Hadron production at chemical freeze-out

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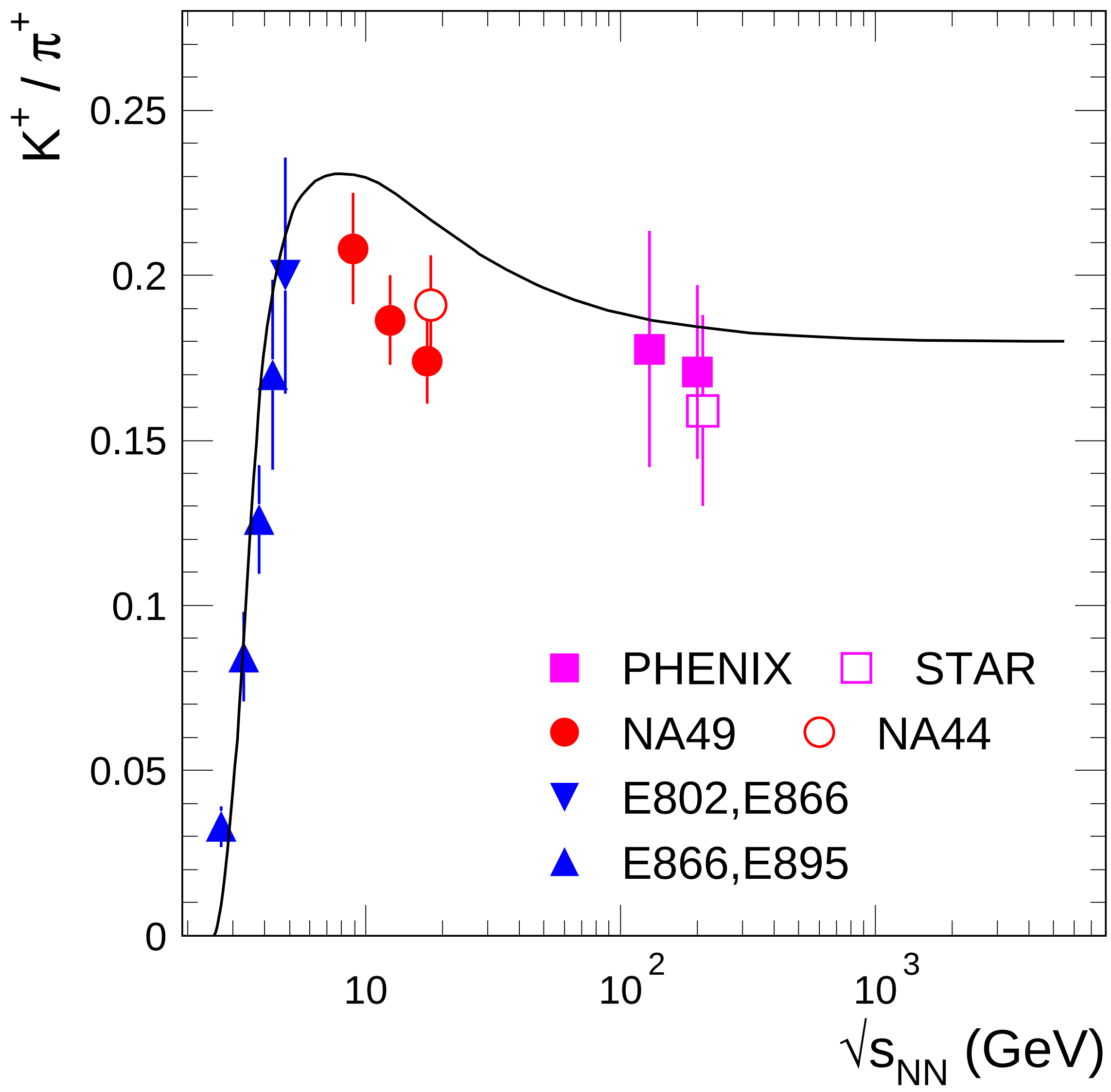
- The thermal model and the thermal fits in (central) AA collisions
- Energy dependence of the thermal parameters (T, μ_b, V)
- Thermal fits and the QCD phase diagram
- Thermal model and heavy-flavored hadrons (in AA and elementary collisions)
- Thermal model for exotica

AA, P.Braun-Munzinger, J.Stachel, Phys. Lett. B 673 (2009) 142

AA, P.Braun-Munzinger, K.Redlich, J.Stachel, Phys. Lett. B 652 (2007) 259; B 678 (2009) 350; arXiv:1002.4441

The horn

... as of 2005 not well reproduced by the thermal model (line)

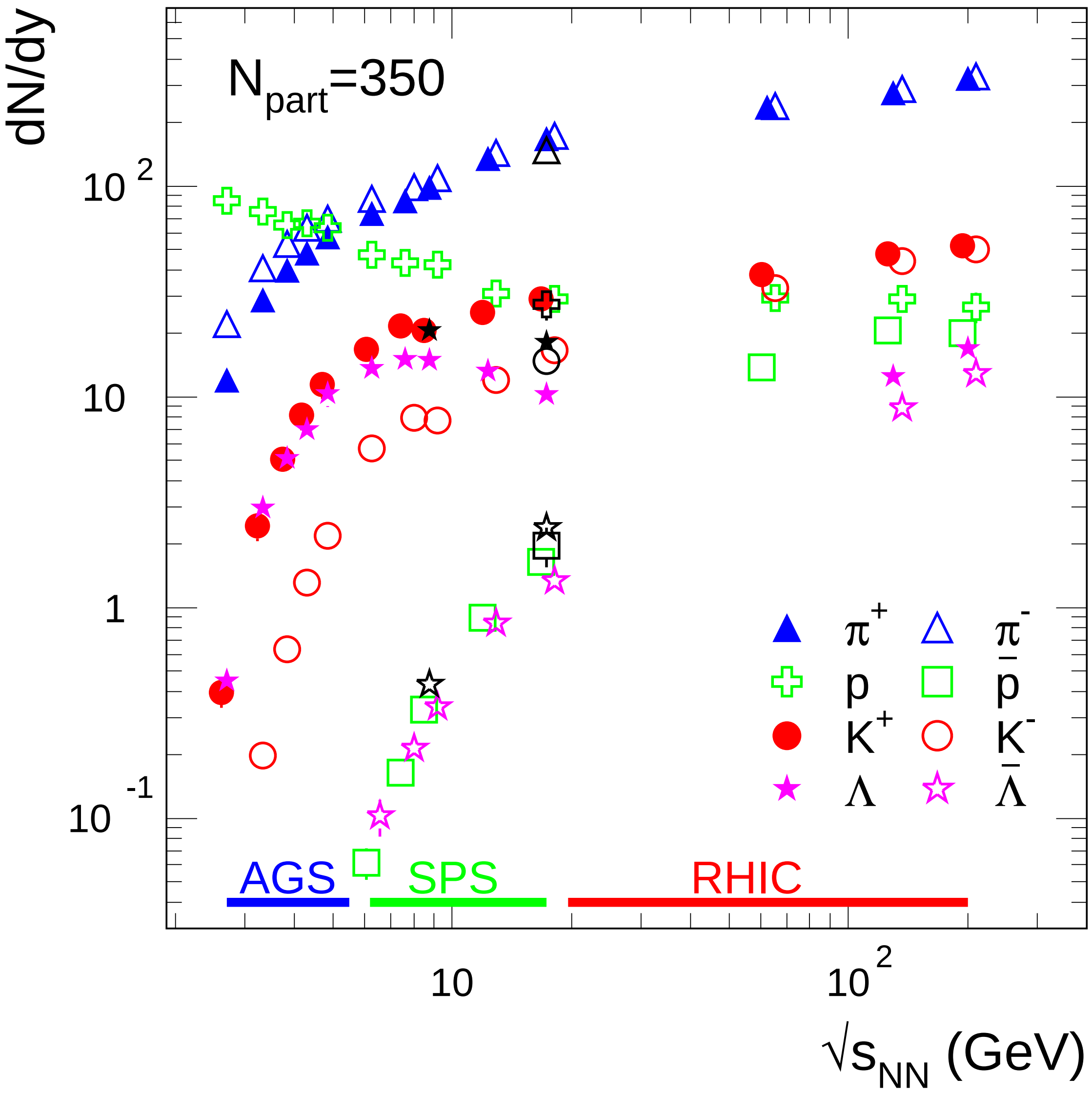


(the 2008 version) taken as experimental evidence for the onset of deconfinement and quark-gluon plasma formation

NA49 collab., Phys. Rev. C **77** (2008)

...as predicted by Gaździcki and Gorenstein, Acta Phys. Polon. B **30** (1999) 2705

Hadron yields 2008 (central collisions)



- lots of particles, mostly newly created ($m = E/c^2$)
- a great variety of species:

  $\pi^{\pm}$ ($u\bar{d}$, $d\bar{u}$), m=140 MeV
  $K^{\pm}$ ($u\bar{s}$, $\bar{u}s$), m=494 MeV
  p (uud), m=938 MeV
  Λ (uds), m=1116 MeV
  also: $\Xi(dss)$, $\Omega(sss)$...

- mass hierarchy in production (u, d quarks: remnants from the incoming nuclei)

The hadron mass spectrum as of 2008

Particle Data Group, Phys. Lett. B **667** (2008) 1

relative increase of calc. dens.

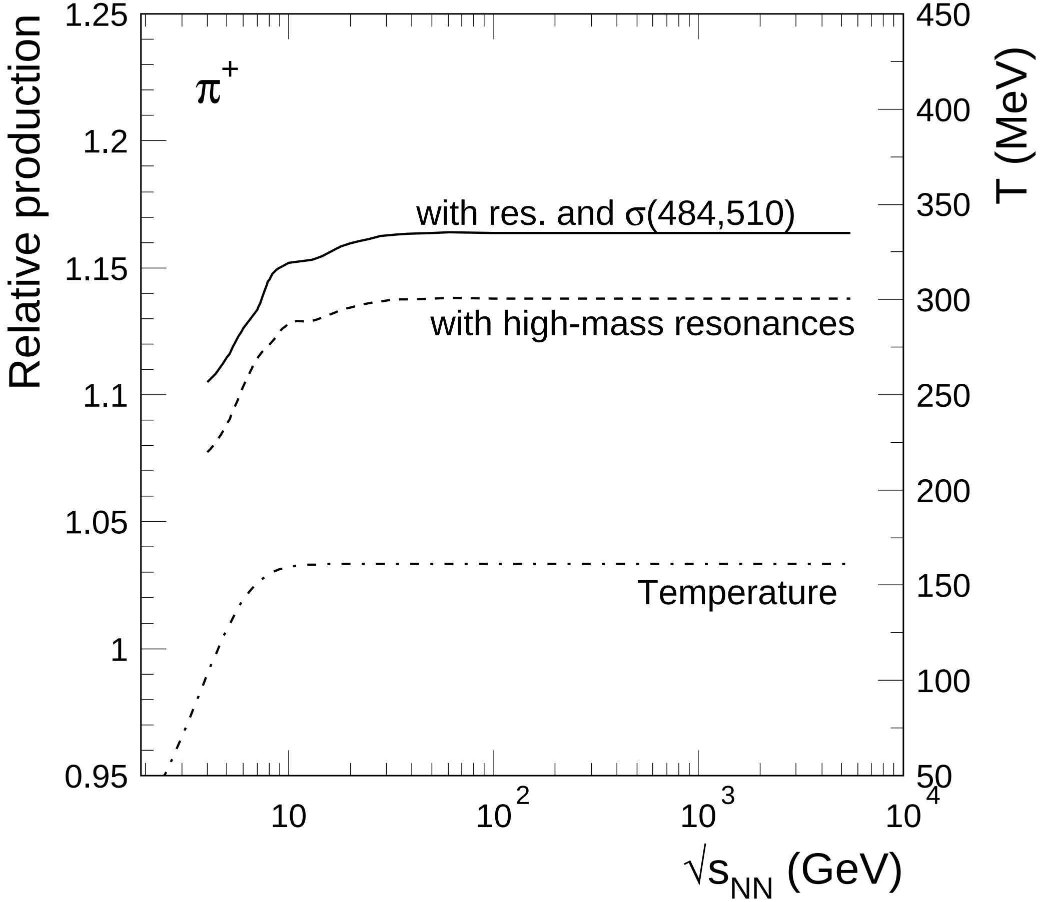
Additions (compared to 2005):

Many new resonances up to 3 GeV
+(86)4 (non)strange mesons
+(36)30 (non)strange baryons

σ meson ($f_0(600)$):
m_σ=484±17 MeV,Γ_σ=510±20 MeV

García-Martín, Peláez, Ynduráin, Phys. Rev. D **76** (2007) 074034

(in total 485 hadron species, incl. composites)



The thermal model

grand canonical partition function for specie i ($\hbar = c = 1$):

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \mathrm{d}p \ln[1 \pm \exp(-(E_i - \mu_i)/T)]$$

$g_i = (2J_i + 1)$ spin degeneracy factor; T temperature;

$E_i = \sqrt{p^2 + m_i^2}$ total energy; (+) for fermions (–) for bosons

$\mu_i = \mu_b B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$

μ ensure conservation (on average) of quantum numbers:

i) baryon number: $V \sum_i n_i B_i = N_B$

ii) isospin: $V \sum_i n_i I_{3i} = I_3^{tot}$

iii) strangeness: $V \sum_i n_i S_i = 0$

iv) charm: $V \sum_i n_i C_i = 0$.

Short-range repulsive core modelled via excluded volume correction (Rischke)

Widths of resonances taken into account

The thermal fits

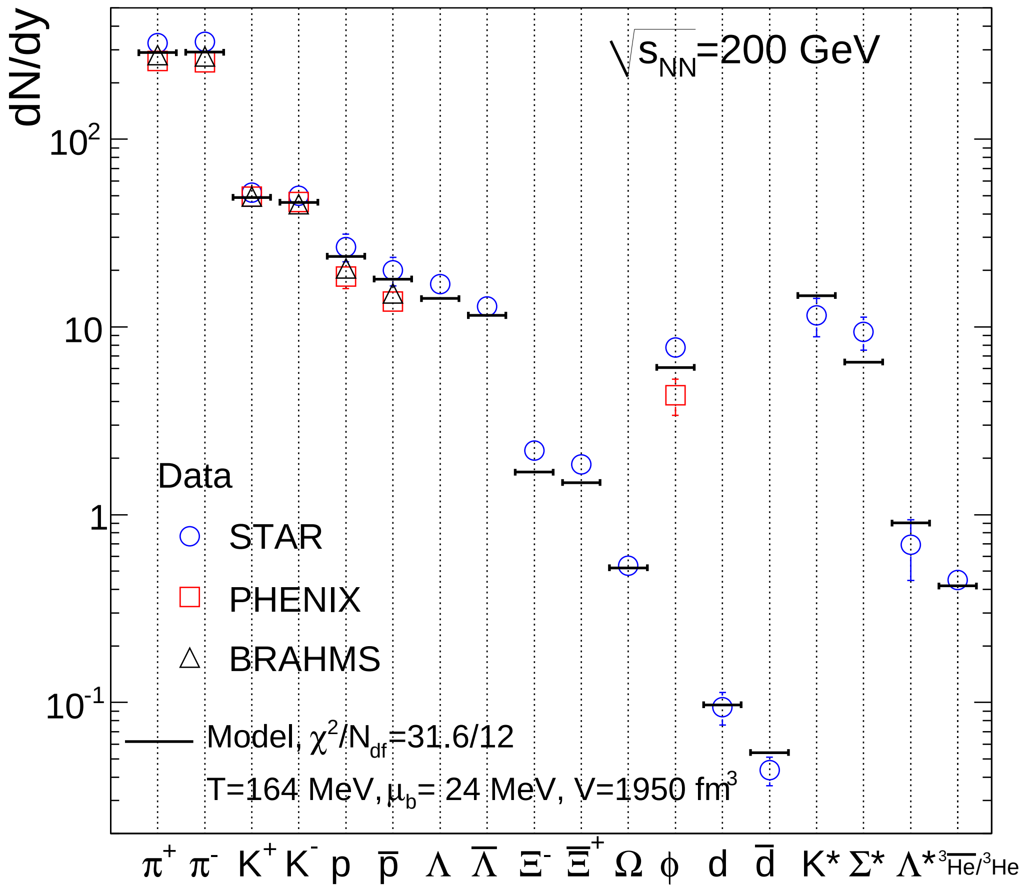
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T]\pm 1}$$

Latest PDG hadron mass spectrum (up to 3 GeV, 485 species)

Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

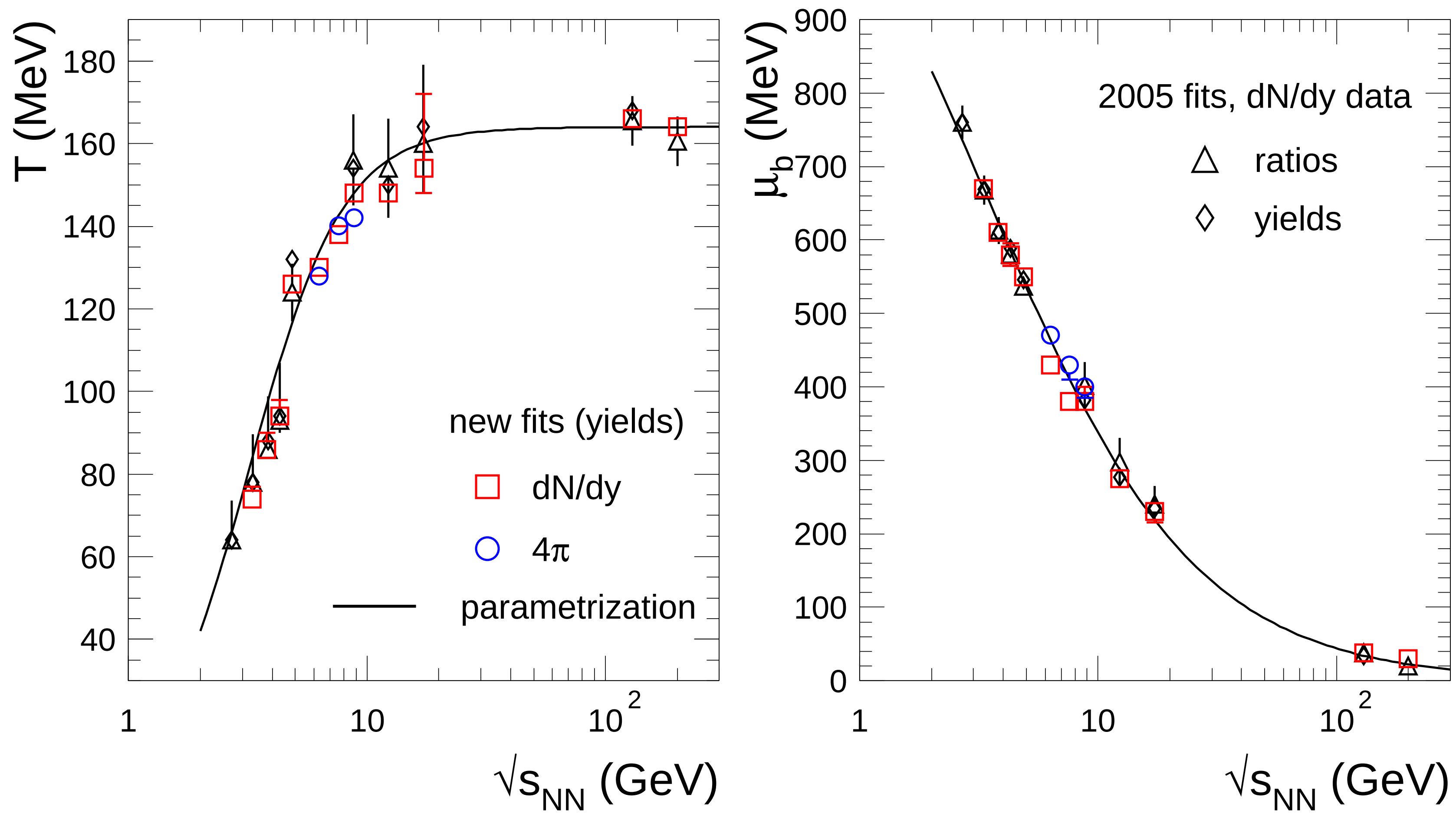
N_i: hadron yield ($\Rightarrow T$, μ_b, V) or yield ratio (no V)

Data: 4π or $\mathrm{d}N/\mathrm{d}y$ (at y=0)



The hadron abundances are in agreement with a thermally equilibrated system

Energy dependence of T, μ_b



thermal fits exhibit a limiting temperature: $T_{lim} = 164 \pm 4$ MeV

$$T = T_{lim}\frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}(\mathrm{GeV})})/0.45)}, \qquad \mu_b[\mathrm{MeV}] = \frac{1303}{1+0.286\sqrt{s_{NN}}(\mathrm{GeV})}$$

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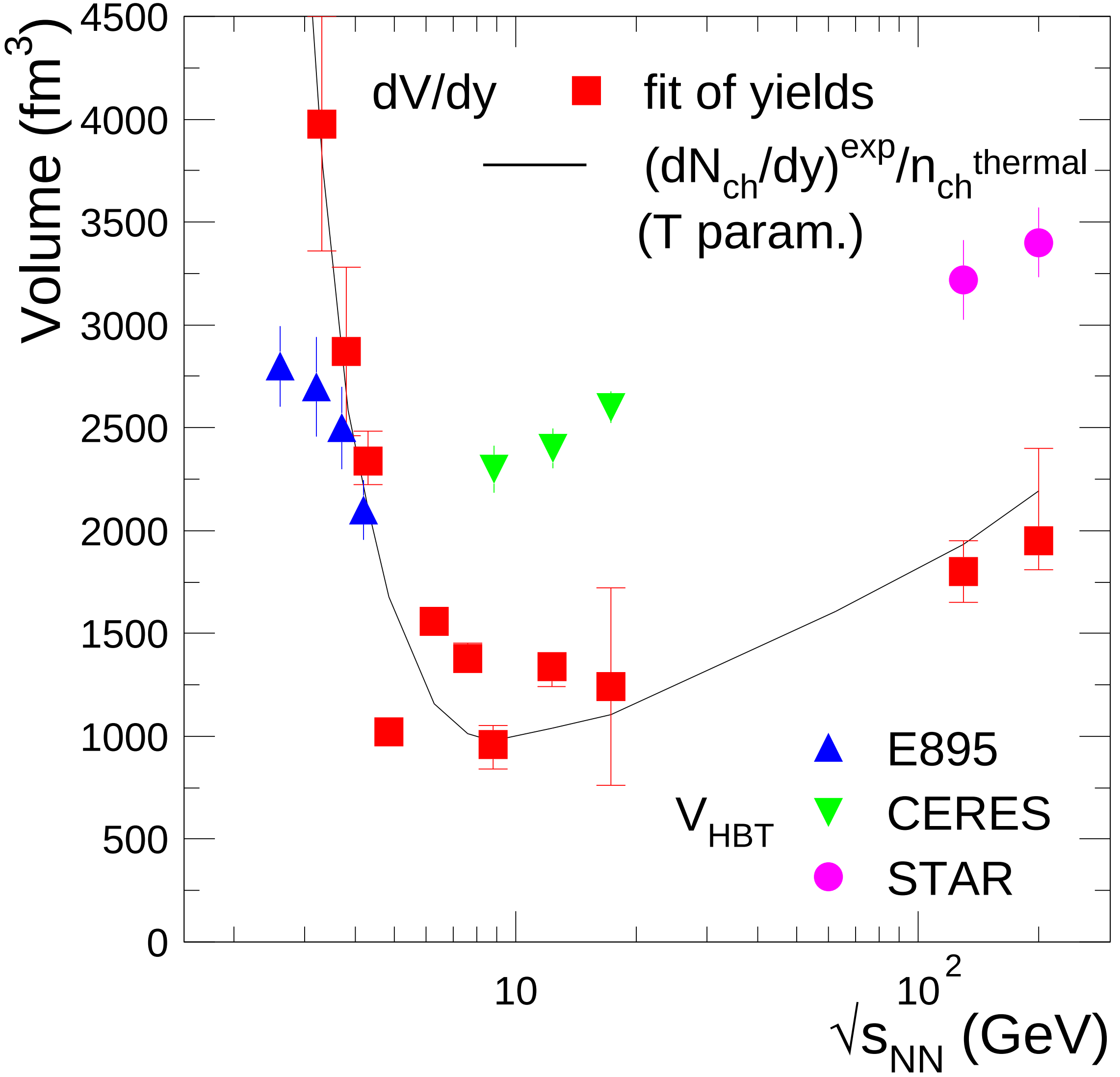
Energy dependence of the freeze-out volume



$\mathrm{d}V/\mathrm{d}y$: volume for one unit rapidity (at midrapidity)

minimum at $T \rightarrow T_{lim}$

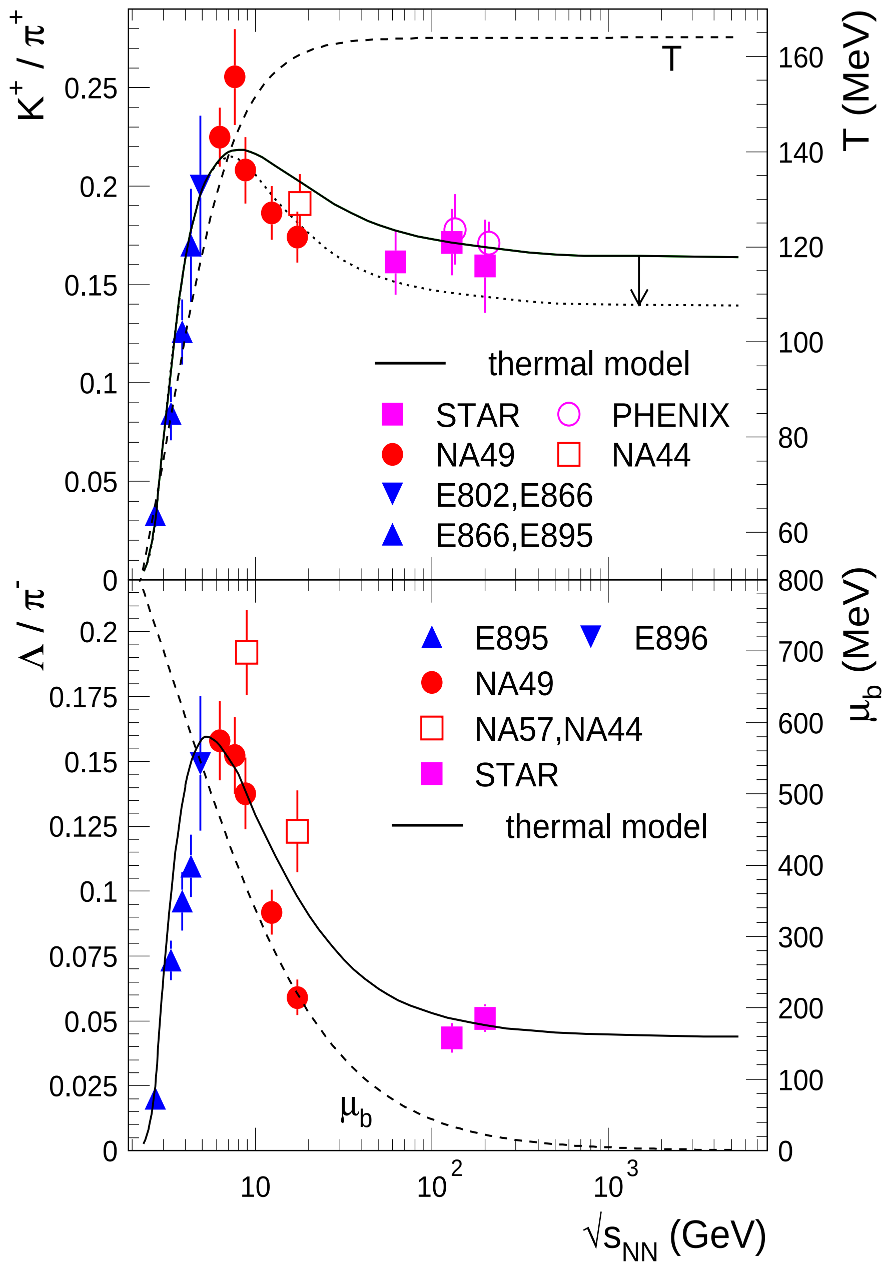
V_{HBT}:

CERES, PRL, 90 (2003) 022301

($\lambda_f \simeq$1 fm)

not fully understood dependence

The horn as of 2009

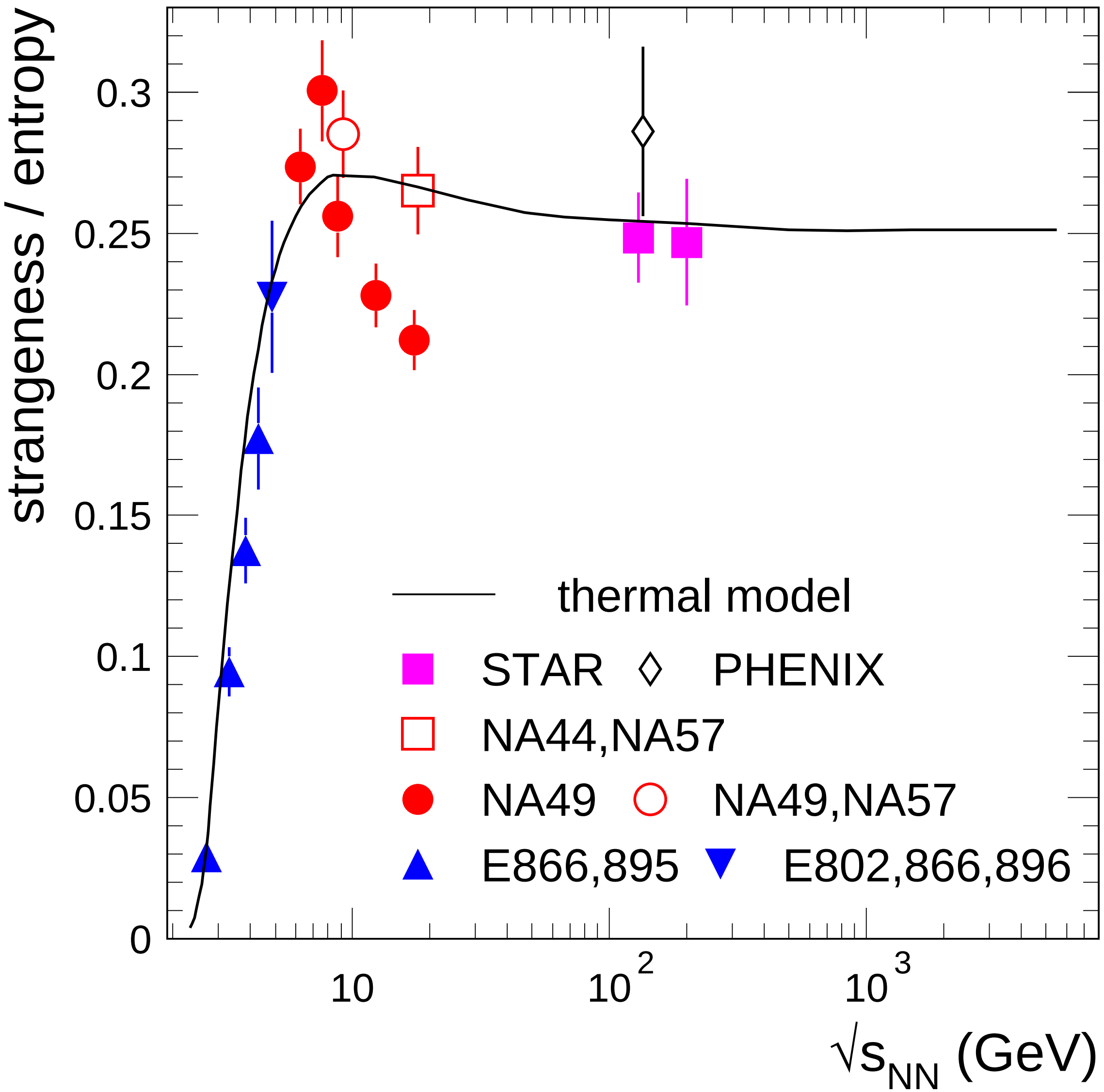


- much better explained by the model
- ...as due to detailed features of the hadron mass spectrum

  ...which leads to a limiting temperature ("Hagedorn", $T < T_H$)

  ...and contains the QCD phase transition
- the horn's sensitivity to the phase boundary is determined (via strangeness neutrality condition) by the Λ abundance (determined by both T and μ_b)

A global ratio: strangeness/entropy



"strangeness":

$$2\times(K^{+}+K^{-})+1.54\times(\Lambda+\bar{\Lambda})$$

"entropy":

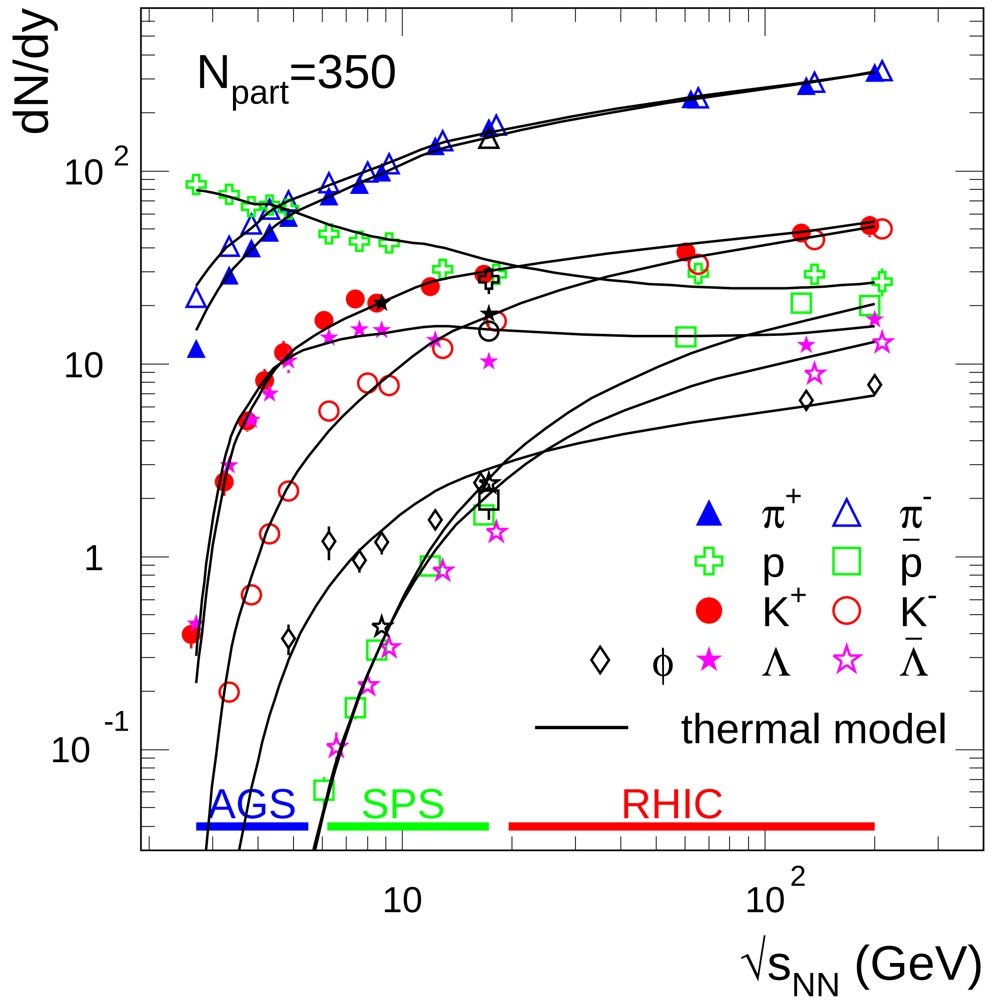
$$1.5\times(\pi^{+}+\pi^{-})+2\times\bar{p}$$

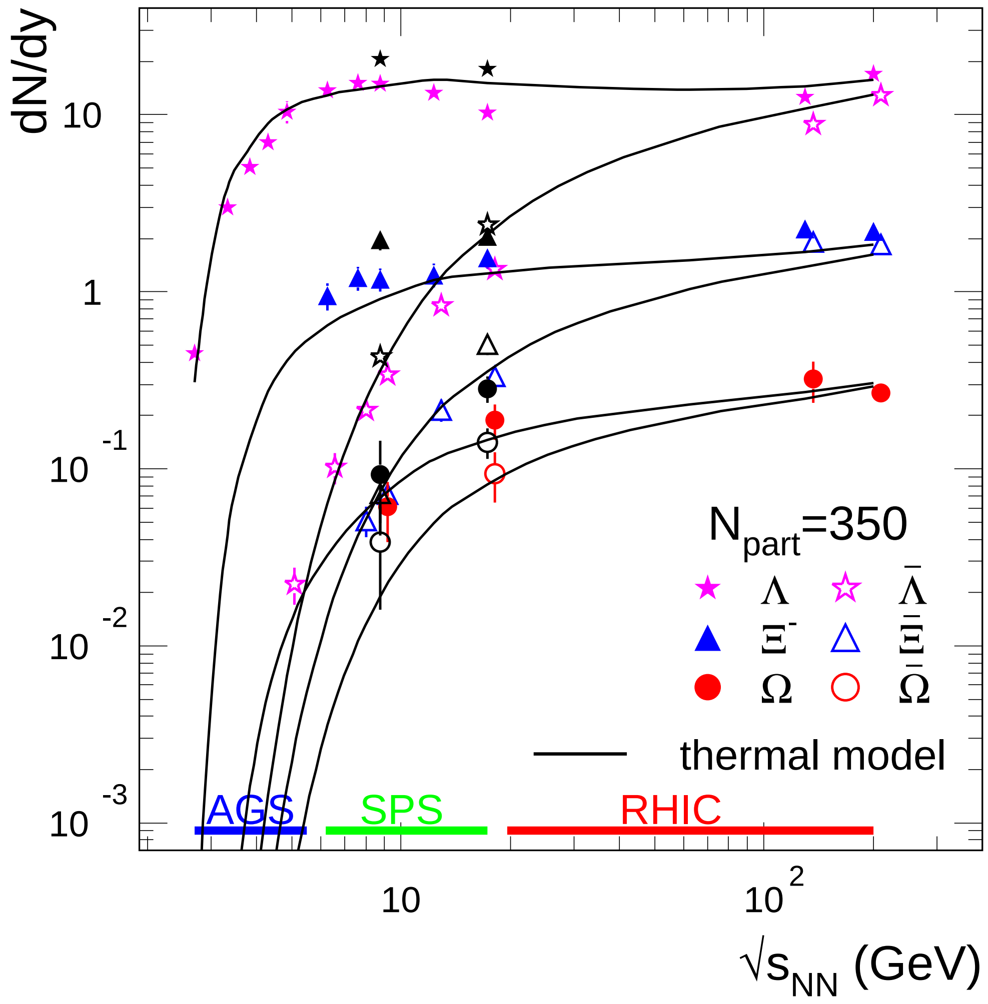
anything beyond thermal?

yes, in NA49 data...

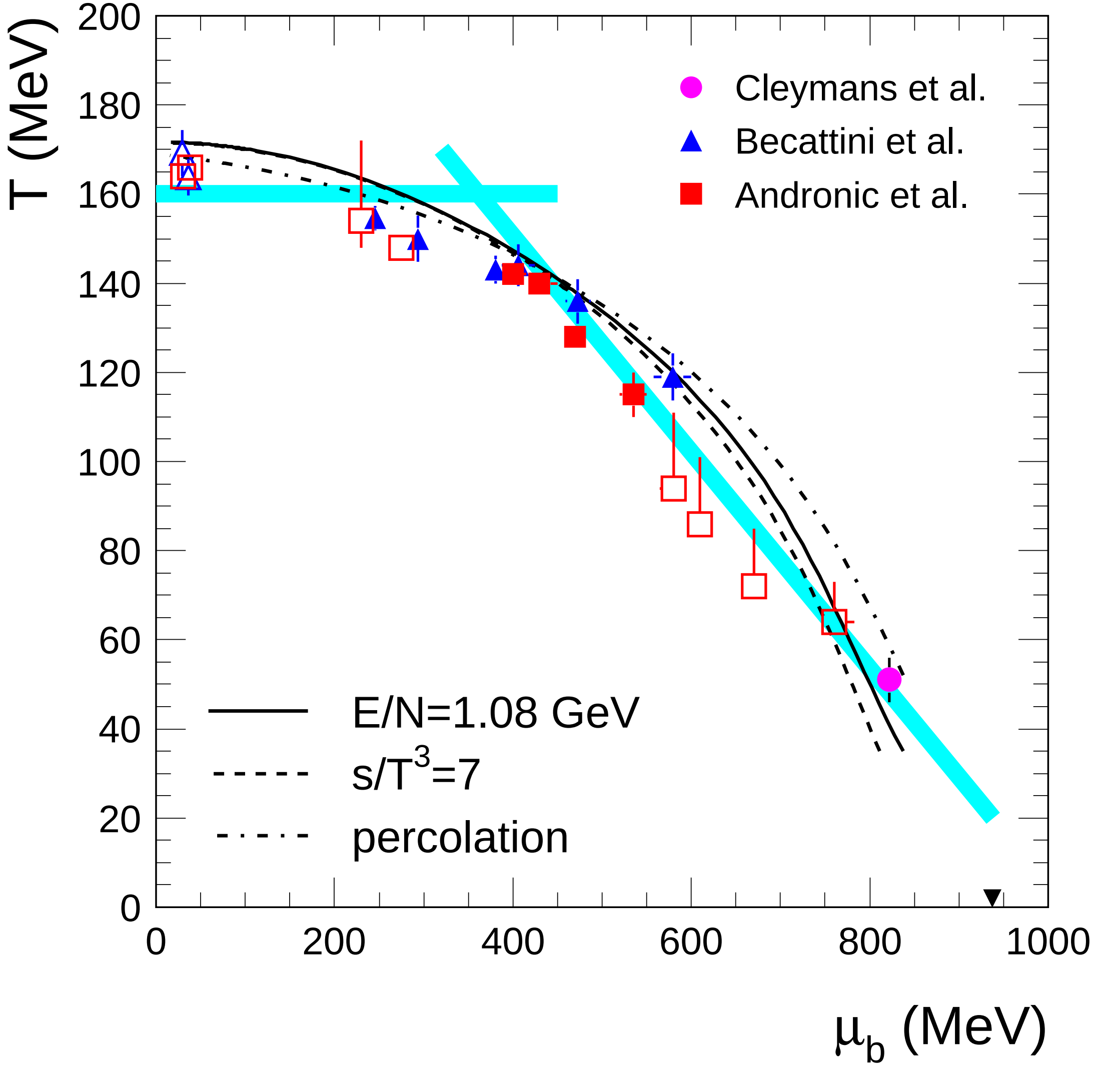
...but hard to argue overall

Yields at mid-rapidity





The phase diagram of QCD



is chemical freeze-out a determination of the phase boundary?
if yes, how is thermalization achieved?

- for SPS energies and higher: driven by the deconfinement transition

  PBM, Stachel, Wetterich, PLB 596 (2004) 61

- for lower energies (SIS100): is the quarkyonic phase transition the "thermalizer"?

  McLerran, Pisarski, NPA 796 (2007) 83; see also: AA et al., NPA 837 (2010) 65

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Statistical model for heavy quark hadrons

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

Assumptions

- 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 numbers conservation
  statistical hadronization ($\neq$ coalescence)

  is freeze-out at/the(?) phase boundary? can we delineate it more with charm?
- no J/ψ survival 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

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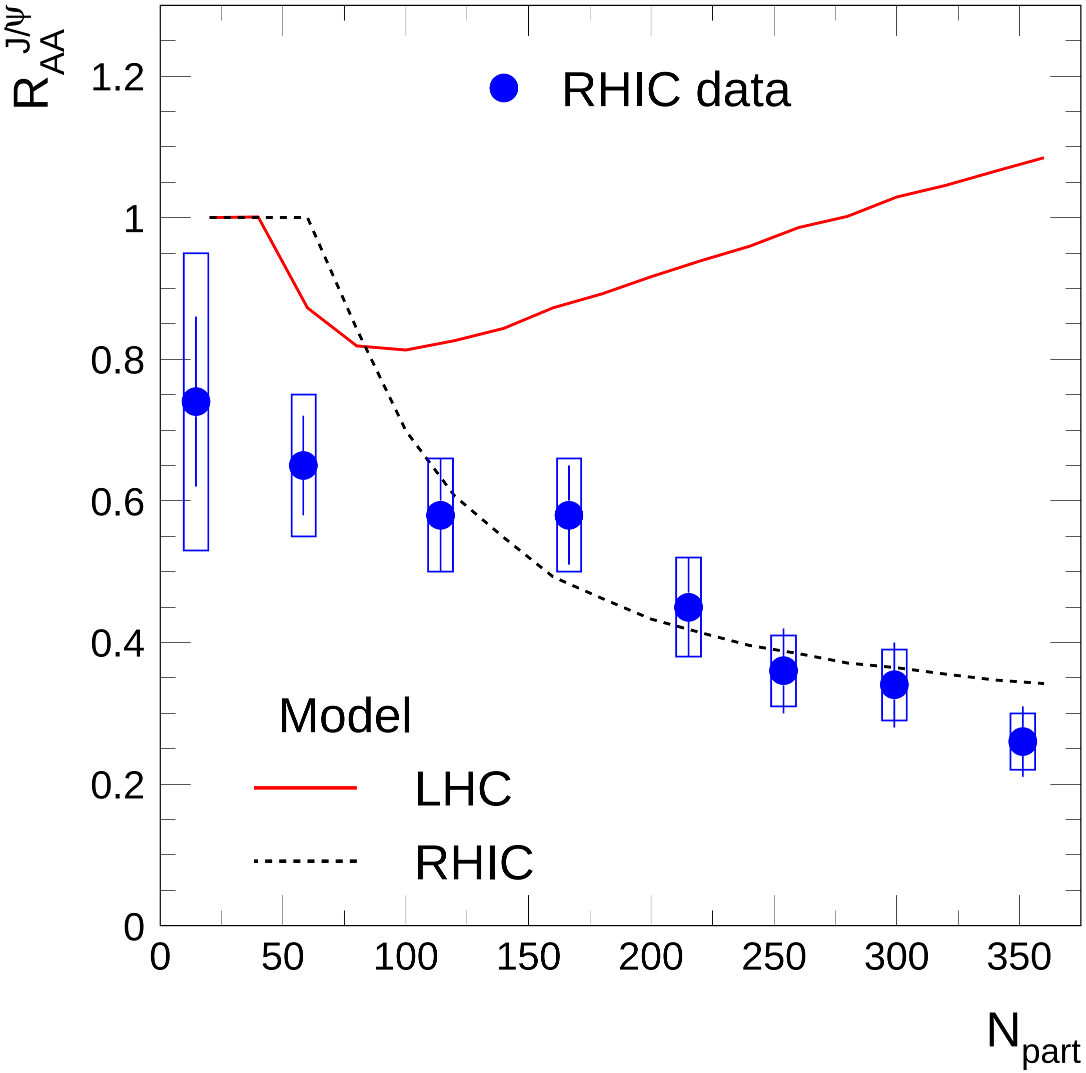
Charmonium (at LHC)

...an ultimate observable to measure the phase boundary (thermal model)

...with the help of charm quarks equilibrating in the deconfined stage



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

R_{AA}=1 if superposition of pp coll.

very different centrality dependence

- "suppression" at RHIC
- "enhancement" at LHC

$N_{J/\psi} \sim (N_{c\bar{c}}^{dir})^2$

What is so different at LHC?

(compared to RHIC)

$\sigma_{c\bar{c}}$: 10x, Volume: 3x

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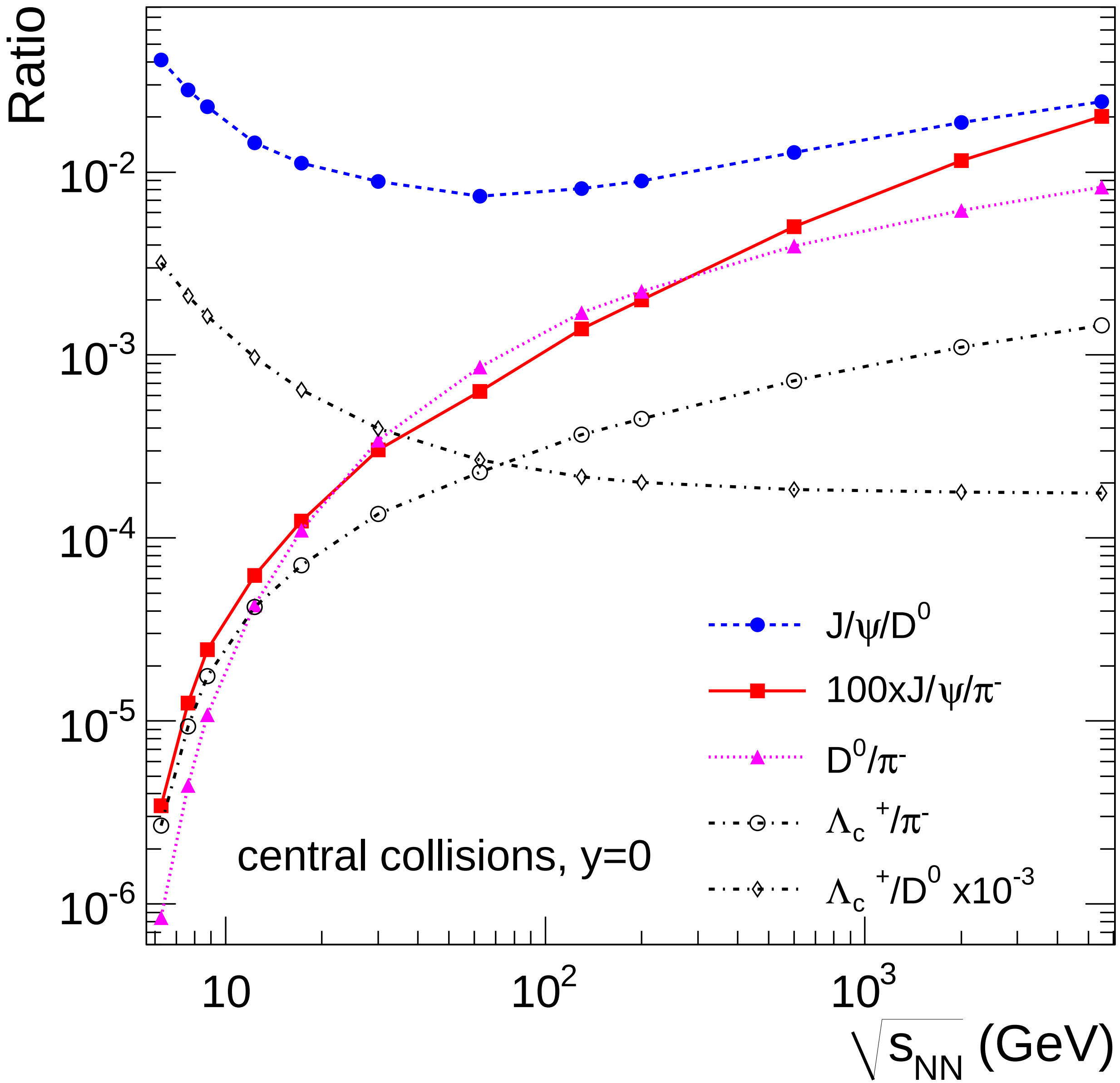
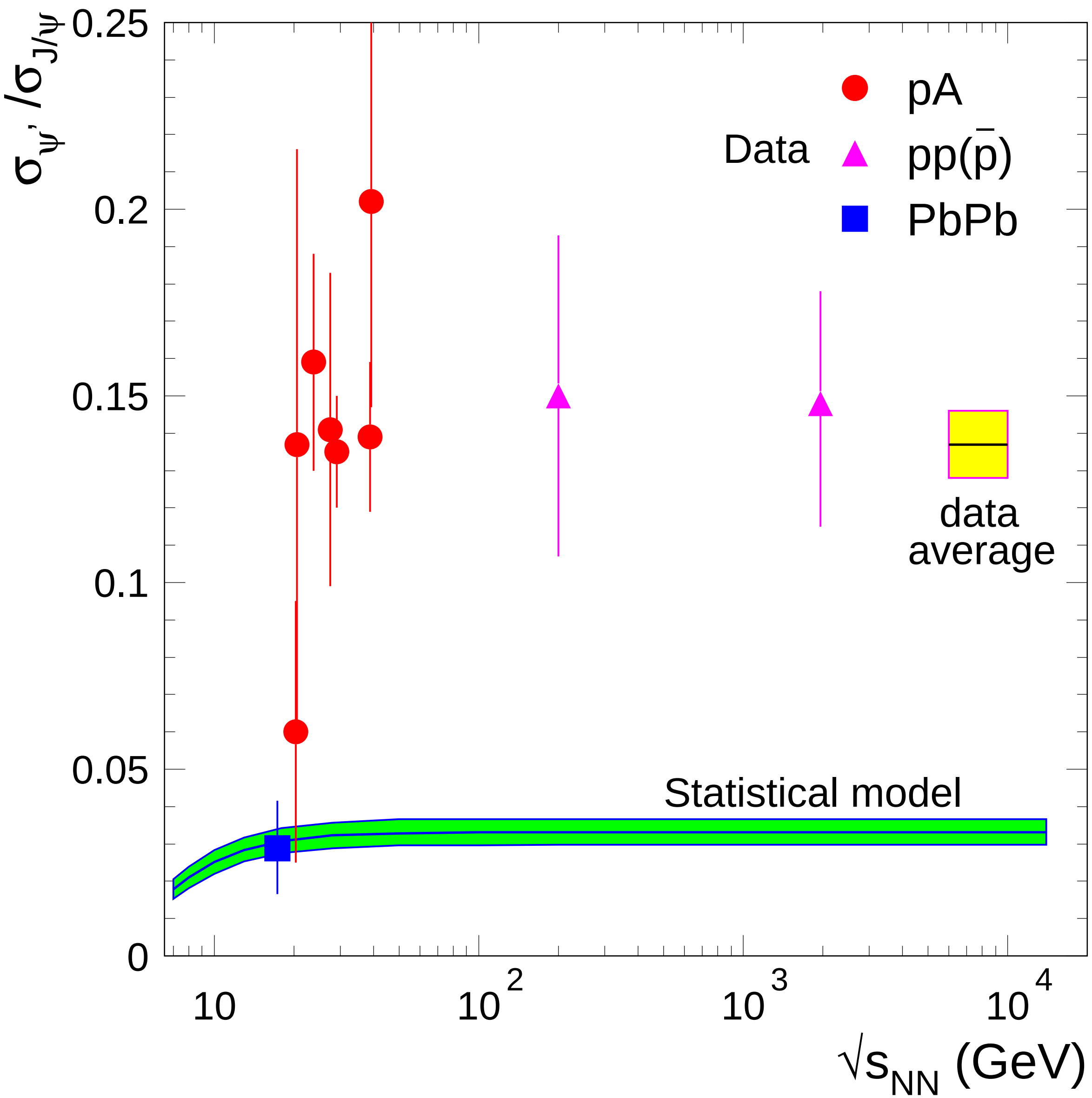
“Horns” for charmed hadrons?



...none ...

suppressed by the minute charm production at low energies

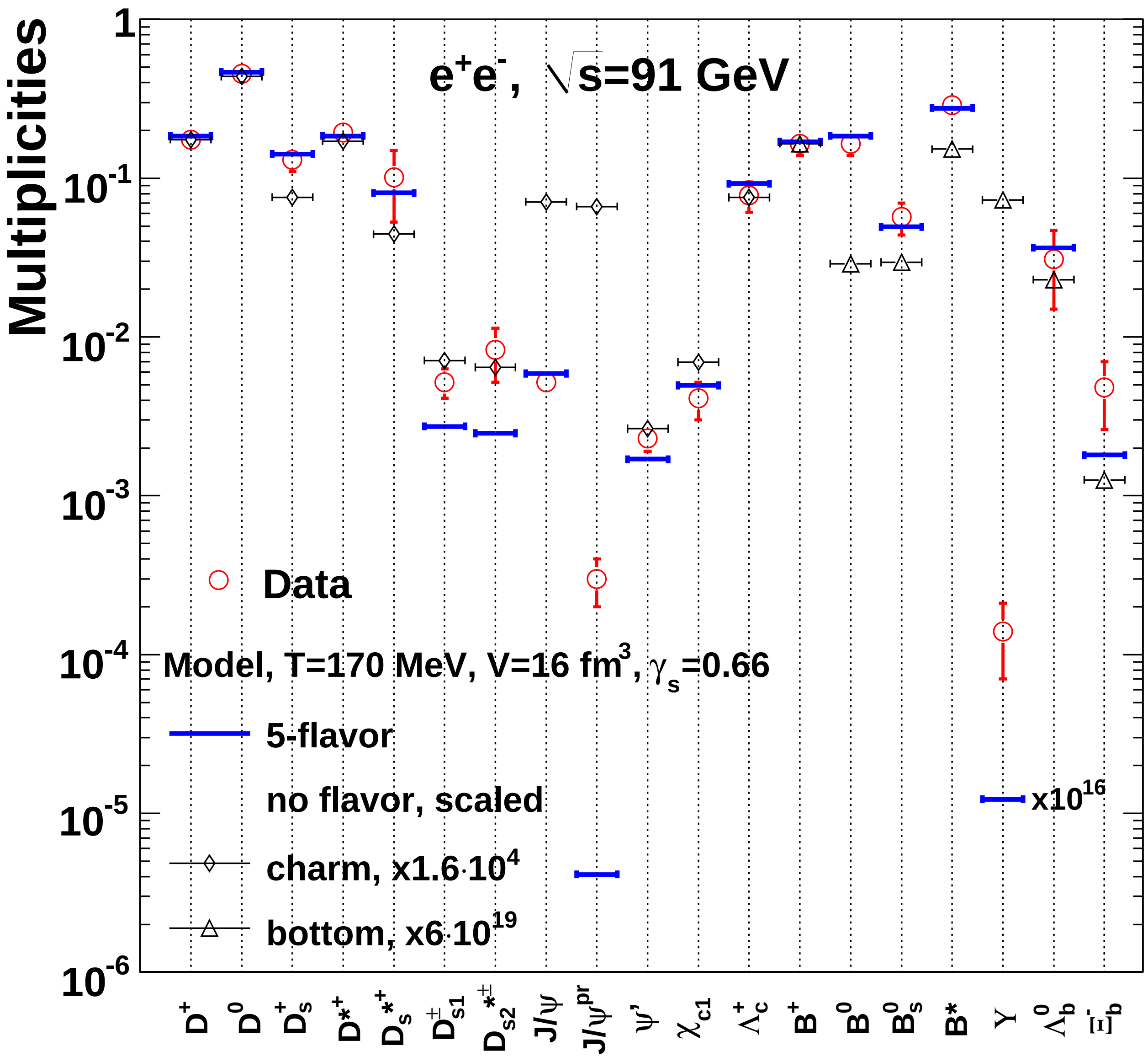
Charmonium in pp(A) collisions



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

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

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

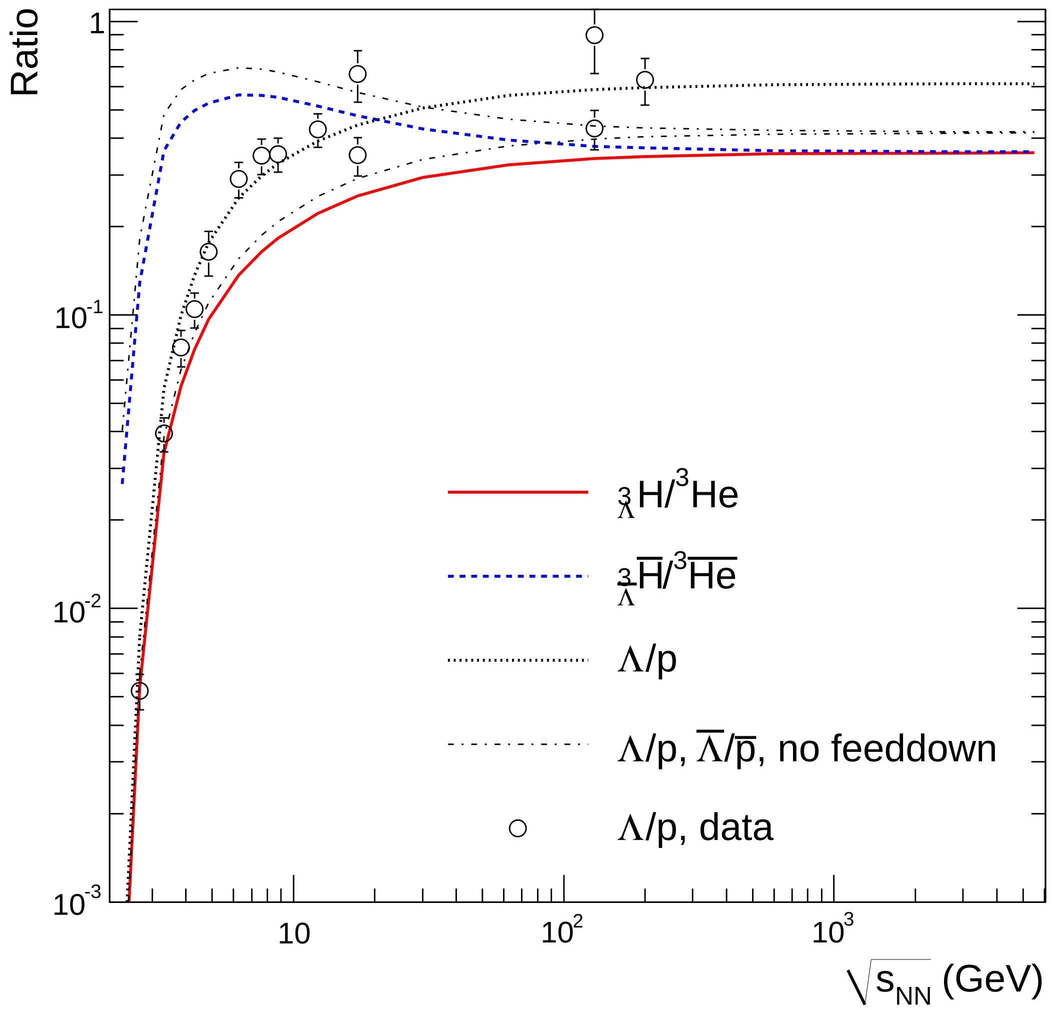
- agreement if BR($Z^0 \rightarrow q\bar{q}$) are used in the model (5-flavor)!

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

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

- quarkonia always strongly underpredicted

Exotica

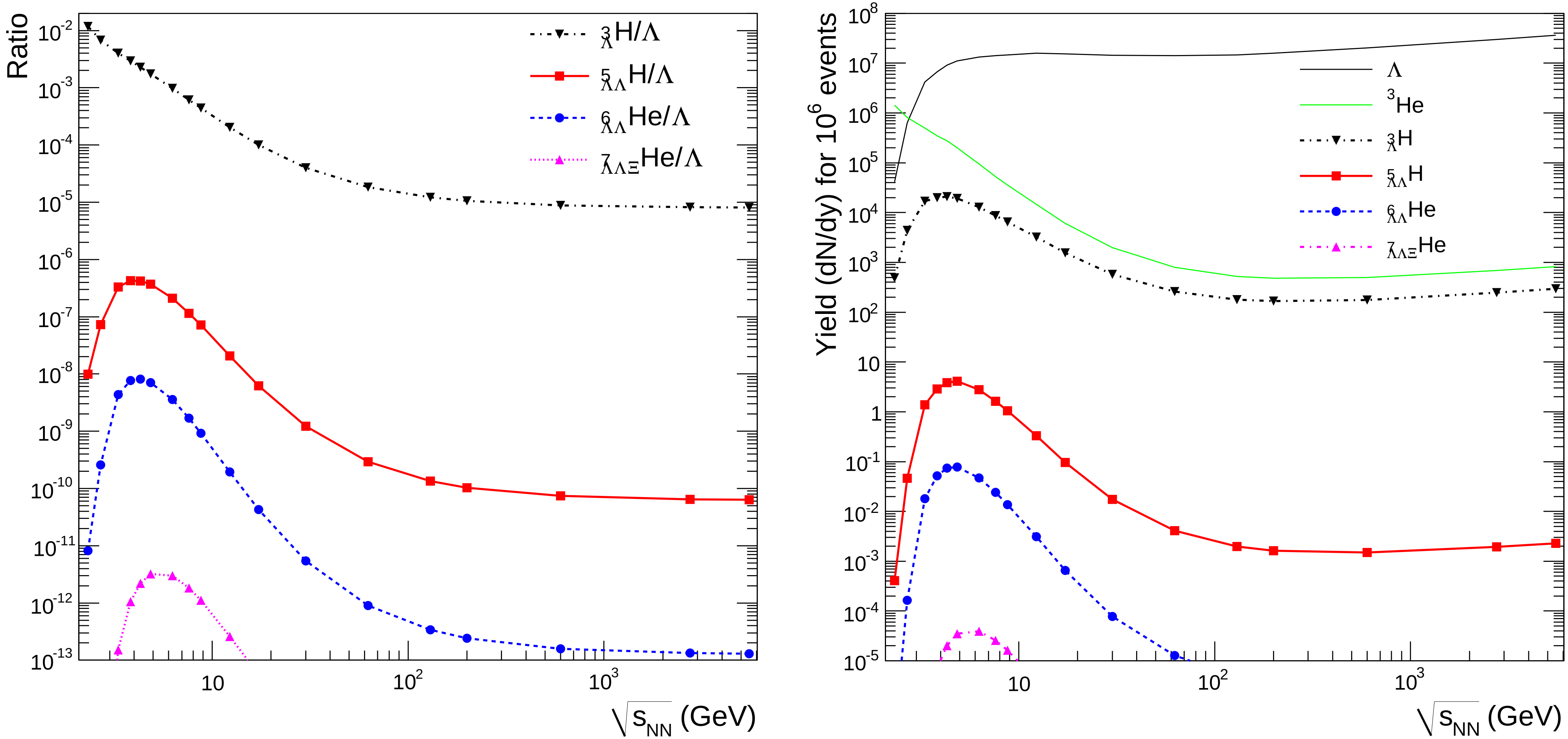


Ratio	Exp. (STAR)	Model
${}^{3}\bar{He}/{}^{3}He$	$0.45\pm0.02\pm0.04$	0.44
${}^{3}_{\bar{\Lambda}}\bar{H}/{}^{3}_{\Lambda}H$	$0.49\pm0.18\pm0.07$	0.46
${}^{3}_{\Lambda}H/{}^{3}He$	$0.82\pm0.16\pm0.12$	0.39
${}^{3}_{\bar{\Lambda}}\bar{H}/{}^{3}\bar{He}$	$0.89\pm0.28\pm0.13$	0.41

STAR data: Science 328 (2010)

Λ/p (without feed-down!) is a proxy for ${}^{3}_{\Lambda}H/{}^{3}He$

More Exotica



FAIR (SIS100) the ideal energy regime

Summary

- thermal fits work remarkably well (AGS-RHIC) $\Rightarrow$ (T,μ_b,V)
- limiting temperature $\Rightarrow$ phase boundary (LQCD)

  $\longrightarrow$ for the skeptics... *LHC case will be decisive* ("bigger,...")
- indications (bad fits) around the critical point? ...maybe, at SPS...

  ...but not a strong case due to disagreements between experiments

  $\longrightarrow$ RHIC low-energy run (and CBM?) will clarify this
- no indications for strangeness non-equilibrium (γ_S) in central collisions

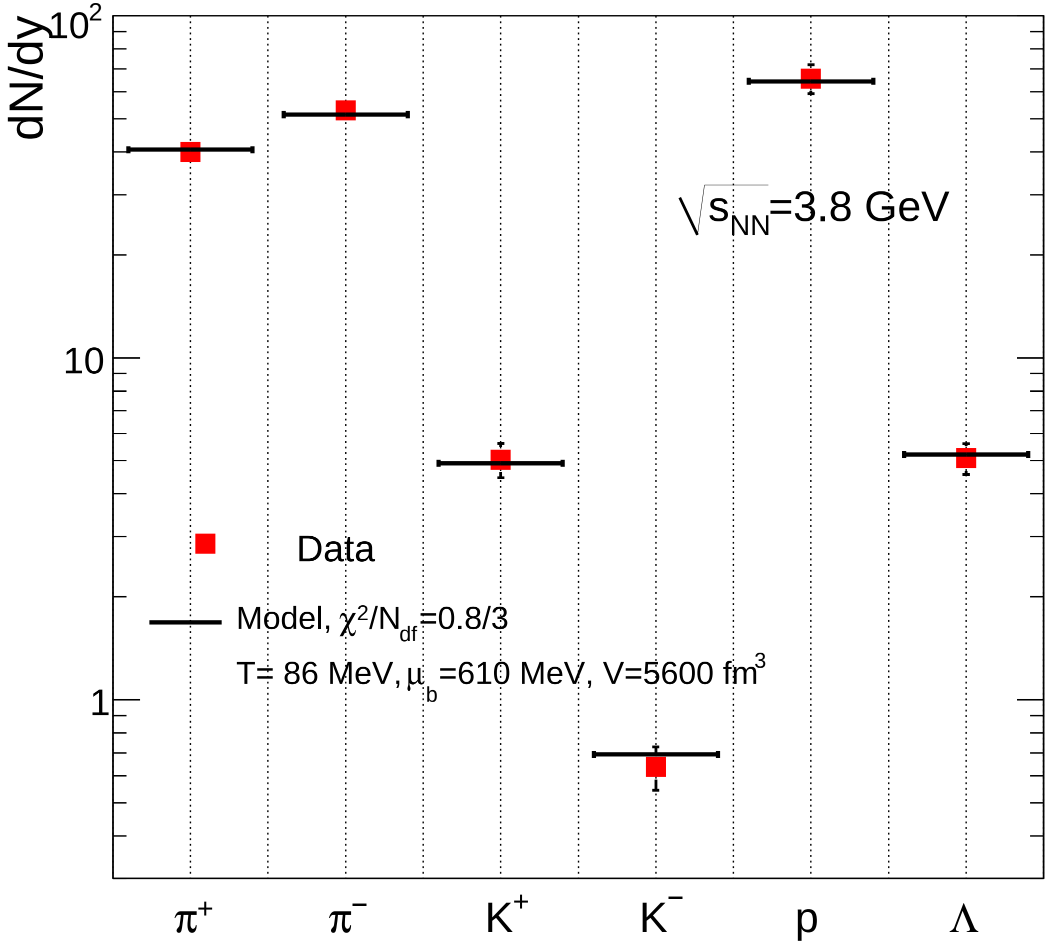
  (other models: not at SIS, RHIC; *some* at AGS-SPS, *some* at RHIC)
- the model explains well charmonium (further tests soon at LHC)

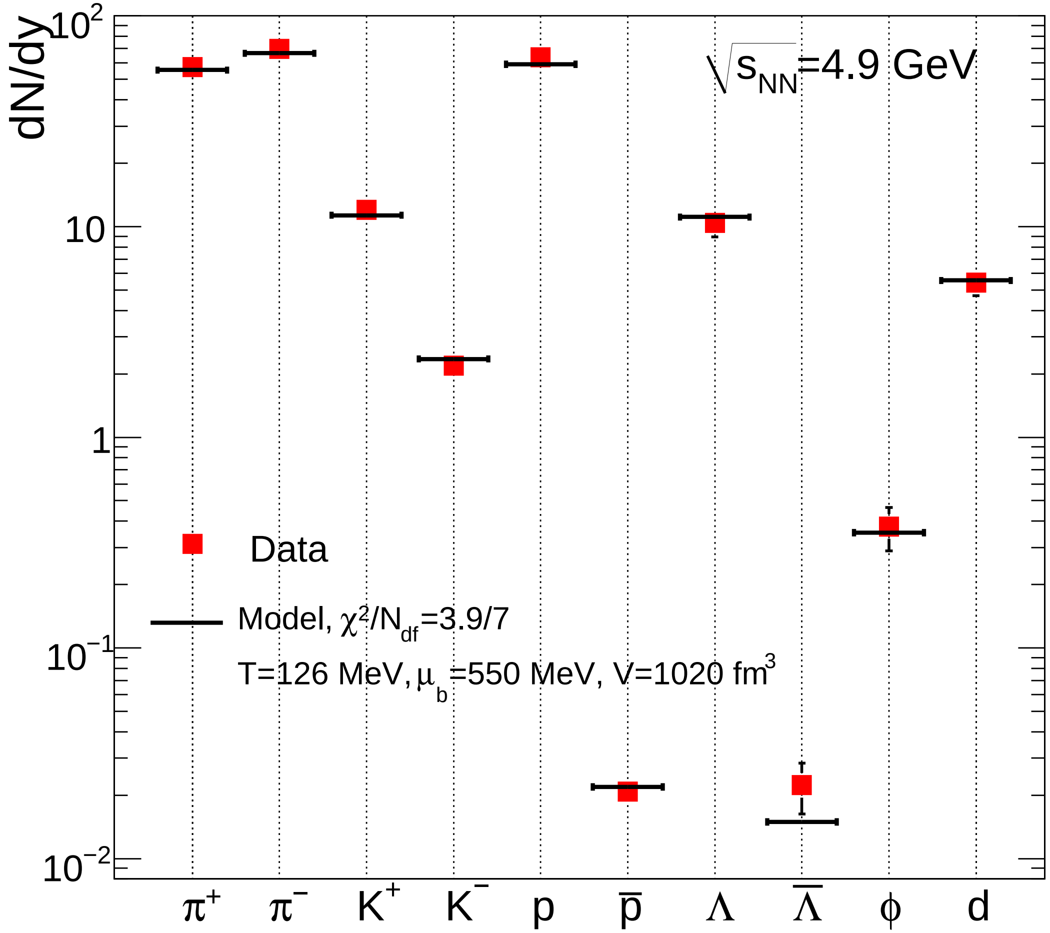
Still needed

a better freeze-out line (or phase boundary?) at high μ_b (>500 MeV)

Backup slides

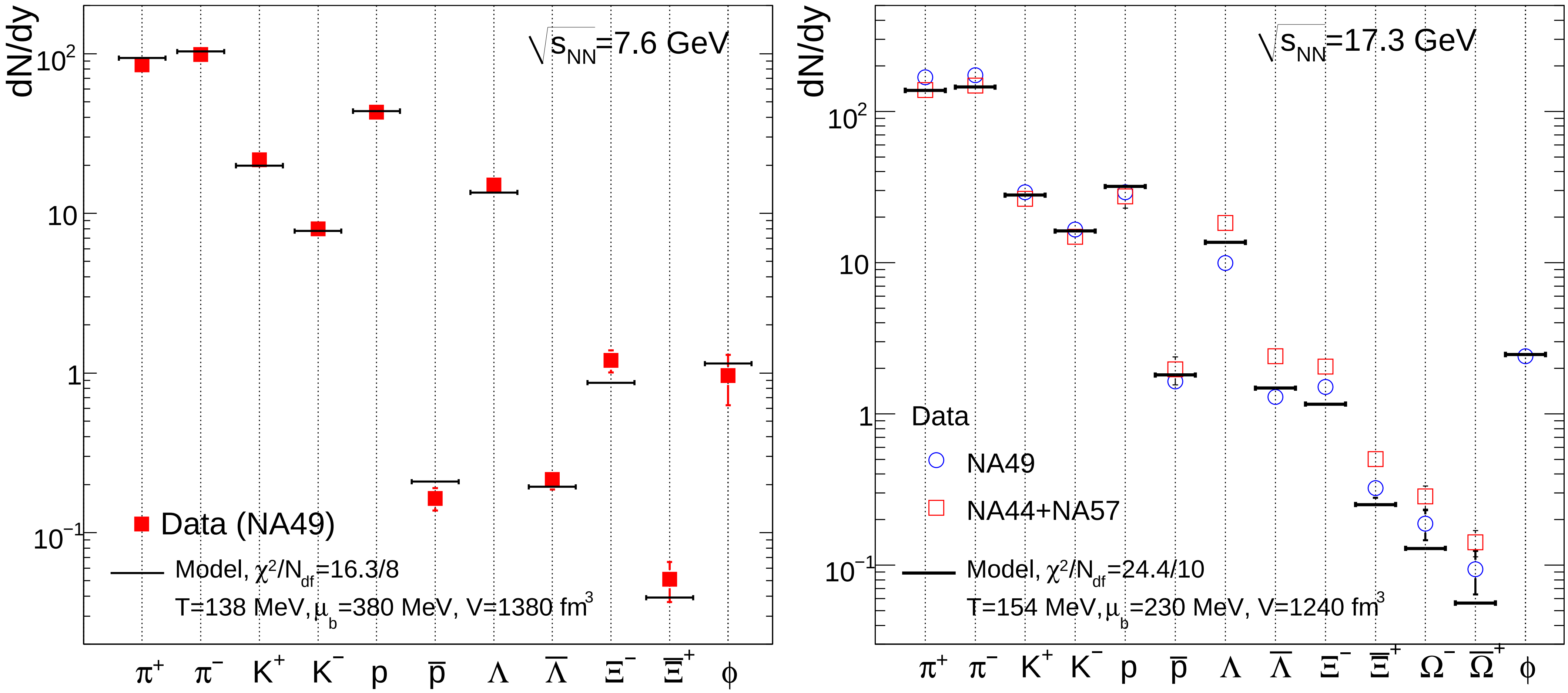
Fits at AGS: 6 and 10.5 AGeV





AGS, 2-8 AGeV: a rather small set of hadron yields measured

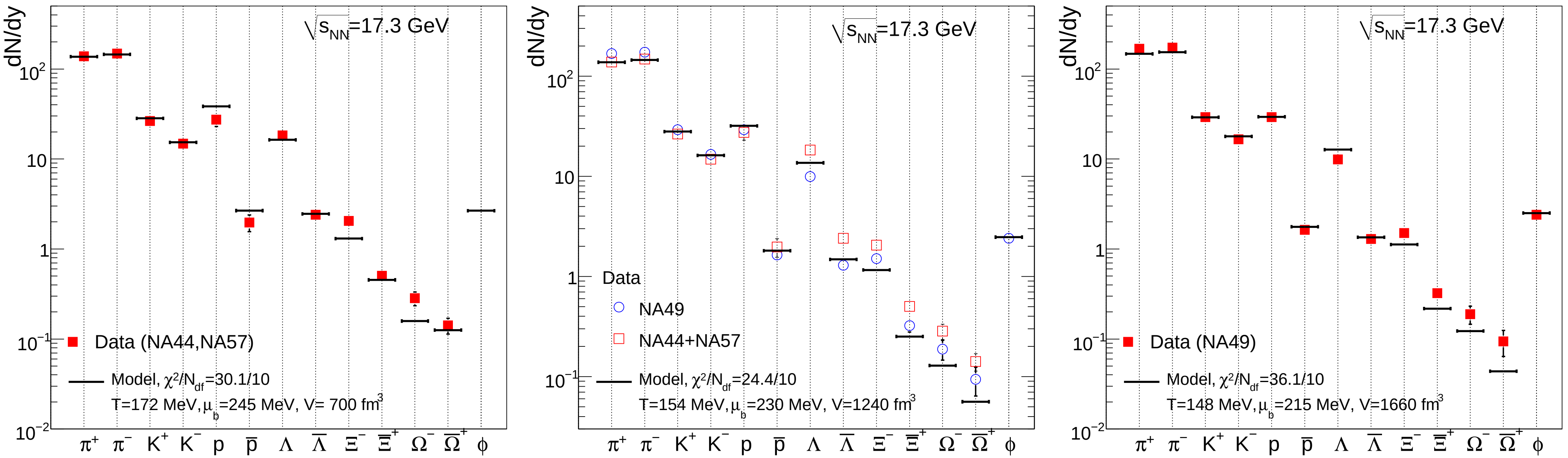
Fits at SPS: 30 and 158 GeV



only NA49 data: T=148 MeV, μ_b=215 MeV, V=1660 fm^3, χ^2/N_{df}=36/10

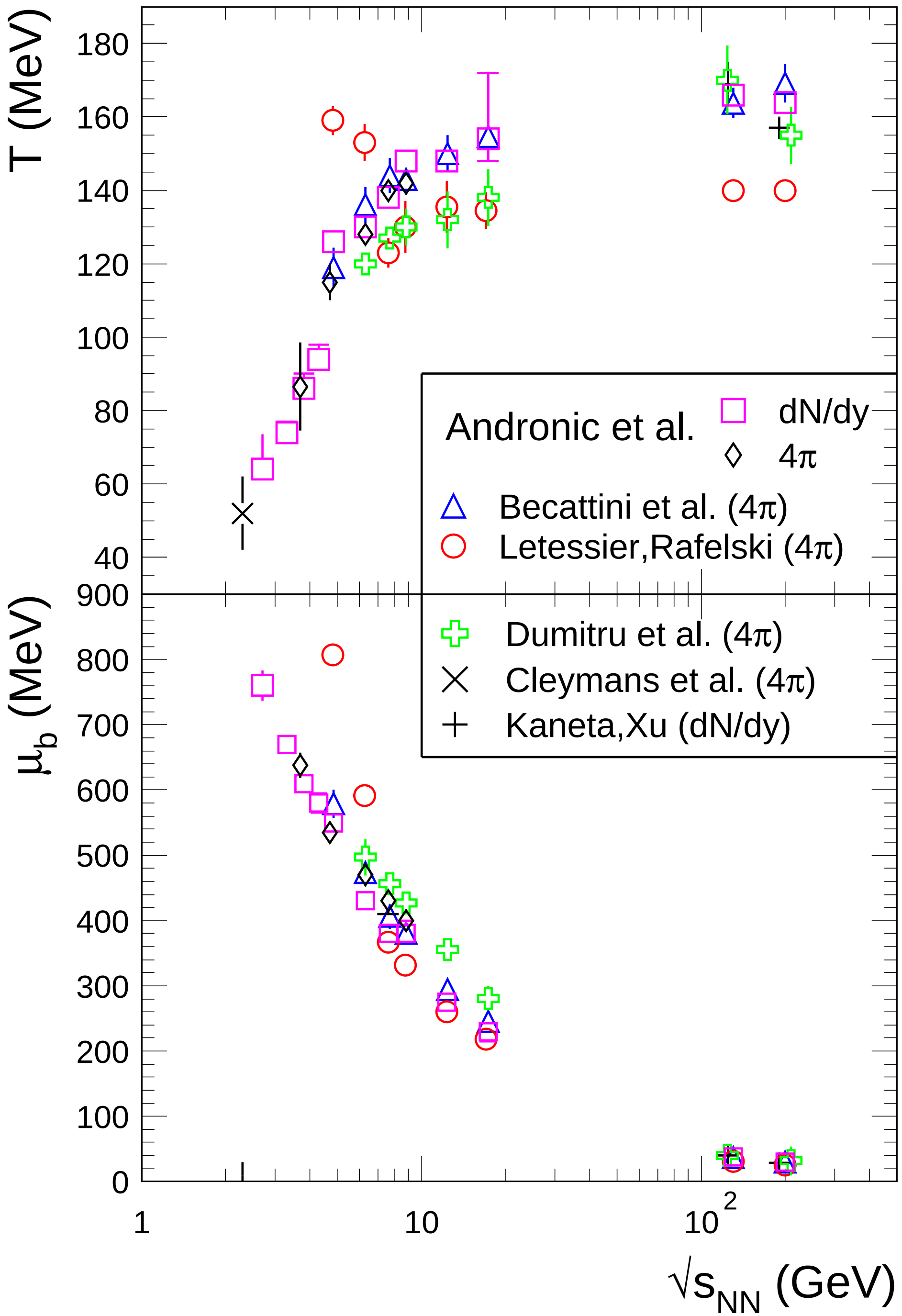
only NA44+NA57: T=172 MeV, μ_b=245 MeV, V=700 fm^3, χ^2/N_{df}=30/10

SPS, 158 AGeV



dN/dy
$\sqrt{s_{NN}}$=17.3 GeV
Data (NA44,NA57)
Model, χ^2/N_{df}=30.1/10
T=172 MeV, μ_b=245 MeV, V= 700 fm^3
Data
NA49
NA44+NA57
Model, χ^2/N_{df}=24.4/10
T=154 MeV, μ_b=230 MeV, V=1240 fm^3
Data (NA49)
Model, χ^2/N_{df}=36.1/10
T=148 MeV, μ_b=215 MeV, V=1660 fm^3
π^+ π^- K^+ K^- p $\bar{p}$ Λ $\bar{\Lambda}$ Ξ^- $\bar{\Xi}^+$ Ω^- $\bar{\Omega}^+$ ϕ

Energy dependence of the thermal parameters



- Becattini et al.: $+\gamma_S$

  Phys. Rev. C 73 (2006) 044905

  Phys. Rev. C 78 (2008) 054901

- Rafelski et al.: $+\gamma_{S,q}$, λ_{q,S,I_3}

  Eur. Phys. J. A 35 (2008) 221

  γ_S=0.18,0.36,1.72,1.64,...

  γ_q=0.33,0.48,1.74,1.49,1.39,1.47...

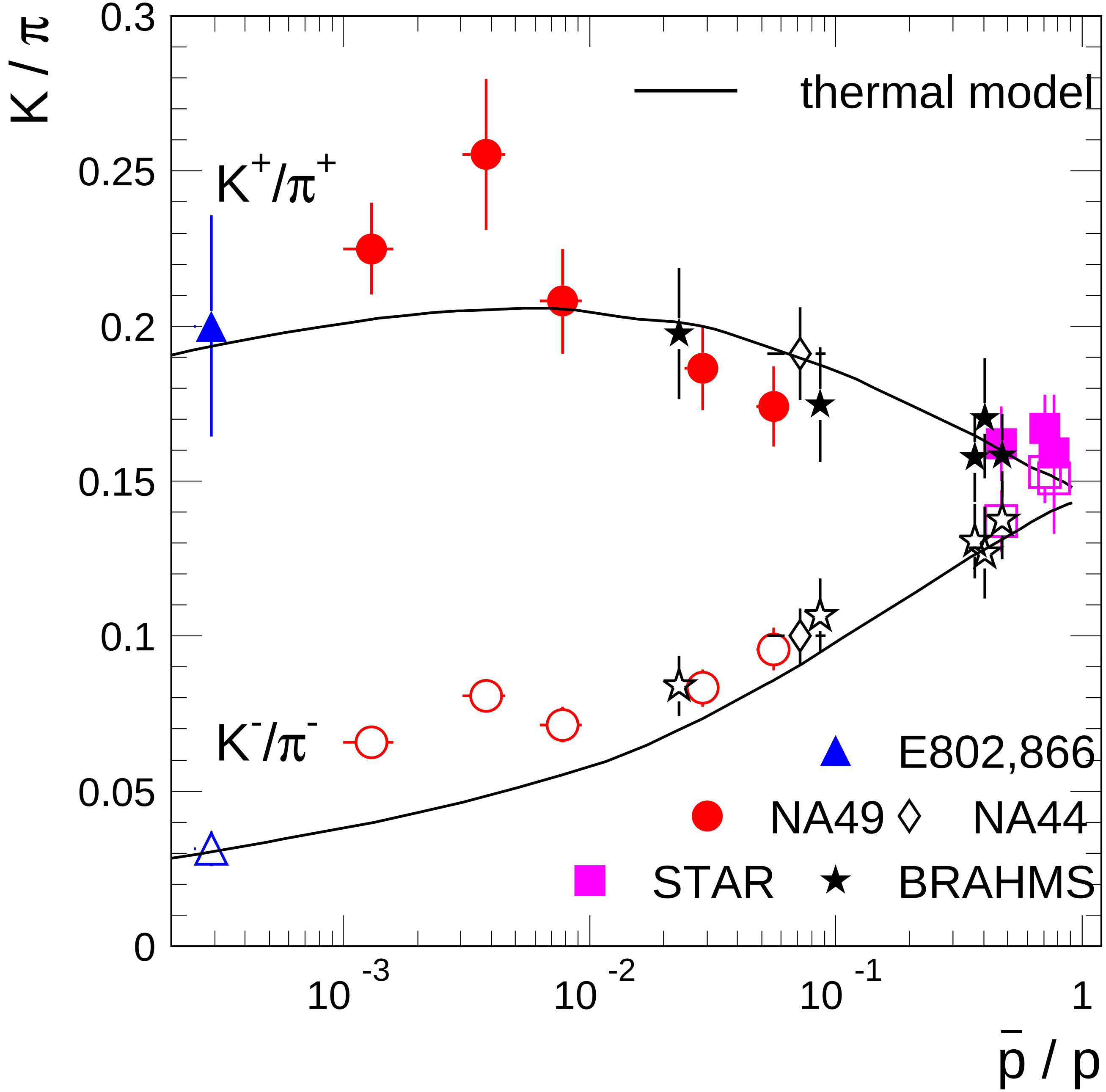
- Dumitru et al.: inhomogeneous freeze-out (δT, $\delta\mu_B$)

  Phys. Rev. C 73 (2006) 024902

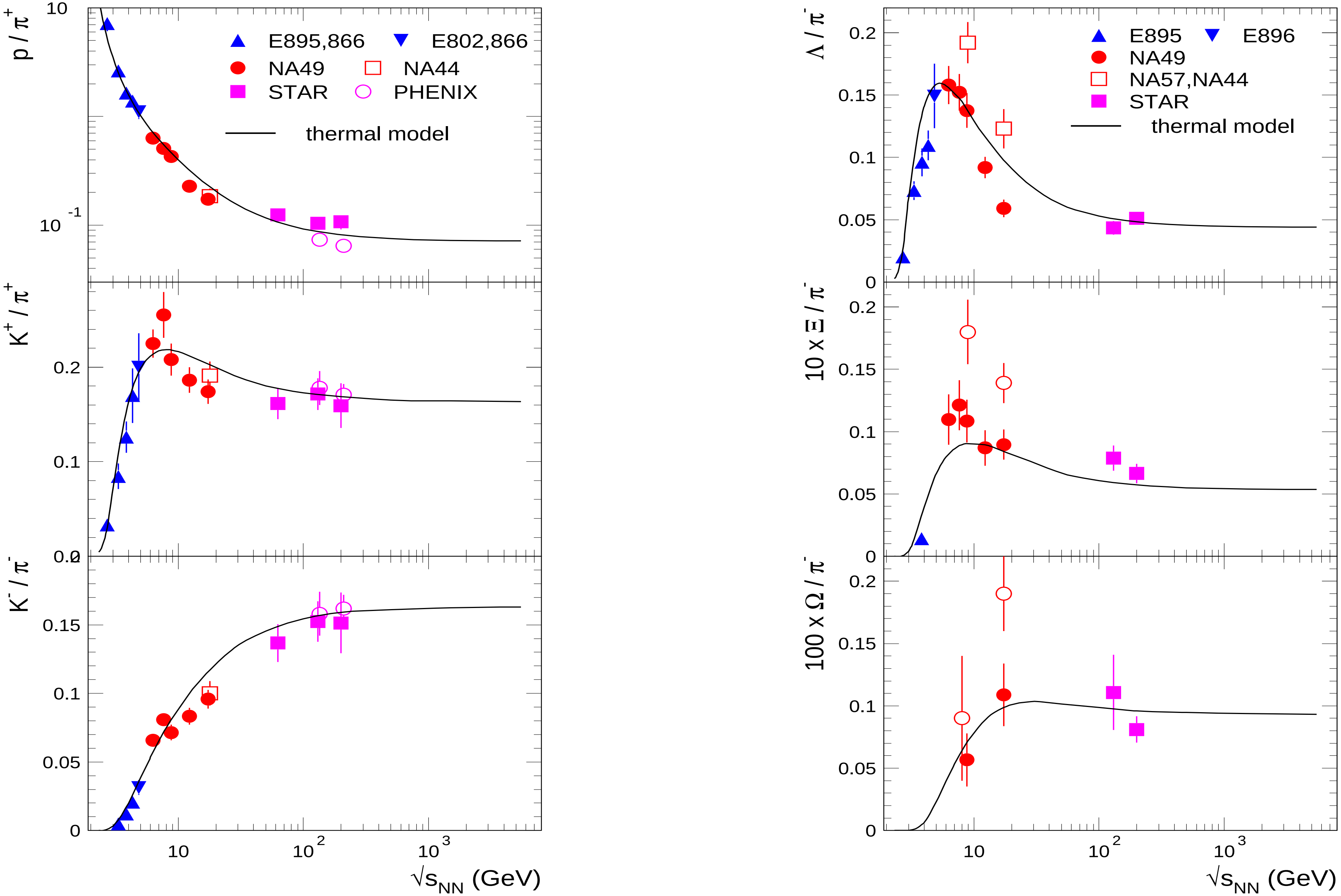
- Kaneta, Xu, nucl-th/0405068

- Cleymans et al., Phys. Rev. C 57 (1998) 3319

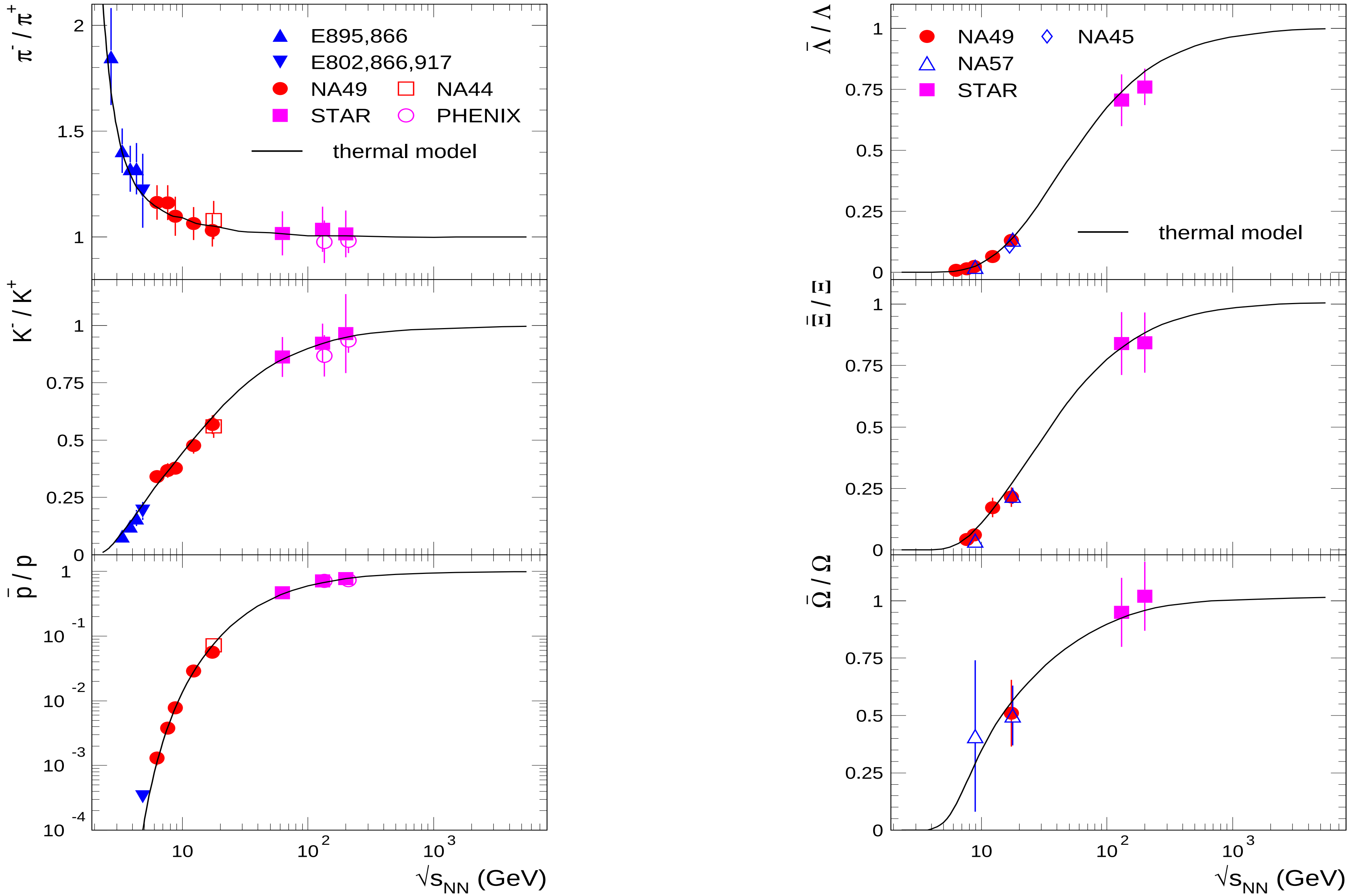
A clever proxy for the horn (BRAHMS collab.)



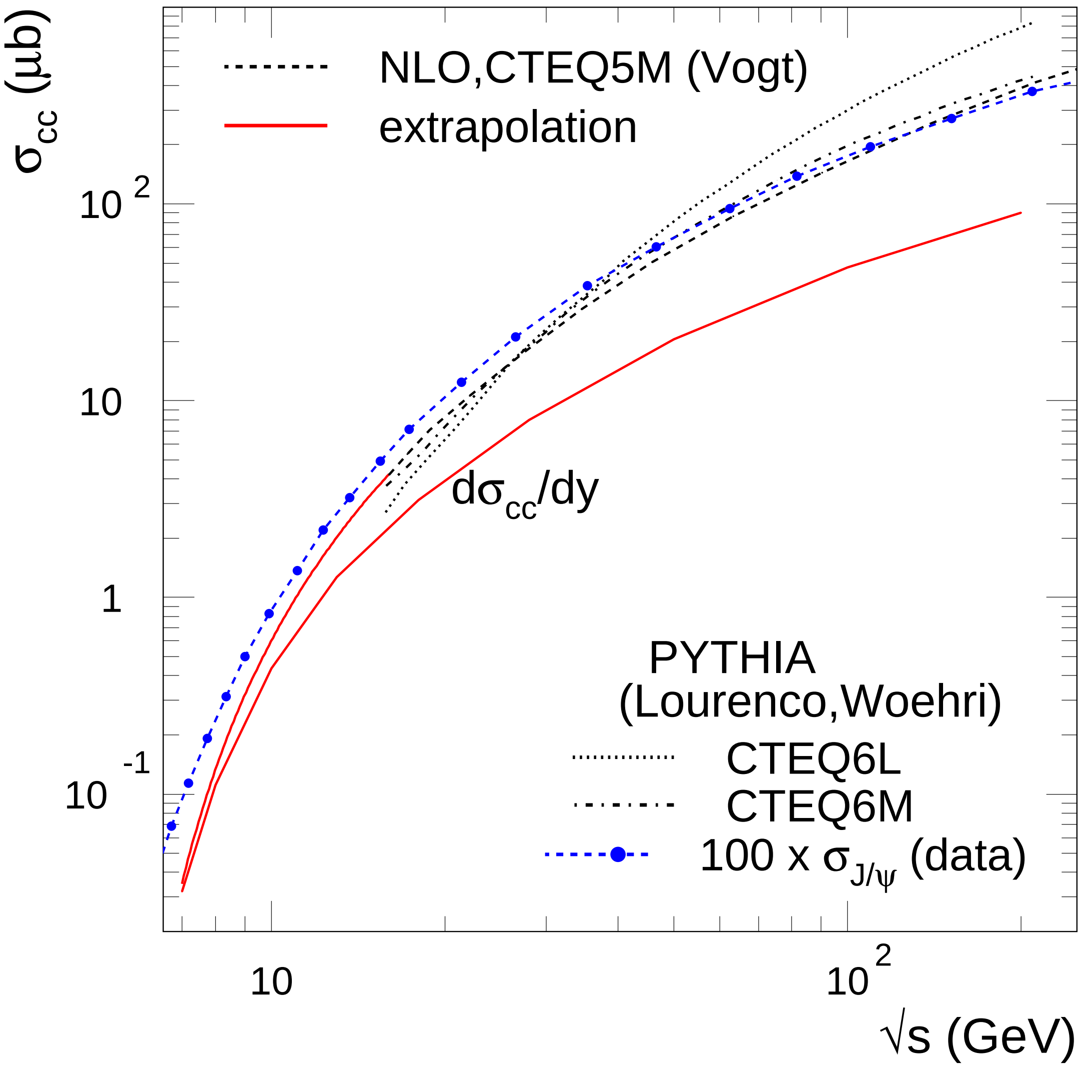
More particle ratios



More particle ratios



$N_{c\bar{c}}^{dir}$ 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)

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

RHIC: ≃1.6, LHC: ≃16

Canonical suppression and charm fugacity

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