Quarkonium as a probe of multiple parton interaction and collectivity in pp collisions with ALICE

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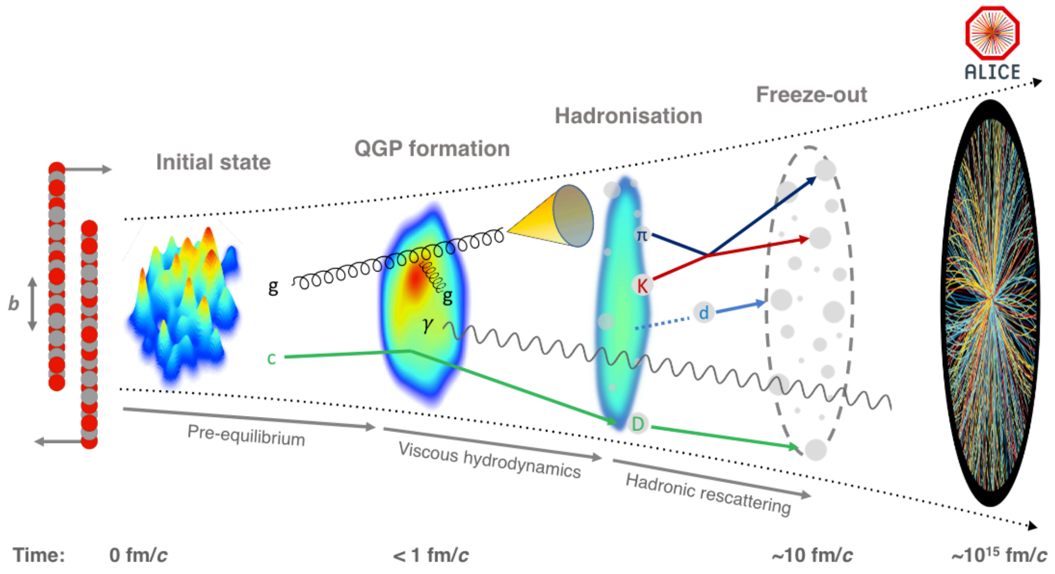
Why study quarkonium in pp collisions?

Quarkonia as a probe of the quark-gluon plasma: Heavy quarks are produced in hard-scattering processes in the early stages of the collision and experience the entire medium evolution



Quarkonium production

- Hard scale: creation of $q\bar{q}$ pairs in initial hard scattering
- Soft scale: binding into a colorless final state

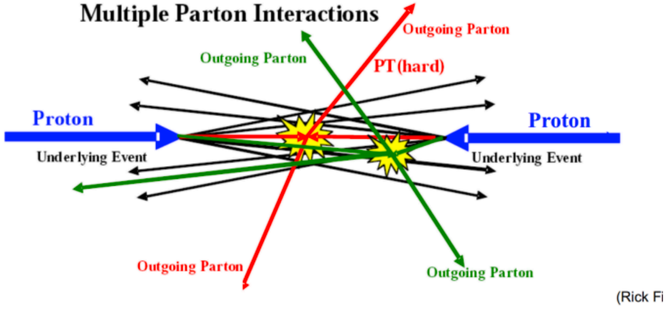
Models of quarkonium production: e.g. Color Evaporation Model (CEM), Non-relativistic QCD (NRQCD)

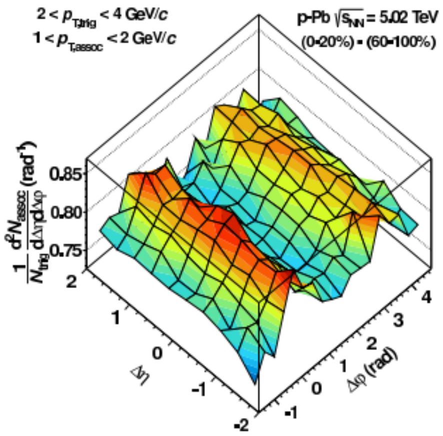
Why study pp collisions?

1) Understand production mechanism
2) Reference for heavy-ion collisions

Quarkonium production in small systems: open questions

- **Hints of collective behaviors** in small systems at high multiplicity
  - Near-side ridge
  - Anisotropic flow of light and heavy-flavor particles
- Opens up two questions
  - Are there collective effects on heavy quarks in high multiplicity pp collisions?
    ALICE result: J/ψ elliptic flow in small systems
  - Collective-like effects due to MPI or QGP droplets?
    ALICE result: J/ψ pair production in pp collisions
    (quarkonium measurements as a function of multiplicity)
  - Quarkonium production: interplay between soft and hard processes
    ALICE result: Inclusive $\psi(2S)$ to J/ψ ratio at midrapidity
    ALICE result: J/ψ fragmentation function in pp collisions
    (quarkonium production cross section and polarization)



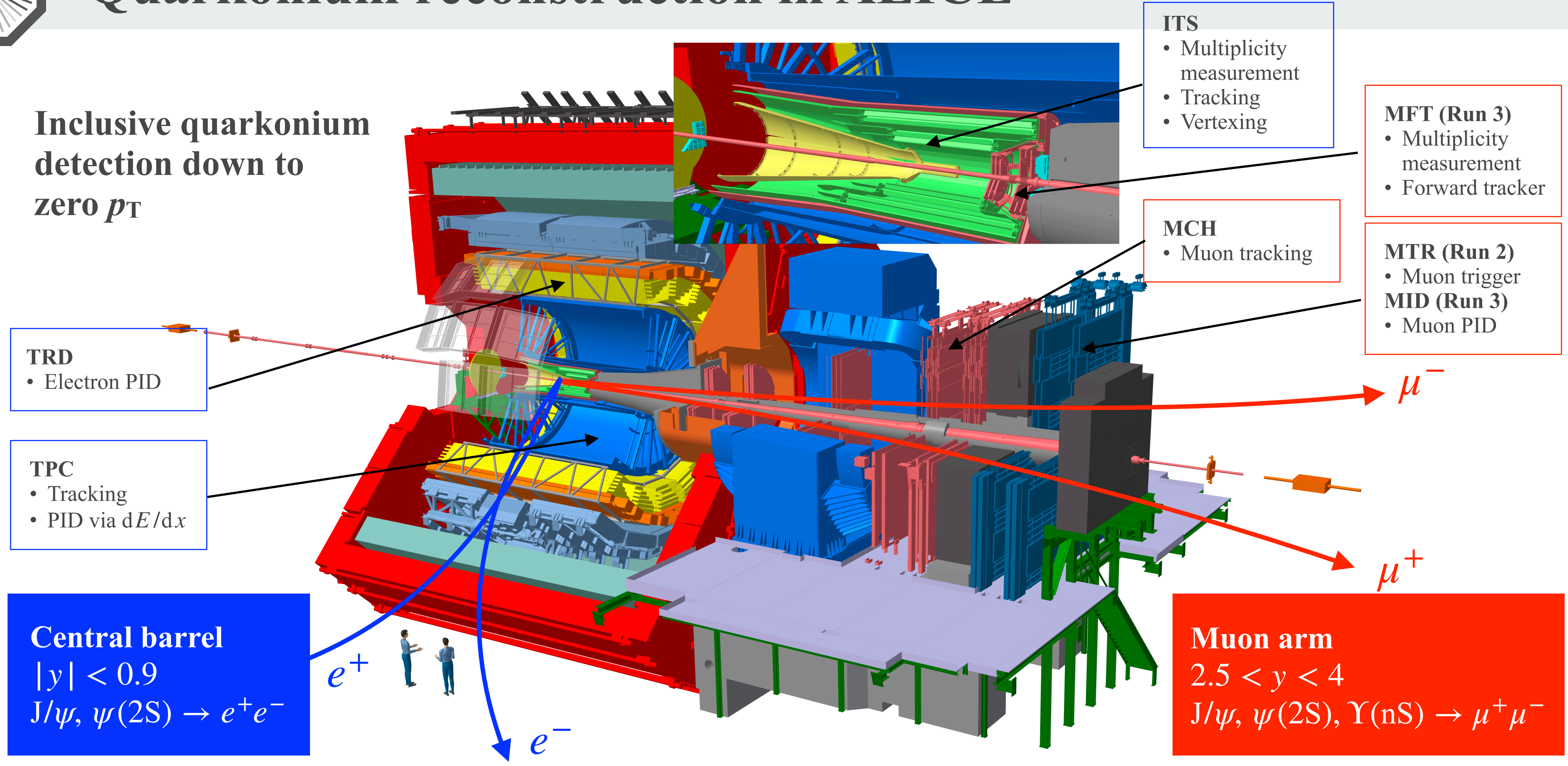


Phys. Lett. B 719 (2013) 29-41

For ALICE quarkonium measurements as a **function of multiplicity**, see Chi Zhang's talk, Monday Nov 20th

Quarkonium reconstruction in ALICE

Inclusive quarkonium detection down to zero p_T



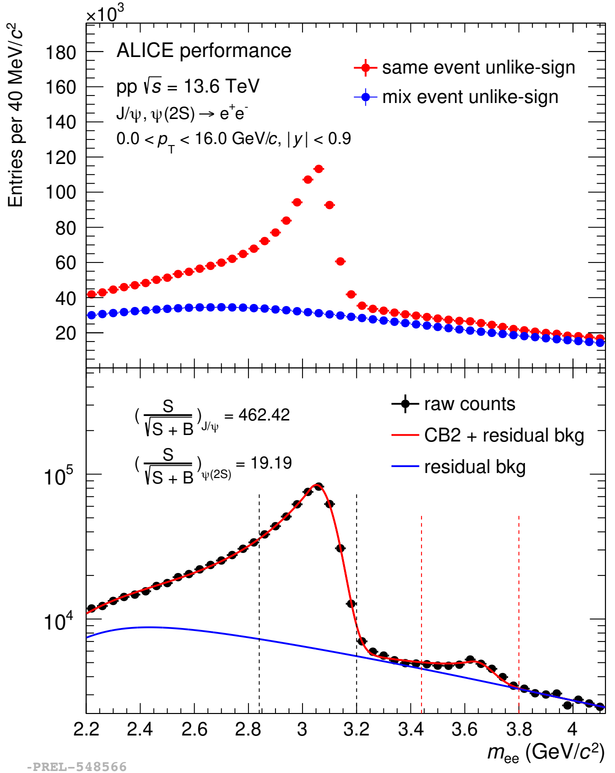
Central barrel
$|y| < 0.9$
J/ψ, $\psi(2S) \rightarrow e^+e^-$

Muon arm
$2.5 < y < 4$
J/ψ, $\psi(2S)$, $\Upsilon(nS) \rightarrow \mu^+\mu^-$

Run 3 upgrade

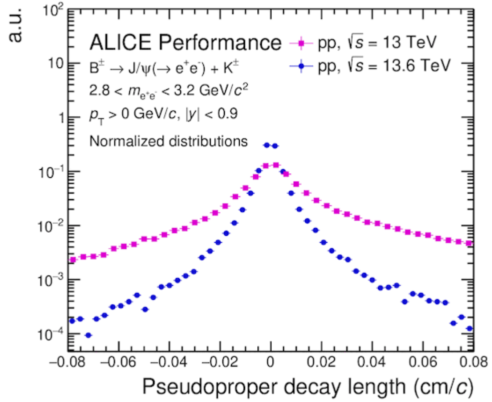
Central barrel (|y| < 0.9)	**TPC**	Replaced readout chambers
	ITS	Increased number of layers (6 to 7) with increased granularity (MAPS)
		Decreased material budget (1.15 % to 0.35 %)
Muon arm 2.5 < y < 4	**MFT**	New forward tracker (MAPS) upstream of the hadron absorber

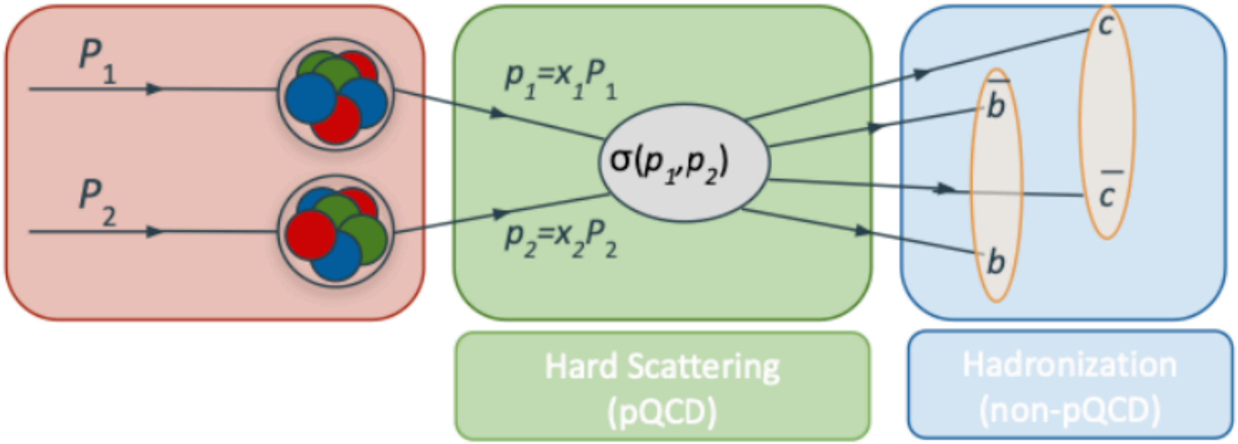
Number of J/ψ candidates at midrapidity in 2022 pp dataset is **already comparable to the full Run 2 statistics**.



Resulting in…

1. **Higher statistics**
   - Continuous readout of Pb—Pb events at an interaction rate up to 50 kHz, ~ 10^2 higher for MB events than Run 2
2. **Improved vertexing resolution in the barrel**
3. **Secondary vertexing capabilities in the muon arm**



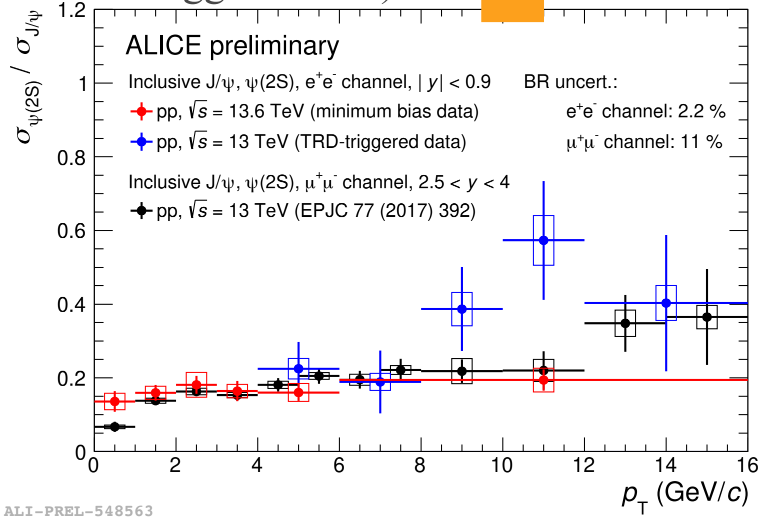


Small systems — a way to study production mechanisms

Inclusive $\psi(2S)$ at midrapidity in pp collisions at $\sqrt{s}$ = 13.6 TeV

Inclusive $\psi(2S)$ to J/ψ ratio at **midrapidity** from e^+e^- decay channel

- At $\sqrt{s}$ = 13.6 TeV (**Run 3**)
- **In agreement with Run 2 results** at forward rapidity and midrapidity (with TRD triggered data)



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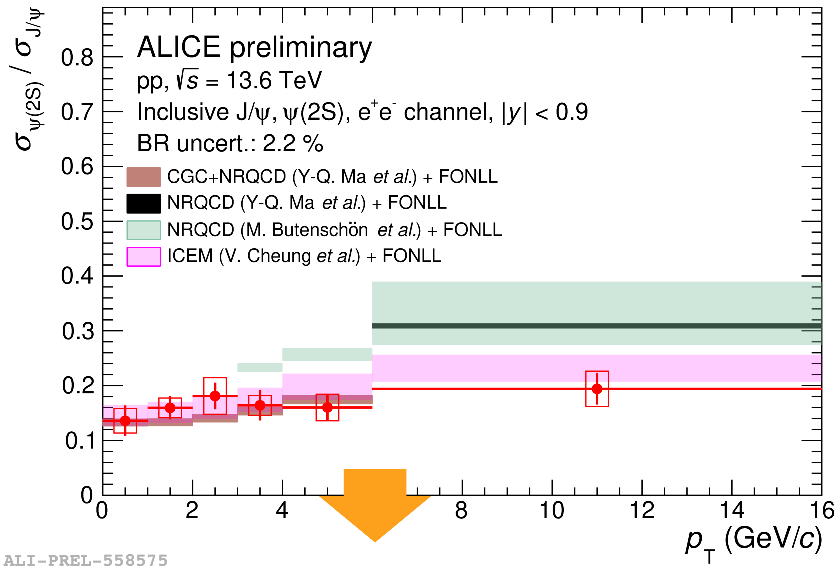

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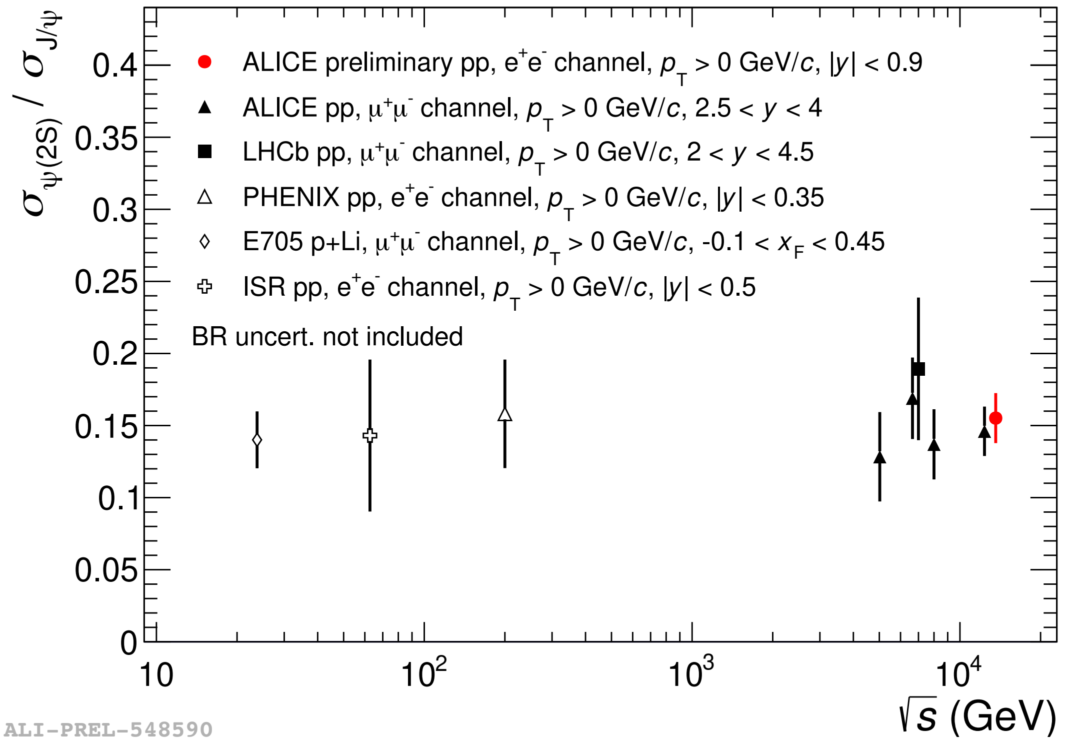
Y-Q. Ma *et al*, Phys.Rev.Lett 106 (2011) 042002
M. Butenschön *et al*, Phys.Rev.Lett 106 (2011) 022003
V. Cheung *et al*, Phys.Rev.D 94 (2016) 11, 114029

- Slight ***p*$_T$-dependence** expected from models
- No significant rapidity dependence
- **Good description** provided by **ICEM**

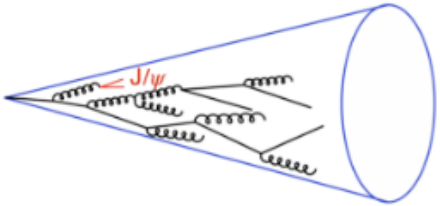
Inclusive $\psi(2S)$ to J/ψ ratio in pp collisions at $\sqrt{s}$ = 13.6 TeV

- In agreement with previous results
- No significant energy and rapidity dependence

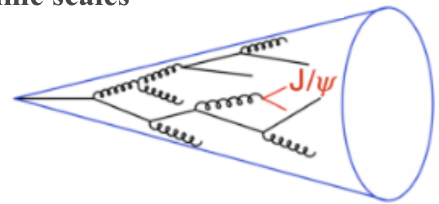


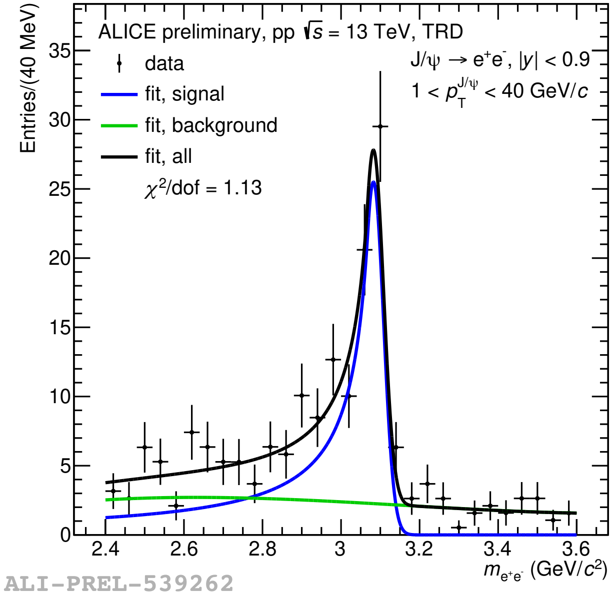
J/ψ fragmentation function in pp collisions

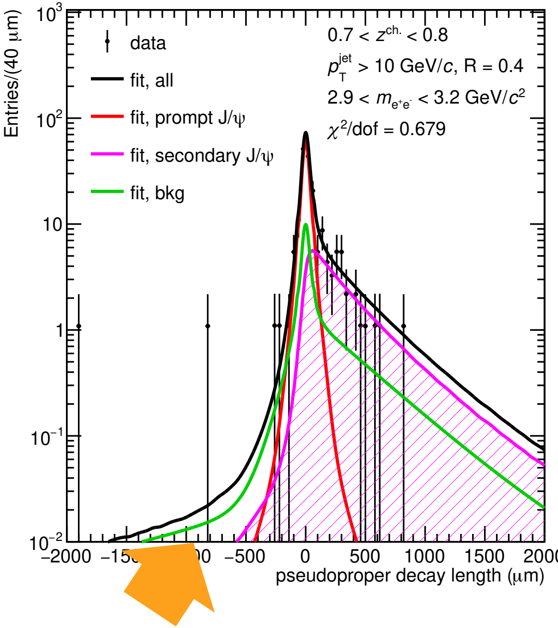
J/ψ production with **small** jet activity ($z^{\text{ch.}} \rightarrow 1$) may indicate **early formation**



J/ψ production with **large** jet activity ($z^{\text{ch.}} < 1$) may indicate production at **later time scales**







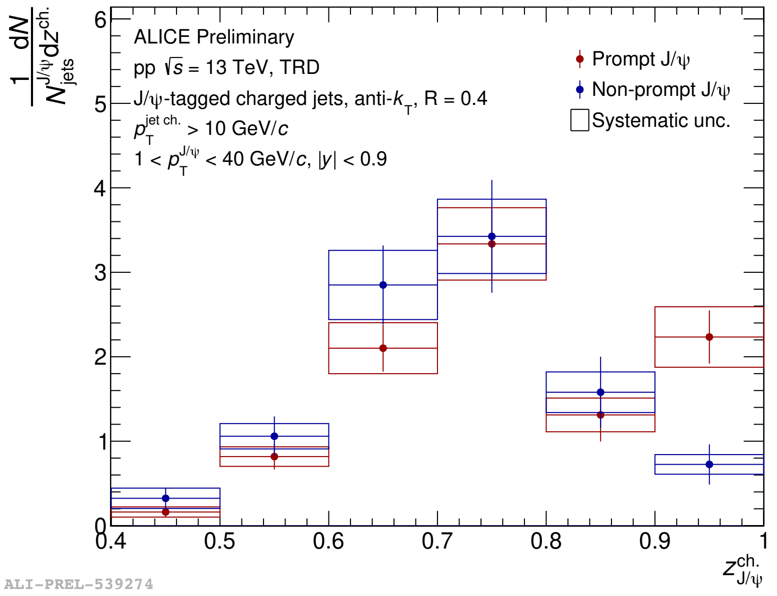
Separation of **prompt** charmonium and **non-prompt** charmonium from *b*-hadron decay based on pseudoproper decay length

$$z^{\text{ch.}} = \frac{p_{\text{T}}^{\text{J}/\psi}}{p_{\text{T}}^{\text{jet, ch.}}}$$

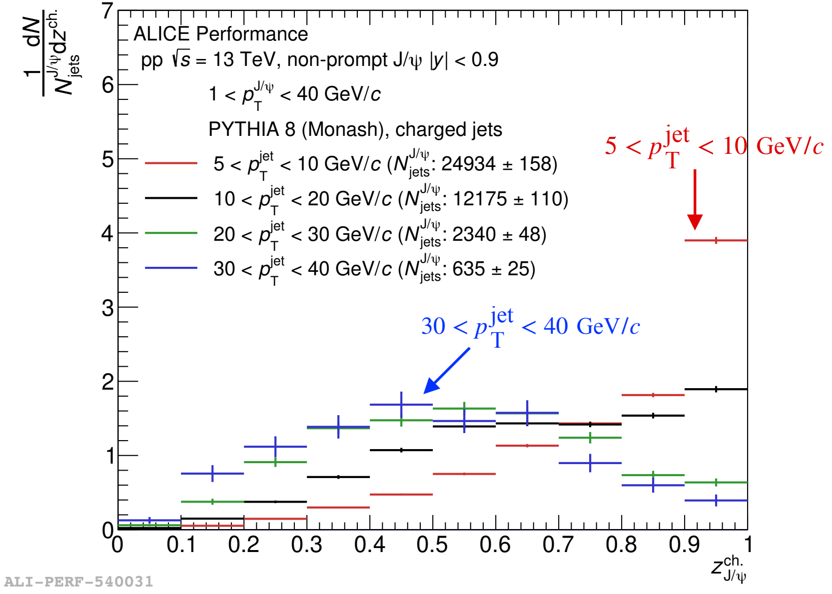
J/ψ fragmentation function in pp collisions

$$z^{ch.} = \frac{p_T^{J/\psi}}{p_T^{jet,\,ch.}}$$

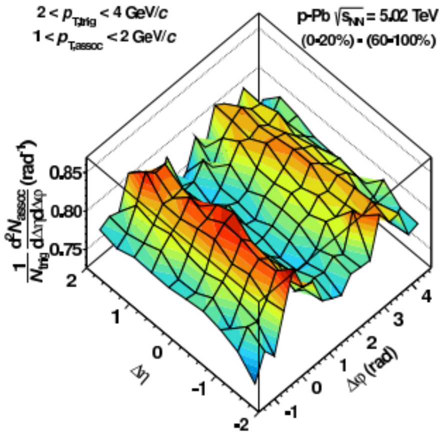
J/ψ fragmentation function



PYTHIA 8 studies



- Prompt and non-prompt J/ψ fragmentation function **similar within uncertainties**
- Comparison to models are needed: fragmentation function is **particularly sensitive** to the chosen jet p_T range



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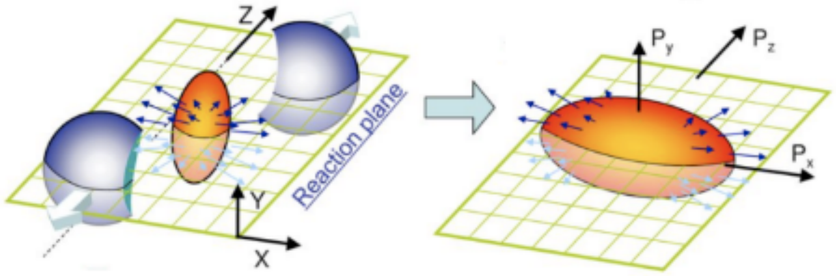
Small systems — a way to study MPI and collective effects

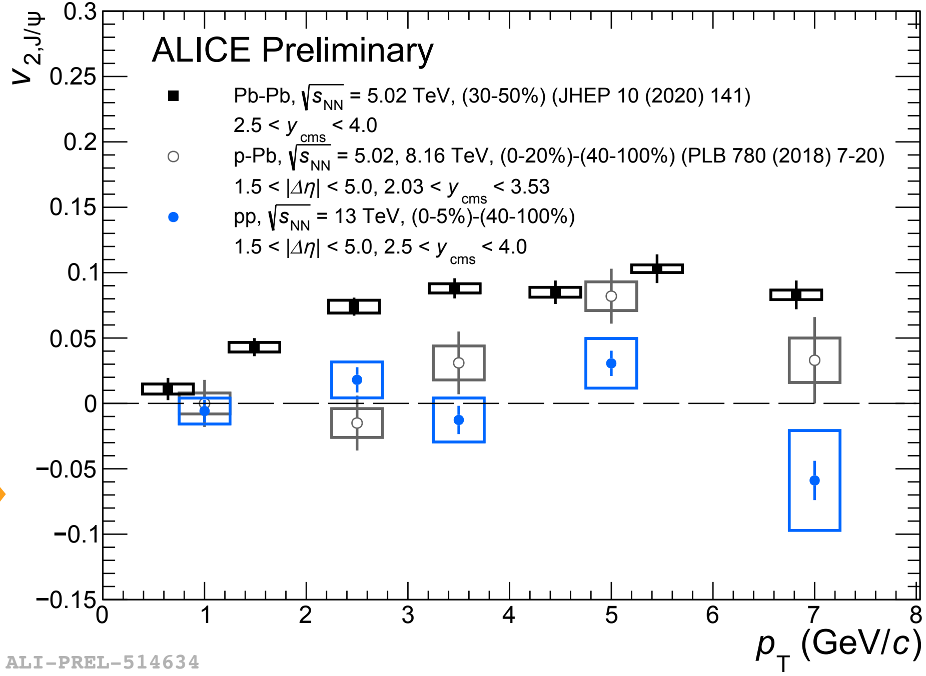
J/ψ elliptic flow in small systems

$$\frac{dN}{d\varphi_\alpha} \propto 1 + 2\sum_n [v_{n,\alpha} \cos n(\varphi_\alpha - \Psi_n)]$$



- Elliptic flow: a probe of collectivity
- J/ψ v_2 in **pp compatible with 0**, contrary to larger systems
  - p-Pb: $v_2 > 0$ for $p_T > 4$ GeV/c
  - Pb-Pb: $v_2 > 0$ for $p_T > 1$ GeV/c

J/ψ v_2 in high mult. pp, p-Pb and Pb-Pb

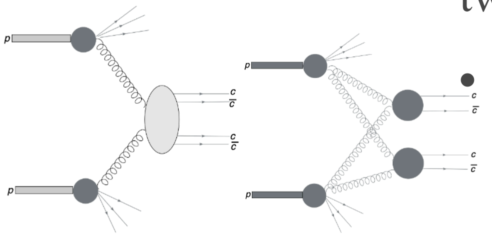


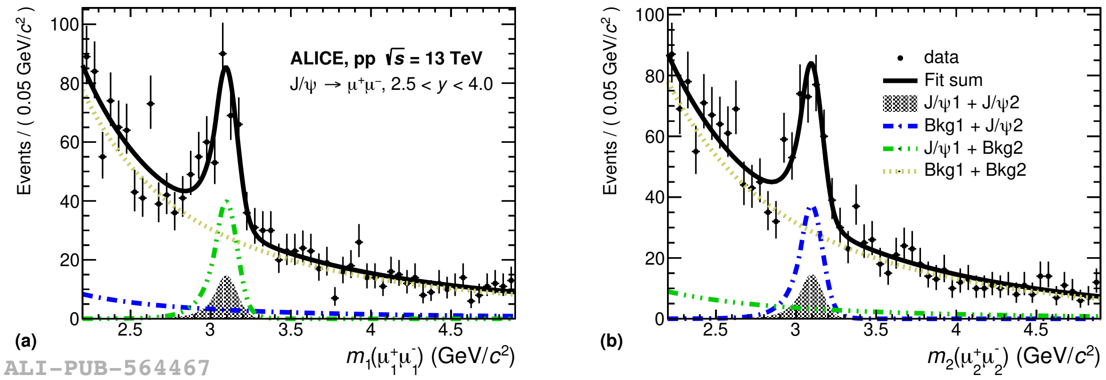
J/ψ pair production in pp collisions Phys. Rev. C 108 (2023) 045203

Double quarkonium as probe to…

- **J/ψ production mechanism** — pair production provides stringent tests of model calculations
- **DPS and partonic structure of proton**: transverse overlap function ~ σ_{eff}.

AIP Conf. Proc. 1523 (2013) 1





ALI-PUB-564467

Consistent with measured LHCb cross section, with two caveats

- Inclusive J/ψ measured in ALICE vs prompt J/ψ measured by LHCb
- Slightly different rapidity intervals

	Cross sections (nb)
ALICE	10.3 ± 2.3(stat.) ± 1.3(syst.)
LHCb	15.2 ± 1.0(stat.) ± 0.9(syst.)

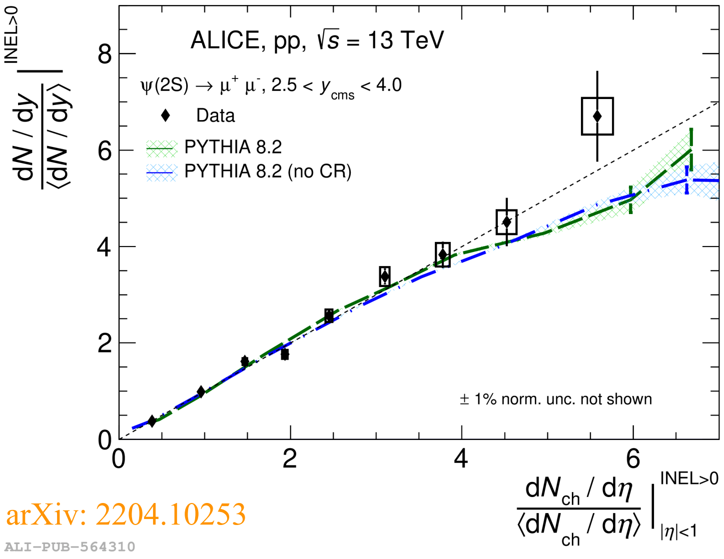
LHCb: JHEP 06 (2017) 047

Conclusions

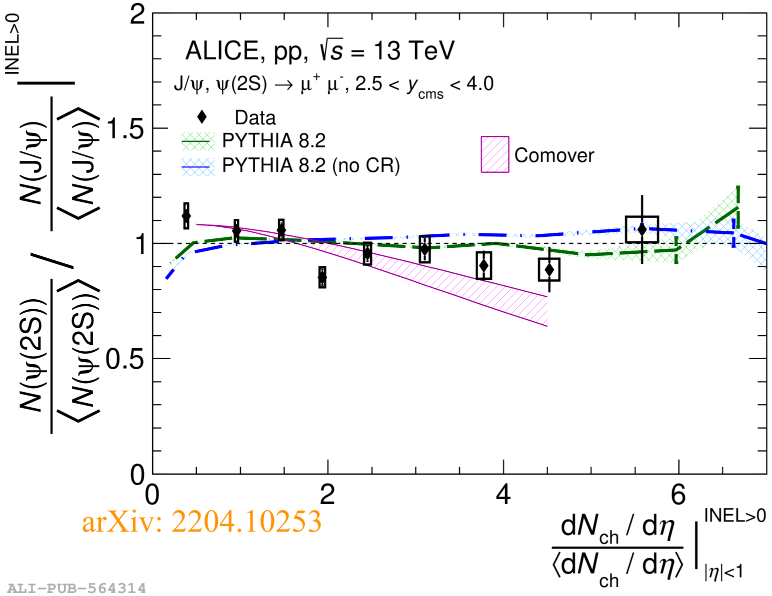
- **Small collision systems as a way to study production mechanism**
  - First ALICE measurement of $\psi(2S)$ at midrapidity: $\psi(2S)$ to J/ψ ratio in agreement with previous results
    → no rapidity dependence, slight p_{T} dependence
  - Similar J/ψ fragmentation functions for prompt and non-prompt J/ψ
- **Small collision systems as a way to study MPI and collectivity**
  - J/ψ v_2 in pp collisions does not show collective effects within uncertainties
  - J/ψ pair production provides important insight into MPI
    → results in agreement with LHCb

Backup slides

Inclusive $\psi(2S)$ to J/ψ ratio in pp collisions at $\sqrt{s}$ = 13 TeV



arXiv: 2204.10253

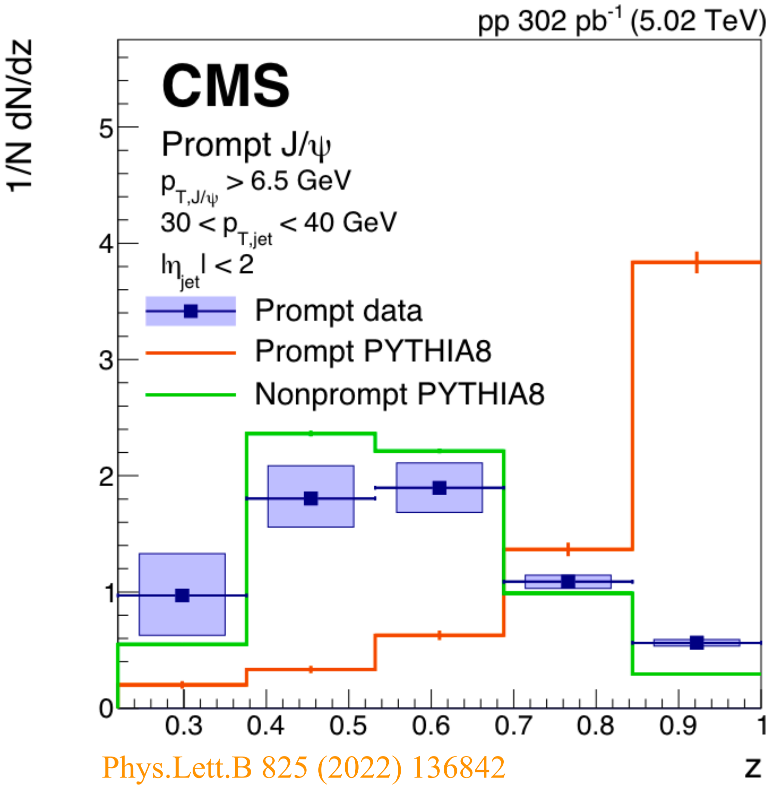


arXiv: 2204.10253

- Inclusive $\psi(2S)$ production at **forward rapidity** shows a **linear dependence** with midrapidity multiplicity
  - Well described by PYTHIA, with/without color reconnection, with some tension at high multiplicity
- $\psi(2S)$ **to J/ψ** double ratio **compatible with unity** → production at forward rapidity **independent of charmonium state**
  - Comover model in agreement with data within uncertainties, tension with PYTHIA at low multiplicity

J/ψ fragmentation function in pp collisions: CMS results

- Naive expectation:
  - Prompt J/ψ produced in singlet state (early formation) will have a higher $\langle z^{\text{ch.}} \rangle$
  - Prompt J/ψ produced in octet state will have a lower $\langle z^{\text{ch.}} \rangle$
  - Non-prompt J/ψ are produced from b hadrons → gluon emission → lower $\langle z^{\text{ch.}} \rangle$
- Possible interpretation of CMS results: prompt J/ψ are primarily produced in CO state / late formation time



Phys.Lett.B 825 (2022) 136842

Quarkonium production: models

- **NRQCD** Phys. Rev. Lett. 106 (2011) 042002
  - Combination of color-singlet and color-octet (CO) state
  - Color neutralization of the CO state is treated as a non-perturbative process.
- **ICEM** Phys.Rev.D 94 (2016) 11, 114029
  - Production cross section of a charmonium state is proportional to the $c\bar{c}$ cross section, integrated between the mass of the charmonium and twice the mass of the lightest D meson
  - invariant mass of the intermediate heavy quark-antiquark pair can be larger than the mass of produced quarkonium
- **PYTHIA 8.2. with Color Reconnection** JHEP08 (2015)003
  - Combination of *initial* and *final state effects*
  - Final state effect at play with MPI where strings are merged based on a QCD full color flow calculation with a loose modeling of dynamical effect via a global saturation
- **Comover model** PBL 731 (2014) 57, JHEP 10 (2018) 094
  - Quarkonia dissociated in final state by interactions with comoving particles