Canonical description of charm and bottom production in e^+e^-, $pA,\ \pi A,\ pp$ *and* $\bar{p}p$ collisions

Krzysztof Redlich

- Statistical Model and exact charge conservation laws:
  Its phenomenological consequences in HIC
- SM application to particle productions in e^+e^- annihilation
  - light flavors production
  - heavy flavors production
- Relative production yields of charm- and bottom-hadrons in $pA,\ \pi A,\ pp$ *and* $\bar{p}p$ collisions and HRG model results

In collaboration with: A. Andronic, F. Beutler, P. Braun-Munzinger J. Stachel

Statistical operator and mass spectrum

- **resonance dominance**

$$\ln Z^{GC}(T,\vec{\mu}) = \int \frac{2V_\mu p^\mu}{(2\pi)^3} \tau(p^2, \mu_B, \mu_S, \mu_Q) e^{-\beta_\mu p^\mu}$$

- **approximate $\tau(m^2, \vec{\mu})$ by experimentally known mass spectrum**

$$\ln Z(T,\vec{\mu}) \approx \frac{VT}{2\pi^2} \sum_{i \in hadrons} d_i e^{\frac{\vec{Q}_i \vec{\mu}}{T}} \int ds\, s\, K_2\left(\frac{\sqrt{s}}{T}\right) F^{B-W}(m_i, s)$$

Breit-Wigner res.

particle yield **thermal density** **BR** **thermal density of resonances**

$$< N_i > = V\,[n_i^{th}(T,\mu_B) + \sum_K \Gamma_{K \to i} n_i^{th-Res.}(T,\mu_B)]$$

- **Only 2-parameters needed to fix all particle yield ratios**

$$e^{i\phi S} H e^{i\phi S} = H \leftrightarrow \quad [S, H] = 0$$

conservation on the average

exact conservation

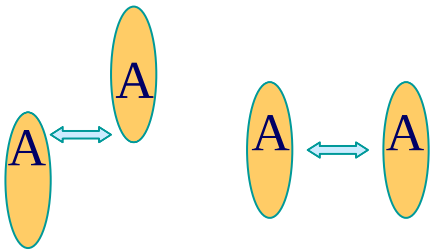
$$Z^{GC}(T, \mu_S, V) = Tr\,[e^{-\beta(H-\mu_S S)}]$$

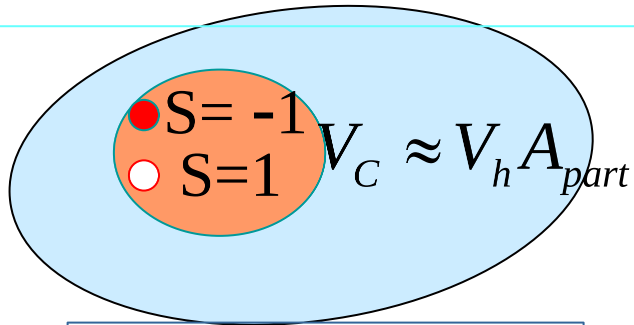
$$Z_S^C(T, V) = Tr_S[e^{-\beta H}]$$

$$Z^{GC} = \sum_{S=-\infty}^{S=+\infty} e^{S\mu_S/T} Z_S^C$$

$$Z_S(T,V) = \frac{1}{2\pi}\int_0^{2\pi} d\varphi e^{-iS\varphi} Z^{GC}(T, \frac{\mu_S}{T} \to i\varphi)$$

Consider thermal system with Total Strangenes "S"=0





$$n_S^C \approx \gamma_s^S n^{GC} \propto \frac{I_S(\gamma_s 2V_C\sqrt{n_{s=-1}^{GC} n_{s=+1}^{GC}})}{I_0(\gamma_s 2V_C\sqrt{n_{s=-1}^{GC} n_{s=+1}^{GC}})}$$

suppression factor $\leq$ 1

$$< N >^{GC} \propto A_{part}$$

$$< N >^{C} \propto A_{part}^2$$

suppression increases with S and with decreasing collision energy

i) Strong, quadratic dependance of |S|=1 particles with A_{part} at SIS

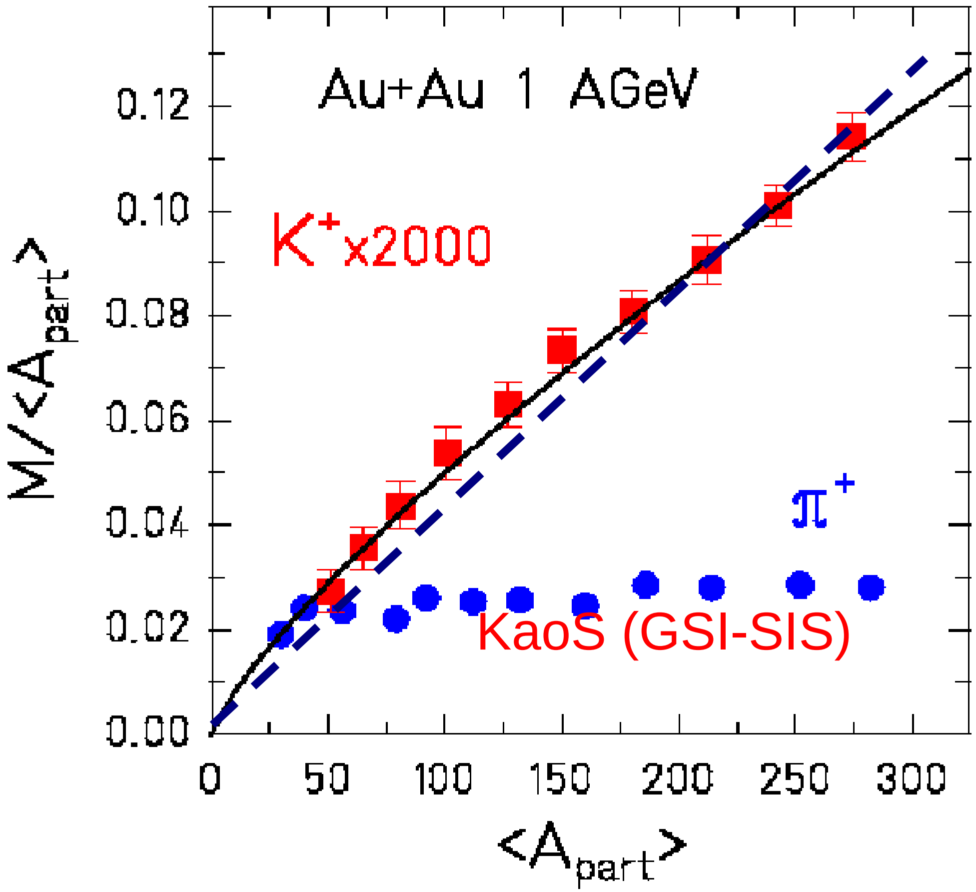
ii) strange anti-particle/particle ratios independent of A_{part}

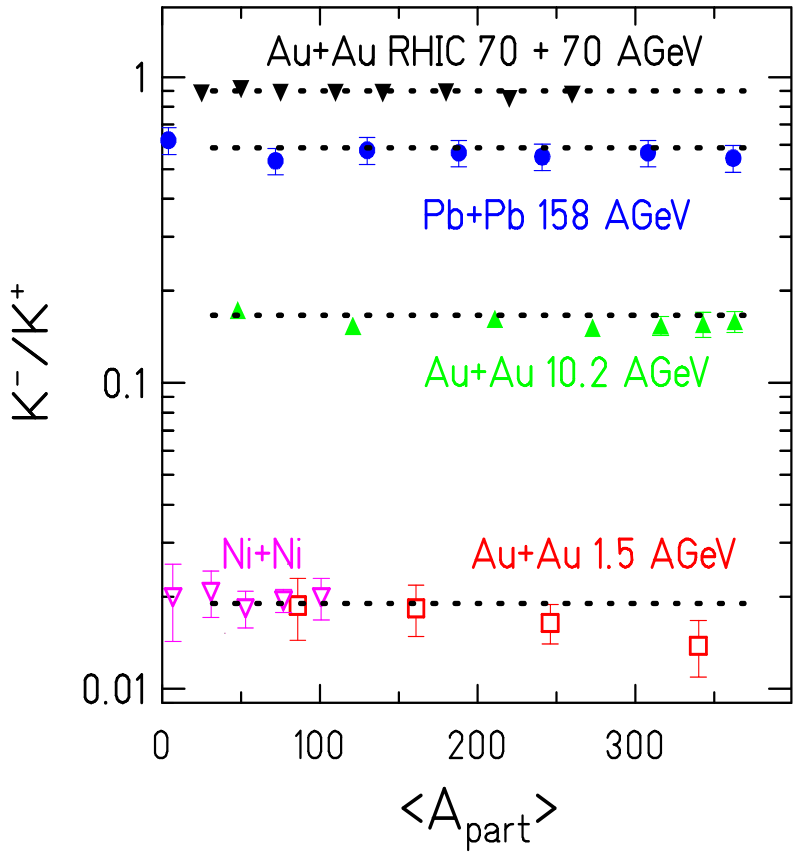
$$\pi + N \rightarrow K^+ + Y$$

$$< K^+ >^C \propto A_{part}^2 e^{-m_k/T} e^{-(m_Y - \mu_B)/T}$$

$$< \pi^+ > \propto A_{part} e^{-(m_\Delta - \mu_B)/T}$$

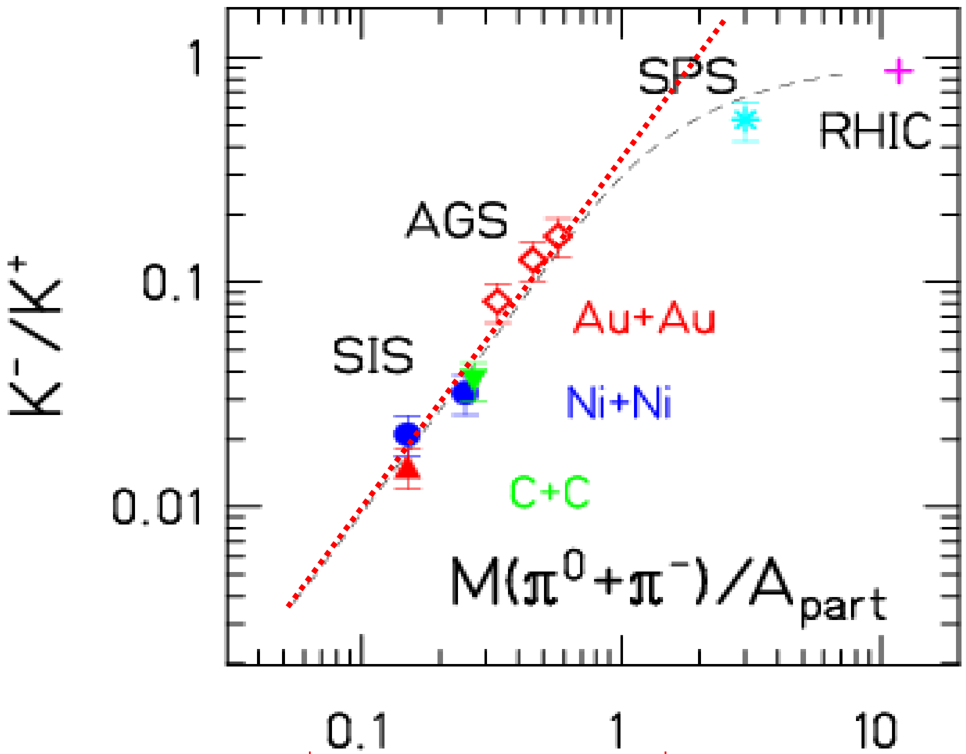
J. Cleymans, H. Oeschler & K.R.



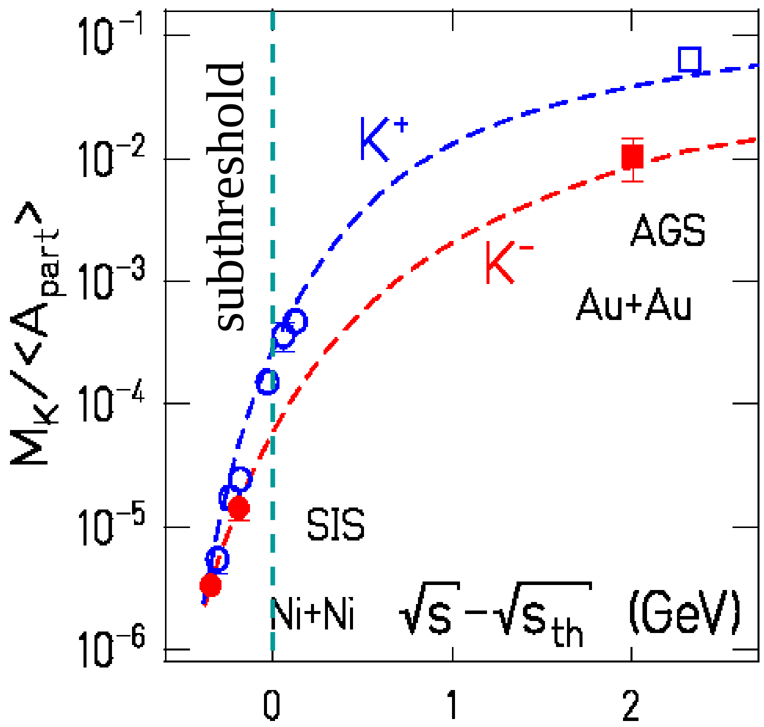


iii) Scaling properties of particle production yields

J. Cleymans, H. Oeschler & K.R.



- Excellent description of kaon production from SIS to AGS



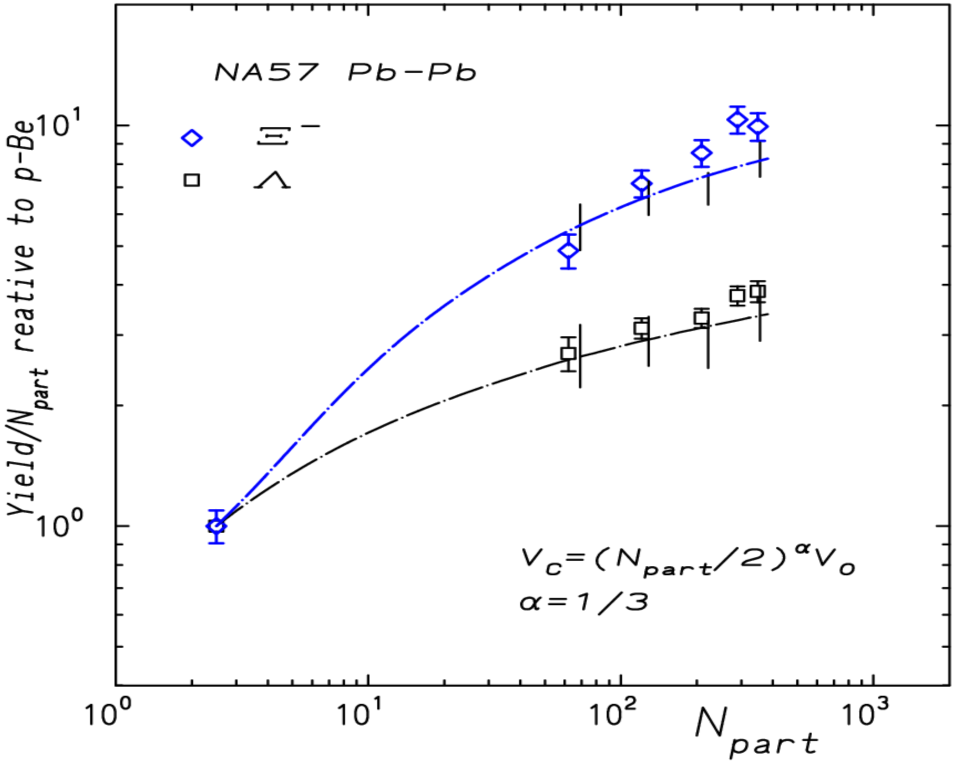
$$\pi + N \to K^+ + \Lambda \Rightarrow [K^+] = [\Lambda]$$

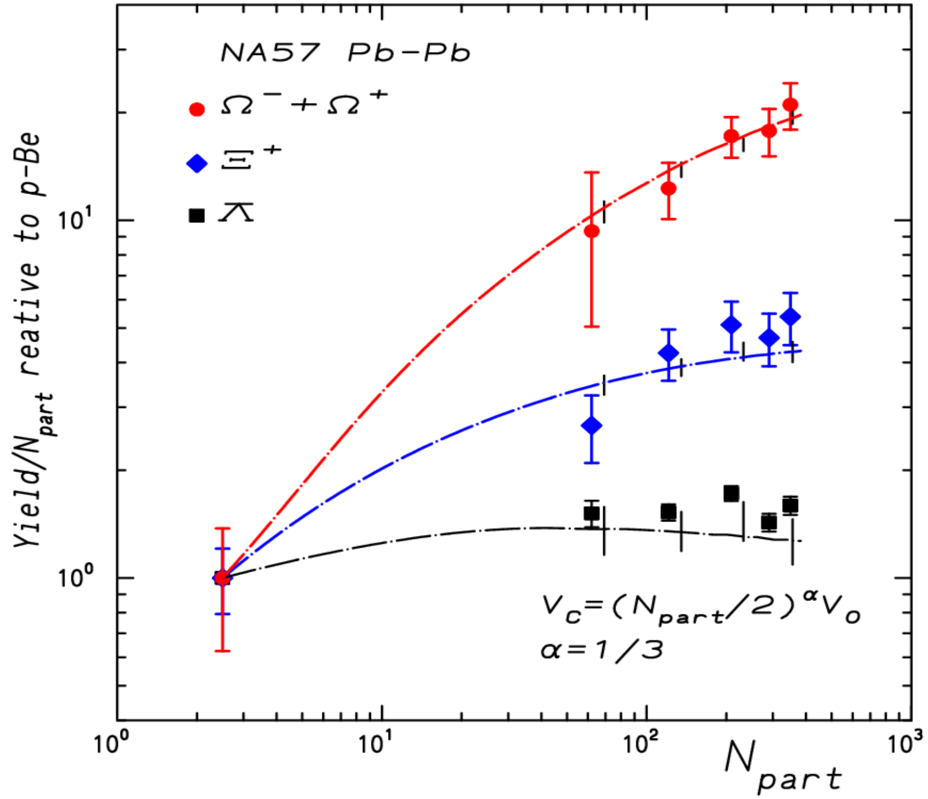
$$\pi + \Lambda \to K^- + N \Rightarrow \frac{[\pi]}{[N]} = \kappa \frac{[K^-]}{[\Lambda]}$$

Scaling: $\frac{[K^-]}{[K^+]} = \kappa \frac{[\pi]}{[N]}$

- similar scaling for $[\Xi^-]/[K^+] = \kappa \cdot [K^+]/[N]$: A. Andronic, P. Braun-Munzinger & K.R.

Strangeness enhancement from p-Be to central Pb-Pb collisions at $\sqrt{s_{NN}} = 17.3\ GeV$

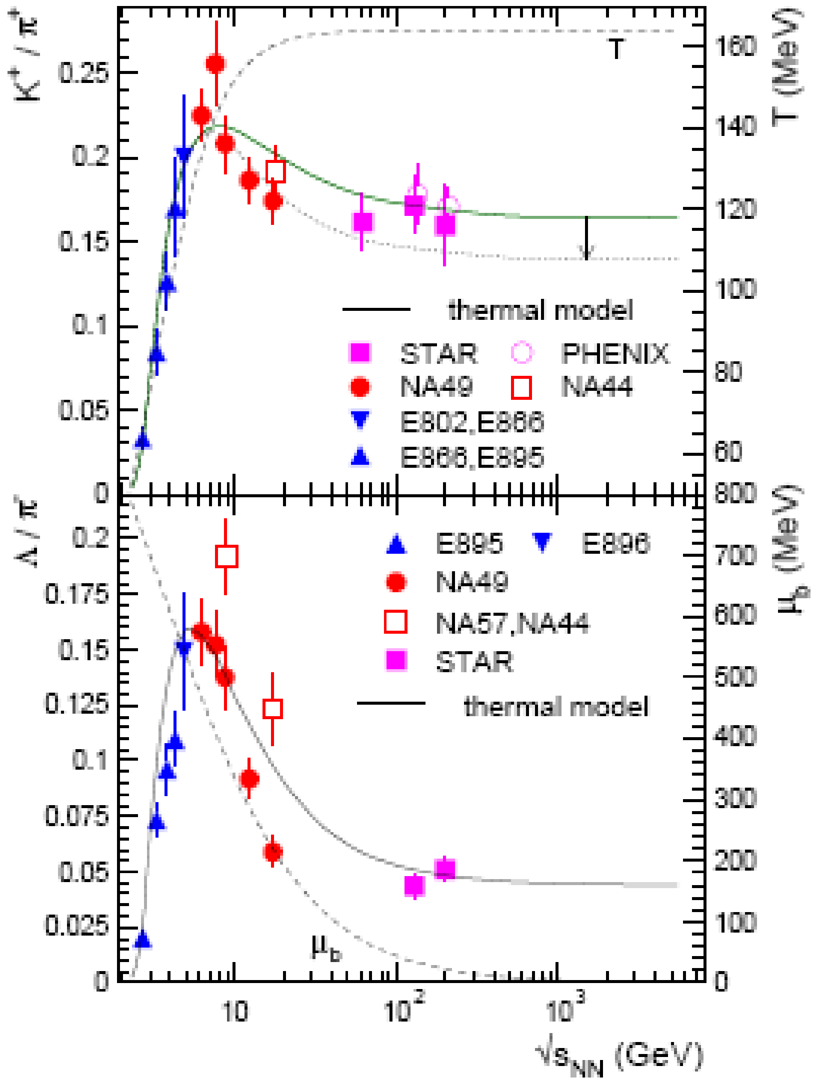




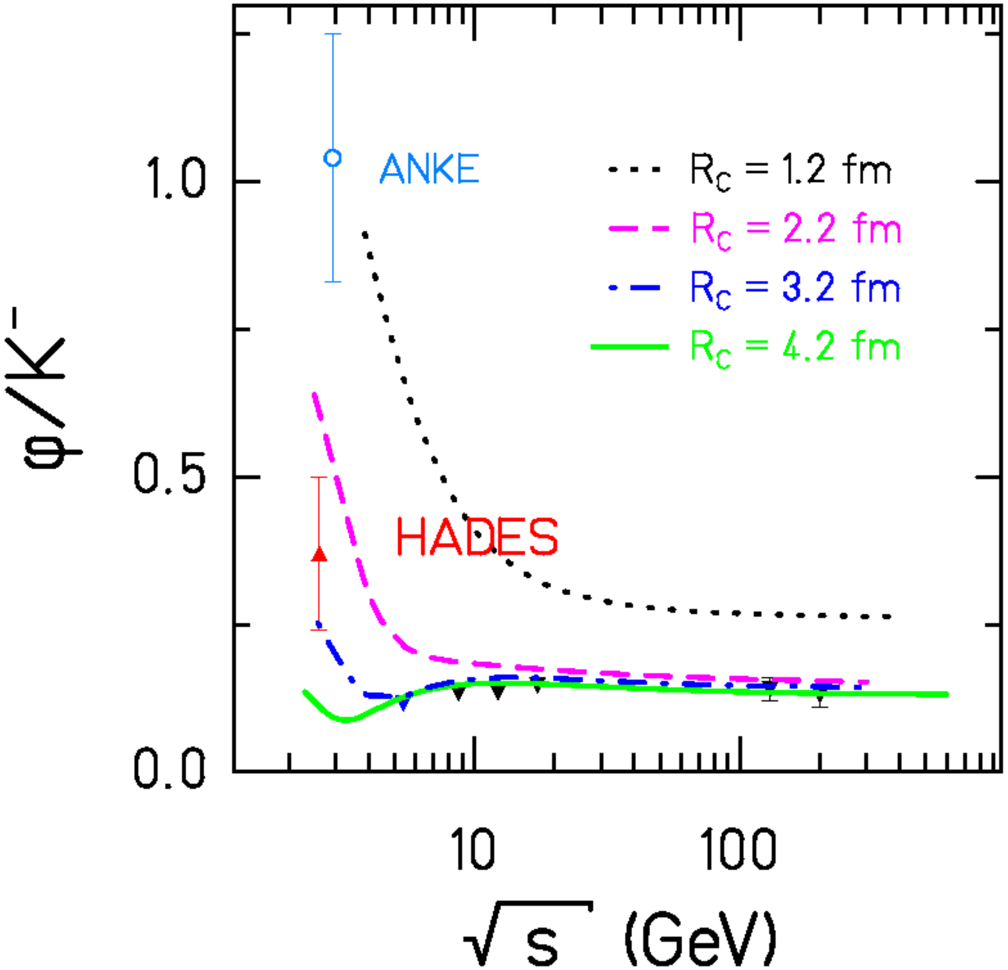
Canonical model with exact strangeness conservation at fixed $T \approx 168\ MeV$ **and** μ_B **being centrality dependent provide good description of NA57 data if the correlation volume scales as:** $V = (A_{part}/2)^{\alpha}\ with\ \alpha \approx 1/3$

Particles excitation functions in HG model

Braun-Munzinger, Cleymans, Oeschler &K.R.
Andronic, Braun-Munzinger &Stachel



Nu Xu & K.R.
H.Oeschler et al.



Canonical model for particle production yields in e^+e^-

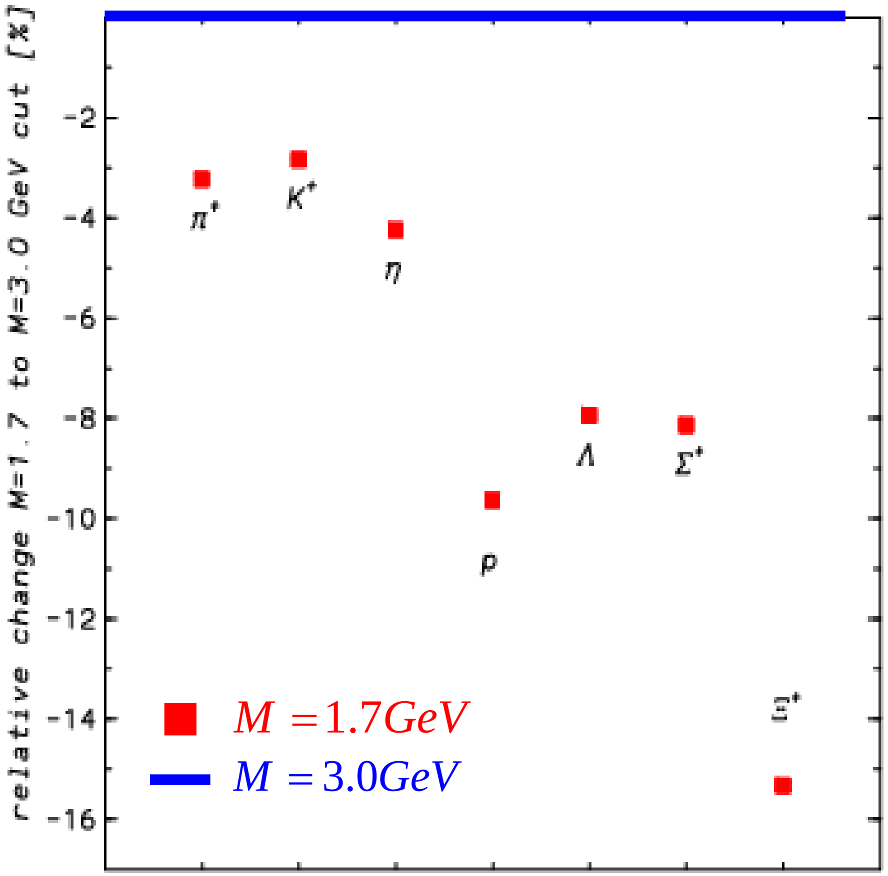
The partition functions with exact, N=Baryon, S=Strangeness, Q=Electric, C=Charm, B=Bottom quantum numbers under quantum statistic constructed from: **L. Turko, Phys. Lett. (1981)**

$$Z^{GC}(T,V,\beta\mu_K \to i\varphi_k)$$

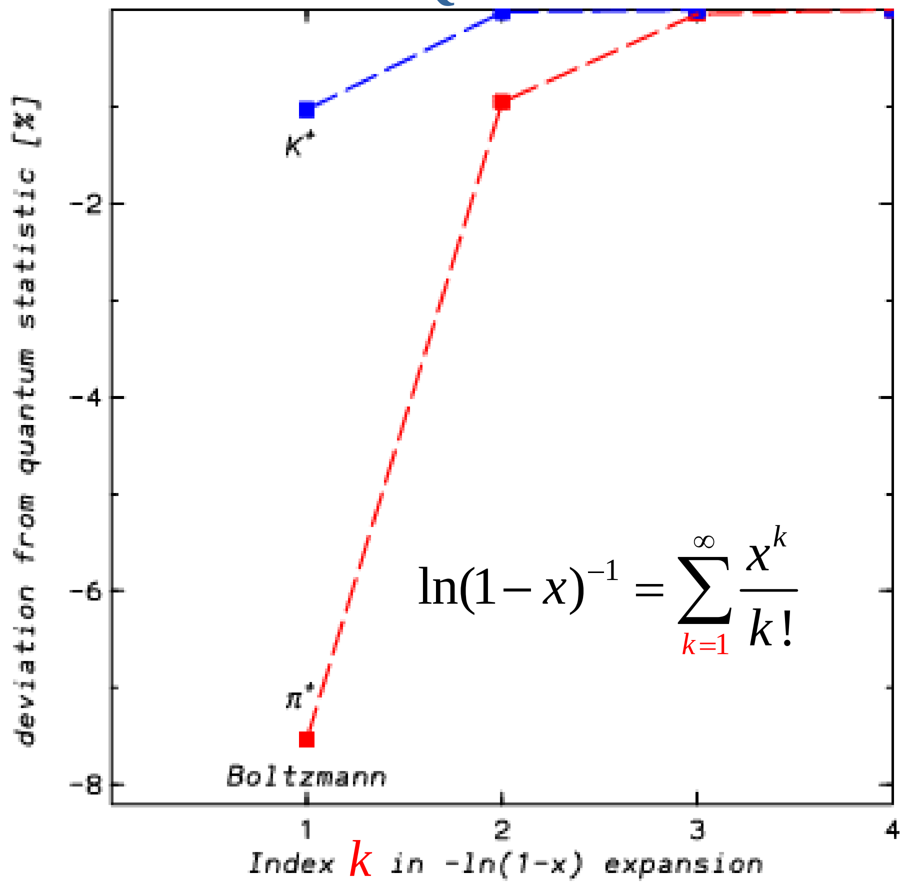
$$Z_{N,S,Q,C,B}(T,V) = \frac{1}{(2\pi)^5}\int_0^{2\pi} d^5\vec{\varphi}\; e^{i\vec{\varphi}\cdot\vec{X}} \exp\left(\sum_i \frac{d_i \cdot V}{(2\pi)^3}\int d^3p \ln(1 \pm e^{-\beta E_i - i\vec{x}_i\cdot\vec{\varphi}_i})^{\pm 1}\right)$$

- The integral is not convenient for numerical analysis as the integrand is a strongly oscillating function
- The partition function and particle multiplicity can be expressed as multi-sum and products of different Bessel functions
- Because of the high precision of the LEP measurements, a high mass cut $M \approx 3GeV$ and quantum statistic are required

Quantum statistic and Mass cut effects on particle yields



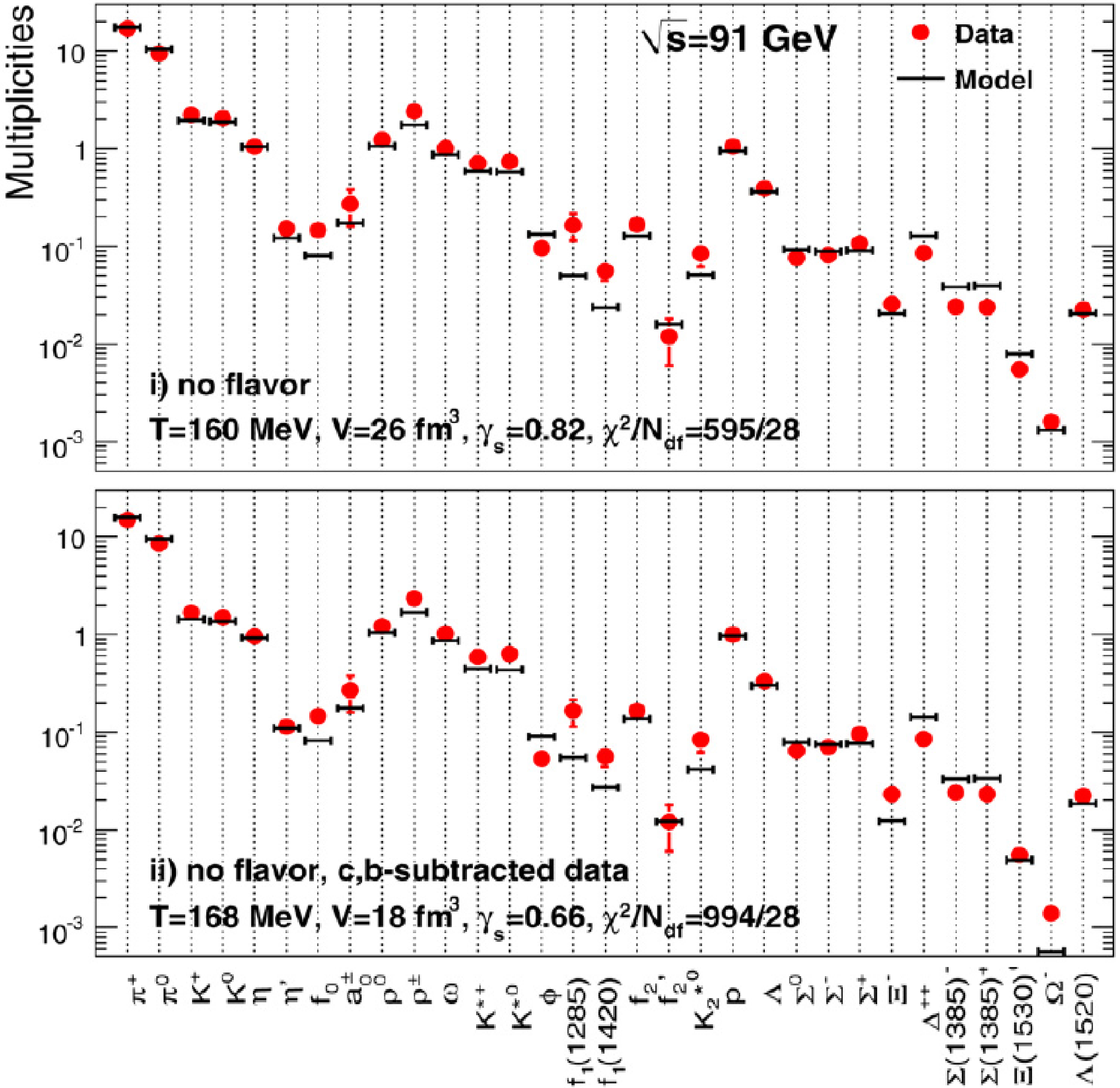
Quantum statistic



Strong, 8-15 % deviation of baryon yields if cutting the mass spectrum at $M \approx 1.7GeV$

Quantum statistic needed for Pions and Kaons

- Most hadronic events in high energy e+e collisions are two-jet events
- Each jet represents an independent fireball



← Problem: Open Charm an Bottom shows dramatic deviations from data

$$< N_B >^{model} / data \approx 10^{-20}$$

$$< N_{D^\pm} >^{model} / data \approx 10^{-2}$$

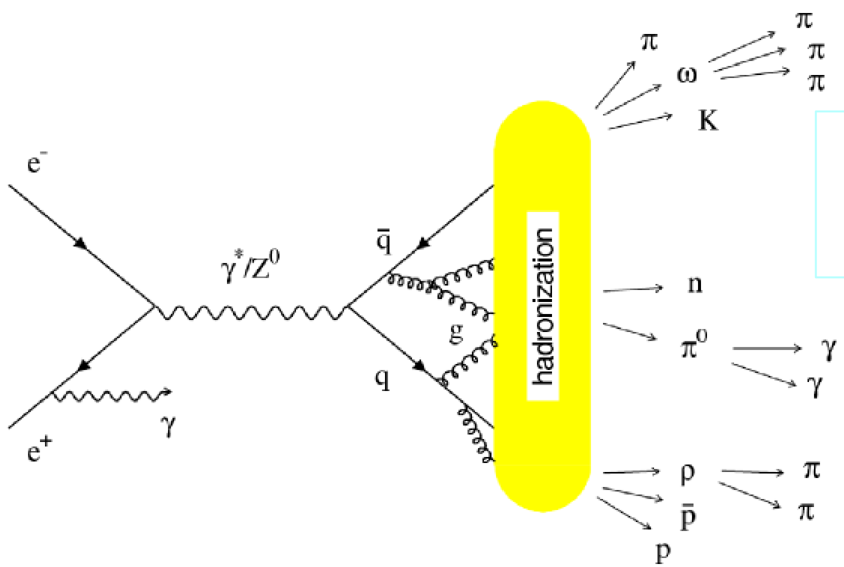
←Subtract the contributions from charm an bottom to lighter particles

e.g. C,B contributions to

$\pi^+ - 11.7\%$, $K^+ - 30.0\%$

$K^{*0}(892) - 16.5\%$, $\phi(1020) - 68.0\%$

Hadron production in e^+e^- annihilation



Jet structure of hadrons production

$$2\text{ jets} : 3\text{ jets} : 4\text{ jets} = \mathcal{O}(\alpha_s^0) : \mathcal{O}(\alpha_s^1) : \mathcal{O}(\alpha_s^2)$$

α_s at $\sqrt{s}$=91 GeV is 0.12 ± 0.0031

$$\Gamma_{q\bar{q}} = \frac{G_F m_Z^3 \beta_q}{2\pi\sqrt{2}} \left[(1+2\eta^2)\left((g_V^q)^2 + (g_A^q)^2\right) - 6\eta^2 (g_A^q)^2 \right]$$

Flavor content of the jets:

$$up\ type\ quarks = (u, c)$$

$$down\ type\ quarks = (d, s, b)$$

$$\Gamma_{u\bar{u}}/\Gamma_{\text{hadron}} \approx 17\%$$

$$\Gamma_{d\bar{d}}/\Gamma_{\text{hadron}} \approx 22\%$$

Can we quantify light and heavy flavor particles within Statistical Model ??

F. Becattini, Z. Phys. C 69 (1996) 485. F. Becattini, P. Castorina, J. Manninen, H. Satz, Eur. Phys. J. C 56 (2008) 493

A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel, Phys. Lett. B **675** (2009) 312 [arXiv:0804.4132].

Canonical effects and charm/bottom mesons

Charge of the system

$$< N_i >^{Q}_{Q_i=\pm1} = \gamma V \cdot z_i^{Q_i} \frac{Z_{\mp1}}{x} \frac{I_{Q\mp1}(2\gamma V x)}{I_Q(2\gamma V x)}$$

Charge of the particle

$$z_i^{Q_i} = \frac{d_i}{(2\pi)^3} \int d^3 p \exp(-\beta(E_i + \vec{b}_i \cdot \vec{\mu}_i))$$

$$Z_{\pm1} = \sum_i z_i^{Q_i=\pm1} \qquad x = \sqrt{Z_{-1} Z_1}$$

Total charge of the system

And small $2V_c x << 1$

$Q = 0$

$$< N_i >^{Q=0}_{Q_i=+1} \approx \gamma V \cdot z_i \cdot \gamma V \cdot Z_{-1}$$

Strong Suppression of thermal particle phase-space

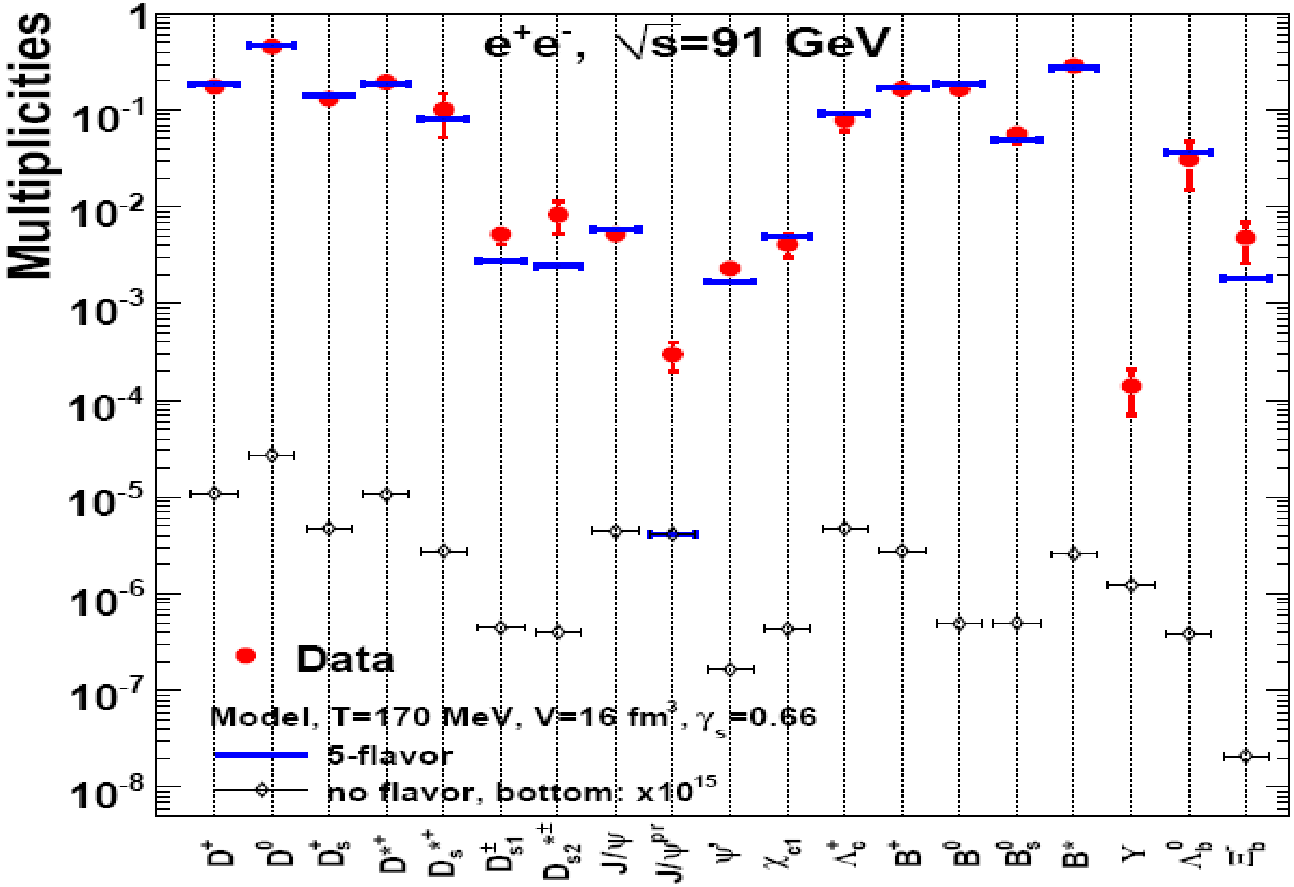
$Q = +1$

$$< N_i >^{Q=+1}_{Q_i=+1} \approx \frac{V\gamma \cdot z_i}{V\gamma \cdot Z_{+1}}$$

Strong Enhancement of thermal particle phase-space

Charge Q=+1 redistributed between different particle species

Charm and Bottom particles at LEP at $\sqrt{s} = 91\ GeV$



Use the same thermal parameters as obtained from the fit to the light quark hadron multiplicities

Very good agreement with $\chi^2/dof = 34/18$ for all data and $\chi^2/dof = 22/16$ when excluding Y and J/ψ

- **Open charm and bottom well described by thermalization of the fireball with overall Charm= ± 1 and Bottom= ± 1**
- $J/\psi,\ \psi'$ **and** χ_c **are entirely coming from Bottom's decays and agree with model**
- **Hidden charm, Y is of non-thermal origin, thus it does not fit to model systematics!**

Statistical Model and relative charm and bottom production in hA and hh collisions at different $\sqrt{s}$

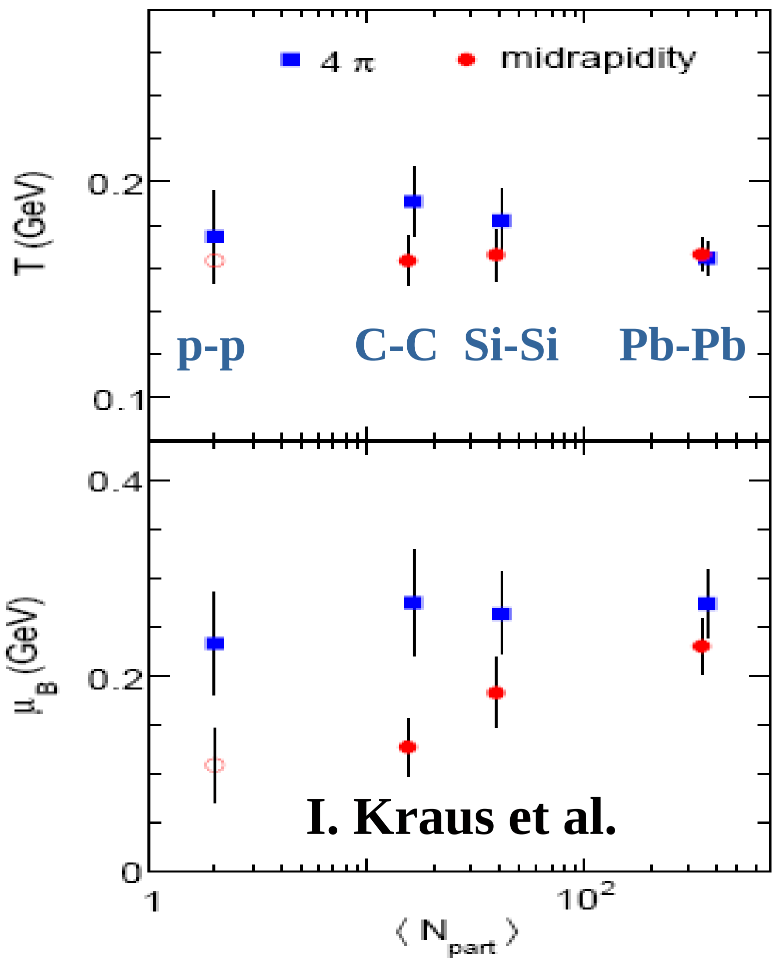
- Fixed thermal parameters in hA and hh collisions within the Statistical model
- Consider particle ratios of open charm only
- Consider ratios of charmonia or bottomonia

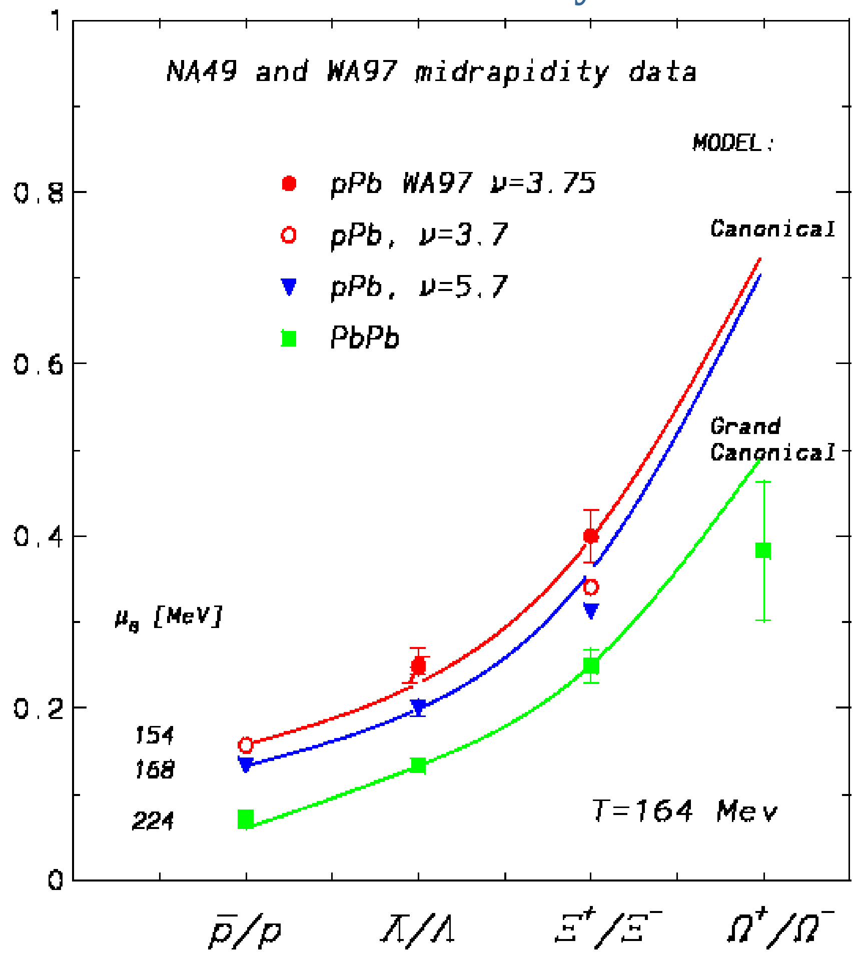
Remark:

In hadronic collisions the relative production cross sections between bottom and charm are much smaller than in e^+e^- *collisions. Even at the LHC energies* $\sigma_b/\sigma_c \simeq 1/10$, *while in 91 GeV e+e-* $B(Z^0 \to b)/B(Z^0 \to c) = 0.22/0.17$.

Fixing thermal parameters in h-A and hh:

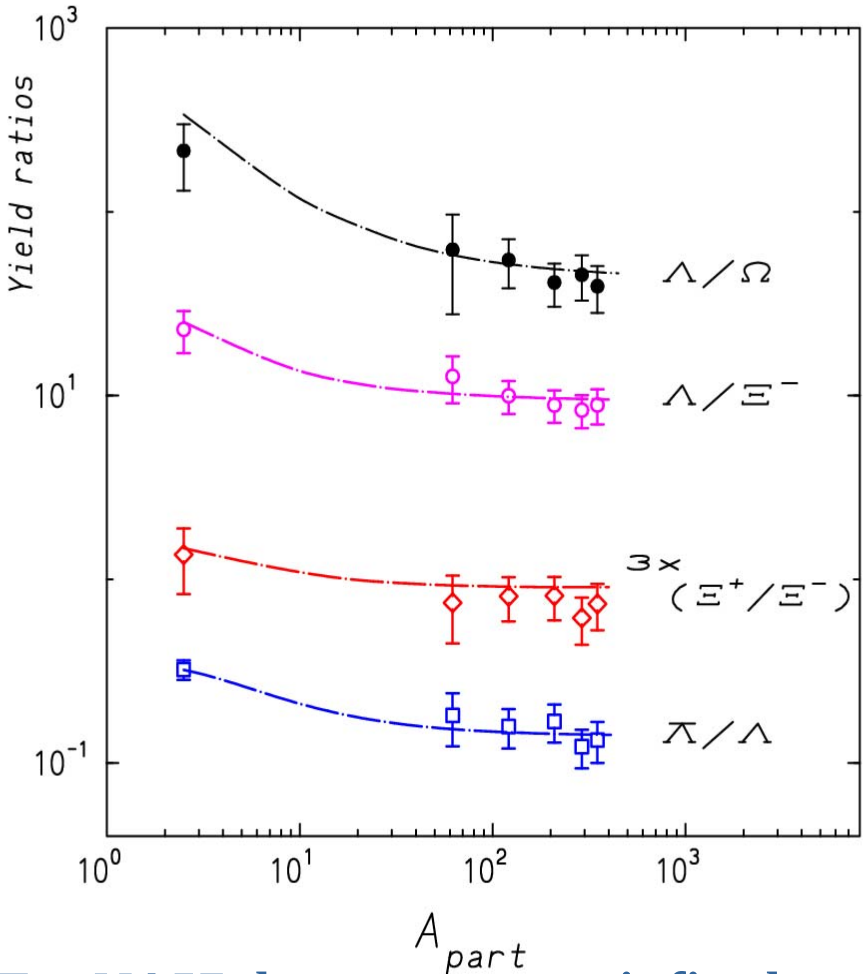
J. Cleymans et al.

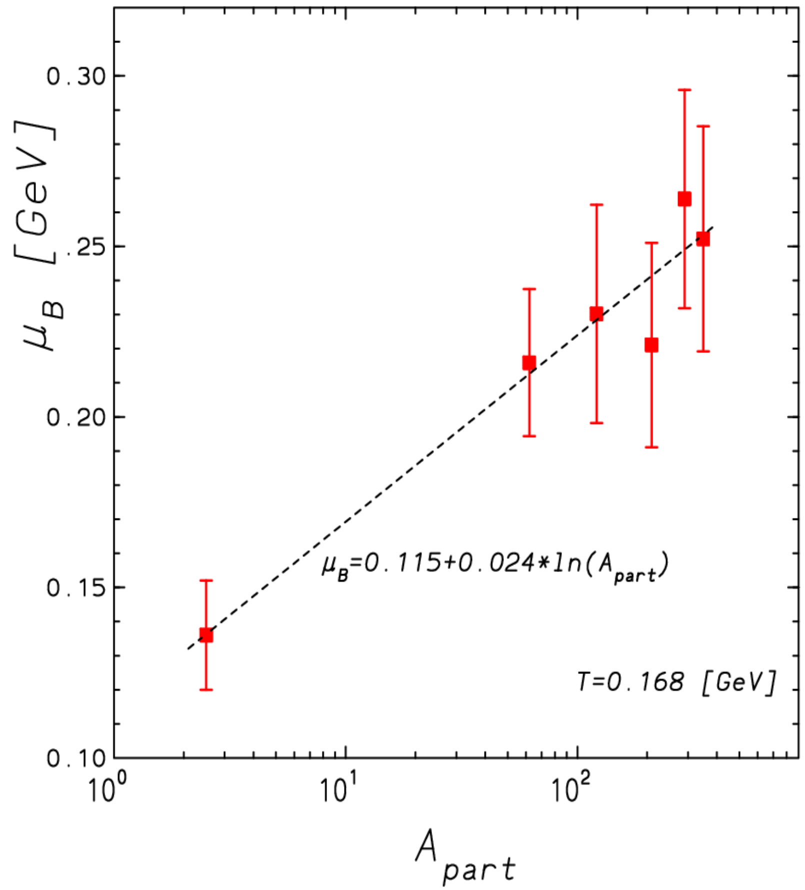




- **Temperature independent of system size and centrality**
- **Strong variation of baryon chemical potential with centrality and system size for mid-rapidity data**

Centrality dependence of baryon chemical potential

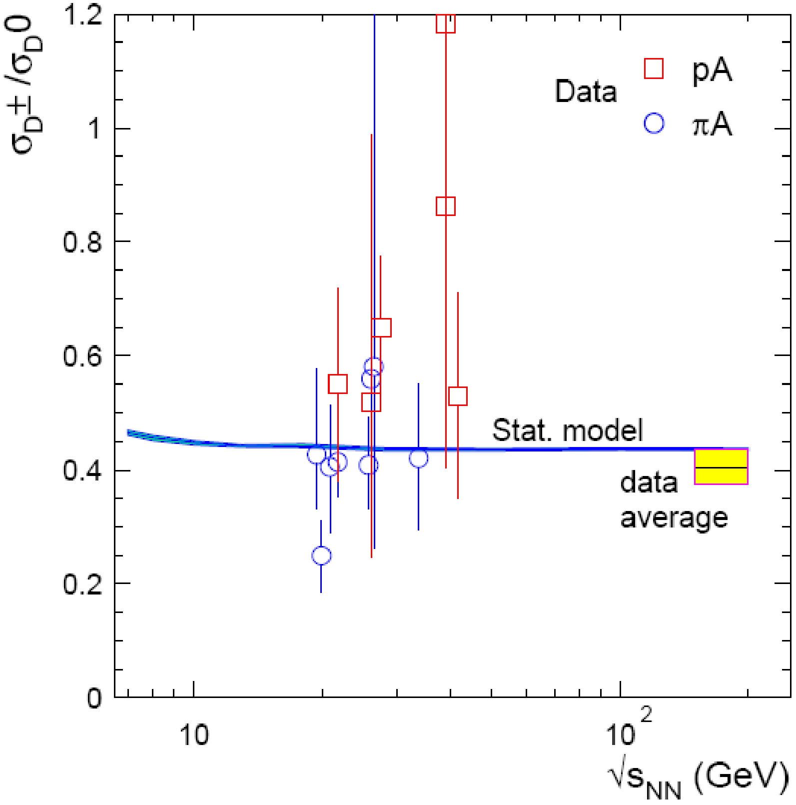




For NA57 the temperature is fixed to $T \approx 168\ MeV$ from central Pb-Pb collisions: (the value consistent with recent analysis of A. Andronic et al.)

Open charm production ratios in p(π)A collisions

Andronic, Beutler, Braun-Munzinger, Stachel &K.R.



Data average with PDG recipe

Data compilation by:

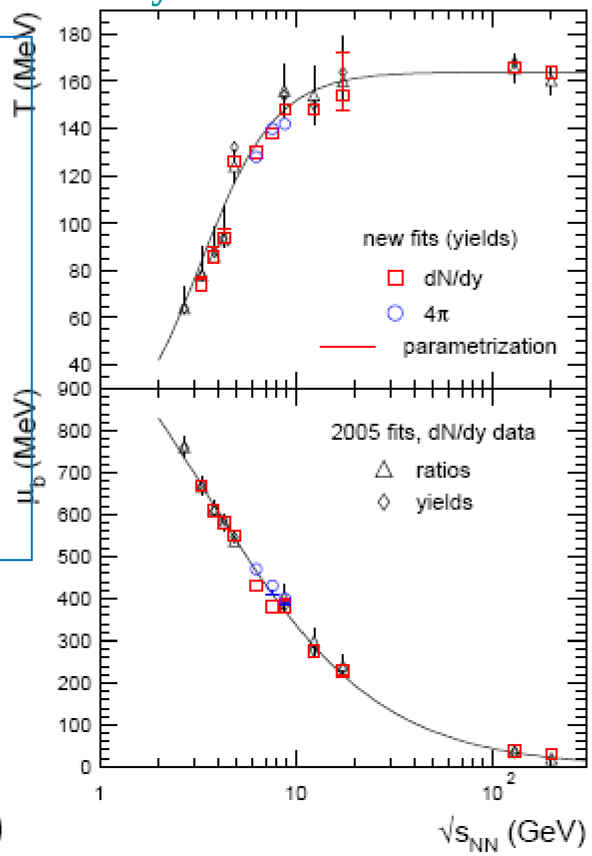
C. Lourenço, H. Wöhri, Phys. Rep. **433** (2006) 127 [hep-ph/06091

The energy dependence of thermal parameters taken from systematic analysis of heavy ion data on different particle yields by:

A.Andronic, P. Braun-Munzinger & J. Stachel

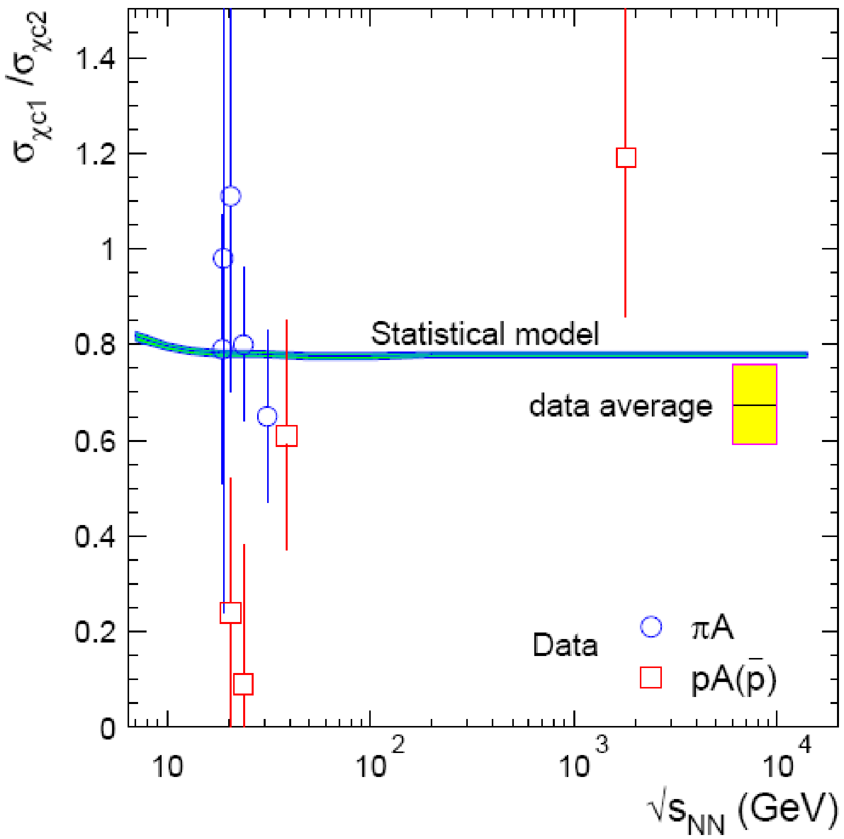
Phys. Lett. B673 142 2009.

Good agreement of Statistical Model and data for the relative production cross section of charged to neutral D-mesons: Particularly with data average by PDG



The relative production of χ_{c_1} *to* χ_{c_2} charmonia

A. Andronic, F. Beutler, P. Braun-Munzinger, J. Stachel &K.R.



The relative production of χ_{c_1} *to* χ_{c2} is seen to be consistent with Statistical Thermal Model. However, due to similar masses

$m_{\chi c_1} \approx 3510\ MeV \qquad m_{\chi c_1} \approx 3556\ MeV$

$$\frac{\chi_{c_1}}{\chi_{c2}} = \frac{d_J^{\chi_{c_1}}}{d_J^{\chi_{c_1}}} * \frac{m^2_{\chi_{c_1}} K_2(m_{\chi_{c_1}}/T)}{m^2_{\chi_{c_1}} K_2(m_{\chi_{c_1}}/T)} \approx \frac{d_J^{\chi_{c_1}}}{d_J^{\chi_{c_1}}} = 0.6$$

is almost consistent with the spin statistic ratio, thus this agreement is trivial

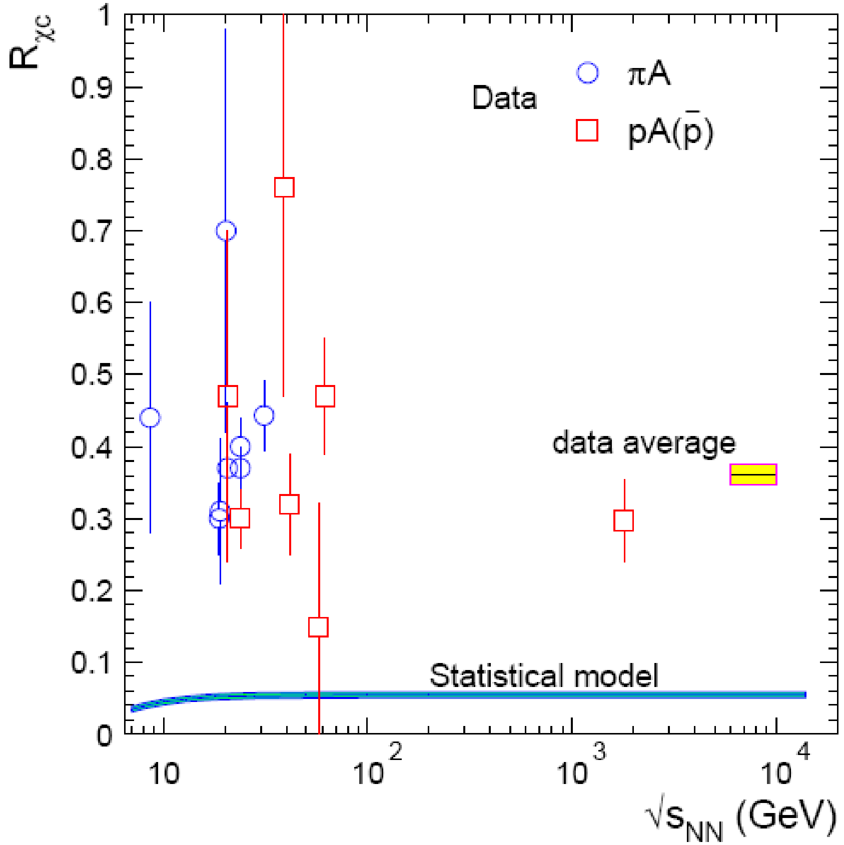
Data compilation by HERA-B Coll.:

I. Abt et al. (HERA-B coll.), Phys. Rev. D **79** (2009) 012001

Data average 0.674 ± 0.084, *with a* $\chi^2/dof = 1.39$

The χ_c contributions to J/ψ meson

A. Andronic, F. Beutler, P. Braun-Munzinger, J. Stachel &K.R.



The fraction of J/ψ from radiative decays of χ_{c_1} *and* χ_{c2} states:

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

is far above the statistical model predictions

- Clear, non-thermal origin of charmonia in hA and $\bar{p}p$ collisions

Data average 0.361 ± 0.015, *with a* $\chi^2/dof = 1.21$

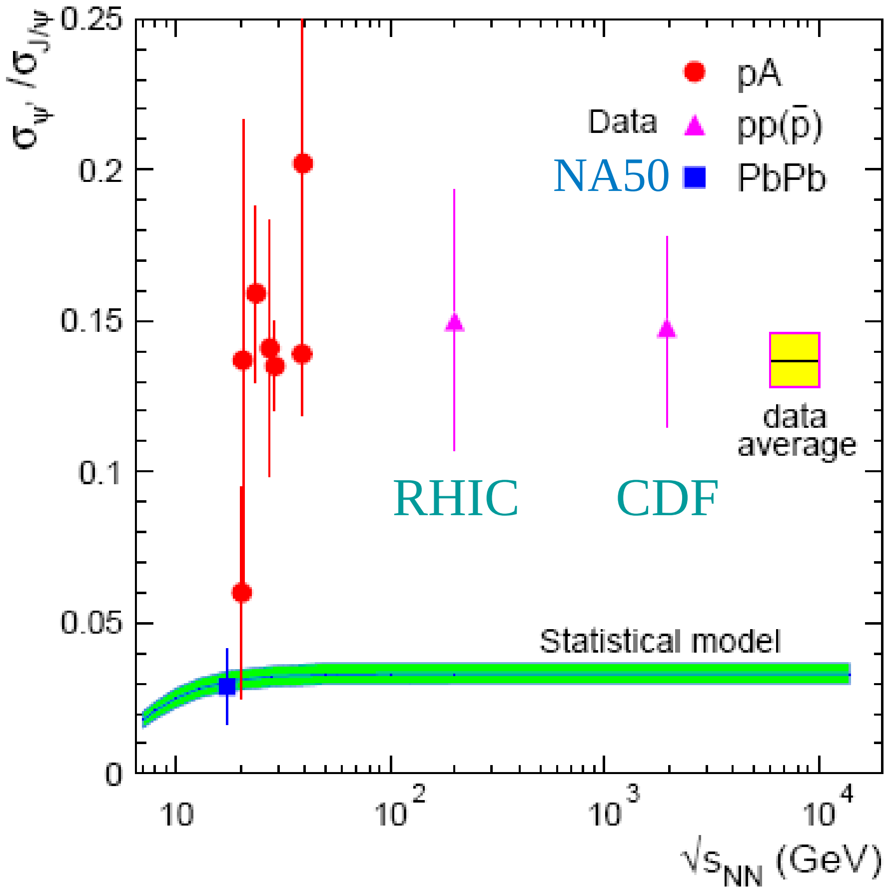
Data average at lower energies: 0.25 ± 0.05
From: P. Faccioli, C. Lourenço, J. Seixas, H.K. Wöhri, , JHEP **0810** (2008) 004

Data compilation by HERA-B Coll.:

I. Abt et al. (HERA-B coll.), Phys. Rev. D **79** (2009) 012001

Production cross section of ψ' relative to J/ψ

A. Andronic, F. Beutler, P. Braun-Munzinger, J. Stachel &K.R.



Data pA compilation by:

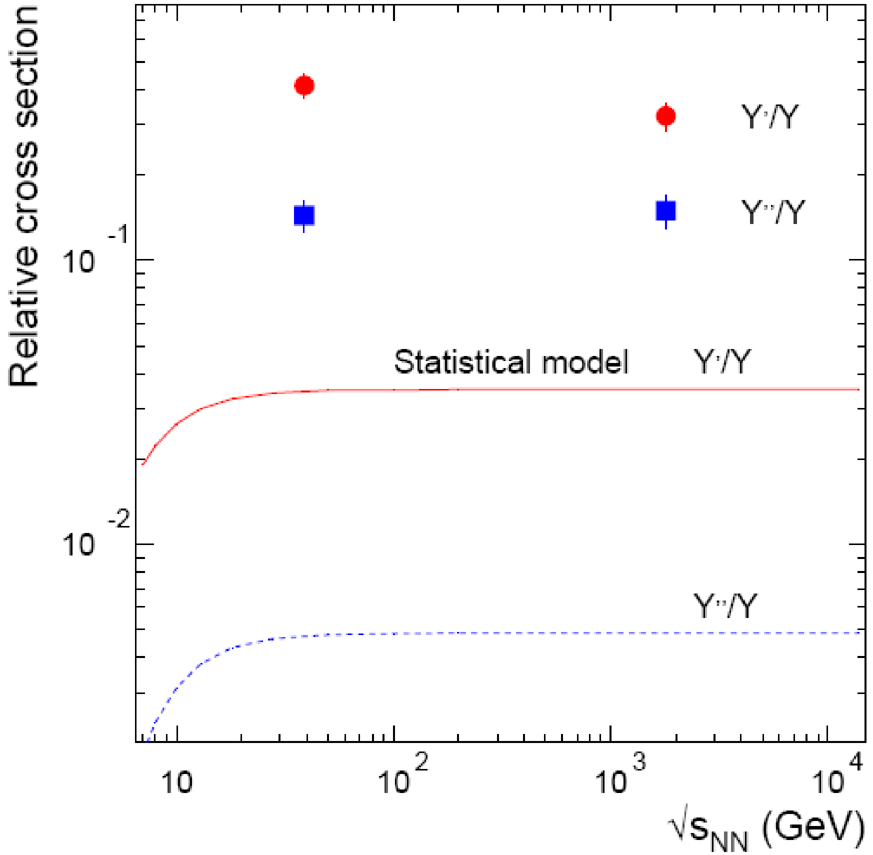
F. Maltoni et al., Phys. Lett. B **638** (2006) 202

The ratio for the Tevatron energy was derived from the CDF data on J/ψ and ψ' and is for $p_t > 1.25\ GeV$:
We have extrapolated the ψ' measurements from $p_t \geq 2\ GeV$ down to $1.25\ GeV$

- Strong suppression of $\psi'/(J/\psi)$ ratio in $PbPb$ relative to pA , pp and $\bar{p}p$
  ⇒ different production mechanism in elementary and heavy ion collisions
- The nuclear modification canceled out in the $\psi'/(J/\psi)$ ratio as the pp value is similar as in pA
- Good agreement of Statistical Model and data in PbPb collisions

The relative production of bottomonia

A. Andronic, F. Beutler, P. Braun-Munzinger, J. Stachel &K.R.



Data are from E866 and CDF Coll.

The relative production of botomonia is strongly inconsistent with Statistical Thermal Model results. Their ratios described by

$$\frac{Y^i}{Y} = \frac{d_J^{Y^i}}{d_J^{Y}} * \frac{m_{Y^i}^2 K_2(m_{Y^i}/T)}{m_Y^2 K_2(m_Y/T)}$$

with $T \approx 170\ MeV$ differ from data by one and even two orders of magnitude indicating:

A non-thermal origin of charmonia and botomonia production in elementary and hA collisions.

L.Y. Zhu et al. (E866/NuSea coll.), Phys. Rev. Lett. **100** (2008) 062301

D. Acosta et al. (CDF coll.), Phys. Rev. Lett. **88** (2002) 161802

Conclusions

- An excellent description of open charm and bottom meson yields in e^+e^- annihilations by the thermal model
- The above yields are almost independent of the fireball volume and/or any factor quantifying deviations from chemical equilibrium
- Hidden bottom in e^+e^- annihilations is not described by the thermal model. Hidden charm is consistent with the model results as it is almost entirely coming from the open bottom decays
- The relative production of D-mesons in hh and hA collisions is well described by the model
- The charmonia and bottomonia ratios in hh and hA collisions are not consistent with the model predictions

This is in contradiction with AA data at the SPS where the ratio $\psi' / (J/\psi)$ is well quantified by the model.

The above indicates a different production mechanism of hidden charm and bottom in hh, hA and AA collisions