Study of charmonium at forward rapidity and Λ_b at midrapidity in heavy-ion collisions using ALICE

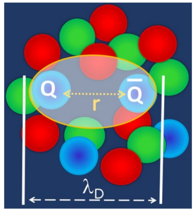
Dr. Biswarup Paul
Ramanujan fellow
Variable Energy Cyclotron Centre
Kolkata, India

ALICE-STAR India Collaboration Meeting
University of Jammu
21st - 24th November 2023

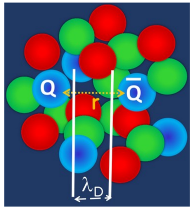
Quarkonium in heavy-ion collisions

- Quarkonium suppression: Quarkonium states are expected to be suppressed in a hot medium by color screening and dynamical dissociation

T. Matsui and H. Satz, PLB 178 (1986) 416
A Rothkopf, Phys. Rept. 858 (2020) 1-117



$T < T_{diss}$
State survived

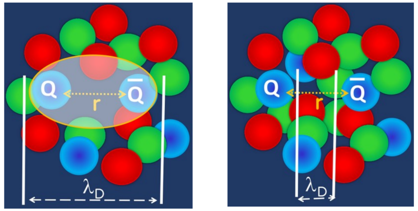


$T > T_{diss}$
State melt

Quarkonium in heavy-ion collisions

- Quarkonium suppression: Quarkonium states are expected to be suppressed in a hot medium by color screening and dynamical dissociation

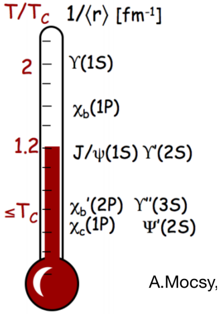
T. Matsui and H. Satz, PLB 178 (1986) 416
A Rothkopf, Phys. Rept. 858 (2020) 1-117



$T < T_{diss}$ State survived $T > T_{diss}$ State melt

- Sequential melting: Differences in the binding energies lead to a sequential melting of quarkonium states with increasing temperature of the quark-gluon plasma (QGP)

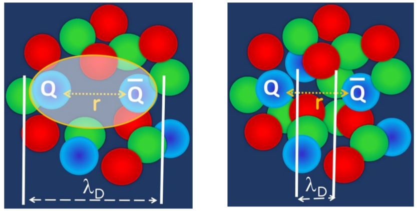
State	Mass [GeV]	ΔE [GeV]	r_0 [fm]
$J/\psi(1S)$	3.096	0.64	0.50
$\chi_c(1P)$	3.530	0.20	0.72
$\psi(2S)$	3.686	0.05	0.90
$\Upsilon(1S)$	9.460	1.10	0.28
$\chi_b(1P)$	9.990	0.67	0.44
$\Upsilon(2S)$	10.023	0.54	0.56
$\chi_b(2P)$	10.260	0.31	0.68
$\Upsilon(3S)$	10.355	0.20	0.78



Quarkonium in heavy-ion collisions

- Quarkonium suppression: Quarkonium states are expected to be suppressed in a hot medium by color screening and dynamical dissociation

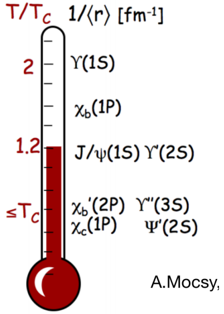
T. Matsui and H. Satz, PLB 178 (1986) 416
A Rothkopf, Phys. Rept. 858 (2020) 1-117

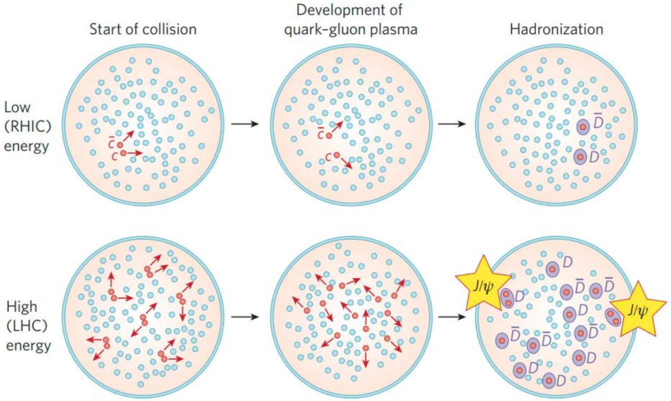


$T < T_{diss}$ State survived $T > T_{diss}$ State melt

- Sequential melting: Differences in the binding energies lead to a sequential melting of quarkonium states with increasing temperature of the quark-gluon plasma (QGP)

State	Mass [GeV]	ΔE [GeV]	r_0 [fm]
$J/\psi(1S)$	3.096	0.64	0.50
$\chi_c(1P)$	3.530	0.20	0.72
$\psi(2S)$	3.686	0.05	0.90
$\Upsilon(1S)$	9.460	1.10	0.28
$\chi_b(1P)$	9.990	0.67	0.44
$\Upsilon(2S)$	10.023	0.54	0.56
$\chi_b(2P)$	10.260	0.31	0.68
$\Upsilon(3S)$	10.355	0.20	0.78

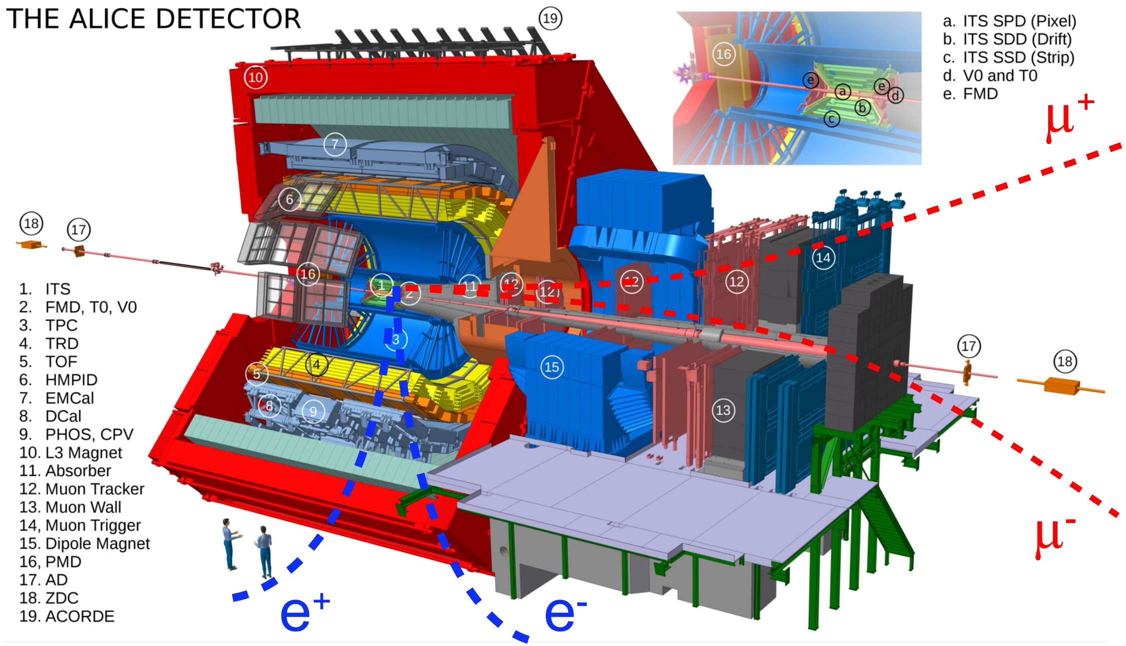




- Quarkonium recombination: Increase of $c\bar{c}$ production cross section at LHC energies → Enhanced quarkonium production via recombination at the phase boundary or during the QGP phase

P. Braun-Muzinger, J. Stachel, PLB 490 (2000) 196
R. Thews et al, Phys. Rev. C 63 (2001) 054905

A Large Ion Collider Experiment



→ Inclusive quarkonium measurements possible down to zero p_T in both rapidity regions

→ Prompt and non-prompt J/ψ can be separated down to very low p_T at midrapidity

Forward muon spectrometer:

J/ψ, ψ(2S), ϒ(nS) → $\mu^+\mu^-$ $(2.5 < y < 4)$

Muons identified and tracked in the muon spectrometer

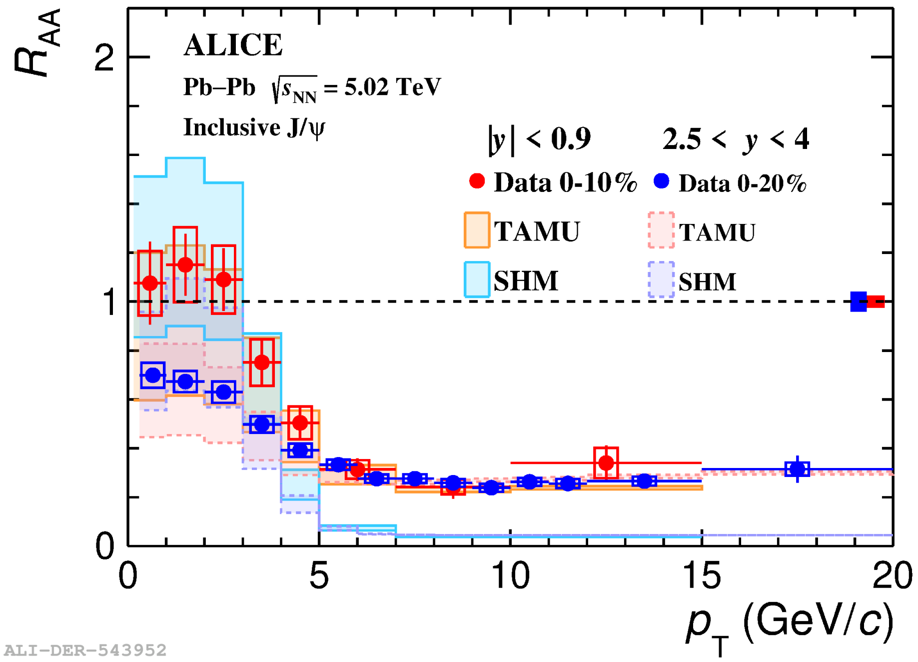
Central barrel:

J/ψ → e^+e^- $(|y| < 0.9)$

Electrons reconstructed using ITS and TPC
Particle identification: TPC dE/dx

V0: (V0A: $2.8 < \eta < 5.1$ & V0C: $-3.7 < \eta < -1.7$)
Trigger, background rejection, centrality measurements in A-A collisions and event plane determination

Nuclear modification factor (R_{AA}) of J/ψ in Pb-Pb collisions



- Measuring quarkonium production in A-A relative to production in pp collisions:

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

→ R_{AA}>1: Enhancement
→ R_{AA}<1: Suppression

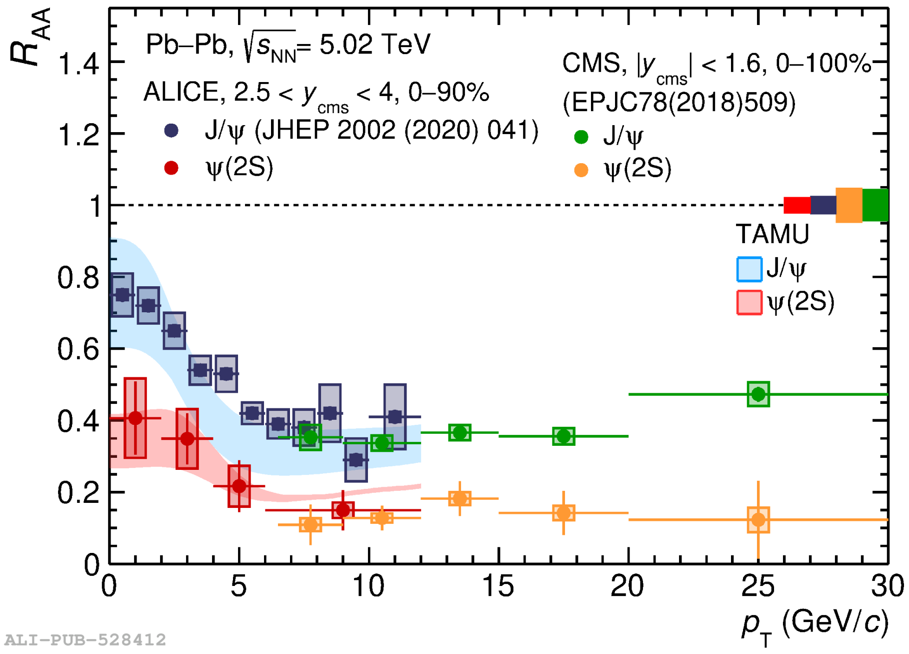
TAMU: X. Du and R. Rapp, Nucl. Phys. A. 943 (2015) 147
SHMc: A. Andronic et. al., Nature 561 no. 7723 (2018) 321

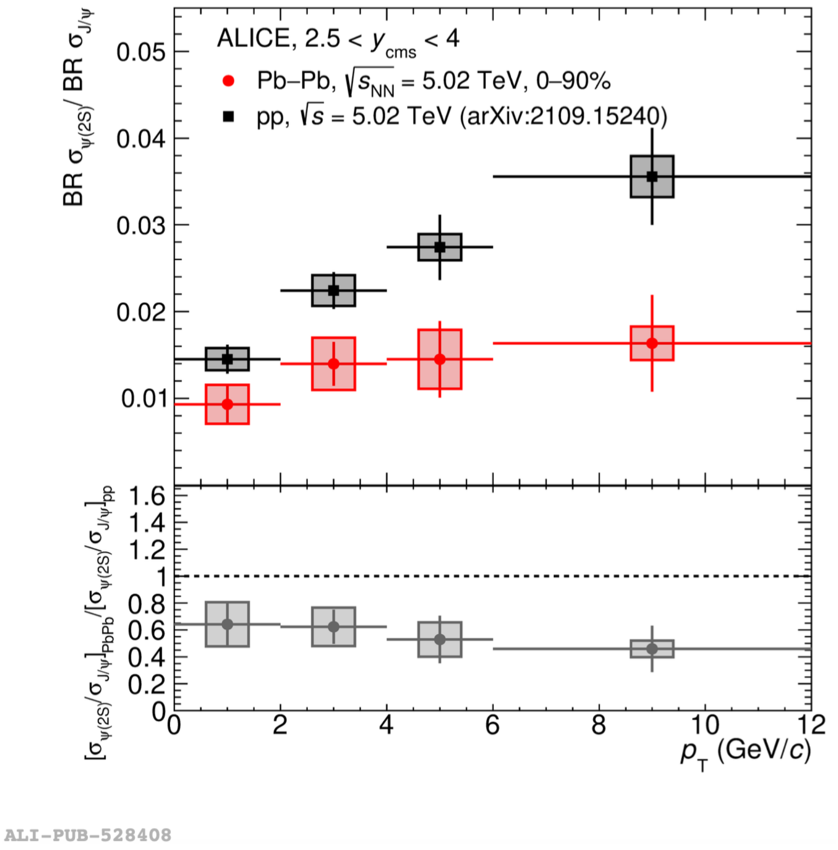
- Rise of inclusive J/ψ R_{AA} at low p_T, stronger effect at midrapidity in central events → strong signature of recombination
- Models that include regeneration either at the phase boundary (SHM) or during the medium evolution (TAMU) are both in agreement with data at low p_T

→ not possible to disentangle between the two different regeneration scenarios using J/ψ only

ALICE, PLB 766 (2017) 212, PC: J. Castillo, R. Arnaldi, B. Audurier, V. Feuillard, B. Paul, E. Scomparin and M. Tarhini
ALICE, JHEP 02 (2020) 041, PC: B. Audurier, B. Paul, E. Scomparin and M. Tarhini

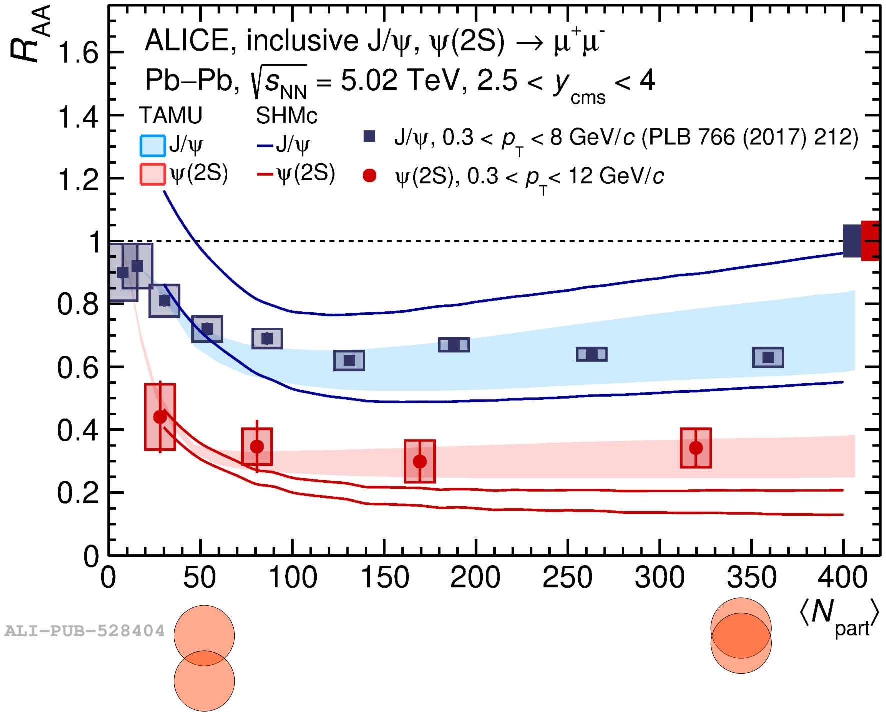
p_T dependence of ψ(2S) production in Pb-Pb collisions

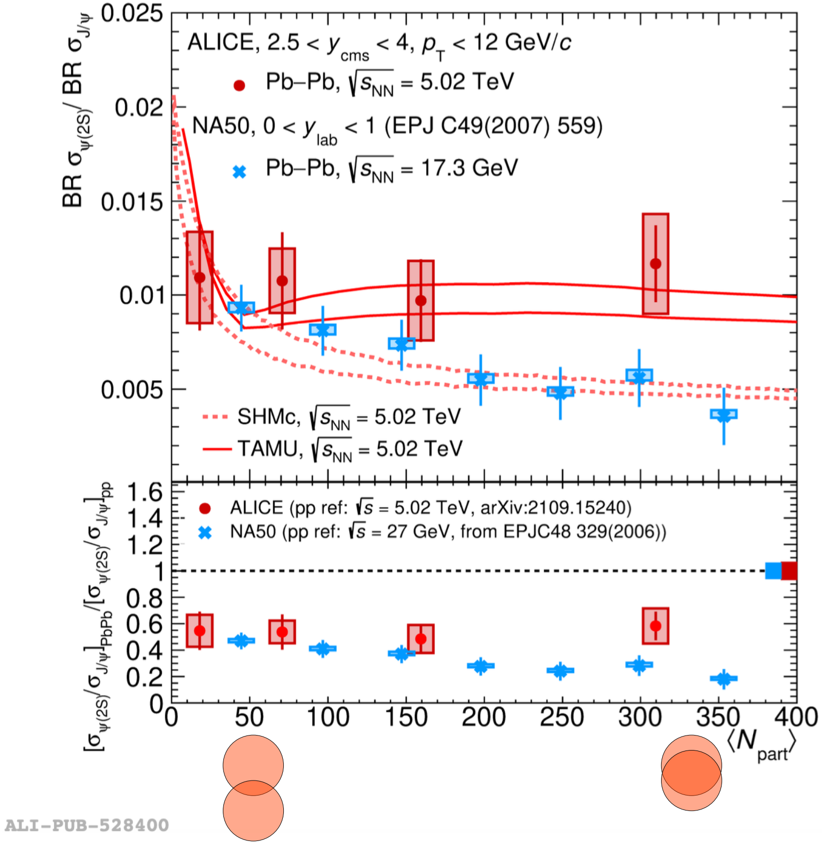




- ψ(2S) more suppressed than J/ψ over the full p_T range
- Stronger suppression at high-p_T and increasing trend of R_{AA} towards low-p_T for both charmonium states → hint of regeneration
- Good agreement with CMS at high p_T, although the rapidity range is different
- TAMU model reproduces the p_T dependence of R_{AA} for both J/ψ and ψ(2S)

Centrality dependence of ψ(2S) production in Pb-Pb collisions



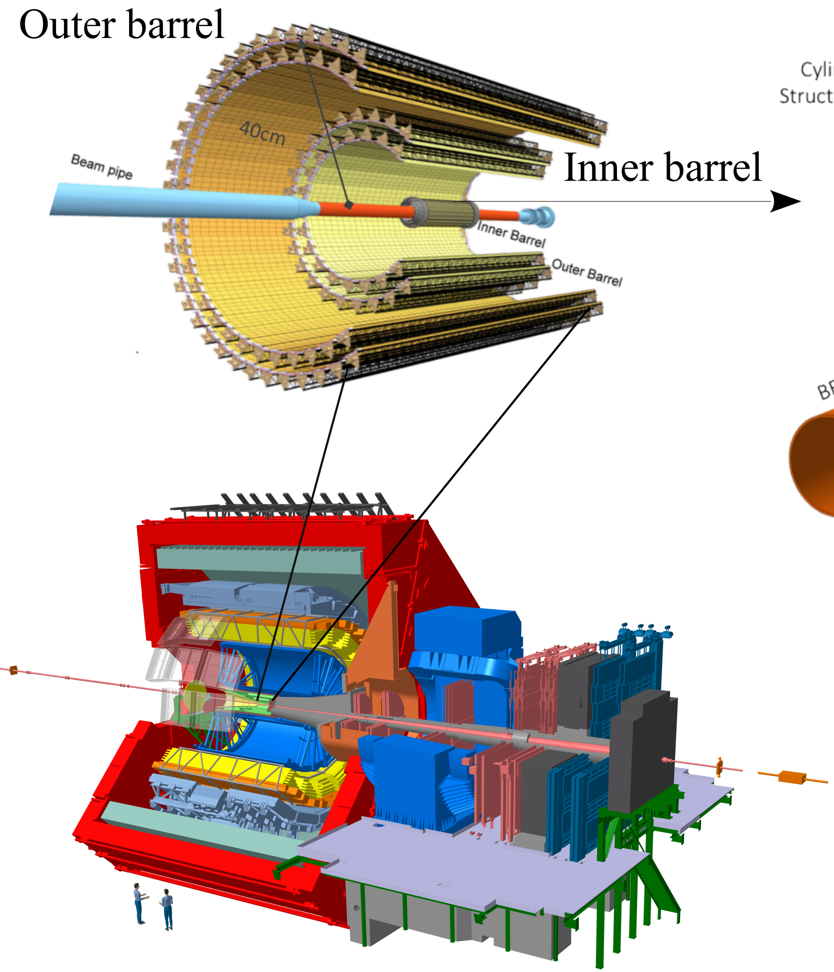


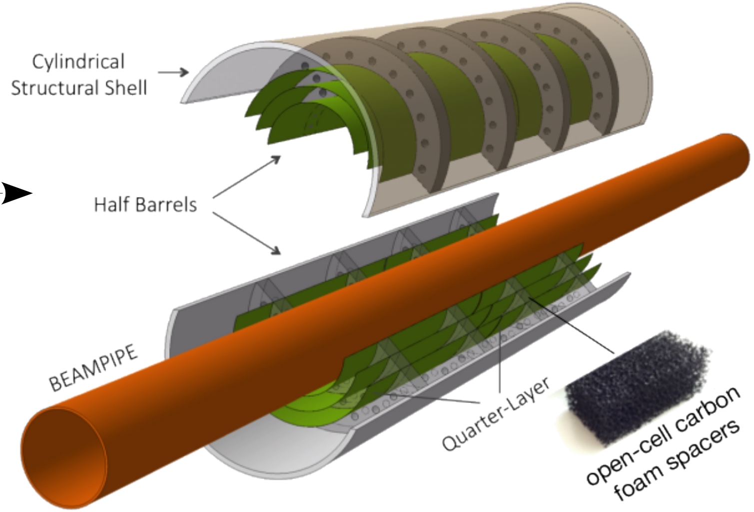
- Flat centrality dependence within uncertainty for both ψ(2S) R_{AA} and ψ(2S)-to-J/ψ (double) ratio at the LHC
- Larger ψ(2S)-to-J/ψ ratio at the LHC compared to SPS towards central collisions
- TAMU model reproduces the centrality dependence of the ψ(2S) and J/ψ R_{AA}, as well as the ψ(2S)-to-J/ψ one

ALICE, arXiv:2210.08893 (accepted in PRL), PC: R. Arnaldi, K. Garg, M. Guilbaud, H. Hushnud, B. Paul and E. Scomparin

Λ_b analysis in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV (simulation) using ITS2 and ITS3

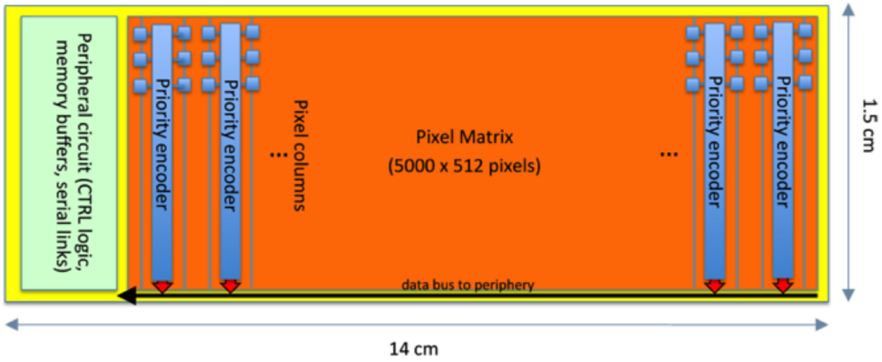
ITS3: Upgraded Inner Tracking System after Long Shutdown 3





→ ultra-thin Si CMOS (20 µm thick)
→ circuitry pushed to periphery
→ can be curved
→ sensors of up to 10×26 cm^2 size which can be bent to half-cylindrical shapes of 18, 24 and 30 mm bending radii for layer 0, 1 and 2 respectively

1D stitched sensor (z direction)

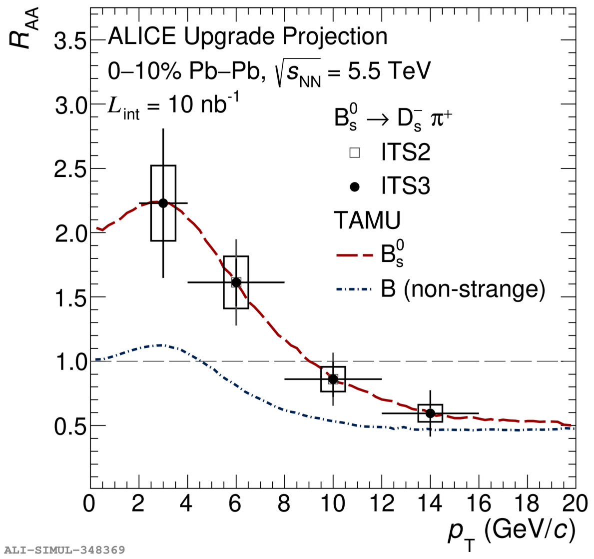


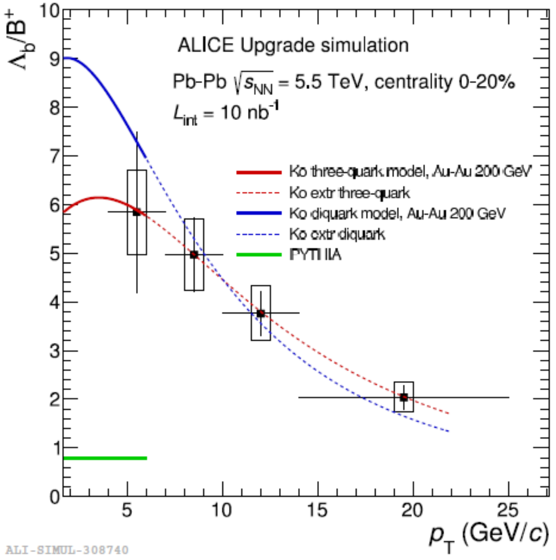
Estimation of expected Λ_b signal and background

$$S = 2\int_{\Delta y}\int_{p_{T,\min}}^{p_{T,\max}} \left(\frac{d^2N}{dp_T dy}\right)^{\Lambda_b^0}_{\text{Pb–Pb},0\text{–}10\%} dp_T dy \times \text{BR} \times (\text{Acc}\times\varepsilon)_{\Lambda_b^0} \times N_{ev}^{exp}$$

$$= 2\int_{p_{T,\min}}^{p_{T,\max}} \left(\frac{d\sigma}{dp_T}\right)^{\text{b-hadr., FONLL}}_{|y|<0.8} dp_T \times f(\text{b}\to\text{B}) \times R_{AA}^{B} \times \left(\frac{\Lambda_b^0}{\text{B}}\right) \times \langle T_{AA}\rangle \times \text{BR} \times (\text{Acc}\times\varepsilon)_{\Lambda_b^0} \times N_{ev}^{exp}$$

$$N_{Bkg} = (N_{Bkg}^{MC}/N_{ev}^{MC}) \times N_{ev}^{exp}$$





- $f(\text{b}\to\text{B}) = 0.407$
- R^{B}_{AA} = Nuclear modification factor of non-strange B meson
- T_{AA} (0-10%) = 23.07 mb^{-1}
- N^{exp}_{ev} (0-10%) = 7.7x10^9
- N^{MC}_{ev} = 2105500 (ITS3) and 705162 (ITS2)
- BR = BR($\Lambda_b \to \Lambda_c\pi$) x BR($\Lambda_c \to pK\pi$)

  = 4.9x10^{-3} x 6.23x10^{-2}

- Caveat: MC and R^{B}_{AA} are in 0-10% centrality but Λ_b/B is in 0-20% centrality

MC sample and analysis procedure

- New MC Production LHC19h1b2 (1,2,3,4): 2M Pb-Pb events at 5.5 TeV
- Lego train number: 632 (https://alimonitor.cern.ch/trains/train.jsp?train_id=131)

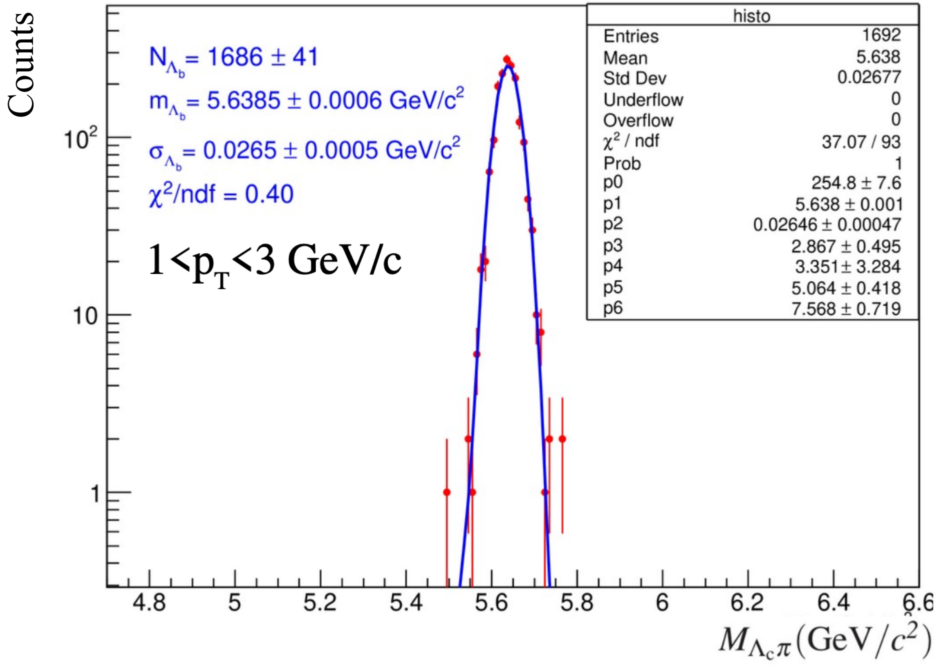
Topological Variables	ITS2 (70% Signal Survival)	ITS3 (70% Signal Survival)
cos_p >	0.9974	0.9994
ctau >	0.019	0.019
norm_dl_xy >	3.925	8.325
norm_dl_xy_Lc >	6.7625	14.1575
|max_norm_d0d0exp_Lc| >	3.175	6.275
d_len >	0.022	0.022
d_len_Lc >	0.035	0.037
|imp_par_Lc| >	0.00485	0.00495
|imp_par_pi| >	0.00925	0.00965

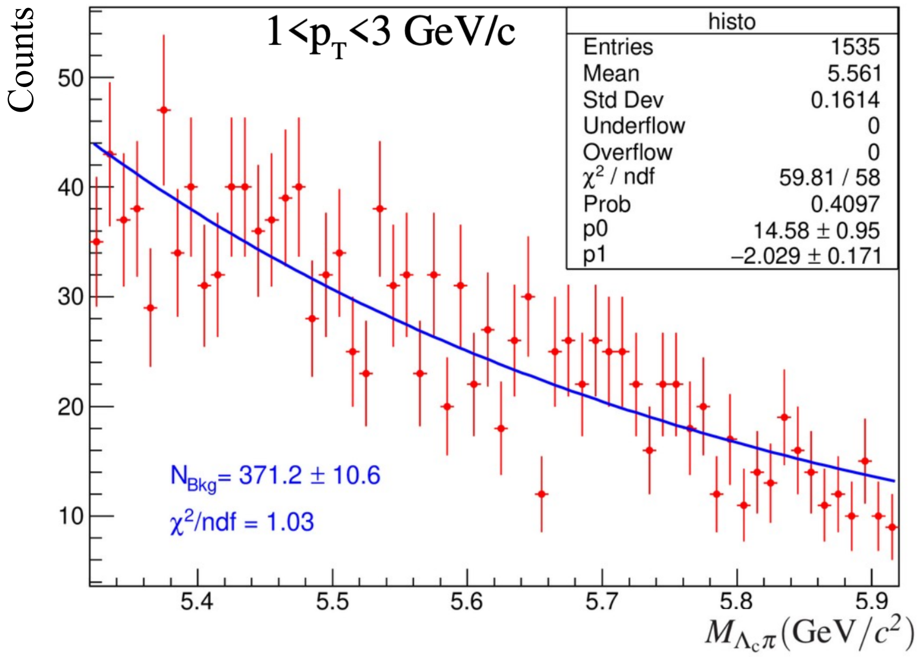
- Procedure:

  - Variables that allow to reject more efficiently background were considered

  - Each variable was tuned in order to keep a given fraction of signal (e.g. 70%, 80%, 90%)

Signal and background extraction (ITS3)

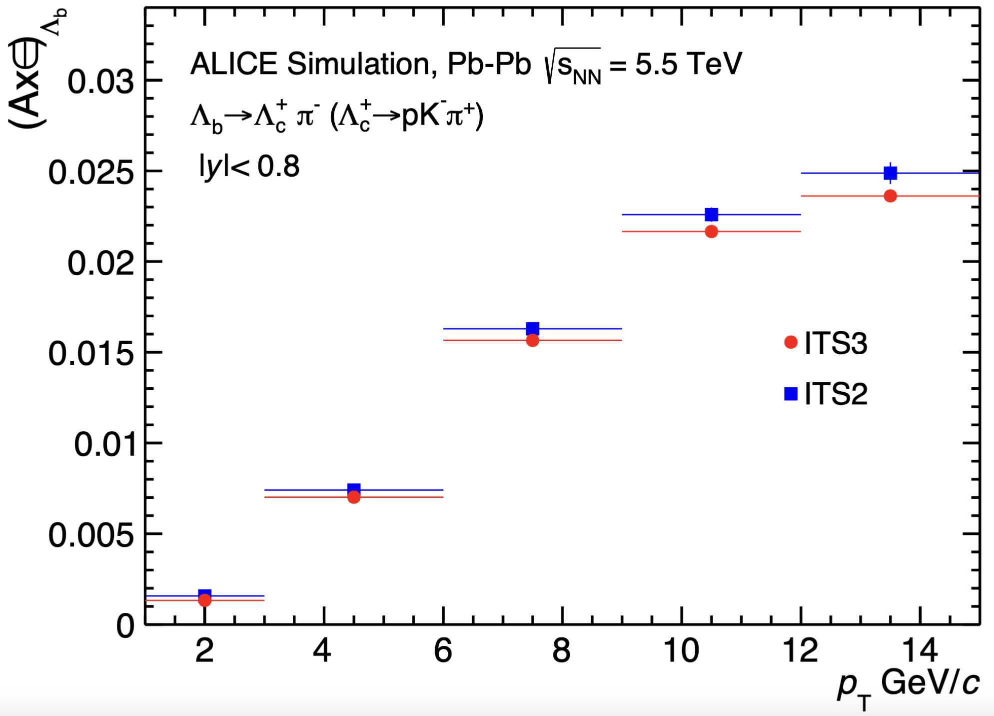


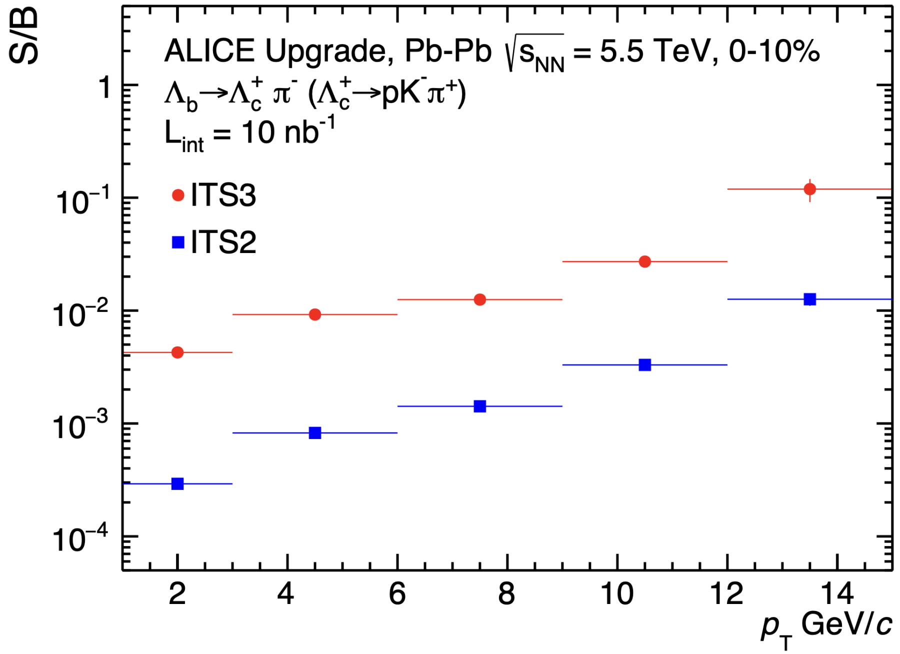


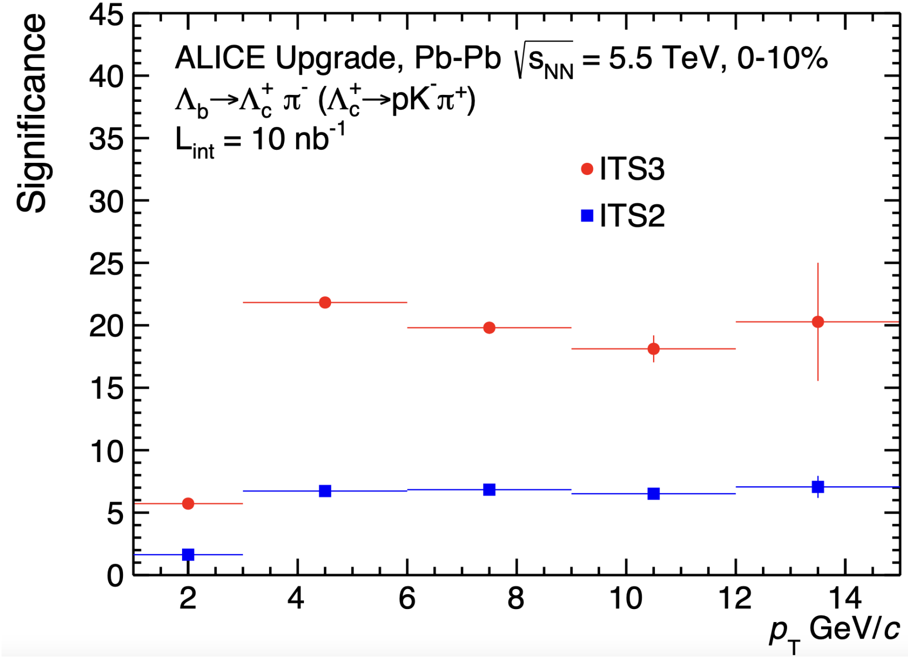
- Signal was fitted with a double Crystal ball function (CB2)
- Background was fitted with a exponential function

Acceptance x efficiency of Λ_b

$$(A\times\varepsilon)_{\Lambda_b,|y|<0.8} = \left(\frac{S^{\Lambda_b}(\text{reco})}{S^{\Lambda_b}(\text{gen})}\right)_{|y|<0.8}$$







- S/B and Significance of Λ_b in 0-10% in |y|<0.8
- With ITS3 it will be possible to measure Λ_b down to p_T = 1 GeV/c

ALICE-PUBLIC-2023-002, PC: A. Rossi, A. Philipp Kalweit, B. Paul, M. Buckland, J. Ditzel, B. Donigus, M. Faggin, P. Ganoti, F. Grosa, J. Norman, S. Politano and L Vermunt

Conclusions

→ The ψ(2S) is more suppressed than the J/ψ in entire p_T and centrality range

→ Comparison of J/ψ and ψ(2S) R_{AA} with transport model shows a fair agreement within uncertainties

→ Transport model, which includes recombination of charm quarks in the QGP phase, reproduces the ψ(2S)-to-J/ψ ratio better than SHMc model for central events

→ The ITS3 will allow for a measurement of Λ_b down to p_T = 1 GeV/c

Prospects for Run 3/4

→ Significant increase of statistical precision expected with $L_{int} \sim 10\ nb^{-1}$, thanks to continuous readout

→ The Muon Forward Tracker (MFT) will allow to separate the prompt charmonium from the contribution originating from beauty hadron decays at forward rapidity

Publications

ALICE

List of journal publications as first/principal author

1. "ψ(2S) production in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV",
   Roberta Arnaldi, Kunal Garg, Maxime Guilbaud, Hushnud Hushnud, Biswarup Paul and Enrico Scomparin (ALICE Collaboration),
   [arXiv:2210.08893[nucl-ex]]. Accepted in PRL
2. "Centrality dependence of J/ψ and ψ(2S) production and nuclear modification in p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV",
   Javier Castillo, Jhuma Ghosh, Luca Micheletti and Biswarup Paul (ALICE Collaboration),
   JHEP **02**, 002 (2021),
3. "Υ production in p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV",
   Roberta Arnaldi, Sukalyan Chattopadhyay Biswarup Paul and Wadut Shaikh (ALICE Collaboration),
   PLB **806**, 135486 (2020),
4. "Studies of J/ψ production at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV",
   Mohamad Tarhini, Benjamin Audurier and Enrico Scomparin and Biswarup Paul (ALICE Collaboration),
   JHEP **02**, 041 (2020),
5. "J/ψ suppression at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV",
   Javier Castillo, Roberta Arnaldi, Benjamin Audurier, Victor Feuillard, Biswarup Paul, Enrico Scomparin and Mohamad Tarhini (ALICE Collaboration),
   PLB **766**, 212-224 (2017),
6. "Suppression of ψ(2S) production in p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV",
   Roberta Arnaldi, Marco Leoncino, Biswarup Paul and Enrico Scomparin (ALICE Collaboration),
   JHEP **12**, 073 (2014),
7. "Measurement of quarkonium production at forward rapidity in pp collisions at $\sqrt{s}$ = 7 TeV",
   Xavier Lopez, Livio Bianchi, Martino Gagliardi, Biswarup Paul, Hugo Pereira Da Costa and Philippe Rosnet (ALICE Collaboration),
   Eur. Phys. J. C **74**, 2974 (2014),

Publications

Theory paper

1. "Systematic study of charmonium production in pp collisions at LHC energies",
   Biswarup Paul, Mahatsab Mandal, Pradip Roy and Sukalyan Chattopadhyay,
   J. Phys. G: Nucl. Part. Phys. **42** 065101 (2015),

ALICE Public Notes

1. "Upgrade of the Inner Tracking System during LS3: study of physics performance"
   Andrea Rossi, Alexander Philipp Kalweit, Biswarup Paul, Matthew Daniel Buckland, Janik Ditzel, Benjamin Donigus, Mattia Faggin, Paraskevi Ganoti, Fabrizio Grosa, Jaime Norman, Stefano Politano and Lucas Anne Vermunt
   PUB-1327, ALICE-PUBLIC-2023-002
2. "Reference pp cross sections for J/ψ and ψ(2S) production studies in p-Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV"
   Javier Castillo, Jhuma Ghosh, Luca Micheletti and Biswarup Paul
   PUB-1089, ALICE-PUBLIC-2020-007
3. "Preliminary Physics Summary: Inclusive Υ production in p-Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV"
   Roberta Arnaldi, Biswarup Paul and Wadut Shaikh
   PUB-820, ALICE-PUBLIC-2018-008
4. "Preliminary Physics Summary: Centrality dependence of J/ψ production in p-Pb collisions at $\sqrt{s_{\rm NN}} =$ 8.16 TeV"
   Roberta Arnaldi, Biswarup Paul and Chiara Oppedisano
   PUB-663, ALICE-PUBLIC-2017-007
5. "Preliminary Physics Summary: Inclusive J/ψ production at forward rapidity in p-Pb collisions at $\sqrt{s_{\rm NN}} =$ 8.16 TeV",
   Roberta Arnaldi, Biswarup Paul and Enrico Scomparin
   PUB-599, ALICE-PUBLIC-2017-001

Publications

Review articles

1. "Prospects for quarkonium studies at the high-luminosity LHC",
   E. Chapon, B. Paul *et al.*
   Progress in Particle and Nuclear Physics **122**, 10390 (2022),
2. "INFN What Next: Ultra-relativistic Heavy-Ion Collisions",
   A. Dainese, B. Paul *et al.*
   Frascati Phys. Ser. **62** (2016),

ALICE Analysis Notes

1. "ψ(2S) production in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV"
   Roberta Arnaldi, Biswarup Paul, Hushnud Hushnud, Kunal Garg
   ANA-1216
2. "Multi-differential studies of the J/ψ production in p-Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV"
   Biswarup Paul
   ANA-751
3. "Centrality dependence of inclusive J/ψ production in p-Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV"
   Biswarup Paul
   ANA-654
4. "Centrality dependence of inclusive Υ(1S) production in p-Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV"
   Biswarup Paul, Wadut Shaikh, Indranil Das and Sukalyan Chattopadhyay
   ANA-753

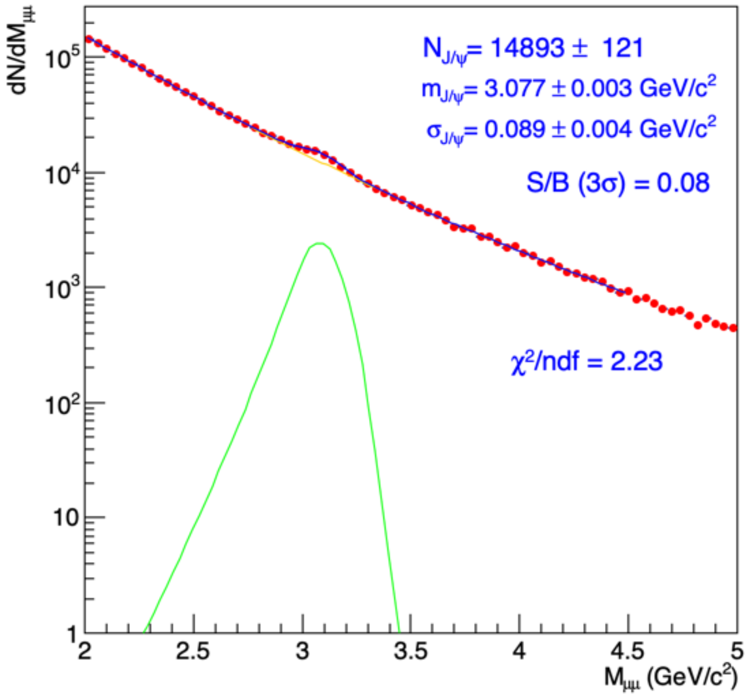
Publications

5. "Inclusive Υ production in p-Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV"
   Wadut Shaikh, Biswarup Paul, Indranil Das and Sukalyan Chattopadhyay
   ANA-714
6. "Inclusive J/ψ production in p-Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV"
   R. Arnaldi. L. Micheletti, B. Paul and E. Scomparin
   ANA-591
7. "Multi-differential studies of the J/ψ production in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV"
   B. Audurier, B. Paul and M. Tarhini
   ANA-581
8. "J/ψ production in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV"
   R. Arnaldi, B. Audurier, J. Castillo, V. Feuillard, B. Paul, P. Pillot, E. Scomparin and M. Tarhini
   ANA-486
9. "Measurement of inclusive charmonium production cross section at forward rapidity in pp collisions at $\sqrt{s} = 8$ TeV"
   Das Indranil, Lardeux Antoine Xavier, Paul Biswarup and Pillot Phillipe
   ANA-395
10. "Measurement of an excess in the yield of J/ψ at very low p_T in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV"
    G. Martinez, L. Massacrier, G. Contreras, B. Paul, P. Pillot, C. Suire and L. Valencia
    Analysis note
11. "p_T dependence of the inclusive ψ(2S) production in pA collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV"
    Roberta Arnaldi, Marco Leoncino, Biswarup Paul and Enrico Scomparin
    ANA-268, CERN-PH-EP-2014-092
12. "ψ(2S) production in pA collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV"
    Laurent Aphecetche, Roberta Arnaldi, Cynthia Hadjidakis, Igor Lakomov, Marco Leoncino, Biswarup Paul and Enrico Scomparin
    ANA-243, CERN-PH-EP-2014-092
13. "Inclusive J/ψ and ψ(2S) production cross sections in pp collisions at $\sqrt{s} = 7$ TeV"
    Biswarup Paul, Roberta Arnaldi, Livio Bianchi, Sukalyan Chattopadhyay, Martino Gagliardi, Enrico Scomparin, Diego Stocco and Lizardo Valencia Palomo
    ANA-182, CERN-PH-EP-2014-042

Thank you

J/ψ in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.36 TeV (Run 3)

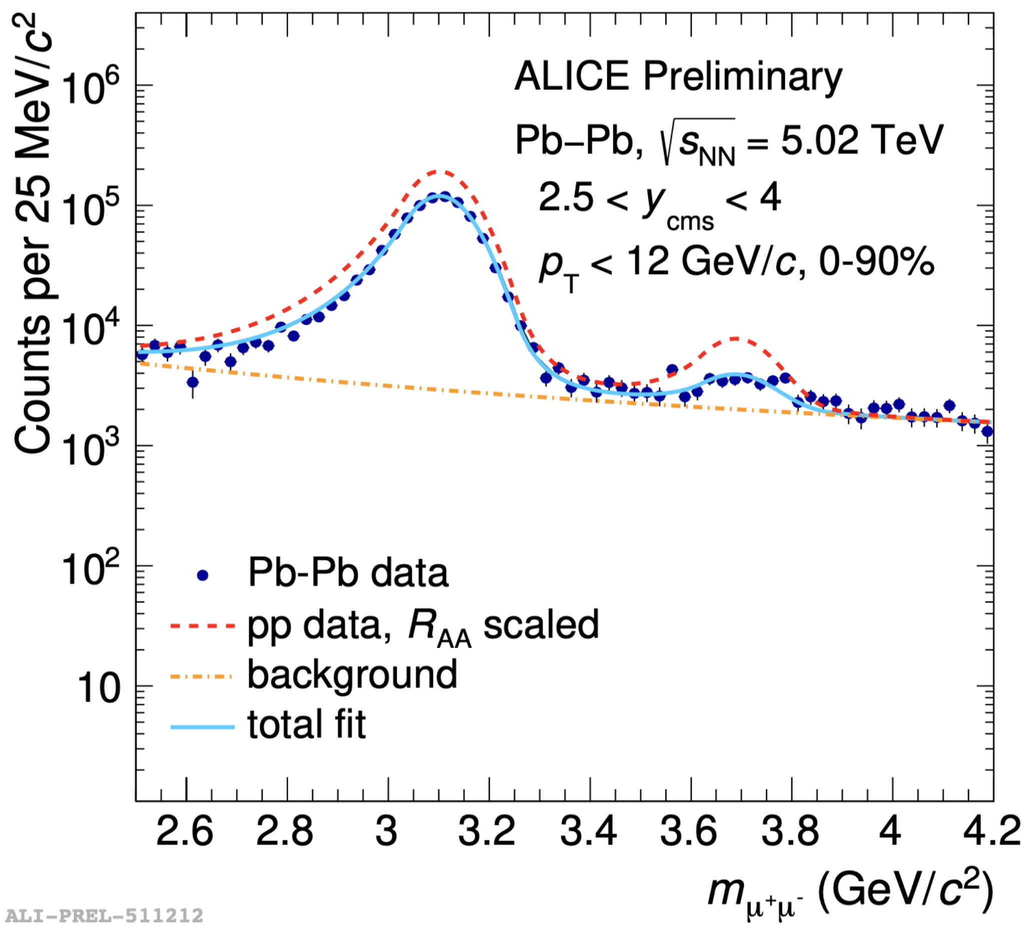
- Dataset: LHC23zx, LHC23zy, LHC23zz, LHC23zzb



Muon cuts:

- $-4 < \eta_{\mu} < -2.5$
- $17.6 < R_{abs} < 89.5$ cm
- pDCA cut
- $\chi^2_{MCH\text{-}MID} > 0$
- Muon $p_T > 0$ GeV/c
- $2.5 < y < 4$

Signal extraction

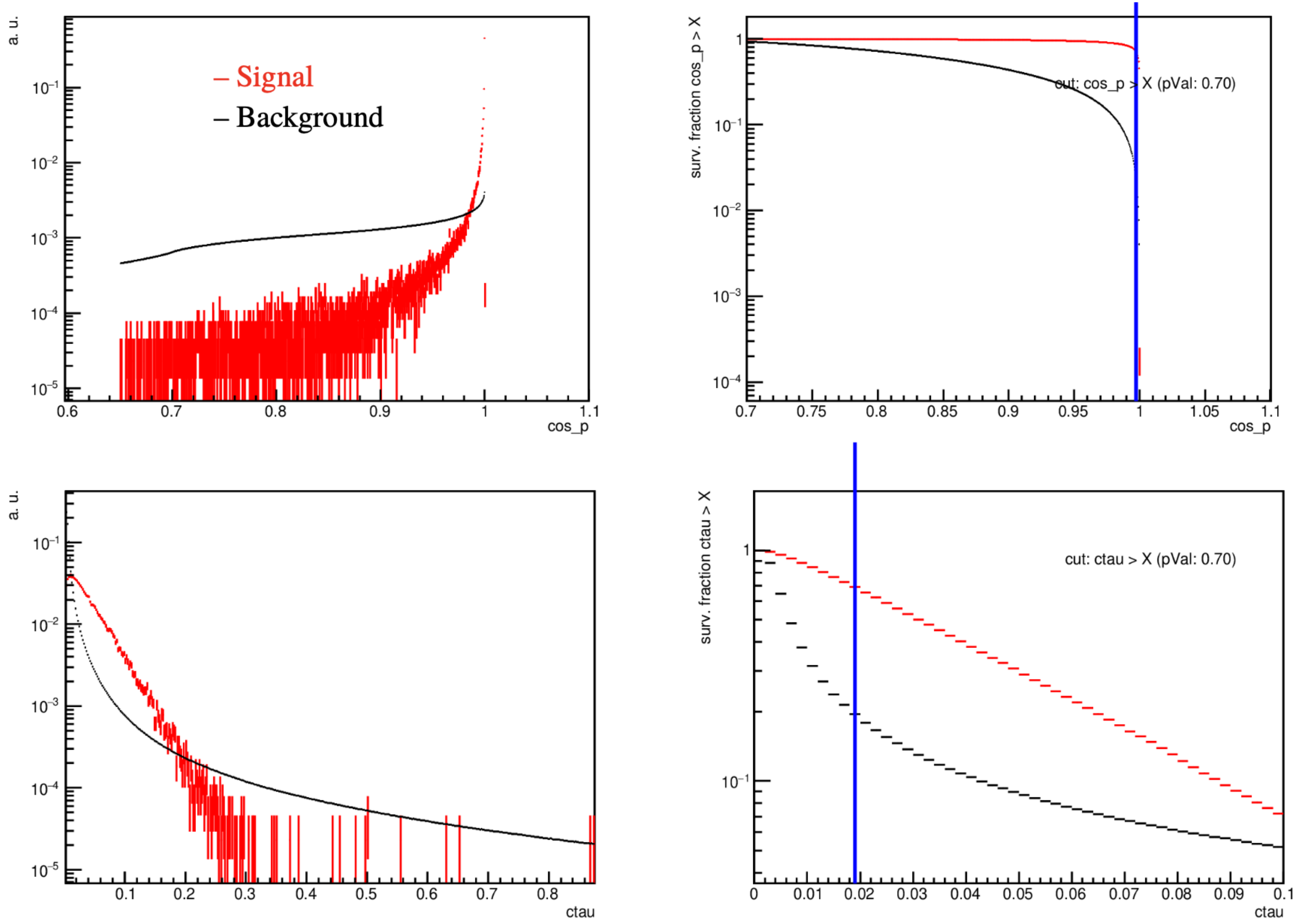


- Physics Selection
- Trigger selection: CMUL7-B-NOPF-MUFAST
- Centrality estimators: V0M
- Standard cuts applied:
  - → 2 muon matching the trigger
  - → 17.6 < R_{abs} < 89.5 cm
  - → $-4 < \eta_{\mu} < -2.5$
  - → $2.5 < y_{\mu\mu} < 4$
  - → pDCA cut
  - → $0 < p_T < 12$ GeV/c

- J/ψ tail parameters have been used for ψ(2S)
- Mass position and width of ψ(2S) are scaled to J/ψ mass position (PDG) and width (ratio from MC)

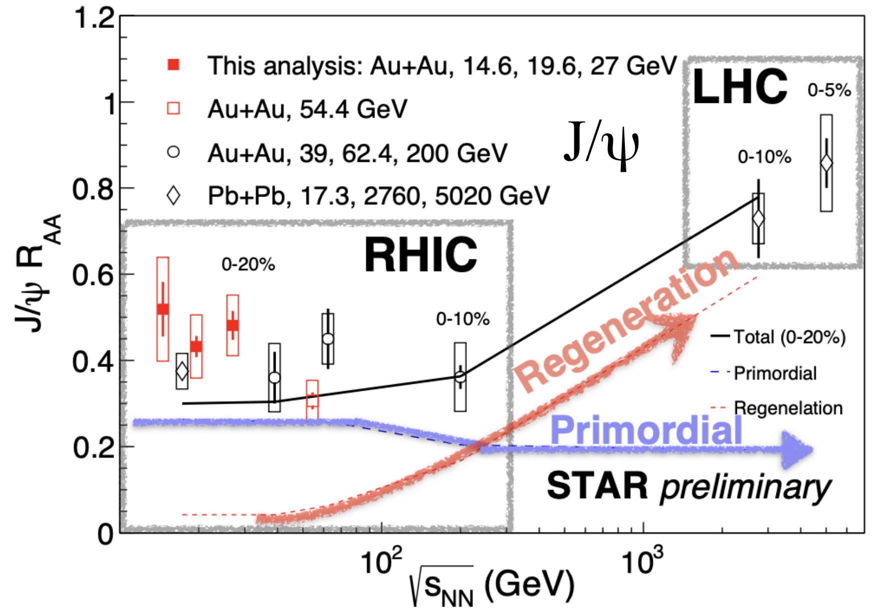
- Signal functions: CB2 functions
- Background functions: Variable Width Gaussian (5 parameters)

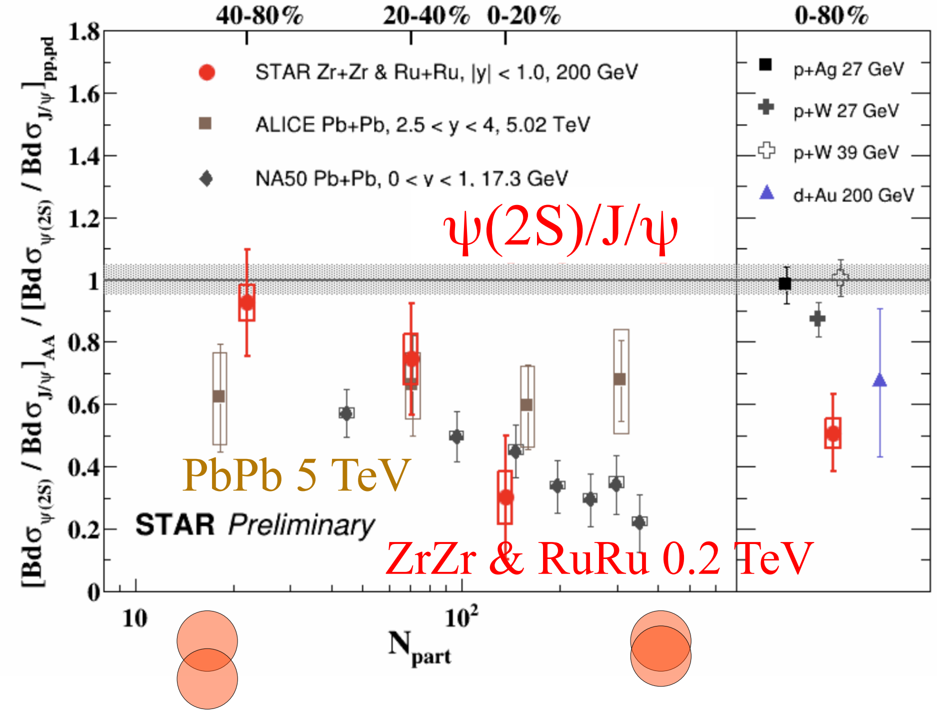
Topological variables (ITS3) [70% signal survival]



- Cumulative histogram: A histogram in which the vertical axis gives not just the counts for a single bin, but rather gives the counts for that bin plus all bins for smaller values of the response variable.

Energy and system size dependence of J/ψ and ψ(2S) R_{AA}





ALICE, PLB 734 (2014) 314
STAR, PLB 771 (2017) 13-20
STAR, PLB 797 (2019) 134917
ALICE, NPA 1005 (2021) 121769

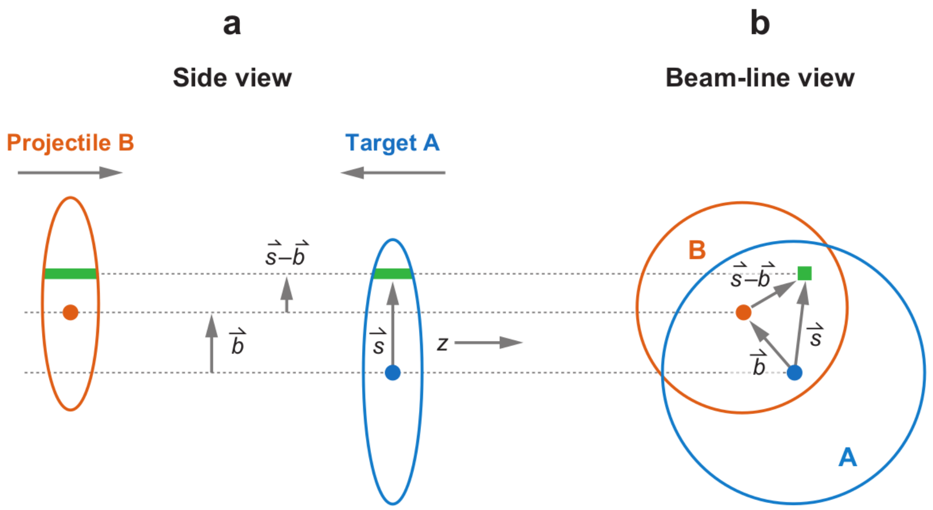
- No significant energy dependence of J/ψ R_{AA} for collision energies up to 200 GeV
  → Interplay between dissociation, regeneration and cold nuclear matter effects (X. Zhao, R. Rapp, PRC 82 (2010) 064905)
- Centrality dependence trend of ψ(2S)/J/ψ at RHIC seems to be more similar to that at SPS than at LHC

Glauber Model

- The probability per unit transverse area of a given nucleon being located in the target flux tube is $\hat{T}_A(\mathbf{s}) = \int \hat{\rho}_A(\mathbf{s}, z_A) dz_A$
- The thickness function or nuclear overlap function:

$$\hat{T}_{AB}(\mathbf{b}) = \int \hat{T}_A(\mathbf{s}) \hat{T}_B(\mathbf{s}-\mathbf{b}) d^2 s$$

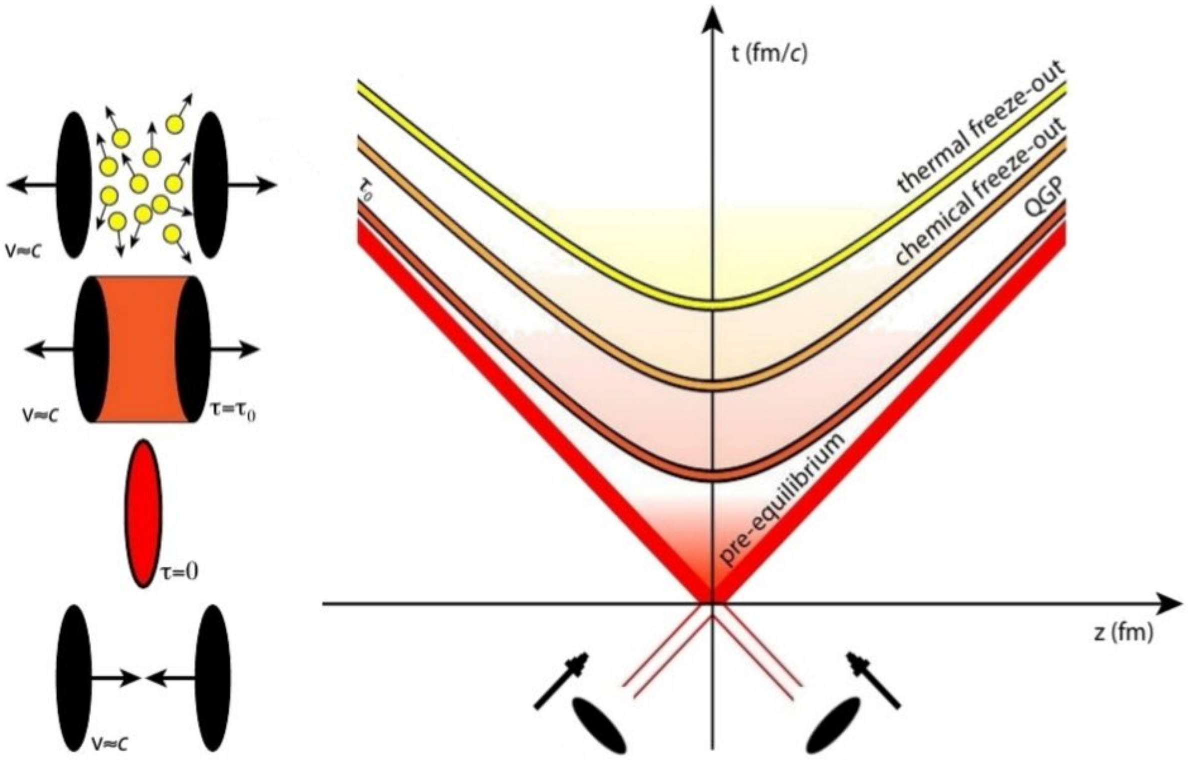
- The effective overlap area for which a specific nucleon in A can interact with a given nucleon in B. The probability of an interaction occurring is then $\hat{T}(\mathbf{b}) \sigma_{inel}^{NN}$
- σ_{inel}^{NN} is the inelastic nucleon-nucleon cross section.



- The probability of having n interactions between nuclei A (with A nucleons) and B (with B nucleons) is given as a binomial distribution: $P(n, \mathbf{b}) = \binom{AB}{n} \left[\hat{T}_{AB}(\mathbf{b}) \sigma_{inel}^{NN}\right]^n \left[1 - \hat{T}_{AB}(\mathbf{b}) \sigma_{inel}^{NN}\right]^{AB-n}$
- The total number of nucleon-nucleon collisions is: $N_{coll}(b) = \sum_{n=1}^{AB} n P(n, b) = AB \hat{T}_{AB}(b) \sigma_{inel}^{NN}$
- The number of participants at impact parameter b is given by:

$$N_{part}(\mathbf{b}) = A \int \hat{T}_A(\mathbf{s}) \left\{1 - \left[1 - \hat{T}_B(\mathbf{s}-\mathbf{b}) \sigma_{inel}^{NN}\right]^B\right\} d^2 s + B \int \hat{T}_B(\mathbf{s}-\mathbf{b}) \left\{1 - \left[1 - \hat{T}_A(\mathbf{s}) \sigma_{inel}^{NN}\right]^A\right\} d^2 s$$

Heavy-ion collision



M. Kleimant et. al.,
DOI 10.1007/978-3-642-02286-9_2

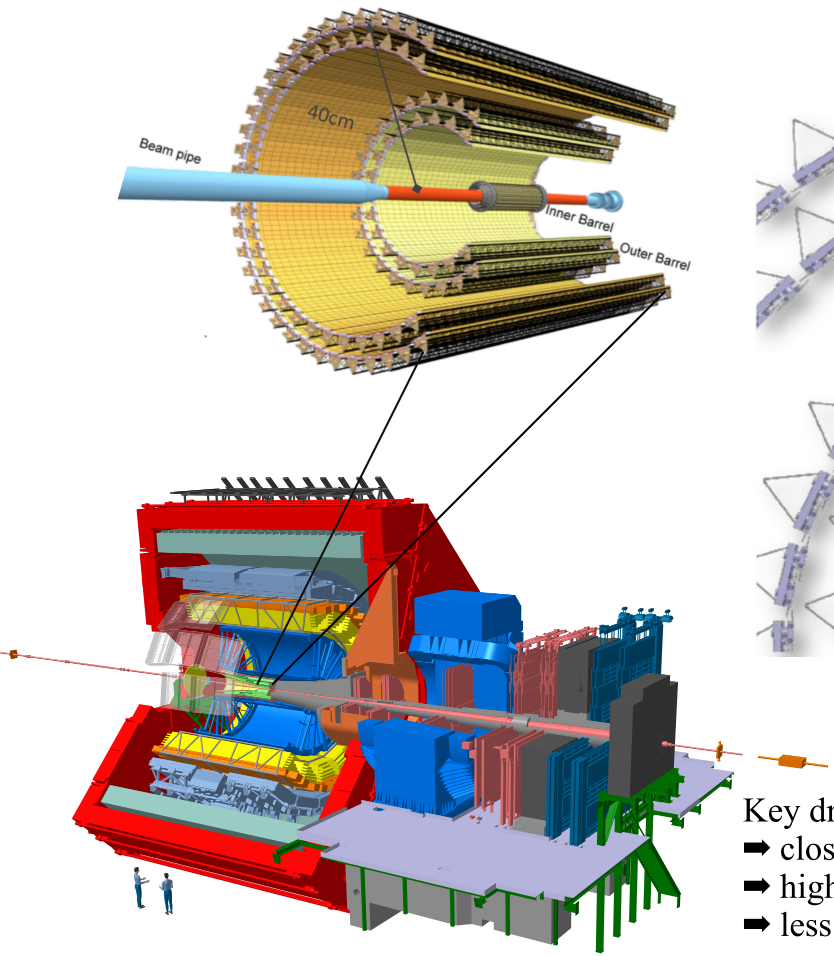
- Thermal freeze-out
  Elastic collisions stopped, kinetic distribution of produced particles get fixed.

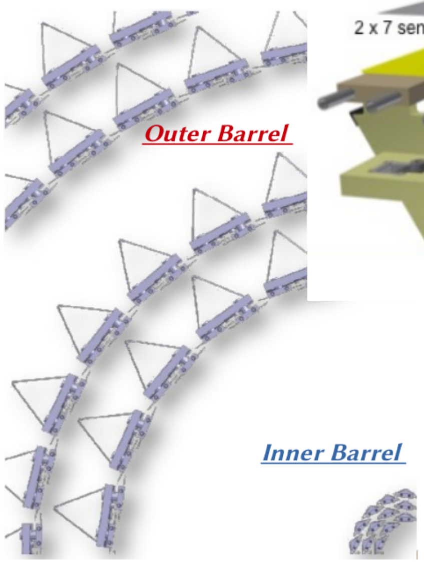
- Chemical freeze-out
  Hadronization. Inelastic collisions stopped, abundances and particle ratios become fixed.

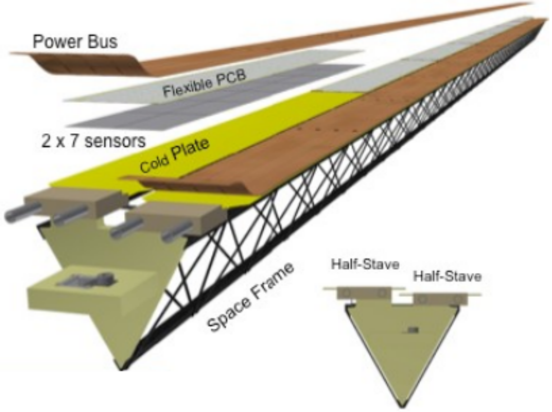
- QGP
  Thermal equilibrium at $\tau = \tau_0 \sim 1$ fm/c $\approx 3\times10^{-24}$ s
  Energy density ~ 10 GeV/fm^3
  Dimension ~ 300 fm^3
  T~ 550 MeV $\approx 5.5\times10^{12}$ K
  lifetime ~10 fm/c $\approx 3\times10^{-23}$ s at LHC.

- Pre-equilibrium
  Hard processes, creation of heavy $Q\bar{Q}$ pairs.
  Formation time of charm quark ~ 0.08 fm/c $\approx 3\times10^{-25}$ s.

ITS2: upgraded Inner Tracking System (ITS) of ALICE

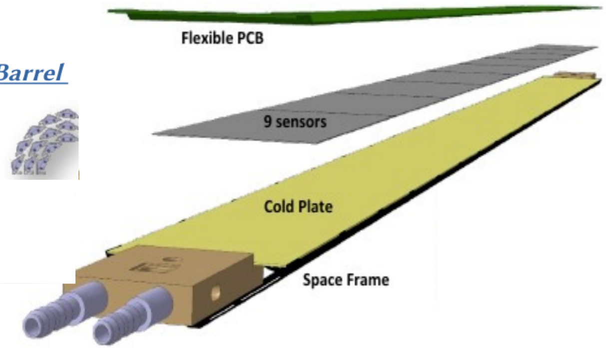






ALPIDE chip based on CMOS technology by TowerJazz

1 module = 2x7 chips
≈ 3 cm x 21 cm,
Up to 7 modules
To build half stave

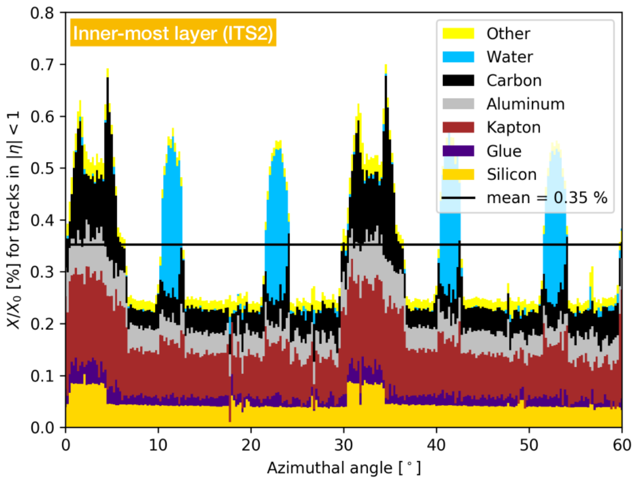


1 module
= 9 chips in a raw,
≈ 1.5 cm x 27 cm,
directly put on stave

Key drivers (vs "ITS1")

➡ closer to interaction: 2.3 cm (3.9 cm)
➡ higher intrinsic resolution: ~5 µm in rφ and z directions (12 and 100 µm)
➡ less material: ~0.35% X_0 (1.1% X_0)
➡ faster readout: 100 kHz Pb-Pb (1 kHz)

ITS3

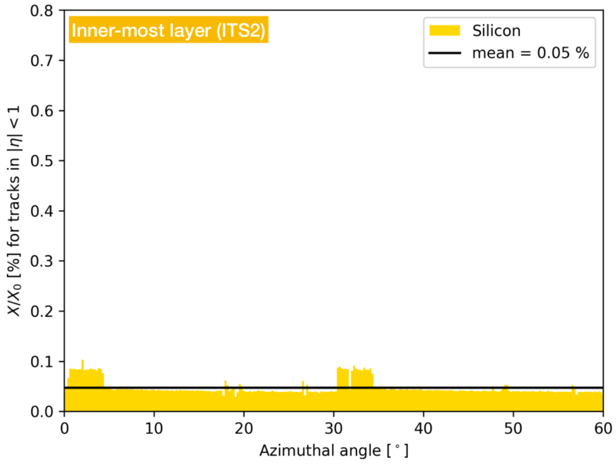


- ➡ Si only 1/7th of total material
- ➡ irregularities due to overlaps + support/cooling

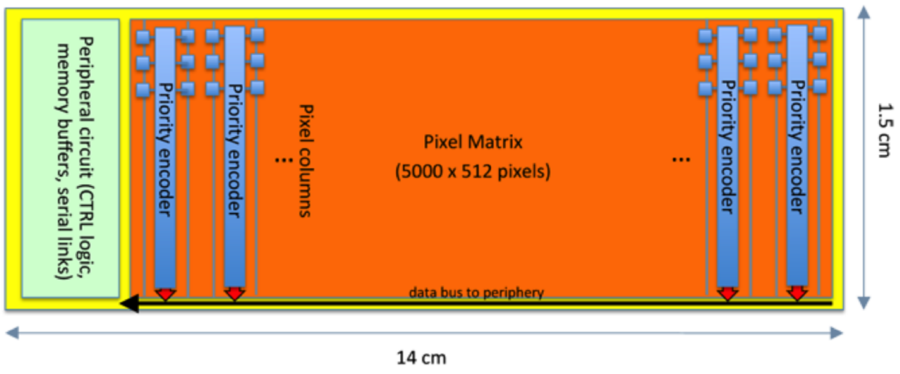
➡ remove water cooling
- ➡ possible by reducing power consumption in fiducial volume to <20 mW/cm²

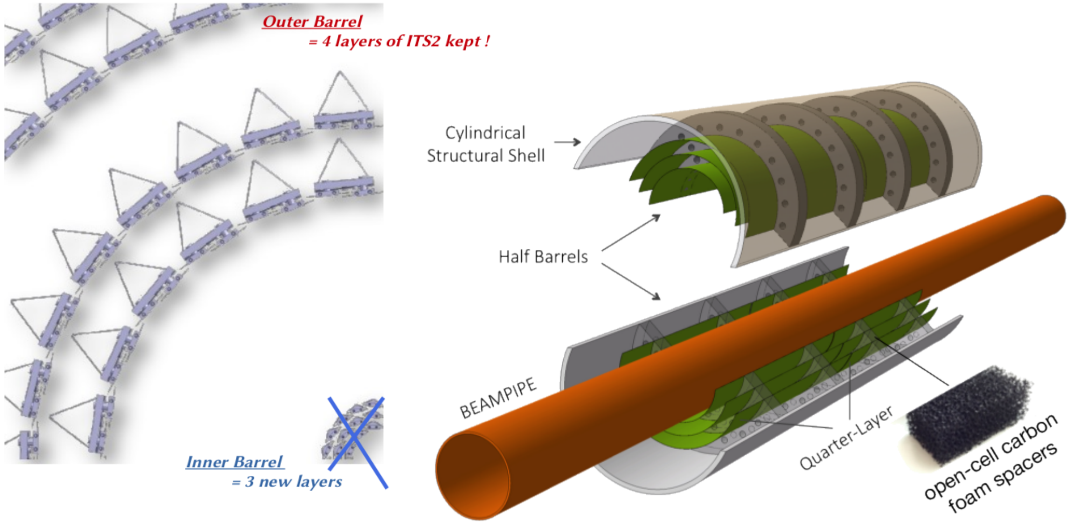
➡ remove external data lines + power distribution
- ➡ possible by making a single large chip and that for distribution

➡ move mechanical support outside acceptance
- ➡ benefit from increased stiffness by rolling Si wafers



1D stitched sensor (z direction)



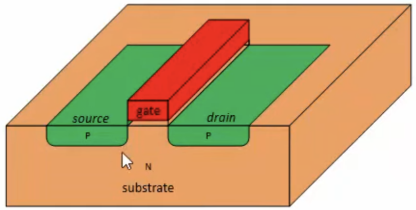


→ ultra-thin Si CMOS (20 µm thick)
→ circuitry pushed to periphery
→ can be curved

Complementary Metal-Oxide-Semiconductor (CMOS)

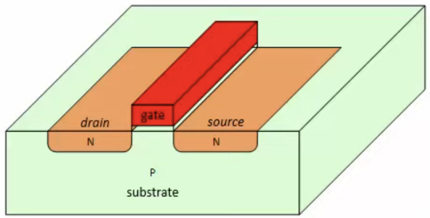
PMOS Transistor

- P-channel MOS transistor
- P-type source and drain, N-type substrate



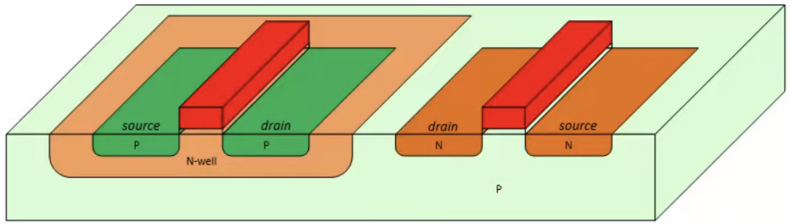
NMOS Transistor

- N-channel MOS transistor
- N-type source and drain, P-type substrate



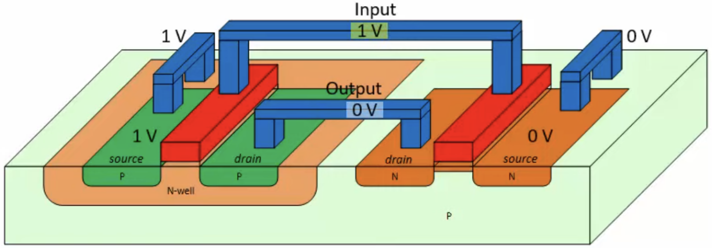
CMOS Technology

- *Complementary* MOS technology
- Both NMOS and PMOS transistors



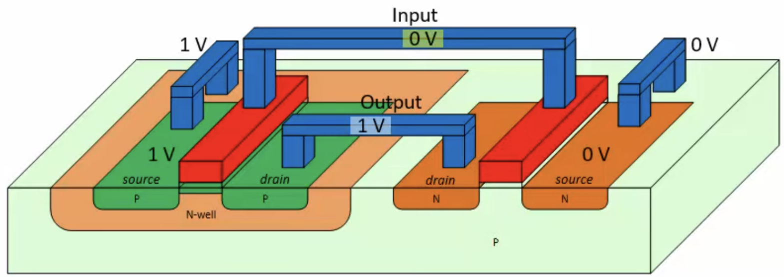
CMOS Technology: Inverter

- Input 1: PMOS off, NMOS on, output = 0

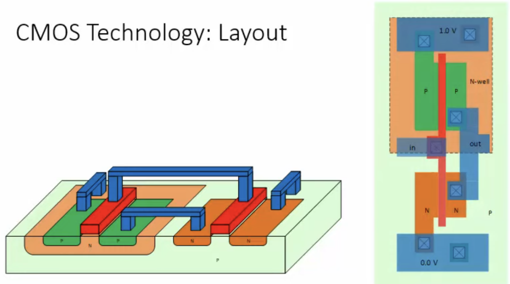


CMOS Technology: Inverter

- Input 0: PMOS on, NMOS off, output = 1



CMOS Technology: Layout



Inner Tracking System (ITS) of ALICE

	ITS1 (SPD = 2 inner)	ITS2 (3 inner)	ITS3 (3 inner)
Beam pipe inner radius/thickness	3.0 cm/0.09 cm	1.82/0.08 cm	1.6/0.05 cm
First-layer radius	3.9 cm	2.3 cm	1.8 cm
X/X° per layer	1.1 %	0.35 %	0.05%
|η| coverage	> 1.4	> 2.0	> 2.0
Number of Sensors per layer	80+160	108+144+180	2 to 4
Technology	Hybrid pixels	CMOS	CMOS
Trigger ?	yes	no	Not foreseen
Pixel size rφ x z	≈ 50x425 μm²	≈ 30x30 μm²	≈ 10x10 μm²
Intrinsic resolution rφ / z	12 μm / 100 μm	5 μm / 5 μm	3 μm / 3 μm
Readout frequency Pb-Pb	< 3 kHz > 300 ns (SPD)	< 50-100 kHz > 20-10 μs	≈ ≤ 200 kHz ≈ ≥ 5 μs
Power dissipation in the pixel matrix	≈ 550-736 mW/cm² i.e. liquid cooled	~40 mW/cm², i.e. liquid cooled	~7 mW/cm², i.e. air flow

Kinematic variables

For a particle with 4-momentum $p^\mu = p^\mu(E, p_x, p_y, p_z)$ the kinematic variables are defined as:

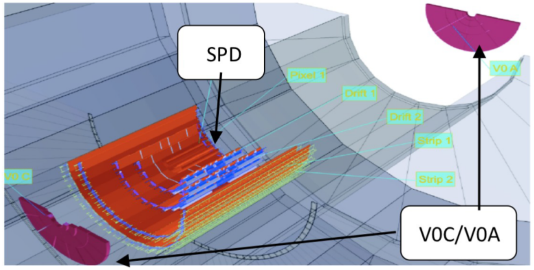
- Transverse momentum: $p_\mathrm{T} = \sqrt{p_x^2 + p_y^2}$
- Rapidity: $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$
- Pseudorapidity: $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] = \frac{1}{2}\ln\left(\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z}\right)$

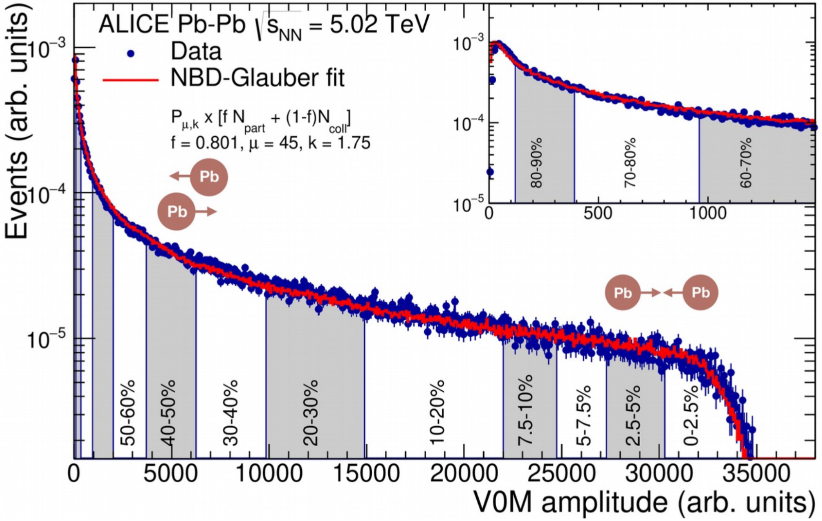
  For a particle with the momentum very large compared to its rest mass $y \approx \eta$

- Center-of-mass energy: $\sqrt{s_\mathrm{NN}} \simeq 2E\sqrt{\frac{Z_1 Z_2}{A_1 A_2}}$

  Example: for Pb-Pb collisions, $Z_1 = Z_2 = 82$, $A_1 = A_2 = 208$, and the energy of the proton beam E = 6.37 TeV, therefore $\sqrt{s_{NN}}$ = 5.02 TeV.

- Centrality estimation:
  Estimated based on a Glauber model fit of the V0M amplitude.





PRL. 116, 222302 (2016)