Investigating quarkonium production in proton–proton collisions with ALICE

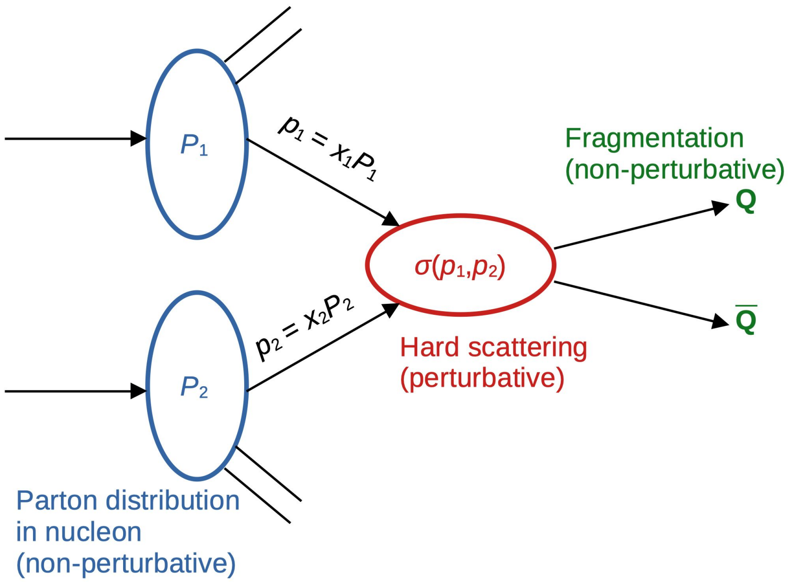
Emilie Barreau, Subatech Nantes FRANCE
on behalf of the ALICE collaboration

08/07/25

Understanding quarkonium production mechanism

Strong interaction described by Quantum Chromodynamic (QCD)

- large α_s at low Q^2: **non-perturbative** correction
- small α_s at high Q^2: **perturbative** QCD



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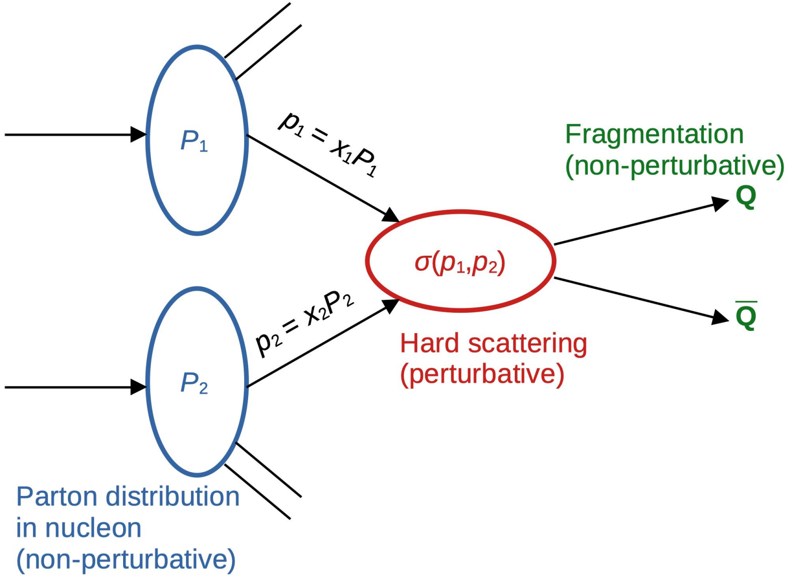
Heavy quarkonium production (charm and beauty quark-antiquark pairs)

- produced at early stage of the collision: hard scattering
  - experience the full system evolution
- $m_c \gg \Lambda_{QCD} \rightarrow$ **perturbative** QCD regime
  - test pQCD predictions
  - weakly bound state: sensitive to quark-gluon plasma (QGP)
- quarkonia bound states $\rightarrow$ **non-perturbative** QCD treatment



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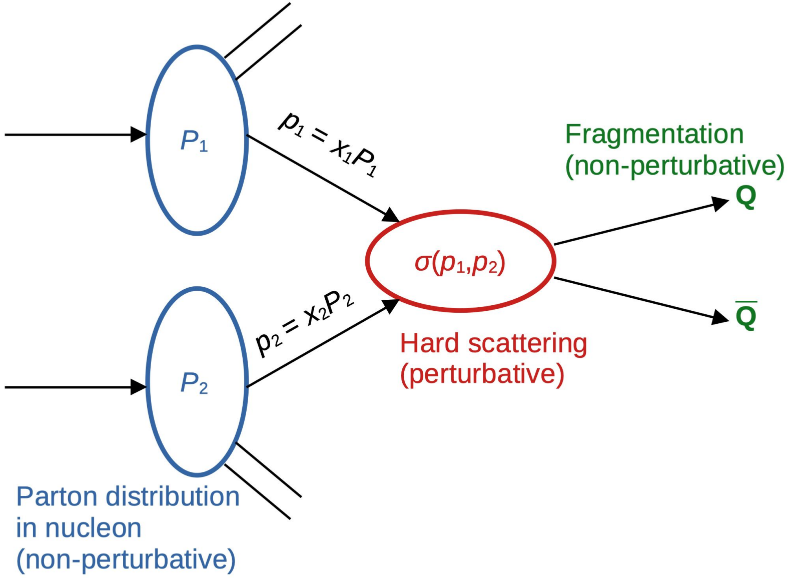
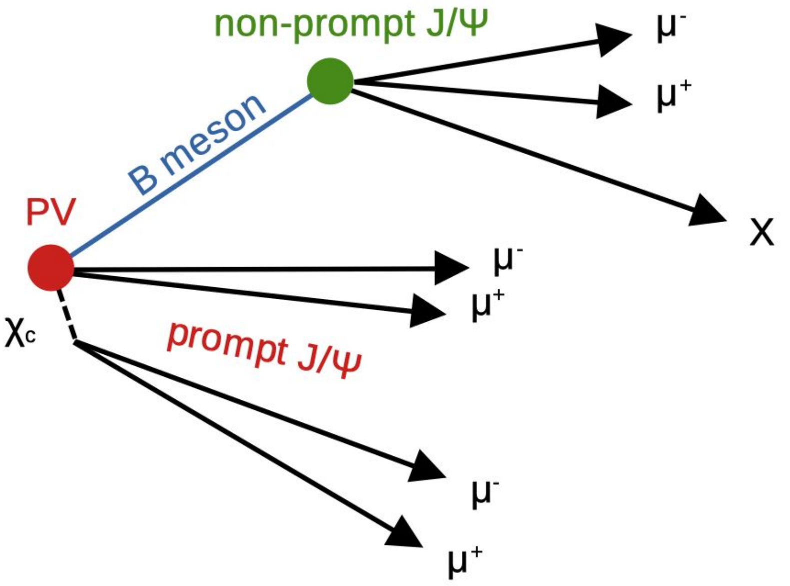


Motivations

- Study quarkonium production mechanisms
- Baseline for studying heavy-ion collisions and quark-gluon plasma properties

J/Ψ and Ψ(2S) production

- Heavy quarkonia mostly produced in pp via gluon fusion
- In ALICE, measurement via leptonic decays modes : e^+e^- or $\mu^+\mu^-$



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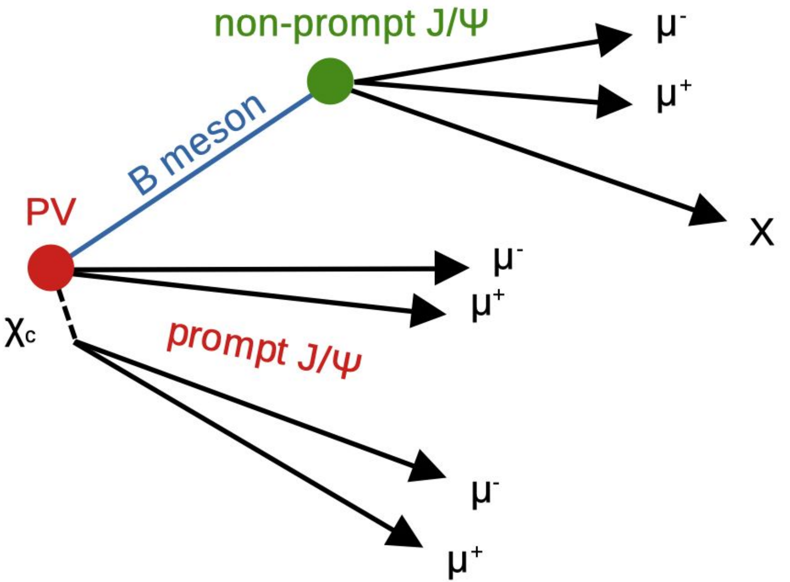
- J/Ψ production:
  - prompt: charm-anticharm pair + radiative decay of other quarkonium states → probing charm production
  - non-prompt: decay product of B hadrons → probing beauty production

- Ψ(2S) heavier and weaker bound state
  - Ψ(2S)-to-J/Ψ ratio expected to be < 1



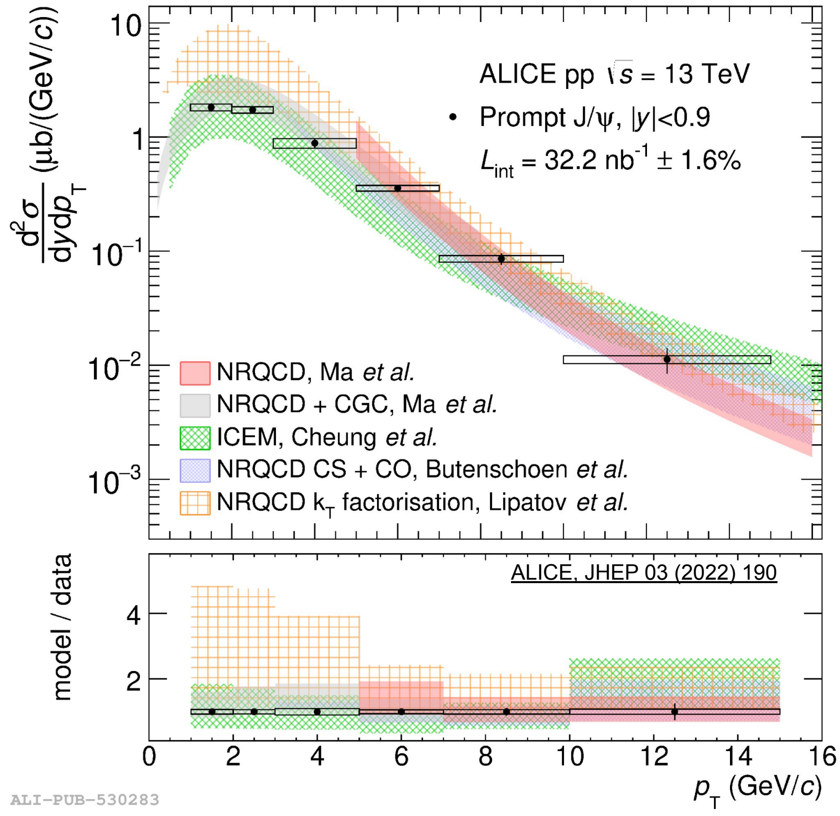
Theoretical models for quarkonia production in pp

Color Singlet Model (**CSM**)

- quarkonium directly produced in color singlet state

Color Octet Mechanism / **Non-Relativistic QCD** (**COM**/**NRQCD**)

- quarkonium produced in a color singlet or octet state
- soft gluon emission to reach final state



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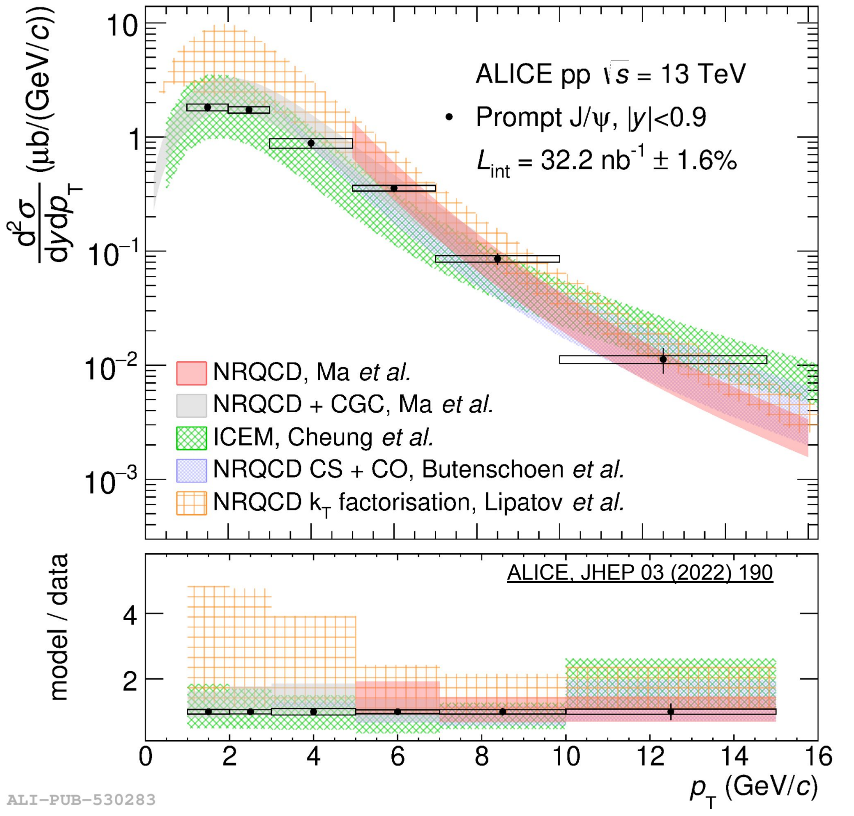
- quarkonium produced from quark-antiquark pair with a constant probability
- neglect spin, color and angular momentum



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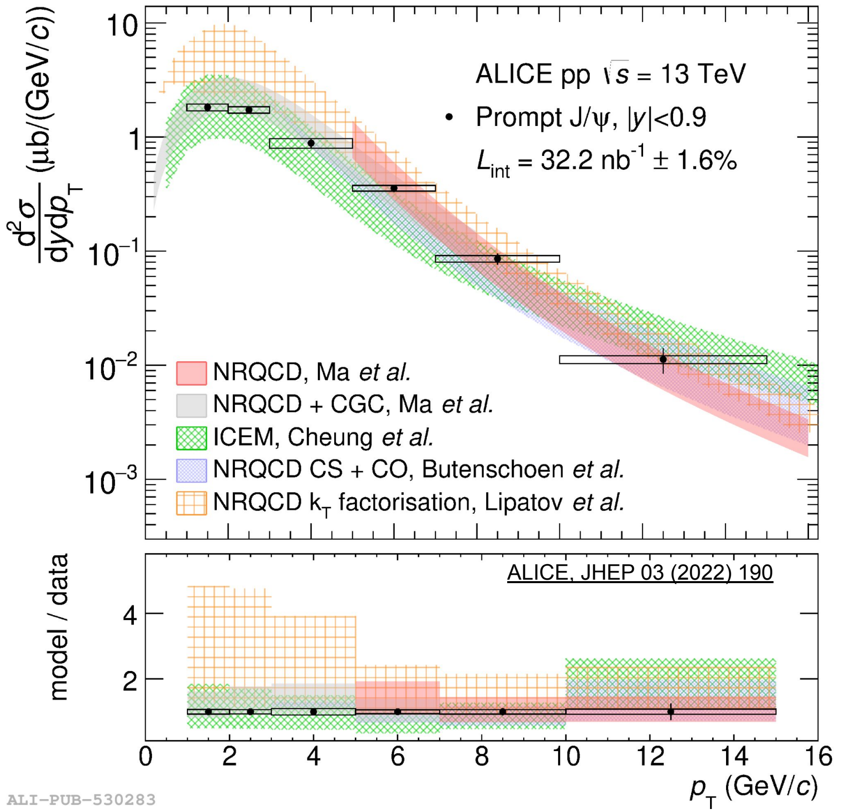
k_T-factorisation
- unintegrated PDFs depending on k_T and x
- initial state partons: off-shell (virtual) with $k_T \neq 0$
- combined with CSM or NRQCD



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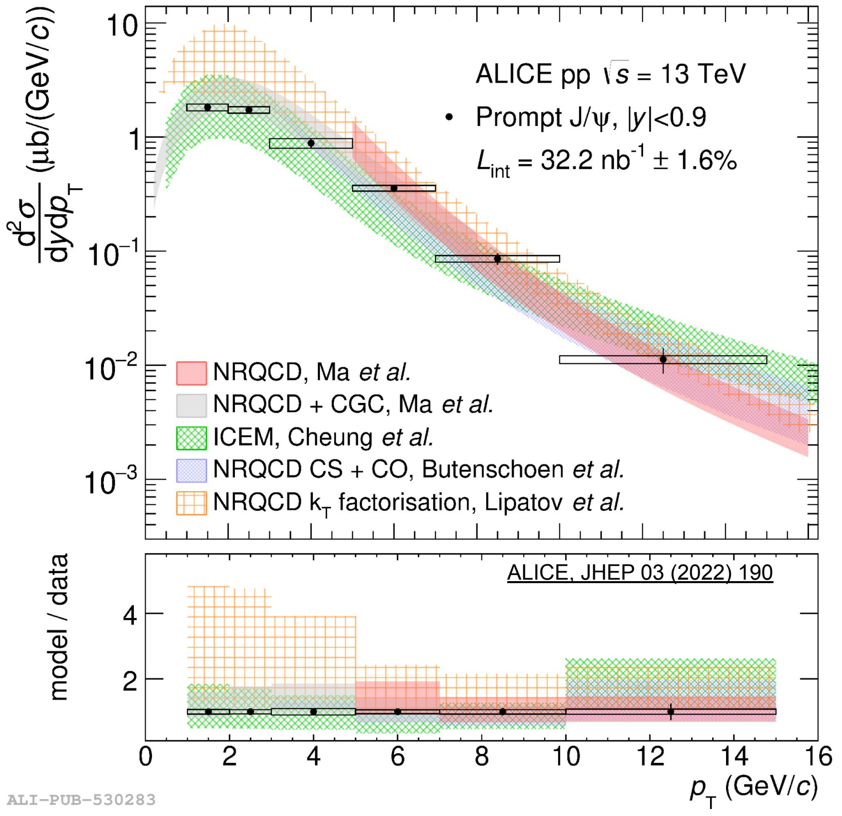
Color-Glass Condensate (CGC+NRQCD)

- saturated gluons in protons at high energy
- combined with NRQCD to describe quarkonium production



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The ALICE Experiment in Run 3

Central barrel → e^+e^-

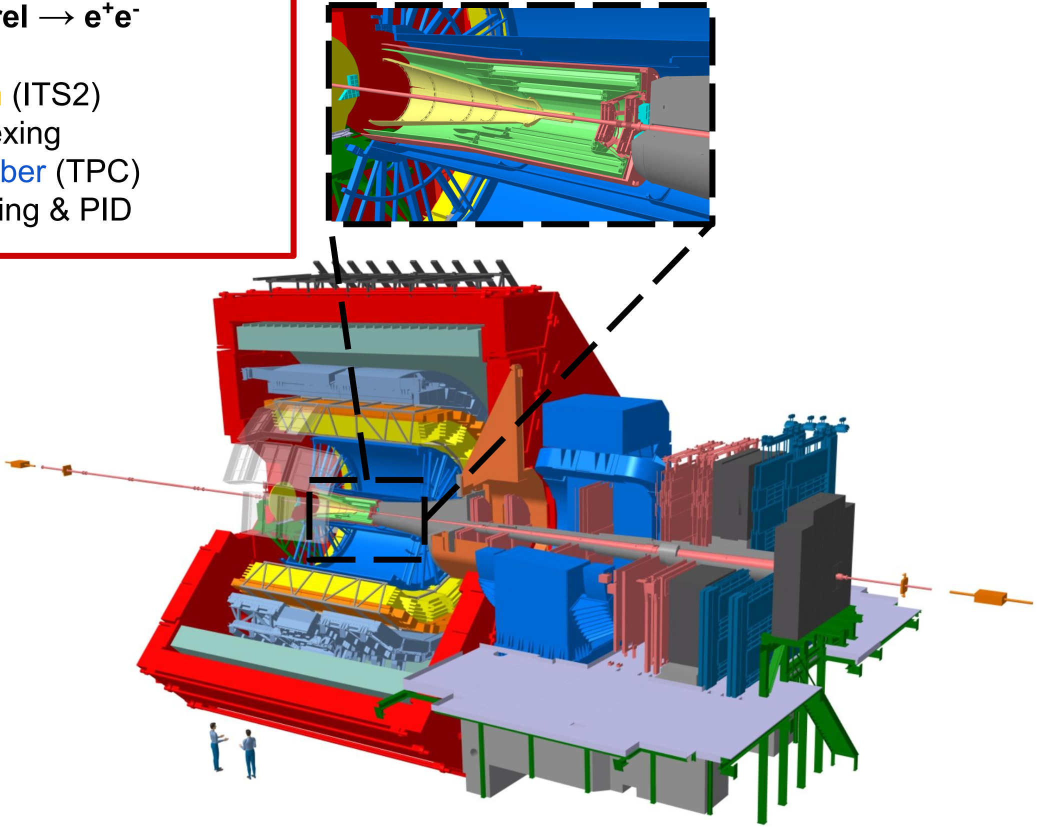
Midrapidity: $|\eta| < 0.9$

Inner Tracking System (ITS2)

- tracking & vertexing

Time Projection Chamber (TPC)

- vertexing, tracking & PID



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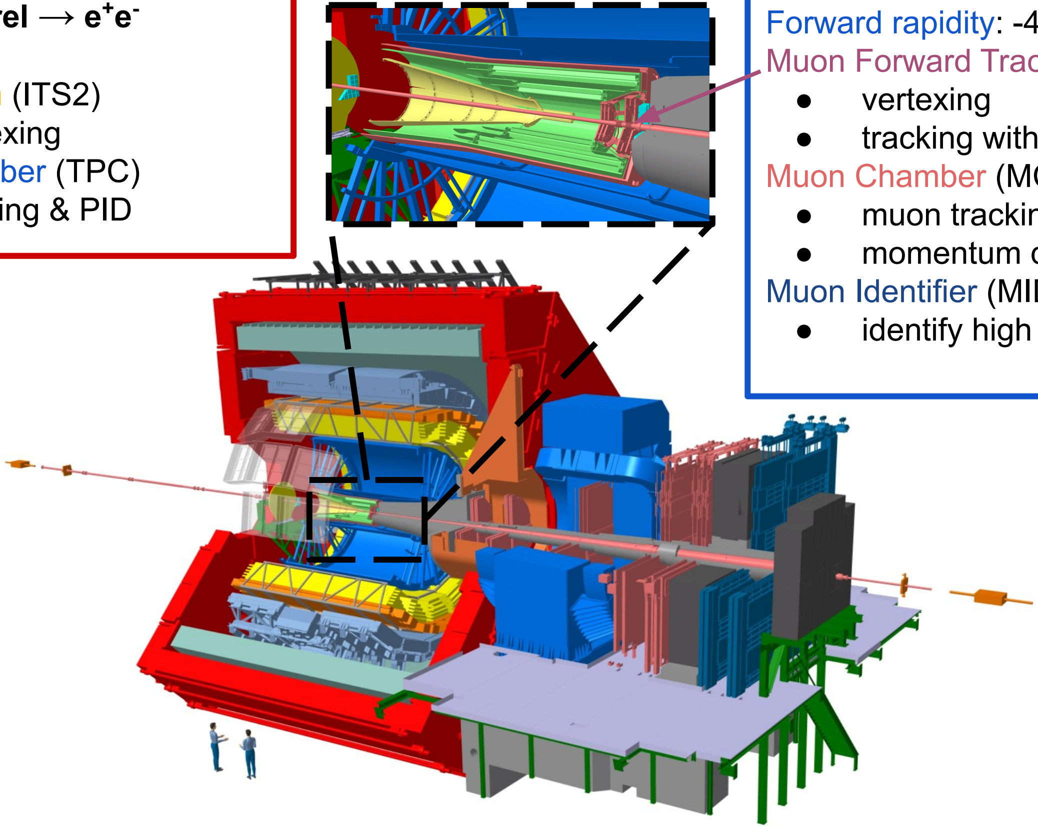
Muon spectrometer → $\mu^+\mu^-$
Forward rapidity: $-4 < \eta < -2.5$
Muon Forward Tracker (MFT) ($-3.6 < \eta < -2.5$)
- vertexing
- tracking with high spatial resolution

Muon Chamber (MCH)
- muon tracking
- momentum determination

Muon Identifier (MID)
- identify high momentum muons (> 4 GeV/c)



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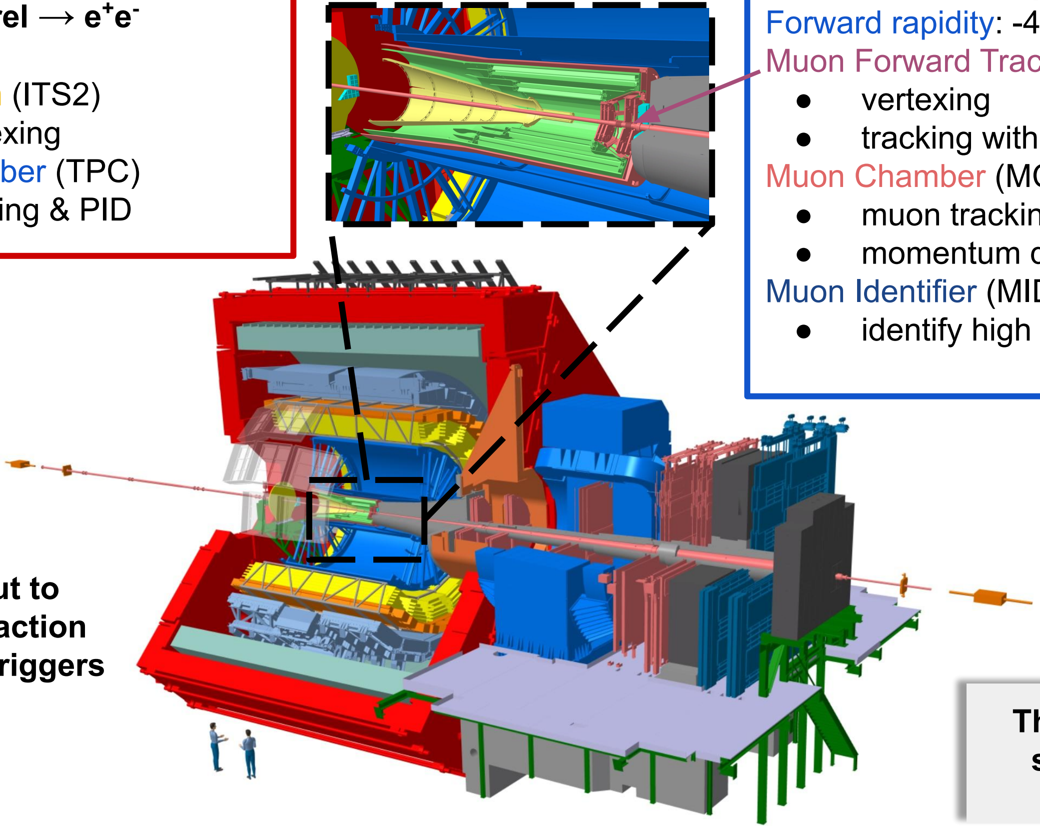


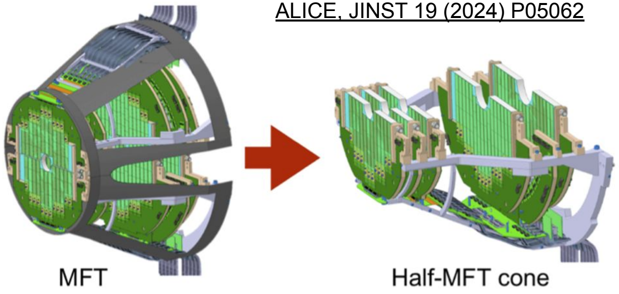
Continuous readout to support higher interaction rates (IR) + software triggers

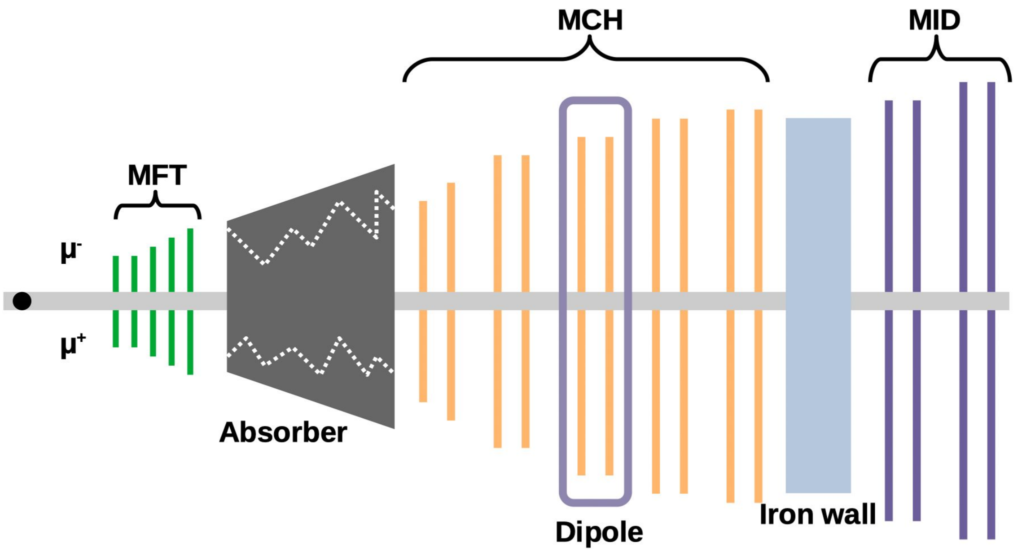
The new ALICE asynchronous software trigger processing
B. Zhang (*07/07 - 2:40 pm*)

ALICE, JINST 19 (2024) P05062

MFT (New for Run 3)

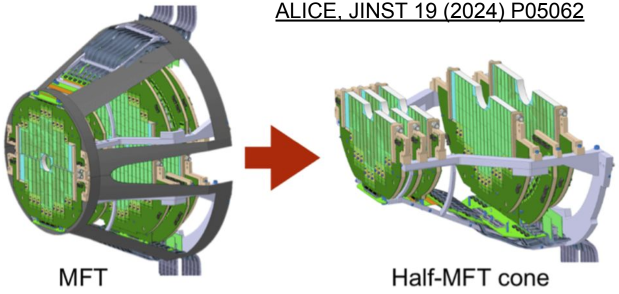
- disks of Si-pixel sensors
- improves spatial resolution of muons
- allows dimuon vertices discrimination





Muon tracking system in Run 3

ALICE, JINST 19 (2024) P05062



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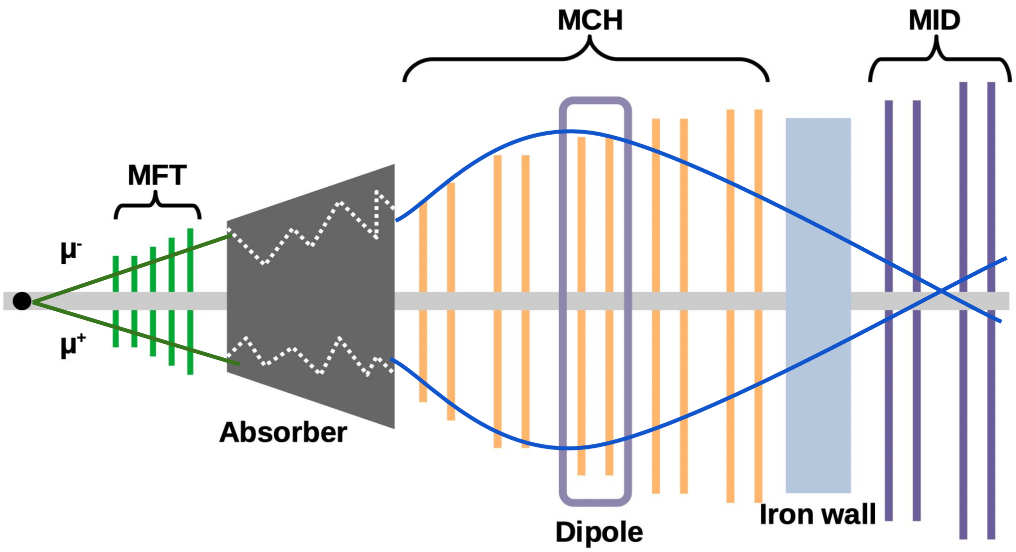
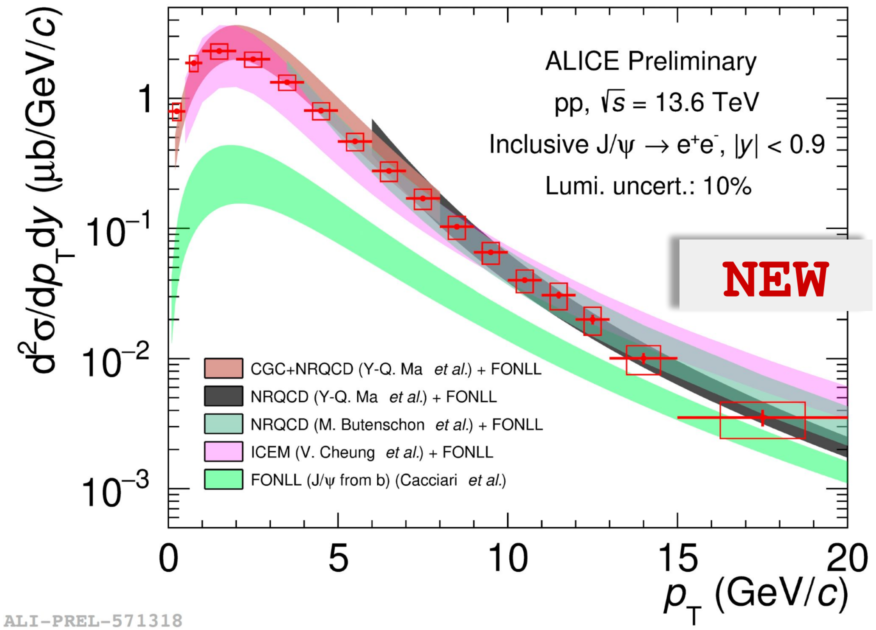


Muon tracking

- MCH + MID track matched to MFT track to find the dimuon vertex
- allows **prompt/non-prompt J/Ψ separation at forward rapidity**

J/Ψ production at midrapidity



ALI-PREL-571318

$$\frac{d^2\sigma}{dp_T dy} = \frac{N(J/\psi \rightarrow l^+l^-)}{(A \cdot \epsilon) \cdot BR_{J/\psi \rightarrow l^+l^-} \cdot dp_T dy \cdot L_{int}}$$

- Good agreement between ICEM, NRQCD models and data
  - main contribution: prompt J/Ψ (non-prompt at higher p_T)

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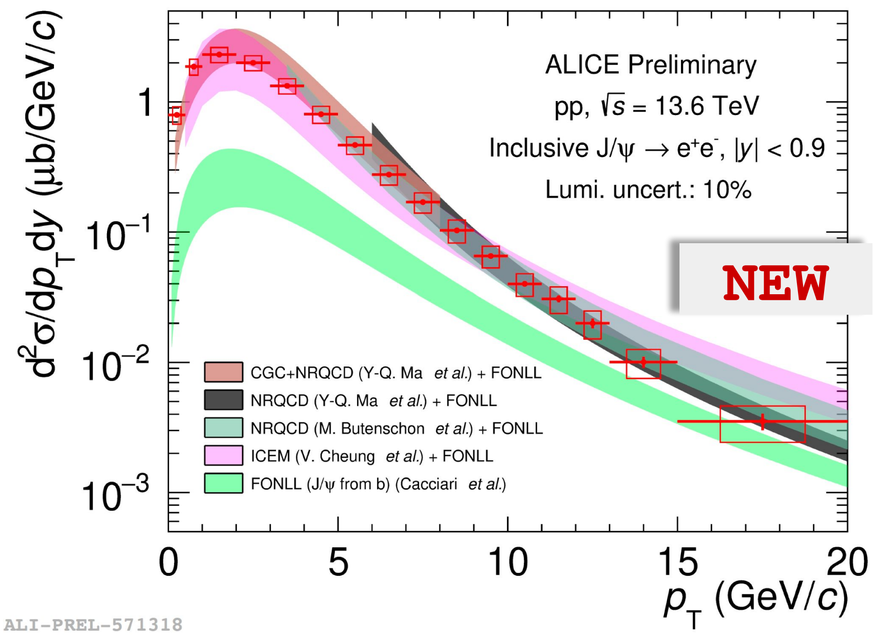

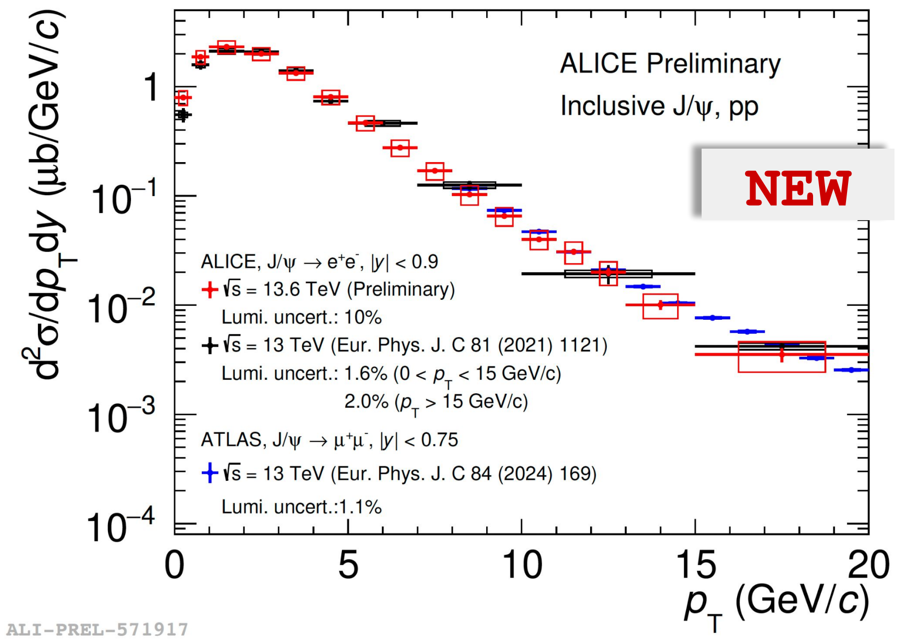

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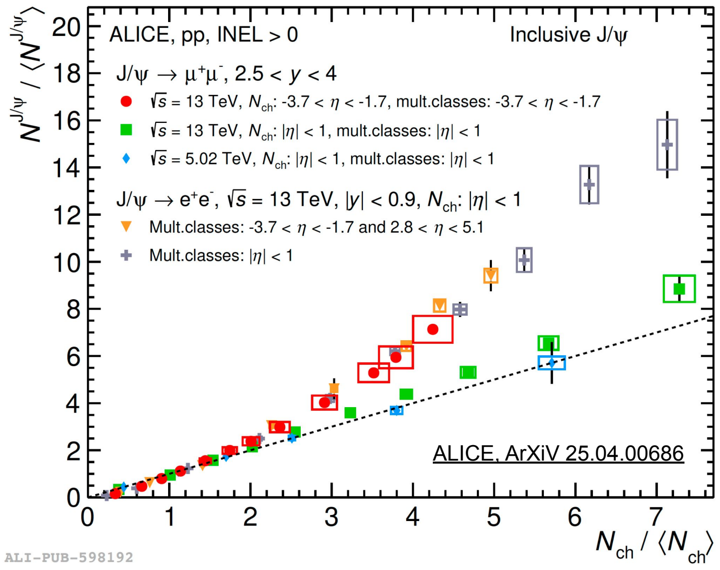
- Consistent results between ALICE (Run 2 & Run 3) and ATLAS

Dependence of inclusive J/Ψ yields on multiplicity in Run 2



- Basic multi-parton interaction (MPI) expected behaviour : **linear trend**
- Similar values at small multiplicity
- Steeper-than-linear trend
  - multiplicity estimator and J/Ψ production in the **same *η* range**
  - autocorrelation effect
- Close-to-linear trend: *η* gap between J/Ψ and multiplicity estimator

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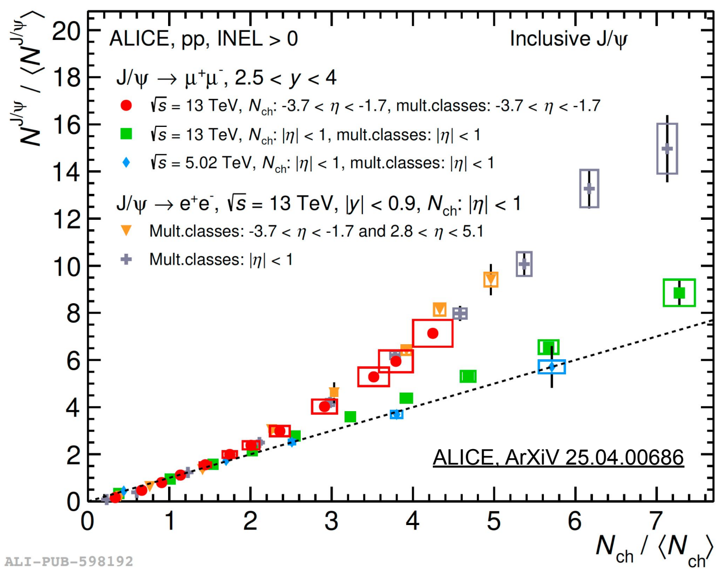

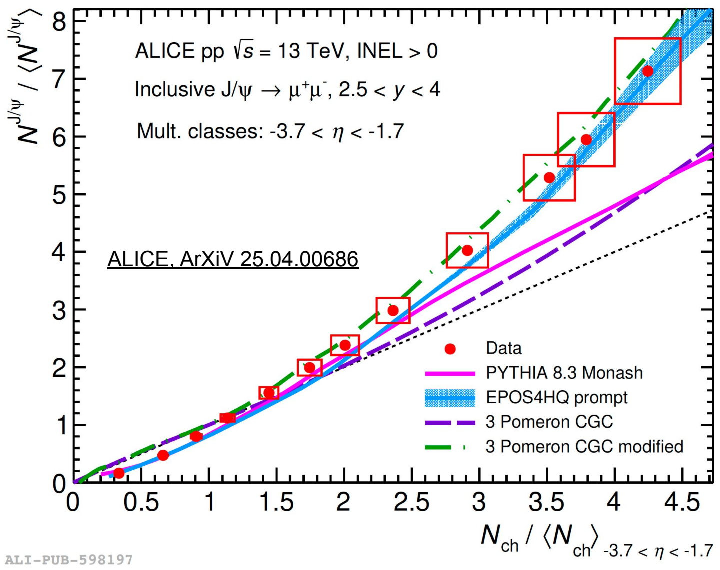

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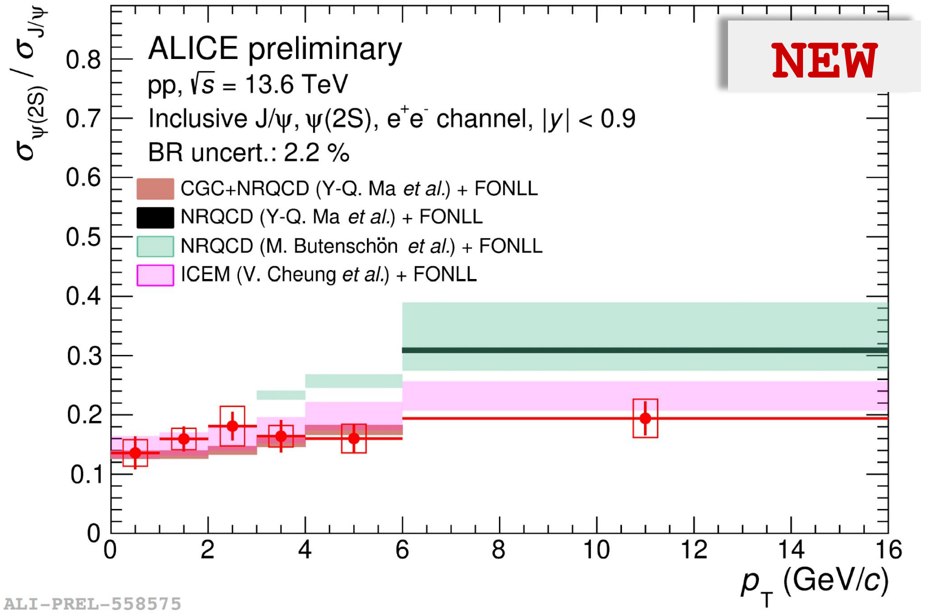
- PYTHIA includes Color Reconnection effects (hypothesis for the STL trend)
- Data well reproduced by EPOS4HQ and 3 Pomeron modified
  - inclusion of non-linear effects + gluonic saturation

Ψ(2S) to J/Ψ ratio at midrapidity



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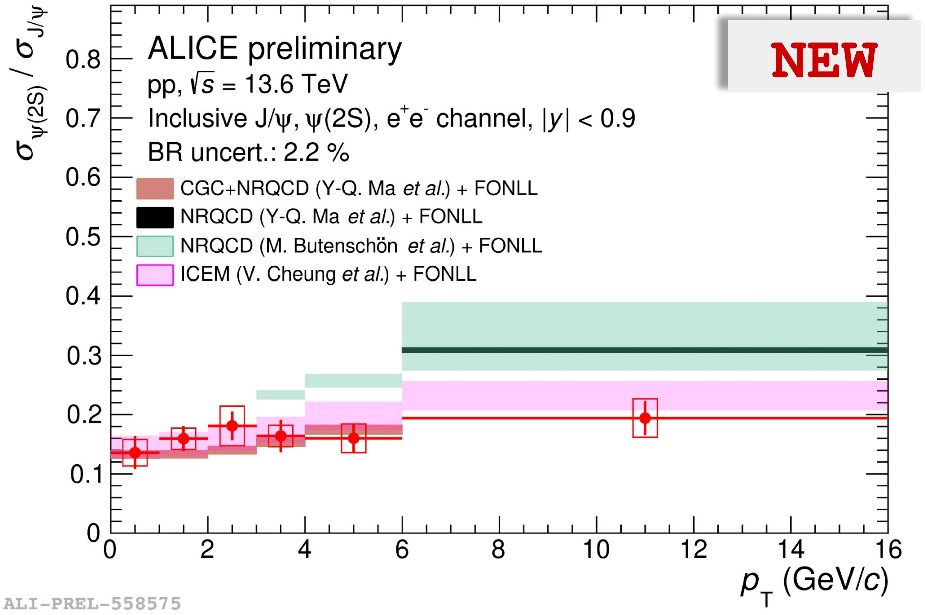

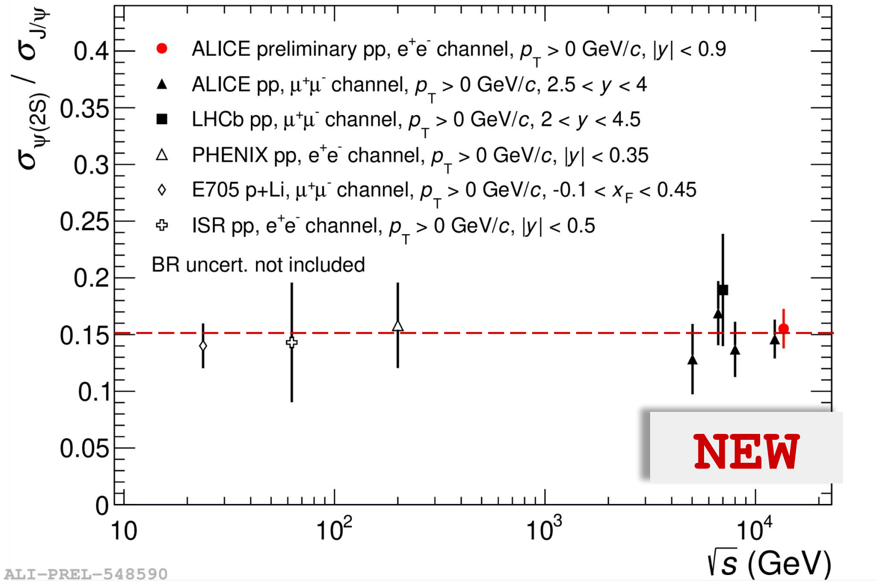

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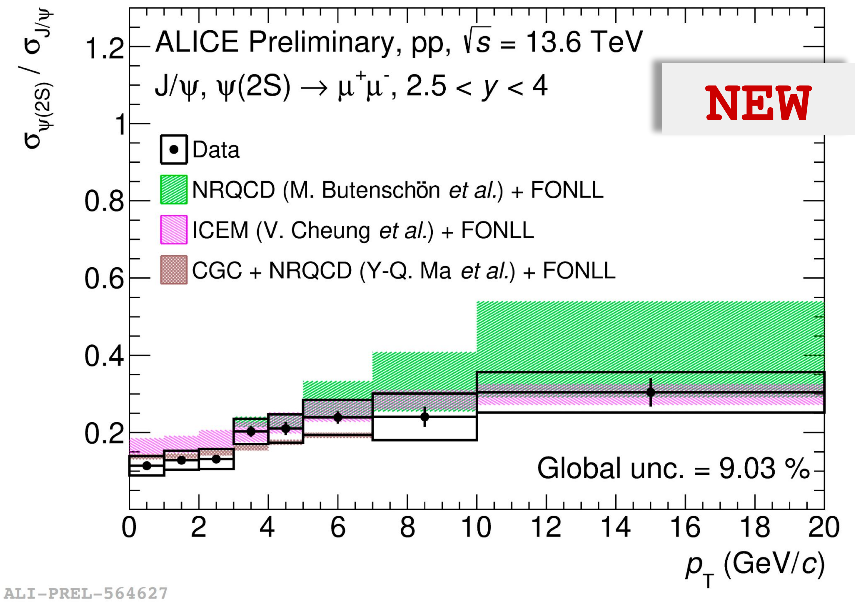
- Agreement between ALICE Run 2 & Run 3
- Mixture of results at different rapidity
- Constant ratio overall energy ranges
  - no dependance in energy

LHCb, J. High Energ. Phys. 2024, 243 (2024)
PHENIX, Phys. Rev. C 105 (2022) 064912
E705, Phys. Rev. Lett. 70 (1993) 383
ISR, Nucl. Phys. B 142 (1978) 29

Ψ(2S) to J/Ψ ratio at forward rapidity



- Data well reproduced by models within large uncertainties
- Same conclusions for models at **mid and forward rapidity** (see backup)

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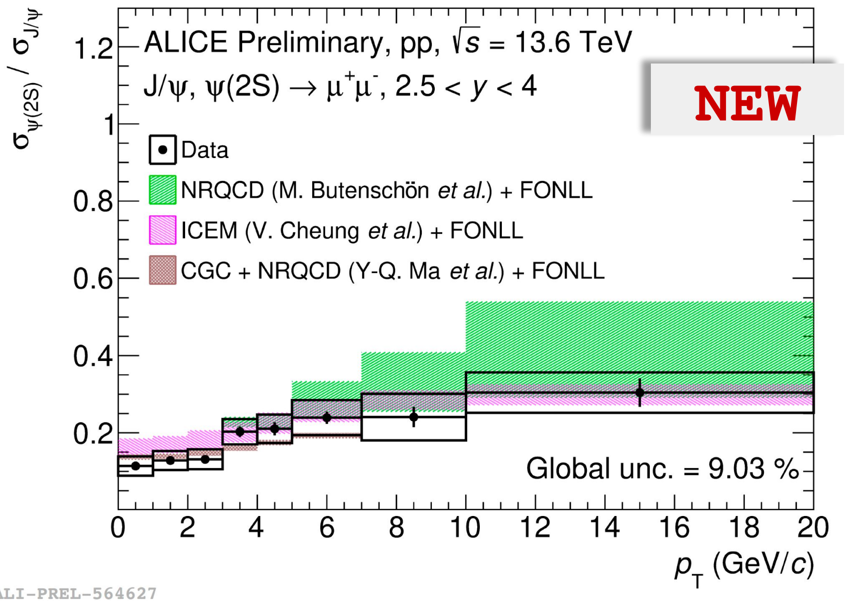

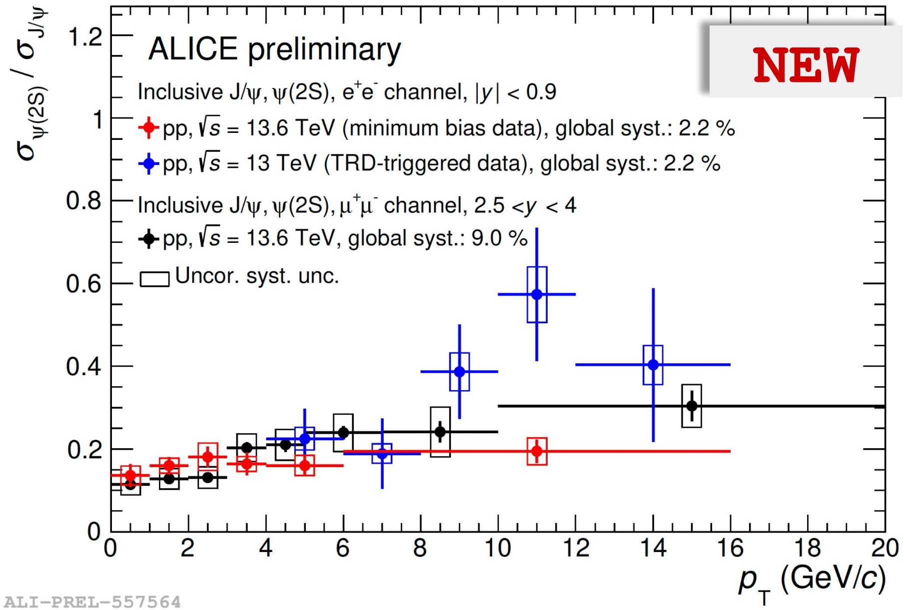

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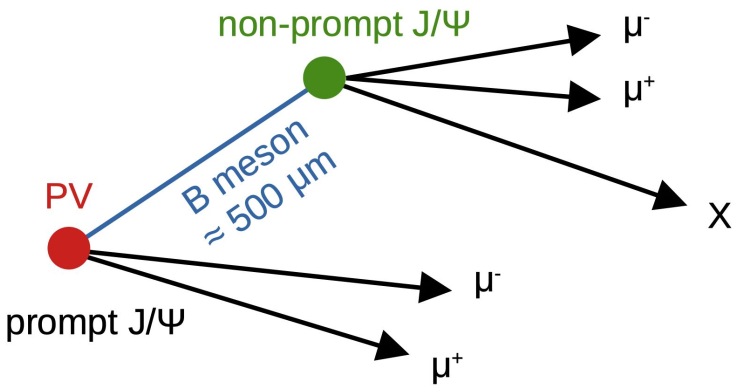
- Similar results at mid and forward rapidity
- Agreement between Run 2 & Run 3 data within 3σ

Prompt/non-prompt J/Ψ separation at forward rapidity

- Pseudo proper decay time τ_z
  - $\tau_z \approx 0$ if prompt
  - $\tau_z > 0$ if non-prompt

$$c\tau_z = c\frac{|z_{J/\psi} - z_{vtx}| M_{J/\Psi}}{p_z}$$



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- Forward: relativistic boost increasing B-meson time of flight
- Pseudo-proper decay length $l_z = c\tau_z$

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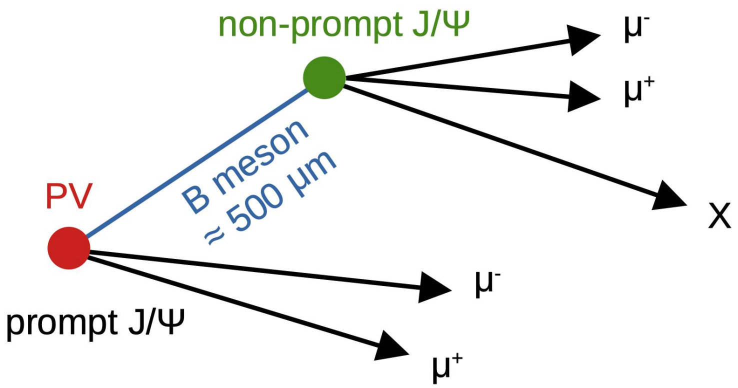

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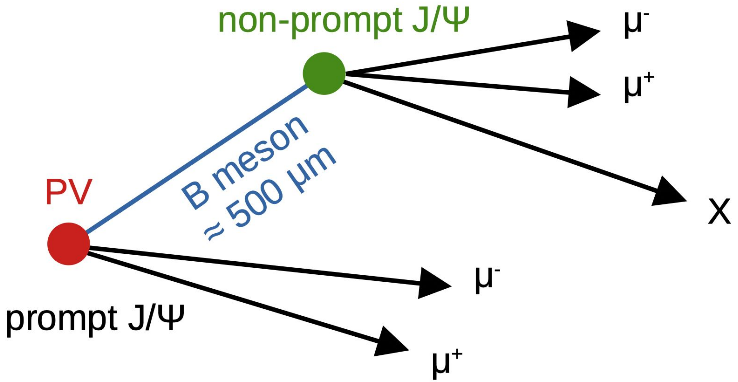
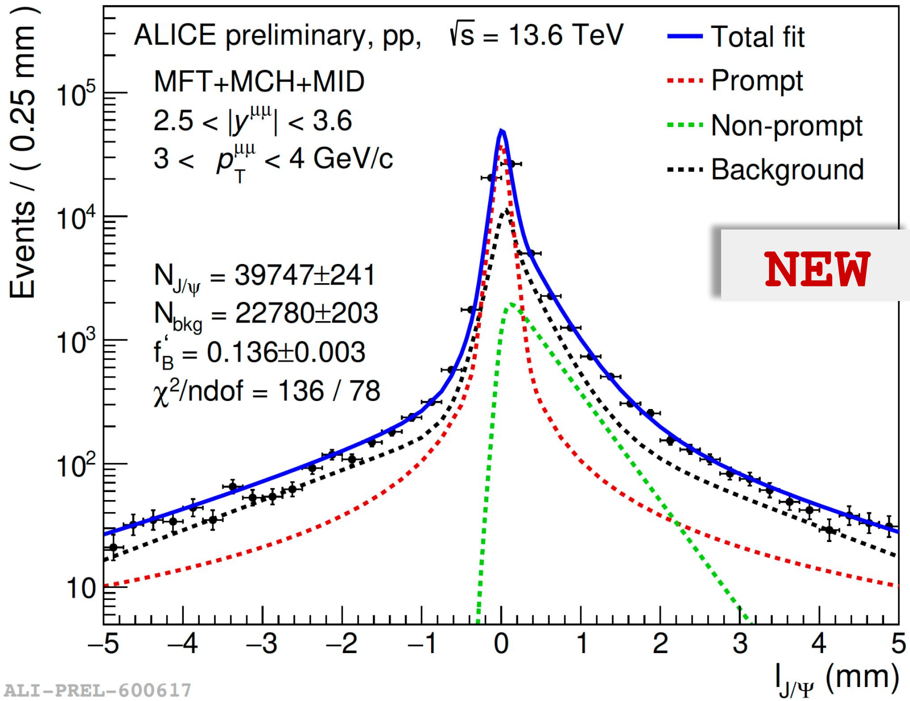


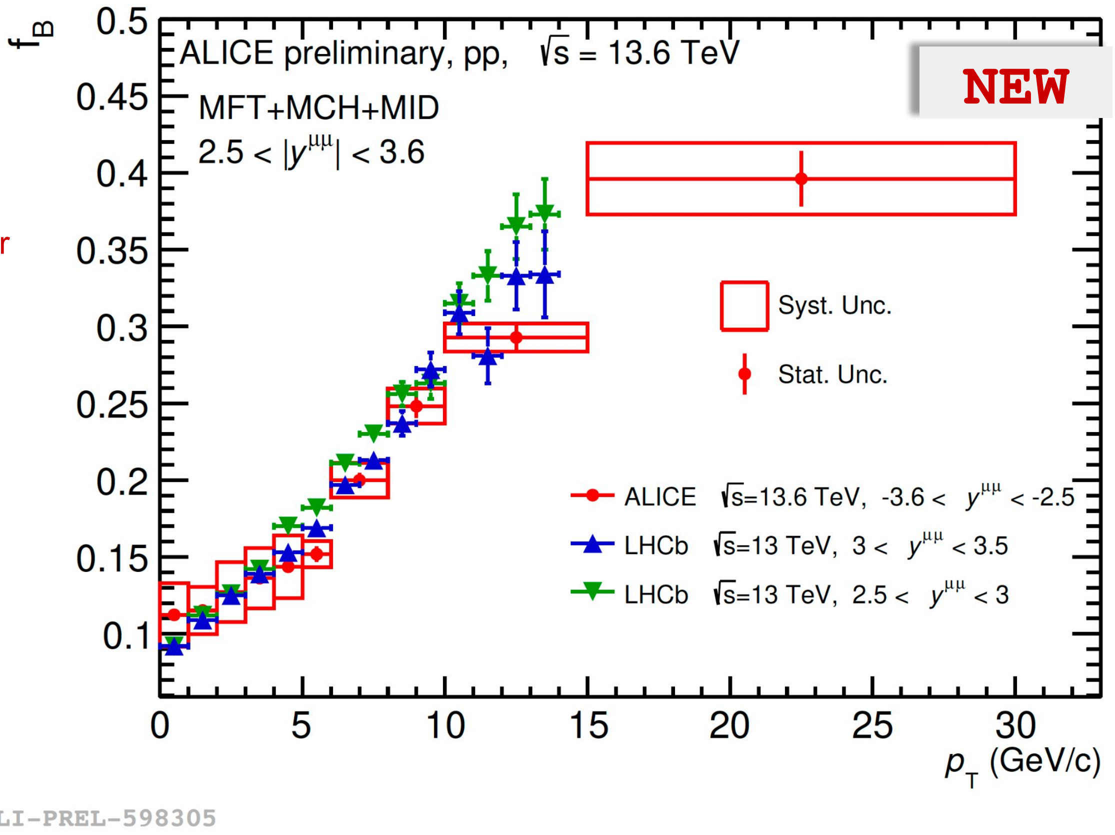


$$f'_B = \frac{N_{J/\psi \leftarrow h_B}}{N_{J/\psi \leftarrow h_B} + N_{J/\psi}}$$

Prompt/non-prompt J/Ψ separation at forward rapidity

- f_B increases with p_T
- Compatible with LHCb results
- First analysis using MFT and muon spectrometer
- **2023 dataset used for this result**
  - **2024 dataset: analysis ongoing**

$$f_B = \left(1 + \frac{1 - f'_B}{f'_B}\frac{\langle A \cdot \epsilon \rangle_{non-prompt}}{\langle A \cdot \epsilon \rangle_{prompt}}\right)^{-1}$$

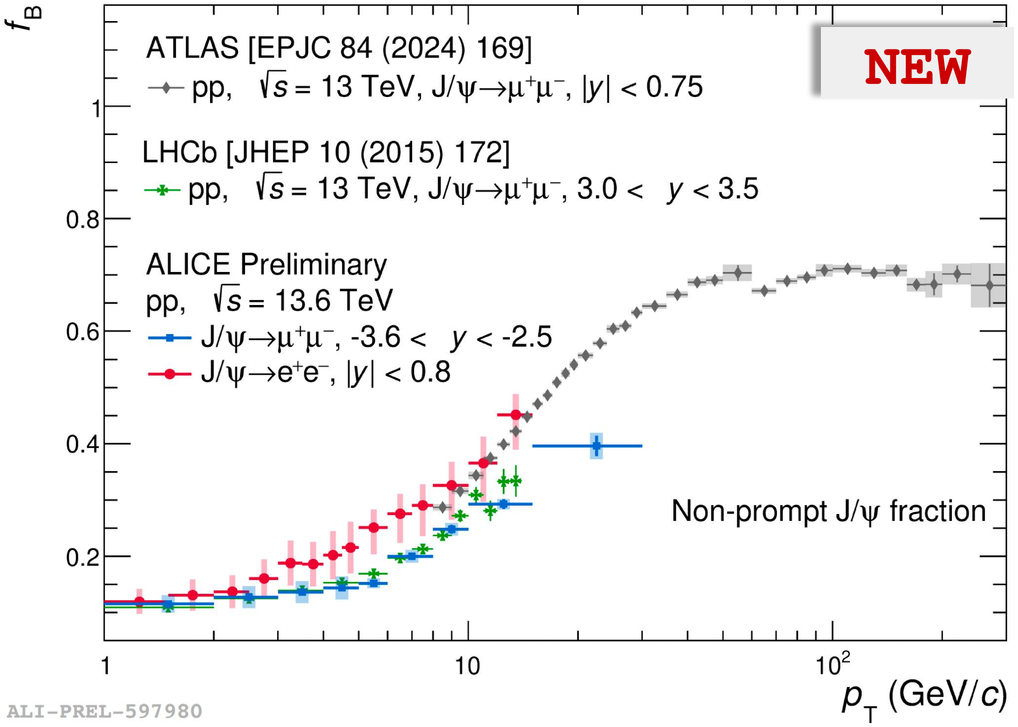


LHCb, J. High Energ. Phys. 172 (2015)

Prompt/non-prompt J/Ψ separation at mid and forward *y*

Comparison between mid and forward rapidity

- f_B higher at midrapidity
- consistent with B production kinematics



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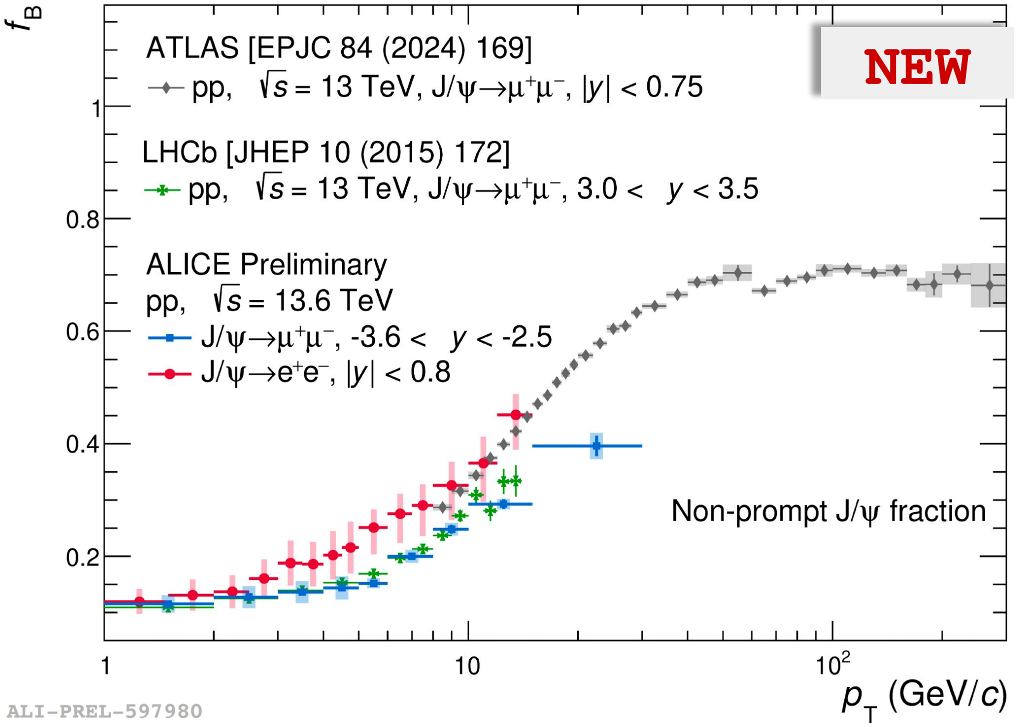
Comparison between ALICE and ATLAS at midrapidity

Emphasizes complementarity of the different experiments

ALICE and ATLAS measurement compatible in similar rapidity ranges at intermediate p_T



Conclusion and outlook

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- understanding initial parton density and multiple partons interactions (MPI)
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- when N_{ch} and $N_{J/\Psi}$ measured close in phase space (η): important autocorrelation effects
- to complete the picture: J/Ψ production at midrapidity with N_{ch} estimator at forward rapidity

Ψ(2S)-to-J/Ψ yield ratio

- no dependance on $\sqrt{s}$
- ratio < 1 in the full p_T interval of the measurement

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- agreement between ALICE, LHCb and ATLAS data

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Quarkonium production and collectivity in heavy-ion collisions with ALICE
L. Micheletti (*09/07 - 4:40 pm*)

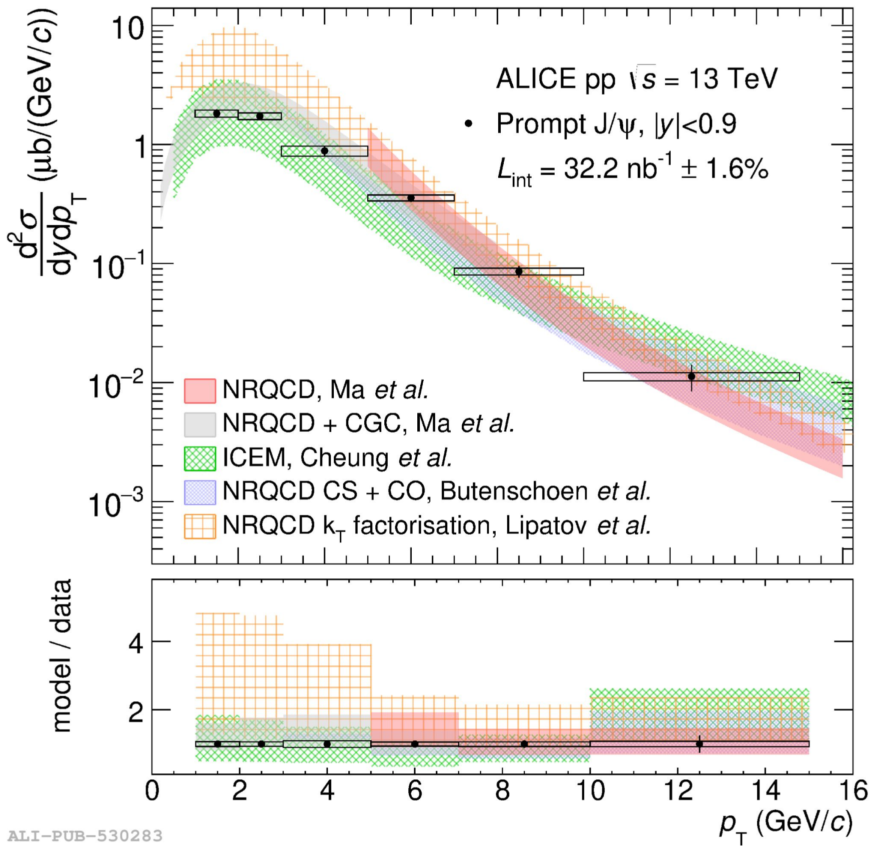
The Run 3 analyses are performed on 2022 and 2023 datasets, stay tuned: the 2024 analysis is ongoing !

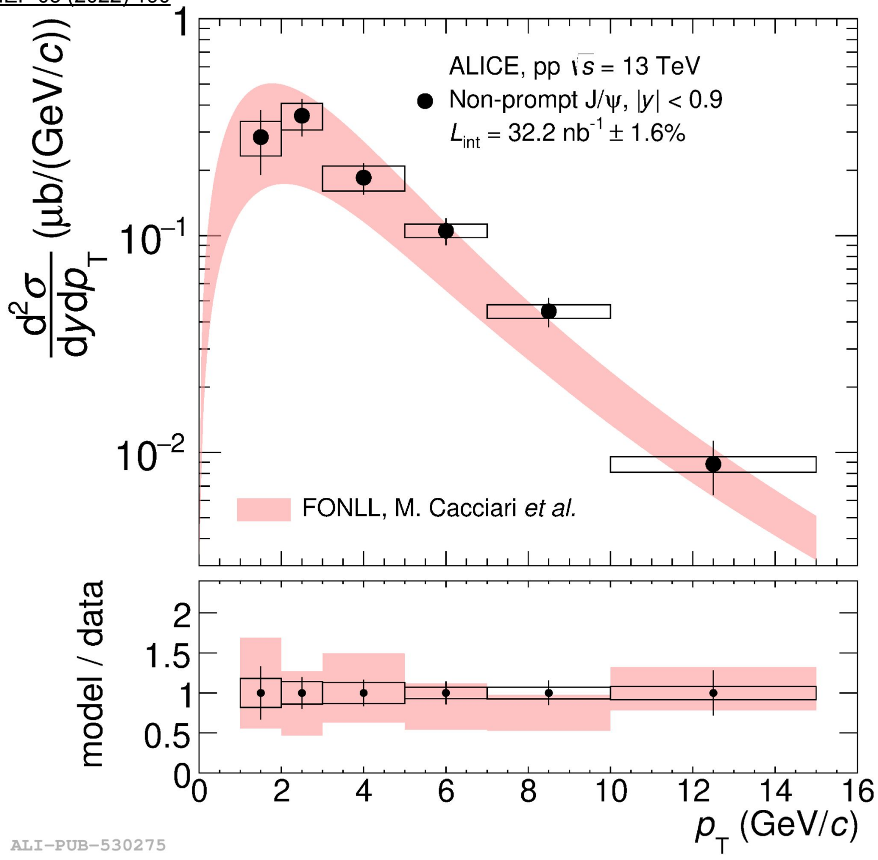
Thank you for your attention !

Backup

Charm and beauty production models

ALICE, JHEP 03 (2022) 190





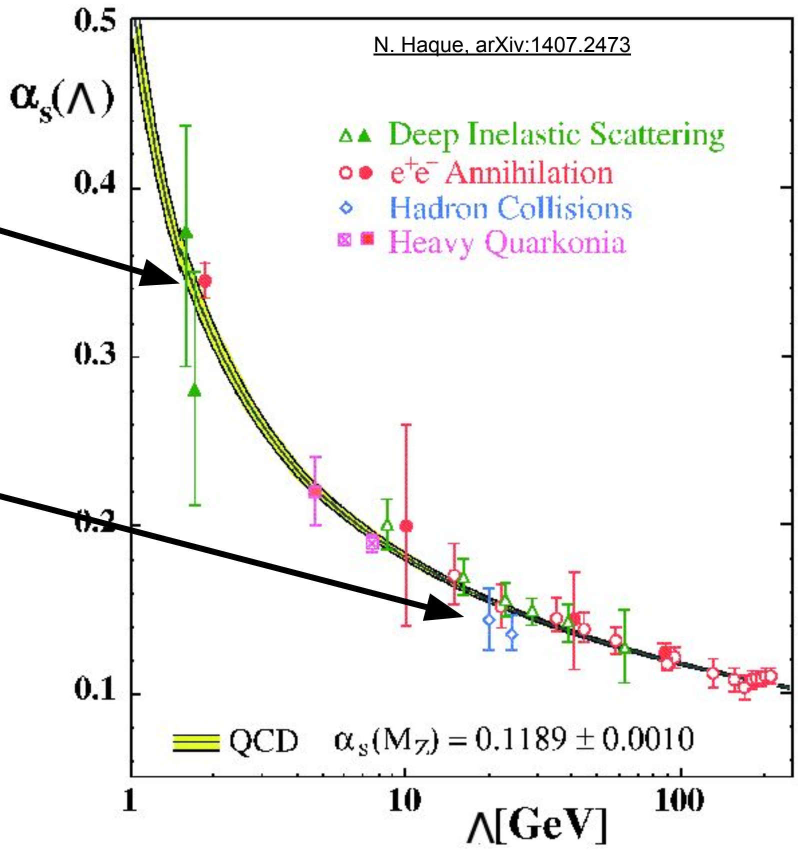
QCD coupling constant

Non-perturbative regime

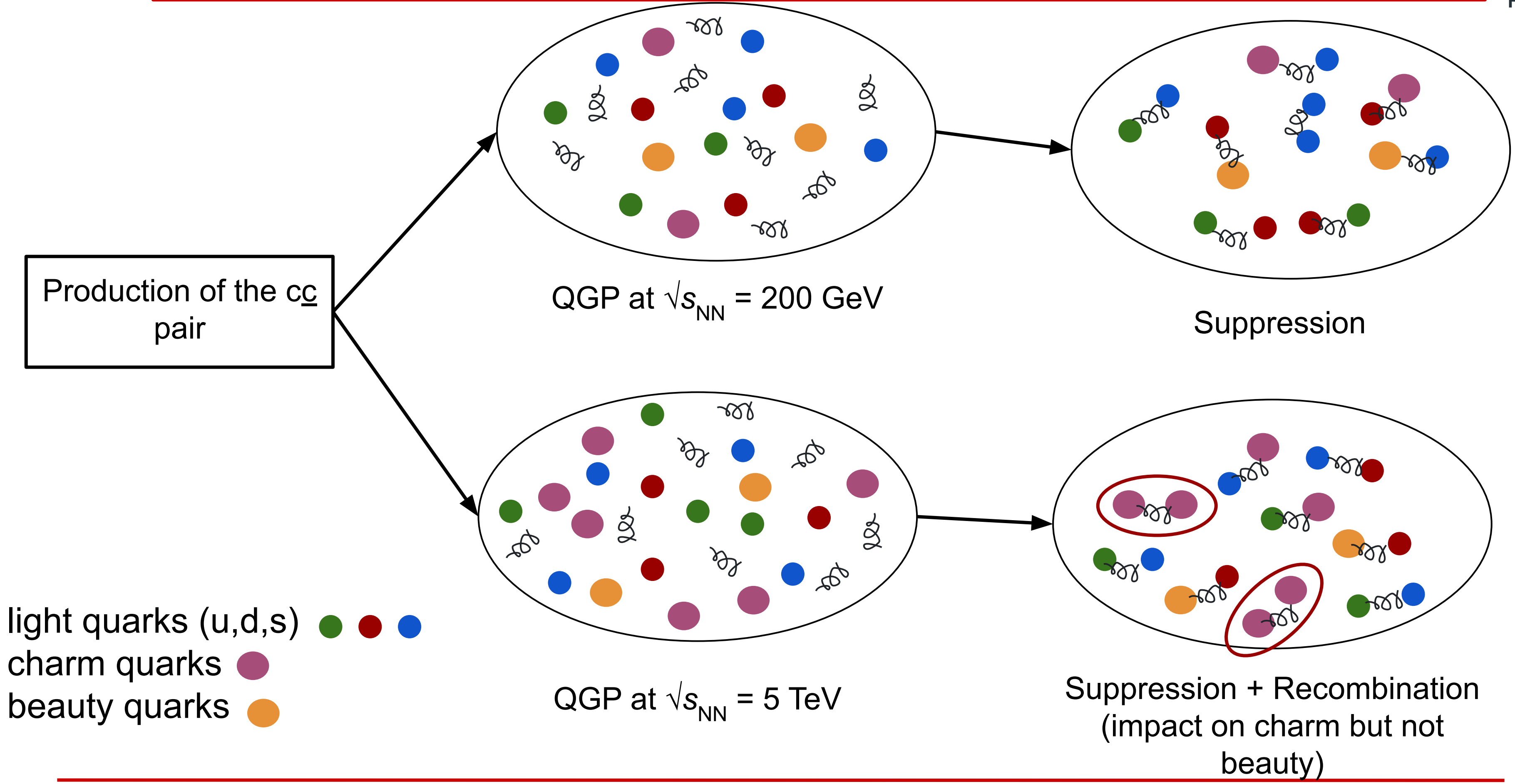
- $Q \rightarrow 0$, r >>1 fm
- divergence of α_s
- lattice QCD

Perturbative regime

- $Q \rightarrow \infty$, r <<1 fm
- $\alpha_s \rightarrow 0$
- perturbative QCD



Suppression and recombination inside a QGP



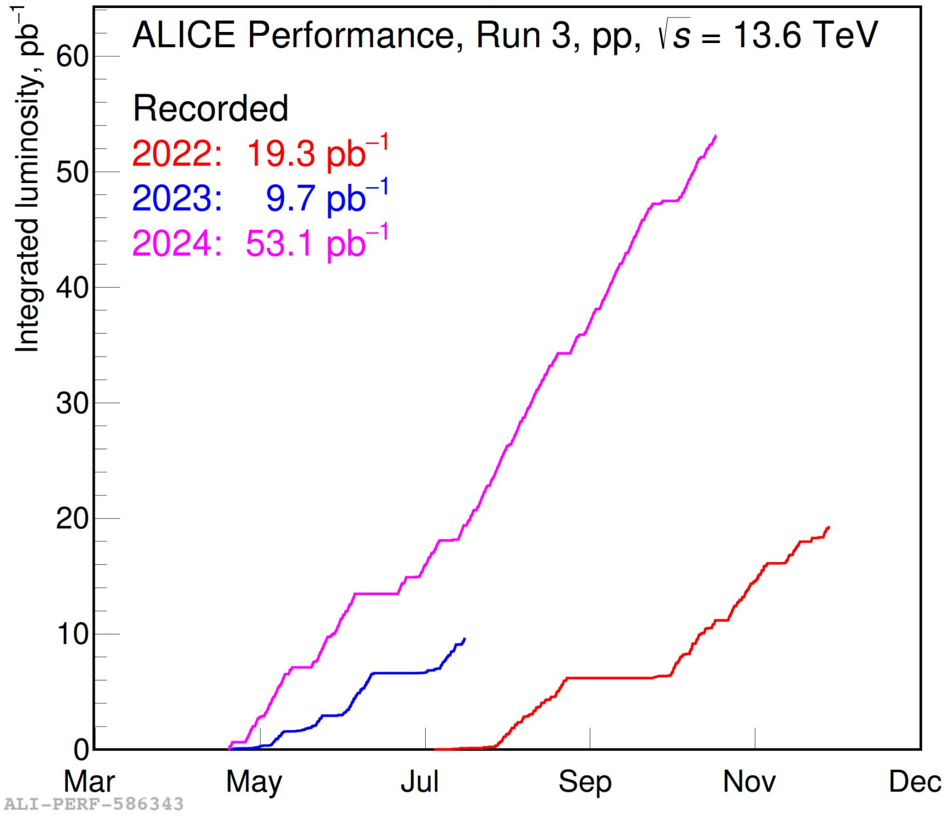
Large Hadron Collider

Top Energy (Run 2 : 2015 - 2018)	Top Energy (**Run 3 : 2022 - now**)
p–p: 13 TeV	p–p: 13.6 TeV
p–Pb: 8.16 TeV	p–Pb: not done yet
Pb–Pb: 5 TeV	Pb–Pb: 5.36 TeV

Luminosity (Run 1 + Run 2)	Luminosity (**Run 3**)
p–p: 41.40 pb^{-1}	p–p: 82.1 pb^{-1}
Pb–Pb: 0.875 nb^{-1}	Pb–Pb: 2.11 nb^{-1}

ALICE Luminosity

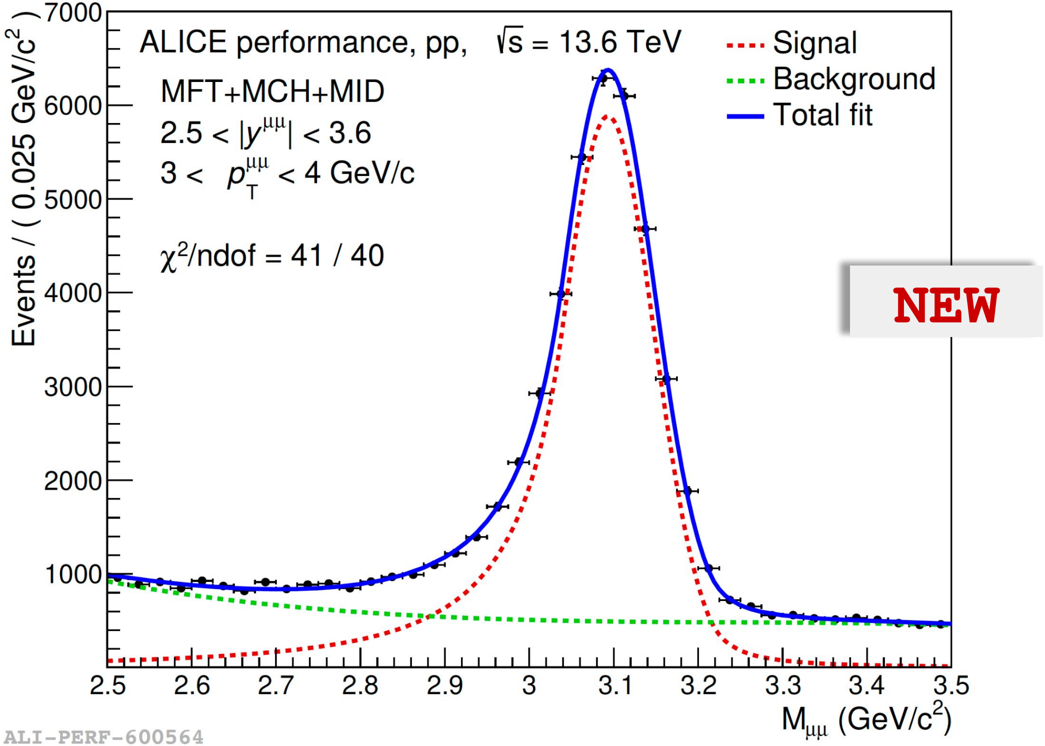
Run 3 : 2022 - 2024	Top Energy	Luminosity
p–p	13.6 TeV	82.1 pb^{-1}
p–Pb	not done yet	not done yet
Pb–Pb	5.36 TeV	2.11 nb^{-1}



Steps of the prompt/non-prompt separation

1. Signal/background separation
   a. need a **discriminating variable**: the **invariant mass**
2. Fit of the signal part (J/Ψ)
   a. **prompt**: fitted and fixed
   b. **non-prompt**: fitted and not fixed
3. Fit of the background part (anything else)
4. **2D fit between invariant mass and τ_z**
   a. all the fit informations leads to the **prompt/non-prompt fraction f_B**
5. Some acceptance-efficiency corrections
   a. results limited by the detector performances: taken into account in the calculation

Step 1 : signal/background separation using sPlot



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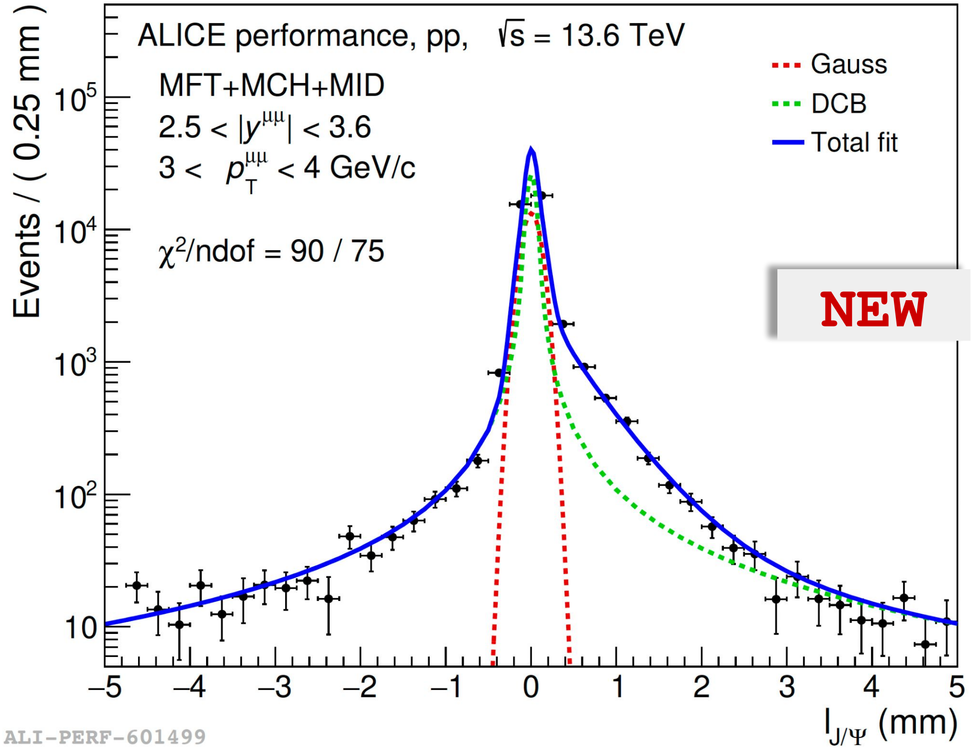
Unbinned Likelihood fits done using **RooFit** methods

Step 2 : l_z prompt part fitting

- Fit of the signal but only left side
  - prompt part of the signal

$$F_{prompt}(l_z) = [f_{res} \cdot Gauss(l_z, \sigma_1, l_0) + (1 - f_{res}) \cdot CB2(l_z, \sigma_2, l_0, \alpha_1, n_1)]$$

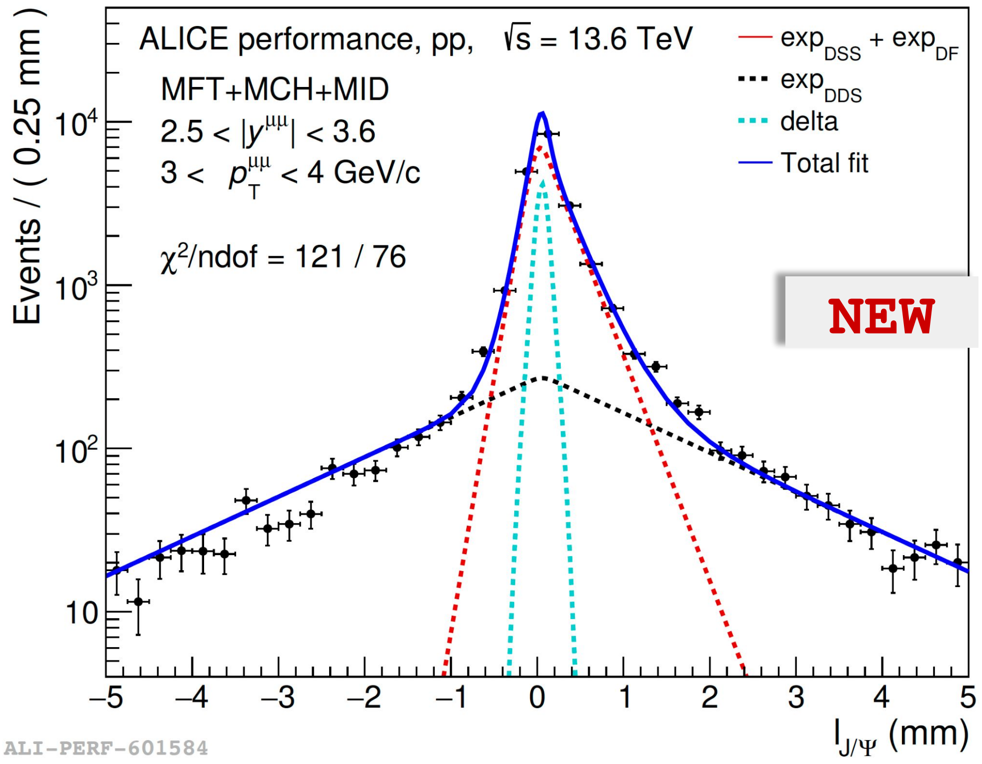
  - **Extract resolution parameter**
- Background and non-prompt fit will be convoluted by resolution
- Pretty good results for every p_T range



Step 4 : l_z background fitting

- **DSS :** Single Sided exp
- **DF :** Flipped exp
- **DDS** : Double Sided exp
- Complicated fit but has been improved

$$F_{bkg}(l_z) = b \cdot [f_{DLIV} \cdot (e^{-|\lambda_{DSS}| l_z} + (1 - f_{DFSS}) \cdot e^{|\lambda_{DF}| l_z}) + (1 - f_{DLIV}) \cdot e^{-|\lambda_{DDS} \cdot l_z|}] + (1 - b) \cdot \delta(l_z)$$

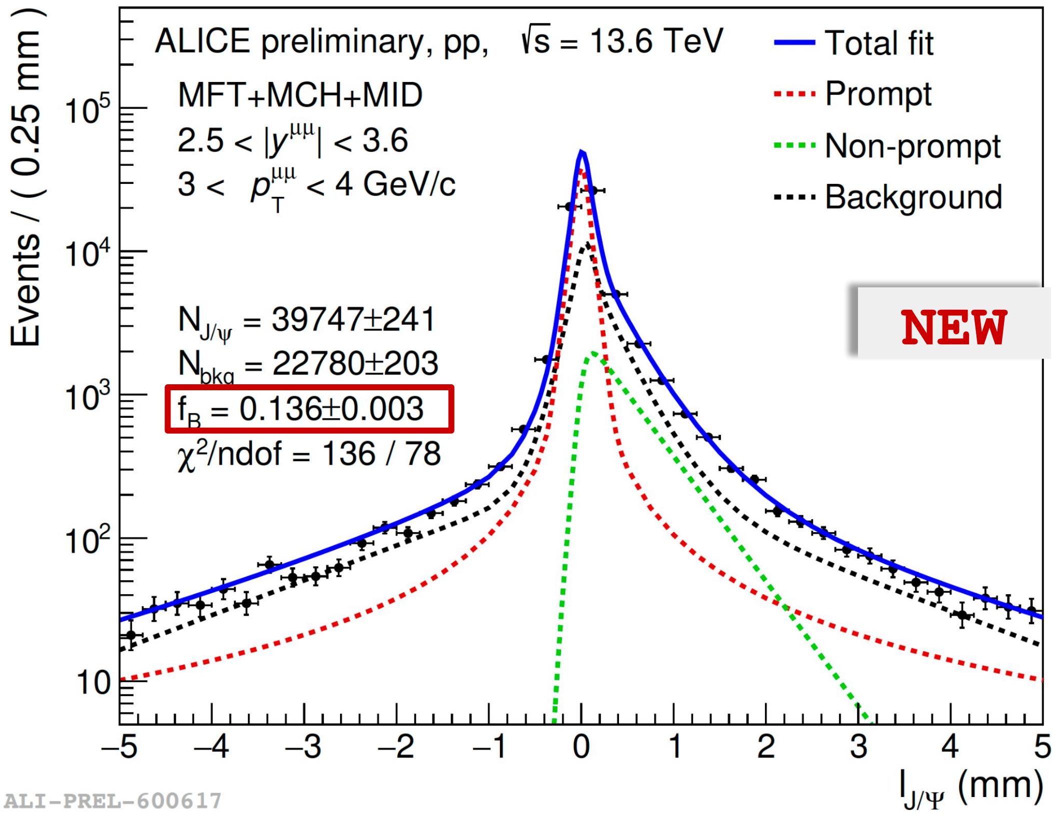


Step 5 : 2D fit and non-prompt fraction

- Only 4 free parameters left
- Integrated fraction coherent with expected value
  - but fit can be improved
  - mainly due to the bkg

- LHCb value for [3,4] GeV/*c* : 13.9 - 14.2
- As expected, better results for differential p_T

$$F(l_{J/\Psi}, m_{\mu\mu}) = N_{signal} \cdot F_{signal}(l_{J/\Psi}) \cdot M_{signal}(m_{\mu\mu}) + N_{bkg} \cdot F_{bkg}(l_{J/\Psi}) \cdot M_{bkg}(m_{\mu\mu})$$



Ψ(2S)-to-J/Ψ ratio

- Extraction of electron tracks done using ITS and TPC
- Extraction of muon tracks done using muon spectrometer
- Identification with invariant mass spectra