A Large Ion Collider Experiment

Hidden charm production in pp collisions at 13.6 TeV

Measurement of the $\eta_c(1S)$, J/ψ, $\psi(2S)$ yields using hyperon decay channel with ALICE

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Hidden-charm meson production

Understand better the charm-quark hadronisation in a collective medium (in AA but also pp)

- Provide a better understanding of charm baryon production
- Provide a better understanding of open- and **hidden-charm meson** productions

Charmonium production is essentially studied with J/ψ and ψ(2S) particles

η_C is relatively unexplored experimentally

$$\eta_C(1S) \rightarrow p\bar{p} \quad (\text{B.R. } 1.35 \times 10^{-3})$$

→ challenging combinatorial background

LHCb Collaboration, Eur. Phys. J. C 80, 191

Measurement of the $\eta_c(1S)$ production cross-section in pp collisions at $\sqrt{s} = 13$ TeV

LHCb collaboration†

Abstract

Using a data sample corresponding to an integrated luminosity of 2.0 fb^{-1}, collected by the LHCb experiment, the production of the $\eta_c(1S)$ state in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV is studied in the rapidity range $2.0 < y < 4.5$ and in the transverse momentum range $6.5 < p_T < 14.0$ GeV. The cross-section for prompt production of $\eta_c(1S)$ mesons relative to that of the J/ψ meson is measured using the $p\bar{p}$ decay mode and is found to be $\sigma_{\eta_c(1S)}/\sigma_{J/\psi} = 1.69 \pm 0.15 \pm 0.10 \pm 0.18$. The quoted uncertainties are, in order,

low-p_T production is the most interesting ←

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$$\eta_{\mathrm{C}}(1\mathrm{S}) \rightarrow \mathrm{p}\overline{\mathrm{p}} \quad (\mathrm{B.R.}\ 1.35 \times 10^{-3})$$

→ challenging combinatorial background

Could drastically be reduced by exploiting **(multi-)strange baryons**

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$$\eta_C(1S) \rightarrow p\bar{p} \quad (B.R.\ 1.35 \times 10^{-3})$$

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Could drastically be reduced by exploiting **(multi-)strange baryons**

$\eta_C(1S) \rightarrow \Lambda\overline{\Lambda} \quad (B.R.\ 1.02 \times 10^{-3})$	$\eta_C(1S) \rightarrow \Xi^-\overline{\Xi}^+ \quad (B.R.\ 9.0 \times 10^{-4})$
$J/\psi \rightarrow \Lambda\overline{\Lambda} \quad (B.R.\ 1.89 \times 10^{-3})$	$J/\psi \rightarrow \Xi^-\overline{\Xi}^+ \quad (B.R.\ 9.7 \times 10^{-4})$
$\chi_{c0}(1P) \rightarrow \Lambda\overline{\Lambda} \quad (B.R.\ 3.59 \times 10^{-4})$	$\chi_{c0}(1P) \rightarrow \Xi^-\overline{\Xi}^+ \quad (B.R.\ 4.45 \times 10^{-4})$
$\chi_{c1}(1P) \rightarrow \Lambda\overline{\Lambda} \quad (B.R.\ 1.27 \times 10^{-4})$	$\chi_{c1}(1P) \rightarrow \Xi^-\overline{\Xi}^+ \quad (B.R.\ 6.0 \times 10^{-5})$
$\chi_{c2}(1P) \rightarrow \Lambda\overline{\Lambda} \quad (B.R.\ 1.07 \times 10^{-4})$	$\chi_{c2}(1P) \rightarrow \Xi^-\overline{\Xi}^+ \quad (B.R.\ 1.46 \times 10^{-4})$
$\psi(2S) \rightarrow \Lambda\overline{\Lambda} \quad (B.R.\ 3.81 \times 10^{-4})$	$\psi(2S) \rightarrow \Xi^-\overline{\Xi}^+ \quad (B.R.\ 2.87 \times 10^{-4})$

→ Pave the way towards a **precise exploration of the whole charmonium spectroscopy**

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Data samples and event selections

- **Data:** pp collisions at $\sqrt{s}$ = 13.6 TeV, 2023 thinned

  - strangeness derived data sample (***LF_LHC23_pass4_Thin_Strangeness***)

  - used only a chunk (50 files): 16.7 x 10^6 events, **pass4**

- **Simulated data:** pp collisions at $\sqrt{s}$ = 13.6 TeV, Pythia 8 Monash 2013 + Geant4

  - strangeness derived data sample (*local simulations done by David*)

  - 0.5 x 10^6 events, enriched (via triggering) in $\eta_c \rightarrow \Lambda\bar{\Lambda}$, $J/\psi \rightarrow \Lambda\bar{\Lambda}$ and $\psi(2S) \rightarrow \Lambda\bar{\Lambda}$

  - 0.5 x 10^6 events, enriched (via triggering) in $\eta_c \rightarrow \Xi^-\bar{\Xi}^+$, $J/\psi \rightarrow \Xi^-\bar{\Xi}^+$ and $\psi(2S) \rightarrow \Xi^-\bar{\Xi}^+$

- **Event selections:**

  - minimum-bias events (*sel8*)

  - $|z_{prim.\ vtx}| < 10$ cm

  - Not at the ITS ROF or TF border

  - IsGoodZvtxFT0VsPV

  - NoSameBunchPileup

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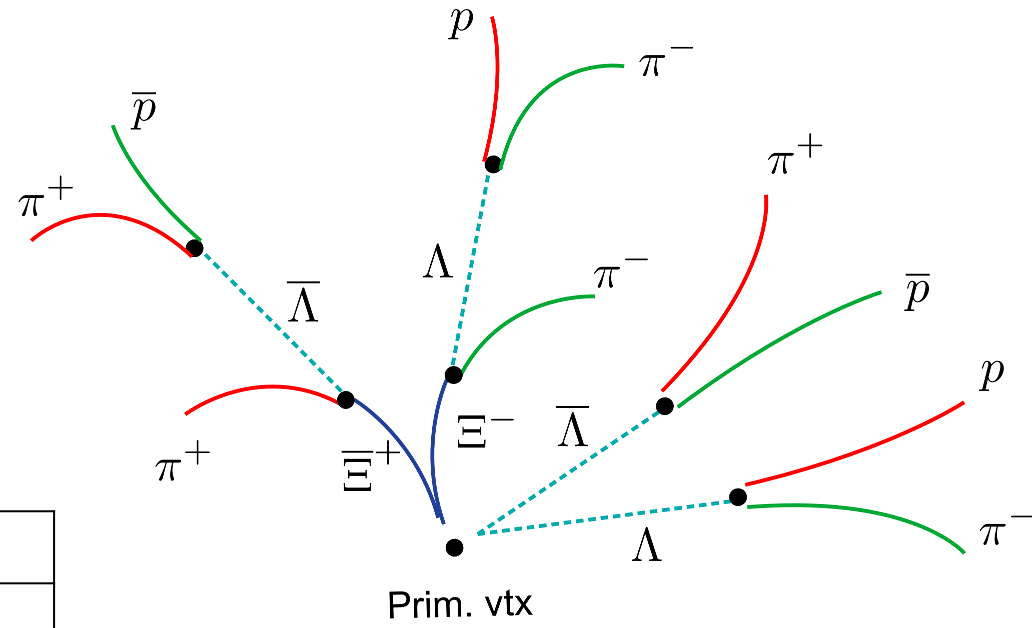
Candidate selections

The $\eta_c(1S)$, J/ψ and $\psi(2S)$ are studied in the following decay channels:

$$\begin{cases} \Lambda \rightarrow p\ \pi^- & \text{B.R. } 63.9\ \% \quad c\cdot\tau = 7.89 \text{ cm} \\ \overline{\Lambda} \rightarrow \overline{p}\ \pi^+ & \text{B.R. } 63.9\ \% \quad c\cdot\tau = 7.89 \text{ cm} \end{cases}$$

$$\begin{cases} \eta_C(1S) \rightarrow \Lambda\overline{\Lambda} & (\text{B.R. } 1.02\times10^{-3}) \\ J/\psi \rightarrow \Lambda\overline{\Lambda} & (\text{B.R. } 1.89\times10^{-3}) \\ \psi(2S) \rightarrow \Lambda\overline{\Lambda} & (\text{B.R. } 3.81\times10^{-4}) \end{cases}$$



V0 reconstruction using topological selections:

$\lvert\eta_{daughters}\rvert$	< 0.8
Nbr of TPC crossed rows	> 70
DCA proton to PV	> 0.05 cm
DCA pion to PV	> 0.1 cm
TPC d*E*/dx	< 5 σ

DCA between V0 daughters	< 1σ
V0 Radius	> 1.2 cm
V0 cos PA	> 0.97
V0 Mass cut	< 0.005 GeV/c^2
Competing mass rejection	> 0.008 GeV/c^2
Lifetime cut	< 3.8 $c\,\tau$

|y|	< 0.5
Correct MC association	Yes (only MC)

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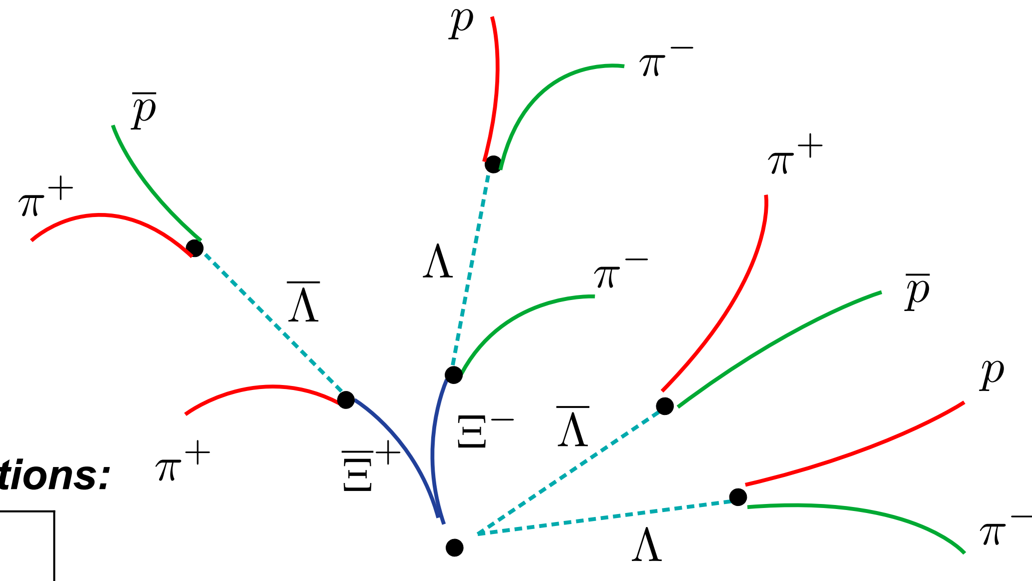
Candidate selections

The $\eta_C(1S)$, J/ψ and $\psi(2S)$ are studied in the following decay channels:

$$\begin{cases} \Xi^- \rightarrow \Lambda\ \pi^- \quad \text{B.R. } 99.9\ \% \quad c \cdot \tau = 4.91 \text{ cm} \\ \overline{\Xi}^+ \rightarrow \overline{\Lambda}\ \pi^+ \quad \text{B.R. } 99.9\ \% \quad c \cdot \tau = 4.91 \text{ cm} \end{cases}$$

$$\begin{cases} \eta_C(1S) \rightarrow \Xi^- \overline{\Xi}^+ \quad (\text{B.R. } 9.0 \times 10^{-4}) \\ J/\psi \rightarrow \Xi^- \overline{\Xi}^+ \quad (\text{B.R. } 9.7 \times 10^{-4}) \\ \psi(2S) \rightarrow \Xi^- \overline{\Xi}^+ \quad (\text{B.R. } 2.87 \times 10^{-4}) \end{cases}$$



Cascade reconstruction using topological selections:

$\lvert\eta_{daughters}\rvert$	< 0.8
Nbr of TPC crossed rows	> 70
DCA bachelor to PV	> 0.1 cm
DCA proton to PV	> 0.05 cm
DCA pion to PV	> 0.1 cm
TPC d*E*/dx	< 5 σ

DCA between V0 daughters	< 1σ
DCA V0 to PV	> 0.05 cm
V0 Radius	> 1.2 cm
V0 cos PA	> 0.97
V0 Mass cut	< 0.008 GeV/c^2

DCA between casc. daughters	< 1 σ
Cascade Radius	> 0.5 cm
Cascade cos PA	> 0.97
Cascade Mass cut	< 0.005 GeV/c^2
Competing Mass rejection	> 0.008 GeV/c^2
Cascade lifetime	< 3 $c\,\tau$

$\lvert y\rvert$	< 0.5
Correct MC association	Yes (only MC)

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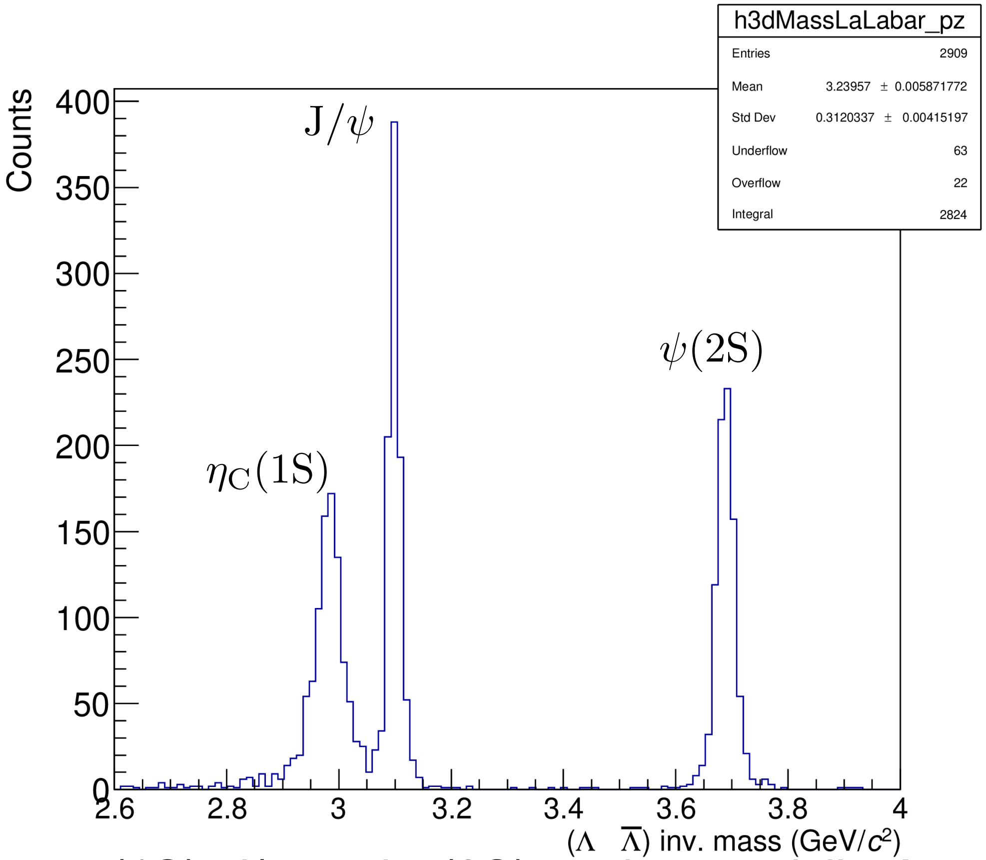
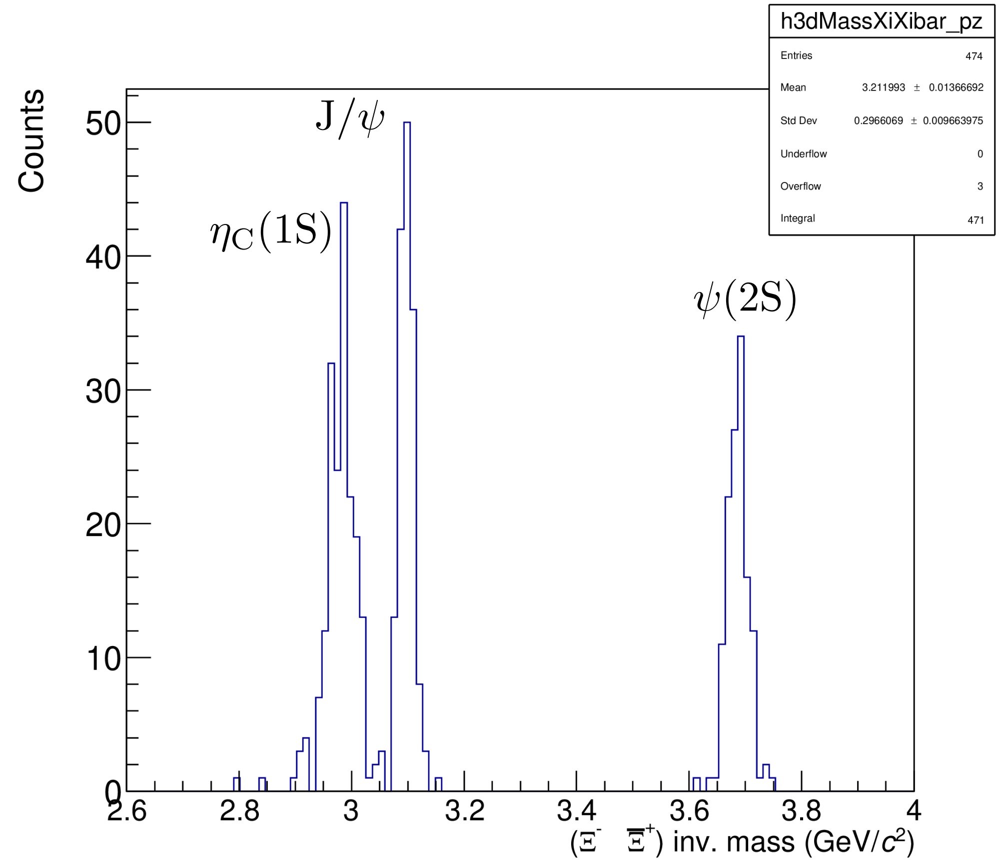
$\Lambda\bar{\Lambda}$ and $\Xi^{-}\bar{\Xi}^{+}$ invariant mass in MC

A first look at the invariant mass distributions of hyperon-antihyperon pairs **in MC**

$$\begin{cases} \eta_C(1S) \to \Lambda\bar{\Lambda} & (\text{B.R. } 1.02 \times 10^{-3}) \\ J/\psi \to \Lambda\bar{\Lambda} & (\text{B.R. } 1.89 \times 10^{-3}) \\ \psi(2S) \to \Lambda\bar{\Lambda} & (\text{B.R. } 3.81 \times 10^{-4}) \end{cases}$$

$$\begin{cases} \eta_C(1S) \to \Xi^{-}\bar{\Xi}^{+} & (\text{B.R. } 9.0 \times 10^{-4}) \\ J/\psi \to \Xi^{-}\bar{\Xi}^{+} & (\text{B.R. } 9.7 \times 10^{-4}) \\ \psi(2S) \to \Xi^{-}\bar{\Xi}^{+} & (\text{B.R. } 2.87 \times 10^{-4}) \end{cases}$$





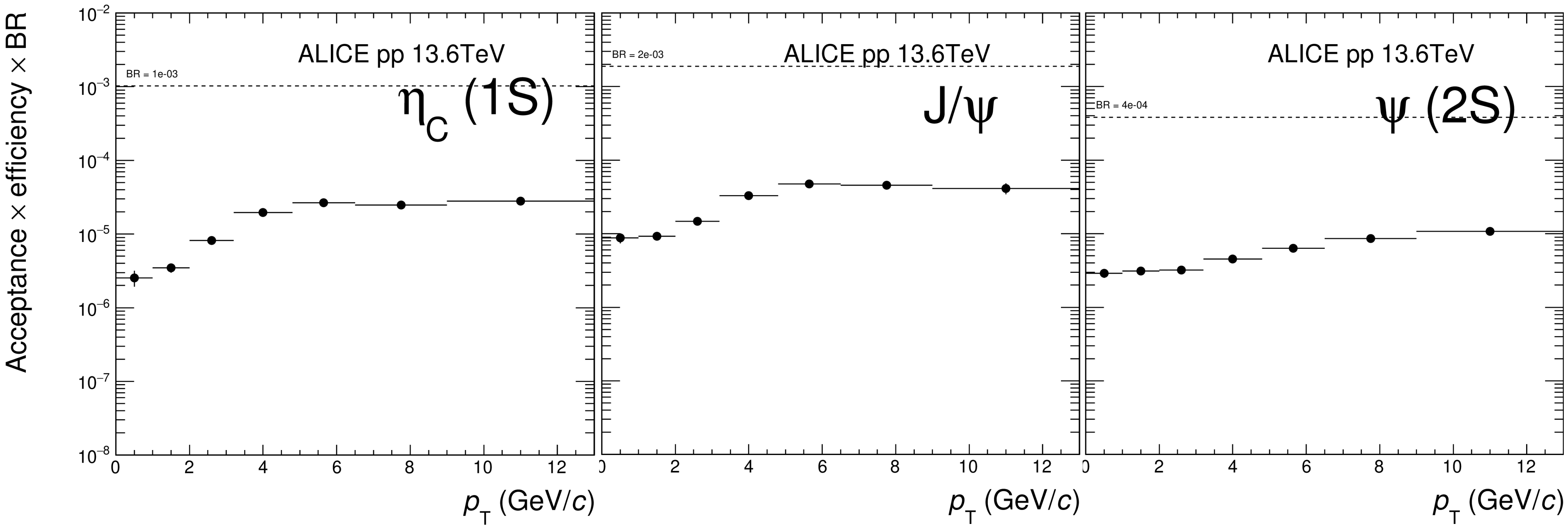
$\eta_C(1S)$, J/ψ and $\psi(2S)$ peaks are visible!

Reconstruction efficiencies

From the $\eta_C(1S)$, J/ψ and ψ(2S) peaks, we can estimate the number of reconstructed charmonia

→ $$\epsilon(p_T) = \frac{N_{\text{reconstructed}}(p_T)}{N_{\text{generated}}(p_T)}$$

$\eta_C(1S) \to \Lambda\overline{\Lambda}$ $\quad$ $J/\psi \to \Lambda\overline{\Lambda}$ $\quad$ $\psi(2S) \to \Lambda\overline{\Lambda}$



Avg eff * BR = 1.62 x 10^{-5} $\quad$ **2.86 x 10^{-5}** $\quad$ **5.64 x 10^{-6}**

→ reconstruction in this decay channel is **extremely challenging**

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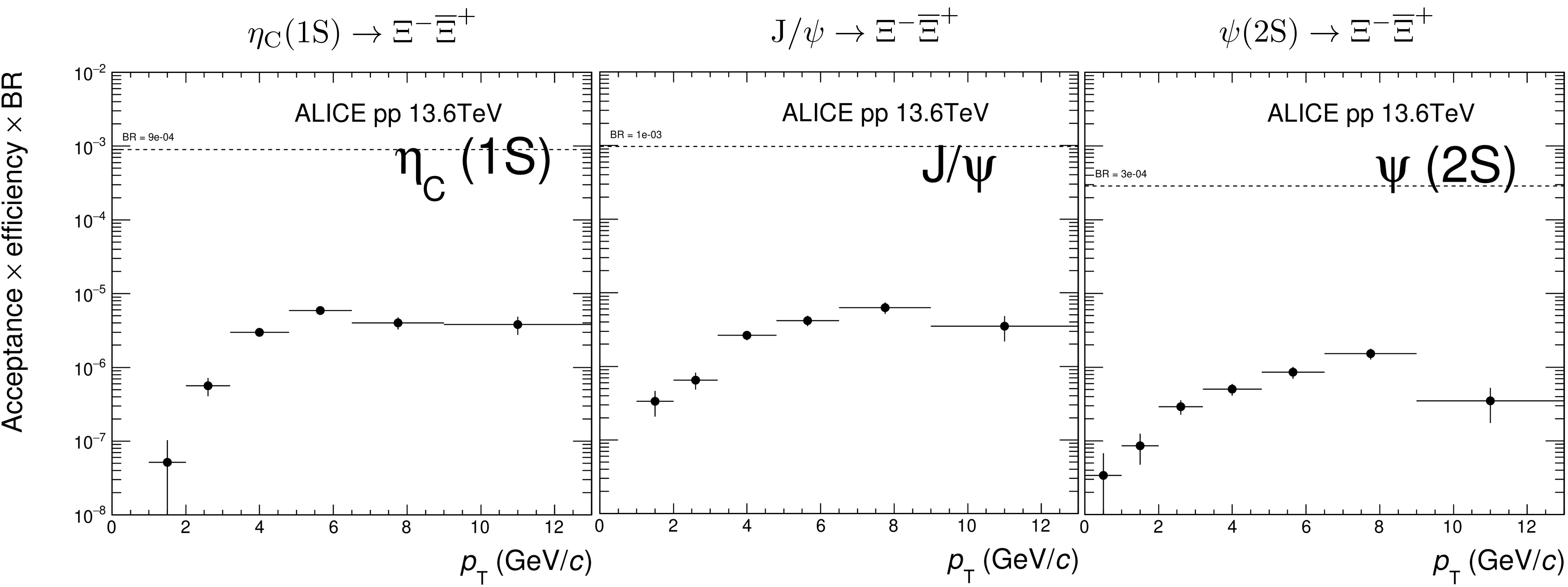

Avg eff * BR = 2.49 x 10^{-6} **2.52 x 10^{-6}** **5.20 x 10^{-7}**

→ reconstruction in this decay channel is **extremely challenging**

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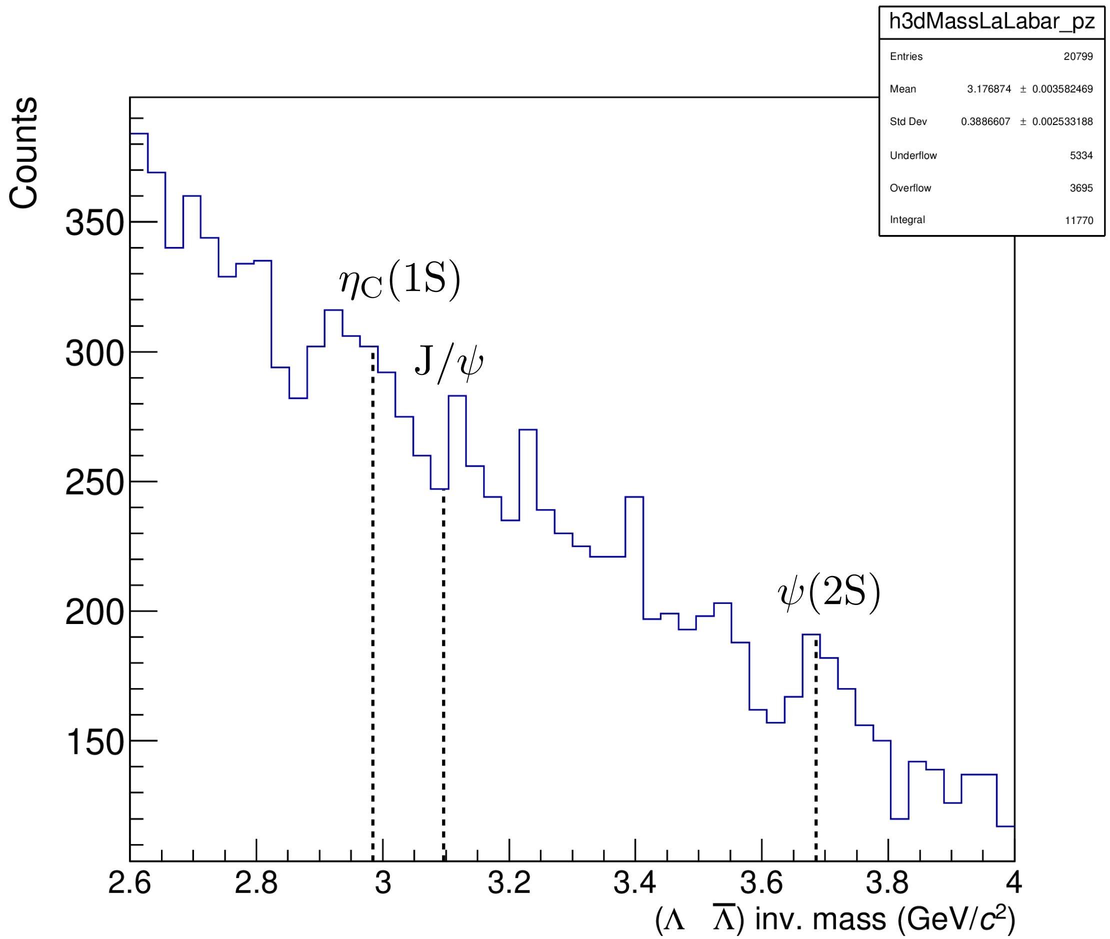
$\Lambda\bar{\Lambda}$ invariant mass in real data

ALICE

Let's run over real data and see what we get!

→ invariant mass distribution of $\Lambda\bar{\Lambda}$ pairs **<u>in data</u>** (0.002 % of all 2023 thinned)



No peak is visible in real data

BUT it allows to estimate the level of background under the peak

B [$\eta_C(1S) \rightarrow \Lambda\bar{\Lambda}$] = 1 175 ± 35

B [$J/\psi \rightarrow \Lambda\bar{\Lambda}$] = 530 ± 123

B [$\psi(2S) \rightarrow \Lambda\bar{\Lambda}$] = 373 ± 20 (*)

Note that this is only in 0.002% of 2023 thinned pp data

Over the full data sample, the uncertainties on the background varies between 3 900 and 6 800

(*): background estimated in a region of [μ ± σ], with μ = mean of the inv. mass peak in MC, σ = width of the inv. mass peak in MC

Is the measurement doable?

ALICE

Based on what was shown, we can estimate the expected number of reconstructed $\eta_C(1S)$, J/ψ, ψ(2S) in the hyperon-antihyperon decay channel

$$N_{\mathrm{expected}} = \mathcal{L}\sigma \times \mathrm{A} \times \epsilon \times \mathrm{B.R.}$$

$$\mathcal{L}\sigma = \left.\frac{\mathrm{d}N}{\mathrm{d}y}\right|_{y<0.5} \times N^{\mathrm{tot.}}_{\mathrm{expected\ \ events}}$$

Estimated from Pythia 8 Monash simulations (thanks David!)

652 x 10^9 events over the whole 2023 thinned pp

$\eta_C(1S) \rightarrow 4.67 \times 10^{-5}$

$J/\psi \rightarrow 2.25 \times 10^{-5}$

$\psi(2S) \rightarrow 3.03 \times 10^{-5}$

Estimated on average over p_T

See slide 9 and 10

$$\begin{cases} N_{\mathrm{expected}}\left(\eta_C(1S) \rightarrow \Lambda\overline{\Lambda}\right) = 494 \text{ events} \\ N_{\mathrm{expected}}\left(J/\psi \rightarrow \Lambda\overline{\Lambda}\right) = 420 \text{ events} \\ N_{\mathrm{expected}}\left(\psi(2S) \rightarrow \Lambda\overline{\Lambda}\right) = 112 \text{ events} \end{cases}$$

$$\begin{cases} N_{\mathrm{expected}}\left(\eta_C(1S) \rightarrow \Xi^-\overline{\Xi}^+\right) = 76 \text{ events} \\ N_{\mathrm{expected}}\left(J/\psi \rightarrow \Xi^-\overline{\Xi}^+\right) = 37 \text{ events} \\ N_{\mathrm{expected}}\left(\psi(2S) \rightarrow \Xi^-\overline{\Xi}^+\right) = 11 \text{ events} \end{cases}$$

Coupled to the overwhelming background in real data, such measurement becomes difficult (at least, with the current approach)

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Conclusion

Such measurements turn out to be rather difficult in pp collisions at 13.6 TeV

$$\begin{cases} \eta_C(1S) \rightarrow \Lambda\overline{\Lambda} & (\text{B.R. } 1.02 \times 10^{-3}) \\ J/\psi \rightarrow \Lambda\overline{\Lambda} & (\text{B.R. } 1.89 \times 10^{-3}) \\ \psi(2S) \rightarrow \Lambda\overline{\Lambda} & (\text{B.R. } 3.81 \times 10^{-4}) \end{cases}$$

$$\begin{cases} \eta_C(1S) \rightarrow \Xi^-\overline{\Xi}^+ & (\text{B.R. } 9.0 \times 10^{-4}) \\ J/\psi \rightarrow \Xi^-\overline{\Xi}^+ & (\text{B.R. } 9.7 \times 10^{-4}) \\ \psi(2S) \rightarrow \Xi^-\overline{\Xi}^+ & (\text{B.R. } 2.87 \times 10^{-4}) \end{cases}$$

→ **Reconstruction efficiencies are very small,** the combinatorial background level is high the production cross sections are low

Open questions:

- Could we perform it in another system, such as ultra-peripheral collisions?

  → ***pros:*** offers a cleaner environment, reduced combinatorial background

  → ***cons:*** different physics case

- Luminosity in pp collisions in 2024 is 4-5 times bigger than in 2023

  → ***pros:*** much more statistics + usage of ΞΞ offline trigger

  → ***cons***: need to rely on to the $\Xi^- \Xi^+$ decay channel → smaller efficiencies

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Backup slides

Is the measurement doable?

Based on what was shown, we can estimate the expected number of reconstructed $\eta_C(1S)$, J/ψ, ψ(2S) in the hyperon-antihyperon decay channel

$$N_{\text{expected}} = \mathcal{L}\sigma \times \text{A} \times \epsilon \times \text{B.R.}$$

$\mathcal{L}$ = 8.31 pb^{-1} from here

σ: From measurements in pp at 13 TeV

$\eta_C(1S)$ → 1.26 μb from LHCb

J/ψ → 8.97 μb from ALICE

ψ(2S) → 63.3 nb from ATLAS

A × ε × B.R.: Estimated on average over p_T

See slide 9 and 10

$$\begin{cases} N_{\text{expected}}\left(\eta_C(1S) \to \Lambda\overline{\Lambda}\right) = 170 \text{ events} \\ N_{\text{expected}}\left(J/\psi \to \Lambda\overline{\Lambda}\right) = 2132 \text{ events} \\ N_{\text{expected}}\left(\psi(2S) \to \Lambda\overline{\Lambda}\right) = 3 \text{ events} \end{cases}$$

$$\begin{cases} N_{\text{expected}}\left(\eta_C(1S) \to \Xi^-\overline{\Xi}^+\right) = 27 \text{ events} \\ N_{\text{expected}}\left(J/\psi \to \Xi^-\overline{\Xi}^+\right) = 188 \text{ events} \\ N_{\text{expected}}\left(\psi(2S) \to \Xi^-\overline{\Xi}^+\right) = 0.27 \text{ events} \end{cases}$$

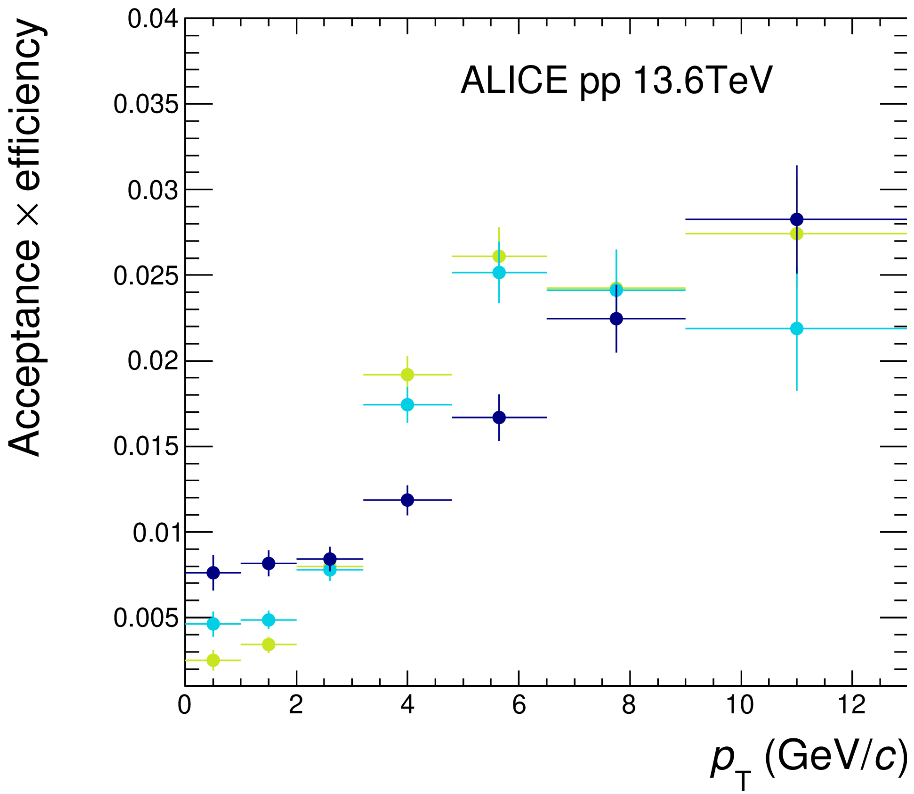
Coupled to the overwhelming background in real data, such measurement becomes difficult (at least, with the current approach)

Reconstruction efficiencies

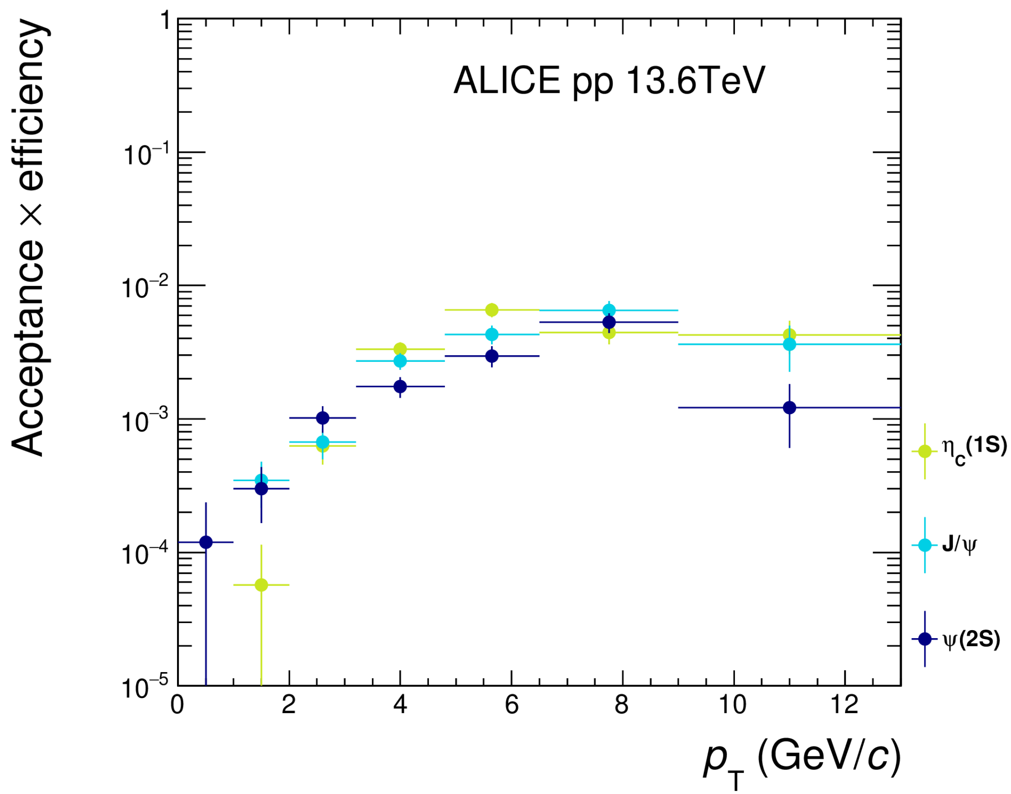
From the $\eta_C(1S)$, J/ψ and $\psi(2S)$ peaks, we can estimate the number of reconstructed charmonia

$$\rightarrow \boxed{\epsilon(p_T) = \frac{N_{\text{reconstructed}}(p_T)}{N_{\text{generated}}(p_T)}}$$

$\eta_C(1S)/J/\psi/\psi(2S) \rightarrow \Lambda\overline{\Lambda}$



$\eta_C(1S)/J/\psi/\psi(2S) \rightarrow \Xi^-\overline{\Xi}^+$



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