the statistical hadronization model at the LHC

Outline:
- hadron yield at LHC and statistical model
- need for additional coalescence mechanism?
- charmonia in the statistical hadronization model

work done in collaboration with
A. Andronic, P. Braun-Munzinger, und K. Redlich

Johanna Stachel, Physikalisches Institut, U. Heidelberg
Strangeness in Quark Matter 2013, Birmingham, July 25, 2013

starting point: the statistical model – grand canonical

partition function: $\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))$

particle densities: $n_i = N/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2\,\mathrm{d}p}{\exp((E_i - \mu_i)/T) \pm 1}$

for every conserved quantum number there is a chemical potential:

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

but can use conservation laws to constrain V, μ_S, μ_{I_3}

→ **fit at each energy provides values for T and μ_b**

- get yields of all hadrons

for dN/dy need in addition volume per unit y - fix to dN_{ch}/deta

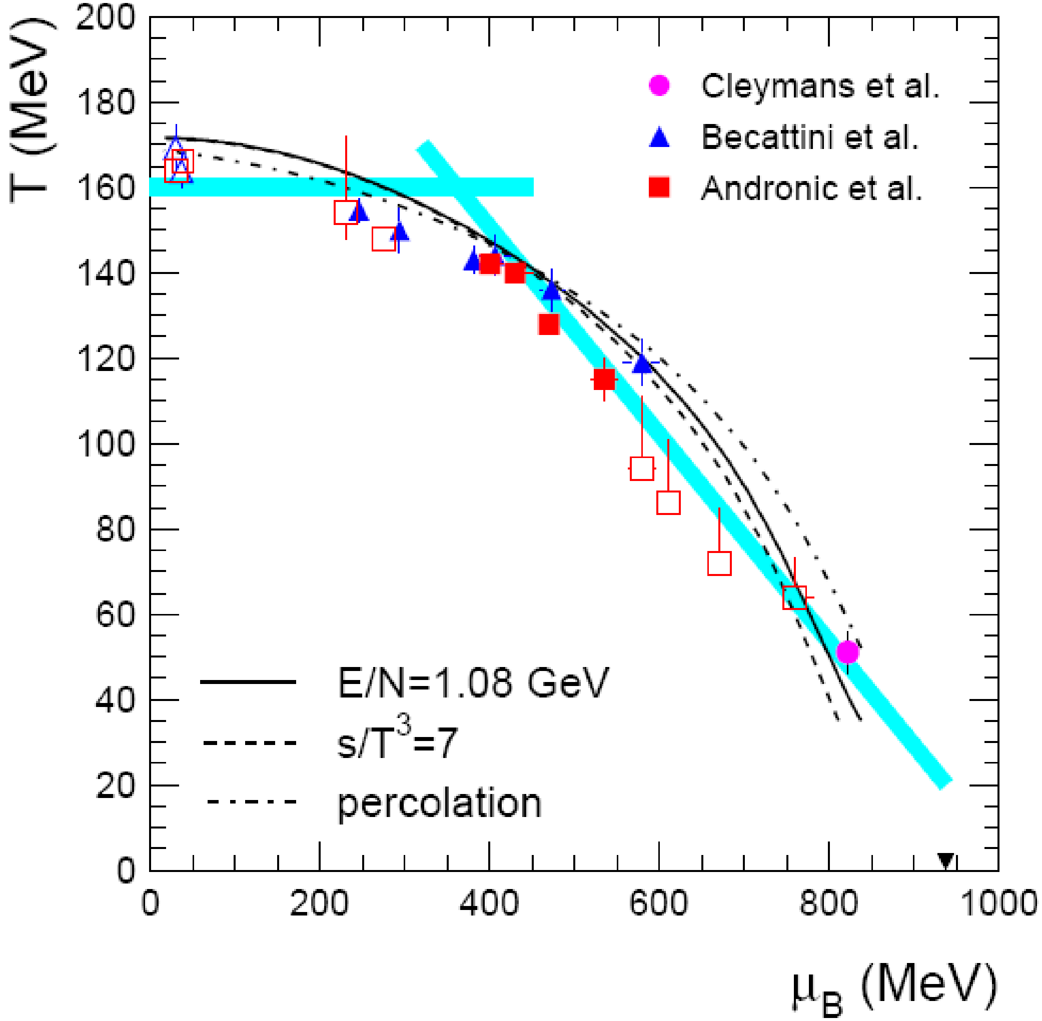
good fit to data for central collisions of heavy nuclei at AGS, SPS, RHIC

see e.g.

A. Andronic, P. Braun-Munzinger, J.S. Nucl. Phys. A722(2006)167 nucl/th/0511071

phase diagram and chemical freeze-out points 2009

A. Andronic et al. ArXiv 0911.4806[hep-ph]



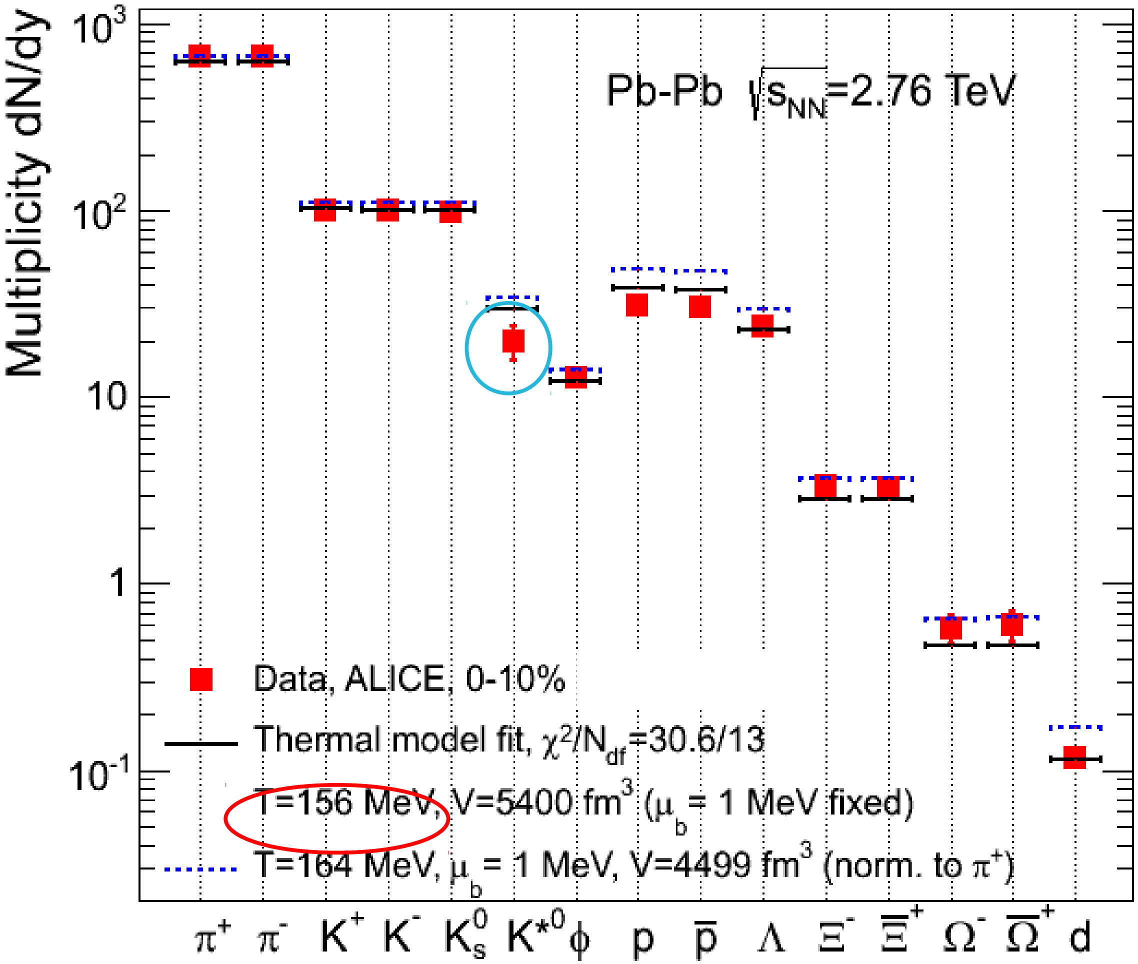
based on this prediction for LHC:

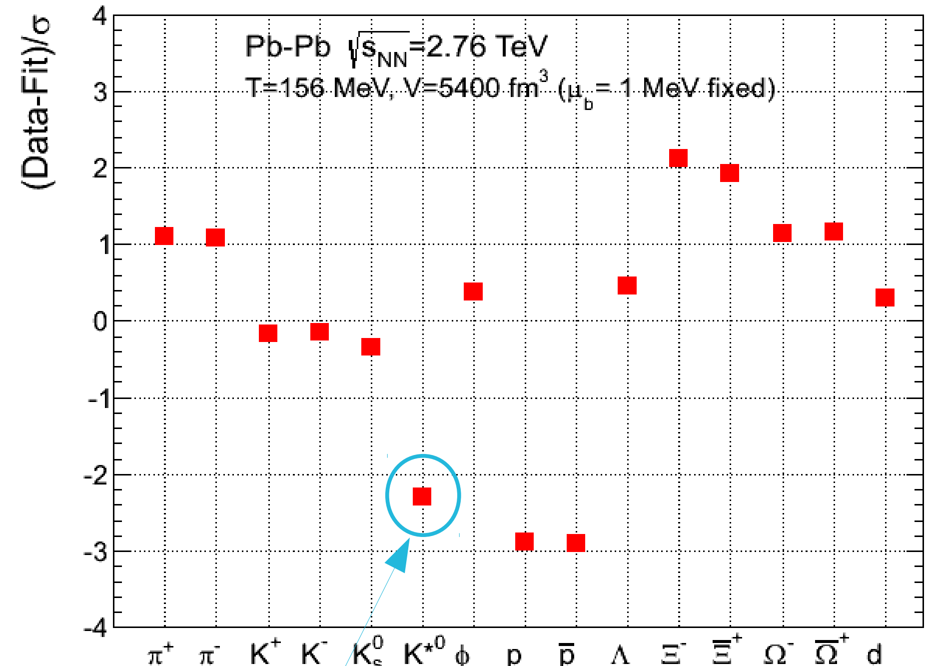
$T = 161 \pm 4$ MeV and $\mu_b = 0.8^{+1.2}_{-0.6}$ MeV

A. Andronic, P. Braun-Munzinger, J.S.
arXiv:0707.4076 [nucl-th]

over the coming years these numbers moved a little due to RHIC data

New: fit to all currently available data from ALICE at LHC



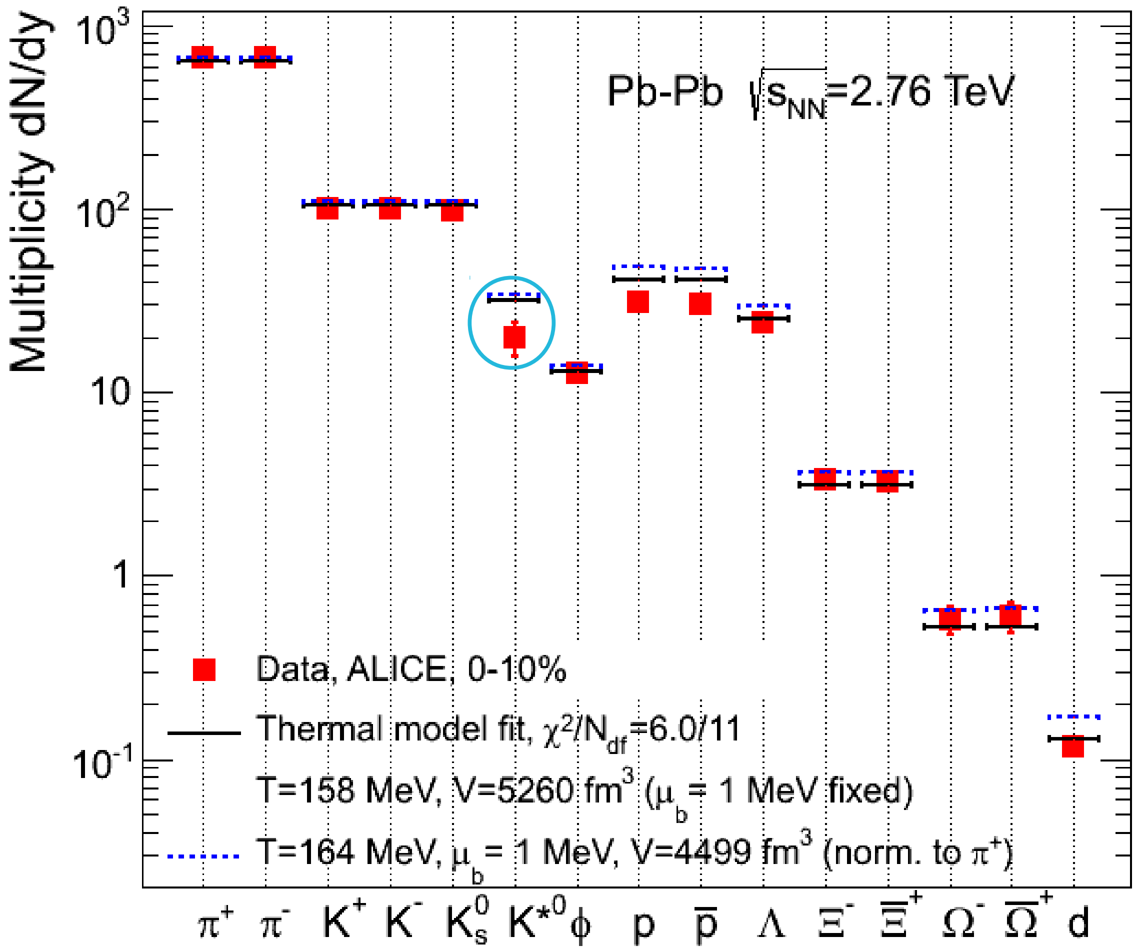


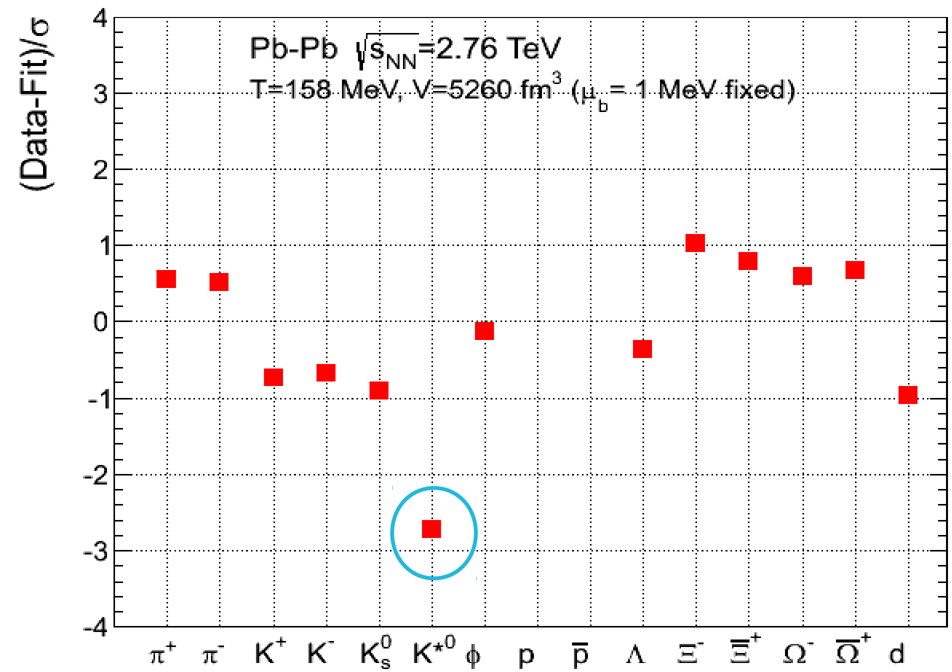
strongly decaying resonance

protons low by 2.9 σ

as compared to 2012: more and final data
T went from 152 to 156 MeV
red. χ^2 went from 4 to 2.35

Fit excluding protons





<u>excluding protons:</u> T goes from 156 to 158 MeV

perfect fit for other hadrons

2012 with partly preliminary data difference was between 152 and 164 MeV

Possible reasons for low proton yield

Incomplete hadron spectrum
Annihilation in the hadronic phase
Non-equilibrium scenario with new parameters
other?

Effect of incomplete hadron spectrum

Effect of incomplete hadron spectrum

we studied this for K/π ratio:

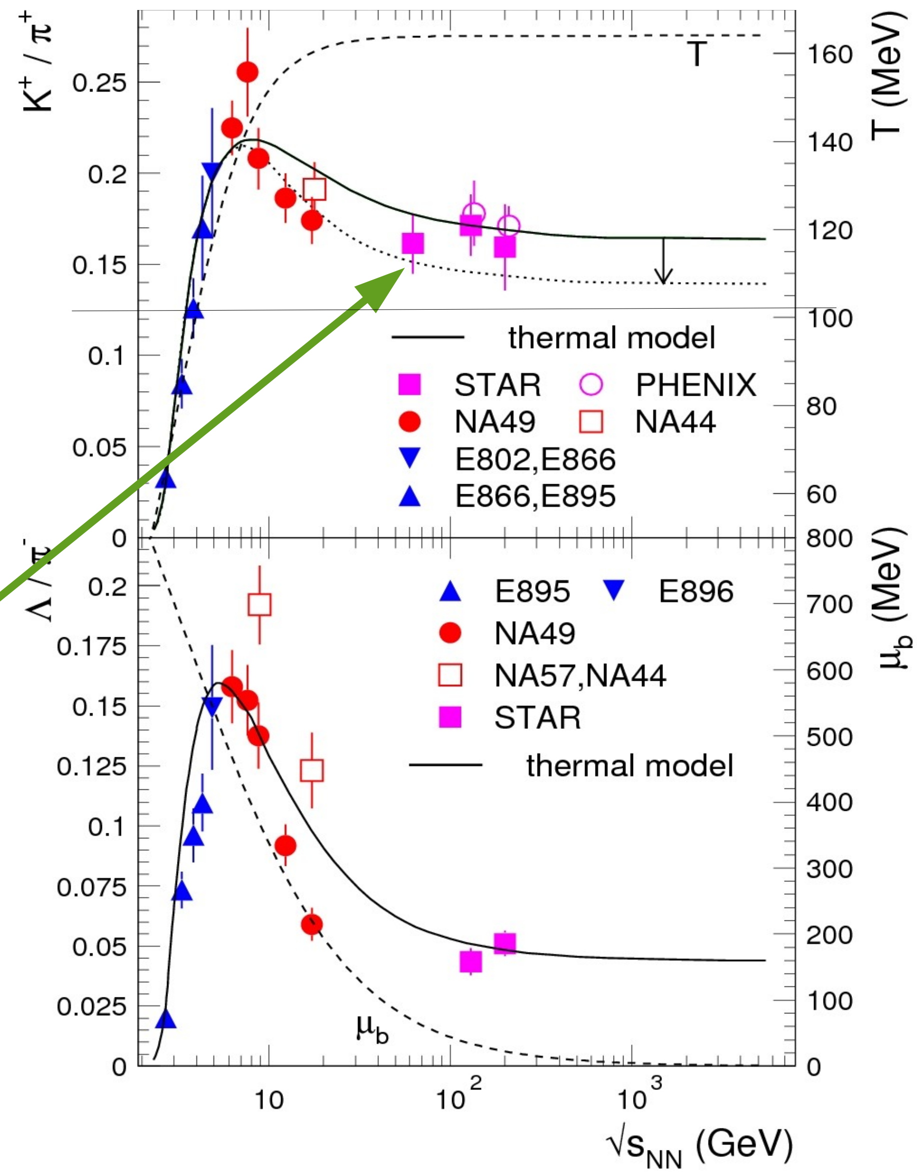
(Andronic, Braun-Munzinger, JS Phys. Lett. B673 (2009) 142)

estimate effect by extending mass spectrum beyond 3 GeV based on TH = 200 MeV and assumption how states decay

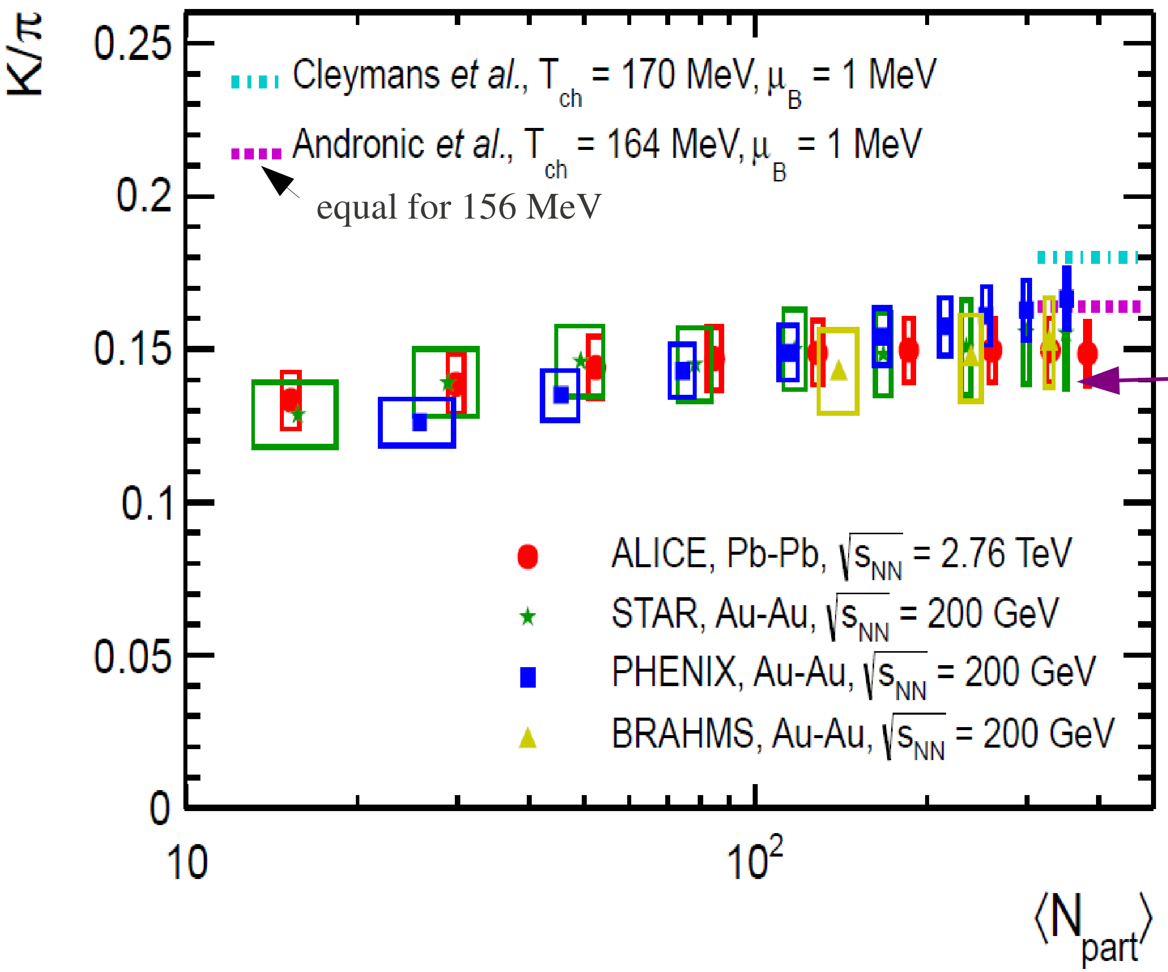
strongest contribution to kaon from K* producing one K

all high mass resonances produce multiple pions

-> further reduction of K^+/π^+

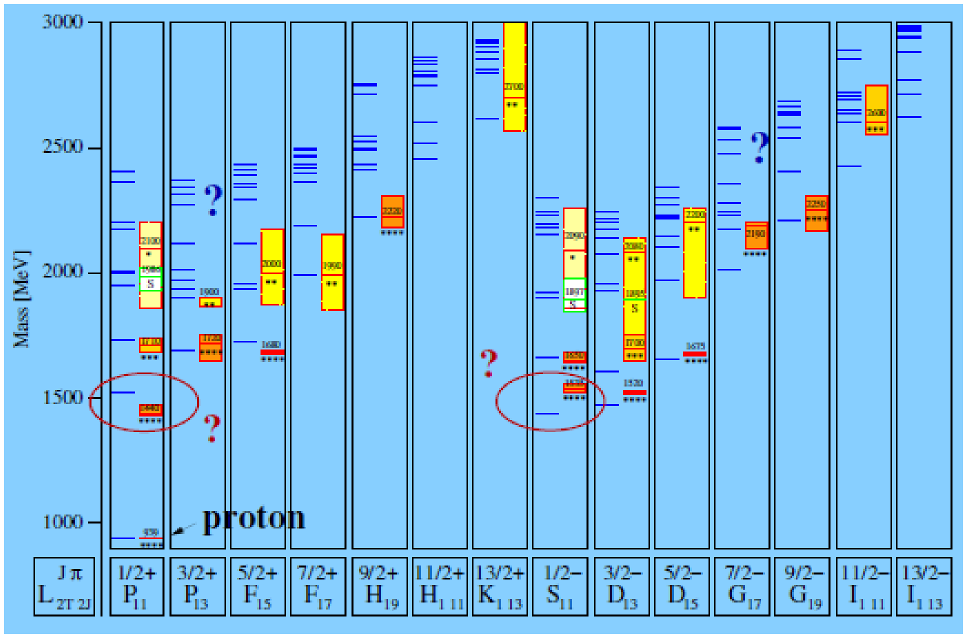


Estimate of 'guessing' the Hagedorn spectrum



K:π goes from 0.163 to 0.14
- better for LHC data

there could be a lot more unfound baryons at low mass and with high spin (degeneracy)



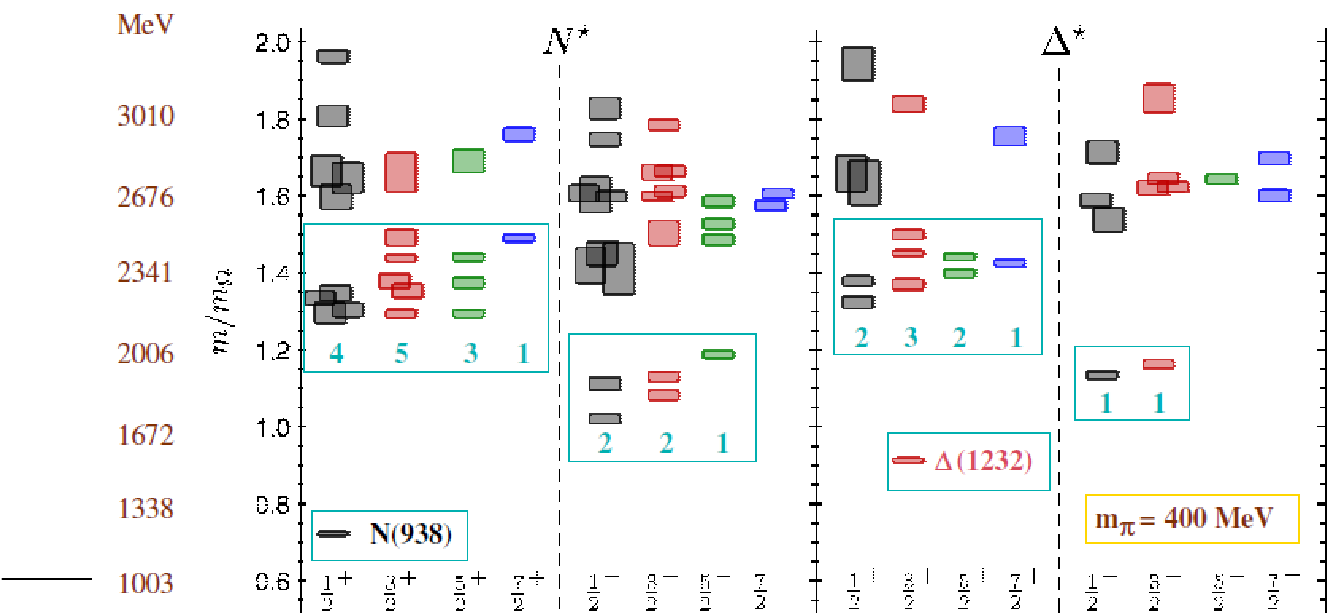
from talk U. Thoma DPG2013

non-strange N* resonances

U. Loering, B. Metsch, H. Petry et al.

relativistic quark model

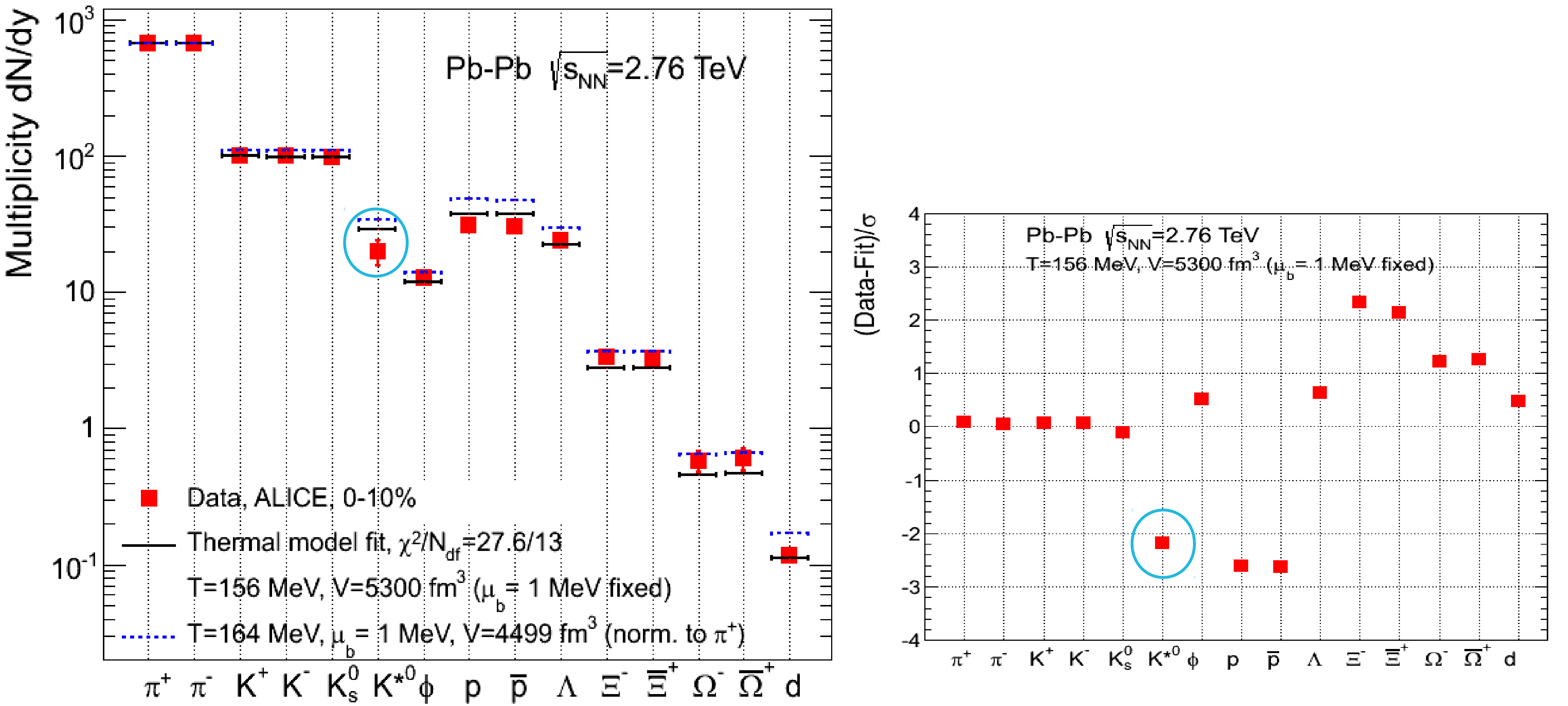
Constituent quarks, confinement potential
+ residual interaction



Excited baryons from lattice QCD:
R. Edwards et al., Phys. Rev. D84 (2011) 074508

some have been found

simple study: add 10% more pions from resonances



instead of adding complete Hagedorn resonance gas, add in addition to all known states 10% more pions

fit improves: red χ^2 goes from 2.35 to 2.1 - more elaborate studies to come

Annihilation in the hadronic phase?

F. Becattini et al., Phys. Rev. C85 (2012) 044921 and arXiv: 1212.2431

Evaluate hadronic interactions after statistical hadronization using RQMD find significant effect of apparent cooling due to hadron rescattering

→ see talk at this conference by F. Becattini

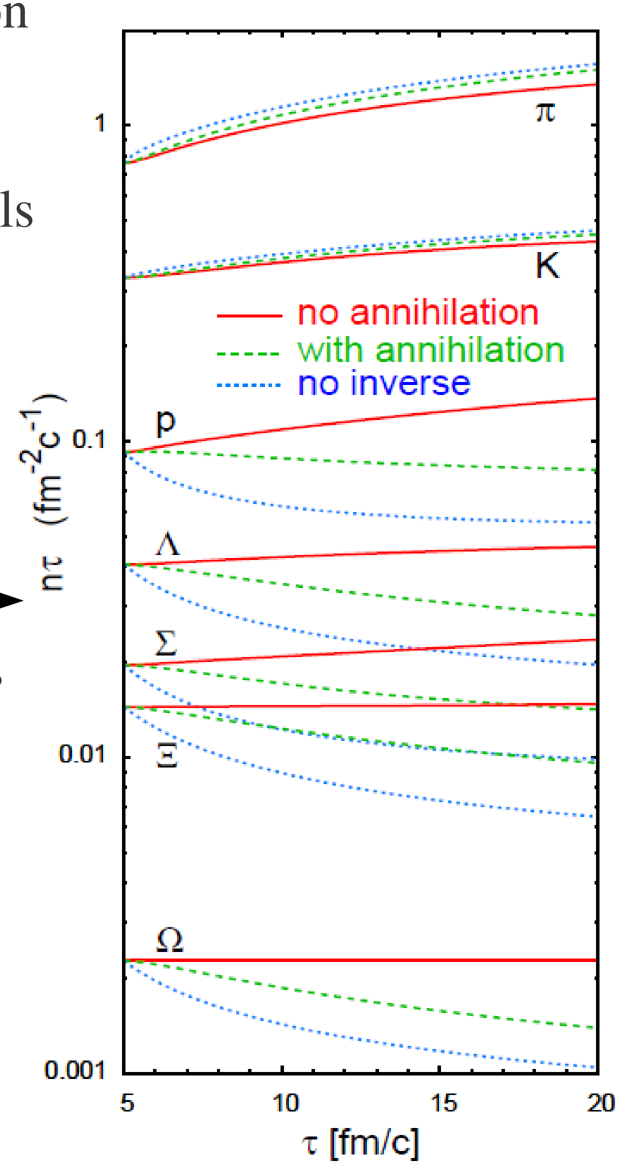
Annihilation in the hadronic phase?

- but need to take into account full detailed balance, backreaction like $5\pi \rightarrow$ ppbar (not in RQMD)

analysis by Rapp and Shuryak 2008 for SPS energies: this cancels the annihilation effect,
equilibrium value at T_{chem} is recovered

recent analysis by Pan and Pratt, PRL 110 (2013) 042501:
taking account backreaction cancels half of the effect of annihilation

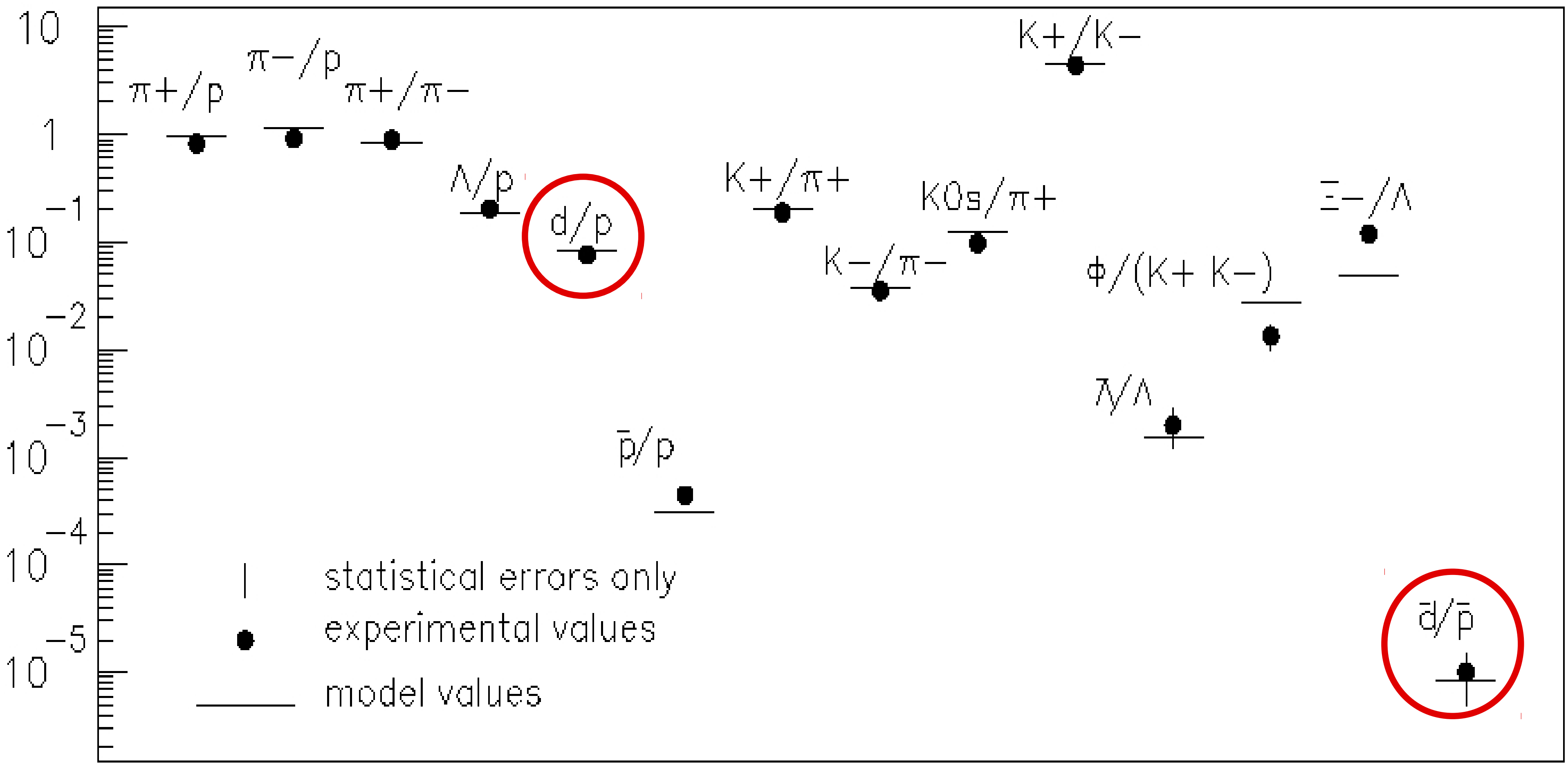
- Why should only proton be affected? and not hyperons? Cross sections should be very similar, e.g. Ω + Nbar $\rightarrow 2\pi + 3$K evalute 10 mb at threshold Braun-Munzinger, JS, Wetterich, Phys. Lett. B596 (2004) 61
  - they show if anything opposite effect
- what about nuclei?? they fit perfectly and their cross sections are larger



First Fit to AGS Data – reproduces yields of d and dbar

14.6 A GeV/c central Si + Au collisions and GC statistical model

P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, PLB 1994



dynamic range: 9 orders of magnitude! No deviation

Should nuclei follow prediction of statistical hadronization at all?

Argument has been made, that coalescence is responsible for their formation and this is different mechanism

However: for system in thermal equilibrium, statistical ensemble and coalescence results agree
d/p is given by entropy per baryon (see already Siemens and Kapusta PRL (1979) 1486)

For System in Thermal Equilibrium Statistical and Coalescence Yields agree

P. Braun-Munzinger, J. Stachel, J. Phys. G21 (1995) L17

	Thermal Model		A.J. Baltz, C.B. Dover, et al., Phys. Lett. B315 (1994) 7
Particles	T=.120 GeV	T=.140 GeV	Coalescence Model
d	15	19	11.7
t+^{3}He	1.5	3.0	0.8
α	0.02	0.067	0.018
H_0	0.09	0.15	0.07
${}^{5}_{\Lambda\Lambda}$H	$3.5 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
${}^{6}_{\Lambda\Lambda}$He	$7.2 \cdot 10^{-7}$	$7.6 \cdot 10^{-6}$	$1.6 \cdot 10^{-5}$
${}^{7}_{\Xi^0\Lambda\Lambda}$He	$4.0 \cdot 10^{-10}$	$9.6 \cdot 10^{-9}$	$4 \cdot 10^{-8}$
${}^{10}_{1}\text{St}^{-8}$	$1.6 \cdot 10^{-14}$	$7.3 \cdot 10^{-13}$	
${}^{12}_{1}\text{St}^{-9}$	$1.6 \cdot 10^{-17}$	$1.7 \cdot 10^{-15}$	
${}^{14}_{1}\text{St}^{-11}$	$6.2 \cdot 10^{-21}$	$1.4 \cdot 10^{-18}$	
${}^{16}_{2}\text{St}^{-13}$	$2.4 \cdot 10^{-24}$	$1.2 \cdot 10^{-21}$	
${}^{20}_{2}\text{St}^{-16}$	$9.6 \cdot 10^{-31}$	$2.3 \cdot 10^{-27}$	

Production of light nuclei and antinuclei at the AGS

E864 Coll., Phys. Rev. C61 (2000) 064908

data cover 10 oom!

addition of every nucleon

-> penalty factor R_p = 48

but data are at very low pt

use m-dependent slopes following

systematics up to deuteron

-> R_p = 26

GC statistical model:

$$R_p \approx \exp[(m_n \pm \mu_b)/T]$$

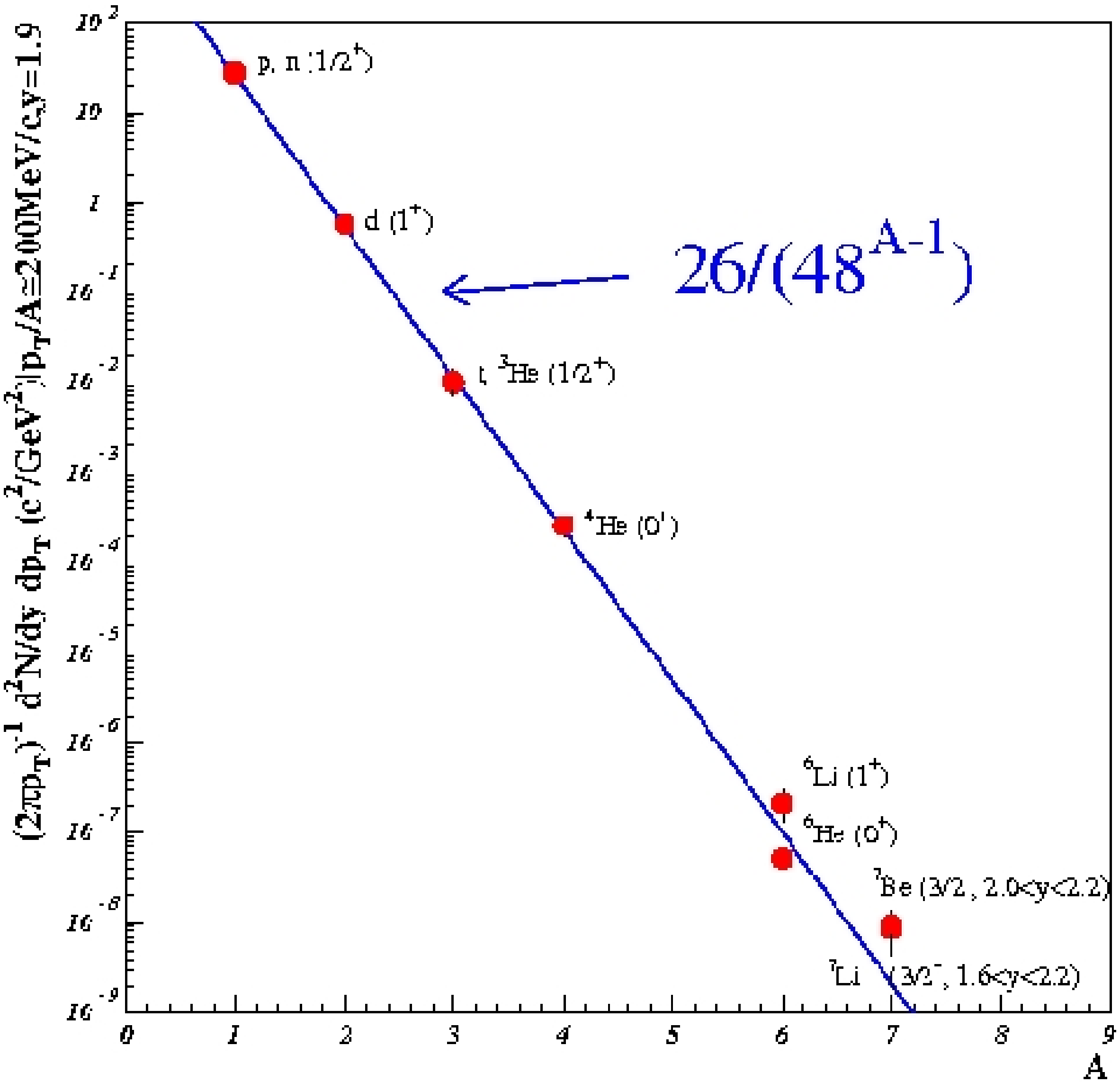
for T=124 MeV and μ_b= 537 MeV

R_p = 24 good agreement

also good for **antideuterons**:

data: $R_p = 2 \pm 1 \cdot 10^5$ SM: $1.3 \cdot 10^5$

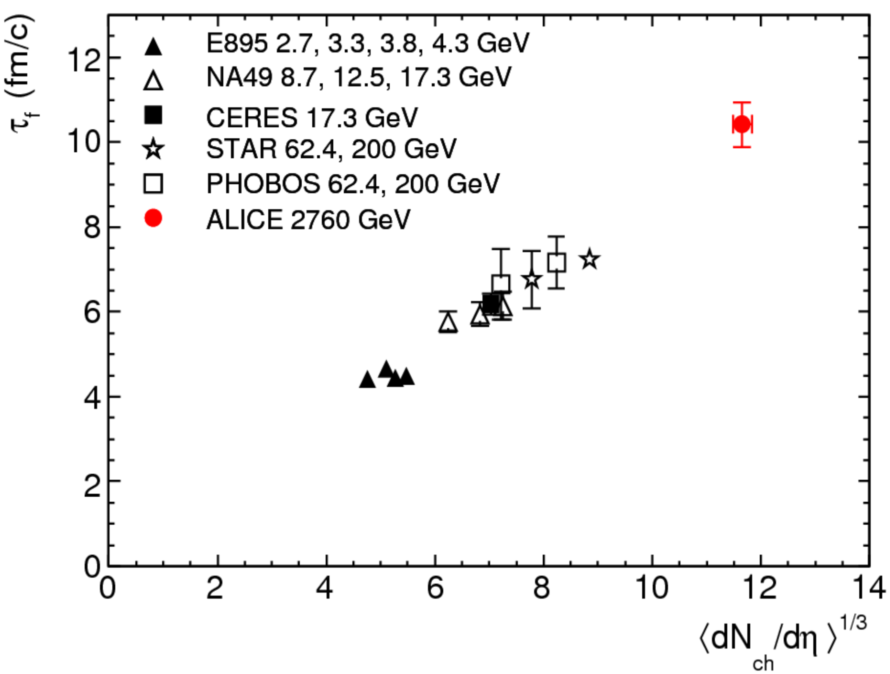
P. Braun-Munzinger, J. Stachel,
J. Phys. G28 (2002) 1971

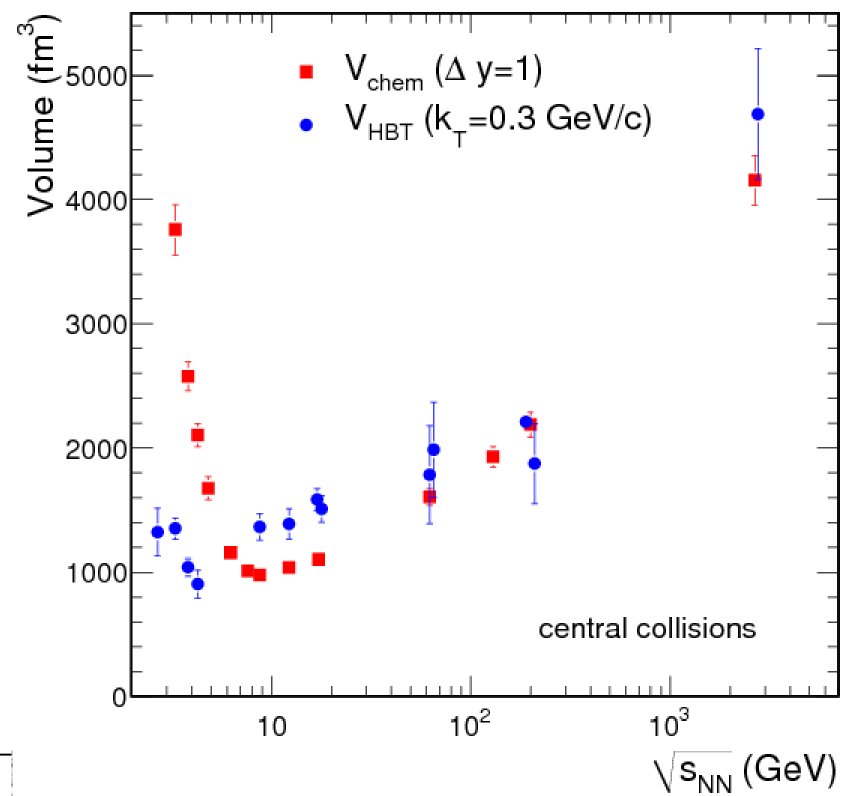


annihilation in hadronic phase

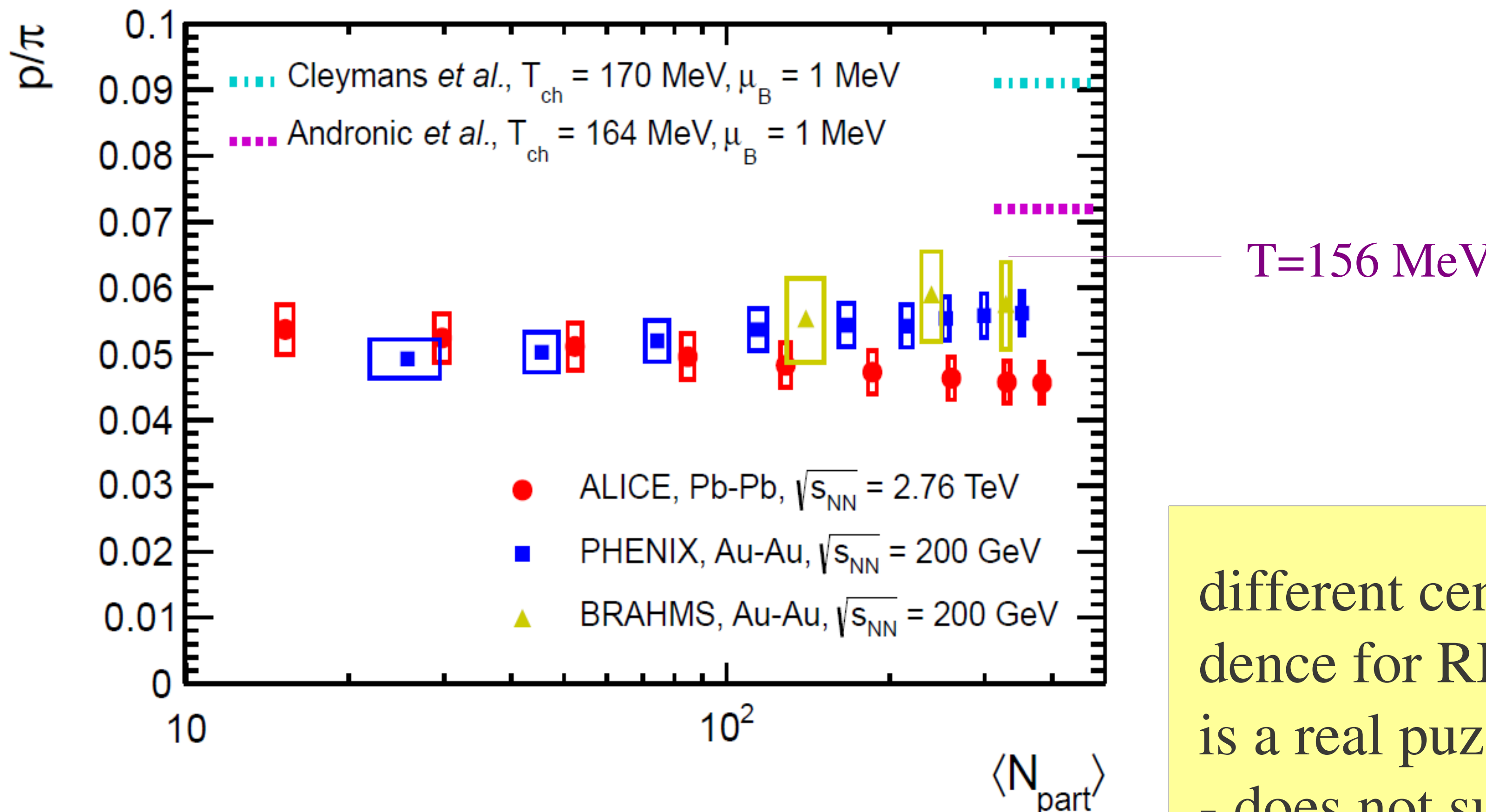
all of this casts serious doubts on the reduction of protons only due to annihilation in hadronic phase

additional argument: in RQMD lifetime of hadronic phase significantly too long (total lifetime of system = 10 fm/c – and volume change between chemical and thermal freeze-out does not allow for longlived hadronic phase)
shorter lifetime reduces effect





Centrality dependence of proton to pion ratio



different centrality dependence for RHIC and LHC is a real puzzle

- does not support annihilation picture
- is it real? physics origin?

Out-of-equlibrium model of hadronization

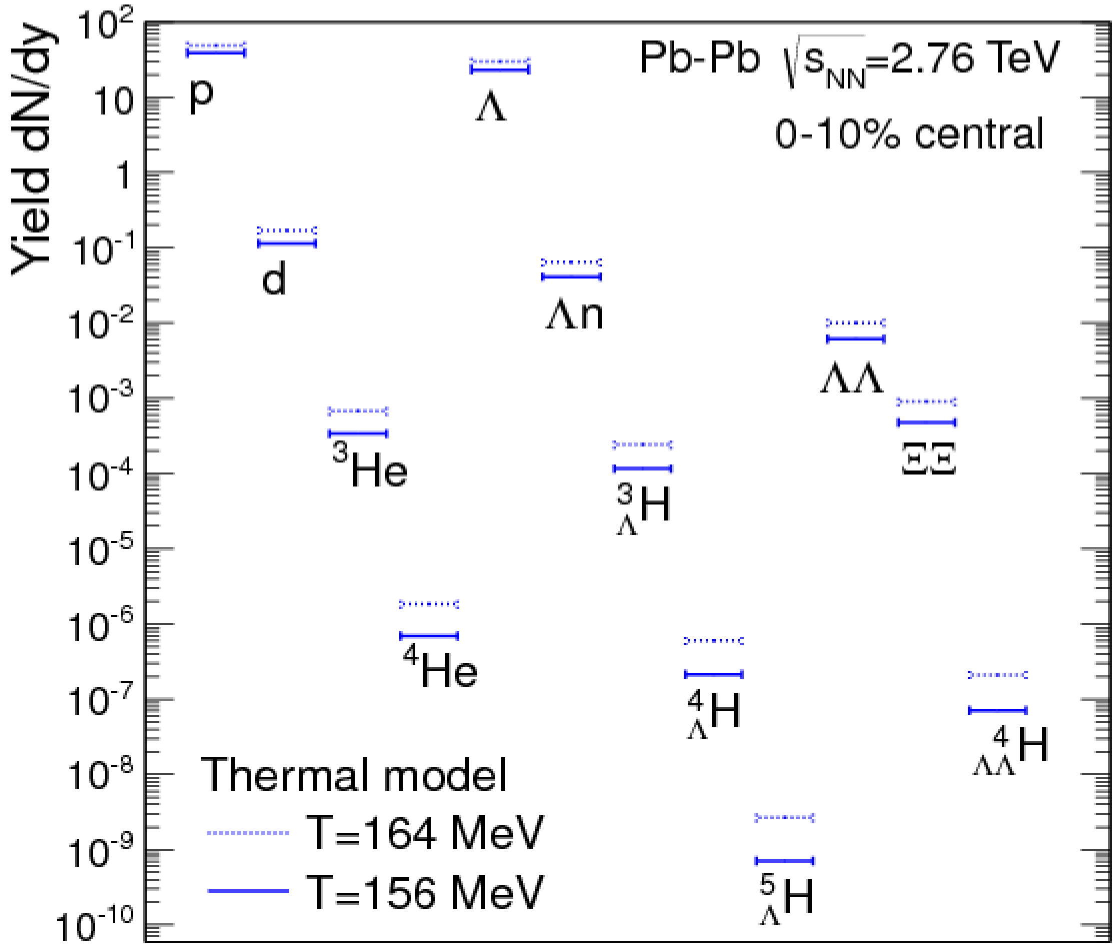
J. Rafelski and collaborators,

→ see talk by M. Petran at this conference

introduction of additional chemical potentials

- systematic variation of parameters with beam energy?
- yield of deuterons prop to γ_q^6 - comparison to data?

Predictions for nuclei and hypernuclei and exotica

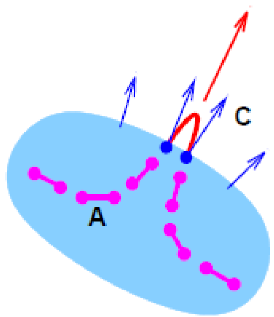


^{3}He and $^{3}{}_{\Lambda}$H and antiparticles soon to be released by ALICE will test statistical hadronization model over another 3 orders of magnitude

Need for additional coalescence mechanism?

Since we argued that coalescence and statistical hadronization are the same for a system in equilibrium, what about the region around 2-6 GeV/c, where coalescence of constituent quarks has been claimed for past 10 years?

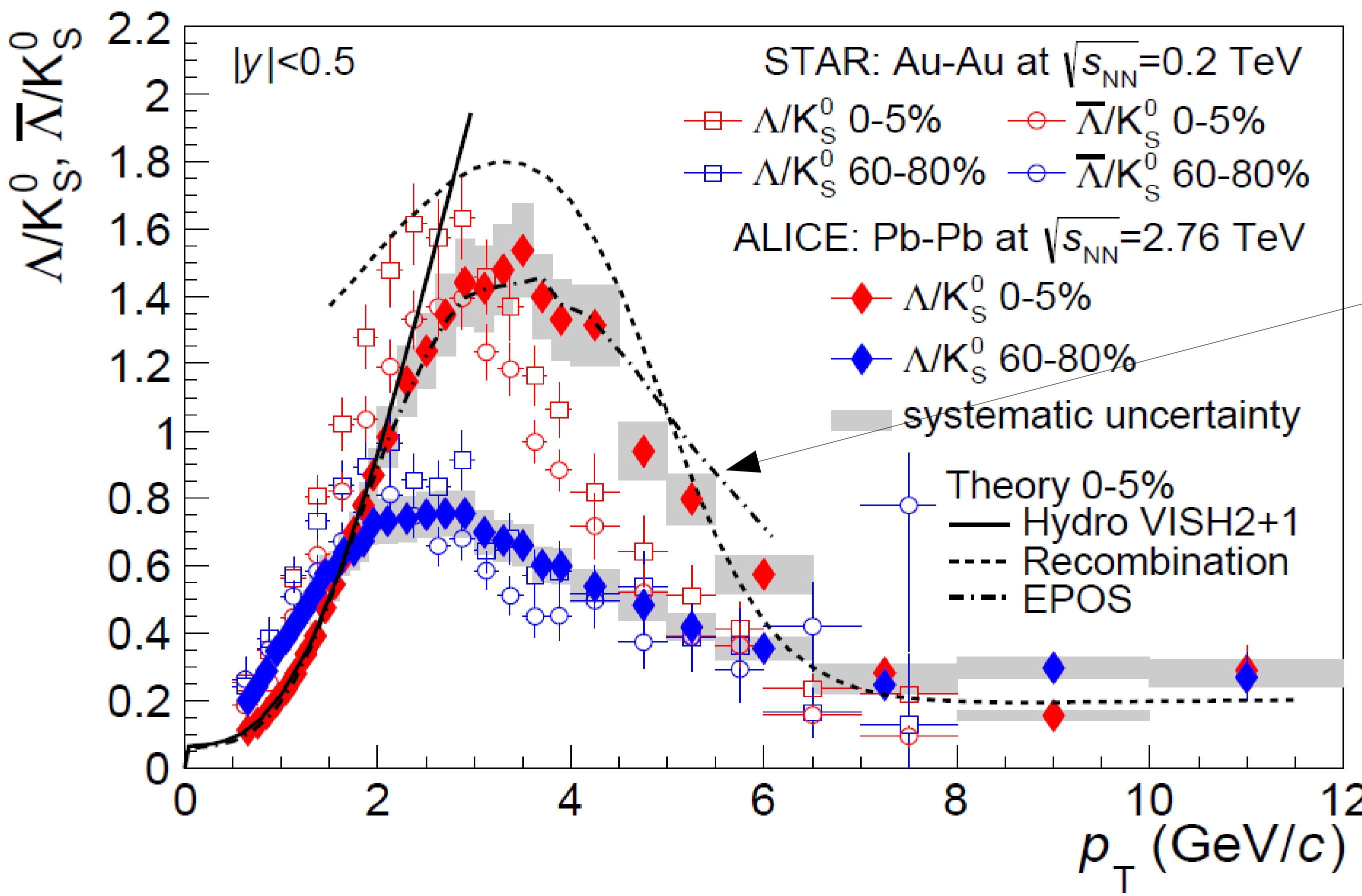
K. Werner and collaborators (see talk at this conference)
Phys. Rev. C85 (2012) 064907 and PRL 109 (2012) 102301



Intermediate p_t region dominated by “jet hadrons”: different formation mechanism from regular string fragmentation
string segments produced inside matter but having enough energy to show up as jets
my understanding: these string segments hadronize statistically inside medium, due to collective expansion they get extra push in transverse momentum
Enhancement of baryons over mesons in intermediate p_t range

Need for additional coalescence mechanism?

new data from ALICE shown at this meeting (B. Hippolyte)
arXiv:1307.5530 [nucl-ex]



peak in Λ/K needs no additional mechanism statistically hadronizing string segments get pushed by collective flow - could be the entire picture

extension of statistical model to include charmed hadrons

- assume: all charm quarks are produced in initial hard scattering; number not changed in QGP
- hadronization at T_c following grand canonical statistical model used for hadrons with light valence quarks

number of charm quarks fixed by a charm-balance equation containing fugacity g_c

$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm}) + g_c^2 V (\sum_i n_{\psi_i}^{therm}) + \ldots$$

and for $N_{c,\bar{c}} << 1 \rightarrow$ canonical: $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{therm} \frac{I_1(g_c N_{oc}^{therm})}{I_0(g_c N_{oc}^{therm})}$

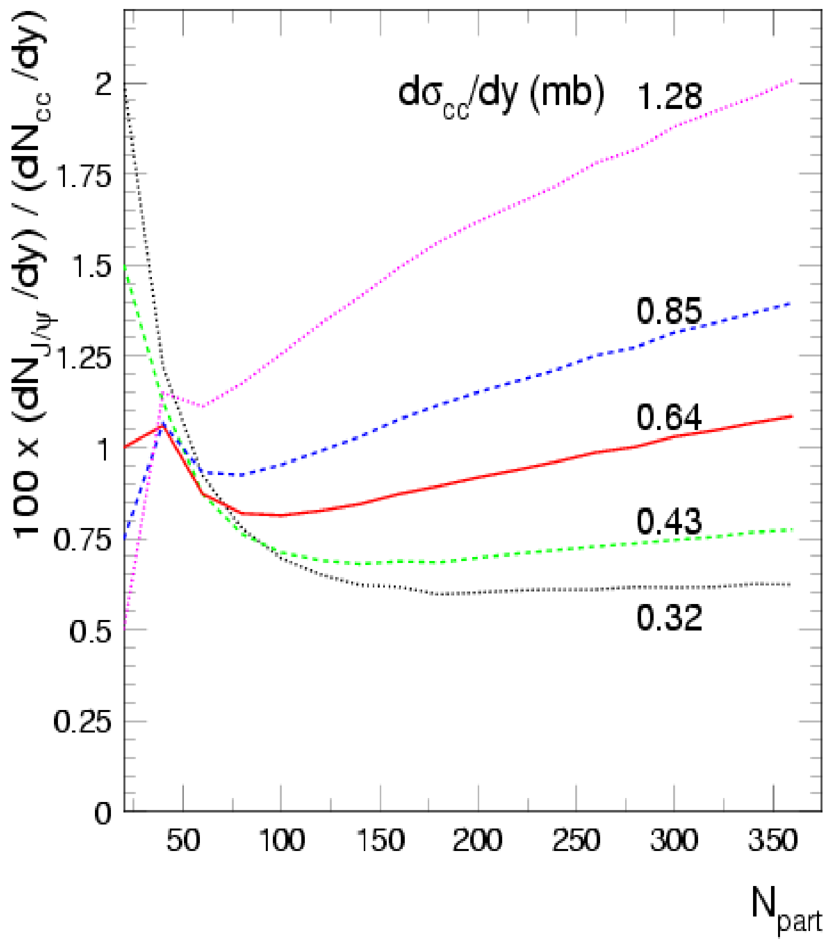
obtain: $N_D = N_D^{therm} \cdot g_c \cdot \frac{I_1}{I_0}$ and $N_{J/\psi} = N_{J/\psi}^{therm} \cdot g_c^2$ and same for all other charmed hadrons

additional input parameters: $V, N_{c\bar{c}}^{direct}$

Volume fixed by $dN_{ch}/d\eta$

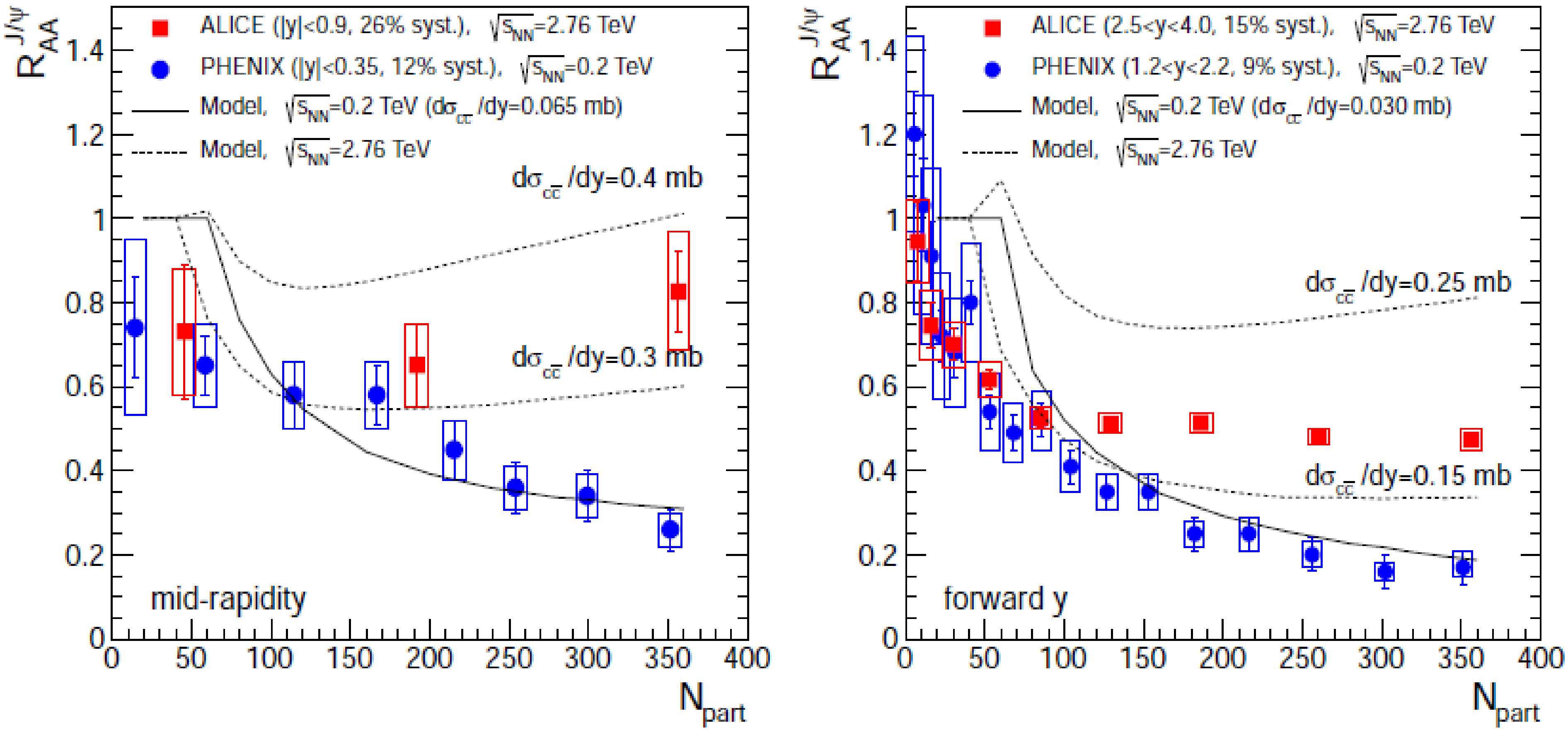
$N_{c\bar{c}}^{direct}$ from pQCD as long as precision data are lacking

Predictions for LHC energies



A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259

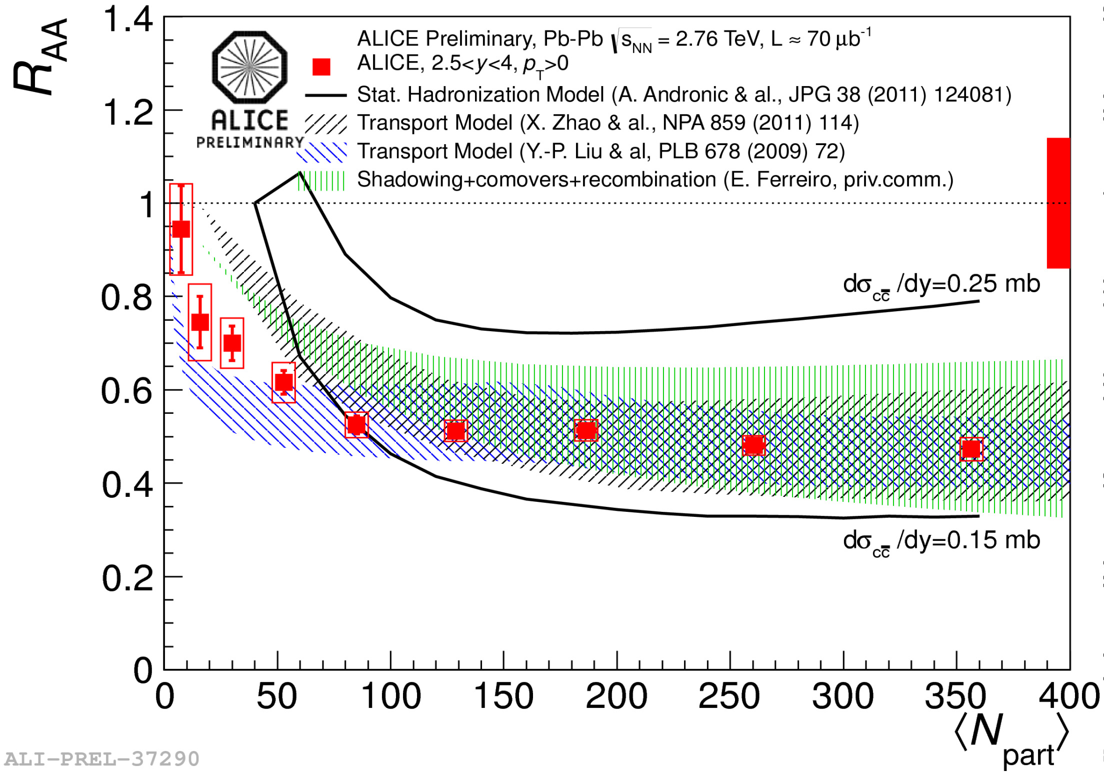
J/psi and Statistical Hadronization at LHC

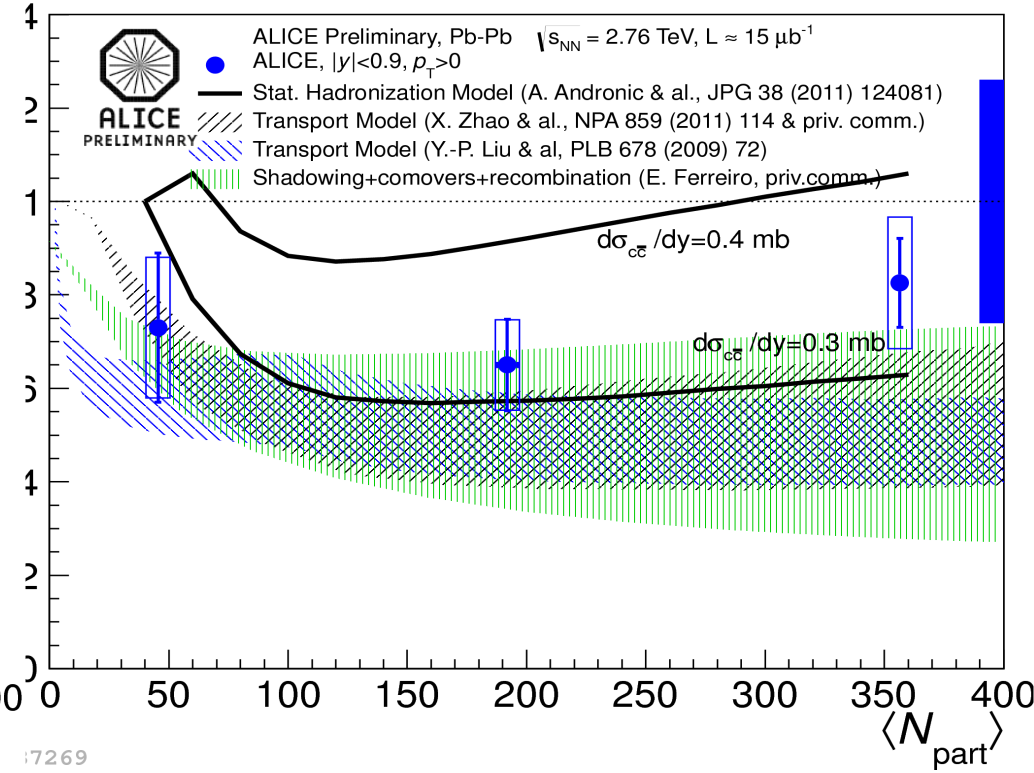


in AA collisions: strong indication of J/ψ regeneration

- production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
- main uncertainties for models: open charm cross section, shadowing in Pb
- need to precisely measure charm cross section in PbPb and pPb collisions

J/psi and transport models (and stat hadronization)



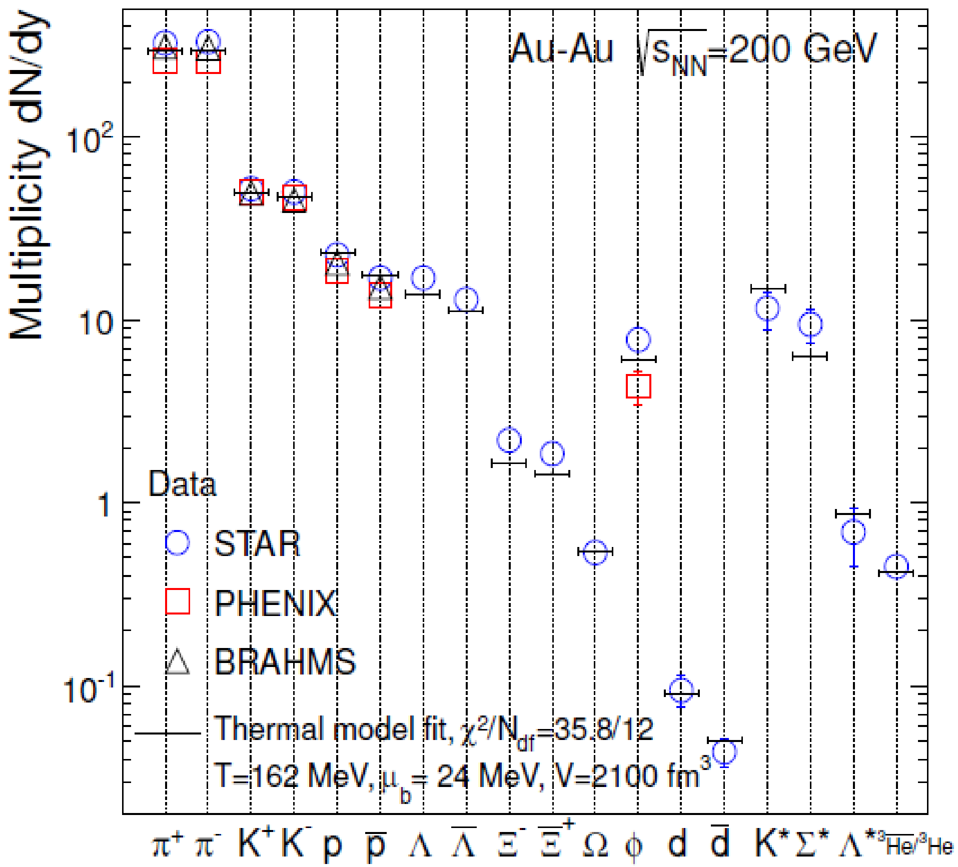


in AA collisions: strong indication of J/ψ regeneration

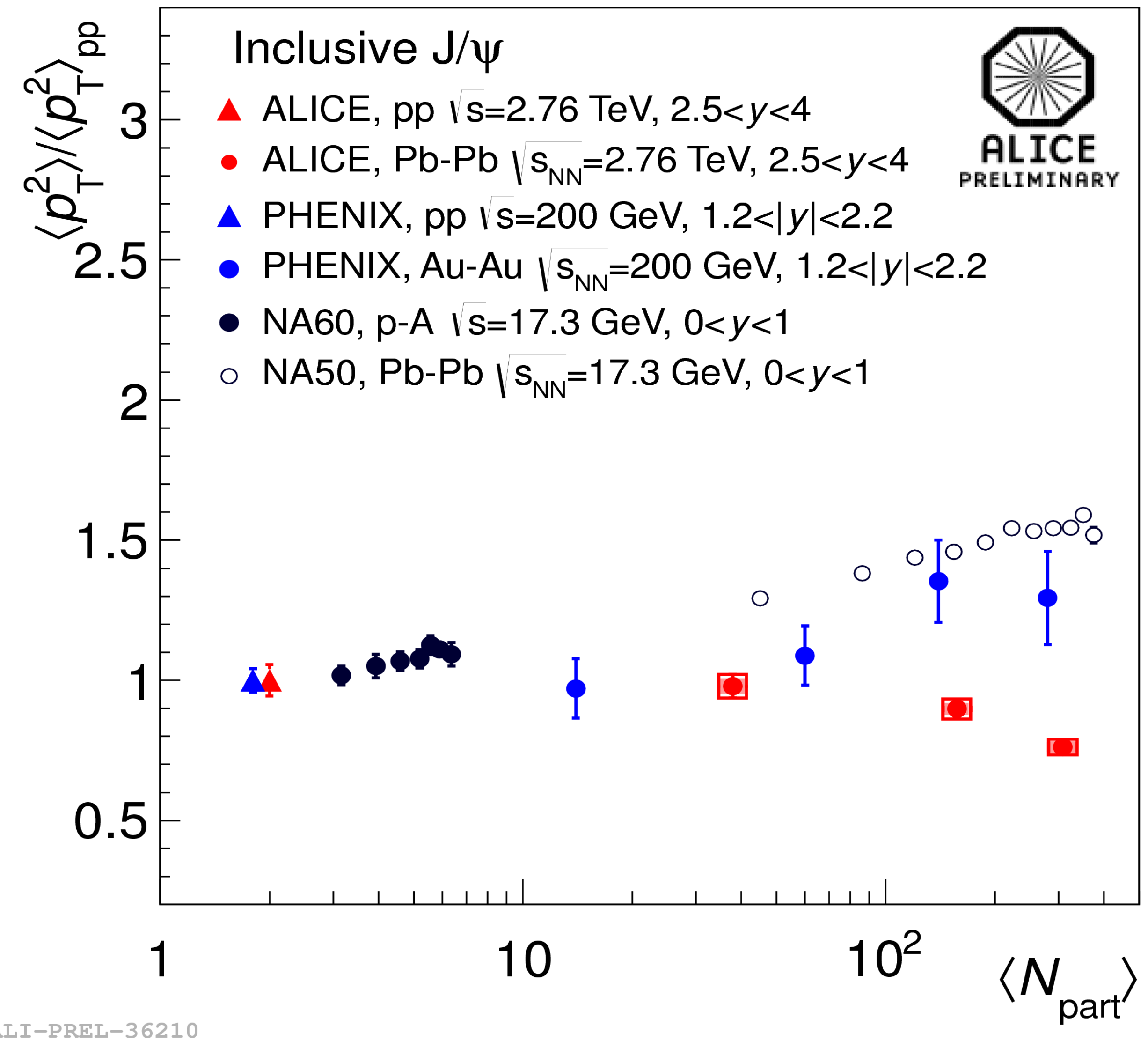
- statistical hadronization model and transport models well in line with R_{AA}
- distinction can come from
  - more precise data (coming very soon)
  - measurement of excited states

backup

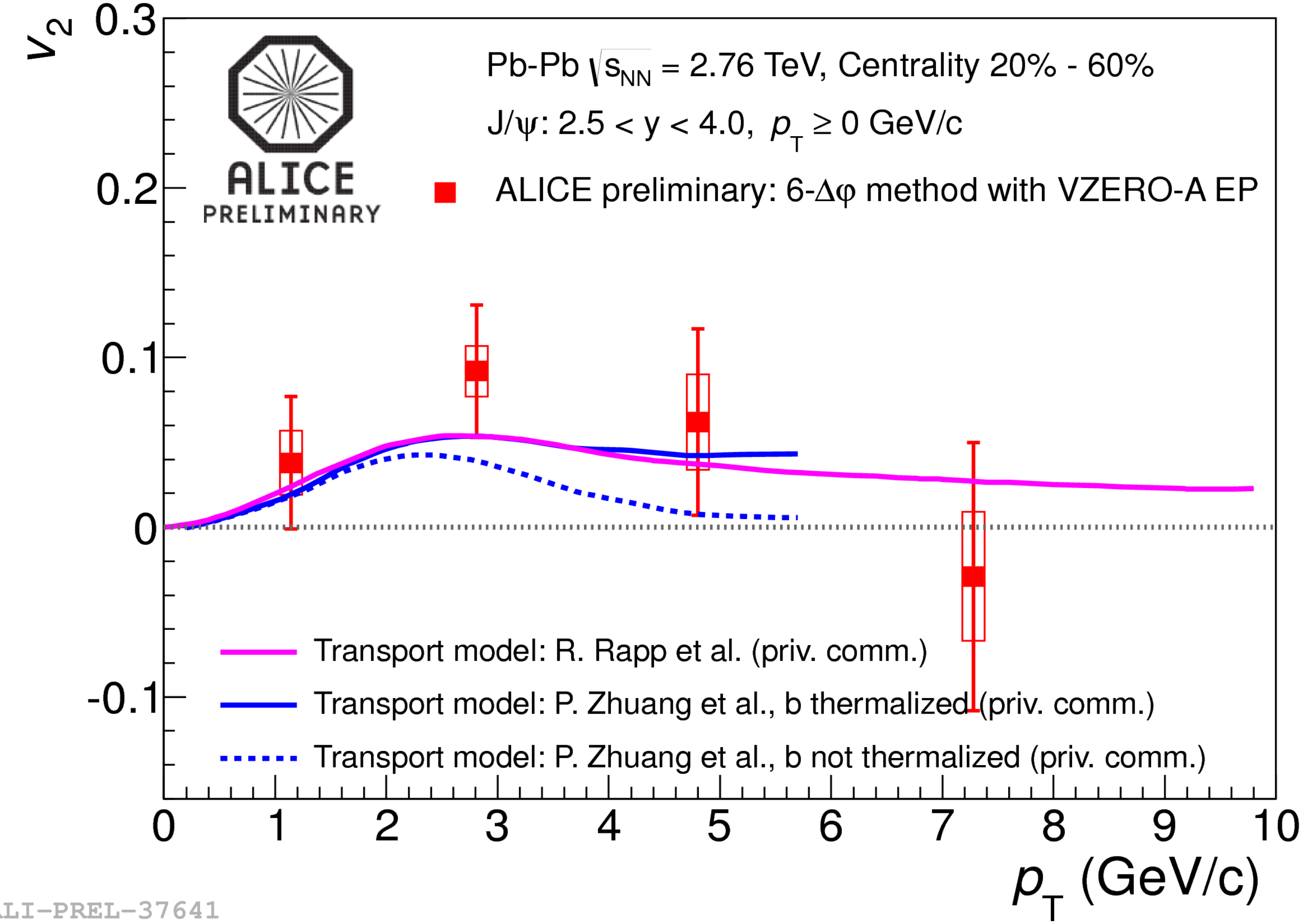
Latest statistical model fit to all RHIC data



Evolution of J/psi pt spectra – evidence for thermalization and charm quark coalescence at the phase boundary



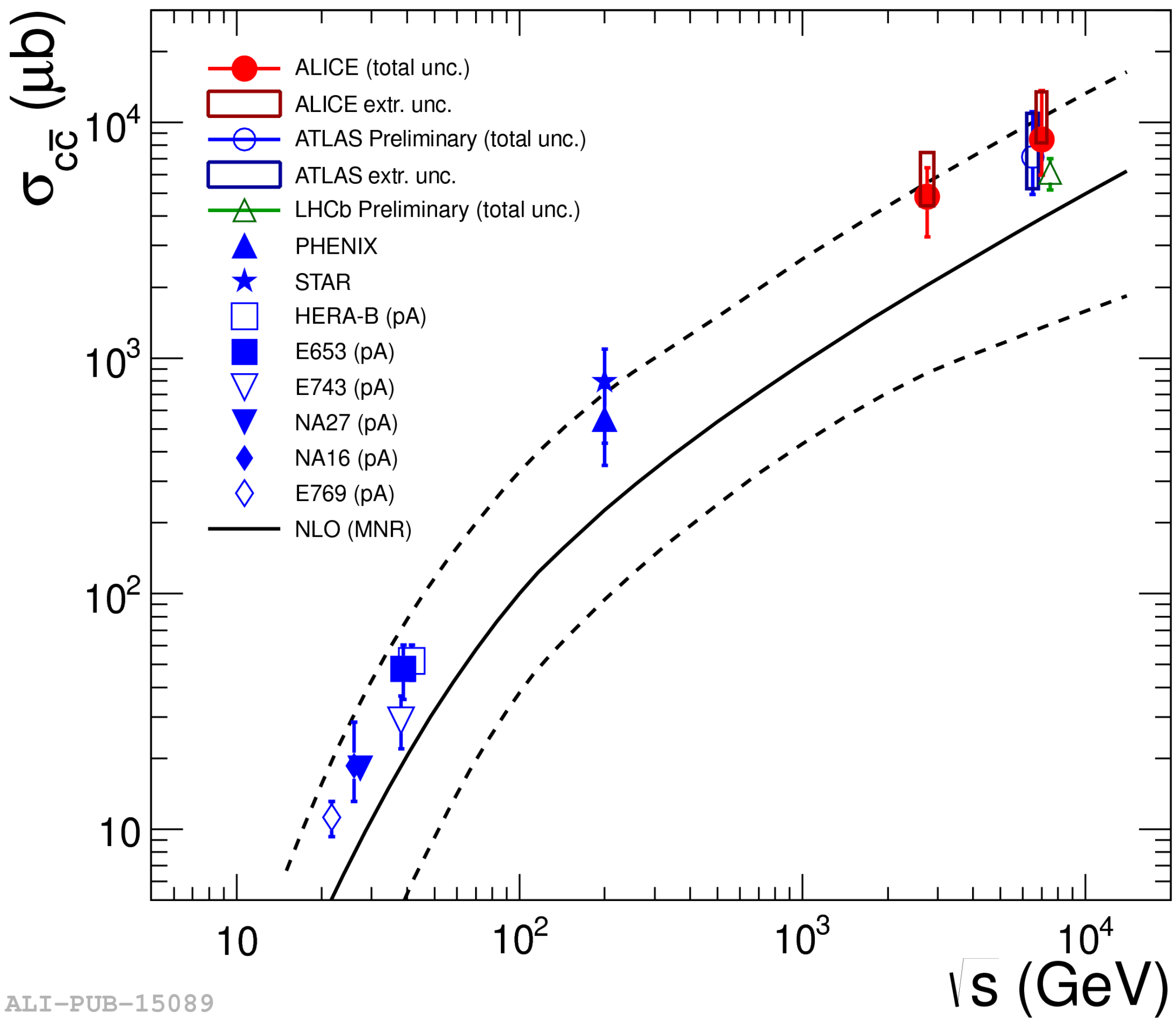
J/psi flow compared to models including (re-) generation



v_2 of J/ψ consistent with hydrodynamic flow of charm quarks in QGP and statistical (re-)generation

a first try at the total ccbar cross section in pp collisions

JHEP 1207 (2012) 191



- good agreement between ALICE, ATLAS and LHCb
- large syst. error due to extrapolation to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL
- soon more accurate 4pi extrapolation at 7 TeV