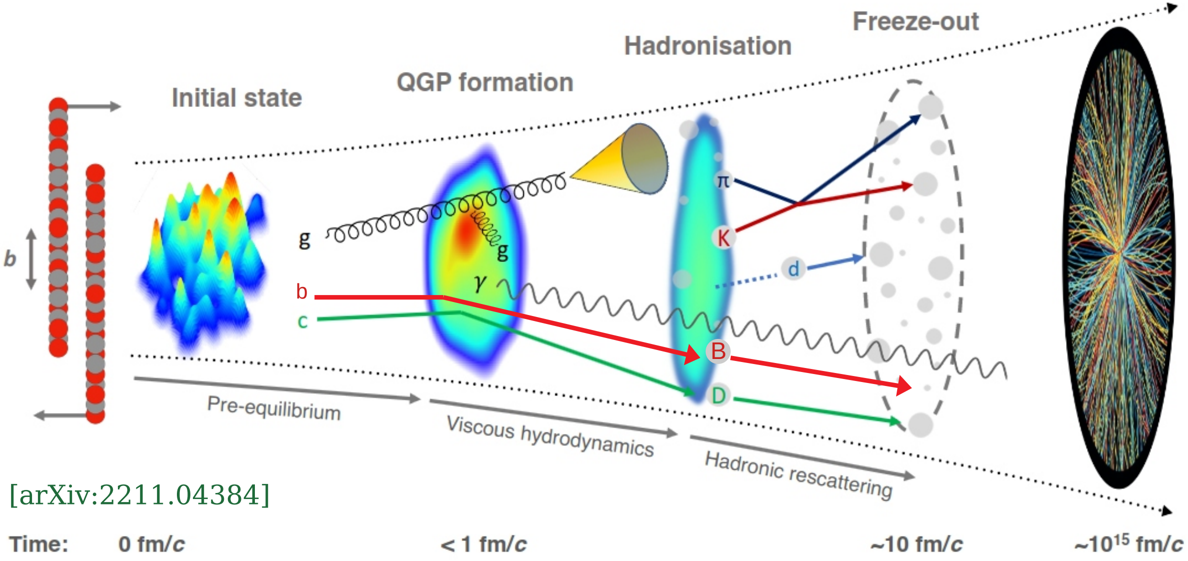
# Investigating the interplay between initial hard processes and final-state effects measuring prompt and non-prompt J/ψ with ALICE

SQM 2024 3th-7th June, Strasbourg

Maurice Coquet on behalf of the ALICE Collaboration, 4th June

# Heavy quarks as probes




[arXiv:2211.04384]

Large mass ($m_c \sim 1.3$ GeV/$c^2$, $m_b \sim 4.2$ GeV/$c^2$)

- heavy quarks produced in the hard scatterings in the initial state, **experience full evolution of the collision**
- probes to study **properties of hot QCD matter**

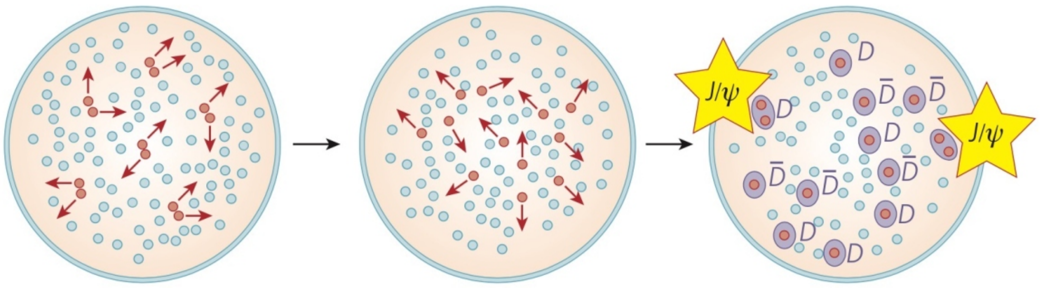
Heavy quarks in small collision systems, **reference for QGP studies** and tool to investigate:

- perturbative production mechanism
- non-perturbative hadronization

# Prompt/non-prompt charmonia in AA

- **Suppression**: quarkonia expected to be suppressed in QGP by color screening and dynamical dissociation
  T. Matsui and H. Satz, PLB 178 (1986) 416
  A Rothkopf, Phys. Rept. 858 (2020) 1-117

- **Recombination** at high energy: large number of $c\bar{c}$ pair produced → enhanced quarkonium production via recombination of uncorrelated $c\bar{c}$ pairs
  P. Braun-Munzinger, J. Stachel, PLB 490 (2000) 196
  R. Thews et al, Phys. Rev. C 63 (2001) 054905

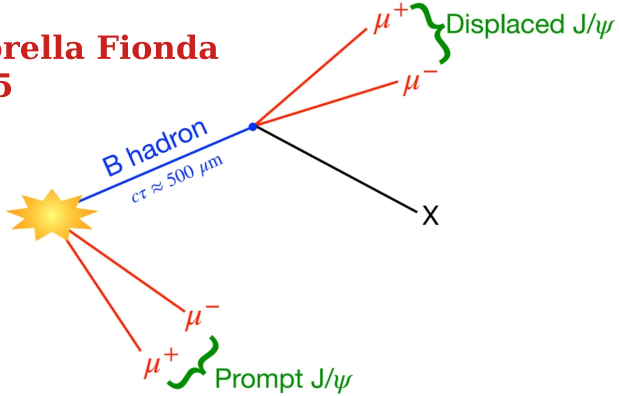



[P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302]

- Inclusive J/ψ yield can be separated between **prompt** and **non-prompt** contributions based on displaced production vertex

- **Non-prompt charmonium** produced by **beauty hadron decays**: corresponding measurements can contribute to the study of **parton energy loss** and **transport coefficients** of heavy quarks inside the QGP

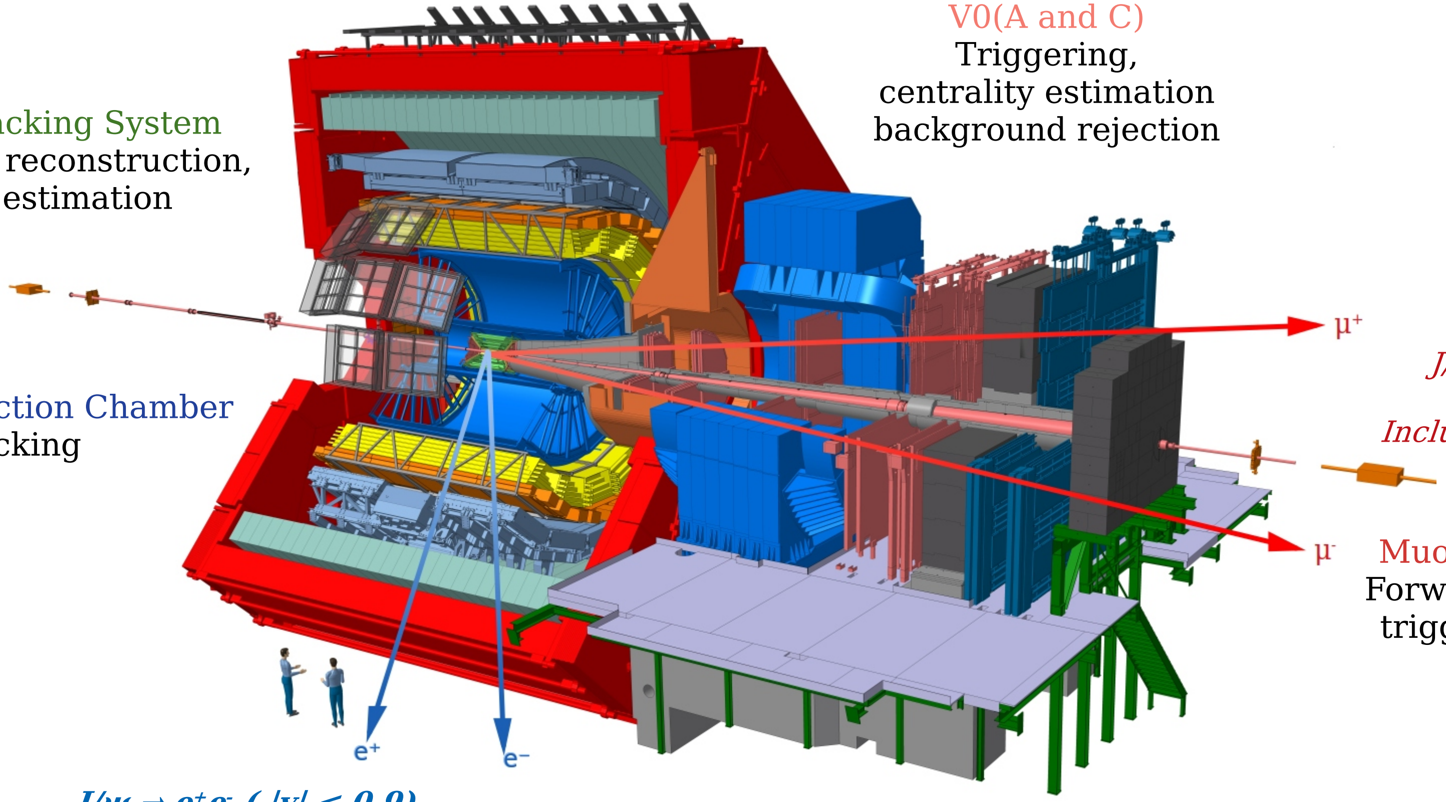
See talk by Fiorella Fionda
3rd june, 11:05



# ALICE in Run 2

V0(A and C)
Triggering,
centrality estimation
background rejection

ITS – Inner Tracking System
Tracking, vertex reconstruction,
multiplicity estimation




*$J/\psi$, $\Psi(2S) \rightarrow \mu^{+}\mu^{-}$*
*$(2.5 < y < 4.0)$*
*Inclusive measurements*

TPC – Time Projection Chamber
PID, tracking

Muon Spectrometer
Forward tracking and
triggering of muons

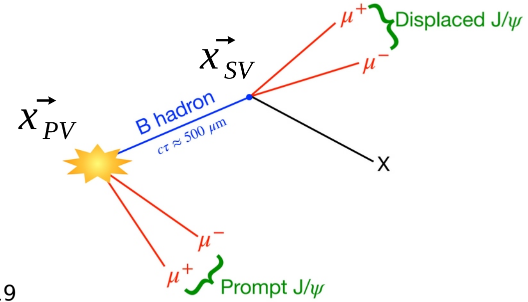
***$J/\psi \rightarrow e^{+}e^{-}$ ( $|y| < 0.9$)***
***Prompt/non-prompt $J/\psi$***
***separation***

# Non-prompt fraction extraction

- Non-prompt J/ψ fraction (***f*<sub></sub>**$_{\mathbf{B}}$) measured by ALICE at midrapidity in **pp at √s=13 TeV** and in **Pb–Pb at √s$_{\mathbf{NN}}$= 5.02 TeV**

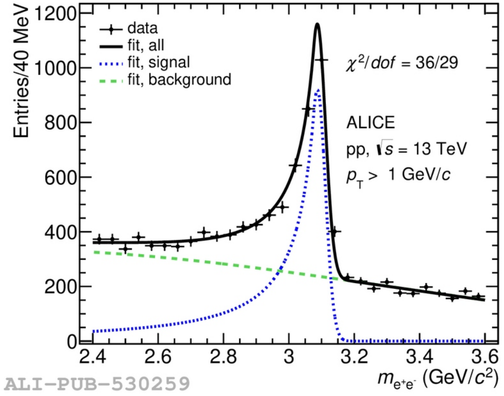
- Analysis based on two-dimensional fit on invariant mass and **pseudoproper decay length** L

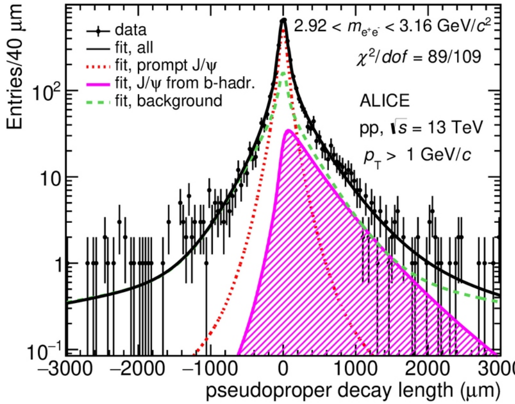
$$L = c\frac{(\vec{x}_{PV}-\vec{x}_{SV})\cdot\vec{p}_T\, m_{J/\psi}}{p_T^2}$$



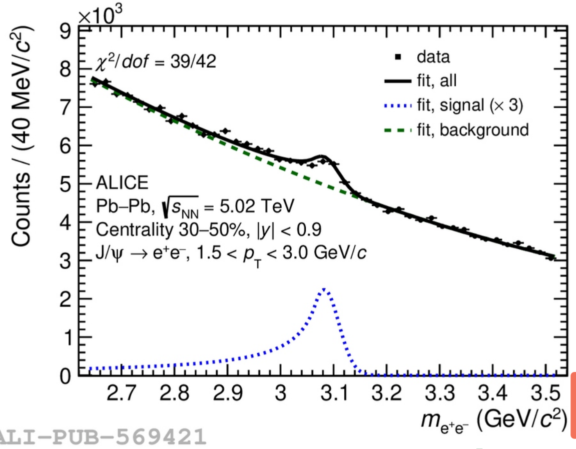

[JHEP 03 (2022) 190]

**pp**




**Pb–Pb**

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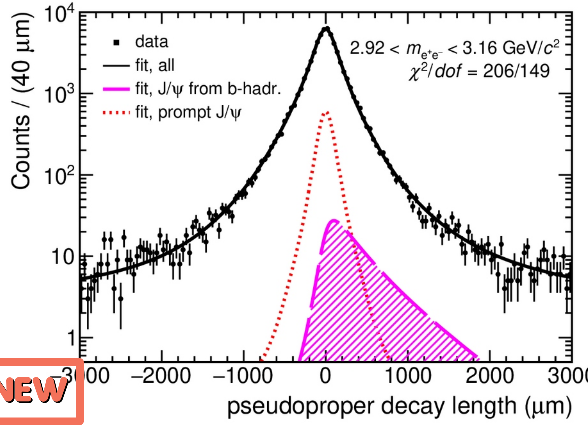
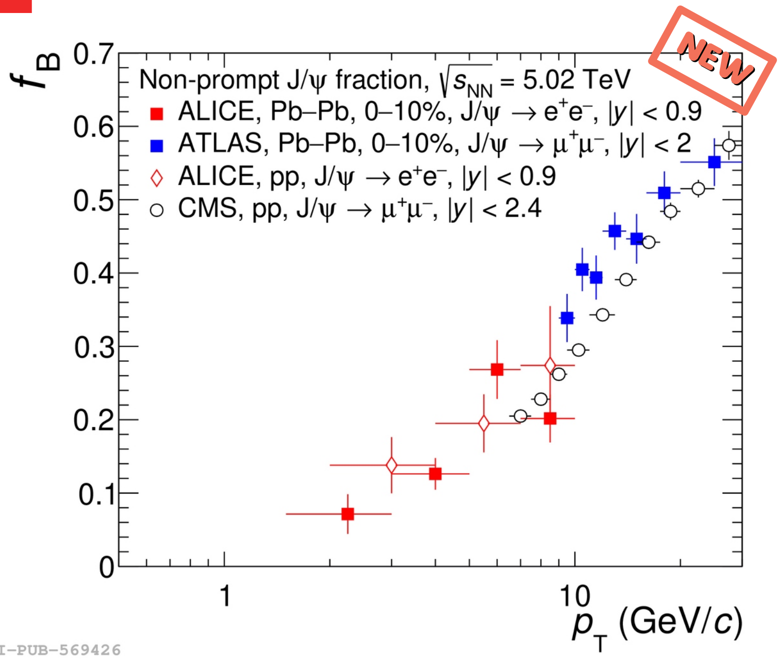
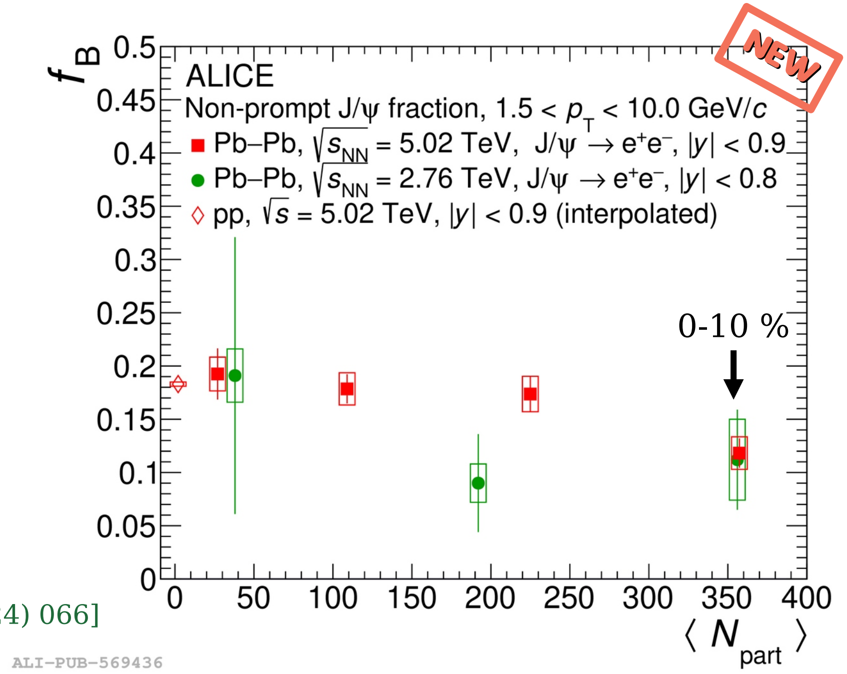



[JHEP 02 (2024) 066]

# Non-prompt J/ψ fraction




[ JHEP 02 (2024) 066]



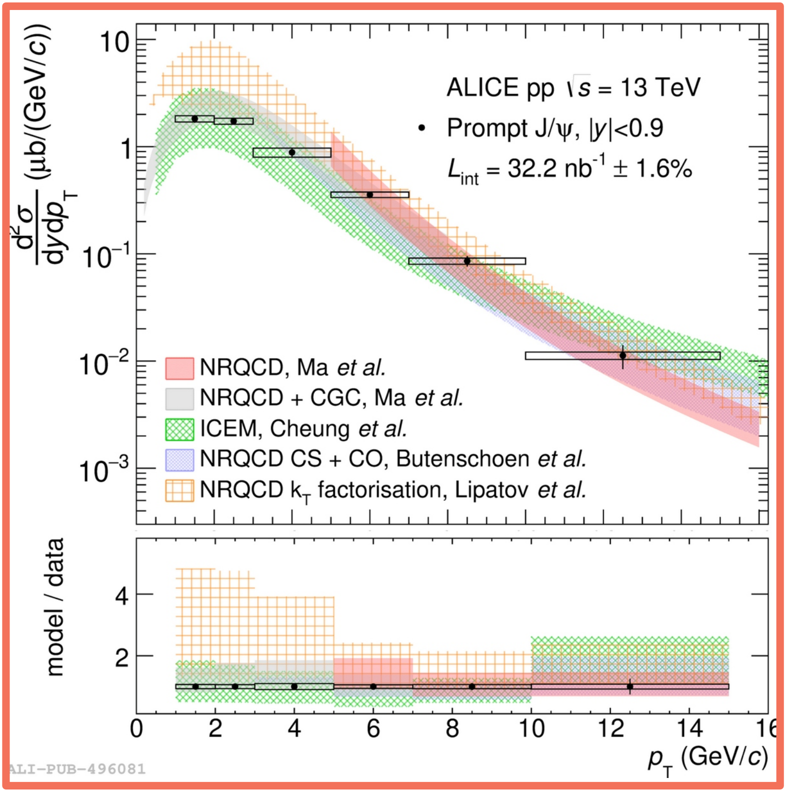

- ALICE results complement the existing high-$p_T$ measurements
- For $p_T$ > 10 GeV/c, **$f_B$ higher in Pb–Pb compared to pp collisions**, suggests stronger suppression of prompt charmonia compared to beauty hadrons
- At low $p_T$, results from both systems are compatible within uncertainties
- **Smaller $f_B$ in the centrality class 0–10%**

# Prompt & non-prompt J/ψ in pp

**prompt**

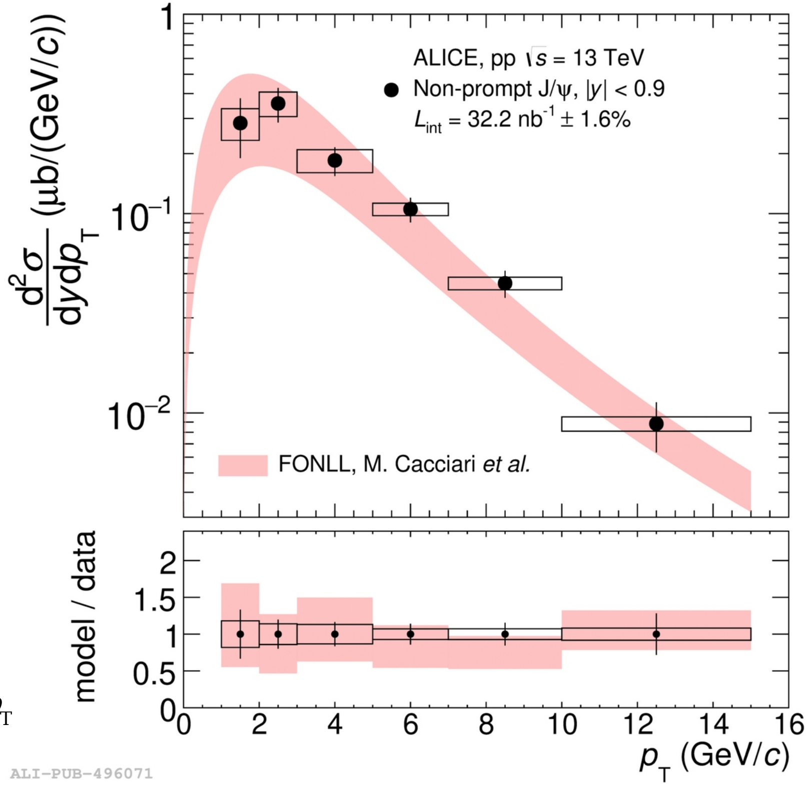
[JHEP 03 (2022) 190]

**non-prompt**




**Models describe well the prompt** differential cross sections at midrapidity, at **√s=13 TeV**

- **NRQCD+CGC**: Color Glass Condensate initial state + non-relativistic QCD hadronization → good agreement over full $p_T$ range
- **ICEM**: Improved Color Evaporation → slightly overshoots at high $p_T$
- **NRQCD + $k_T$ factorization**: overestimates data at low $p_T$

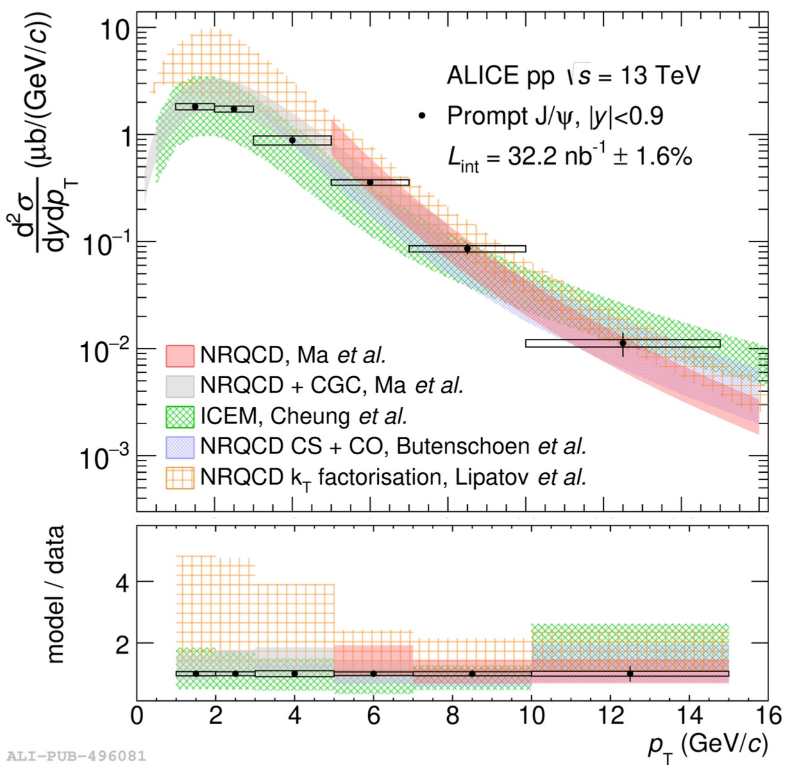




NRQCD CS+CO : Butenschoen, Phys. Rev. Lett. 106 (2011) 022003
NRQCD : Ma, Phys. Rev. Lett. 106 (2011) 042002
NRQCD+CGC : Ma, Phys. Rev. Lett. 113 no. 19 (2014) 192301
ICEM : Cheung, Phys. Rev. D 98 no. 11, (2018) 114029
NRQCD+$k_T$ fact. : Lipatov, Phys. Rev. D 100 no. 11, (2019) 114021

# Prompt & non-prompt J/ψ in pp

**prompt**

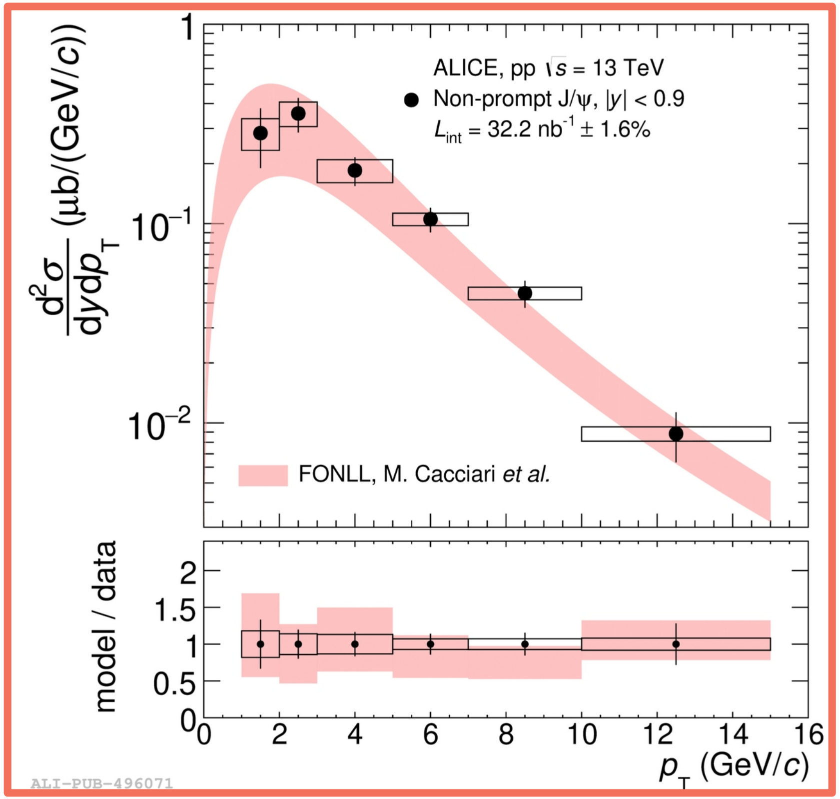



[JHEP 03 (2022) 190]

**Models describe well the non-prompt** J/ψ differential cross sections at midrapidity, at **√s=13 TeV**

- **FONLL**: Fixed-Order-Next-to-Leading-Log perturbative calculation

**non-prompt**



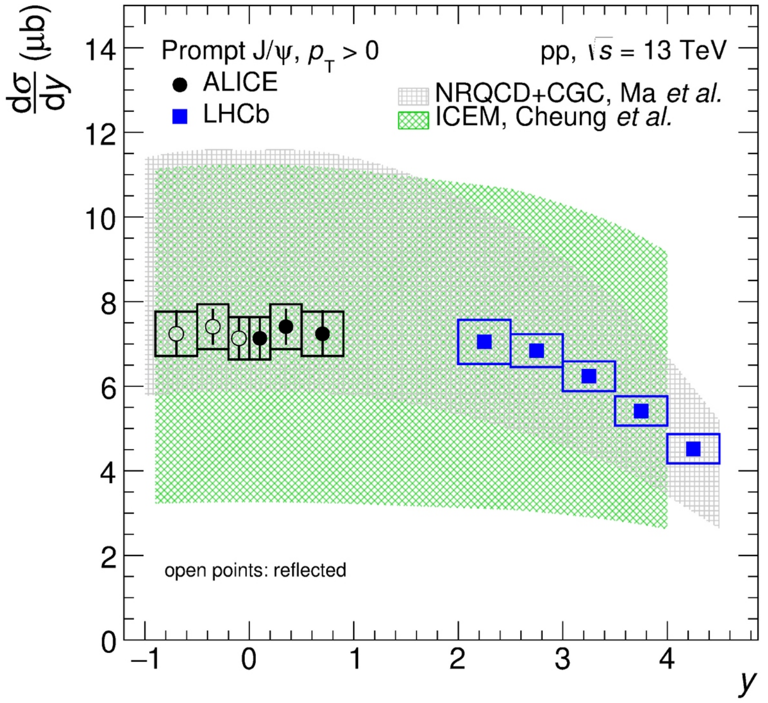

FONLL : Cacciari, JHEP 05 (1998) 007

# Prompt & non-prompt J/ψ in pp

**prompt**

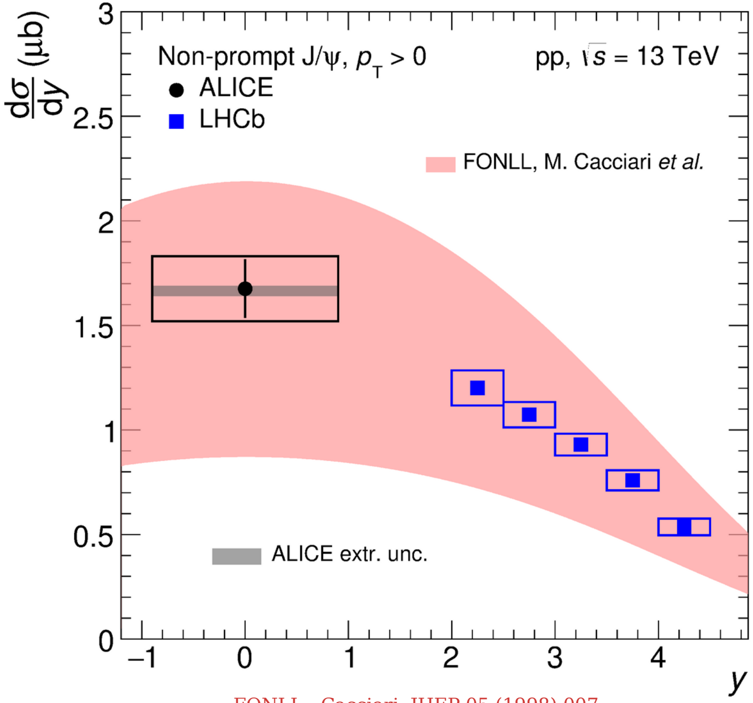
[JHEP 03 (2022) 190]

**non-prompt**




ALI−PUB−530295

NRQCD+CGC : Ma, Phys. Rev. Lett. 113 no. 19 (2014) 192301
ICEM : Cheung, Phys. Rev. D 98 no. 11, (2018) 114029



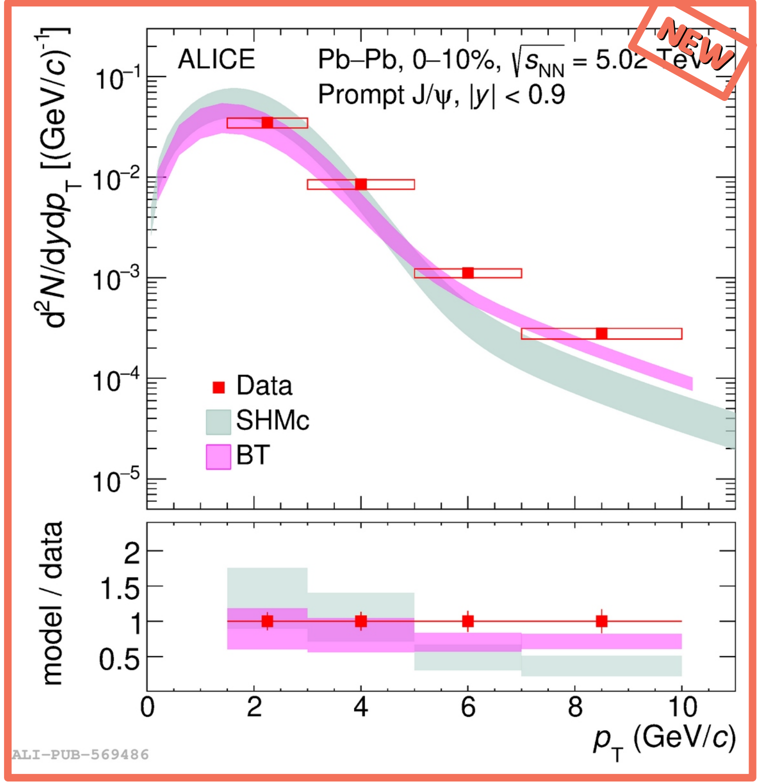

ALI−PUB−530291

FONLL : Cacciari, JHEP 05 (1998) 007

- Models also describe the **rapidity-differential** cross sections at midrapidity, at √s=13 TeV
- Large uncertainties on model predictions (main contribution from scale uncertainties)

# Prompt & non-prompt J/ψ in Pb–Pb

**prompt**




SHMc: PLB 797 (2019) 134836
BT: CPC43 (2019) 124101

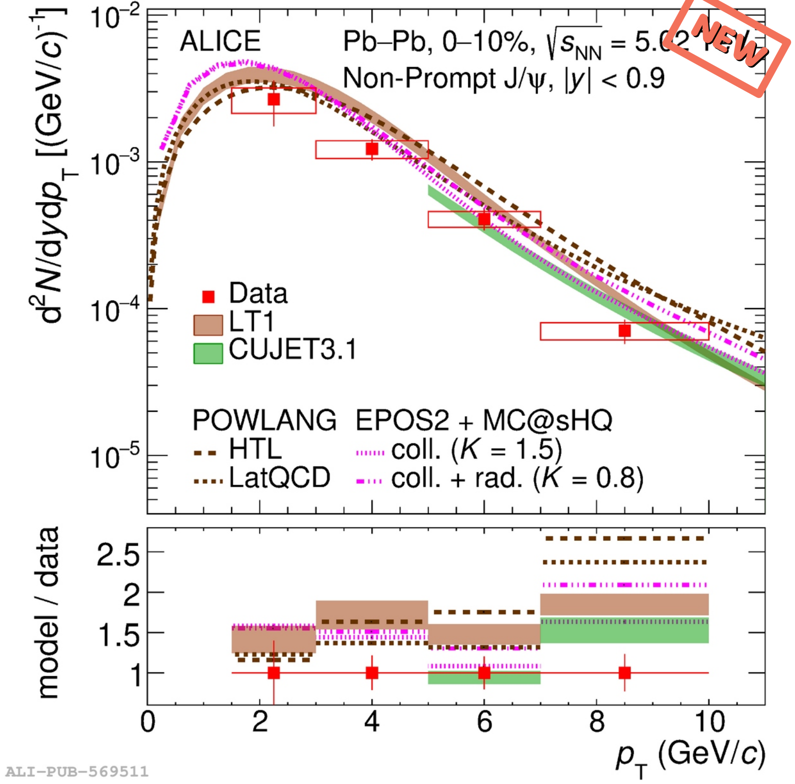
[JHEP 02 (2024) 066]

**Models describe the prompt** differential cross sections in **Pb–Pb**, at **$\sqrt{s_{NN}}$=5.02 TeV**

- **SHMc**: Statistical Hadronization Model
- **BT**: Boltzmann Transport model

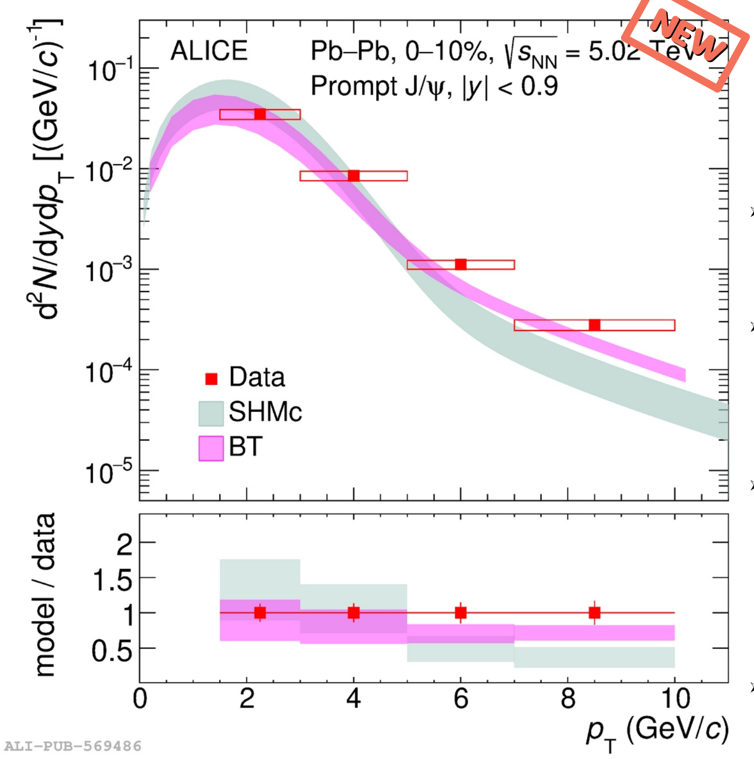
- For $p_T$ < 5 GeV/$c$, SHMc & BT models show good agreement with data
- For $p_T$ > 5 GeV/$c$ , BT on lower side, SHMc underpredicts the data

**non-prompt**



# Prompt & non-prompt J/ψ in Pb–Pb

**prompt**

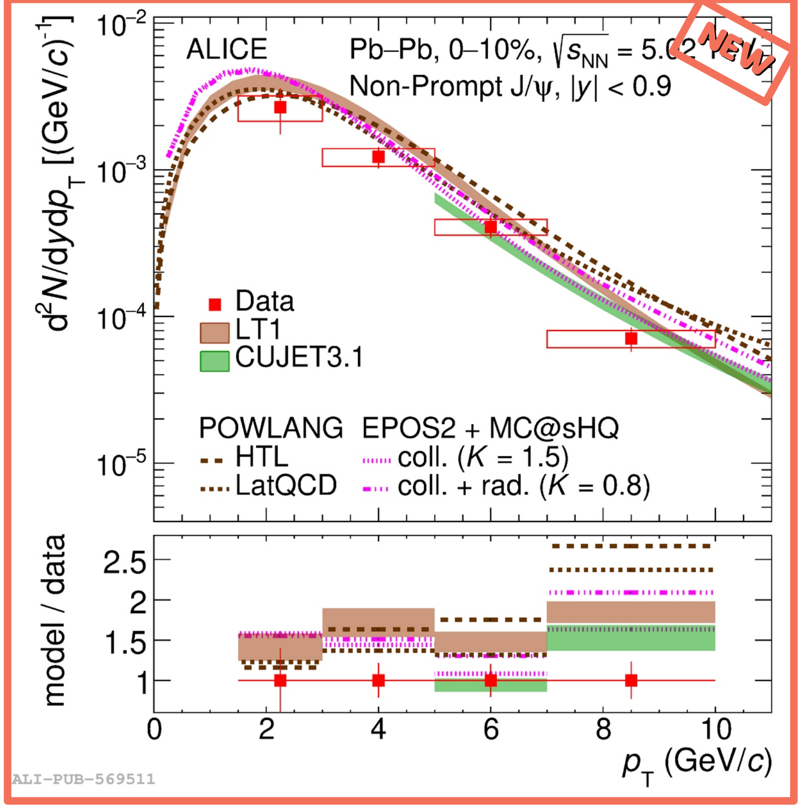



[JHEP 02 (2024) 066]

**Models describe well the non-prompt** J/ψ differential cross sections in **Pb–Pb**, at **$\sqrt{s_{NN}}$=5.02 TeV**

- **LT1**, **POWLANG**: Langevin transport for b-quark
- **EPOS2+MC@sHQ**: EPOS2 initial state + MC Boltzmann transport
- Higher values than data, especially POWLANG at high $p_T$ (due to **no radiative energy loss** ?)
- **CUJET3.1**: jet energy loss framework, compatible with data at high $p_T$

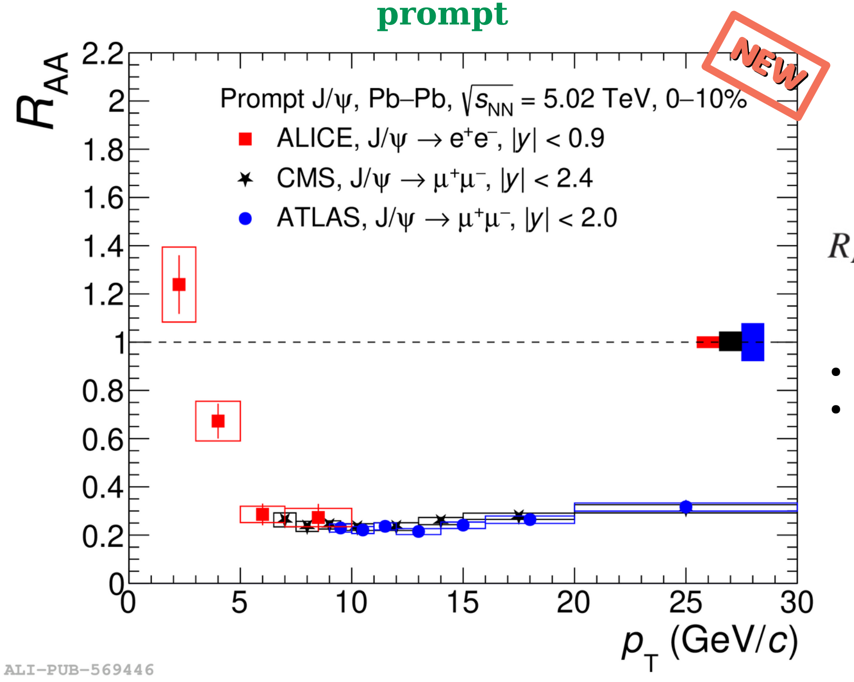
**non-prompt**




LT1: PRC107, 054917 (2023)
POWLANG: JHEP 05 (2021) 279, EPJC 75 (2015) 121
CUJJET3.1: CPC 43 (2019) 044101
EPOS2+MC@sHQ : PRC 93 (2016) 044909

# Nuclear modification factor

**prompt**

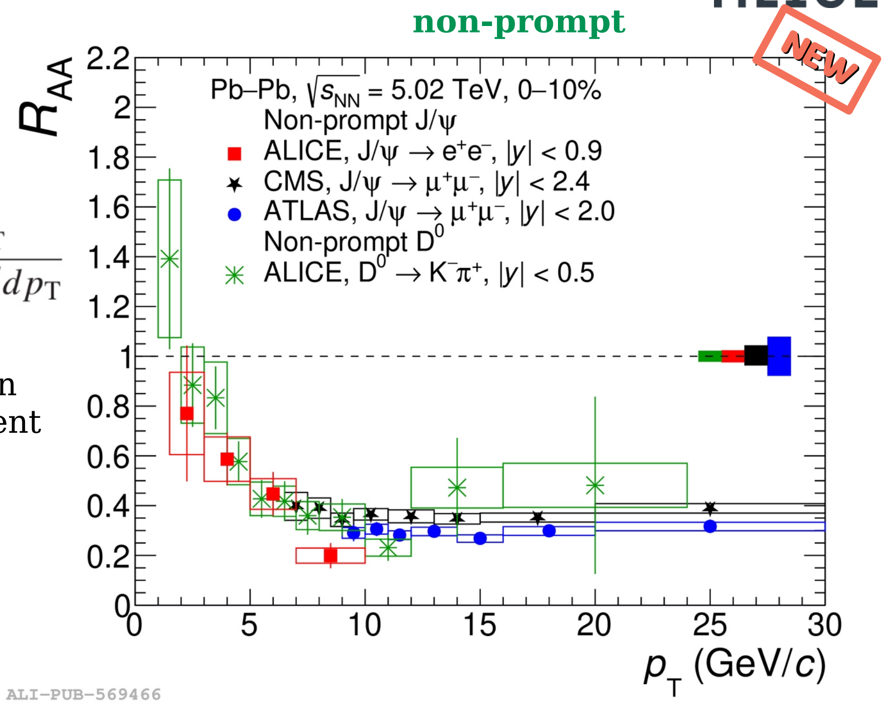



[JHEP 02 (2024) 066]

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

- $R_{AA} < 1$ → suppression
- $R_{AA} > 1$ → enhancement

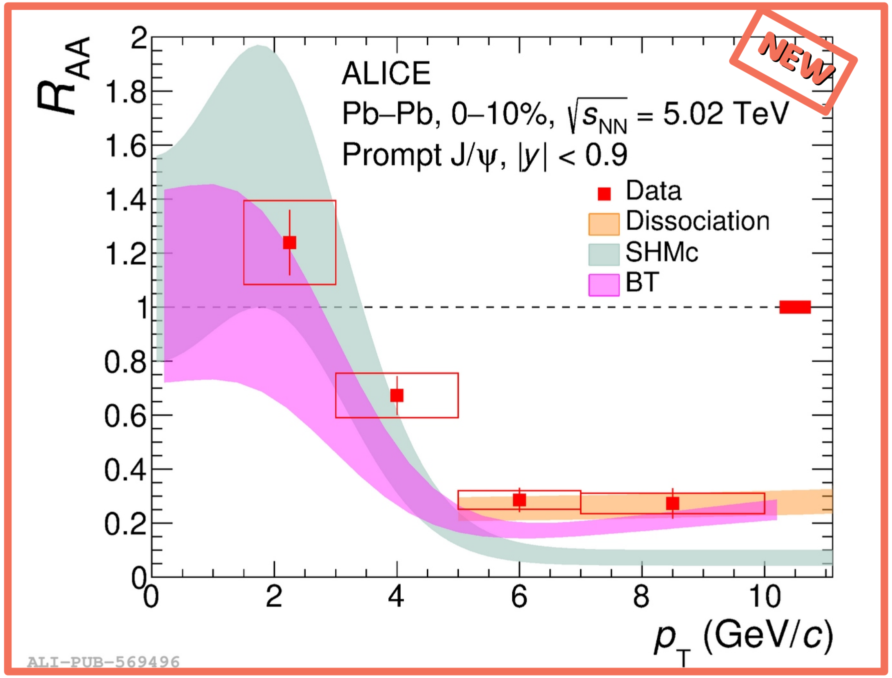
**non-prompt**

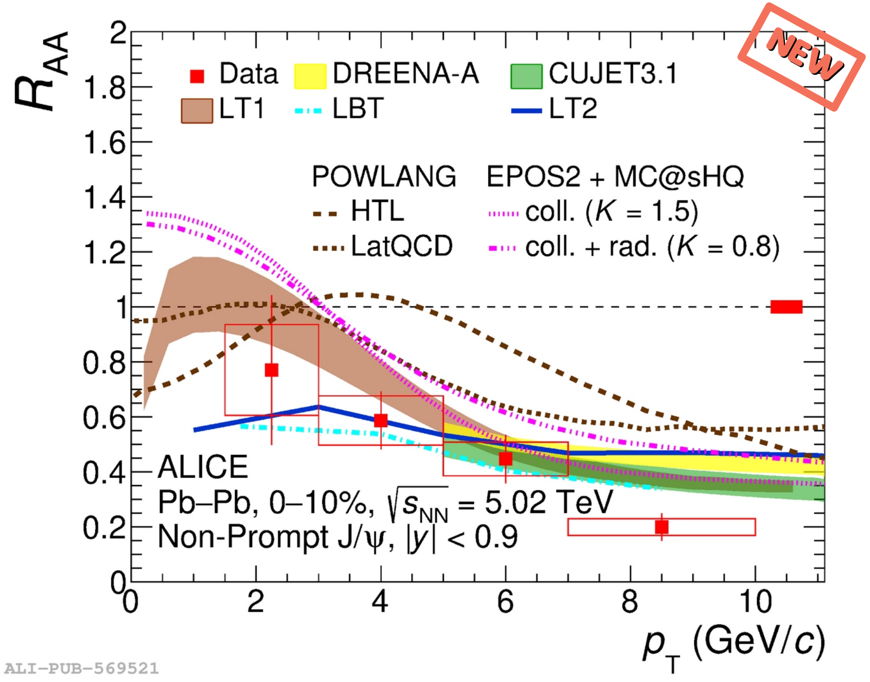



- Agreement among results from LHC experiments in the overlapping $p_T$ range, ALICE extends the reach down to $p_T = 1.5$ GeV/$c$
- Similar trends for **non-prompt J/ψ** and **non-prompt D⁰ $R_{AA}$** (small differences could arise from the different decay kinematics)

# Nuclear modification factor

**prompt** [JHEP 02 (2024) 066] **non-prompt**




SHMc: PLB 797 (2019) 134836
BT: CPC43 (2019) 124101
Dissociation: PLB 778 (2018) 384-391

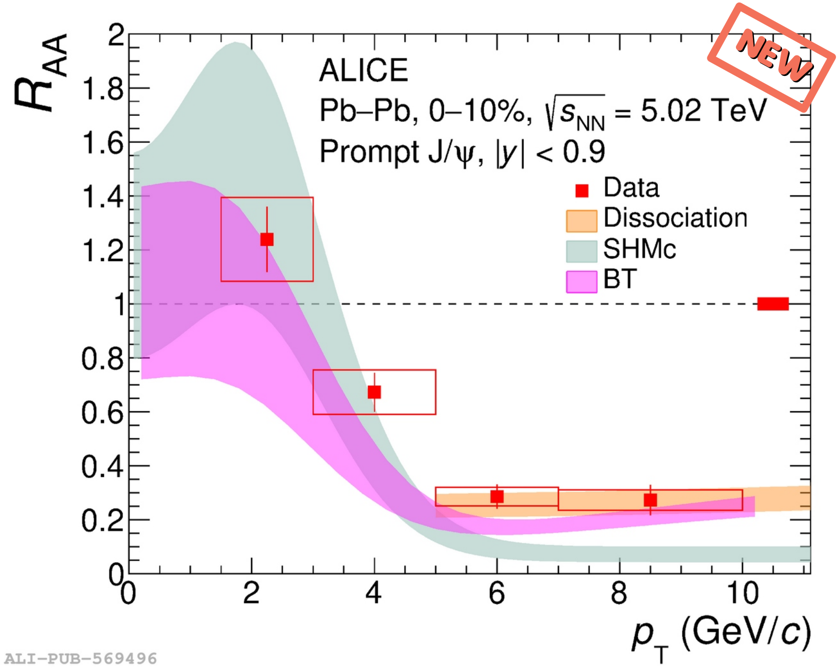
- For $p_T > 5$ GeV/$c$, **BT** on lower side, **SHMc** underestimates the data
- **Dissociation model**: rate equation, collisional and color screening, provides a good description for $p_T > 5$ GeV/$c$

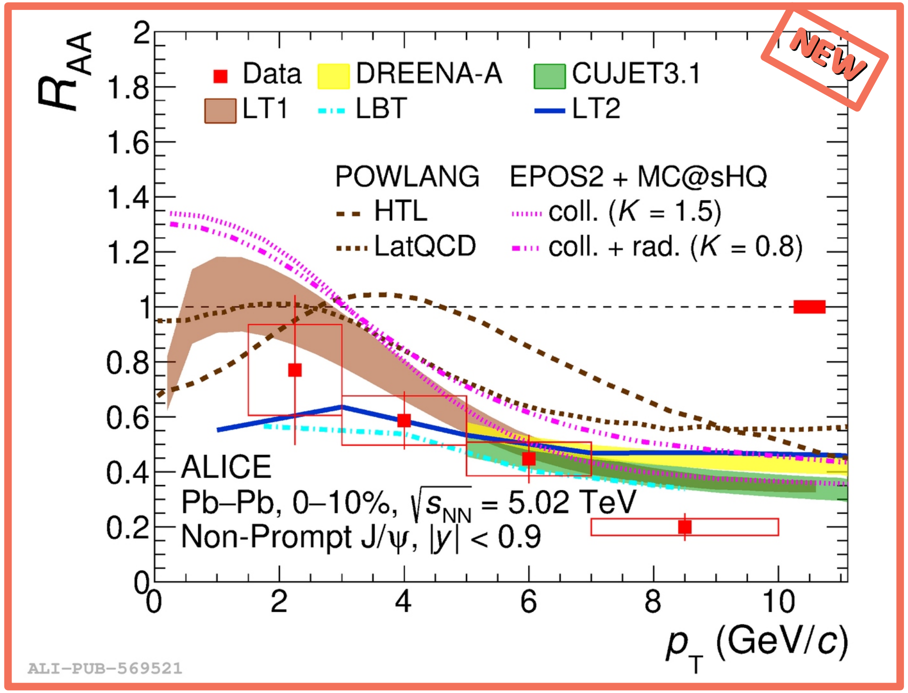
# Nuclear modification factor

**prompt**

[JHEP 02 (2024) 066]

**non-prompt**

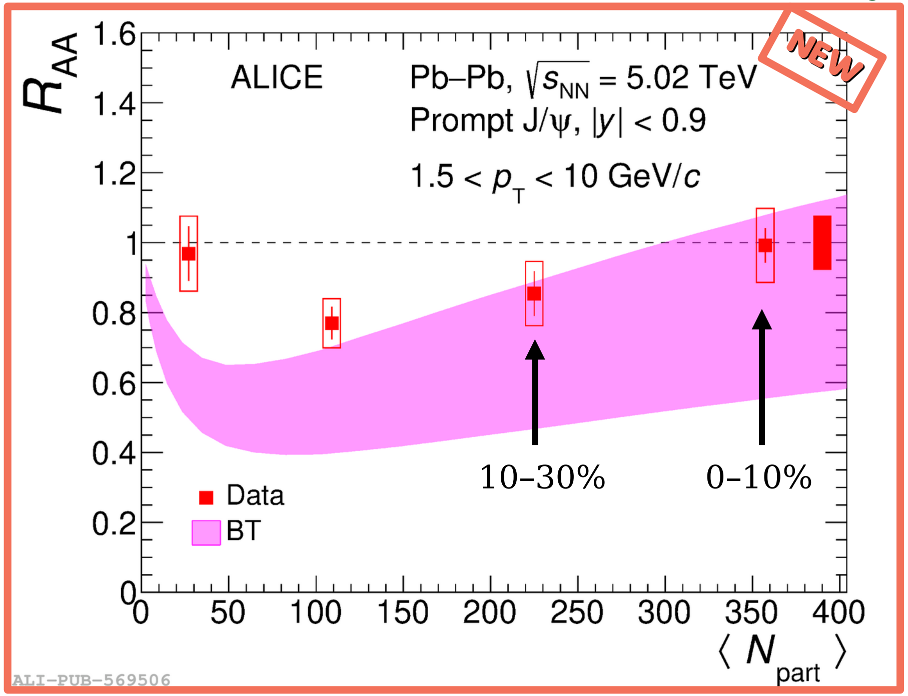


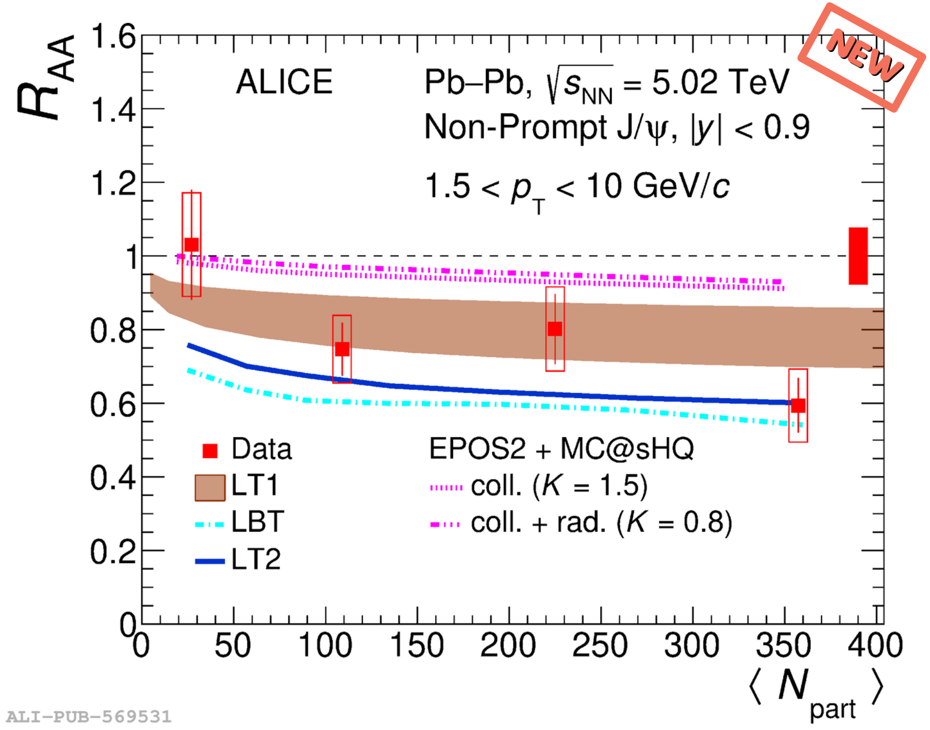

- For $p_T$ > 5 GeV/$c$, **POWLANG** overpredicts $R_{AA}$ while other models show agreement with data
- For $p_T$ < 5 GeV/$c$, **EPOS2+MC@sHQ** overpredicts the data
- **LBT** (Linear Boltzmann Transport) **LT2** (imporved Langevin transport) are compatible with the measured $R_{AA}$ in the full $p_T$ range


DREENA-A: Phys. Rev. C 105, L021901
CUJJET3.1: CPC 43 (2019) 044101
LT1: PRC107, 054917(2023)
LBT: PLB838(2023) 137733
LT2: EPJC 81 848 (2021) 1035

# Centrality dependence




[JHEP 02 (2024) 066]



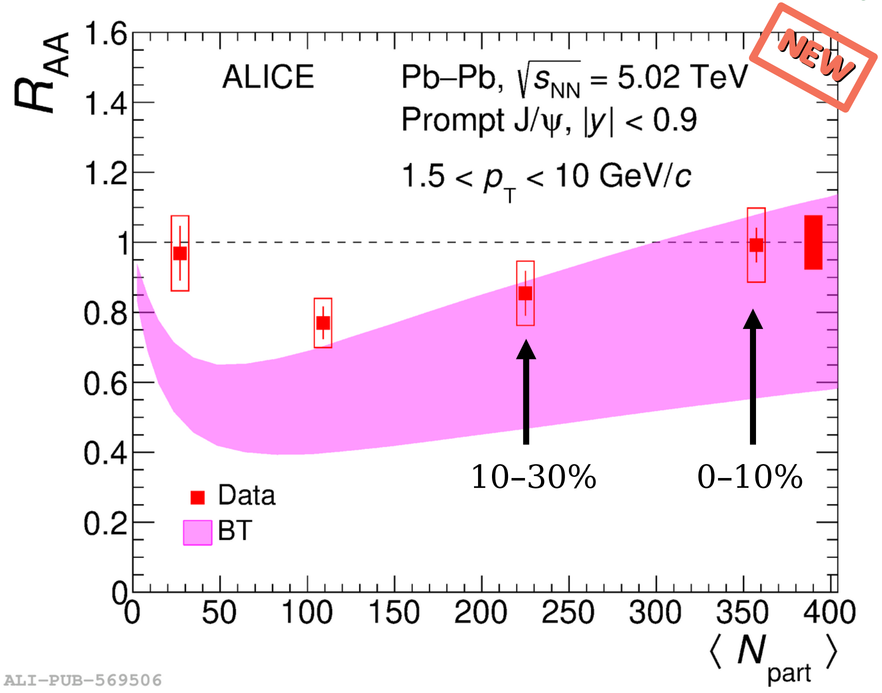

- **BT** model is in good agreement with data in **0–10%** and **10–30%** centrality classes
- Agreement between data and models worsens below ⟨$N_{part}$⟩ ∼ 50

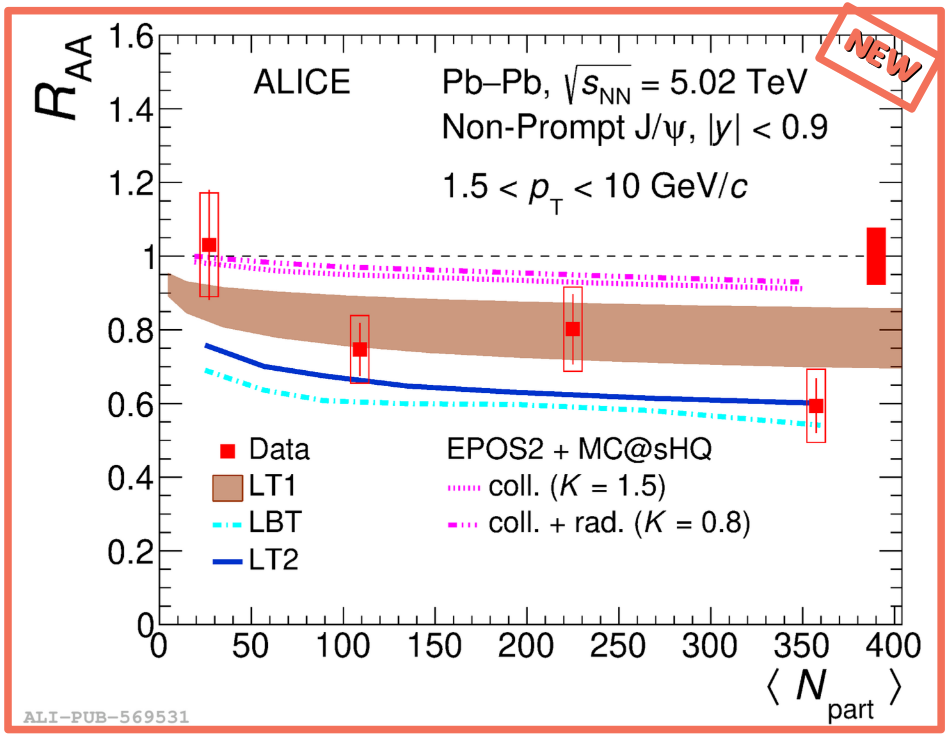
# Centrality dependence

prompt

[JHEP 02 (2024) 066]

non-prompt

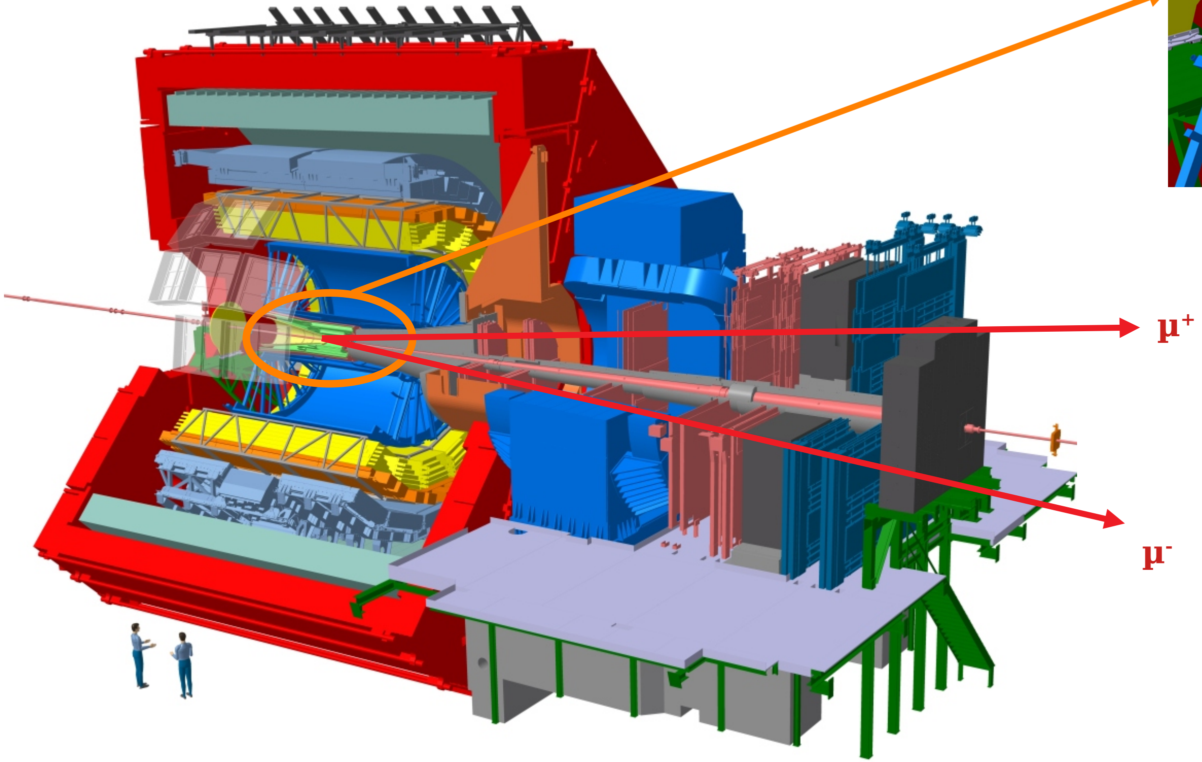


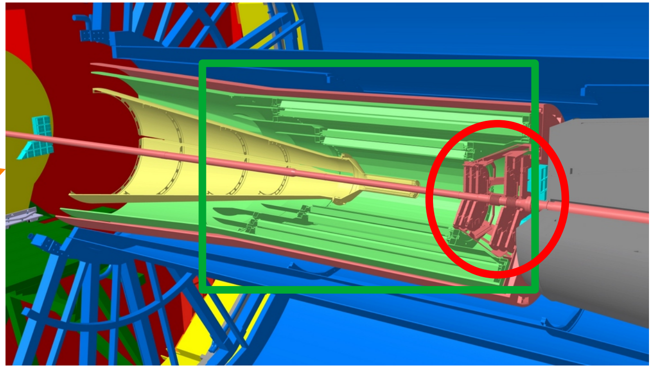




- **LT1** compatible with data within uncertainties
- **LBT** and **LT2** slightly underpredict data except for 0-10 % centrality class
- **EPOS+MC@sHQ** tends to overestimate data except for most peripheral centrality class

# ALICE in Run 3

**New global acquisition strategy, allowing operations in continuous readout mode**



**ITS2** [CERN-LHCC-2013-024]

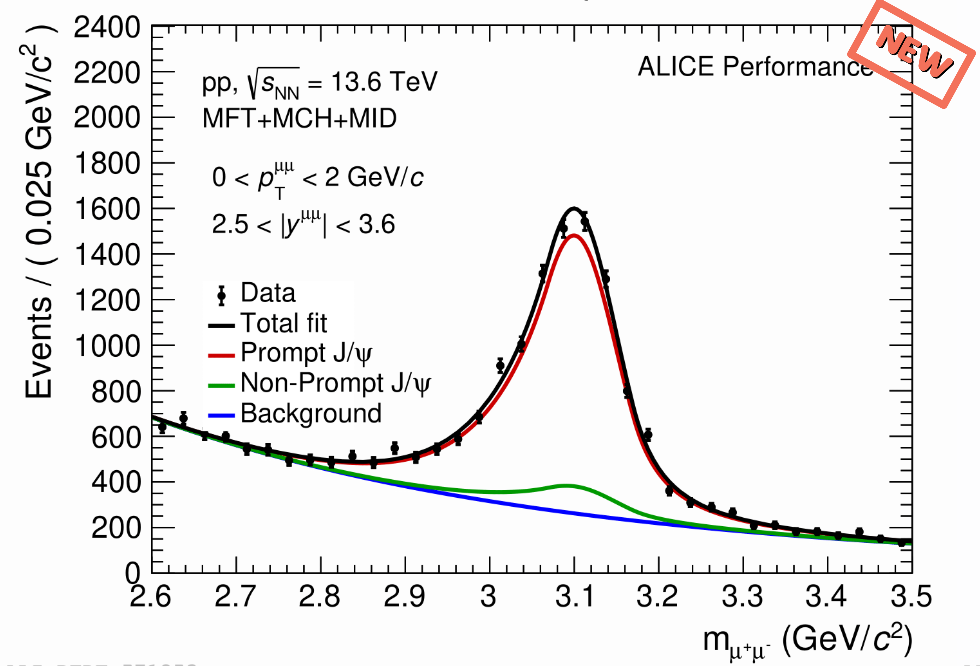
Upgraded detector, **improved precision of primary vertex and secondary vertices** reconstruction

**MFT – Muon Forward Tracker** [CERN-LHCC-2015-001]

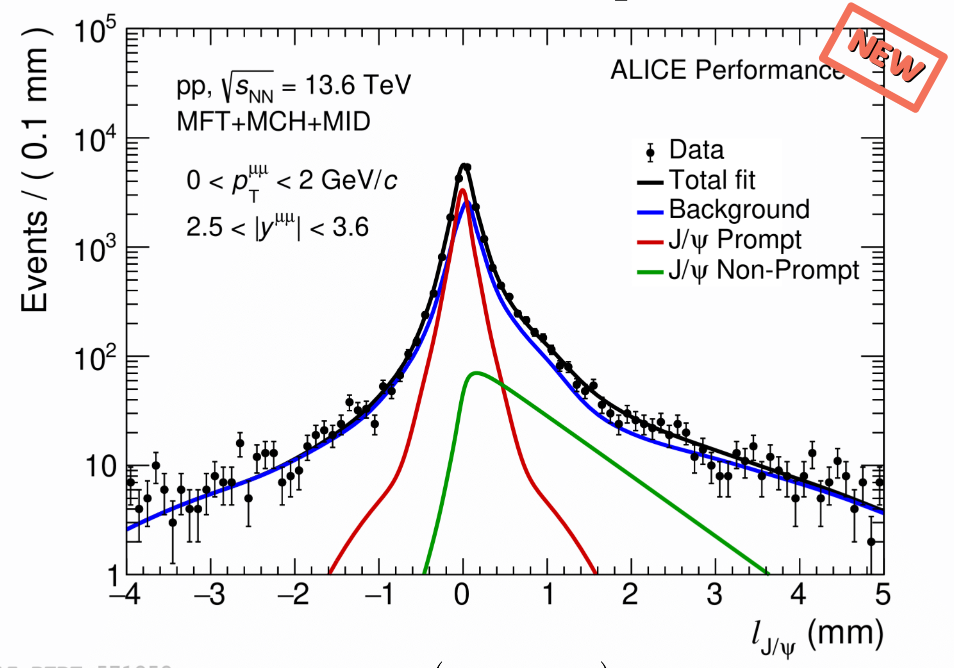
Providing vertexing performance for muon spectrometer, **allowing prompt/non-prompt separation at forward rapidity** in ALICE

# Run 3 performance at forward rapidity

- Performance in pp using muons tracks detected in all muon detectors: **MFT+MCH+MID**
- **First prompt/non-prompt J/ψ separation at forward rapidity in ALICE**
- Boost at forward rapidity allows non-prompt fraction measurement **down to $p_T = 0$**




ALI-PERF-571253




ALI-PERF-571258

**Poster by Emilie Barreau**
**Talk by Maolin Zhang**
**5th june, 11:05**

$$l_{J/\psi} = c\frac{(z_{PV} - z_{SV})\, m_{J/\psi}}{p_z}$$

# Conclusion & outlook

- Prompt/non-prompt J/ψ separation at mid-rapidity in Pb–Pb collisions achievable in ALICE down to $p_{\mathrm{T}} = 1.5$ GeV/$c$

- In pp: prompt/non-prompt production is well described by models

- In Pb–Pb:
  - Prompt J/ψ results described by models including **(re)generation at low $p_{\mathrm{T}}$** and in central collisions, and **dissociation at high $p_{\mathrm{T}}$** → tensions to describe semicentral collisions
  - Non-prompt J/ψ suppression at high $p_{\mathrm{T}}$ described by models implementing **collisional and radiative parton energy loss** in medium

- **In Run 3**, prompt/non-prompt charmonia measurement is possible at forward rapidity thanks to the installation of the **Muon Forward Tracker (MFT)**, down to $p_{\mathrm{T}} = 0$

# Thank you !