Measurements of production of charm-hadron pairs in pp collisions with ALICE

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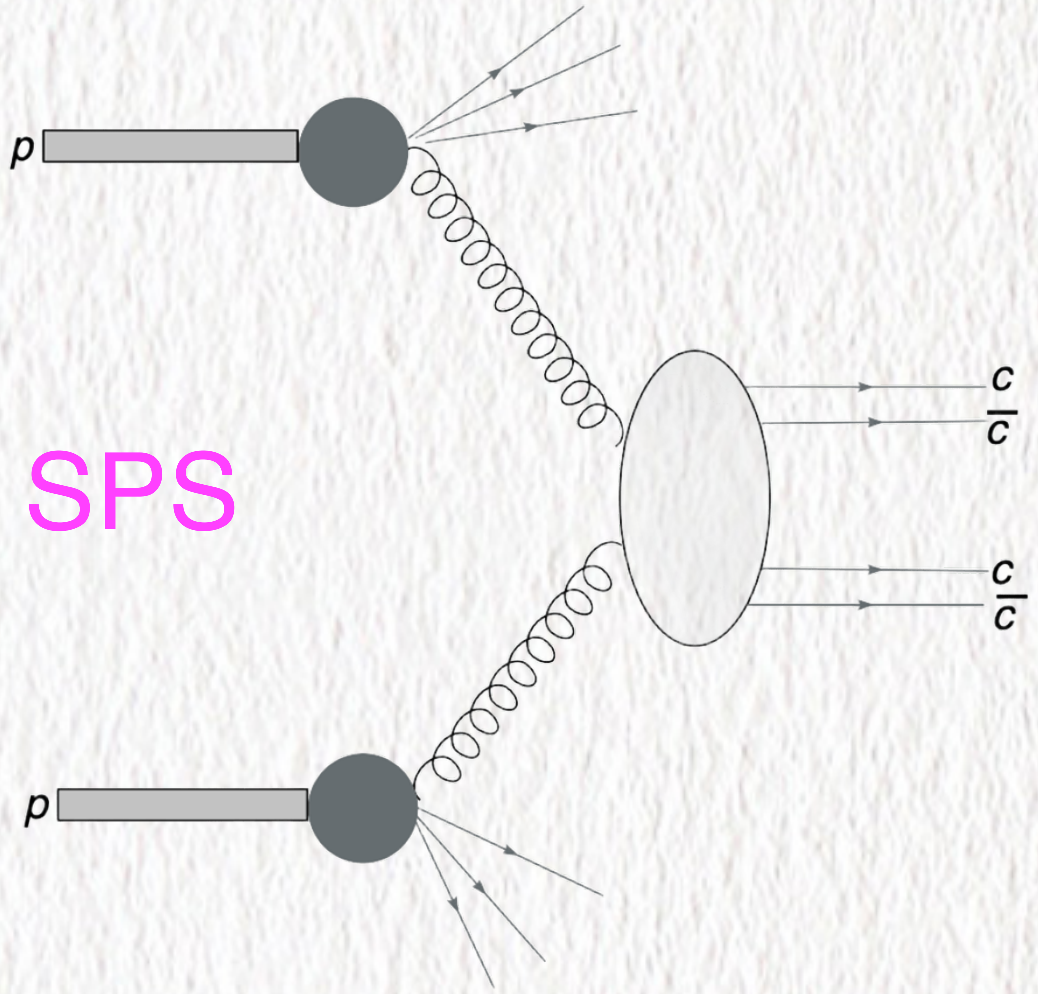
Motivation

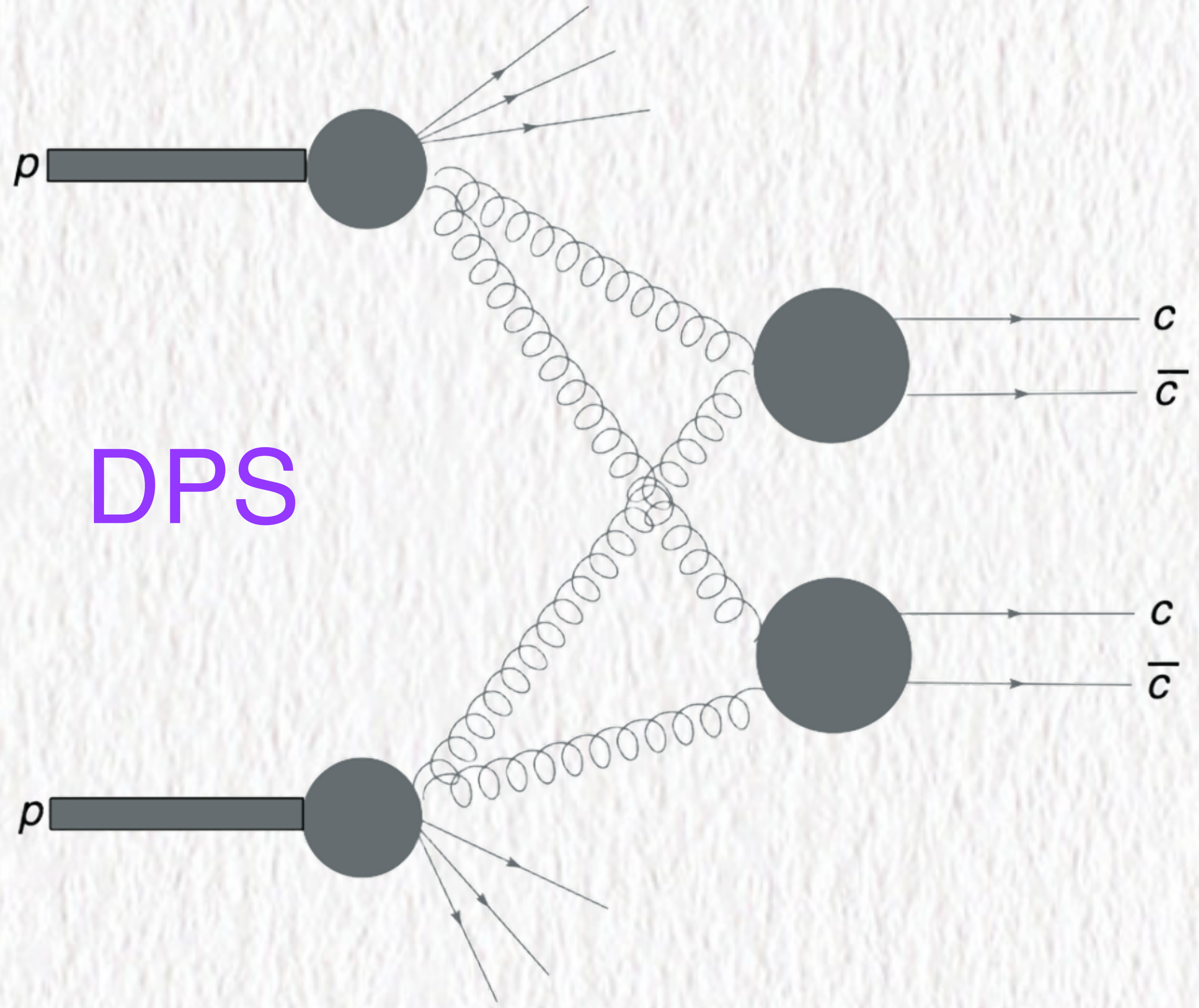
- Heavy quarks (c, b) are primarily produced through hard scattering processes.
- The production of c-hadron pairs provides an opportunity to study both Single Parton Scattering (SPS) and Double Parton Scattering (DPS).

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]

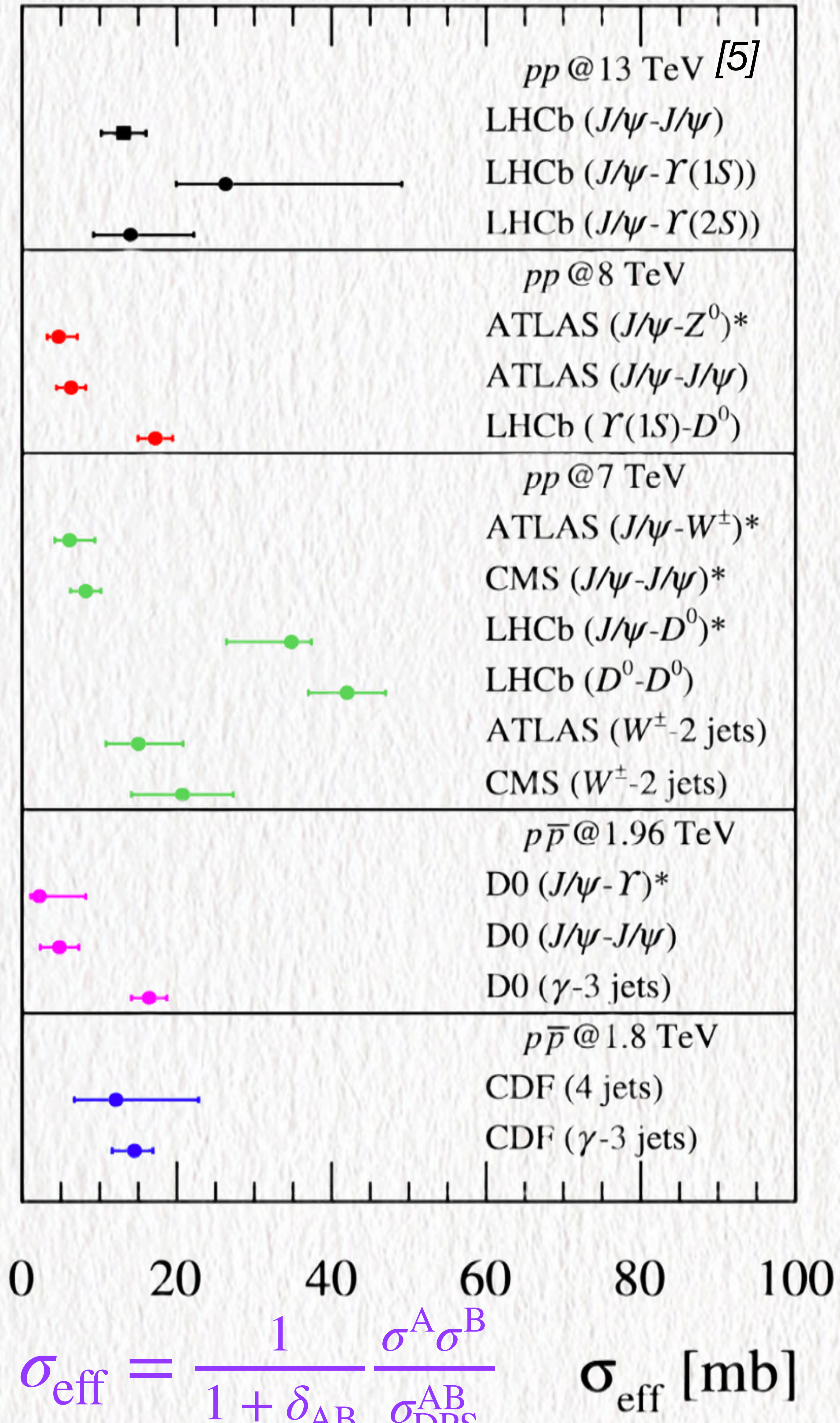
DPS



- 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] PLB 784 (2018) 217
[2] JHEP 06 (2017) 247
[3] EPJC 79 (2019) 1006
[4] PRD 57 (1998) 503

Effective cross-section summary

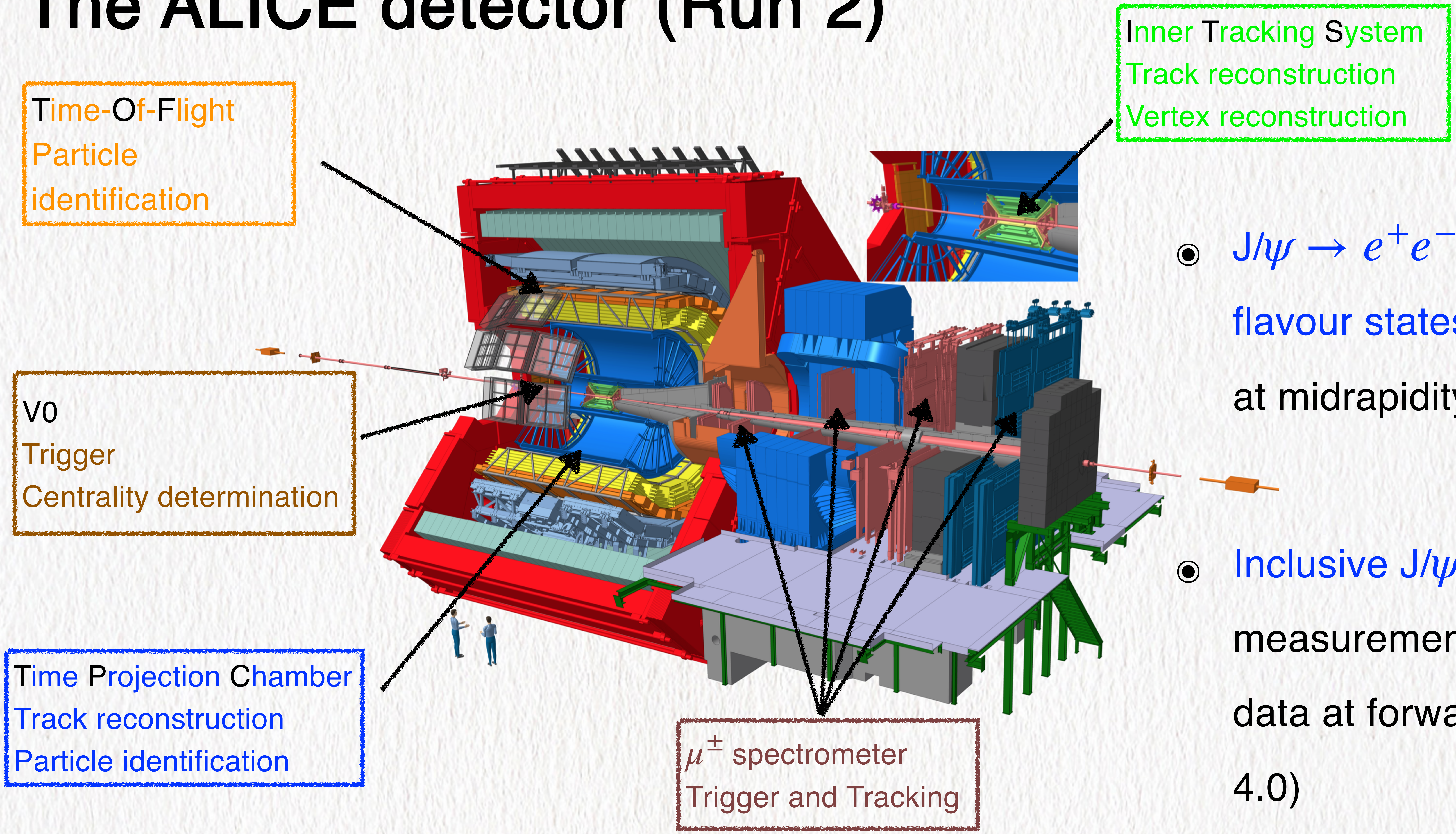


$$\sigma_{\rm eff} = \frac{1}{1+\delta_{\rm AB}} \frac{\sigma^{\rm A}\sigma^{\rm B}}{\sigma^{\rm AB}_{\rm DPS}}$$

- The general purpose of DPS measurements is to measure the $\sigma_{\rm eff}$
  - 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] JHEP 03 (2024) 088

The ALICE detector (Run 2)



- $J/\psi \rightarrow e^{+}e^{-}$ 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:

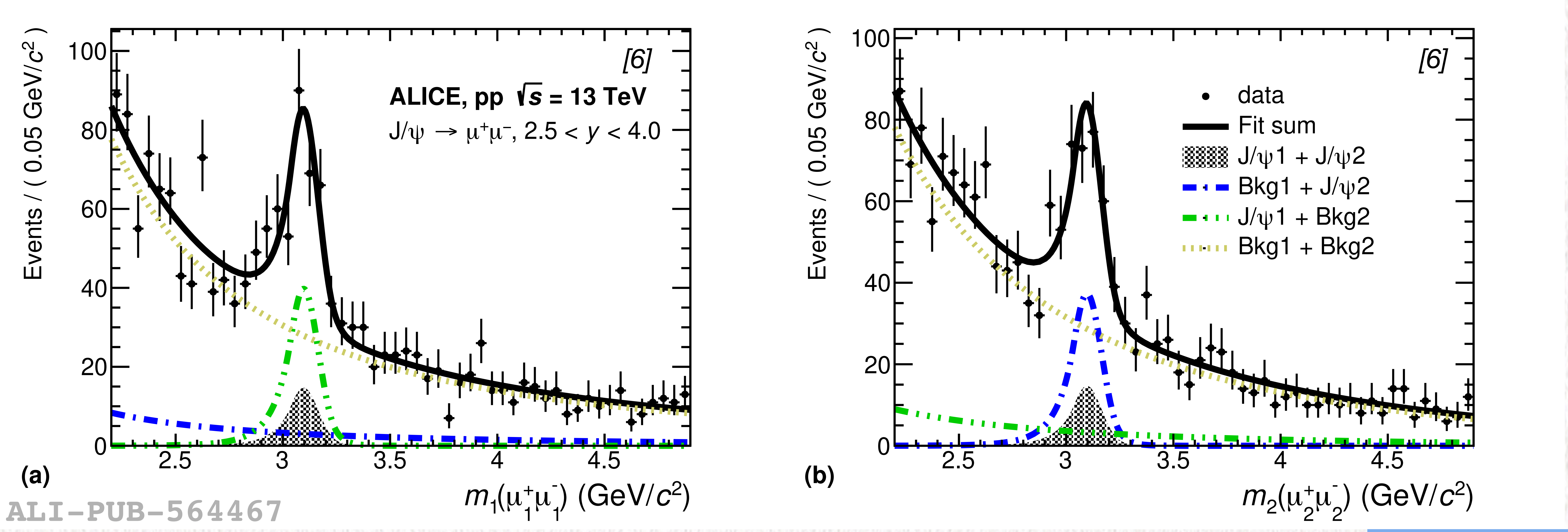
$2.5 < y_{\mu\mu} < 4.0$

- 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

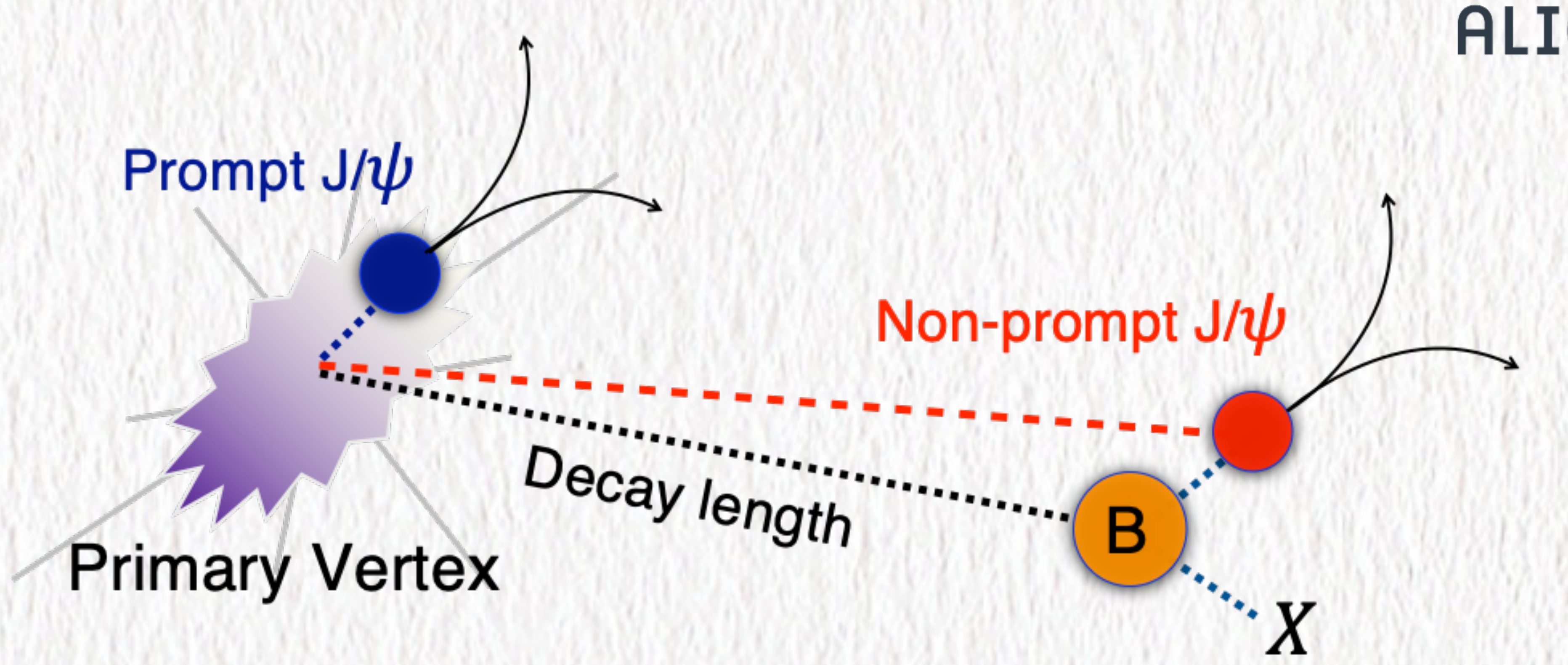
- Acceptance-times-efficiency correction and lumi. normalisation



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

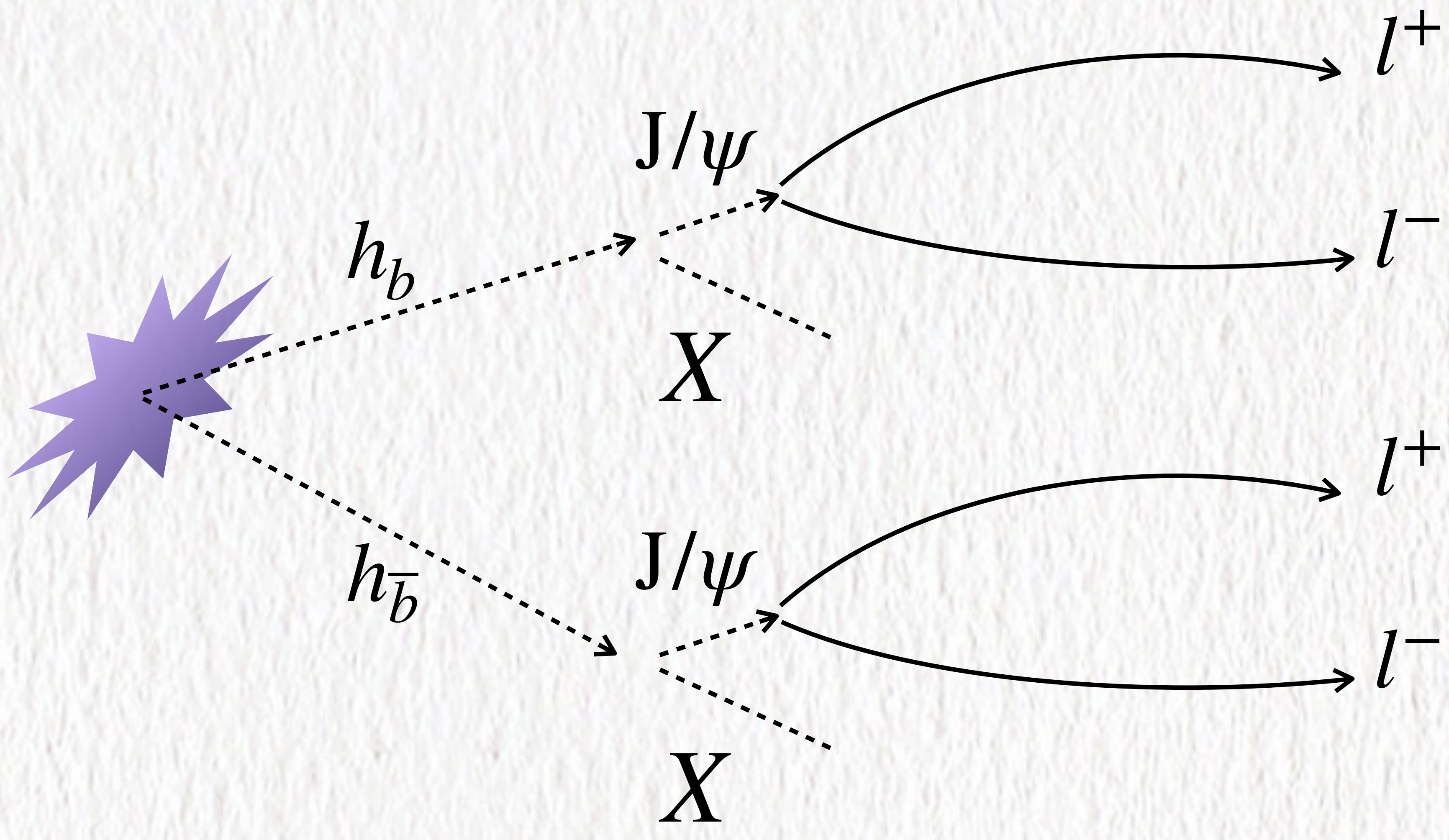
Estimation of the non-prompt contribution

- Inclusive σ(J/ψ, J/ψ) = 10.3 ± 2.3 (stat.) ± 1.3 (syst.) nb [6]



Estimation on the non-prompt contribution

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



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

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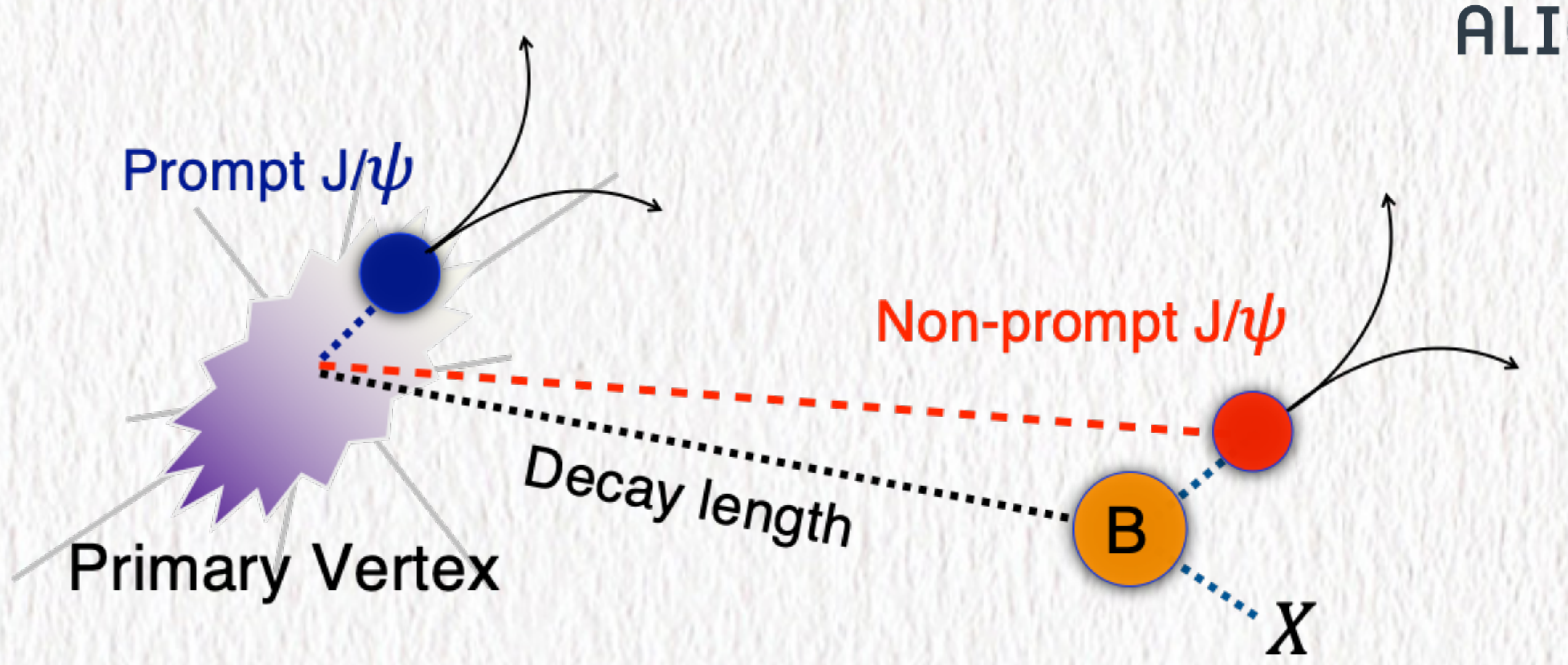

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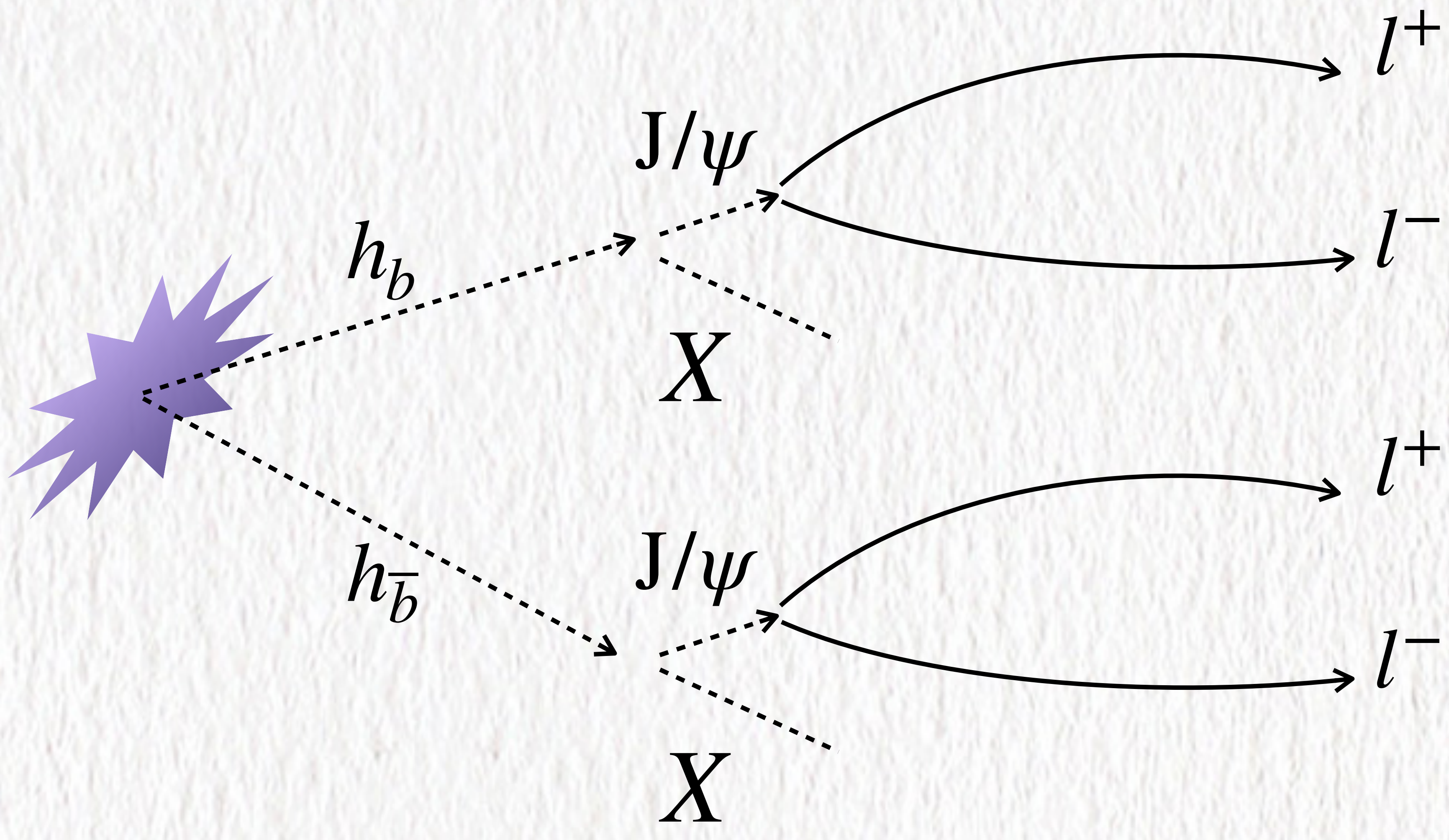

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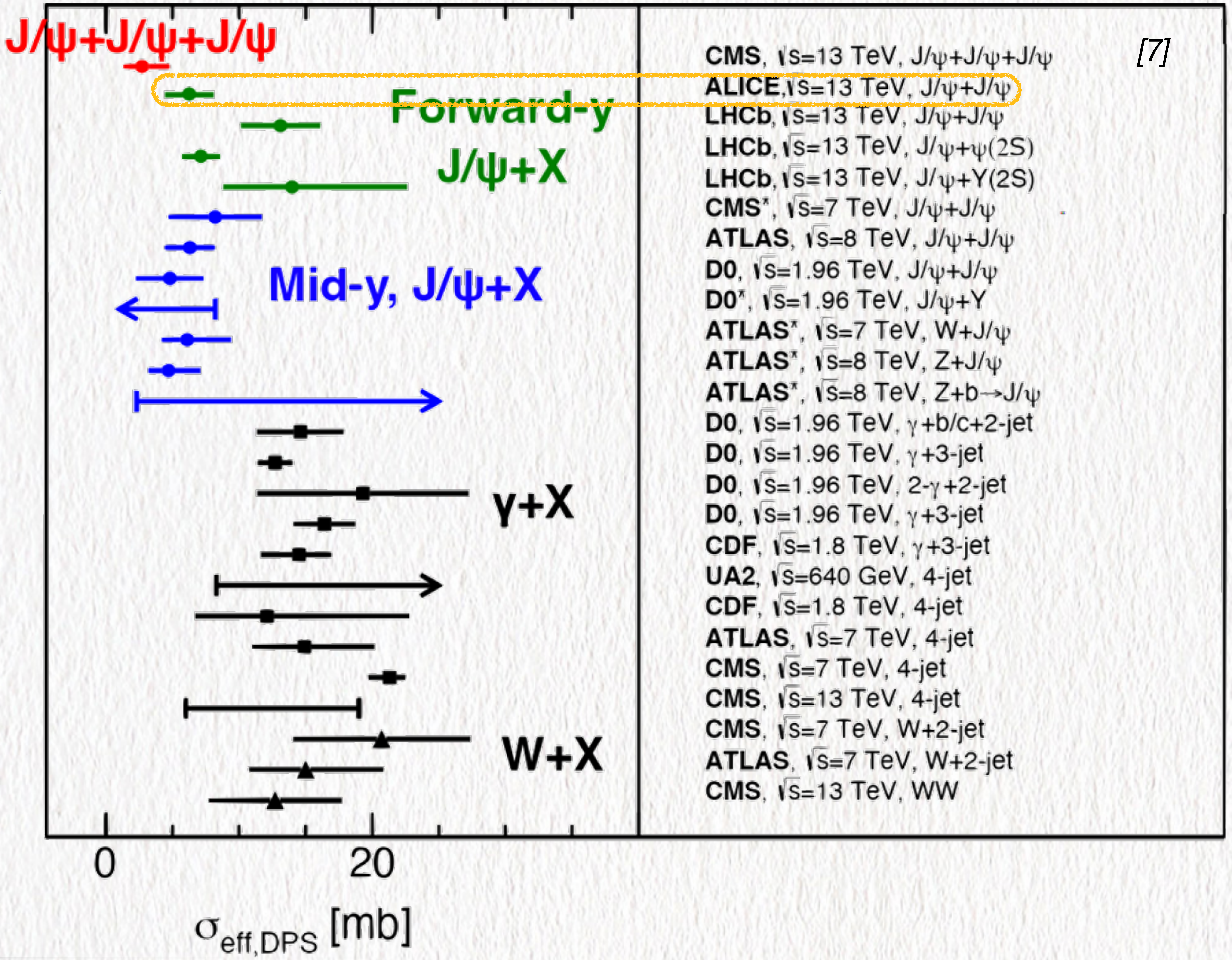
  - $\sigma_{\mathrm{prompt}}(\mathrm{J}/\psi, \mathrm{J}/\psi) = \sigma_{\mathrm{inclusive}}(\mathrm{J}/\psi, \mathrm{J}/\psi) - \sigma_{\mathrm{non-prompt}}(\mathrm{J}/\psi, \mathrm{J}/\psi)$

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

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

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

Estimation on the eff. σ and Results discussion



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

- 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

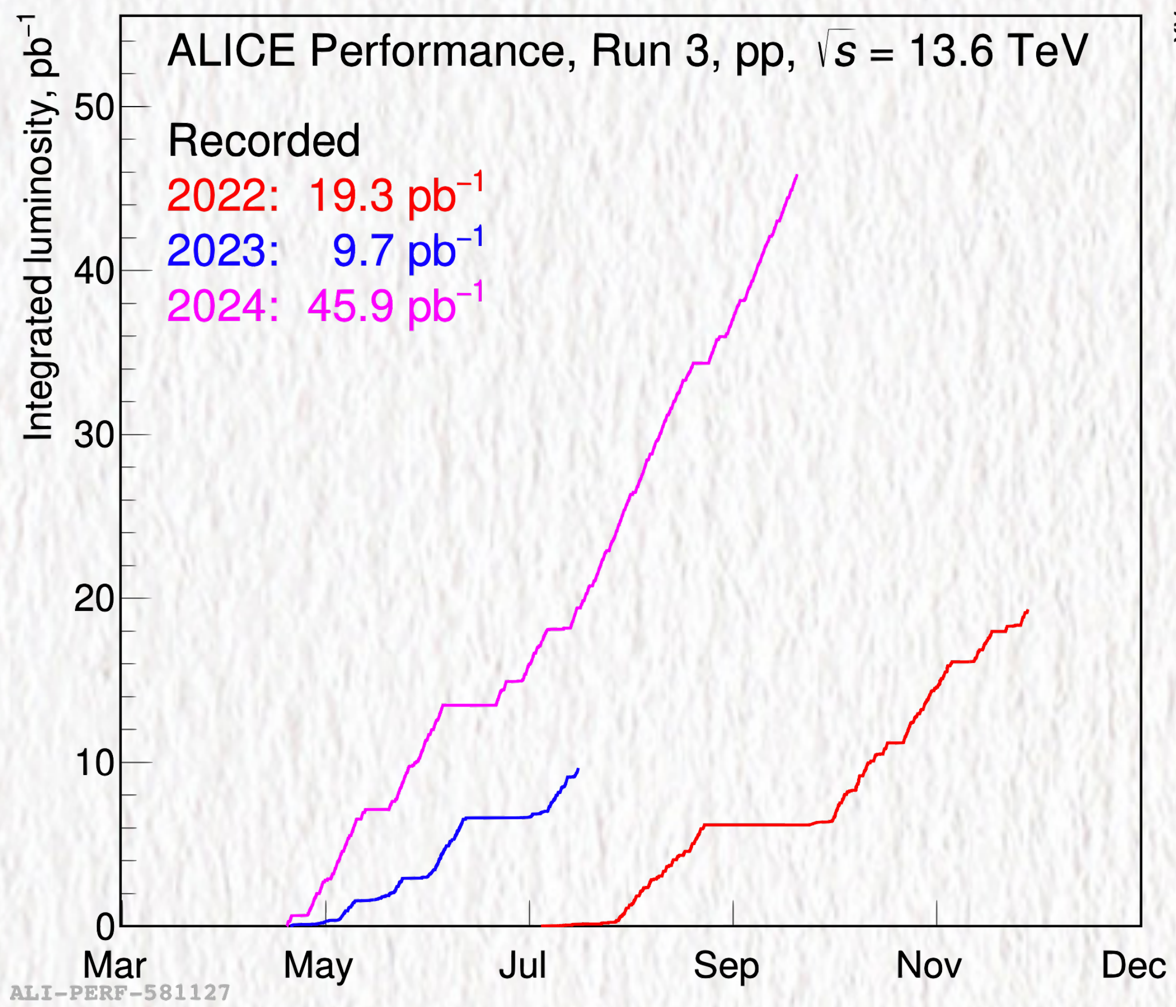
[7] QM2023, Andre Ståhl talk

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 (O²)
- 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



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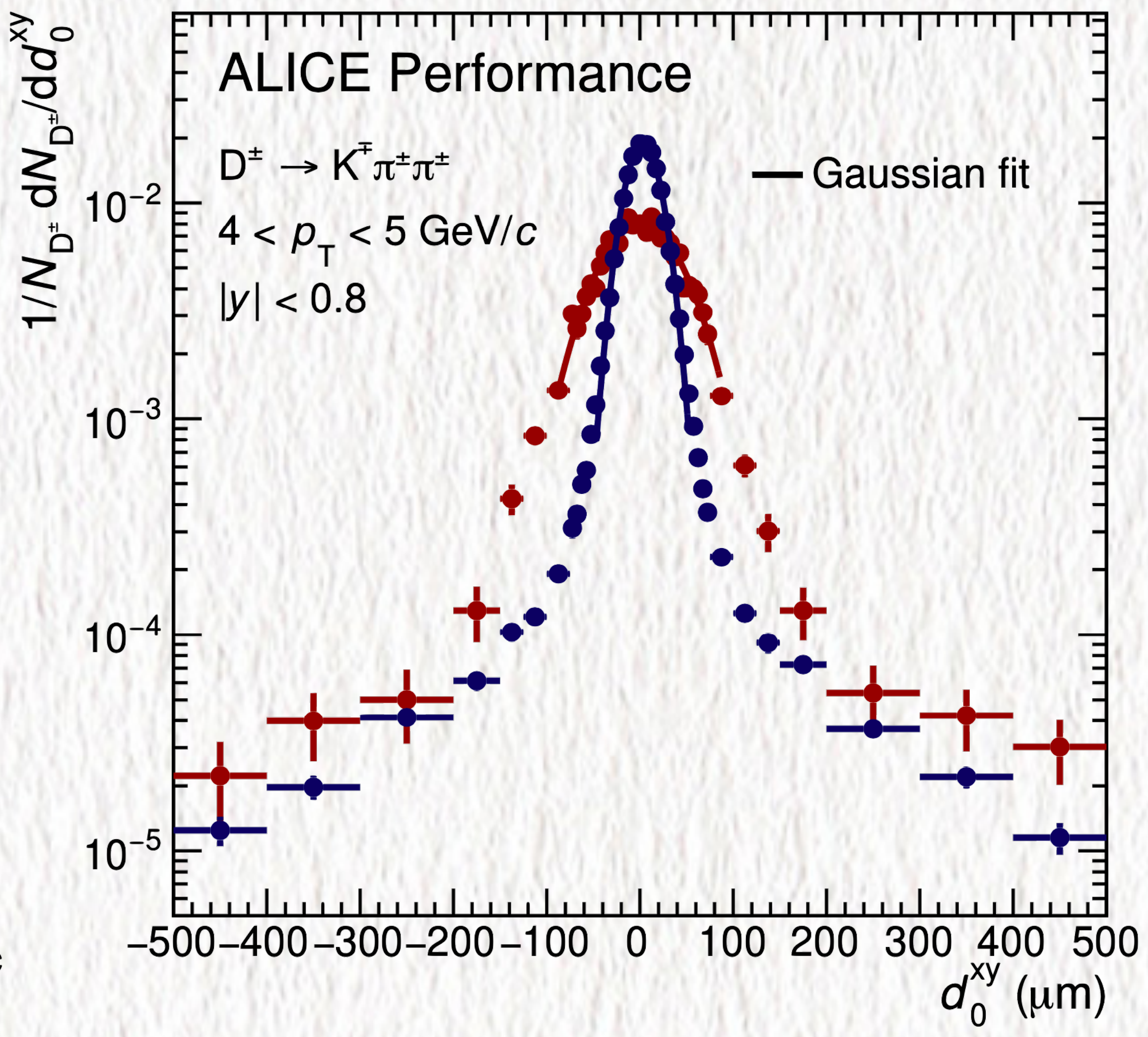

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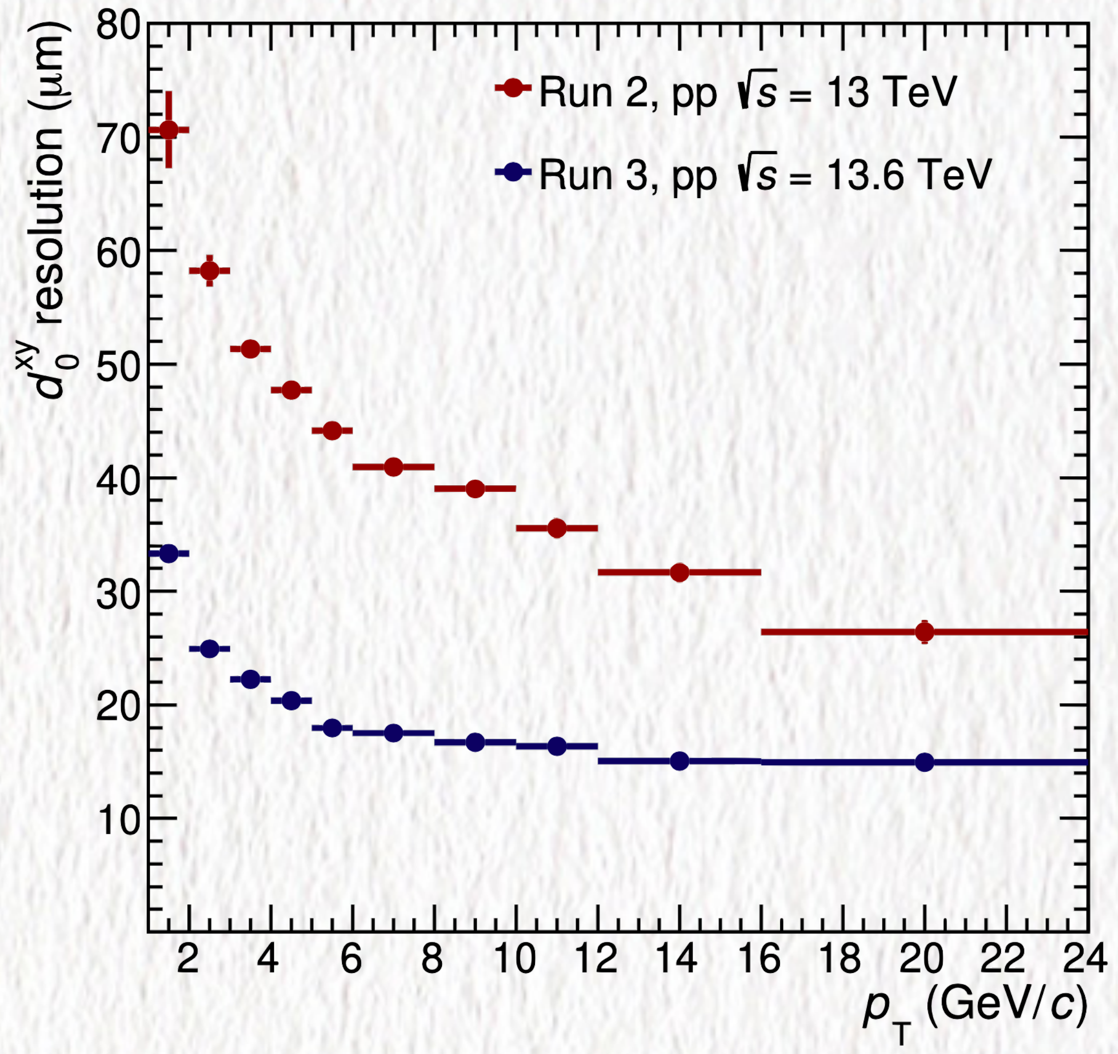
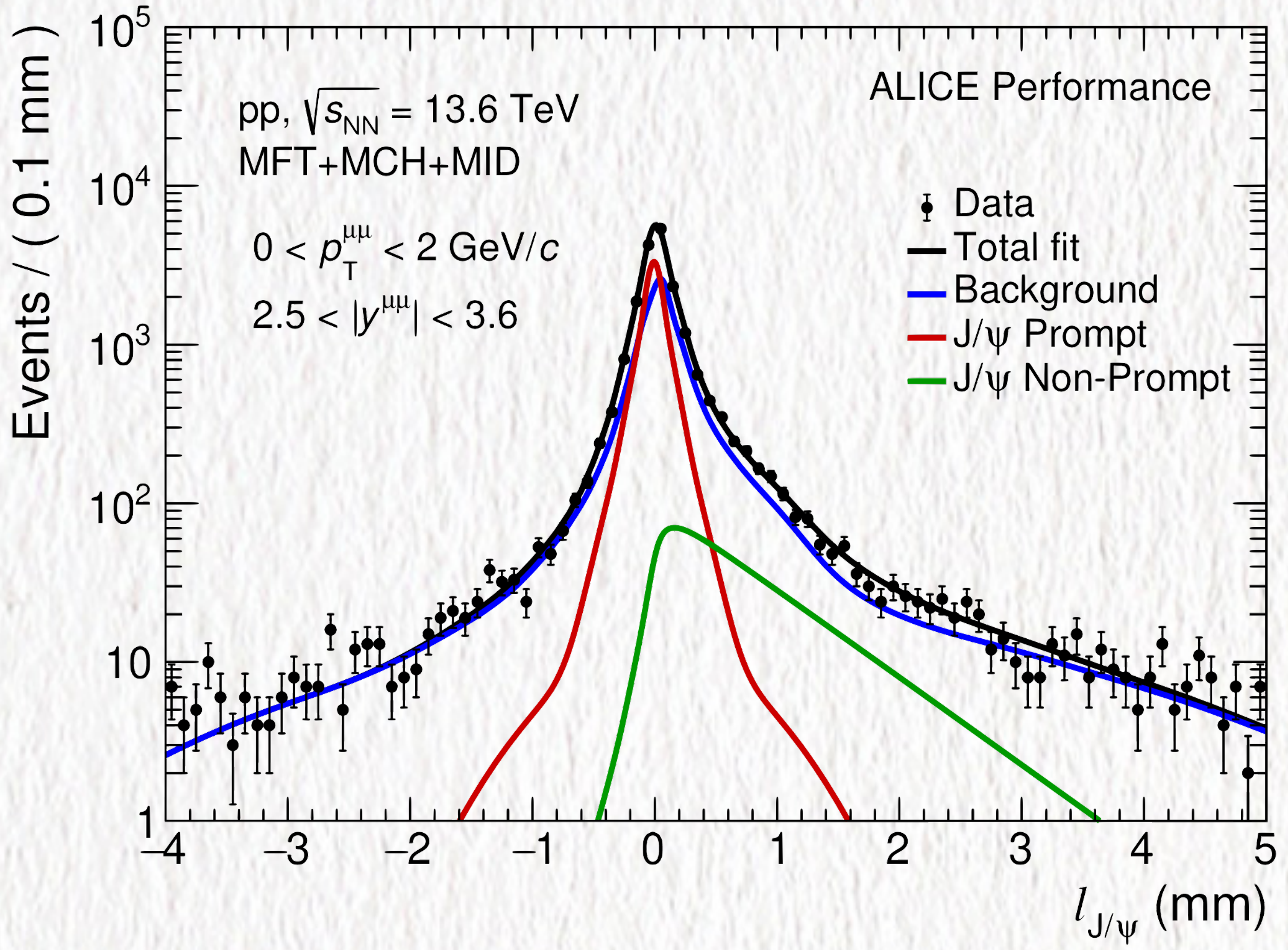
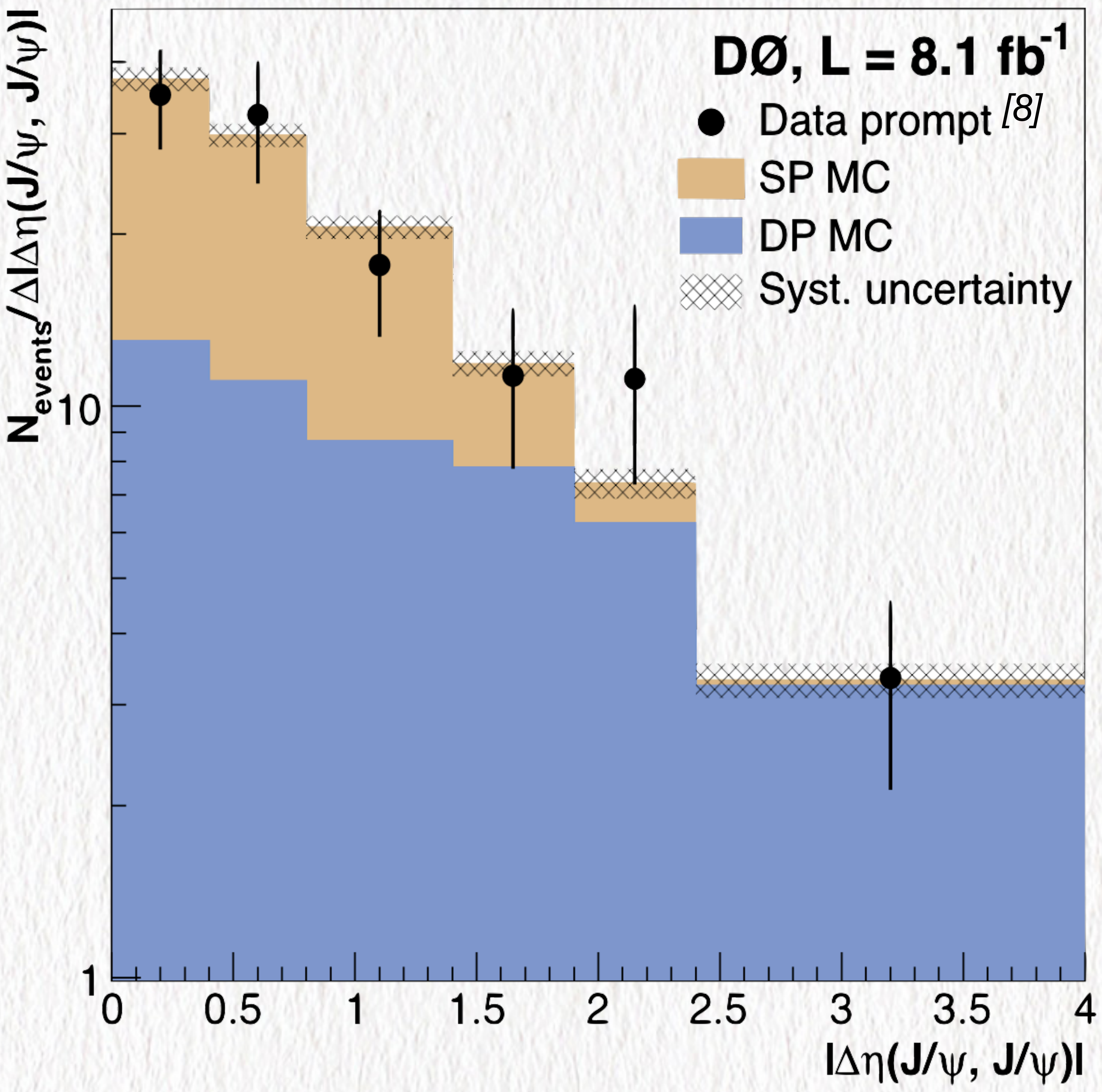




ALI-PERF-571258

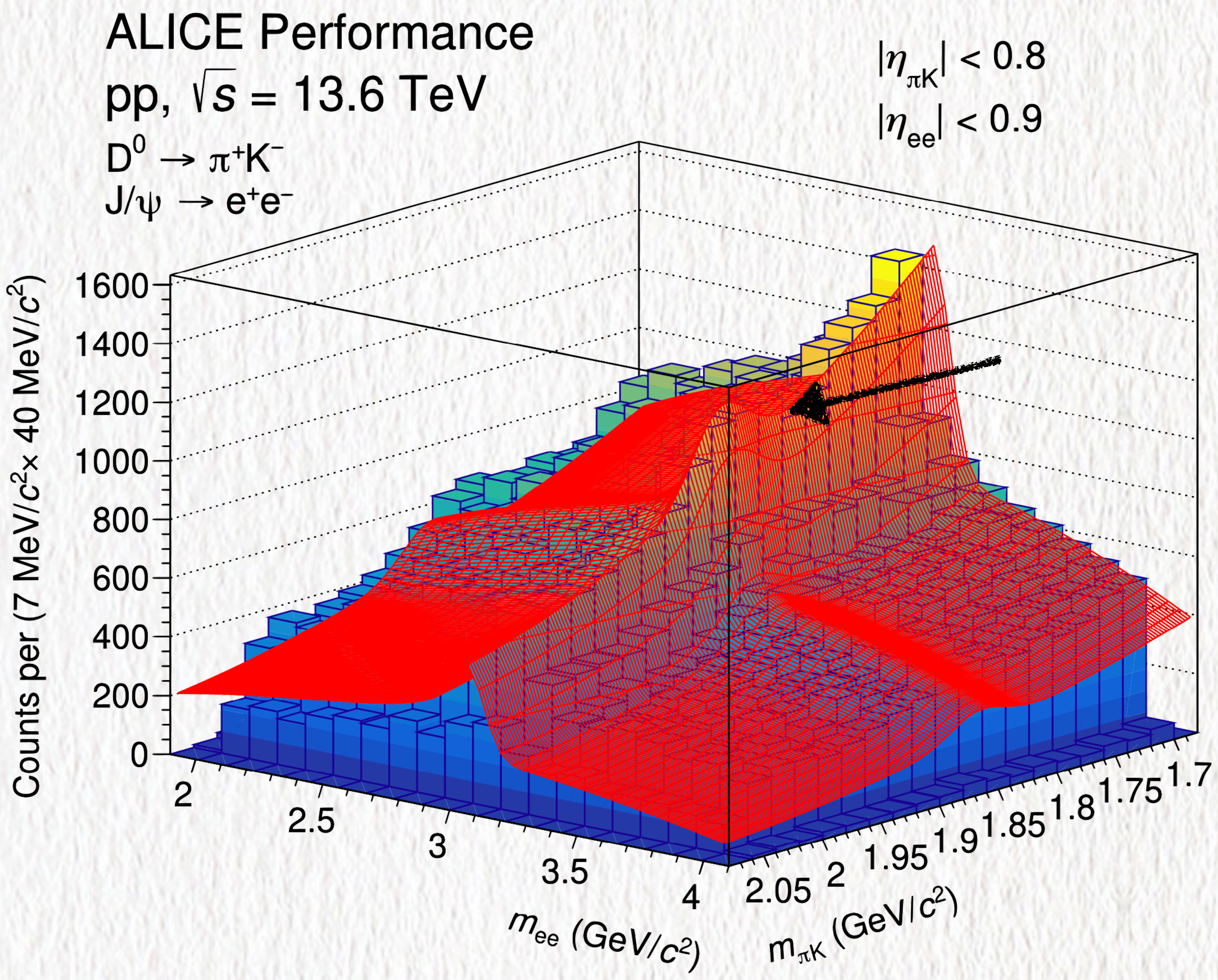
Opportunities on ALICE Run 3

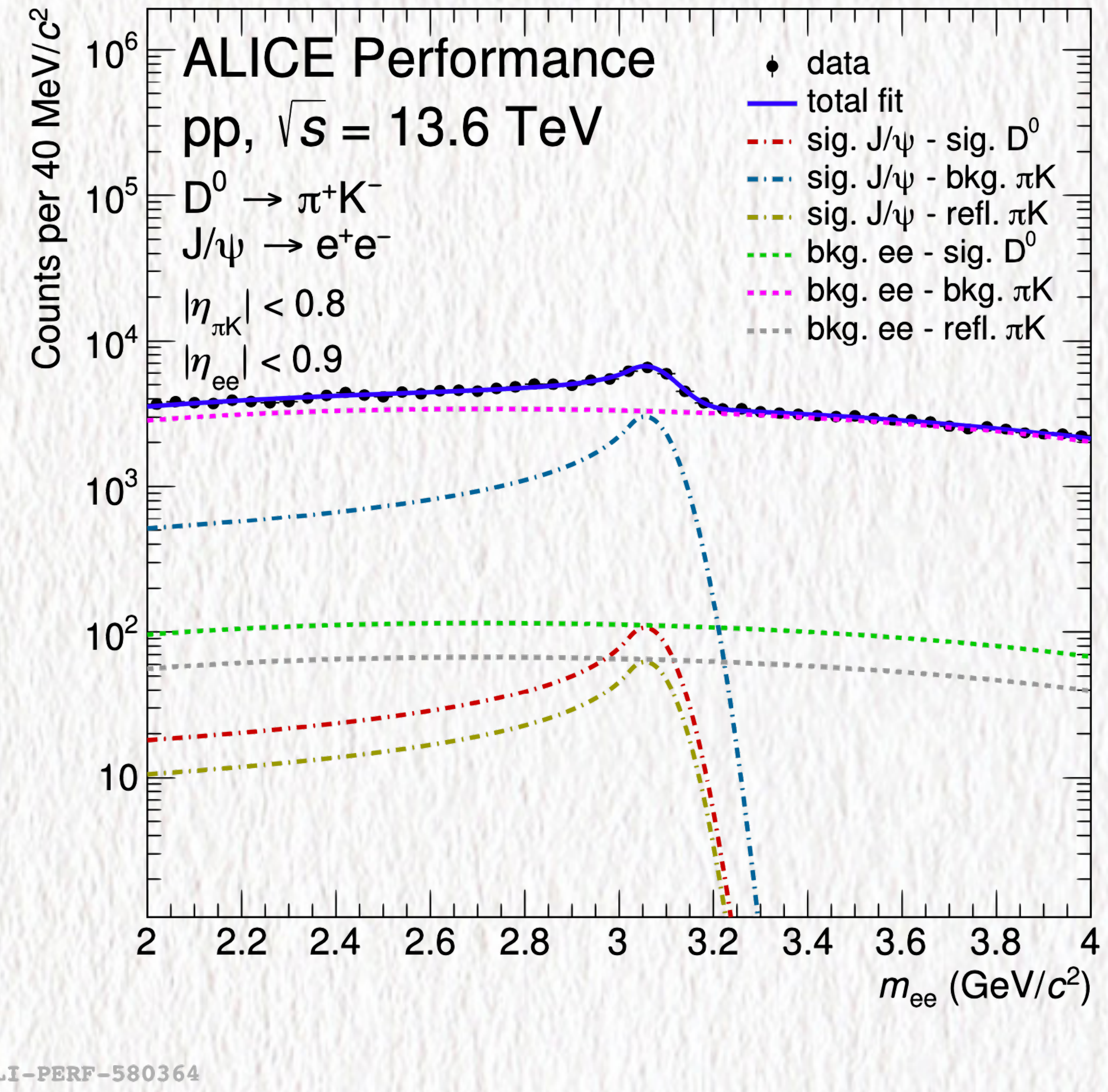
- In Run 3, ALICE has the possibility to conduct many new analyses, such as:
  - Combined analyses of the central barrel – μ spectrometer ($D^0(|y| < 0.8)$–$J/\psi(2.5 < y < 4.0)$)
  - Prompt/non-prompt separation for forward rapidity J/ψ reconstruction
- SPS –DPS separation sensitive to Δy
- Exploit ALICE's unique capabilities at the LHC to extend Δy coverage up to ~ 5

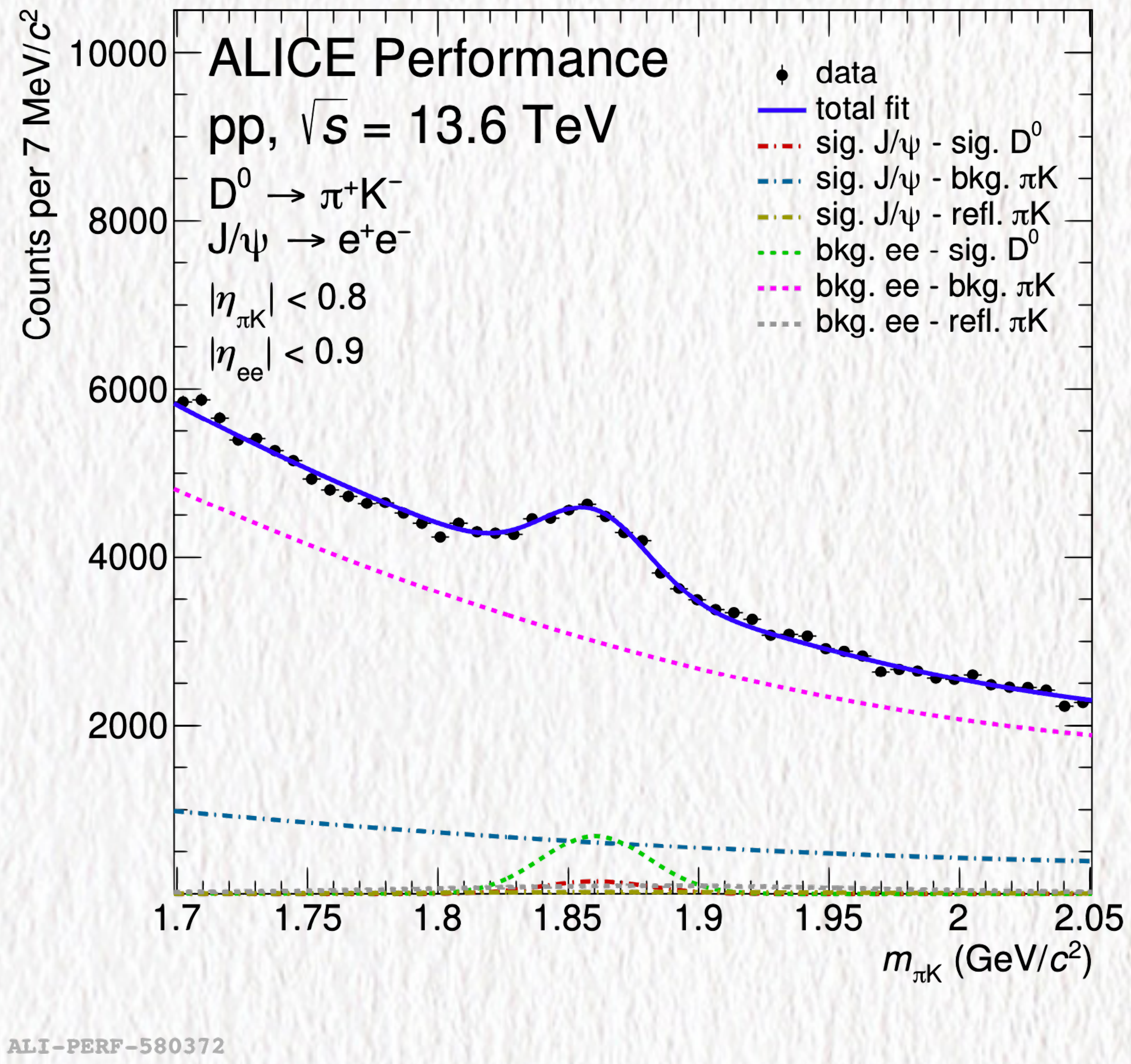


[8] Phys. Rev. D 90, 111101

J/ψ–D⁰ at midrapidity





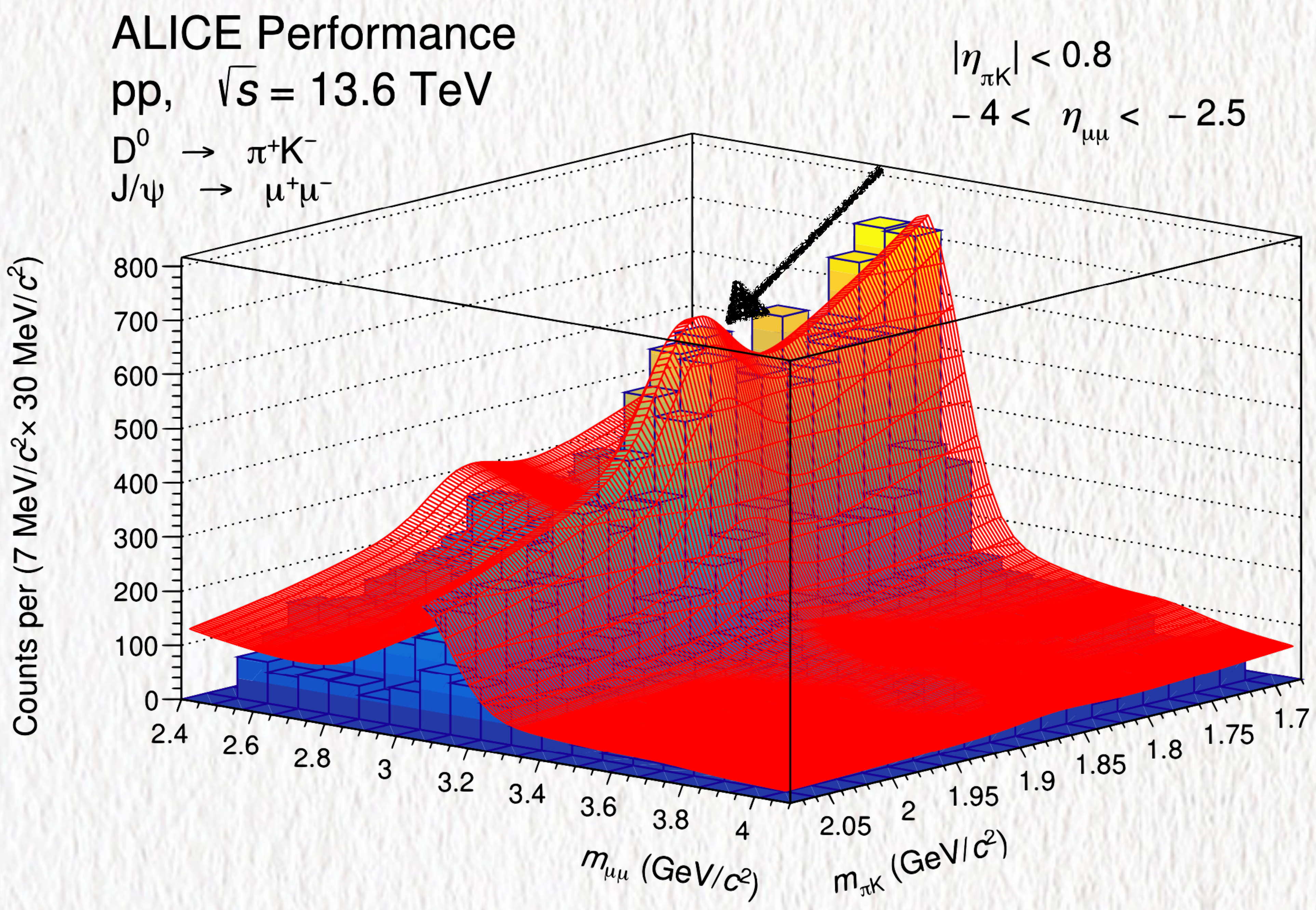


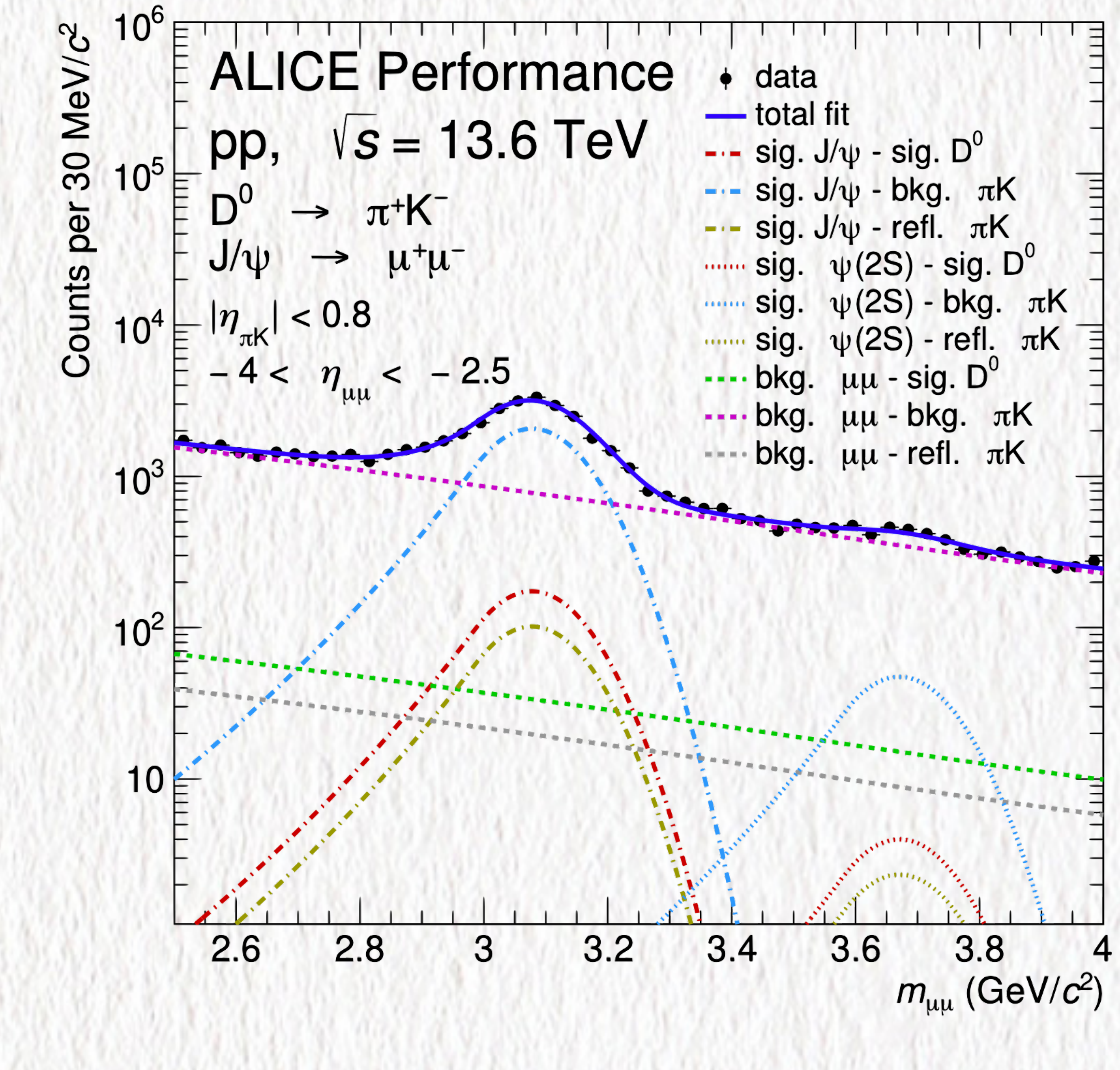
- Begin by examine the associated production of J/ψ—D⁰ using an unbinned maximum likelihood fit.
- Account for reflections* from the D⁰ reconstruction.
- A notable associated signal of J/ψ—D⁰ can be observed.

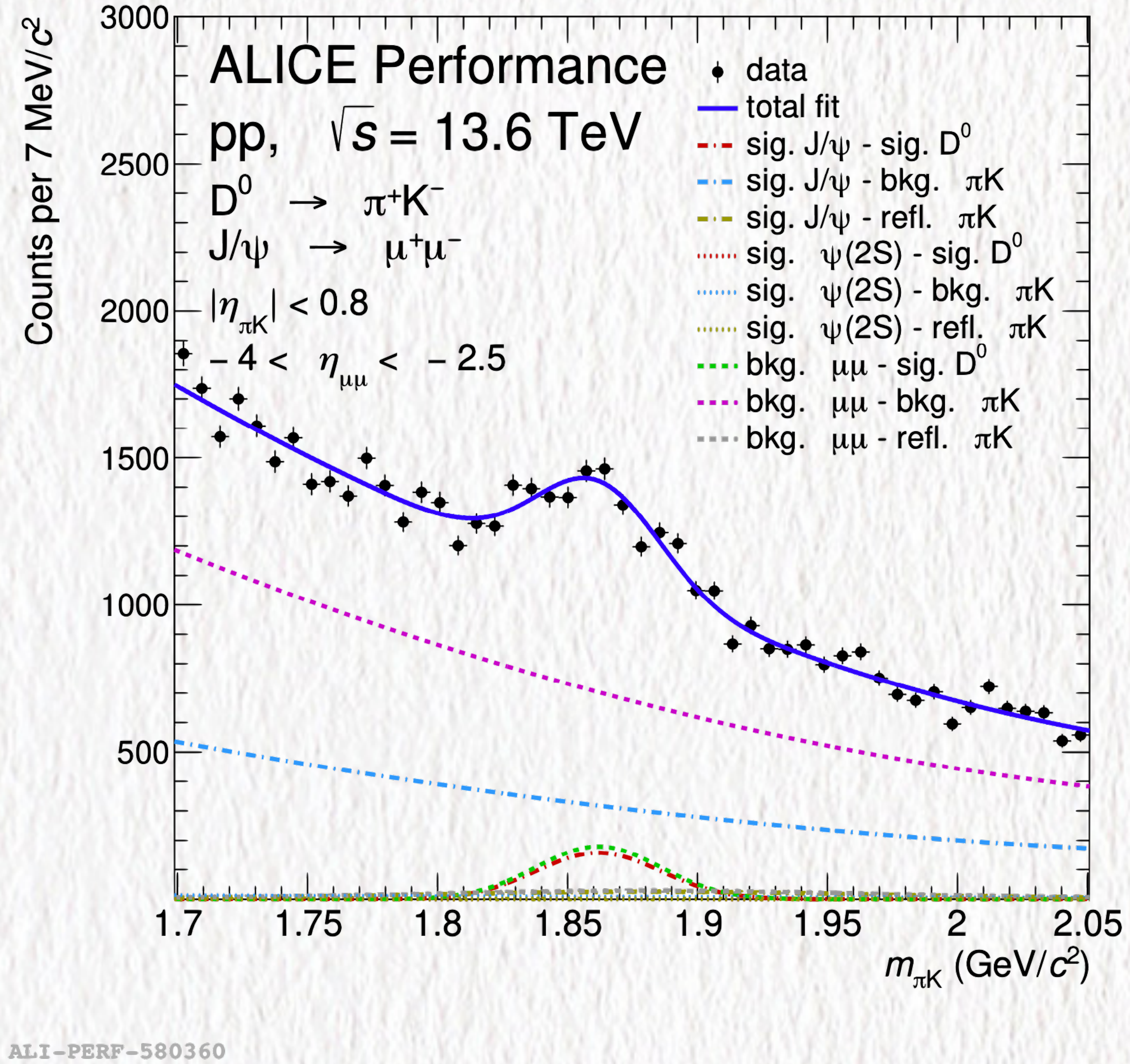
$|\Delta y(\mathrm{J}/\psi, \mathrm{D}^0)| < 1.7$

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

J/ψ (2.5 < y < 4.0)–D⁰







- Investigate the associated production of D⁰ in conjunction with a forward rapidity J/ψ.
- Additionally, consider the presence of the ψ(2S).
- Improved S/B can be achieved in forward rapidity J/ψ reconstruction.

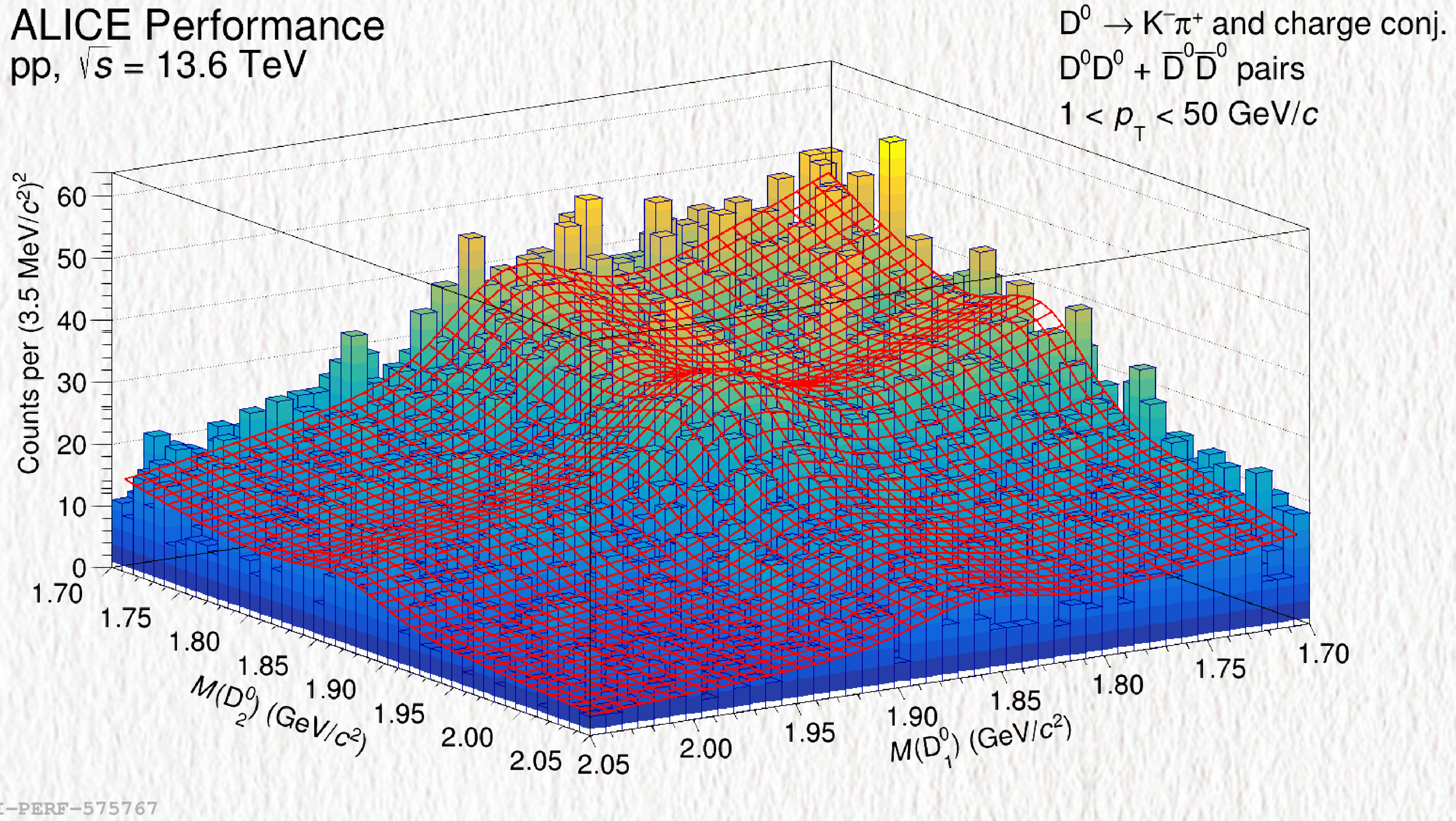
$1.3 < |\Delta y(\mathrm{J}/\psi, \mathrm{D}^0)| < 4.8$

Cover the full Δy range up to ~ 5

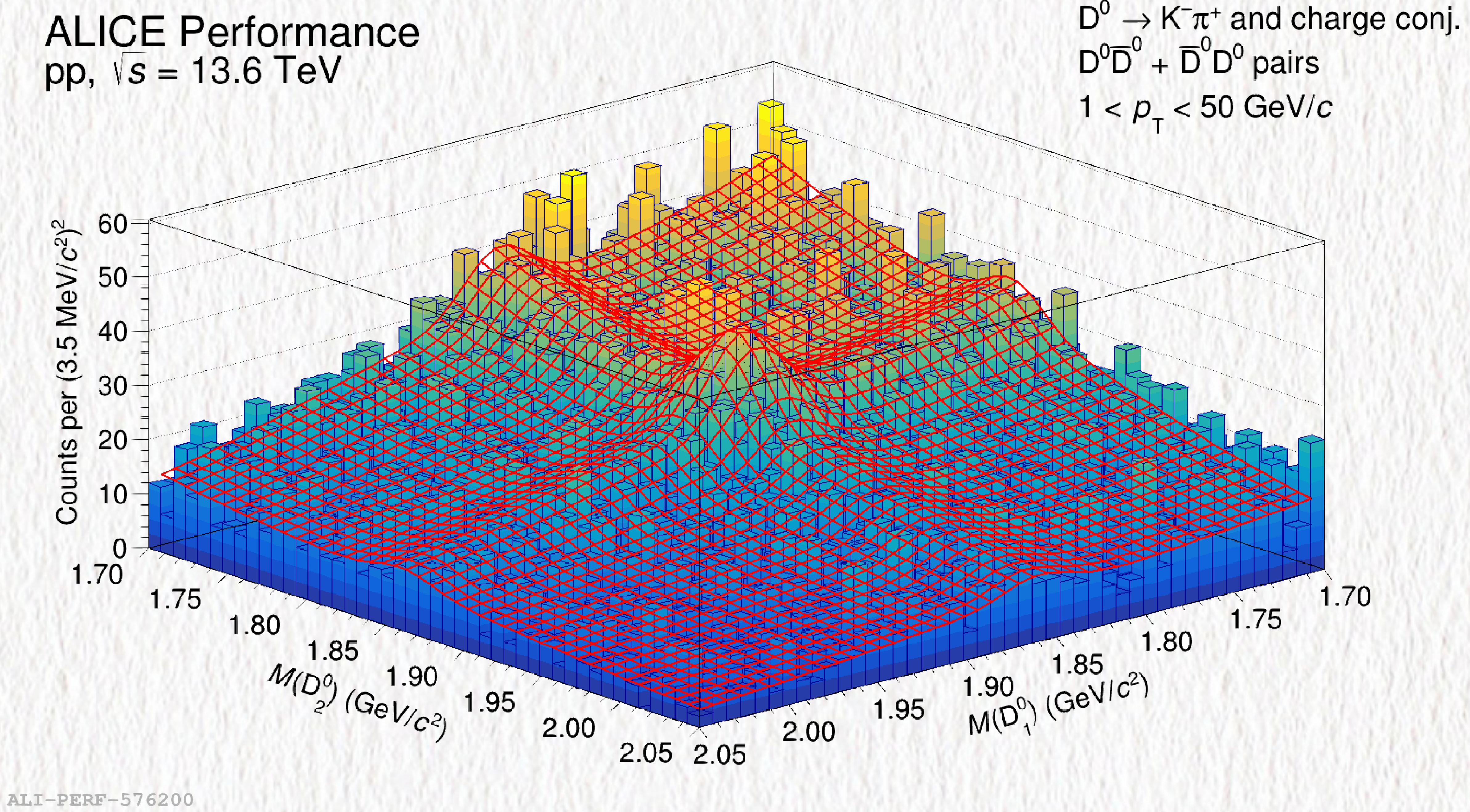
D0–D0 at midrapidity

$|\Delta y(D^0, D^0)| < 1.6$

D0 same-sign pairs



D0 opposite-sign pairs



- Double open charm hadron production is also a crucial supplementary measurement.
- Investigate the differences between D0 same-sign pairs (D^0–D^0, $\overline{D}^0$–$\overline{D}^0$) and opposite-sign pairs (D^0–$\overline{D}^0$) production.

Summary

ALICE

In ALICE Run 2:

- The first measurement of double J/ψ production was conducted using pp data.
- The σ_{eff} is consistent with measurements of open and hidden charm pair production.

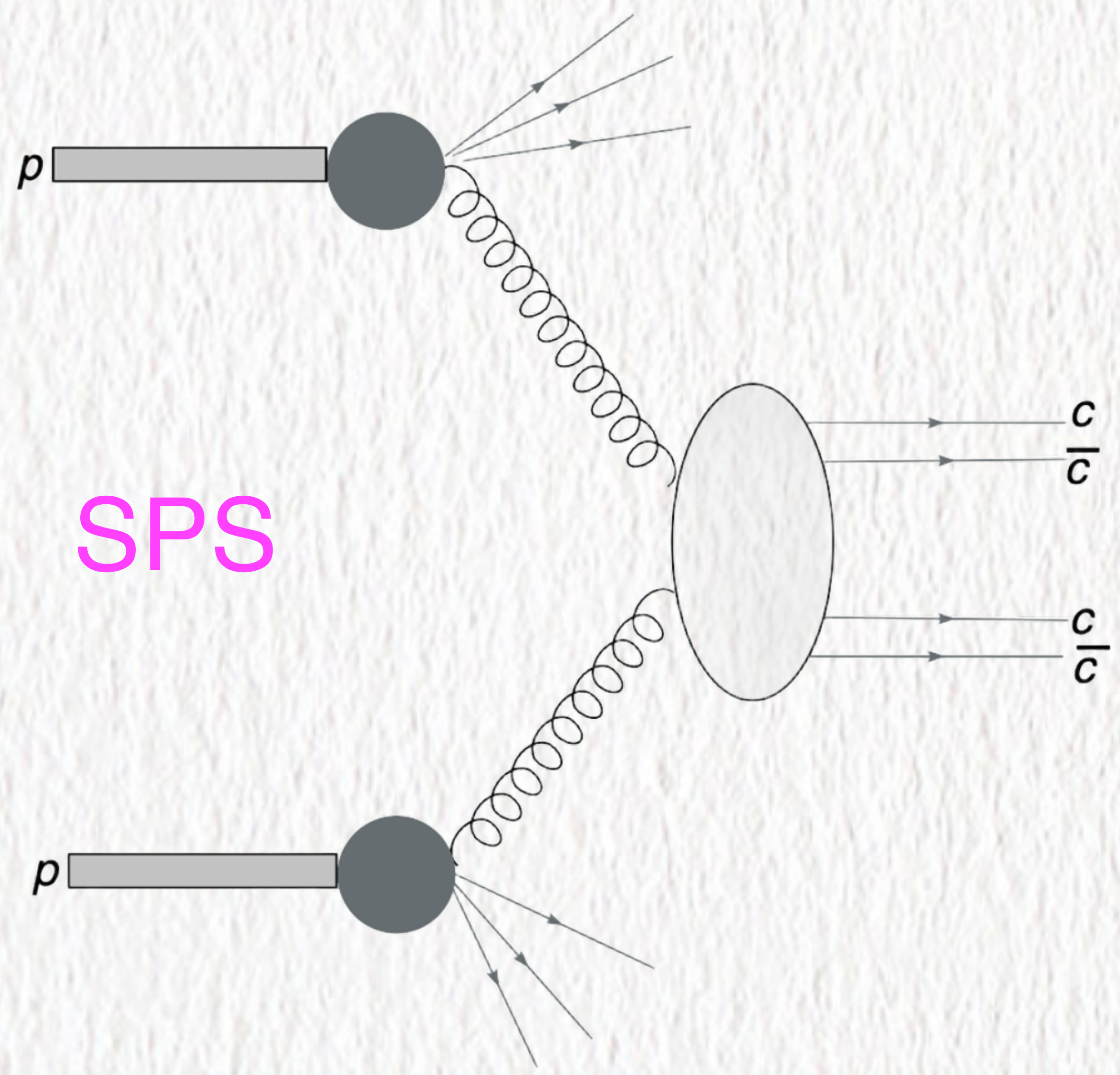
In ALICE Run 3:

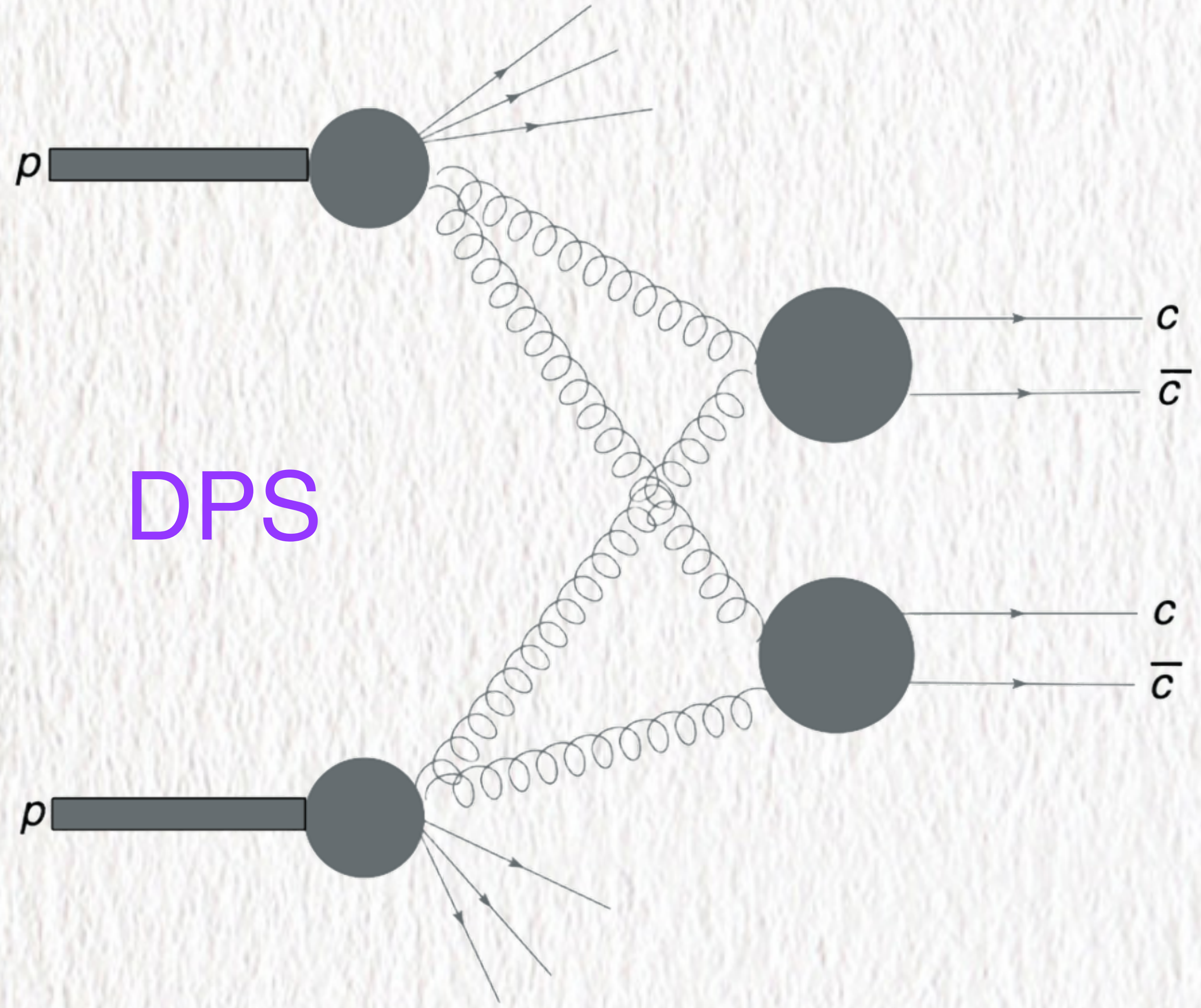
- Thanks to the detector upgrades and the large data samples,
  - The J/ψ–D^0 measurements are now feasible in pp and promising in Pb–Pb collisions
  - Extend the Δy coverage up to ~ 5

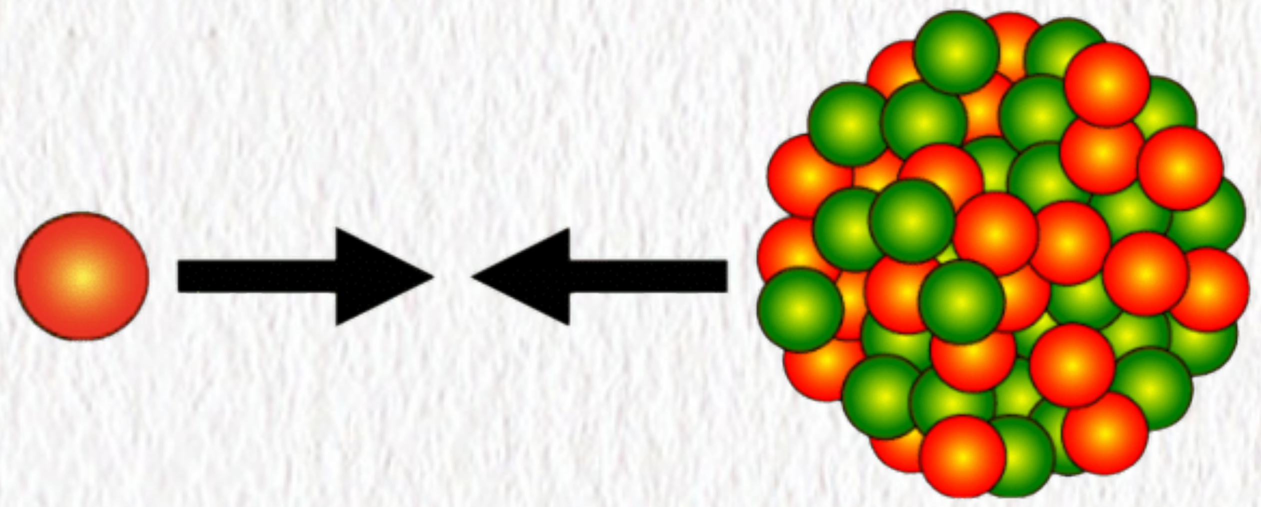
Thank you for your attention!

Additional slides

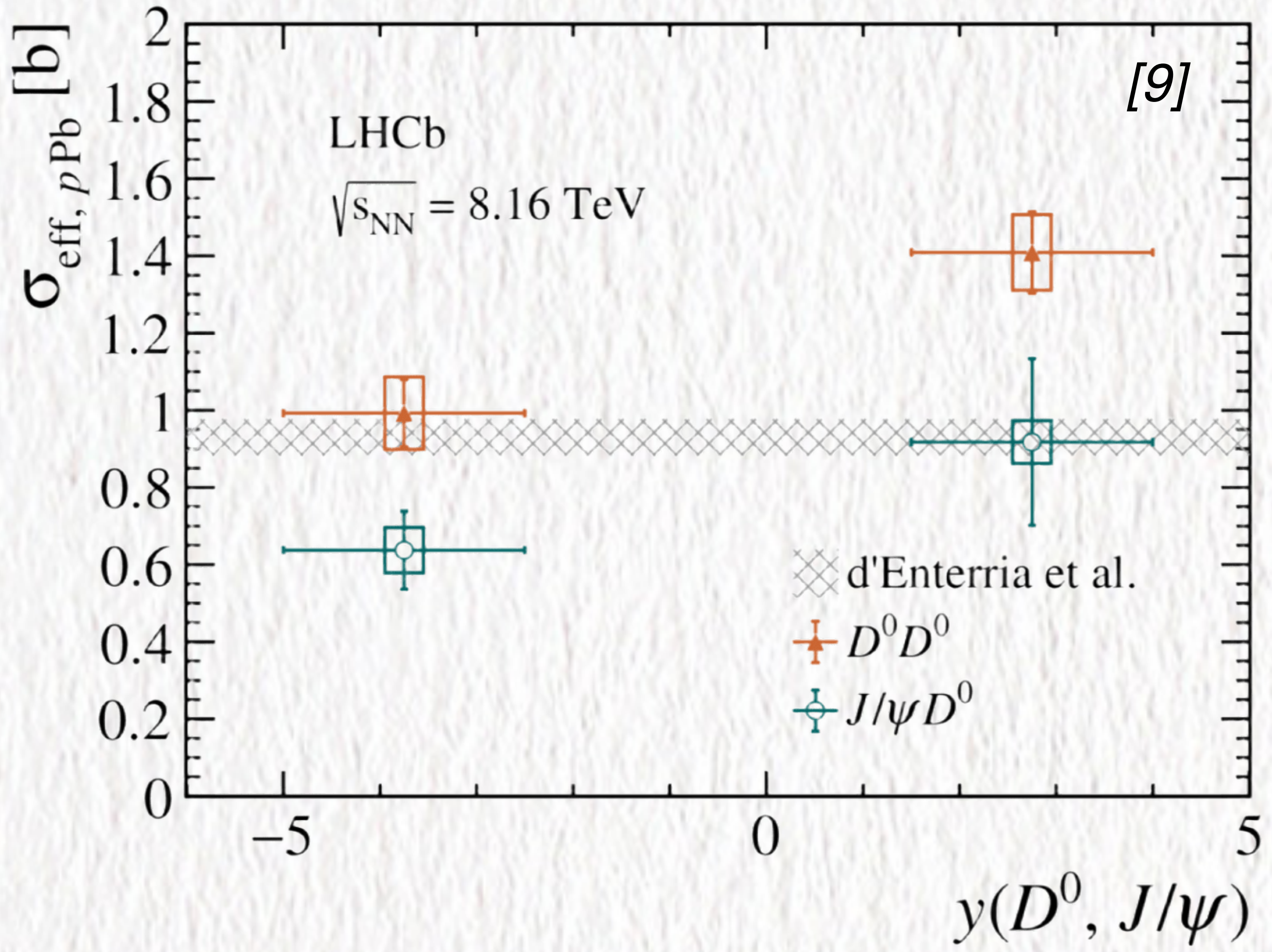
Double charm production in p–Pb collisions







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?

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