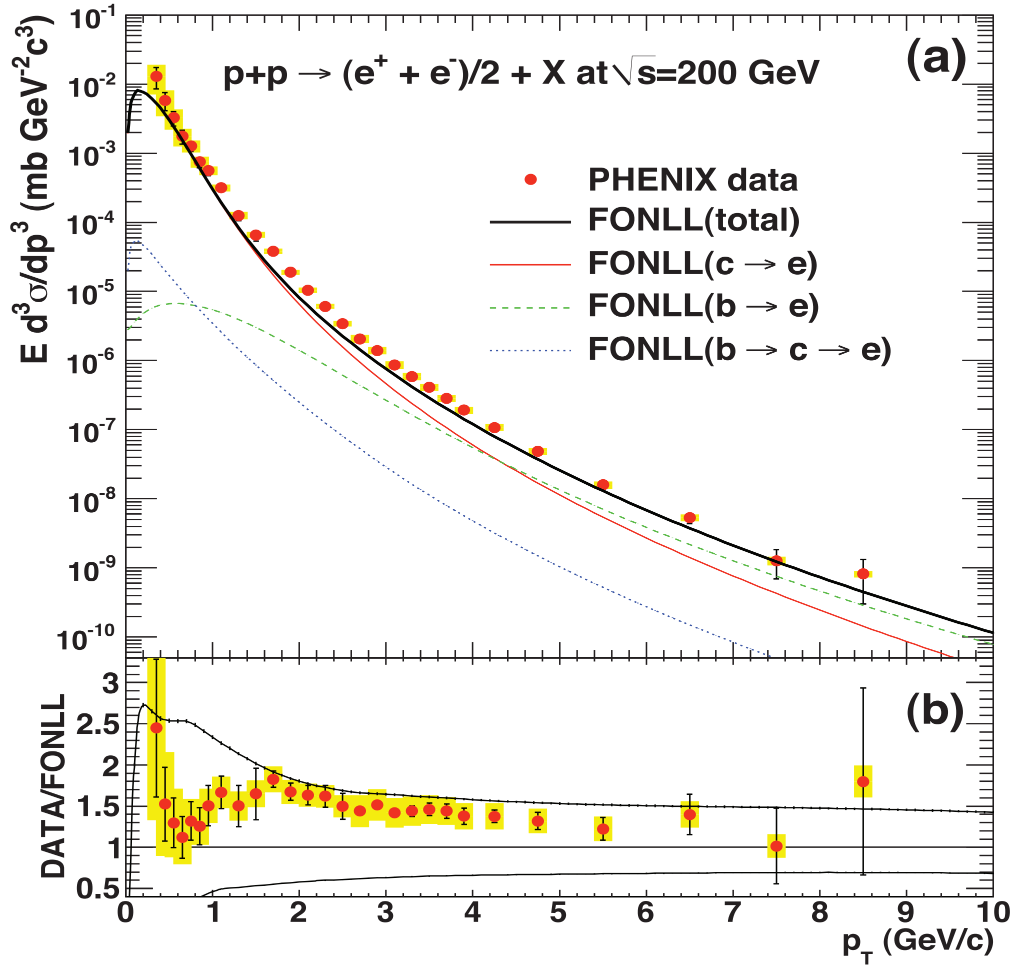


- Good agreement with the data
- Scale, mass and PDF uncertainties summed in quadrature

Garishvili on Tue

Heavy flavor electron spectrum in p+p collisions @ 200 GeV

- Necessary baseline measurement for heavy ion collisions
- Latest cocktail (Including J/ψ contribution at high p_T)
- Agreement with FONLL (c+b) prediction **PRL 95 122001(2005)**
- Good agreement in spectral shape
- σ_{cc}= 567 ± 57(stat) ± 224(sys) mb
- For bottom cross section need to know bottom to charm production ratio within HF electron spectrum



arXiv:1005.1627 (PHENIX)

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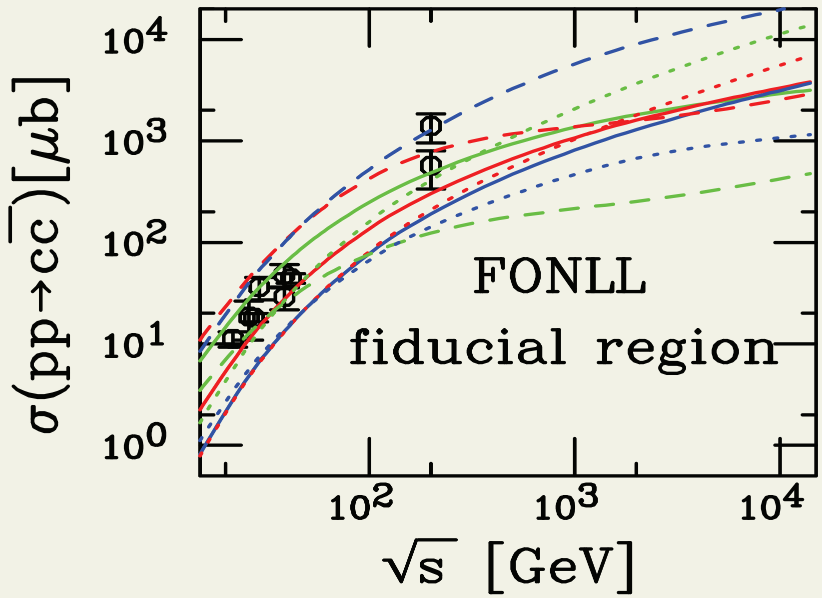
Choosing Parameters for J/ψ Calculations I: FONLL

J/ψ parameters based on FONLL parameter sets varying mass and scales around central value $(m, \mu_F/m, \mu_R/m) = (1.5\,\mathrm{GeV}, 1, 1)$ (left)

None of the FONLL sets fit the data

No convergence for $\mu_R/m < 1$ (large α_s)

Problems with backward evolution of PDFs for $\mu_F/m \le 1$ (near or below minimum scale of PDFs)



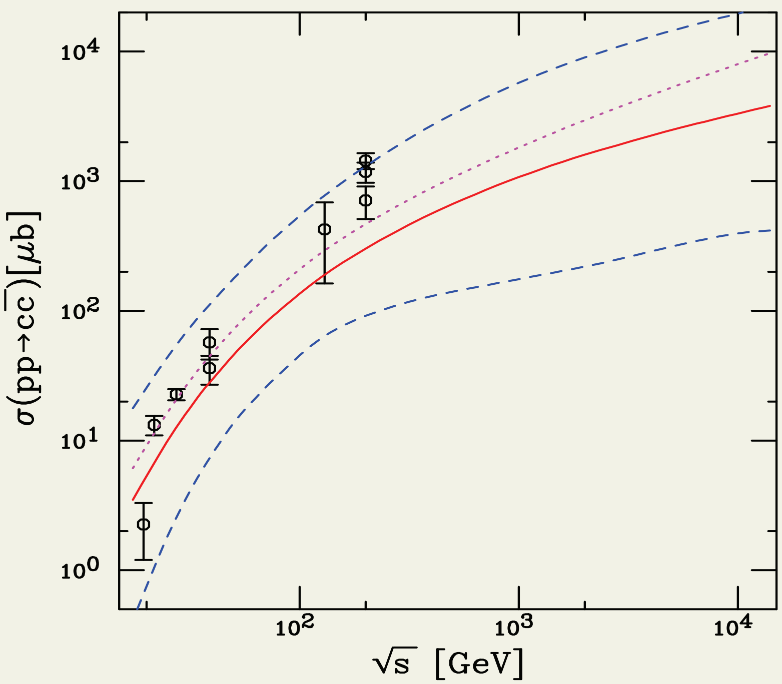
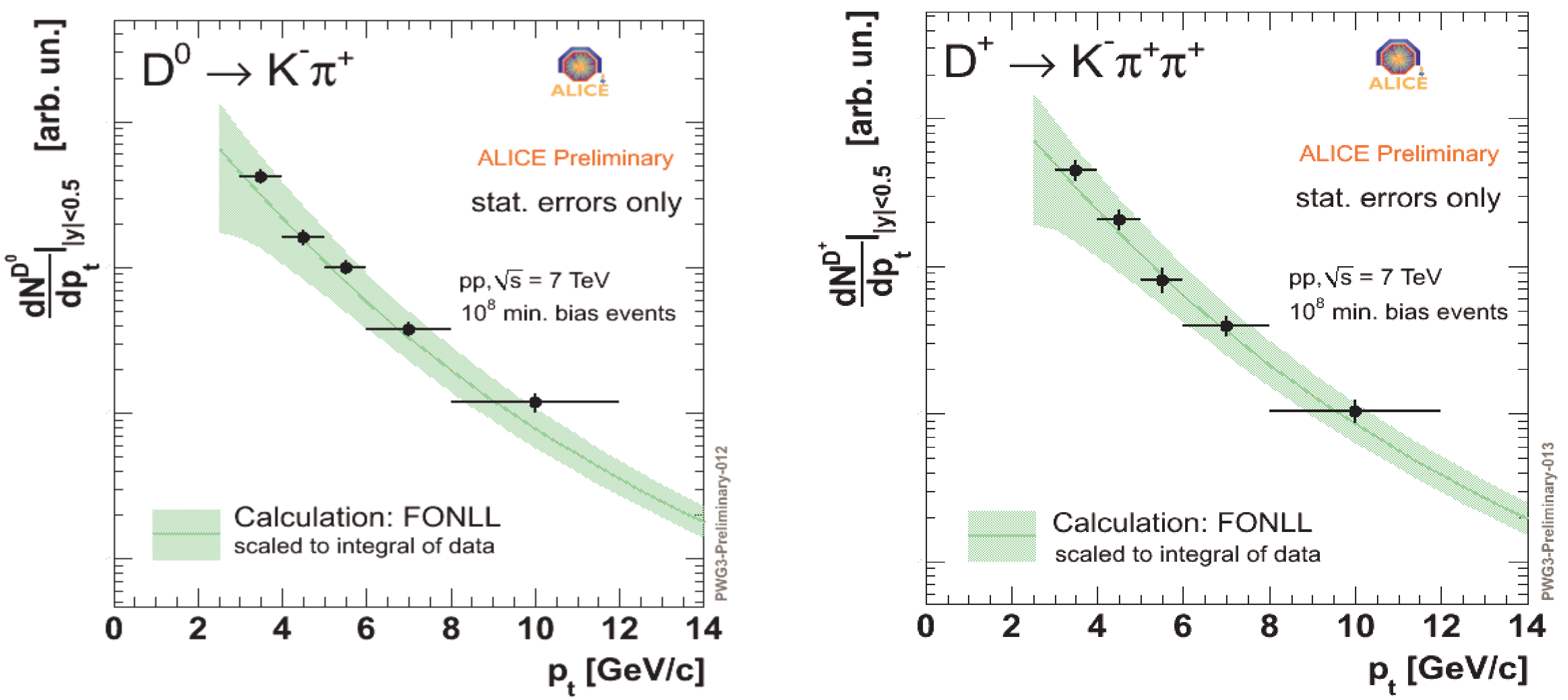


Figure 2: (Left) Total $c\bar{c}$ cross sections calculated using CTEQ6M. The solid red curve is the central value $(m, \mu_F/m, \mu_R/m) = (1.5\,\mathrm{GeV}, 1, 1)$. The green and blue solid curves are $(1.3\,\mathrm{GeV}, 1, 1)$ and $(1.7\,\mathrm{GeV}, 1, 1)$ respectively. The red, blue and green dashed curves correspond to $(1.5\,\mathrm{GeV}, 0.5, 0.5)$, $(1.5\,\mathrm{GeV}, 1, 0.5)$ and $(1.5\,\mathrm{GeV}, 0.5, 1)$ while the red, blue and green dotted curves are for $(1.5\,\mathrm{GeV}, 2, 2)$, $(1.5\,\mathrm{GeV}, 1, 2)$ and $(1.5\,\mathrm{GeV}, 2, 1)$. (Right) Uncertainty band formed from adding mass and scale uncertainties in quadrature.

Cortese today

D^0 and D^+ dN/dp_t

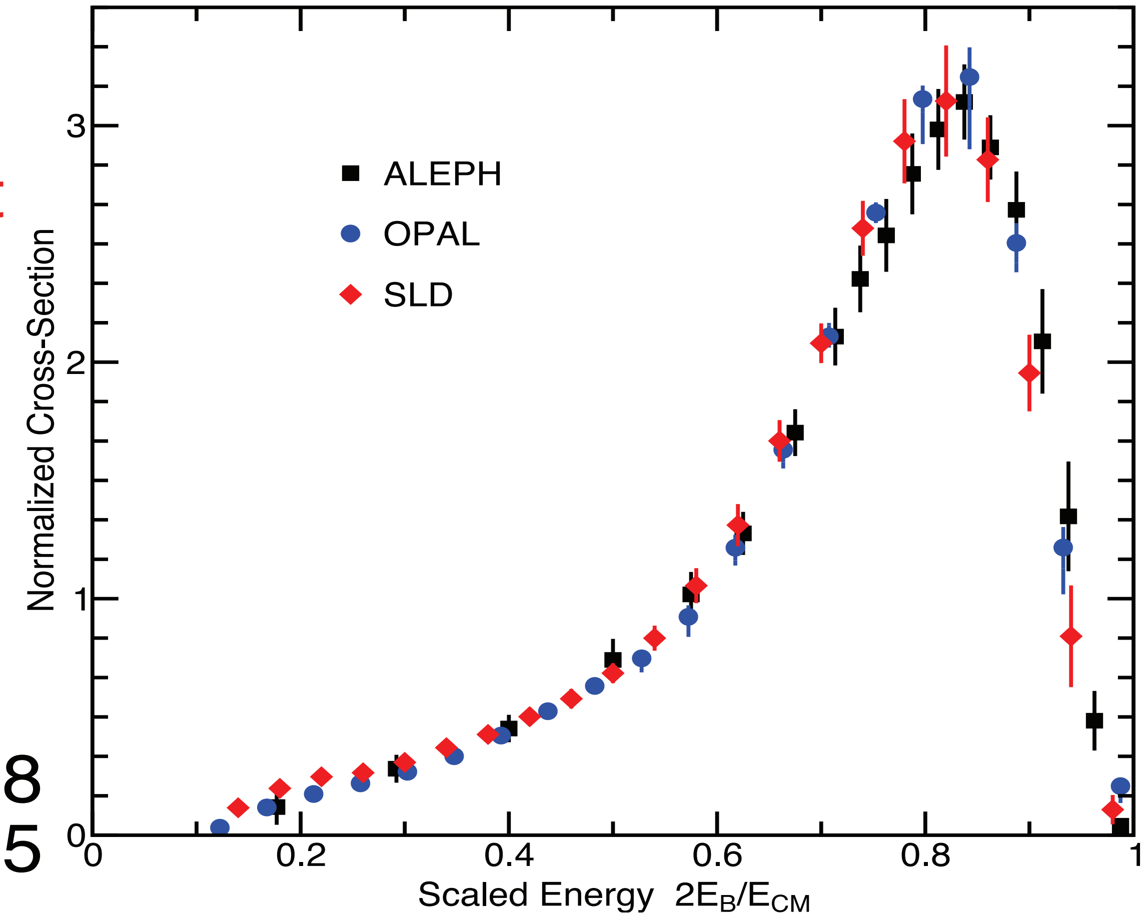


- Only statistical errors
- Shape compares well with pQCD (FONLL)

Purdue University, Jan. 6, 2011 Pietro Cortese 38

Inclusive (weakly decaying) B hadron FF

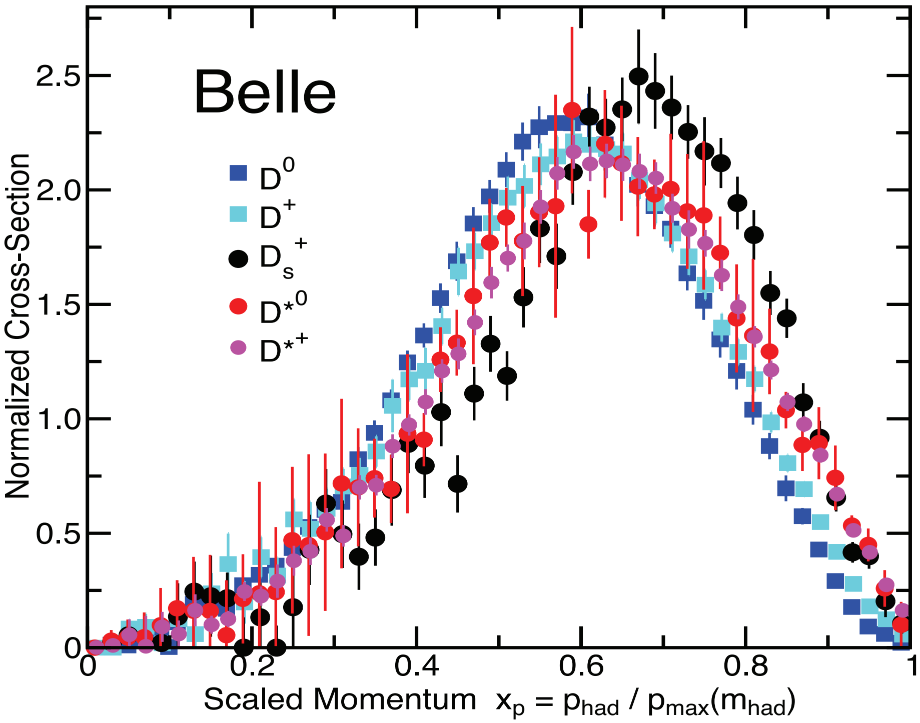
- estimate the energy of the B hadron
  - → use measured E/p, kinematic constraints
  - → achieve 10-20% resolution
- this is one of the best measured FFs
  - → covers the full kinematic range
  - → errors must be considered a shape envelope
  - → good precision on
    $\langle x_E \rangle_b = 0.702 \pm 0.008$
    $(x_E)_{max} = 0.835 \pm 0.005$

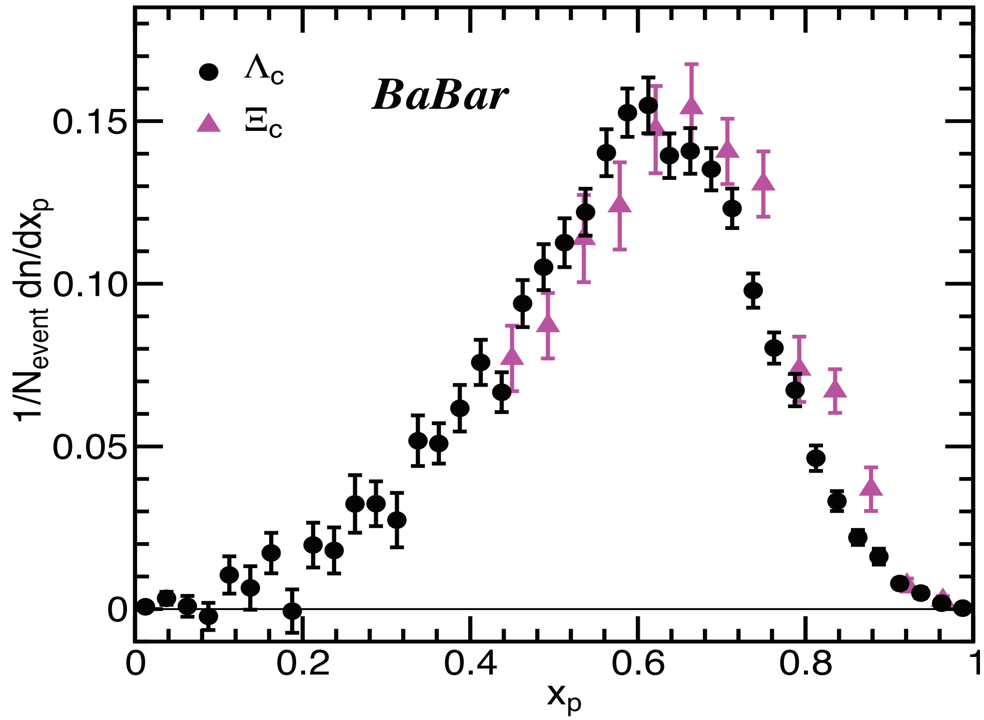


- FFs for a few excited states measured imprecisely
  - → estimate that primary spectrum has $\langle x_E \rangle \sim 0.722$

D meson, baryon fragmentation functions

- can measure some of the FFs precisely
  - → no B background when running at E_{CM}<10.57 GeV
  - → ...or for x>0.48, the kinematic limit for B decays





- the heavier particles have harder FFs
  - → shapes are similar for all mesons, also all baryons
  - → mesons have entries near x=1; heavier/excited mesons have more of them

open issues:

- heavy flavor polarization
- production at high rapidity (high x_F)
- correlated heavy flavor production (Λ_c)

also heavy flavor opportunities: Qiu on Tue

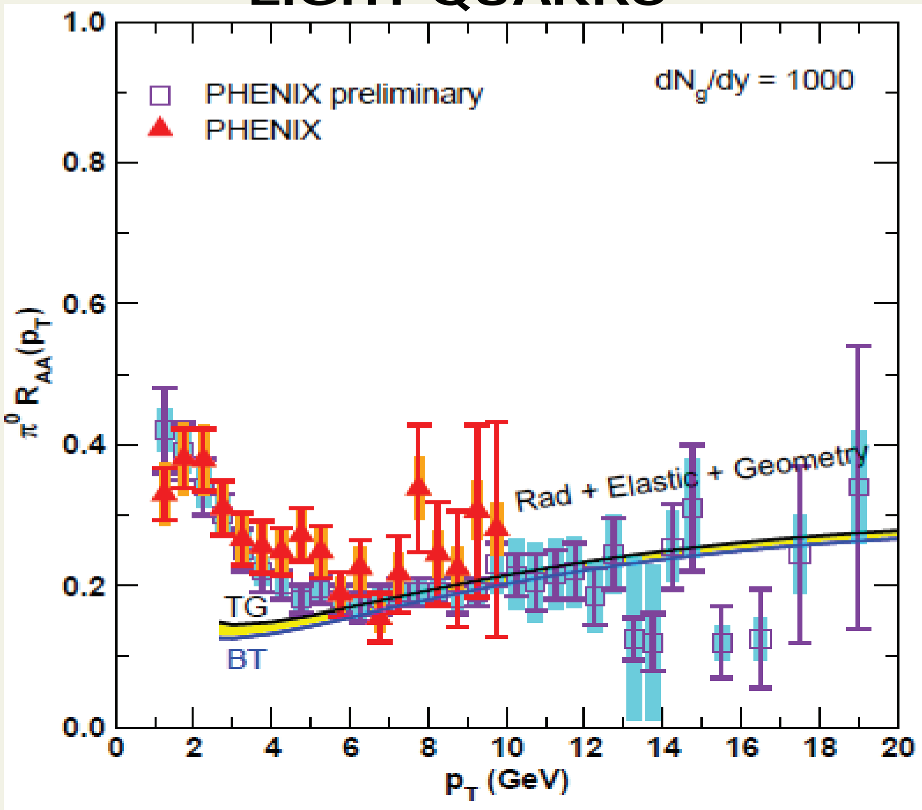
- better constrain the gluon spin contribution
- learn about parton correlations in proton (trigluon correlation)

In heavy-ion collisions, big puzzles

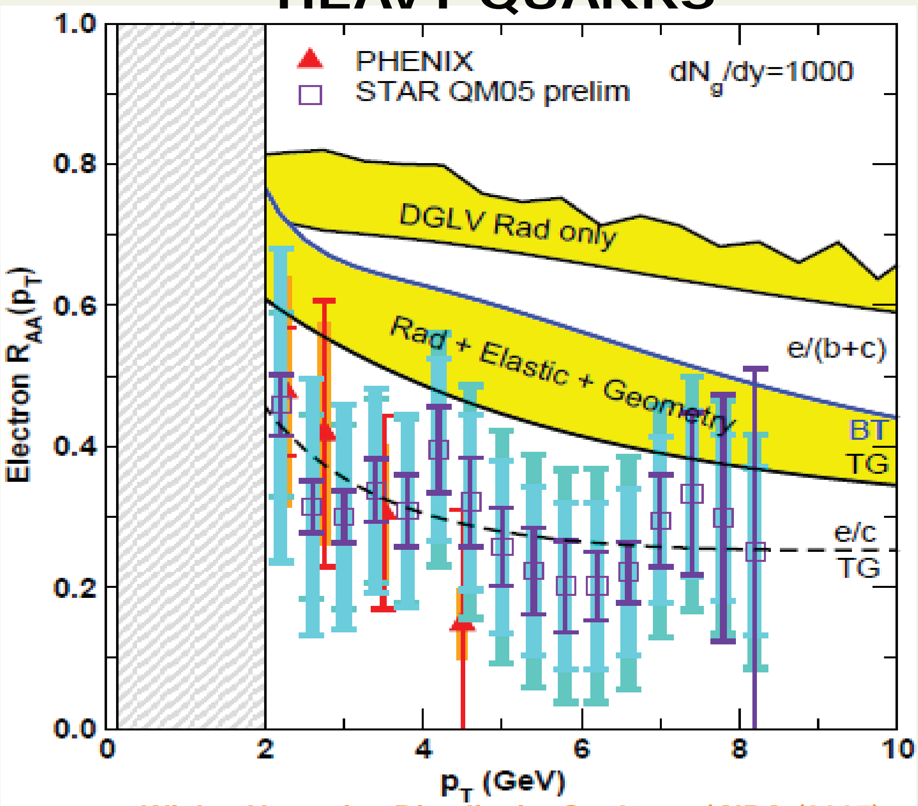
Buzzatti on Wed

Light and Heavy Quarks R_{AA}

LIGHT QUARKS



HEAVY QUARKS



Wicks, Horowitz, Djordjevic, Gyulassy / NPA (2007)

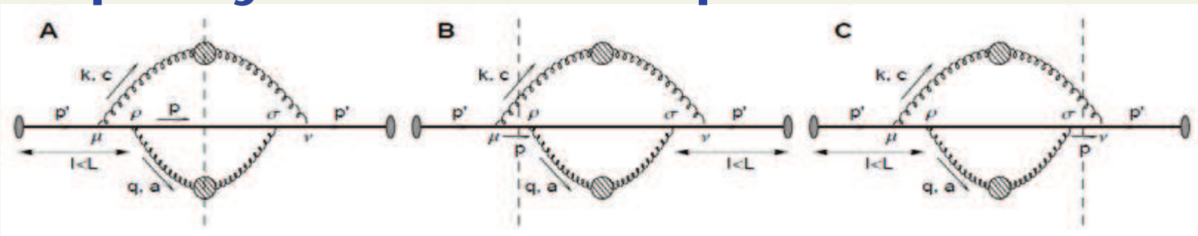
DGLV is not sufficient to explain electron data observed at RHIC

– need to increase Radiative Energy losses for charm and bottom quarks

Buzzatti on Wed

Opacity expansion: DGLV, MD

- **DGLV** (M. Djordjevic and M. Gyulassy, Nucl. Phys. A 733, 265, 2004)
  - Energy loss is obtained as a series in powers of opacity L/λ
  - Assumes static scattering centers, modeled by Yukawa potential
- **MD (Magdalena Djordjevic)** (Djordjevic, Heinz / Phys.Rev.Lett.101:022302,2008)
  - Dynamical model: includes recoils of scattering centers
  - New effective potential: $\frac{1}{(q^2+\mu^2)^2} \to \frac{1}{q^2(q^2+\mu^2)}$
  - No magnetic screening at order gT
  - Diagrams evaluated in Thermal Field Theory, only first order in opacity has been computed



- **Multigluon emission included via Poisson ansatz**

Buzzatti on Wed

JET Collaboration

Beyond first order in opacity

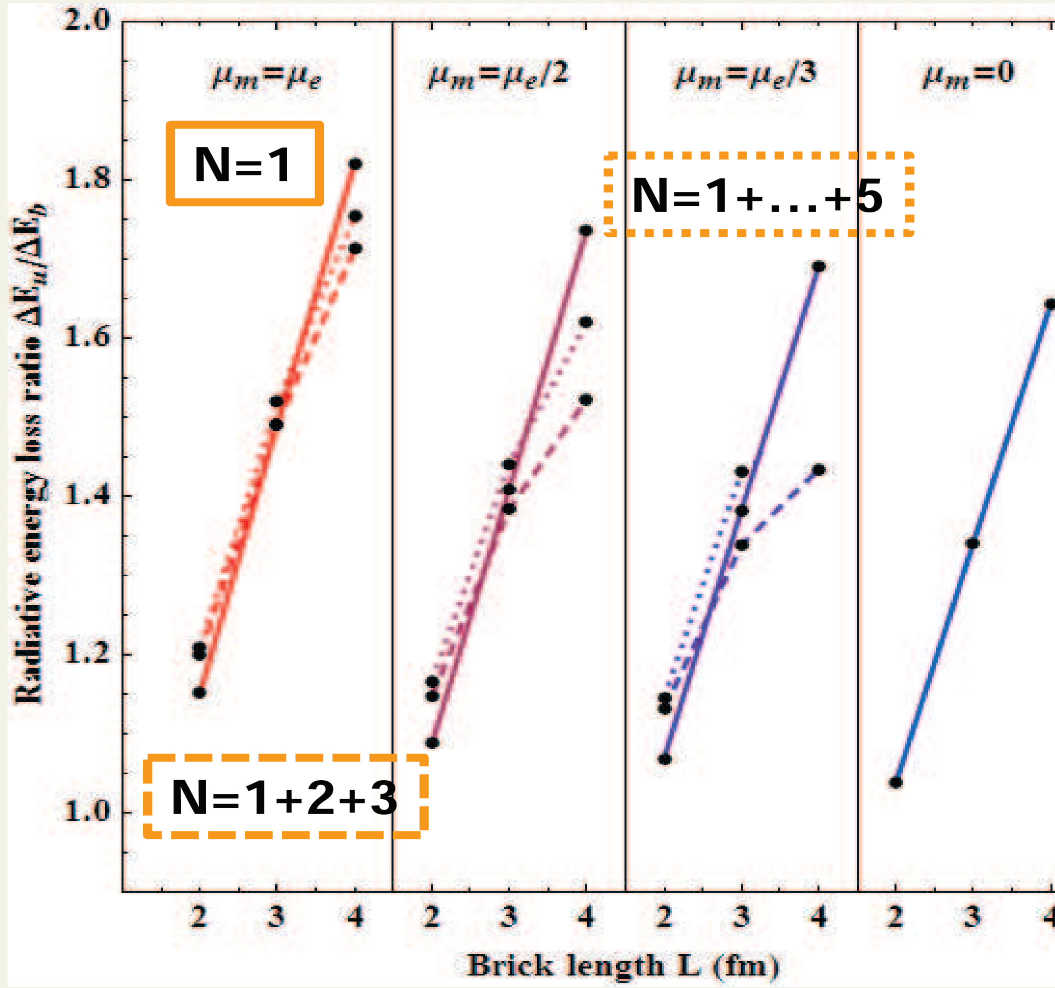
Interpolate between DGLV and MD with a new effective potential

$$\frac{1}{(q^2+\mu^2)^2} \xleftarrow{DGLV} \frac{1}{(q^2+\mu_m^2)(q^2+\mu_e^2)} \xrightarrow{MD} \frac{1}{q^2(q^2+\mu^2)}$$

It is possible to study the limit $\mu_m \to 0$ for values of $\mu_m \gtrsim \mu_e/3$

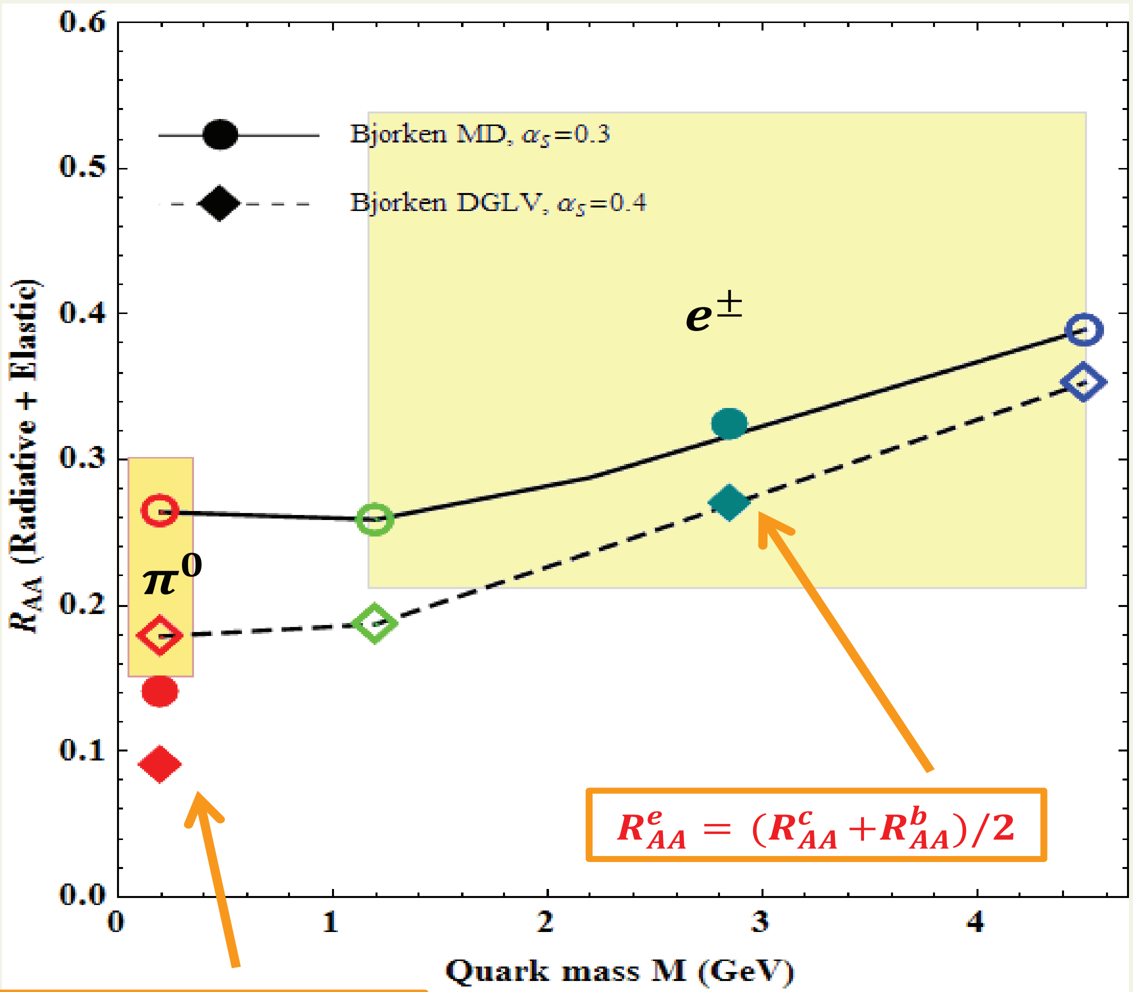
- The mean free path $\frac{1}{\lambda} = \int d\mathbf{q} \frac{d\sigma}{dq} \rho$ is divergent for μ_m=0

$\left(\frac{\Delta E_u}{\Delta E_b}\right)$ ratio improves for N>1 and $\mu_m \to 0$, but likely not enough.



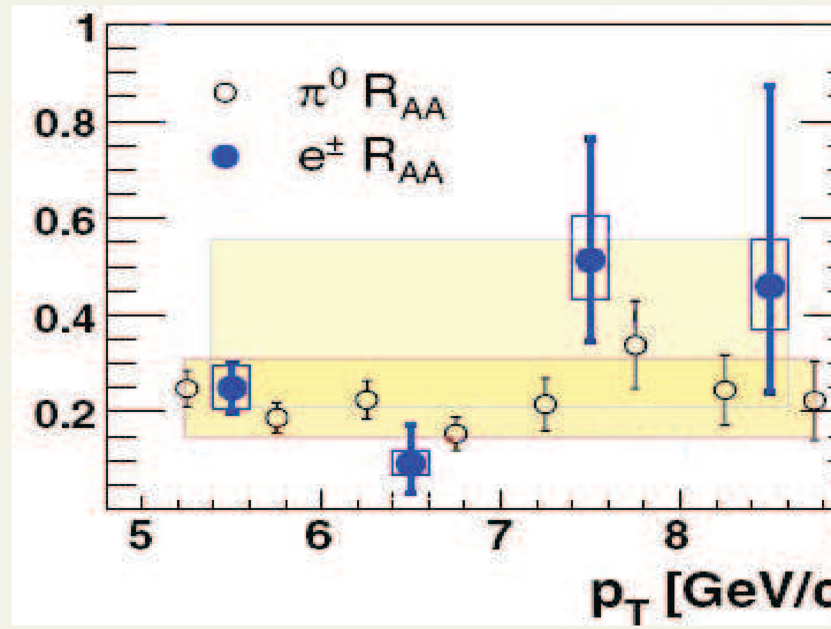
Alessandro Buzzatti – Columbia University

Schematic R_{AA}



$R^{\pi}_{AA} = (R^l_{AA} + R^g_{AA})/2$

PHENIX : PRL98, 172301 (2007)



e± data is extremely poor resolution on c and b quenching separately

Conclusion:

There is not much wiggle room left in pQCD medium induced Energy Loss to resolve the current Light/Heavy Puzzle

Modulo possible exception see Andrej Leonodiv's talk HP10 (but this does not solve pQCD's inability to account for eta/s ~0.1)

However, even strongly coupled AdS Holography (top down conformal nor bottom up nonconformal) Cannot eliminate mass dependence

DE(bottom) < DE(charm) !

Therefore the heavy quark puzzle remains unsolved from both Ends.

1) Maybe electron data are wrong ?? or maybe we underestimate True systematic errors in this complex observable

2) Highest priority (in my opinion) at both RHIC and LHC Is to measure B and D nuclear modification up to highest pT

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concerted theory effort to improve energy loss formalism

oration http://jet.lbl.gov/

Topical Collaboration on

Jet and Electromagnetic Tomography

of Extreme Phases of Matter in Heavy-ion Collisions

JET Collaboration

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The scientific goal of the JET Collaboration is:

- extend the theoretical framework for jet-medium interaction beyond soft and collinear approximations and thereby reduce uncertainties intrinsic to the current theoretical studies
- develop new and powerful Monte Carlo algorithms for jet propagation and evolution inside a dynamic medium
- implement in the jet-medium interaction a realistic space-time evolution of the bulk medium as described by a combination of viscous hydrodynamics with parton and hadron cascades
- carry out systematic phenomenological studies of experimental data on single hadron (including heavy flavors) and photon spectra, multi-hadron and γ-hadron correlation and jet shape

The JET Collaboration will also coordinate with broader joint theory-experiment efforts to develop strategies and computational tools for the phenomenological interpretation of experimental data on hard and EM signals, and provide training of graduate students and postdoctoral fellows with annual summer schools on theoretical techniques that are required to carry out many of the proposed studies.

To subscribe to future news letters and announcements from the JET Collaboration, please send email to: jet-request@lists.lbl.gov with subject: subscribe or go to https://lists.lbl.gov/sympa/info/jet to register and manage your subscription.

Number of visits since Feb., 2010
3,390

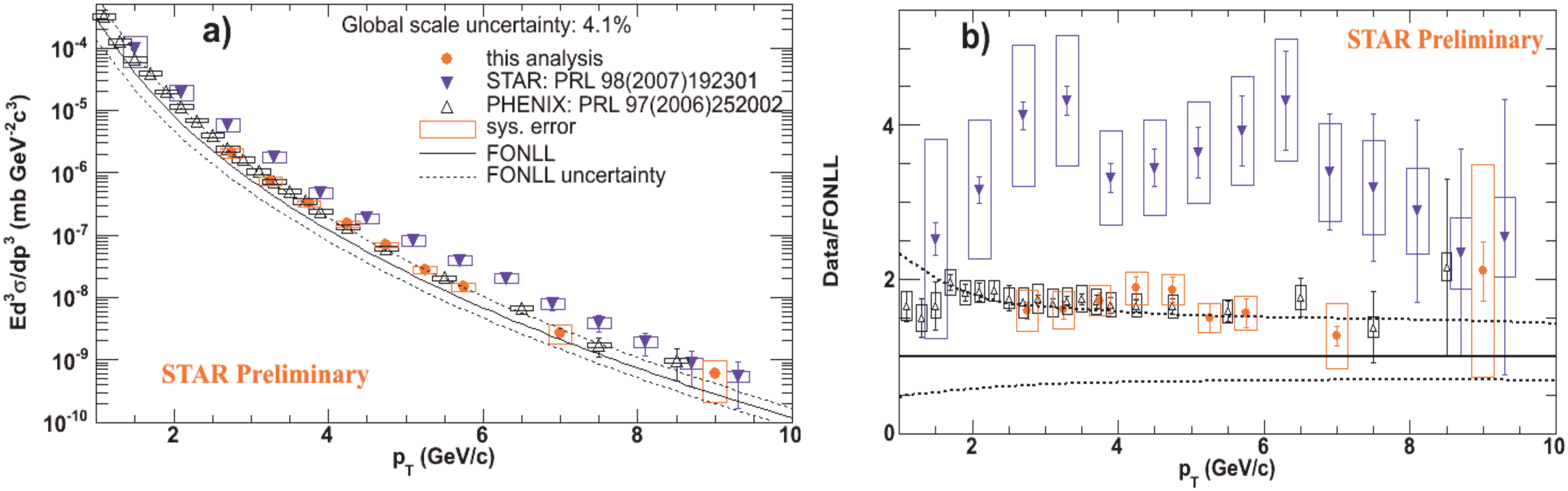
News:

Theory position in Department of Physics at the University of Colorado , Boulders

MUST redo R_{AA} now !   Wang on Tue

Comparison with the Published NPE Results

Wei Xie, HP2010 talk



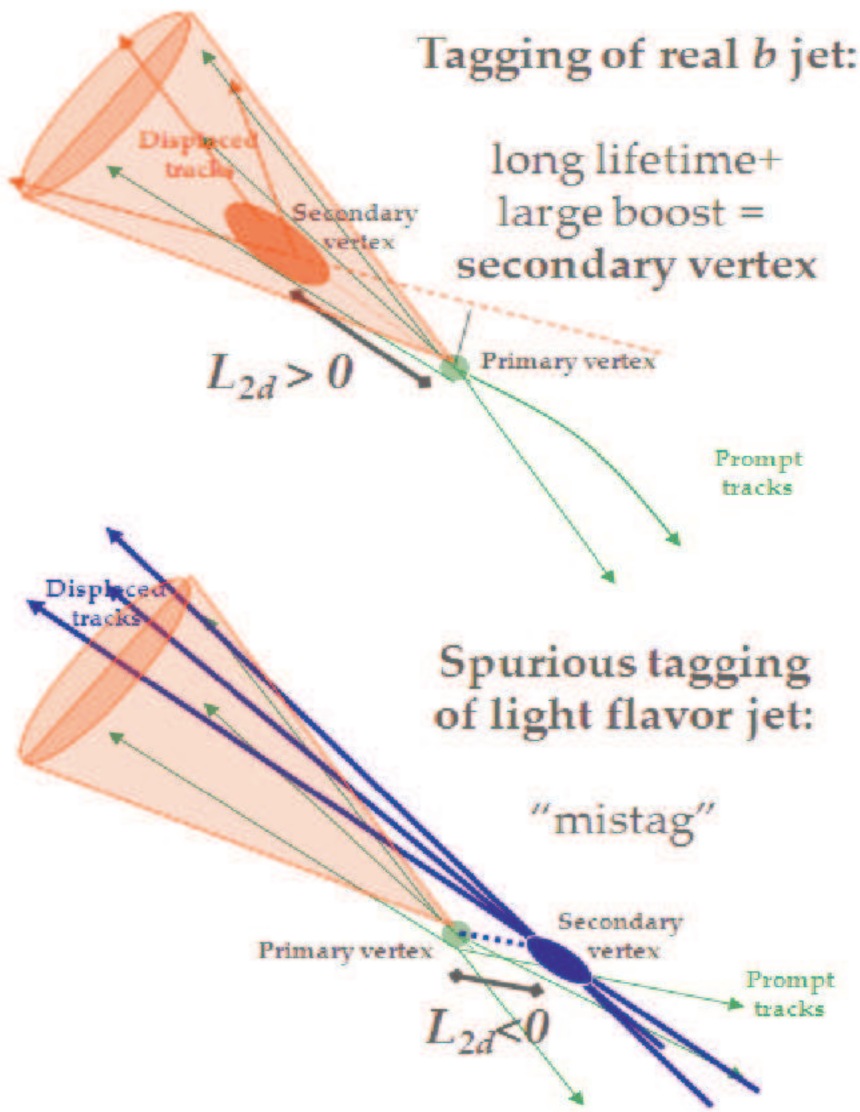
STAR and PHENIX NPE result in 200GeV p+p collisions

✓ **consistent within errors at p_T > 2.5 GeV/c**

STAR High p_T NPE results are consistent with FONLL in 200GeV p+p collisions

See Wenqin Xu's talk for details on e_B x-section!   15

Jones on Wed

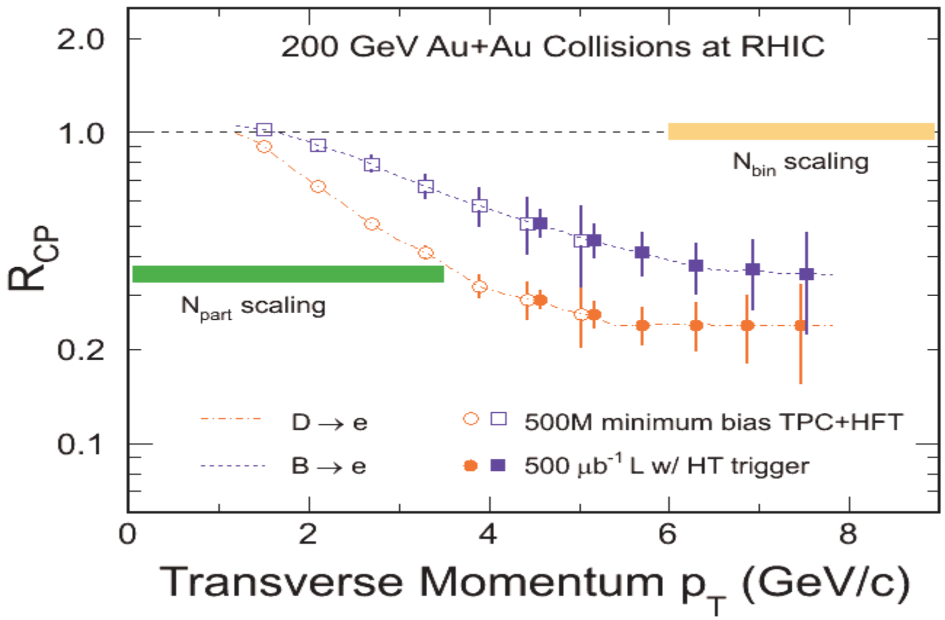


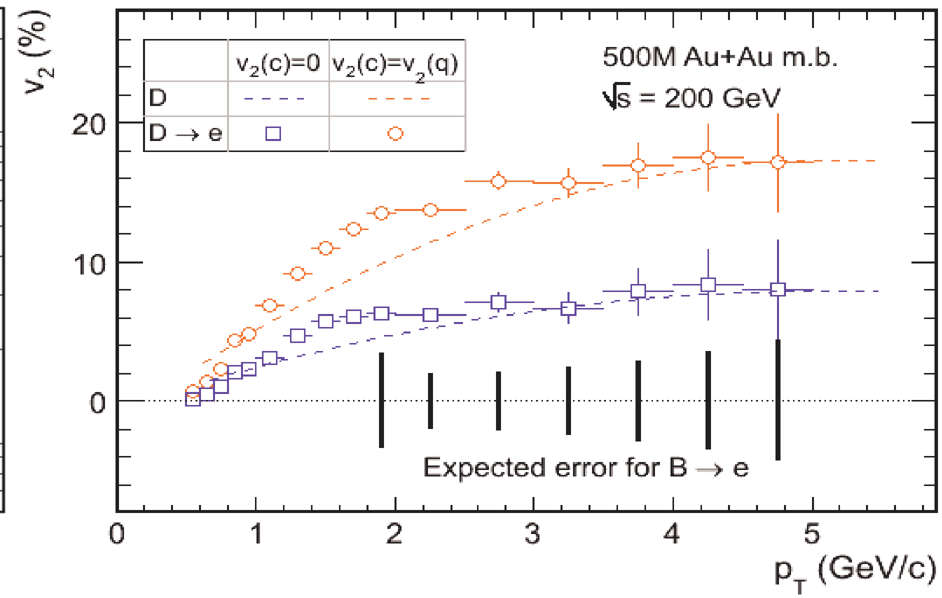
- Heavy flavor jets:
  - vertices with positive 2d decay length
- Light flavor jets:
  - equal numbers of positive and negative 2d decay length vertices
  - not quite... correct for:
    - K^0_S and Λ decays
    - nuclear interactions

January 6, 2011 18

STAR HFT coming Dong today

Statistical Projections on e_B Spectra / v_2





Curves: H. van Hees *et al*. Eur. Phys. J. **C61**, 799(2009).

➢ (B→e) spectra obtained via the subtraction of charm decay electrons from inclusive NPEs:

no model dependence, reduced systematic errors.

PHENIX VTX installed, FVTX coming

Nouicer

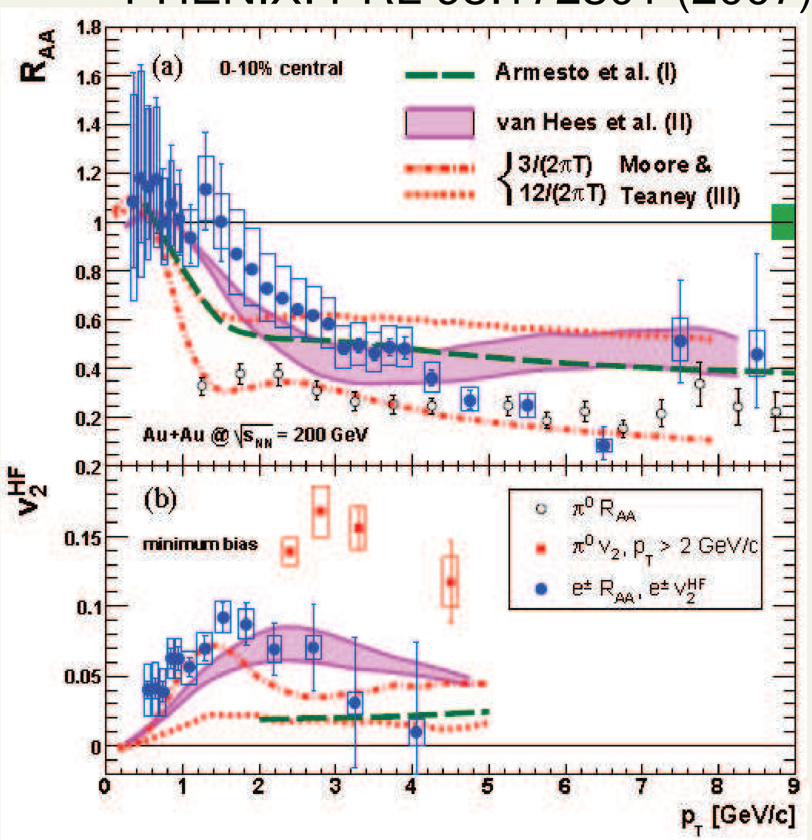
today

VTX Motivation

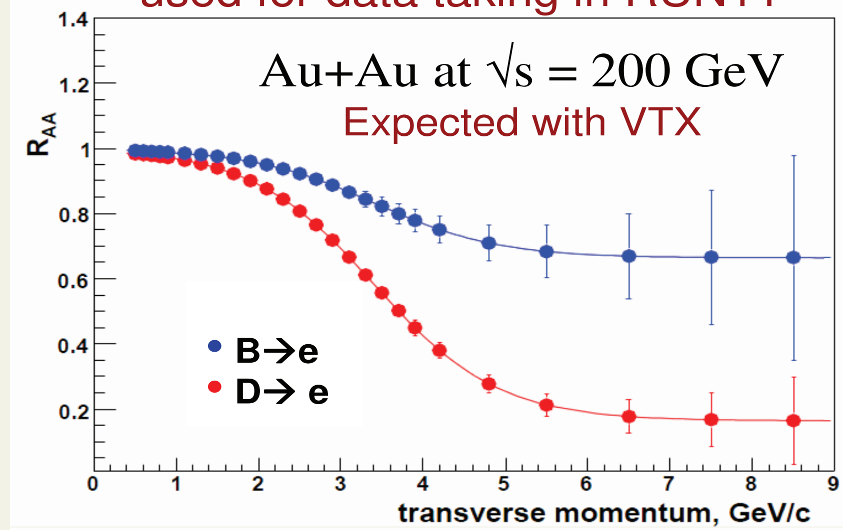
m_{charm}= 1.5 GeV, m_{bottom}= 5 GeV

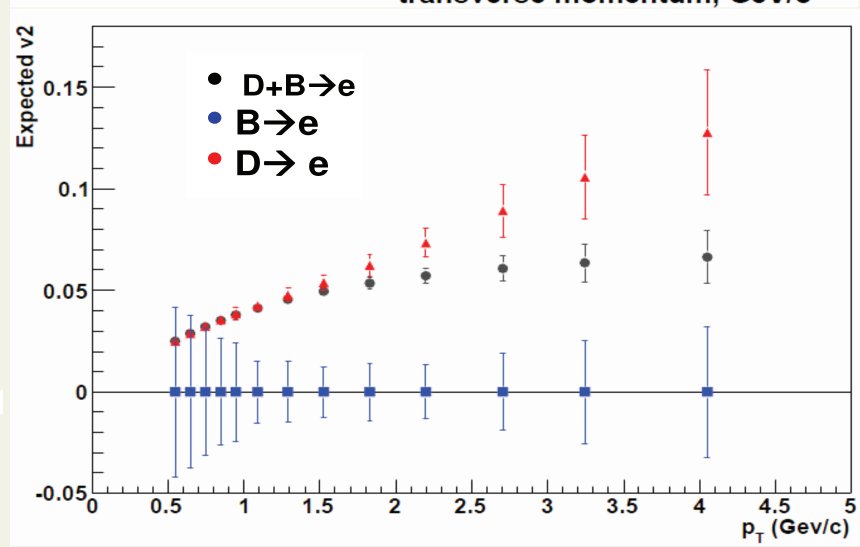
Present

PHENIX: PRL 98:172301 (2007)



Assumption here: Full 8 weeks used for data taking in RUN11

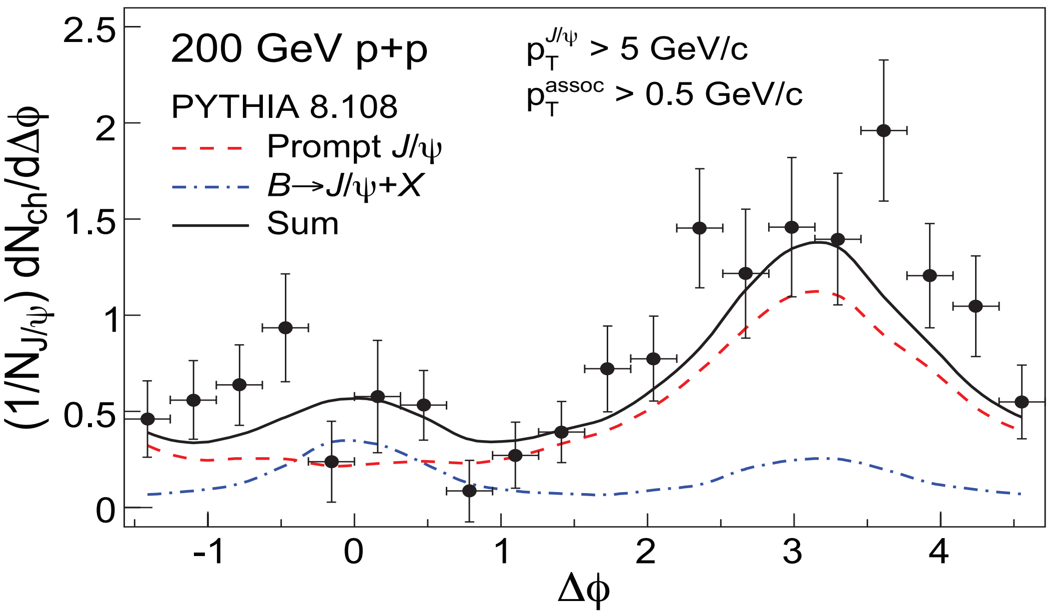




- VTX can separately measure v_2 and R_{AA} of b→e and c→e

Rachid Nouicer-BNL Heavy Quark Workshop 2010 18

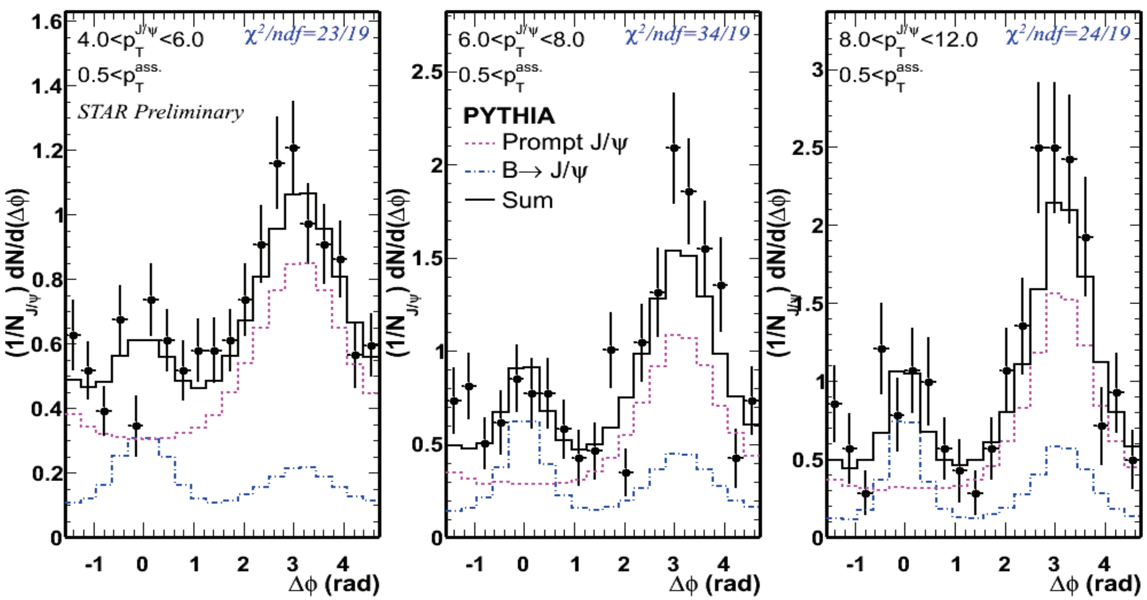
Constraining bottom contribution



Previous result:

- No significant near side J/ψ-hadron azimuthal angle correlation
- Correlation show low B contribution (13 ± 5) %

STAR, PRC80, 041902(R), 2009



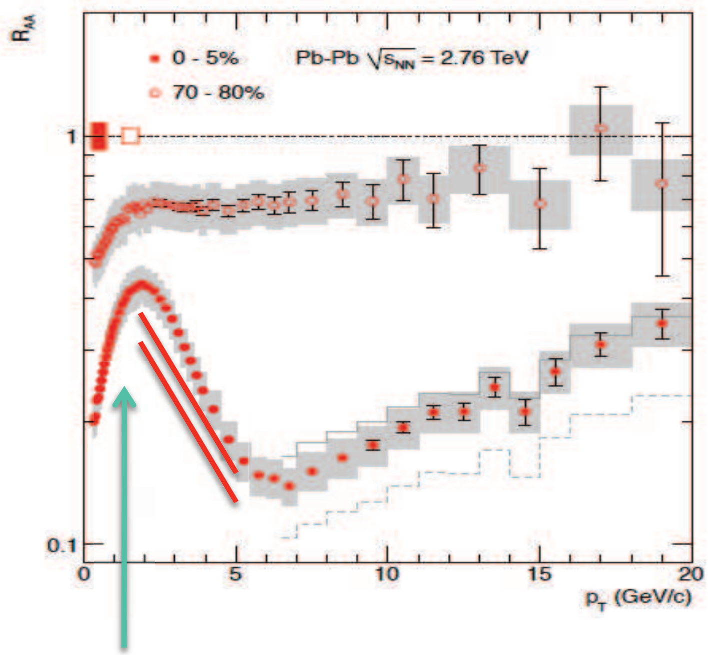
Run 9:

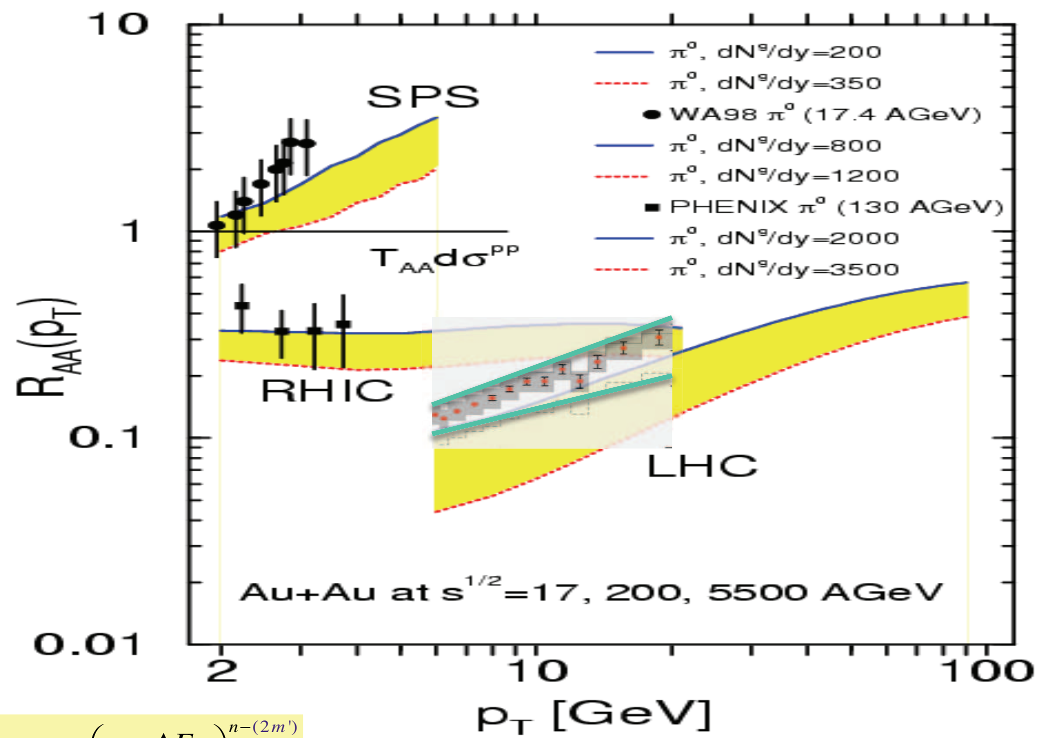
- Higher statistics
- Divide into 3 p_T bins

Vitev on Tue

I. Leading Particle Suppression at the LHC

K. Amadot et al, (2011)





IV, (2005)

$$\text{Observable} \sim \frac{1}{E_T^n},\ R_{AA}^{Observable} \approx \left(1-\frac{\Delta E_T}{E_T}\right)^{n-(2m')}$$

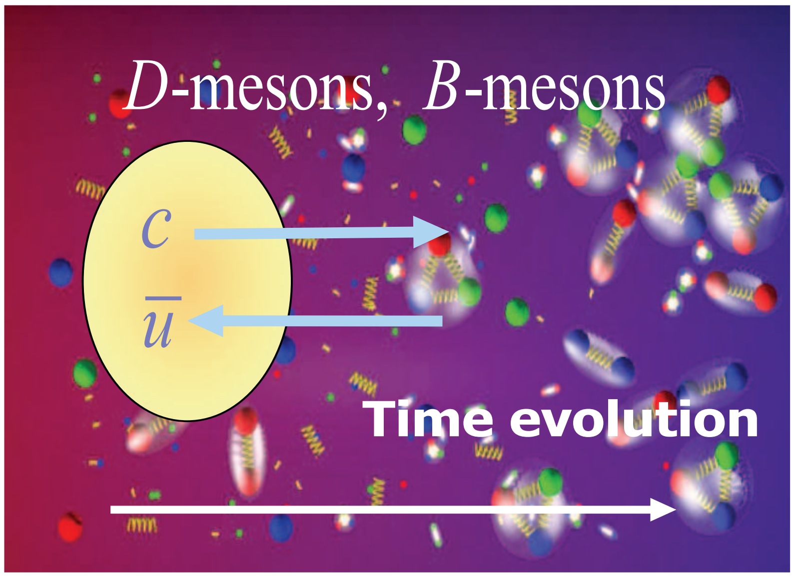
I.V., M. Gyulassy (2002)

- The p_T dependence and magnitude of the ~ suppression is consistent with predictions form 2002 and 2005

Vitev on Tue

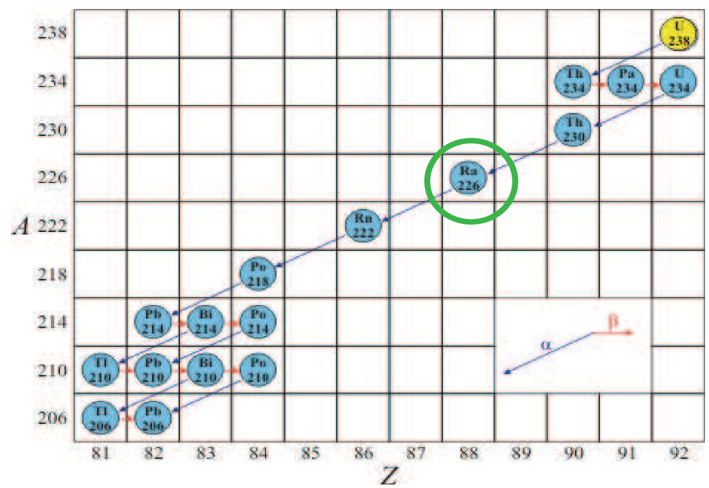
II. Collisional Dissociation of D / B Mesons

- An alternative



Simultaneous fragmentation and dissociation call for solving a system of coupled equations

- Example: radioactive decay chain



$$\frac{dN_i}{dt} = \lambda_{i-1} N_{i-1} - \lambda_i N_i$$

- Both emulate energy loss and lead to suppression of the final observable spectra

Adil, IV (2007)

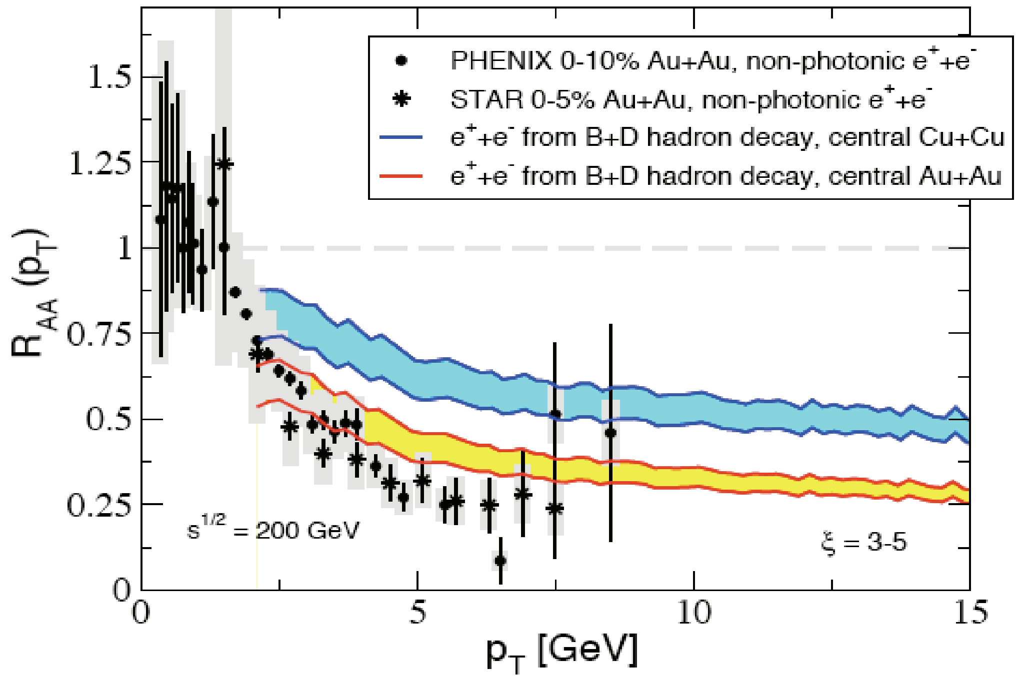
Vitev on Tue

VI. RHIC Results on Non-photonic Electrons

- Employ a full simulation of the D and B meson semi-leptonic decay,. PYTHIA subroutin.e

T. Sjostrand et al (2006)

- The predicted suppression is still slightly smaller than the quenching of inclusive particles
- It is compatible with the experimental data within the error bars
- Improved direct measurements are needed to pinpoint the magnitude and relative contribution of B/D



R. Sharma et al. (2010)

Another approach - Fokker-Planck/Langevin $N_{coll} \gg 1$

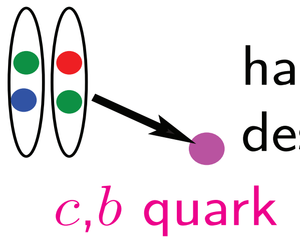
- **totally unlike $N_{coll} \sim few$ in DGLV/MD**

- **come in many variants and flavors**

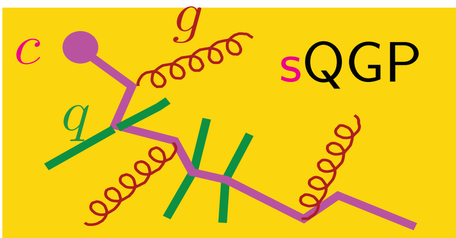
- **gives up on light partons (no cross-check at high pT)**

van Hees on Tue

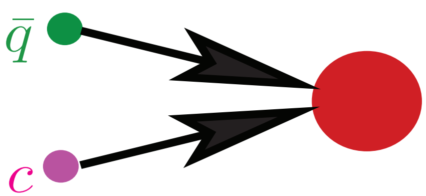
Heavy Quarks in Heavy-Ion collisions



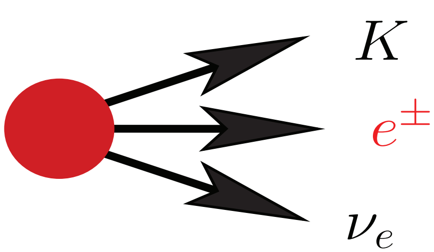
hard production of HQs
described by PDF's + pQCD (PYTHIA)



HQ rescattering in QGP: Langevin simulation
drag and diffusion coefficients from
microscopic model for HQ interactions in the sQGP



Hadronization to D,B mesons via
quark coalescence + fragmentation
V. Greco, C. M. Ko, R. Rapp, PLB **595**, 202 (2004)



semileptonic decay $\Rightarrow$
"non-photonic" electron observables
$R_{AA}^{e^+e^-}(p_T)$, $v_2^{e^+e^-}(p_T)$

$2\pi TD \approx 1.5$ **Young on Wed**

Quarkonium dynamics in sQGP as a stochastic process

When M_{HQ} is sufficiently larger than T, the dynamics of each heavy quark can be described by

$$\frac{dp_i}{dt} = -\eta p_i + \xi_i - \nabla_i U, \quad (1)$$

where

$$\langle \xi_i(t)\xi_j(0)\rangle = \kappa\delta_{ij}\delta(t). \quad (2)$$

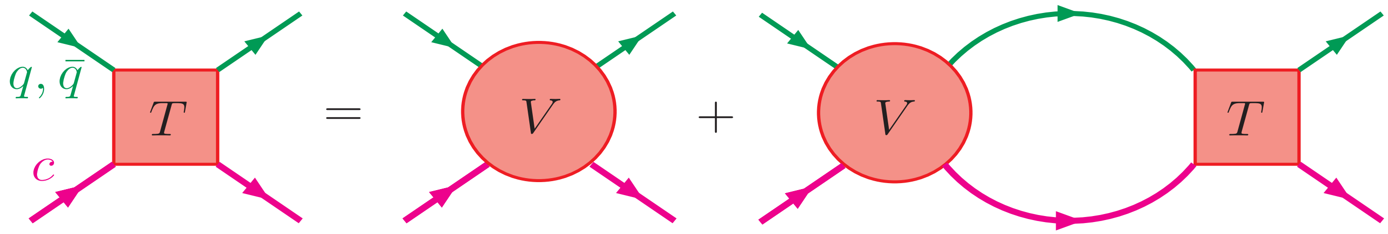
Requiring thermalization to temperature T yields the Einstein relation between noise and dissipation:

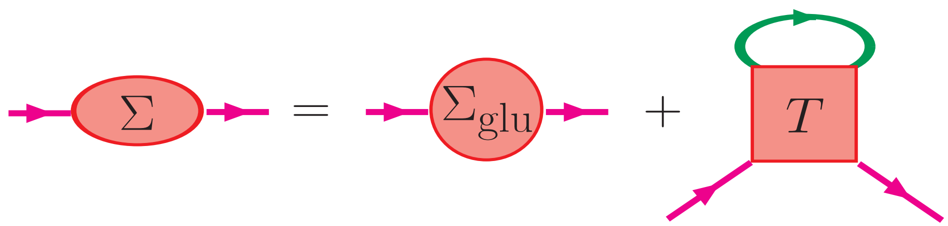
$$\eta = \frac{\kappa}{2MT}. \quad (3)$$

van Hees on Tue

T-matrix

- Brueckner many-body approach for elastic Qq, $Q\bar{q}$ scattering





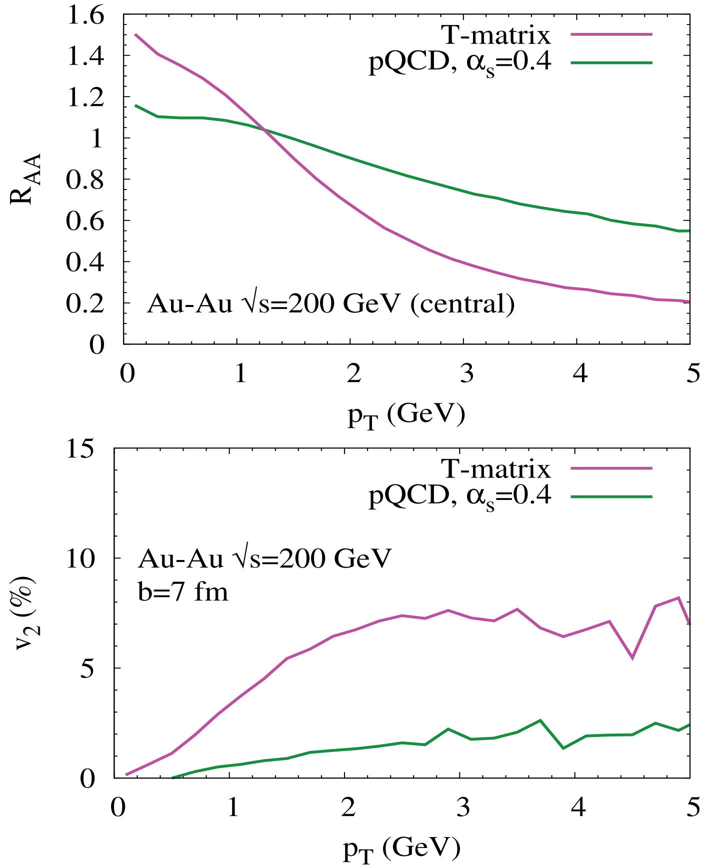
- reduction scheme: 4D Bethe-Salpeter $\rightarrow$ 3D Lipmann-Schwinger
- S- and P waves
- same scheme for light quarks (self consistent!)
- Relation to invariant matrix elements

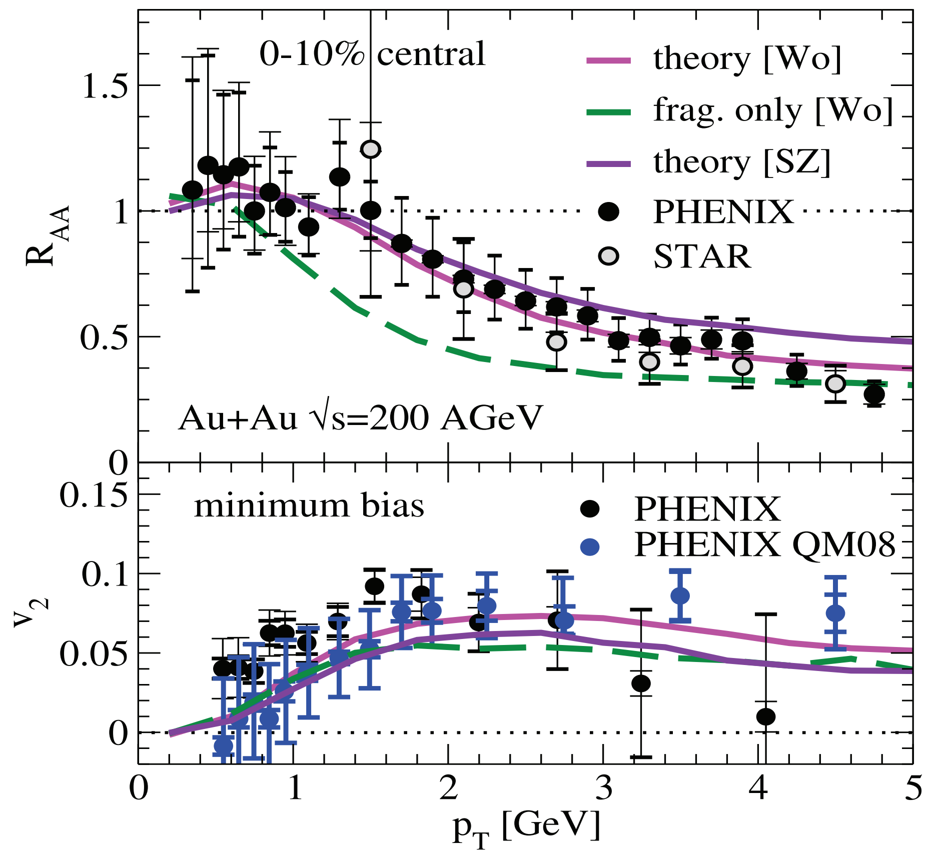
$$\sum |\mathcal{M}(s)|^2 \propto \sum_q d_a \left(|T_{a,l=0}(s)|^2 + 3|T_{a,l=1}(s)|^2 \cos\theta_{\text{cm}} \right)$$

van Hees on Tue

Non-photonic electrons at RHIC

- same model for bottom
- quark coalescence+fragmentation $\to D/B \to e + X$





- coalescence crucial for description of data
- increases both, R_{AA} and v_2 $\Leftrightarrow$ "momentum kick" from light quarks!
- "resonance formation" towards T_c $\Rightarrow$ coalescence natural [Ravagli, Rapp 07]

HTL pQCD noise

Caron-Huot on Tue

Result

$$\kappa = \frac{C_H g^4 T^3}{18\pi} \left\{ \left(N_c + \frac{N_f}{2}\right) \left(\ln \frac{2T}{m_D} + \xi\right) + \frac{N_f \ln 2}{2} + \frac{N_c m_D}{T} C + \mathcal{O}(g^2) \right\}$$

Braaten& Thoma
Svetitsky
Moore& Teaney

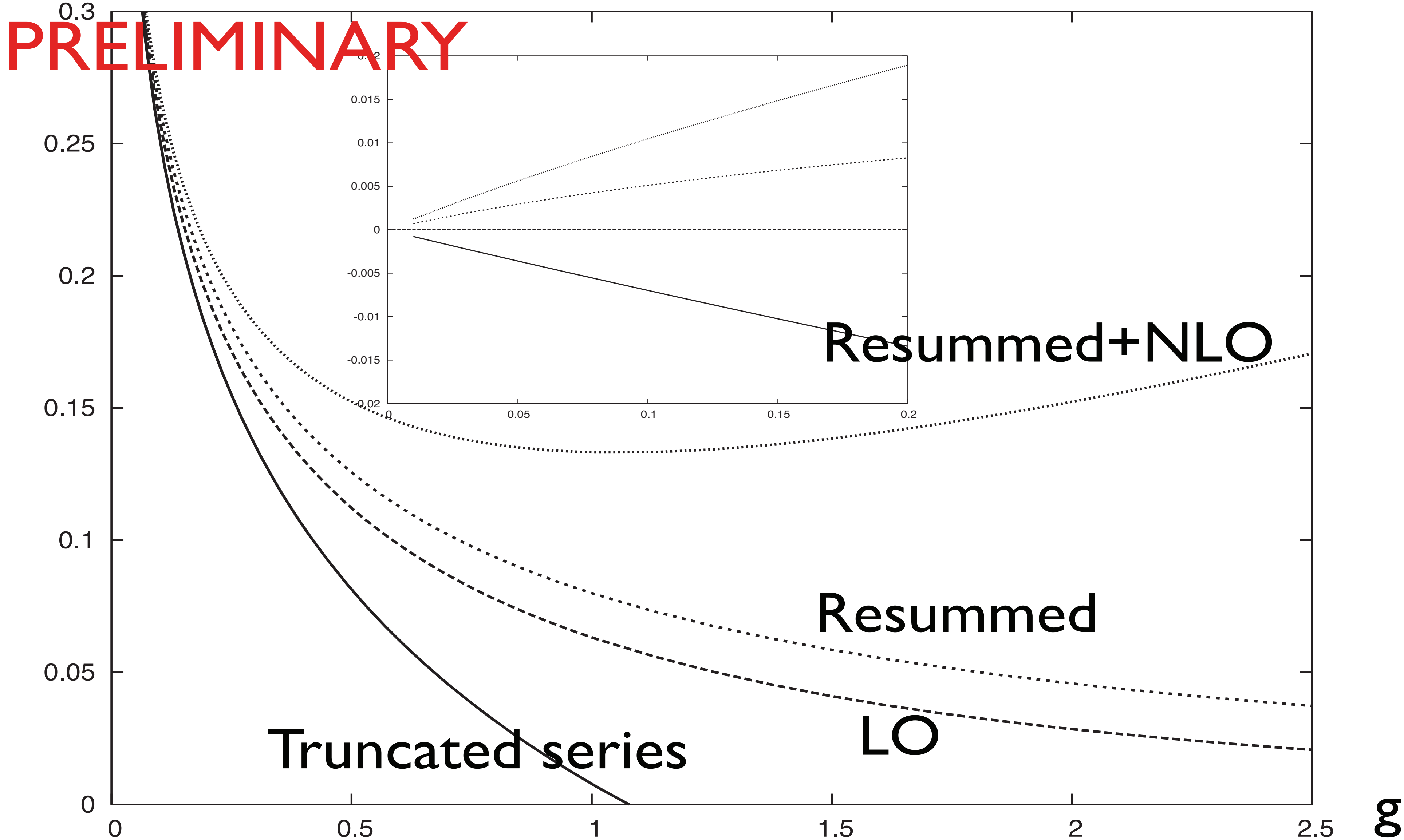
Our computation

$C \approx 2.3302$

Tuesday, January 4, 2011

Partial resummation

$$\kappa \approx 0.1 g_s^3 T^3$$
$$(\alpha_s(2\pi T) \sim 0.2 \div 0.4)$$



running α_s + reduced Debye $\mu_D^2 \to \sim 0.2\mu_D^2$ **Gossiaux on Tue**

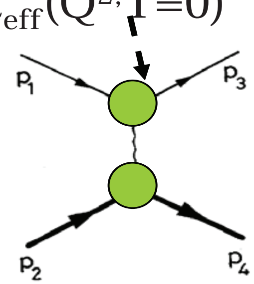
Collisional E loss : The Peshier – Gossiaux – Aichelin approach (2008)

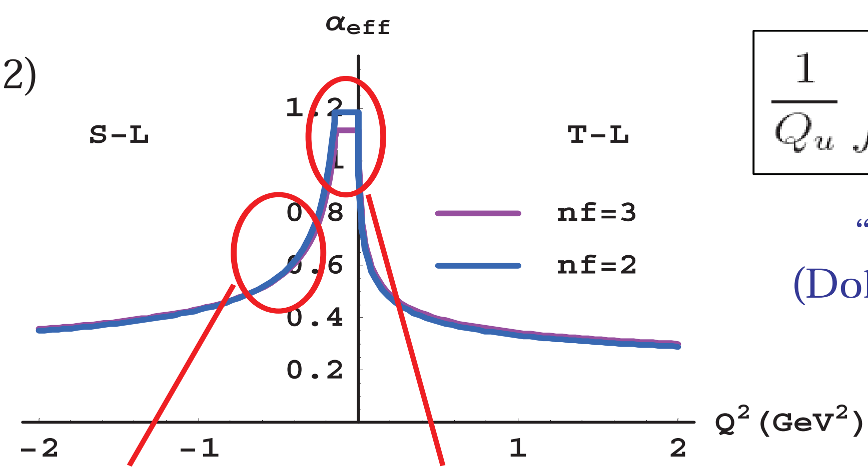
Motivation: Even a fast parton with the largest momentum P will undergo collisions with moderate q exchange and large $\alpha_s(Q^2)$. The running aspect of the coupling constant has been "forgotten/neglected" in most of approaches

Effective $\alpha_s(Q^2)$

(Dokshitzer 95, Brodsky 02)

$\alpha_{eff}(Q^2, T=0)$





$$\frac{1}{Q_u}\int_{|Q^2|\le Q_u^2} dQ\,\alpha_s(Q^2) \approx 0.5$$

"Universality constrain" (Dokshitzer 02) helps reducing uncertainties:

Large values for intermediate momentum-transfer => larger cross section

IR safe. The detailed form very close to $Q^2=0$ is not important does not contribute to the energy loss

A model; not a renormalizable theory

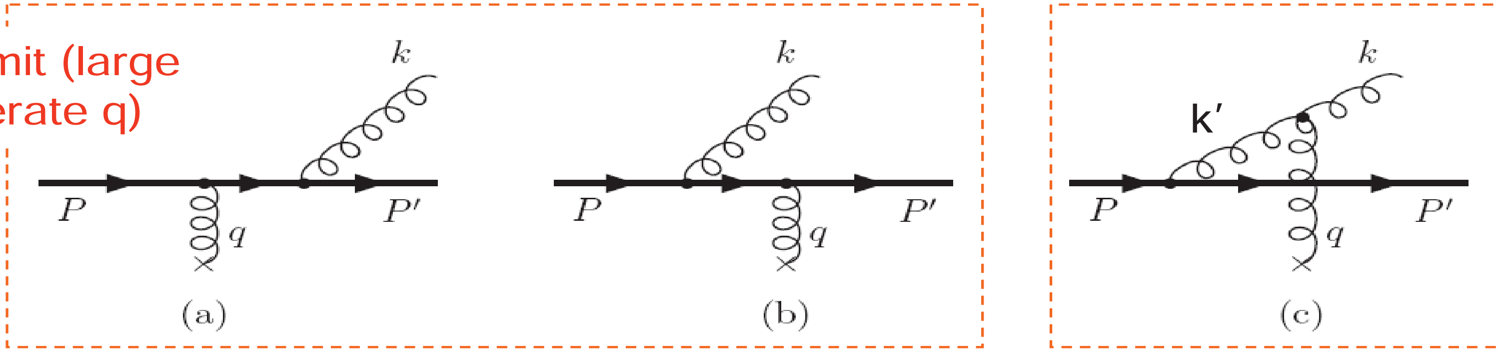
Heavy quarks production in heavy ions collisions 02

Gossiaux on Tue

Basic (massive) Gunion-Bertsch

Radiation α deflection of current (semi-classical picture)

Eikonal limit (large E, moderate q)



Dominates as small x as one "just" has to scatter off the virtual gluon k′

$$\omega \frac{d^3\sigma_{\rm rad}^{x\ll 1}}{d\omega d^2k_\perp dq_\perp^2} = \frac{N_c\alpha_s}{\pi^2}(1-x) \times \frac{J_{\rm QCD}^2}{\omega^2} \times \frac{d\sigma_{\rm el}^{Qq}}{dq_\perp^2}$$

with

$$\frac{J_{\rm QCD}^2}{\omega^2} = \left(\frac{\vec{k}_\perp}{k_\perp^2 + x^2M^2 + (1-x)m_g^2} - \frac{\vec{k}_\perp - \vec{q}_\perp}{\left(\vec{k}_\perp - \vec{q}_\perp\right)^2 + x^2M^2 + (1-x)m_g^2} \right)^2$$

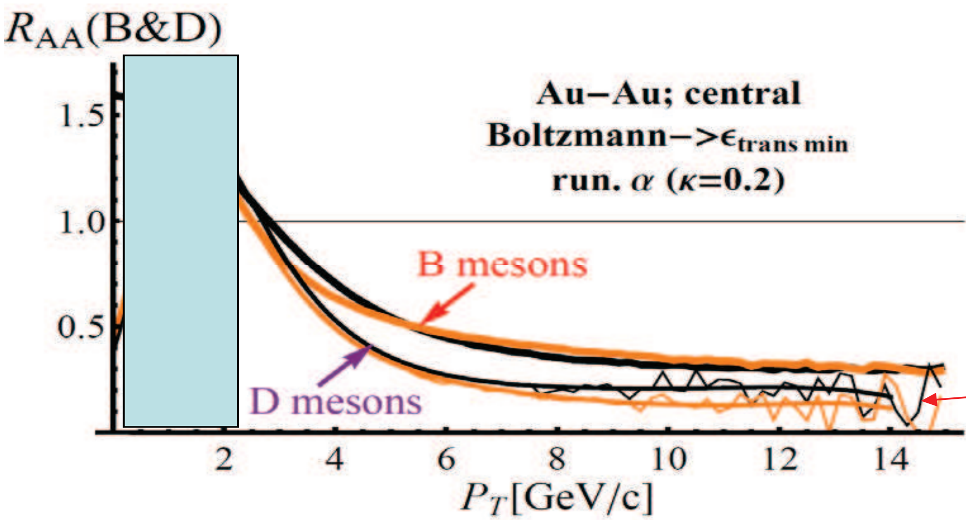
Gluon thermal mass ~2T (phenomenological; not in BDMPS)

Quark mass

Both cures the colinear divergences and influence the radiation spectra

Heavy quarks production in heavy ions collisions 07

D & B meson: RHIC II (radiat + collisional)



Collis., rate x 2

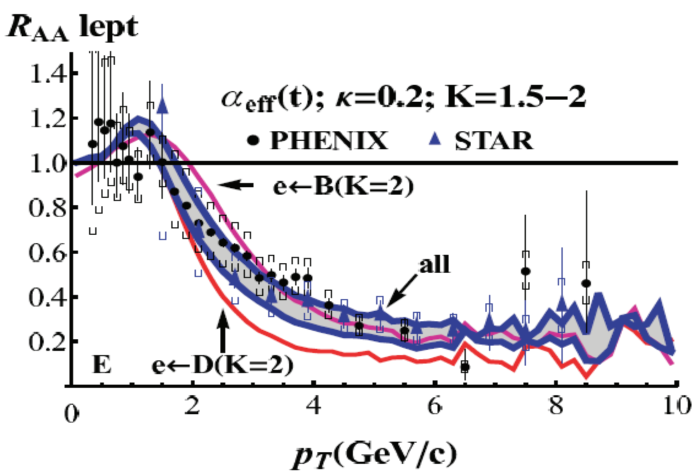
Collis. + Rad (LPM), rate x 0.6

α_s(rad)=0.3

… some small deviations for D spectra at large p_T

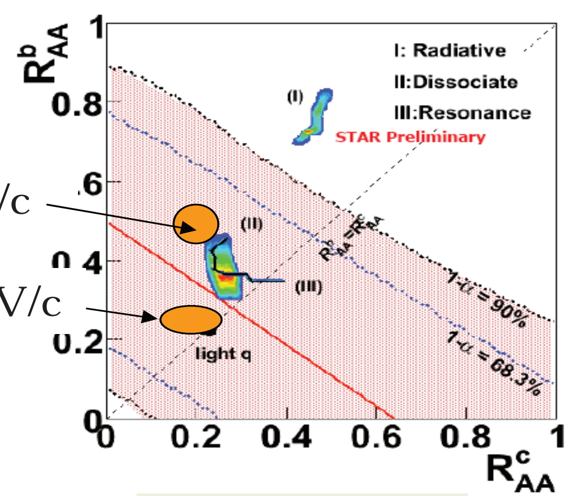
Z. Xu (sqm08)

PRC 78 (fig 9)



p_T=5GeV/c

p_T=10GeV/c



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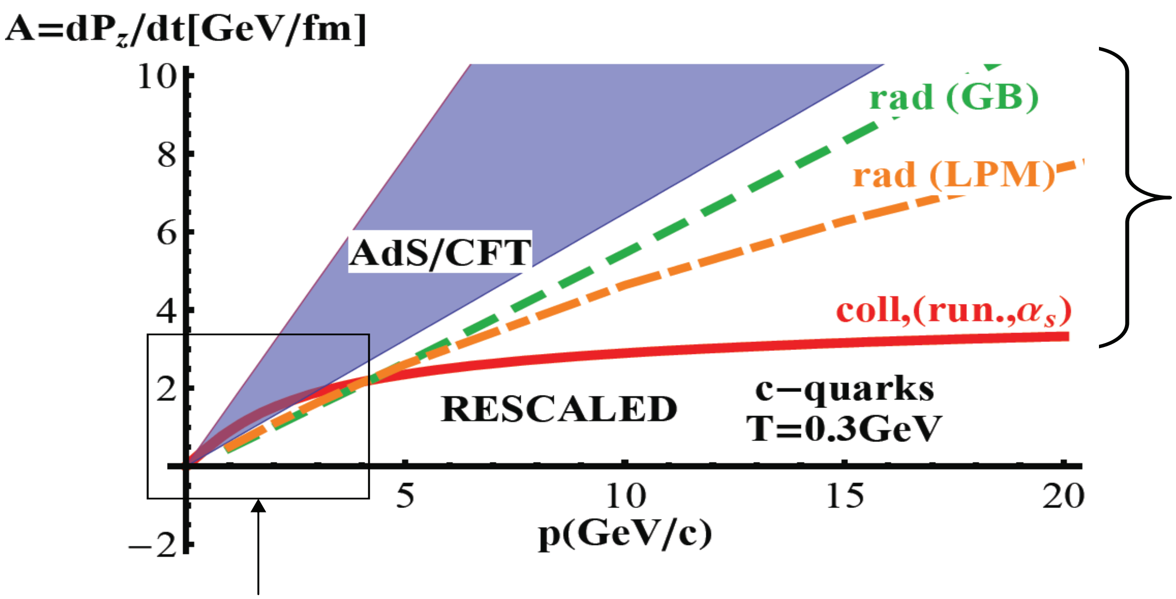
Heavy quarks production in heavy ions collisions

Gossiaux on Tue

Gossiaux on Tue

QGP properties: stopping power

Gathering all *rescaled* models (*coll. and radiative*):



Seems “under control”

Challenge

Exp. cannot resolve between those various trends

quite consistent as the drag coefficient reflects the average momentum loss (per unit time) => large weight on x ~ 1

Heavy quarks production in heavy ions collisions

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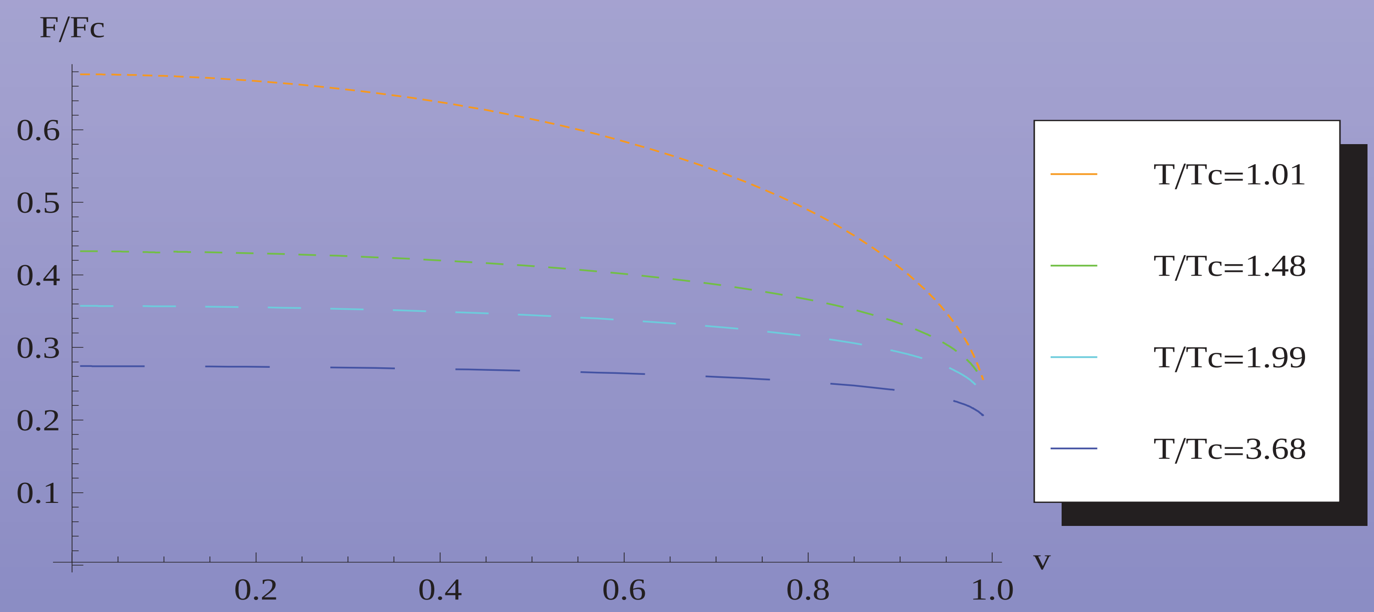
- The drag force is found to be:
- $F = -\frac{\pi}{2}\sqrt{\lambda}T^2\frac{v}{\sqrt{1-v^2}} = -\frac{p}{\tau}$,
- and the diffusion time
- $\tau = \frac{2M_q}{\pi\sqrt{\lambda}T^2}$.
- $\tau_{charm} \sim 2fm$, $\tau_{bottom} \sim 6fm$, for $T = 250MeV$.

Some properties of the model.

- The terms of the dilaton potential are determined by requiring:
- Asymptotic freedom close to the boundary.
- Matching the spectrum of the glueballs with the lattice.
- Matching thermodynamics with lattice for high temperatures.
- These conditions give a first order transition - Hawking Page between the confined and the deconfined phase at $T_C \sim 250 MeV$.

Drag force in iHQCD



The ratio of the drag force in iHQCD to the conformal $\mathcal{N} = 4$ SYM case is shown. For high velocities and high temperatures asymptotic freedom becomes important. For $\mathcal{N} = 4$ SYM the 't Hooft coupling is chosen to be 6.

Luckily, still some control:

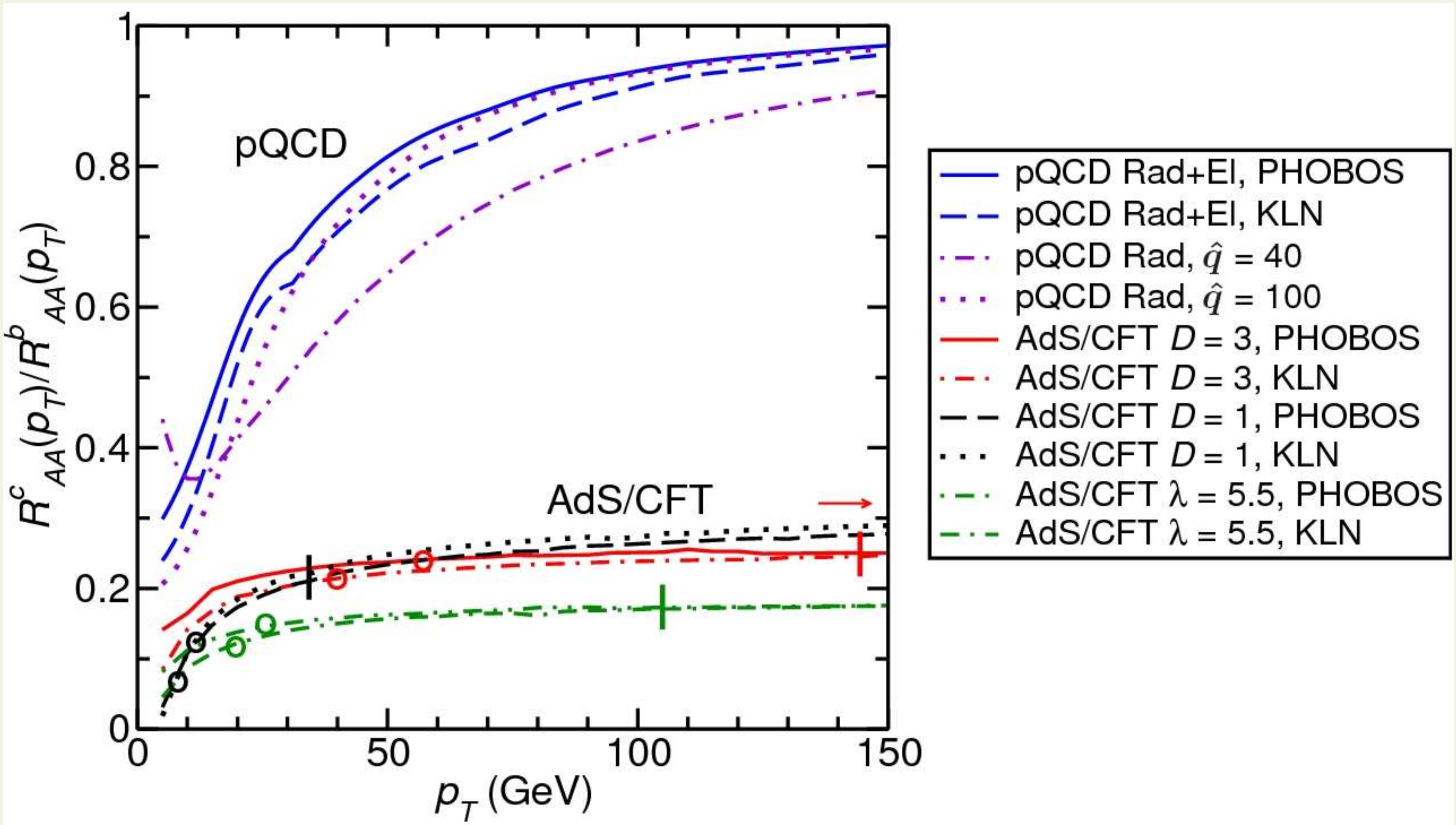
- heavy vs heavier - c vs b

- different observables, centrality

- energy dependence - LHC vs RHIC

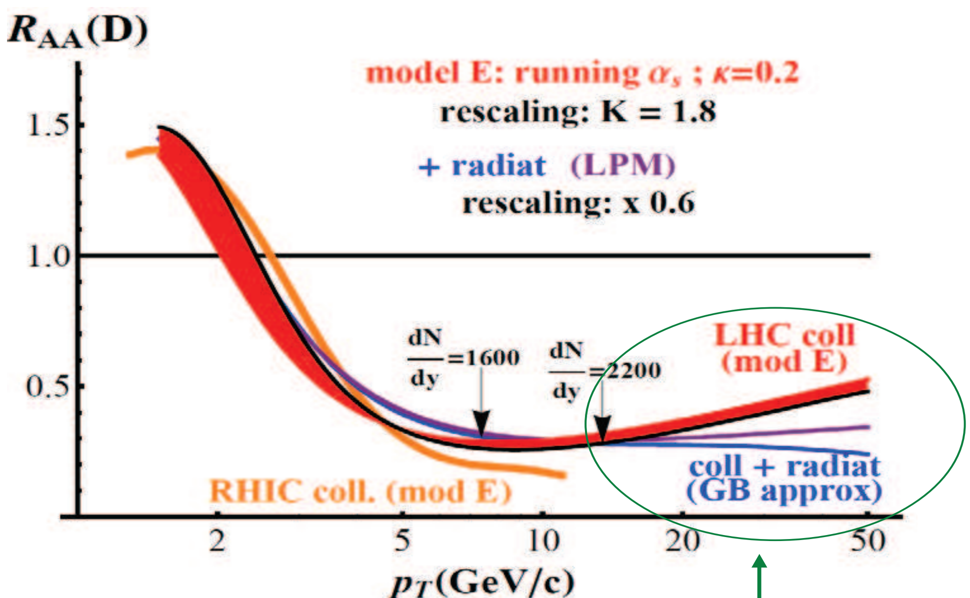
- cross-check with quarkonia

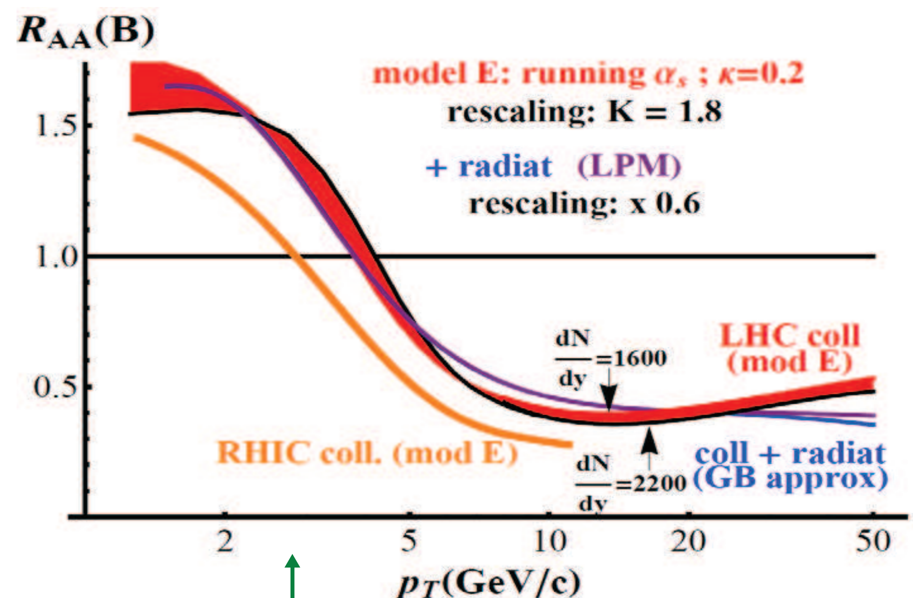
Horowitz & Gyulassy, PLB666 ('08): pQCD vs 'vanilla' AdS at the LHC



how does the picture change for this new type of AdS model?

D & B meson: LHC (radiat + collisional)





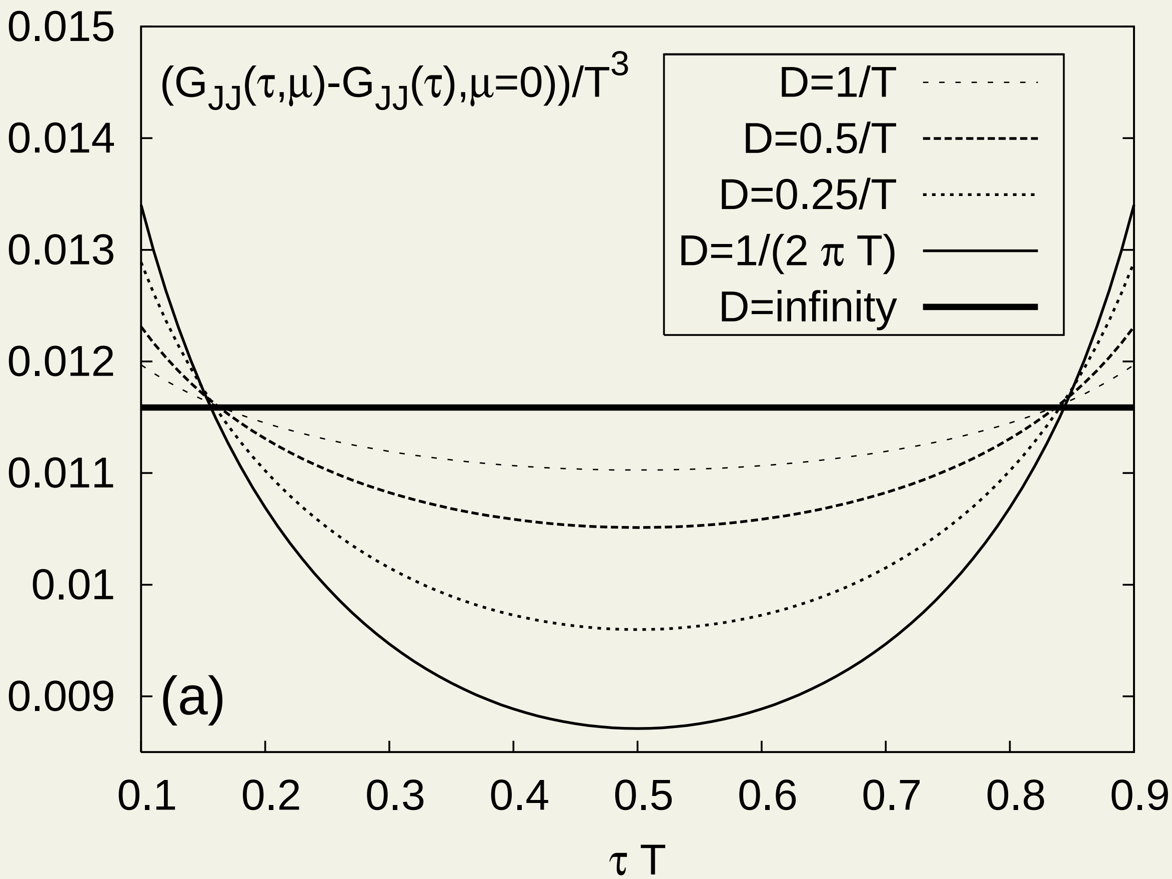
D spectra in Pb-Pb (5.5 TeV): Some window to decipher between the various Energy-loss models, for $p_T > 20$ GeV/c

B spectra in Pb-Pb (5.5 TeV): Pretty independent of E-loss model (properly calibrated w.r.t. RHIC data)

Gossiaux on Tue

Teaney & Petreczky, PRC73 ('06): heavy-quark transport from lattice

$T = 0$: $\sigma_{JJ}(\omega \approx 0) \sim \delta(\omega)$ **but at finite** T: $\sim \eta_D/(\omega^2 + \eta_D^2)$



could be feasible with few TFlop-years (2006 claim)

Details matter

Time evolution of the fire ball

- Elliptic fire-ball parameterization
  fitted to hydrodynamical flow pattern [Kolb '00]

$$V(t) = \pi(z_0 + v_z t)a(t)b(t), \quad a, b\text{: semi-axes of ellipse},$$
$$v_{a,b} = v_\infty[1 - \exp(-\alpha t)] \mp \Delta v[1 - \exp(-\beta t)]$$

- Isentropic expansion: $S = \text{const}$ (fixed from N_{ch})
- QGP Equation of state:

$$s = \frac{S}{V(t)} = \frac{4\pi^2}{90} T^3 (16 + 10.5 n_f^*), \quad n_f^* = 2.5$$

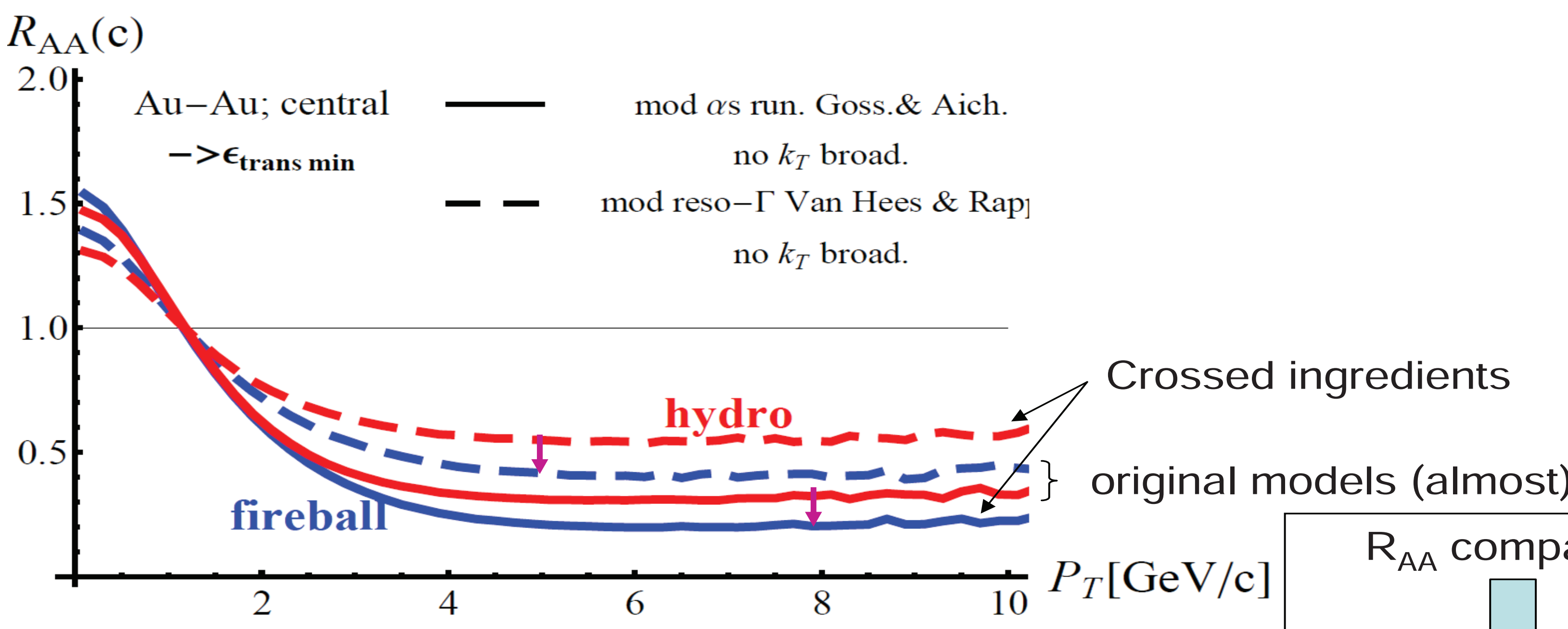
- obtain $T(t) \Rightarrow A(t,p)$, $B_0(t,p)$ and $B_1 = TEA$
- for semicentral collisions ($b = 7$ fm): $T_0 = 340$ MeV,
  QGP lifetime $\simeq 5$ fm$/c$.
- simulate FP equation as relativistic Langevin process

real hydro matters - Gossiaux on Tue

Heavy quark evolution

All heavy quarks observables evaluated with the pre-point prescription

Nuclear Modification factor



R_{AA} compatible

⇓

How can we conclude ?

↓ : More quenching with the fireball then with the (original) KH hydro

Heavy quarks production in heavy ions collisions

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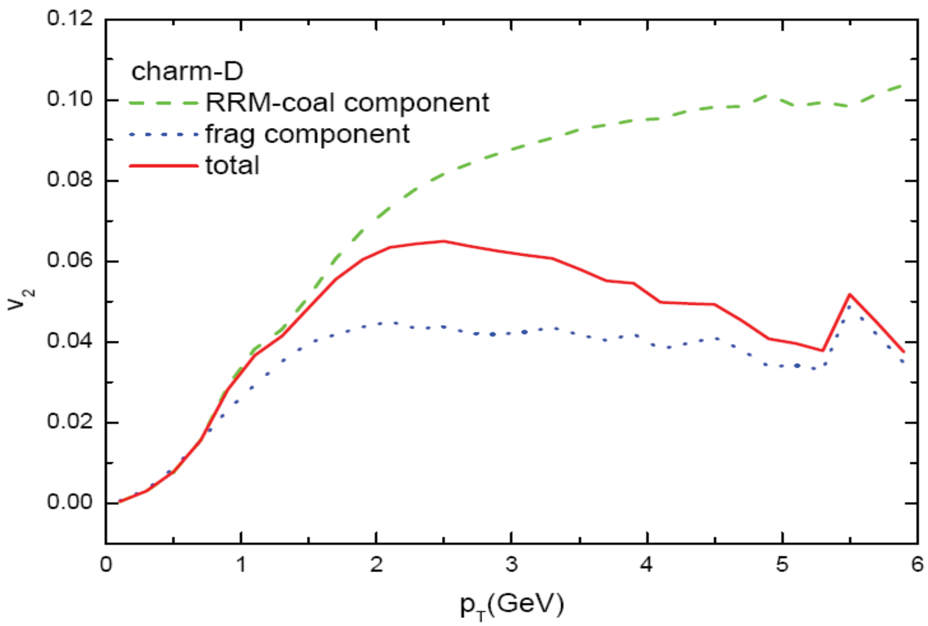
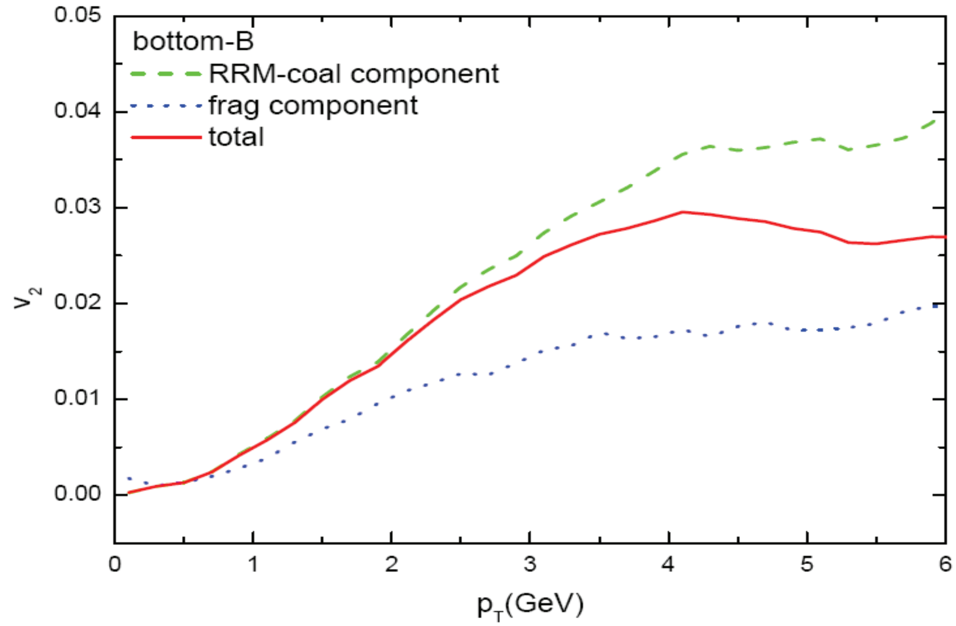
Hadronization: coal. vs frag.





coal. vs frag. : relatively normalized with the calculated coal. probability

$$\frac{\mathrm{d}N_D^{\mathrm{tot}}}{\mathrm{d}y\,\mathrm{d}^2p_T} = \frac{\mathrm{d}N_D^{\mathrm{coal}}}{\mathrm{d}y\,\mathrm{d}^2p_T} + \frac{\mathrm{d}N_c^{\mathrm{frag}}}{\mathrm{d}y\,\mathrm{d}^2p_T}$$

fragmentation: preserves the charm quark v_2 from charm → D
coalescence: adds p_T and v_2 from the light quarks to charm quarks

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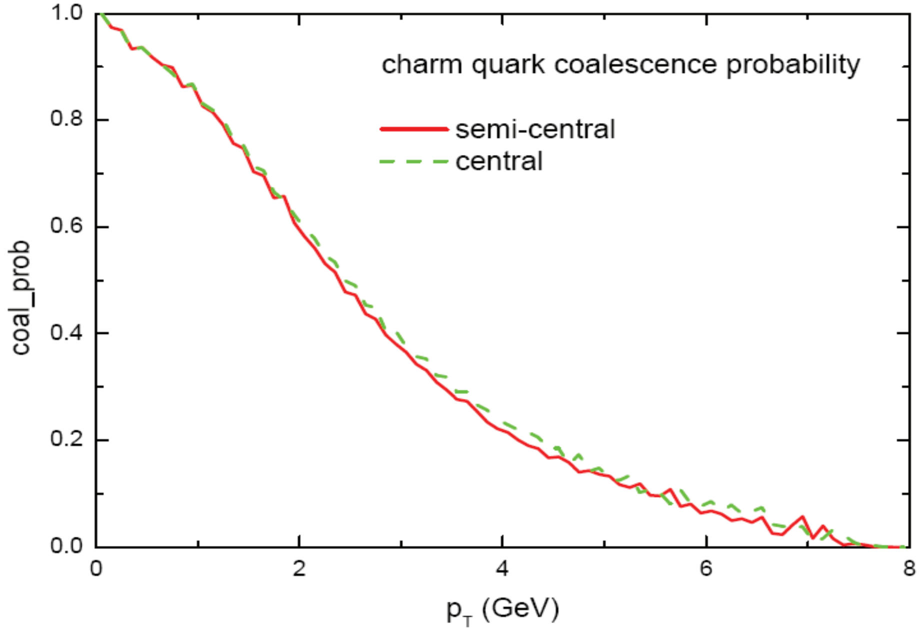
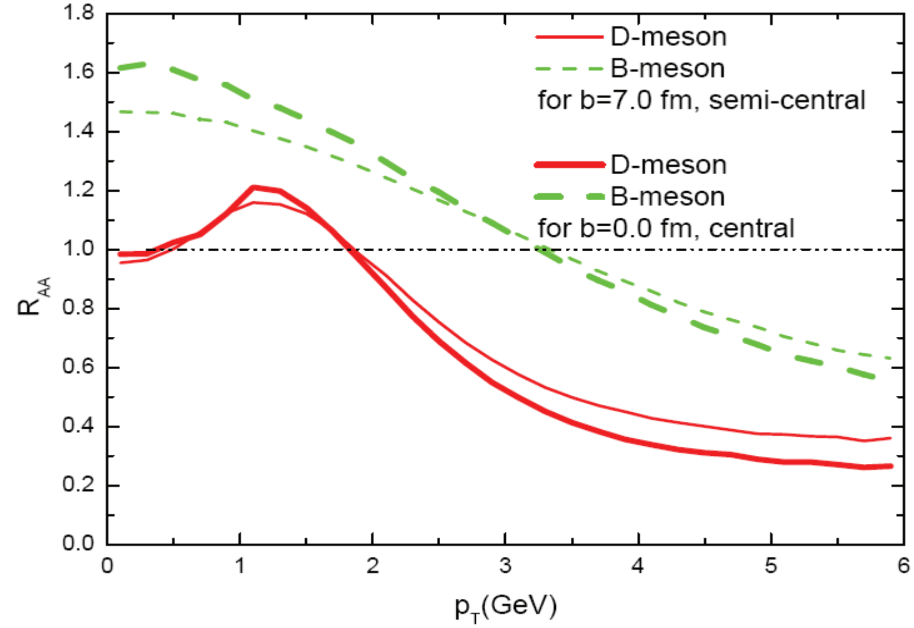
Hadronization: coal. vs frag.



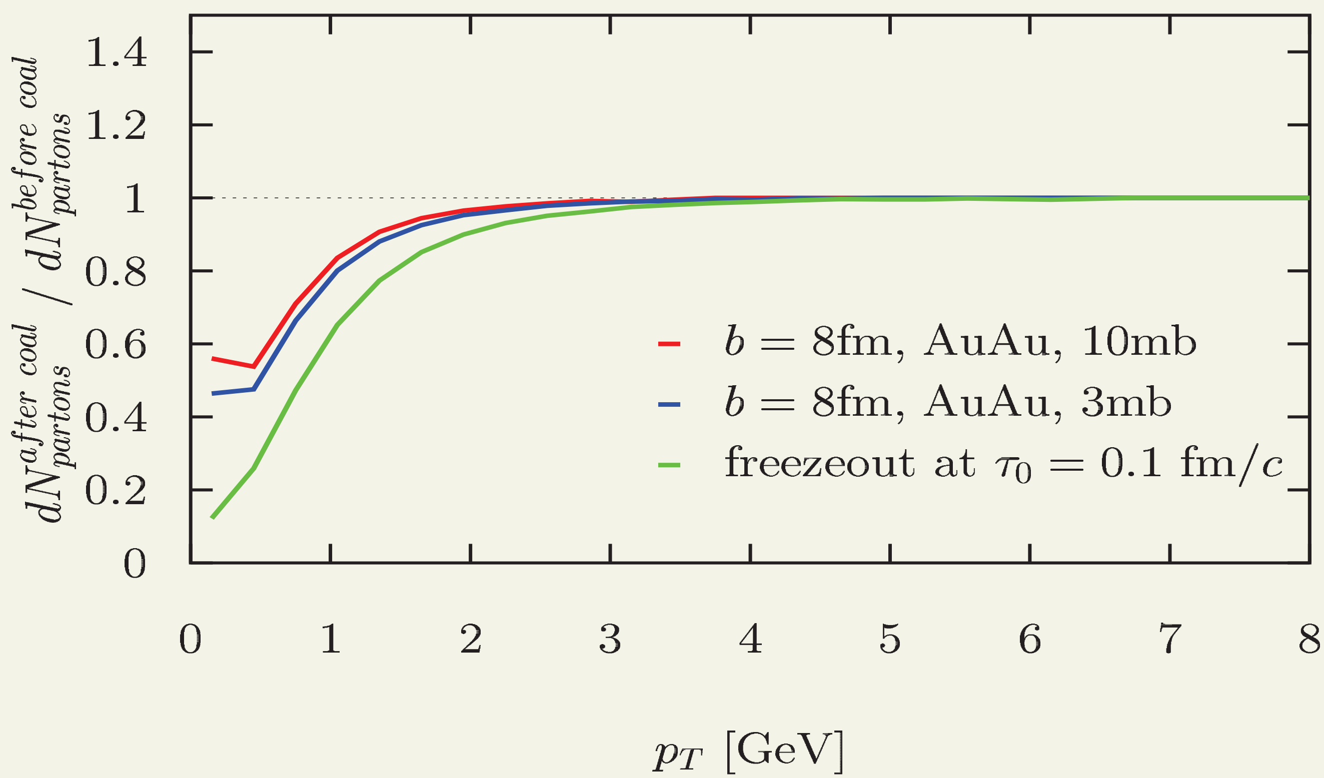


charm quark coal. probability: high p_T c-quark finds light quark of low phase density ; normalized to 100% at zero momentum

the remaining c-quarks get hadronized through independent fragmentation: $D(z) = \delta(z-1)$

13

fraction of partons that fragment vs parton pT DM, JPG31 ('04): **MPC + coal**

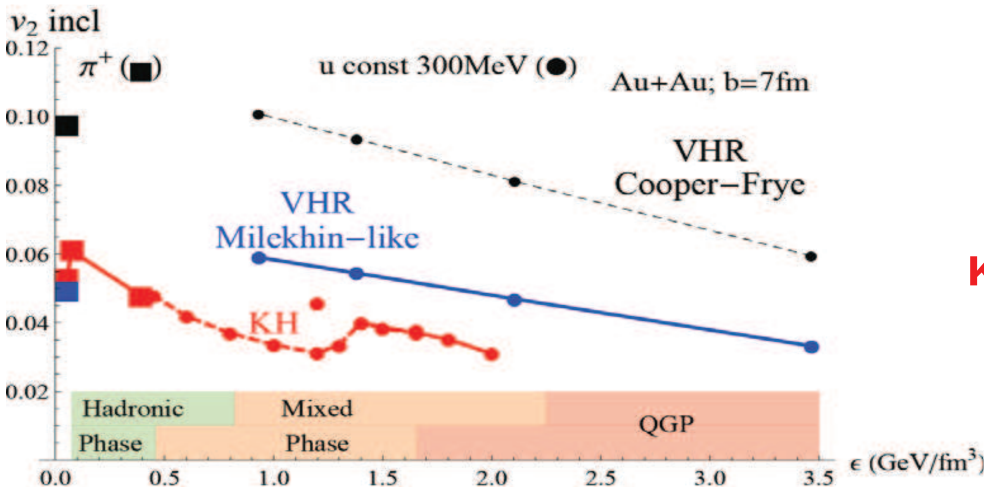


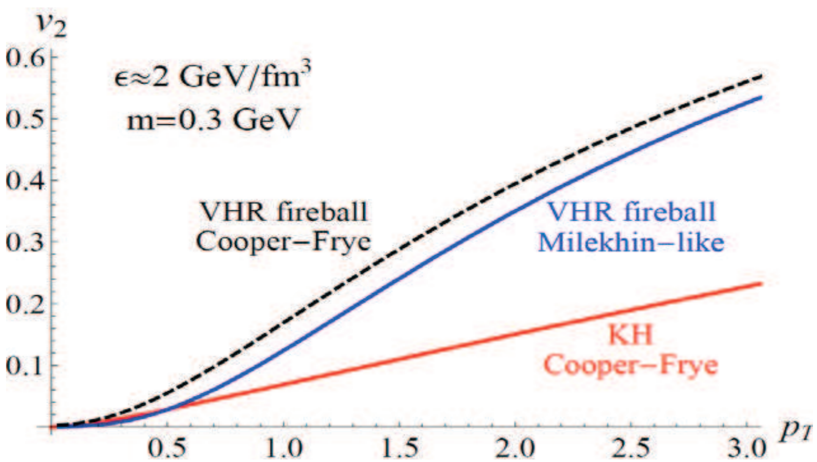
large fragmentation contributions, even for most optimistic earliest freezeout

$\Rightarrow$ **spoils flow scaling and B/M enhancement**

Back on the bulk v2 and on calibration

II. Elliptic flow of light quarks and ensuing pions





Particle spectra:

$$\frac{EdN}{d^3p} = \int d\sigma_\mu p^\mu f(p,T)$$

$$f = e^{-\frac{p\cdot u}{T}}$$

KH with Cooper-Frye freeze out

Fireball: freeze out at constant lab time t

$$\frac{d^3N}{d^3p} = \int_{\mathcal{V}} \frac{dV}{(2\pi\hbar)^3} f\left(\frac{p\cdot u}{T(t)}\right)$$

$$f = \frac{p\cdot u}{p^0} e^{-\frac{p\cdot u}{T}}$$

Asymptotic distribution in the VHR post-point Langevin

$$f = e^{-\frac{p\cdot u}{T}}$$

fireball with Cooper-Frye freeze out

fireball with Milekhin-like freeze out

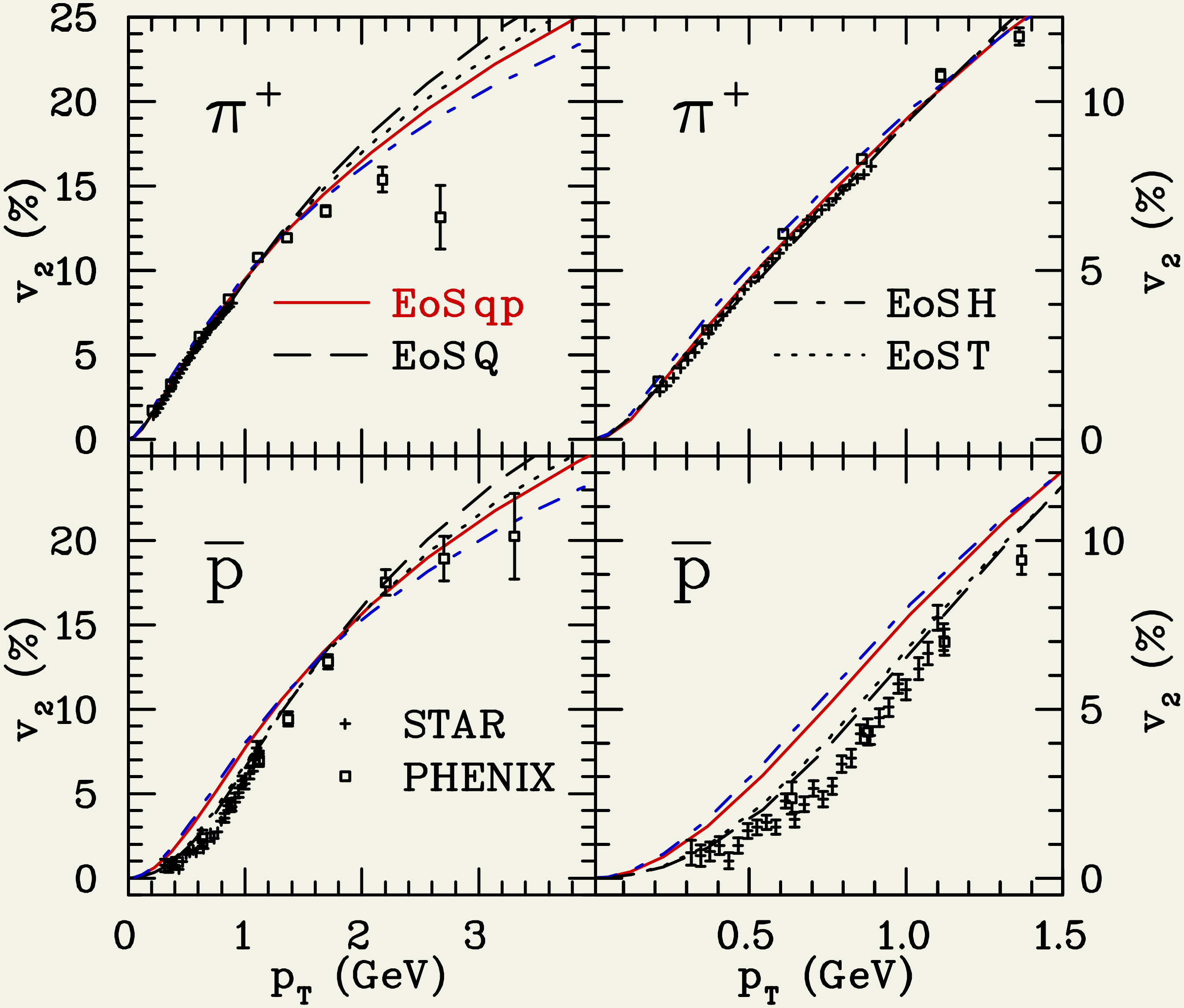
$$d\sigma_\mu = d\bar{V} u_\mu$$

30

Heavy quarks production in heavy ions collisions

Realistic EOS matters

lattice EOS much closer to hadron gas... for proton-pion v2 splitting



Huovinen, NPA761, 296 ('05)

Q: bag model

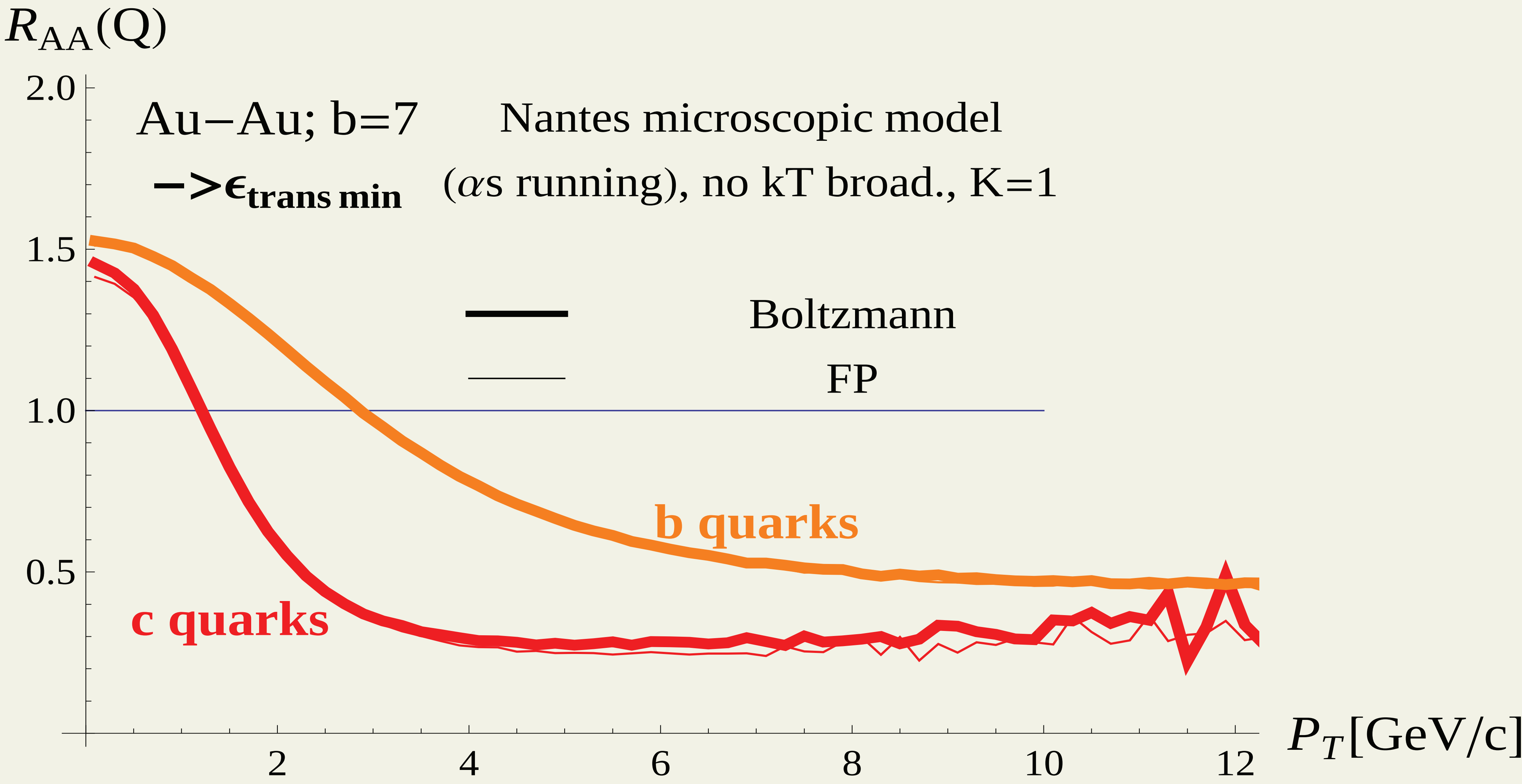
qp: lattice fit ($T_c = 170$ MeV)

H: hadron gas

T: interpolated $\varepsilon(T)$ between hadron gas and $\varepsilon \propto T^4$ plasma

MUST test particle species dependence from viscous hydro!

Fokker-Planck at 10 GeV?! Gossiaux 2011 (private comm.)



Braaten on Tue

Production of Heavy Quarkonium

Creation of heavy quark pair?
Binding to form heavy quarkonium?

Theoretical developments

- Color-Singlet Model 1976-1981
- Color-Evaporation Model 1977
- Fragmentation Mechanism 1993
- NRQCD Factorization 1995
- $Q\bar{Q}$ Fragmentation 2010

$Q\bar{Q}$ Fragmentation

Braaten on Tue

Dramatic new development in 2010!
Proof of factorization for quarkonium production at large p_T

Kang, Qiu, Sterman (in progress)

- at leading order in m_Q/p_T,
  fragmentation of single partons (Q, $\bar{Q}$, g)

  Collins & Soper 1983

- at order $m_Q{}^2/p_T{}^2$,
  $Q\bar{Q}$ fragmentation into quarkonium

- at order $m_Q{}^4/p_T{}^4$, factorization breaks down

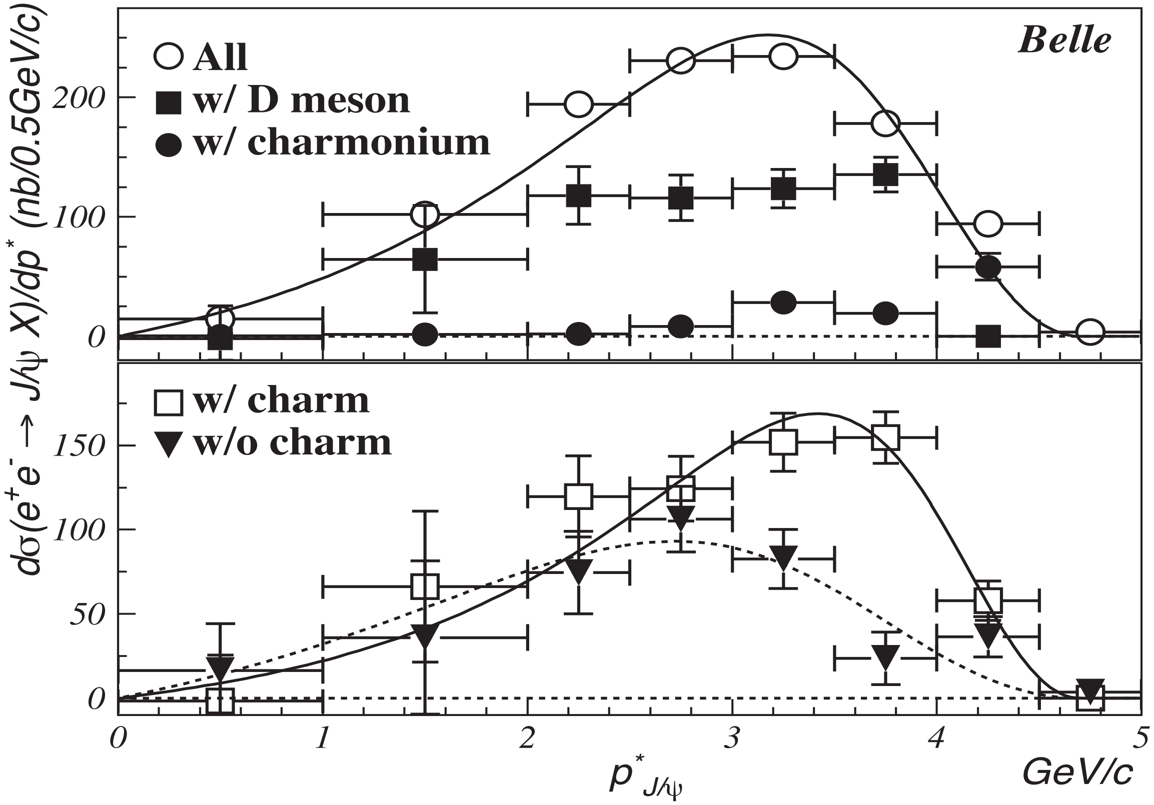
$$
\begin{aligned}
d\sigma[H_{c\bar{c}}(P)] \quad = \quad & \sum_{i=c,\bar{c},g} \int_0^1 dz \; d\hat{\sigma}[i(P/z)] \; D_{i\to H_{c\bar{c}}}(z) \\
& + \int_0^1 dz \; d\hat{\sigma}[c\bar{c}(P/z)] \; D_{c\bar{c}\to H_{c\bar{c}}}(z) \\
& + \mathcal{O}(m_c^4/p_T^4)
\end{aligned}
$$

Charmonium production

$E_q / M_{had} = 1.7$

- inclusive J/ψ and ψ(2S) spectra measured
  - → one of the earliest Belle results
  - → very nice recent follow-up, in-depth study
- the inclusive FF is very hard!
  - → expected for $c\bar{c}$ pairs from the hadronization stage
- look for additional $c\bar{c}$
  - → many rec'd D/$\bar{D}$ mesons: expected
  - → and charmonium (see next slide)
  - → but ~30% have none: gluon splitting, or ...?

⇒ relative $c\bar{c}$ production in hadronization >~ 2×10^{-4}



Vogt today

CEM Comparison to RHIC pp J/ψ Data

CEM calculation reproduces shape of J/ψ p_T and y distributions rather well

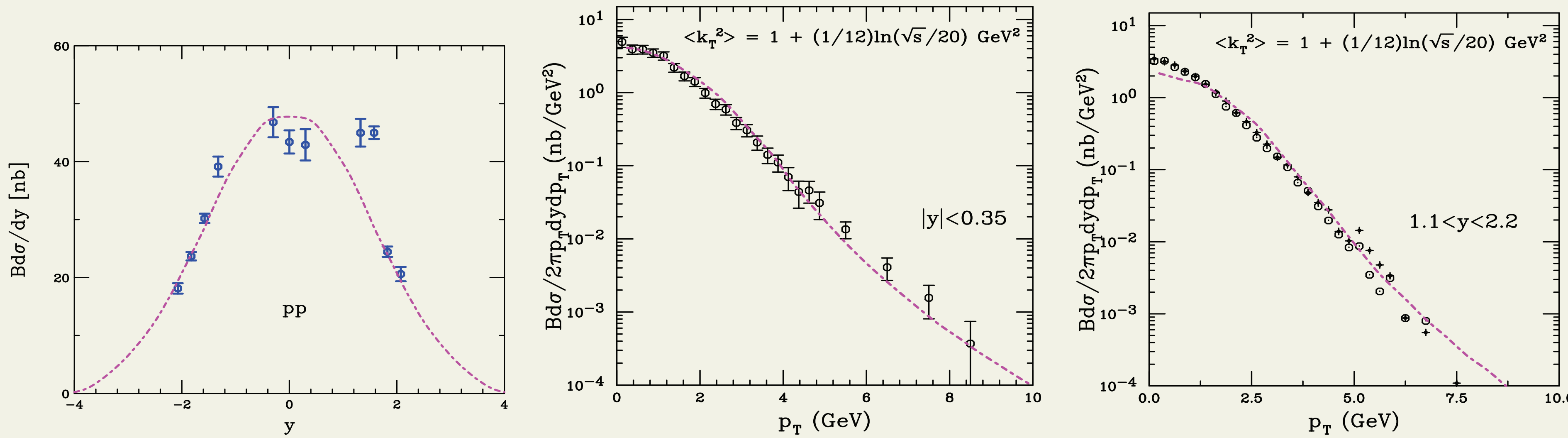


Figure 7: **PHENIX** pp **measurements compared to CEM calculation at** $\sqrt{s}$ = 200 **GeV. The** J/ψ **rapidity distribution (left) and transverse momentum distributions at midrapidity (center) and in the muon arms (right). The results are calculated with CTEQ6M,** $(m, \mu_F/m_T, \mu_R/m_T) = (1.2, 2, 2)$, $\langle k_T^2 \rangle = 1.38$ **GeV**^{2}**. The forward result is scaled up by a factor of** ≈ 1.4.

Vogt today

CEM Comparison to LHC pp Quarkonium Data

CEM calculation reproduces shape of J/ψ and $\Upsilon(1S)$ p_T distributions using CTEQ6M with $(m, \mu_F/m_T, \mu_R/m_T) = (1.2\text{ GeV}, 2, 2)$, $\langle k_T^2 \rangle = 1.38$ GeV^2.
No 'fudge' factor included

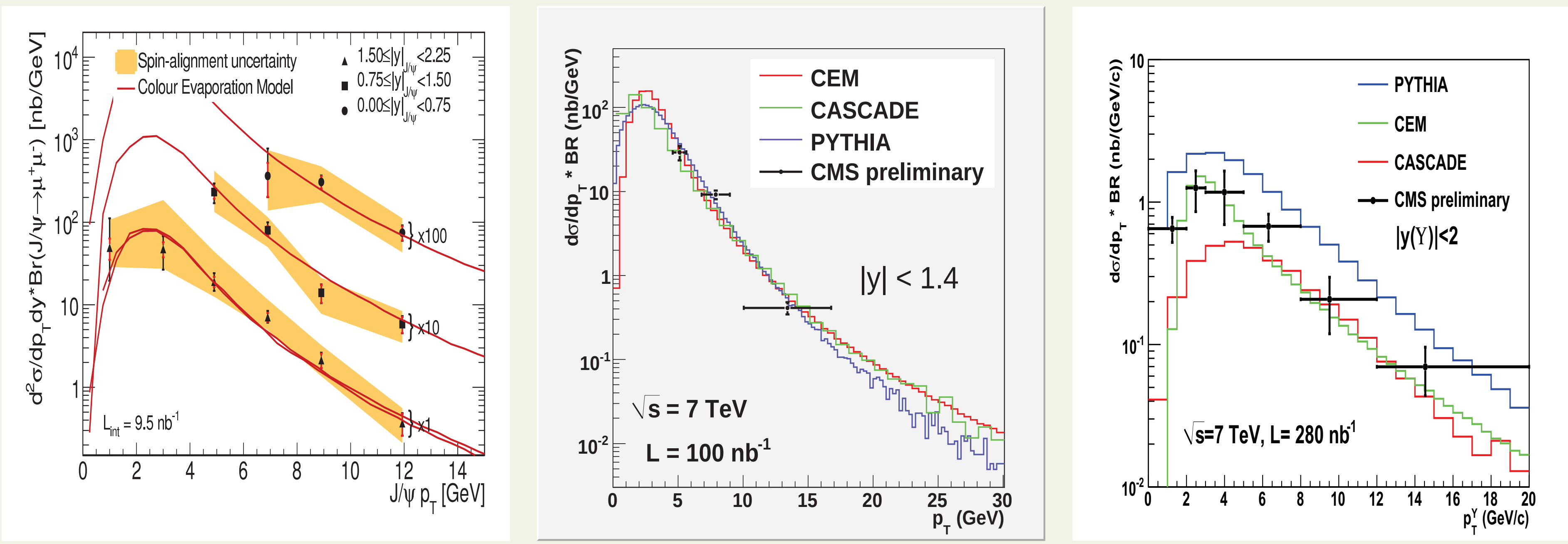
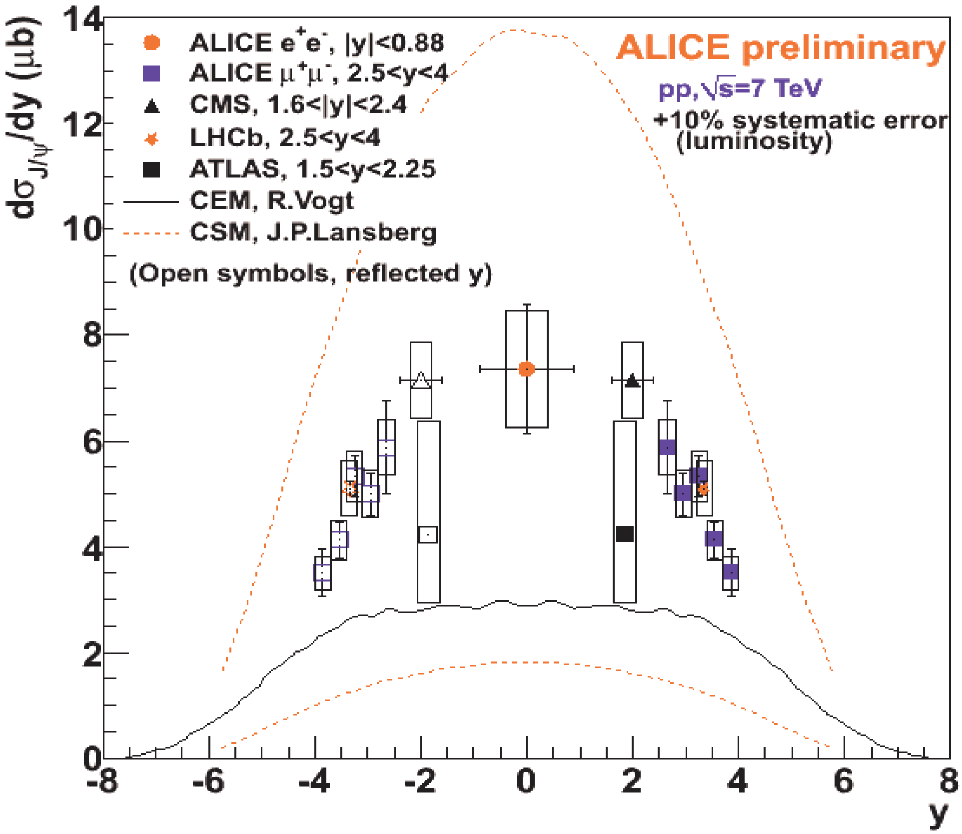


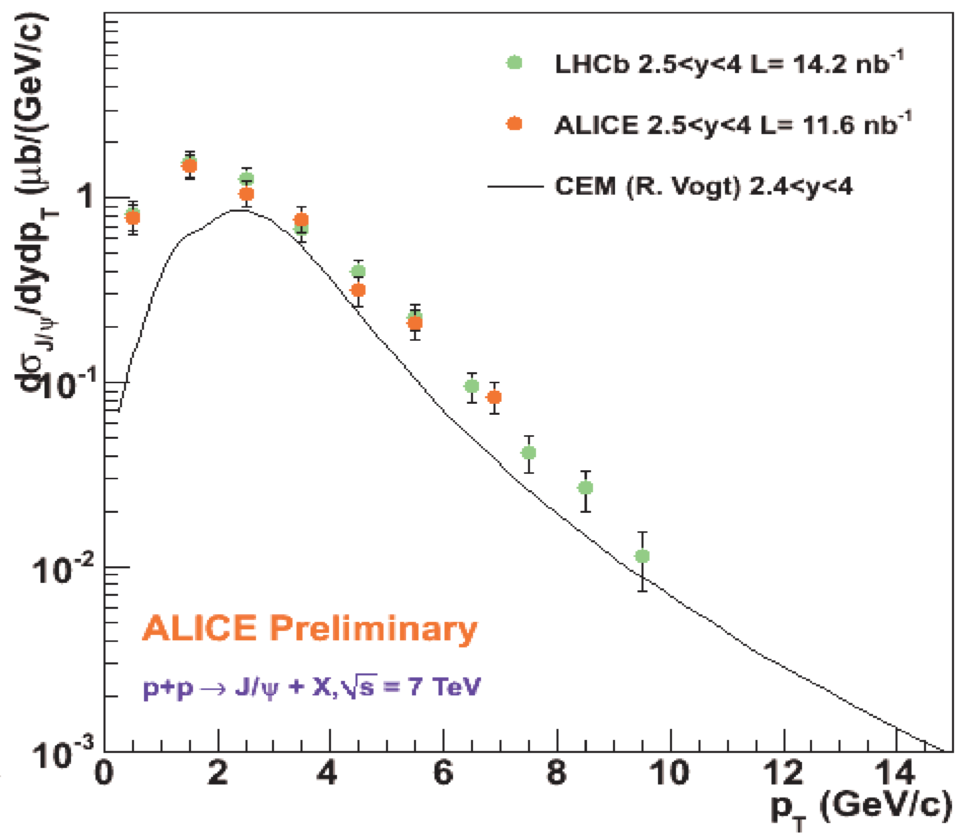
Figure 8: **ATLAS (left) and CMS (middle) J/ψ and CMS $\Upsilon(1S)$ (right) cross sections at 7 TeV compared to CEM calculations.**

low-pT puzzle

Cortese today

Preliminary comparison(s)





- **Model calculations:**
  - **R.Vogt, Phys. Rev. C 81 (2010) 044903**
  - **J.P. Lansberg, arXiv:1006.2750**
- **CMS: p_T-integrated cross section 1.6<y<2.4 from (arXiv:1011.4193)**
- **ATLAS: dσ/dy 1.5<y<2.25, ATLAS-CONF-2010-062**
- **LHCb: dσ/dy 2.5<y<4 from LHCb-CONF-2010-010**

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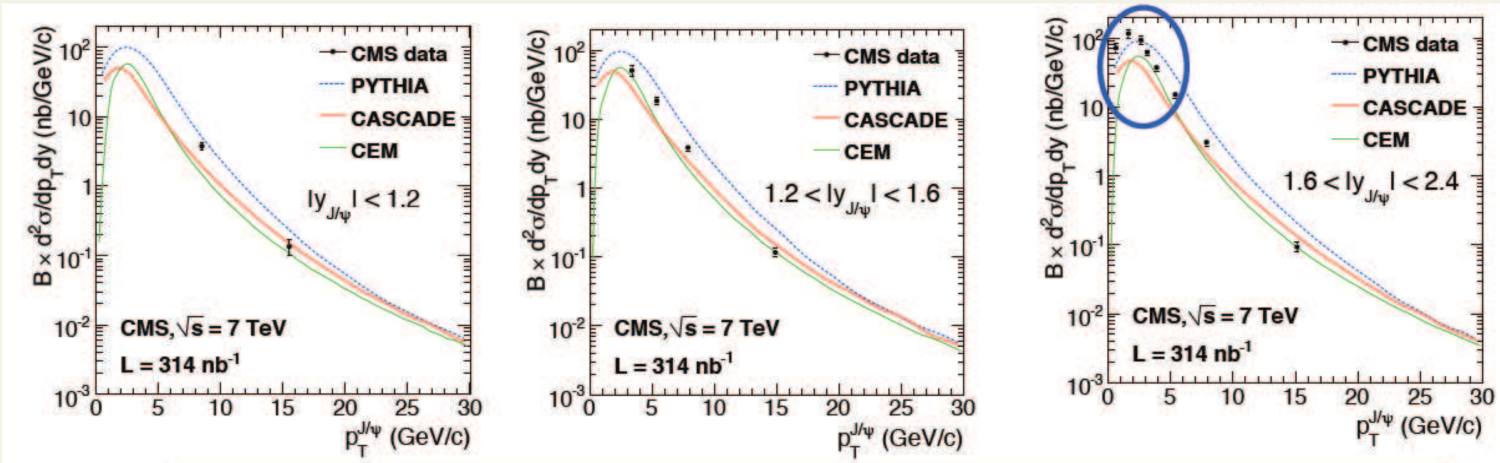
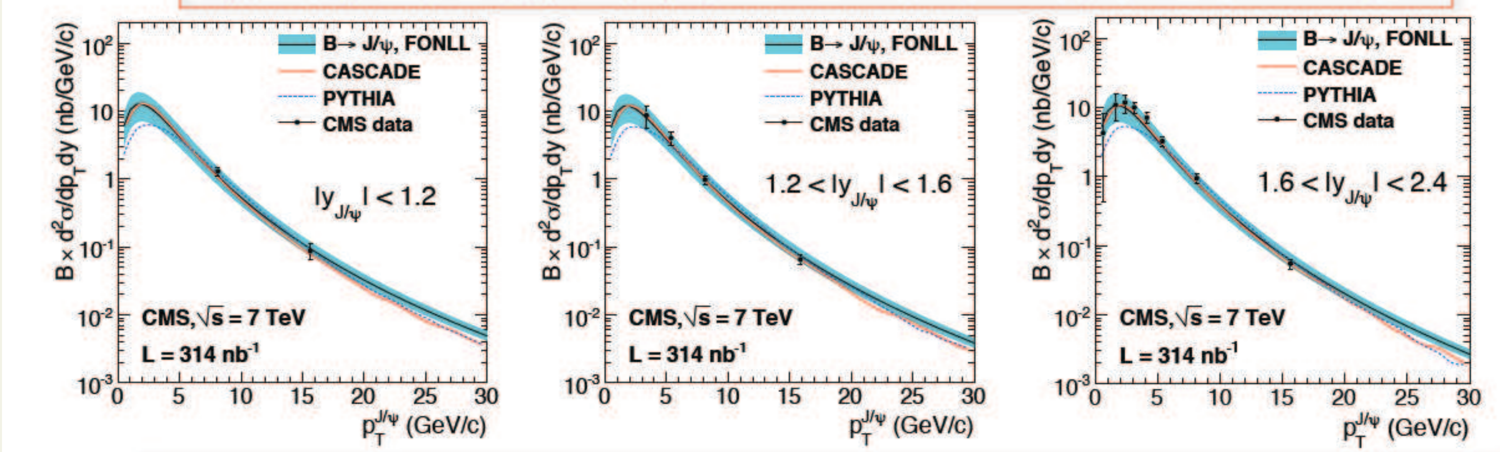
p-p J/ψ Theory Comparison cont.

prompt



$$\sigma(pp \to J/\psi + X) \cdot BR(J/\psi \to \mu^+\mu^-) = 70.9 \pm 2.1(\text{stat}) \pm 3.0(\text{syst}) \pm 7.8(\text{luminosity})\ \text{nb}$$

non-prompt



$$\sigma(pp \to bX \to J/\psi X) \cdot BR(J/\psi \to \mu^+\mu^-) = 26.0 \pm 1.4\ (\text{stat}) \pm 1.6\ (\text{syst}) \pm 2.9\ (\text{luminosity})\ \text{nb}$$

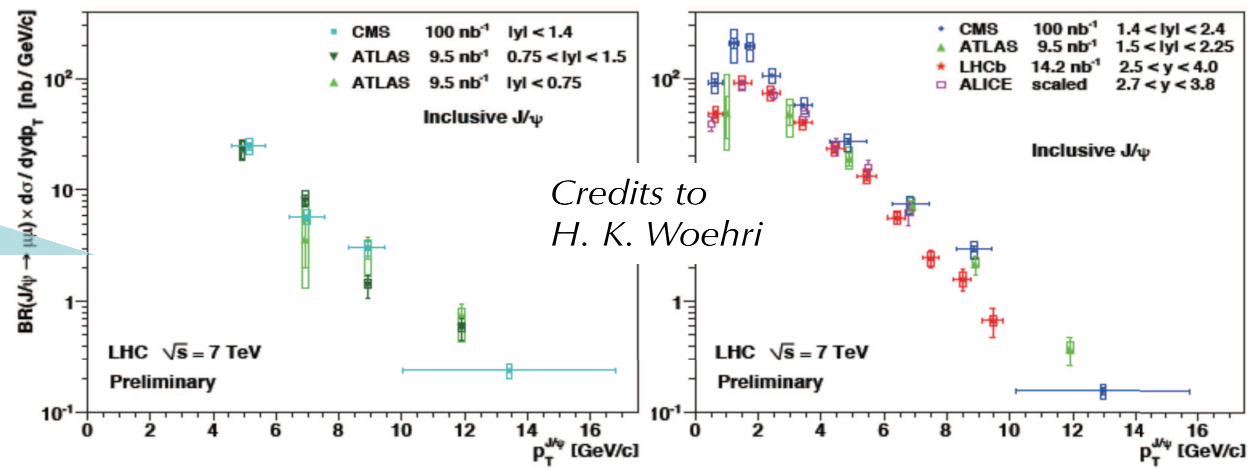
Comparison only with models that include feed down from higher states

g.j.kunde@lanl.gov

Musto today

Comparison of results…

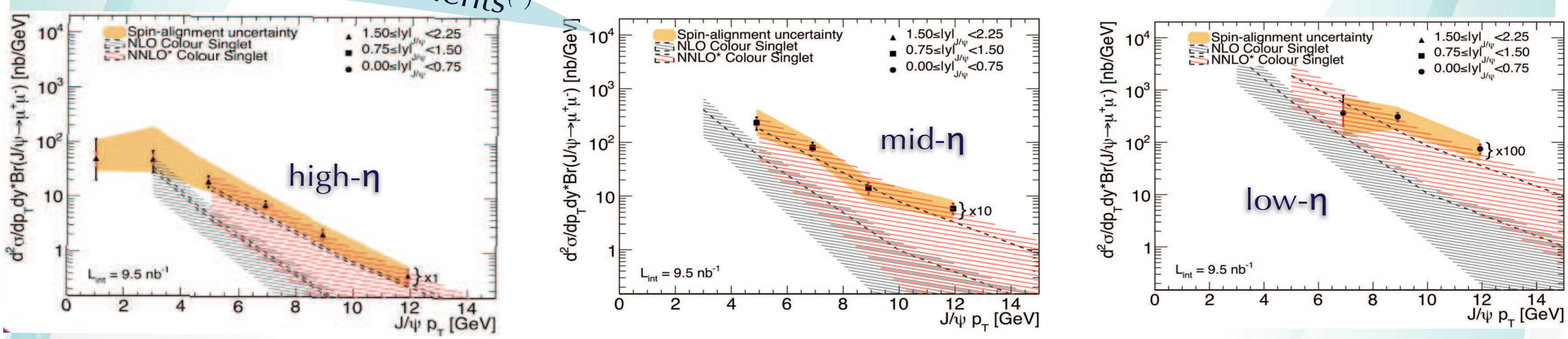
central region — forward region



Credits to H. K. Woehri

….with other LHC experiment shows a very good agreement!

….with theory needed some further improvements(*)



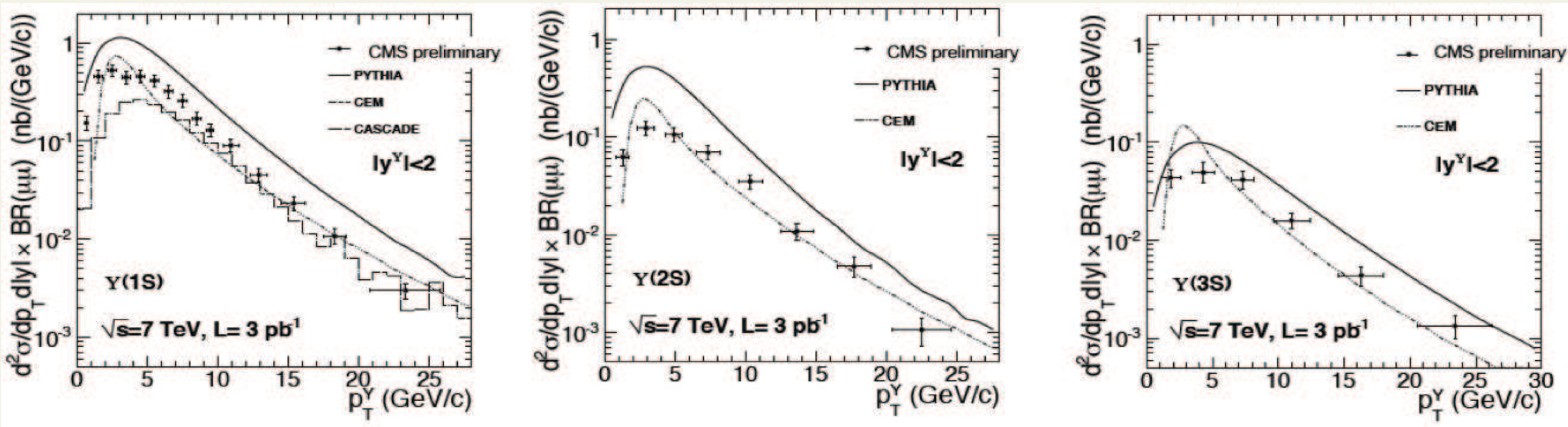
(*) 1. Used correction factor (from CDF) to account for

- non prompt B->J/ψ contribution (also measured by ATLAS)

- ψ(2S) and χc feed-down (P. Faccioli et al JHEP10(2008)004)

2. χc corrections not available to NLO accuracy

p-p Upsilon Theory Comparisons



- PYTHIA – FONLL Cascade - Color Evaporation Model

H. Jung *Comp.Phys.Commun.* **143** (2002) 100.

F. Halzen, "CVC for Gluons and Hadroproduction of Quark Flavors", *Phys. Lett.* **B69** (1977) 105. doi:10.1016/0370-2693(77)90144-7.

H. Fritzsch, "Producing Heavy Quark Flavors in Hadronic Collisions: A Test of Quantum Chromodynamics", *Phys. Lett.* **B67** (1977) 217. doi:10.1016/0370-2693(77)90108-3.

M. Gluck, J. F. Owens, and E. Reya, "Gluon Contribution to Hadronic J/psi Production", *Phys. Rev.* **D17** (1978) 2324. doi:10.1103/PhysRevD.17.2324.

V. D. Barger, W.-Y. Keung, and R. J. N. Phillips, "On psi and Upsilon Production via Gluons", *Phys. Lett.* **B91** (1980) 253. doi:10.1016/0370-2693(80)90444-X.

Quarkonia in nuclear matter

- cold nuclear matter effects already puzzling **Vogt today**

  comover absorption, (anti) shadowing, energy loss, ...

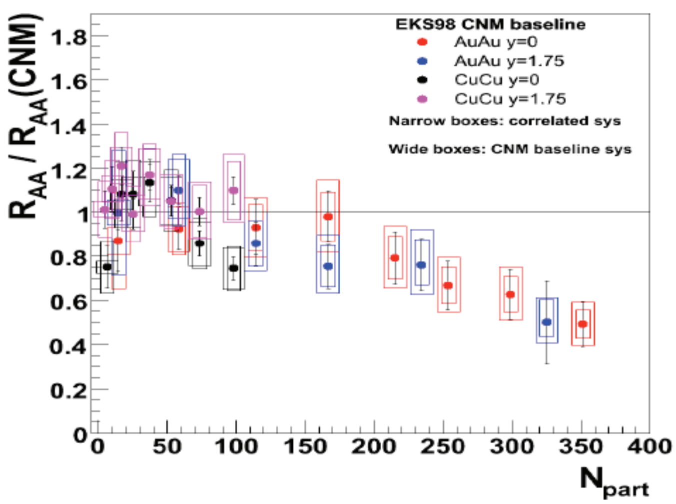
- hot and dense medium yet another challenge

Motivation: J/ψ suppression in heavy-ion collisions

Matsui and Satz, 1986: Changes in the heavy quark-antiquark potential result in changes in the quarkonium spectrum: when $r_{bind} > r_{Debye}$, no bound states exist. This is the first prediction of *significant* J/ψ suppression.

2009: The latest analysis of "anomalous" R_{AA} in many heavy-io collision experiments

Slow decrease in the ratio at large $N_{\rm part}$ cannot be explained simply from examining changes in the charmonium spectrum



with lattice potential (U) **Young on Wed**

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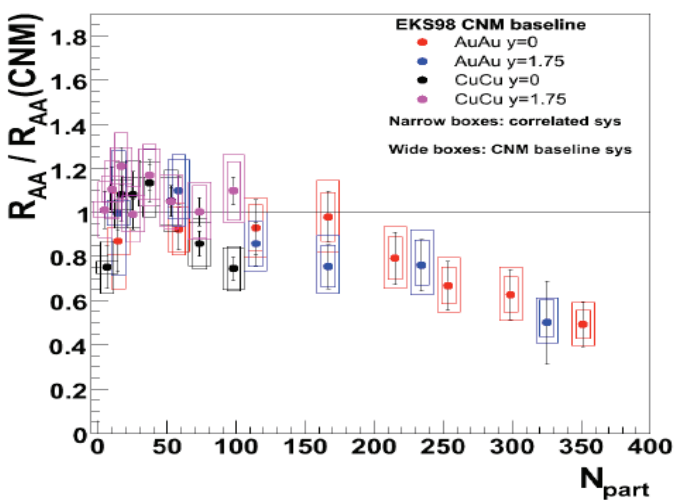
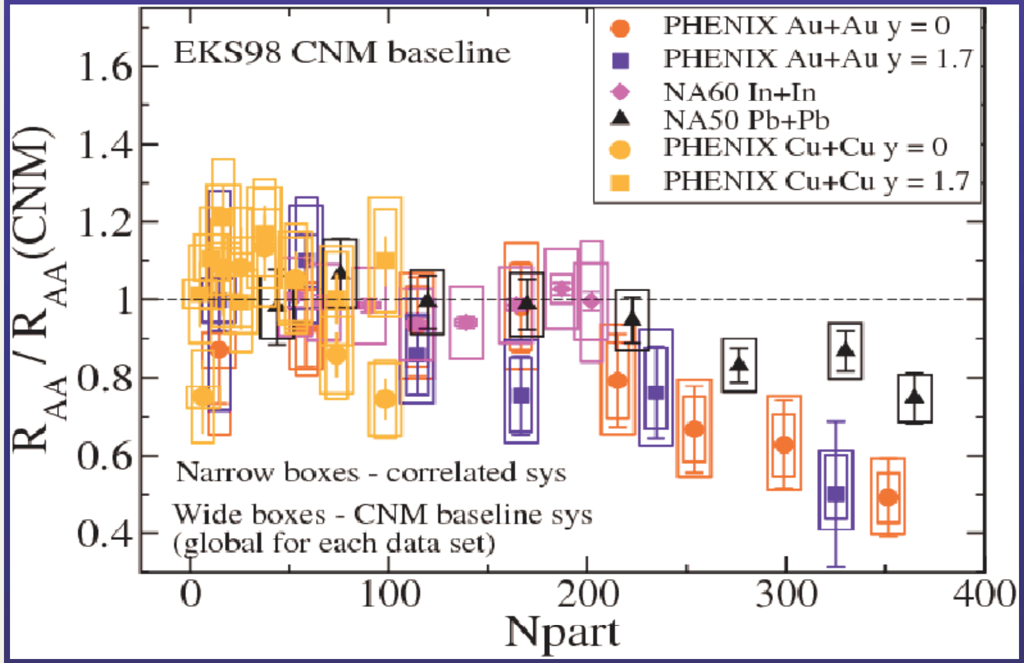


Cortese on Mon

Anomalous suppression: SPS vs RHIC

- SPS results compared with RHIC R_{AA} results normalized to R_{AA}(CNM)

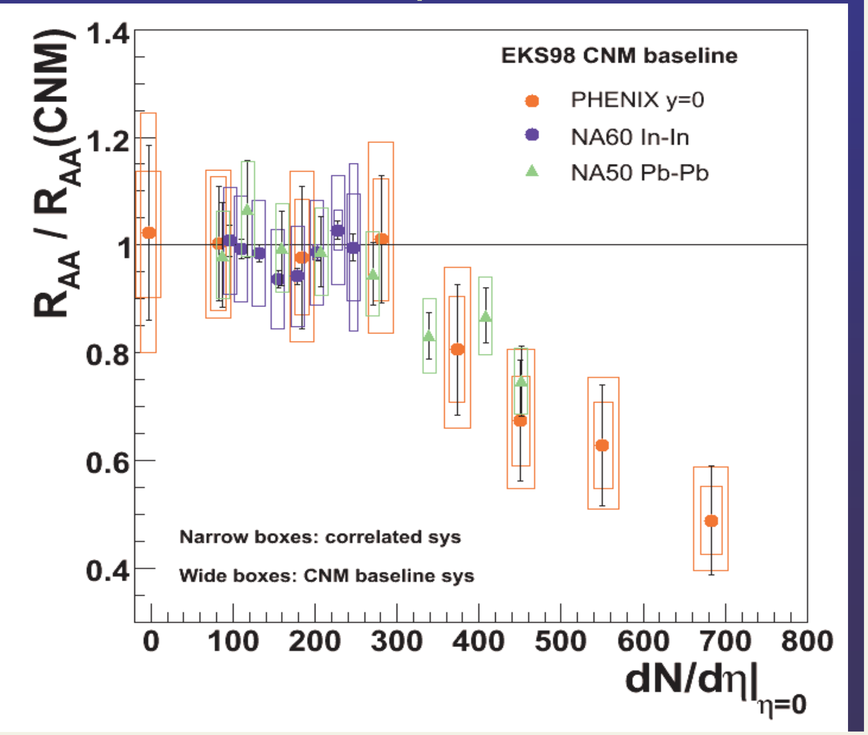


M. Leitch (E866), workshop on "Quarkonium in Hot Media:From QCD to Experiment", Seattle 2009

→ Both Pb-Pb and Au-Au seem to depart from the reference curve at N_{part}~200

→ For central collisions more important suppression in Au-Au with respect to Pb-Pb

- Agreement between SPS and RHIC results as a function of the charged particle multiplicity

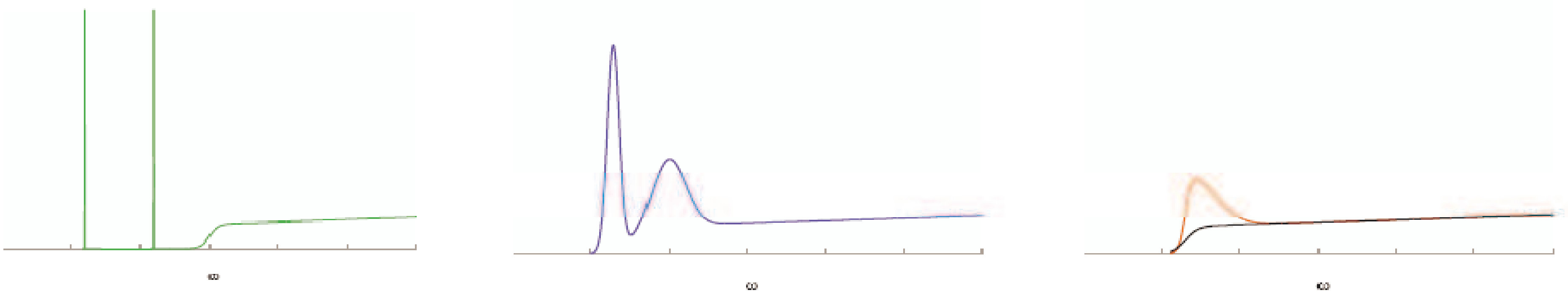


Quarkonium spectral functions

In-medium properties and/or dissolution of quarkonium states are encoded in the spectral functions

$$\sigma(\omega, p, T) = \frac{1}{2\pi} \,\mathrm{Im} \int_{-\infty}^{\infty} dt e^{i\omega t} \int d^3x e^{ipx} \langle [J(x,t), J(x,0)] \rangle_T$$

Melting is see as progressive broadening and disappearance of the bound state peaks



Due to analytic continuation spectral functions are related to Euclidean time quarkonium correlators that can be calculated on the lattice

$$G(\tau, p, T) = \int d^3x e^{ipx} \langle J(x, -i\tau), J(x, 0) \rangle_T$$

$$G(\tau, p, T) = \int_0^{\infty} d\omega \sigma(\omega, p, T) \frac{\cosh(\omega \cdot (\tau - \frac{1}{2T}))}{\sinh(\omega/(2T))}$$

MEM → $\sigma(\omega,p,T)$

$1S$ charmonium survives to $1.6T_c$??

Umeda et al, EPJ C39S1 (05) 9, Asakawa, Hatsuda, PRL 92 (2004) 01200, Datta, et al, PRD 69 (04) 094507, ...

Ryan on Wed

Heavy quarks in lattice qcd: an old story

In lattice QCD care must be taken that $am_q < 1$ to control errors $\mathcal{O}(am_q)$.
$am_b < 1$ on isotropic lattices, is still not (really) feasible.

- effective field theories (EFT):
  - Static: $m_Q \to \infty$; renormalisable; but $m_b \sim 5Gev$ far from ∞.
  - NRQCD: m_Q non-relativistic; expansion in HQ velocity v; nonrenormalisable; systematically improvable,
  - Fermilab: mass-dependent renormalisation of parameters; smooth interpolation from light to heavy; expensive to improve beyond $\mathcal{O}(a)$
- anisotropic lattices: $a_\tau << a_s$ so that $a_\tau m_b < 1$; requires large ξ; $\mathcal{O}(a_s m_q)$ effects?

For bottomonium at nonzero temperature combine NRQCD and anisotropic lattices.

Ryan on Wed

Results: Zero temperature spectroscopy

J^{PC}	state	$a_\tau \Delta E$	Mass (MeV)	Exp. (MeV) (PDG)
0^{-+}	$^1S_0(\eta_b)$	0.118(1)	9438(7)	9390.9(2.8)
0^{-+}	$^1S_0(\eta_b[2S])$	0.197(2)	10009(14)	-
1^{--}	$^3S_1(\Upsilon)$	0.121(1)	9460*	9460.30(26)
1^{--}	$^3S_1(\Upsilon')$	0.198(2)	10017(14)	10023.26(31)
1^{+-}	$^1P_1(h_b)$	0.178(2)	9872(14)	-
0^{++}	$^3P_0(\chi_{b0})$	0.175(4)	9850(28)	9859.44(42)(31)
1^{++}	$^3P_1(\chi_{b1})$	0.176(3)	9858(21)	9892.78(26)(31)
2^{++}	$^3P_2(\chi_{b2})$	0.182(3)	9901(21)	9912.21(26)(31)

Zero temperature bottomonium spectroscopy from NRQCD. *The $1^3S_1(\Upsilon)$ state is used to set the scale.

Petreczky on Wed

Lattice QCD based potential model

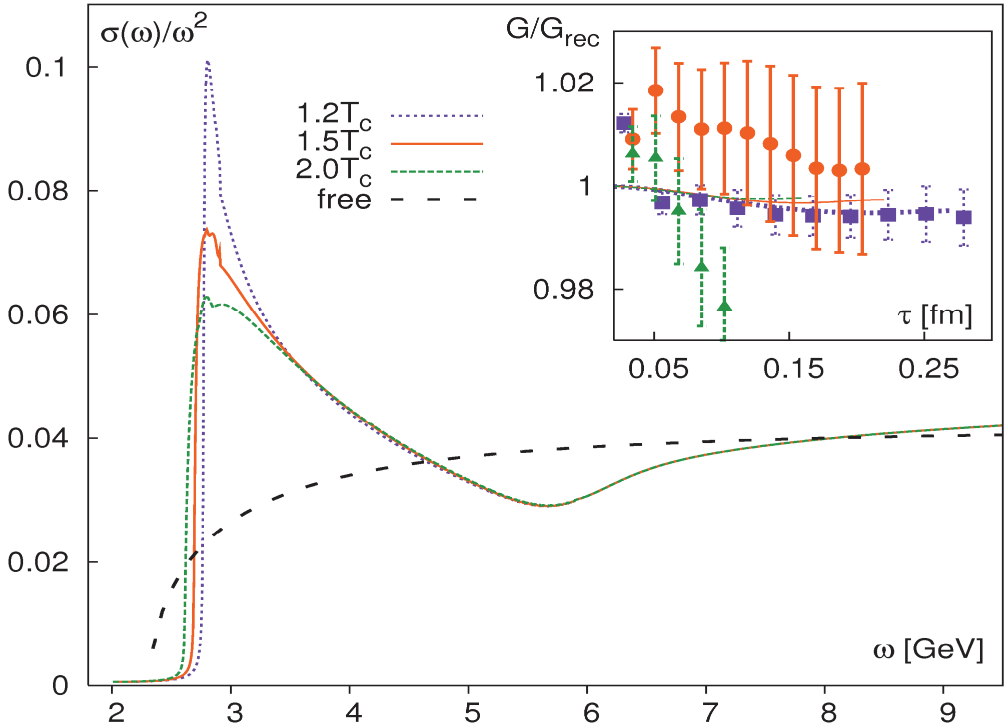
If the octet-singlet interactions due to ultra-soft gluons are neglected :

$$\left[i\partial_0 - \frac{-\nabla^2}{m} - V_s(r,T)\right] S(r,t) = 0 \quad \Rightarrow \quad \sigma(\omega, T)$$

potential model is not a model but the tree level approximation of corresponding EFT that can be systematically improved

Test the approach vs. LQCD : quenched approximation, $F_1(r,T) < \mathrm{Re}V_s(r,T) < U_1(r,T)$, $\mathrm{Im}V(r,T) \approx 0$

Mócsy, P.P., PRL 99 (07) 211602, PRD77 (08) 014501, EPJC ST 155 (08) 101



- resonance-like structures disappear already by $1.2T_c$
- strong threshold enhancement above free case

  => indication of correlations
- height of bump in lattice and model are similar

- The correlators do not change significantly despite the melting of the bound states => it is difficult to distinguish bound state from threshold enhancement in lattice QCD

The role of the imaginary part for charmonium

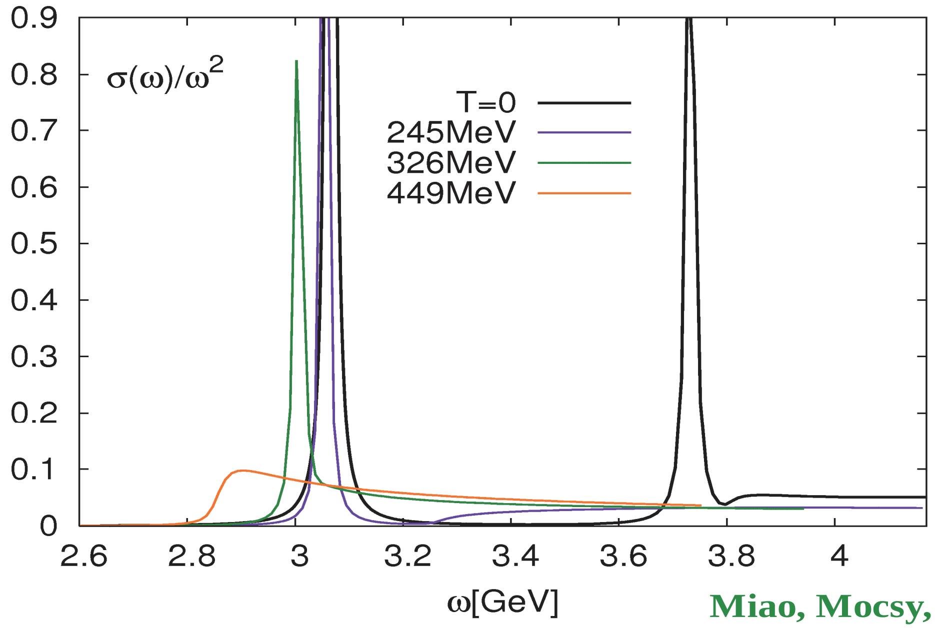
Take the upper limit for the real part of the potential allowed by lattice calculations

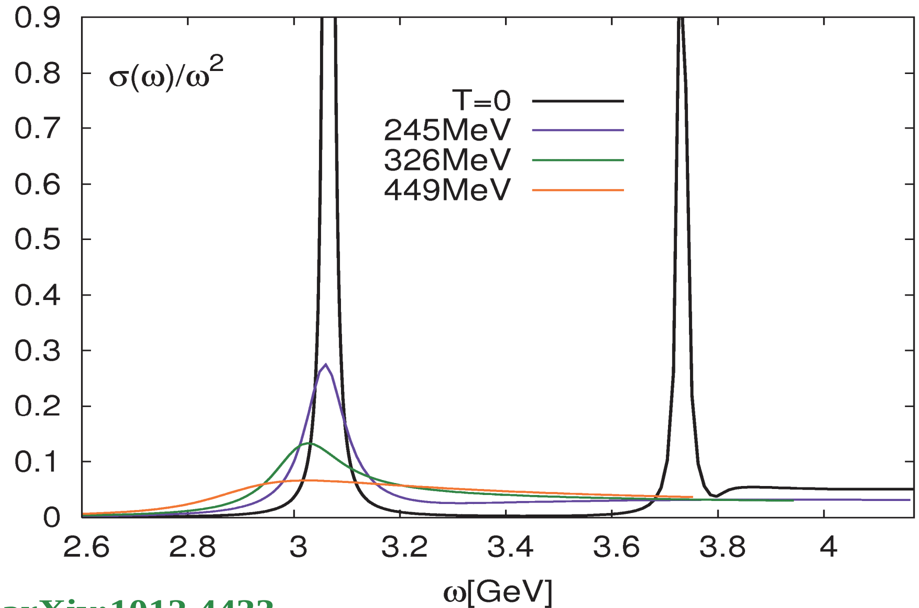
Mócsy, P.P., PRL 99 (07) 211602,

Take the perturbative imaginary part
Burnier, Laine, Vepsalainen JHEP 0801 (08) 043

Im $V_s(r) = 0$:
1S state survives for $T = 330$ MeV

imaginary part of $V_s(r)$ is included :
all states dissolves for $T > 240$ MeV





Miao, Mocsy, P.P., arXiv:1012.4433

no charmonium state could survive for $T > 240$ MeV
this is consistent with our earlier analysis of **Mócsy, P.P., PRL 99 (07) 211602** ($T_{dec} \sim 204 MeV$)
as well as with **Riek and Rapp, arXiv:1012.0019 [nucl-th]**

Petreczky on Wed

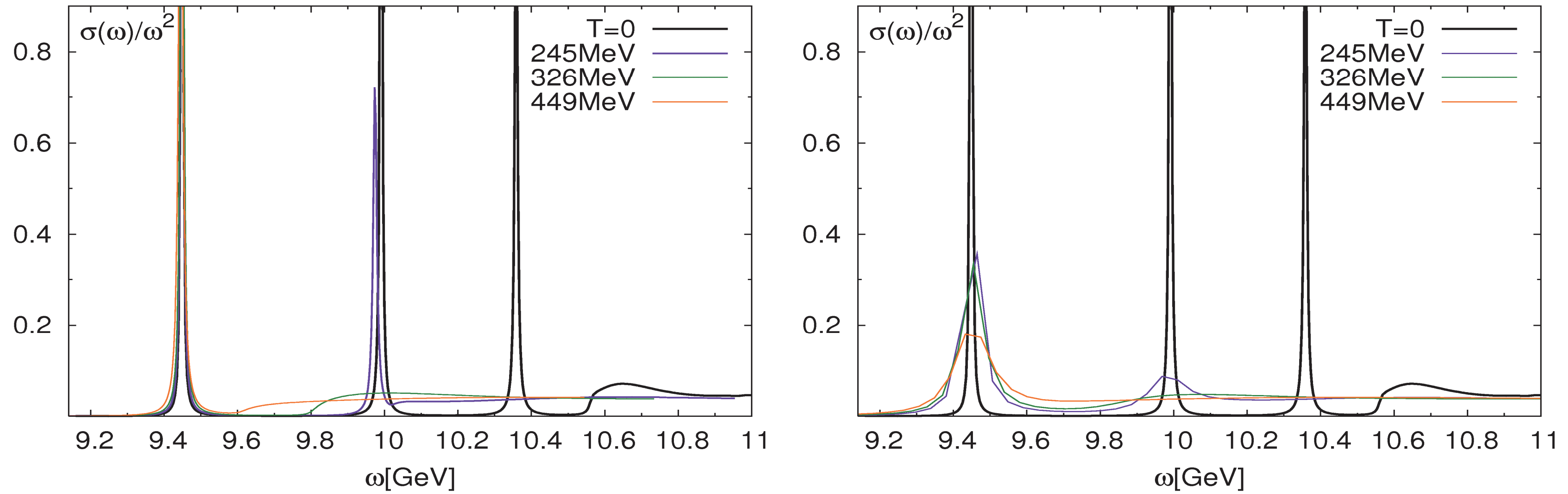
The role of the imaginary part for bottomonium

Take the upper limit for the real part of the potential allowed by lattice calculations
Mócsy, P.P., PRL 99 (07) 211602,

Take the perturbative imaginary part
Burnier, Laine, Vepsalainen JHEP 0801 (08) 043

Im $V_s(r)$ *=0:*
2S state survives for $T > 245$ MeV
1S state could survive for $T > 450$ MeV

with imaginary part:
2S state dissolves for $T > 245$ MeV
1S states dissolves for $T > 450$ MeV

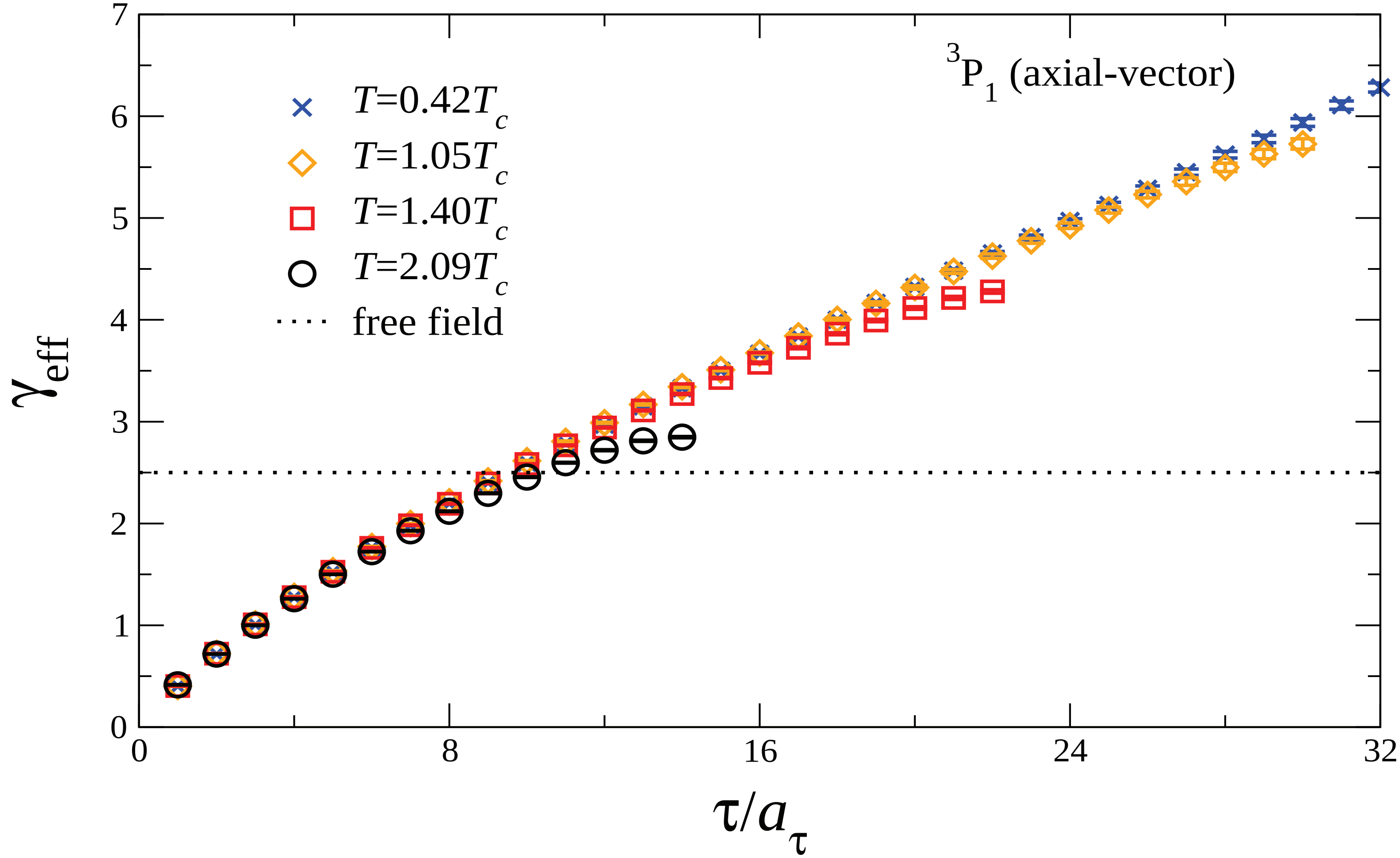


Miao, Mocsy, P.P., arXiv:1012.4433

Excited bottomonium states melt for $T \approx 250$ MeV ; 1S state melts for $T \approx 450$ MeV
this is consistent with our earlier analysis of **Mócsy, P.P., PRL 99 (07) 211602** ($T_{dec} \sim 204$MeV)
as well as with **Riek and Rapp, arXiv:1012.0019 [nucl-th]**

$\gamma_{eff} = d \ln G(\tau) / d \ln \tau$ **Ryan on Wed**

Effective power: P waves



- tendency to flatten out: power decay at large euclidean time.
- effective exponent tends towards noninteracting result at highest temperature we consider.

Quarkonium dynamics in sQGP as a stochastic process

When M_{HQ} is sufficiently larger than T, the dynamics of each heavy quark can be described by

$$\frac{dp_i}{dt} = -\eta p_i + \xi_i - \nabla_i U, \tag{1}$$

where

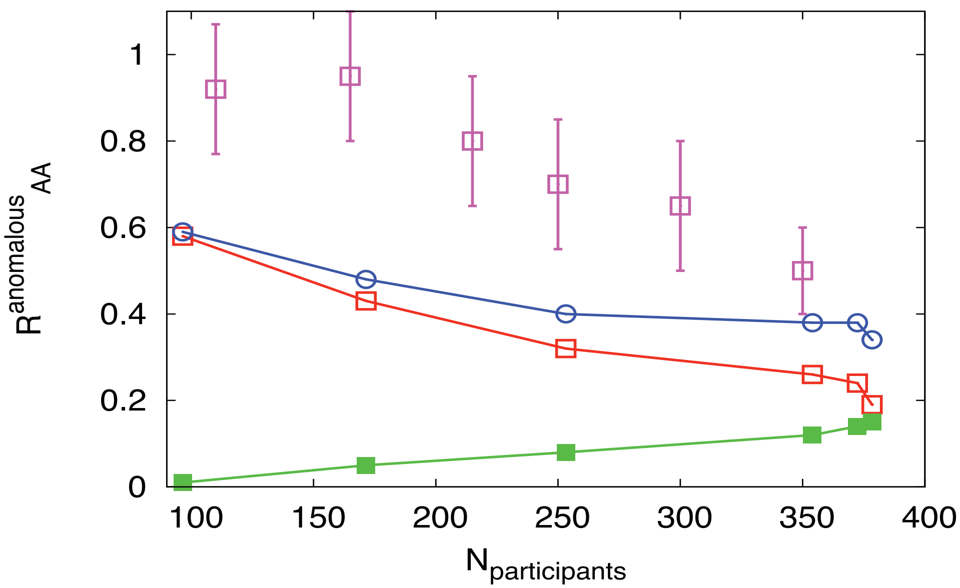
$$\langle \xi_i(t) \xi_j(0) \rangle = \kappa \delta_{ij} \delta(t). \tag{2}$$

Requiring thermalization to temperature T yields the Einstein relation between noise and dissipation:

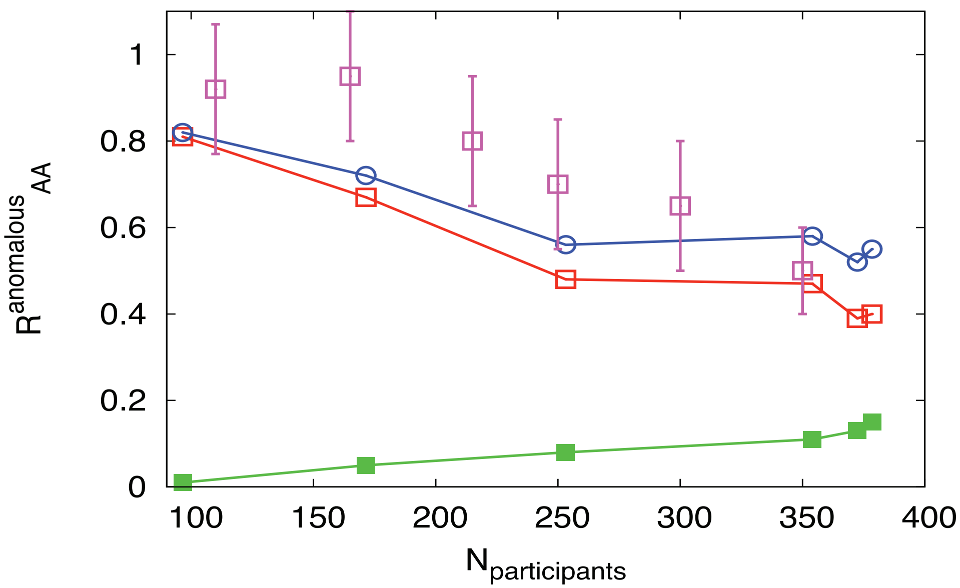
$$\eta = \frac{\kappa}{2MT}. \tag{3}$$

Anomalous J/ψ suppression for two values of T_c

For $T_c = 165\ \mathrm{MeV}$:

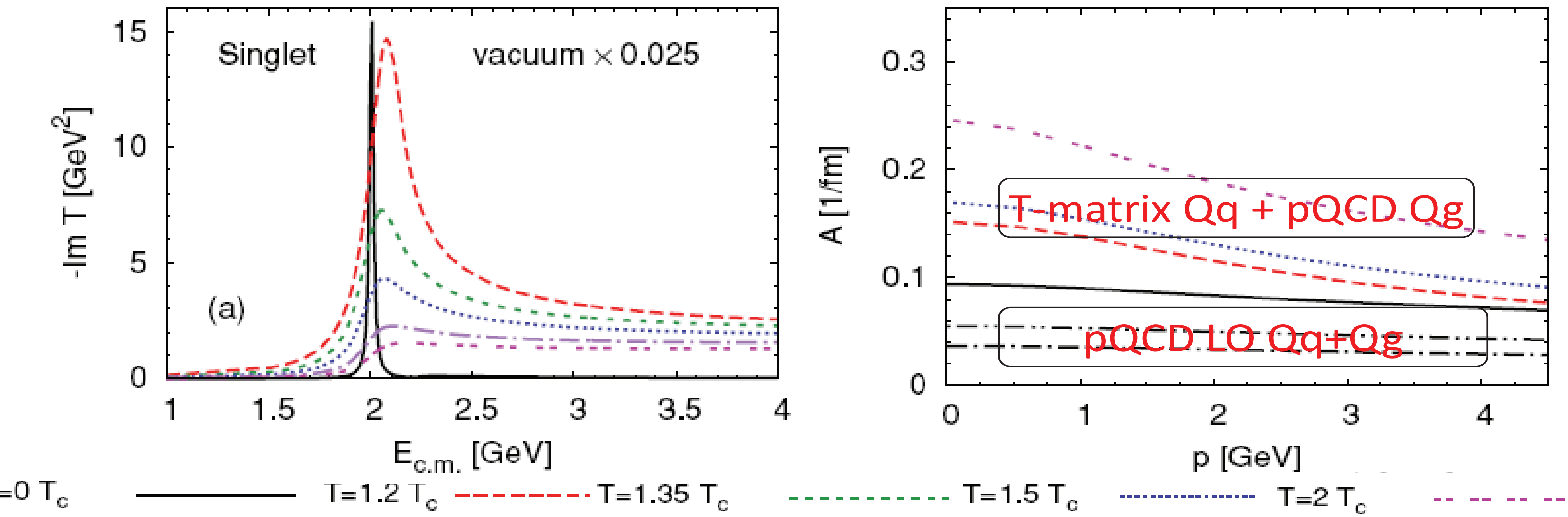


For $T_c = 190\ \mathrm{MeV}$:



Similar to the results of Zhao and Rapp

Relaxation rate: T-matrix (continue)



- **the color single and antitriplet channels feature broad Feshbach resonance up to ~1.5 T_C**
- **this resonance correlation will be reiterated in our hadronization-coalescence model**

- **T-matrix relaxation rate: a factor ~4-5 larger than LO pQCD at T=1.2 T_c**
- **T-dependent behavior: screening potential vs light parton density**
- **p-dependent behavior: less contribution from threshold Feshbach resonance as p increases**

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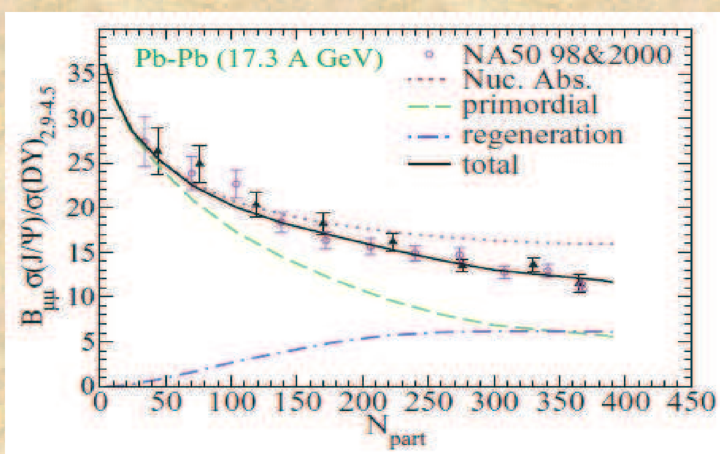
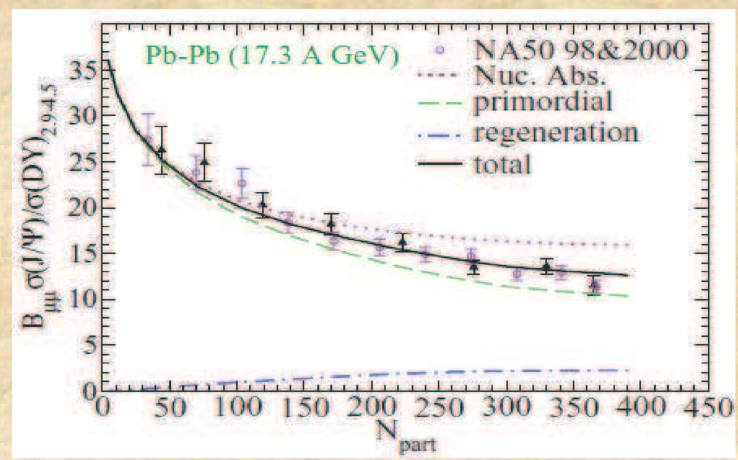
Compare to data from SPS NA50

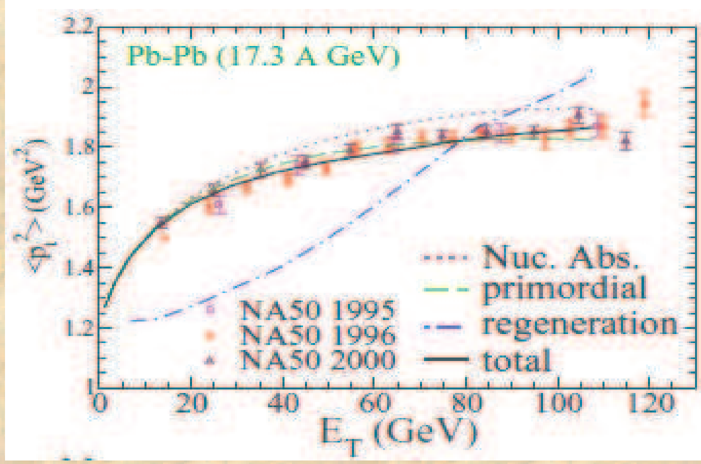
weak binding (V=F) strong binding (V=U)

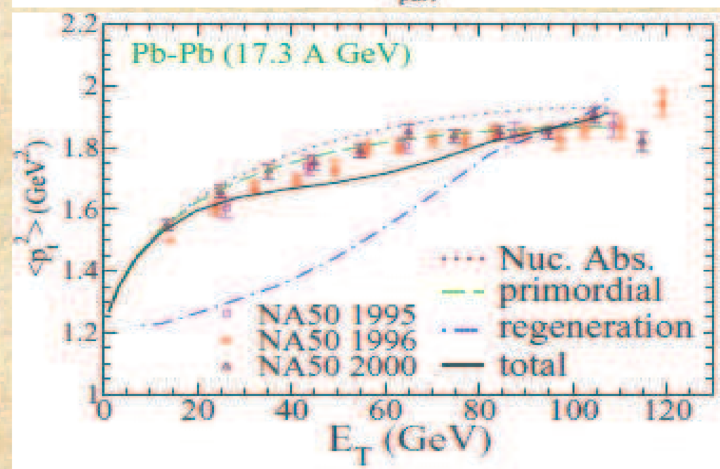
incl. J/psi yield





trans. momentum





- primordial production dominates in strong binding scenario

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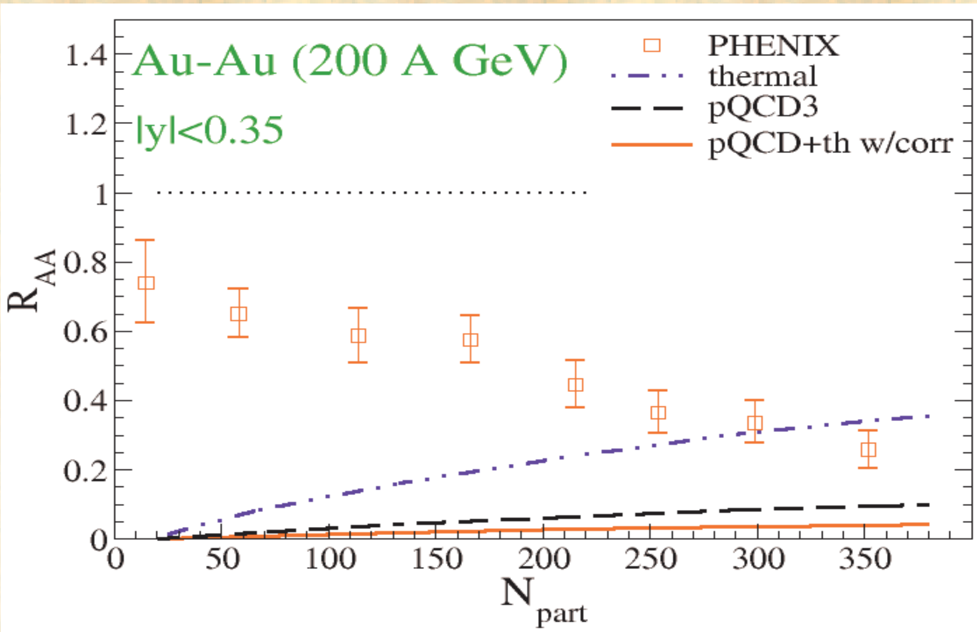
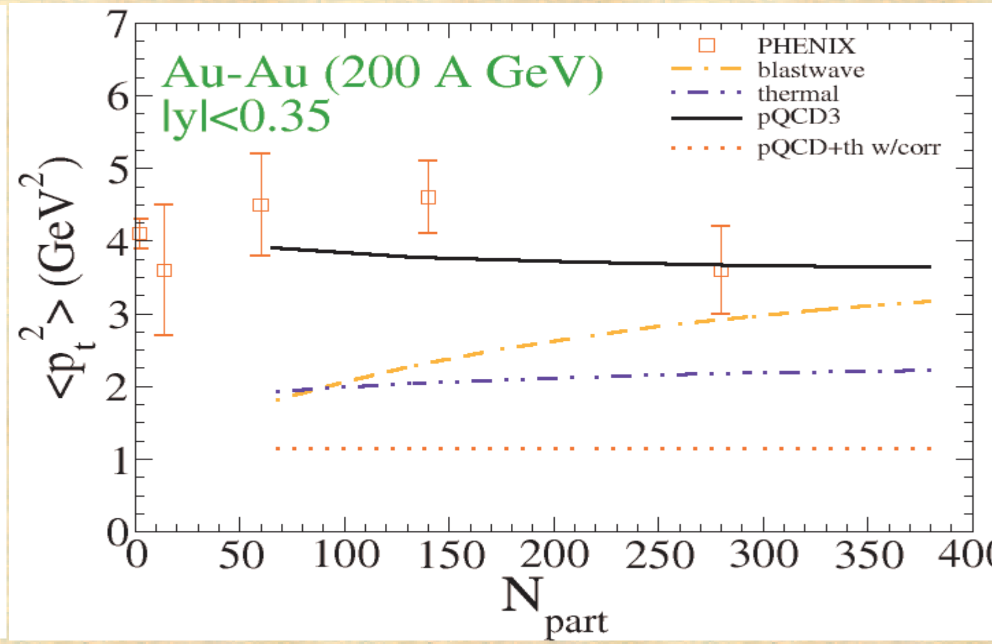
Zhao on Thu

Ψ Regeneration from Different c Spectra





- strongest regeneration from thermal charm spectra
- pQCD spectra lead to larger $<p_t^2>$ of regenerated Ψ
- c   angular correlation lead to small reg. and low $<p_t^2>$
- blastwave overestimates $<p_t^2>$ from thermal charm spectra

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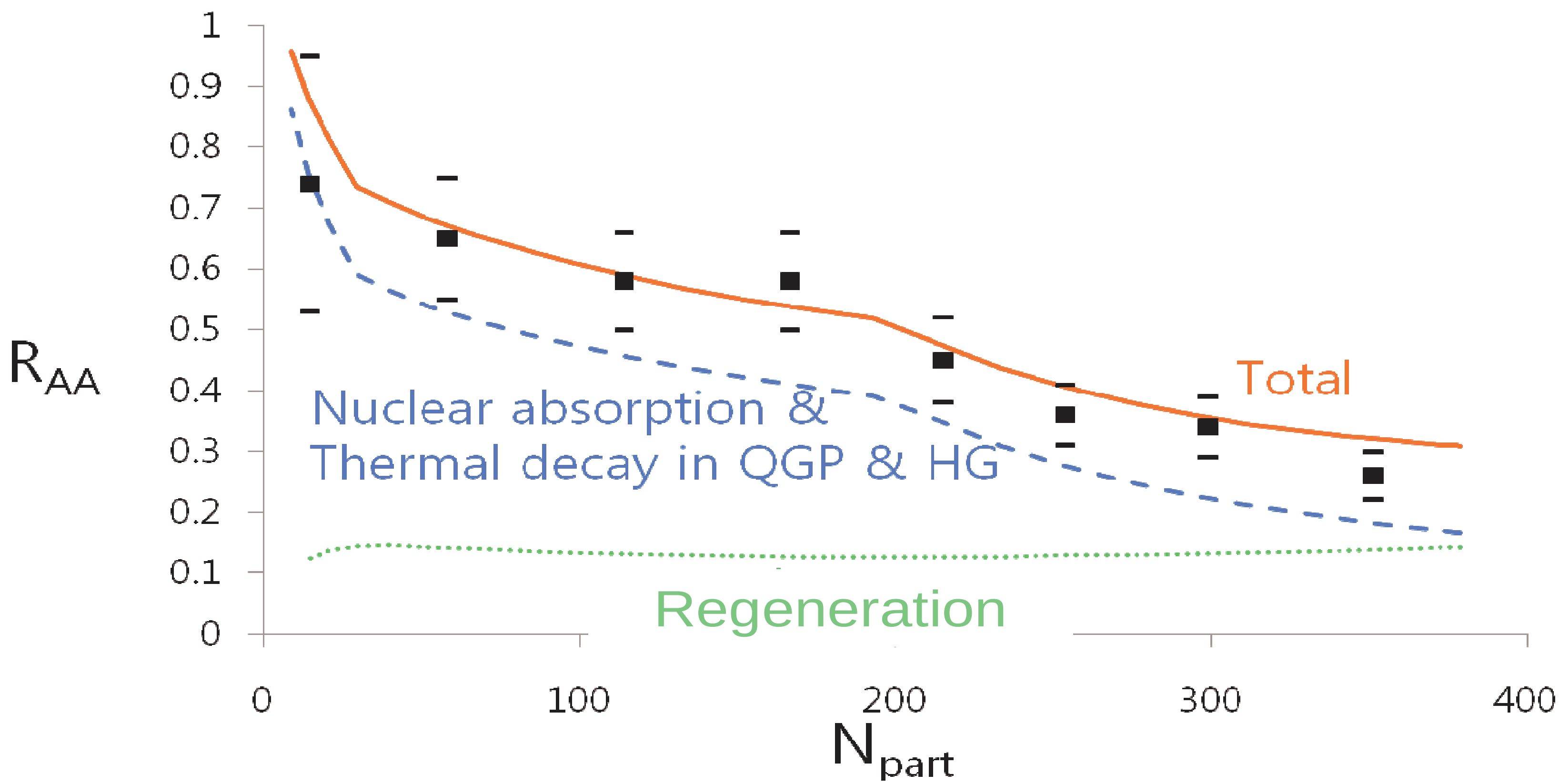
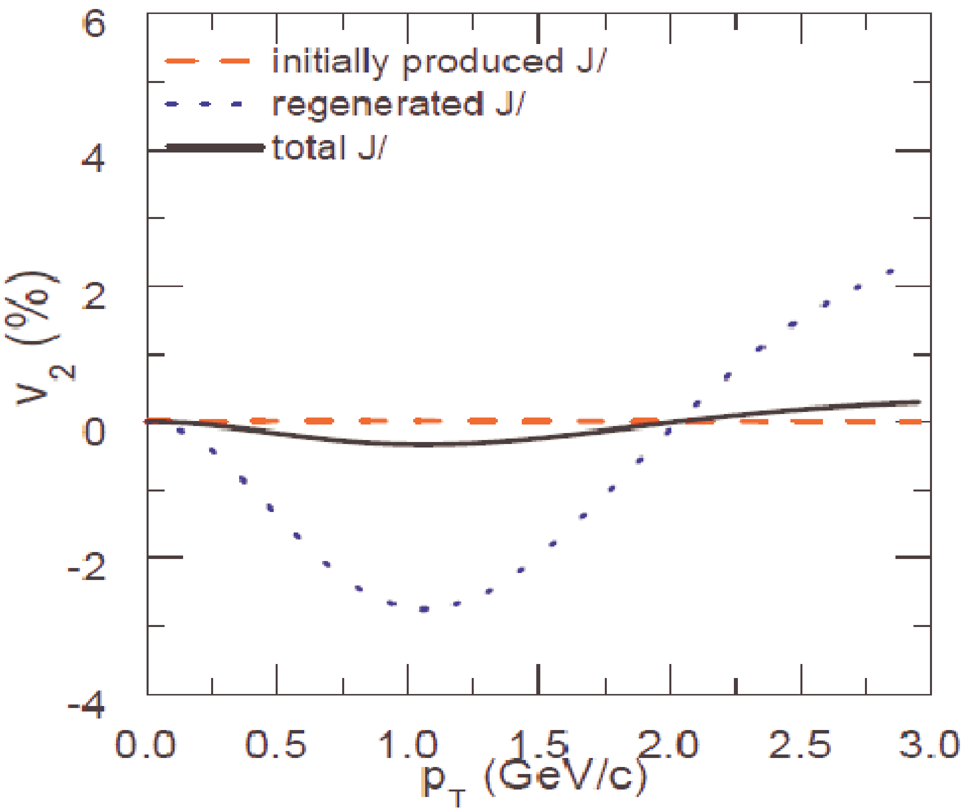
R_{AA} of J/ψ as a function of N_{part}

(near midrapidity in Au+Au collision at √s=200 GeV)



Song on Wed

v_2 of J/ψ (b=9 fm)



<Assumption>

1. Elastic cross section of J/ψ(color singlet) in QGP is much smaller than that of charm quark.
2. For J/ψ, inelastic collision is more effective than elastic collision in QGP because of its small binding energy and large radius at high T.

Details likely matter

- interactions - Newtonian potential, Bethe-Salpeter, ...

  quantum transport Blaschke on Wed

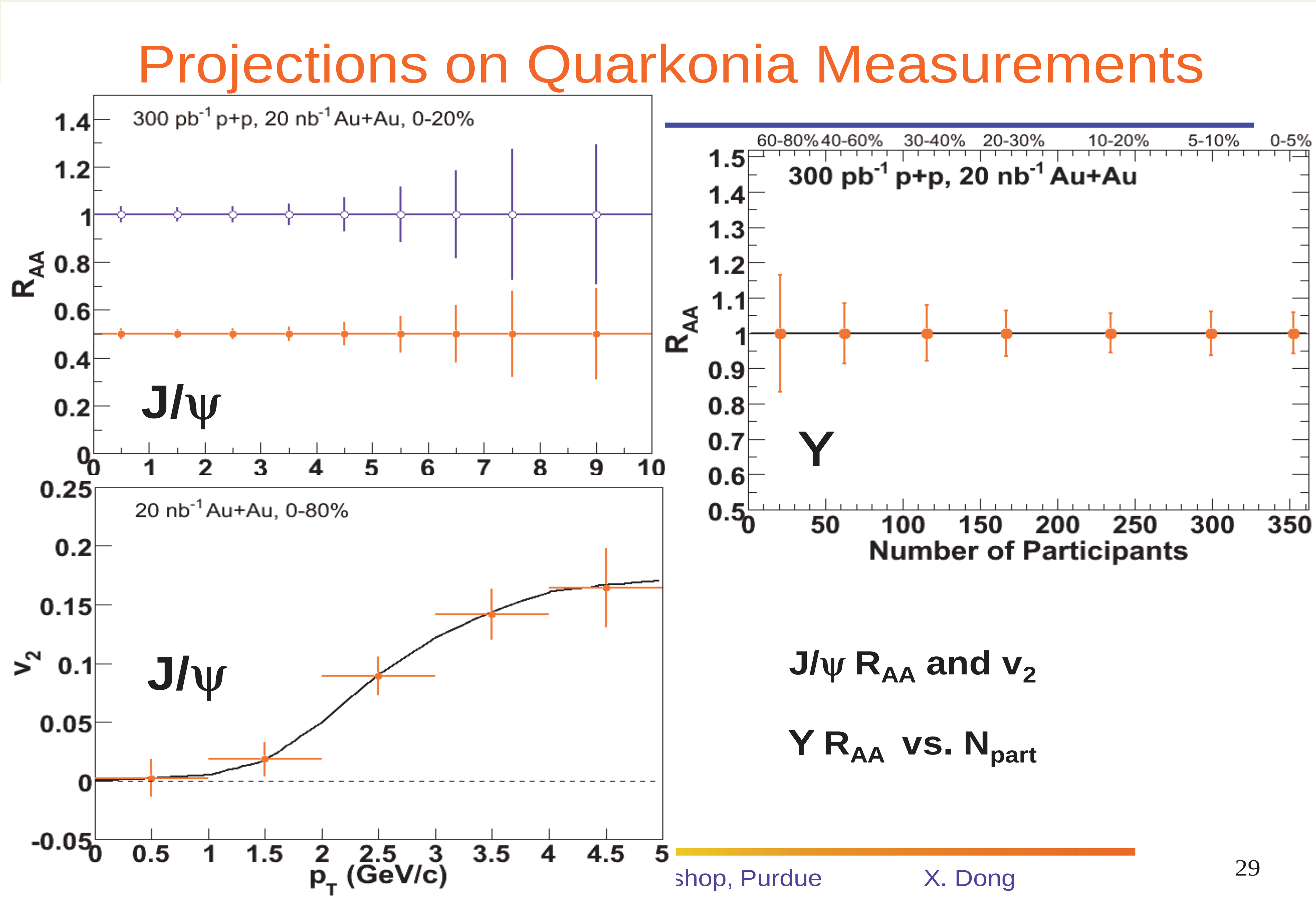
- initial conditions (production, Cronin, ...)

- medium evolution (real hydro, realistic EOS, ...)

- freezeout/hadronization (coalescence or sg else)

$\rightarrow$ crosschecks: open heavy flavor, R_{AA} vs v_2, bottom?

STAR MTD　　　　Dong today



Summary

- Lot of exciting progress, but theory still evolving - especially for quarkonia, and nuclear collisions. Many puzzles.

- Crucial to settle the light-heavy quenching puzzle - the RHIC sQGP paradigm hangs on it. Independent D and B measurements needed, with consistent results from multiple experiments, both at RHIC and LHC. cnm Looking forward to RHIC upgrades + LHC data.

- Heavy quarkonia are an important cross-check - models should strive to address both open and hidden heavy flavor observables. Quarkonium v_2 measurements, please.

- Lots of homework on the theory side. Heavy Flavor Transport Collaboration?

Stay tuned...

Thanks to all organizers

Y. Akiba (RBRC), A. Dion (SUNY), H. Huang (UCLA) , H. Ritter (LBNL), R. Rapp (TAMU), C. Silva (LANL), W. Xie (PURDUE)

+ the Purdue Conference Division

and to everyone for coming

Qiu on Tue

Role of heavy quark production in p+p

- **Gluon fusion dominates heavy quark production:**

  Provide the complimentary constraint on ΔG

  But, unlikely to be the channel to give the best precision on ΔG

- **A_N – beyond leading collinear parton approximation:**

  ✧ P_T distribution of open Charm meson production

  – tri-gluon correlation

  ✧ Heavy quarkonium production

  – Sensitivity on the production mechanism

Qiu on Tue

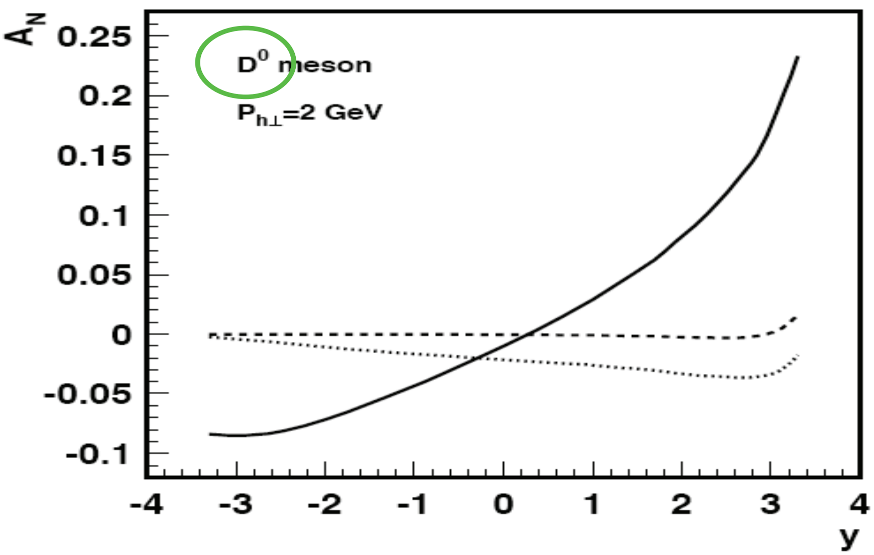
SSA of D-meson production at RHIC

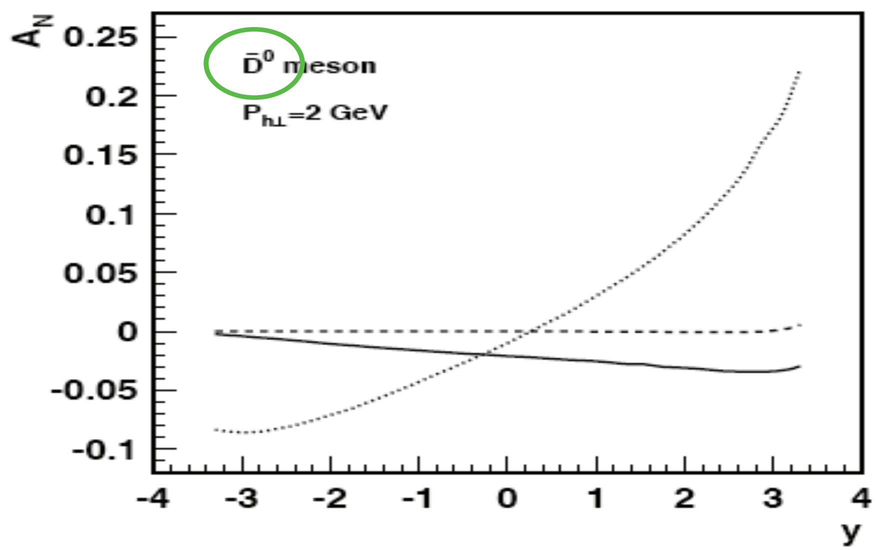
❑ Model for tri-gluon correlation functions:

$$T_G^{(f,d)}(x,x) = \lambda_{f,d} G(x) \qquad \lambda_{f,d} = \pm\lambda_F = \pm 0.07\text{GeV}$$

$$D - \text{meson} \propto T_G^{(f)} + T_G^{(d)} \qquad \overline{D} - \text{meson} \propto T_G^{(f)} - T_G^{(d)}$$

❑ Rapidity: $\sqrt{s} = 200\ \text{GeV} \quad \mu = \sqrt{m_c^2 + P_{h\perp}^2} \quad m_c = 1.3\ \text{GeV}$





Solid: (1) $\lambda_f = \lambda_d = 0.07\ \text{GeV}$ $\quad T_G^{(f)} = T_G^{(d)}$

Dashed: (2) $\lambda_f = \lambda_d = 0$ $\quad T_G^{(f)} = T_G^{(d)} = 0$

Dotted: (3) $\lambda_f = -\lambda_d = 0.07\ \text{GeV}$ $\quad T_G^{(f)} = -T_G^{(d)}$

No intrinsic Charm included