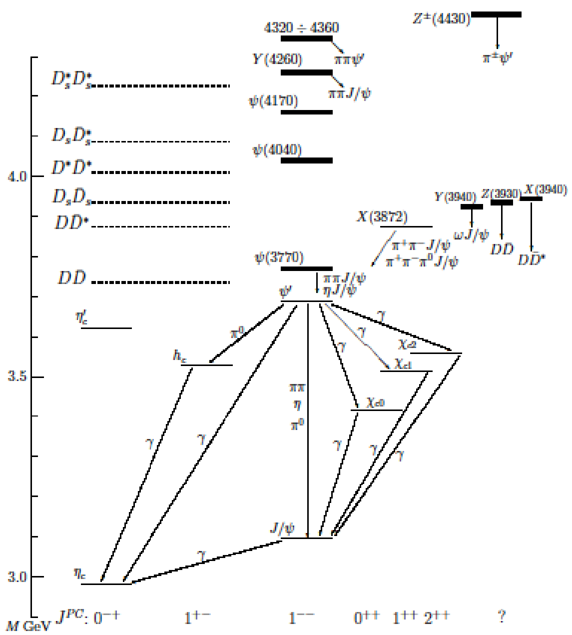
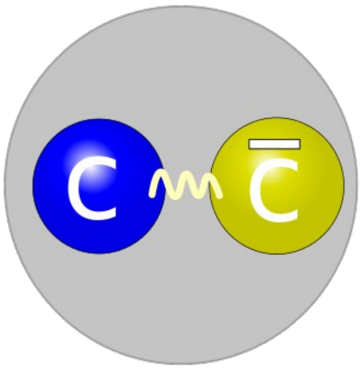
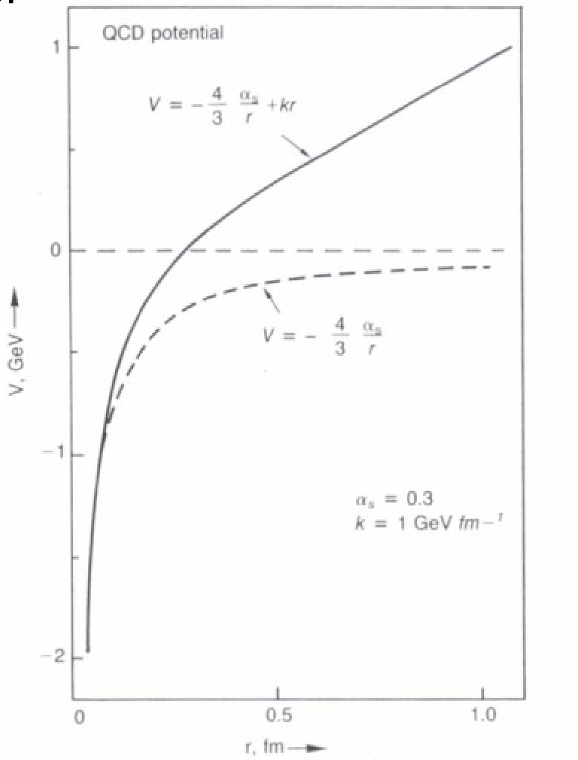
charmonia and deconfinement

charmonia are mesons made from a charm and anti-charm quark

discovered in 1974, Nobel prize in 1976 to sam Ting and Burton Richter







State (nL)	J^{PC}	m_Ψ [MeV]	Γ_{tot} [MeV]	$m_\Psi - 2m_D$ [MeV]
η_c (1S)	0^{-+}	2980±1	27±3	-750
J/ψ (1S)	1^{--}	3097	0.093±0.002	-633
χ_{c0} (1P)	0^{++}	3415	10.2±0.7	-315
χ_{c1} (1P)	1^{++}	3511	0.89±0.05	-219
h_c (1P)	1^{+-}	3526	<1	-204
χ_{c2} (1P)	2^{++}	3556	2.03±0.12	-174
η_c' (2S)	0^{-+}	3637±4	14±7	-92
ψ' (2S)	1^{--}	3686	0.32±0.01	-44
ψ'' (3S)	1^{--}	3773±3	27.3±1	+43

in a deconfined medium (QGP), the confining part of the potential should disappear, the potential is screened

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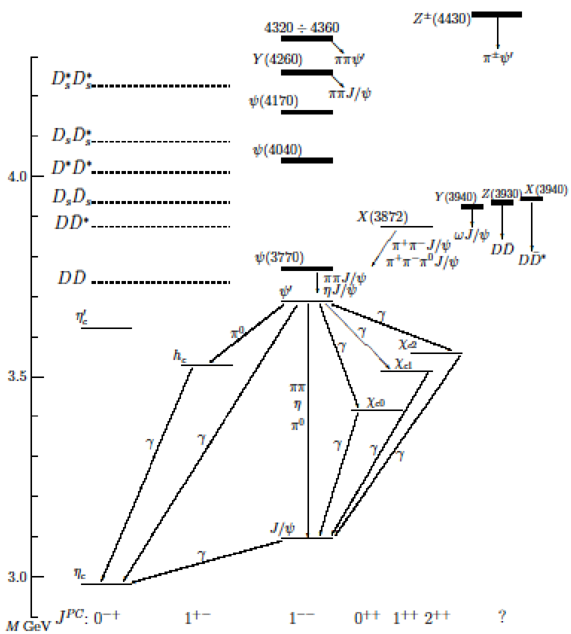

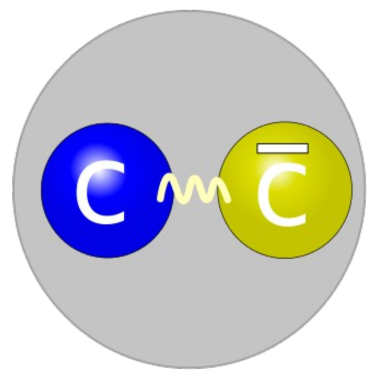

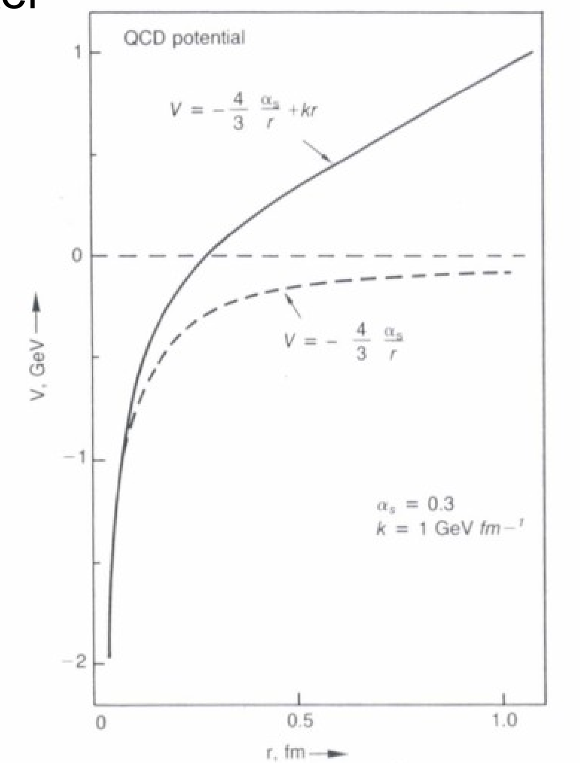

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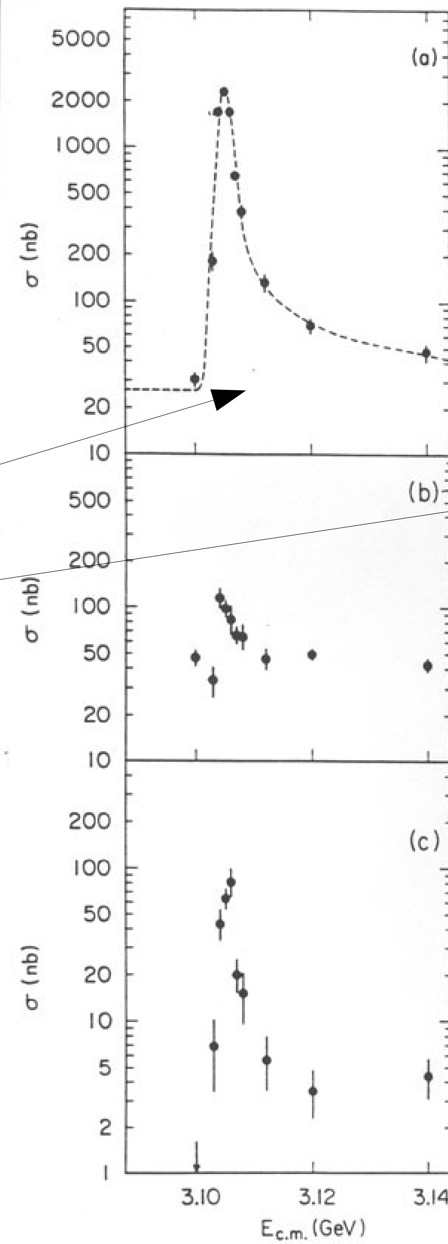
in a deconfined medium (QGP), the confining part of the potential should disappear, the potential is screened back-to-back discovery papers in the 2 Dec. 1974 issue of PRL

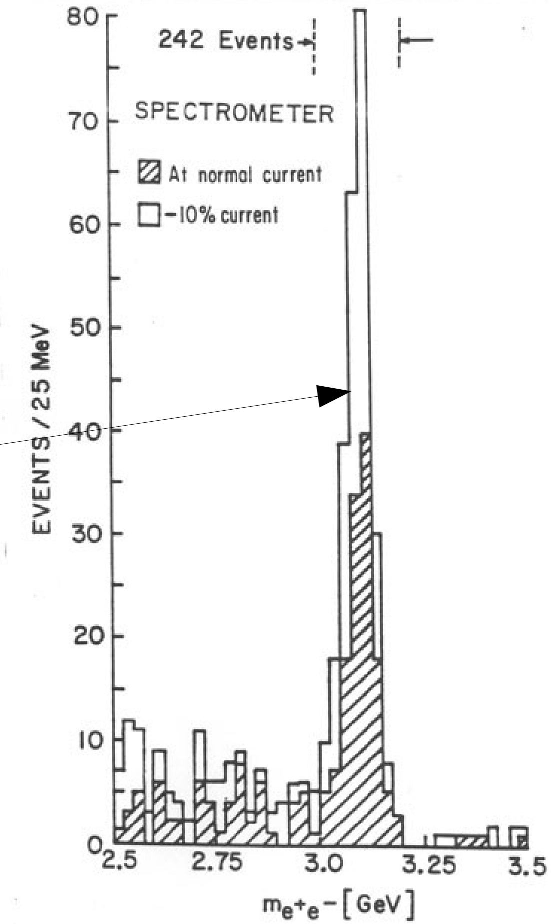
Burton Richter et al., SLAC

Sam Ting et al., BNL

soon, a whole spectrum of states was discovered

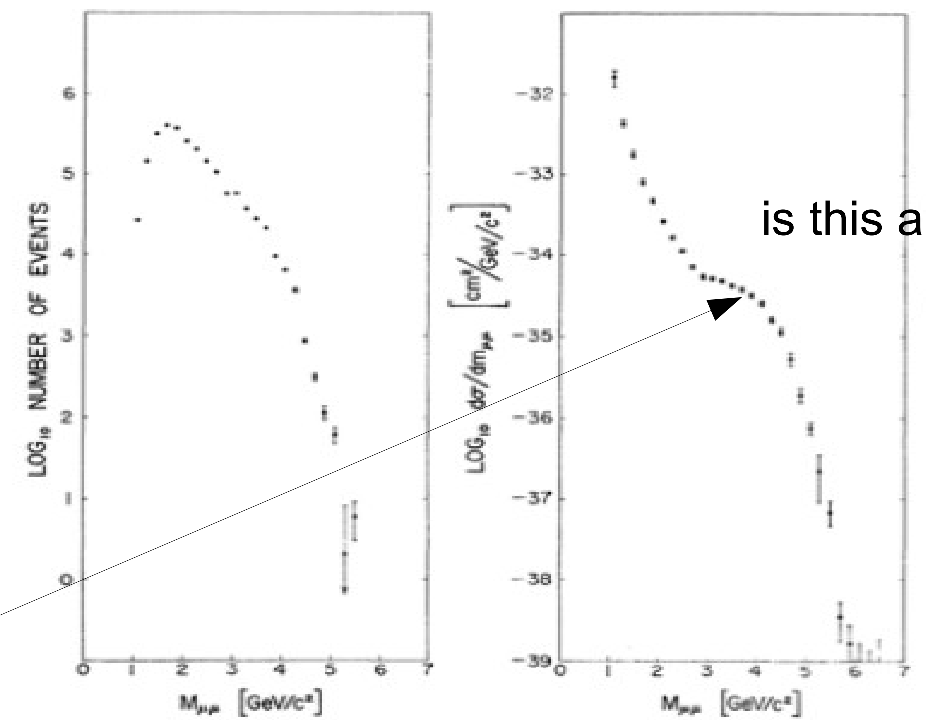


ꟳIG. 1. Cross section versus energy for (a) multi-
ıdron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$,
π^-, and K^+K^- final states. The curve in (a) is the ex-
ːcted shape of a δ-function resonance folded with the
ussian energy spread of the beams and including
diative processes. The cross sections shown in (b)



ꟳIG. 2. Mass spectrum showing the existence of J.
sults from two spectrometer settings are plotted
owing that the peak is independent of spectrometer
rrents. The run at reduced current was taken two
nths later than the normal run.

… was nearly discovered in 1970 by J. Christensen and L. Lederman



is this a peak?

p + U → μ+μ- + X

Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

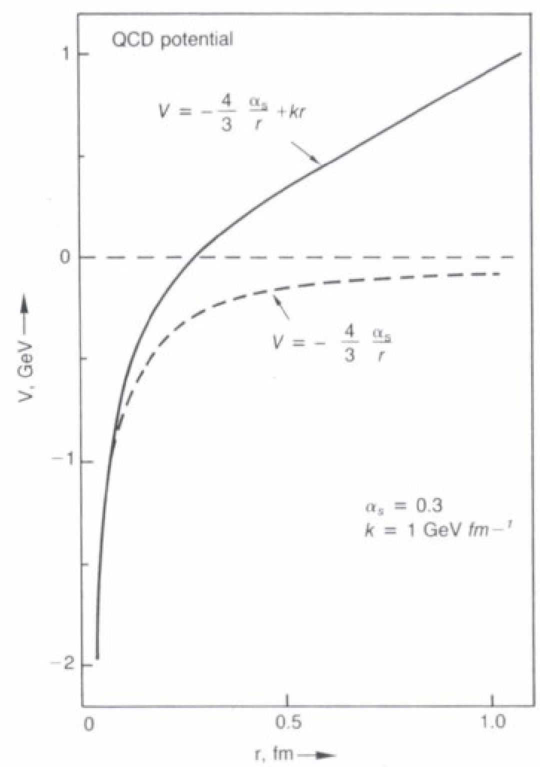
E. Zavattini
CERN Laboratory, Geneva, Switzerland

(Received 8 September 1970)

Muon pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c^2 have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32}/m_{\mu\mu}^5$ cm^2 (GeV/c)$^{-2}$ and exhibits no resonant structure. The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

J/psi melting and (re-)generation in the QGP

inside a QGP, charmonia should loose their binding because the confining part of the potential disappears, so J/psi mesons should be suppressed (Matsui and Satz, 1986). But the charm quarks in the QGP can combine at the QCD phase transition to form J/psi, a unique signal of deconfinement (Braun-Munzinger and Stachel, 2000). An alternative option was soon afterwards put forward (Thews, Schroeder, Rafelski, 2001). For a modern view including results from the LHC, see Nature 2018 (Andronic, Braun-Munzinger, Redlich, Stachel).



Phys.Lett.B 178 (1986) 416 Matsui and Satz

Phys.Lett.B 490 (2000) 196 Braun-Munzinger and Stachel

Phys.Rev.C 63 (2001) 054905   Thews, Schroeder and Rafelski

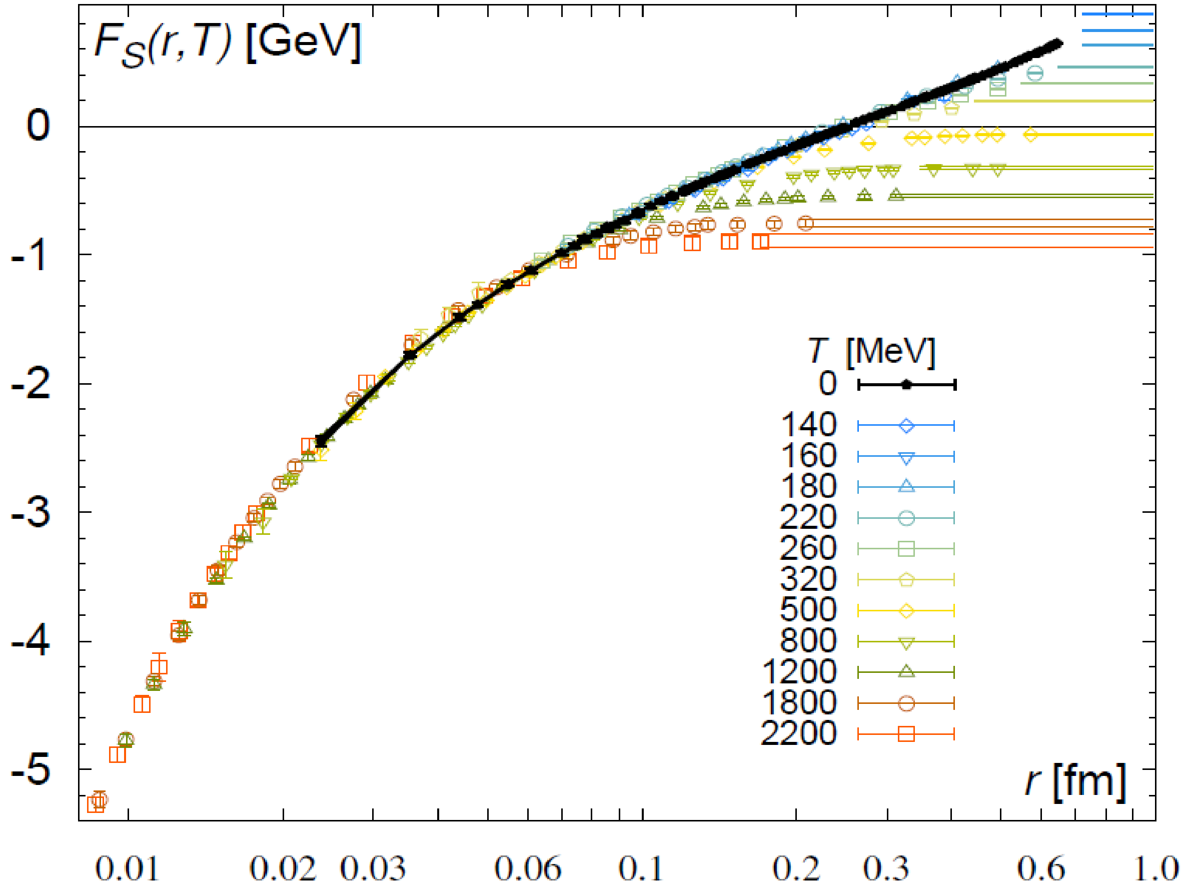
Nature 561 (2018) 7723, 321-330 Andronic, Braun-Munzinger, Redlich, Stachel

the color singlet free energy from Lattice determines the charm-anticharm binding potential

after a decade of debate, now some agreement how to extract effective heavy quark potential, starting from color singlet free energy
general consensus: potential has real and imaginary part

A. Rothkopf,
Quarkonium production and suppression: Theory,
[arXiv:2002.04938 [hep-ph]].

arXiv:1804.10600



… for T > 200 MeV the potential exhibits 'screening'

now experimental data for:

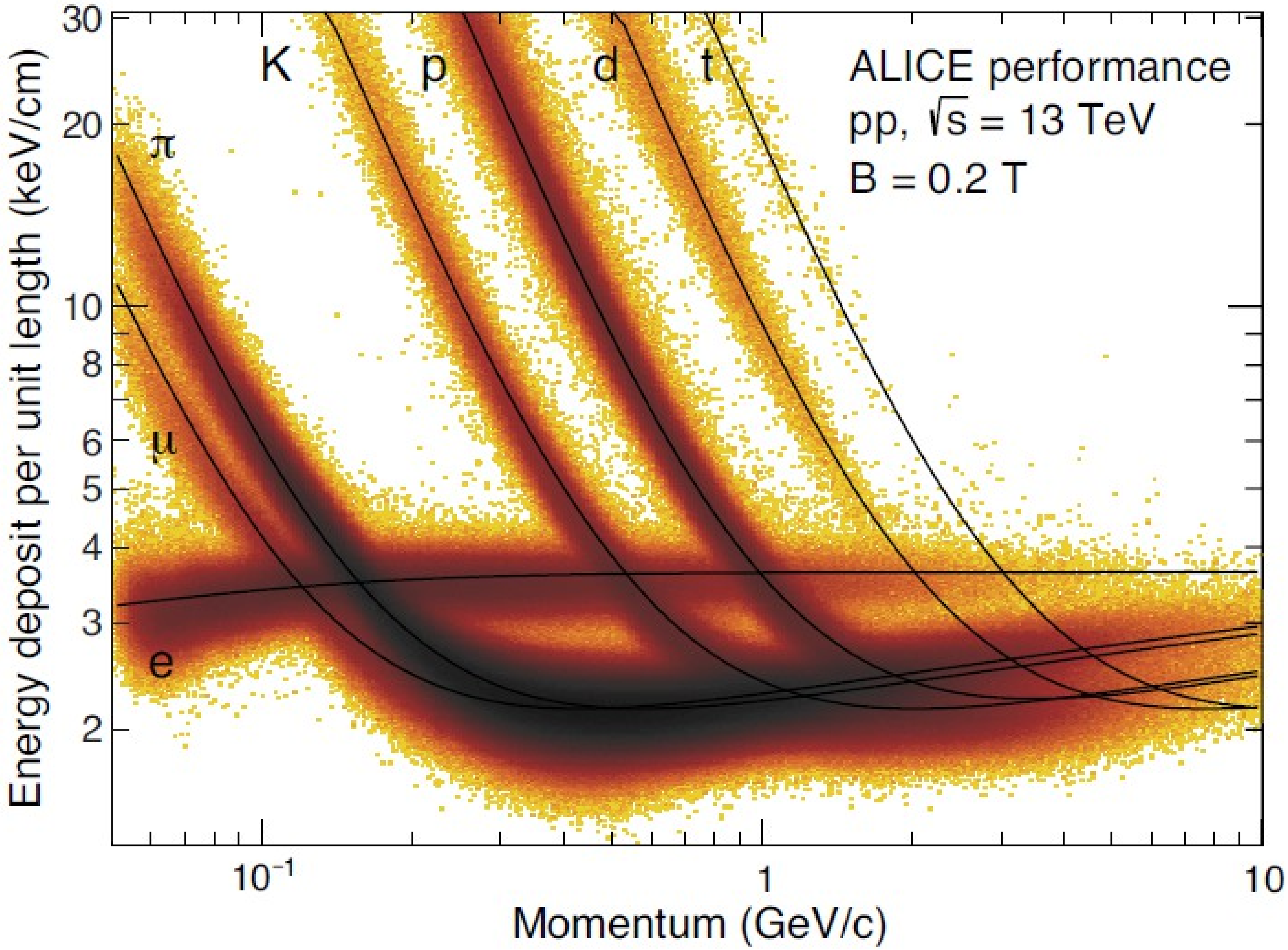
open charm production in pp and pPb collisions

charmonium production in pp, pPb, and Pb-Pb collisions

for both the measurement of open charm and charmonium production we need to separate experimentally all produced hadrons and electrons, determine their production vertex by using the ALICE ITS system, and determine the particles momenta with precision by measureing the tracks of charged particles in the ITS, the TPC, and the TRD detector

particle identification with the ALICE TPC

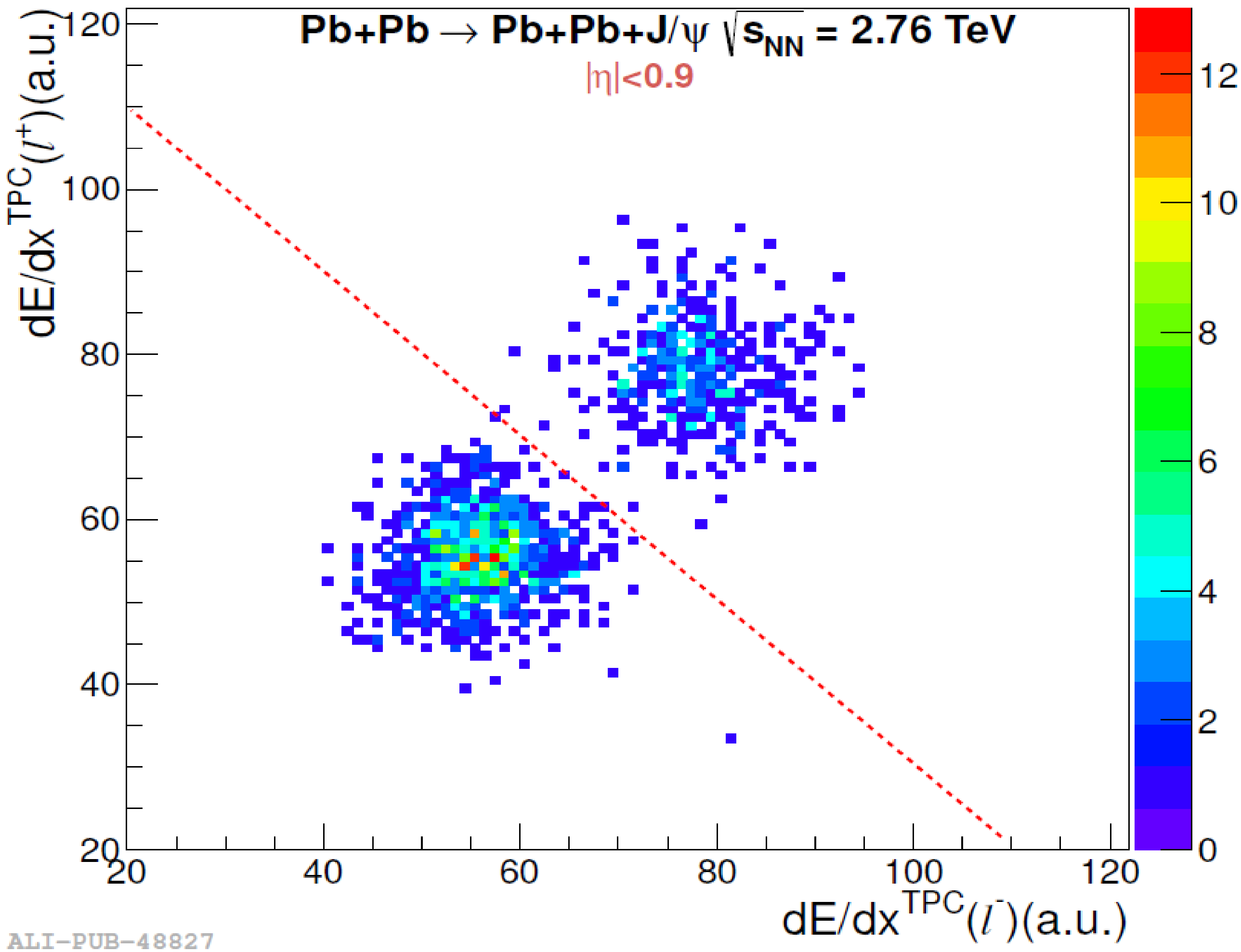
from 50 MeV to 50 GeV



now PDG standard

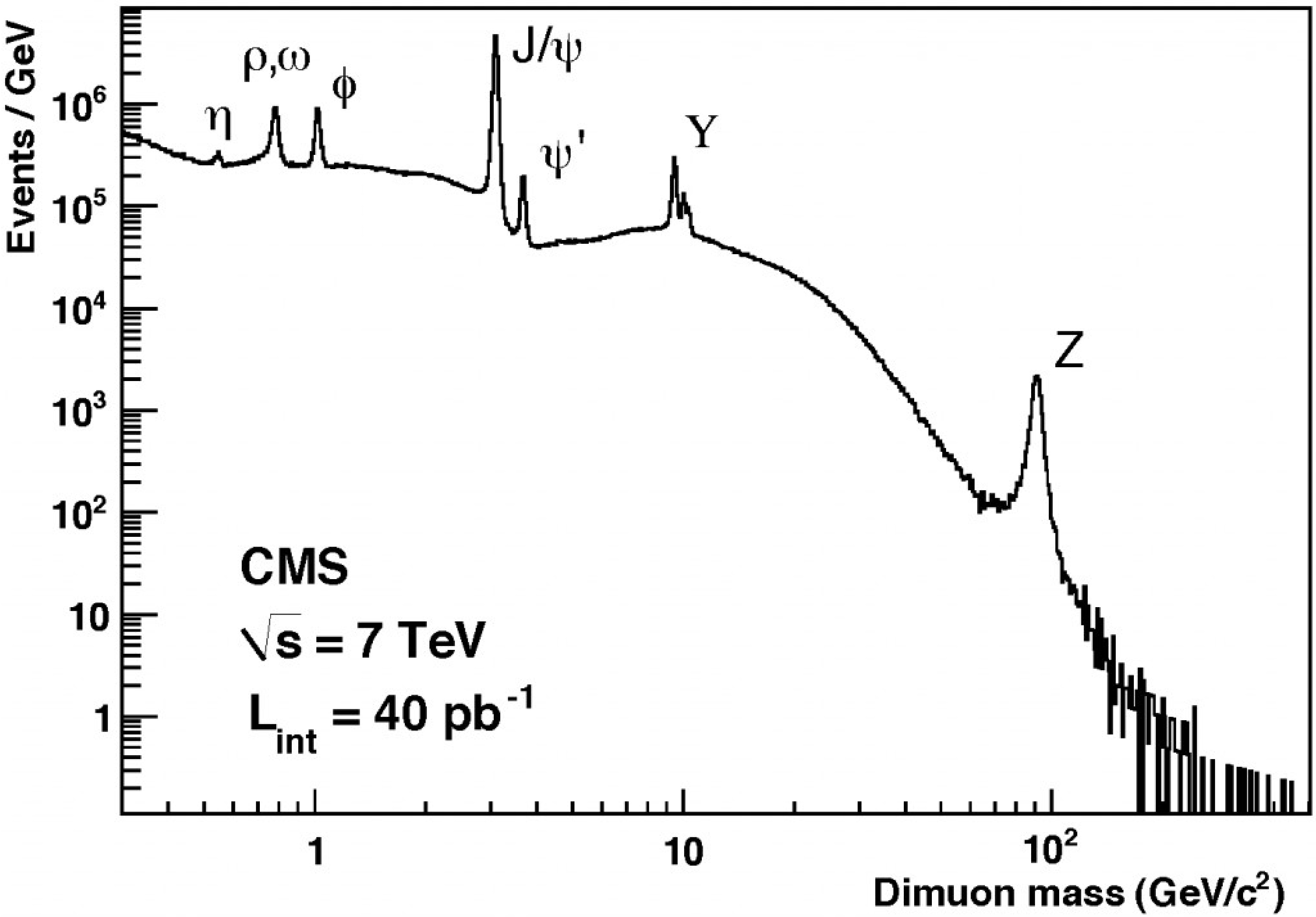
M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001, Fig. 34.15

electron-muon separation in the ALICE TPC

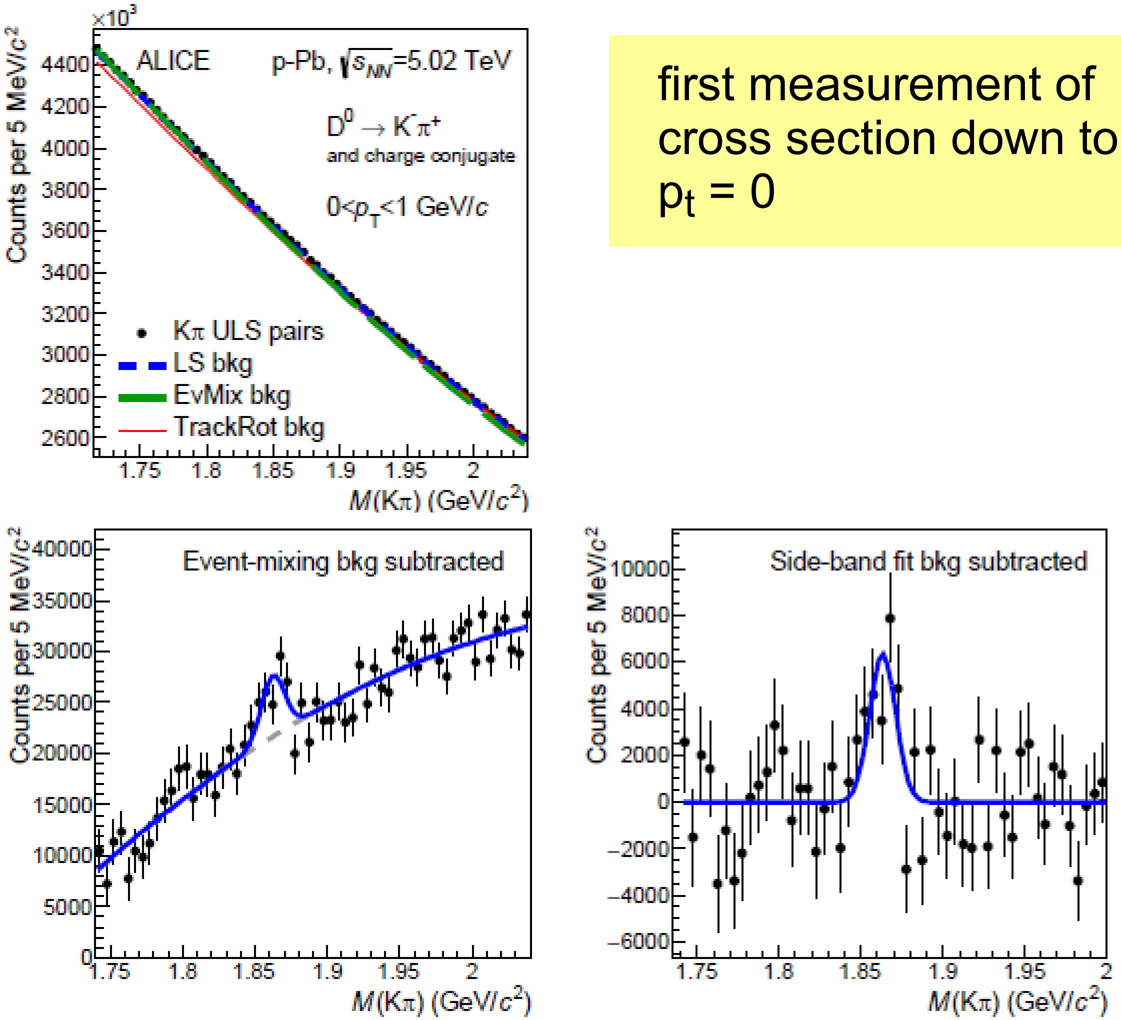


dE/dx of the positive lepton as a function of the negative one, as measured in the TPC for J/ψ candidates

muons and electrons are clearly separated, with the latter showing an higher dE/dx the modern (CMS at LHC) era, dimuon mass spectrum at LHC energy

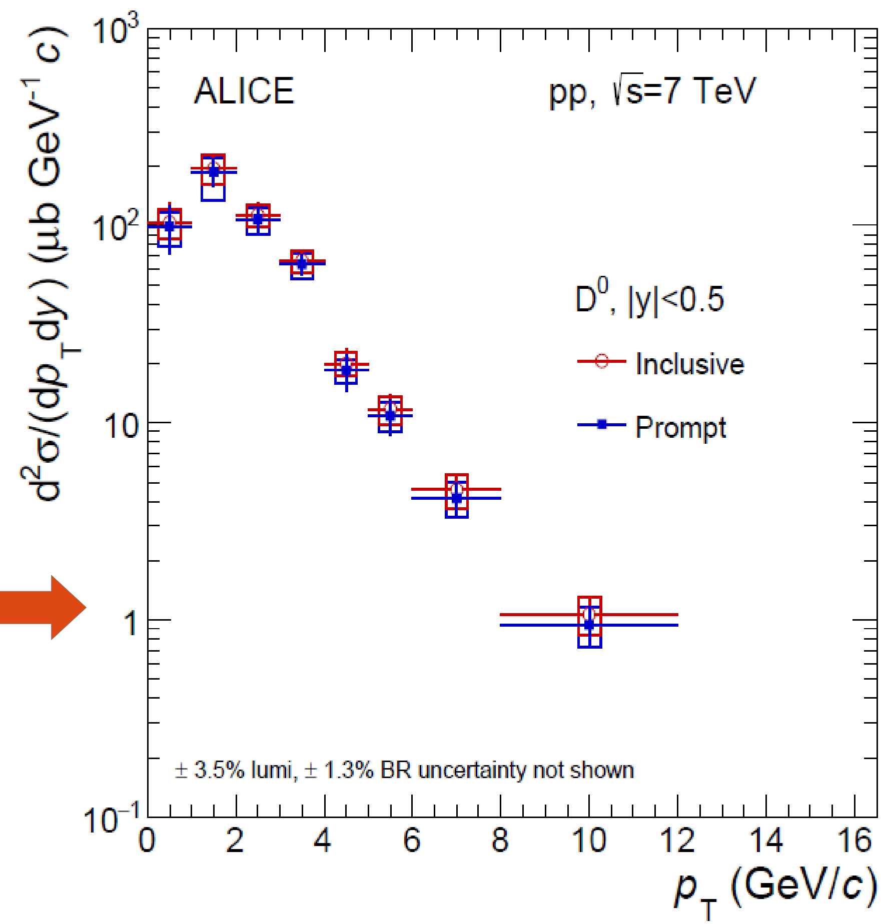


measuring quarkonia in pp collisions at the LHC easurements of charm production cross section, a crucial input to understand charmonium production

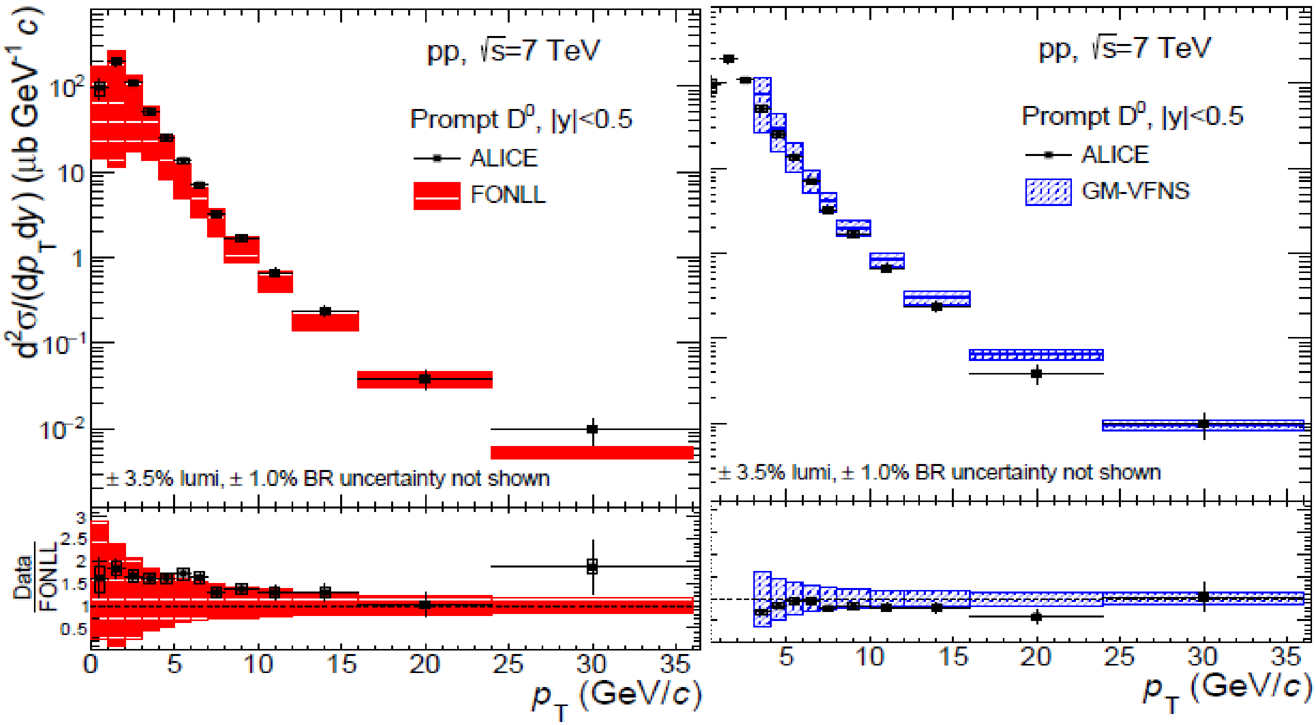


first measurement of cross section down to $p_t = 0$

PRC94(2016) 054908 arXiv: 1605.07569



very hard struggle to deal with (irreducible) combinatorial background, successful



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

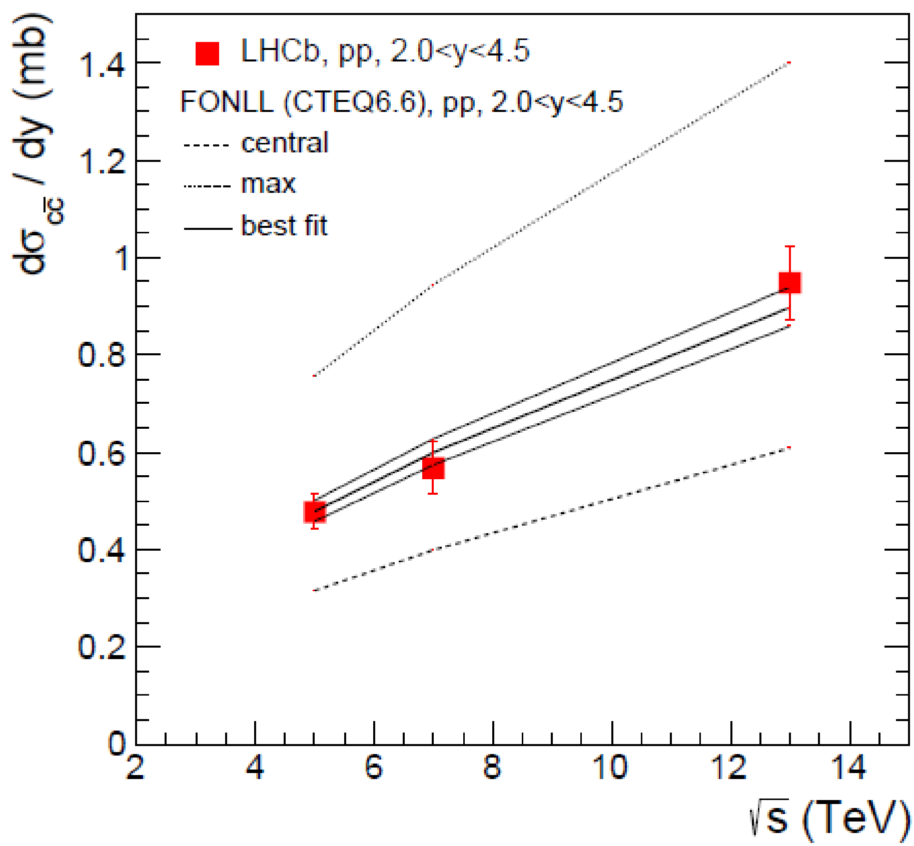
data are compared to QCD perturbation theory
good agreement

mid-y cross sections:

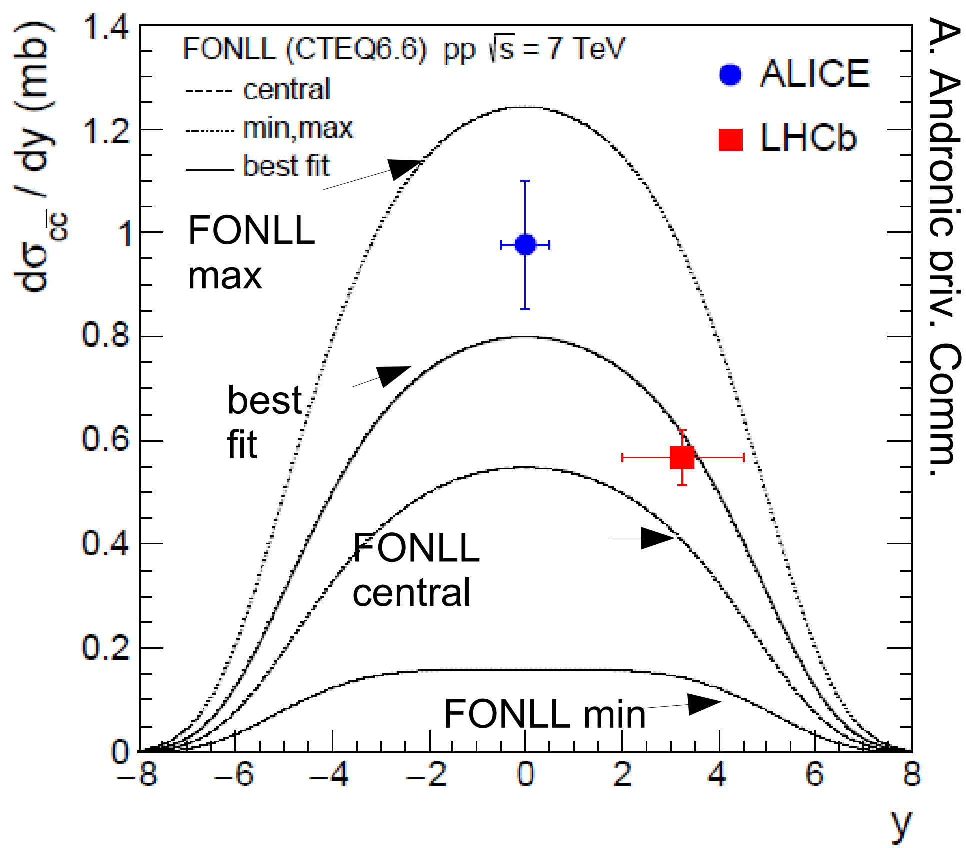
	Extr. factor to $p_T > 0$	$d\sigma/dy\,|_{|y|<0.5}$ (μb)
D^0	$1.0002^{+0.0004}_{-0.0002}$	$512 \pm 37(\text{stat}) \pm 39(\text{syst}) \pm 18(\text{lumi}) \pm 5(\text{BR})$
D^+	$1.25^{+0.29}_{-0.09}$	$235 \pm 19(\text{stat}) \pm 26(\text{syst}) \pm 8(\text{lumi}) \pm 6(\text{BR})^{+54}_{-16}(\text{extrap})$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

current baseline for the interpretation of PbPb data

use shape of FONLL to interpolate to proper √s and y-interval
long. momentum measure = rapidity y: 0 = 90° to beam
8 = beam momentum



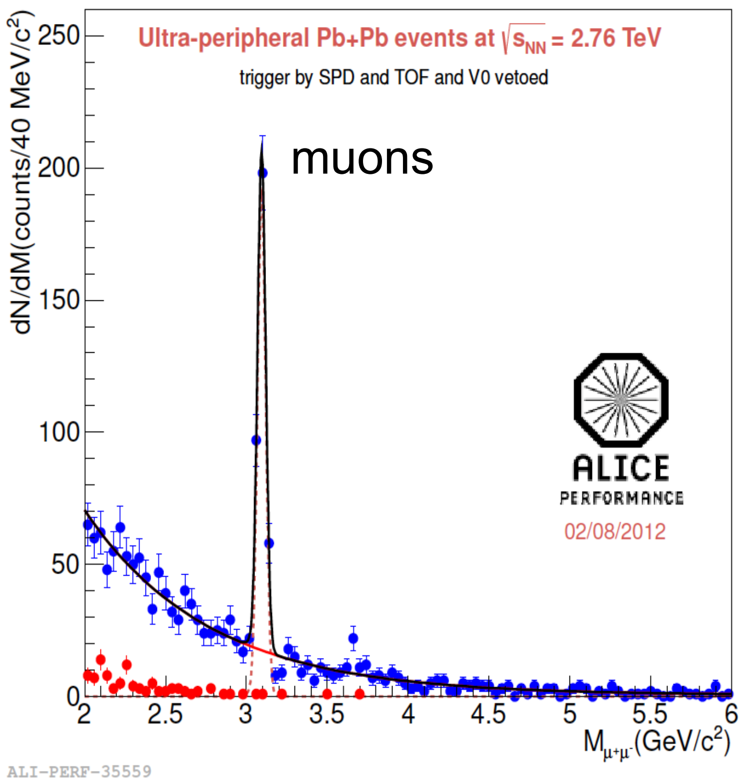
LHCb: 5 TeV arXiv:1610.02230
7 TeV NPB 871 (2013) 1
13 TeV JHEP 03 (2016) 159 plus erratum

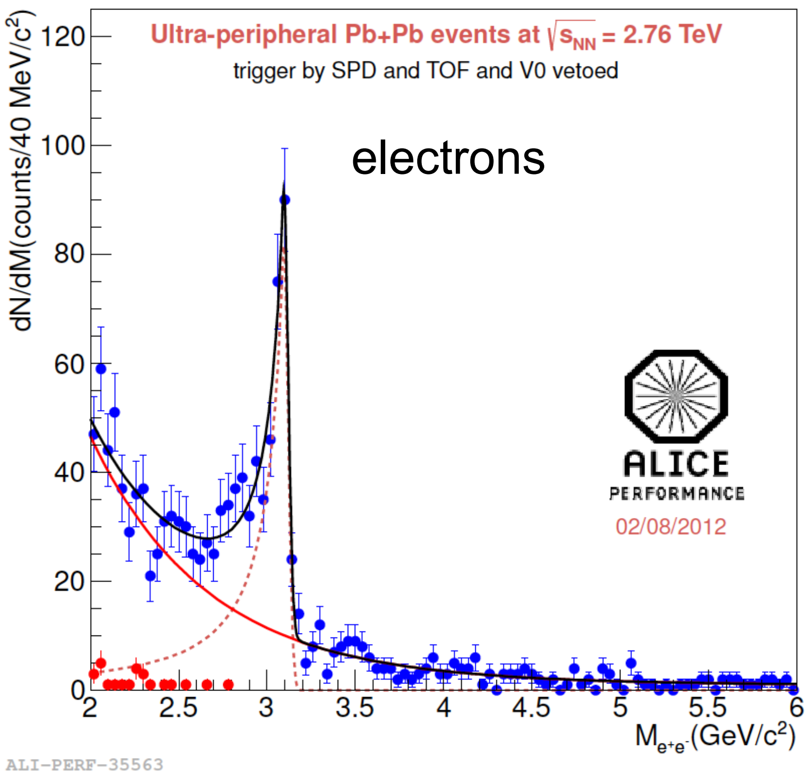


ALICE: 7 TeV PRC94 (2016) 054908
and 1702.00766

J/psi line shape in ultra-peripheral Pb—Pb collisions

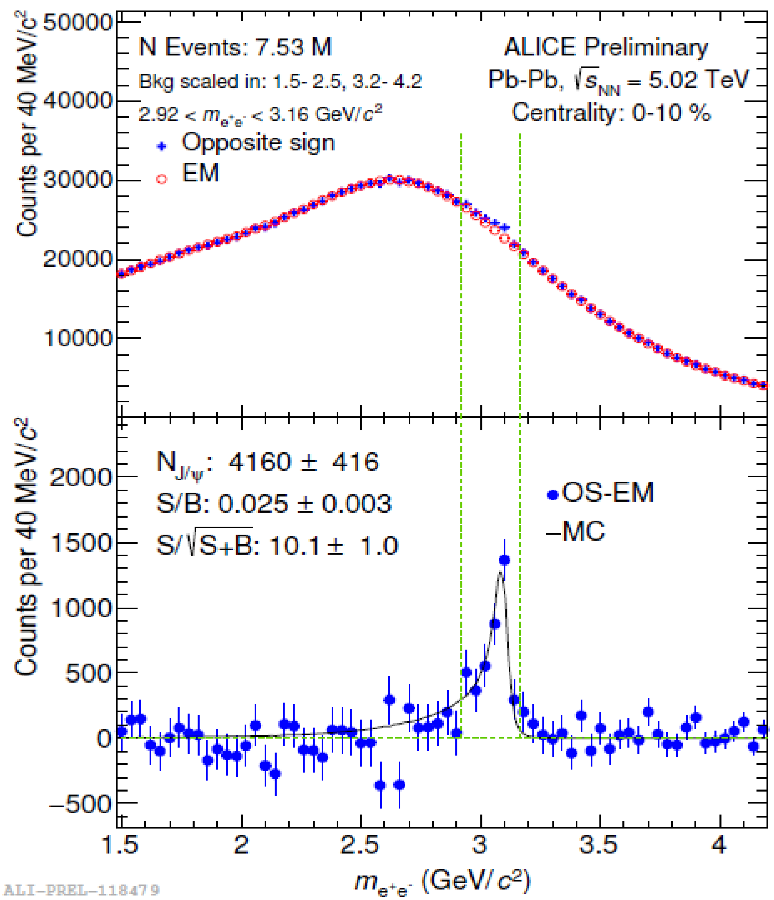
resolution: about 23 MeV for J/psi, precision determination of tail due to internal and external bremsstrahlung





measuring J/psi in Pb-Pb collisions via e+e- channel, ALICE experiment 2018

mid |y| < 0.8



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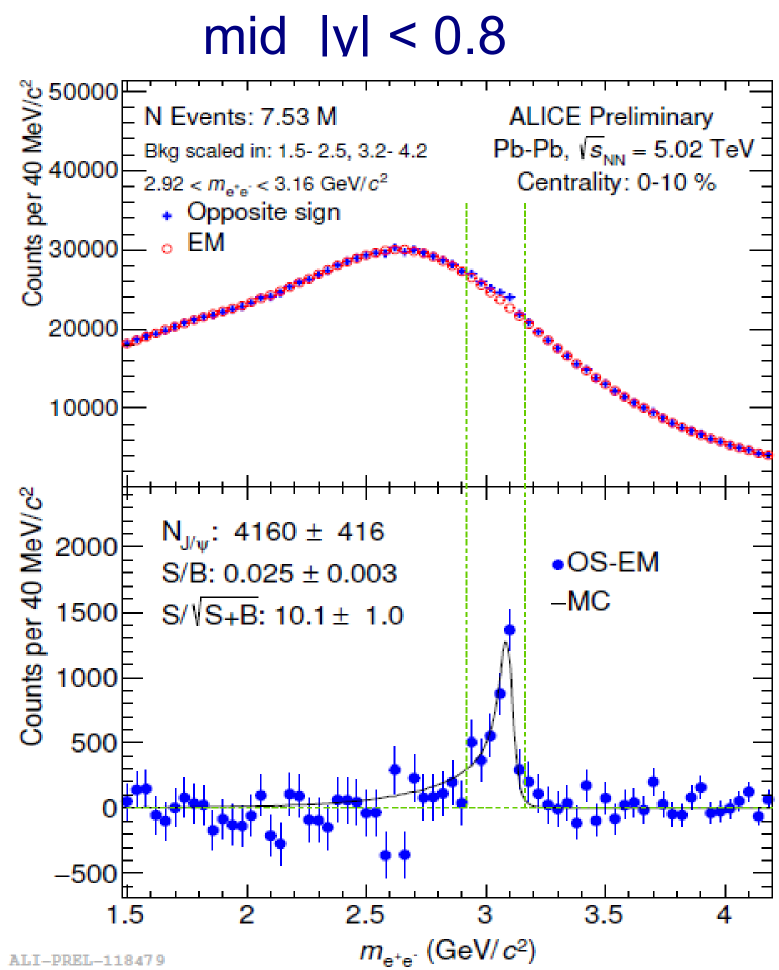


before looking at data for charmonium production we will first first explain the physics underlying the analysis strategy

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 only experimental input is the open charm cross section

[Braun-Munzinger and Stachel, PLB 490 (2000) 196]
[Andronic, Braun-Munzinger and Stachel, NPA 789 (2007) 334]

- Charm quarks are produced in initial hard scatterings ($m_{c\bar{c}} \gg T_c$) and production can be described by pQCD ($m_{c\bar{c}} \gg \Lambda_{QCD}$) or, better, measured in Pb-Pb collisions
- Charm quarks survive and *thermalise* in the QGP
- Full screening before T_{CF}
- Charmonium is formed at phase boundary (together with other hadrons)
- Thermal model input ($T_{CF}, \mu_b \rightarrow n_X^{th}$)

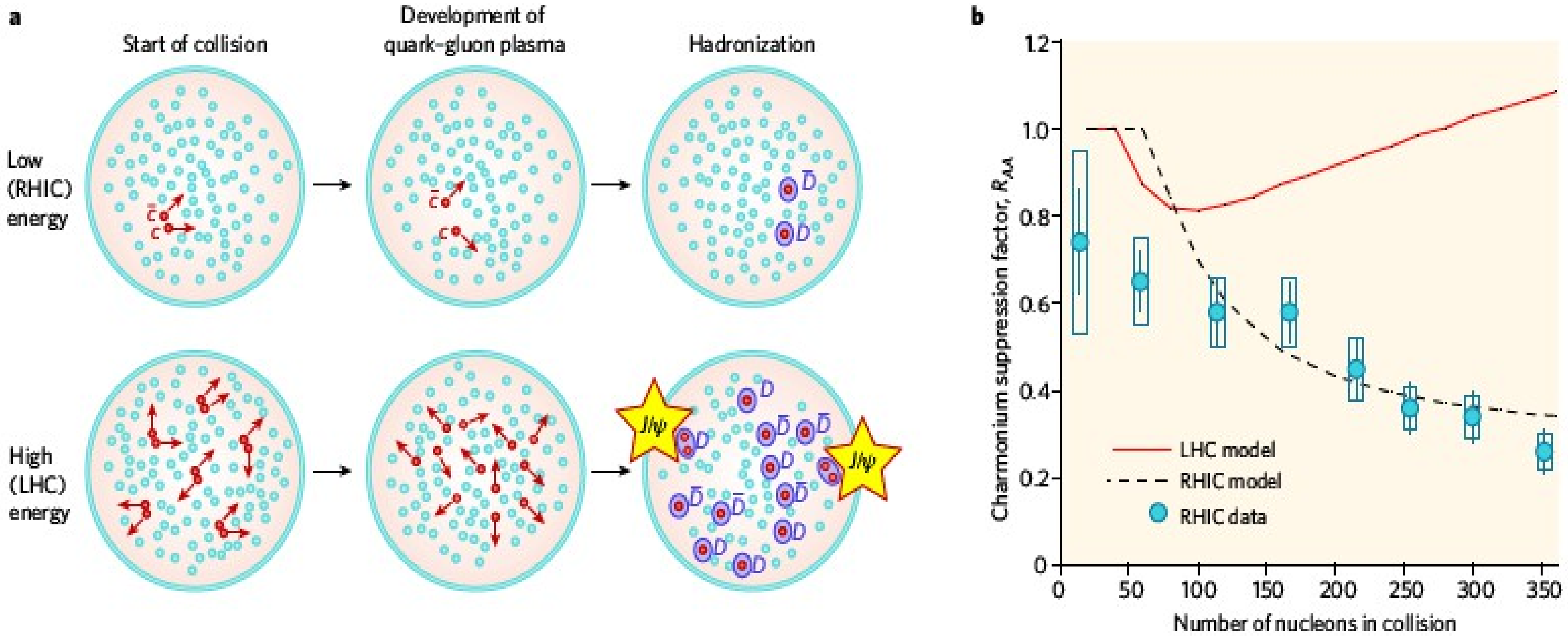
$$N_{c\bar{c}}^{dir} = \underbrace{\frac{1}{2} g_c V \left(\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th} + \cdots \right)}_{\text{Open charm}} + \underbrace{g_c^2 V \left(\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th} + \cdots \right)}_{\text{Charmonia}}$$

- Canonical correction is applied to n_{oc}^{th}
- Outcome $N_{J/\psi}, N_D, \ldots$

$N_{J/\psi} = g_c^2 V n^{th}_{J/\psi}$ $N_D = g_c V n^{th}_D$ $N_{\Omega ccc} = g_c^3 V n^{th}_{\Omega ccc}$ …
for all mesons and baryons with charm or beauty quarks
n.b. the thermal densities are obtained from the statistical hadronization model outlined in Lect. 22, g_c is determined using the charm balance equation above

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.



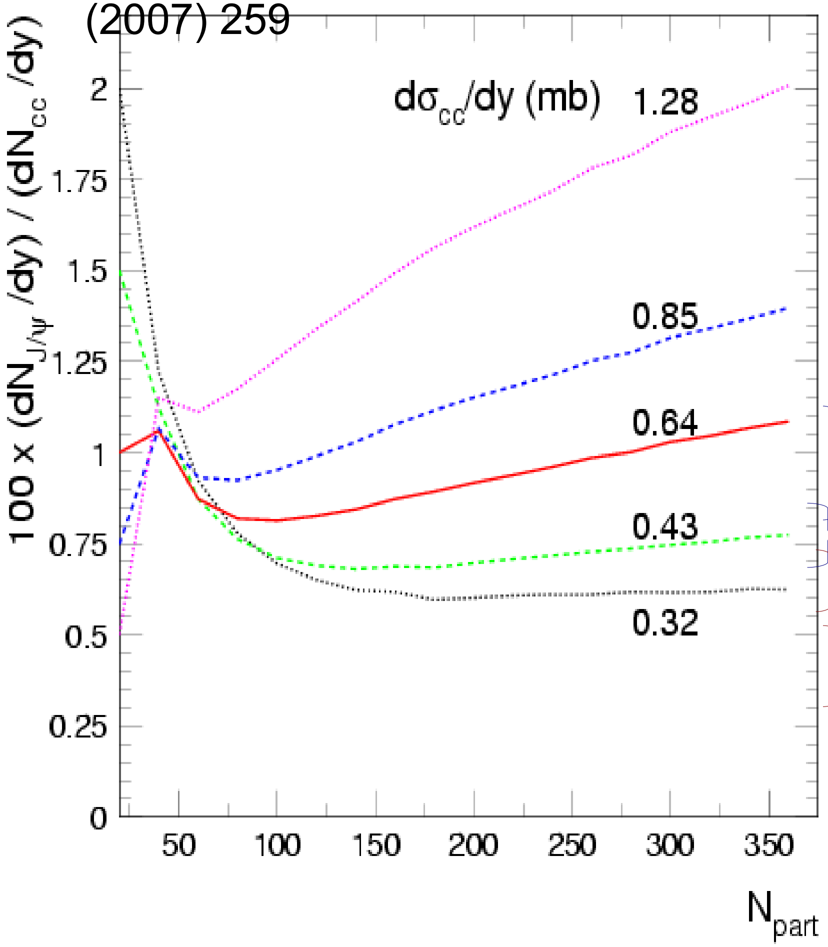
charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

prediction long before the LHC started data taking

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

Energy dependence of quarkonium production in statistical hadronization model

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

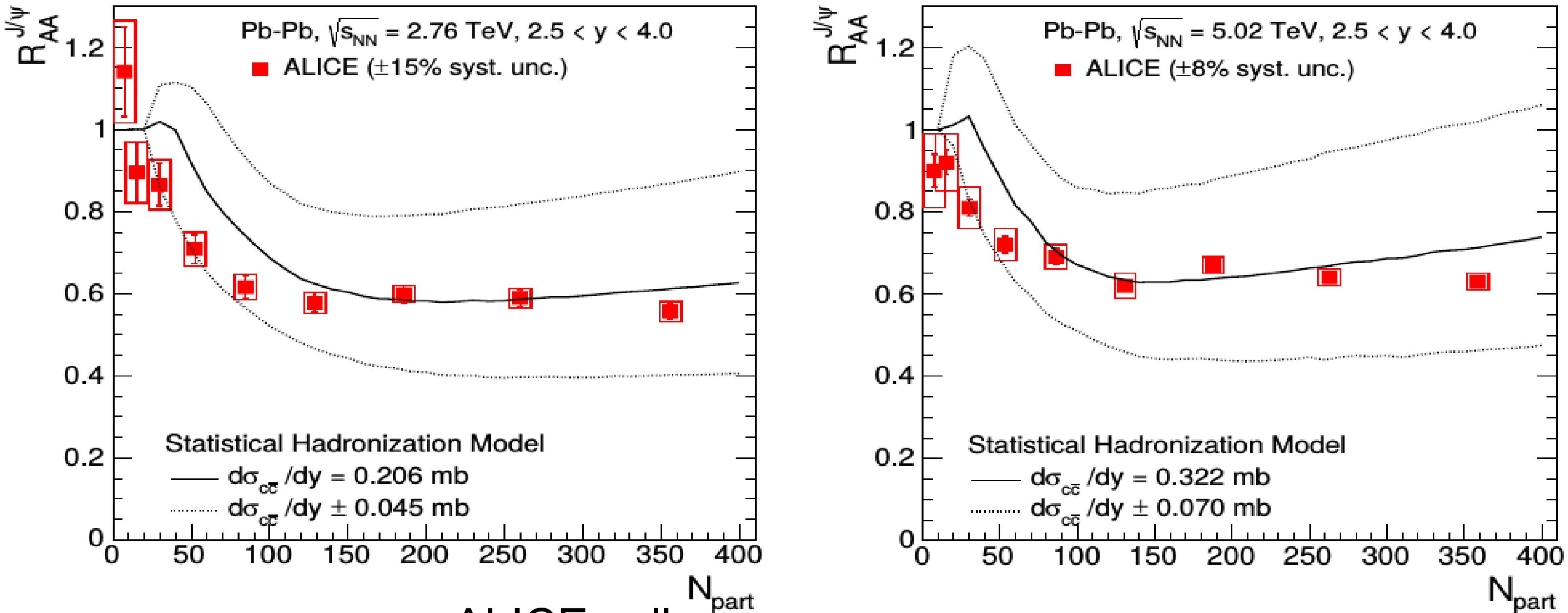


measured ccbar cross sections in pp at appropriate rapidity by ALICE and LHCb and shadowing from measured D and J/Φproduction in pPb collisions compared to pQCD

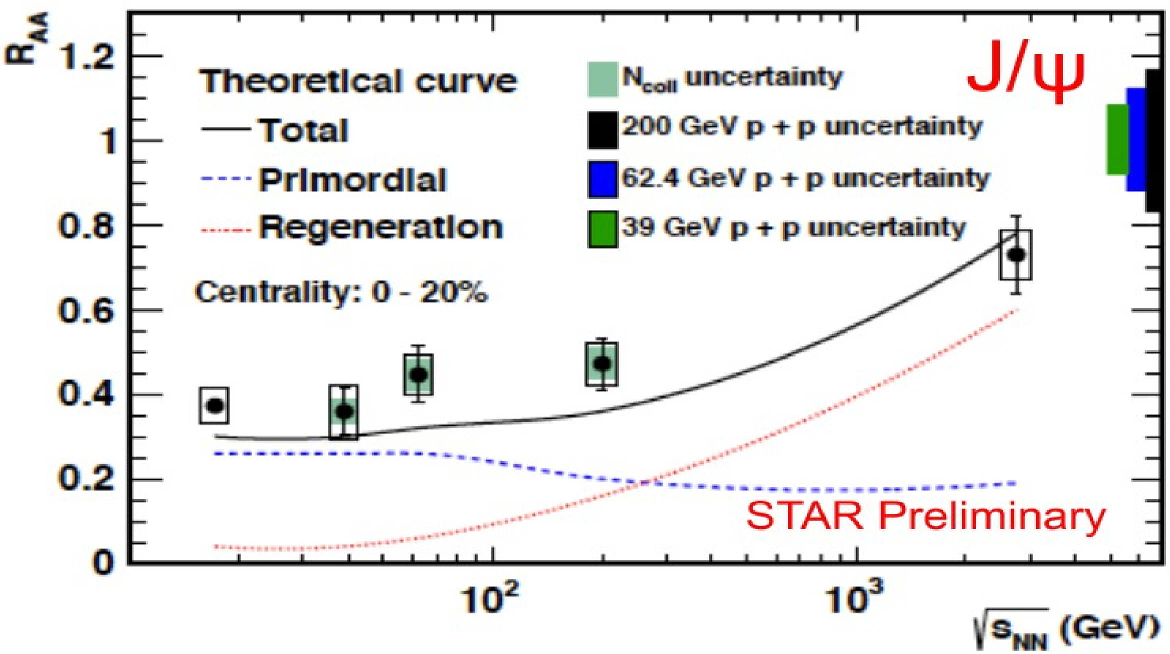
mid-y LHC 2.76 and 5.02 TeV including shadowing

forward-y LHC 2.76 and 5.02 TeV including shadowing

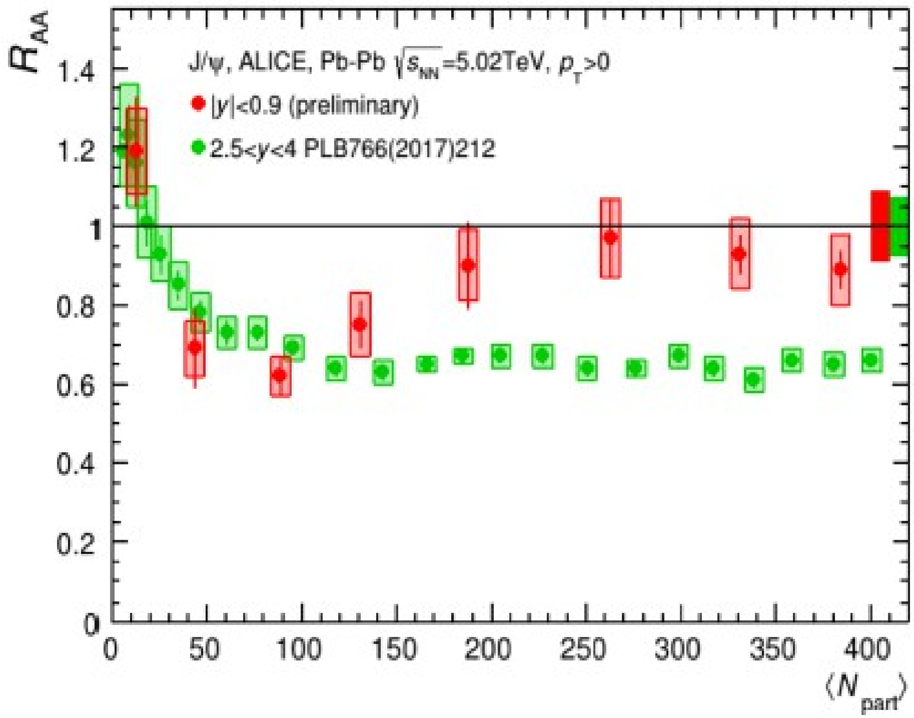
predictions from 2000/2007 beautifully confirmed by RHIC and, in particular, LHC data

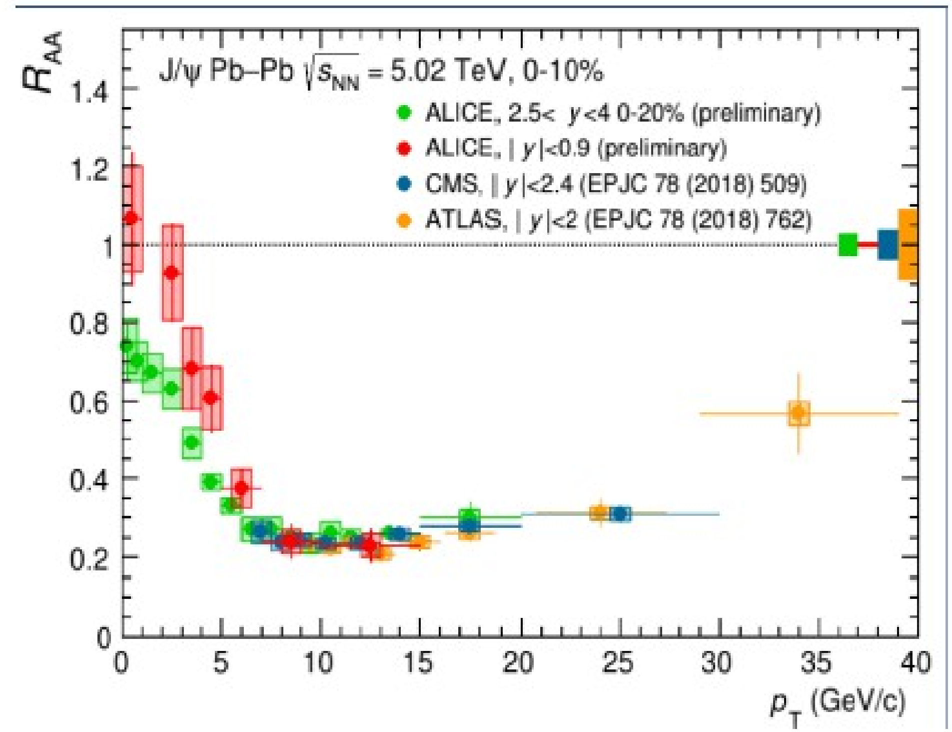


ALICE coll.,
arXiv:1606.08197



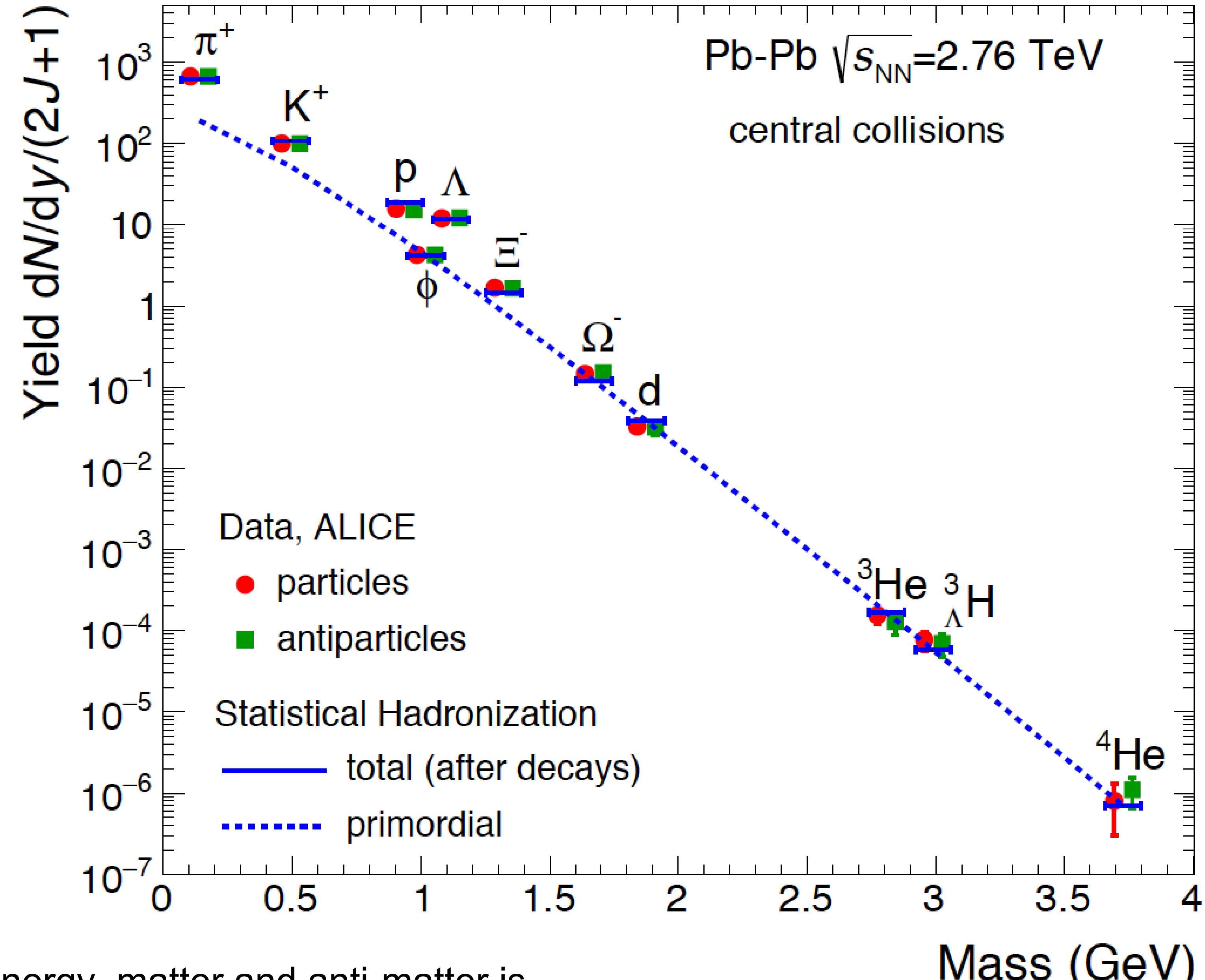
Enhancement is at low (transverse) momentum and at angles perpendicular to the beam direction, as expected for a thermal, nearly isotropic source





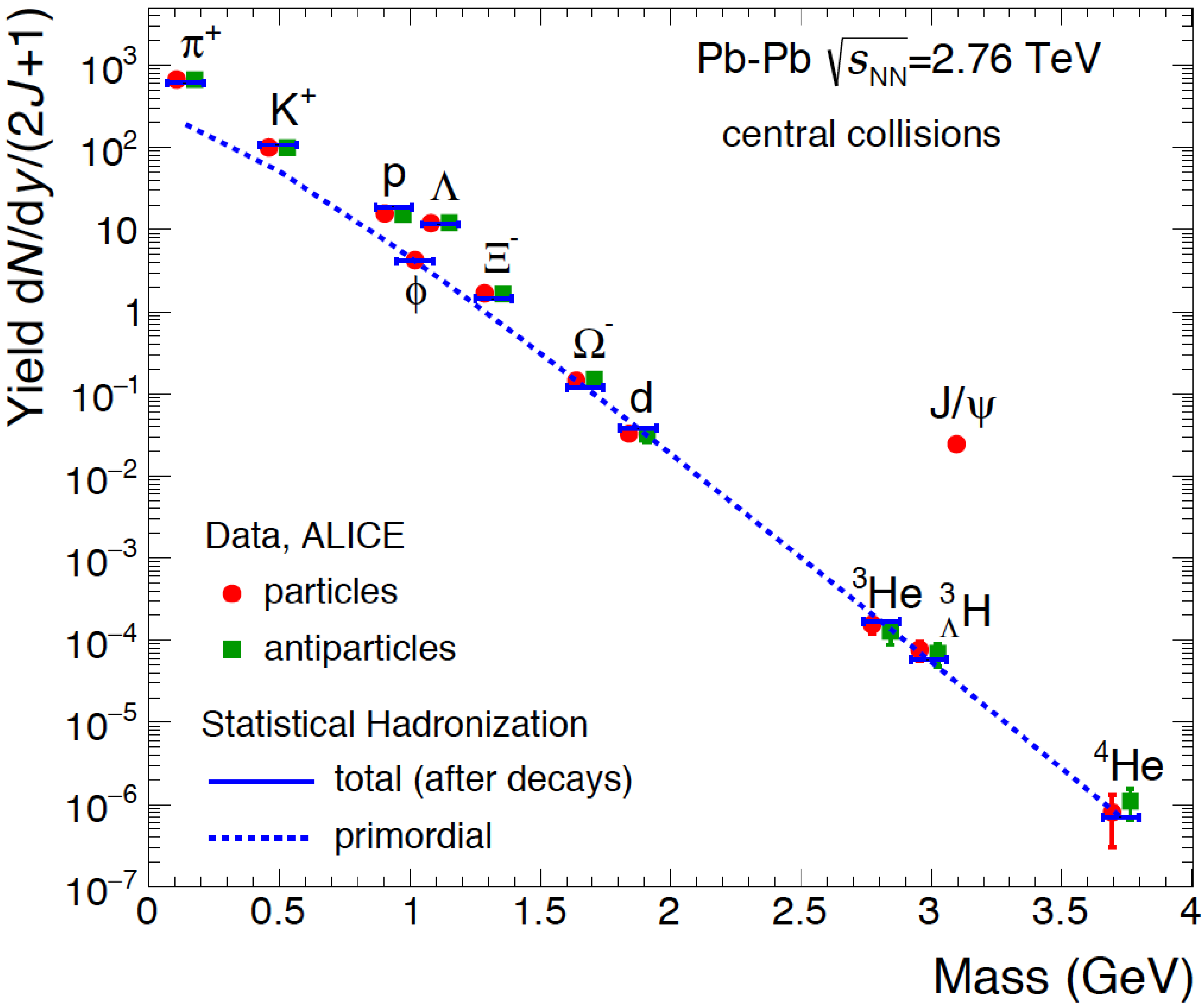
enhancement is due to statistical combination of charm- and anti-charm quarks these heavy quarks have masses O(1 GeV) and are not produced thermally since T_{cf} = 156 MeV << 1 GeV. Interactions in the hot fireball bring the charm quarks close to equilibrium → production probability scales with $N(_{ccbar})^2$

at LHC energy, production of (u,d,s) hadrons is governed
by mass and quantum numbers only
quark content does not matter

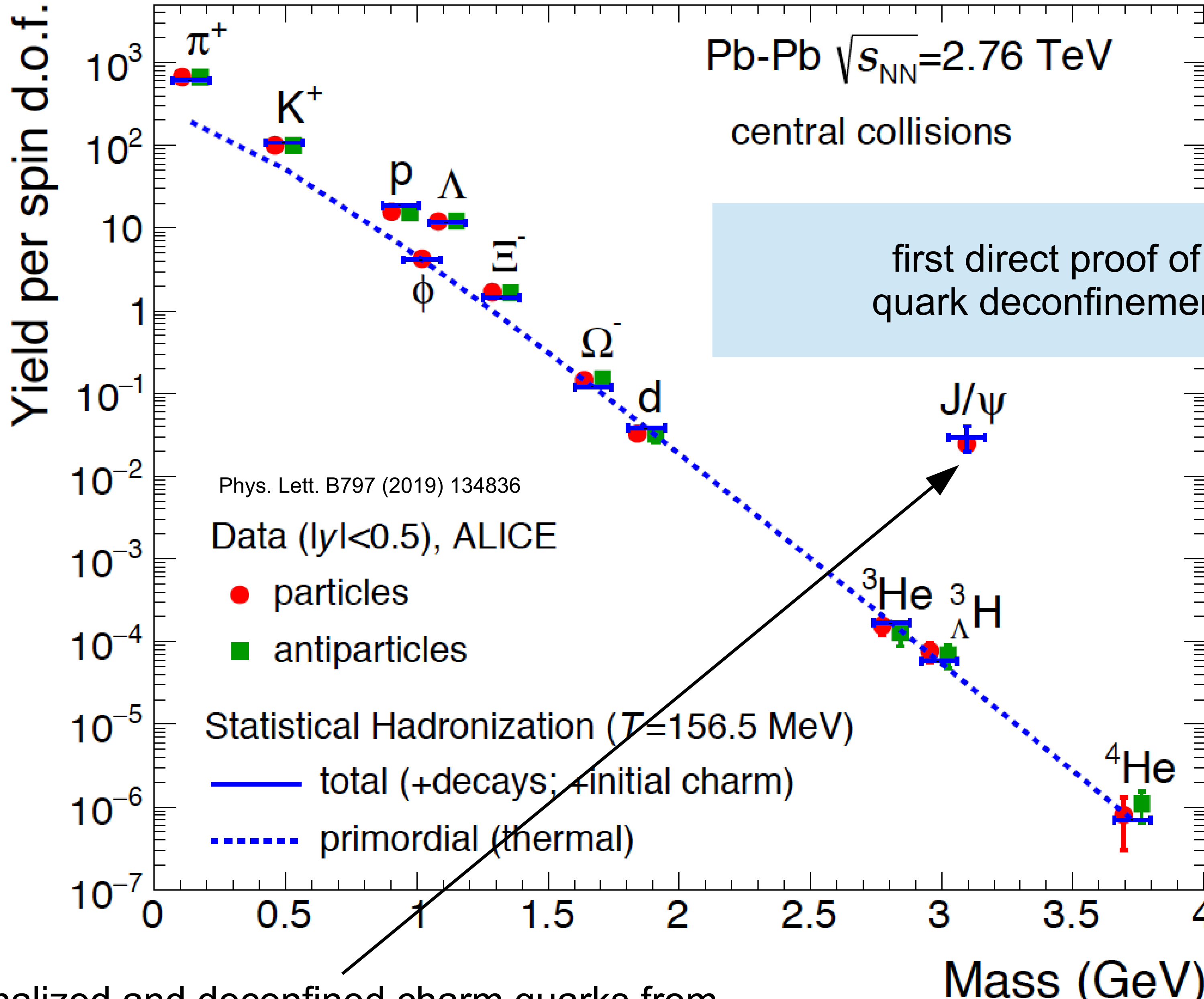


at LHC energy, matter and anti-matter is
produced with equal yields

J/psi mass is close to that of hypertriton, where is enhancement by 3 orders of magnitude from?



enhancement is precisely prediction by Statistical Hadronization Model
for quadratic scaling in number of charm quarks, they have to travel freely over
the size of the fireball of 10 fm, about 10 times the radius of a proton



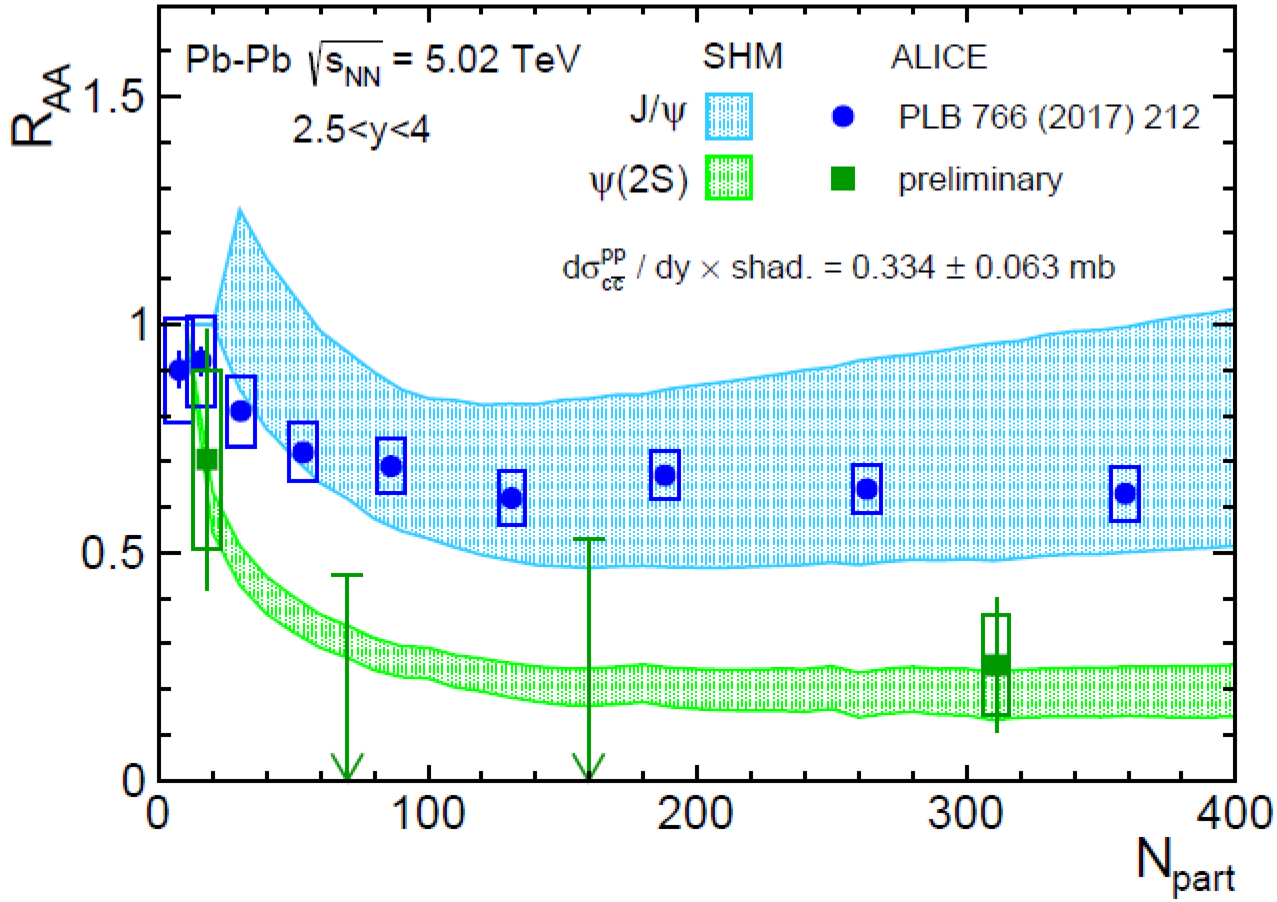
first direct proof of
quark deconfinement

with thermalized and deconfined charm quarks from
initial hard scattering

Andronic, pbm, Koehler, Redlich, Stachel,
Phys. Lett B797 (2019) 134836

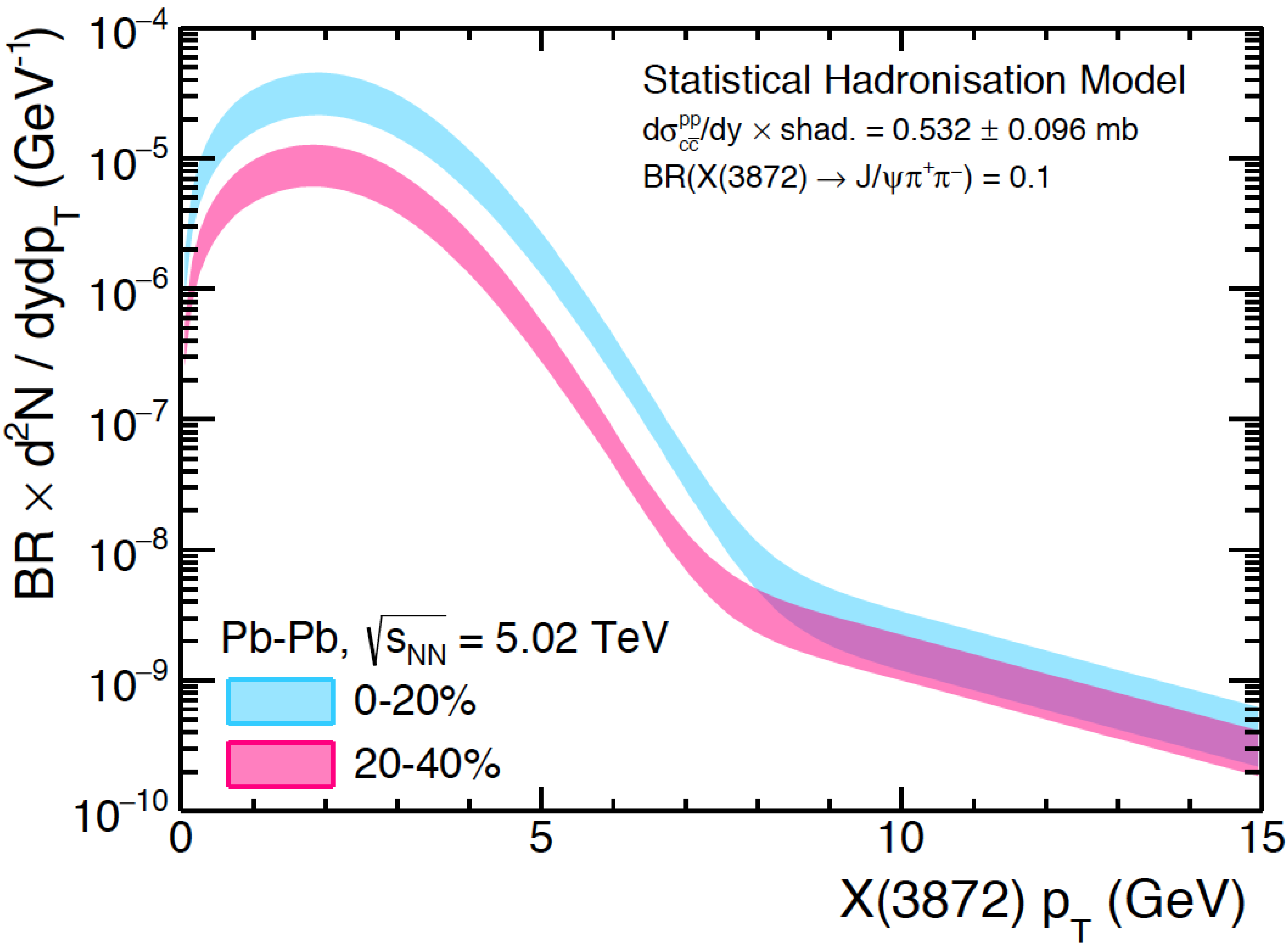
what about ψ(2S)?

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



also excited state population completely in line, suppressed by Boltzmann factor
errors will decrease with more data in LHC Run3/4

transverse momentum spectrum for X(3872) in the statistical hadronization model Pb-Pb collisions at 5 TeV/u



summary

- statistical hadronization model is an effective tool to understand the phenomenology of hadron production in relativistic nuclear collisions from SIS to LHC energy with predictive power for future facilities

- deeply rooted in duality 'hadrons – quarks' near QCD phase boundary

- present precision is mostly limited by incomplete knowledge of hadron mass spectrum and related branching ratios for decays

- works also for hadrons with charm quarks → charmonium and open charm enhancement in QGP, direct proof of deconfinement for charm quarks

key results:
experimental location of QCD phase boundary for μ_b < 300 MeV:
T_c = 156.5 ± 3 MeV
new insight into deconfinement and hadronization