Heavy quark(onium) at LHC: the statistical hadronization case

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- The statistical hadronization model: assumptions and inputs
- Charmonium: the LHC case in light of the SPS and RHIC data
- Complete charm chemistry and charm at FAIR
- Quarkonium in elementary (e^+e^-, pp, pA) vs. AA collisions
- 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

PLB 675 (2009) 334, arXiv:0804.4132 ; PLB 678 (2009) 350, arXiv:0904.1368

Statistical hadronization: assumptions

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

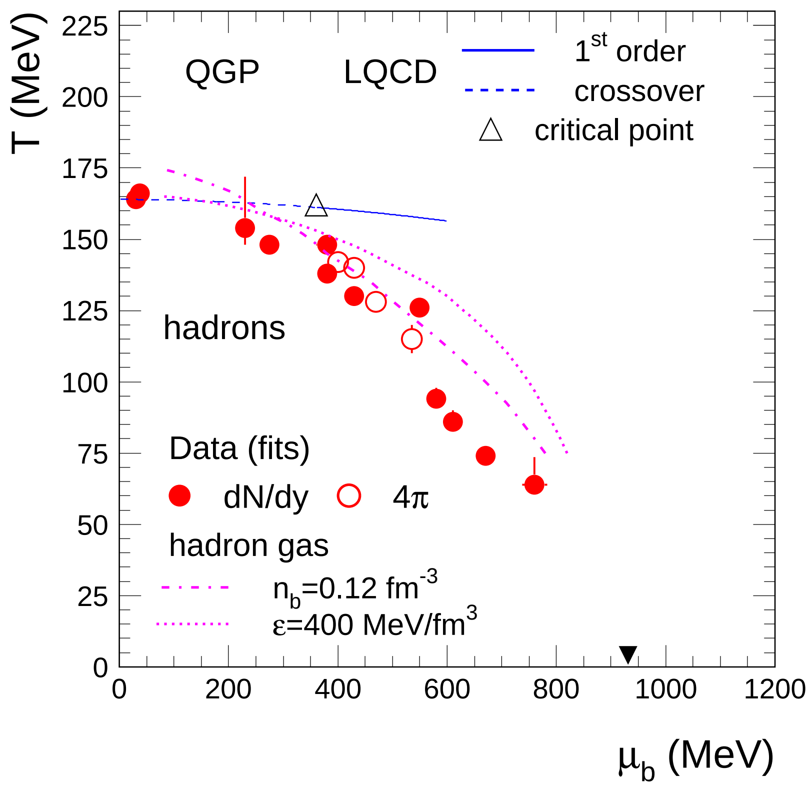
- all charm quarks are produced in primary hard collisions ($t_{c\bar{c}} \sim 1/2m_c \simeq$ 0.1 fm/c)
- survive and thermalize **in QGP** (thermal, but not chemical equilibrium)
- charmed hadrons are formed at chemical freeze-out together with all hadrons

  statistical laws, quantum nr. conservation

  stat. hadronization $\neq$ coalescence

  is freeze-out at(/the?) 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

Timescales for charm(onium) 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

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):

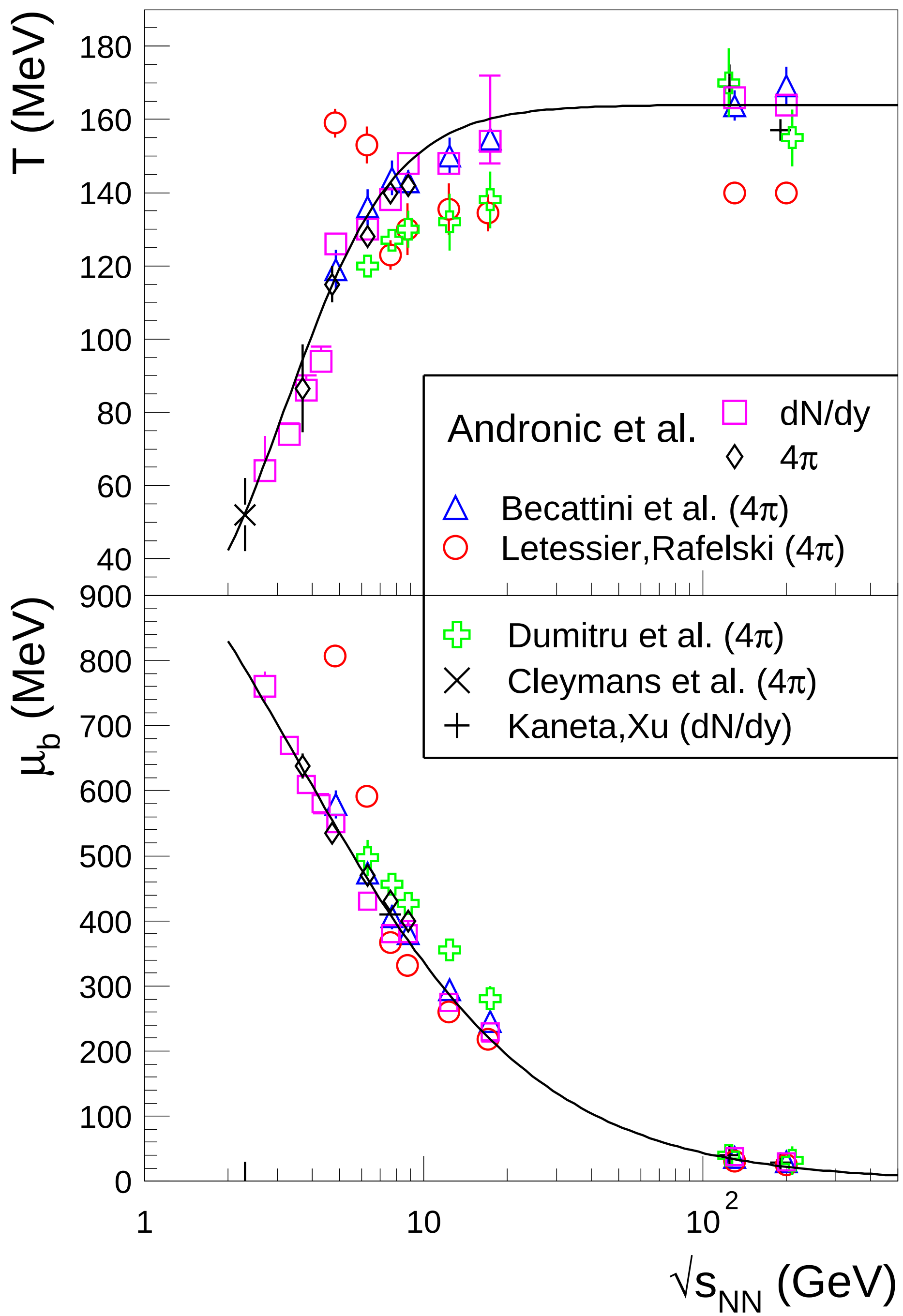
$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c \text{ (charm fugacity)}$$

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.)

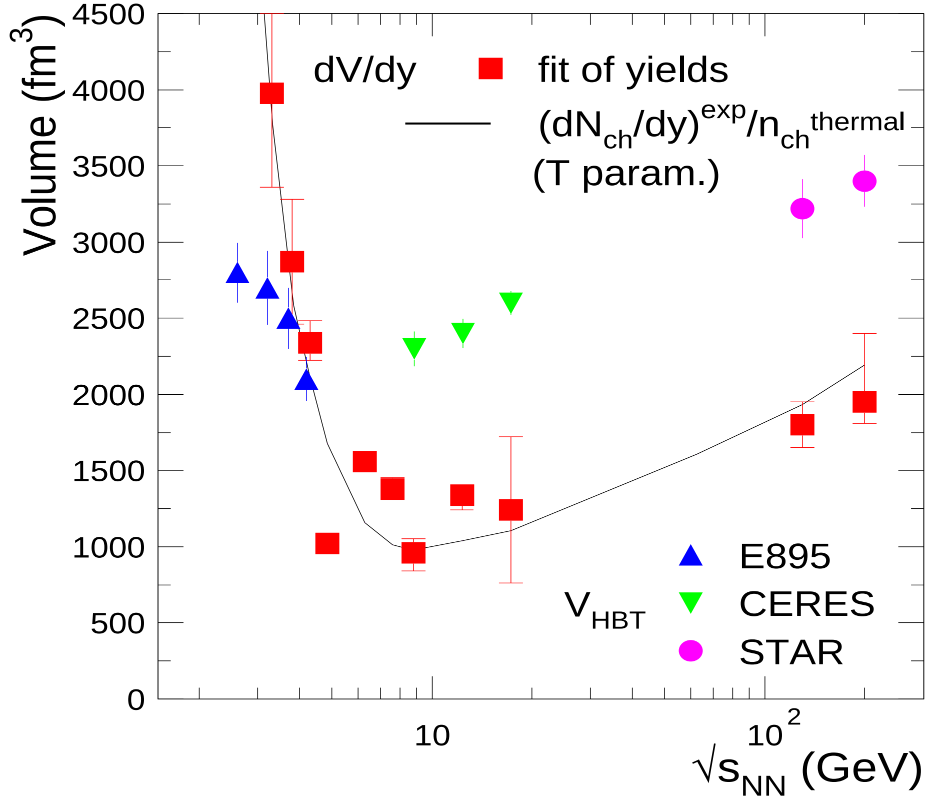
Minimal volume for QGP: V_{QGP}^{min}=400 fm^3

Thermal parameters: from fits to data



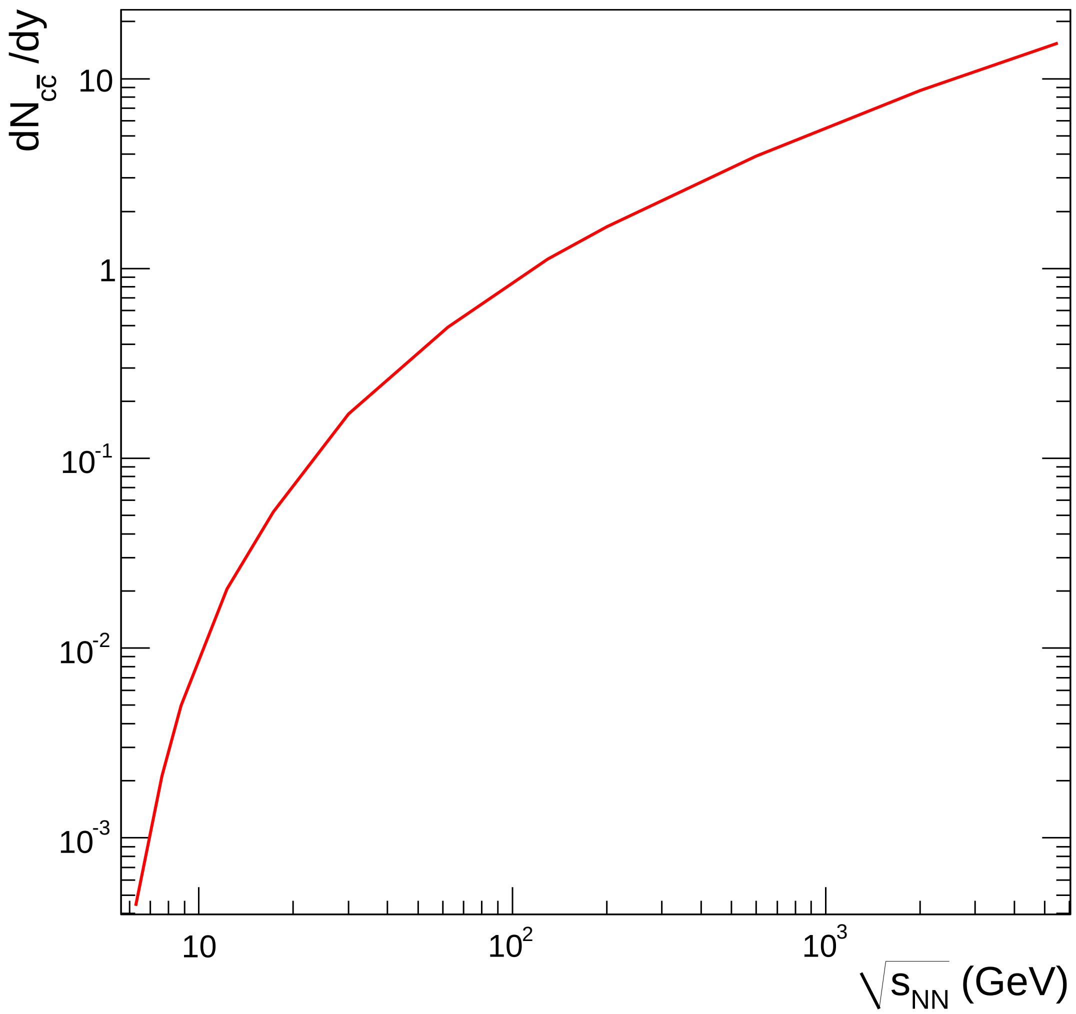
...well constrained

PLB 673 (2009) 142



LHC: (T,μ_b)=(164,0.8) MeV
dV/dy=6200 fm^3

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



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

NLO (CTEQ5M) extrapolated below 15 GeV (large uncertainty)

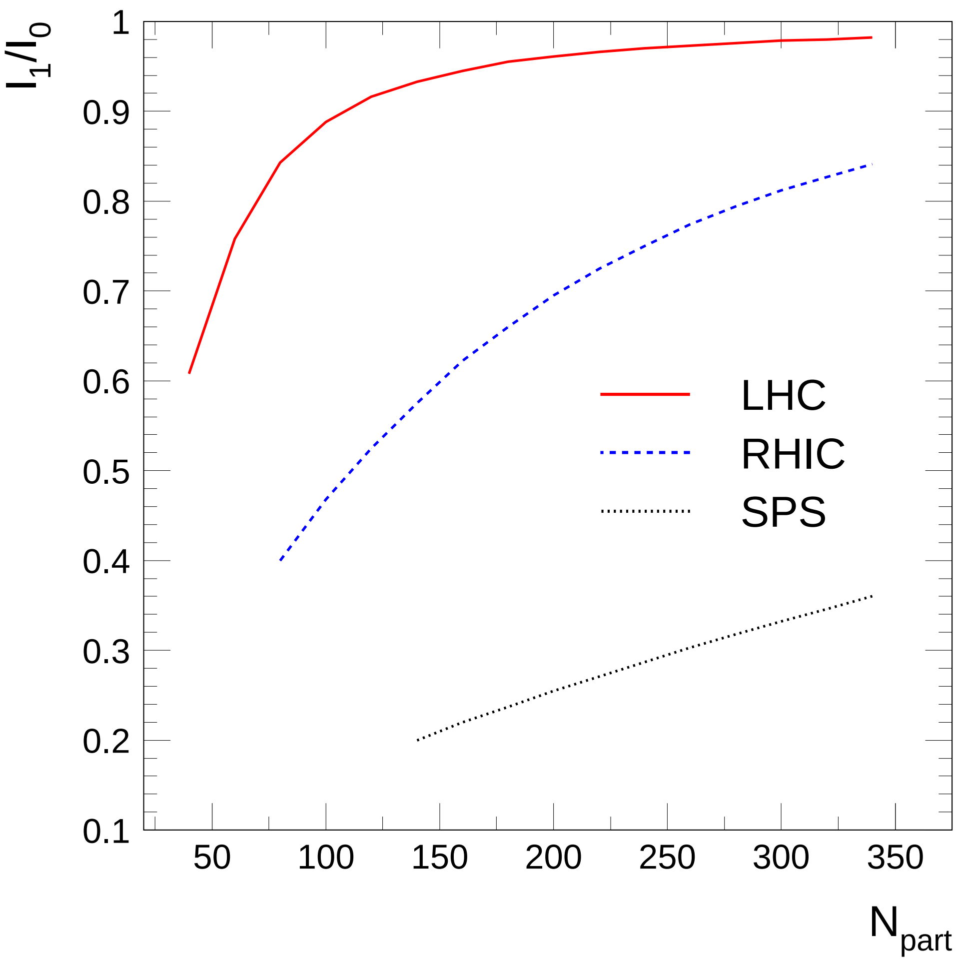
pQCD is not parameter-free!
(PDF, m_c, μ_R, μ_F) ...$\times$2 err.↑↓

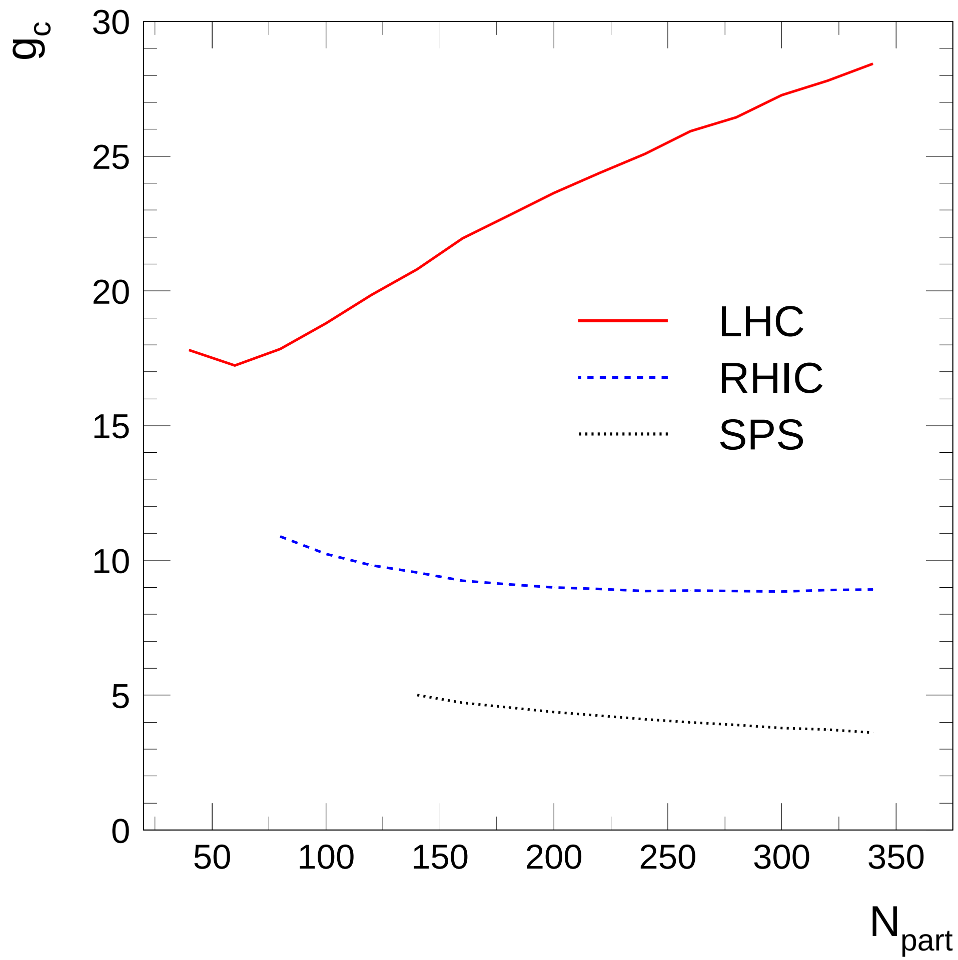
$dN_{c\bar{c}}/dy$ for central collisions (N_{part}=350):

SPS: $\simeq$0.05, RHIC: $\simeq$1.6, LHC: $\simeq$16

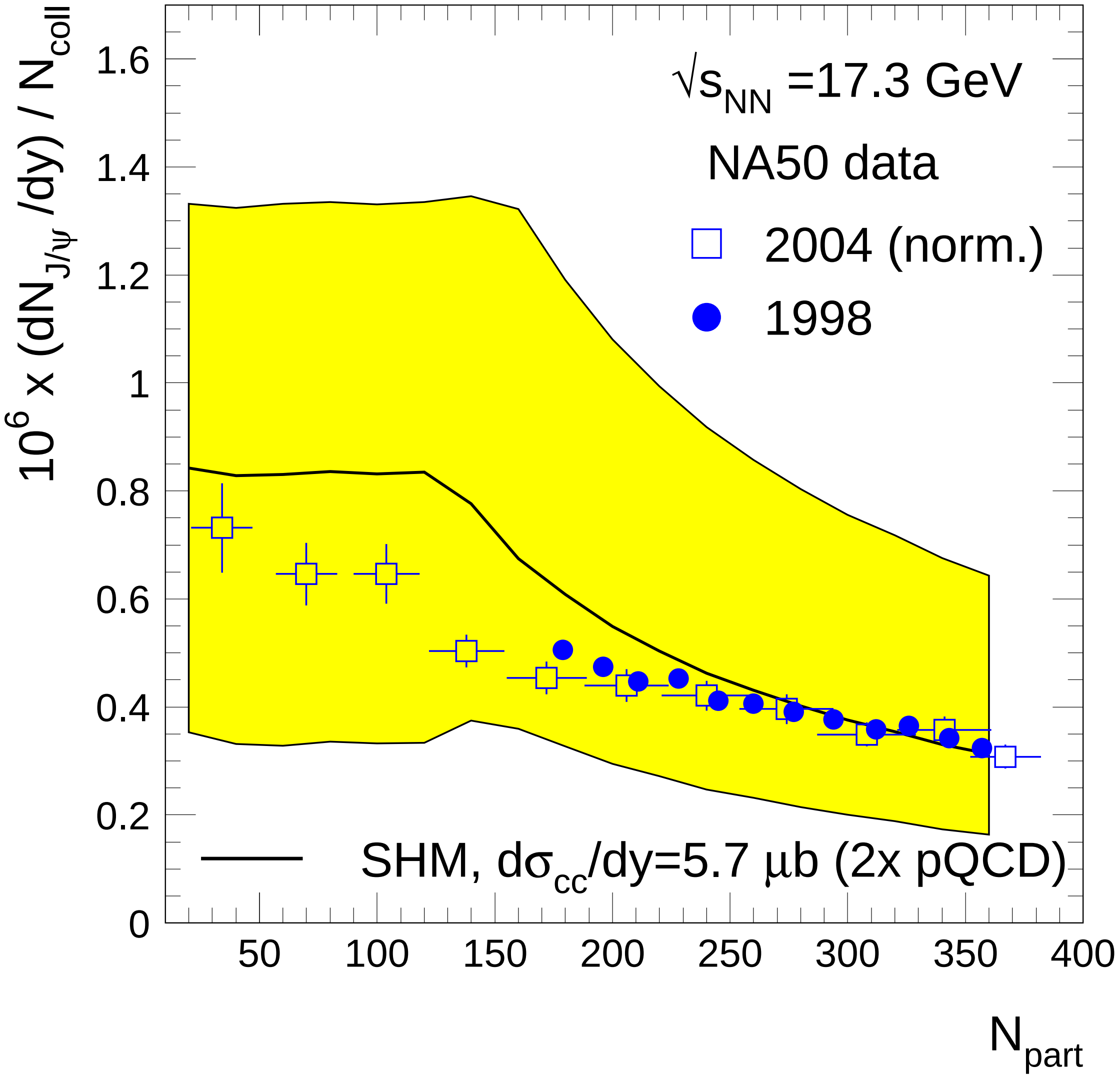
Canonical suppression and charm fugacity

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





J/ψ at SPS

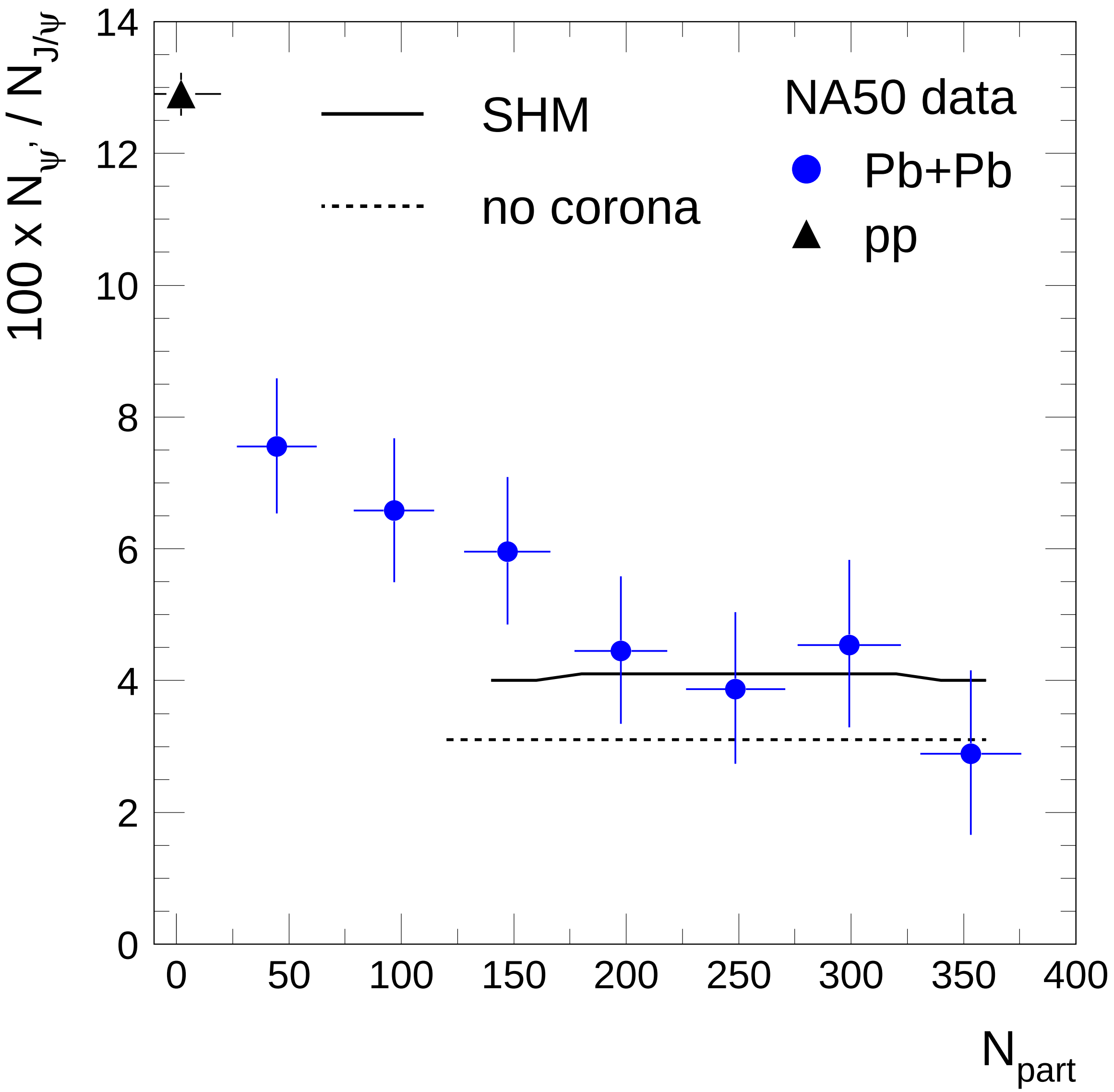


data explained with charm enhancement (2×pQCD)

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

Another powerful charmonium: ψ' (SPS)



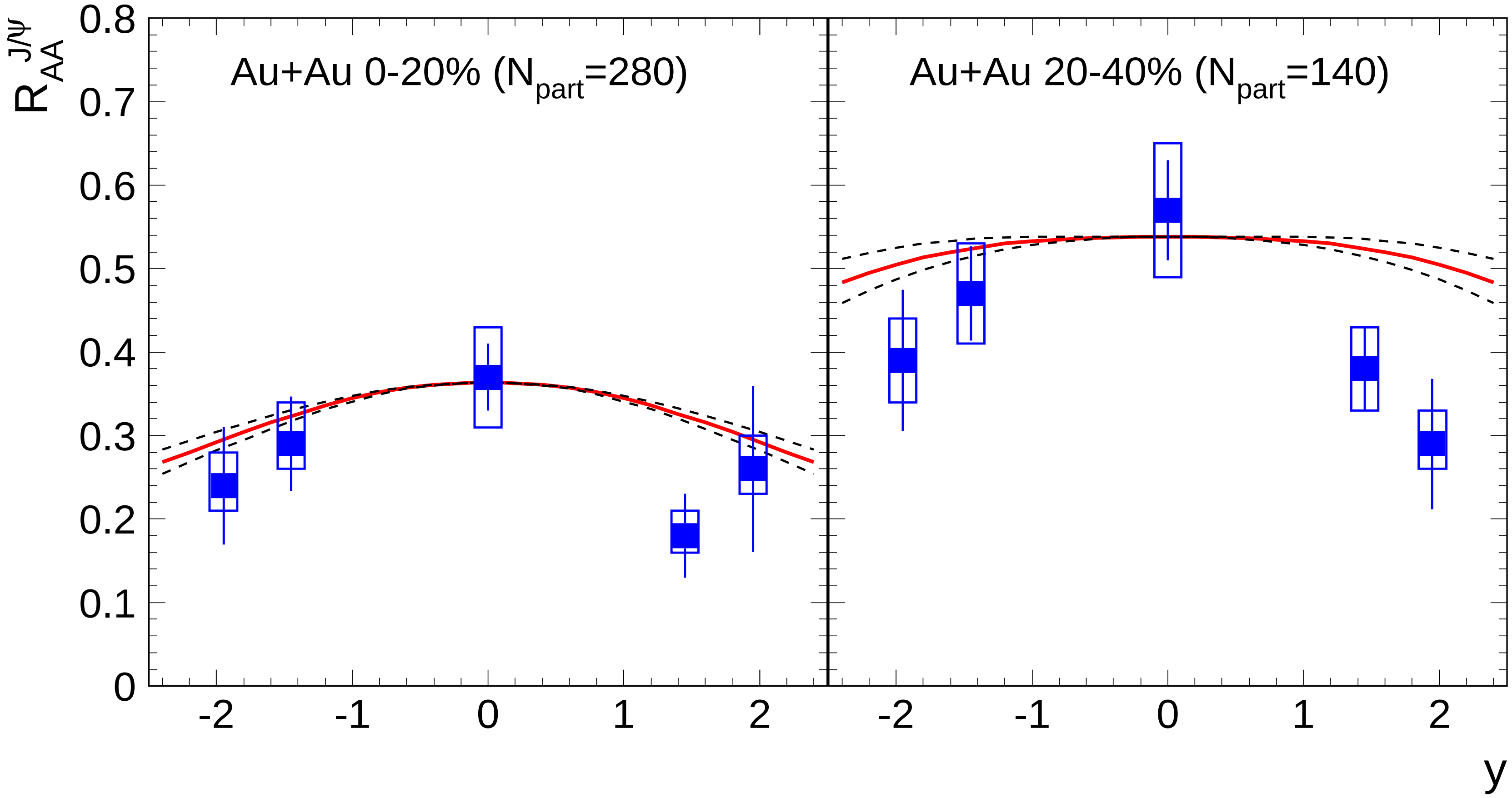
NA50 Data:
PbPb: EPJ C49 (2007) 559
pp: PLB 466 (1999) 408

good agreement
(good agreement also for J/ψ)

$N_{\psi'}/N_{\psi} \neq 0$!
contradicts screening model
(LQCD: ψ' melted at T_c)

strong indication of ψ' prod. via statistical hadronization

J/ψ at RHIC: rapidity dependence, R_{AA}

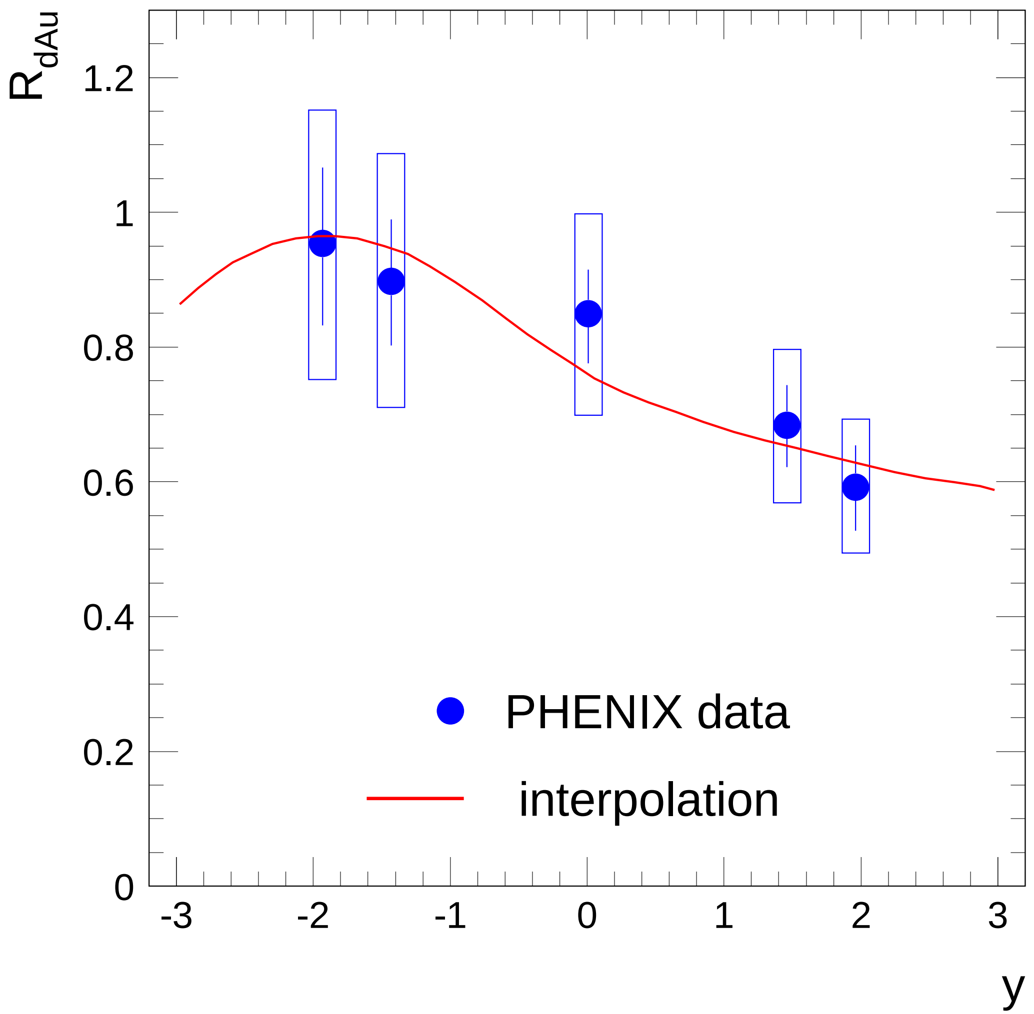


Model: red: J/ψ pp ref. fit 1-gaussian (dotted: error on σ); pQCD $\sigma_{c\bar{c}}$

evidence for statistical hadronization of charmonium (enhanced at y=0)

J/ψ in dAu (RHIC)

PHENIX, PRC 77 (2008) 024912, arXiv:0711.3917



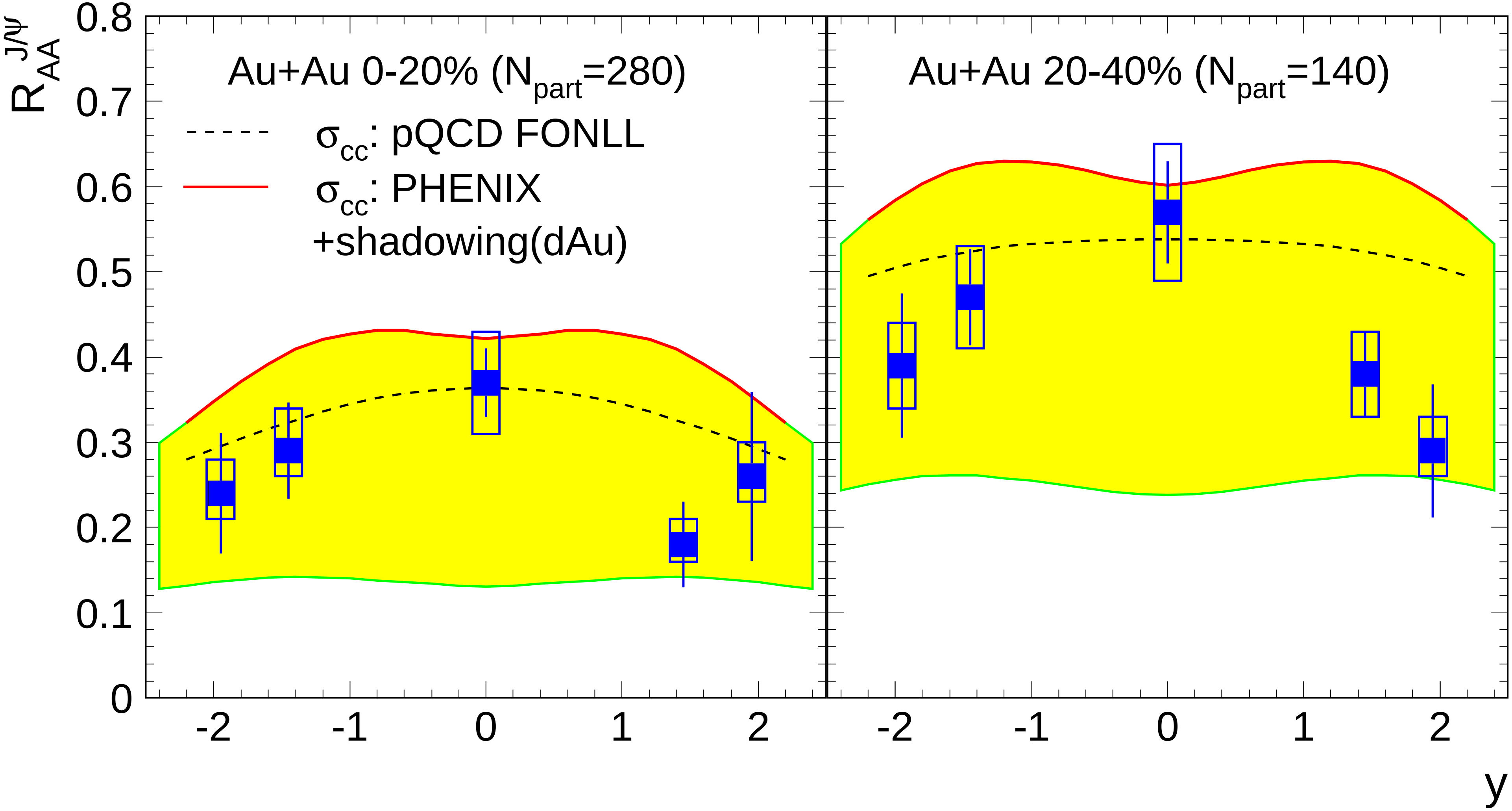
assume R_{dAu} of J/ψ as due only to shadowing of initial charm production cross section:

$$\sigma_{AuAu}^{c\bar{c}} = R_{AuAu}^{J/\psi-shad} \cdot \sigma_{pp}^{c\bar{c}}$$

where $R_{AuAu}^{J/\psi-shad}$ (nuclear modification due to shadowing) is:

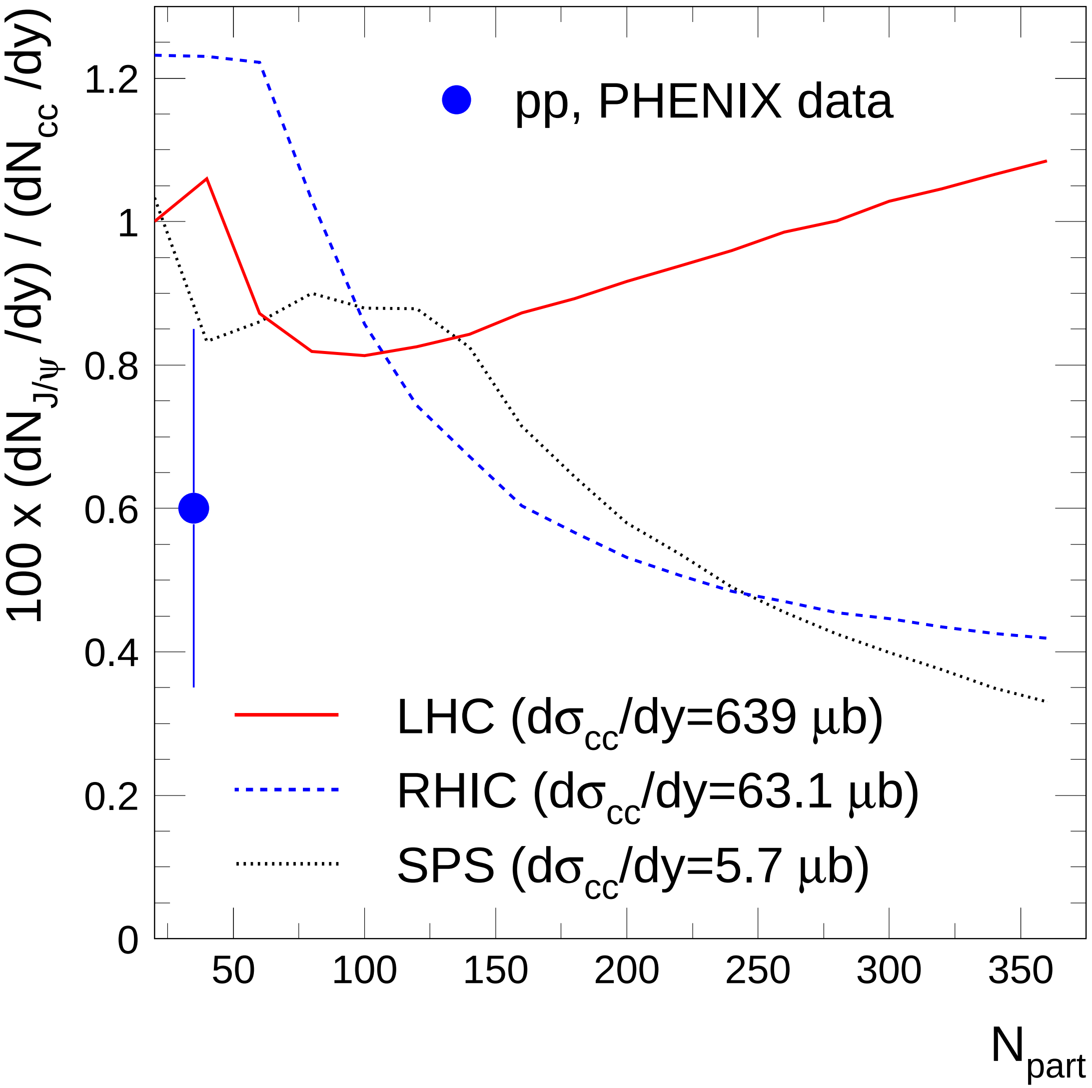
$$R_{AuAu}^{J/\psi-shad}(|y|) = R_{dAu}^{J/\psi}(y) * R_{dAu}^{J/\psi}(-y)$$

J/ψ at RHIC: effect of shadowing



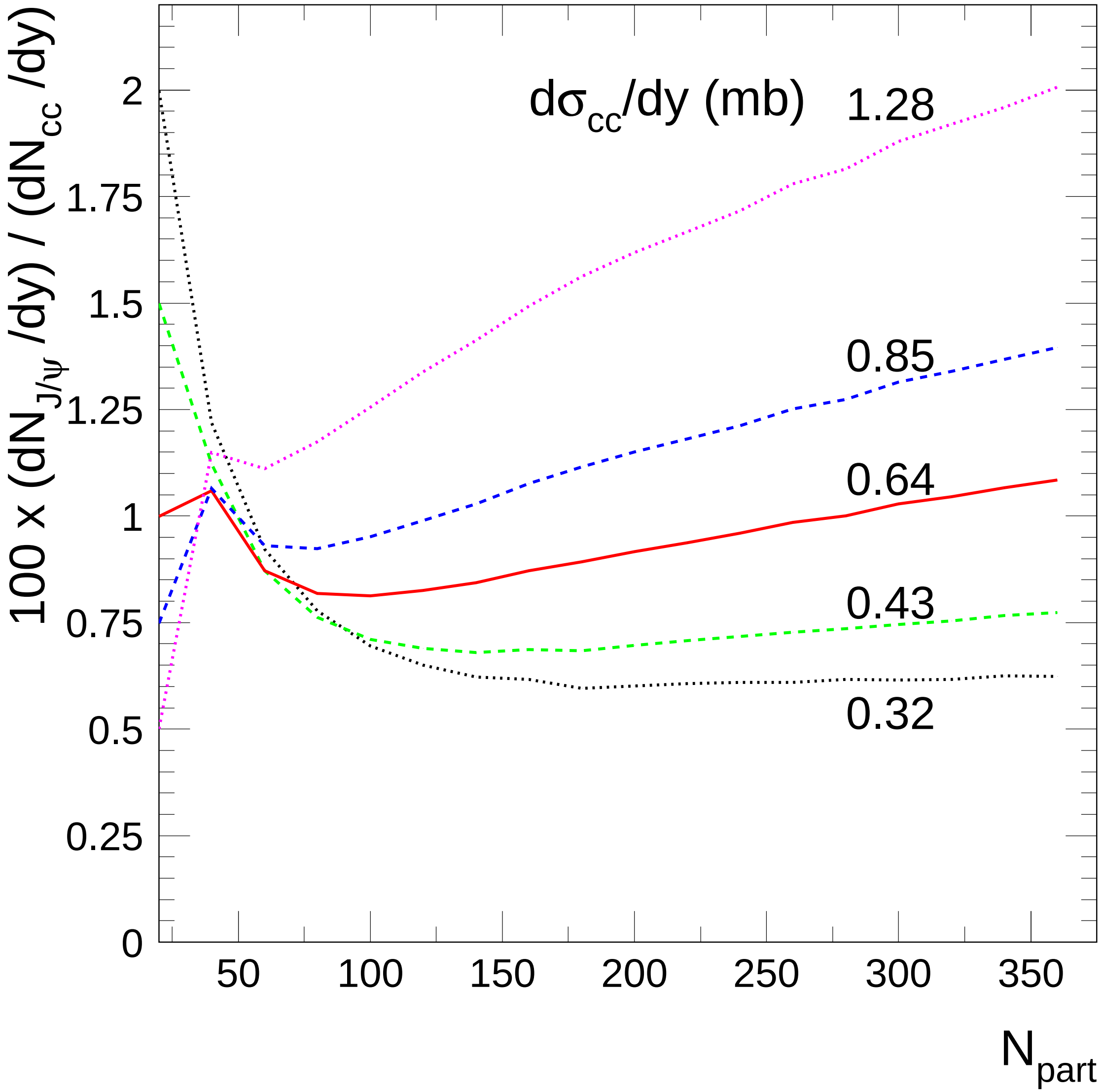
model describes data with PHENIX $\sigma_{c\bar{c}}$ (lower error plotted)

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

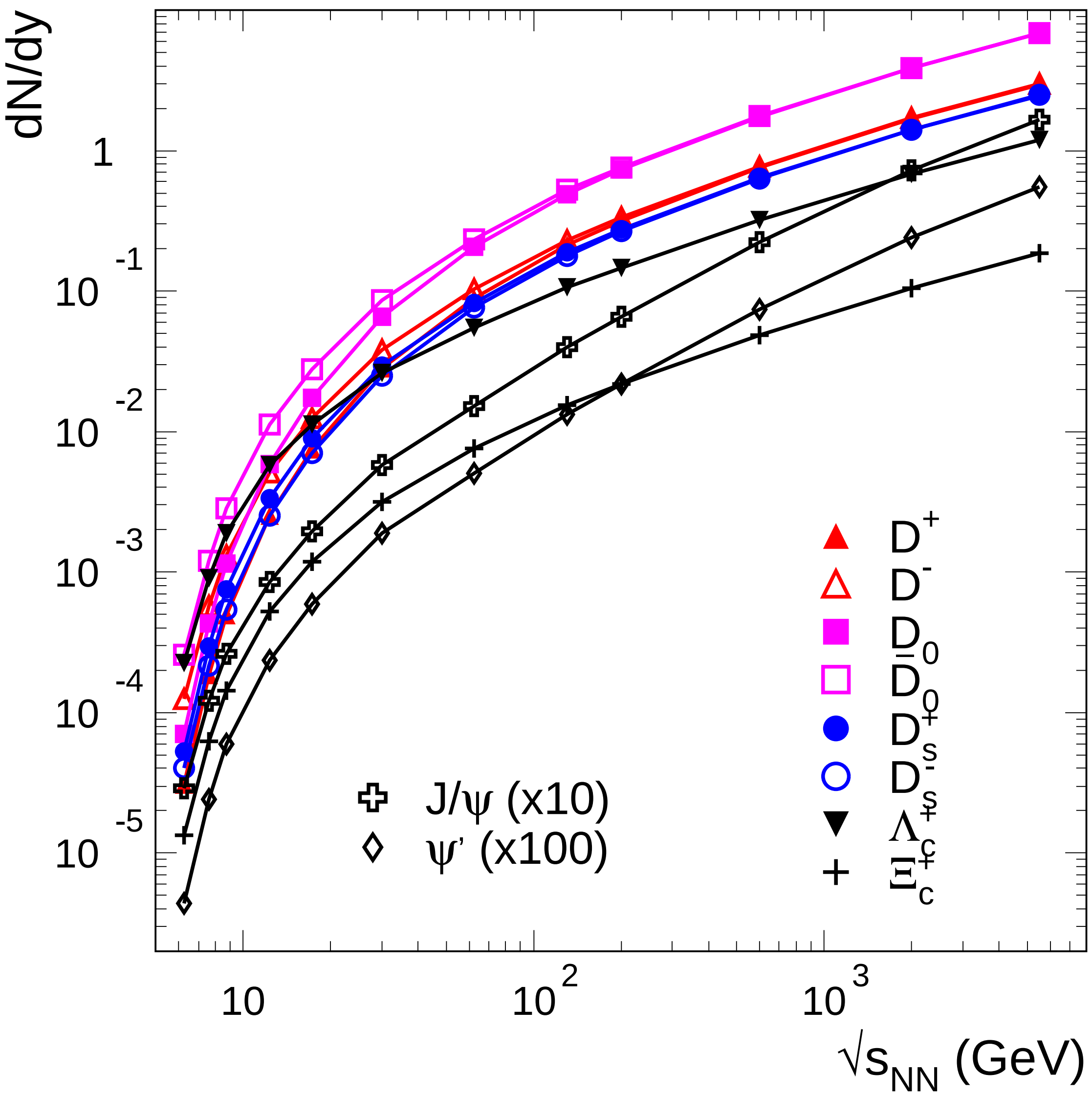
J/ψ at LHC



solid expectations for LHC

...providing we know well (from measurements) the charm production cross section

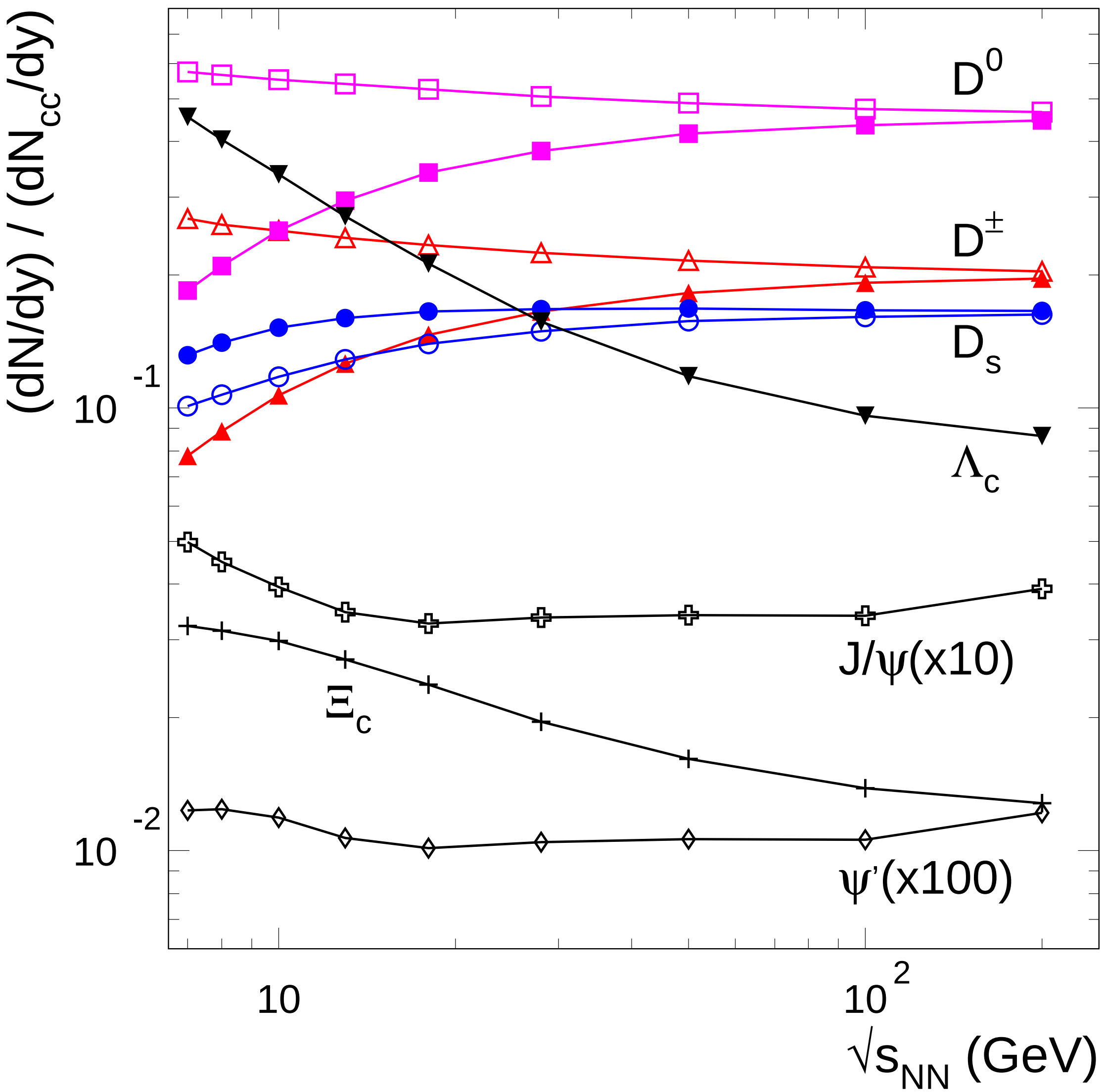
Overall charm chemistry



yields per initial charm pair

- Λ_c prod. favored at large μ_b
  ...it's a must at FAIR (CBM)
- isospin is important
- 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

Overall charm chemistry



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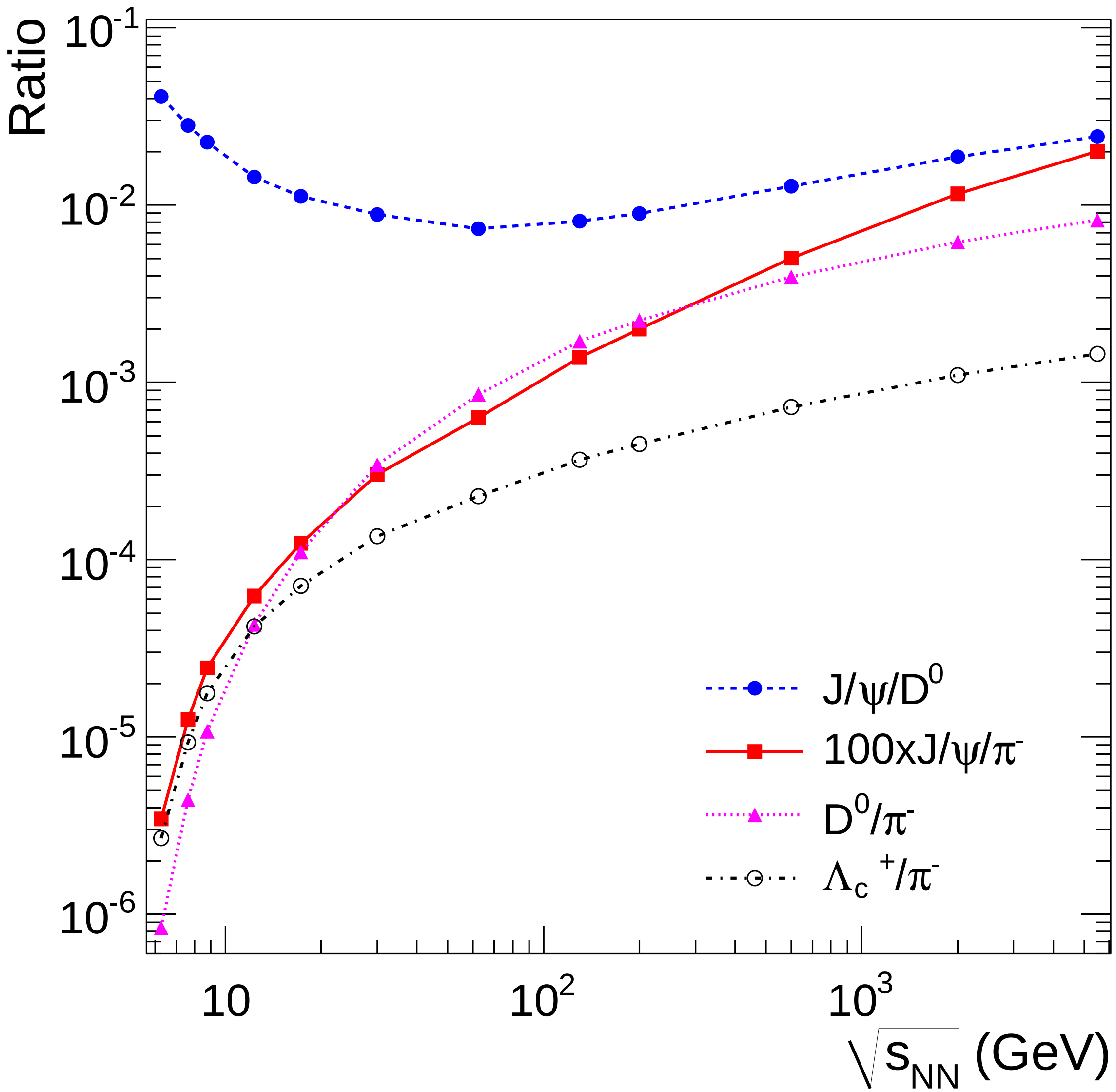
Ratios of charmed hadrons to pions



- no "horn"-type structues (at variance to strangeness)
- ...due to strong canonical suppression (up to RHIC)
- $J/\psi/D^0$: non-monotonic due to can. suppr. (of D) and energy dep. of $\sigma_{c\bar{c}}$

Effect of modified masses

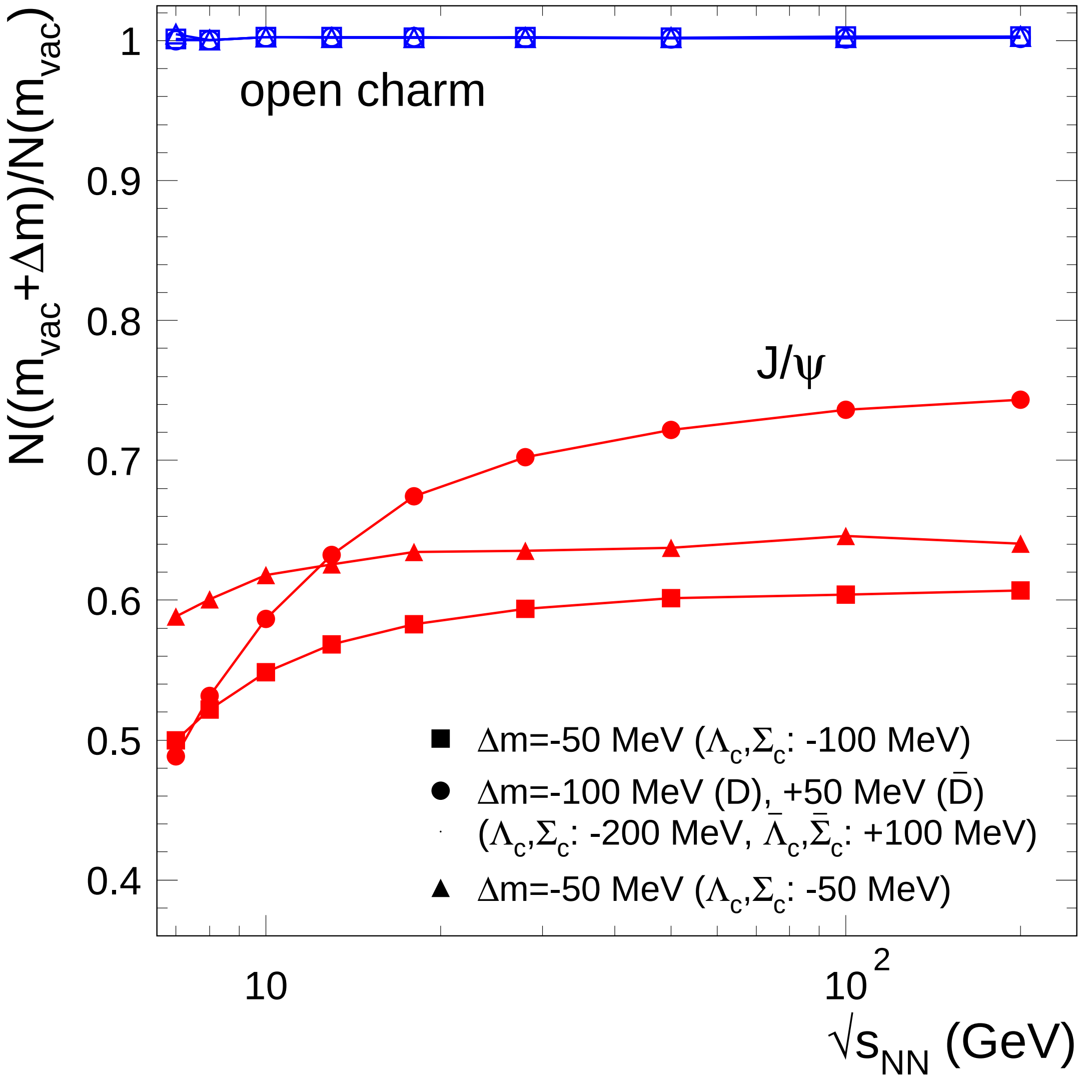
yield with in-medium mases (for open charm hadrons) relative to vacuum masses

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

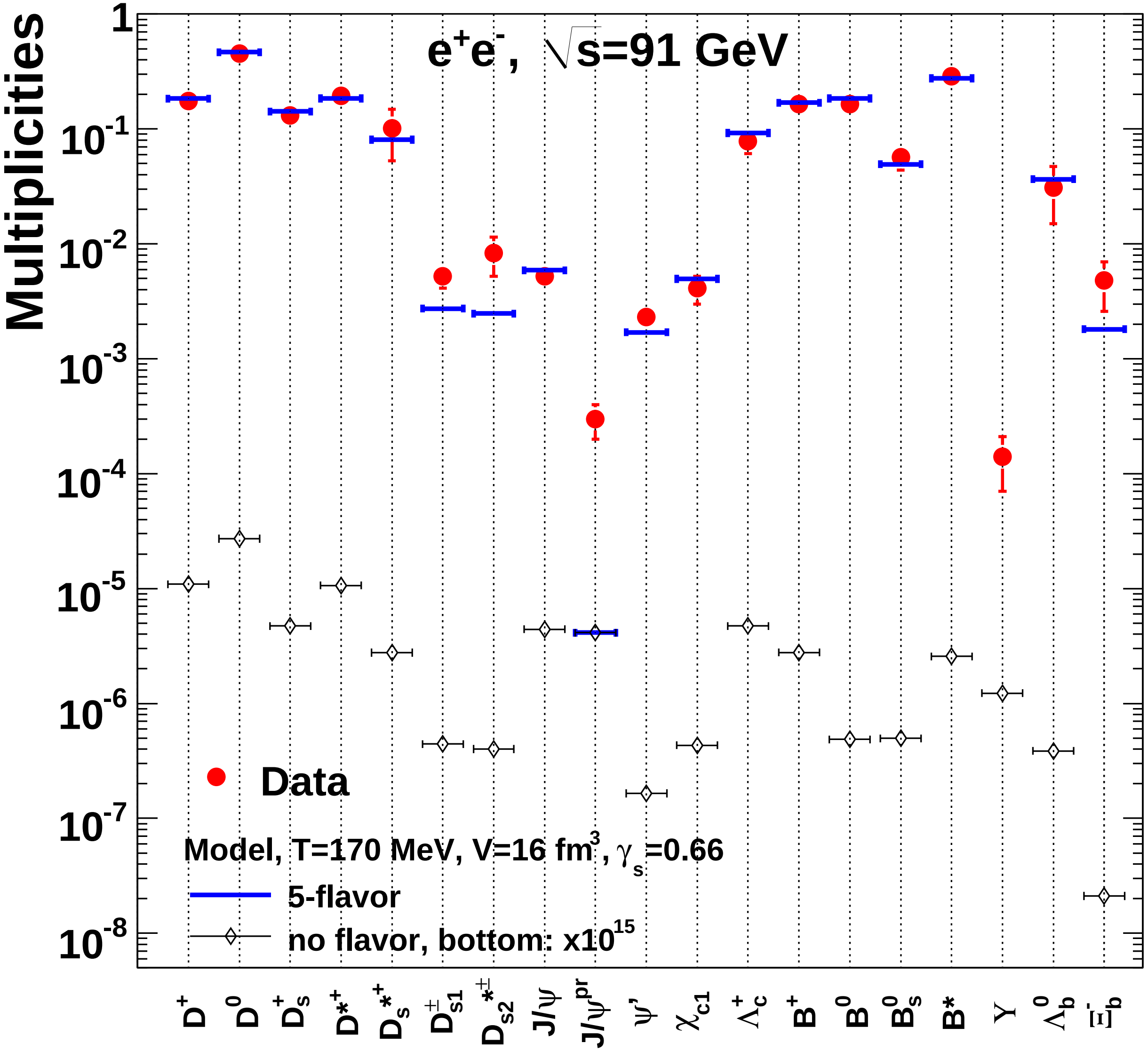
$\sigma_{c\bar{c}} = \frac{1}{2}(\sigma_D + \sigma_{\Lambda_c} + \sigma_{\Xi_c} + ...) + (\sigma_{\eta_c} + \sigma_{J/\psi} + \sigma_{\chi_c} + ...)$

is not affected by medium

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



Heavy quarks in e^+e^- collisions



- open flavor hadrons strongly underpredicted in a pure thermal model (no flavor)

  very different compared to u,d,s flavors

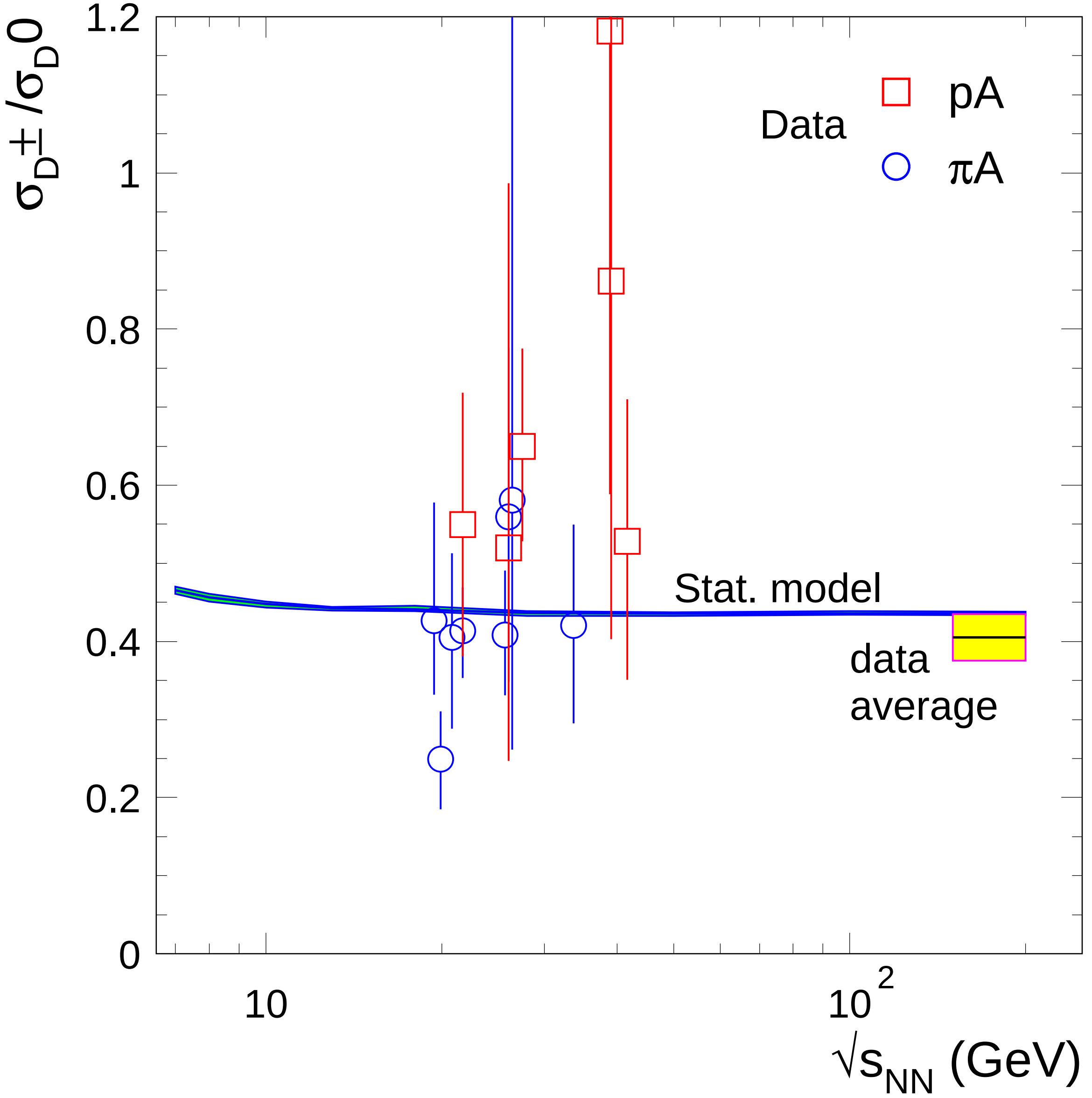
- agreement if $\mathrm{BR}(Z^0 \rightarrow q\bar{q})$ are used in the model (5-flavor)!

  (T, γ_s, V from fits of u,d,s flavors)

  see also Becattini et al, EPJ C 56 (2008) 493

- quarkonia strongly underpredicted (95% J/ψ is from B!)

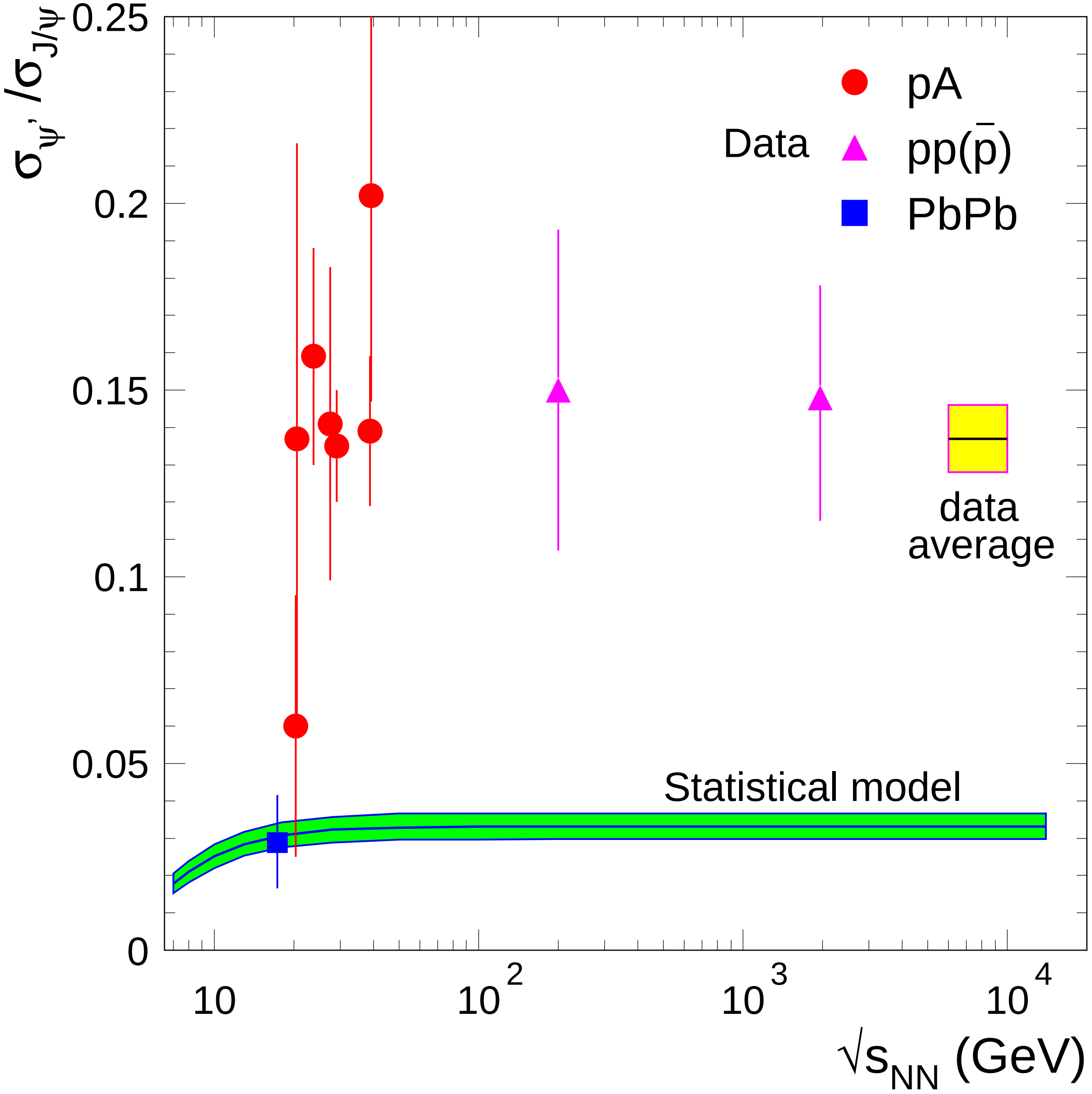
Open charm in p(π)A collisions



- ... appears "thermalized" (model as for AA)

  ...in the sense of c distribution into hadrons

Charmonium in pp(A) collisions

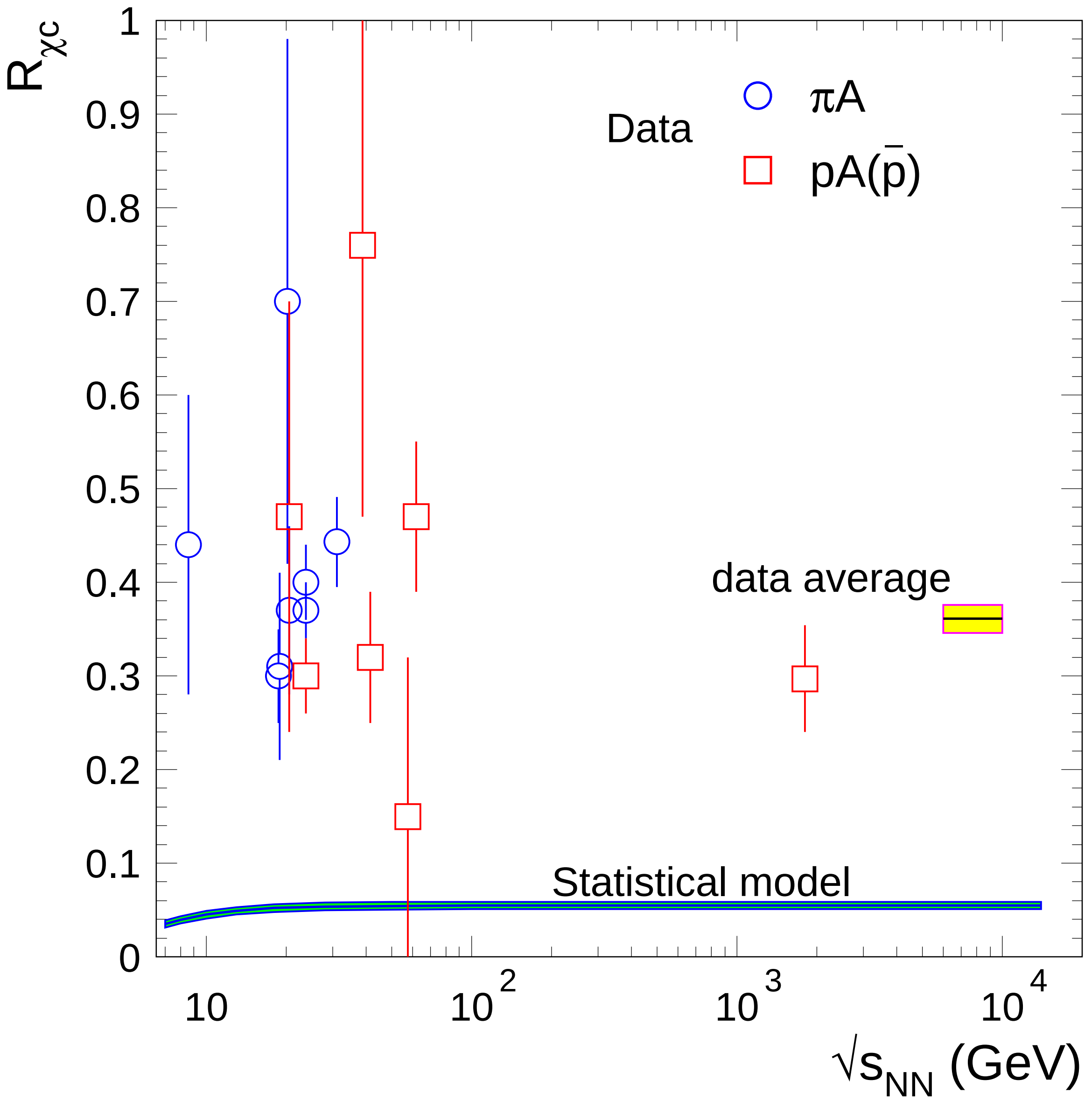


- ...is far from thermalized

  ...while a thermal value is reached in central PbPb (NA50, SPS)

  $\psi'/J/\psi$ dep. only on T (model as for AA)

Charmonium in pp(A) collisions 2

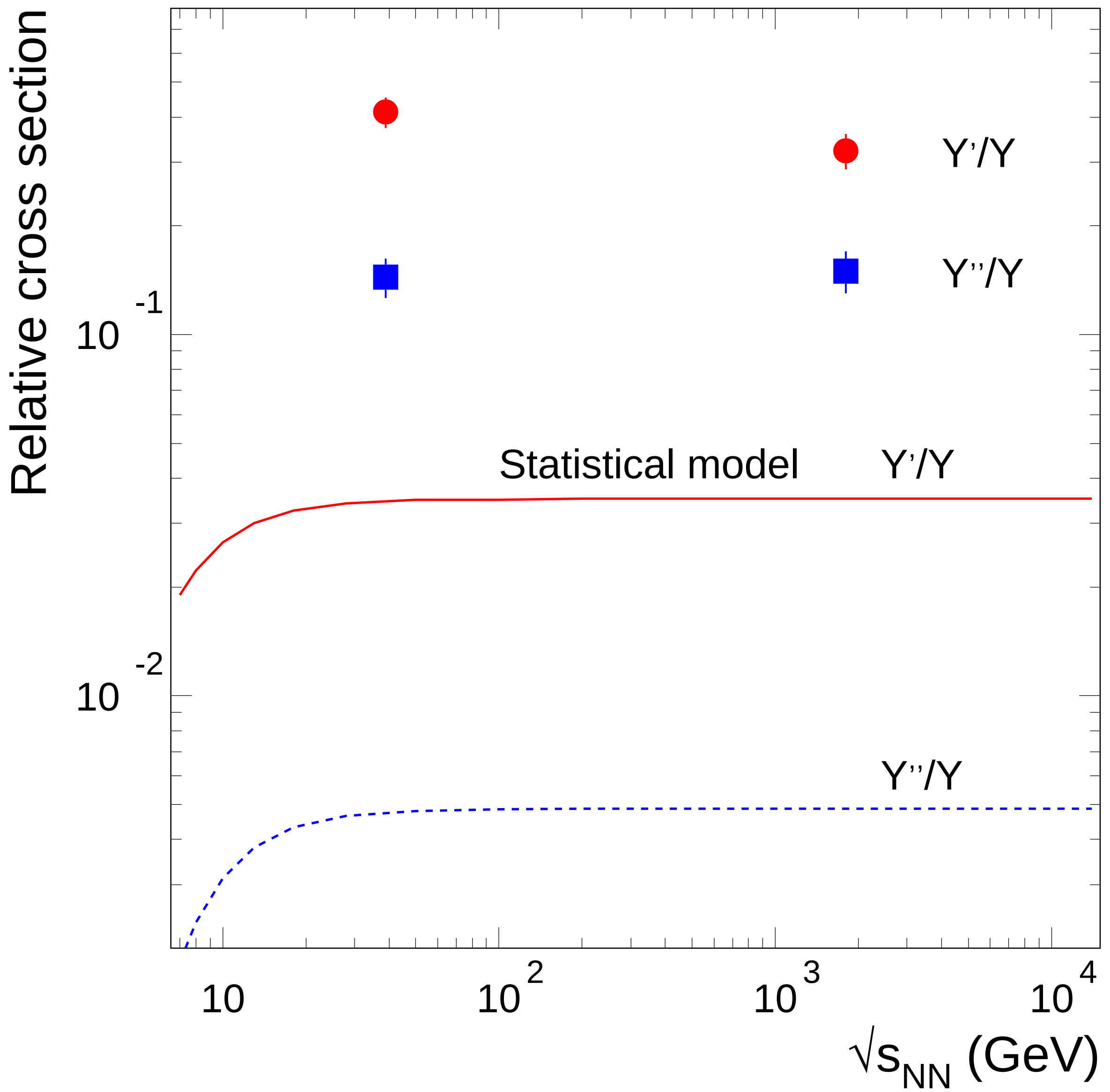


$$R_{\chi_c} = \frac{\sum_{J=1}^{2} \sigma(\chi_{cJ}) Br(\chi_{cJ} \to J/\psi\,\gamma)}{\sigma(J/\psi)}$$

(fraction of J/ψ mesons from radiative decays of χ_c)

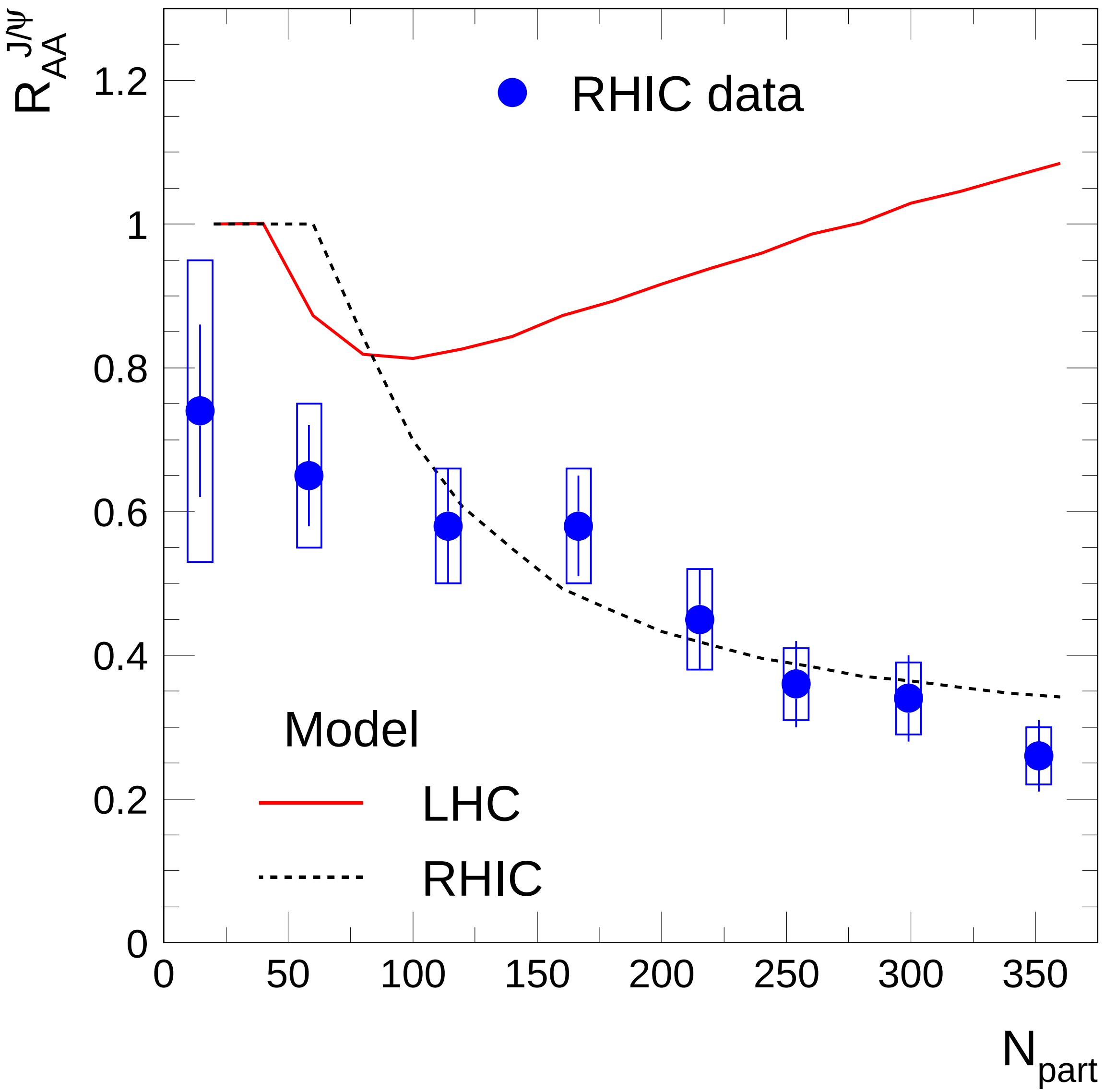
- ...is far from thermalized (model as for AA)

Bottomonium in pp collisions



- ...is very far from "thermalized"

J/ψ: the big difference LHC makes



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

    determined by canonical suppression

    (of open charm hadrons)
  - "enhancement" at LHC

ALICE needs 10^4 central events to measure 100 $J/\psi \rightarrow e^+e^-$

Υ in line for scrutinity...

model predicts a "suppression" pattern (RHIC-like)

Summary and outlook

statistical hadronization of heavy quarks
(produced exclusively in hard collisions, survive and thermalize in QGP)

...explains 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 at SPS and RHIC? (LQCD? AdS/CFT?)

LHC will provide a clear answer ...and further FAIR will trace onset

Have we lost J/ψ as a QGP probe? No, lost only as a "thermometer"

...but we gained it as an ultimate probe of the phase boundary