Statistical hadronization of charm: energy dependence and in-medium effects

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- The statistical hadronization model: assumptions and inputs
- SPS, RHIC energies (including p_t spectra)
- Charm chemistry and effect of in-medium masses of charmed hadrons (SPS energy and below)
- Summary and outlook

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

NPA 789 (2007) 334, nucl-th/0511071; PLB 659 (2008) 149, arXiv:0708.1488

Statistical hadronization: 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?

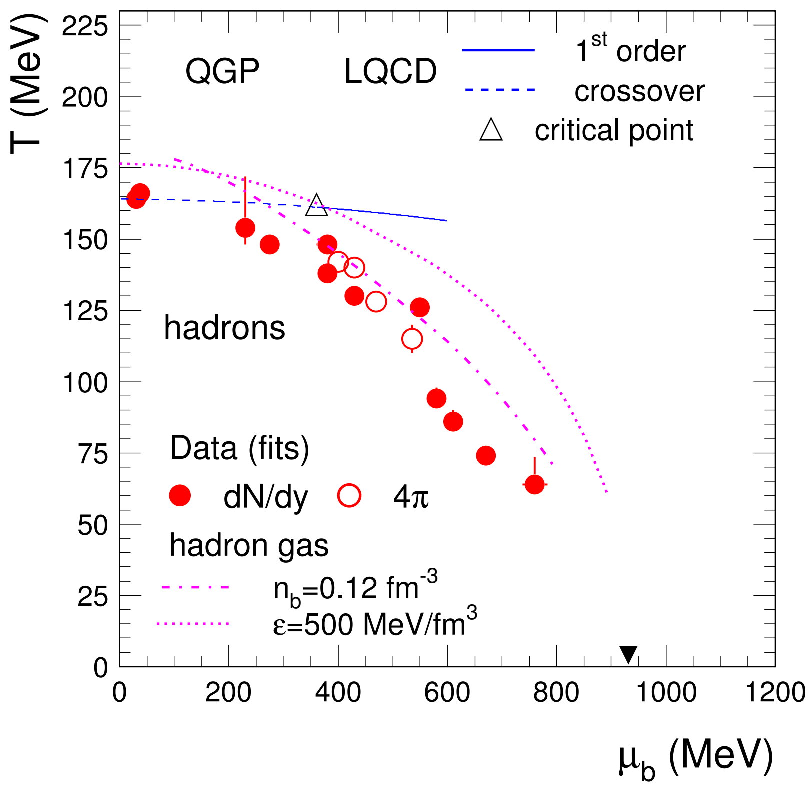
  LQCD: T_c=151-192 MeV (hep-lat/0609068-0608013)

- no J/ψ surv. in QGP (full screening)

  can J/ψ survive above T_c? (LQCD)

  Asakawa, Hatsuda, PRL 92 (2004) 012001

  Mocsy, Petreczky, PRL 99 (2007) 211602



Statistical hadronization: method and inputs

- Thermal model calculation (grand canonical) T,μ_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):

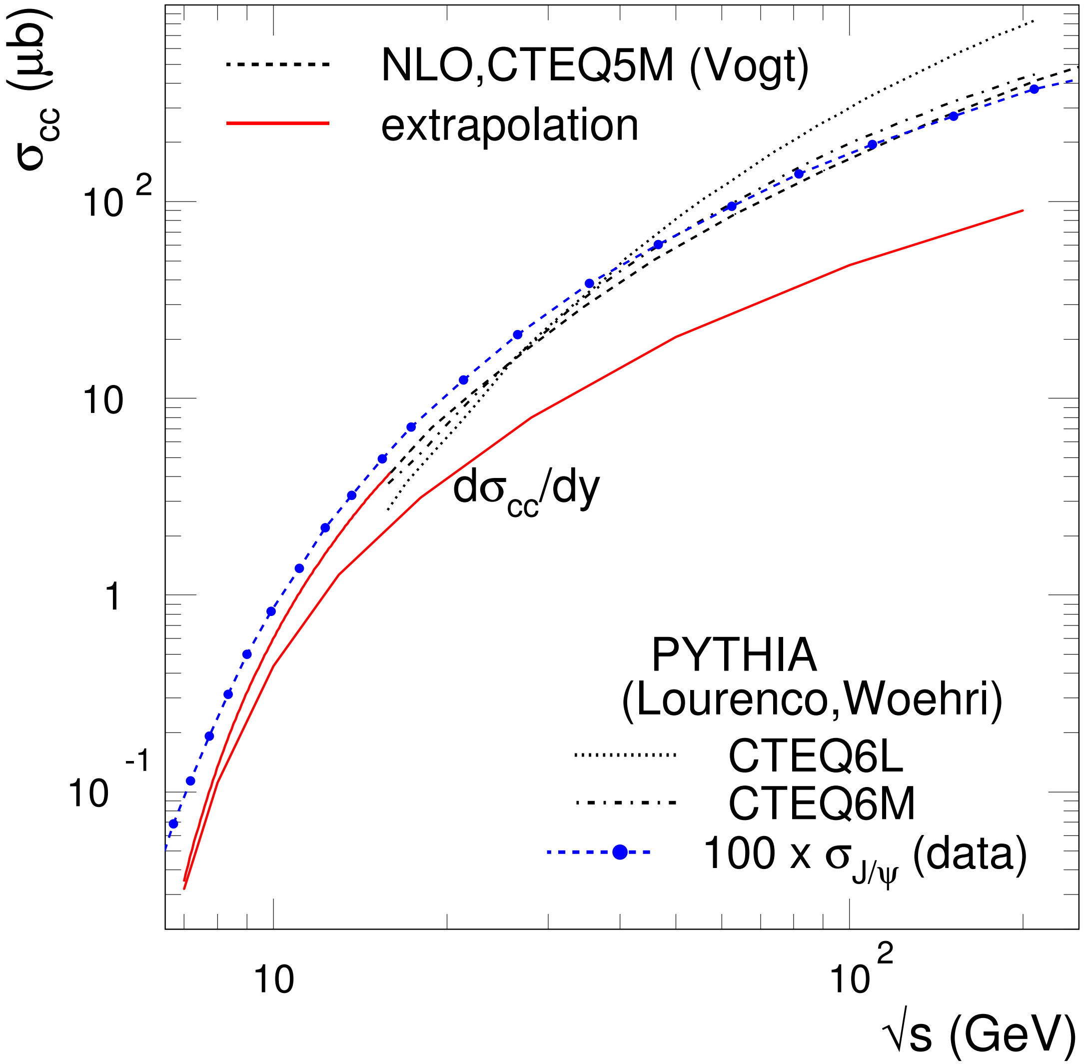
$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c \text{ (charm fugacity)}$$

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, μ_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

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



R.Vogt, IJMP E12 (2003) 211
[hep-ph/0111271]

pQCD is not parameter-free!
(PDF, m_c, μ_R, μ_F)

extrapolation:

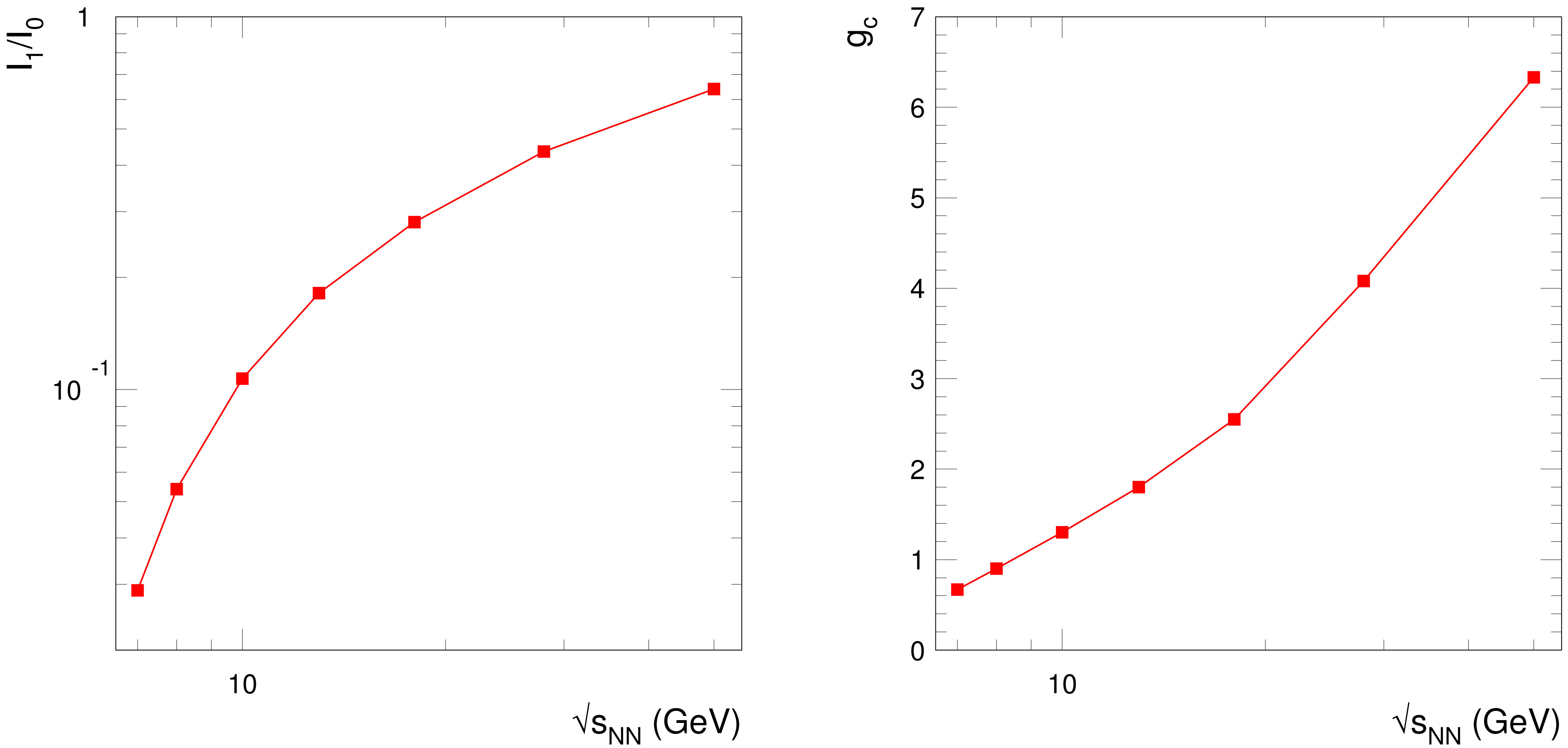
$$\sigma_{c\bar{c}} = c\left(1 - \frac{\sqrt{s_{thr}}}{\sqrt{s}}\right)^a \left(\frac{\sqrt{s_{thr}}}{\sqrt{s}}\right)^b$$

$\sqrt{s_{thr}}$=5.1 GeV (m_c=1.7 GeV)
a=4.0, b=-1.35, c=4.2

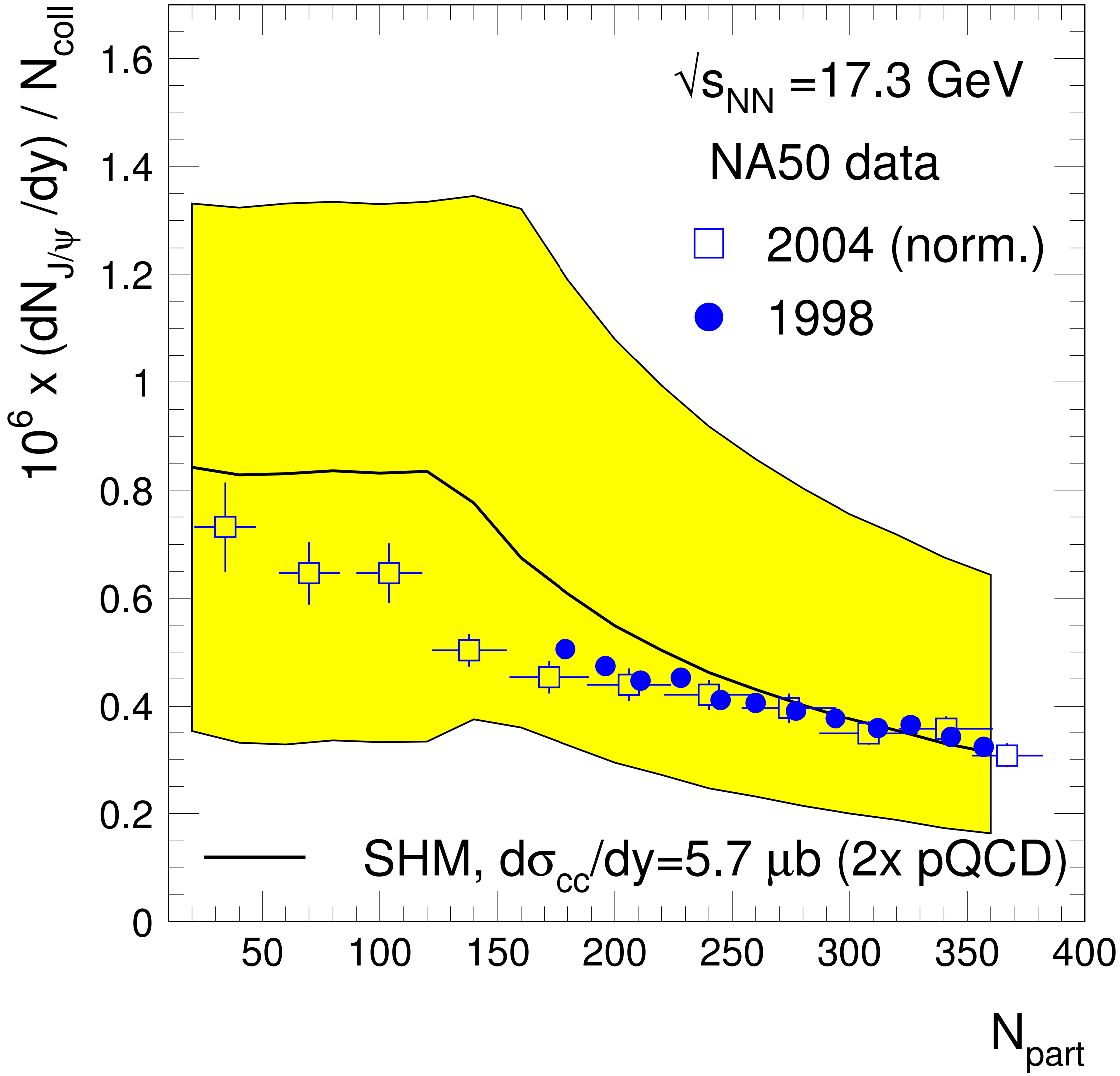
...subject to large uncertainties

Canonical suppression and charm fugacity

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



J/ψ at SPS

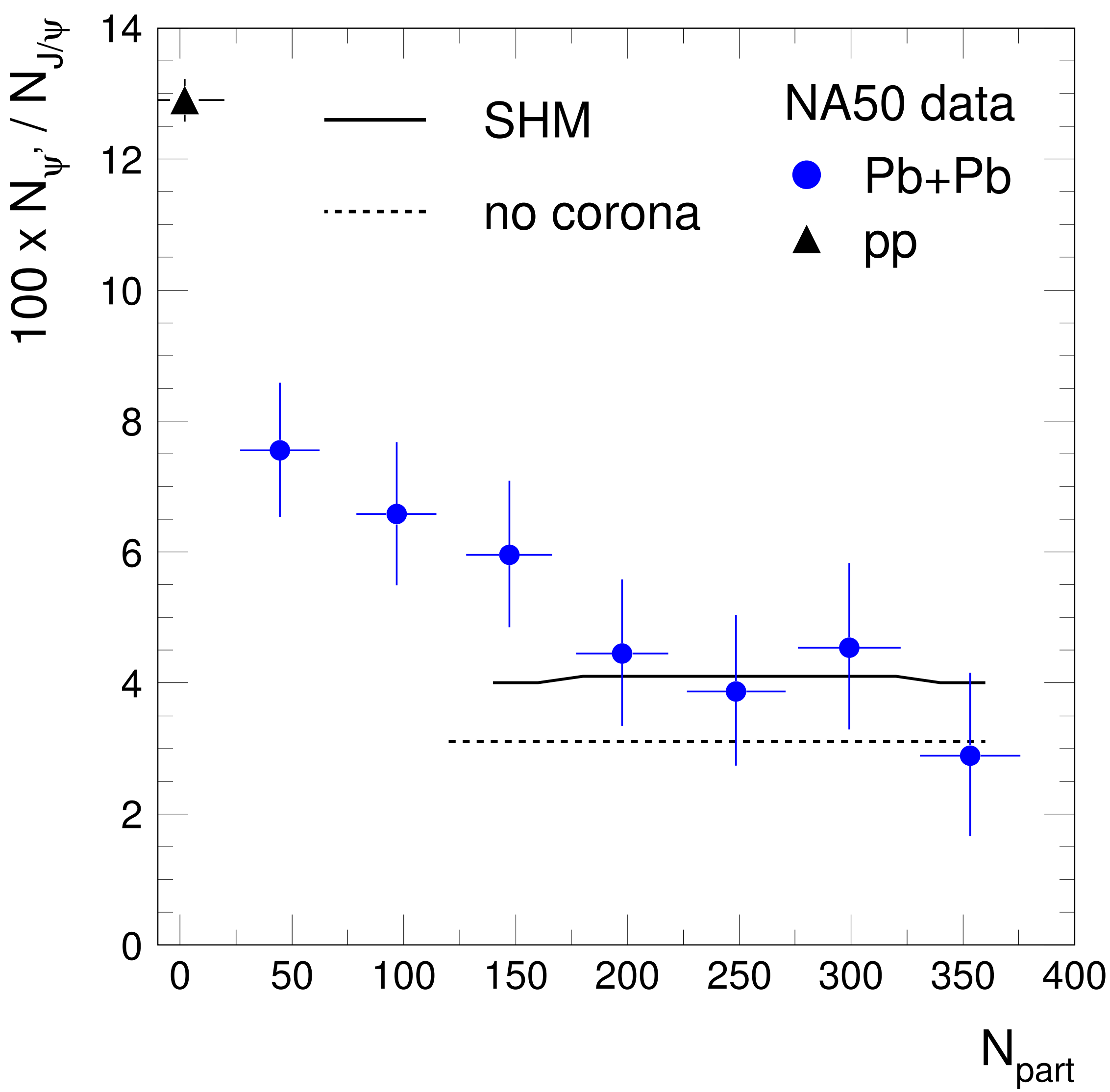


data explained with charm enhancement (2×pQCD)

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/ψ/DY, normalized):
EPJ C 39 (2005) 335

ψ' at SPS



NA50 Data:
PbPb: EPJ G49 (2007) 559
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

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

$=$0 in the screening model

(LQCD: ψ' melted at T_c)

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

Transverse momentum distribution

Expected shape:

Core: $\frac{1}{p_t} \cdot \frac{\mathrm{d}N}{\mathrm{d}p_t} \sim m_t \cdot I_0(\frac{p_t \mathrm{sinh} y_t}{T}) \cdot K_1(\frac{p_t \mathrm{cosh} y_t}{T})$,

$m_t = \sqrt{m_0^2 + p_t^2}, \qquad y_t = \tanh^{-1}(\beta)$

E. Schnedermann, J. Sollfrank, U. Heinz, Phys. Rev. C 48 (1993) 2462

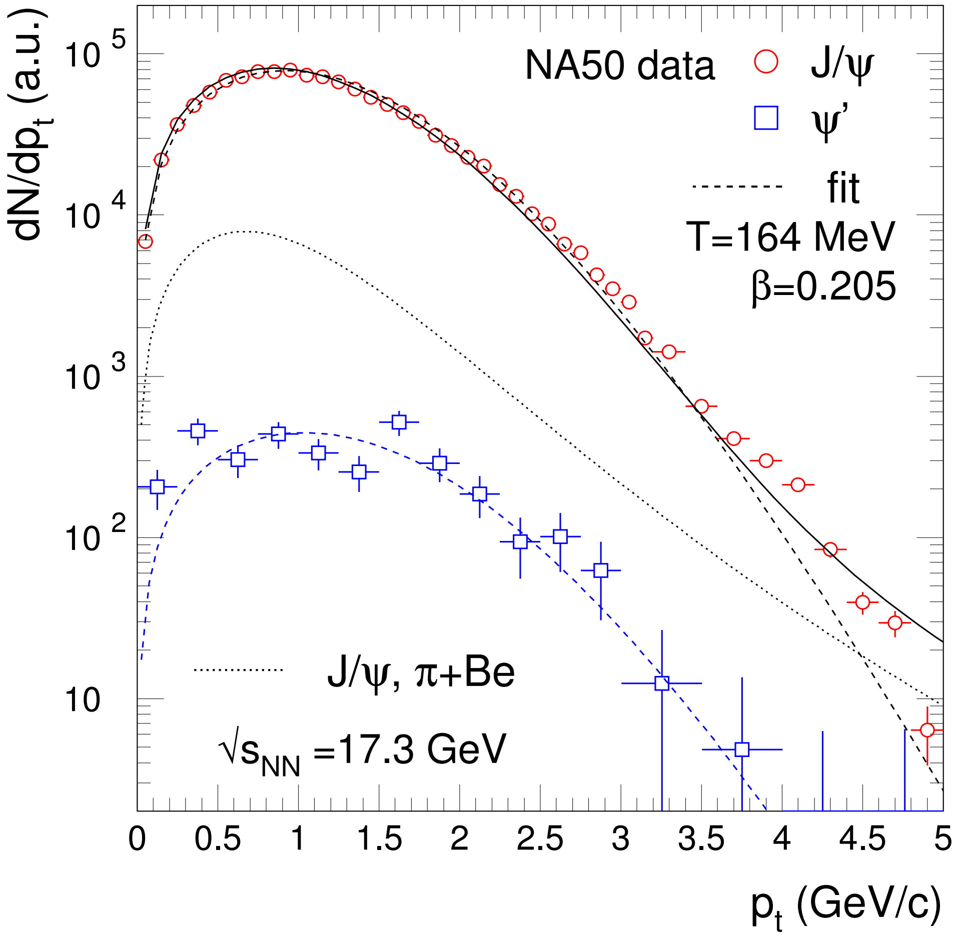
T = hadronization temperature (chemical freeze-out)

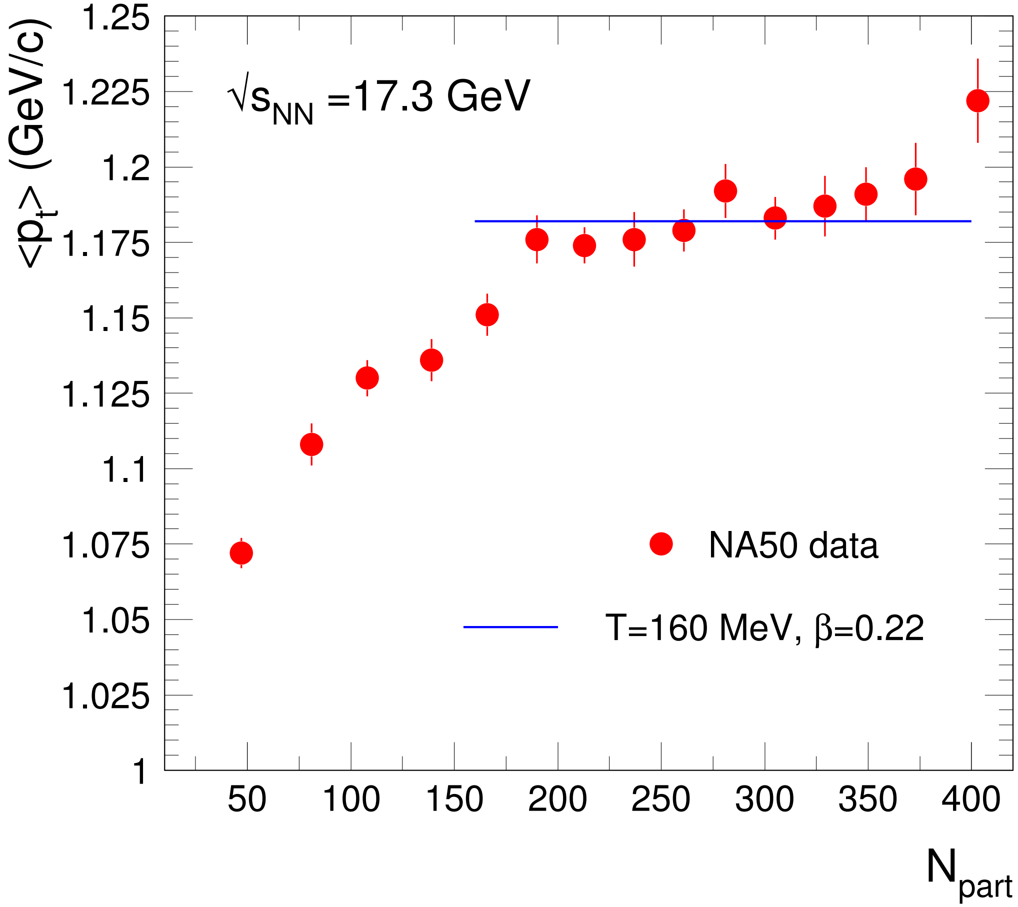
β = collective velocity acquired in QGP (average)

demonstrated at SPS: Gorenstein, Bugaev, Gazdzicki, PRL 88 (2002) 132301
first pointed out by Grandchamp, Rapp, PLB 523 (2001) 60

Corona: spectrum as in pp collisions

Transverse momentum: SPS

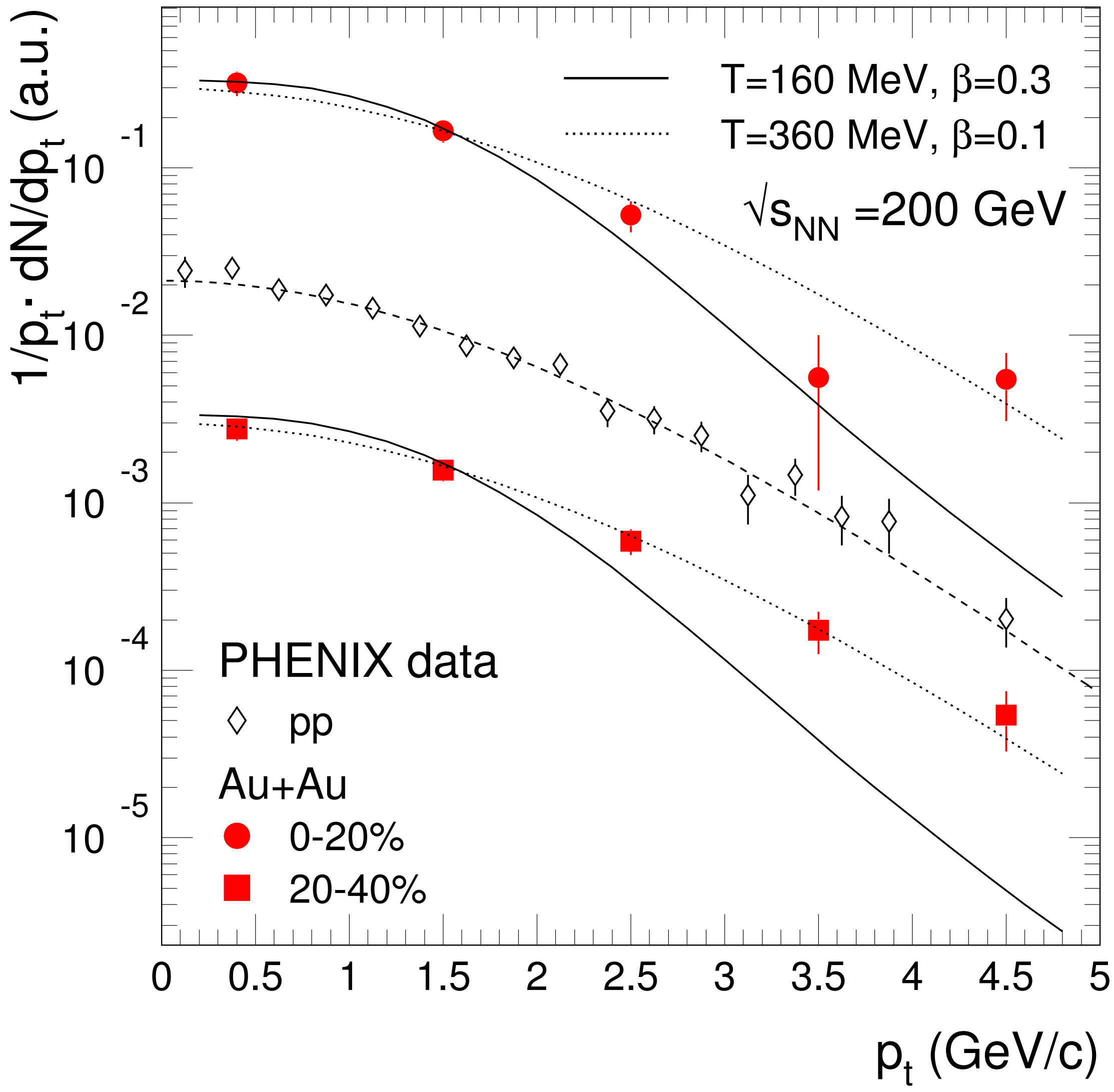




NA50 data, PLB 499 (2001) 85; spectra available only for MinB

good agreement with SH picture; $< p_t >$ cannot constrain T and β

J/ψ transverse momentum at RHIC

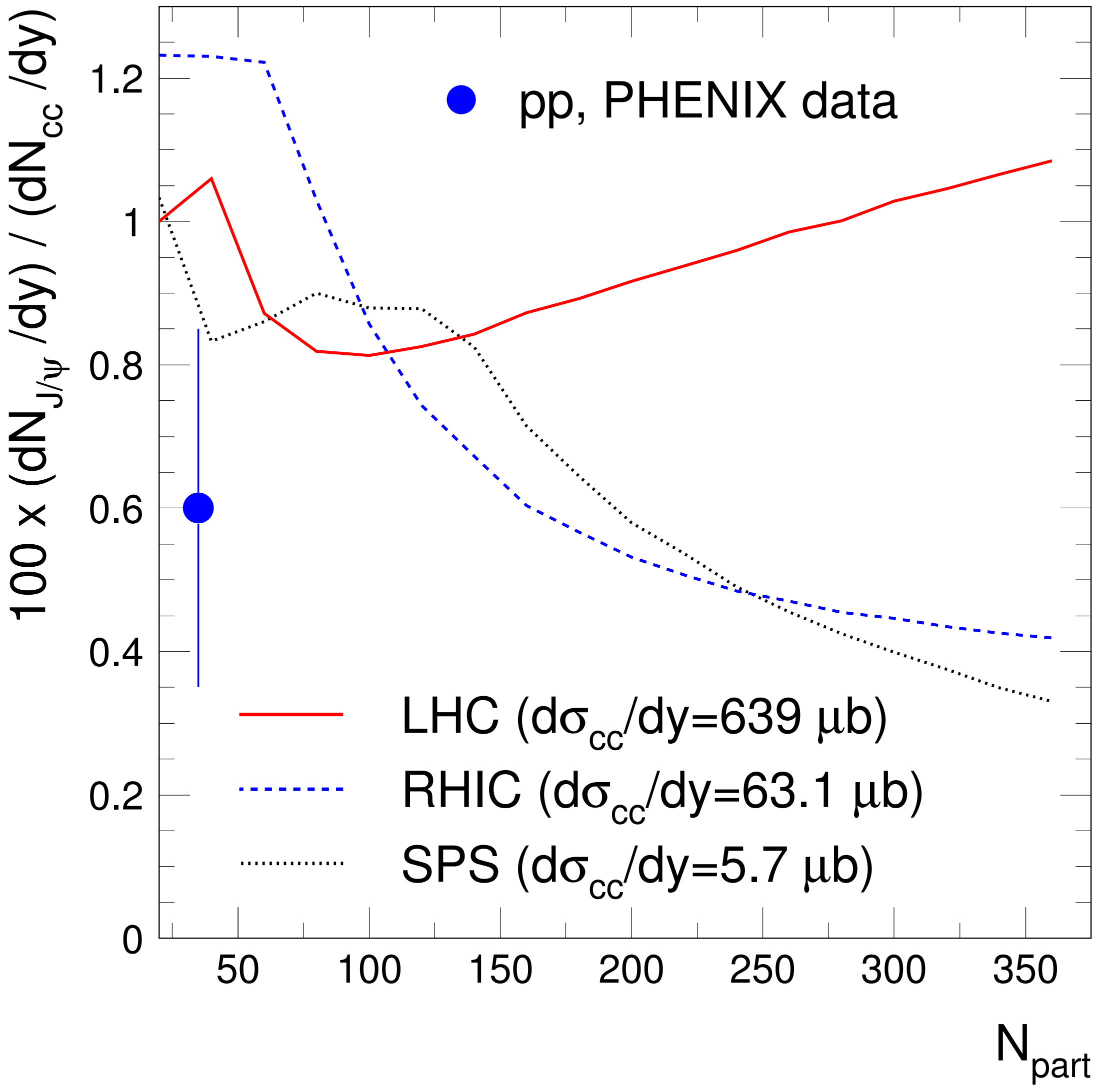


- consistent with SH picture
  $T=$ chemical freeze-out
  $\beta <$ kinetic freeze-out (0.4-0.6)
- ...but also consistent to pp-like

  see also:

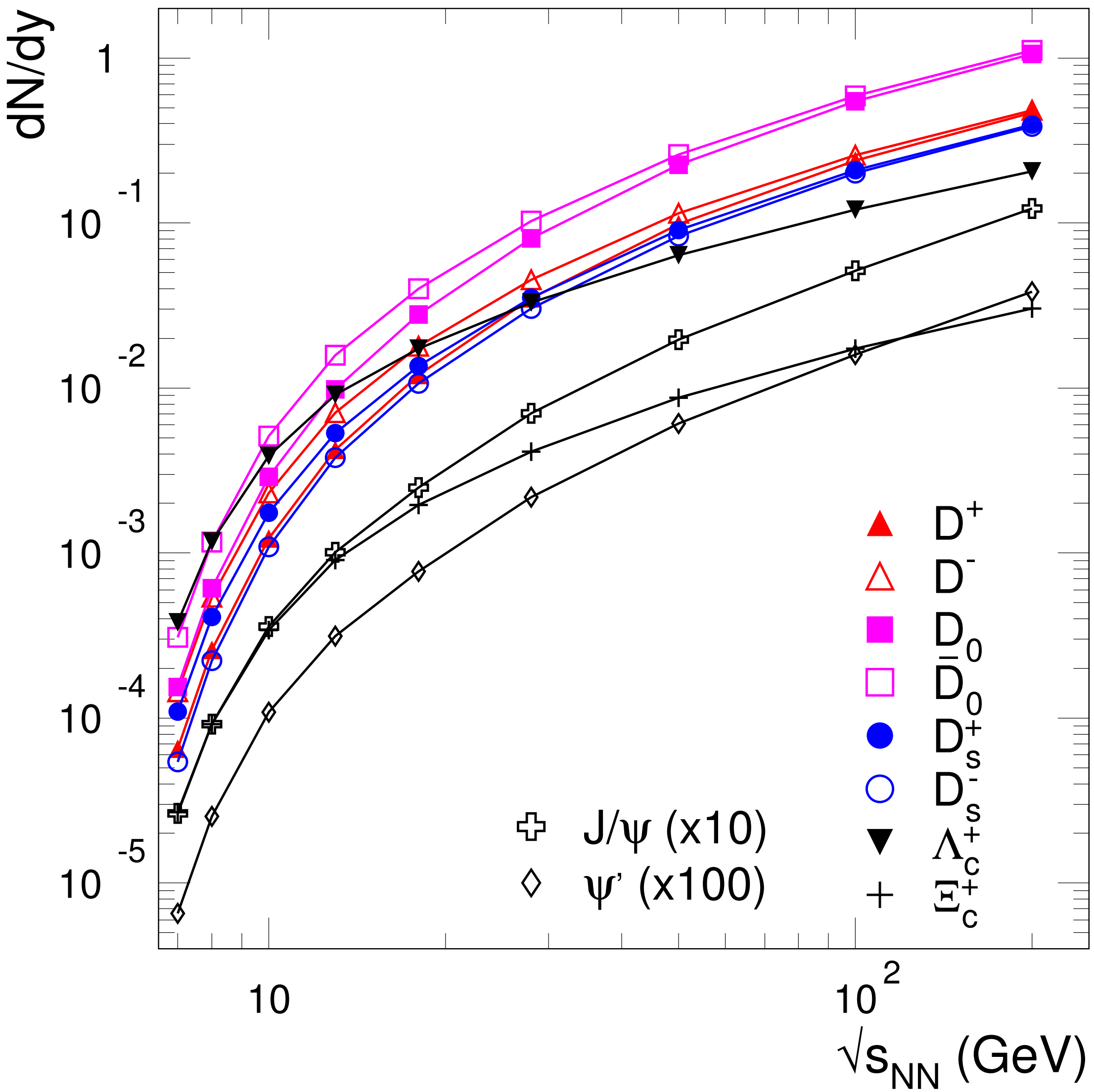
  Thews, Mangano, PRC 73 (2006) 014904

J/ψ production relative to charm



- ...the most "solid" observable
  ...with similar features as R_{AA}
- similar values at RHIC and SPS
  ...with differences in fine details
  ...determined by canonical suppression of open charm
- enhancement-like at LHC
  can. suppr. lifted, quadratic term dominant

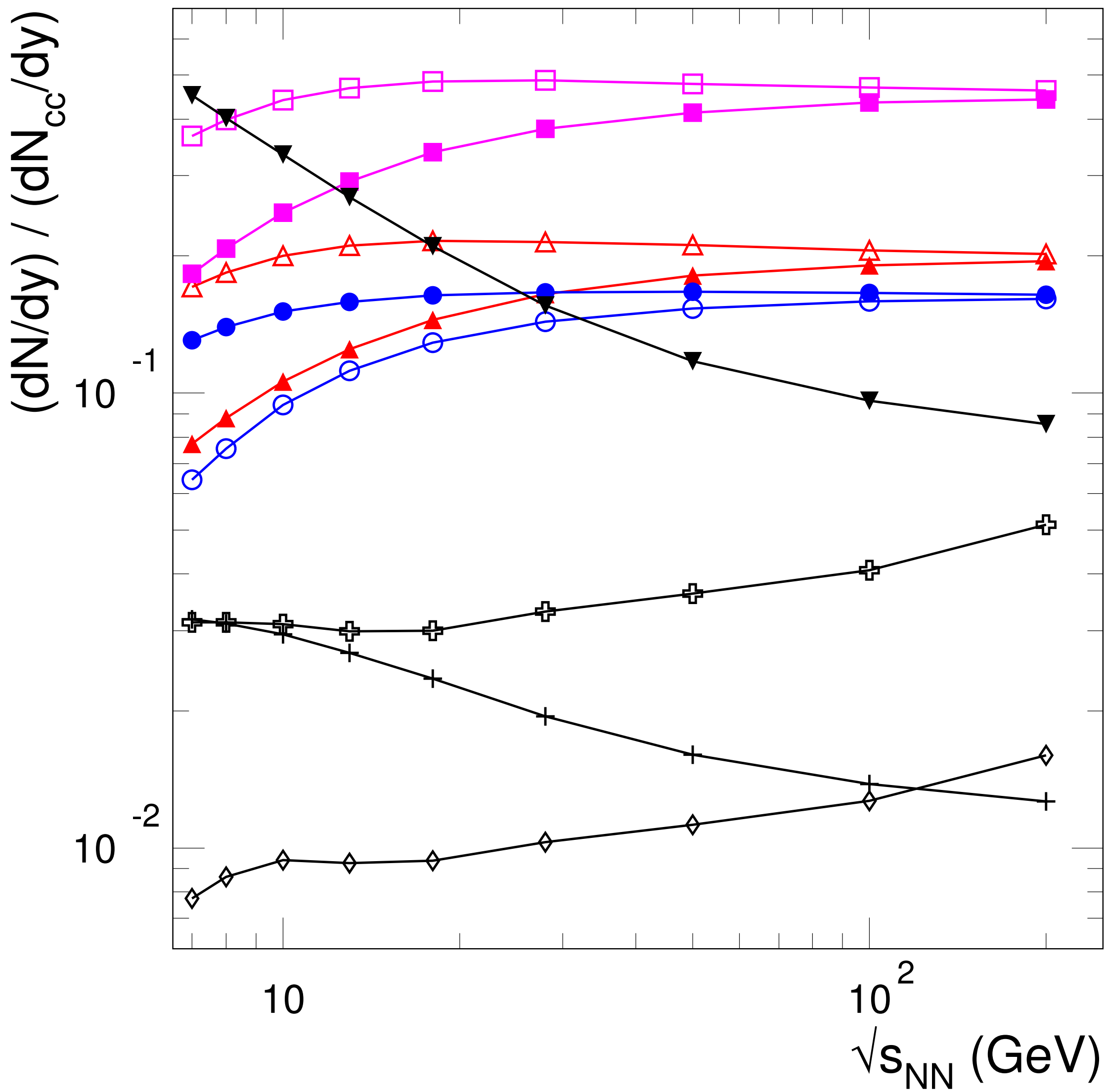
Charm at lower energies



- is charm thermalized?
- strong decrease of yields determined by initial charm production cross section
- Λ_c prod. favored at large μ_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 2

yields per initial charm pair



- Λ_c:
  dominant at low energies
  exp. reconstruction difficult
  it's a must at FAIR (CBM)
- ψ'/ψ 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

Reminder of timescales for charm production

Karsch & Petronzio, PLB 193 (1987) 105, Blaizot & Ollitrault, PRD 39 (1989) 232

- QGP formation time, t_{QGP}
  - SPS (FAIR): $t_{QGP} \simeq 1$ 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/ψ at SPS/FAIR energies? $(T_d \sim T_c)$

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

cold nuclear suppression (breakup) important at SPS/FAIR energies?

shadowing is yet another (cold nuclear) effect - important at LHC (RHIC?)

NB: the only way to distinguish: measure $\sigma_{c\bar{c}}$ in pA and AA

More timescales

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

Scenarios of in-medium modified masses

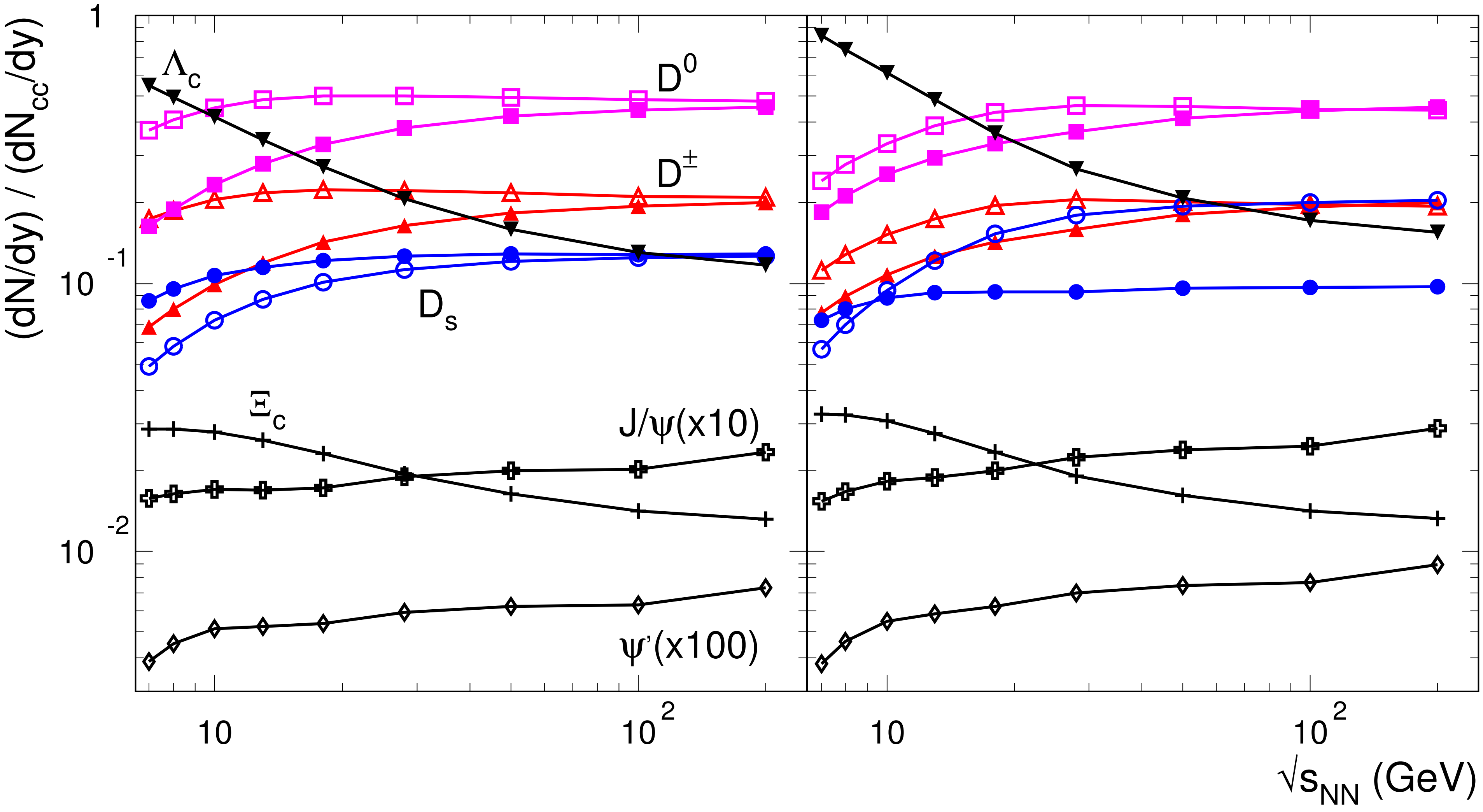
modification of the constituent quark masses of light (u and d) quarks
(no change of J/ψ mass, $\Delta m_{\Lambda_c}/2$ for Ξ_c)

case	Δm_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 (Λ_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

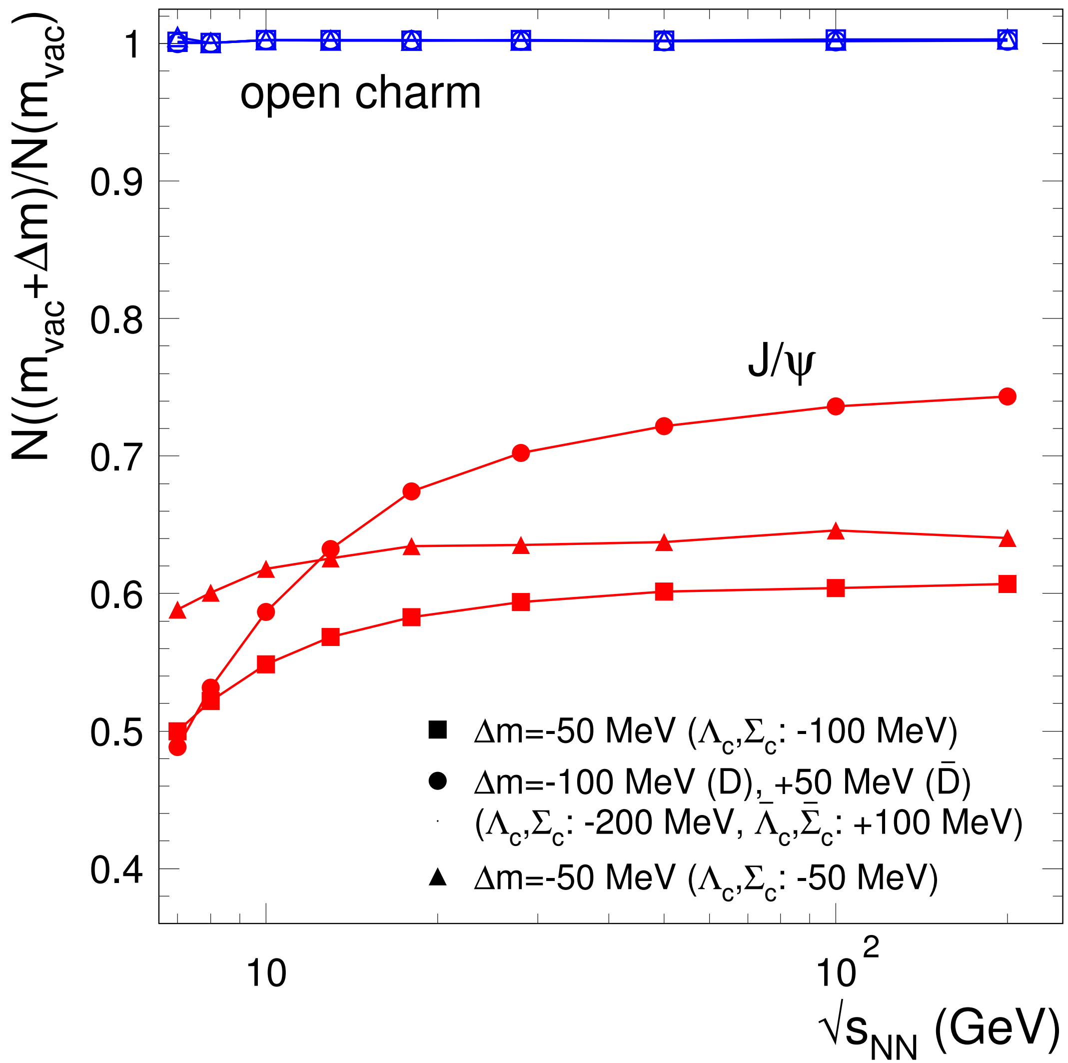
- open charm: very small increase
- ...with large effect on charmonia

  (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])
- of similar magnitude as other (cold) effects



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/ψ data at SPS and RHIC

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

Open questions

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

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