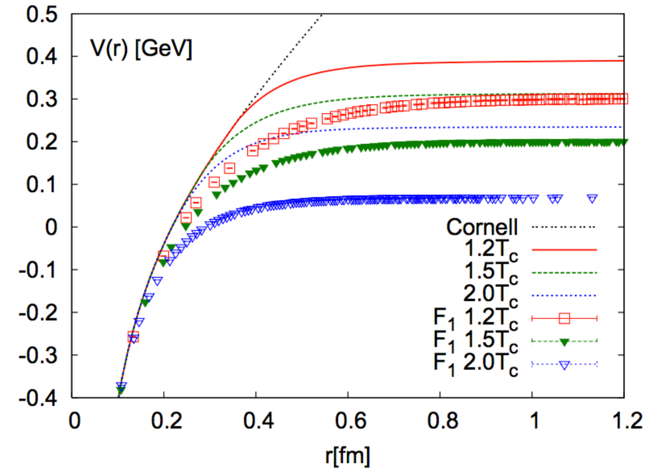
Bottomonia production in AA collisions

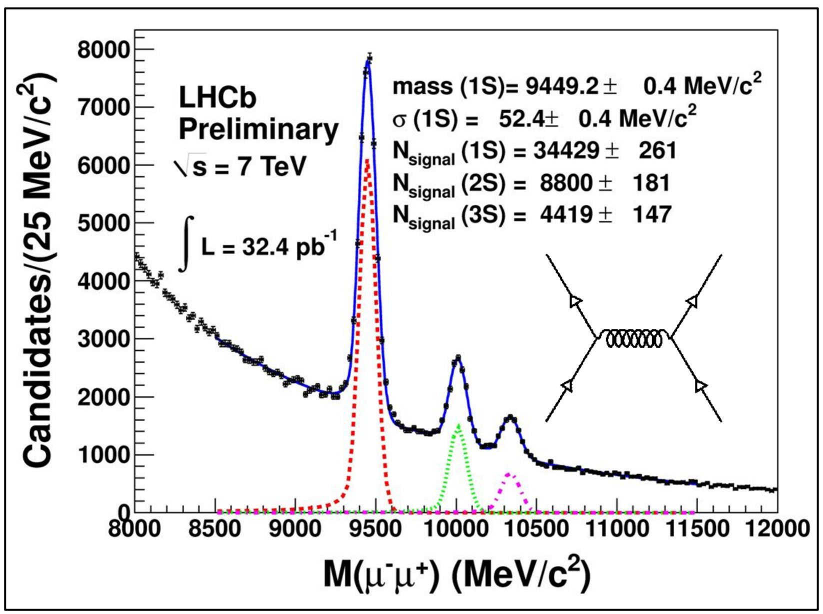
Michael Strickland
Kent State University
Kent, OH USA

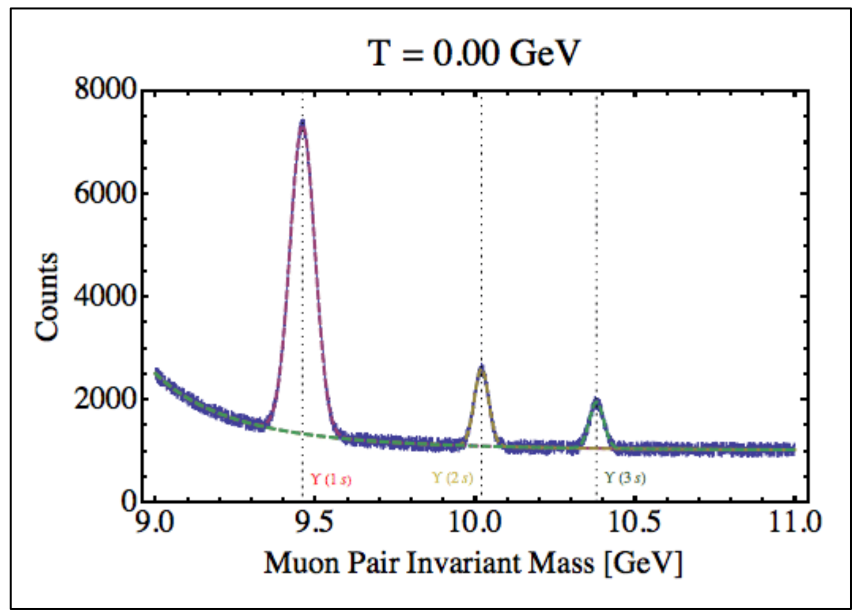
6th Workshop of the APS Topical Group on Hadronic Physics
April 8 2015

Heavy Quarkonium Suppression

- In a high temperature quark gluon plasma we expect **weaker color binding** (Debye screening + asymptotic freedom)
- Also, high energy plasma particles which slam into the bound states cause them to have shorter lifetimes → **larger spectral widths**

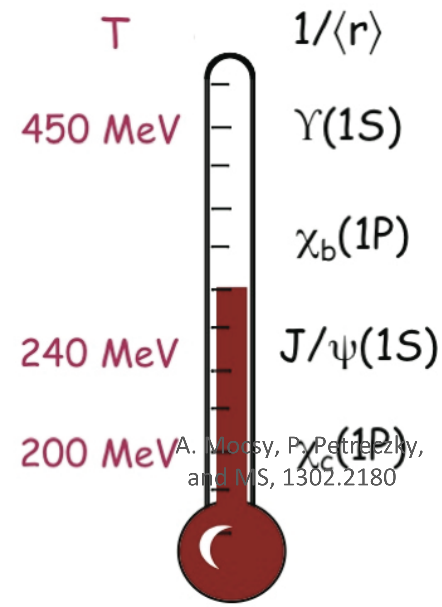






Why Bottomonia in AA?

- Heavy quark effective theory on surer footing than for charmonia
- Cold nuclear matter (CNM) effects are much smaller than for the charmonia
- The masses of bottomonia are much higher than the temperature (T < 1 GeV) generated in HICs → bottomonia production dominated by initial hard scatterings
- Since bottom quarks and anti-quarks are relatively rare in LHC HICs, the probability for regeneration of bottomonia through statistical recombination is much smaller than for charm quarks
[see e.g. E. Emerick, X. Zhao, and R. Rapp, arXiv:1111.6537]

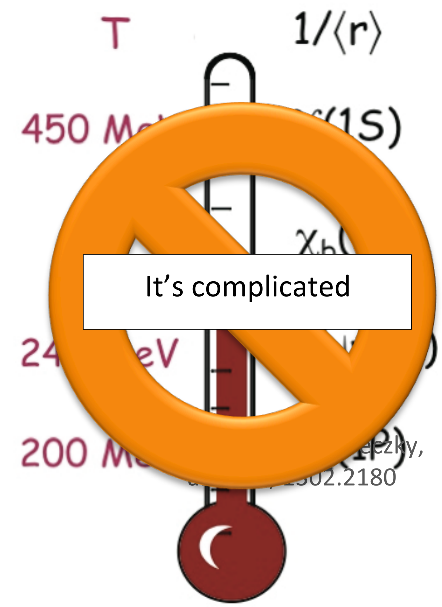


A. Mocsy, P. Petreczky, and MS, 1302.2180

Why Bottomonia in AA?

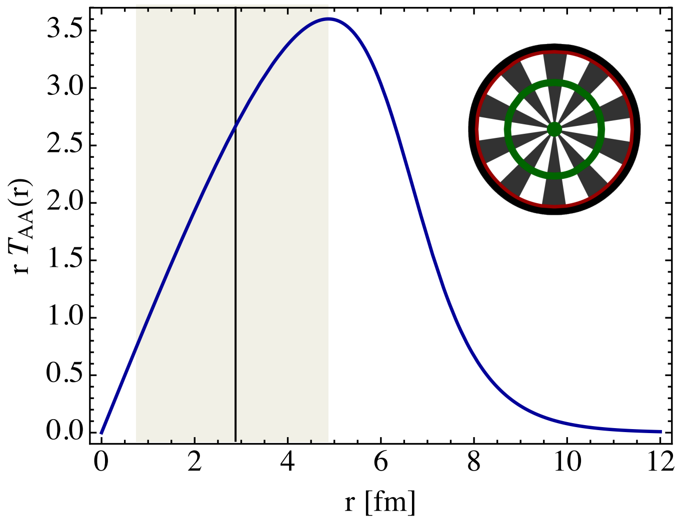
- Heavy quark effective theory on surer footing than for charmonia
- Cold nuclear matter (CNM) effects are much smaller than for the charmonia
- The masses of bottomonia are much higher than the temperature (T < 1 GeV) generated in HICs → bottomonia production dominated by initial hard scatterings
- Since bottom quarks and anti-quarks are relatively rare in LHC HICs, the probability for regeneration of bottomonia through statistical recombination is much smaller than for charm quarks

[see e.g. E. Emerick, X. Zhao, and R. Rapp, arXiv:1111.6537]



Good news and bad news

- Large binding energies → short formation times
- Formation time for Υ(1s), for example, is ≈ 0.2 fm/c
- This comes at a cost: **We need to reliably model the early-time dynamics since quarkonia are born into it**
- In addition, production vertices can be anywhere in the transverse plane, not just the central hottest region
- For example, for a central collision the most probable <r> ~ 3.2 fm

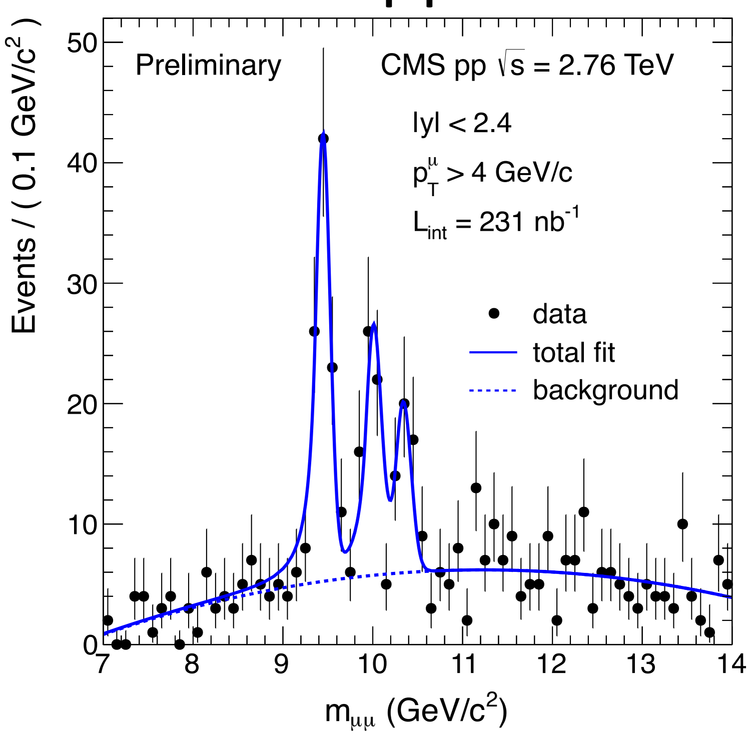


- **Therefore, we also need to reliably describe the dynamics in the full transverse plane**

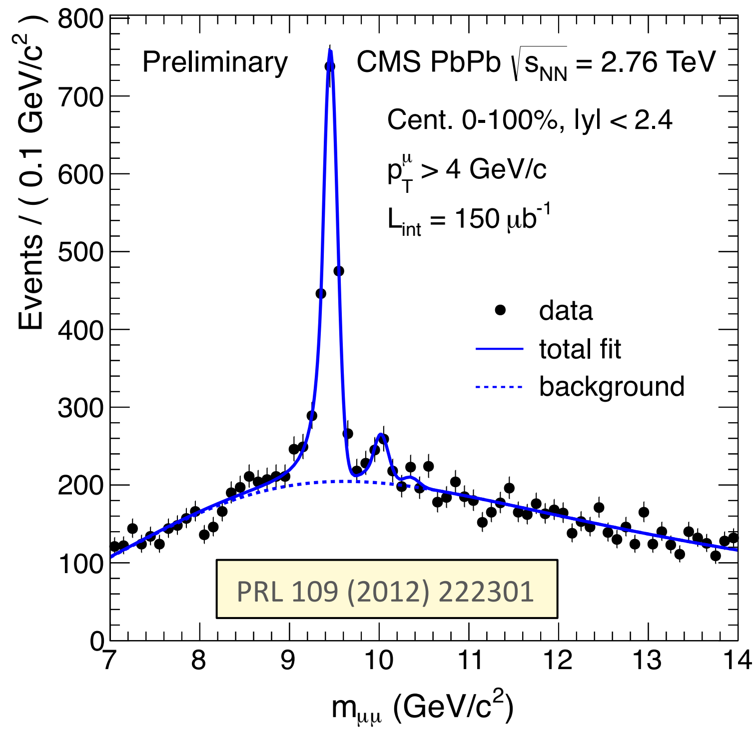
2011 CMS Data

The **CMS** (Compact Muon Solenoid) experiment has measured bottomonium spectra for both pp and Pb-Pb collisions. With this we can extract R_{AA} experimentally

p-p

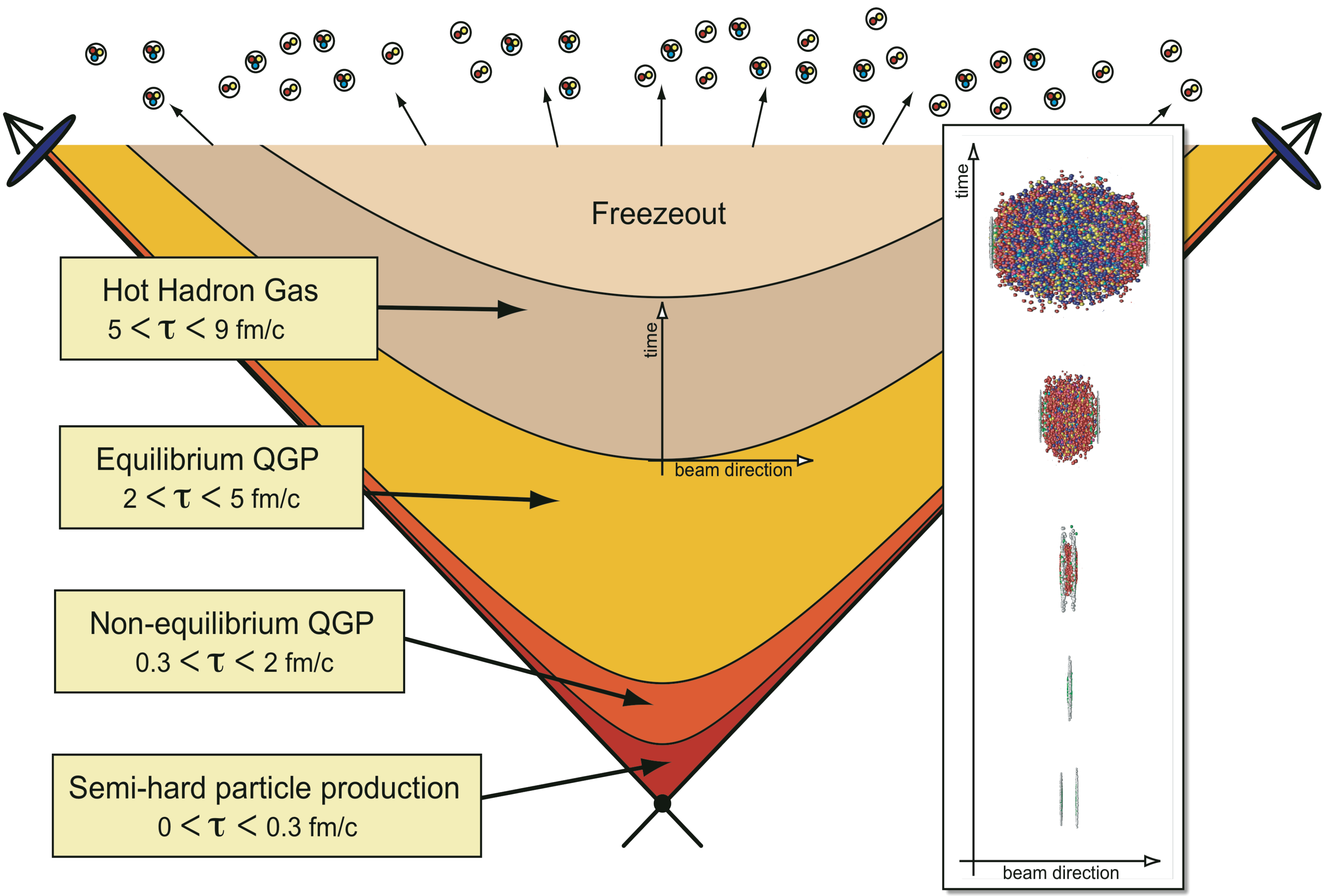


Pb-Pb

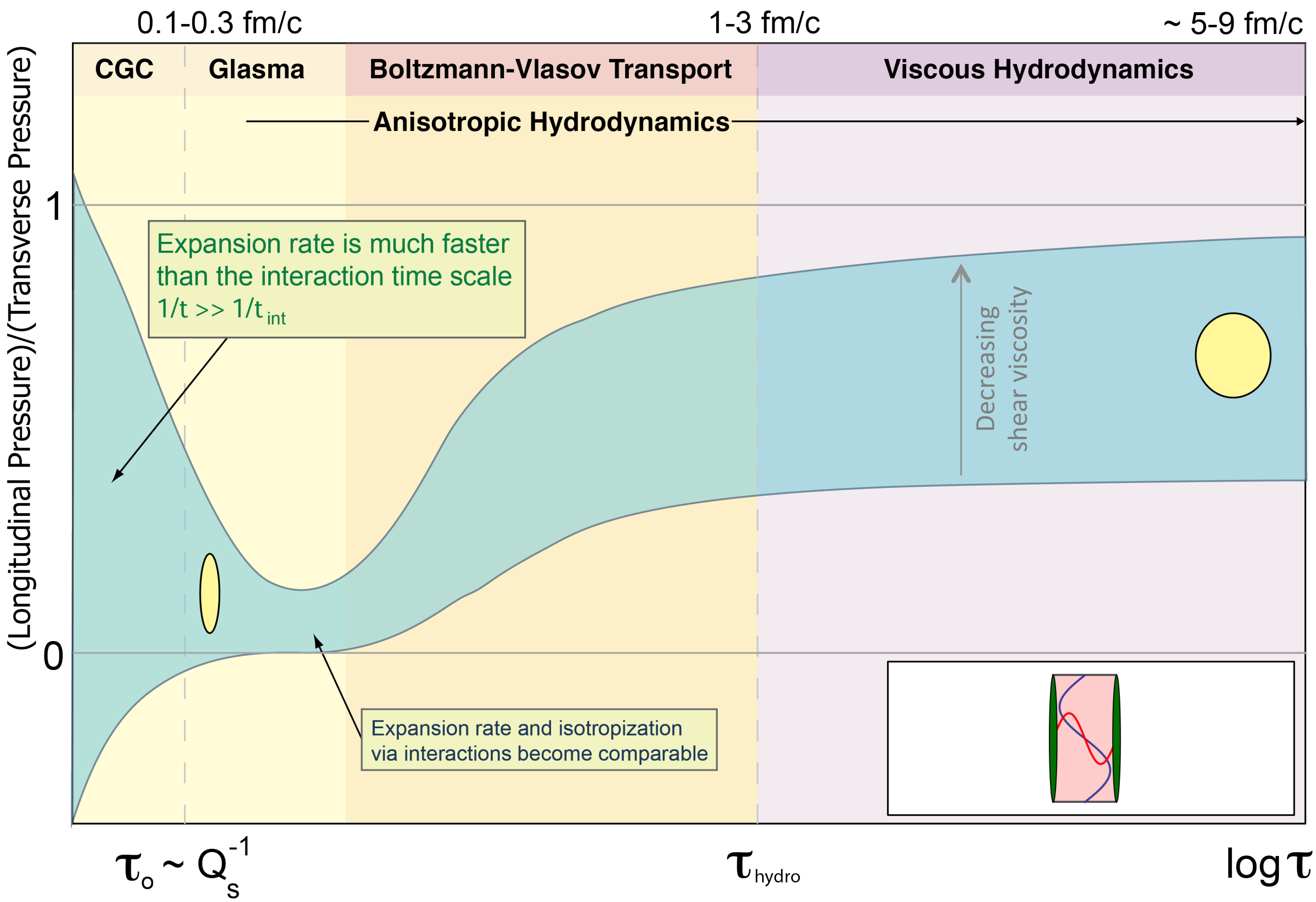


QGP Dynamics

LHC Heavy Ion Collision Timescales



QGP momentum anisotropy cartoon



Anisotropic Hydrodynamics Basics

M. Martinez and MS, 1007.0889
W. Florkowski and R. Ryblewski, 1007.0130

Viscous Hydrodynamics Expansion

$$f(\tau,\mathbf{x},\mathbf{p}) = \underbrace{f_{\rm eq}(\mathbf{p}, T(\tau,\mathbf{x}))} + \delta f$$

Isotropic in momentum space

Anisotropic Hydrodynamics Expansion

Treat this term "perturbatively"

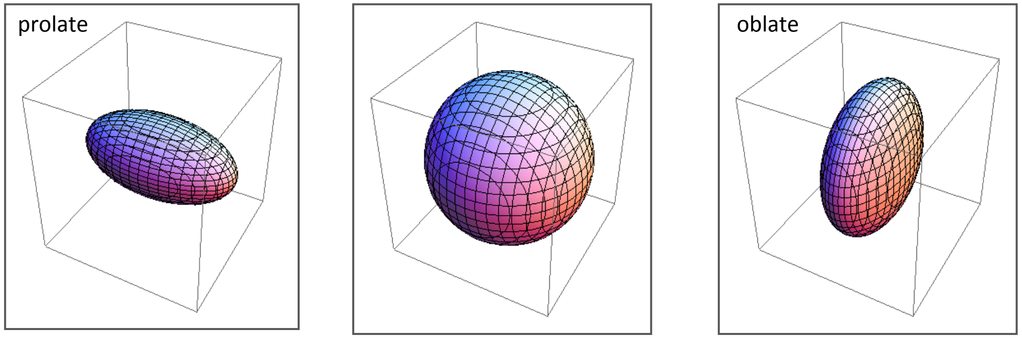
D. Bazow, U. Heinz, and MS, 1311.6720

$$f(\tau,\mathbf{x},\mathbf{p}) = f_{\rm aniso}(\mathbf{p}, \underbrace{\Lambda(\tau,\mathbf{x})}_{T_\perp}, \underbrace{\xi(\tau,\mathbf{x})}_{\text{anisotropy}}\ ) + \delta\tilde{f}$$

→ "Romatschke-Strickland" form in LRF

$$f^{LRF}_{\rm aniso} = f_{\rm iso}\left(\frac{\sqrt{\mathbf{p}^2 + \xi(\mathbf{x},\tau) p_z^2}}{\Lambda(\mathbf{x},\tau)}\right)$$

$$\xi = \frac{\langle p_T^2\rangle}{2\langle p_L^2\rangle} - 1$$



$-1 < \xi < 0$ $\qquad$ $\xi = 0$ $\qquad$ $\xi > 0$

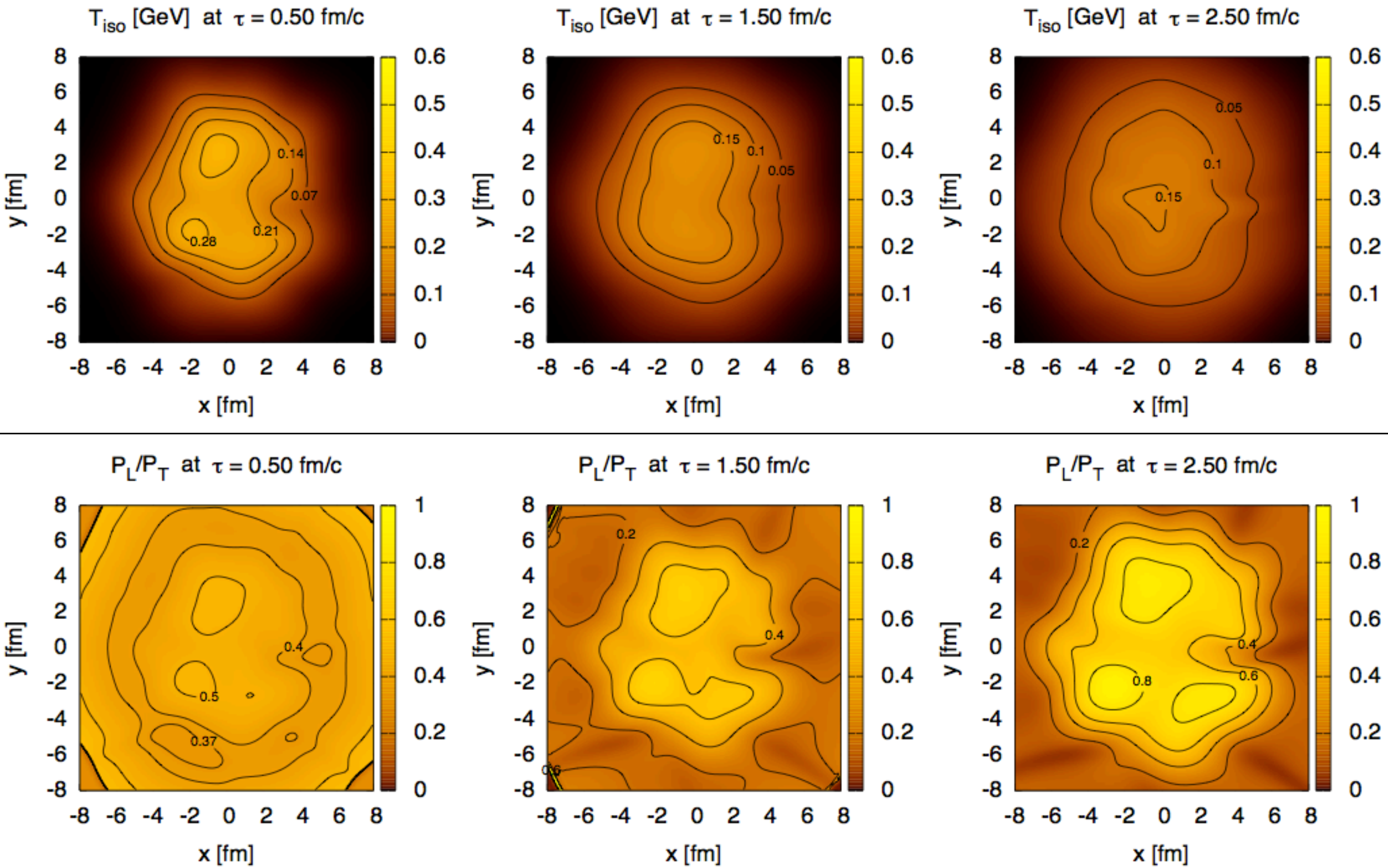
$\mathcal{P}_L > \mathcal{P}_T$ $\qquad$ $\mathcal{P}_L = \mathcal{P}_T$ $\qquad$ $\mathcal{P}_L < \mathcal{P}_T$

Transverse Dynamics

M. Martinez, R. Ryblewski, and MS, 1204.1473

Pb-Pb @ 2.76 TeV
T_0 = 600 MeV
τ_0 = 0.25 fm/c
b = 7 fm

$$\frac{\eta}{\mathcal{S}} = \frac{1}{4\pi}$$



Heavy Quark Potential

Anisotropic Heavy Quark Potential

Using the real-time formalism one can express the potential in terms of the *static* advanced, retarded, and Feynman propagators

$$V(\mathbf{r},\xi) = -g^2 C_F \int \frac{d^3\mathbf{p}}{(2\pi)^3} \left(e^{i\mathbf{p}\cdot\mathbf{r}} - 1\right) \frac{1}{2} \left(D^{*L}_{R} + D^{*L}_{A} + D^{*L}_{F} \right)$$

Real part can be written as

$$\mathrm{Re}[V(\mathbf{r},\xi)] = -g^2 C_F \int \frac{d^3\mathbf{p}}{(2\pi)^3}\, e^{i\mathbf{p}\cdot\mathbf{r}} \frac{\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2}{(\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2)(\mathbf{p}^2 + m_\beta^2) - m_\delta^4}$$

With <u>direction-dependent masses</u>, e.g.

$$m_\alpha^2 = -\frac{m_D^2}{2p_\perp^2\sqrt{\xi}} \left(p_z^2 \arctan\sqrt{\xi} - \frac{p_z \mathbf{p}^2}{\sqrt{\mathbf{p}^2 + \xi p_\perp^2}} \arctan\frac{\sqrt{\xi} p_z}{\sqrt{\mathbf{p}^2 + \xi p_\perp^2}} \right)$$

Anisotropic potential calculation: Dumitru, Guo, and MS, 0711.4722 and 0903.4703
Gluon propagator in an anisotropic plasma: Romatschke and MS, hep-ph/0304092

Full anisotropic potential

- Result can be parameterized as a Debye-screened potential with a direction-dependent Debye mass

$$V_{\rm screened}(r,\theta,\xi,\Lambda) = -C_F \alpha_s \frac{e^{-\mu(\theta,\xi,\Lambda) r}}{r}$$

D Bazow and MS, 1112.2761; MS, 1106.2571.

- The potential also has an imaginary part coming from the Landau damping of the exchanged gluon!

Internal Energy

$$V_{\rm R}(\mathbf{r}) = -\frac{\alpha}{r}\,(1+\mu\,r)\exp\left(-\mu\,r\right) + \frac{2\sigma}{\mu}\left[1-\exp\left(-\mu\,r\right)\right] - \sigma\,r\,\exp(-\mu\,r) - \frac{0.8\,\sigma}{m_Q^2\,r}$$

Dumitru, Guo, Mocsy, and MS, 0901.1998

- This imaginary part also exists in the isotropic case
Laine et al hep-ph/0611300

- Used this as a model for the free energy (F) and also obtained internal energy (U) from this.

$$V_{\rm I}(\mathbf{r}) = -C_F \alpha_s p_{\rm hard}\left[\phi(\hat{r}) - \xi\left(\psi_1(\hat{r},\theta)+\psi_2(\hat{r},\theta)\right)\right]$$

Dumitru, Guo, and MS, 0711.4722 and 0903.4703
Burnier, Laine, Vepsalainen, arXiv:0903.3467 (aniso)

Solve the 3d Schrödinger EQ with complex-valued potential

Yager-Elorriaga and Ms; 0901.1998; Margotta, MS, et al, 1101.4651

Obtain real and imaginary parts of the binding energies for the $\Upsilon(1s)$, $\Upsilon(2s)$, $\Upsilon(3s)$, χ_{b1}, and χ_{b2}

Full anisotropic potential

- Result can be parameterized as a Debye-screened potential with a direction-dependent Debye mass
- The potential also has an imaginary part coming from the Landau damping of the exchanged gluon!
- This imaginary part also exists in the isotropic case
  Laine et al hep-ph/0611300
- Used this as a model for the free energy (F) and also obtained internal energy (U) from this.

$$V_{\rm screened}(r,\theta,\xi,\Lambda) = -C_F\alpha_s \frac{e^{-\mu(\theta,\xi,\Lambda)r}}{r}$$

D Bazow and MS, 1112.2761; MS, 1106.2571.

Internal Energy

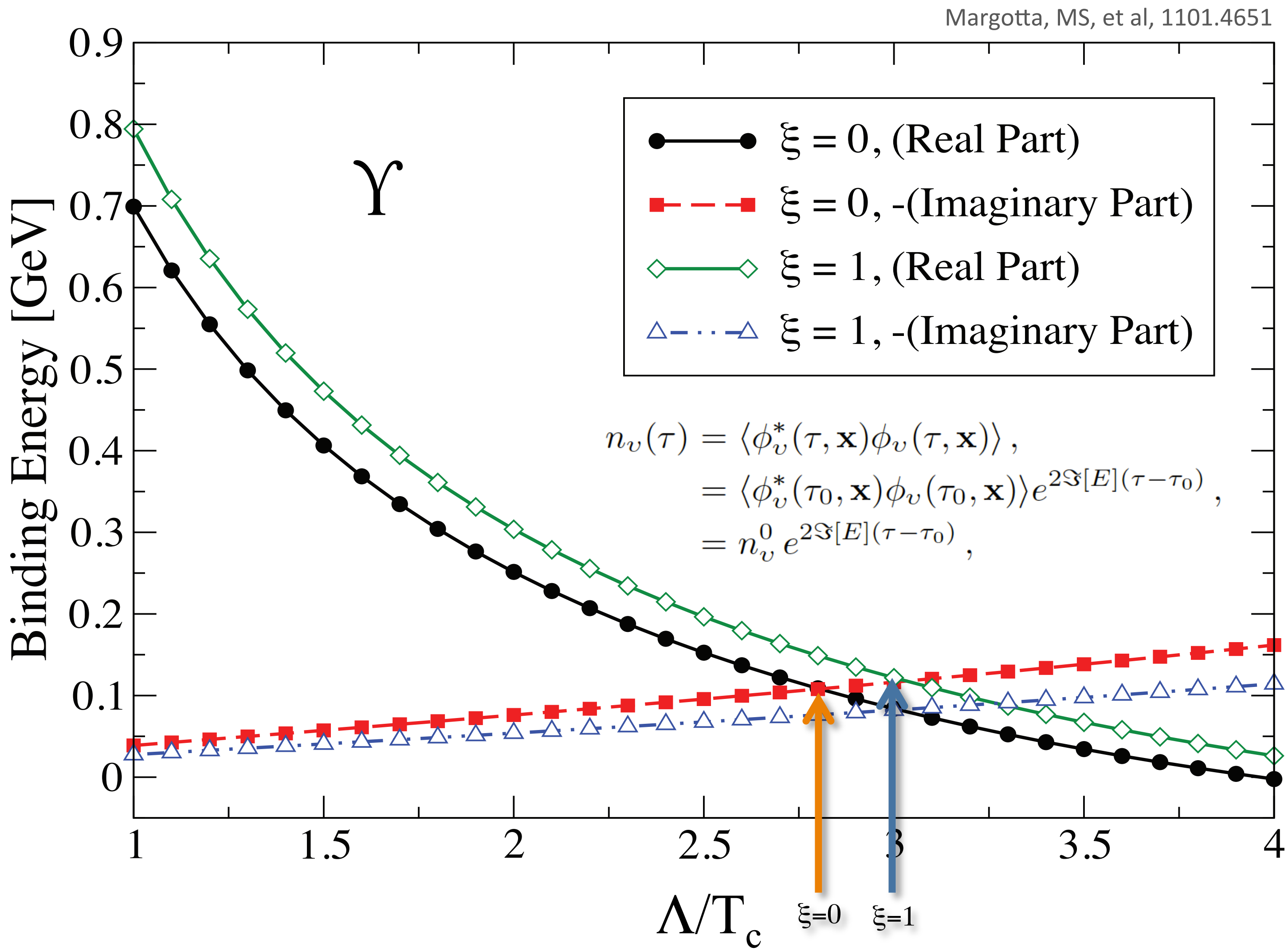
$$\begin{aligned} V_{\rm R}(\mathbf{r}) = &-\frac{\alpha}{r}\left(1+\mu\, r\right)\exp\left(-\mu\, r\right) \\ &+\frac{2\sigma}{\mu}\left[1-\exp\left(-\mu\, r\right)\right] \\ &-\sigma\, r\, \exp(-\mu\, r) - \frac{0.8\,\sigma}{m_Q^2\, r} \end{aligned}$$

Dumitru, Guo, Mocsy, and MS, 0901.1998

$$V_{\rm I}(\mathbf{r}) = -C_F\alpha_s p_{\rm hard}\left[\phi(\hat{r}) - \xi\left(\psi_1(\hat{r},\theta)+\psi_2(\hat{r},\theta)\right)\right]$$

Dumitru, Guo, and MS, 0711.4722 and 0903.4703
Burnier, Laine, Vepsalainen, arXiv:0903.3467 (aniso)

Results for the $\Upsilon(1s)$ binding energy



The suppression factor

- Resulting decay rate $\Gamma_T \equiv -2\,\mathrm{Im}[E_{bind}]$ is a function of τ, $x_\perp$, and ς (spatial rapidity). First we need to integrate over proper time

$$\bar{\gamma}(\mathbf{x}_\perp, p_T, \varsigma, b) \equiv \int_{\max(\tau_{\rm form}(p_T),\tau_0)}^{\tau_f} d\tau\, \Gamma_T(\tau, \mathbf{x}_\perp, \varsigma, b)$$

- From this we can extract R_{AA}

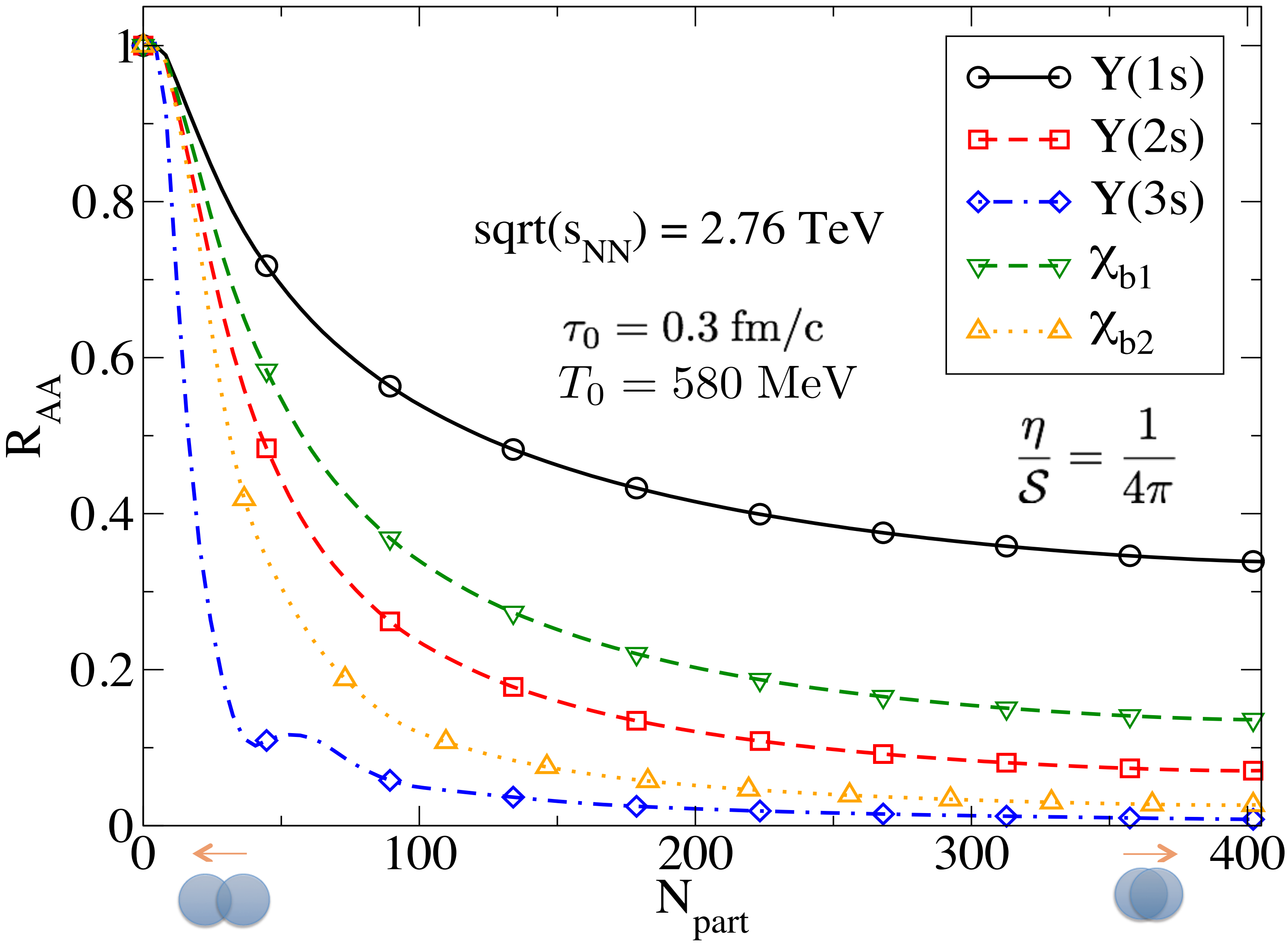
$$R_{AA}(\mathbf{x}_\perp, p_T, \varsigma, b) = \exp(-\bar{\gamma}(\mathbf{x}_\perp, p_T, \varsigma, b))$$

- Use the overlap density as the probability distribution function for quarkonium production vertices and geometrically average

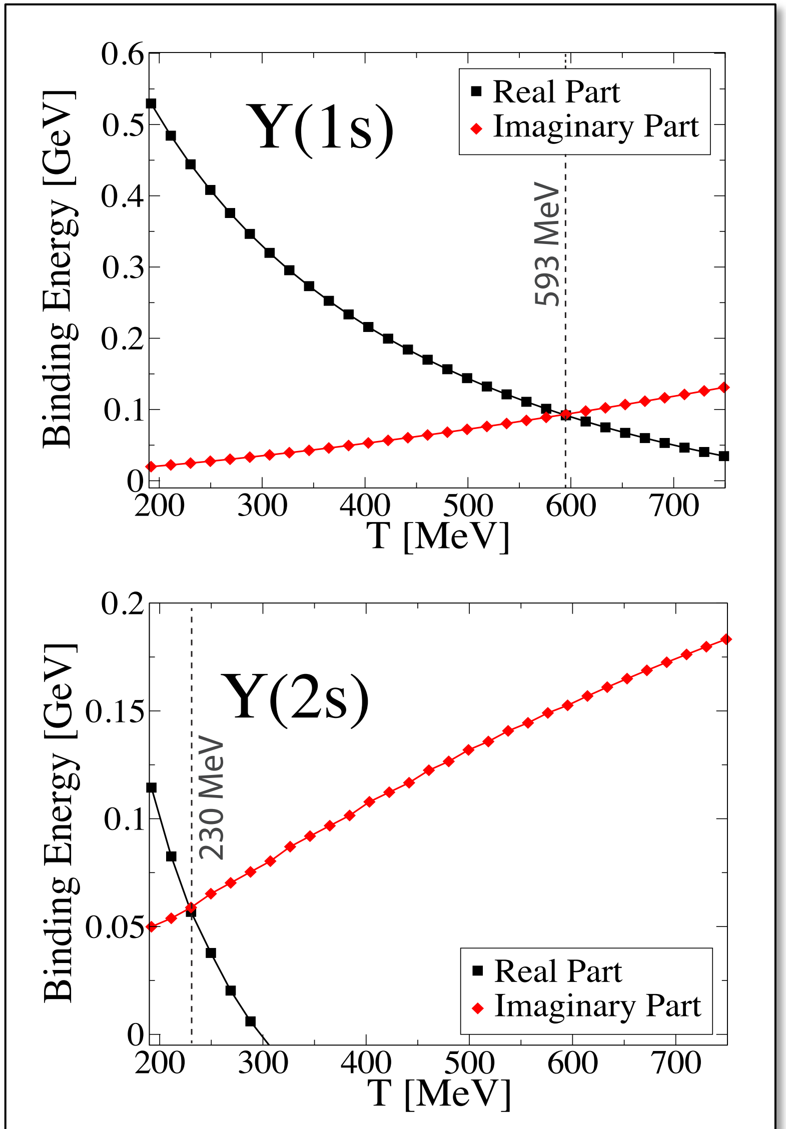
$$\langle R_{AA}(p_T, \varsigma, b)\rangle \equiv \frac{\int_{\mathbf{x}_\perp} d\mathbf{x}_\perp\, T_{AA}(\mathbf{x}_\perp)\, R_{AA}(\mathbf{x}_\perp, p_T, \varsigma, b)}{\int_{\mathbf{x}_\perp} d\mathbf{x}_\perp\, T_{AA}(\mathbf{x}_\perp)}$$

State Suppression Factors, $R_{AA}{}^{i}$

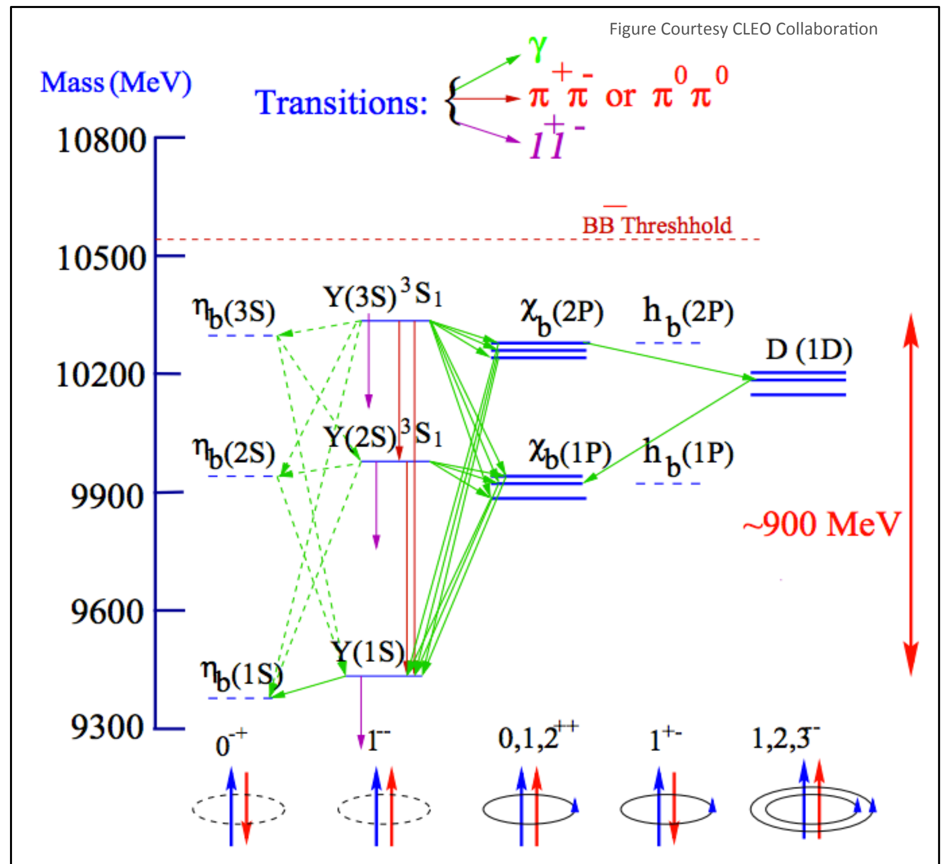
D Bazow and MS, Nucl. Phys. A 879, 25 (2012); MS, PRL 107, 132301 (2011).



Sequential Suppression

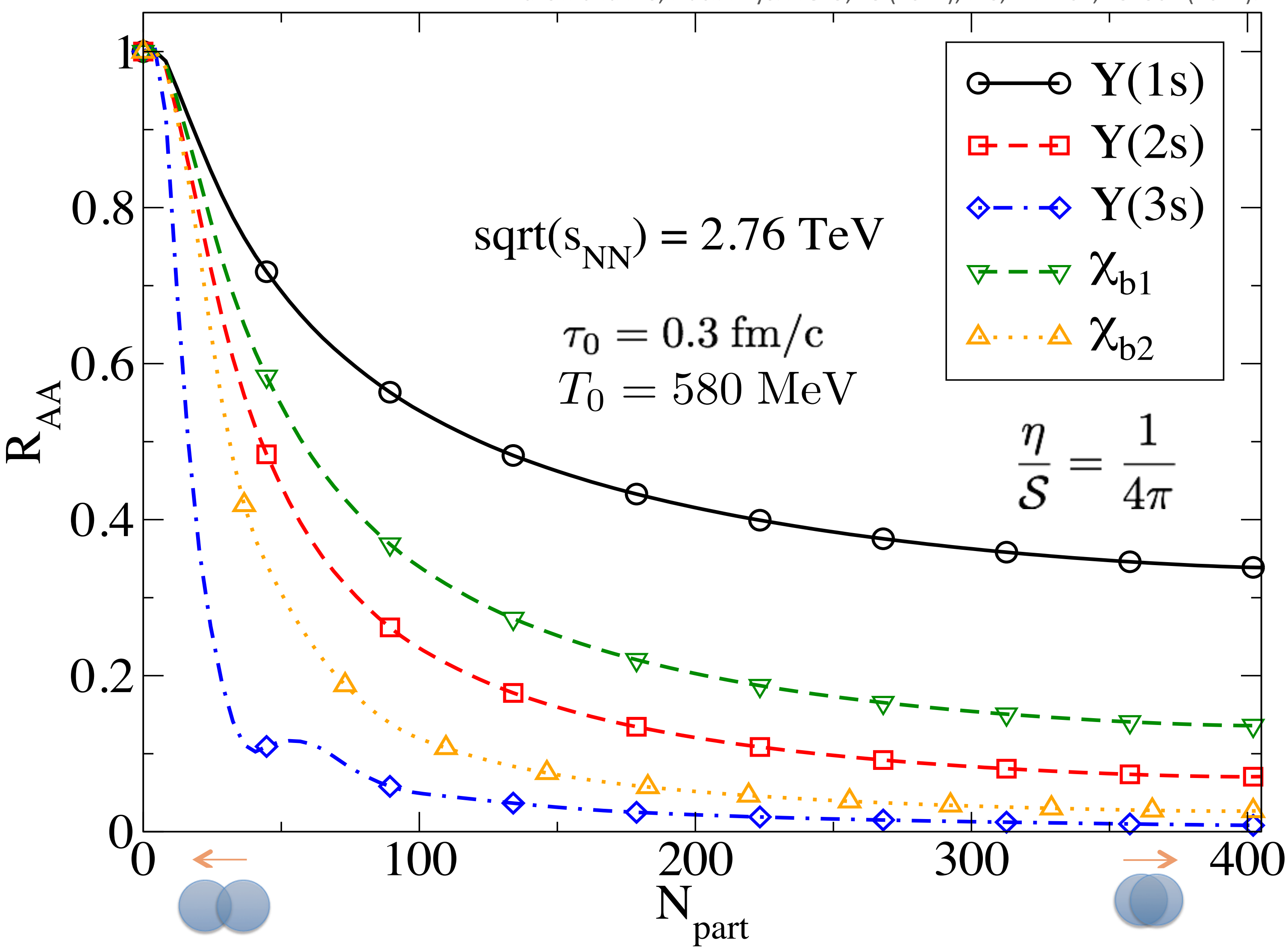


Excited states "melt" at lower temperatures. Since they "feed down" (decay) to the ground state this will result in a suppression of the ground state.

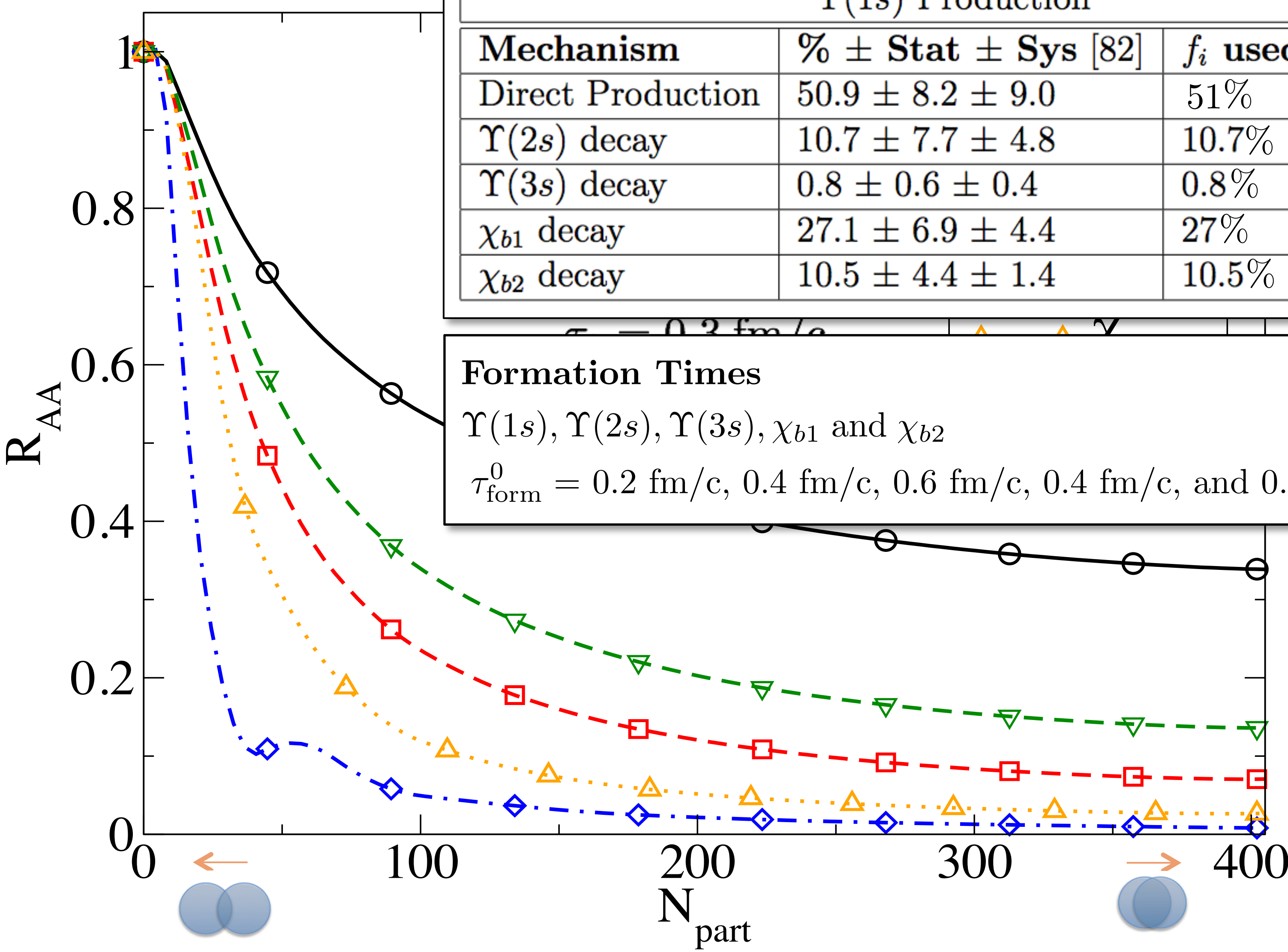


State Suppression Factors, $R_{AA}{}^{i}$

D Bazow and MS, Nucl. Phys. A 879, 25 (2012); MS, PRL 107, 132301 (2011).



State Suppression Factors, $R_{AA}{}^{i}$



$\Upsilon(1s)$ Production		
Mechanism	**% ± Stat ± Sys** [82]	f_i **used herein**
Direct Production	50.9 ± 8.2 ± 9.0	51%
$\Upsilon(2s)$ decay	10.7 ± 7.7 ± 4.8	10.7%
$\Upsilon(3s)$ decay	0.8 ± 0.6 ± 0.4	0.8%
χ_{b1} decay	27.1 ± 6.9 ± 4.4	27%
χ_{b2} decay	10.5 ± 4.4 ± 1.4	10.5%

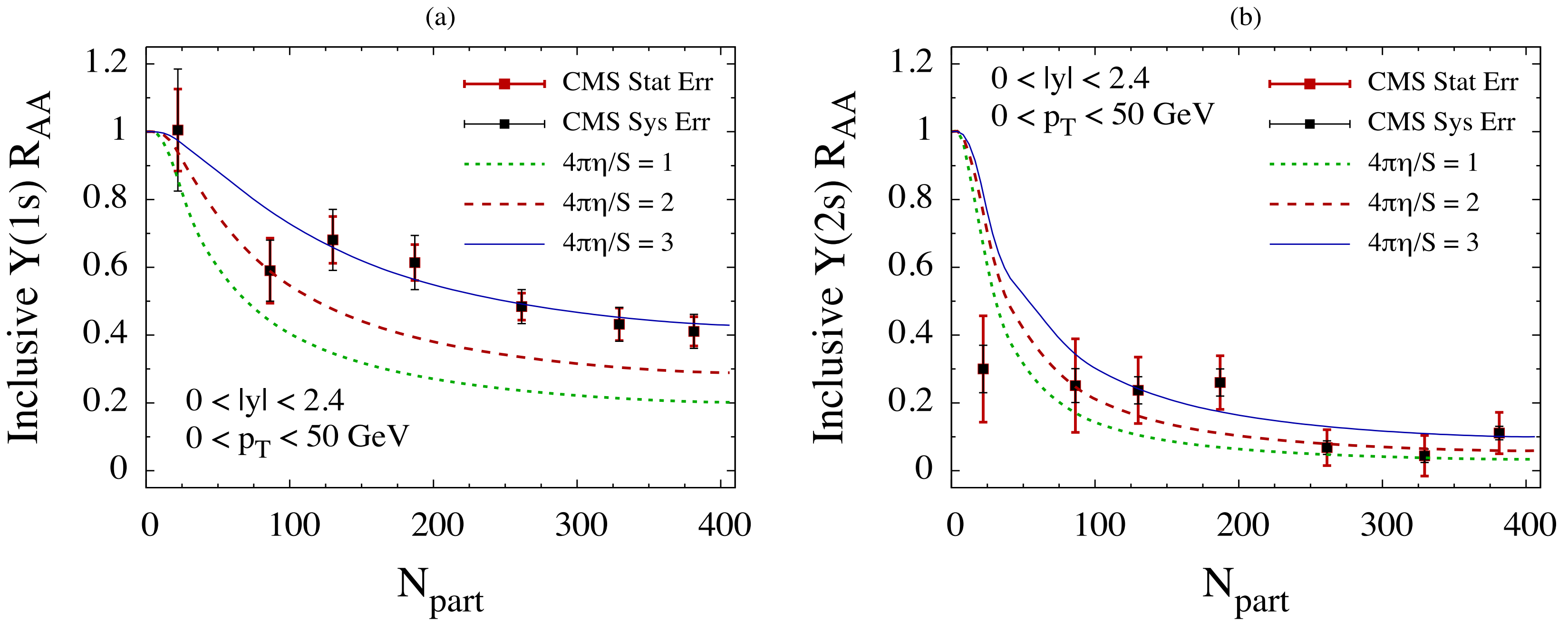
Formation Times

$\Upsilon(1s), \Upsilon(2s), \Upsilon(3s), \chi_{b1}$ and χ_{b2}

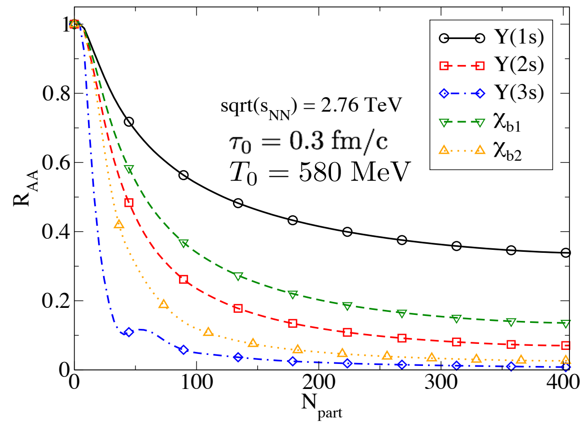
$\tau^0_{\rm form}$ = 0.2 fm/c, 0.4 fm/c, 0.6 fm/c, 0.4 fm/c, and 0.6 fm/c

Inclusive Bottomonium Suppression

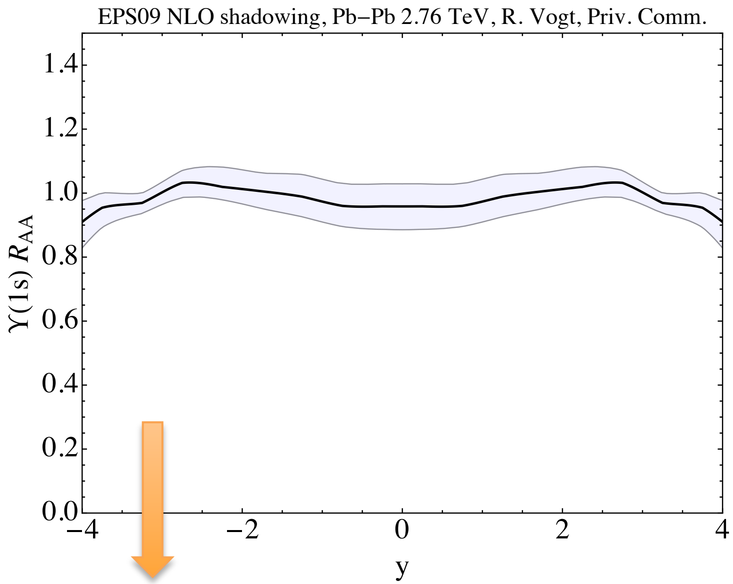
MS, arXiv:1207.5327; MS and D. Bazow, arXiv:1112.2761; MS arXiv:1106.2571

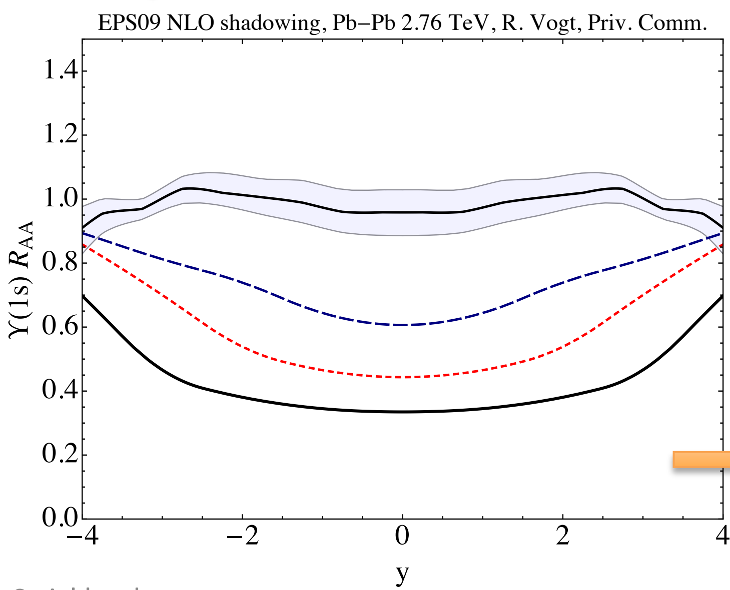


- **Comparison with CMS 2011 data**
- More Υ(1s) data with smaller error bars
- Υ(2s) data as well
- Would be nice to have rapidity and transverse momentum dependence from CMS

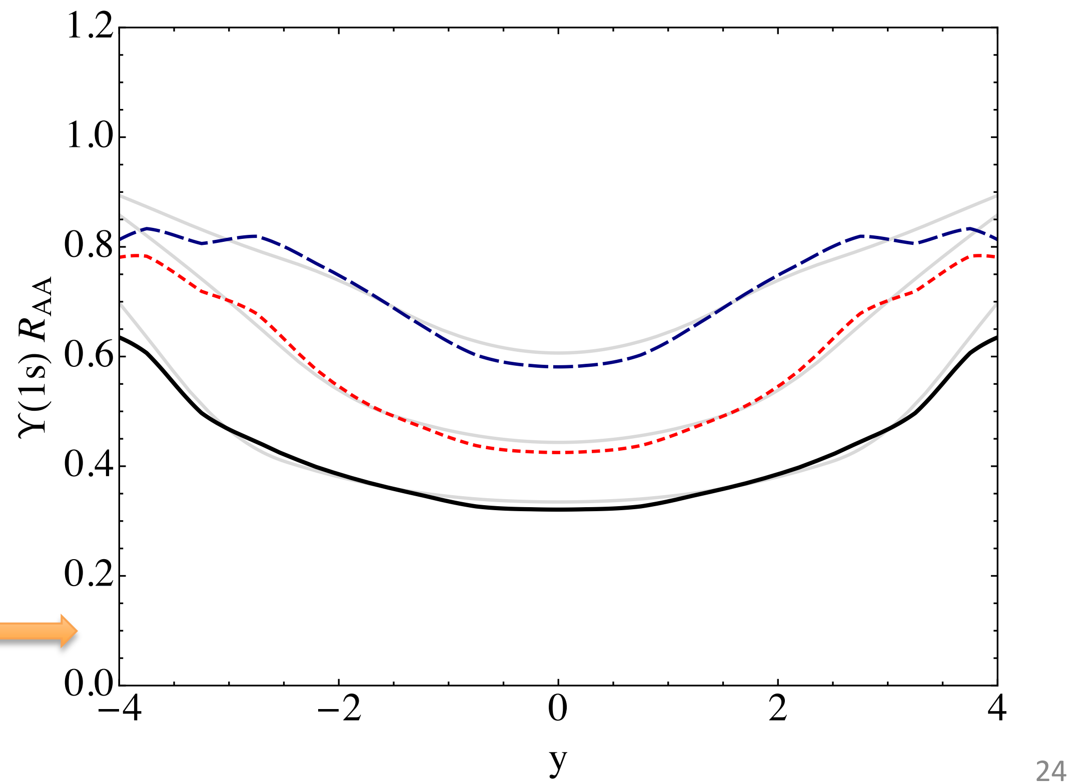


Estimate CNM effect on Bottomonium in A-A





- Estimate of CNM using EPS09 NLO shadowing provided by R. Vogt
- Effect seems to be quite small
- This is good news for isolating the medium effect we are after, but doesn't help to explain the ALICE forward "anomaly"



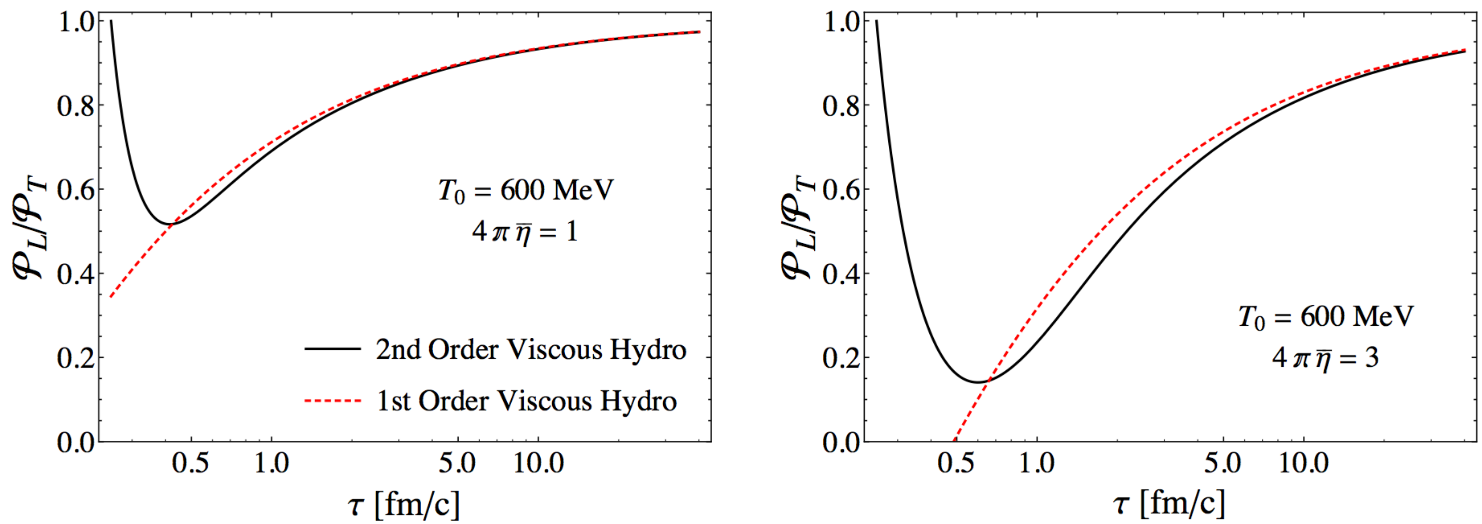
Conclusions

- All signs point to an momentum-space anisotropic QGP → need to self-consistently calculate rates including this fact of life
- At central rapidities, the aHydro+screening model seems to work reasonably well
- CNM effects are quite small
- For the 1s state, there is a large dependence on the assumed value of η/s
- This offers the possibility to constrain η/s using bottomonia R_{AA}

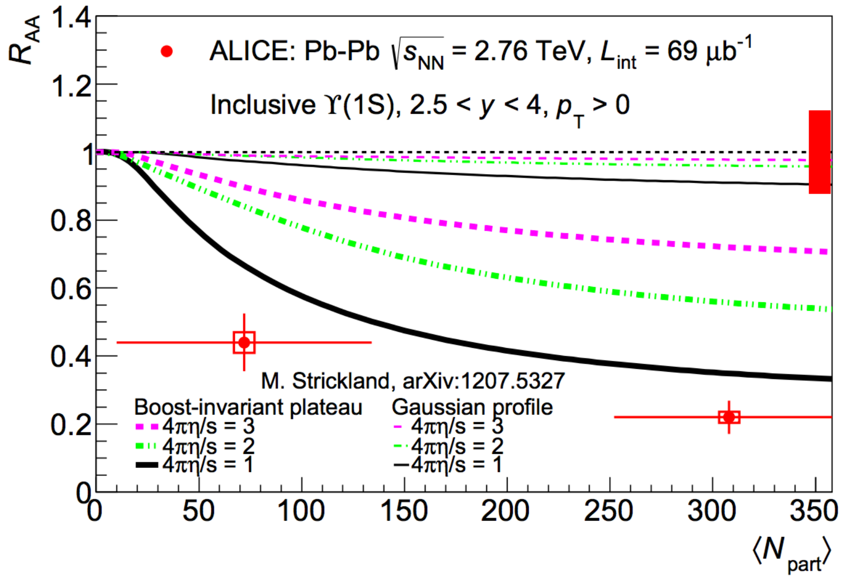
Backup slides

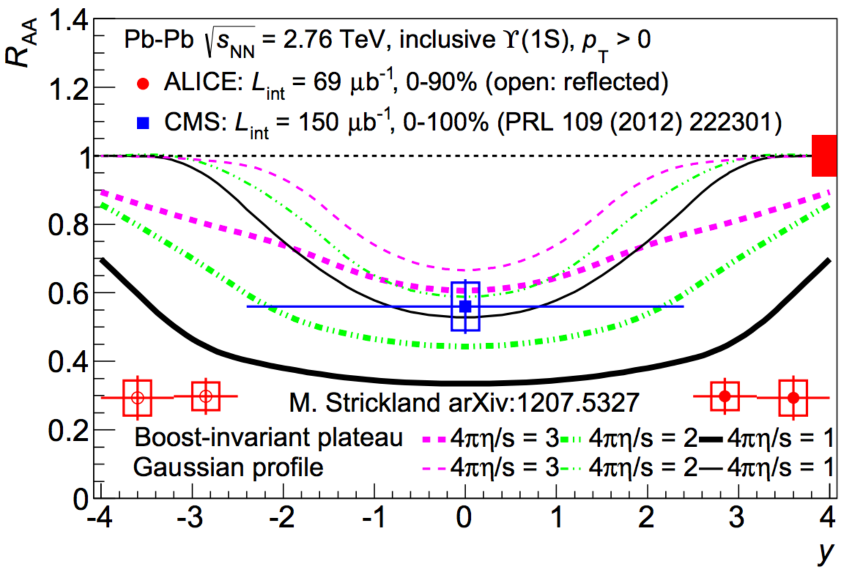
Estimating Early-time Pressure Anisotropy

- CGC @ leading order predicts negative → approximately zero longitudinal pressure
- QGP scattering + plasma instabilities work to drive the system <u>towards</u> isotropy on the fm/c timescale, but do not fully restore it
- Viscous hydrodynamics predicts early-time anisotropies ≤ 0.35 → 0.5
- AdS-CFT dynamical calculations in the strong coupling limit predict anisotropies of ≤ 0.3



Conflict with ALICE forward data





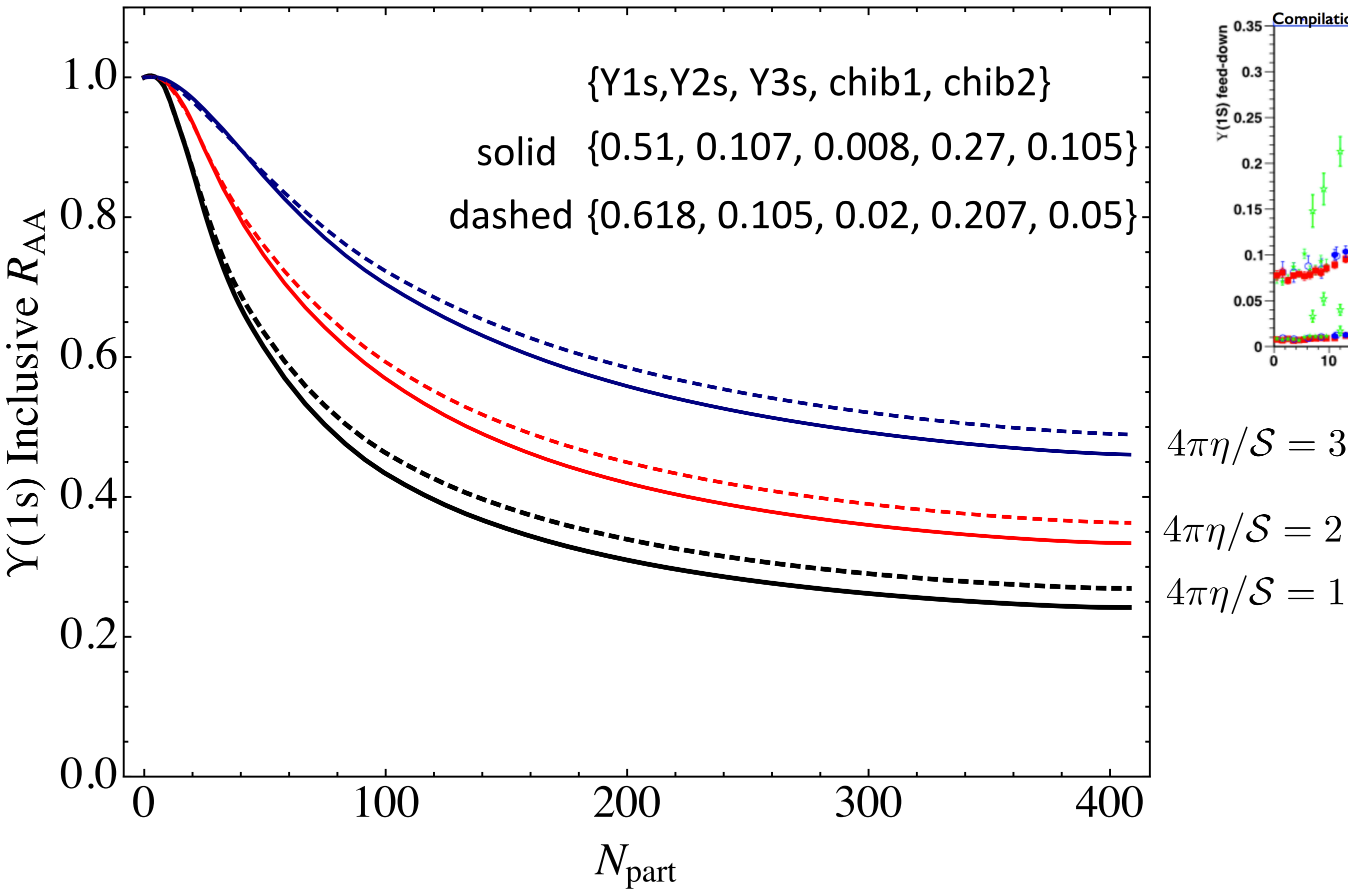
- Thermal suppression model has R_{AA} approaching 1 at forward/backward rapidity since there one has T → 0
- Using a Gaussian rapidity profile (*Landau-hydro inspired*) does not even come close to the data
- Using a Bjorken-like rapidity profile gives enhanced suppression, **but also doesn't describe what is seen by ALICE!**
- **p-p reference?**

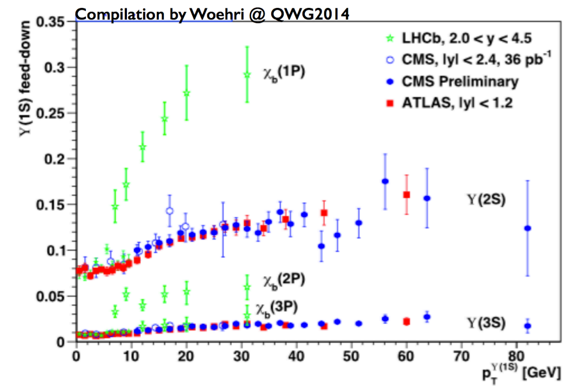
(Some of) the problems with my first calculation

- Small anisotropy expansion used for the imaginary part of the potential [unknown level of theoretical error; IN PROGRESS (Al Qhatani/Naseen)]
- Dynamics was not 3+1d and I used smooth initial conditions [could be important; 3+1 with fluctuations IMPLEMENTED and being tested (Krouppa)]
- No regeneration included [expected to be small effect <~ 10% (Krouppa)]
- No CNM effects [can be included straightforwardly, small effect, see next slide]
- No singlet/octet transition in Im[V] [affects all rapidities; ??]
- Simplistic model of how the anisotropy affects the long range part of the potential [unknown level of theoretical error; IN PROGRESS]
- **Speculation**: At RHIC μ_B ~ 200 MeV @ |y| ~ 3 based on statistical model fits to BRAHMS data [see e.g. Biedron and Broniowski, nucl-th/0610083]
  → increased Debye mass and enhanced suppression at forward rapidity even though T is lower
  [could be important; need experimental and theoretical input to further constrain the magnitude of the baryo-chemical potential at LHC energies]

Updated feed down fractions

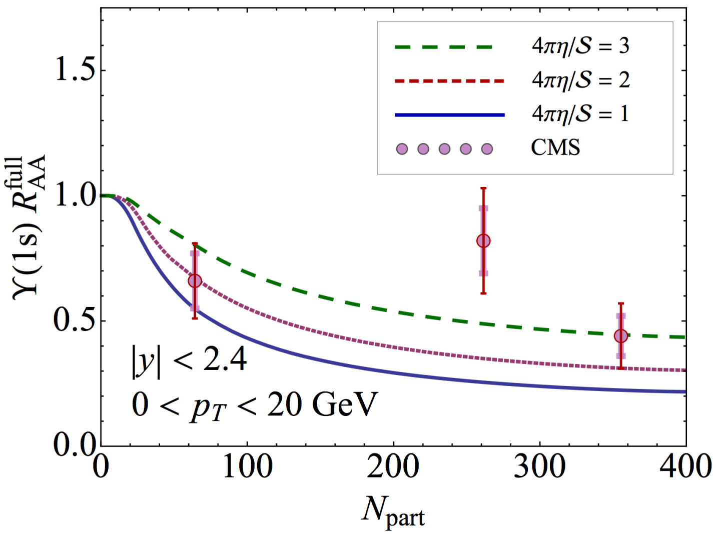
- Original feed down fractions came from CDF collaboration at Fermilab
- CMS has recently measured these using their (better) detector/statistics



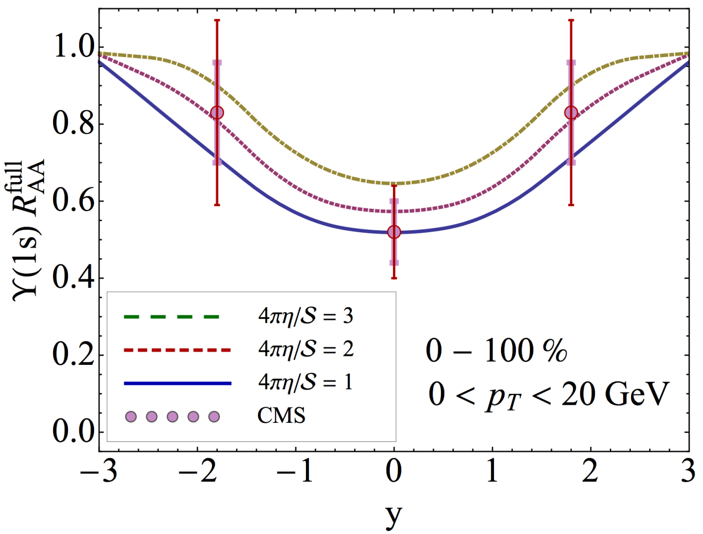


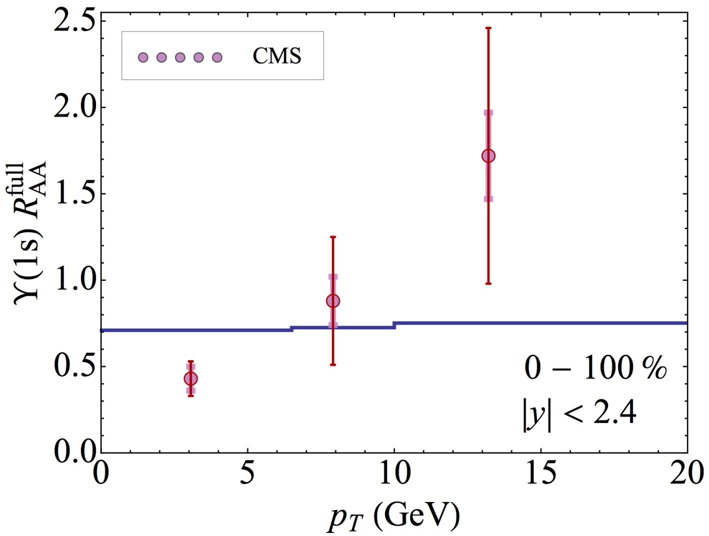
Inclusive Bottomonium Suppression

MS, PRL, arXiv:1106.2571



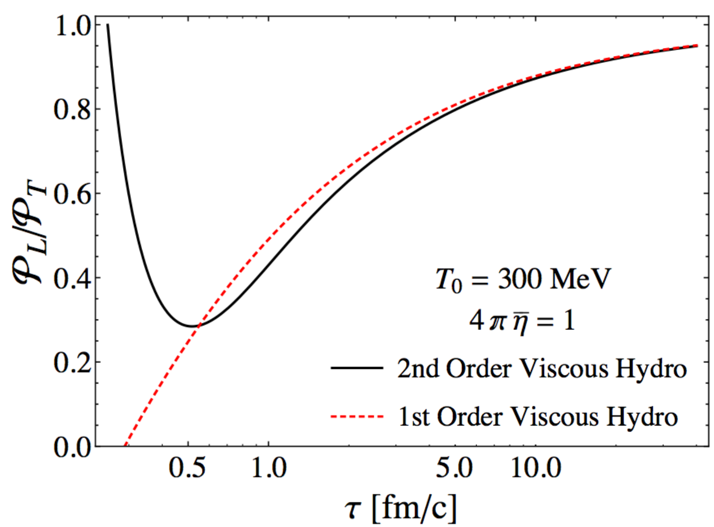
- Comparison with CMS 2010 data
- Initial temperature taken from Schenke hydro simulation fits to v_2
- For each η/S I adjusted the initial temperature to keep the final particle multiplicity fixed

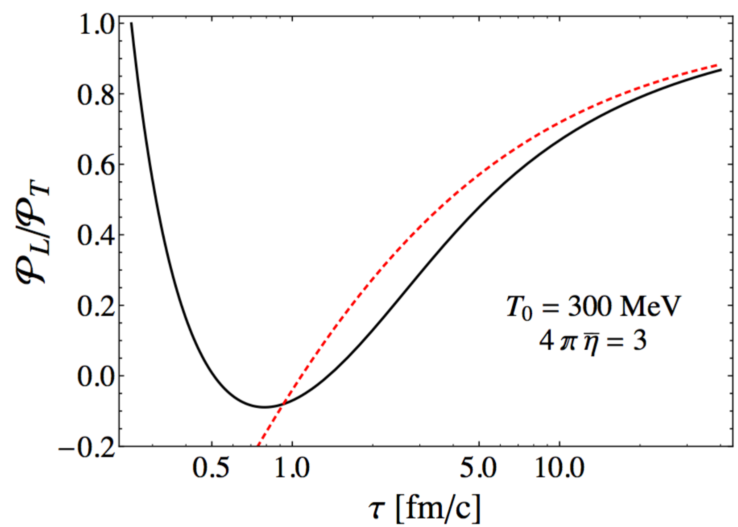




Estimating Early-time Pressure Anisotropy

- CGC @ leading order predicts negative → approximately zero longitudinal pressure
- QGP scattering + plasma instabilities work to drive the system <u>towards</u> isotropy on the fm/c timescale, but do not fully restore it
- Viscous hydrodynamics predicts early-time anisotropies ≤ 0.35 → 0.5
- AdS-CFT dynamical calculations in the strong coupling limit predict anisotropies of ≤ 0.3





Estimating Anisotropy – AdS/CFT

- In the 0+1d case there are numerical solutions of Einstein's equations to compare with.
  Heller, Janik, and Witaszczyk, 1103.3452
  see also Chesler and Yaffe, 1011.3562

- They studied a wide variety of initial conditions and found a kind of universal lower bound for the thermalization time.

RHIC 200 GeV/nucleon:
T_0 = 350 MeV, τ_0 > 0.35 fm/c

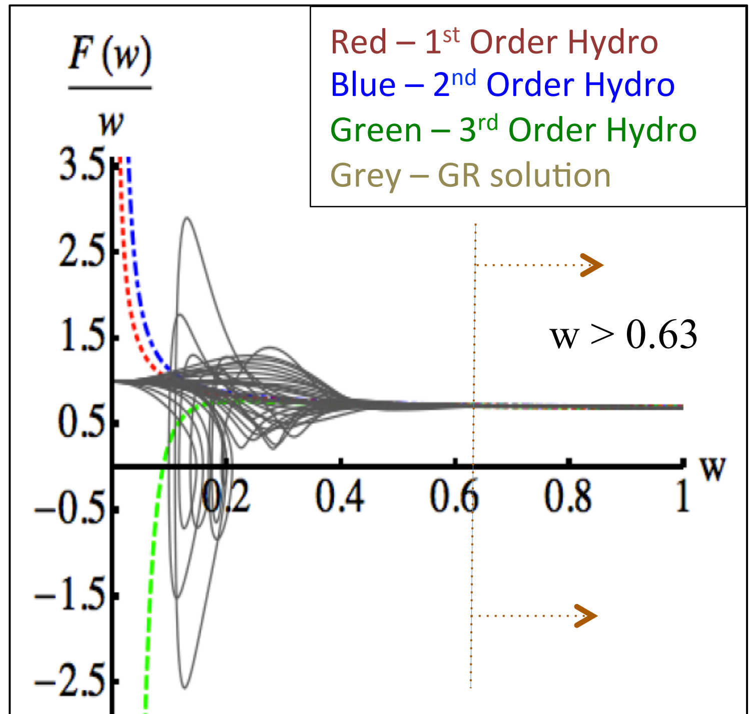
LHC 2.76 TeV/nucleon:
T_0 = 600 MeV, τ_0 > 0.2 fm/c

$$\langle T_{\tau\tau}\rangle \equiv \varepsilon(\tau) \equiv N_c^2 \cdot \frac{3}{8}\pi^2 \cdot T_{eff}^4 \cdot$$

$$w = T_{eff} \cdot \tau$$

$$\frac{\tau}{w}\frac{d}{d\tau}w = \frac{F_{hydro}(w)}{w},$$

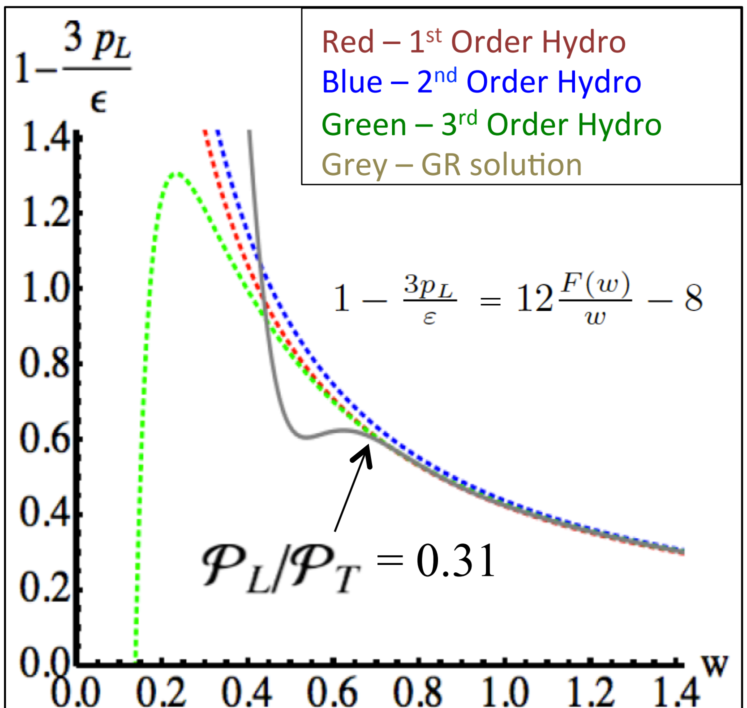
F_{hydro} known up to 3rd order hydro analytically



Heller, Janik, and Witaszczyk, 1103.3452

N=4 SUSY using AdS/CFT

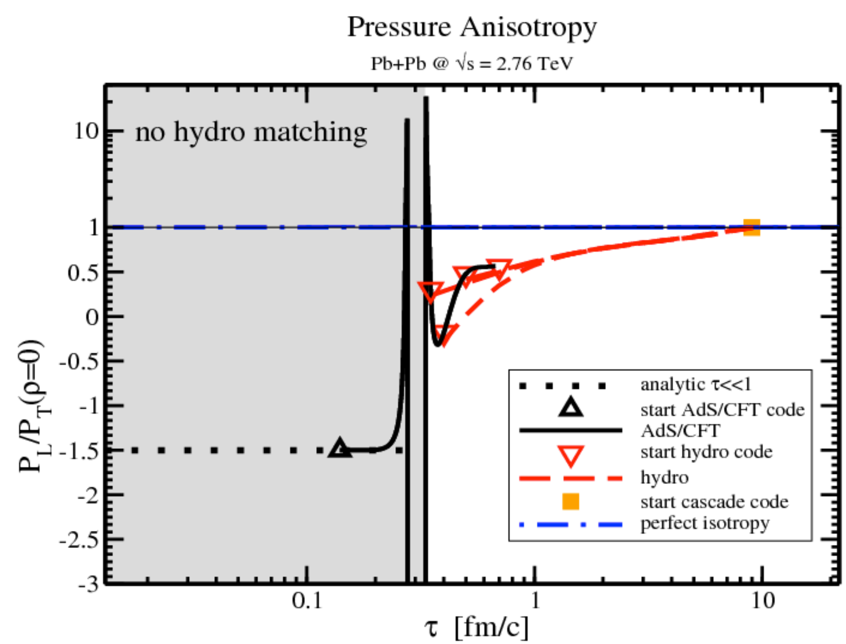
However, at that time the system is not isotropic and it remains anisotropic for the entirety of the evolution



Heller, Janik, and Witaszczyk, 1103.3452

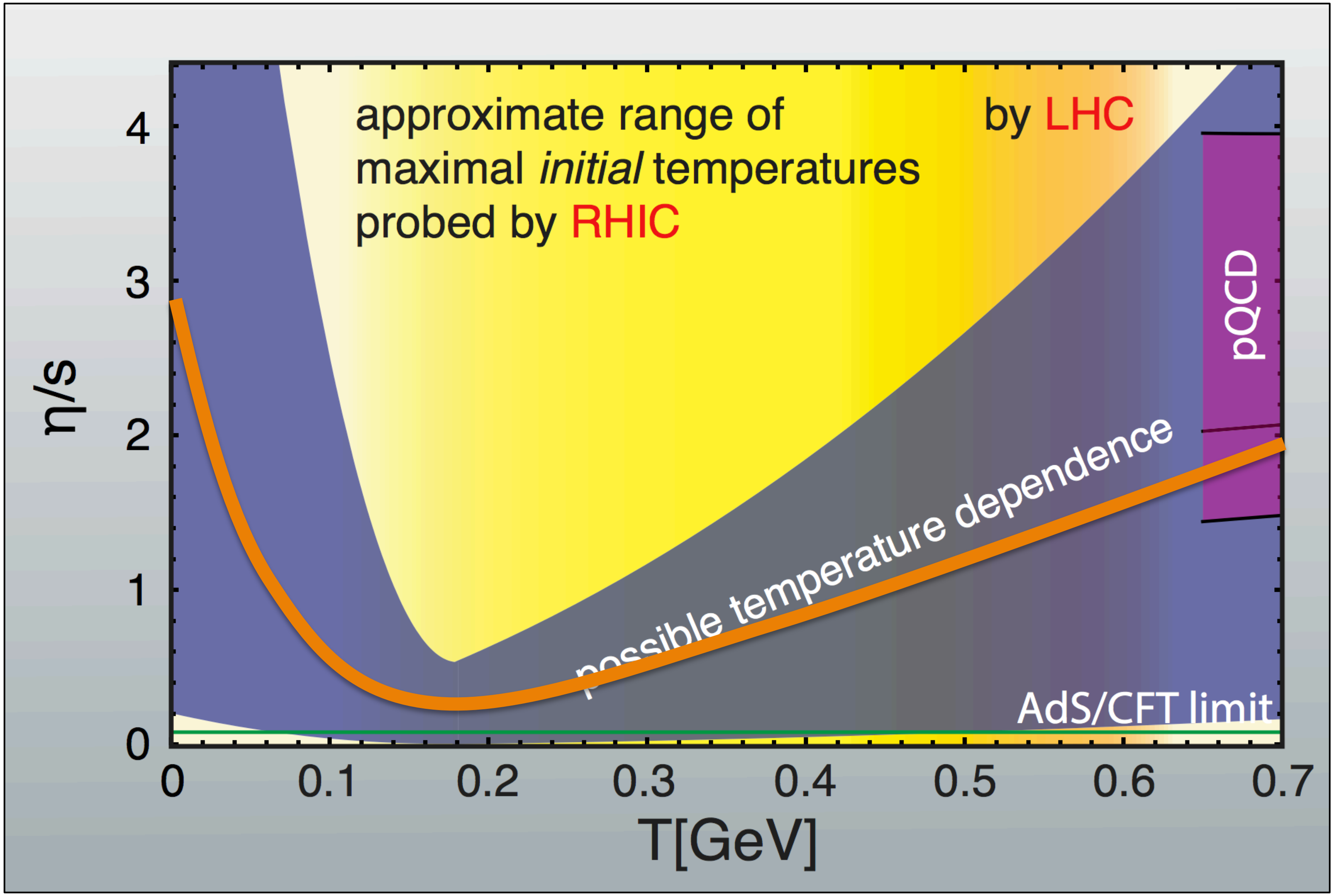
Other AdS/CFT numerical studies which include transverse expansion reach a similar conclusion

van der Schee et al. 1307.2539



See also J. Casalderrey-Solana et al. arXiv: 1305.4919

Temperature dependence of η/S



Hot and Dense QCD Matter, Community Whitepaper 2014

The suppression factor

- The suppression factor, $\mathbf{R_{AA}}$, is the ratio of the number of a particular type of particle produced in a collision of two symmetric nuclei (AA) to the amount produced in a proton-proton (pp) collision scaled by the expected number of nucleon collisions

$$R_{AA} = \frac{N_{AA}}{n_{binary} \cdot N_{pp}}$$

N_{AA}: Number produced in a nucleus-nucleus collision

N_{pp}: Number produced in a proton-proton collision

n_{binary}: Number of pp collisions per nucleus collision

Results for the χ_{b1} binding energy

Margotta, MS, et al, 1101.4651