Bottomonium suppression in the quark-gluon plasma

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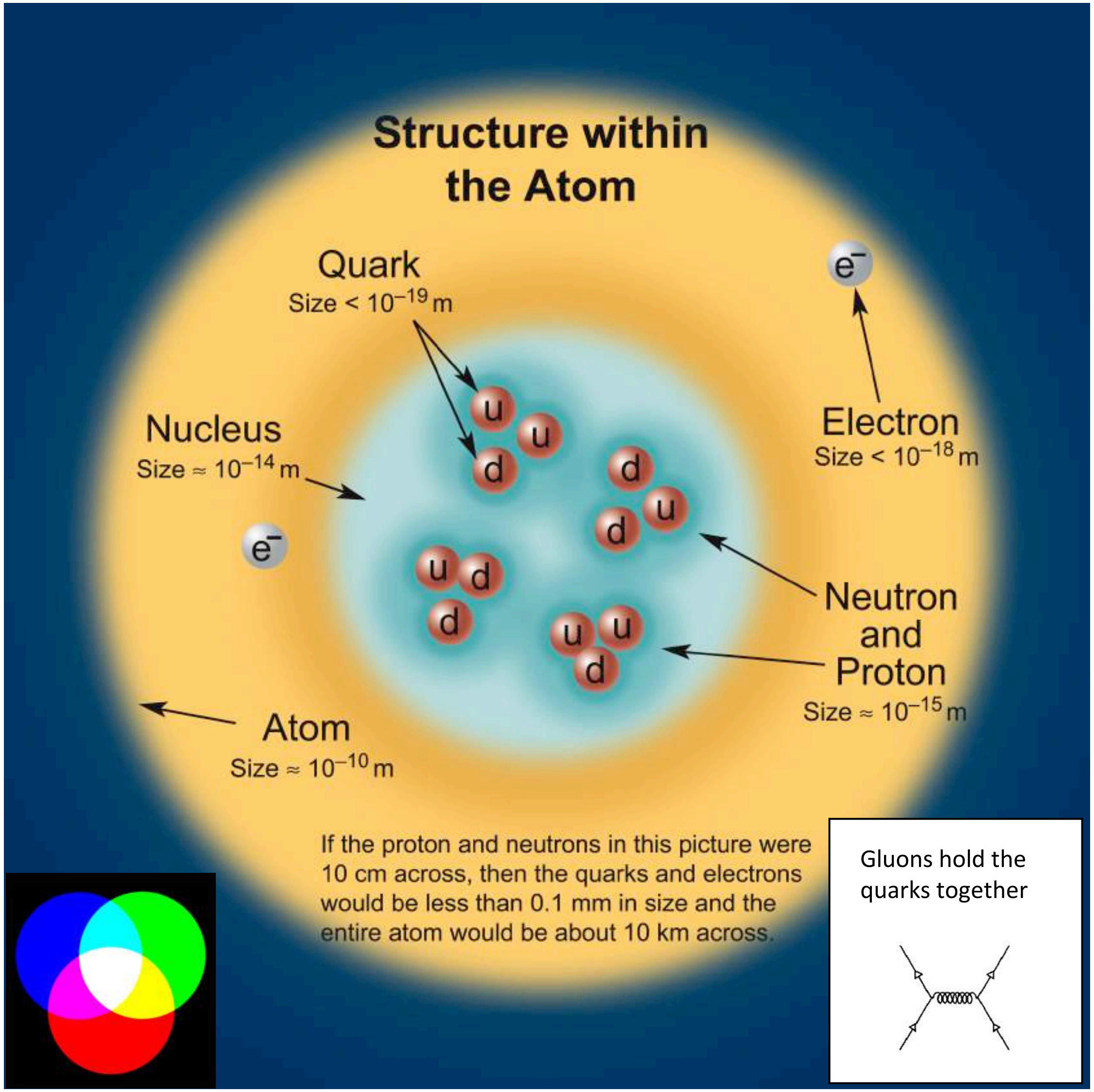
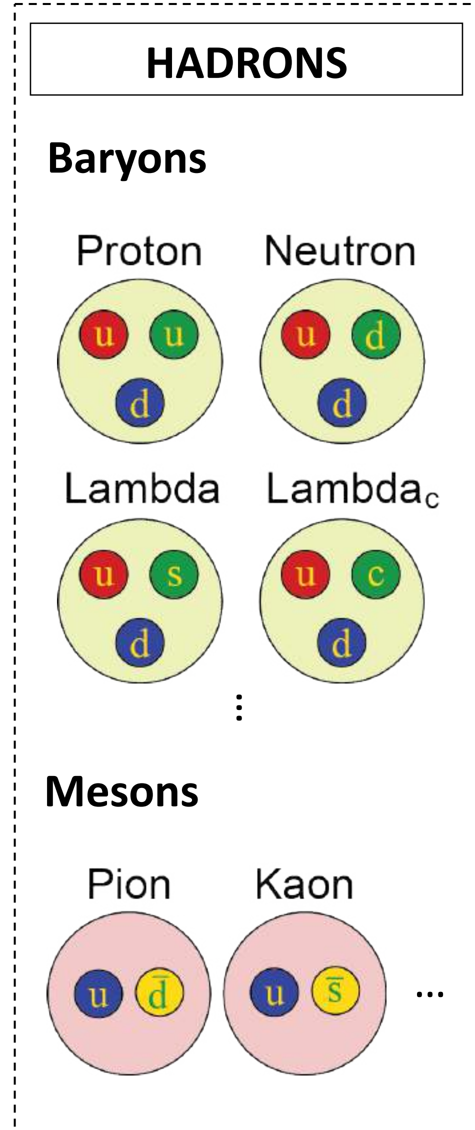
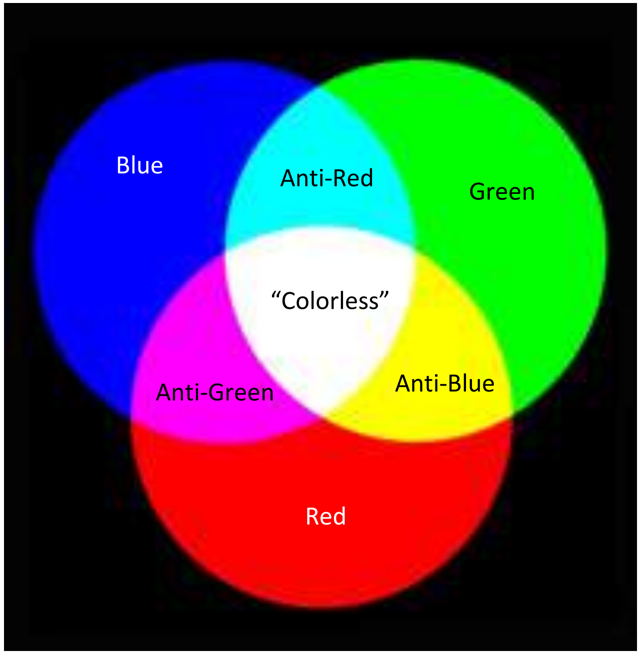
Quarks are normally "confined" inside hadrons

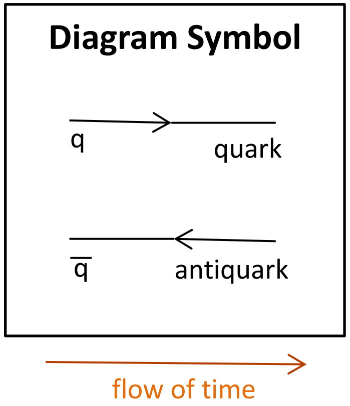




Quarks and anti-quarks

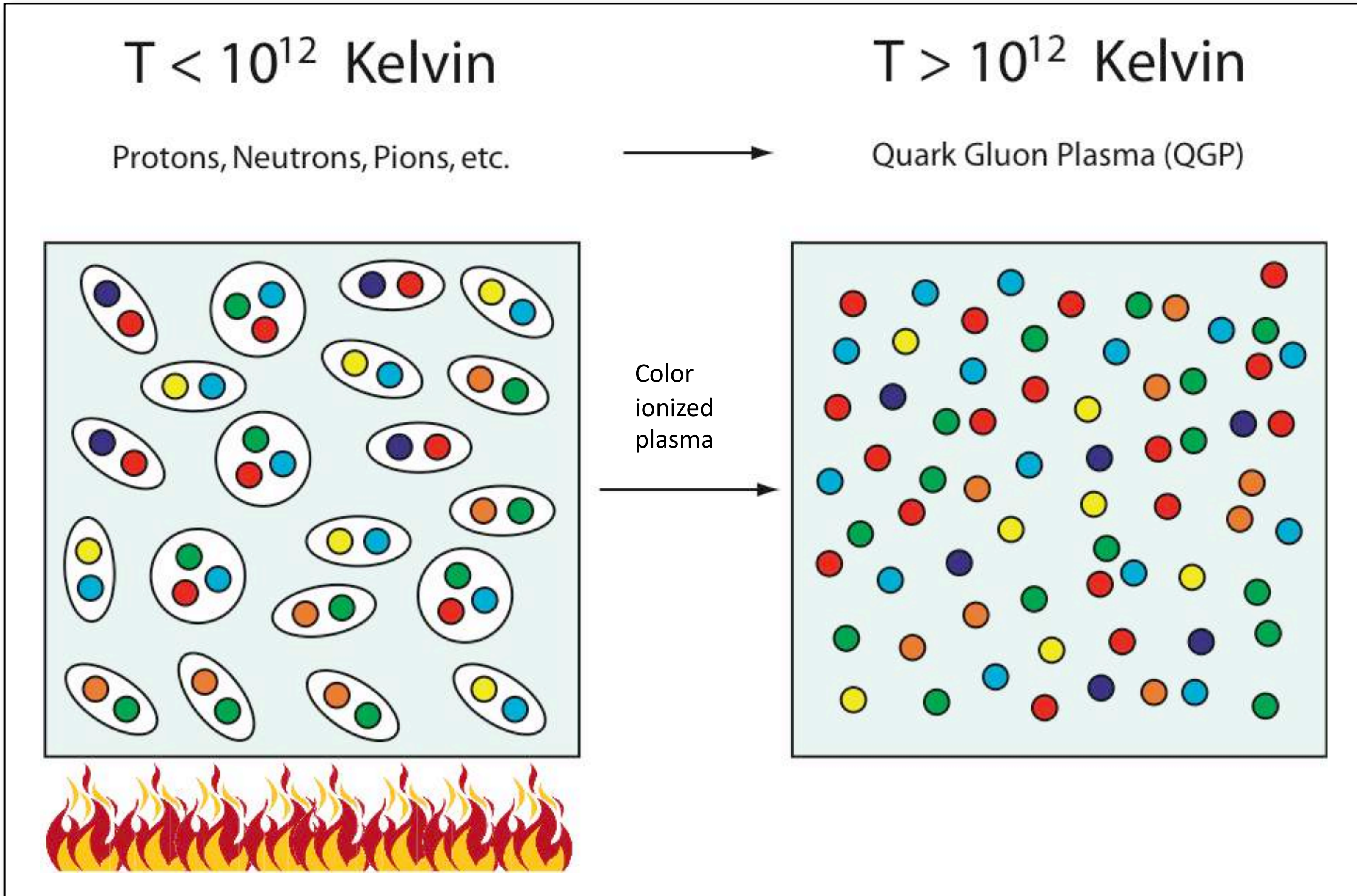
Name		Mass [GeV/c^2]	Electric Charge
Up	u	0.0024	+2/3
Down	d	0.0048	-1/3
Strange	s	0.104	-1/3
Charm	c	1.27	2/3
Bottom	b	4.2	-1/3
Top	t	171.2	2/3



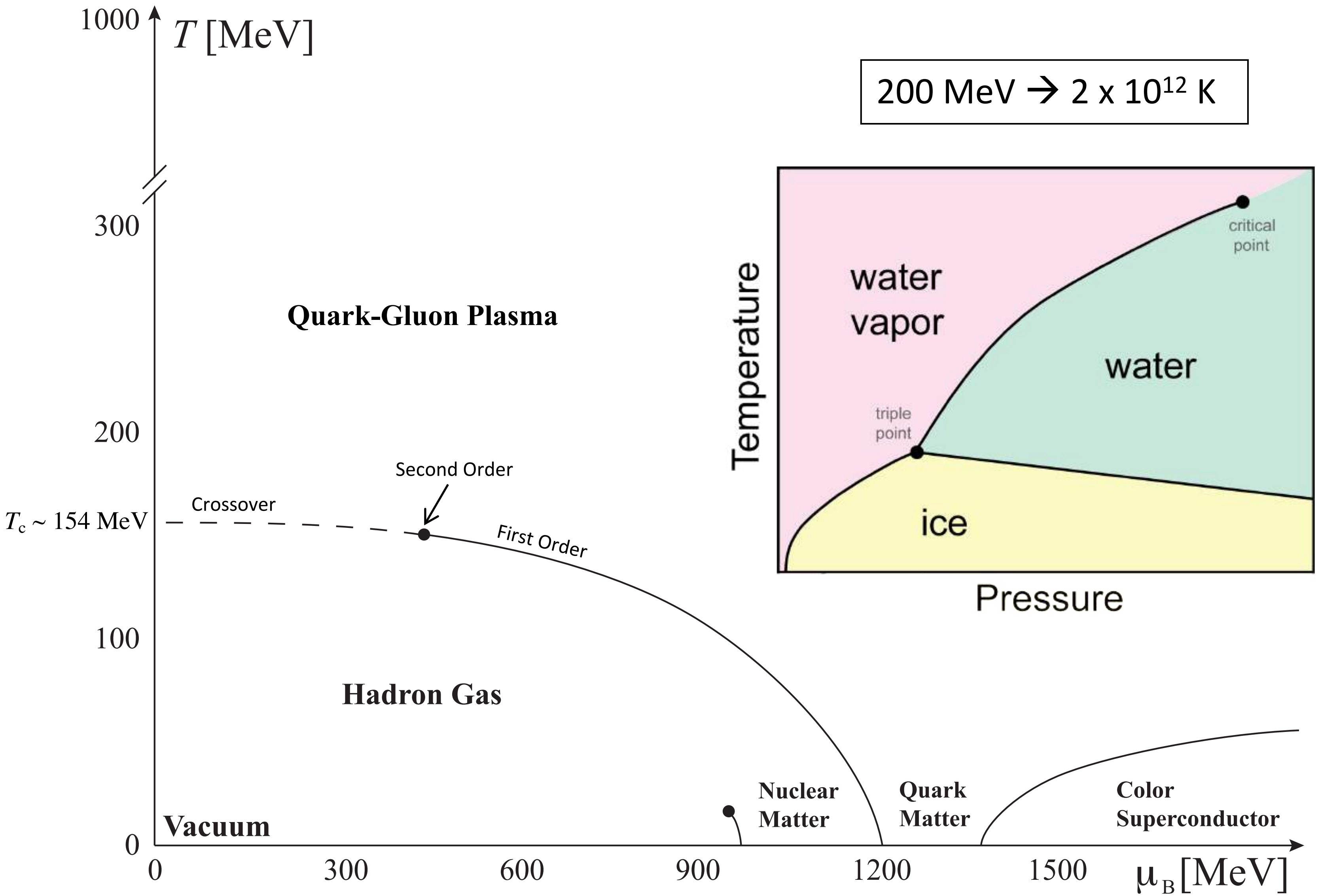


- Quarks are fermions (spin ½);
  have electric charge and "color charge"
- There are also anti-quarks that have the opposite electric charge and "anti-color charge"
- The proton is (primarily) composed of uud
- Compare the masses above to the mass of the proton which is ~ 1 GeV

Melting hadrons

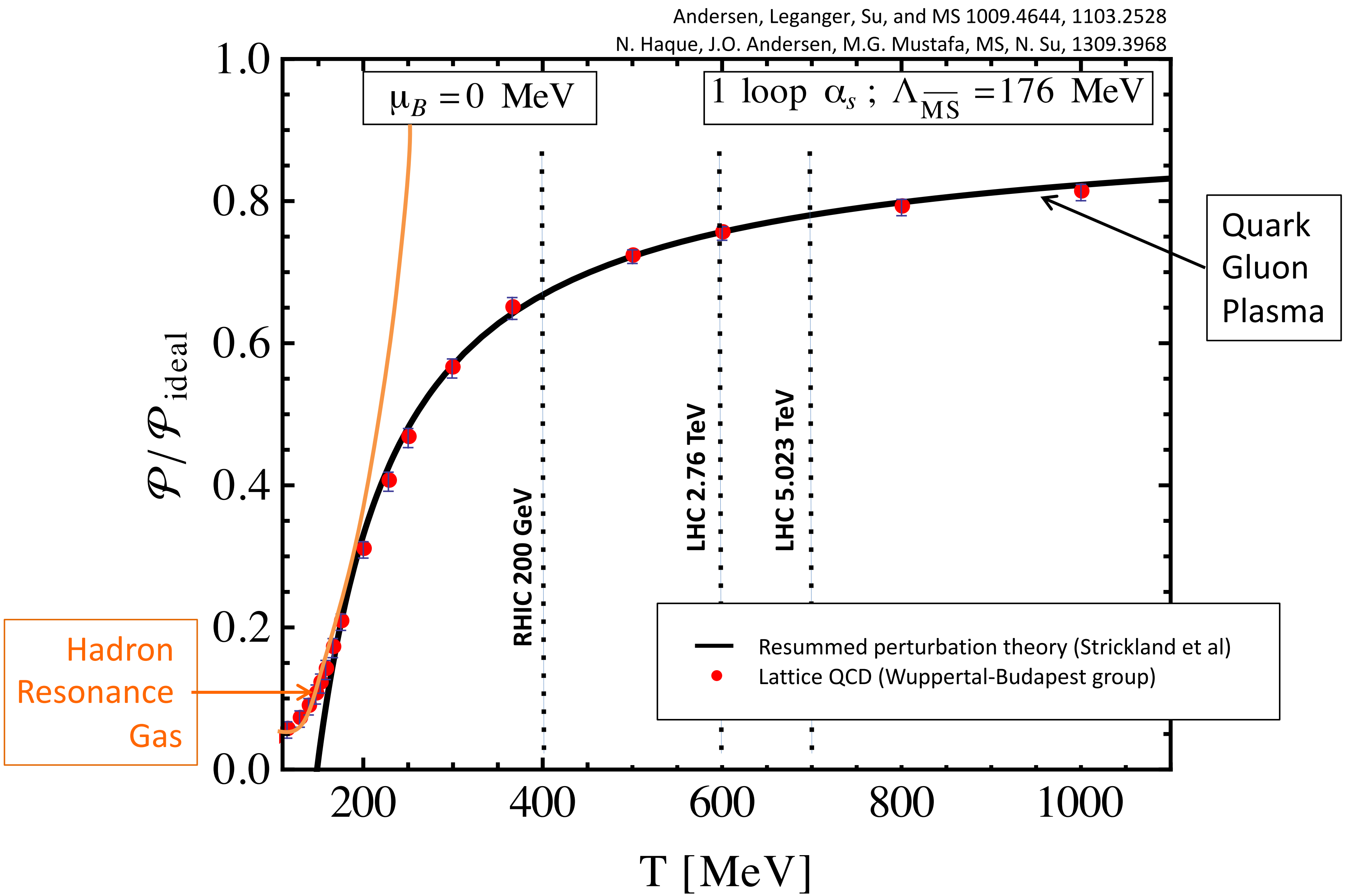


Quantum chromodynamics (QCD) phase diagram

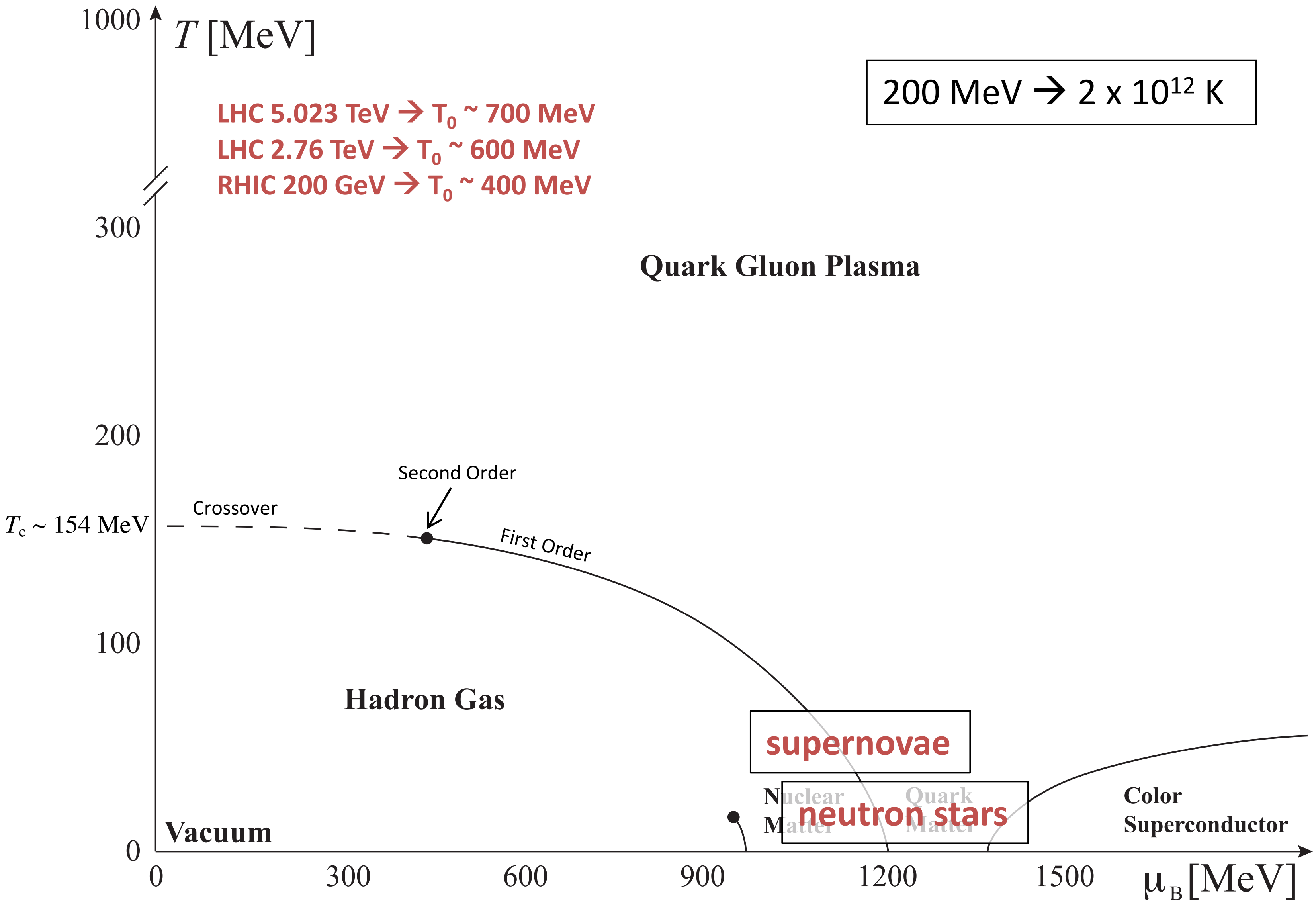


200 MeV → 2 x 10^{12} K

Pressure vs temperature – μ_B = 0 MeV

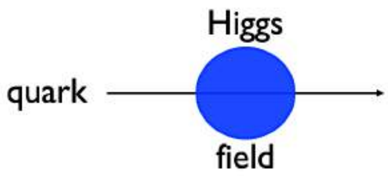


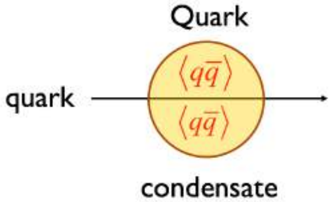
QCD phase diagram



98% of the mass in the universe is made during the QGP transition

- The Higgs boson only provides a small fraction of the mass of observed hadronic matter.
- Most of the mass around us emerges from the strong force.





Bashir et al, Commun. Theor. Phys. 58 (2012) 79-134.

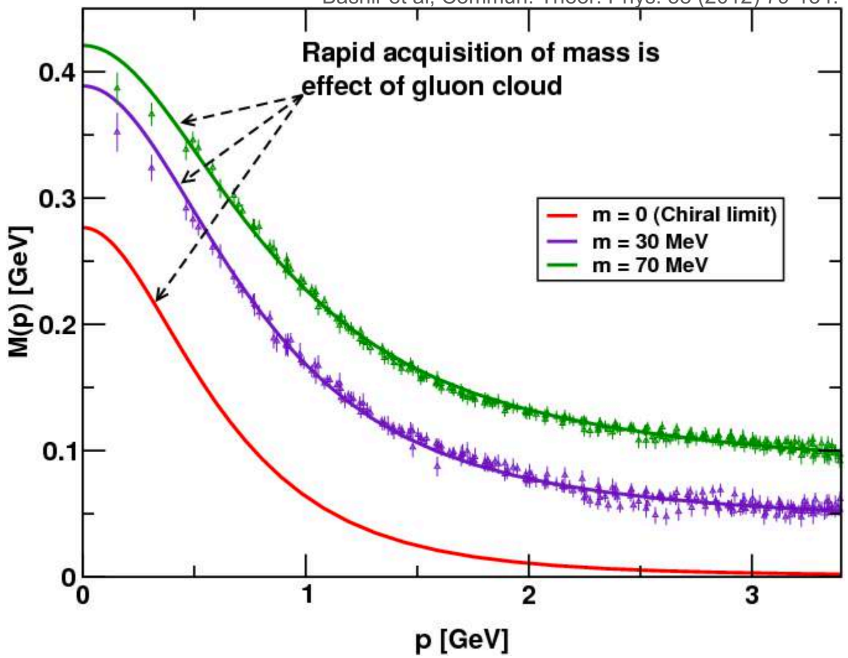
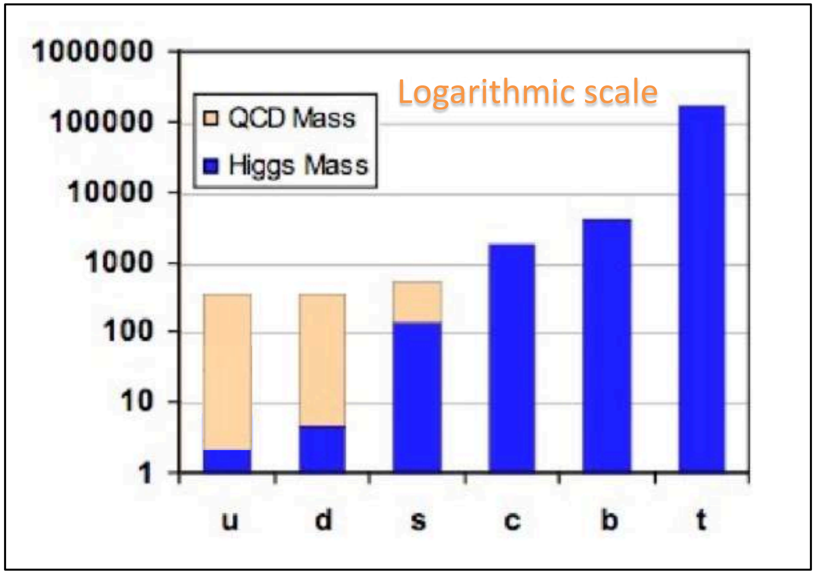


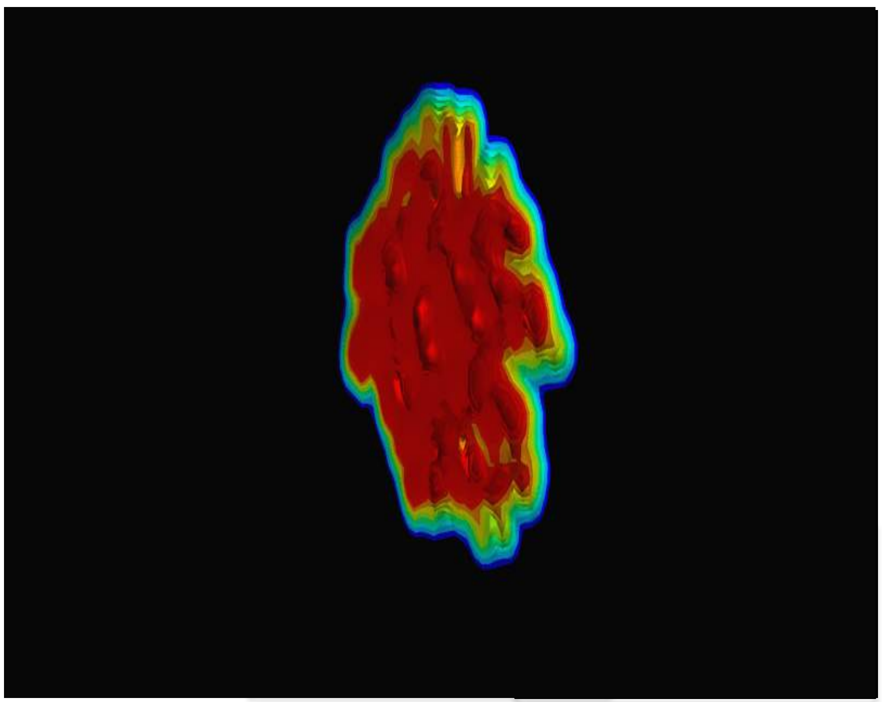
Figure courtesy B. Muller

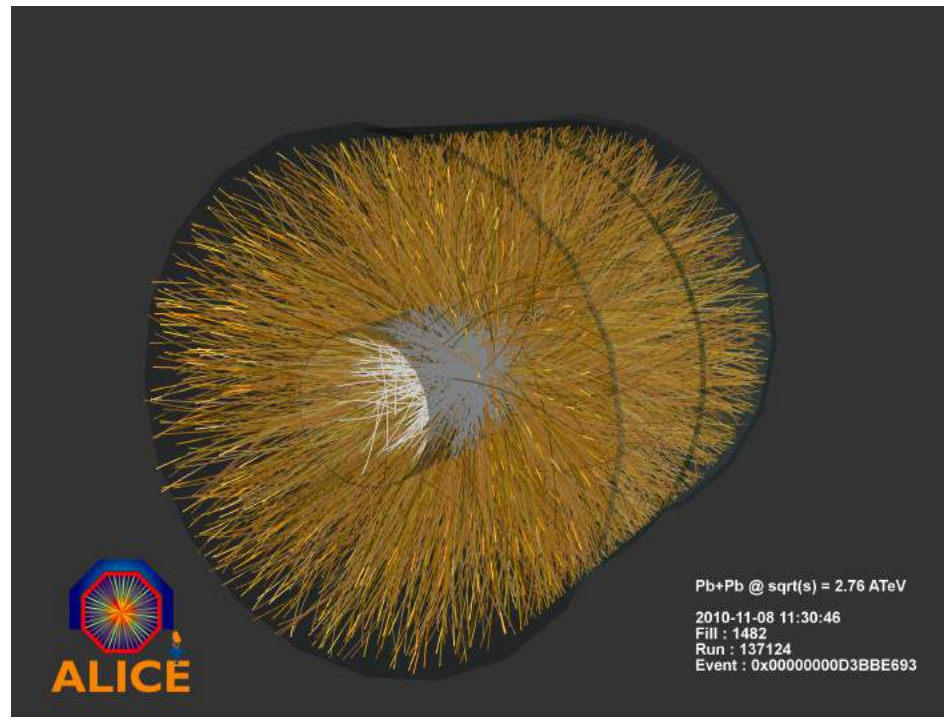


Experiments and Phenomenology

Ultrarelativistic heavy-ion collisions

- **RHIC**, BNL – Au-Au @ 200 GeV/nucleon (highest energy) → $T_0 \sim 400$ MeV
- **LHC**, CERN – Pb-Pb @ 2.76 TeV → $T_0 \sim 600$ MeV
- **LHC**, CERN – Pb-Pb @ 5.03 TeV → $T_0 \sim 700$ MeV
- **RHIC**, BNL **BES** – Au-Au @ 7.7 - 39 GeV → $T_0 \sim 30\text{-}100$ MeV [+finite density]
- **FAiR** (GSI), **NICA** (Dubna) – U-U @ 35 GeV -> $T_0 \sim 100$ MeV [+finite density]





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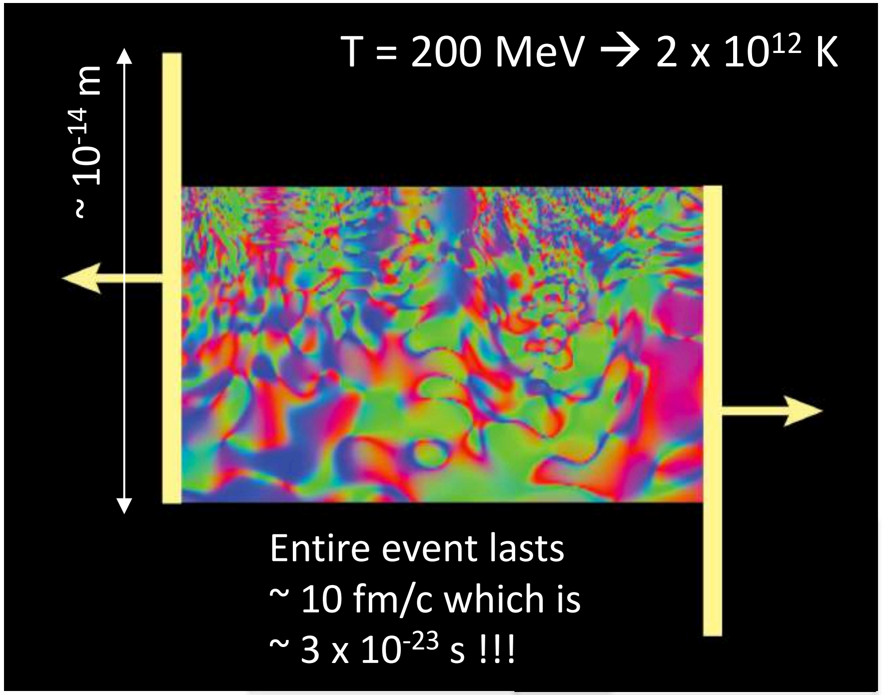

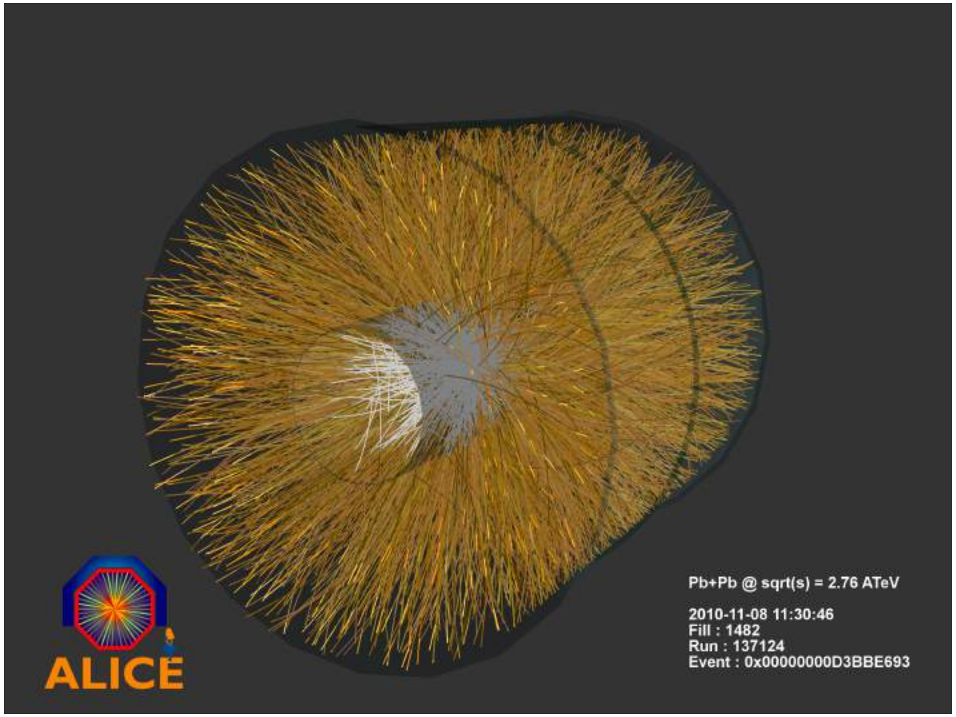

Some Key Experimental Observables

- **Collective Flow** – flow of the matter provides evidence of collectivity in the QGP and allows us to extract transport coefficients like the shear viscosity
- **Jet Quenching** – effects of plasma interactions on high-energy particle propagation; provides information about momentum diffusion and energy loss of partons in the QGP
- **Suppression of heavy quarkonia** – provides information about screening and bound state survival in the QGP
- **Electromagnetic Radiation** – high energy photons and dileptons provide information about initial conditions
- **Particle spectra across species** – provides information about the degree to which final particle distributions are thermalized
- **Multiparticle correlations such as Hanbury-Brown-Twiss (HBT) interferometry** – provides information about the size of the QGP and collective flow profiles

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Why heavy quarkonia?

What is bottomonia?

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2019 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

$b\bar{b}$ MESONS
(including possibly non-$q\bar{q}$ states)

INSPIRE search

$\Upsilon(1S)$ $\quad I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(1S)$ MASS	9460.30 ± 0.26 MeV (S = 3.3)
$\Upsilon(1S)$ WIDTH	54.02 ± 1.25 keV

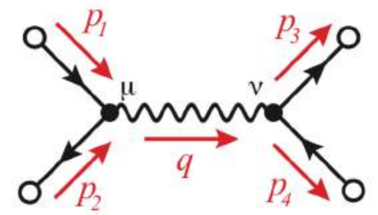
Decay Modes

Expand all decays

Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P (MeV/c)
Γ_1	$\tau^+\tau^-$	$(2.60 \pm 0.10)\%$		4384
Γ_2	e^+e^-	$(2.38 \pm 0.11)\%$		4730
Γ_3	$\mu^+\mu^-$	$(2.48 \pm 0.05)\%$		4729

- **Hadronic decays**
- **Radiative decays**
- **Lepton Family number (LF) violating modes**
- **Other decays**

E288 exp @ Fermilab, 1977



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Vacuum decay lifetime
= 3654 fm/c
~ 10^{-20} s

$b\bar{b}$ MESONS
(including possibly non-$q\bar{q}$ states)

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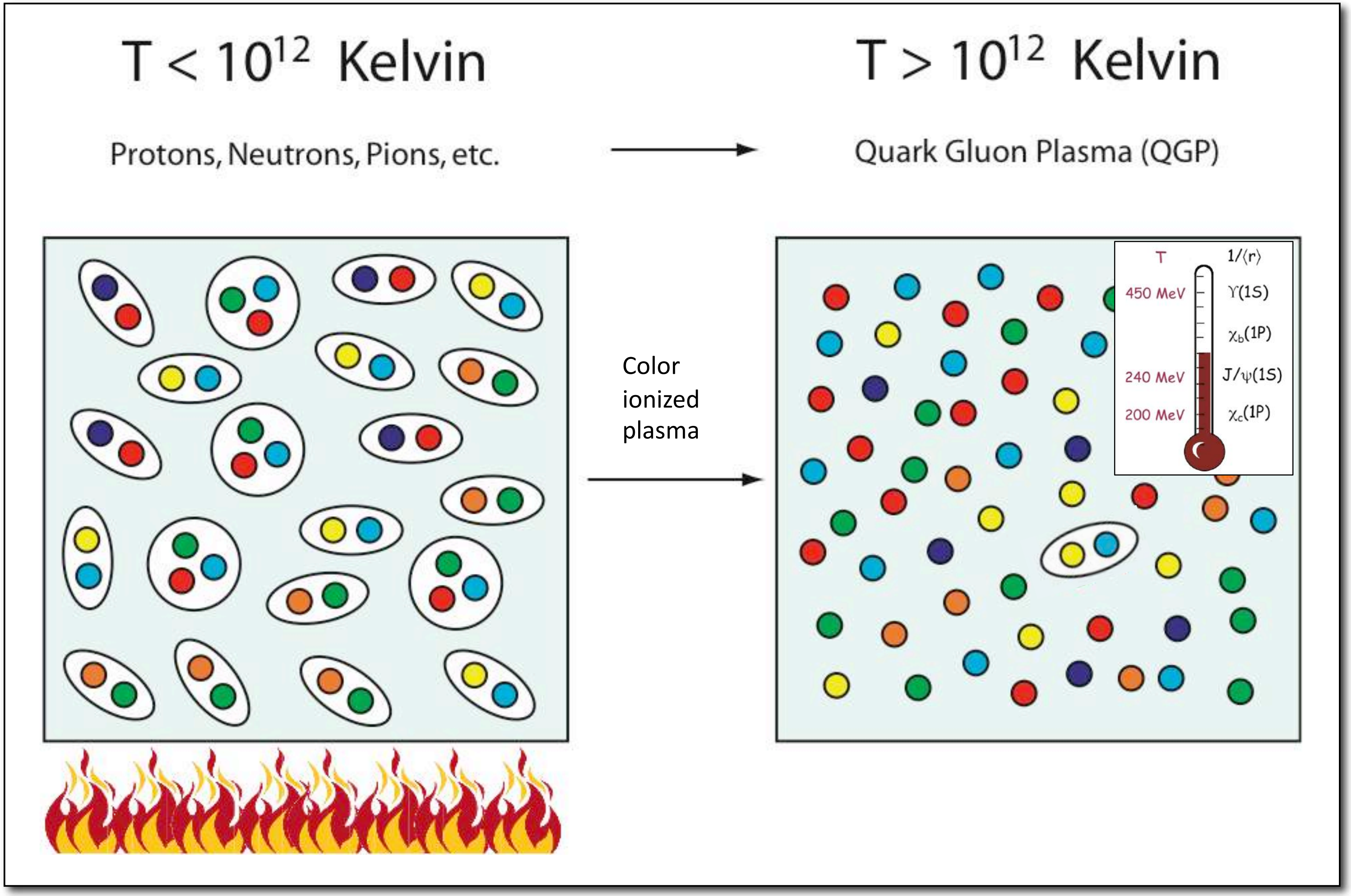
- **Hadronic decays**
- **Radiative decays**
- **Lepton Family number (LF) violating modes**
- **Other decays**

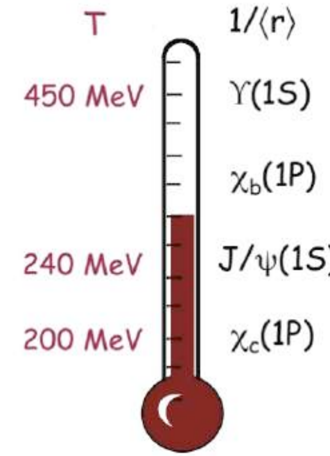
Vacuum bindng energy of Y(1s) is ~ 1 GeV

Melting hadrons – conceptual correction



Why bottomonia in AA?

- Can reliably use heavy quark effective theory
- Cold nuclear matter (CNM) effects in AA decrease with increasing quark mass
- The masses of bottomonia (~ 10 GeV) are much higher than the temperature (T < 1 GeV) generated in HICs → bottomonia production dominated by initial hard scatterings



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

- 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]

Heavy quark effective theory

Name		Mass [GeV/c²]	Electric Charge
Up	u	0.0024	+2/3
Down	d	0.0048	-1/3
Strange	s	0.104	-1/3
Charm	c	1.27	2/3
Bottom	b	4.2	-1/3
Top	t	171.2	2/3

- Normally, for QCD bound states one needs a fully relativistic treatment
- If the quark mass is sufficiently high then one can take the "heavy quark limit"
- This reduces the problem to having to deal with a non-relativistic terms plus relativistic corrections

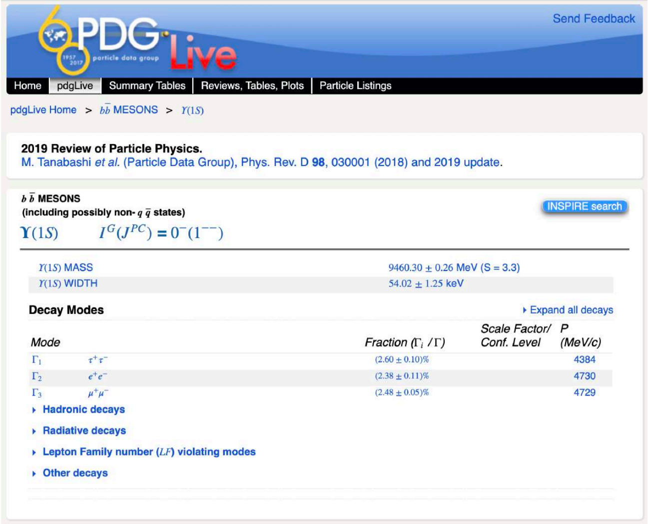
$$\begin{aligned} H &= \frac{1}{2m}\left(\vec{p}_\varphi - q\vec{A}_\varphi^{QED}\right)^2 + \frac{1}{2m}\left(\vec{p}_\chi + q\vec{A}_\chi^{QED}\right)^2 - \frac{4\alpha_s}{3}\frac{1}{r} + \sigma r - \frac{q}{2m}\,(\vec{\sigma}_\varphi + \vec{\sigma}_\chi)\cdot\vec{B}_{background} \\ &\quad -\frac{\alpha_s}{3m^2}\frac{1}{r^3} - \frac{1}{2m^2}\left(\frac{\alpha_s}{3}\frac{1}{r^3} + \frac{\sigma}{4}\frac{1}{r}\right)(\vec{\sigma}_\varphi\cdot\vec{r}\times\vec{p}_\varphi - \vec{\sigma}_\chi\cdot\vec{r}\times\vec{p}_\chi) + 2m\,, \qquad (90) \end{aligned}$$

How well does this work?

State	Name	Exp. [92]	Model	Rel. Err.
1^1S_0	$\eta_b(1S)$	9.398 GeV	9.398 GeV	0.001%
1^3S_1	$\Upsilon(1S)$	9.461 GeV	9.461 GeV	0.004%
1^3P_0	$\chi_{b0}(1P)$	9.859 GeV	9.869 GeV	0.21%
1^3P_1	$\chi_{b1}(1P)$	9.893 GeV		
1^3P_2	$\chi_{b2}(1P)$	9.912 GeV		
1^1P_1	$h_b(1P)$	9.899 GeV		
2^1S_0	$\eta_b(2S)$	9.999 GeV	9.977 GeV	0.22%
2^3S_1	$\Upsilon(2S)$	10.002 GeV	9.999 GeV	0.03%
2^3P_0	$\chi_{b0}(2P)$	10.232 GeV	10.246 GeV	0.05%
2^3P_1	$\chi_{b1}(2P)$	10.255 GeV		
2^3P_2	$\chi_{b2}(2P)$	10.269 GeV		
2^1P_1	$h_b(2P)$	-		
3^1S_0	$\eta_b(3S)$	-	10.344 GeV	-
3^3S_1	$\Upsilon(3S)$	10.355 GeV	10.358 GeV	0.03%

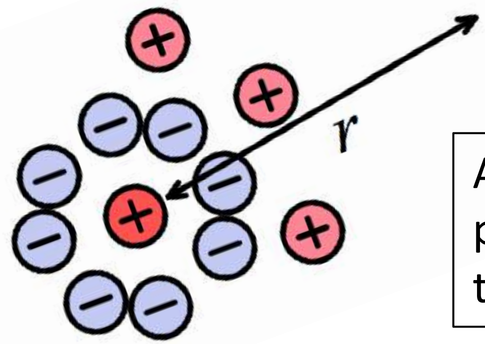
J. Alford and MS, 1309.3003

- As the table to the right shows, it works quite well
- Maximum error in the masses of the bottomonium sates is 0.22%



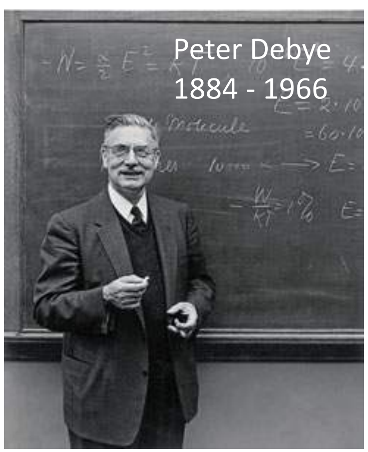
Debye-screening in a plasma

Screening of electric interaction with screening length $r_D = 1/m_D$



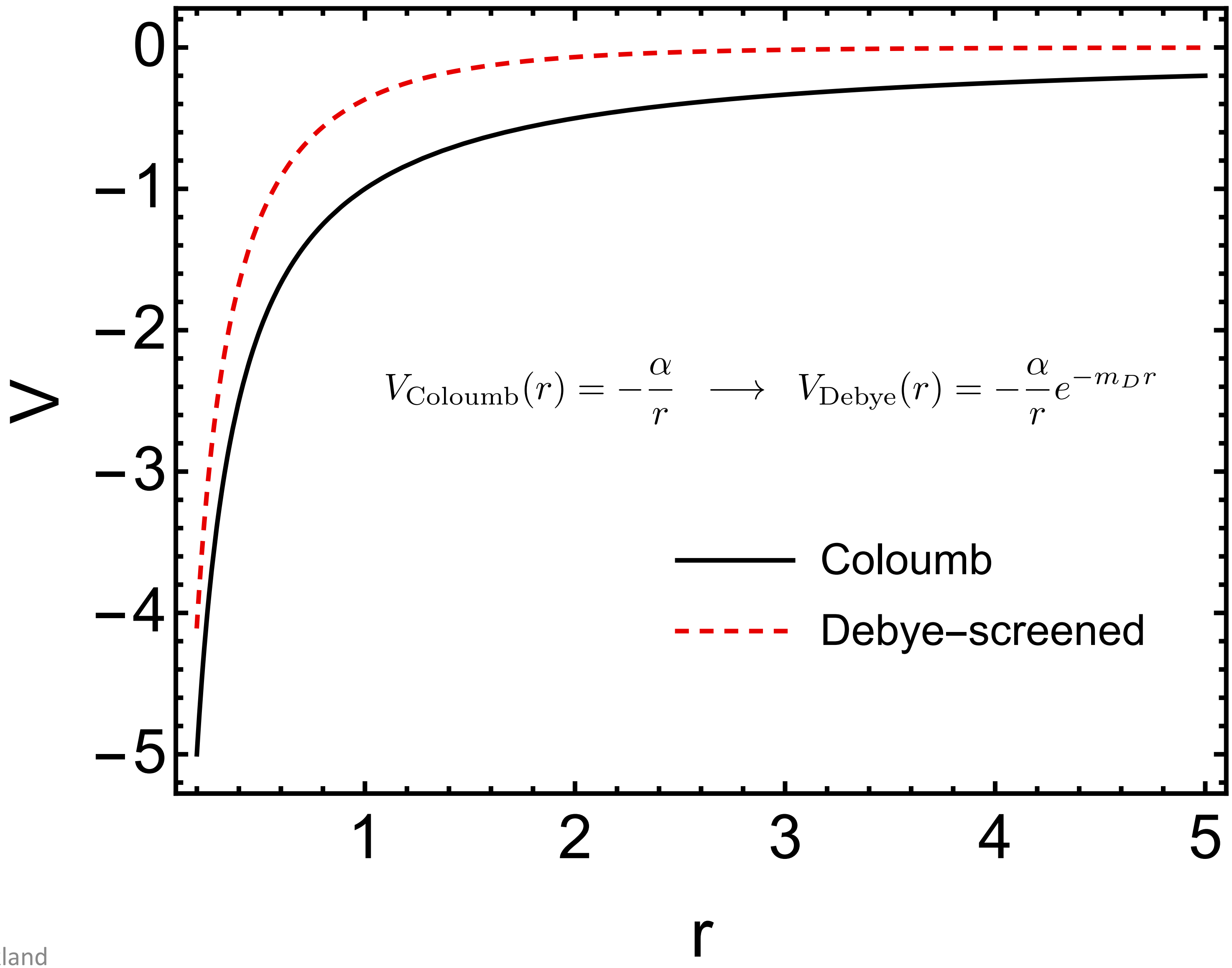
A test charge polarizes the particles of the plasma and they "screen" its charge

$$V_{\text{Coloumb}}(r) = -\frac{\alpha}{r} \quad \longrightarrow \quad V_{\text{Debye}}(r) = -\frac{\alpha}{r} e^{-m_D r}$$



- The same phenomena that occurs in an electric plasma occurs in the QGP
- A screening mass $m_D \sim gT$ is generated by strong interactions of quarks and gluons

Debye-screening in a plasma



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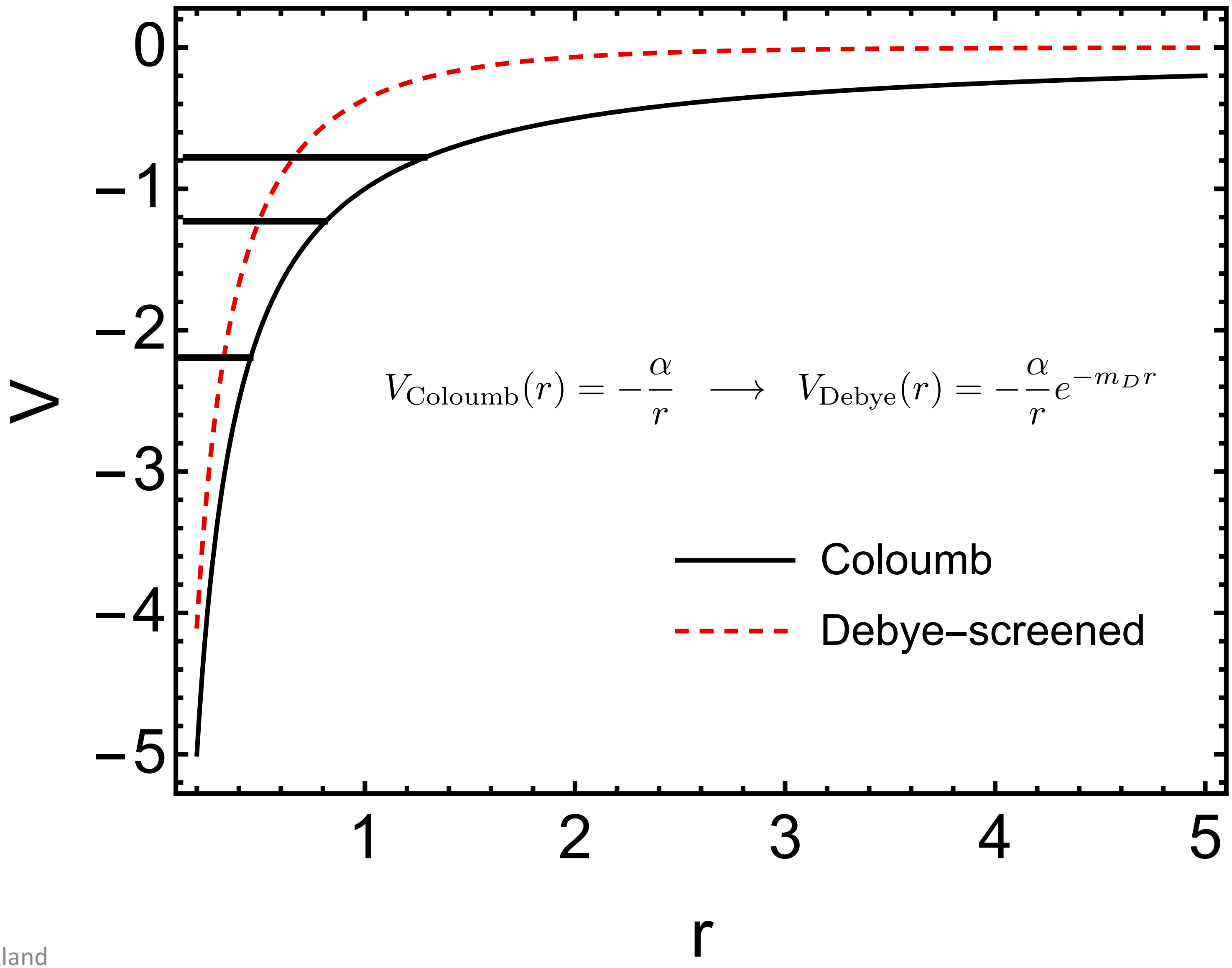

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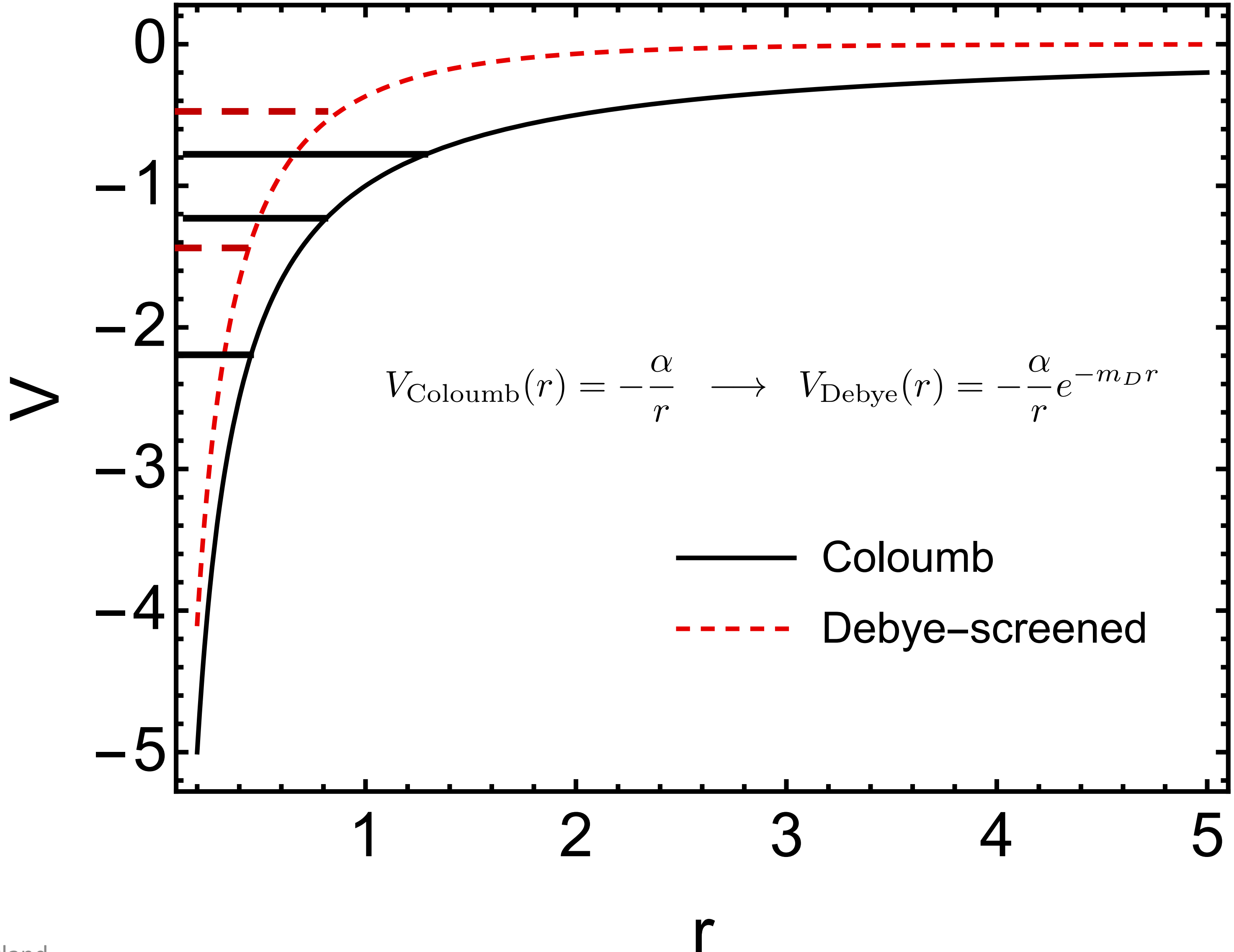


$$V_{\text{Coloumb}}(r) = -\frac{\alpha}{r} \longrightarrow V_{\text{Debye}}(r) = -\frac{\alpha}{r}e^{-m_D r}$$

In-medium breakup (decay) rates

- In addition to Debye screening, which reduces the effective coupling between quarks and antiquarks, the states also acquire a **temperature dependent breakup rate (width)** which increases as the temperature increases.

- Primarily, heavy quark bound states breakup via strong processes which result in the quark/antiquark becoming unbound inside of the QGP, e.g. **Landau damping**, **collisional disassociation**, etc.

In-medium 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 direction-dependent masses, 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

Complex-valued Potential

- Anisotropic potential 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.

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

MS, 1106.2571; Bazow and MS, 1112.2761

Internal Energy

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

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)

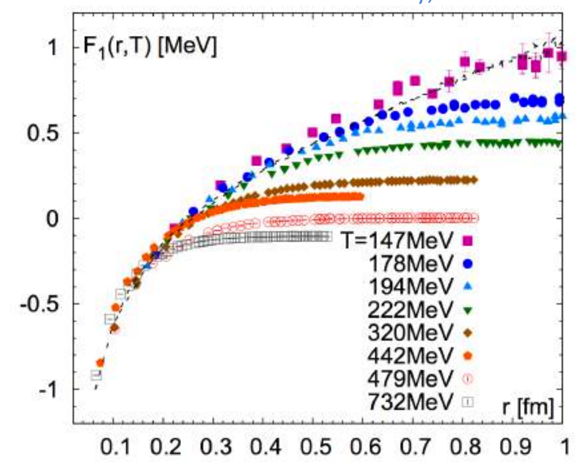
Heavy Quarkonium Suppression

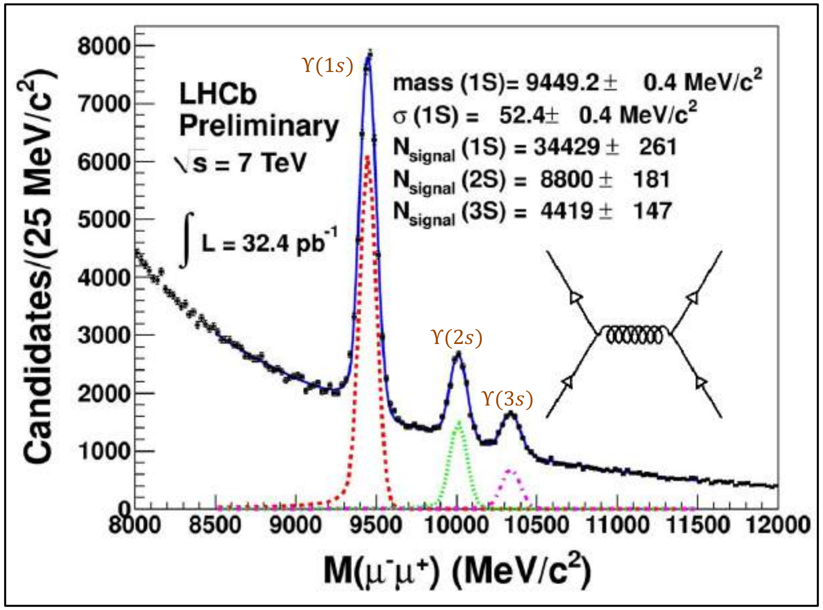
- In a high temperature quark-gluon plasma we expect **weaker color binding** (Debye screening + asymptotic freedom)

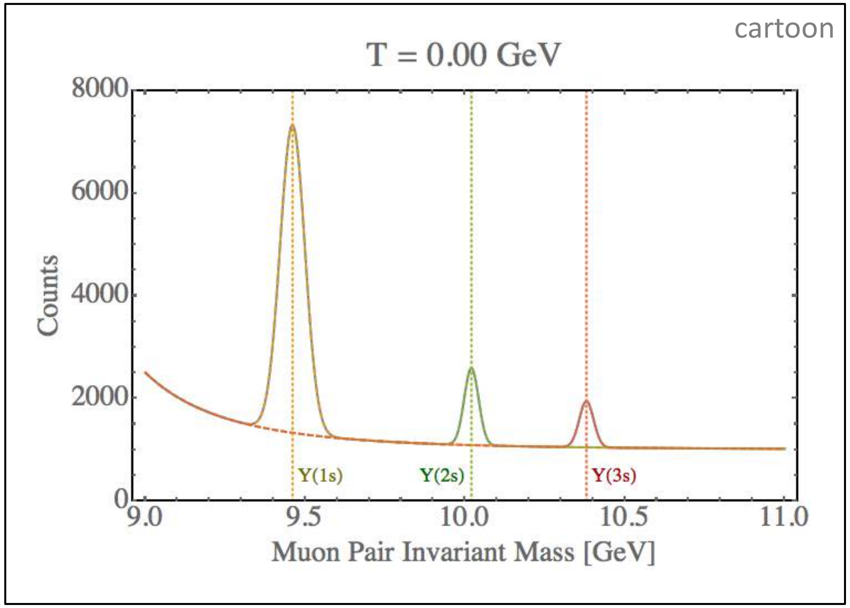
E. V. Shuryak, Phys. Rept. 61, 71–158 (1980)
T. Matsui, and H. Satz, Phys. Lett. B178, 416 (1986)
F. Karsch, M. T. Mehr, and H. Satz, Z. Phys. C37, 617 (1988)

- Also, high energy plasma particles which slam into the bound states cause them to have shorter lifetimes → **larger spectral widths**

A. Bazavov and P. Petreczky, 1211.5638







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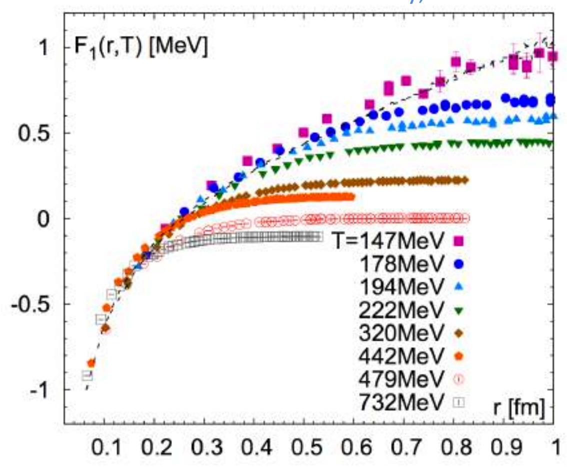

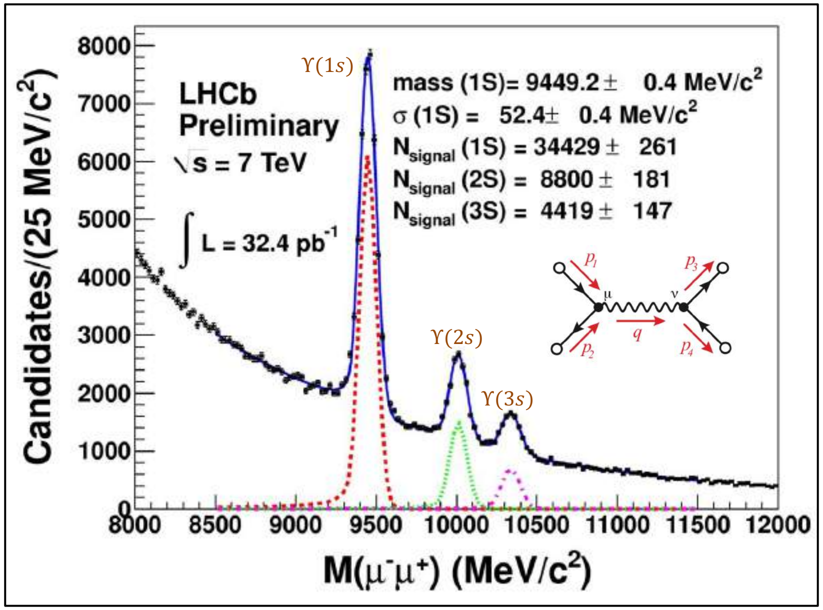

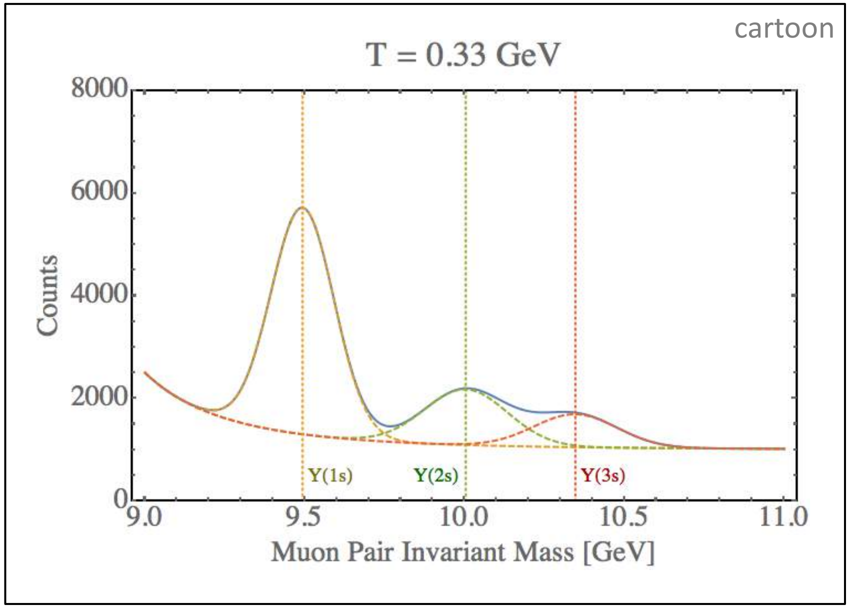

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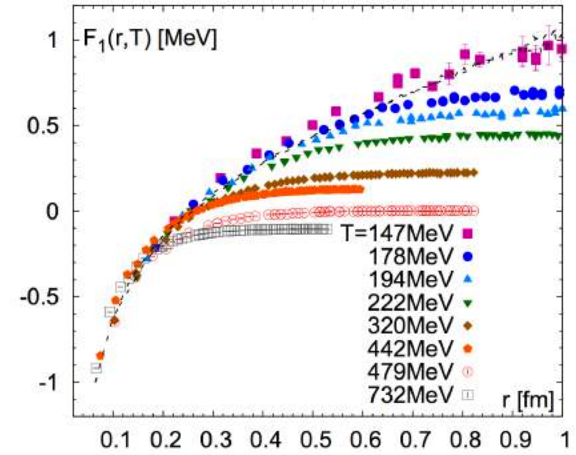
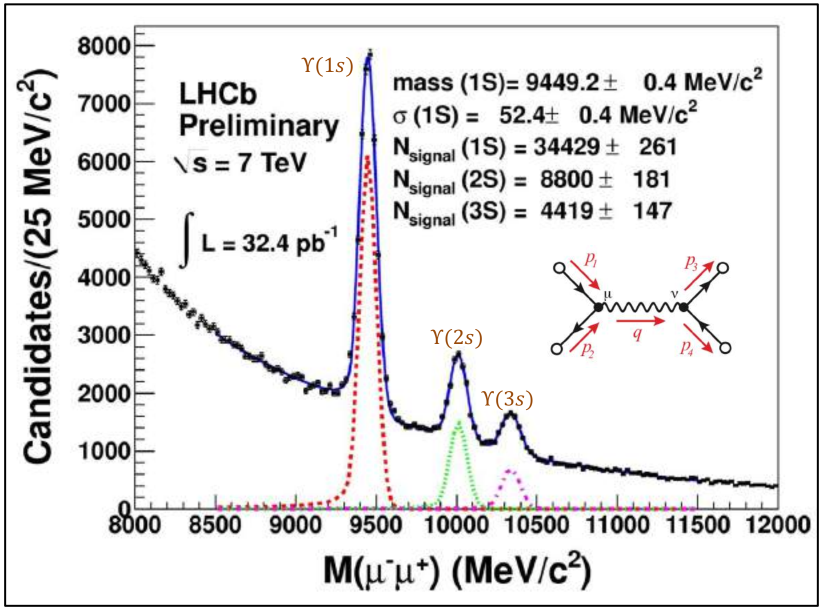
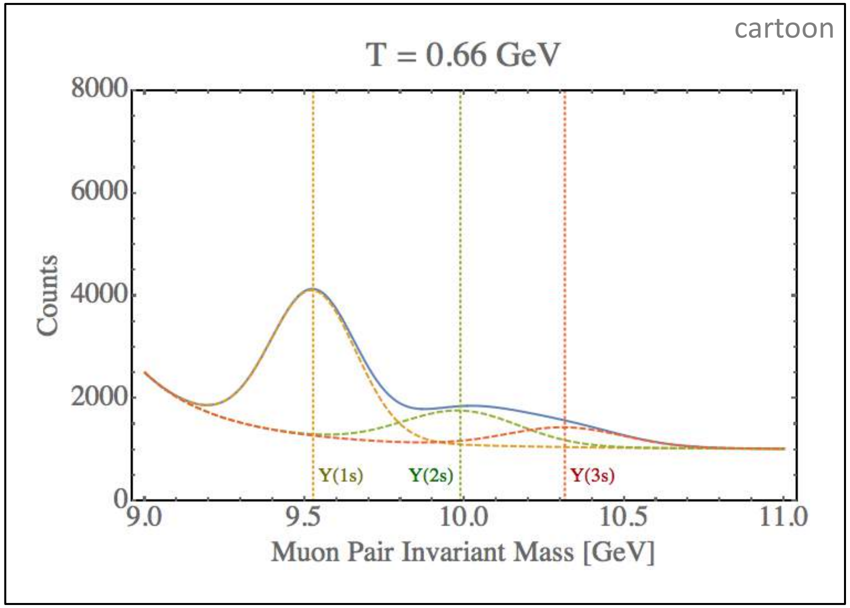






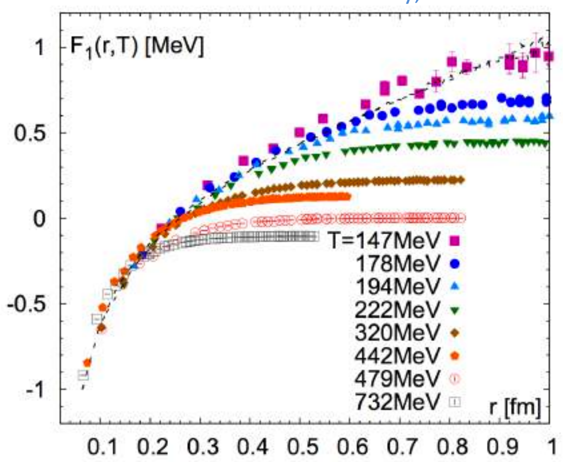
Heavy Quarkonium Suppression

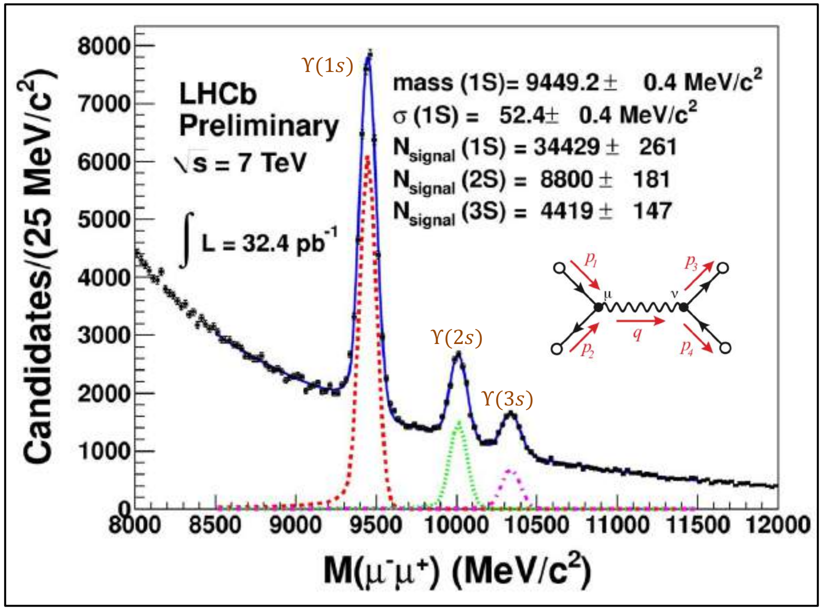
- In a high temperature quark-gluon plasma we expect **weaker color binding** (Debye screening + asymptotic freedom)

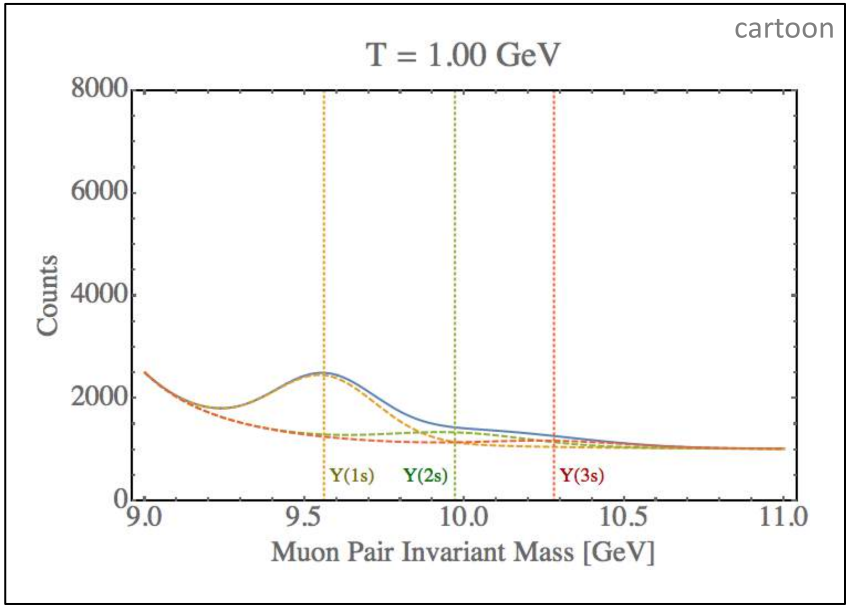
E. V. Shuryak, Phys. Rept. 61, 71–158 (1980)
T. Matsui, and H. Satz, Phys. Lett. B178, 416 (1986)
F. Karsch, M. T. Mehr, and H. Satz, Z. Phys. C37, 617 (1988)

- Also, high energy plasma particles which slam into the bound states cause them to have shorter lifetimes → **larger spectral widths**

A. Bazavov and P. Petreczky, 1211.5638







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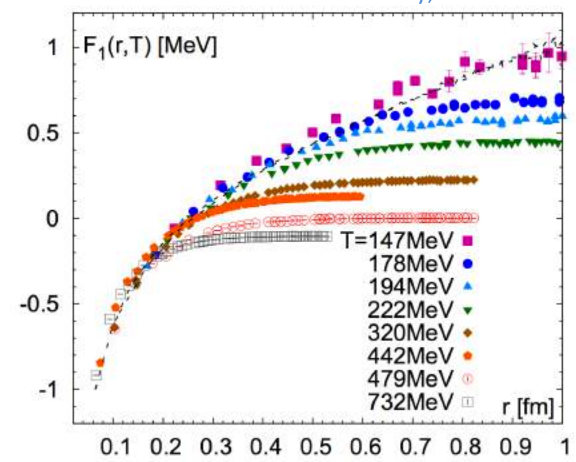
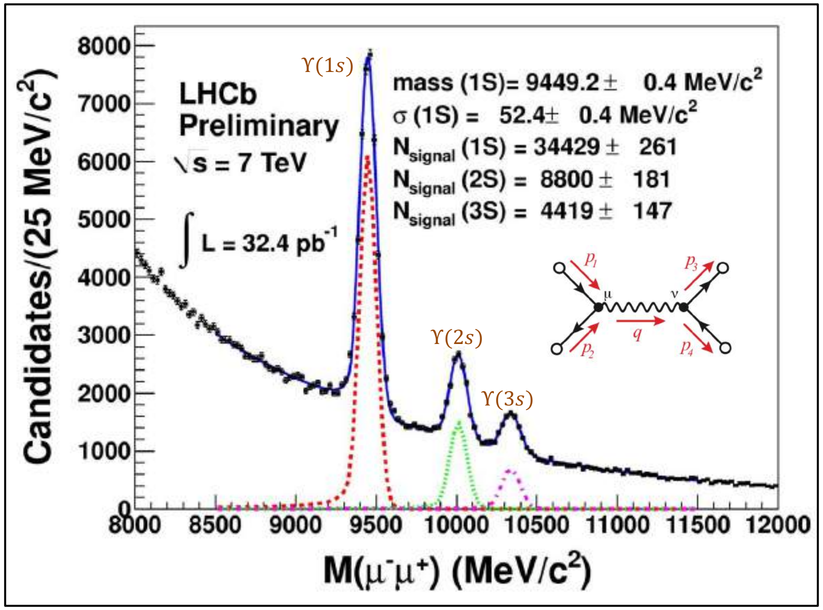
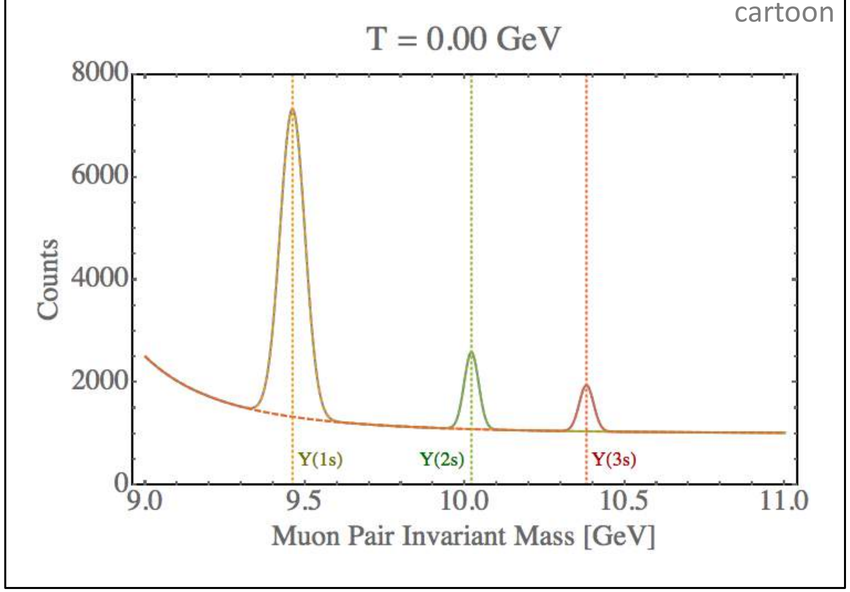




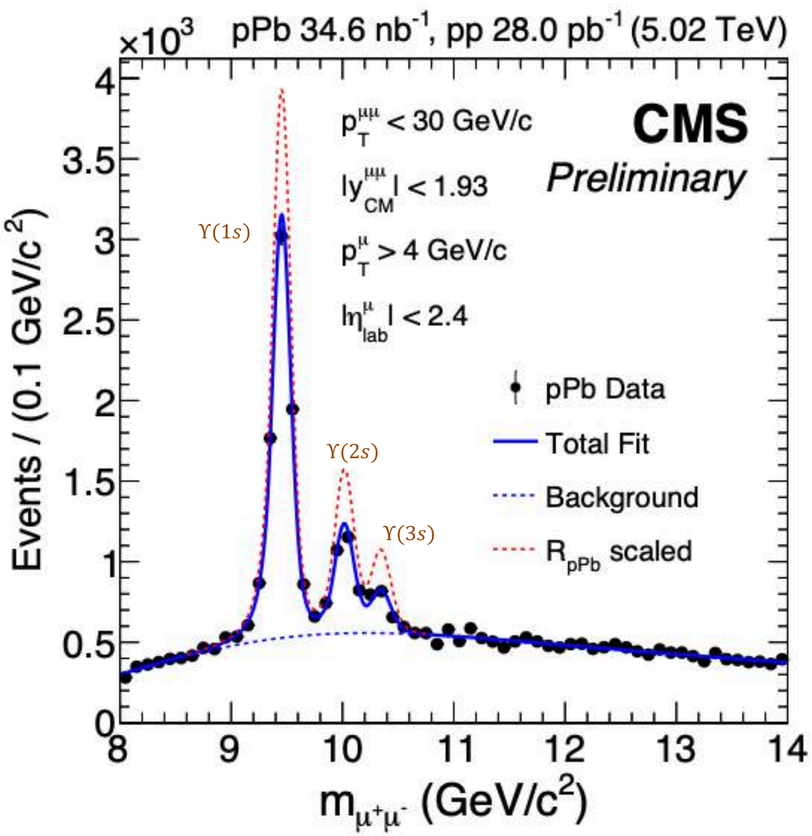
cartoon



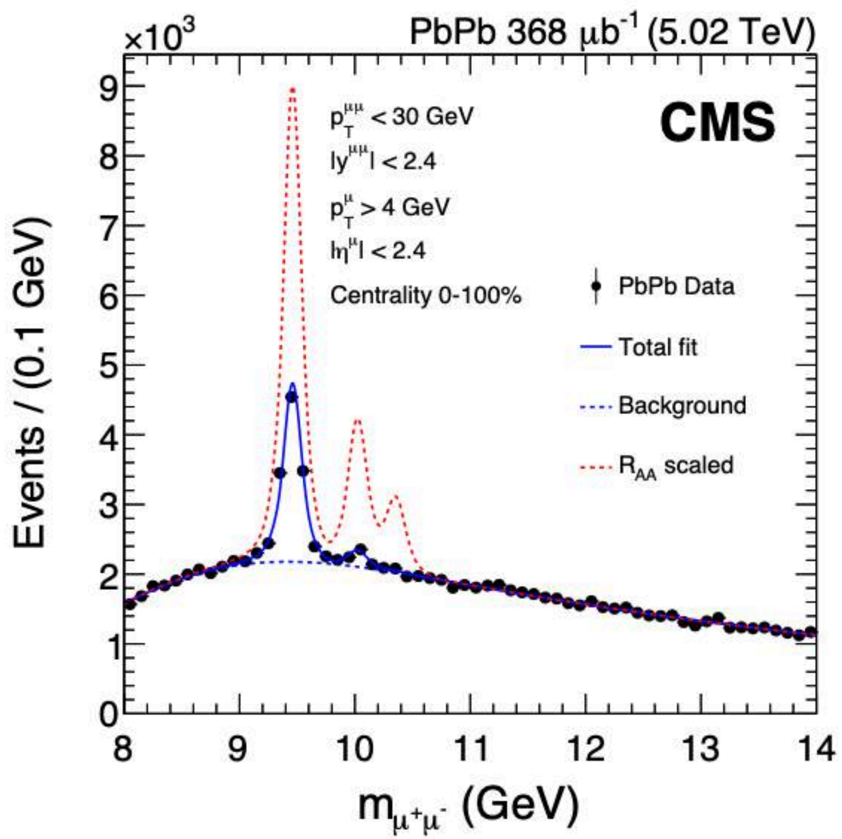
CMS 2019 Data – 5.02 TeV Dimuon Spectra

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.

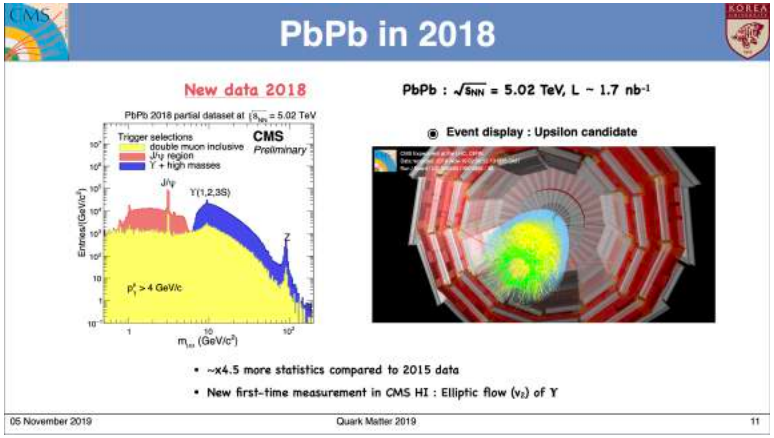
pp



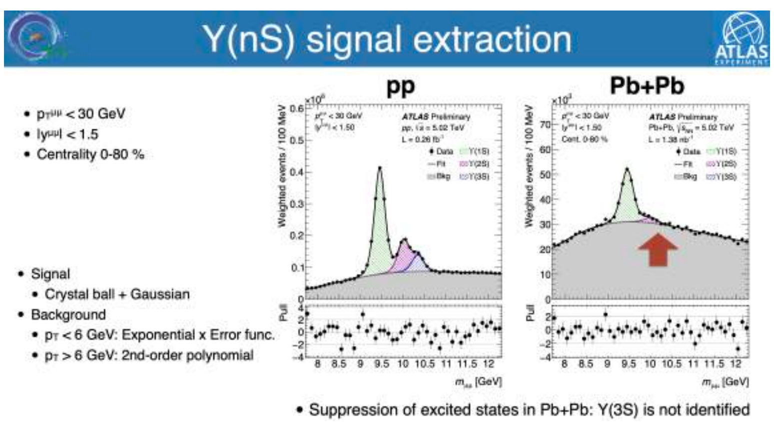
PbPb

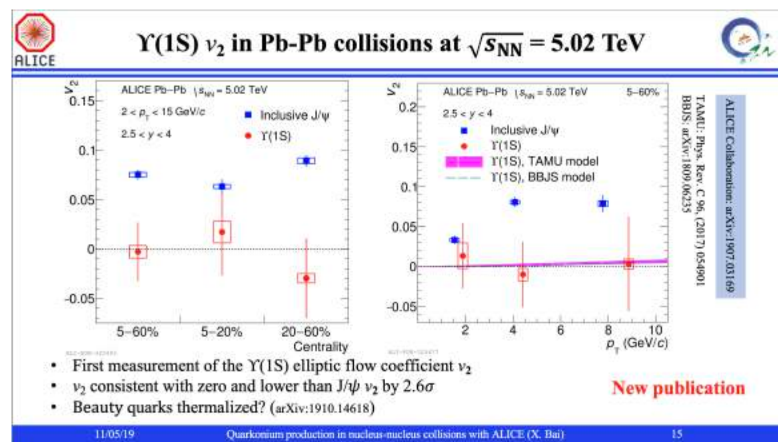


New data at QM19



- New data from CMS and ALICE
- Sufficient statistics to start extracting production anisotropies
- First data from ATLAS collaboration; data explained well by KSU in-medium breakup model
- LHCb is joining the effort (high mom res)

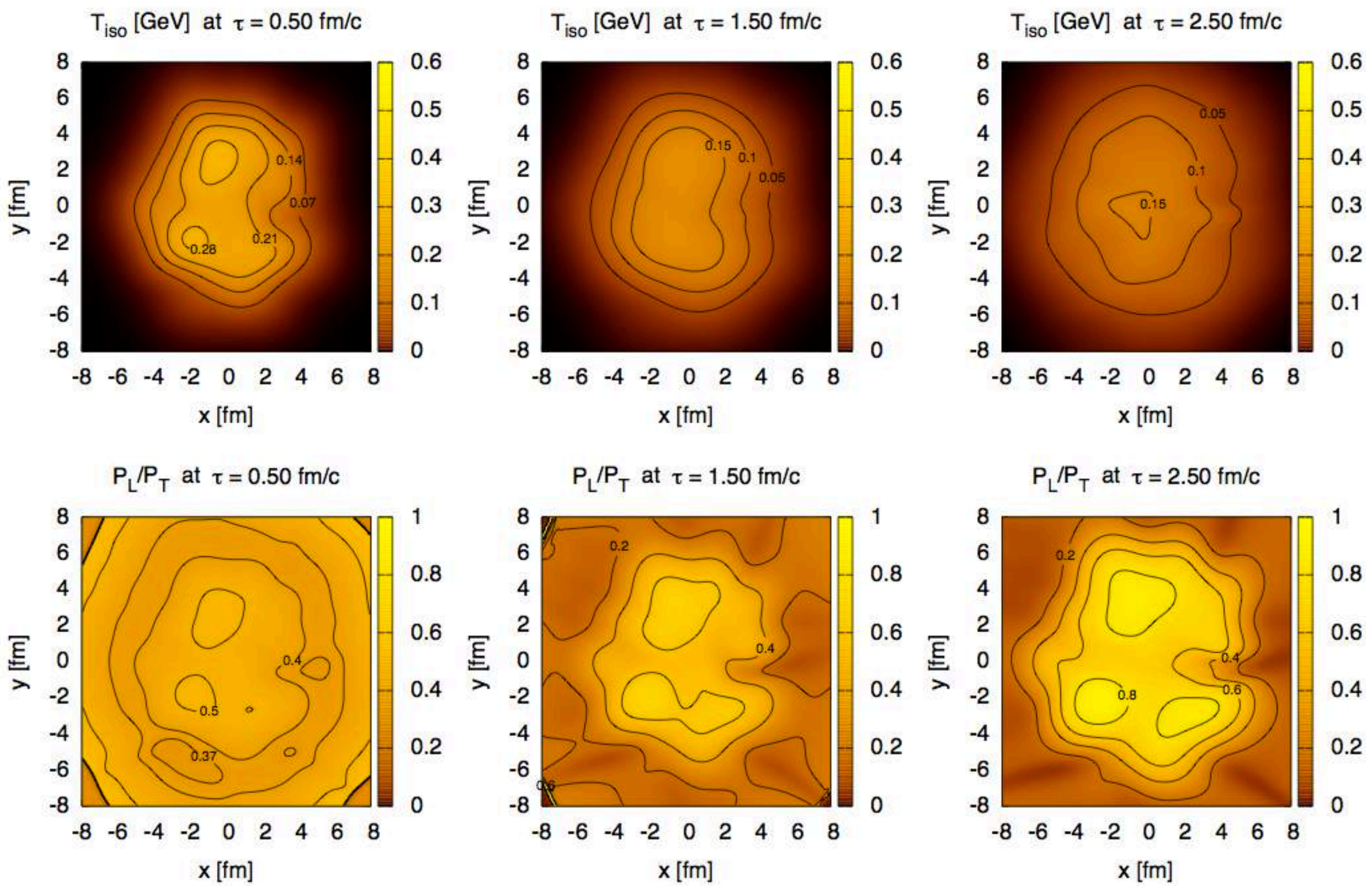




Theory

Conceptually simple calculation

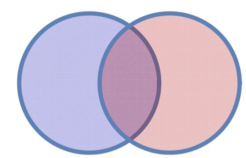
For in-medium suppression, given the population of quarkonia states at some τ_0, we can simply integrate the <u>instantaneous decay/regeneration rate</u> of the state $\Gamma(\tau,x,y,\eta)$ over the QGP spatiotemporal evolution to obtain the **survival probability**.



M. Martinez, R. Ryblewski, MS, arXiv:1204.1473

1 fm/c = 3 x 10^{-24} seconds

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



b = 7 fm

Summary of adiabatic the method

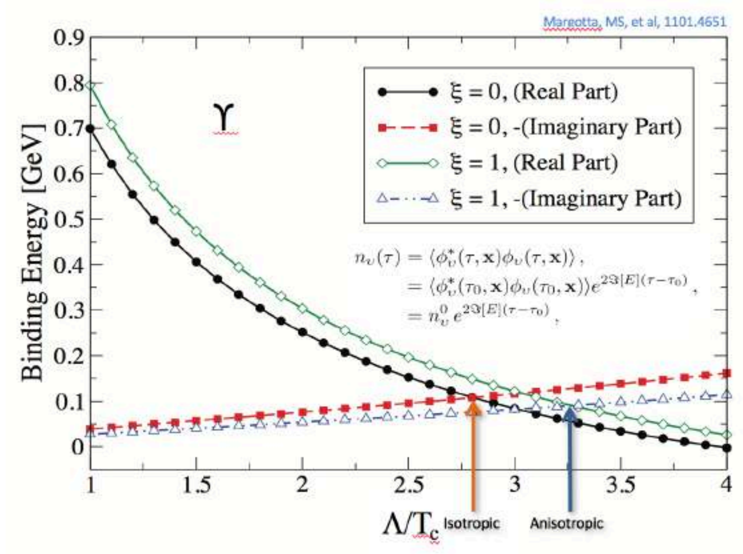
Solve the 3d Schrödinger EQ
with a complex-valued potential

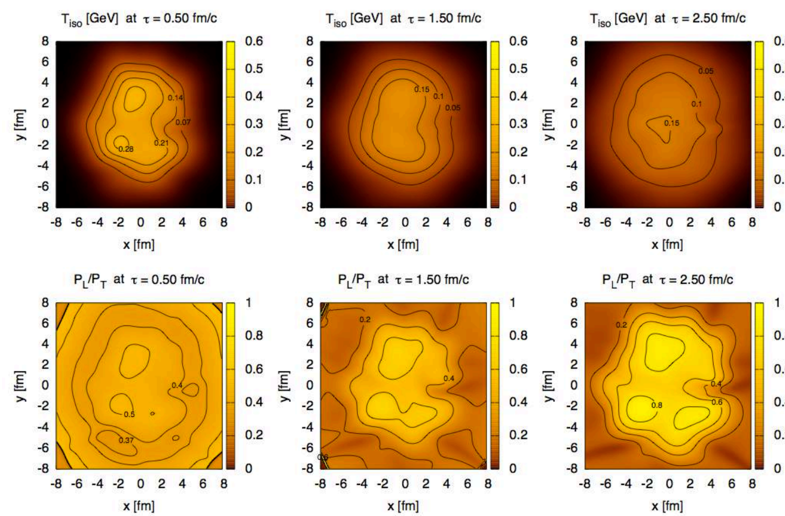
↓

Obtain the real and imaginary parts of the binding energies for the Υ(1s), Υ(2s), Υ(3s), χ_{b1}, and χ_{b2} as function of energy density and momentum-anisotropy.
Yager-Elorriaga and MS, 0901.1998;
Margotta, MS, et al, 1101.4651

↓

Fold together with the non-EQ spatiotemporal evolution to obtain the **survival probability**.





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-nucleon collisions

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

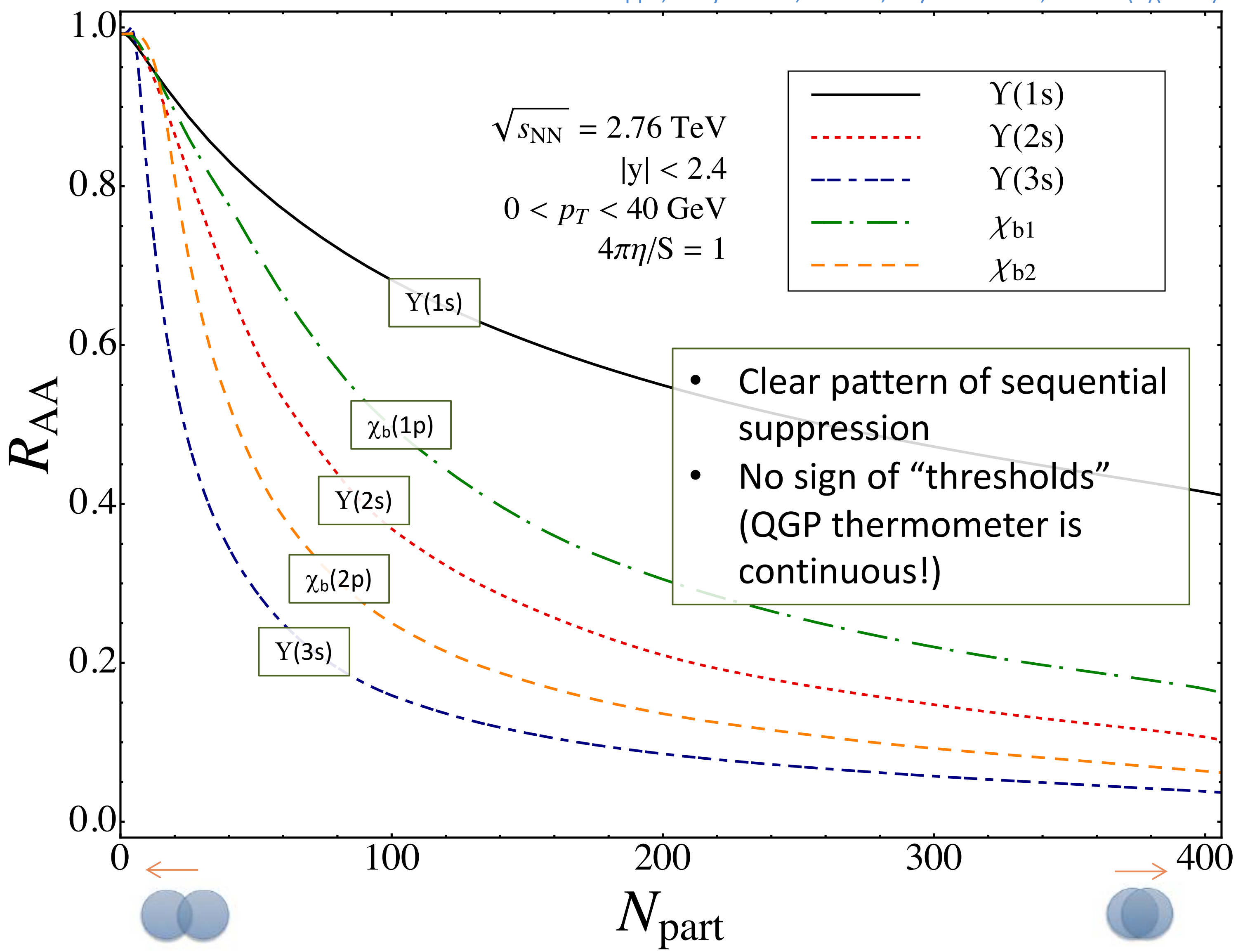
N_{AA}: Number produced in a nucleus-nucleus collision

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

n_{binary}: Number of nucleon-nucleon collisions per nucleus collision

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

B. Krouppa, R. Ryblewski, and MS, Phys. Rev. C 92, 061901(R)(2015).



- Clear pattern of sequential suppression
- No sign of “thresholds” (QGP thermometer is continuous!)

ϒ(1S) Feed Down Fractions	
ϒ(1S)	0.668
ϒ(2S)	0.086
ϒ(3S)	0.010
$\chi_b(1P)$	0.170
$\chi_b(2P)$	0.051
$\chi_b(3P)$	0.015

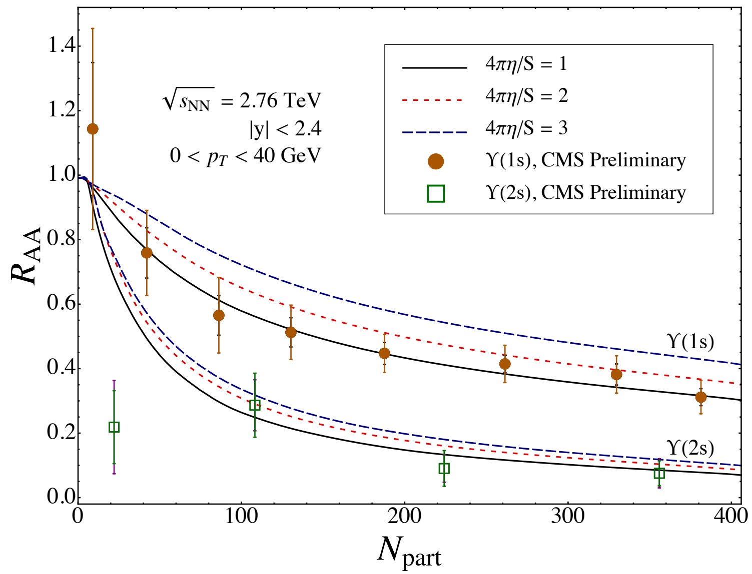
ϒ(2S) Feed Down Fractions	
ϒ(2S)	0.604
ϒ(3S)	0.043
$\chi_b(2P)$	0.309
$\chi_b(3P)$	0.044

Facing the experimental data...

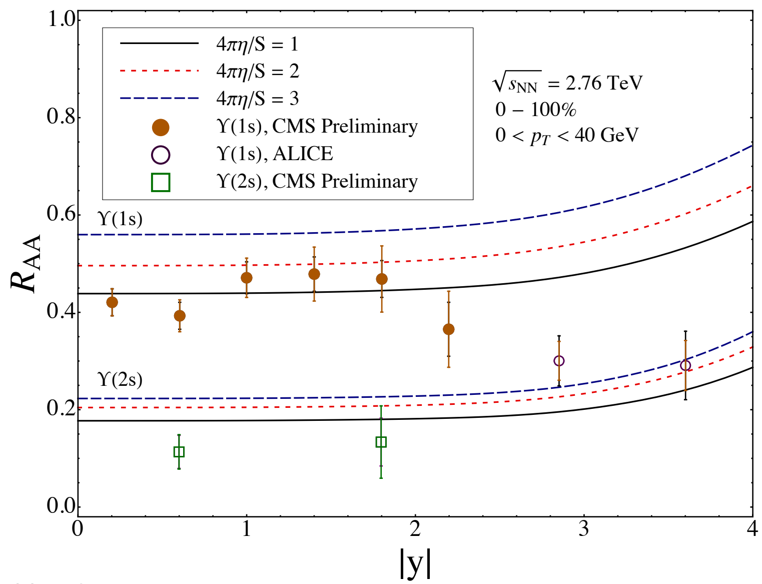
Adiabatic approximation

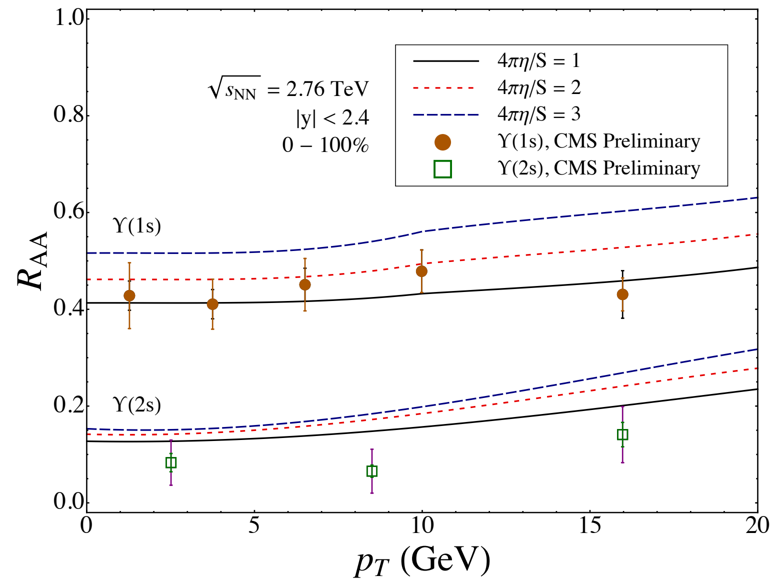
Inclusive Bottomonium Suppression @ 2.76 TeV

B. Krouppa, R. Ryblewski, and MS, Phys. Rev. C 92, 061901(R) (2015).



- Compare model to 2.76 TeV data from CMS and ALICE
- Reasonable agreement with CMS data but not perfect
- Disagreement with ALICE data in rapidity range 2.5 < y < 4
- Model slightly underpredicts Υ(2s) suppression





Inclusive Bottomonium Suppression @ 2.76 TeV

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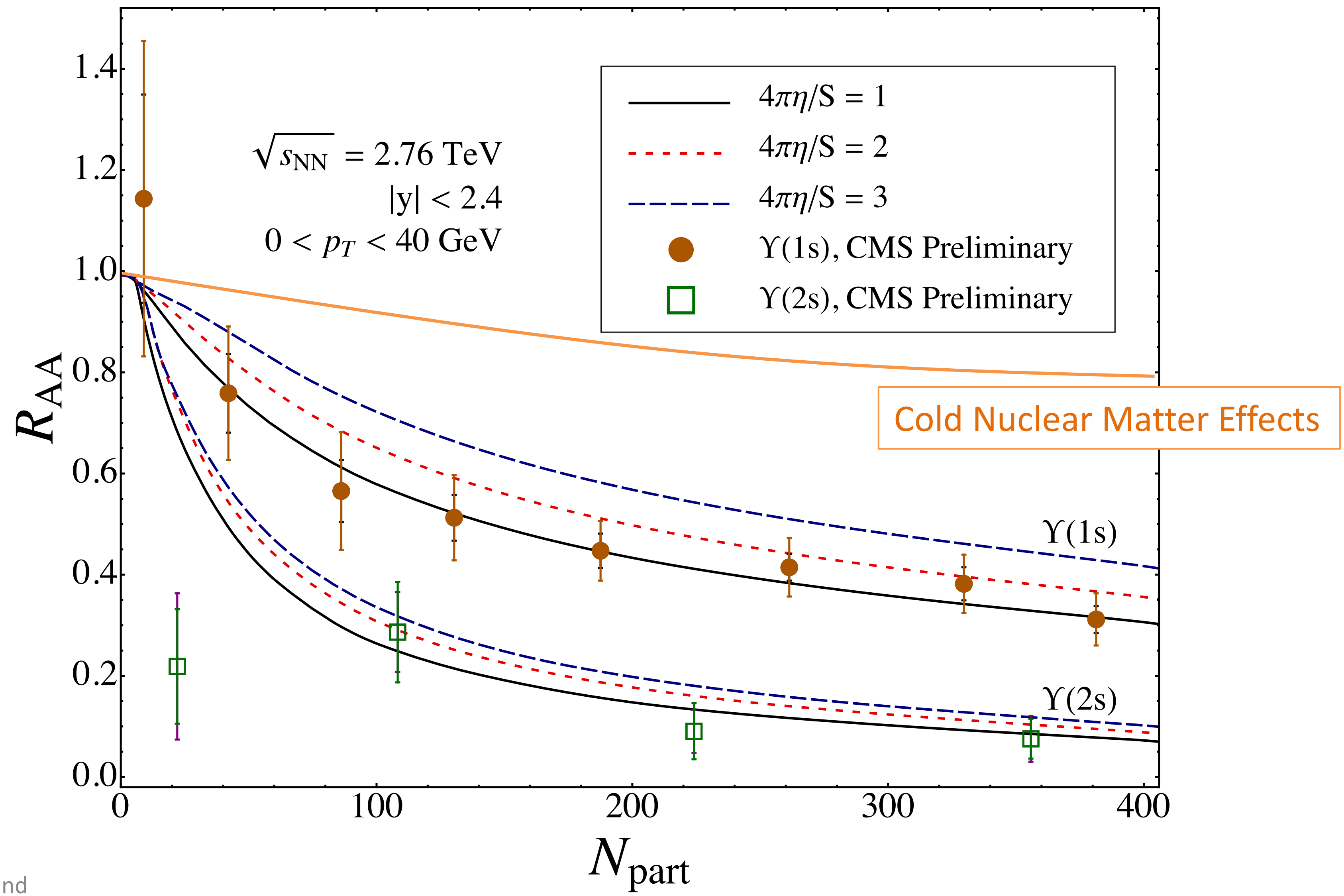
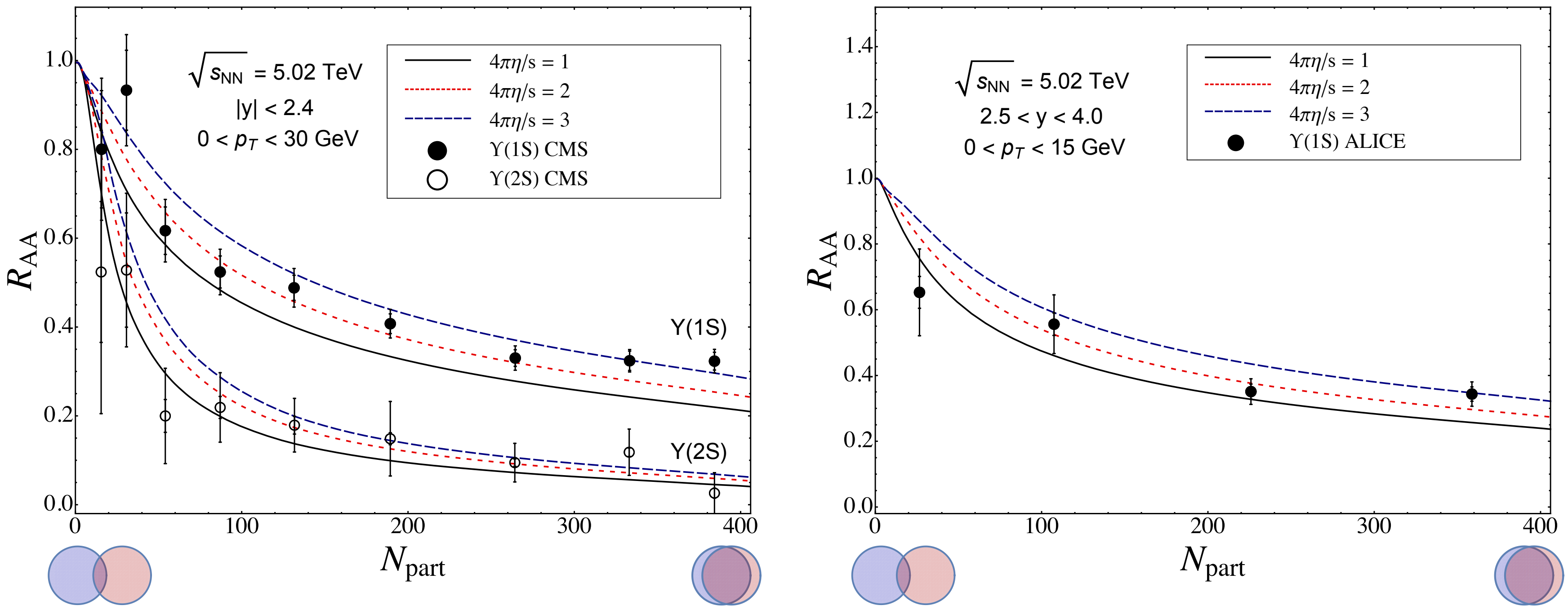


Inclusive Bottomonium Suppression @ 5.02 TeV

B. Krouppa, R. Ryblewski, and MS 1704.02361

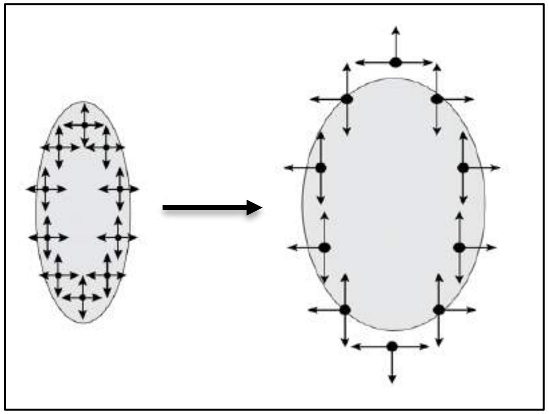
- Model predictions compared to CMS data (left) and ALICE data (right)
- Results below are as a function of N_{part}



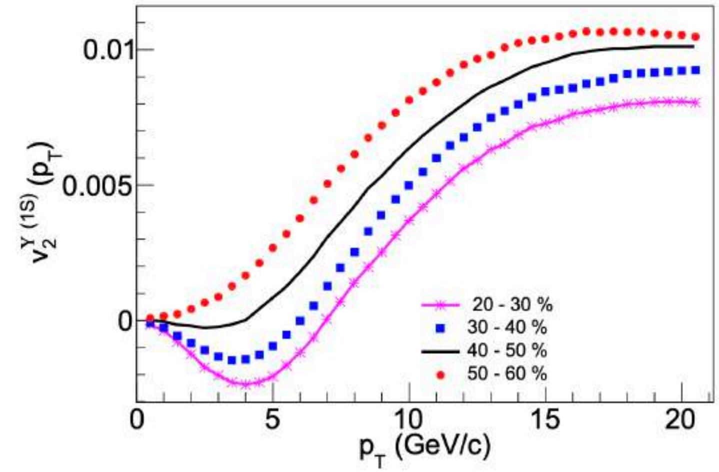
- CMS (left) covers central rapidity (|y| < 2.4) and ALICE (right) covers forward rapidity (2.5 < |y| < 4)

Bottomonium “flow” … or lack thereof

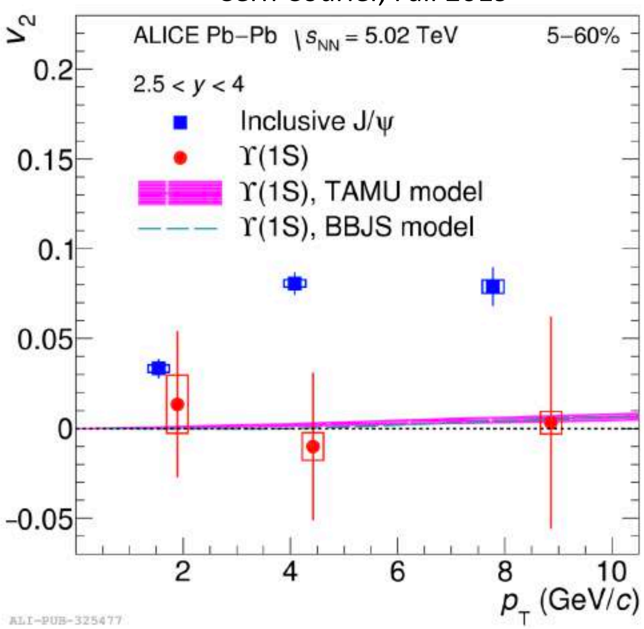
4d flow tomography



Bhadhuri, Alqahtani, Borghini, Jaiswal, and MS, 2007.03939



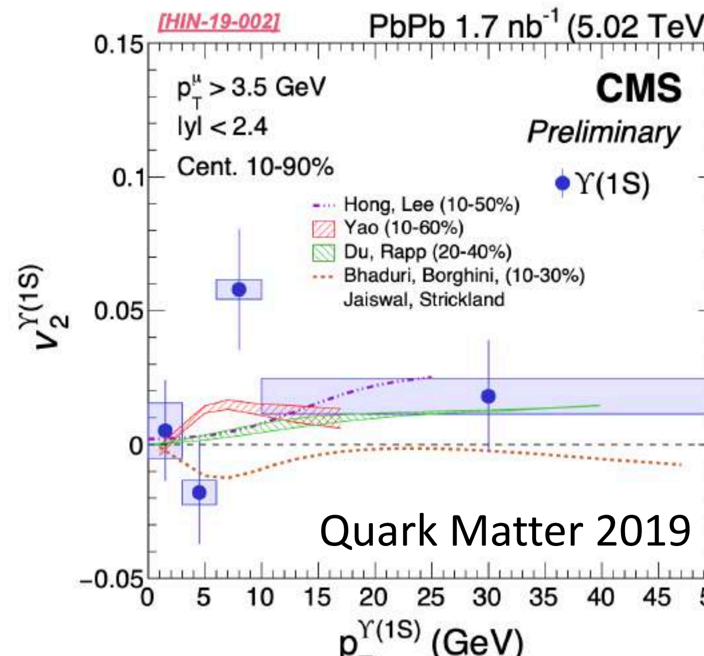
Cern Courier, Fall 2019



TAMU: Phys. Rev. C 96, (2017) 054901

BBJS: arXiv:1809.06235

ALICE Collaboration: arXiv:1907.03169



Quark Matter 2019

Facing the experimental data...

Real-time quantum evolution

NEW: Heavy Quarkonium Quantum Dynamics (HQQD)

A. Islam and MS, forthcoming.

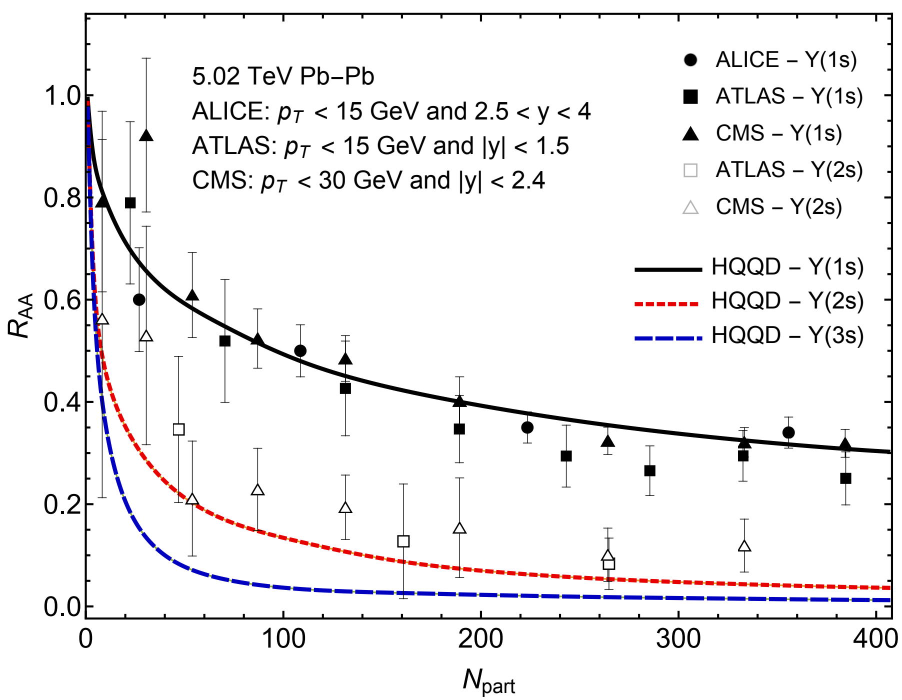
- Sample bottomonium production points from binary collision overlap profile
- Sample bottomonium initial momentum using pp experimental results
- Calculate suppression for each of the states under consideration (1s, 2s, 3p, 3s, 3p) by solving 3D Schrödinger equation numerically for each trajectory.
- Compute total number of produced states of each type
- Then, take into account late-time feed down using a feed-down matrix constructed from PDG branching

$$\vec{N}_{\text{final}} = F\vec{N}_{\text{QGP}} \qquad F = \begin{pmatrix} 1 & 0.265 & 0.184 & 0.0657 & 0.0650 \\ 0 & 0.735 & 0 & 0.1060 & 0.0946 \\ 0 & 0 & 0.816 & 0 & 0.0047 \\ 0 & 0 & 0 & 0.8283 & 0 \\ 0 & 0 & 0 & 0 & 0.8357 \end{pmatrix}$$

- To obtain RAA, we then divide by the Nbin-scaled pp-production cross sections.
- To obtain vn, we compute <cos(nf)>
- Errors reported are statistical → 1.2 million sampled trajectories

HQQD RAA vs experimental data

A. Islam and MS, forthcoming.



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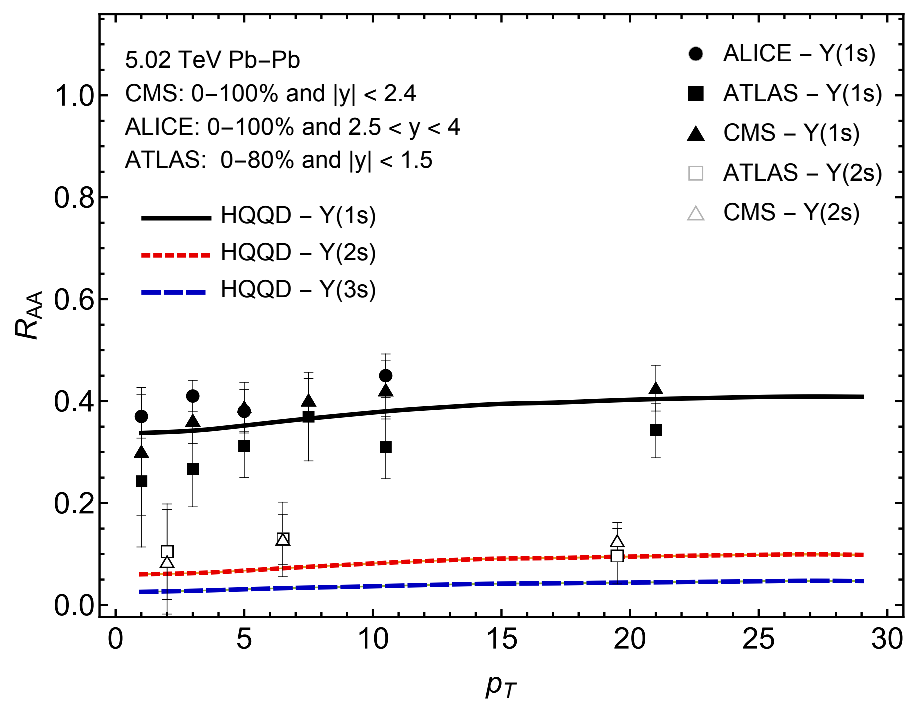
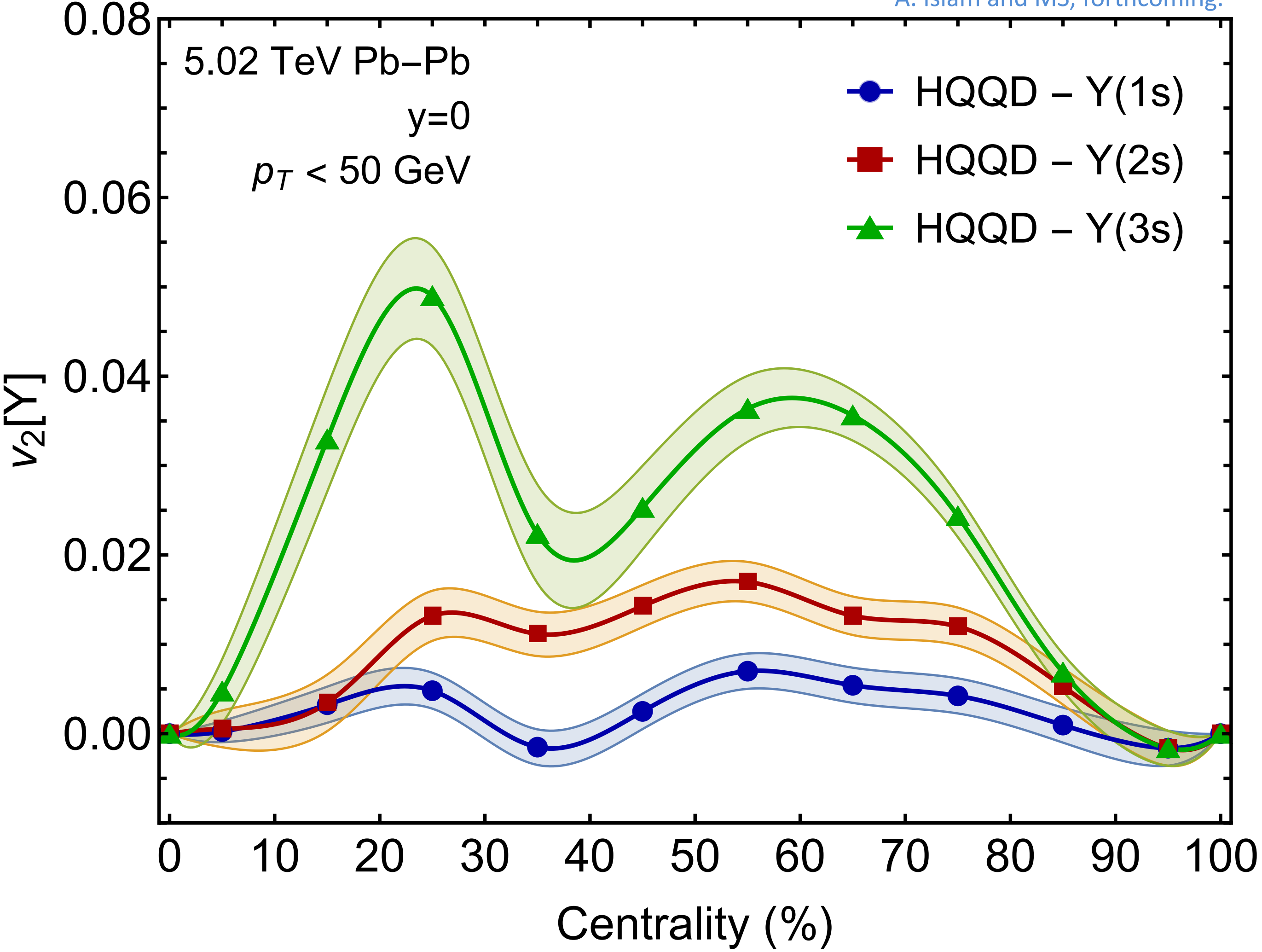


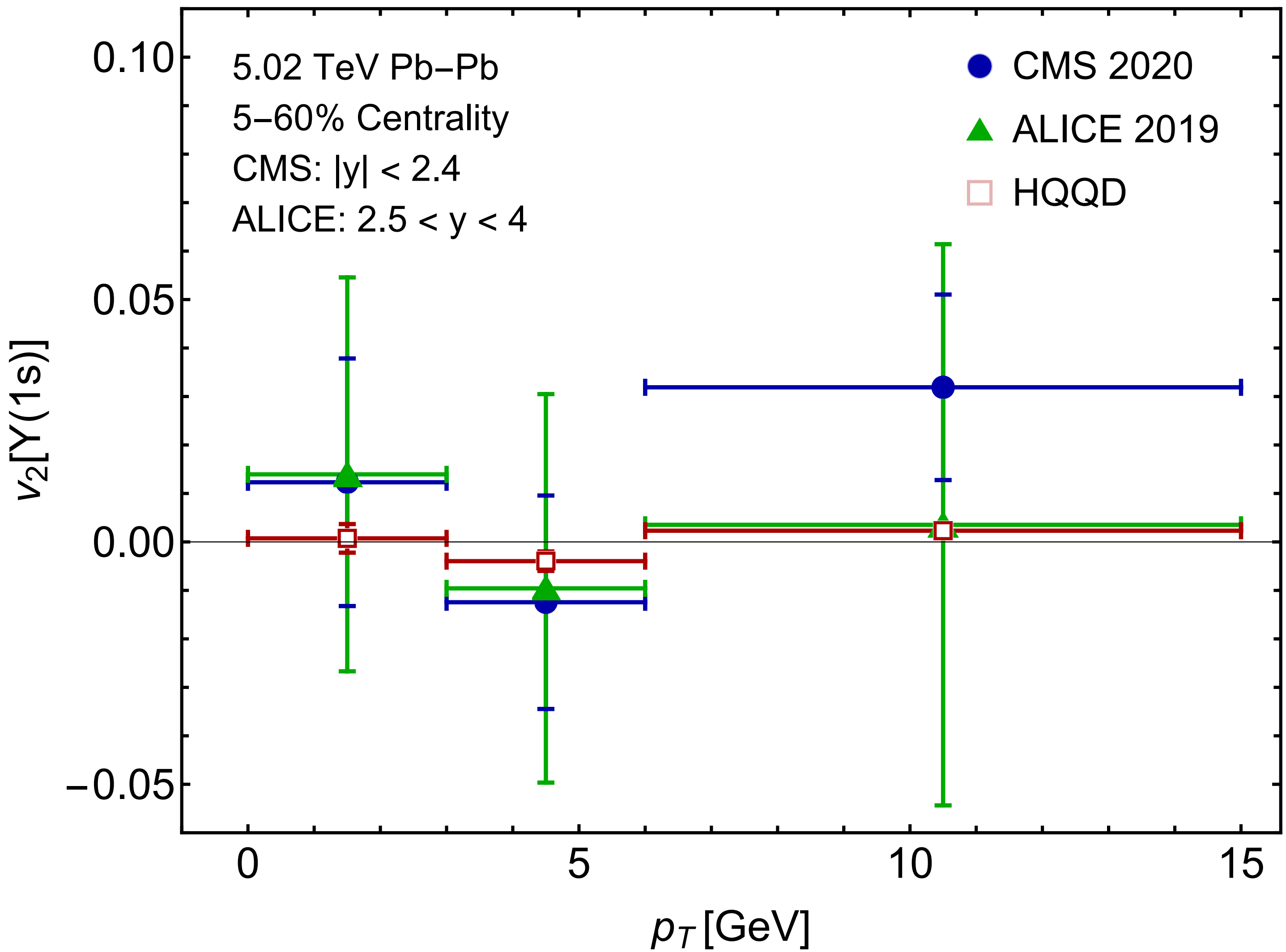
HQQD v2 predictions

A. Islam and MS, forthcoming.



HQQD comparison to data

A. Islam and MS, forthcoming.



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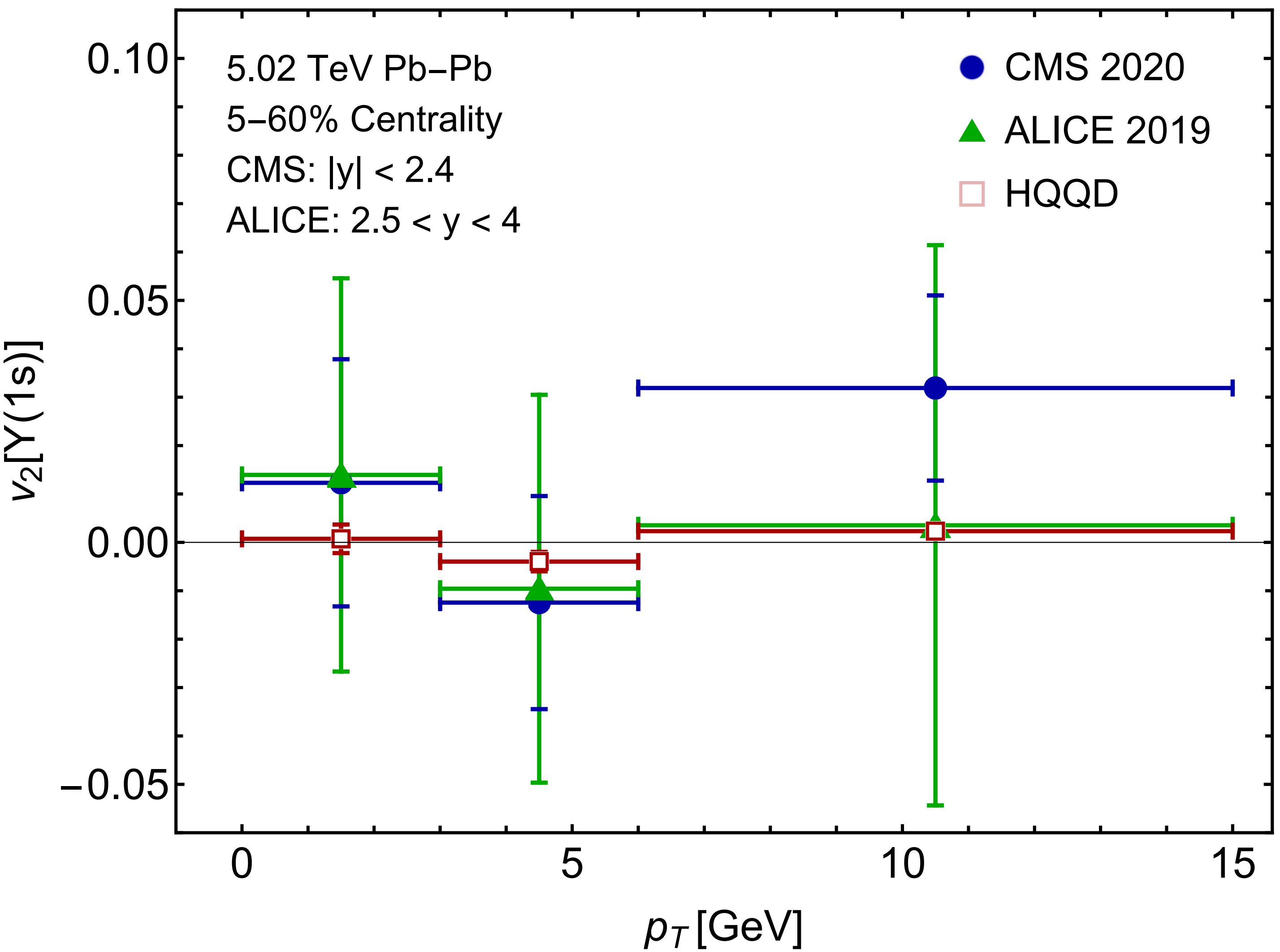
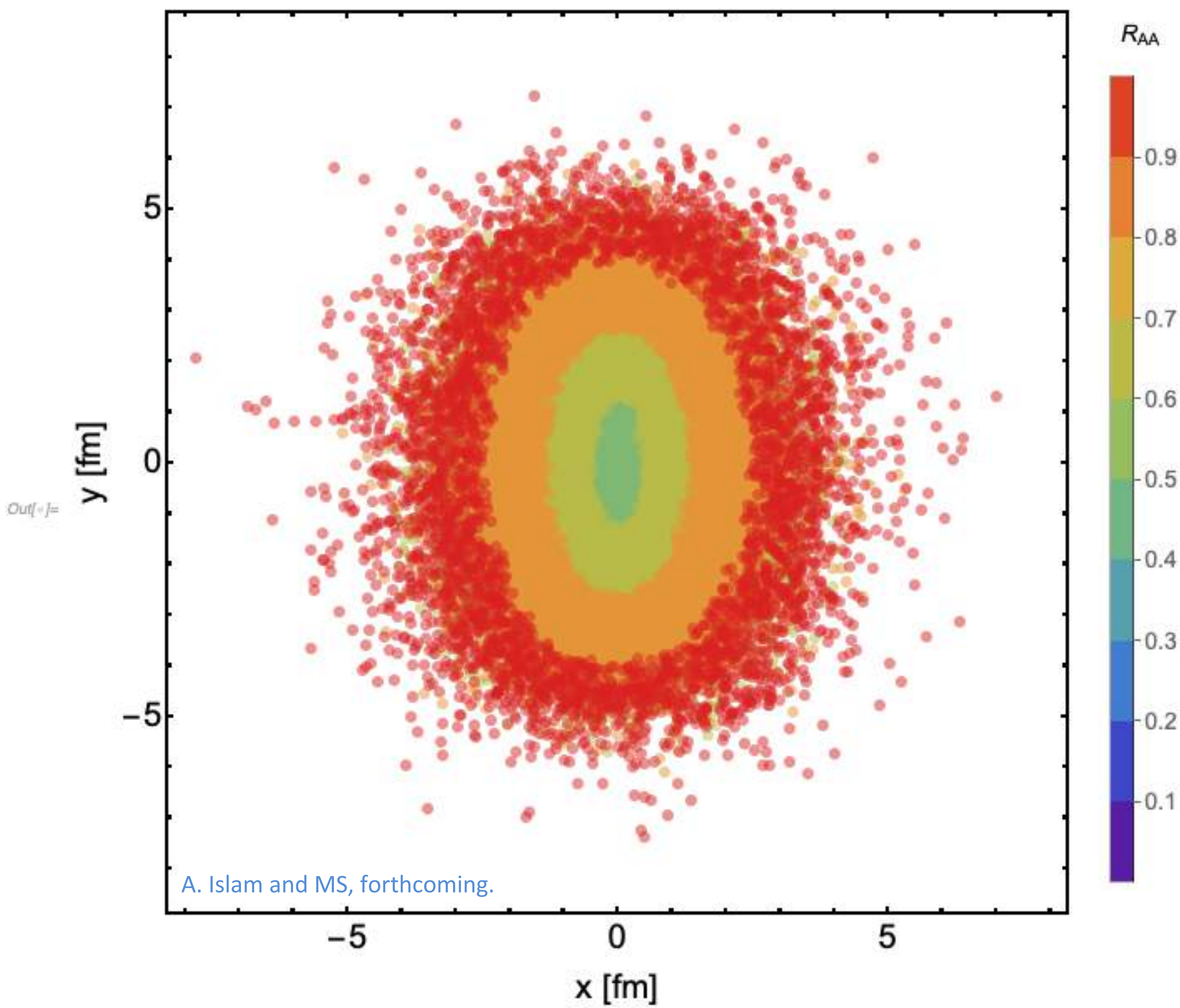


QGP tomography



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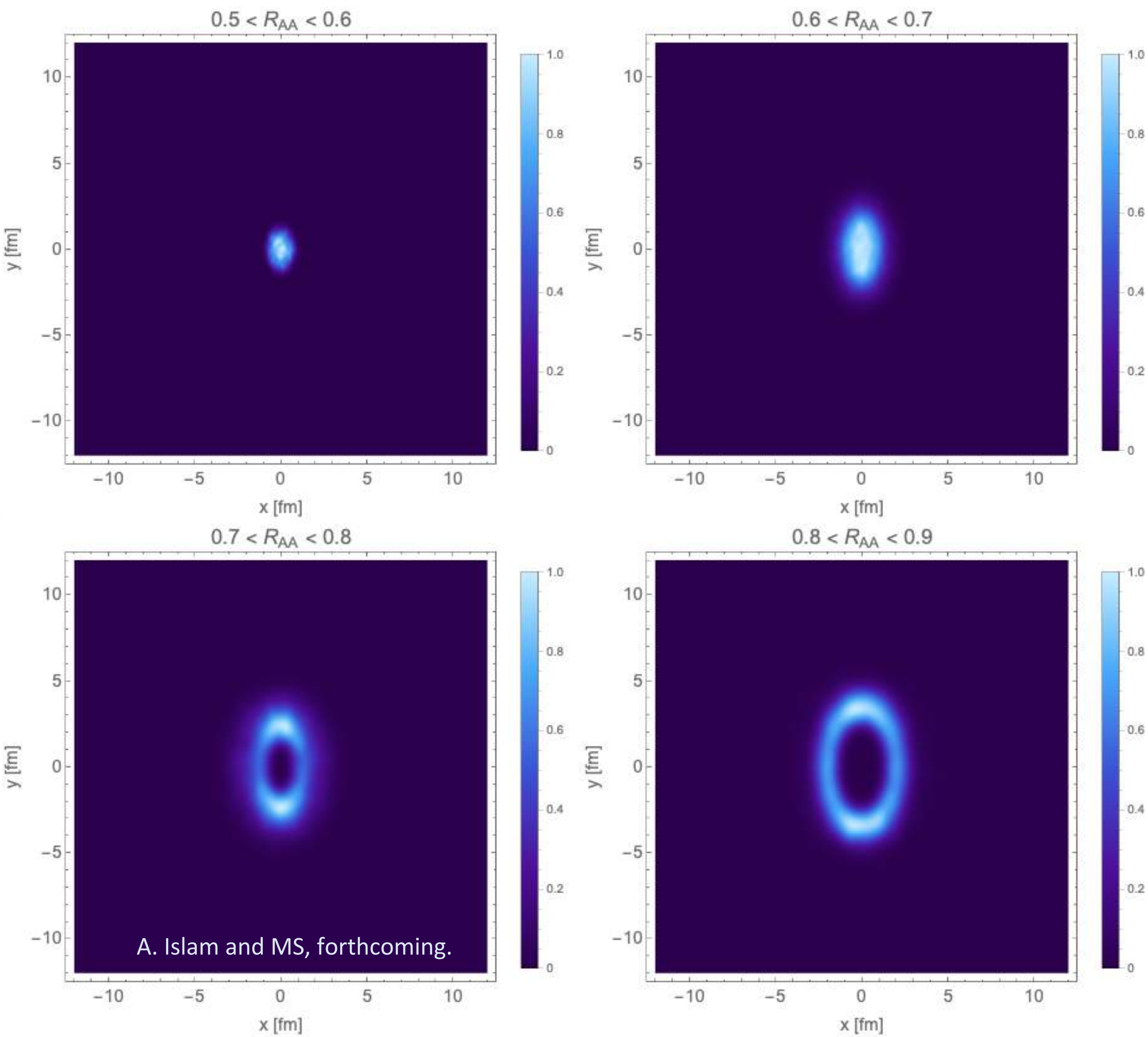

Conclusions and Outlook

- **The suppression of bottomonium is a smoking gun for the creation of the QGP**
- Initial state effects (aka cold nuclear matter effects) are not enough to explain the experimental observations.
- **Complex screening model works reasonably well to describe the suppression seen at LHC → QGP!**
- There is much work to do on this problem. One thing I did not discuss today was "**regeneration**". This occurs when the density of heavy (anti-)quarks becomes large, making it probable for a pair to recombine in the QGP. **At very high temperatures/beam energies this effect is important for charm quarks, but still not so important for bottom quarks.**
- Showed forthcoming work on improving calculations to **include full real-time in-medium Schrödinger equation evolution** (student A. Islam) → <u>in-medium quantum regeneration</u>