Transport Study on Heavy Quarkonium Production as QGP Probe

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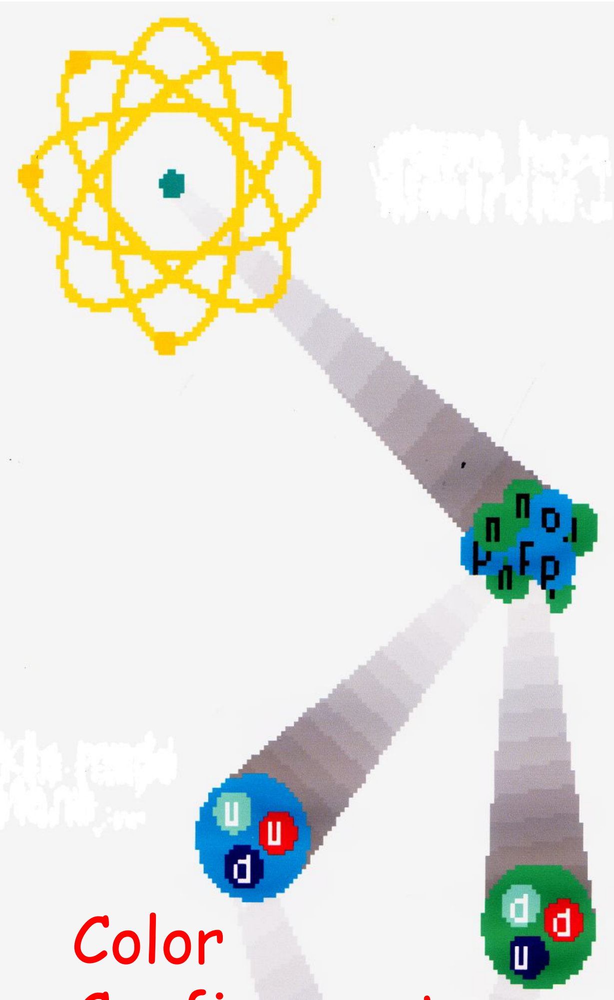
Tsinghua Group

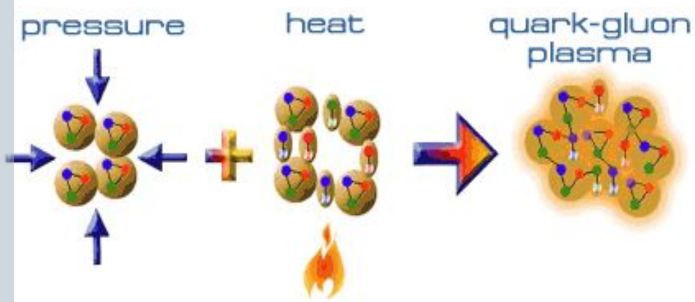
2 main directoins: phase transition and heavy ion collisions

物理 Deepest Structure and State

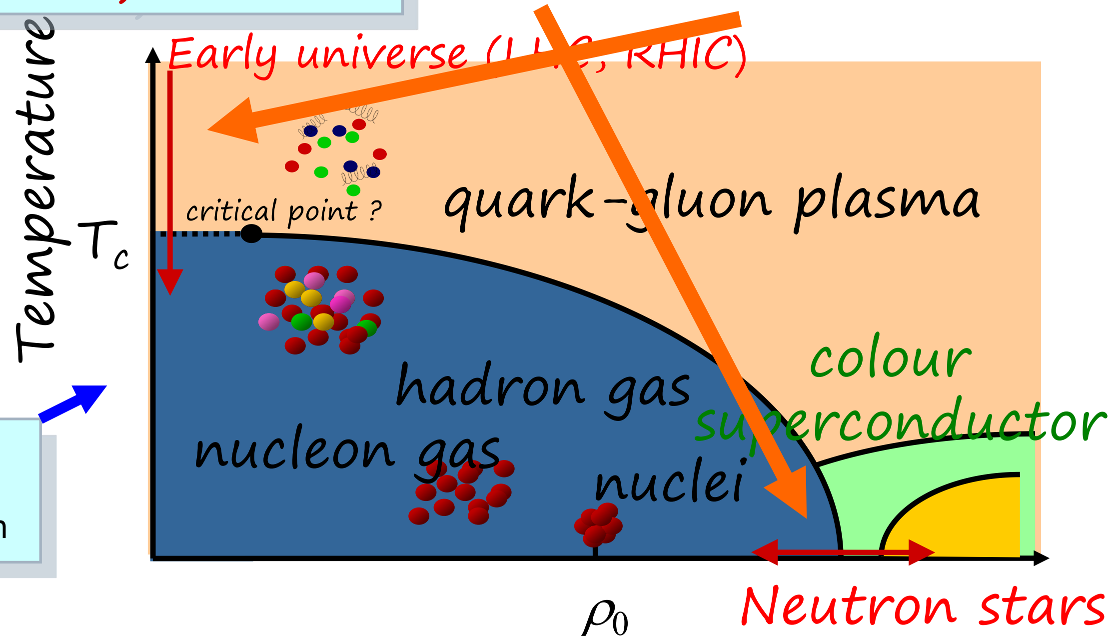


Color Confinement

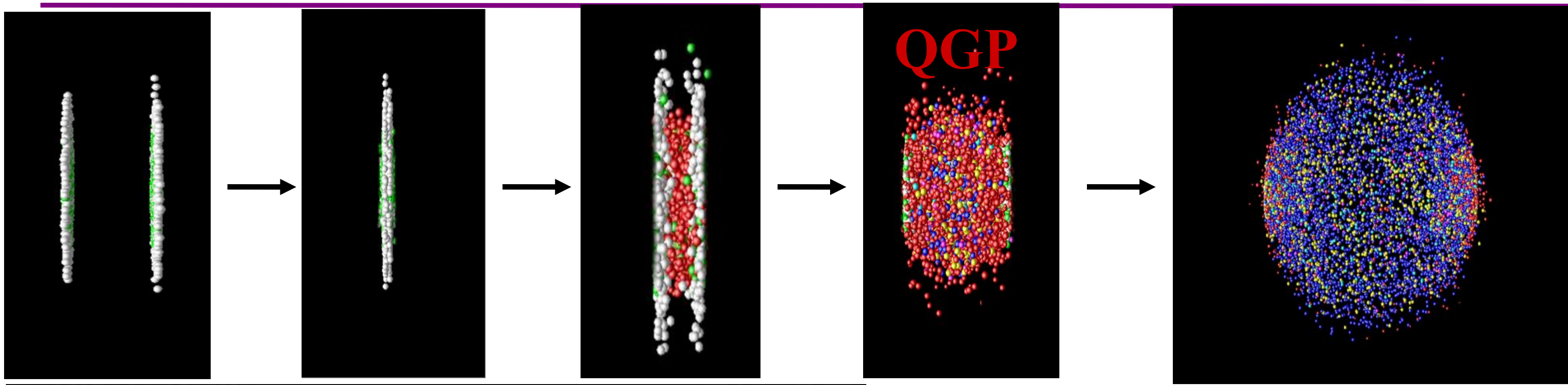
Thermal QCD predicts:
At high temperature or high density circumstances, quarks and gluons will be liberated from hadrons to form a new state of matter: QGP (Quark Gluon Plasma)

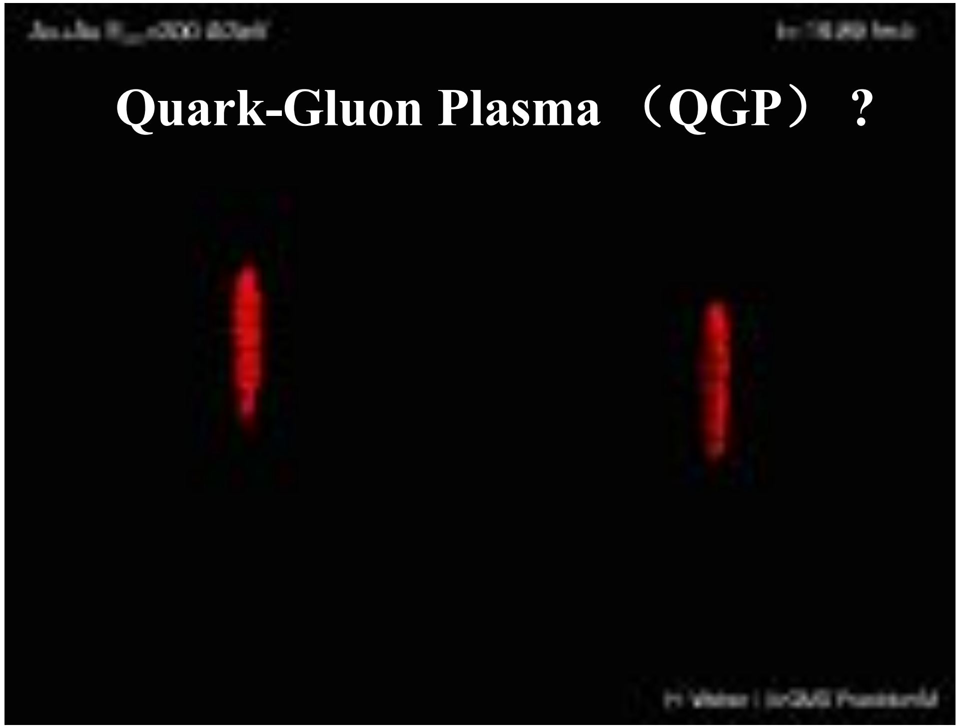


QCD Phase Diagram



Heavy Ion Collisions and QGP





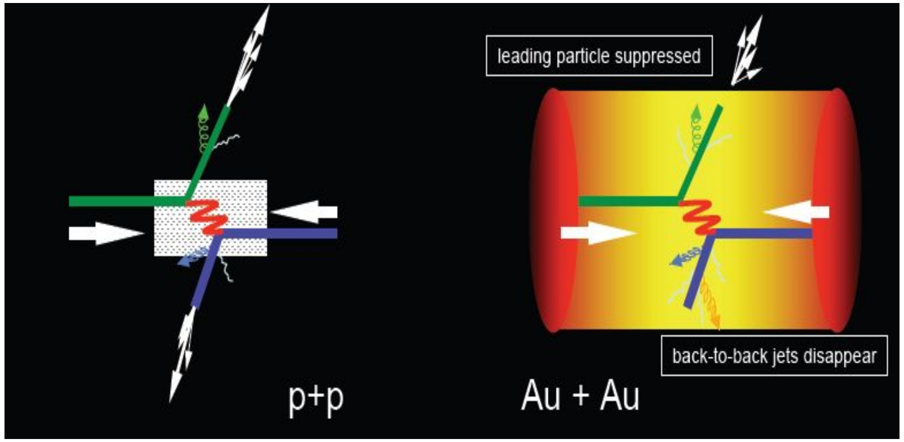
Heavy Ion Facilities:

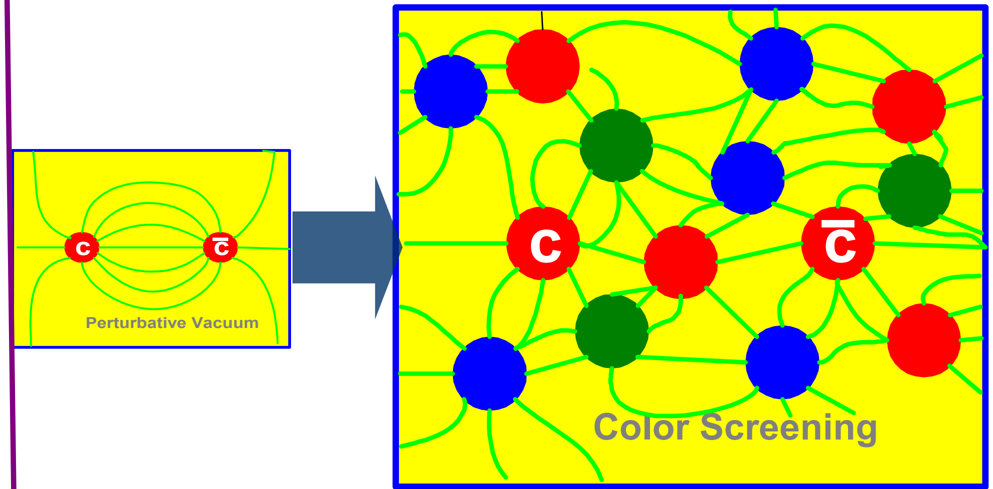
SPS/CERN :Pb-Pb@17.3 AGeV
RHIC/LBNL:Au-Au@200 AGeV
LHC/CERN :Pb-Pb@2760AGeV
5500AGeV

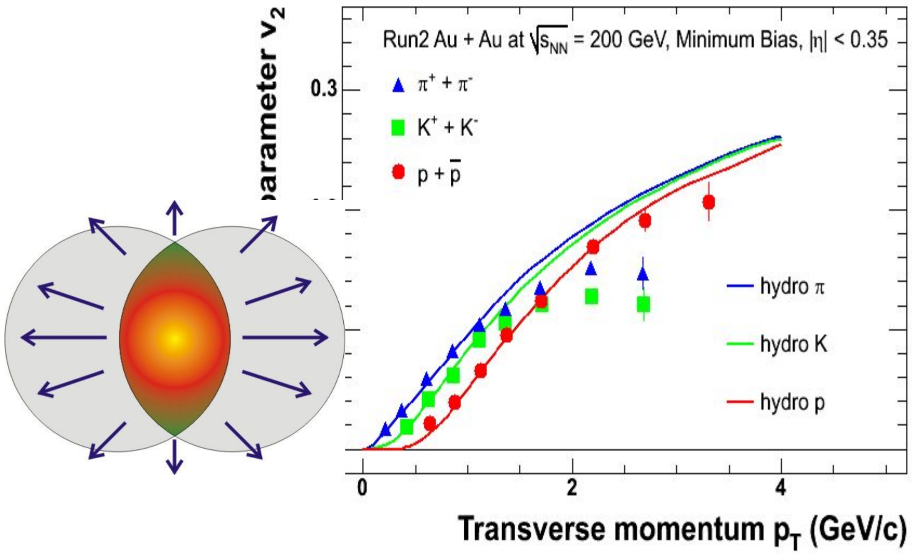
Problems:

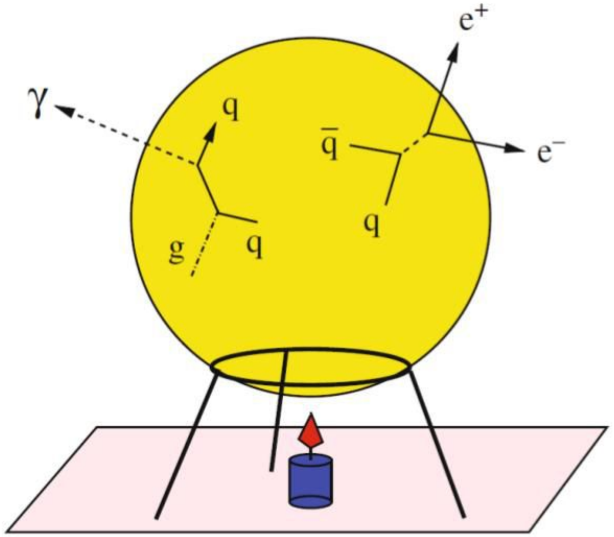
- QGP is short-lived !
- Only final hadrons/leptons

Observables and QGP signals





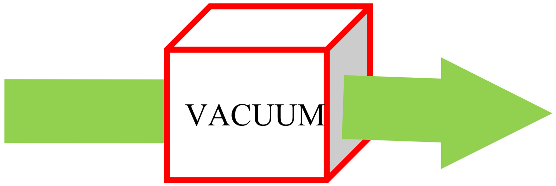




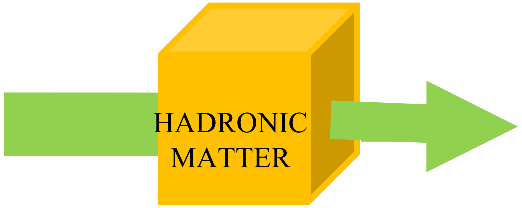
Intro— what's a good QGP probe?

Matsui and Satz: PLB178, 416(1986):
J/Psi suppression as a probe of QGP in HIC

- ❑ in Vacuum under control



- ❑ in Hadronic no(slightly) affected



- ❑ in QGP highly affected!

Intro— from Vacuum to Medium

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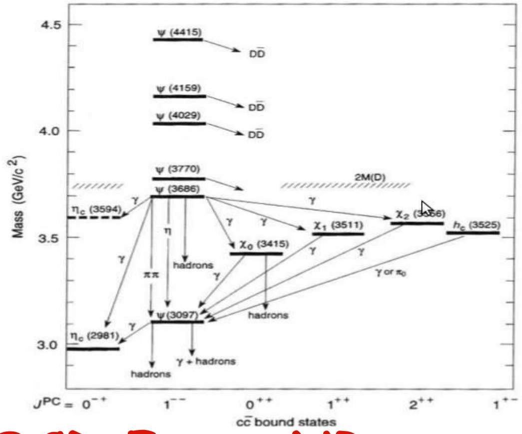
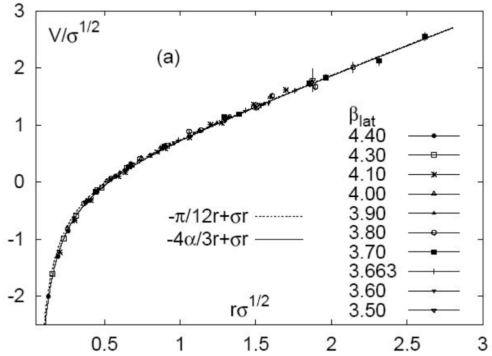
- **Heavy *Quarkonium*:** $q\bar{q}$ **mesons**

State	J/ψ (1S)	χ_c (1P)	ψ' (2S)
m (GeV/c^2)	3.10	3.53	3.68
r_0 (fm)	0.50	0.72	0.90

Υ (1S)	χ_b (1P)	Υ' (2S)	χ'_b (2P)	Υ'' (3S)
9.46	9.99	10.02	10.26	10.36
0.28	0.44	0.56	0.68	0.78



- ***Potential in Vacuum*** $m_c >> \Lambda_{QCD}$ **A Calibrated QCD Force:NR potentia**

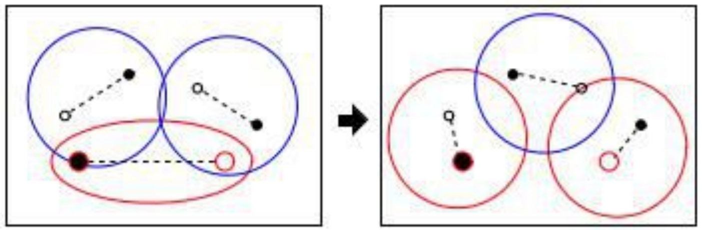


confining potential $V(r) = -\alpha_c / r + kr$

spectroscopy well described

(Effective Potential model; NRQCD...)

- ***Color Screening in QGP*** $1/k_g^2 \to 1/(k_g^2 - \mu_D^2)$



$$1/r \to e^{-\mu_D r} / r$$

$$r \to r(1 - e^{-\mu_D r}) / \mu_D r$$

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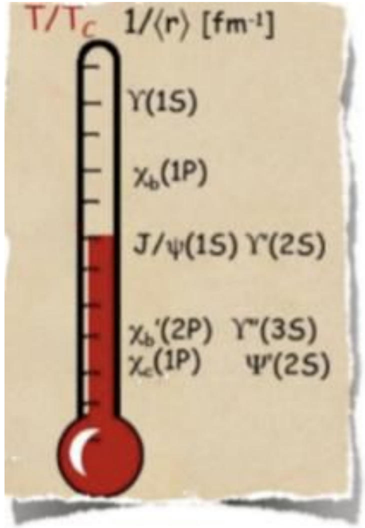
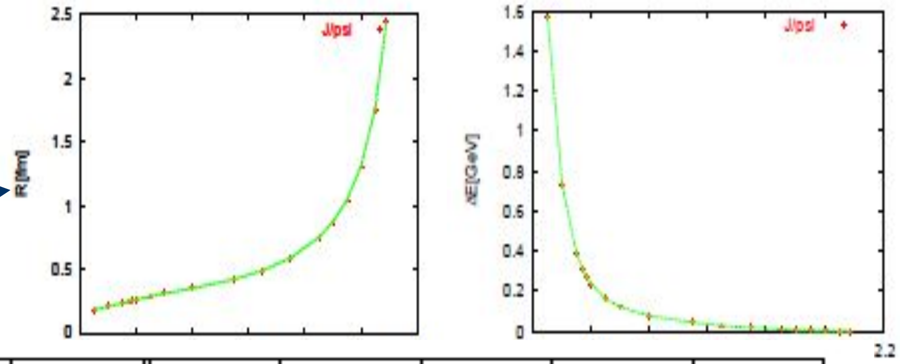
Intro— in-medium Modification

- **Dissociation :**

$$\langle r\rangle(T_D)\rightarrow\infty,\quad \varepsilon(T_D)\rightarrow 0$$

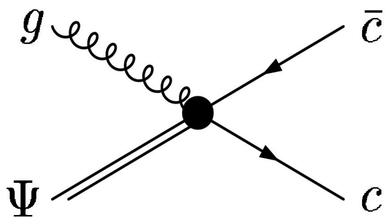
for V=U (Satz et al)





state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60	1.19	1.17

Dynamical realization:
(gluon dissociation)



- **Observation :** $$R_{AA}=\frac{N^{AA}_{J/\psi}}{N_{coll}N^{pp}_{J/\psi}}\sim\frac{\text{"}QCD_{medium}\text{"}}{\text{"}QCD_{vacuum}\text{"}}\begin{cases}=1 & \text{No medium effect}\\ <1 & \text{Suppression}\\ >1 & \text{Enhancement}\end{cases}$$

Intro— Our Motivation

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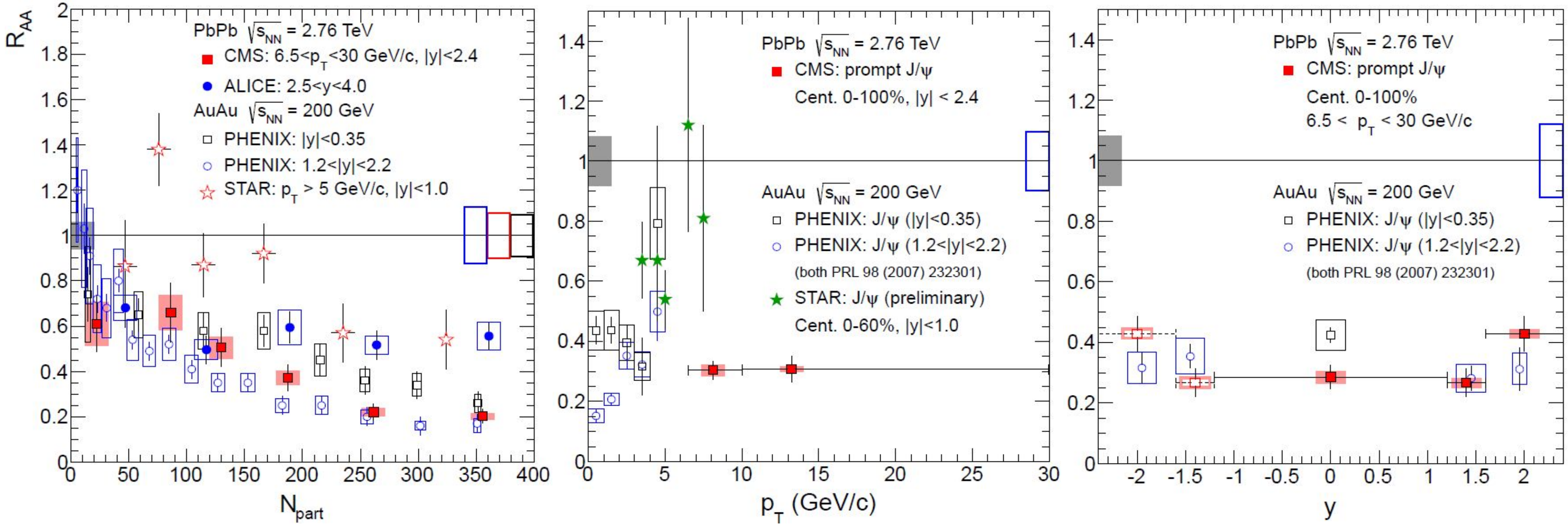
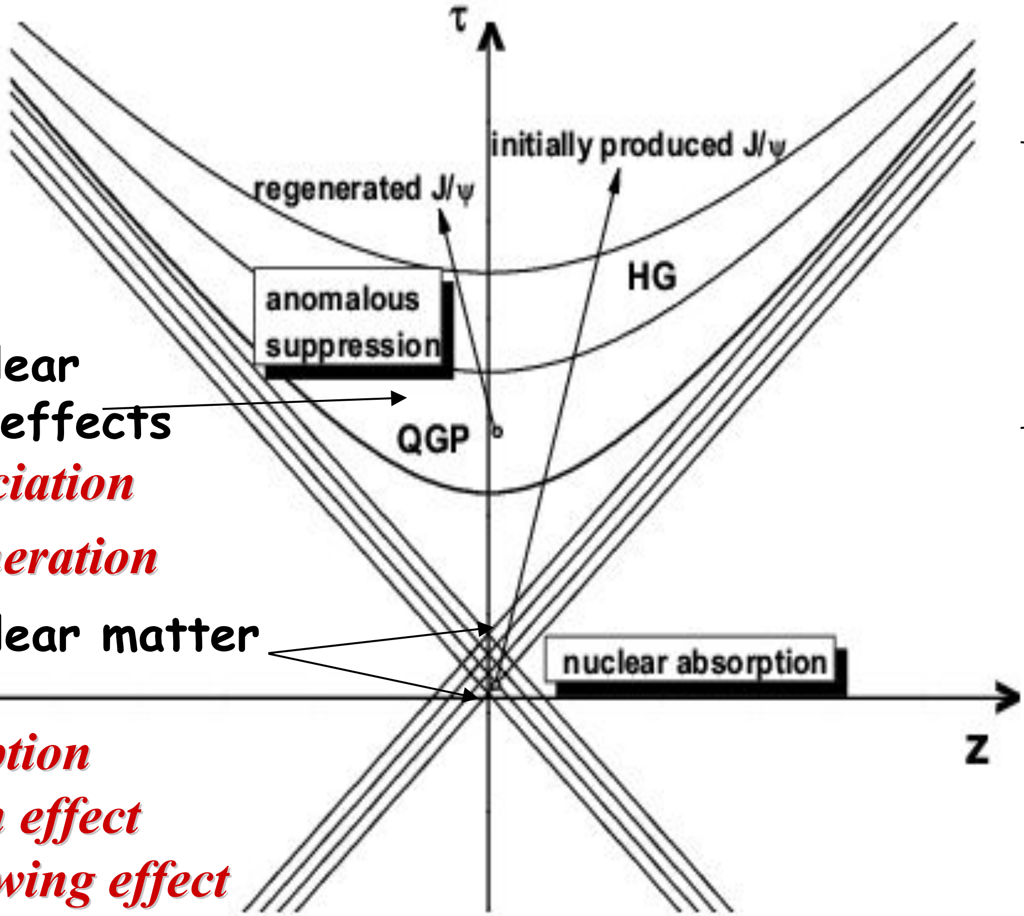
Now, from SPS to RHIC, we are at LHC era



- ***Unifed model including interplay of Cold and Hot matter effects***
- ***With increasing coll.energy, Hot medium effects increase? where?***

Our Model: Transport(cold&hot) + Hydrodynamic



hot nuclear matter effects

1)Dissociation

2)Regeneration

Transport Equation for Jpsi

cold nuclear matter effects

1)Absorption

2)Cronin effect

3)Shadowing effect

Hydrodynamic Evolution for the medium

Hot Nulcear Matter Effects

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- **quarkonium distribution function in phase space** $f_\psi(\vec{p},\vec{x},t)$

$$\left(\partial_\tau+\vec{v}_t\cdot\vec{\nabla}_t\right)f_\psi(\tau,\vec{x}_t,\vec{p}_t)=-\alpha\cdot f_\psi(\tau,\vec{x}_t,\vec{p}_t)+\beta$$

$$g+\Psi\leftrightarrow Q+\overline{Q}$$

$$\underrightarrow{\alpha}\qquad\qquad \underleftarrow{\beta}$$

$$1/(e^{p_g^\mu u_\mu/T}-1)$$

Hot Effect

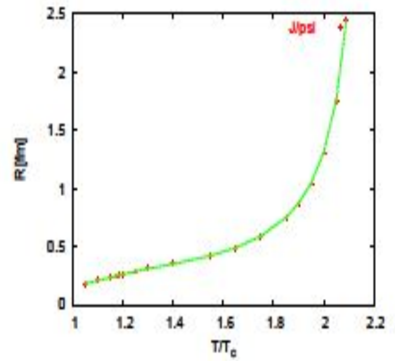
$$\begin{cases}\alpha=\dfrac{1}{2m_t}\displaystyle\int\dfrac{d^3\vec{k}}{(2\pi)^3 2E_g}\sigma_{g\Psi}\cdot 4F_{g\Psi}f_g(k,x)\\[2ex]\beta=\dfrac{1}{2m_t}\displaystyle\int\dfrac{d^3\vec{k}}{(2\pi)^3 2E_g}\dfrac{d^3\vec{q}_1}{(2\pi)^3 2E_Q}\dfrac{d^3\vec{q}_2}{(2\pi)^3 2E_{\overline{Q}}}(2\pi)^4\delta^4(p+k-q_1-q_2)W_{pro}(s)f_Q(k,x)f_{\overline{Q}}(k,x)\end{cases}$$

gluon dissociation cross section by OPE (Peskin,1999)

regeneration by detailed balance !

$$\sigma_{g\Psi}(T)=\sigma_{g\Psi}(T=0)\frac{<r_\Psi{}^2>(T)}{<r_\Psi{}^2>(T=0)}$$

from Potential Model:



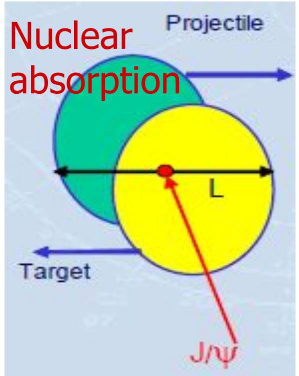
Cold Nuclear Matter Effects

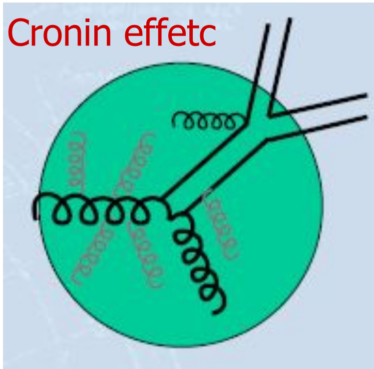
- **initial condition** $f(\vec{p},\vec{x},t_0)$ **for transport**

Superposition from pp collisions (Glauber model) along with modification from CNM:

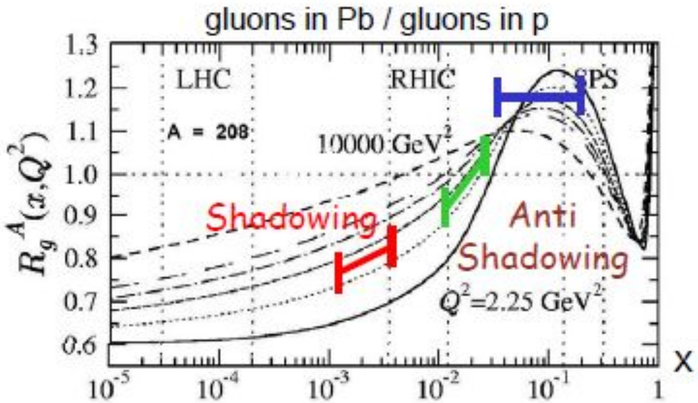
Cold Effects

- ***Absorption***
- ***Cronin***
- ***Shadowing***





nPDF vs. PDF



Cold 1——Absorption & Cronin effect

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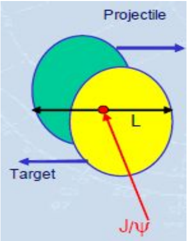
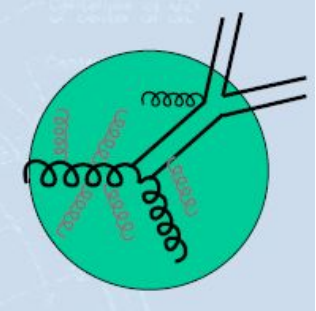


Absorption $\times \quad e^{-\sigma_{abs}\left(T_A(\vec{x}_t, z_A, +\infty)+T_B(\vec{x}_t-\vec{b}, -\infty, z_B)\right)}$

$t_{coll} << t_{\Psi}$ (so at LHC can safly be neglected)



Cronin pT broadening (use Gaussian smearing)

$$\bar{f}_{pp}(\vec{p}_T, \vec{x}_T, z_A, z_B) = \frac{1}{\pi a_{gN} \cdot l(\vec{x}_T, z_A, z_B)} \int d^2 \vec{p}_T^{\,'} e^{-\frac{p_T^{'2}}{a_{gN} \cdot l(\vec{x}_T, z_A, z_B)}} f_{pp}(|\vec{p}_T - \vec{p}_T^{\,'}|)$$

$a_{gN} = \Delta^2(\mu)\sigma_{pp}^{inelasitic}\rho_0$ $\qquad a_{gN} = 0.15 GeV^2/c^2$ @ LHC Pb-Pb 2.76TeV

Init.J.Mod.Phys.E.12,211(2003)
Phys.Rev. C 73, 014904(2006)

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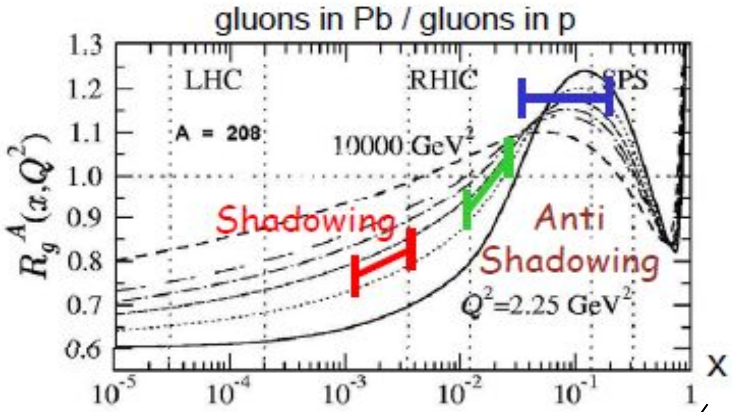
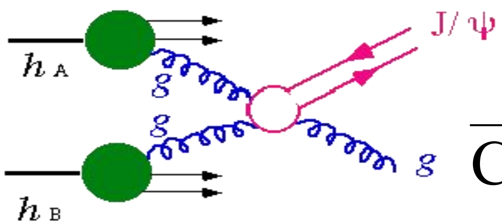
Shadowing $R_g^A(x,\mu_F) = \frac{f_g^A(x,\mu_F)}{Af_g^{Nucleon}(x,\mu_F)}$

for open & hiden heavy mesons





(2->1)process

Color Evaporation Model

$$x_{1,2}^g = \frac{\sqrt{m_{c\bar{c}}^2 + p_T^2}}{\sqrt{s_{NN}}} e^{\pm y}$$

pp

$$\frac{d\sigma_{pp}^\psi}{dp_T^\psi dy_\psi} = \int dy_g x_1 x_2 \cdot f_g(x_1,\mu_F) f_g(x_2,\mu_F) \frac{d\sigma_{gg\to\psi g}}{dt}$$

AA

$$f_0(\vec{p},\vec{x}_T) = \frac{(2\pi)^3}{E_T^\Psi \cosh y_\Psi} \frac{d\sigma_{pp}^\Psi}{dy} \int dz_A dz_B \rho_A(\vec{x}_T, z_A) \cdot \rho_B(\vec{x}_T - \vec{b}, z_b) \mathcal{R}_g(\vec{x}_T, x_1, \mu_f) \cdot \mathcal{R}_g(\vec{x}_T - \vec{b}, x_2, \mu_f) \bar{f}_{pp}(\vec{p}_T, \vec{x}_T, z_A, z_B)$$

$$\mathcal{R}_g(\vec{x}_T, x, \mu_f) = 1 + N_{A,\rho}[R_g^A(x,\mu_f) - 1] \frac{T_A(\vec{x}_T)}{T_A(0)}$$

R.Vogt et al. PRL91 (2003) 142301.
PRC71(2005) 054902

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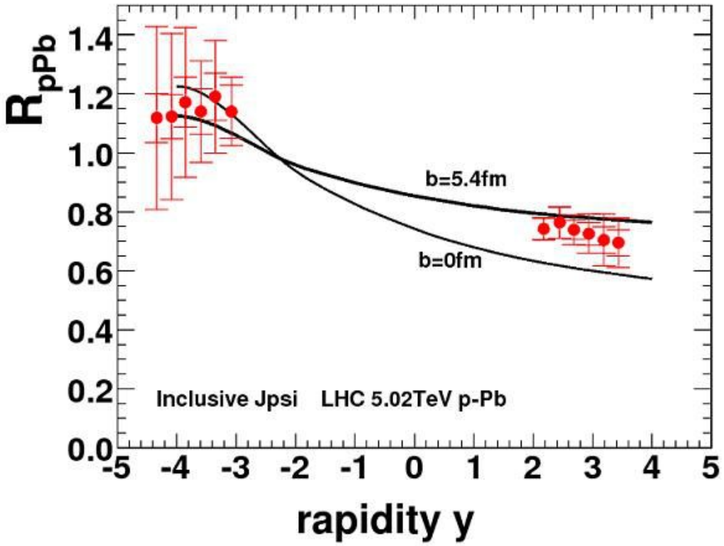
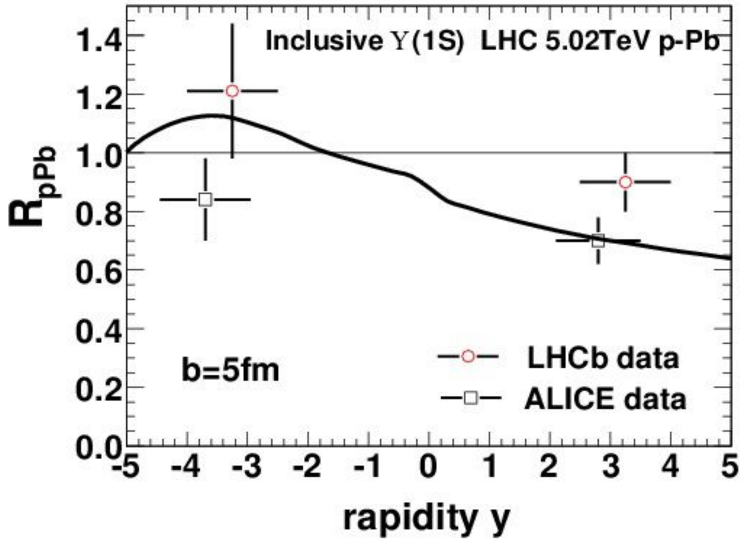
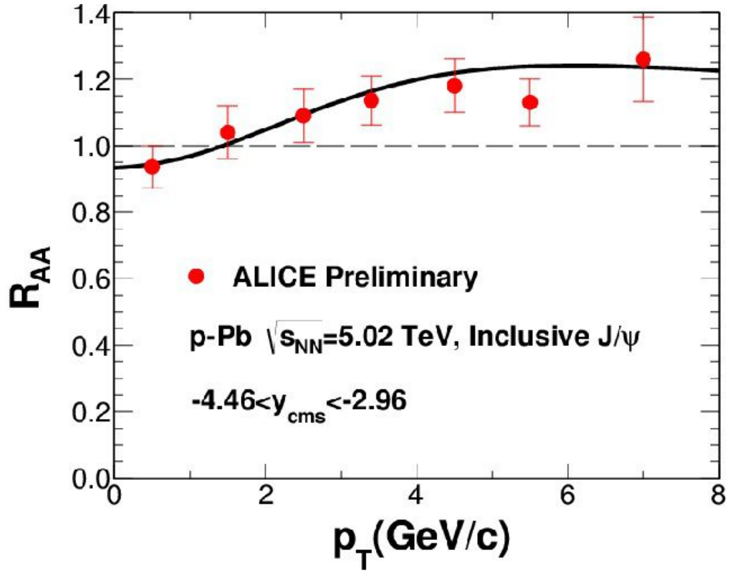
Test: Cold effects in p-Pb Collisions







Cronin + Shadowing(EKS98) can describe the p-Pb data well !

Ideal Hydrodynamics

● **2+1D hydrodynamics($\mu_B = 0$)**

$$\partial_\tau \rho_T + \nabla_T \cdot (\rho_T \vec{v}_T) = 0 \quad (\rho_T(\vec{x}_T, \tau) = \tau \cdot n_{c\bar{c}}^{Lab})$$

← ***heavy quark thermalization***

$$\partial_\tau E + \nabla_T \cdot \vec{M}_T = -(E+p)/\tau$$

$$\partial_\tau M_x + \nabla_T \cdot (M_x \vec{v}_T) = -M_x/\tau - \partial_x p$$

$$\partial_\tau M_y + \nabla_T \cdot (M_y \vec{v}_T) = -M_y/\tau - \partial_y p$$

← $\partial_\mu T^{\mu\nu} = 0$, ***Boost Invariance***

$$E = (\varepsilon + p)\gamma^2 - p \qquad \vec{M} = (\varepsilon + p)\gamma^2 \vec{v}$$

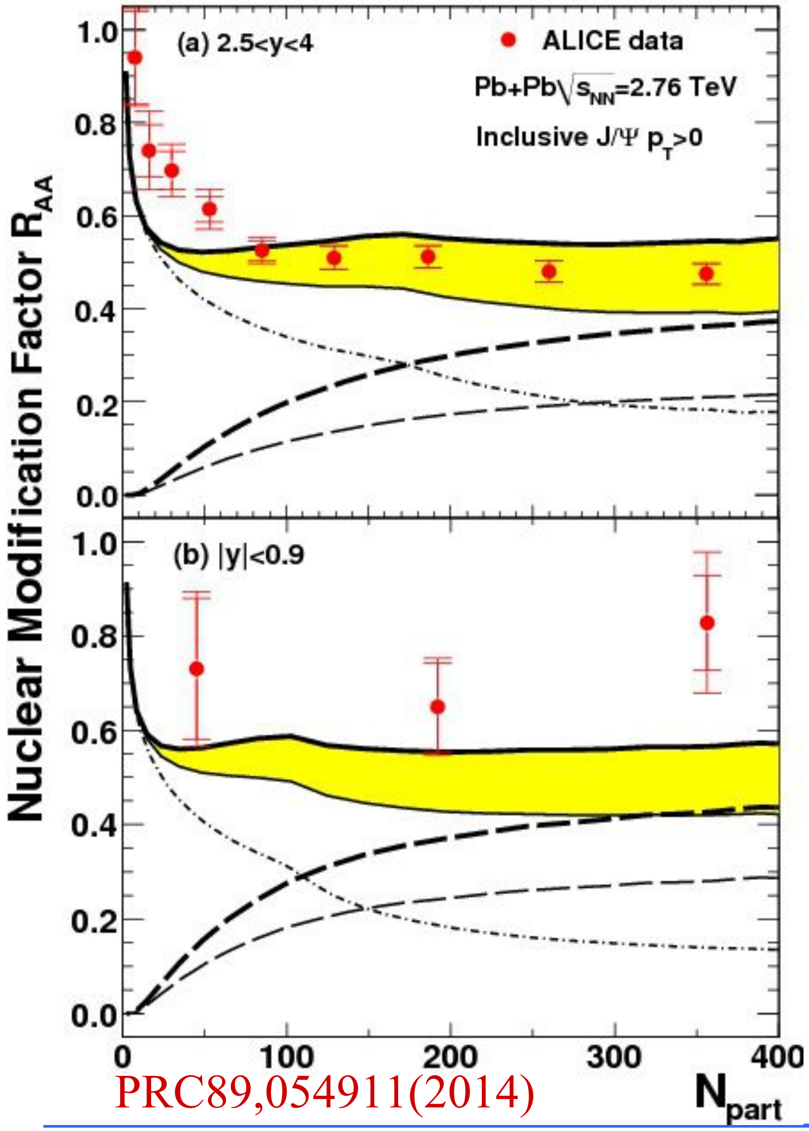
● **Equation Of State:**

Ideal Gas with quarks and gluons for QGP & HRG

● **Initialization:**

Glauber model & constrained by fitting Charged Multiplicities
and also from other well tested hydro study

Results—Yield's Centrality depen. (all pT)



PRC89,054911(2014)

1、Being different from low energy case(SPS,RHIC), Regeneration play an important roll in most of centralities, and can be dominant in mid-rapidity.

2、Competition between Regeneration and Suppression of initial production leads to platform structure in most centralities.

3、In mid-rapidity, at most central collisions, model results are lower than measurment, due to possible thermal charm production.

Results—Yield's Centrality depen. (pT bin)

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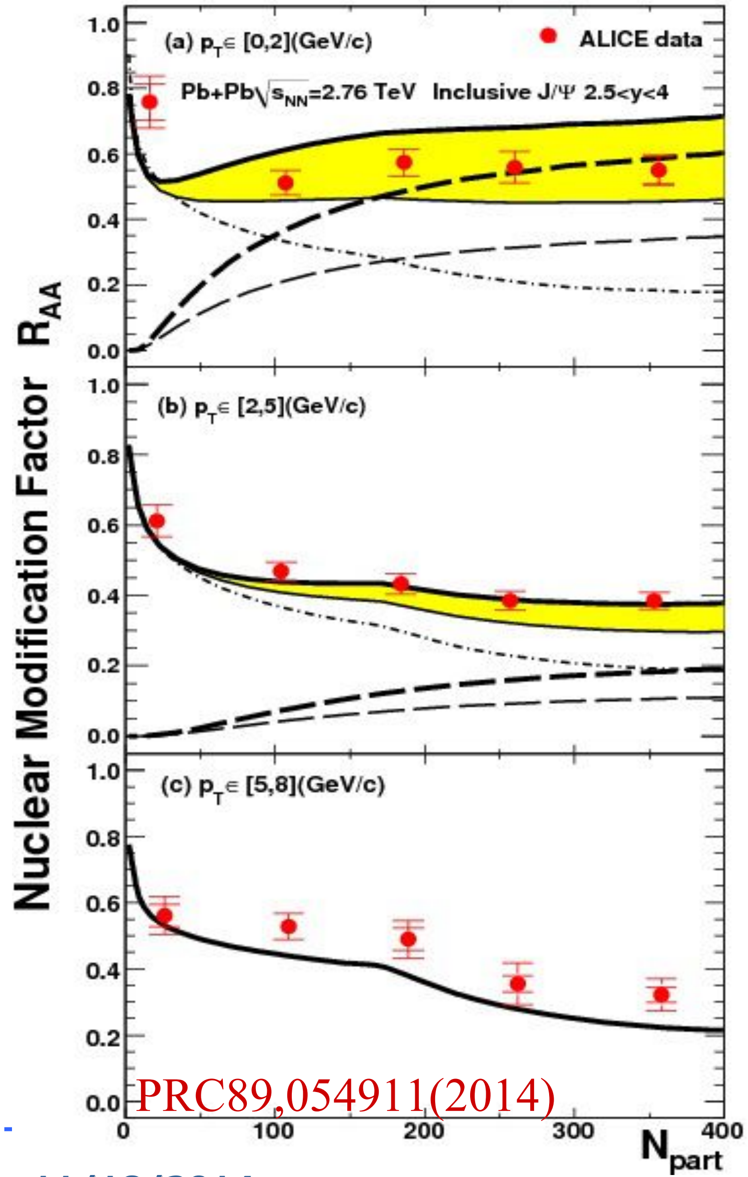

PRC89,054911(2014)

Forward Rapidity

1、Regeneration are mostly contributed in low pT part.

2、Jpsi naturally provide two probes:

a） Hard Probe: high pT, Color Screen

b） Soft Probe: low pT, Thermalization

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Results—Yield's Centrality depen. (pT bin)

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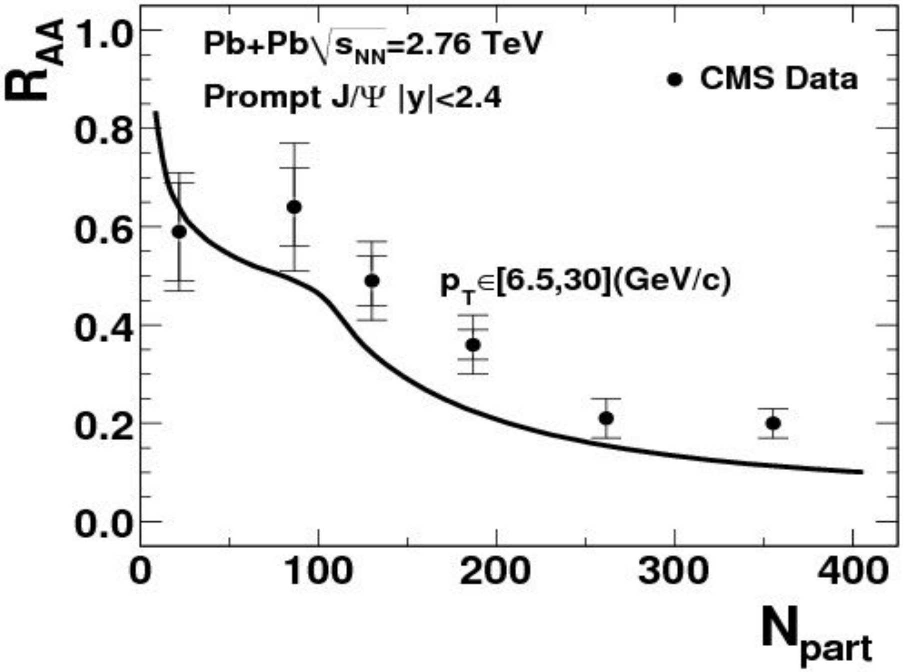
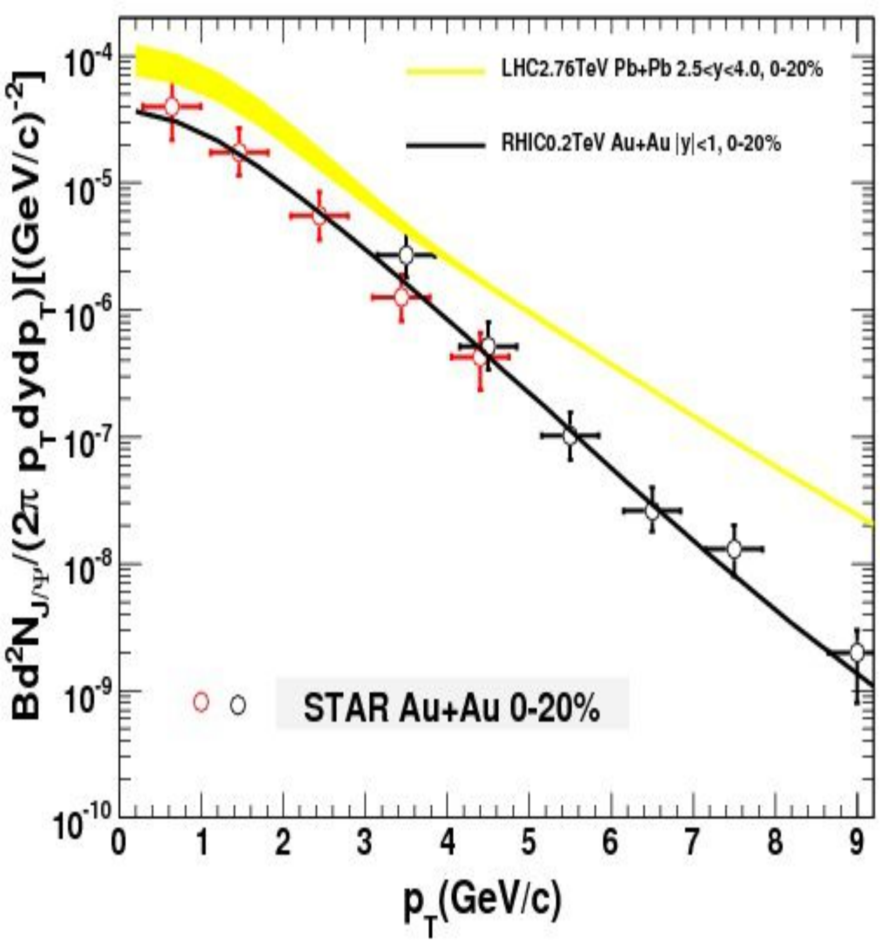
<u>Mid-Rapidity</u>



PRC89,054911(2014)

Note the "kink"----
Melting Tempereature from
Color Screening

Results—Momentum distribution



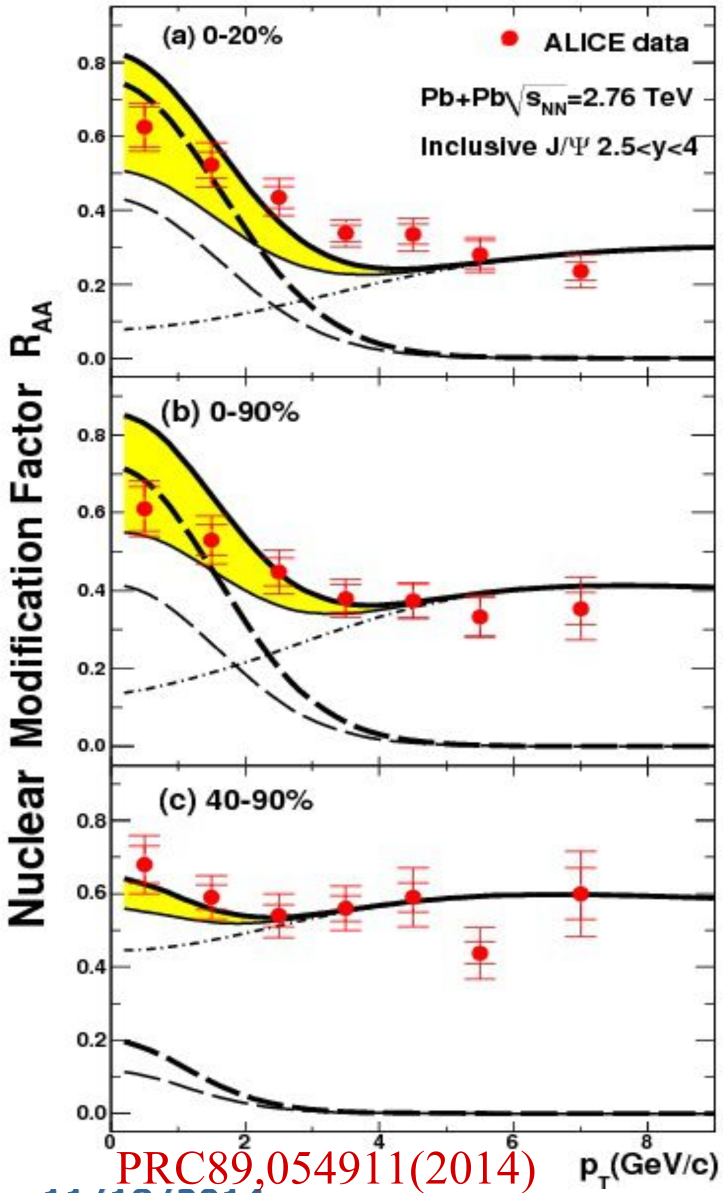
JPG as Review

1、Model results for RHIC agrees well with data。

2、Spectrum itself can't reveal the nature of QGP and also heavy production mechanism。

3、Need to compare to pp, then one can highlight the medium's effect—>RAA。

Results—RAA(pT)



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Forward Rapidity

1、Obviously: Regeneration dominates low pT, Initial production controles high pT.

2、The Competition leads to: along with pT, it firstly decrease and then slightly increase or go to saturation.

3、The decrease behavior clearly indicates the in-medium regeneration mechanism, further the QGP existence.

Results—RAA(pT)

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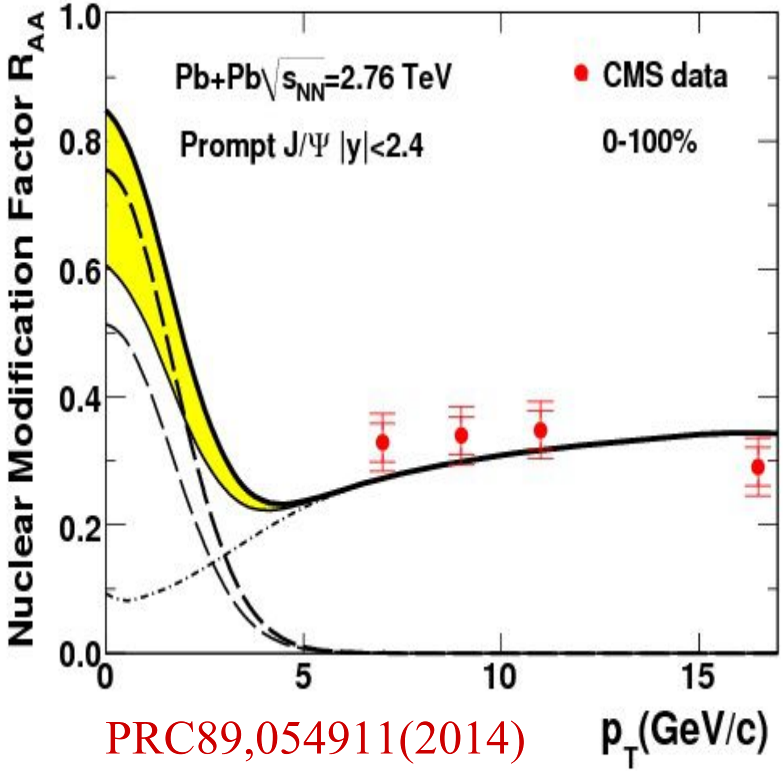

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Mid-Rapidity

"Valley" struture more clearly

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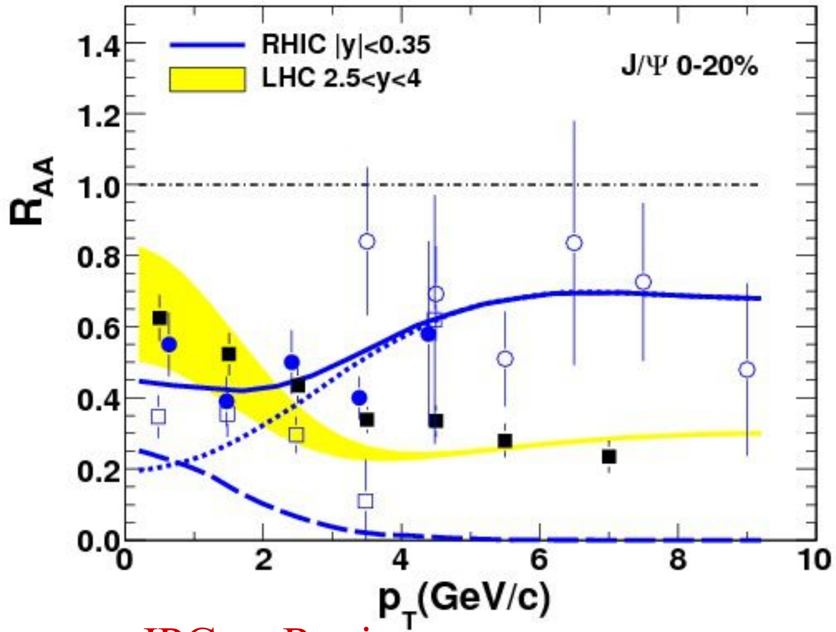
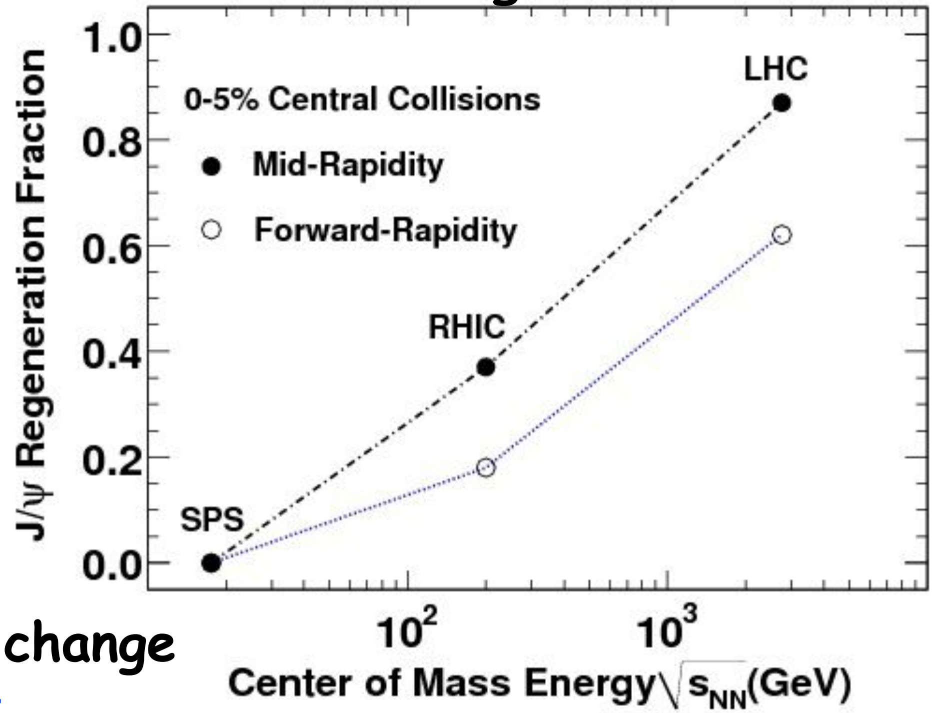
Results—different collision energy



JPG as Review

It can distinguish diff. medium at diff. energy, but for Experiment, since it's differential pT distribution, it's a little harder and need more statistics to get.



What's the most important?

Regeneration are more and more important and can take over initial production's role

quantity change leads to qualitative change

Results—Modification for Trans. pT: rAA

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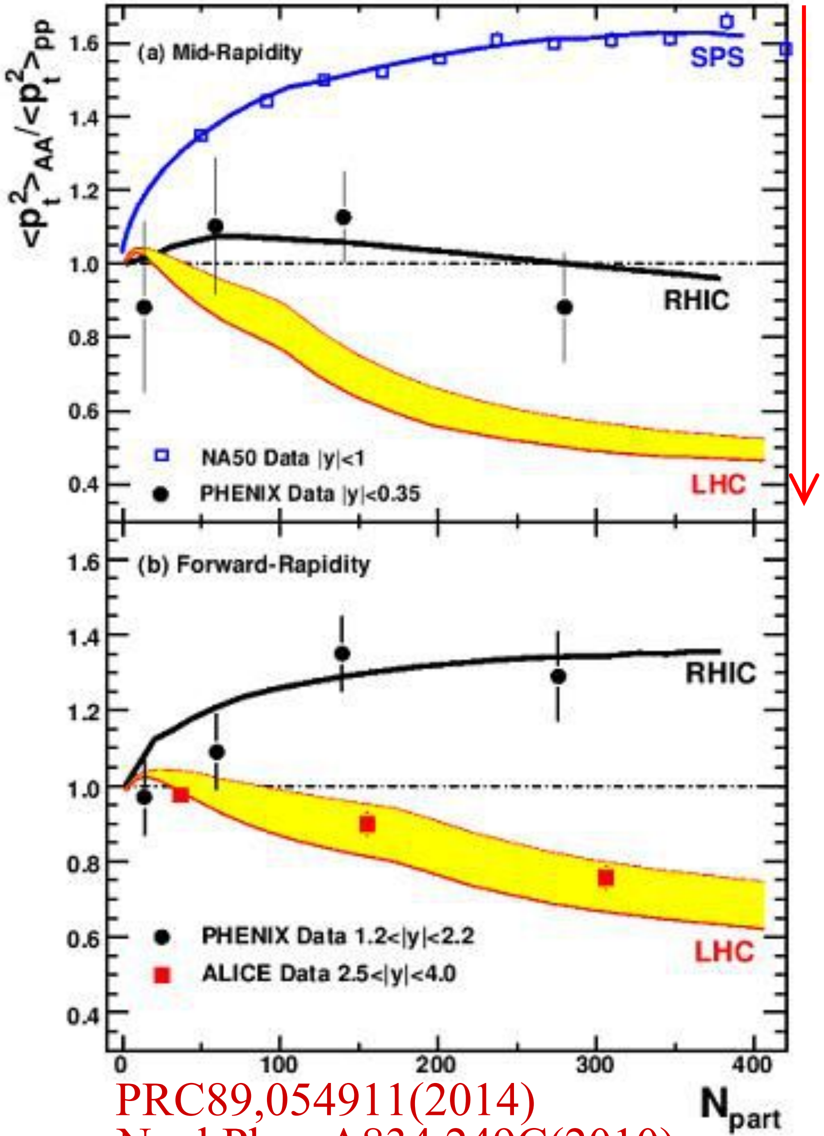

PRC89,054911(2014)
Nucl.Phys.A834,249C(2010)

$\sqrt{s_{NN}} \uparrow$

$QGP \uparrow$

$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

$$r_{AA} = f_{reg} \cdot r_{AA}(reg.) + (1 - f_{reg}) \cdot r_{AA}(init.)$$

a, rAA(reg.) <<rAA(init.)
b, QGP stronger-----f_reg larger.

1, compared to total yield, more sensitive to the ----the hot medium effects. it can indicate the production mechanism at play.

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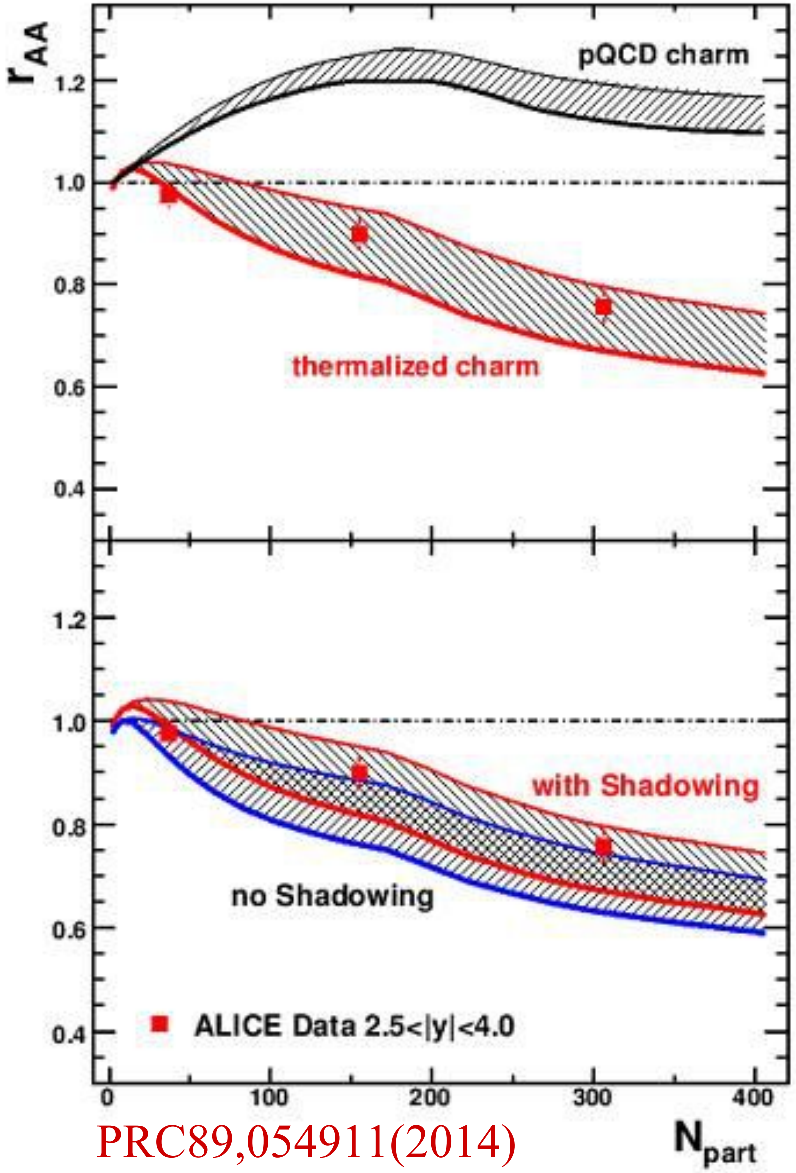
Results—Modification for Trans. pT: rAA



PRC89,054911(2014)

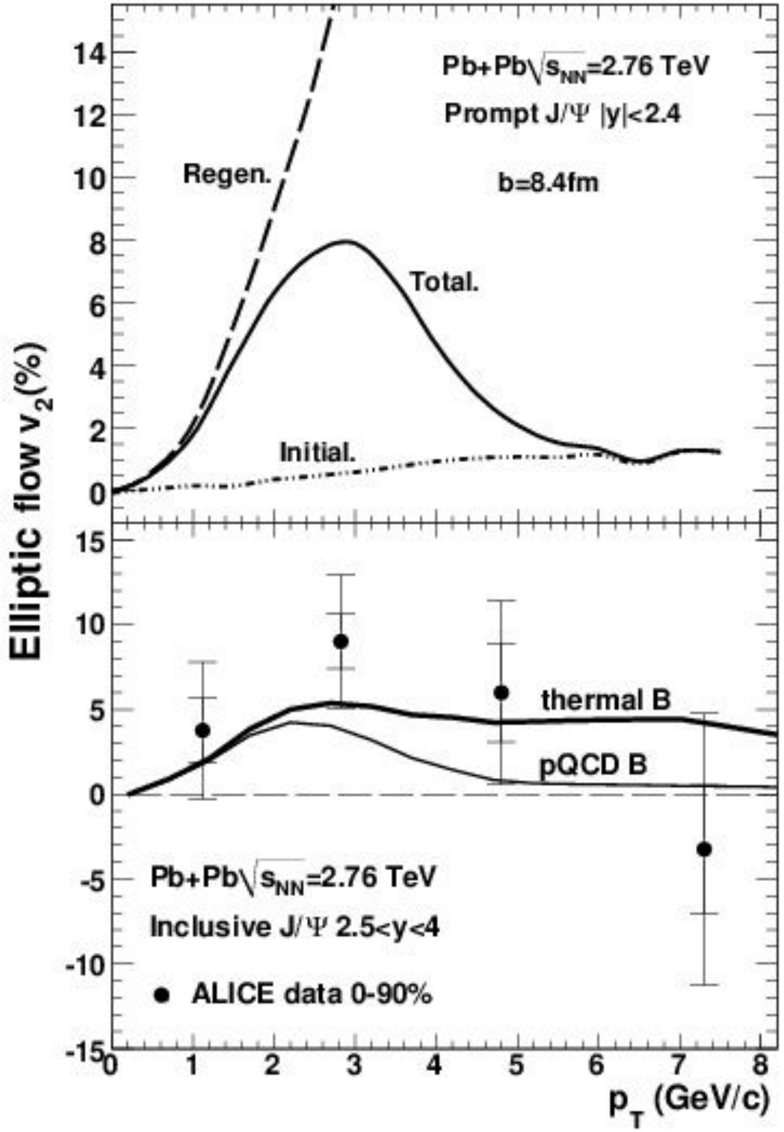
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

2, sensitive to the degree of heavy quark thermalization.

3, not sesitive to the cold nuclear matter effect------Shadowing effect.

clearly indicates QGP's medium effects

Results—Eilliptic flow v2



1, most v2 is from Regeneration since strong energy loss for heavy quark.

2, "Ridge"struture from two-component:

- hard (initial、jet)
- soft (regeneration、hydro)

3, v2 for high pT indicates B meson's thermalization

PRC89,054911(2014)

Results—Bottomonium differsV=U or V=F

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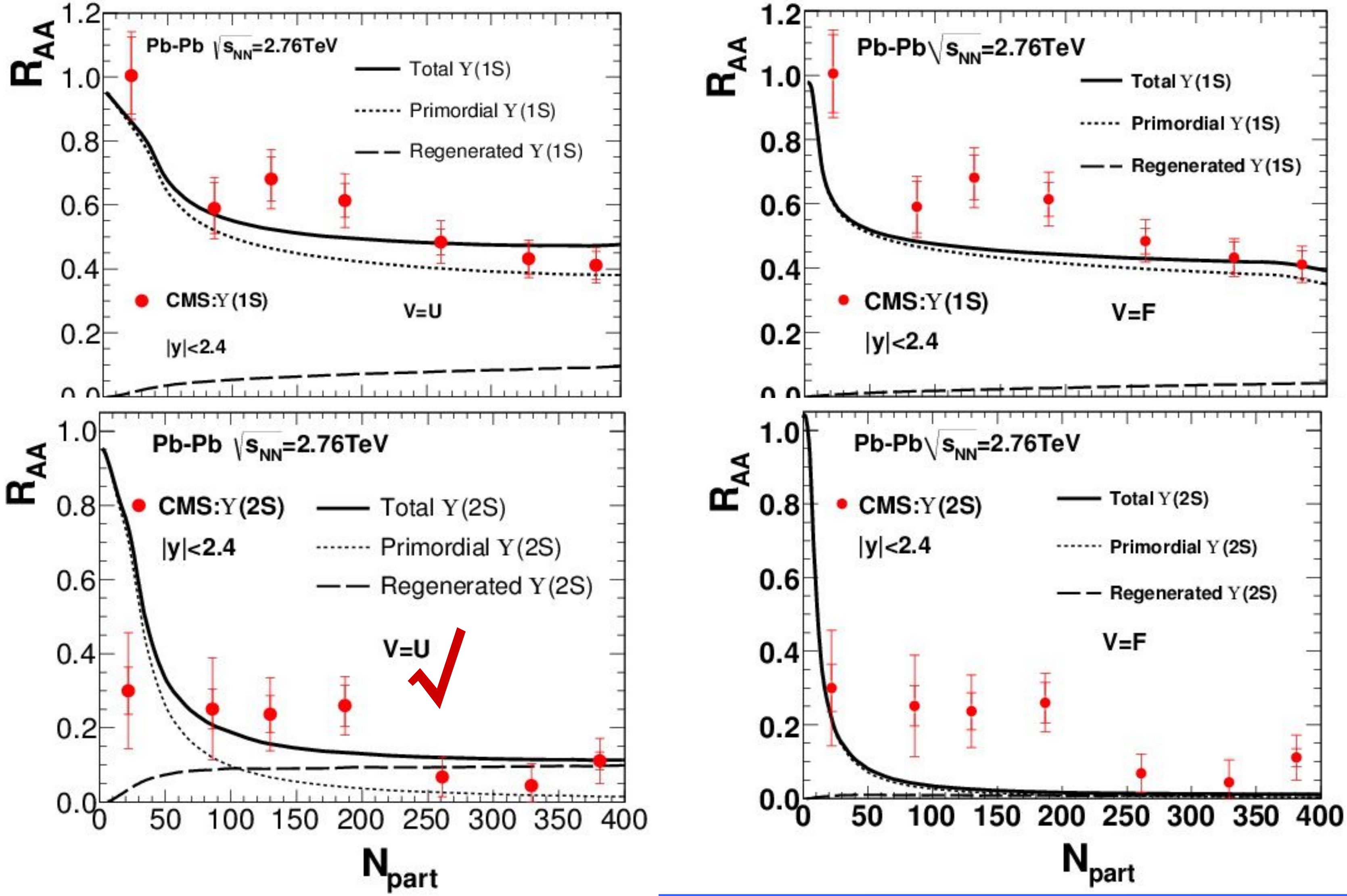

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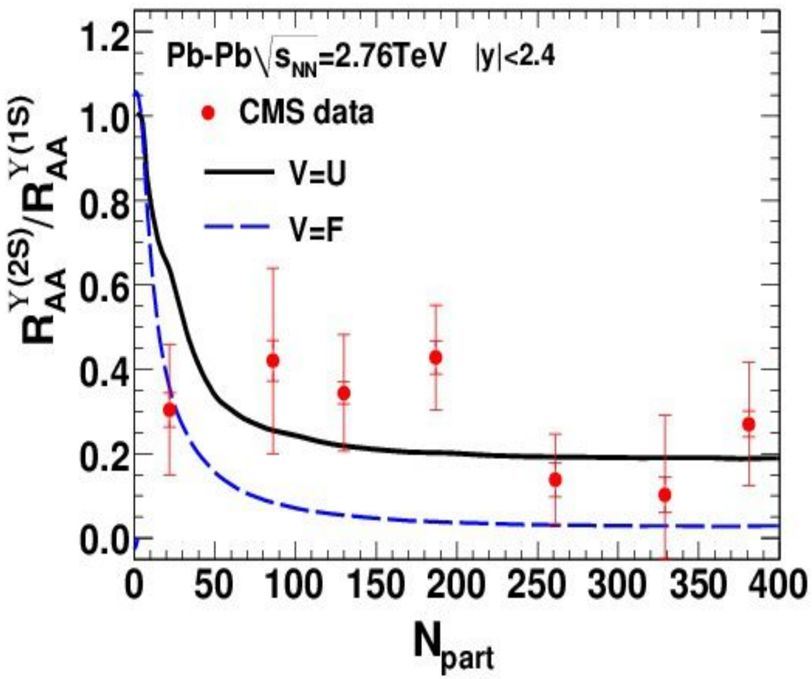
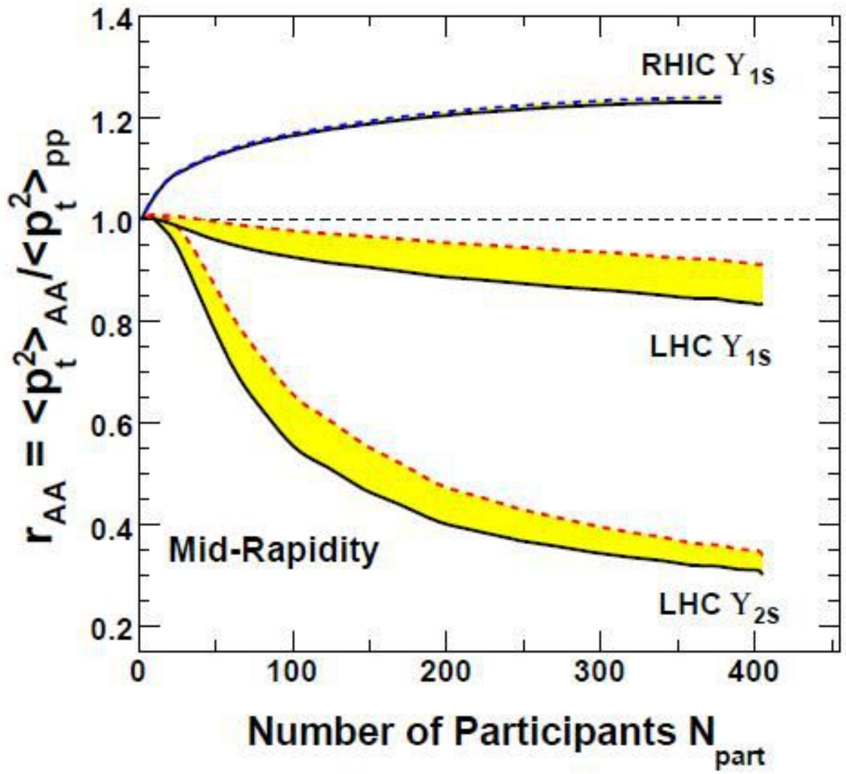
Results—Bottomonium



- can distinguish V=F or V=F



- importance of regeneration for Υ(2S) !

Summary for Heavy Quarkonium

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- Both Cold and Hot medium effects are included self-consistently
- Regeneration dominant at LHC, and also dominant at low pT
- From low energy to High energy, the most import change is the increasing for Reneneration fraction
- We introduce the Nuclear Modification Factor for Transverse Momentum, $r_{AA} = \langle p_T^2 \rangle_{AA} / \langle p_T^2 \rangle_{pp}$ which can clearly distinguish the diff. medium at diff. energy. It's sensitive to the Hot medium properties and also the thermalization for heavy quark
- $\Upsilon(2S)$ can distinguish V=U or V=F and also the re-generation!

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Thank You !