Quarkonium Suppression in a Hadron Gas

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Charmonium in the QGP

Matsui-Satz, PLB (1986)

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r}\, e^{-r/r_D} \qquad r_D < r_\psi$$

If screening radius is smaller than Bohr radius:

Quark and antiquark do not bind ! -> SUPPRESSION

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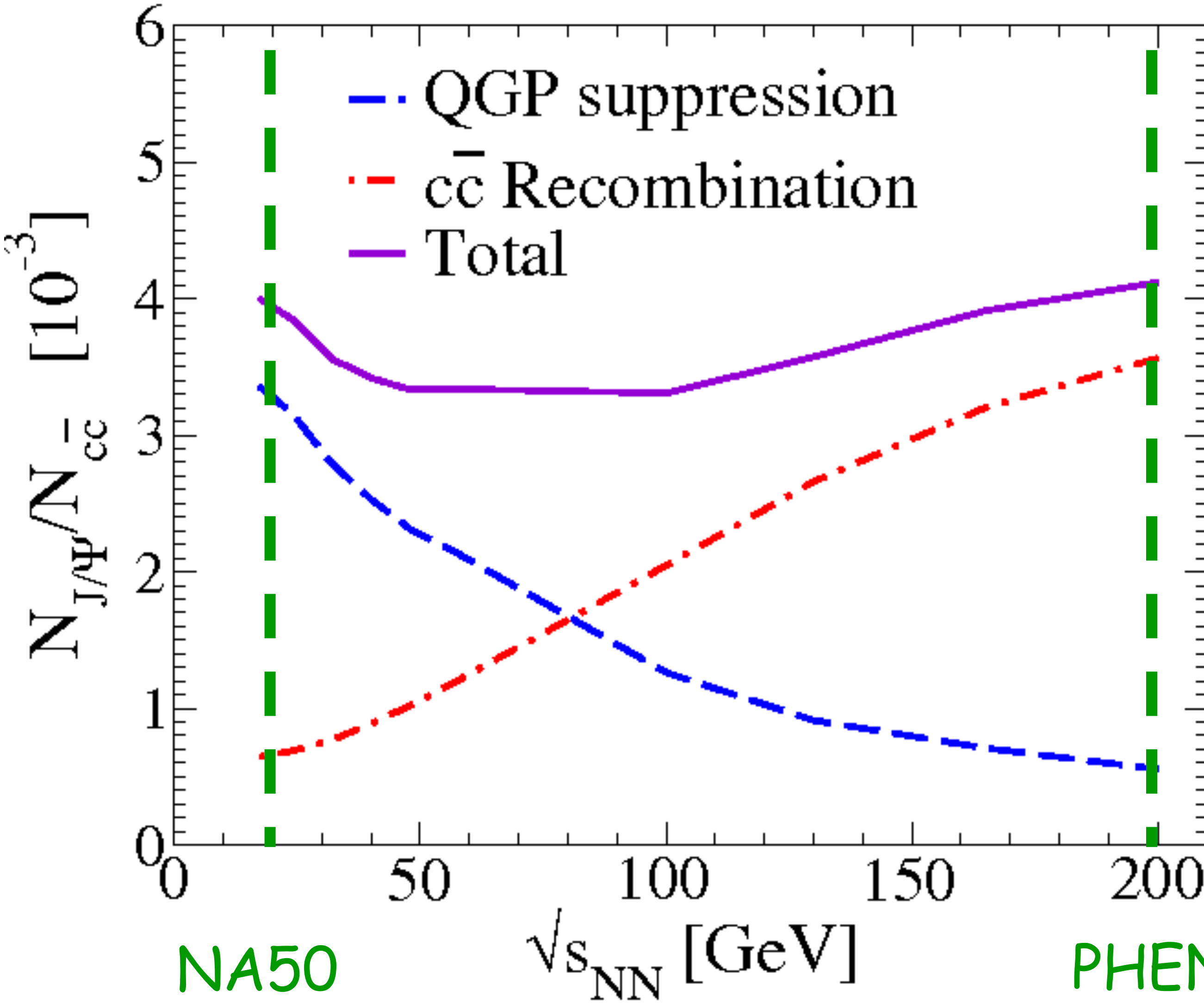
Thews-Schroedter-Rafelski, PRC (2001)

Large number of charm quarks

Quarks from different parent gluons form bound states

Recombination -> ENHANCEMENT

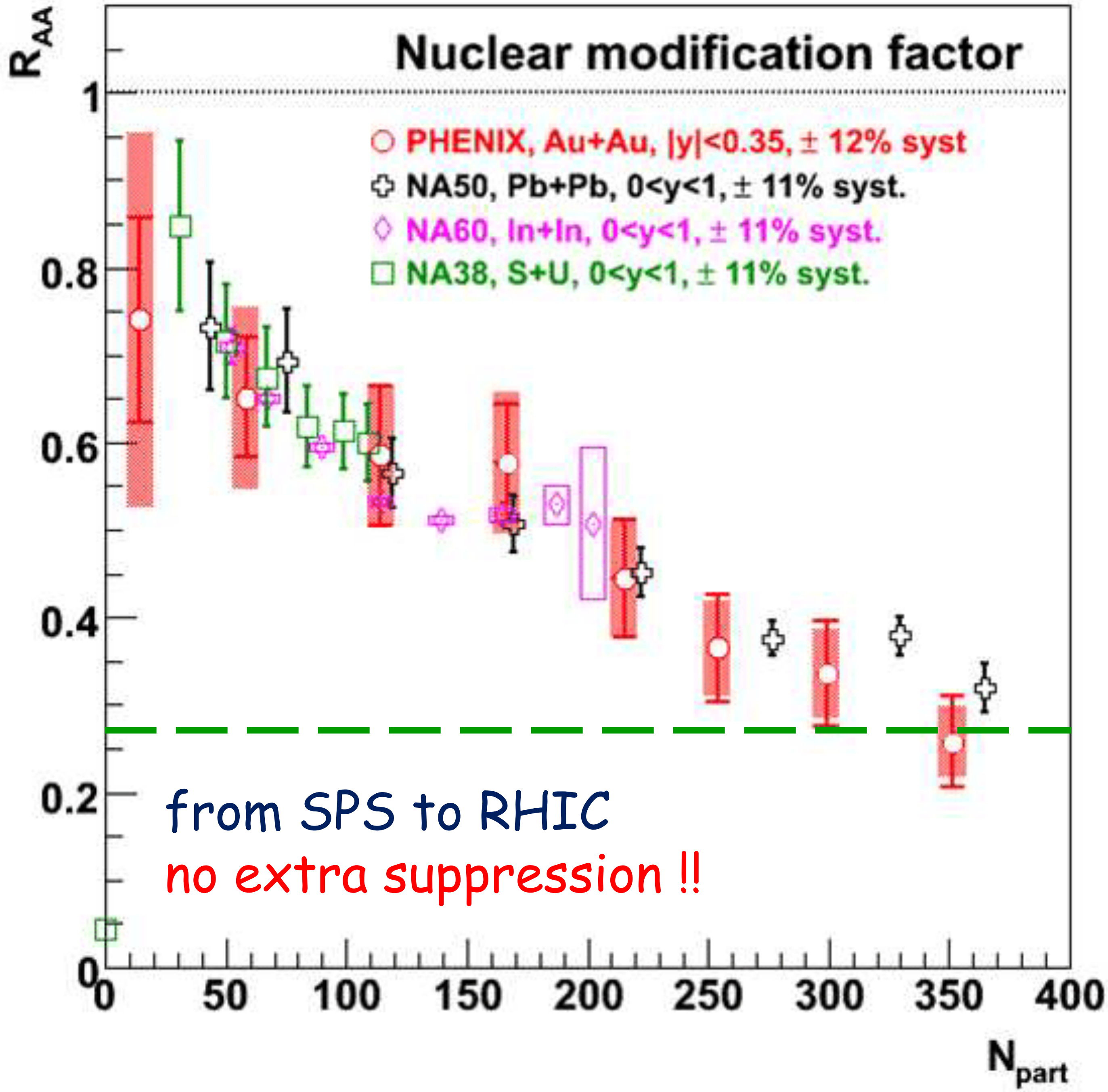
Recombination in the QGP



NA50

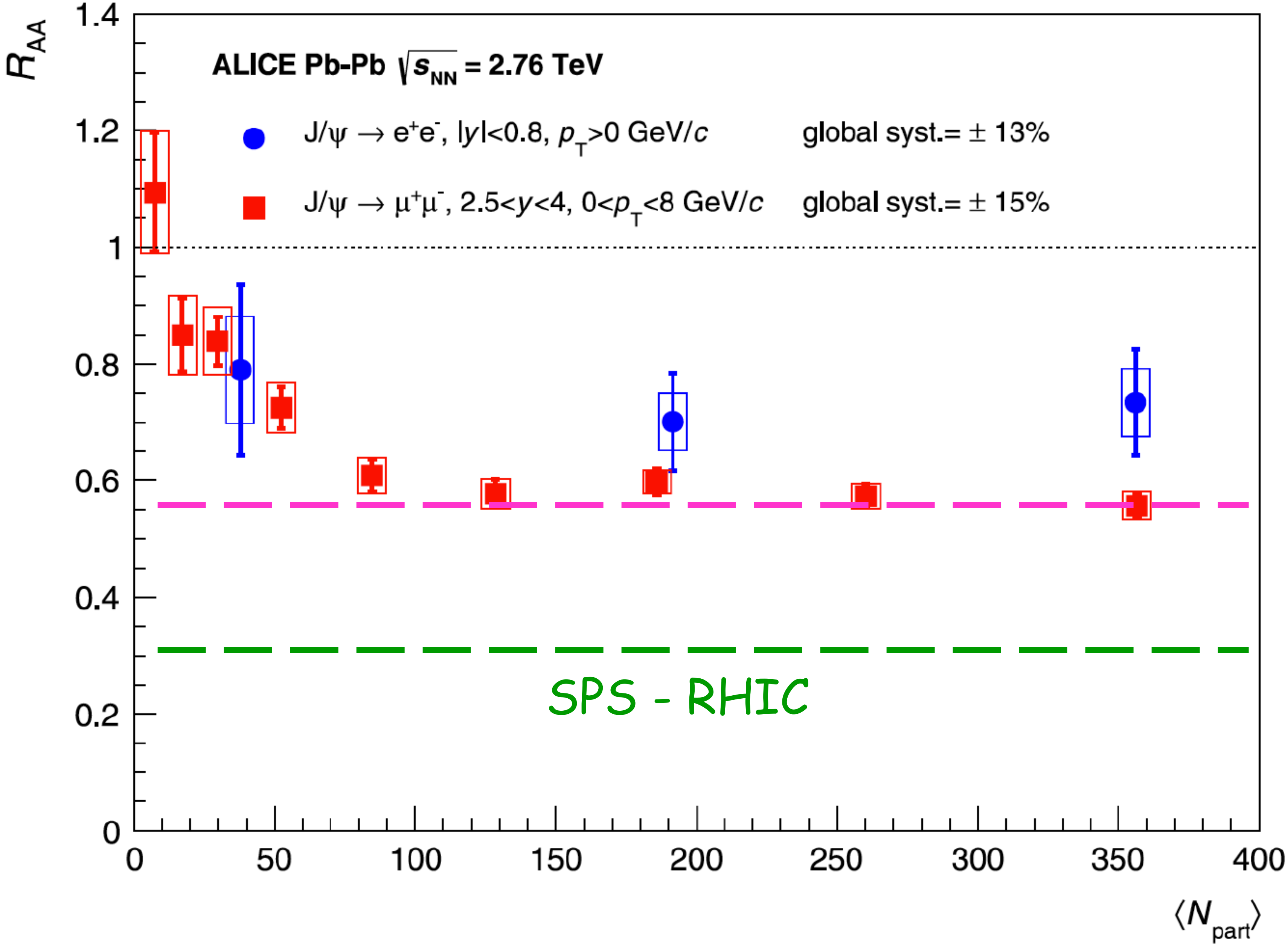
PHENIX

from
R. Rapp

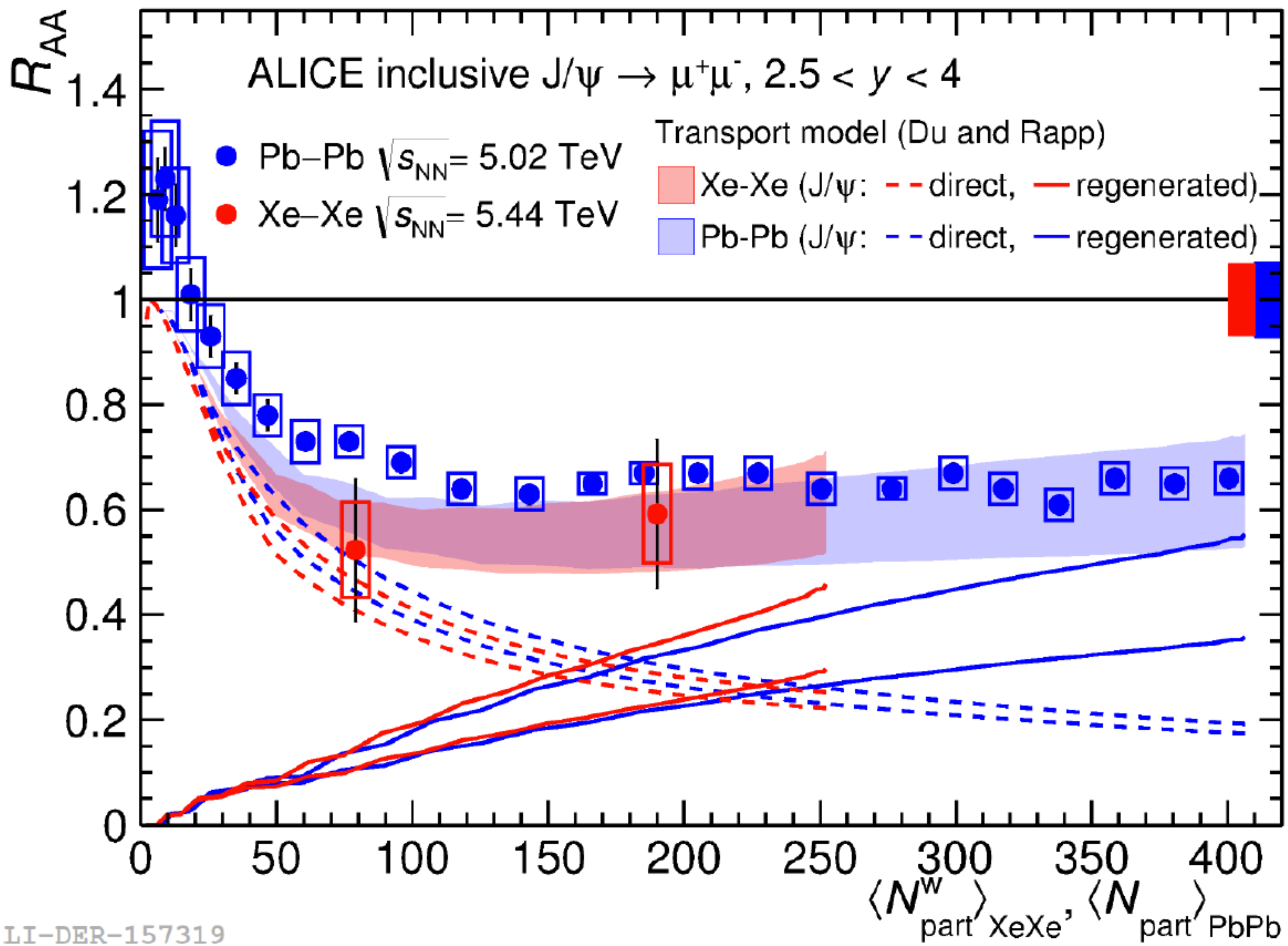


Nuclear modification factor
R_{AA}
PHENIX, Au+Au, |y|<0.35, ± 12% syst
NA50, Pb+Pb, 0<y<1, ± 11% syst.
NA60, In+In, 0<y<1, ± 11% syst.
NA38, S+U, 0<y<1, ± 11% syst.
from SPS to RHIC
no extra suppression !!
N_{part}
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
300
350
400

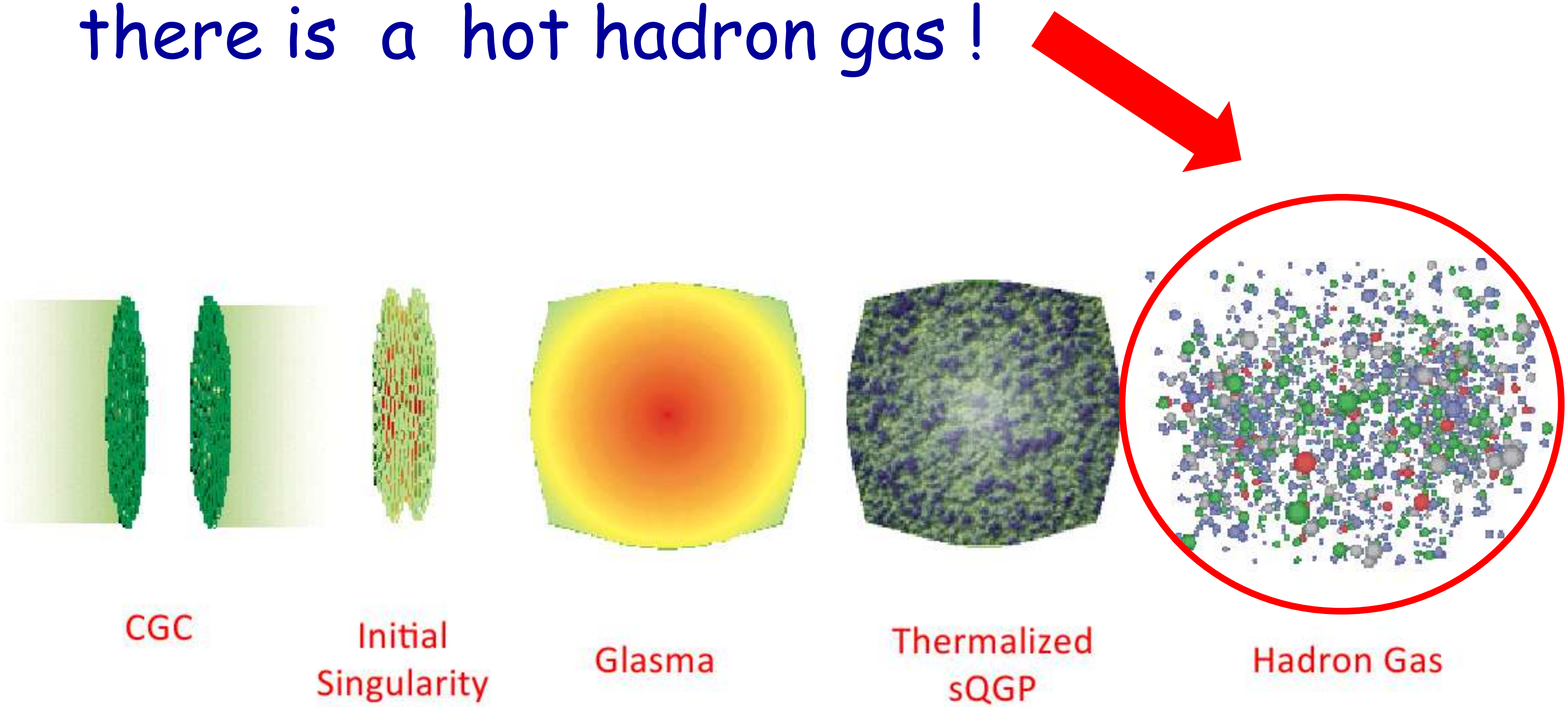
"Unsuppression"



"Unsuppression" is robust !

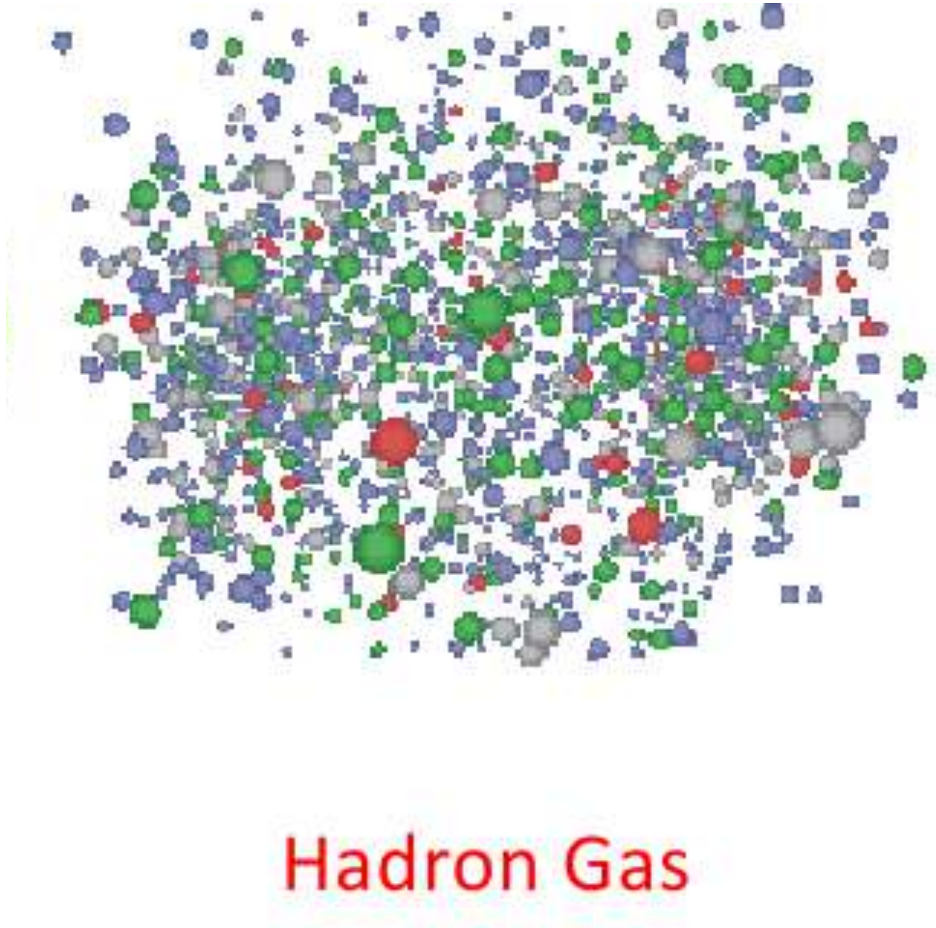


In heavy ion collisions there is a hot hadron gas !

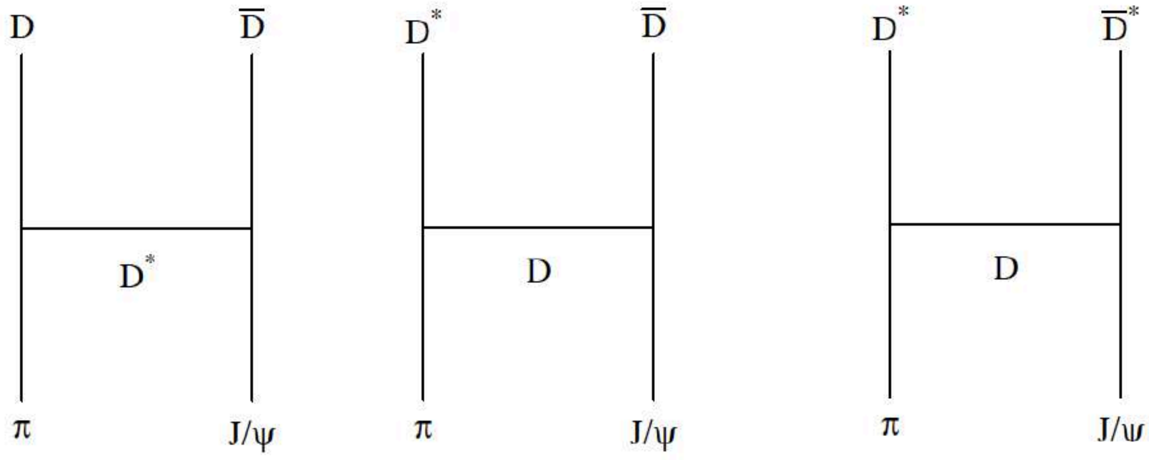


Charmonium suppression in the HG

Abreu et al., arxiv:1712.06019

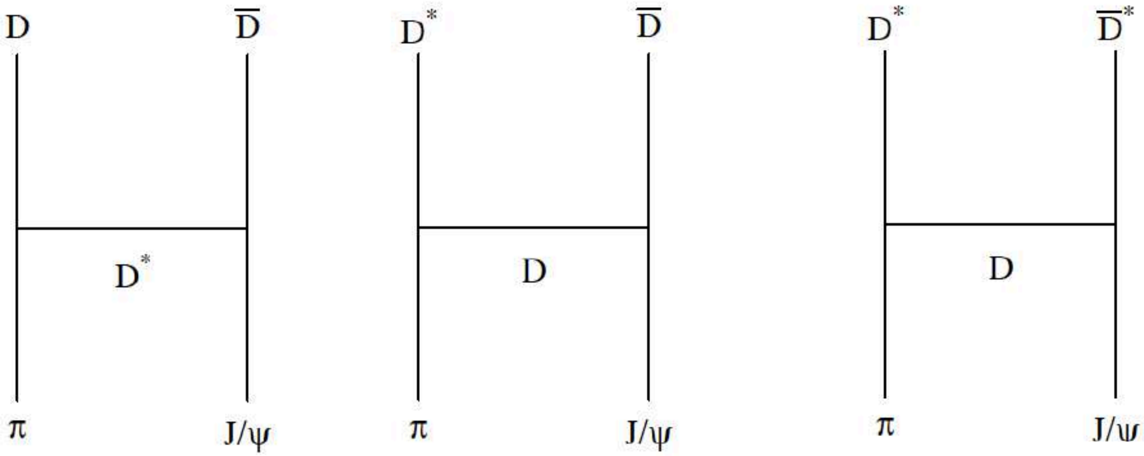


Meson Exchange Model



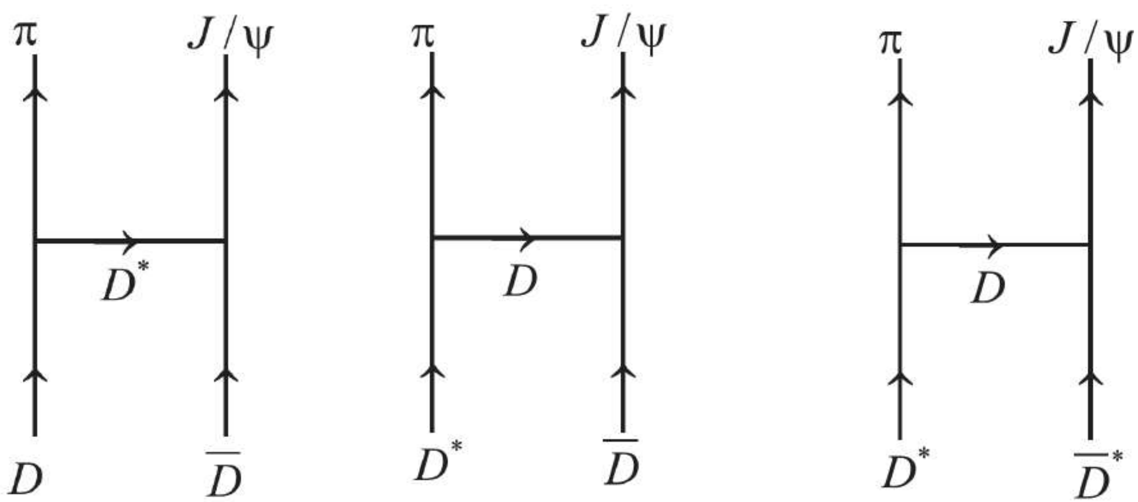
S.G. Matinyan and B. Muller,
PRC (1998)

Meson Exchange Model



S.G. Matinyan and B. Muller, PRC (1998)

Inverse processes can also happen



Charmonium can be produced !!!

F. Carvalho, F.O. Duraes, FSN and M. Nielsen, PRC (2005)

SU(4) Effective Lagrangians

$$
\begin{aligned}
\mathcal{L}_{PPV} &= -ig_{PPV}\langle V^\mu[P,\partial_\mu P]\rangle, \\
\mathcal{L}_{VVV} &= ig_{VVV}\langle \partial_\mu V_\nu\,[V^\mu, V^\nu]\rangle, \\
\mathcal{L}_{PPVV} &= g_{PPVV}\langle PV^\mu[V_\mu, P]\rangle, \\
\mathcal{L}_{VVVV} &= g_{VVVV}\langle V^\mu V^\nu[V_\mu, V_\nu]\rangle,
\end{aligned}
$$

$$
V_\mu = \begin{pmatrix}
\frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\
\rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & K^{*0} & D^{*-} \\
K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\
D^{*0} & D^{*+} & D_s^{*+} & J/\psi
\end{pmatrix}_\mu
$$

$$
P = \begin{pmatrix}
\frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ & \bar{D}^0 \\
\pi^- & \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 & D^- \\
K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta' & D_s^- \\
D^0 & D^+ & D_s^+ & \eta_c
\end{pmatrix}
$$

Anomalous Parity Terms

$$\begin{aligned}
\mathcal{L}_{PVV} &= -g_{PVV}\,\varepsilon^{\mu\nu\alpha\beta}\langle\partial_\mu V_\nu \partial_\alpha V_\beta P\rangle, \\
\mathcal{L}_{PPPV} &= -ig_{PPPV}\,\varepsilon^{\mu\nu\alpha\beta}\langle V_\mu(\partial_\nu P)(\partial_\alpha P)(\partial_\beta P)\rangle, \\
\mathcal{L}_{PVVV} &= ig_{PVVV}\,\varepsilon^{\mu\nu\alpha\beta}\left[\langle V_\mu V_\nu V_\alpha \partial_\beta P\rangle \right. \\
&\quad \left. + \frac{1}{3}\langle V_\mu(\partial_\nu V_\alpha)V_\beta P\rangle\right].
\end{aligned}$$

Oh, Song, Lee, PRC (2001)

amplitudes

$$\begin{cases} \mathcal{M}_1^{(\varphi)} = \sum_i \mathcal{M}_{1i}^{(\varphi)\mu} \epsilon_\mu(p_2), \\ \mathcal{M}_2^{(\varphi)} = \sum_i \mathcal{M}_{2i}^{(\varphi)\mu\nu\lambda} \epsilon_\mu(p_2) \epsilon_\nu^*(p_3) \epsilon_\lambda^*(p_4), \\ \mathcal{M}_3^{(\varphi)} = \sum_i \mathcal{M}_{3i}^{(\varphi)\mu\nu} \epsilon_\mu(p_2) \epsilon_\nu^*(p_3), \\ \mathcal{M}_4^{(\varphi)} = \sum_i \mathcal{M}_{4i}^{(\varphi)\mu\nu} \epsilon_\mu(p_2) \epsilon_\nu^*(p_4). \end{cases}$$

$$\varphi = \pi\,,\ \rho\,,\ K\,,\ K^*$$

amplitudes

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$$\mathcal{M}_4^{(\varphi)} = \sum_i \mathcal{M}_{4i}^{(\varphi)\mu\nu} \epsilon_\mu(p_2)\epsilon_\nu^*(p_4).$$

$$\varphi = \pi\,,\ \rho\,,\ K\,,\ K^*$$

averaged amplitudes

$$\overline{\sum_{S,I}} |\mathcal{M}_r|^2 = \frac{1}{g_1 g_2} \sum_{S,I} |\mathcal{M}_r|^2$$

spin, isospin

$$g_1 = (2I_{1i,r}+1)(2S_{1i,r}+1),\ g_2 = (2I_{2i,r}+1)(2S_{2i,r}+1)$$

amplitudes

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$$g_1 = (2I_{1i,r}+1)(2S_{1i,r}+1),\ g_2 = (2I_{2i,r}+1)(2S_{2i,r}+1)$$

cross sections

$$\sigma_r^{(\varphi)}(s) = \frac{1}{64\pi^2 s} \frac{|\vec{p}_f|}{|\vec{p}_i|} \int d\Omega \overline{\sum_{S,I}} |\mathcal{M}_r^{(\varphi)}(s,\theta)|^2$$

Form factors

Account for higher order corrections and for the spatial structure of hadronic vertices

$$F_3 = \frac{\Lambda^2}{\Lambda^2 + \mathbf{q}^2}; \quad F_4 = \frac{\Lambda^2}{\Lambda^2 + \bar{\mathbf{q}}^2} \frac{\Lambda^2}{\Lambda^2 + \bar{\mathbf{q}}^2},$$

$$\mathbf{q} = (\mathbf{p_1} - \mathbf{p_3})^2$$

$$\bar{\mathbf{q}} = [(\mathbf{p_1} - \mathbf{p_3})^2 + (\mathbf{p_2} - \mathbf{p_3})^2]/2.$$

Can be calculated with QCD sum rules

Bracco, Chiapparini, FSN, Nielsen, PPNP (2012)

Coupling constants

Directly from experiment: $D^* \to D\,\pi$ $g_{D^*D\pi}$

Experiment + VDM: $D^* \to D\,\gamma$ $g_{D^*DJ/\psi}$

Heavy quark symmetry: $g_{D^*D^*\pi} \simeq g_{D^*D\pi}$

SU(4) relations

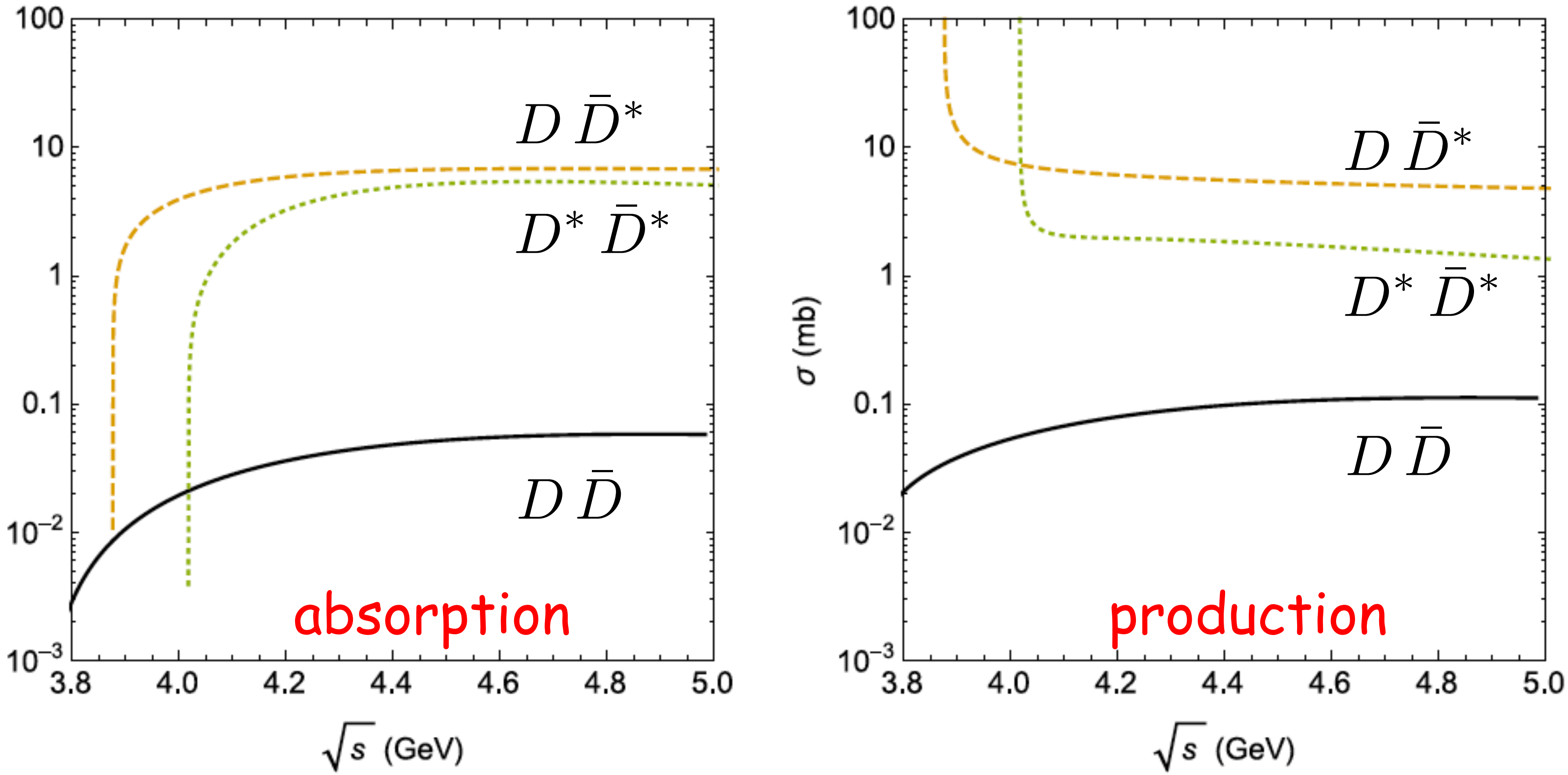
Can be calculated with QCD sum rules

Bracco, Chiapparini, FSN, Nielsen, PPNP (2012)

SU(4) relations are violated by ~ 30 %
(except for the pion : ~ 70 %)

J/Psi cross sections

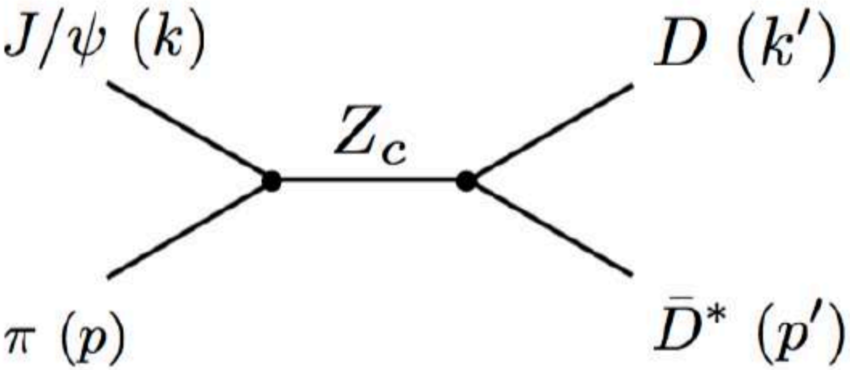
$$\pi + J/\psi \to M_1 + M_2 \qquad\qquad M_1 + M_2 \to \pi + J/\psi$$

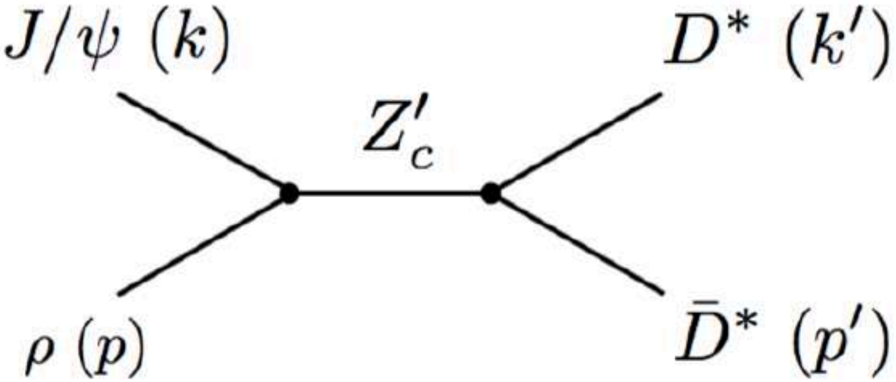


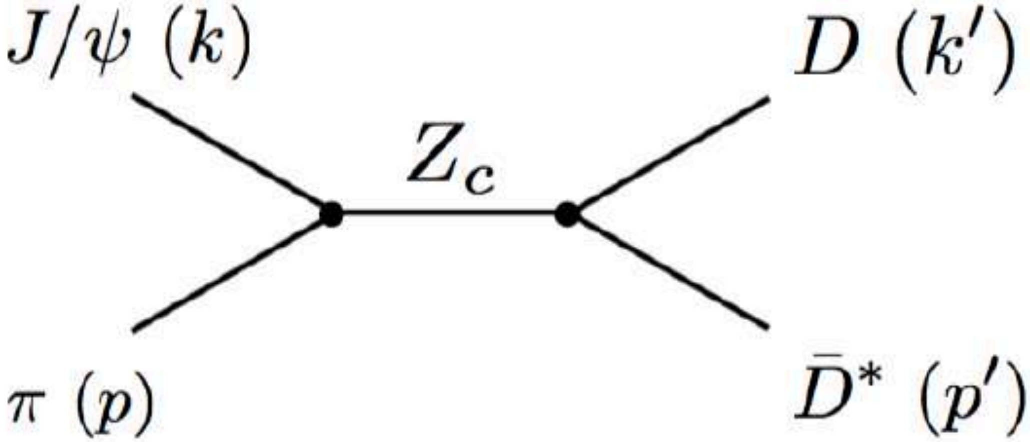
Impact of exotic charmonium

2003 X(3872) : a multiquark state $c\,\bar{c}\,q\,\bar{q}$

2013 Z_c(3900) , Z_c(4025) : charged state $c\,\bar{c}\,u\,\bar{d}$



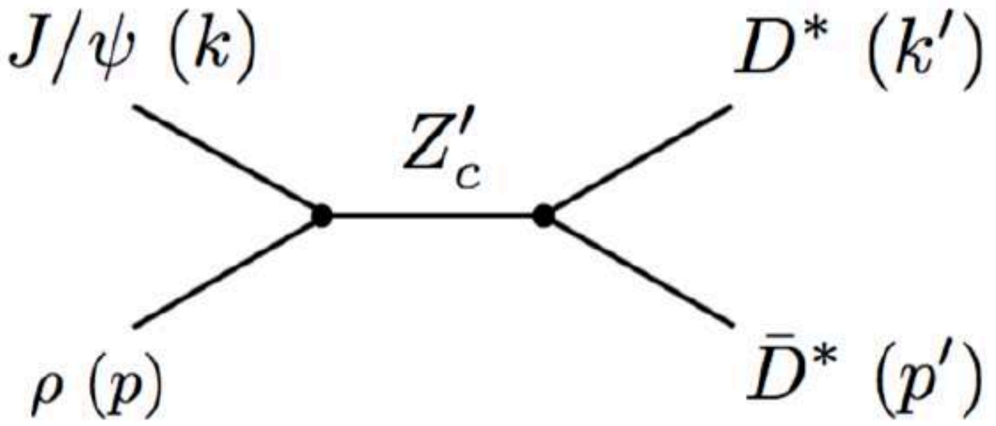




$$\mathcal{M}_Z = \alpha_{J/\psi\pi}\,\alpha_{D\bar{D}^*}\frac{1}{s - M_Z^2 + iM_Z\Gamma_Z} \times \left(-g^{\mu\nu} + \frac{p^\mu k'^\nu}{M_Z^2}\right)\epsilon^\mu(k)\epsilon^{\nu\,*}(p'),$$

Couplings from experiment

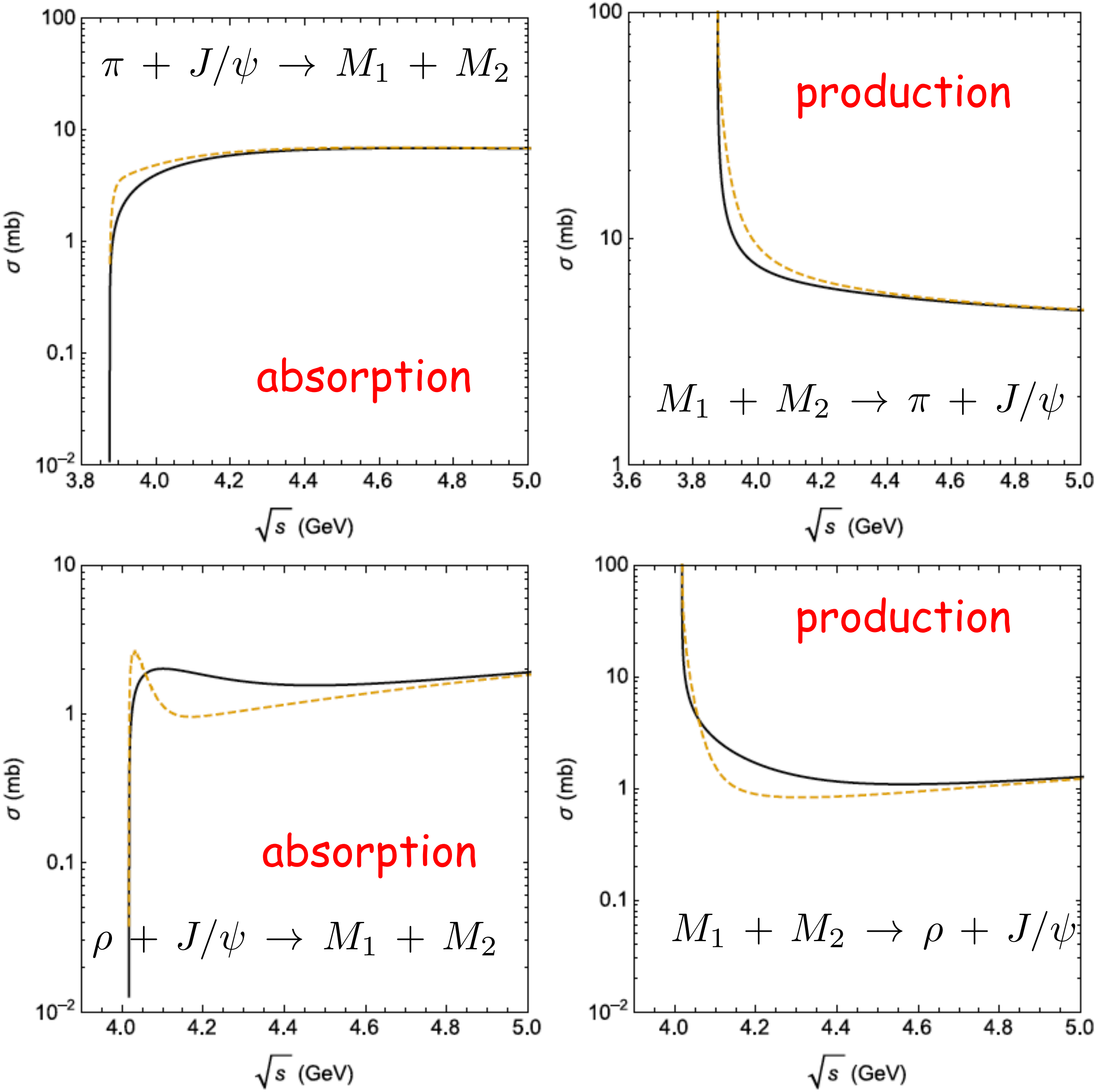
Abreu et al., arxiv:1712.06019



$$\mathcal{M}_{Z'} \;=\; \eta_{J/\psi\rho}\,\eta_{D^*\bar{D}^*}\frac{1}{s - M_{Z'}^2 + iM_{Z'}\Gamma_{Z'}} \times P^{\mu\nu\alpha\beta}(q)\epsilon_\mu(k)\epsilon_\nu(p)\epsilon^*_\alpha(k')\epsilon^*_\beta(p'),$$

Couplings from experiment

Abreu et al., arxiv:1712.06019



$\pi + J/\psi \to M_1 + M_2$
absorption
production
$M_1 + M_2 \to \pi + J/\psi$
$\rho + J/\psi \to M_1 + M_2$
absorption
production
$M_1 + M_2 \to \rho + J/\psi$
σ (mb)
$\sqrt{s}$ (GeV)

Averaged thermal cross sections

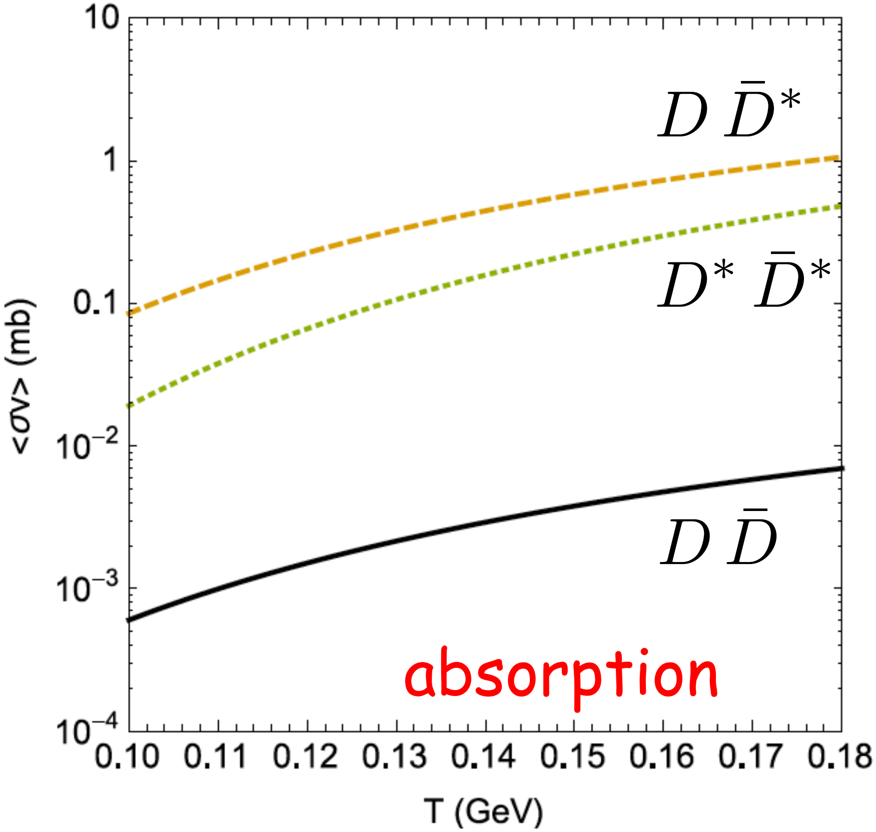
$$\langle \sigma_{ab}\, v_{ab} \rangle = \frac{\int d^3p_a\, d^3p_b\, f_a(p_a)\, f_b(p_b)\, \sigma_{ab}\, v_{ab}}{\int d^3p_a\, d^3p_b\, f_a(p_a)\, f_b(p_b)}$$

$f_a(p_a)$ = Bose-Einstein distribution of meson a

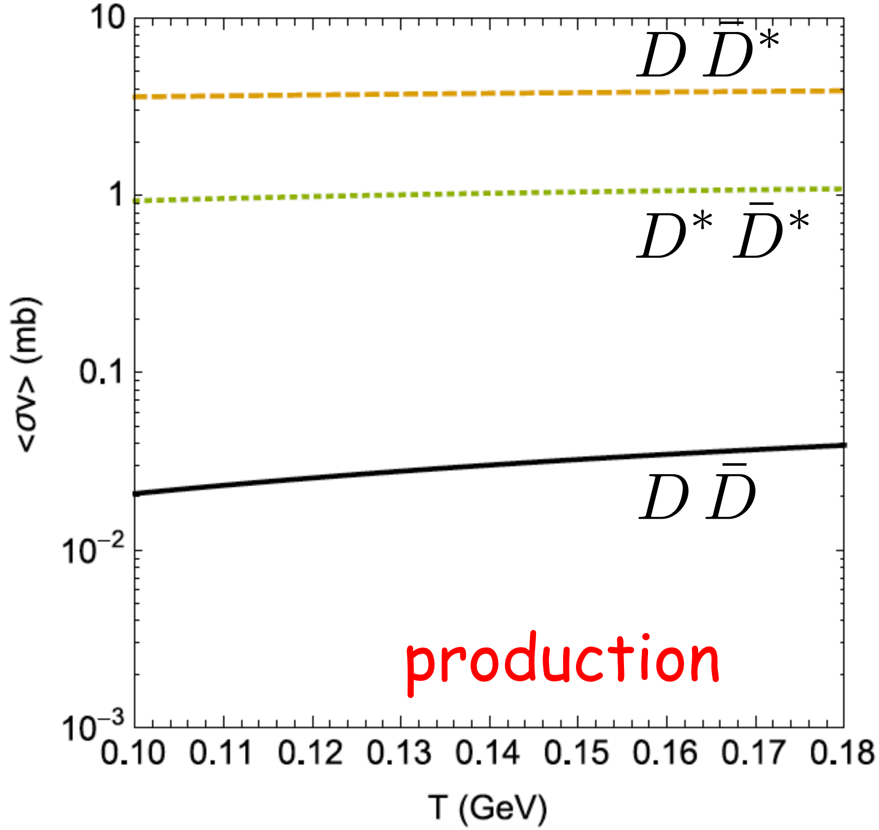
σ_{ab} = cross section of meson a + meson b

v_{ab} = relative velocity of meson a and meson b

$$\pi + J/\psi \rightarrow M_1 + M_2$$



$$M_1 + M_2 \rightarrow \pi + J/\psi$$



Time evolution of charmonium multiplicity

Solve the rate equation including gain and loss terms:

gain loss

$$
\begin{aligned}
\frac{dN_{J/\psi}(\tau)}{d\tau} = \sum_{\varphi=\pi,\rho K,K^*} & \Big[\big\langle \sigma_{D_{(s)}\bar{D}\to\varphi J/\psi} v_{D_{(s)}\bar{D}}\big\rangle n_{D_{(s)}}(\tau) N_{\bar{D}}(\tau) - \langle \sigma_{\varphi J/\psi\to D_{(s)}\bar{D}} v_{\varphi J/\psi}\rangle n_{\varphi}(\tau) N_{J/\psi}(\tau) \\
& + \big\langle \sigma_{D^*_{(s)}\bar{D}^*\to\varphi J/\psi} v_{D^*_{(s)}\bar{D}^*}\big\rangle n_{D^*_{(s)}}(\tau) N_{\bar{D}^*}(\tau) - \langle \sigma_{\varphi J/\psi\to D^*_{(s)}\bar{D}^*} v_{\varphi J/\psi}\rangle n_{\varphi}(\tau) N_{J/\psi}(\tau) \\
& + \big\langle \sigma_{D^*_{(s)}\bar{D}\to\varphi J/\psi} v_{D^*_{(s)}\bar{D}}\big\rangle n_{D^*_{(s)}}(\tau) N_{\bar{D}}(\tau) - \langle \sigma_{\varphi J/\psi\to D^*_{(s)}\bar{D}} v_{\varphi J/\psi}\rangle n_{\varphi}(\tau) N_{J/\psi}(\tau) \\
& + \big\langle \sigma_{D_{(s)}\bar{D}^*\to\varphi J/\psi} v_{D_{(s)}\bar{D}^*}\big\rangle n_{D_{(s)}}(\tau) N_{\bar{D}^*}(\tau) - \langle \sigma_{\varphi J/\psi\to D_{(s)}\bar{D}^*} v_{\varphi J/\psi}\rangle n_{\varphi}(\tau) N_{J/\psi}(\tau)\Big] \\
& + \sum_{\varphi=\bar{\pi},\bar{\rho},\bar{K},\bar{K}^*} \Big[\big\langle \sigma_{\bar{D}_{(s)}D\to\varphi J/\psi} v_{\bar{D}_{(s)}D}\big\rangle n_{\bar{D}_{(s)}}(\tau) N_{D}(\tau) - \langle \sigma_{\varphi J/\psi\to \bar{D}_{(s)}D} v_{\varphi J/\psi}\rangle n_{\varphi}(\tau) N_{J/\psi}(\tau) \\
& + \big\langle \sigma_{\bar{D}^*_{(s)}D^*\to\varphi J/\psi} v_{\bar{D}^*_{(s)}D^*}\big\rangle n_{\bar{D}^*_{(s)}}(\tau) N_{D^*}(\tau) - \langle \sigma_{\varphi J/\psi\to \bar{D}^*_{(s)}D^*} v_{\varphi J/\psi}\rangle n_{\varphi}(\tau) N_{J/\psi}(\tau) \\
& + \big\langle \sigma_{\bar{D}^*_{(s)}D\to\varphi J/\psi} v_{\bar{D}^*_{(s)}D}\big\rangle n_{\bar{D}^*_{(s)}}(\tau) N_{D}(\tau) - \langle \sigma_{\varphi J/\psi\to \bar{D}^*_{(s)}D} v_{\varphi J/\psi}\rangle n_{\varphi}(\tau) N_{J/\psi}(\tau) \\
& + \big\langle \sigma_{\bar{D}_{(s)}D^*\to\varphi J/\psi} v_{\bar{D}_{(s)}D^*}\big\rangle n_{\bar{D}_{(s)}}(\tau) N_{D^*}(\tau) - \langle \sigma_{\varphi J/\psi\to \bar{D}_{(s)}D^*} v_{\varphi J/\psi}\rangle\Big],
\end{aligned}
$$

Model of the fireball evolution

Cho et al ExHIC Collaboration, PPNP (2017)

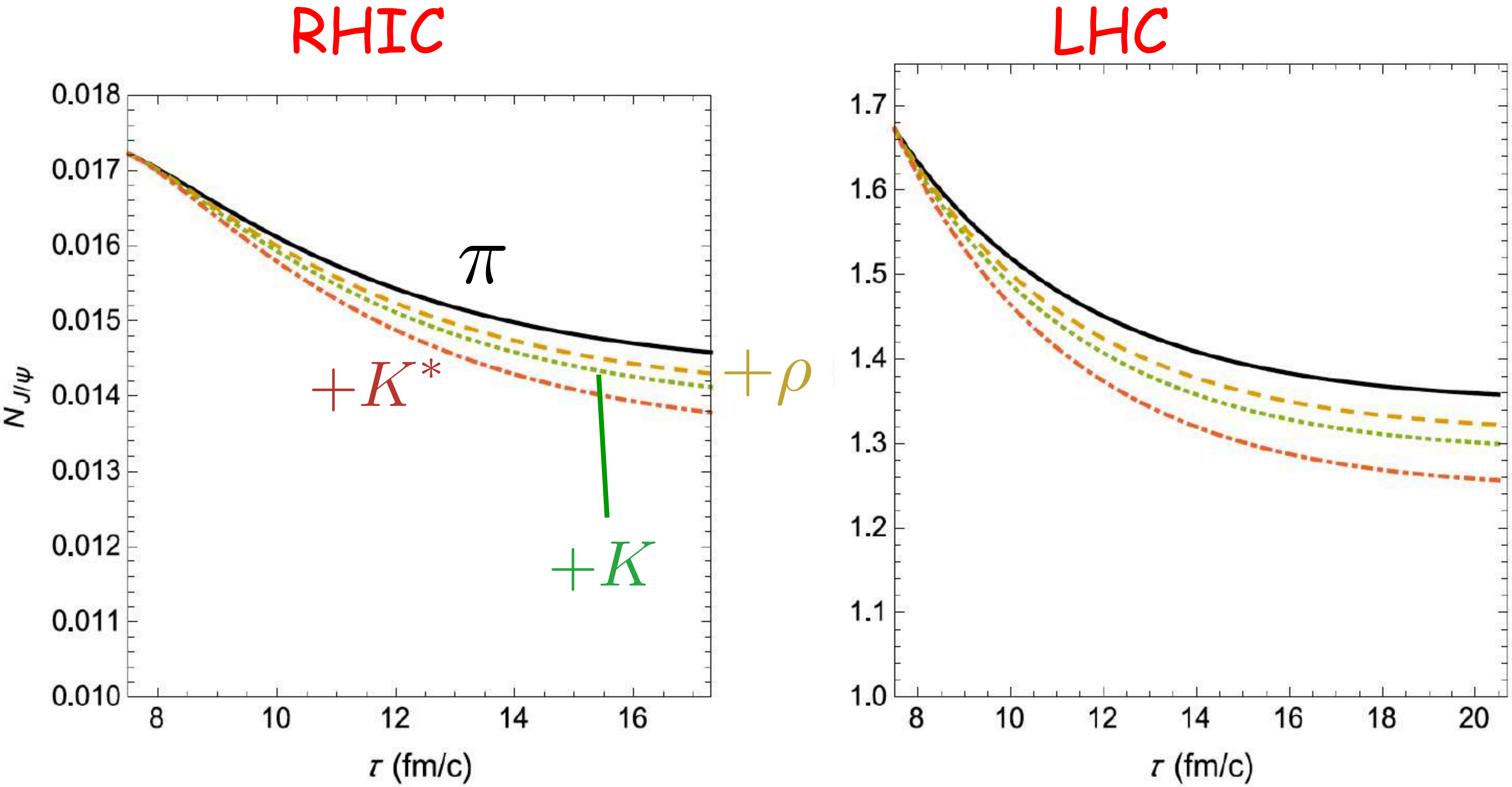
$$n_i(\tau) \approx \frac{1}{2\pi^2}\gamma_i g_i m_i^2 T(\tau) K_2\left(\frac{m_i}{T(\tau)}\right)$$

$$T(\tau) = T_C - (T_H - T_F)\left(\frac{\tau - \tau_H}{\tau_F - \tau_H}\right)^{\frac{4}{5}},$$

$$V(\tau) = \pi\left[R_C + v_C(\tau - \tau_C) + \frac{a_C}{2}(\tau - \tau_C)^2\right]^2 \tau_C$$

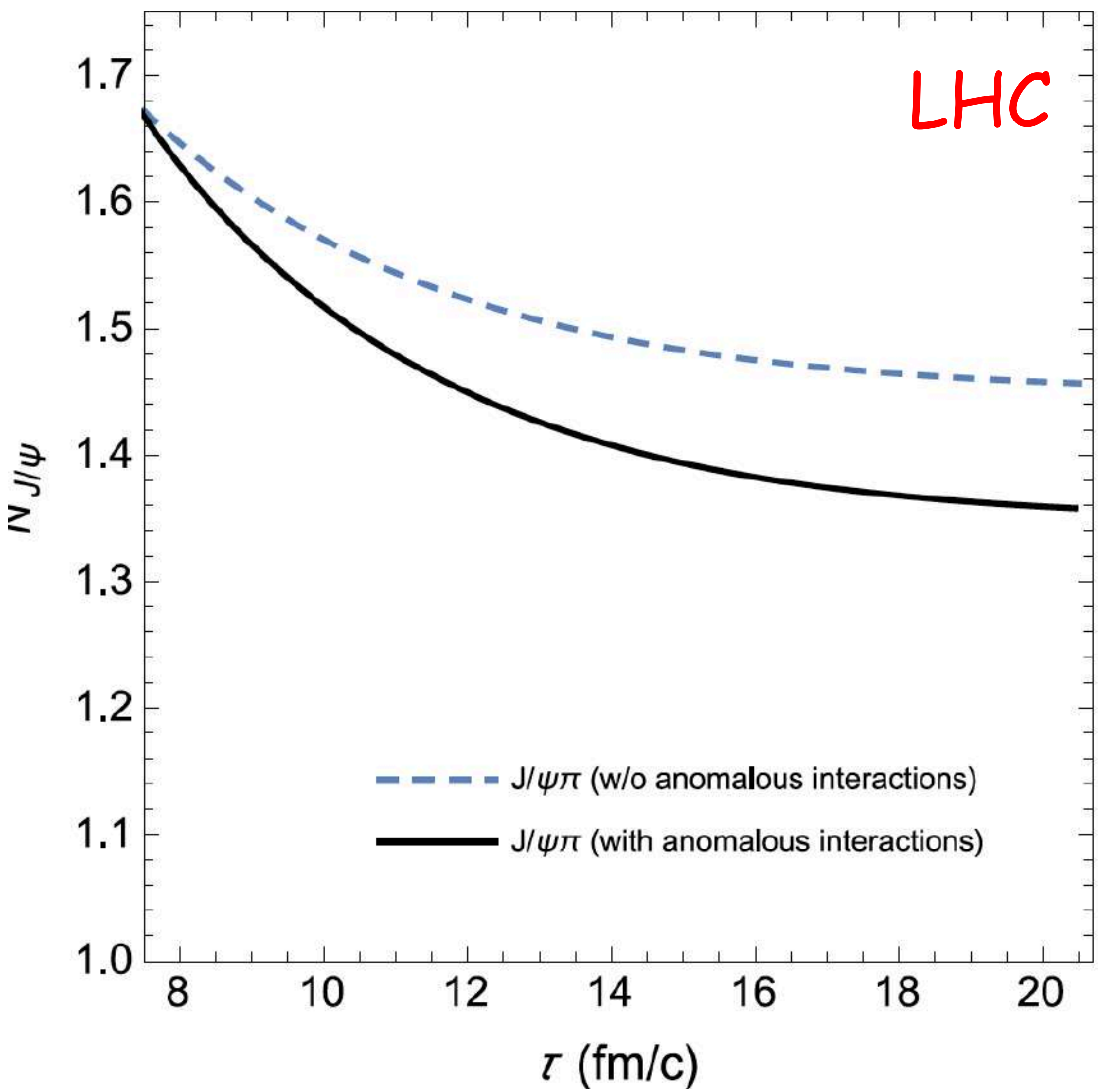
	$\sqrt{s_{NN}}$ (TeV)	v_C (c)	a_C (c^2/fm)	R_C (fm)	τ_C (fm/c)	τ_H (fm/c)	τ_F (fm/c)	γ_c	$N_{J/\psi}$
RHIC	0.2	0.4	0.02	8	5	7.5	17.3	6.4	0.017
LHC	5	0.6	0.044	13.11	5	7.5	20.7	15.8	1.67

20-24 % reduction of the number of Psi's



Abreu, Khemchandani, Martinez Torres, FSN and M. Nielsen, Phys. Rev. C (2018)

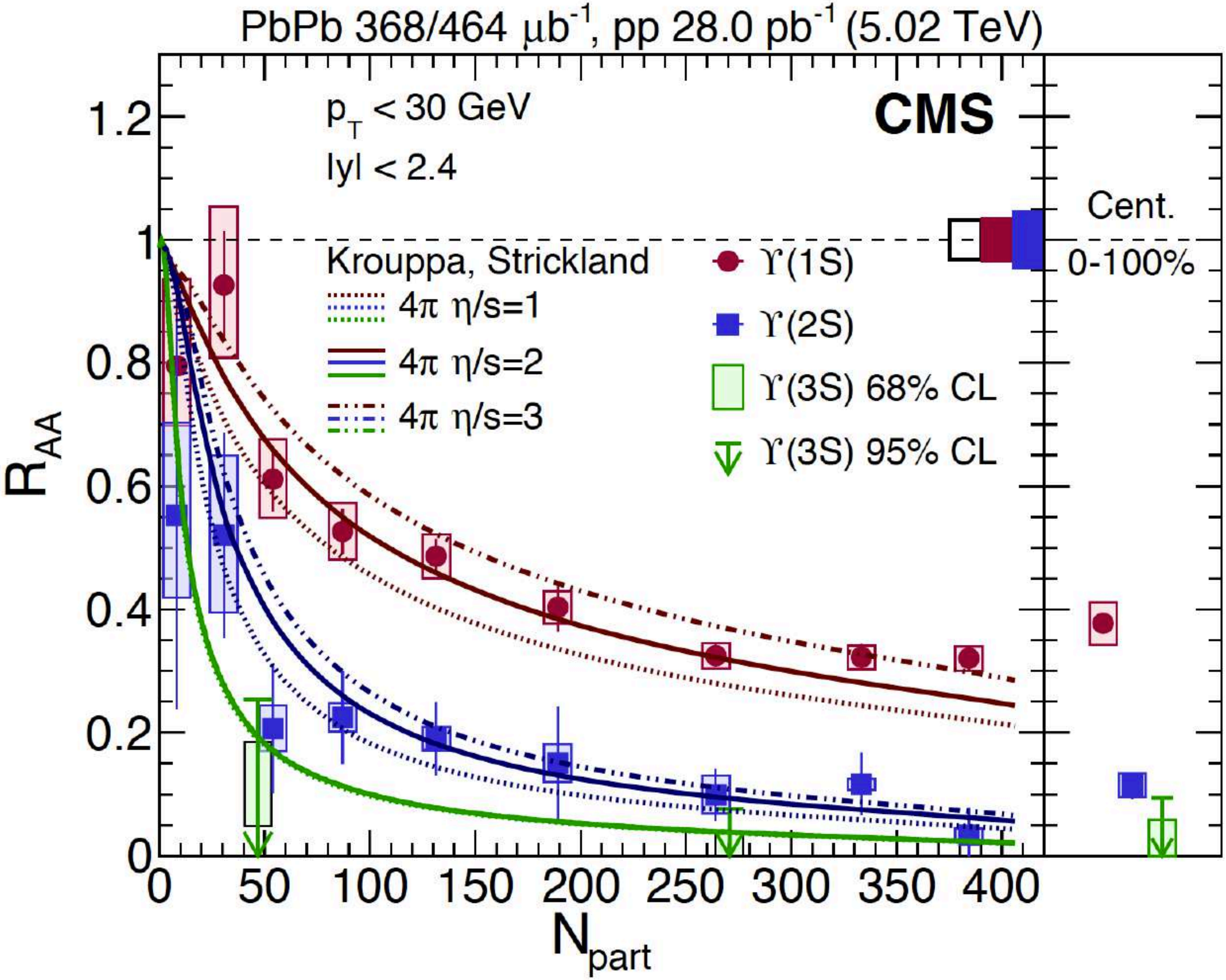
Role of anomalous interactions



reduction of ~7 %

Bottomonium

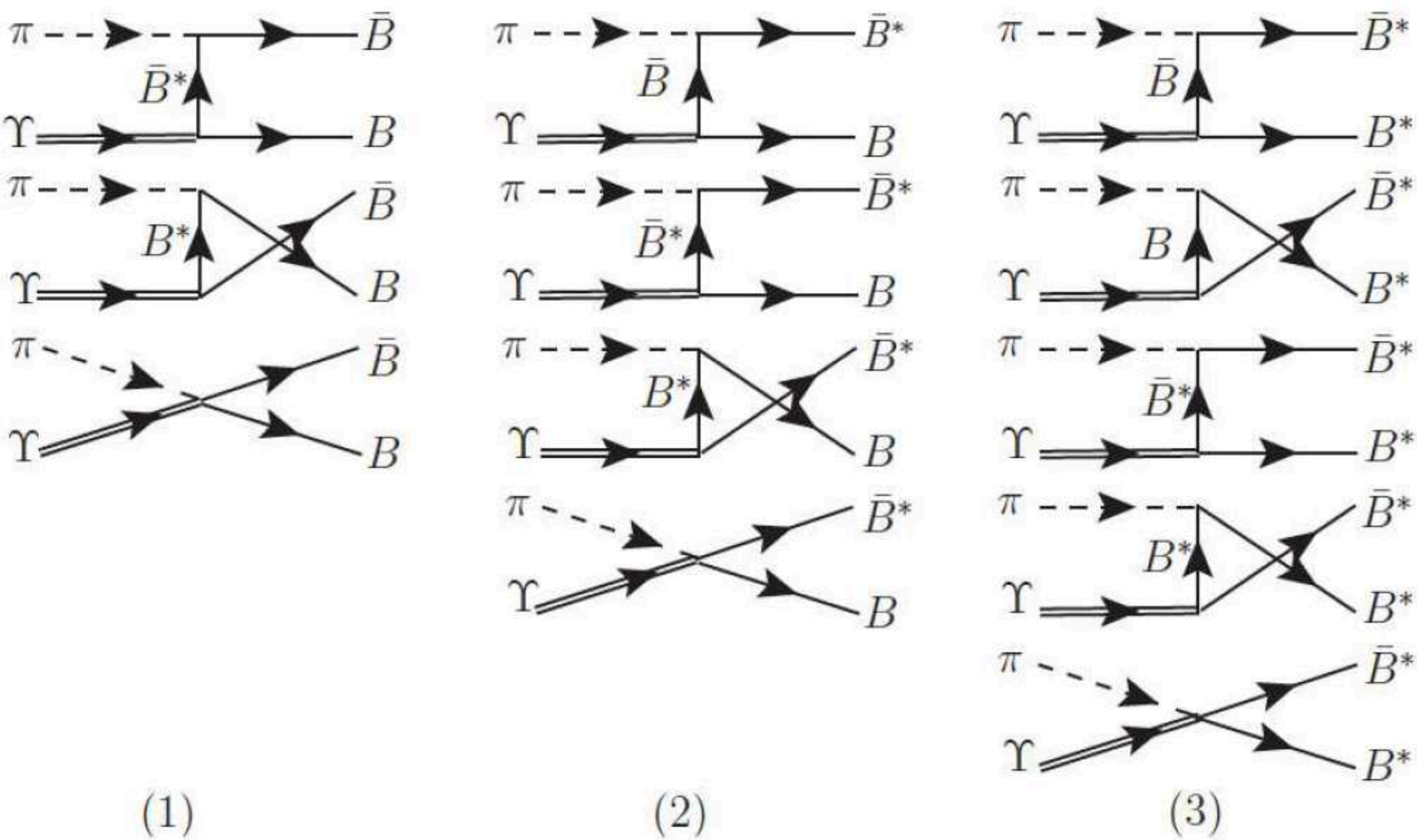
Abreu, FSN, Nielsen, arxiv:1807.05081

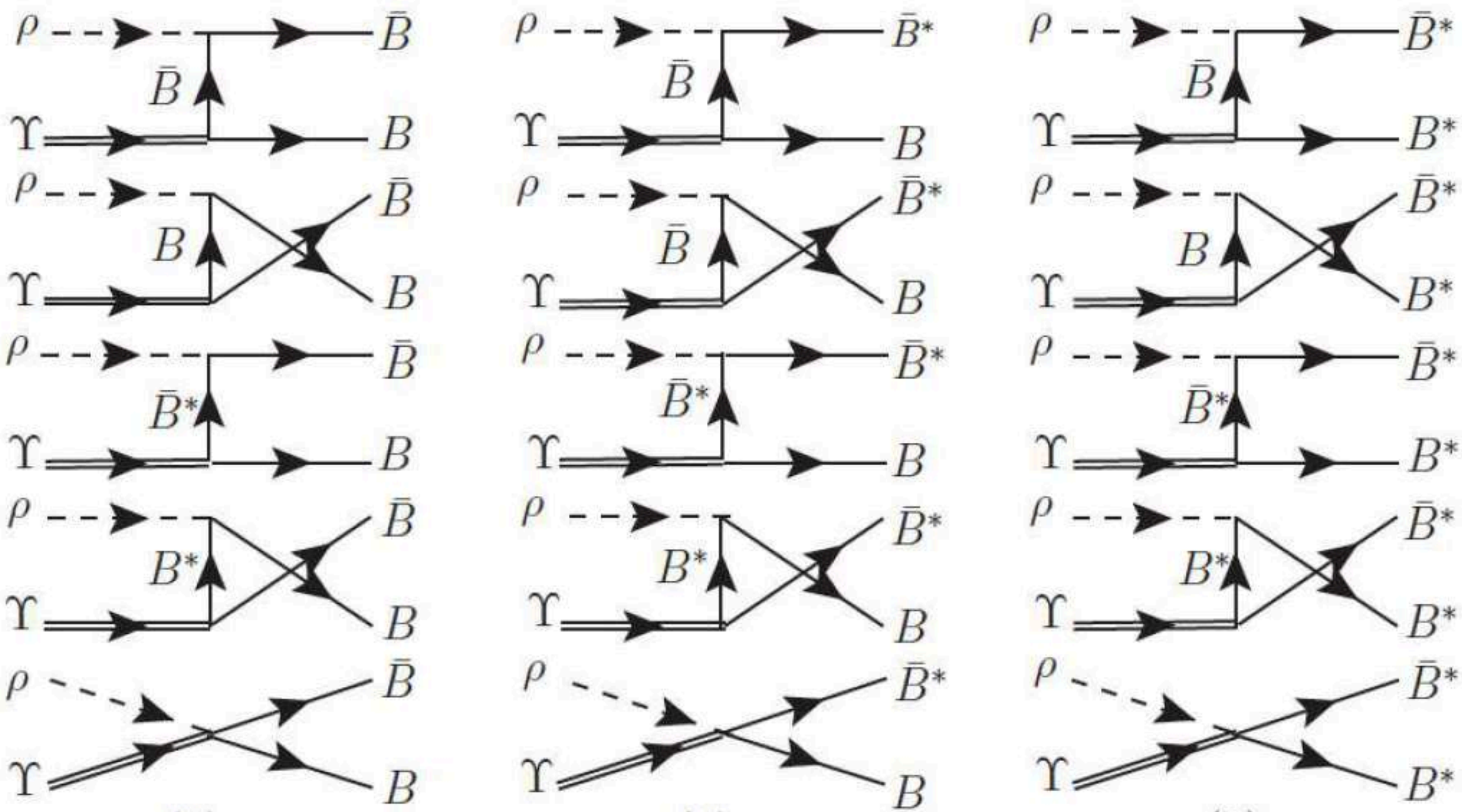


PbPb 368/464 μb-1, pp 28.0 pb-1 (5.02 TeV)
CMS
pT < 30 GeV
|y| < 2.4
Cent.
0-100%
Krouppa, Strickland
4π η/s=1
4π η/s=2
4π η/s=3
ϒ(1S)
ϒ(2S)
ϒ(3S) 68% CL
ϒ(3S) 95% CL
RAA
Npart
0
0.2
0.4
0.6
0.8
1
1.2
0
50
100
150
200
250
300
350
400

Bottomonium in a hadron gas

Lin,Ko, PLB (2001) : meson exchange model in SU(5)

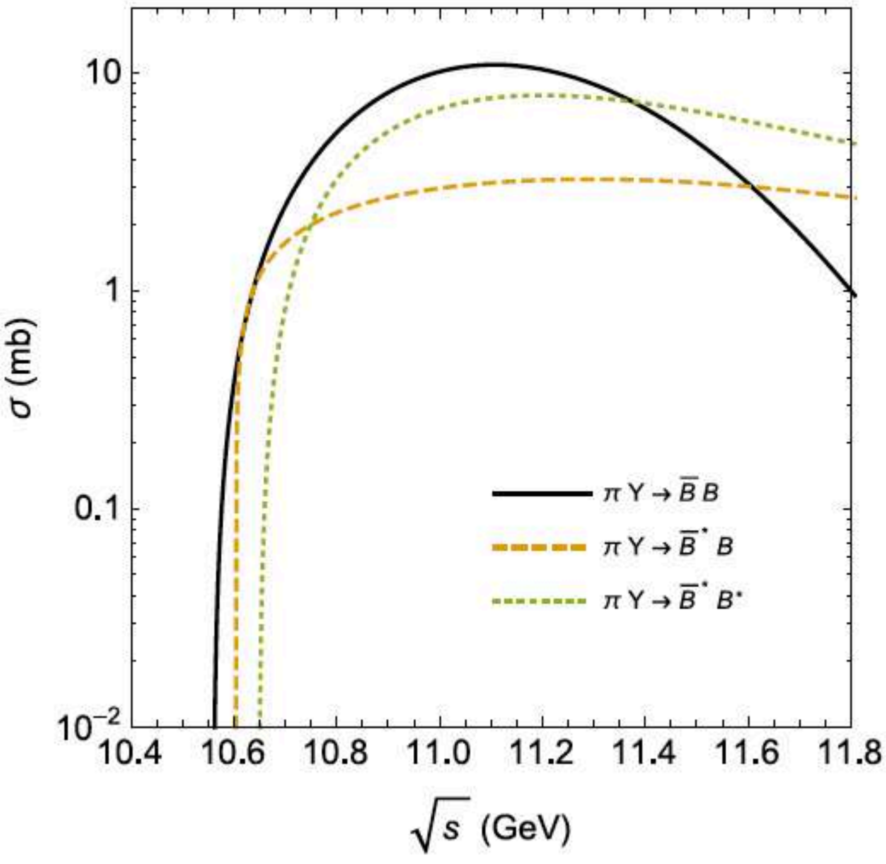




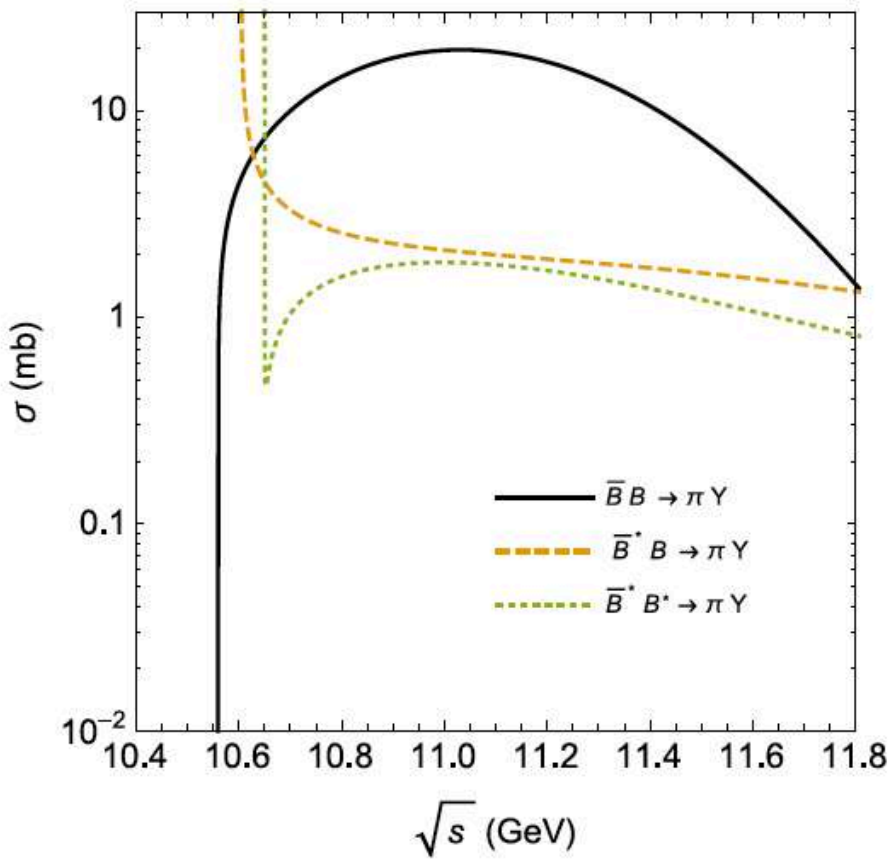
(1) (2) (3)

Upsilon - pion cross sections

$$\pi + \Upsilon \rightarrow M_1 + M_2$$



$$M_1 + M_2 \rightarrow \pi + \Upsilon$$



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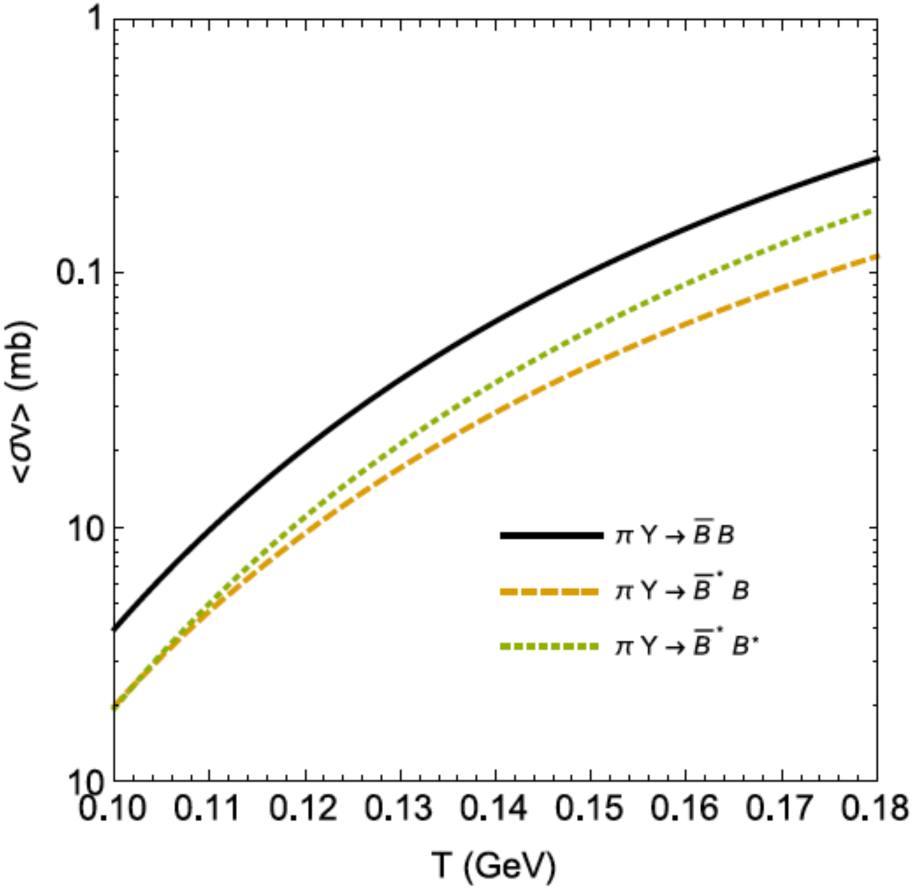

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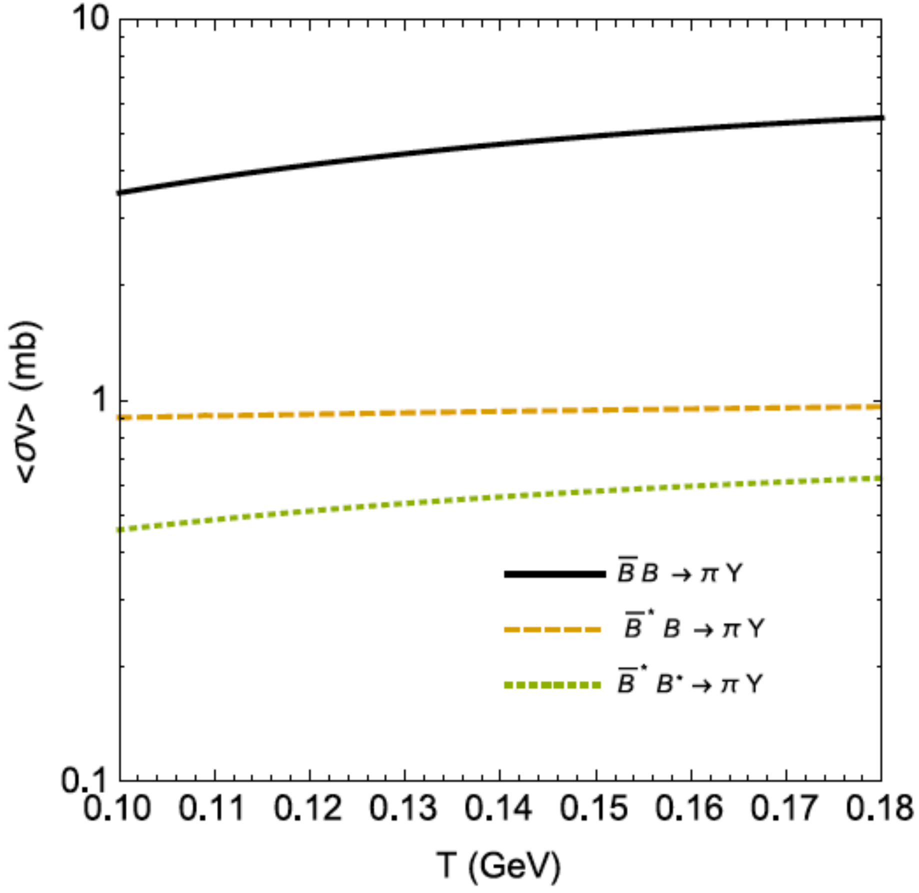
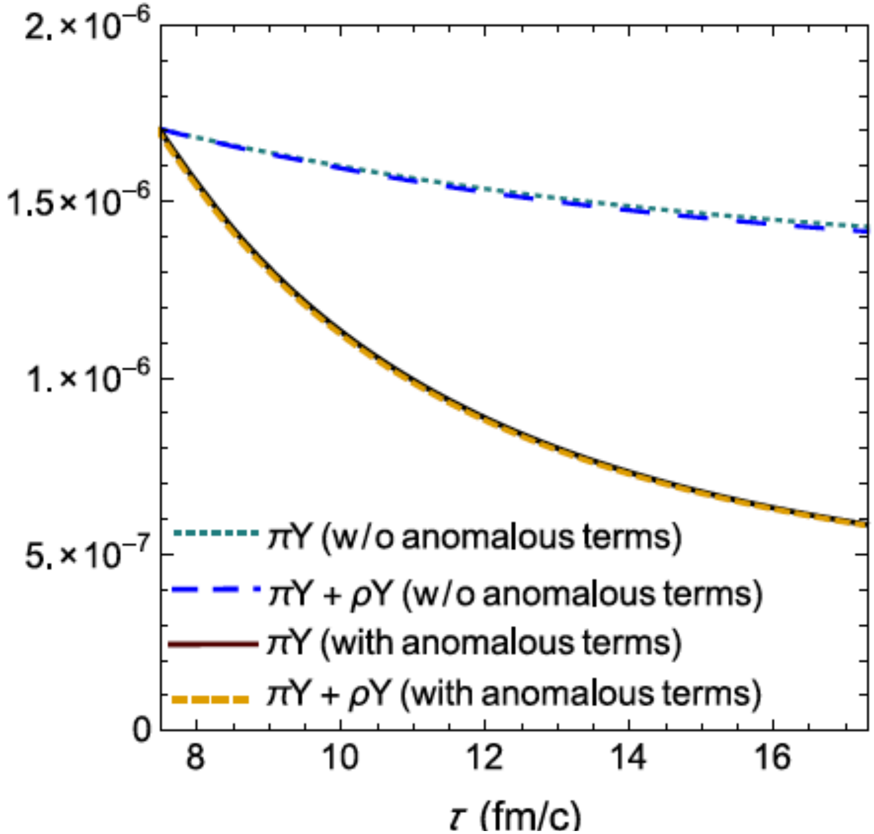
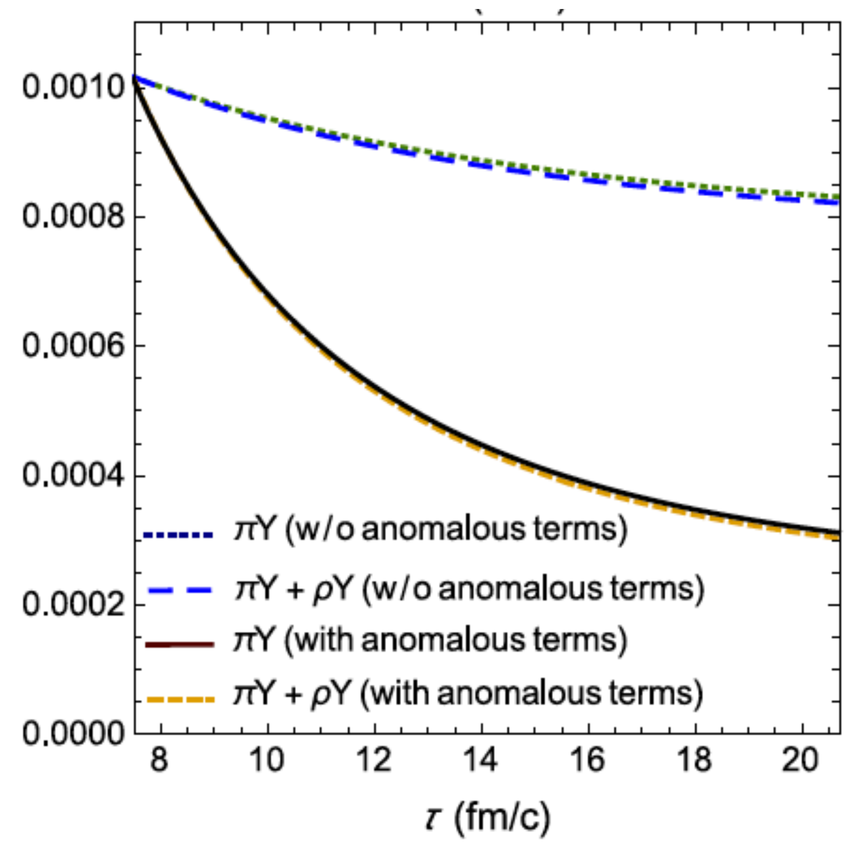


Upsilon multiplicity and anomalous terms

RHIC



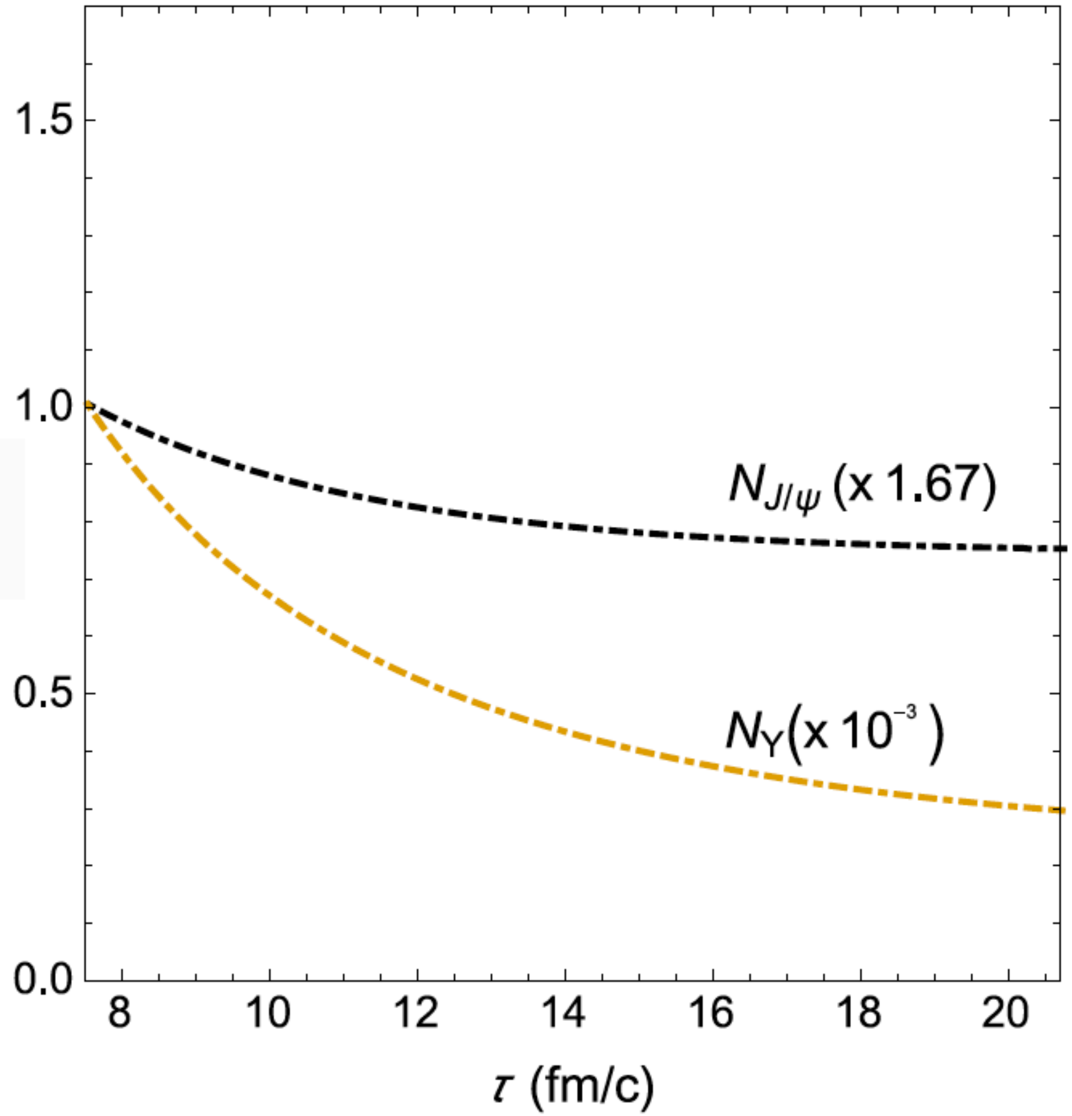
LHC



reduction of 60 %

reduction of 65 %

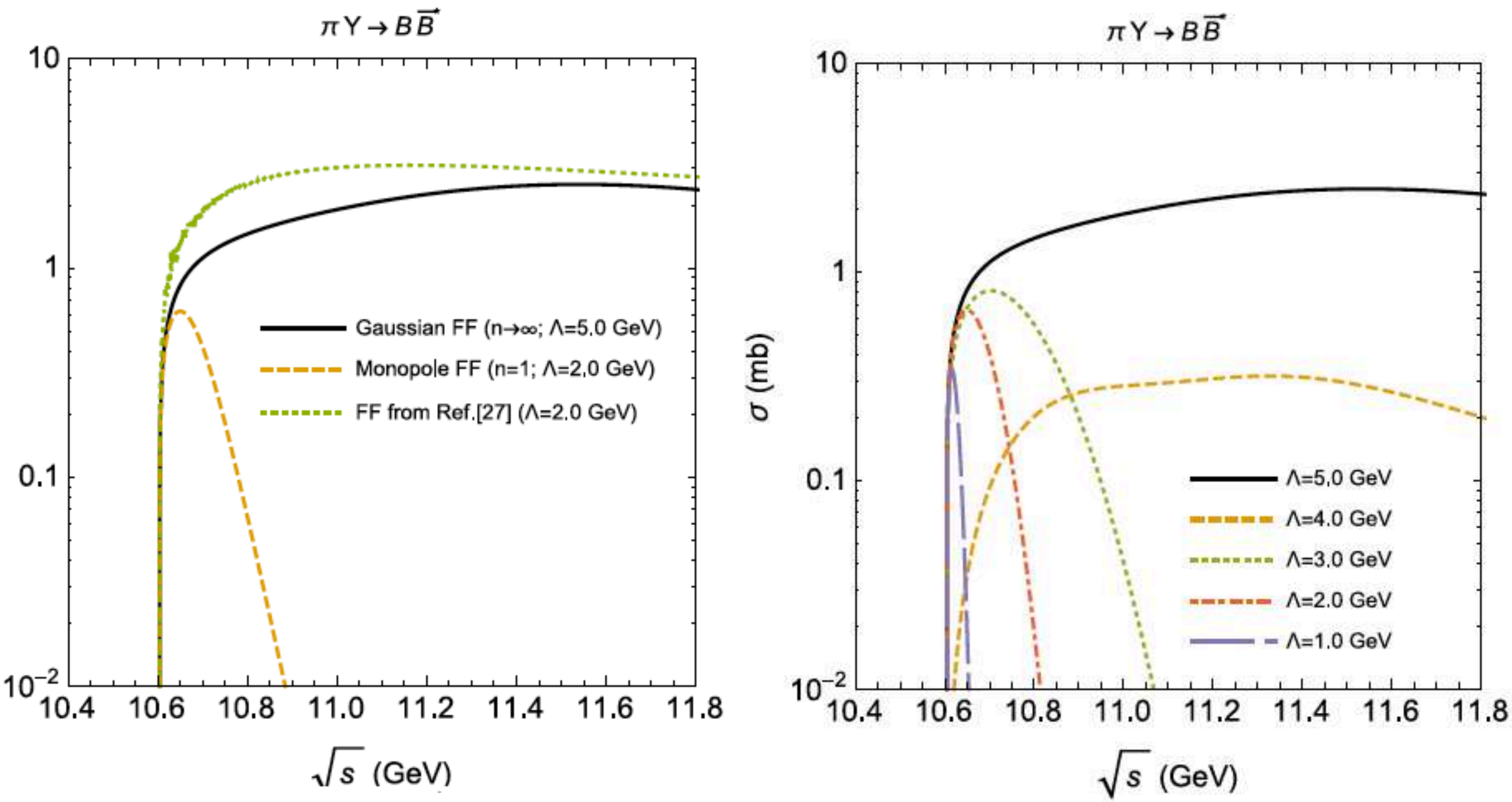
Charmonium X Bottomonium



reduction of 25 %

reduction of 65 %

Problem: dependence on form factors



Hope: cure with QCD sum rules

Summary

We have studied the production and absorption of heavy quarkonium in a hadron gas with an effective Lagrangian model

Role of pi, rho, kaon, kstar

Role of exotic resonances Z(3900), Z(4025)

Role anomalous terms

Role of couplings and form factors

RHIC and LHC

Effective Lagrangian approach
can be systematically improved with QCDSR

As in data we find suppression with:

--Weak energy dependence

--Bottom more suppressed than charm

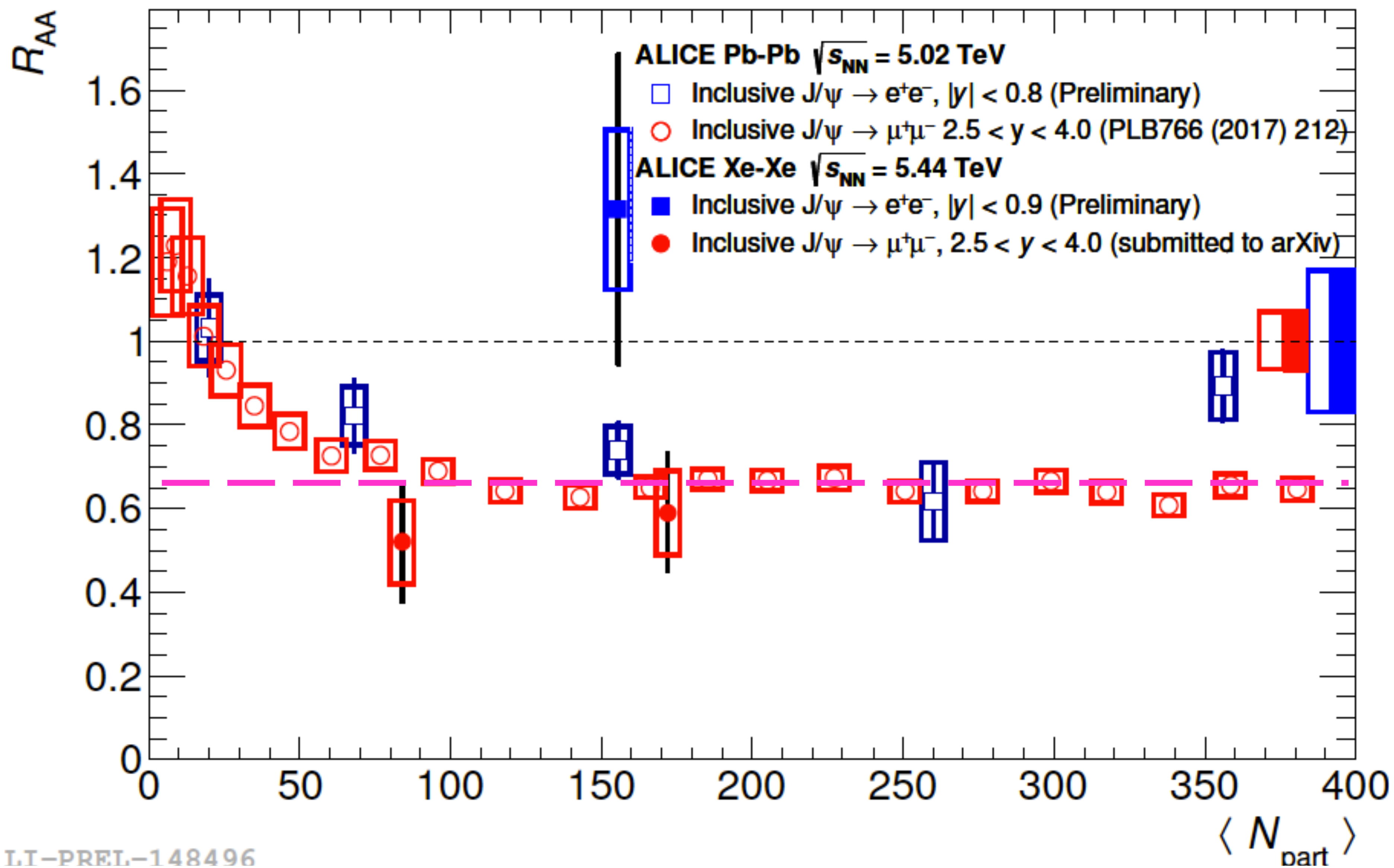
Hadronic phase is important !

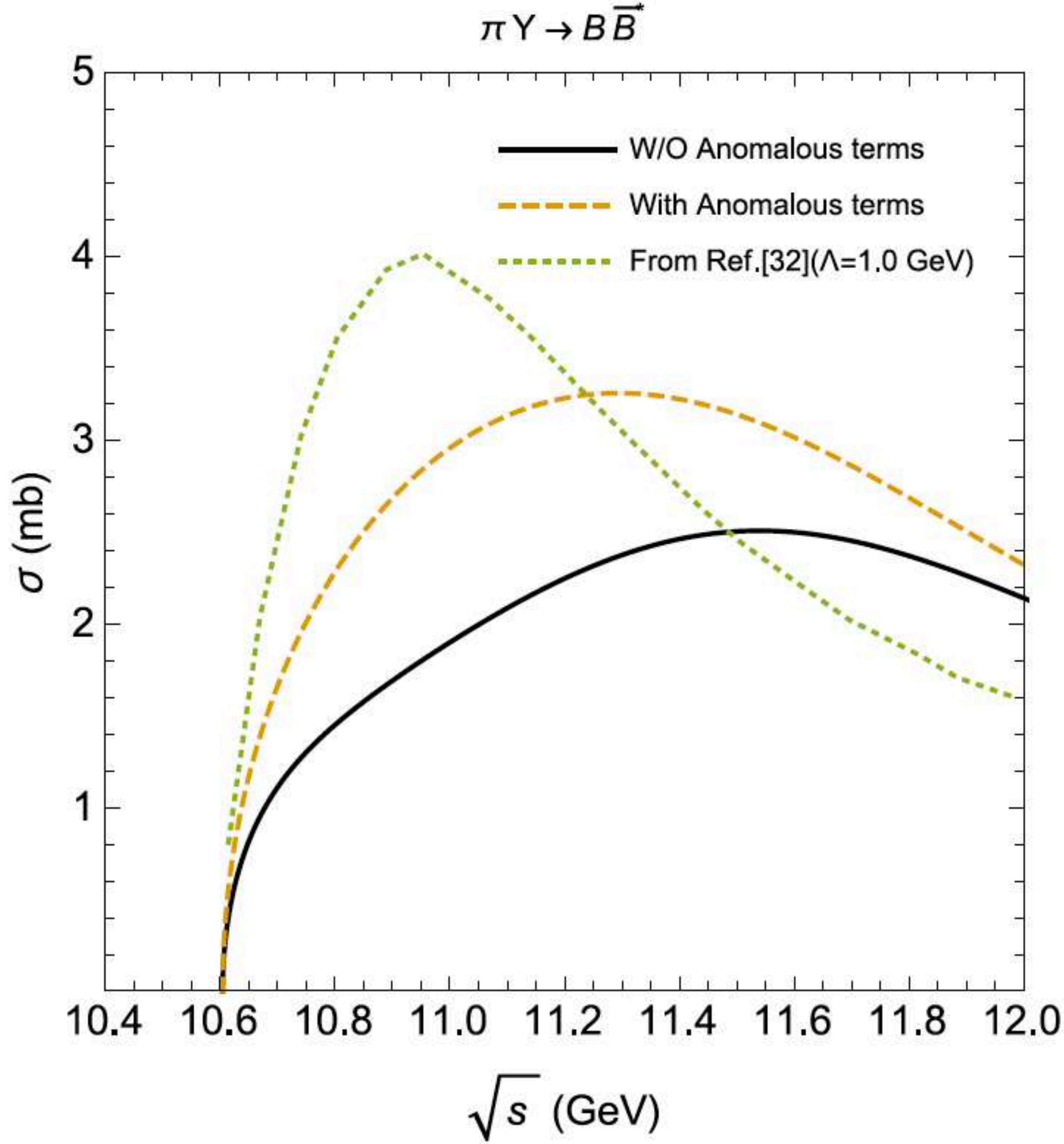
Back-ups

Charmonium

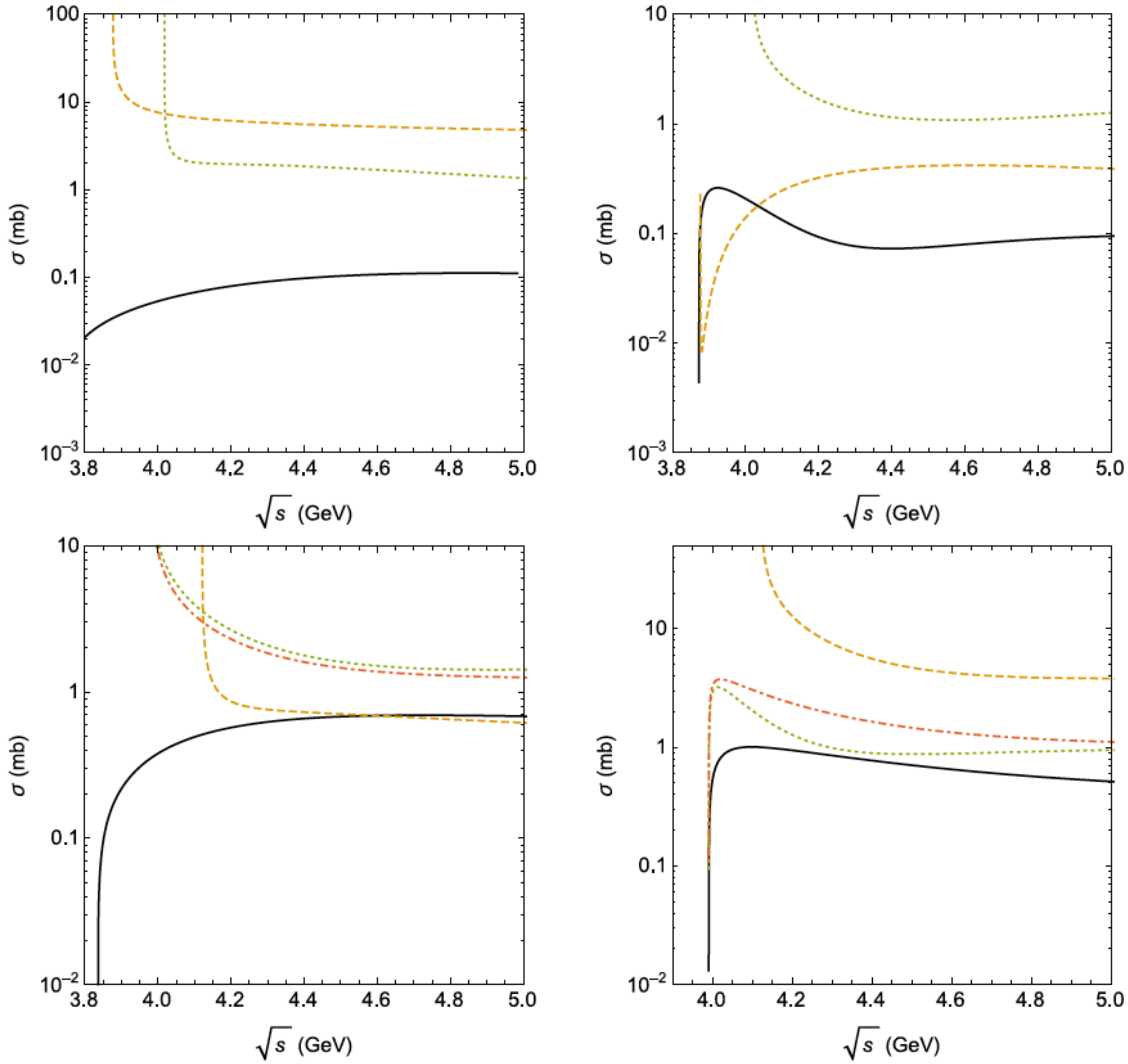
Abreu et al., arxiv:1712.06019

“Unsuppression” is robust !

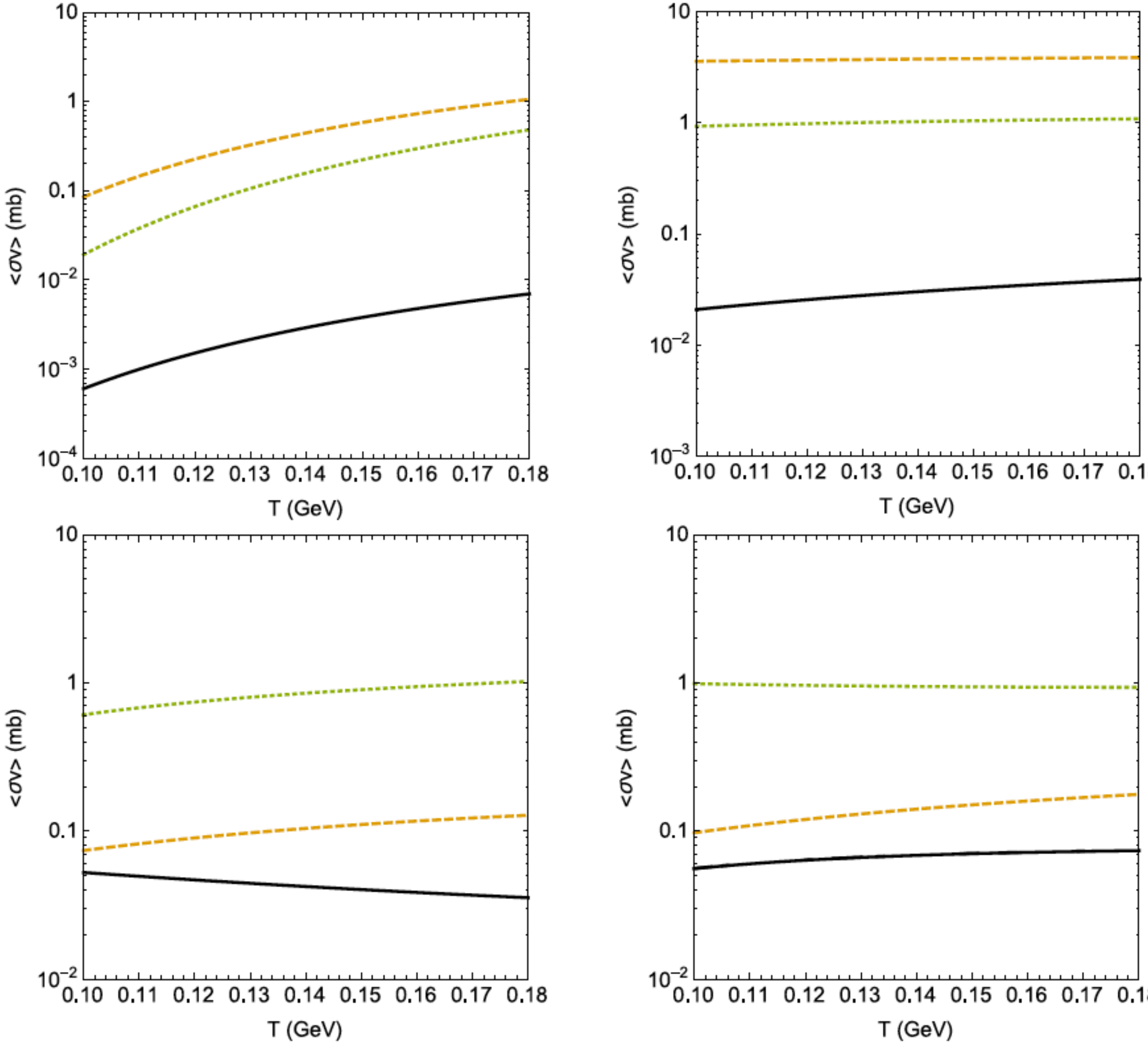




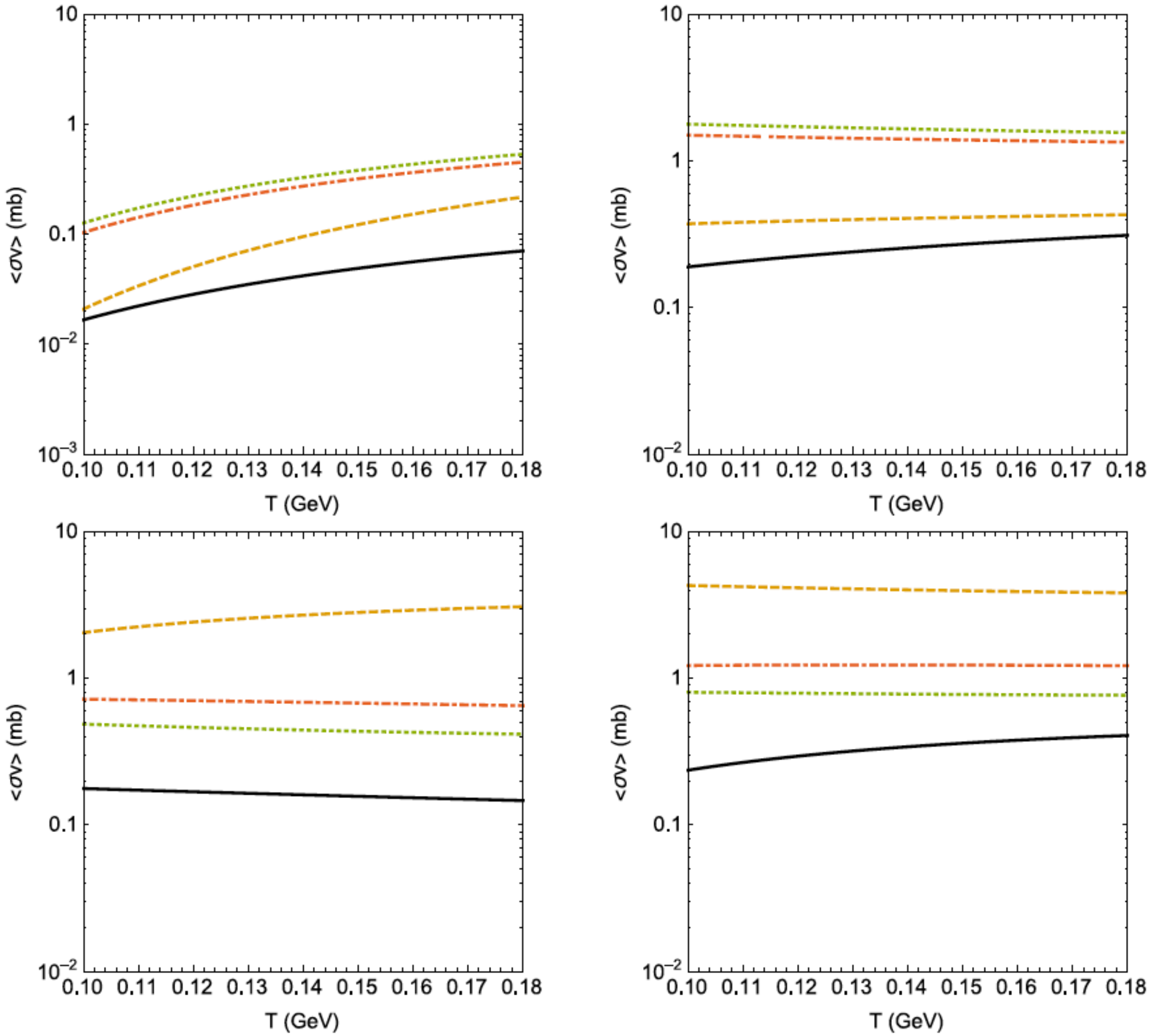
$\pi\Upsilon \to B\bar{B}^*$
W/O Anomalous terms
With Anomalous terms
From Ref.[32](Λ=1.0 GeV)
σ (mb)
$\sqrt{s}$ (GeV)
5
4
3
2
1
10.4
10.6
10.8
11.0
11.2
11.4
11.6
11.8
12.0



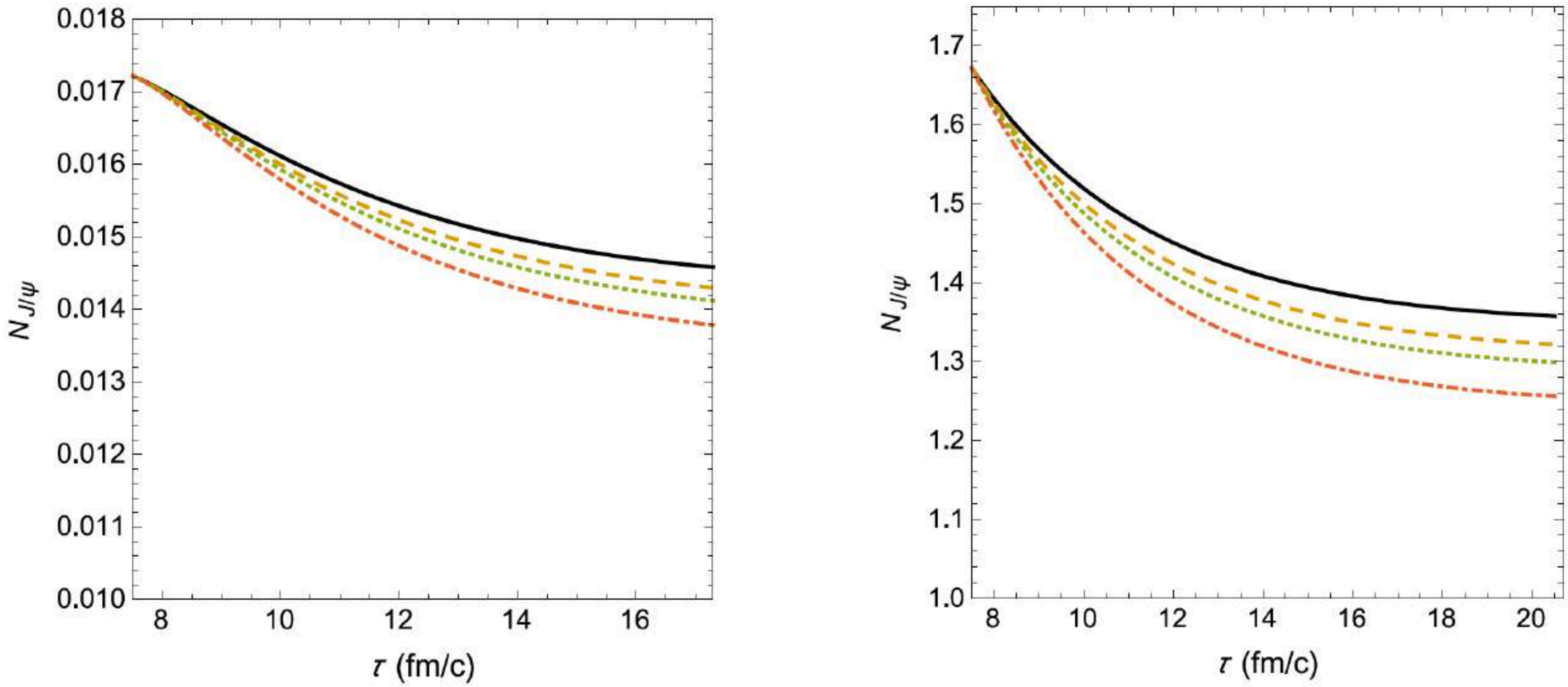
σ (mb)
√s (GeV)

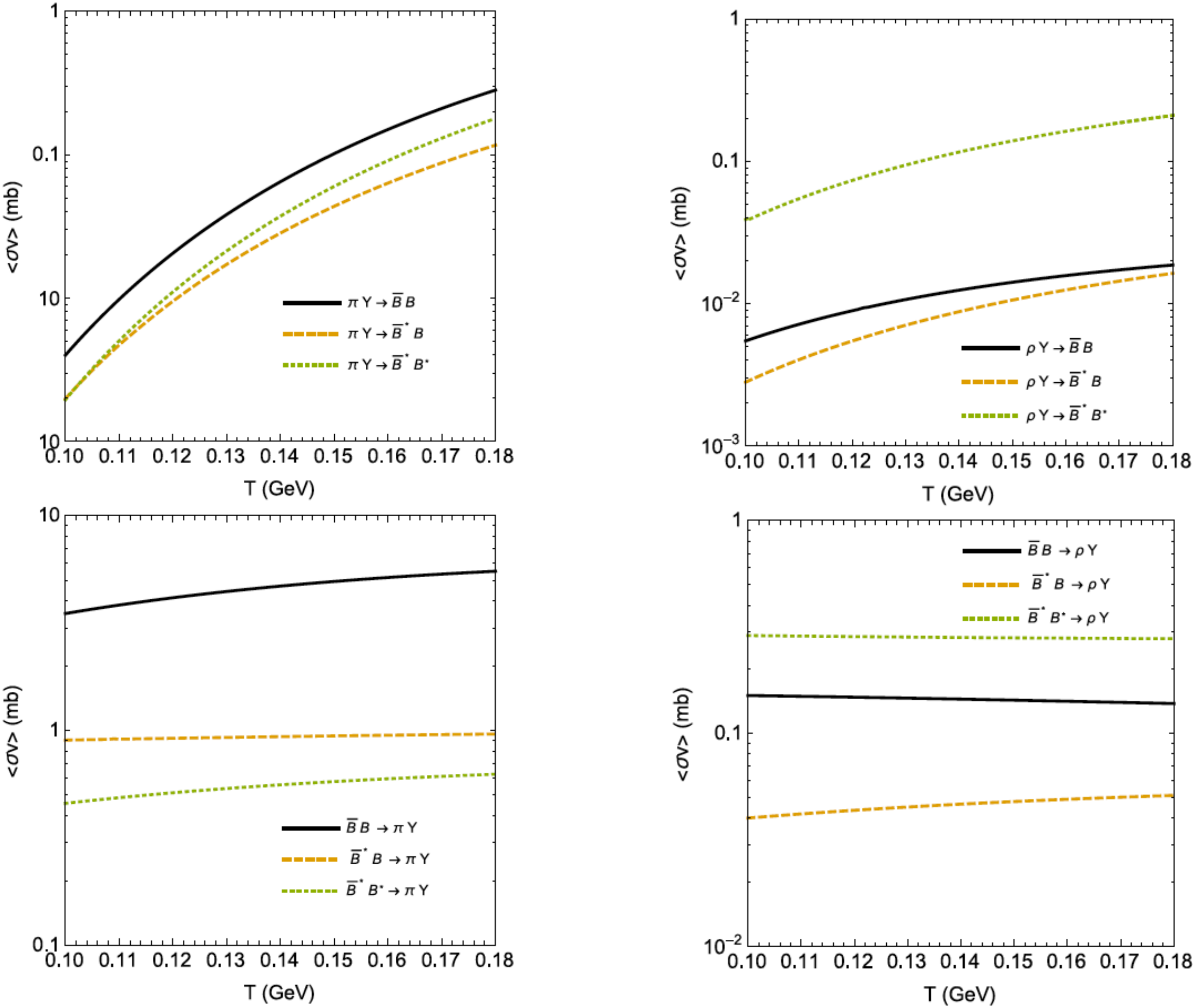


<σv> (mb)
T (GeV)
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
0.10 0.11 0.12 0.13 0.14 0.15 0.16 0.17 0.18



<σv> (mm)
T (GeV)
10
1
0.1
10^{-2}
10^{-3}
0.10 0.11 0.12 0.13 0.14 0.15 0.16 0.17 0.18


0.018
0.017
0.016
0.015
0.014
0.013
0.012
0.011
0.010
$N_{J/\psi}$
8
10
12
14
16
τ (fm/c)
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
$N_{J/\psi}$
8
10
12
14
16
18
20
τ (fm/c)



<σv> (mb)
T (GeV)
πϒ → B̄B
πϒ → B̄* B
πϒ → B̄* B*
ρϒ → B̄B
ρϒ → B̄* B
ρϒ → B̄* B*
B̄B → πϒ
B̄* B → πϒ
B̄* B* → πϒ
B̄B → ρϒ
B̄* B → ρϒ
B̄* B* → ρϒ

Quarkonium suppression in the QGP

$T = 0$ $$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$$

$T > T_c$ $$V(r) = -\frac{4}{3}\frac{\alpha_s}{r}$$

$T > 1.5\,T_c$ $$V(r) = -\frac{4}{3}\frac{\alpha_s}{r}\, e^{-r/r_D}$$

If screening radius is smaller than Bohr radius:

$$r_D < r_\psi$$

Quark and antiquark do not bind !

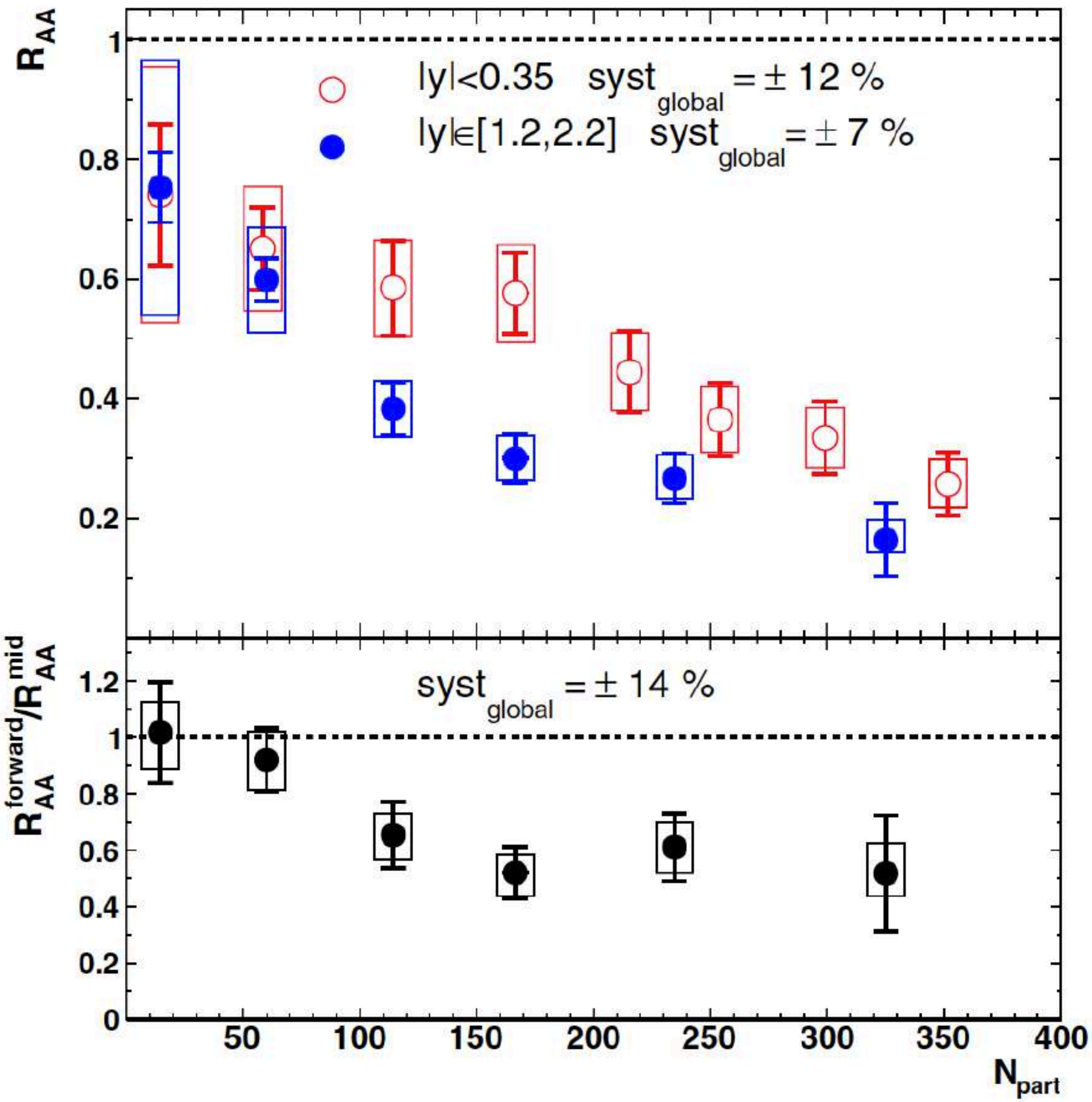
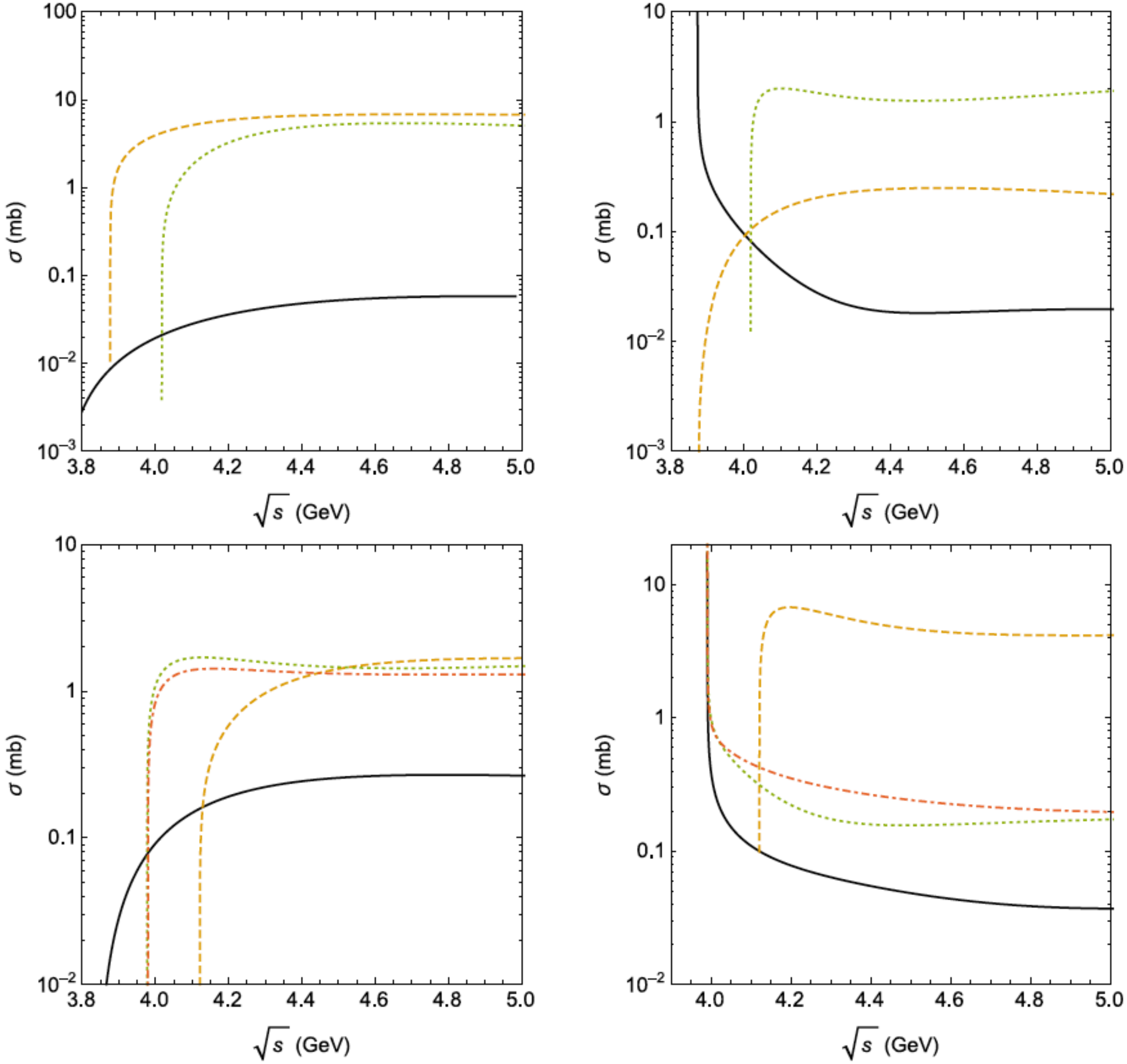
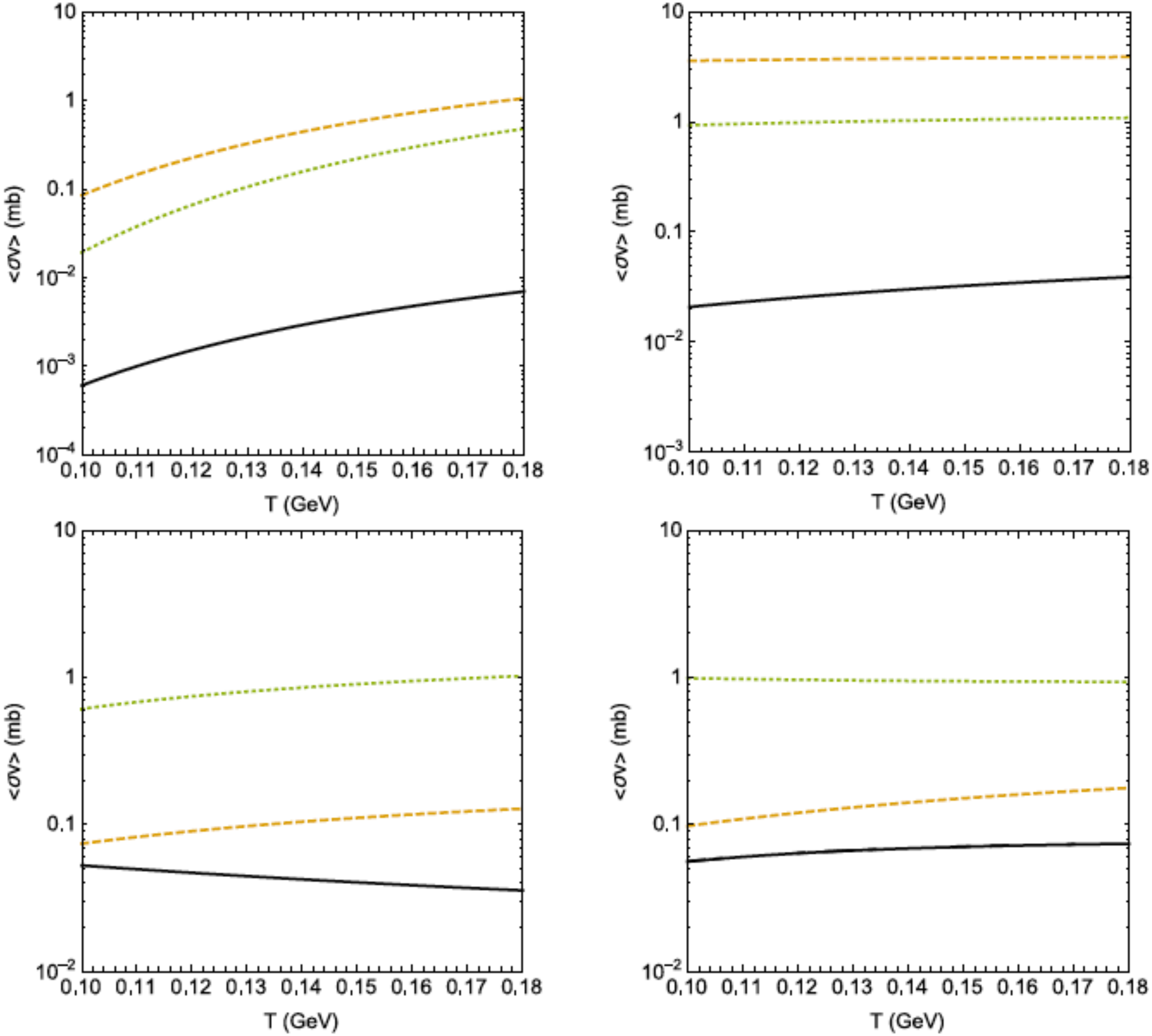


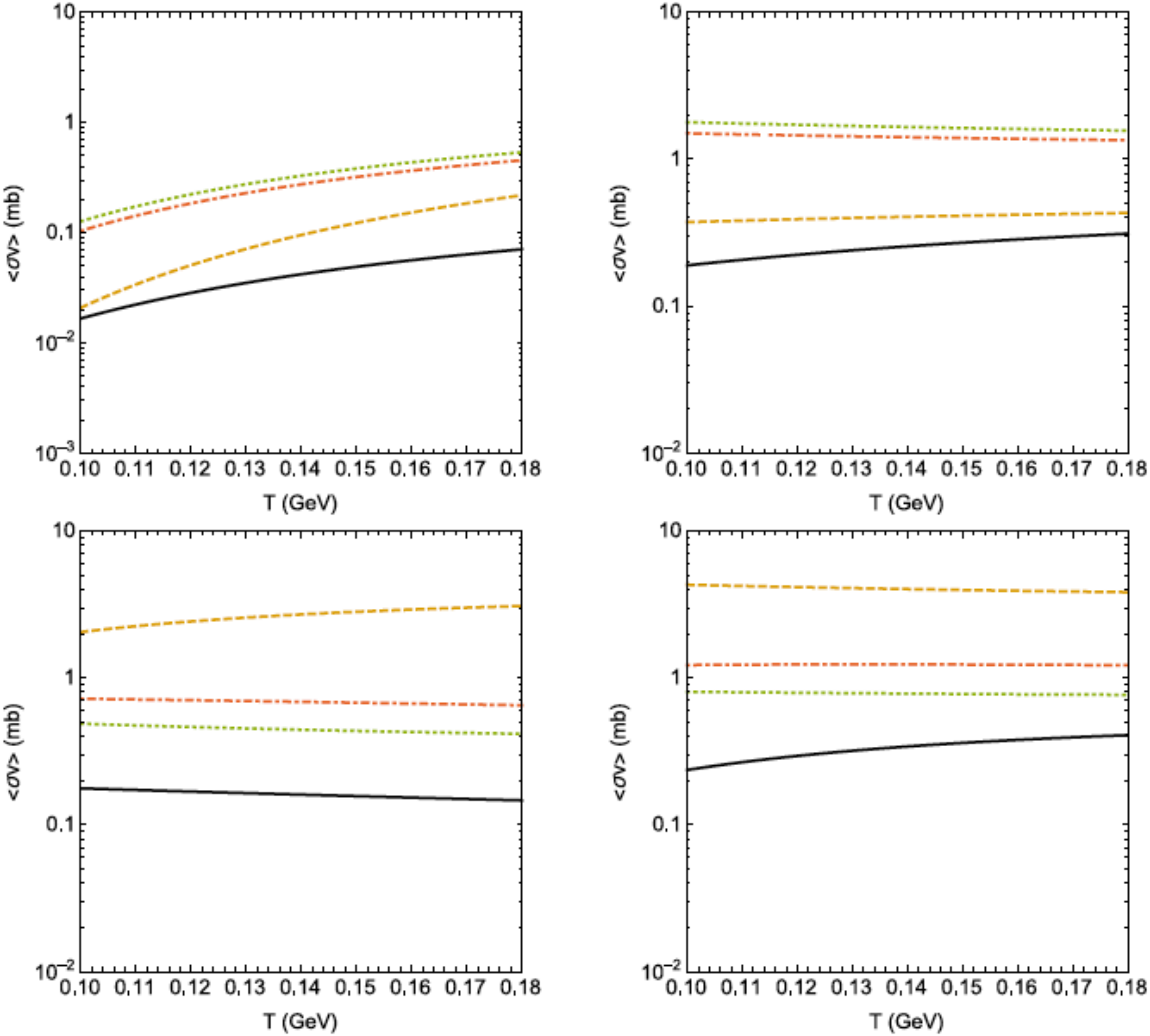
FIG. 5 (color online). (a) J/ψ R_{AA} versus N_{part} for Au + Au collisions. Mid (forward) rapidity data are shown with open (solid) circles. (b) Ratio of forward or midrapidity J/ψ R_{AA} versus N_{part}. For the two most central bins, midrapidity points



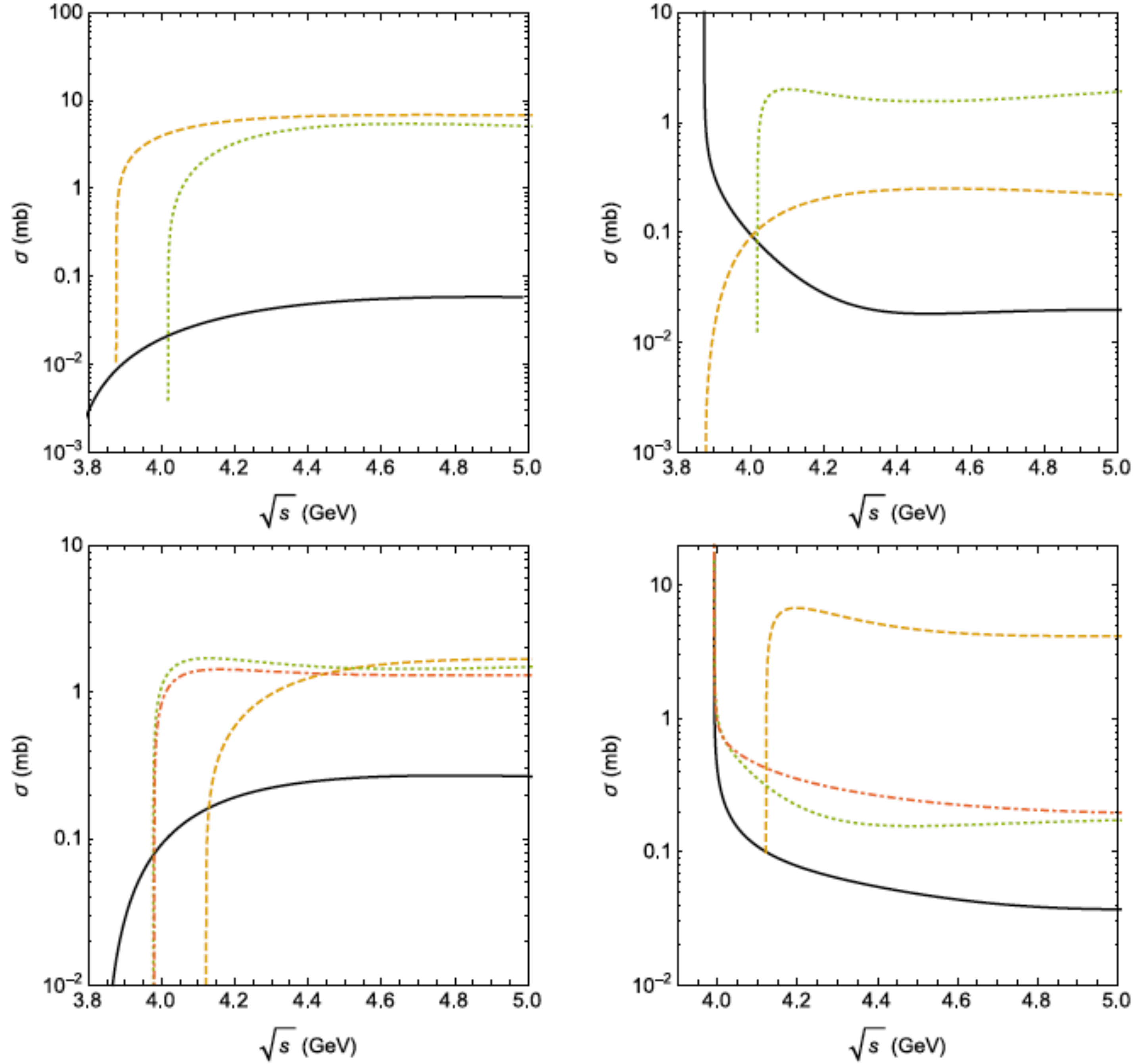
σ (mb)
√s (GeV)
100
10
1
0.1
10^-2
10^-3
3.8
4.0
4.2
4.4
4.6
4.8
5.0
σ (mb)
√s (GeV)
10
1
0.1
10^-2
10^-3
3.8
4.0
4.2
4.4
4.6
4.8
5.0
σ (mb)
√s (GeV)
10
1
0.1
10^-2
3.8
4.0
4.2
4.4
4.6
4.8
5.0
σ (mb)
√s (GeV)
10
1
0.1
10^-2
4.0
4.2
4.4
4.6
4.8
5.0



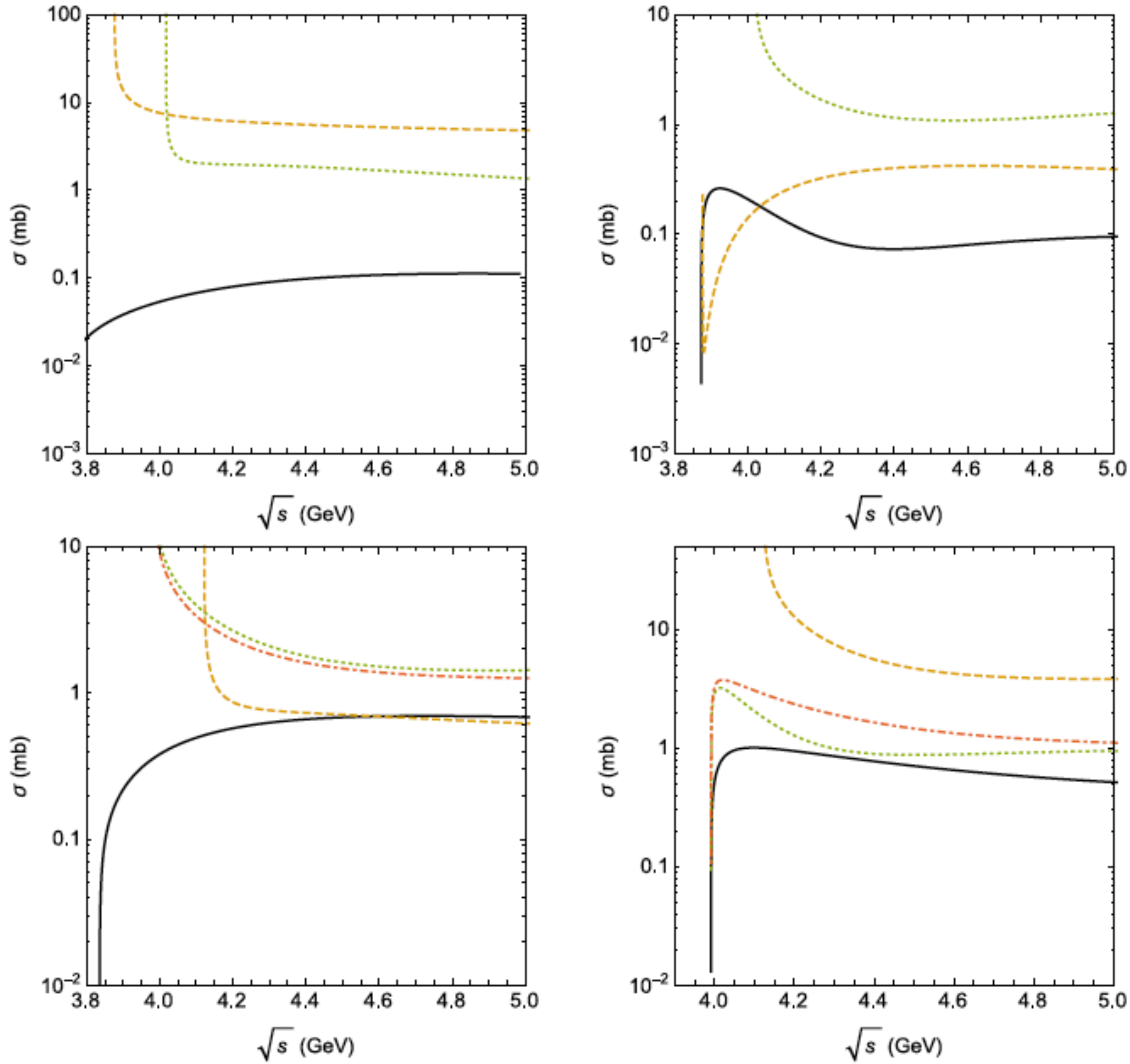
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
<σv> (mb)
0,10 0,11 0,12 0,13 0,14 0,15 0,16 0,17 0,18
T (GeV)
10
1
0.1
10^{-2}
10^{-3}
<σv> (mb)
0,10 0,11 0,12 0,13 0,14 0,15 0,16 0,17 0,18
T (GeV)
10
1
0.1
10^{-2}
<σv> (mb)
0,10 0,11 0,12 0,13 0,14 0,15 0,16 0,17 0,18
T (GeV)
10
1
0.1
10^{-2}
<σv> (mb)
0,10 0,11 0,12 0,13 0,14 0,15 0,16 0,17 0,18
T (GeV)

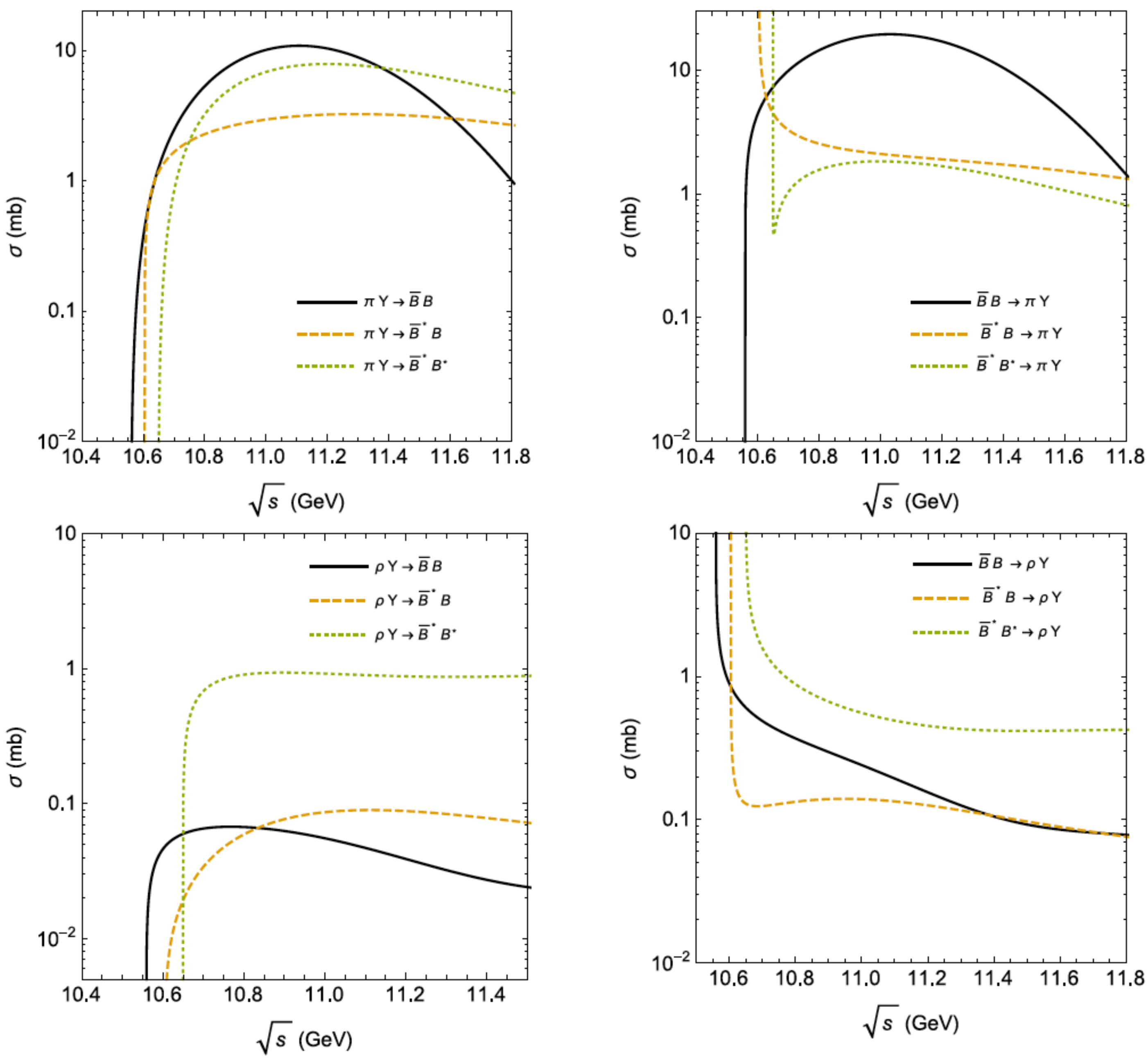


<σv> (mb)
T (GeV)
10
1
0.1
10^{-2}
10^{-3}
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18

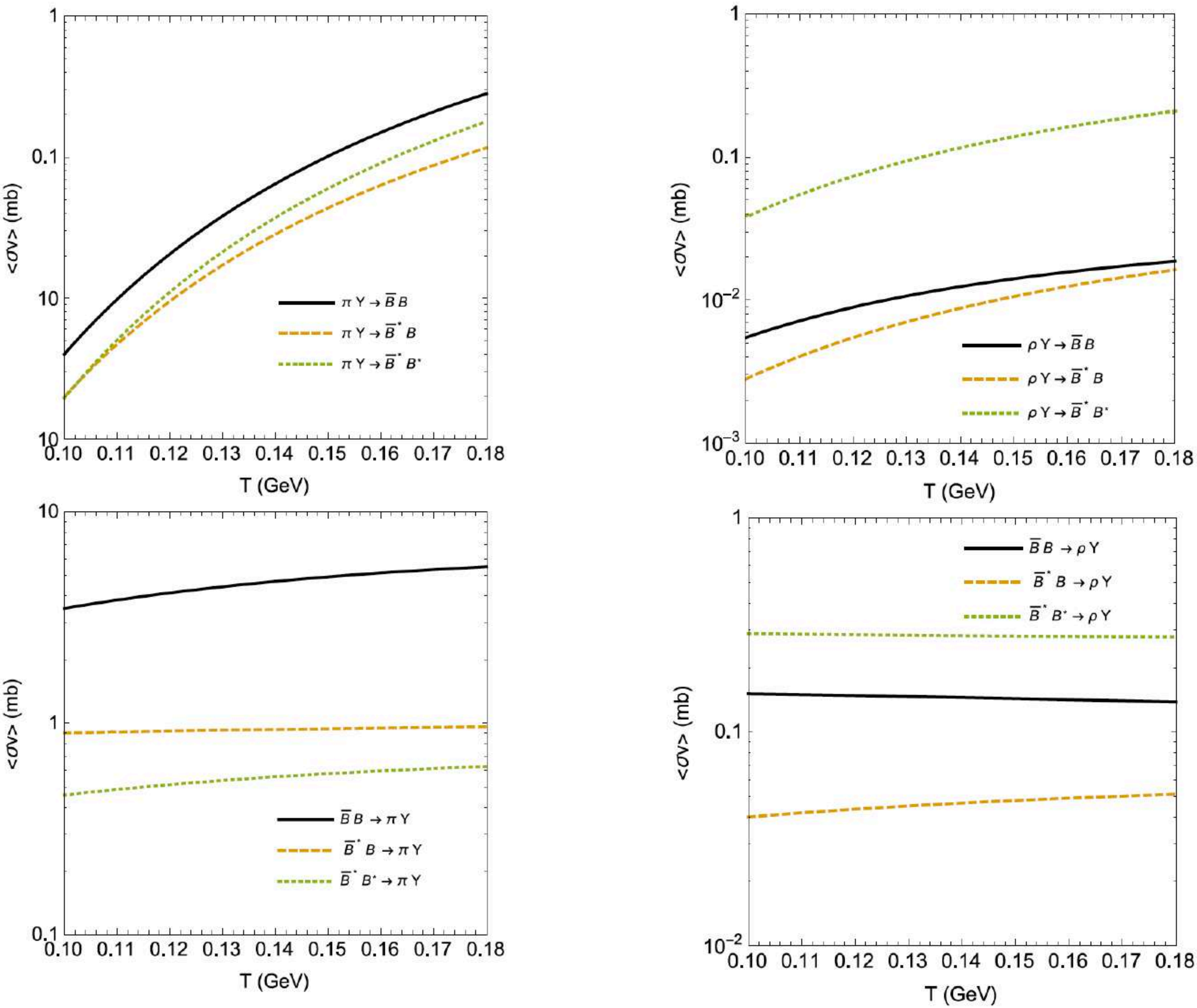


100
10
1
0.1
10^{-2}
10^{-3}
σ (mb)
3.8
4.0
4.2
4.4
4.6
4.8
5.0
$\sqrt{s}$ (GeV)
10
1
0.1
10^{-2}
10^{-3}
σ (mb)
3.8
4.0
4.2
4.4
4.6
4.8
5.0
$\sqrt{s}$ (GeV)
10
1
0.1
10^{-2}
σ (mb)
3.8
4.0
4.2
4.4
4.6
4.8
5.0
$\sqrt{s}$ (GeV)
10
1
0.1
10^{-2}
σ (mb)
4.0
4.2
4.4
4.6
4.8
5.0
$\sqrt{s}$ (GeV)


σ (mb)
√s (GeV)
100
10
1
0.1
10^{-2}
10^{-3}
3.8
4.0
4.2
4.4
4.6
4.8
5.0

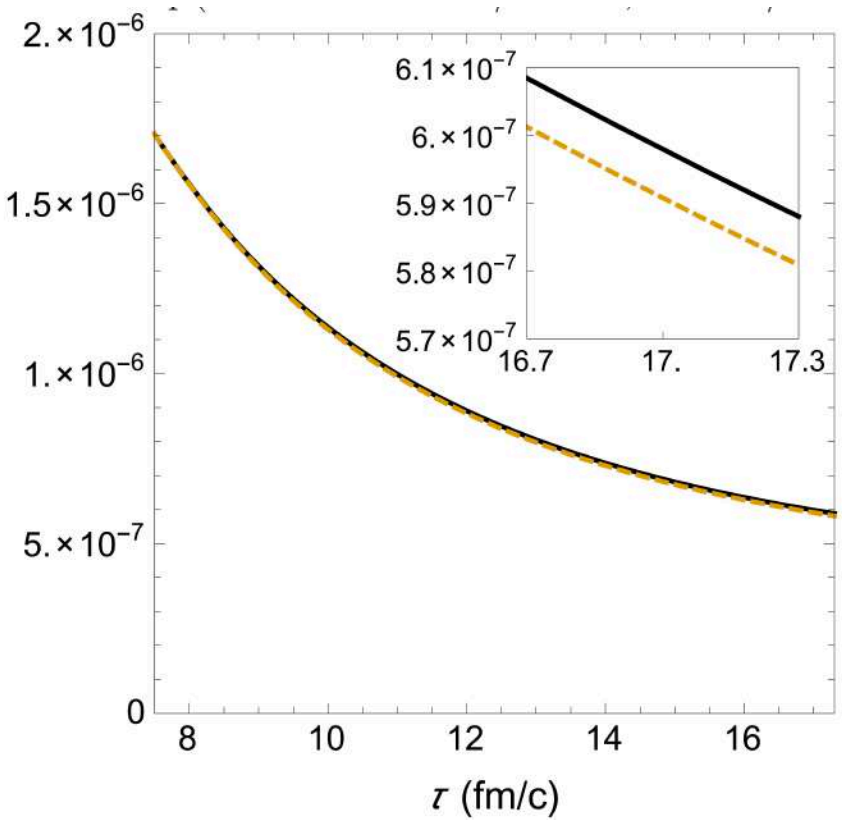


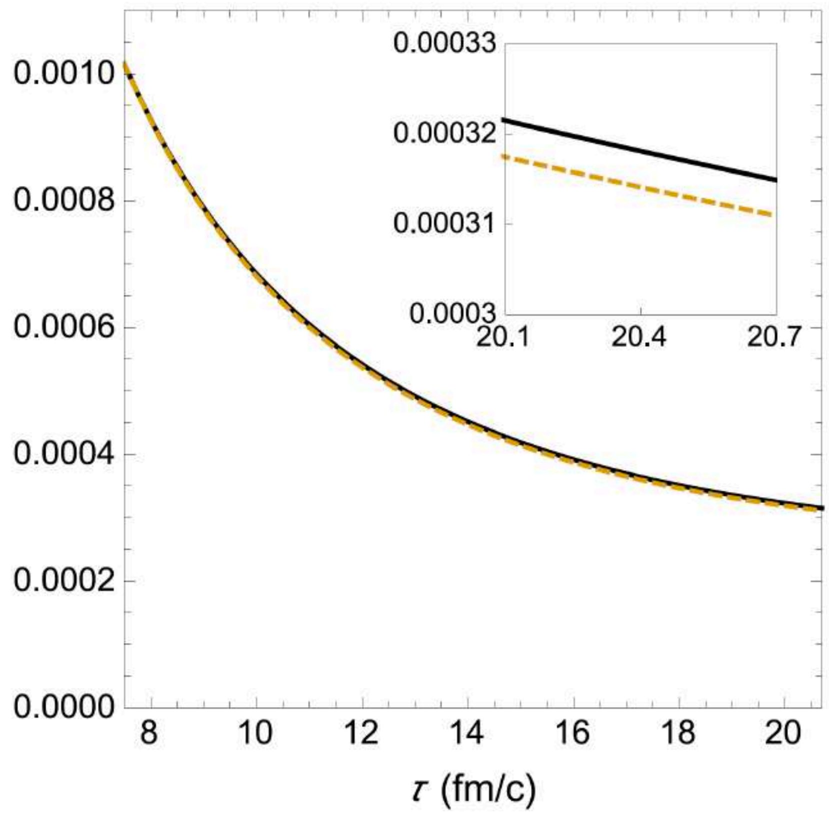
σ (mb)
$\sqrt{s}$ (GeV)
$\pi \Upsilon \to \bar{B} B$
$\pi \Upsilon \to \bar{B}^* B$
$\pi \Upsilon \to \bar{B}^* B^*$
$\bar{B} B \to \pi \Upsilon$
$\bar{B}^* B \to \pi \Upsilon$
$\bar{B}^* B^* \to \pi \Upsilon$
$\rho \Upsilon \to \bar{B} B$
$\rho \Upsilon \to \bar{B}^* B$
$\rho \Upsilon \to \bar{B}^* B^*$
$\bar{B} B \to \rho \Upsilon$
$\bar{B}^* B \to \rho \Upsilon$
$\bar{B}^* B^* \to \rho \Upsilon$



<σv> (mb)
T (GeV)
0.10 0.11 0.12 0.13 0.14 0.15 0.16 0.17 0.18
1
0.1
10
10
π Υ → B̄ B
π Υ → B̄* B
π Υ → B̄* B*
1
0.1
10⁻²
10⁻³
ρ Υ → B̄ B
ρ Υ → B̄* B
ρ Υ → B̄* B*
10
1
0.1
B̄ B → π Υ
B̄* B → π Υ
B̄* B* → π Υ
1
0.1
10⁻²
B̄ B → ρ Υ
B̄* B → ρ Υ
B̄* B* → ρ Υ

Upsilon in a hadron gas

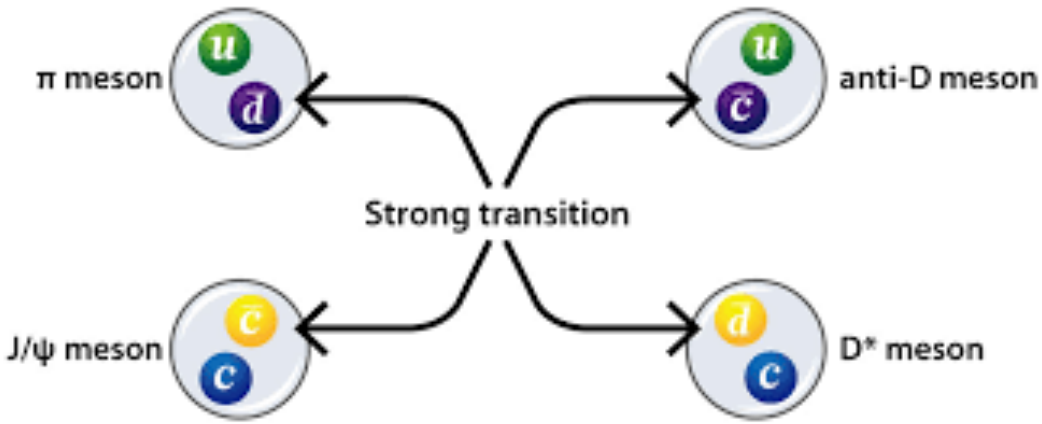


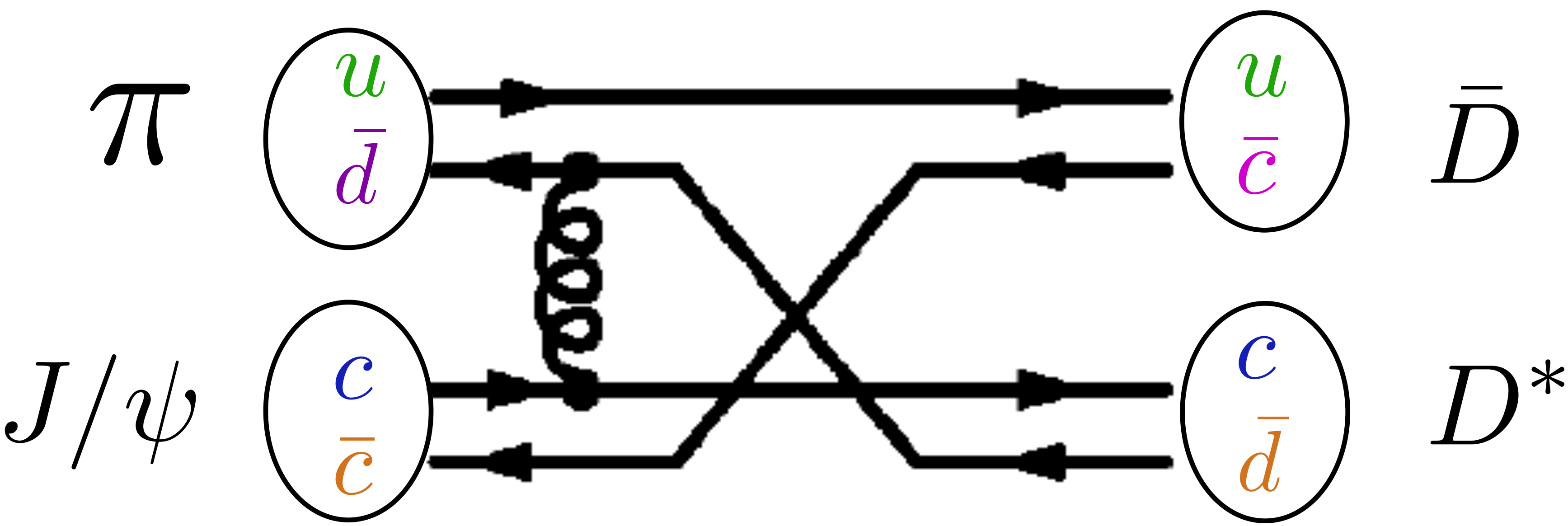


Suppression by a factor 3 in the hadron gas !

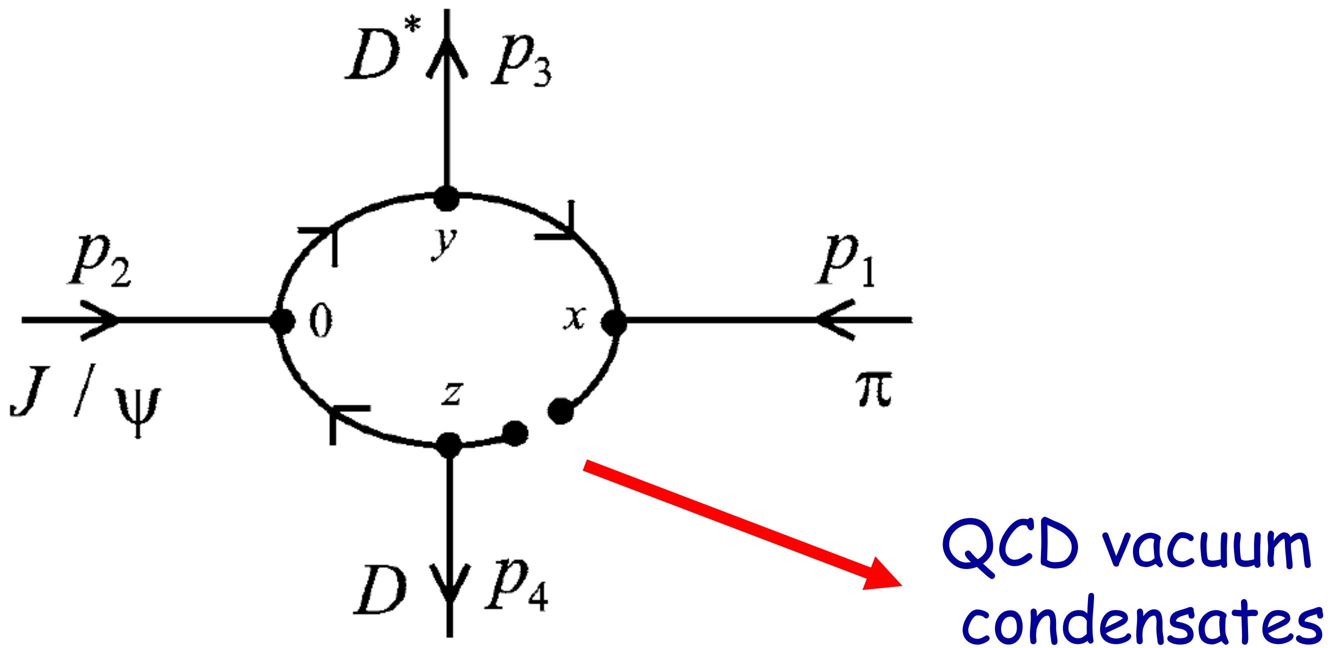
Abreu, FSN and M. Nielsen, arXiv:1807.05081

Quark Exchange Models





QCD Sum Rules



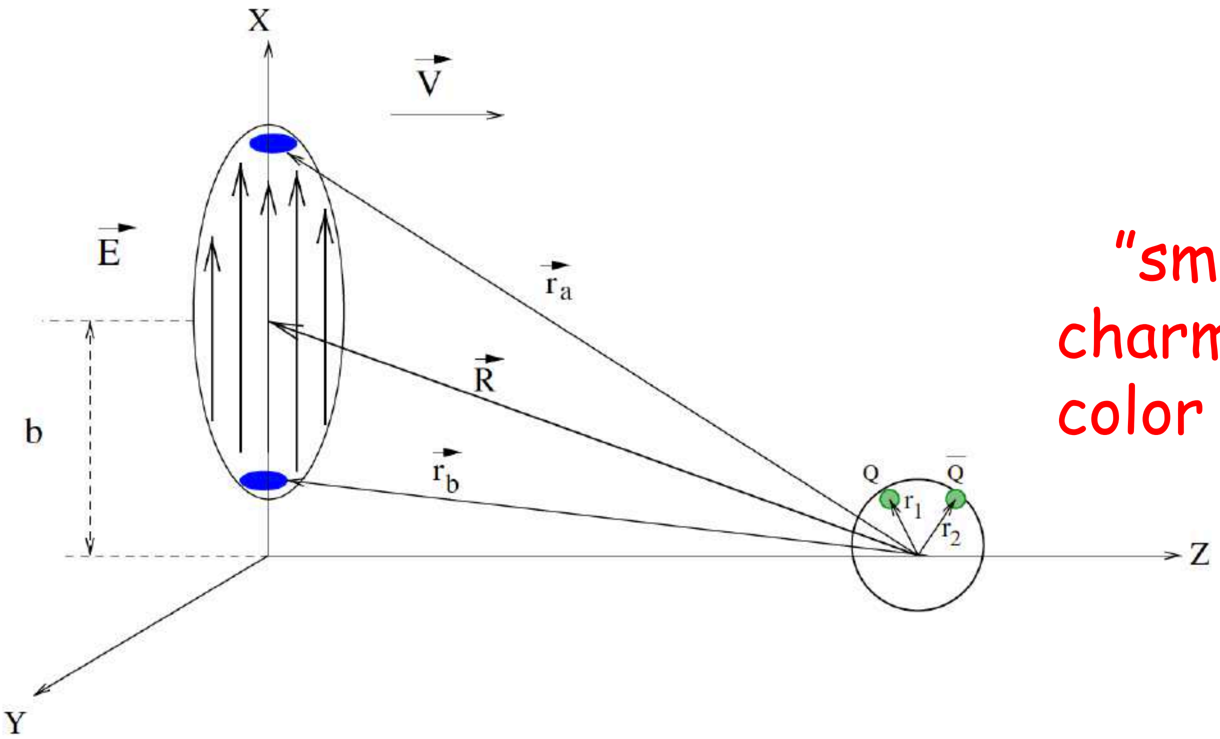
FSN, M. Nielsen, R.S. Marques de Carvalho and G. Krein, Phys. Lett. B (2002)

F.O. Duraes, S.H. Lee, FSN and M. Nielsen, Phys. Lett. B (2003)

F.O. Duraes, H. Kim, S.H. Lee, FSN and M. Nielsen, Phys. Rev. C (2003)

Semi-classical model: dipole in a color capacitor

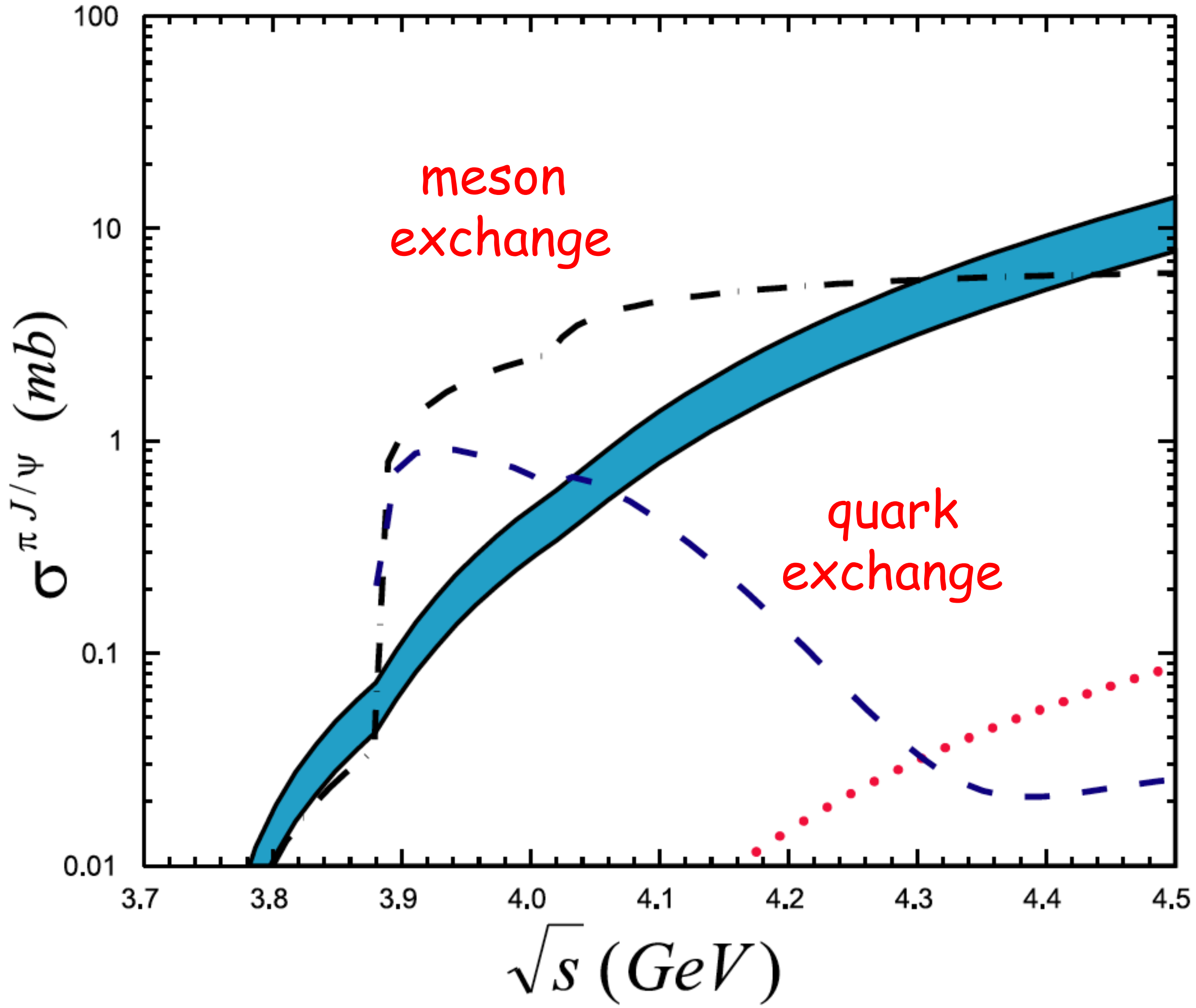
"big" pion capacitor



"small" charmonium color dipole

Kugeratski, FSN, Phys. Rev. C (2005)

Results

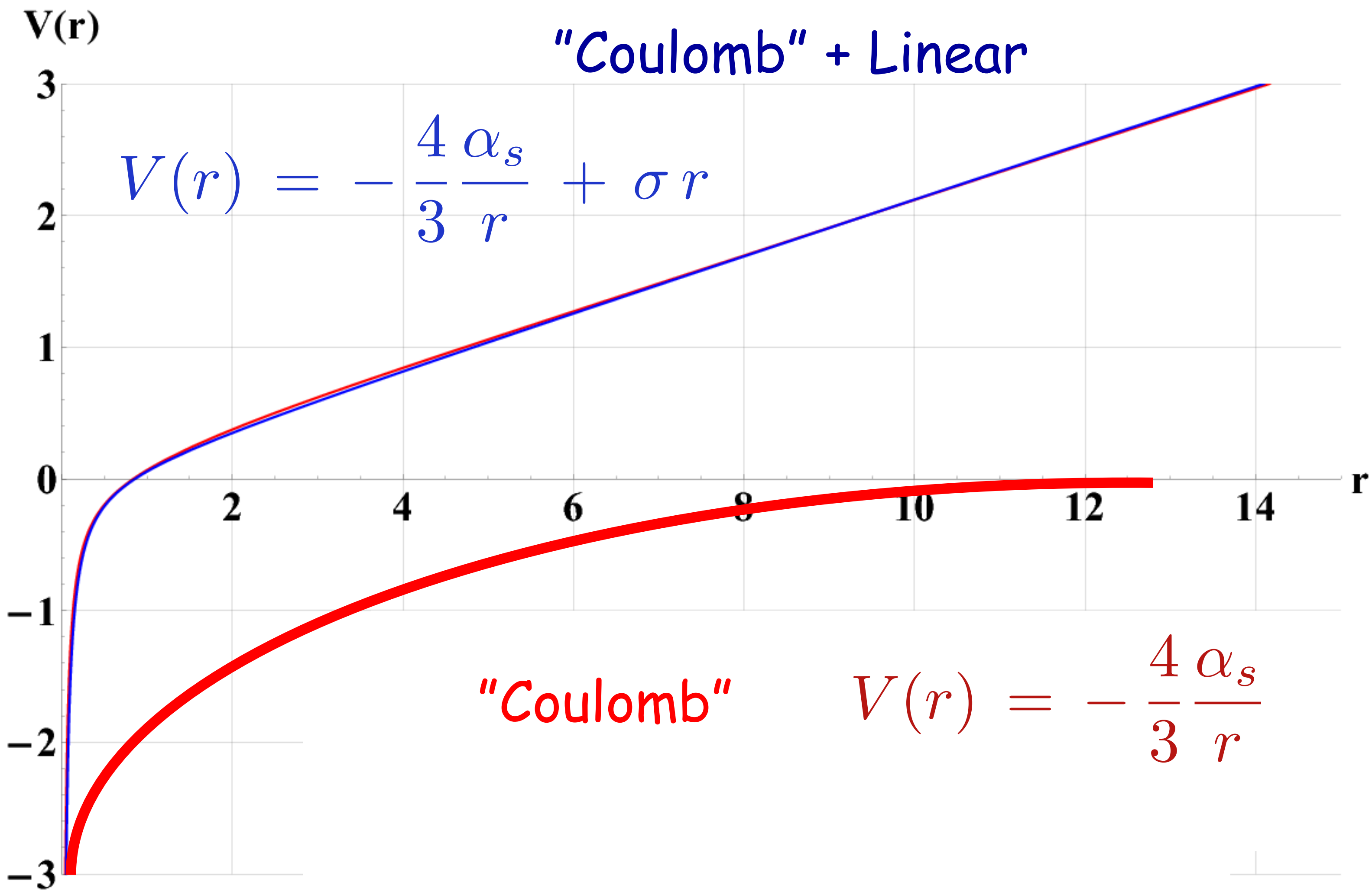


QCDSR

short distance QCD

Kharzeev, Satz, Phys. Lett. B (1994)

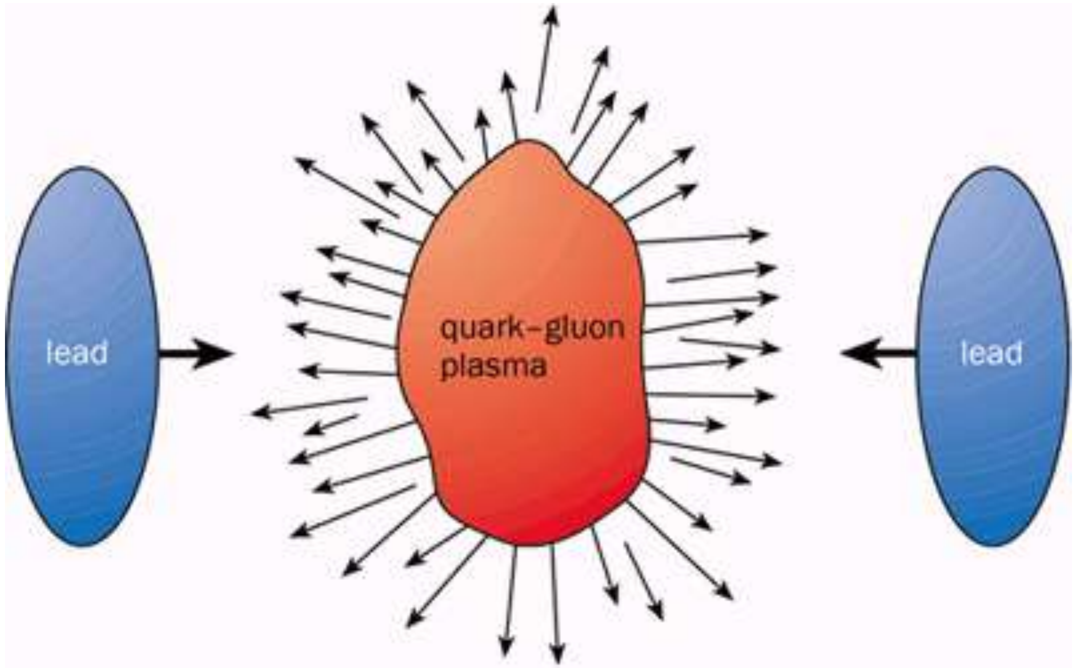
Confinement: infinite energy to separate quarks



No confinement: they bind but can be separated

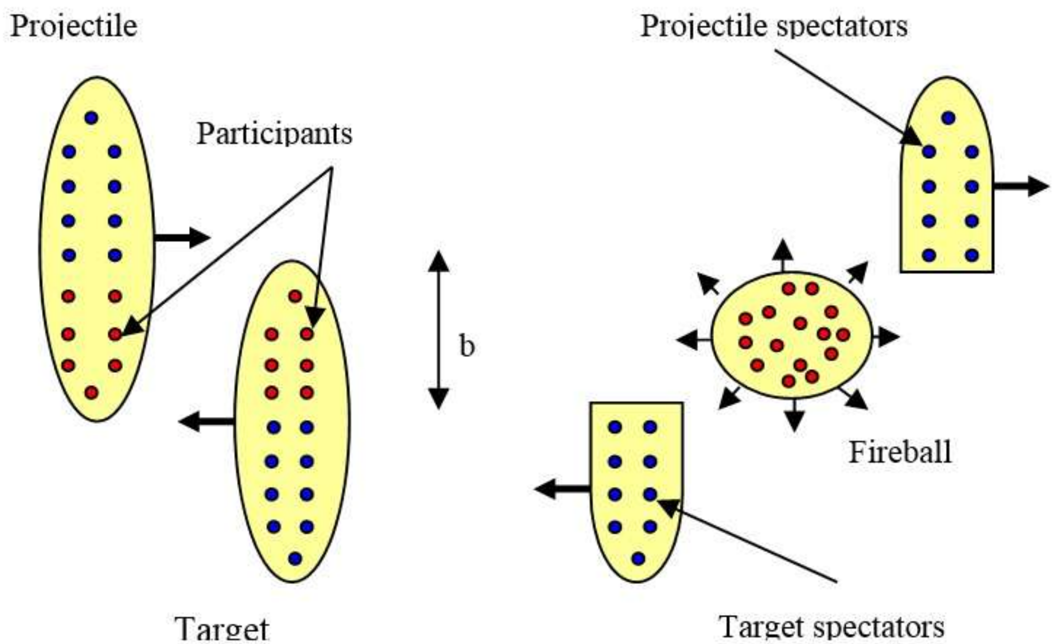
Central Collisions

More participants larger N_{part}

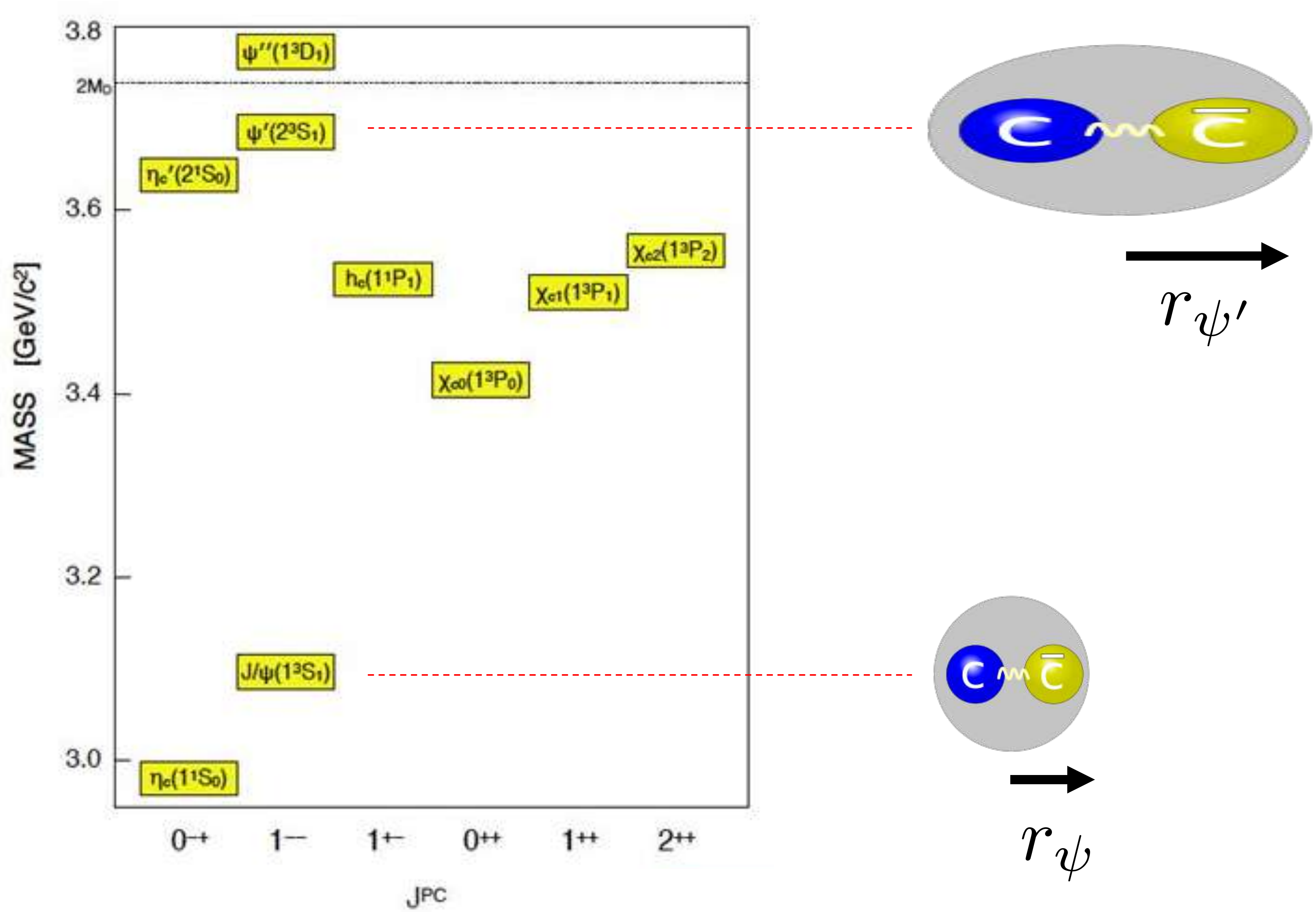


Noncentral Collisions

Less participants smaller N_{part}



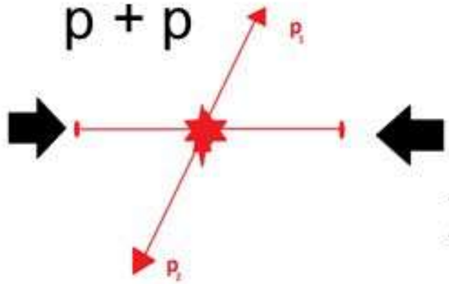
Quarkonium spectrum



Nuclear Modification Factor

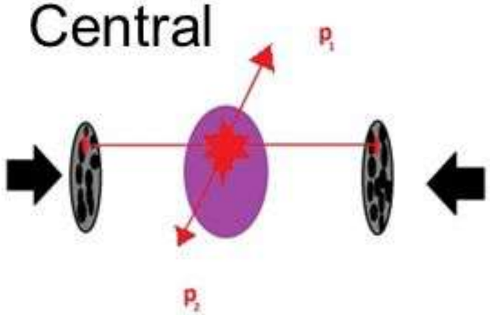
hard scatterings produce early high p_T probes

p + p

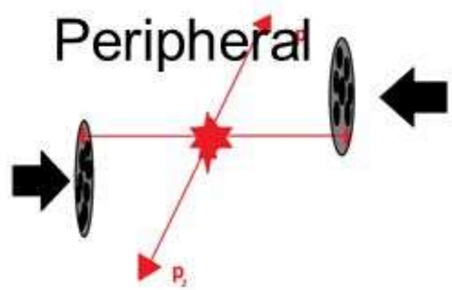


$$R_{AA} = \frac{1}{(N_{bin})_{AA}} \times \frac{\left(\frac{d^2N}{p_T dp_T d\eta}\right)_{AA}}{\left(\frac{d^2N}{p_T dp_T d\eta}\right)_{pp}}$$

Au + Au
Central



Au + Au
Peripheral



$$R_{CP} = \frac{(N_{bin})_P}{(N_{bin})_C} \times \frac{\left(\frac{d^2N}{p_T dp_T d\eta}\right)_{C}}{\left(\frac{d^2N}{p_T dp_T d\eta}\right)_{P}}$$

N_{bin} ≡ number of binary collisions (from Glauber)

Machines and energy per nucleon-pair

CERN - SPS $\sqrt{s} \simeq 20\,\mathrm{GeV}$

NA38, NA50, NA60

BNL - RHIC $\sqrt{s} \simeq 200\,\mathrm{GeV}$

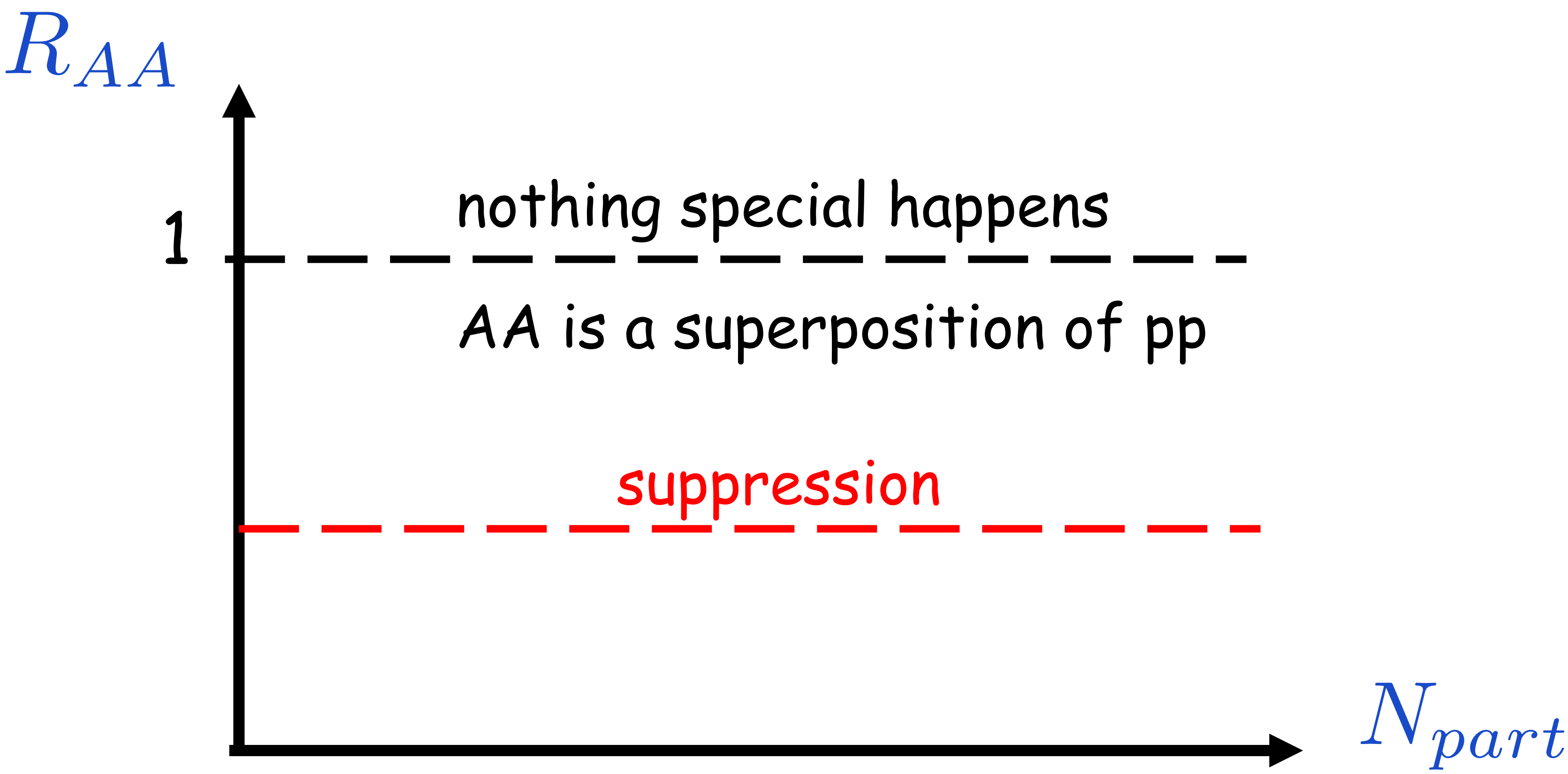
STAR, PHENIX

CERN - LHC $\sqrt{s} \simeq 2000\,\mathrm{GeV}$

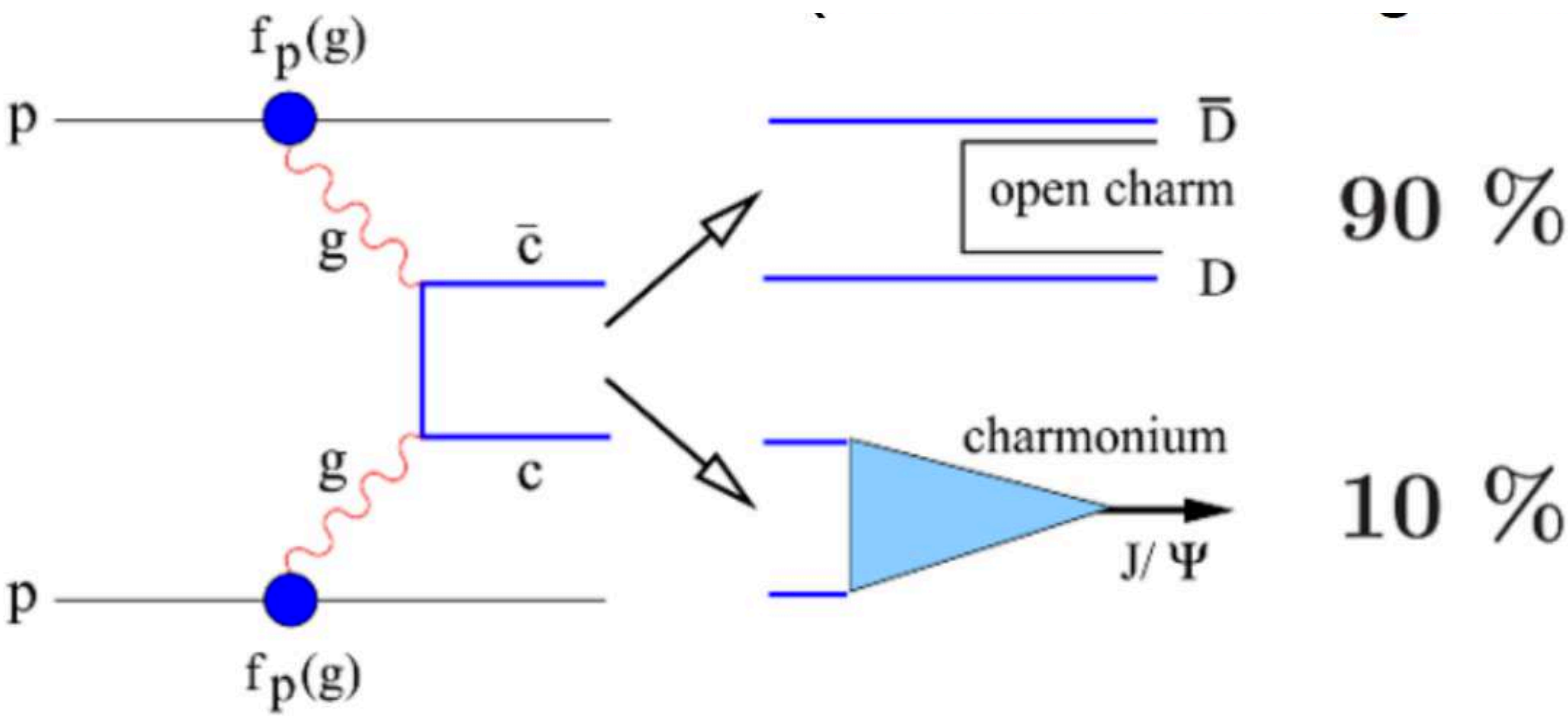
ALICE, CMS, ATLAS

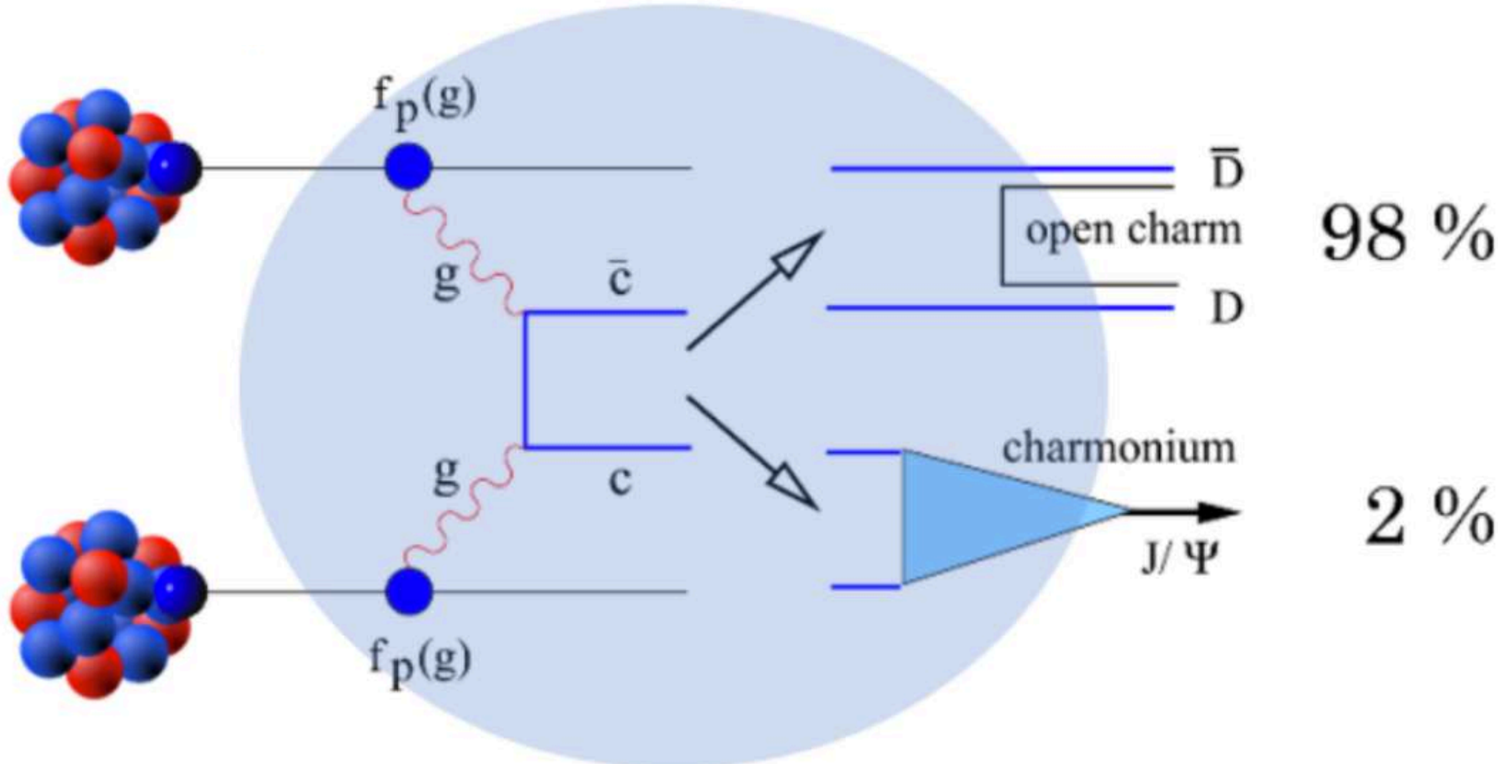
Data on R_{AA} versus N_{part}

("number" of J/Psi's) ("amount" of QGP)



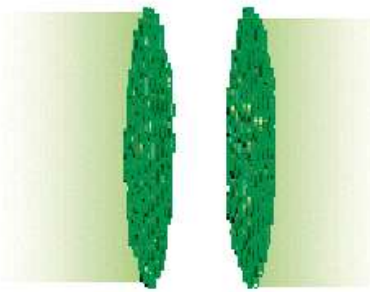
In calculations



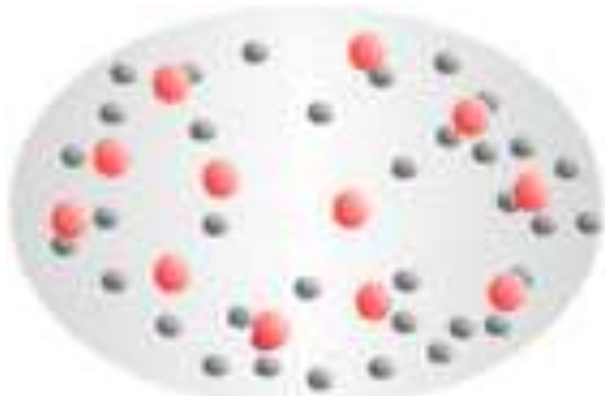


In A+A color screening reduces charmonia production → reduction of fraction of $c\bar{c}$ pairs going into charmonia in respect to p+p at the same energy

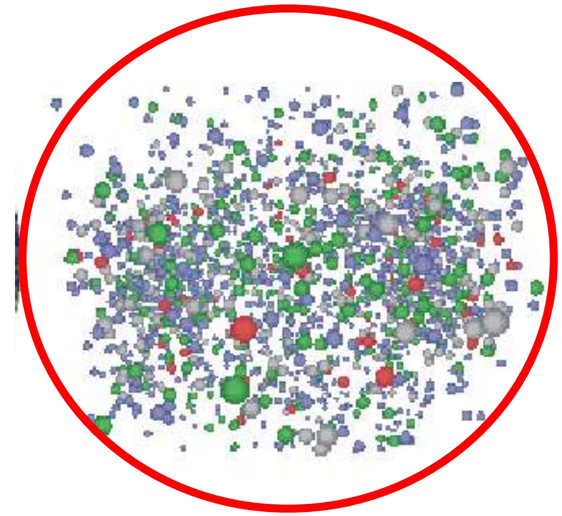
but there may be no
quark gluon plasma ...



CGC



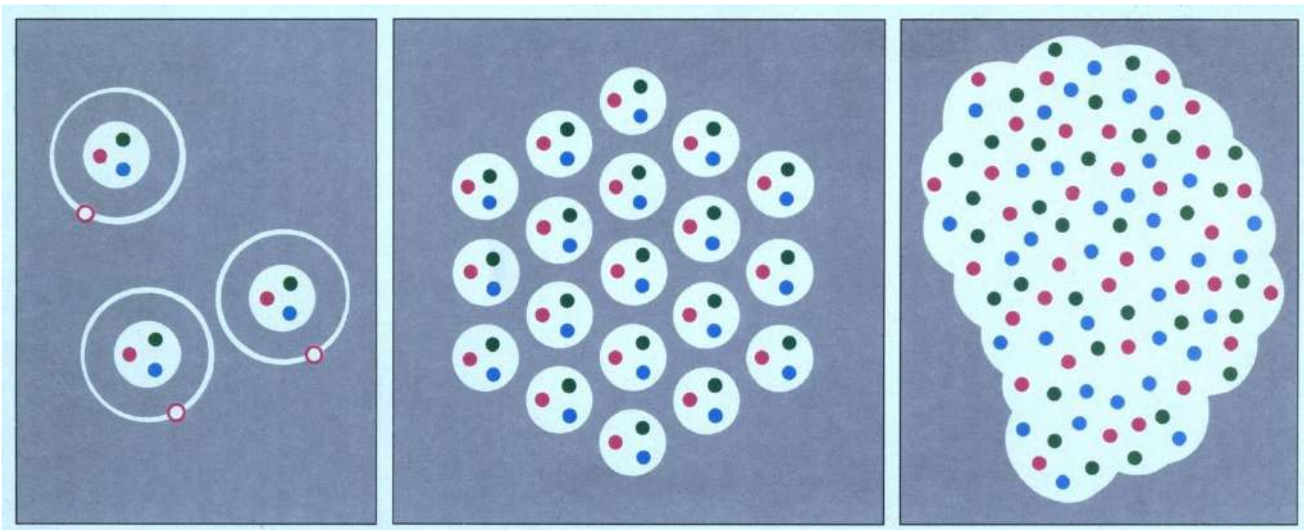
Hotter Hadron Gas



Hadron Gas

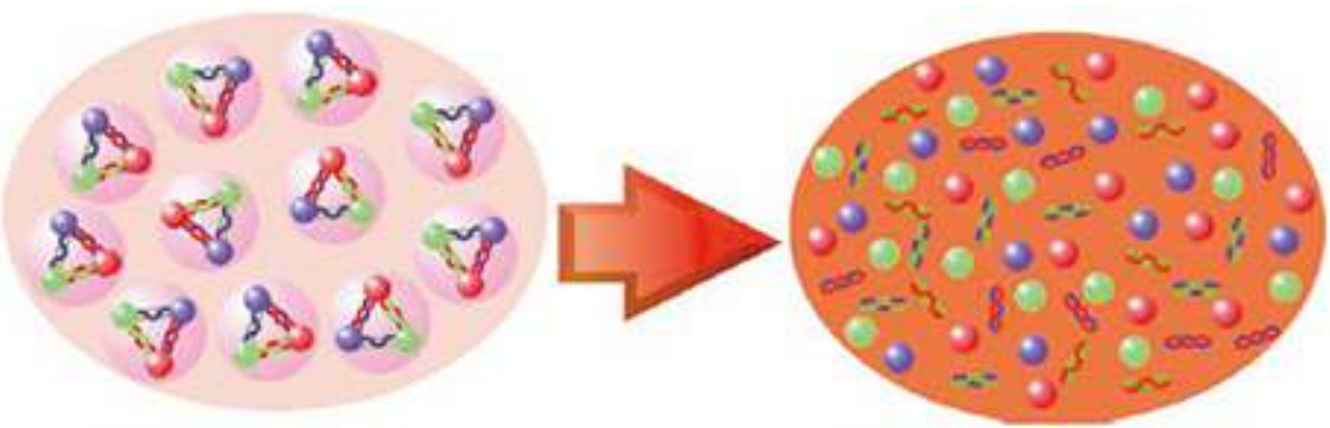
Even without QGP charmonium
is destroyed in the hadron gas (pions) !

We can compress matter and create a quark gluon plasma !



T = 0

Quarks are free to move everywhere



T > T_c

通常の核物質
クォークが核子に閉じ込められている。

QGPの状態
閉じ込めが破れてクォークとグルーオンが動き回っている。

Best explanation: “cocktail” with

-suppression of the primordial Psi’s

and

-regeneration in the QGP

Enhanced J/ψ production in deconfined quark matter

Robert L. Thews, Martin Schroedter, and Johann Rafelski
Department of Physics, University of Arizona, Tucson, Arizona 85721
(Received 29 August 2000; published 23 April 2001)

Phys. Rev. C (2001)

(Non) thermal aspects of charmonium production and a new look at J/ψ suppression ☆

P. Braun-Munzinger [a], J. Stachel [b]

[a] *Gesellschaft für Schwerionenforschung, D 64291 Darmstadt, Germany*
[b] *Physikalisches Institut der Universität Heidelberg, D 69120 Heidelberg, Germany*

Received 26 July 2000; accepted 17 August 2000
Editor: J.-P. Blaizot

Phys.. Lett. B (2000)

Thermal versus direct J/Ψ production in ultrarelativistic heavy-ion collisions

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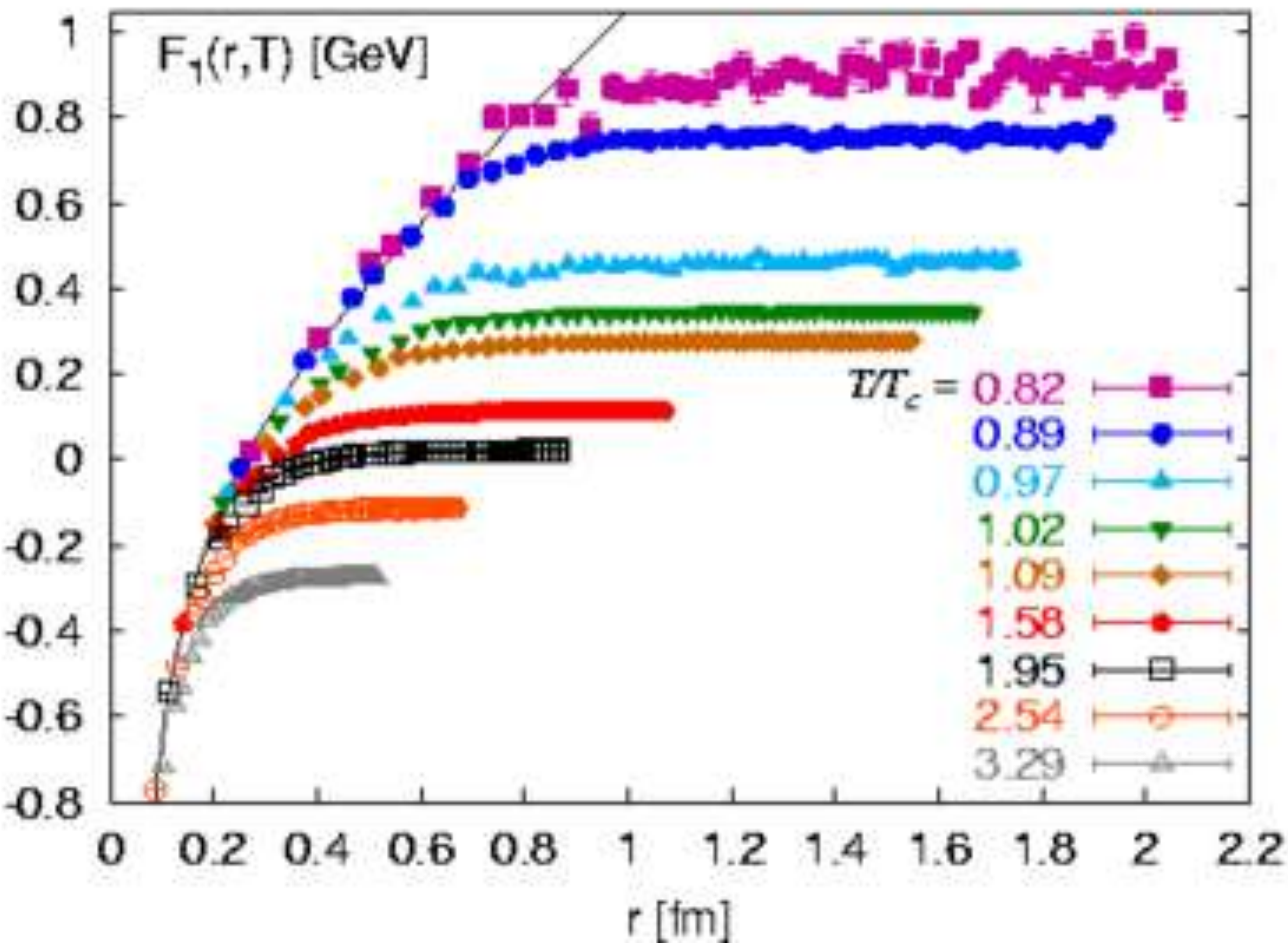
[a] *Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794-3800, USA*
[b] *IPN Lyon, IN2P3-CNRS et UCBL, 43 Bd. du 11 Novembre 1918, 69622 Villeurbanne Cedex, France*

Received 29 March 2001; received in revised form 19 June 2001; accepted 15 October 2001
Editor: J.-P. Blaizot

Phys. Lett. B (2001)

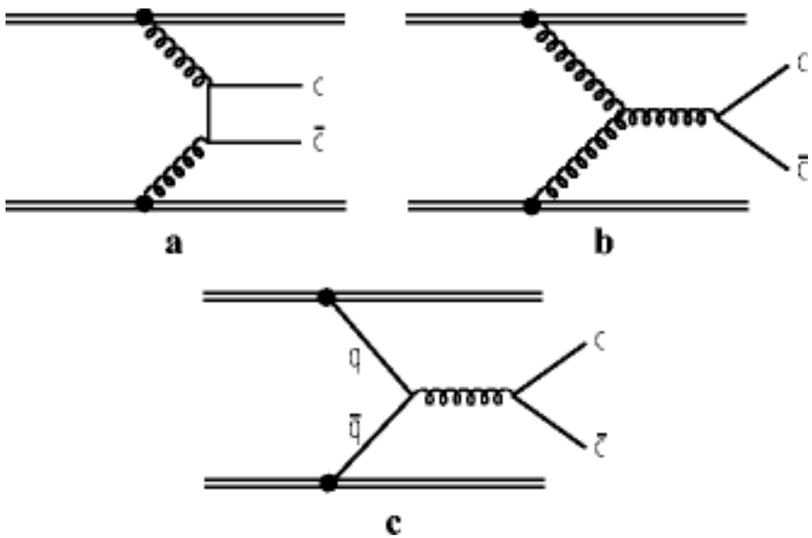
In a thermal bath

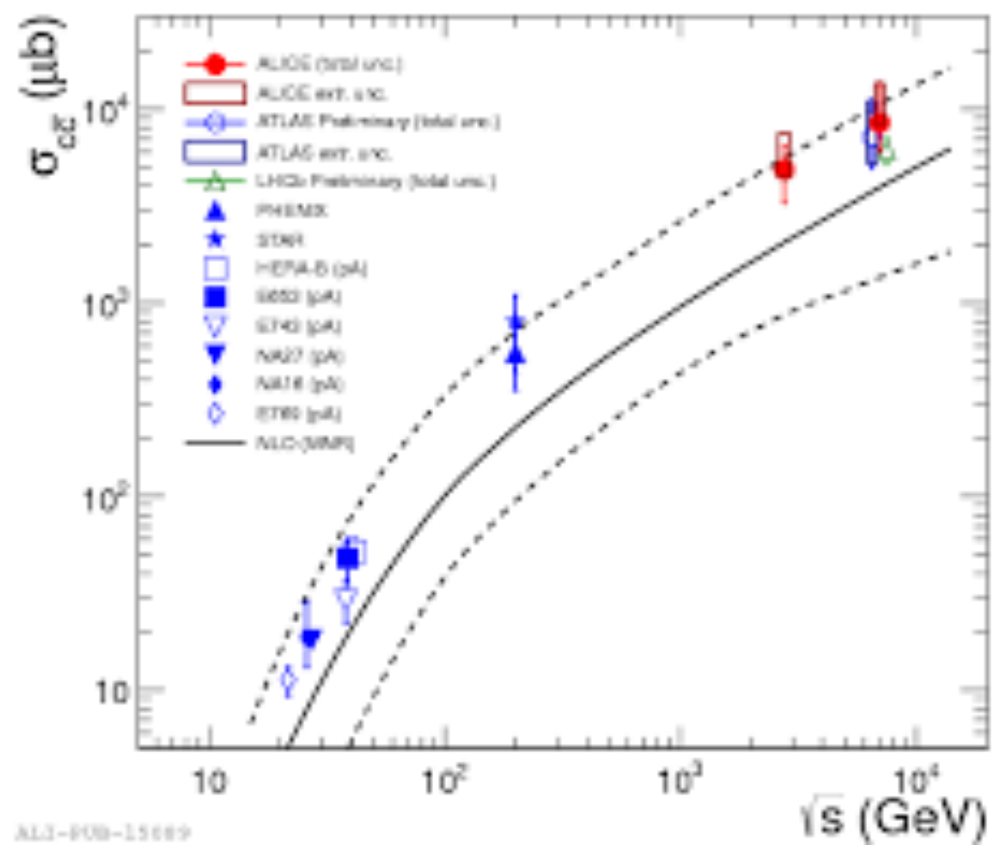
Deconfinement: quarks can be free



A real calculation in Lattice QCD

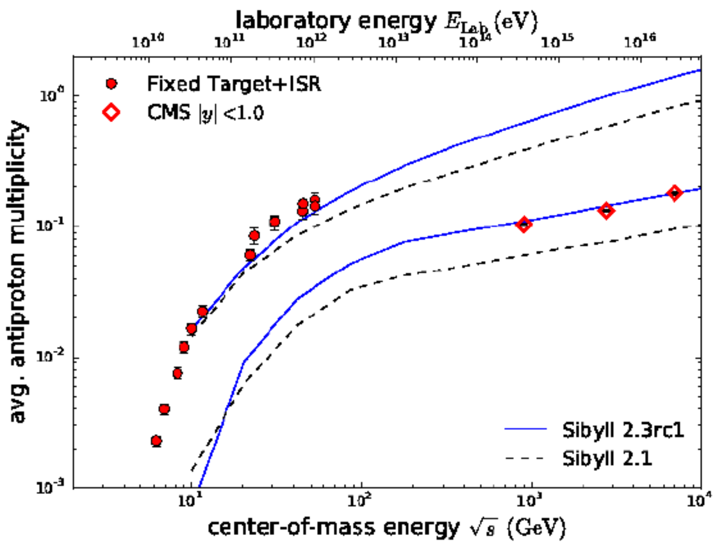
Charmonium production in proton-proton collisions

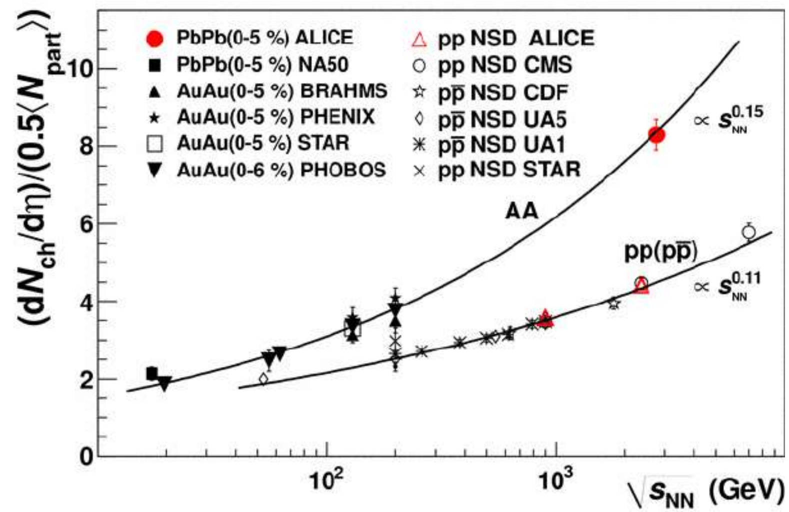


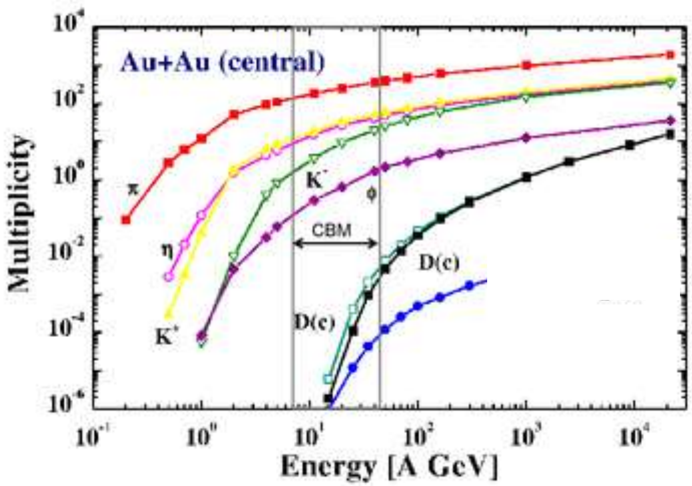


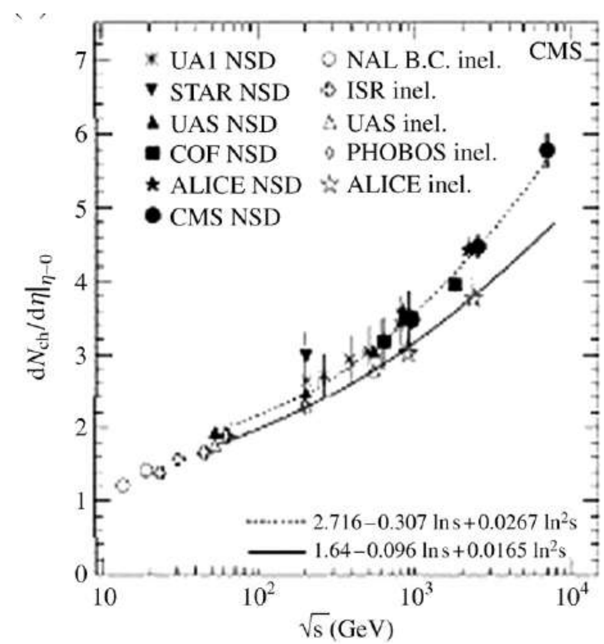
Higher energies
more charmonium !

In general: more energy, more particles









Sequential melting