Quarkonium: an experimental overview

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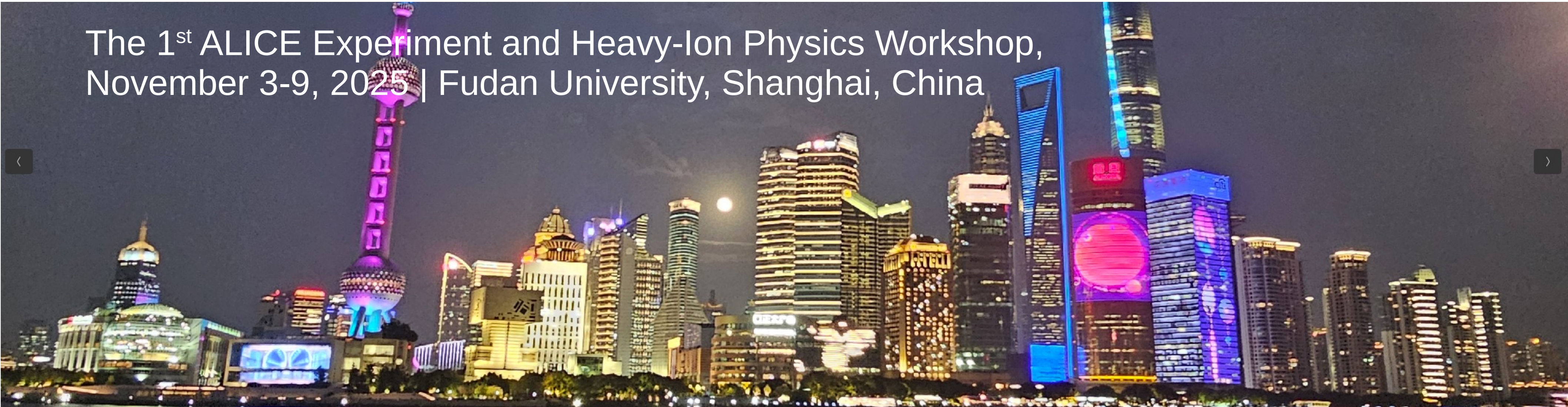
2025/11/07



Outline

- A brief historical overview
- Quarkonium properties and production in vacuum
- How is quarkonium reconstructed
- Physics case
- J/ψ measurements at the SPS, RHIC and LHC
- Bottomonium
- Excited charmonia
- Anisotropic flow
- Conclusions and outlook

1970s 1980s 1990s 2000s 2010s 2020s 2030s...

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
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and

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(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

This experiment is part of a large program to study the behavior of timelike photons in $p + p \to e^+ + e^- + x$ reactions[1] and to search for new particles which decay into e^+e^- and $\mu^+\mu^-$ pairs.

We use a slow extracted beam from the Brookhaven National Laboratory's alternating-gradient synchrotron. The beam intensity varies from 10^{10} to 2×10^{12} p/pulse. The beam is guided onto an extended target, normally nine pieces of 70-mil Be, to enable us to reject the pair accidentals by requiring the two tracks to come from the same origin. The beam intensity is monitored with a secondary emission counter, calibrated daily with a thin Al foil. The beam spot size is 3×6 mm^2, and is monitored with closed-circuit television. Figure 1(a) shows the simplified side view of one arm of the spectrometer. The two arms are placed at 14.6° with respect to the incident beam; bending (by $M1$, $M2$) is done vertically to decouple the angle (θ) and the momentum (p) of the particle.

The Cherenkov counter C_0 is filled with one atmosphere and C_e with 0.8 atmosphere of H_2. The counters C_0 and C_e are decoupled by magnets $M1$ and $M2$. This enables us to reject knock-on electrons from C_0. Extensive and repeated calibra-

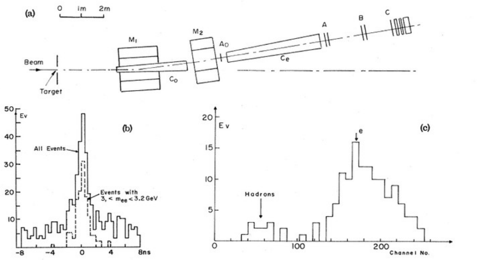

FIG. 1. (a) Simplified side view of one of the spectrometer arms. (b) Time-of-flight spectrum of e^+e^- pairs and of those events with $3.0 < m < 3.2$ GeV. (c) Pulse-height spectrum of e^- (same for e^+) of the e^+e^- pair.

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proximately 10^{-34} cm^2.

The most striking feature of J is the possibility that it may be one of the theoretically suggested charmed particles[2] or a's[3] or Z_0's,[4] etc. In order to study the real nature of J,[5] measurements are now underway on the various decay modes, e.g., an $e\pi\nu$ mode would imply that J is weakly interacting in nature.

It is also important to note the absence of an e^+e^- continuum, which contradicts the predictions of parton models.[6]

We wish to thank Dr. R. R. Rau and the alternating-gradient synchrotron staff who have done an outstanding job in setting up and maintaining this experiment. We thank especially Dr. F. Eppling, B. M. Bailey, and the staff of the Laboratory for Nuclear Science for their help and encouragement. We thank also Ms. I. Schulz, Ms. H. Feind, N. Feind, D. Osborne, G. Krey, J. Donahue, and E. D. Weiner for help and assistance. We thank also M. Deutsch, V. F. Weisskopf, T. T. Wu, S. Drell, and S. Glashow for many interesting conversations.

†Accepted without review under policy announced in Editorial of 20 July 1964 [Phys. Rev. Lett. 13, 79 (1964)].

[1]The first work on $p + p \to \mu^+ + \mu^- + x$ was done by L. M. Lederman *et al.*, Phys. Rev. Lett. 25, 1523 (1970).
[2]S. L. Glashow, private communication.
[3]T. D. Lee, Phys. Rev. Lett. 26, 801 (1971).
[4]S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967), and 27, 1688 (1971), and Phys. Rev. D 5, 1412, 1962 (1972).
[5]After completion of this paper, we learned of a similar result from SPEAR. B. Richter and W. Panofsky, private communication; J.-E. Augustin *et al.*, following Letter [Phys. Rev. Lett. 33, 1404 (1974)].
[6]S. D. Drell and T. M. Yan, Phys. Rev. Lett. 25, 316 (1970). An improved version of the theory is not in contradiction with the data.

Discovery of a Narrow Resonance in $e^+ e^-$ Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
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(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ in the Stanford Linear Accelerator Center (SLAC)–Lawrence Berkeley Laboratory magnetic detector[1] at the SLAC electron-positron storage ring SPEAR. The resonance has the parameters

$$E = 3.105 \pm 0.003 \text{ GeV},$$

$$\Gamma \leq 1.3 \text{ MeV}$$

(full width at half-maximum), where the uncertainty in the energy of the resonance reflects the uncertainty in the absolute energy calibration of the storage ring. [We suggest naming this structure $\psi(3105)$.] The cross section for hadron production at the peak of the resonance is ≥ 2300 nb, an enhancement of about 100 times the cross section outside the resonance. The large mass, large cross section, and narrow width of this structure are entirely unexpected.

Our attention was first drawn to the possibility of structure in the $e^+e^- \to$ hadron cross section during a scan of the cross section carried out in 200-MeV steps. A 30% (6 nb) enhancement was

Brookhaven:
PRL33 (1974) 1404

Stanford:
PRL33 (1974) 1406

- 1964: Charm quarks predicted by **Bjorken and Glashow**
- 1974: The “november revolution”
  - J/ψ discovery in p-A (BNL) and e^+e^- (SLAC) collisions

Burton Richter and Samuel Ting, 1976

- Late 1970: J/ψ hadro-production in pp collisions at CERN ISR

1970s **1980s** 1990s 2000s 2010s 2020s 2030s...

- **Fermilab** fixed-target program
  - Extensive J/ψ production and nuclear suppression studies in p-A collisions

- **CERN SPS**
  - Proton and heavy-ion fixed-target experiments (NA38, NA50, and later NA60)

- **DESY PETRA**
  - Early e^+e^- collider charmonium production studies

1970s 1980s **1990s** 2000s 2010s 2020s 2030s...

- **Cornell CESR (CLEO)**
  - High precision e^+e^- spectroscopy, J/ψ and ψ(2S) decay branching ratios
- **BEPC / BES**
  - Dedicated J/ψ factory for spectroscopy and rare decay studies
- **DESY HERA ep collider**
  - J/ψ photoproduction constraining gluon PDFs and diffractive mechanisms
- **Tevatron (CDF, DØ)**
  - High energy hadroproduction, first polarization and p_T-differential studies

1970s 1980s 1990s **2000s** 2010s 2020s 2030s...

- **CERN SPS (NA60)**
  - Refined heavy-ion suppression and cold nuclear matter studies
- **BNL RHIC (PHENIX, STAR)**
  - Charmonium suppression and regeneration in hot QCD matter (Au+Au, Cu+Cu, pp)
- **KEKB (Belle) and PEP-II (BaBar)**
  - B-factories: J/ψ production in B decays and via ISR

1970s 1980s 1990s 2000s **2010s** **2020s** 2030s...

- **CERN LHC (ALICE, ATLAS, CMS, LHCb)**
  - pp, pA, A-A collisions at TeV energies
  - Detailed studies of suppression, regeneration, polarization, and photoproduction

- **BEPCII / BESIII**
  - Second generation J/ψ factory with huge datasets; precision decays and transitions

- **Jefferson Lab (CLAS, GlueX)**
  - Near-threshold J/ψ photoproduction on nucleons and nuclei

1970s 1980s 1990s 2000s 2010s **2020s** **2030s...**

Future facilities

- **FAIR / PANDA**
  - Precision charmonium spectroscopy in $p\bar{p}$ annihilation

- **J-PARC**
  - Fixed target charmonium production

- **EIC**
  - Exclusive J/ψ photoproduction for nPDFs, precise nuclear medium formation effects, near-threshold charmonium production

- **ALICE3 and High-Lumi LHC (ATLAS, CMS and LHCb)**
  - High precision quarkonia production in pp, pA and AA collisions

From discovery to QGP probe...

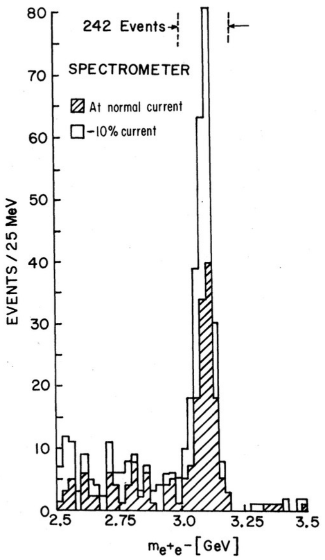


FIG. 2. Mass spectrum showing the existence of *J*. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

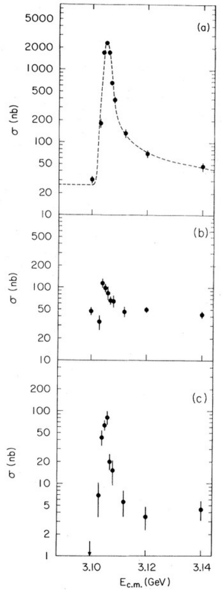


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

THE PRODUCTION OF J/Ψ
IN 200 GeV/NUCLEON OXYGEN–URANIUM INTERACTIONS

NA38 Collaboration

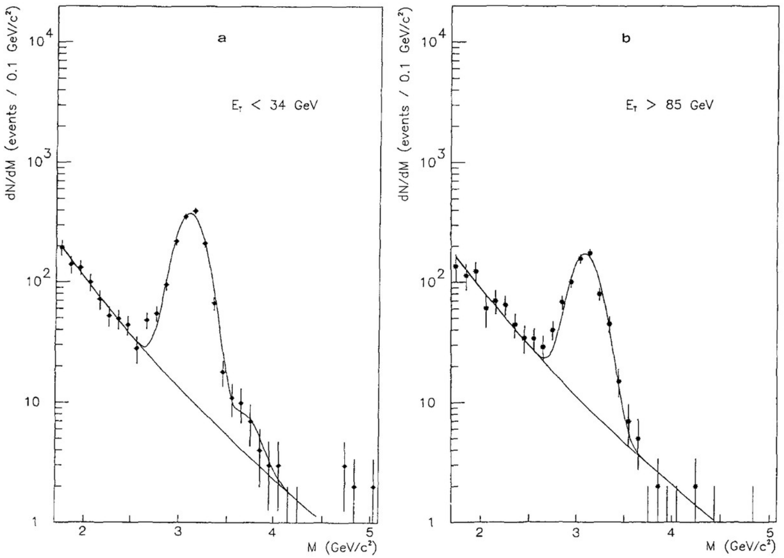


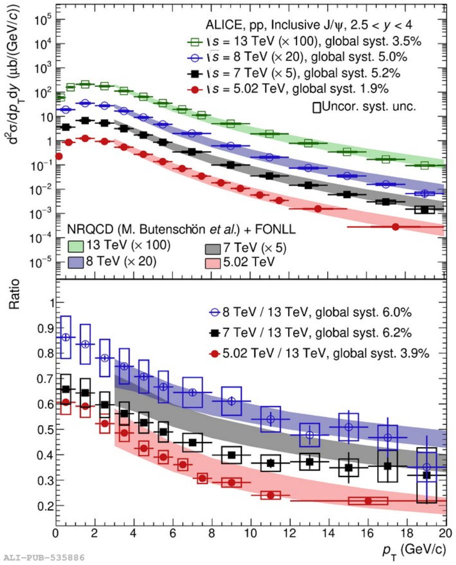
Fig. 5. Mass spectrum and fit of the signal muon pairs in two different E_T bins: $E_T < 34$ GeV (a) and $E_T > 85$ GeV (b).

PLB220 (1989) 471

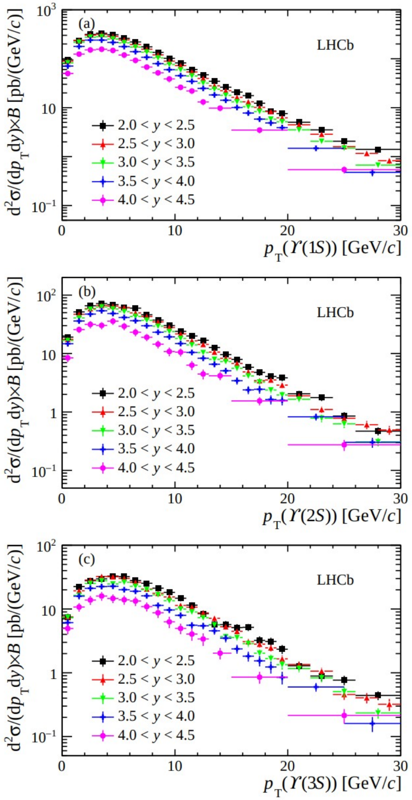
Observation of J/ψ in e^+e^- collisions

Relative suppresion of J/ψ in O-U collisions with high activity

...to a complex tool for QCD

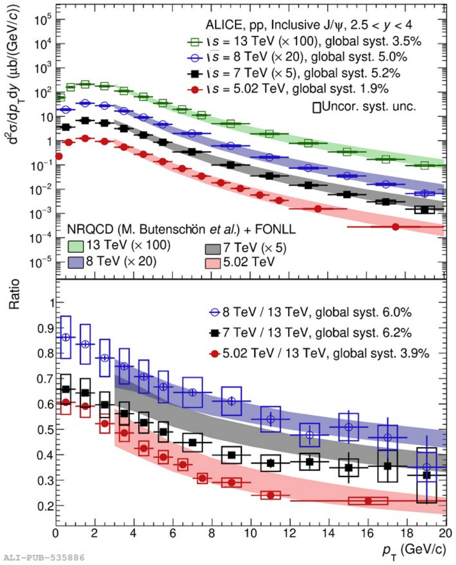


(Differential J/ψ yields)

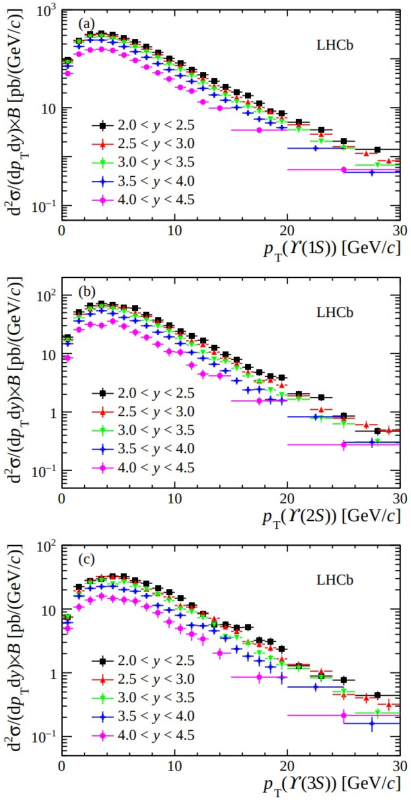


(Differential Υ yields)

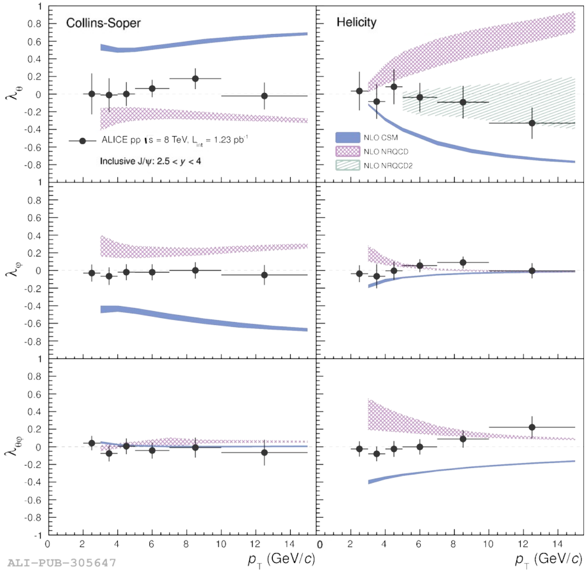
...to a complex tool for QCD



(Differential J/ψ yields)

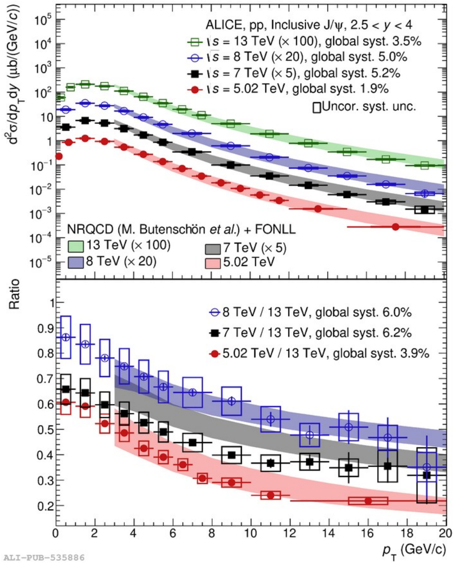


(Differential Υ yields)

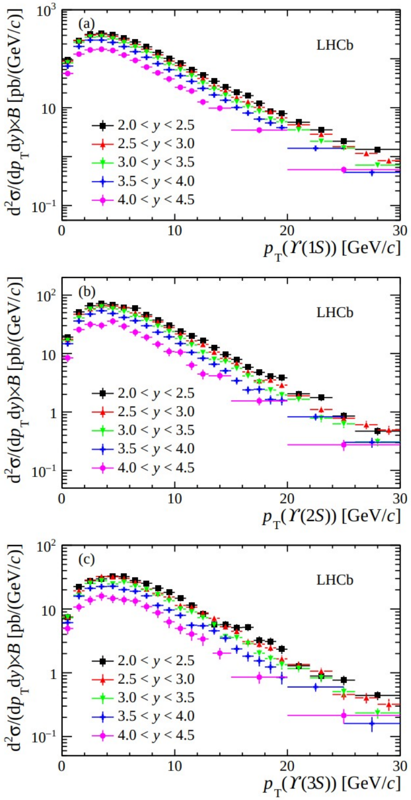


(J/ψ polarization)

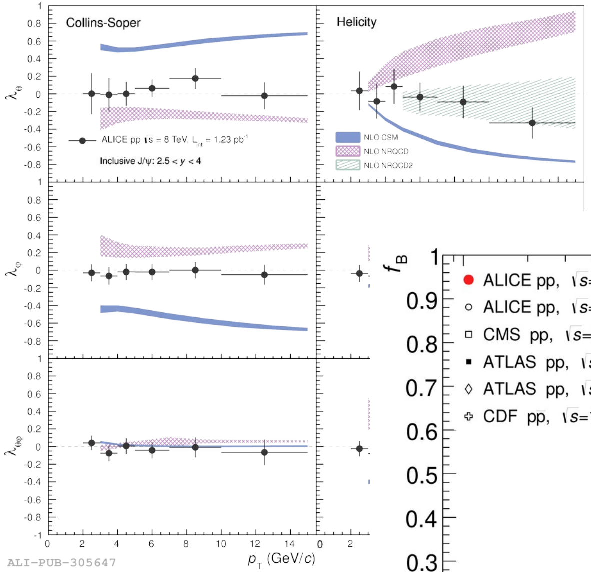
...to a complex tool for QCD



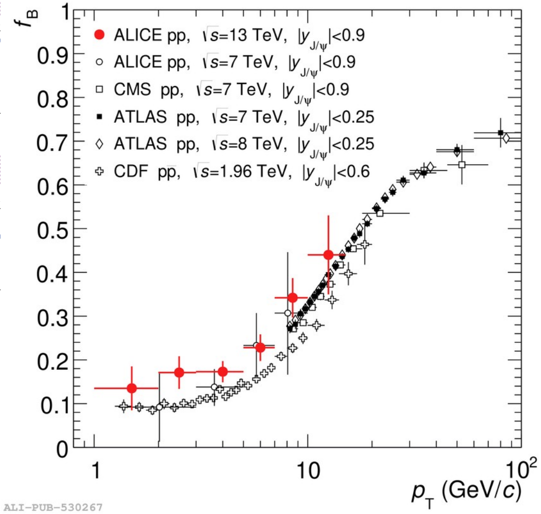
(Differential J/ψ yields)



(Differential Υ yields)

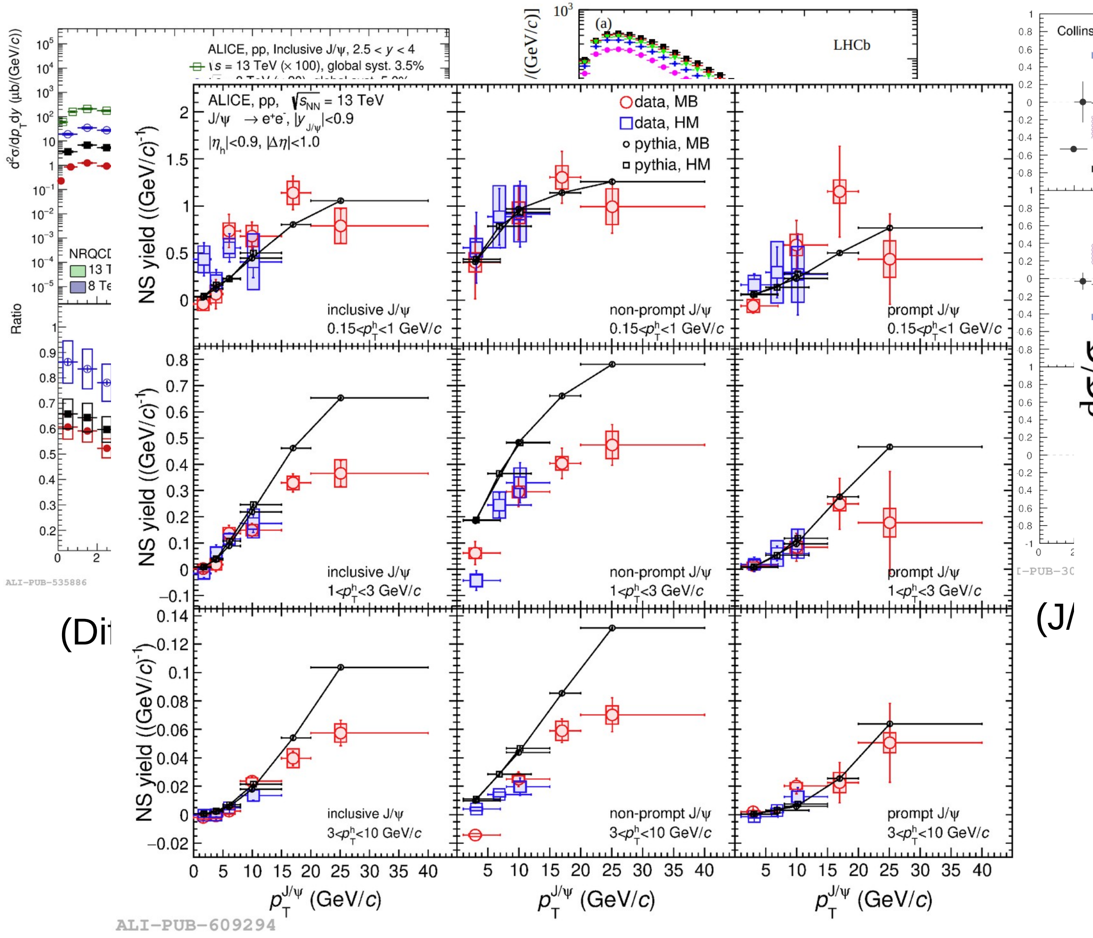


(J/ψ polarization)



(J/ψ fraction from beauty)

...to a complex tool for QCD



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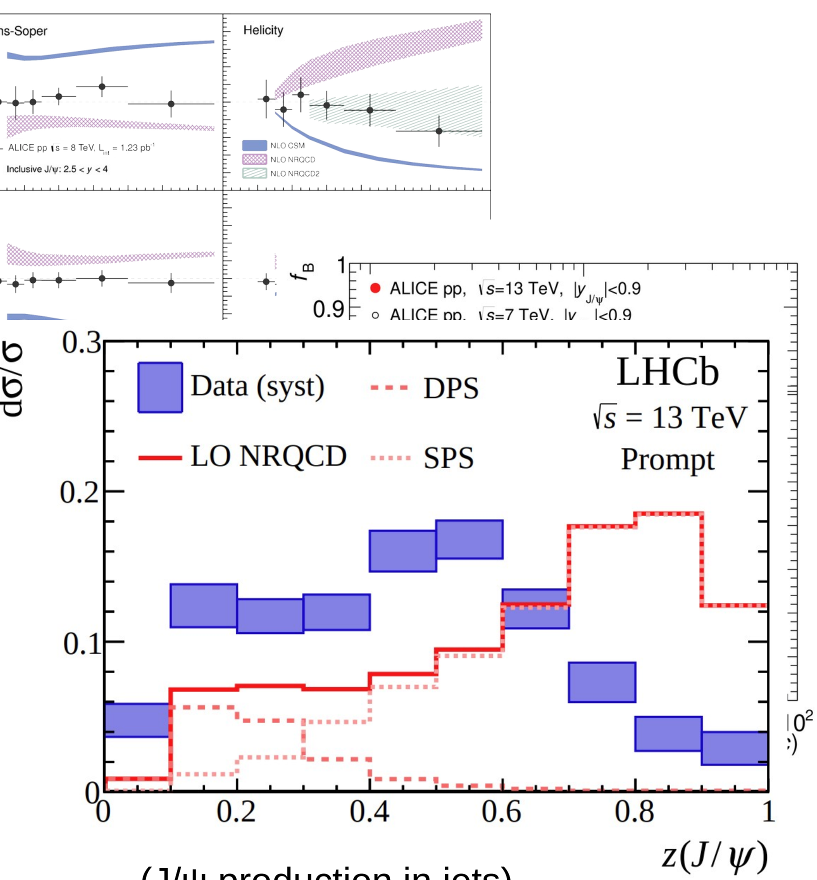
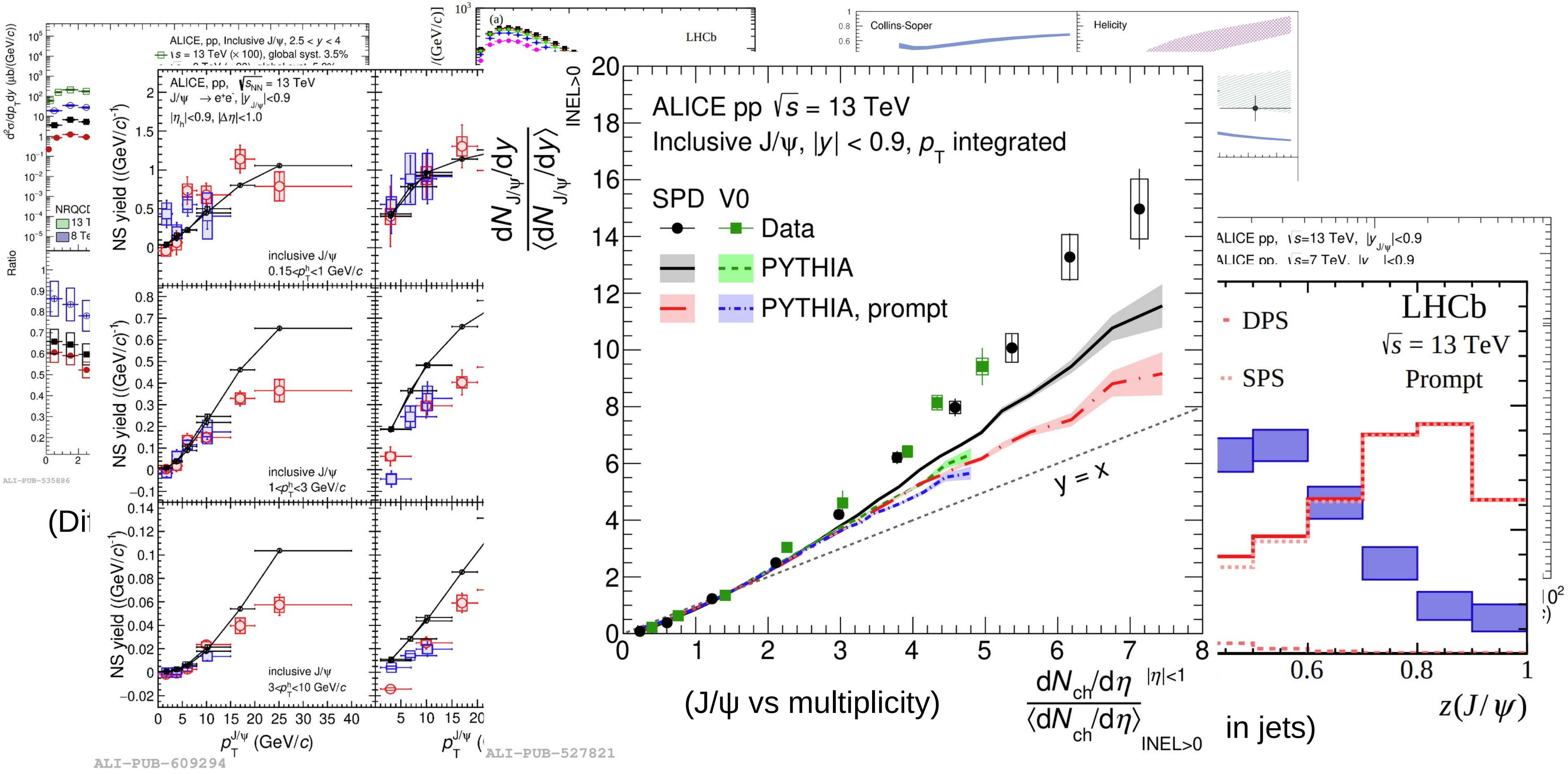


(J/ψ production in jets)

(J/ψ – hadron correlations)

...to a complex tool for QCD



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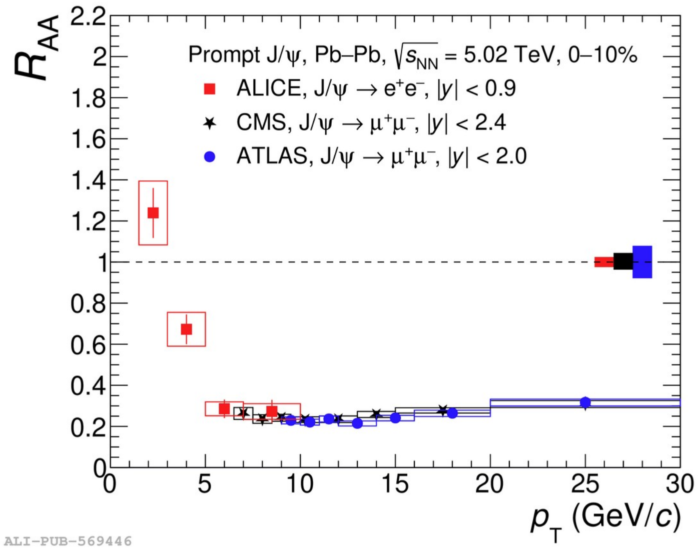
(J/ψ vs multiplicity)

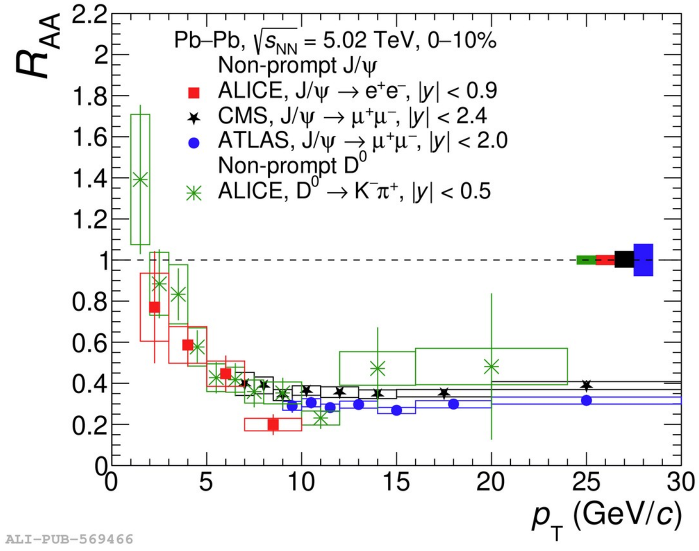
in jets)

(J/ψ – hadron correlations)

and heavy-ion collisions

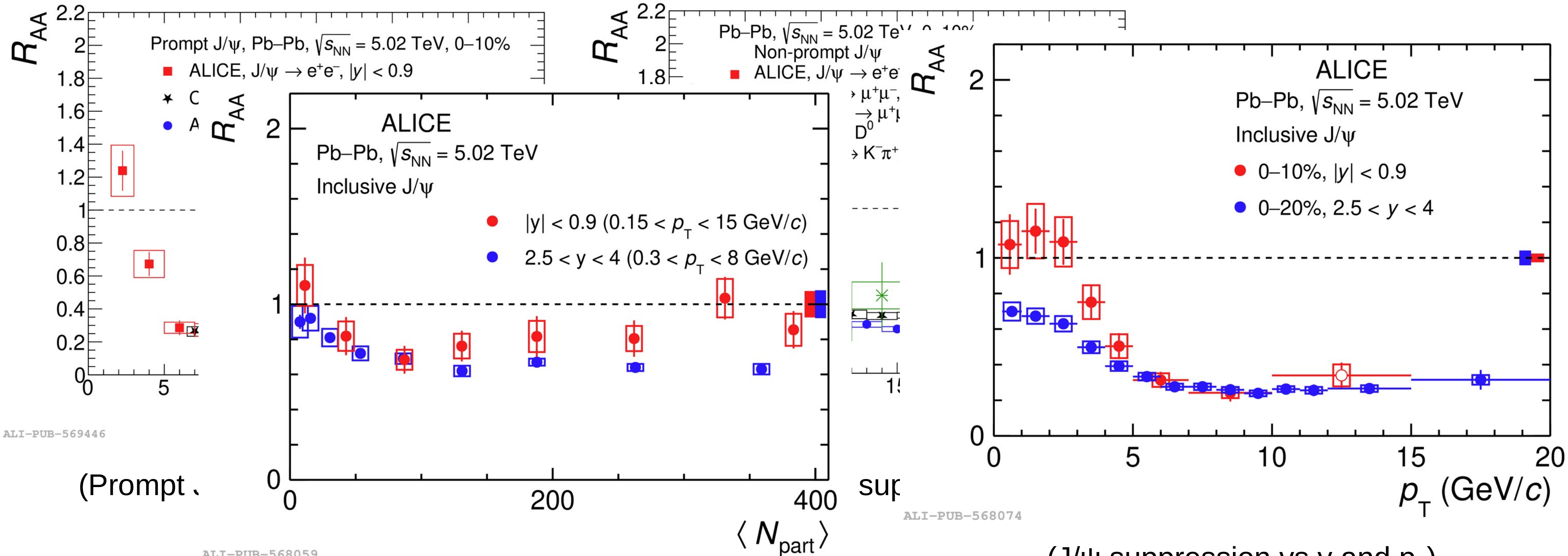


(Prompt J/ψ suppression vs pT)



(Non-prompt J/ψ suppression vs pT)

and heavy-ion collisions

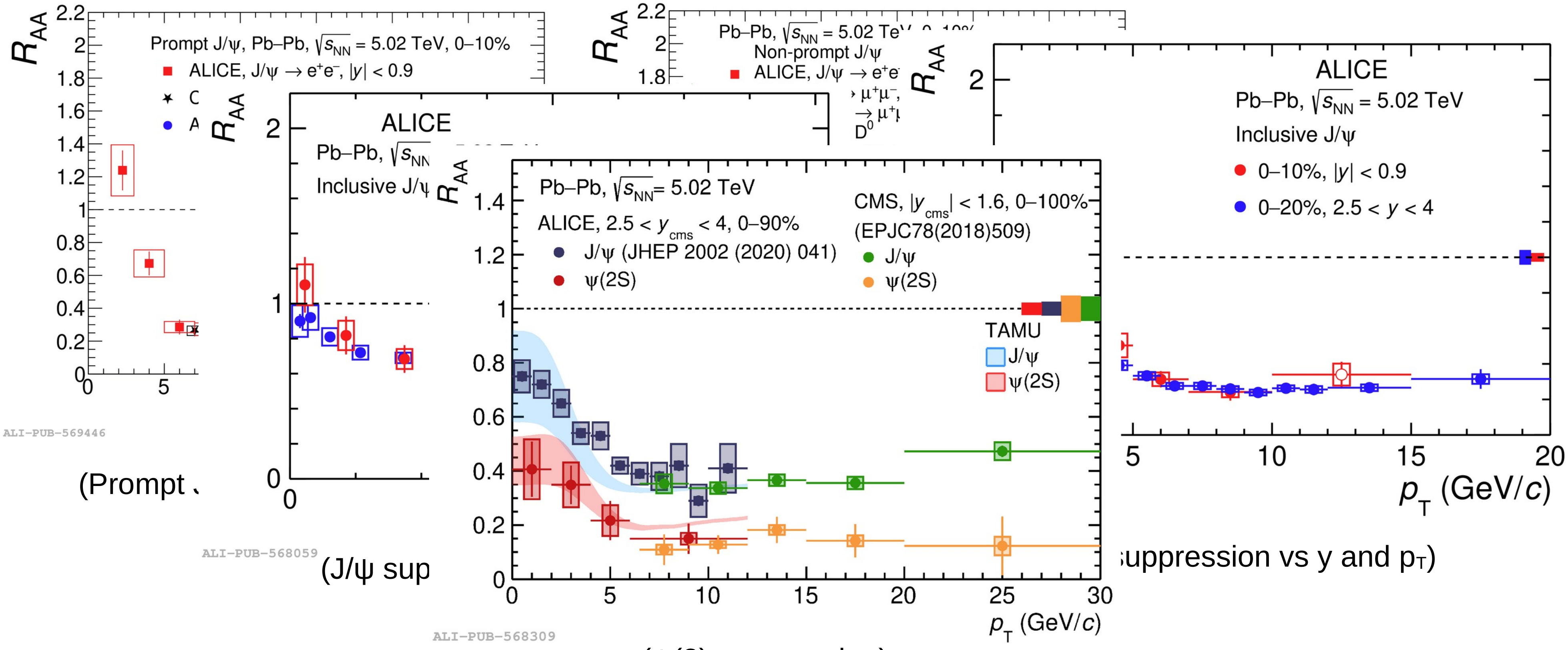


(Prompt ... sup

(J/ψ suppression vs y and centrality)

(J/ψ suppression vs y and p_T)

and heavy-ion collisions



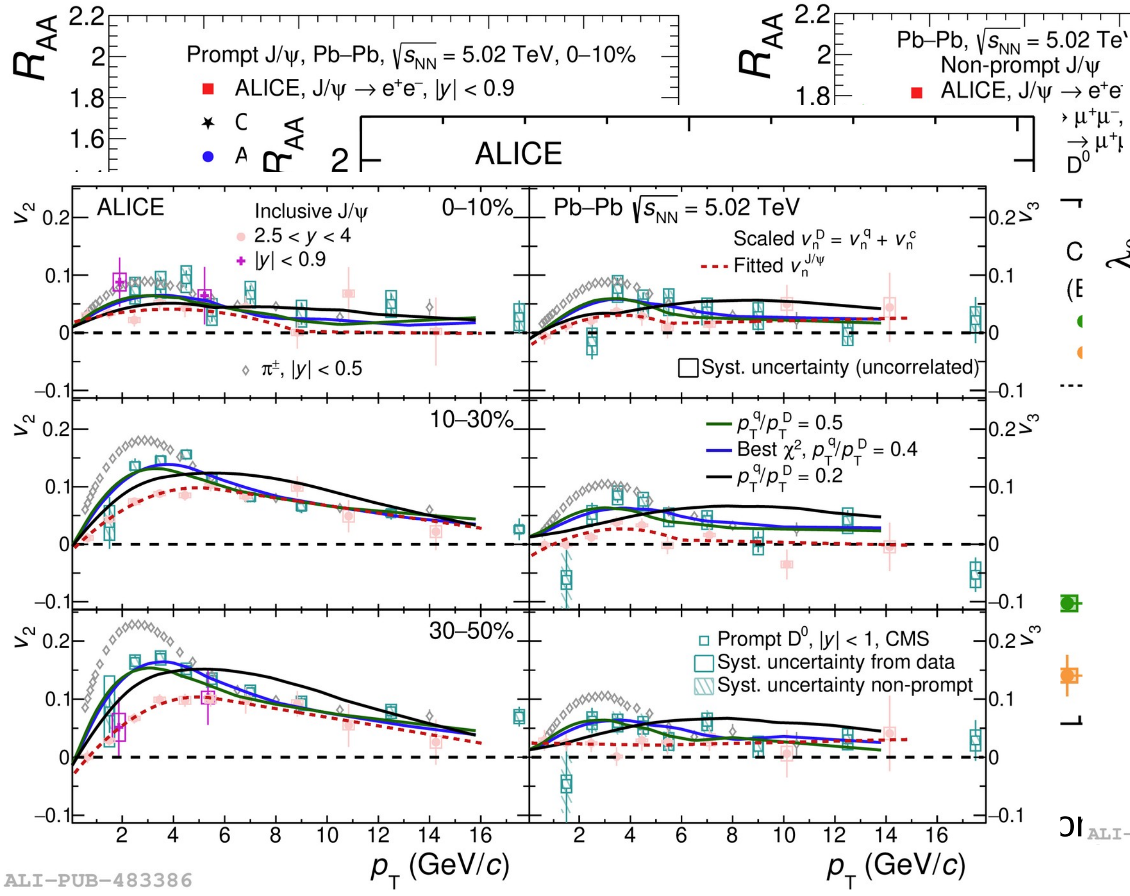
(Prompt J…

(J/ψ sup…

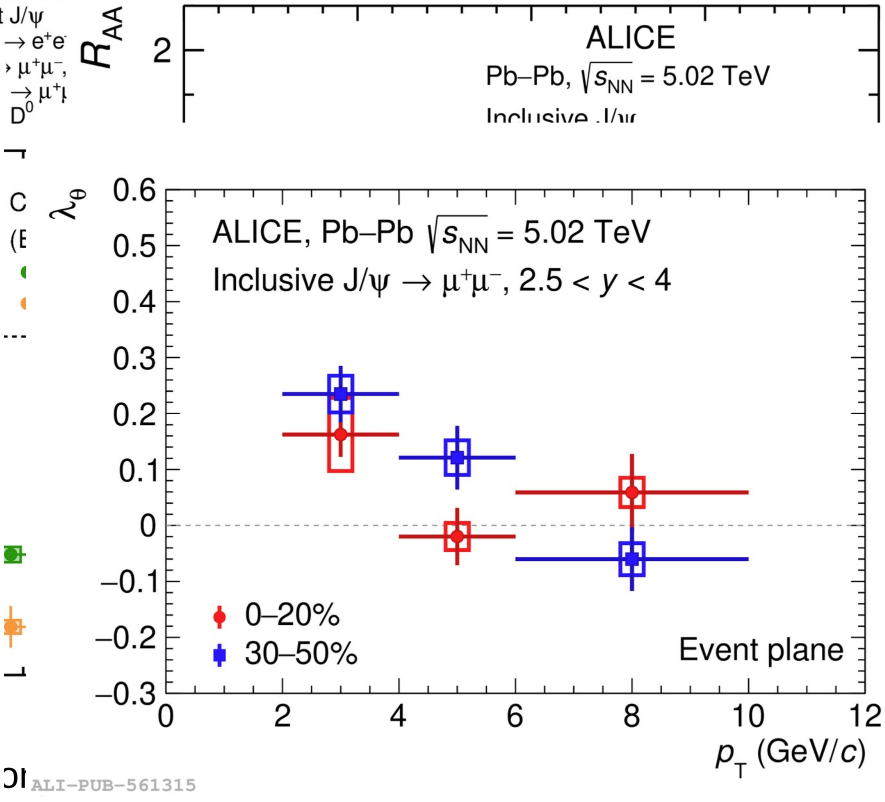
…uppression vs y and p_T)

(ψ(2) suppression)

and heavy-ion collisions

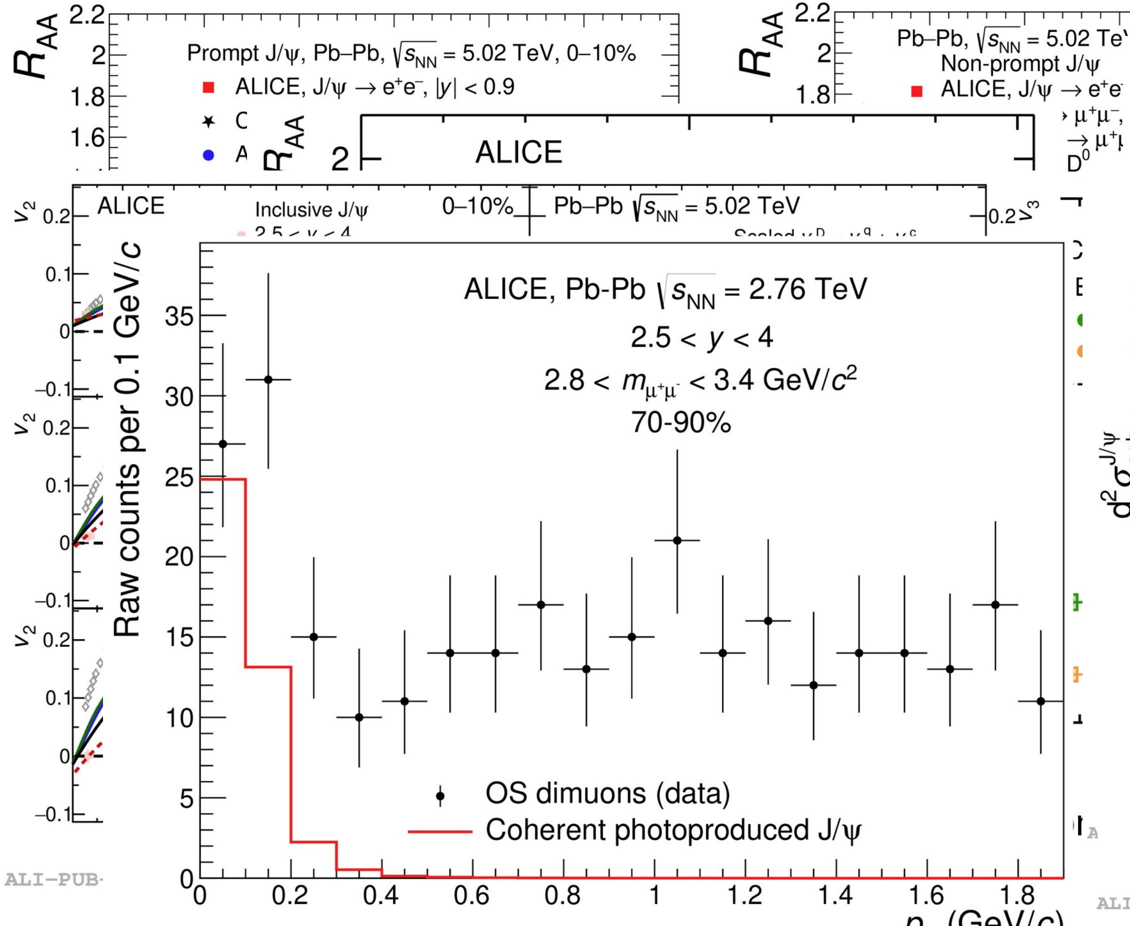


(ψ(2) anisotropic flow)

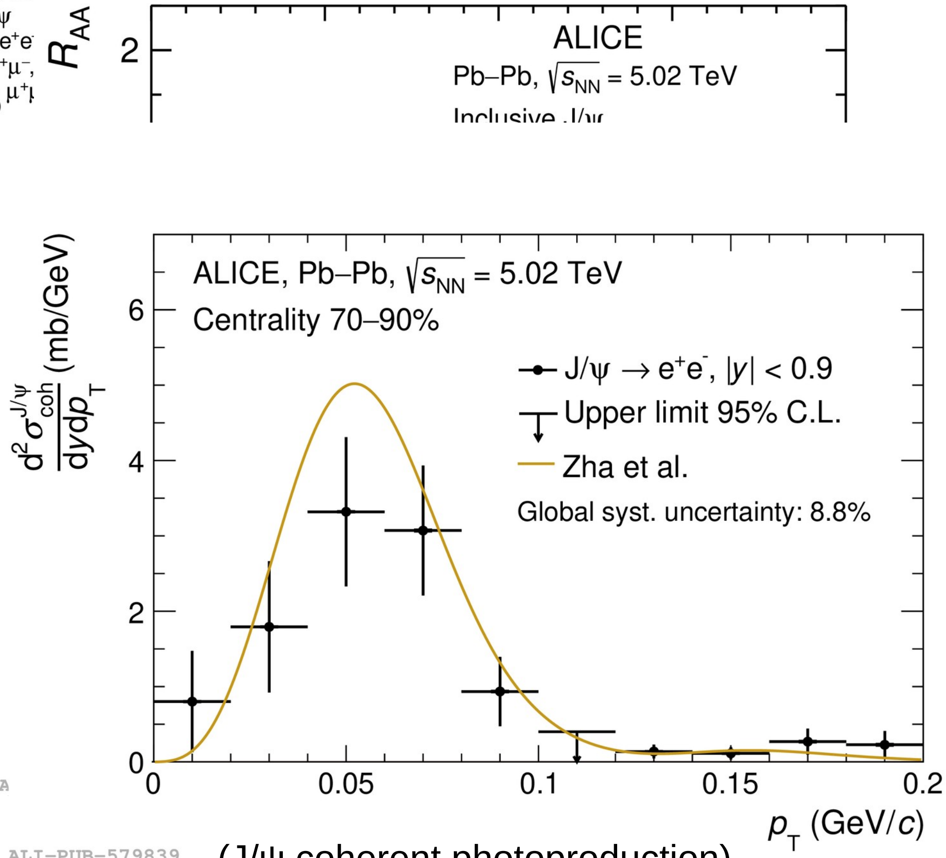


(J/ψ global polarization)

and heavy-ion collisions



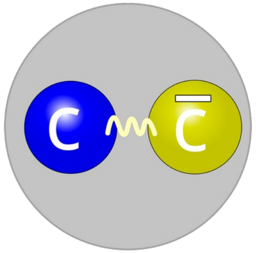
(J/ψ coherent photoproduction)

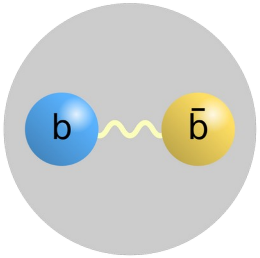


(J/ψ coherent photoproduction)

What is quarkonium ?

- Flavorless meson made of a **heavy** quark and its own anti-quark
  - Bound states well defined in terms of a quark-antiquark pair of a given flavour
  - No light-quark quarkonia !
  - No $t\bar{t}$ quarkonia !



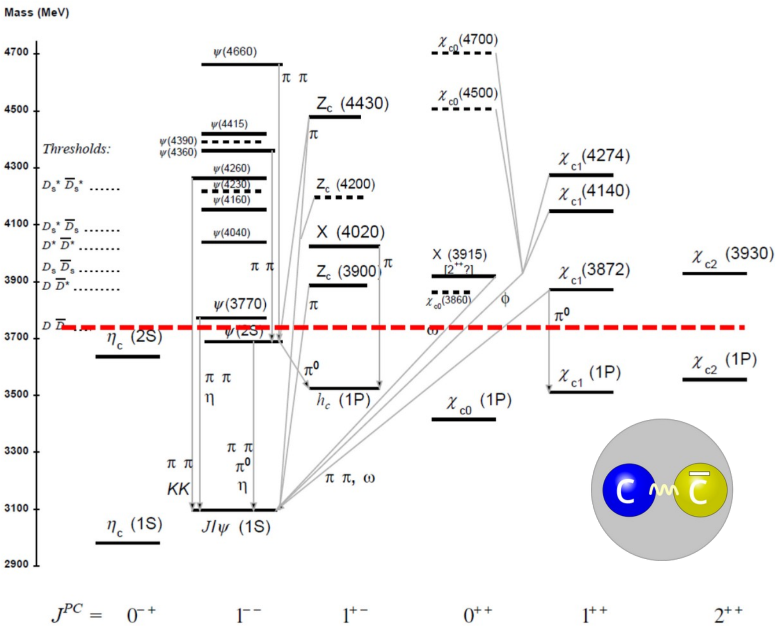


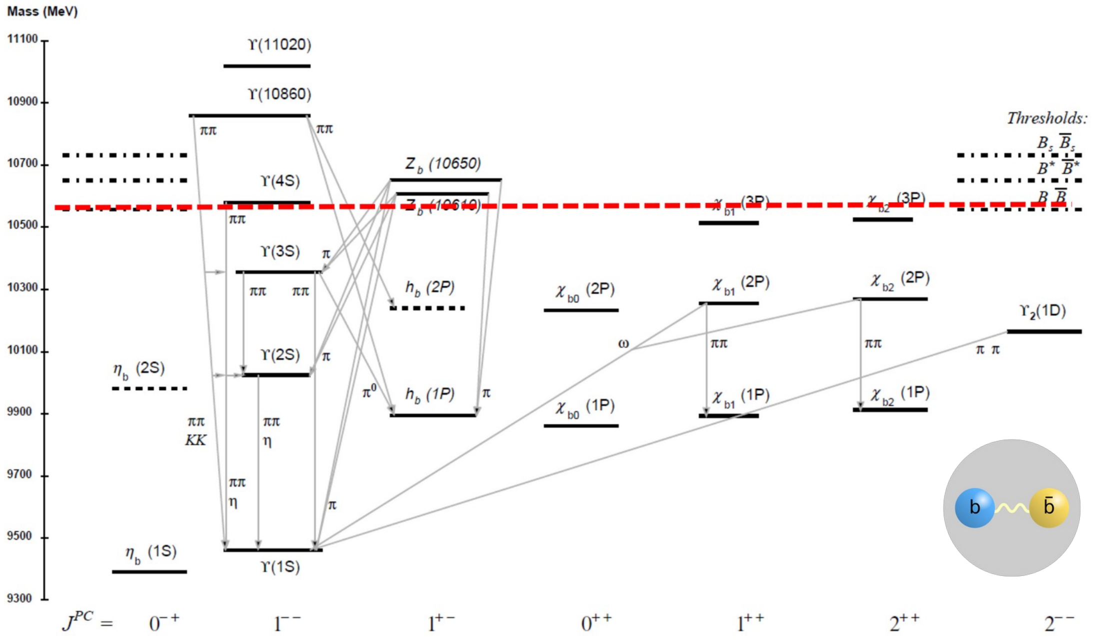
- Typical masses
  - $c\bar{c}$: m > 2.9 GeV/c^2 (m_c ~ 1.27 GeV/c^2)
  - $b\bar{b}$: m > 9.3 GeV/c^2 (m_b ~ 4.6 GeV/c^2)
- Non-relativistic quark-antiquark system
  - Properties can be explored to a fairly good precision using Schrodinger equation

$$H=\frac{\boldsymbol{p}^2}{2\mu}+V_{total}$$

$$V_{total}=(-q)\frac{q}{4\pi r}+kr$$

Quarkonium spectroscopy

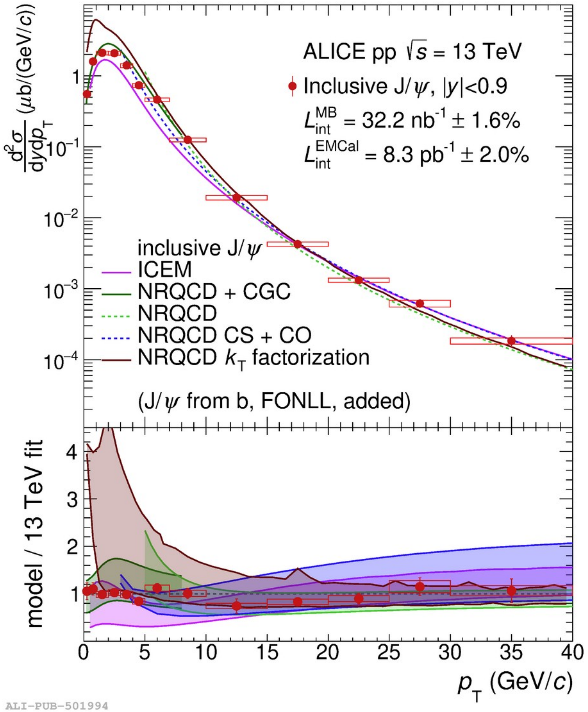




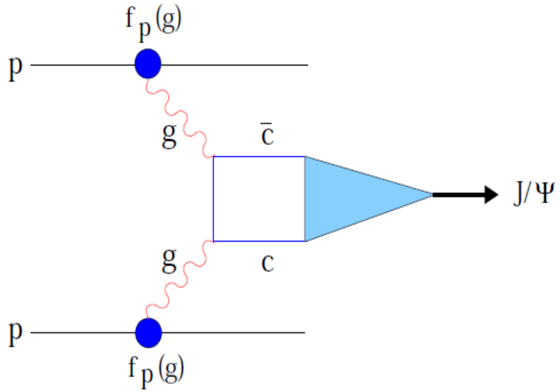
Thanks to data from CLEO, BELLE, BES, BABAR, CDF

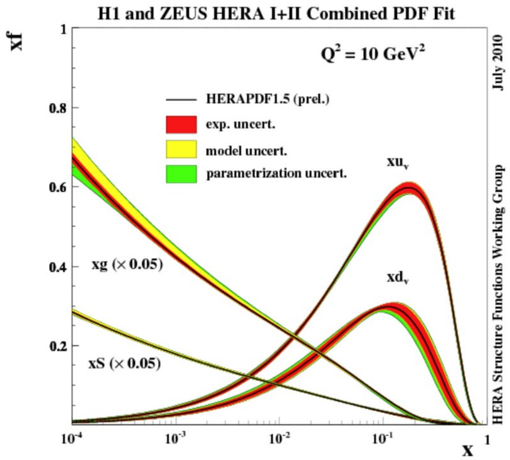
- Below open heavy flavor threshold
  - Very narrow widths, Γ < 1 MeV for most vector states
  - Large binding energy, e.g. > 1 GeV for Y(1S)

Quarkonium production in the vacuum



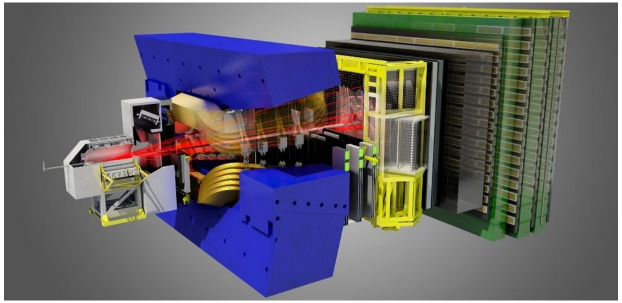
(Differential J/ψ yields)

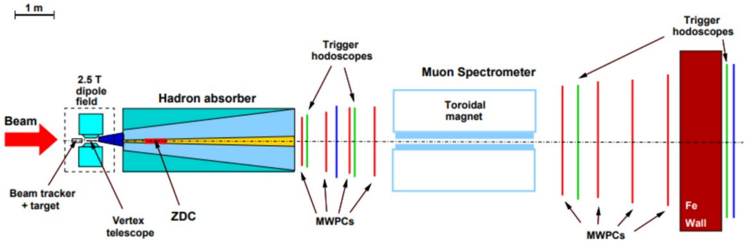


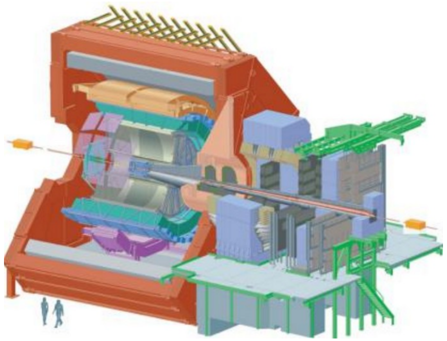


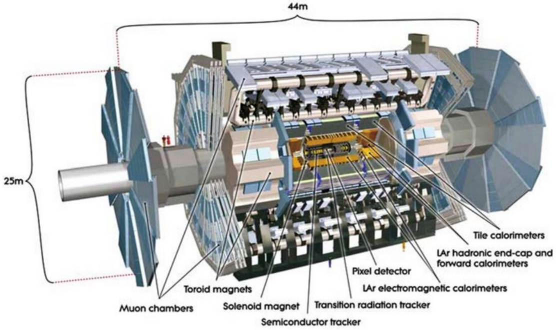
- Quarkonia predominantly produced via hard gluon fusion
- Unique test for QCD
  - Large momentum transfer for the $Q\bar{Q}$ pair creation (pQCD)
  - Small quark velocities in $Q\bar{Q}$ frame (non-perturbative)
- Main theoretical model: Non-Relativistic QCD (NRQCD)
  - Effective field theory
  - Based on the factorization of the soft and hard scales
- Production in pp is an important reference for the nuclear medium effects

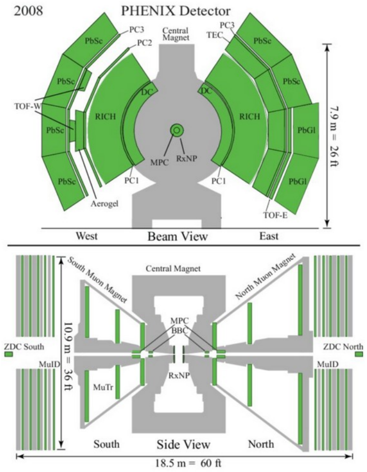
Quarkonium measurements in heavy-ion collisions







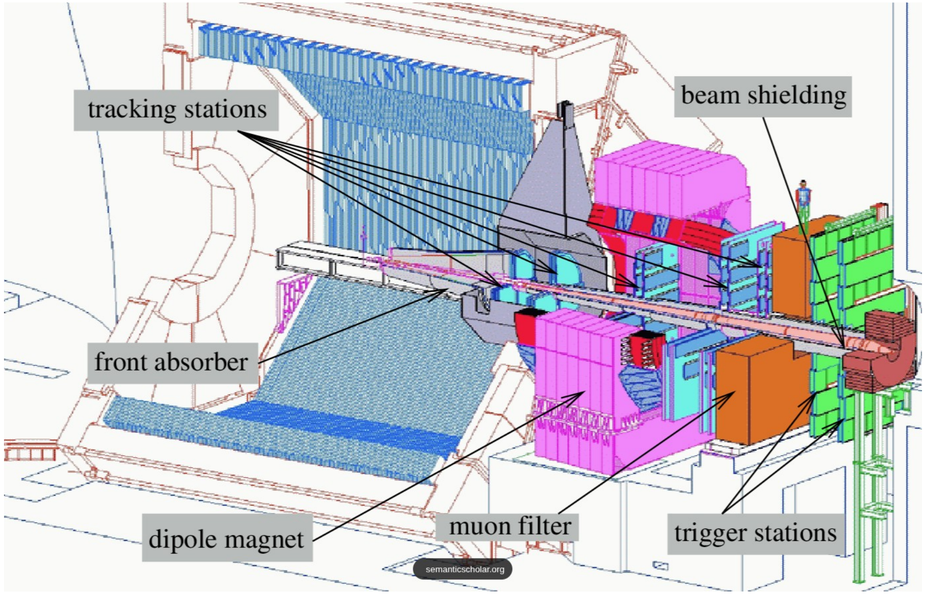


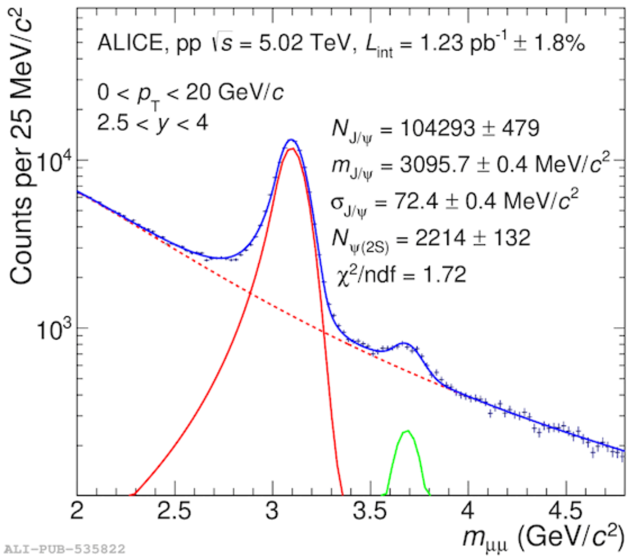


- Due to large hadronic backgrounds, measurements are mostly limited to the ψ and Υ families
- Decay channels exploited: e^+e^- and $\mu^+\mu^-$ a
- Experimental methods
  - Dimuons: spectrometers placed behind hadron absorbers
  - Dielectrons: tracking+PID, calorimeters, transition radiation

Measurements in the dimuon channel

ALICE MUON spectrometer

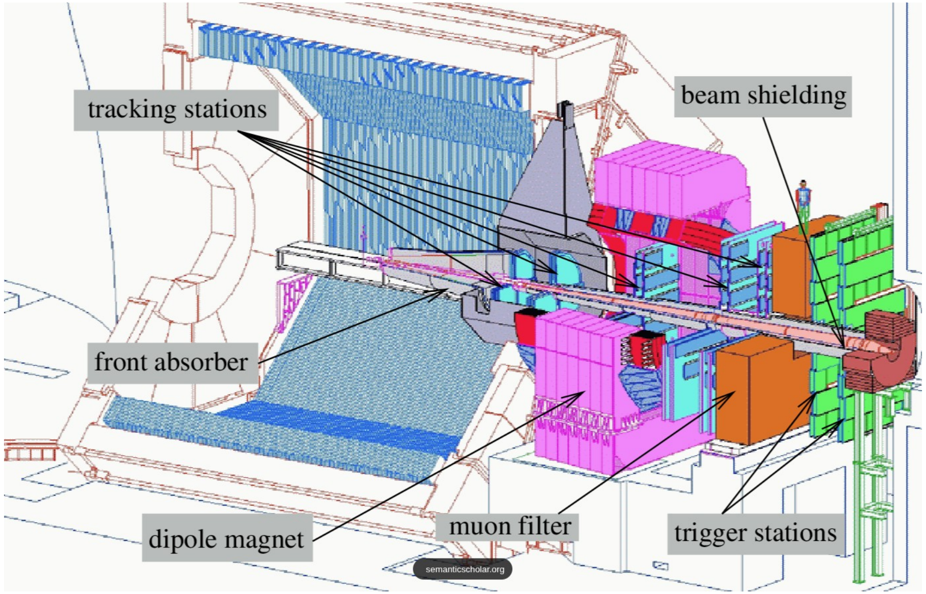




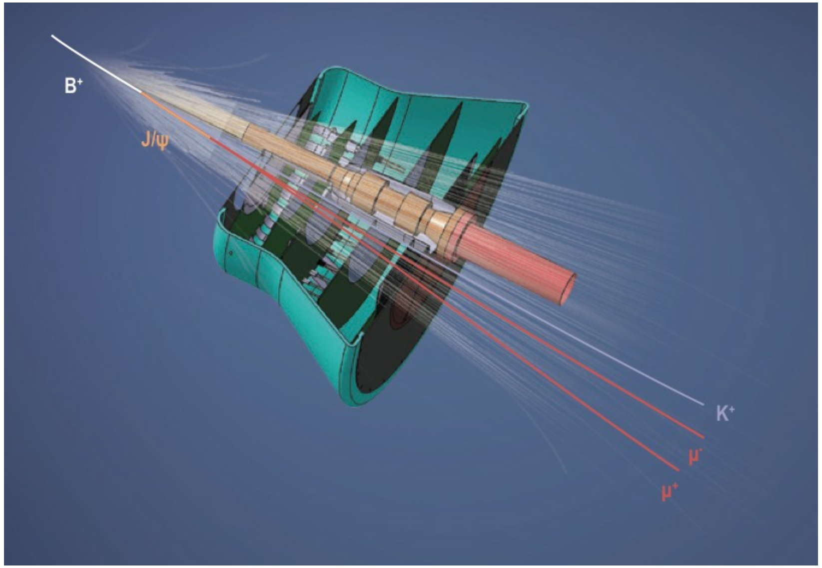
- "Passive" muon identification: filter out hadrons using thick absorbers
- Surviving tracks are likely muons → clean and high signal S/B ratio

Measurements in the dimuon channel

ALICE MUON spectrometer

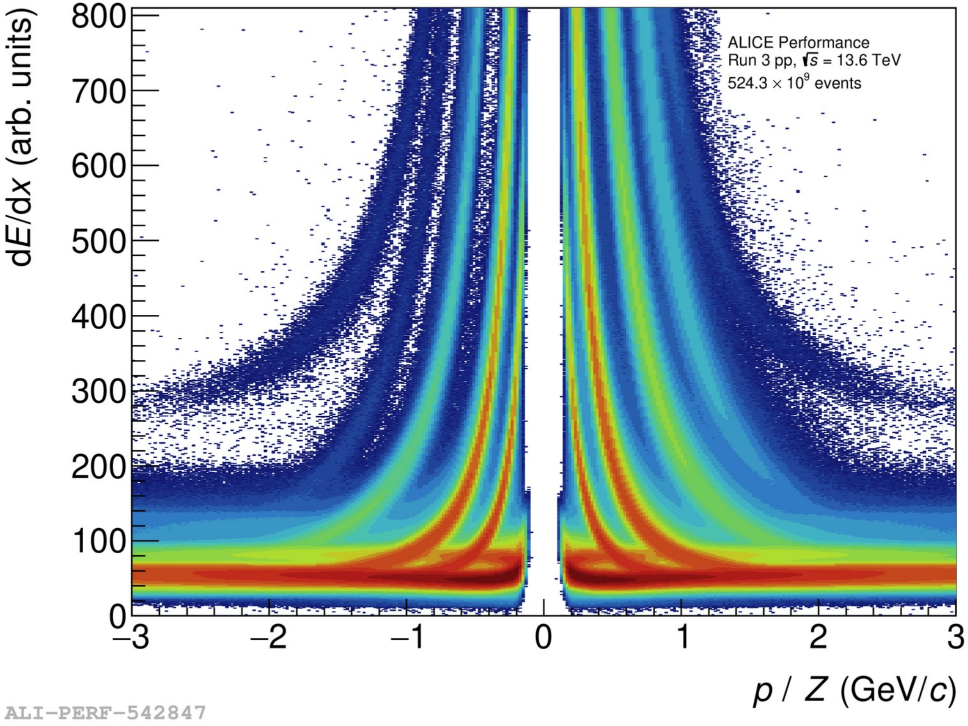


ALICE MUON Forward Tracker (MFT)

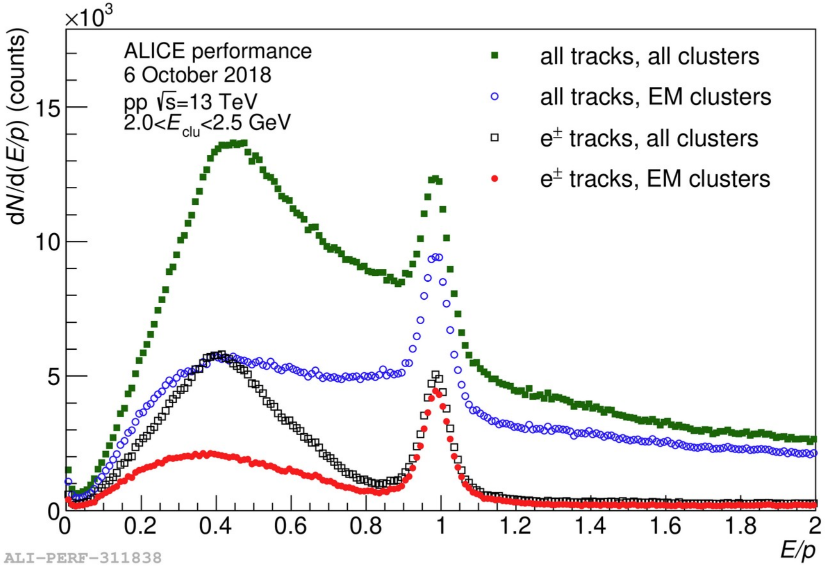


- “Passive” muon identification: filter out hadrons using thick absorbers
- Surviving tracks are likely muons → clean and high signal S/B ratio
- Adding a high precision in front of the absorber provides capability for secondary vertex reconstruction → measure non-prompt J/ψ
- **Pros:** negligible effects from radiative decays of J/ψ
- **Cons:** worse momentum resolution, experimentally require large detectors (absorbers + tracking beyond absorbers)

Measurements in the dielectron channel



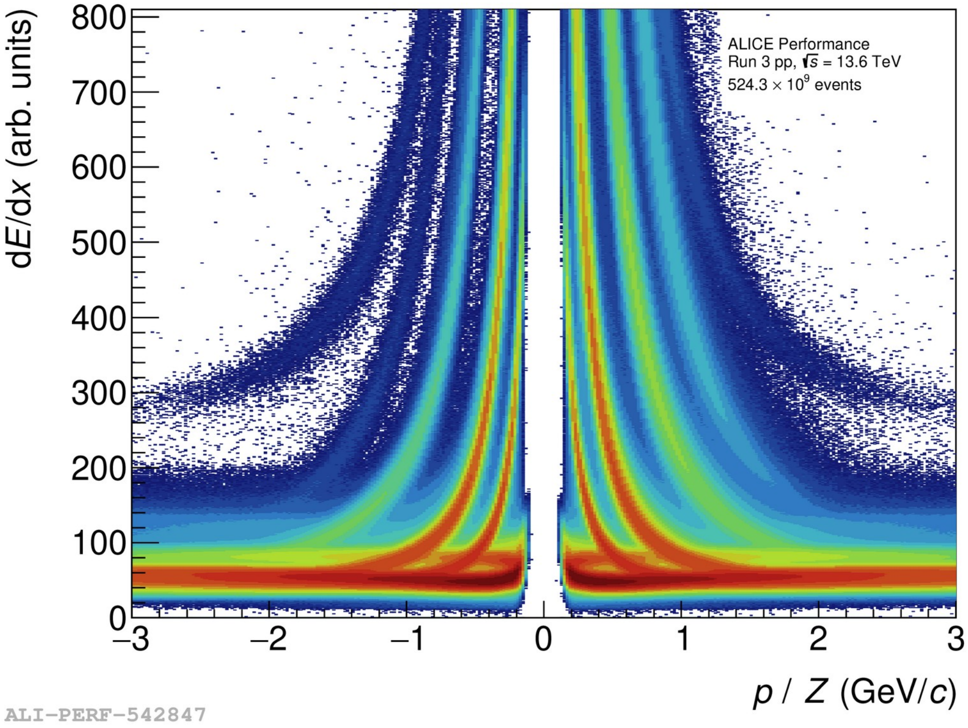
TPC dE/dx

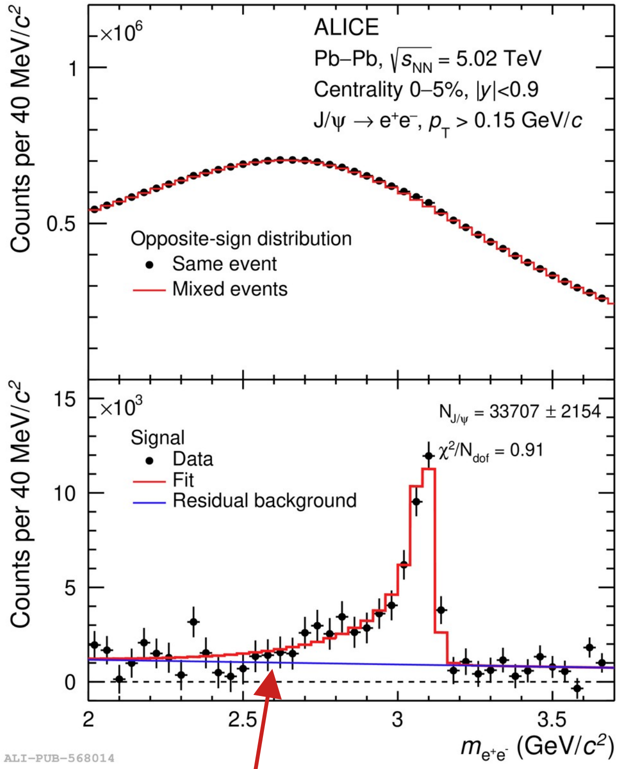


EMCAL E/p

- Electron identification mainly using Time Projection Chambers (TPC) and electro-magnetic calorimeters
- Pros: better momentum resolution, does not require dedicated detectors (TPC and EMCAL are multipurpose)
- **Cons:** relatively smaller S/B (depending on PID resolution), bremsstrahlung radiation

Measurements in the dielectron channel





TPC dE/dx

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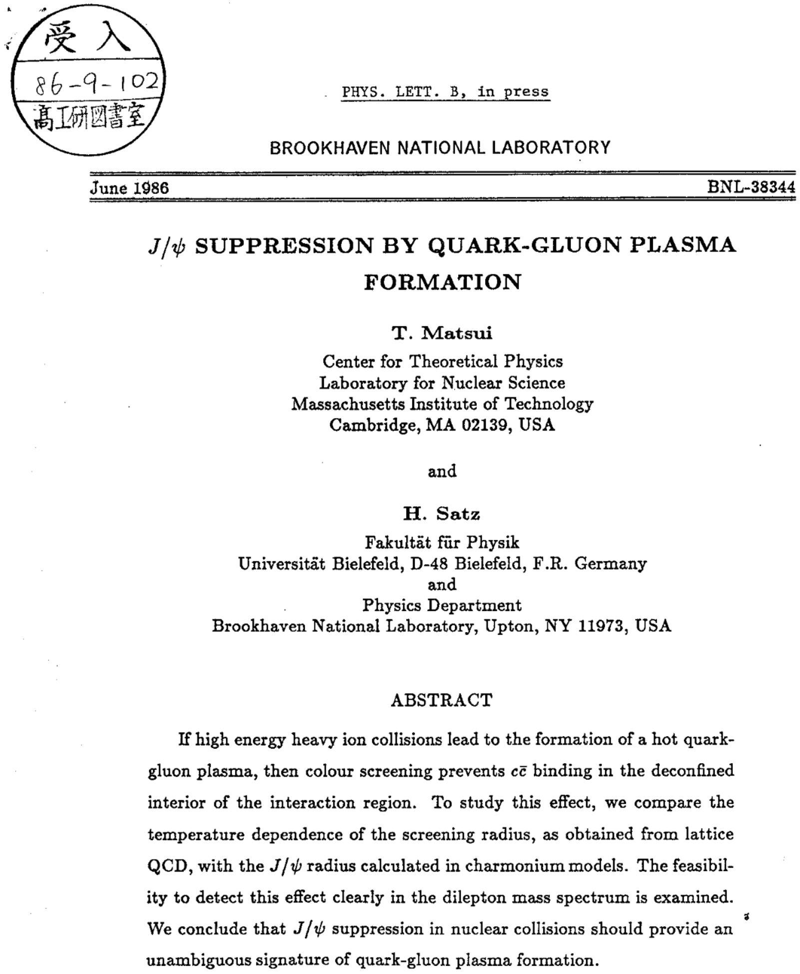
- Pros: better momentum resolution, does not require dedicated detectors (TPC and EMCAL are multipurpose)
- **Cons:** relatively smaller S/B (depending on PID resolution), bremsstrahlung radiation

The initial argument,



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高工研図書室

PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

T. Matsui

Center for Theoretical Physics
Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

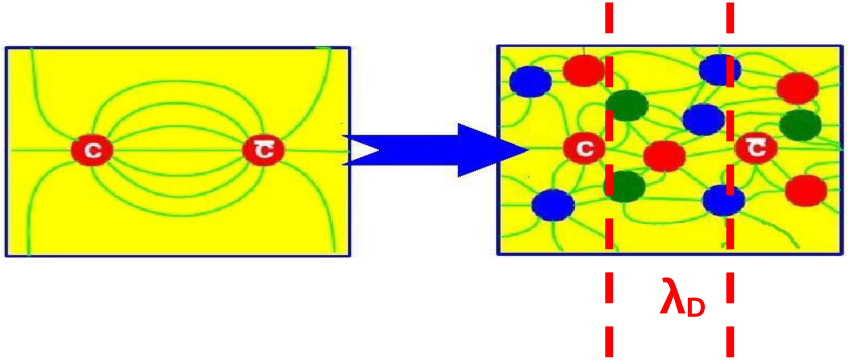
and

H. Satz

Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany
and
Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.



Vacuum potential (Cornell): $V_{total} = (-q)\dfrac{q}{4\pi r} + kr$

In-medium potential (Yukawa-like): $V_{medium}(\boldsymbol{r}) = \dfrac{q}{4\pi}\dfrac{e^{-r/\lambda_D}}{r}$

Debye screening length: $\lambda_D \simeq \dfrac{1}{T}$

Quarkonium states are melted if $r > \lambda_D$

The initial argument,

PHYS. LETT. B, in press

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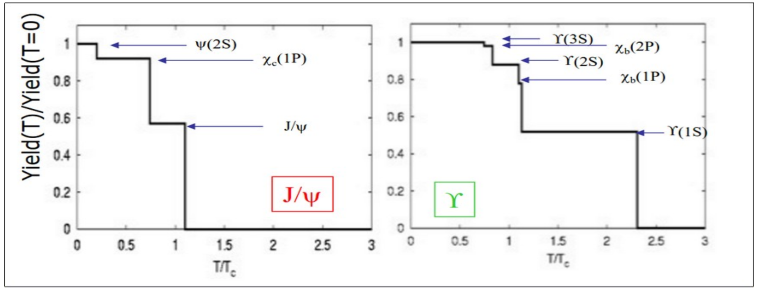
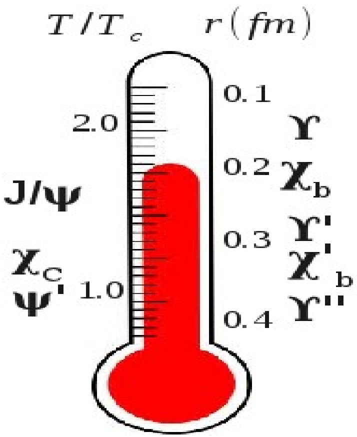
If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

($m_c = 1.25$ GeV, $m_b = 4.65$ GeV, $\sqrt{\sigma} = 0.445$ GeV, $\alpha = \pi/12$)





the initial observation

THE PRODUCTION OF J/Ψ
IN 200 GeV/NUCLEON OXYGEN–URANIUM INTERACTIONS

NA38 Collaboration

C. BAGLIN, A. BUSSIERE, J.P. GUILLAUD, H. OGREN [1], F. STALEY

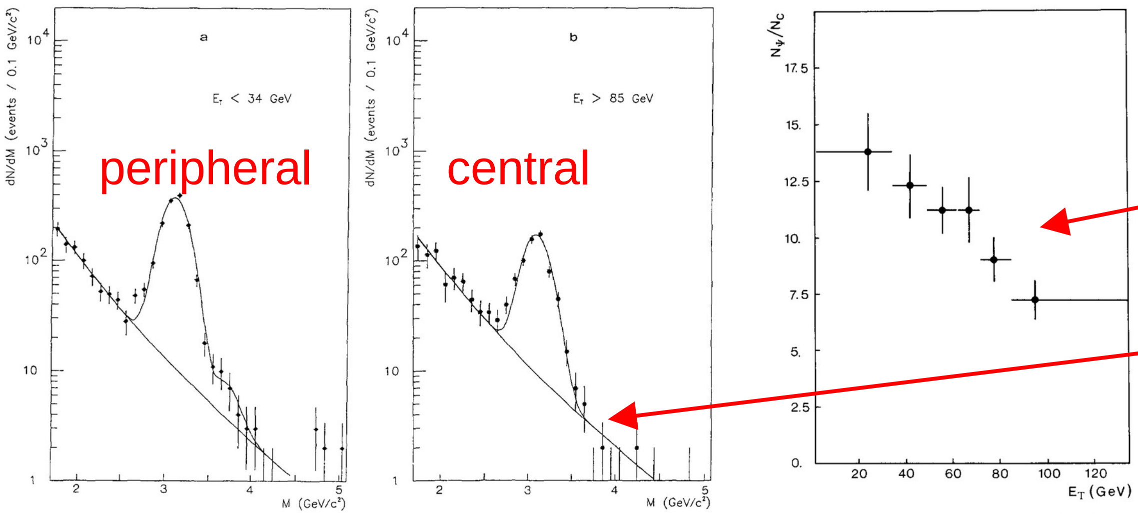


Fig. 5. Mass spectrum and fit of the signal muon pairs in two different E_T bins: $E_T < 34$ GeV (a) and $E_T > 85$ GeV (b).

Fig. 6. The evolution of $S = N_\Psi / N_c$ as a function of E_T.

- O-U collisions at $\sqrt{s_{NN}}$ ~ 20 GeV
- N_ψ / N_c decreases by a factor 2 from peripheral to central collisions
- Hint of ψ(2S) suppression

PLB220 (1989) 471

Z.Phys. 38 (1988) 117

...and the first debates

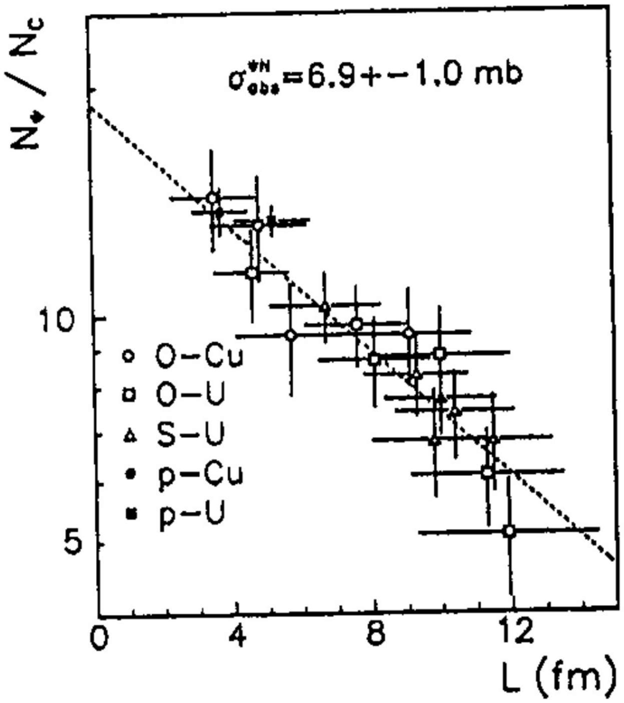


Fig.3 : E_T-dependence of J/ψ-suppression in NA38 data plotted as a function of L.

IPNO-DRE 92 - 01

Comparison of J/y-Suppression in Photon, Hadron and Nucleus-Nucleus Collisions :Where is the Quark-Gluon Plasma?

C. Gerschel[a] and J. Hüfner[b]

[a] Institut de Physique Nucléaire, 91406 Orsay Cedex, France
[b] Institut für Theoretical Physik, Universität Heidelberg, Germany

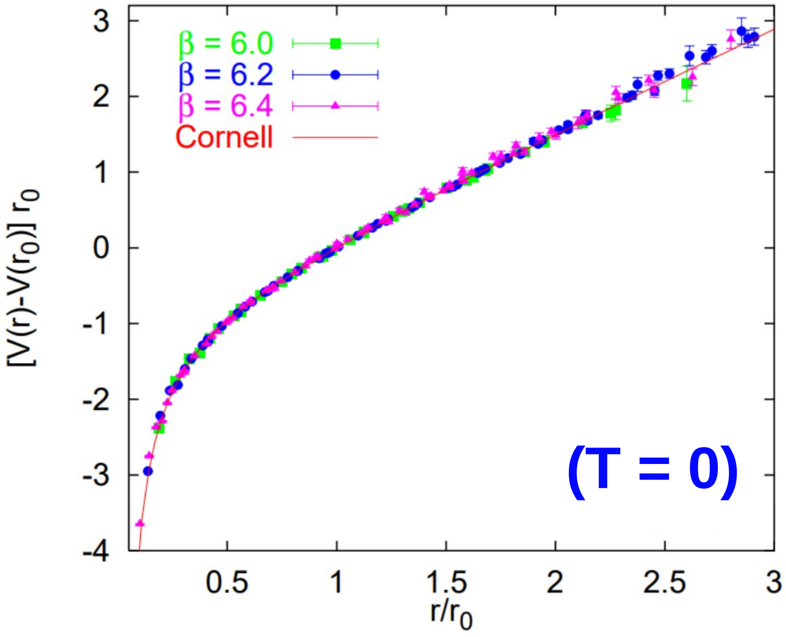
- J/ψ "suppression" in A-A and p-A depend on the average path length in cold nuclear matter
  - Dissociation in "cold" nuclear matter
  - Nuclear absorption: σ_{abs} ~ 7mb

- Nuclear absorption is a crucial ingredient in interpreting the data
- O – U system not hot/large enough for QGP formation?

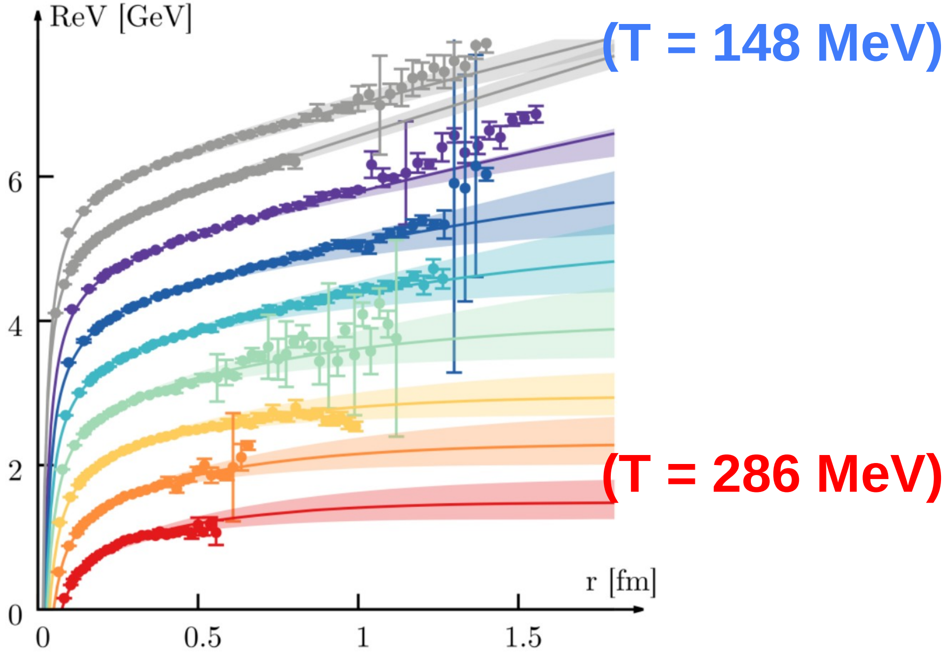
Gershel et al., PLB207 (1988) 253

Lattice calculations

G.S.Bali, Phys.Rep.343 (2001) 1-136

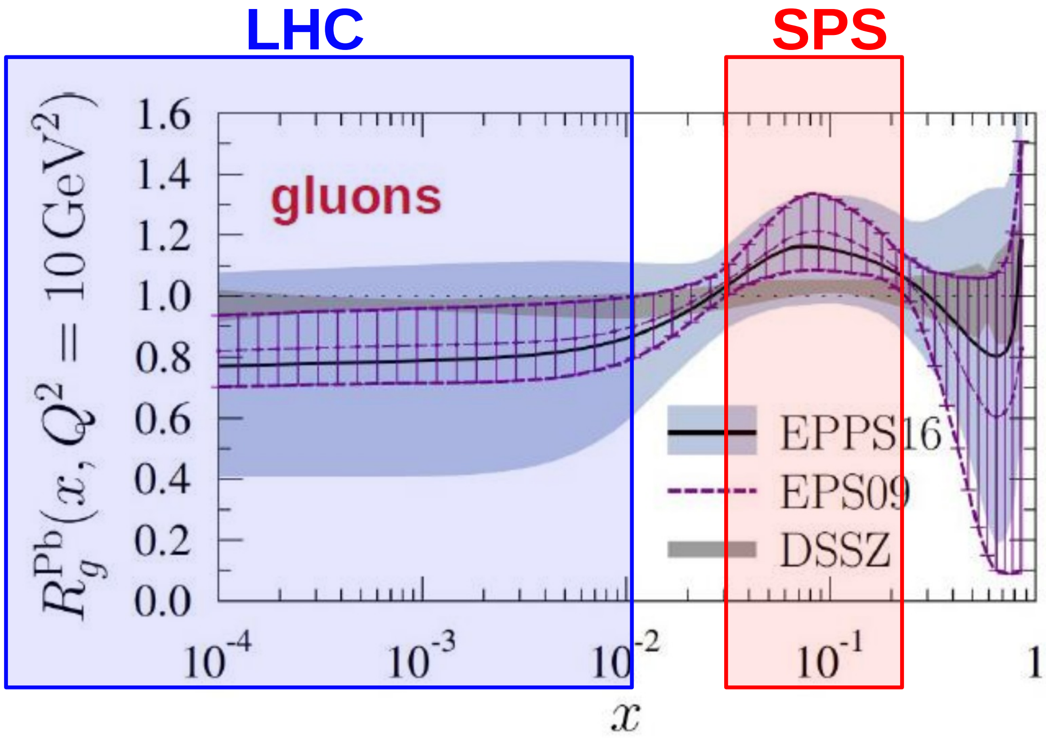


Lafferty and Rothkopf, PRD101 (2020) 056010



- Potential models provide a very good description of available lattice data
- Gradual transition from a Cornell potential to a Debye-screened behaviour
- Additional imaginary part of the potential features decaying of the QQ correlation due to gluonic damping in the plasma

Non-QGP effects (cold-nuclear matter): initial state



Charmonium production rate affected by the modification of parton PDFs in the nucleus

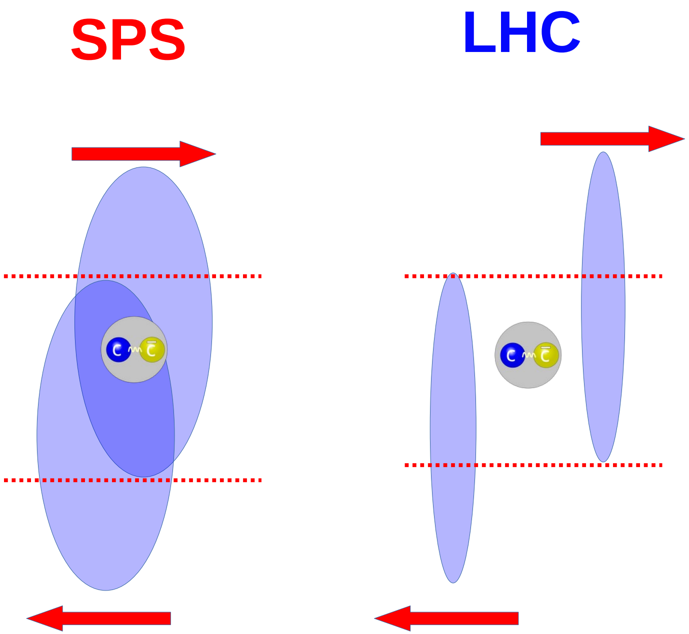
SPS:

moderate anti-shadowing, $x \sim 10^{-1}$ (y=0)

LHC:

shadowing, $x < 10^{-2}$ ($|y| < 3$)

Non-QGP effects (cold-nuclear matter): final state



Crossing time: $\tau = L/(\beta_z\gamma)$

After being produced, charmonia can be broken-up in the interaction with the nuclear remnants

SPS:

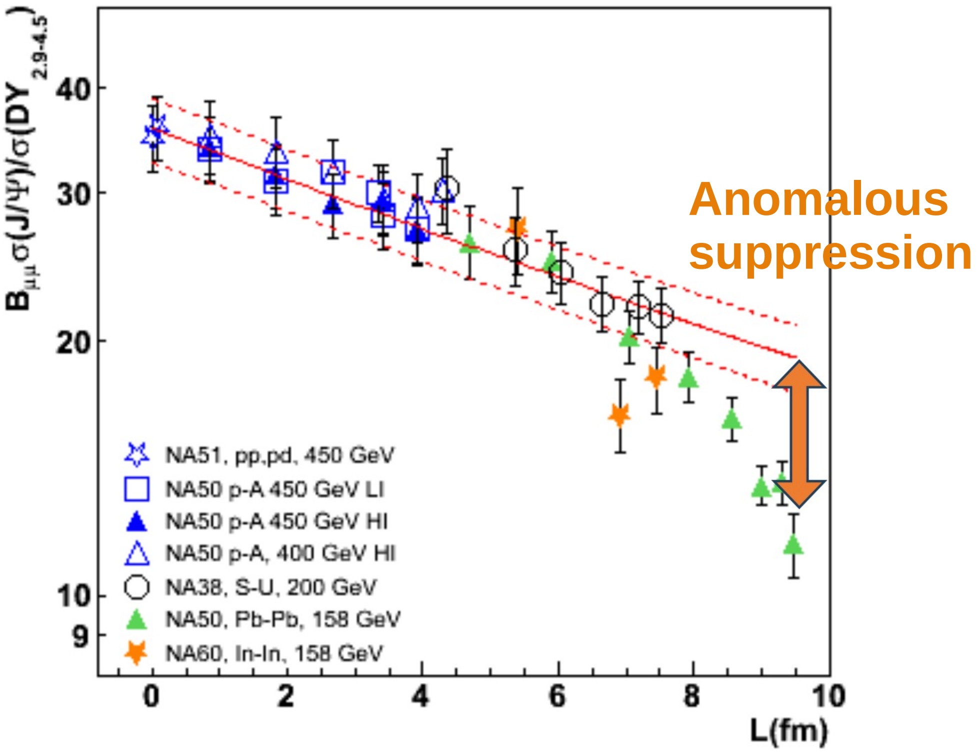
Break-up in nuclear matter, $\tau \sim 0.5$ fm/c

LHC

Very short crossing time, negligible break-up, $\tau <\sim 10^{-2}$ fm/c

The “anomalous” J/ψ suppression: Pb-Pb at the SPS

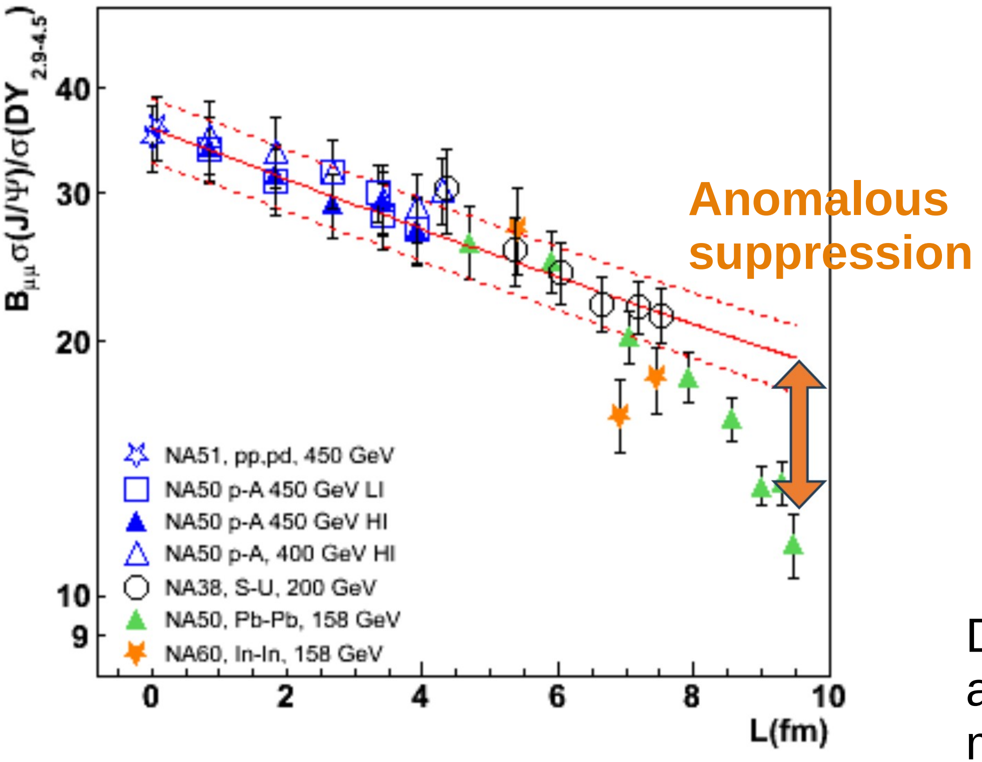
NA50, PLB410 (1997) 337

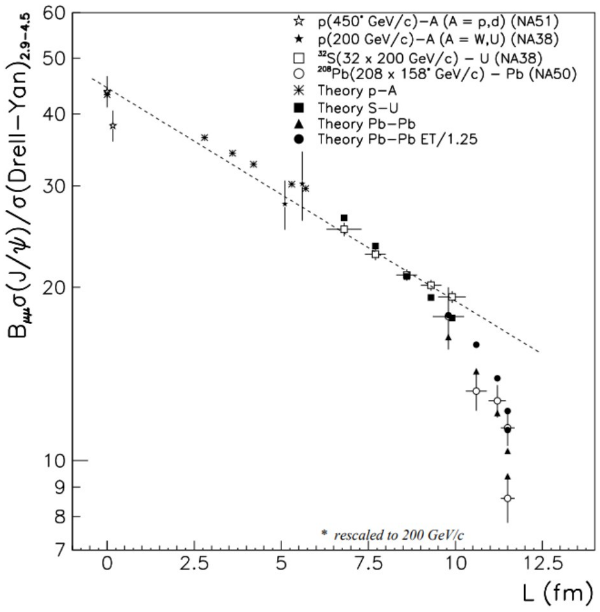


Central Pb-Pb collisions indicate suppression beyond the expectations from nuclear break-up

The “anomalous” J/ψ suppression: Pb-Pb at the SPS

NA50, PLB410 (1997) 337



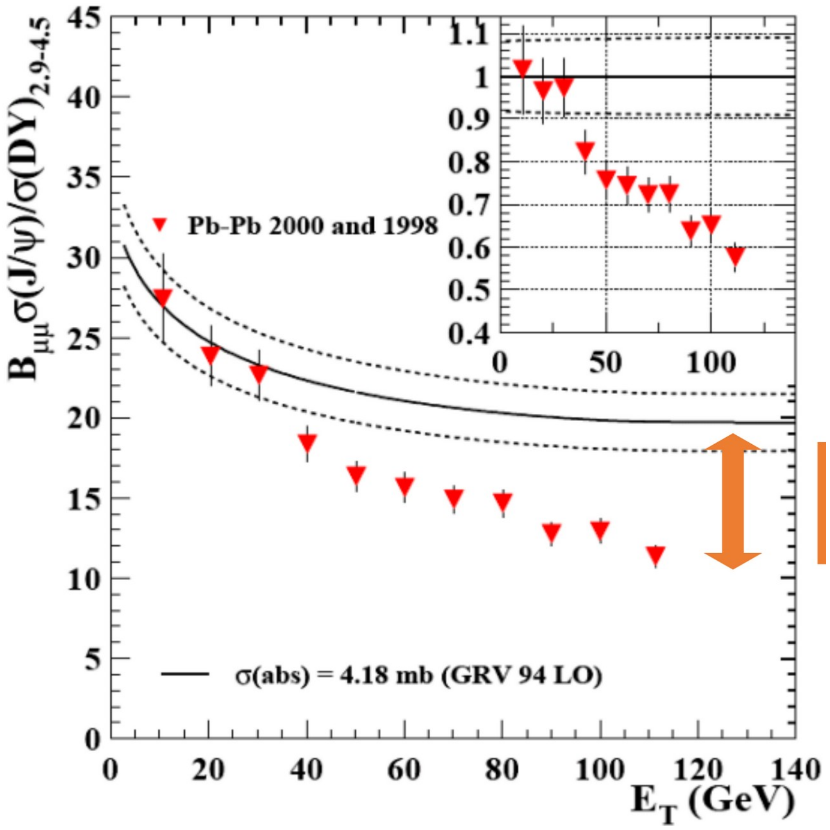


Central Pb-Pb collisions indicate suppression beyond the expectations from nuclear break-up

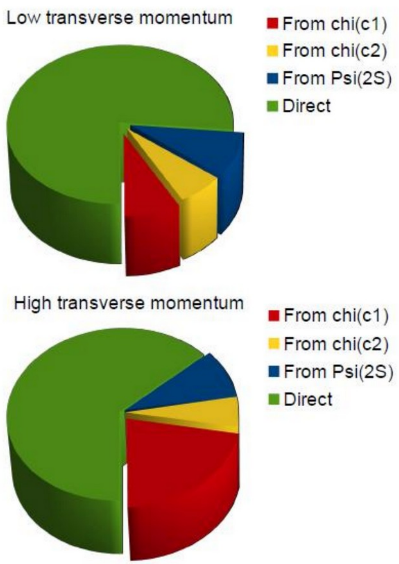
Data explained by combining nuclear absorption and final state interaction with co-moving hadrons. **A.Capella**

The “anomalous” J/ψ suppression: Pb-Pb at the SPS

NA50, EPJC 39 (2005) 335

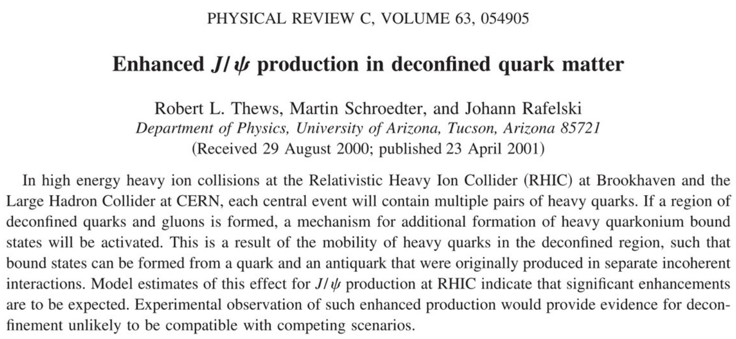


J.P.Lansberg, Phys.Rept. 889 (2020) 1



- The amplitude of the anomalous suppression compatible with the contribution of decays from ψ(2S) and χ_c
- Sequential suppression of weaker bound charmonia ?

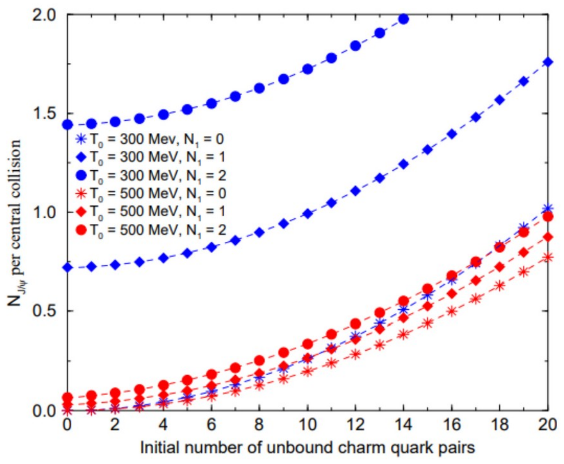
RHIC: J/ψ enhancement

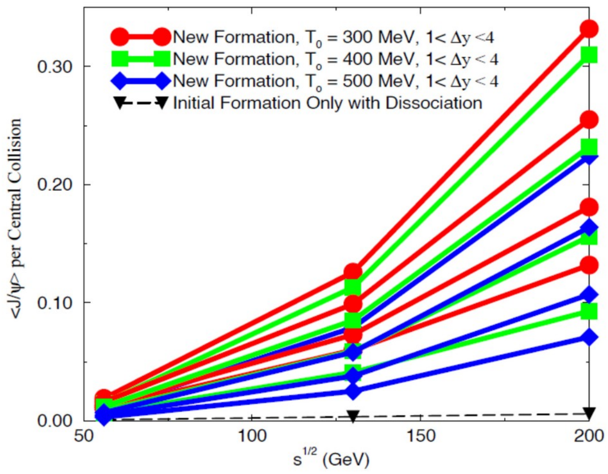

PHYSICAL REVIEW C, VOLUME 63, 054905

Enhanced J/ψ production in deconfined quark matter

Robert L. Thews, Martin Schroedter, and Johann Rafelski
Department of Physics, University of Arizona, Tucson, Arizona 85721
(Received 29 August 2000; published 23 April 2001)

In high energy heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and the Large Hadron Collider at CERN, each central event will contain multiple pairs of heavy quarks. If a region of deconfined quarks and gluons is formed, a mechanism for additional formation of heavy quarkonium bound states will be activated. This is a result of the mobility of heavy quarks in the deconfined region, such that bound states can be formed from a quark and an antiquark that were originally produced in separate incoherent interactions. Model estimates of this effect for J/ψ production at RHIC indicate that significant enhancements are to be expected. Experimental observation of such enhanced production would provide evidence for deconfinement unlikely to be compatible with competing scenarios.





Thews et al.

- Strong prediction of J/ψ enhancement due to
  - Many charm quark pairs per event produced at RHIC
  - Recombination of the initial unbound charm quarks into charmonium
    - Quadratic dependence on initial charm quark number

RHIC: J/ψ enhancement

Physics Letters B
Volume 490, Issues 3–4, 5 October 2000, Pages 196-202

(Non)thermal aspects of charmonium production and a new look at J/ψ suppression ☆

P. Braun-Munzinger [a], J. Stachel [b]

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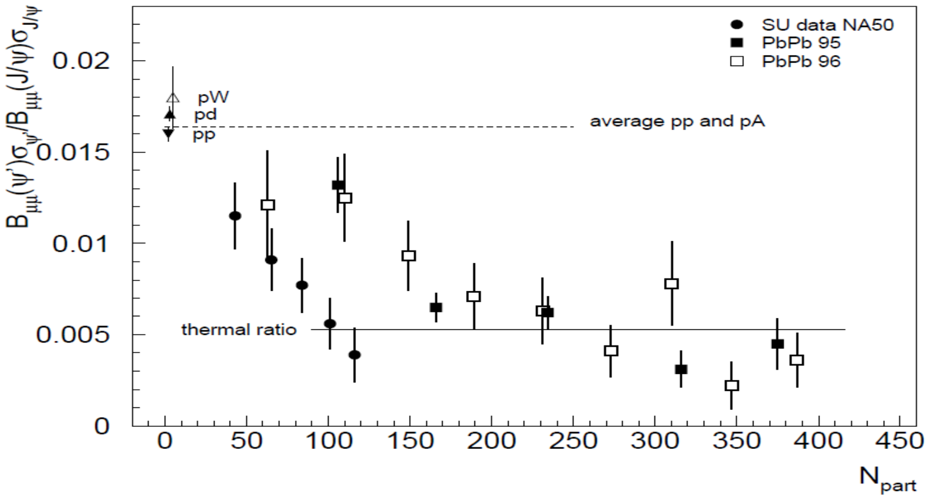
Abstract

To investigate a recent proposal that J/ψ production in ultra-relativistic nuclear collisions is of thermal origin we have reanalyzed the data from the NA38/50 Collaboration within a thermal model including charm. Comparison of the calculated with measured yields demonstrates the non-thermal origin of hidden charm production at SPS energy. However, the ratio $\psi'/(J/\psi)$ exhibits, in central nucleus-nucleus collisions, thermal features which lead us to a new interpretation of open charm and charmonium production at SPS energy. Implications for RHIC and LHC energy measurements will be discussed.



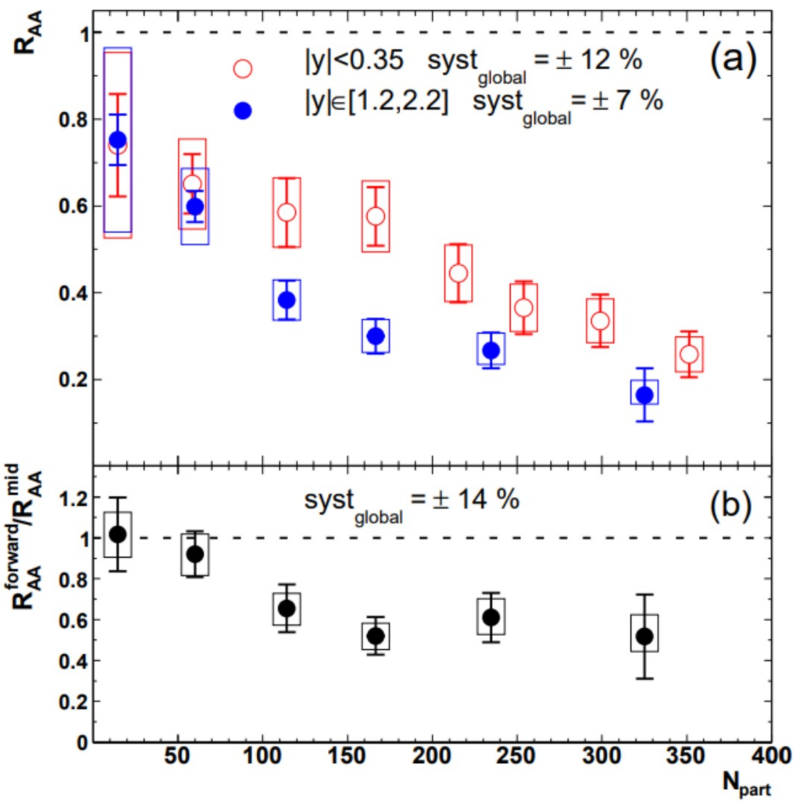
$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V \left(\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm}\right) + g_c^2 V \left(\sum_i n_{\psi_i}^{therm}\right) + \ldots.$$

P.Braun-Munzinger and J.Stachel

- J/ψ yields are not thermal !
- Ratio of ψ(2S) / J/ψ converges to the expected thermal ratio
- Direct production of charm quarks followed by statistical hadronization at freeze-out

RHIC: the J/ψ suppression measurement

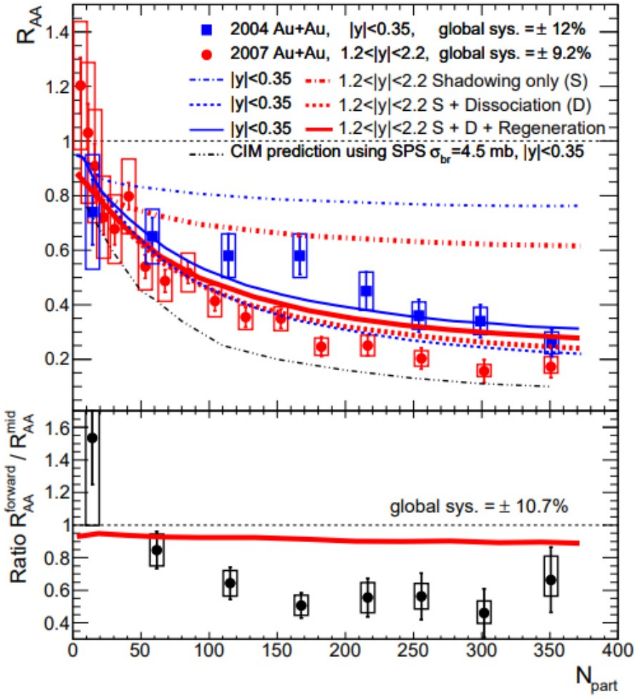
PHENIX, PRL 98 (2007) 232002



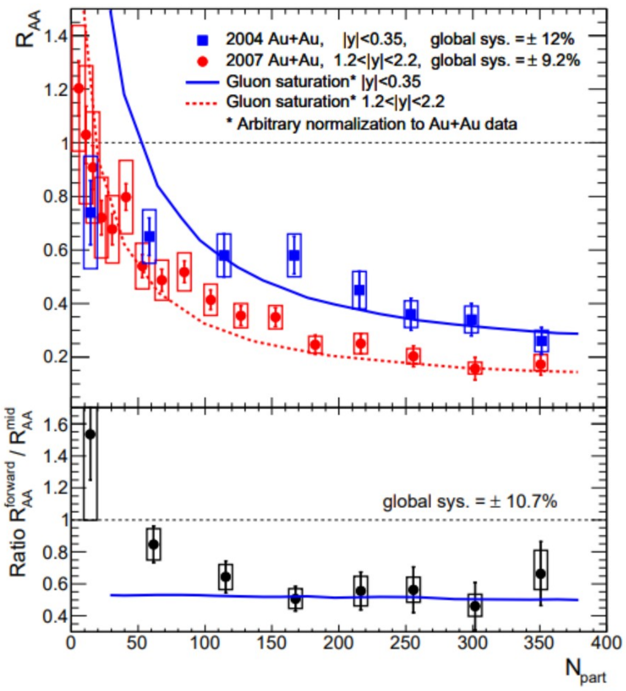
- Nuclear suppression measurements at RHIC done using the nuclear modification factor R_{AA}
  - Drell-Yan reference not easily accesible in high energy experiments
- Measurement done both at mid- and forward rapidity
- Counter-intuitive results
  - Expectation: higher energy density at mid-y leads to stronger suppression
  - Can regeneration explain the observations?

RHIC: the J/ψ suppression measurement

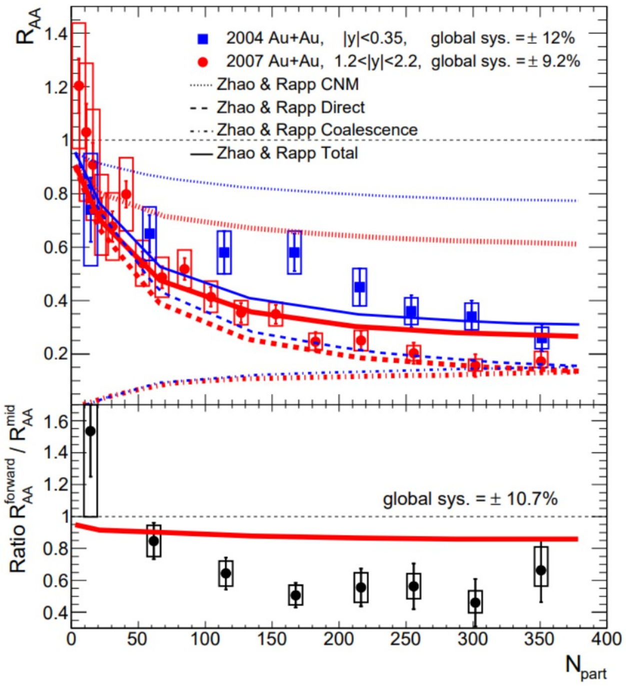
PHENIX, PRC 84, 054912



Comover interaction model



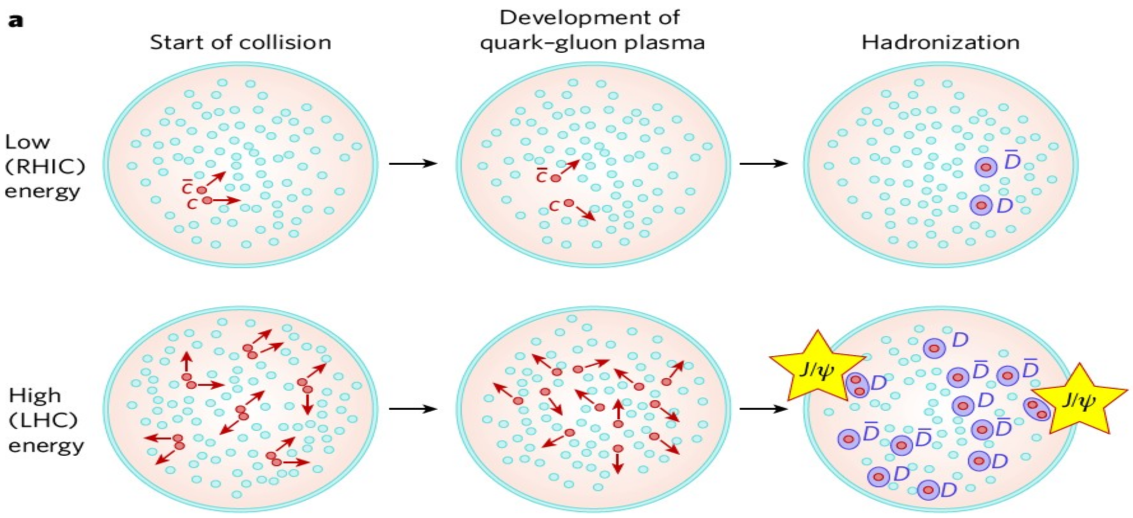
Gluon saturation model



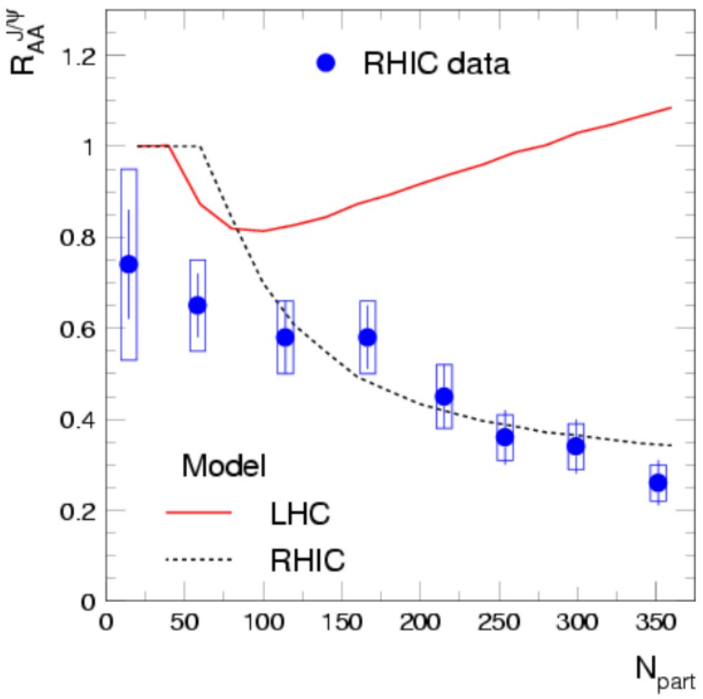
QGP/Hadron gas model

- Explaining the data requires a combination of cold and hot matter effects
  Difficult task for phenomenology !

Moving to the LHC: charmonium



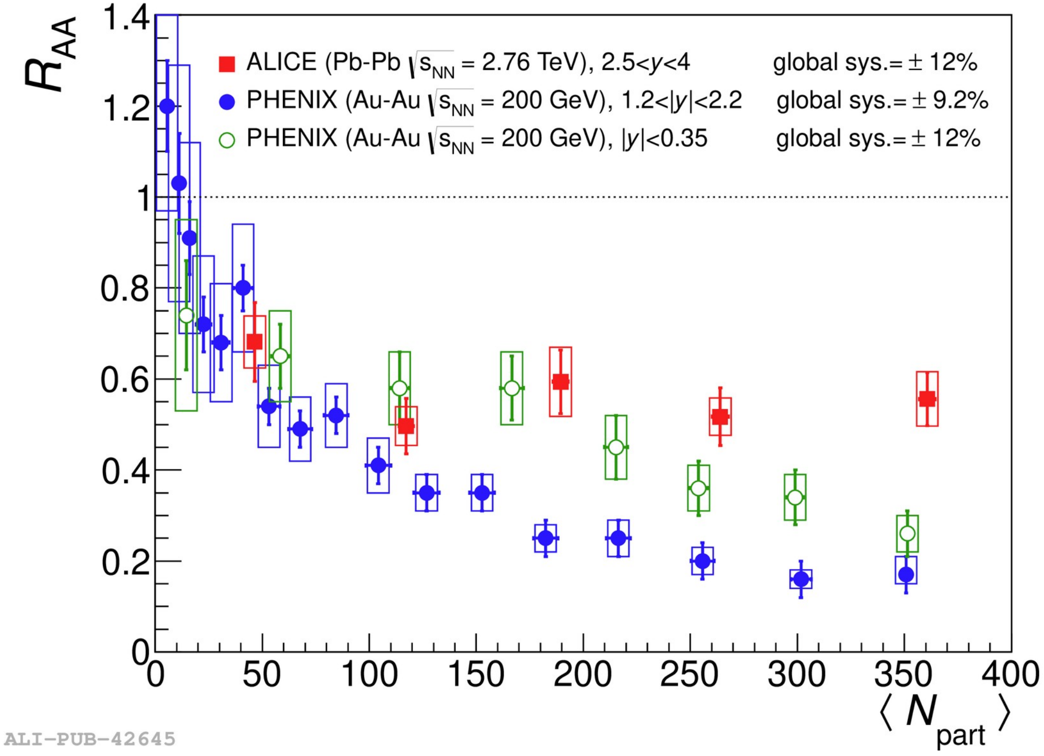
A.Andronic et al., NPA789 (2007) 334
P.Braun-Munzinger, J.Stachel, PLB490 (2000) 196



- Predictions based on the Statistical Hadronization Model (SHM)
  - Charm produced in primary hard collisions
  - Total number of charm is conserved
  - Main assumption: Charm becomes thermally equilibrated in the QGP
  - Quarkonia (and other charm hadrons) are generated with thermal weights at freeze-out

J/ψ suppression at the LHC

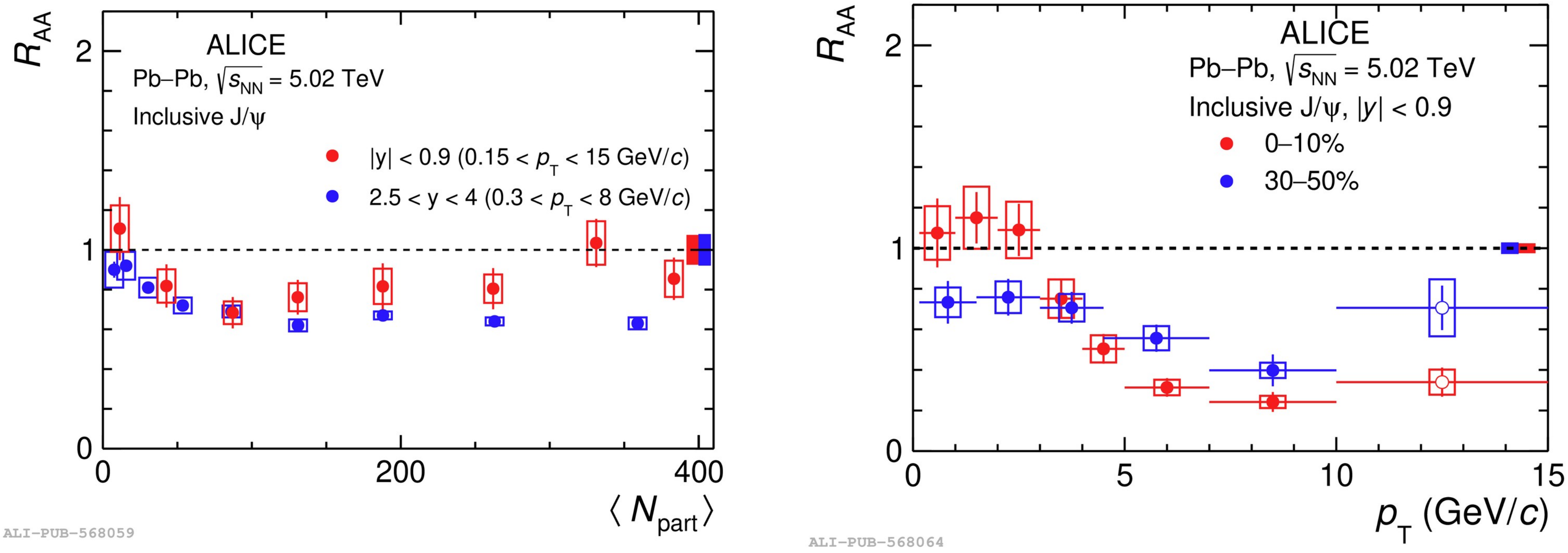
ALICE, PRL 109 (2012) 072301



- RHIC to LHC: factor > 10 in energy increase
- R_{AA} larger by factor 2 at LHC in central Pb-Pb
- Regeneration effects at play ?

J/ψ suppression at the LHC at mid-rapidity

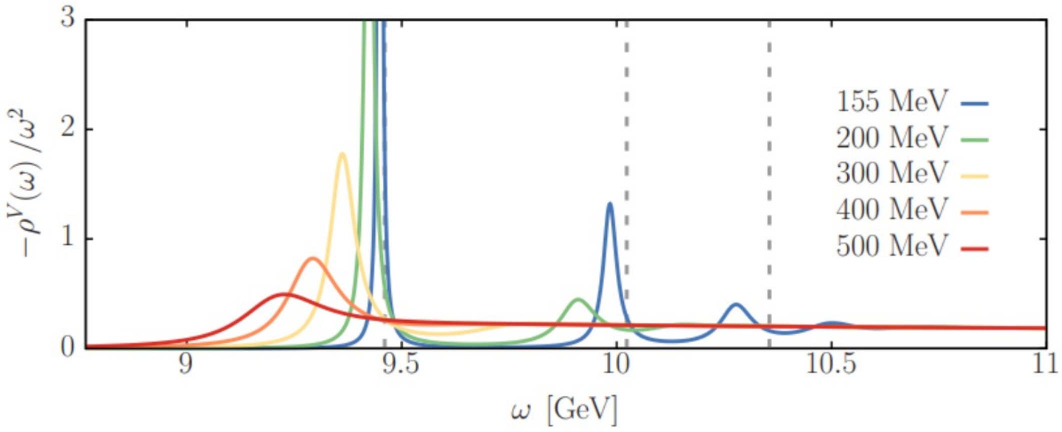
ALICE, PLB 849 (2024) 138451

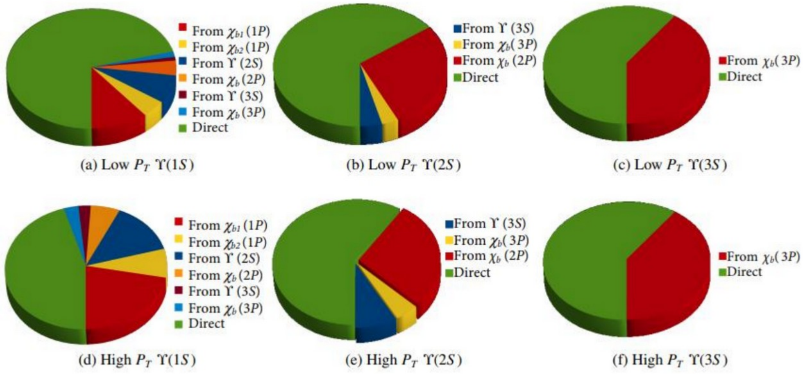


- R_{AA} larger at mid-y
  - Integrated R_{AA} seems to become larger towards central collisions
  - p_T-differential R_{AA} is larger at low-p_T
- Expected if regeneration plays a dominant role due to higher charm density

What about bottomonium ?

Lafferty and Rothkopf, PRD 101 (2020) 056010



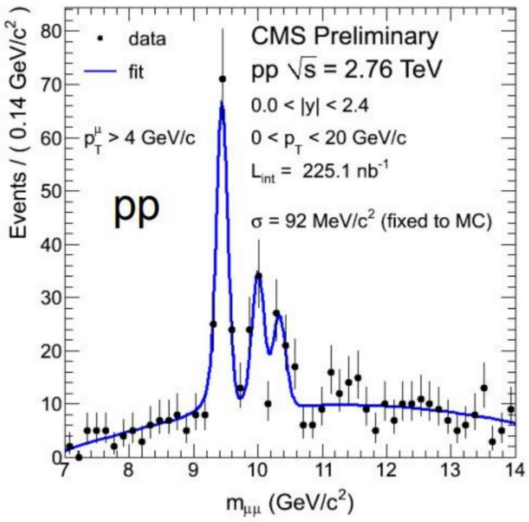


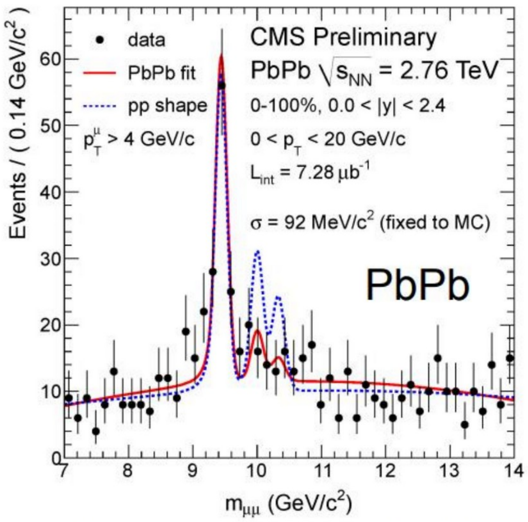
J.P.Lansberg, Phys.Rep. 889 (2020) 1

- Bottomonium expected to be much less sensitive to recombination effects
- In-medium resonance peaks become washed-out at very different temperatures
- Complicated feed-down structure, needs to be taken into account when interpreting data

Bottomonium sequential suppression

CMS, J.Phys.G38(2011) 124071, PRL107 (2011) 052302





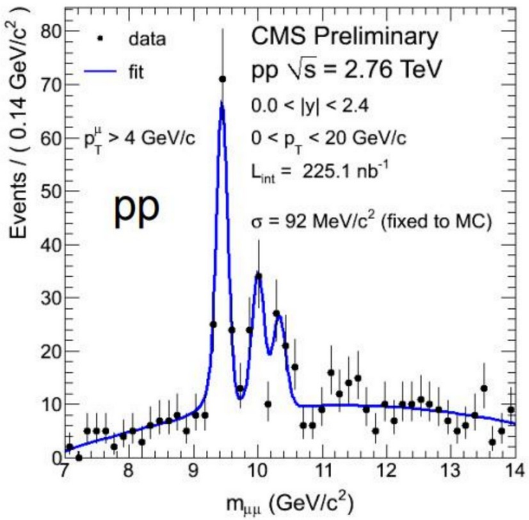
$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$

$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

- First evidence for sequential suppression in the bottomonium sector

Bottomonium sequential suppression

CMS, J.Phys.G38(2011) 124071, PRL107 (2011) 052302



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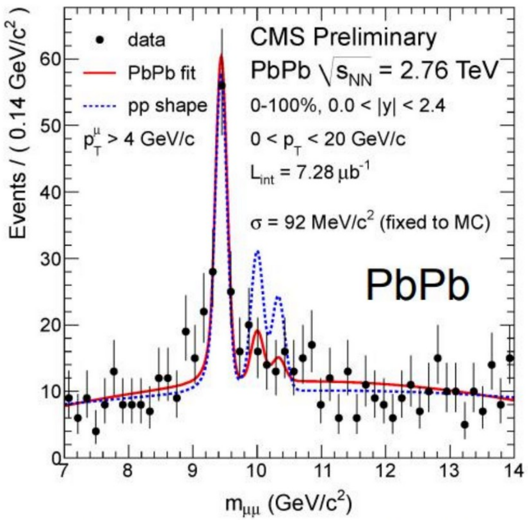

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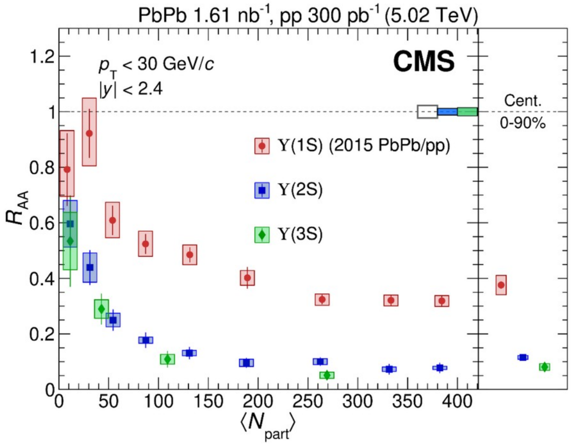
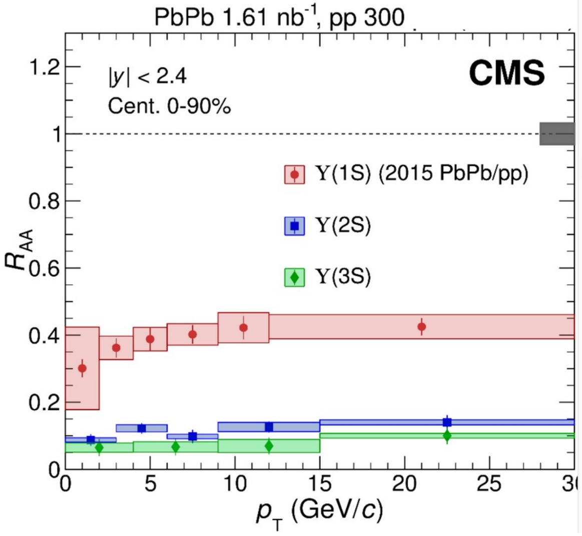
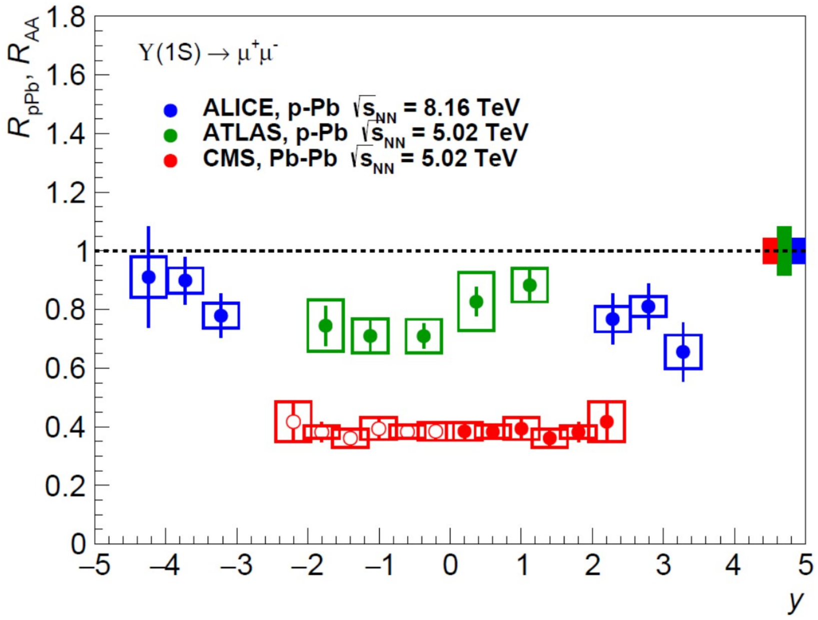




- First evidence for sequential suppression in the bottomonium sector
- Hierarchy of suppression for the 1S, 2S and 3S states
- No significant p_T dependence of the R_{AA}

CMS, PRL133 (2024) 022302

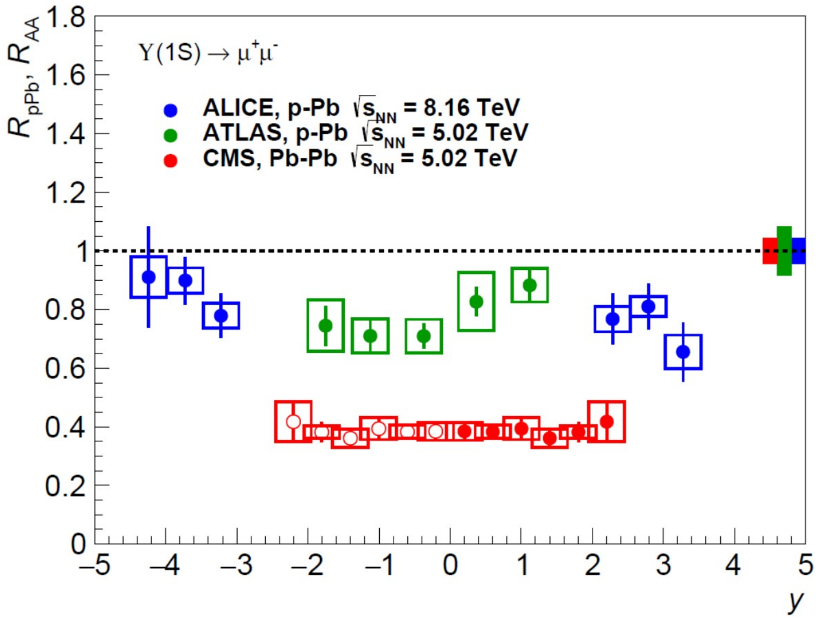
Is Υ(1S) really suppressed ?



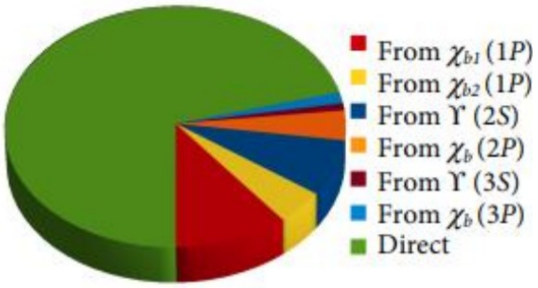
Υ(1S) suppression in p-Pb

- Non-negligible CNM effects on Υ(1S): gluon shadowing

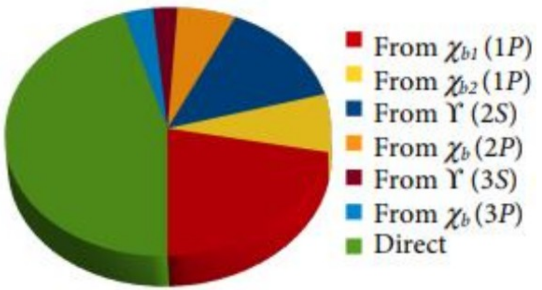
Is Υ(1S) really suppressed ?



Υ(1S) suppression in p-Pb



(a) Low P_T Υ(1S)



(d) High P_T Υ(1S)

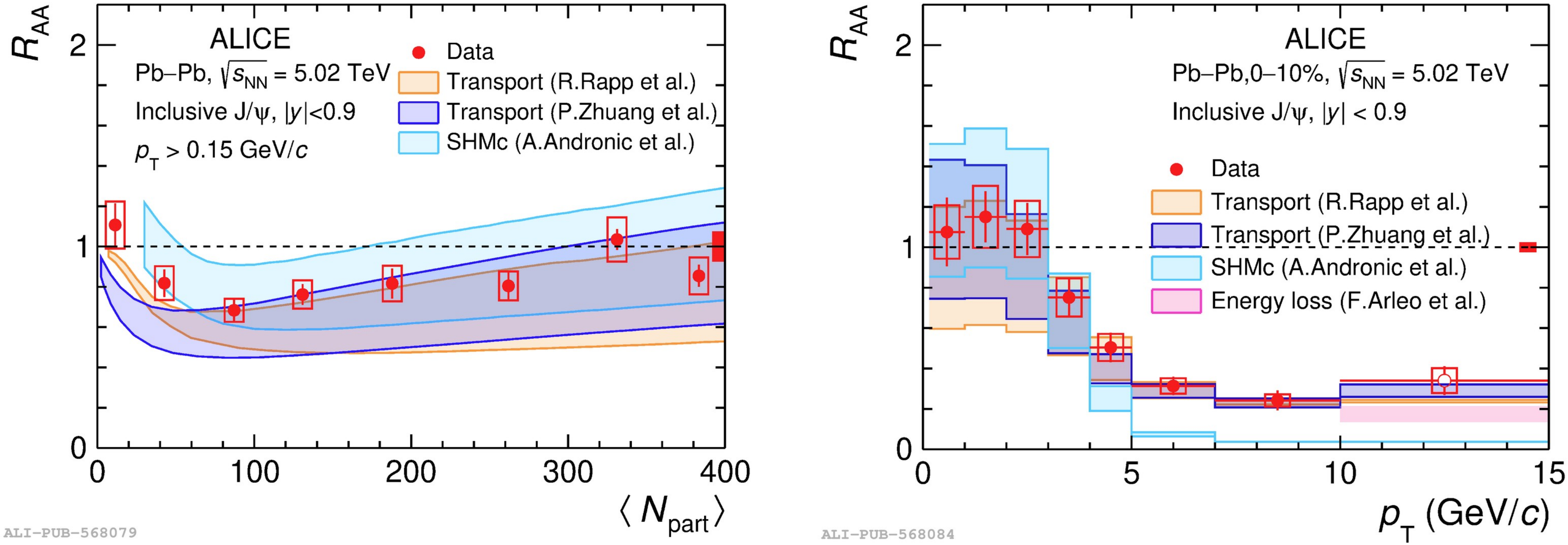
- Non-negligible CNM effects on Υ(1S): gluon shadowing
- Feed-down contribution of 30-55% from higher mass, less bound bottomonia

Back to charmonia: microscopic transport pheno models

- Main implementations:
  - Texas model: *X.Zhao, R.Rapp NPA859 (2011) 114*
  - Tsingua model: *P.Zhuang et al. PLB678 (2009) 72*
- Boltzmann equation accounting for both suppression and regeneration reactions
- Spectral properties of charmonia from lattice QCD
- Modeling of the medium evolution
- **See slides by Pengfei!**

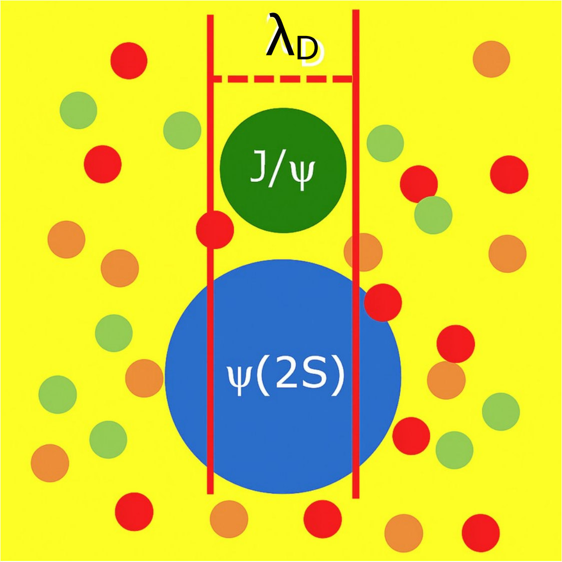
Data / model comparisons

ALICE, PLB 849 (2024) 138451



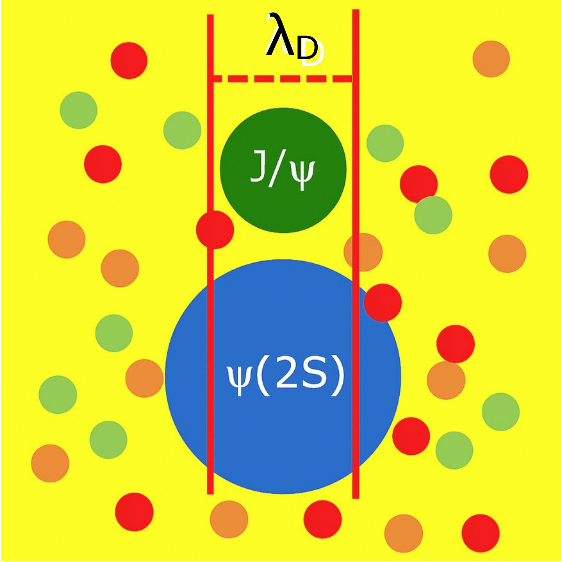
- Both transport and SHM approaches describe data well
- Main source of model uncertainty is the total open-charm cross-section and its shadowing in Pb-Pb collisions
- There are also other approaches, e.g. comovers, energy loss

Production of excited charmonia at the LHC: ψ(2S)

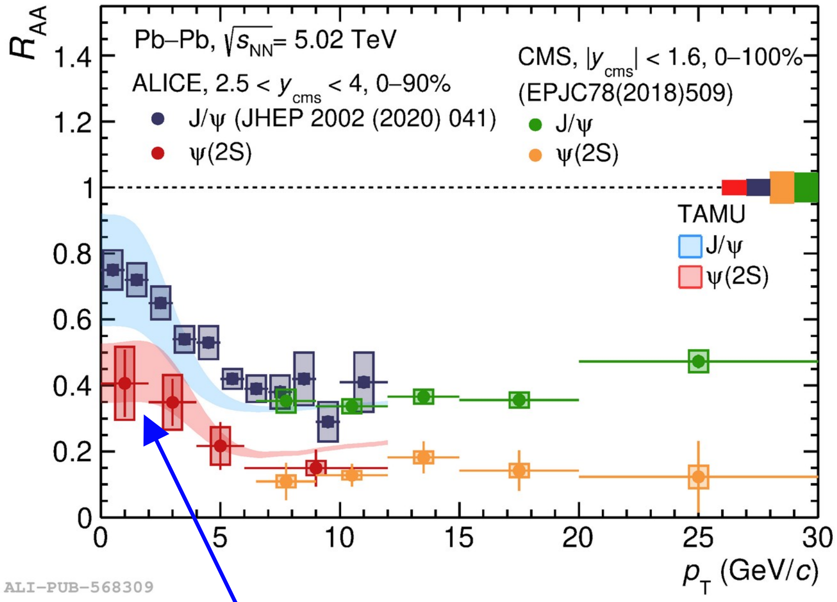


- Much lower binding energy: ~60 MeV
- Stronger dissociation effects (already seen at SPS)
- Recombination effects could be important also for ψ(2S), especially when the system is more diluted, at later times

Production of excited charmonia at the LHC: ψ(2S)



ALICE, PRL 132 (2024) 042301



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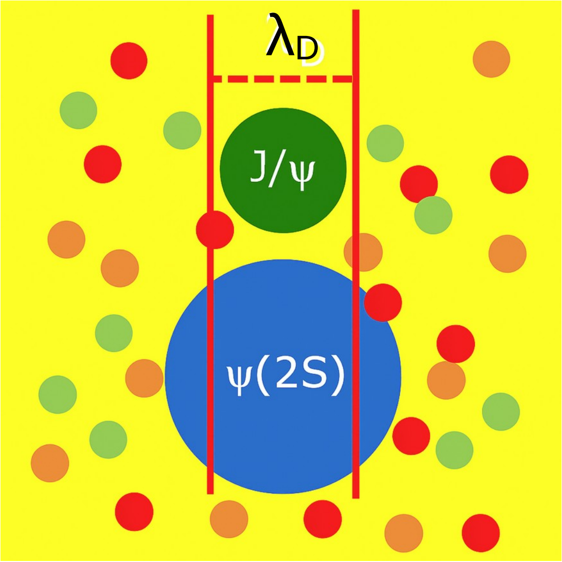
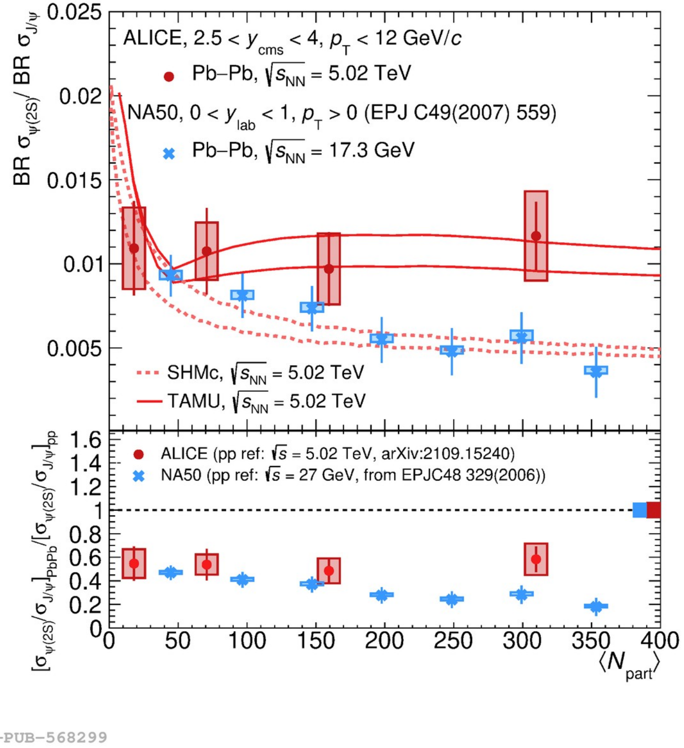
Indication of an increase of the R_{AA} towards low p_T

Production of excited charmonia at the LHC: ψ(2S)

ALICE, PRL 132 (2024) 042301





- Much lower binding energy: ~60 MeV
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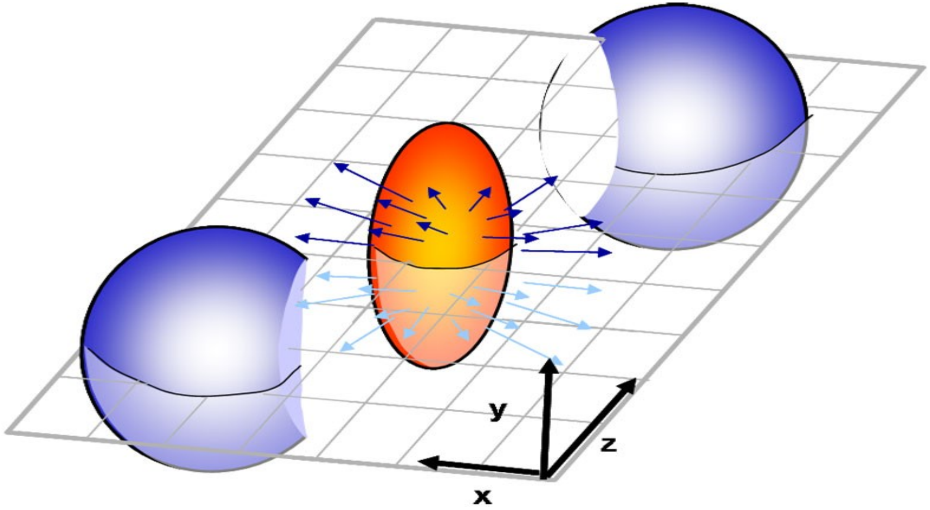
- Recombination effects could be important also for ψ(2S), especially when the system is more diluted, at later times

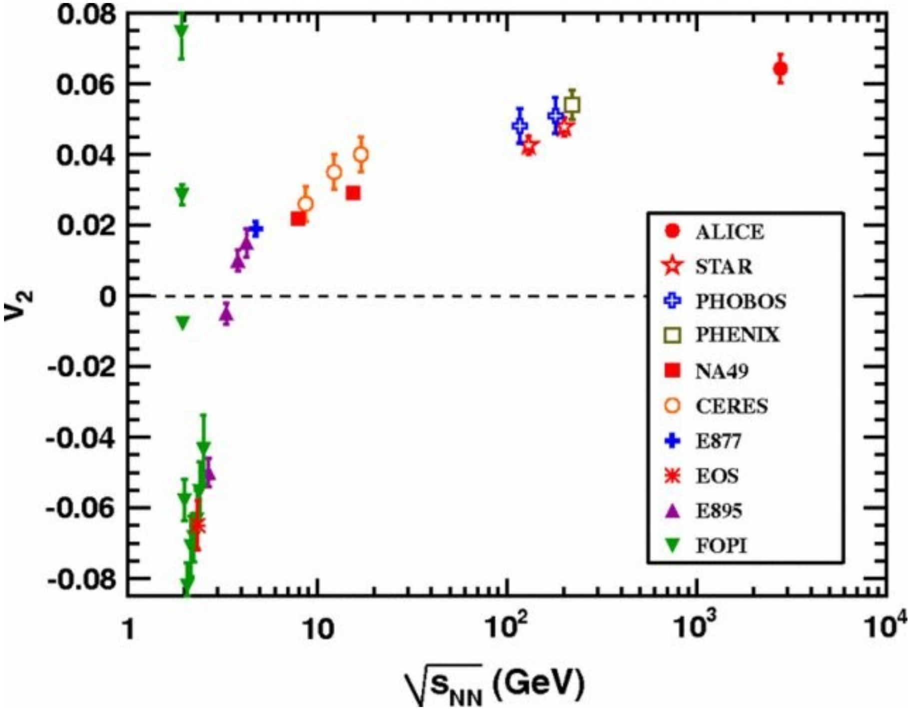
First indication of ψ(2S) / J/ψ ratio deviating from thermal expectation

Anisotropic flow



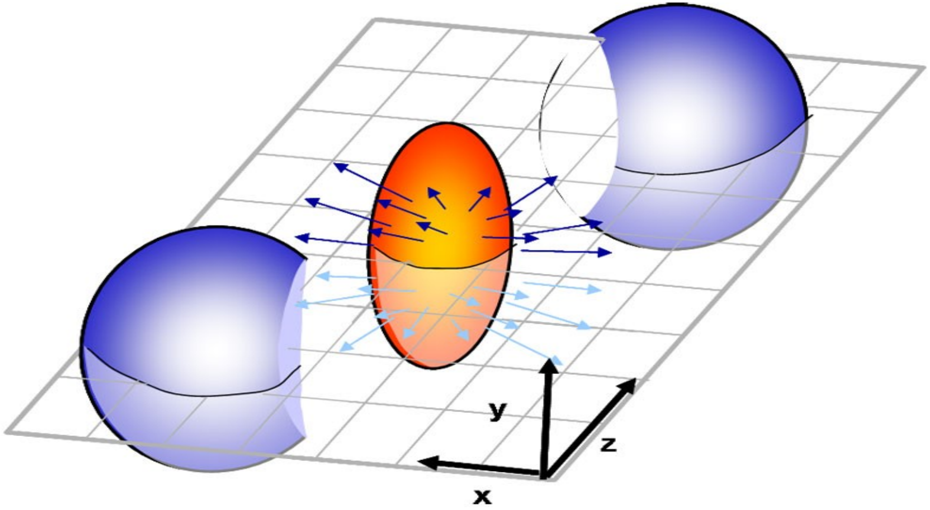
$$\frac{dN}{d\phi} \simeq 1 + 2v_1 \cos(\phi - \Psi_r) + 2v_2 \cos(2(\phi - \Psi_r)) + \dots$$

Initial spatial anisotropy of energy density is transformed in final state momentum anisotropy



- Very good measure for collision dynamics
- Sensitive to the bulk properties of the (de)confined nuclear medium

Anisotropic flow



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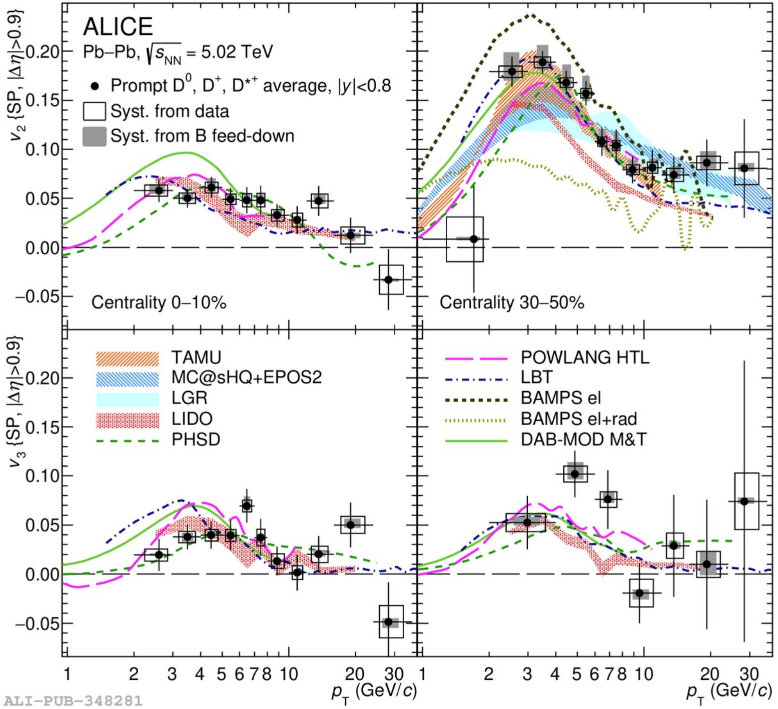
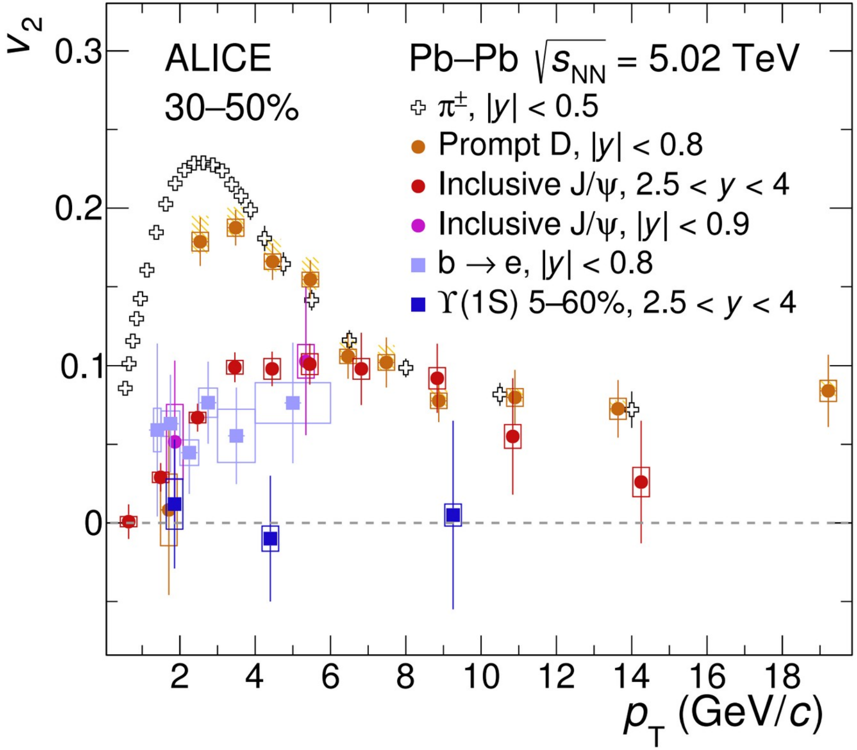


D-mesons flow → charm quarks kinetically equilibrate in the QGP and participate in the collective flow

What about J/ψ ?

Anisotropic flow of light and charm hadrons

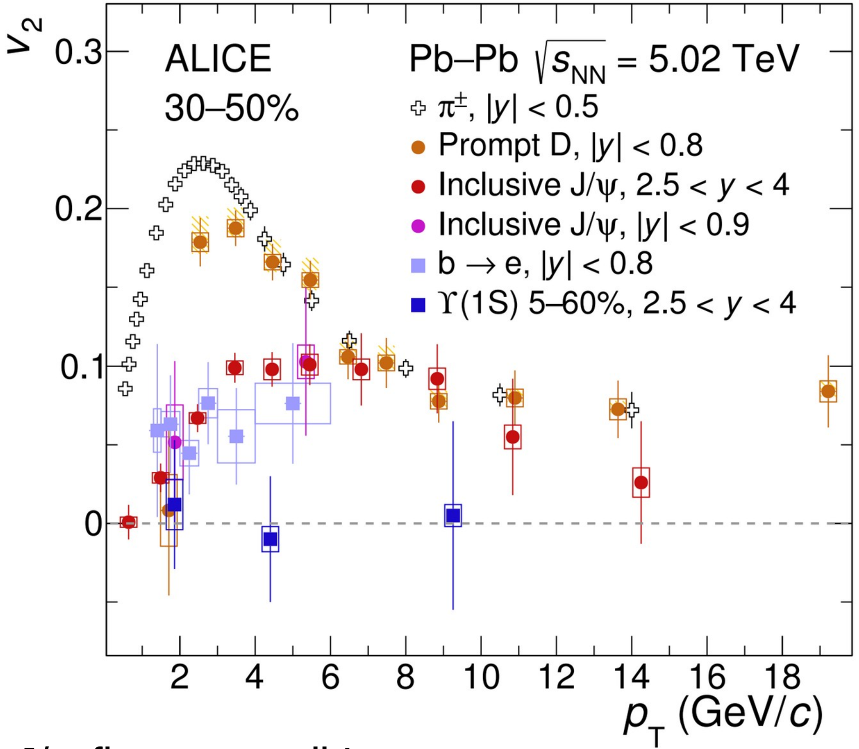
ALICE, JHEP 10 (2020) 141

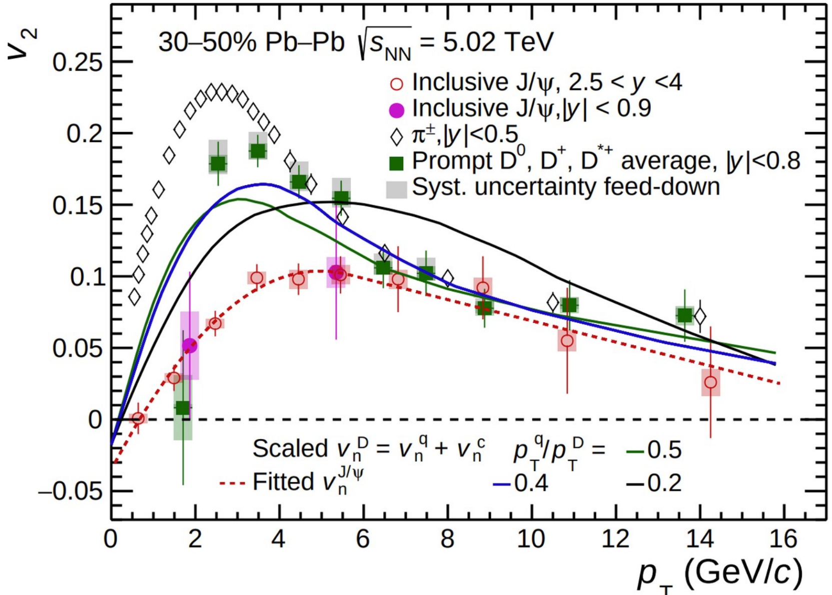


- J/ψ flows as well !
- Very good v_2 measurement with the ALICE MUON arm
- $v_2(\pi) > v_2(D) > v_2(J/\psi) > v_2(b \rightarrow e) > v_2(Y)$

Anisotropic flow of light and charm hadrons

ALICE, JHEP 10 (2020) 141





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- If charm equilibrates in the QGP and J/ψ is mainly produced via coalescence, is there any relation between the v_2 of light, D and J/ψ mesons?

$$v_n^{D}(p_T^{D}) = v_n^{q}(p_T^{q}) + v_n^{c}(p_T^{c}),$$

$$v_n^{J/\psi}(p_T^{J/\psi}) = 2 \cdot v_n^{c}(p_T^{J/\psi}/2)$$

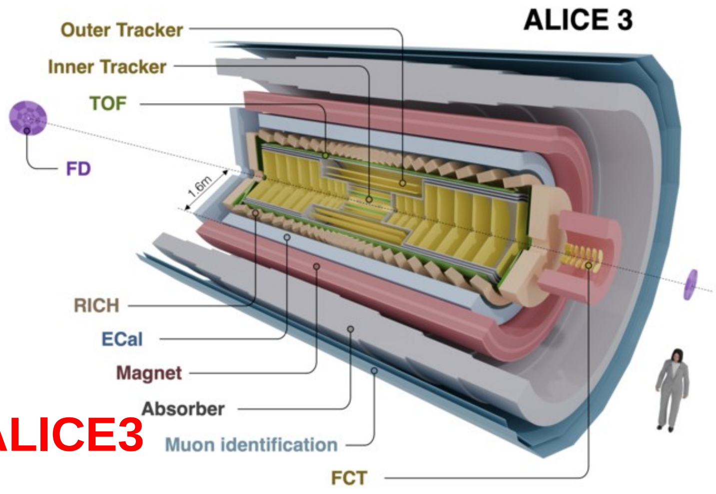
$$v_n^{\pi}(p_T^{\pi}) = 2 \cdot v_n^{q}(p_T^{\pi}/2)$$

Many of the questions still to be answered...

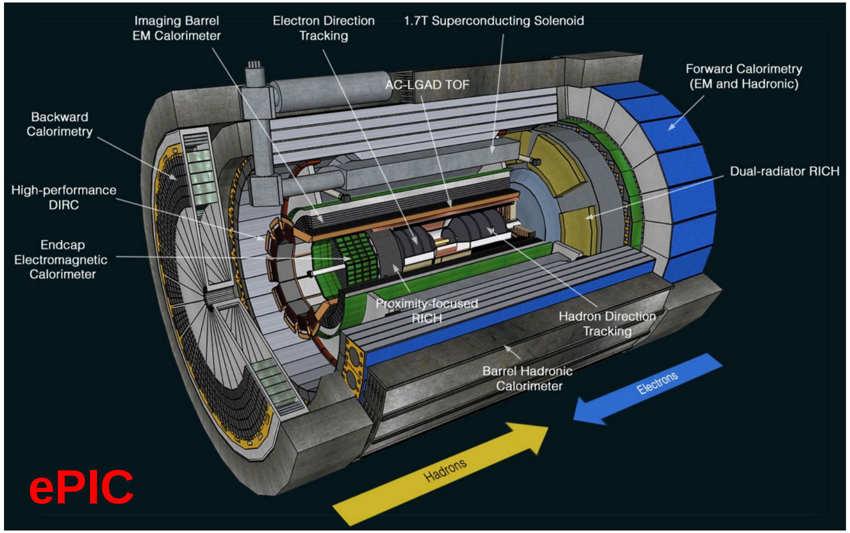
- Quarkonium production mechanism
  - statistical hadronization vs transport models vs open quantum systems
- Degree of charm thermalization in the QGP
- What is the impact of cold nuclear matter effects
  - Are measurements in p-Pb a good handle to constrain CNMs ?

- … but Run-3&4 is coming with a huge increase in statistics for all collision systems

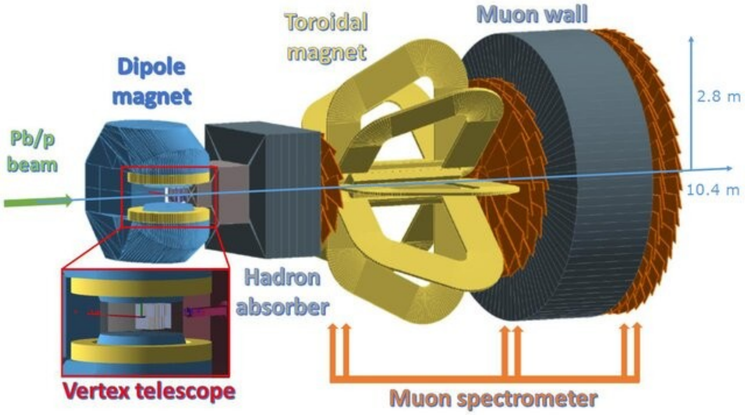
Future: 2030+



ALICE3



ePIC



NA60+

- NA60+ : explore the SPS energy range
- ALICE3 : precision measurements at LHC energies
- ePIC : precision mapping of nuclear PDFs