Production of hadrons with light and heavy quarks and the QCD phase boundary

- soft probes
- charm content of the FCC fireball
- charmonia

FIAS-Frankfurt

Sundry topics on QGP physics at the FCC

In collaboration with
Anton Andronic, Krzysztof Redlich, Johanna Stachel

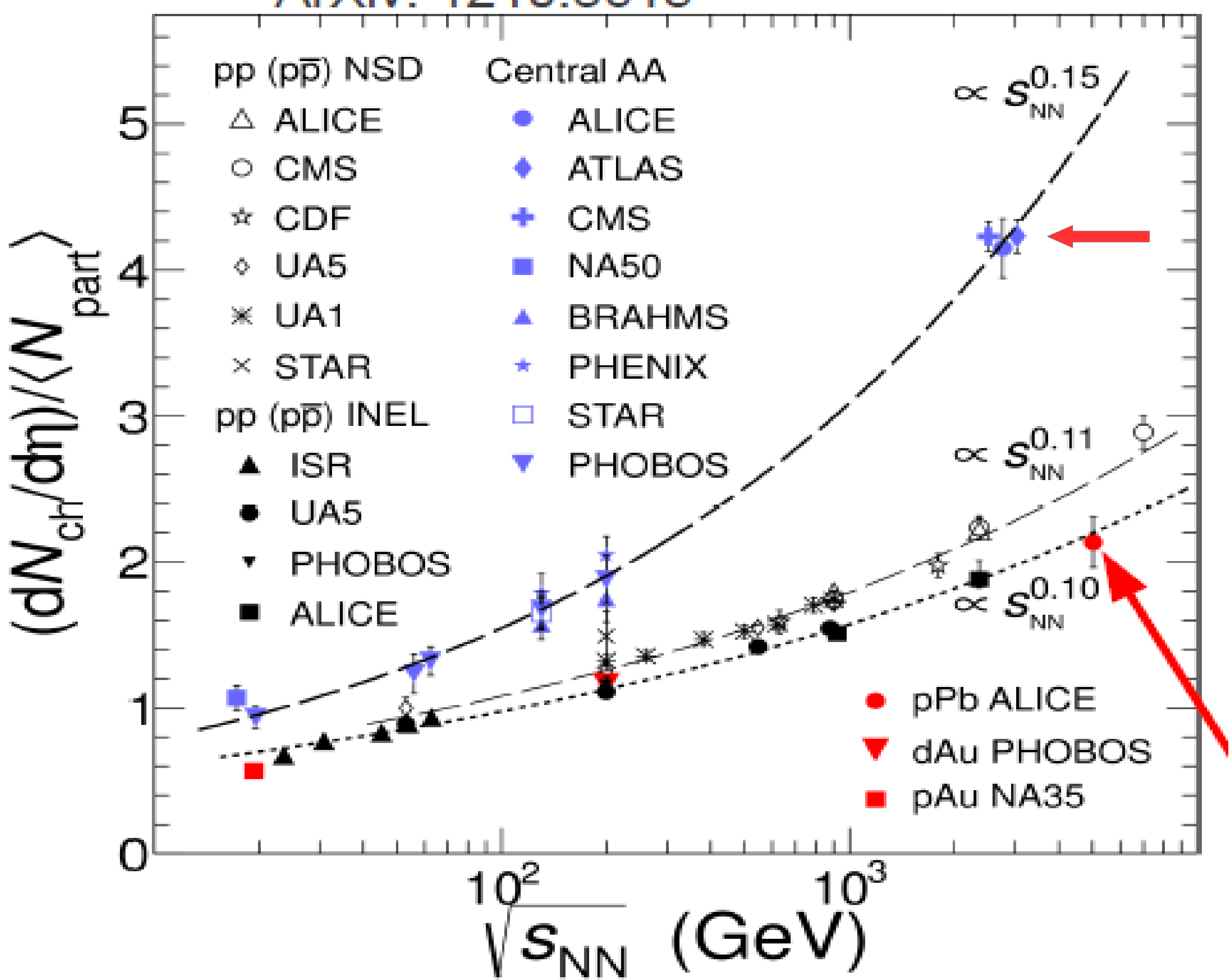
FCC workshop
CERN
Sep. 22-23, 2014

Peter Braun-Munzinger

Hadron production and the QCD phase boundary

Charged particle multiplicity in pp, pPb and central PbPb collisions

ArXiv: 1210.3615



increase with beam energy significantly steeper than in pp

pPb similar to pp inelastic

can the fireball formed in central nuclear collisions be considered matter in equilibrium?

Phys. Rev. Lett. 105(2010)252301

Basic numbers

Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3

Quark-gluon plasma and hadron yields in central nuclear collisions

QCD implies duality between (quarks and gluons) – hadrons

Hadron gas is equilibrated state of all known hadrons

QGP is equilibrated state of deconfined quarks and gluons

at a critical temperature T_c a hadronic system arises from a QGP

consequence:

QGP in central nuclear collisions if:

1. all hadrons in equilibrium state at common temperature T
2. as function of cm energy the hadron state must reach a limiting temperature T_{lim}
3. all hadron yields must agree with predictions using the full QCD partition function at the QCD critical temperature $T_c = T_{lim}$

Thermal model of particle production and QCD

Partition function Z(T,mu_b,V) contains sum over the full hadronic mass spectrum and is fully calculable in QCD

For each particle species i, the statistical operator is:

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

Particle densities are then calculated according to:

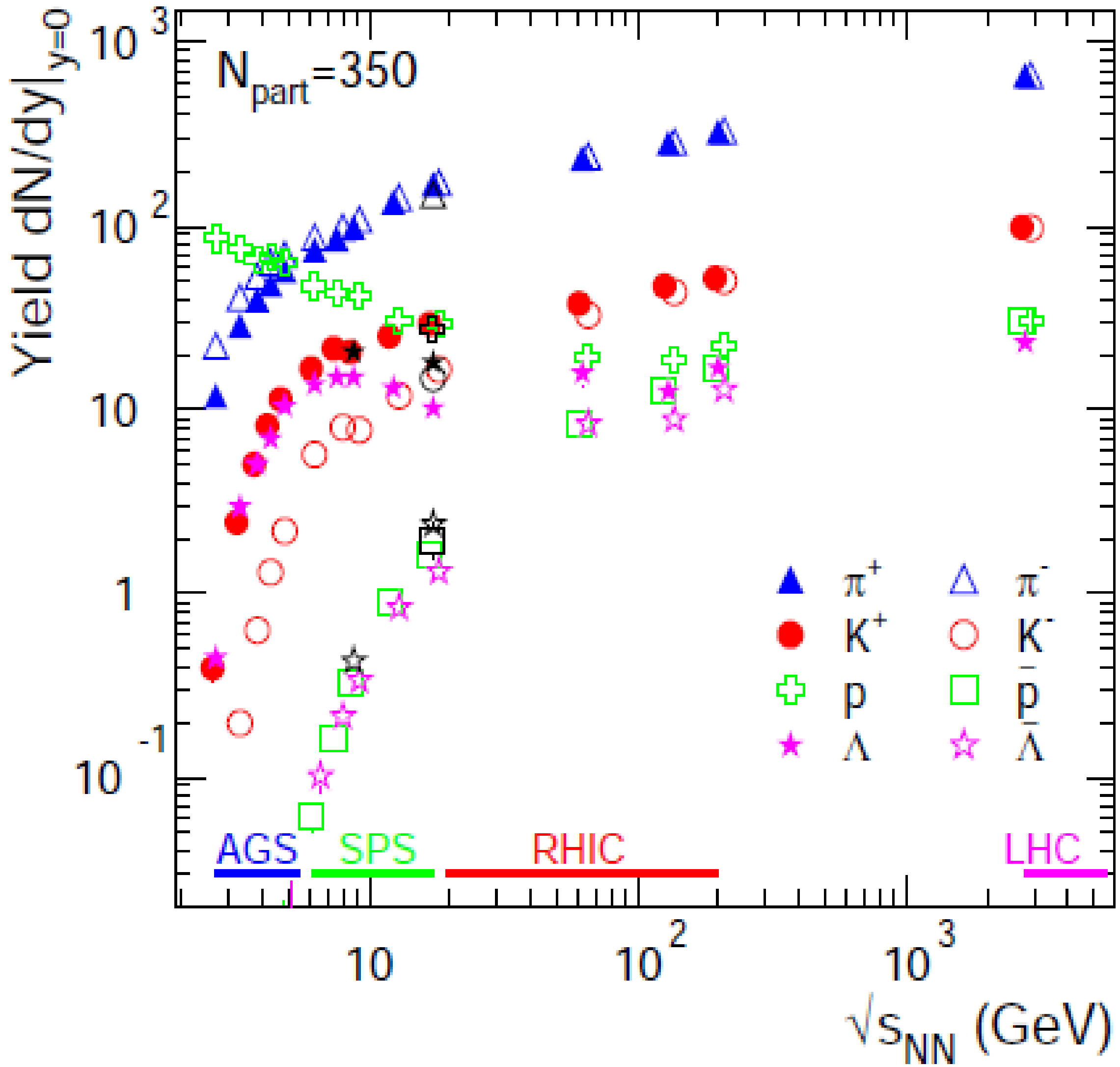
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

From analysis of all available nuclear collision data we now know the energy dependence of the parameters T, mu_b, and V over an energy range from threshold to LHC energy and can confidently extrapolate to even higher energies

In practice, we use the full experimental hadronic mass spectrum from the PDG compilation to compute the 'primordial yield'

Comparison with measured hadron yields needs evaluation of all strong (and electromagnetic) decays

The experimental input: 25 years of data from the GSI, AGS, SPS, RHIC and LHC collaborations



CERN experiments:

SPS:
NA35, NA36, NA44, NA45, NA49, NA50, NA57, NA60, NA61 WA80. WA87, WA98

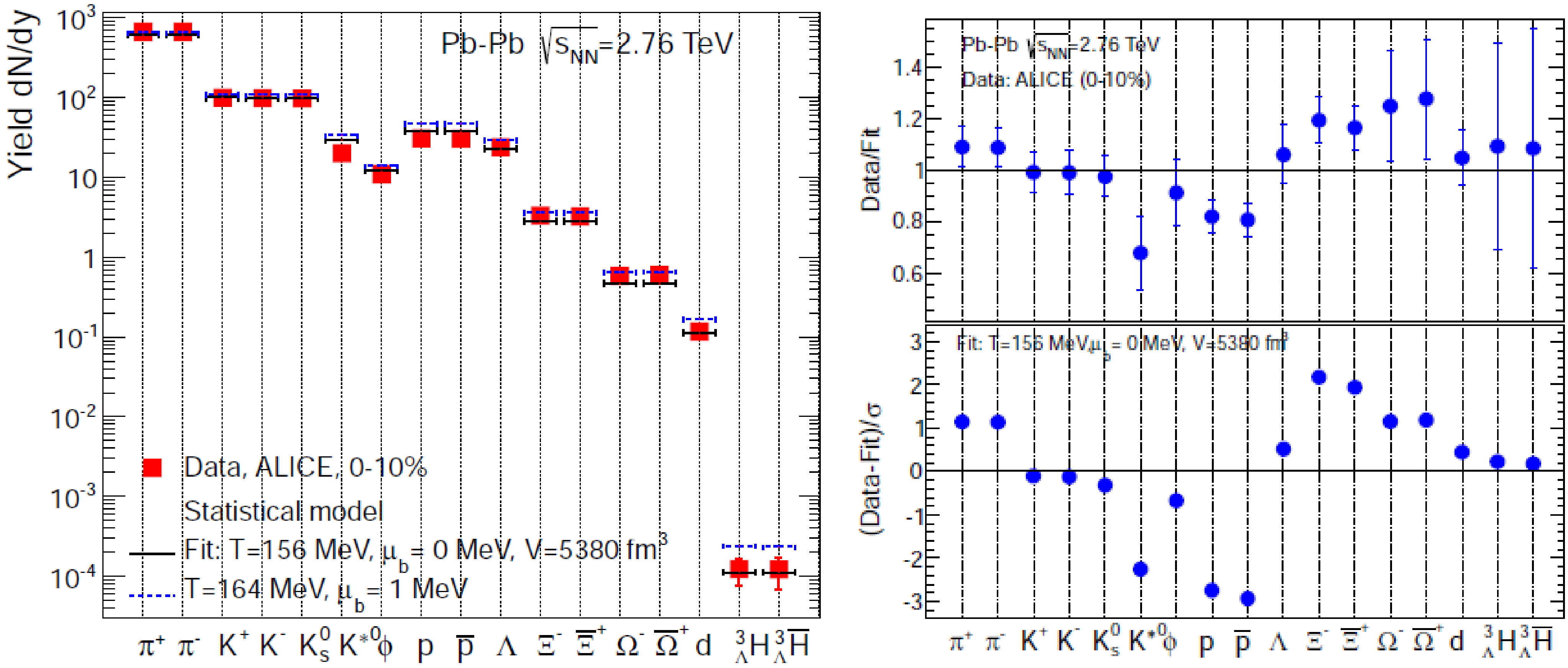
LHC:
ALICE, ATLAS, CMS, LHCb

GSI experiments:
FOPI, KAOS

BNL experiments:
AGS:
E802/E859/E866, E810, E814/E877, E864, E895

RHIC:
BRAHMS, PHENIX, PHOBOS, STAR

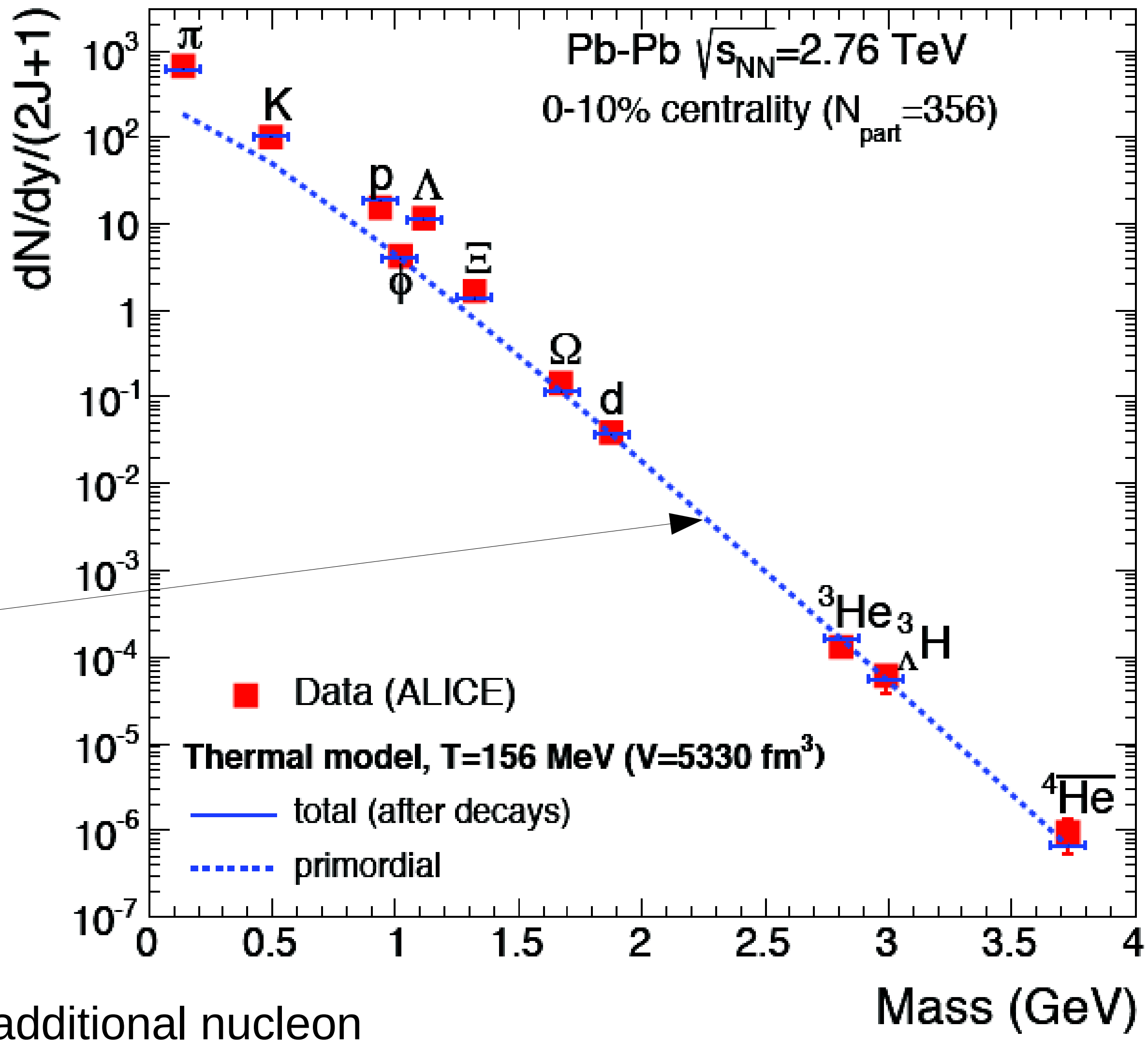
Excellent description of LHC data



fit includes loosely bound systems such as deuteron and hypertriton
hypertriton is bound by only 100 keV, it is the **ultimate halo nucleus,**
produced at T=156 MeV.

This result is important for the understanding of the production of exotica, see below.

Mass dependence of primordial and total yield compared to LHC data



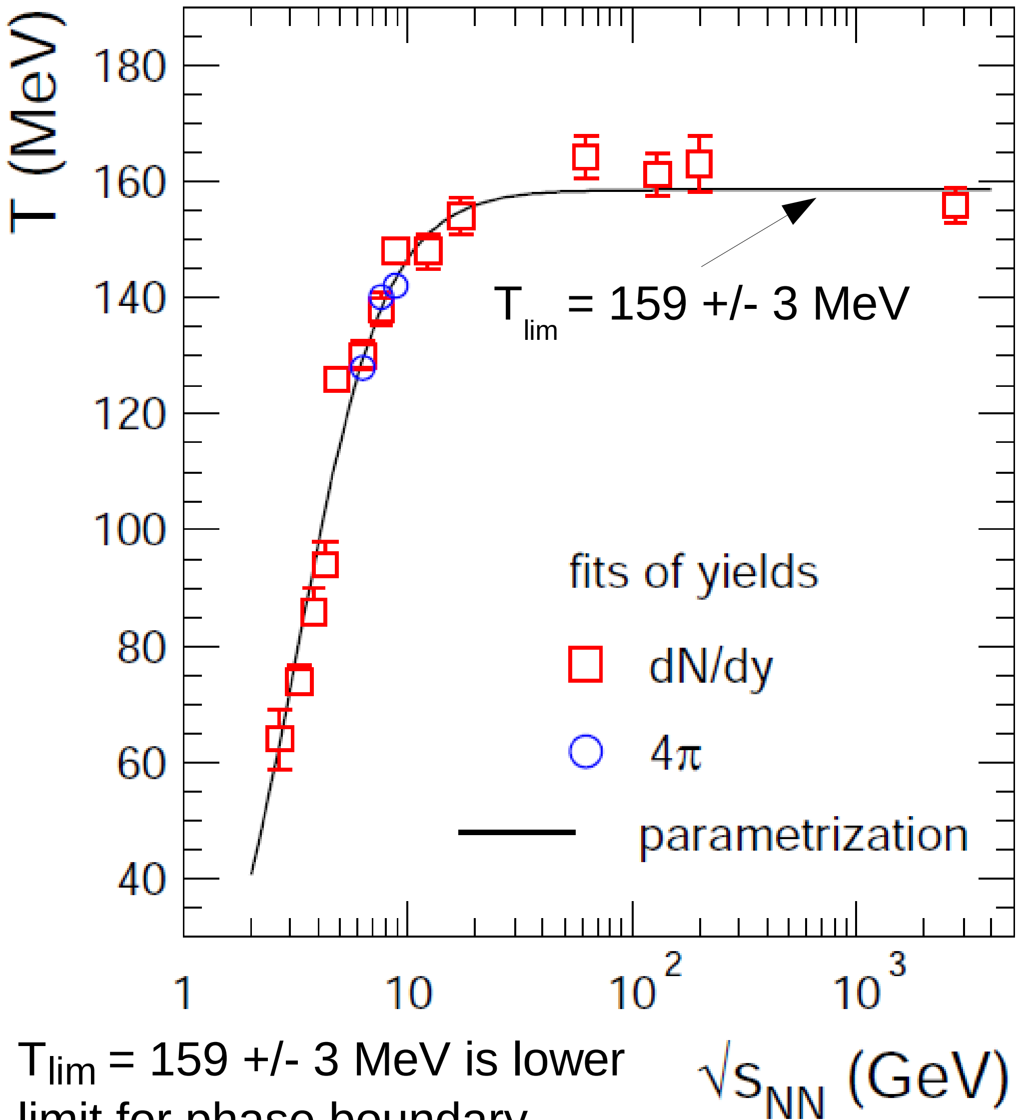
prediction using 'primary' QCD statistical operator, no feeding from strong decays, no fitting of temperature

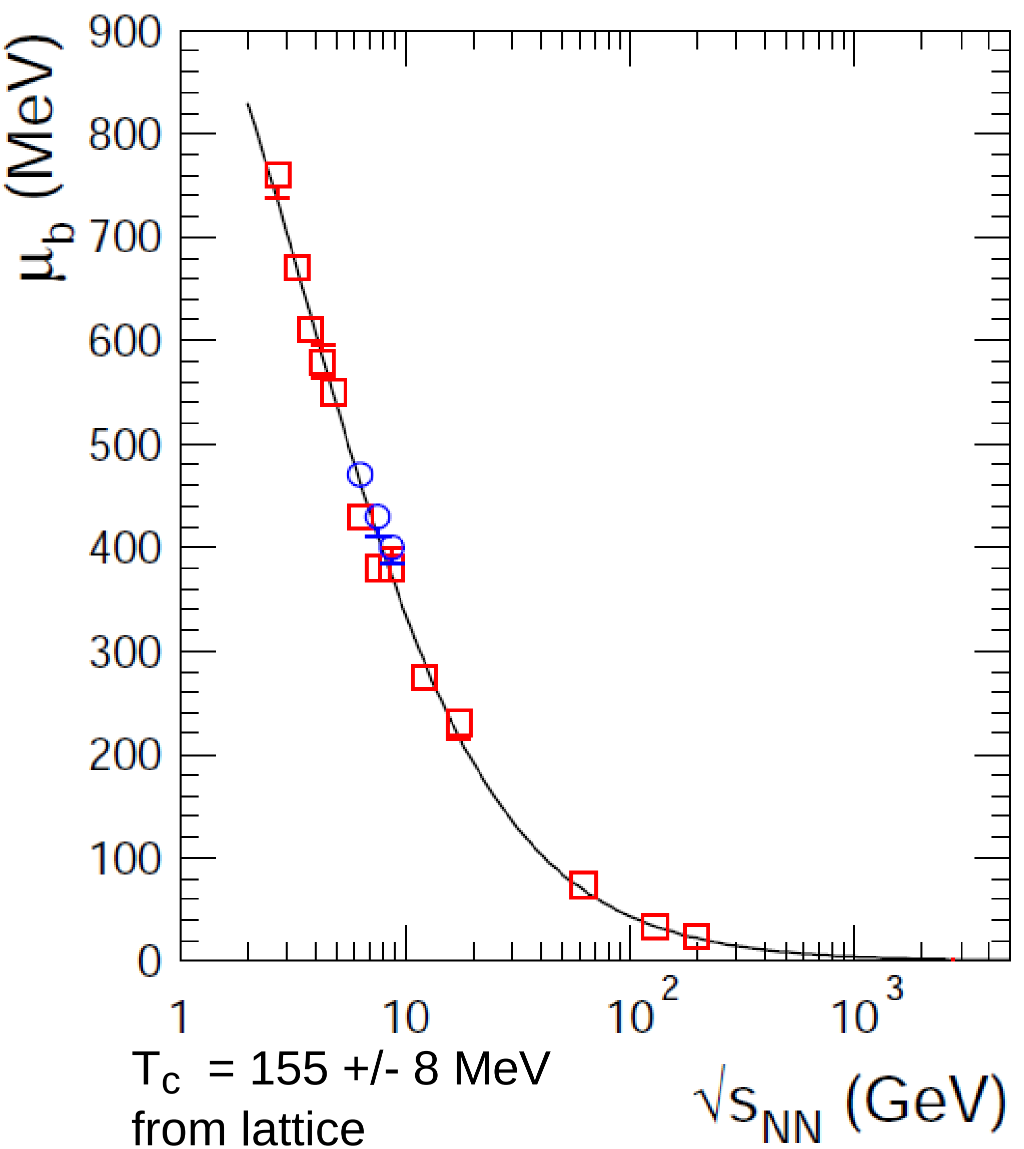
penalty factor $p_N = 300$ for each additional nucleon

next stable (anti)-nucleus is A = 6, difficult to get even with triggering or continuous read-out, but other exotica

Energy dependence of temperature and baryo-chemical potential

is phase boundary ever reached for $\sqrt{s_{NN}}$ < 10 GeV?

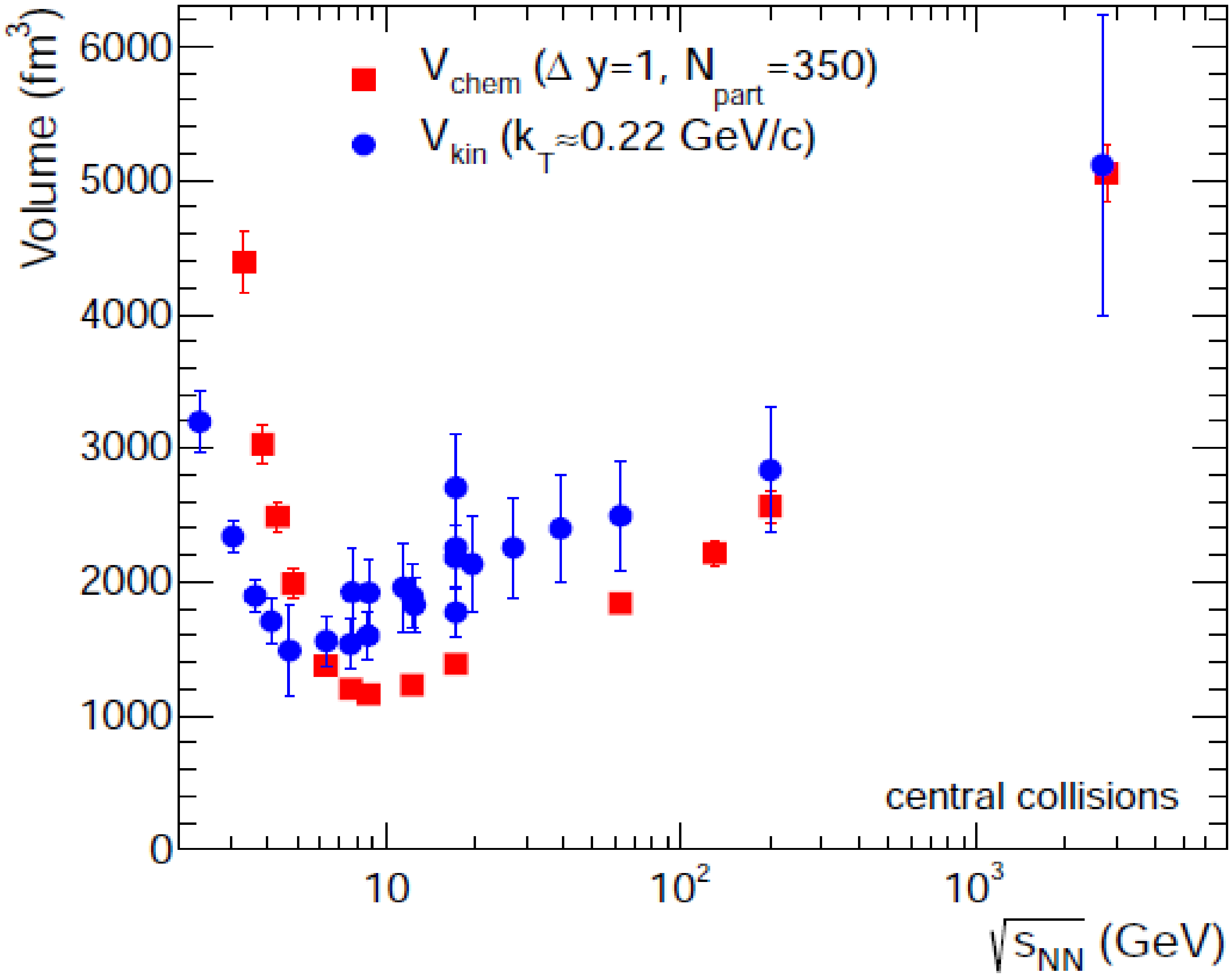




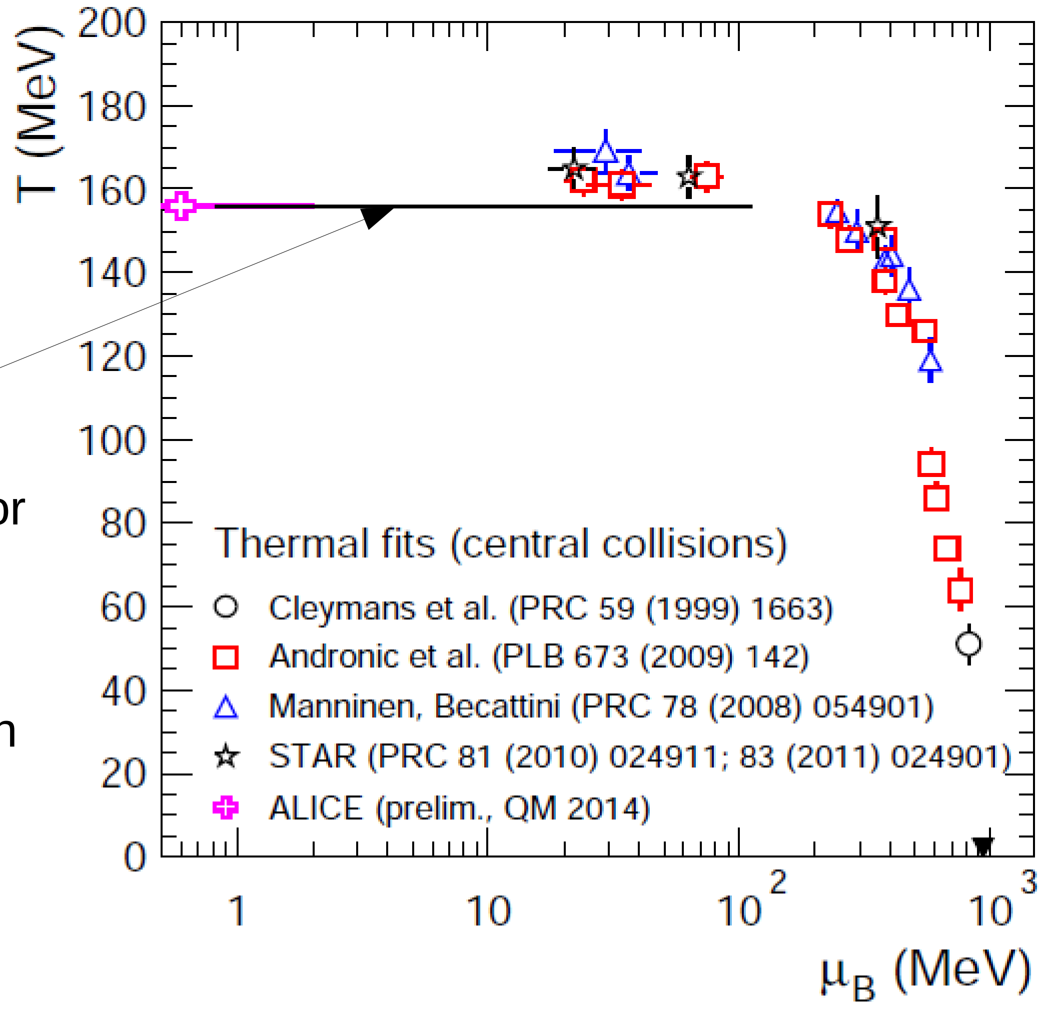
T_{lim} = 159 +/- 3 MeV is lower limit for phase boundary

T_c = 155 +/- 8 MeV from lattice

Energy dependence of (chemical freeze-out) volume



central nucleus-nucleus collision data and the QCD phase boundary



Lattice QCD,
T_c = 155 +/- 8 MeV for
mu_b = 0

mu_b dependence
from Taylor expansion
Hot-QCD coll.

Limiting temperature predicted by Hagedorn 50 years ago and observed in the data is very close to critical temperature from lattice QCD

This includes mu_b dependence for mu_b < 250 MeV (top SPS energy)

Nuclear collisions, open and hidden charm hadrons, and QCD

hadrons containing charm quarks can also be described provided open charm cross section is known

recent ALICE data imply Debye screening near T_c for charmonium and deconfined heavy quarks

could it be that increasing number of charm quarks changes (lowers) T_c?
an issue for the FCC!

Charmonium production at LHC energy: deconfinement and color screening

- Charmonia formed at the phase boundary → full color screening at T_c
- Debye screening length < 0.4 fm near T_c
- Combination of uncorrelated charm quarks into J/psi → deconfinement

statistical hadronization picture of charmonium production provides most direct way towards information on the degree of deconfinement reached as well as on color screening and the question of bound states in the QGP

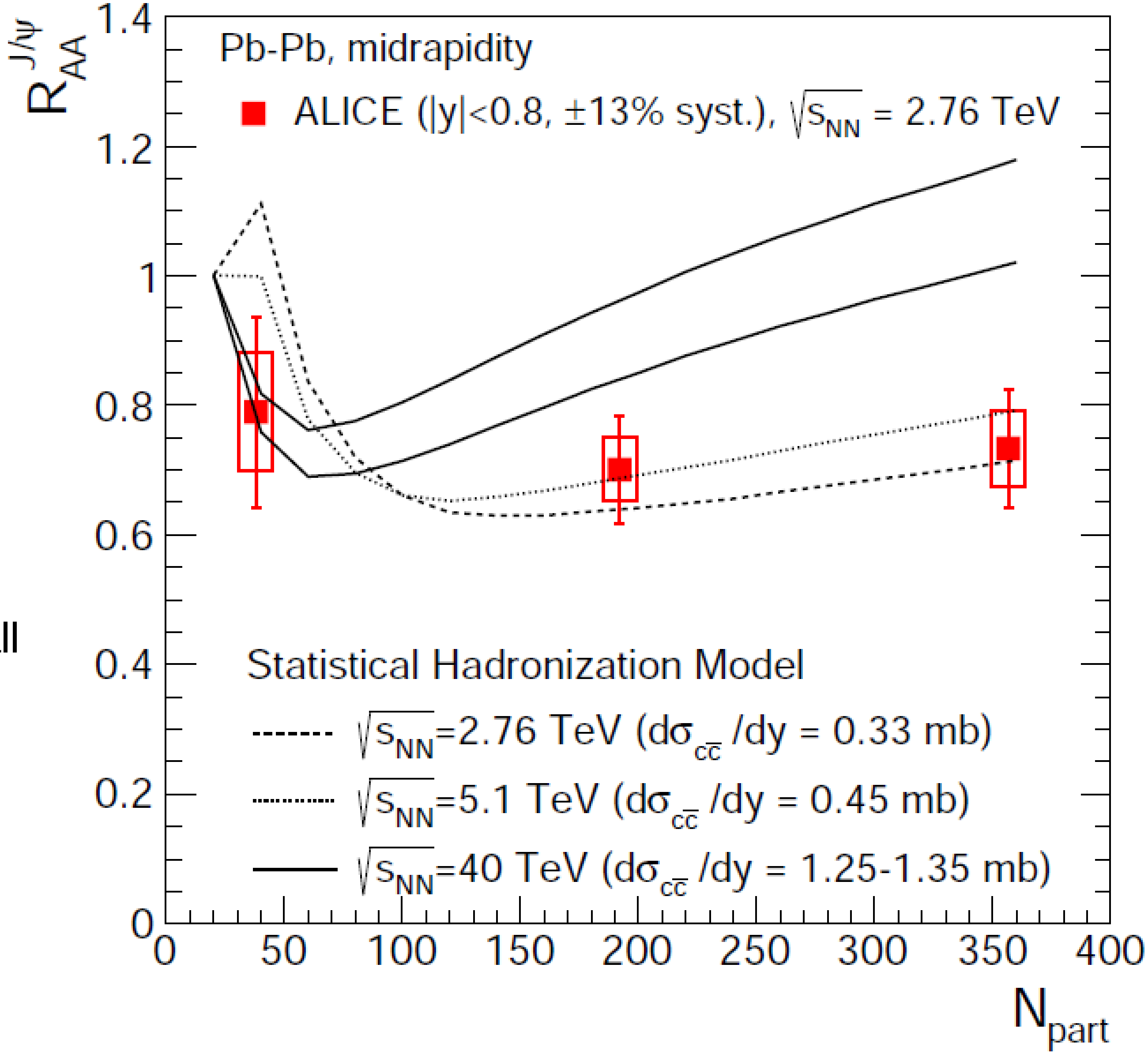
Open charm cross section for Run2 and at FCC

dsigma/dy_pp (mb)	sqrt{s_{NN}} (TeV)	dN(c+c_bar)/dy Pb--Pb
0.07	0.2	3.4
0.33	2.76	12.5
0.5	5.5	17.5
1.35	40	51

prediction of J/psi cross section at mid-rapidity for run2 and FCC

uncertainty in energy dependence of open charm cross section and volume still large

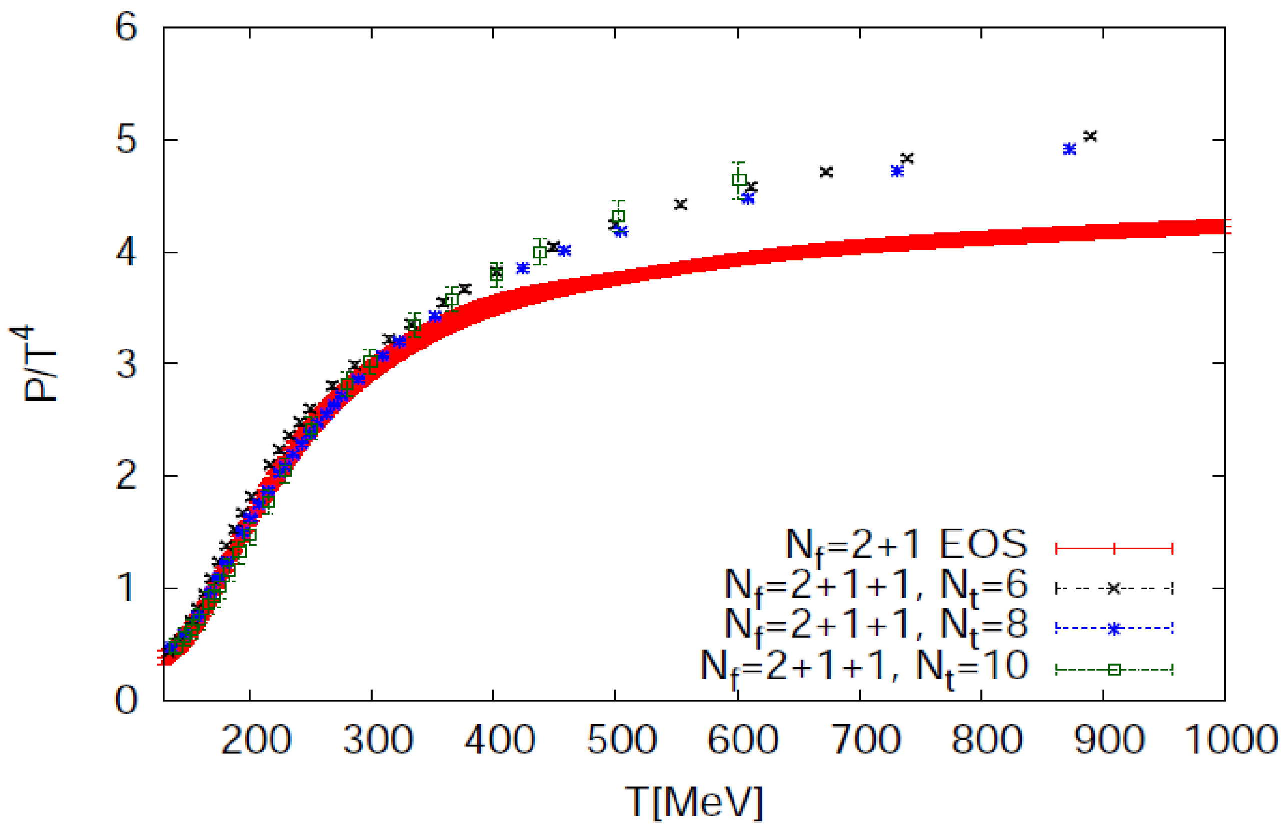
new analysis based on all existing data to come soon.



can thermalized open charm change the QGP equation of state?

LQCD calculations imply deviation above T = 300 MeV in EoS when adding purely thermal charm .

But in Pb-Pb collisions the number of thermalized charm quarks is at least equal to that produced in hard collisions!

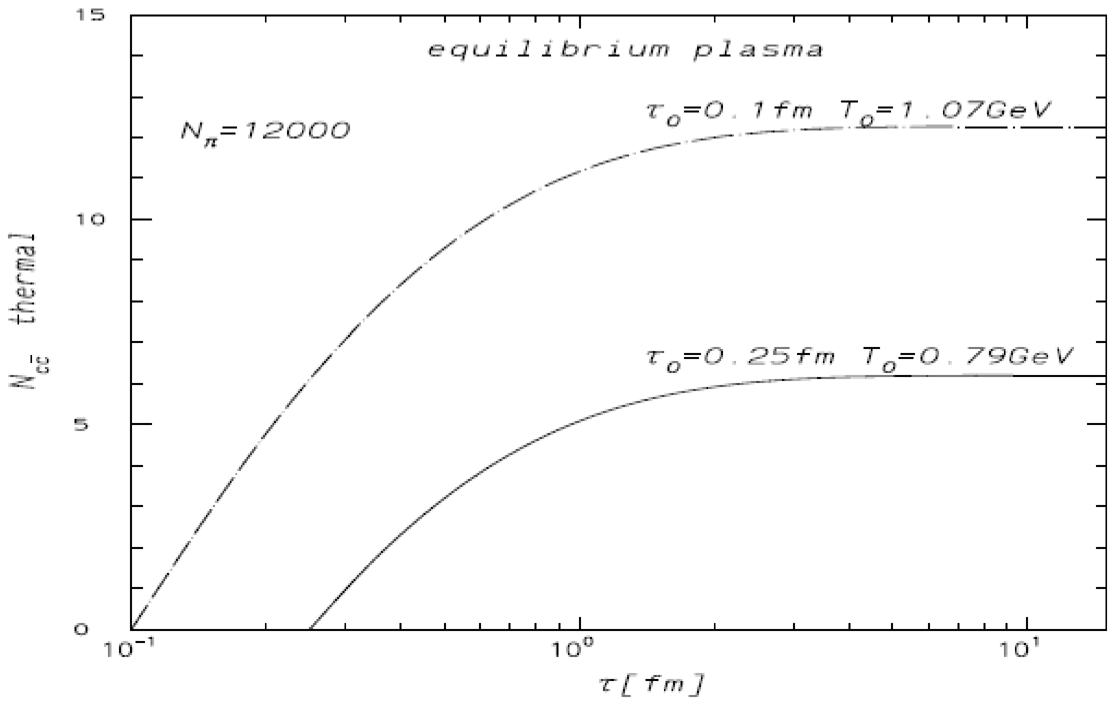


The QCD equation of state and the effects of the charm

arXiv:1204.0995

Szabolcs Borsanyi[a], Gergely Endrodi[b], Zoltan Fodor[a,c,d], Sandor D. Katz[a,d], Stefan Krieg[*a,c], Claudia Ratti[e], Chris Schroeder[a,f], Kalman K. Szabo[a]

Thermal charm production in the QGP



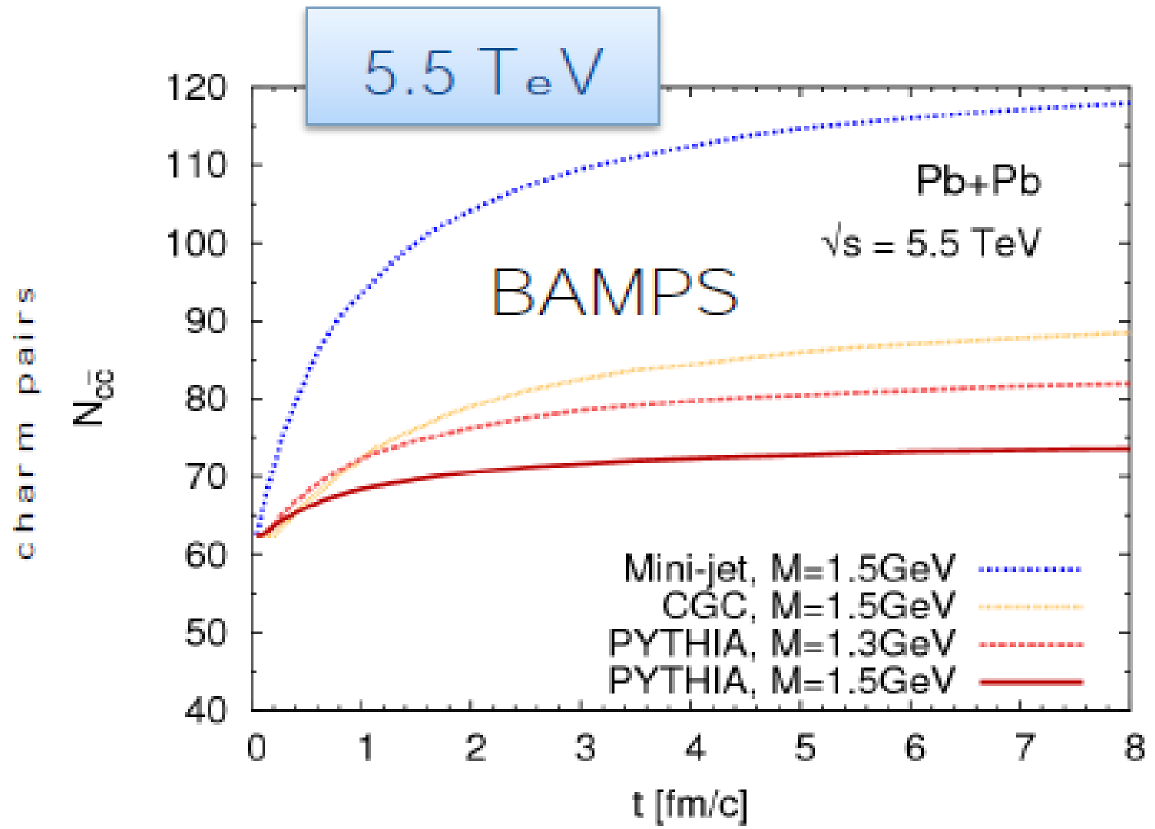
could get up to 25 charm + anti-charm quarks per unit rapidity from thermal production in a central Pb-Pb collision

Charmonium production from the secondary collisions at LHC energy

Peter Braun-Munzinger (Darmstadt, GSI), Krzysztof Redlich (Wroclaw U.). Jan 2000. 19 pp.

Published in Eur.Phys.J. C16 (2000) 519-525

newest evaluation from Uphoff et al.



numbers are for full phase space

Large secondary production
→ **Can even be comparable to** initial production

JU, Fochler, Xu, Greiner
Phys. Rev. C 82 (2010)

energy density from charm quarks in the QGP for FCC energy

assume: m_c = 1.3 GeV T_c = 156 MeV

volume at chem. freeze-out (= T_c) = 11000 fm^3 = V_c

critical line is curve of constant energy density

eps_charm = N(c+c_bar) x (m_c+3/2 T_c)/V_c

n(c+c_bar)	eps_charm (MeV/fm^3}
50	7
100	14

since dT/T = ¼ d(eps)/eps

expect dT = 1 – 2 MeV only

but this is lower limit due to neglect of interactions...