Quarkonium polarization at the LHC energies with ALICE

Seminario de Física de Altas Energías

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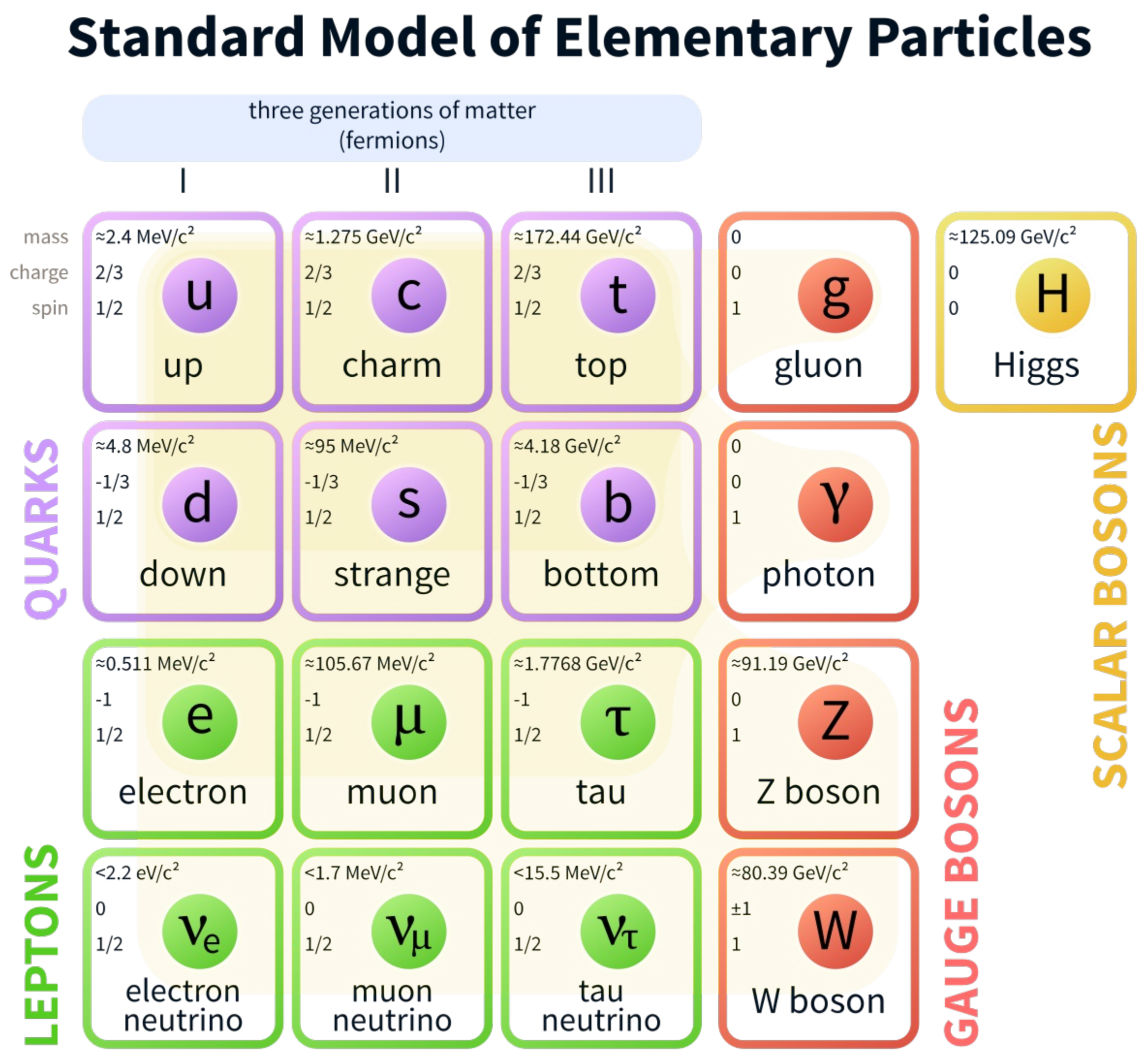
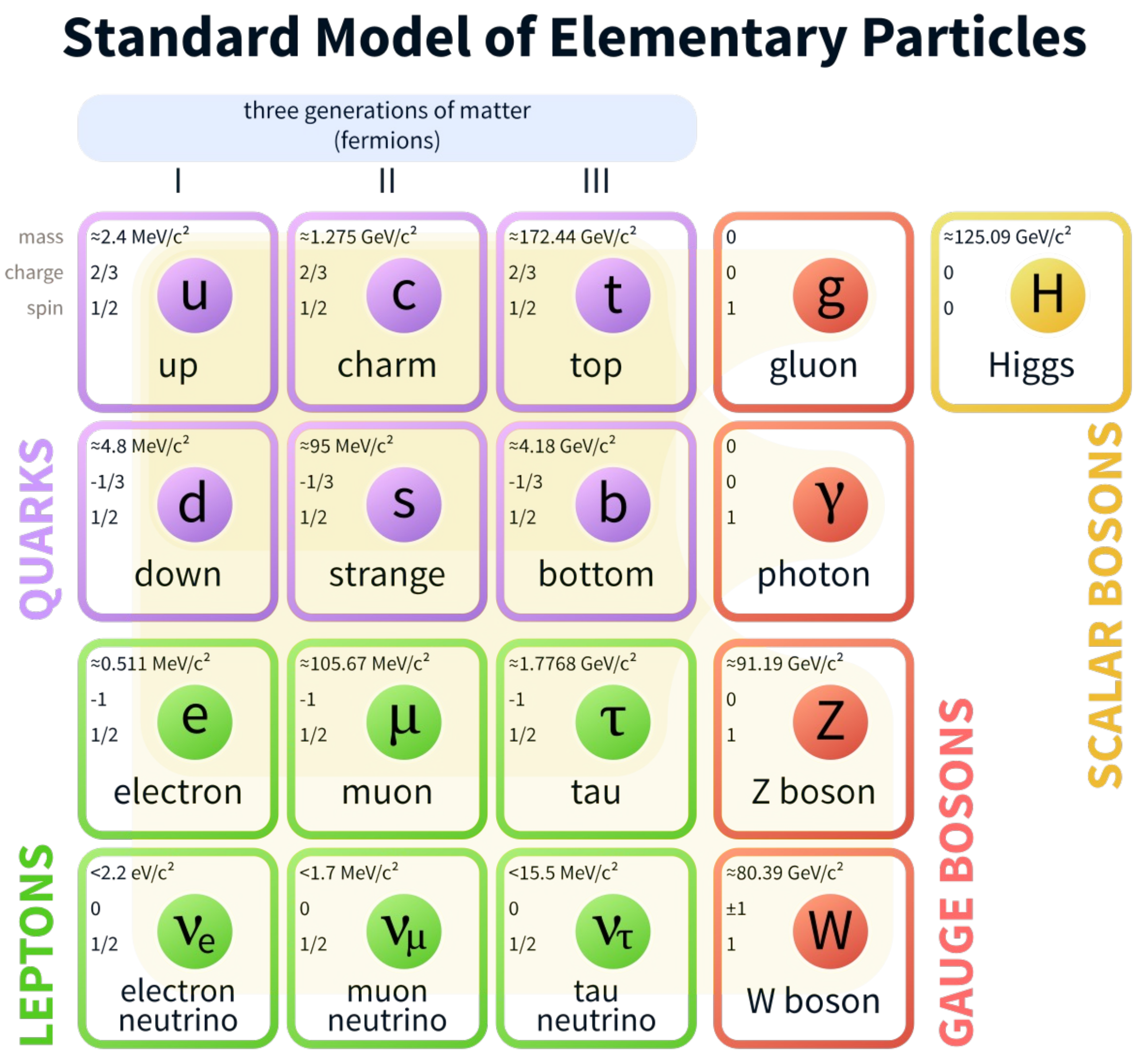
Introduction:



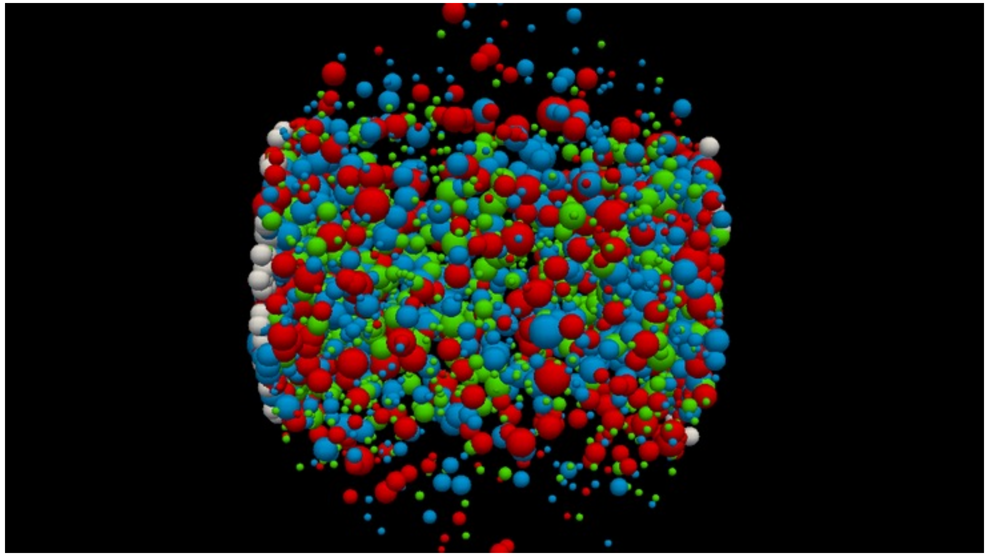
http://cms.web.cern.ch/news/what-do-we-already-know

Introduction:

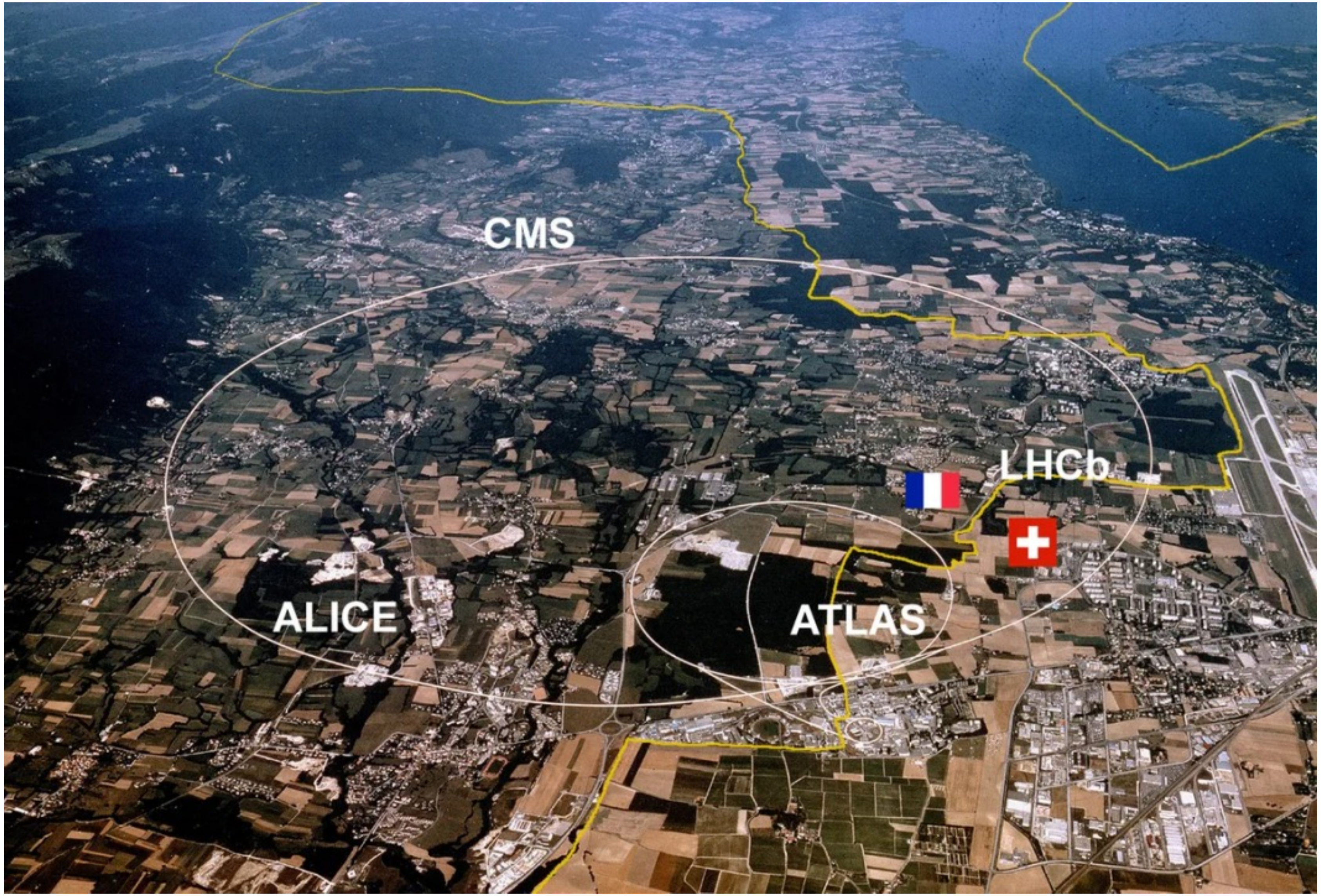


http://cms.web.cern.ch/news/what-do-we-already-know

- Quarks and gluons interact strongly
- QCD is the governing theory
- At very high energies/densities, hadrons become deconfined
- Quark-Gluon Plasma (QGP)



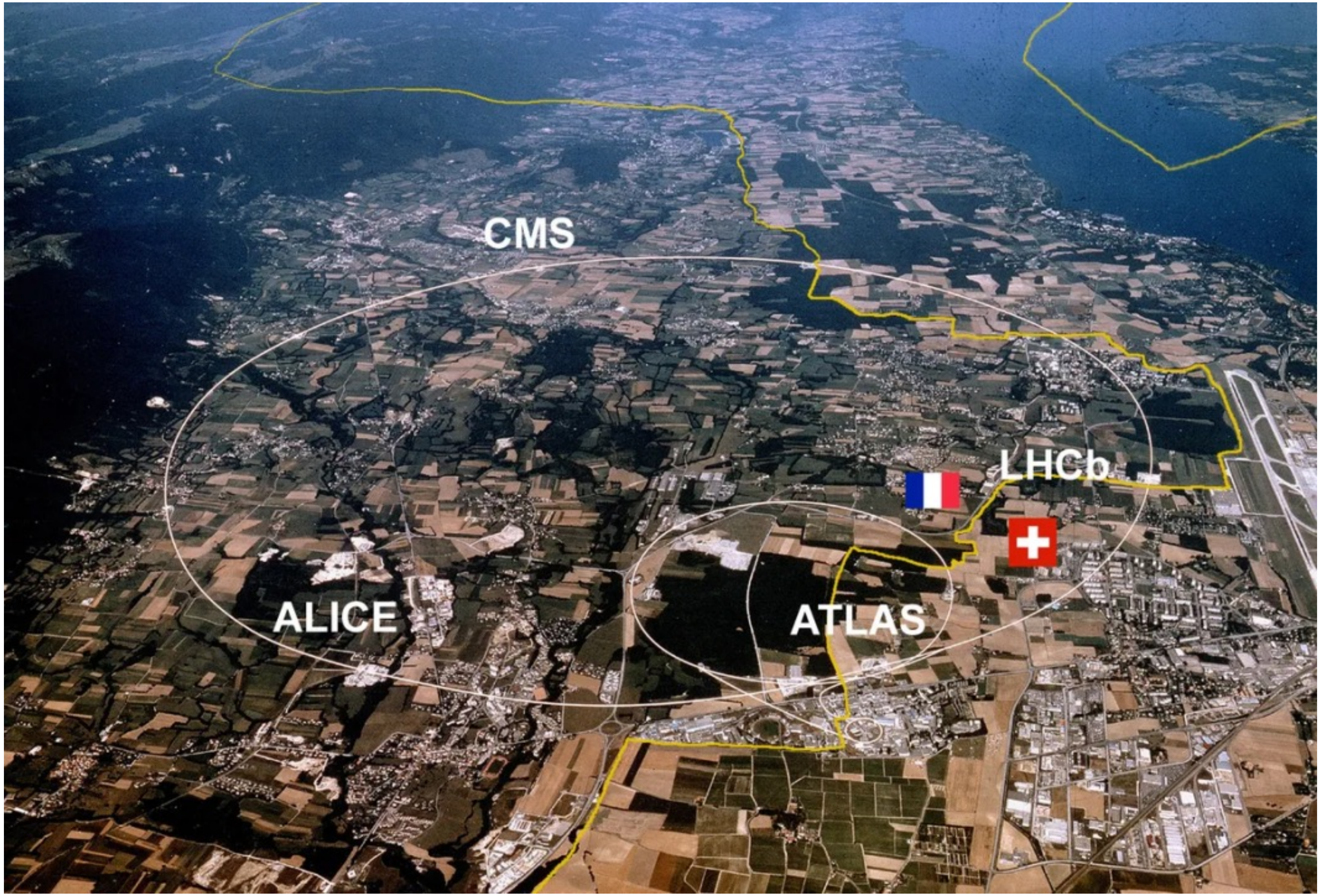
The Large Hadron Collider



Four main experiments at CERN:

- ATLAS
- **ALICE**
- CMS
- LHCb

The Large Hadron Collider



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PWG-DQ
(Dileptons and Quarkonia)

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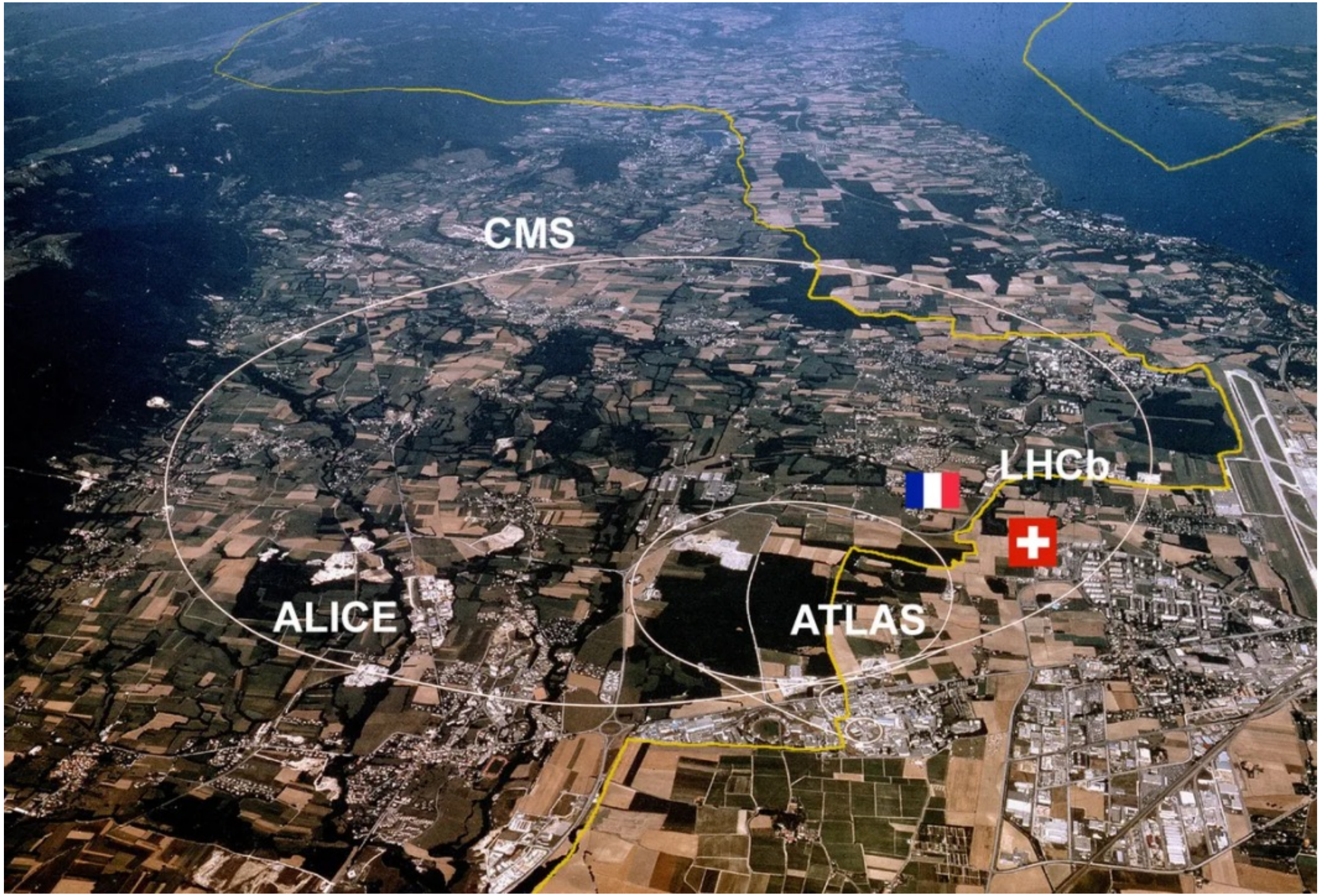

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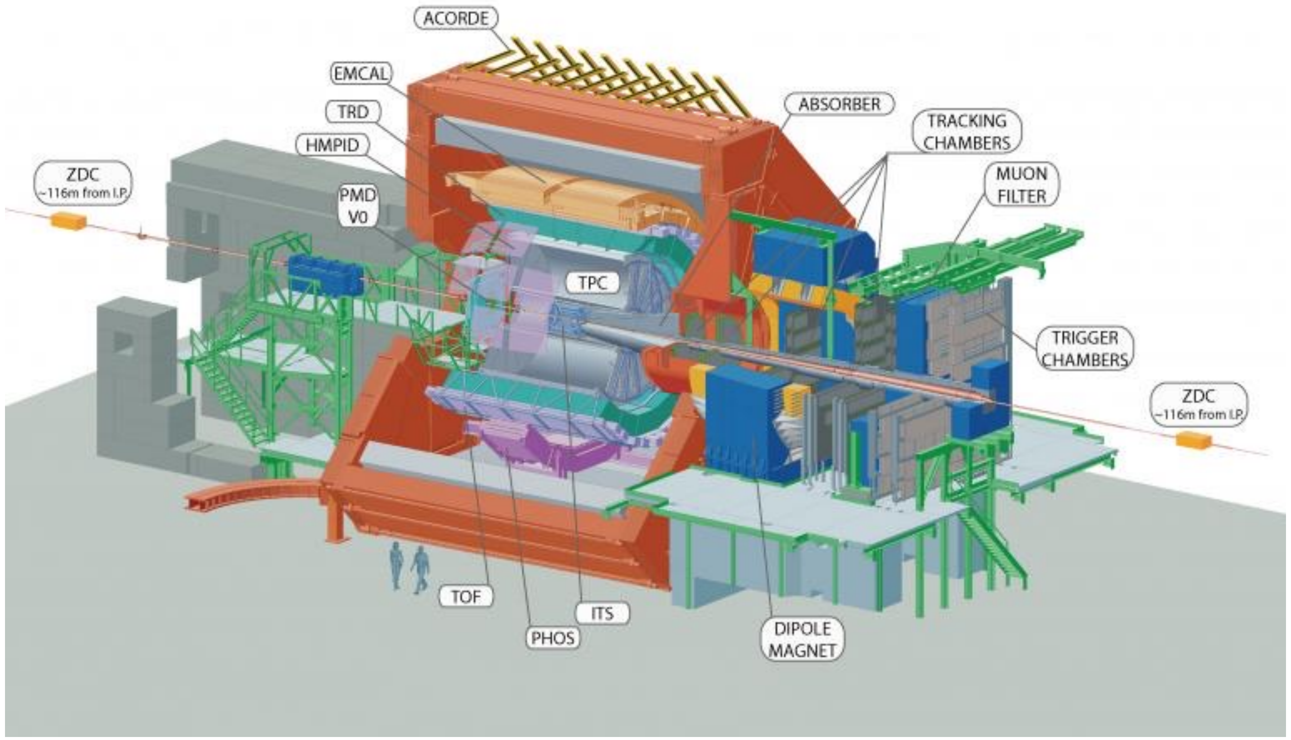
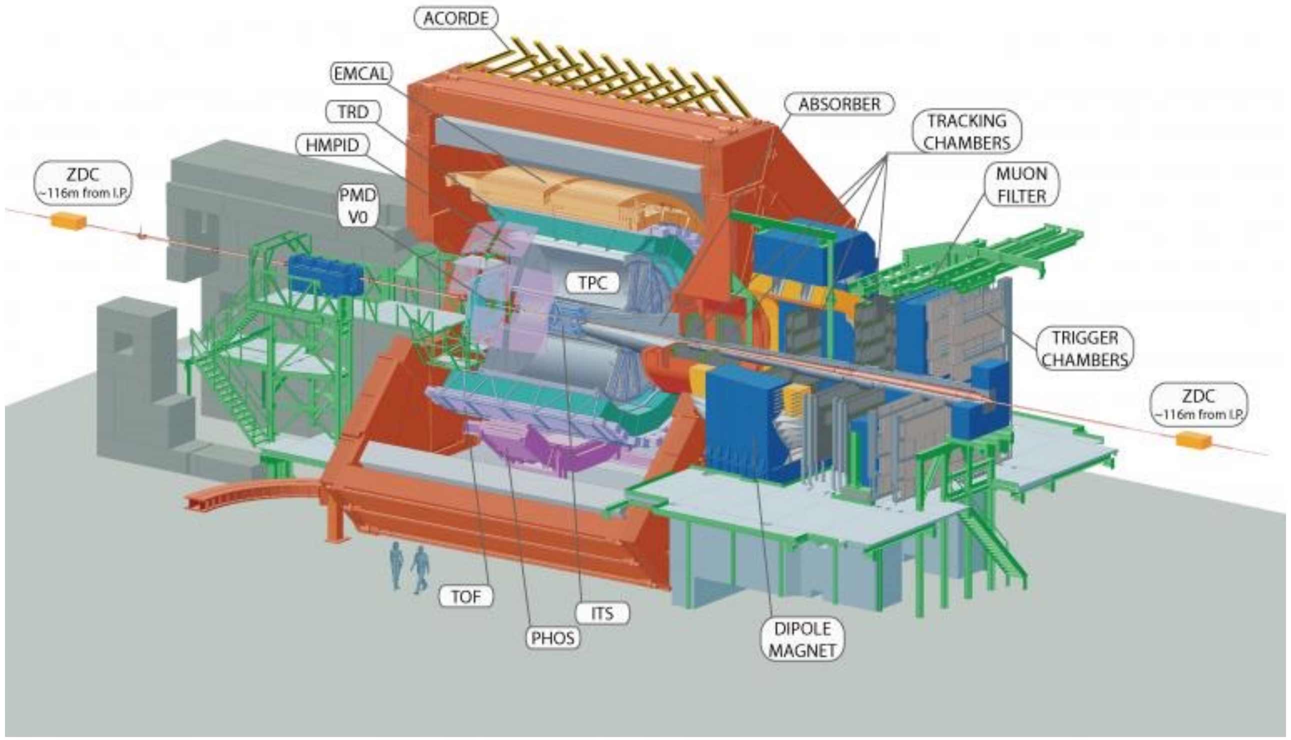
PWG-DQ
(Dileptons and Quarkonia)

JPsi2ee	**QQ2MuMu**
$J/\psi \rightarrow e^+e^-$	$J/\psi \rightarrow \mu^+\mu^-$

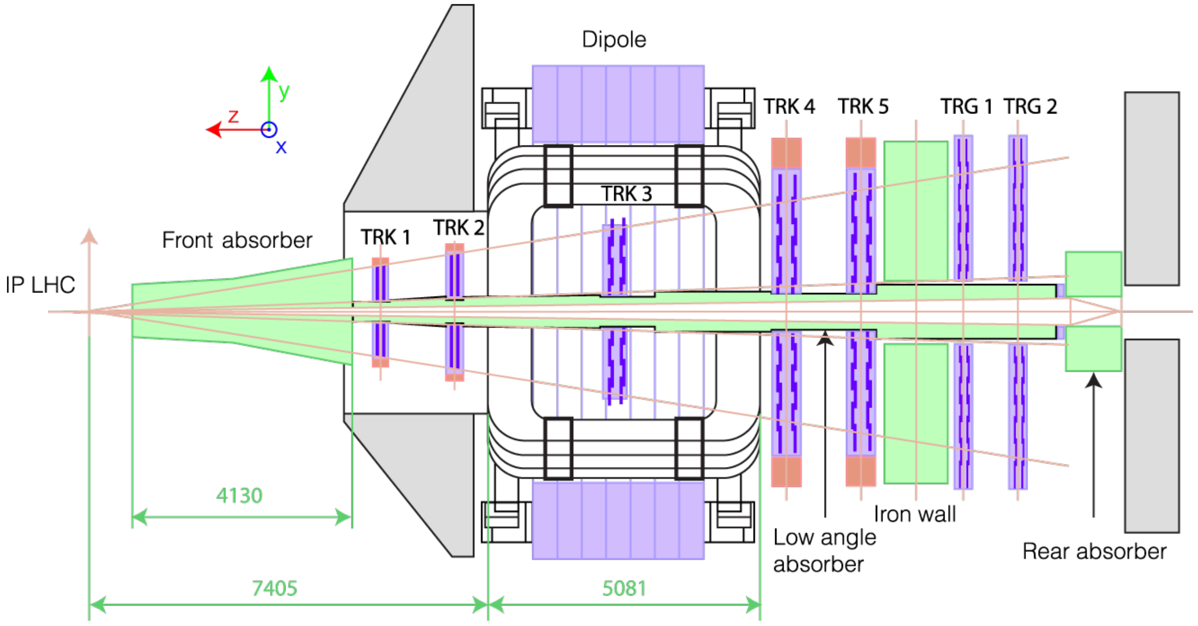
ALICE detector (Run 2)



ALICE detector (Run 2)



[ALICE Muon spectrometer]



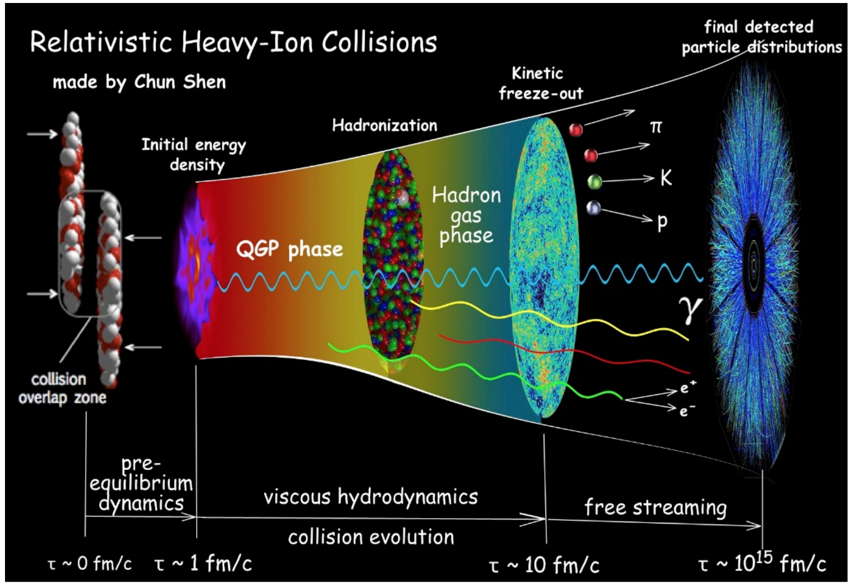
- Dedicated to the study of quarkonium decaying to dimuons
- Muon spectrometer acceptance -2.5 $< \eta <$ -4.0 corresponding to $2^0 < \theta < 9^0$

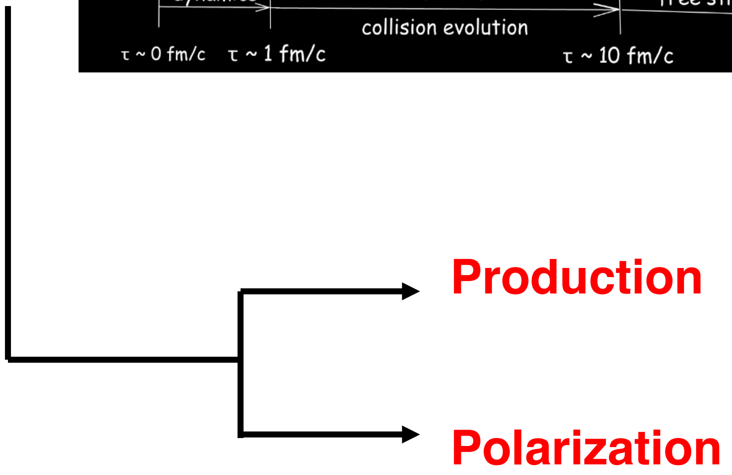
Measurements from Run 2 datasets

- pp : $\sqrt{s}$ = 13 TeV
- Pb-Pb : $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

Quark Gluon Plasma

- What is quark—gluon plasma (QGP)?
  - Deconfined thermalized state of quarks and gluons
  - Shows collectivity
  - Formed at extremely high temperature and energy density
- ALICE detector at CERN is devoted to the characterization of the QGP
- Governing theory of strong ineraction: Quantum Chromodynamics (QCD)





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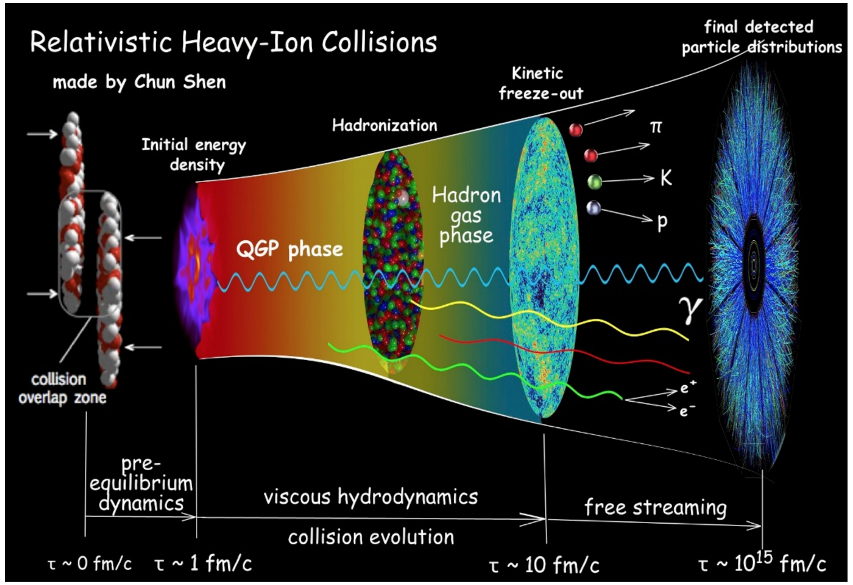
- ALICE detector at CERN is devoted to the characterization of the QGP
- Governing theory of strong ineraction: Quantum Chromodynamics (QCD)
- Several signatures of QGP have been observed in heavy-ion collisions
  - Strangeness enhancement
  - Quarkonium (heavy quark-antiquark bound state) suppression
  - Formation of ridge-like structures as an indication of collectivity
  - Jet quenching



Production

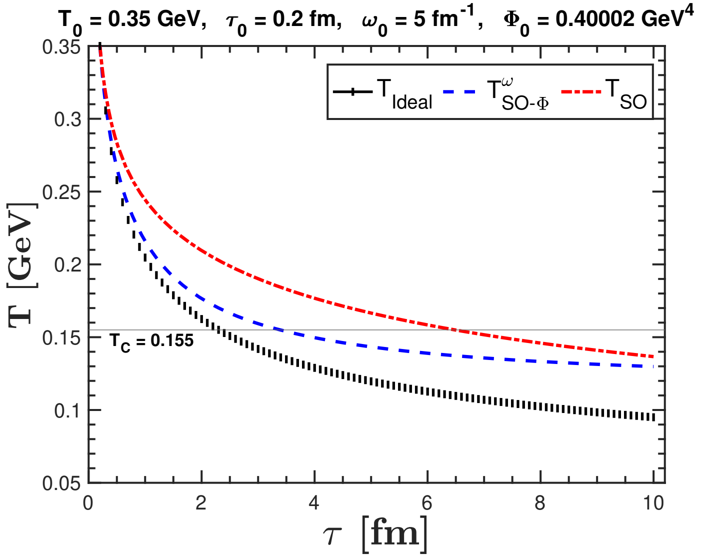
Polarization

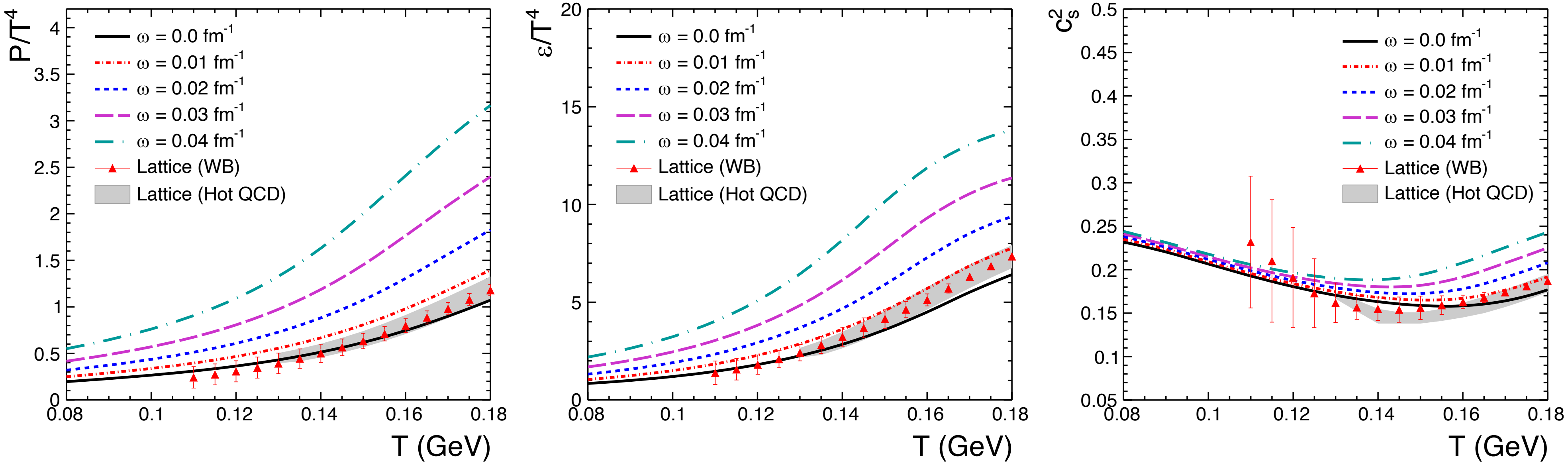
Vorticity in heavy-ion collisions

- The fundamental Euler's thermodynamic equation gets modified in the presence of finite rotation, adding a new Rotational Chemical Potential:

$$\varepsilon + P = sT + n\mu + W\omega$$

- Modifies the evolution of the fireball
- Thermodynamic and transport properties get changed
- Is the main cause of polarization in heavy-ion systems



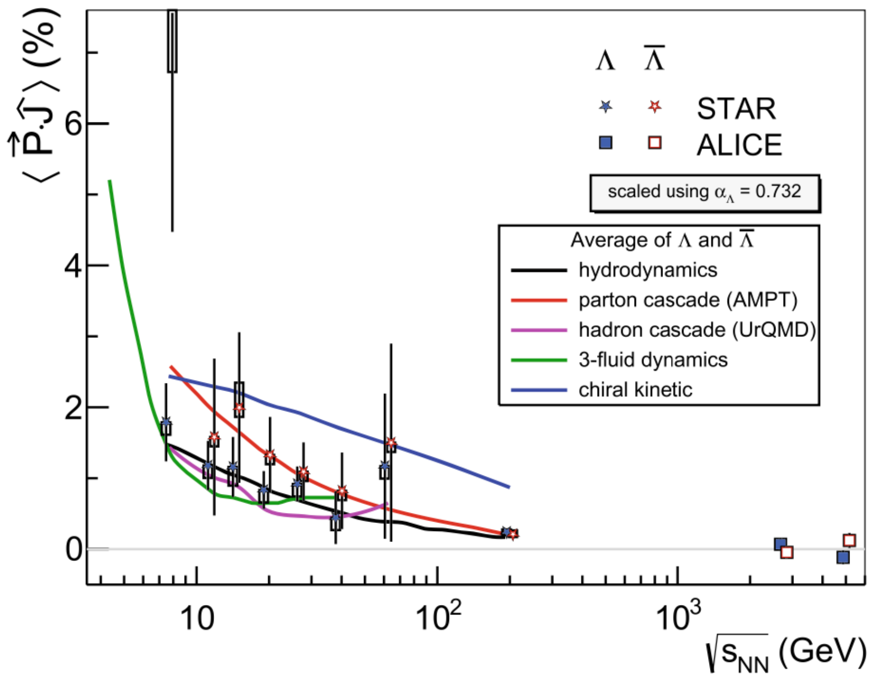


[B. Sahoo, C. R. Singh, D. Sahu, R. Sahoo and J. e. Alam, Eur. Phys. J. C 83, 873 (2023)]

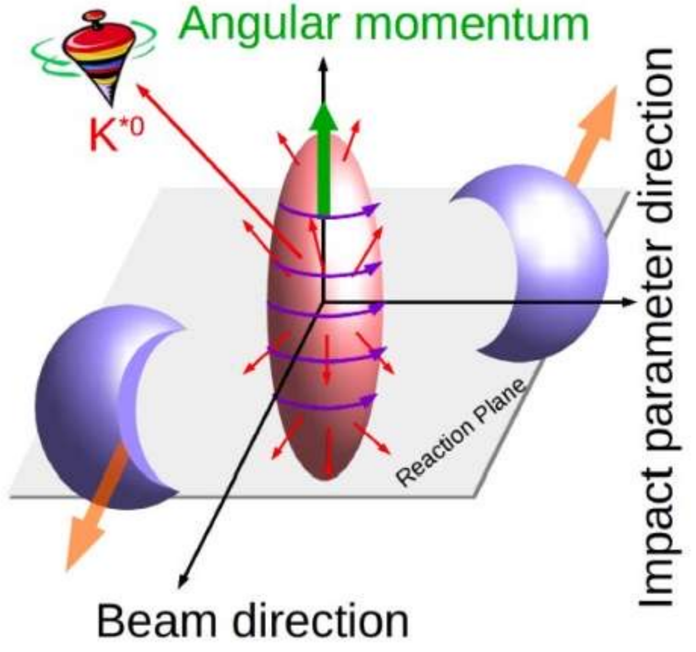
[K. K. Pradhan, B. Sahoo, D. Sahu and R. Sahoo, Eur. Phys. J. C 84, 936 (2024)]

Polarization

- ✓ Polarization is the measure of how much the spin of a particle is aligned in a given direction
- ✓ Polarization from vorticity and other sources
- ✓ Spin-angular momentum coupling requires thermalization in the medium
- ✓ Λ – hyperon and vector meson polarization in heavy-ion collisions
- ✓ Polarization as a second-generation QGP signature

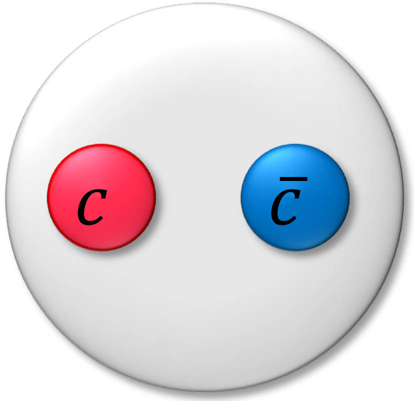


[Ann. Rev. Nucl. Part. Sci. **70**, 395 (2020)]
[STAR Collaboration, Nature **548**, 62 (2017)]



Charmonia

- Why charmonia (J/ψ , ψ(2S), etc.)?
  - Charm and anti-charm quarks produced early in the system's evolution : during the pre-equilibrium phase
  - J/ψ remains largely undiffused in the hadronic phase
  - Provide powerful tests of quantum chromodynamics (QCD)



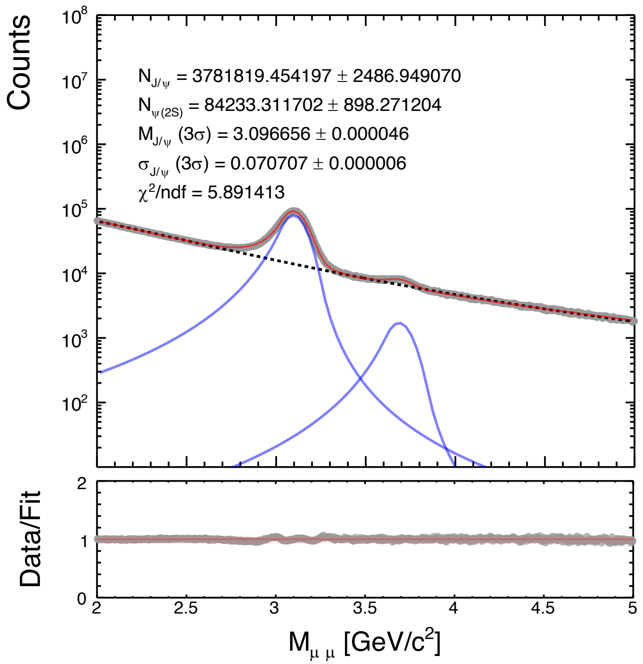
Mass: 3.1 GeV/c^2

Spin: 1

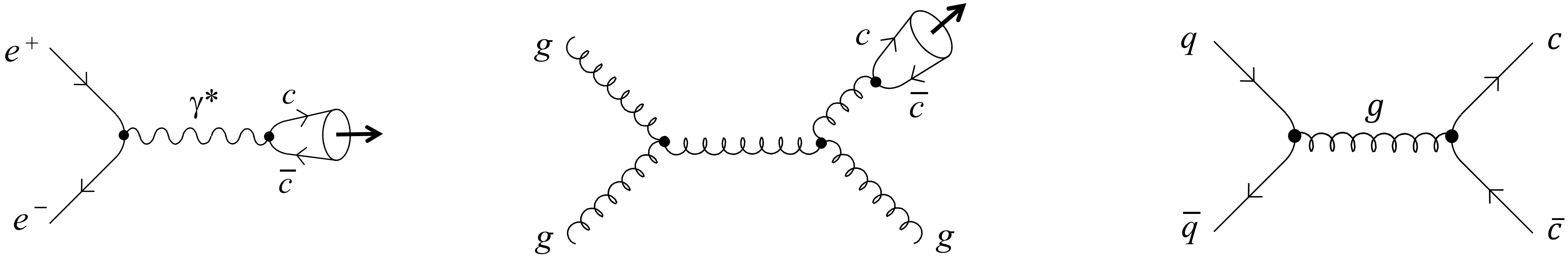
Lifetime: 7.2x10^{-21}s

~ 2000 fm/c

- Polarization in pp collisions:
  - Polarization is the measure of how much the spin of a particle is aligned in a given direction
  - In two-body decays, the spin-alignment will be reflected in the angular distribution of the decay particles



Polarization

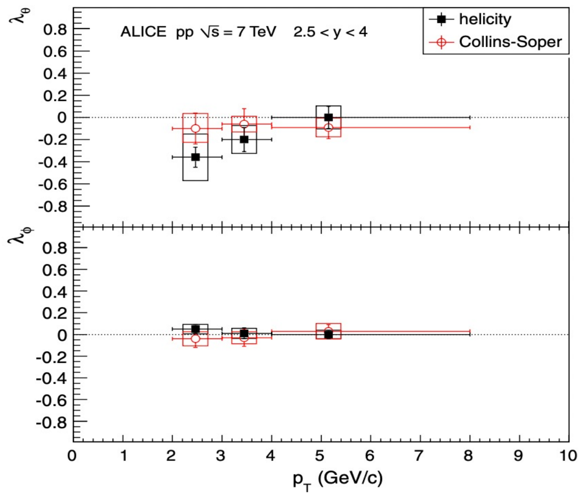


- $h = \frac{S.p}{|p|}$ → Helicity operator
- Vector ($J^{PC} = 1^{--}$) quarkonia have the same charge-parity as an electron-positron pair and can be produced in electron-positron annihilation via an intermediate photon
- The states originating from this process are polarized, as a consequence of helicity conservation, a general property of QED (QCD) in the relativistic (massless) limit
- For our case, gluon fragmentation dominates the high p_T region, while Drell-Yan process dominates the low p_T region

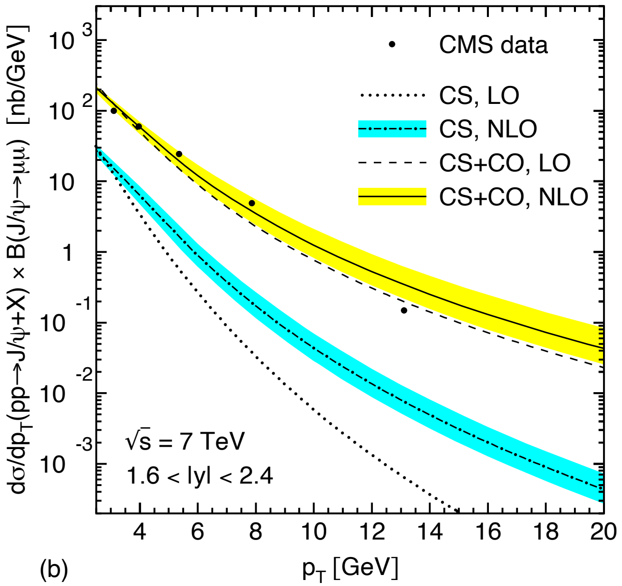
Polarization puzzle

J/ψ polarization puzzle ?

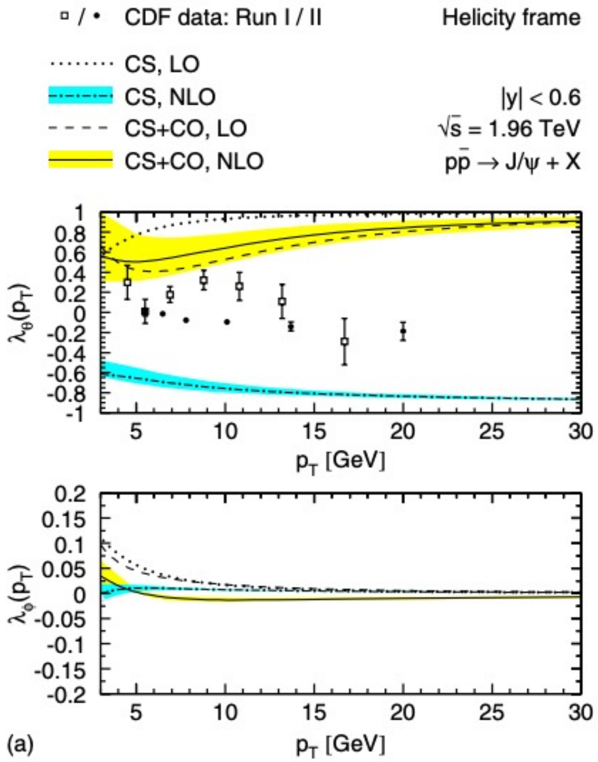
- Measurements of polarization parameters from Tevatron, RHIC and LHC show almost no J/ψ polarization in hadronic collisions
- Conflicting theoretical results from non-relativistic quantum chromodynamics (NRQCD) and Color Singlet Model
- NRQCD explains the production, but not the polarization



[ALICE Collaboration, Phys. Rev. Lett. 108, 082001 (2012)]



[Phys. Rev. Lett. 106, 022003 (2011)]

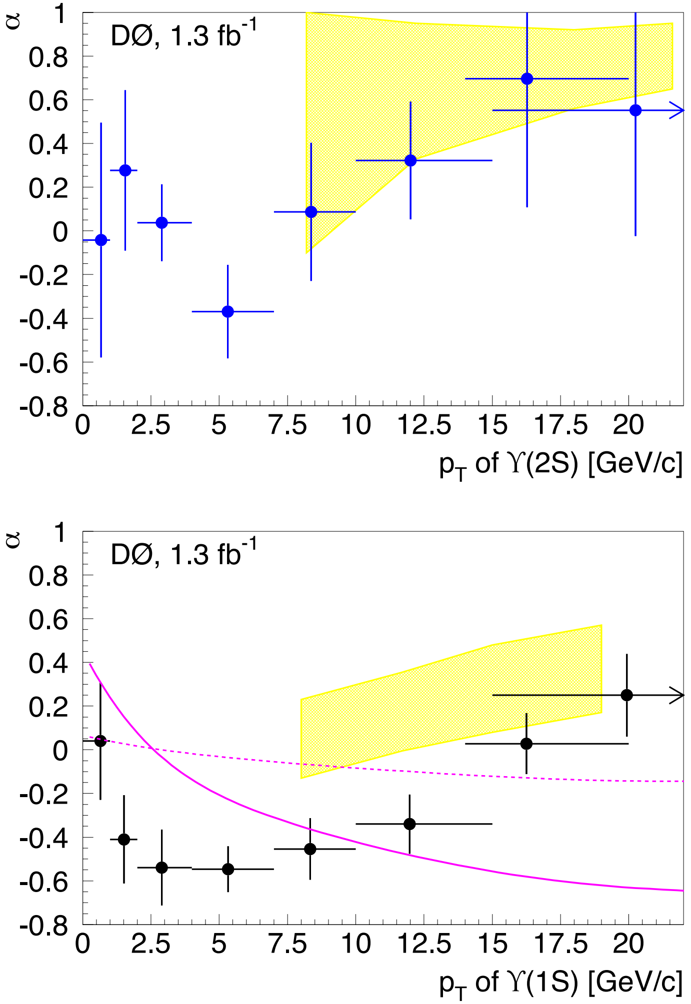


[Phys. Rev. Lett. 108, 172002 (2012)]

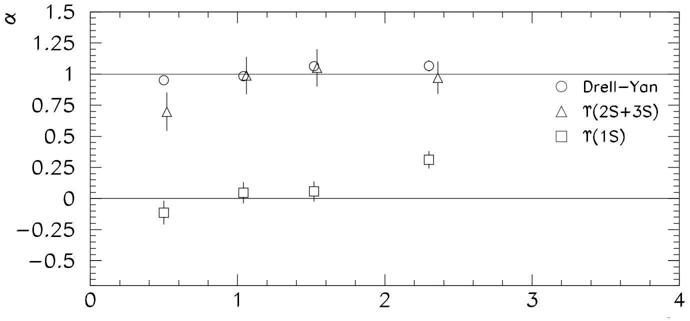
Polarization

Importance of Υ(nS) polarization study :

- $b\bar{b}$ system satisfies the non-relativistic calculations at high p_T much better than the $c\bar{c}$
- Better probe for QCD
- Results from Tevatron show almost no (CDF) or longitudinal polarization for $\Upsilon(1S)$ (D0)
- At lower energy and p_T , the E866 experiment has shown yet a different polarization pattern: the $\Upsilon(2S)$ and $\Upsilon(3S)$ states have maximal transverse polarization
- Unexpectedly, the $\Upsilon(1S)$ found to be only weakly polarized

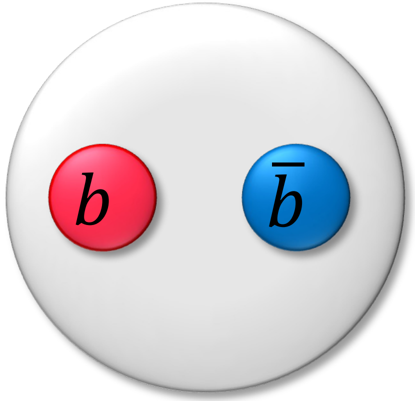


[DΦ Collaboration, Phys. Rev. Lett. 101, 182004 (2008)]



[NuSea Collaboration, Phys. Rev. Lett. 86, 2529 (2001)]

[CDF Collaboration, Phys. Rev. Lett. 88, 161802 (2002)]

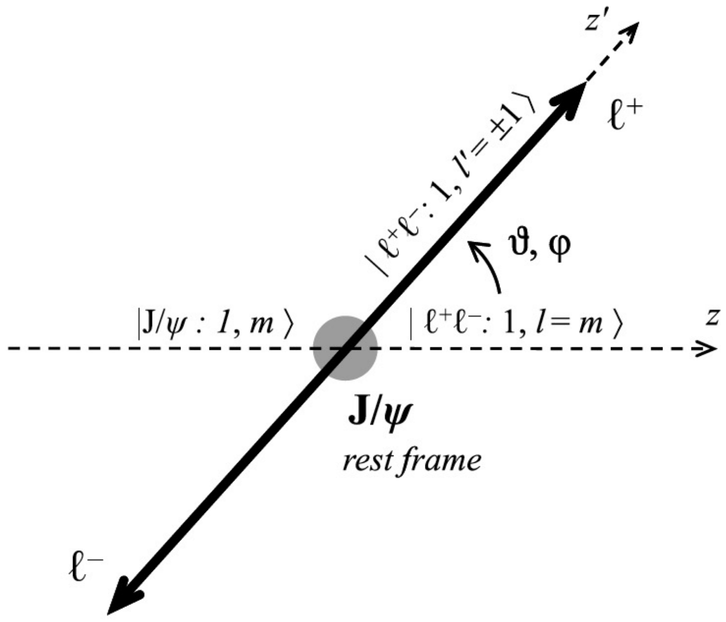


Polarization

- The angular distribution in dilepton decay:

$$\frac{d^2N}{dcos\theta\ d\phi} = \frac{3}{4\pi(3+\lambda_\theta)}(1+\lambda_\theta\ cos^2\theta + \lambda_\phi\ sin^2\theta\ cos2\phi + \lambda_{\theta\phi}\ sin2\theta\ cos\phi)$$

[P.Faccioli, et. al., Eur. Phys. J. C 69, 657 (2010)]



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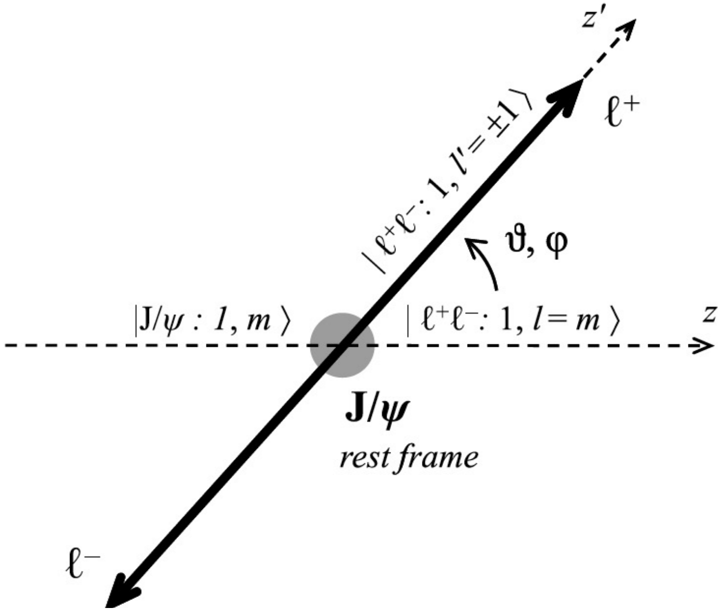
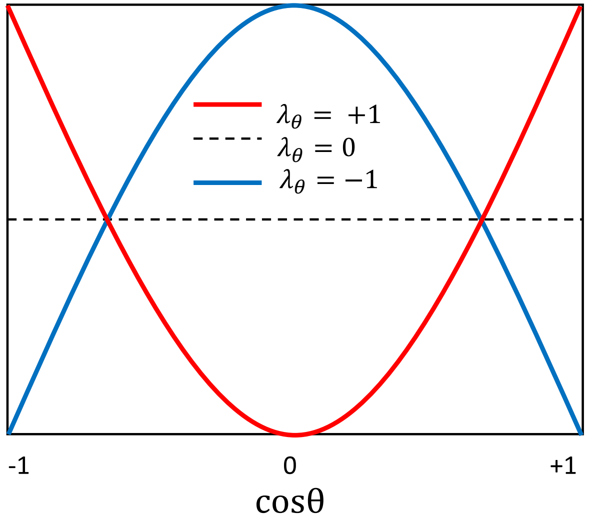


$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (1, 0, 0)$ ⟶ Transverse polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1, 0, 0)$ ⟶ Longitudinal polarization

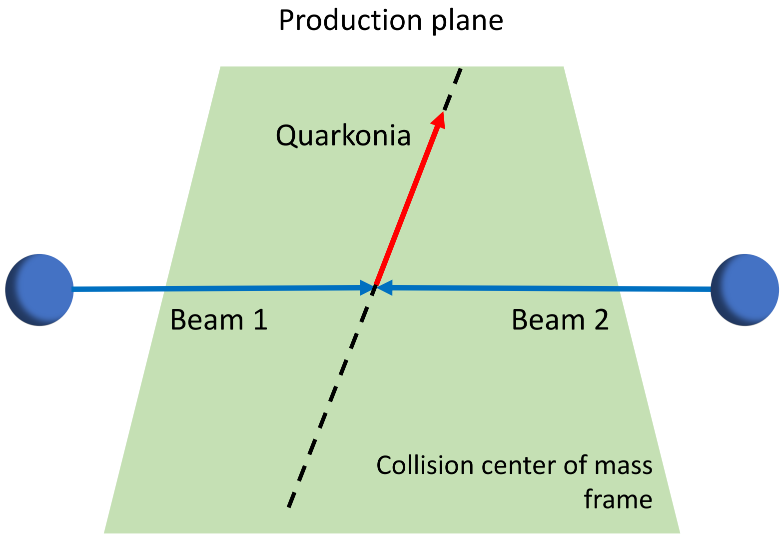
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0, 0, 0)$ ⟶ Unpolarized state

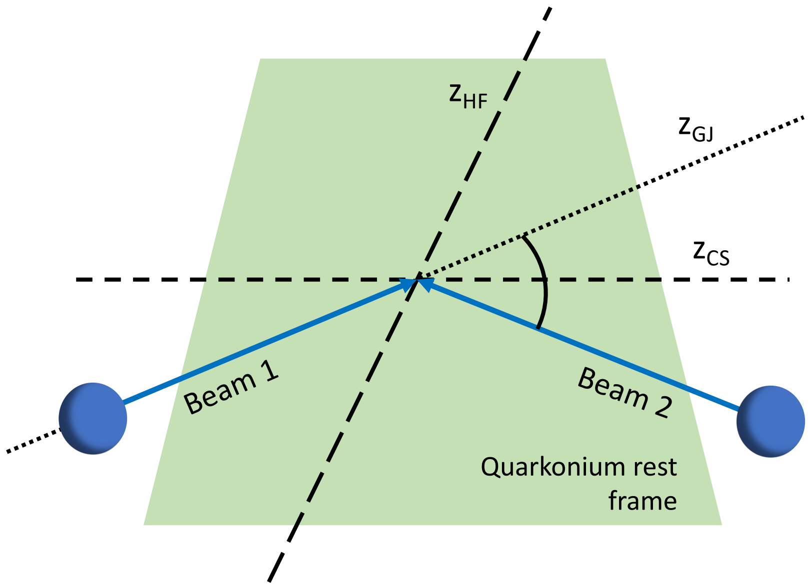


Polarization

Frames of reference

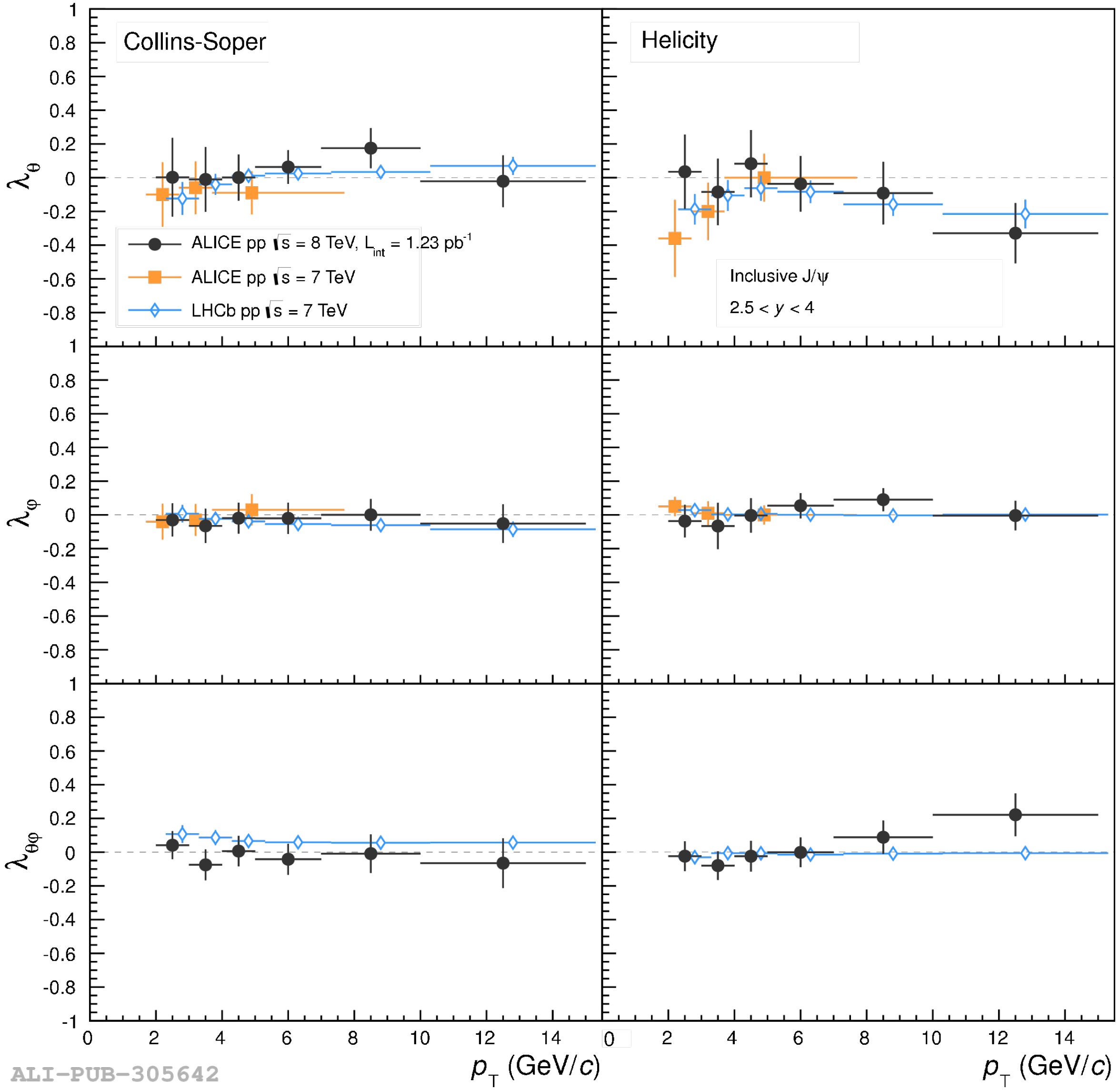
- The helicity frame uses the $\psi(2S)$ momentum as the quantization axis
- In the Collins–Soper frame, the quantization axis is chosen to be the bisector of the angle between the two incoming beams in the rest frame of the $\psi(2S)$ meson





[B. Sahoo, **D. Sahu,** S. Deb, C. R. Singh and R. Sahoo, Phys. Rev. C 109, 034910 (2024)]

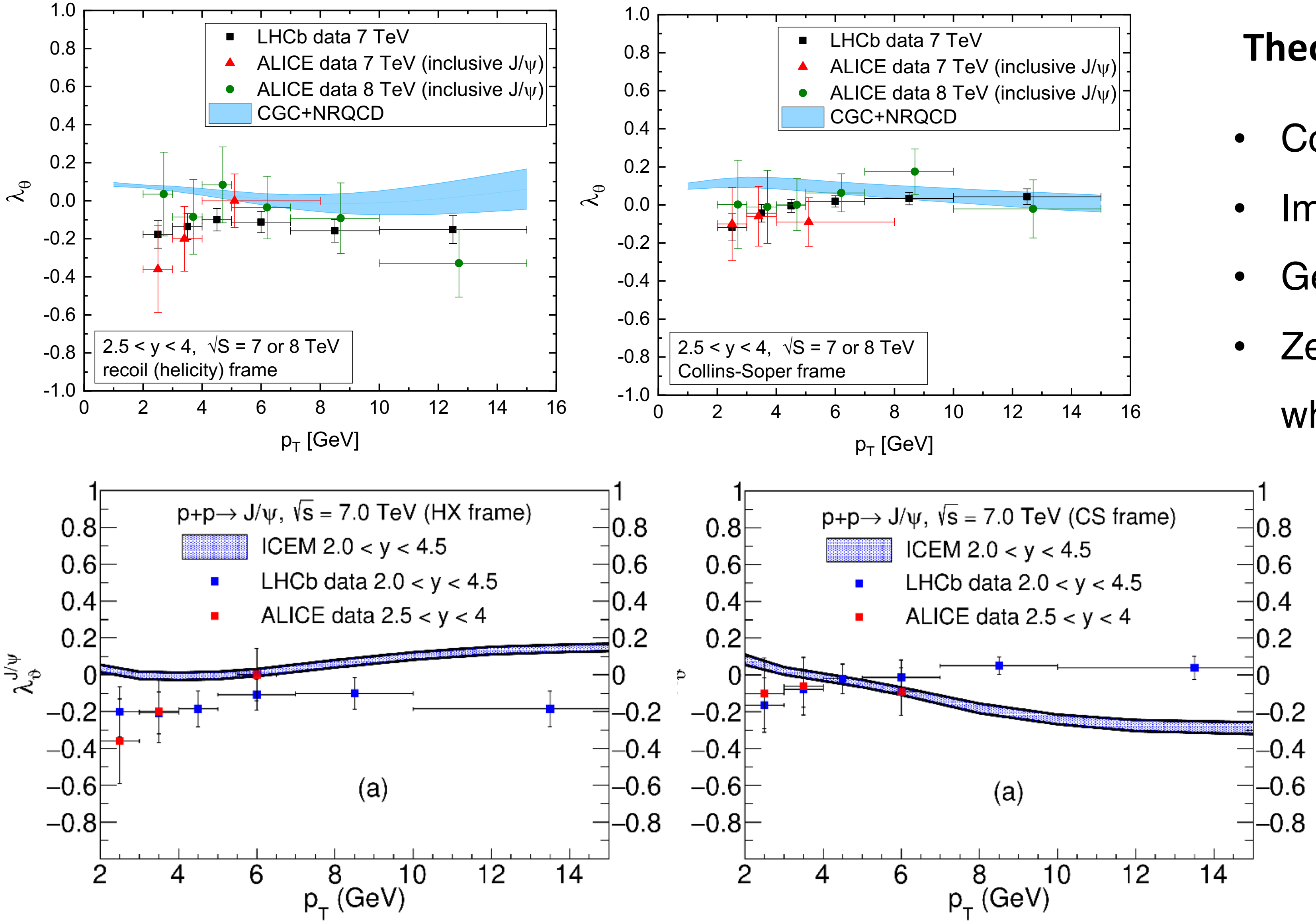
Quarkonium polarization in pp collisions



- J/ψ polarization measured in pp collisions in the CS and HE frames
- Dataset : ALICE $\sqrt{s}$ = 7 TeV (2010)
  ALICE $\sqrt{s}$ = 8 TeV (2012)
  LHCb $\sqrt{s}$ = 7 TeV (2011)
- No significant polarisation observed by ALICE and LHCb at forward rapidity
- Need for studies with higher center of mass energies
  - ✓ New ongoing analyses of J/ψ and ψ(2S) in pp collisions at $\sqrt{s}$ = 13 TeV

ALICE Collaboration, Phys. Rev. Lett. 108, 082001 (2012)
ALICE Collaboration, Eur. Phys. J. C 78, 562 (2018)
LHCb Collaboration, Eur. Phys. J. C 73, 2631 (2013)

Quarkonium polarization in pp collisions



Theoretical comparison:

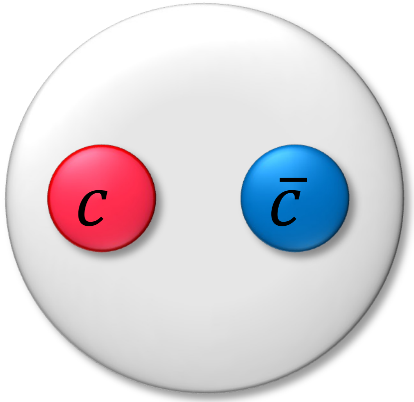
- Color Glass Condensate + NRQCD
- Improved Color Evaporation Model (ICEM)
- General agreement between predictions
- Zero or small polarization predicted in the whole transverse momentum range

JHEP 12, 057 (2018)
Phys. Rev. D 104, 094026 (2021)

Quarkonium polarization in pp collisions

Importance of ψ(2S) polarization study :

- ψ(2S) is a resonance state of J/ψ
- A small prompt J/ψ polarization can be interpreted as reflecting a mixture of directly produced mesons with those produced in the decays of heavier (P-wave) charmonium states
- ψ(2S) is unaffected by feed-down decays from heavier charmonia
- Clean polarization signal from ψ(2S)

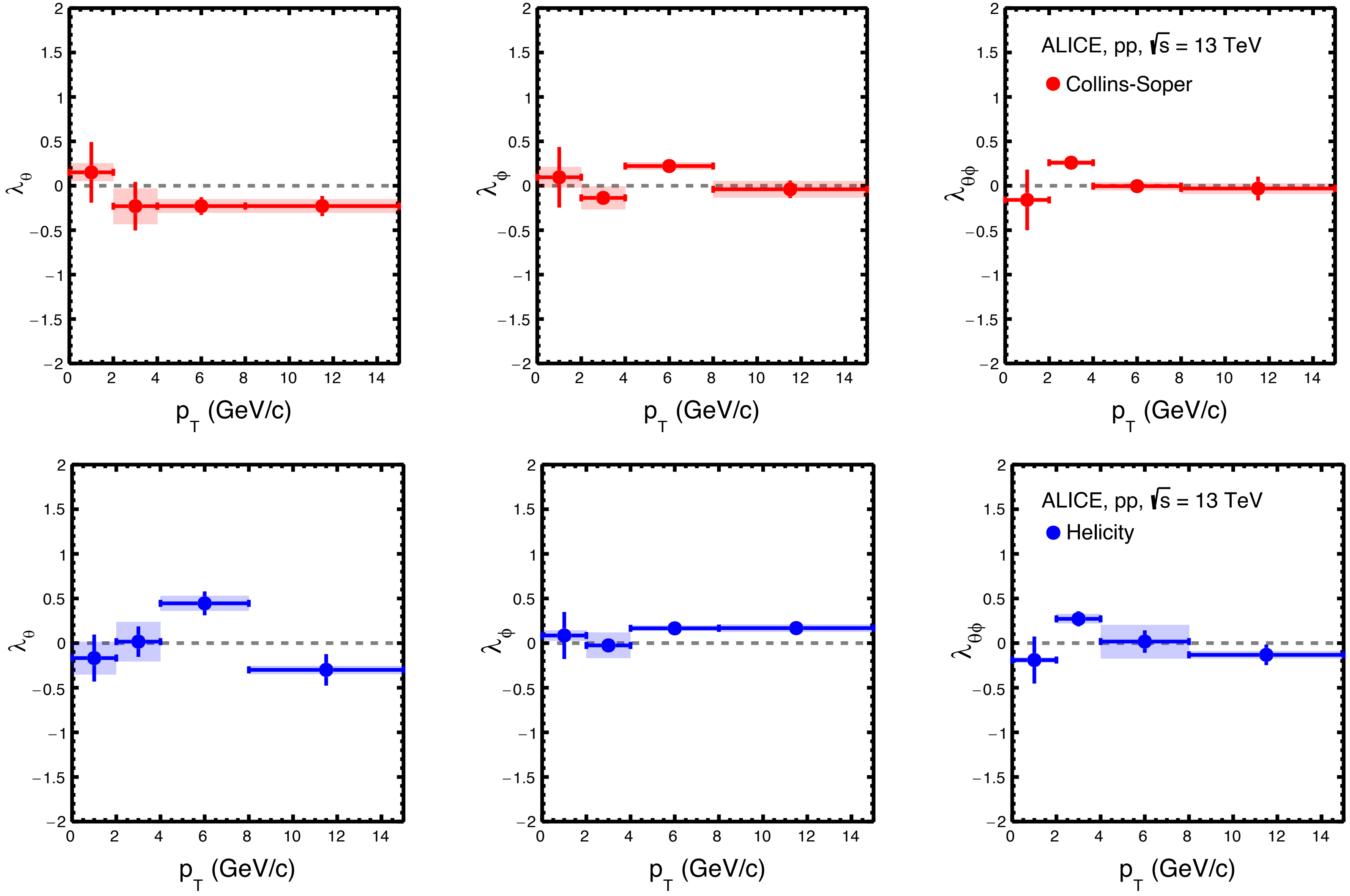


Mass: 3.69 GeV/c^2

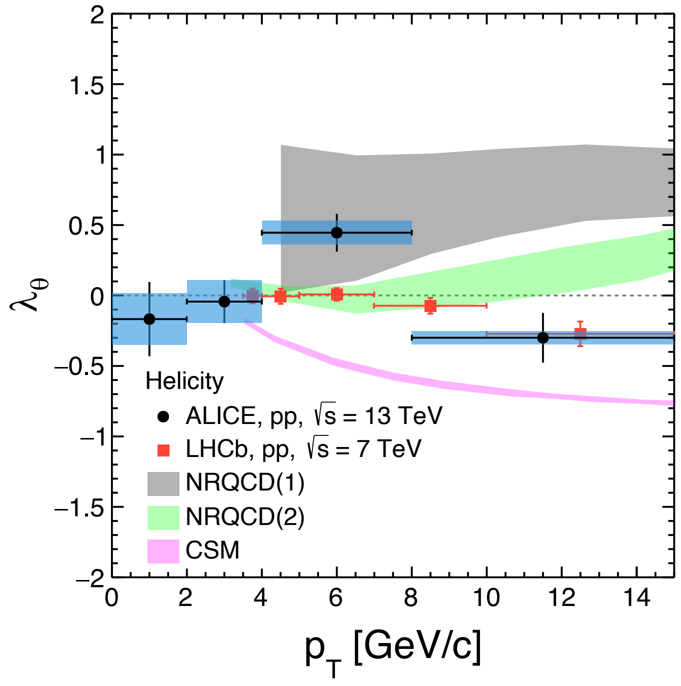
Spin: 1

Lifetime: ~ 688 fm/c

Quarkonium polarization in pp collisions

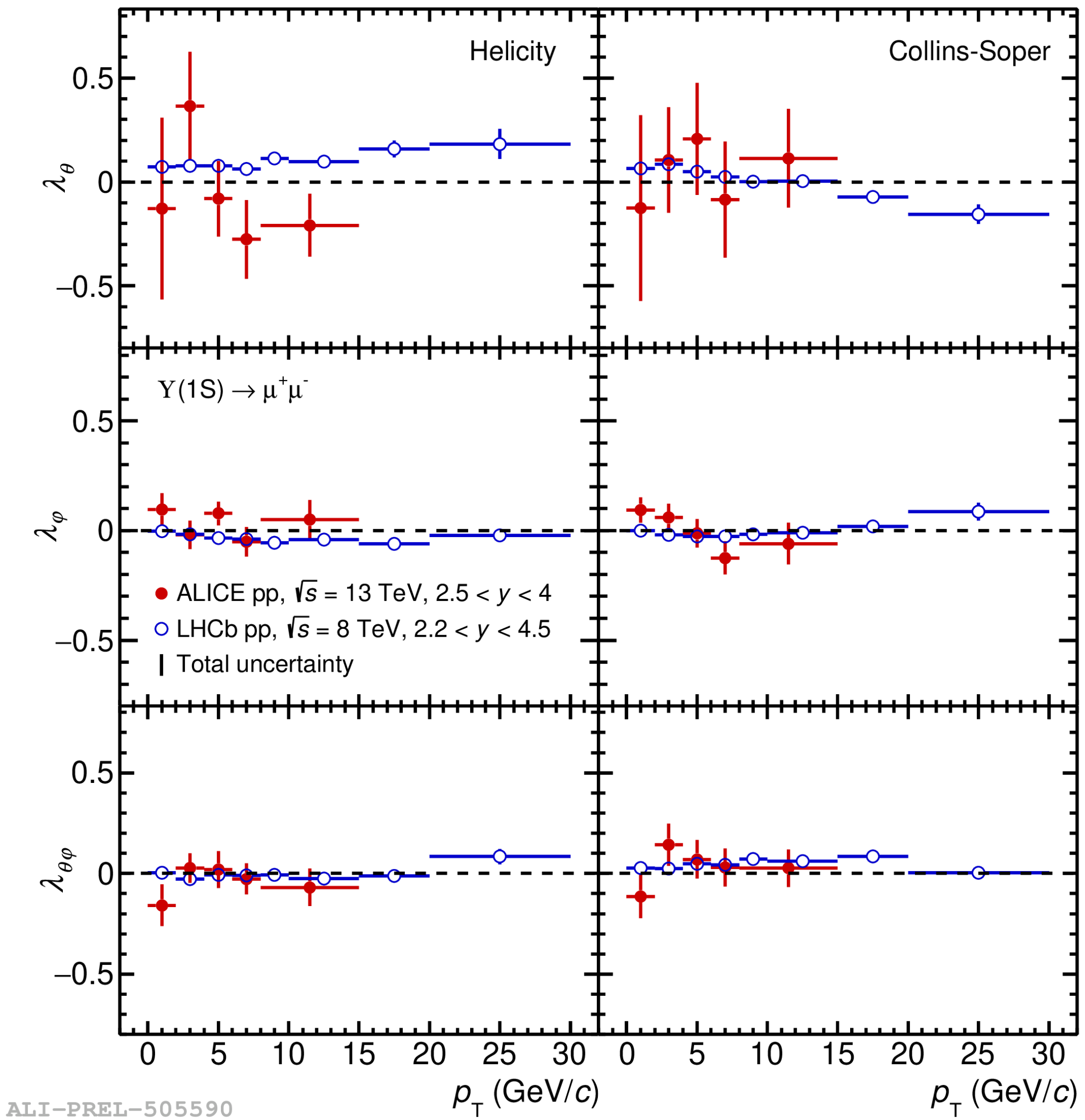


- Zero polarization within uncertainties for Collins-Soper frame
- 1.58σ deviation from zero in helicity frame for $4 < p_T < 8$ GeV/c



Analysis Note: ψ(2S) polarization measurement in pp collisions at $\sqrt{s}$ = 13 TeV, https://alice-notes.web.cern.ch/node/1472 (ALICE internal)

Quarkonium polarization in pp collisions

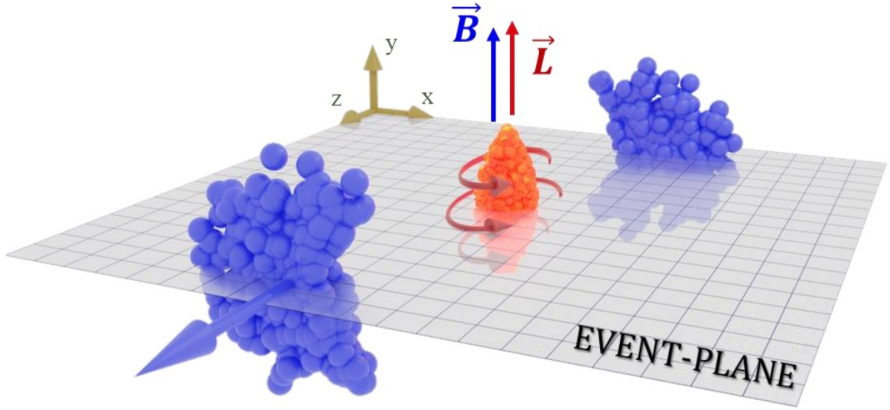


- Recent preliminary measurement of $\Upsilon(1S)$ polarization at $\sqrt{s}$ = 13 TeV from ALICE
- Results compatible with previous LHCb measurements at $\sqrt{s}$ = 8 TeV
- Polarization is evaluated down to $p_T \sim 0$
- All values compatible with zero within uncertainties
- Large uncertainties due to limited statistical precision

LHCb Collaboration, JHEP 12, 110 (2017)

Quarkonium polarization in Pb−Pb collisions

- Large non-zero magnetic field in non-central heavy-ion collisions
- Production of vorticity due to large initial angular momentum
- Both the external magnetic field and the initial angular momentum produced in the non-central heavy-ion collisions may influence the quarkonium polarization
- Event Plane (EP) frame: direction of the polarization axis orthogonal to the event plane in the centre-of-mass of the colliding beams



Magnetic field ($\vec{B}$):

- Huge intensity (10^{14} T)
- Short lived ($\tau = 1\ fm/c$)

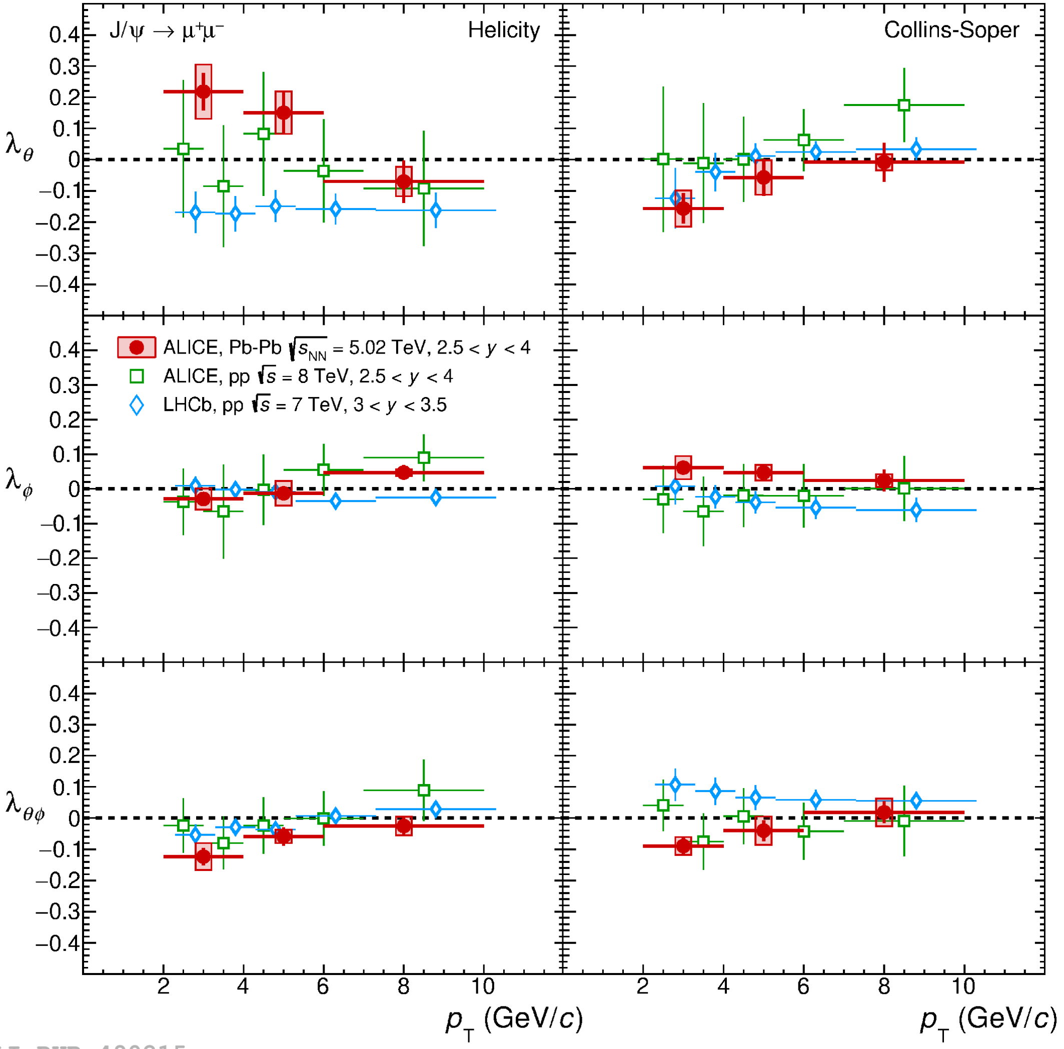
[Kharzeev et al., NPA 803 (2008)]

Angular momentum ($\vec{L}$):

- Largest in semicentral collisions
- Can affect the system evolution till freeze-out

[Becattini et al., PRC 77 (2008) 024906]

Quarkonium polarization in Pb−Pb collisions

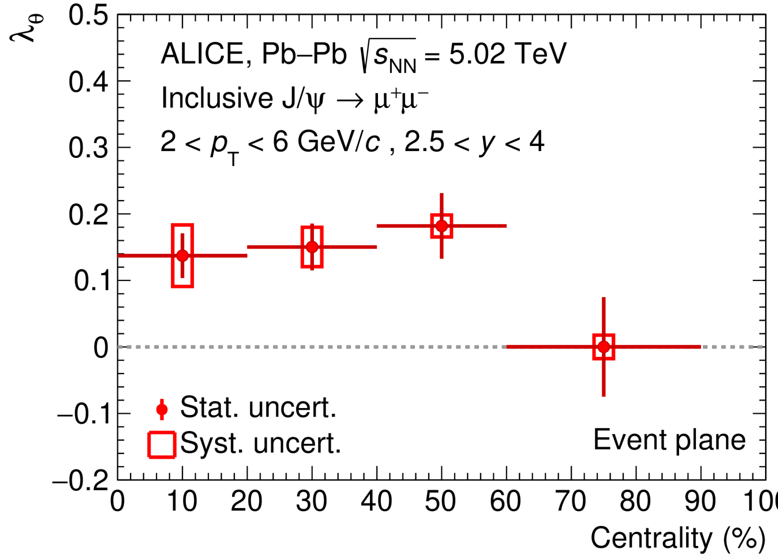


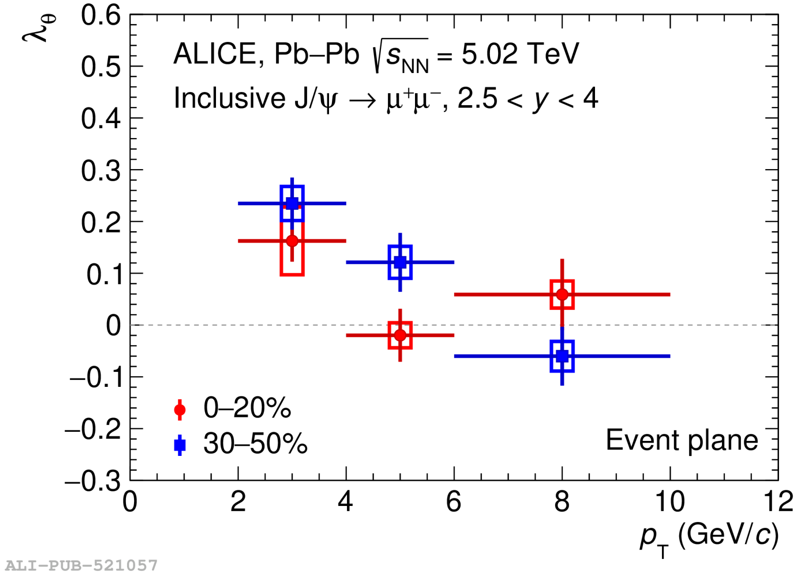
ALI-PUB-490215

- ALICE measurement of J/ψ polarization in Pb−Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV in Helicity (HE) and Collins-Soper (CS) reference frames
- λ_θ shows a 2σ deviation from zero at low p_{T}
- 3σ deviation from LHCb measurement in pp collisions in the Helicity frame
- Values compatible with ALICE results in pp collisions within uncertainties

ALICE Collaboration, Phys. Lett. B 815, 136146 (2021)
ALICE Collaboration, Eur. Phys. J. C 78, 562 (2018)
LHCb Collaboration, Eur. Phys. J. C 73, 2631 (2013)

Quarkonium polarization in Pb−Pb collisions



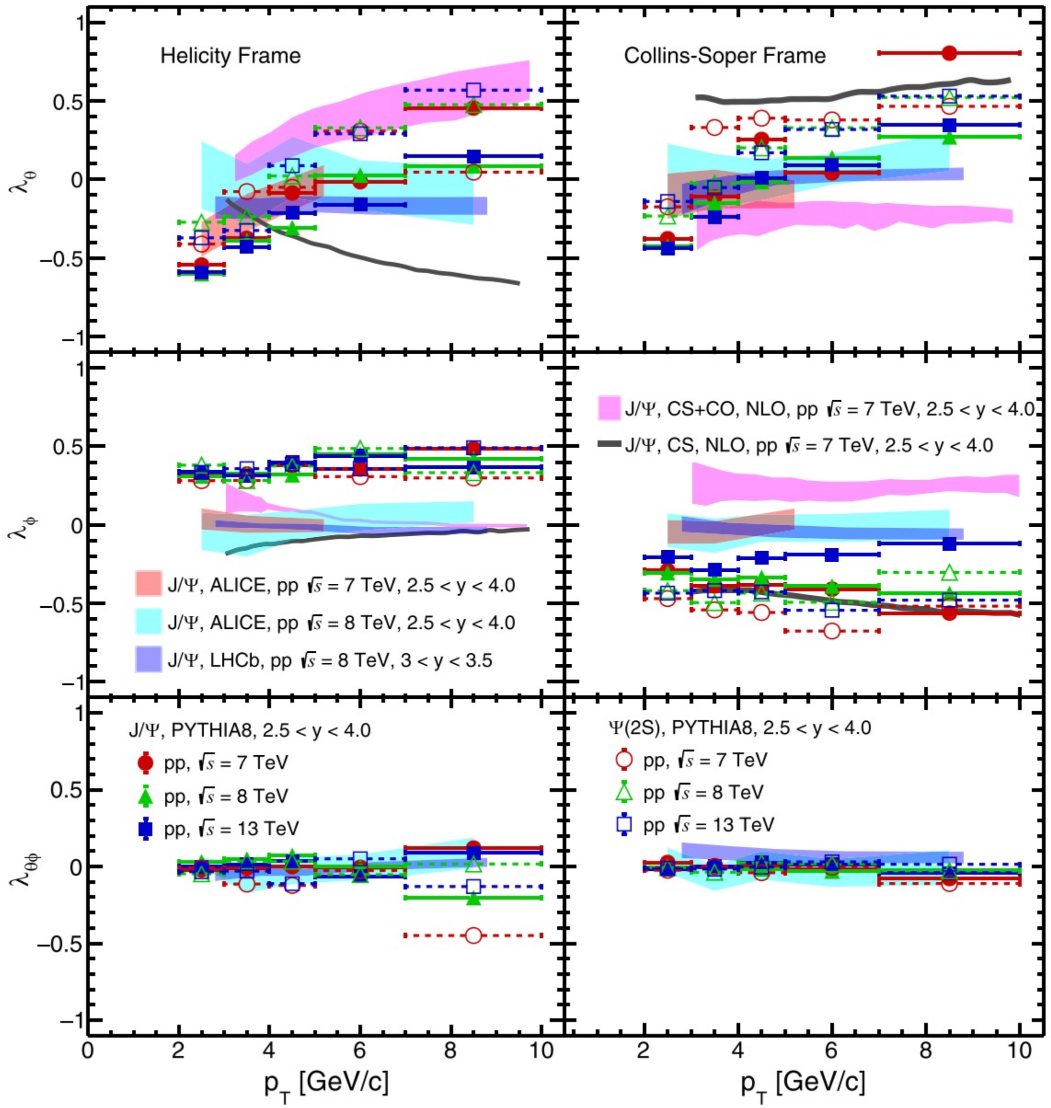


- ALICE measurement of J/ψ polarization in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- First measurement with respect to the Event Plane (EP)
- Small but significant polarization (3.5σ), particularly in the 40-60% centrality range
- Effect more pronounced at low transverse momentum ($2 < p_T < 4$ GeV/c) in centrality 30-50%
- Qualitatively in agreement with spin alignment observed for light vector mesons [Phys. Rev. Lett. 125, 012301 (2022)]

[ALICE Collaboration, Phys. Rev. Lett. 131, 042303 (2023)]

Polarization with PYTHIA8

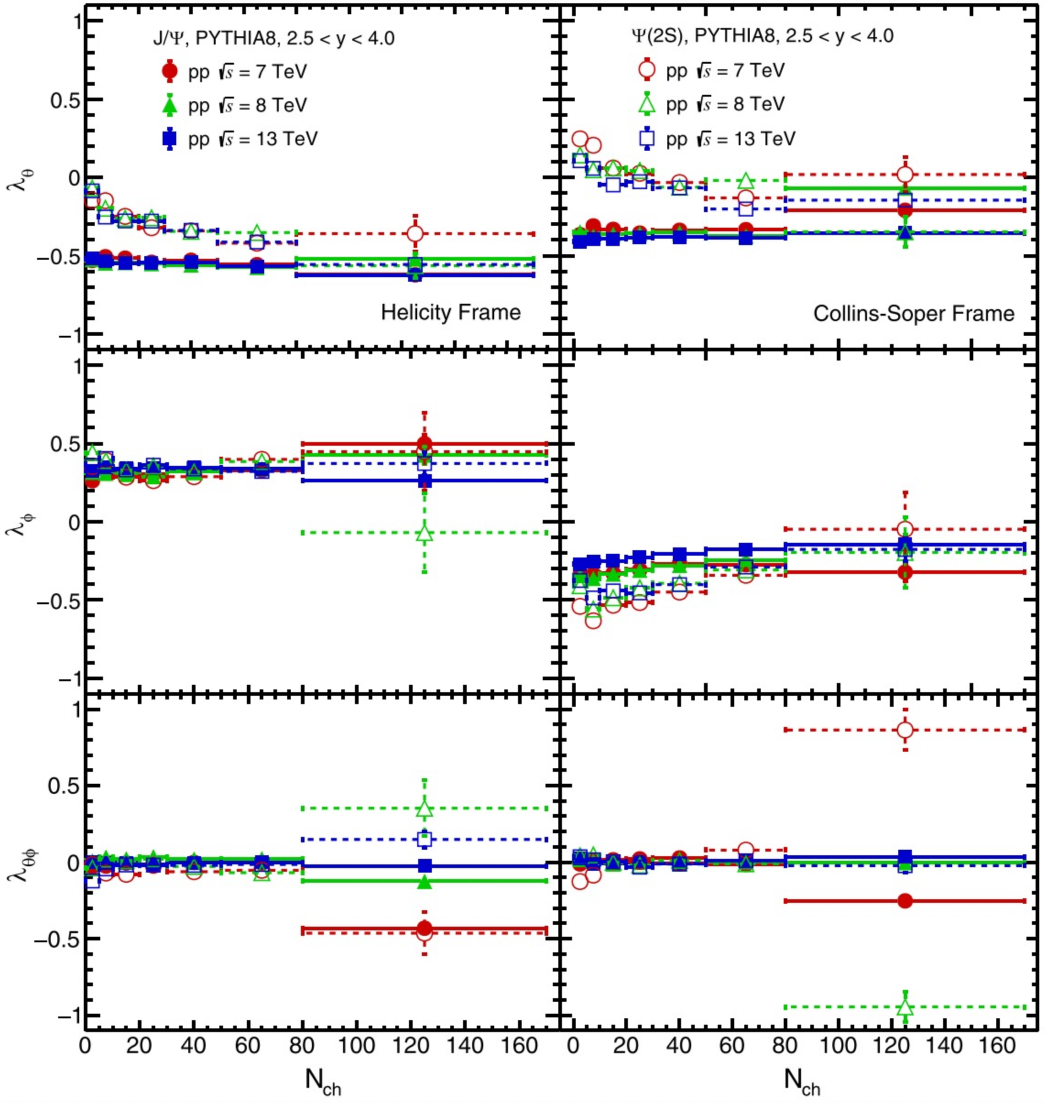
- PYTHIA8 with color reconnection (CR) explains the charmonia transverse momentum spectra
- Trend is the same as ALICE and LHCb
- Values incompatible with experimental data
- Possible issues?



[B. Sahoo, **D. Sahu,** S. Deb, C. R. Singh and R. Sahoo, Phys. Rev. C 109, 034910 (2024)]

Polarization with PYTHIA8

- Charged-particle multiplicity dependent study might shed light on possible thermalization in small collision systems
- PYTHIA8 gives finite polarization as a function of multiplicity in both helicity and Collins-Soper frame
- No experimental observations till now due to low statistics
- ALICE RUN 3 will provide substantially higher statistics for such analysis



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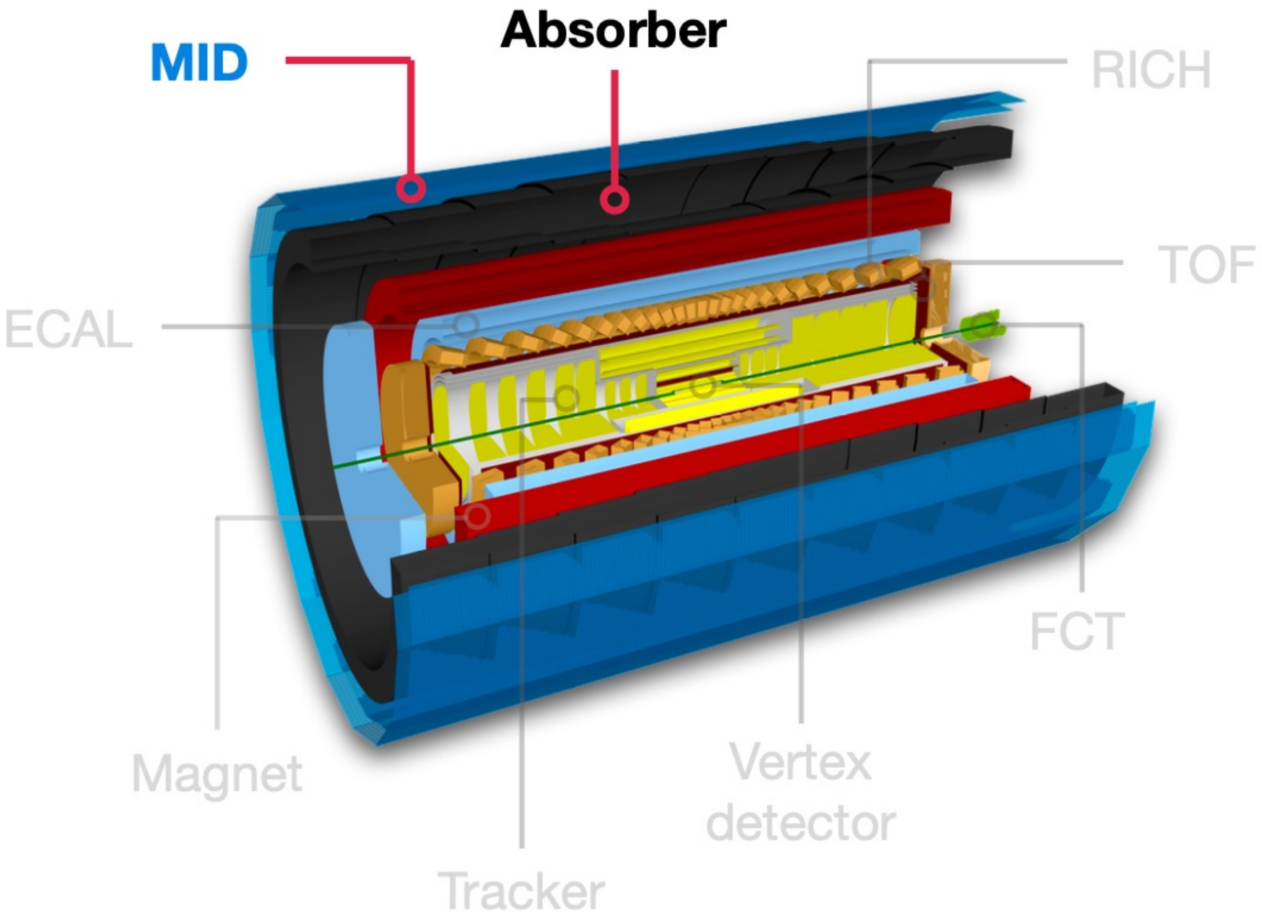
Muon Identifier (MID) in ALICE 3



ALICE 3 features:

Muon identification for charmonia and exotic hadrons

CMS and **ATLAS**: μ identification down to $p_T \approx 3 - 4$ GeV/c

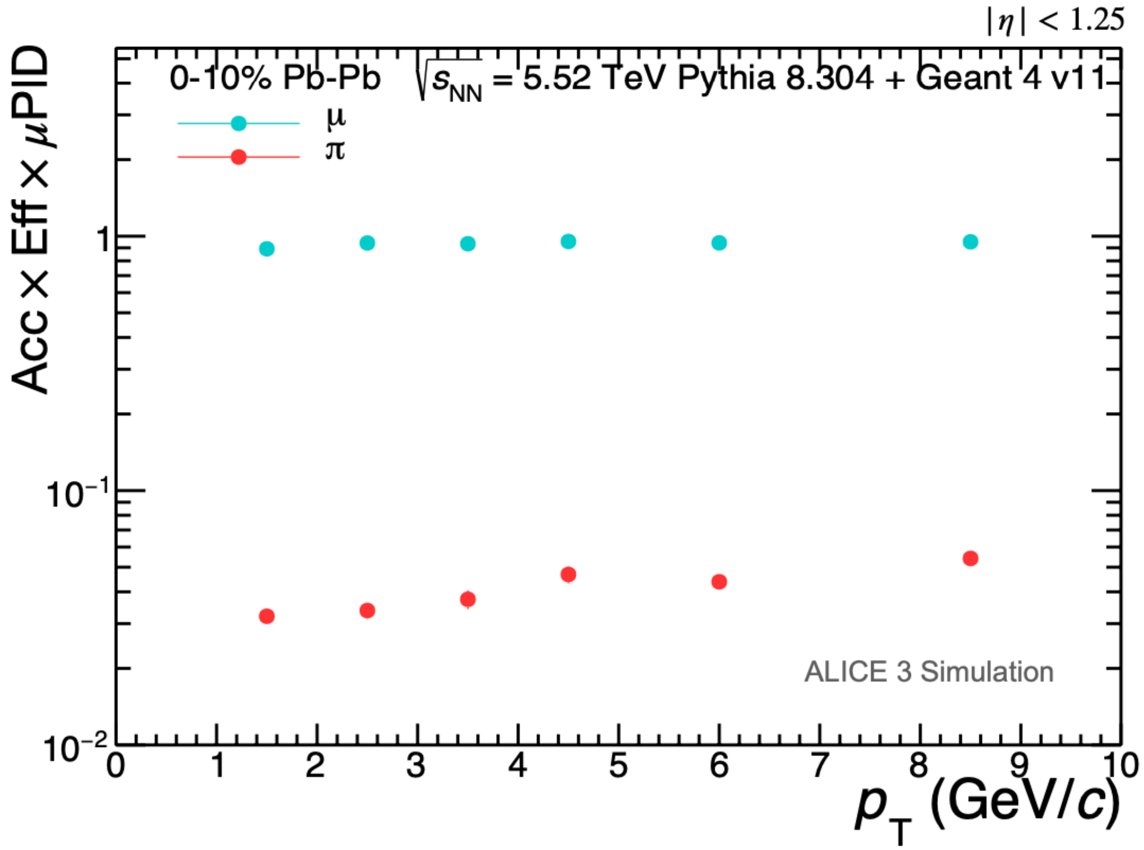
ALICE 3: optimized to identify μ down to $p_T = 1.5$ GeV/c

vs

LHCb: J/ψ at rest but only at forward rapidity

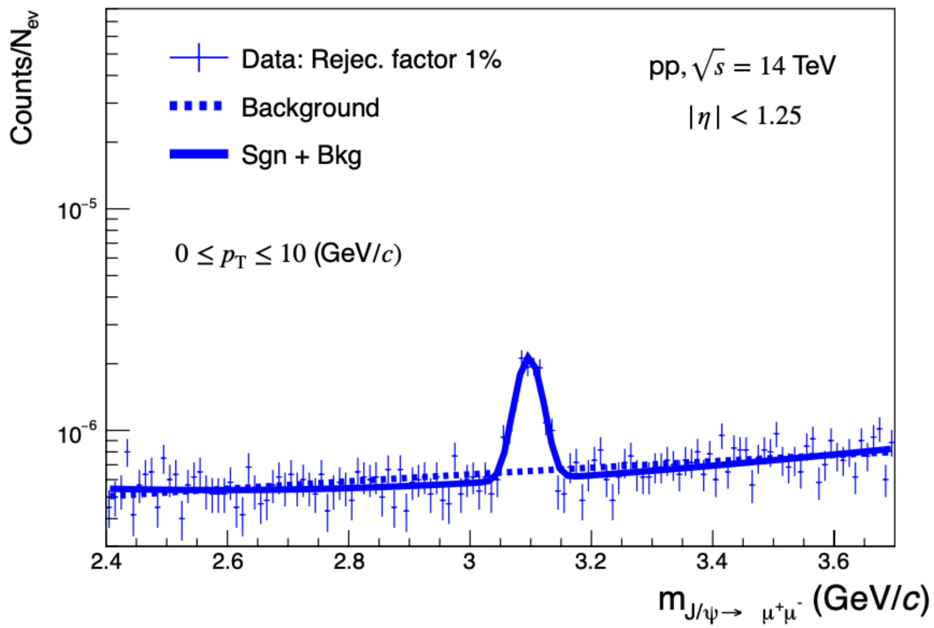
ALICE 3: J/ψ at rest for a wider rapidity $|y| < 1.24$

Muon Identifier (MID) in ALICE 3



- Muon efficiency around 94% for $p_T > 1.5$ GeV/c
- Pion rejection at the level of 3-5%

The MID will allow the reconstruction of J/ψ down to $p_T = 0$ via its dimuon decay channel



Conclusion and Outlook

- ALICE has measured the polarization of several quarkonium states both in pp and Pb−Pb collisions
- No significant quarkonium polarization till now in pp collisions
- New J/ψ and ψ(2S) polarization analyses ongoing in pp collision at $\sqrt{s}$ = 13 TeV (In preparation for publication)
- Results are more or less compatible with other LHC measurements and recent model predictions
- Hint for non-zero polarization at low p_{T} in the HE and CS frames in Pb−Pb collisions
- From the results of EP frame analysis, possible correlation with $\vec{B}$ and $\vec{L}$ in the QGP formed in heavy-ion collision
- ALICE Run 3 with high luminosity will provide significant statistics and precision measurements
- Need of an update to MC models and other theoretical models
- Need for event classifier dependent study of polarization to better understand heavy-flavor in QCD

Publications

1. **D. Sahu**, S. Tripathy, G. S. Pradhan and R. Sahoo, **Phys. Rev. C 101, 014902 (2020)**
2. **D. Sahu** and R. Sahoo, **J. Phys. G 48, 125104 (2021)**
3. **D. Sahu** , S. Tripathy, R. Sahoo and S. K. Tiwari, **Eur. Phys. J. A 58, 78 (2022)**
4. A. N. Mishra, **D. Sahu** and R. Sahoo, **MDPI Physics 4, 315 (2022)**
5. **D. Sahu** and R. Sahoo, “ψ(2S) polarization measurement in pp collisions at $\sqrt{s}$ = 13 TeV”, https://alice-notes.web.cern.ch/node/1472 (ALICE internal)
6. **D. Sahu**, S. Tripathy, R. Sahoo and A. R. Dash, **Eur. Phys. J. A 56, 187 (2020)**
7. **D. Sahu** and R. Sahoo, **MDPI Physics 3, 207 (2021)**
8. S. Deb, **D. Sahu**, R. Sahoo and A. K. Pradhan, **Eur. Phys. J. A 57, 158 (2021)**
9. K. Goswami, **D. Sahu** and R. Sahoo, **Phys. Rev. D 107, 014003 (2023)**
10. K. K. Pradhan, **D. Sahu**, R. Scaria and R. Sahoo, **Phys. Rev. C 107, 014910 (2023)**
11. G. S. Pradhan, **D. Sahu**, S. Deb and R. Sahoo, **J. Phys. G 50, 055104 (2023)**
12. R. Scaria, **D. Sahu**, C. R. Singh, R. Sahoo and J. e. Alam, **Eur. Phys. J. A 59, 140 (2023)**
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16. G. S. Pradhan, **D. Sahu**, R. Rath, R. Sahoo and J. Cleymans, **Eur. Phys. J. A 60, 52 (2024)**
17. B. Sahoo, **D. Sahu**, S. Deb, C. R. Singh and R. Sahoo, **Phys. Rev. C 109, 034910 (2024)**
18. K. Goswami, **D. Sahu**, J. Dey, R. Sahoo and R. Stock, **Phys. Rev. D 109, 074012 (2024)**
19. K. K. Pradhan, B. Sahoo, **D. Sahu** and R. Sahoo, **Eur. Phys. J. C 84, 936 (2024)**
20. K. Goswami, K. K. Pradhan, **D. Sahu**, J. Dey and R. Sahoo, **Phys. Rev. D 111, 014029 (2025)**
21. K. K. Pradhan, R. Scaria, **D. Sahu** and R. Sahoo, **arXiv:2308.09337**
22. K. K. Pradhan, **D. Sahu**, C. R. Singh and R. Sahoo, **arXiv:2212.09288**
23. K. Singh, K. K. Pradhan, **D. Sahu** and R. Sahoo, **arXiv:2502.16853**

THANK YOU!