Observation of Double Charm Production in pp collisions with ALICE

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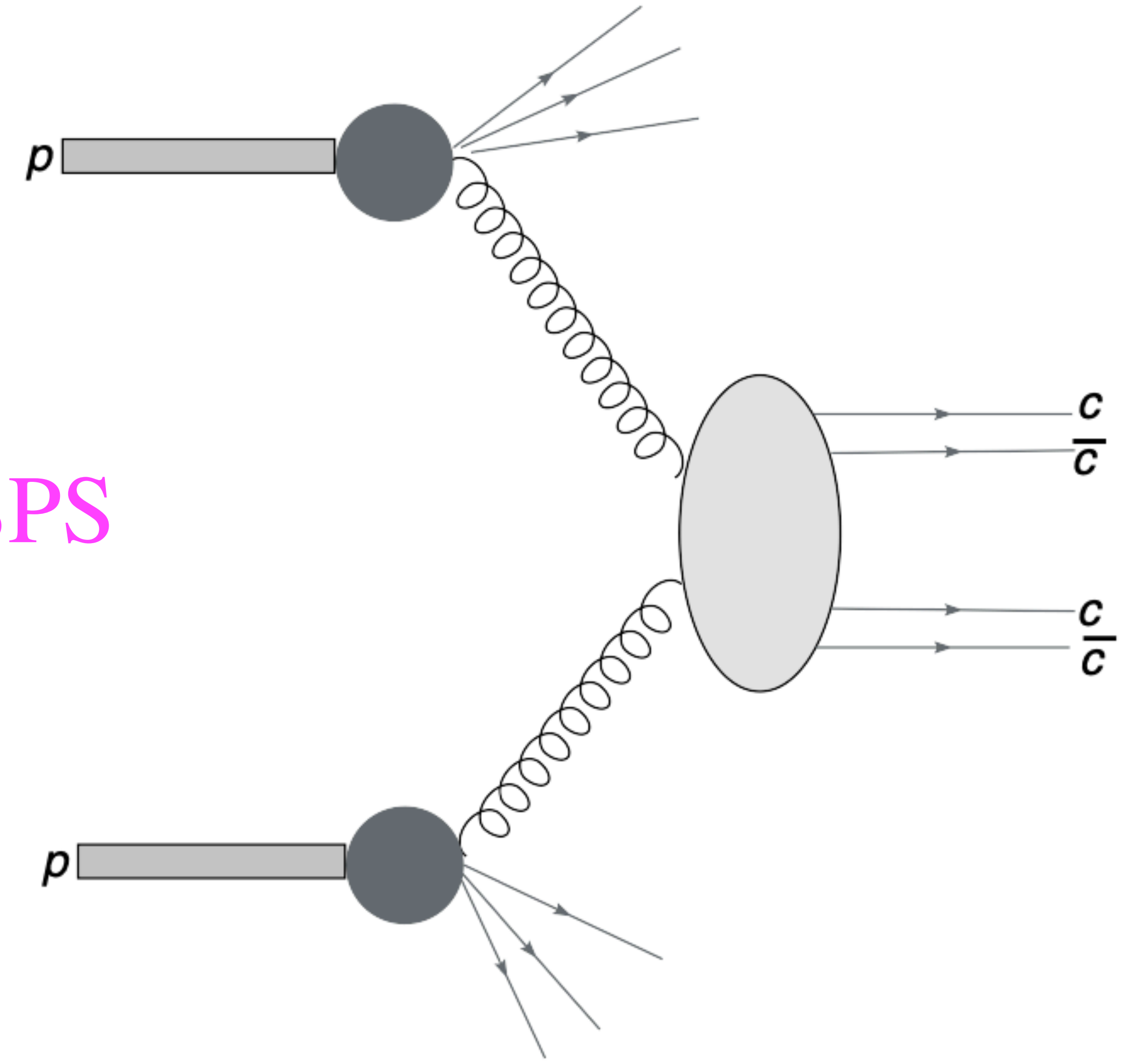
The 10th China LHC Physics-2024, Aoshan Bay, Qingdao.

Motivation

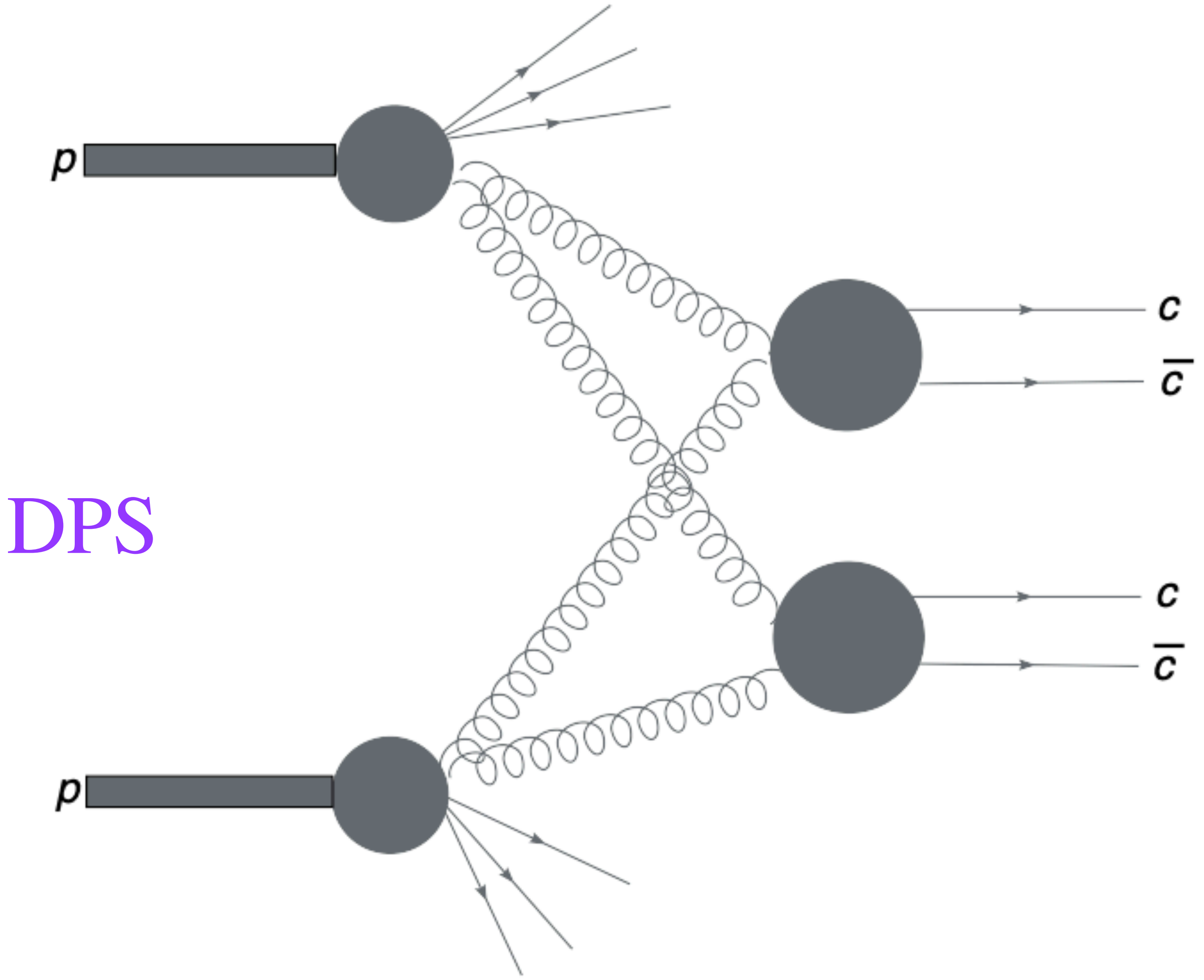
- During hard scattering processes heavy quarks (charm c, bottom b) are produced
- The production of charm-quark pairs provides an opportunity to study both Single Parton Scattering (SPS) and Double Parton Scattering (DPS)

- 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]

SPS



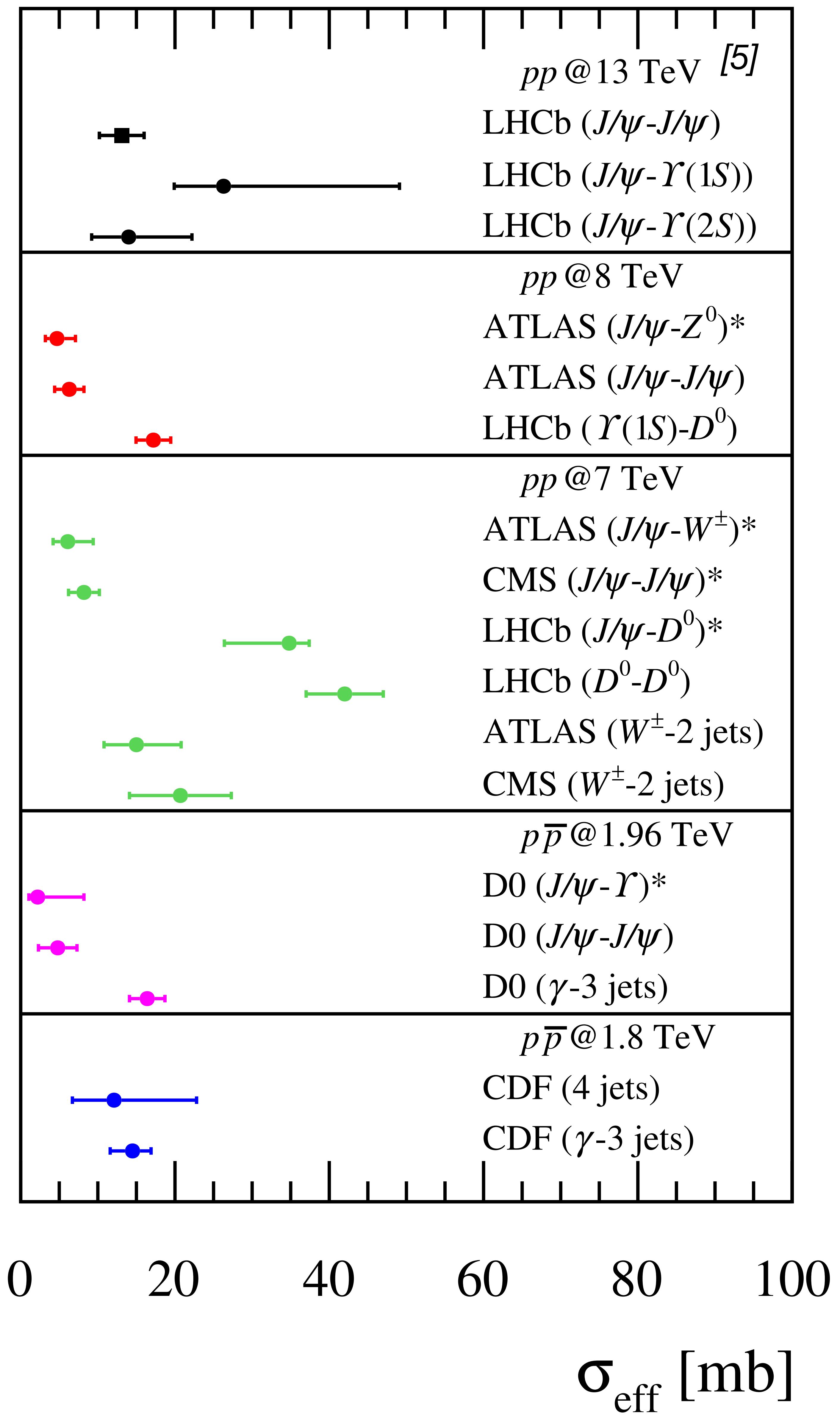
DPS



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

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

Effective cross-section summary



- The general purpose of DPS measurements is to measure the σ_{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

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

[5] JHEP 03 (2024) 088

The ALICE Detector Run 2

Time Projection Chamber (TPC)

- Charged-particle tracking and identification

Inner Tracking System (ITS)

- Vertex reconstruction, track reconstruction

V0 detectors

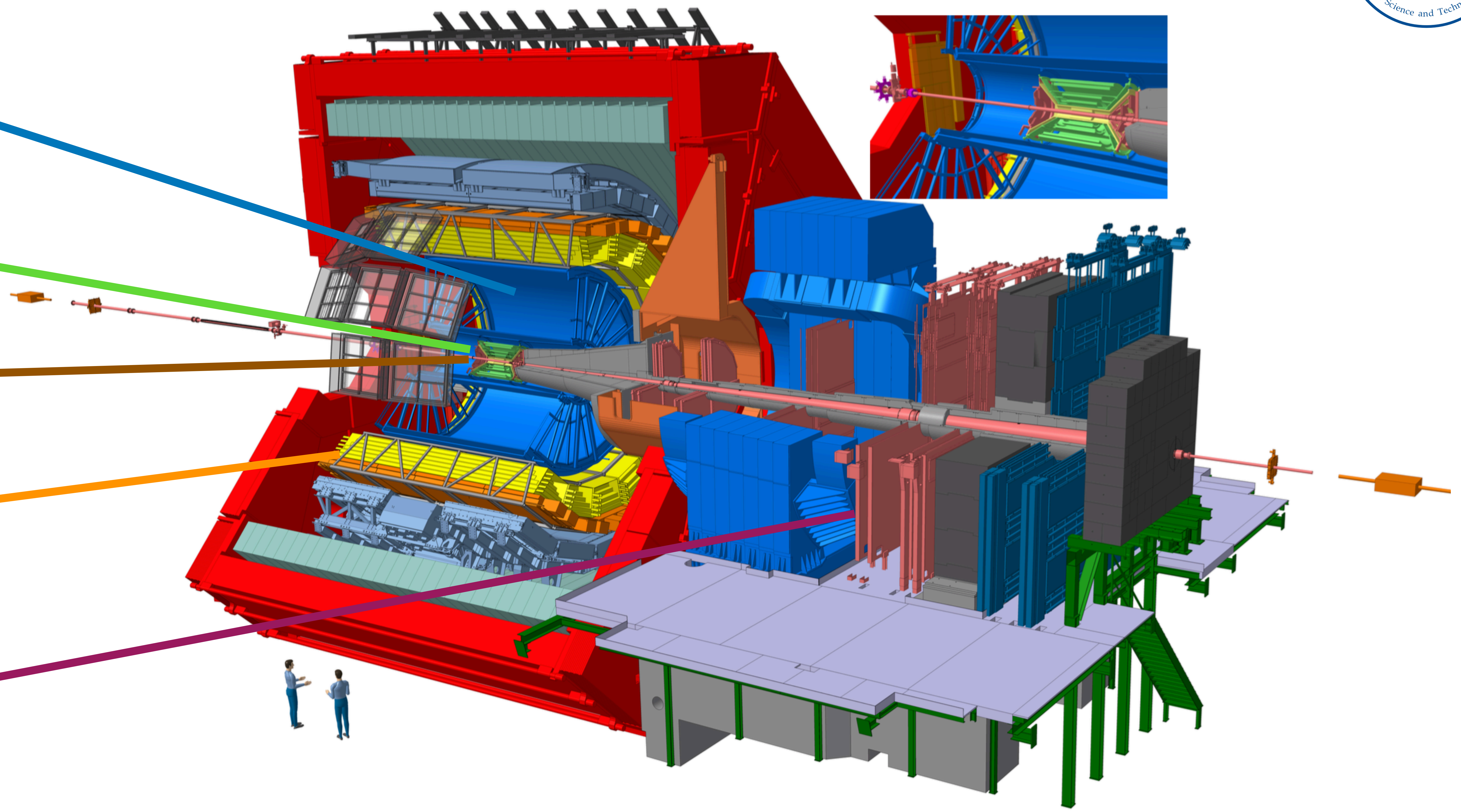
- Triggering

Time Of Flight (TOF)

- PID

μ-Spectrometer

- Trigger and tracking



- $J/\psi \rightarrow e^{+}e^{-}$ and open heavy-flavour states measurements at mid-rapidity $|\eta| < 0.9$
- $J/\psi \rightarrow \mu^{+}\mu^{-}$ 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 $(2.5 < y < 4.0)$

The ALICE Detector Run 3 (upgrade)

TPC upgrade

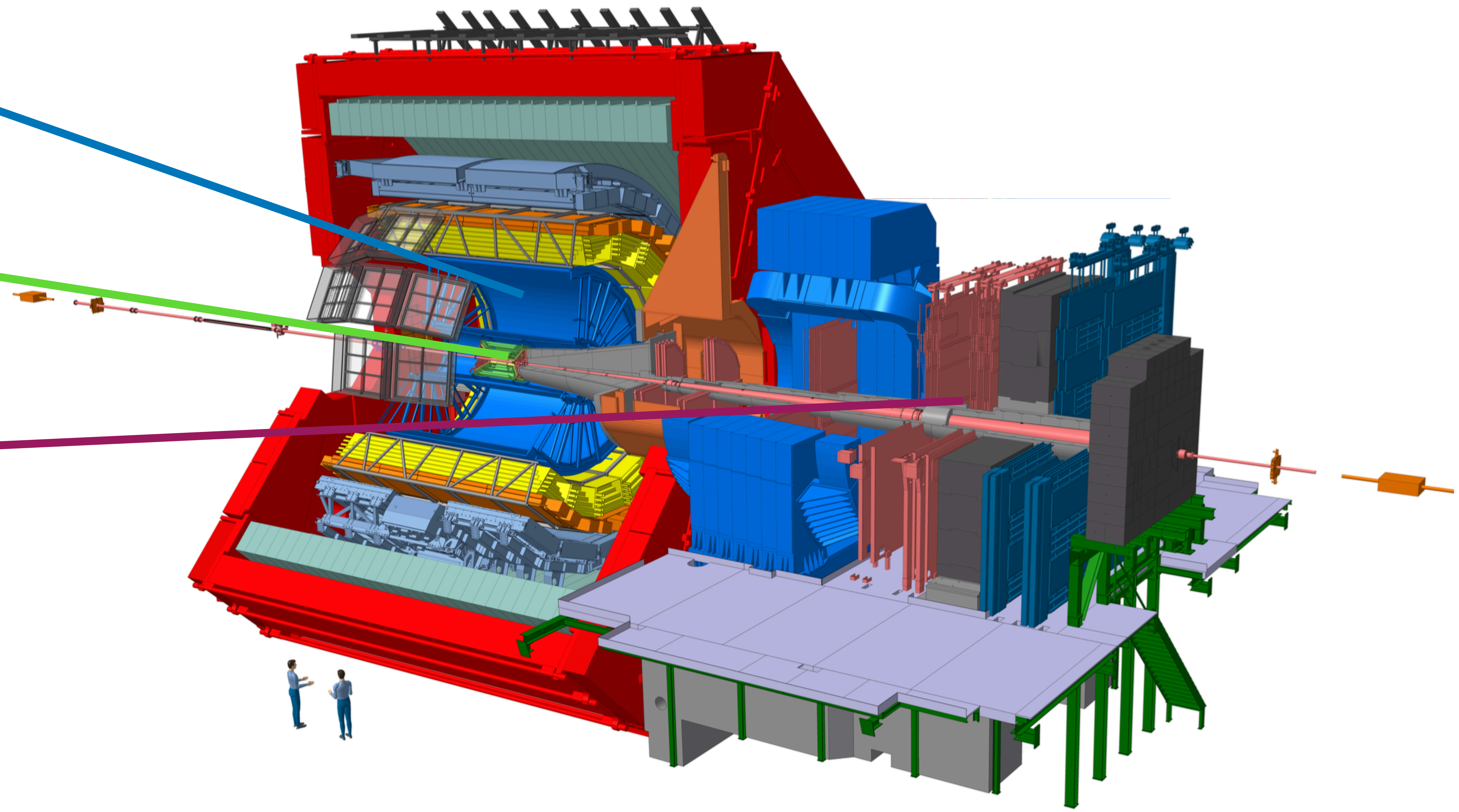
- New readout Gas Electron Multiplier detector (GEM)

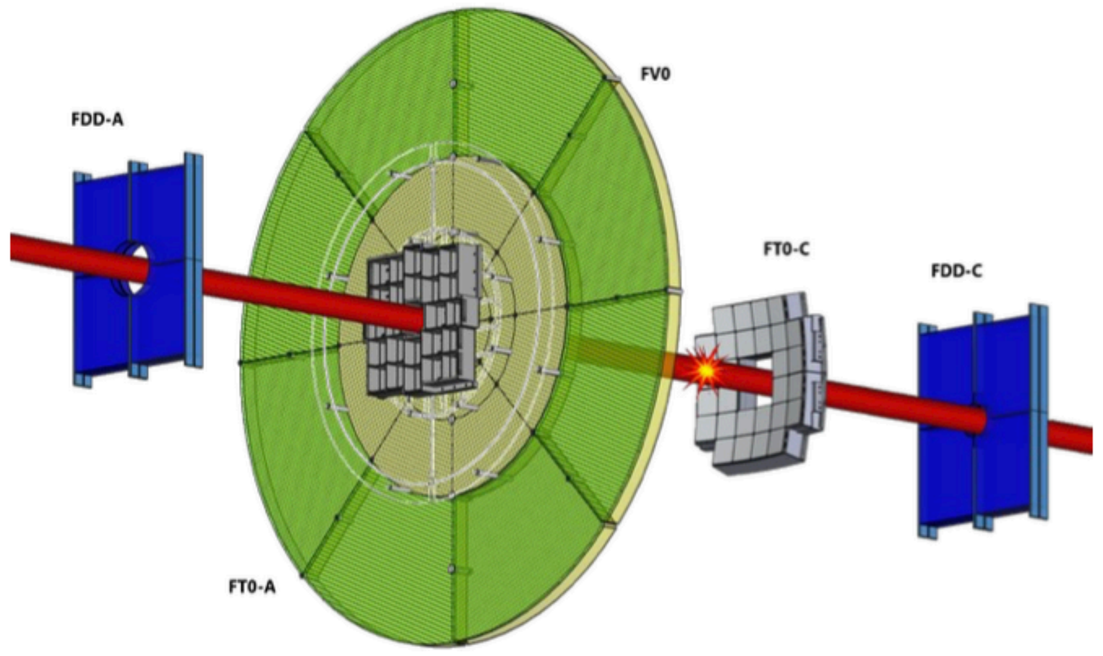
ITS upgrade

- 7 layers of Monolithic Active Pixel Sensors (MAPS) 1st layer at 20 mm

New Muon Forward Tracker (MFT)

- 5 layers of MAPS at forward rapidity
- Forward vertexing and muon tracking





New Fast Interaction Trigger (FIT)

- Fast interaction trigger

J/ψ pair production in pp collision at forward rapidity

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

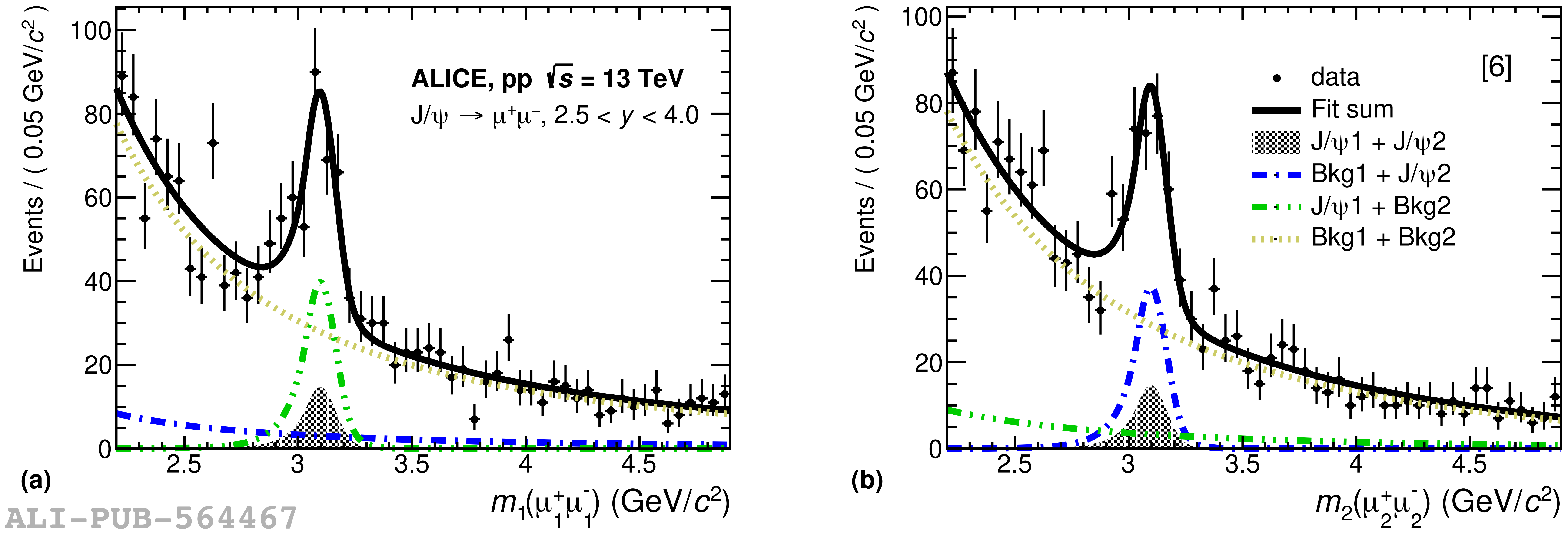
Loop over all combinations of double di-μ pairs in the same event:

- 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 (red)
Mixed Signals and background (blue, green)
Double background (brown)

- Acceptance-times-efficiency correction and lumi. normalisation



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

Estimation of the non-prompt contribution

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

Estimation on the non-prompt contribution

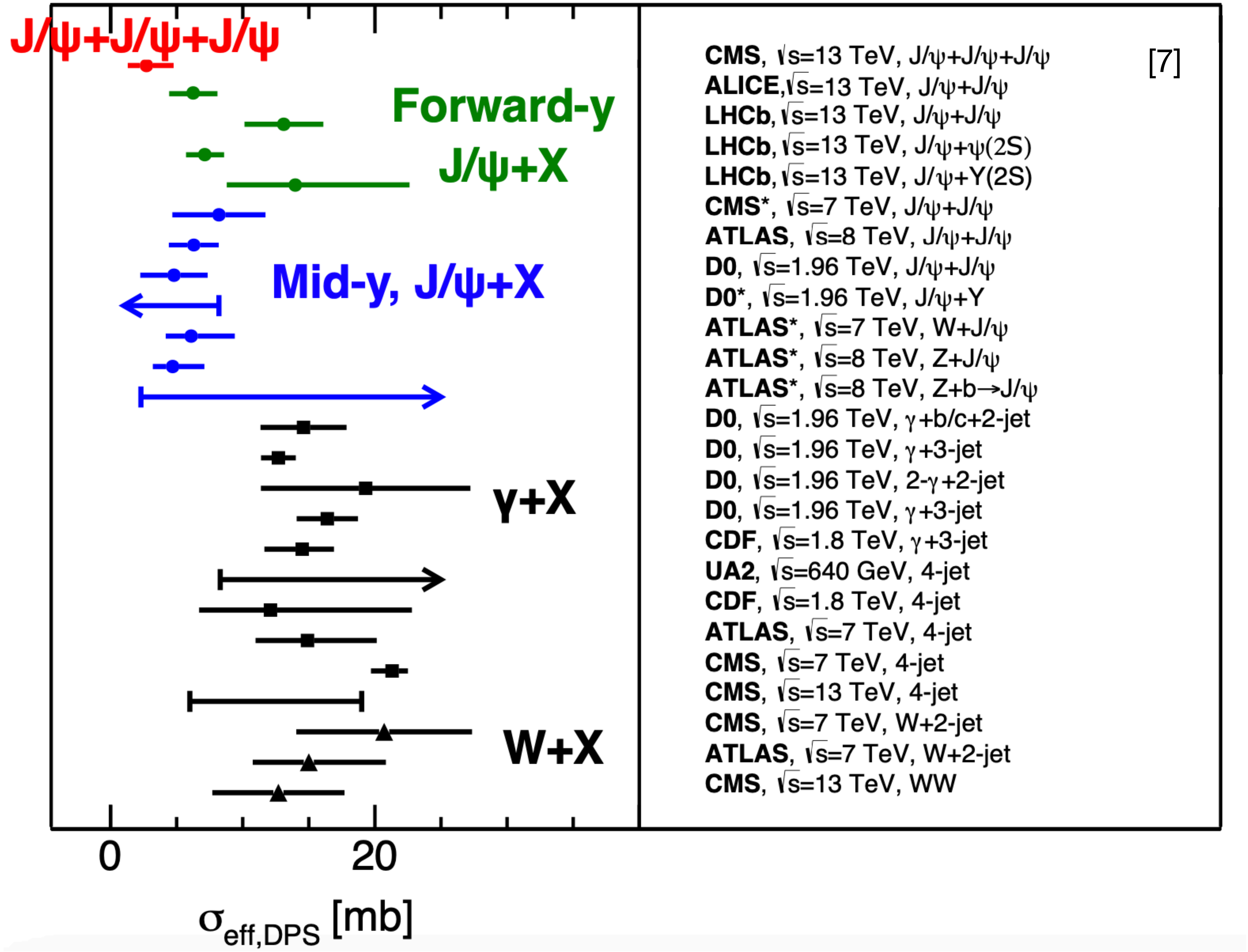
- For single J/ψ production:
  - $\sigma_{non-prompt}(\mathrm{J}/\psi) = 2 \times \sigma_{\mathrm{b\bar{b}}}^{\mathrm{total}} \times \beta \times \mathrm{B}(\mathrm{h_b} -> \mathrm{J}/\psi + \mathrm{X})$ β is the acc. simulated by PYTHIA 8
  - $\sigma_{prompt}(\mathrm{J}/\psi) = \sigma_{\mathrm{inclusive}}(\mathrm{J}/\psi)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

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

Assuming DPS production is the only production mechanism, the effective cross-section σ_{eff} can be calculated using the prompt source

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

Estimation on the eff.σ and Results discussion



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

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

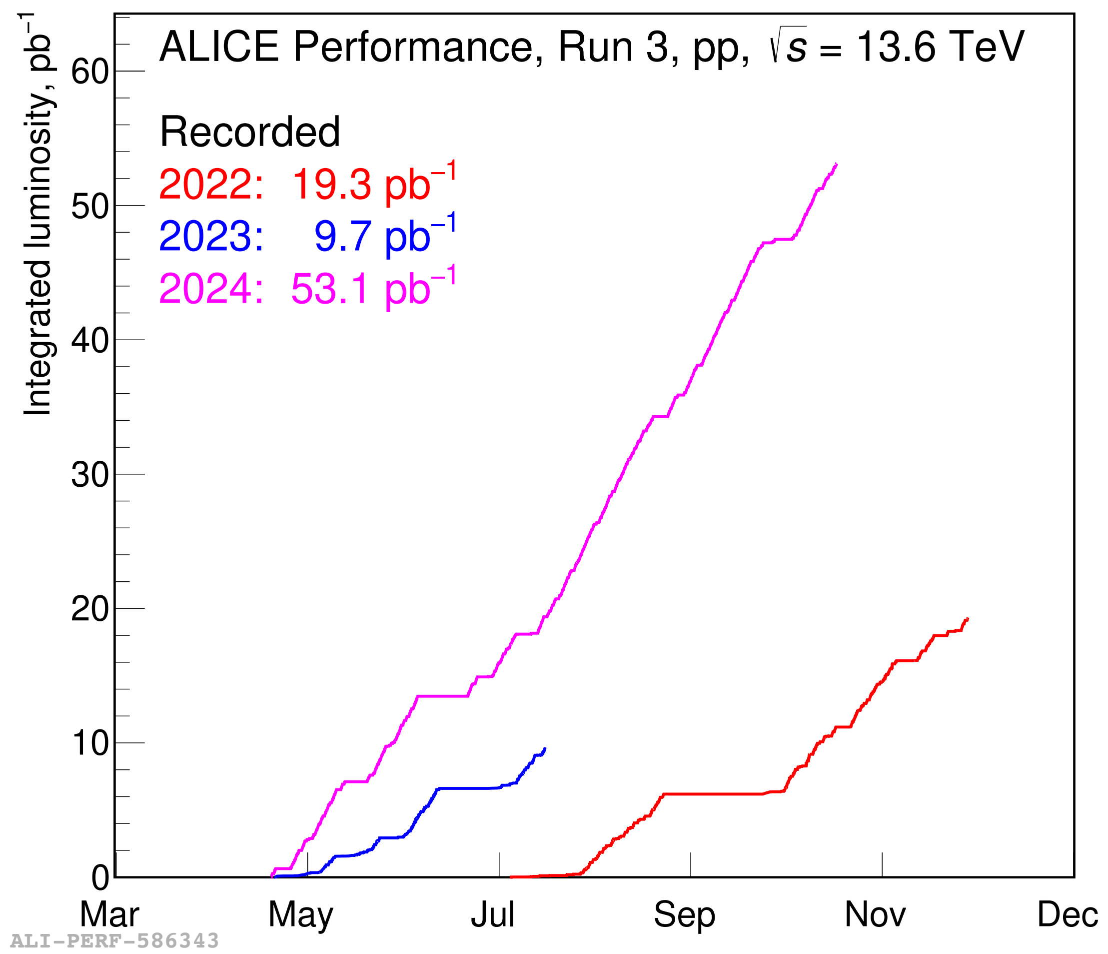
ALICE requires more precise measurements

[7] QM2023, Andre Ståhl talk

Improvement of ALICE detector (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



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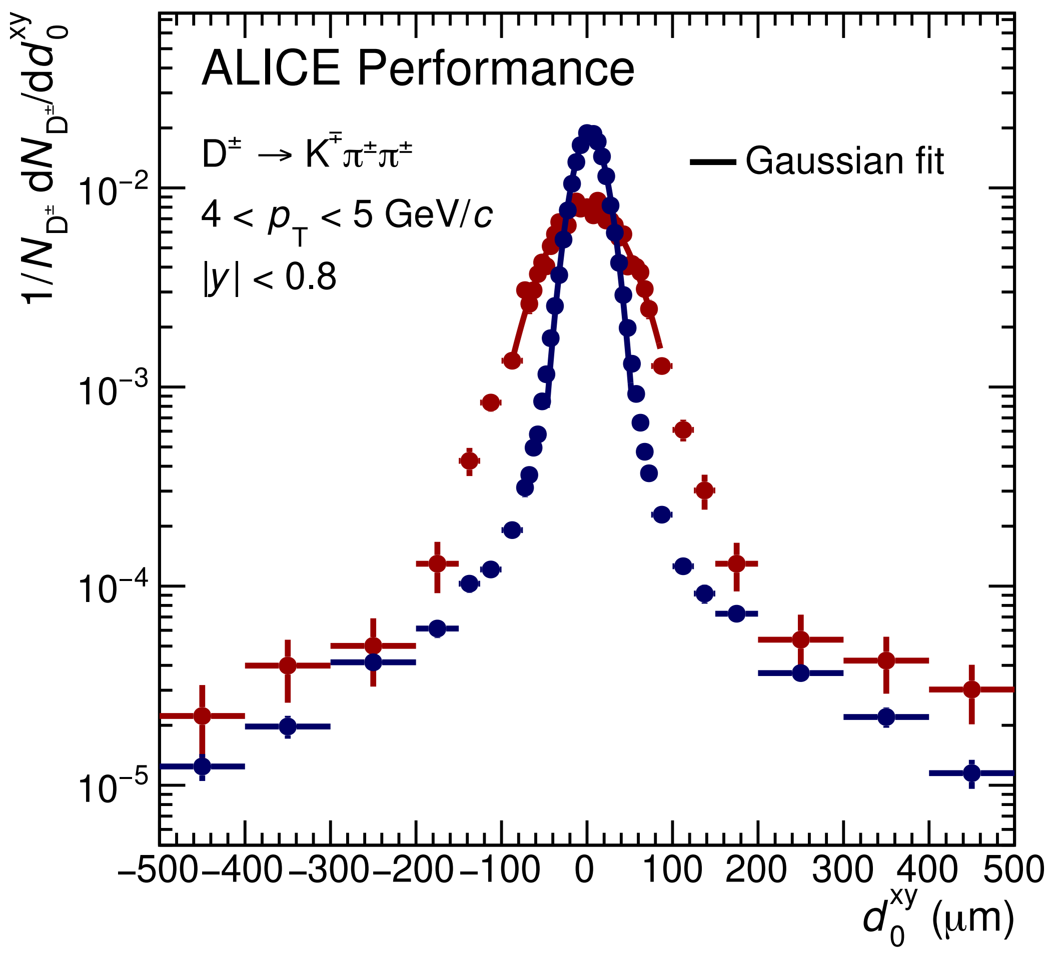

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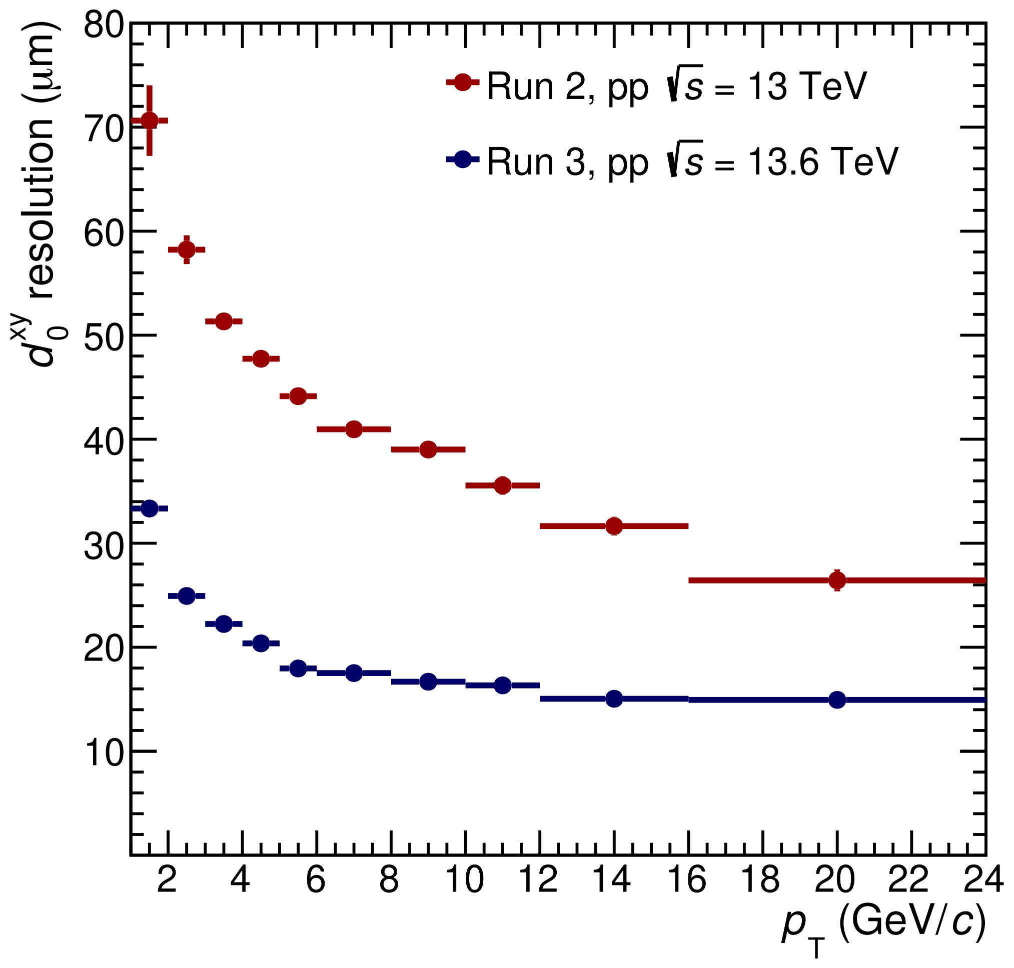
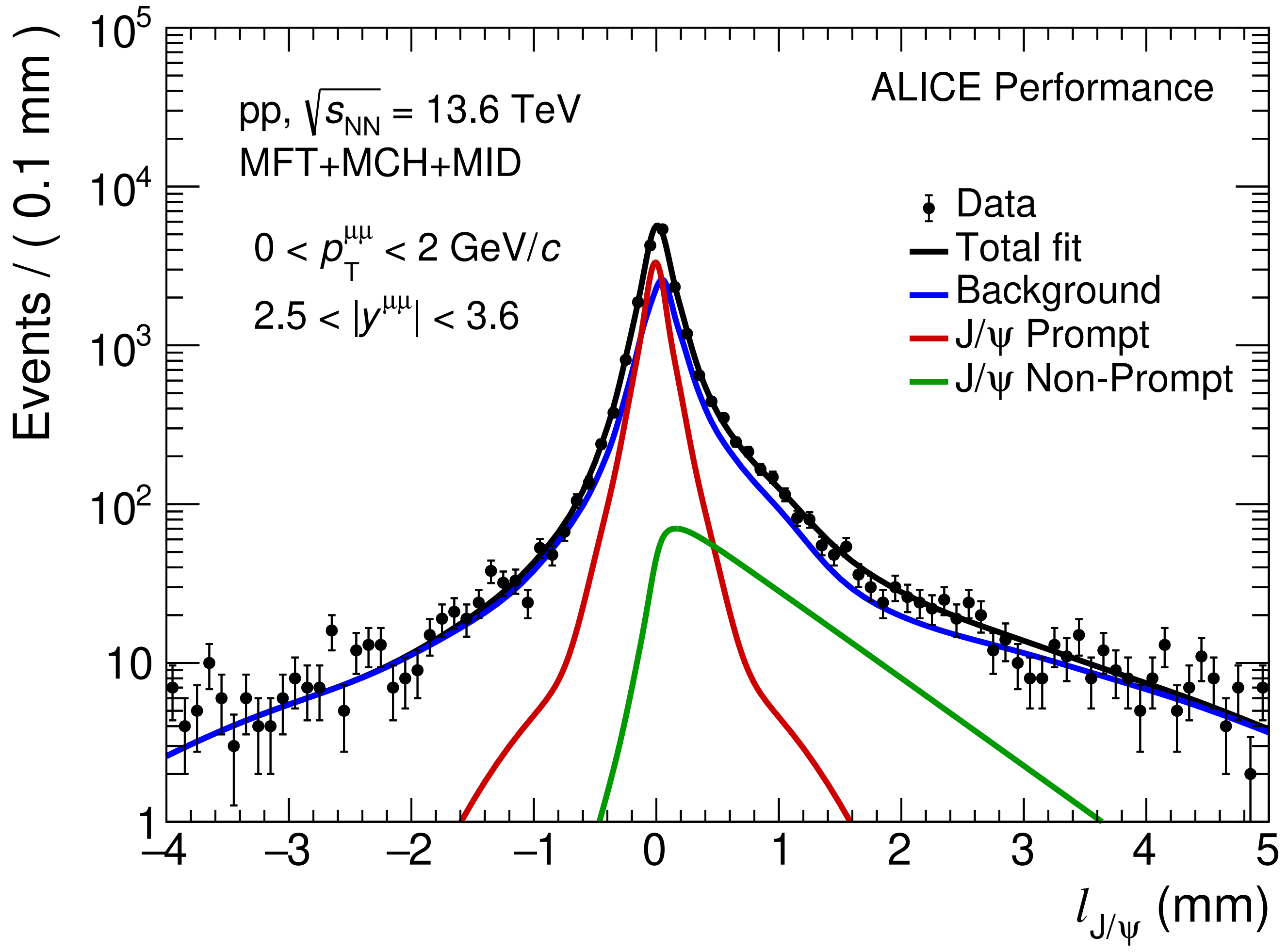


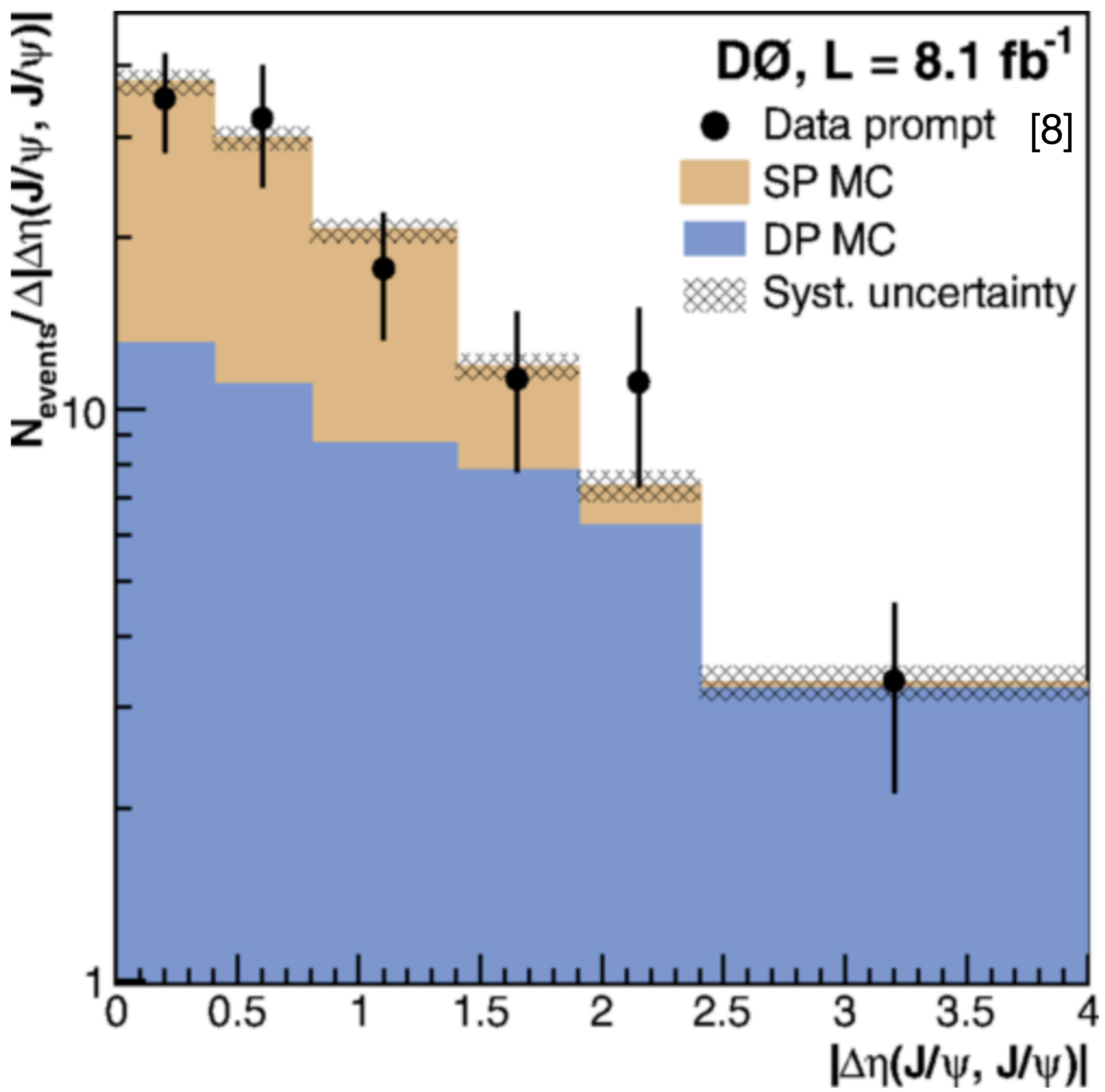


ALI-PERF-571258

- Excellent performance across all upgraded detectors

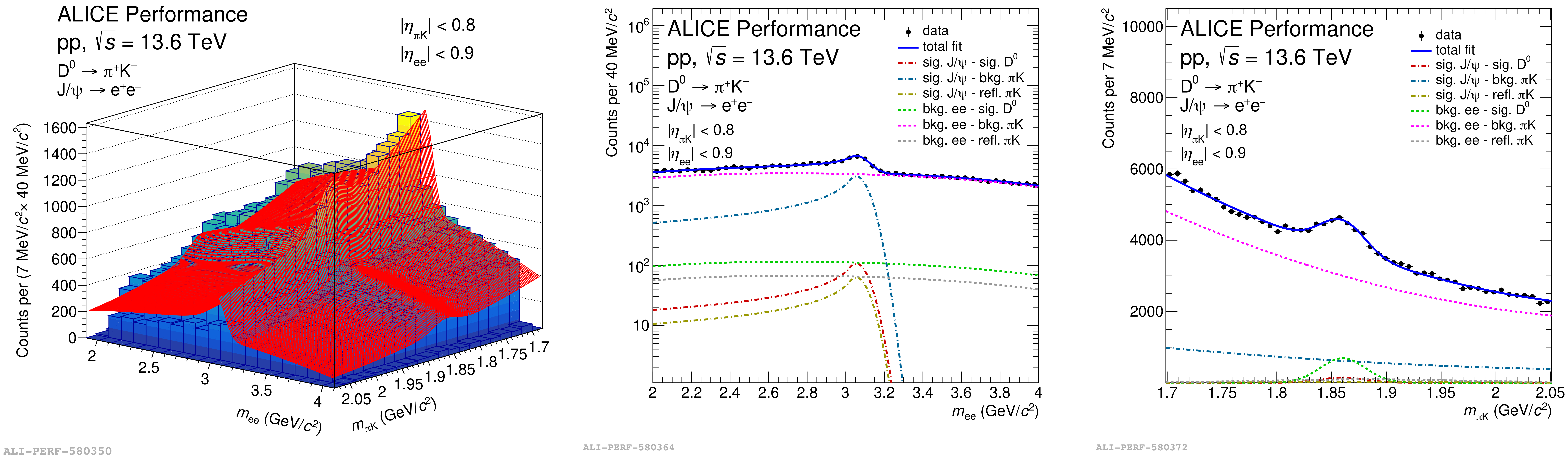
Opportunities on ALICE Run 3

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



[8] Phys. Rev. D 90, 111101

J/ψ –D⁰ at midrapidity

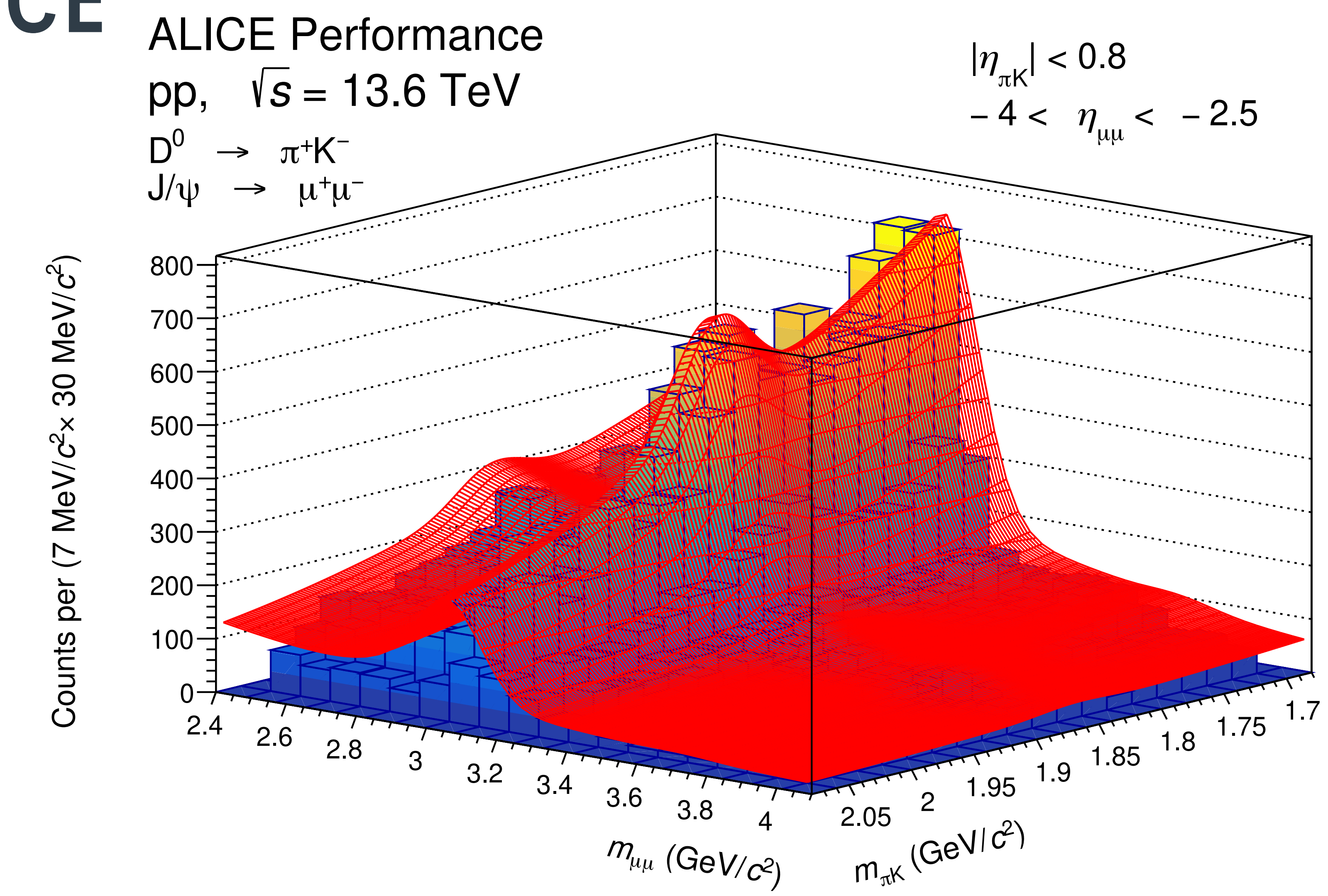


- Begin by examine the associated production of J/ψ –D^0 using an unbinned maximum likelihood fit
- Account for reflections* from the D^0 reconstruction
- A notable associated signal of J/ψ –D^0 can be observed

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

*reflection: $D^0(\to K^-\pi^+$ and c.c.) built with the wrong mass hypothesis

Associated–D^0 with J/ψ at forward rapidity



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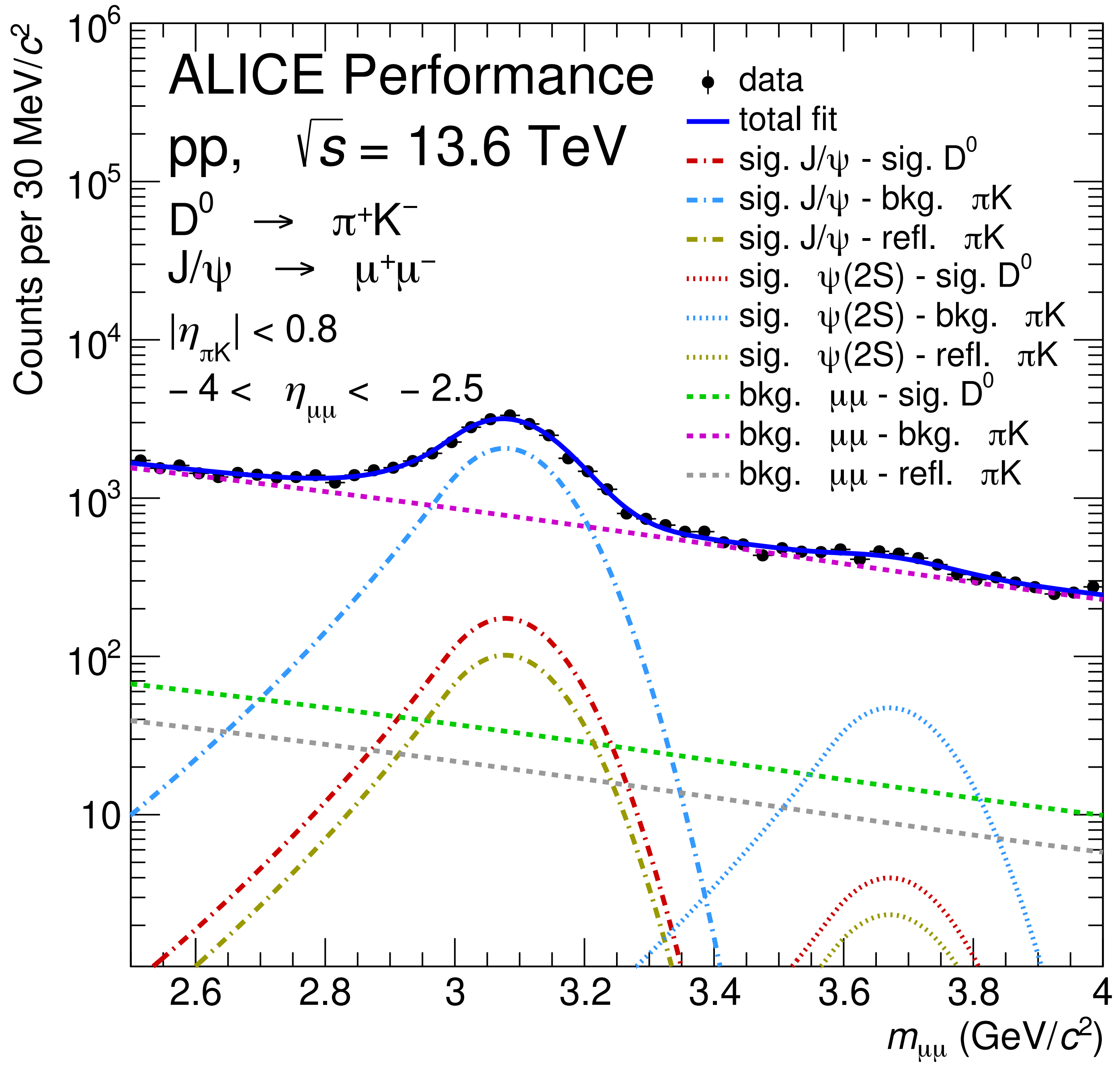

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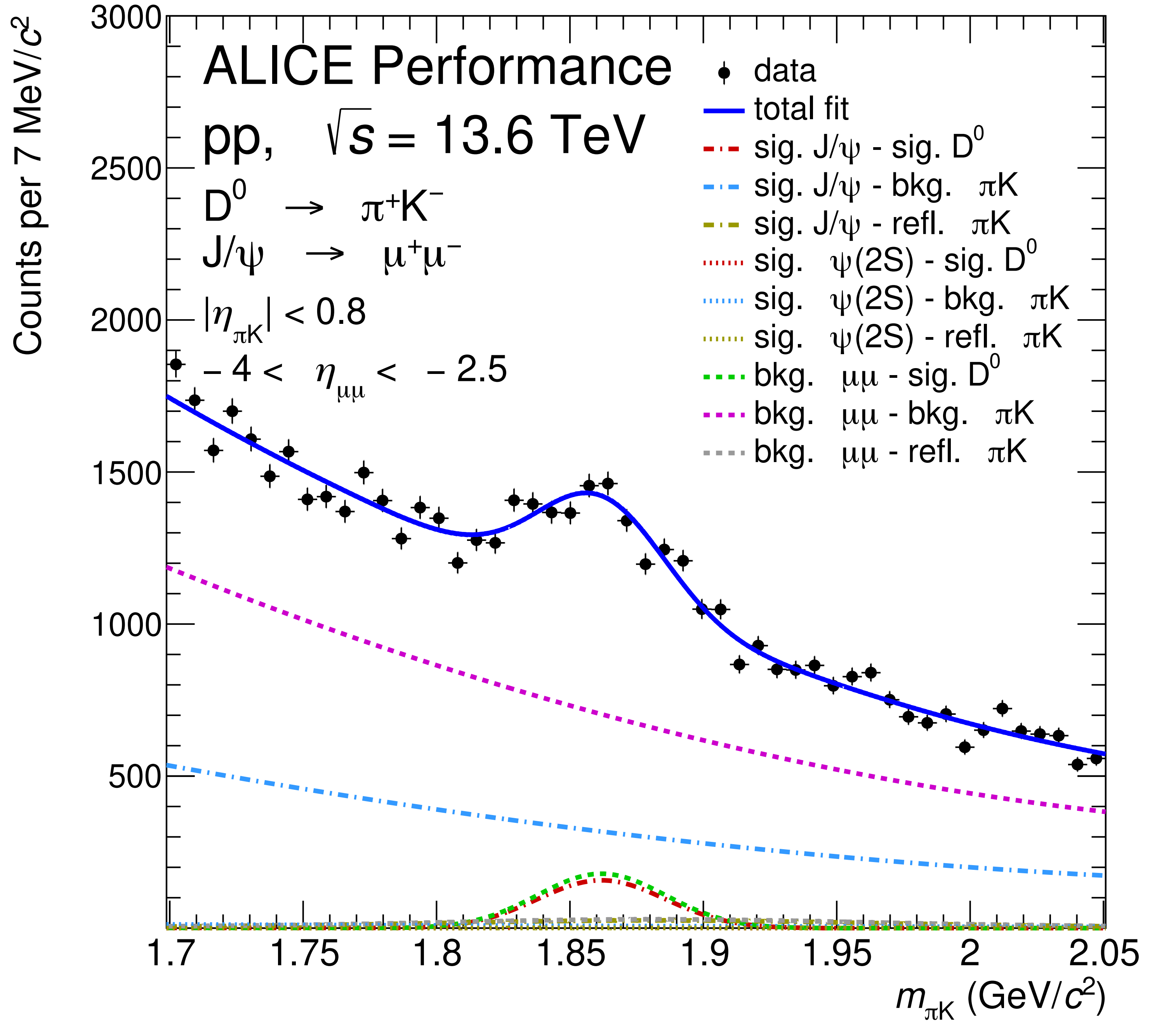


ALI-PERF-580360

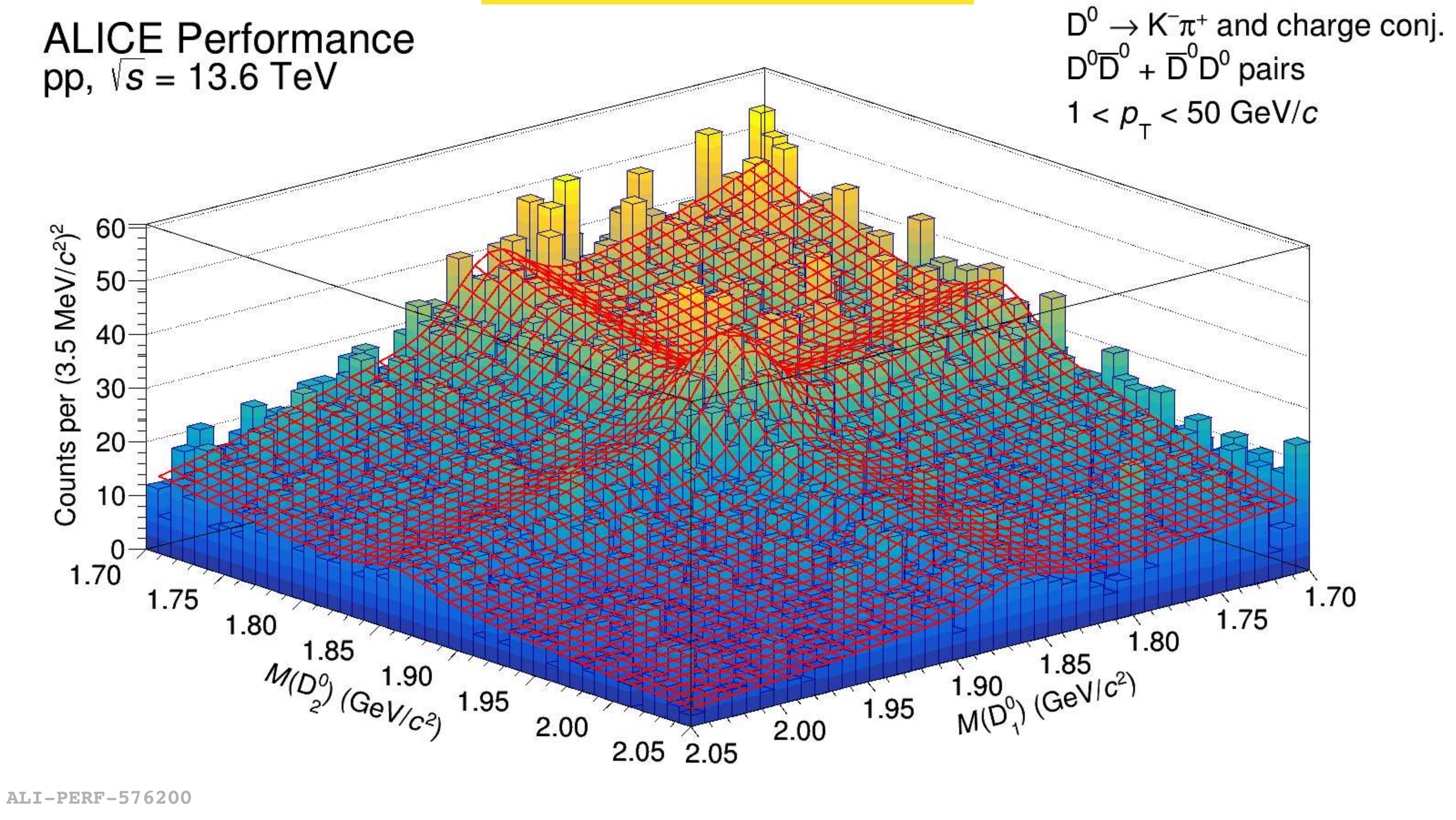
- Investigate the associated production of D^0 in conjunction with a forward rapidity J/ψ
- Additionally, consider the presence of the $\psi(2S)$
- improved S/B can be achieved in forward rapidity J/ψ reconstruction

Cover the full Δy range up to ~ 5

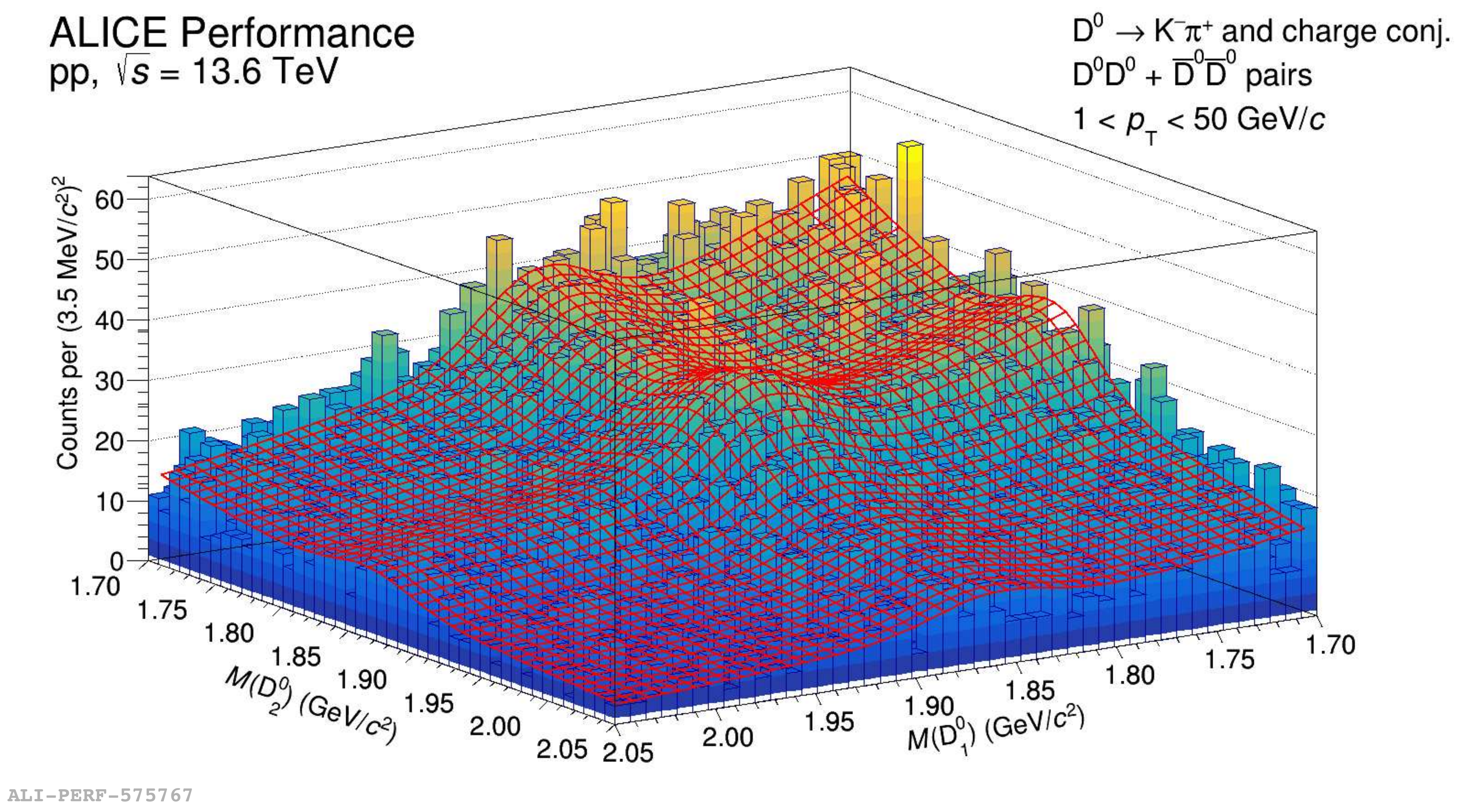
D^0–D^0 at midrapidity

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

D^0 same-sign pairs



D^0 opposite-sign pairs



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

Summary

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.
  - Cover the full Δy range up to ~ 5

Thank you for your attention!

Backup