Prompt and non-prompt J/ψ production in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

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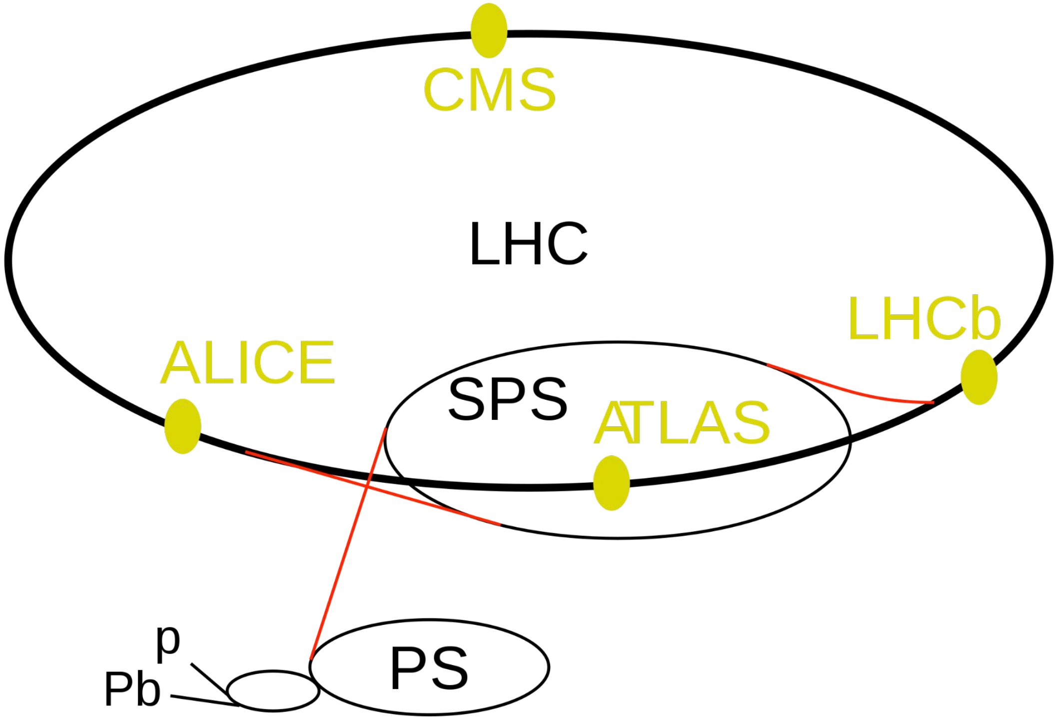
Outline

- Quark-gluon plasma
- Theoretical motivations
  - Quarkonium systems
  - The J/ψ particle
  - Open-heavy flavour
  - Charmonia
- The ALICE experiment
- Non-prompt J/ψ production in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - Prompt and non-prompt J/ψ separation procedure
  - Prompt and non-prompt J/ψ nuclear modification factor

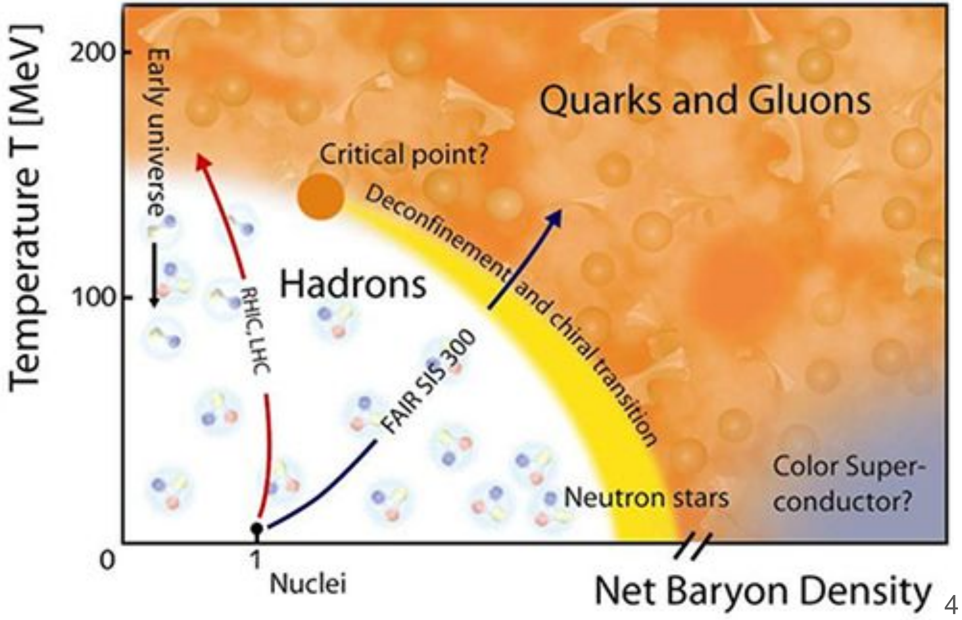
Experiments at CERN



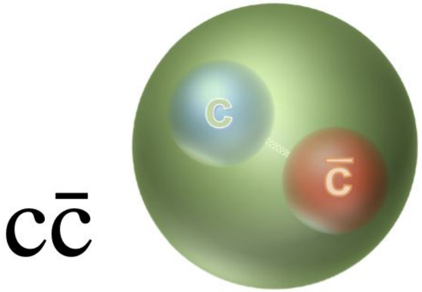
The Quark-gluon plasma

- Hadronic matter under extreme conditions (temperature, net baryon density)
  - Phase transition into Quark-Gluon Plasma
  - Quarks and gluons are deconfined
  - Achieved in heavy-ion collisions

- Why study the QGP?
  - Possible to access quasi-free quarks and gluons
  - Deeper understanding of the strong interaction
  - Understand the building blocks of the universe

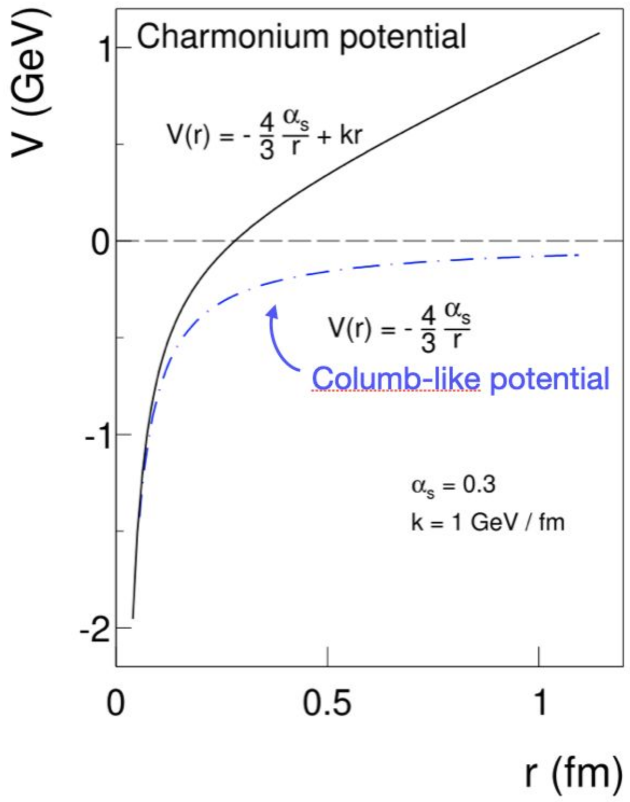


Quarkonium Systems

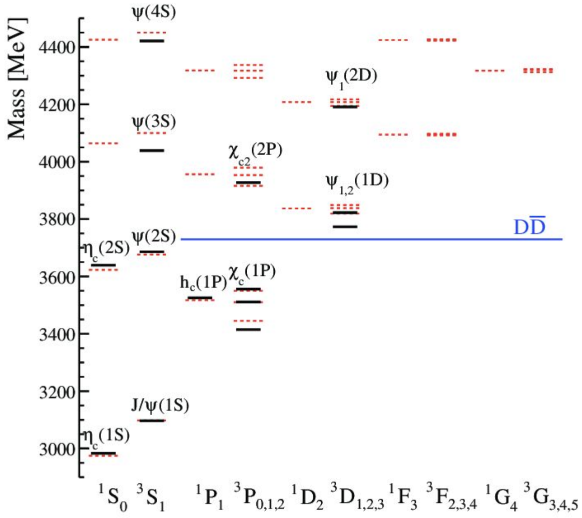


- Bound system of heavy quarks
- "positronium of quantum chromodynamics (QCD)"
  - Cornell Potential
- Quarkonium appears in a variety of states
  - Characterized by mass and binding energy
- Today:
  - Focus on J/ψ - charmonium ground state
    - "long lifetime" → decays through dilepton channel
  - Beauty-hadron production via non-prompt J/ψ

AAPPS Bull 31 (2021) 8

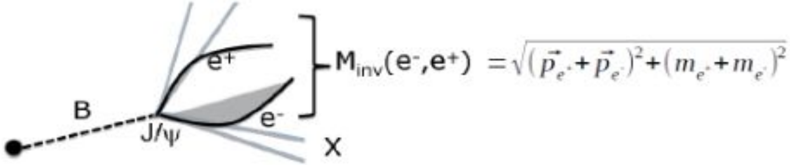


The J/ψ particle



Inclusive J/ψ consists of two main contributions:

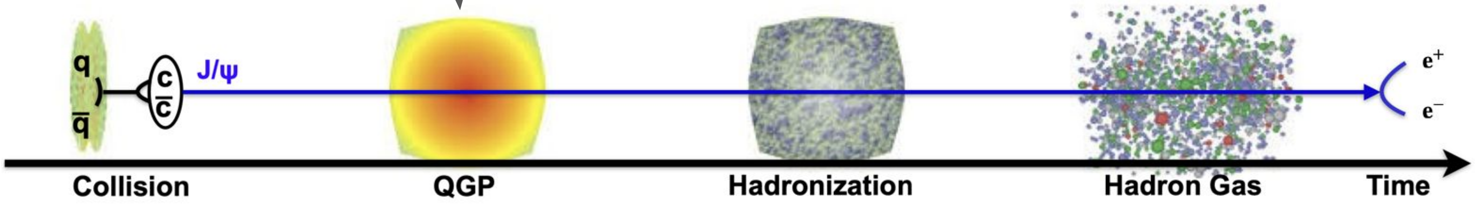
- **Prompt J/ψ**
    - Direct production from hard partonic scattering
    - Decay from higher excited charmonium states, e.g. ψ(2S)
- **Non-prompt J/ψ**
    - Originated from decays from beauty-flavoured hadrons (about 10% at low p_T)
        - Secondary vertex displaced by about ~500 micrometers from the main event vertex → **We can take advantage of the displacement to reconstruct such particles**



Quarkonium production from small to large colliding systems

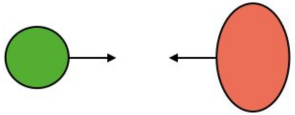
Quarkonium is produced during the early stages of the collision

Heavy collisions only



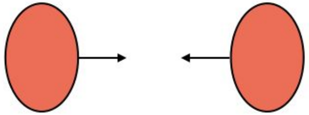
Proton—proton

- Probe the charmonium production mechanism
- Reference measurements



Proton—Pb

- Probe cold nuclear matter effects



Pb—Pb

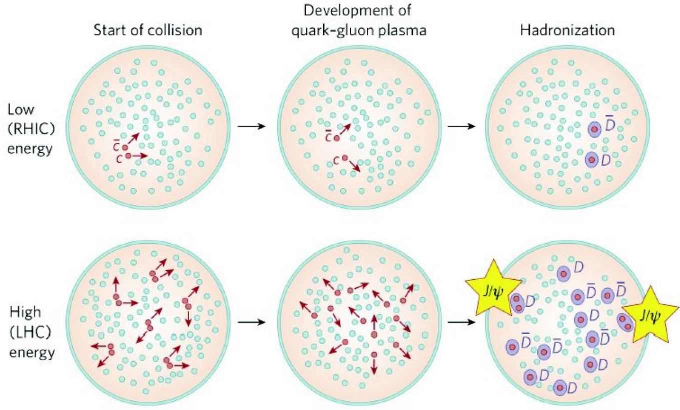
- Probe the quark-gluon plasma (QGP)

This presentation!

Charmonium production as probe of QGP in heavy-ion collisions

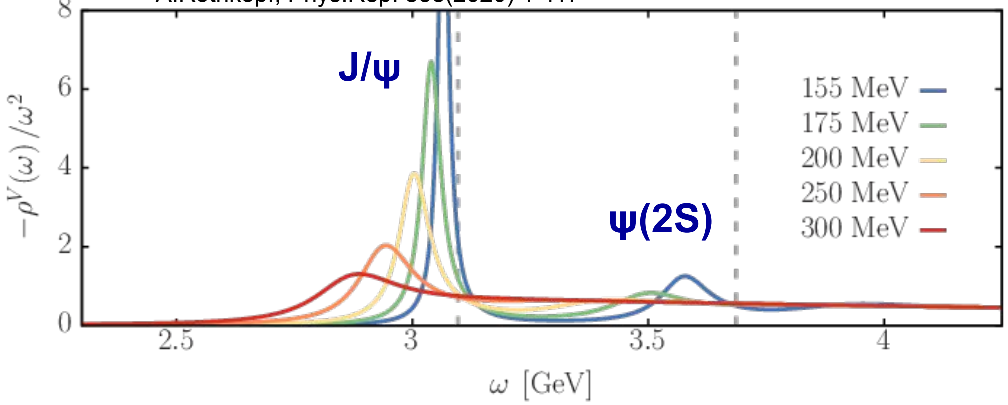
- Sequential dissociation of quarkonium states in medium according to their binding energies: expectation of stronger suppression for ψ(2S) w.r.t J/ψ

- (Re)generation of charmonium states at the LHC energies, at the phase boundary and/or during the QGP phase



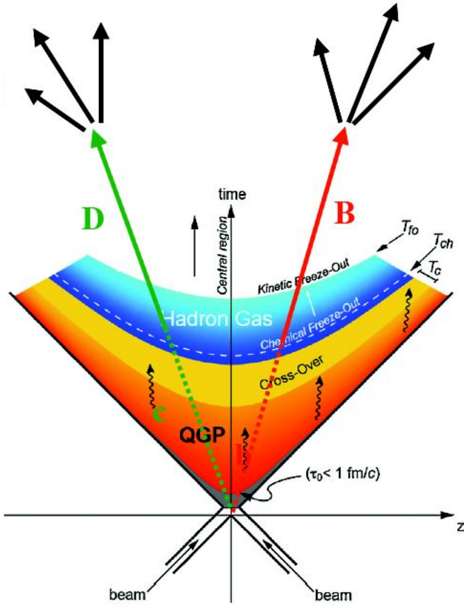
Braun-Munzinger, P., Stachel, J. The quest for the quark–gluon plasma. *Nature* 448, 302–309 (2007)

A.Rothkopf, Phys.Rep. 858(2020) 1-117



The in-medium heavy quarkonium spectral functions in the S-wave channel for charmonium evaluated at different temperatures

Heavy-flavour as hard probes of QGP

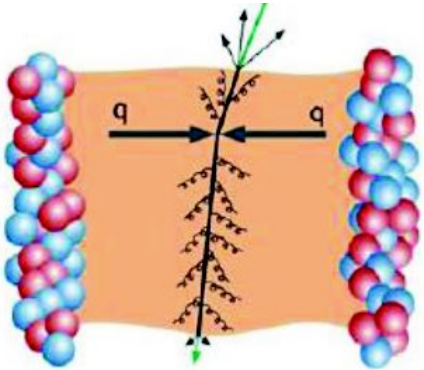


- Heavy quarks, charm and beauty, produced early in heavy-ion collisions via hard parton-parton scatterings
  - Experience full evolution of Pb–Pb collisions, interacting with the QGP via collisional and radiative processes and lose energy

- Energy loss of partons:
  - Difference between gluons and quarks due to different colour charges
  - Small angle radiation from heavy quark suppressed due to finite mass

$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$$

- Nuclear modification factor R_{AA} used to quantify energy loss effects

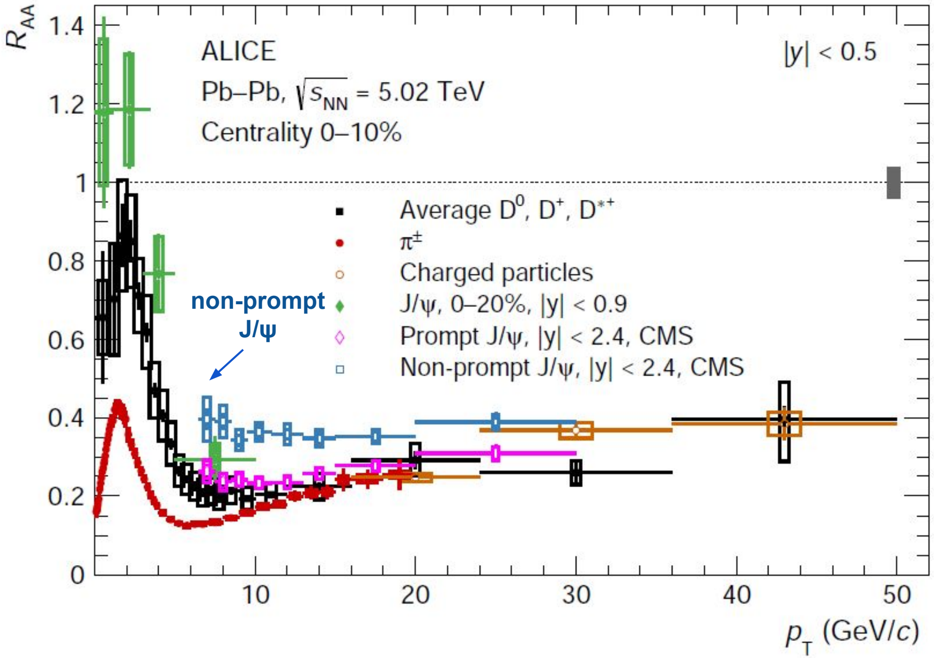


$$R_{AA} = \frac{1}{N_{coll}} \times \frac{(dN/dy)_{AA}}{(dN/dy)_{pp}}$$

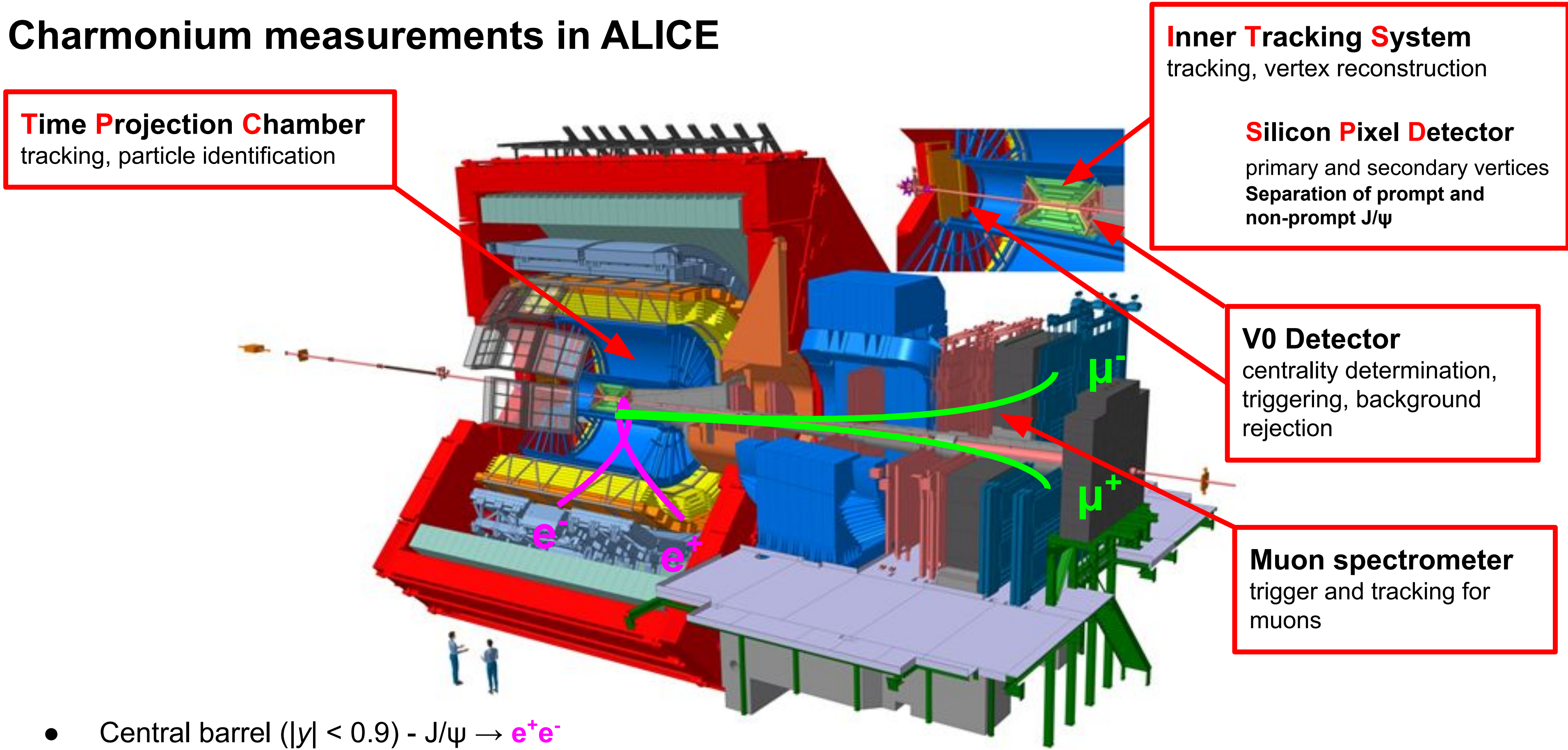
Heavy-flavour as hard probes of QGP

- Heavy quarks, charm and beauty, produced early in heavy-ion collisions via hard parton-parton scatterings
  - Experience full evolution of Pb–Pb collisions, interacting with the QGP via collisional and radiative processes and lose energy

Mass dependence of parton energy loss →
Hierarchy expected for R_{AA} of light and heavy-flavor hadrons!

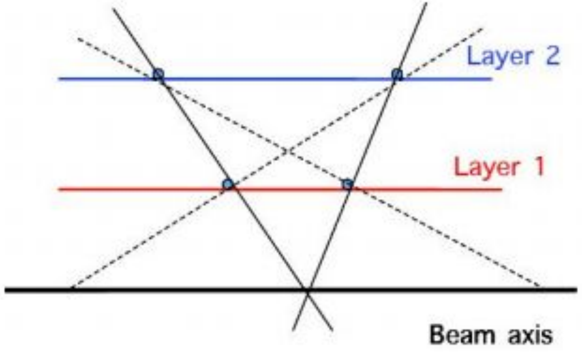


Charmonium measurements in ALICE

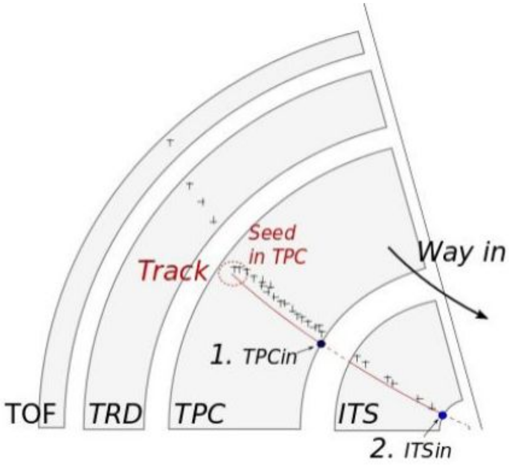


- Central barrel ($|y| < 0.9$) - J/ψ → e^+e^-
  - Possibility to separate prompt and non-prompt J/ψ down to low p_T
- Muon Spectrometer ($2.5 < y < 4$) - J/ψ, ψ(2S) → $\mu^+\mu^-$
- Mid- and forward-y inclusive charmonium measurements down to zero p_T

Track reconstruction in ALICE

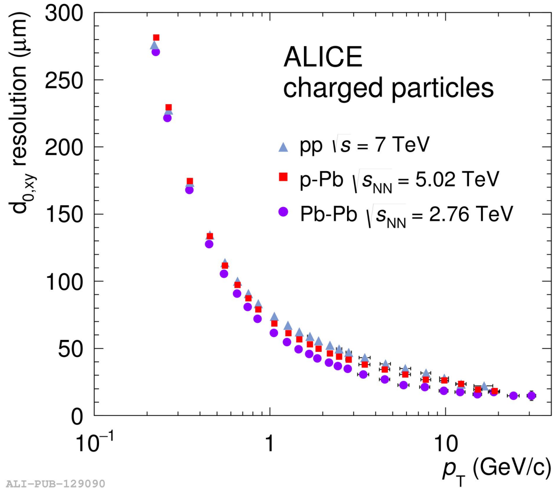


- Primary particle selection based on Inner Tracking System (ITS) and Time Projection Chamber (TPC)



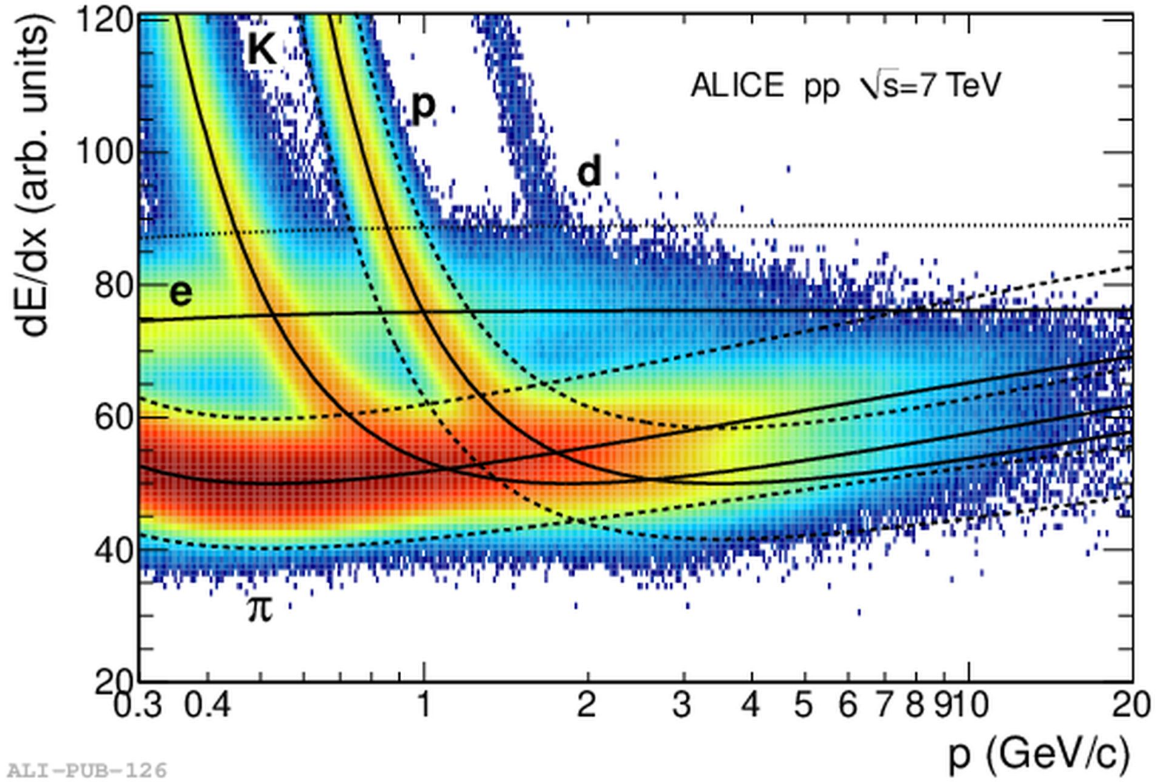
- Primary vertex (collision point) determined from pairs of SPD points
- Track reconstruction by combining clusters (detector hits)

Impact parameter resolution is good at low p_T (determined by the SPD)



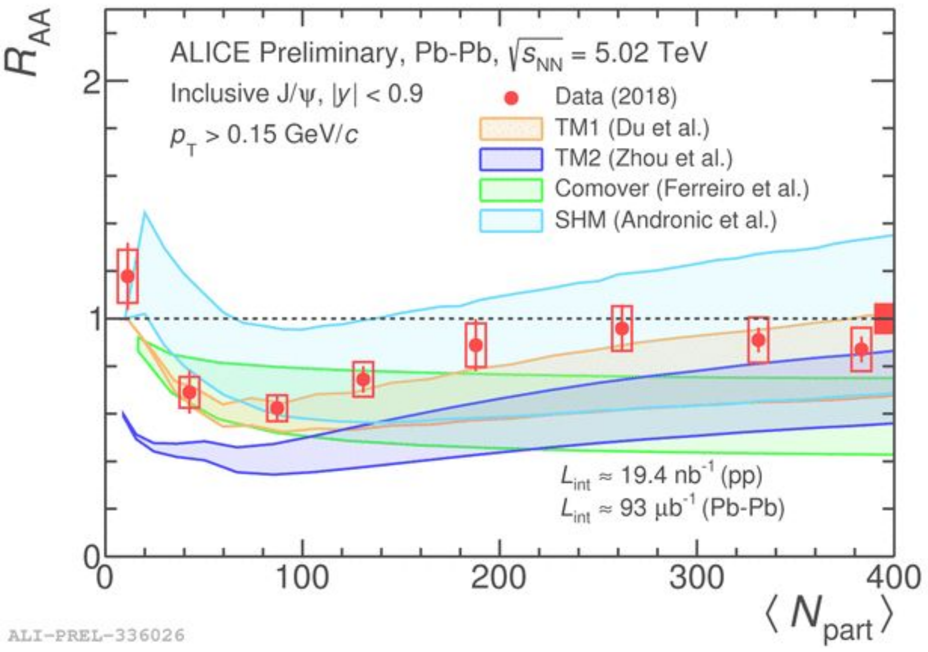
Particle identification in ALICE

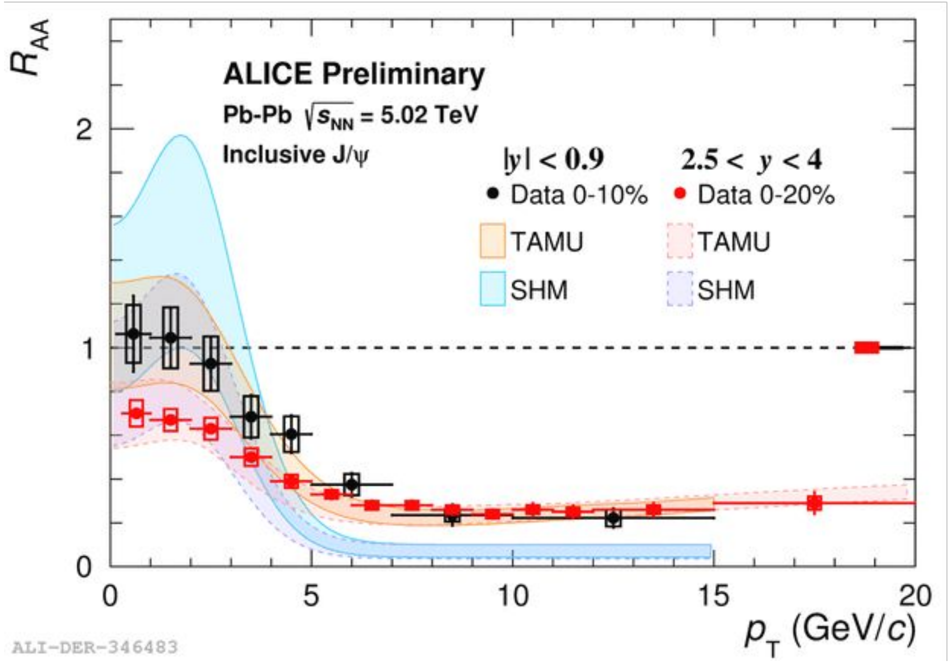
$$n\sigma = \frac{(dE/dx)_{meas} - (dE/dx)_{exp.}}{\sigma_{exp.}}$$



- Charged particles lose energy by ionizing TPC gas
- PID based on measured energy loss and momentum
- Select electron candidates based on deviation from expected Bethe Bloch curve

Inclusive J/ψ R_{AA} results





- Models implementing charmonium regeneration, either at the freeze-out (SHM) or during the fireball lifetime (transport models), in agreement with data
  - Both centrality and p_T dependencies are qualitatively well described
  - Rapidity dependence is also described by recombination models when we compare mid- and forward-y

- Conclusions on the J/ψ production phenomenology are hindered by the large model uncertainties

TM2: Zhou *et al.*, Phys. Rev. C 89, 054911 (21 May 2014)
Comover: Ferreiro E. *et al.*, PLB 731 (2014) 57
SHM: Andronic A. *et al.*, Phys. Lett. B797 (2019) 134836,
TM1/TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158

Prompt and non-prompt J/ψ separation

Non-prompt J/ψ analysis details

- **Data samples:**
  - PbPb 2018, pass 3 → ~193 million accepted events (all triggers)
  - PbPb 2015, pass 1 → ~130 million accepted minimum-bias triggered events
- **Event selection:**
  - Central, semicentral and minimum-bias triggered events (only min. bias for 2015), pile-up rejection, $|z_{Vtx}|$ < 10 cm
- **Track selections:**
  - Kinematic cuts: remove combinatorial background from low-pt electrons
  - Track quality cuts
  - **PID cuts**
  - Rejection of electrons from photon conversion (prefilter)
- **Pair selection:**
  - $|y|<0.9$, **spd-First requirement used at low p_T (most central);**
    For high p_T rejection of candidates where there are no hits (for both legs) in the first SPD layer

→ Selection identical to that of inclusive J/ψ analysis, except for tighter SPD and PID requirements

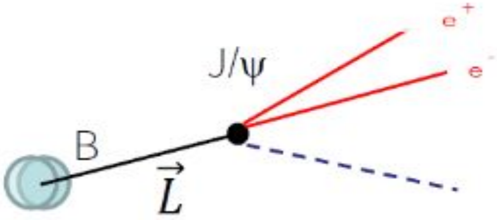
Pseudo-proper decay length (x)

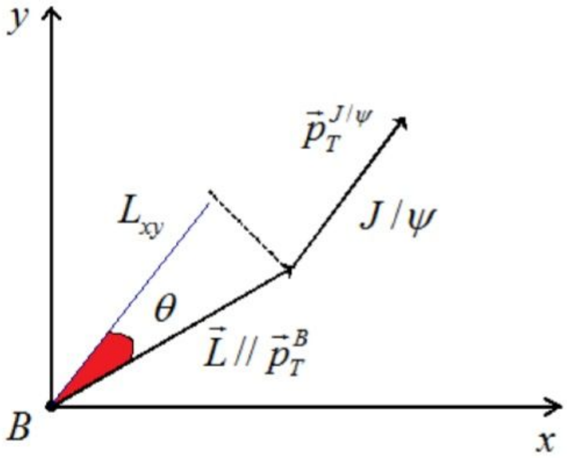
$$x = \frac{c\, L_{xy}\, m_{J/\psi}}{p_t^{J/\psi}} \qquad L_{xy} = \vec{L}\cdot\vec{p}_t^{\,J/\psi} / p_t^{J/\psi}$$

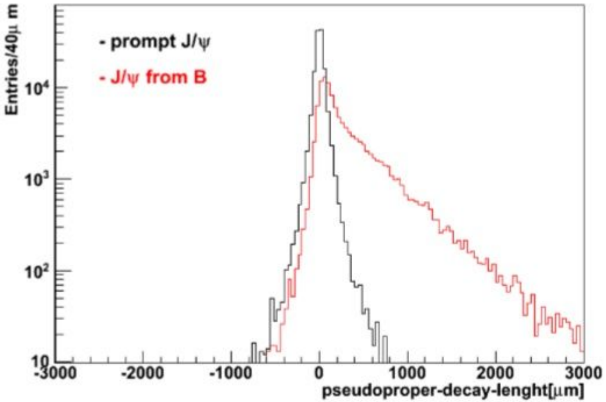
$$\ln L = \sum_{i=1}^{N} \ln F(x, m_{e^+e^-})$$

- If substituting mass and transverse momentum values of beauty hadrons in the equations in place of those of the J/ψ, x would actually be the proper decay length of the beauty hadron.

- Since neither the momenta nor the masses of beauty hadrons are exclusively reconstructed, the corresponding values of the J/ψ are used in the definition of the x.







Prompt and non-prompt J/ψ separation

- Analysis technique: based on maximization of 2D likelihood function → invariant mass (m_{ee}) and **pseudo-proper decay length (x)** fitted simultaneously

$$F(x, m_{ee}, p_T, SPDtype) = \underbrace{f_{Sig} \times F_{Sig}(x) \times M_{Sig}(m_{ee})}_{\text{Signal}} + \underbrace{(1 - f_{Sig}) \times F_{Bkg}(x) \times M_{Bkg}(m_{ee})}_{\text{Background}}$$

$$F_{Sig}(x) = \underbrace{f_B \times T(x)}_{\text{Non-prompt}} + \underbrace{(1 - f_B) \times R(x)}_{\text{Prompt}}$$

f_B: fraction of non-prompt J/ψ

- Signal PDFs fixed from MC
- Background PDFs constrained on data

Prompt and non-prompt J/ψ separation

- Analysis technique: based on maximization of 2D likelihood function → invariant mass (m_{ee}) and **pseudo-proper decay length (x)** fitted simultaneously

Signal / Background

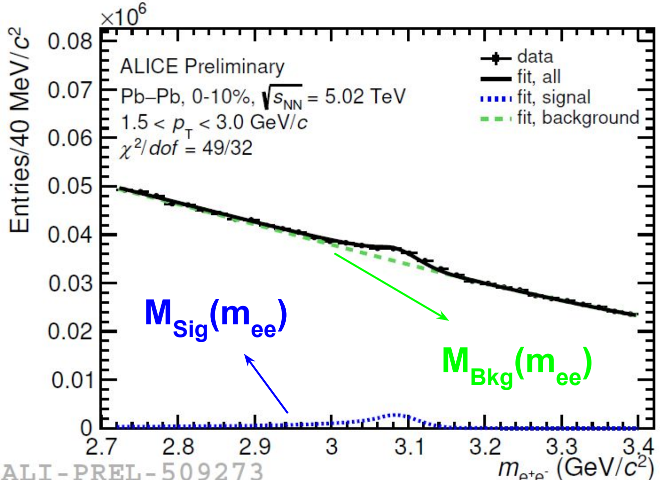
$$F(x, m_{ee}, p_T, SPDtype) = \underbrace{f_{Sig} \times F_{Sig}(x) \times M_{Sig}(m_{ee})}_{\text{Signal}} + \underbrace{(1 - f_{Sig}) \times F_{Bkg}(x) \times M_{Bkg}(m_{ee})}_{\text{Background}}$$

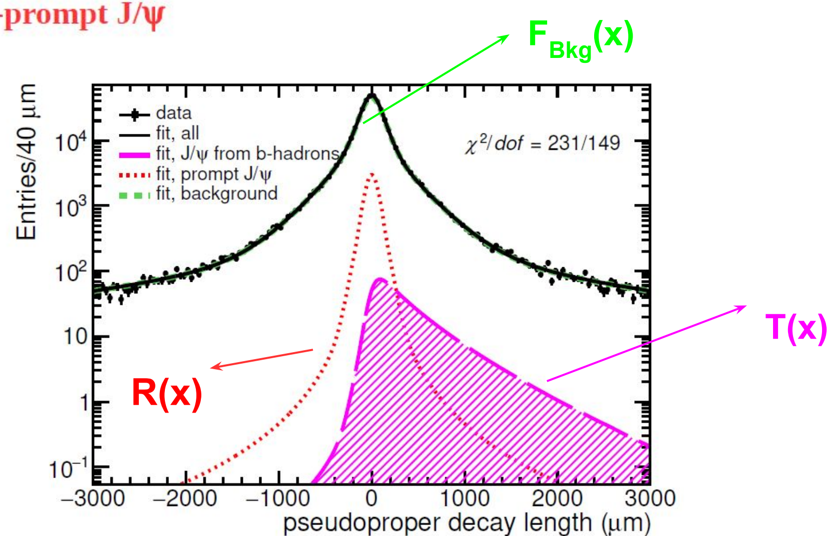
Non-prompt / Prompt

$$F_{Sig}(x) = \underbrace{f_B \times T(x)}_{\text{Non-prompt}} + \underbrace{(1 - f_B) \times R(x)}_{\text{Prompt}}$$

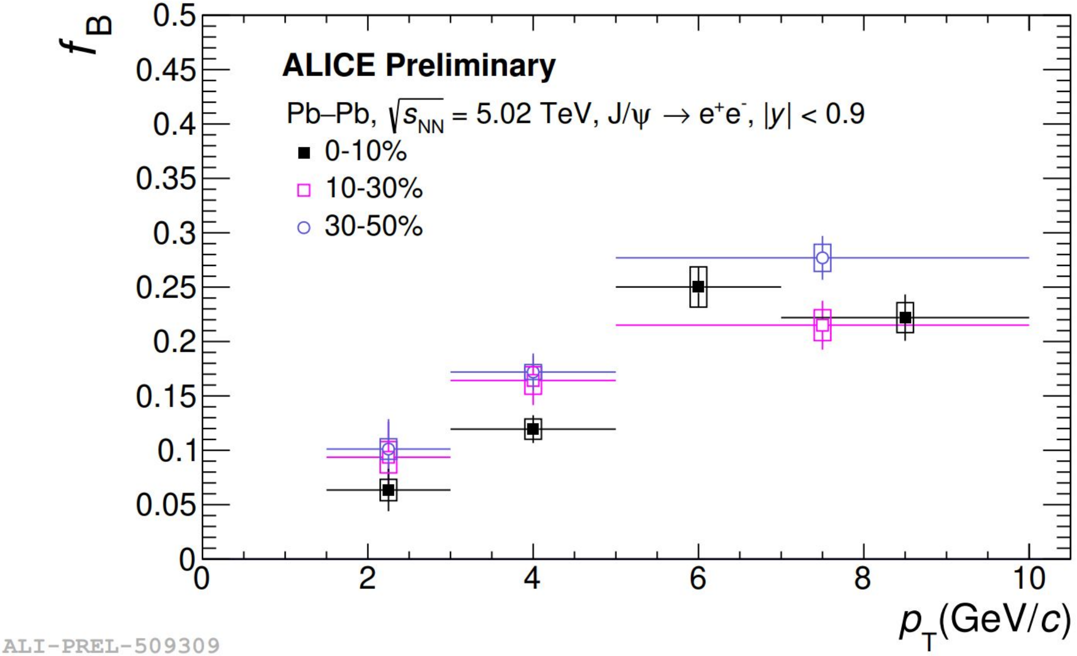
f_B → **fraction of non-prompt J/ψ**

- Signal PDFs fixed from MC
- Background PDFs constrained on data





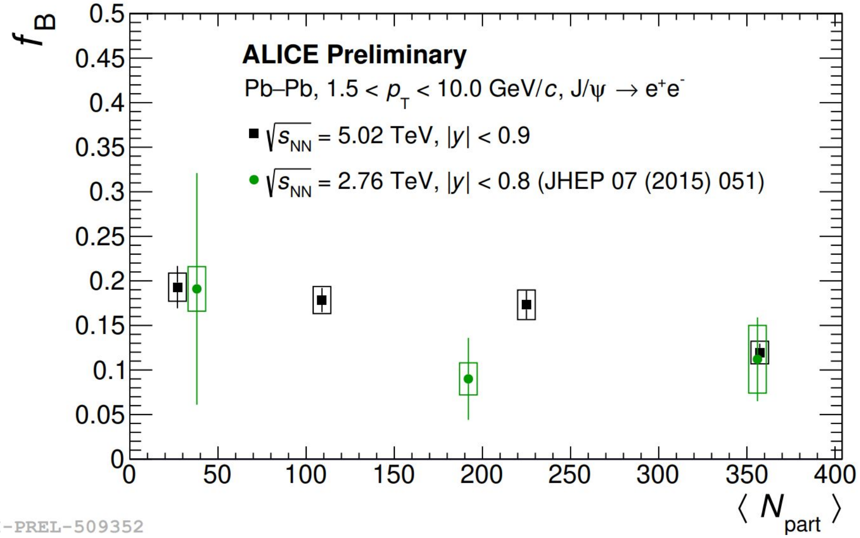
Non-prompt J/ψ fraction in Pb–Pb collisions

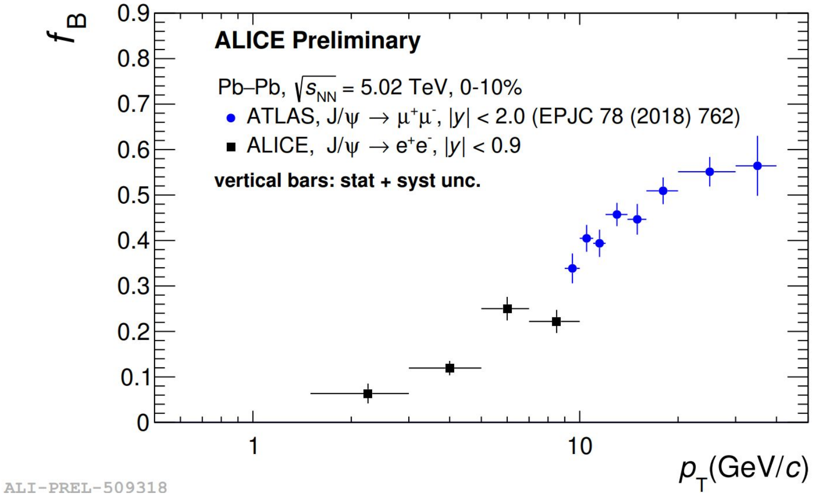


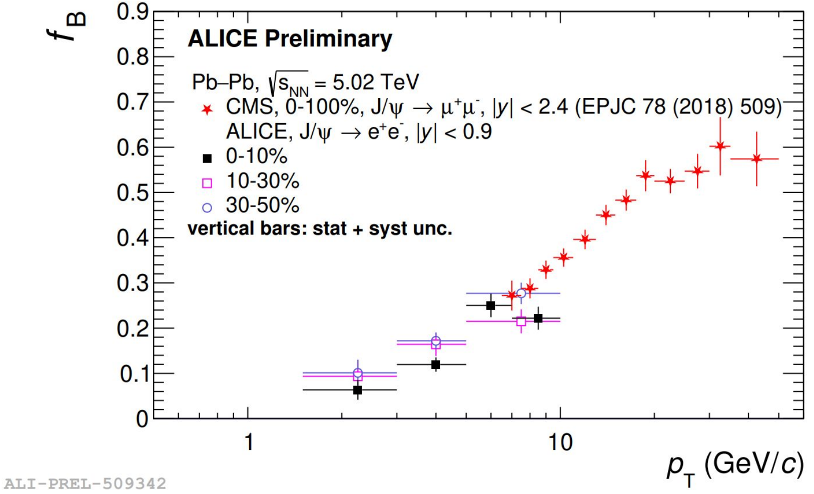
Analysis technique based on maximization of 2D likelihood function → invariant mass (m_{ee}) and **pseudo-proper decay length (x)** fitted simultaneously

- Non-prompt J/ψ fraction measured down to p_T = 1.5 GeV/*c* in different centralities:
  - Smaller non-prompt J/ψ fraction towards low p_T

Non-prompt J/ψ fraction in Pb–Pb collisions





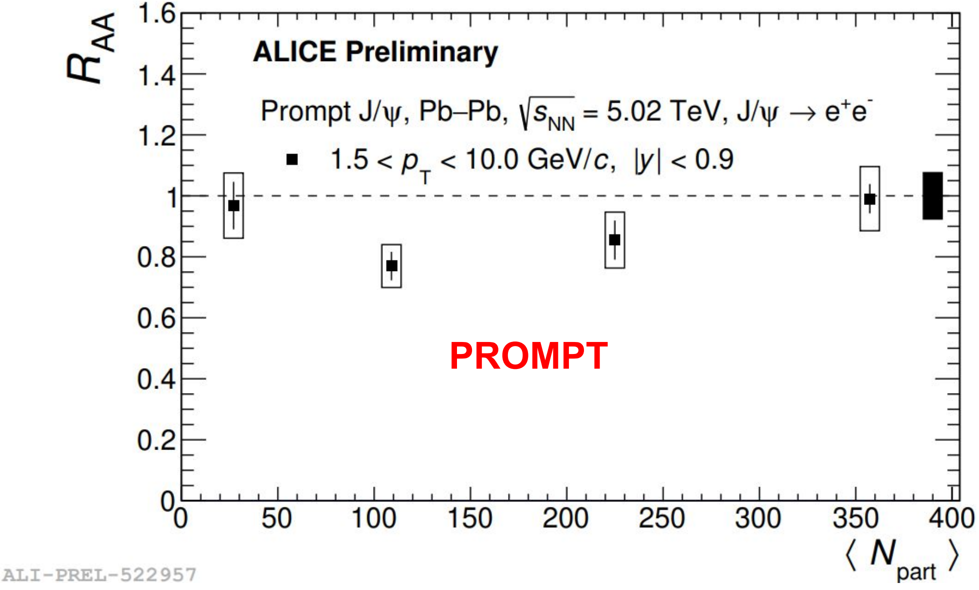


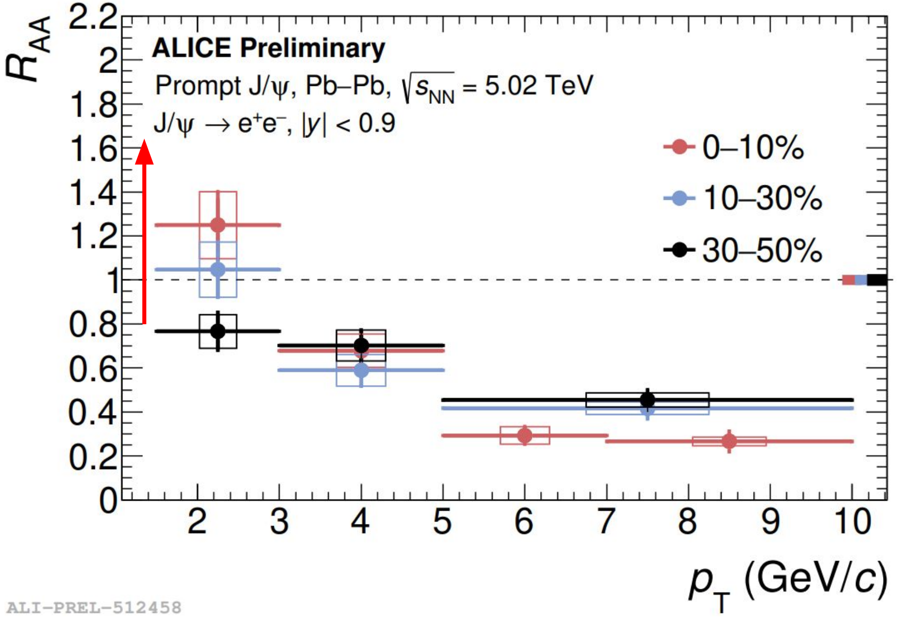
- No major centrality dependence observed within uncertainties
- The precision of the new measurement is improved significantly compared to Run 1
- In agreement with trends of CMS and ATLAS
  - ALICE extends measurements down to very low p_T

Prompt J/ψ R_{AA} measurements

$$R_{\mathrm{AA}}^{\text{prompt J}/\psi} = \frac{1 - f_{\mathrm{B}}^{\text{Pb-Pb}}}{1 - f_{\mathrm{B}}^{\text{pp}}} R_{\mathrm{AA}}^{\text{inclusive J}/\psi}$$

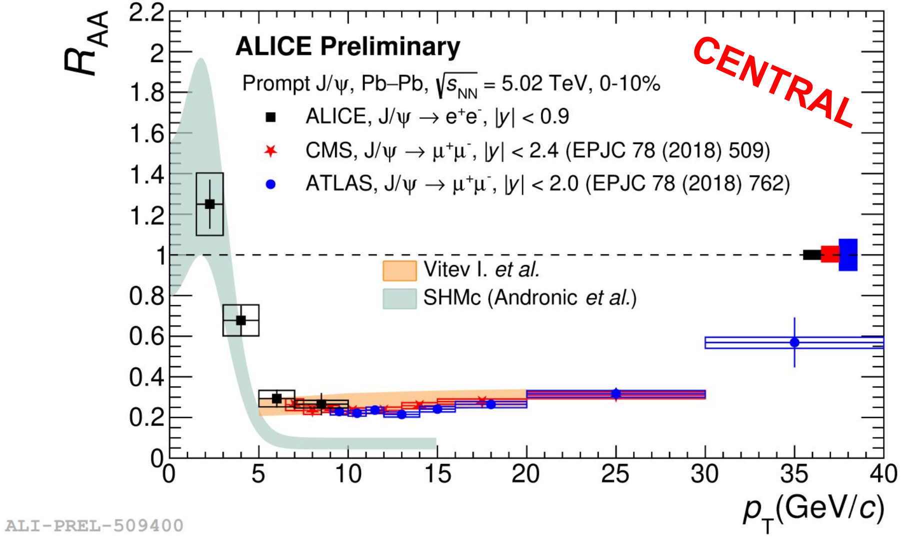
Prompt J/ψ R_{AA} as a function of ⟨N_{part}⟩ and p_T

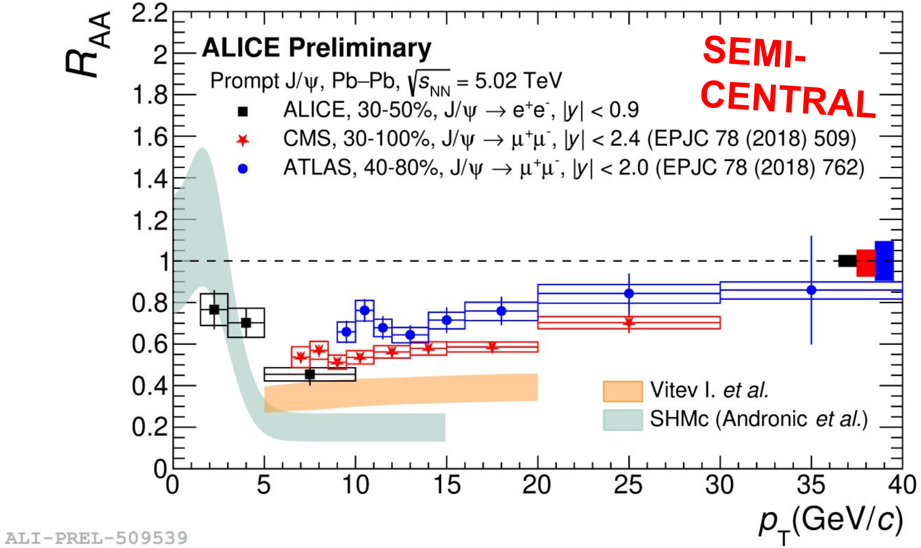




- Prompt J/ψ R_{AA} increases towards more central collisions (effect more visible at low p_T) → expected trend from J/ψ regeneration

Prompt J/ψ R_{AA} in central and semicentral Pb–Pb collisions





- Increasing R_{AA} at low p_T in central collisions compatible with a regeneration scenario
- Overlapping with ATLAS and CMS measurements in central collisions at high p_T
- Vitev: Dissociation of charmonia via microscopic description of interactions inside the medium
  - ALICE results compatible within uncertainties with the model for p_T > 5 GeV/*c*
- Good agreement with calculations from SHM extended to the charm sector (SHMc) for p_T < 5 GeV/*c*

SHMc: A. Andronic et al., JHEP07 (2021) 035
(+ private communication)
Vitev I. et al. arXiv:1709.02372, arXiv:1906.04186

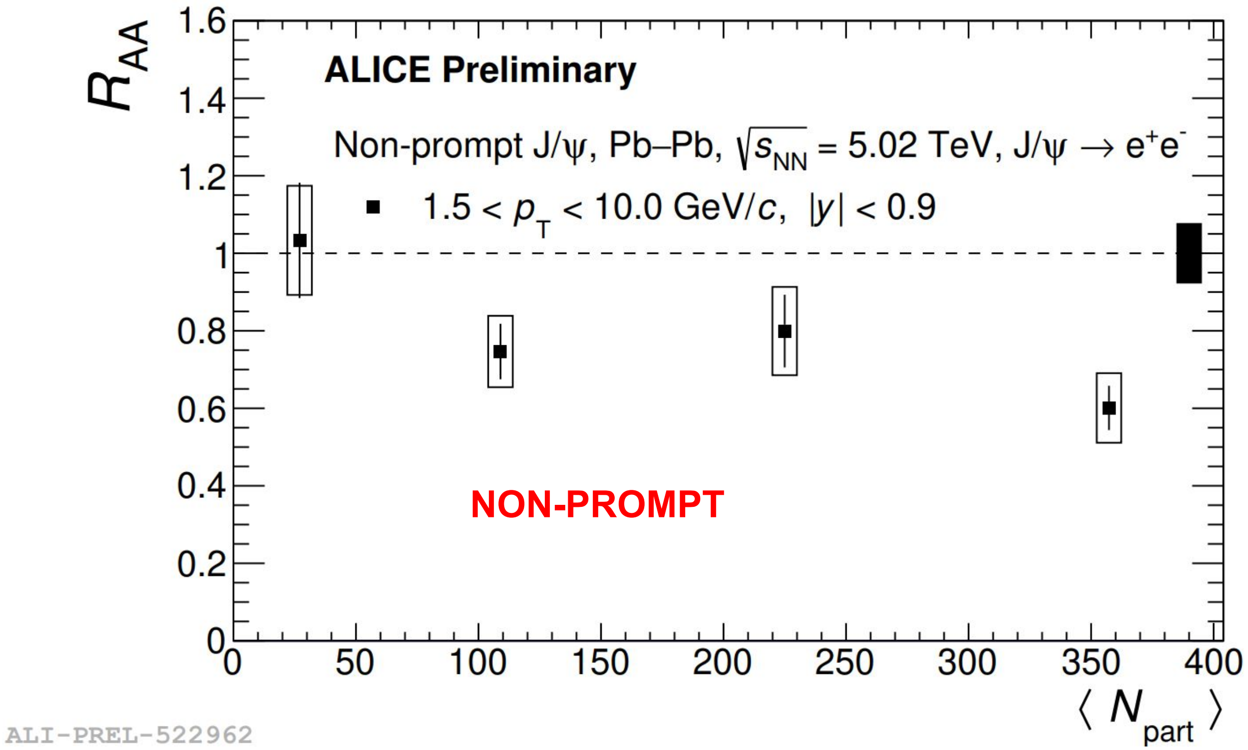
Qualitatively compatible with transport models TM1 and TM2 at low p_T which include also non-prompt J/ψ (not shown)

Models shown in the same centrality and rapidity ranges of ALICE measurements

Non-prompt J/ψ R_{AA} measurements

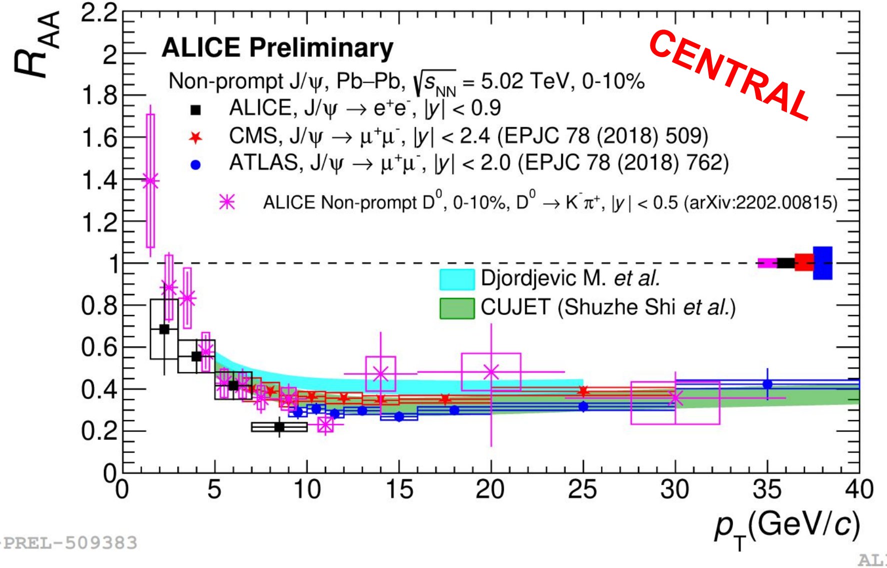
$$R_{\mathrm{AA}}^{\mathrm{non-prompt\ J}/\psi} = \frac{f_{\mathrm{B}}^{\mathrm{Pb-Pb}}}{f_{\mathrm{B}}^{\mathrm{pp}}}\, R_{\mathrm{AA}}^{\mathrm{inclusive\ J}/\psi}$$

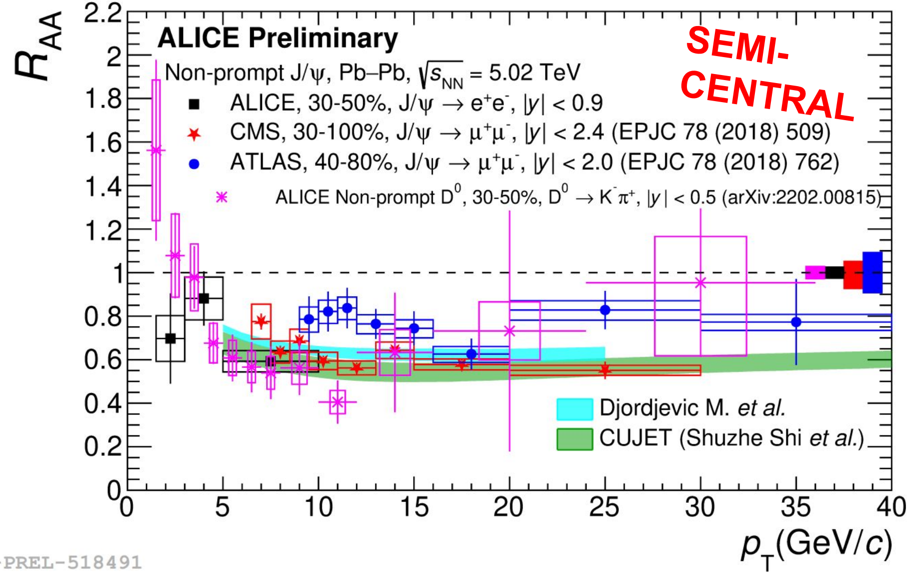
Non-prompt J/ψ R_{AA} as a function of $\langle N_{part} \rangle$



- Non-prompt J/ψ R_{AA} more suppressed towards more central collisions → expected trend from heavy quark energy loss

Non-prompt J/ψ R_{AA} in central and semicentral Pb–Pb collisions



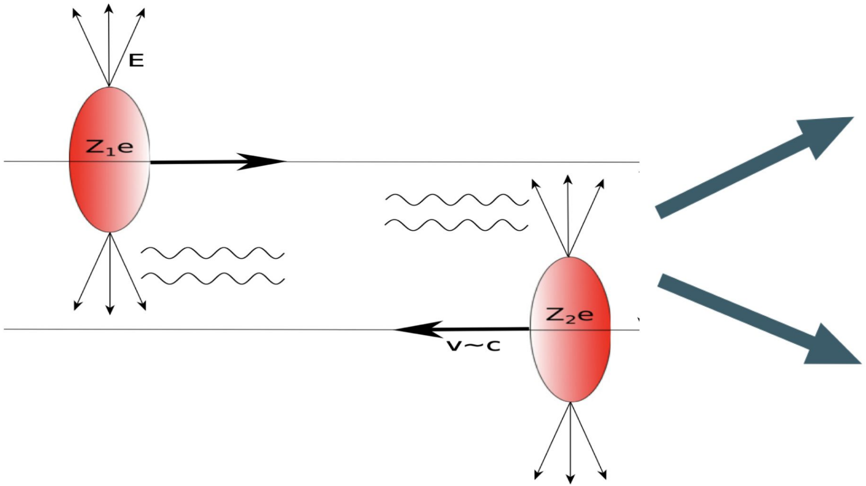


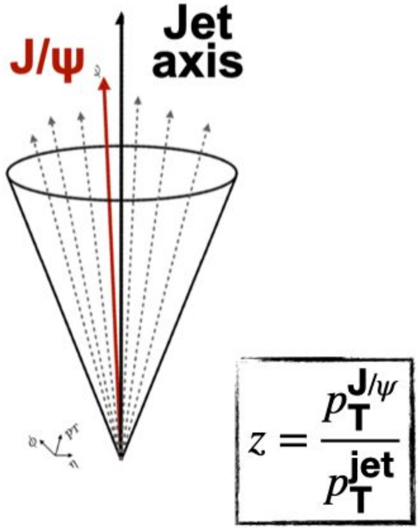
- Similar trends for non-prompt J/ψ and non-prompt D^0 R_{AA} (differences can arise due to the decay kinematic in two cases)
  - Strong suppression at high p_T (> 5 GeV/*c*)
  - Increase towards low p_T (< 5 GeV/*c*) → hints that heavy quarks are pushed towards lower p_T
- Models containing collisional and radiative energy loss consistent with data (p_T > 5 GeV/*c*)
- ALICE measurements complementary to ATLAS and CMS

CUJET: Shuzhe S. *et al.* *Chin.Phys.C* 43 (2019) 4, 044101, *Chin.Phys.C* 42 (2018) 10, 104104
Djordjevic M. *et al*. arXiv:2110.01544

Other ongoing analysis activities in ALICE Norway group

- Jet substructure physics using J/ψ tagged jets
- Exclusive B meson decays, e.g. B+ → J/ψ + K+
- Photoproduction of vector mesons in UPC and peripheral collisions
- Analysis software upgrade (Run2 → Run3)
- Analysis of the alice FOCAL upgrade (run4) simulations





Summary and conclusions

- One of several analyses worked on by the Norwegian ALICE community
- ALICE can measure beauty production through the non-prompt J/psi decay channel

Prompt J/ψ R_{AA}

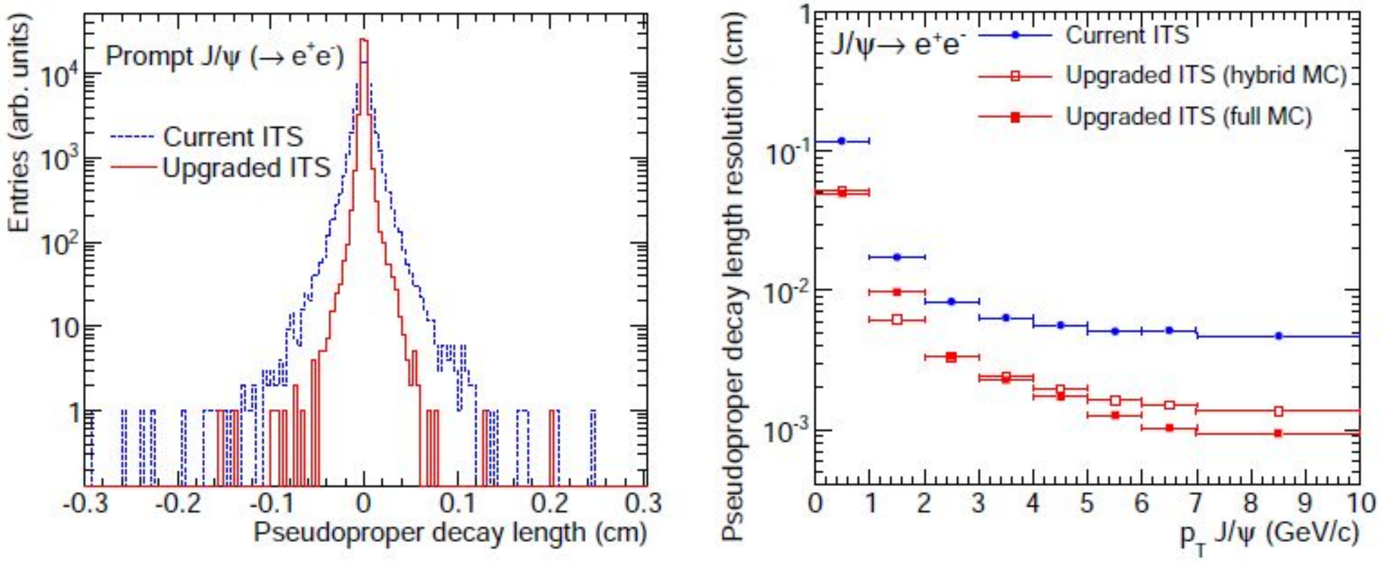
- Prompt J/ψ R_{AA} measurements show regeneration at low p_T, suppression at high p_T
- Models implementing charmonium regeneration manage to describe data!

Open beauty R_{AA} via non-prompt J/ψ

- Increasing suppression towards central collisions
- ALICE measurements
  - Extend down to very low p_T
  - Compatible with models implementing energy loss mechanisms!

Outlook

- Significant improvement expected for Run-3 / Run-4 (major upgrade of the ALICE detector during LS2)



CERN-LHCC-2013-024 ; ALICE-TDR-017

Thank you for listening!

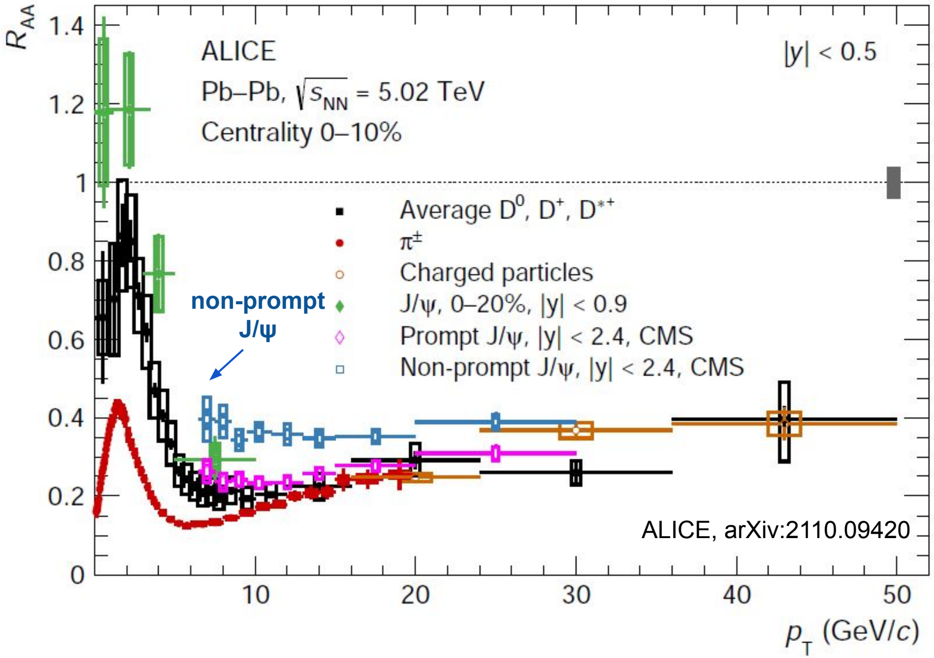
BACKUP

Measuring Beauty via non-prompt J/ψ

- A sizeable fraction of charmonia comes from beauty hadron decays
  → possibility to access open heavy-flavor production!

- Heavy quarks, charm and beauty, produced early in heavy-ion collisions via hard parton-parton scatterings → lose energy in the QGP via collisional and radiative processes
  - Dead cone effect reduces radiative losses for beauty

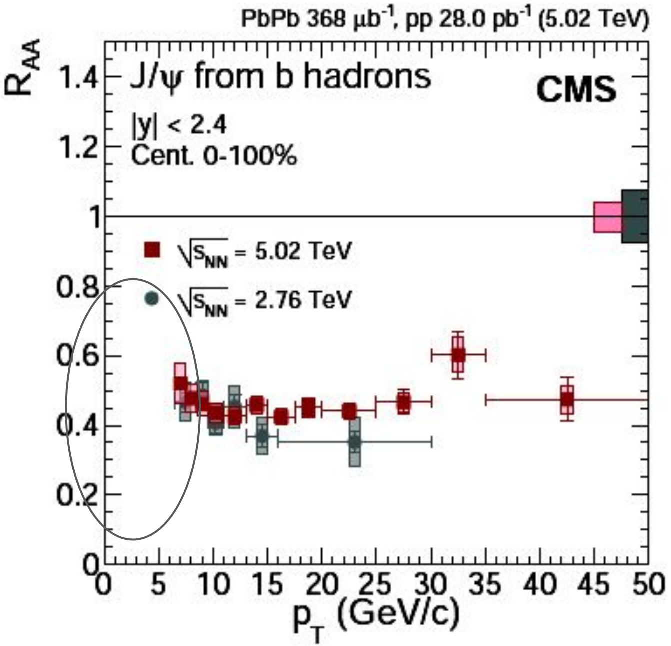
Mass dependence of parton energy loss →
Hierarchy expected for R_{AA} of light and heavy-flavor hadrons!



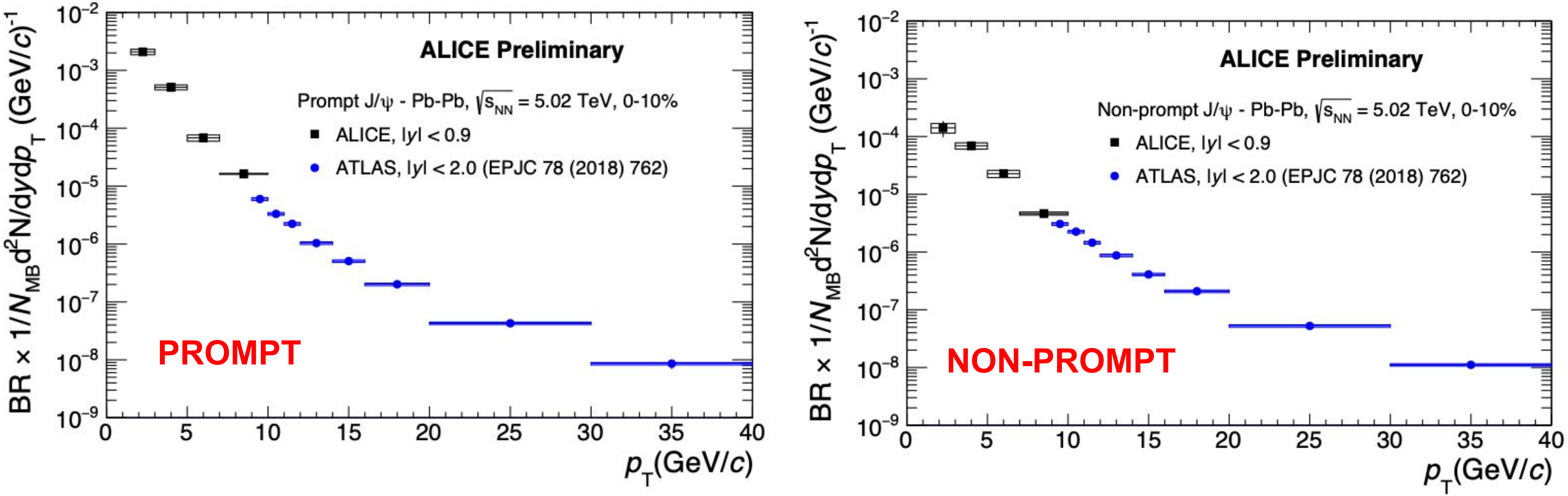
Beauty production via non-prompt J/ψ in ALICE

- Beauty production measurements performed in Run-1 / Run-2 by ALICE at midrapidity and **through "inclusive" decay channels**:
  - D mesons originating from beauty hadron decays (or "non-prompt" D mesons)
  - electrons from heavy-flavour / beauty decays
  - **non-prompt J/ψ**

- Focus of this talk: non-prompt J/ψ measurements in Pb–Pb at $\sqrt{s_{NN}}$ = 5 TeV using full Run 2 statistics:
  - Improve Run 1 measurements
  - Complement existing prompt and non-prompt J/ψ R_{AA} measurements from CMS and ATLAS available for p_T > 6.5 GeV/c



Prompt and non-prompt J/ψ yields in central collisions



- Compatible trends between ALICE and ATLAS
- ALICE extends prompt and non-prompt J/ψ measurements at midrapidity down to very low p_T at the LHC