Statistical hadronization at the QGP phase boundary

Outline:
- hadron yields and statistical model from AGS to LHC
- (anti-)nuclei
- connection to phase boundary
- charmonia

Johanna Stachel, Physikalisches Institut, U. Heidelberg
QCD Thermodynamics – pressure and passion, Schloss Waldthausen
August 24-26, 2016

EMMI
ISOQUANT SFB1225
RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG

this talk was supposed to be given by K. Redlich who has not recovered yet enough from surgery - but too important to leave out if one wants to honor Peters contributions to physics

1. **Hadron production in Au - Au collisions at RHIC**

(606) P. Braun-Munzinger, D. Magestro (Darmstadt, GSI), K. Redlich (Darmstadt, GSI & Wroclaw U.), J. Stachel (Heidelberg U.). May 2001. 10 pp.
Published in **Phys.Lett. B518 (2001) 41-46**
GSI-2001-15
DOI: 10.1016/S0370-2693(01)01069-3
e-Print: **hep-ph/0105229** | PDF

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Detailed record - Cited by 606 records 500+

2. **Chemical equilibration in Pb + Pb collisions at the SPS**

(555) P. Braun-Munzinger (Darmstadt, GSI), I. Heppe, J. Stachel (Heidelberg U.). Mar 1999. 12 pp.
Published in **Phys.Lett. B465 (1999) 15-20**
DOI: 10.1016/S0370-2693(99)01076-X
e-Print: **nucl-th/9903010** | **PDF**

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Detailed record - Cited by 555 records 500+

3. **Thermal equilibration and expansion in nucleus-nucleus collisions at the AGS**

(508) P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu (SUNY, Stony Brook). Oct 1994. 13 pp.
Published in **Phys.Lett. B344 (1995) 43-48**
SUNY-RHI-94-11
DOI: 10.1016/0370-2693(94)01534-J
e-Print: **nucl-th/9410026** | PDF

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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Detailed record - Cited by 508 records 500+

4. **Hadron production in central nucleus-nucleus collisions at chemical freeze-out**

(504) A. Andronic, P. Braun-Munzinger (Darmstadt, GSI), J. Stachel (Heidelberg U.). Nov 2005. 31 pp.
Published in **Nucl.Phys. A772 (2006) 167-199**
DOI: 10.1016/j.nuclphysa.2006.03.012
e-Print: **nucl-th/0511071** | PDF

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Detailed record - Cited by 504 records 500+

about 5000 citations for the most important papers

1. **Hadron production in central nucleus-nucleus colli**
A. Andronic, P. Braun-Munzinger (Darmstadt, GSI), J. Stachel (Hei
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e-Print: **hep-ph/0105229** | PDF
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DOI: 10.1016/0370-2693(94)01534-J
e-Print: **nucl-th/9410026** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | E
ADS Abstract Service
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1. **Particle production in heavy ion collisions**
(452) Peter Braun-Munzinger (Darmstadt, GSI), Krzysztof Redlich (Bielefeld U. & Wroclaw U.), Johanna Stachel (Heidelb
Published in **In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 491-599**
GSI-PREPRINT-2003-13
e-Print: **nucl-th/0304013** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; CERN Library Record
Detailed record - Cited by 452 records 250+

2. **Thermal and hadrochemical equilibration in nucleus-nucleus collisions at the SPS**
(431) P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu (SUNY, Stony Brook). Aug 1995. 14 pp.
Published in **Phys.Lett. B365 (1996) 1-6**
SUNY-RHI-95-8
DOI: 10.1016/0370-2693(95)01258-3
e-Print: **nucl-th/9508020** | PDF
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ADS Abstract Service
Detailed record - Cited by 431 records 250+

3. **(Non)thermal aspects of charmonium production and a new look at J / psi suppression**
(409) P. Braun-Munzinger (Darmstadt, GSI), J. Stachel (Heidelberg U.). Jul 2000. 12 pp.
Published in **Phys.Lett. B490 (2000) 196-202**
DOI: 10.1016/S0370-2693(00)00991-6
e-Print: **nucl-th/0007059** | PDF
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CERN Document Server; ADS Abstract Service
Detailed record - Cited by 409 records 250+

4. **Heavy Ion Collisions at the LHC - Last Call for Predictions**
(306) N. Armesto (ed.) (UC, Davis & LLNL, Livermore) *et al.*. Nov 2007. 185 pp.
Published in **J.Phys. G35 (2008) 054001**
DOI: 10.1088/0954-3899/35/5/054001
Presented at Conference: C07-05-14.6
e-Print: **arXiv:0711.0974 [hep-ph]** | **PDF**
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CERN Document Server ; CERN Document Server ; CERN Document Server ; CERN Document Server ; CE
Document Server ; CERN Document Server ; CERN Document Server ; CERN Document Server ; CERN Do
Service
Detailed record - Cited by 306 records 250+

5. **Thermal hadron production in relativistic nuclear collisions: The Hadron mass spectrum**
(278) A. Andronic (Darmstadt, GSI), P. Braun-Munzinger (Darmstadt, GSI & Darmstadt, Tech. Hochsch.), J. Stachel (Hei
Published in **Phys.Lett. B673 (2009) 142-145**, Erratum: **Phys.Lett. B678 (2009) 516**
DOI: 10.1016/j.physletb.2009.06.021, 10.1016/j.physletb.2009.02.014
e-Print: **arXiv:0812.1186 [nucl-th]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

First steps in 1989

Pions from resonance decay
in Brookhaven relativistic heavy-ion collisions ☆

G.E. Brown, J. Stachel and G.M. Welke
Physics Department, State University of New York at Stony Brook, Stony Brook, NY 11794-3800, USA

Received 21 September 1990 PLB 253 (1991) 19

$$\frac{\rho_i}{\rho_t} = \frac{1}{\rho_t}\frac{g_i}{2\pi^2}\int_0^\infty \mathrm{d}p \frac{p^2}{\exp[\beta(\epsilon_i-\mu)]+1}$$

at Peters suggestion we set out to calculate the pion spectrum with decay contributions from nucleon resonances
'cool pions from hot nucleons'
and got good agreement for
T ≈ 150 MeV

State	J^P	g_i	$(g_i e^{-\epsilon_i/T})/Z$	ρ_i/ρ_t
p, n	$\frac{1}{2}^+$	4	0.546	0.424
N(1440)	$\frac{1}{2}^+$	4	0.019	0.026
N(1520)	$\frac{3}{2}^-$	8	0.023	0.033
N(1535)	$\frac{1}{2}^-$	4	0.010	0.015
N(1650)	$\frac{1}{2}^-$	4	0.005	0.008
N(1675)	$\frac{5}{2}^-$	12	0.012	0.020
N(1680)	$\frac{5}{2}^+$	12	0.012	0.020
N(1700)	$\frac{3}{2}^-$	8	0.007	0.012
N(1710)	$\frac{1}{2}^+$	4	0.003	0.005
N(1720)	$\frac{3}{2}^+$	8	0.006	0.010
Δ(1230)	$\frac{3}{2}^+$	16	0.310	0.342
Δ(1620)	$\frac{1}{2}^-$	8	0.012	0.019
Δ(1700)	$\frac{3}{2}^-$	16	0.014	0.023
Δ(1900)	$\frac{1}{2}^-$	8	0.002	0.004
Δ(1905)	$\frac{5}{2}^-$	24	0.005	0.010
Δ(1910)	$\frac{1}{2}^+$	8	0.002	0.003
Δ(1920)	$\frac{3}{2}^+$	16	0.003	0.006
Δ(1930)	$\frac{5}{2}^-$	24	0.004	0.009
Δ(1950)	$\frac{7}{2}^+$	32	0.005	0.011

and even earlier some thoughts in that direction ...

VIEW C VOLUME 37, NUMBER 5

Detailed balance description of energetic photons in heavy-ion collisions

M. Prakash, P. Braun-Munzinger, and J. Stachel
Physics Department, State University of New York at Stony Brook, Stony Brook, New York 11794

N. Alamanos
Centre d'Etudes Nucléaires de Saclay, Service de Physique Nucléaire a Basse Énergie, Saclay, F-91191, Gif-sur-Yvette, Cedex, France

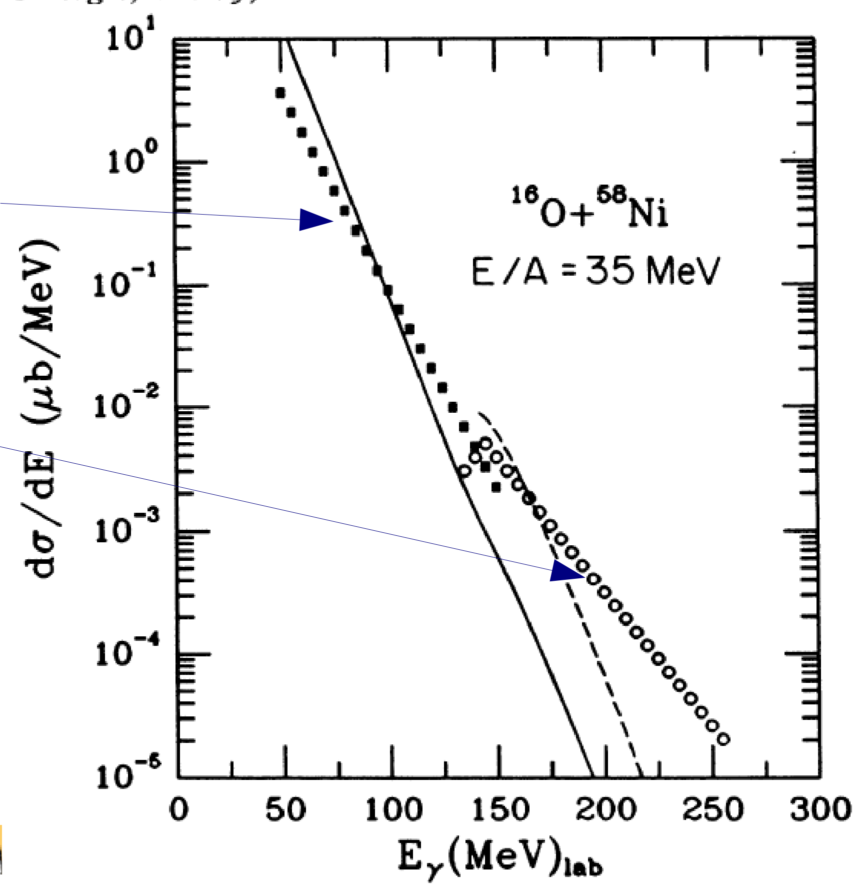
(Received 22 December 1987)

photons

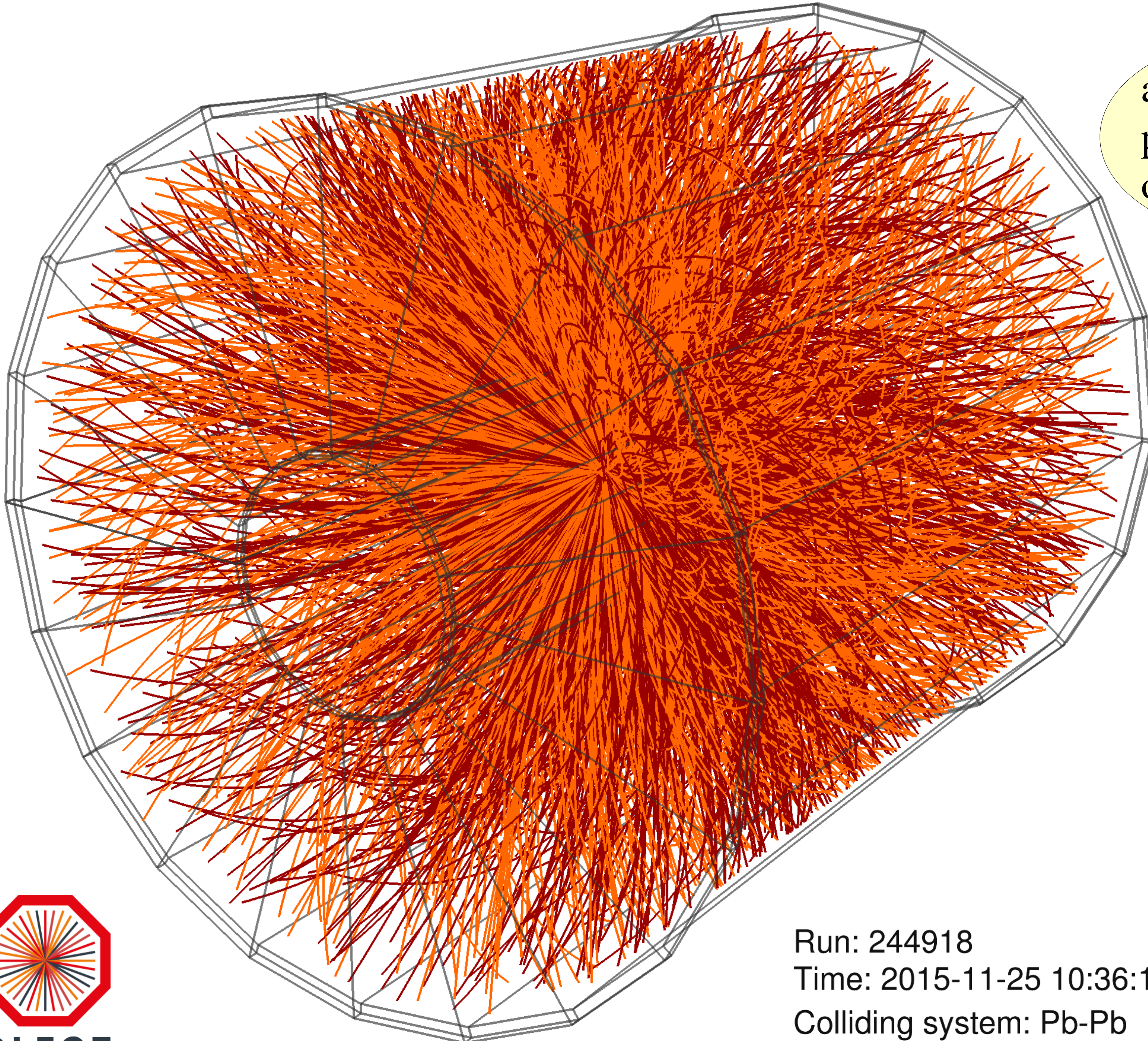
and

pions

emitted from a fireball
at a given excitation energy



a central PbPb collision at LHC at $\sqrt{s}$ = 5.02 A TeV



about 3500 charged particles in 1.8 units of pseudorapidity

what are these particles and how can we understand the hadro-chemical composition?

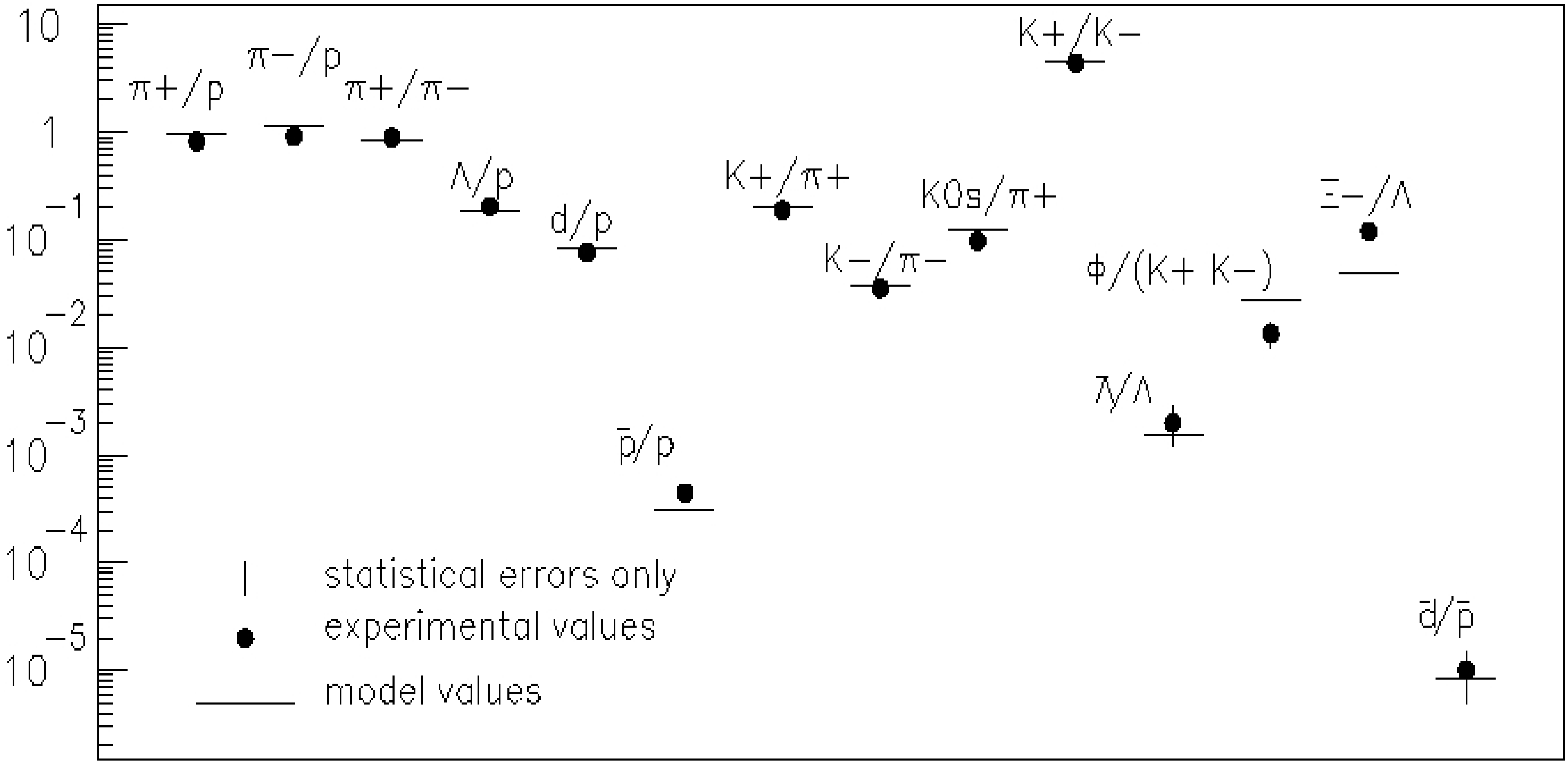
Run: 244918
Time: 2015-11-25 10:36:18
Colliding system: Pb-Pb
Collision energy: 5.02 TeV

ALICE

first successful application of thermal model - AGS data

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

P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, PLB344 (1995) 43



dynamic range: 9 orders of magnitude! No deviation

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

For a review see: Braun-Munzinger, Redlich, Stachel, QGP3,
R. Hwa ed. (Singapore 2004) 491-599; nucl-th/0304013

implementation of our statistical model

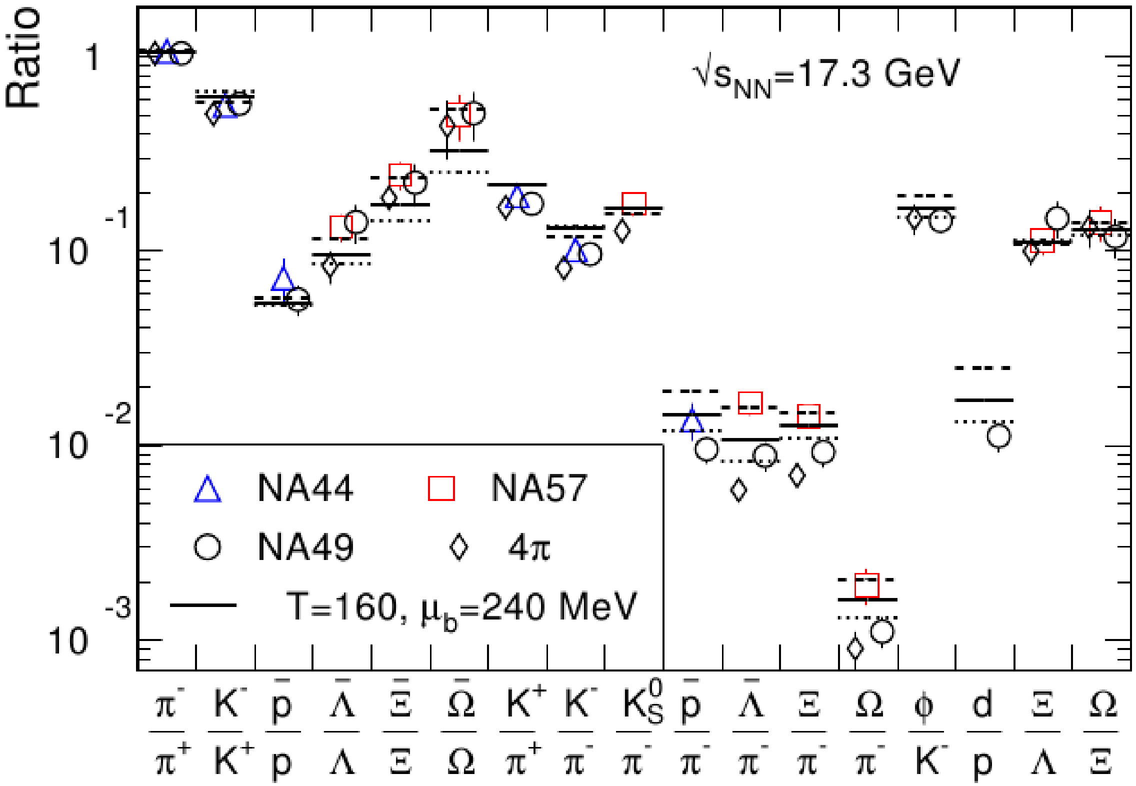
in total 426 hadrons and composites (nuclei etc.) included – all states considered confirmed by PDG - precision of e+e- data and LHC data requires this

finite volume correction (Balian and Bloch)

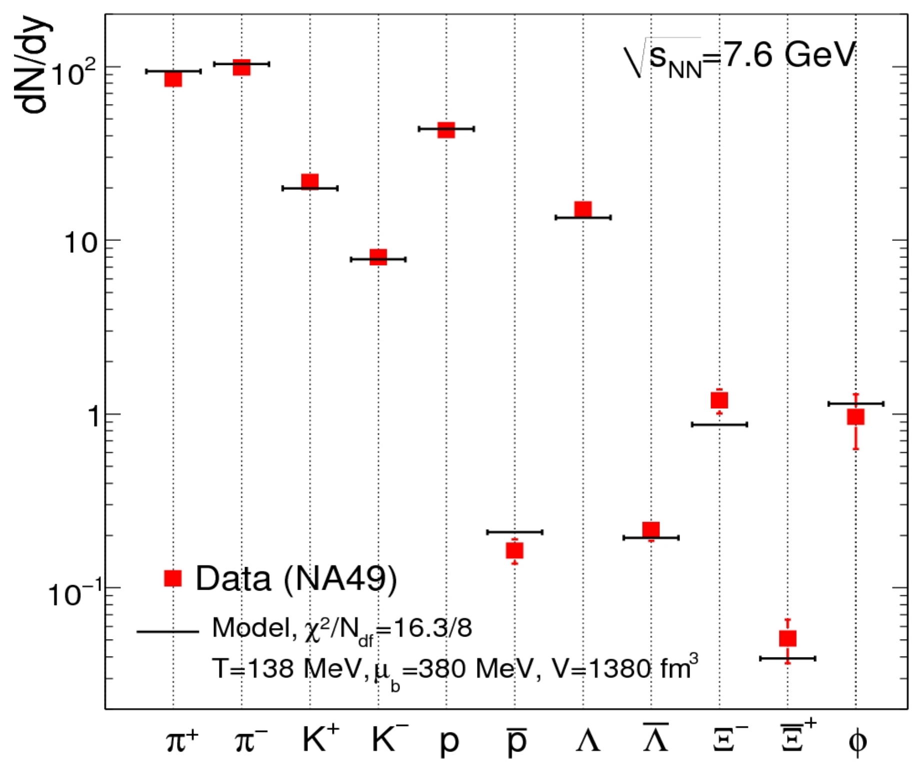
interactions as van der Waals gas via excluded volume
(following Rischke, Gorenstein, Stoecker, Greiner, 1991)
standard: r=0.3 fm, systematic checks r = 0 – 0.5 fm

for inclusion of charm-quarks canonical correction factors
following Redlich et al.

SPS Pb + Pb data and thermal model



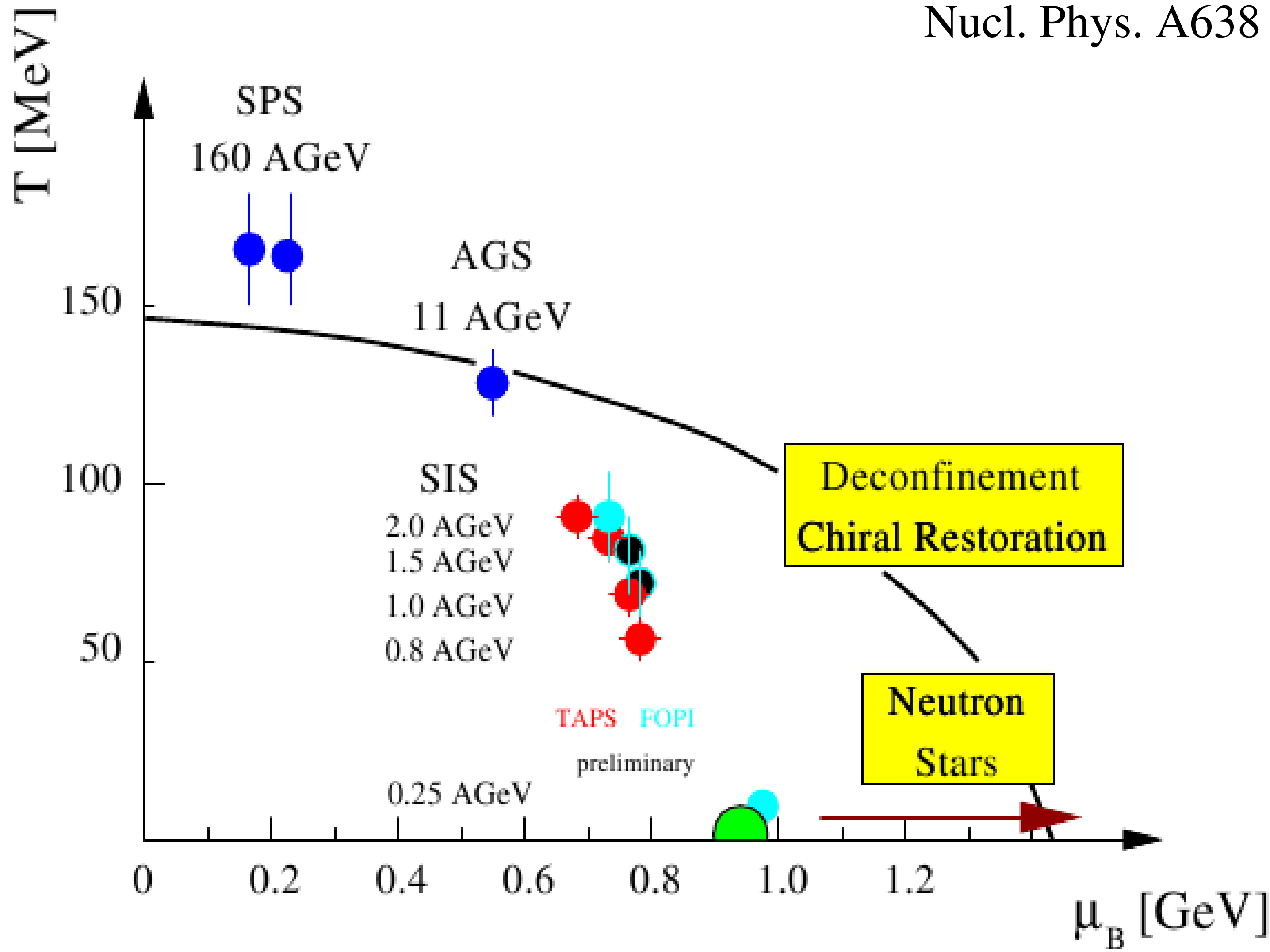
full energy – largest amount of data but also some problems in data revealed



figures from A. Andronic, P. Braun-Munzinger, J.S. Nucl. Phys. A772 (2006) 167

leading to the first phase diagram with experimental points

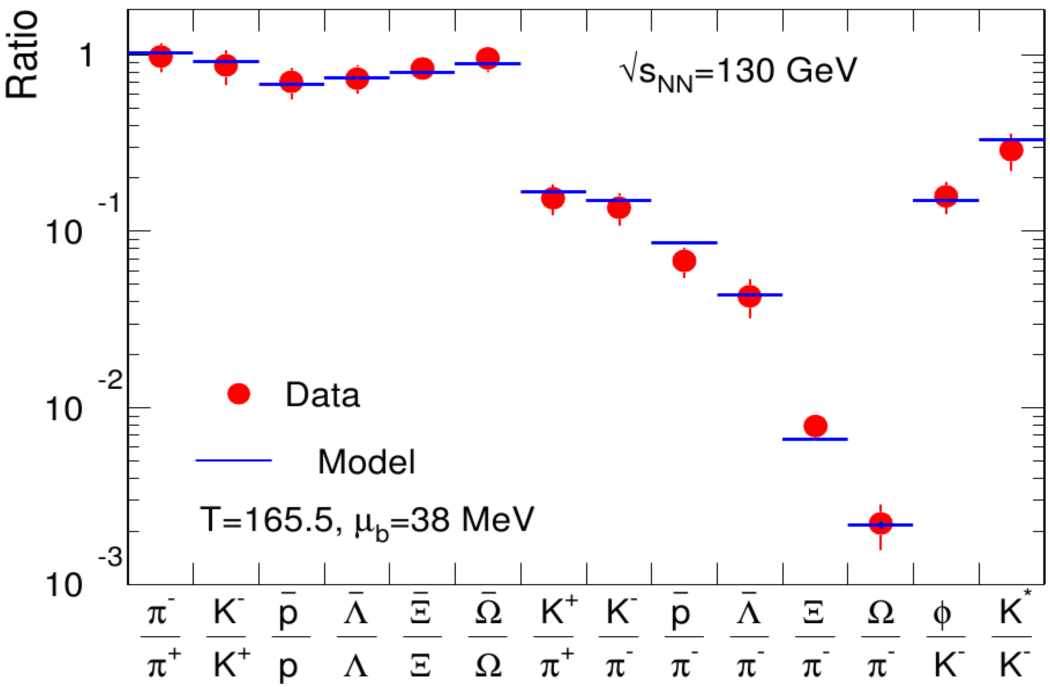
P.Braun-Munzinger and J. Stachel, nucl-th/9803015, Nucl. Phys. A638 (1998) 3

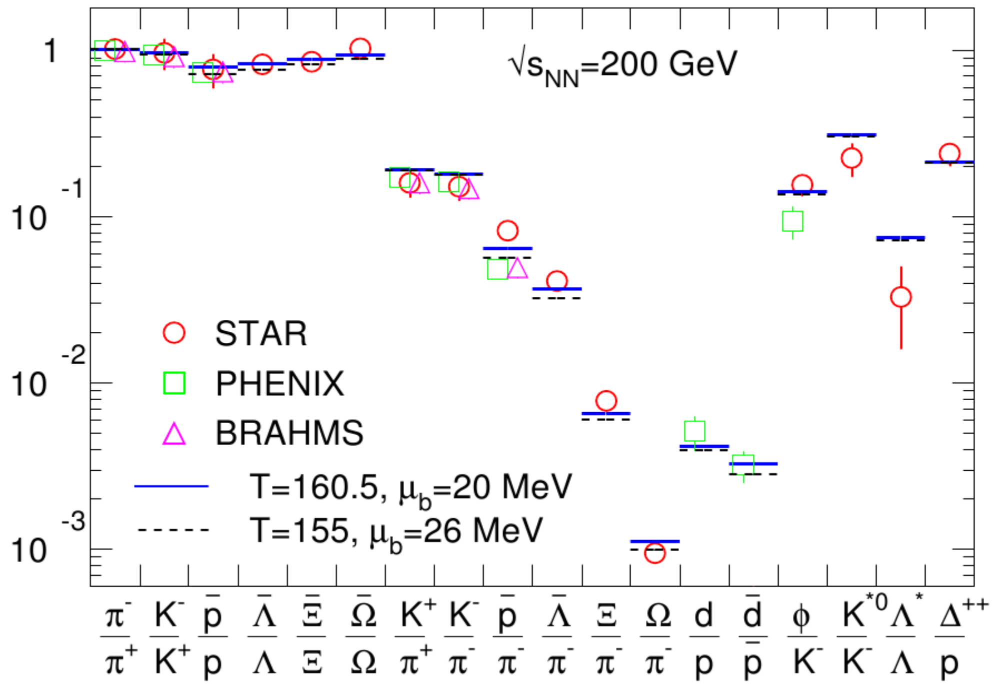


RHIC hadron yields reproduced really well compared to statistical model (GC)

130 GeV data in excellent agreement with thermal model predictions

prel. 200 GeV data fully in line still some experimental discrepancies

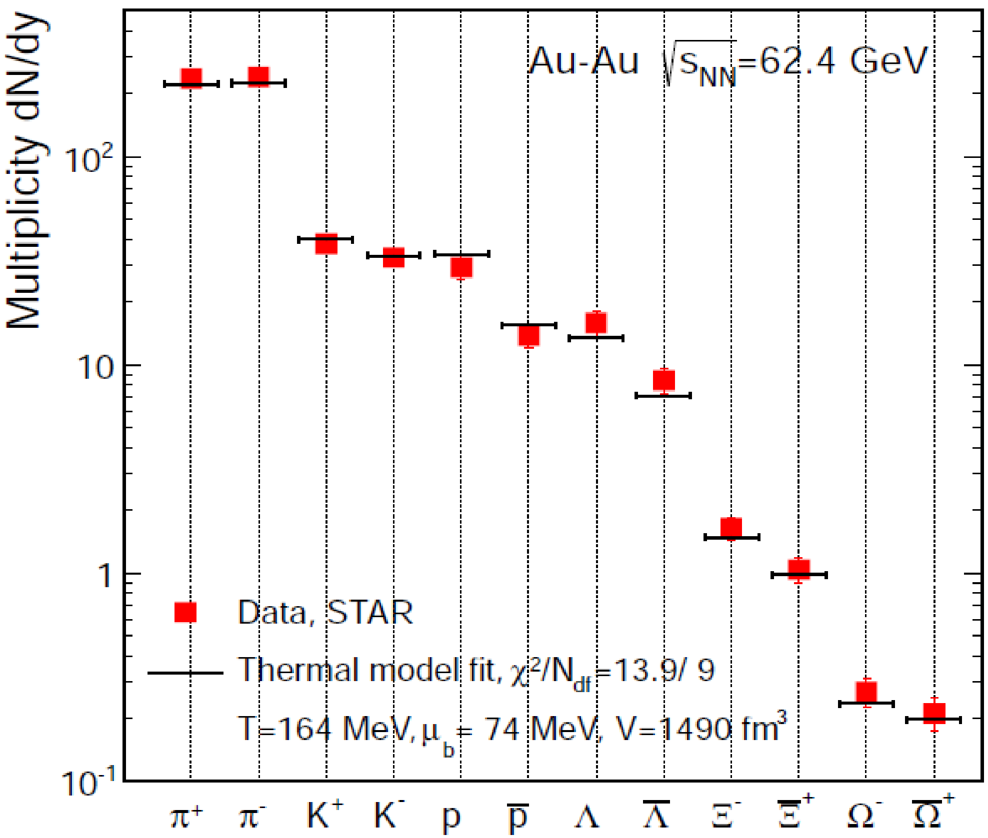




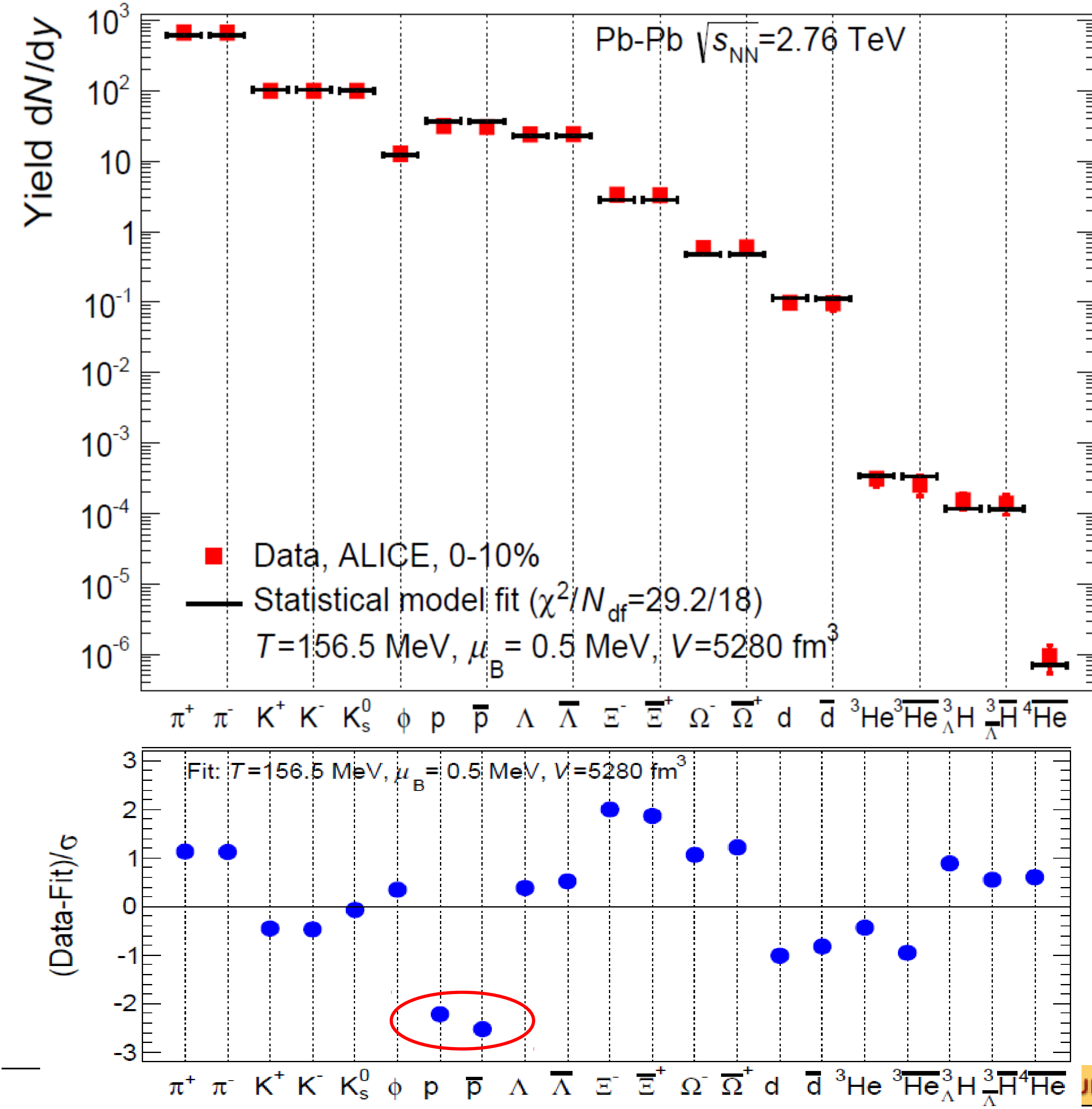
chemical freeze-out at: $T = 165 \pm 5$ MeV

P. Braun-Munzinger, D. Magestro, K. Redlich, J. Stachel, Phys. Lett. B518 (2001) 41
A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772 (2006) 167
confirmed by Xu and Kaneta and by F. Becattini

lower RHIC energies, - STAR data only



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

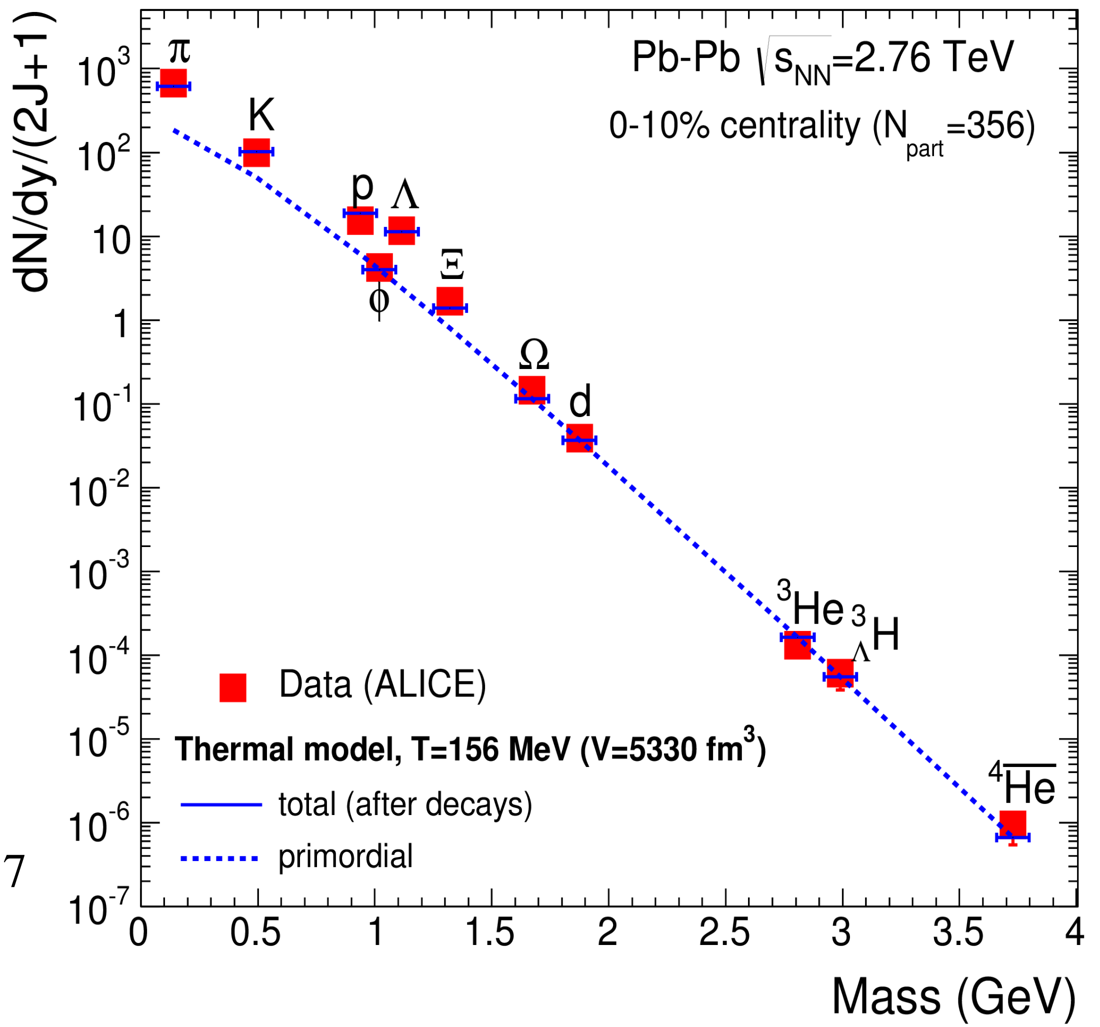


as compared to 2012 1rst fit:
more and final data
T went from 152 to 156 MeV
red. χ^2 went from 1.62

protons low by 2.7 σ
wo. protons red. χ^2 = 1.0
various explanation attempts failed; maybe wait for 5 TeV data

Quark- hadron duality

agreement over 9 orders of magnitude with QCD statistical operator prediction
(- strong decays need to be added)



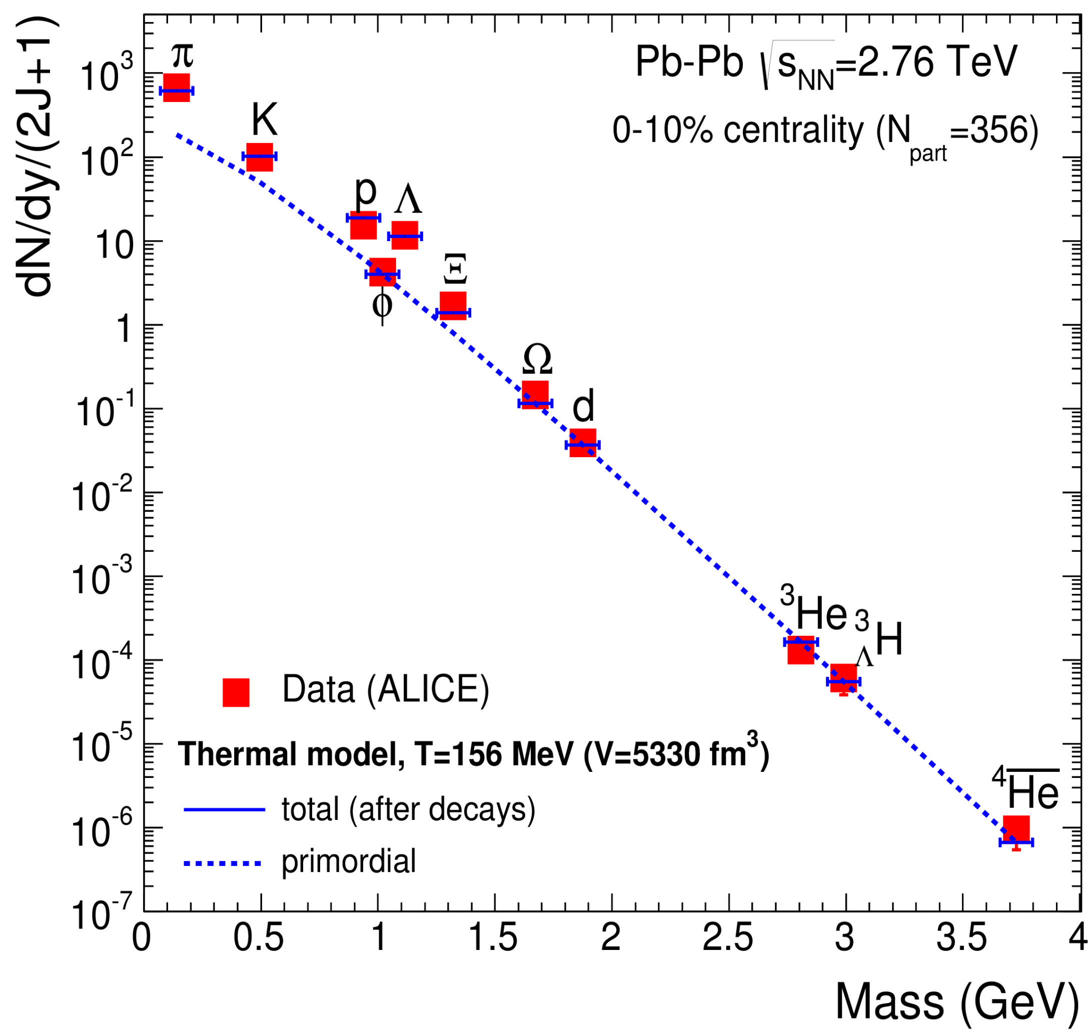
works equally well for nuclei and loosely bound (anti)hyper-nuclei

prediction P. Braun-Munzinger, J.S., J.Phys. G28 (2002) 1971-1976, J.Phys. G21 (1995) L17

strong indication of isentropic expansion in hadronic phase

Loosely bound states in PbPb collisions

PbPb central collisions: even Efimov-like states (hypertriton) produced with yields fixed at the phase boundary
T 3 oom higher than Lambda separation energy



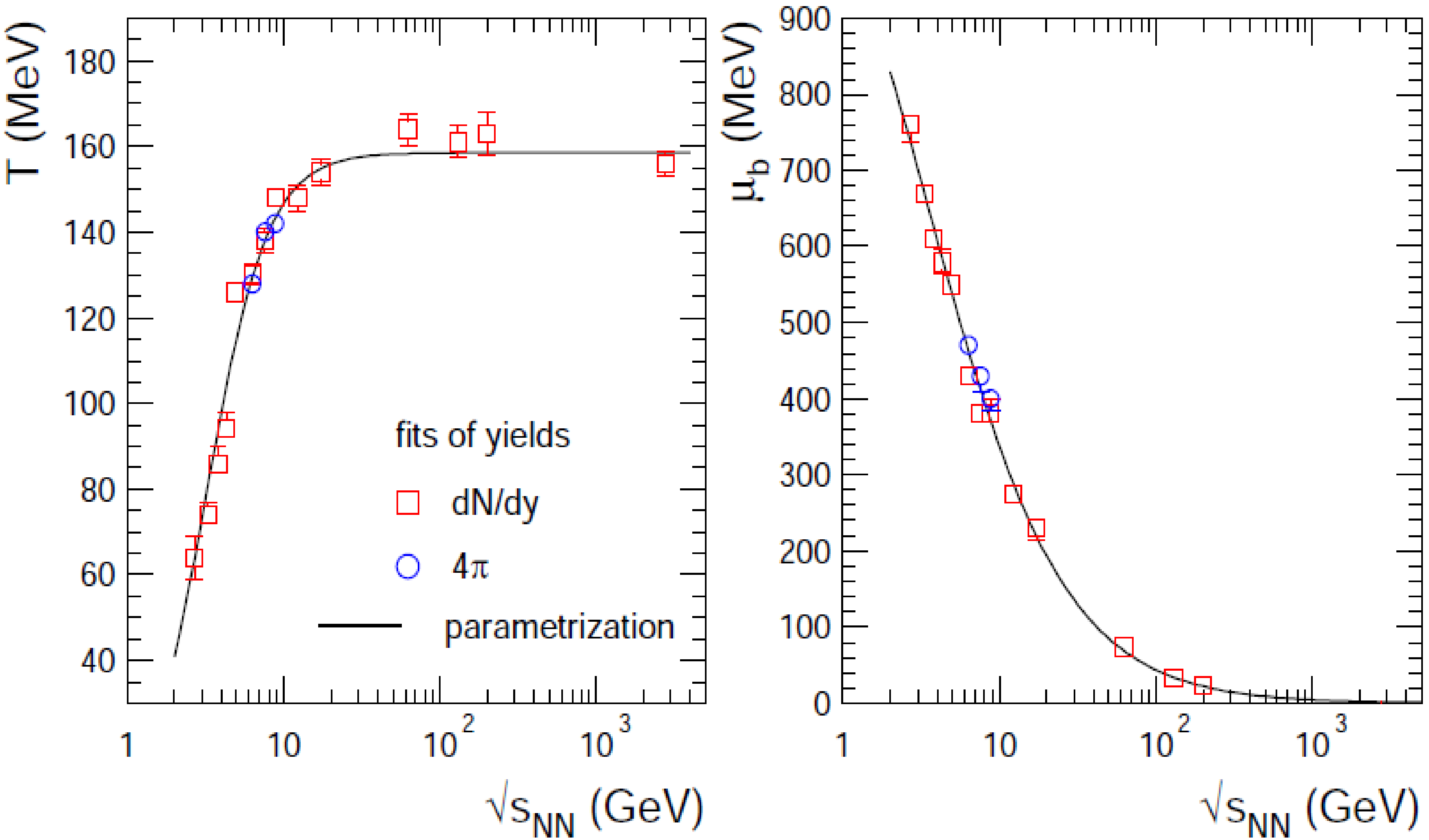
for system in thermal equilibrium statistical and coalescence yields agree

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

A.J. Baltz, C.B. Dover, et al., Phys. Lett. B315 (1994) 7

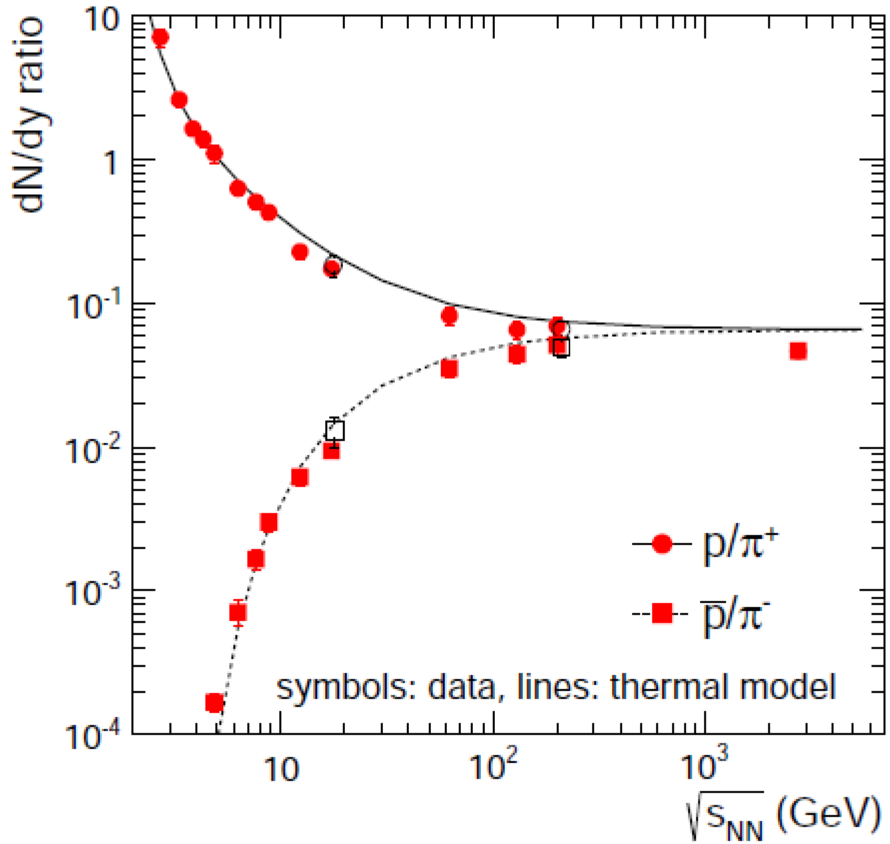
Particles	Thermal Model		Coalescence Model
	T=.120 GeV	T=.140 GeV	
d	15	19	11.7
t+^{3}He	1.5	3.0	0.8
α	0.02	0.067	0.018
H_0	0.09	0.15	0.07
${}^{5}_{\Lambda\Lambda}$H	$3.5 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
${}^{6}_{\Lambda\Lambda}$He	$7.2 \cdot 10^{-7}$	$7.6 \cdot 10^{-6}$	$1.6 \cdot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

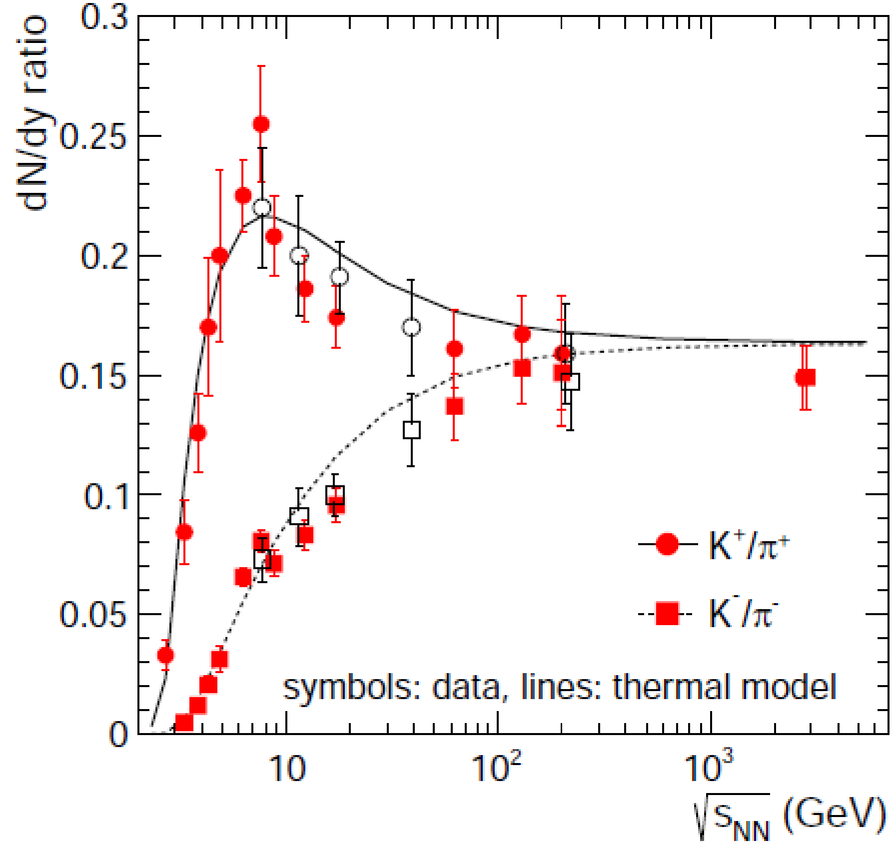
global fit to T and mub



beam energy dependence of hadron yields from AGS to LHC

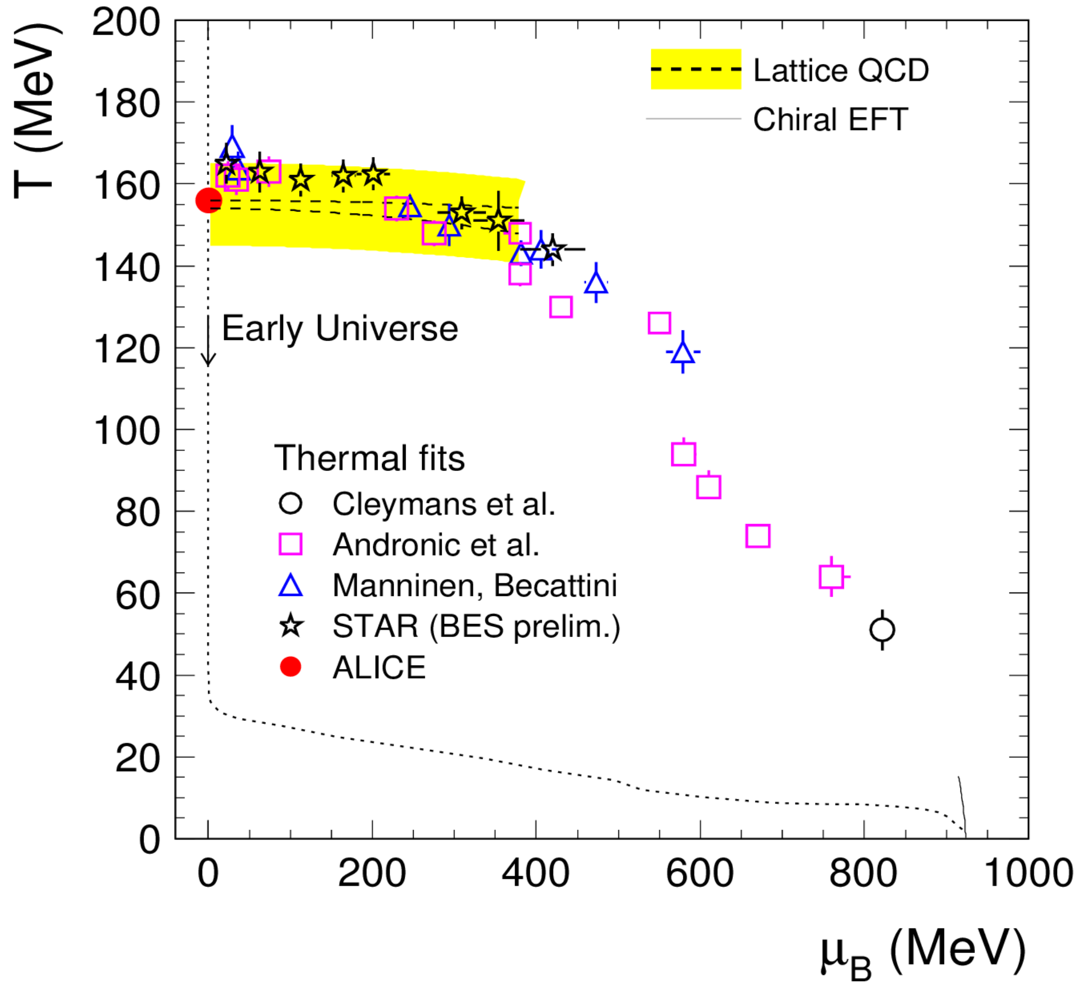
following the above T and μ_b evolution, features of proton/pion and kaon/pion ratios reproduced in detail





The QCD phase diagram – experiment and lattice QCD

experimental hadronic freeze-out points coincide with pseudocritical temperature T_c from state-of-the-art lattice QCD for high collision energies



QGP and hadron yields

QCD implies duality between quarks/gluons and hadrons
- hadron gas: equilibrated state of all known hadrons
- QGP: equilibrated state of quarks and gluons

at pseudocritical temperature T_c, QGP converts to hadrons

existence of QGP in central nuclear collisions implies that at hadronization
- hadron yields correspond to equilibrium state of common temperature T
- hadron yields must agree with predictions using the full QCD partition function at this temperature T

near T_c, hadron densities very large, can rapidly drive system into equilibrium between hadronic species by multi-particle reactions (critical opalescence)
- conversely, rapidly dropping densities (reduction of dof and T^3 drop of entropy density) imply cooling system falls out of equilibrium, i.e. freezes out
  T bounded by T_c within a few MeV

analysis of hadron production $\rightarrow$ experimental determination of T_c

P. Braun-Munzinger, J.S., C. Wetterich, PLB 596 (2004) 61

Heavy quark sector

does statistical hadronization picture also apply to hadrons with charm (and beauty) quark?

to the extent that heavy quarks are unconfined and thermalize in the QGP, it should

- first application to charmonium sector and SPS data: P. Braun-Munzinger and J. S., Phys. Lett. 490 (2000) 196
- real relevance expected for collider data, in particular LHC

Extension of statistical model to include charmed hadrons

- assume: all charm quarks are produced in initial hard scattering; number not changed in QGP

  $N_{c\bar{c}}^{direct}$ from data (total charm cross section) or from pQCD

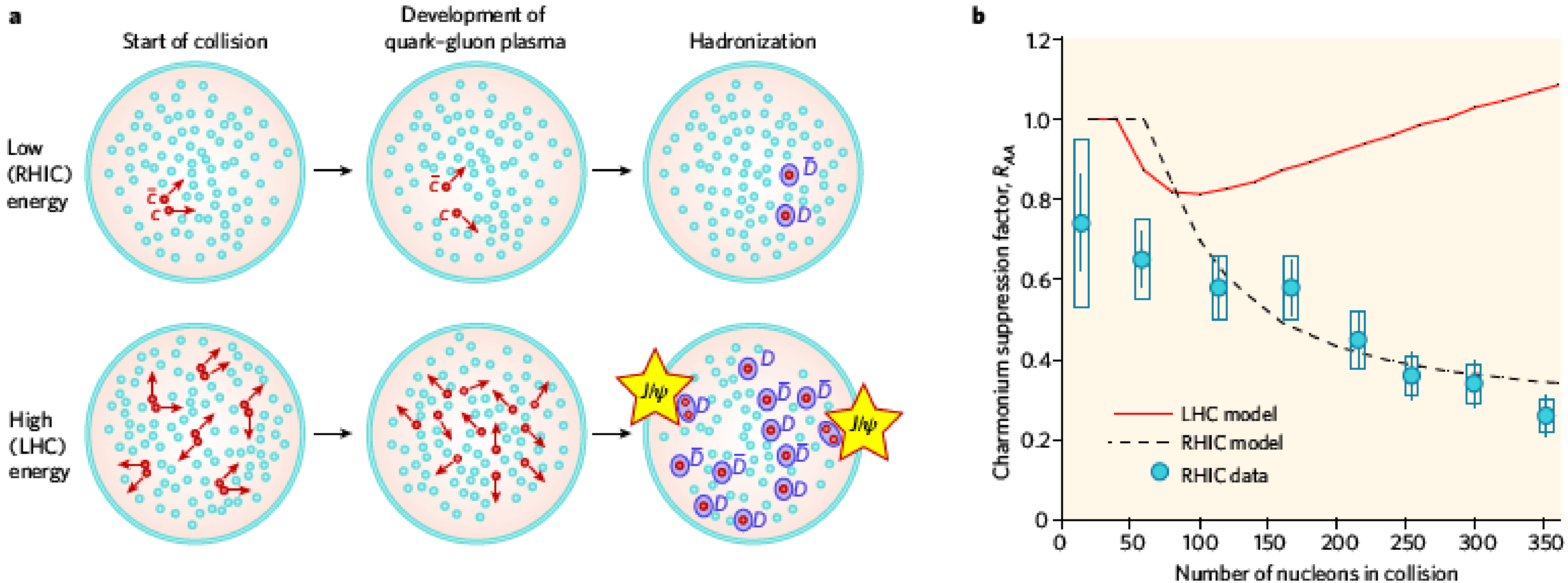
- hadronization at T_c following grand canonical statistical model used for hadrons with light valence quarks (canonical corr. if needed)
  technically number of charm quarks fixed by a charm-balance equation containing fugacity g_c

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

↑ the only additional free parameter

Quarkonium as a probe for deconfinement at the LHC the statistical hadronization picture

P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma, Nature **448** Issue 7151, (2007) 302-309.



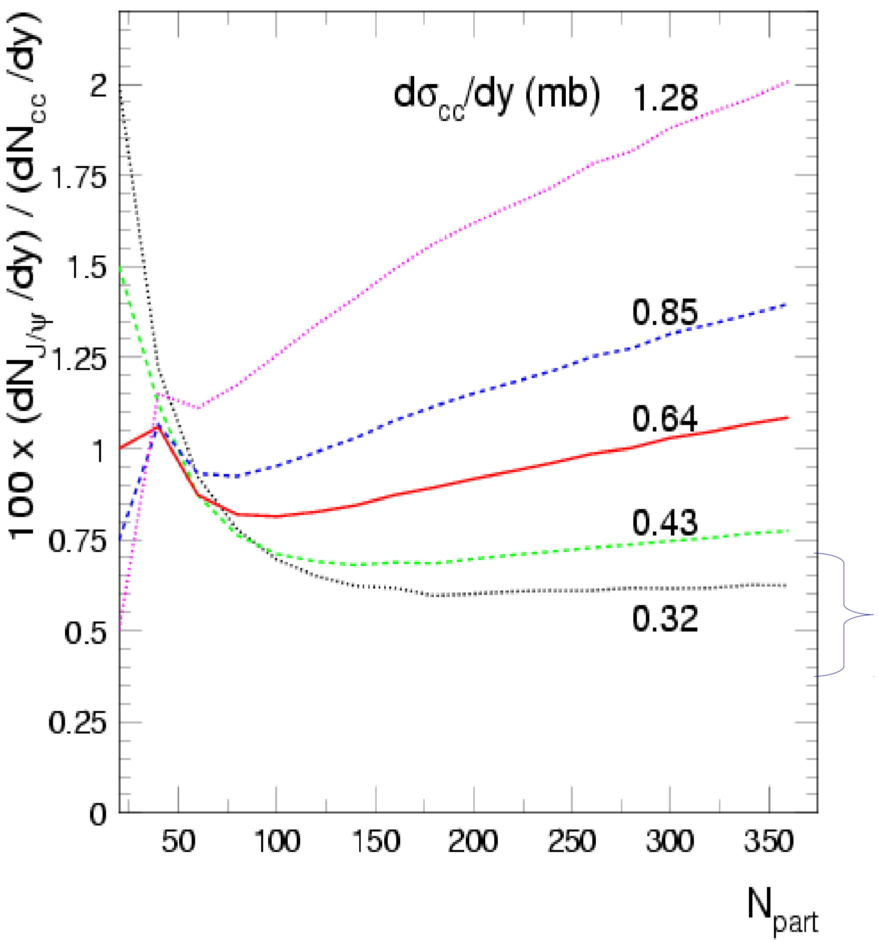
charmonium enhancement as fingerprint of deconfinement at LHC energy

only free parameter: open charm cross section in nuclear collision

Braun-Munzinger, J.S., Phys. Lett. B490 (2000) 196 and

Andronic, Braun-Munzinger, Redlich, J.S., Phys. Lett. B652 (2007) 659

Consequences of charm cross section for J/ψ production at LHC energies



open charm is natural and essential normalization

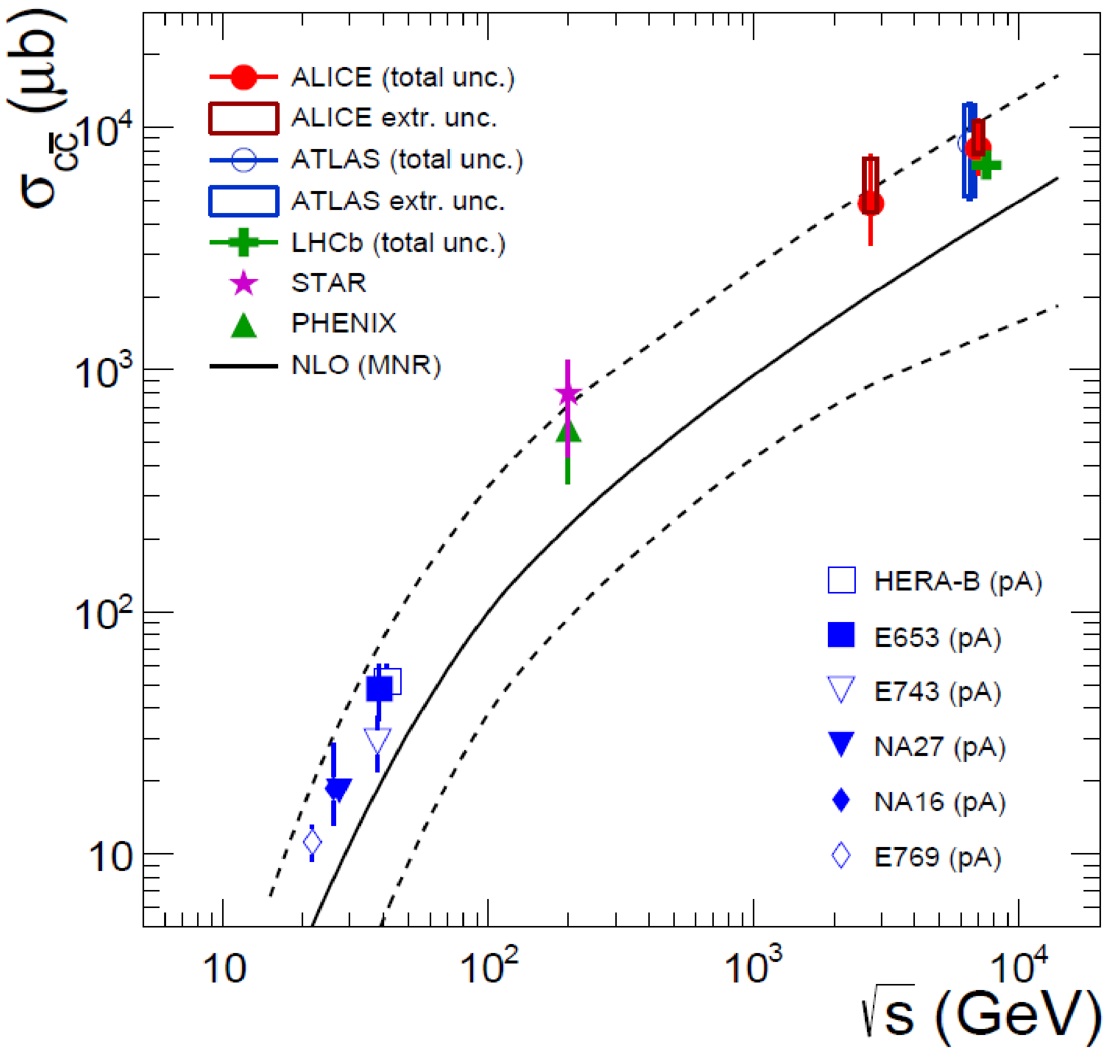
precision measurement needed

LHC 2.76 TeV including shadowing (more below)

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

Currently best measurement of the total ccbar cross section in pp at LHC

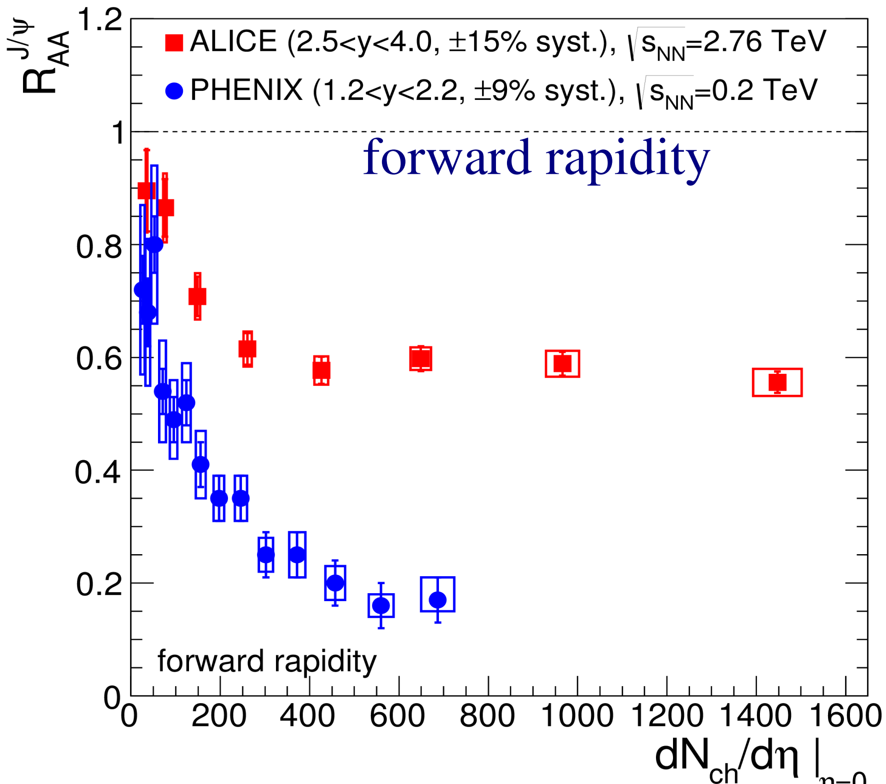
arXiv: 1605.07569

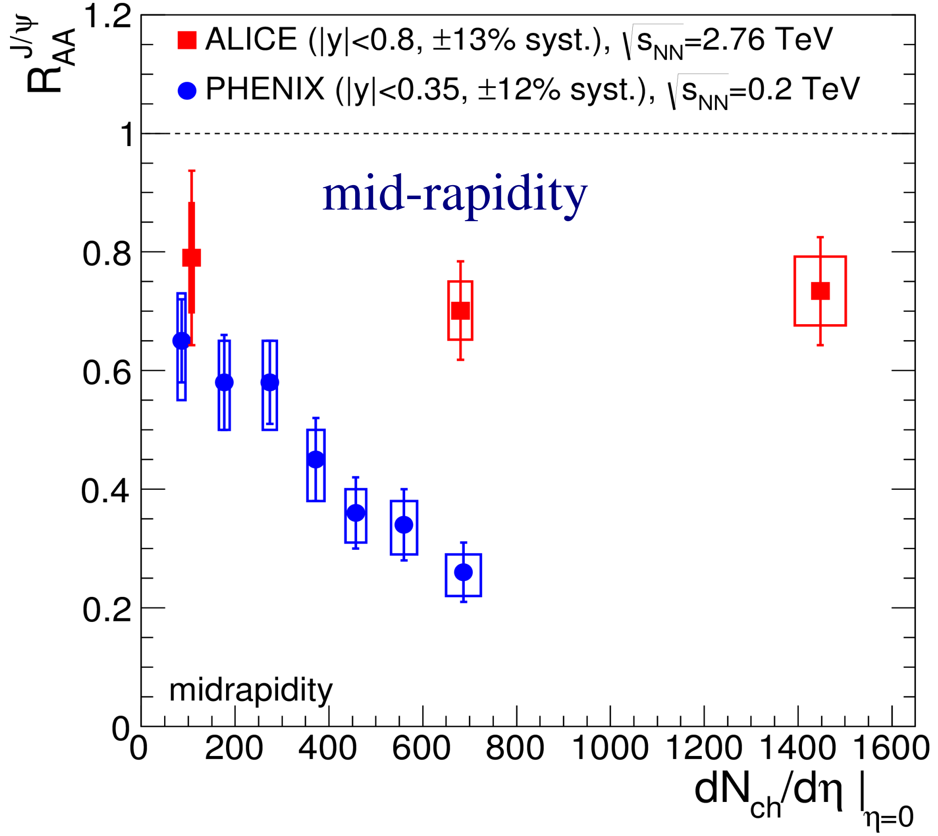


- good agreement between ALICE, ATLAS and LHCb
- ALICE and LHCb at 7 TeV measurement down to zero p_t, much reduced syst. error
- data at upper edge of NLO pQCD band but well within uncertainty
- beam energy dependence follows well NLO pQCD

J/ψ production in PbPb collisions: LHC relative to RHIC

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$



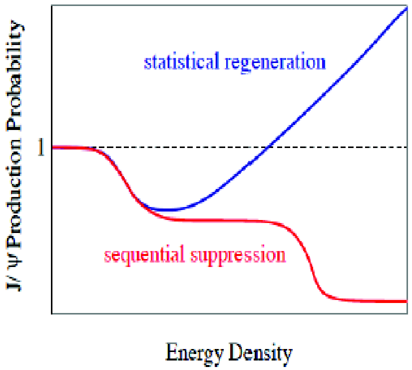


energy density -->

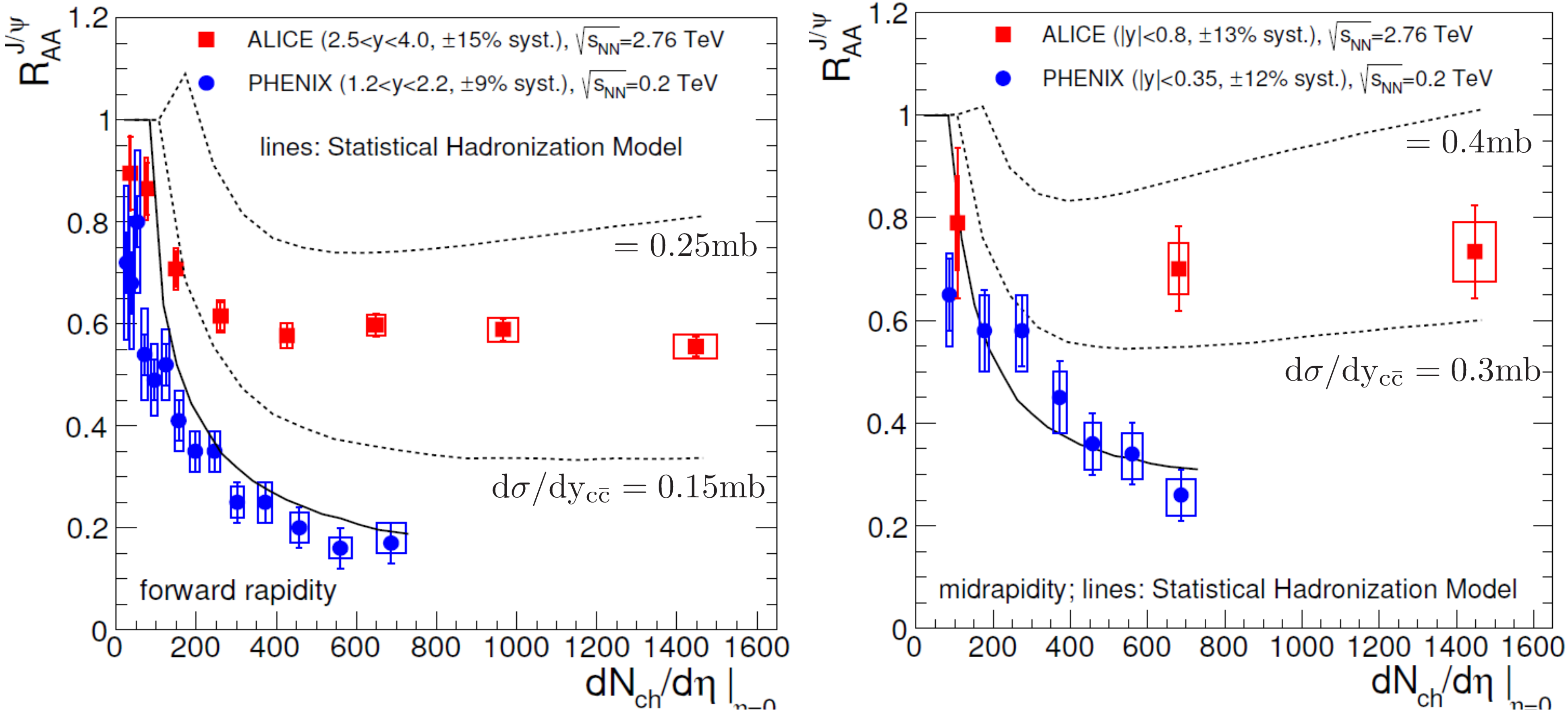
melting scenario not observed

rather: enhancement with increasing energy density!

(from RHIC to LHC and from forward to mid-rapidity)



J/ψ and statistical hadronization



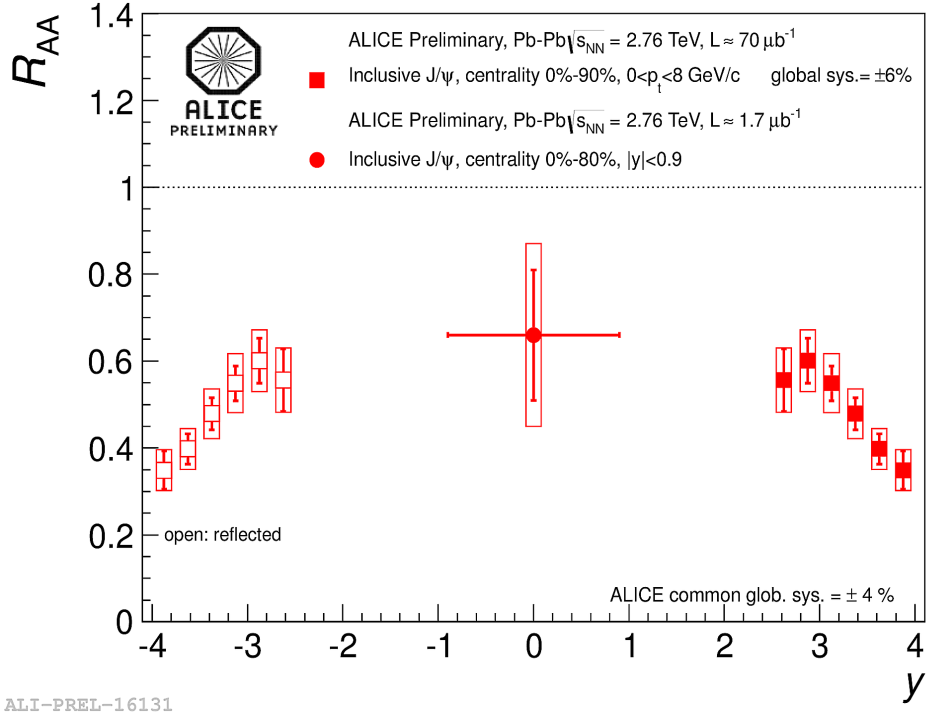
production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties

transport models also in line with R_{AA} but different open charm cross section used

(0.5-0.75mb TAMU and 0.65-0.8 mb Tsinghua vs. 0.3-0.4 mb SHM) more below

main uncertainties for models: open charm cross section, shadowing in Pb

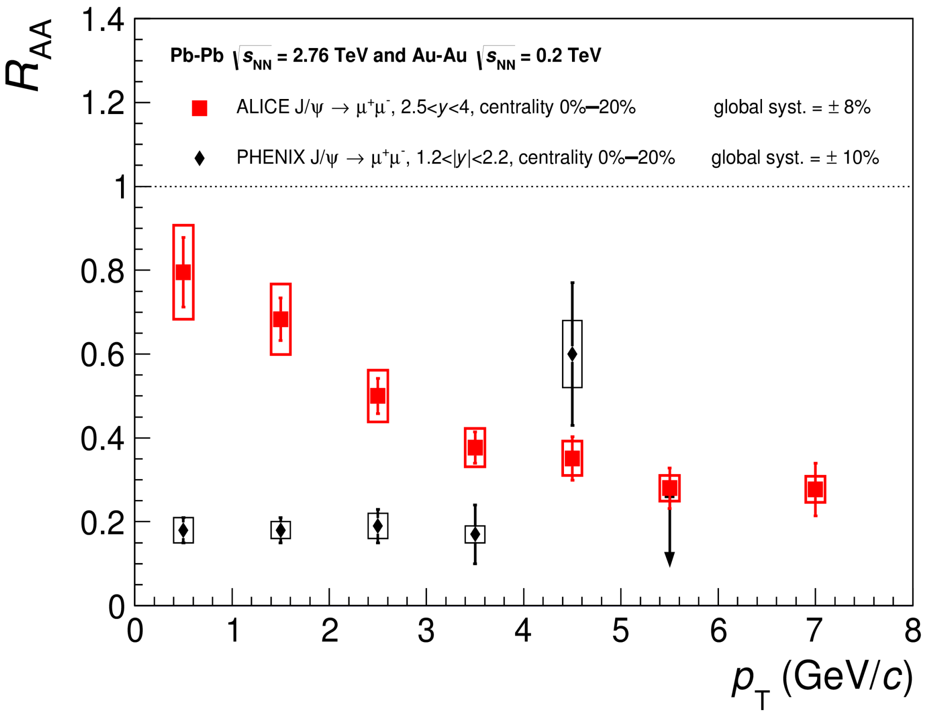
Rapidity dependence of R_{AA}

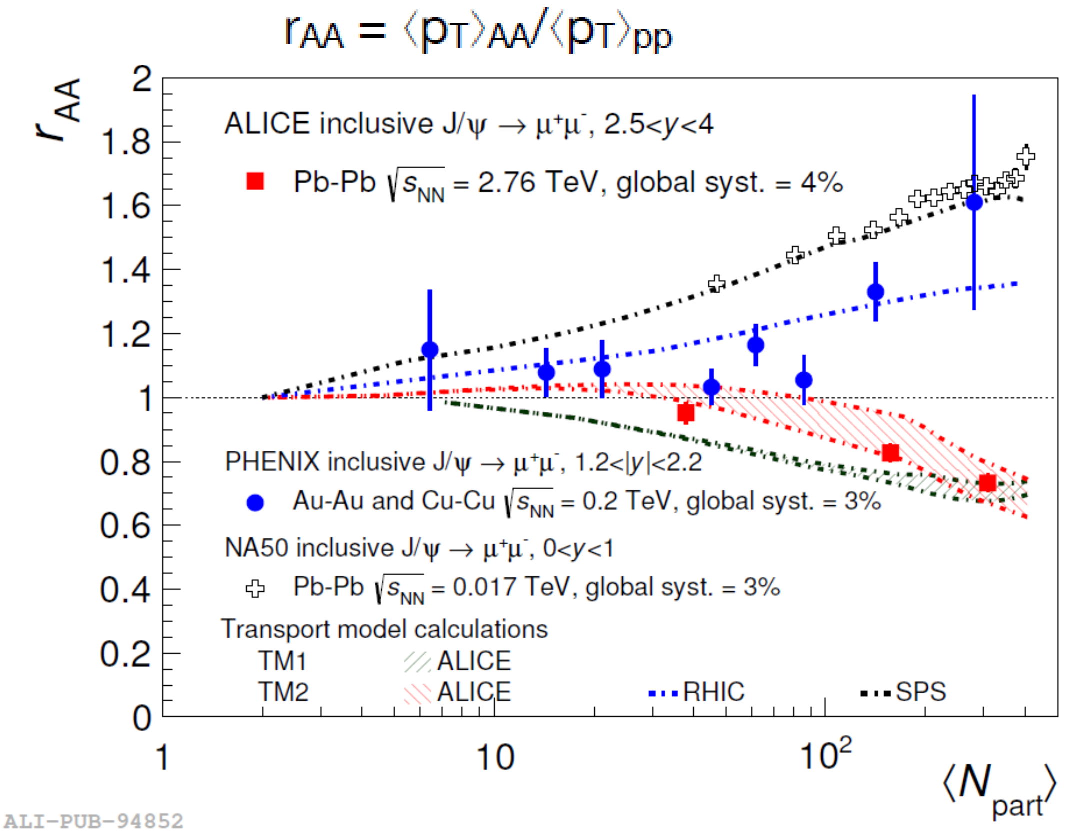


yield in PbPb peaks at mid-y where energy density is largest

for statistical hadronization J/ψ yield proportional to N_c^2 - higher yield at mid-rapidity predicted in line with observation (at RHIC and LHC)

p_t dependence of R_{AA} supports dominance of new production mechanism at LHC at small p_t



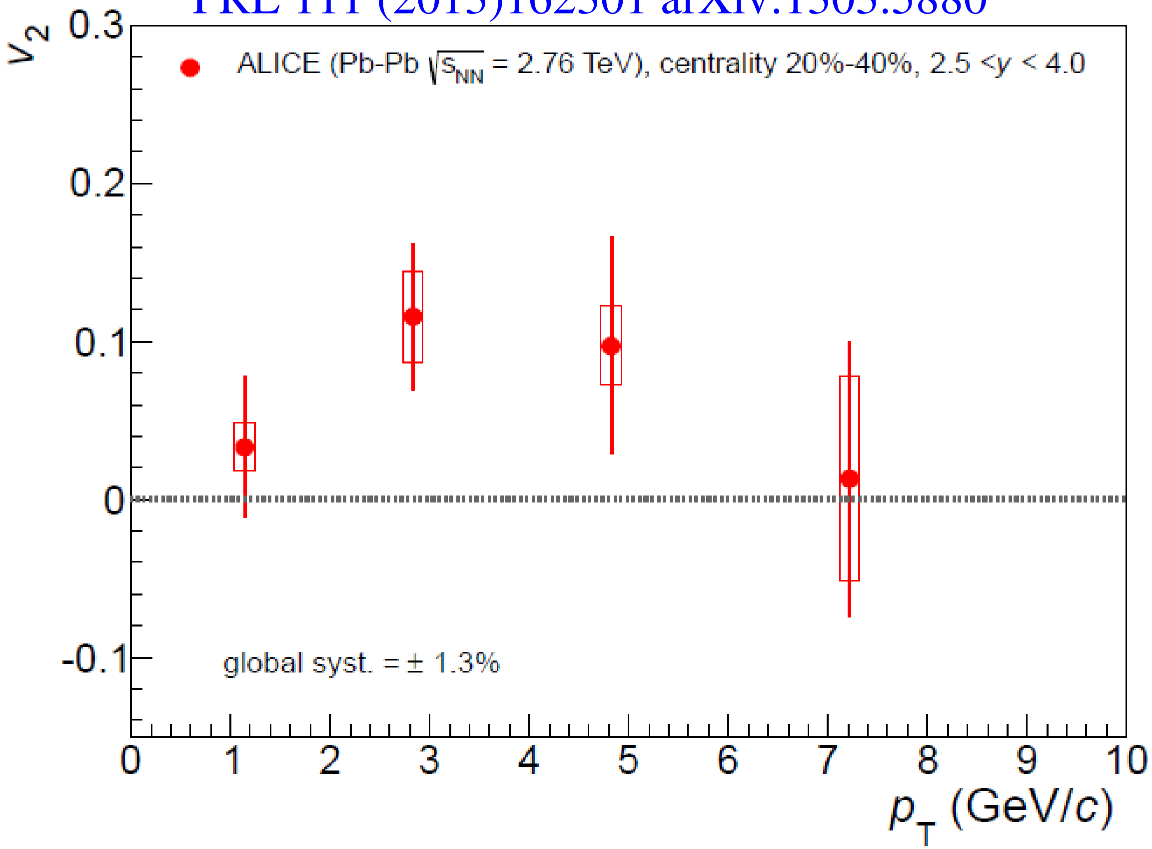


p_t dependence at LHC opposite to RHIC and SPS

supports argument: thermalized deconfined charm quarks hadronize into J/ψ

elliptic flow of J/ψ vs p_t

PRL 111 (2013)162301 arXiv:1303.5880



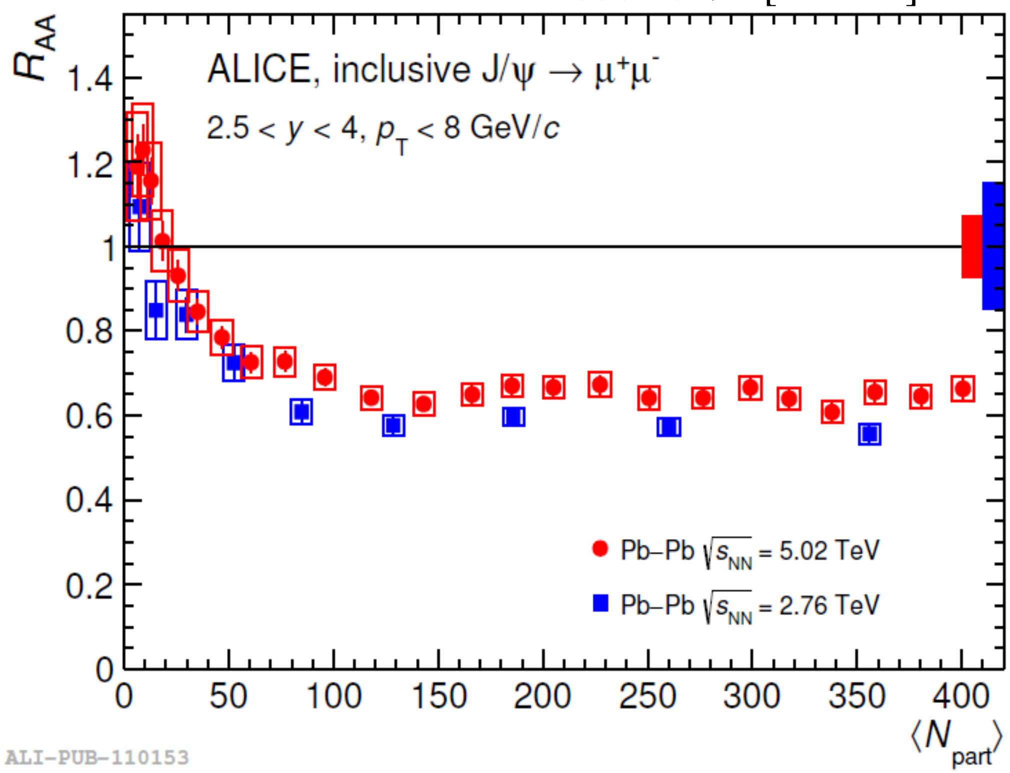
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

- expect build-up with p_t as observed for π, p. K, Λ, …
  and vanishing signal for high p_t region where J/ψ not from hadronization of thermalized quarks

first observation of J/ψ v_2
in line with expectation from statistical hadronization

J/ψ in PbPb at $\sqrt{s_{NN}} = 5.02$ TeV

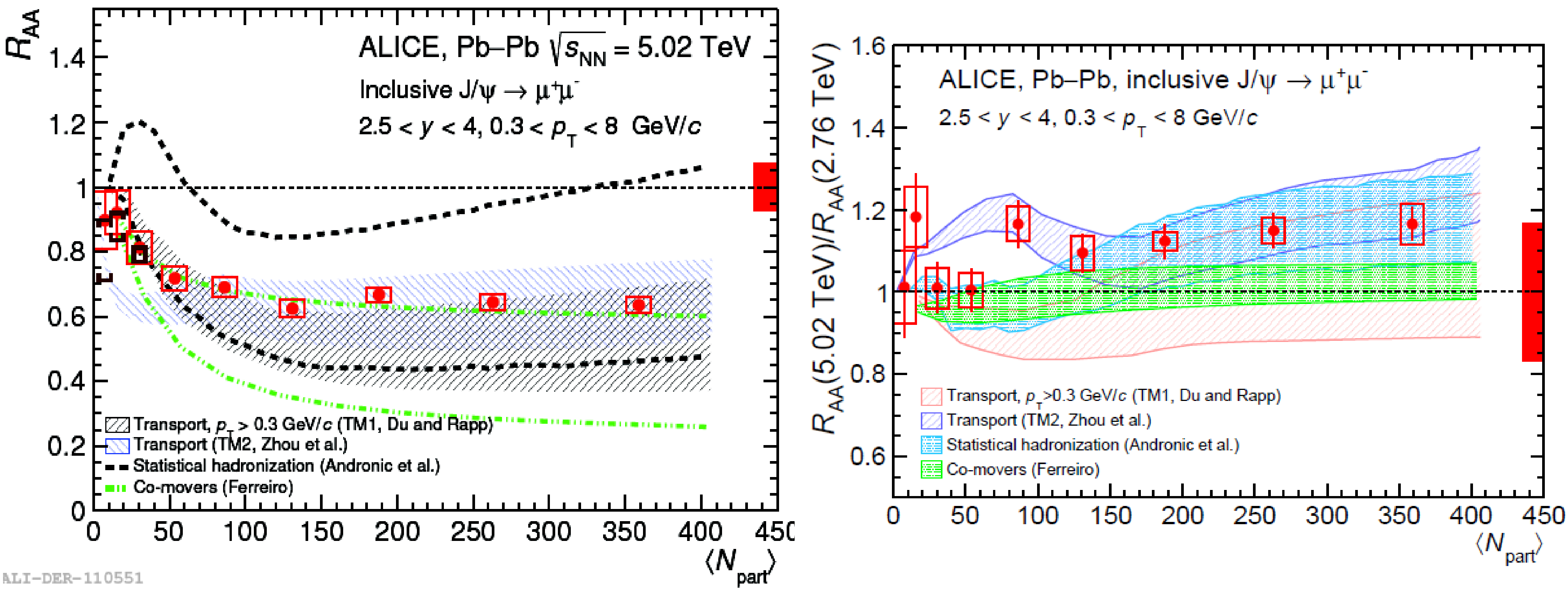
arXiv:1606.08197 [nucl-ex]



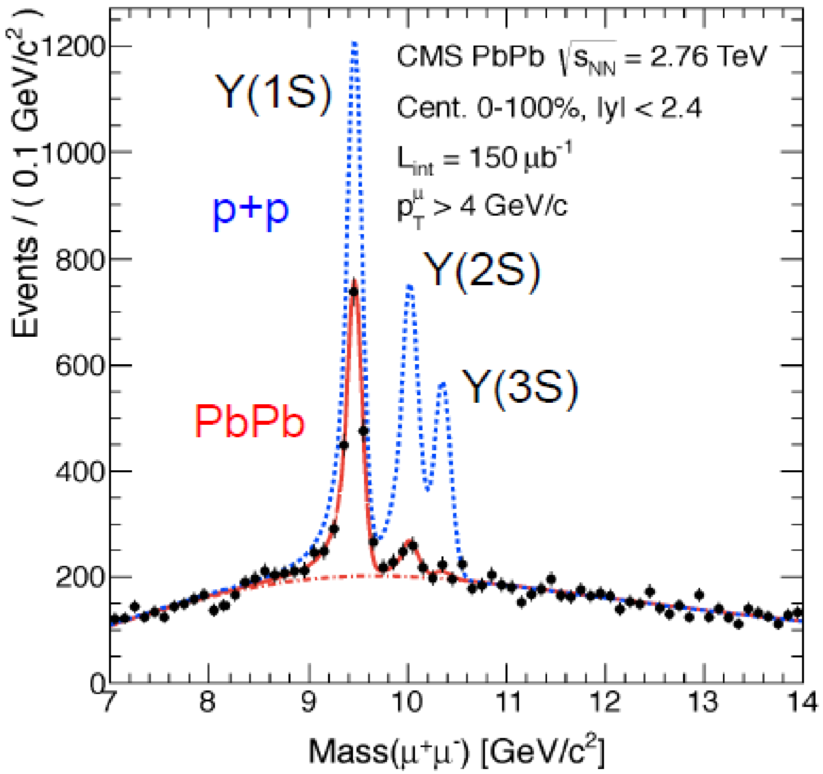
$R_{AA}^{0\text{-}90\%}(5.02\text{ TeV}) / R_{AA}^{0\text{-}90\%}(2.76\text{ TeV}) = 1.13 \pm 0.02(\text{stat}) \pm 0.18(\text{syst})$

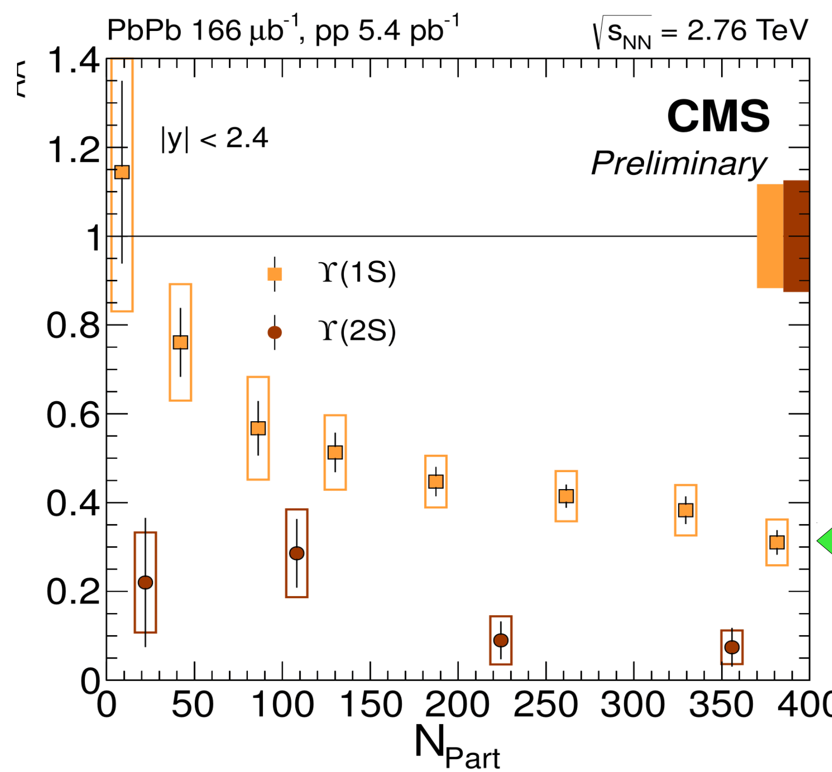
increase of J/ψ R_{AA} for all centralities and over large range of p_t (but within 1 σ)

J/ψ R_{AA} at $\sqrt{s_{NN}}$ = 5.02 TeV compared to stat. hadronization and transport models



suppression of Upsilon states





not consistent with just excited state suppression (LHCb data: only 25 % feed-down in pp at LHC)

$$R_{AA}(\Upsilon(1S)) = 0.425 \pm 0.029 \pm 0.070$$
$$R_{AA}(\Upsilon(2S)) = 0.116 \pm 0.028 \pm 0.022$$
$$R_{AA}(\Upsilon(3S)) < 0.14 \text{ at } 95\% \text{ CL},$$

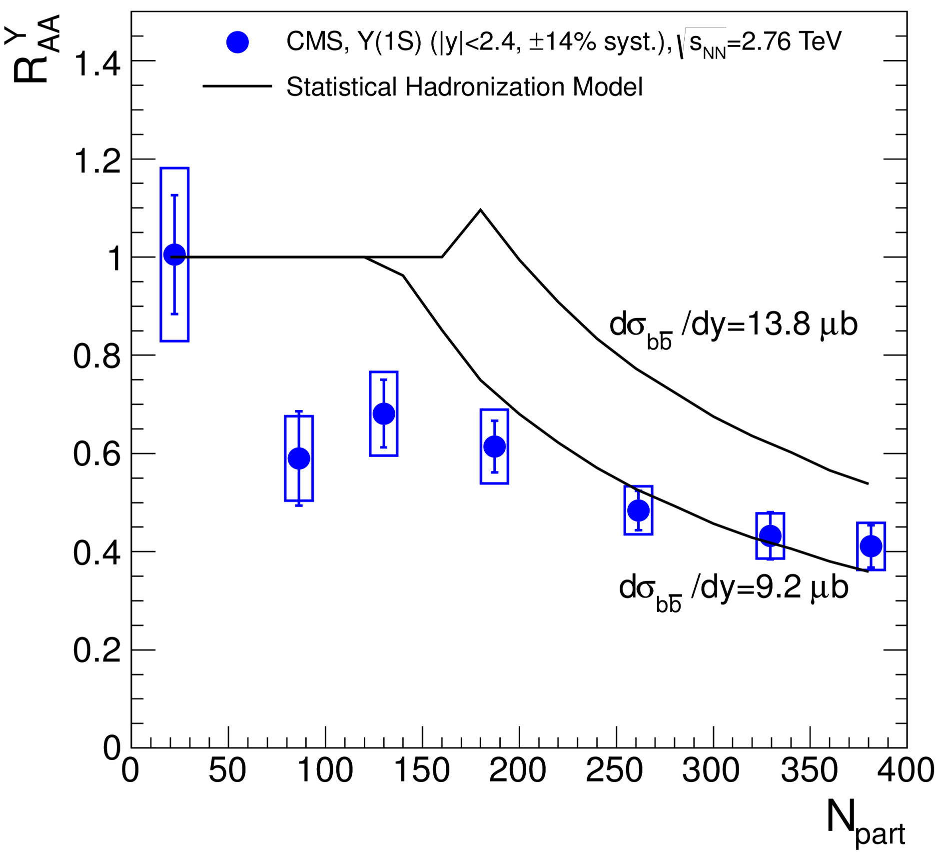
+ R_{AA} (Y(1S)) = 0.30 ± 0.05 ± 0.04 (at forward rapidity)

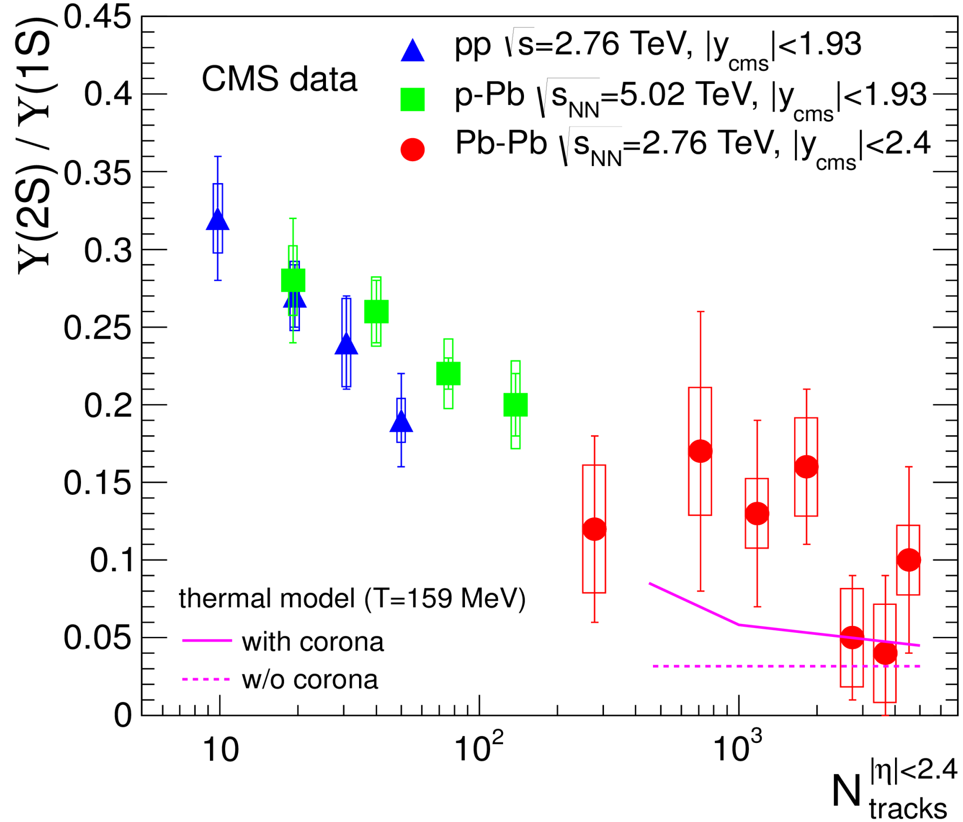
CMS, PRL109 (2012) 222301
ALICE, PLB738 (2014) 361

another puzzle: radius of Upsilon(2S) similar to radius J/ψ, but at mid-y R_{AA} = 0.12 vs 0.70

the Upsilon could also come from statistical hadronization

SHM/thermal model: Andronic et al.



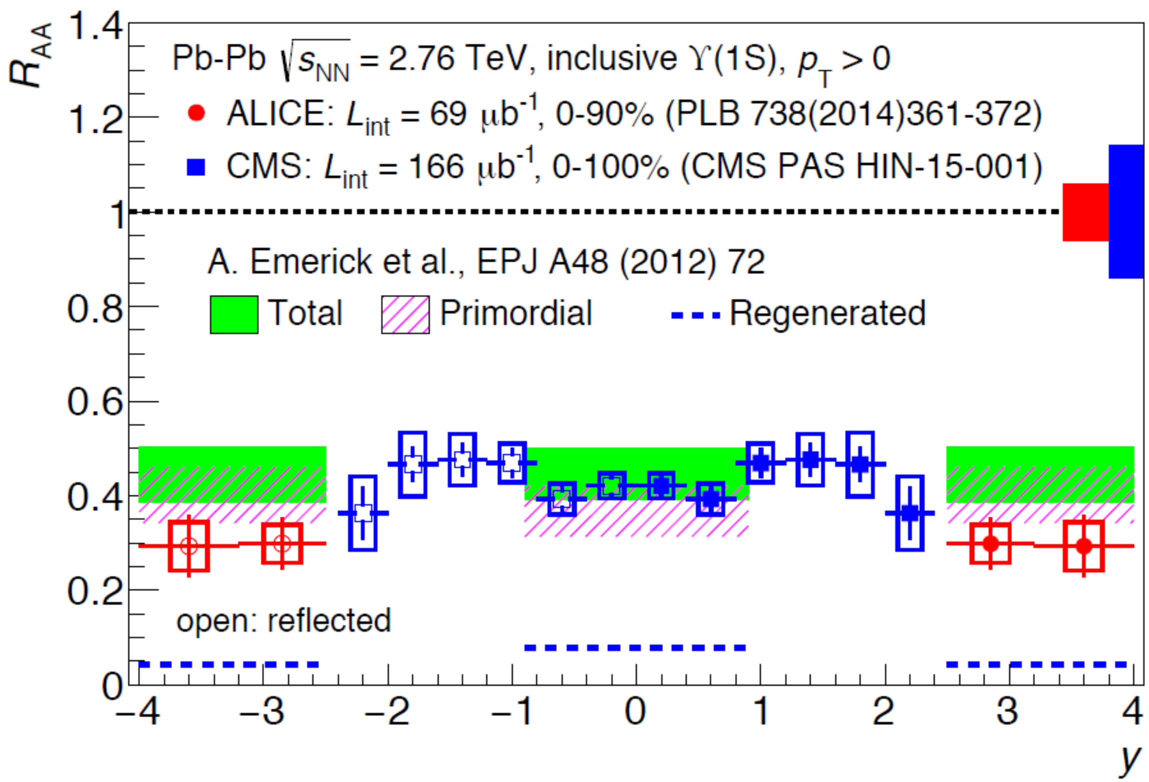


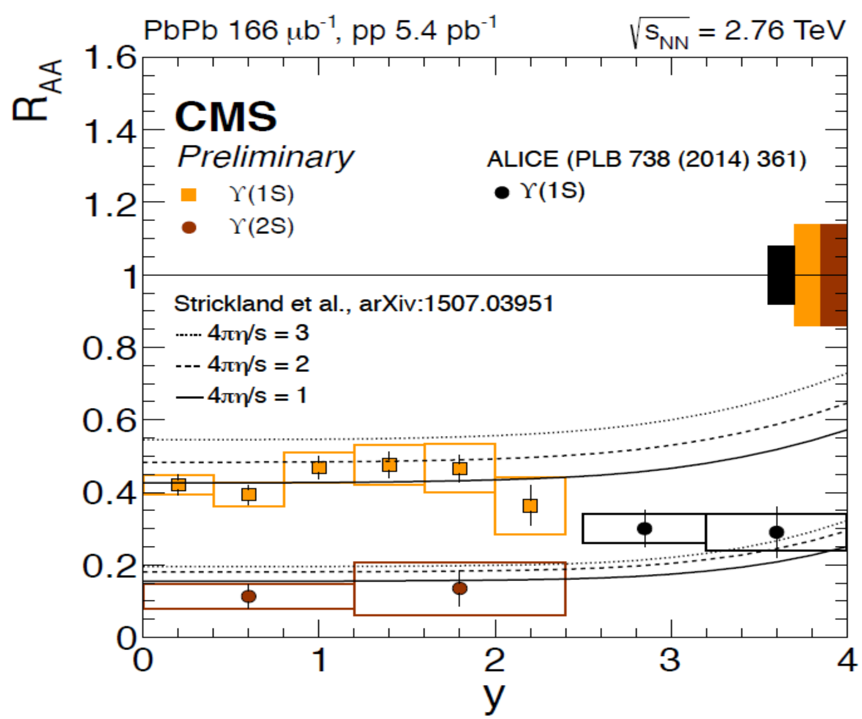
in this picture, the entire Upsilon family is formed at hadronization
but: need to know first – do b-quark thermalize at all? spectra of B
- total b-cross section in PbPb

Upsilon R_{AA} rapidity dependence

CMS 20 times more statistics in pp than previously published

M. Jo, CMS-HIN-15-001





R_{AA} still peaked at mid-y like for J/ψ not in line with collisional damping in expanding medium (Strickland)

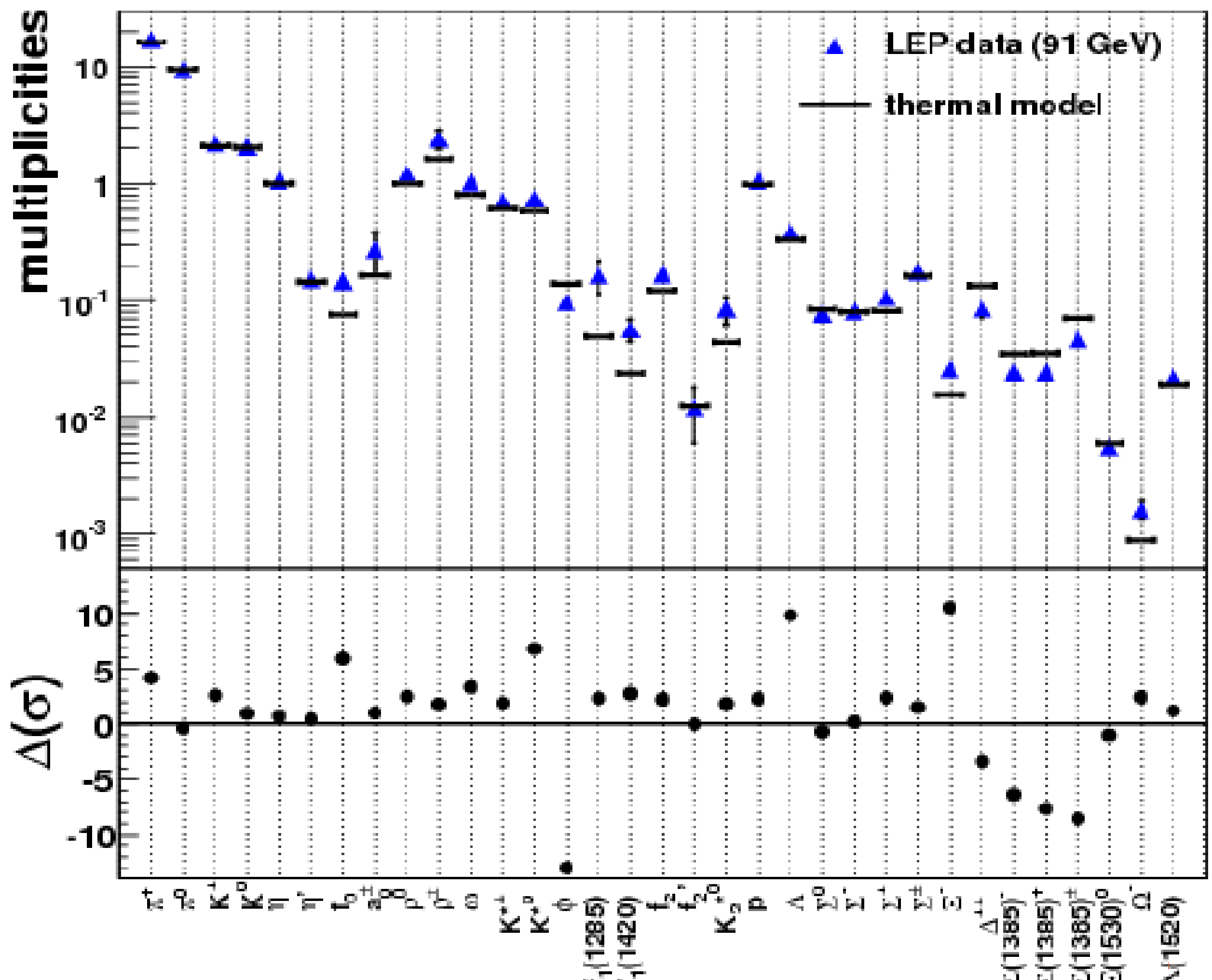
instead of a summary

- it was great fun to work with Peter on this project the past 25 years
- we had many great collaborators!
- looking forward to many new projects … actually some are just starting

backup

e+e- collisions: initialize thermal model with u,d,s,c,b – jets according to measurement (weak isospin)

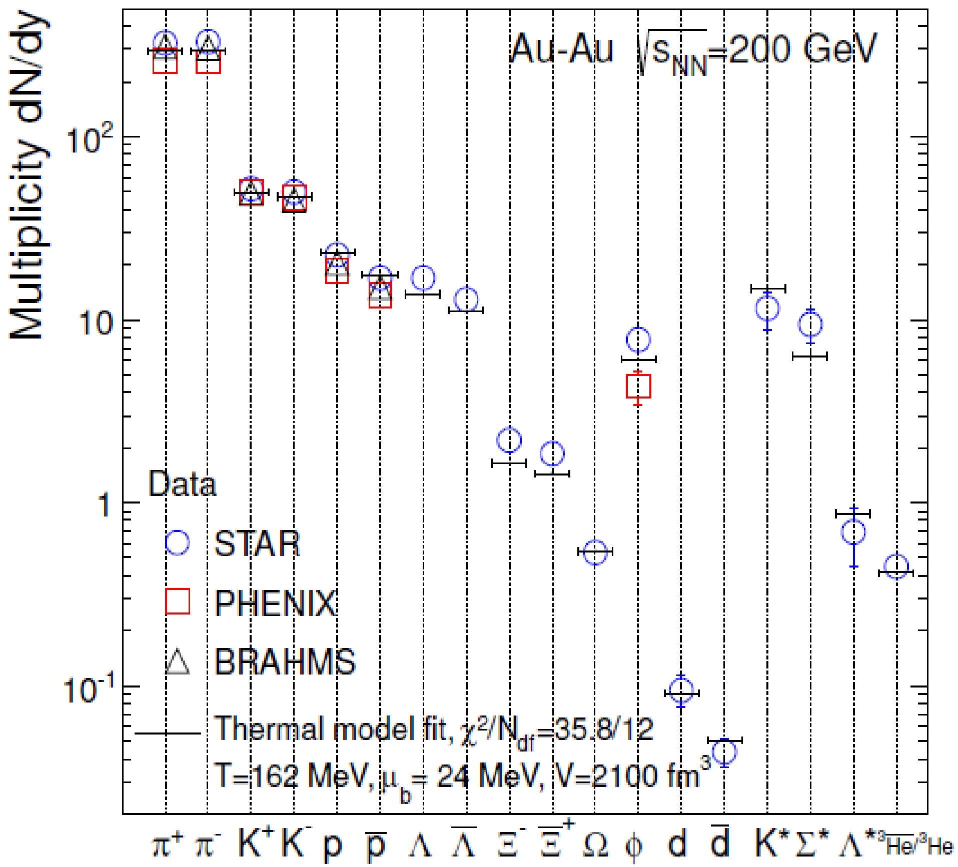
A. Andronic, P. Braun-Munzinger, F. Beutler, K. Redlich, J. Stachel, Phys. Lett. B678 (2009)
arXiv 0804.4132



strangeness supressed – fit still not good!

parameter set: T=164 MeV, V=20 fm^3, γ_s=0.72 with χ^2=718/30

Latest statistical model fit to all RHIC data



top AGS energy Au + Au data

GC statistical model applied successfully to 10.7 A GeV/c Au + Au

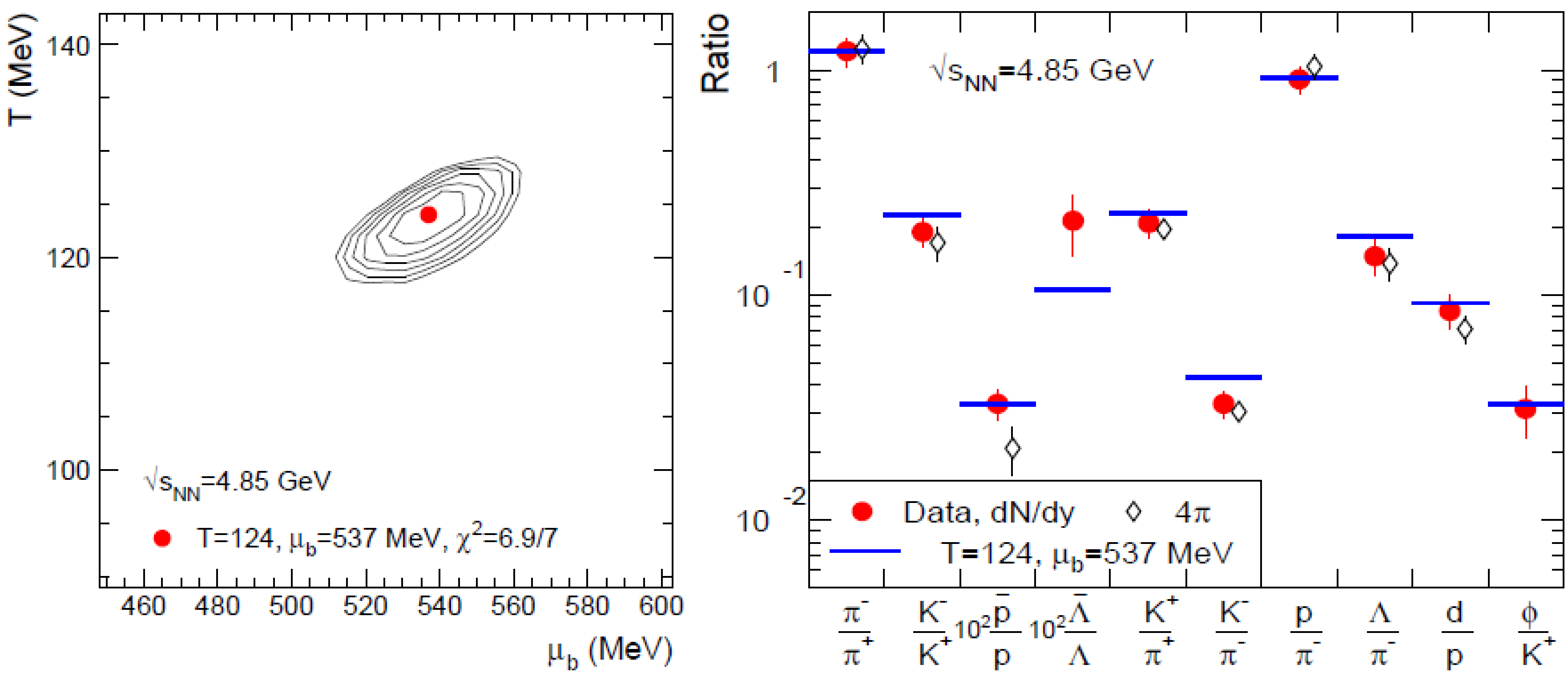
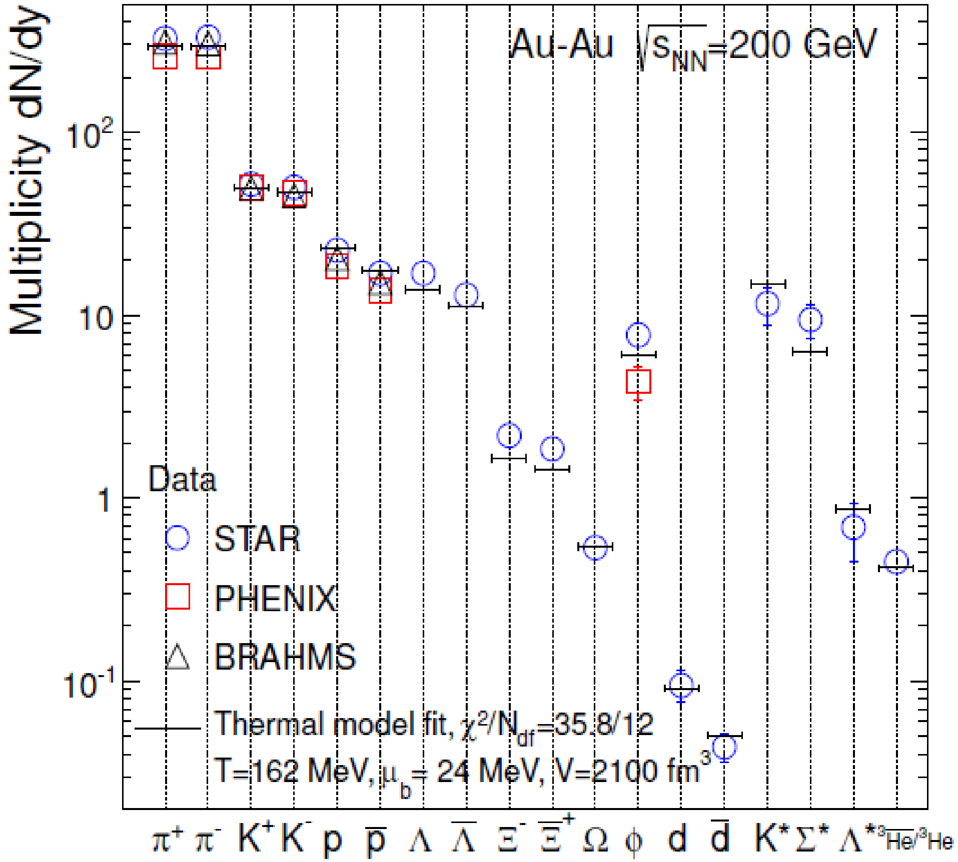
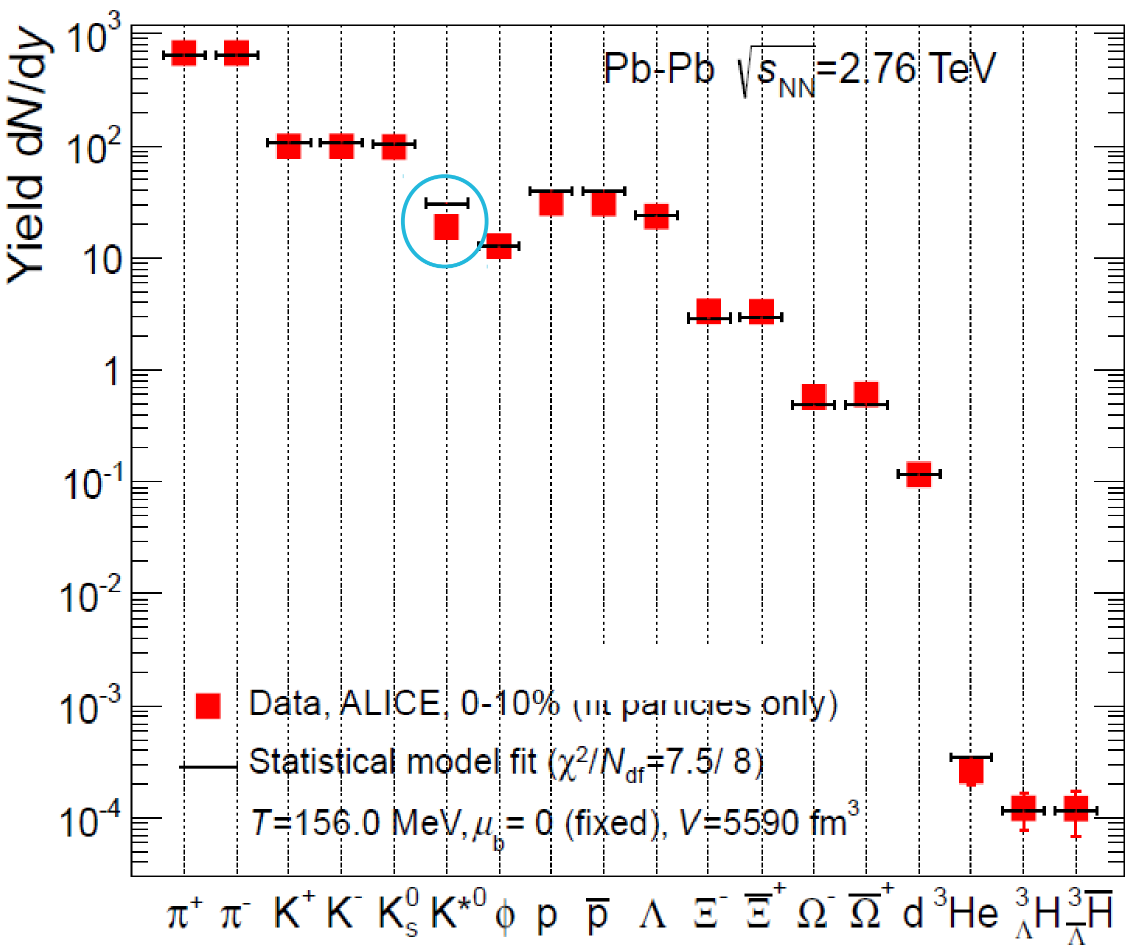


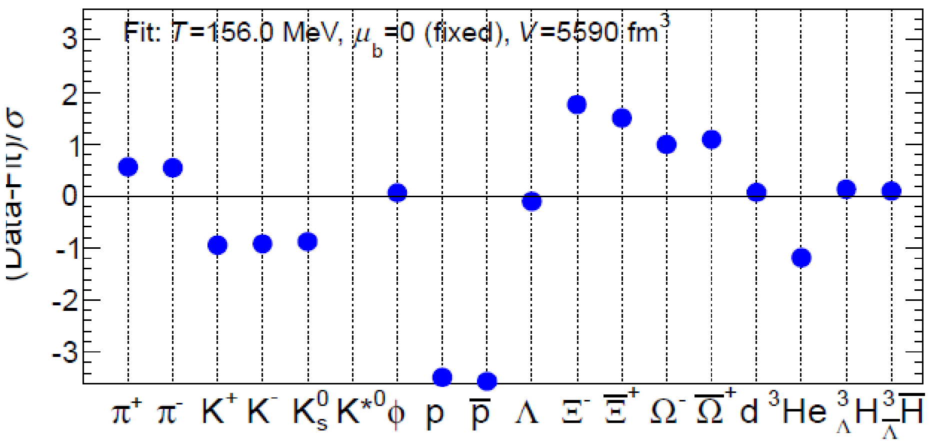
Figure from A. Andronic, P. Braun-Munzinger, J.S. Nucl. Phys. A772 (2006) 167

Latest statistical model fit to all RHIC data



fit excluding protons





<u>excluding protons:</u> T unchanged

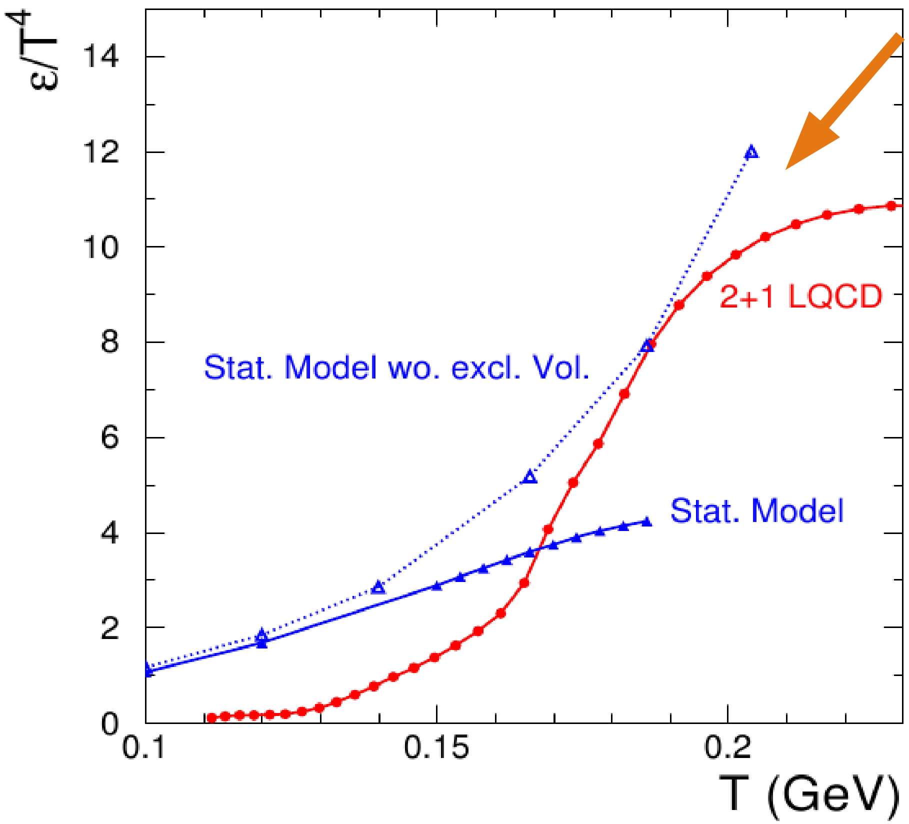
perfect fit for other hadrons

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

equilibration driven by high densities near T_c

rapid equilibration within a narrow temperature interval around T_c by multi-particle collisions due to steep temperature dependence of densities

P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B596 (2004)61

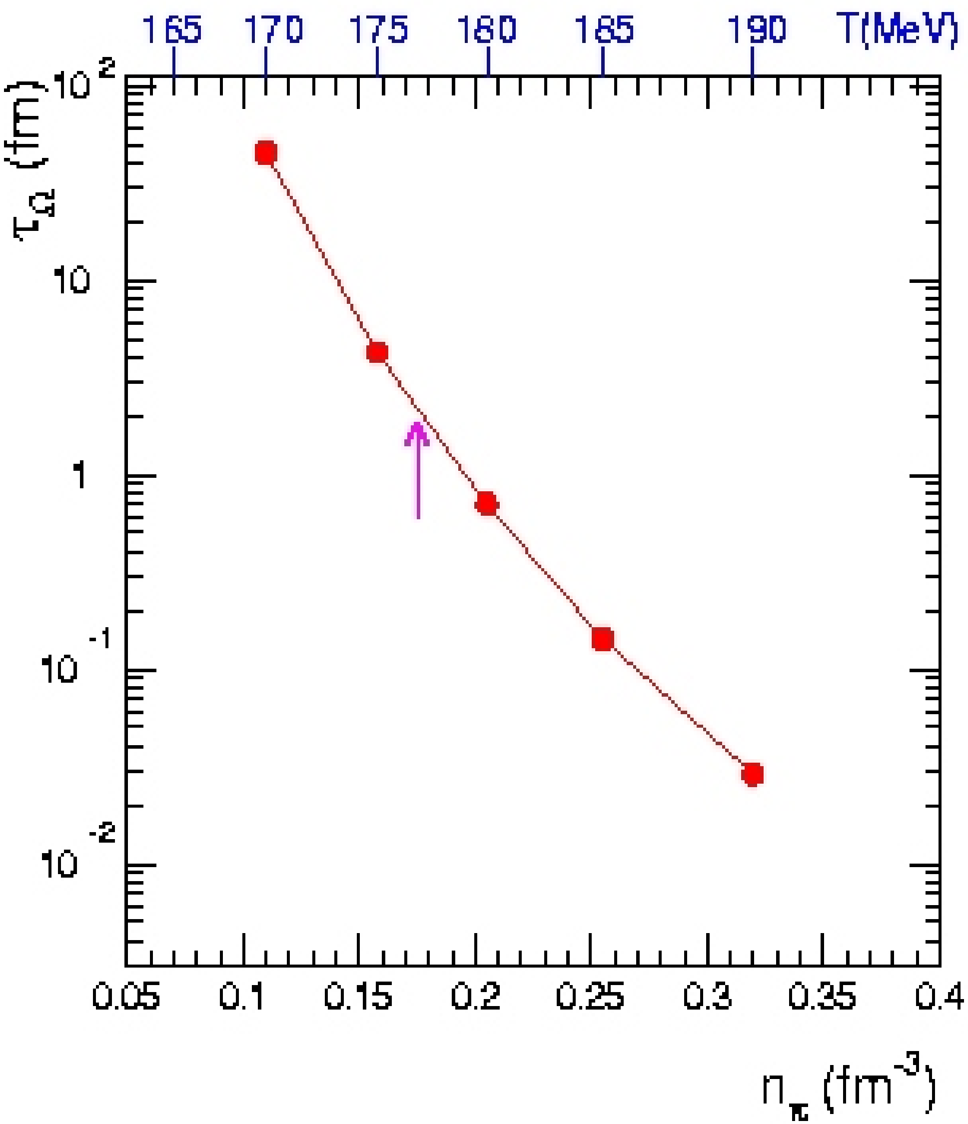


for T_{ch} 20-30 MeV below T_c very hard to maintain scenario of simultaneous freeze-out of all hadron species

estimate upper limit of $T_c - T_{ch} = 5$ MeV

→ requires T_c = 160 - 170 MeV experimental determination!

density dependence of characteristic time for strange baryon production

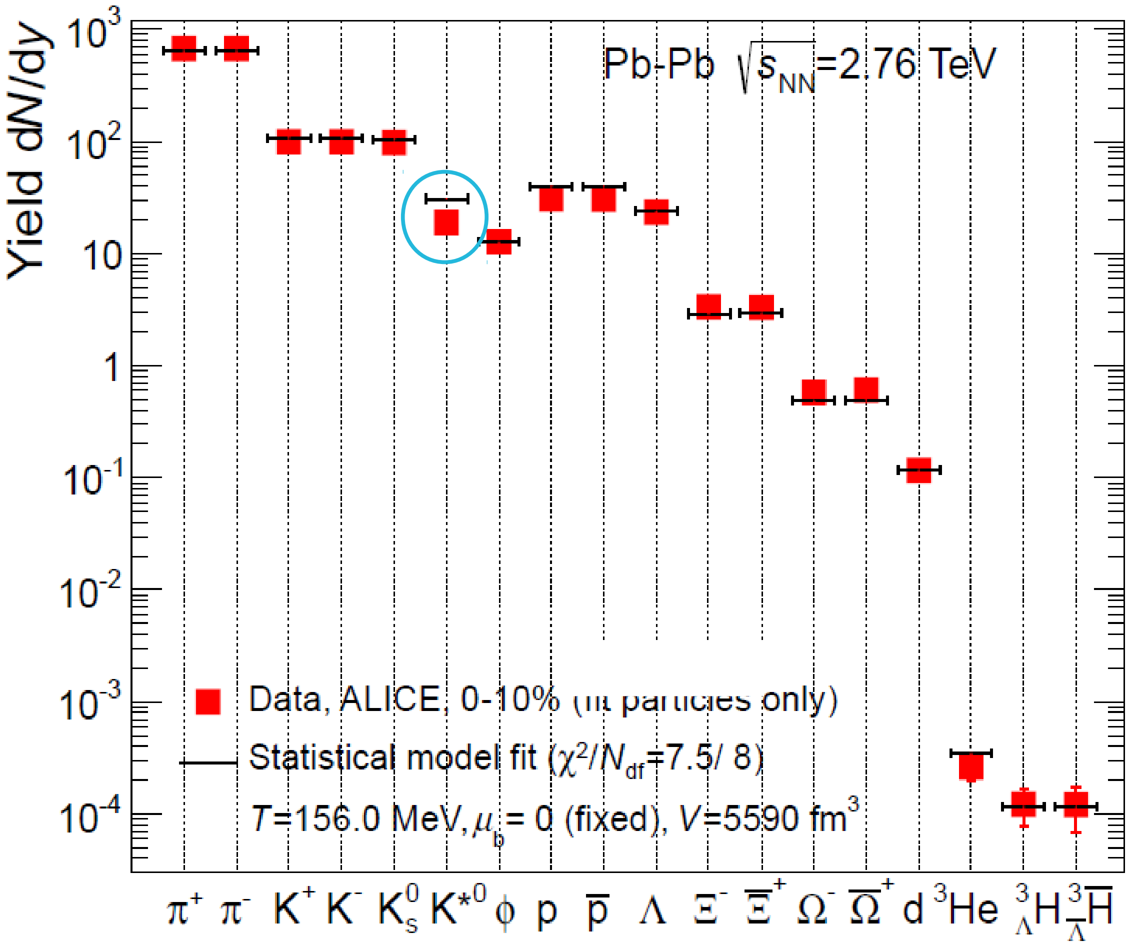


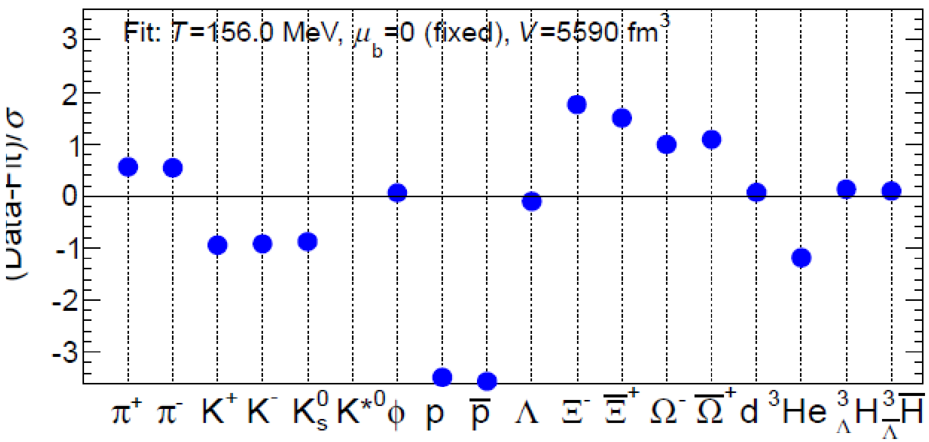
- near phase transition particle density varies rapidly with T (see previous slide)
- for SPS energies and above reaction such as 2π+KKK→ Ω Nbar bring multi-strange baryons close to equilibrium rapidly
- in region around T_c equilibration time $\tau_\Omega \propto T^{-60}$!
- increase n_π by 1/3: τ = 0.2 fm/c (corresponds to increase in T by 8 MeV) decrease n_π by 1/3: τ = 27 fm/c

→ all particles freeze out within a very narrow temperature window due to the extreme temperature sensitivity of multi-particle reactions

P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B596 (2004)61

fit excluding protons





<u>excluding protons:</u> T unchanged

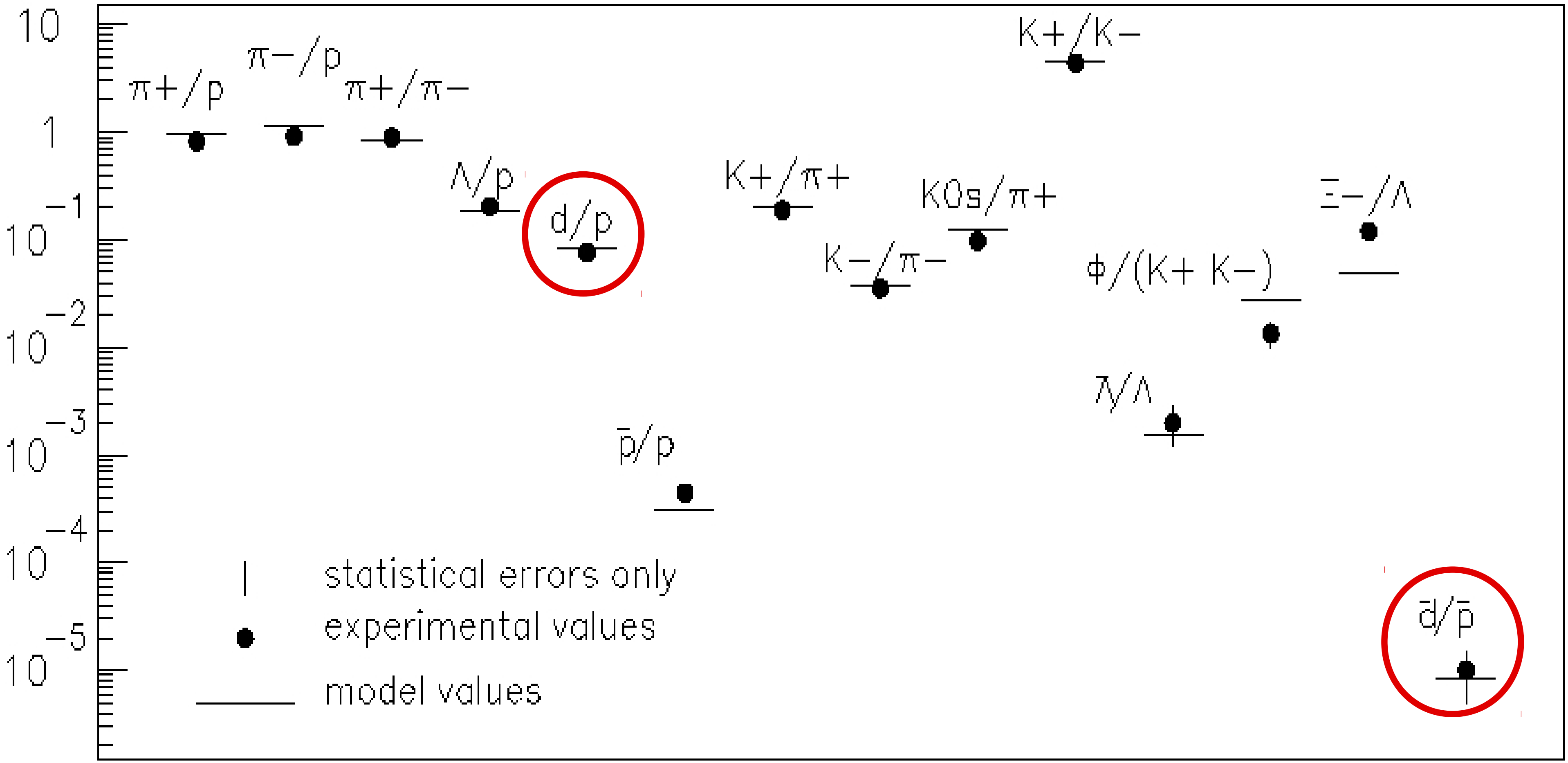
perfect fit for other hadrons

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

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 43 (1979) 1486)
while lightly bound nuclei are destroyed and built again during isentropic expansion, ratio of their abundance doesn't change

for system in thermal equilibrium statistical and coalescence yields agree

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

A.J. Baltz, C.B. Dover, et al., Phys. Lett. B315 (1994) 7

	Thermal Model		
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	$4.0 \cdot 10^{-10}$	$9.6 \cdot 10^{-9}$	$4 \cdot 10^{-8}$
$^{10}_{1}\mathrm{St}^{-8}$	$1.6 \cdot 10^{-14}$	$7.3 \cdot 10^{-13}$	
$^{12}_{1}\mathrm{St}^{-9}$	$1.6 \cdot 10^{-17}$	$1.7 \cdot 10^{-15}$	
$^{14}_{1}\mathrm{St}^{-11}$	$6.2 \cdot 10^{-21}$	$1.4 \cdot 10^{-18}$	
$^{16}_{2}\mathrm{St}^{-13}$	$2.4 \cdot 10^{-24}$	$1.2 \cdot 10^{-21}$	
$^{20}_{2}\mathrm{St}^{-16}$	$9.6 \cdot 10^{-31}$	$2.3 \cdot 10^{-27}$	

Production of light nuclei and antinuclei at the AGS

<u>data cover 10 oom!</u>

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

<u>GC statistical model:</u>

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

for T=124 MeV and μ_b= 537 MeV

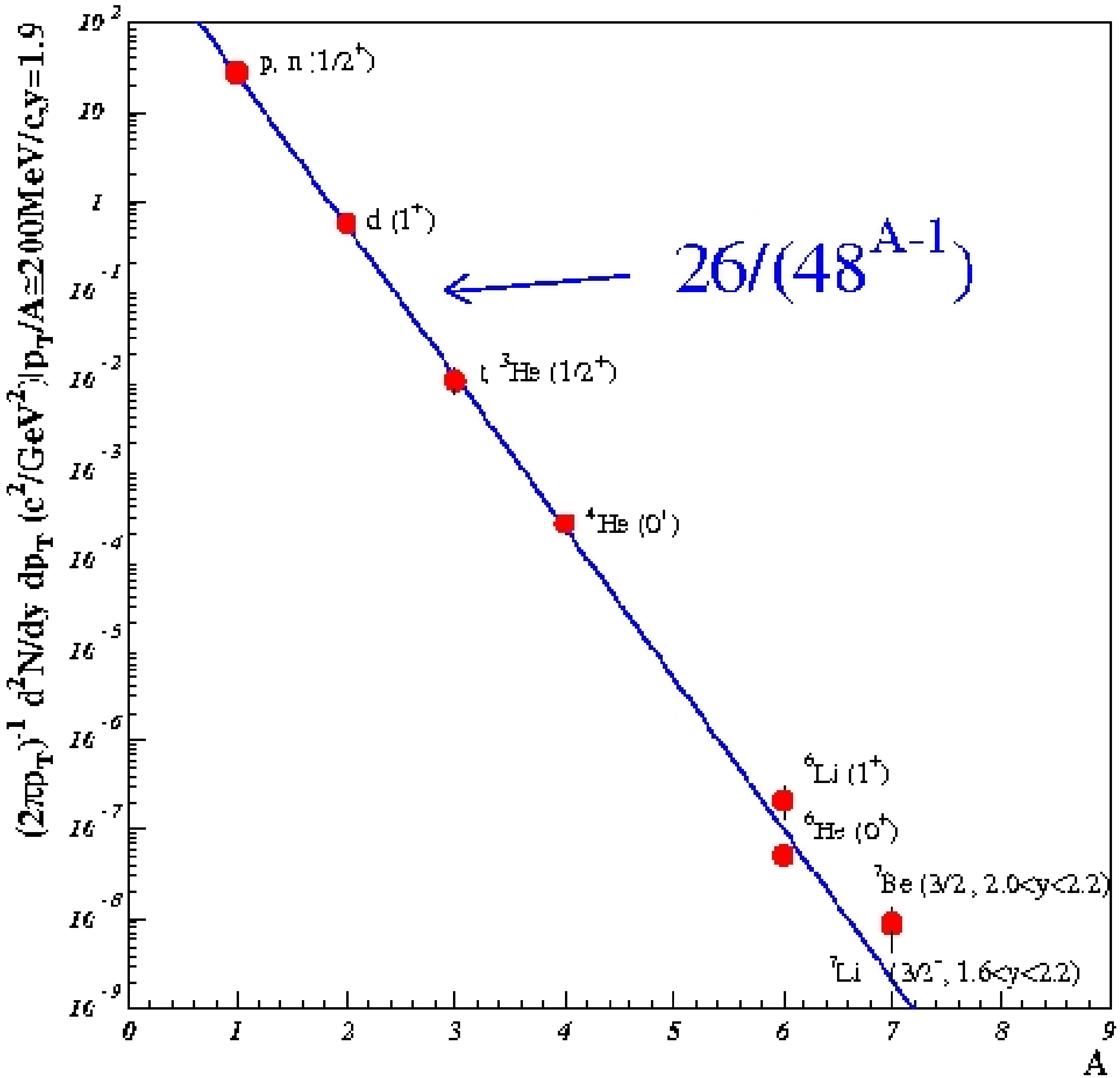
R_p = 24 good agreement

also good for **antideuterons**:

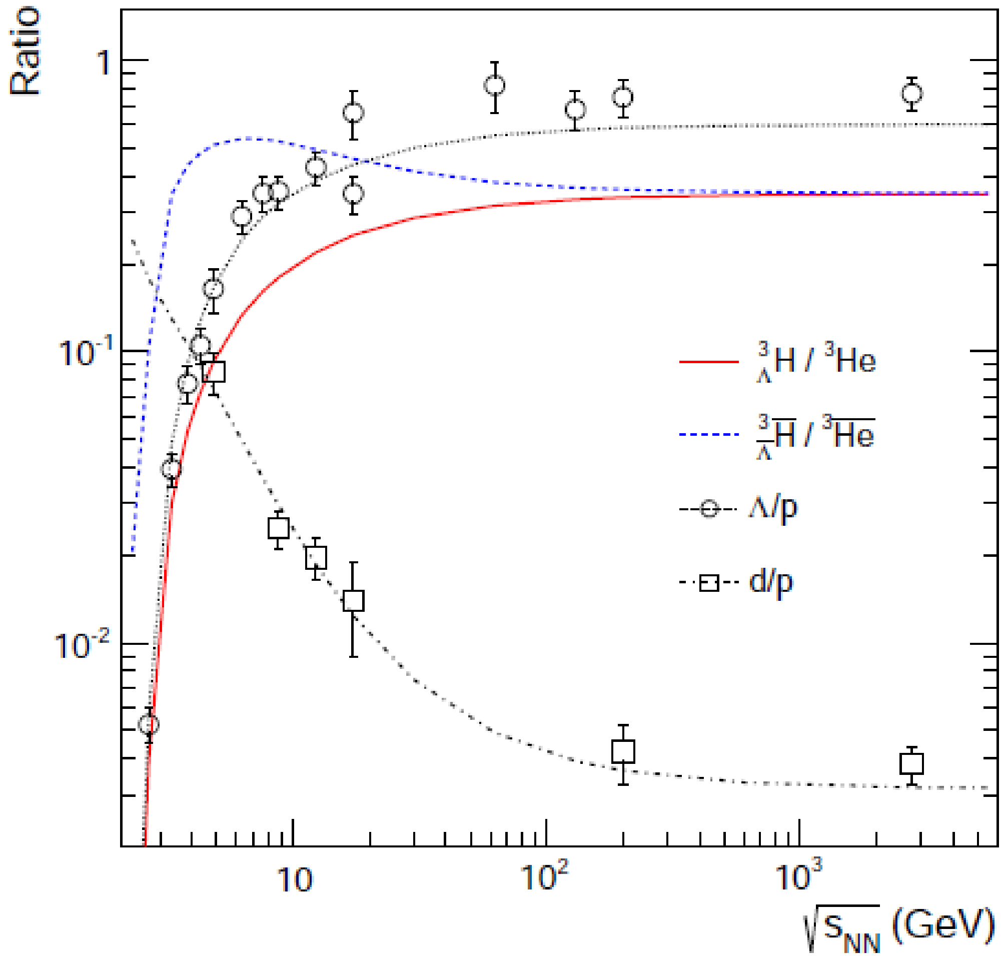
data: $R_p = 2 \pm 1 \cdot 10^5$ SM: $1.3 \cdot 10^5$

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

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



energy dependence of d/p ratio and themal model prediction



agreement of data from Bevalac/SIS energies up to LHC
with thermal model prediction
A.Andronic, P.Braun-Munizinger, J.S., H. Stöcker, PLB697 (2011)203

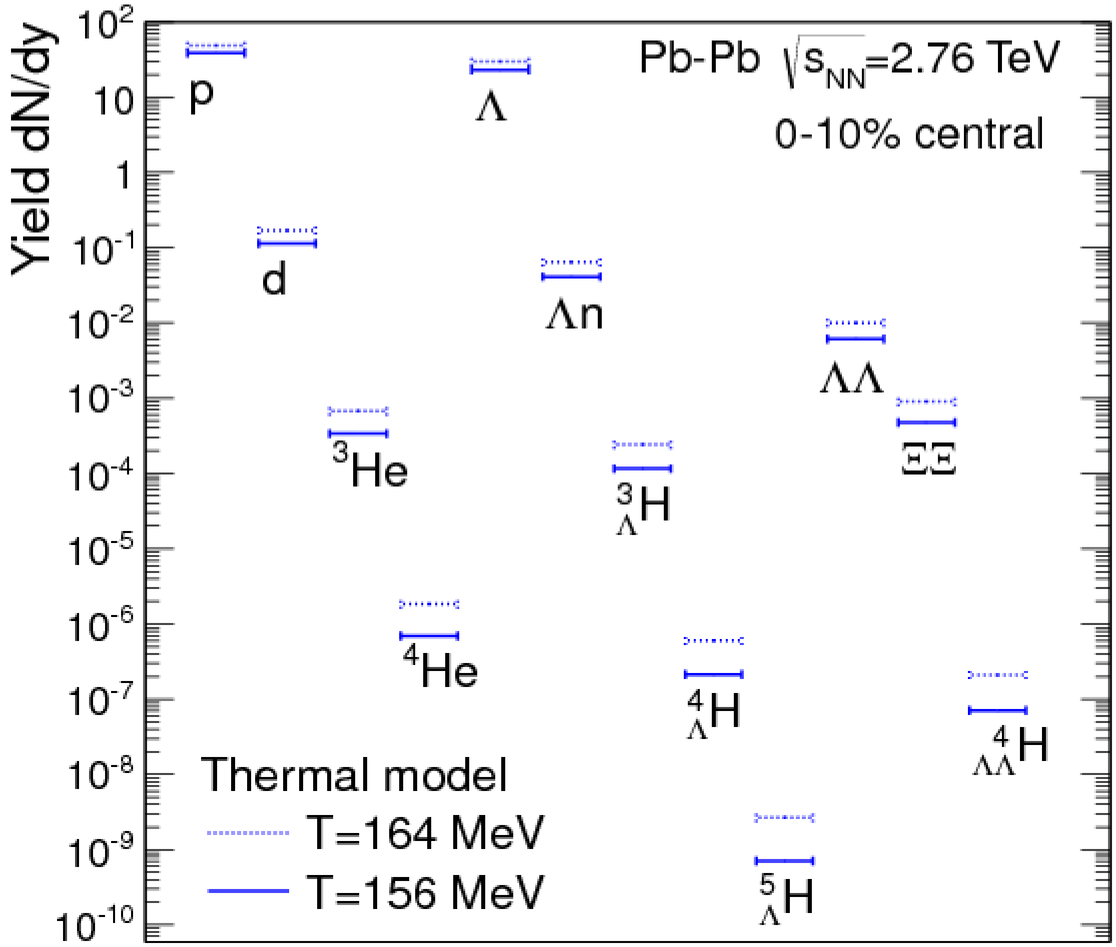
Out-of-equlibrium model of hadronization

J. Rafelski and collaborators

introduction of additional chemical potentials

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

Predictions for nuclei and hypernuclei and exotica



^{3}He and $^{3}{}_{\Lambda}$H were prediction and are in excellent agreement with new data from ALICE

test of statistical hadronization model over another 3 orders of magnitude

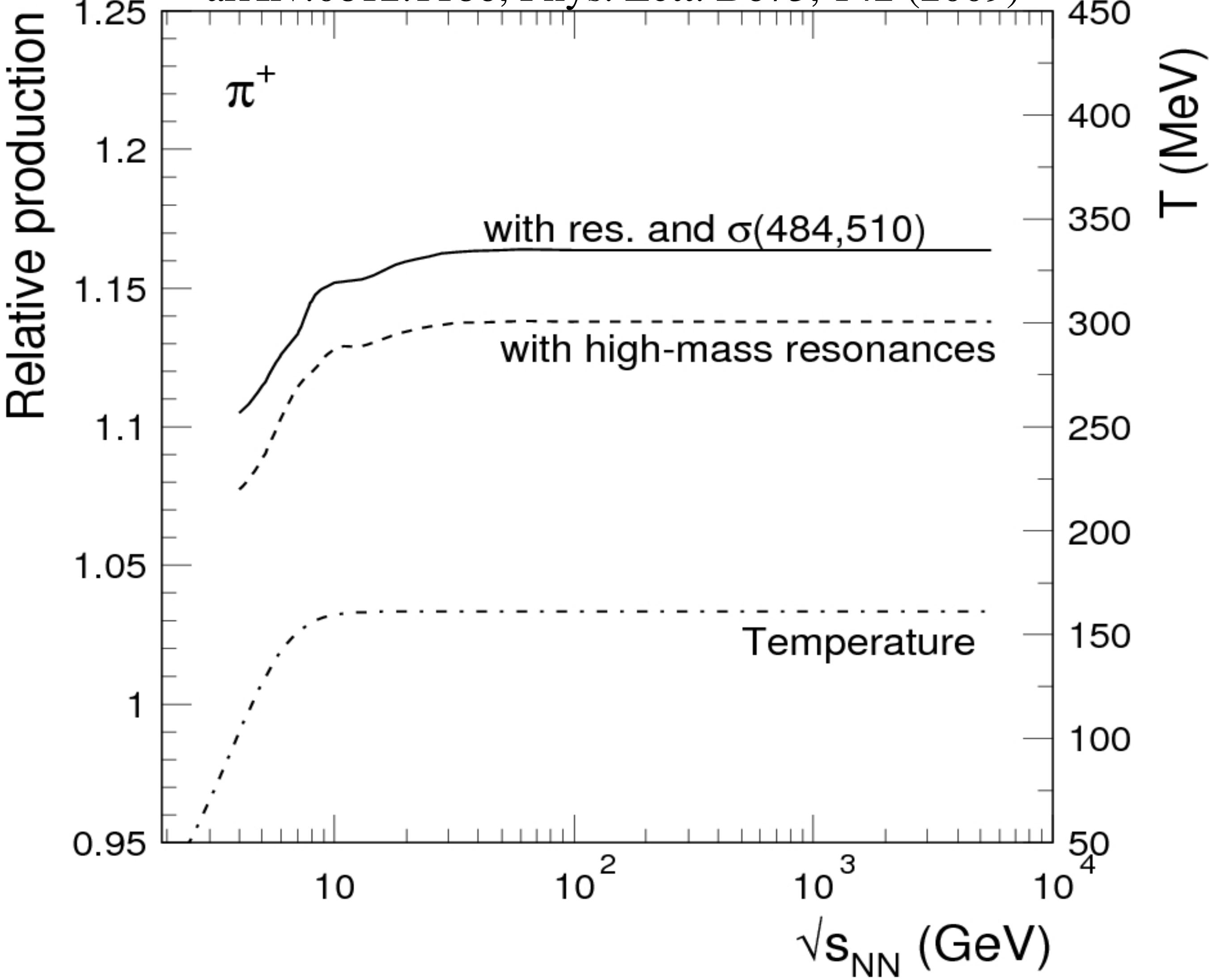
possible reasons for low proton yield

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

effect of incomplete hadron spectrum

relative change in pion yield with more high mass resonances and the σ

A. Andronic, P. Braun-Munzinger, J. Stachel, arXiv:0812.1186, Phys. Lett. B673, 142 (2009)



as T levels off, so does the increase in pion yield

Effect of incomplete hadron spectrum

we studied this for K/π ratio:

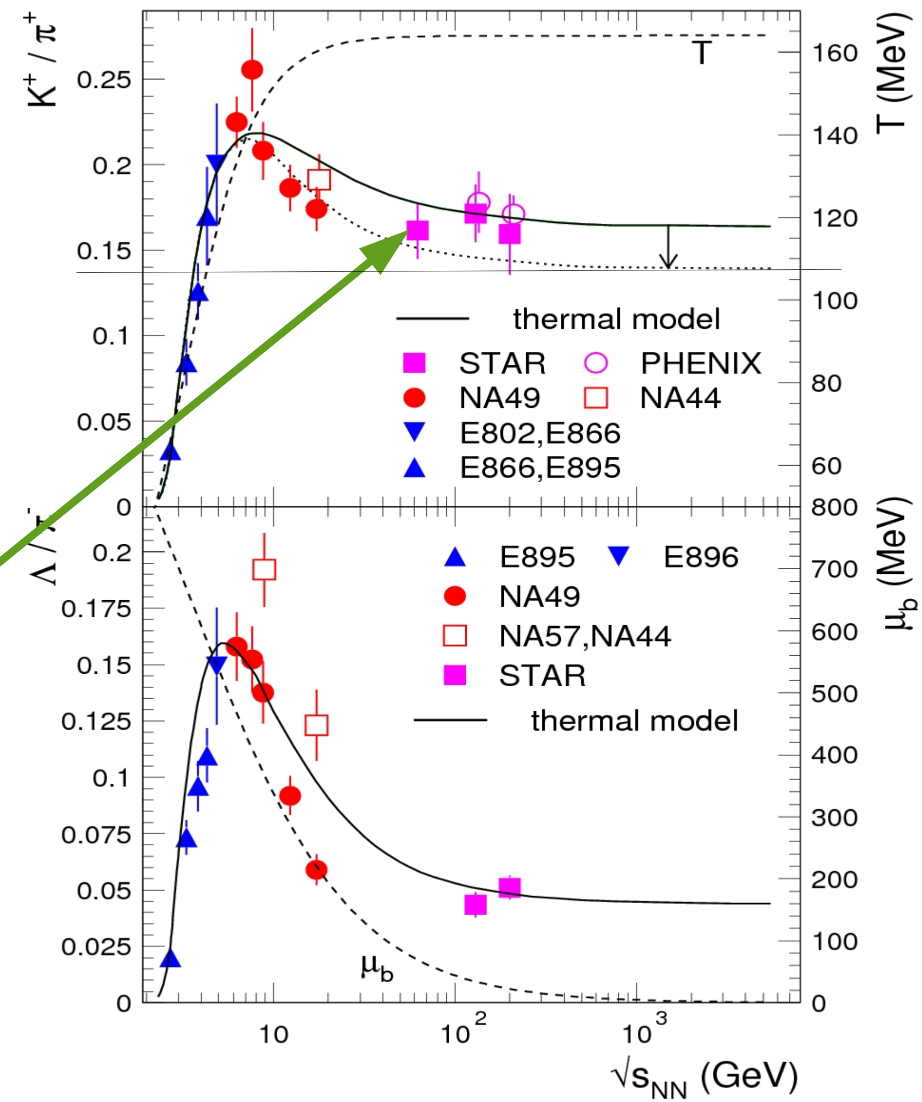
(Andronic, Braun-Munzinger, JS Phys. Lett. B673 (2009) 142)

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

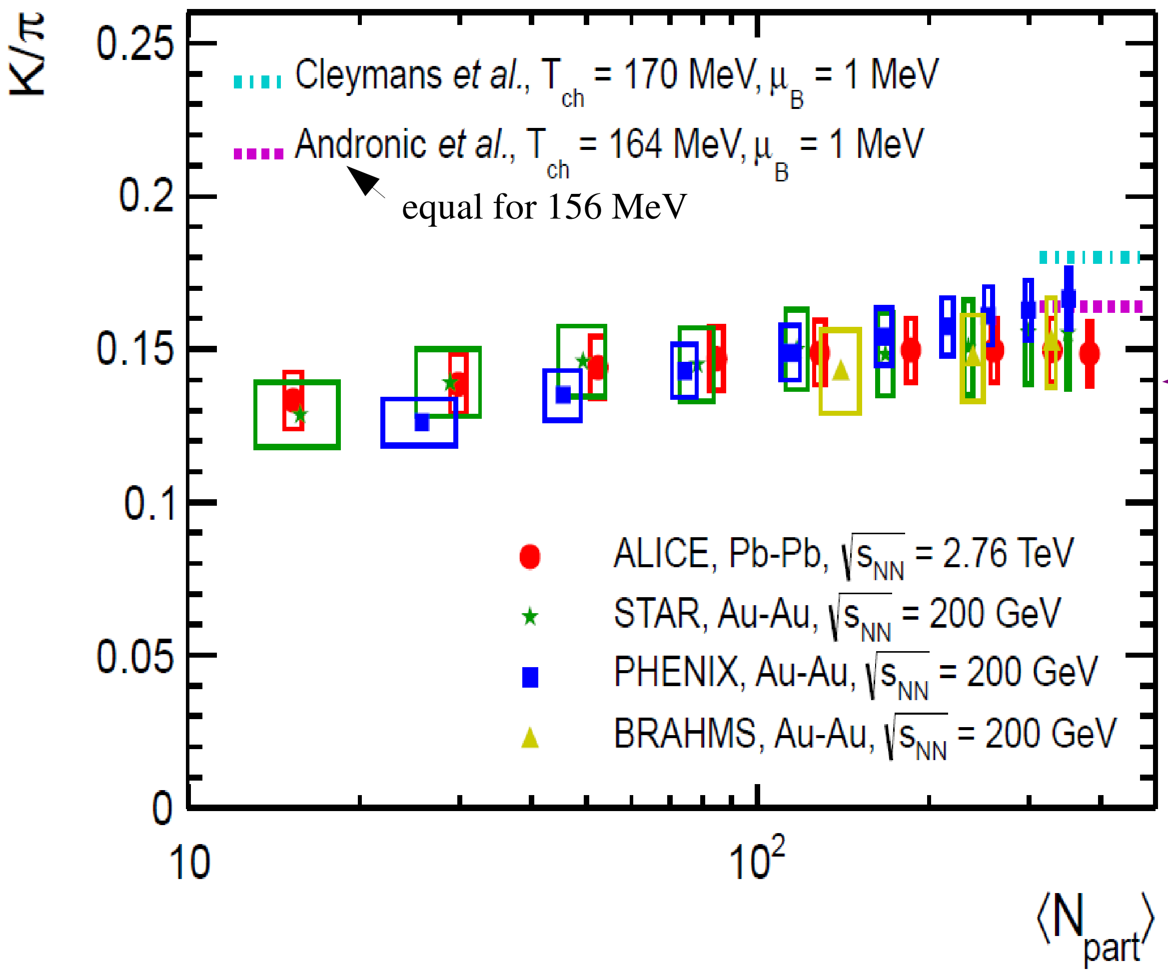
strongest contribution to kaon from K* producing one K

all high mass resonances produce multiple pions

-> further reduction of K^+/π^+

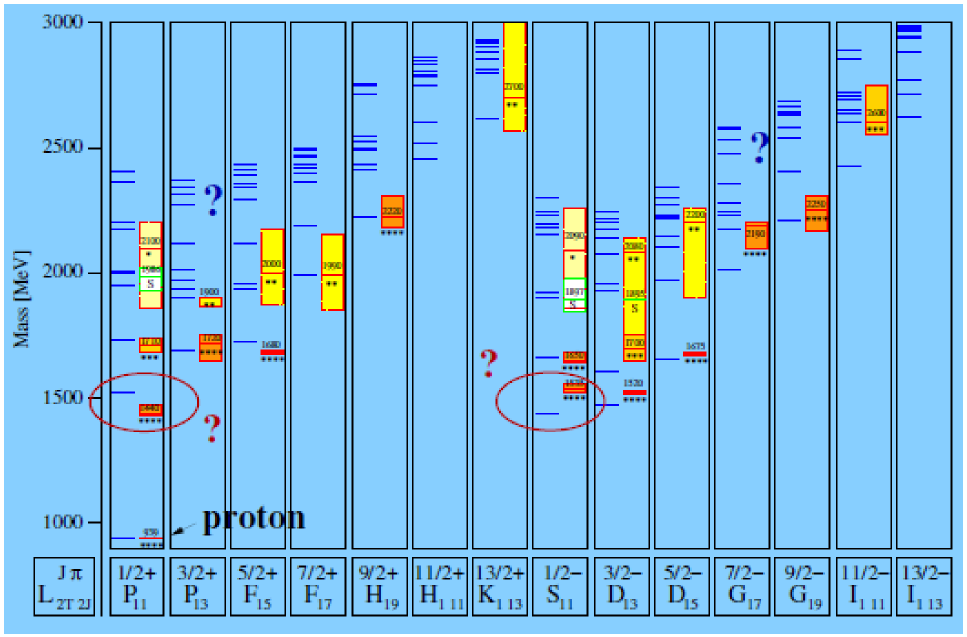


estimate of 'guessing' the Hagedorn spectrum



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)



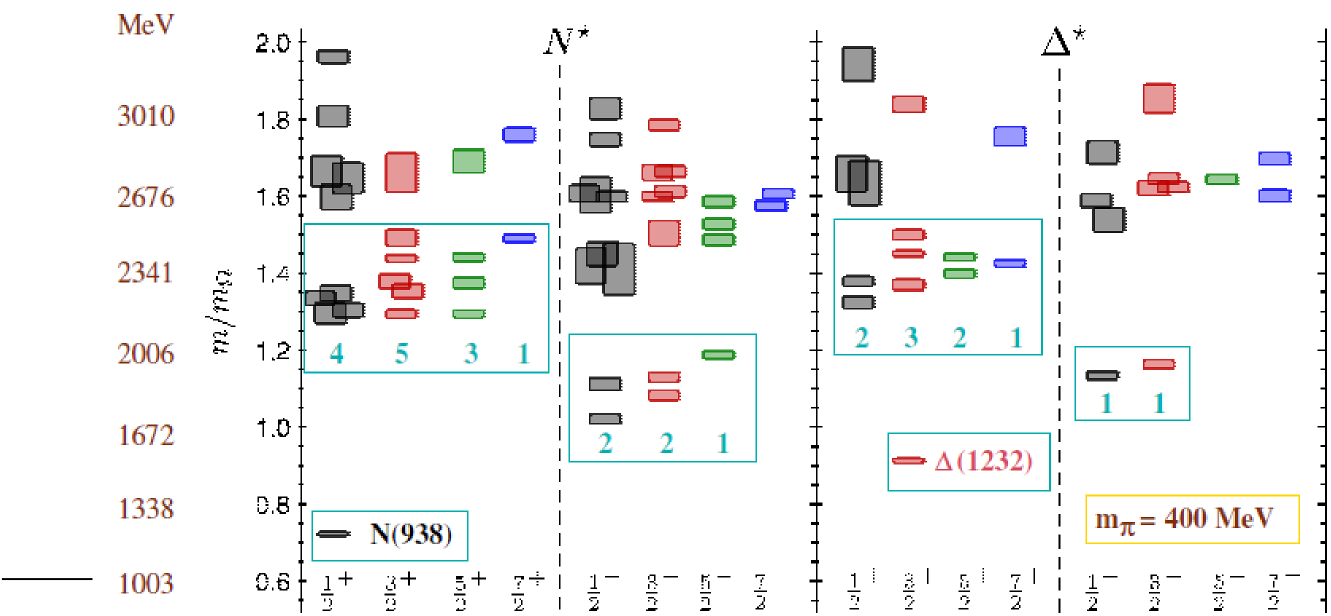
from talk U. Thoma DPG2013

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

annihilation in the hadronic phase?

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

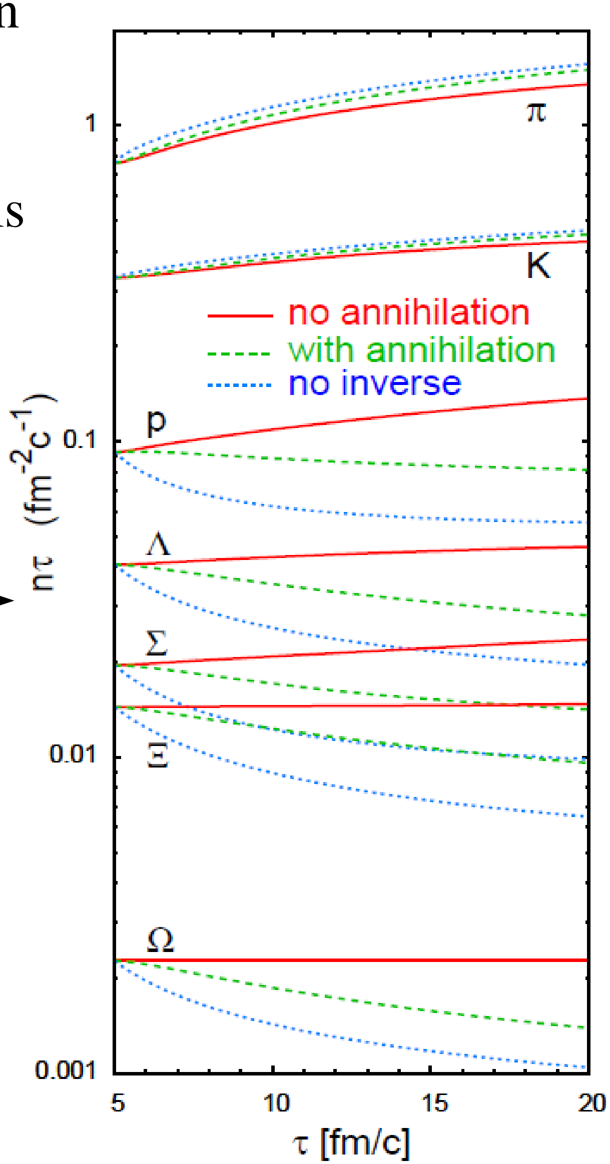
Evaluate hadronic interactions after statistical hadronization using RQMD
find significant effect of apparent cooling due to hadron rescattering

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

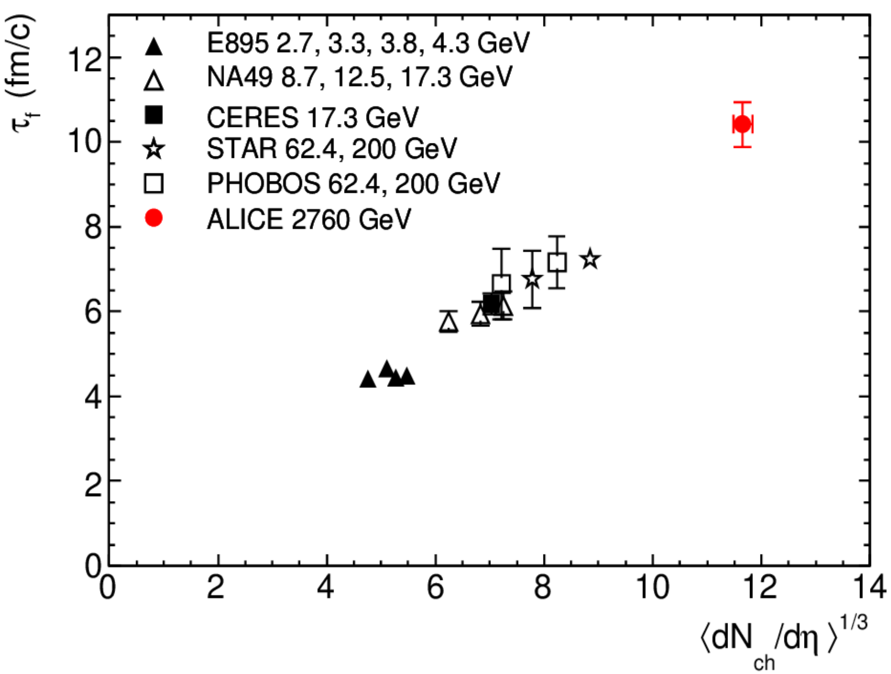


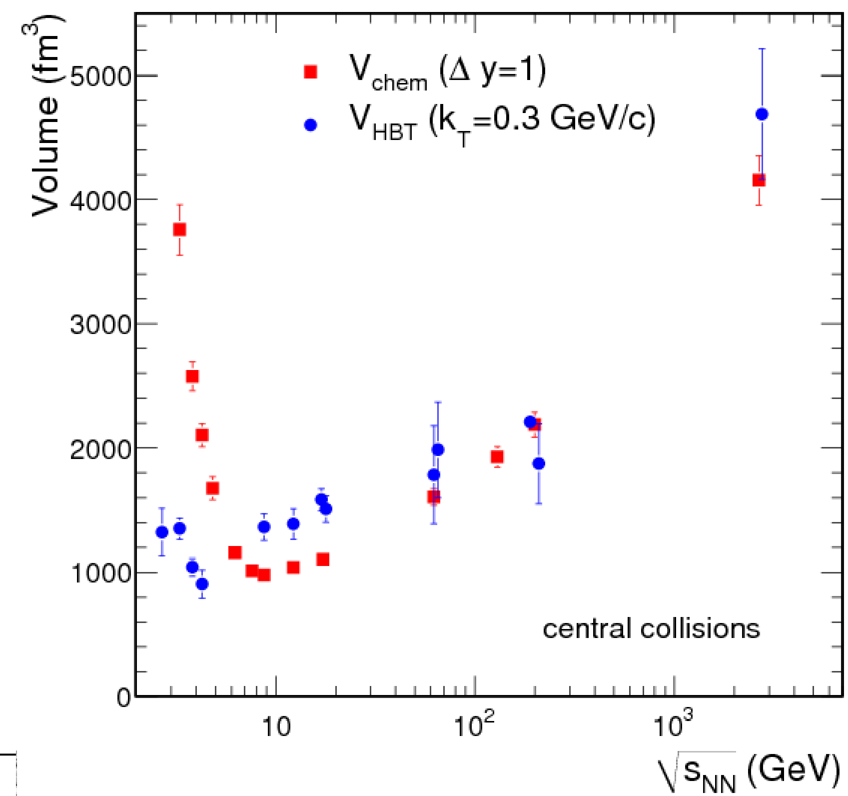
- Why should only proton be affected? and not hyperons? Cross sections should be very similar, e.g. Ω + Nbar $\rightarrow 2\pi$ + 3K evalute 10 mb at threshold Braun-Munzinger, JS, Wetterich, Phys. Lett. B596 (2004) 61
- they show if anything opposite effect
- what about nuclei?? they fit perfectly and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

annihilation in hadronic phase

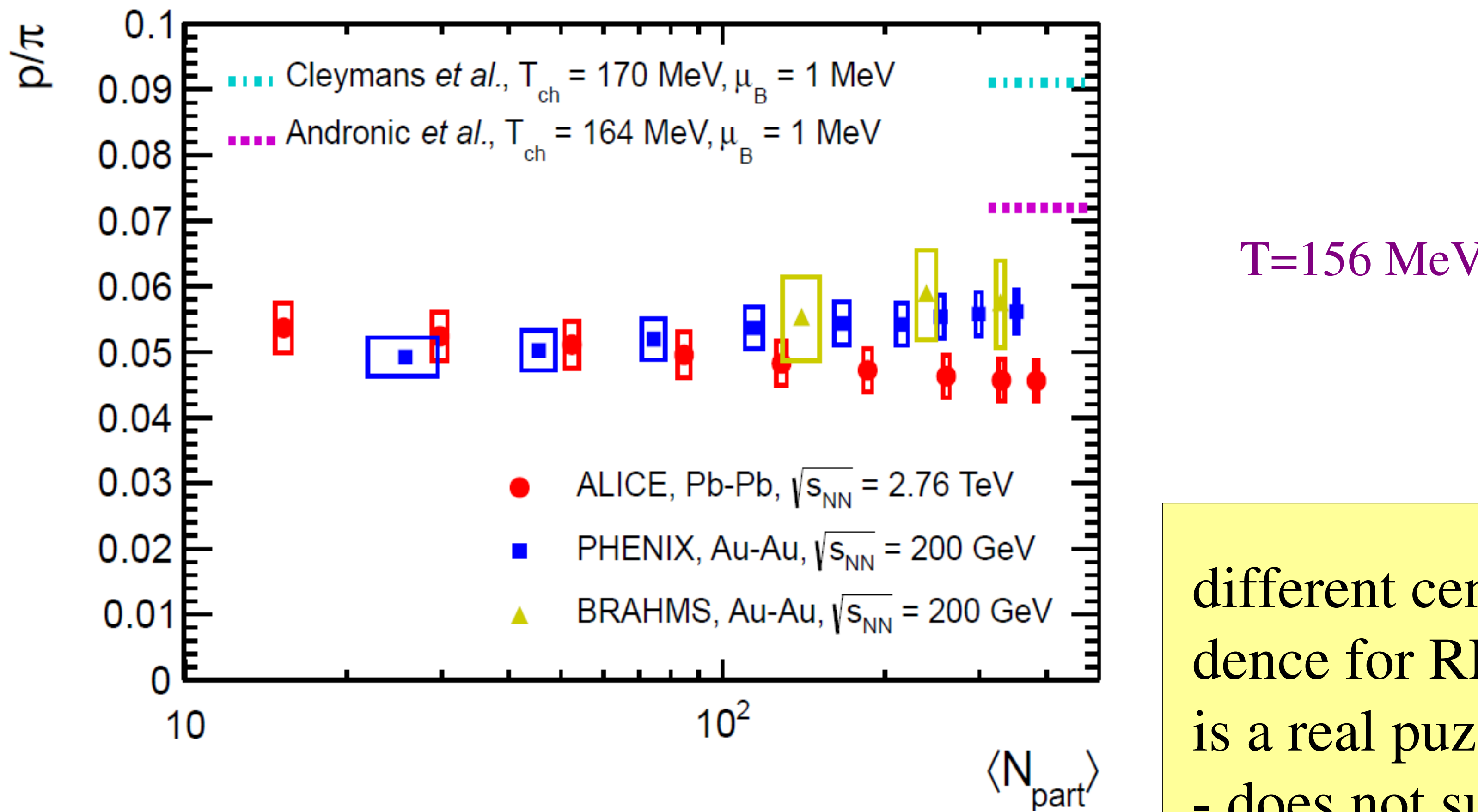
all of this casts serious doubts on the reduction of protons only due to annihilation in hadronic phase

additional argument: in RQMD lifetime of hadronic phase significantly too long (from HBT: 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



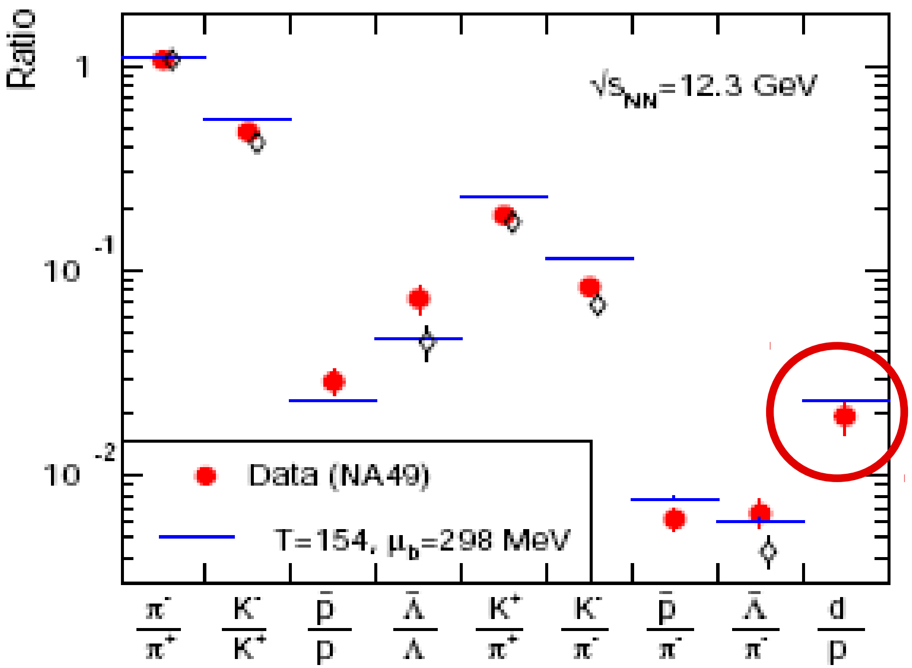


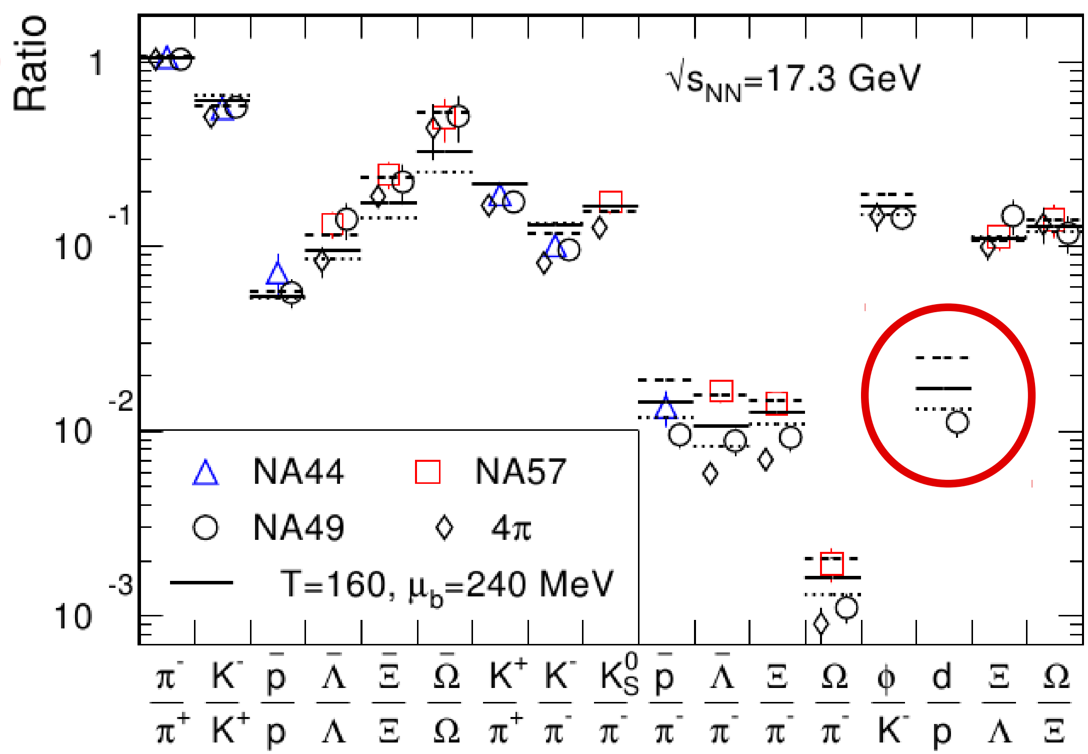
Centrality dependence of proton to pion ratio



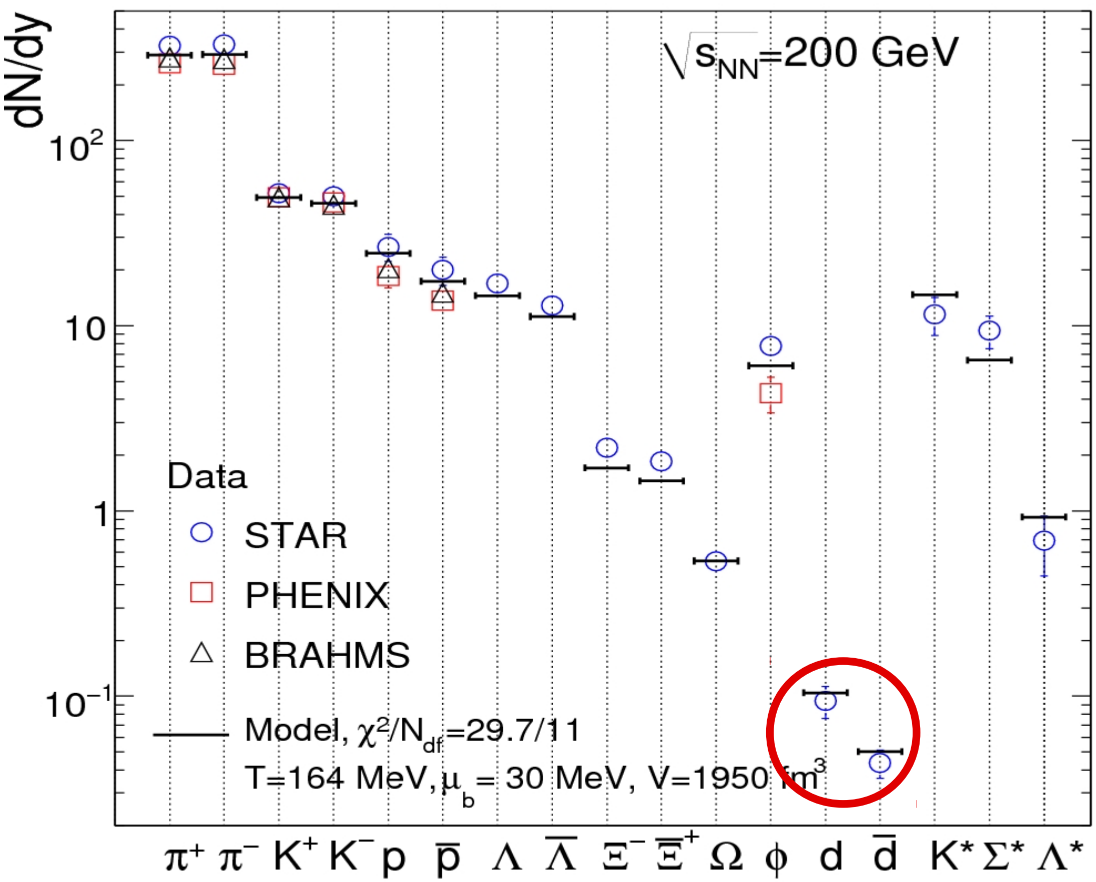
different centrality dependence for RHIC and LHC is a real puzzle
- does not support annihilation picture
- is it real? physics origin?

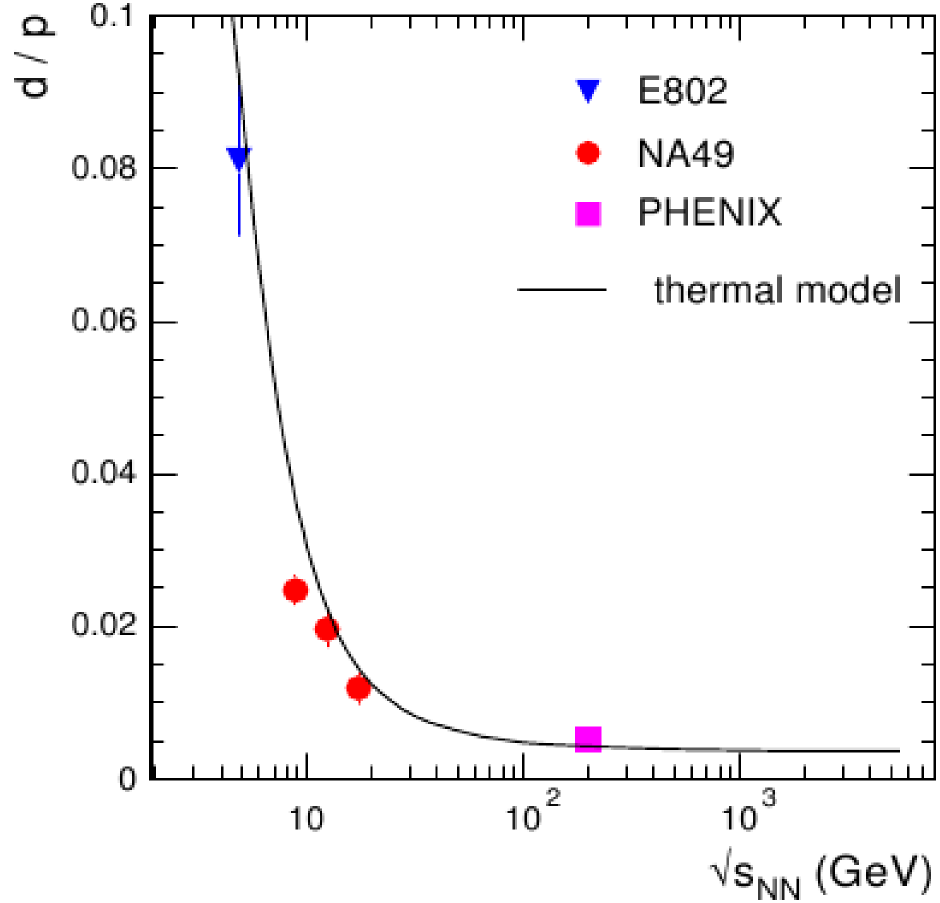
Deuterons at SPS energies reproduced as well



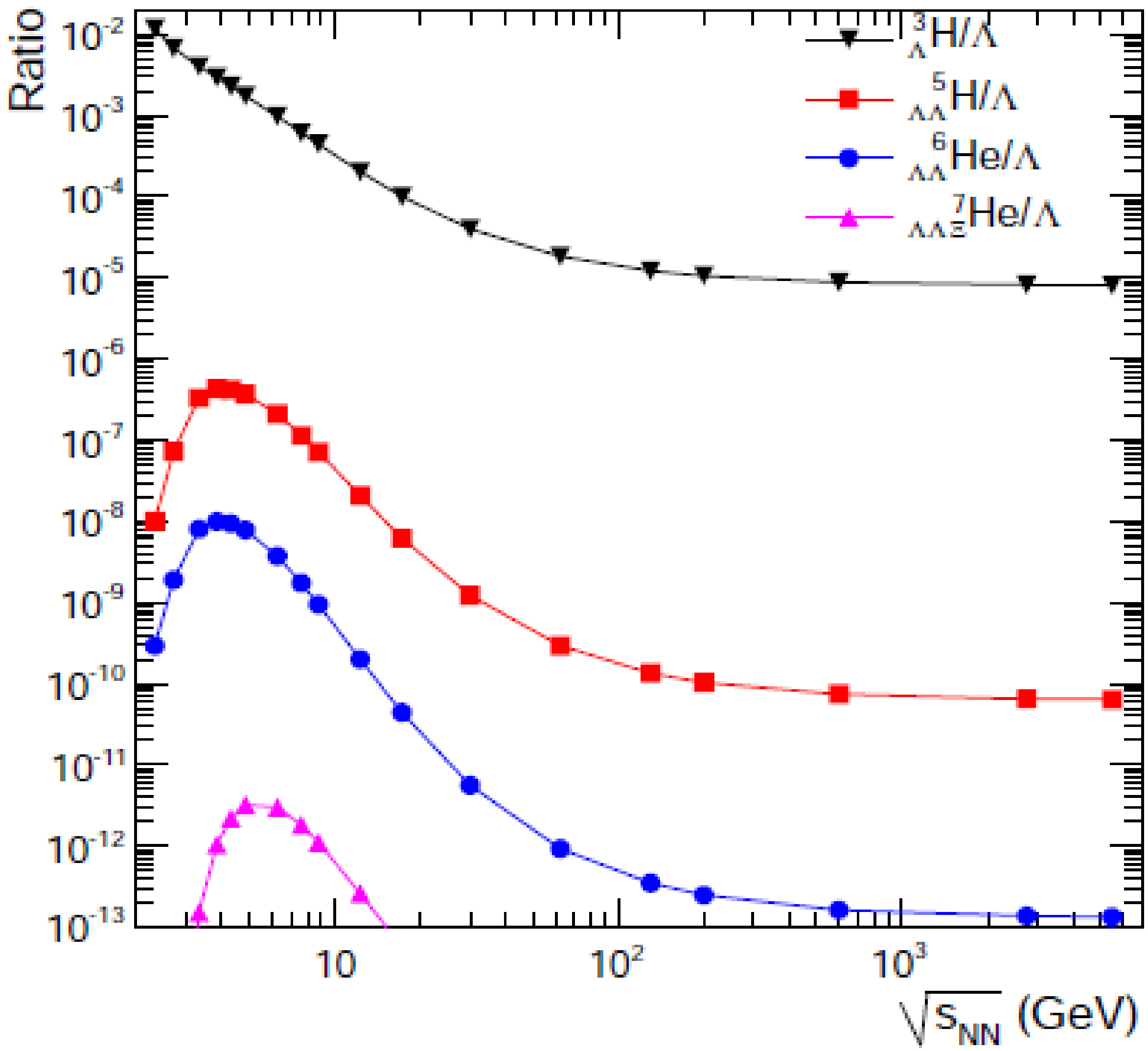


and at RHIC description equally good
- beam energy dependence driven by μ_b





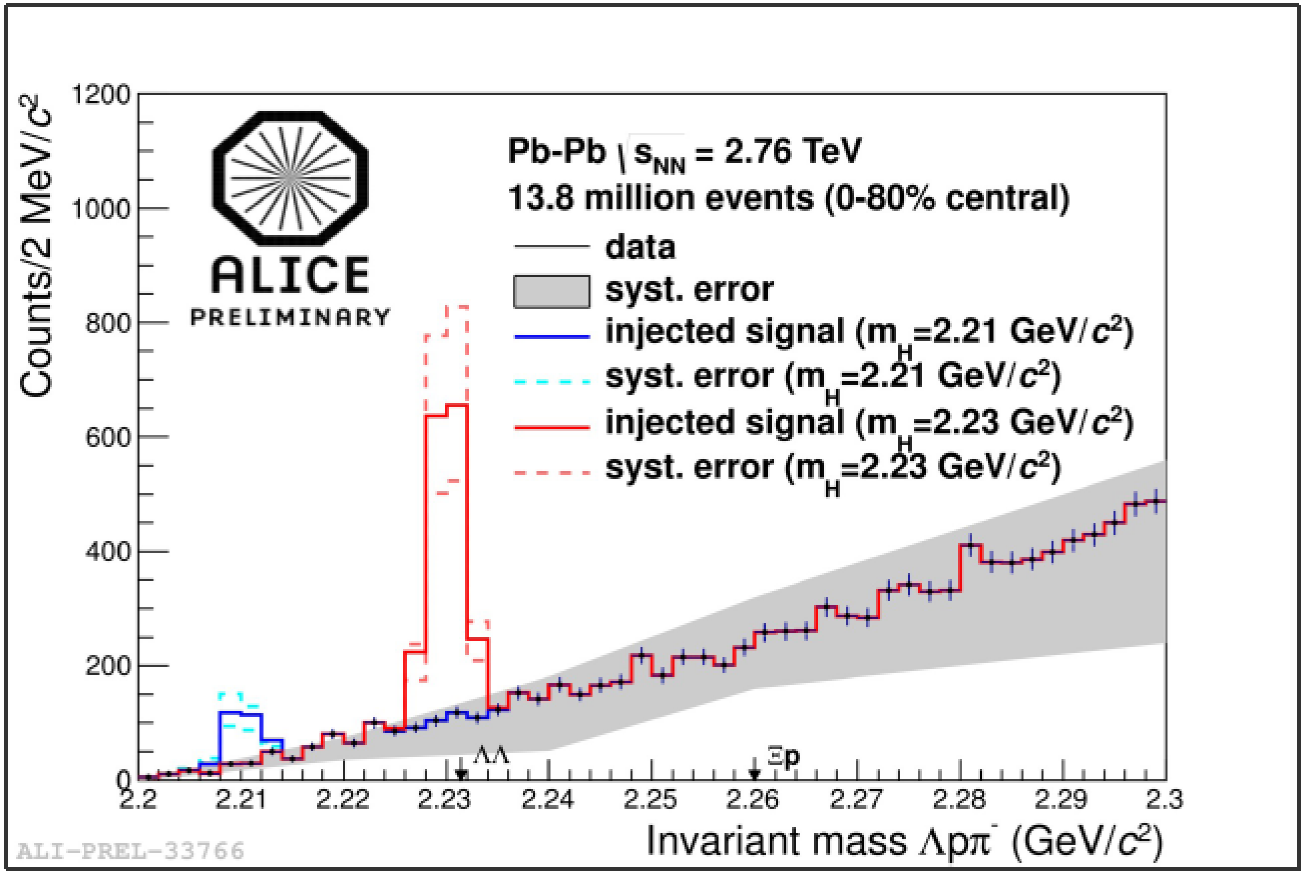
Energy dependence of the yields of exotic objects



note: yield peaks at low (SIS100) energies
an exciting but tough prospect for FAIR

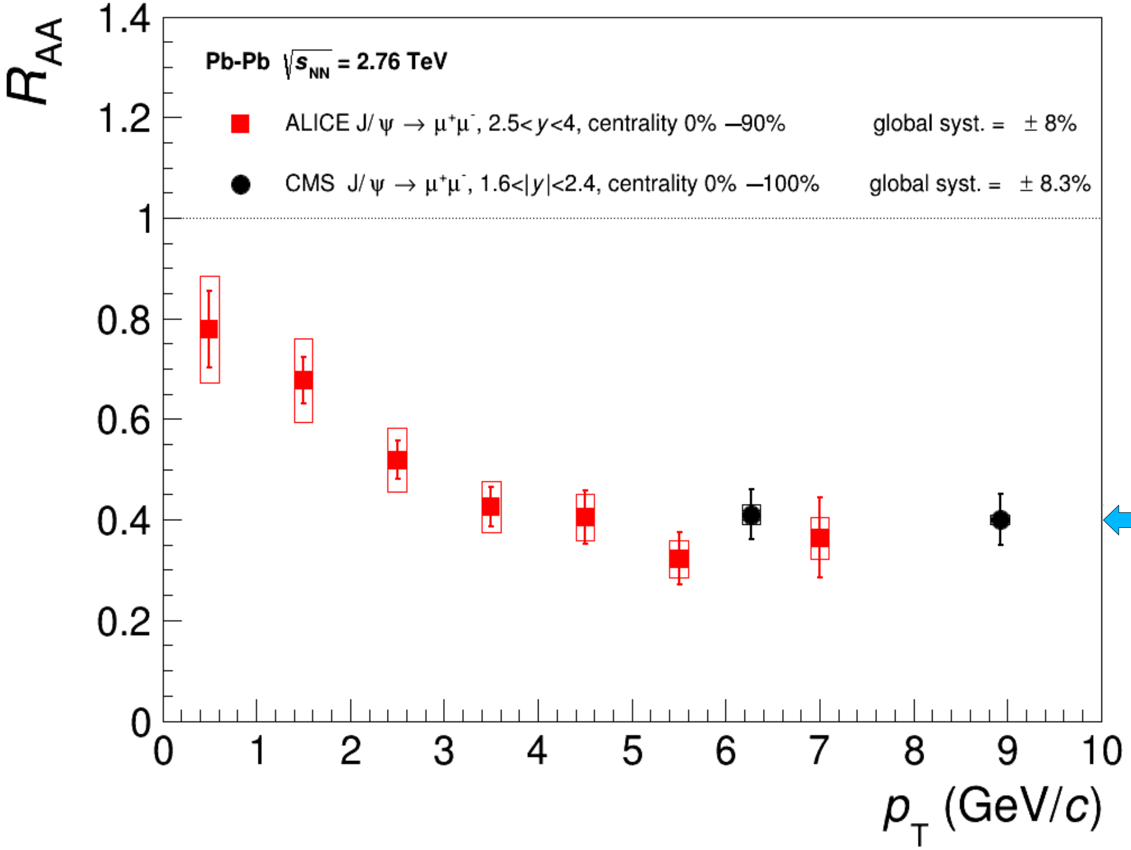
example: search for H-Dibaryon

Ramona Lea, SQM2013



No signal observed, H yield is < 0.1 x (thermal model prediction)
Much more stringent limits to come soon

p_t dependence of R_{AA}

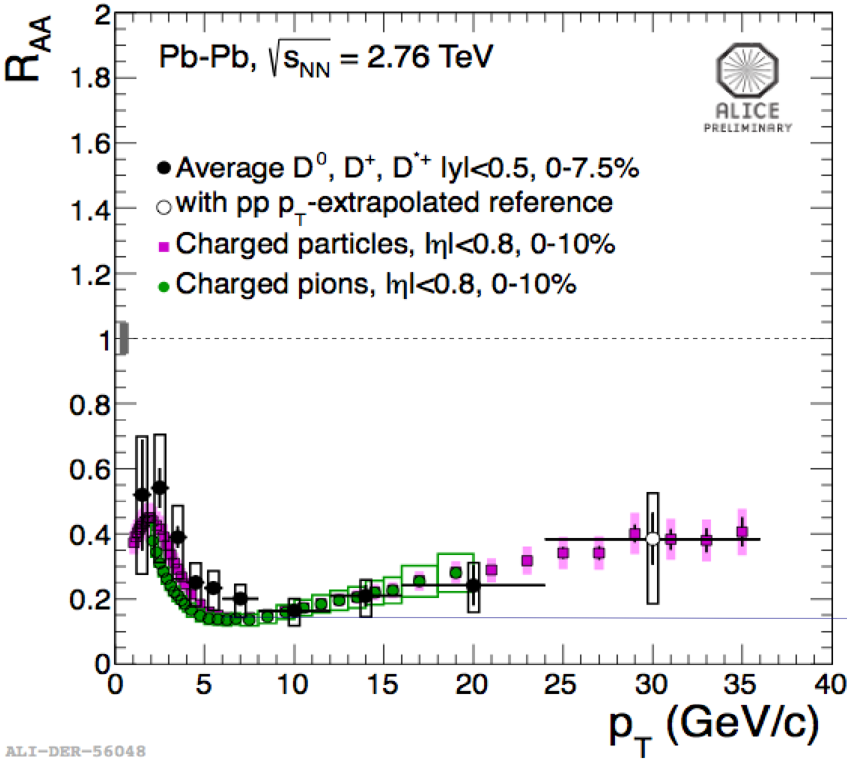


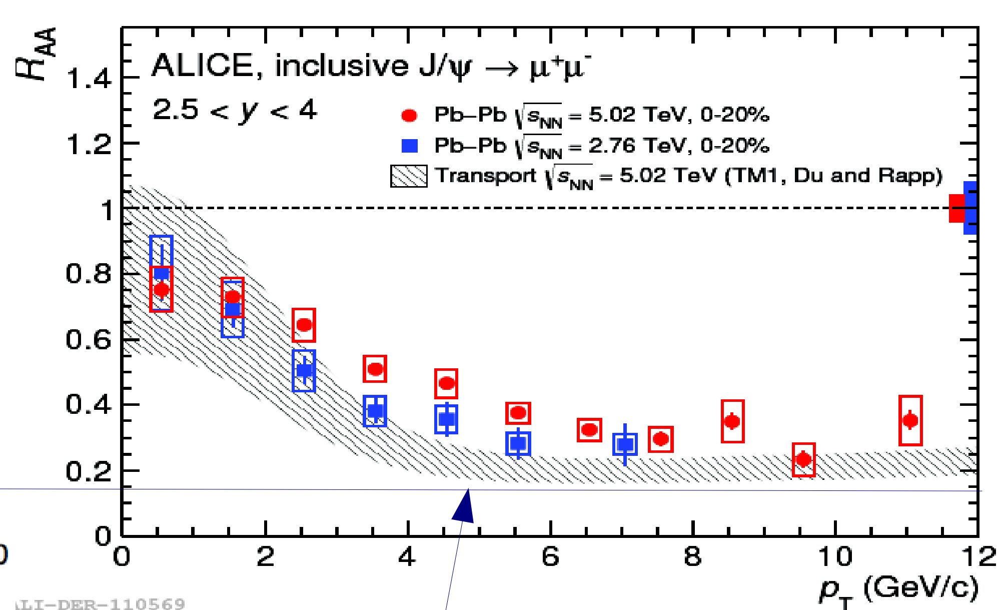
relative yield larger at low p_t in nuclear collisions

what effects to expect?

- statistical hadronization in p_t range where charm quarks are reasonably thermal
- modification of spectrum relative to pp due to radial flow
- suppression in R_{AA} due to charm quark energy loss (see D mesons)

p_t dependence of R_{AA}

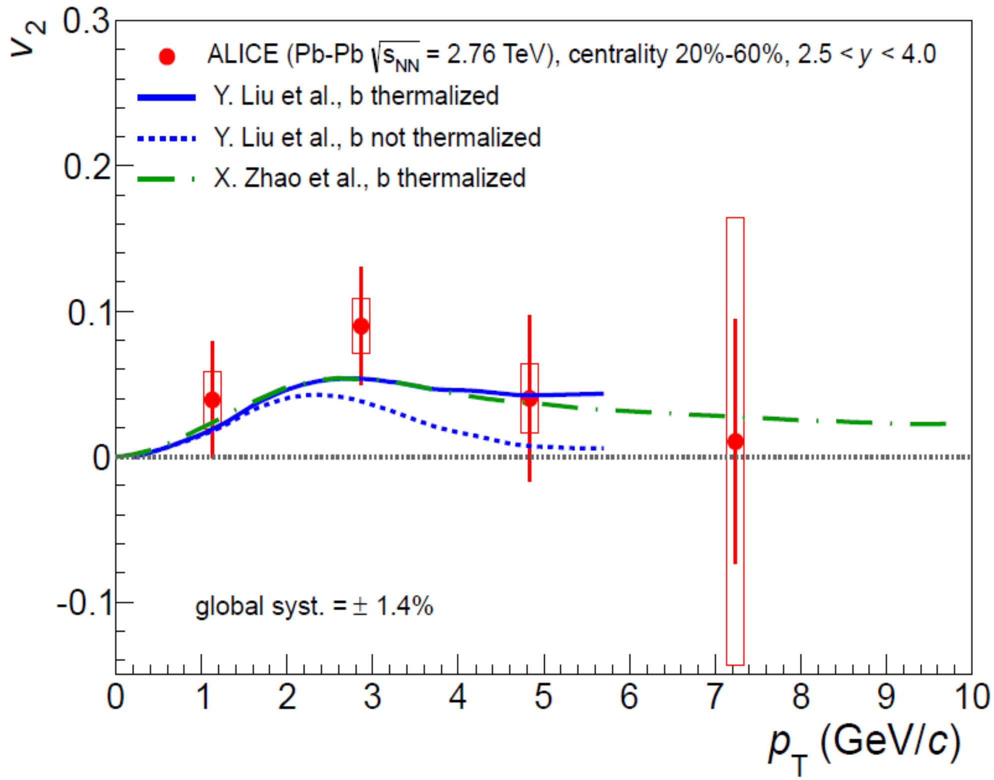




is high p_t part indicative of the same charm quark energy loss seen for D's out to what p_t is statistical hadronization/regeneration relevant?

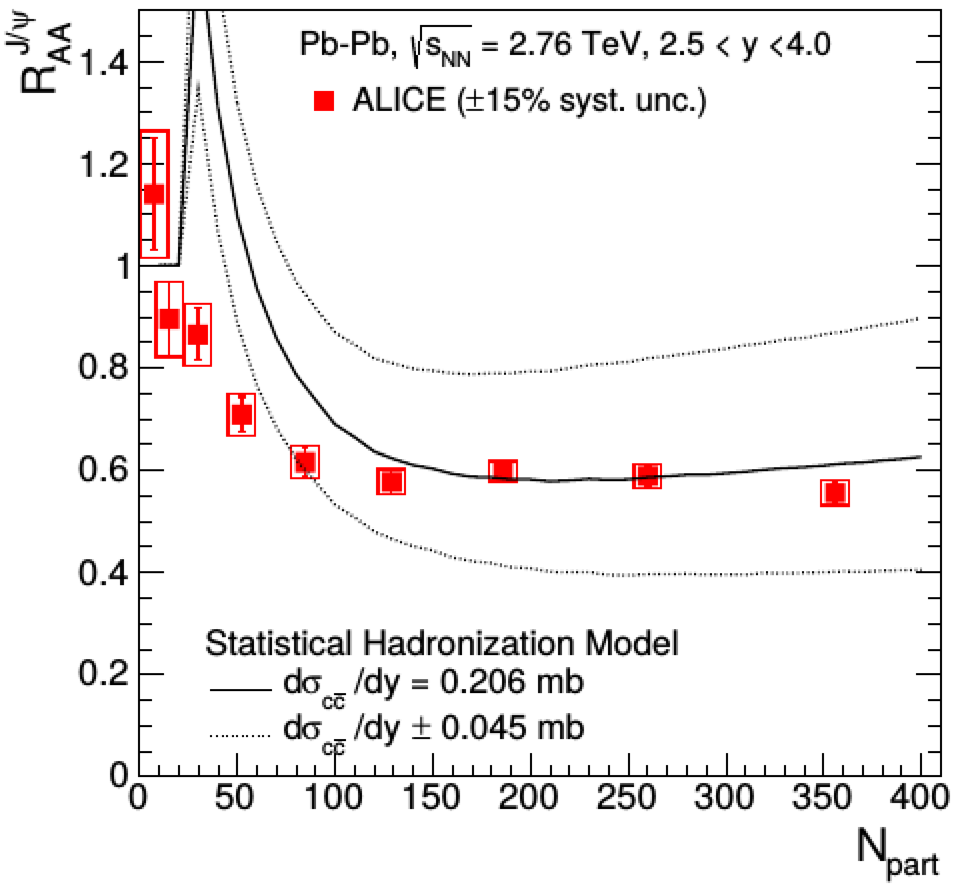
J/ψ flow compared to models including (re-) generation

PRL 111 (2013)162301 arXiv:1303.5880

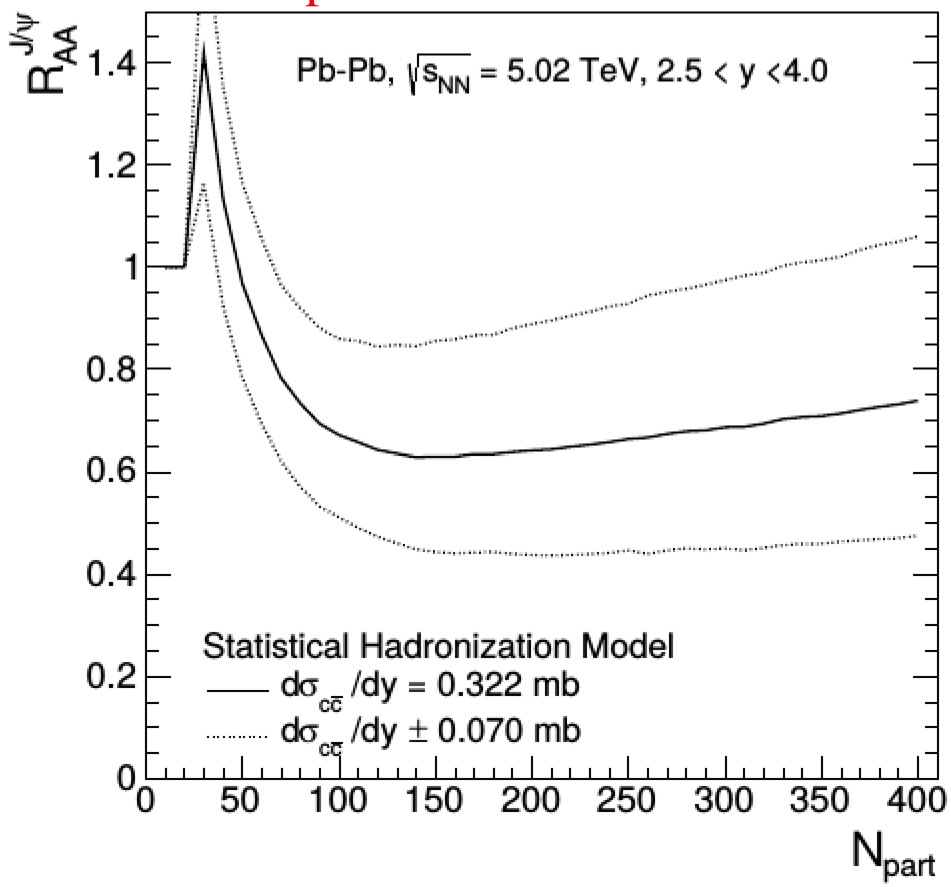


v_2 of J/ψ consistent with hydrodynamic flow of charm quarks in QGP and statistical (re-)generation

newest results with updated charm cross section



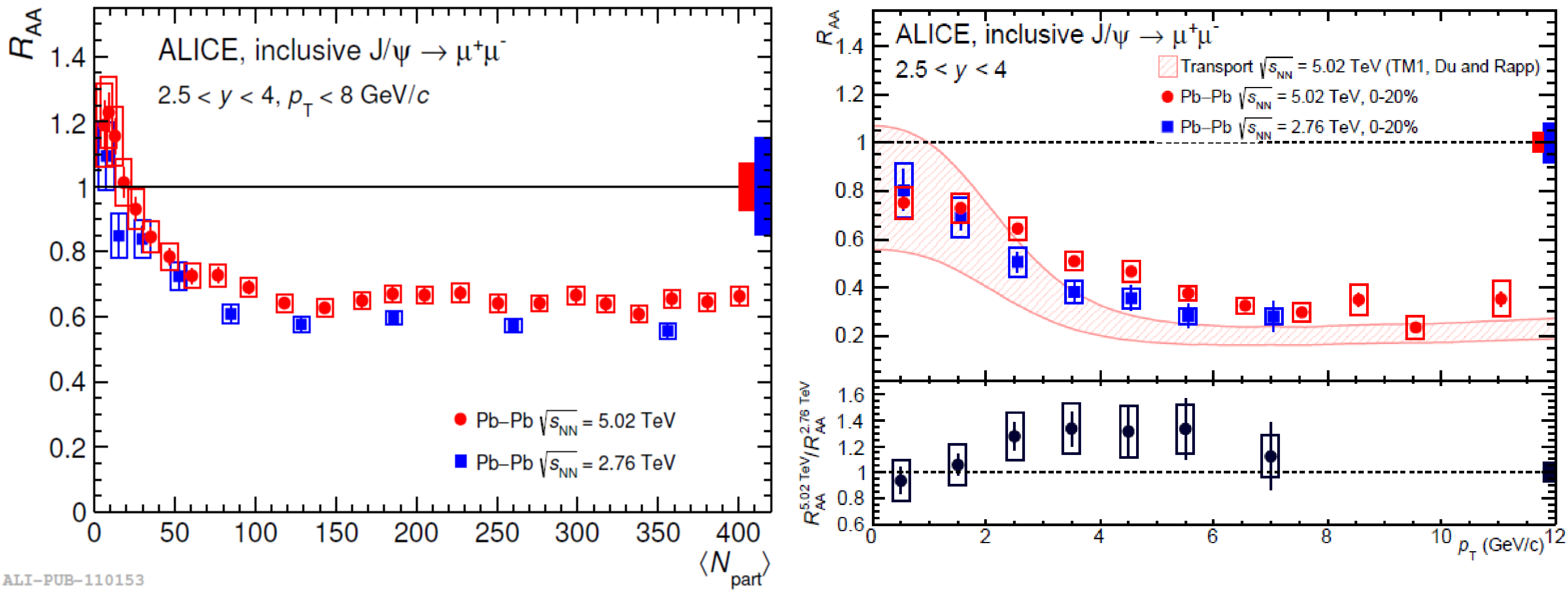
prediction for run2



to constrain models more: need precise ccbar cross section for PbPb
for sqrt(s_NN) = 5 TeV expect increase for central collisions by about 10-15%
transport models should use this same ccbar cross section

J/ψ in PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV

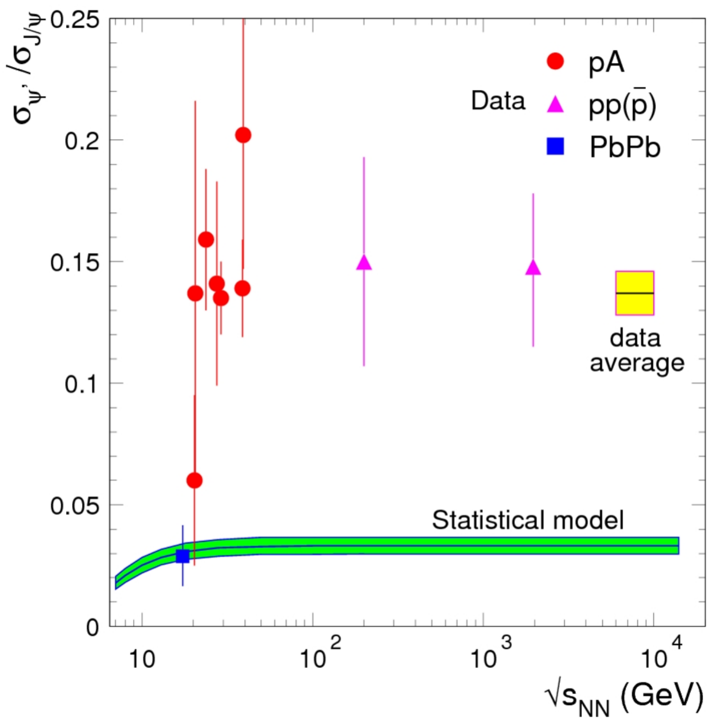
arXiv:1606.08197 [nucl-ex]

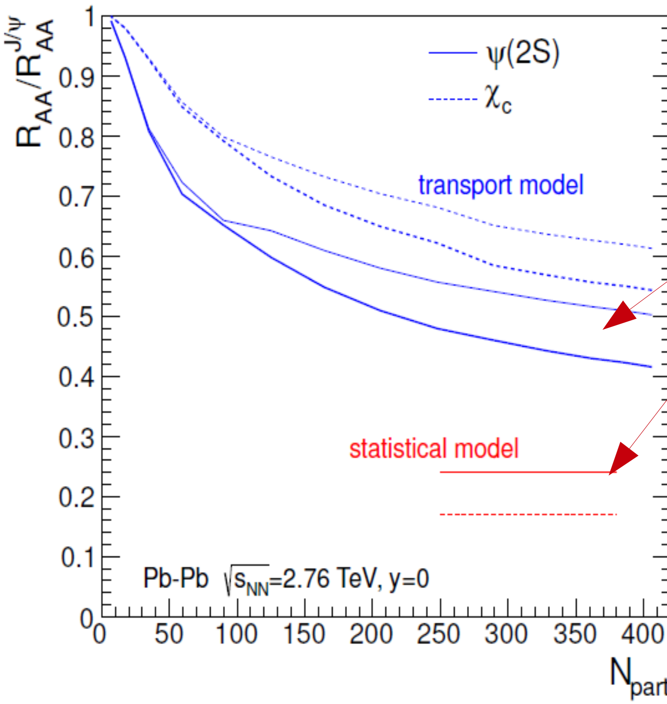


$R_{AA}^{0\text{-}90\%}(5.02\text{ TeV}) / R_{AA}^{0\text{-}90\%}(2.76\text{ TeV}) = 1.13 \pm 0.02(\text{stat}) \pm 0.18(\text{syst})$

increase of J/ψ R_{AA} for all centralities and over large range of p_t (but within 1 σ)

excited charmonia crucial to distinguish between models





in fact here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

for statistical hadronization need to see suppression by Boltzmann factor

χ_c even bigger difference

expected ALICE performance muon arm run2 and run3