summary, perspectives, opportunities

- general remarks
- open heavy flavor in pp and pPb
- open heavy flavor in Pb-Pb
- quarkonia
  - pp and pPb
  - Pb-Pb
- successes and failures
- open questions

pbm

workshop on 'heavy flavor in high energy collisions'

Berkeley, Ca

Oct.. 30 – Nov. 1, 2017

ISOQUANT SFB1225

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

EMMI

GSI

selected experimental issues and open questions

- quarkonia and open HF
  - proper normalization is to open charm and open beauty cross section in Pb-Pb collisions (not p-Pb) → implies measurements to p_t = 0 for charm and beauty
  - role of Lambda_c and Cascade_c (charmed baryons) → coalescence?
  - need precision measurement of psi'/(J/psi) in Pb-Pb → are there colorless bound states in the QGP?
  - need rapidity dependence of quarkonium production – sequential suppression scenario implies minimum in R_AA at y=0, (re-)generation implies maximum at y=0
  - multiplicity dependence of charm production from pp – Pb-Pb → is there a similar picture for strangeness and charm

- strangeness and charm
  - D_s and Lambda_c measurement to low p_t → comparison to predictions from statistical hadronization model

selected theoretical issues and open questions

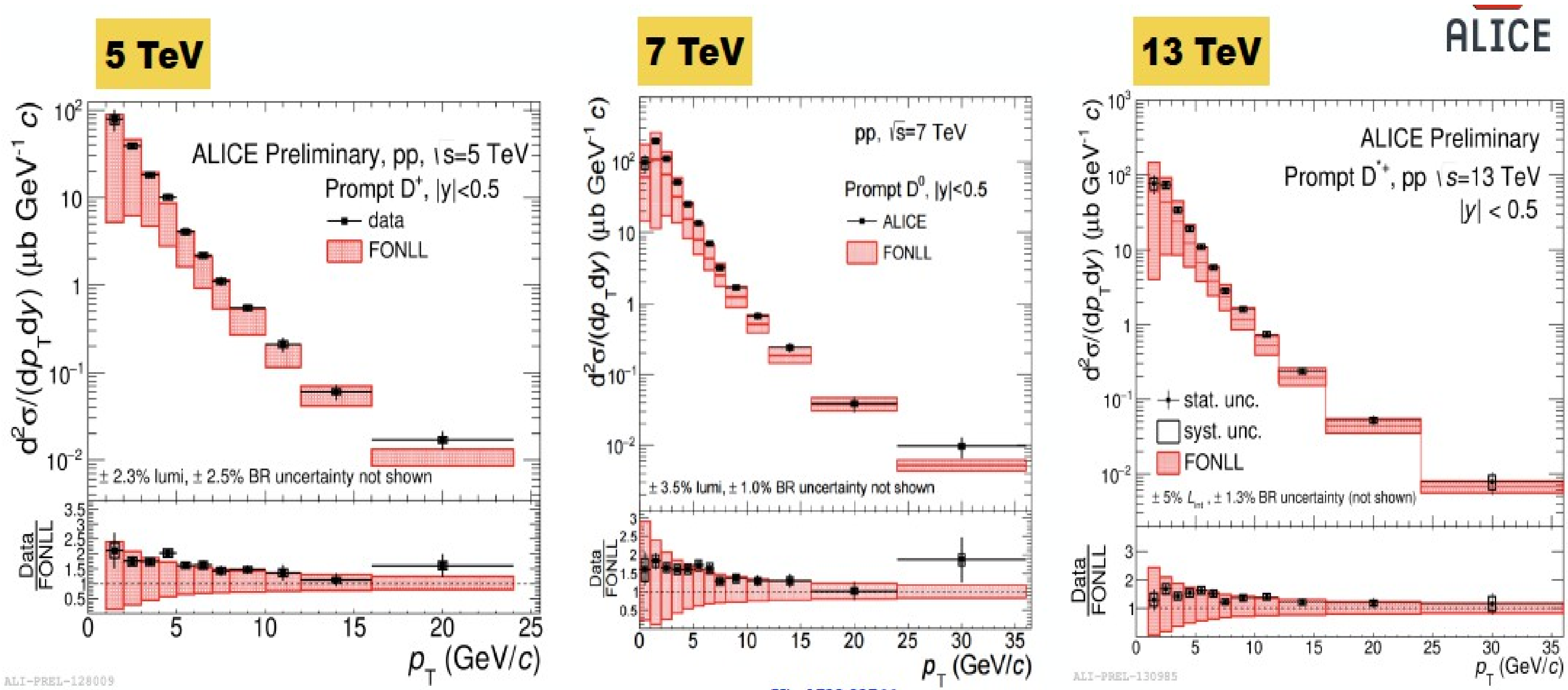
- can lattice results on T dependence of correlation functions and screening masses be mapped to experimental observations?
- is coalescence picture appropriate for hadron production at intermediate p_T (2 GeV) in view of conservation law issue?
- are there colorless bound states in the QGP?
- how can energy loss picture be merged with quarkonium production?

open charm and open beauty

general remark: to understand physics in the quarkonium sector, we need the open charm and open beauty cross section as function of p_T and y for Pb-Pb (Au-Au) collisions - **good progress reported in pp and pPb(Au) collisions at this workshop, but we are not yet there for Pb-Pb (Au-Au)- new trackers at LHC, but RHIC?**

I look forward to the time when the nuclear modification factor R_{AA} will not be needed anymore to quantify the data

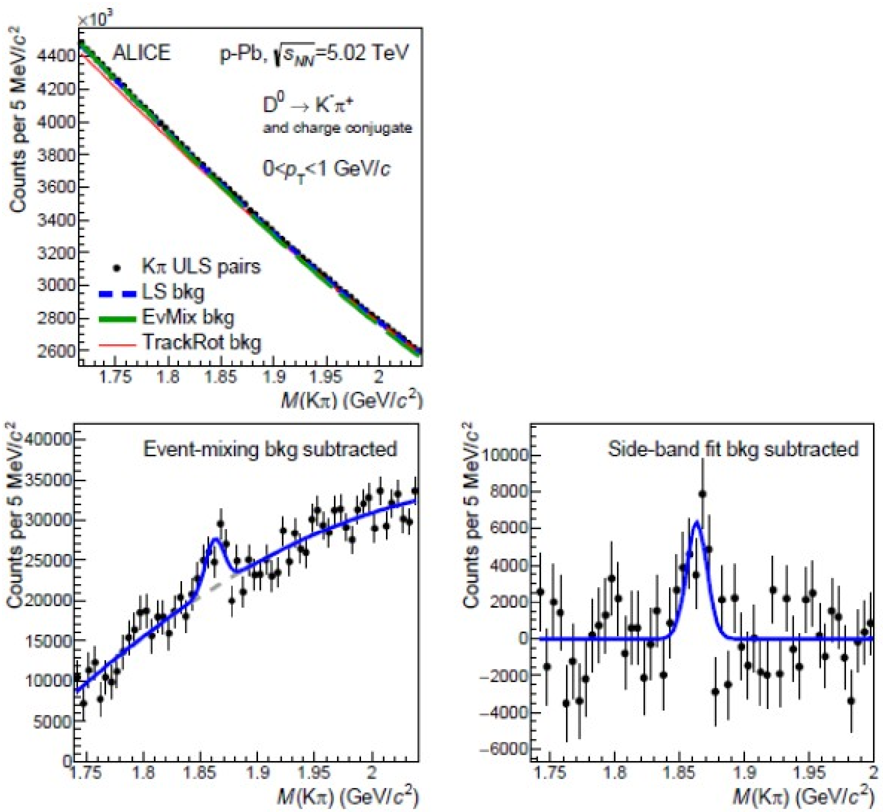
ALICE results in pp down to p_T = 0 --Grelli



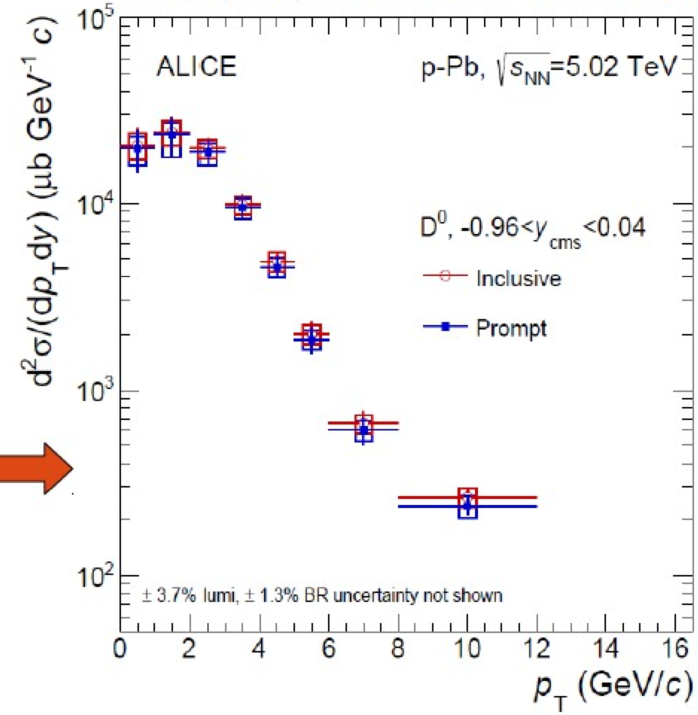
arXiv:1702.00766

PQCD rules, but all data are upper part of uncertainty band

ALICE results in pp and p-Pb down to p_T = 0



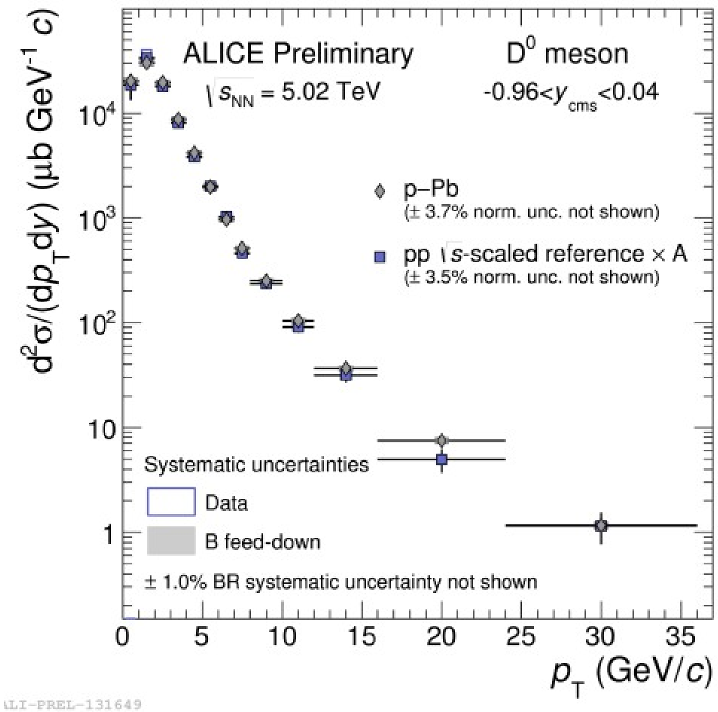
PRC94(2016) 054908 arXiv: 1605.07569

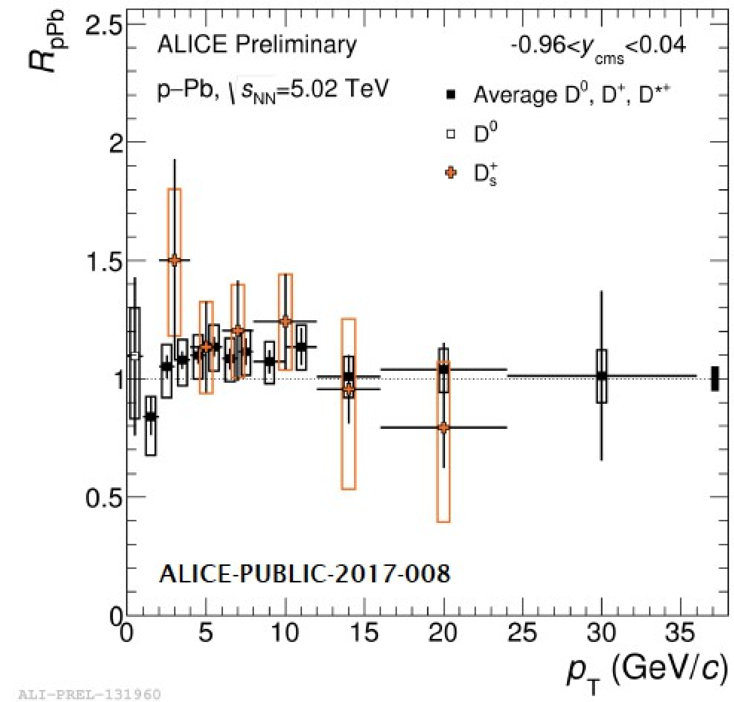


big effort to reduce systematic uncertainties

ALICE results in pp and p-Pb down to p_T = 0

$$R_{\mathrm{pPb}} = \frac{(\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}})_{\mathrm{pPb}}}{A \times (\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}})_{\mathrm{pp}}}$$





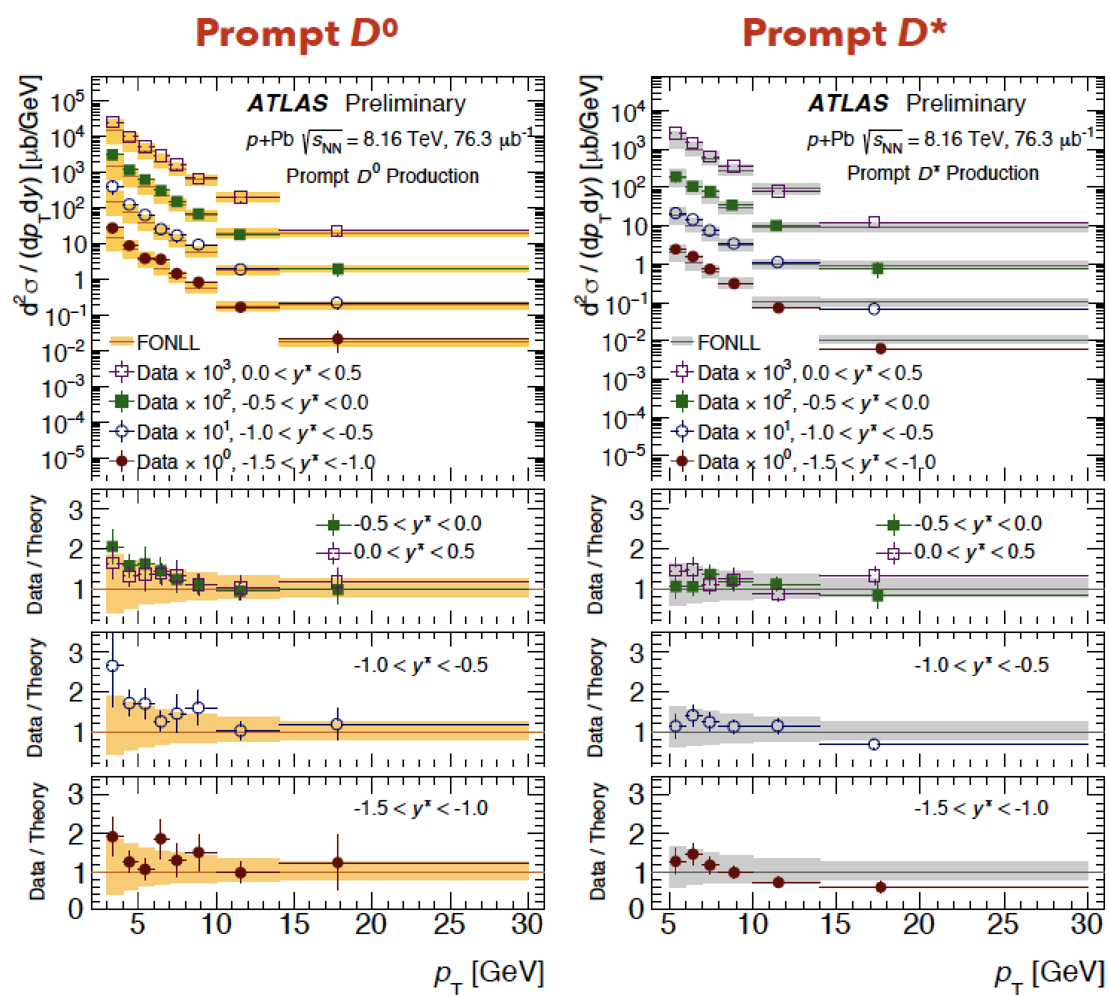
☑ R_{AA} of strange and non-strange D mesons compatible with unity. Consistent with small initial state effects at LHC.

big effort to reduce systematic uncertainties

Atlas results in pPb – QiPeng Hu

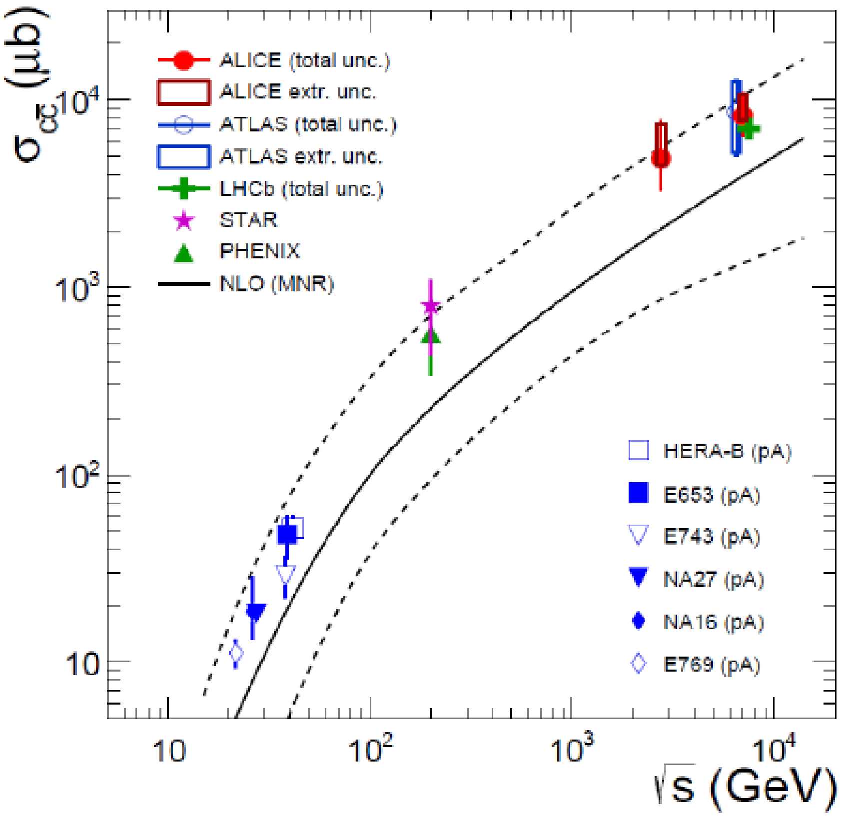
Cross sections

- Data and FONLL are comparable in whole kinematic range
- Relatively small modification in p+Pb



open charm cross section on pp collisions
a combined effort by many experiments

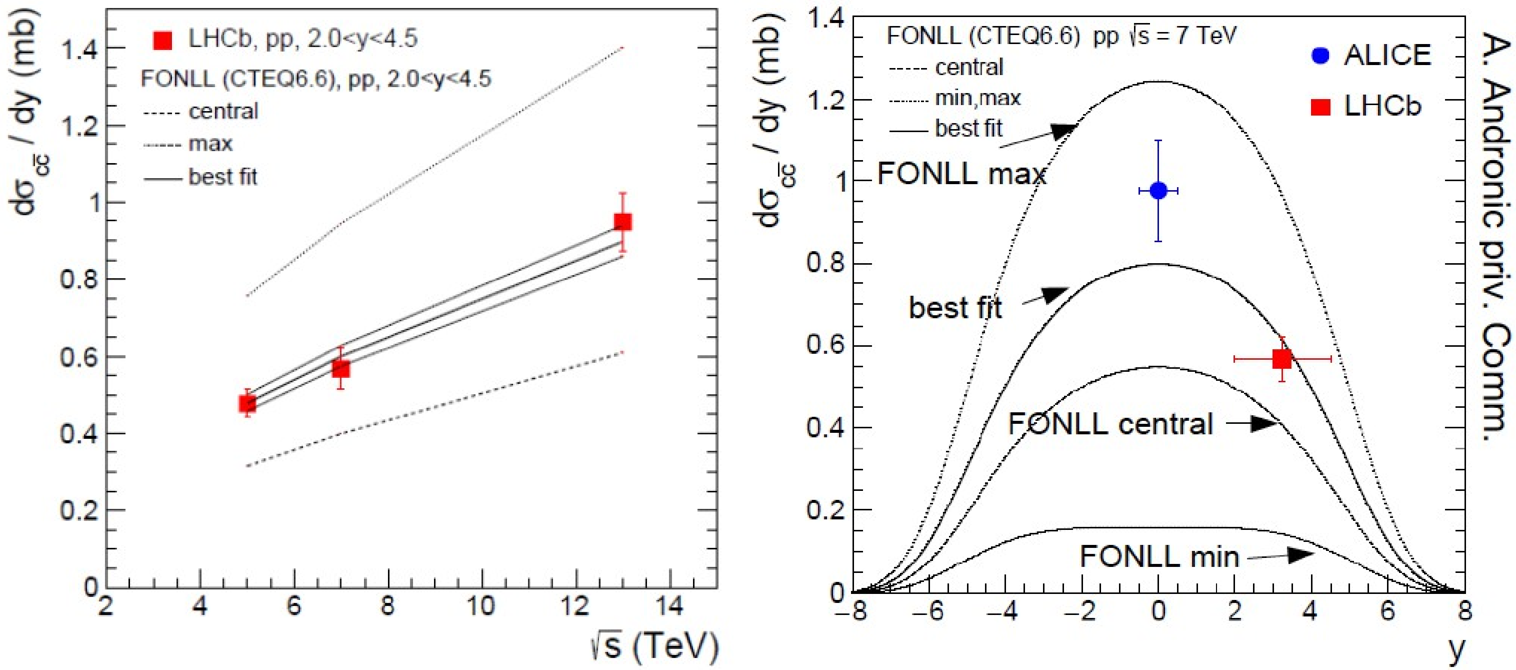
PRC94(2016) 054908 arXiv: 1605.07569



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

baseline for charmonia in absence of charm in Pb-Pb

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

now charmonium story

charmonium as a probe for the properties of the QGP

the original idea: (Matsui and Satz 1986) implant charmonia into the QGP and observe their modification, in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – sequential melting

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfined, thermalized charm quarks production probability scales with $N(_{ccbar})^2$

reviews: L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010

nearly simultaneous: Thews, Schroeder, Rafelski 2001

formation and destruction of charmonia inside the QGP

n.b. at collider energies there is a complete separation of time scales

$t_{coll} << t_{QGP} < t_{Jpsi}$

implanting charmonia into QGP is an inappropriate notion

this issue was already anticipated by Blaizot and Ollitrault in 1988

the idea

heavy quarks are not thermally produced, since their mass m >> T

at collider energies, heavy quarks are copiously produced through QCD hard scattering

the developing hot fireball formed in the collision thermalizes the heavy quarks

all charmed hadrons and charmonia are deconfined near T_c

the fireball expands and cools until it reaches the phase boundary

there, charmonia are formed with thermal/statistical weights

since charmonium formation scales with $N(_{ccbar})^2$ and since the charm cross section increases strongly with energy, we expect enhanced charmonium production at collider energy

this brings the thermal model into the heavy quark era with a large heavy quark fugacity

note: mass of charm quark is about 300 times heavier than mass of light quarks

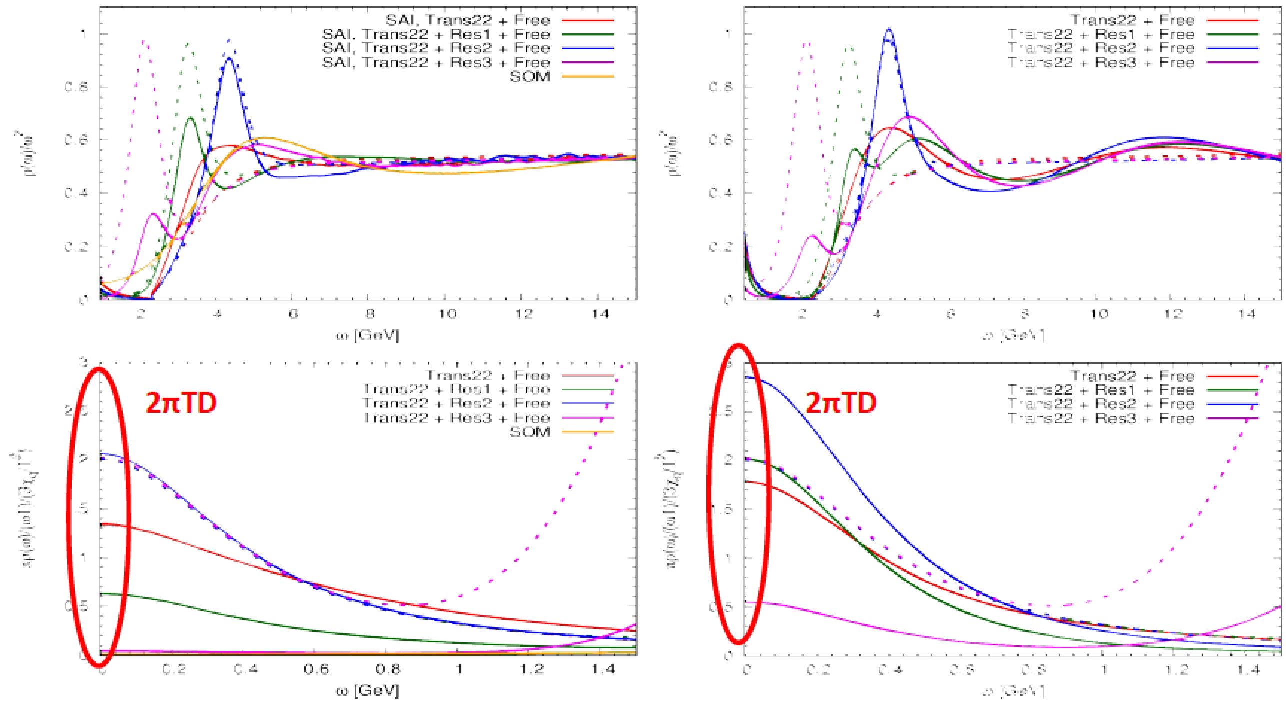
Input from new lattice studies - Ohno

DM dependence of the charmonium SPF at $1.5T_c$

Stochastic methods | MEM

High ω

Low ω



bottom (Y)
maybe for T < 1.5 T_c

DM = Trans + Free, Trans + Res(1-3) + Free (Trans is fixed)

The resonance peak is unstable and highly sensitive to DMs.

→ J/Ψ seems to melt already $T < 1.5T_c$.

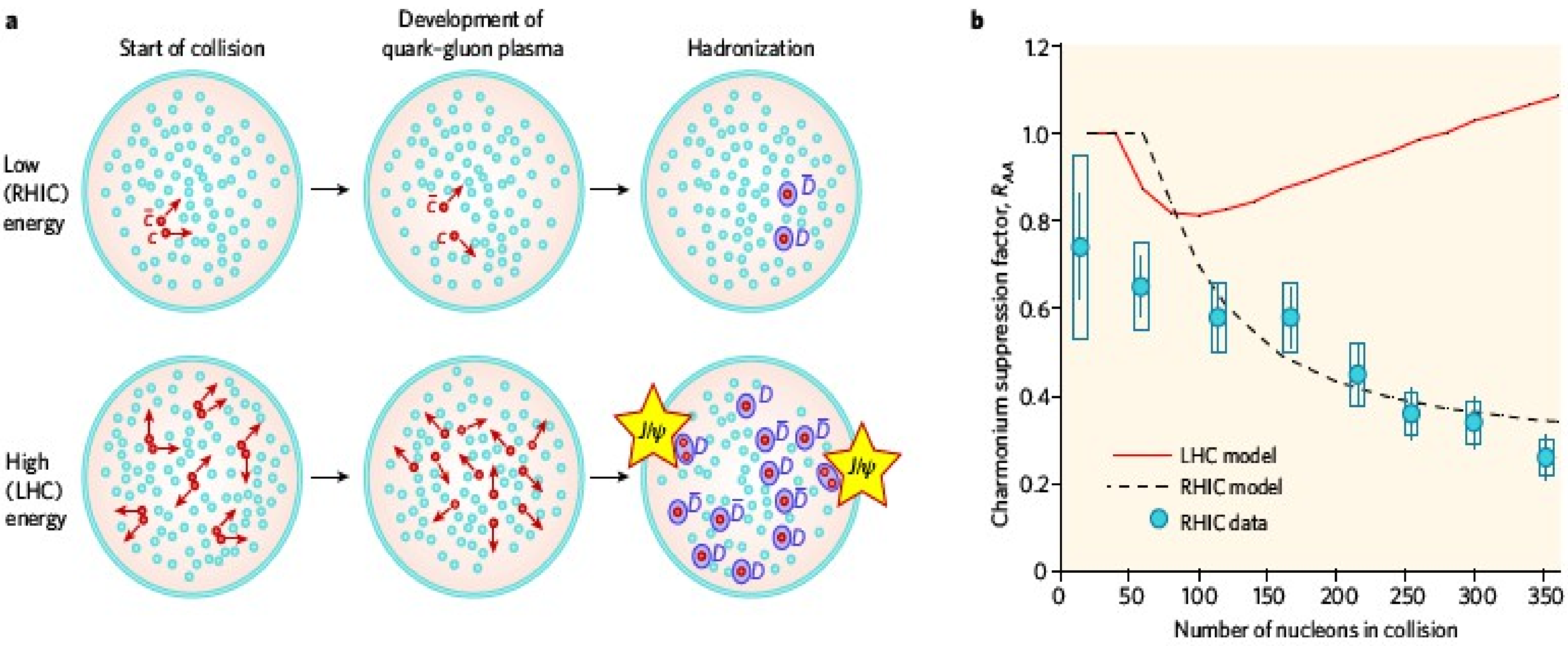
The transport peak is also sensitive to DMs.

H. Ohno
HF Workshop 2017

Quarkonium spectral functions on the lattice

quarkonium as a probe for deconfinement at the LHC
the statistical (re-)generation picture

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

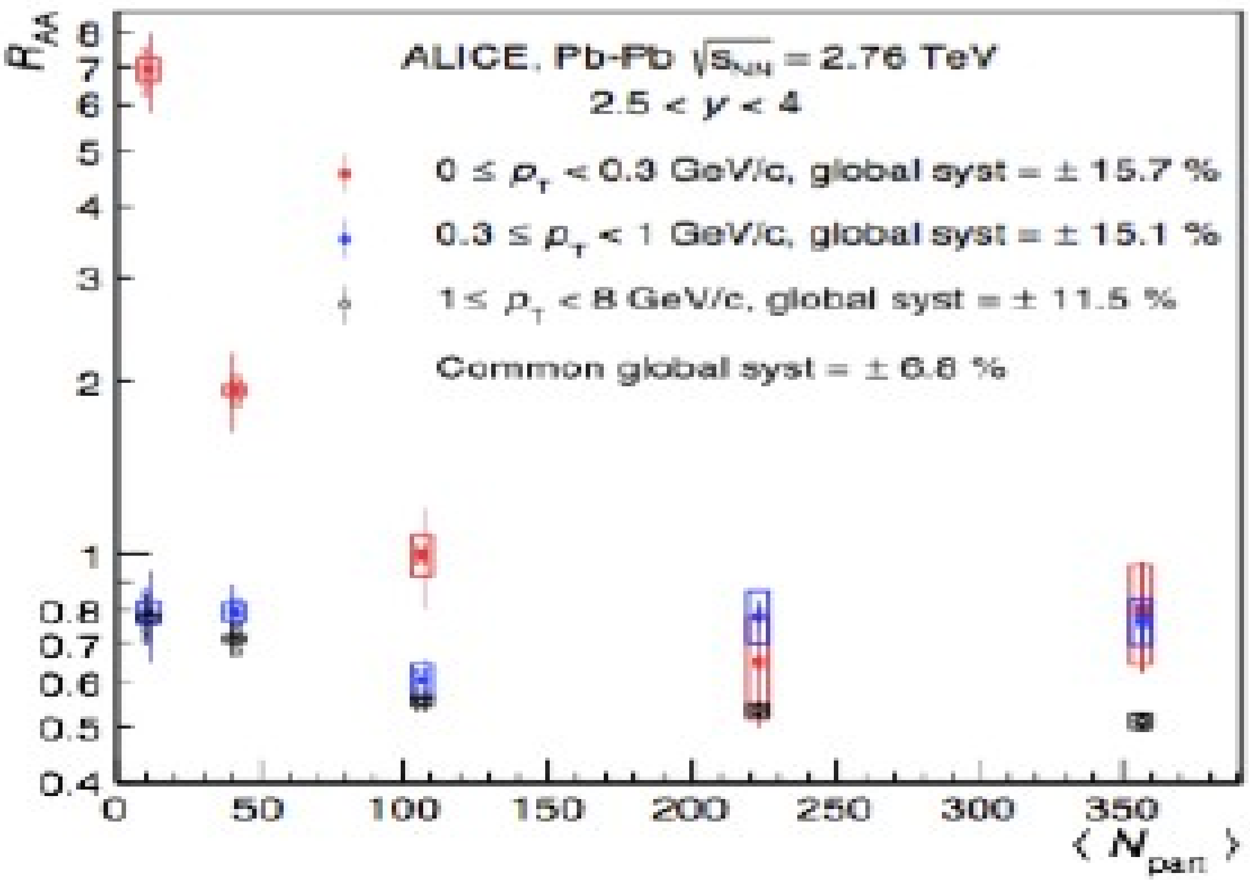


charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

pbm, Stachel, Phys. Lett. B490 (2000) 196
Andronic, pbm, Redlich, Stachel, Phys. Lett. B652 (2007) 659

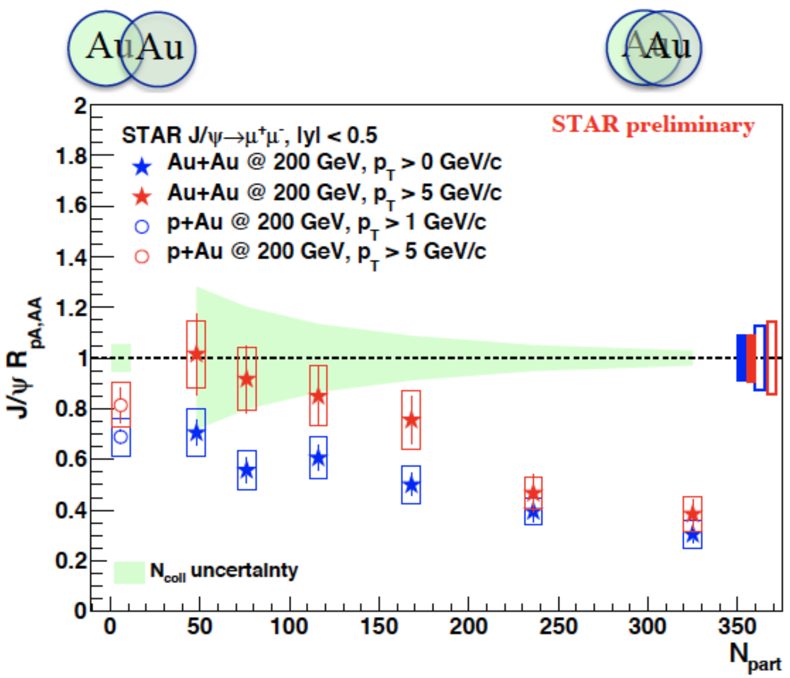
An aside on very low p_T (Spencer Klein)

production rate and kinematics of peak isd consistent with photo-production in peripheral nuclear collisions, no need for 'exotic' explanation

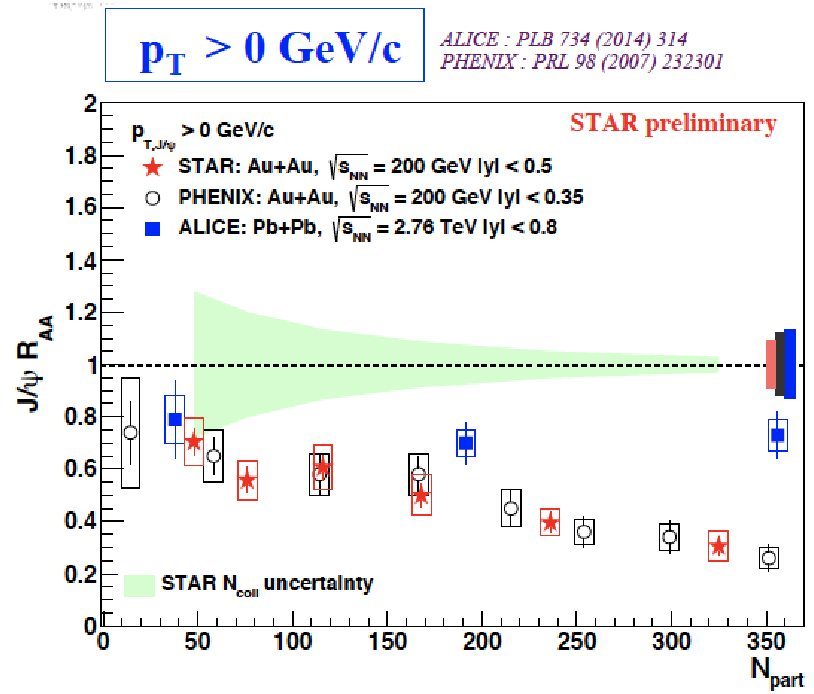


new J/psi data from STAR – Rongrong Ma

J/ψ R_{AA} vs. centrality

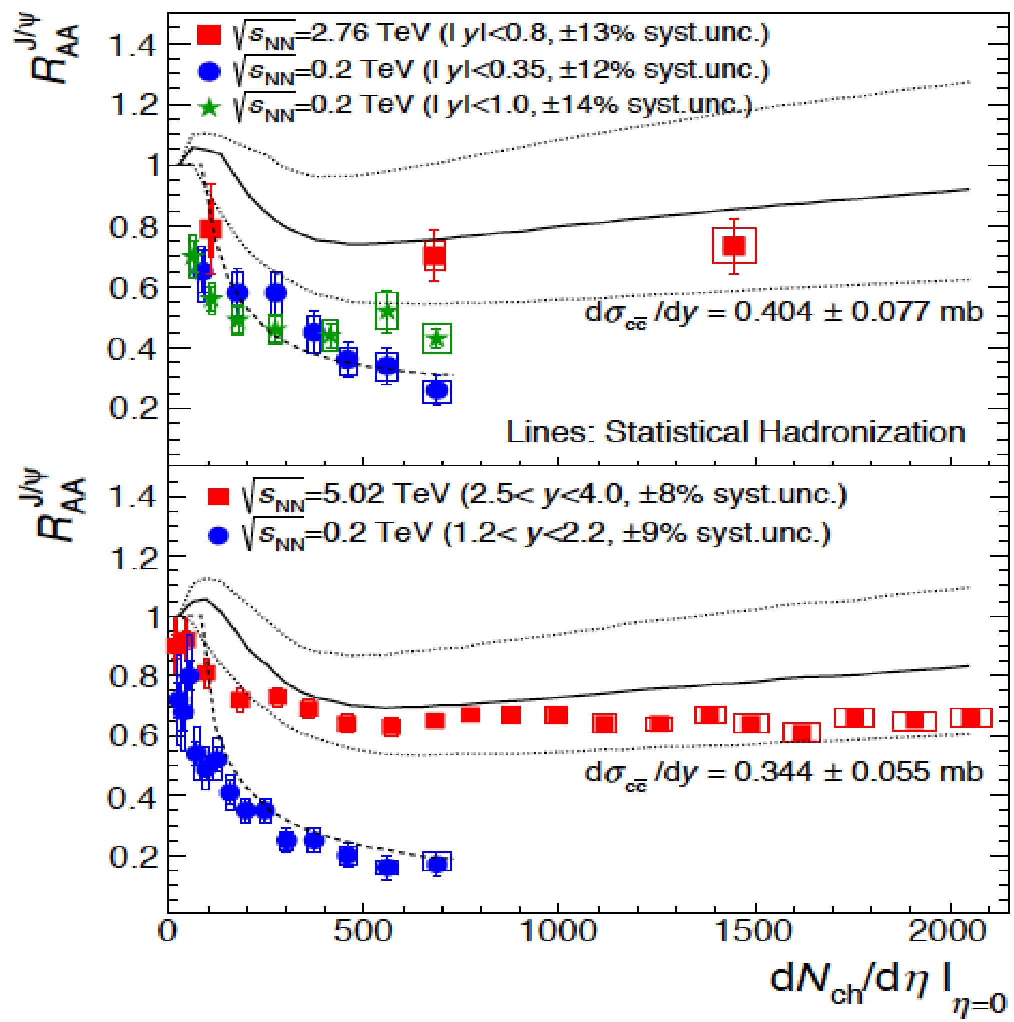


Comparison with PHENIX and ALICE

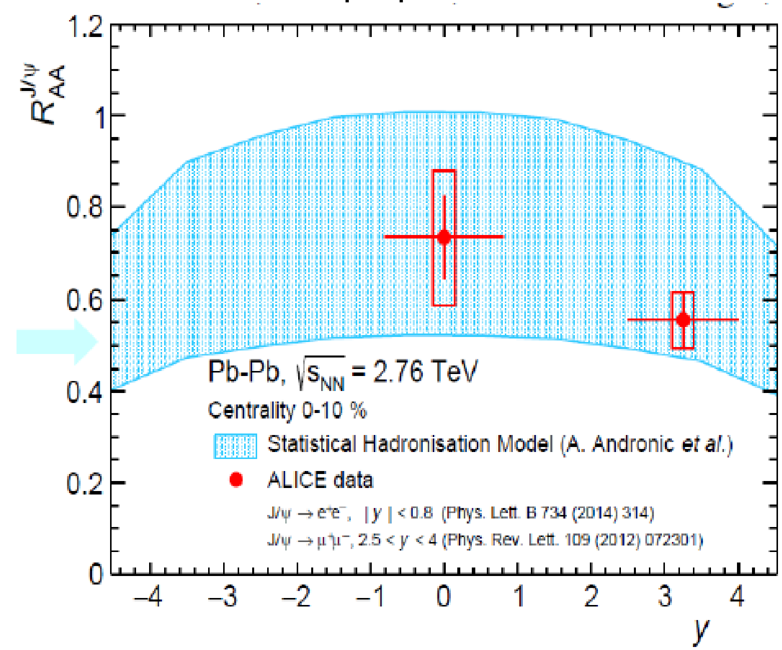


good agreement with 2007 prediction from statistical hadronization model

latest statistical hadronization model calculations



M. Koehler, Andronic, pbm, Stachel
in preparation

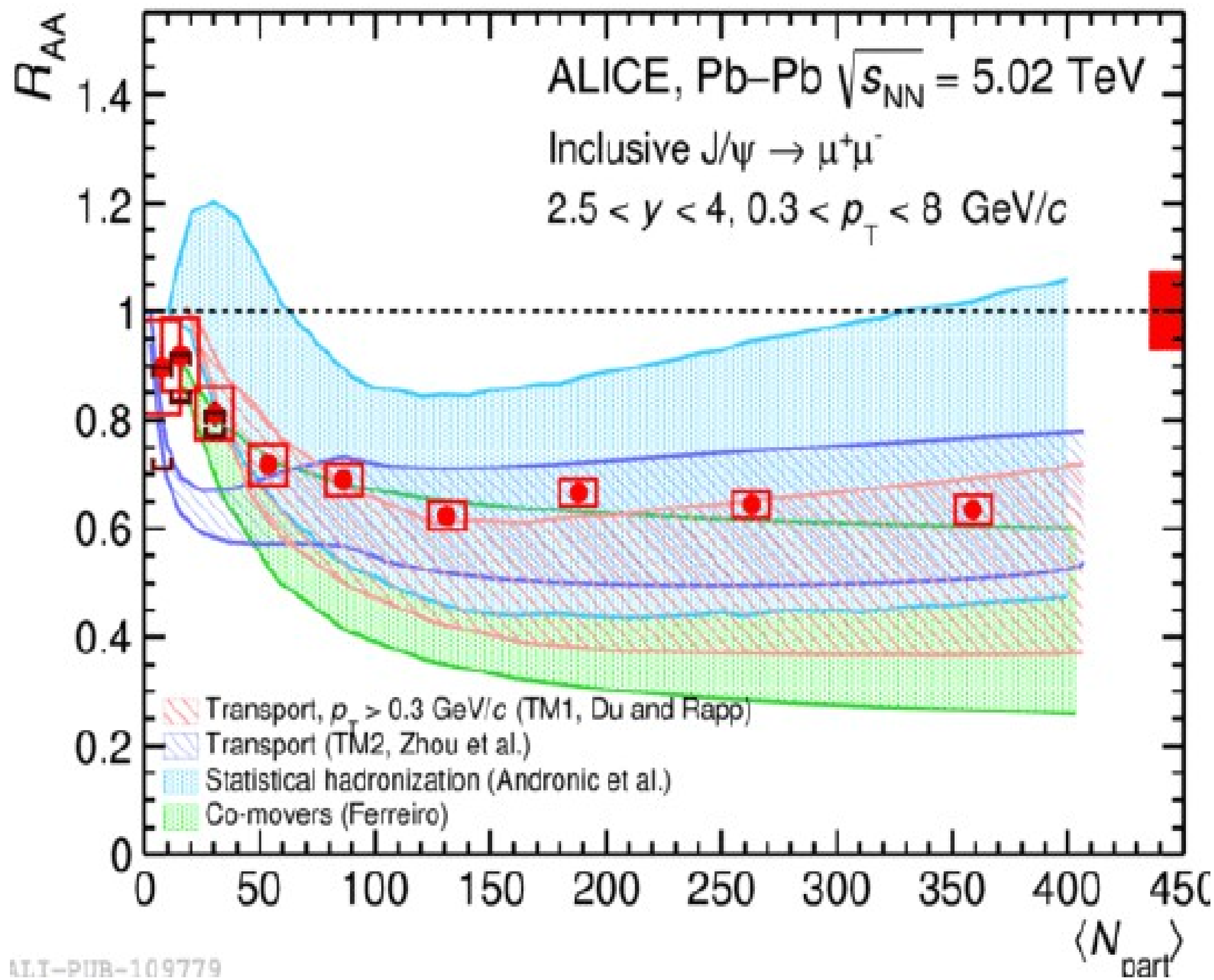


data exhibit maximum at y=0

Andronic, pbm, Stachel, Redlich, arXiv:1710.09425

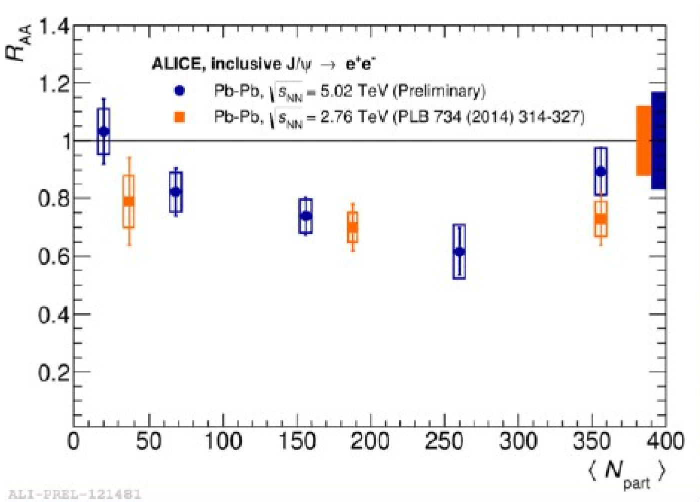
comparison to ALICE, STAR, PHENIX data at 0.2, 2.76 and 5.02 TeV
calculation uses most recent info on open charm cross section

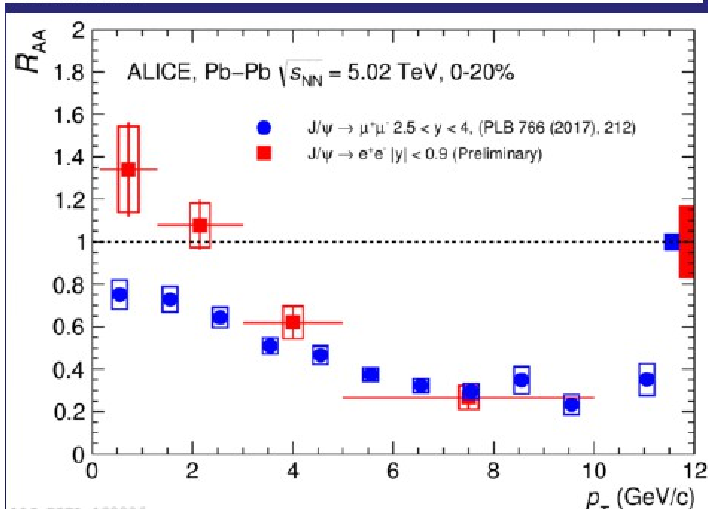
comparison to model predictions - Scomparin

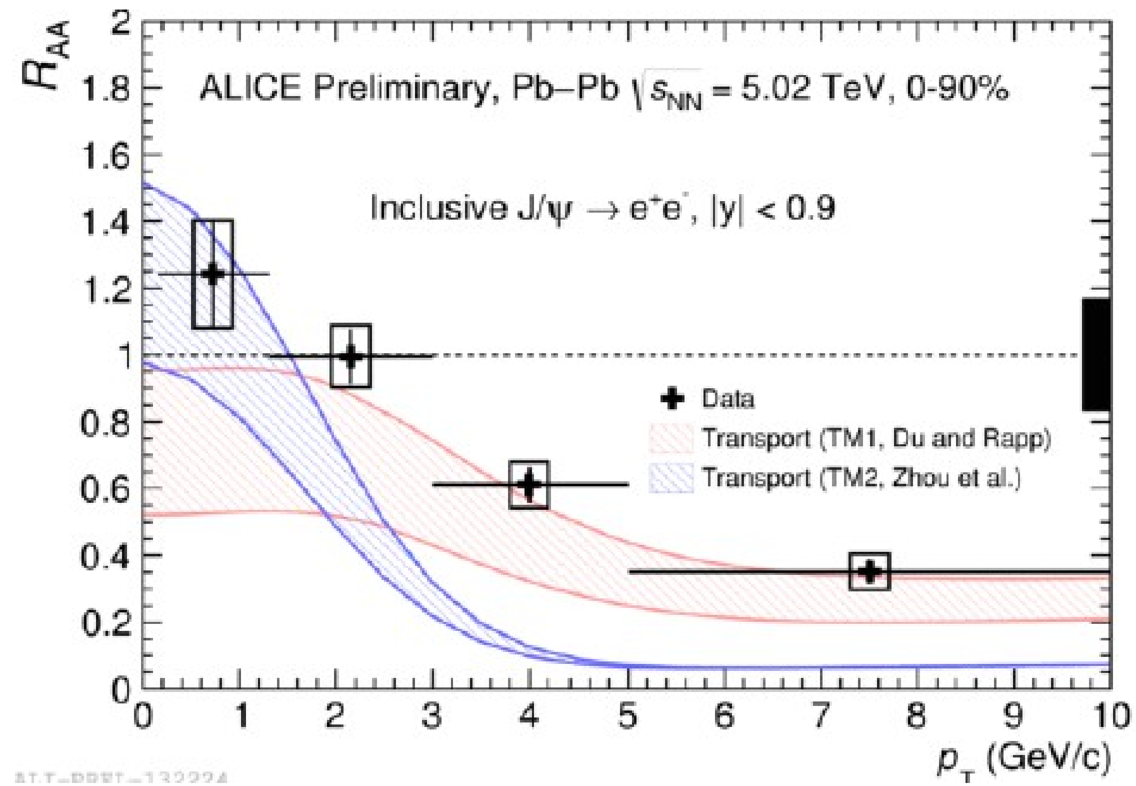


data already much more precise than models - open charm cross section!

ALICE mid-rapidity results - Scomparin



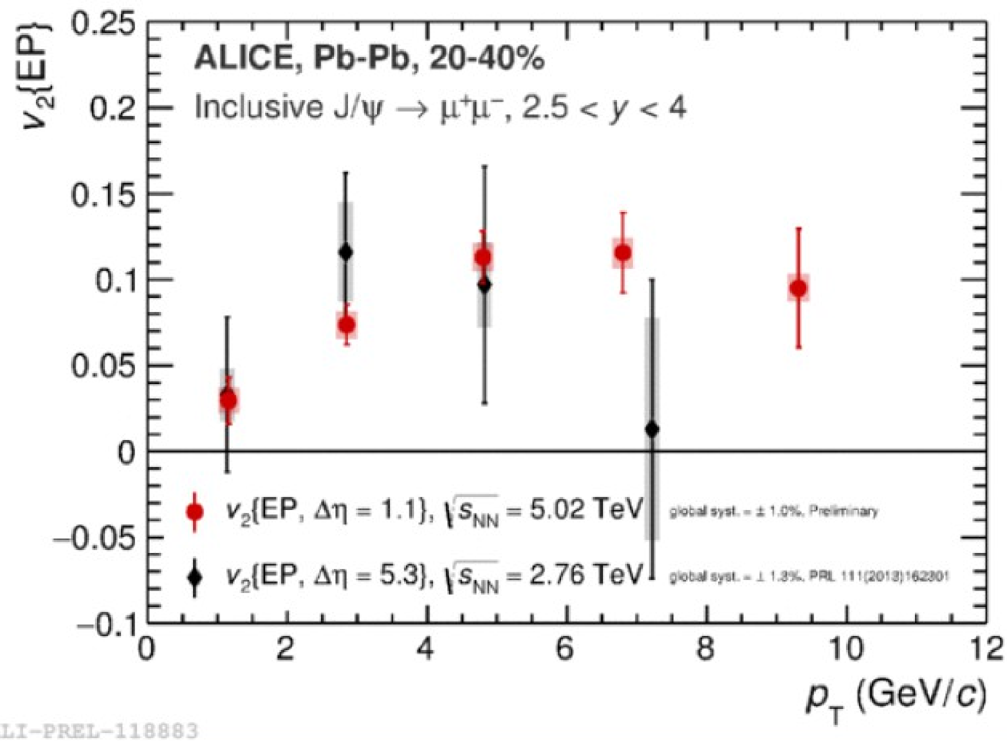




first indication of R_AA > 1

J/psi enhancement!

elliptic flow of charmonium

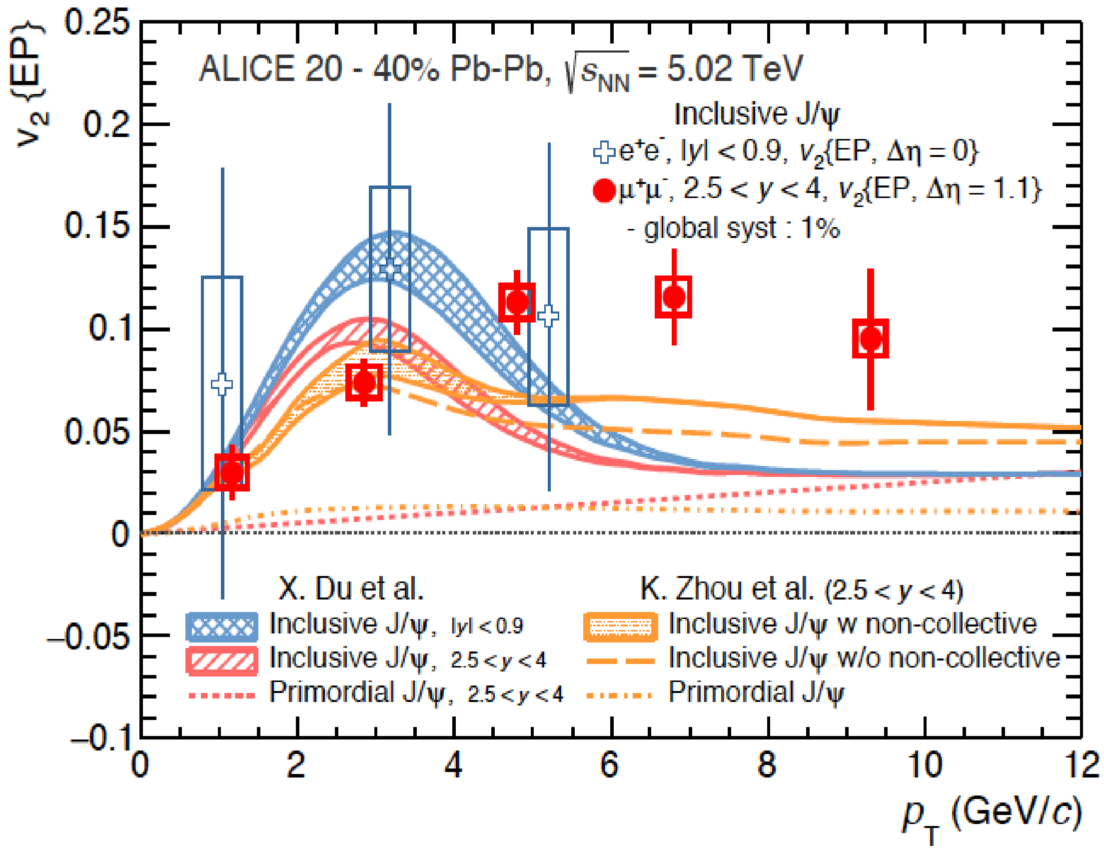


arXiv:1709.05260

p_T (GeV/c)	0-2	2-4	4-6	6-8	8-12
$\Delta\eta=1.1$	2.2σ	6.3σ	7.4σ	5.0σ	2.8σ
$\Delta\eta=5.3$	1.4σ	6.2σ	5.0σ	3.3σ	1.3σ

most recent LHC Run2 result,
charm quarks participate in the hydrodynamical evolution of the QGP fireball
support for statistical hadronization of deconfined charm quarks

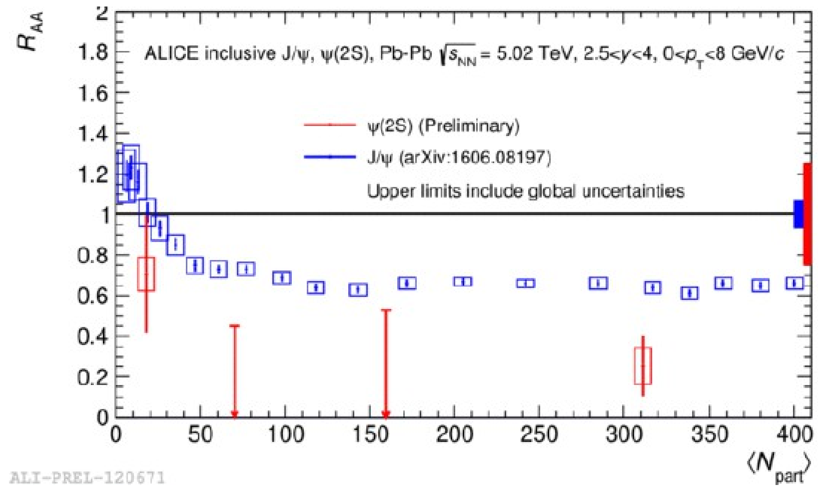
J/psi flow at mid-rapidity and forward rapidity



J/psi flow larger than expected at high transverse momentum transition from hydrodynamic flow to energy loss?

arXiv:1709.05260

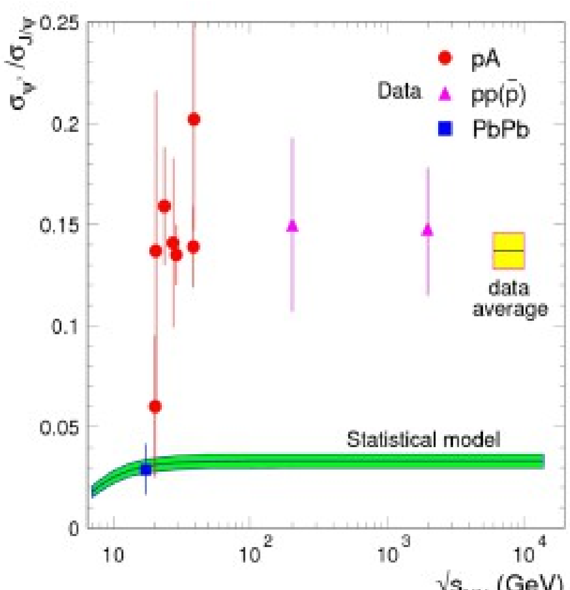
the psi'/psi ratio and colorless bound states in the QGP

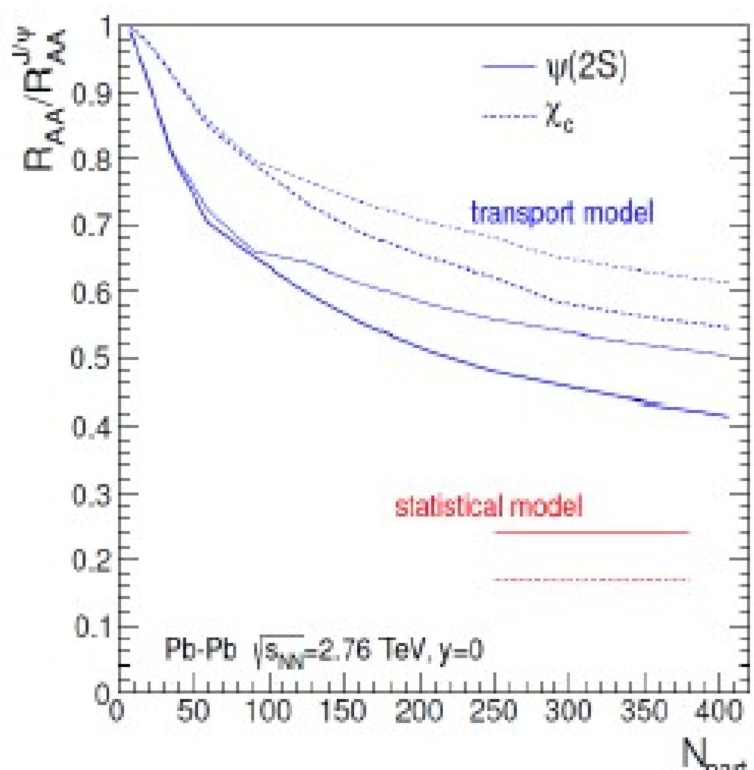


latest ALICE data - Scomparin

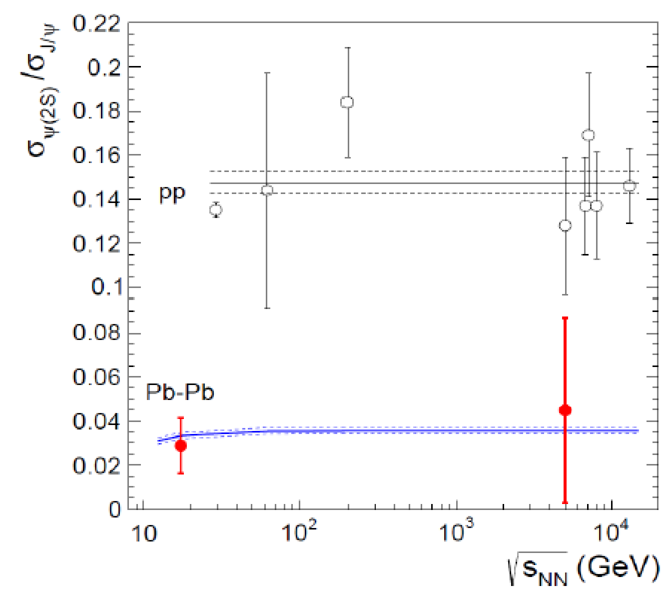
data not yet conclusive – much more to come

If substantiated → no colorless bound states in QGP





ALICE preliminary central collisions



Andronic, pbm, Stachel, Redlich, arXiv:1710.09425 statistical hadronization analysis → Debye mass determination near T_{pc}= 156 MeV

J/psi formation via statistical hadronization at T_c implies
experimental determination of Debye length (mass) and temperature
$\lambda_D < 0.4$ fm at T = 156 MeV   or $\omega_D/T > 3.3$
can compare to theory:

quite ok

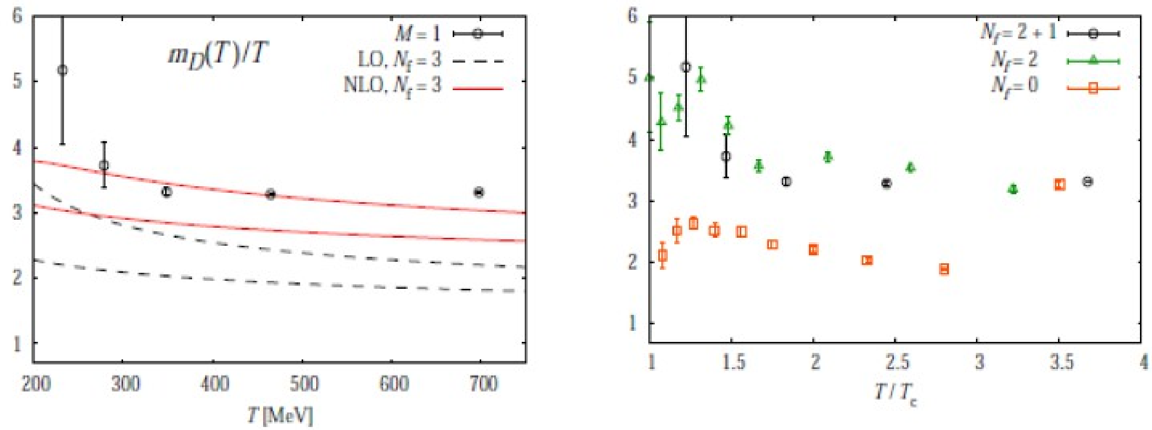


Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi T$ $(3\pi T)$, where μ is the renormalization point. (Right) Flavor dependence of the Debye screening masses. We assume the pseudo-critical temperature for 2 + 1-flavor QCD as $T_c \sim 190$ MeV.

arXiv:1112.2756 WHOT-QCD Coll.

bottomonia

issues and questions

- is there suppression for Y(1s)?
- is there sequential suppression?
- role of (re-)generation
- p_T and rapidity distributions

note: (re-)generation effects are vsible even if there is only 1 b bbar pair
diagonal term

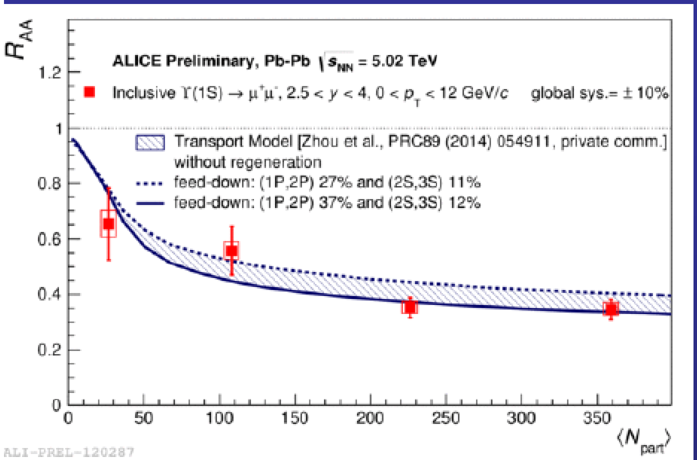
bottomonia

issues and questions

- is there suppression for Υ(1s)?
- is there sequential suppression?
- role of (re-)generation
- p_T and rapidity distributions

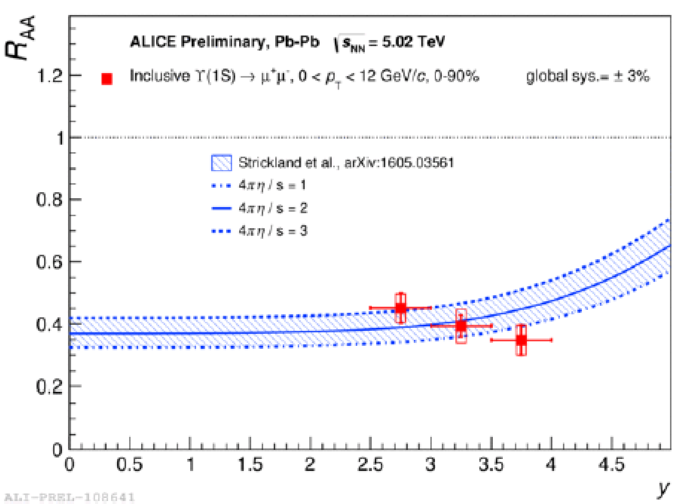
note: (re-)generation effects are vsible even if there is only 1 b bbar pair
diagonal term

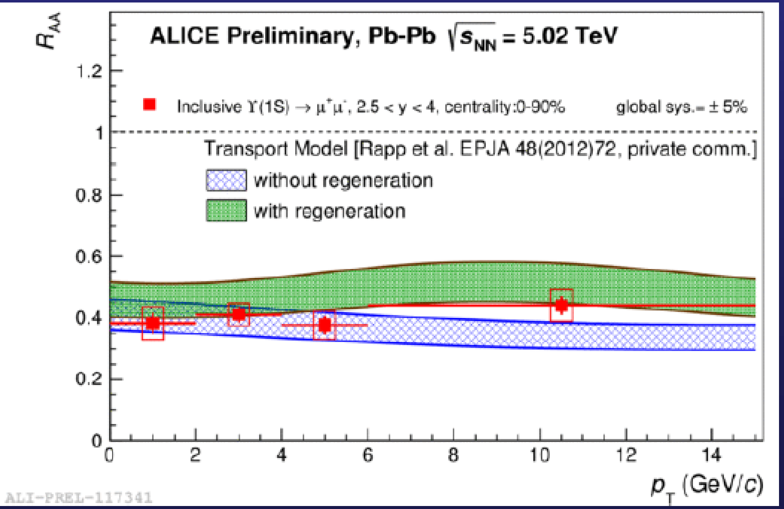
ϒ results in Pb-Pb: run 2



- Transport and anisotropic hydrodynamical models **qualitatively describe** the centrality and p_T–dependence of ϒ(1S) R_{AA}
- Some tension in the y-dependence ?
- **Contribution of regeneration is small**

- **R_{AA} (ϒ(2S))** = 0.26± 0.12 ± 0.06(sys.)
  < R_{AA} (ϒ(1S)) = 0.40 ± 0.03 ± 0.04(sys.)

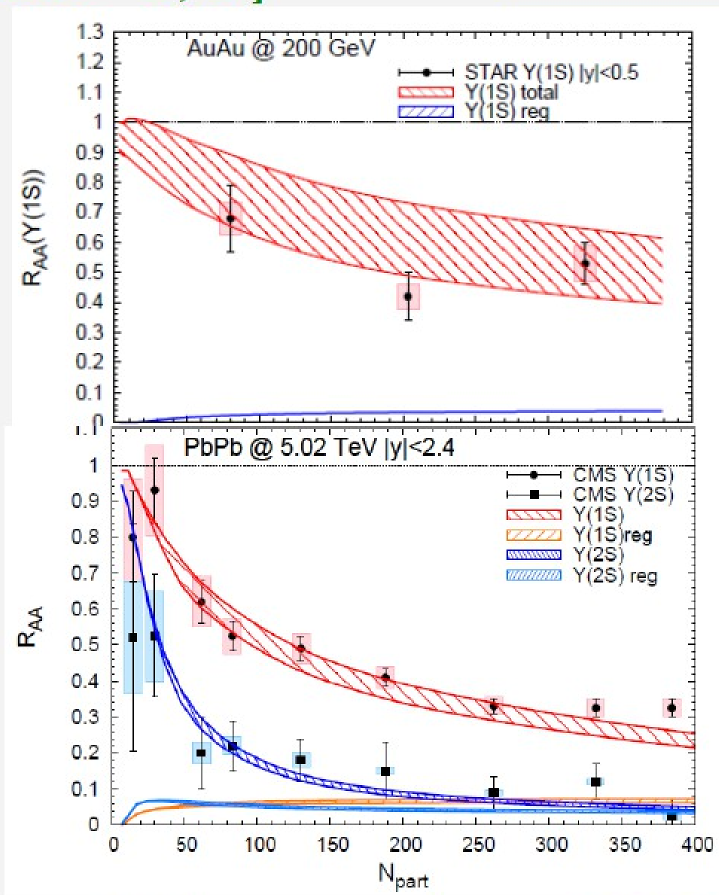




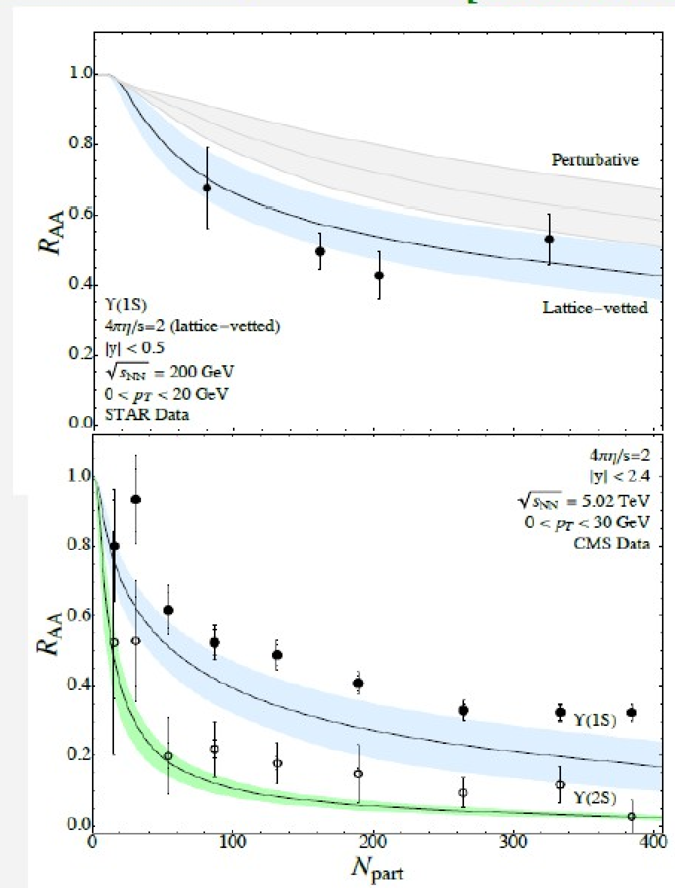
new analysis from Ralf Rapp

Lattice-based potentials

[TAMU ‘11,’17]

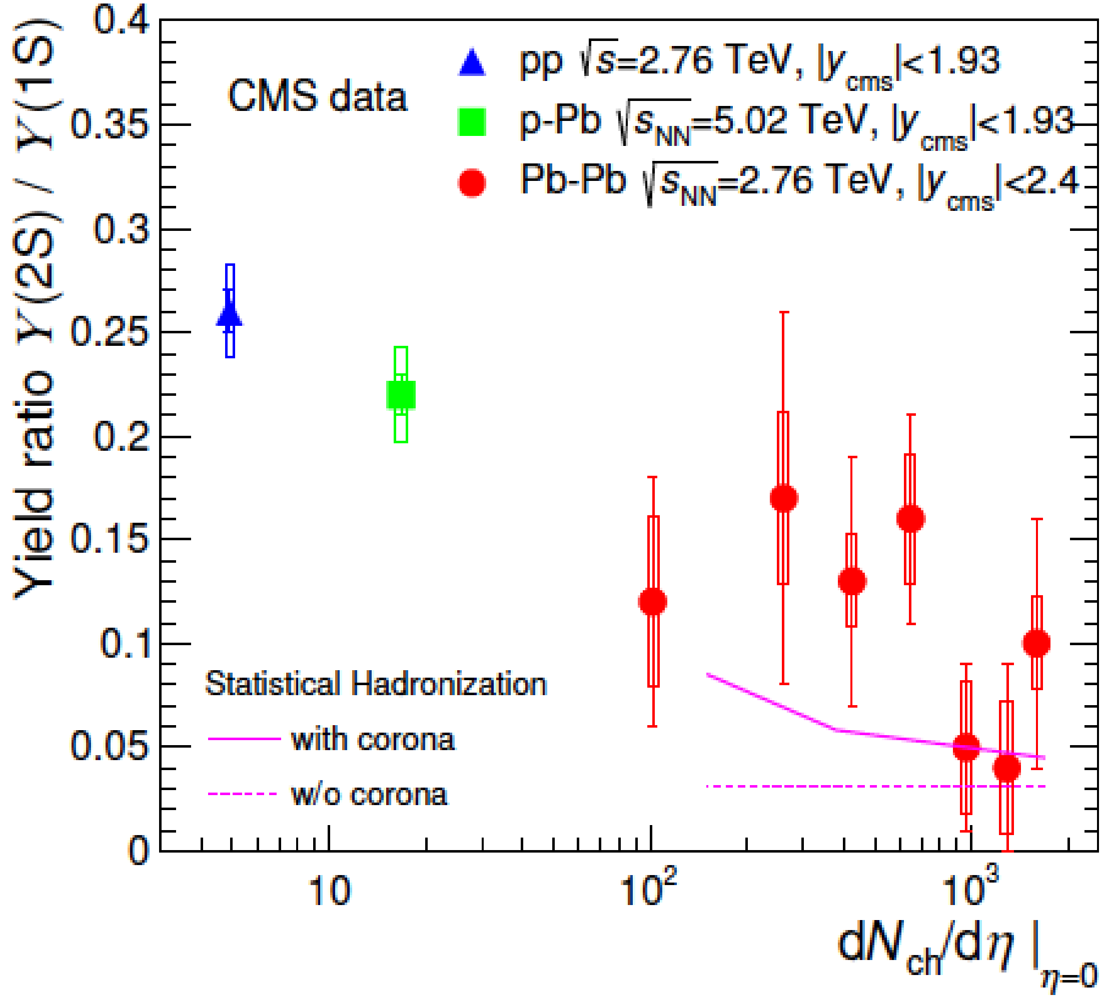


[Kent St ‘17]



- **Υ(1S)** suppression at **RHIC** → regeneration at **LHC**
- Regeneration dominant for **Υ(2S)** in central **PbPb** at **LHC**?

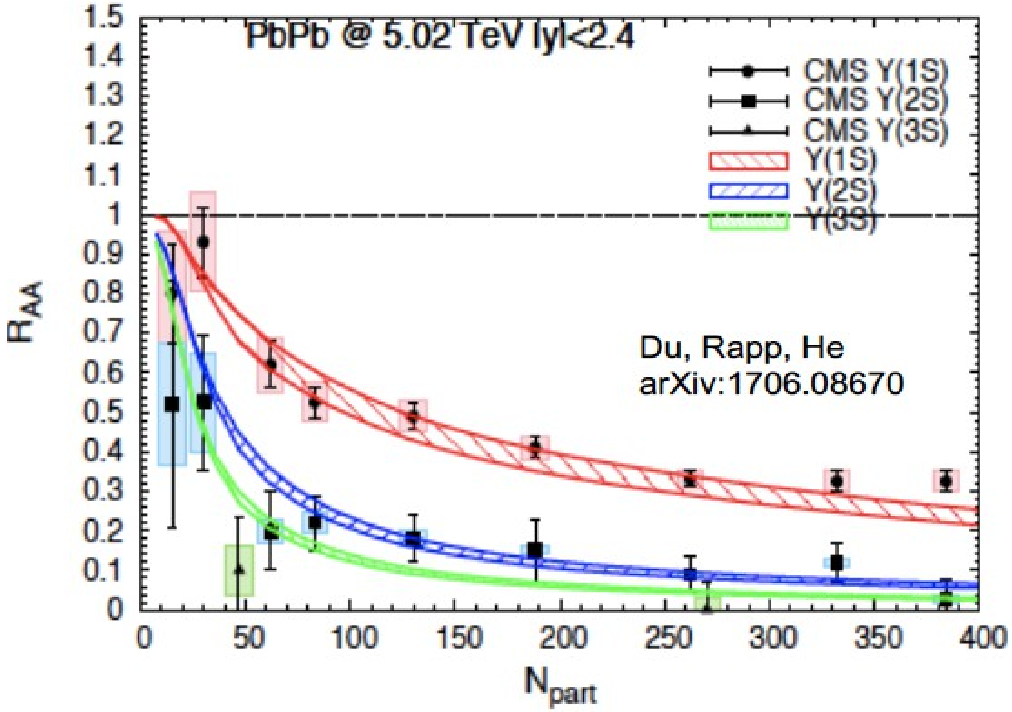
statistical hadronization model prediction



Andronic, pbm, Stachel, Redlich, arXiv:1710.09425

calculation assumes full suppression of all Y states
at T_pc and production at the phase boundary

CMS Υ data – Calderon de la Barca

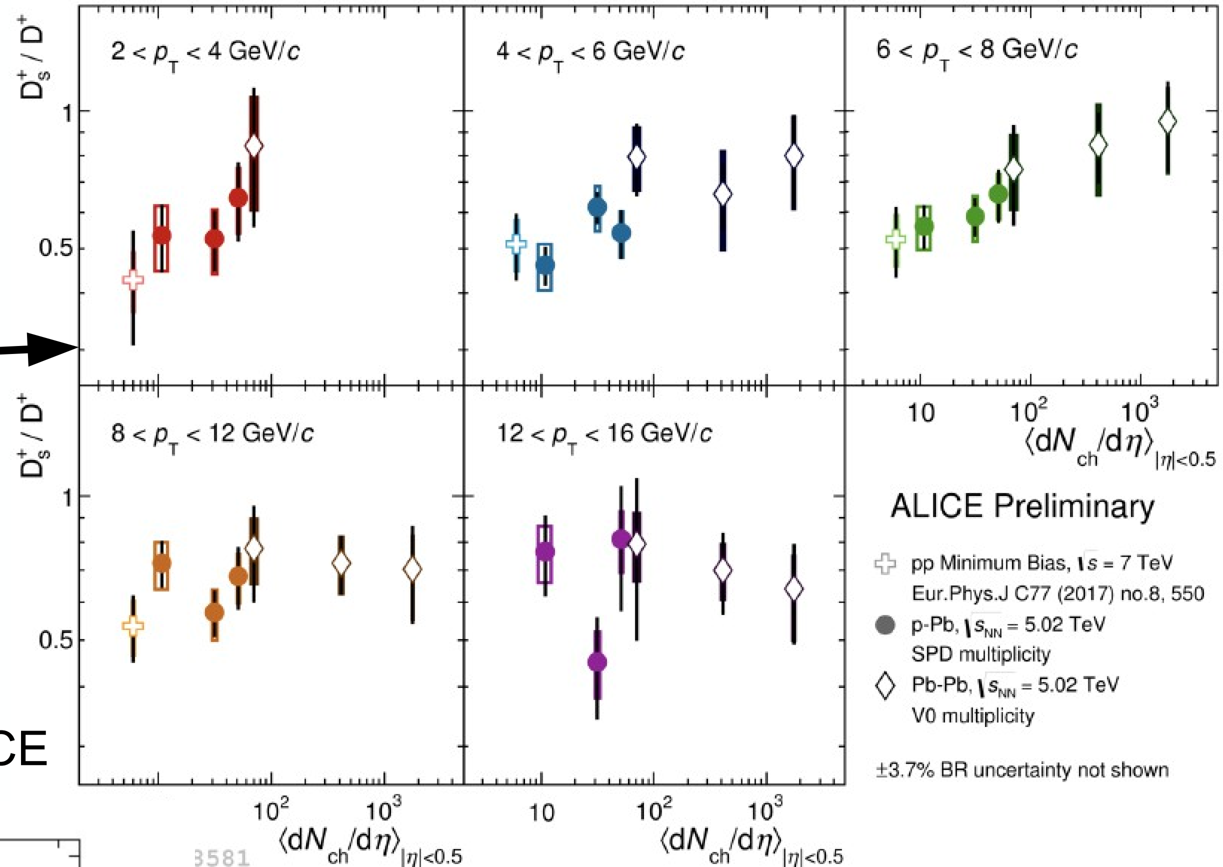


- Rapp et al.:
- T-Matrix Binding Scenario (TBS): Binding energy depends on Temperature.
- Strong Binding Scenario (SBS): Binding energy is constant
- Comparison to data prefers TBS
- Ground state is only slightly dissociated: feed-down
  - Regeneration contribution modest for 1S
- Excited states: primordial suppression is dramatic, R_{AA}~0
  - Finite R_{AA} : due to regeneration contribution

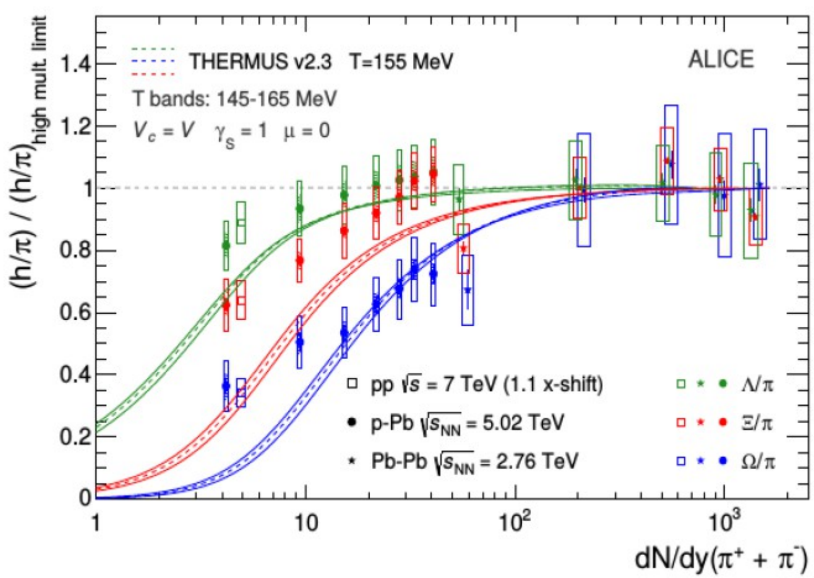
now open heavy flavor in AA collisions

ALICE – Grelli   multiplicity dependence of D_s/D^+

looks similar to ALICE strangeness/pi ratio



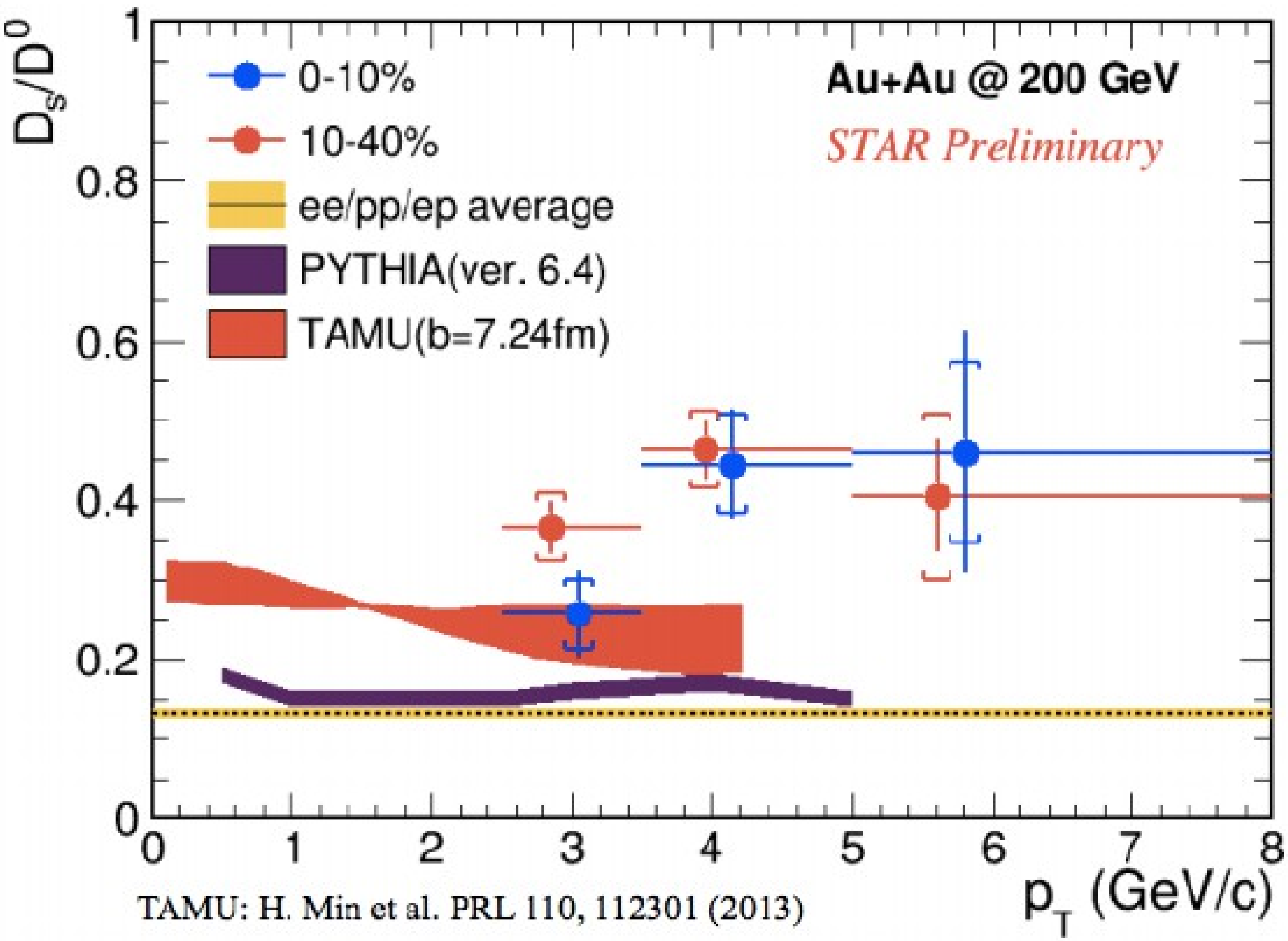
strangeness/pi ratio from ALICE



main features, but not details, are captured well – needs further study

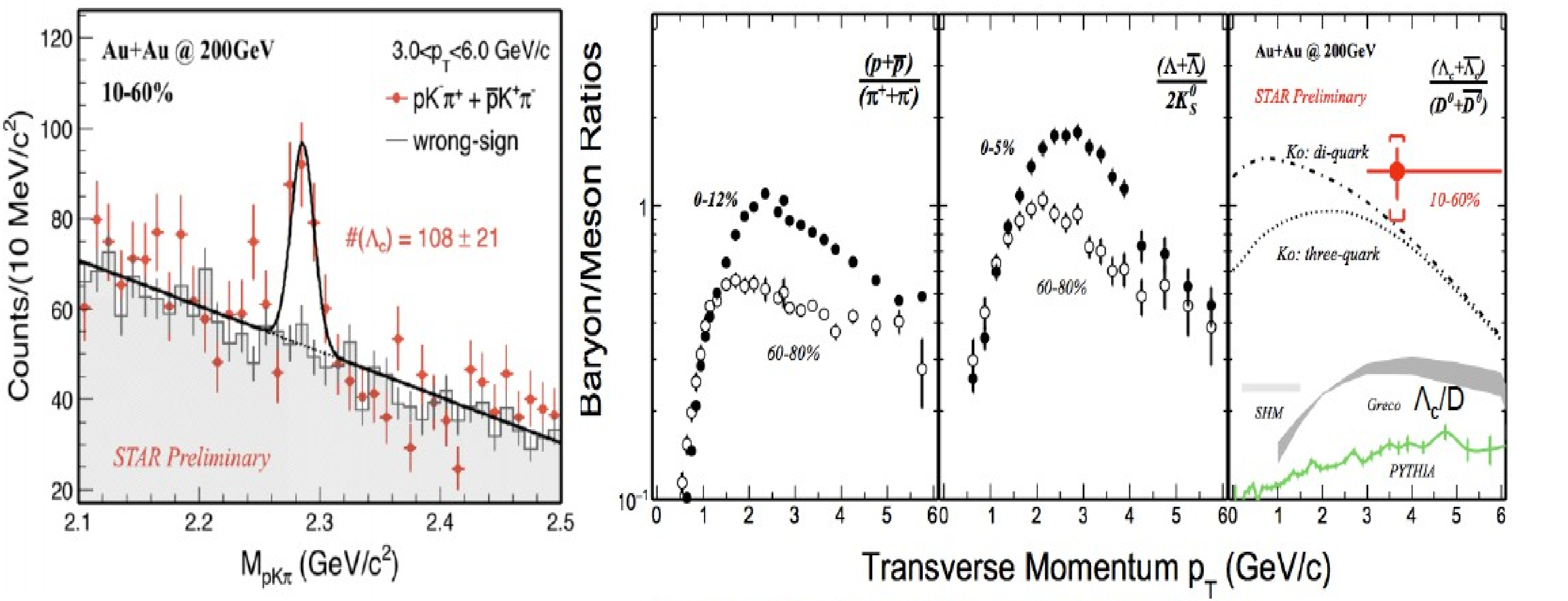
arXiv:1512.07227 ALICE

STAR results on D_s/D0



STAR results on Lambda_c in Au-Au collisions
Zhengyu Ye

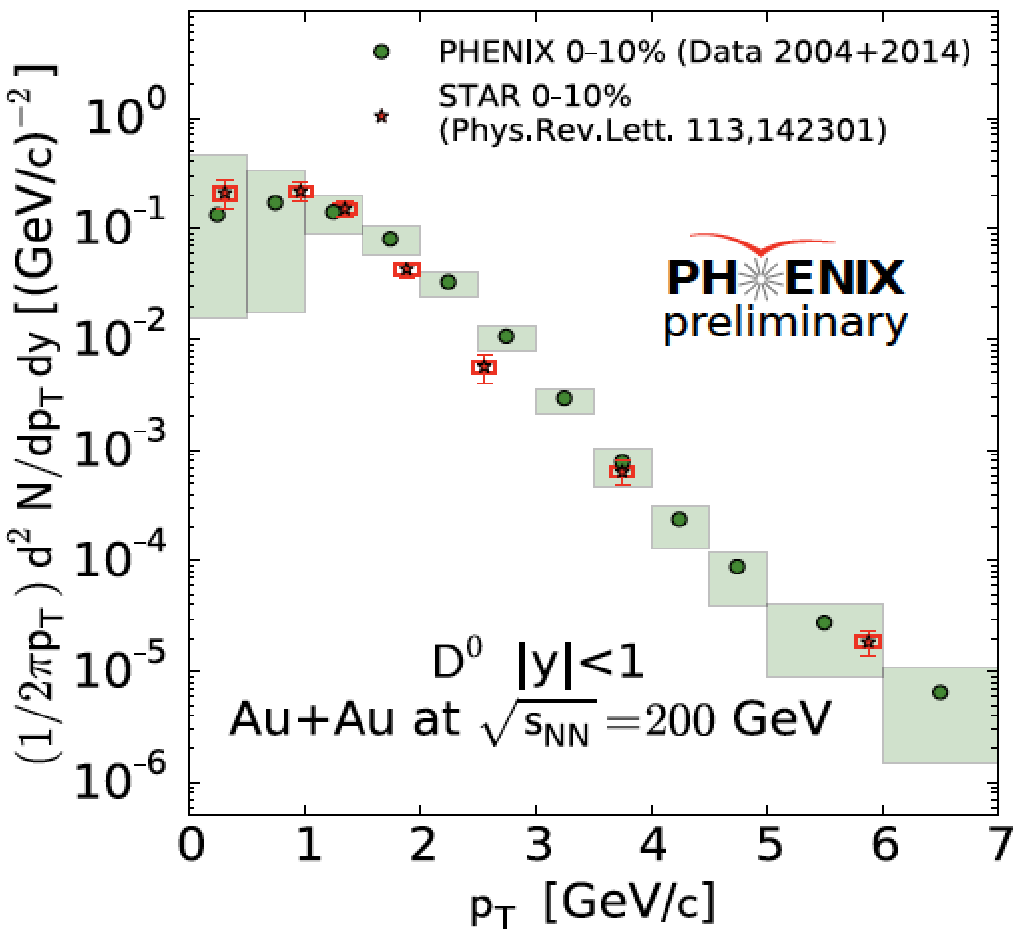
First measurement of charmed baryon in heavy-ion collisions



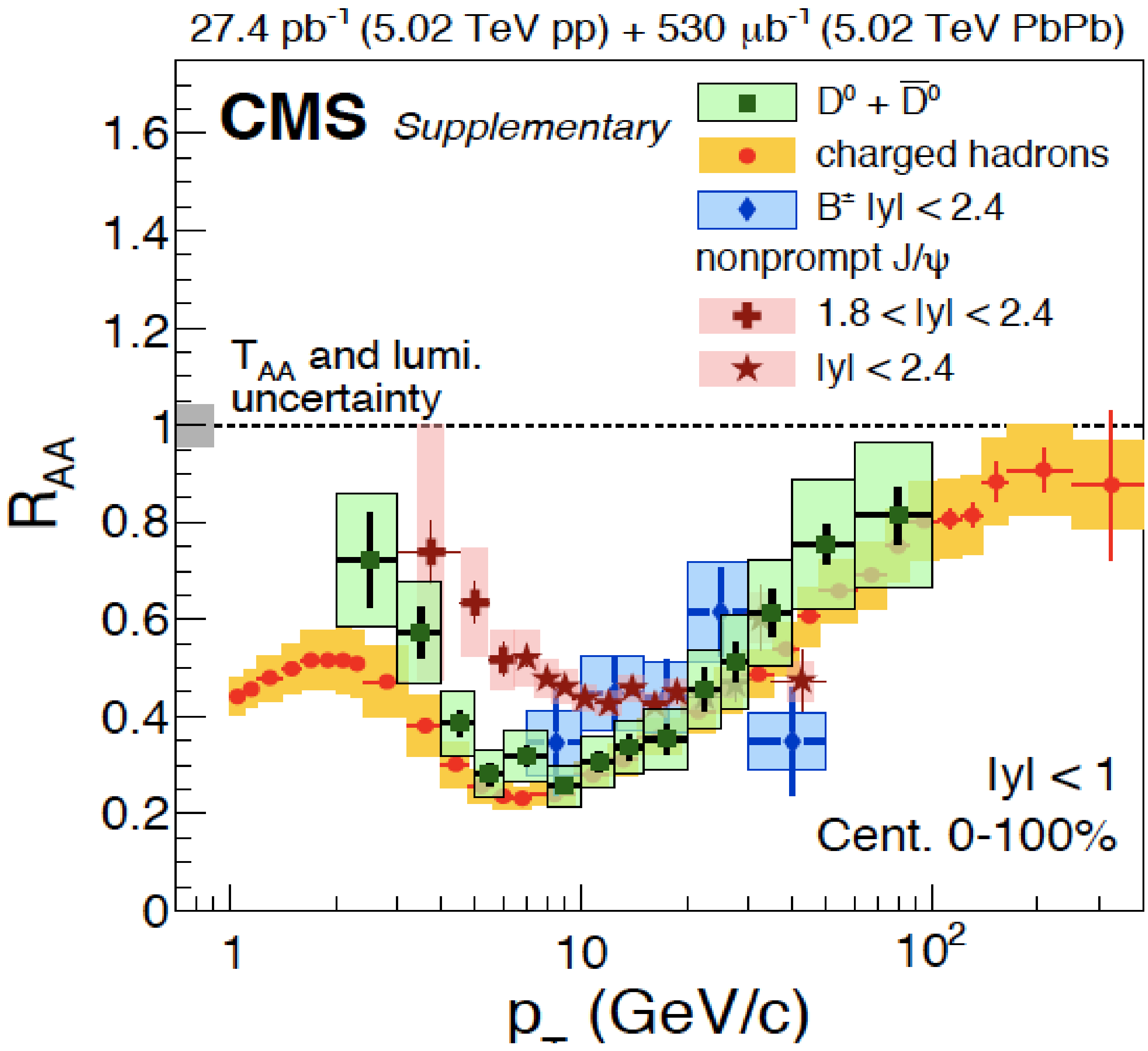
Ko: PRL 100 222301 (2008), PRC 79 (2009) 044905
Greco: PRD 90 054018 (2014)

beautiful, but need to move towards p_T=0

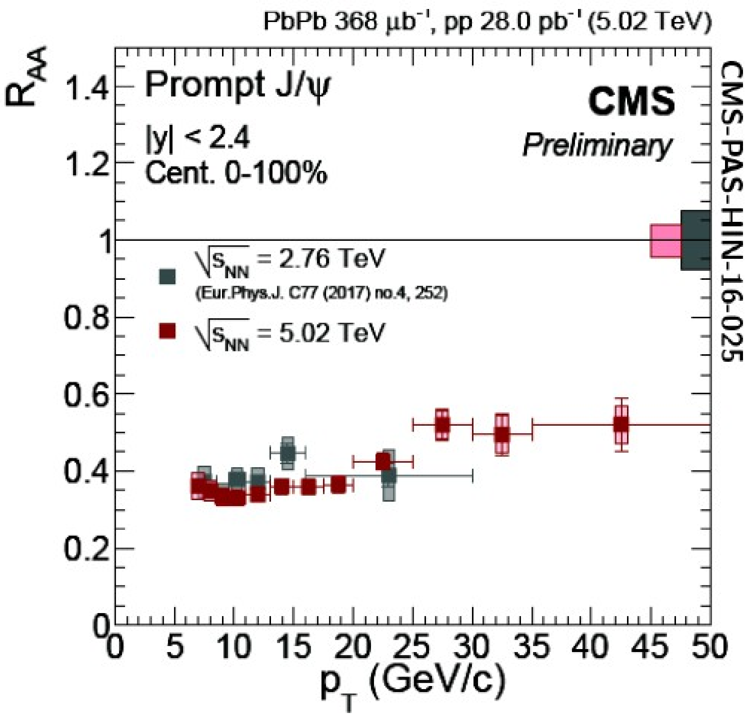
STAR and PHENIX D_0 measurements in Au-Au collisions

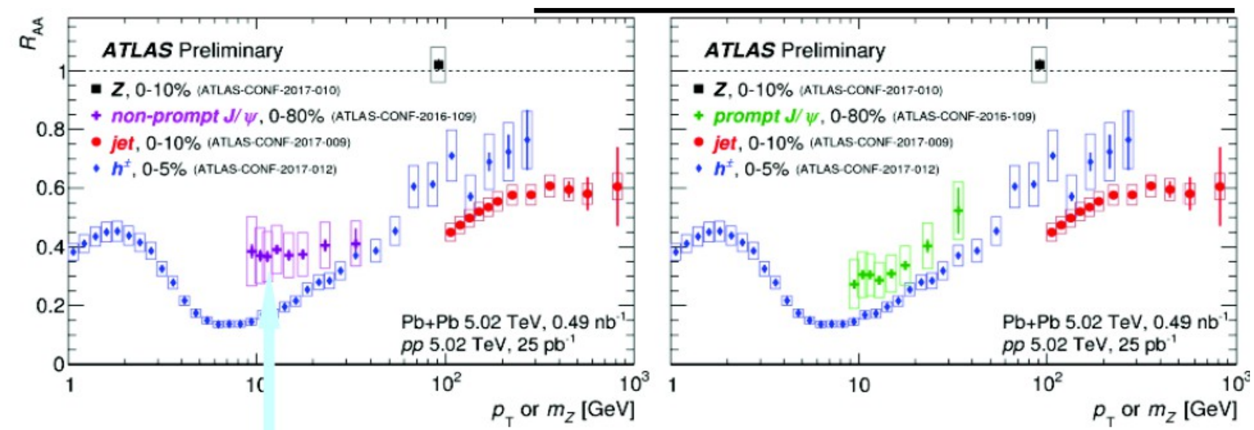


CMS – Innocenti: flavor dependence of energy loss

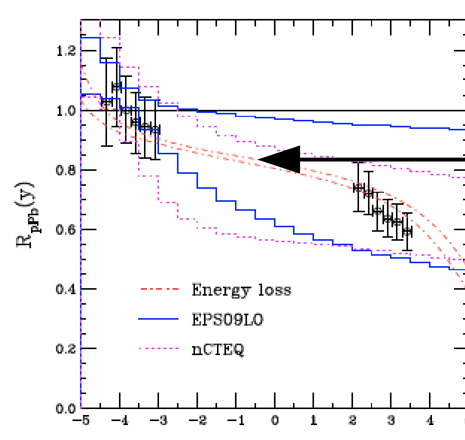


J/\psi production at high p_T (> 6 GeV) looks very much like energy loss and not like color screening





while J/psi from B exhibits lower energy loss at moderate p_t

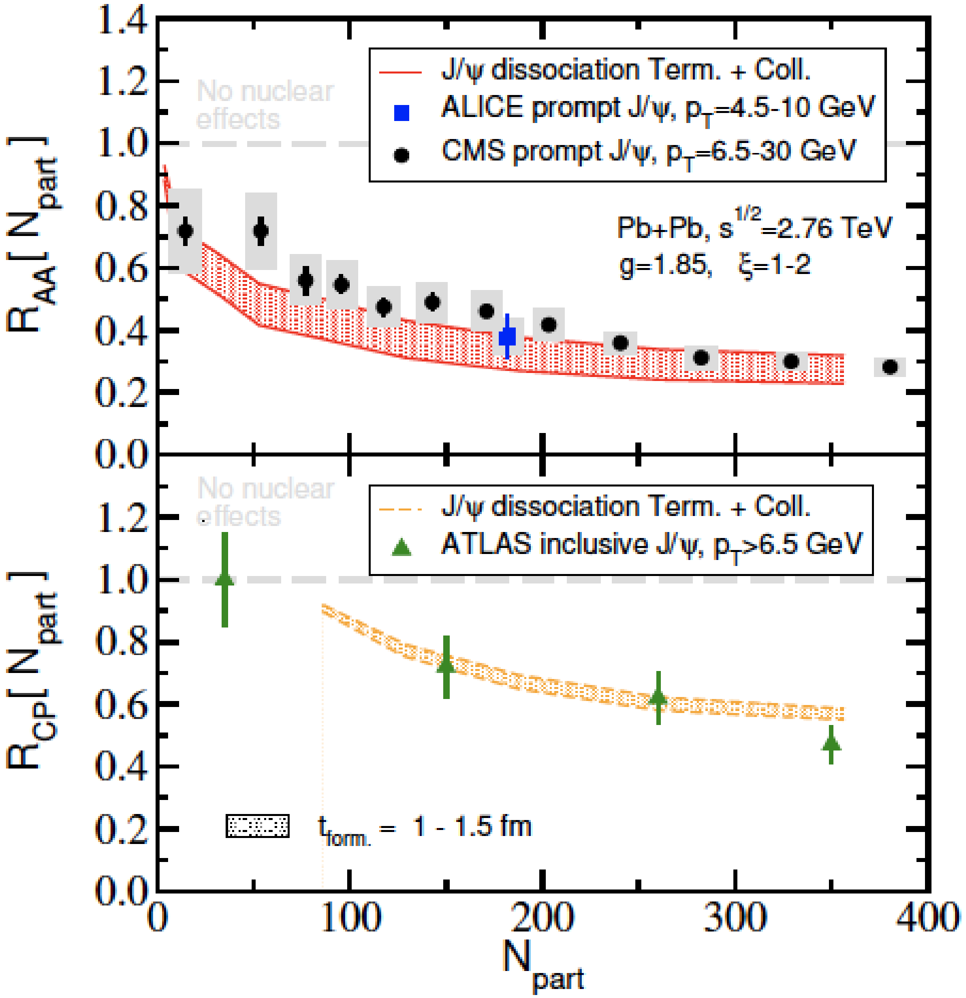


also energy loss in cold nuclear matter (R. Vogt)

Contrasting picture – Ivan Vitev high p_T J/psi as probe of the medium

would like to see explicit p_T dependence

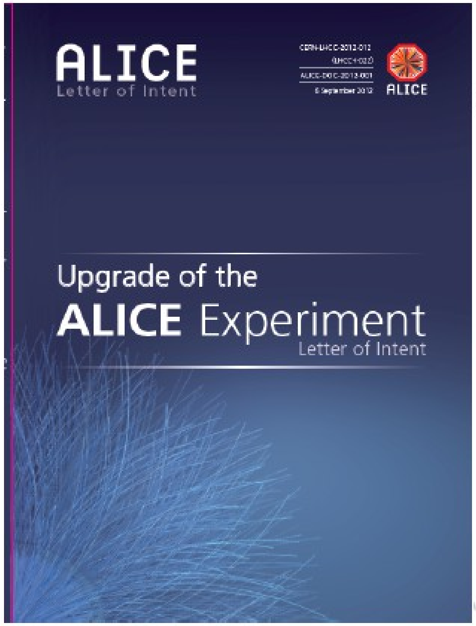
Perform full feed down

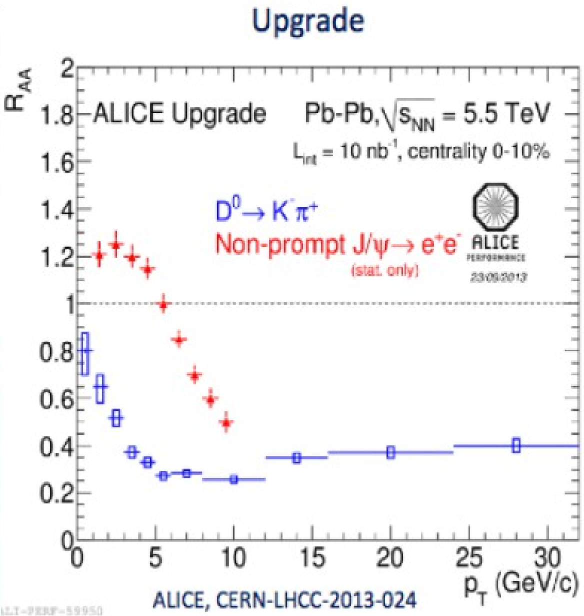


S. Aronson *et al.* (2017)

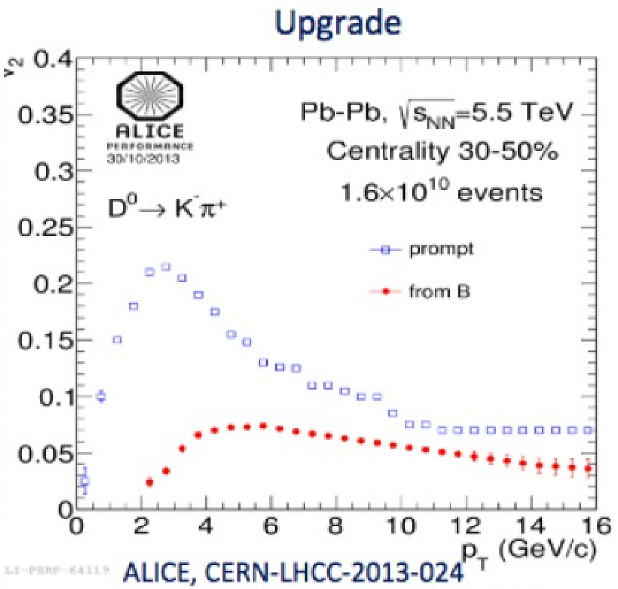
future with new ALICE ITS tracker

new high performance ITS plus rate increase (TPC upgrade)





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

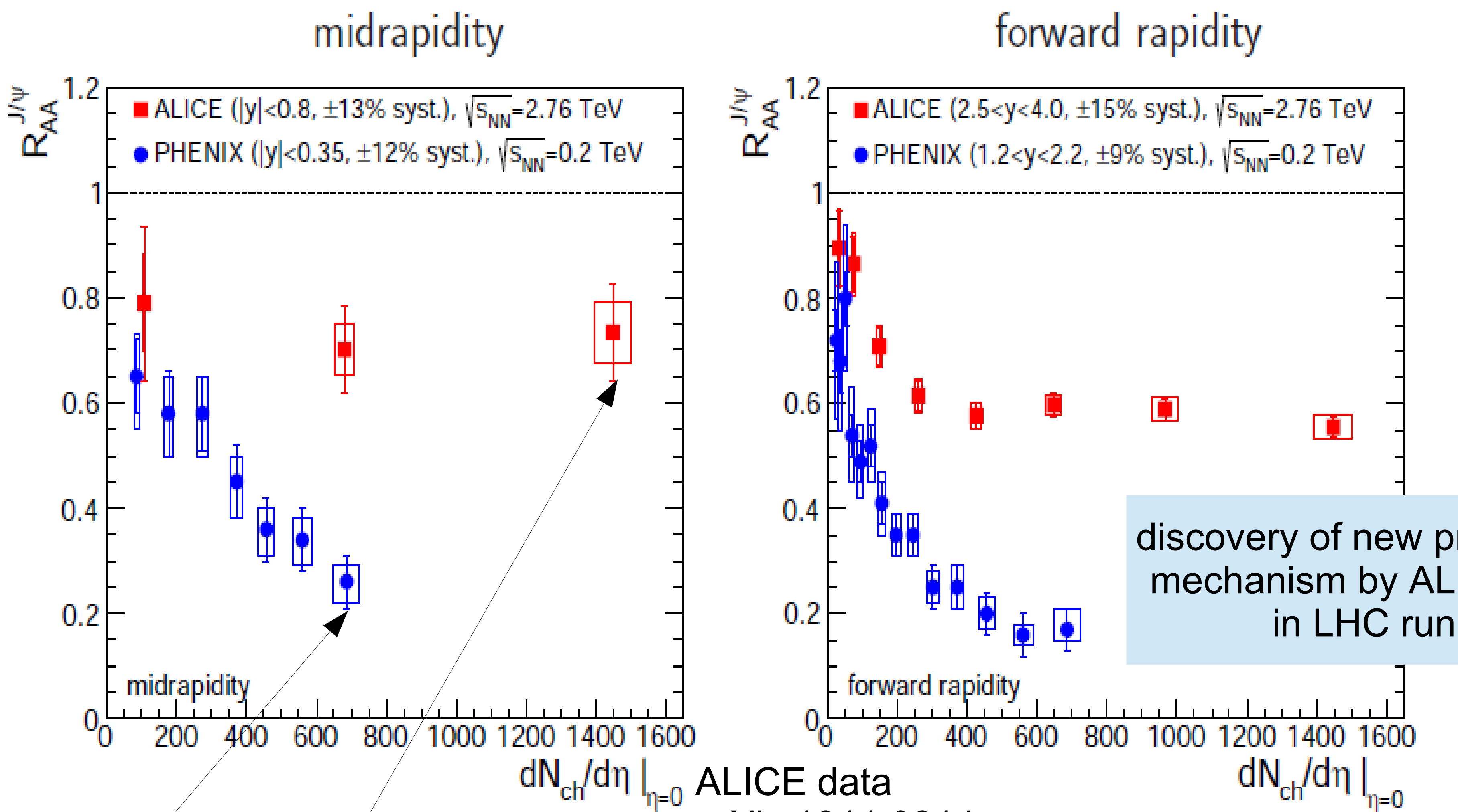


Input values from BAMPS model: C. Greiner et al. arXiv:1205.4945

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

additional slides

less suppression when increasing the energy density



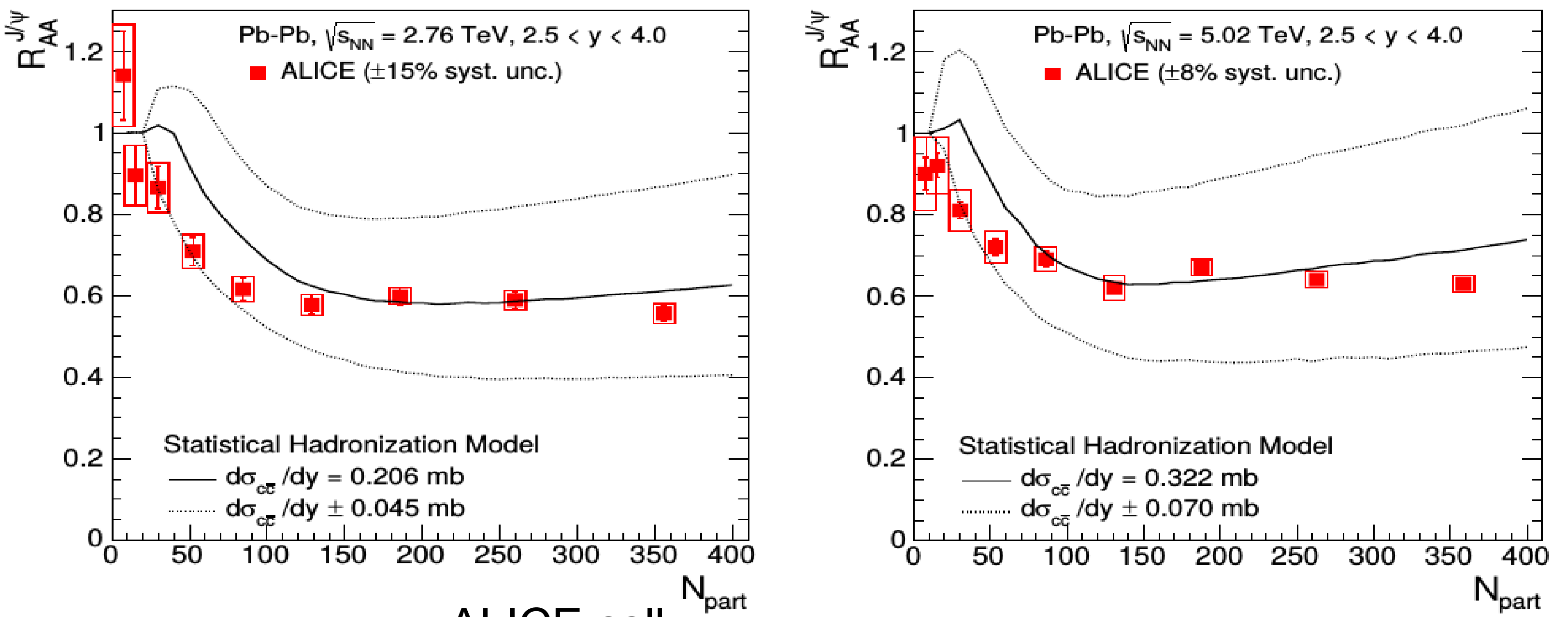
discovery of new production mechanism by ALICE coll. in LHC run1

ALICE data
arXiv:1311.0214
Phys.Lett. B734 (2014) 314-327

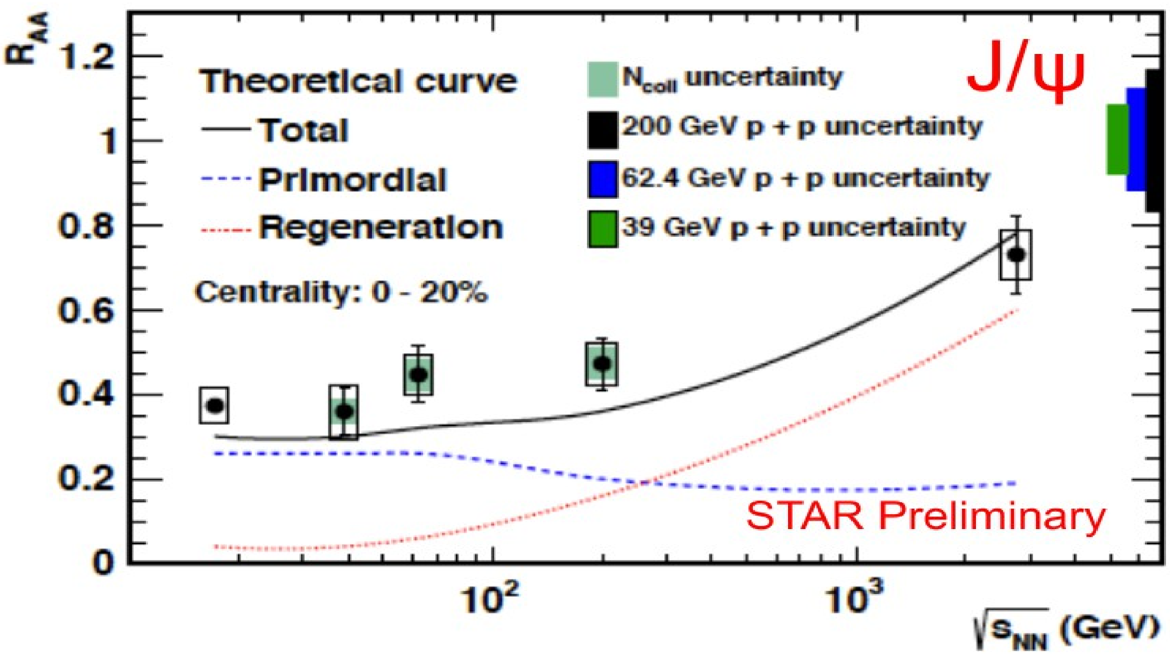
from here to here more than factor of 2 increase in energy density, but R_{AA} increases by more than a factor of 3

2007 prediction impressively confirmed by LHC data

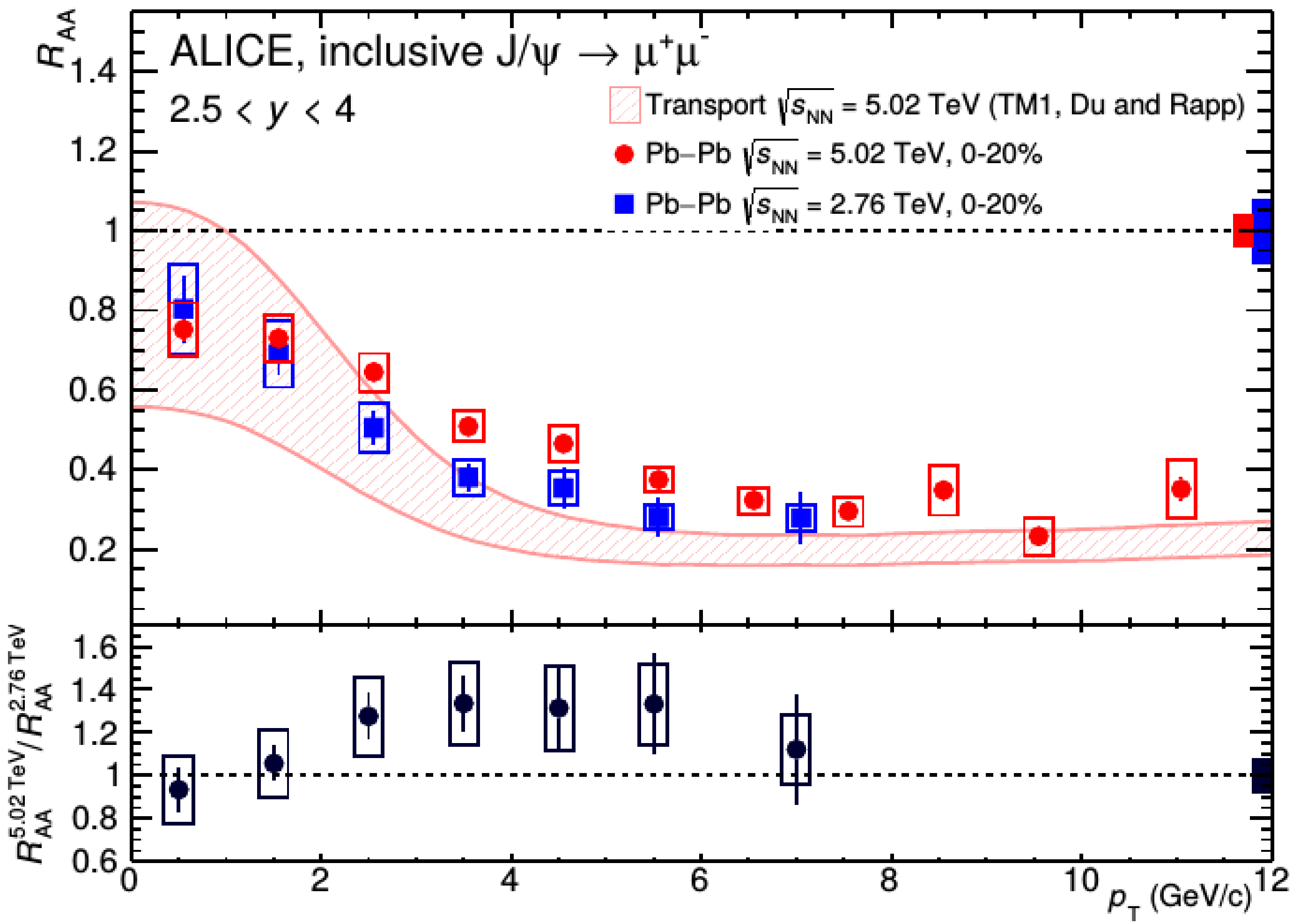
predictions from 2000/2007 beautifully confirmed by RHIC and LHC data



ALICE coll., arXiv:1606.08197

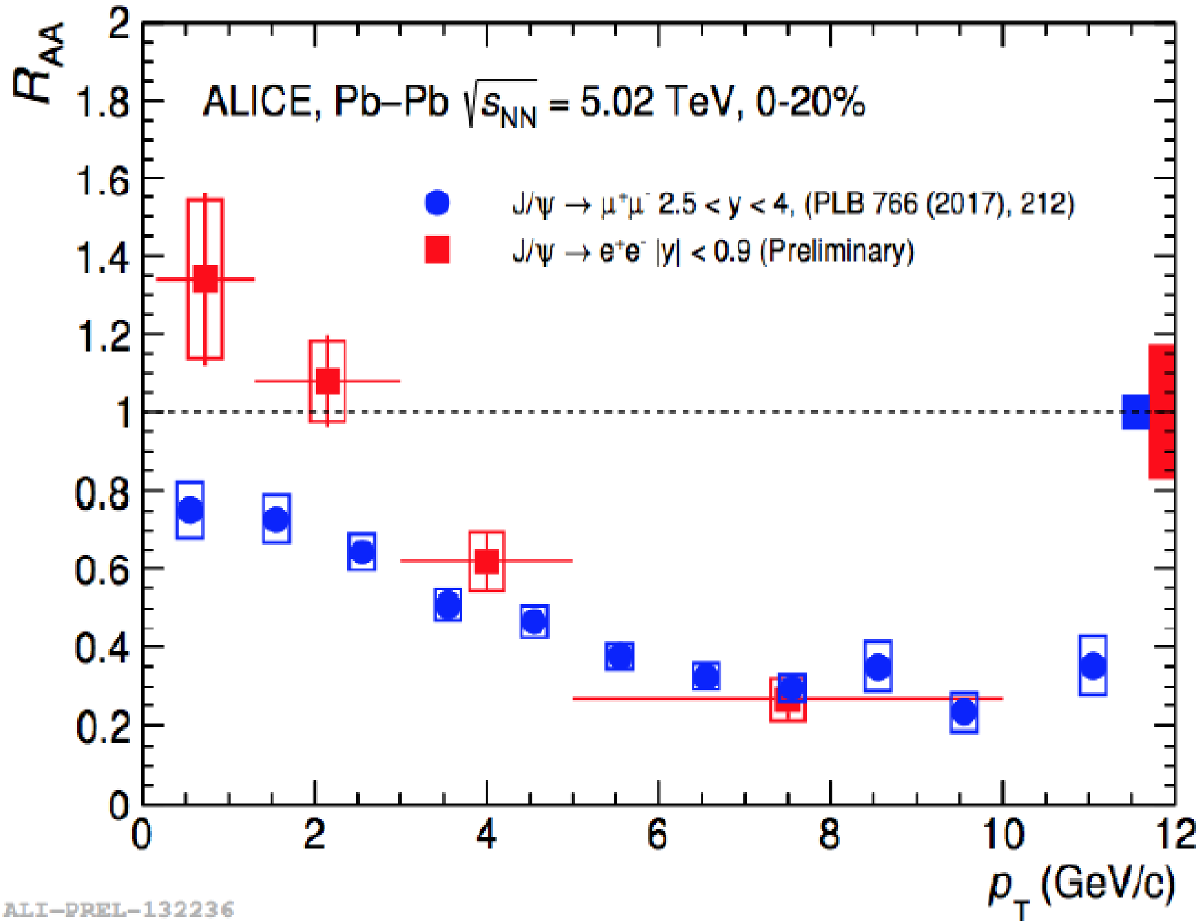


dependence on transverse momentum (1)
forward rapidity



ALICE coll., arXiv:1606.08197

dependence on transverse momentum (II)
mid-rapidity vs forward rapidity



indication of J/psi enhancement at low p_t near mid-rapidity