European Nuclear Physics Conference 2025

Quarkonium production in pp collisions at $\sqrt{s}$ = 13.6 TeV with ALICE

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on behalf of the ALICE Collaboration

Outline

- **Quarkonium Production**
- **A Large Ion Collider Experiment**
  - Experimental apparatus
  - Data-taking mode in Run 3
- **Results**
  - Charmonium production
  - $\psi(2S)$-to-J/ψ cross-section ratio
  - Charmonium polarization
  - J/ψ-D^0 associated production
- **Conclusions and Outlook**

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Quarkonium states and their production mechanism

Quarkonium =
bound state of a heavy quark antiquark pair

- **charmonium**: charm + anticharm
- **bottomonium**: bottom + antibottom

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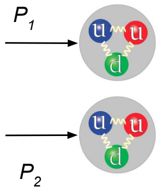

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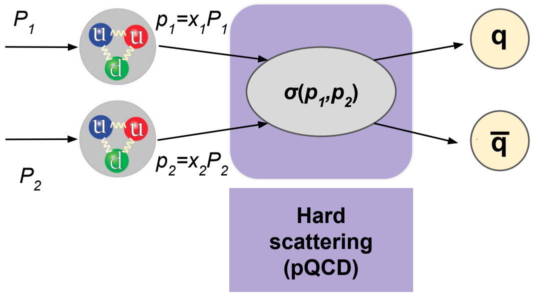

- **Hard scattering** to produce high-mass quark pair → small α_S → perturbative QCD calculation possible

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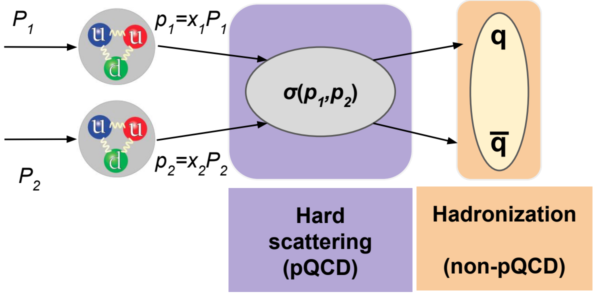
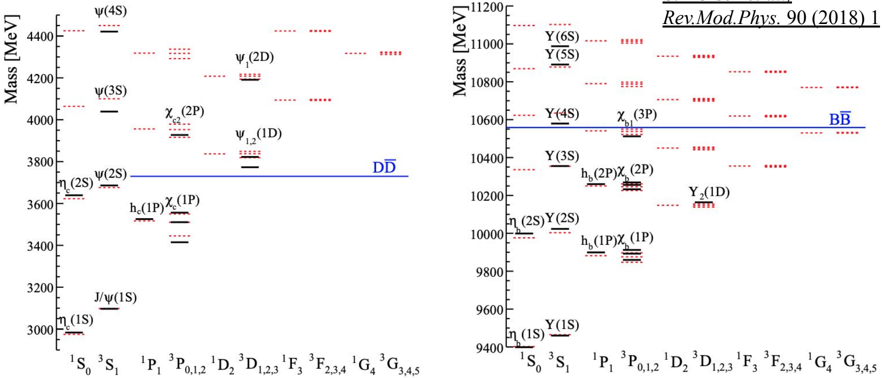


S.L Olsen *et al.*, *Rev.Mod.Phys.* 90 (2018) 1



- Hard scattering to produce high-mass quark pair → small α_S → perturbative QCD calculation possible
- **Binding into quarkonium states** → larger α_S → non-perturbative QCD process

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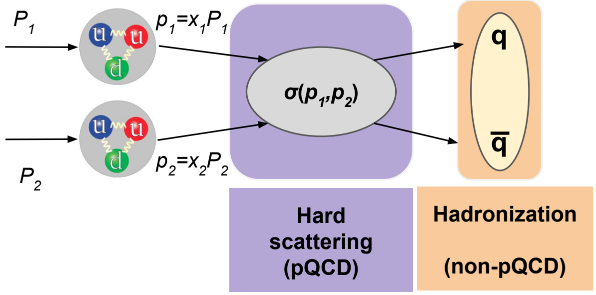
PRODUCTION MECHANISM IN pp COLLISIONS



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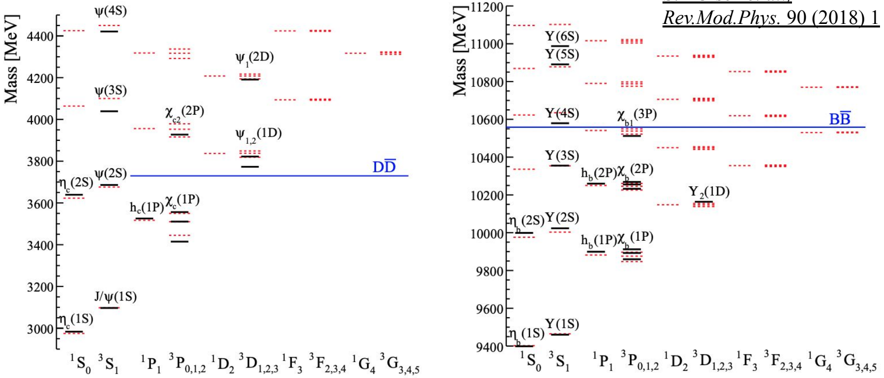

- Hard scattering to produce high-mass quark pair → small α_S → perturbative QCD calculation possible
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The **interplay between perturbative and non-perturbative QCD** is described by **phenomenological models**
→ **need experimental measurements to constrain the models**

pp measurements are also a baseline for studying quark-gluon plasma properties from heavy-ion collisions (see next talk)

Phenomenological models for quarkonium production in pp

Color Singlet Model (CSM) 📖

The quarkonium is directly produced in a color-singlet state.

Non-Relativistic QCD (NRQCD) 📖 📖

The quarkonium can be produced in a singlet or octet state, with soft gluon emission to reach the final state.

NRQCD + Color Glass Condensate 📖

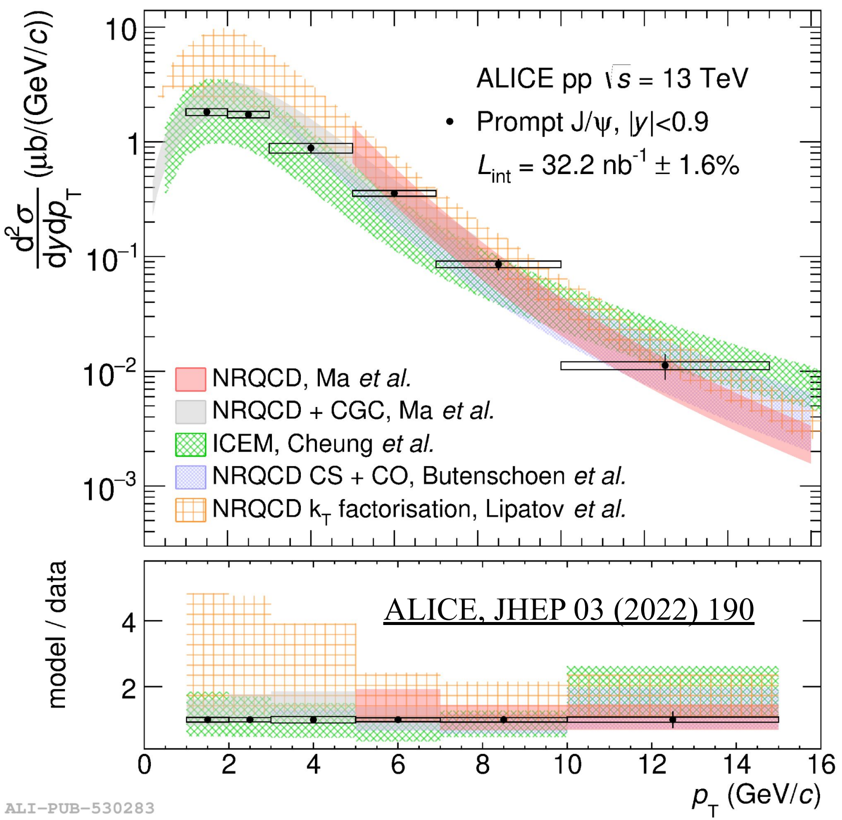
Improvement in the agreement with data at low p_T taking into account the gluon saturation regime.

Improved Color Evaporation Model (ICEM) 📖

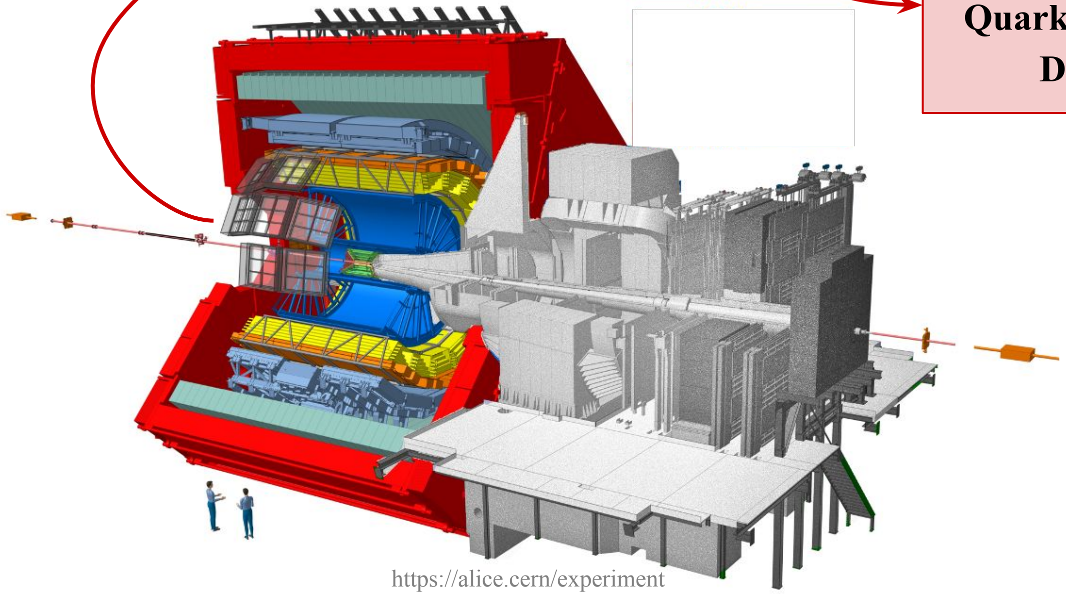
The quark-antiquark pair evolves into a quarkonium state with a constant probability factor (energy-, momentum- and process-independent).

NRQCD with k_T factorization 📖

It also takes into account the transverse momentum of gluons.



A Large Ion Collider Experiment



https://alice.cern/experiment

Central Barrel

Coverage: $|\eta| < 0.9$

Quarkonium → e^+e^-

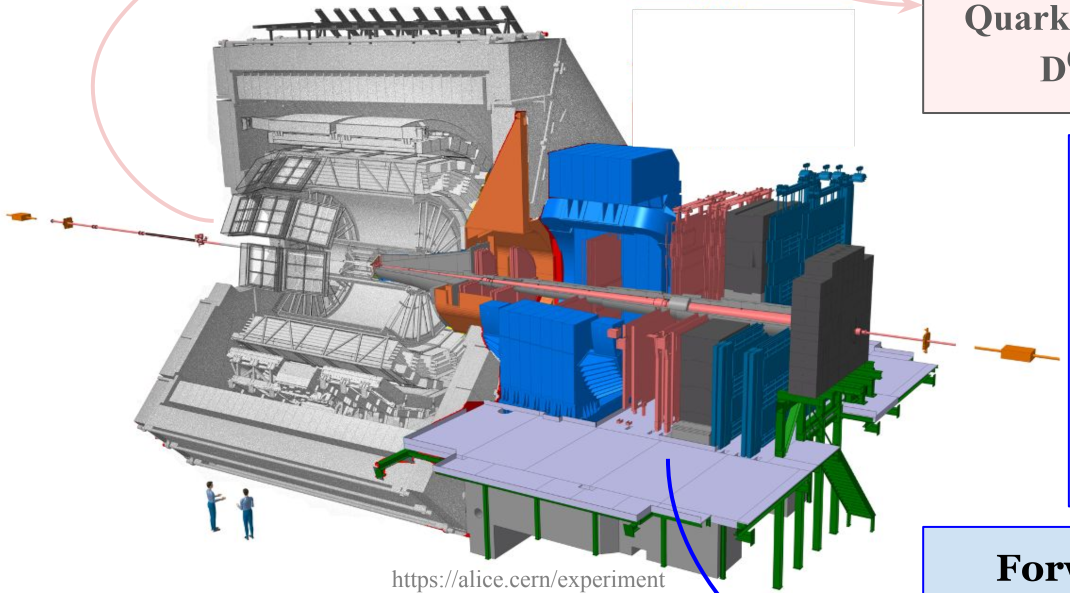
$\mathbf{D^0 \rightarrow K^+\pi^-}$

Inner Tracking System and **Time Projection Chamber**
→ particle tracking and identification

Time Of Flight
→ particle identification

$\eta = -\ln(\tan(\theta/2))$,
θ = polar angle

A Large Ion Collider Experiment



Central Barrel

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Quarkonium → e^+e^-

$D^0 \rightarrow K^+\pi^-$

MCH+MID ⇒ inclusive charmonium measurements
(presented in the next slides)

+ Muon Forward Tracker (MFT)
new in Run 3 for prompt/non-prompt separation (see dedicated talk)

Forward Muon Spectrometer

Coverage: $2.5 < \eta < 4.0$

Quarkonium → $\mu^+\mu^-$

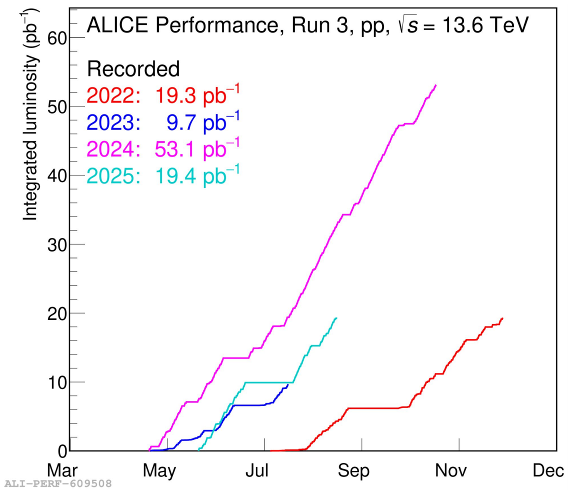
Muon CHambers
→ $\mu^\pm$ tracking

Muon IDentifier
→ $\mu^\pm$ identification

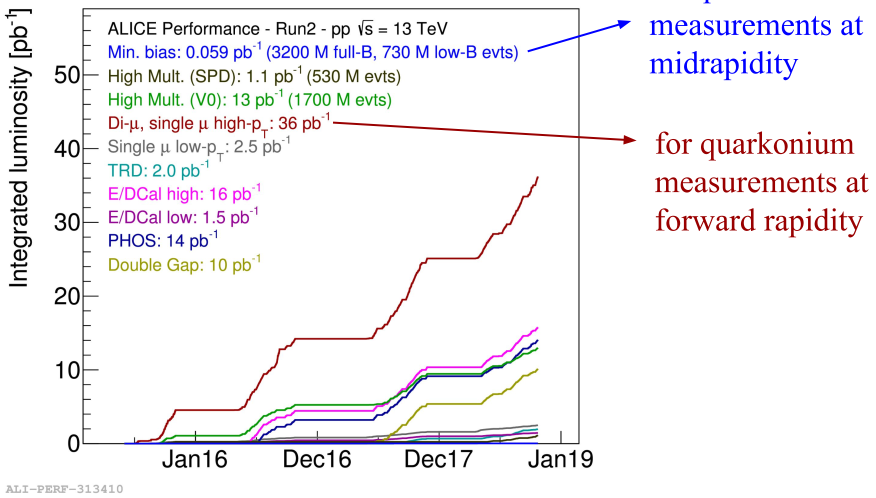
$\eta = -\ln(\tan(\theta/2))$,
θ = polar angle

Inclusive quarkonium production: from hardware to software trigger

Run 3



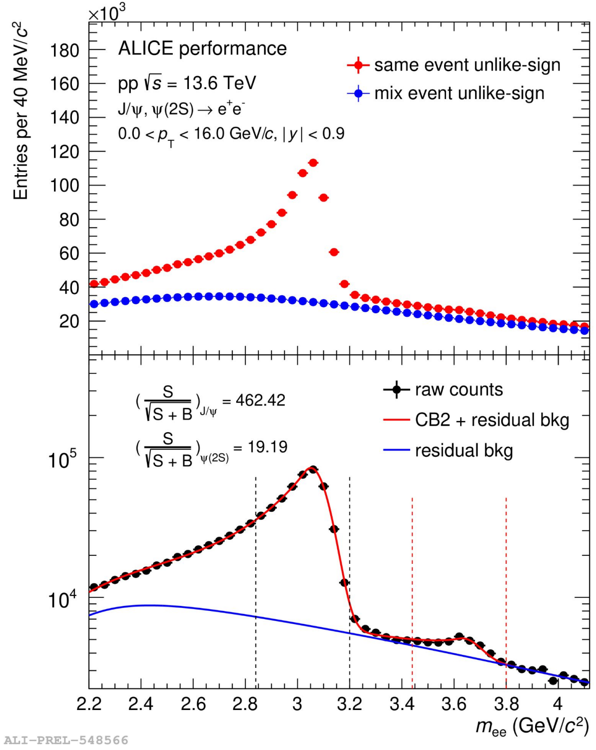
Run 2

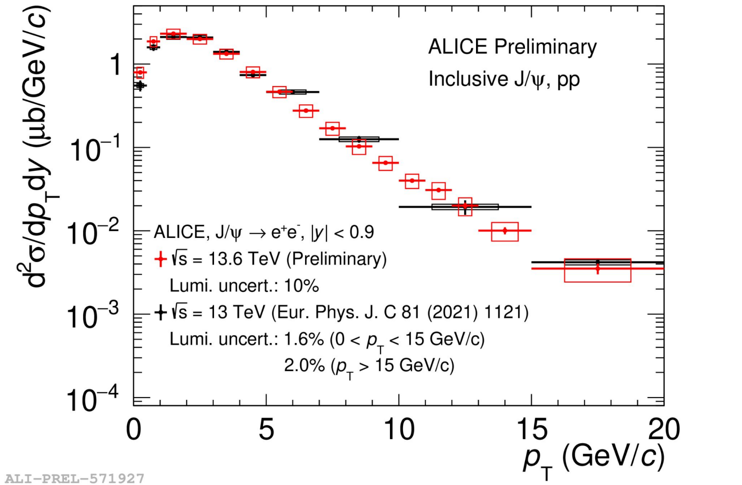


New data-taking mode using **continuous readout + software trigger** (vs Run 2: hardware triggers)

- ➔ Possibility of measuring **ψ(2S) at midrapidity down to $p_T = 0$**
- ➔ Larger data samples → **increased statistical precision** of the measurements at mid and forward rapidity

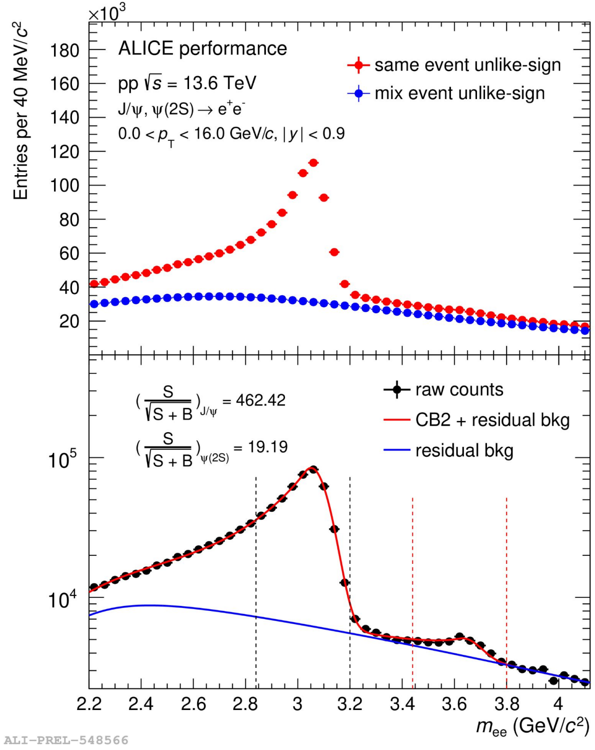
Charmonium production at midrapidity

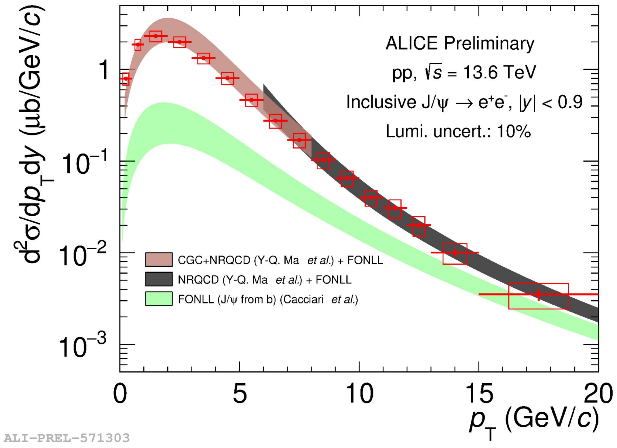


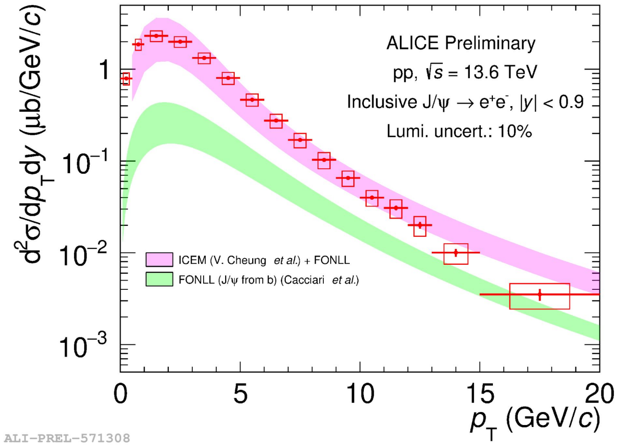


- J/ψ and ψ(2S) signal extraction performed in differential p_T ranges
- J/ψ Run 3 preliminary cross section at $\sqrt{s}$ = 13.6 TeV at midrapidity is **compatible with Run 2** publication at $\sqrt{s}$ = 13 TeV

Charmonium production at midrapidity

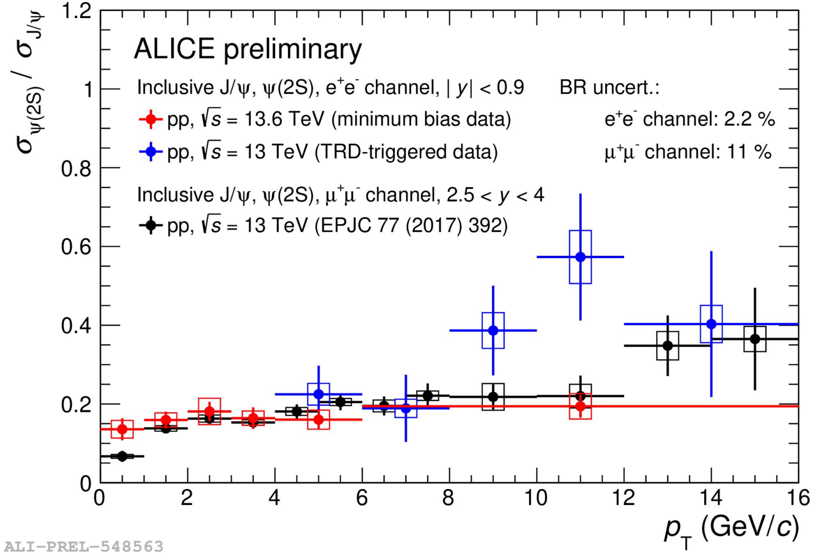






- J/ψ and ψ(2S) signal extraction performed in differential p_T ranges
- J/ψ Run 3 preliminary cross-section at $\sqrt{s}$ = 13.6 TeV at midrapidity is compatible with Run 2 publication at $\sqrt{s}$ = 13 TeV
- Good agreement with **NRQCD at high p_T** and with **NRQCD+CGC at low p_T**
- **Good agreement with ICEM** as well
  + FONLL computation of non-prompt J/ψ production

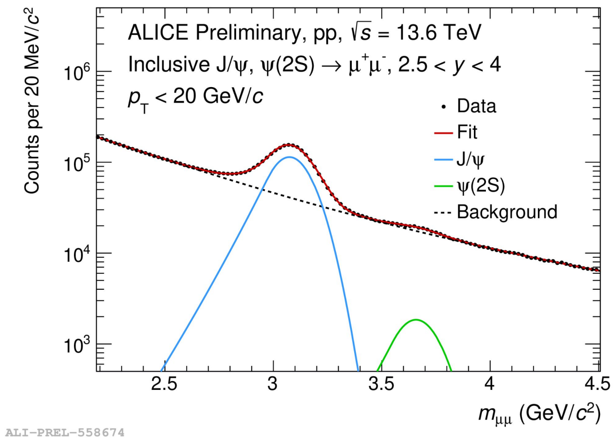
Charmonium production ratio at midrapidity

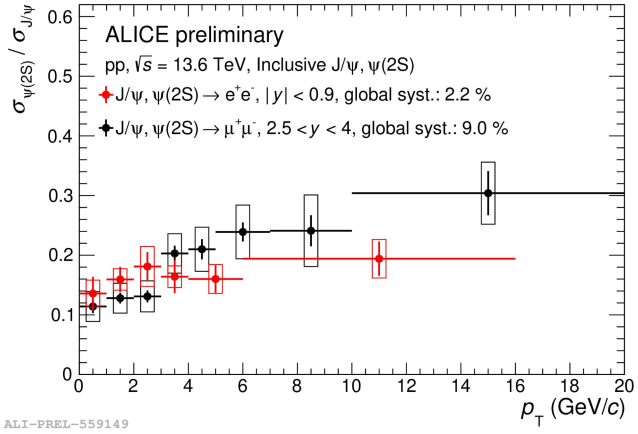


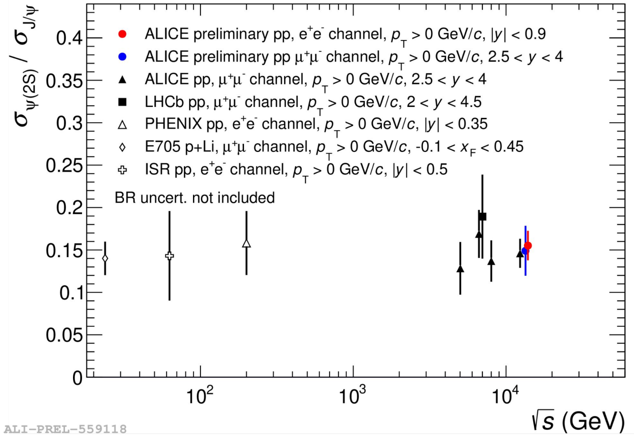
- Interesting to look at the **$\psi(2S)$-to-J/ψ cross-section ratio**
  - It provides access to the fraction of **$\psi(2S)$ from J/ψ decay** (**feed-down factor**)
  - **Systematic uncertainties are partially cancelled in the ratio**
- Midrapidity ratios vs p_T at $\sqrt{s}$ = 13.6 TeV and $\sqrt{s}$ = 13 TeV → both in agreement with forward-rapidity publication at $\sqrt{s}$ = 13 TeV

$$f^{\psi(2S)} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} \cdot BR_{\psi(2S)\to J/\psi}$$

Charmonium production ratio at forward rapidity







- Preliminary ψ(2S)-to-J/ψ cross-section ratio extraction vs p_T at forward rapidity at $\sqrt{s}$ = 13.6 TeV is consistent with the corresponding measurement at midrapidity

- Integrated result over p_T and y compared to previous measurements→ **no energy dependence**

ψ(2S)-to-J/ψ ratio: comparison with phenomenological models

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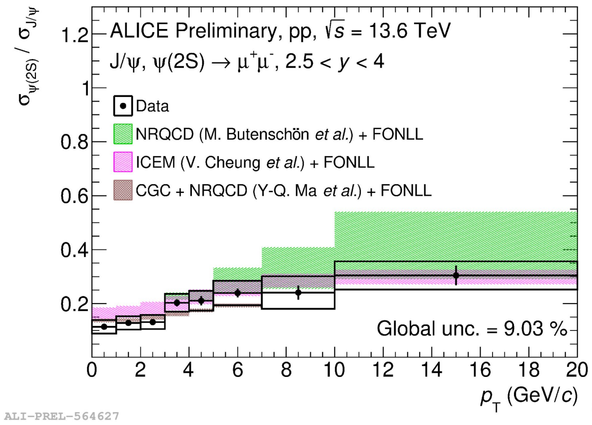
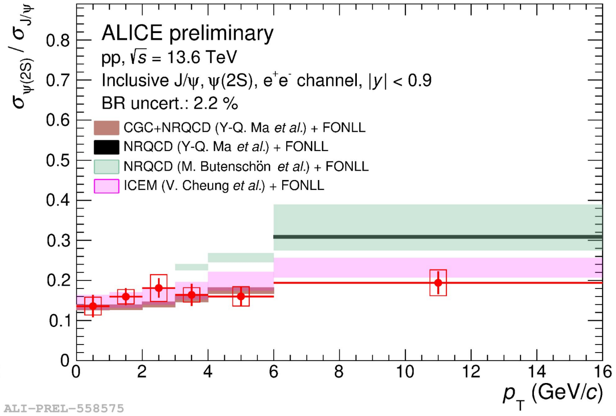


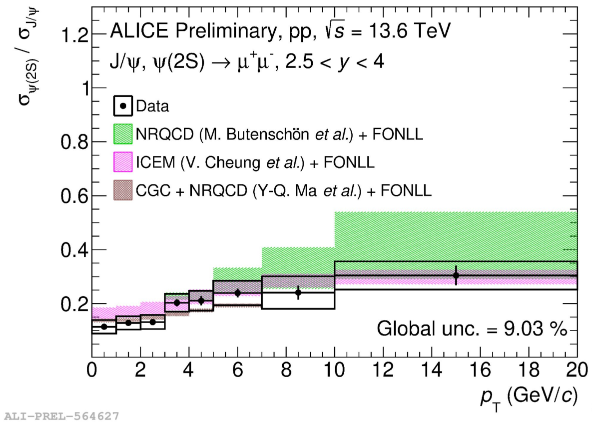


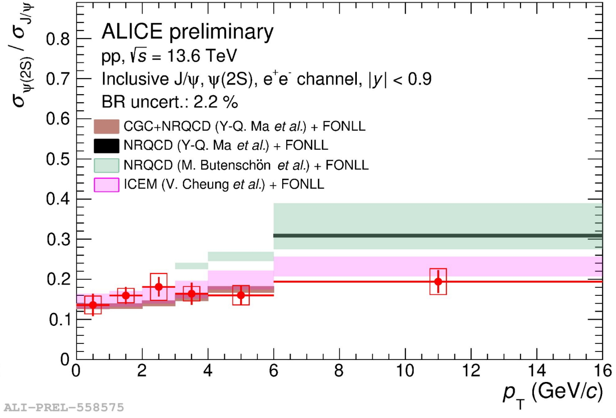
Preliminary ratios vs p_T are compared to phenomenological models

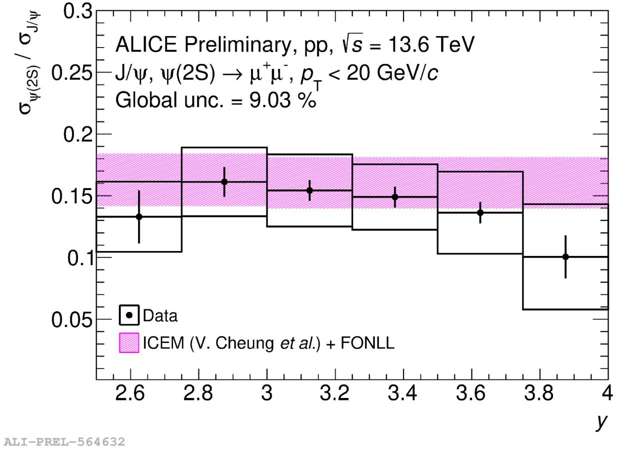
- **Both NRQCD and ICEM can describe the ratio at forward rapidity**
- **At midrapidty, NRQCD overestimates the measurements**

Increasing the sample size will allow for better investigation

ψ(2S)-to-J/ψ ratio: comparison with phenomenological models







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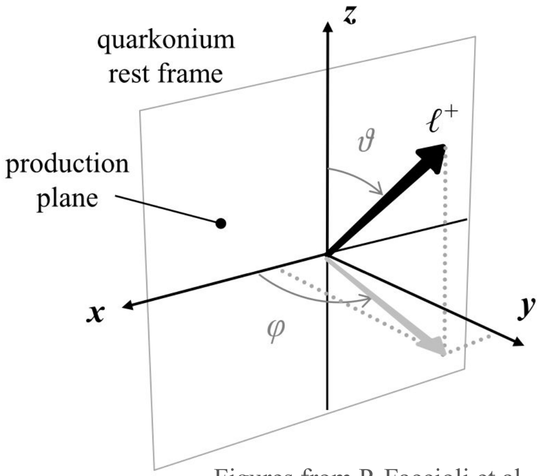
Preliminary ratios vs rapidity at forward rapidity are well reproduced by ICEM → **no significant *y* dependence**

An improved measurement using the whole data sample will reduce the uncertainties on the experimental points and allow for a better constraint

Polarization of quarkonium states

Polarization → alignment of particle spin with respect to a quantization axis

Two-body decay → **the angular distribution of the decay products reflects the polarization of the quarkonium state**

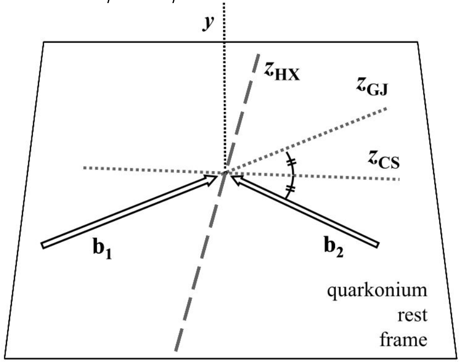


Figures from P. Faccioli et al. EPJ C69 (2010) 657-673

Observable angular distribution:

$$W(\cos\theta, \varphi) \propto \frac{1}{3 + \lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi)$$

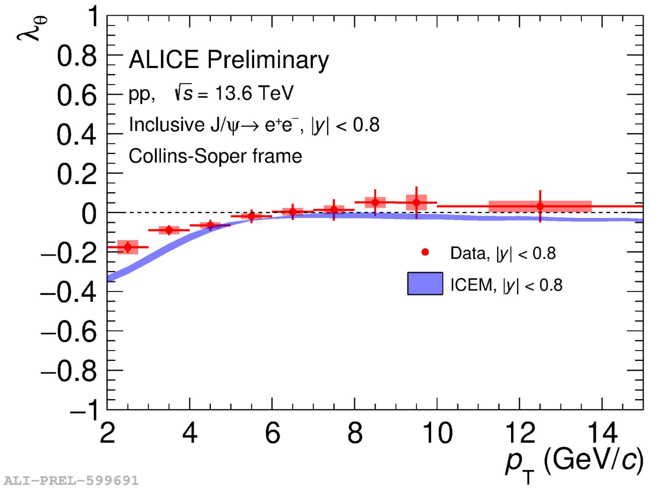
$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (+1, 0, 0) \Rightarrow$ Pure transverse polarization
$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (-1, 0, 0) \Rightarrow$ Pure longitudinal polarization
$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (0, 0, 0) \Rightarrow$ Zero polarization

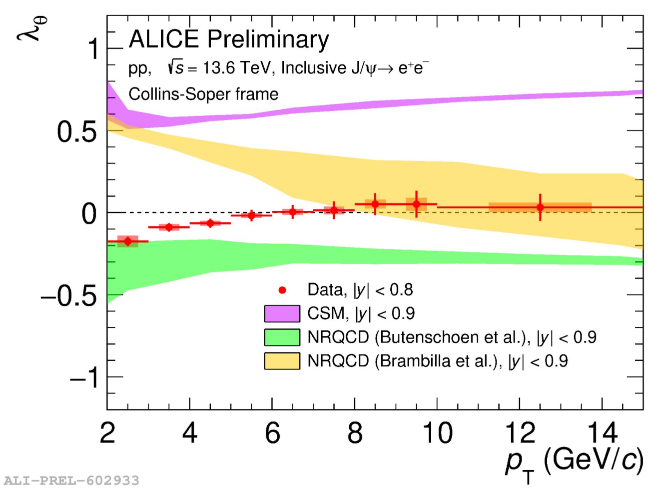


Polarization parameters depend on the reference frame (choice of polarization axis)

- **Helicity frame**: quarkonium direction in the collision center-of-mass frame
- **Collins-Soper frame**: bisector of the angle of one beam and the opposite of the other beam in the quarkonium rest frame

Charmonium polarization





- **Huge discrepancy among the models** (different models can even predict opposite polarizations)
  ⇒ experimental measurements bring essential constraints to their predictions
- **Sizeable J/ψ longitudinal polarization (negative λ_θ) in the Collins-Soper frame at low p_T** in the dielectron channel at $\sqrt{s}$ = 13.6 TeV → **qualitatively in agreement with ICEM predictions** 📖

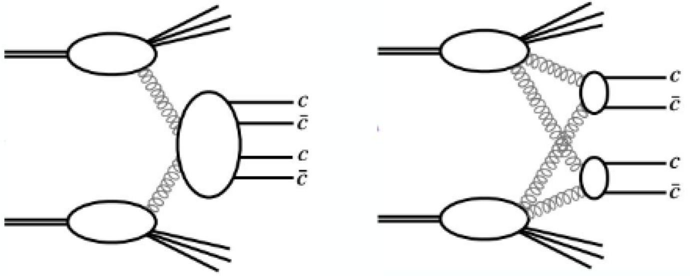
- Brambilla's NRQCD 📖 → does not reproduce the measured polarization at low p_T
- Butenschoen's NRQCD 📖 → only reproduces the lowest measured p_T range
- CSM 📖 → fails to reproduce polarization in the whole momentum range

Associated production of charm mesons

- New insight on the production mechanisms and the **role of Multiple Parton Interactions (MPI) in pp collisions**
- Investigate **relative contributions of single parton scattering (SPS) and double parton scattering (DPS)**
- Inputs to tune MC generators

$$\sigma^{DPS}_{A,B} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

m=1 if A=B
m=2 otherwise



Single Parton Scattering

Double Parton Scattering

σ_{eff}= scaling factor → physical observable
→ Independent on process and collision energy in the simplest model

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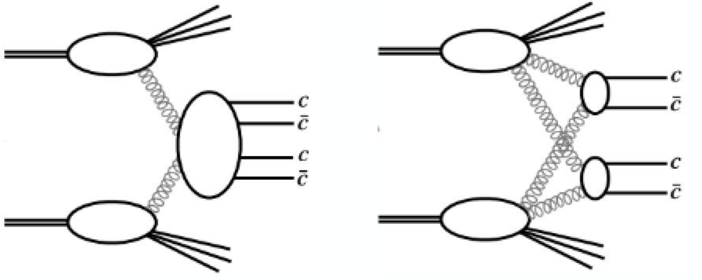


Single Parton Scattering   Double Parton Scattering

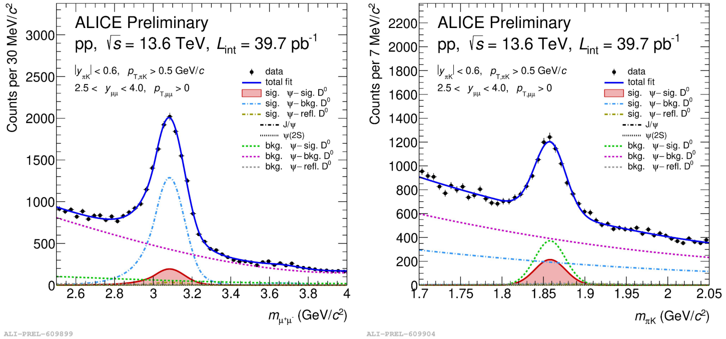
σ_{eff}= scaling factor → physical observable
→ Independent on process and collision energy in the simplest model

J/ψ-D^0 associated production: contribution from both Single and Double Parton Scattering (SPS and DPS) → possibility to extract σ_{eff}

Analysis strategy:
- $J/\psi \rightarrow \mu^+\mu^-$ at fwd. rapidity
- $D^0 \rightarrow K^-\pi^+$ at mid rapidity

$1.9 < \Delta y < 4.6$

Yield extraction using a **bidimentional invariant-mass fit**

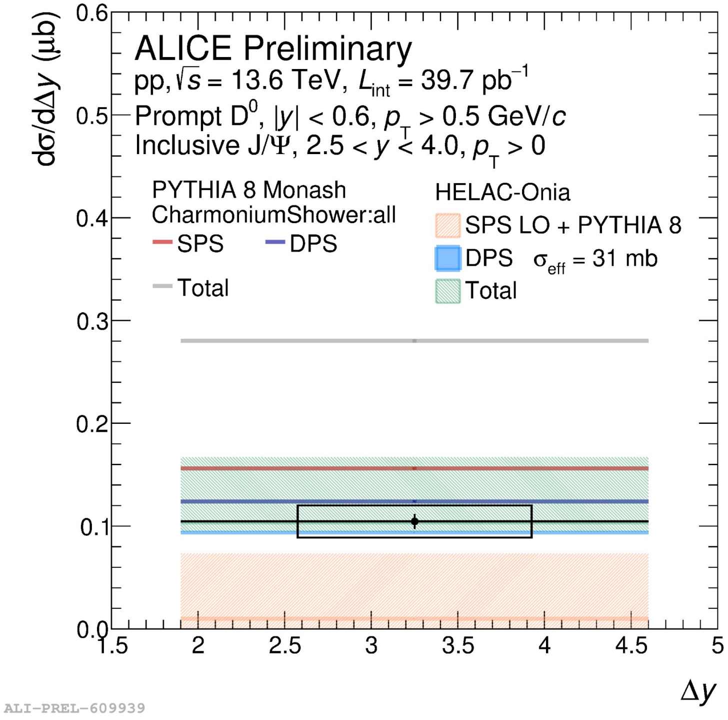


J/ψ-D^0 associated production

Integrated cross section in the Δy range vs predictions from different MC generators:

- **PYTHIA 8**
  [T . Sjöstrand et al., Comput. Phys. Commun. 191 (2015), 159-177]
  (Monash Tune + Charmonium Shower:All)
  - both SPS and DPS cross sections computed from the simulation
  - overestimates J/ψ-D^0 cross section

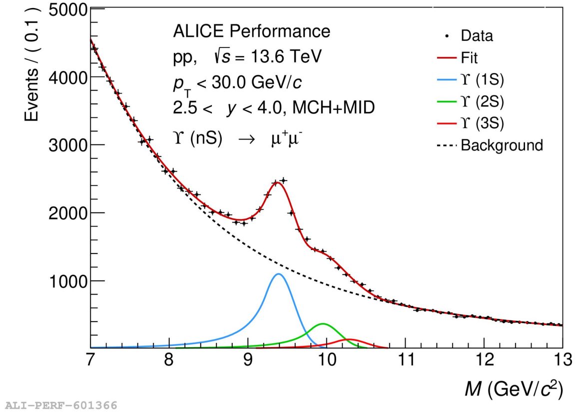
- **Helac-Onia**
  [H.-S. Shao, Comput. Phys. Commun. 184 (2013) 2562–2570]
  - SPS cross section computed from the simulation
  - DPS component is based on σ_{eff} value which is extracted from a fit to the data → $\boldsymbol{\sigma_{eff}}$ **= 31 mb**

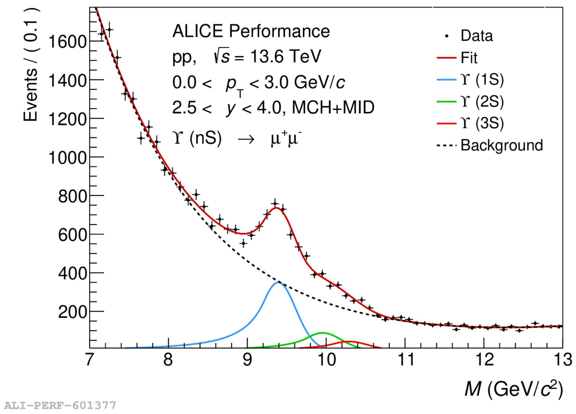


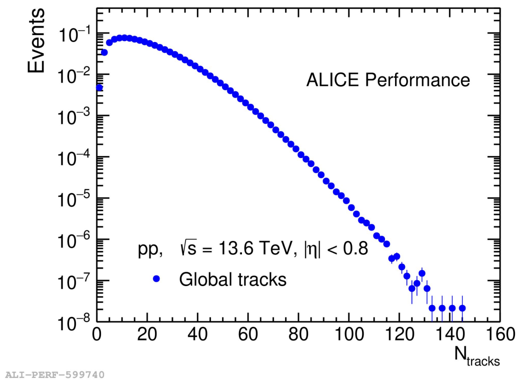
Outlook: Run 3 analyses in progress

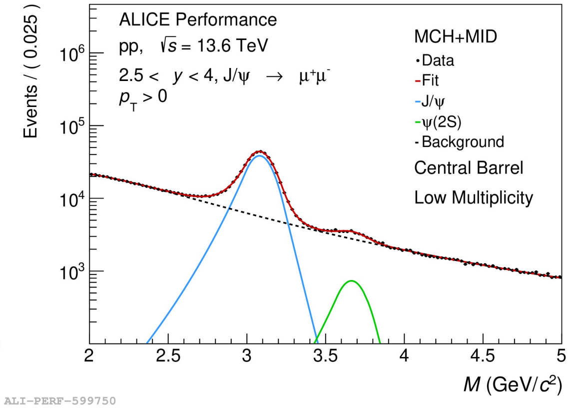
Currently working on bottomonium measurements at $\sqrt{s} = 13.6$ TeV

Signal extraction → possibility to discriminate **Υ(1S)**, **Υ(2S)**, and **Υ(3S)** states both in the integrated spectrum (left) and in the p_T-differential (right)









Ongoing measurements of charmonium production as a function of multiplicity at $\sqrt{s} = 13.6$ TeV

Multiplicity measured at midrapidity and charmonia at forward rapidity

Conclusions

Several preliminary results in pp collisions at $\sqrt{s}$ = 13.6 TeV in the charmonium sector

- **J/ψ cross section** → compatible with the measurement at $\sqrt{s}$ = 13 TeV and phenomenological predictions
- **ψ(2S)-to-J/ψ cross-section ratio** → compatible with measurements at $\sqrt{s}$ = 13 TeV and phenomenological models, little to no energy or rapidity dependence
- **J/ψ polarization** → sizable longitudinal polarization measured at low p_T : qualitative agreement with the ICEM prediction, disagreement with CSM and NRQCD
- **J/ψ-D^0 cross section** → overestimated by PYTHIA, compatible with Helac-Onia if σ_{eff} = 31 mb

Other analyses in progress in pp collisions at $\sqrt{s}$ = 13.6 TeV:

- Bottomonium cross-section
- Charmonium yield as a function of multiplicity

Conclusions

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Other important results by ALICE Run 3 in quarkonia discussed at this conference:

➢ Separation of prompt and non-prompt charmonia at forward rapidity in pp collisions
→ ***Beauty production in proton-proton collisions at $\sqrt{s}$ = 13.6 TeV*** by E. Barreau (previous talk)

➢ Quarkonium measurements in Pb-Pb collisions
→ ***Quarkonium collectivity in Pb-Pb collisions at $\sqrt{s_{NN}}$ =5.36 TeV with ALICE*** by R. Cerri (next talk)

Comprehensive overview on quarkonium and heavy-flavor production:
→ ***Heavy-flavor and quarkonium measurements from pp to AA collisions*** by S. Trogolo

THANK YOU
FOR YOUR ATTENTION

BACKUP

Production of Quarkonia

- Charm and bottom quarks are produced in the first instants of the partonic collision, i.e. in large energy scatterings: QCD predictions can be computed
- Their binding into quarkonia is instead characterized by smaller energy scale and cannot be described by perturbative QCD but rather by phenomenological models (non perturbative)

Color Evaporation Model (CEM or ICEM):

$$\boldsymbol{\sigma(H) = \text{const} \times \int_{2m_q}^{2M_{\text{meson}}} dm_{q\bar{q}} \frac{d\sigma_{q\bar{q}}}{dm_{q\bar{q}}}}$$

- $\sigma(H)$: Production cross-section of quarkonium H
- const: Proportionality factor which does not depend on y or p_T
- $2M_{\text{meson}}$: Mass of the lightest corresponding open heavy-flavor meson (D or B)
- $\frac{d\sigma_{q\bar{q}}}{dm_{q\bar{q}}}$: $q\bar{q}$ production cross-section

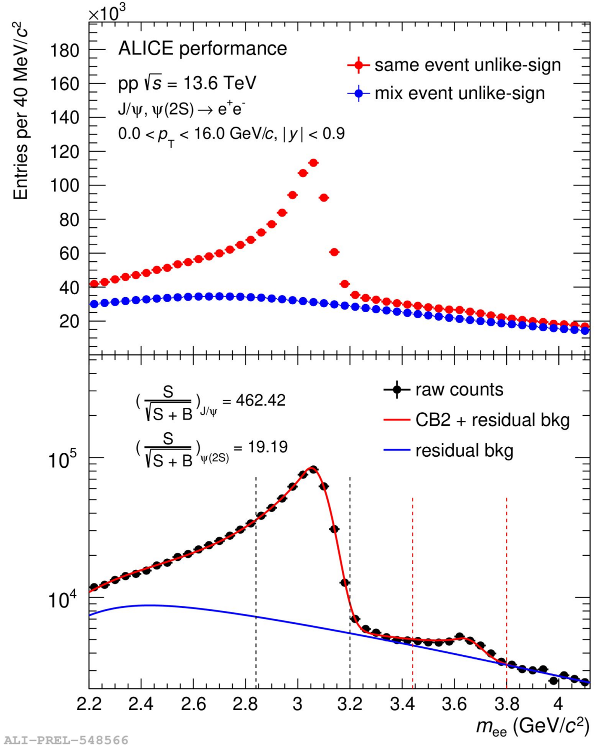
Non-Relativistic QCD

$$\sigma(H) = \sum_{\{n\}} \sigma_n(\Lambda) \cdot \langle \mathcal{O}_n^H(\Lambda) \rangle$$

- $\sigma(H)$: Production cross-section of quarkonium H
- $\sigma_n(\Lambda)$: $q\bar{q}$ production cross-section
- $\langle \mathcal{O}_n^H(\Lambda) \rangle$: Non-perturbative matrix elements describing hadronization

In the case of charmonia:
Contribution of charmonia from b quark decay (non prompt) in the **FONLL** (Fixed Order + Next to Leading Logarithm) formalism

Charmonium production at midrapidity

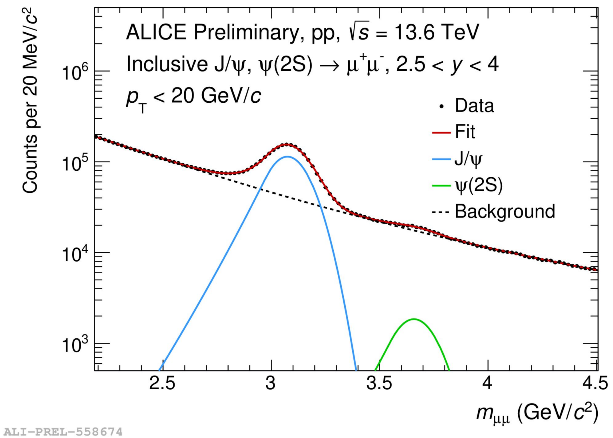


SIGNAL EXTRACTION STRATEGY

1. Combine **opposite-sign electrons in the same event**.
2. Subtract **opposite-sign electrons taken from mixed-events**
   ⇒ remove part of the background.
3. Fit the residual distribution with two **gaussian functions with asymmetric tails** (**J/ψ** and **ψ(2S)**), and a **phenomenological function** for the residual background.

Charmonium production ratio at forward rapidity

ALICE



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SIGNAL EXTRACTION STRATEGY

1. The **dimuon** invariant-mass spectrum is built by combining **opposite-sign muons in the same event**
2. No subtraction of mixed-event distribution (different strategy from midrapidity)
3. The signal is fitted with two **gaussian functions with asymmetric tails** (**J/ψ** and **ψ(2S)**), and a **phenomenological function** for the residual background

Rapidity and Pseudorapidity

Rapidity: measurement of velocity in special relativity, defined as

$$y = \frac{1}{2}\ln\left(\frac{E + p_L c}{E - p_L c}\right)$$

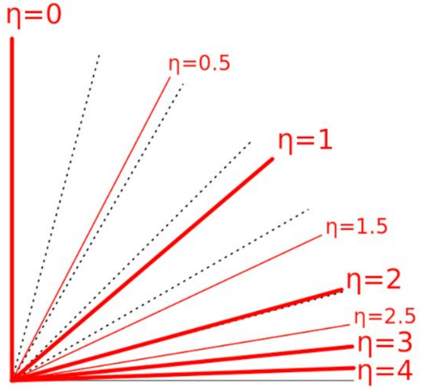
Transformation law:

$y' = y - y_\beta$, $y_\beta = \frac{1}{2}\ln\left(\frac{1+\beta}{1-\beta}\right)$ and β is the relative velocity of R' wrt R

Rapidity is complex to measure: it requires particle identification or combined measurement of energy and longitudinal momentum

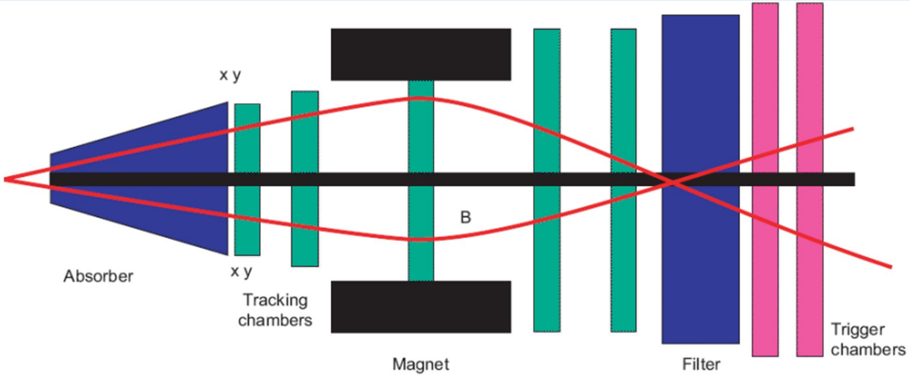
It is more convenient to use pseudorapidity, defined as

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) = \frac{1}{2}\ln\left(\frac{|\vec{p}| + p_L}{|\vec{p}| - p_L}\right)$$



For a relativistic particle, $|\vec{p}|c \sim E$ and therfore $\eta \approx y$

2) ALICE Muon Spectrometer



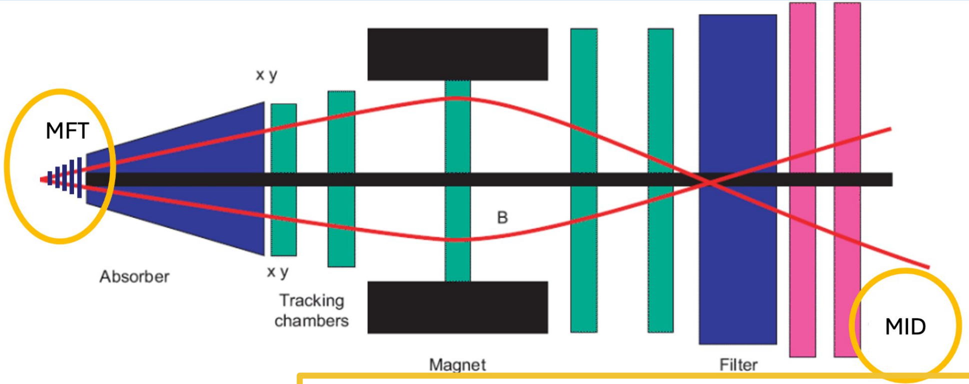
MCH, MID: $2.5 < \eta < 4$

<u>Run 2</u> (2015-2018)

1. Hadron Absorber
2. Muon (tracking) Chambers (MCH)

3. Muon Trigger

2) ALICE Muon Spectrometer



MCH, MID: $2.5 < \eta < 4$

MFT: $2.5 < \eta < 3.6$

Run 2 (2015-2018)

1. Hadron Absorber
2. Muon (tracking) Chambers (MCH)
3. Muon Trigger

Run 3 (2022-ongoing)

0. **New Muon Forward Tracker (MFT) before absorber**
1. Hadron Absorber
2. Muon (tracking) Chambers (MCH): new front-end electronics and readout chain
3. **Muon Identifier (MID) with new front-end electronics and readout chain**

Major changes to provide:

- **Discrimination between primary and secondary vertices (through MFT)**
- **Continuous readout (no trigger) through upgrade of front-end and read-out electronics**

Muon Tracking Chambers

Made of 5 stations of 2 planes of multi-wire proportional chambers

Both Cathode Pad Chamber (CPC) and Cathode Strip Chamber technologies are used in order to provide 2D information

Muon Tracking Chambers

2 stations of 2 planes of Resistive Plate Chambers (RPC) each

Multi-parton interactions

Multiple parton interactions (MPI) in a single hadronic collision

- can explain QGP-like effects in small systems
- inputs to tune MC generators

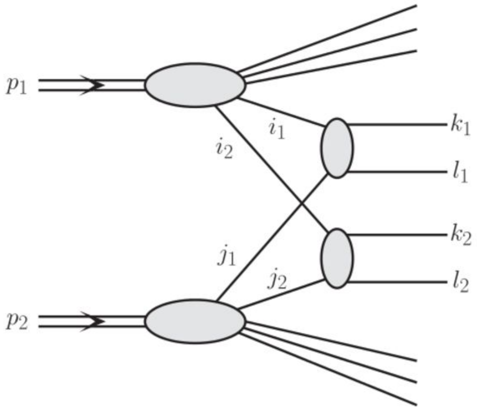
Simplest case: **double-parton-scattering (DPS)**

$$\sigma^{DPS}_{A,B} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

m=1 if A=B
m=2 otherwise

σ_{eff} = scaling factor → physical observable

Independent on process and collision energy in the simplest model

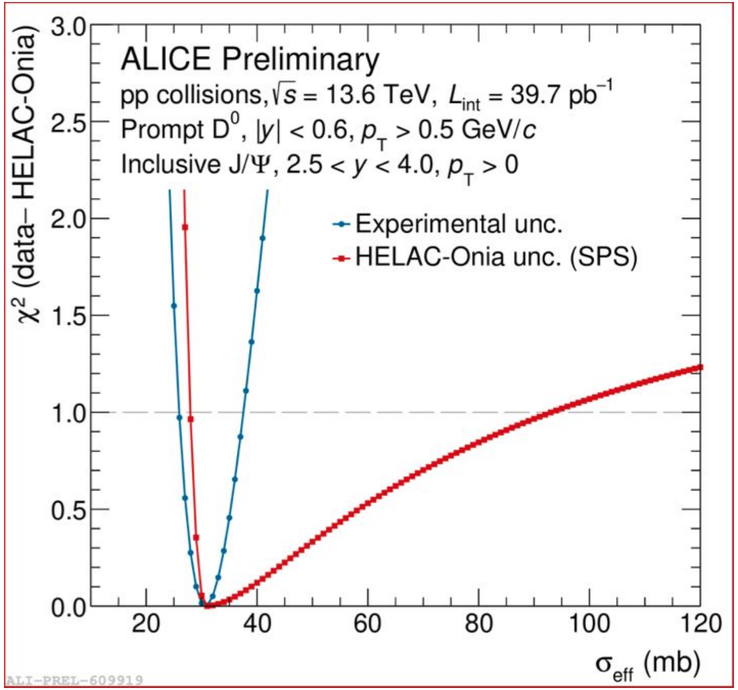


J/ψ-D^0 associated production

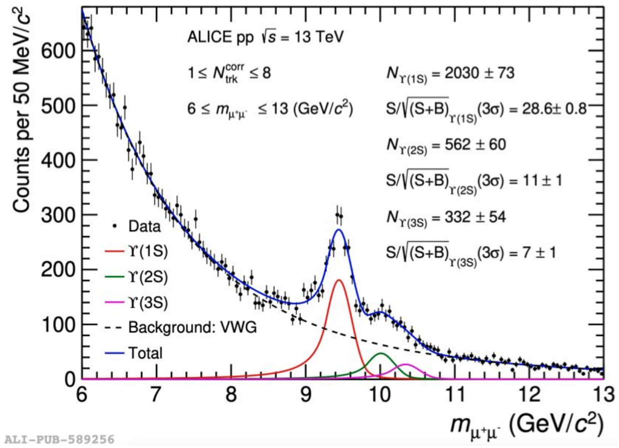
Fit to extract σ_{eff} using Helac-Onia predictions

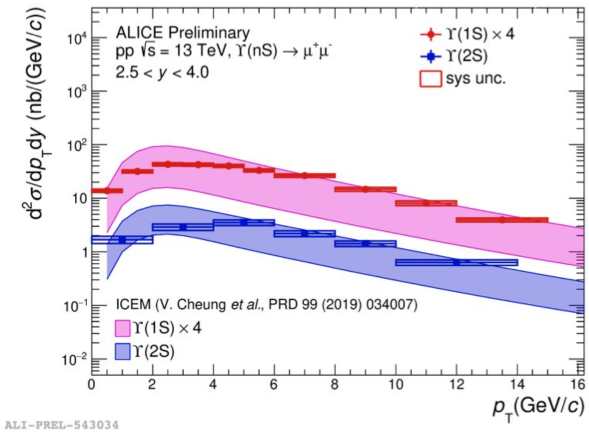
Uncertainties on σ_{eff} extraction are currently dominated by theoretical prediction

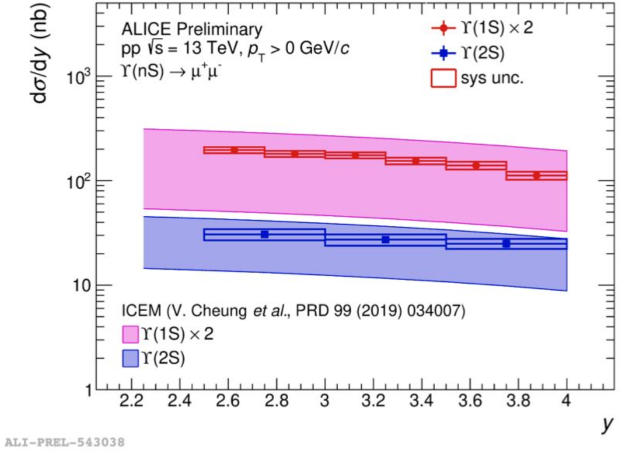
→ σ_{eff} = 31 mb



Bottomonium production in Run 2

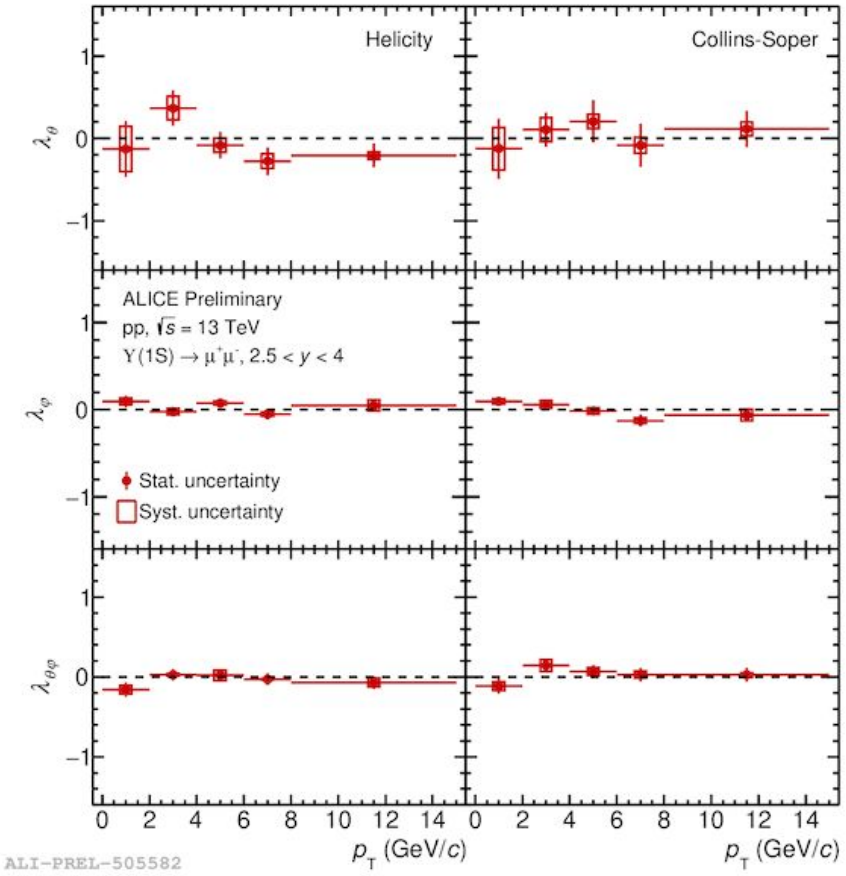






- As for bottomonia, the signal extraction allows for discrimination of Υ(1S), Υ(2S), and Υ(3S) states
- **ICEM correctly predicts differential yields of Υ(1S) and Υ(2S) vs p_T and rapidity at 13 TeV at forward rapidity**
- Measurements at 13.6 TeV at forward rapidity are ongoing

Bottomonium polarization in Run 2

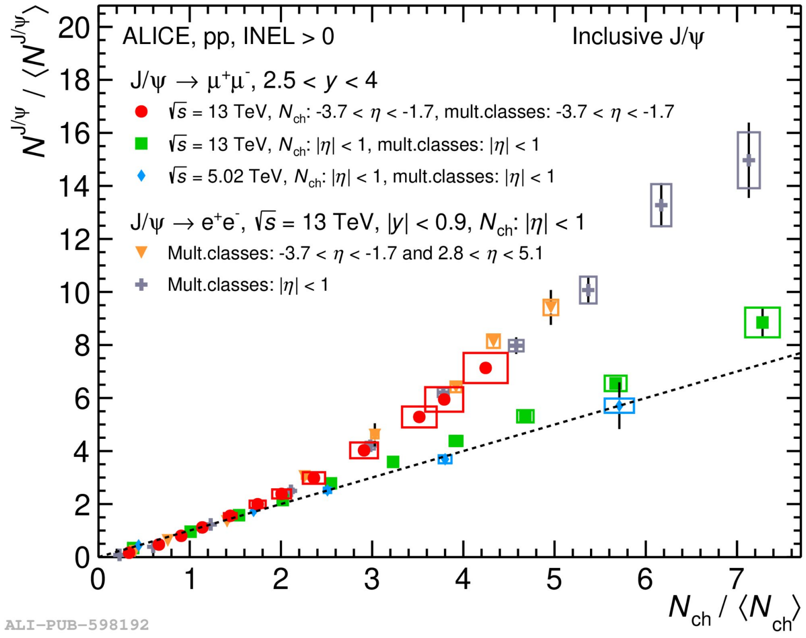


- All **ϒ(1S) polarization** coefficients measured at **13 TeV** are found to be **compatible with 0** within the statistical and systematic uncertainties in both the Helicity and the Collins-Soper frames

- Ongoing measurement at 13.6 TeV with the aim of increasing the sample size and reducing the uncertainties

Charmonium production vs multiplicity (Run 2)

Quarkonium production as a function of the total number of produced particles in a collision (multiplicity)
→ understand the **role of multi-parton interactions** in quarkonium production in pp collisions



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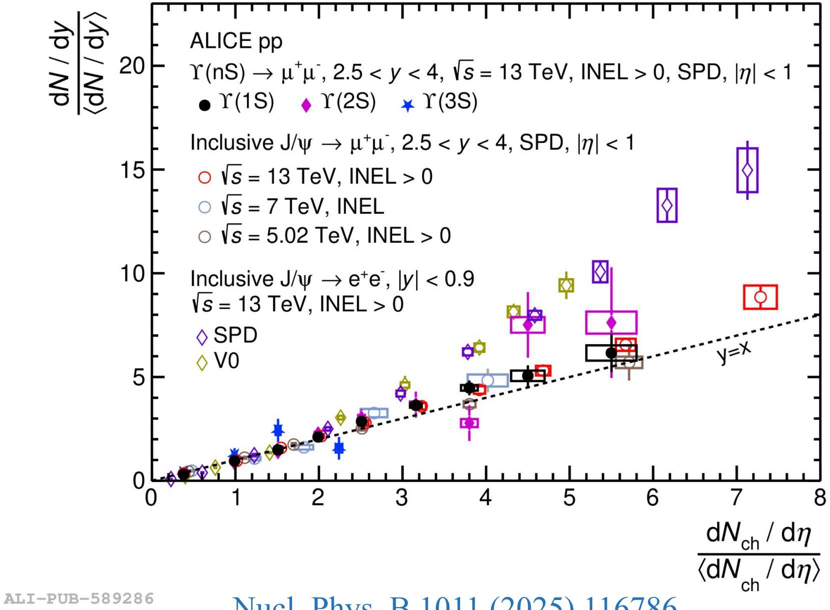
Charmonia at 13 TeV:

- **Linear dependence** vs multiplicity at **low multiplicities**
- At high multiplicities:
  - **J/ψ at forward rapidity, multiplicity estimator at midrapidity → linear dependence**
  - **J/ψ at forward rapidity, multiplicity estimator at forward rapidity → steeper-than-linear dependence**
  - **J/ψ at midrapidity with both multiplicity estimators → steeper-than-linear dependence**

Bottomonium production vs multiplicity (Run 2)

Quarkonium production as a function of the total number of produced particles in a collision (multiplicity) → understand the **role of multi-parton interactions** in quarkonium production in pp collisions



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Bottomonia at 13 TeV:

- **Linear dependence** vs multiplicity at **low multiplicities**
- **At high multiplicities**:
  - **Compatible with linear correlation**