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

Also see:
- **NEW:** $D^{*+}$ polarization in pp at 13 TeV
- **NEW:** Non-prompt $\Lambda_c$ production in small systems
- **NEW:** Non-prompt and prompt $\Lambda_c/D^0$ 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

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
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**

*J/ψ pair production in pp at 13 TeV*

\[ pp, \sqrt{s} = 13 \text{ TeV} \]
Quarkonium studies – Production – forward rapidity

Quarkonium cross sections at forward rapidity in pp

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

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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**

$\rho_{00}$, 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)
Non-prompt $\Lambda_C$ study in pp and p-Pb

Production of non-prompt $\Lambda_C^+$ 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 $\Lambda_C^+$ also measured in p-Pb collisions:

$R_{pPb}$ compatible with unity and with prompt $\Lambda_C^+$ $R_{pPb}$ within the large uncertainties
Non-prompt and prompt $\Lambda_c/D^0$ 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 $\Lambda_c$ 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)**

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**Figure Description:**

- **Graph Title:** ALICE preliminary
- **Data Points:**
  - $\sqrt{s} = 13$ TeV, $|y| < 0.8$
  - $b \rightarrow c \rightarrow e$
  - $b,c \rightarrow e$
- **Legend:**
  - FONNL
- **Energy Values:**
  - $\sqrt{s} = 7$ TeV
  - $\sqrt{s} = 5.02$ TeV
  - $\sqrt{s} = 2.76$ TeV
- **Luminosity Uncertainty:**
  - ±3.8 % (not shown)
  - ±2.6 % (not shown)

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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 $\rightarrow$ 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)

\[ ALICE\ Preliminary \]

\[ V_2, J/\psi \]

**0.2**

**0.15**

**0.1**

**0.05**

**0.0**

**-0.05**

**-0.1**

**-0.15**

**0**

**2**

**4**

**6**

**8**

**10**

**12**

**p_T (GeV/c)**

**V0M (0-5%)-(40-100%)**

pp, $\sqrt{s_{\text{NN}}} = 13$ TeV

2.5 < $y_{\text{cms}}$ < 4.0

1.5 < |$\Delta \eta$| < 5.0

5.9% global syst. uncertainty

*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

**ALICE Preliminary**
- Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV, (30-50%) (JHEP 10 (2020) 141)
  - $2.5 < y_{\text{cms}} < 4.0$
- p-Pb, $\sqrt{s_{NN}} = 5.02, 8.16$ TeV, (0-20%)-(40-100%) (PLB 780 (2018) 7-20)
  - $1.5 < |\Delta \eta| < 5.0, 2.03 < y_{\text{cms}} < 3.53$
- pp, $\sqrt{s_{NN}} = 13$ TeV, (0-5%)-(40-100%)
  - $1.5 < |\Delta \eta| < 5.0, 2.5 < y_{\text{cms}} < 4.0$

**J/ψ **$v_2$ in pp compatible with 0

Appears lower than in larger systems especially from intermediate $p_T$ (above 3 GeV/c)
Study of $\psi(2S)$ production in pp and p-Pb

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

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

- Same behaviour regardless of charmonium state or system size

Multiplicty dependent charmonium production

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

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Normalized $\psi(2S)$ yield goes linearly with charged particle multiplicity, and $\psi(2S)$-to-$j/\psi$ 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

$J/\psi$ collective flow mechanism in p-Pb still to be understood, $J/\psi$ 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
**Large Ion Collider Experiment**

- **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

**Inclusive measurements**

- *e^+e^-, pK_S^0, ... decay channels (|y| < 0.9)*
  Distinction prompt (produced at primary vertex) / non-prompt (b-hadron decays)

- *μ^+μ^- decay channels (2.5 < y < 4.0)*
  Inclusive measurements

**Central barrel**

- **ITS** – Inner Tracking System
- **V0**
- **EmCal**
- **TRD**
- **TPC**

**Forward tracking and triggering of muons**

- **Muon Spectrometer**
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

ALICE Preliminary
pp, \( \sqrt{s} = 13 \text{ TeV} \)
\( \Lambda_c^+ \rightarrow pK_s^0 \) and charge conj.
\( 2 < p_T < 4 \text{ GeV/c} \)
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

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

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

\[
\frac{dN^{\text{pairs}}}{d\Delta\phi} \propto (1 + \sum_{n=1}^{\infty} 2v_n^2 \cos(n\Delta\phi)).
\]

- \( v_2 \) (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

Taken from Universe, 2017