HADRONS 2025 Porto Alegre

Heavy flavour probes: a key to understanding the Quark-Gluon Plasma

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Quark-Gluon Plasma and Heavy-Ion Collisions

What are Heavy-Ion Collisions (HIC)?

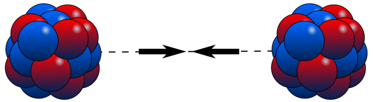
→ Collisions of large nuclei (e.g., Pb-Pb at the LHC, Au-Au at the RHIC) at ultra-relativistic energies.

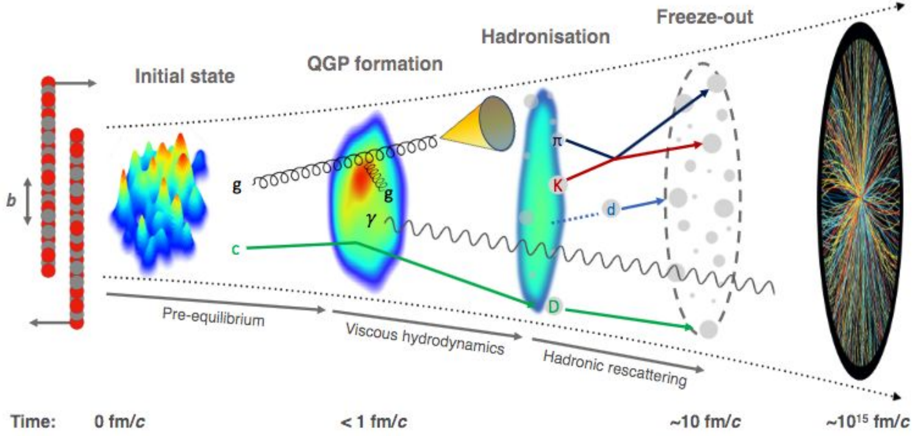
→ Generate an extremely hot and dense state of matter.

What is the Quark-Gluon Plasma (QGP)?

→ A deconfined state of quarks and gluons, where they move freely instead of being confined in hadrons.

→ Exhibits collective behavior and strong interactions.

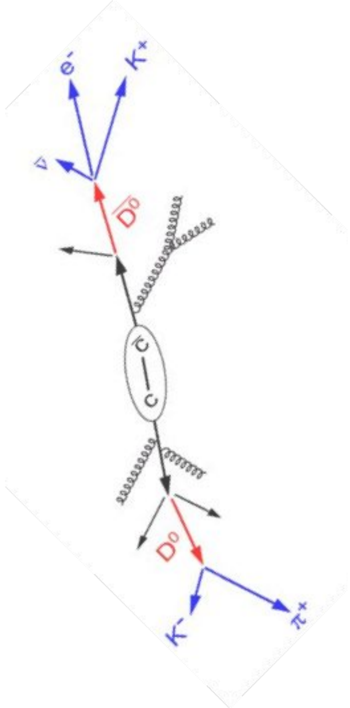


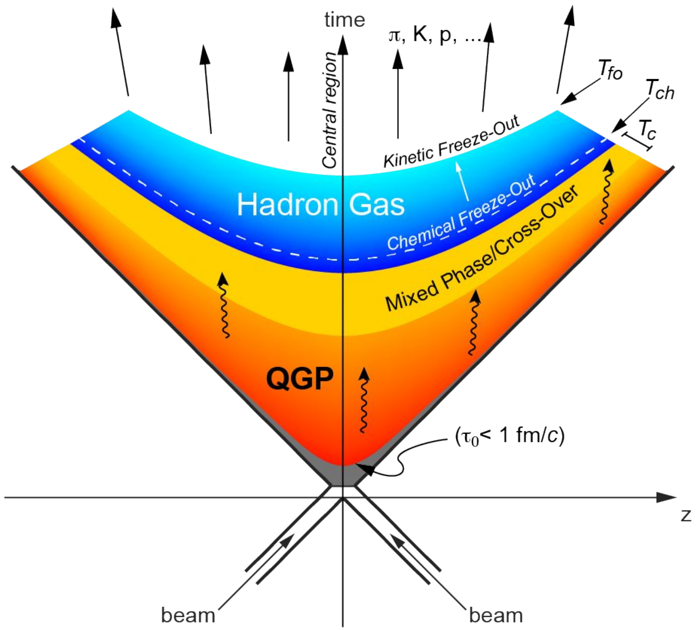


A heavy-ion collision evolves through several stages: initial partonic interactions, formation of a deconfined quark-gluon plasma, hydrodynamic expansion with collective flow, hadronization into bound states, and a final hadronic phase before freeze-out and detection.

Heavy-flavour probes

Why to use heavy-flavour probes?





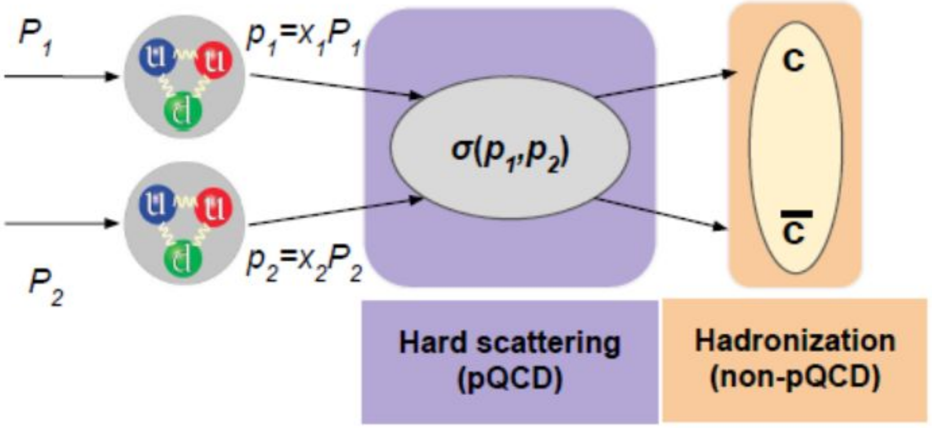
- Heavy quarks are created early in the collisions and can live longer than the QGP
  → Experience full evolution of the medium

- Excellent probe of the medium properties due to energy loss

Heavy-flavour probes: quarkonia

Quarkonia production (J/ψ, ψ(2S), Υ(nS)) involves both perturbative (production of heavy quark pairs) and non-perturbative (hadronization into quarkonium) approaches.

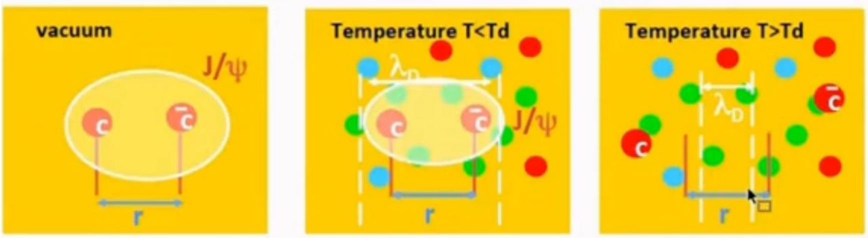
→ already challenging in pp



Heavy-flavour probes: quarkonia in HIC

Vacuum potential between q qbar pair grows linearly at large distances

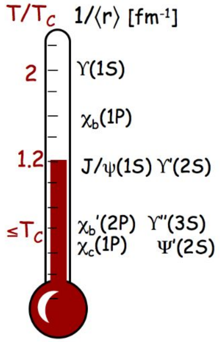
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$



In a deconfined medium the potential is modified:

$$V(r) = -\frac{\alpha_s}{r} e^{-r/\lambda_D}$$

- Coulomb potential is Debye screened
- Quarkonium states will be melted if $r > \lambda_D$
  → Quarkonia suppression = QGP signature
- Maximum distance allowed for formation of a bound pair decreases with T
  → Differents states melts at different energies



https://arxiv.org/pdf/0811.0337.pdf

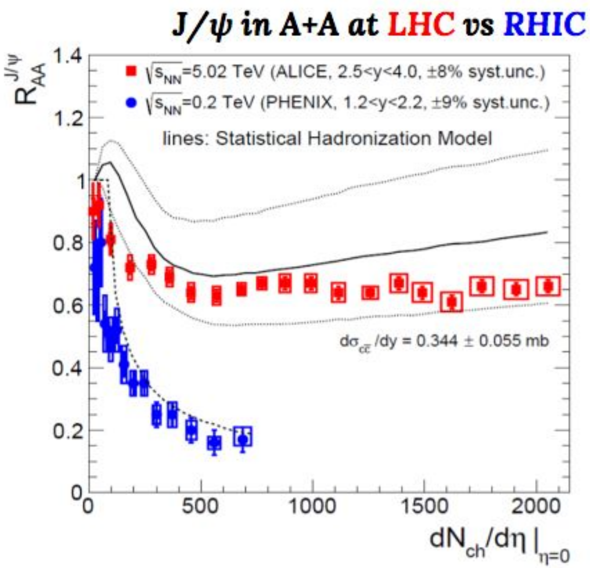
Heavy-flavour probes: quarkonia in HIC

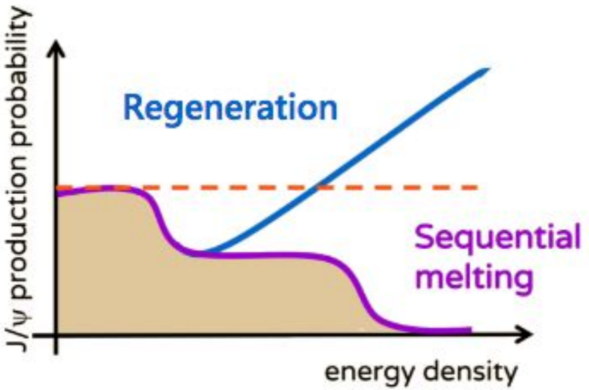
Sequential melting observed at RHIC
But at LHC energies, an additional effect was observed and called as Regeneration

Nuclear modification factor:

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

ALICE, PLB 766 (2017) 212
PHENIX, PRC 84 (2011) 054912





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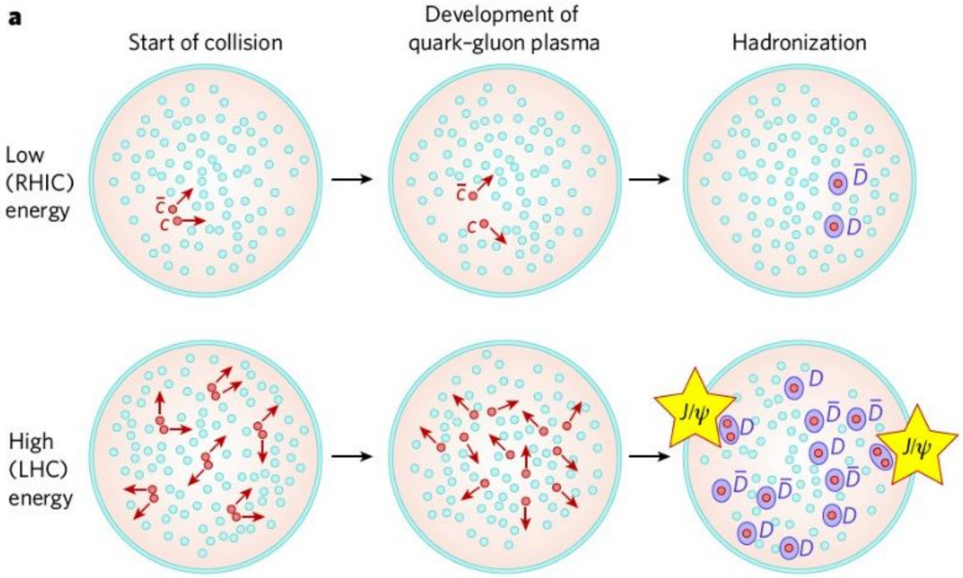


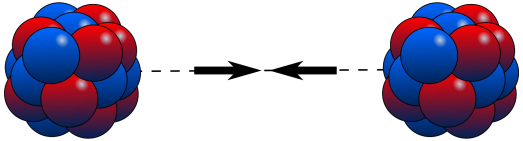
PLB490 (2000) 196

How to study quarkonia?

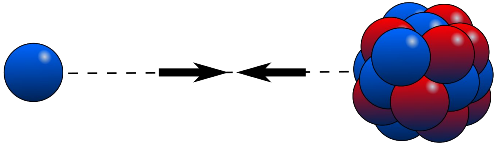
To understand QGP formation in Pb–Pb collisions, we need references!

How well is quarkonia described in proton-proton and proton–Pb collisions?

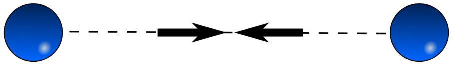
- Heavy-ion collisions:
    - Quarkonium as a hint of deconfinement (QGP)



- p–Pb collisions:
    - Cold nuclear matter effects

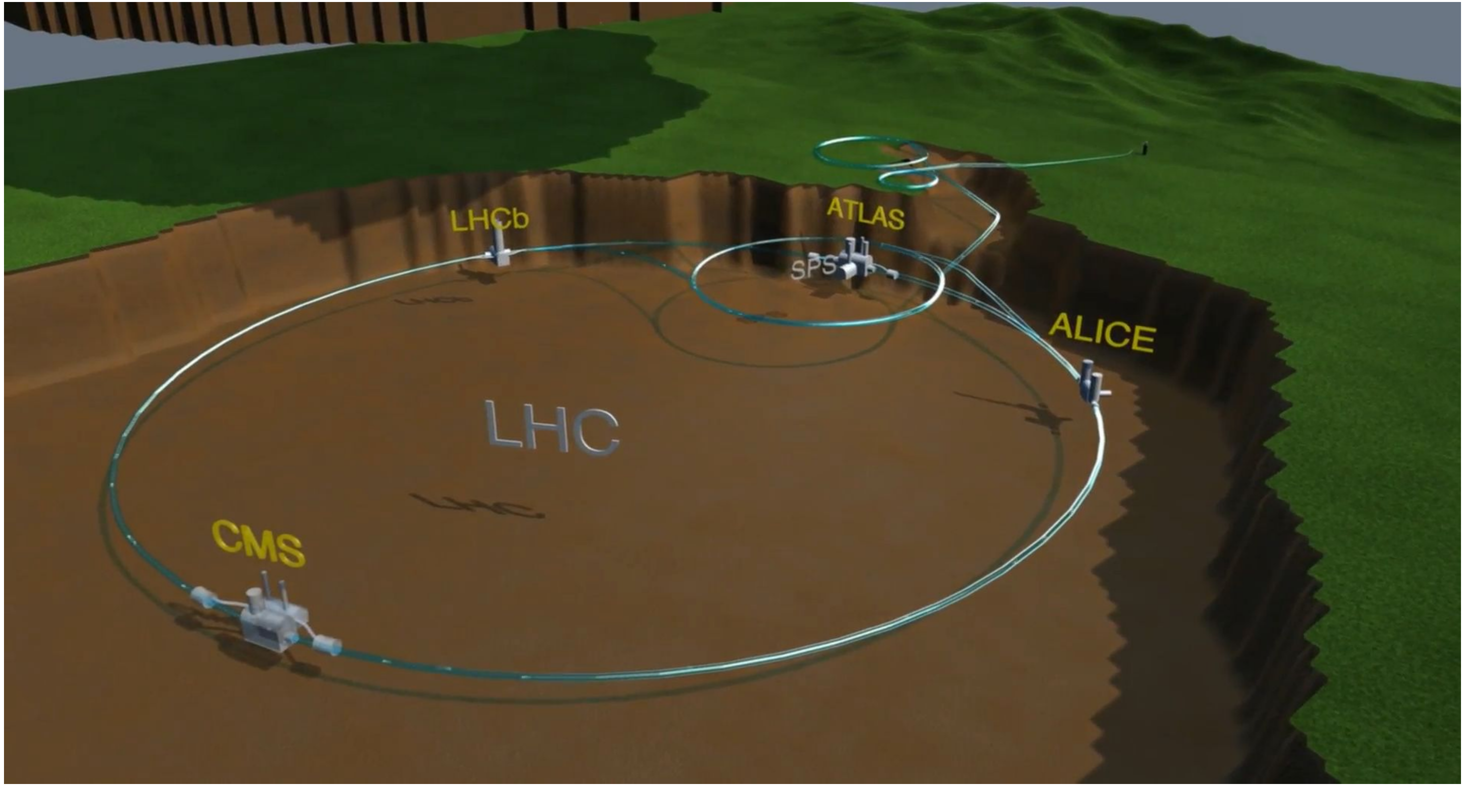


- pp collisions:
    - Quantum Chromodynamics (QCD)

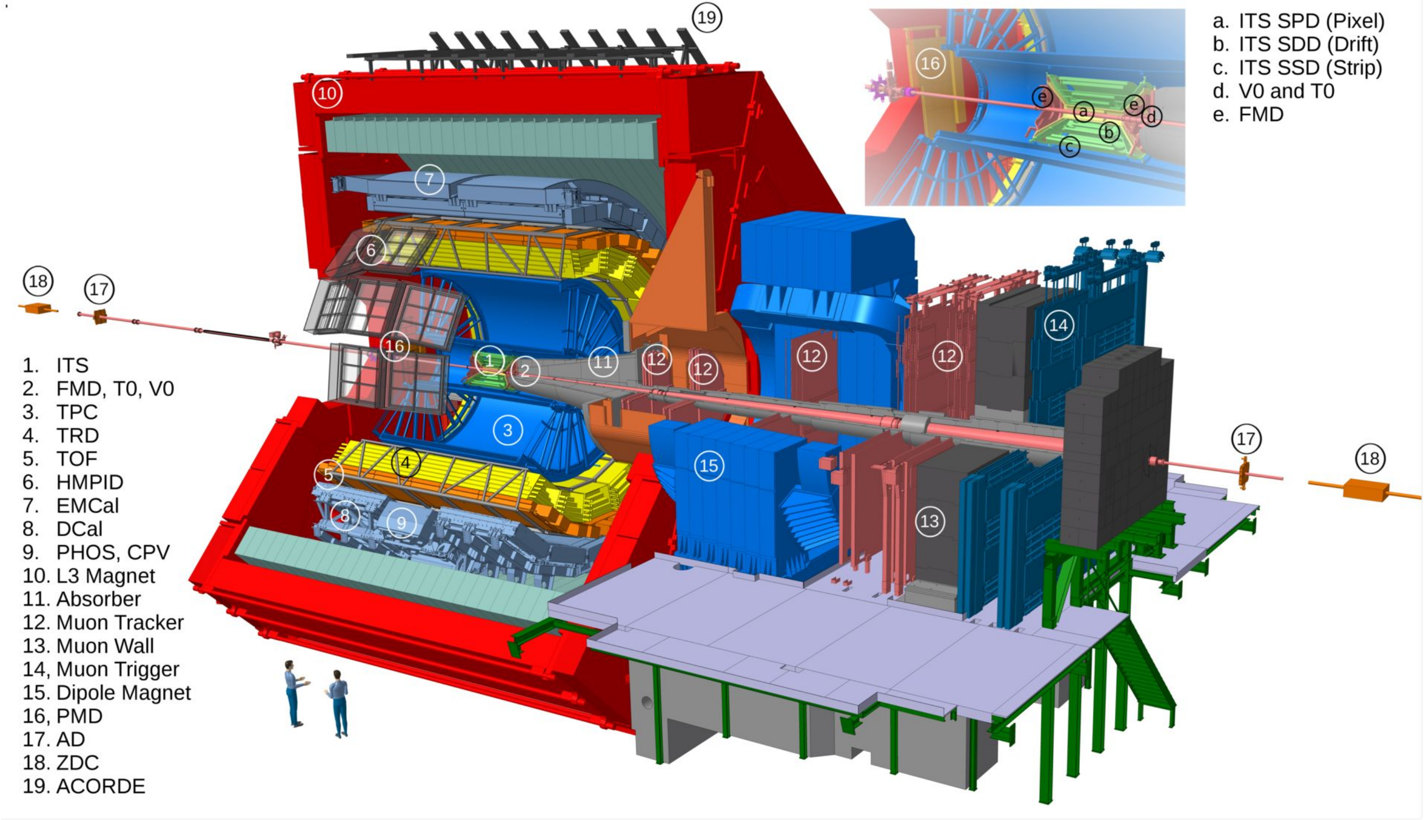


LHC: Large Hadron Collider

LHC: Large Hadron Collider

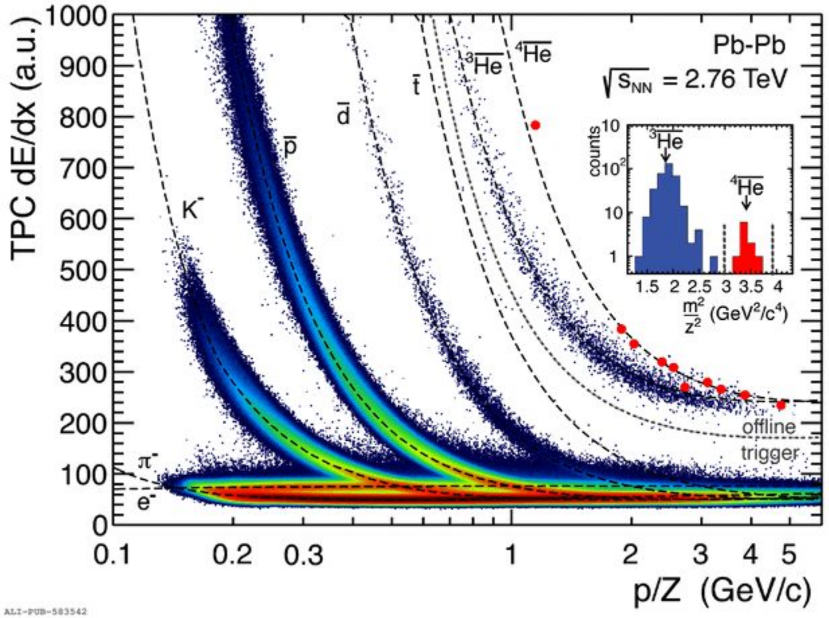


ALICE: A Large Ion Collider Experiment

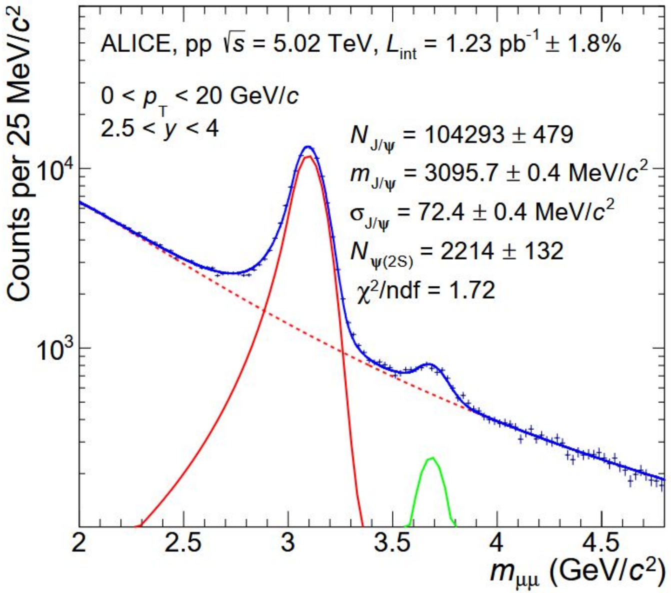


ALICE performance

ALICE can separate very well different species of particles:



J/ψ reconstruction:

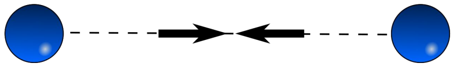


https://arxiv.org/pdf/2109.15240

A few results…

What have we learned about quarkonia formation and their interaction with the QGP?

Results in pp collisions



J/ψ and ψ(2S) production in pp

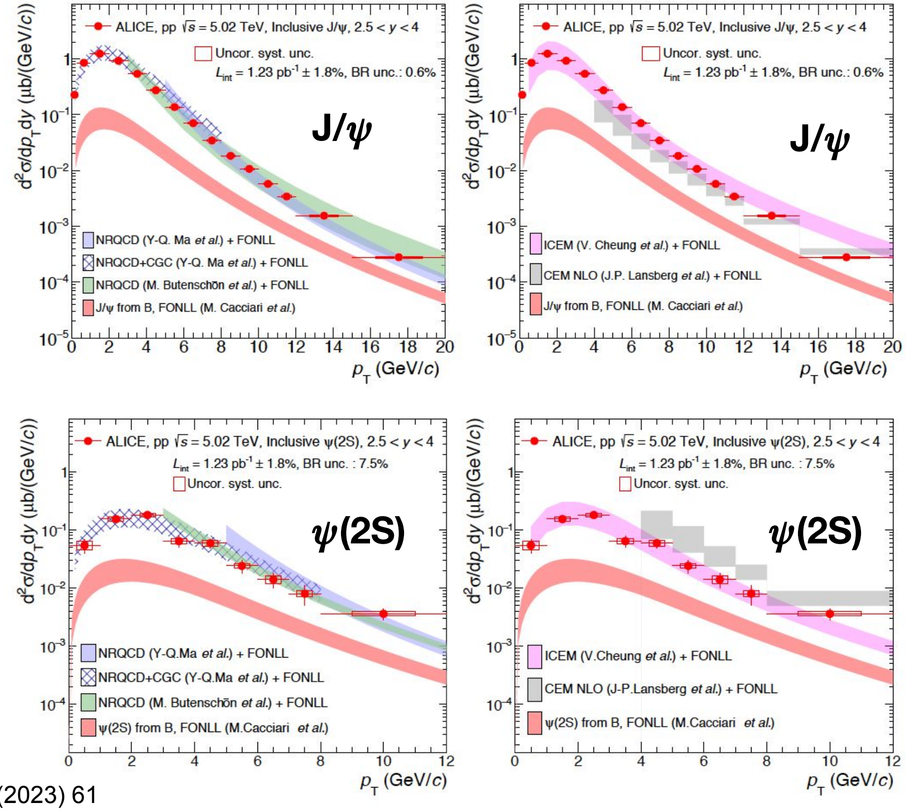
Cross section measurements to probe quarkonia production

→ Good description of J/ψ and ψ(2S) cross sections at low and intermediate p_T by **NRQCD/NRQCD** and **ICEM**

→ NRQCD is based on QCD factorization and includes explicit color octet contributions, while ICEM is an empirical approach relying on statistical hadronization of c cbar pairs.

→ Low p_T: **NRQCD + CGC** is used

→ gluon saturation and small-x effects in the initial state



Eur. Phys. J. C 83 (2023) 61

ψ(2S)/J/ψ in pp

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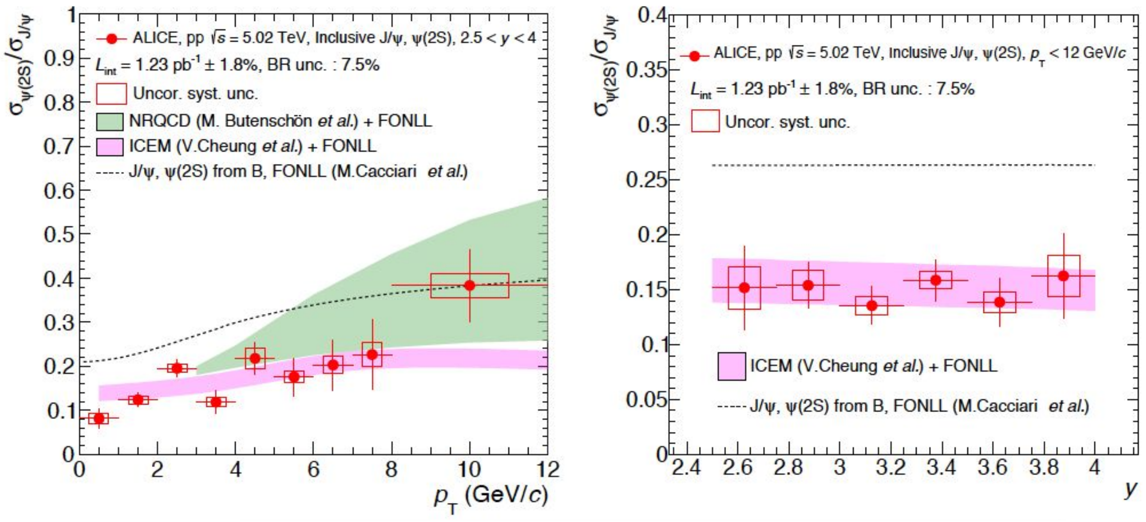
Excited to ground state ratio is used to investigate final effects → ψ(2S)/J/ψ ratio mostly **removes initial-state effects**

→ theoretical uncertainty is considered as correlated among the two states and partially cancel in the ratio calculation

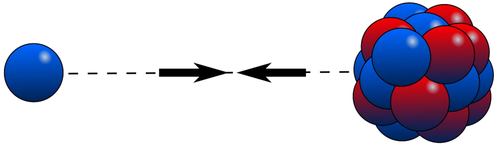
The **NRQCD** calculations describe well the p_T dependence of the cross section ratio within the large model uncertainties.

The **ICEM** can describe the p_T and y dependence of the ψ(2S)/J/ψ cross section ratio

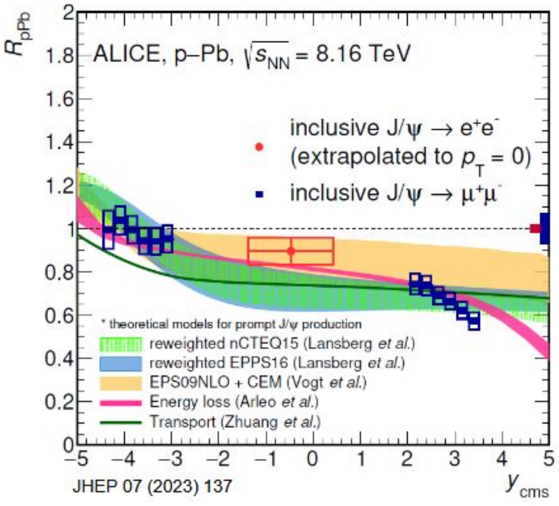


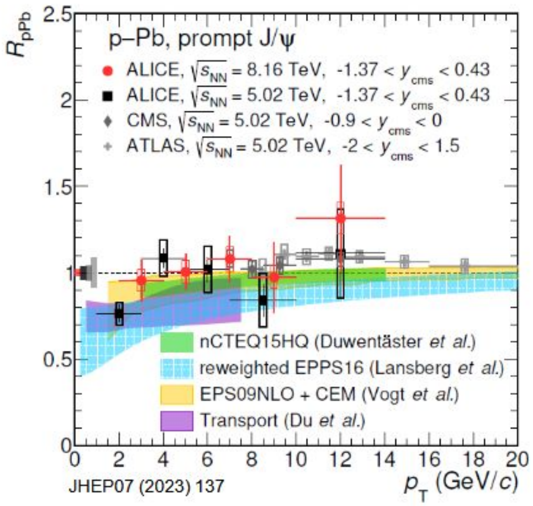
Eur. Phys. J. C 83 (2023) 61

Results in p–Pb collisions



J/ψ nuclear modification factor in p–Pb





Theoretical models in good agreement with inclusive J/ψ, despite the very different approaches:

- Shadowing (EP09NLO, nCTEQ15, EPPS16)
- CGC (NRQCD, CEM)
- Energy loss of charm in Cold Nuclear Matter
- Final state effects (Transport, comovers)

J/ψ and ψ(2S) nuclear modification factor in p–Pb

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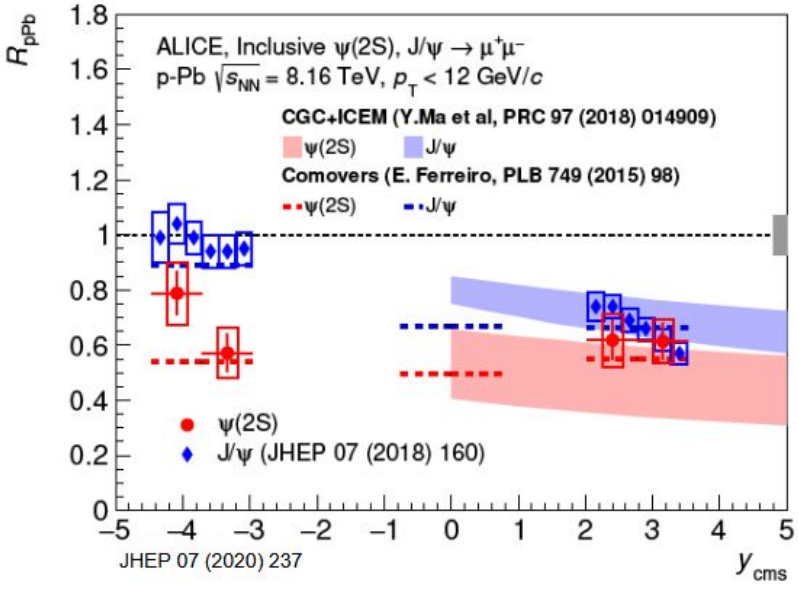
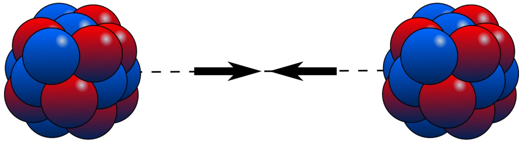


- At forward rapidity, the **J/ψ** and **ψ(2S)** suppression are similar, suggesting that initial-state effects dominate charmonium modification.
- At backward rapidity, the results show a **larger suppression for ψ(2S)** than for **J/ψ**, suggesting final-state effects in small systems for the A-going direction

ψ(2S) is a more weakly bound state than **J/ψ** → higher probability to be broken up by interactions with the nuclear medium or comovers.

Results in Pb–Pb collisions



Nuclear modification factor of J/ψ and ψ(2S)

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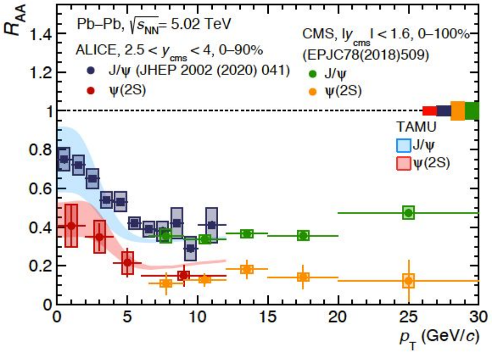
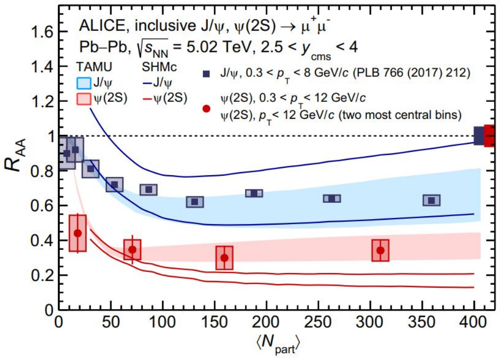
J/ψ and **ψ(2S)** differ in binding energy and in size.

Dissociation of the charmonium states depends on the temperature of the medium and is expected to occur sequentially

→ **ψ(2S)** is suppressed by a factor of ~2 with respect to the **J/ψ**

→ The **ψ(2S) R_{AA}** show a hint for a decrease as a function of p_T → charm quark recombination processes.





Phys. Rev. Lett. 132 (2024) 042301

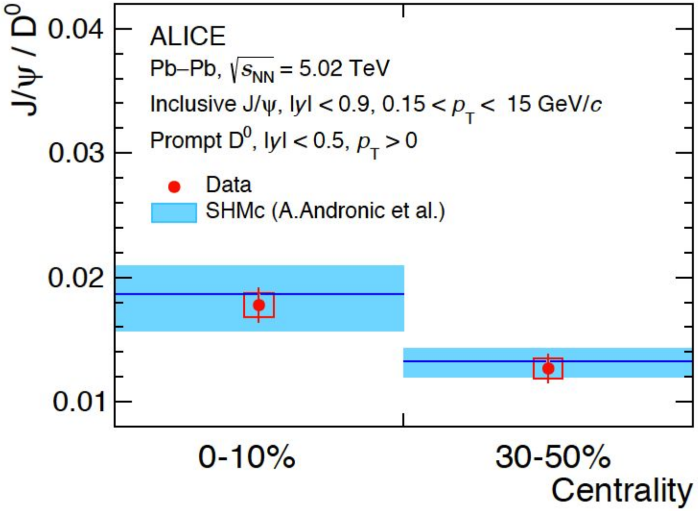
TAMU: uses an expanding fireball; lower dissociation temperature of the ψ(2S) relative to the J/ψ.

SHMc: all charm quarks are produced during the initial hard partonic interactions and then thermalize in the QGP.

→ Model implements a hydro-inspired freeze-out hypersurface.

Ratio J/ψ over D^0

J/ψ/D^0 measurement provides a tight constraint to models because some of the model parameters and most model uncertainties related to the ccbar cross section cancel in the ratio

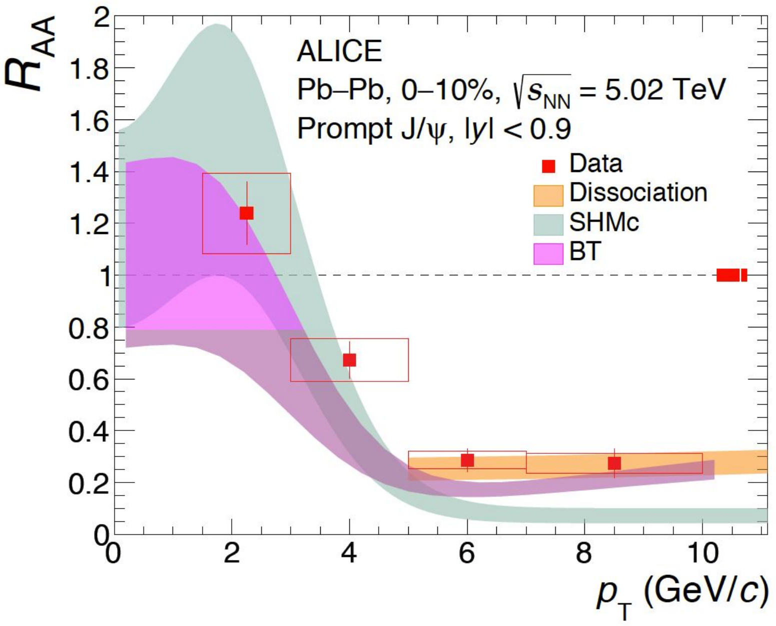


Phys. Lett. B 849 (2024) 138451

- The results suggest a higher value for this ratio in central compared to semicentral collisions.
- This is supported by the **SHMc calculations**, which suggests both the J/ψ and D^0 are produced via the coalescence of charm quarks at the phase boundary
    - Ratio being determined by the charm fugacity.
- The model uncertainty from the SHMc model is due to uncertainties on the charm fugacity parameter, which is fitted to the ALICE D^0 data

Nuclear modification factor of prompt J/ψ

JHEP 02 (2024) 066



Dissociation model: employs rate equations and the collisional dissociation of charmonia.

SHMc: assumes that all charm quarks are produced during the initial hard partonic interactions and then thermalize in the QGP.
→ Model implements a hydro-inspired freeze-out hypersurface.

BT: Boltzmann-type transport equation, including terms of dissociation and regeneration. The dissociation:

- melting of the bound states due to colour Debye screening.
- collisional processes of charmonia with the medium constituents.

Both **SHMc** and **BT** models describes the data at low p_T

In summary:

pp

- Good description of J/ψ and $\psi(2S)$ cross sections at low and intermediate p_T by NRQCD and ICEM

p-Pb

- $\psi(2S)$ suppression at backward rapidity: clear evidence of final-state effects for the A-going direction

Pb-Pb

- Suppression of J/ψ and ψ(2S) due to the formation of QGP
- Including regeneration processes in the model is necessary to describe the data
  - charm quark recombination
- The regeneration becomes more important at lower momenta and in central collisions

→ charm quarks stay in the medium long enough to recombine

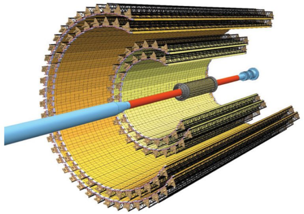
ALICE future perspectives

What to expect from the future?

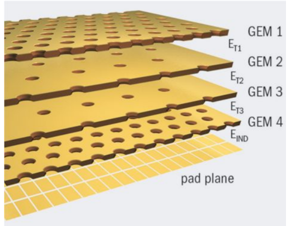
ALICE future perspectives

NOW: ALICE 2:

- new readout for all detectors
- new TPC readout (GEMs)
- new Fast Interaction Trigger (FIT)
- new silicon trackers (MFT & ITS2)
- new online/offline system (O^2)



J. Phys. G 41 (2014) 087002



JINST 16 (2021) P03022

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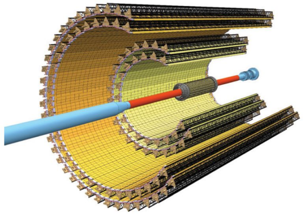

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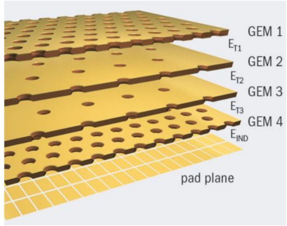

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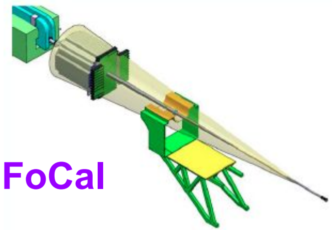
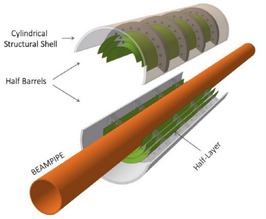
~ 2026-2029
data: ~ 2030

FoCal



ITS3



ALICE-PUBLIC-2018-013

CERN-LHCC-2020-009

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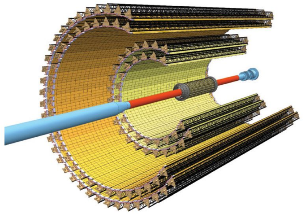

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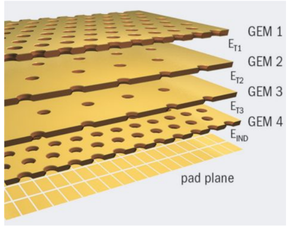

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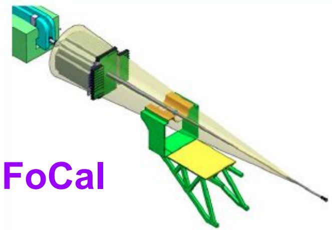

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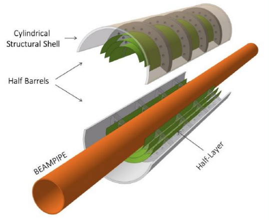

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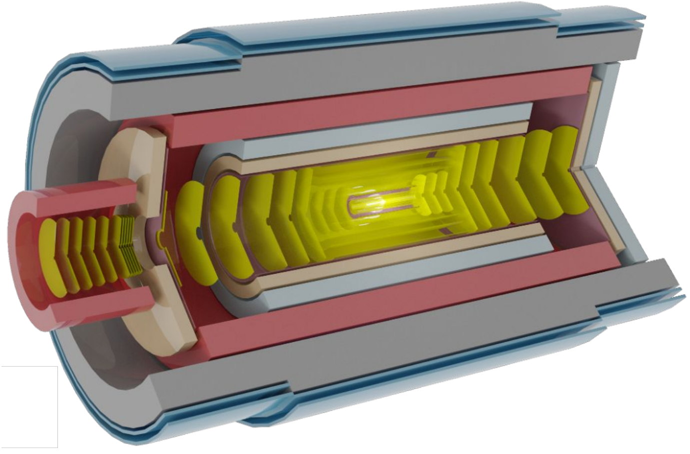
CERN-LHCC-2020-009

~ 2034-2036
data: ~ 2036
ALICE 3

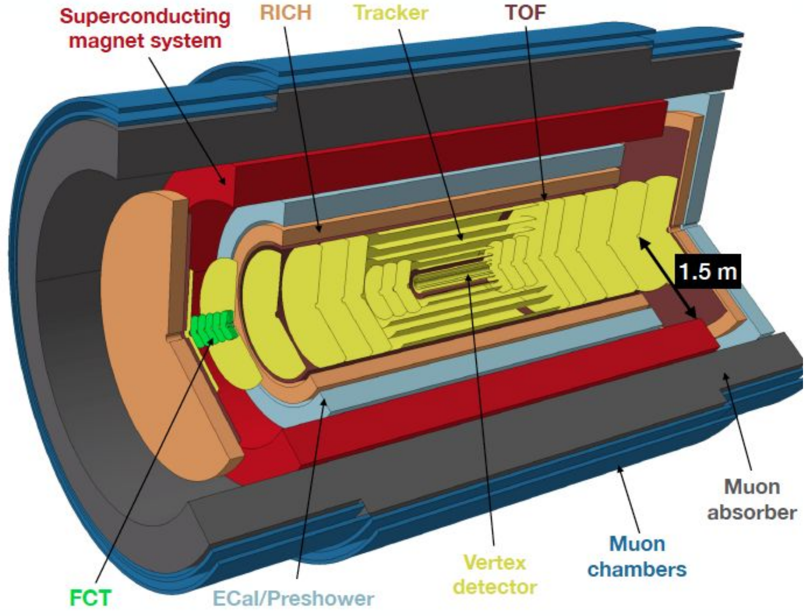


arXiv:1902.01211v2

Letter of intent:
https://cds.cern.ch/record/2803563

ALICE 3

- ➔ Compact all-silicon tracker with high-resolution vertex detector
- ➔ Superconducting magnet system → **to be build in Brazil**
- Studies of A–A collisions at luminosities a factor of 5-10 times higher than possible now.
- Ultrasoft region of phase space



arXiv:1902.01211v2
https://indico.cern.ch/event/1063724/

ALICE 3

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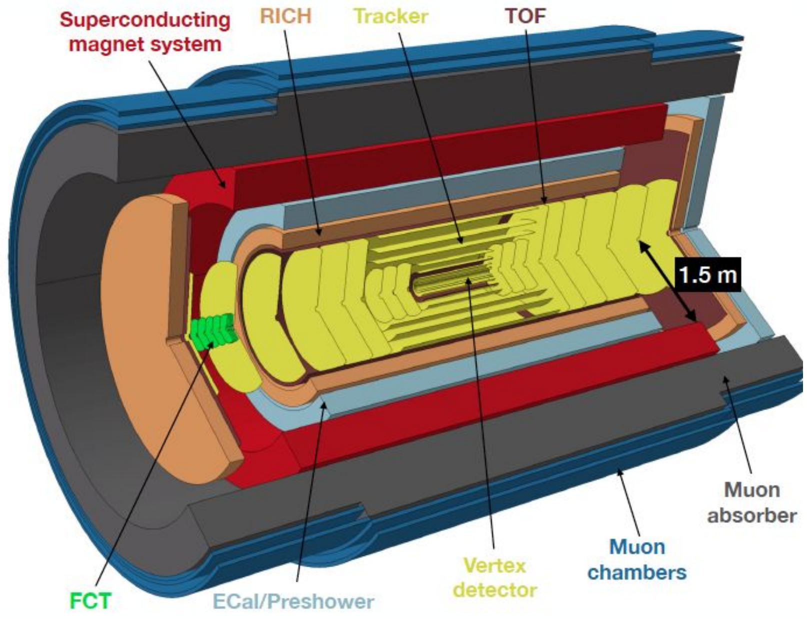


Thank you for your attention!

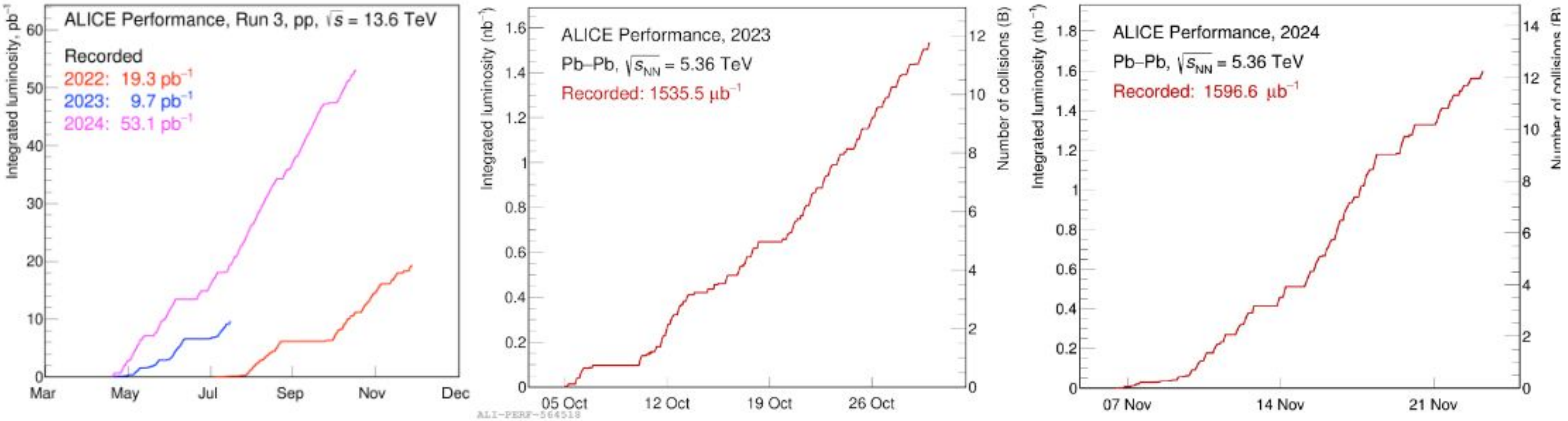
arXiv:1902.01211v2
https://indico.cern.ch/event/1063724/

Backup

Luminosities in Run 2

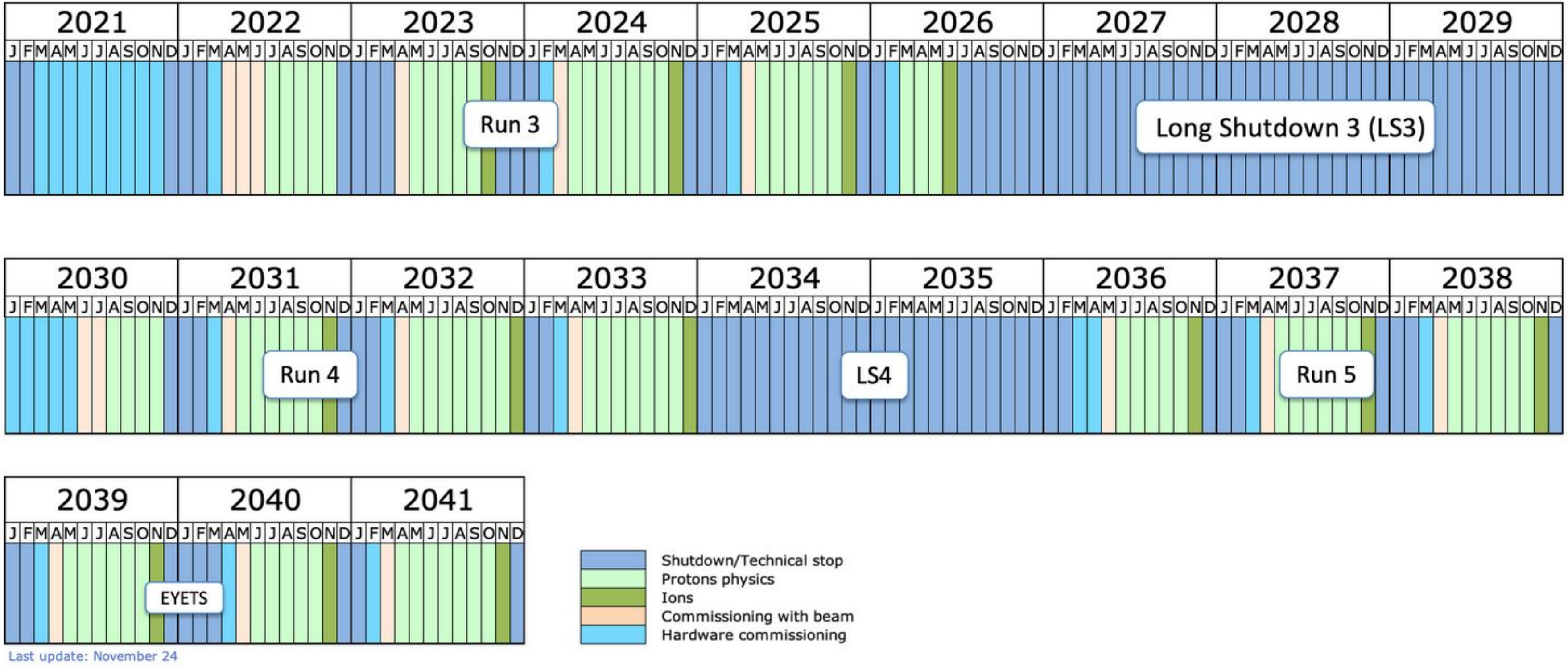
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	75 μb^{-1} 800 μb^{-1}
Xe-Xe	2017	5.44	0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	15 nb^{-1} 3 nb^{-1}, 25 nb^{-1}
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	200 μb^{-1}, 100 nb^{-1} 1.5 pb^{-1}, 2.5 pb^{-1} 1.3 pb^{-1} 36 pb^{-1}

Luminosities in Run 3

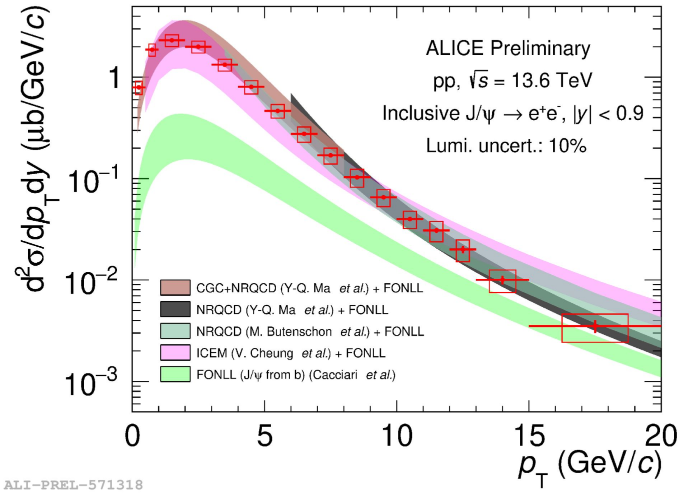


- Collected pp integrated luminosity so far is ~2 x Run 2 for muon channel, ~1000 x Run 2 for (min-bias) e^+e^- channel
- Collected Pb-Pb integrated luminosity so far is ~4 x Run 2 for muon channel, ~70 x Run 2 for (min-bias) e^+e^- channel

Longer term LHC schedule



Results in pp@13.6TeV



Nuclear modification factor of prompt J/ψ

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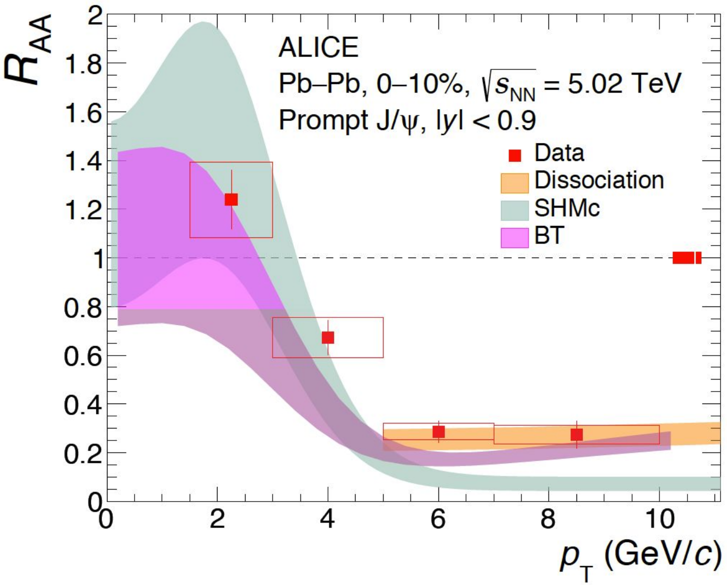


Both **SHMc** and **BT** models describes the data at low p_T

Dissociation model: employs rate equations and the collisional dissociation of charmonia includes thermal effects on the wave function due to the screening of the ccbar attractive potential from the free colour charges in the QGP.

Medium as a (2+1)-dimensional viscous hydrodynamic model. NRQCD is used to obtain the baseline nucleon–nucleon cross sections for charmonia and the p_T-dependent feed-down from excited states.

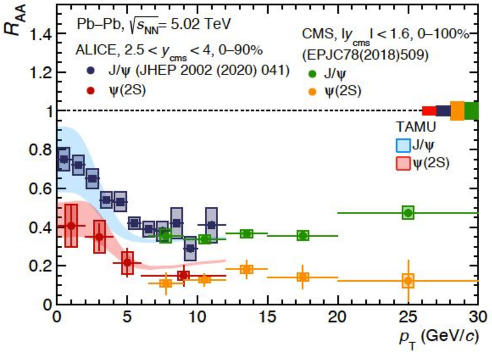
SHMc: the totality of charm quarks are produced in the initial hard parton–parton scatterings and thermalise inside the QGP

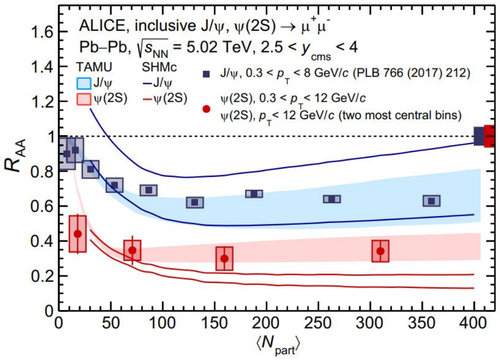
BT: Boltzmann-type transport equation, including terms of dissociation and regeneration. The dissociation arises from the melting of the bound states due to colour Debye screening, as well as from collisional processes of charmonia with the medium constituents, and in particular from gluon dissociation.

Nuclear modification factor of J/ψ and ψ(2S)

J/ψ and **ψ(2S)** differ in binding energy and in size.
Dissociation of the charmonium states depends on the temperature of the medium and is expected to occur sequentially

→ **ψ(2S)** is suppressed by a factor of ~2 with respect to the **J/ψ**
→ The **ψ(2S) R_{AA}** show a hint for a decrease as a function of p_T, reminiscent of the same effect observed for the J/ψ and connected with charm quark recombination processes.





Phys. Rev. Lett. 132 (2024) 042301

TAMU: uses an expanding fireball; lower dissociation temperature of the ψ(2S) relative to the J/ψ. This implies a sequential freezeout of those two mesons, with most of the ψ(2S) regeneration occurring later in the fireball evolution

SHMc: assumes that all charm quarks are produced during the initial hard partonic interactions and then thermalize in the QGP.
→ Model implements a hydro-inspired freeze-out hypersurface.

Comparing data with model calculations

UNICAMP

- Suppression of J/ψ and ψ(2S) due to the formation of QGP
- Including regeneration processes in the model is very important to understand the data
  - charm quark recombination at hadronization (coalescence)

- The regeneration becomes more important at lower momenta and in central collisions, reinforcing the idea that charm quarks stay in the medium long enough to recombine

- Probe of transport properties.
  - Diffusion coefficients: how charm quarks propagate in the medium?
    - Extracted from model fitted to the nuclear modification factor
  - In-medium decay rate: how fast quarkonia dissociate?
    - How the binding energy and dissociation of quarkonia change in the QGP.
    - ~ 0.1–0.4 GeV for temperatures 1.5–2 Tc. This corresponds to a lifetime of ~ 0.5 - 2 fm/c before dissociation (QGP exists for 4–7 fm/c).

$$1.5 < 2\pi T D_s < 5$$

SHM

In the Statistical Hadronization Model (SHM), charm fugacity is a parameter that accounts for the total number of charm quarks in the system. It ensures that the final hadron yields correctly reflect the conservation of charm quark number across the transition from the quark-gluon plasma (QGP) to the hadronic phase.

- It modifies the Boltzmann factor in the statistical model to adjust for charm quark abundance.
- Since charm quarks are predominantly produced in hard scatterings at the beginning of the collision (not thermally), their number is approximately fixed throughout the system's evolution.
- The yield of charmed hadrons (e.g., J/ψ, D0, Λc) depends on the charm fugacity, meaning the relative abundances of charmonium states vs. open charm hadrons are influenced by it.