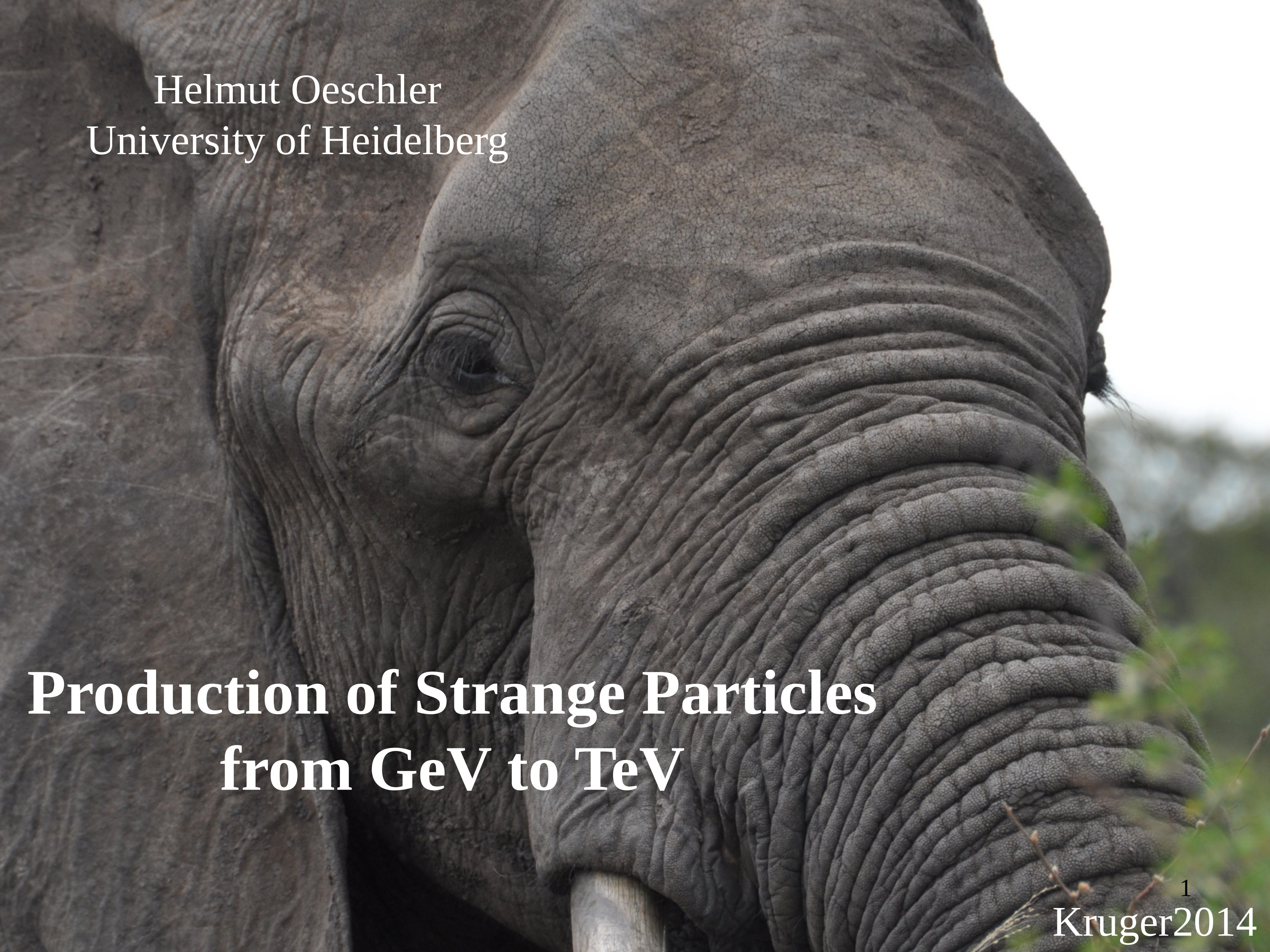


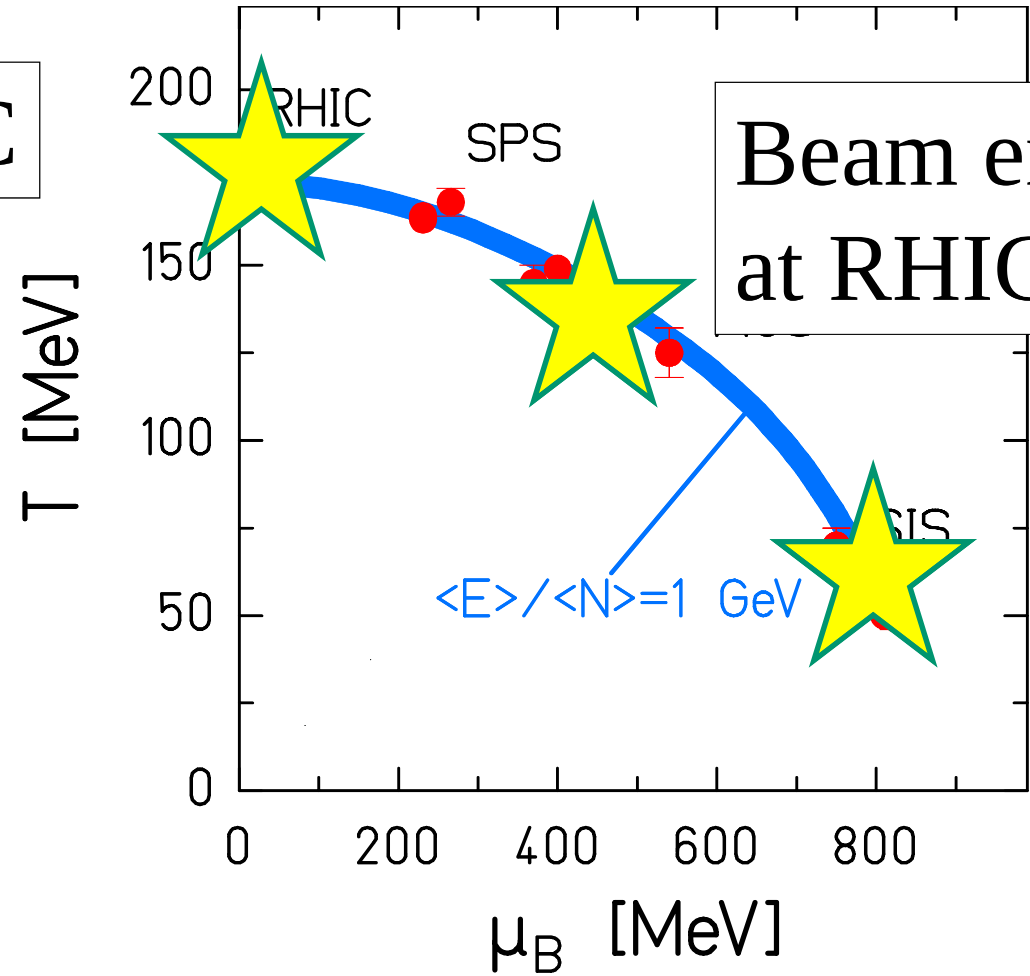
Helmut Oeschler
University of Heidelberg

Production of Strange Particles from GeV to TeV

Kruger2014

Chemical Freeze Out

LHC



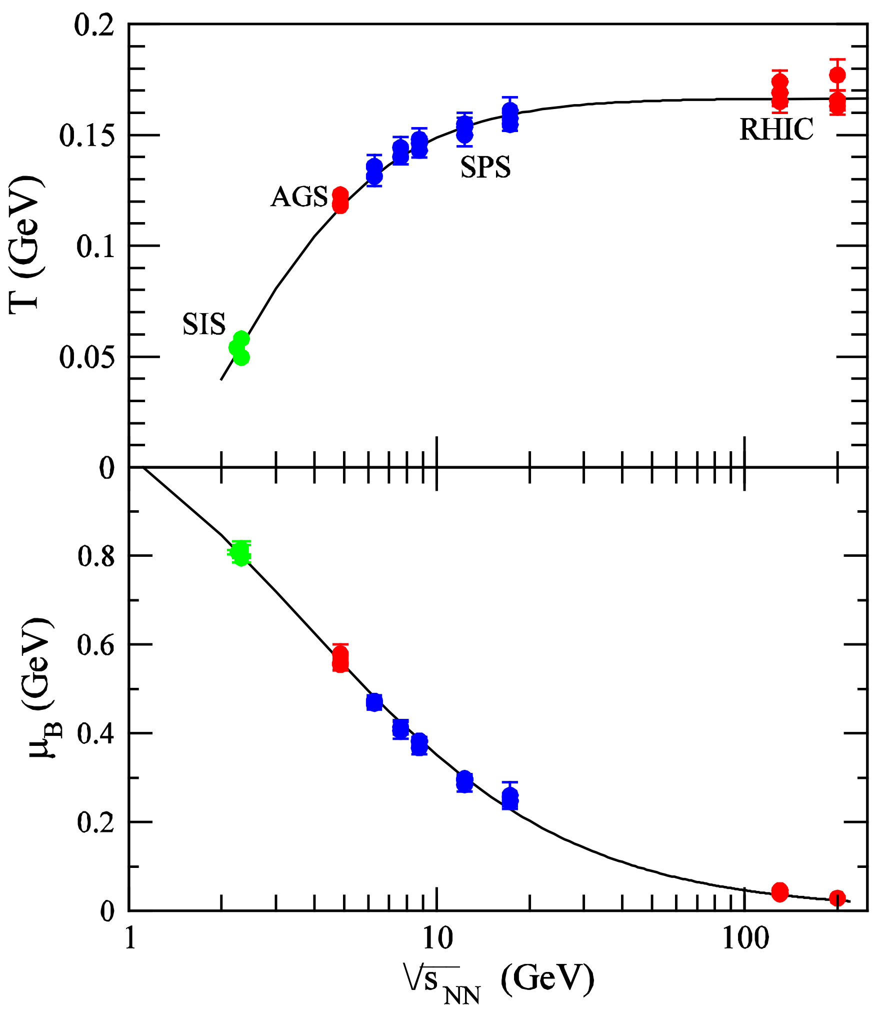
Beam energy scan at RHIC

SIS at GSI

J. Cleymans and K. Redlich, PRL 81 (1998) 5284

Towards LHC energies

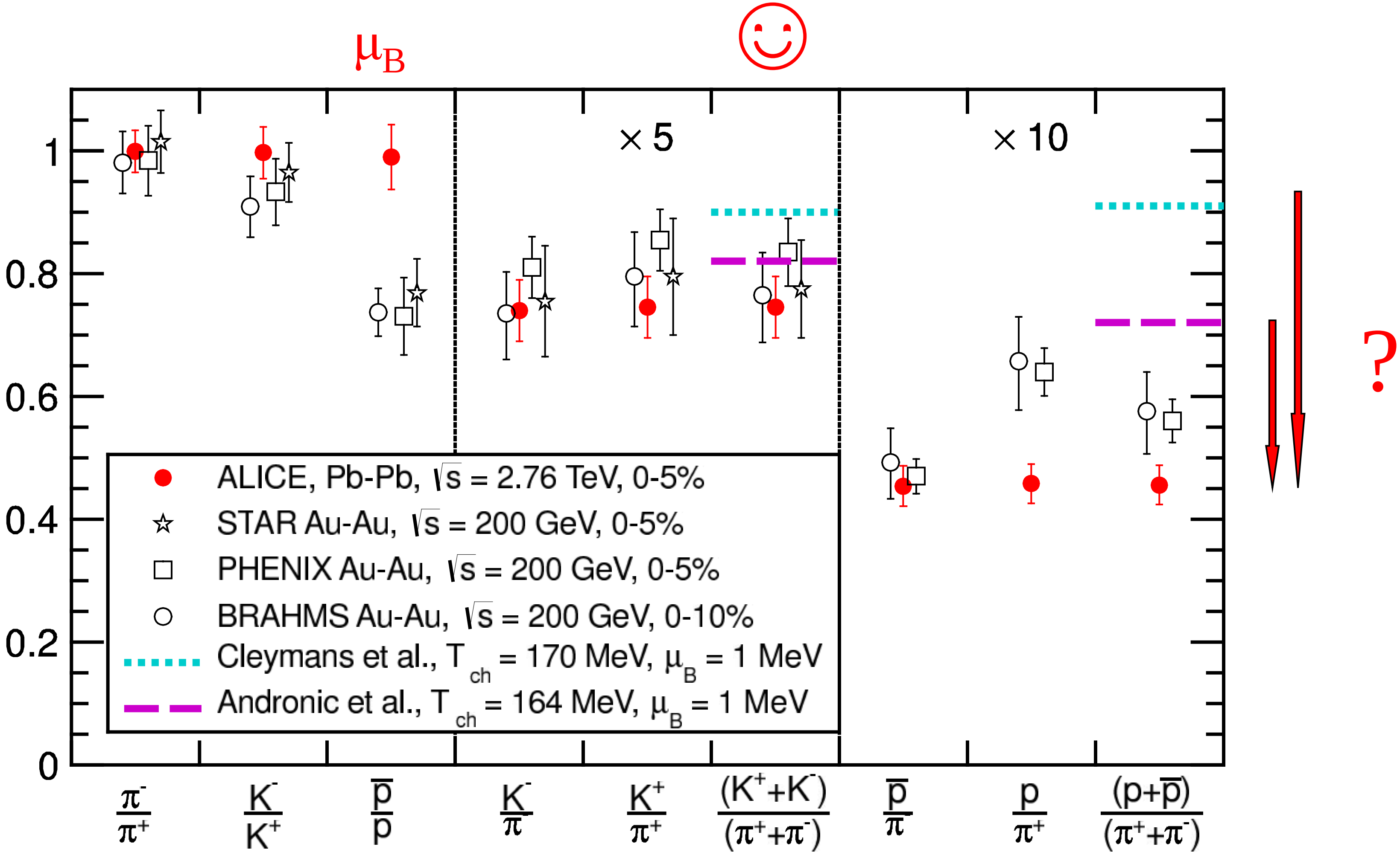
J. Cleymans, HO, K. Redlich, S. Wheaton, Phys. Rev. C 73 (2006) 034905



- Chemical decoupling conditions extracted from SIS up to RHIC feature common behaviour

- Similar to Andronic et al., Nucl. Phys. A 772 (2006) 167

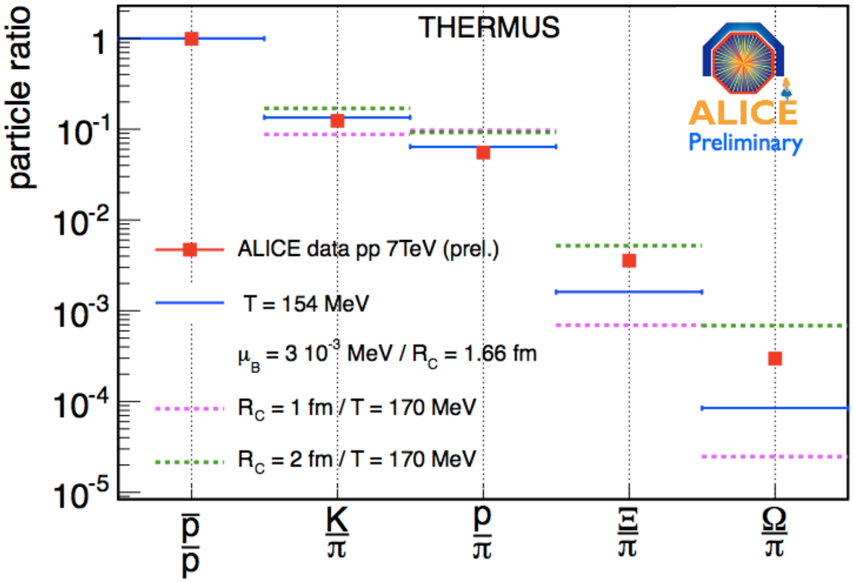
Particle ratios in HIC



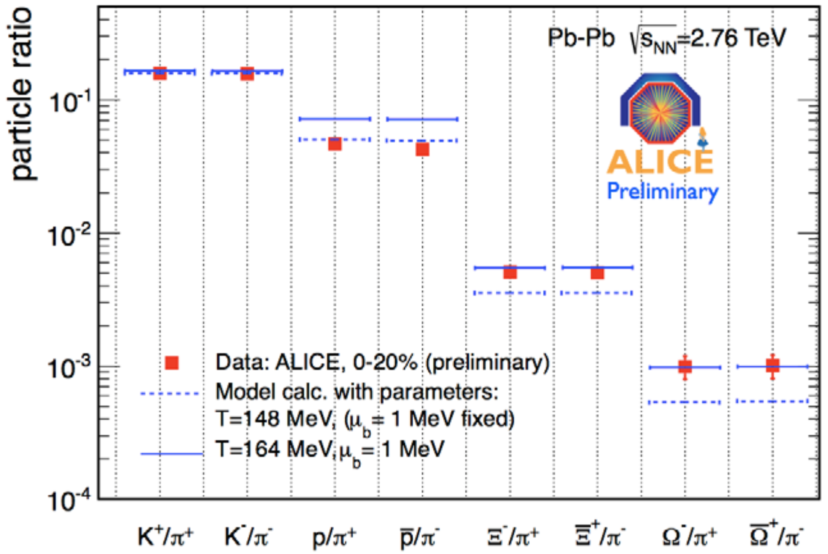
ALICE Coll., Phys. Rev. Lett. 109, 252301 (2012)

LHC Energies

pp 7 TeV



Pb-Pb 2.76 TeV



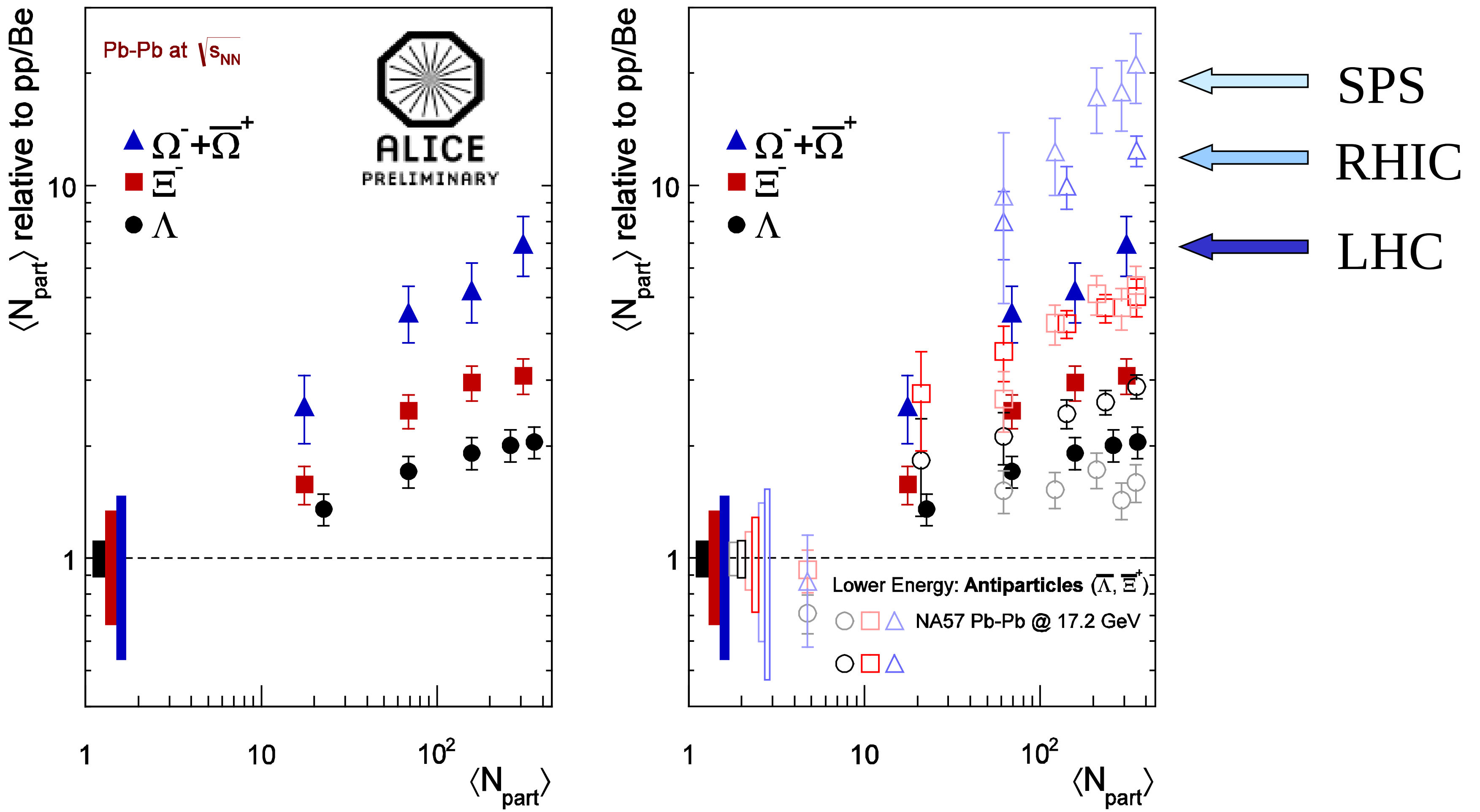
p/π the same in pp and Pb-Pb,

BUT lower than expected from stat. models

K/π in pp is lower than in Pb-Pb, expected from stat. model!

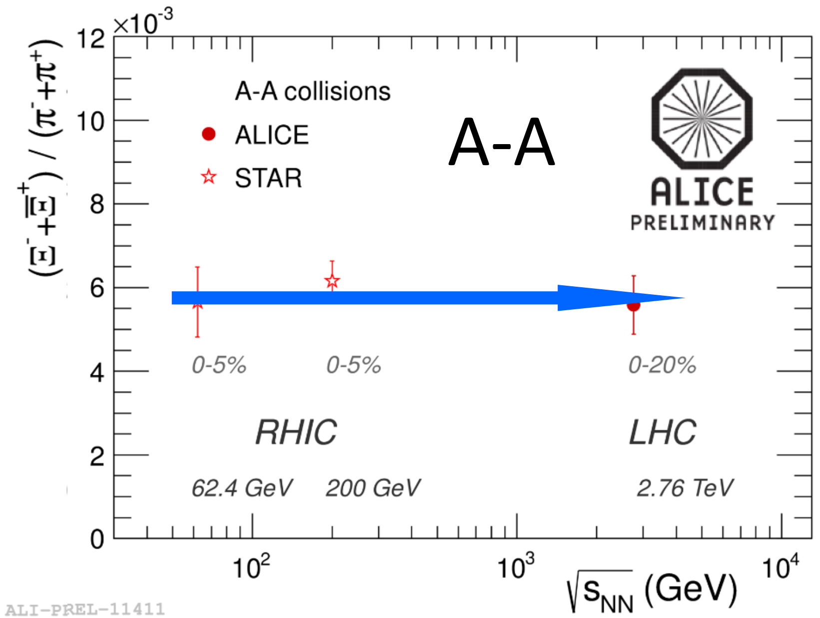
Strangeness is okay!

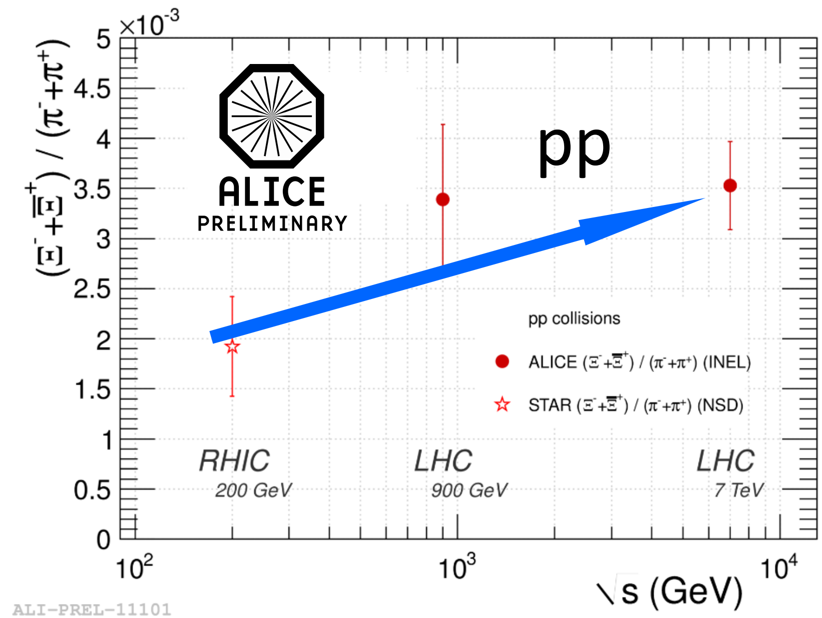
Strangeness Enhancement



What causes the decrease? pp or Pb-Pb

Strangeness in pp and Pb-Pb



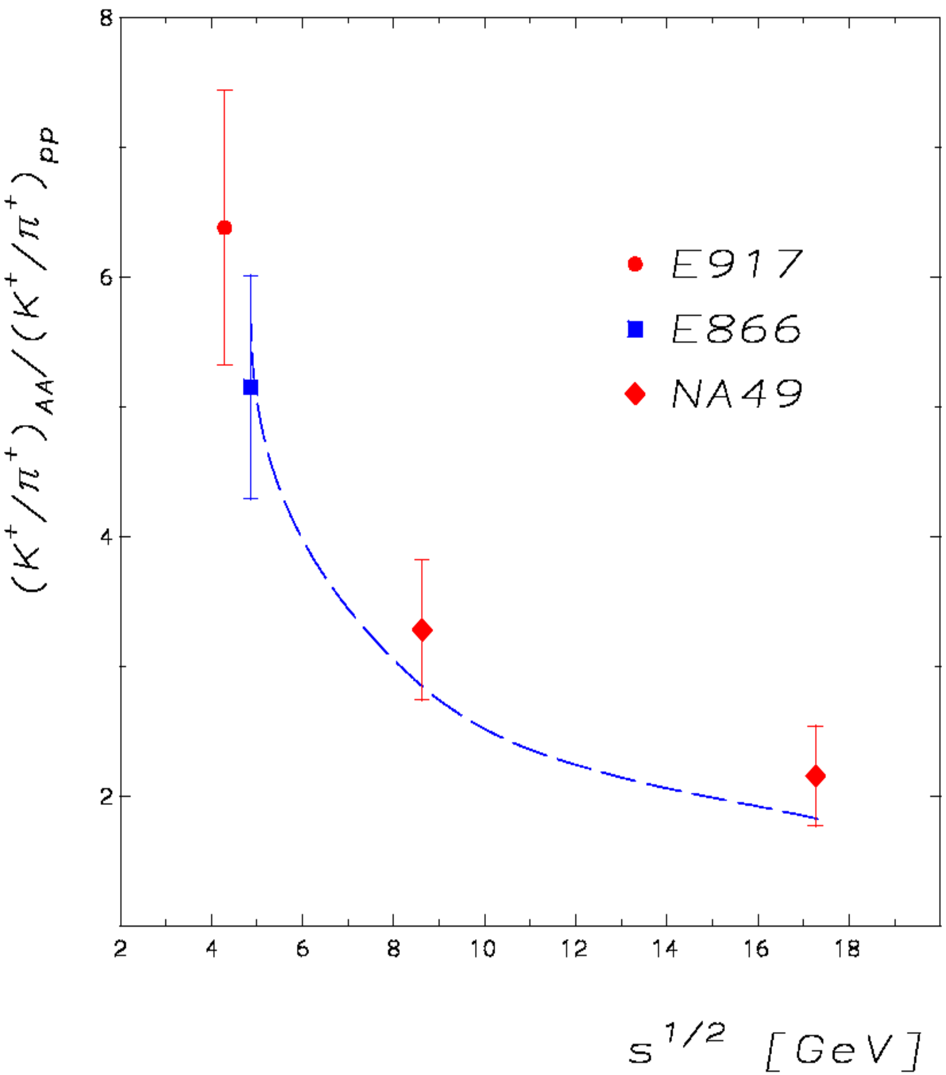


In HIC, the ratio Ξ/π remains constant, while in pp it rises!
What is behind?

At which energy has the highest strangeness enhancement been observed?

$$(X(S)/\pi)/N_{part}(HIC) \;\; / \;\; (X(S)/\pi)/N_{part}\,(pp)$$

Strangeness enhancement larger for lower energy



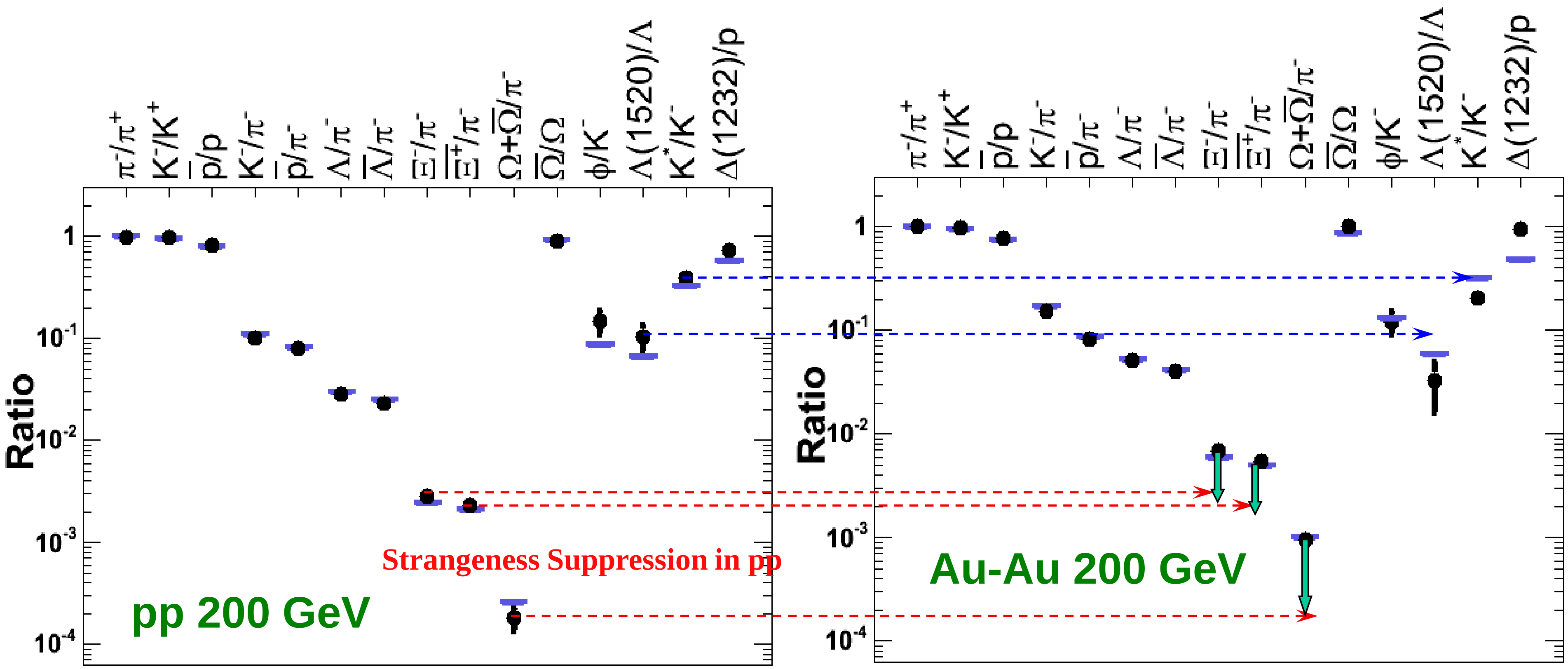
Dashed line:

Statistical model

K. Redlich

At LHC: ≈1.5

Statistical Model for pp and HIC



- In *pp* particle ratios are well described using canonical description
- In *Au+Au* only stable particle ratios are well described

Canonical Approach

Pion density

$n(\pi) = exp(-E_\pi/T)$

Strangeness is conserved!

Kaon density

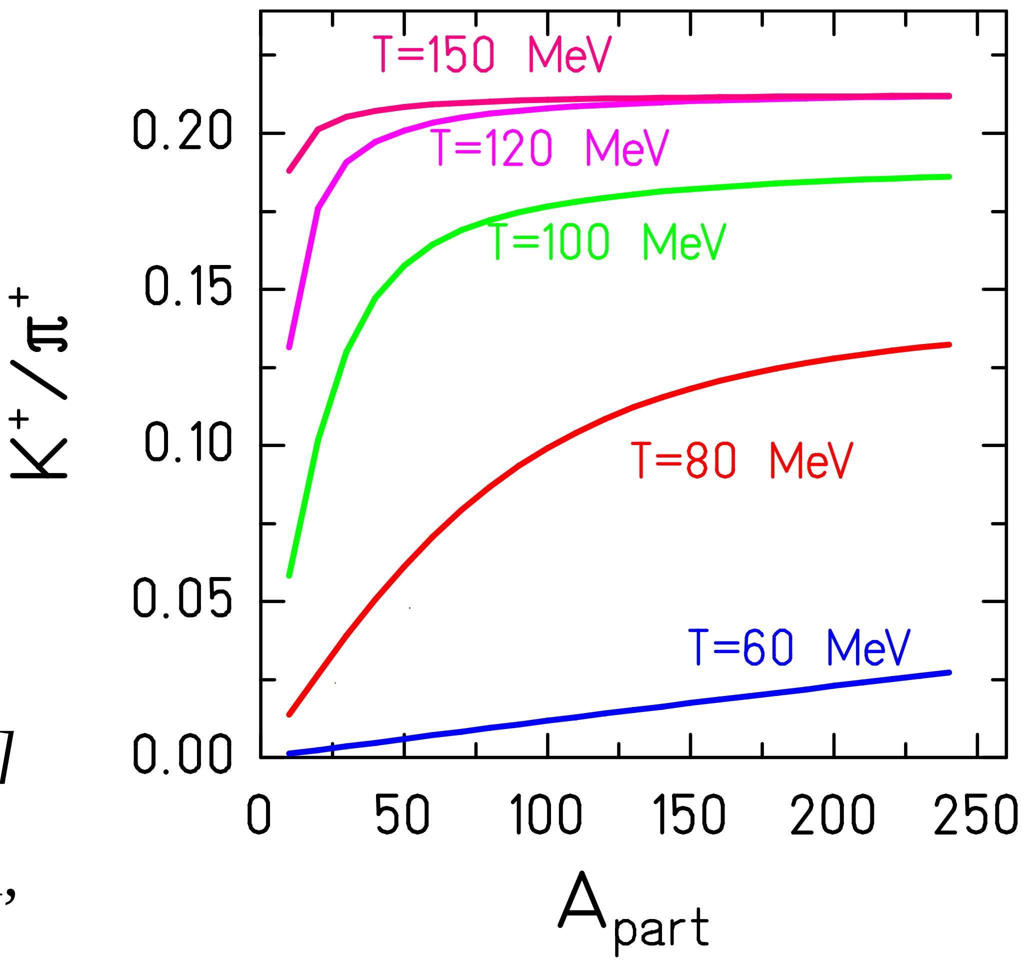
$NN \rightarrow N \Lambda K^+$

$n(K) = exp(-E_K/T)$

$[g\ V\ \int \dots exp[-(E_\Lambda - \mu_B)/T]$

J. Cleymans, HO, K. Redlich,

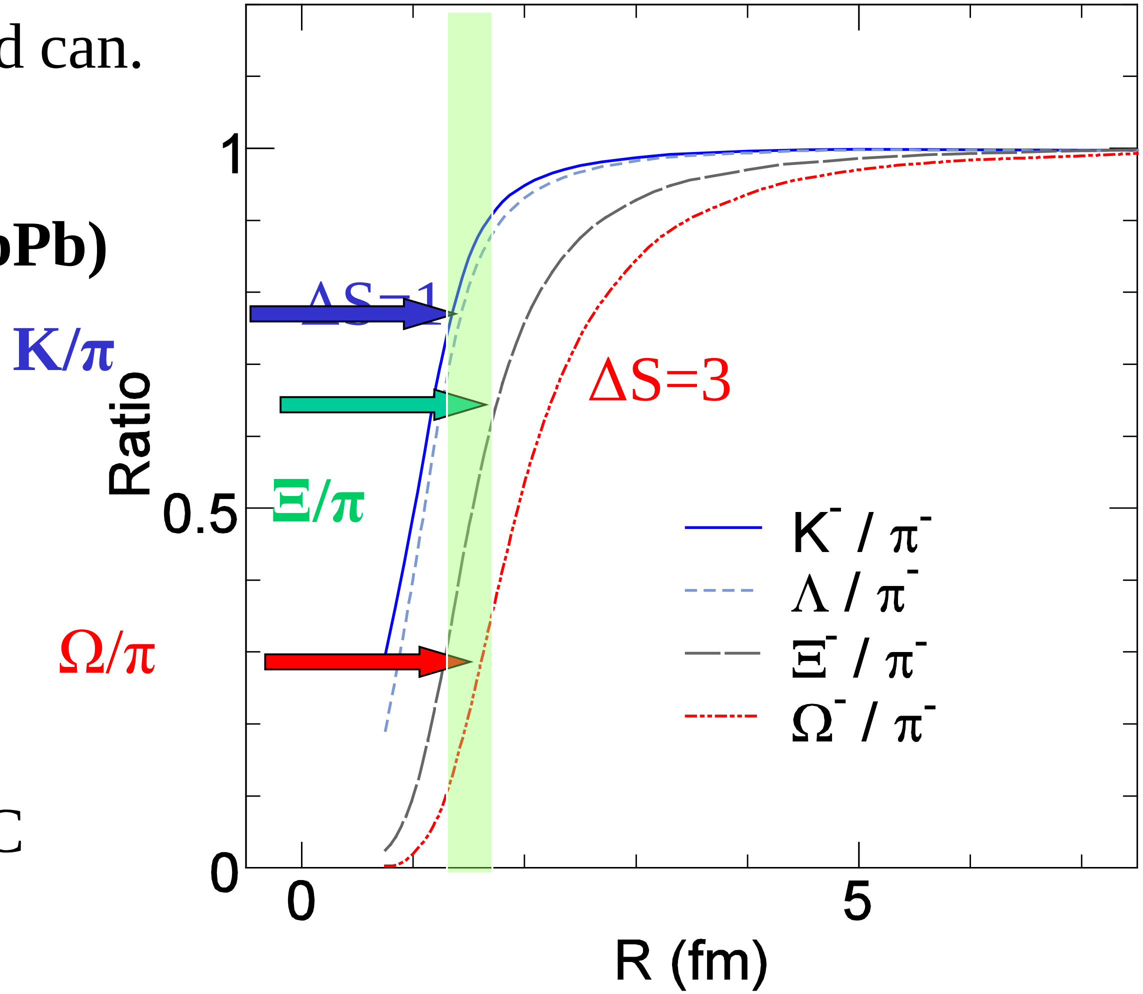
PRC 60 (1999)



Testing Canonical Suppression at LHC

can./grand can.

Measured ratio(pp)/ratio(PbPb)



Example:

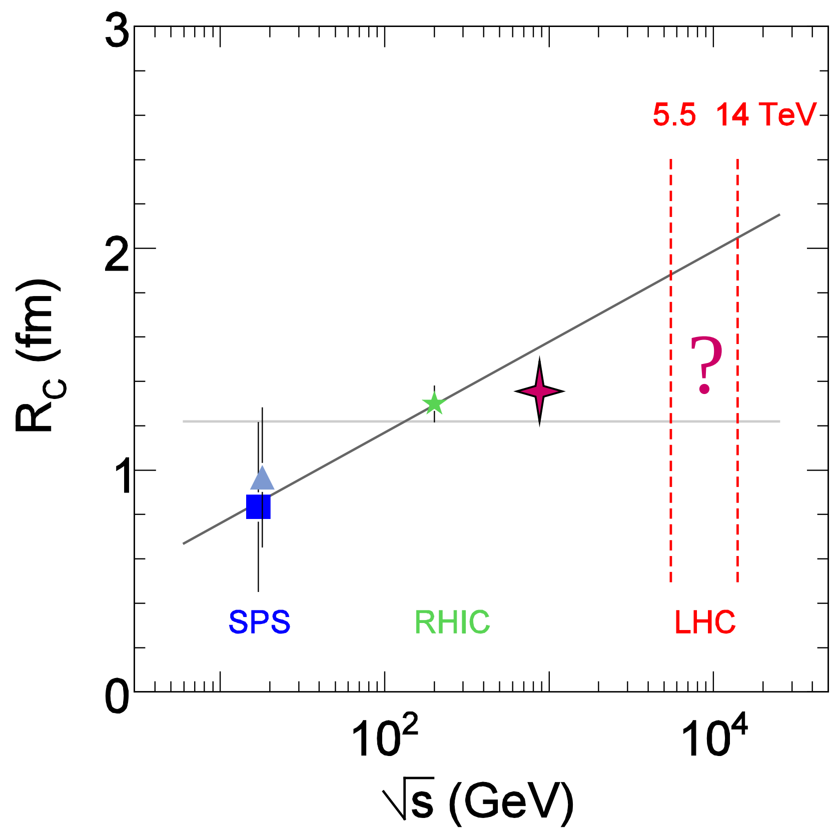
T = 170 MeV

μ_B = 1 MeV

Values for LHC

Prediction: I. Kraus et al., PR C 79 (2009) 014901

Correlation Radii at LHC



pp 900 GeV thermal fit: arXiv:1102.2745

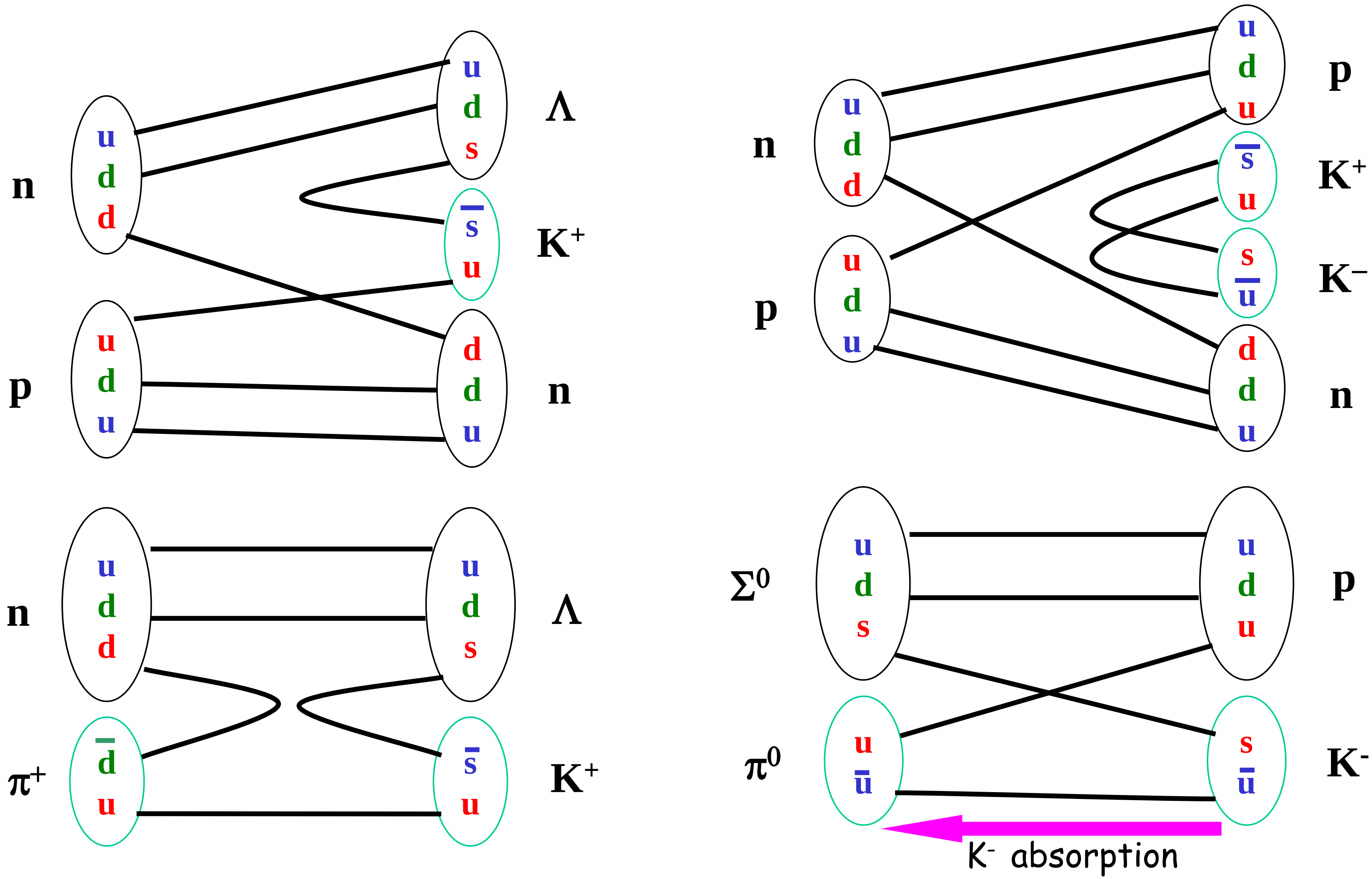
Next: high-multiplicity events in pp 7 TeV !!!???

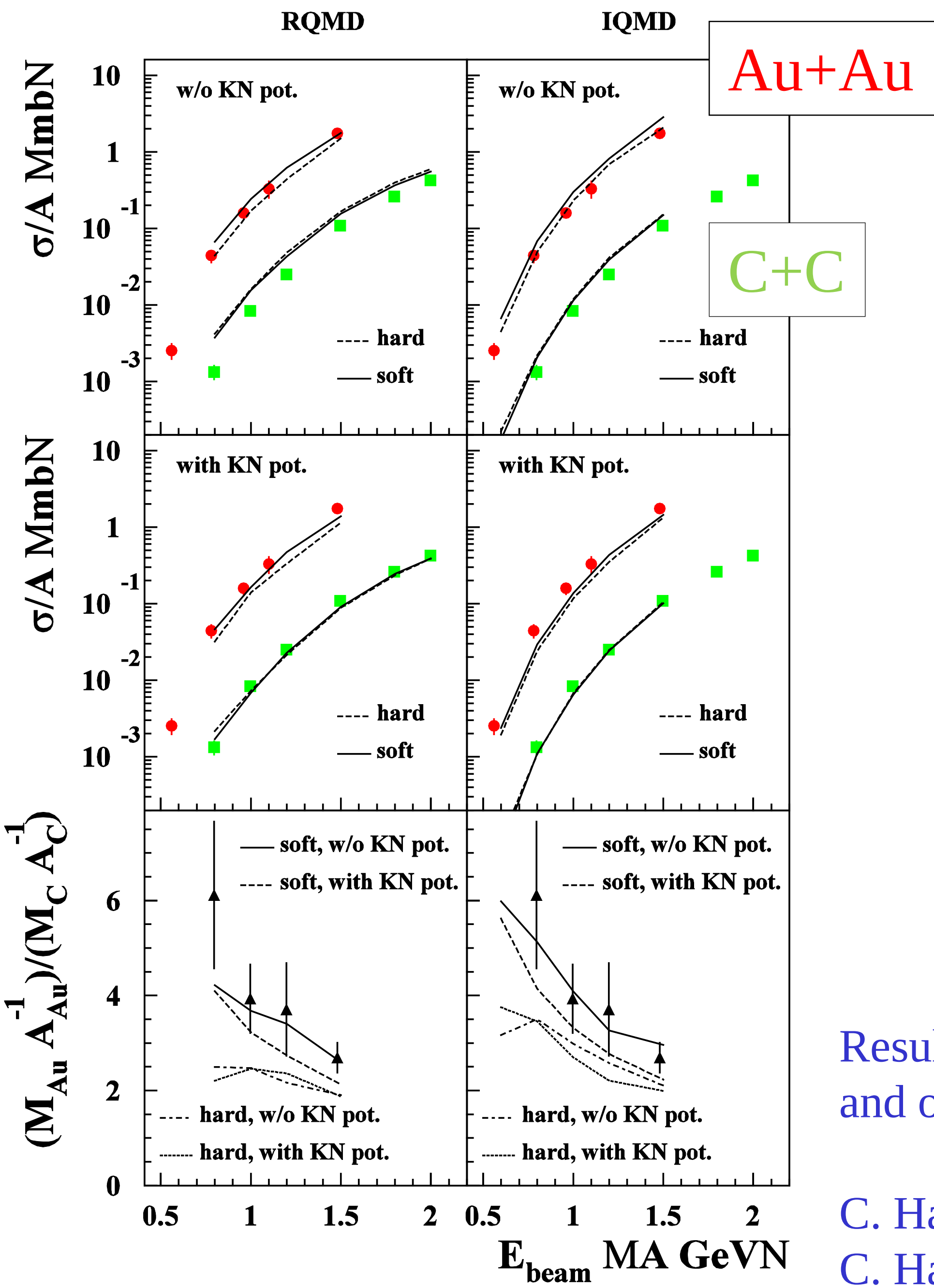
Will pp collisions approach GC limit, i.e. HIC

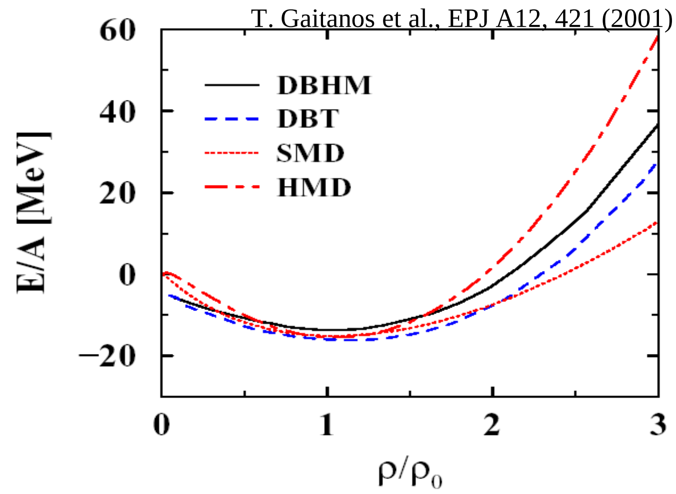
Next: very low energies!

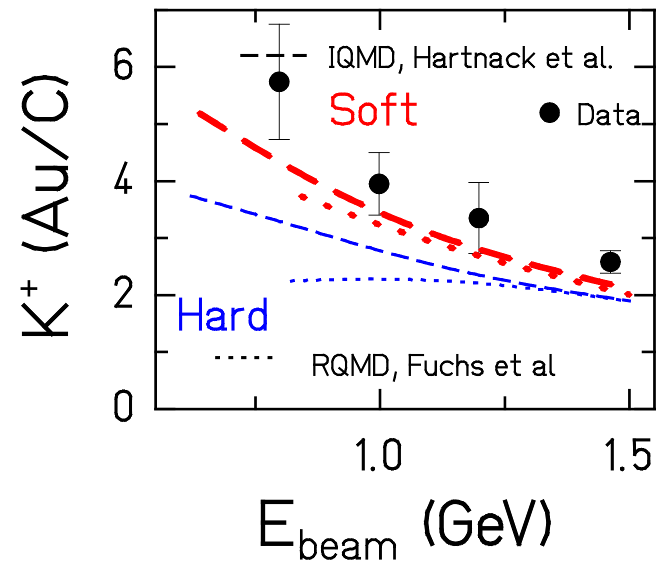
- Now in a hadronic world!

Creation of Strange Mesons









Results confirmed also with several calculations and other observables!

C. Hartnack, HO, J. Aichelin, PRL 96 (2006)
C. Hartnack, et al., Phys.Rept. 510 (2012) 119

Strangeness vs. Charm

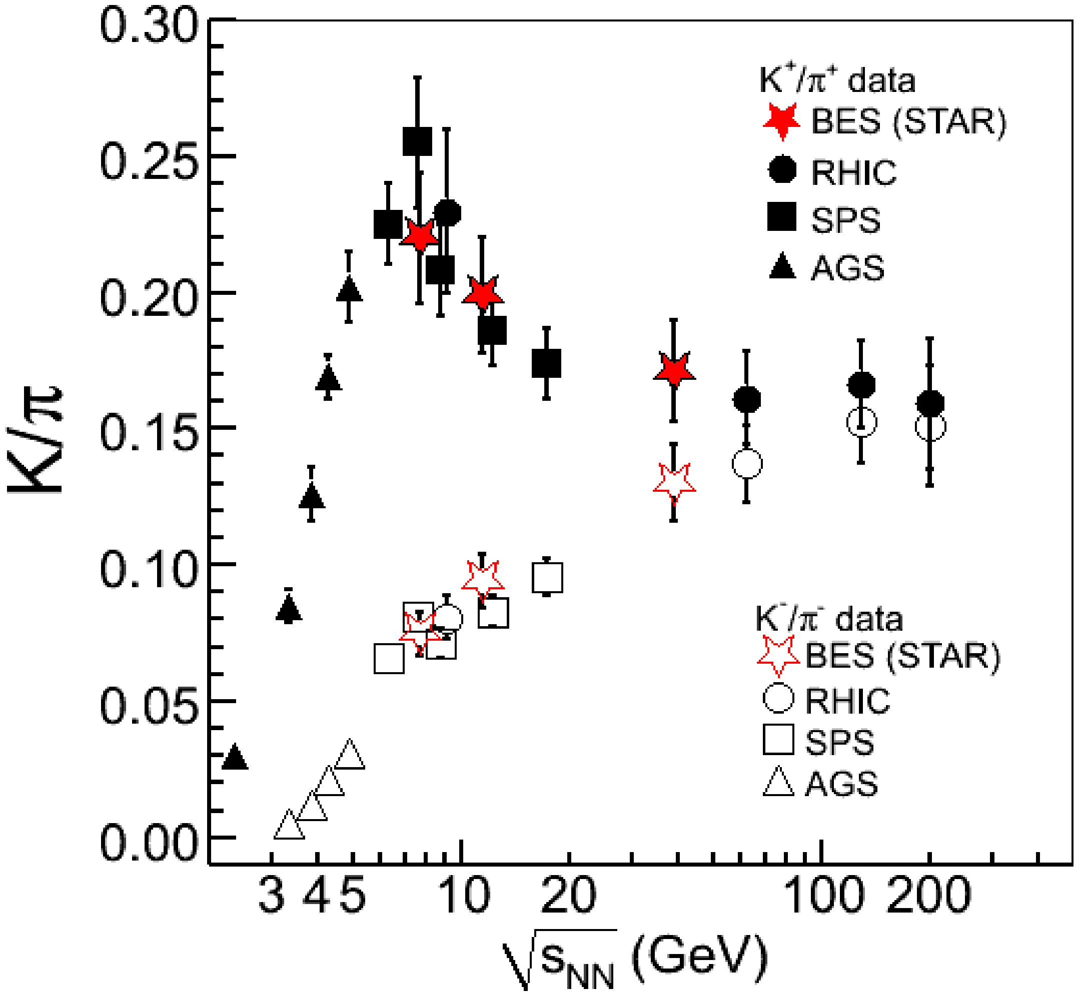
- Strange particles are produced at low $\sqrt{s}$ in secondary collisions
- heavy system: yield is enhanced
- K+ does not change due to conservation of S and energy
- yield of other strange particles according to thermal law ???
- Question: uds thermal

- Charm is produced at the very first collisions
- heavy system: yield reduced
- number of c cbar does not change
- yield of charmed hadron possibly distributed thermally ????
- uds thermal but c beyond thermal value as produced early

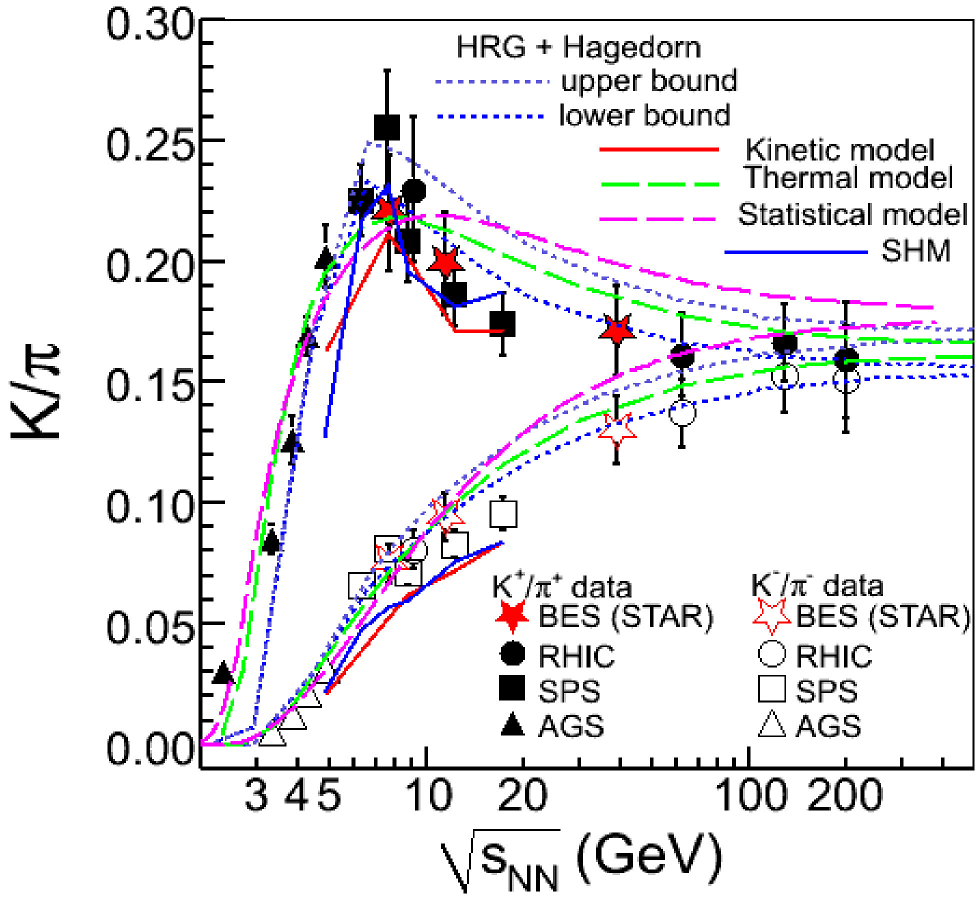
Maximum Strangeness content

around $\sqrt{s_{NN}} \approx 8$ GeV

RHIC, STAR Coll. QM2011



Maximum strangeness content



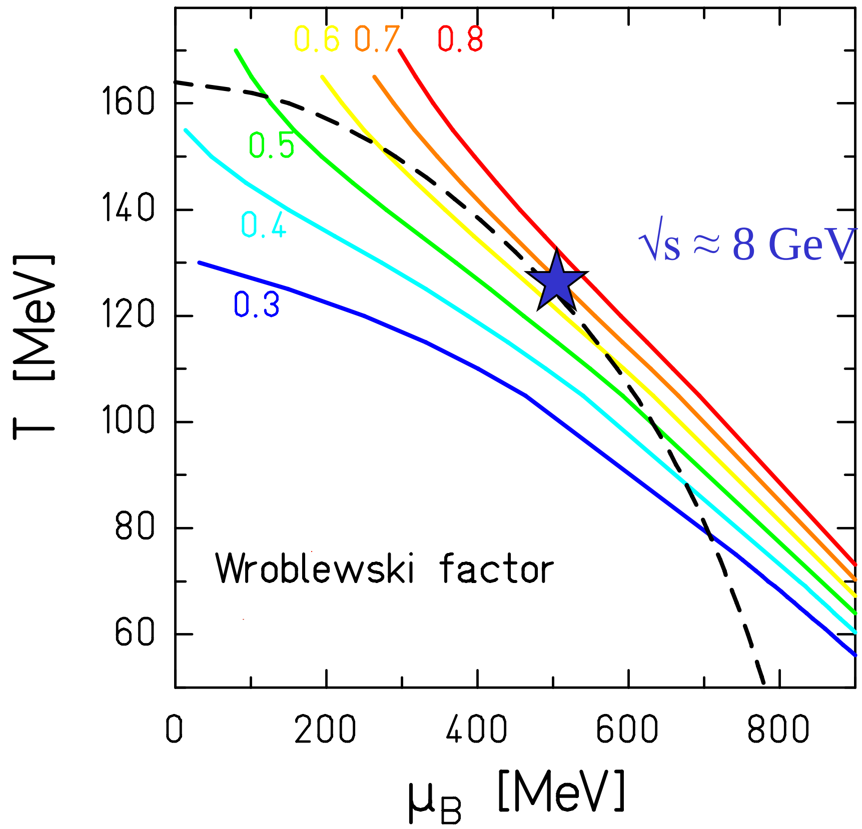
STAR Coll., QM2011

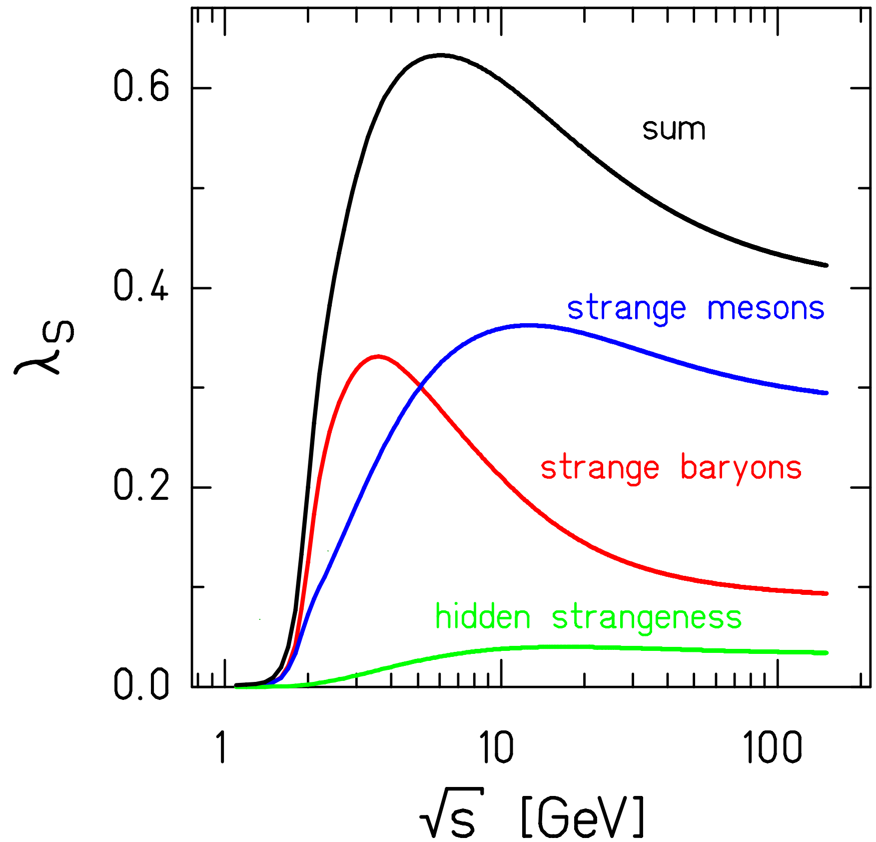
Thermal Model,

A. Andronic et al., PLB 673(2009)

Why K^+/π^+ so different from K^-/π^-?

Maximum Strangeness around 30 AGeV





$$\lambda_s \equiv \frac{2\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle}$$

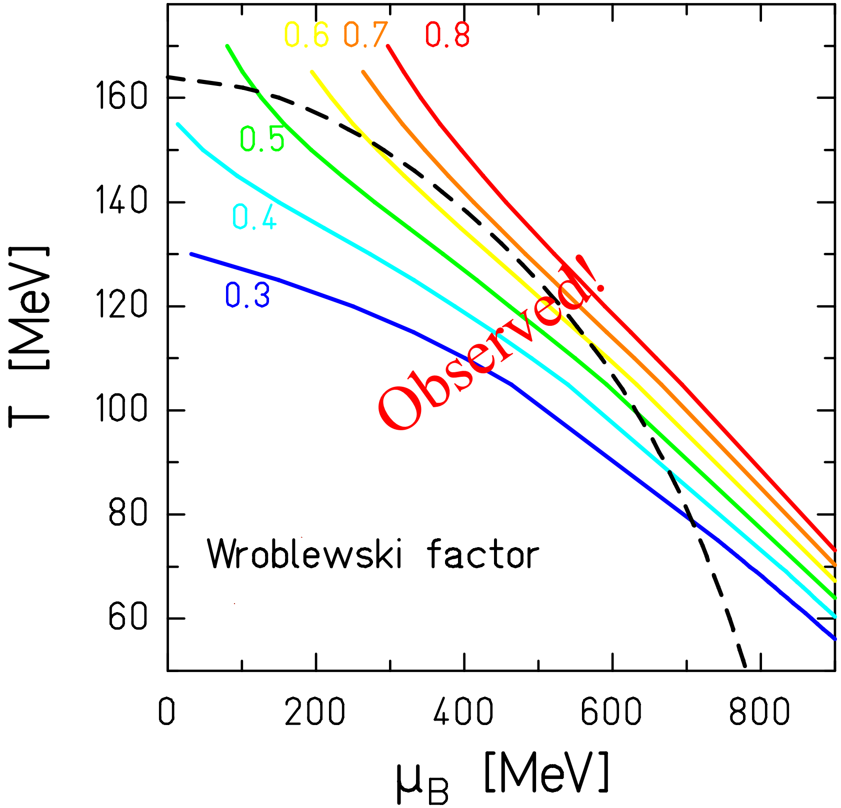
K^+ are produced together with a Λ, influence of μ_B

K^- together with a K^+

P. Braun-Munzinger, J. Cleymans, HO, K. Redlich, NPA 697(2002) 902

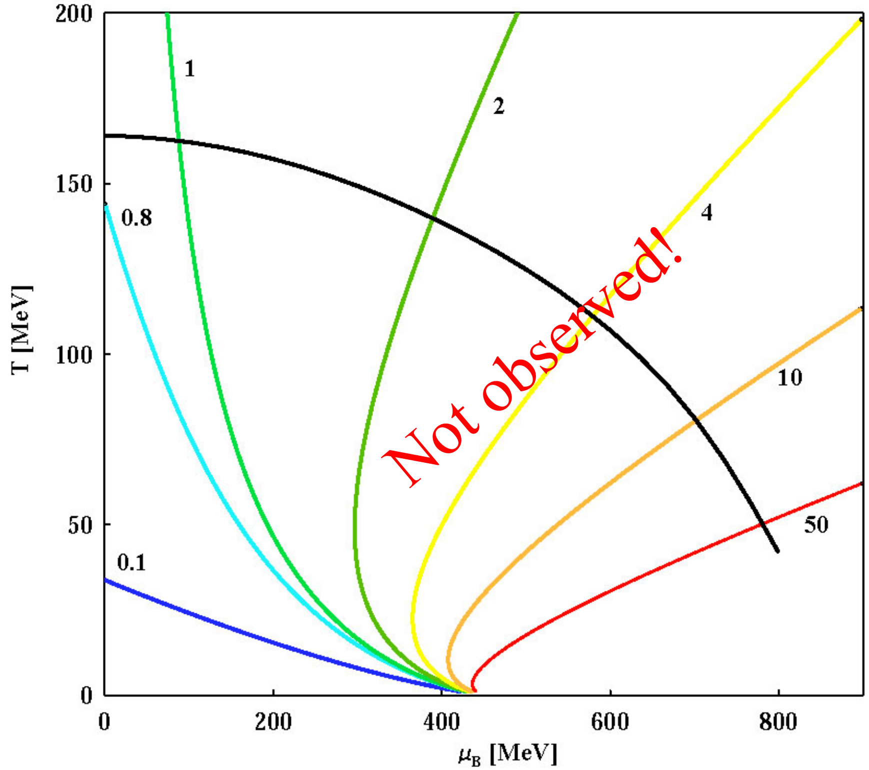
Strangeness Content

in a hadron gas



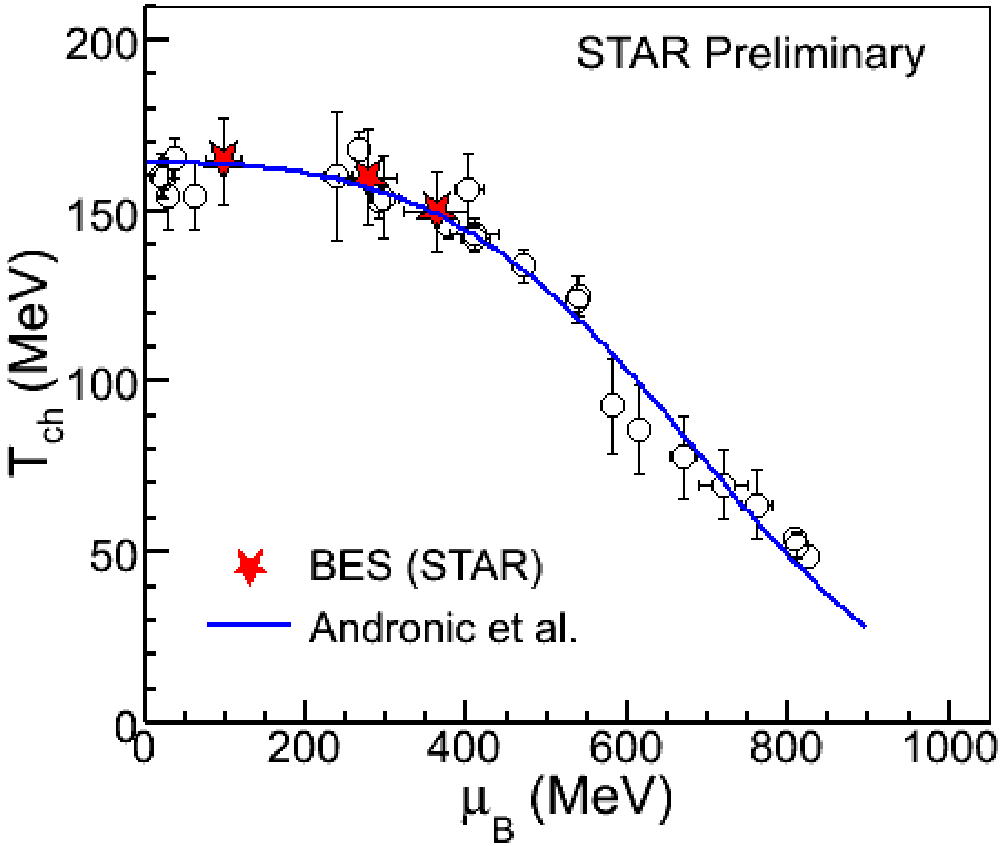
P. Braun-Munzinger, J. Cleymans, HO, K. Redlich, NPA 697(2002) 902

in a QGP



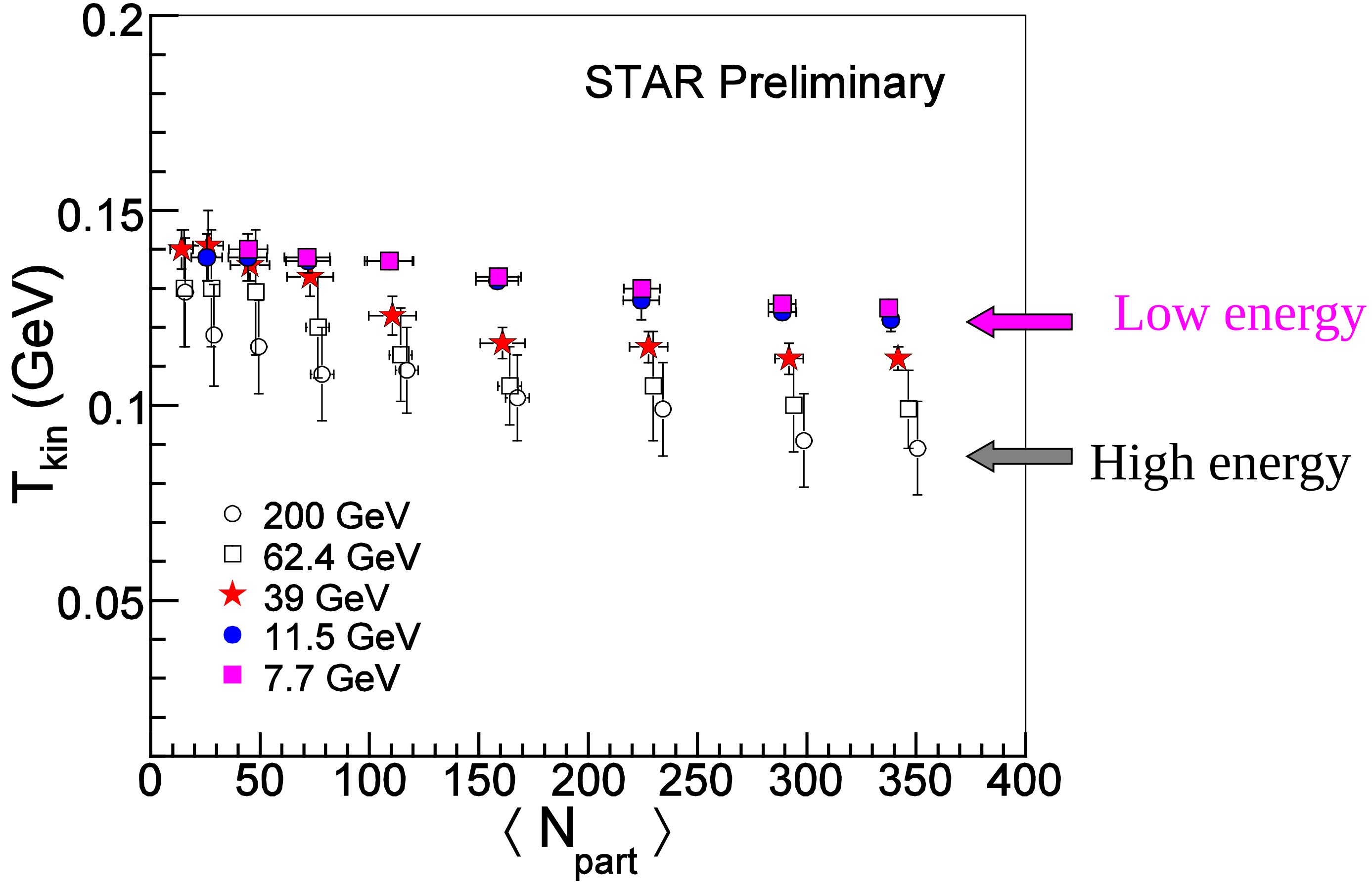
A. Schmah et al., TU Darmstadt

Freeze-out from the STAR beam energy scan



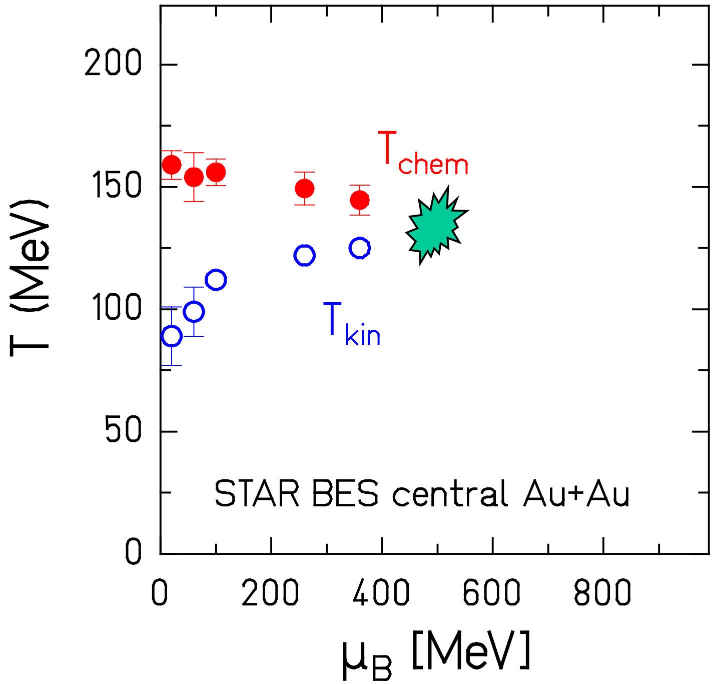
L. Kumar, QM2011

Kinetic freeze out – STAR BES



From STAR Coll., CPOD 2011

Merging of T_{chem} and T_{kin}



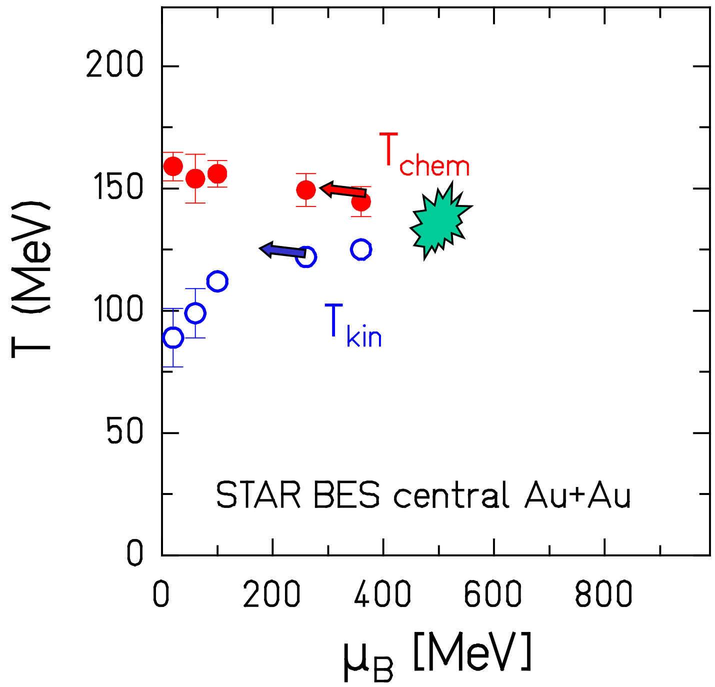
At LHC and RHIC:

$T_{chem} > T_{kin}$

At SIS and AGS:

$T_{chem} = T_{kin}$

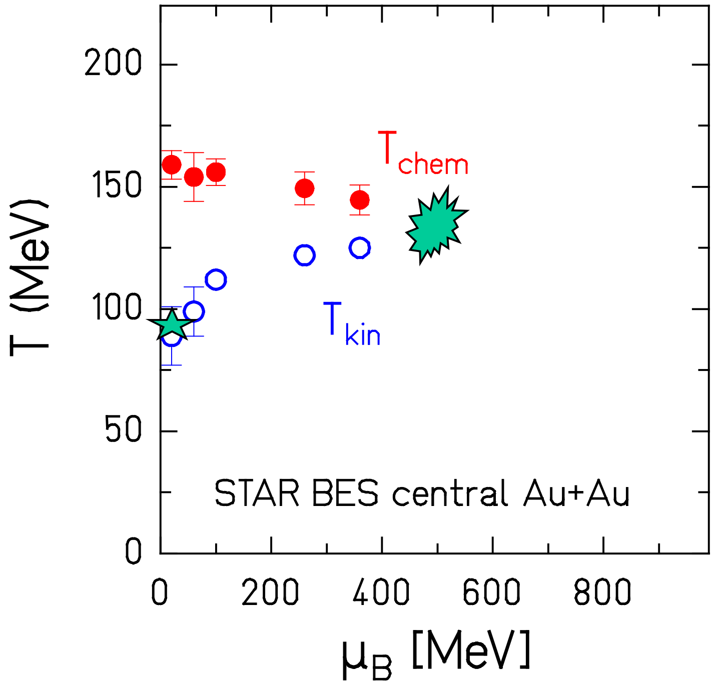
Central to peripheral collisions



Variation of centrality causes a walk ON the chem. freeze out curve!

The kinetic freeze out changes such that the separation between chem. and kin. gets smaller!

At LHC?



In central Pb-Pb:

T_{chem} = 156 ± ? MeV

T_{kin} = 95 ± 10 MeV

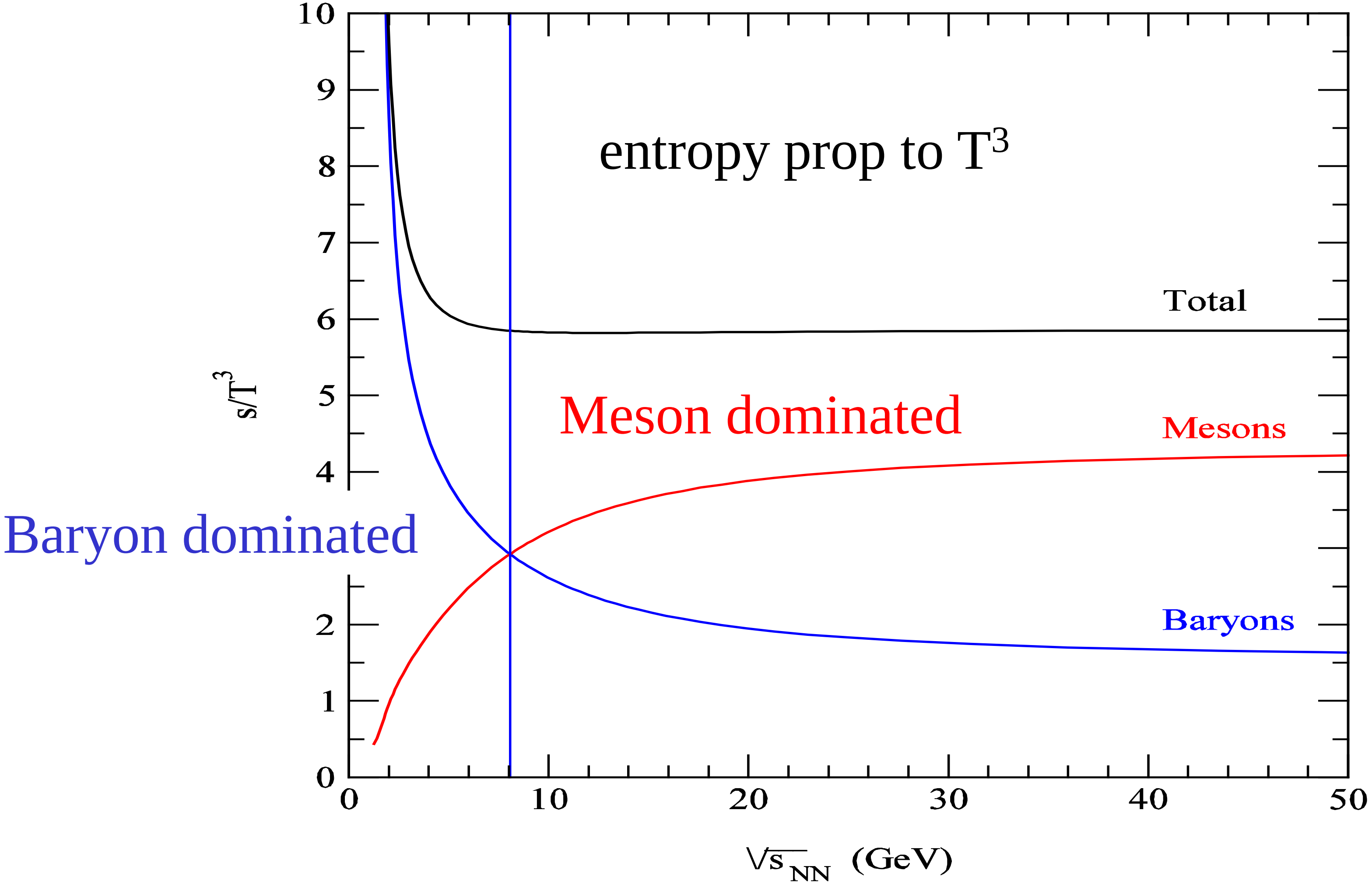
ALICE

Phys. Rev. Lett. 109, 252301 (2012)

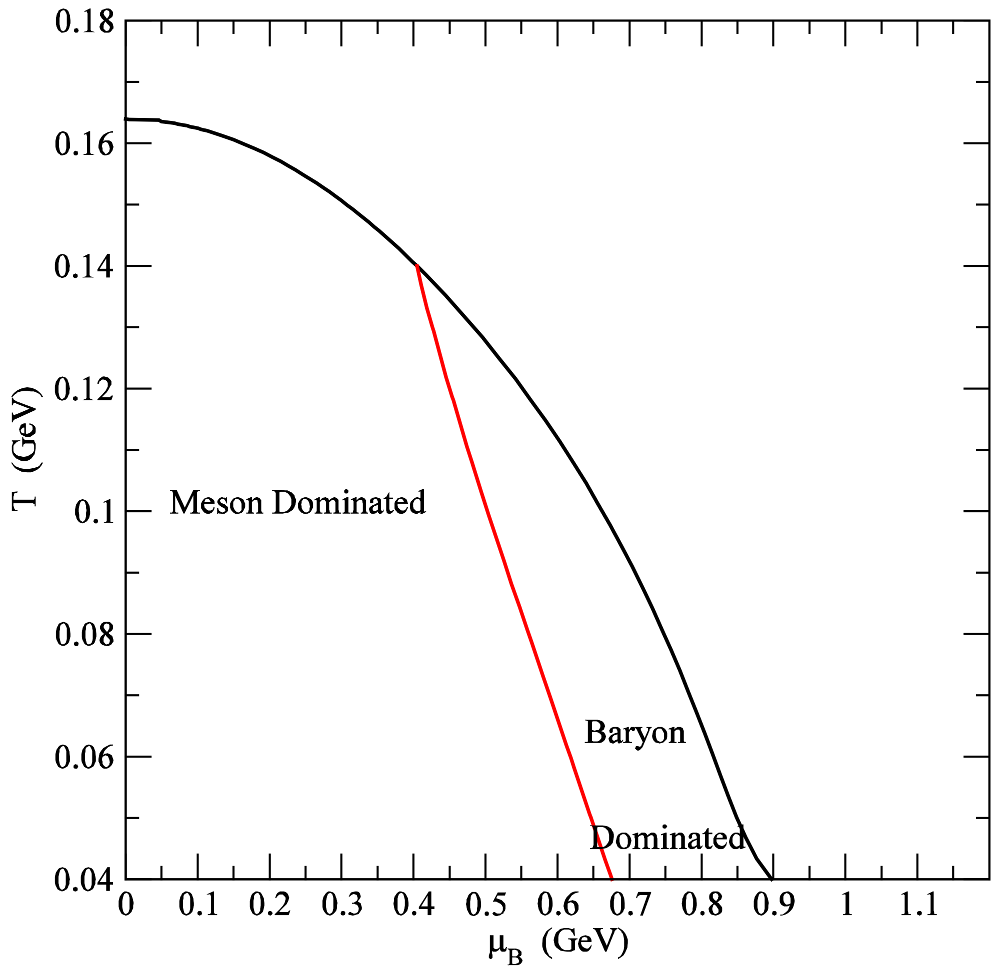
Long phase between chem. and kin. freeze out!!!
Large HBT radii!!

Transition from baryonic to mesonic freeze out

J. Cleymans, H.O., K. Redlich, S. Wheaton, Phys. Lett. B615 (2005)

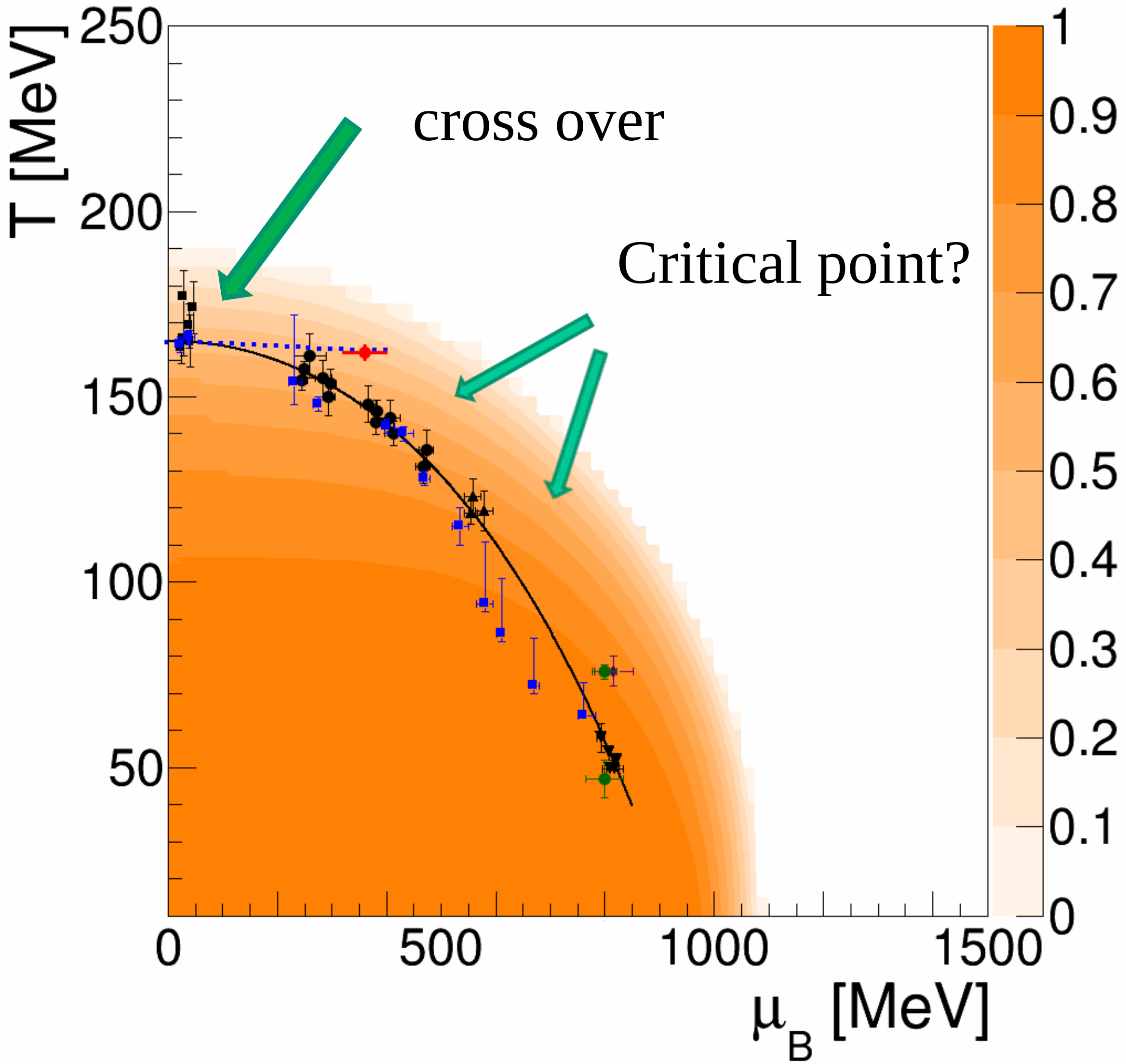


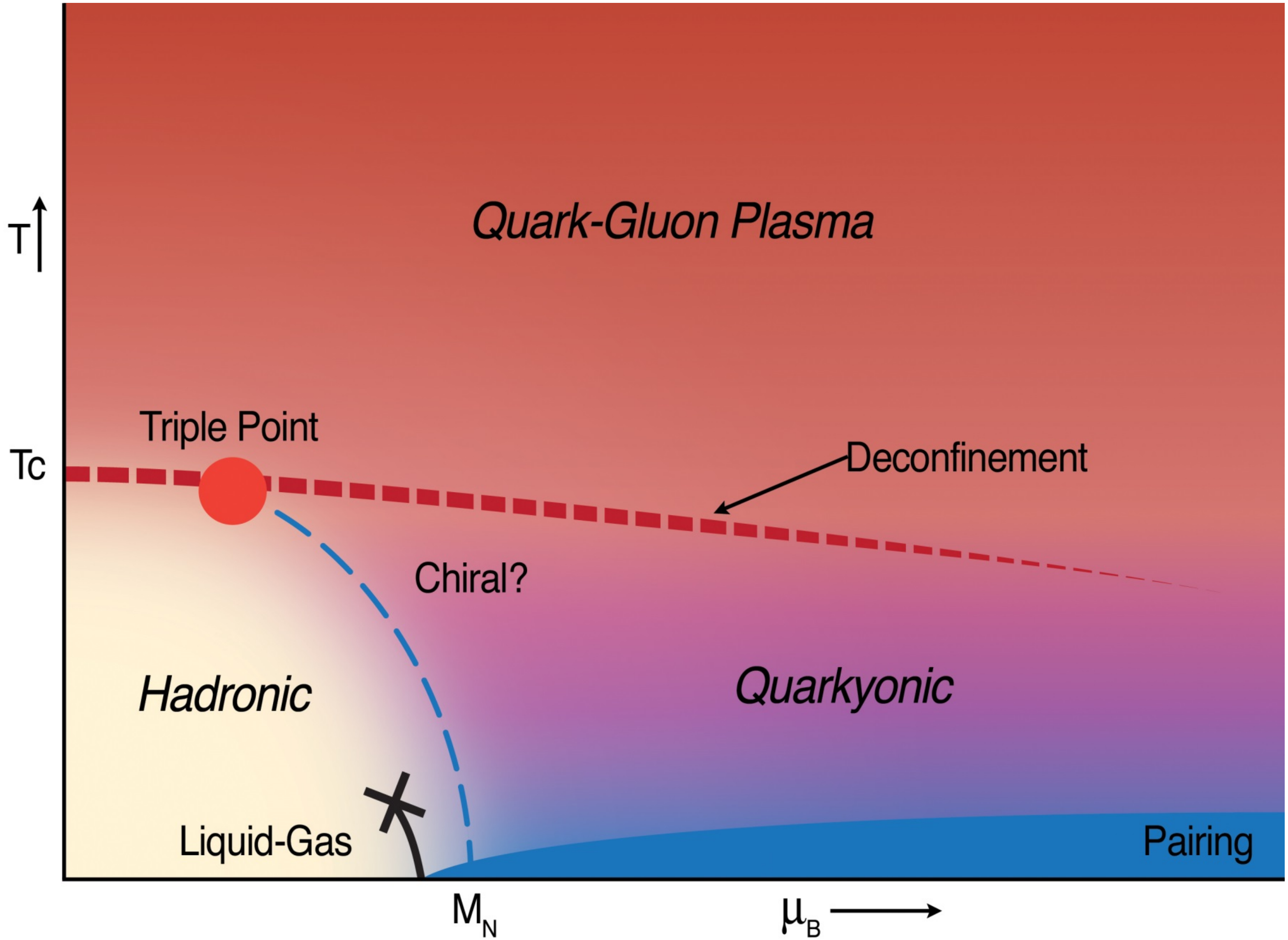
Transition from baryonic to mesonic freeze out



J. Cleymans et al., Phys.Lett. B615 (2005) 50

Where are we with the phase diagram?





Quarkyonic matter, A. Andronic et al., Nucl.Phys. A837 (2010) 65

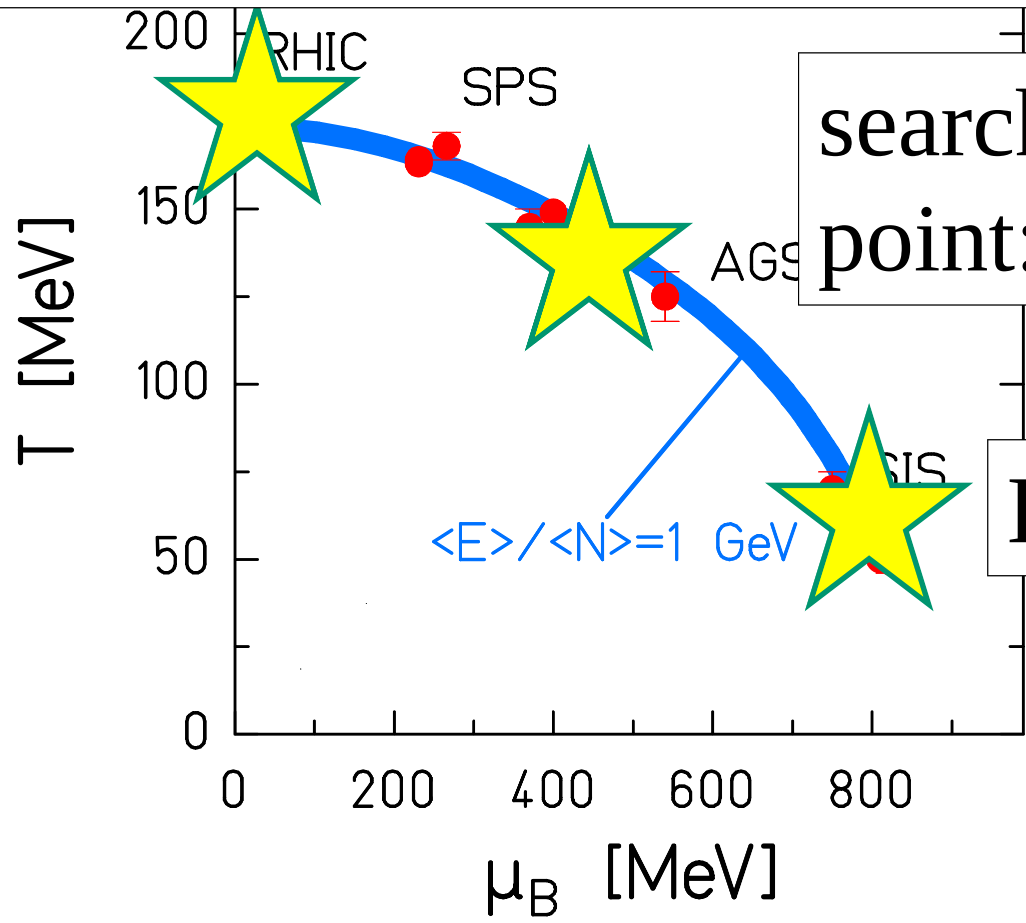
conclusions

- thermal-statistical model can be described:
- change of strange particles yield with $\sqrt{s}$
- behaviour of multistrange
- difference pp – HIC
- Open: Yield of protons at LHC!!!
- Maximum strangeness content around $\sqrt{s} \approx 8$ GeV and the recent results from beam energy scan as due to muB and saturation in T. Different behaviour of K+, K-, Λ, Ξ, Ω described
- At $\sqrt{s} \approx 8$ GeV separation of Tchem and Tkin. At this energy the freeze out changes from being dominated by baryons to one goverened by pions. At higher incident energies chemical and kinetec freeze out become separate.
- At low $\sqrt{s}$, argumments using hadronic terms
- at high $\sqrt{s}$, words as QGP, needed to explain equilibration!
- Transition?

LHC: phase transiton at chem. freeze out

search for critical point: fluctuation

Equilibrium?



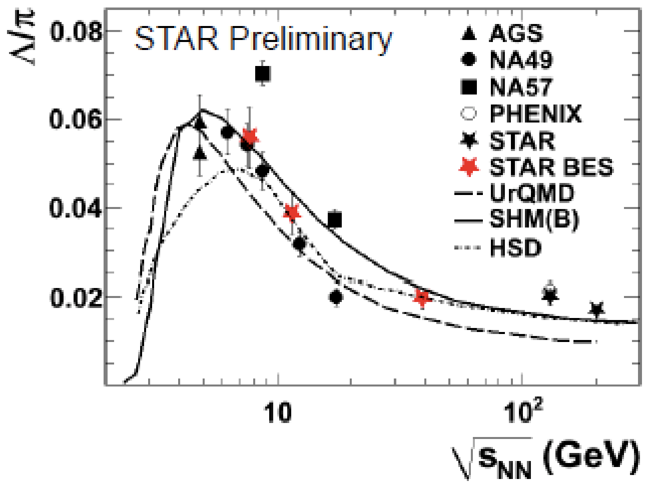
J. Cleymans and K. Redlich, PRL 81 (1998) 5284


Thank you

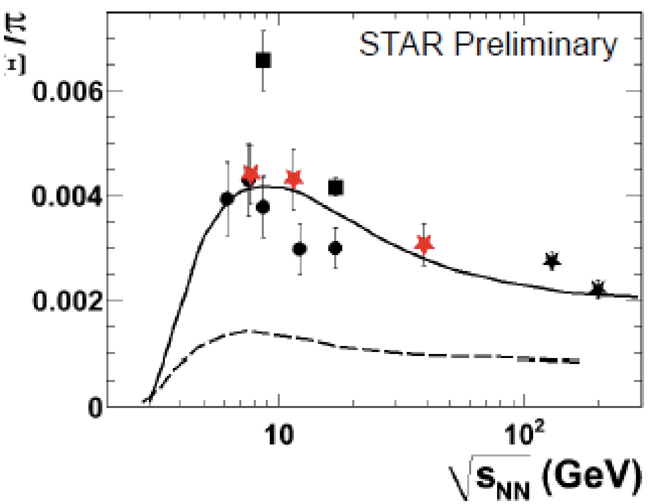

Thank you!

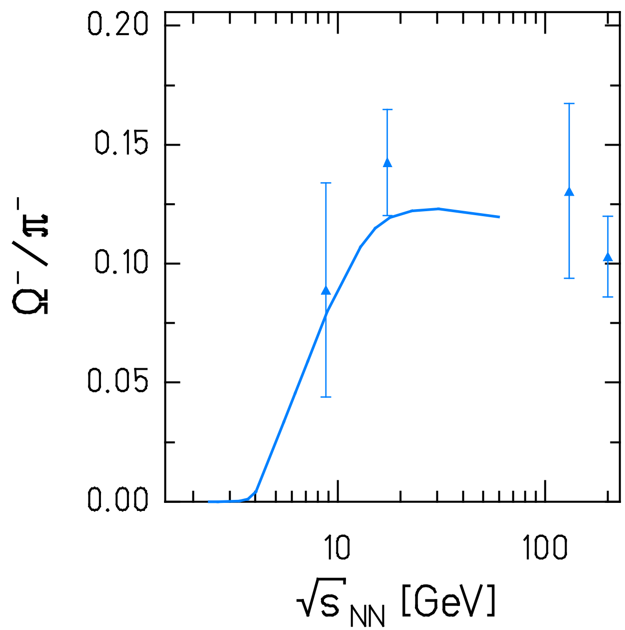

-40
-20
0
20
40
Thank you

Results from STAR BES



Now, we need the Ω/π ratio to see whether the maximum is at a higher $\sqrt{s_{NN}}$!

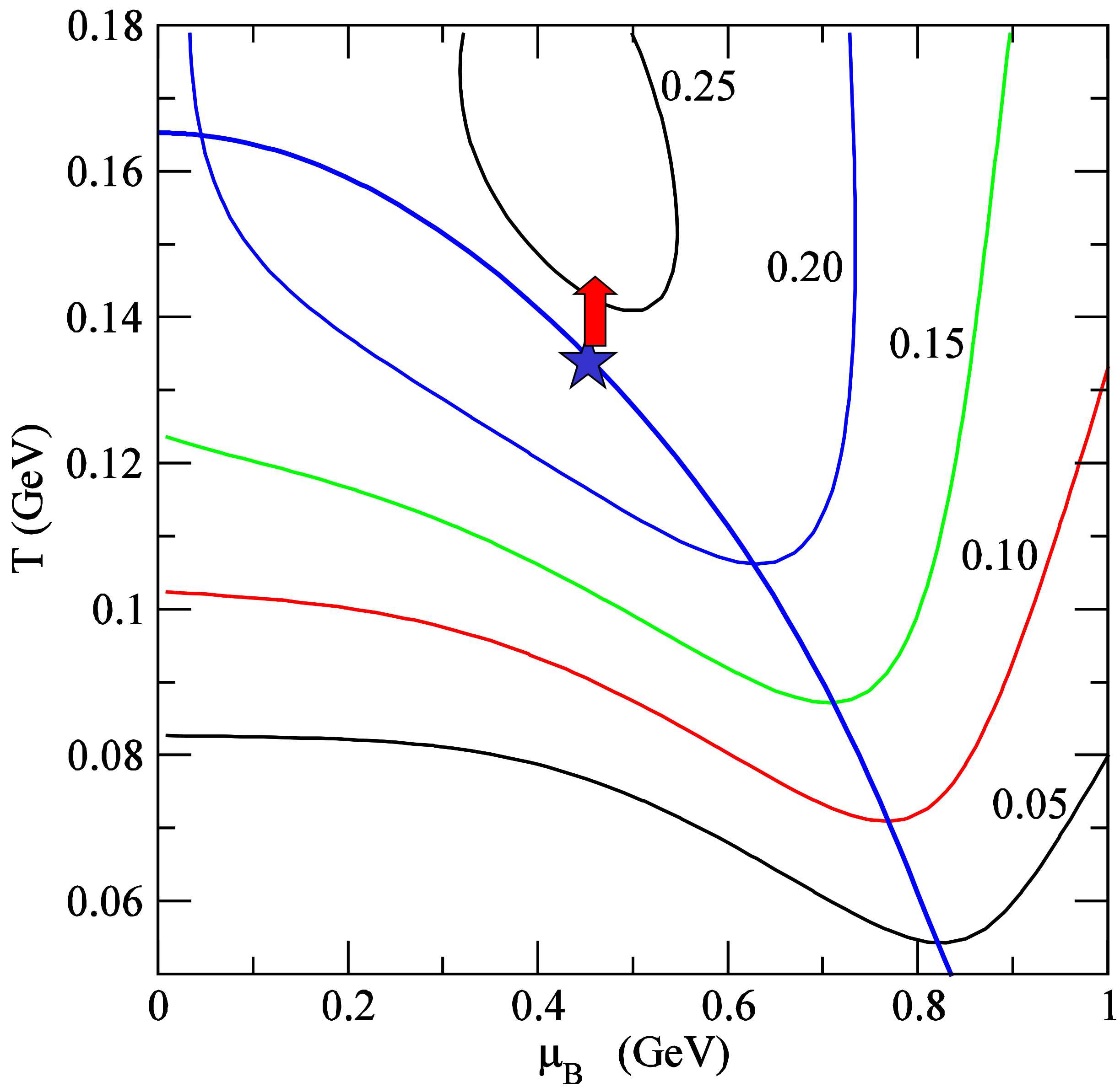




$\star$ 25 A GeV

K^+/π^+ Ratio

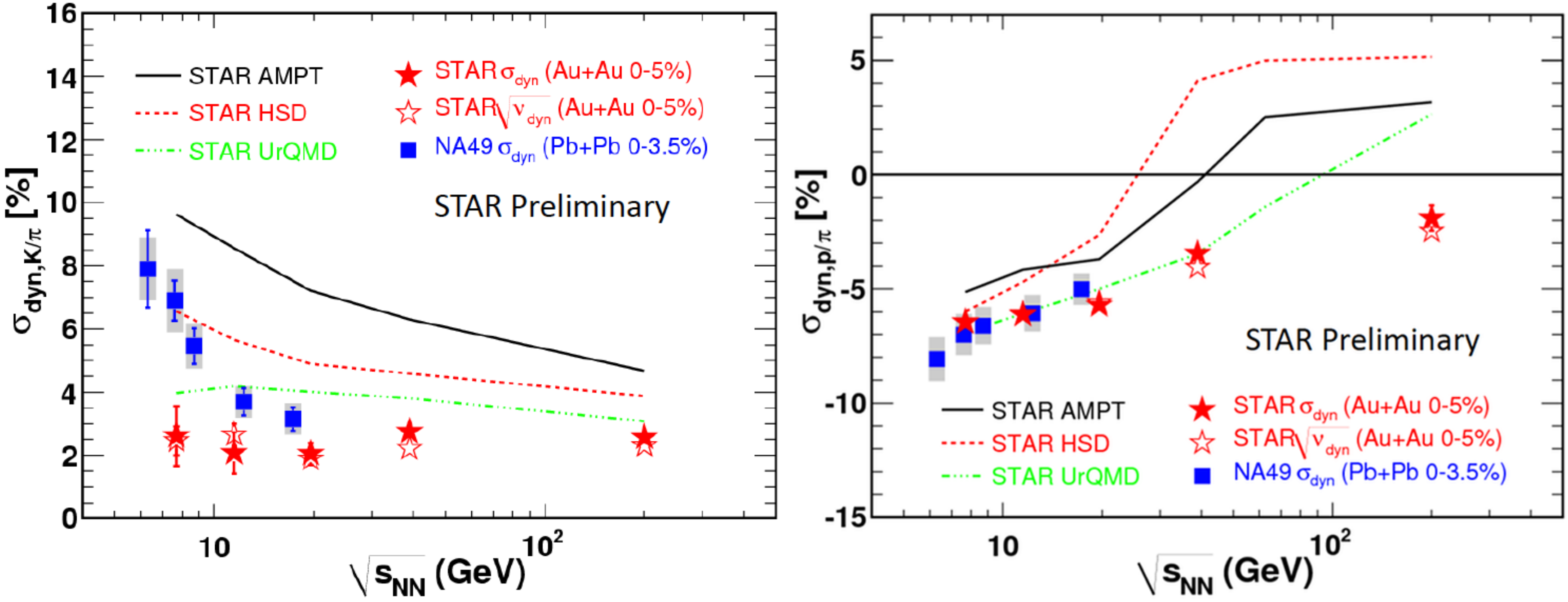
S.Wheaton, et al.



Outline

- Hadrons with light flavor are suited to test the phase transition, the chemical and the kinetic freeze out
- Goal: to develop a detailed view of the time evolution
- 1. Results at LHC energies
- 2. The maximum strangeness content and recent results from the RHIC beam energy scan
- 3. Sketch of the phases

Fluctuations as a test of the critical point

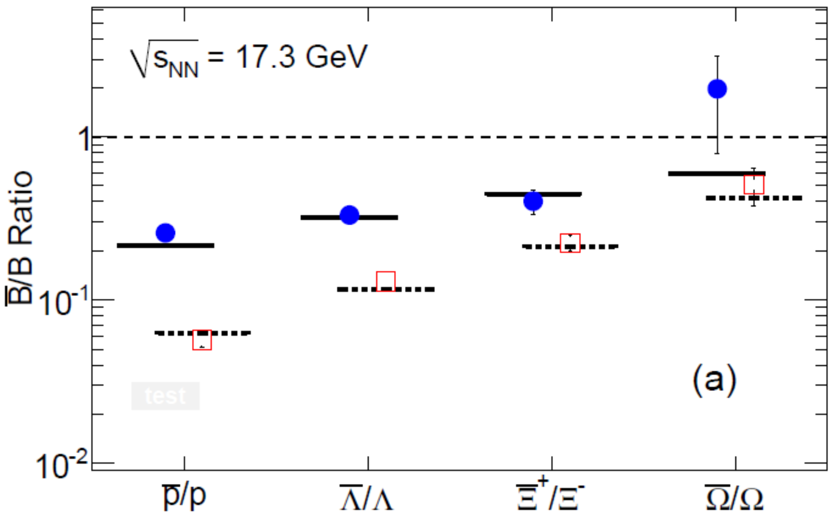


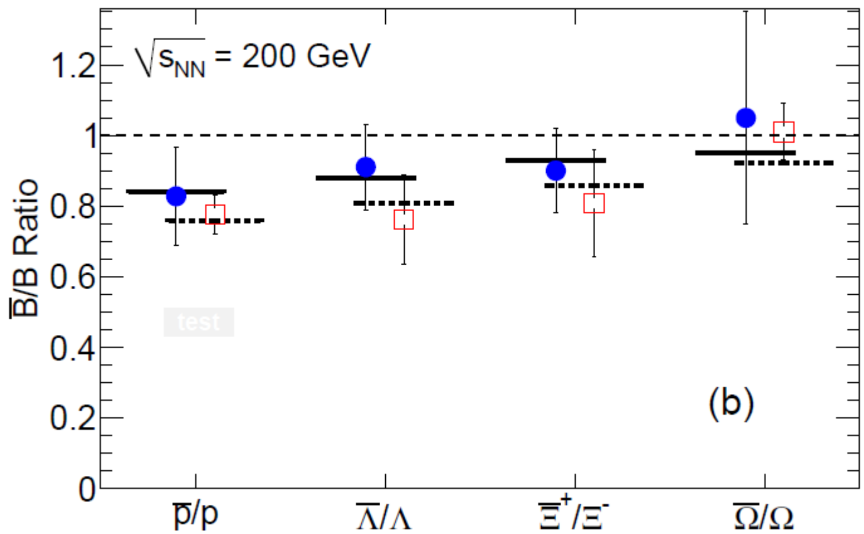
No signal of a critical point!!!!!! (?)

STAR, A. Schmah CPOD2011

Anti-baryon/baryon ratios

Central heavy-ion collisions - pp





$$\frac{n_{\overline{\mathrm{B}}}}{n_{\mathrm{B}}} = \exp[-2(\mu_B - N_S\mu_S)/T],$$

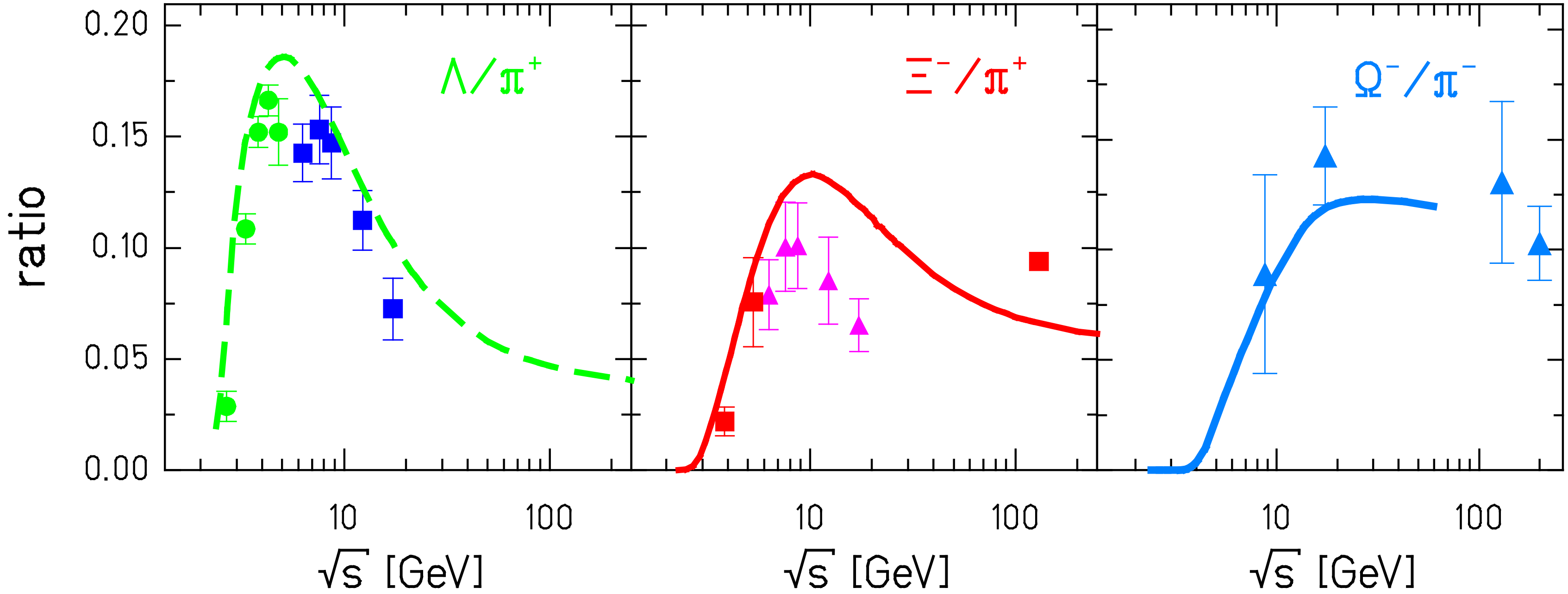
μ_B decreases with $\sqrt{s}$

μ_S is smaller than μ_B

μ_B in pp smaller than in HIC

J. Cleymans et al., arXiv:1105:3719

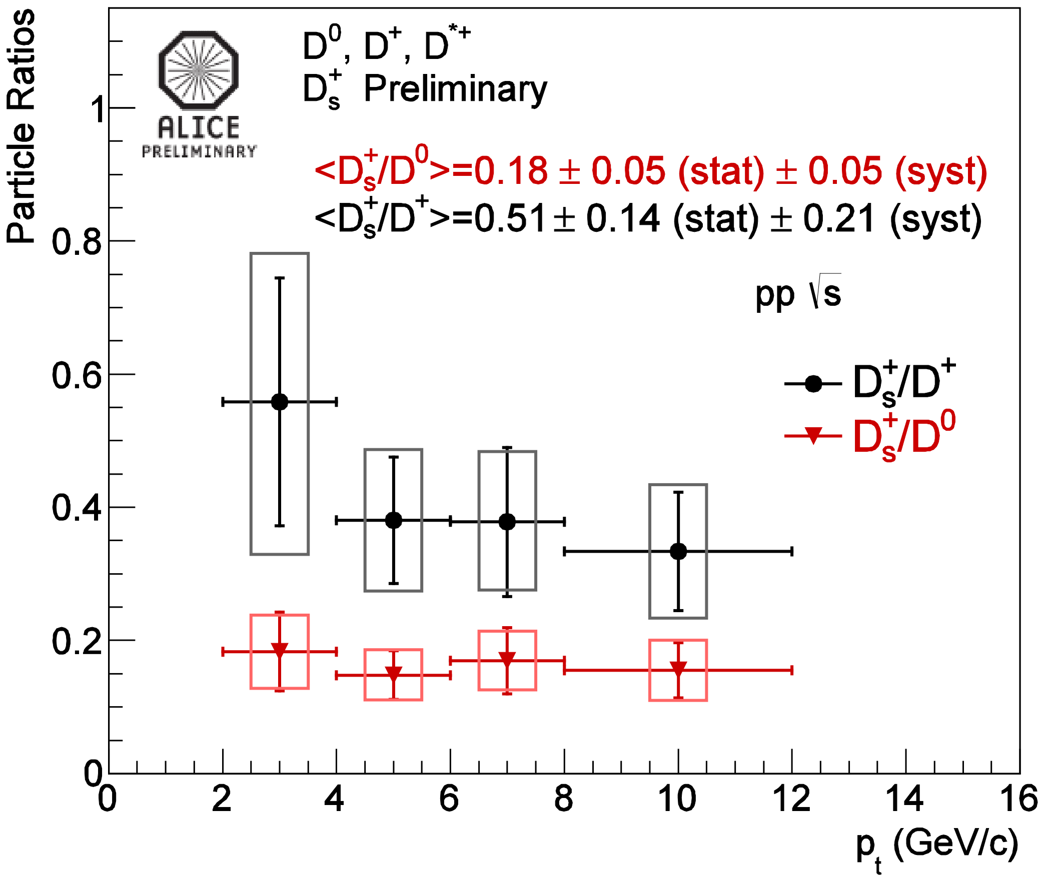
Baryons



Stat. Mod. : All exhibit maxima, but at different locations

4π values from NA49 2008 publication, NA57 higher!

D mesons in pp at 7 TeV



D+s/D0

ALICE ≈ 0.2

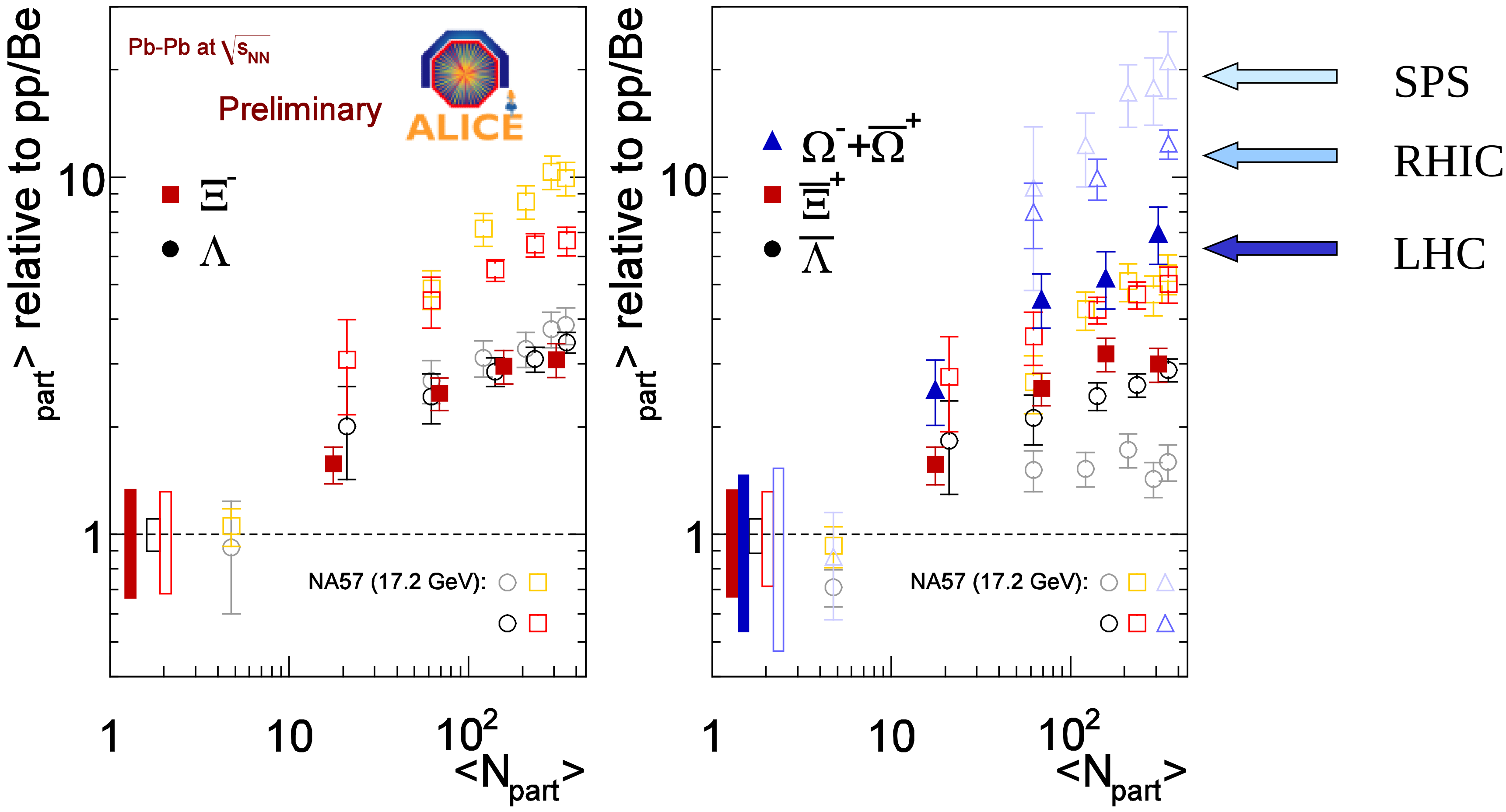
(JHEP 01 (2012) 128)

Stat. Model = 0.35 GC

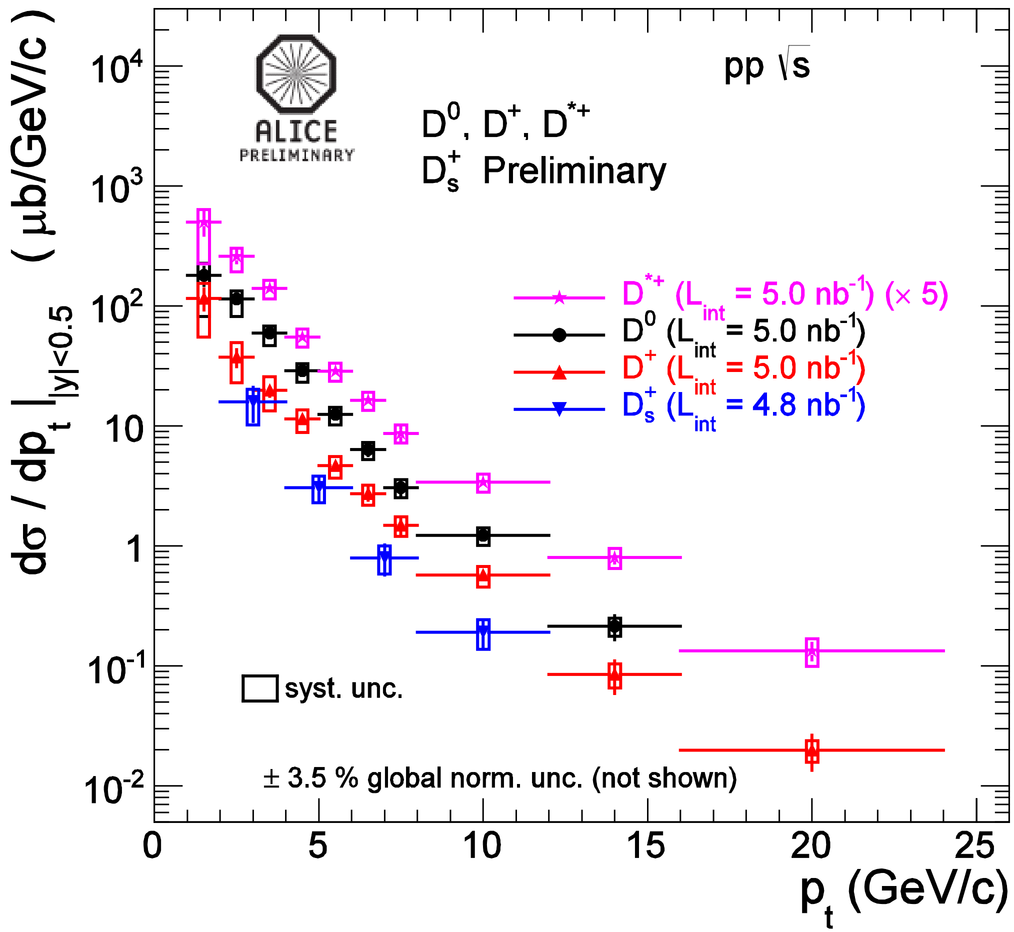
Ratio canonical/GC ≈0.7 (from K/π in Pb-Pb and pp)

To see yield of D in PbPb!!

Strangeness Enhancement



Distribution of s and c quarks



$\mathbf{D^+_{s}/D^0} \approx 0.2$

(JHEP 01 (2012) 128)

Stat. Model = 0.35 GC

Ratio canonical/GC ≈0.7 (from K/π in Pb-Pb and pp)

To see yields of $\mathbf{D^+_s/D^0}$ in PbPb!!

ALICE arXiv:1208.1948, PL B accepted

Predictions for LHC

Prediction for
heavy ions:

Grand can. (blue)

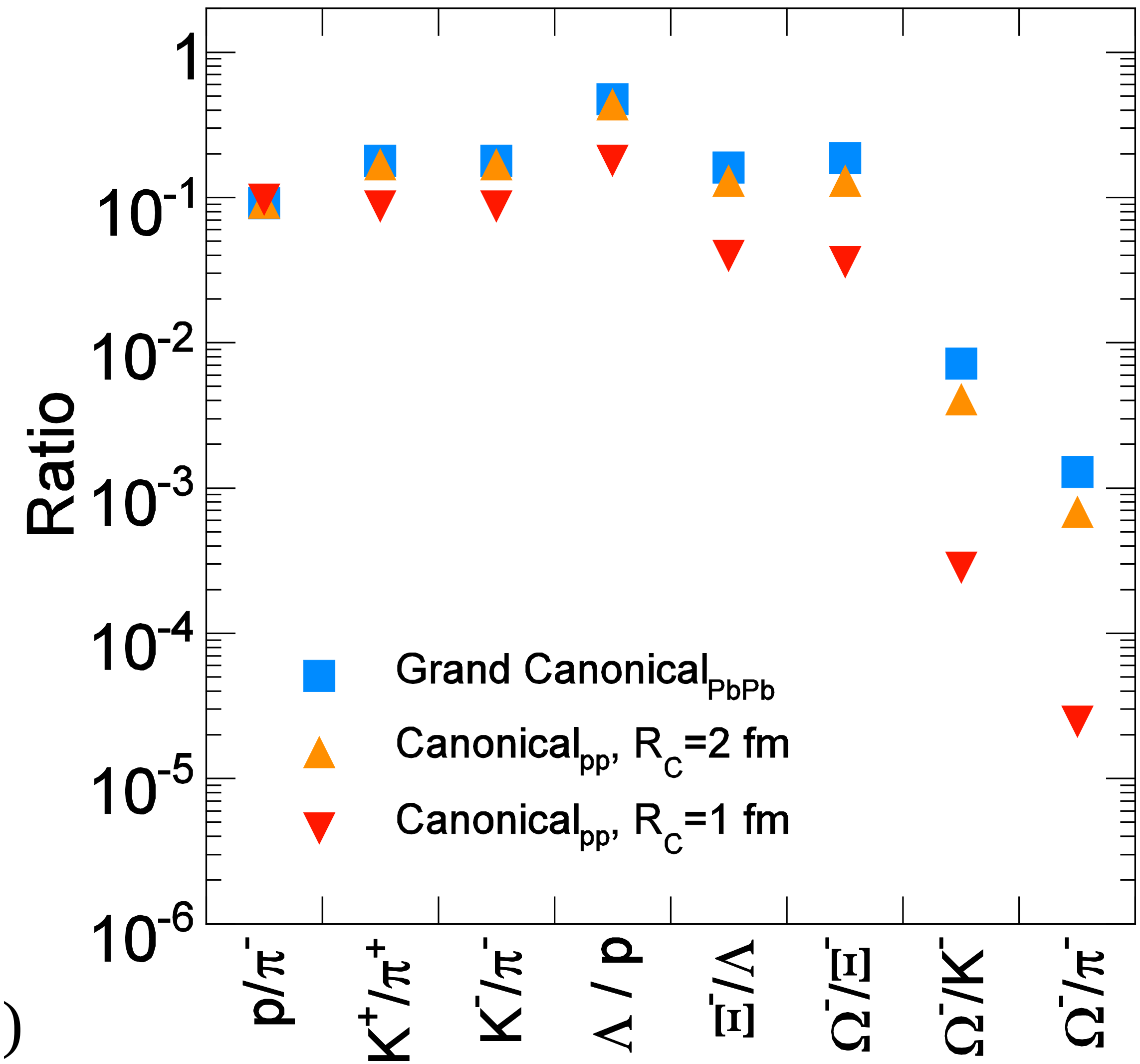
I. Kraus et al.,

PRC 74 (2007)

For pp collisions:

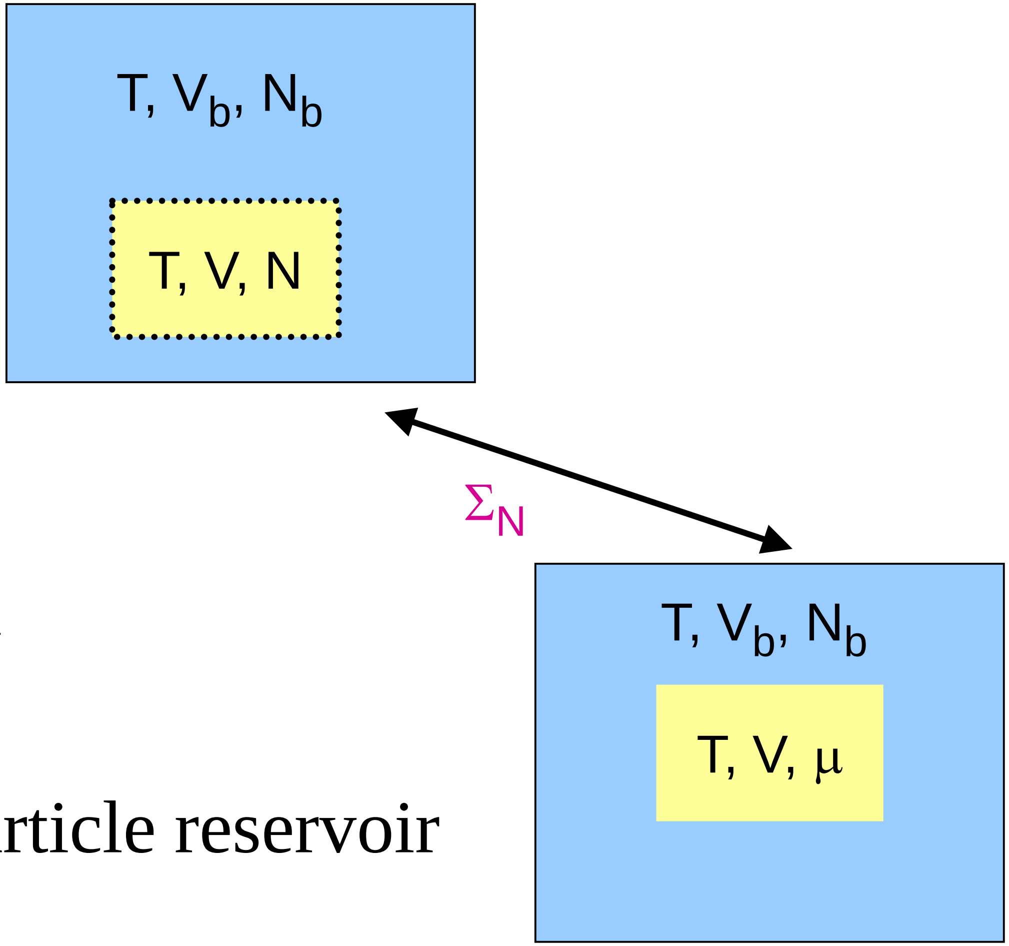
Canonical (yellow
and red)

I. Kraus et al.,
PRC 79(2009)



Statistical Ensembles

- Canonical
  - heat bath
  - T, V, N fix



- Grand-canonical
  - open system
  - heat bath and particle reservoir
  - T, V, μ fix

Density and Ratios

- Approx. modified Bessel function

$$n_i \approx \frac{\sqrt{\frac{\pi}{2}} \cdot g_i \cdot (T \cdot m_i)^{3/2}}{2\pi^2} \cdot e^{\frac{\vec{N}_i \vec{\mu}}{T}} \cdot e^{-\frac{m_i}{T}}$$

- Particle ratio

$$\frac{n_1}{n_2} \approx \frac{g_1}{g_2} \left(\frac{m_1}{m_2} \right)^{3/2} e^{\frac{(\vec{N}_1 - \vec{N}_2)\vec{\mu}}{T}} \cdot e^{-\frac{m_1 - m_2}{T}}$$

- Antiparticle/Particle ratio

$$\frac{n_{\bar{1}}}{n_1} \approx e^{\frac{2\vec{N}_{\bar{1}}\vec{\mu}}{T}} \approx e^{\frac{2N_{B,\bar{1}}\mu_B + 2N_{S,\bar{1}}\mu_S}{T}}$$

- Model parameters
  - T and μ_B
  - V cancels in ratios

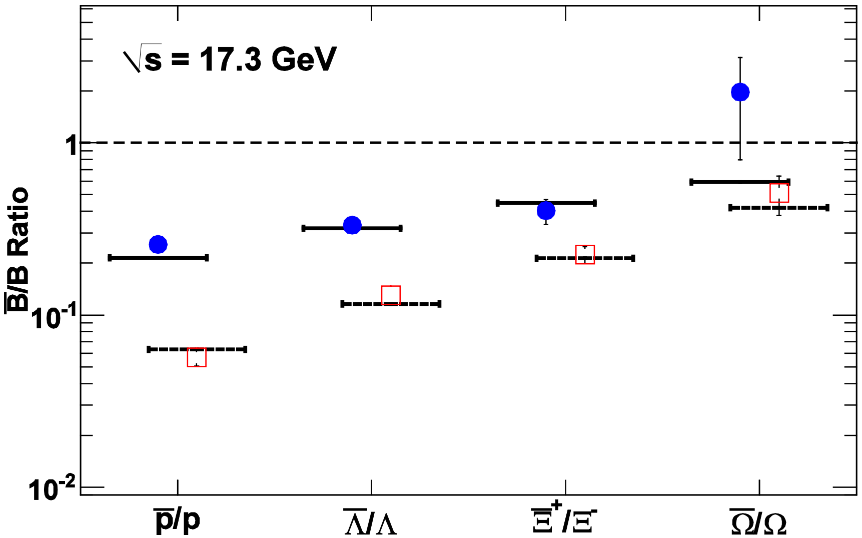
μ_S constrained by strangeness neutrality

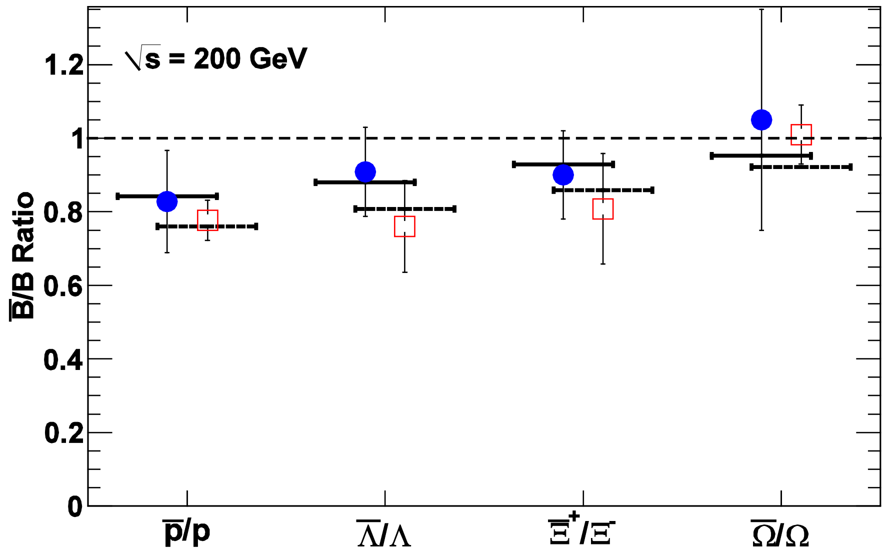
μ_Q constrained by charge of nuclei

Approx. In the limit m>T

Antiparticle-particle ratios

Central heavy ion collisions - pp





$$\frac{n_{\overline{B}}}{n_B} = e^{-(2\mu_B - N_S\mu_S)/T}$$

μ_B decreases with $\sqrt{s}$

μ_S is smaller than μ_B

μ_B in pp smaller than in HIC

Xi at AGS! and SIS?

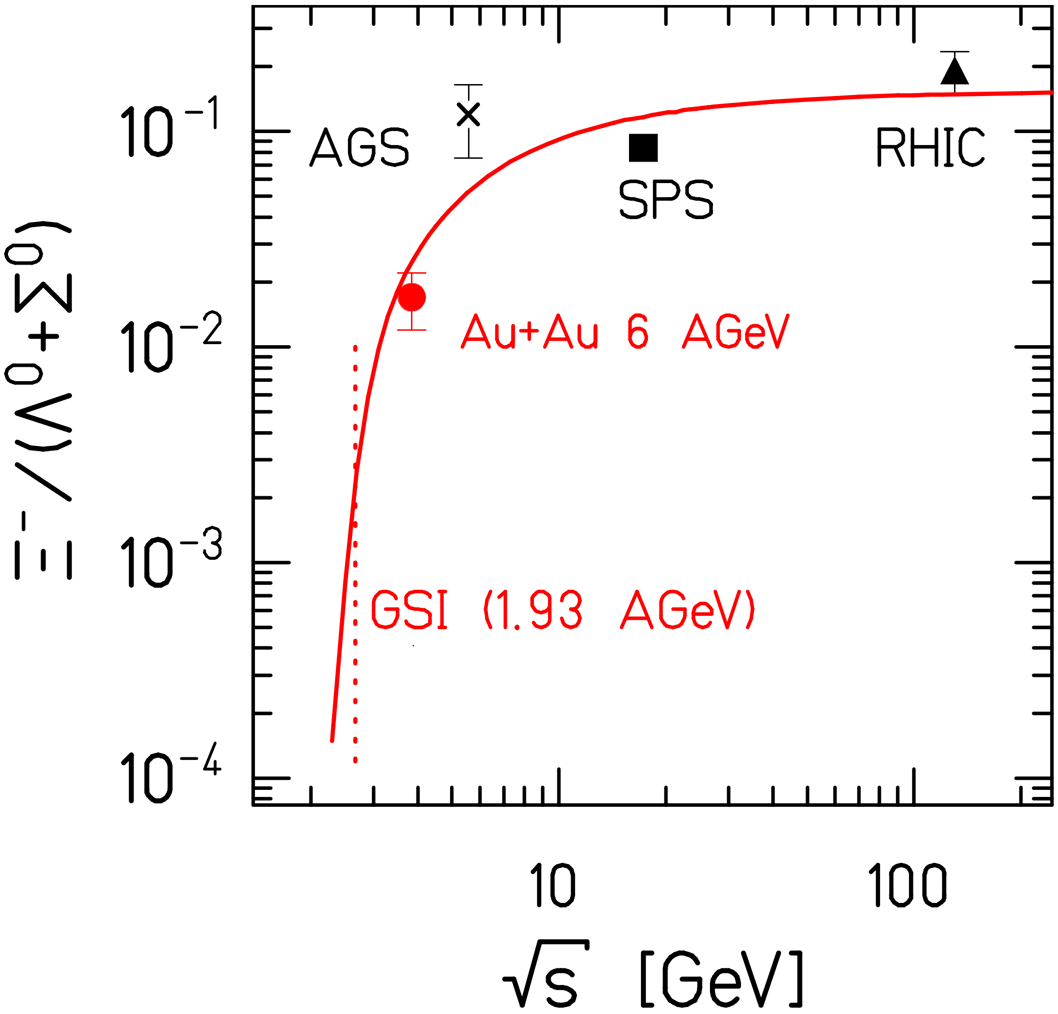
P. Chung et al.,

E895 Collaboration,

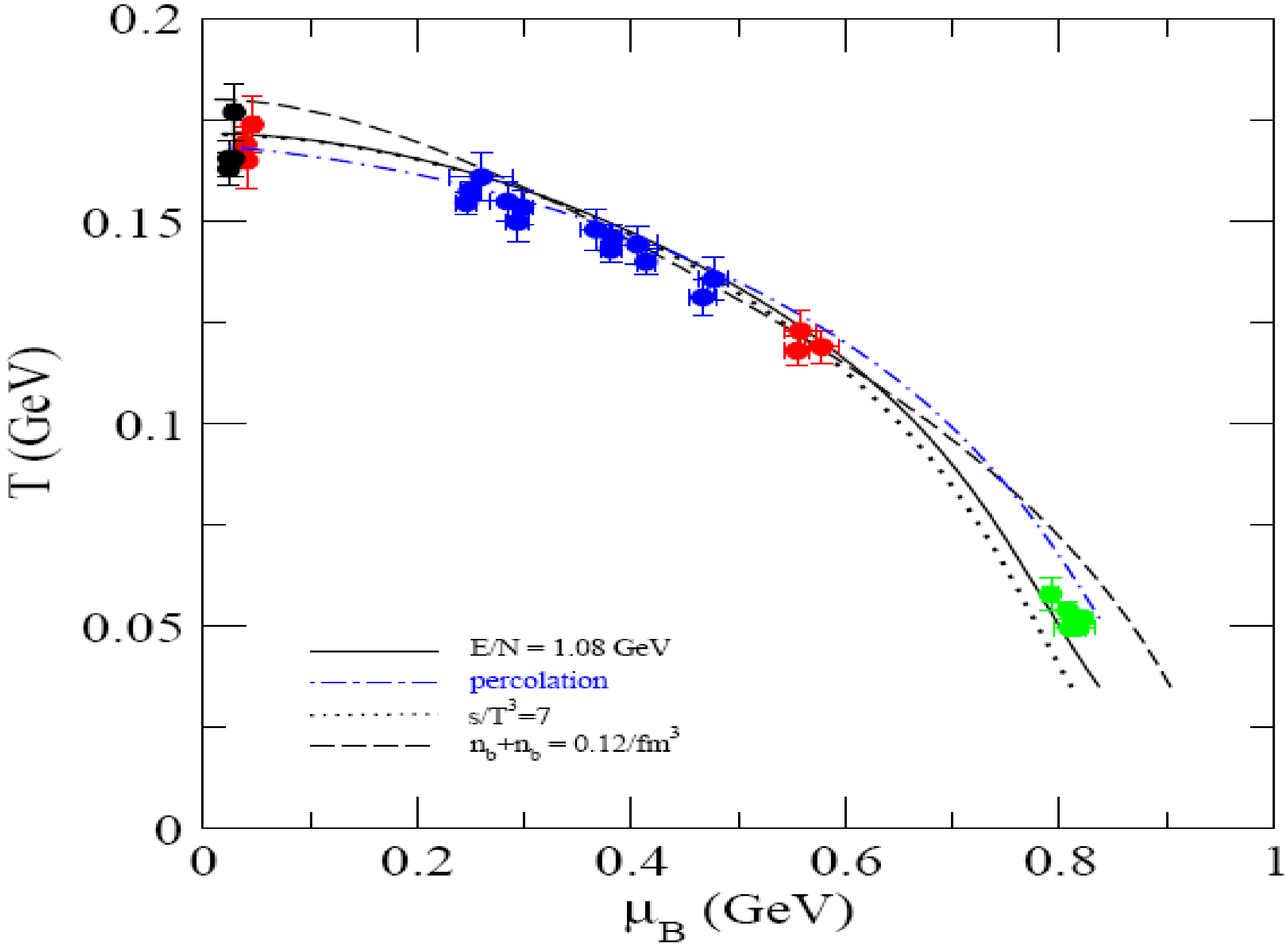
PRL 91 (2003)202301

FOPI Collaboration

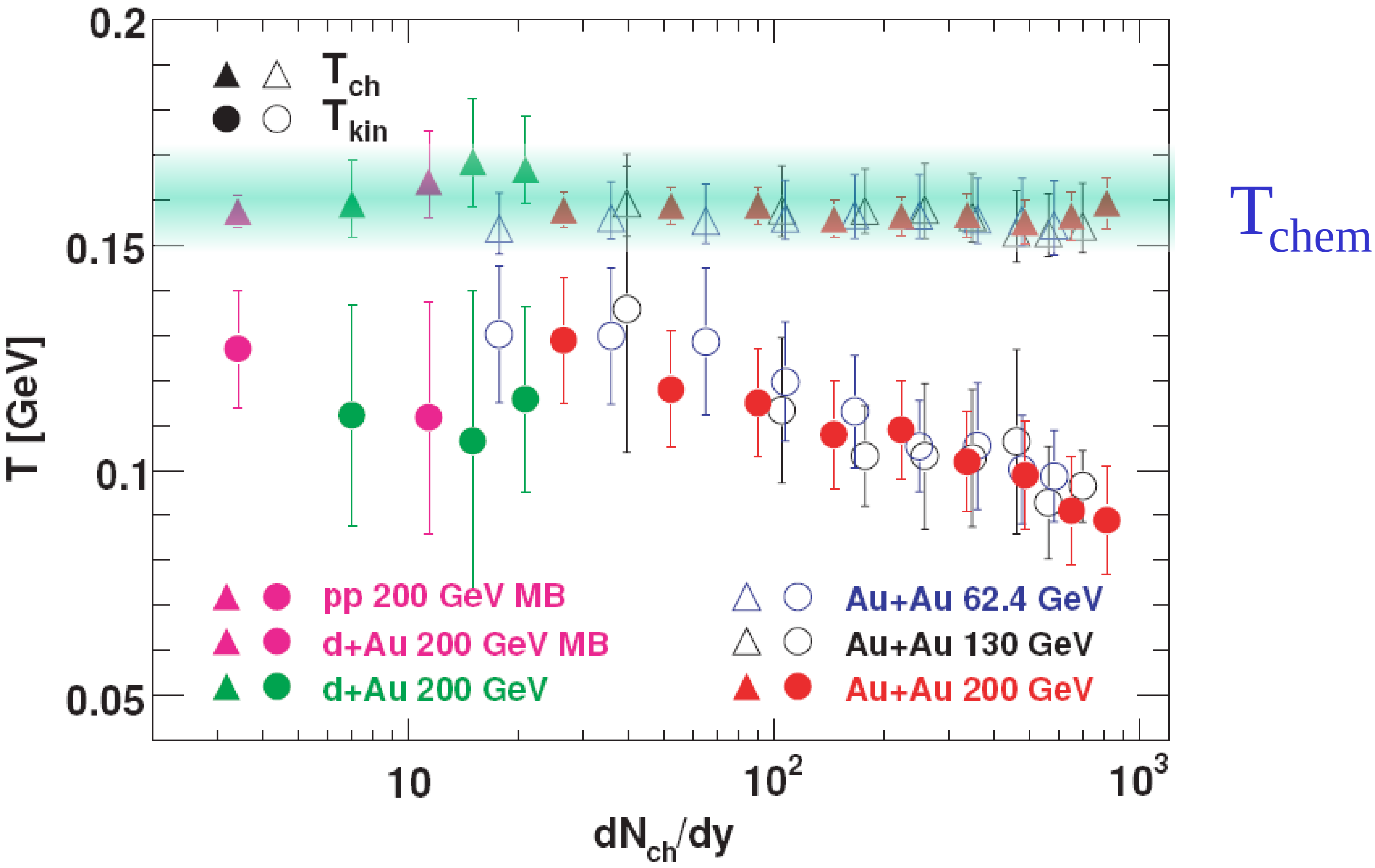
Data are taken



Freeze-out criteria



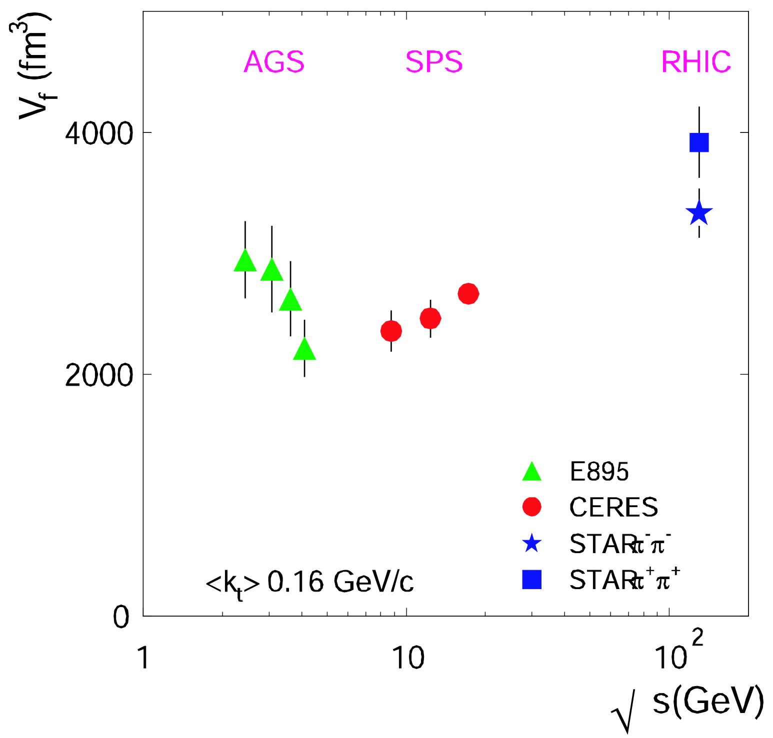
J. Cleymans, HO, K. Redlich, S. Wheaton, Phys. Rev. C73 (2006)

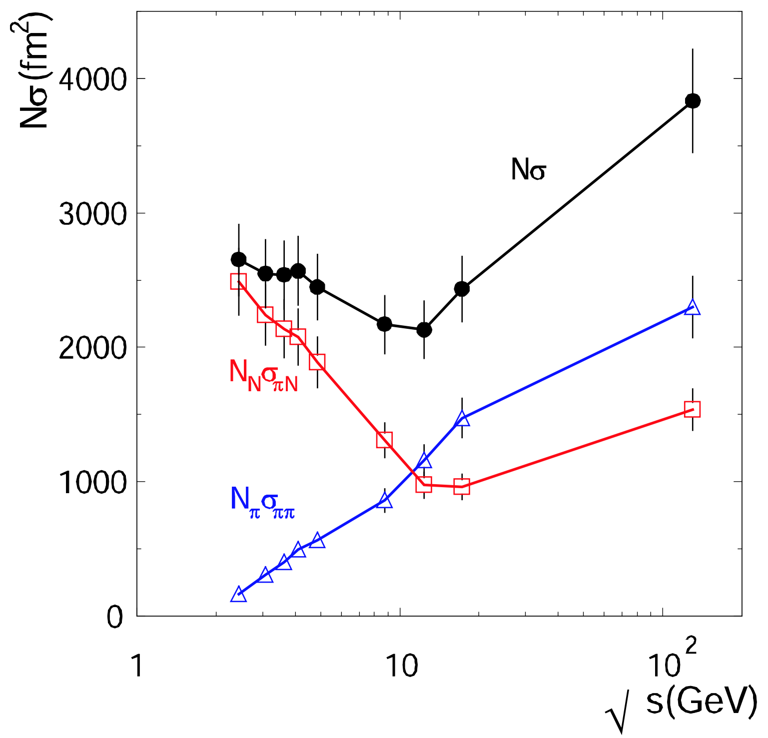


STAR, PRC 79 (2009) 034909

Freeze-Out Volume from HBT

D. Adamova et al., CERES, PRL 90 (2003)





Freeze-Out Volume from HBT

D. Adamova et al., CERES, PRL 90 (2003)