# Statistical hadronization of heavy quarks in ultra-relativistic nucleus-nucleus collisions: from FAIR to LHC

**A.Andronic – GSI Darmstadt**

- The statistical hadronization model
  - motivations and assumptions / method and inputs
- Results
  - SPS, RHIC, LHC: centrality, $y$, $p_t$ dependence
  - extension towards lower energies
  - effect of in-medium masses of charmed hadrons
- Summary and outlook

**AA, P. Braun-Munzinger, K. Redlich, J. Stachel:**

**NPA 789(2007)334,PLB 652(2007)259, arXiv:0708.1488**

# Statistical hadronization: first ideas

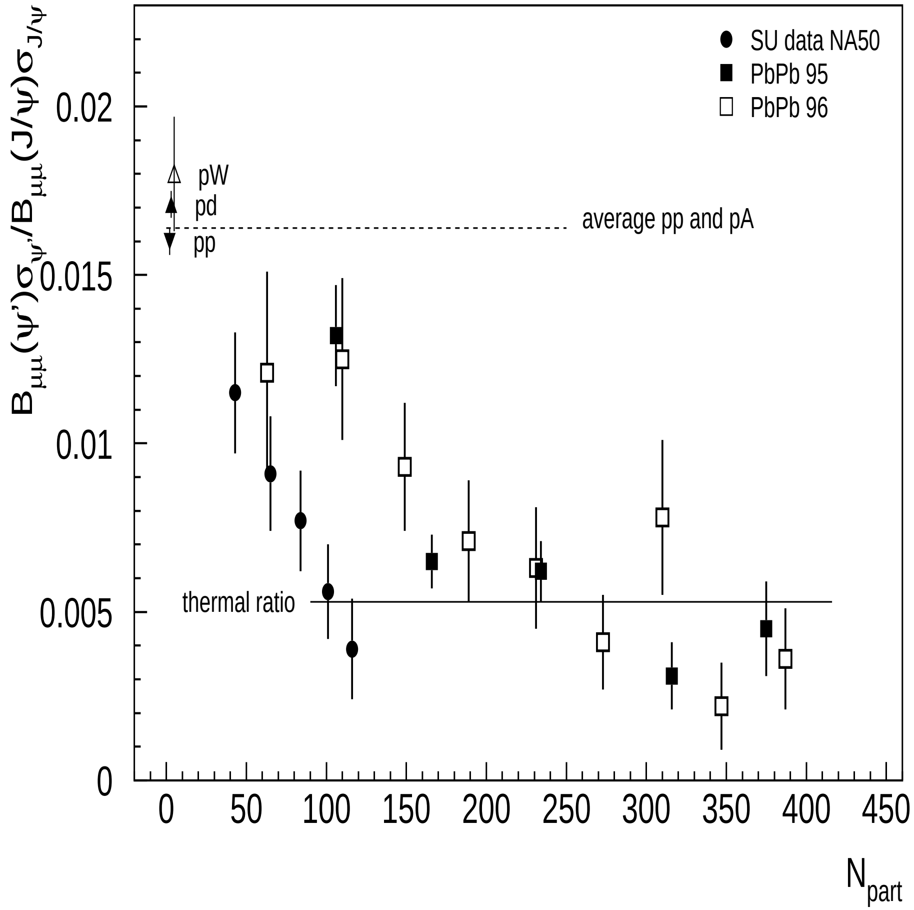
P.Braun-Munzinger, J.Stachel, PLB 490 (2000) 196

- $\psi'/\psi$ approaches thermal value for N$_{part}$ >150 $\longrightarrow$

  also noted in: H.Sorge et al., PRL 79 (1997) 2775

  another idea (J/$\psi$/h$^-$ = therm.): statistical production of J/$\psi$ Gazdzicki & Gorenstein, PRL 83 (1999) 4009

- charmed hadrons cannot be therm. produced in equilibrated hadron gas (x-sections ~100x smaller than for strange hadrons)



# ... and assumptions

P.Braun-Munzinger, J.Stachel, PLB 490 (2000) 196

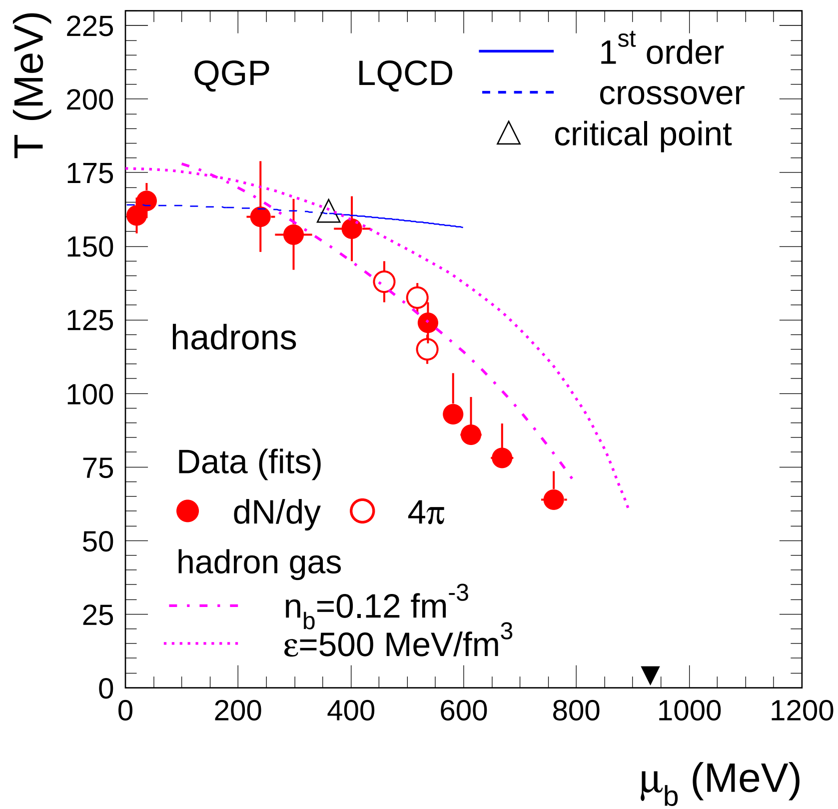
- all charm quarks are produced in primary hard collisions
- survive and thermalize **in QGP** (thermal, but not chemical equilibrium)
- charmed hadrons are formed at chemical freeze-out together with all hadrons

  statistical laws, quantum nr. conservation

  stat. hadronization $\neq$ coalescence

  is freeze-out at phase boundary?

  LQCD: $T_c$=151-192 MeV (hep-lat/0609068-0608013)




- no $J/\psi$ surv. in QGP (full screening)

  can $J/\psi$ survive above $T_c$? (LQCD)

  Asakawa, Hatsuda, PRL 92 (2004) 012001

  Mocsy, Petreczky, arXiv:0705.2559

# Annihilation of charm in QGP

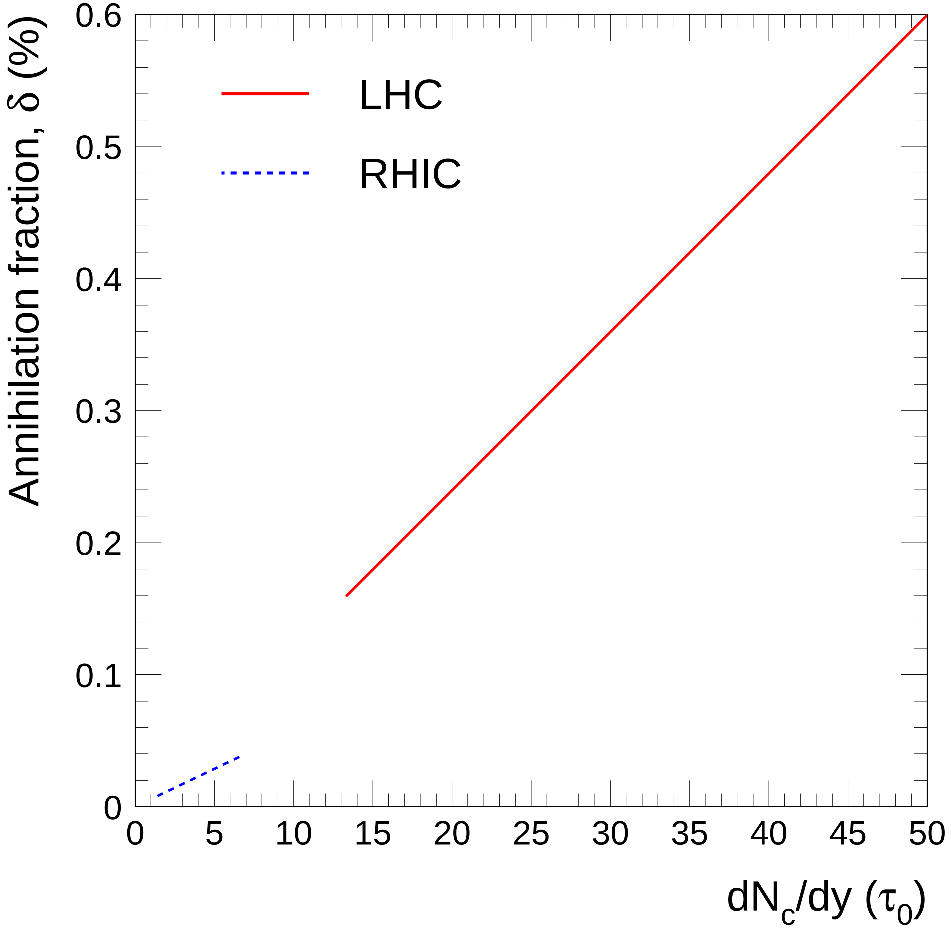
$c + \bar{c} \rightarrow g + g, \quad c + \bar{c} \rightarrow q + \bar{q}$

$\frac{dr_{c\bar{c}}}{d\tau} = n_c n_{\bar{c}} \langle \sigma_{c\bar{c}\rightarrow gg} v_r \rangle$

$\langle\rangle(T)$: Lin, Ko, PRC 62 (2000) 034903

M. Glück, J.F. Owens, E. Reya, Phys. Rev. D 17 (1978) 2324:
$g + g \rightarrow c + \bar{c}$ (& detailed balance)
we use: $\alpha_s = 1$, $m_c = 1.5$ GeV

$$n_c = \frac{dN_c/dy(\tau)}{V(\Delta y{=}1,\tau)} \leq \frac{dN_c/dy(\tau_0)}{V(\Delta y{=}1,\tau)}$$



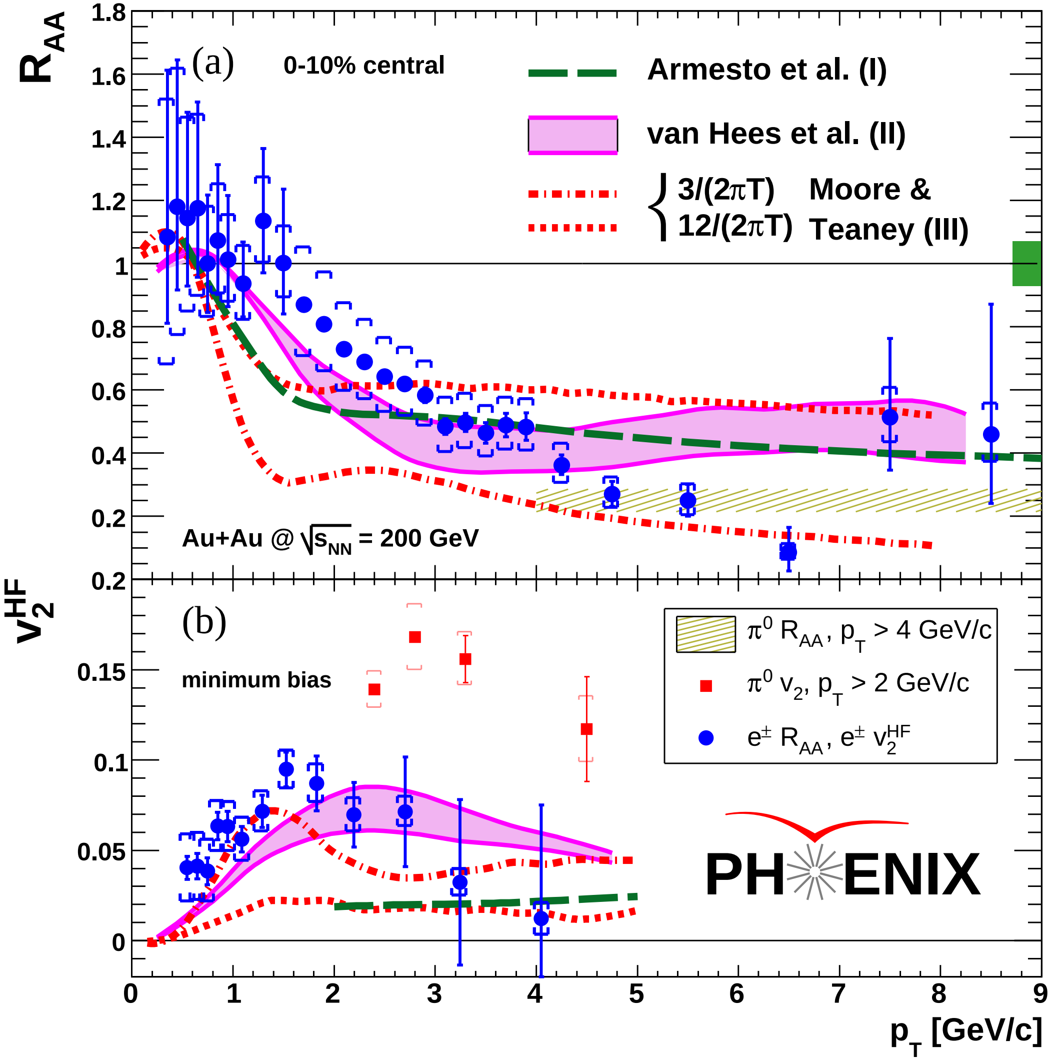

1-d Bjorken: $\frac{\pi^2}{45}(32 + 21N_f)T^3\tau = 3.8\frac{dN/dy}{A_\perp}$; $V(\Delta y = 1, \tau) = A_\perp \tau$ ($A_\perp \simeq$150 fm$^2$)

RHIC: $\tau_c = 2.7$ fm, $T(\tau_0) = 225$ MeV, $dN_{ch}/dy$=660 LHC: $\tau_c = 8.3$ fm, $T(\tau_0) = 325$ MeV, $dN_{ch}/dy$=2000

Annihilation loss of charm in QGP is very small **(NPA 789(2007)334)**

# Charm thermalization

...from data (electrons from heavy-flavors), PHENIX, PRL 98(2007)172301




- energy loss $(R_{AA} < 1)$
- large elliptic flow $(v_2)$

Models:

Langevin approach (diff. coeff.):
Moore, Teaney, PRC 71 (2005) 064904
van Hees et al., PRC 73 (2006) 034913

pQCD (BDMPS, $\hat{q}$=14 GeV$^2$/fm):
Armesto et al., PLB 637 (2006) 362

big unknown: charm/bottom content

how is thermalization achieved?

via hadr. resonances [in QGP]:
van Hees, Rapp, PRC 71 (2005) 034907

thermalization at lower energies?

# Statistical hadronization: method and inputs

- Thermal model calculation (grand canonical) $T$,$\mu_B$: $\rightarrow n_X^{th}$
- $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi i}^{th})$
- $N_{c\bar{c}} << 1 \rightarrow$ Canonical (J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137):

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c \text{ (charm fugacity)}$$

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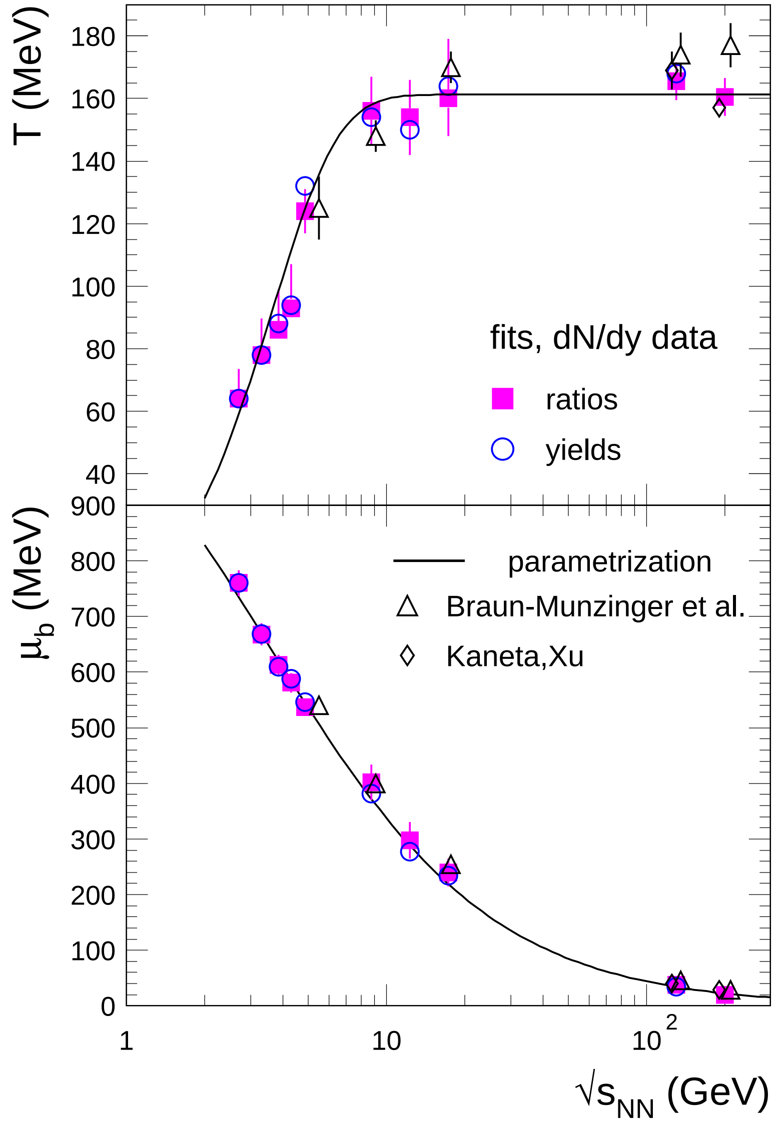
Outcome: $N_D = g_c V n_D^{th} I_1/I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

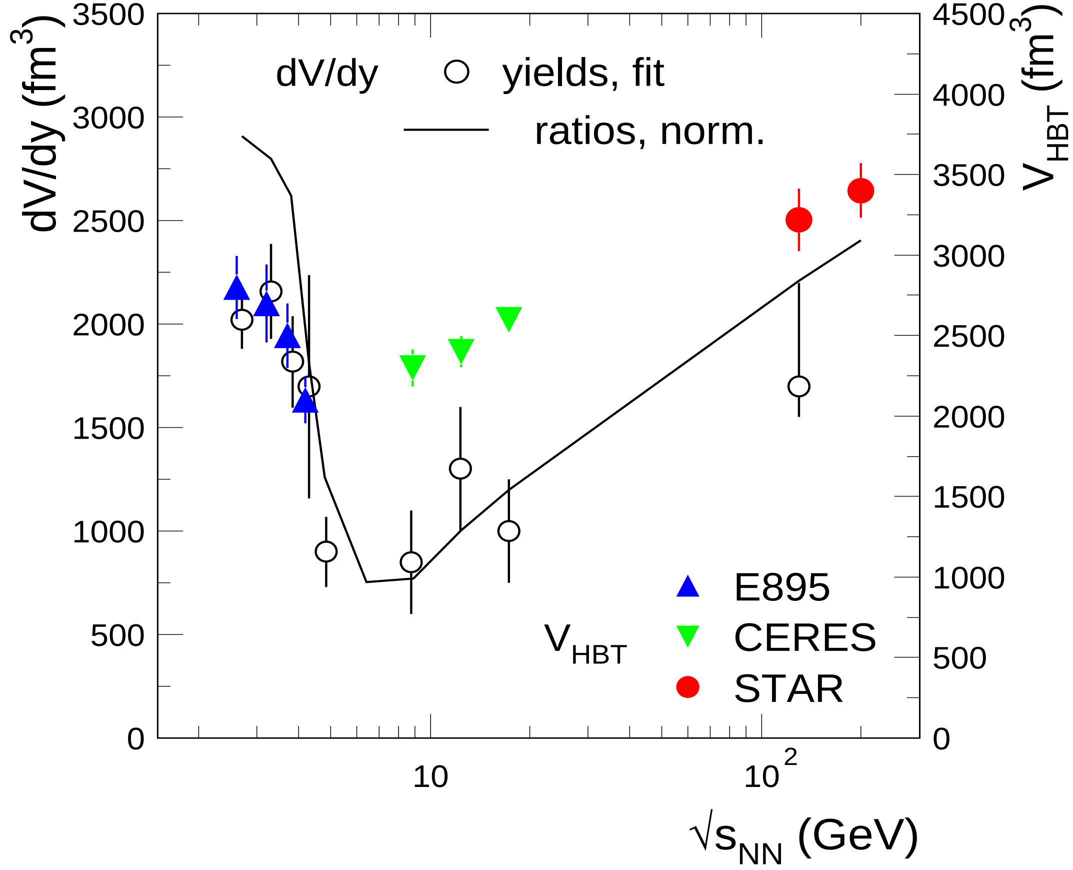
Inputs: $T$, $\mu_B$, $V_{\Delta y=1} (= (\mathrm{d}N_{ch}^{exp}/\mathrm{d}y)/n_{ch}^{th})$, $N_{c\bar{c}}^{dir}$ (pQCD or exp.)

Minimal volume for QGP: $V_{QGP}^{min}$=400 fm$^3$

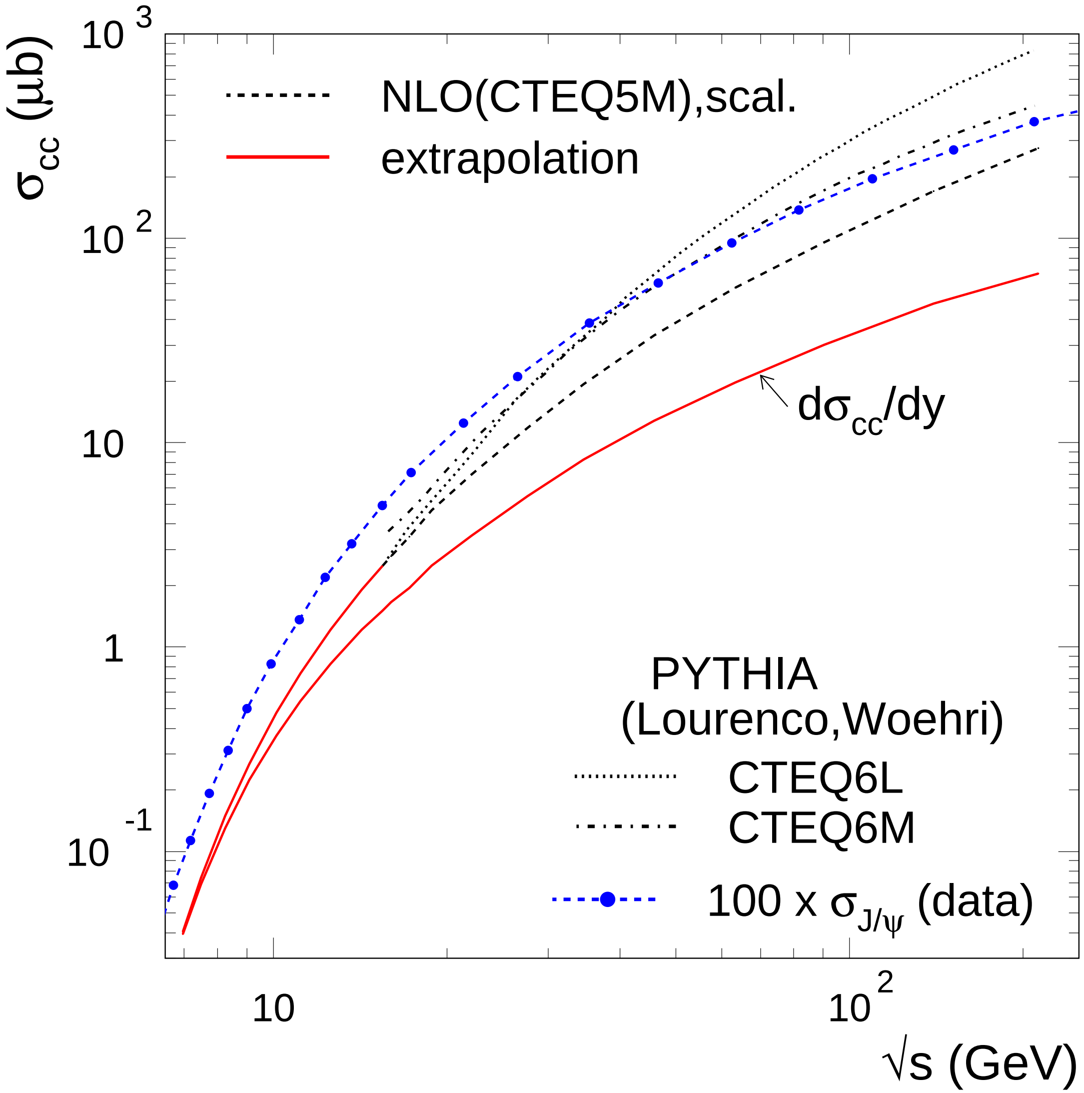
# Thermal parameters: from fits to data

NPA 772 (2006) 167 [nucl-th/0511071]



# $N_{c\bar{c}}^{dir}$ from pQCD calculations (pp)




R.Vogt, IJMP E12 (2003) 211

[hep-ph/0111271]

pQCD is not parameter-free!
(PDF, $m_c$, $\mu_R$, $\mu_F$)

extrapolation:

$$\sigma_{c\bar{c}} = k\left(1 - \frac{\sqrt{s_{thr}}}{\sqrt{s}}\right)^a \left(\frac{\sqrt{s_{thr}}}{\sqrt{s}}\right)^b$$

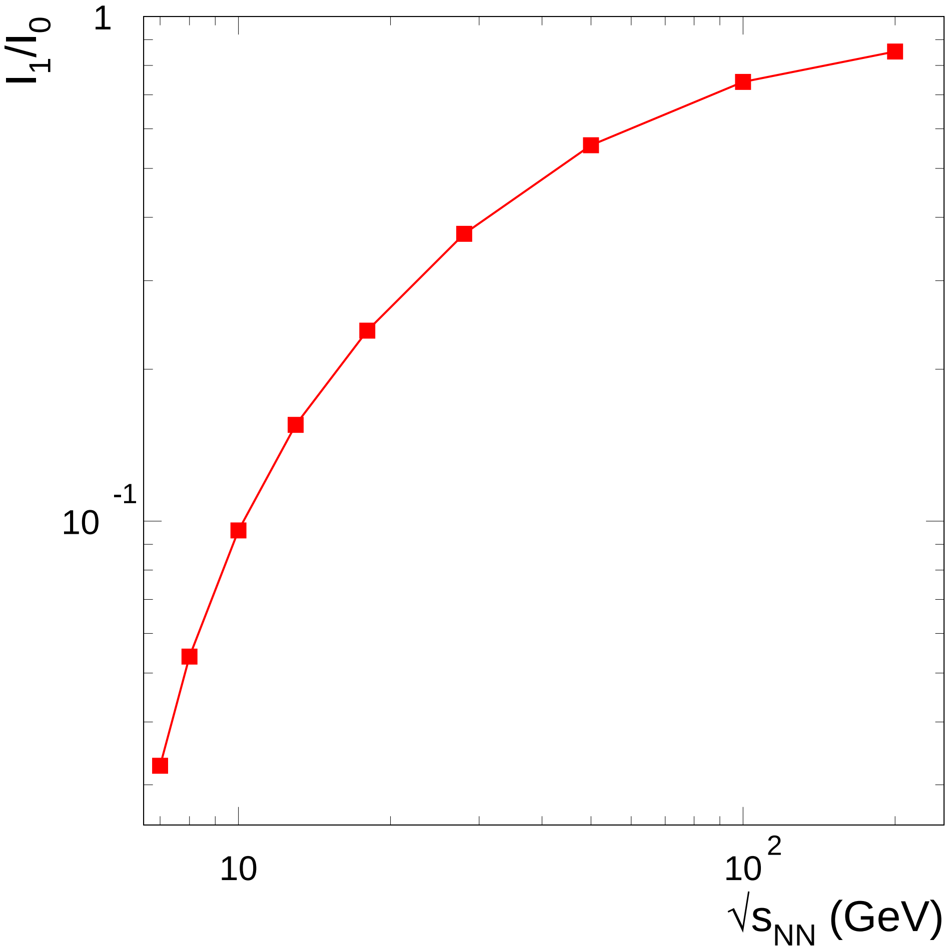
$k$=1.85 μb, $a$=4.3, and $b$=-1.44,
$\sqrt{s_{thr}}$=4.5 GeV ($m_c$=1.3 GeV)

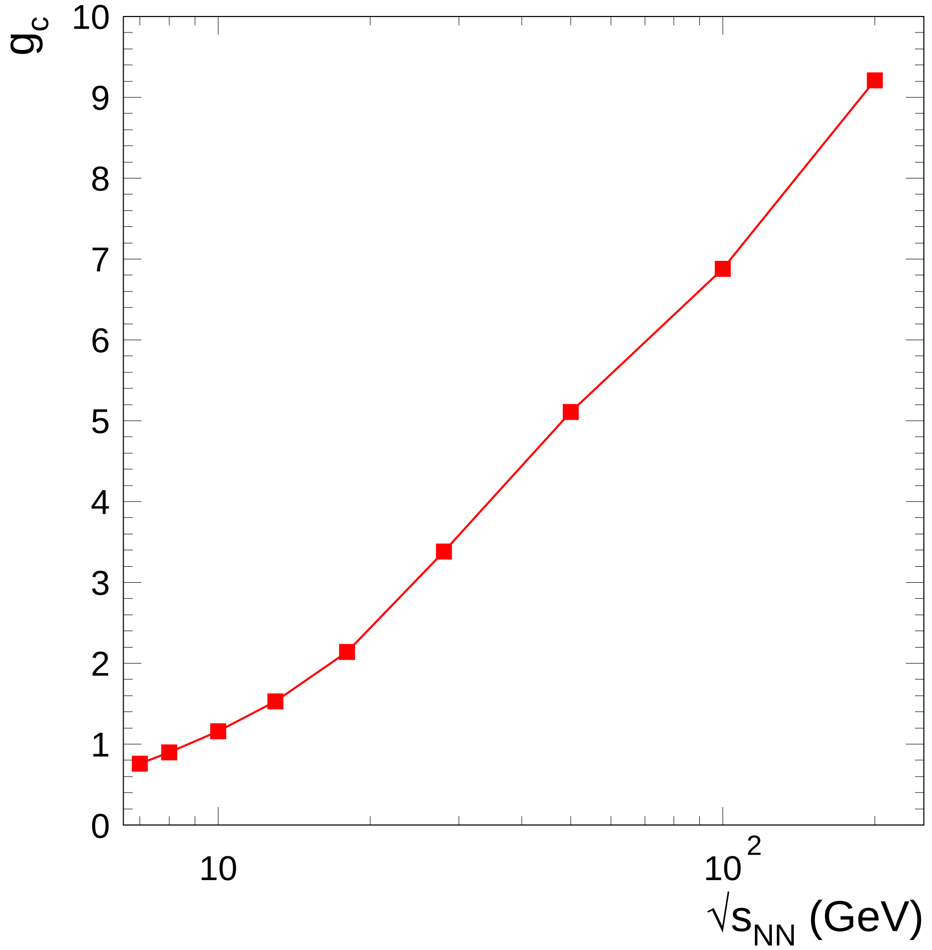
...subject to large uncertainties

$$\mathrm{d}N_{c\bar{c}}^{dir}/\mathrm{d}y = 1.1 \cdot 10^{-3} - 1.7$$

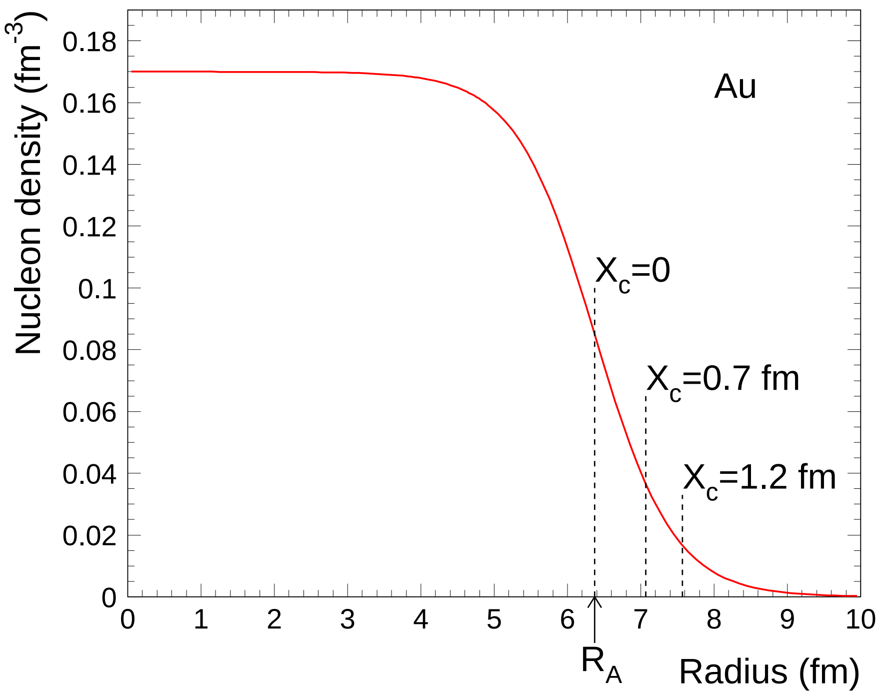
# Canonical suppression and charm fugacity

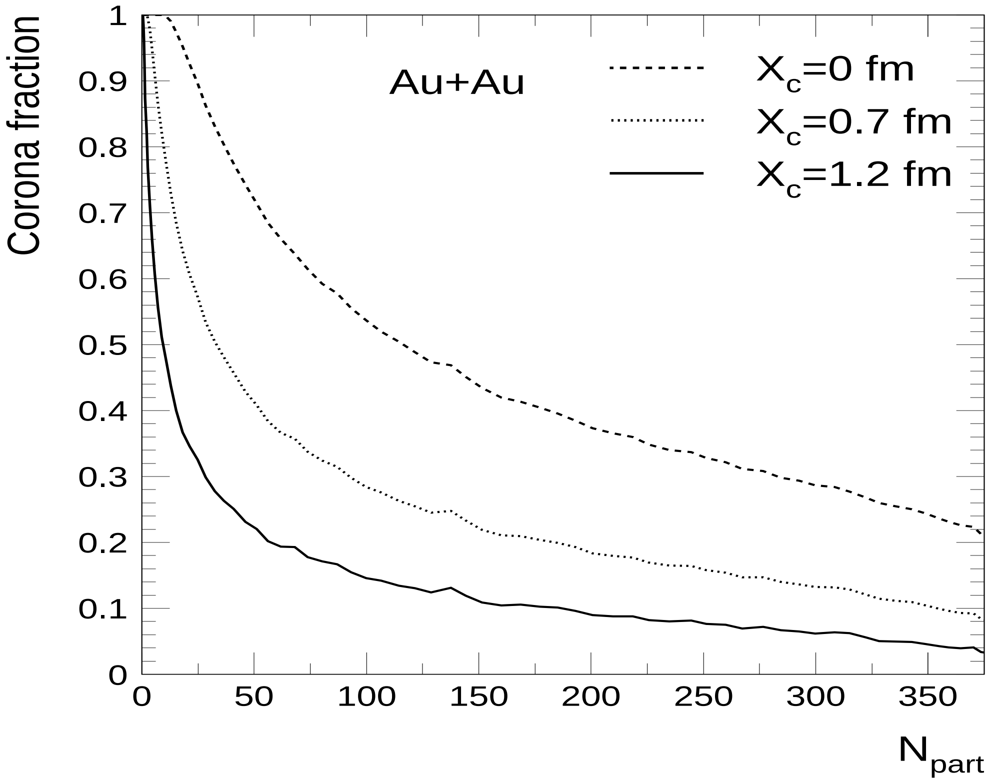
$$n_{i,c}^{C} = n_{i,c}^{GC} I_1(N_c)/I_0(N_c),\ N_c = \sum_i n_{i,c}^{GC} \cdot V; \qquad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$$



# One more ingredient: "corona" contribution

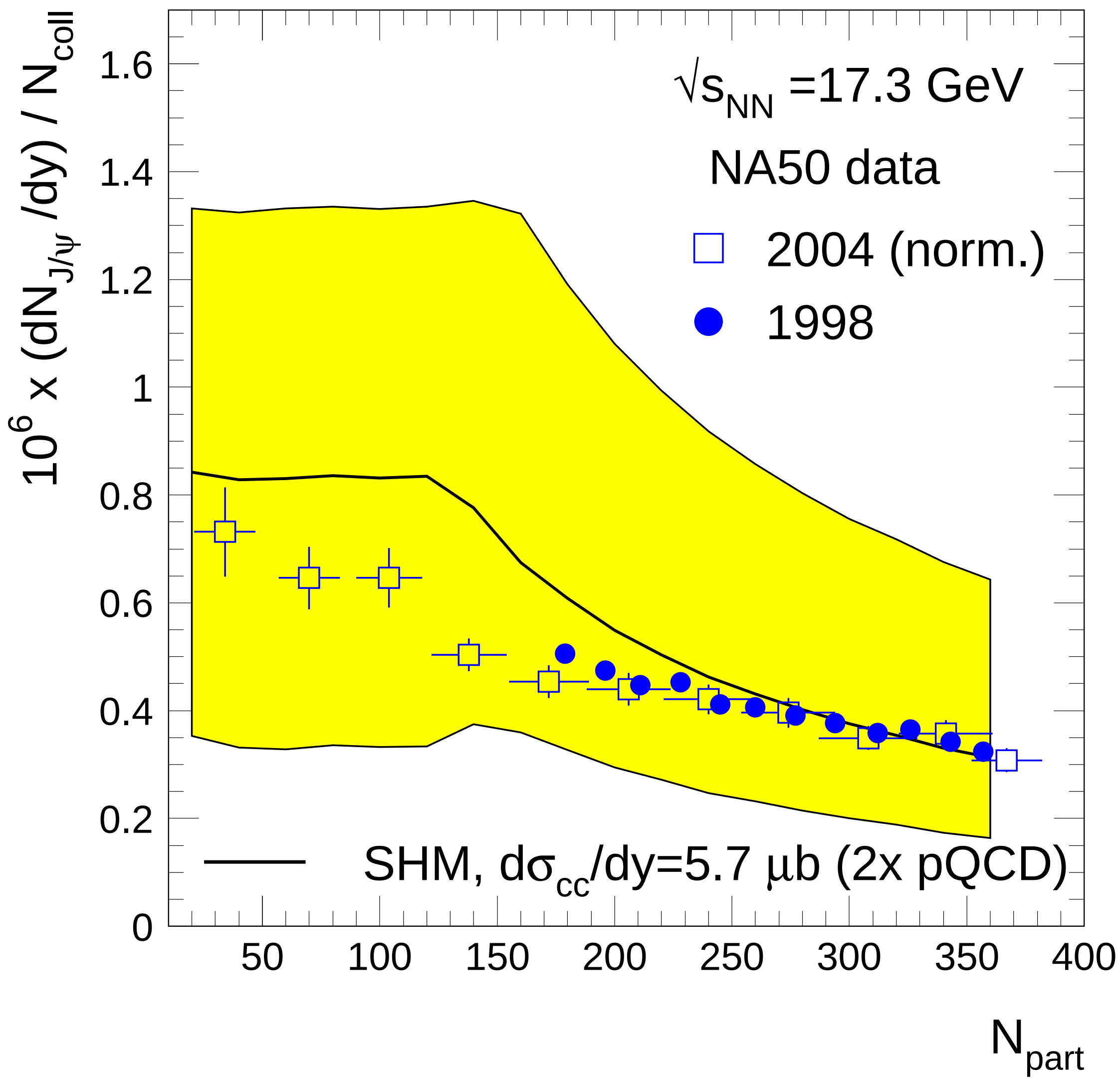



**core:** stat. hadr., **corona** ($X_c$**=1.2 fm): pp** $\Rightarrow N_{J/\psi} = N_{J/\psi}^{core} + N_{J/\psi}^{corona}$

$$N_{J/\psi}^{core} = g_c^2 n_{J/\psi}^{th} V^{core} \qquad N_{J/\psi}^{corona} = N_{coll}^{corona} \sigma_{J/\psi}^{pp} / \sigma_{inel}^{pp}$$

# $J/\psi$ at SPS

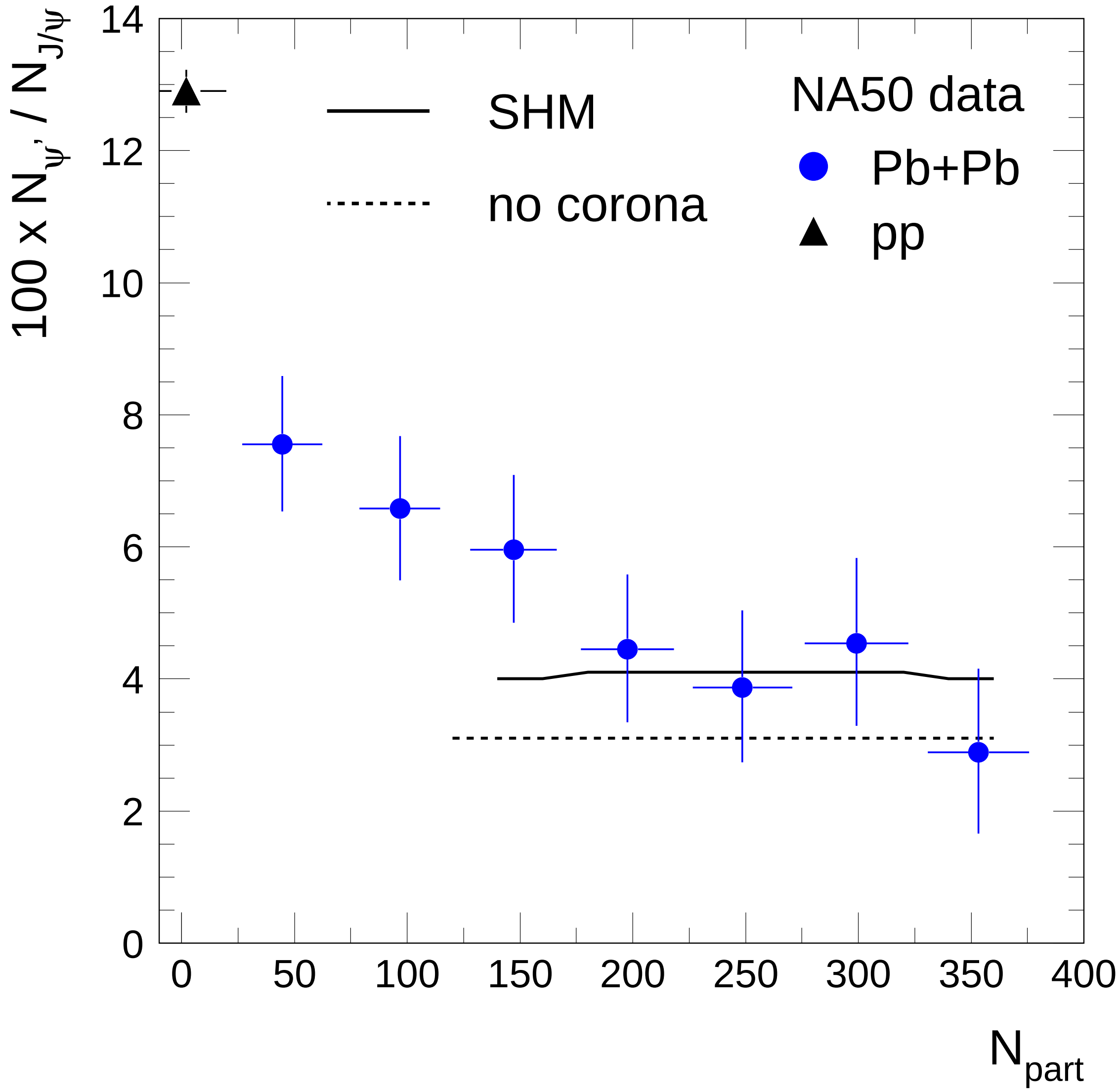



**data explained with charm enhancement (2×pQCD)**

see also: NPA 690 (2001) 119c, PLB 571 (2003)36
Grandchamp, Rapp, PLB 523 (2001) 60, NPA 709 (2002) 415
Gorenstein et al., PLB 509 (2001) 277, PLB 524 (2002) 265

NA50 data:
1998 ("unofficial"):
J. Gosset et al., EPJ C 13 (2000) 63
2004 ($J/\psi$/DY, normalized):
EPJ C 39 (2005) 335

# $\psi'$ at SPS




NA50 Data:
PbPb: nucl-ex/0612013
pp: PLB 466 (1999) 408

good agreement

$$N_{J/\psi}/N_{\psi'} = \exp\left(-\frac{m_{\psi'}-m_{J/\psi}}{T}\right)$$

corona is important

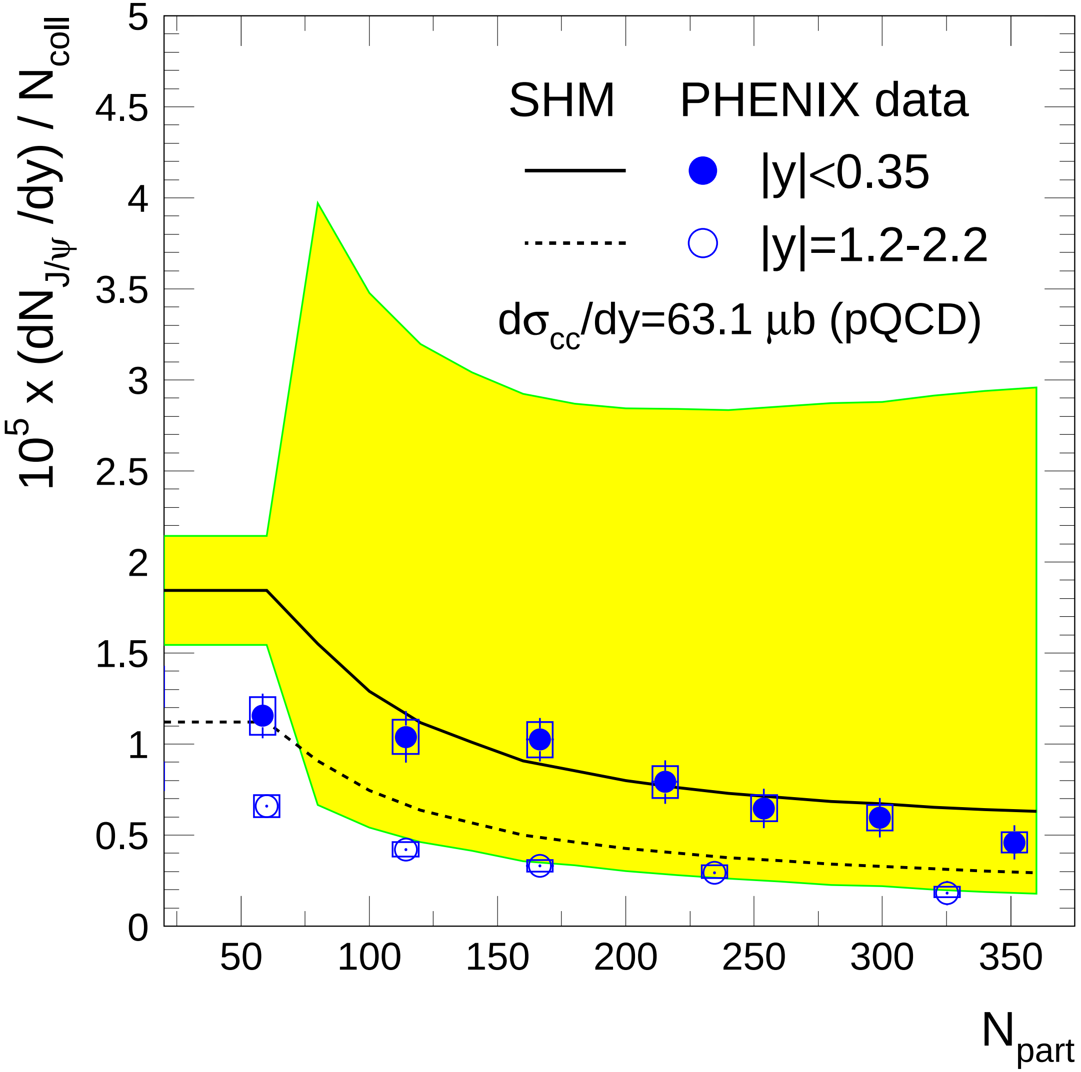
$N_{\psi'}/N_{\psi} \neq 0$ !

contradicts screening model

(LQCD: $\psi'$ melted at $T_c$)

$\Rightarrow$ $\psi'$ prod. by stat. hadr.!

# $J/\psi$ at RHIC: centrality dependence




pQCD charm cross section

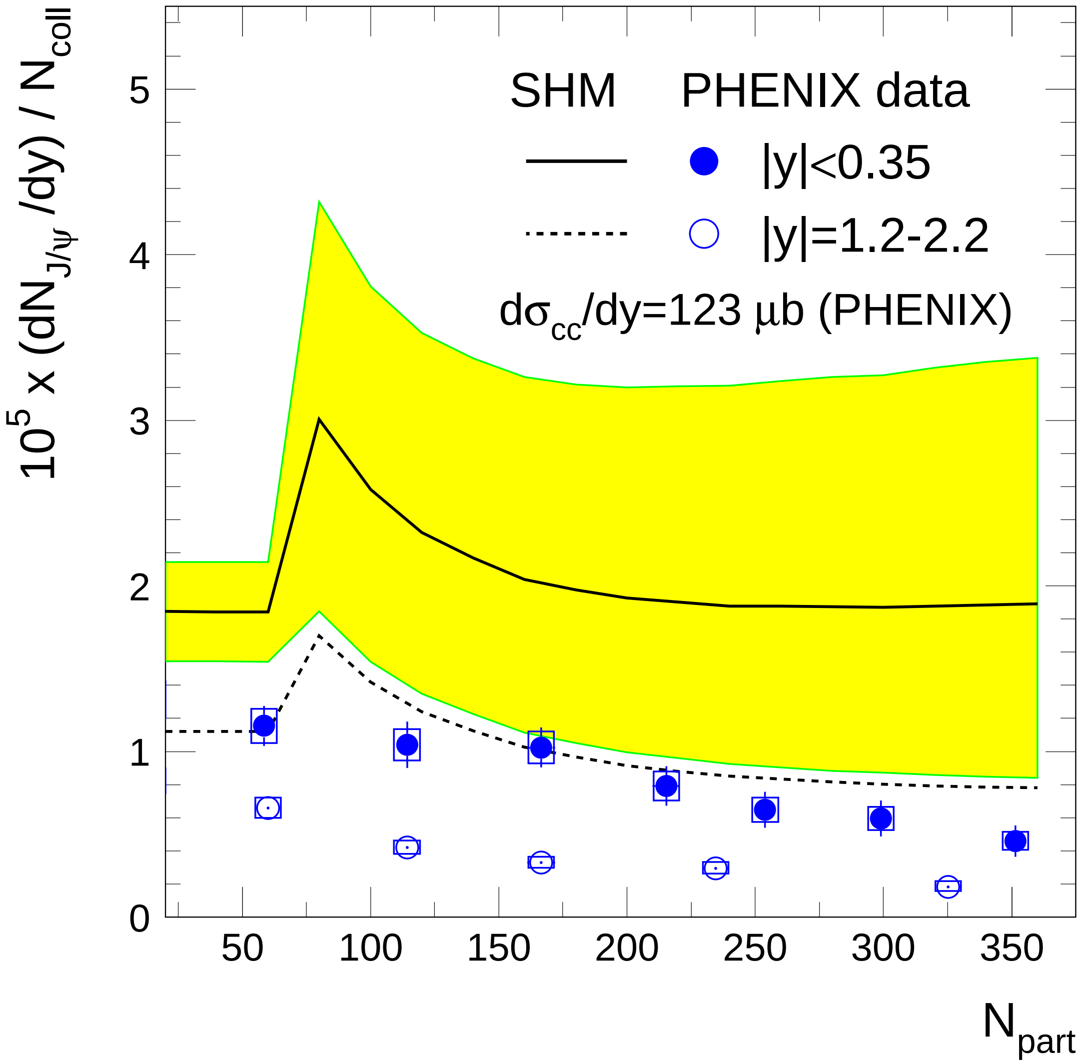
M. Cacciari, P. Nason, R. Vogt,
Phys. Rev. Lett. 95 (2005) 122001

**the model explains data**

(PHENIX, PRL 98(2007)232301)

yellow band: $\sigma_{c\bar{c}}$ uncertainty

# J/$\psi$ at RHIC: centrality dependence




PHENIX charm cross section

hep-ex/0611020

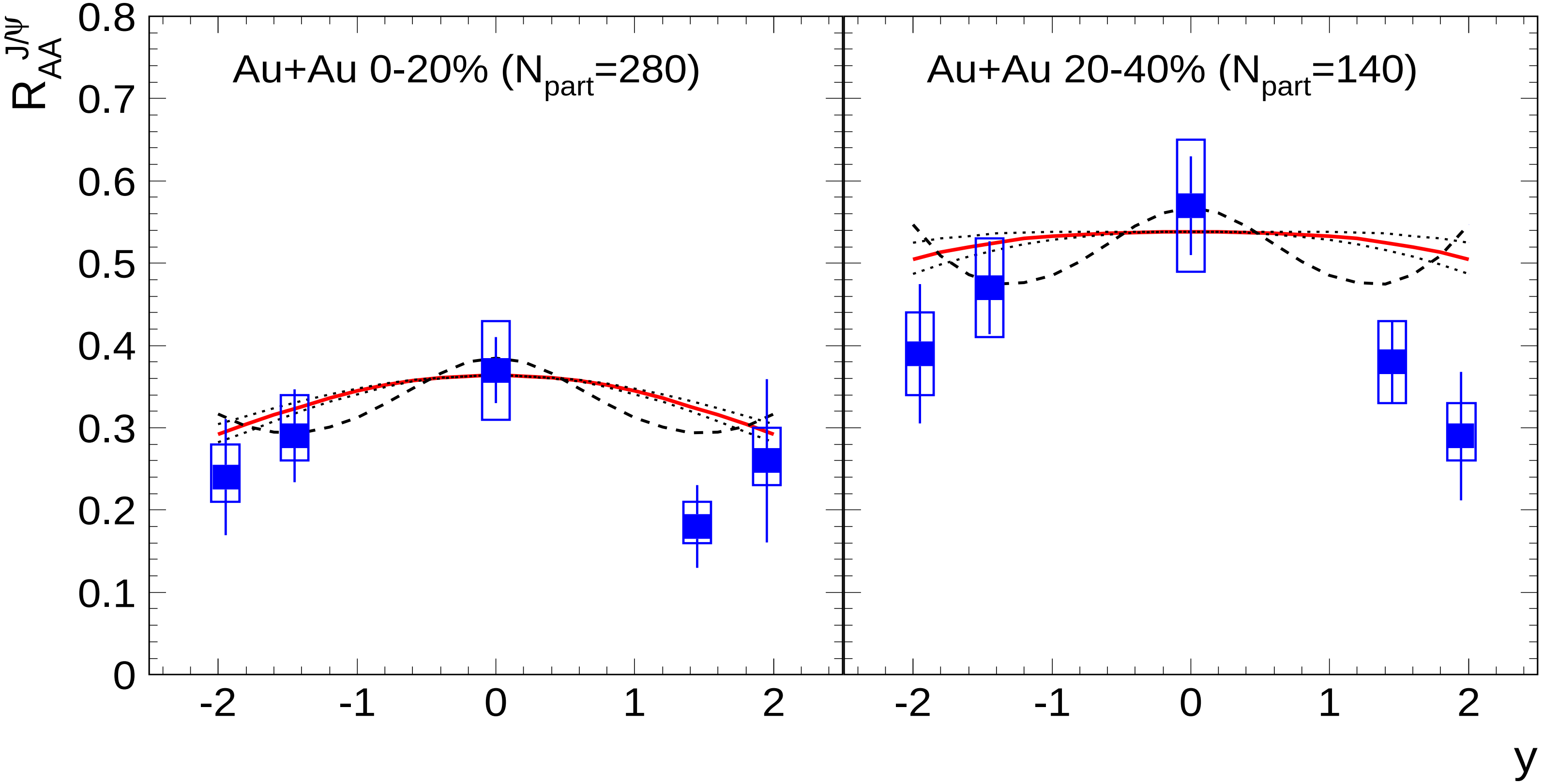
**model compatible with data**

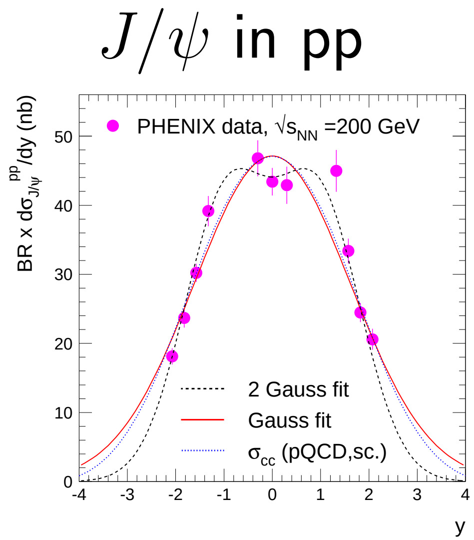
if STAR charm cross section

Phys. Rev. Lett. 94 (2005) 062301

**strong disagreement**

# J/$\psi$ at RHIC: rapidity dependence, $R_{AA}$



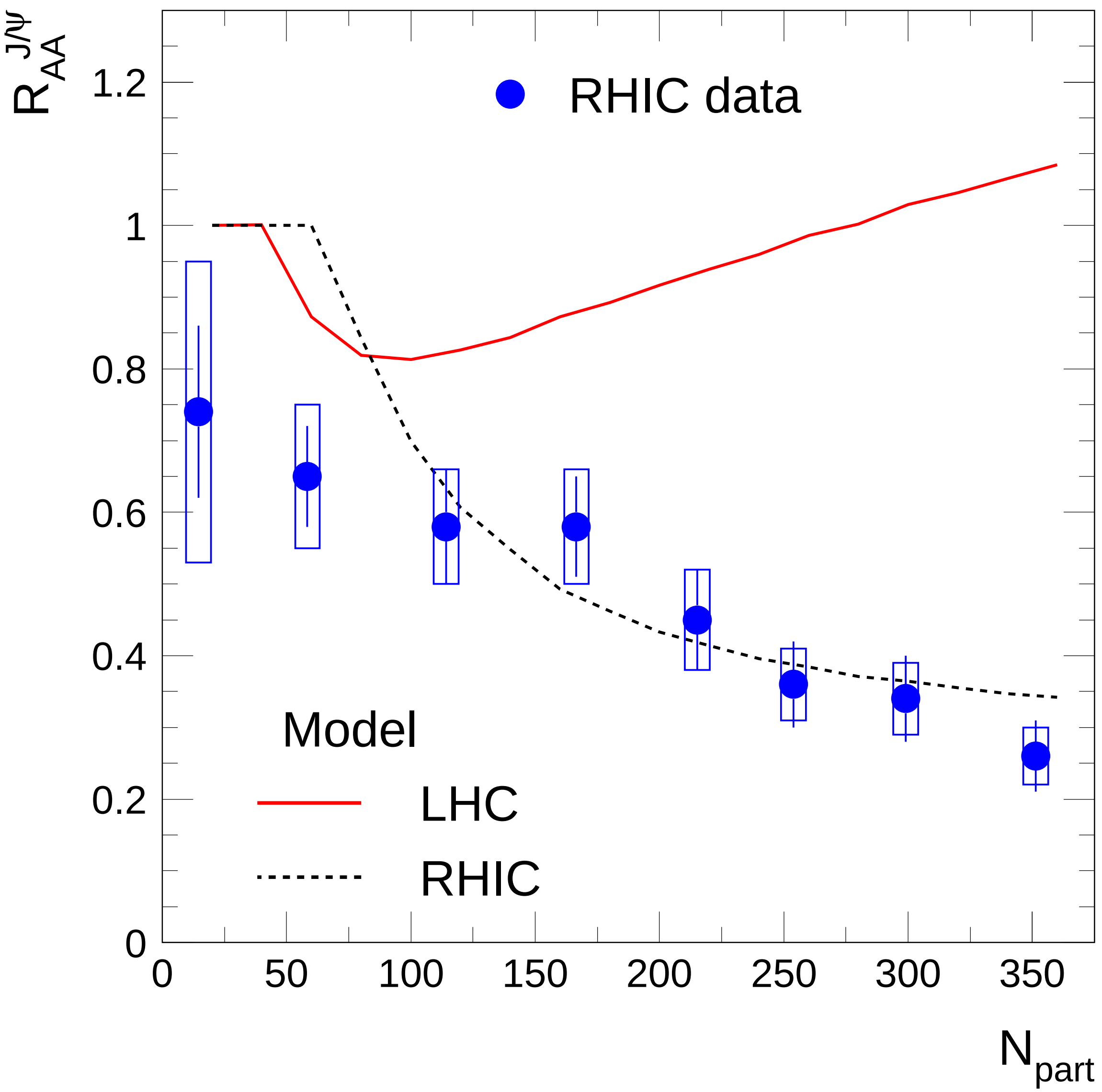




$$R_{AA} = (\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y)/(N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y)$$

direct indication of statistical hadronization (stronger at y=0) of charm quarks

constant $R_{AA}$ (or opposite trend) expected within Debye screening model

# $J/\psi$ $R_{AA}$: RHIC and LHC energies



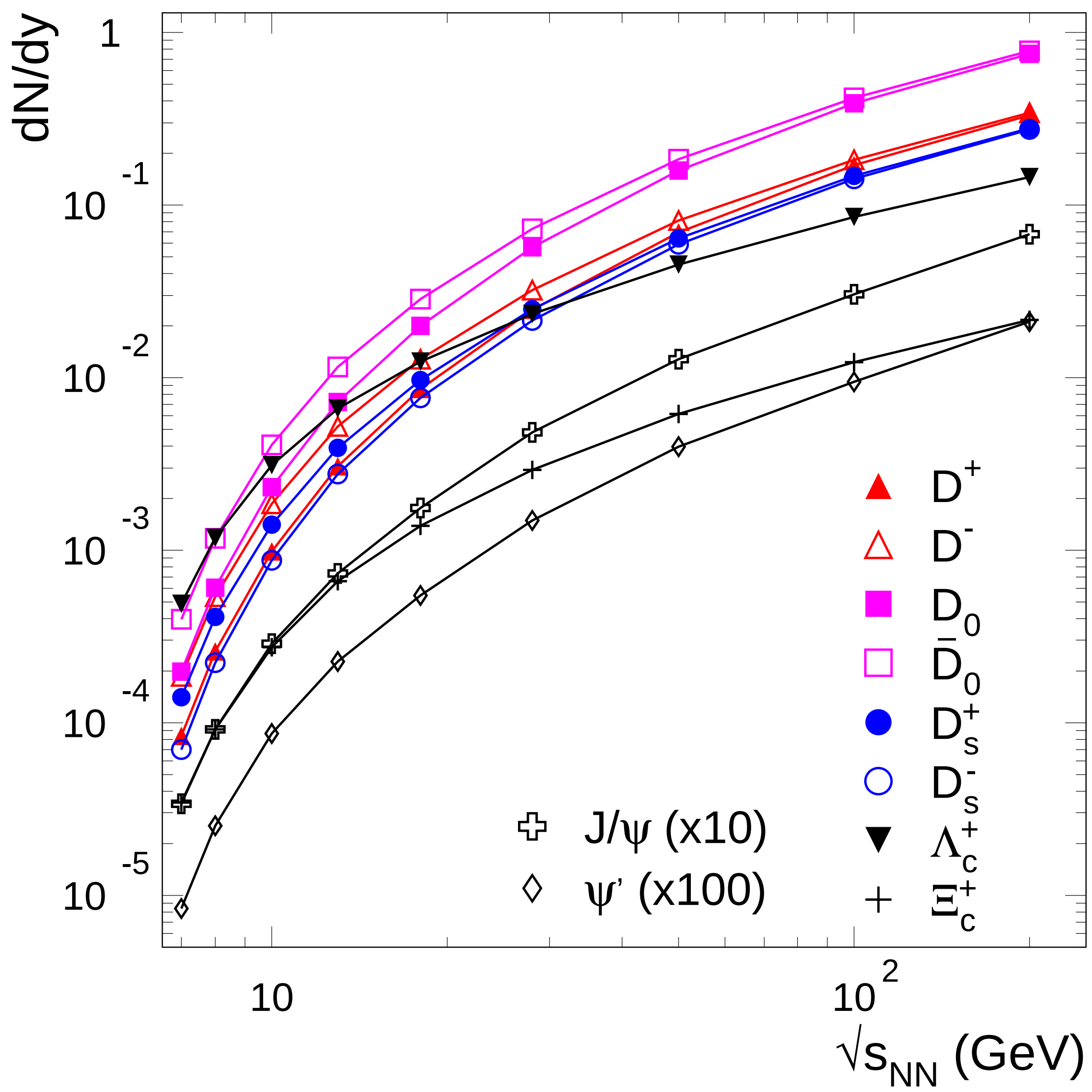

- very different centrality dep.
  - "suppression" at RHIC
  - "enhancement" at LHC

  determined by canonical suppression (open charm)
- RHIC (and SPS) verified

  ...LHC to come soon

  ...and later FAIR

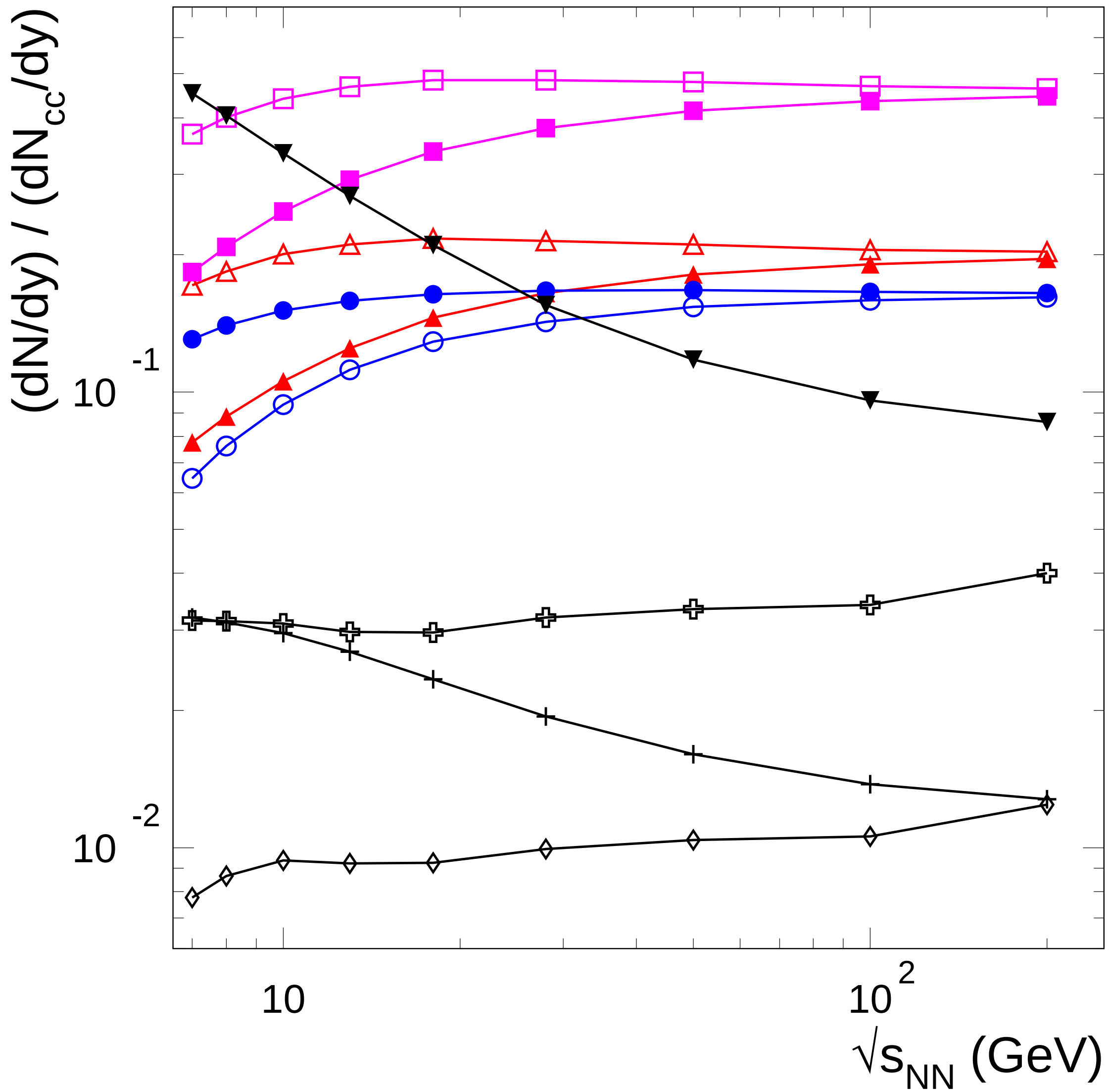
# Charm at lower energies




- is charm thermalized?
- strong decrease of yields determined by initial charm production cross section
- $\Lambda_c$ prod. favored at large $\mu_b$
- isospin is important
- model is valid only if QGP
  ...prior to onset of QGP:
  pp-like (relative) yields
- charmed hadrons can trace onset

# Charm at lower energies (relative)

yields per initial charm pair




- $\Lambda_c$:
  dominant at low energies
  exp. reconstruction difficult
  it's a must at FAIR (CBM)
- $\psi'/\psi$ relative yield:
  3% in QGP, 13% in pp
  decreases at low energies
  $\sqrt{s_{NN}}$=7-10 GeV:
  $T$=151-161 MeV
- charmed hadrons can signal the onset of QGP

# Timescales for charm production

effect of in-medium modified masses...(and/or widths?) of charmed hadrons?

- charm could only be produced in initial hard collisions (pQCD)
  $t_{c\bar{c}} \sim 1/2m_c \simeq$ 0.1 fm/c ($m_c \simeq$1.3 GeV $>> \Lambda_{QCD}$)
- charmed hadrons produced in $t_{J/\psi} \gtrsim$1 fm/c
- charm conservation:

$$\sigma_{c\bar{c}} = \frac{1}{2}(\sigma_D + \sigma_{\Lambda_c} + \sigma_{\Xi_c} + ...) + (\sigma_{\eta_c} + \sigma_{J/\psi} + \sigma_{\chi_c} + ...)$$

in our model the effect of mass change is compensated by the constraint to initial charm:

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th}$$

Consequence: the only freedom is in redistribution of the charm quarks

Charm @ FAIR $\neq$ strangeness @ SIS ( $m_s \simeq \Lambda_{QCD}$)

# More timescales

formation and destruction of J/$\psi$ (charmed hadrons)

- QGP formation time, $t_{QGP}$
  - FAIR, SPS: $t_{QGP} \simeq$ 1 fm/c $\sim t_{J/\psi}$
  - RHIC, LHC: $t_{QGP} \lesssim$ 0.1 fm/c $\sim t_{c\bar{c}}$

survival of initially-produced $J/\psi$ at FAIR/SPS energies? ($T_d \sim T_c$)

- collision time, $t_{coll} = 2R/\gamma_{cm}$
  - FAIR, SPS: $t_{coll} \gtrsim t_{J/\psi}$
  - RHIC: $t_{coll} < t_{J/\psi}$, LHC: $t_{coll} << t_{J/\psi}$

cold nuclear suppression important at FAIR/SPS energies?

# Scenarios of in-medium modified masses

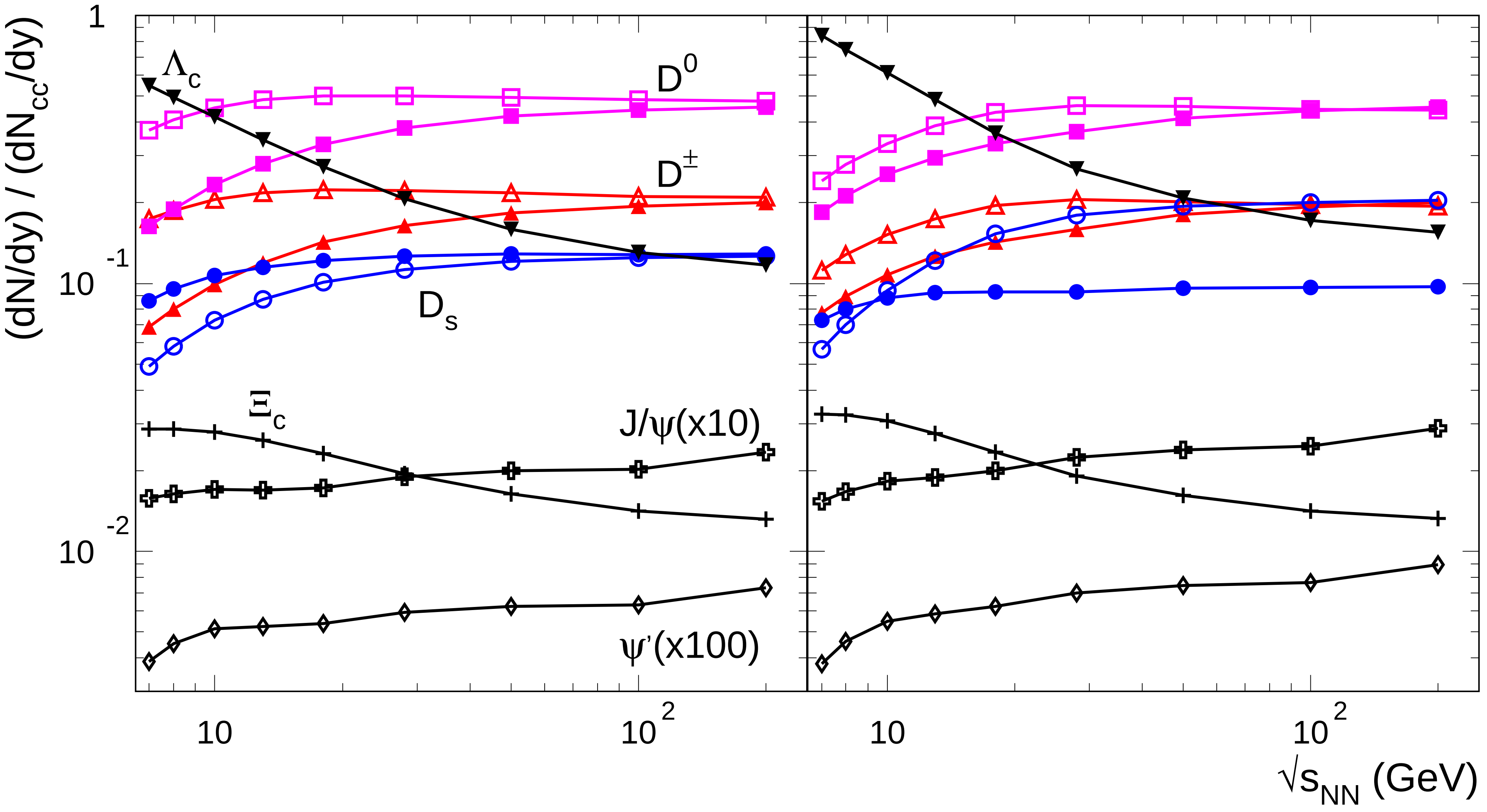
modification of the constituent quark masses of light ($u$ and $d$) quarks
(no change of J/$\psi$ mass, $\Delta m_{\Lambda_c}/2$ for $\Xi_c$)

| case | $\Delta m_D$ | $\Delta m_{\Lambda_c,\Xi_c}$ |
|---|---|---|
| i) | -50 MeV ($D, \bar{D}$) | -100 MeV ($\Lambda_c, \bar{\Lambda}_c$) |
| ii) (FAIR) | -100 MeV ($D$), $+$50 MeV ($\bar{D}$) | -200 MeV ($\Lambda_c$), $+$100 MeV ($\bar{\Lambda}_c$) |
| iii) | -50 MeV ($D, \bar{D}$) | -50 MeV ($\Lambda_c, \bar{\Lambda}_c$) |


Tsushima et al.,PRC 59 (1999) 2824 [nucl-th/9810016].
Sibirtsev et al., EPJA 6 (1999) 351 [nucl-th/9904016]; PLB 484 (2000) 23 [nucl-th/9904015].
Hayashigaki, PLB 487 (2000) 96 [nucl-th/0001051].
Cassing et al., NPA 691 (2001) 753 [nucl-th/0010071].
Friman et al., PLB 548 (2002) 153 [nucl-th/0207006].
Grandchamp et al., PRL 92 (2004) 212301 [hep-ph/0306077].
Tolos et al, PLB 635 (2006) 85 [nucl-th/0509054].
Lutz, Korpa, PLB 633 (2006) 43 [nucl-th/0510006].
Morita, Lee, arXiv:0704.2021.

# Effect of modified masses

scenarios i) and ii)



# Effect of modified masses

change in yield compared to vacuum masses

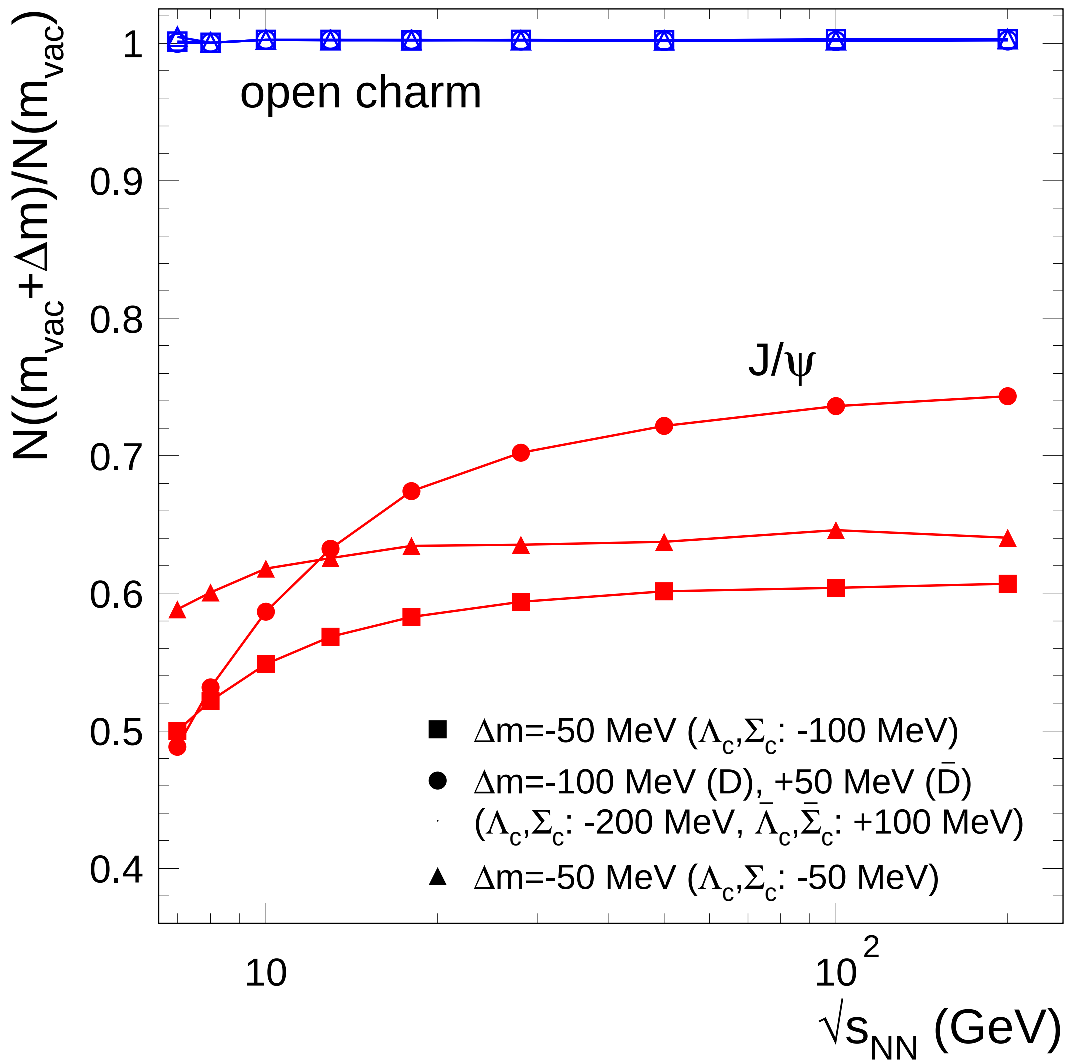
- open charm: very small increase
- ...with large effect on charmonia

(different than $\psi', \chi_c \rightarrow D\bar{D}$

Sibirtsev et al., PLB 484 (2000) 23 [nucl-th/9904015];

Friman et al., PLB 548 (2002) 153 [nucl-th/0207006];

Grandchamp et al., PRL 92 (2004) 212301 [hep-ph/0306077])



# Summary and outlook

statistical hadronization of heavy quarks
(produced exclusively in hard collisions, survive and thermalize in QGP)
most input parameters are well constrained by experimental observables

- Good agreement with $J/\psi$ data at SPS and RHIC

  ... further tests (incl. phase space distr.) to come soon, in particular at LHC

Open questions

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- main uncertainty from charm cross section: more theoretical (NNLO pQCD some time ahead) and experimental progress needed
- survival of $J/\psi$ in QGP (LQCD)

...will be to a good extent clarified at LHC (RHIC)
...and further at FAIR