Experimental test of gauge theories: the QCD phase diagram at high temperature

the QCD phase diagram
EOS, the chiral and the deconfinement phase transions in lattice QCD
experimental access to the QCD phase diagram
- delineating the phase boundary from hadron yields
- access to chiral criticality via fluctuations of conserved charges
- deconfinement and quarkonia

work done over the past 18 years in collaboration with Peter Braun-Munzinger, Anton Andronic, Krzysztof Redlich

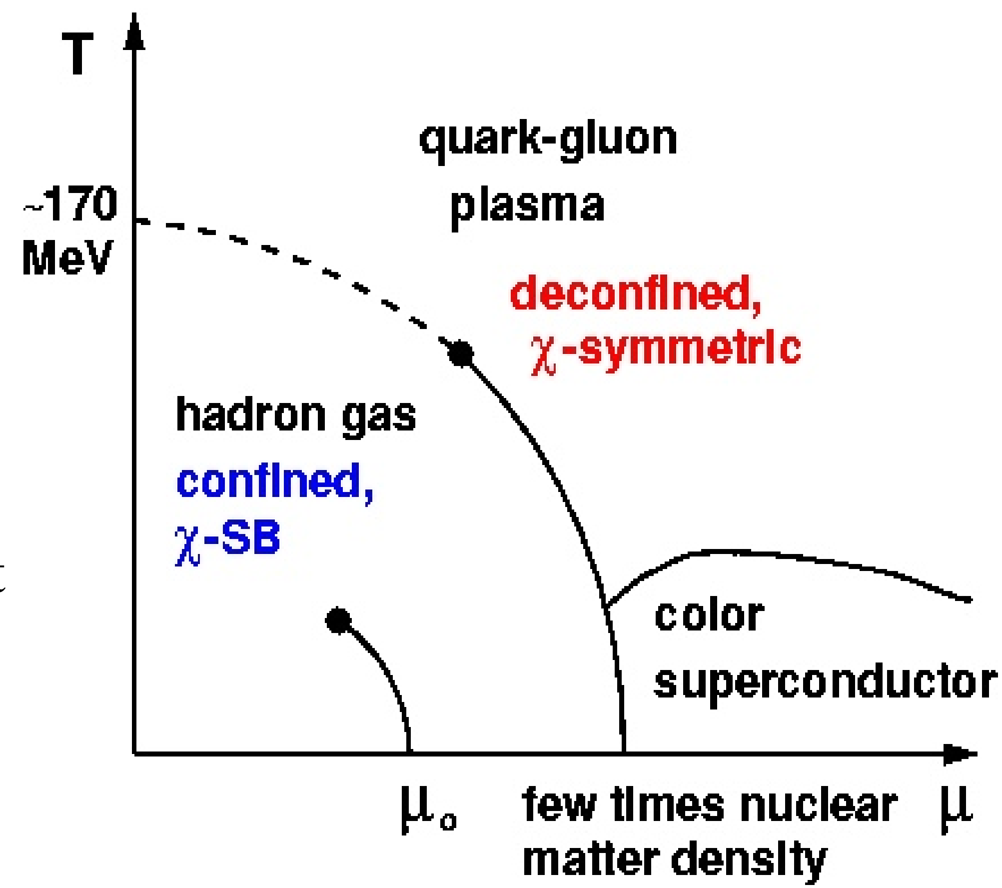
Johanna Stachel – Universität Heidelberg
678th Wilhelm und Else Heraeus-Seminar
" Hundred Years of Gauge Theory"
Physikzentrum Bad Honnef, July 30 – August 3, 2018

Phase diagram of strongly interacting matter

at low temperature and normal density
colored quarks and gluons are bound in colorless hadrons - confinement
chiral symmetry is spontaneously broken (generating 99% of proton mass e.g.)
1972 QCD (Gross, Politzer, Wilczek)
asymptotic freedom at small distances

at high temperature and/or high density
quarks and gluons freed from confinement
-> new state of strongly interacting matter
1975 (Collins/Perry and Cabibbo/Parisi)

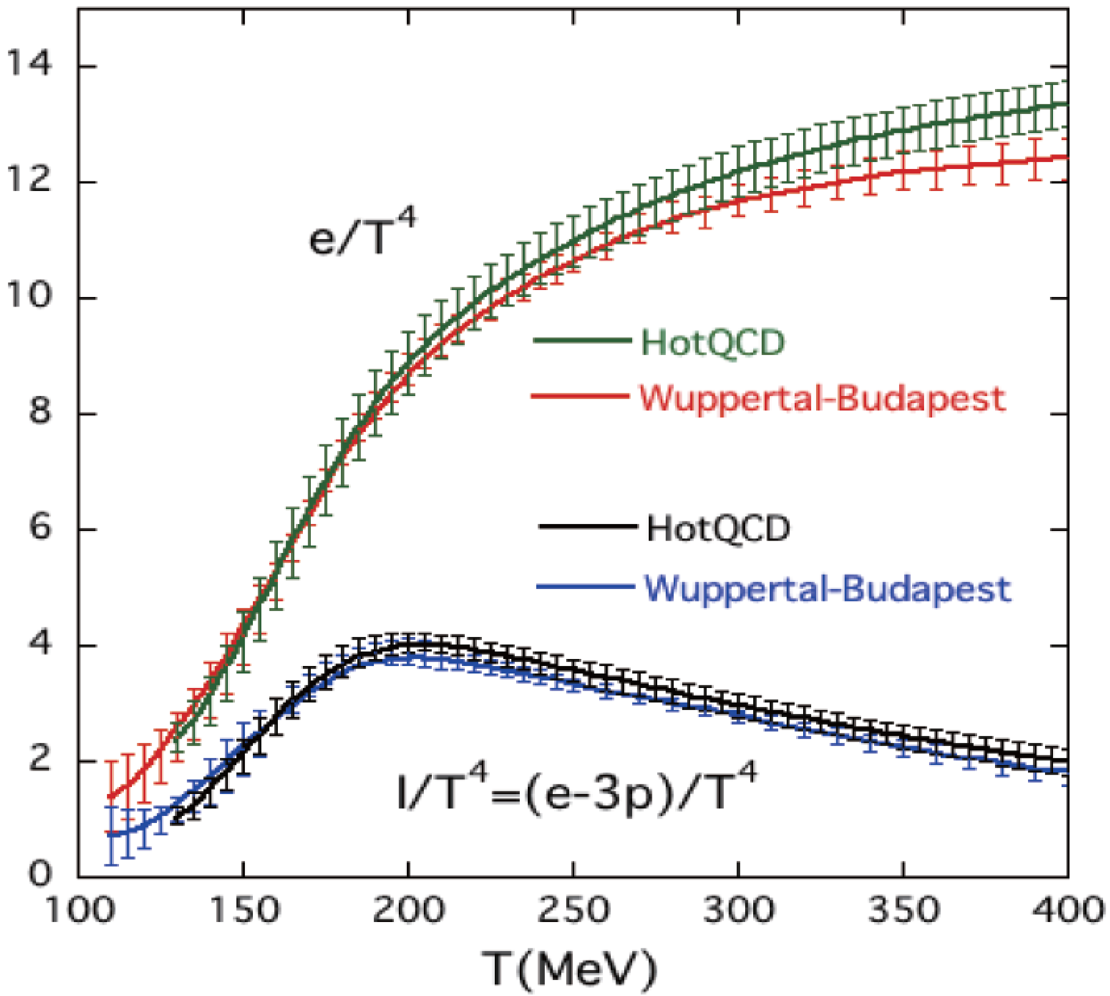
called **Quark-Gluon Plasma (QGP)**



Equation of state of hot QCD matter in lattice QCD

computation of QCD EoS one of the major goals in lQCD community since 1980

A.Ukawa, arXiv:1501.04215



consolidated results on EoS from different groups, extrapolated to continuum and chiral limit

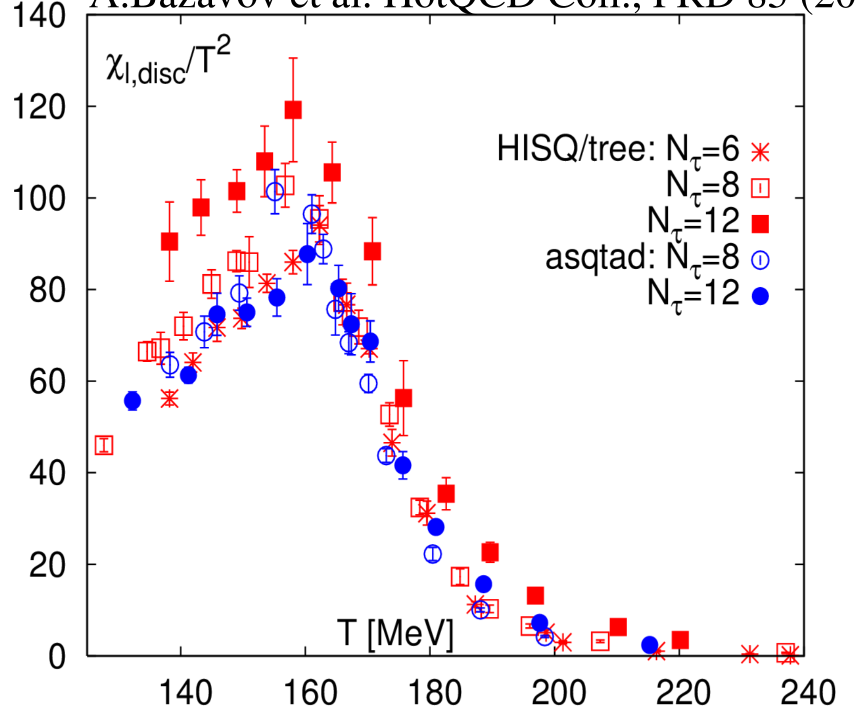
rapid rise of energy density (normalized to T^4 rise for relativistic gas)

- signals rapid increase in degrees of freedom due to transition from hadrons to quarks and gluons
- lQCD points to continuous cross over transition

Measure for chiral symmetry restoration in lQCD

order parameter: chiral condensate, its susceptibility peaks at T_c

S.Borsayi et al. Wuppertal-Budapest Coll., JHEP 1009 (2010) 073
A.Bazavov et al. HotQCD Coll., PRD 85 (2012) 054503



$$\langle\bar{\Psi}\Psi\rangle = \frac{T}{V}\frac{\partial \ln Z}{\partial m}$$

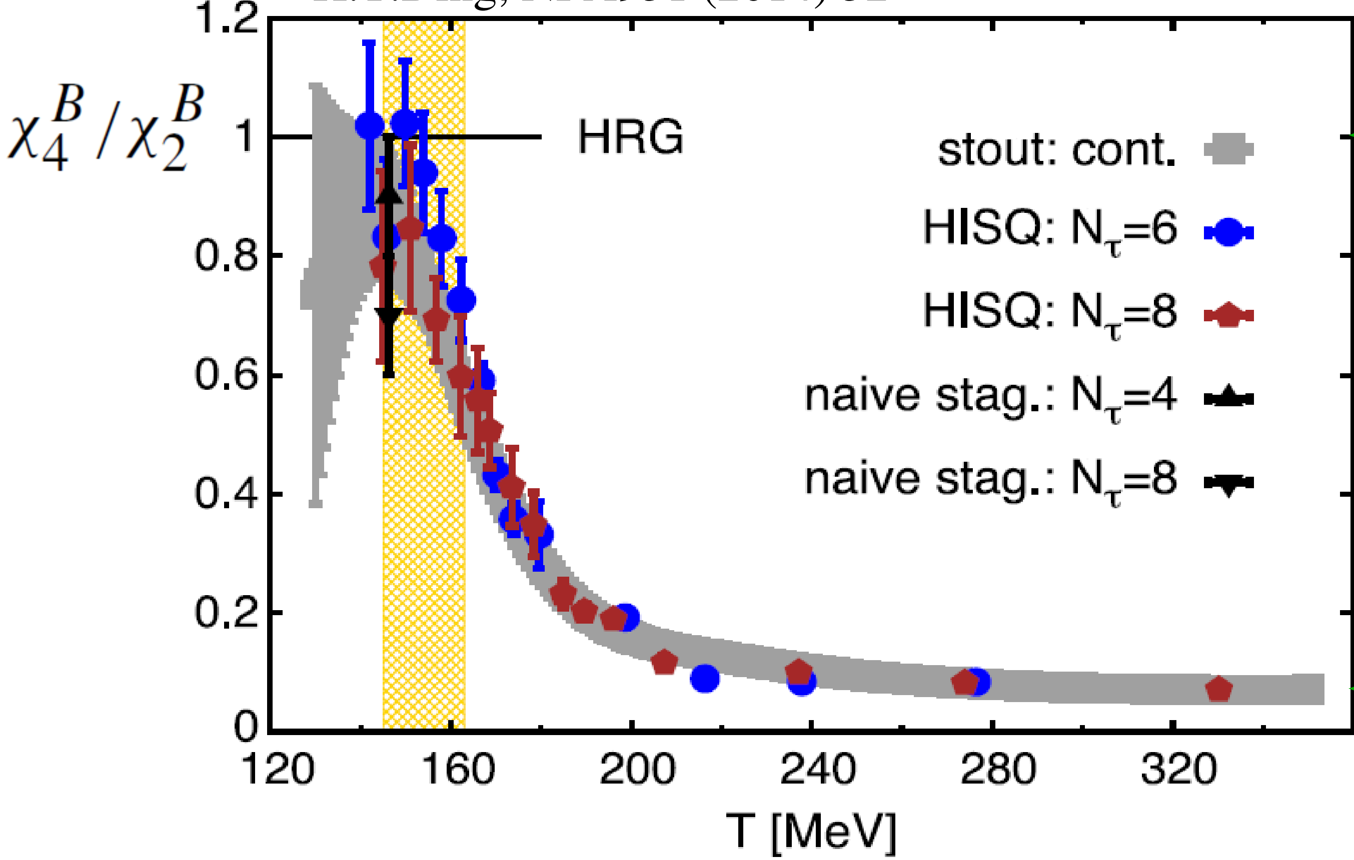
$$\chi_{\bar{\Psi}\Psi} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m^2}$$

comparing different measures and different fermion actions, consensus:
pseudocritical temperature T_c = 154 ± 9 MeV for chiral restoration

Measure of deconfinement in lQCD

$\chi_4^B/\chi_2^B \propto \text{baryon number}^2$

H.T.Ding, NPA931 (2014) 52



confined: 1

measure suggested by Ejiri, Karsch, Redlich (2006)

deconfined: $6/9\pi^2$

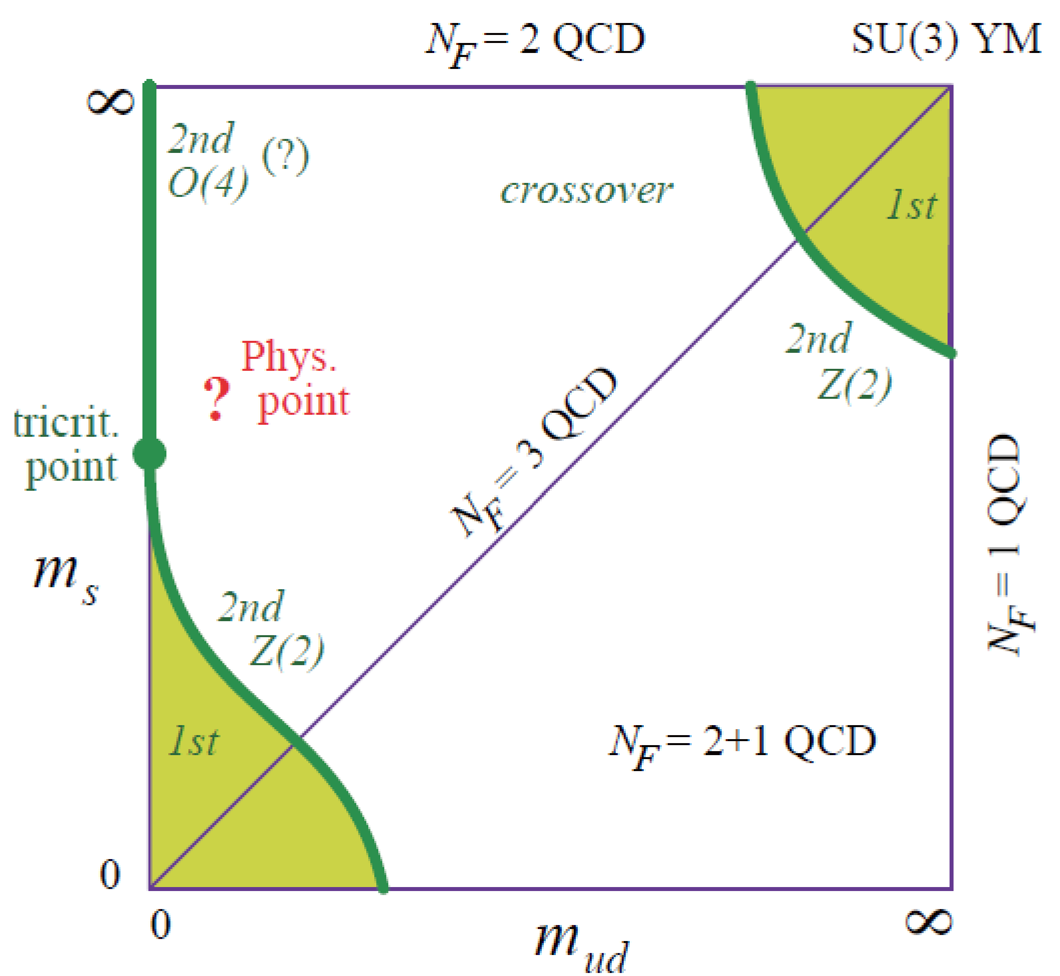
rapid drop suggests: chiral cross over and deconfinement appear in the same narrow temperature range

Phase diagram of 2+1 flavor QCD from lattice

lQCD finds continuous analytic cross over for physical quark masses

meaning for deconfinement?

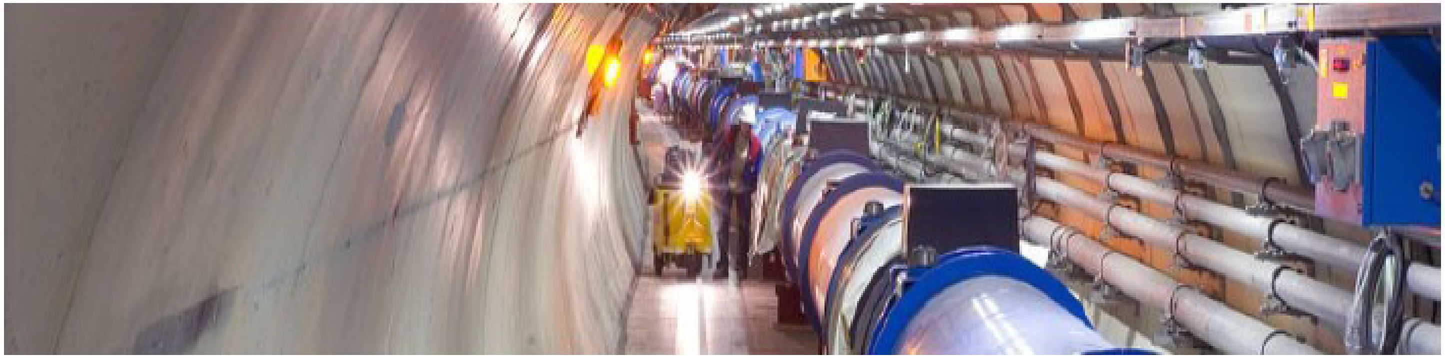
closeness of physical point to 2nd order O(4) transition could have observable consequences in fluctuations



'Columbia plot' Kanaya, Lattice 2010

Experiment

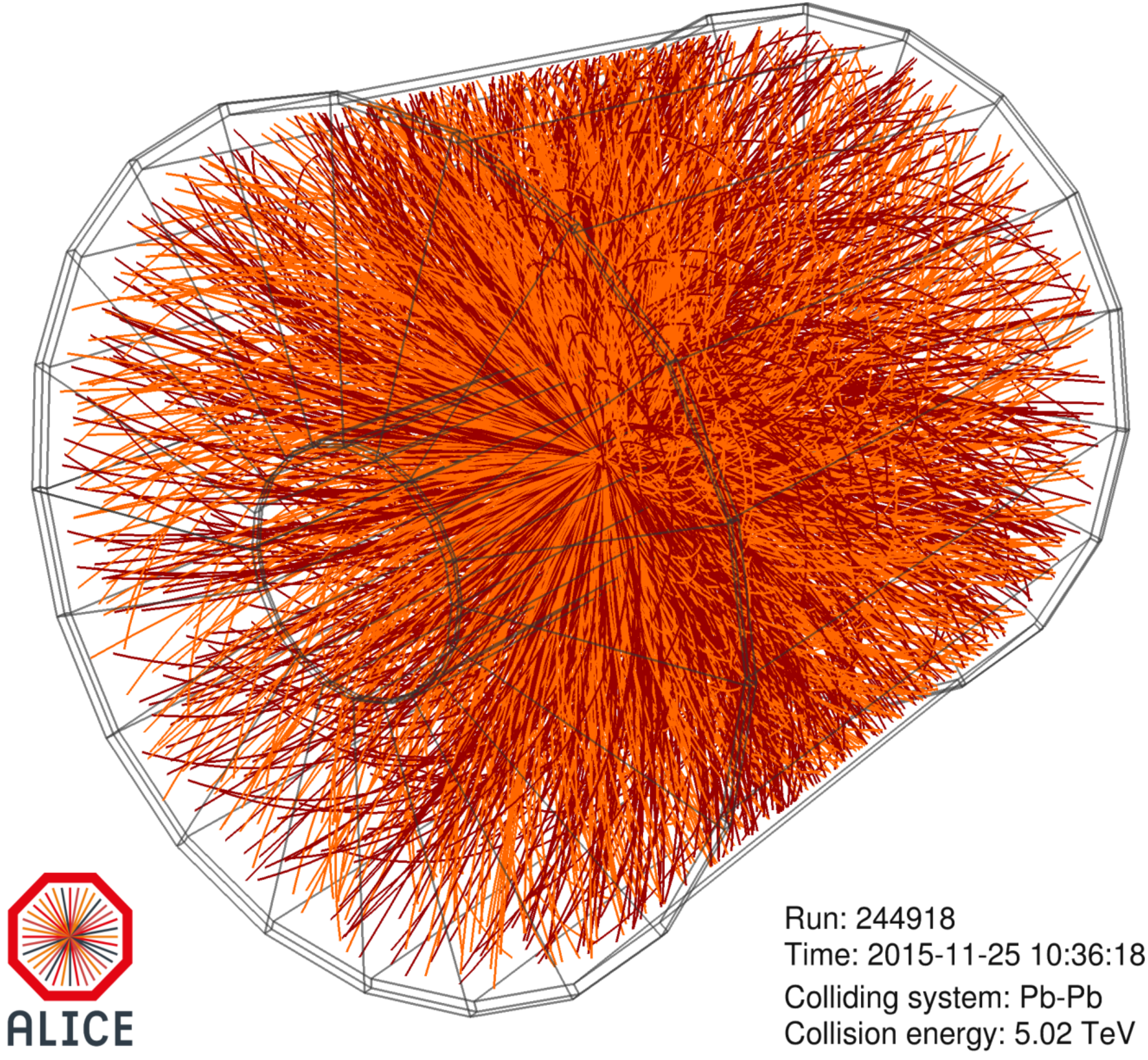
QGP and phase diagram studied in high energy collisions of nuclei
since 1987 at AGS/SPS,
since 2000 at RHIC,
since 2010 at the LHC at $\sqrt{s_{NN}}$ = 2.76 TeV, now 5.02 TeV



nuclear collision rates 2018: 8 kHz, from 2021: 50 kHz

first PbPb collisions at LHC at √s = 5.02 A TeV

about 3750 charged particles in 1.8 units of pseudorapidity



Experimental Observables

… and link to QCD phase diagram

Hadro-chemical composition of the fireball

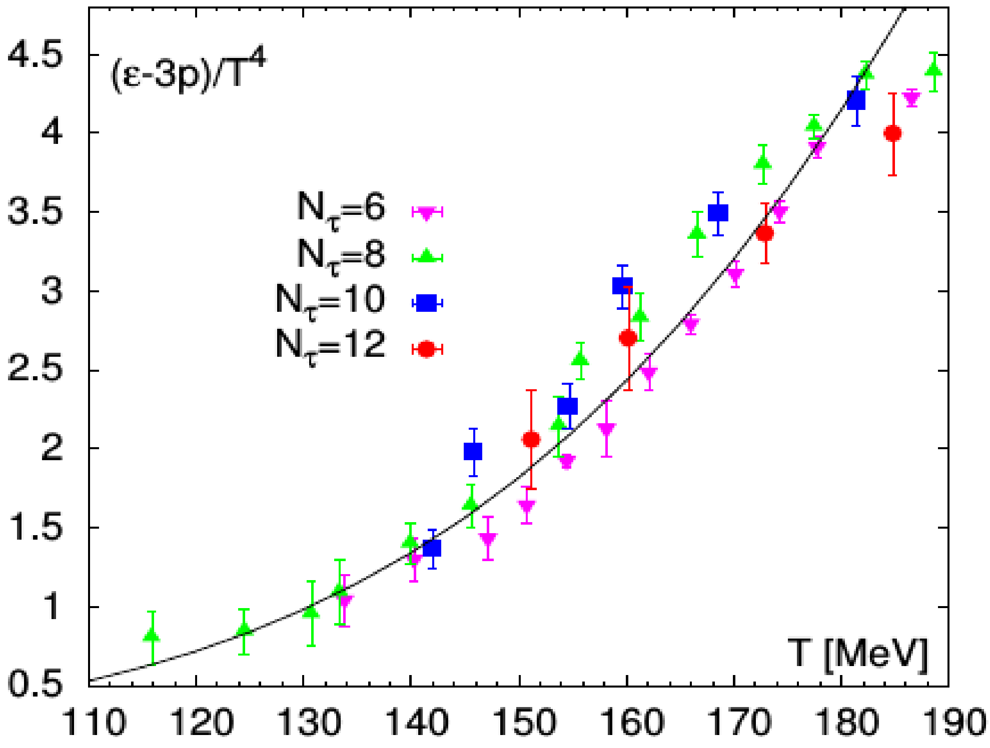
what are the 25 800 hadrons observed in the final state at LHC?
(32 300 at full LHC energy)

Duality between hadrons and quarks/gluons (I)

all thermodynamic quantities derived from full QCD partition function Z
e.g. the pressure $\frac{p}{T^4} = \frac{1}{T^3} \frac{\partial \ln Z(V,T,\mu)}{\partial V}$

trace anomaly from lQCD
full dynamical quarks with realistic pion mass (HotQCD coll. PRD 90 (2014) 094503)
perfectly matched by
hadron resonance gas prediction
(solid line)

similar agreement seen for many other observables



Duality between hadrons and quarks/gluons (II)

in the dilute limit T < 165 MeV:

$$\ln Z(T,V,\mu) \approx \sum_{i \in\, mesons} \ln \mathcal{Z}^{M}_{M_i}(T,V,\mu_Q,\mu_S) + \sum_{i \in\, baryons} \ln \mathcal{Z}^{B}_{M_i}(T,V,\mu_b,\mu_Q,\mu_S)$$

- partition function of hadron resonance model expressed in mesonic and baryonic components.
- chemical potentials reflect the baryon number, charge and strangeness

Thermal model of particle production and QCD

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

for each hadron species i, the grand canonical statistical operator is:

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

leading to particle densities:

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

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}

use full hadronic mass spectrum from the PDG to compute 'primordial yields' and feeding from strong decays → **Fit at each energy provides values for T and μ_b**

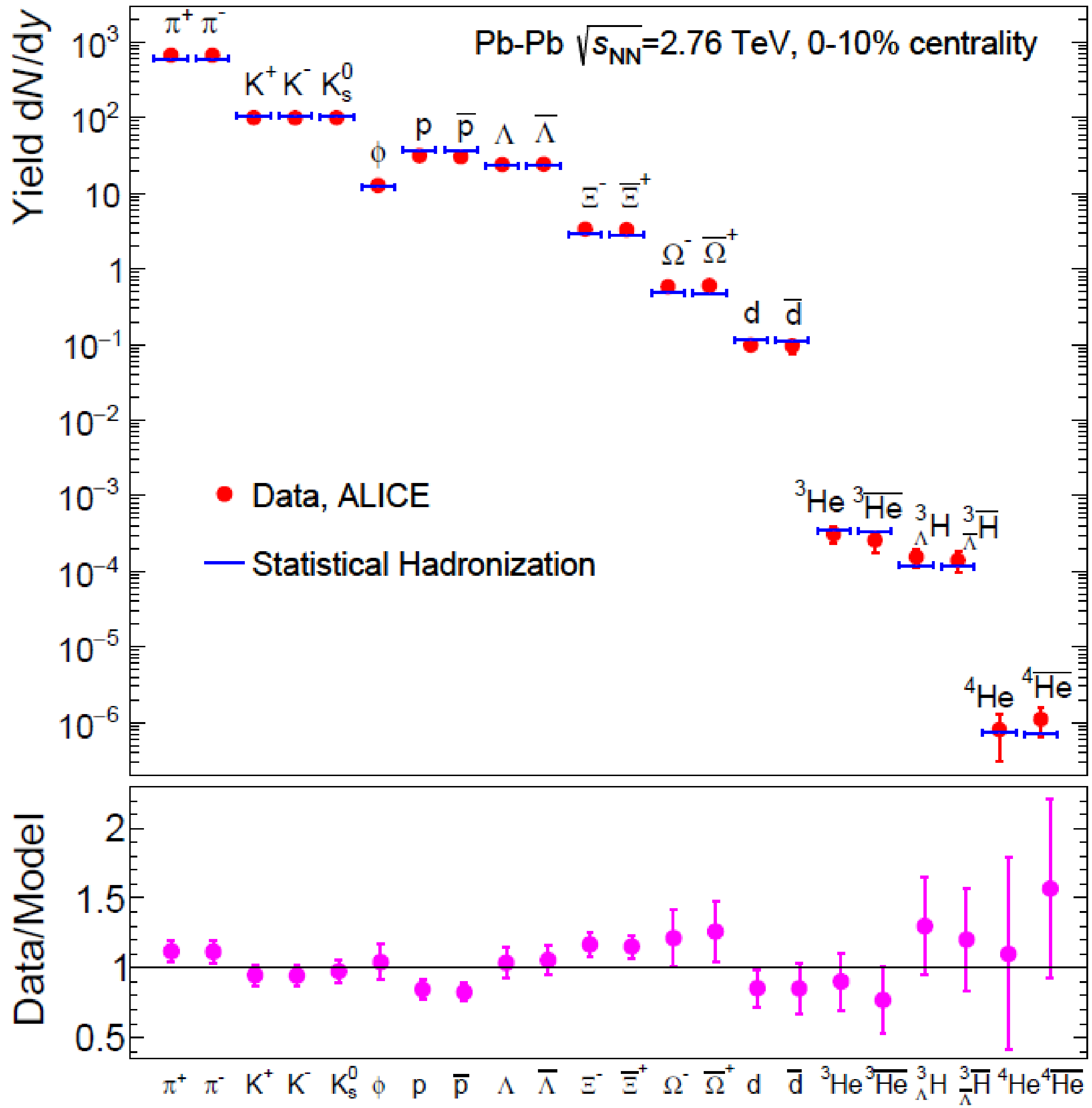
Hadro-chemistry at the LHC

A. Andronic, P. Braun-Munzinger, K. Redlich, JS
Nature (in print) arXiv: 1710.09425

excellent description of ALICE@LHC data with grand canonical (GC) statistical ensemble
T = 156.5 ± 1.5 MeV

fit includes nuclei

2.7 sigma deviation for protons solved in the mean time
χ^2/dof = 19.7/19



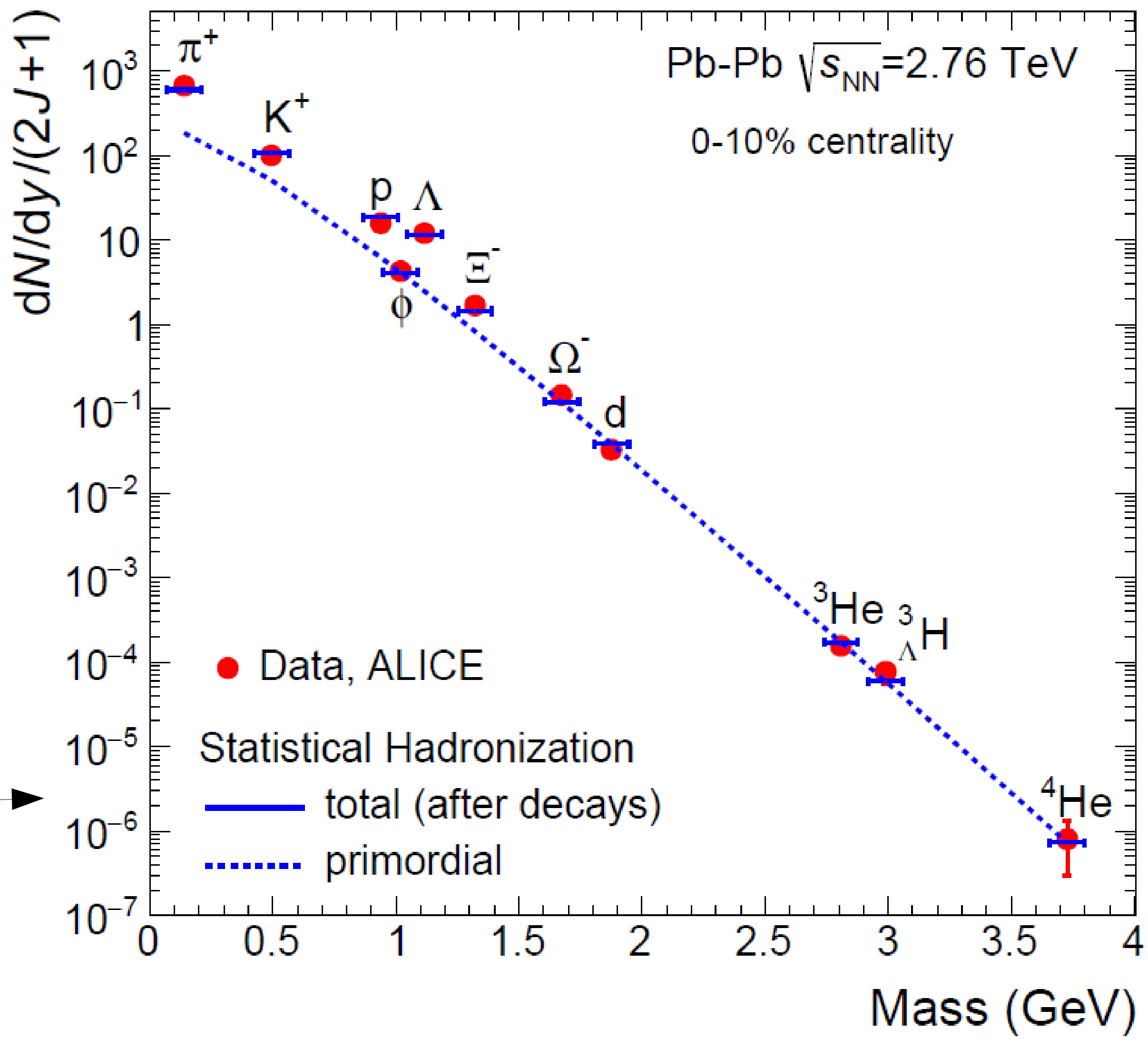
Statistical model (grand canonical) describes production of hadrons and (anti-)nuclei at LHC

A. Andronic, P. Braun-Munzinger, K. Redlich, JS
arXiv: 1710.09425

1 free parameter: temperature T
T = 156.5 ± 1.5 MeV

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

particles and antiparticles →



Statistical model (grand canonical) describes production of hadrons and (anti-)nuclei at LHC

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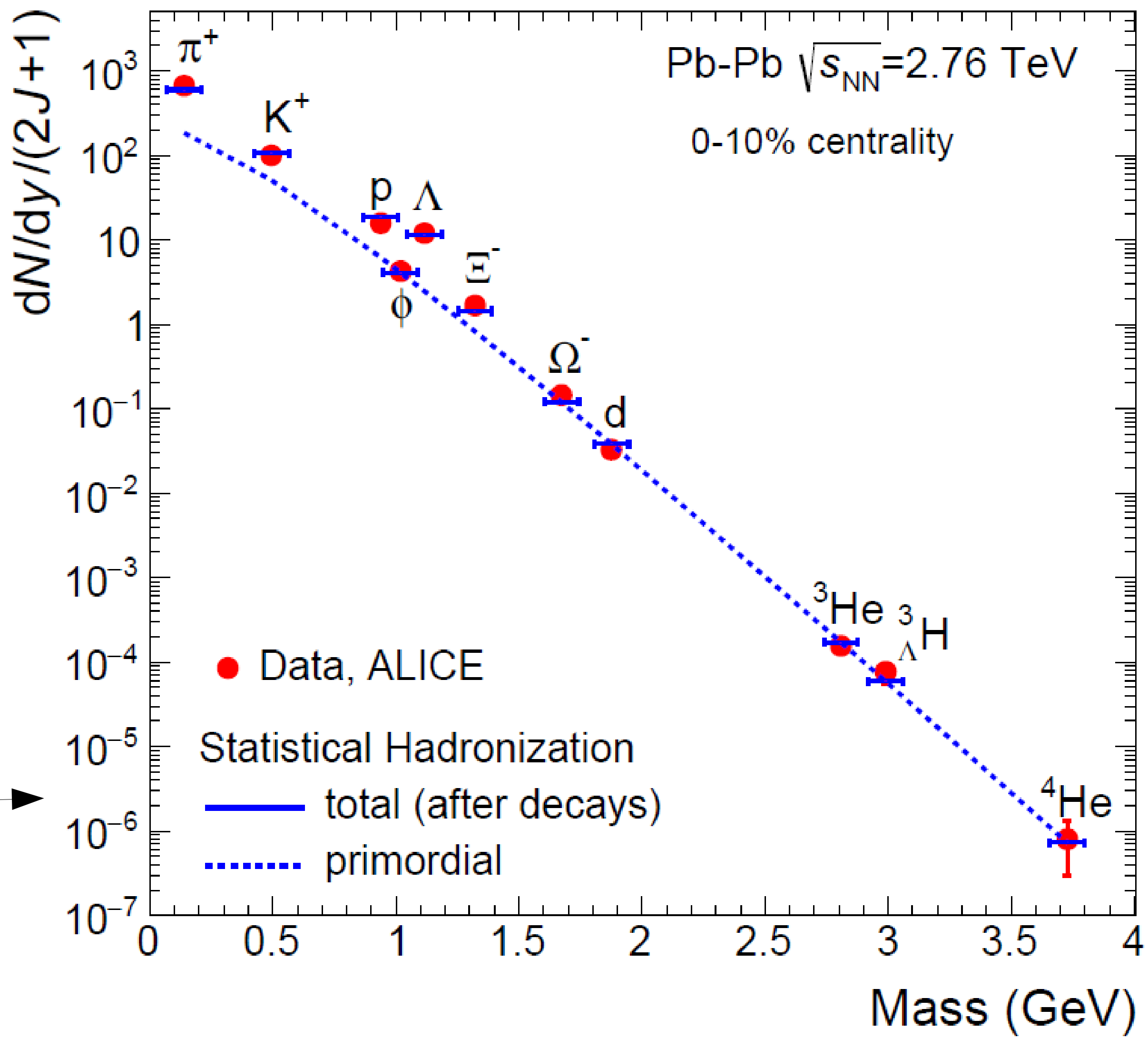
PbPb central collisions: even losely bound nuclei produced with yields fixed at the phase boundary
how can it be?

particles and antiparticles



The Hypertriton

mass = 2990 MeV, binding energy = 2.3 MeV

Λ separation energy = 0.13 MeV

molecular structure: (p+n) + Λ

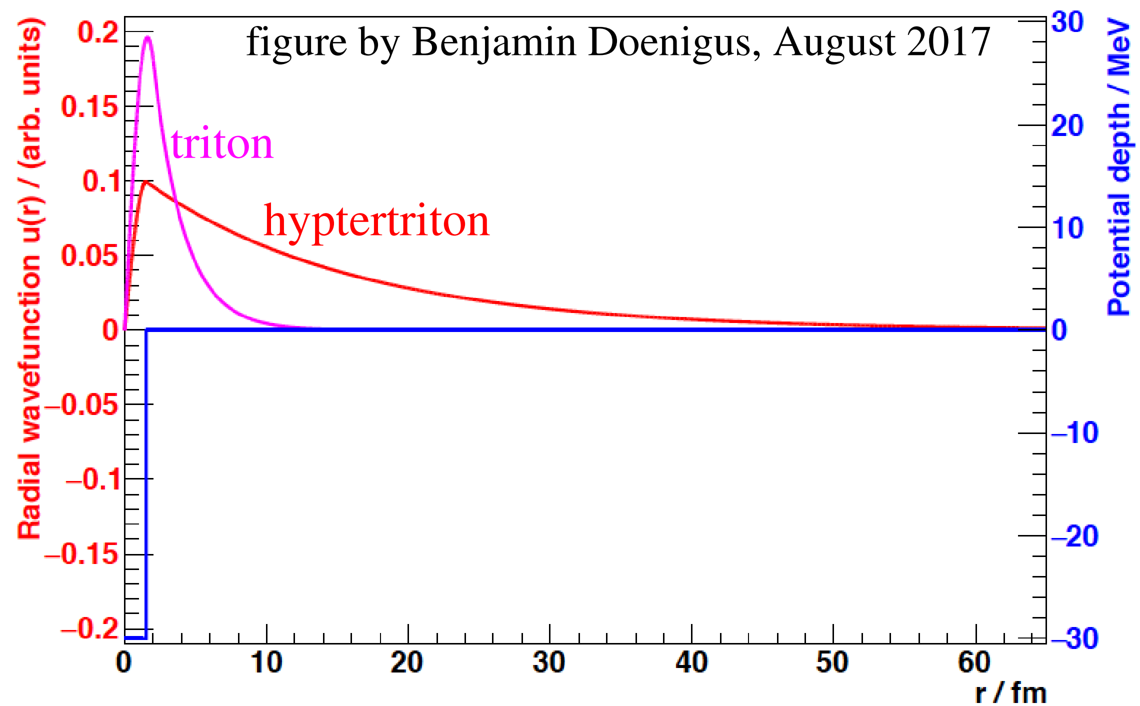
rms radius =rms separation between d and Λ = $(4\ \mathrm{B.E.}\ \ M_{red})^{-1/2}$ = 10.6 fm

in that sense: hypertriton = (pnΛ) = (dΛ) is the ultimate halo state

yet production yield is fixed at
156 MeV temperature
(about 1000 x separation energy.)

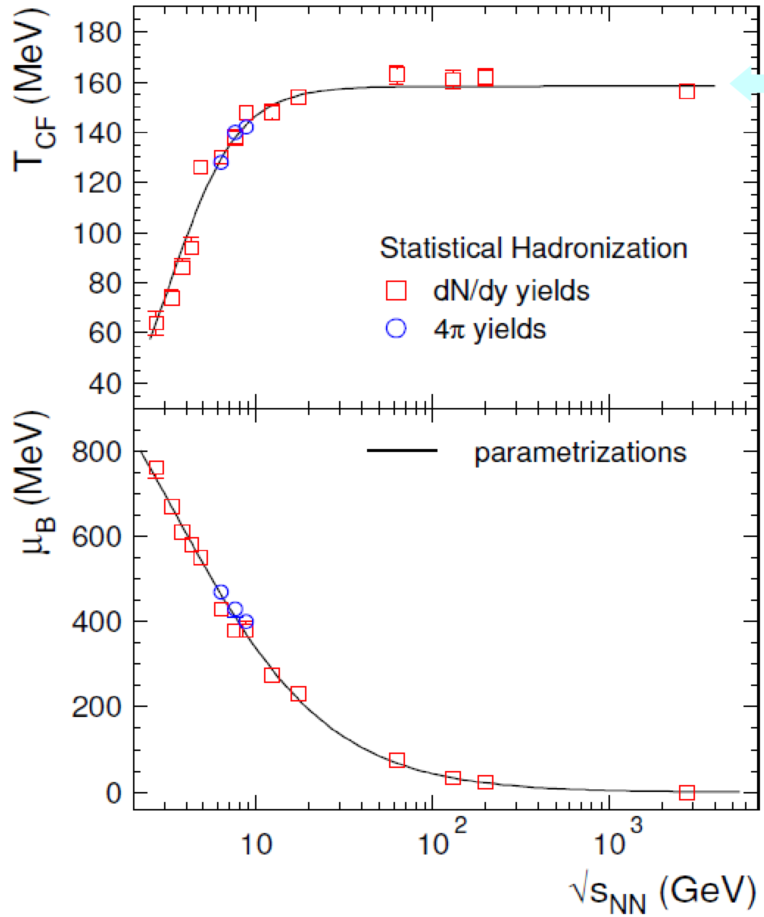
hypothesis: all nuclei and hyper-nuclei are formed as compact multi-quark states at the phase boundary. Then slow time evolution into hadronic respresentation.

Andronic, Braun-Munzinger, Redlich, JS, arXiv :1710.09425

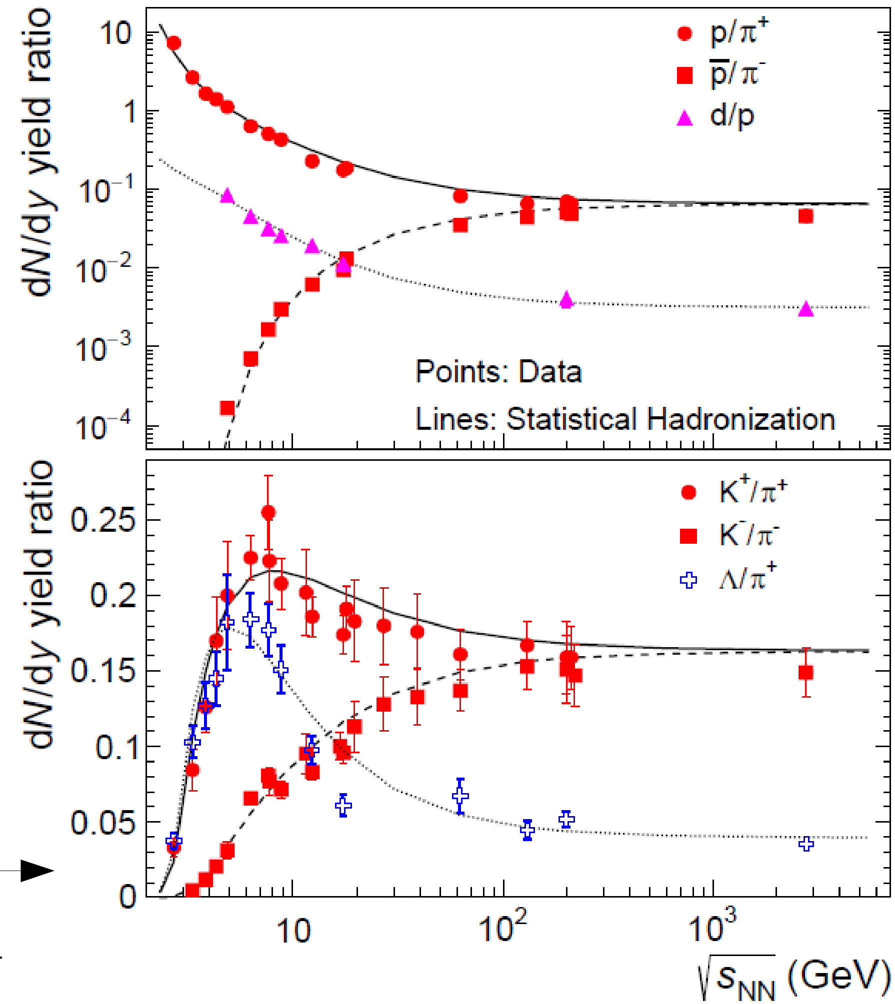


Statistical analysis for lower collision energy data

arXiv:1710.09425



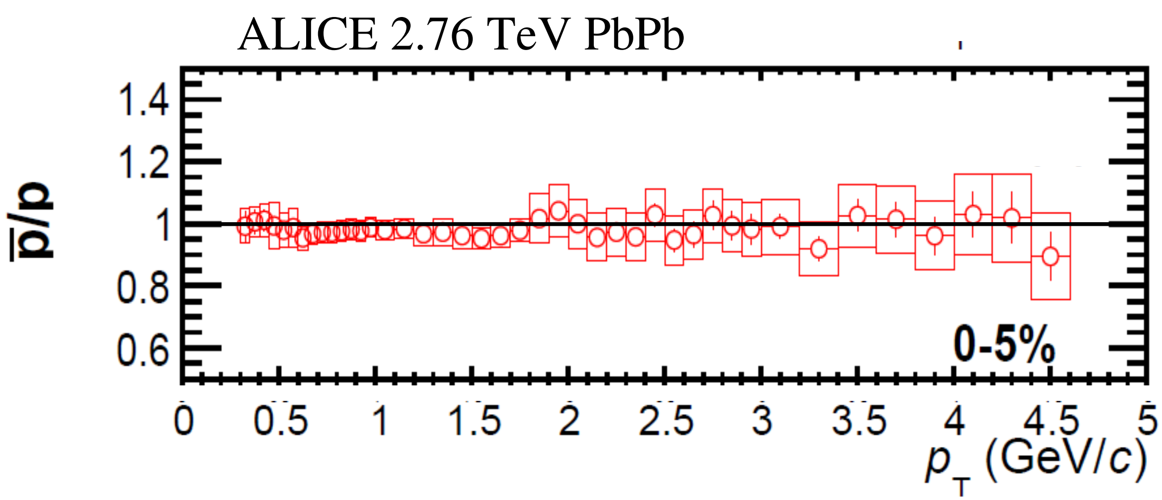
systematic evolution of chemical freeze-out parameters as function of cm energy



hadron yields for Pb-Pb central collisions from LHC down to RHIC, SPS, AGS well described by a statistical ensemble

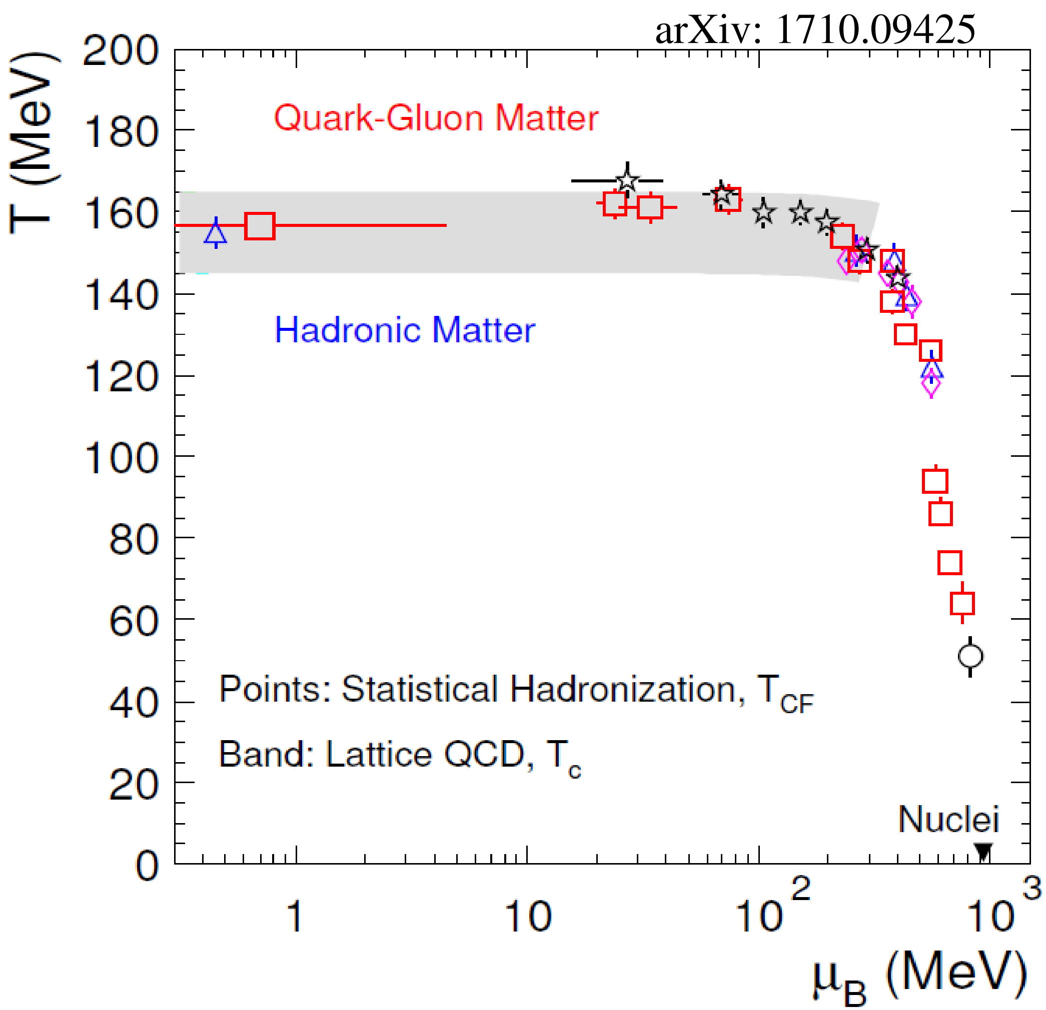
Biggest difference LHC compared to lower energies

- matter and anti-matter produced in equal proportions at LHC
- consistent with net-baryon free central region, (μ_b = 0.7 ± 3.8 MeV) similar to early universe



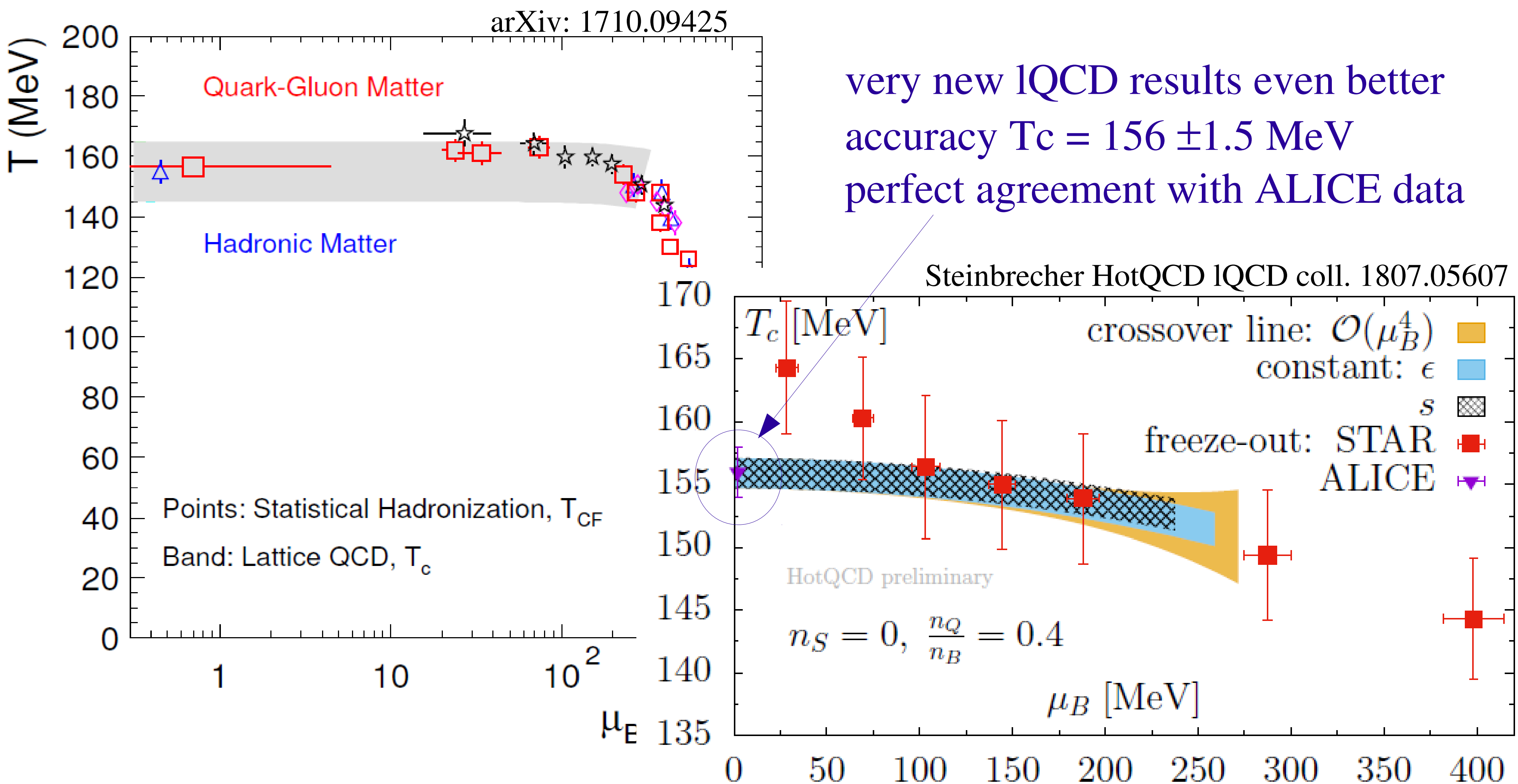
- even 10 anti-^{4}He nuclei observed!

Energy dependence of temperature and baryochemical potential



quantitative agreement of chemical freeze-out parameters with lQCD predictions of $\mu_B < 300$ MeV or $\sqrt{s_{NN}} \geq 10$ GeV

Energy dependence of temperature and baryochemical potential



very new lQCD results even better accuracy Tc = 156 ±1.5 MeV perfect agreement with ALICE data

a direct comparison of LHC data and lattice QCD

fluctuations of conserved charges (baryon number, strangeness, charge) sensitive to criticality related to spontaneous breaking of chiral symmetry.
- in lQCD susceptibilities exhibit characteristic properties governed by universal part of free energy in vicinity of O(4) critical region of chiral transition

$$\chi_{ijk}^{BQS}(T) = \left.\frac{\partial P(T,\hat{\mu})/T^4}{\partial\hat{\mu}_B^i \partial\hat{\mu}_Q^j \partial\hat{\mu}_S^k}\right|_{\hat{\mu}=0} \quad \text{with } \hat{\mu}_X \equiv \mu_X/T$$

can we see signs of this criticality in experimental data?

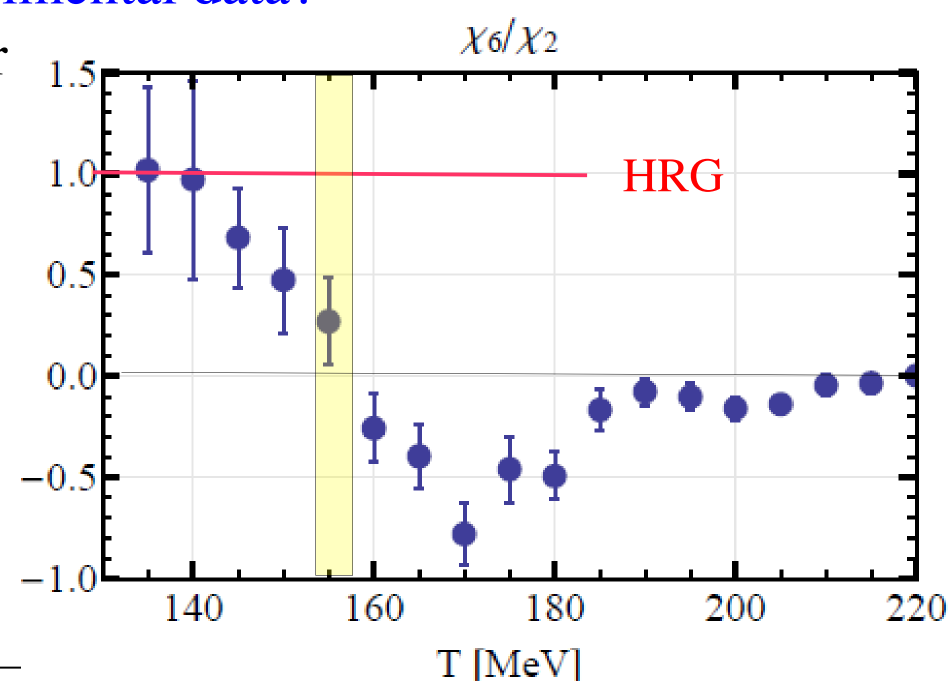
- look at moments of e.g. net baryon number

$$\Delta N_B = N_B - \bar{N_B}, \quad \mu_i = \langle(\Delta N_B - \langle\Delta N_B\rangle)^i\rangle$$

cumulants of this distribution are directly linked to lQCD susceptibilities

$$\kappa_2 = \mu_2 = VT^3\chi_2^B$$
$$\kappa_3 = \mu_3 = VT^3\chi_3^B$$
$$\kappa_4 = \mu_4 - 3\mu_2^2 = VT^3\chi_4^B$$

….



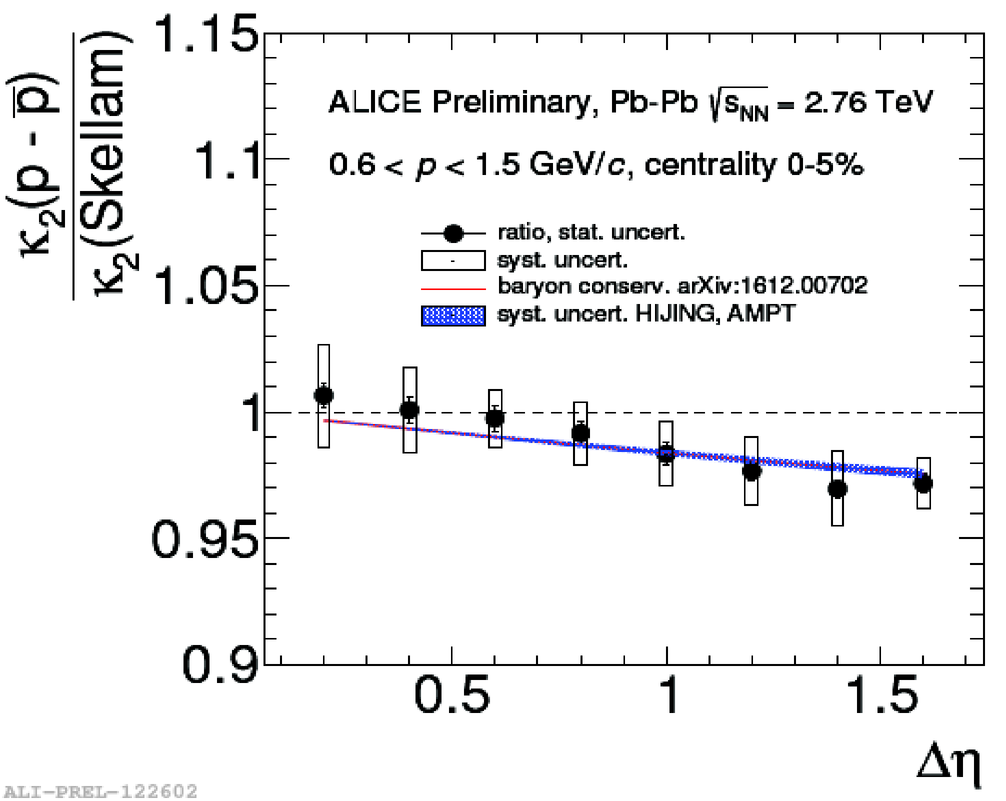
Wuppertal-Budapest lQCD coll. 1805.04445

Moments of net proton distribution

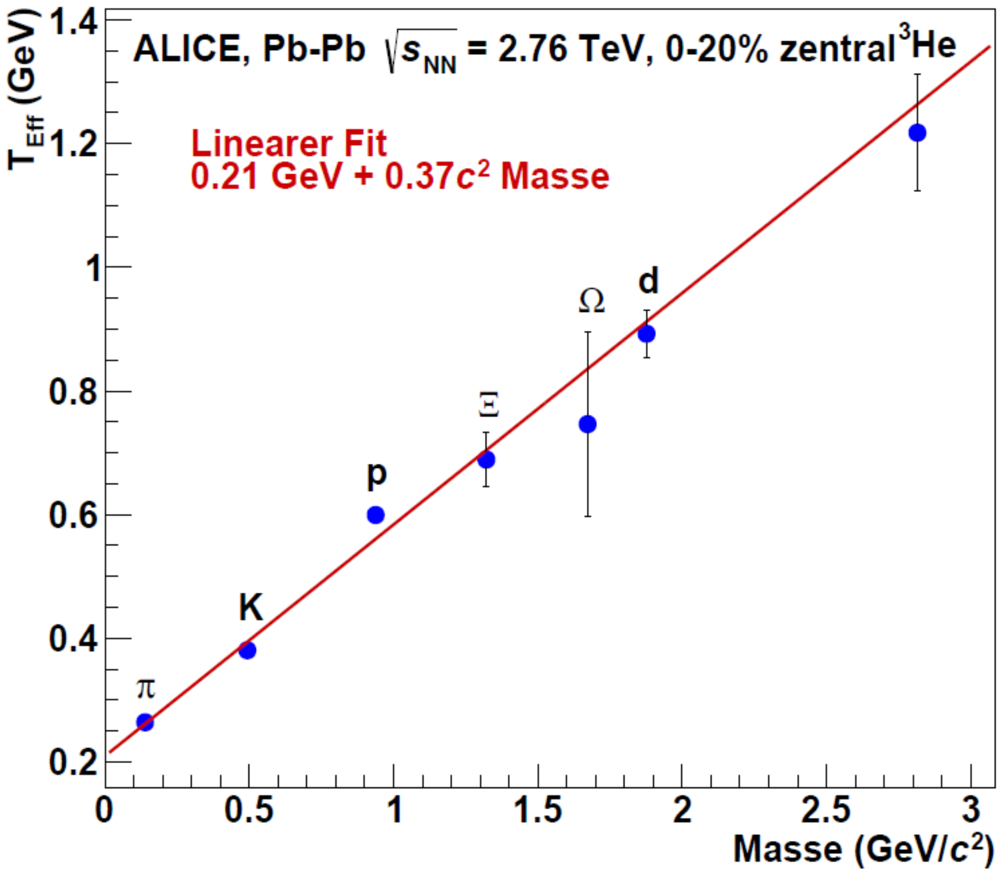
take net proton distribution as a proxy for net baryons
need a number of corrections before comparing to lQCD
- correct for volume fluctuations
- correct for baryon number conservation
- …

second moment of ALICE net proton distribution completely understood and comparison to lQCD baseline fulfilled

higher moments very statistics hungry and need very good understanding of all experimental fluctuation (efficiency
3rd and 4th moments from 2018 data
up to 6th moment LHC run3



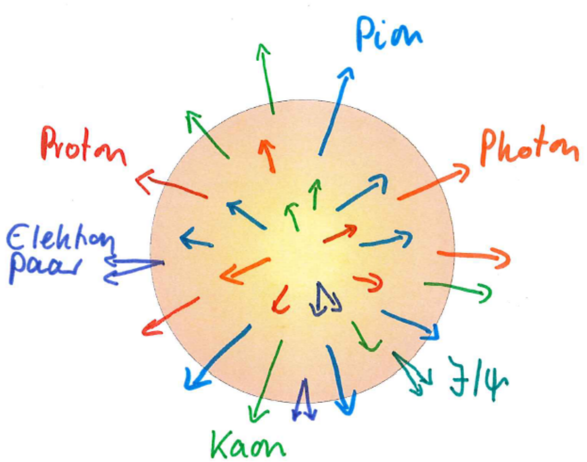
Rapid radial expansion of nuclear fireball



slope constant of spectra $T_{eff} \propto m$ reflects superposition of random thermal motion and collective expansion

at surface velocity ¾ speed of light

even fragile objects as deuteron follow radial flow



Charmonia as probe of deconfinement

the original idea (Matsui and Satz 1986): implant charmonia into the QGP and observe their modification (Debye screening of QCD), in terms of suppressed production in nucleus-nucleus collisions with plasma formation

table from H. Satz, J. Phys. G32 (2006) 25

in the QGP, the screening length $\lambda_{Debye}(T)$ decreases with increasing T. If $\lambda_{Debye}(T) < r_{charmonium}$ the system becomes unbound ↔

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

→ notion of charmonia as thermometer – sequential melting
signature of deconfinement, but no direct link to phase boundary

Charmonia and statistical hadronization

new insight (Braun-Munzinger, J.S. 2000):
QGP screens all charmonia (as proposed by Matsui and Satz), but charmonium production takes place at the phase boundary,

→ enhanced production at colliders – signal for deconfinement
production probability from thermalized charm quarks scales with N_{ccbar}^2

yields of charmonia (and open charm hadrons) directly linked to phase boundary and hadronization temperature
still probe of deconfinement

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)

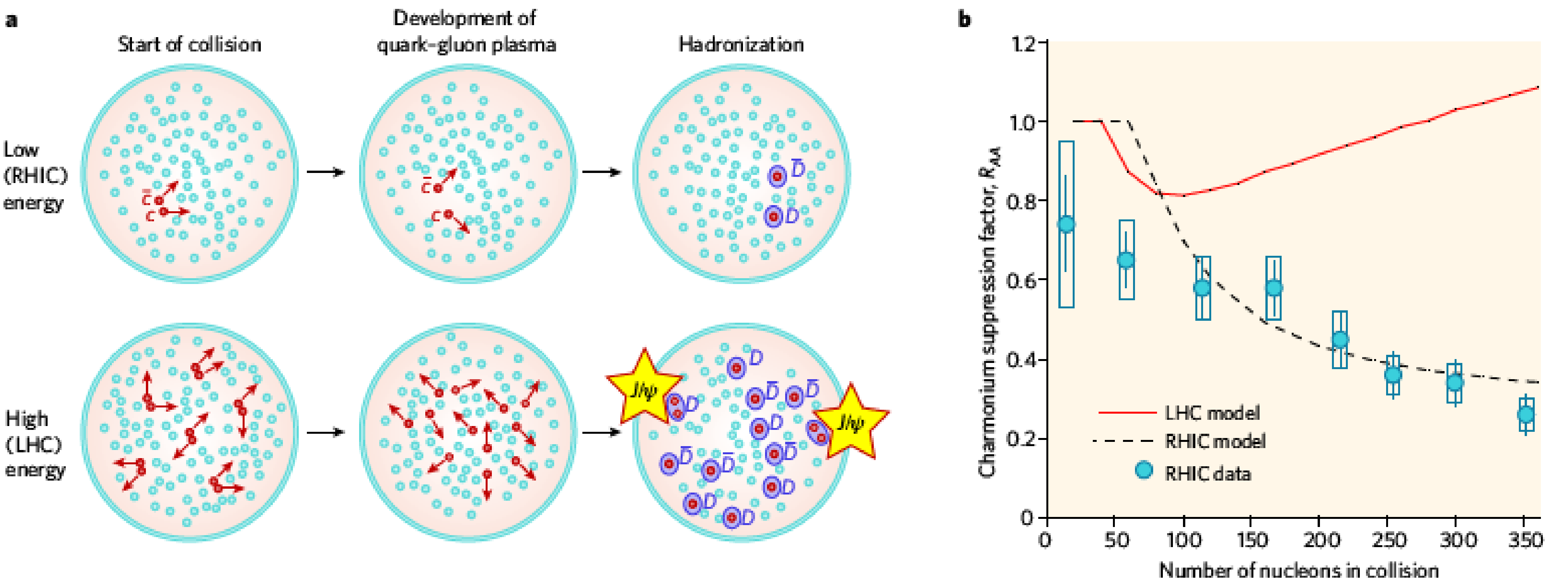
  technically number of charm quarks fixed by a charm-balance equation containing fugacity g_c

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

↑

the only additional free parameter

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



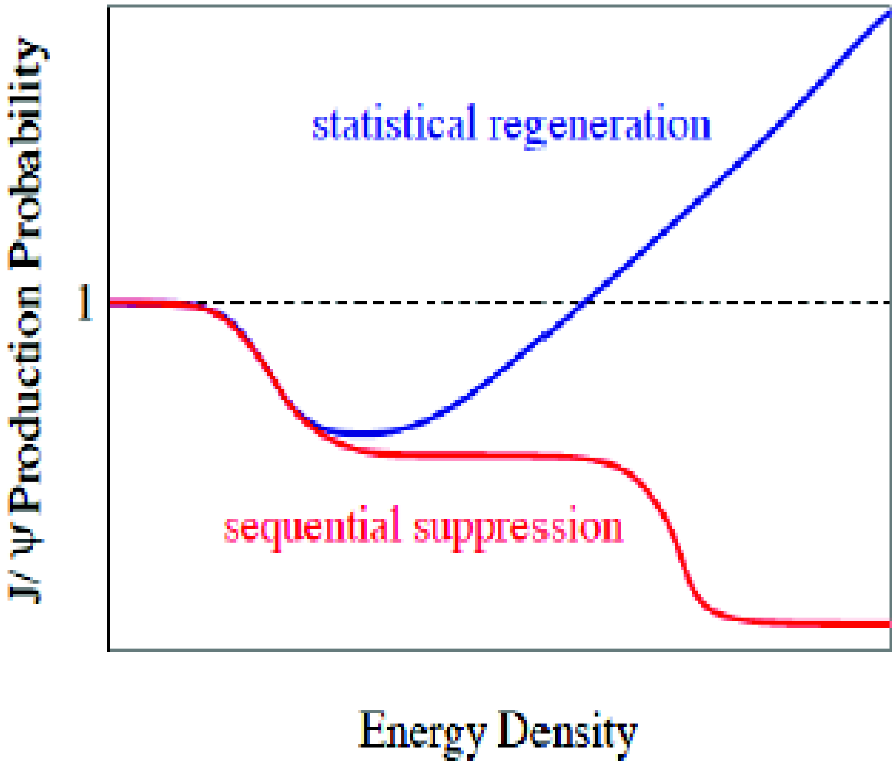
charmonium enhancement as fingerprint of deconfinement at LHC energy - a prediction!

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

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

Expectations for LHC

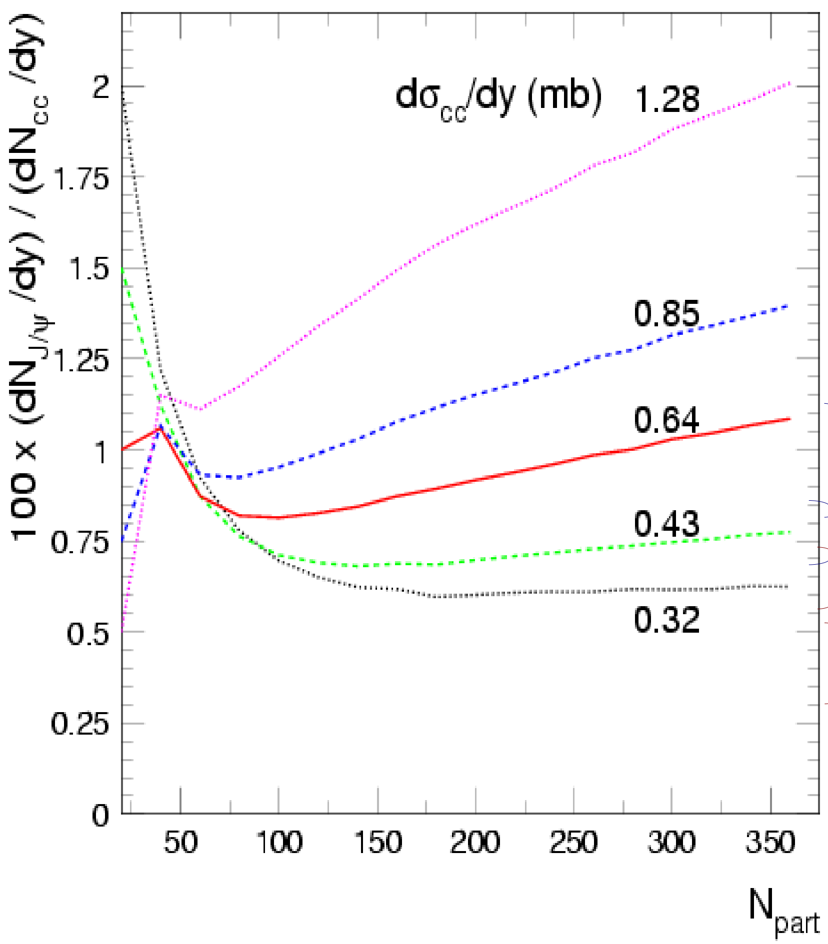
2 possibilities:



H.Satz 2009

Expectations for LHC from measured ccbar cross section in pp collisions

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



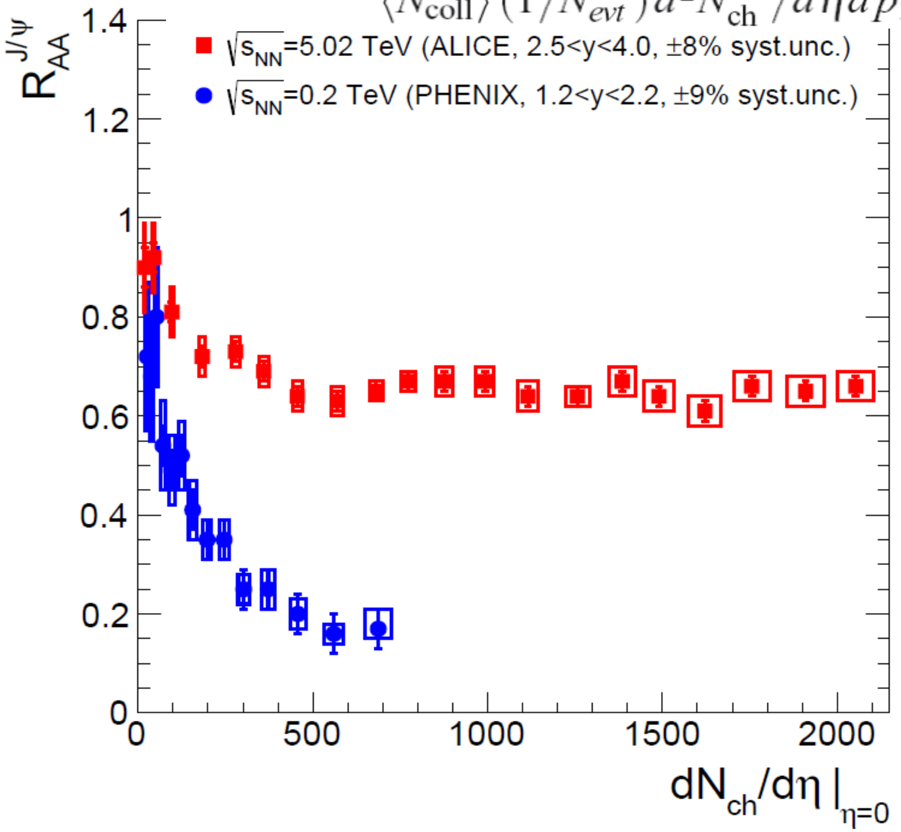
mid-y LHC 2.76 and 5.02 TeV including shadowing

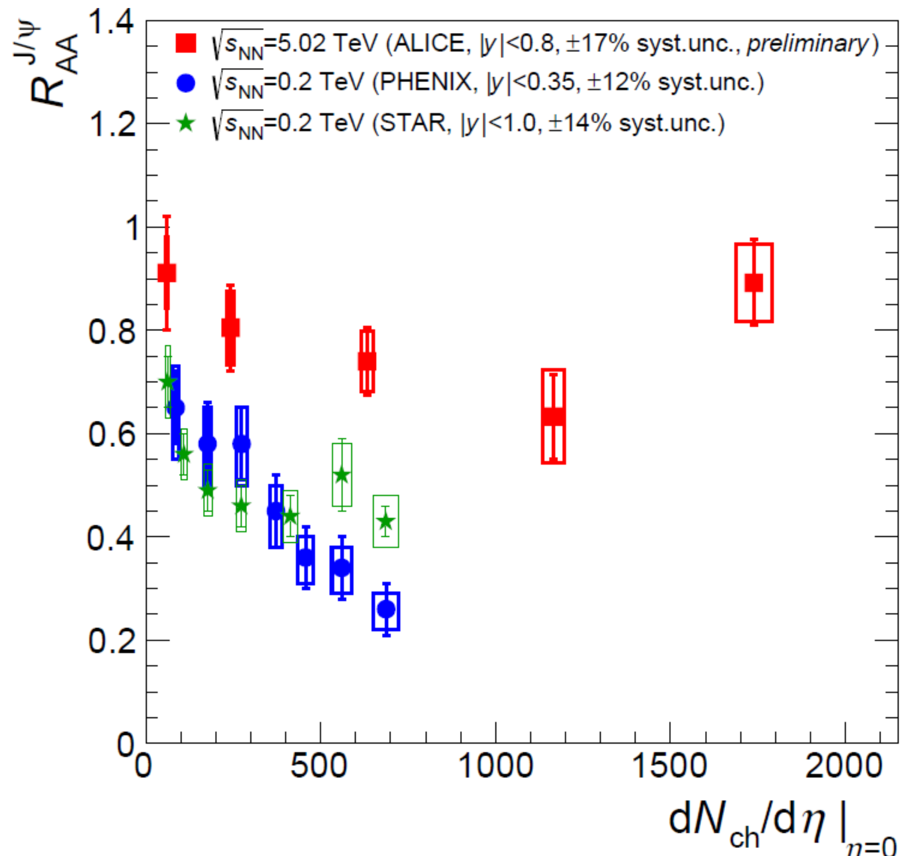
forward-y LHC 2.76 and 5.02 TeV including shadowing

measured ccbar cross sections at appropriate rapidity by ALICE and LHCb and shadowing from measured J/psi production in pPb collisions compared to pQCD

J/ψ production in PbPb collisions: LHC rel. to RHIC

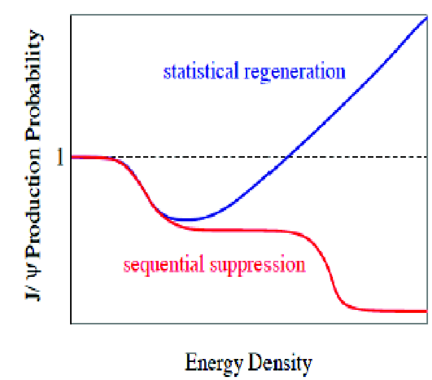
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$



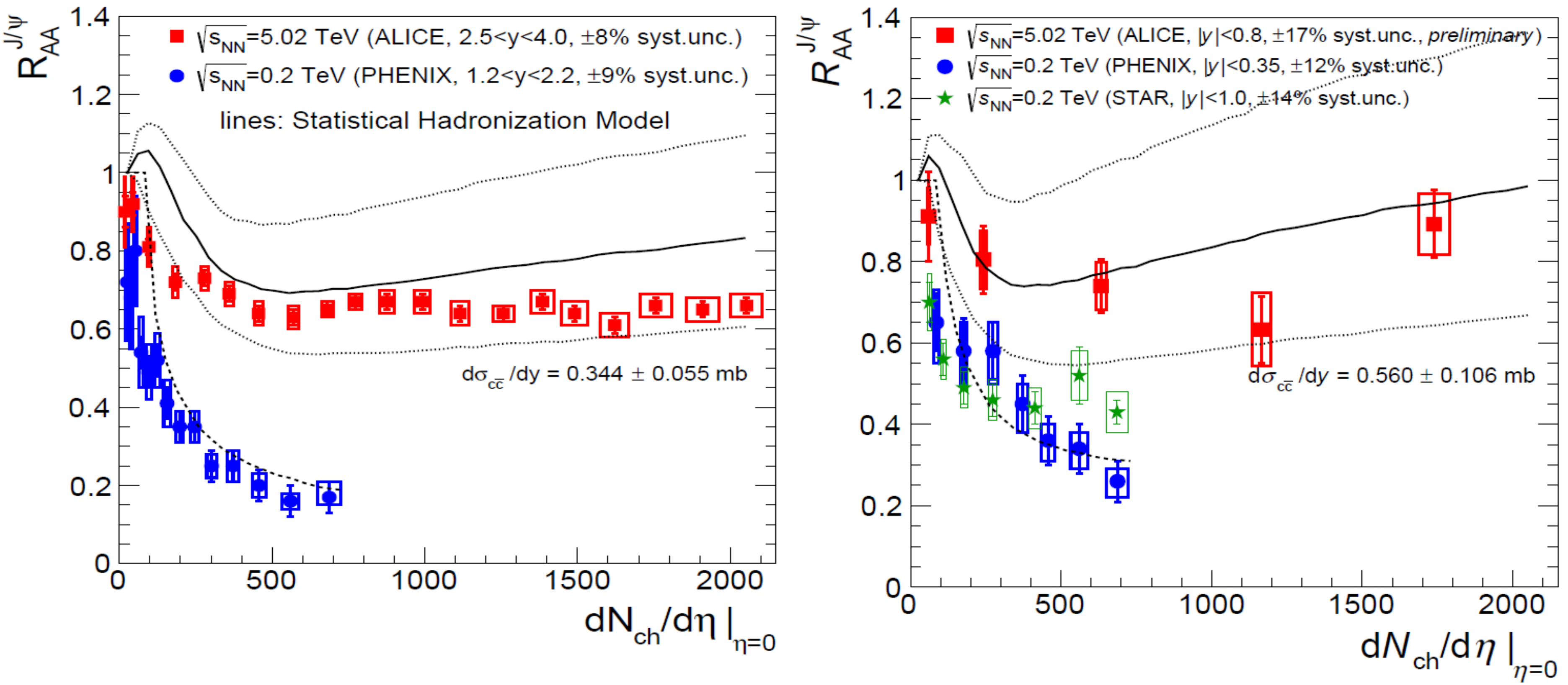


energy density -->

sequential 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

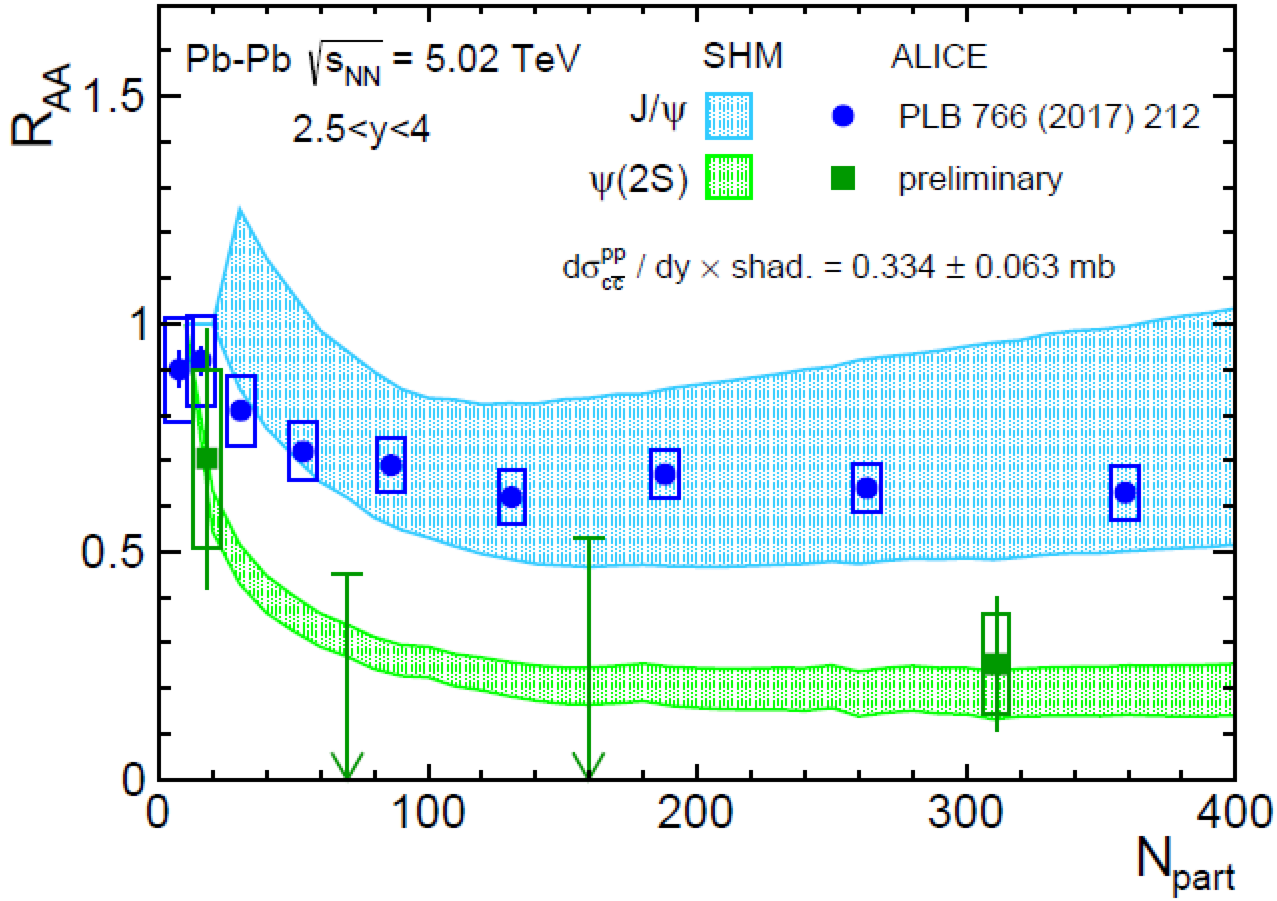


production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties

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

What about ψ(2S)?

M. Köhler, A. Andronic, P. Braun-Munzinger, JS, arXiv:1807.01236

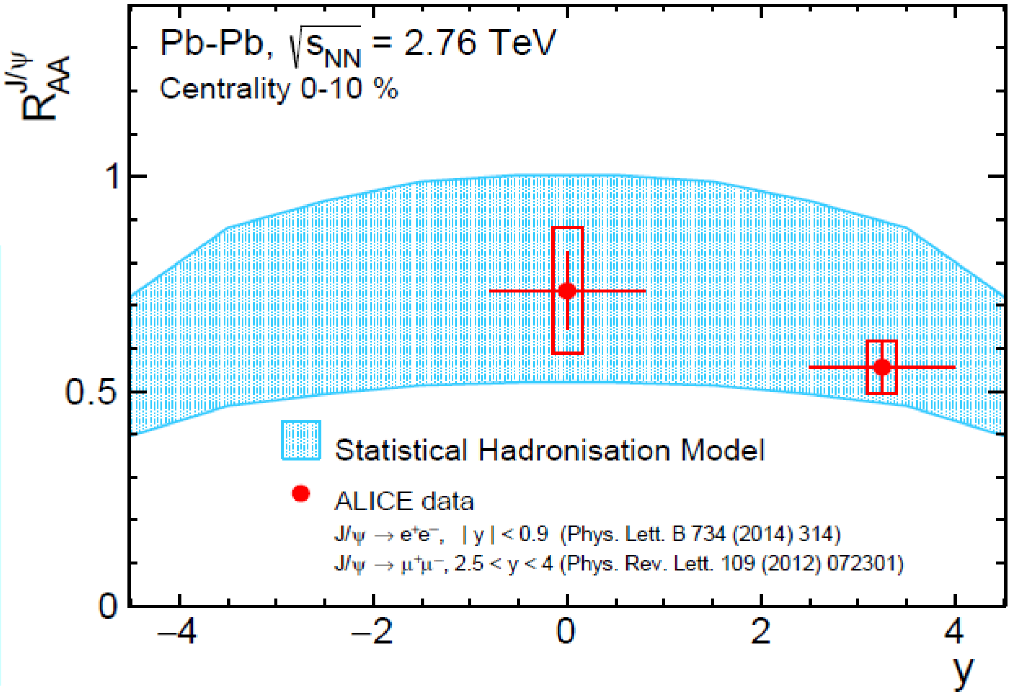


also excited state completely in line, suppressed by Boltzmann factor
errors will decrease with more data

Rapidity dependence of R_{AA}

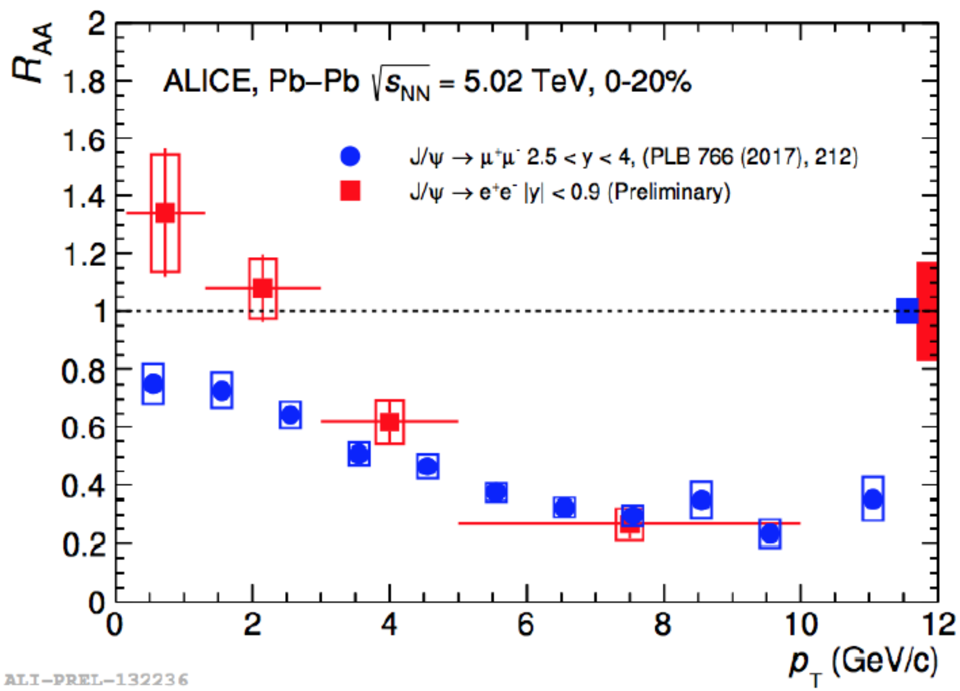
yield in PbPb peaks at mid-y
where energy density is largest
?

M. Köhler, A. Andronic, P. Braun-Munzinger, JS
arXiv:1807.01236



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)

Transverse momentum dependence



compared to pp collisions enhancement at small p_t!

– was predicted for statistical hadronization component

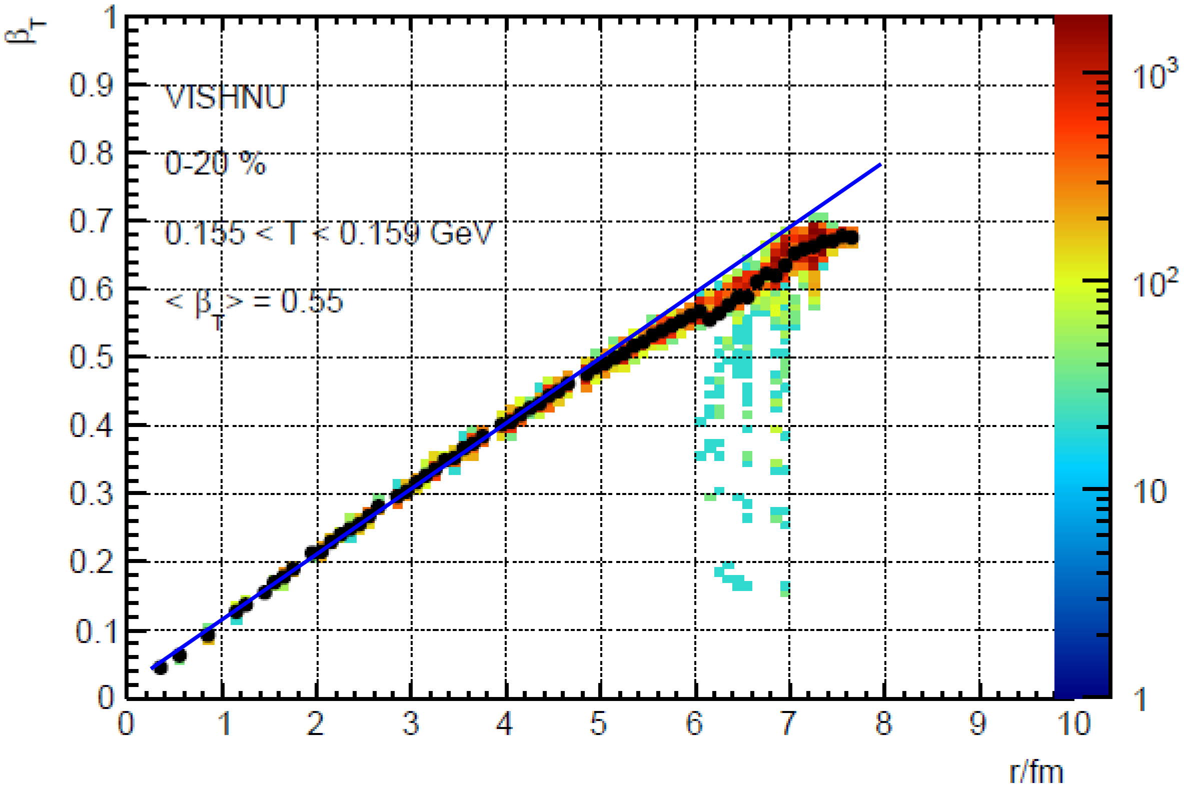
what does statistical hadronization have to say about p_t spectrum?

the physical picture: charmonia are formed at hadronization from charm quarks in the medium

implies: they should exhibit – as other hadrons – a spectrum characterized by the temperature and the flow of the surrounding medium

recipe: take flow characteristics at T_c from a good hydro describing the other light flavor observables, normalization given by ccbar cross section

Transverse hydro velocity profile at T_c

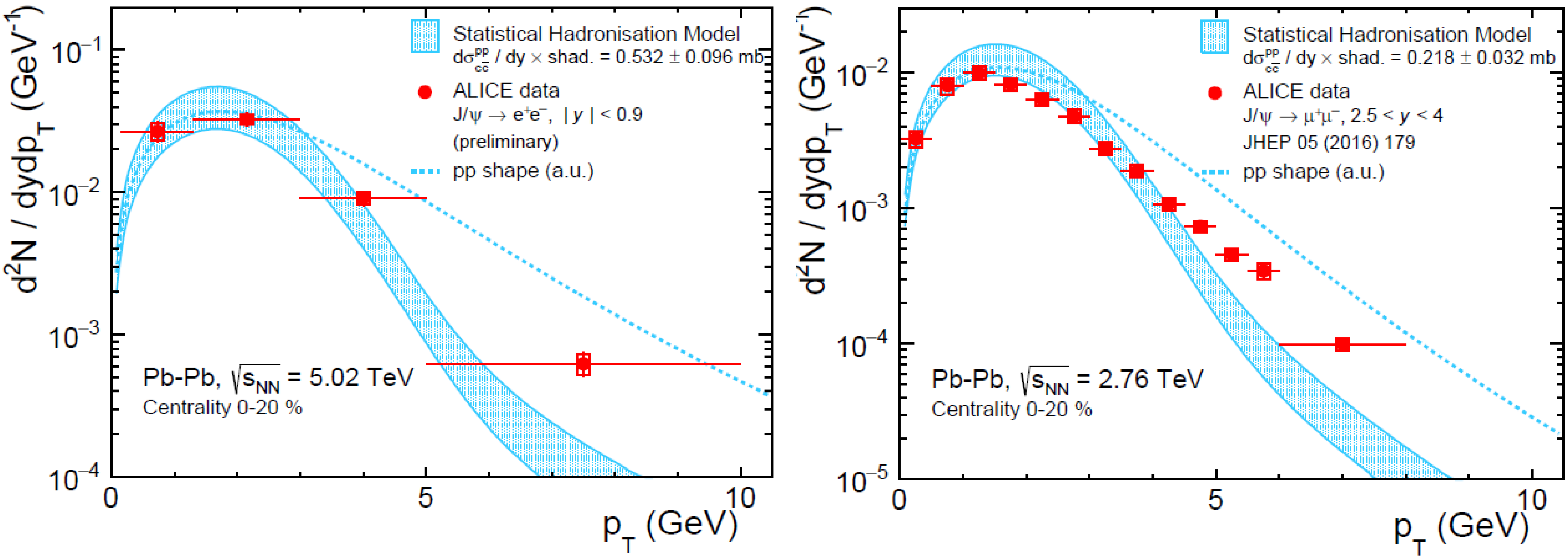


- velocity profile linear in r
- average transverse velocity: 0.55 c

<u>first approach:</u> use blast wave parameterization with hydro input, i.e. linear velocity profile and correct mean velocity and $T=T_c$ and $m=m(J/\psi)$ for core and pp spectrum for corona

J/ψ transverse momentum spectra from stat. hadr.

M. Köhler, A. Andronic, P. Braun-Munzinger, JS, arXiv:1807.01236



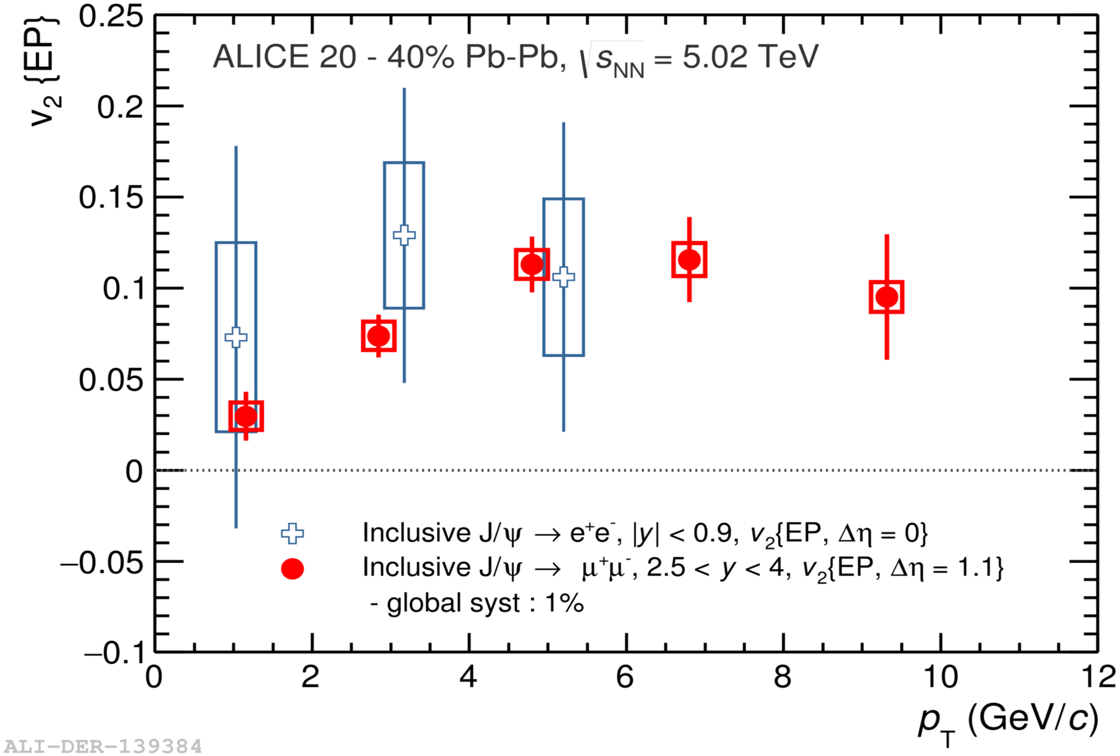
quite reasonable agreement without any free parameters
J/ψ formed at hadronization at T_c from deconfined thermalized charm quarks flowing with the rest of the medium

Elliptic flow of J/ψ vs p_t

semi-central collisions: asymmetric overlap region → asym expansion velocity profile

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

PRL119 (2017) 242301, arXiv:1709.05260



- expect build-up with p_t as observed for π, p. K, Λ, …
  and vanishing signal for high p_t
  region not dominated by flow

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

Summary

Hadronization of the QGP delineates the phase boundary as computed with lattice QCD

Even yields of fragile nuclei determined by this temperature

Fluctuations of conserved charges developed as tool to access chiral pseudo-criticality, measurements of higher moments start appearing

Global, Hubble-like expansion of the nuclear fireball

Charmonia give evidence for deconfinement, formation at hadronization of the fireball together with the rest

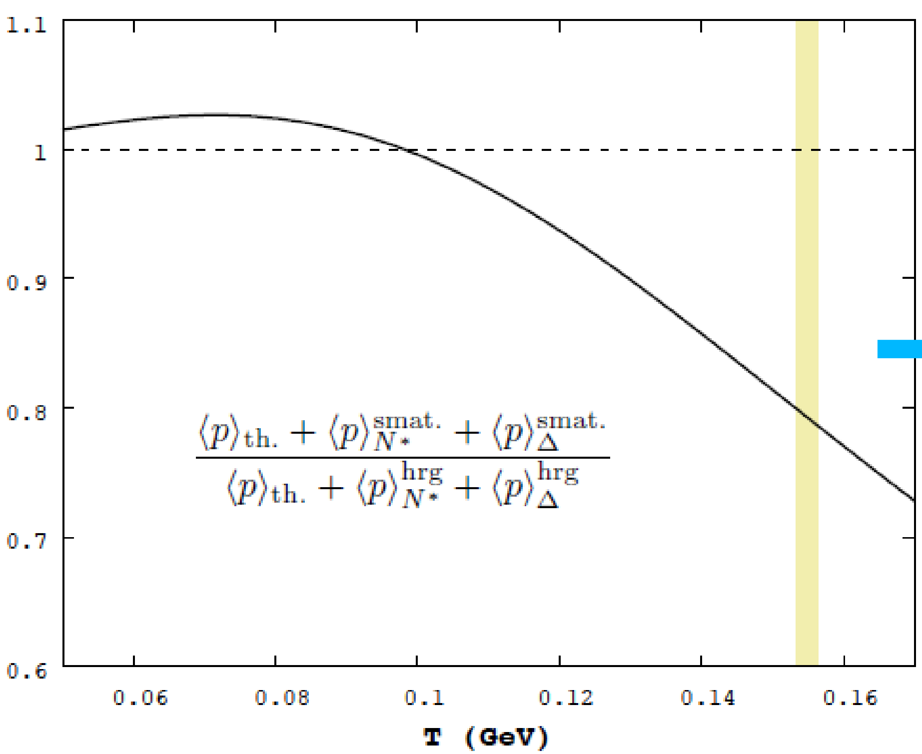
backup

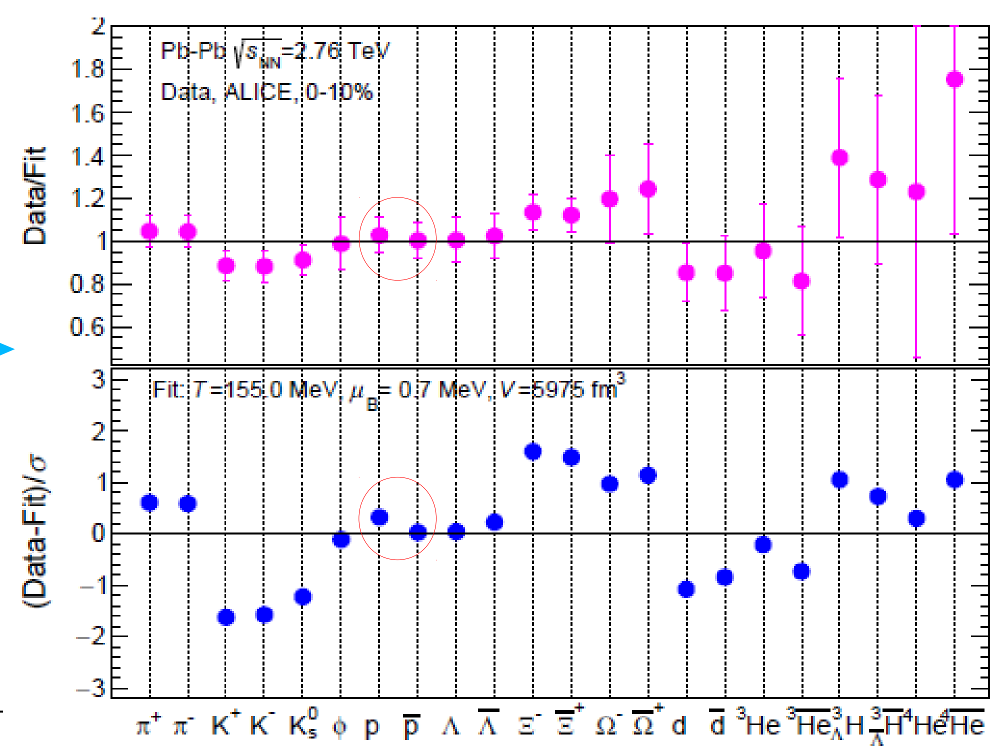
Solution of the proton puzzle

The thermal proton yield anomaly in Pb-Pb collisions at the LHC and its resolution

Anton Andronic,[1] Peter Braun-Munzinger,[2,3,4] Bengt Friman,[5]
Pok Man Lo,[6] Krzysztof Redlich,[6,7,2] and Johanna Stachel[3,2]

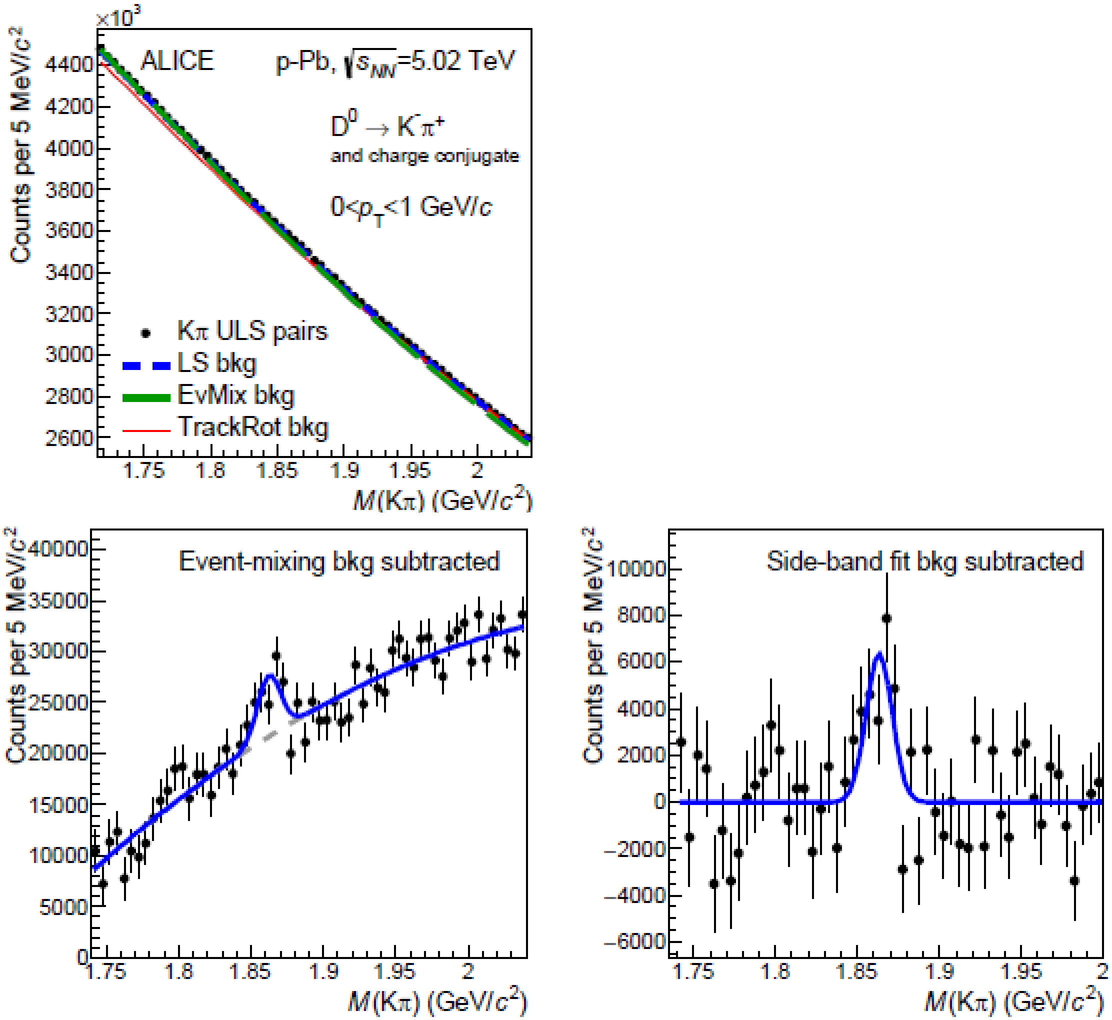
use S-matrix formalism to include πN interaction in hadron resonance gas (analysis of measured phase shifts)



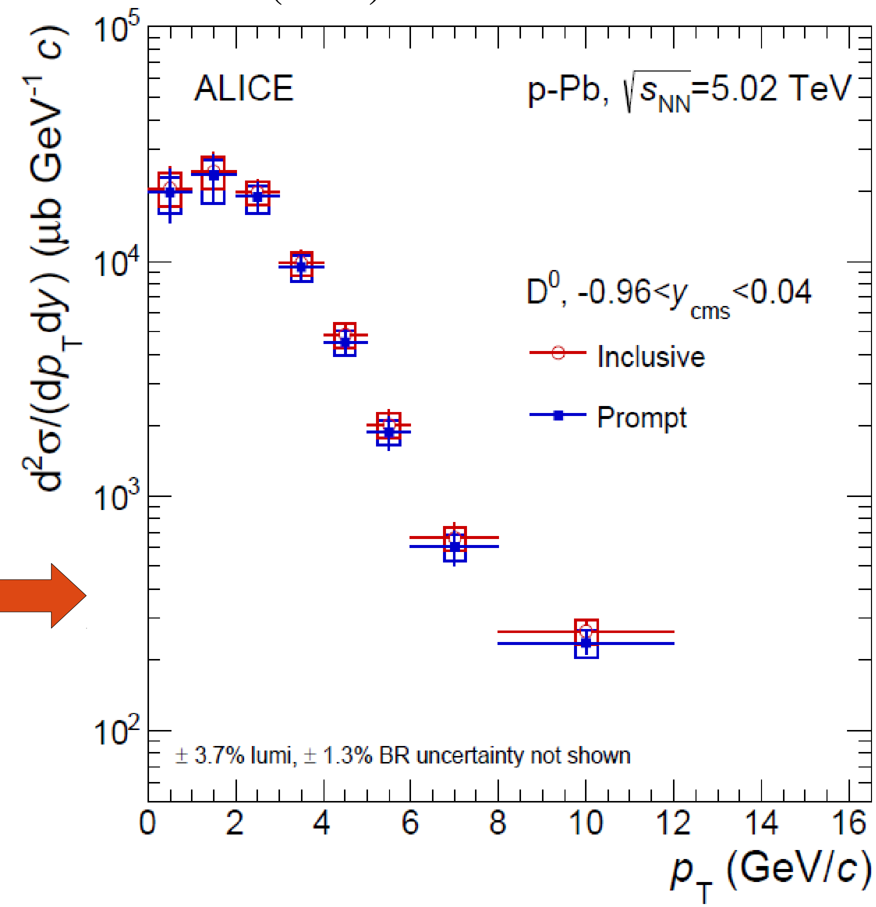


Production of ccbar - open charm

first measurements of open charm down to p_t = 0 at y=0

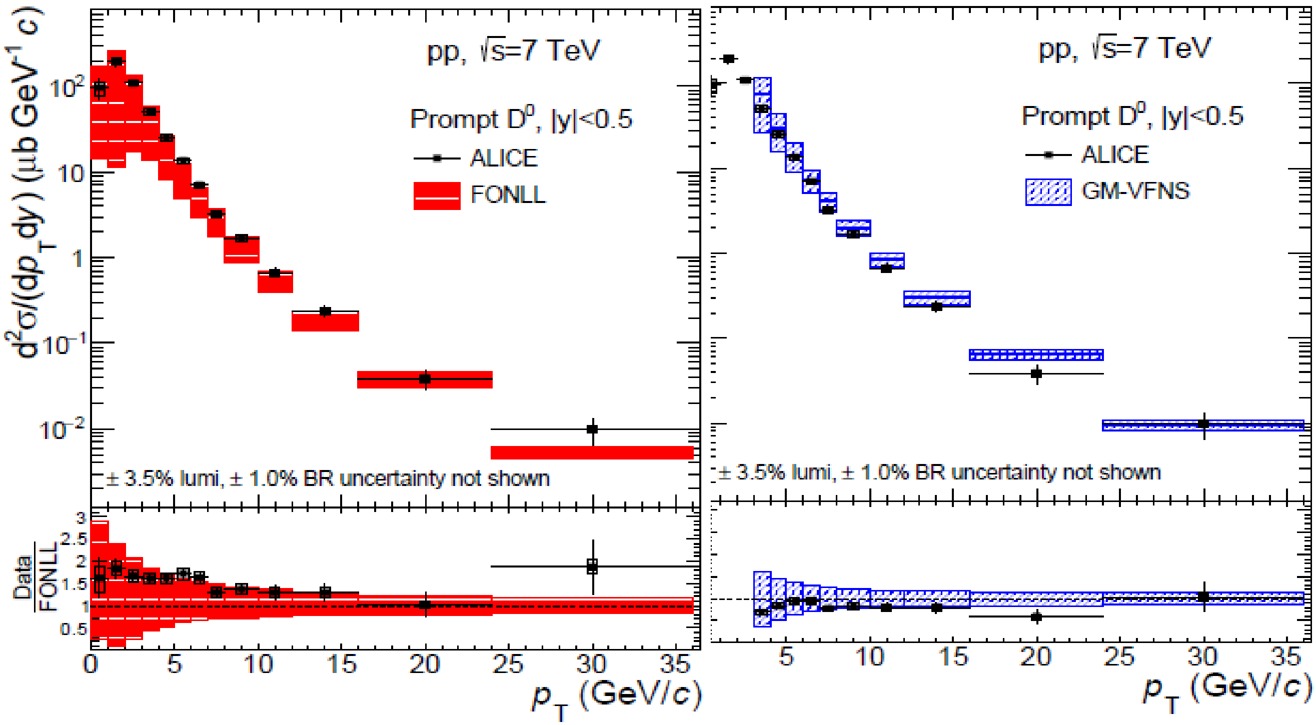


PRC94(2016) 054908 arXiv: 1605.07569



very hard struggle to deal with (irreducible) combinatorial background,
very recently successful for D^0 in pp and pPb

measurements in pp at 7 TeV agree well with state of the art pQCD calculations



ALICE: 1702.00766
FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

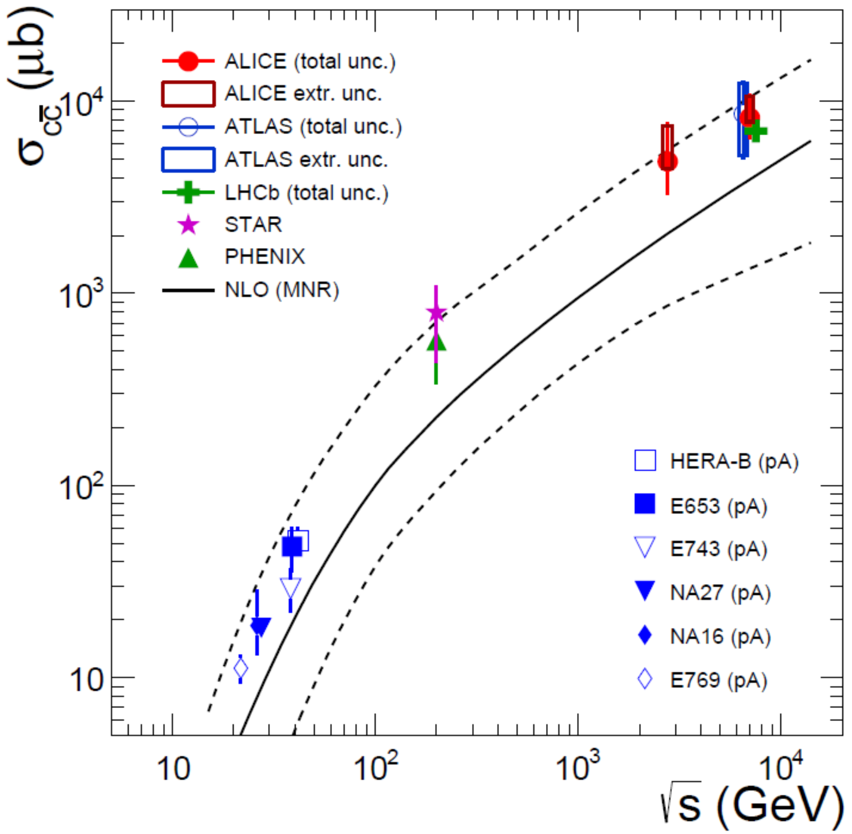
data are compared to perturbative QCD calculations
reasonable agreement
- at upper end of FONLL and
  at lower end of GM-VFNS

mid-y cross sections

	Extr. factor to $p_T > 0$	$d\sigma/dy\,\|_{\|y\|<0.5}$ (μb)
D^0	$1.0002^{+0.0004}_{-0.0002}$	$512 \pm 37(\text{stat}) \pm 39(\text{syst}) \pm 18(\text{lumi}) \pm 5(\text{BR})$
D^+	$1.25^{+0.29}_{-0.09}$	$235 \pm 19(\text{stat}) \pm 26(\text{syst}) \pm 8(\text{lumi}) \pm 6(\text{BR})^{+54}_{-16}(\text{extrap})$
D^{*+}	$1.21^{+0.28}_{-0.08}$	$251 \pm 29(\text{stat}) \pm 24(\text{syst}) \pm 9(\text{lumi}) \pm 3(\text{BR})^{+58}_{-16}(\text{extrap})$
D_s^+	$2.23^{+0.71}_{-0.65}$	$89 \pm 18(\text{stat}) \pm 11(\text{syst}) \pm 3(\text{lumi}) \pm 3(\text{BR})^{+28}_{-26}(\text{extrap})$

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

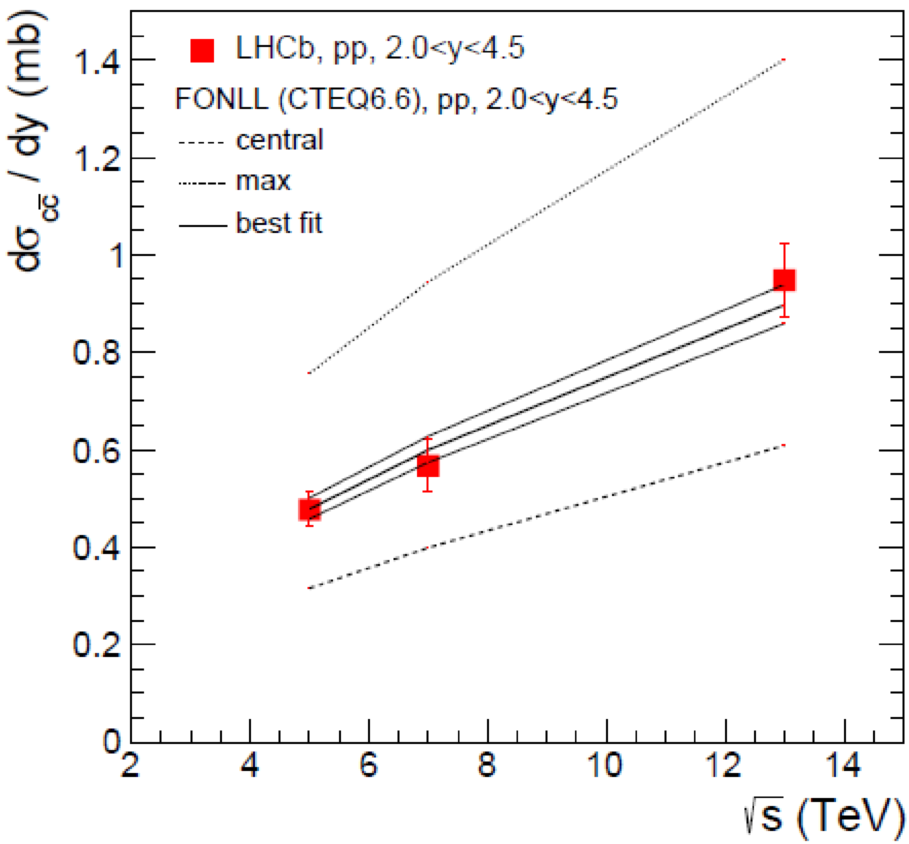
PRC94(2016) 054908 arXiv: 1605.07569

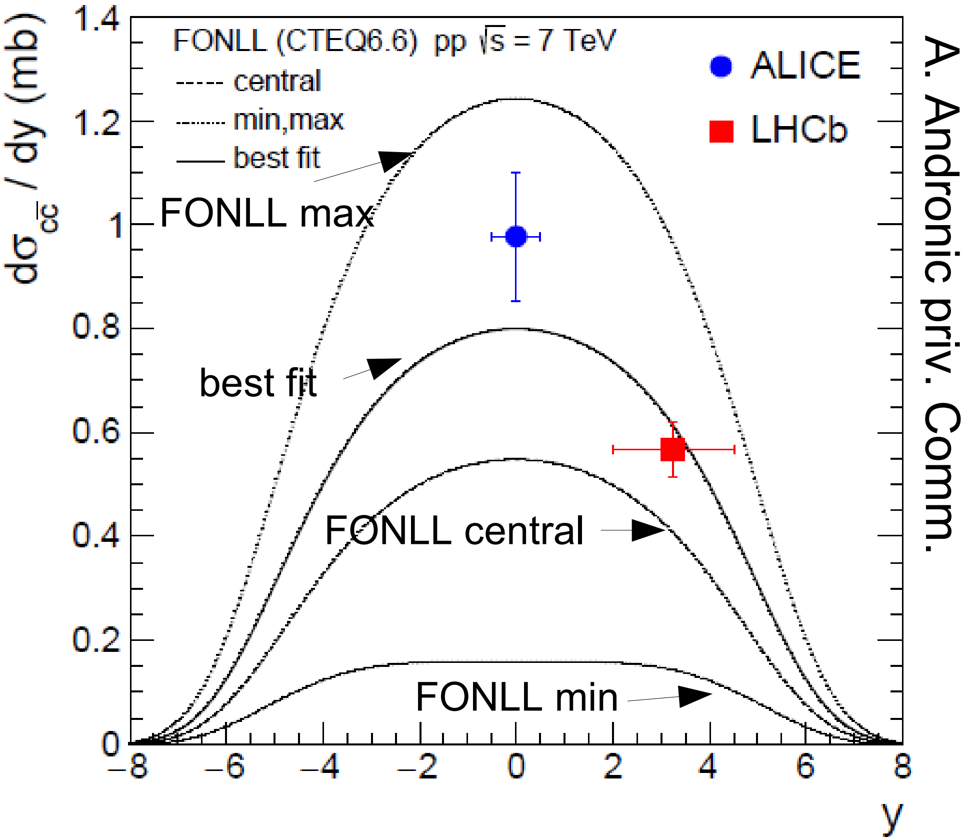


- cross sections in good agreement with NLO pQCD (at upper end of band but well within uncertainty)
- beam energy dependence follows well NLO pQCD

the baseline for the interpretation of PbPb data

use shape of FONLL to interpolate to proper √s and y-interval

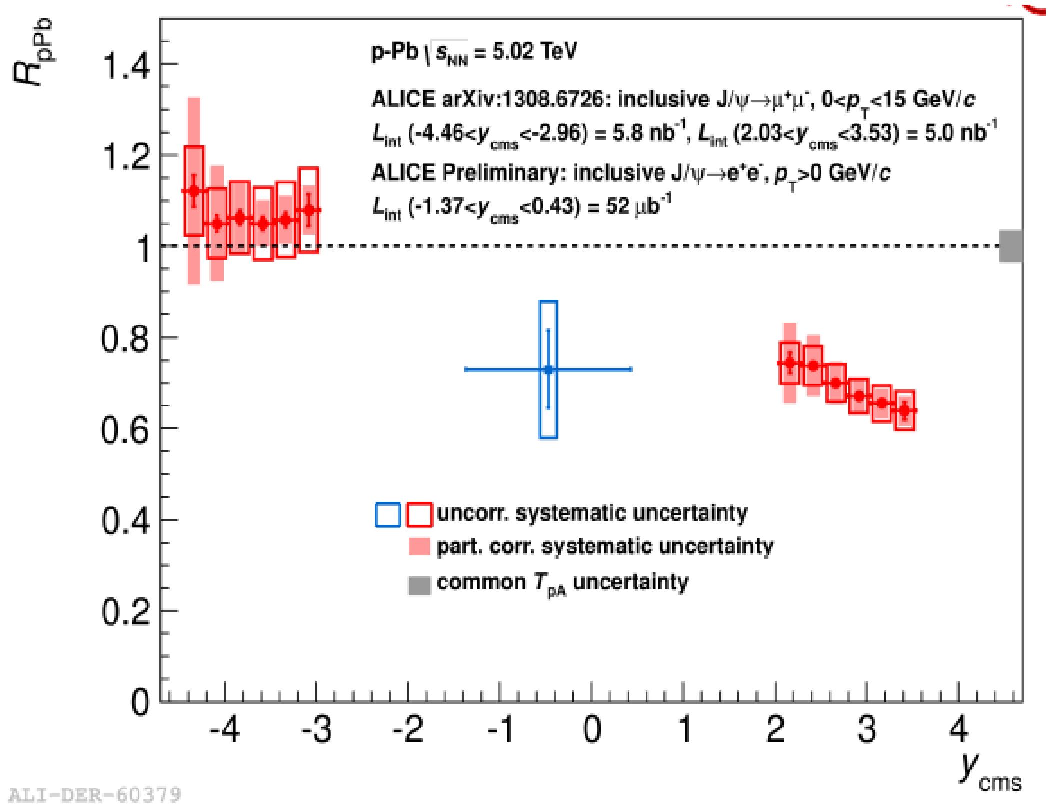




LHCb: 5 TeV arXiv:1610.02230
7 TeV NPB 871 (2013) 1
13 TeV JHEP 03 (2016) 159
plus erratum

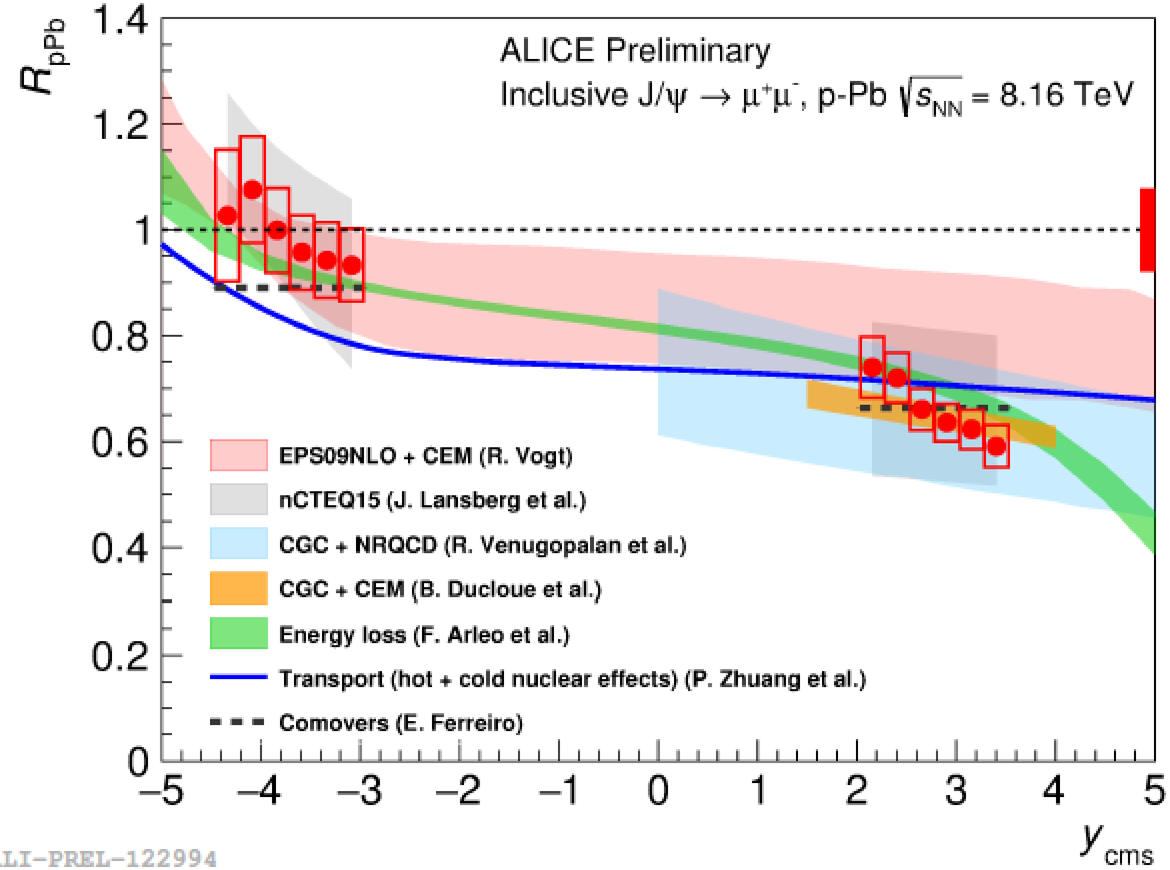
ALICE: 7 TeV PRC94(2016) 054908
and 1702.00766

J/psi rapidity distribution in pPb compared to pp



ALICE forward/backward arXiv:1308.6726
good agreement with LHCb arXiv:1308.6729
ALICE mid-y hard probes 2013

J/psi rapidity distribution in pPb compared to pp

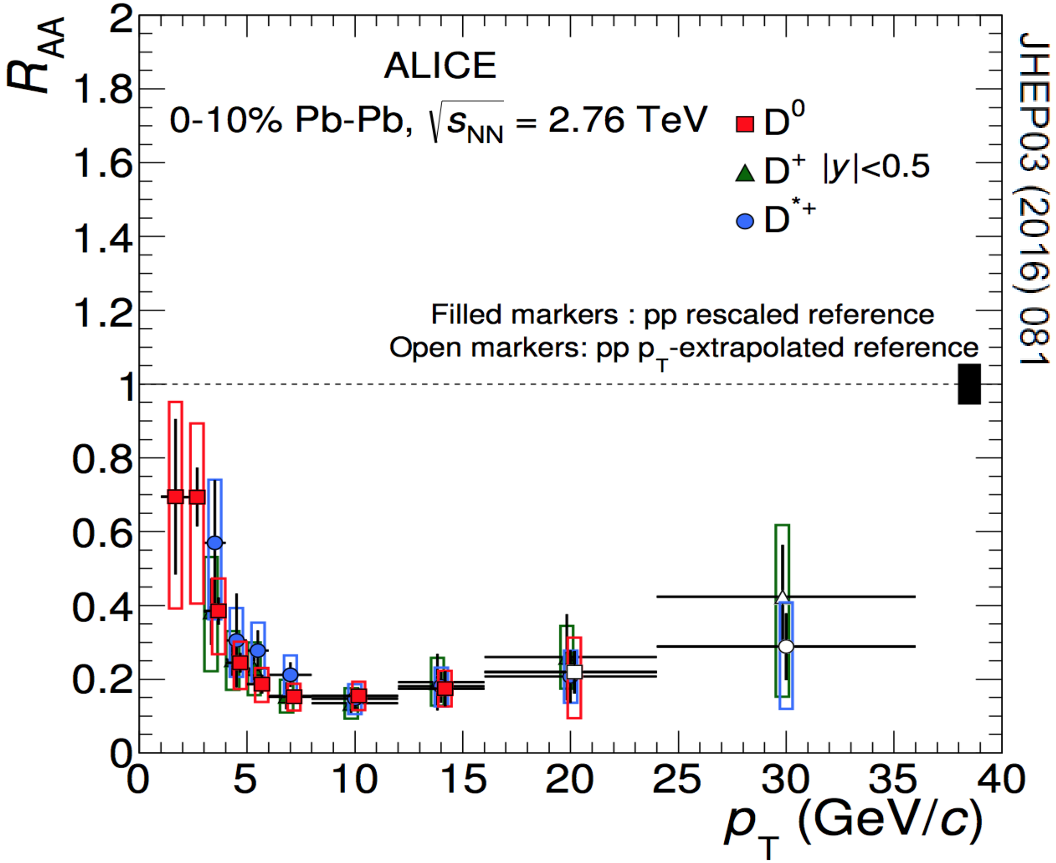


ALICE new 8.16 TeV data

good agreement with shadowing calculations
also with energy loss models wo shadowing
and CGC calculation

pp open charm dσ/dy plus nuclear effects from J/ψ in pPb form current baseline for charmonia in PbPb

suppression of charm at LHC energy

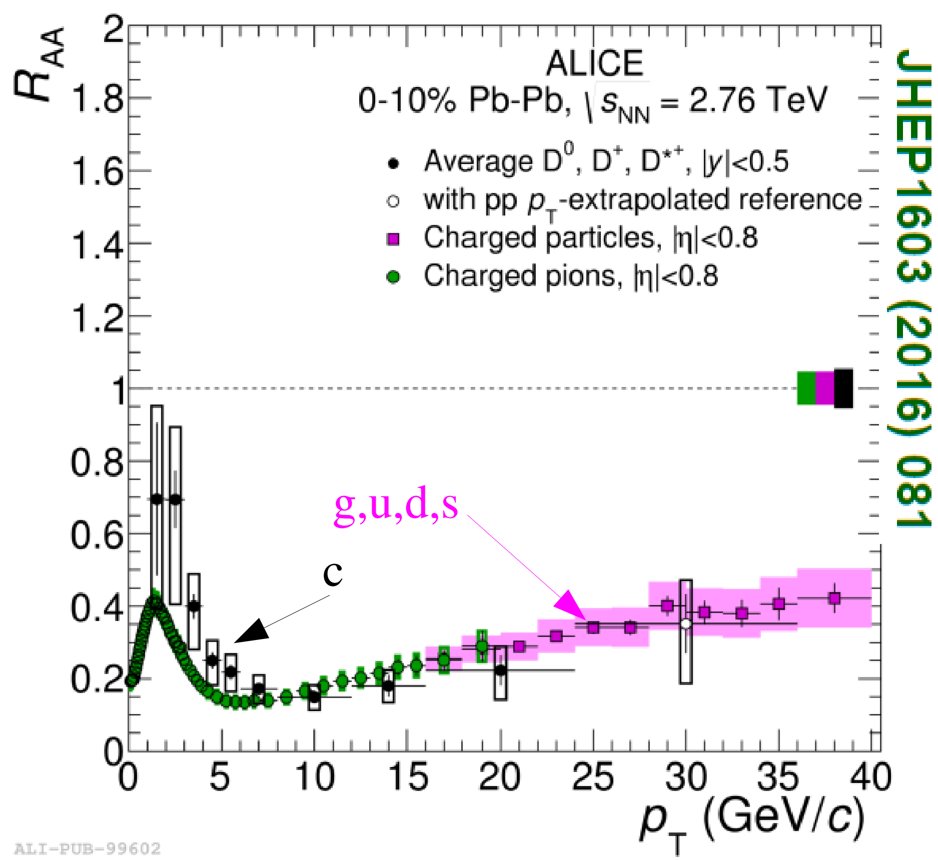


energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 5 for 5-15 GeV/c

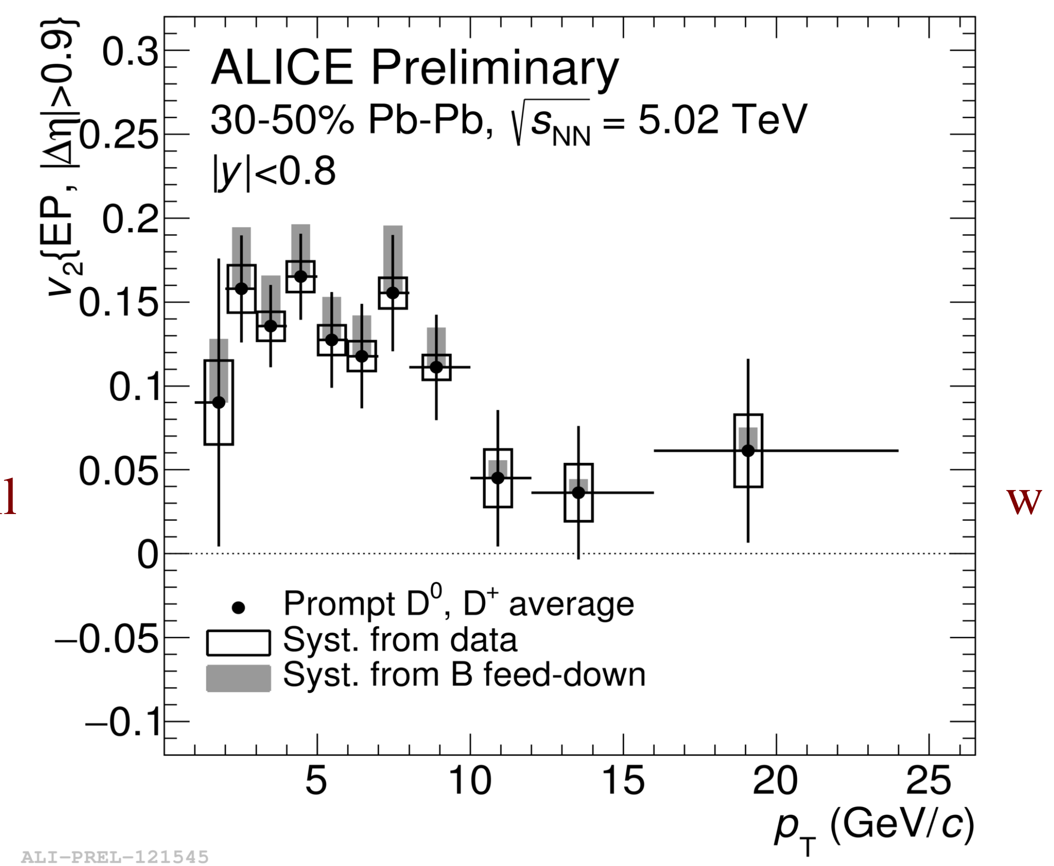
charm quarks thermalize to large degree in QGP

strong energy loss of charm quarks

elliptic flow for charm – participation in coll. flow



ell

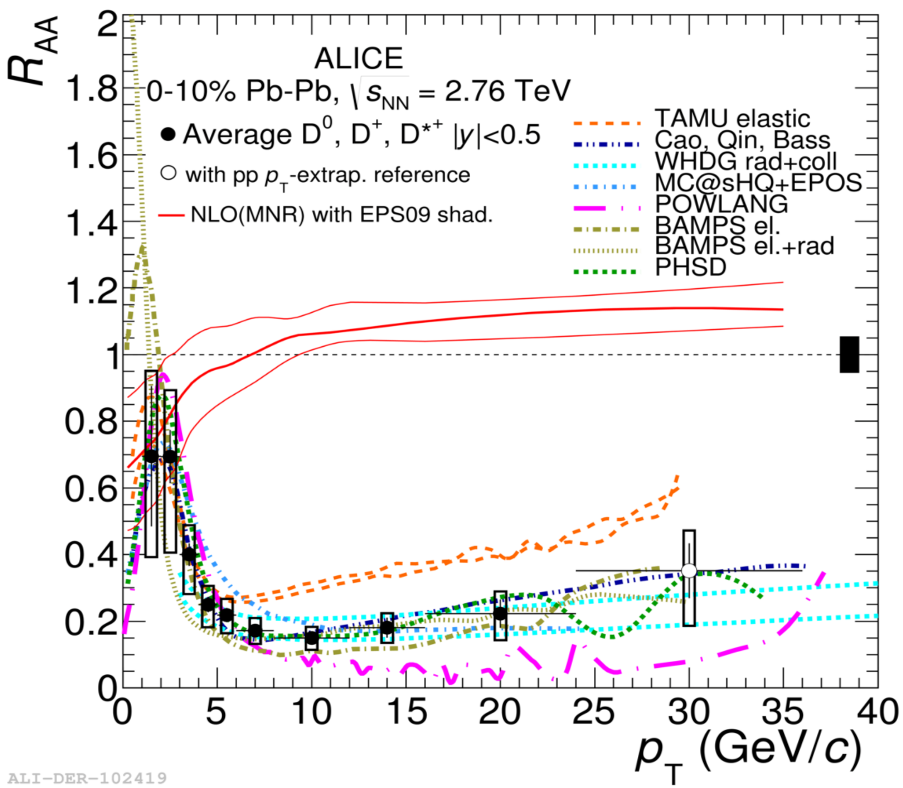


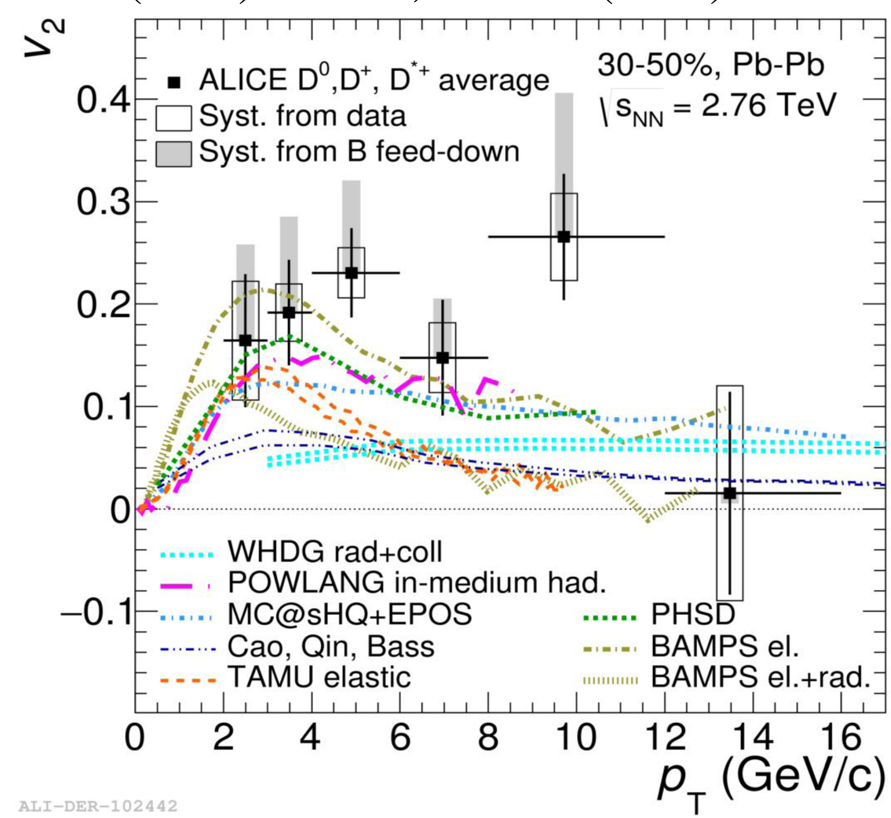
w

M.Djordjevic, arXiv:1307.4098:
equal R_{AA} is a conspiracy of different fragmentation functions of light quarks, gluons, charm and different color factors in energy loss

models constrained by simultaneous fit of R_{AA} and v_2

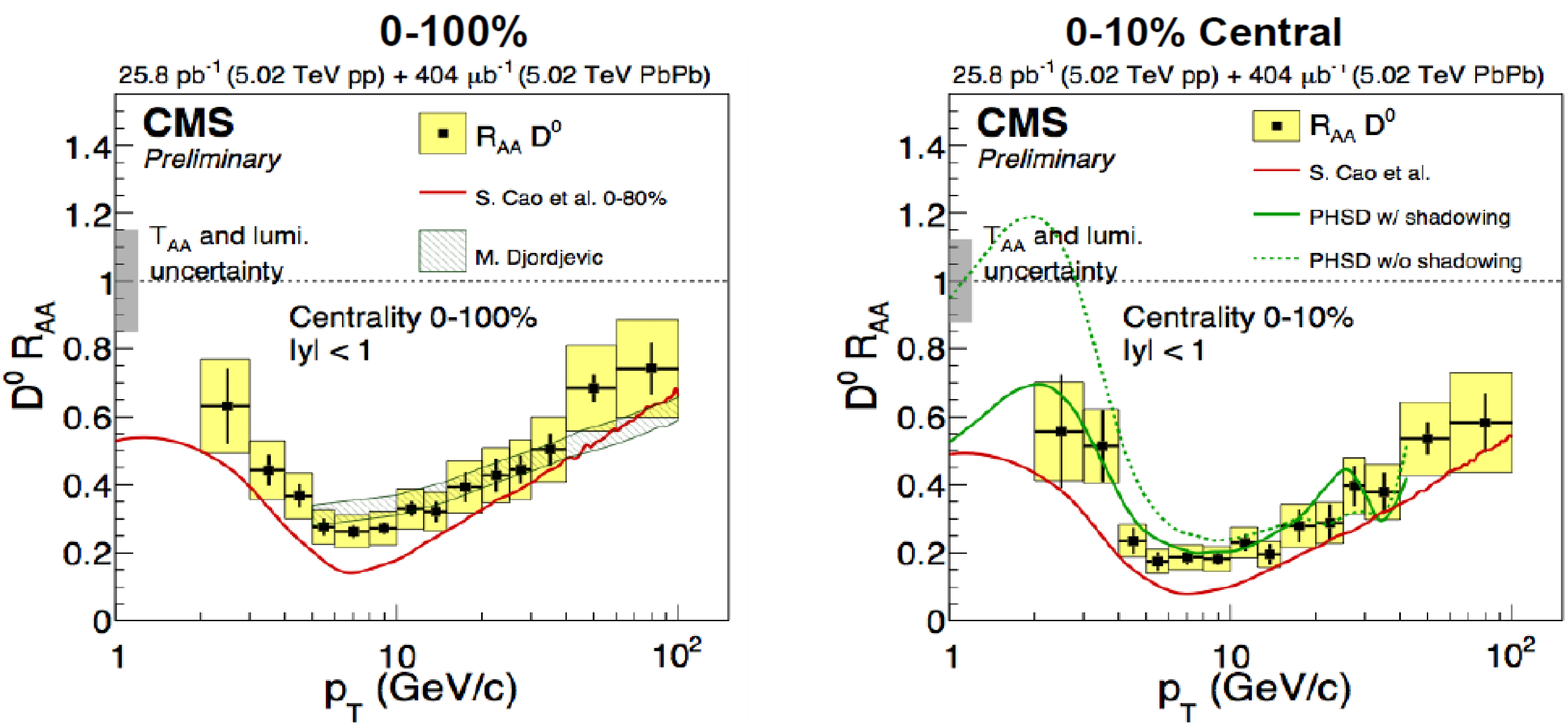
PRL 111 (2013) 102301, PRC 90 (2014) 034904





models capture various relevant aspects leading to thermalization of charm
– serious need to put together a coherent picture
- a difficult theoretical challenge, that is being addressed
- recently an EMMI rapid reaction task force took up the issue
(Andronic, Averbeck, Gossiaux, Masciocchi, Rapp)

D^0 R_{AA} compared to models



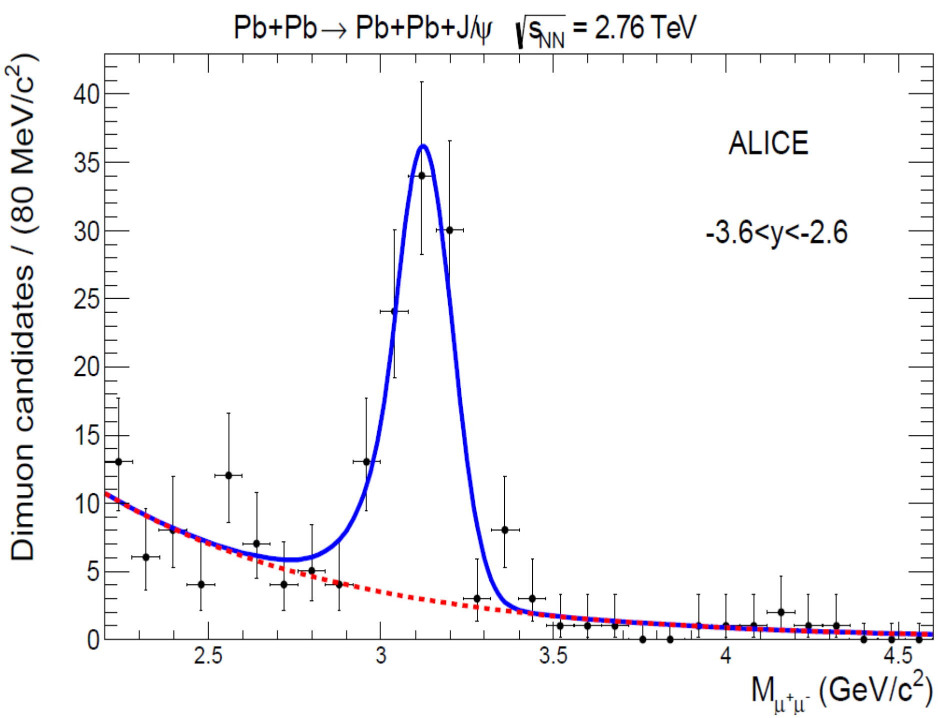
models: predictions before run2 data

- PHSD (Parton-Hadron-String Dynamics model[2])
- S.Cao et al. (Linearized Boltzmann transport model + hydro) arXiv:1605.06447v1
- M. Djordjevic (QCD medium of finite size with dynamical scattering centers with collisional and radiative energy loss) Phys. Rev. C 92 (Aug, 2015) 024918

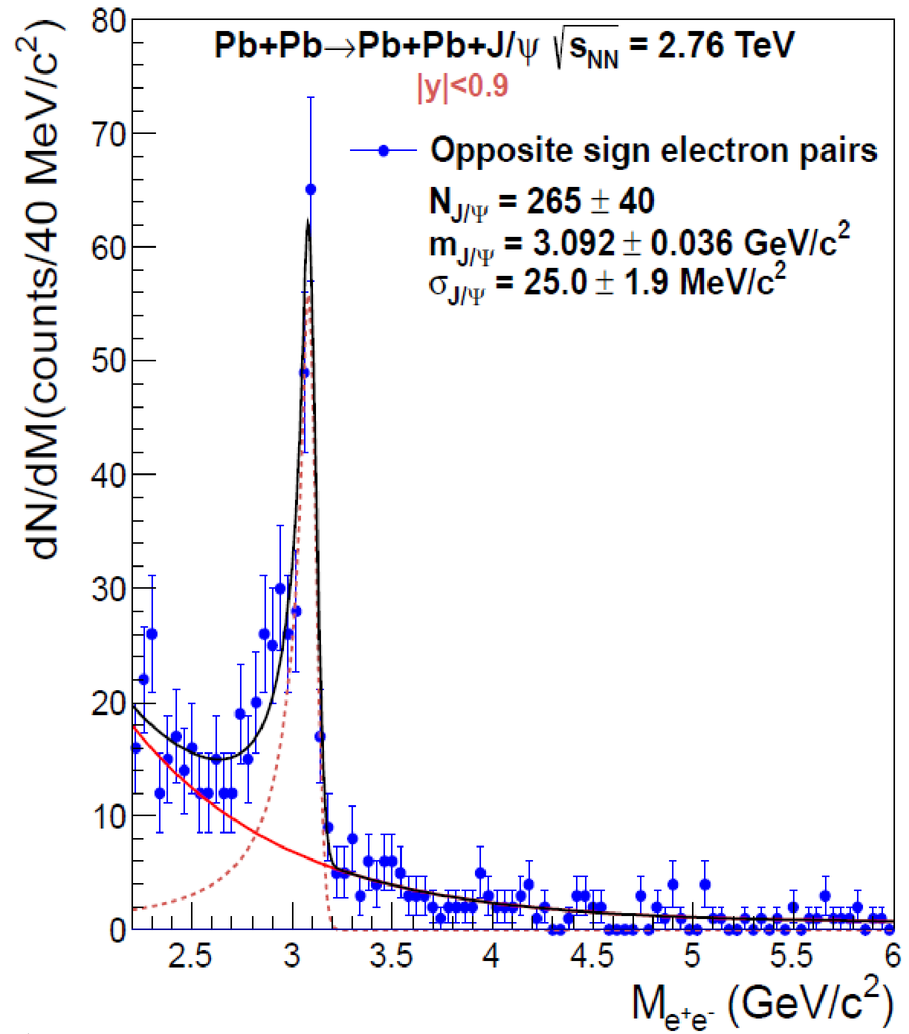
charmonia

reconstruction of J/ψ via mu⁺mu⁻ and e⁺e⁻ decay

PLB 718 arXiv:1209.3715



ALICE EPJ C73 arXiv:1305.1467



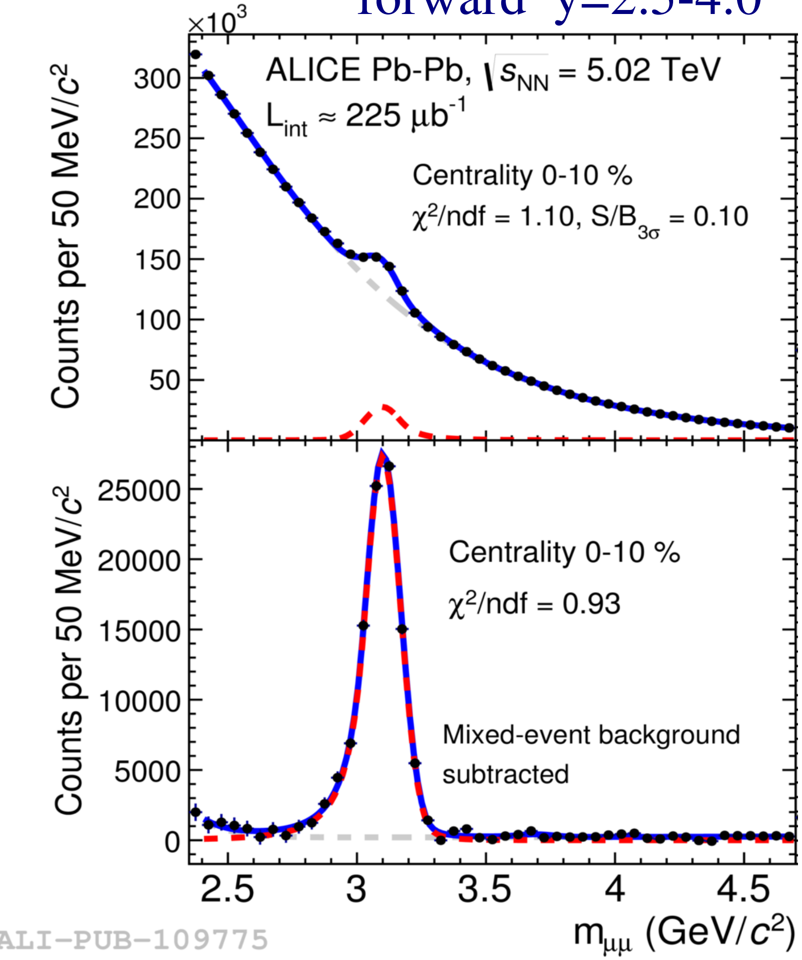
photoproduction in ultra-peripheral PbPb collisions – excellent signal to background

very good understanding of line shape

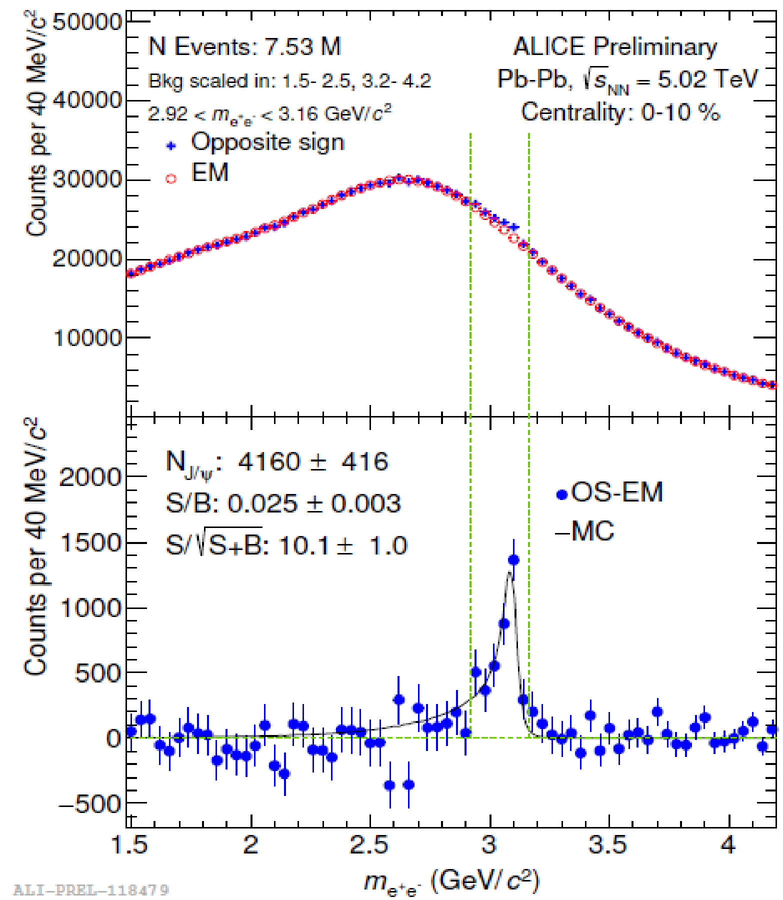
(probes nuclear gluon shadowing, not discussed here)

Reconstruction of J/ψ via $\mu^+\mu^-$ and e^+e^- decays

forward y=2.5-4.0

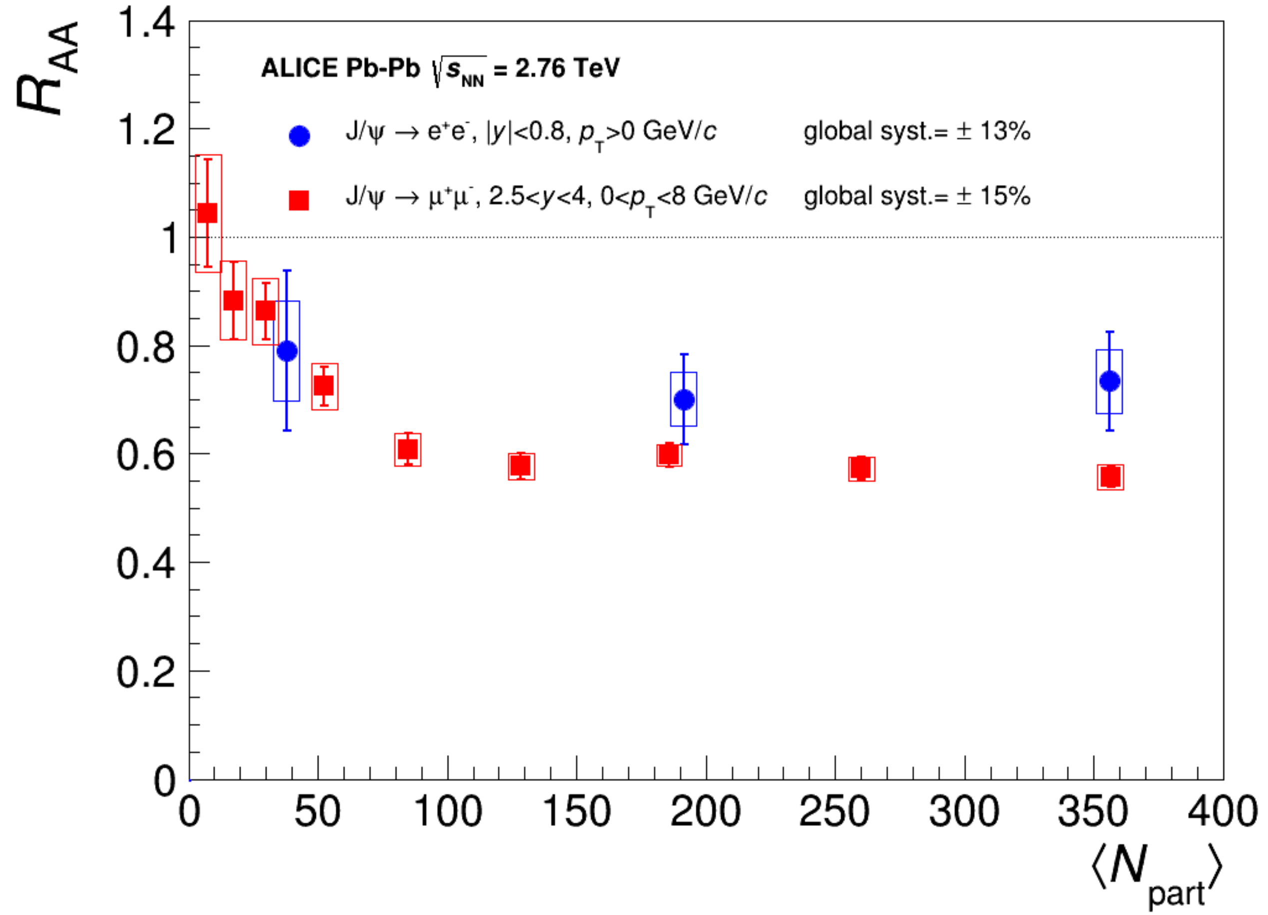


mid |y| < 0.8

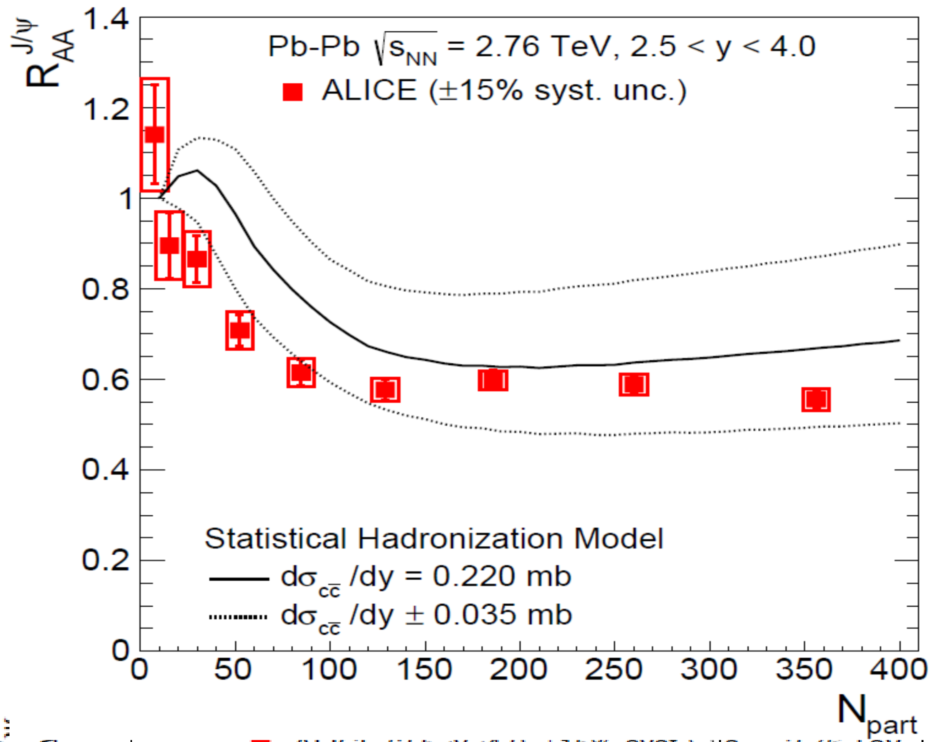


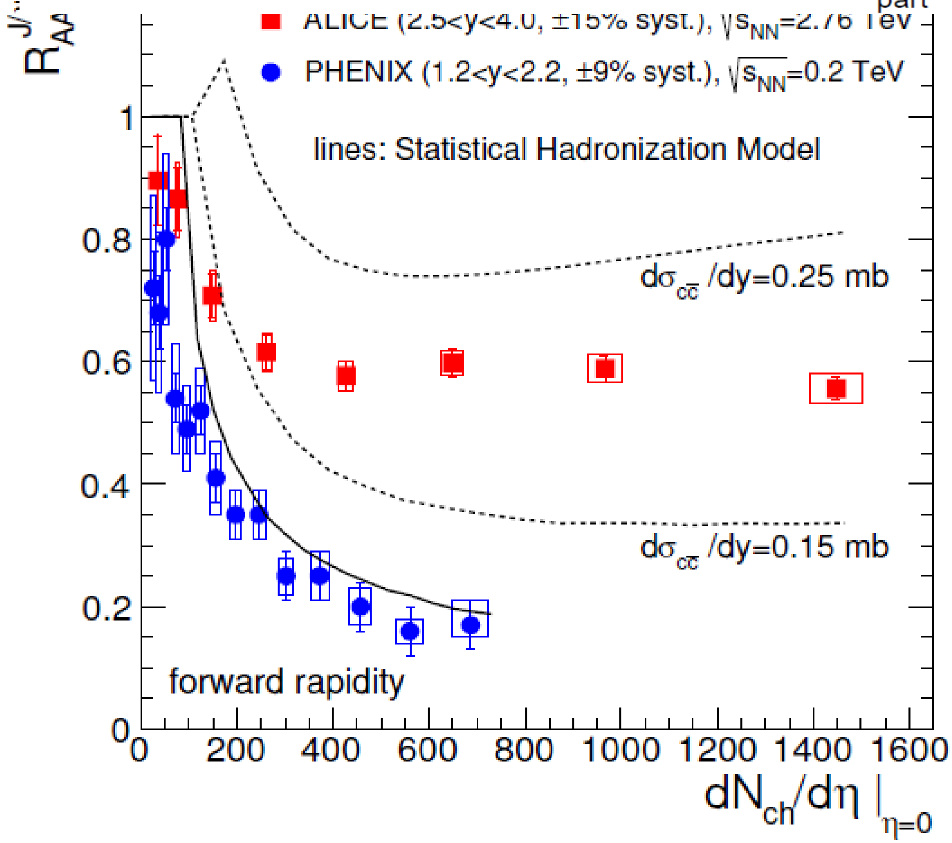
most challenging: central PbPb collisions
in spite of formidable combinatorial background
(true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

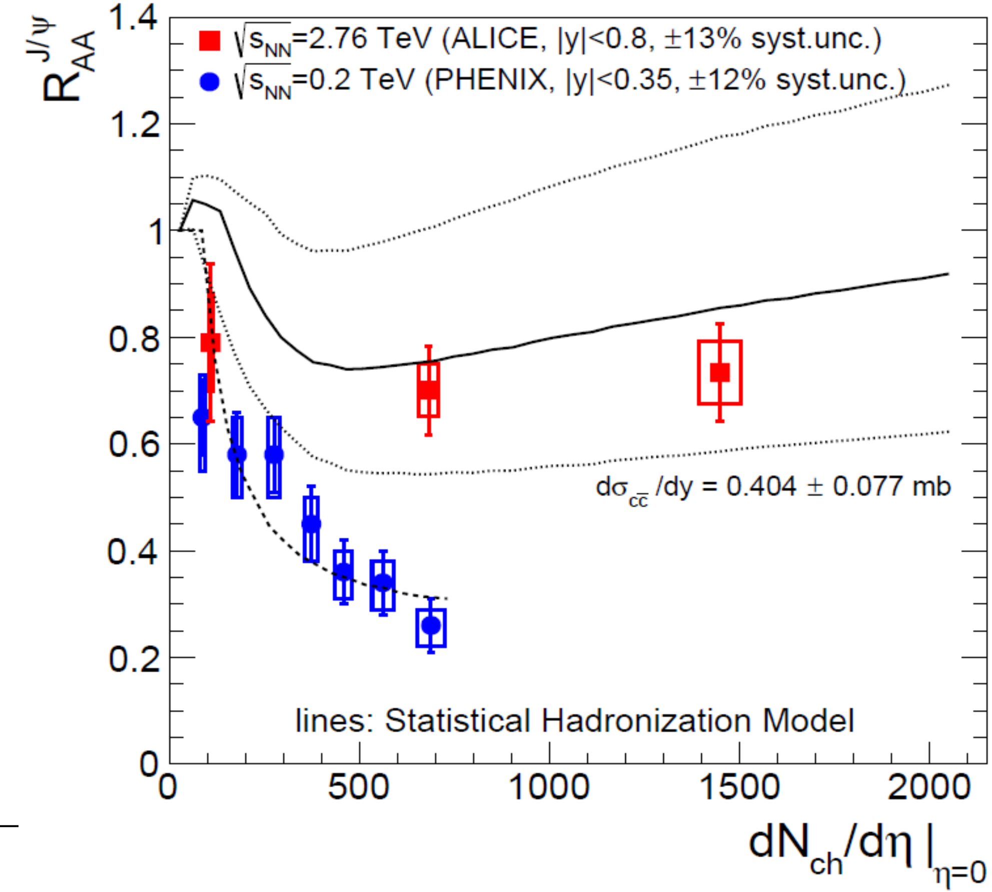
J/psi in PbPb collisions relative to pp



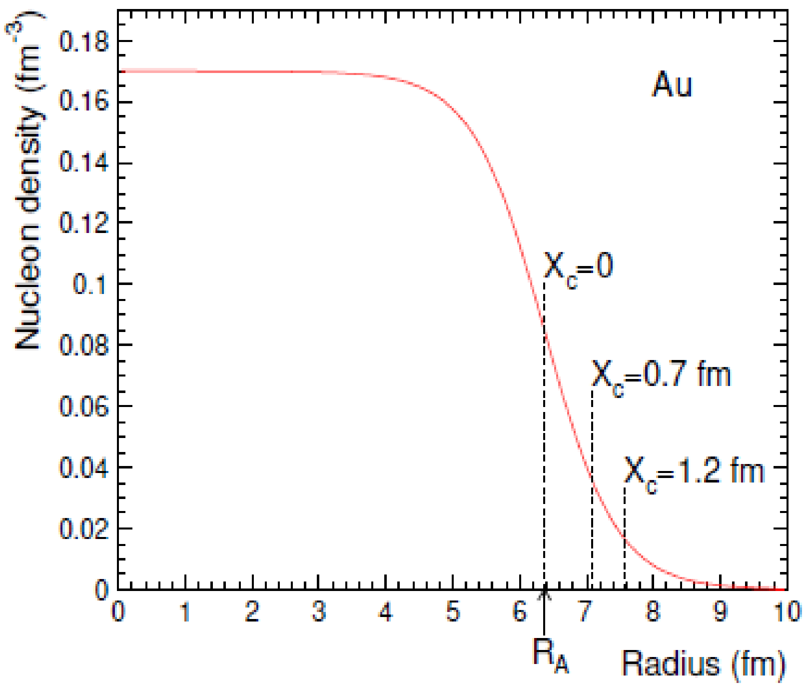
- nearly flat over large centrality range
- indication of rise for most central and mid-rapidity

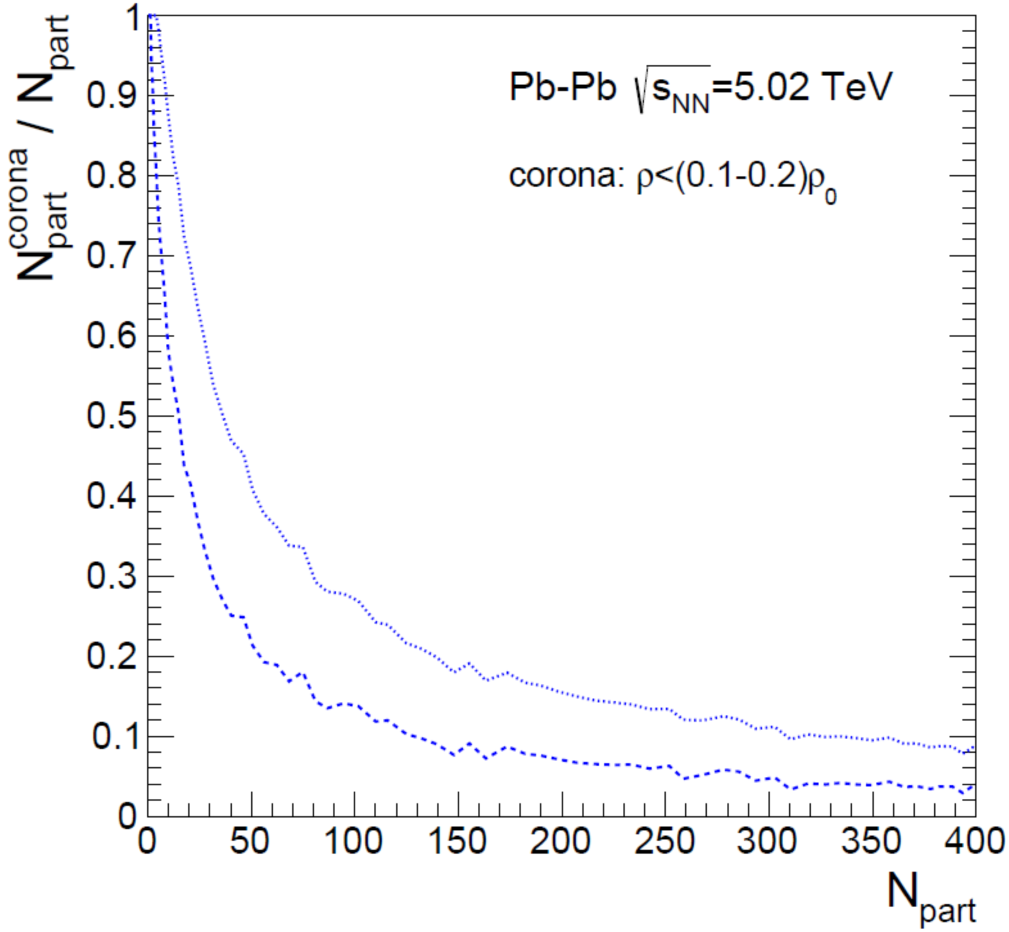

Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV, 2.5 < y < 4.0
ALICE (±15% syst. unc.)
Statistical Hadronization Model
$d\sigma_{c\bar{c}}/dy$ = 0.220 mb
$d\sigma_{c\bar{c}}/dy$ ± 0.035 mb
$R_{AA}^{J/\psi}$
N_{part}


PHENIX (1.2<y<2.2, ±9% syst.), $\sqrt{s_{NN}}$=0.2 TeV
lines: Statistical Hadronization Model
$d\sigma_{c\bar{c}}/dy$=0.25 mb
$d\sigma_{c\bar{c}}/dy$=0.15 mb
forward rapidity
$dN_{ch}/d\eta|_{\eta=0}$


$\sqrt{s_{NN}}$=2.76 TeV (ALICE, |y|<0.8, ±13% syst.unc.)
$\sqrt{s_{NN}}$=0.2 TeV (PHENIX, |y|<0.35, ±12% syst.unc.)
$d\sigma_{c\bar{c}}/dy$ = 0.404 ± 0.077 mb
lines: Statistical Hadronization Model
$R_{AA}^{J/\psi}$
$dN_{ch}/d\eta|_{\eta=0}$

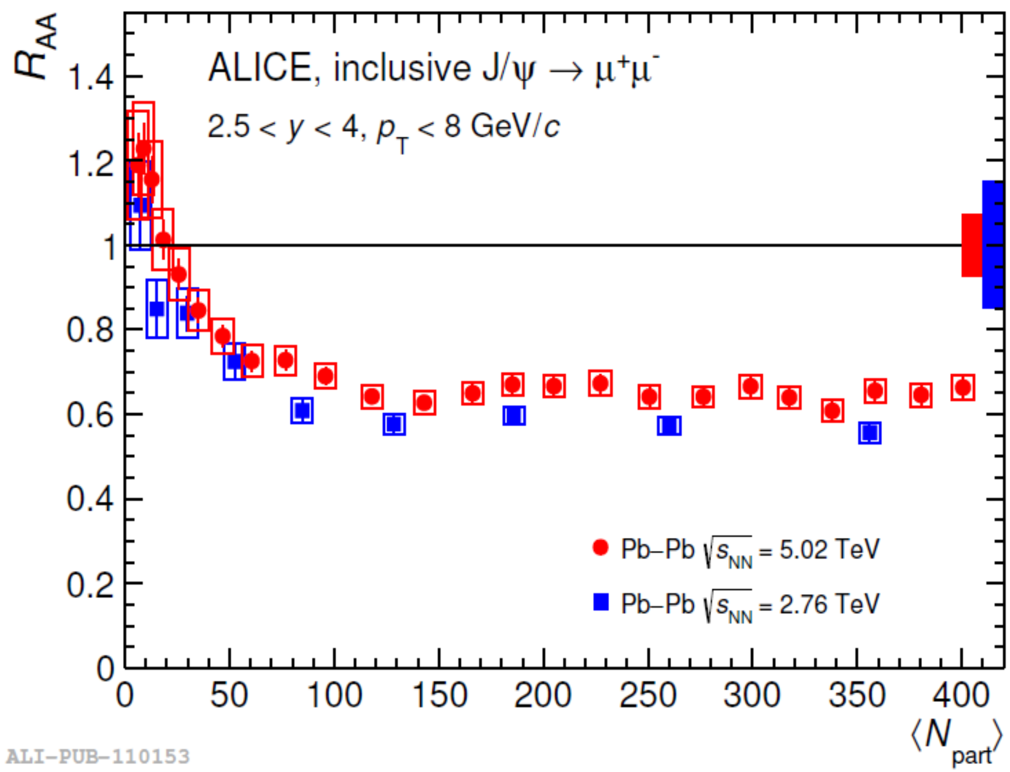
Corona fraction in PbPb collisions





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

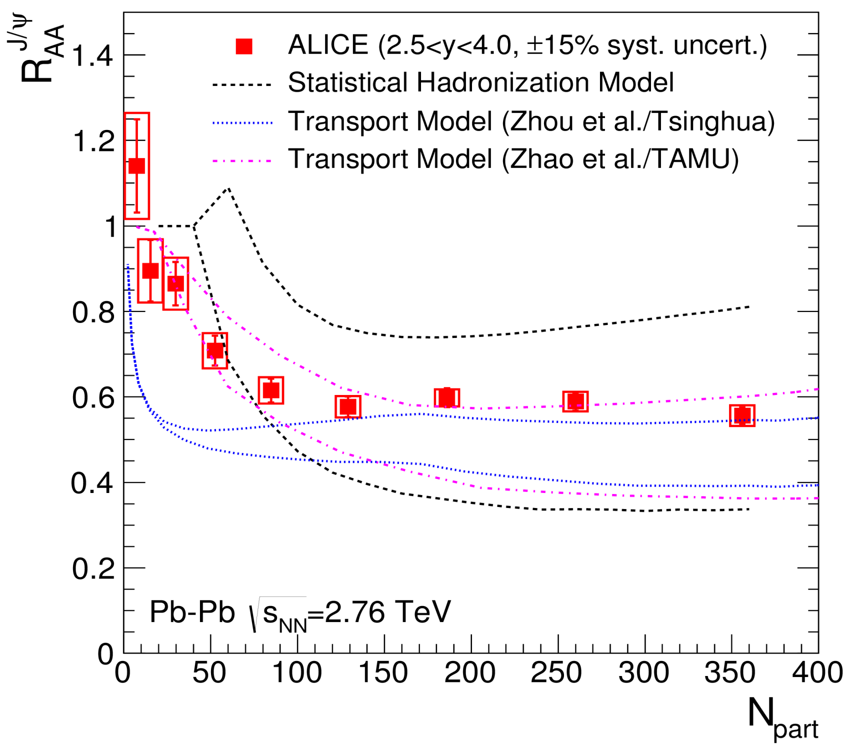
arXiv:1606.08197 [nucl-ex]

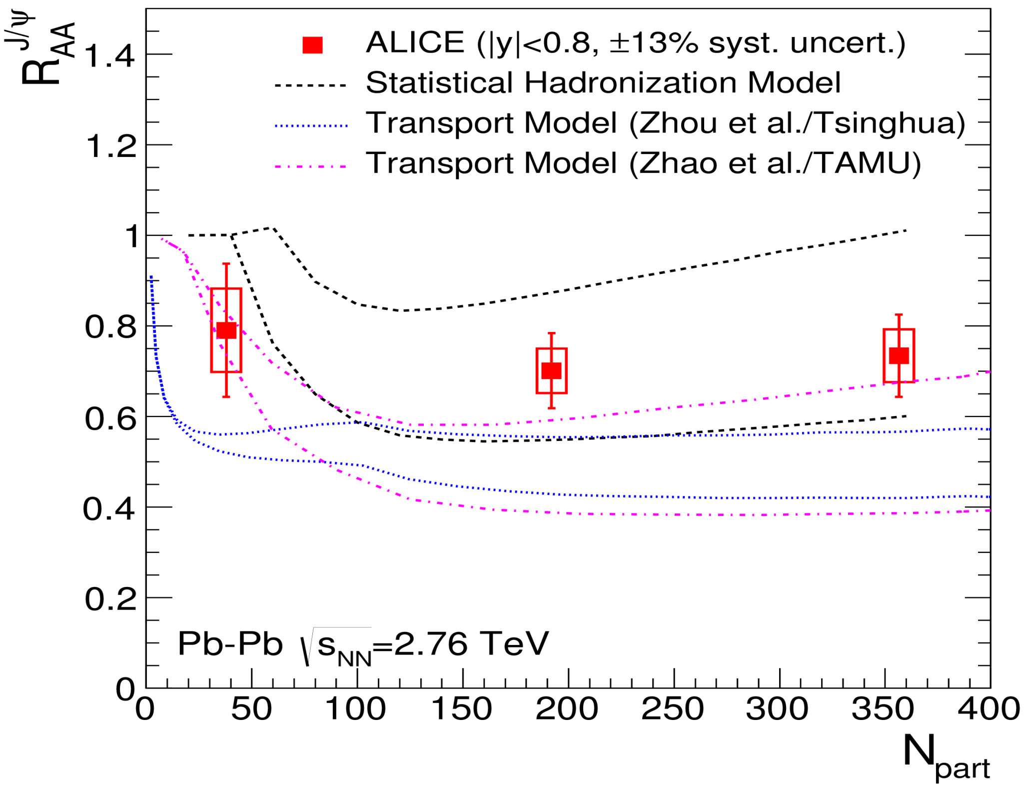


$R_{AA}^{0\text{-}90\%}$(5.02 TeV) / $R_{AA}^{0\text{-}90\%}$(2.76 TeV) = 1.13 ± 0.02(stat) ± 0.18(syst)

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

J/psi and transport models (and stat hadronization)





in transport models (Rapp et al. & P.Zhuang, N.Xu et al.) J/psi generated both in QGP and at hadronization

- transport models also in line with R_{AA}

  part of J/psi from direct hard production, part dynamically generated in QGP, part at hadronization, 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)

Attempt to determine Debye mass from data

J/ψ formation via statistical hadronization at T_c implies in classical picture:

$\lambda_D < r_{J/\psi} \simeq 0.5$ fm at T = 156 MeV or $\omega_D/T > 2.5$

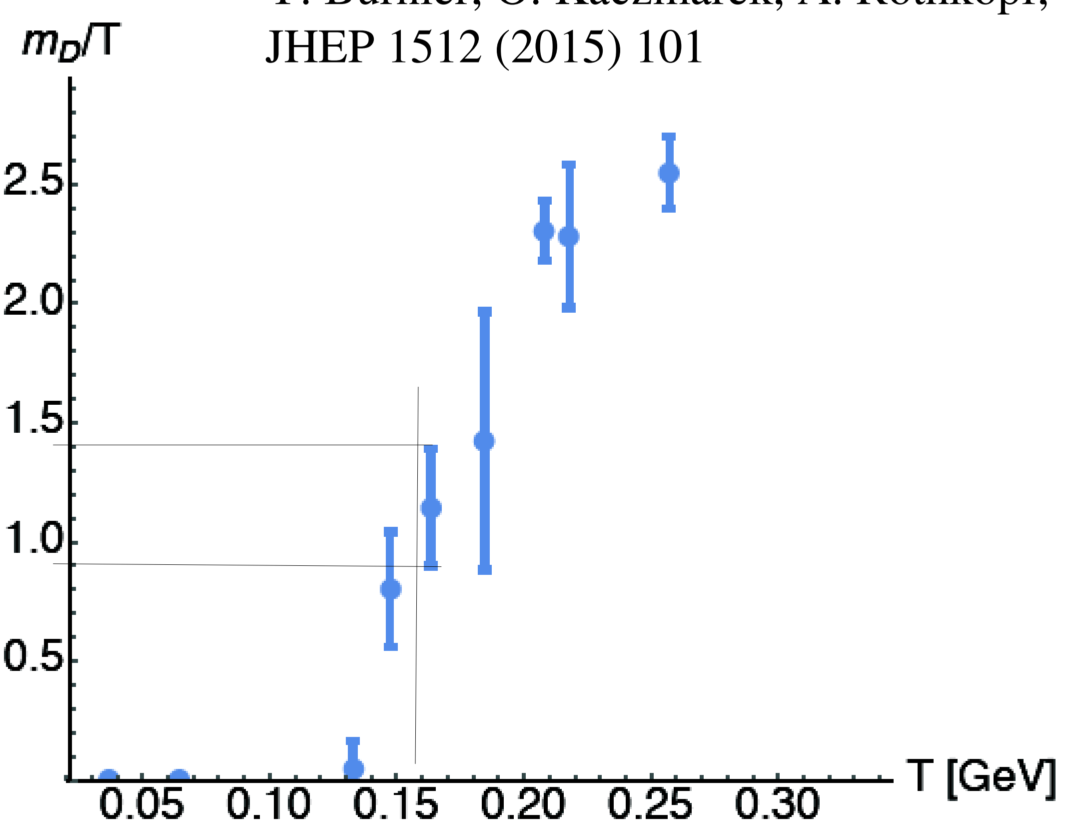
compare to recent finite temperature lQCD potential result:

- value at T_c lower
- systematics?
- and: lattice potential has real and imaginary part, both contribute to screening

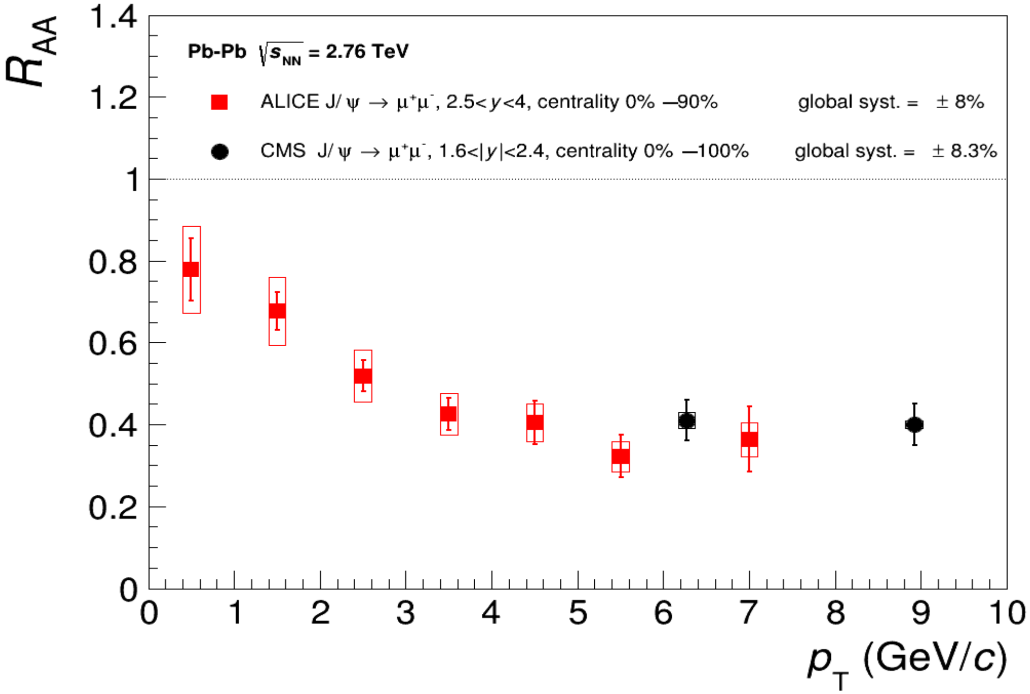
other observable to determine λ_D ?

e.g. ψ' vs J/ψ

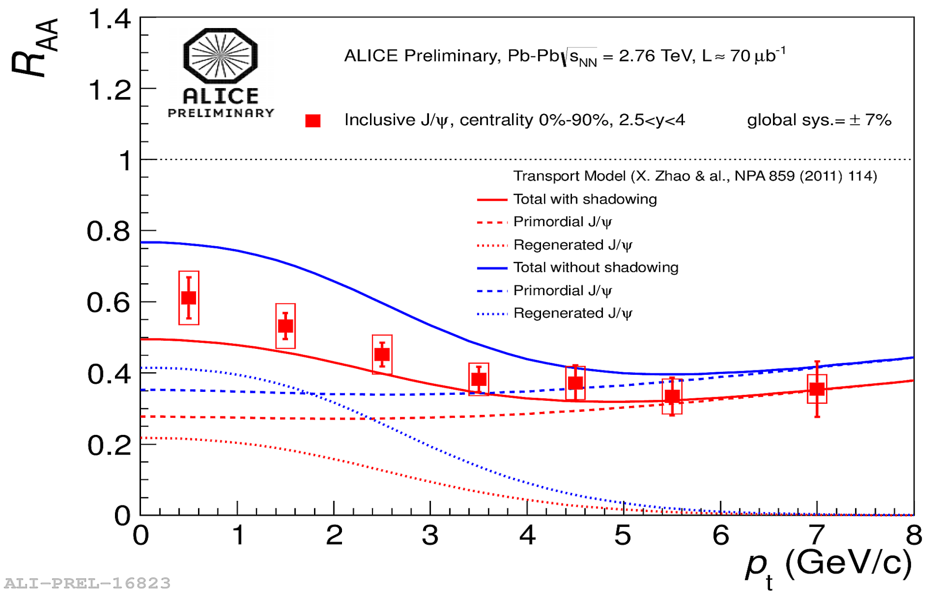
Y. Burnier, O. Kaczmarek, A. Rothkopf, JHEP 1512 (2015) 101



p_t Dependence of J/psi R_{AA}

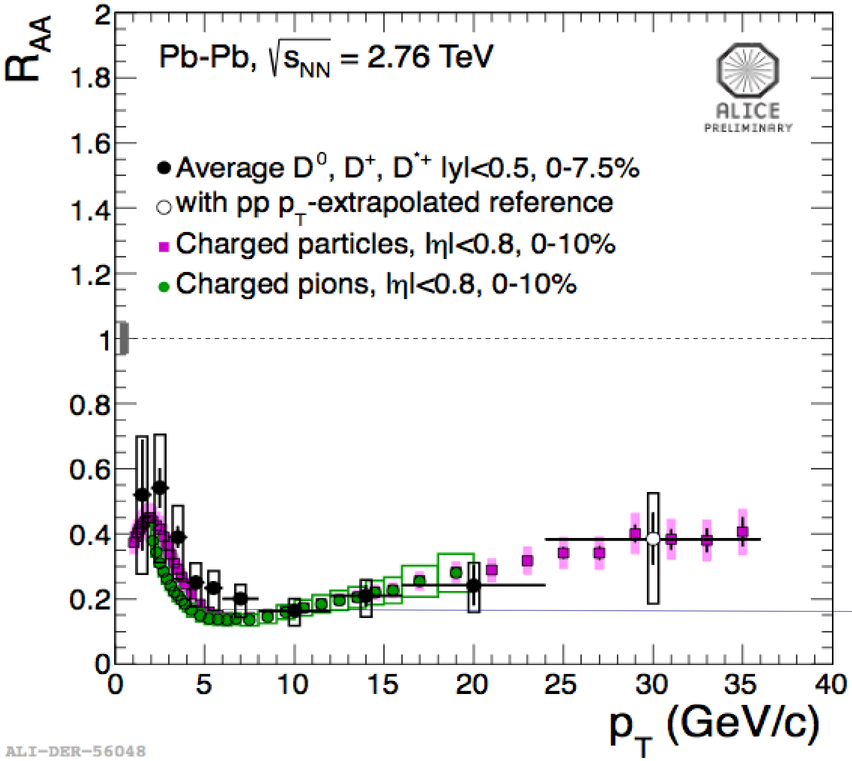


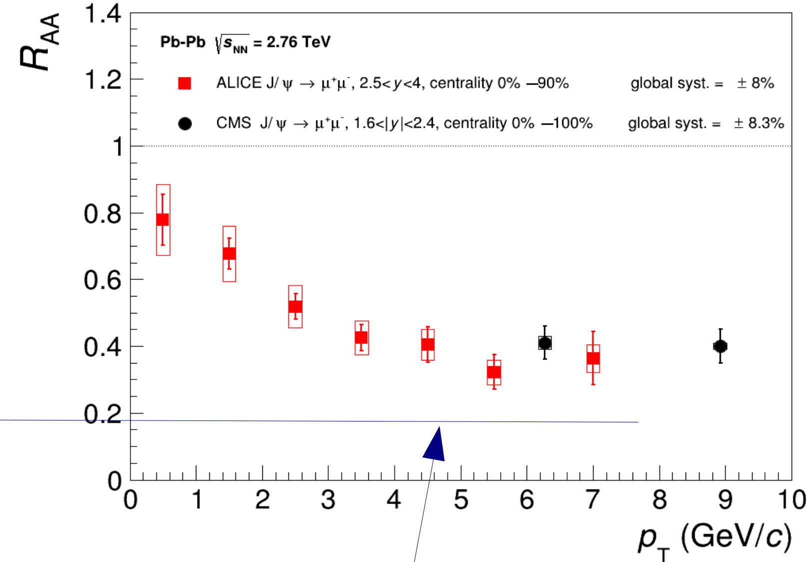
relative yield larger at low p_t in nuclear collisions
good agreement with CMS at high pt



statistical hadronization only expected for charm quarks thermalized in the QGP
p_t dependence in line with this prediction
in CMS only suppression

p_t dependence of R_{AA}

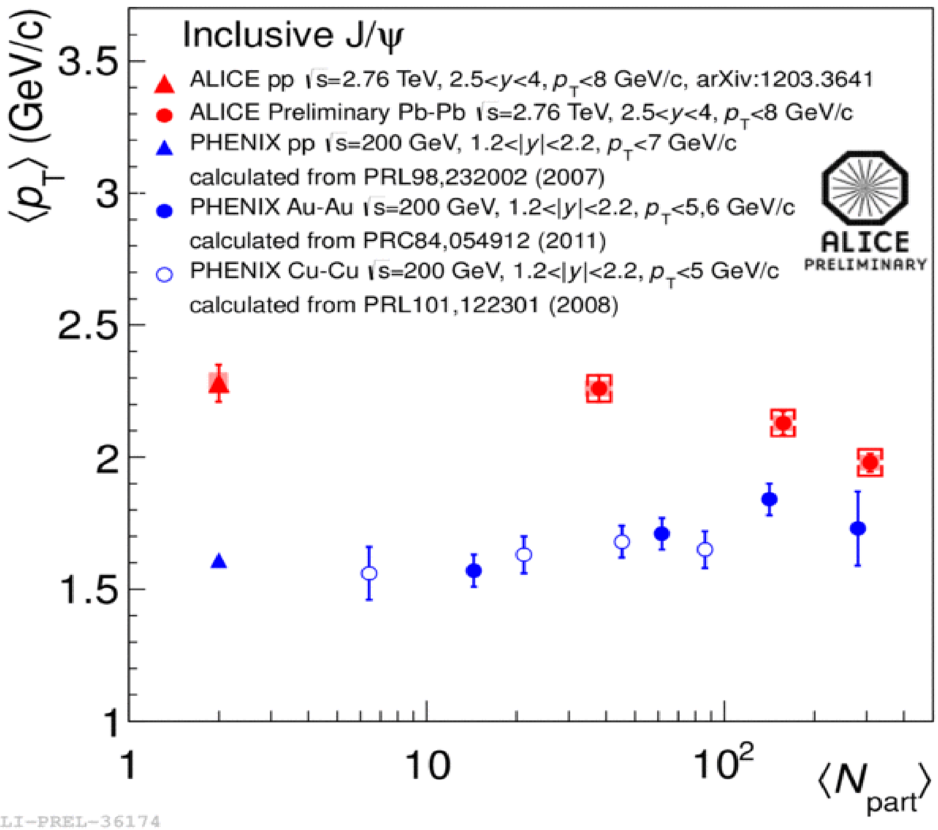


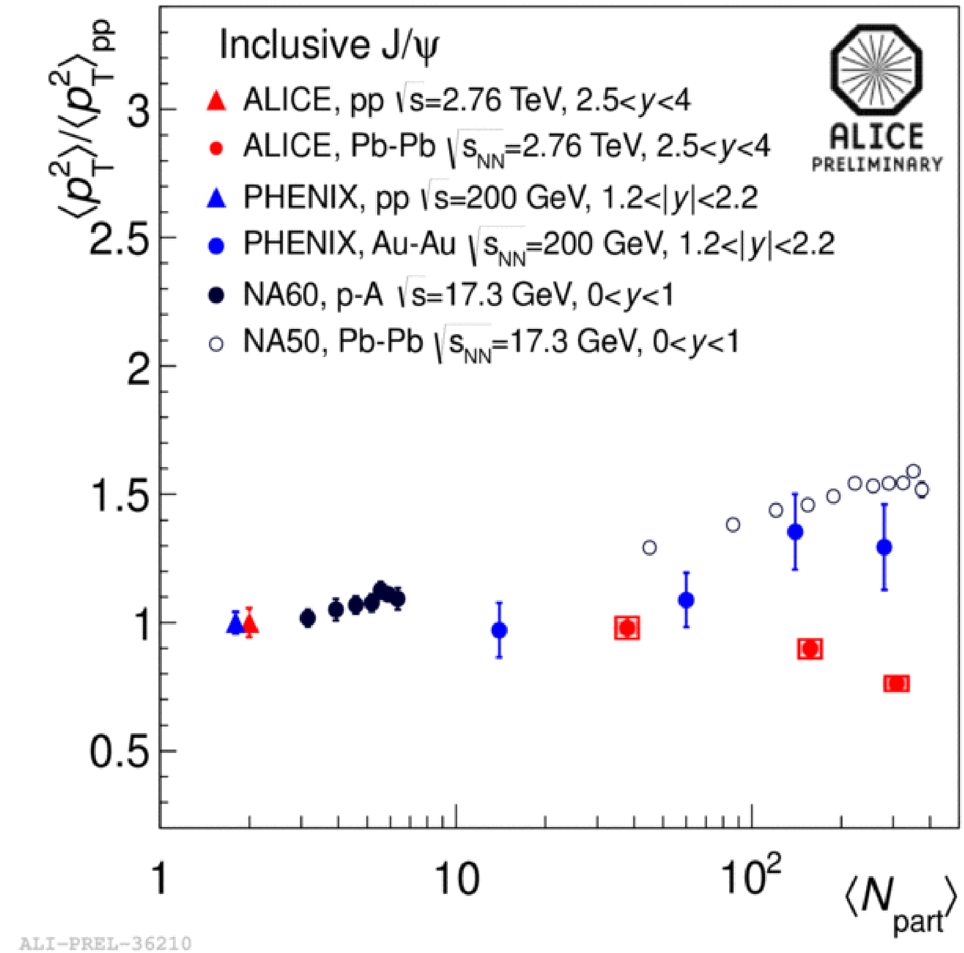


is high p_t part indicative of the same charm quark energy loss seen for D's

out to what p_t is statistical hadronization/regeneration relevant?

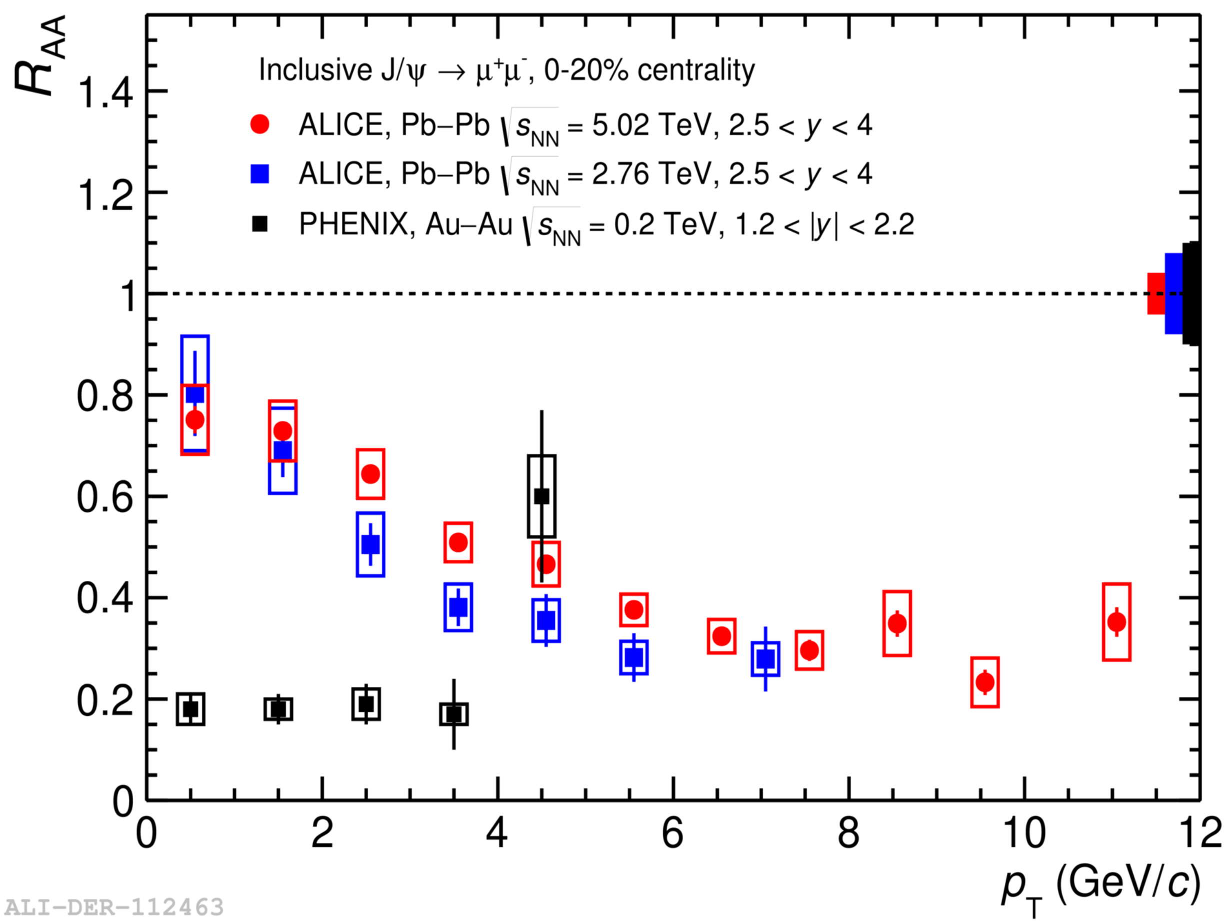
Softening of J/psi p_t distributions for central PbPb collisions





At LHC for central collisions softening relative to peripheral collisions and relative to pp (opposite trend to RHIC) - consistent with formation of J/psi from thermalized c-quarks

Transverse momentum spectrum



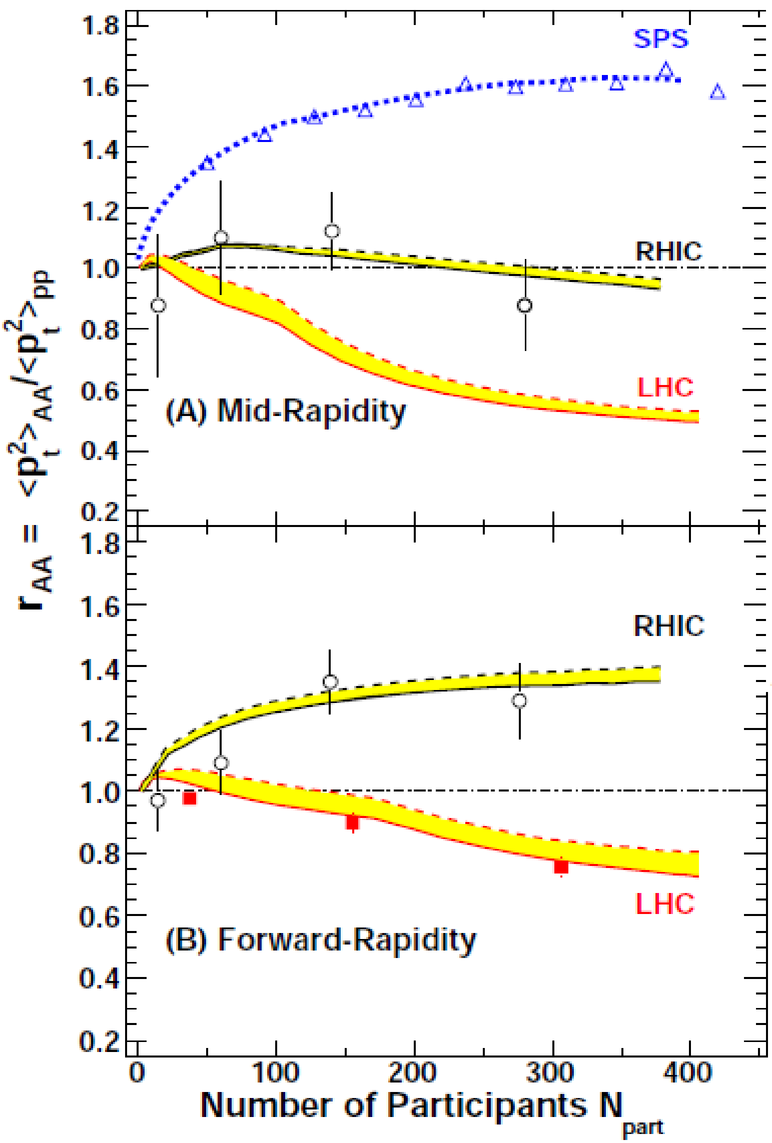
softer in PbPb as compared to pp

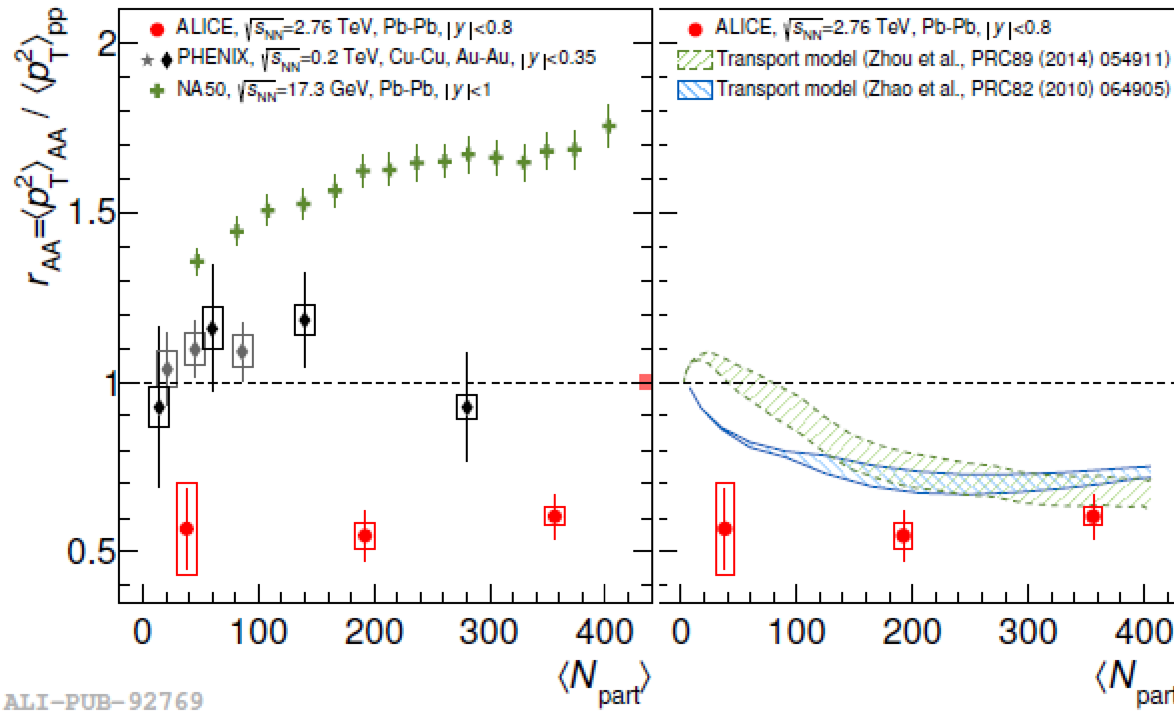
a qualitatively new feature as compared to RHIC where the trend is opposite

in line with thermalized charm in QGP at LHC, forming charmonia

Analysis of transverse momentum spectra

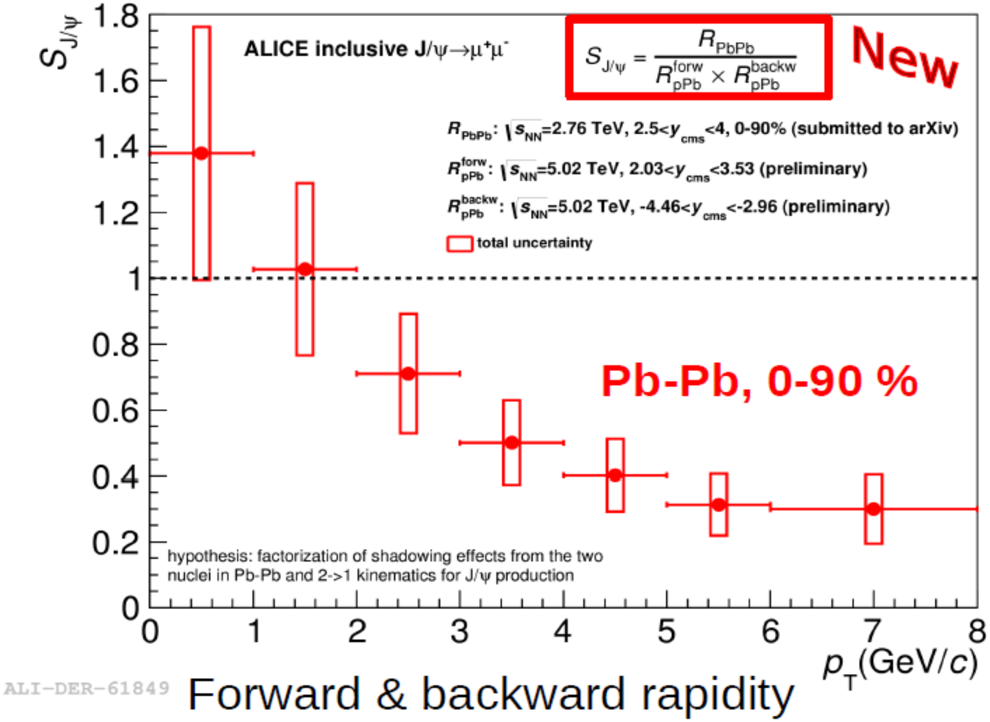
Zhou, Xu, Zhuang, arXiv:1309.7520

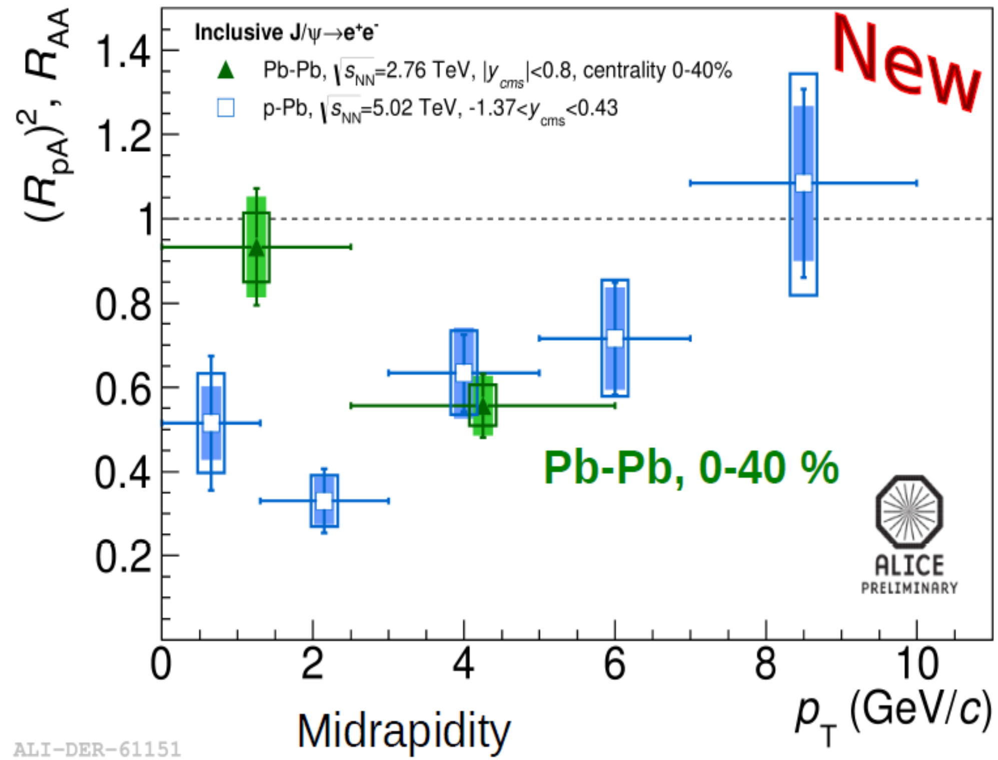




- at LHC energy, mostly (re-) generation of charmonium
- p_t distribution exhibits features of strong energy loss and approach to thermalization for charm quarks
- **challenge to regeneration models**

J/psi vs pt in PbPb collisions relative to pPb collisions

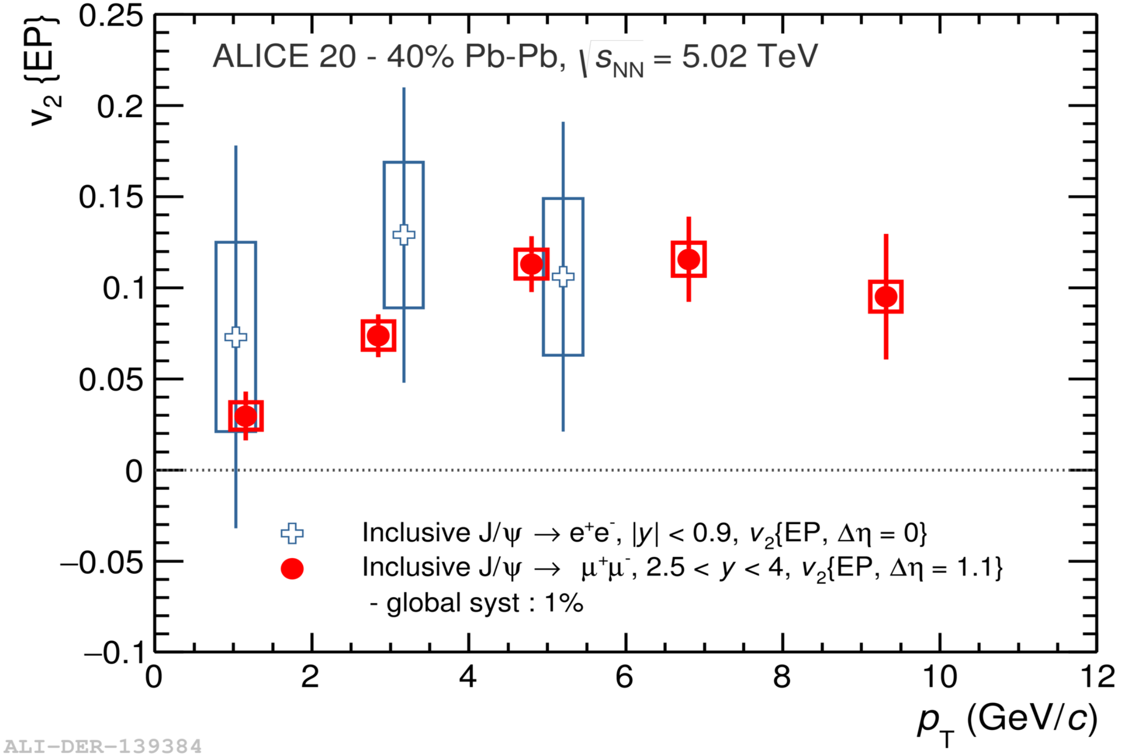




at low pt yield in nuclear collisions above pPb collisions
J/psi production enhanced in nuclear collisions over mere shadowing effect

Elliptic flow of J/ψ vs p_t

arXiv:1709.05260



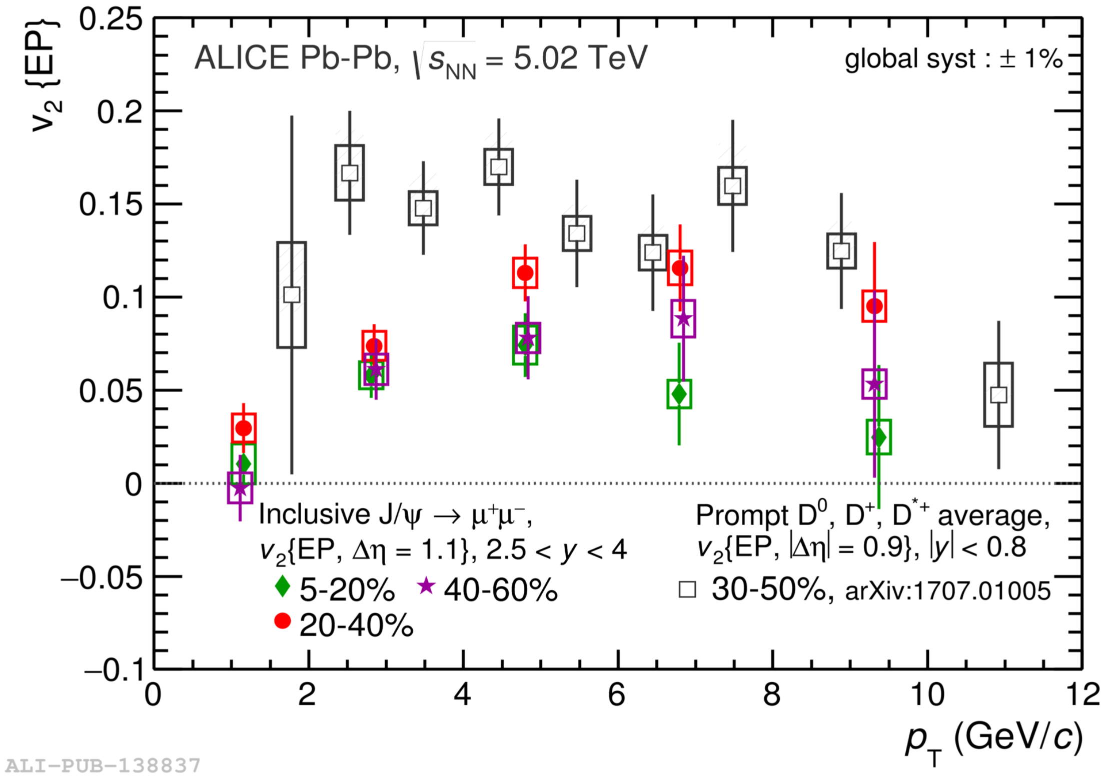
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

- expect build-up with p_t as observed for π, p. K, Λ, … and vanishing signal for high p_t region not dominated by flow

first observation of significant J/ψ v_2 in line with expectation from statistical hadronization
can be computed following approach above with hydro velocity profile

Elliptic flow of J/ψ vs p_t

arXiv:1709.05260

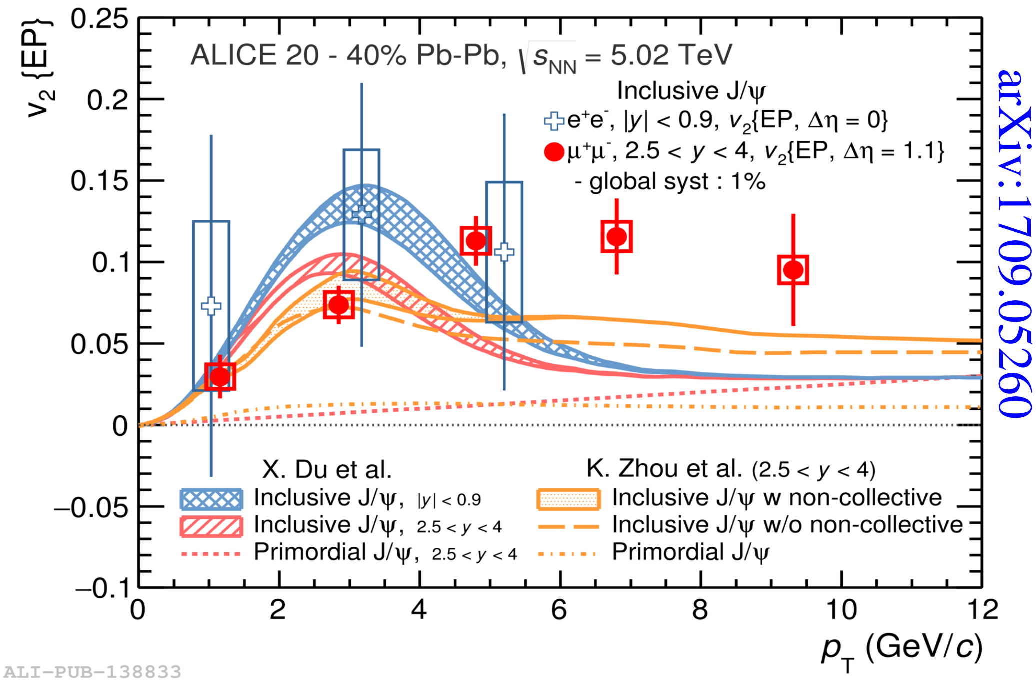


Strength of J/ψ v_2 similar to D-mesons

Elliptic flow of J/ψ

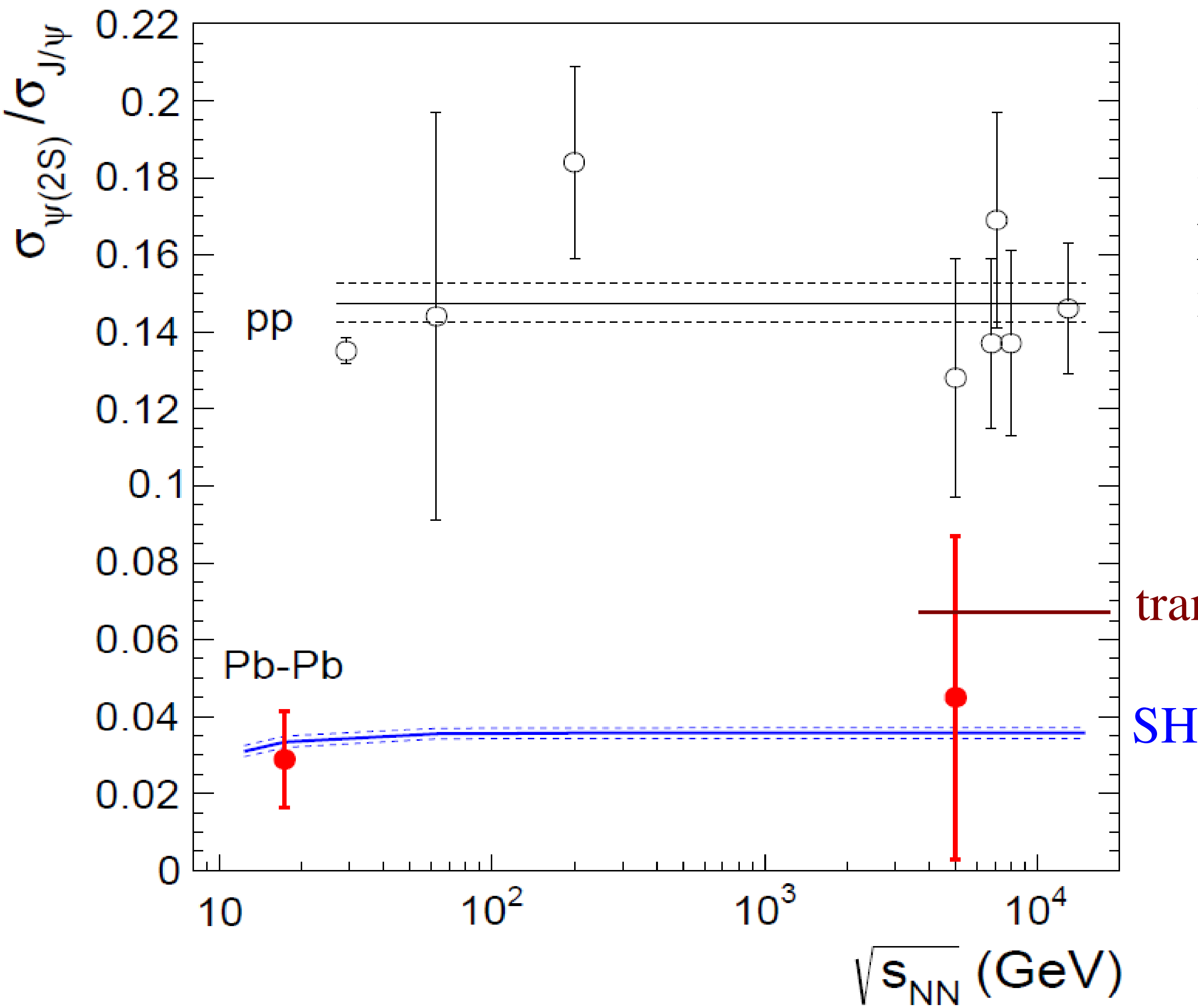
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

first observation of significant J/ψ v_2 both at forward and mid rapidity



J/ψ elliptic flow in line with expectation from statistical hadronization

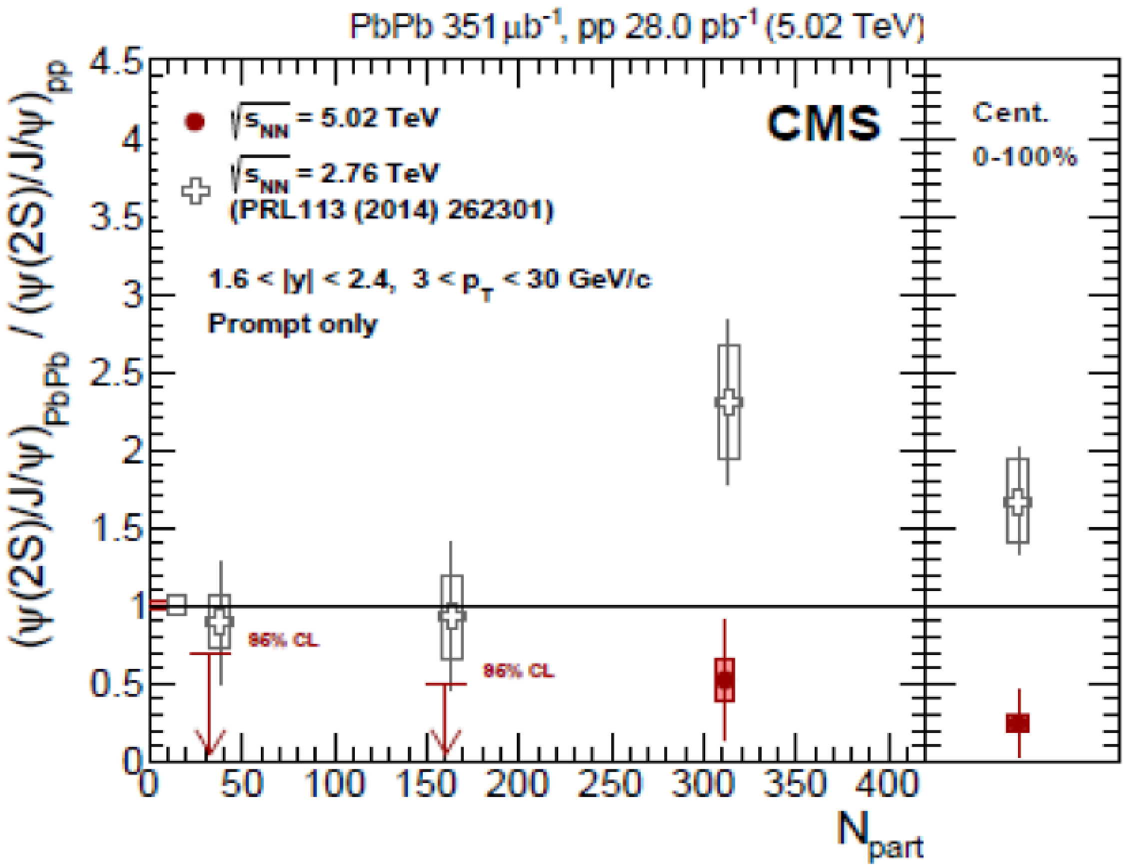
ψ(2S)



first data in line with expectation from statistical hadronization at phase boundary but transport model prediction also inside 1 sigma error

ψ(2S)

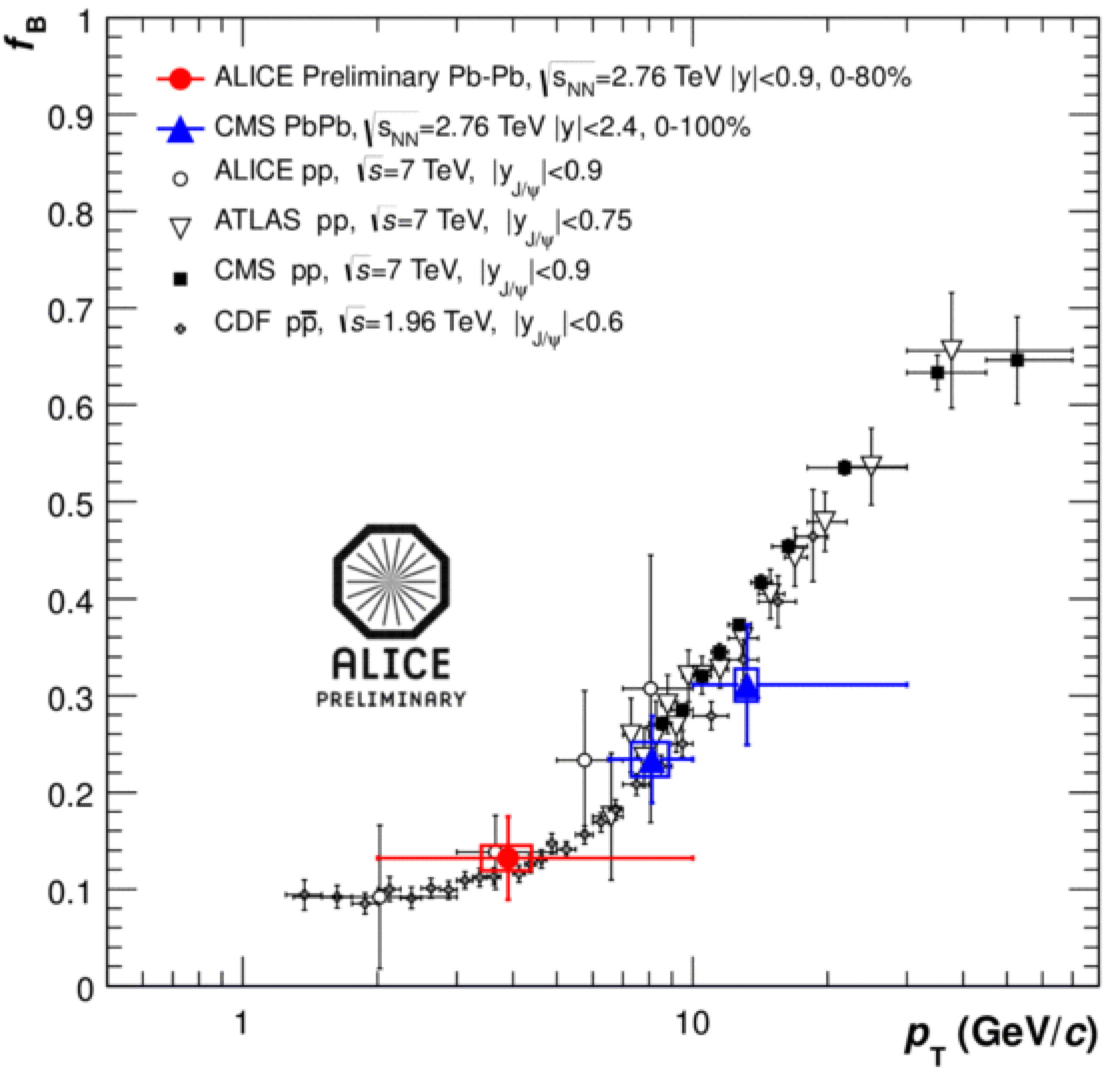
in picture where psi is created from deconfined quarks in QGP or at hadronization, psi(2S) is suppressed more than J/psi – run1 CMS results indicate the opposite!



expect value of 1/3 for inclusive pt and central collisions

the anomaly (enhancement relative to pp) from 2.76 TeV is not there at 5.02 TeV - very nice ALICE data from pt=0 to be approved this week

Fraction of J/psi from B-decays



p_t integrated non-prompt B-fraction of small
within current errors no significant difference in pp and PbPb collisions

Outlook – what ALICE can do in the future

LHC run1:

2 PbPb runs

- 2010 $O(10\ \mu b^{-1})$
- 2011 $O(150\ \mu b^{-1})$

luminosity reached $\mathscr{L}=2\ 10^{26}\ cm^{-2}\ s^{-1}$ twice design lumi at this energy

1 pPb run

- 2012/2013 $O(30\ nb^{-1})$

from 2/2013 until end of 2014 LS1: consolidation of LHC to allow full energy

LHC run2: 2015-2018 PbPb running at $\sqrt{s_{NN}} = 5.5$ TeV

to achieve approved initial goal of 1 nb^{-1}

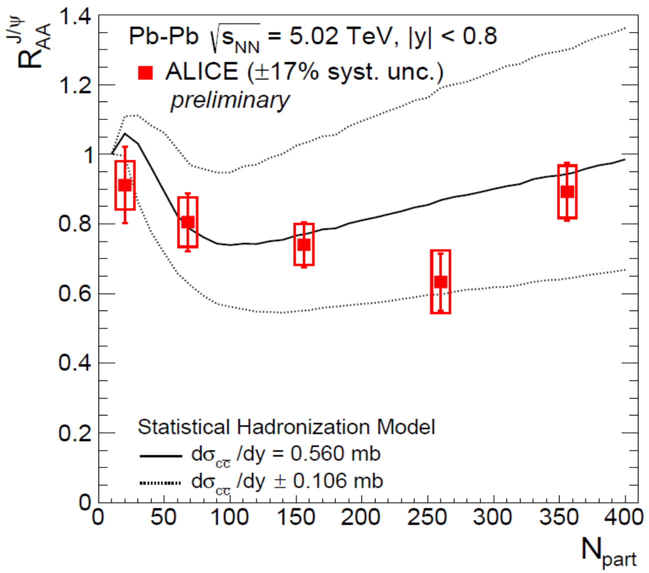
2019 start LS2 – increase of LHC luminosity und experiment upgrade, LHCb will join PbPb!

LHC run3: 2021 onwards - expect $\mathscr{L}=6\ 10^{27}\ cm^{-2}\ s^{-1}$ or PbPb interactions at 50 kHz

achieve for PbPb 10 nb^{-1} corresponding to $8\ 10^{10}$ collisions sampled

plus a low field run of 3 nb^{-1} + pp reference running + pPb - a program for about 6 years

J/psi as probe of deconfinement



well on the way towards goal for run2
expect still a huge jump in performance
for runs3/4

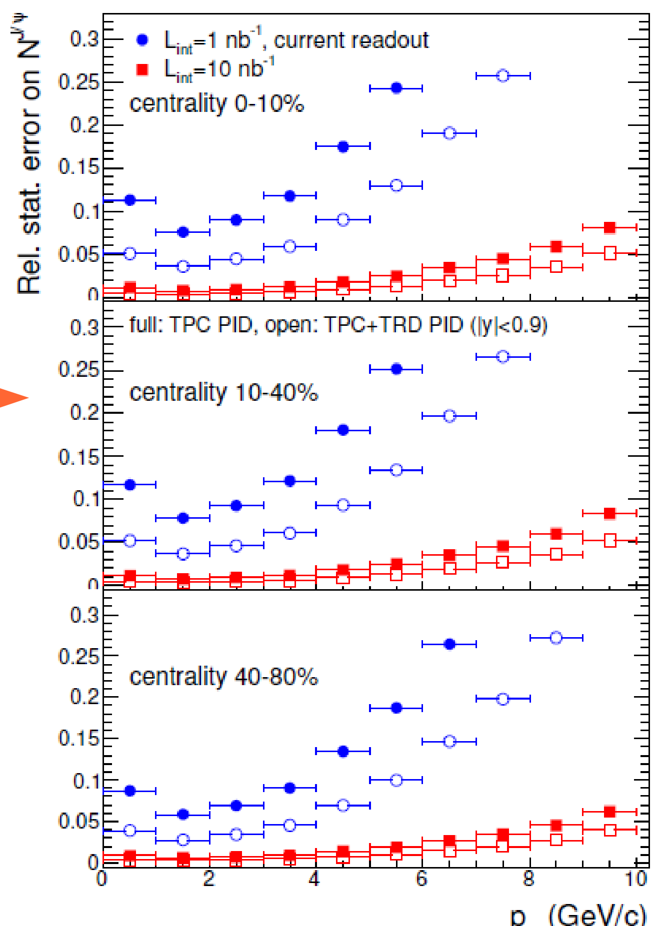
di-electrons statistics limited, 10 nb^{-1} will have huge effect

but also syst uncertainties will decrease with upgrade:

will also add TRD for electron id - reduced comb background

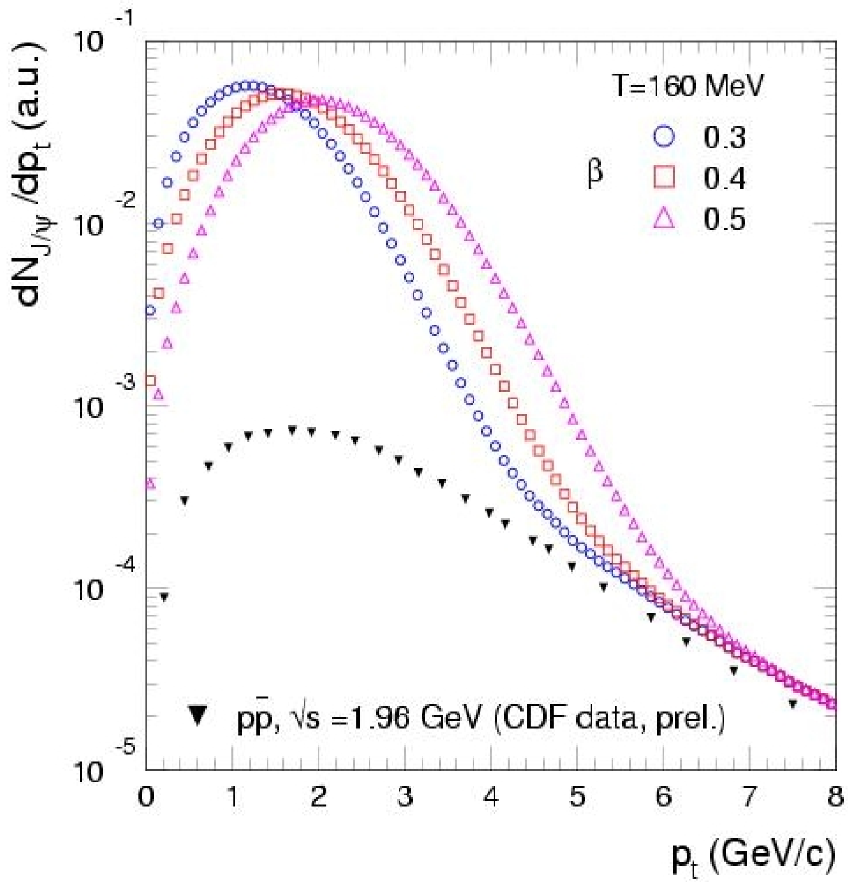
thinner ITS reduced radiation tail

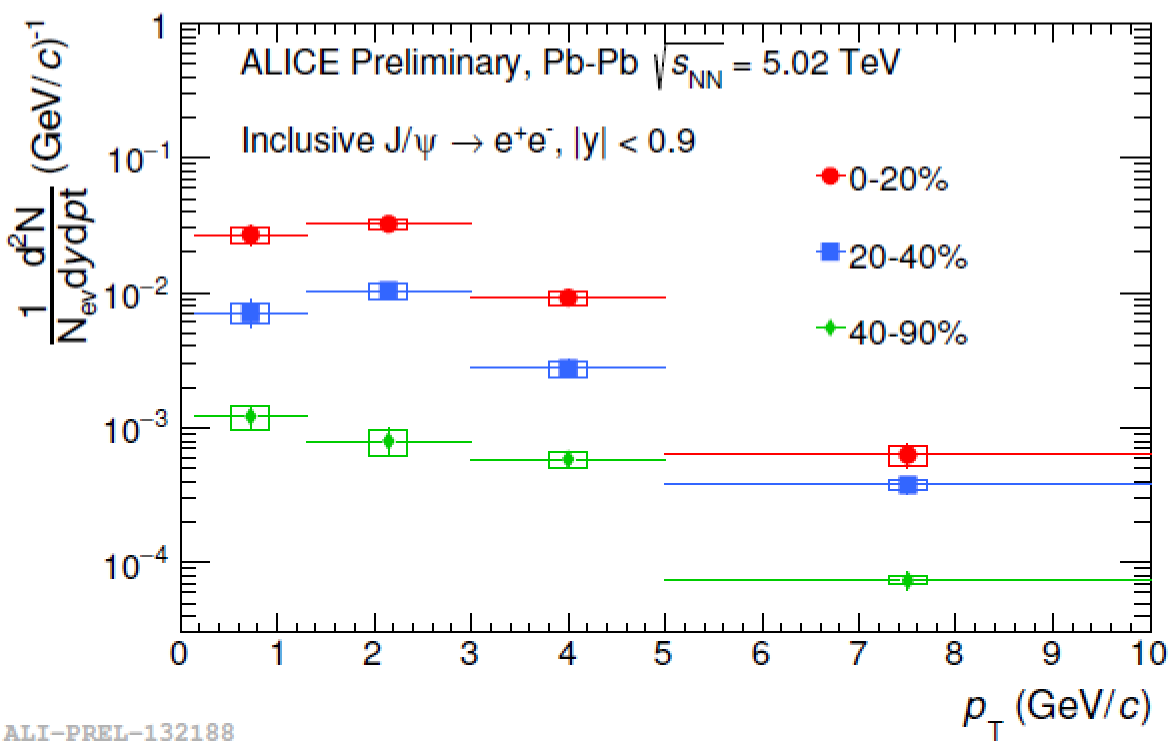
both affect signal extraction



spectral distribution is key to thermalization

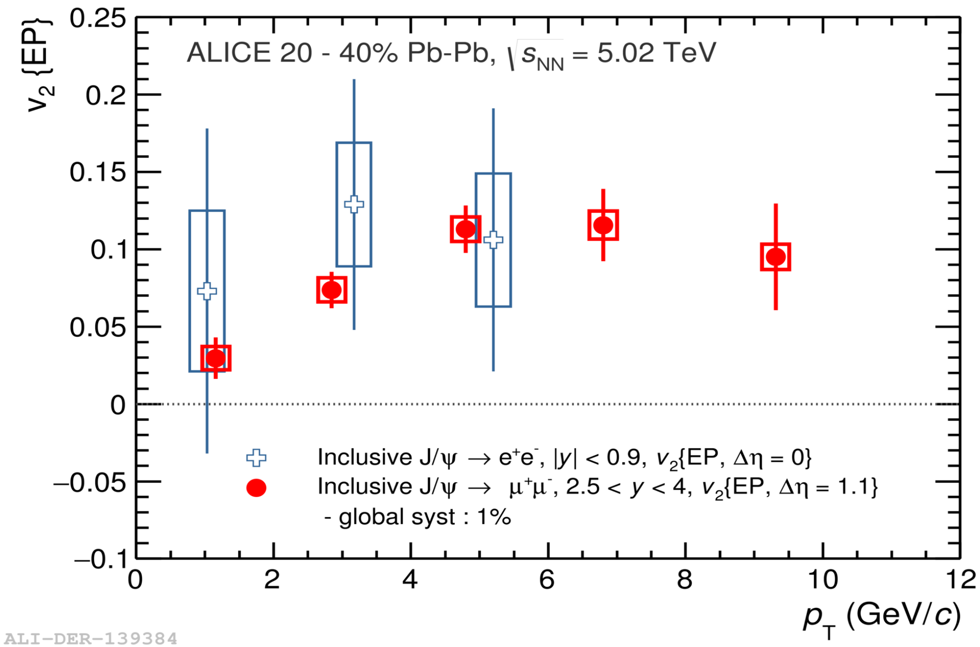
if charm quark thermalize, their spectral distributions should also reflect collective flow of liquid





first spectra a mid-y appearing
much more to come
we are computing spectra

J/psi elliptic flow

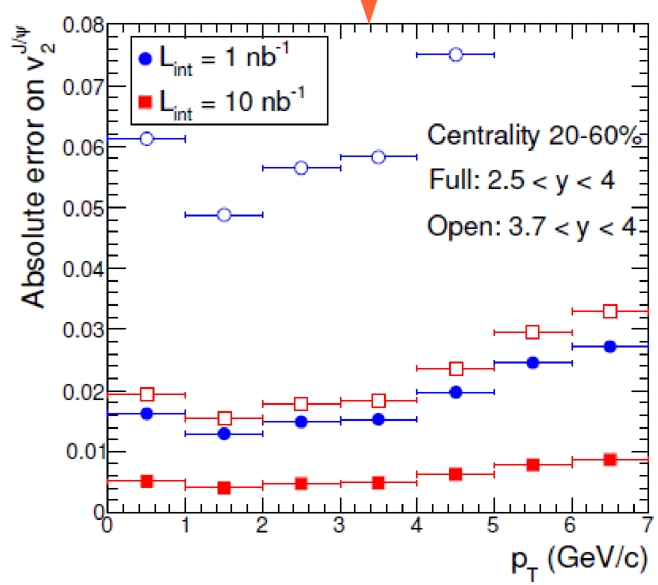


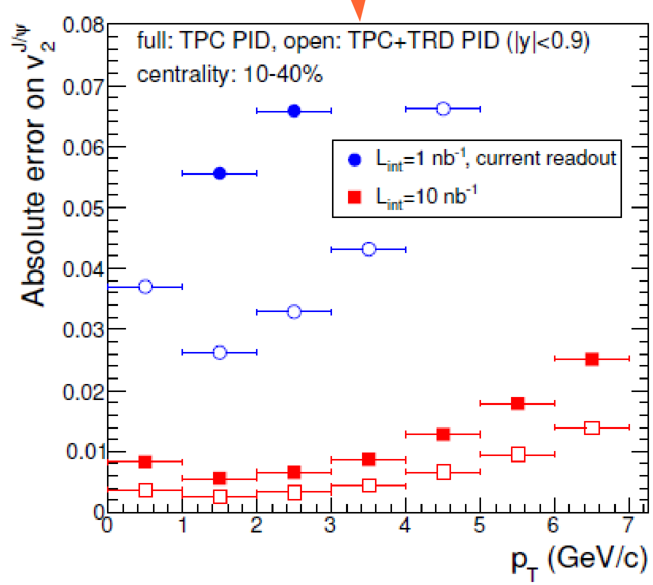
goal for run2 in muon arm already achieved
for e+e- at mid-y getting there

future statistical errors

muon arm

central barrel



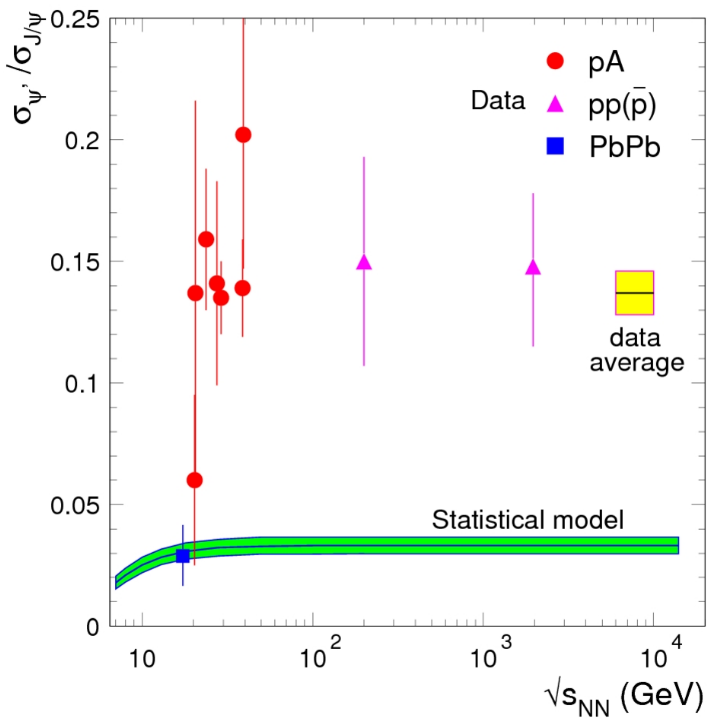


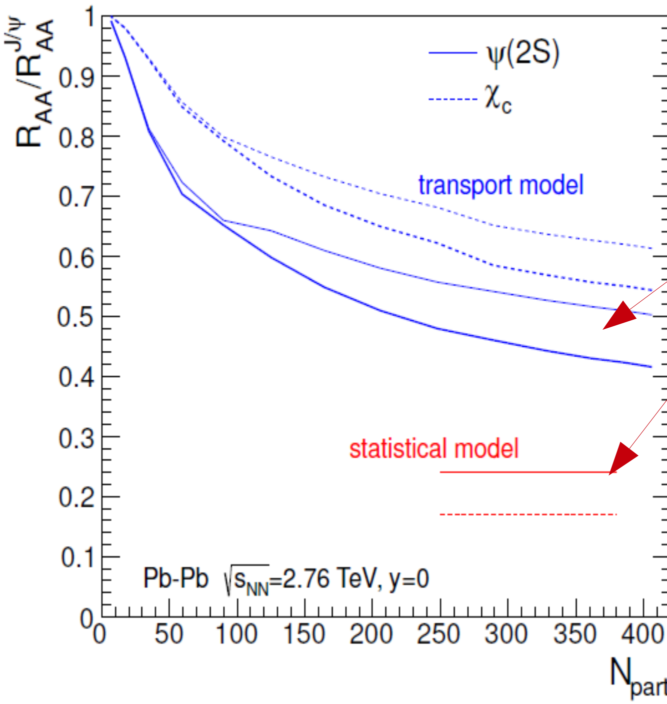
How to distinguish between statistical hadronization and transport models with J/ψ beyond T_c?

not a detail, which model is right, but fundamental question
link to phase boundary and existence of bound states beyond T_c at stake

- R_{AA} can be reproduced by both, albeit with different charm cross sections
  go away from R_{AA}, normalize to open charm cross
- spectra: transport models start to be challenged, need more precise data
  and more refined hydro based computation
- similar: v_2 of J/ψ
- maybe decisive: excited state population

excited charmonia crucial to distinguish between models



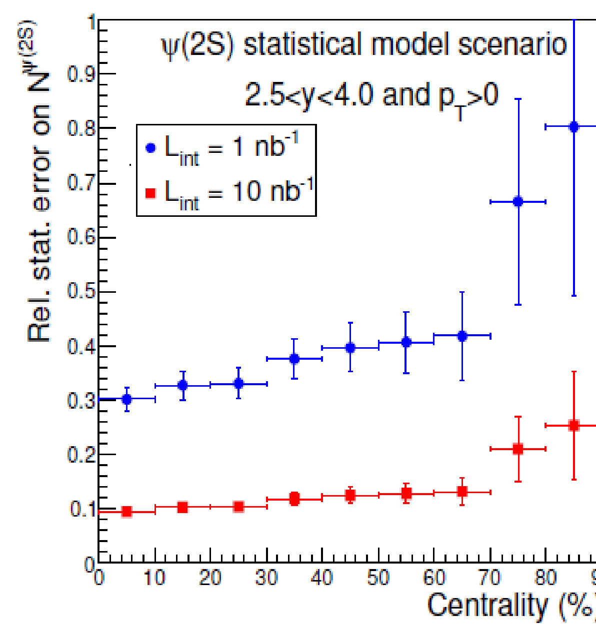


in fact here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

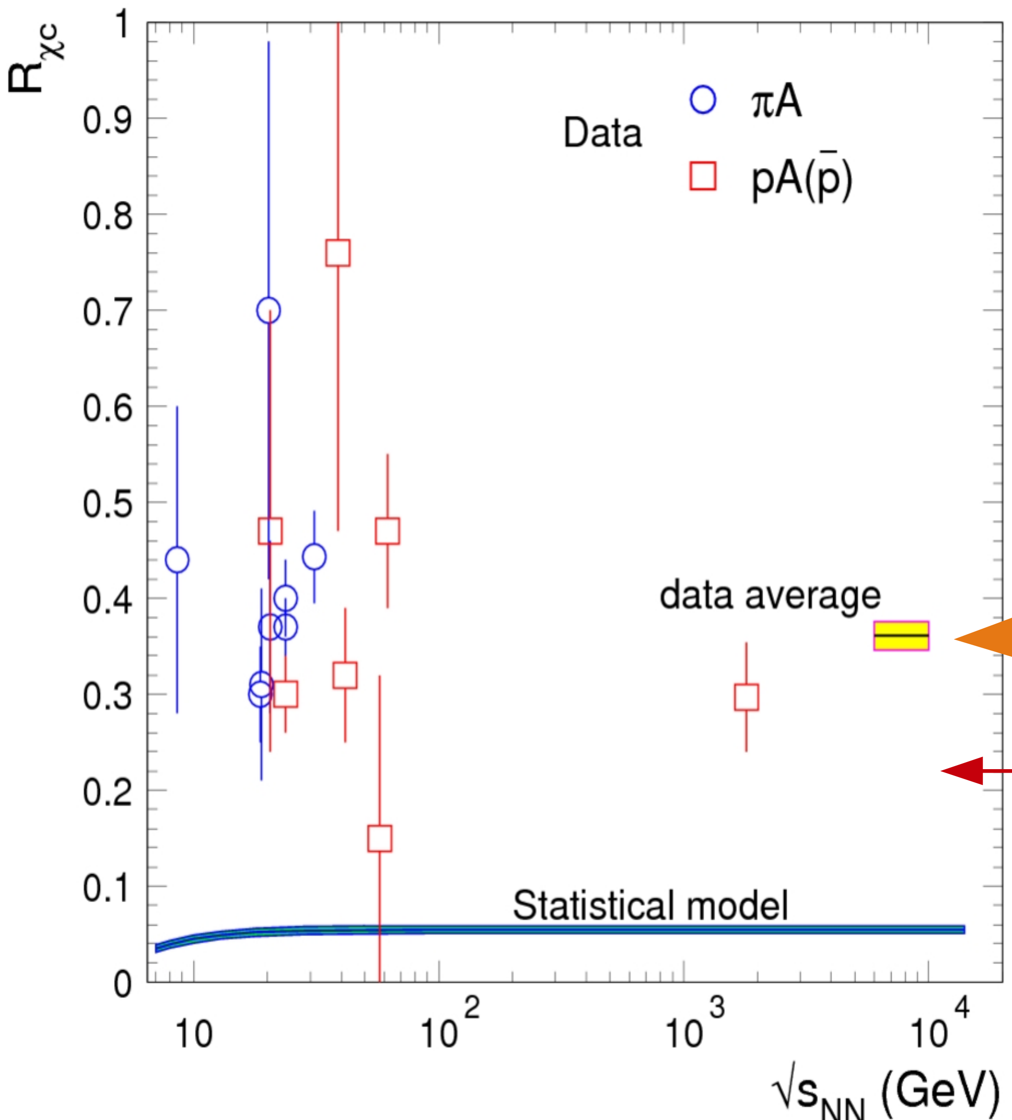
for statistical hadronization need to see suppression by Boltzmann factor

χ_c even bigger difference

expected ALICE performance muon arm run2 and run3



Situation even more dramatic for P-states

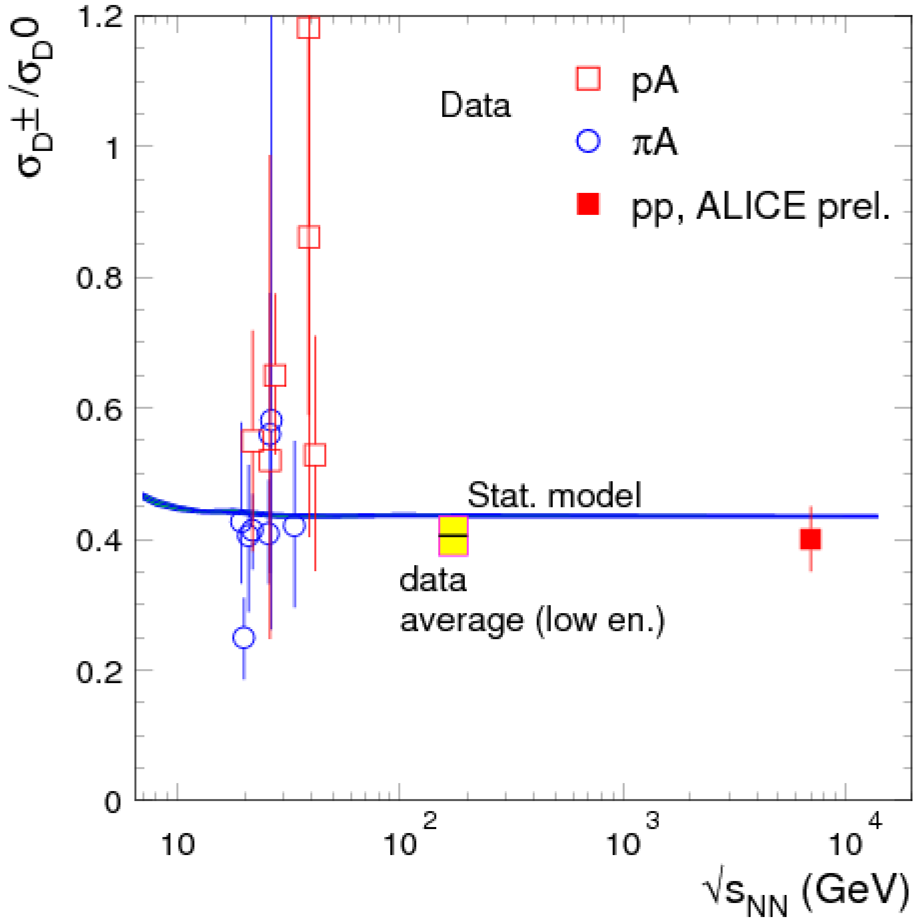


pA and πA data on average factor 7 avove statistical model prediction

Transport model (Rapp)

A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B678 (2009) 350

Charged to neutral D-mesons

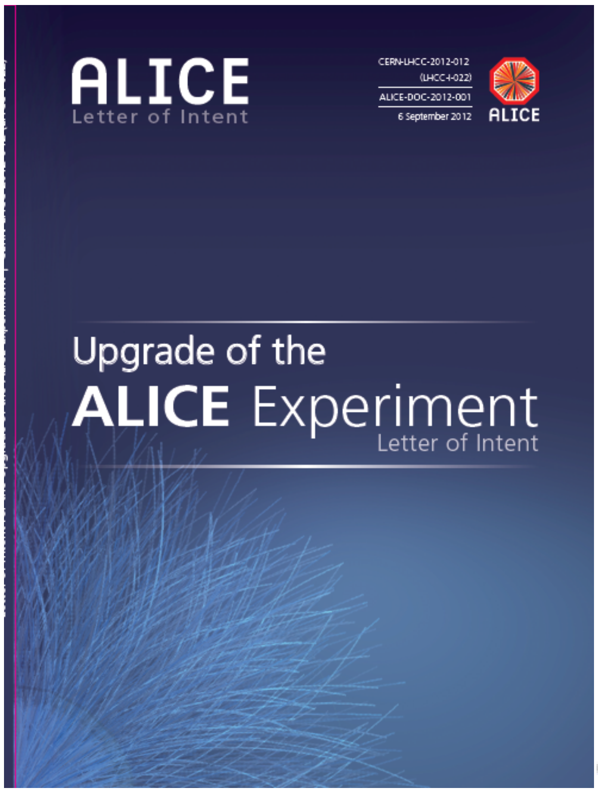


open charm hadrons in pp collisions consistent with quarks hadronizing at about T = 165 MeV

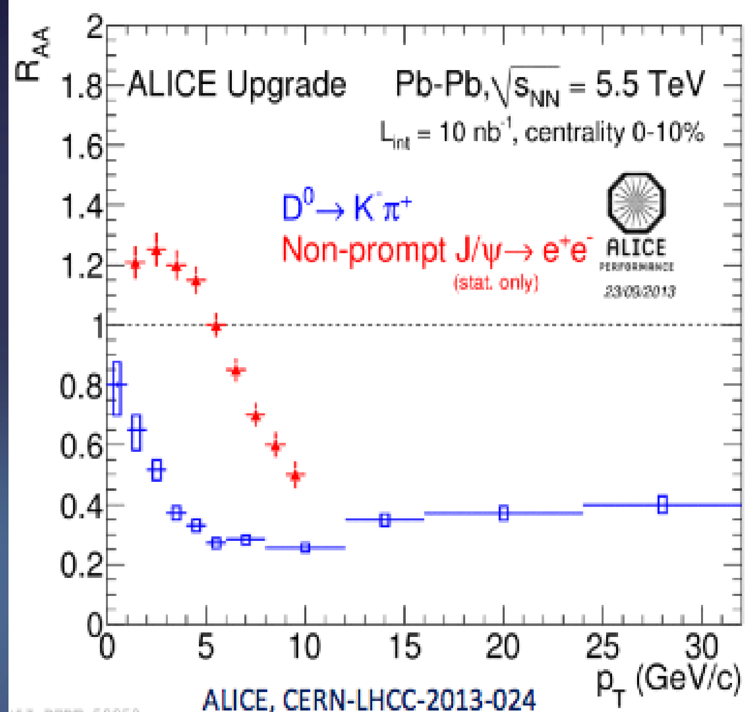
what about PbPb collisions? all D and Λ_c states predicted. Data to come soon!

outlook open heavy flavor – LHC run3

new high performance ITS plus rate increase (TPC upgrade)

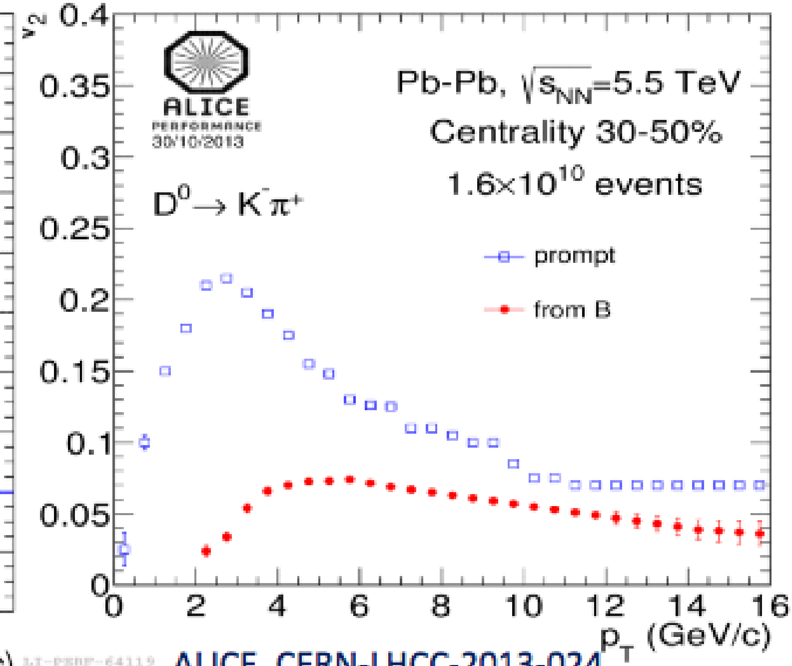


Upgrade



Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ

Upgrade

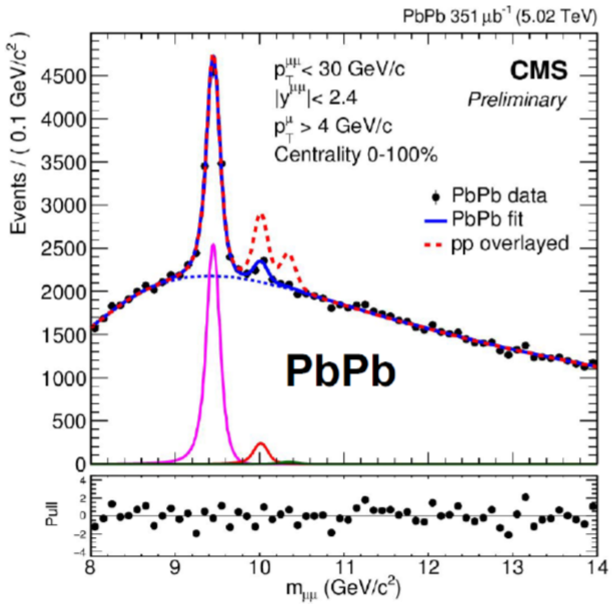


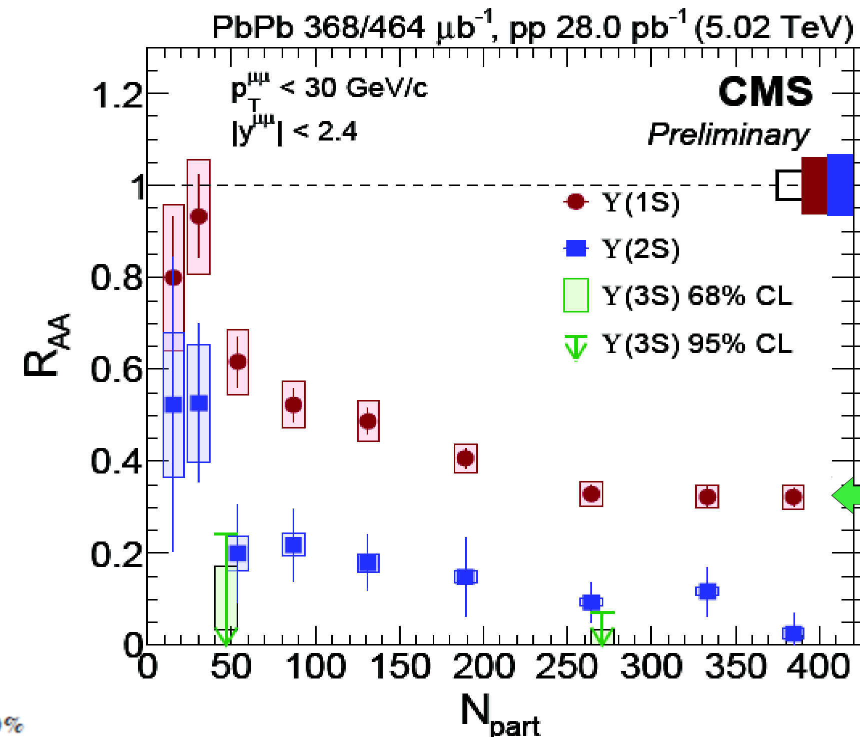
Input values from BAMPS model: C. Greiner et al. arXiv:1205.4945

Charm v_2 down to p_T~0 using prompt and beauty v_2 down to B p_T~0 using B-decay D^0

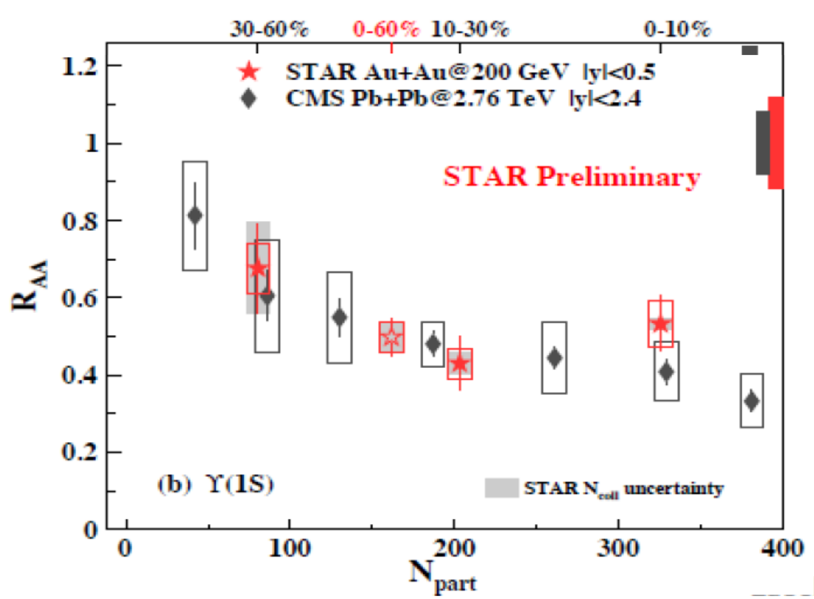
bottomonia

Suppression of Upsilon states



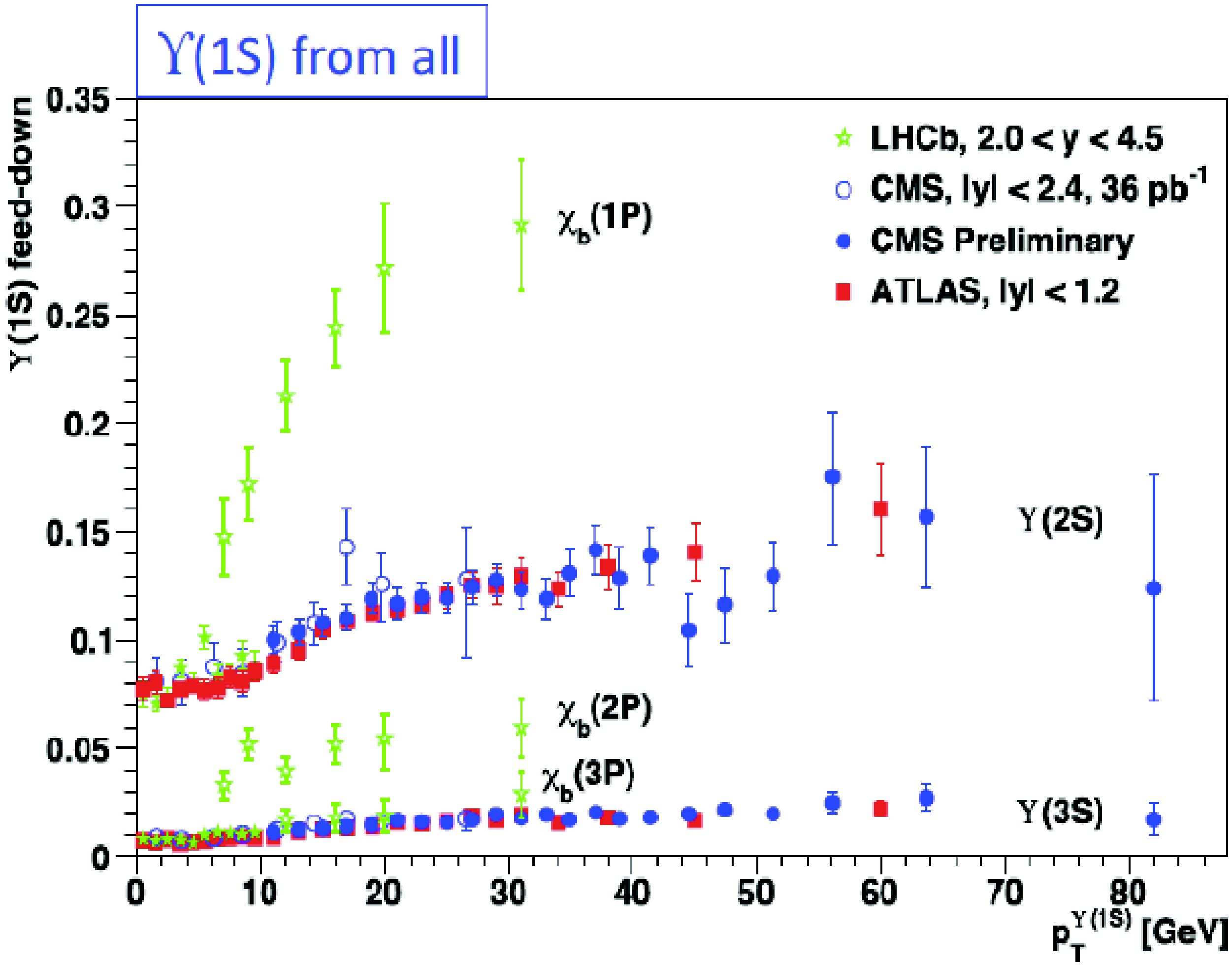


not consistent with just excited state suppression (LHCb data: only 25 % feed-down in pp at LHC)

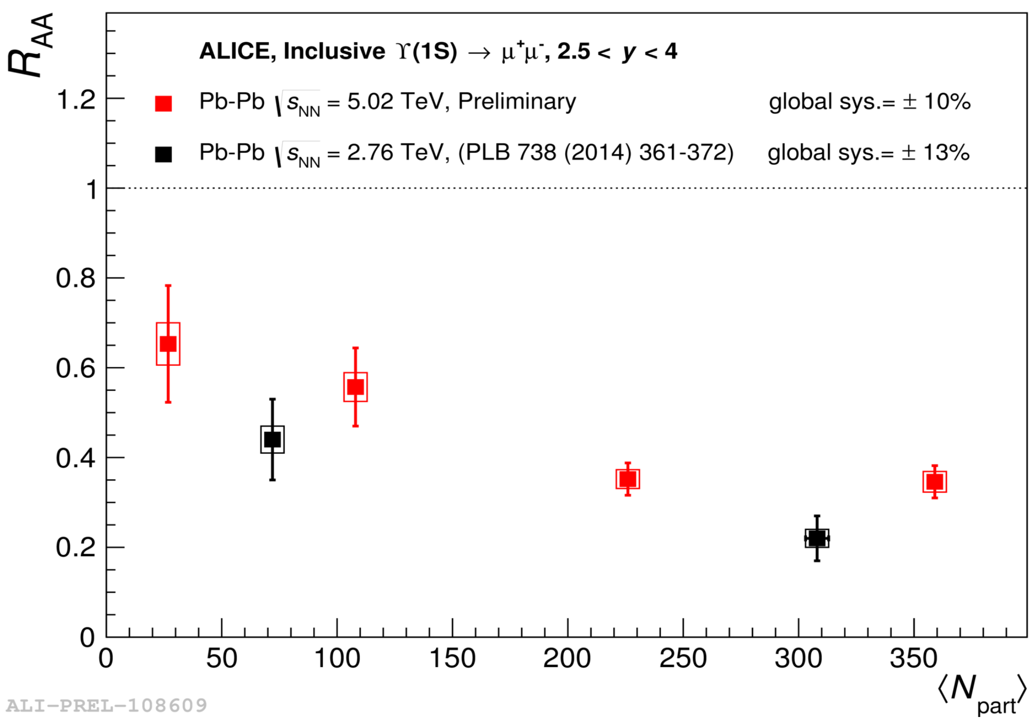


genuine Upsilon suppression
- real and imaginary part of potential at finite temperature play a role
- similarity of RHIC and LHC suppression reminiscent of SPS and RHIC for J/ψ
- possibility of statistical hadronization?

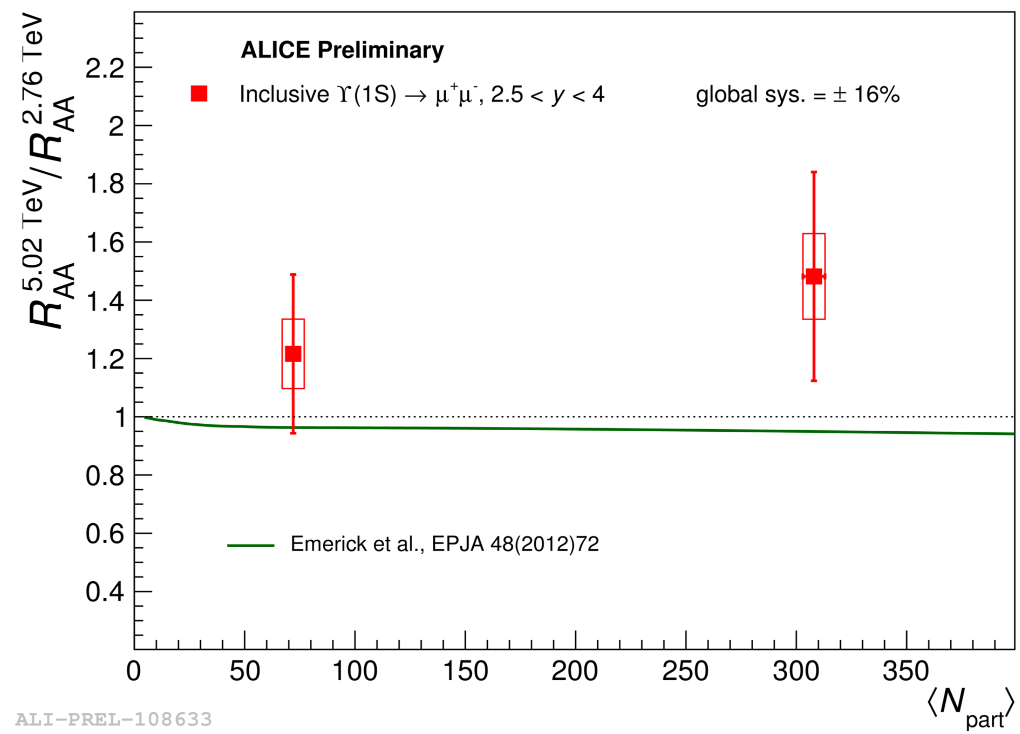
Feeding into Upsilon (1S)



Upsilon in PbPb at 5 TeV compared to 2.76 TeV



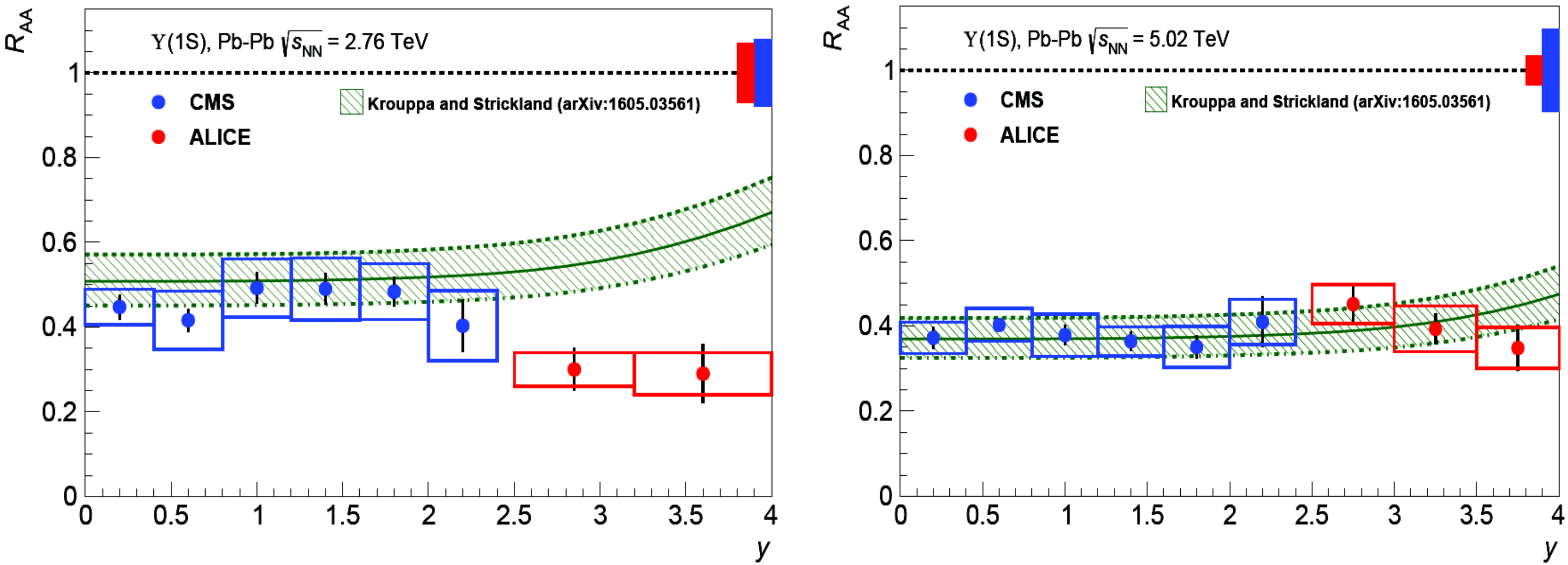
yield of Upsilon(1S) increases with beam energy



dissociation of Upsilon in a hydrodynamically medium will not produce an increase with increasing energy density

$R_{AA}^{0\text{-}90\%}(5.02\ \text{TeV}) / R_{AA}^{0\text{-}90\%}(2.76\ \text{TeV}) = 1.3 \pm 0.2(\text{stat}) \pm 0.2(\text{syst})$

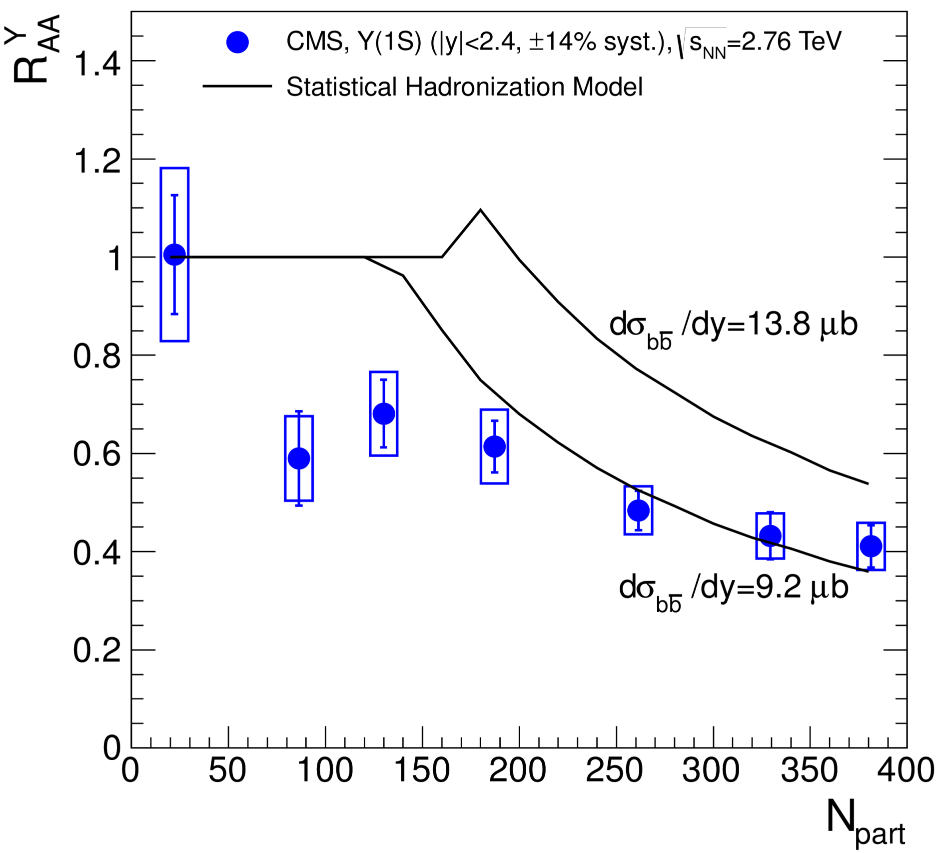
Upsilon R_{AA} rapidity dependence

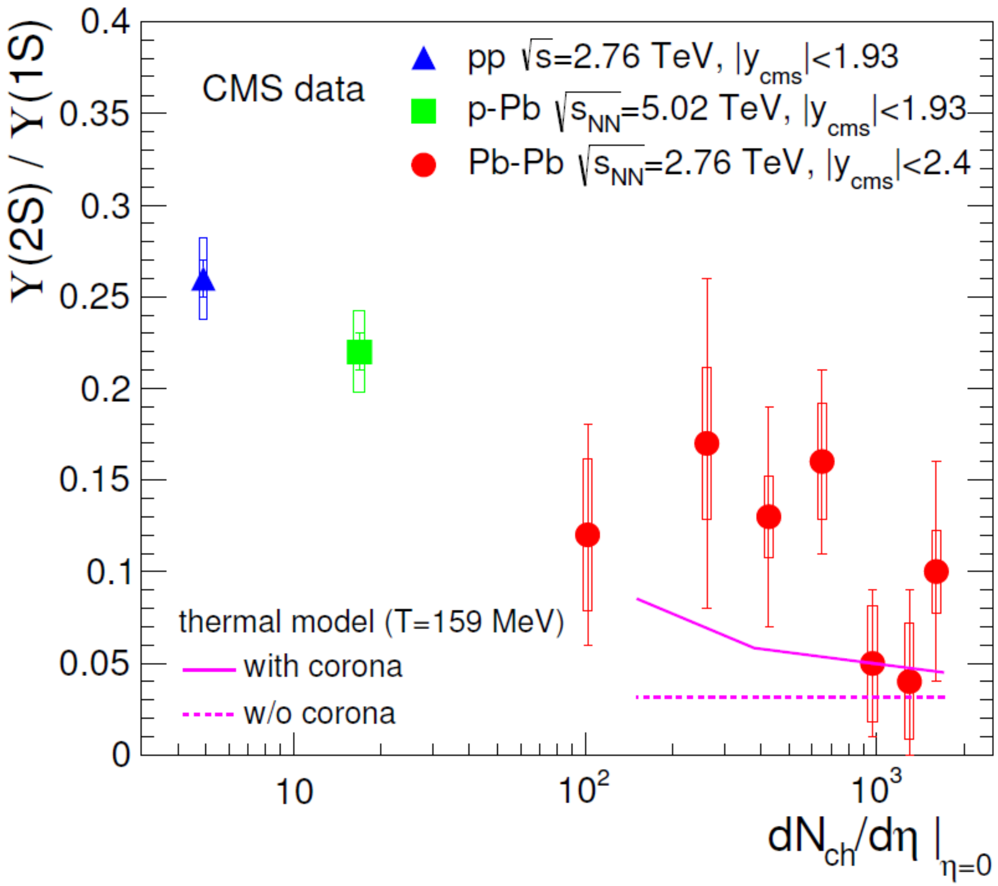


Indication: R_{AA} peaked at mid-y like for J/ψ
not in line with collisional damping in expanding medium

the Upsilon could also come from statistical hadronization

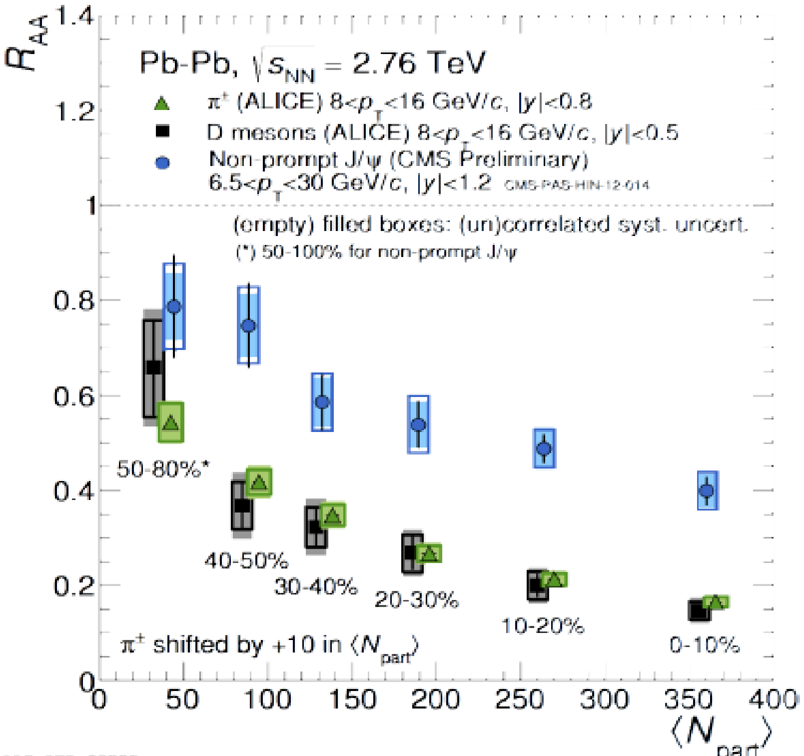
SHM/thermal model: Andronic et al.





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

what about b-quark energy loss and thermalization?



Charm: D mesons

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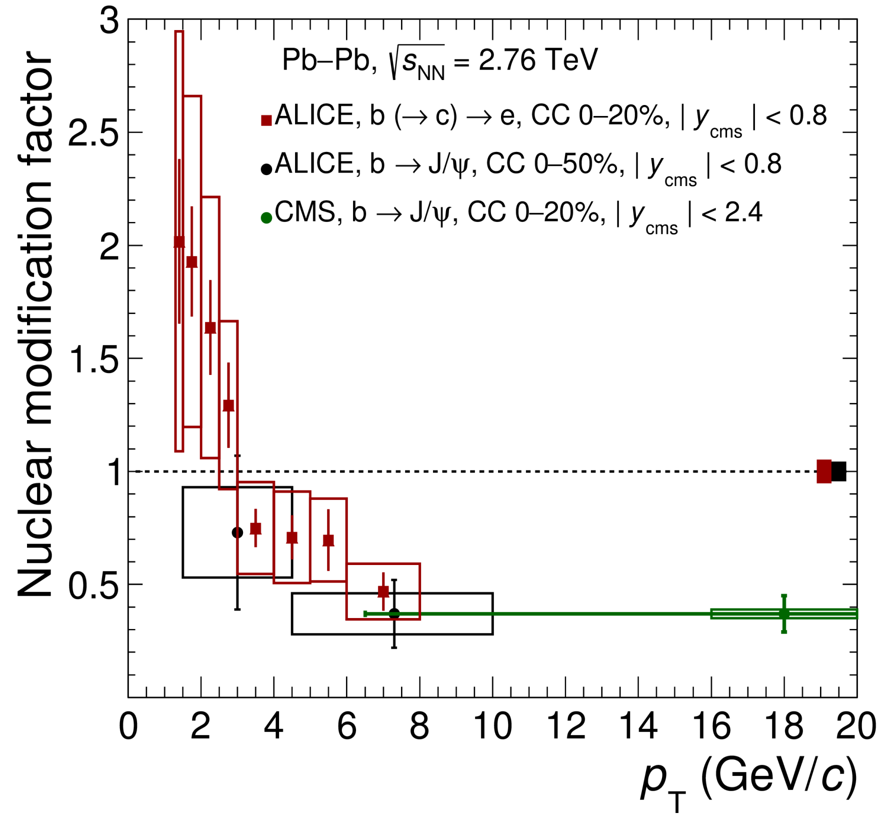
Beauty: non-prompt J/ψ

arXiv:1610.00613



b → c → e arXiv:1609.03898

separation via impact parameter distribution

- mass ordering between charm and beauty observed
- for more central collisions, electrons from b-decay show suppression for p_t > 3 GeV/c