CLHCP2025 新乡

J/ψ–D^0 associated production measurements in pp collisions with ALICE Run 3

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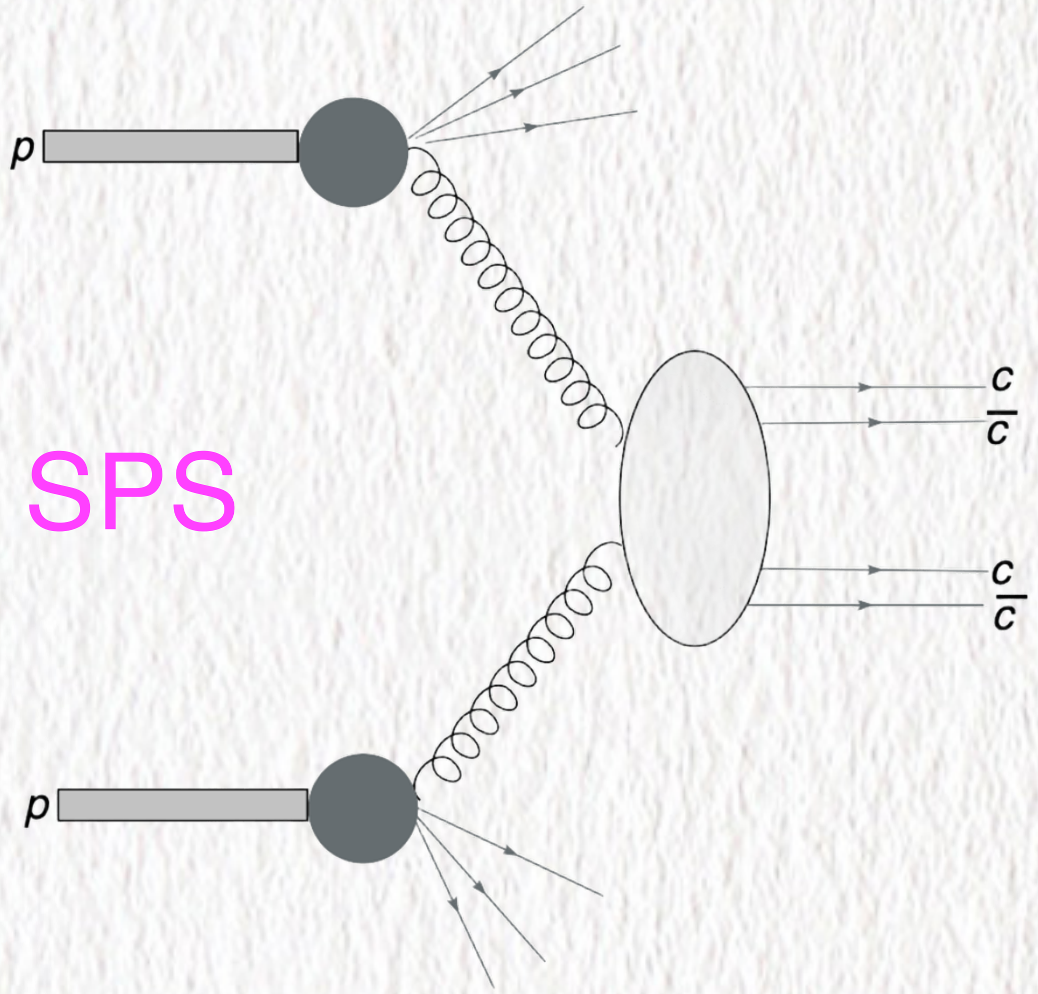
Motivation

ALICE

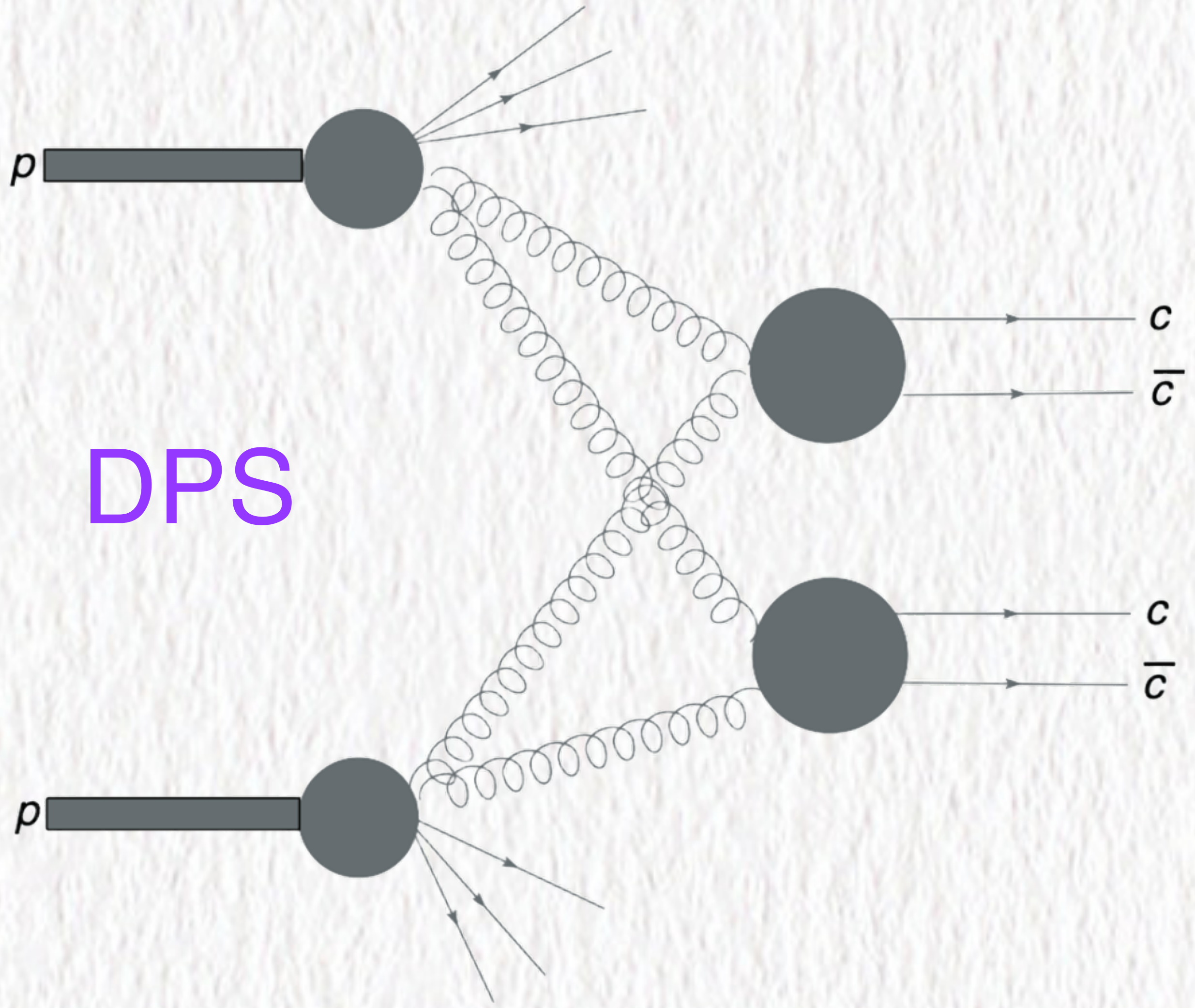
- Heavy quarks (c, b) are primarily produced through hard scattering processes.
- The production of c-hadron pairs provides an opportunity to study both Single Parton Scattering (SPS) and Double Parton Scattering (DPS).

SPS



- Access the internal dynamics of protons
  - Study the transverse-momentum dependent distributions of gluons[1] [2]
- Investigate the puzzle surrounding the quarkonium production mechanism[3]

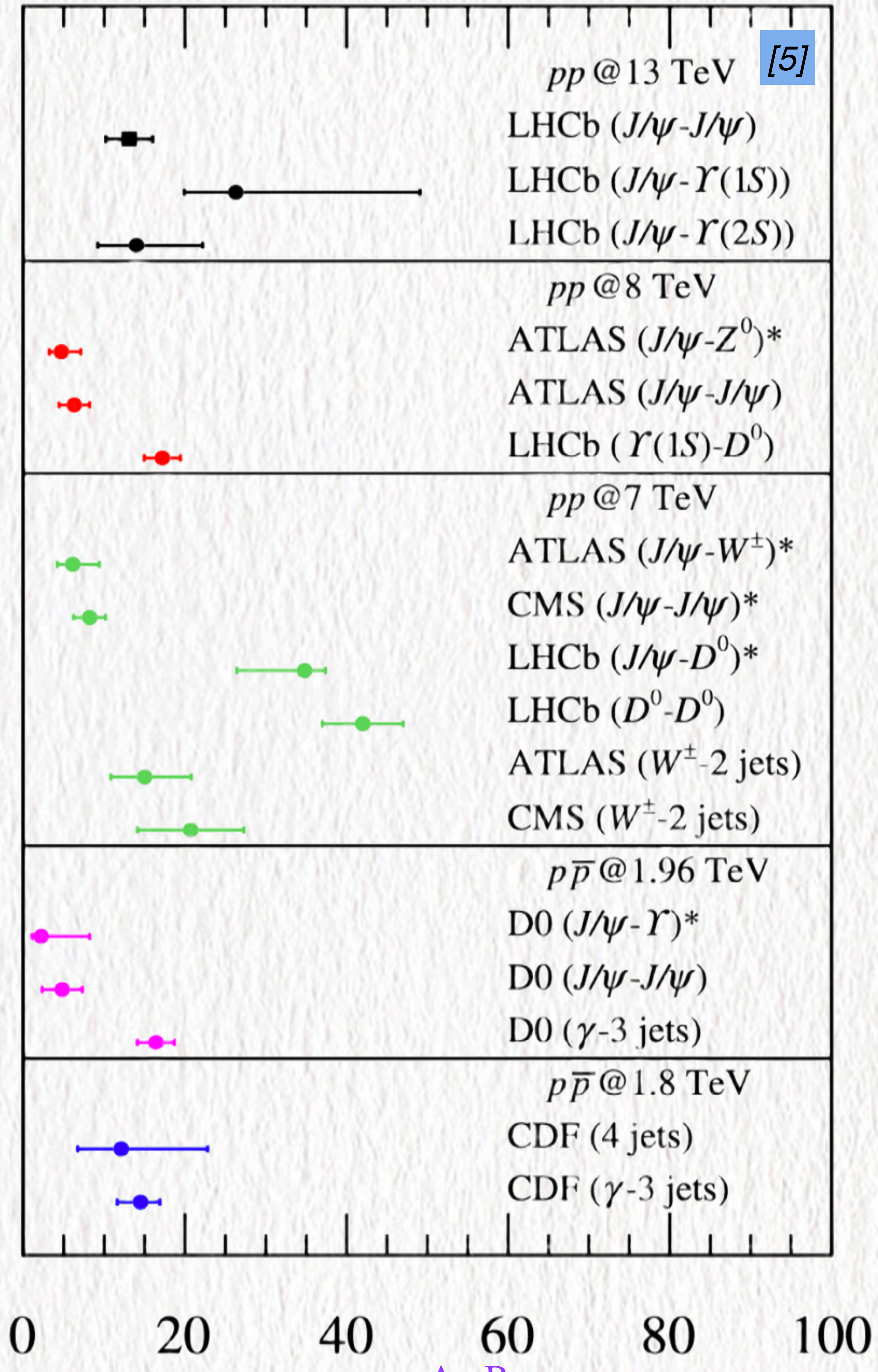
DPS



- Study the parton transverse profile and correlations[4]
  - Pocket formula: $\sigma_{\text{eff}} = \frac{1}{1+\delta_{\text{AB}}}\frac{\sigma^{\text{A}}\sigma^{\text{B}}}{\sigma^{\text{AB}}_{\text{DPS}}}$, $\delta_{\text{AB}} = 1$ if $A = B$ else 0
- Improve our understanding of the background ($Z + b\bar{b}$, $W^+ + W^+$ etc.) in searches for new physics

[1] JPL et al., PLB 784 (2018) 217
[2] CMS Collaboration, JHEP 06 (2017) 247
[3] JPL et al., Eur.Phys.J.C 79 (2019) 12, 1006
[4] G. Calucci et al., Phys.Rev.D 57 (1998) 503-511

Effective cross-section summary



$$\sigma_{\mathrm{eff}} = \frac{1}{1+\delta_{\mathrm{AB}}}\frac{\sigma^{\mathrm{A}}\sigma^{\mathrm{B}}}{\sigma^{\mathrm{AB}}_{\mathrm{DPS}}}$$

- The general purpose of DPS measurements is to measure the σ_{eff}
  - Commonly used in phenomenological models
  - Considered **independent of the process and energy** in the simplest possible models
  - Measurements show **process-dependent differences**
  - **Aim to validate its universality or probe its dependence on process and energy**
- The production of charm-hadron pairs at ALICE will serve as important input

[5] LHCb Collaboration, JHEP 03 (2024) 088

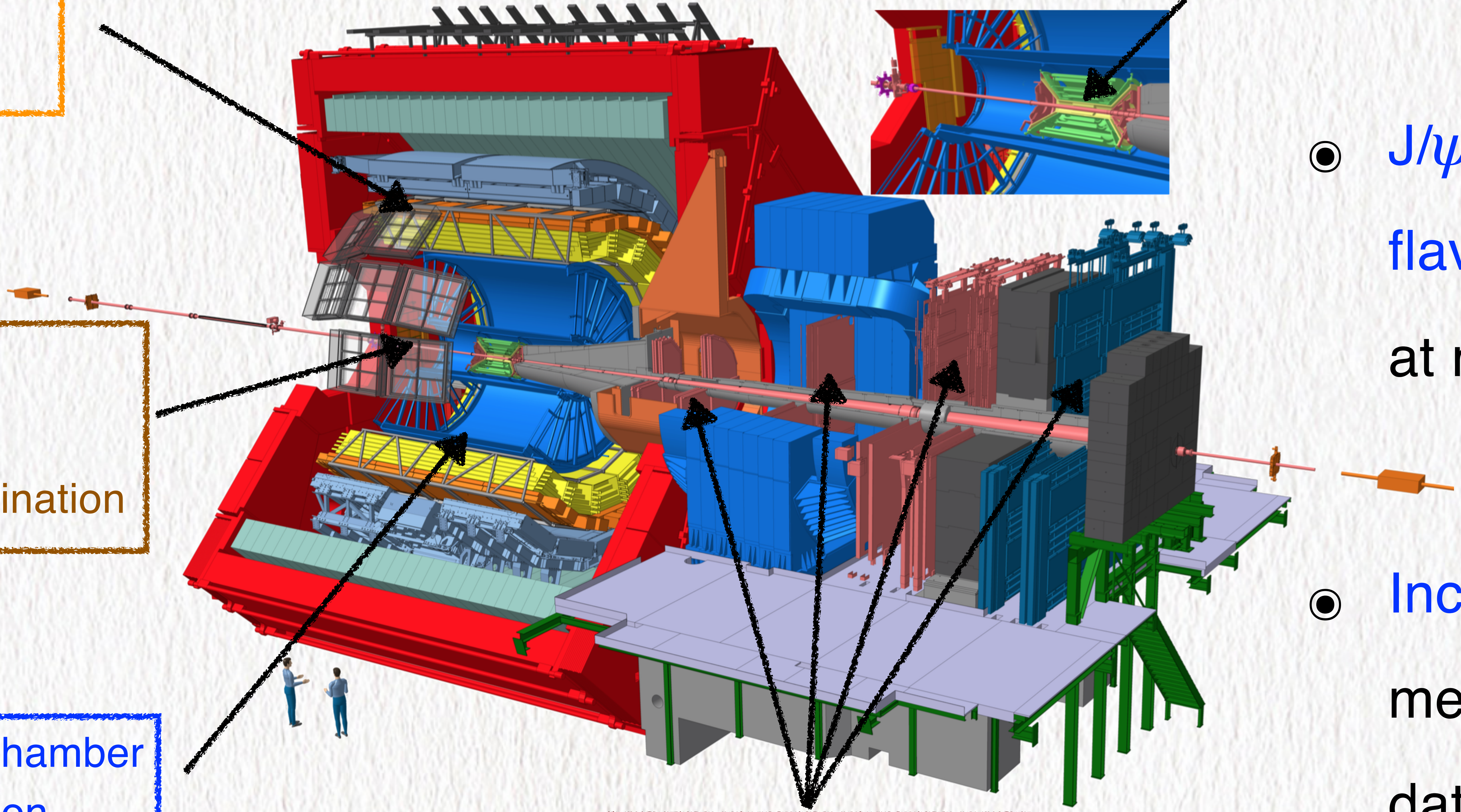
The ALICE detector (Run 2)

Time-Of-Flight
Particle identification

V0
Trigger
Centrality determination

Time Projection Chamber
Track reconstruction
Particle identification

Inner Tracking System
Track reconstruction
Vertex reconstruction



$\mu^{\pm}$ spectrometer
Trigger and Tracking

- $J/\psi \rightarrow e^{+}e^{-}$ and open heavy-flavour states measurements at midrapidity ($|y| < 0.9$)
- Inclusive $J/\psi \rightarrow \mu^{+}\mu^{-}$ measurements with di-μ triggered data at forward rapidity ($2.5 < y < 4.0$)

During Run 2, ALICE already conducted measurements of J/ψ pair production at forward rapidity ($2.5 < y < 4.0$)

J/ψ–J/ψ at forward rapidity: analysis strategy

Loop over all combinations of double di-μ pairs in the same event:

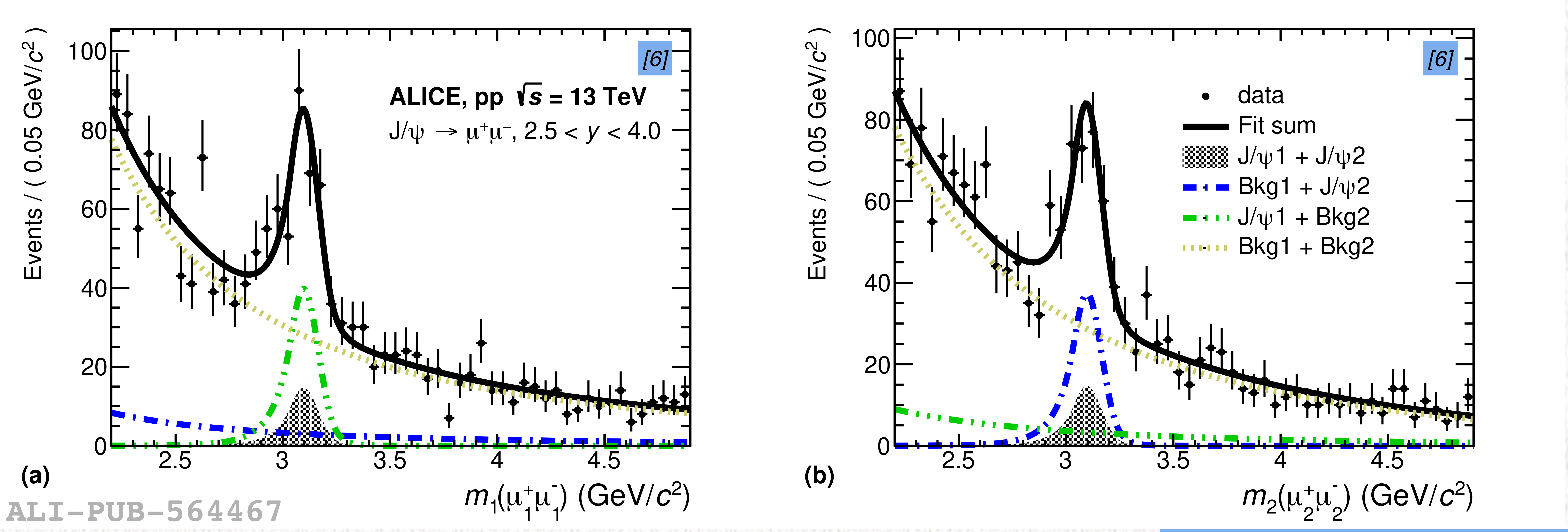
$2.5 < y_{\mu\mu} < 4.0$

- Compute the 2D invariant mass spectrum
  - Arbitrary ordering between the double di-μ pairs
- Model the 2D spectrum with J/ψ shape constrained from the J/ψ standard alone analysis

$$F(m_1, m_2) = N_{S_1^{J/\psi}, S_2^{J/\psi}} \times S_1^{J/\psi}(m_1) \times S_2^{J/\psi}(m_2) + N_{B_1^{J/\psi}, S_2^{J/\psi}} \times B_1^{J/\psi}(m_1) \times S_2^{J/\psi}(m_2) + N_{S_1^{J/\psi}, B_2^{J/\psi}} \times S_1^{J/\psi}(m_1) \times B_2^{J/\psi}(m_2) + N_{B_1^{J/\psi}, B_2^{J/\psi}} \times B_1^{J/\psi}(m_1) \times B_2^{J/\psi}(m_2)$$

Di-J/ψ
Mixed signals and background
Double backgrounds

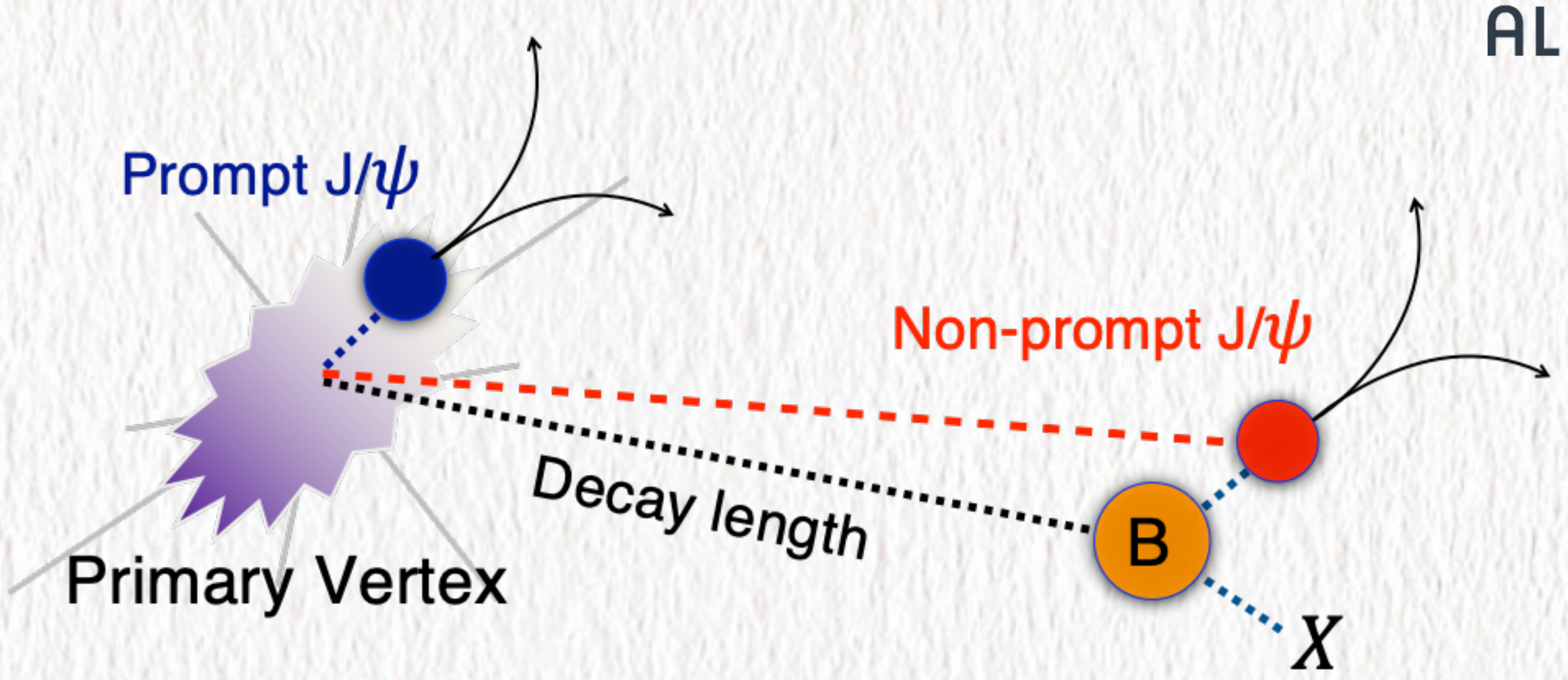
- Acceptance-times-efficiency correction and lumi. normalisation



[6] ALICE Collaboration, Phys.Rev.C 108 (2023) 045203

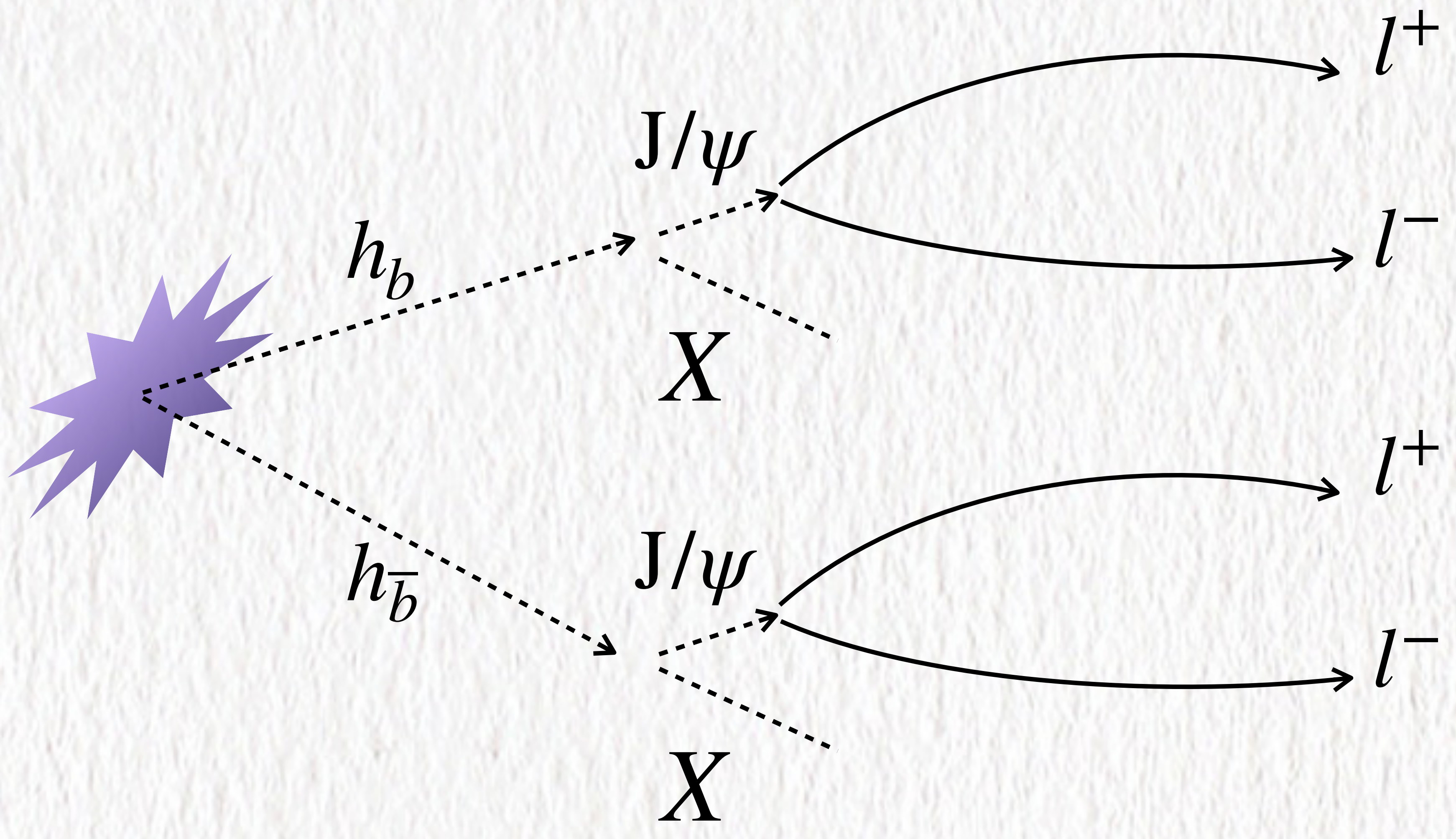
Estimation of the non-prompt contribution

- Inclusive $\sigma(\mathrm{J}/\psi, \mathrm{J}/\psi)$ = 10.3 ± 2.3 (stat.) ± 1.3 (syst.) nb [6]



Estimation on the non-prompt contribution

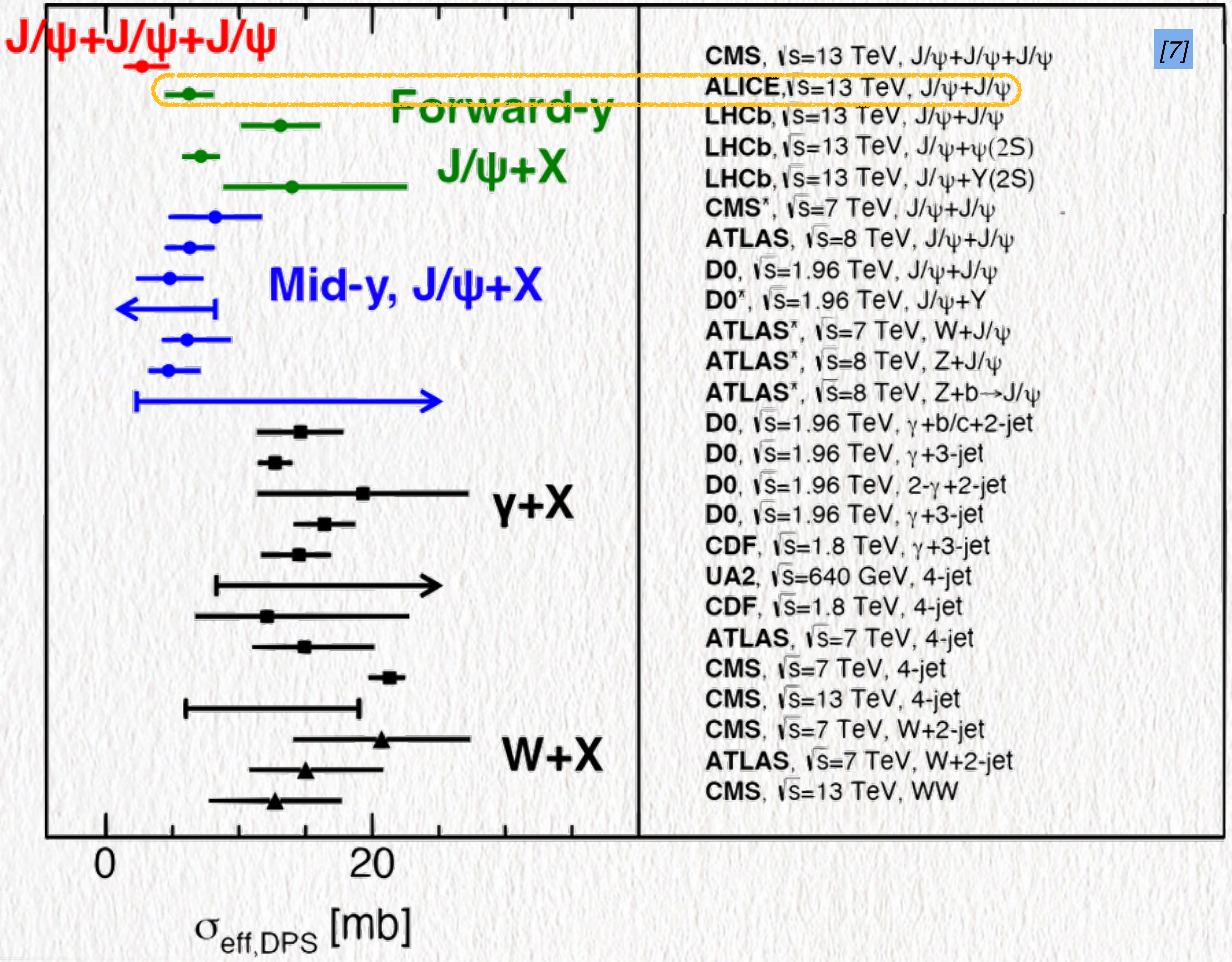
- For single J/ψ production:
  - $\sigma_{\text{non-prompt}}(\mathrm{J}/\psi) = 2 \times \sigma_{\mathrm{b\bar{b}}}^{\text{total}} \times \beta \times B\left(h_{\mathrm{b}} \to \mathrm{J}/\psi + \mathrm{X}\right)$, β is the acc. simulated by PYTHIA 8
  - $\boxed{\sigma_{\text{prompt}}(\mathrm{J}/\psi) = \sigma_{\text{inclusive}}(\mathrm{J}/\psi) - \sigma_{\text{non-prompt}}(\mathrm{J}/\psi)}$



- For the J/ψ pair production:
  - $\sigma_{\text{non-prompt}}(\mathrm{J}/\psi, \mathrm{J}/\psi) = \sigma_{\mathrm{b\bar{b}}}^{\text{total}} \times \alpha \times B^2\left(h_b \to \mathrm{J}/\psi + \mathrm{X}\right)$, α is the acc.
  - $\boxed{\sigma_{\text{prompt}}(\mathrm{J}/\psi, \mathrm{J}/\psi) = \sigma_{\text{inclusive}}(\mathrm{J}/\psi, \mathrm{J}/\psi) - \sigma_{\text{non-prompt}}(\mathrm{J}/\psi, \mathrm{J}/\psi)}$

[6] ALICE Collaboration, Phys.Rev.C 108 (2023) 045203

Estimation on the eff. σ and Results discussion



- Assuming solely DPS production, one can calculate the σ_{eff} using the prompt sources

$$\frac{1}{2}\frac{\sigma_{\text{prompt}}(J/\psi)^2}{\sigma_{\text{prompt}}(J/\psi, J/\psi)} = 6.7 \pm 1.6\,(\text{stat.}) \pm 2.7\,(\text{syst.})\ \text{mb}$$

It is an approximation, since we should expect the SPS as well

- First charmonium pair production measurement in ALICE
- Despite caveats from SPS and DPS contributions, this effective value aligns with quarkonium-pair production measurements

ALICE requires more precise measurements

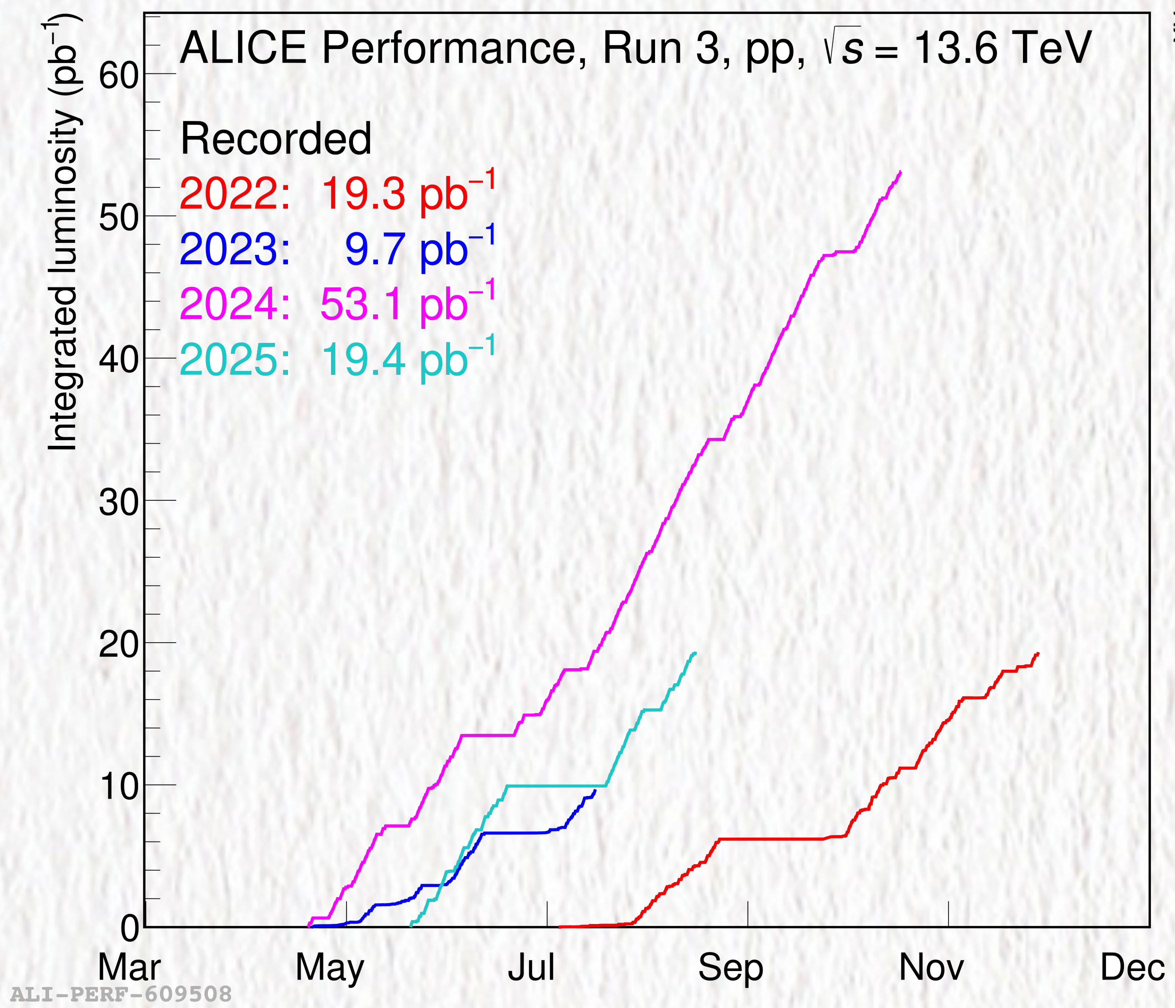
[7] QM2023, Andre Ståhl talk

ALICE detector upgrades for Run 3

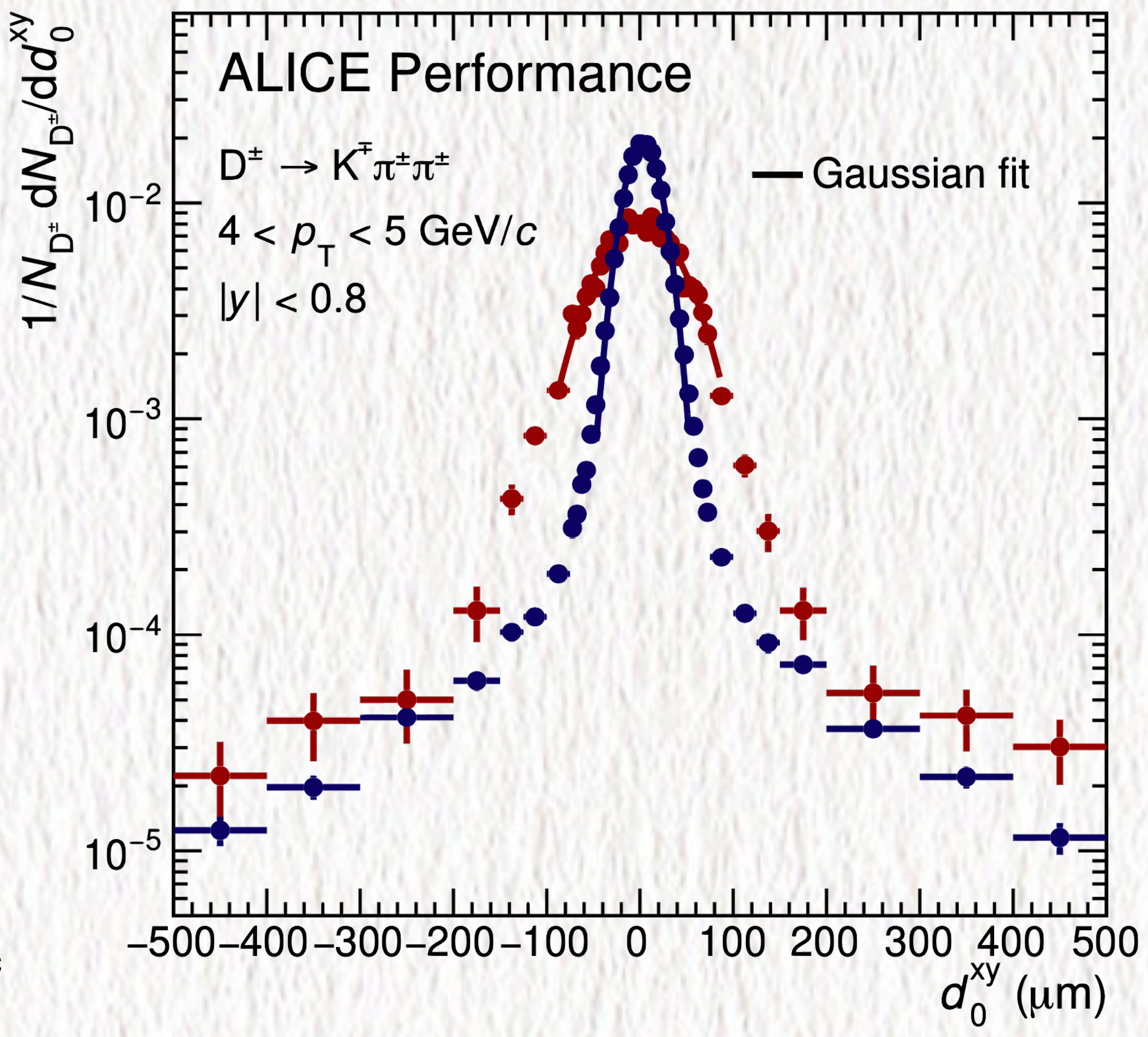
Major upgrade of the ALICE detector (2019-2021), and in production since 2022

- Continuous readout: up to 500 kHz in pp and 50 kHz in Pb–Pb
  - Full Online and Offline software upgrade (O^2)
- Already now improvement 2–3 times in x-y direction and 5–6 in z direction
- Secondary vertexing at forward rapidity

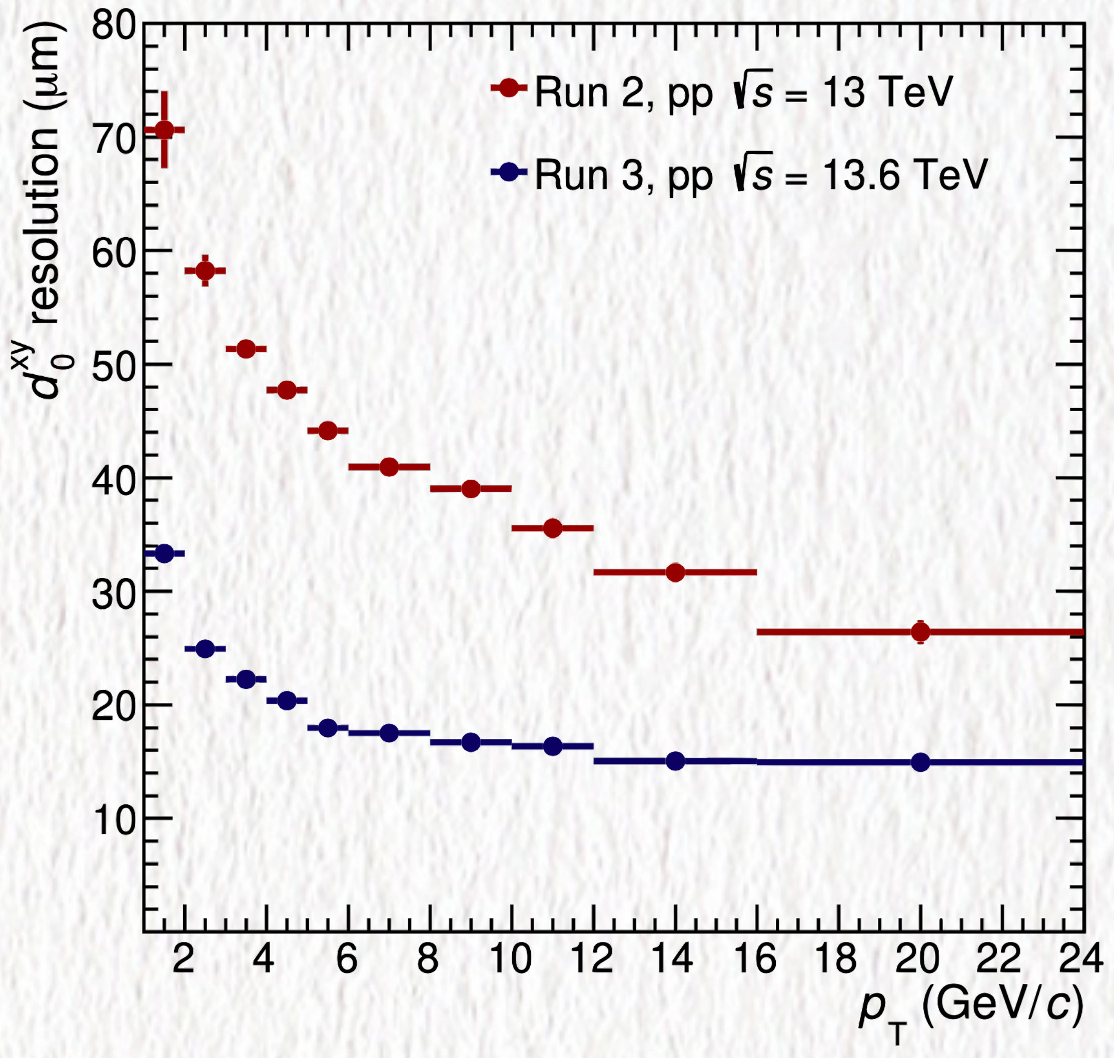
Excellent performance across all upgraded detectors

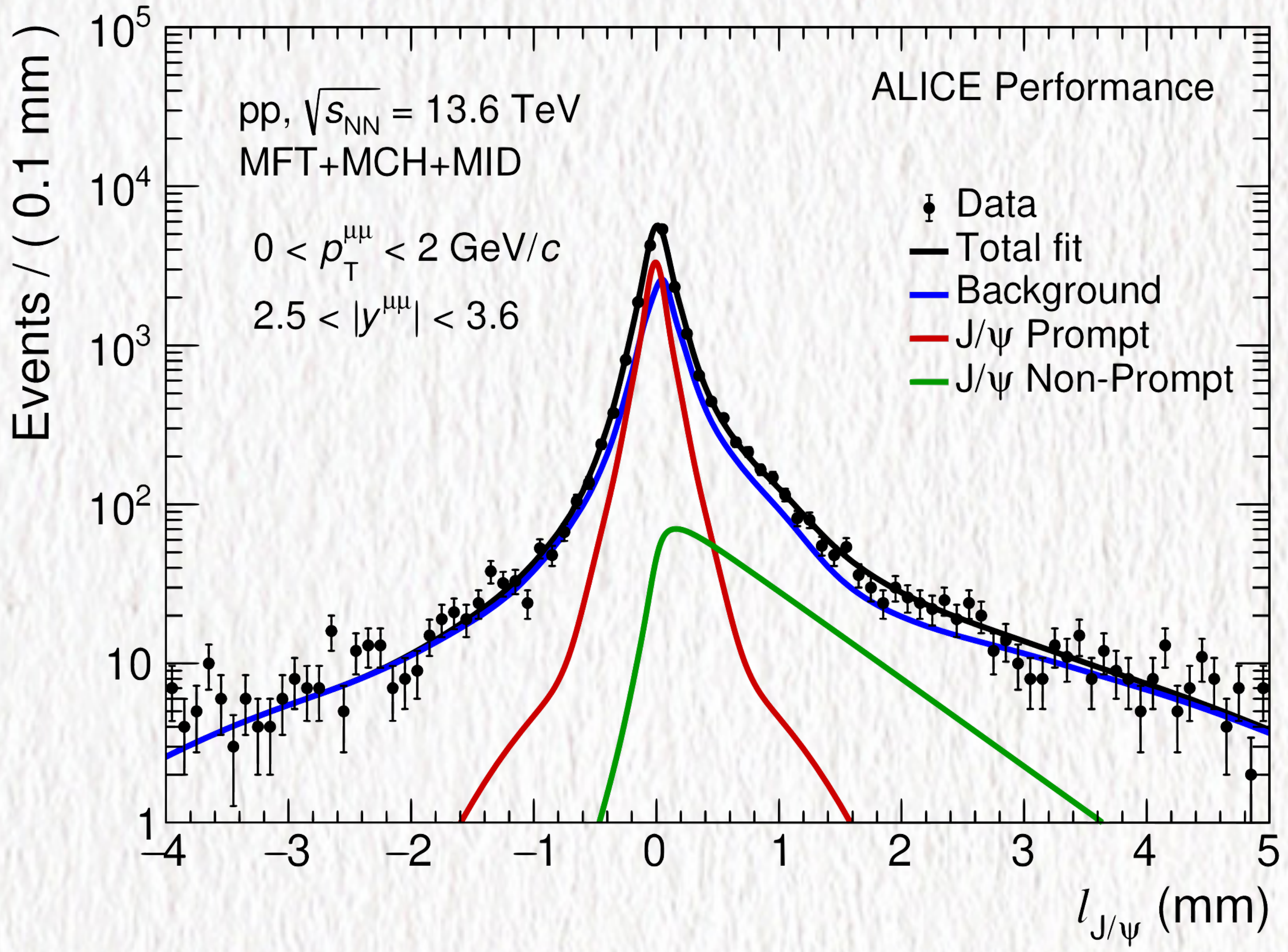


ALI-PERF-609508



ALI-PERF-577966





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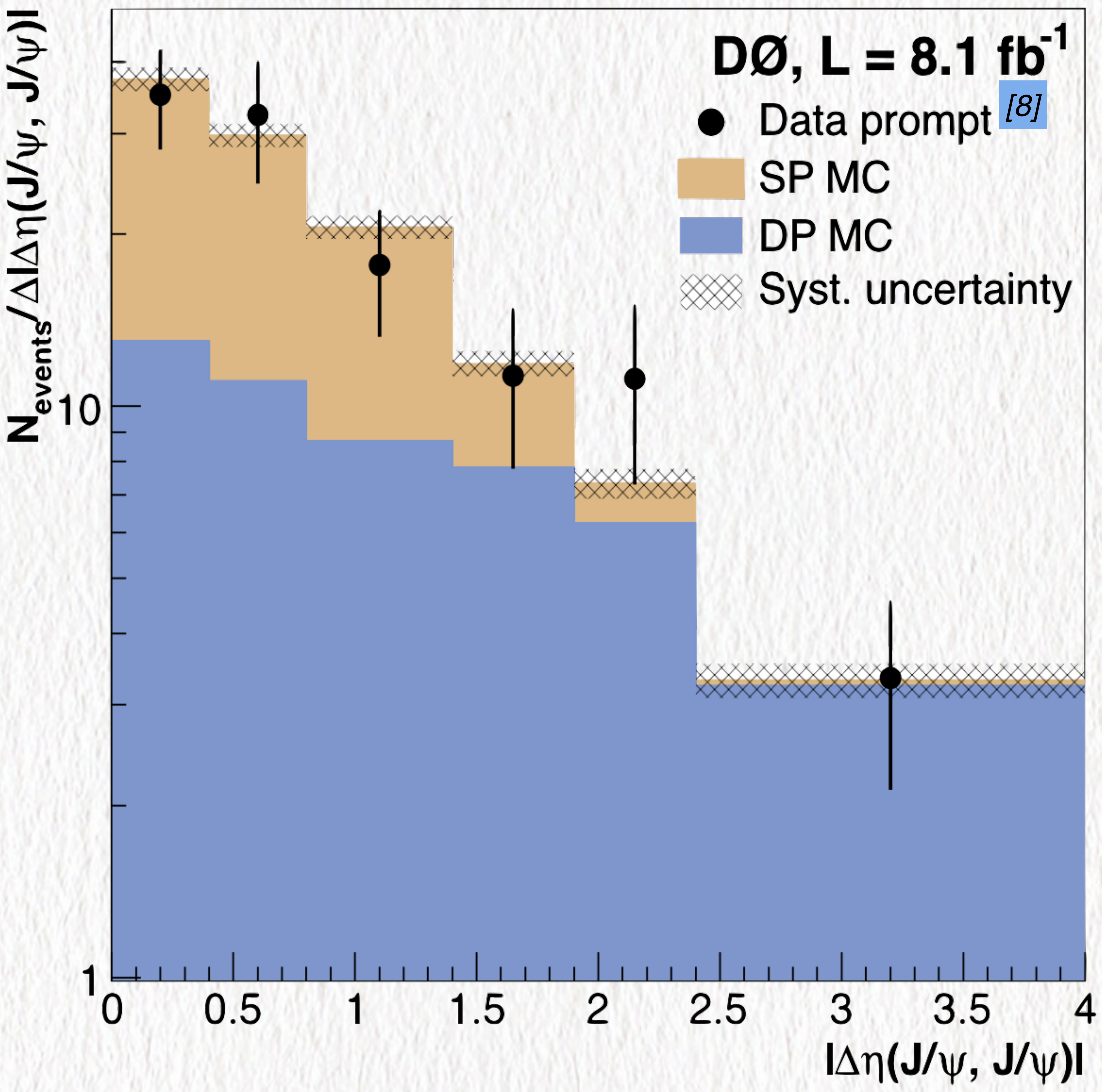
Opportunities on ALICE Run 3

- In Run 3, ALICE has the possibility to conduct many new analyses, such as:
  - Combined analyses of the central barrel – μ spectrometer ($D^0(|y| < 0.6)$–$J/\psi(2.5 < y < 4.0)$)
  - Prompt/non-prompt separation for forward rapidity J/ψ reconstruction
- SPS –DPS separation sensitive to Δy
- Exploit ALICE's unique capabilities at the LHC to extend Δy coverage up to ~ 5



[8] D0 Collaboration, Phys. Rev. D 90, 111101

J/ψ–D⁰ production in Run 3

- Use the ALICE **Offline Trigger Selection** to select J/ψ candidates, which are later paired to D⁰ candidates
- Adopt a **Machine Learning** based approach for D⁰ selection

- Analysis strategies:
  - Yields extracted using a two-dimensional invariant mass fit
  - $A \times \epsilon$ correction performed on a candidate-by-candidate basis
  - Prompt D⁰ fraction extracted using a data-driven method

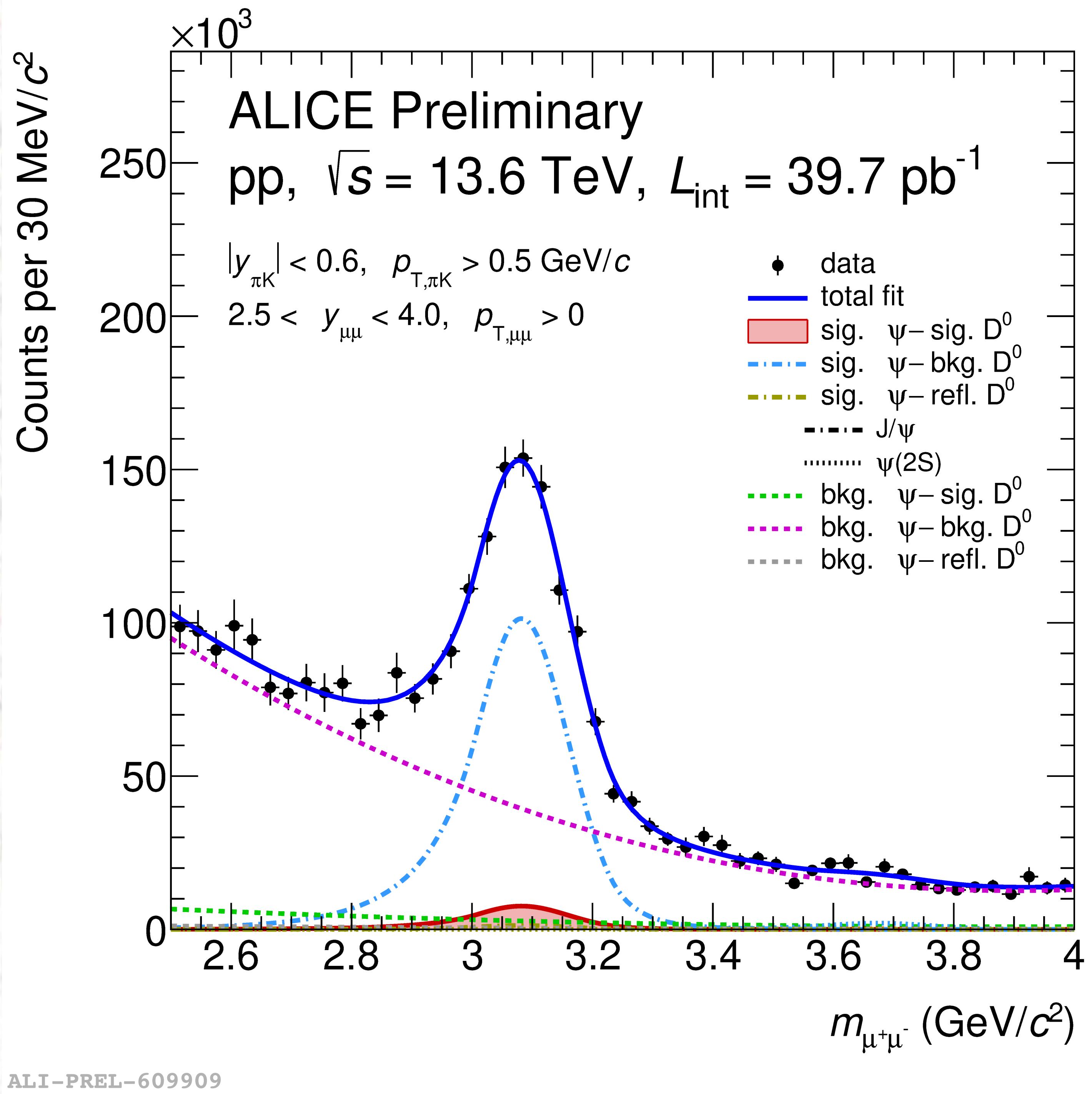
See more in backup

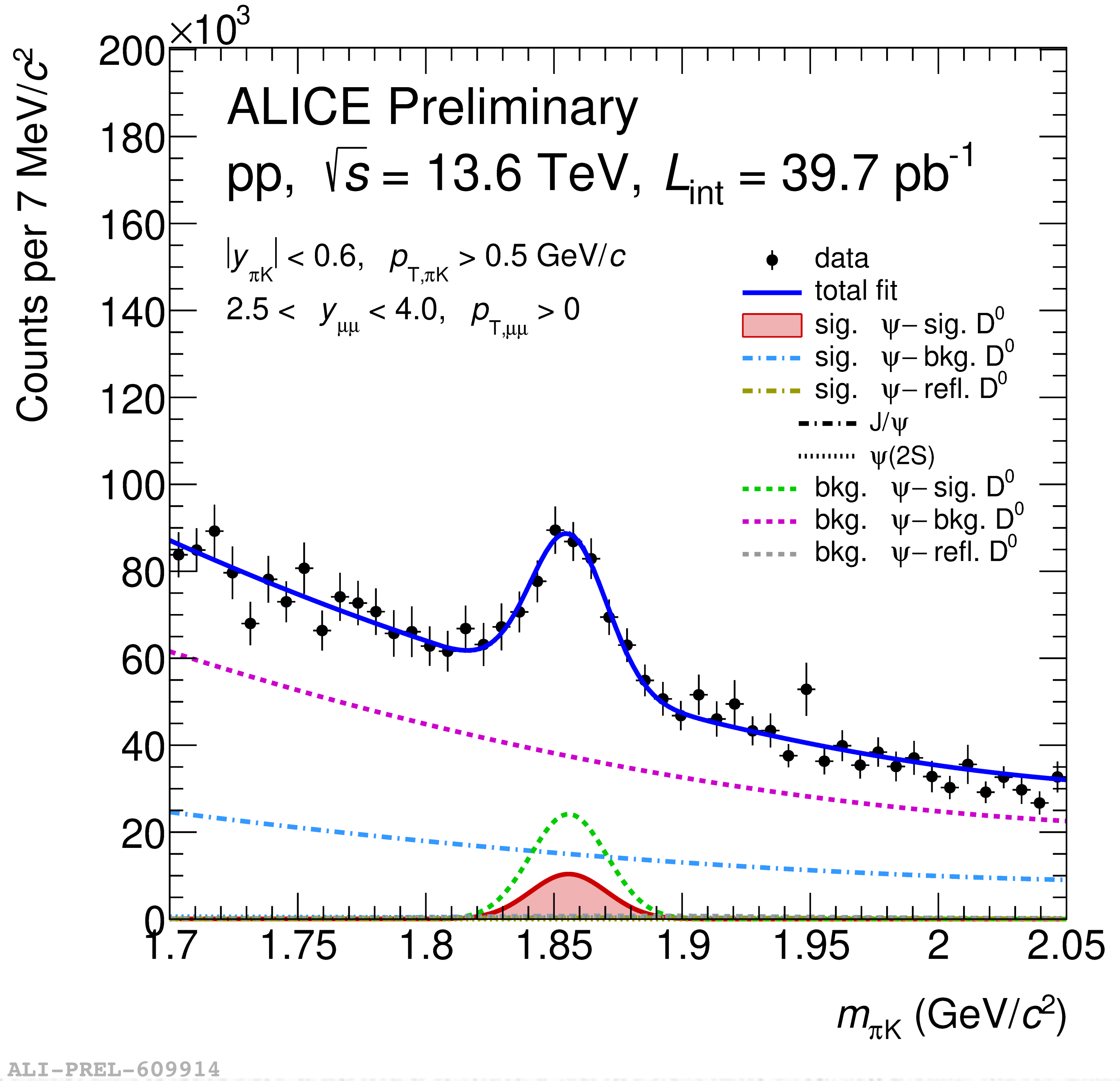
pp collisions at $\sqrt{s}$ = 13.6 TeV

Selected channels:

$J/\psi \to \mu^+\mu^-$ (2.5 $< y <$ 4.0, $p_T > 0$)

$D^0 \to K^-\pi^+$ ($|y| <$ 0.6, $p_T >$ 0.5 GeV/c)

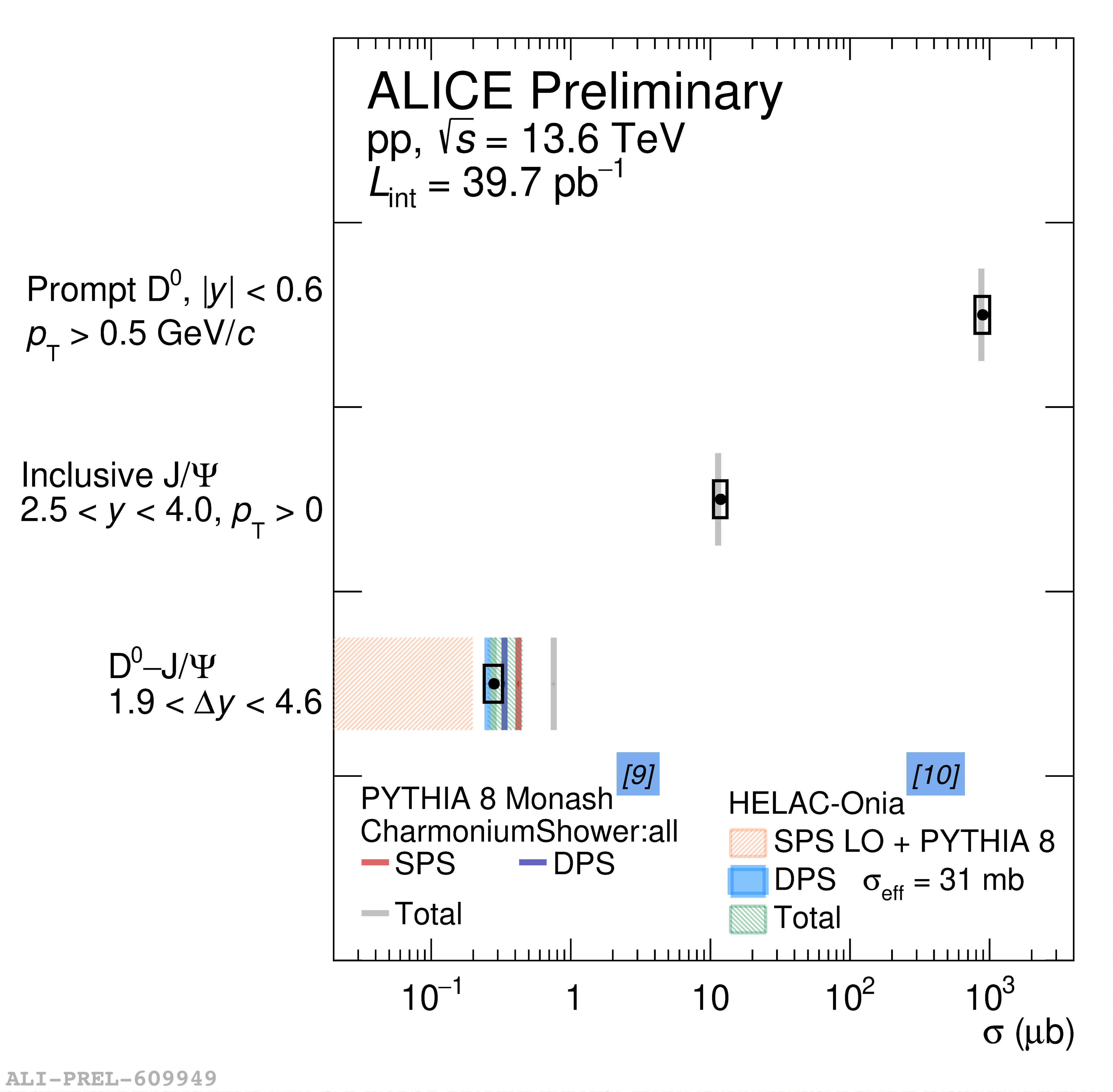




$1.9 < |\Delta y(J/\psi, D^0)| < 4.6$

*reflection: D⁰($\to K^-\pi^+$and c.c.) built with the wrong mass hypothesis

J/ψ–D^0 cross section



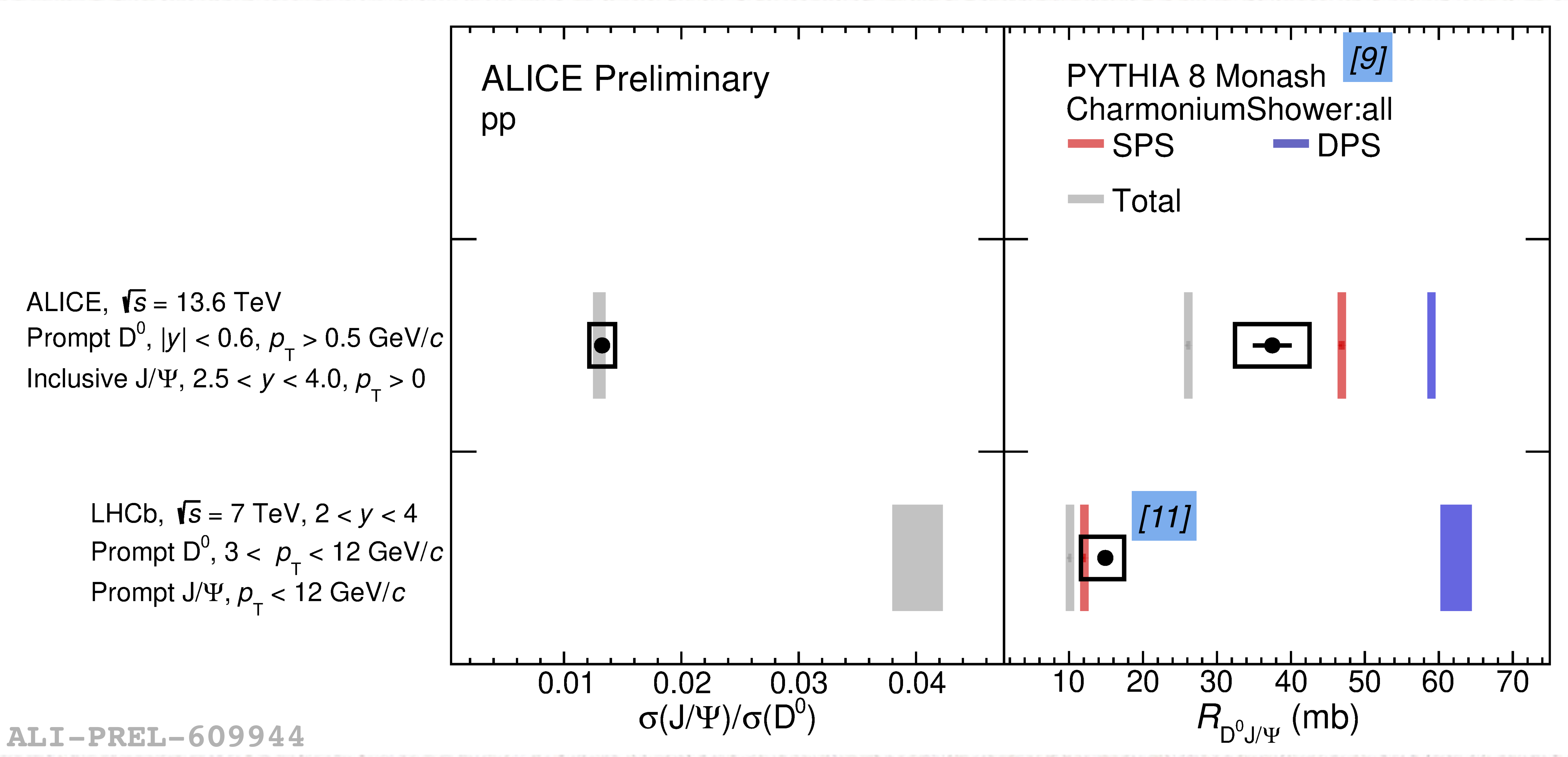
- p_{T}-integrated associated cross section compared to the single prompt D^0 and inclusive J/ψ cross sections and theoretical predictions
- PYTHIA 8 simulations:

  (Monash tune + CharmoniumShower:all)
  - Compatible with single $\sigma_{\mathrm{D}^0}^{\mathrm{prompt}}$ and $\sigma_{\mathrm{J}/\psi}^{\mathrm{inclusive}}$
  - Overestimate the $\sigma_{\mathrm{D}^0-\mathrm{J}/\psi}$
- HELAC-onia:

  See more in backup
  - Reproduce the considering a σ_{eff} = 31 mb
  - Large $\sigma_{\mathrm{D}^0-\mathrm{J}/\psi}$ uncertainties from SPS (LO+PYTHIA 8) calculations → to be improved using NLO calculations

[9] Torbjörn Sjöstrand et al., Comput.Phys.Commun. 191 (2015) 159-177
[10] Hua-Sheng Shao, Comput.Phys.Commun. 184 (2013) 2562-2570

$\sigma(\mathrm{J}/\psi)/\sigma(\mathrm{D}^0)$ and $R_{\mathrm{D}^0\mathrm{J}/\psi}$

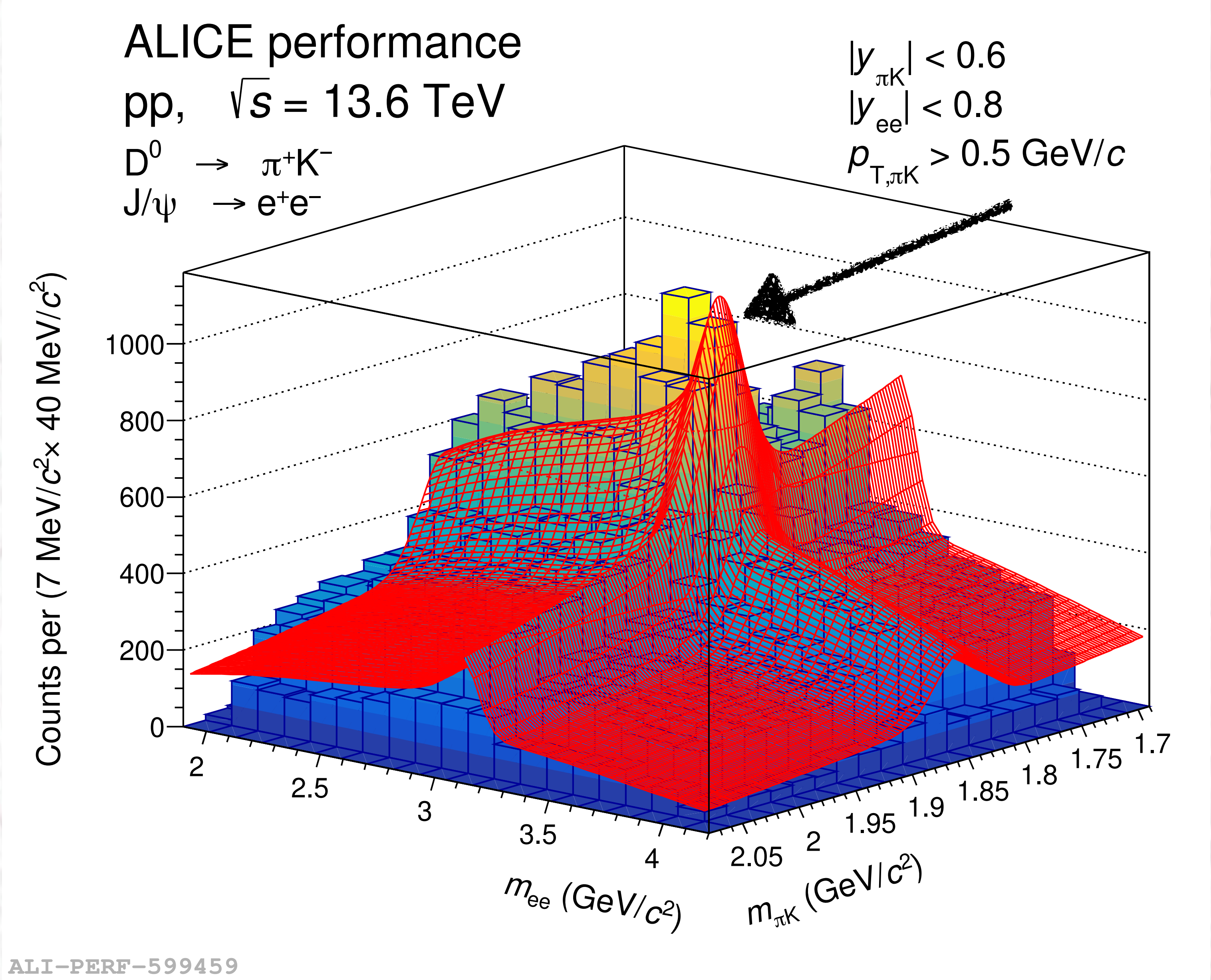


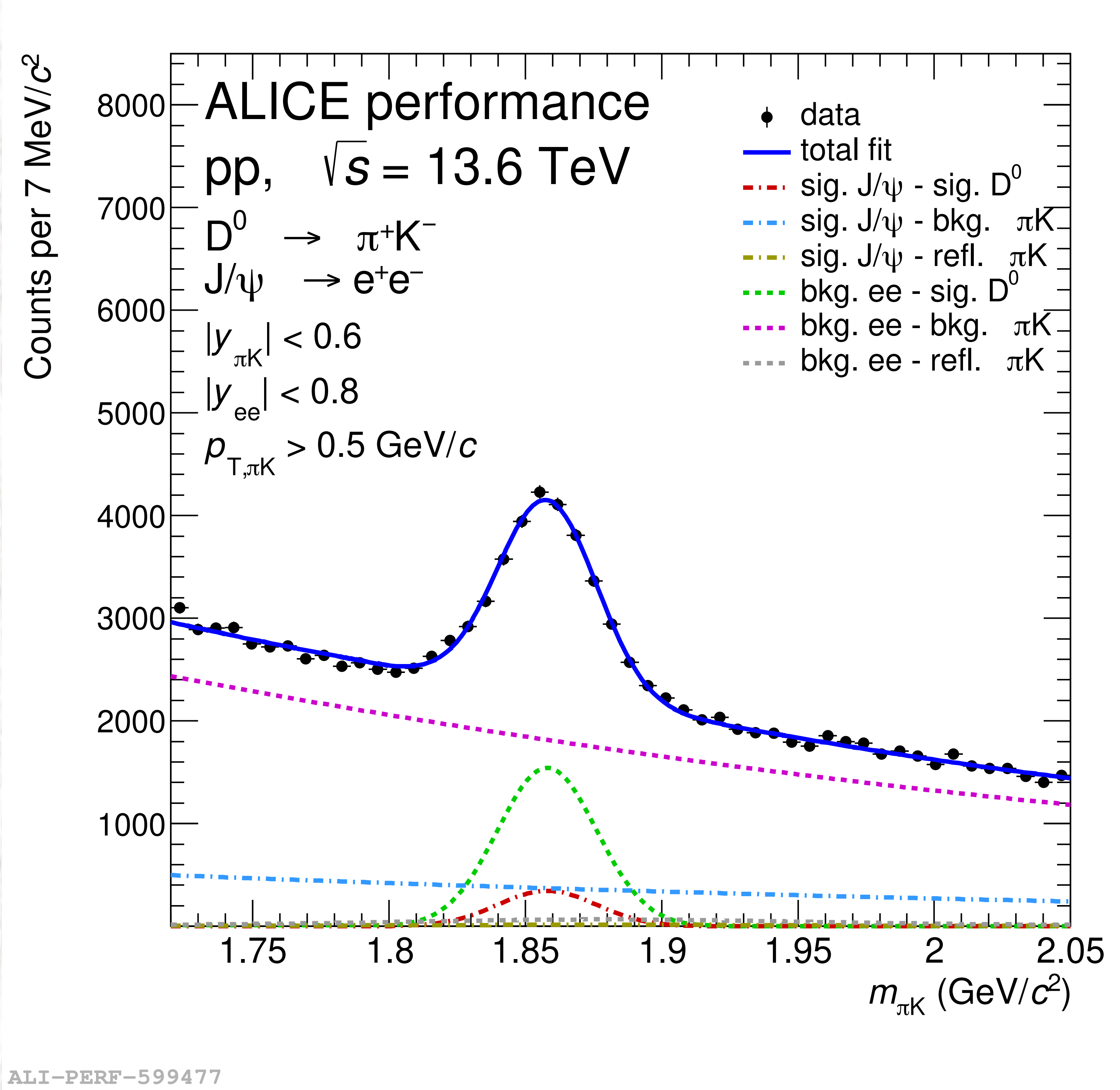
- **Left panel ($\sigma(\mathrm{J}/\psi)/\sigma(\mathrm{D}^0)$):**
  - Cancel the common initial-state effects
  - Compatible with PYTHIA 8 simulations (Monash+CharmoniumShower:all)
- **Right panel ($R_{\mathrm{D}^0\mathrm{J}/\psi}$):**
  - PYTHIA tends to underestimate the $R_{\mathrm{D}^0\mathrm{J}/\psi}$ results from both ALICE and LHCb

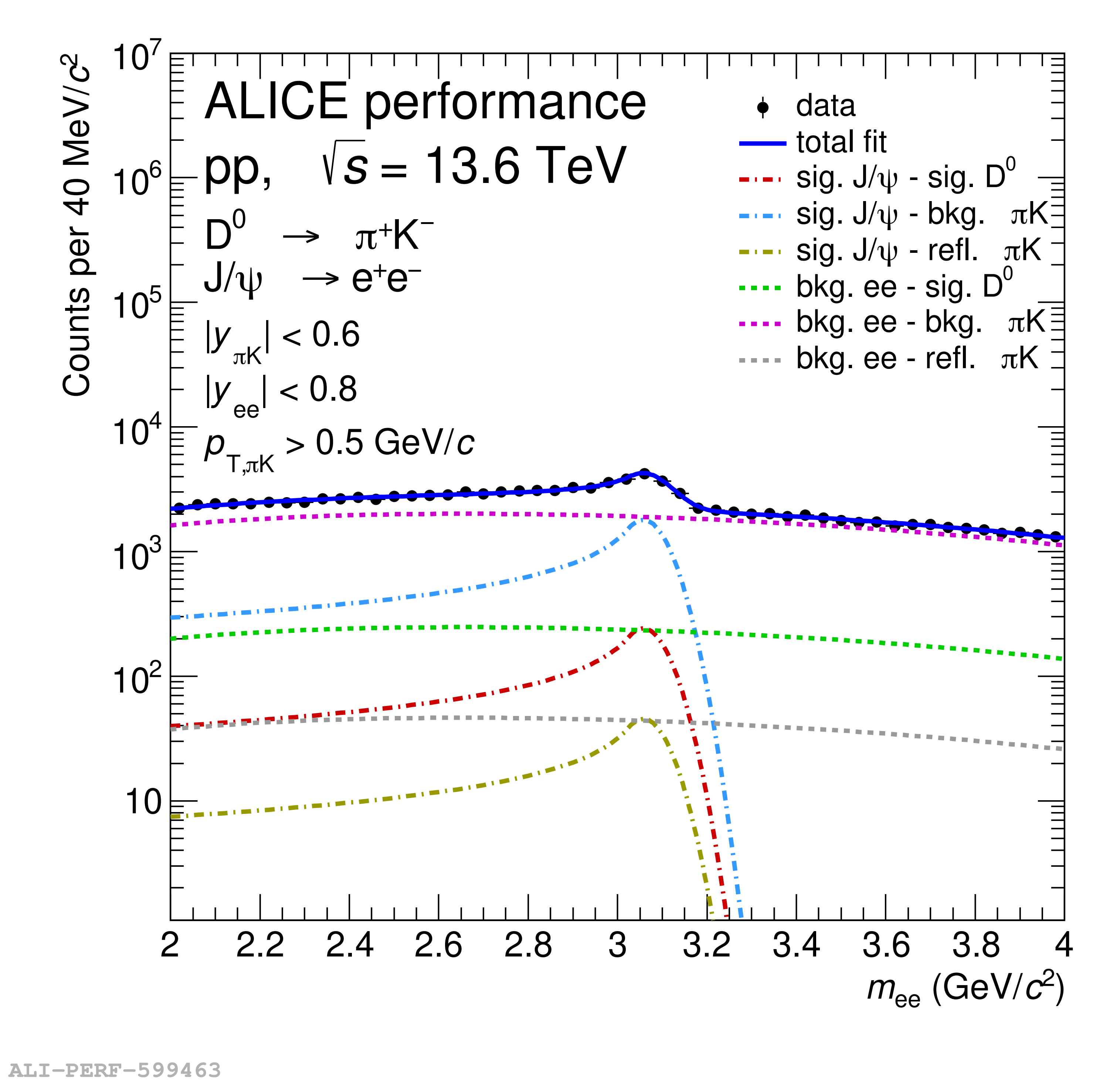
$$R_{\mathrm{D}^0\mathrm{J}/\psi} = \frac{\sigma(\mathrm{D}^0)\sigma(\mathrm{J}/\psi)}{\sigma(\mathrm{D}^0\mathrm{J}/\psi)}$$

[9] *Torbjörn Sjöstrand et al., Comput.Phys.Commun.* 191 (2015) 159-177
[11] LHCb Collaboration, JHEP 06 (2012) 141

J/ψ–D⁰ production at midrapidity







$J/\psi \rightarrow e^+e^-\ (|y| < 0.8)$
$D^0 \rightarrow K^-\pi^+\ (|y| < 0.6)$

- The associated production of J/ψ—D⁰ at midrapidity is on-going
- **Results will come soon…**

*reflection: D⁰($\rightarrow K^-\pi^+$ and c.c.) built with the wrong mass hypothesis

D^0–D^0 associated production

- Adopt a **Machine Learning** based approach for D^0 selection
- **Two types of pairs:** $\mathrm{D^0\overline{D}^0}$ (dominated by SPS contribution) and $\mathrm{D^0D^0}$ (both SPS and DPS)

- Similar Analysis strategies:
  - Yields extracted using a two-dimensional invariant mass fit
  - $\mathrm{A} \times \epsilon$ correction performed on a candidate-by-candidate basis
  - Prompt D^0 fraction extracted using a data-driven method

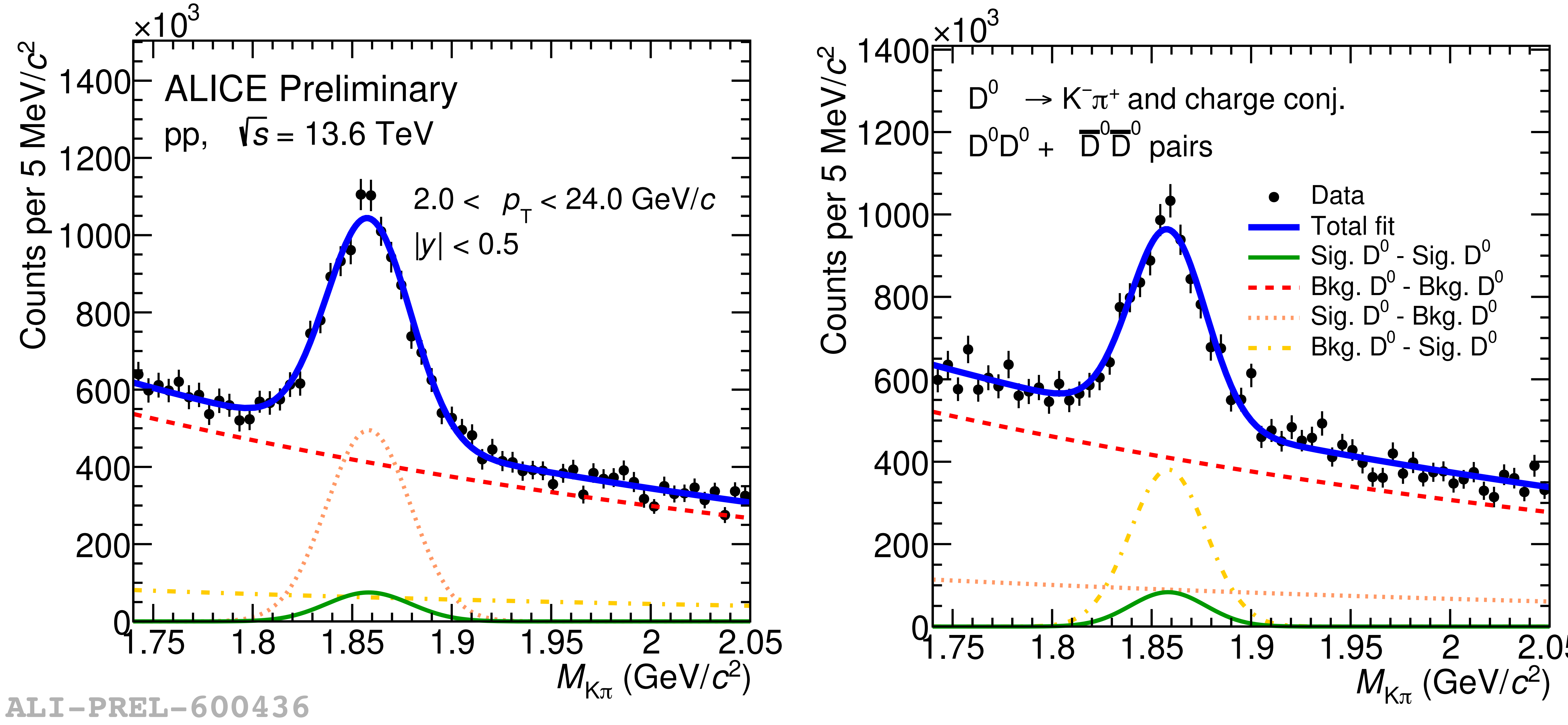
See more in backup

pp collisions at $\sqrt{s}$ = 13.6 TeV

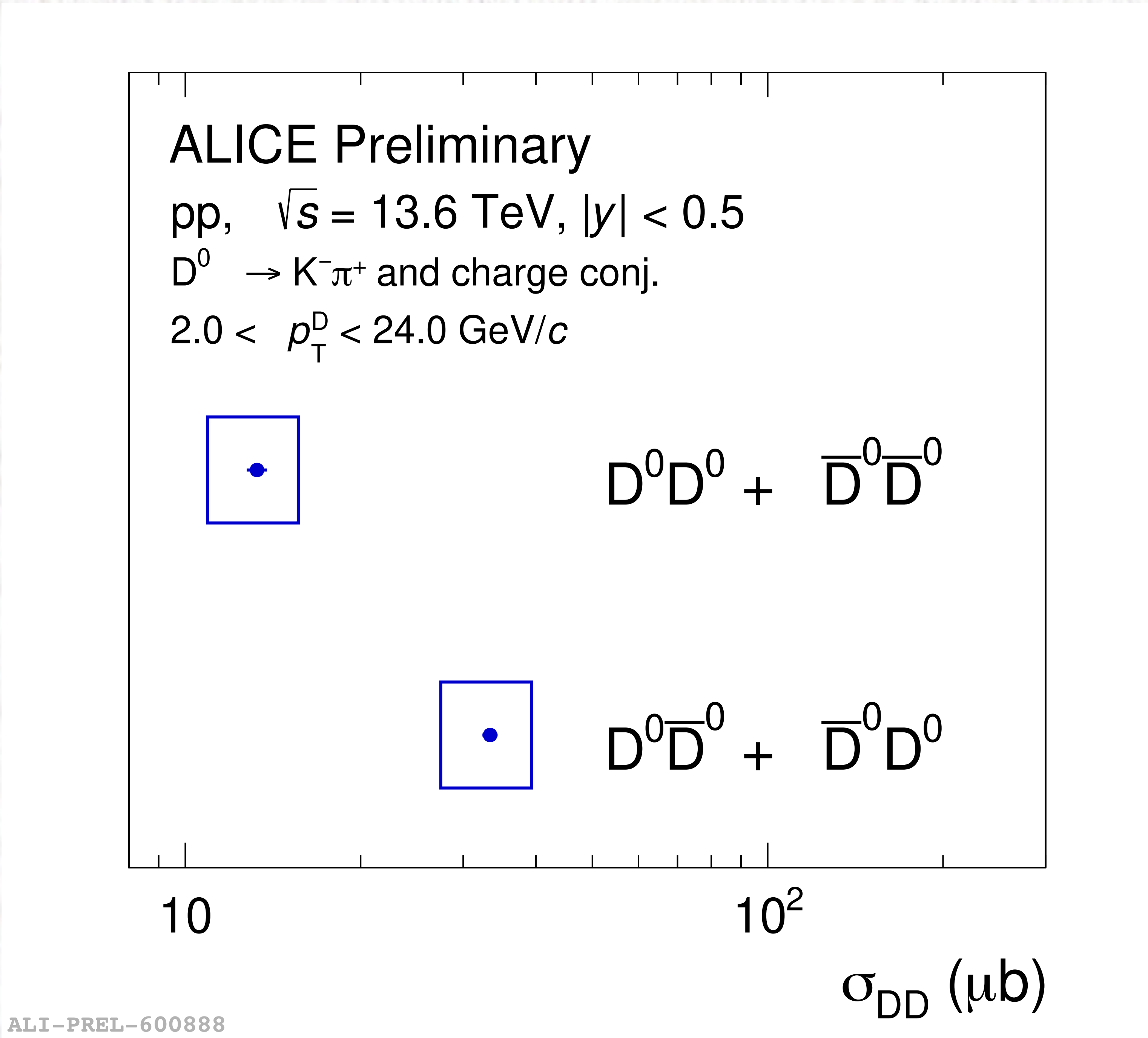
Selected channels:

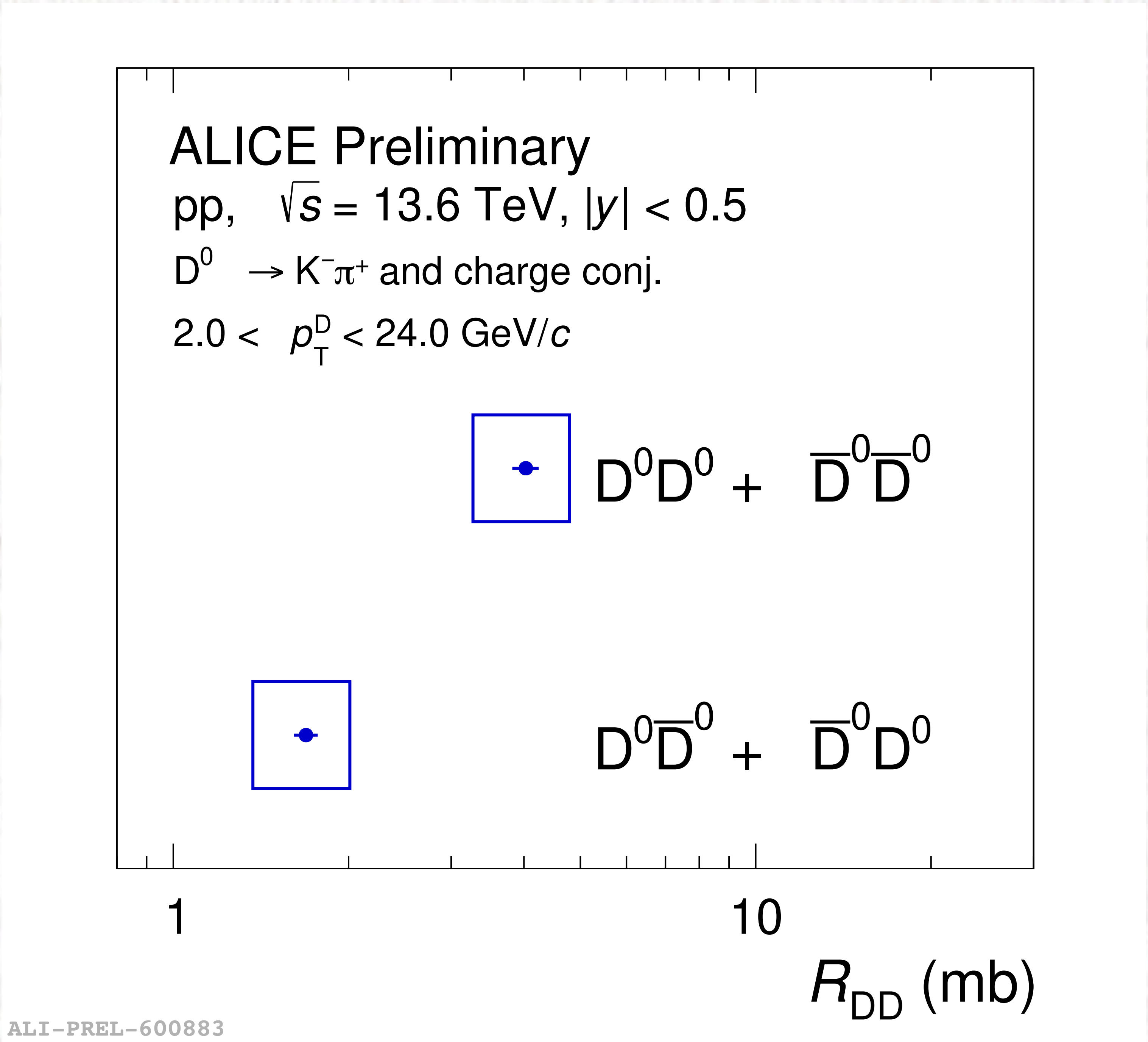
$\mathrm{D^0} \rightarrow \mathrm{K^-}\pi^+$ and its charge conjugation

$(|y| < 0.5, 2 < p_\mathrm{T} < 24$ GeV/c)



D^0 associated production cross section





$$R_{D^0D^0+\overline{D}^0\overline{D}^0} = \alpha \frac{\sigma(D^0+\overline{D}^0)\sigma(D^0+\overline{D}^0)}{\sigma(D^0D^0+\overline{D}^0\overline{D}^0)}$$

, $\alpha = 1/4$

- $\sigma_{DD}^{\text{prompt}} = \dfrac{N_{\text{corr.}} \cdot f_{\text{prompt}}^2}{BR^2\left(D^0 \rightarrow K^+\pi^-\right) \cdot \mathscr{L}_{\text{int}}}$
- Data-driven method to determine the f_{prompt}

See more in backup

- $R_{D^0D^0+\overline{D}^0\overline{D}^0}$ ~ the average of $\sigma_{\text{eff}}^{D^0D^0}$ and $\sigma_{\text{eff}}^{\overline{D}^0\overline{D}^0}$
- Single D^0 production cross section taken from measurement at 13 TeV [11]
- R_{DD} is of the same order of magnitude as the σ_{eff}

[12] ALICE Collaboration, JHEP. 2023, 86（2023)

Summary

- ALICE has a unique rapidity coverage to study MPIs via J/ψ–J/ψ, D^0–J/ψ, and D^0–D^0.
- Studies on **J/ψ–J/ψ production in Run 2** provided compatible results with previous measurements of open and hidden charm pair production, but limited by available dataset sizes
- Thanks to the detector upgrades and the large data samples in **ALICE Run 3**,
  - The **J/ψ–D^0 and D^0–D^0** measurements offer new possibilities to compute the σ_{eff}
  - Extend the Δy coverage up to $\sim$ 5 for SPS and DPS separation

Thank you for your attention!

Additional slides

The cut-variation method

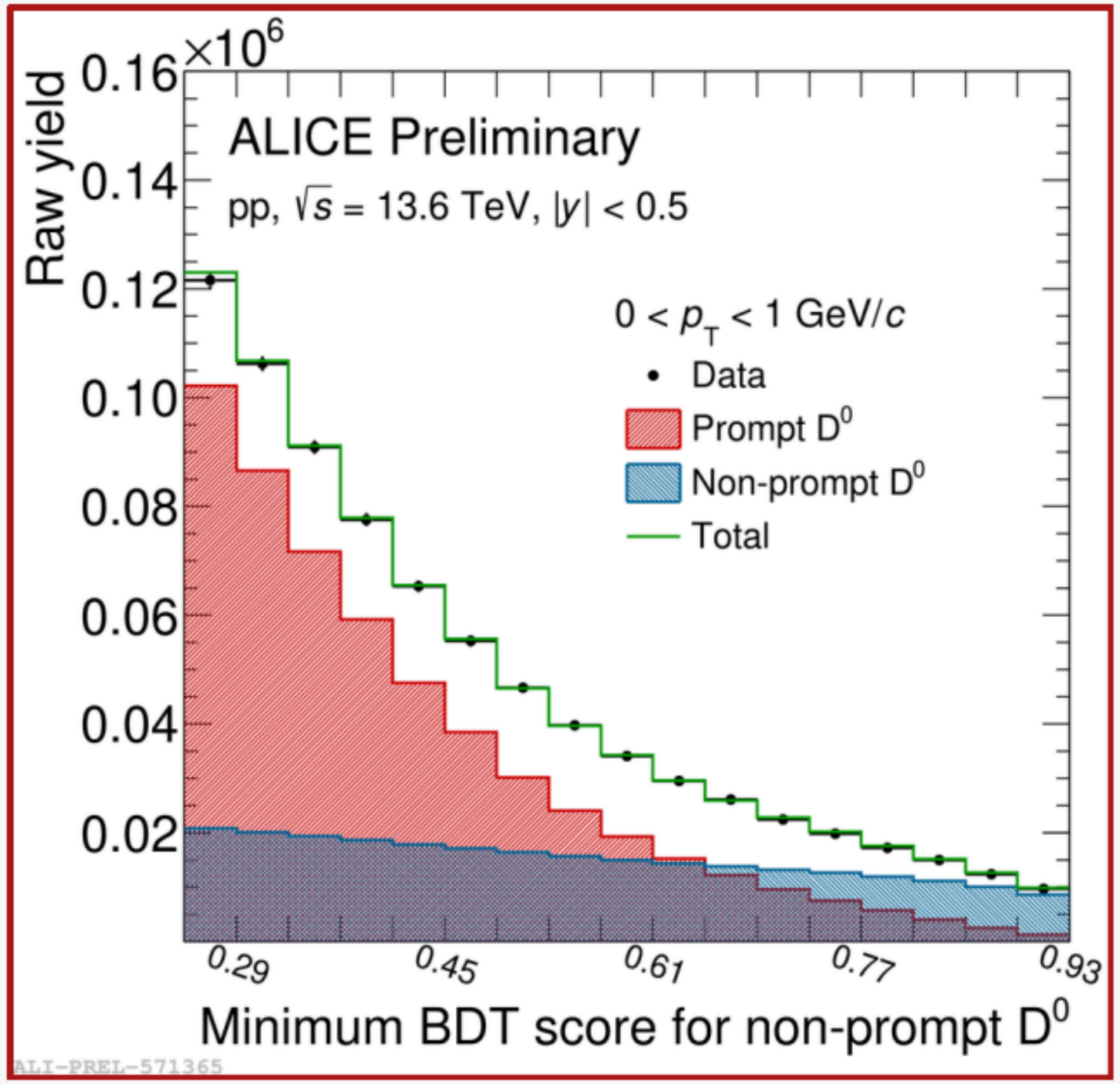
A data-driven procedure to extract the (non-)prompt fraction

- Procedure based on **solving a set of equations** of the form:

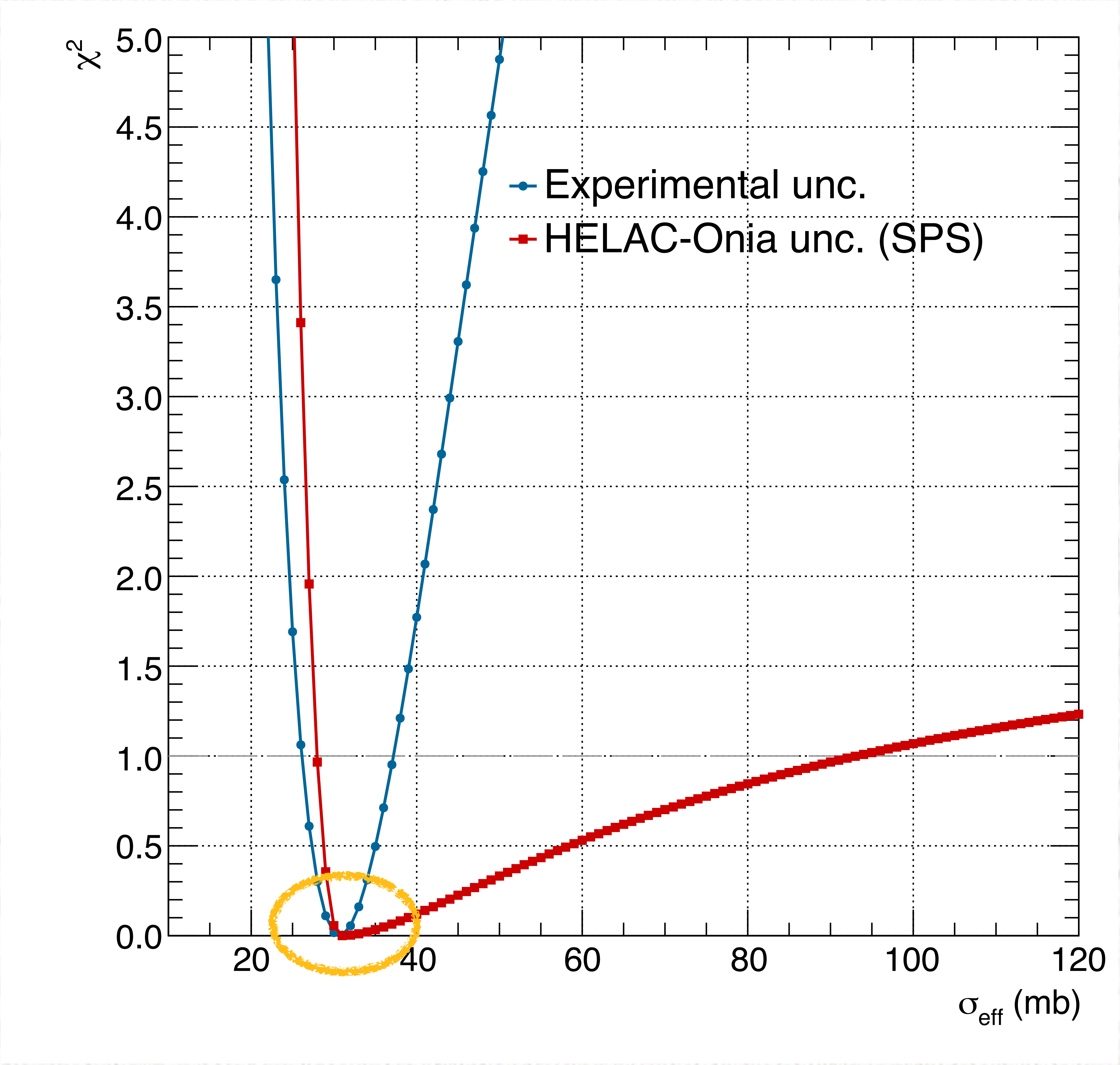
$$(\mathrm{Acc} \times \epsilon)_i^{\mathrm{prompt}} \cdot N_{\mathrm{prompt}} + (\mathrm{Acc} \times \epsilon)_i^{\mathrm{non\text{-}prompt}} \cdot N_{\mathrm{non\text{-}prompt}} = Y_i$$

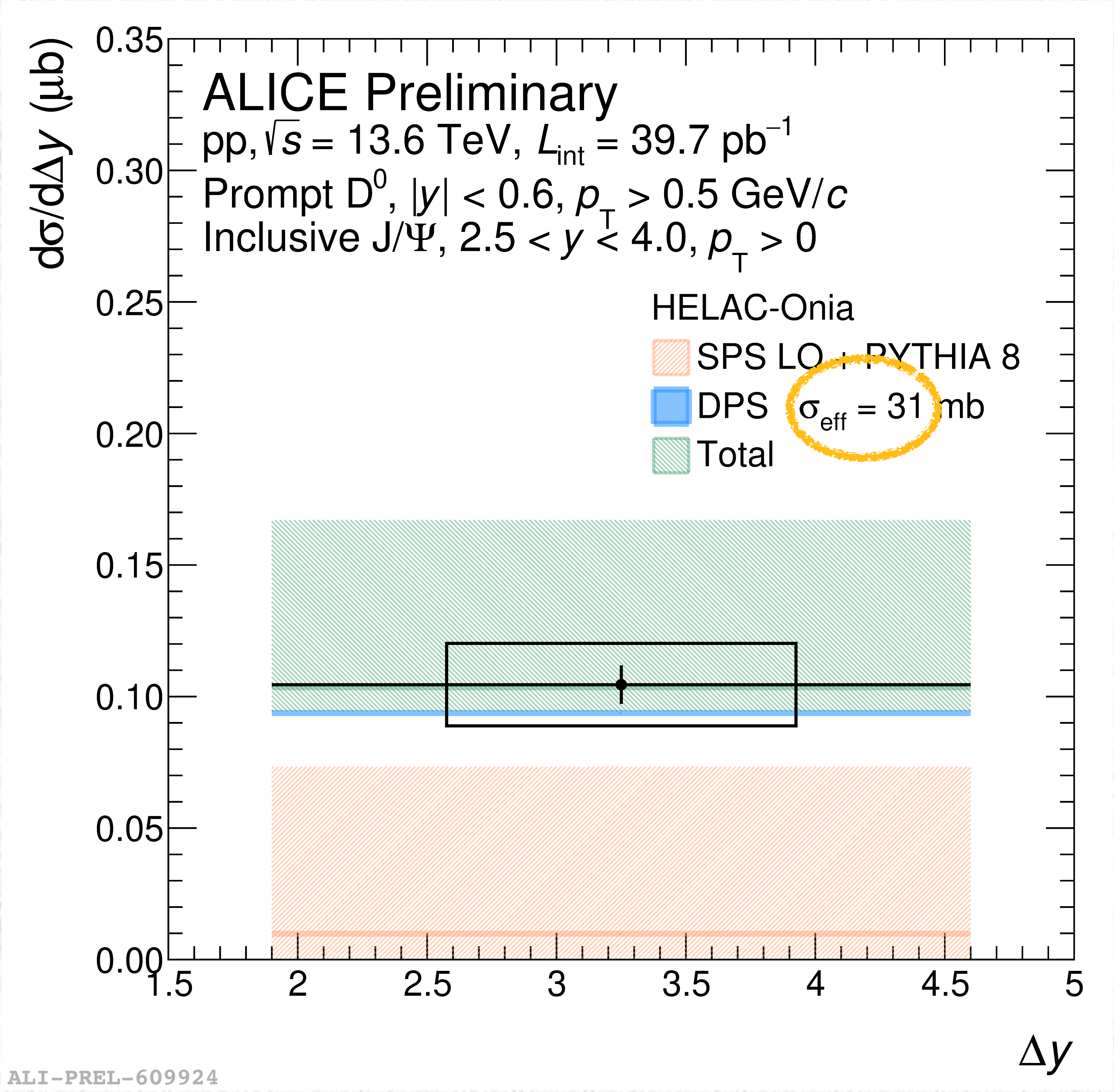
  Each equation corresponds to a different selection on the ML output score
- The full system of equations can be solved iteratively by **minimising the χ^2**, obtaining N_{prompt} and $N_{\mathrm{non\text{-}prompt}}$
- The final **non-prompt fraction** can be calculated as:

$$f_{\mathrm{non\text{-}prompt}} = \frac{(\mathrm{Acc} \times \epsilon)^{\mathrm{non\text{-}prompt}} \cdot N_{\mathrm{non\text{-}prompt}}}{(\mathrm{Acc} \times \epsilon)^{\mathrm{non\text{-}prompt}} \cdot N_{\mathrm{non\text{-}prompt}} + (\mathrm{Acc} \times \epsilon)^{\mathrm{prompt}} \cdot N_{\mathrm{prompt}}}$$

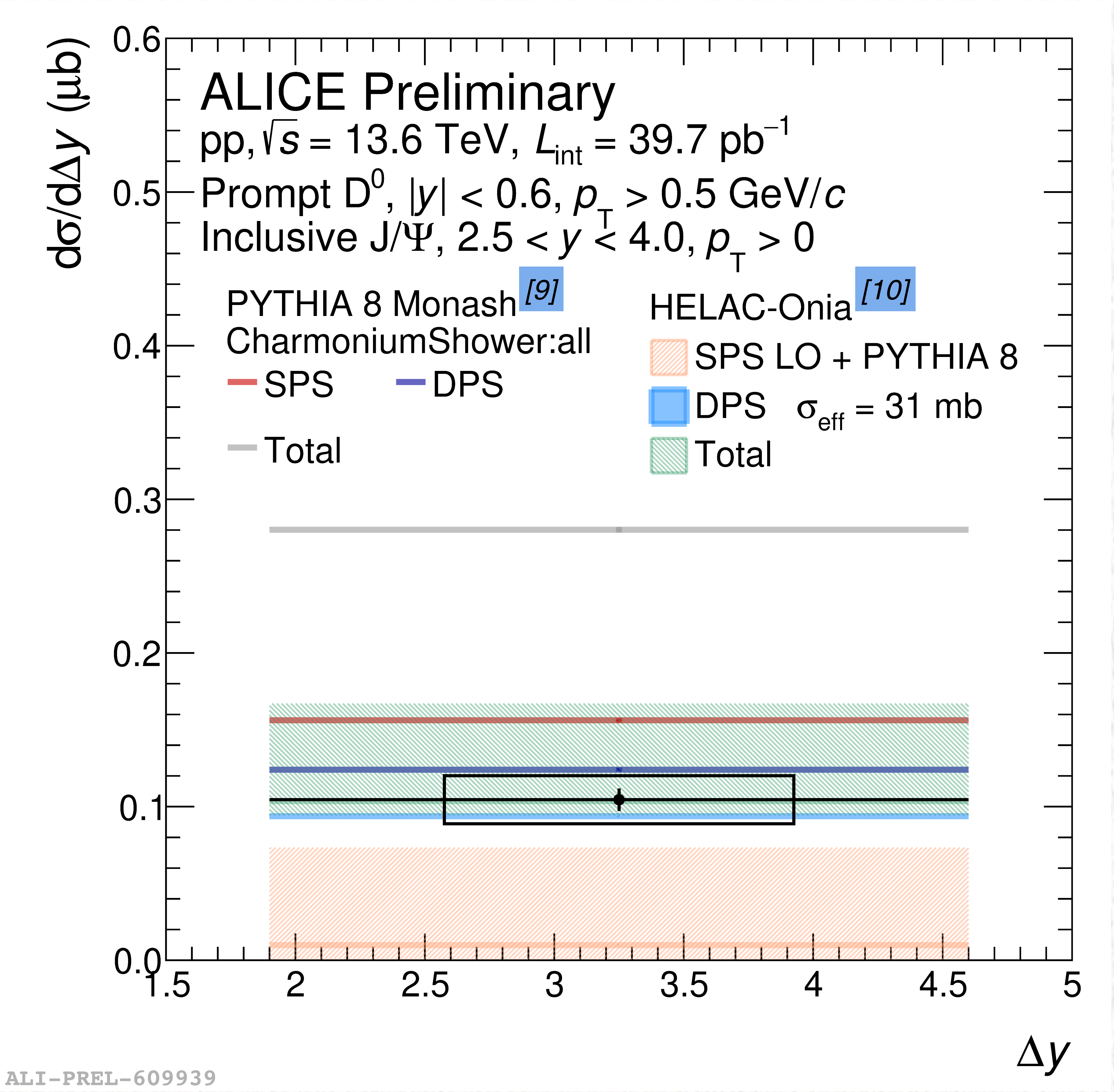


Estimation of σ_{eff}





$\sigma(\mathrm{J}/\psi, \mathrm{D}^0)$



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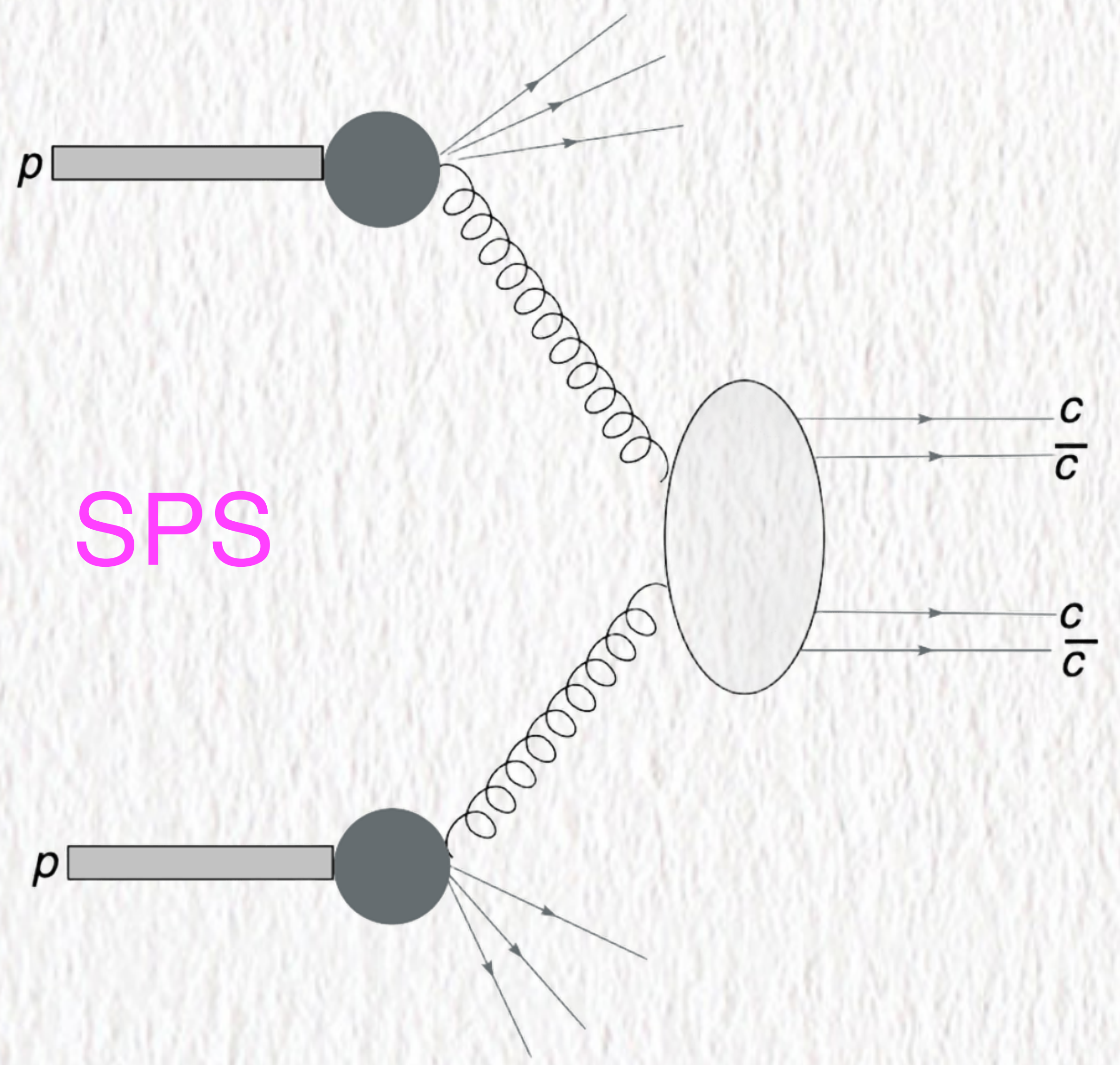
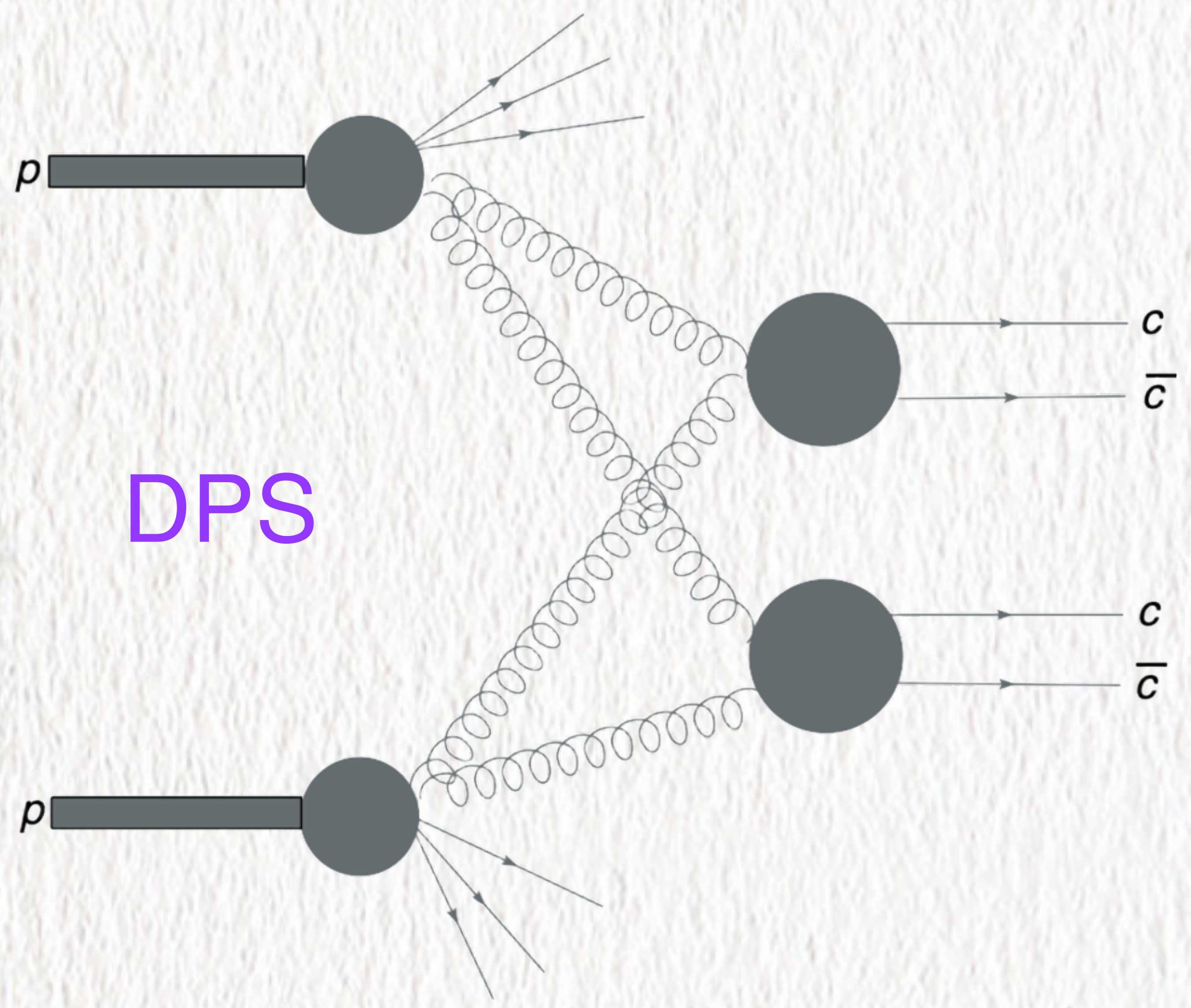
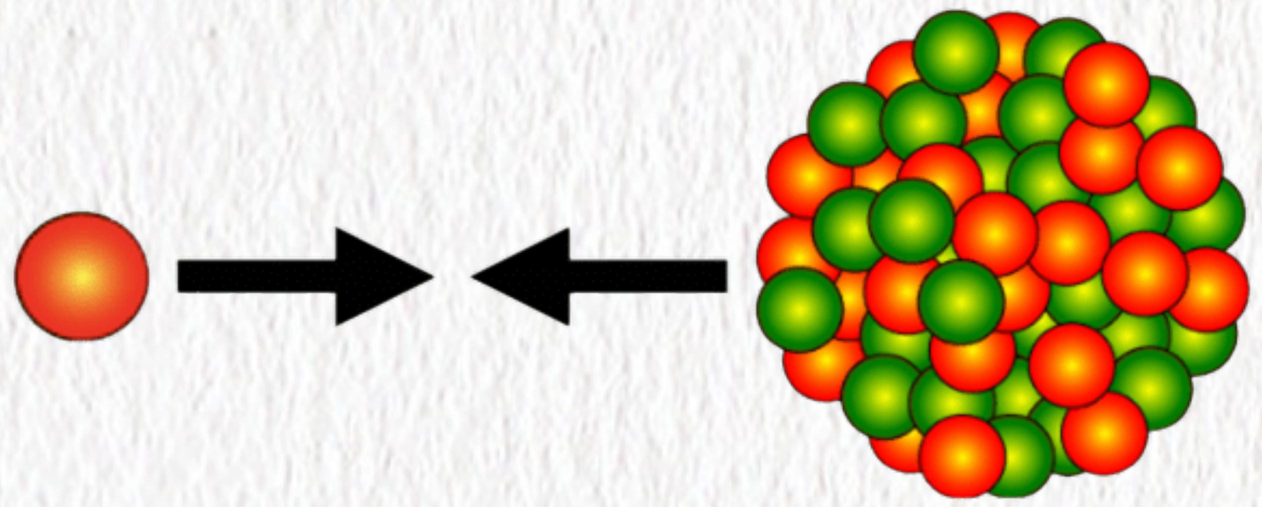
[9] *Comput.Phys.Commun.* 191 (2015) 159-177
[10] *Comput.Phys.Commun.* 184 (2013) 2562-2570

Double charm production in p–Pb collisions

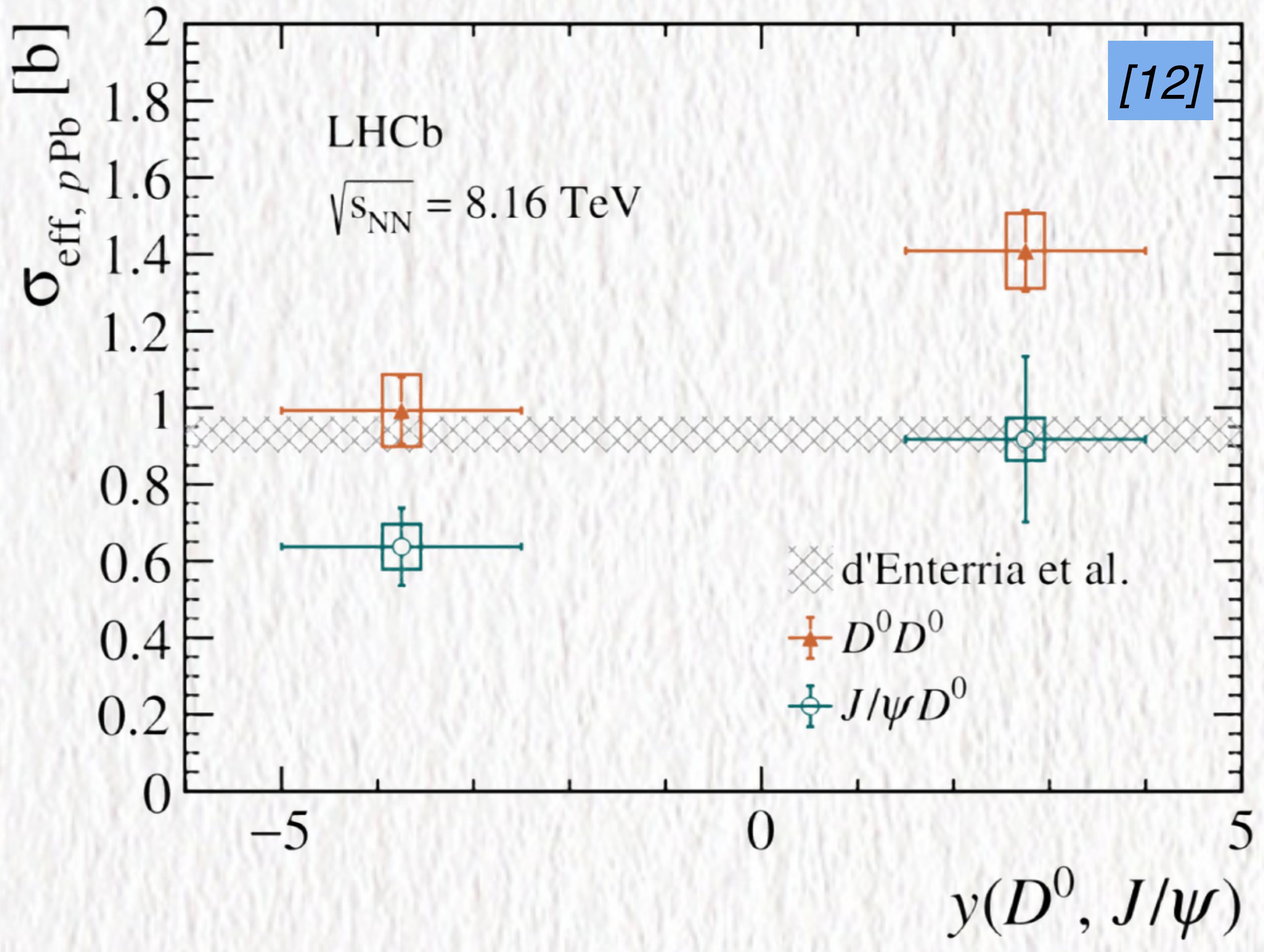






Enhancement of DPS is expected in pA w.r.t pp

- The double c-hadron are correlated in SPS, uncorrelated in DPS
- Correlations can be modified relative to pp due to the nuclear effects:
  - Modifications of the nuclear PDF?
  - Cronin effect, energy loss crossing nucleus, hydrodynamic effects?



[12] PHYS. REV. LETT. 125 (2020) 212001