Workshop on physics performance studies at NICA (NICA-2022)

Heavy-flavor measurements at future collider experiment ALICE-3 at HL-LHC

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Heavy flavour measurements

- The study of the production of hadrons containing heavy quarks, i.e. charm and beauty, at LHC energies is a sensitive test of QCD calculations based on the factorisation approach.
- HF is ideal probe to study initial and final state effects on particle production
- Initial state
  - Modification of Parton Distribution Functions
  - Gluon saturation and Color-Glass Condensate (CGC) [1]
- Final state
  - Parton energy loss in QGP ($\Delta E_g > \Delta E_q > \Delta E_Q$) [2]
  - Hadronization mechanisms (fragmentation/recombination)

[1] E. Iancu et al. Nucl. Phys.A692 (2001) 583
[2] Yu. L. Dokshitzer et al. 1991 J. Phys. G: Nucl. Part. Phys. 17 1602

Quarkonia in heavy ion collisions

- Heavy quarks are produced at the beginning of the collision and therefore experience the entire evolution of quark-gluon medium produced in heavy-ion collisions.
- Various mechanisms affect production of bound states $c\bar{c}$ and $b\bar{b}$ [1-3]
  - Binding of heavy quarks is suppressed because of color screening
  - Once the bound state is formed, it may dissociate because of interaction with medium
  - If there are enough $Q\bar{Q}$ pairs, quarkonium states can be formed, either at the freeze-out or inside the QGP: recombination [3,4]
- Different quarkonium properties (binding energies, Debye radius, …) might lead to different behaviors in the QGP and in vacuum.

[1] L. Kluberg and H. Satz, “Color Deconfinement and Charmonium Production in Nuclear Collisions”, [arXiv:0901.3831 [hep-ph]].

[2] Matsui & Satz, Phys. Lett. B 178 (1986) 416

[2] Rothkopf, Phys. Rep. 858 (2020) 1-117

[3] Braun-Munzinger & Stachel, Phys. Lett. B 490 (2000) 196

[4] Thews, Schroedter & Rafelski, Phys. Rev. C 63, 054905

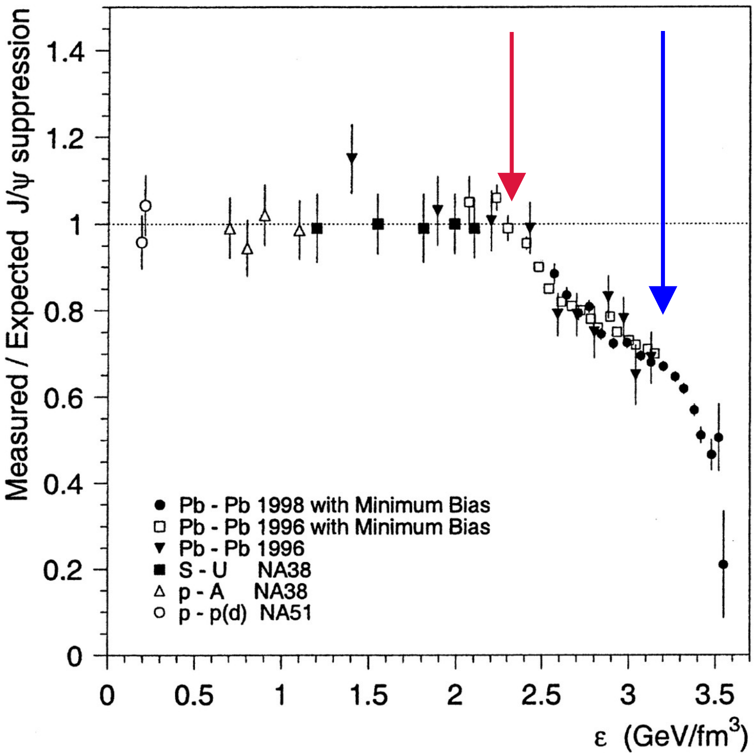
Properties of quarkonia 1S vs 1P

- J/ψ (1S):
  - m=3096.90 MeV/c^2
  - Br(J/ψ→e^+e^-)=5.97%
  - E_{bind} = 0.64 GeV
- χ_{c0} (1P):
  - m=3414.75 MeV/c^2
  - Br(χ_{c0}→J/ψ γ)=1.27%
  - E_{bind} = 0.32 GeV
- χ_{c1} (1P):
  - m=3510.66 MeV/c^2
  - Br(χ_{c1}→J/ψ γ)=33.9%
  - E_{bind} = 0.22 GeV
- χ_{c2} (1P):
  - m=3556.20 MeV/c2)
  - Br(χ_{c2}→J/ψ γ)=19.2%
  - E_{bind} = 0.18 GeV

- Υ (1S):
  - m=9460.20 MeV/c^2
  - Br(Υ→e^+e^-)=2.38%
  - E_{bind} = 1.10 GeV
- χ_{b0} (1P):
  - m=9859.44 MeV/c^2
  - Br(χ_{b0}→Υ γ)=1.76%
  - E_{bind} = 0.70 GeV
- χ_{b1} (1P):
  - m=9892.78 MeV/c^2
  - Br(χ_{c1}→Υ γ)=33.9%
  - E_{bind} = 0.67 GeV
- χ_{c2} (1P):
  - m=9912.21 MeV/c2)
  - Br(χ_{c2}→Υ γ)=19.1%
  - E_{bind} = 0.64 GeV

- Systematic studies of different quarkonia in the same experiment can give hints on:
  - Study $c\bar{c}$ and $b\bar{b}$ interaction range and color screening in QGP
  - Quarkonium dissociation
  - Enhancement through regeneration
- Measurements of χ_{cJ} (1P) spectra is also needed for precise discrimination of prompt and non-prompt J/ψ, since χ_{cJ} is a dominant source of decay J/ψ
- Main challengies for bottomonia:
  - Smaller cross section
  - Smaller mass splitting of 1P states

J/ψ suppression at SPS



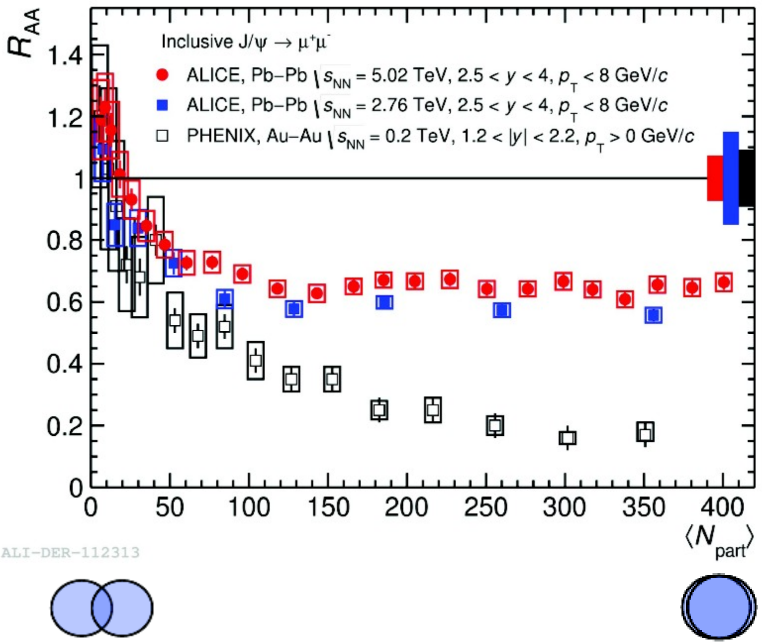
One of the first evidence of existence of deconfined quark-gluon matter was observation of J/ψ suppression in Pb-Pb collision at $\sqrt{s_{NN}}$=17 GeV (NA50, SPS [1])

- **ε > 2.3 GeV/fm³**: the first drop in J/ψ yield due to the disappearance of the **χ_c** , responsible for a fraction of the observed J/ψ
- **ε > 3.1 GeV/fm³**: stronger suppression due to dissolving the more tightly bound **J/ψ**
- Observed suppression can be naturally anticipated and understood in a deconfinement scenario as resulting from the **melting** of the charmonia states above a certain energy density

[1] M. C. Abreu et al. [NA50], “Evidence for deconfinement of quarks and gluons from the J/psi suppression pattern measured in Pb+Pb collisions at the CERN SPS,” Phys. Lett. B 477 (2000)

J/ψ suppression at RHIC and LHC

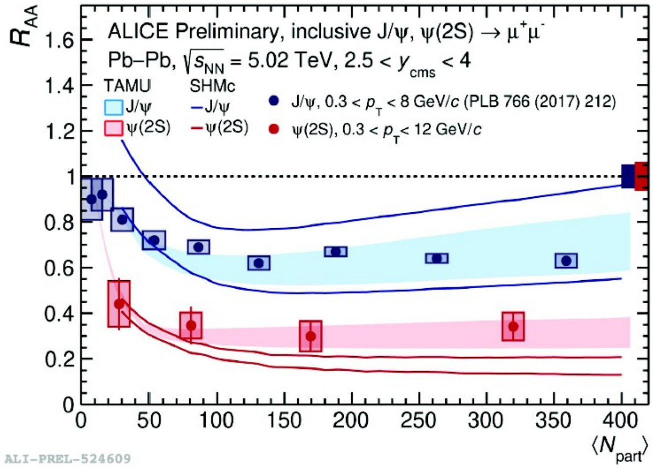
$$R_{AA} = \frac{dN_{AA}/dy}{\langle N_{coll} \rangle \times dN_{pp}/dy}$$

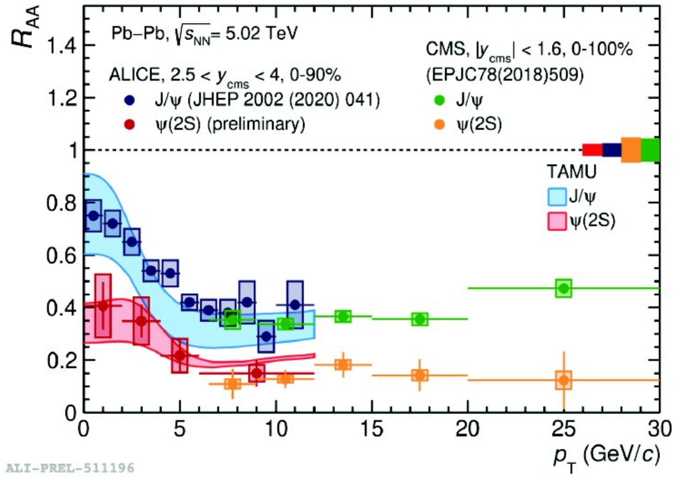


- ALICE [1] and PHENIX [2] observed a clear J/ψ suppression at forward rapidity
- Suppression description calls for variety of physics mechanisms including gluon saturation, gluon shadowing, initial-state parton energy loss, cold nuclear matter breakup, color screening, and charm recombination.
- Smaller suppression for central events at LHC vs RHIC despite a collision energy more than 10 times higher → First clear sign of charmonium regeneration
- Quarkonium polarization in AA (as compared to the one in pp) can also probe regeneration
- In addition, quarkonium polarization (vs Event Plane) can probe initial stages of HI collisions: impact of strong magnetic field in QGP and large vorticity

[1] ALICE collaboration, PLB766 (2017) 212
[2] PHENIX collaboration, Phys. Rev. C 84 (2011) 054912

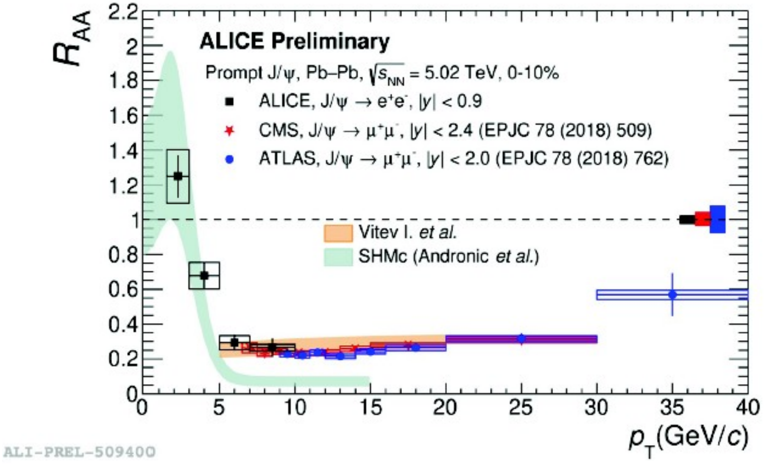
ψ(2S) suppression at LHC

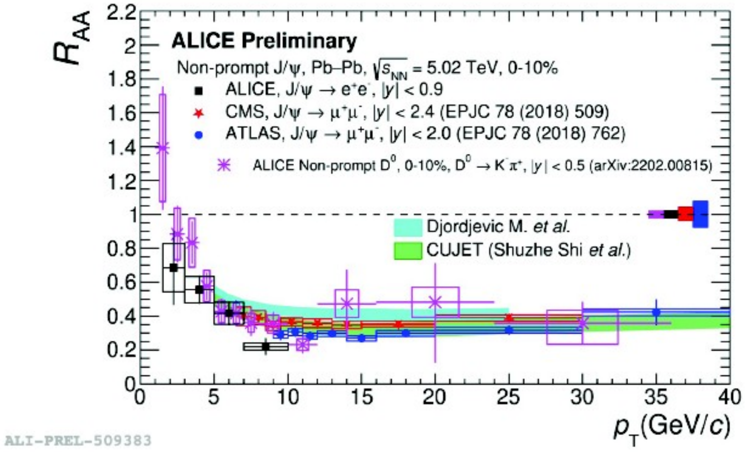




- As a function of p_T, increasing trend of the J/ψ and ψ(2S) RAA at low p_T
  - indication of recombination
- ψ(2S) shows a stronger suppression than the J/ψ in all centralities
- ψ(2S) suppression does not depend on centrality centrality within the current uncertainties

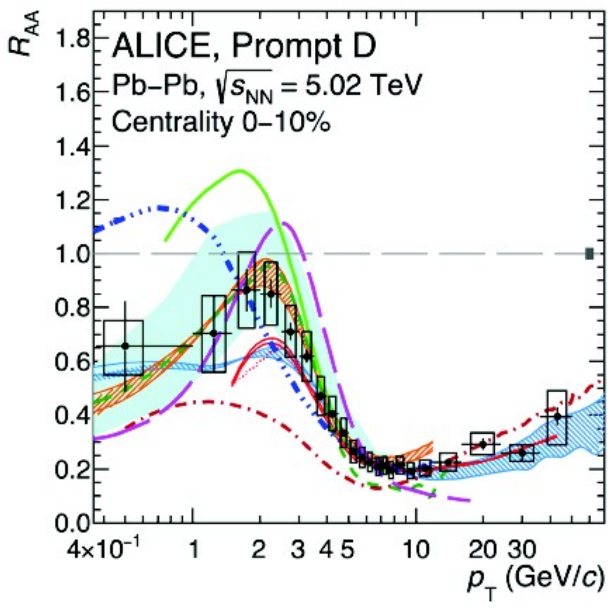
Prompt and non-prompt J/ψ at LHC

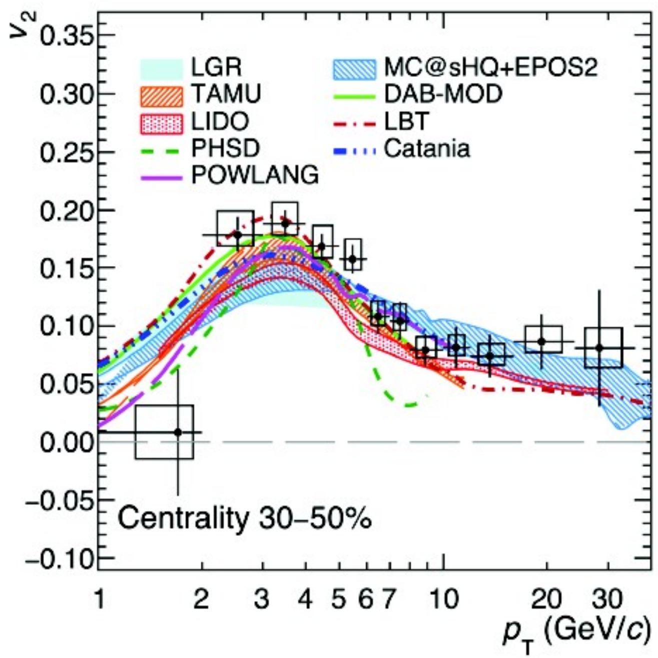




- Non prompt J/ψ are more suppressed than prompt J/ψ in central collisions, prompt J/ψ are less suppressed at low p_T than at higher p_T (and even enhanced at low p_T)
  - indication of recombination
- Non-prompt J/ψ data is compatible with models implementing beauty quark energy loss at high p_T

Open charm in heavy ion collisions

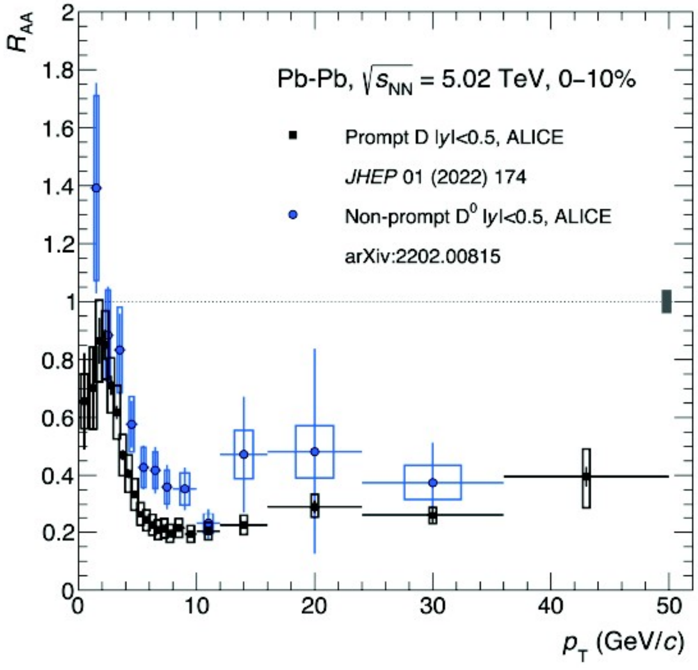


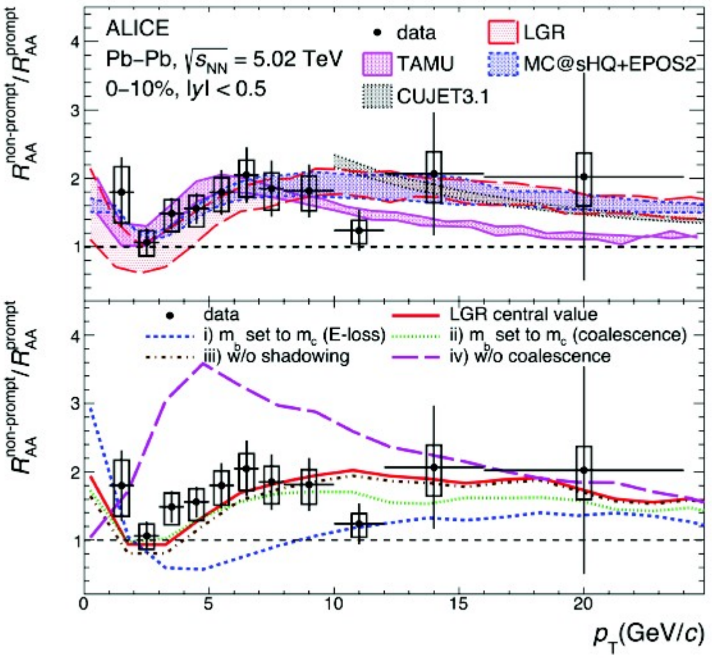


Heavy quarks as hard probes investigate medium for whole momentum domain

- Hard scale given by the quark mass
- Most charm-quark transport models describe both the R_{AA} and anisotropic flow (v_2)
- Radiative energy loss critical for high momentum

Charm vs beauty energy loss





- D mesons from bottom decays less suppressed than those formed from charm
- Indication of mass dependent collisional and radiative suppression e.g. dead cone effect

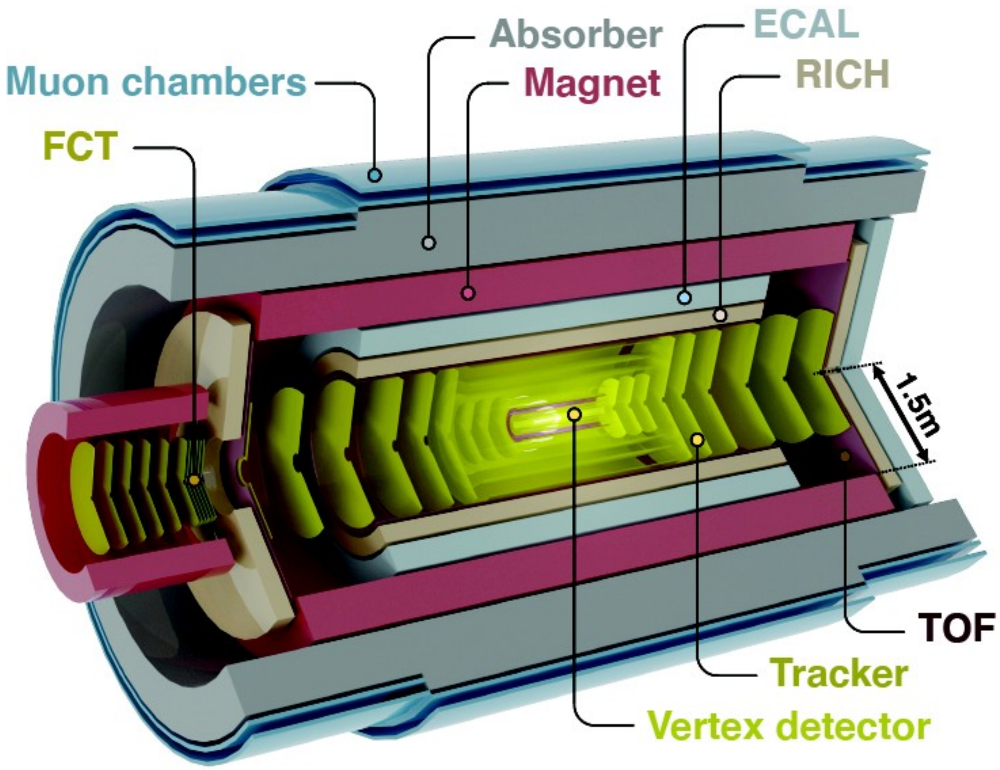
Lessons from HF studies

- Over last 20 years of charmonium studies in heavy-ion collisions advances of experiments were going along with theory development
- For understanding underlying physics of quarkonium production and evolution in QCD medium, precision measurements of different charmonium and bottomonium states are needed:
  - Statistics enhancement via increased luminosity and faster detector readout
  - Systematic uncertainties improvement via better particle identification and background suppression
  - Direct measurements of states other than J/ψ are needed to probe effects of color screening, dissociation, recombination
- The next-generation heavy-ion experiment **ALICE 3** at LHC will pursue these studies in Run 5 and beyond

ALICE 3 concept

Advanced detector:

- Compact all-silicon tracker with high-resolution vertex detector
- Superconducting magnet system
- Particle Identification over large acceptance:
  - muons, electrons, hadrons, photons
- Fast read-out and online data processing

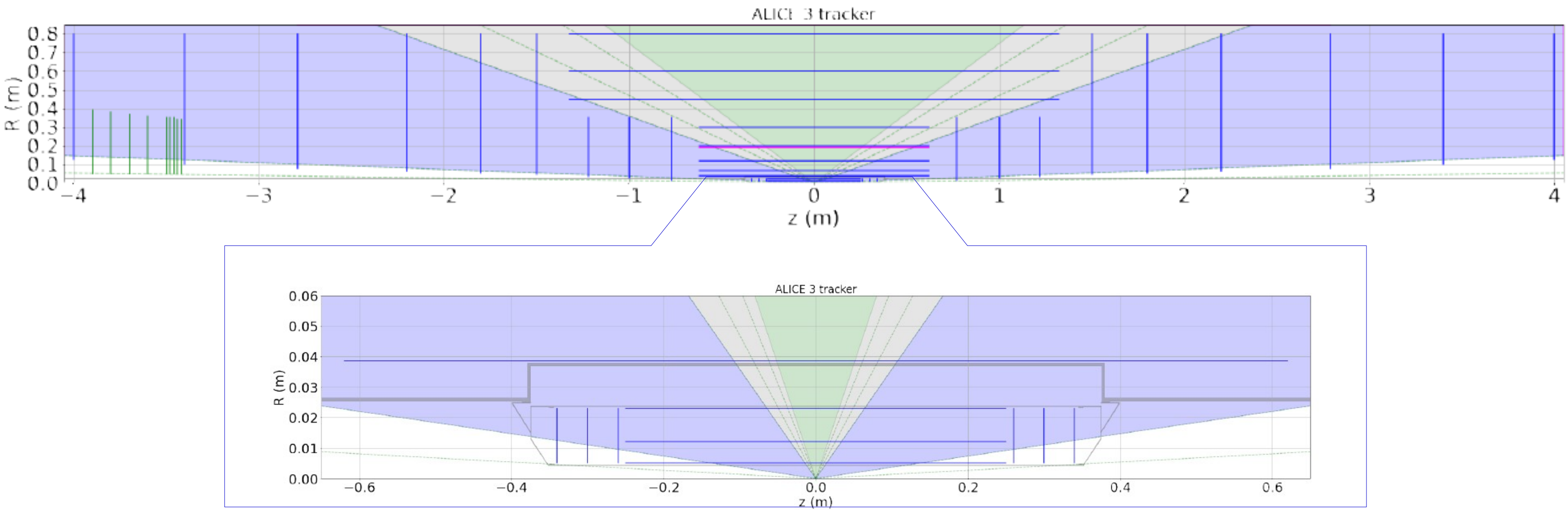


Running scenario for 6 years with ALICE 3

- Heavy ions: 1 month/year 35 nb^{-1} for Pb-Pb
- Under study: lighter species for higher luminosity
- pp at = 14 TeV: 3 fb^{-1} / year compared to Run 3+4

ALICE collaboration, Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC.
CERN-LHCC-2022-009 ; LHCC-I-038 http://cds.cern.ch/record/2803563

ALICE 3 tracker and vertex detector



Tracker and vtx detector consists of 11 barrel layers and 2x12 forward discs:

- Pseudorapidity: $|\eta|<4$
- Longitudinal extension: $|z|<400$ cm
- Radial positions: $0.5 < R < 80$ cm

Layer	Material thickness ($\%X_0$)	Intrinsic resolution (µm)	Barrel layers: Length ($\pm z$) (cm)	Barrel layers: Radius (r) (cm)	Forward discs: Position ($\|z\|$) (cm)	Forward discs: R_{in} (cm)	Forward discs: R_{out} (cm)
0	0.1	2.5	50	0.50	26	0.50	3
1	0.1	2.5	50	1.20	30	0.50	3
2	0.1	2.5	50	2.50	34	0.50	3
3	1	10	124	3.75	77	5	35
4	1	10	124	7	100	5	35
5	1	10	124	12	122	5	35
6	1	10	124	20	150	5	80
7	1	10	124	30	180	5	80
8	1	10	264	45	220	5	80
9	1	10	264	60	279	5	80
10	1	10	264	80	340	5	80
11	1				400	5	80

Primary vtx reconstruction: better than 10 µm
Secondary vtx (D^0, Λ_c): better than 5 µm
Momentum resolution: better than 0.6 mm at B=2T

ALICE 3 ECAL

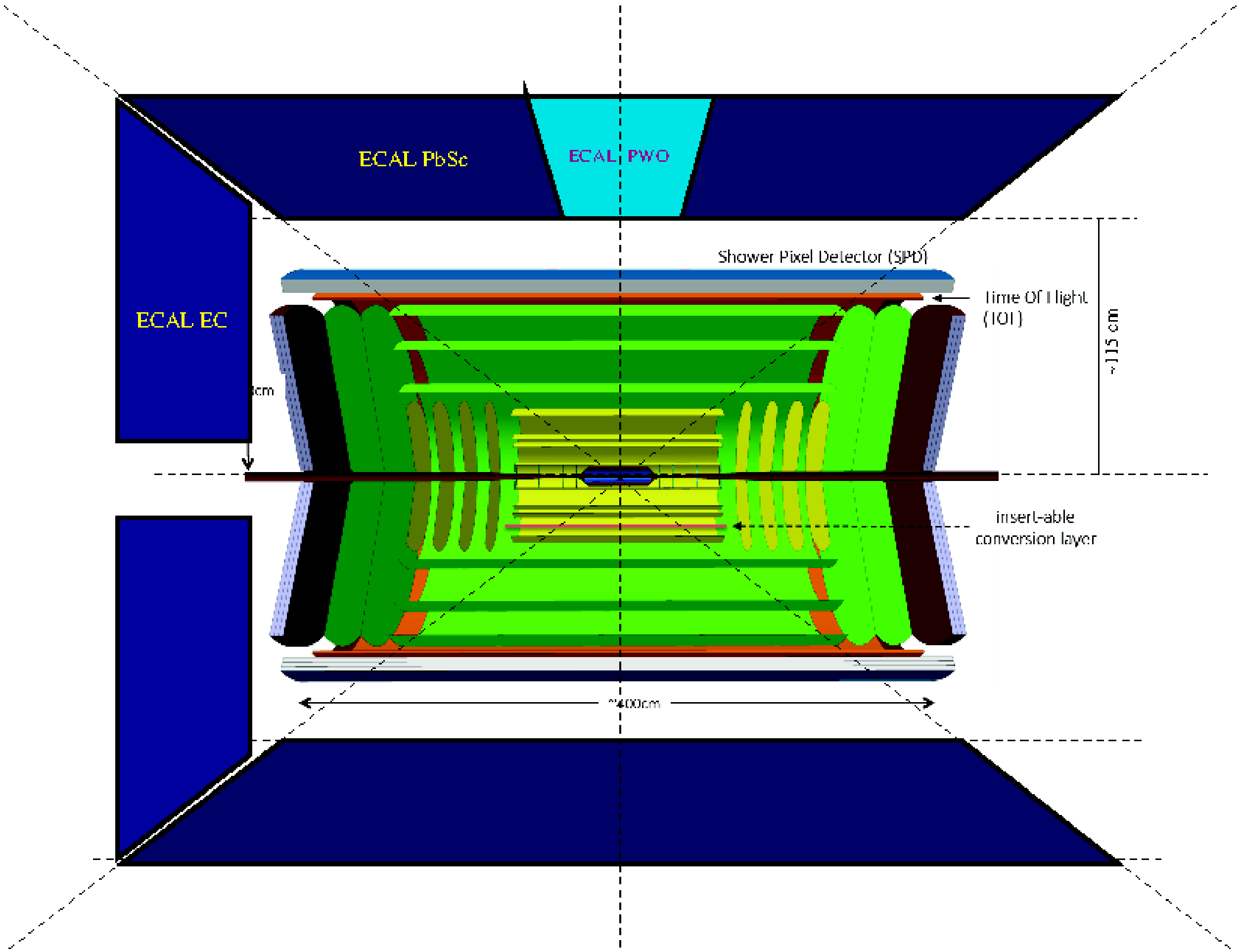
- The Electromagnetic Calorimeter (ECal) is planned to cover the full central barrel region and one forward region, i.e. an rapidity range of $-1.6 < \eta < 4$.
- Most of the rapidity range will be instrumented with a **sampling calorimeter**.
- A fraction of the central barrel will be covered by the existing **$PbWO_4$ crystals** for the measurement of χ_c and soft direct photons.

ECAL energy resolution:

$$\frac{\sigma_E}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c$$

ECal module	Barrel sampling	Endcap sampling	Barrel high-precision
acceptance	$\Delta\varphi = 2\pi$, $\lvert\eta\rvert < 1.5$	$\Delta\varphi = 2\pi$, $1.5 < \eta < 4$	$\Delta\varphi = 2\pi$, $\lvert\eta\rvert < 0.33$
geometry	$R_{in} = 1.15$ m, $\lvert z\rvert < 2.7$ m	$0.16 < R < 1.8$ m, $z = 4.35$ m	$R_{in} = 1.15$ m, $\lvert z\rvert < 0.64$ m
technology	sampling Pb + scint.	sampling Pb + scint.	$PbWO_4$ crystals
cell size	30×30 mm^2	40×40 mm^2	22×22 mm^2
no. of channels	30 000	6 000	20 000
energy range	$0.1 < E < 100$ GeV	$0.1 < E < 250$ GeV	$0.01 < E < 100$ GeV
b, GeV$^{1/2}$	0.1	0.1	0.02

ALICE3 detector layout



Quarkonia measurement at ALICE 3

S-state quarkonia will be detected in traditional dilepton decay channel:

- $J/\psi(\Upsilon) \rightarrow e^+e^-, \mu^+\mu^-$

P-state quarkonia will be reconstructed via 2-prong decay:

- $\chi_{cJ} \rightarrow J/\psi\ \gamma$; $\chi_{bJ} \rightarrow \Upsilon\ \gamma$ (J=0,1,2)

Leptons will be detected and identified in central tracker with muon identifier and electromagnetic calorimeter

Photons will be detected with precise electromagnetic calorimeter and via photon conversion

Muon chambers at central rapidity

- ~70 cm non-magnetic steel hadron absorber
- search spot for muons ~0.1 x 0.1 ( )
- ~5 x 5 cm2 cell size
- matching demonstrated with 2 layers of muon chambers
- scintillator bars
- wave-length shifting fibers
- SiPM read-out
- possibility to use using RPCs as muon chambers optimized for reconstruction down to p_T = 0 GeV/c

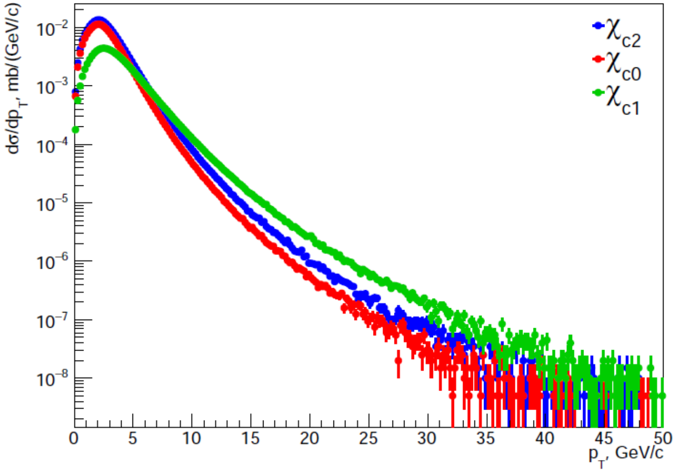
Large acceptance ECal (2π coverage)

- sampling calorimeter O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)
- $PbWO_4$-based high energy resolution segment critical for measuring P-wave quarkonia and thermal radiation via real photons

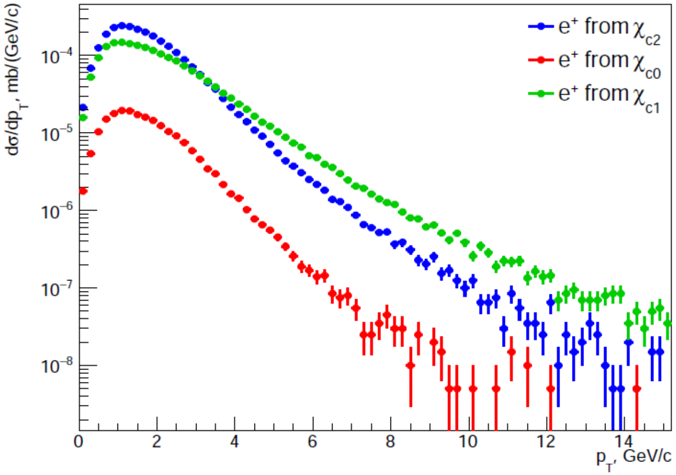
X-section and kinematics of χ_{cJ} (1P)

Pythia8 simulations pp @ 13 TeV

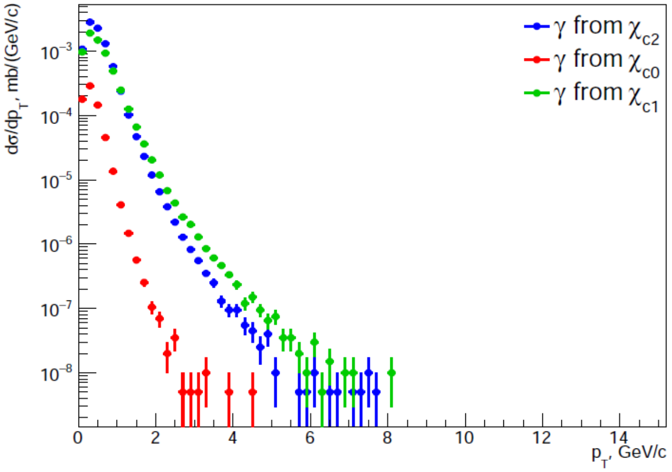
Production x-section



Electrons |y|<0.5

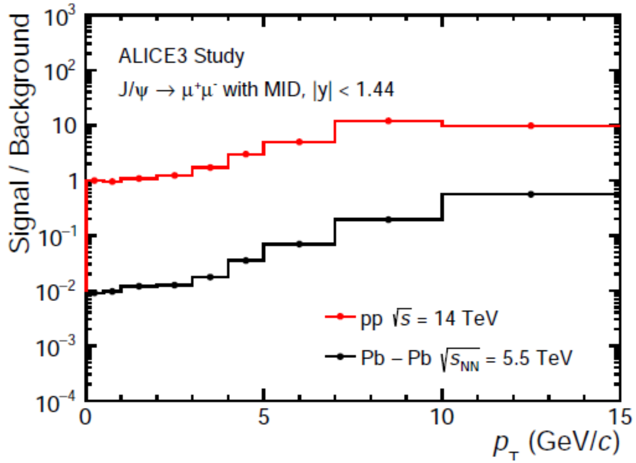


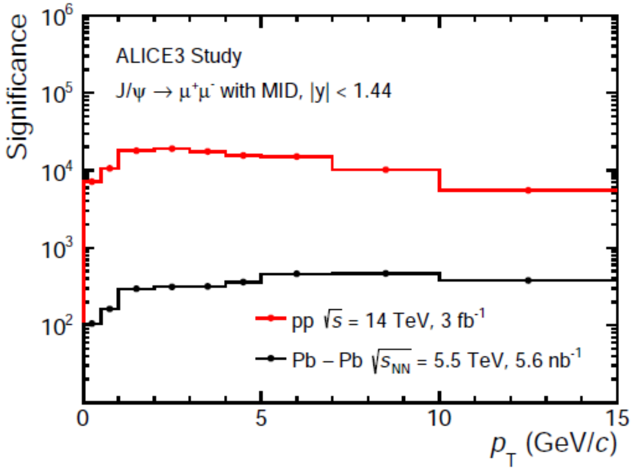
Photons |y|<0.12



Due to small mass difference of χ_{c1} and J/ψ, photons are essentially low-energy

Benchmark of J/ψ reconstruction ALICE 3

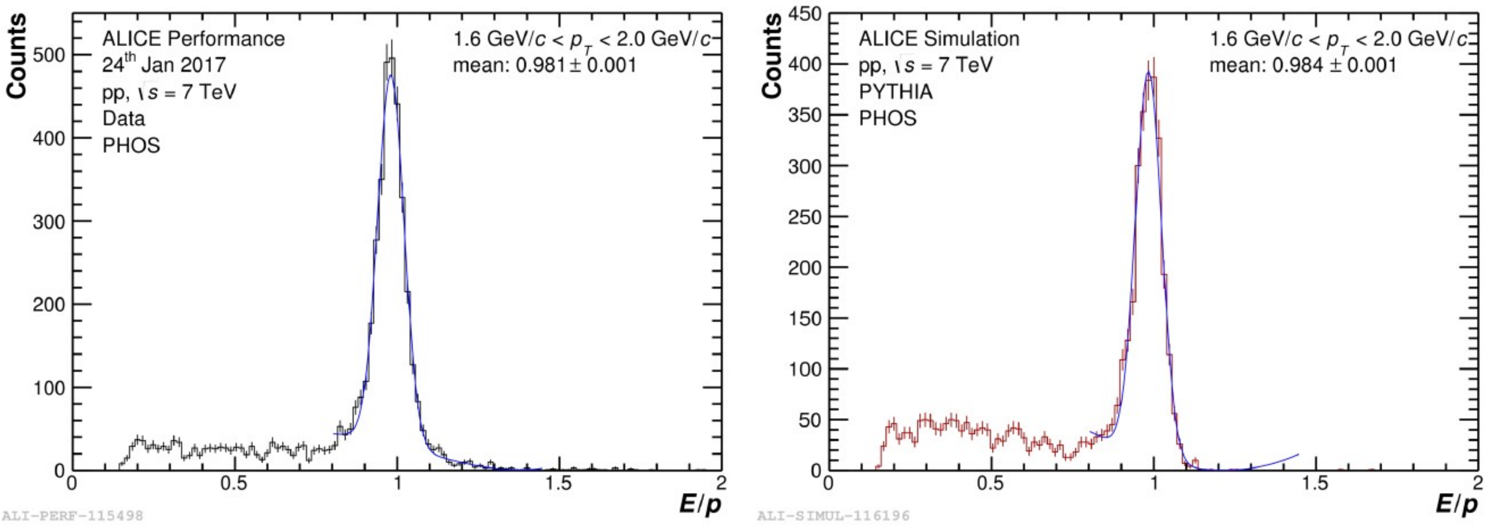




Decays of J/ψ in the muon channel are reconstructed by selecting tracks with muon ID in the MID, implying a minimum transverse momentum of ∼ 1.5 GeV/c at η = 0.

J/ψ signal-to-background and significance in pp collisions at $\sqrt{s}$ = 14 TeV (L_{int} = 3 fb^{-1}) and in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV (L_{int} = 5.6 nb^{-1}), corresponding to one-year data taking.

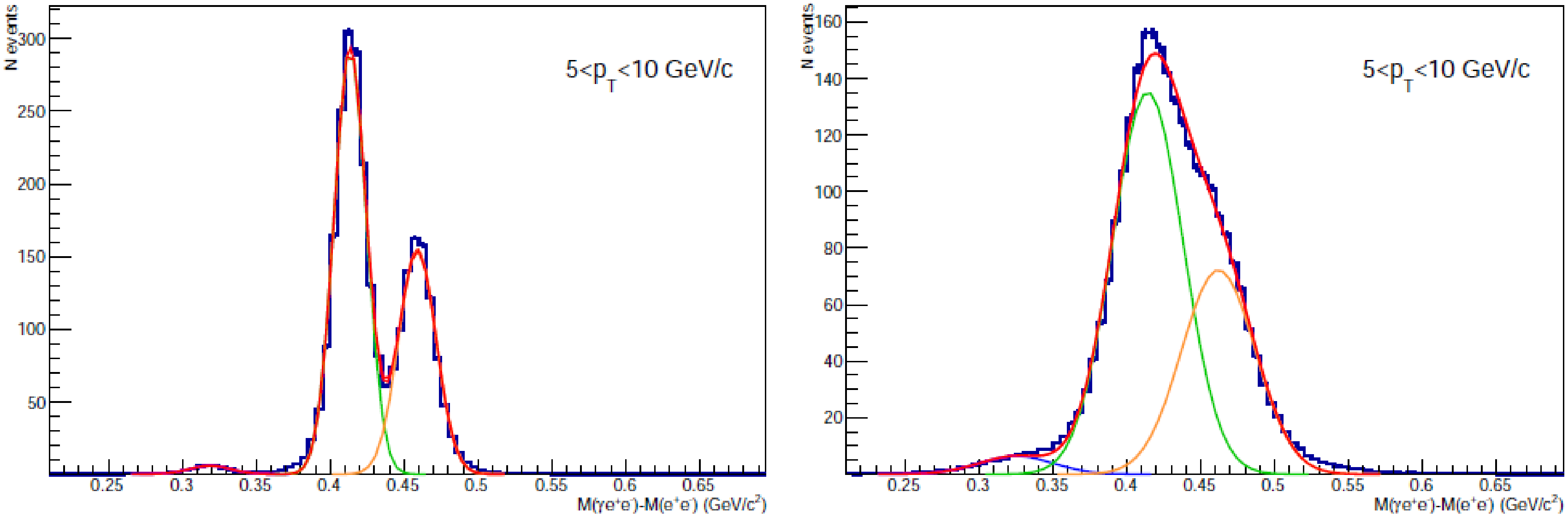
ECAL for electron ID



Relation of electron energy deposited in ECAL and electron track momentum reconstructed in tracking system is a measure for electron ID.

- At high electron momentum (p>1 GeV/c), efficiency and purity of e-ID with ECAL is high in pp collisions.
- In Pb-Pb collisions, e-ID purity is expected to be lower because of accidental track-cluster matching in high-multiplicity environment
- At low momentum, e-ID in ALICE 3 is provided by TOF and RICH

ECAL performance for χ_c mass resolution



Invariant mass difference spectra of decay $\chi_{cJ} \rightarrow J/\psi\ \gamma$ with a photon detected in the ECal at mid-rapidity assuming different stochastic term of the photon energy resolution: $b = 0.02$ GeV$^{1/2}$ (left) and $b = 0.05$ GeV$^{1/2}$ (right).

Only high-precision ECAL is suitable for separation of χ_{c1} and χ_{c2}.

Open charm in ALICE3

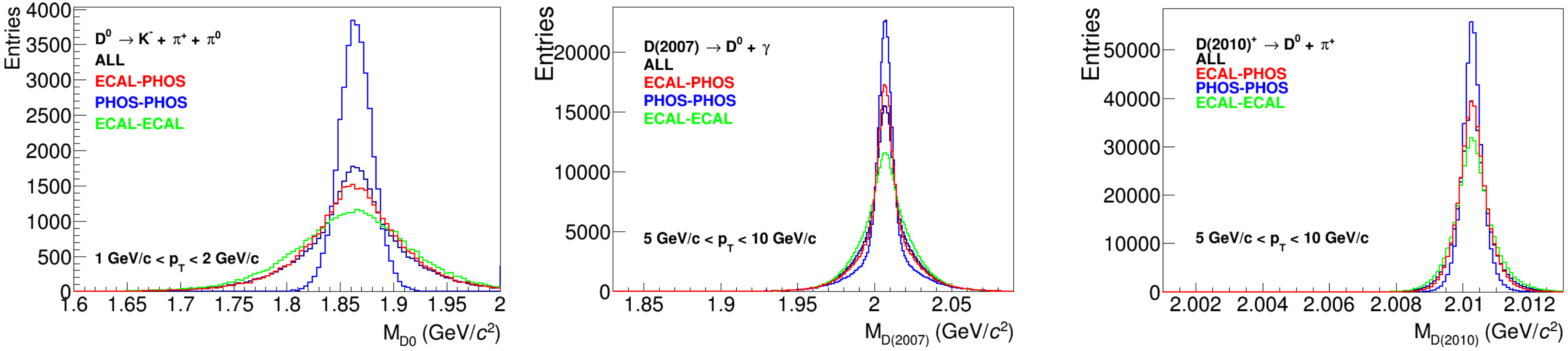
D-meson decays detectable in tracking system and in calorimeter are considered:

- $D^0 \rightarrow K^- \pi^+ \pi^0$ (BR=14.4±0.5% including intermediate resonances),
- $D^{0*}(2007) \rightarrow D^0 \pi^0$ (BR=64.7±0.9 %)
- $D^{\pm *}(2010) \rightarrow D^0 \pi^\pm$ (BR=67.7±0.5 %)

Final state reconstruction:

- Charged tracks K^-, π^+, are reconstructed and identified in ALICE3 central tracker
- π^0 are detected via 2γ decays in ALICE3 ECAL

D-mesons in pp 13 TeV

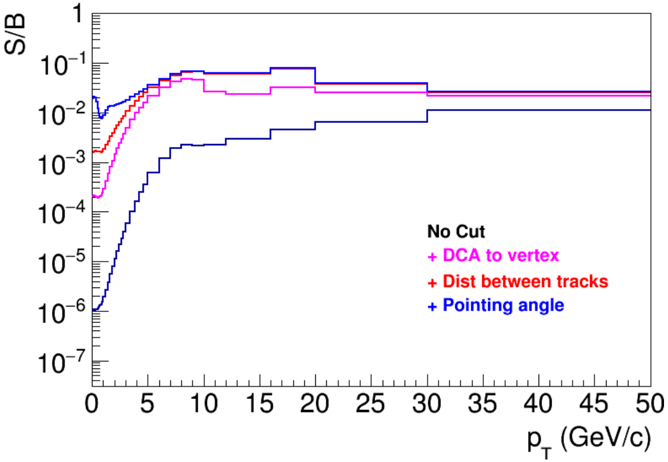


Signal width on invariant mass spectra depends on π^0 candidate selection which, in turns, is defined by ECal energy resolution.

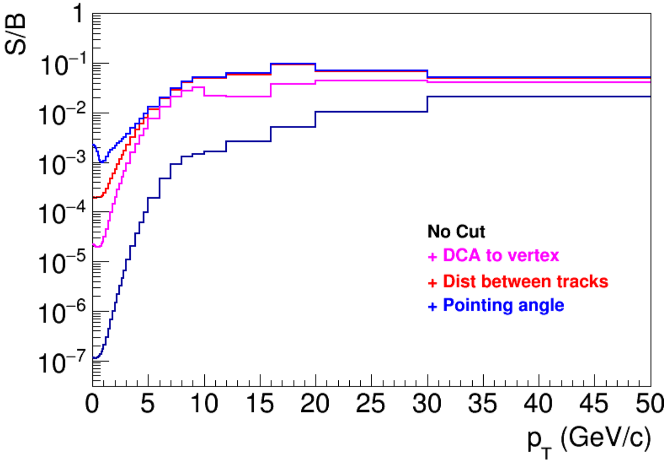
- The most narrow D^0-meson peak is achieved when both photons from π^0 decay hit the central high-resolution ECal sector

Signal/background in pp

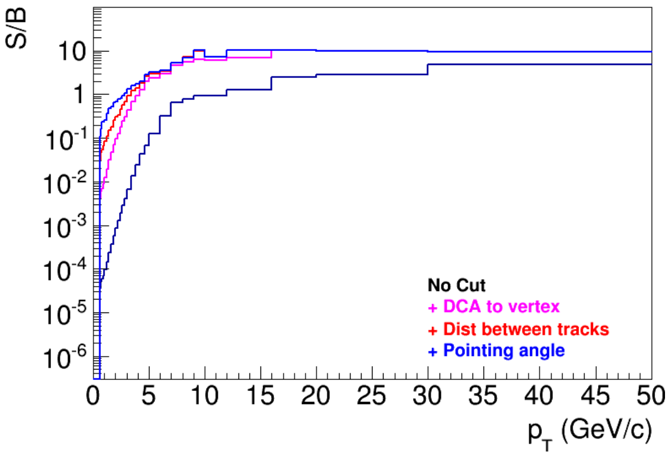
D^0



$D^{*0}(2007)$



$D^{*\pm}(2010)$



ALICE 3 simulations show that S/B of D-mesons reconstruction is enough for spectra measurements with high statistical significance in a wide p_T range

Summary

- Heavy flavour production in heavy-ion collisions remains one of the major signatures of deconfined QCD matter
- Systematic analysis of charmonium production in heavy-ion collisions at different energies and centralities reveal several physics effects responsible for production, dissociation and recombination of bound $Q\overline{Q}$ states
- Quantitative probe of various effects will be pursued in the future ALICE 3 experiment, a successor of ALICE at LHC Point 2 which is planned beyond LS4.