Open and hidden heavy-flavour production in small systems with ALICE

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On behalf of the ALICE collaboration

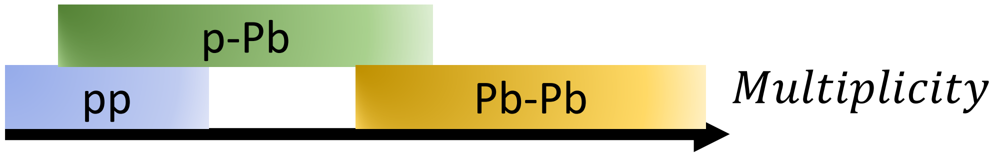
XXIXth International Conference - Quark Matter 2022
Wednesday, April 6th 2022

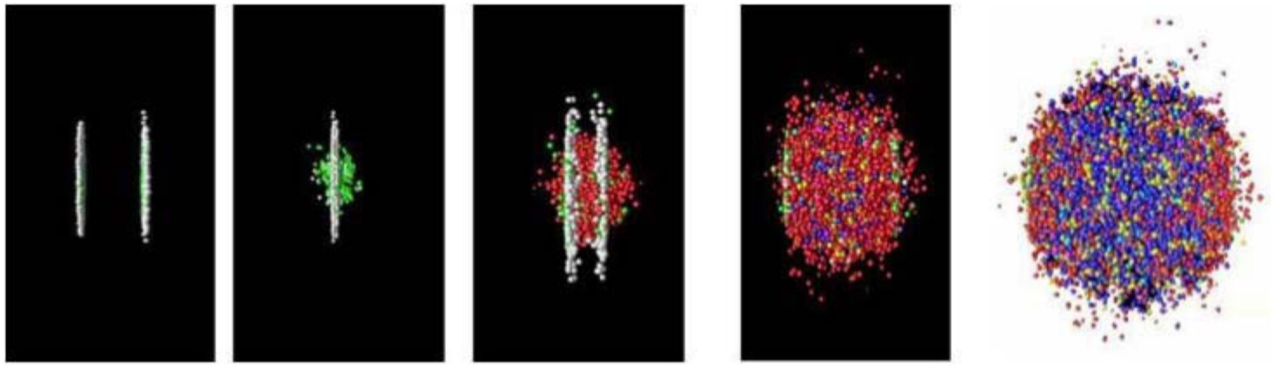
Heavy flavour in small systems: physics motivations

Reference systems to study quark-gluon plasma (QGP)

Hints of collective behaviours

- Study similarities in small systems and Pb-Pb collisions
- Use of observables directly linked to collectivity (flow)
- Multiplicity dependent analyses (behaviour accross system size)





Open and hidden heavy flavour probes from small to large systems

- Heavy flavour quarks formed at early stages (hard scale)
- pp: Allows to test perturbative QCD predictions, study production mechanisms

Outline of presented results

Quarkonium

- **NEW:** J/ψ pair production in pp at 13 TeV
- **NEW:** Quarkonia production cross sections at forward rapidity in pp
- J/ψ production cross section at midrapidity in pp
- **NEW:** J/ψ elliptic flow in small systems
- **NEW:** $\psi(2S)$ multiplicity dependent production in small systems

Also see:

- ***Alexandra Neagu (Parallel T09 – Thu. 7th – 9:20)***
- ***Jon-Are Saetre (Parallel T11 – Thu. 7th – 14:40)***

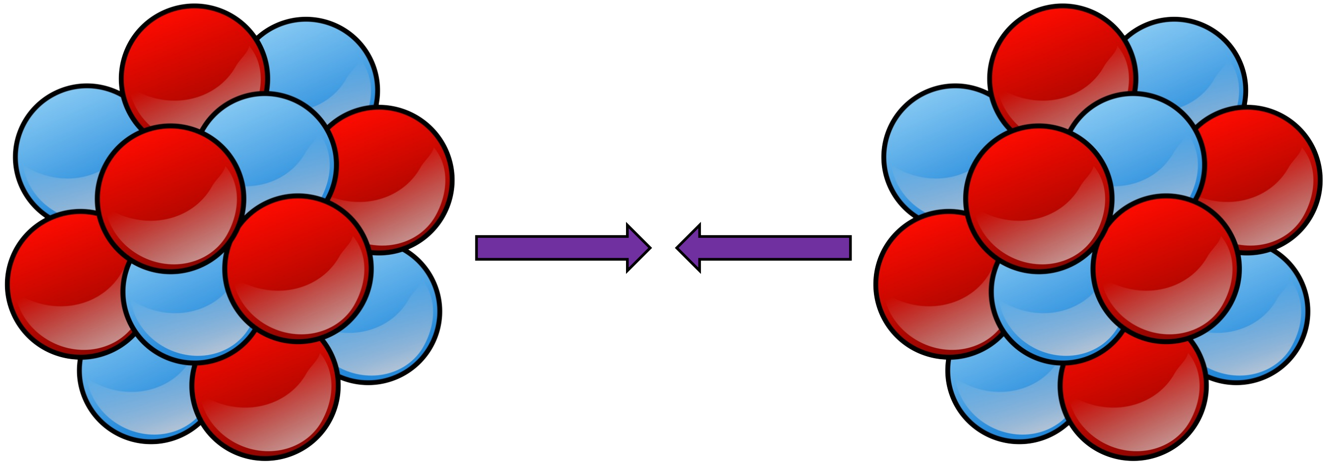
Open-beauty

- **NEW:** D^{*+} polarization in pp at 13 TeV
- **NEW:** Non-prompt Λ_{C} production in small systems
- **NEW:** Non-prompt and prompt $\Lambda_{\mathrm{C}}/\mathrm{D}^0$ in pp
- **NEW:** Beauty hadron to electron decay in pp
- **NEW:** Multiplicity dependence of non prompt D production

Open-charm

Not the focus of this presentation, see:

- ***Mattia Faggin (Parallel T11 – Thu. 7th – 11:10)***
- ***Luigi Dello Stritto (Parallel T14 – Thu. 7th – 16:00)***
- ***Marianna Mazzilli (Parallel T04 – Wed. 6th – 14:40)***



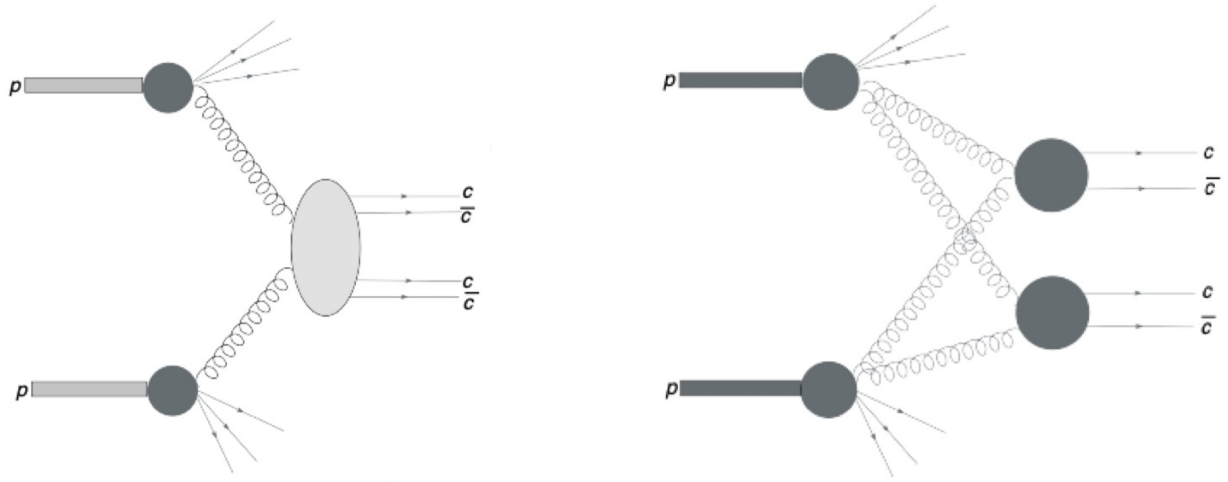
Small systems, a reference for nucleus-nucleus collisions

Quarkonium studies - Production

J/ψ pair production in pp at 13 TeV

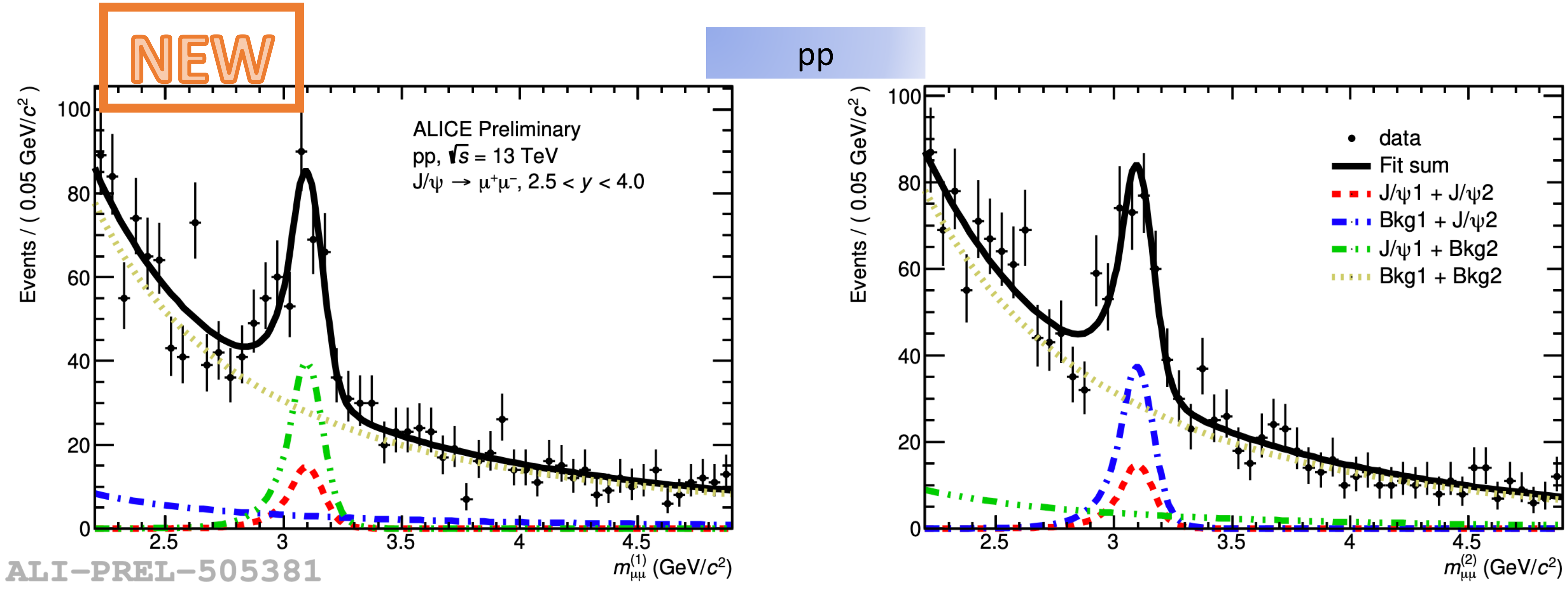
Insight on:

- Single J/ψ production
- NRQCD constraints
- Double-parton scattering



AIP Conf. Proc. 1523 (2013) 1, 255-259

pp



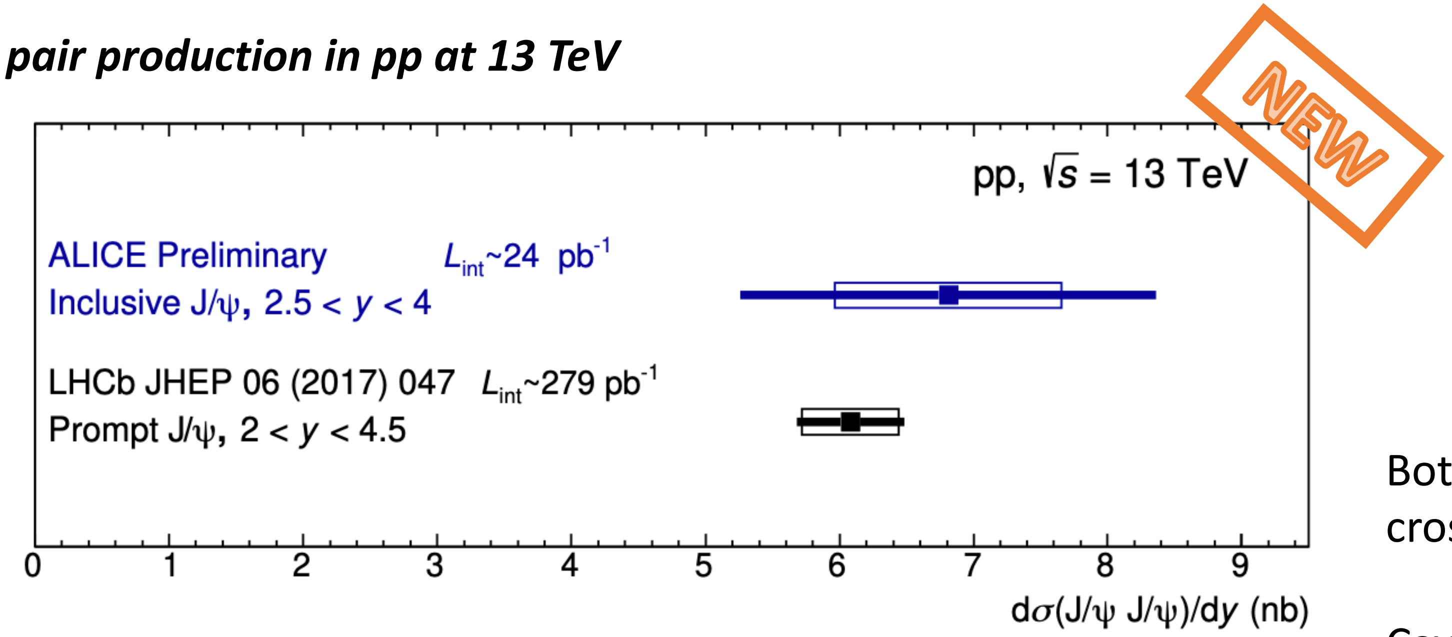
2D invariant mass fit:

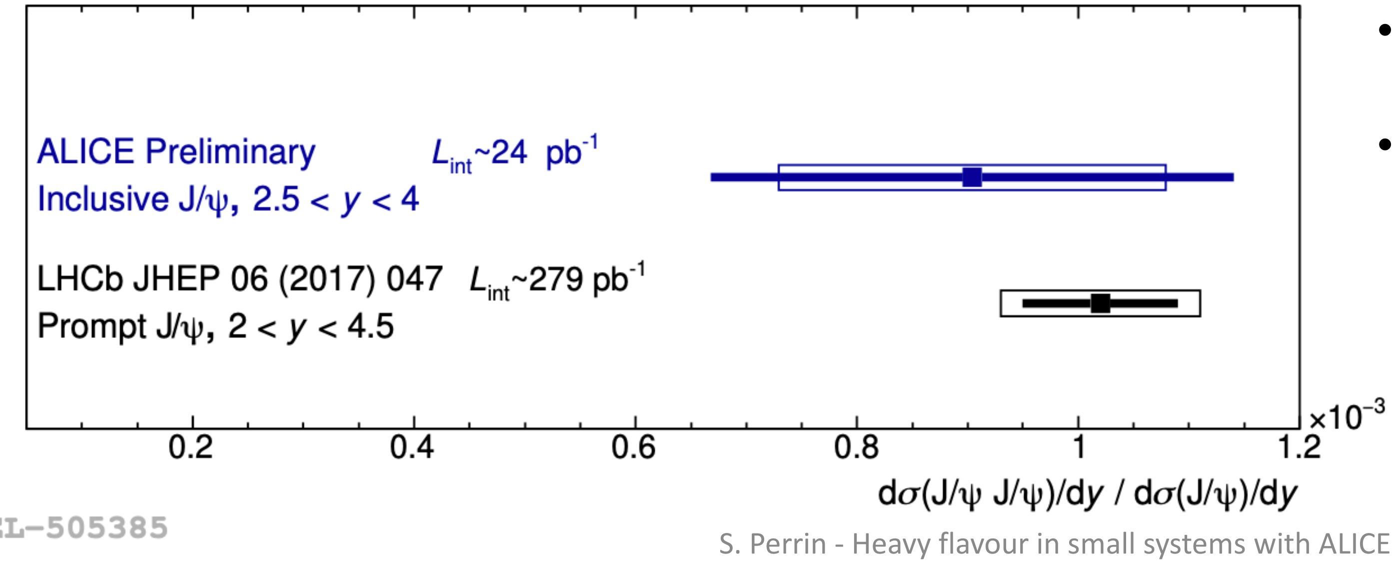
Mass distributions of first $m_{\mu\mu}^{1}$ and second $m_{\mu\mu}^{2}$ reconstructed unlike-sign dimuon pairs

← **1D projections of the fit**

Quarkonium studies - Production

J/ψ pair production in pp at 13 TeV





Both results on di-J/ψ and di-J/ψ to single J/ψ cross section are in good agreement with LHCb

Caveat:

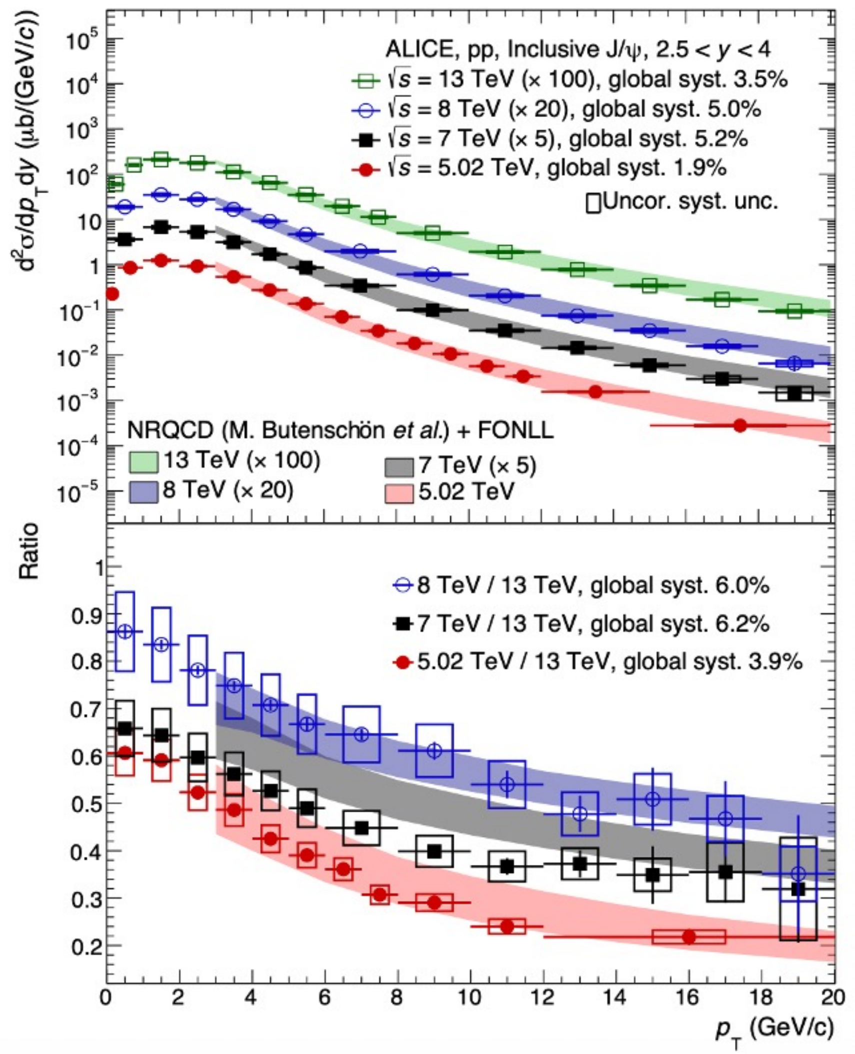
- ALICE measures inclusive J/ψ and LHCb prompt J/ψ
- Slightly different rapidity ranges

Quarkonium studies – Production – forward rapidity

Quarkonium cross sections at forward rapidity in pp

pp

[arXiv:2109.15240]

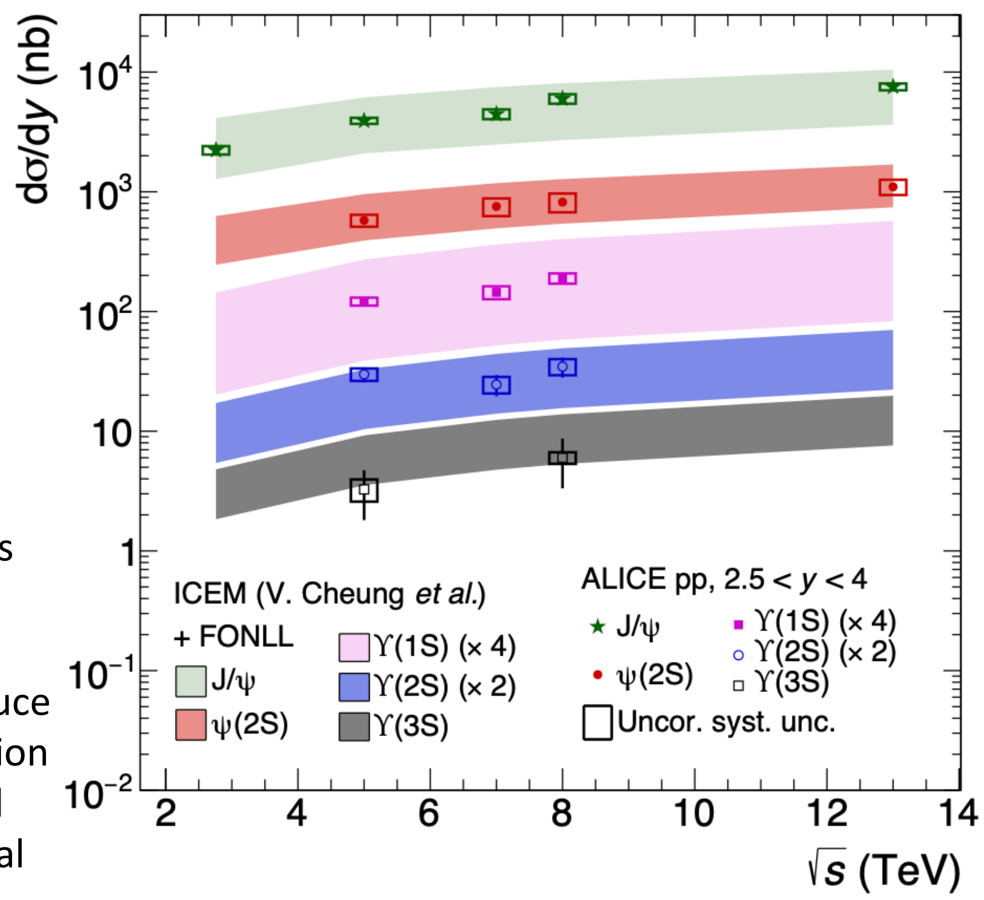


New measurement done at 5 TeV (10 times the statistics available in earlier publication)

Cross section ratios impose additional constraints on models (partial cancellation of theoretical uncertainties in ratios)

Cross sections are reproduced by both NRQCD and ICEM calculations at all energies

Models have difficulties to reproduce at the same time all the cross section ratios among energies, but are still compatible within the experimental precision



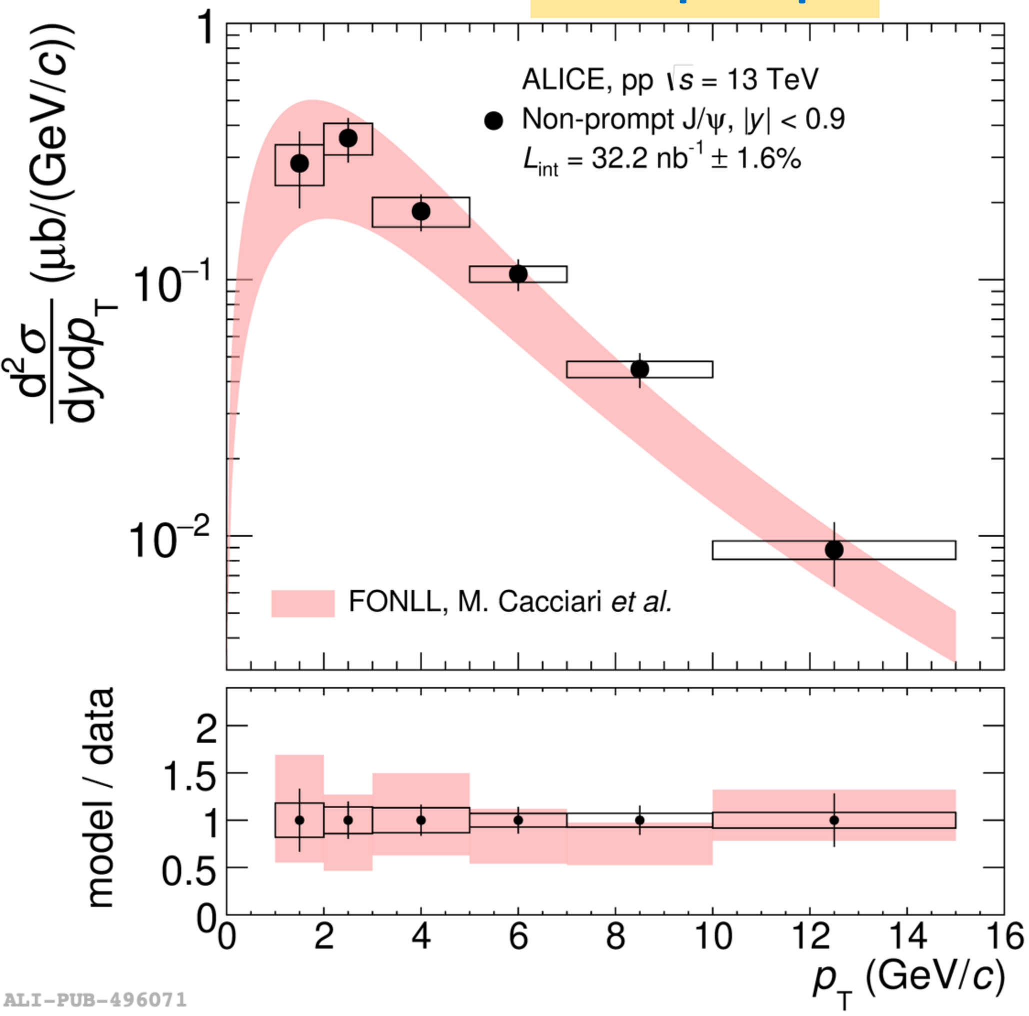
Behaviour of $q\bar{q}$ production with energy well reproduced by ICEM calculations for different species

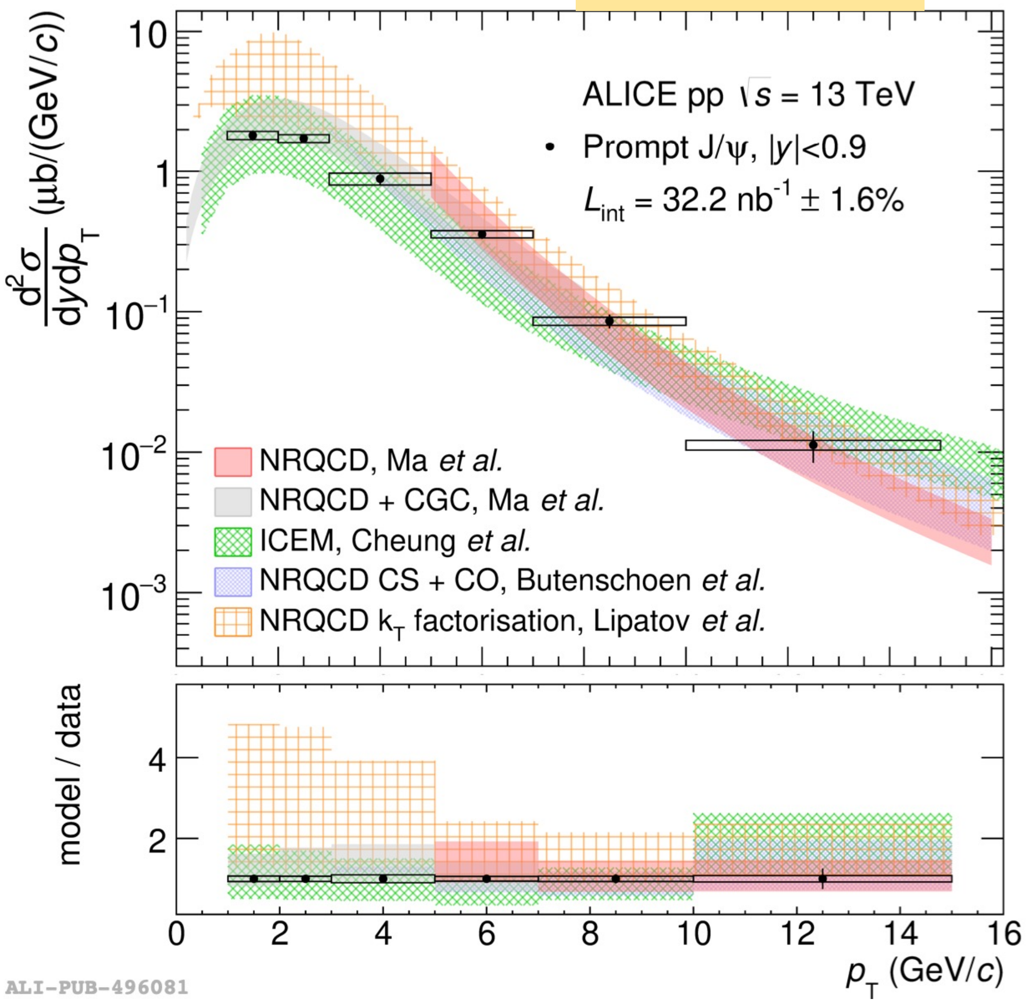
Quarkonium studies – Production – midrapidity

J/ψ cross sections in pp

[arXiv:2108.02523]

Non-prompt pp **Prompt**





Models describe well the prompt (NRQCD, ICEM) and non-prompt (FONLL) differential cross sections at midrapidity, at 13 TeV

Similar agreement is found at 5 TeV as well

Same models manage to describe data in both rapidity ranges and in a large range of energies

Open beauty at midrapidity - Polarization

D^{*+} *polarization in pp at 13 TeV*

ρ_{00}, spin matrix element
- 1/3 if no polarization

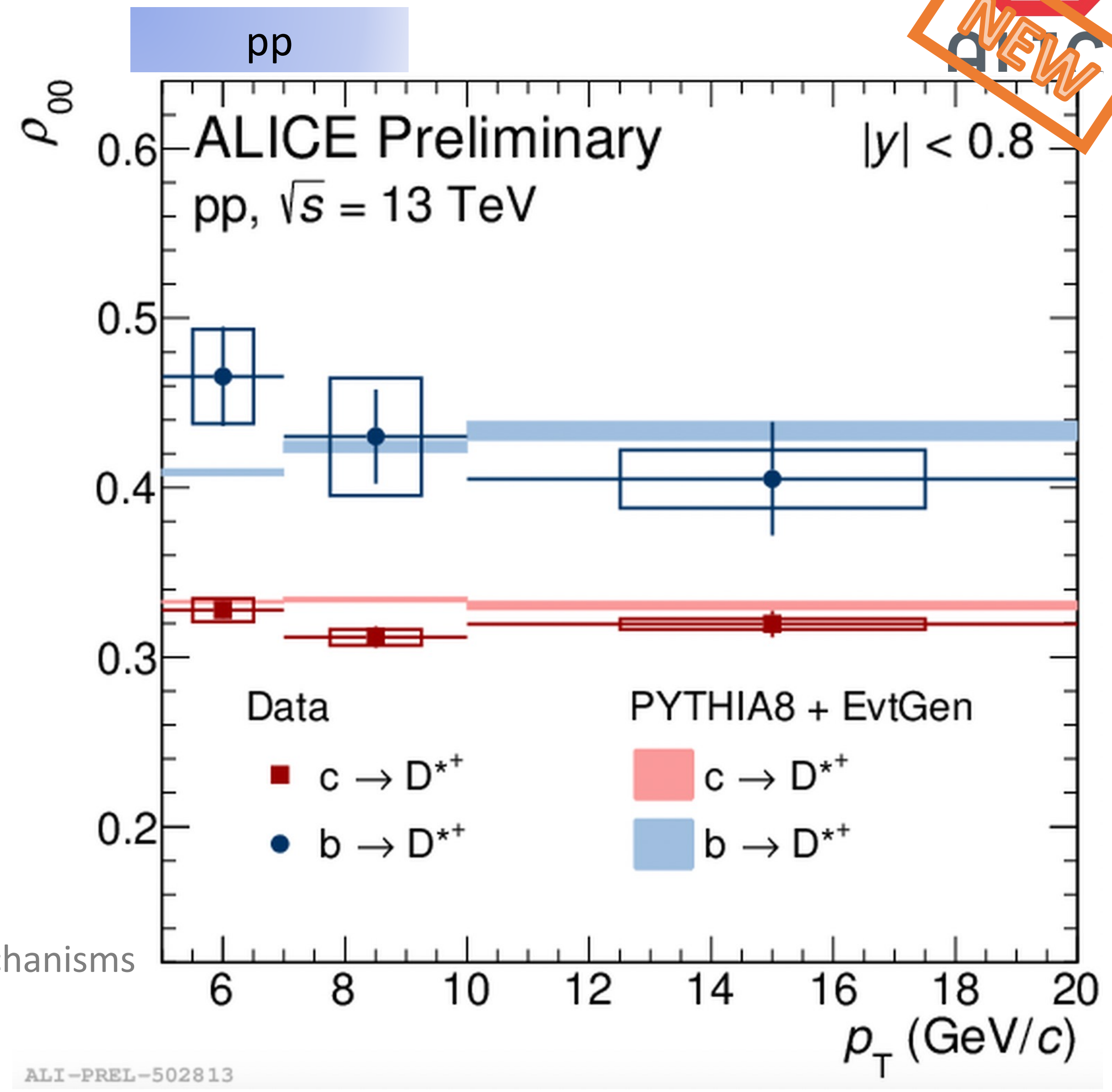
Machine learning (ML) techniques (Boosted Decision Tree) applied to separate prompt from non-prompt contribution

- Prompt D^{*+} unpolarized
- Non-zero polarization for non-prompt D^{*+}

Both predicted by PYTHIA 8 + EVTGEN

Demonstrates the ability to separate prompt and non-prompt and to measure open beauty polarization

Baseline for Pb-Pb system, impacted by strong initial magnetic fields and angular momentum.



Quarkonium polarization in small systems sets constraints on production mechanisms

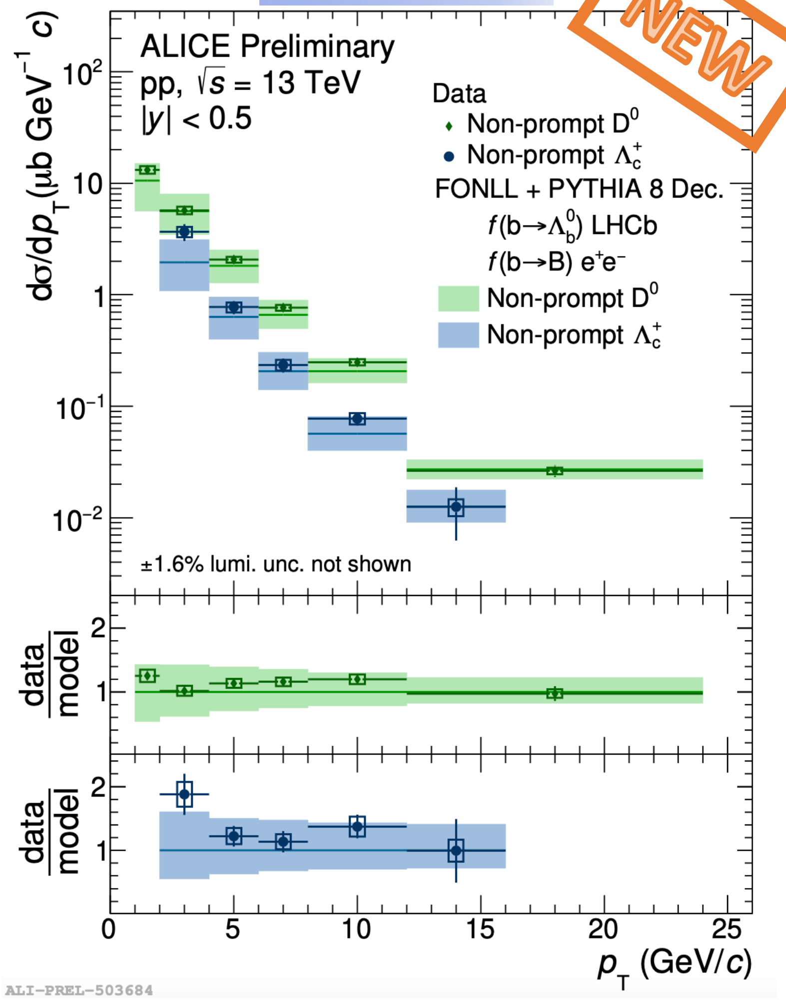
Luca Micheletti's talk (Parallel T02 – Tuesday 5th – 16:50)

Yanchun Ding's poster (Session 3 T11_1 – Friday 8th – 14:12)

Open beauty at midrapidity – Production

Non-prompt Λ_C study in pp and p-Pb

pp



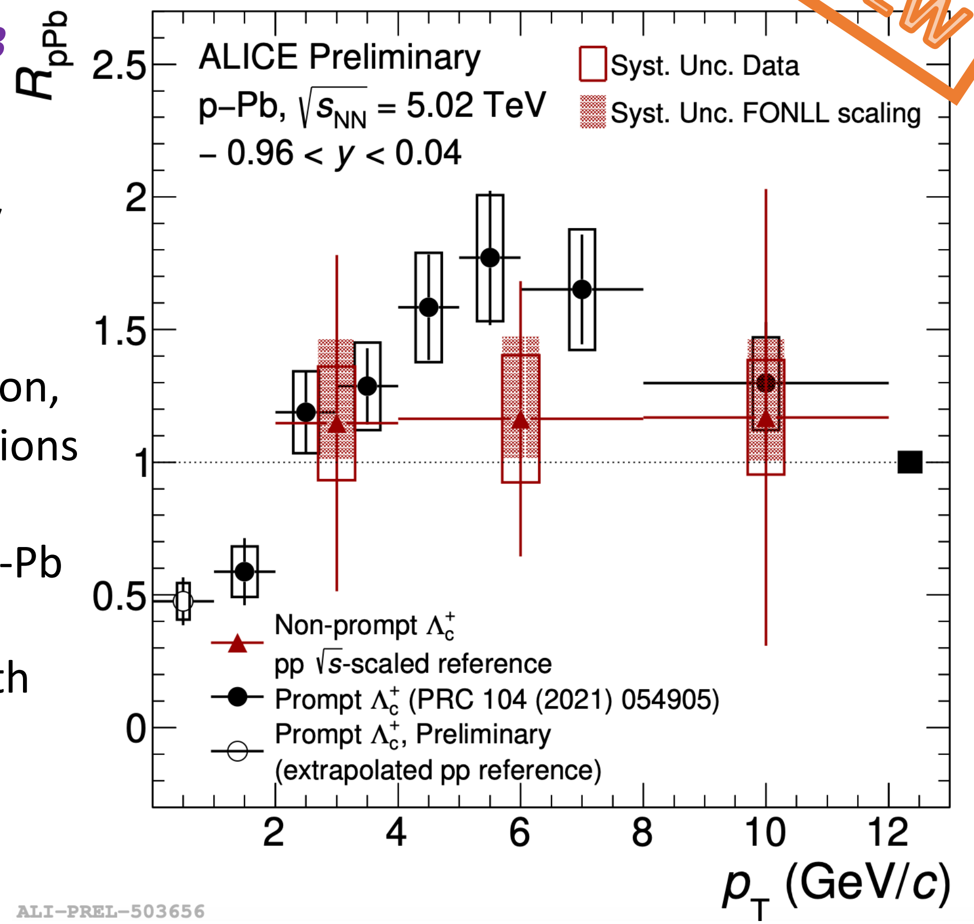
Production of non-prompt Λ_C^+ in pp:
Daniel Battistini's poster (Session 3 T11_2 – Fri. 8th – 14:04)

p_T dependence well reproduced by theoretical calculations

Measurement of non-prompt fraction, avoids use of theoretical extrapolations

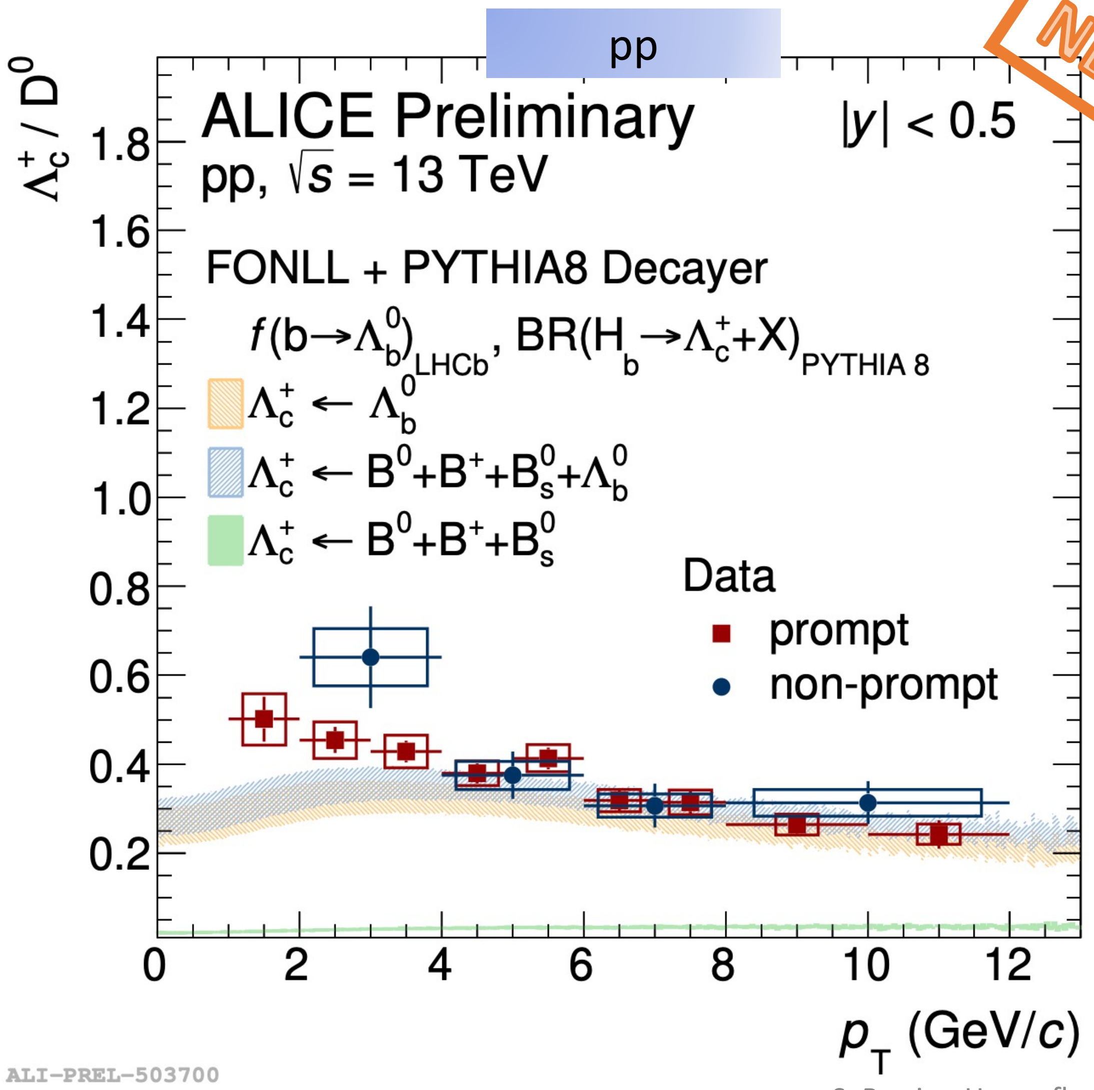
Non-prompt Λ_C^+ also measured in p-Pb collisions:
R_{pPb} compatible with unity and with prompt Λ_C^+ R_{pPb} within the large uncertainties

p-Pb



Open beauty at midrapidity – Production

Non-prompt and prompt Λ_c/D^0 in pp



NEW

Non-prompt Λ_C^+/D^0 in pp:

The fragmentation fraction of $b \rightarrow \Lambda_b$ measured by LHCb **[Phys. Rev. D 100, 031102(R)]**

p_T dependence well reproduced by FONLL+PYTHIA 8 for p_T > 4 GeV/c, tensions at lower p_T, as was the case for the individual species

Similar baryon-to-meson ratio enhancement between prompt and non-prompt

Non-prompt Λ_C gives access to beauty baryons

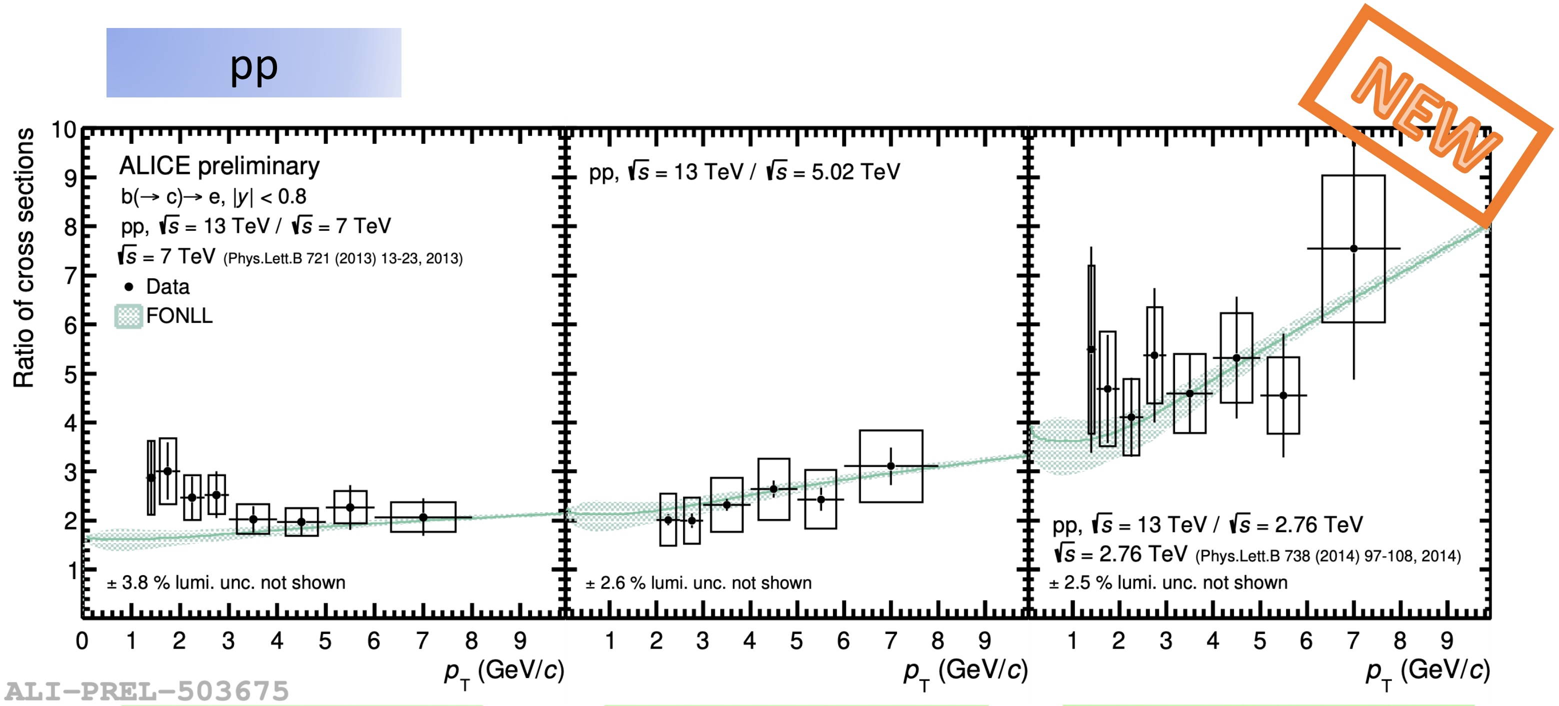
Electrons from beauty hadron decays at midrapidity

Beauty decays dominate heavy flavour electrons as p_{T} increases: very good agreement with FONLL calculations

p_{T} dependence of electrons from beauty cross sections ratios at different energies: very good agreement with FONLL calculations

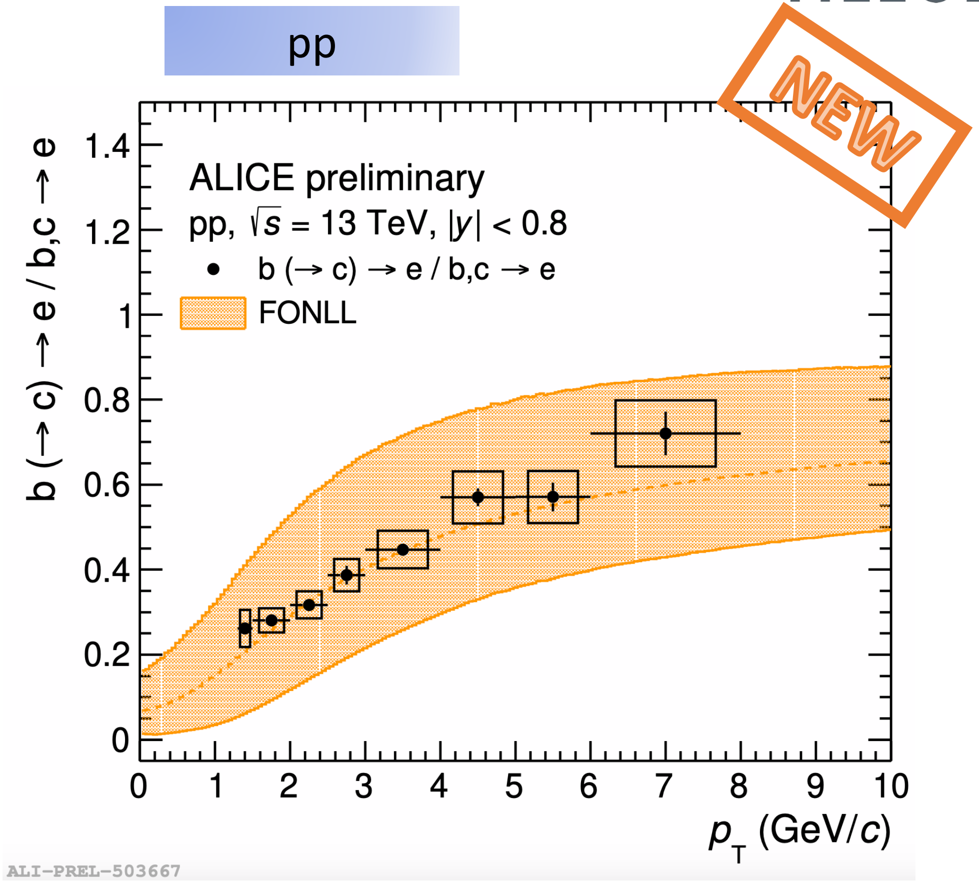
Jonghan Park's and Vivek Singh's poster (Session 3 T11_1 – Fri. 8th – 14:48)

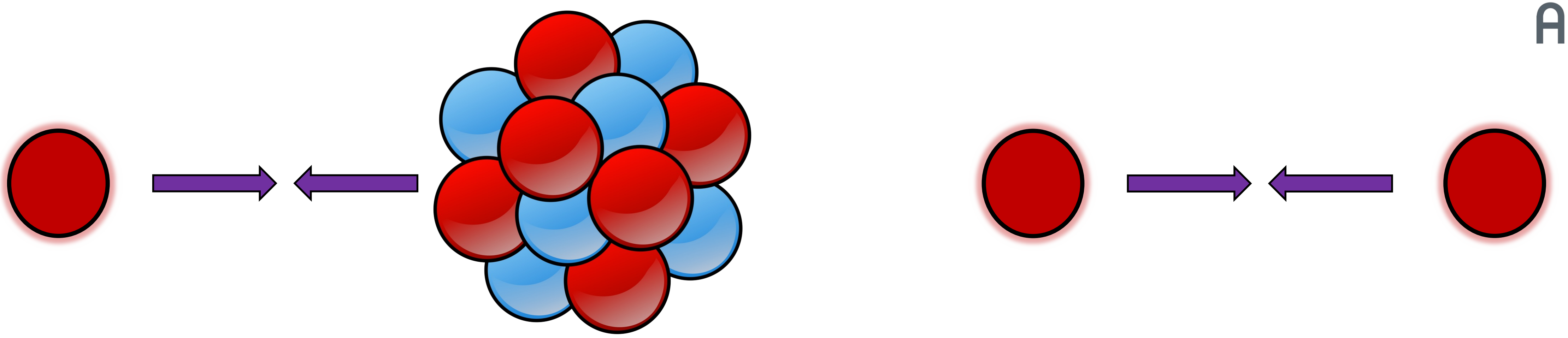
pp



√s = 13 TeV / √s = 7 TeV | √s = 13 TeV / √s = 5.02 TeV | √s = 13 TeV / √s = 2.76 TeV

pp





Small systems, a tool to study collective effects

J/ψ elliptic flow in small systems

Collective effects already assessed for light flavours (***Su-Jeong Ji's poster (Session 1 T05_2 – Wed. 6th – 17:30)***), open question for heavy flavours

p-Pb, p-p: angular correlations in high-multiplicity and low-multiplicity events

Non-flow effects (e.g. jets) suppressed by subtracting low-multiplicity yields from high-multiplicity yields

p-Pb: **[PLB 780 (2018) 7-20]**

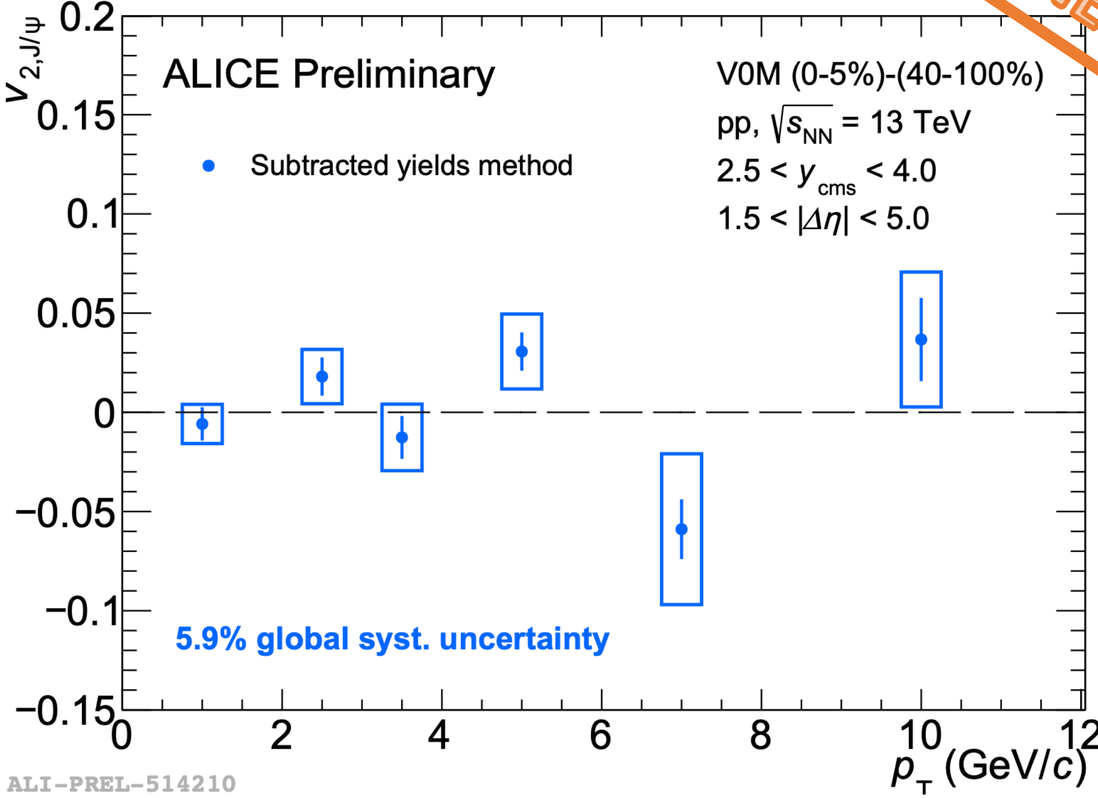
- For p_{T} > 3 GeV/c, significant flow
- Results close to AA → hints at common flow mechanism regardless of system size
- Transport model description valid for Pb-Pb does not hold in p-Pb, no explanation for p-Pb flow
- Motivates pp study

pp:

- No significant p_{T} dependence
- p_{T}-integrated v_2 compatible with 0 (within 1σ)

pp

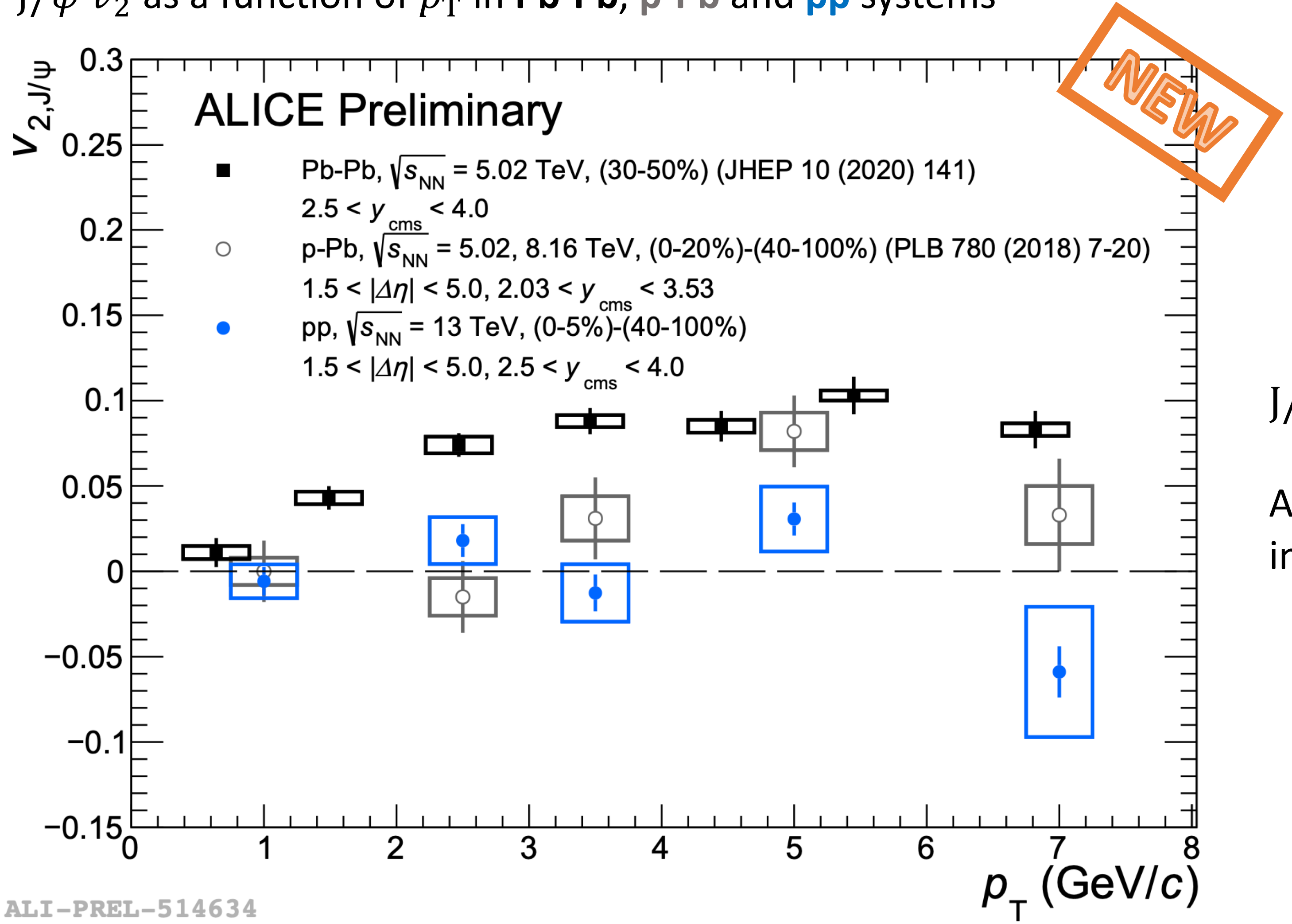
NEW



J/ψ v_2 as a function of p_{T} from **subtracted yields method**

J/ψ elliptic flow in small systems – Comparison

J/ψ v_2 as a function of p_T in **Pb-Pb**, **p-Pb** and **pp** systems



J/ψ v_2 in pp compatible with 0

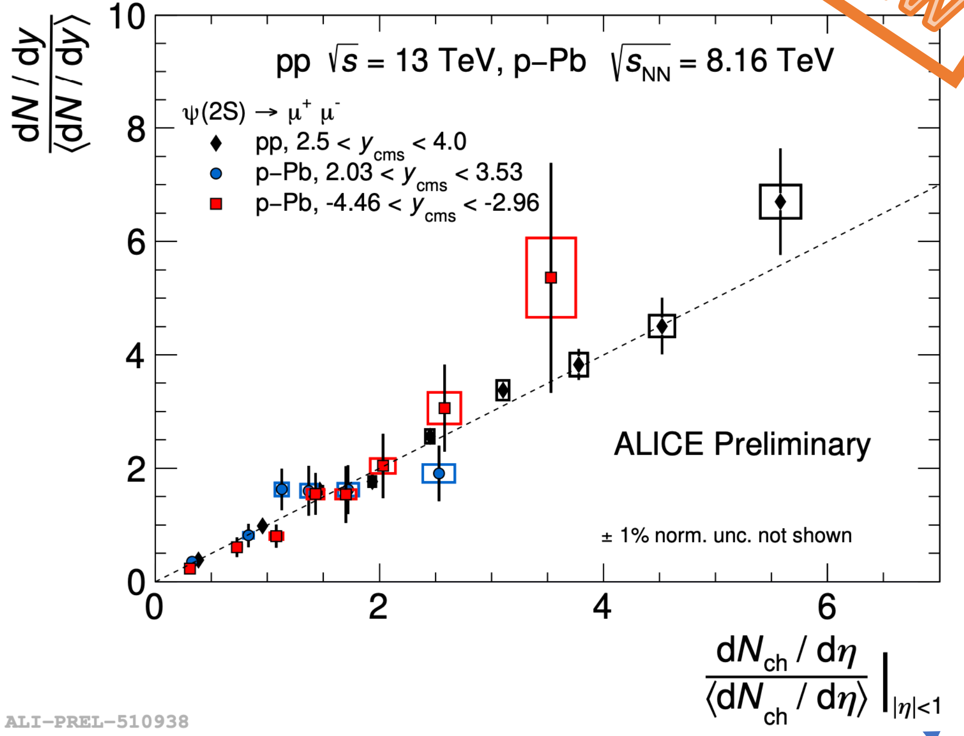
Appears lower than in larger systems especially from intermediate p_T (above 3 GeV/c)

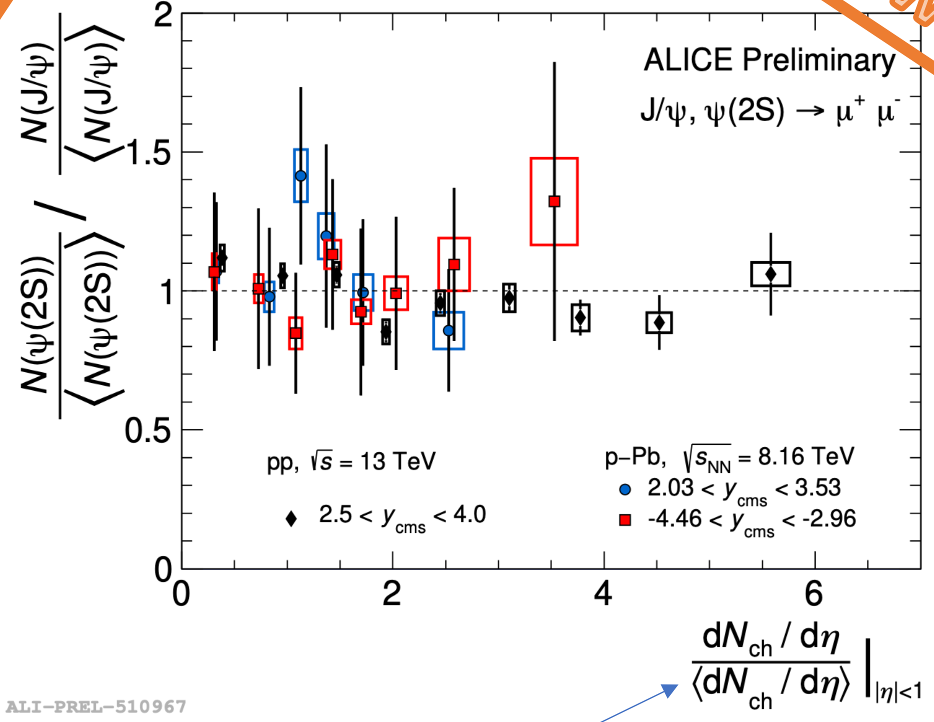
Multiplicity dependent charmonium production

Study of $\psi(2S)$ production in pp and p-Pb

Theera Tork's poster (Session 1 T05_1 – Wed. 6th – 17:42)

[ALICE-PUBLIC-2022-013]





Normalized $\psi(2S)$ yield goes linearly with charged particle multiplicity, and $\psi(2S)$-to-J/ψ ratio is compatible with unity

- Same behaviour regardless of charmonium state or system size

Probe at forward rapidity **VS** **Multiplicity at midrapidity**

Multiplicity dependent charmonium production

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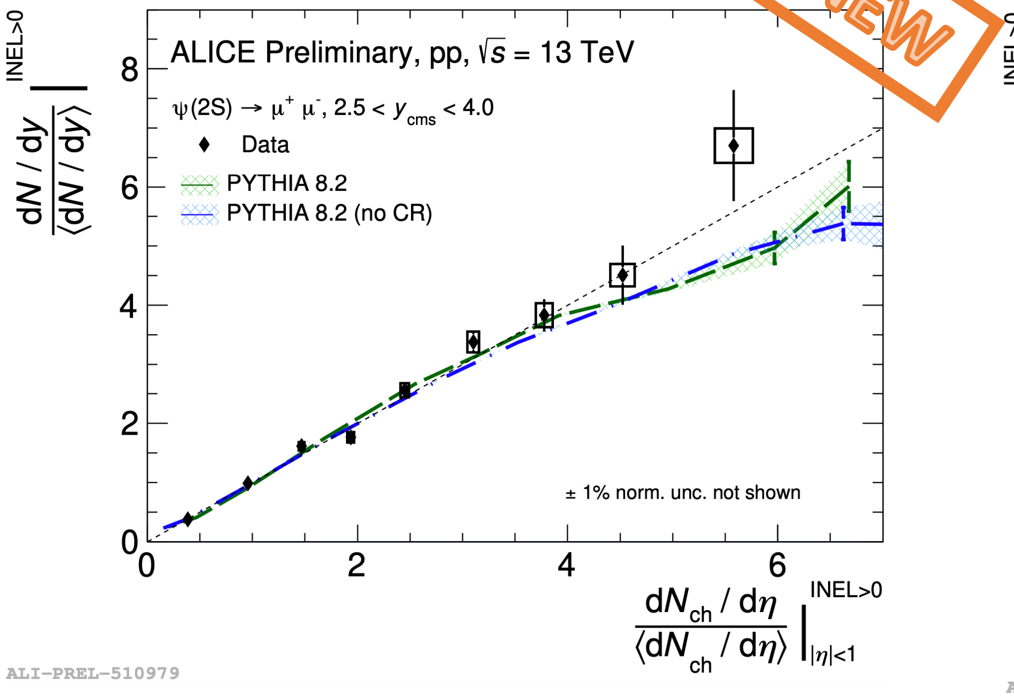
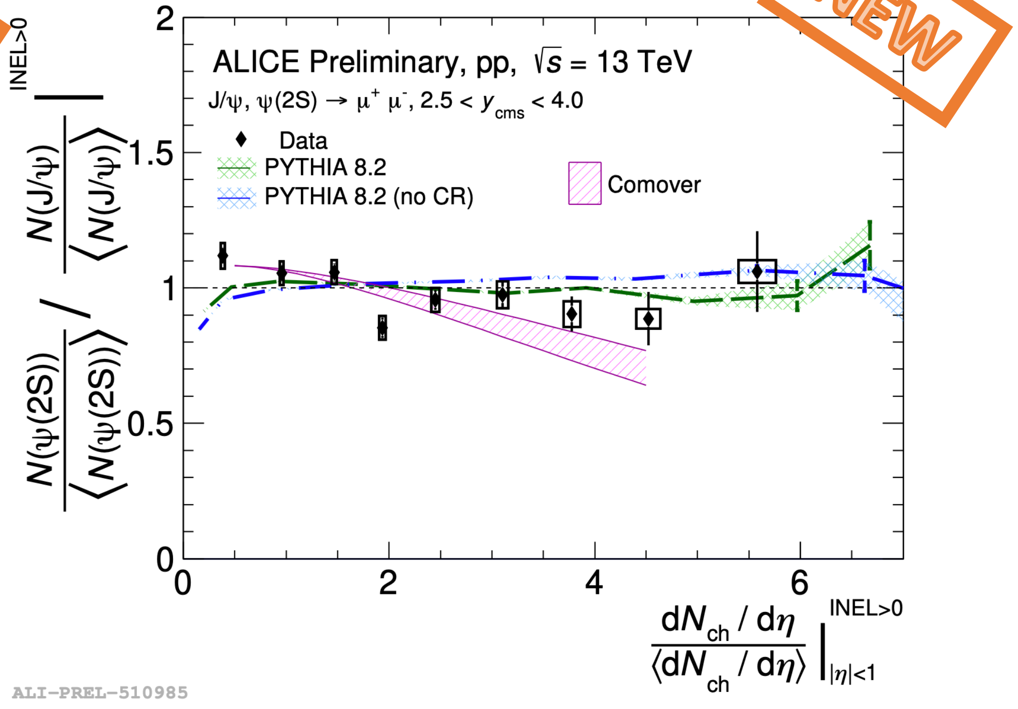


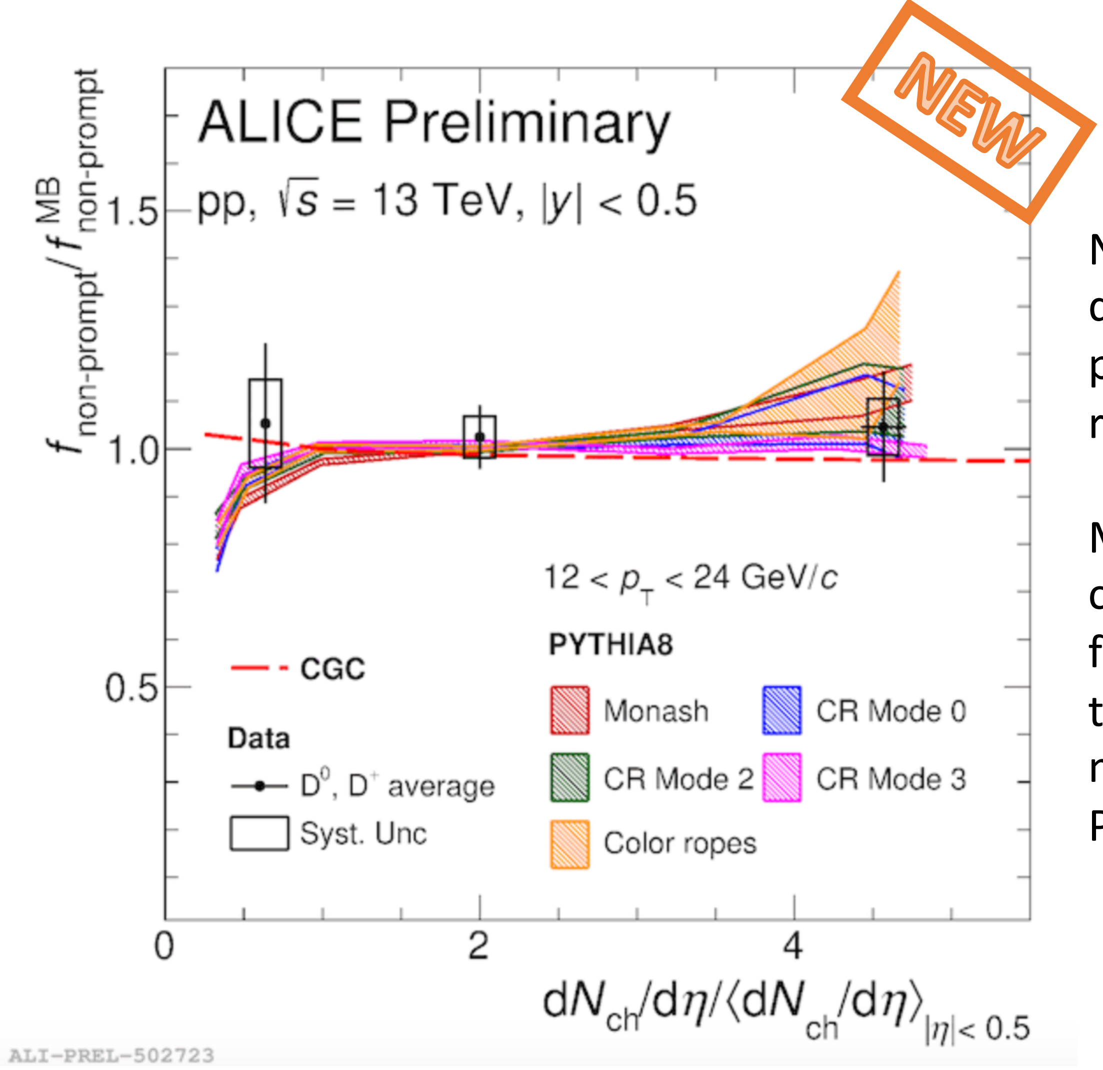


Normalized $\psi(2S)$ yield goes linearly with charged particle multiplicity, and $\psi(2S)$-to-J/ψ ratio is compatible with unity

- Same behaviour regardless of charmonium state or system size
- Agreement with PYTHIA and comovers model at low multiplicity, tensions at high multiplicity between PYTHIA and normalised yield data

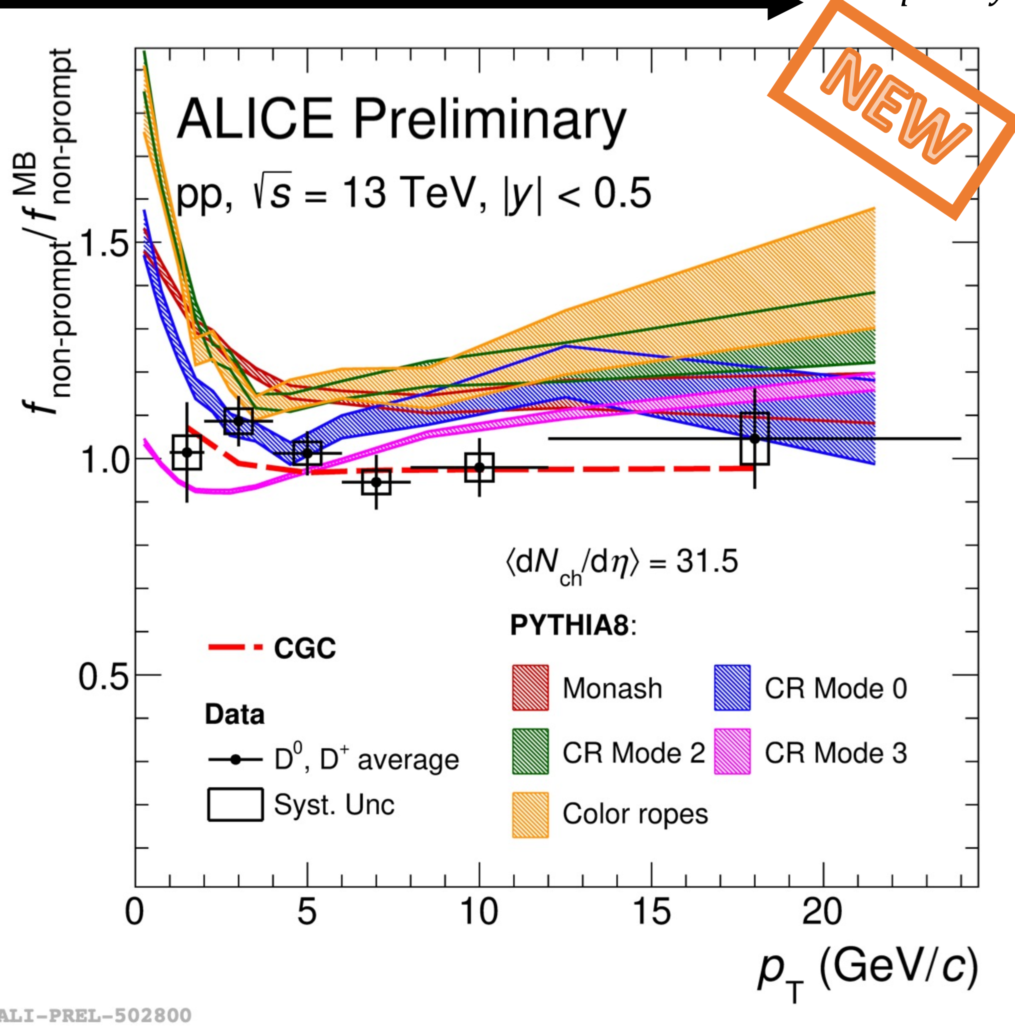
Multiplicity dependent open beauty production

Study of non-prompt D multiplicity dependence in pp
Provides comparison to hadronization models



No strong dependence of non-prompt fraction with respect to multiplicity

Measurements compatible with CGC framework, more tensions at very high multiplicity with some PYTHIA 8 tunes



Conclusions

Many new results on heavy-flavour in small systems released by ALICE !

Small systems as a way to study production mechanisms

Production and **polarization** of heavy flavours in small systems **is well described by theory**

Small systems as a way to study collectivity

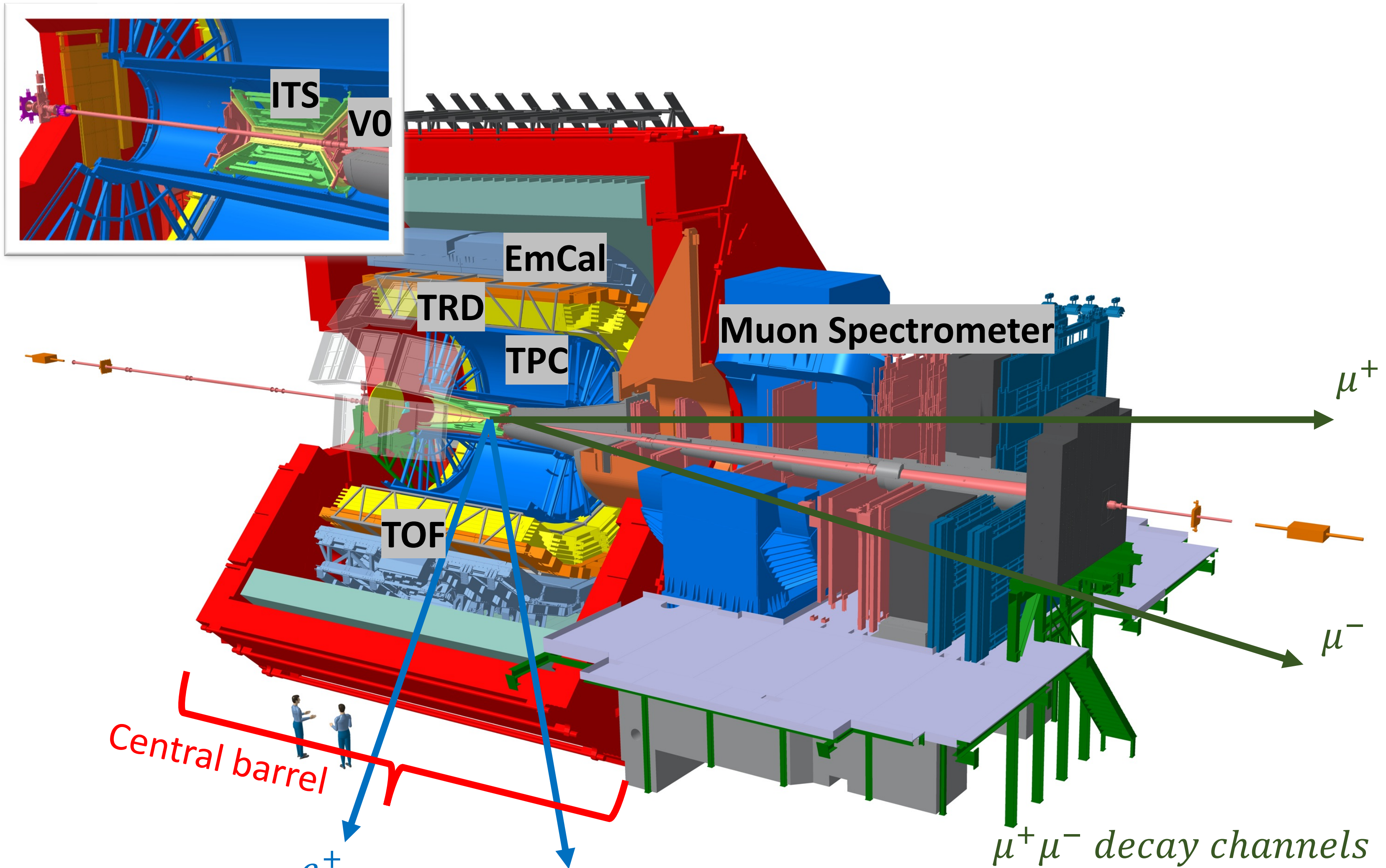
J/ψ collective flow mechanism in p-Pb still to be understood, **J/ψ in pp does not show collective flow** effects within uncertainties

Heavy flavours **multiplicity dependent production** measurements show **weak dependence on system size or excitation** states.

Thank you for your attention !

Backup slides

A Large Ion Collider Experiment



$e^+e^-, pK_S^0, \ldots$ *decay channels* ($|y| < 0.9$)

Distinction prompt (produced at primary vertex) / non-prompt (b-hadron decays)

$\mu^+\mu^-$ *decay channels* ($2.5 < y < 4.0$)

Inclusive measurements

ITS – Inner Tracking System
Tracking, vertex reconstruction, multiplicity estimation

V0(A and C)
Triggering, centrality estimation, background rejection

TPC – Time Projection Chamber
PID, tracking

EmCal – Electromagnetic Calorimeter
Triggering, PID

TRD – Transition Radiation Detector
Triggering, PID

TOF – Time Of Flight detector
PID

Muon Spectrometer
Forward tracking and triggering of muons

Machine learning (ML) techniques for signal extraction

Use of Boosted Decision Trees (BDT)

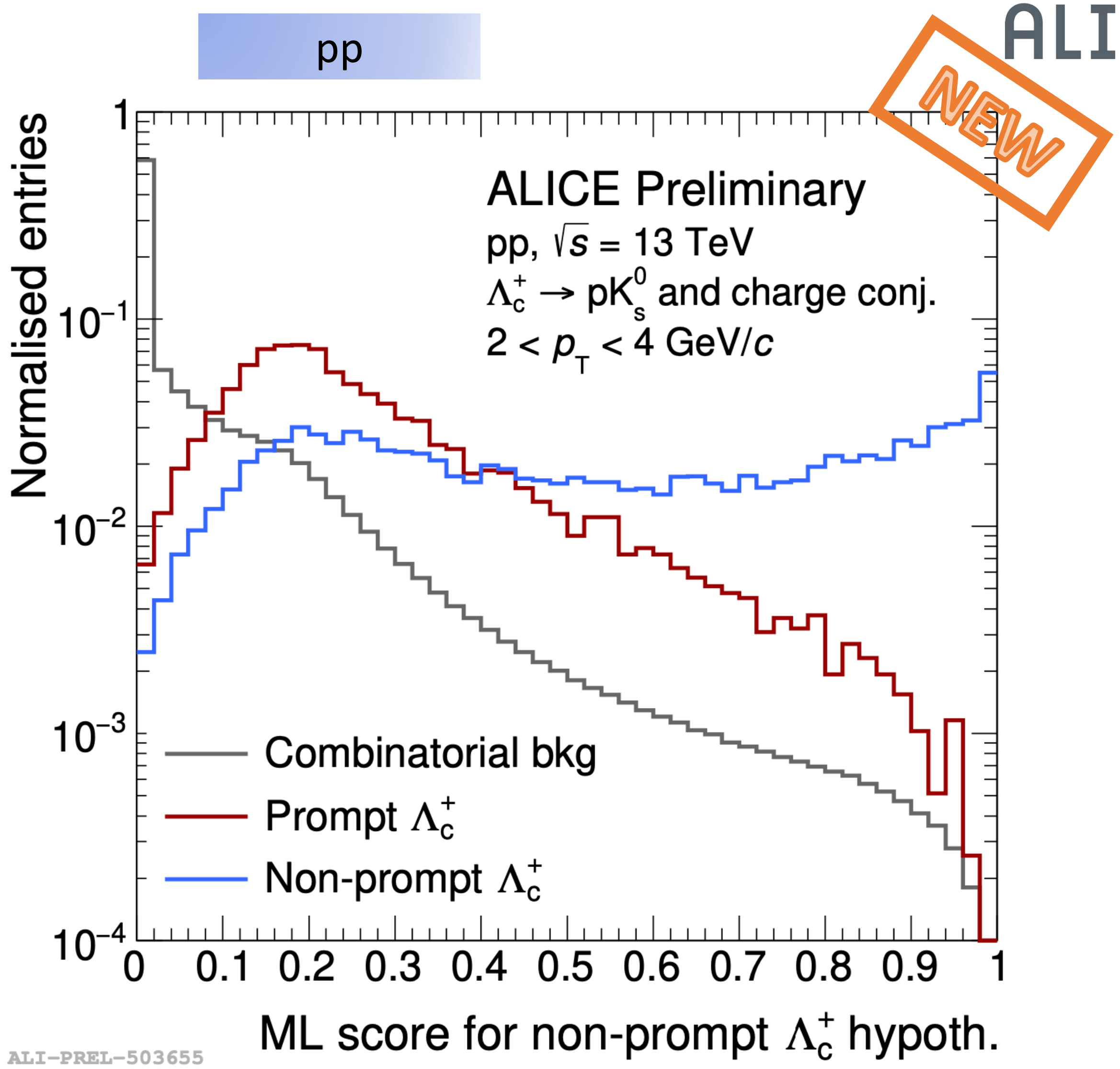
- Input: Set of variables
- Output: Score
- Can classify events according to the score

In practice

- Test which variables are the most discriminatory (avoiding correlations)
- Let the algorithm learn characteristics from set of events (MC, sidebands, etc.)
- Determine a threshold (Working Point) on score for event classification (tradeoff purity/biases/statistics)

Used to separate

- Signal from background
- Prompt from non-prompt

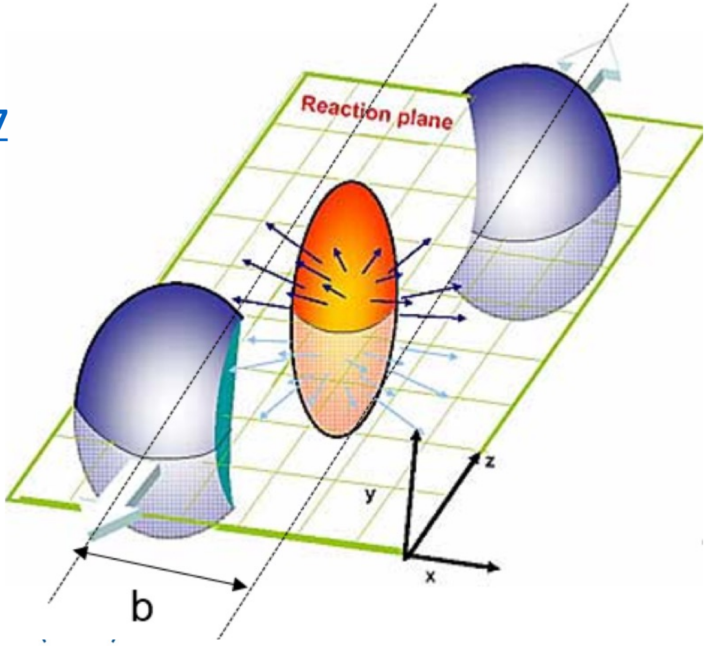


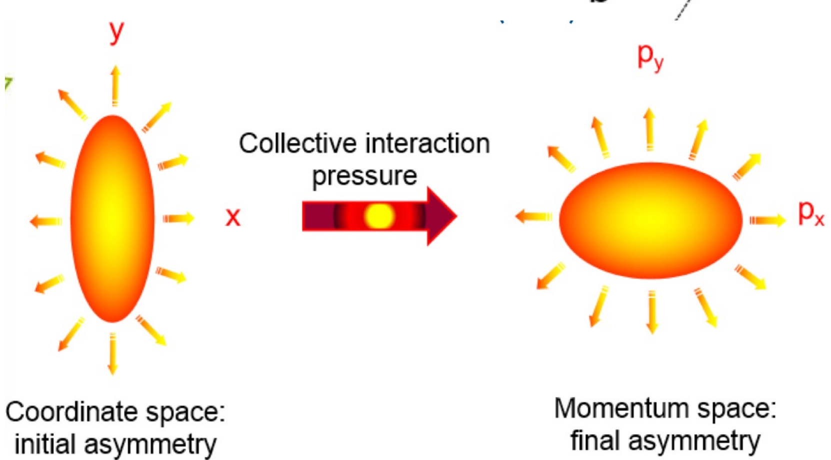
Elliptic flow: observable for collectivity

In Heavy-ion collisions, **anisotropic collision** region for b > 0

- **Anisotropies in momentum** distribution
- **Long-range correlations** of produced particles

Taken from Universe, 2017





Azimuthal correlations of particles quantified by Fourier coefficients in ϕ angle distribution (wrt event plane if large multiplicity), or 2-particle correlations (in smaller systems)

$$\frac{dN}{d\phi} = \left\langle \frac{dN}{d\phi} \right\rangle \left(1 + \sum 2v_n \cos[n(\phi - \Psi_n)] \right)$$

$$\frac{dN^{pairs}}{d\Delta\phi} \propto \left(1 + \sum_{n=1}^{\infty} 2v_n^2 \cos(n\Delta\phi)\right).$$

v_2 (elliptic) : sensitive to thermalization of the medium
v_3 (triangular) : sensitive to fluctuations of the initial state

Flow points to collective behaviours : signature of QGP

Constrains theoretical models