Quarkonia and open heavy-flavours in high-multiplicity proton-proton collisions with ALICE

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Heavy-flavour production vs multiplicity

- Heavy-flavour (HF) quarks (charm and beauty) are produced in hard scattering processes
  - Multiplicity dependent production measurements allow to study interplay between soft and hard particle production mechanisms
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  1. Initial hard scattering process: relevant for HF quarks production
  2. Underlying event (UE):
     - semi-hard MPI interactions → still relevant for hard processes at LHC energies!
     - soft hadronic processes → important for “bulk” particle production (including multiplicity)

  shed light on MPI → additional selections (e.g. event shape) and new “observables” (e.g. HF-hadron correlations) provide relevant constraints to MPI-based models
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- **Intriguing observation**: multiplicity-dependent studies in small colliding systems show remarkable similarities with AA collisions (e.g. strong hints for collectivity, strangeness enhancement,...)

  phenomena considered signatures of deconfinement in heavy-ions observed in high-multiplicity pp!
The ALICE detector

Multiplicity dependent heavy-flavour analyses in pp collisions ($\sqrt{s} = 5, 7, 8, 13$ TeV):

- $D^0 \rightarrow K\pi^+$
- $D^+ \rightarrow K\pi^+\pi^+$
- $D^{*+} \rightarrow D^0\pi^+$
- $J/\psi \rightarrow e^+e^-$
- $B \rightarrow J/\psi \rightarrow e^+e^-$
- $c, b \rightarrow e^+X$

$D^0$ vs spherocity

$J/\psi-h$ correlations

HF-cross sections from dielectron continuum
The ALICE detector

- EMCAL: triggering, electron ID
- TOF: PID
- TRD: Tracking; Electron ID
- TPC: Tracking; PID via dE/dx
- Muon spectrometer: -4<|η|<2.5
- ITS: vertexing, tracking, triggering (SPD)
- MUON ARM: triggering, tracking, muon PID

✓ Multiplicity dependent heavy-flavour analyses in pp collisions (√s = 5, 7, 8, 13 TeV):

\[
\begin{align*}
D^0 & \rightarrow K^{-}\pi^{+} \\
D^+ & \rightarrow K^{-}\pi^{0}\pi^{+} \\
D^{*+} & \rightarrow D^{0}\pi^{+} \\
J/\psi & \rightarrow e^{+}e^{-} \\
B & \rightarrow J/\psi e^{+}e^{-} \\
c, b & \rightarrow e+X \\
\end{align*}
\]

\[
D^0 \text{ vs spherocity} \\
J/\psi - h \text{ correlations} \\
HF-\text{cross sections from dielectron continuum}
\]

\[
J/\psi \rightarrow \mu^{+}\mu^{-} \\
c, b \rightarrow \mu+X
\]

LHCp 2018
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Multiplicity selection

✓ Multiplicity estimators used to define event classes:

✓ **Mid-y**: number of reconstructed tracklets in the two innermost layers of the ITS ($|\eta| < 1$), consisting of Silicon Pixel Detectors (SPD)

✓ **Forward-y**: percentiles of the V0M amplitude distribution measured in the V0A+V0C detectors (arrays of scintillators placed on each side of the interaction region, covering the pseudo-rapidity regions $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$)

✓ used for triggering high-multiplicity events in Run II
HF-hadron production vs multiplicity
- summary of Run I results
- latest results from Run II
Inclusive J/ψ yields vs multiplicity


- Approximately linear increase of J/ψ yield ($p_T > 0$ GeV/c) with charged-particle density
- Multiplicity dependent measurements of J/ψ extended up to 4 times the minimum-bias multiplicity
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Multiplicity dependent measurements of J/ψ extended up to 4 times the minimum-bias multiplicity

Relative yields versus multiplicity not reproduced by PYTHIA 6.4 simulations (J/ψ produced only in the main hard scattering)
Similar trend for prompt J/ψ and open charm → suggests that it is mainly related to the cc production processes and it's not significantly affected by hadronization.

Similar trend for open charm and beauty, but larger statistical uncertainties for the latter → significant improvement expected using Run II data!
HF decay muons reconstructed at forward rapidity show faster than linear increase vs multiplicity.

Steepness more pronounced at high $p_T$ (not possible to conclude due to large uncertainties).

Future D meson measurements may clarify whether D mesons at mid-rapidity have a stronger increase than HF decay muons in $2.5 < y < 4$.

Possible "auto-correlation" effects due to the overlapping between pseudo-rapidity regions of HF measurements and multiplicity estimator.
HF decay electron production vs multiplicity

- Faster than linear trend observed also for HF decay electrons
- Different trend, especially at low multiplicity, compared to HF decay muons → possible "auto-correlation" effects?
- Faster increase observed at high $p_T$
- Fair agreement with PYTHIA 8.2 (Monash2013 tune)
Inclusive $J/\psi$ yields vs multiplicity in pp at $\sqrt{s} = 13$ TeV

- Significantly higher multiplicities exploited thanks to high-multiplicity triggered data!
- Very similar trend observed for open and hidden HF measurements → confirmation of Run I results

(Chart showing inclusive $J/\psi$ yields vs multiplicity with markers indicating data points and error bars)

ALICE Preliminary

$pp$, $\sqrt{s} = 13$ TeV, $|\eta_{ch}| < 1$

- $c,b \rightarrow e (0.5 < p_T < 4.5 \text{ GeV/c}, |y| < 0.8)$
- Inclusive $J/\psi \rightarrow e^+e^-$ ($|y| < 0.9$)

$\pm 5\%$ uncertainty on multiplicity not shown
Inclusive $J/\psi$ yields vs multiplicity in pp at $\sqrt{s} = 13$ TeV

- **Run I mult. reach for $J/\psi$**
  - Significantly higher multiplicities exploited thanks to high-multiplicity triggered data!
  - Very similar trend observed for open and hidden HF measurements → confirmation of Run I results

- **PYTHIA8 (Monash 2013)**
  - Initial hard processes
  - Hard processes in MPI
  - ISR / FSR

- **EPOS3**
  - Gribov-Regge formalism (MPI included)
  - Hydro evolution of the system

- **Kopeliovich et al.**
  - Contributions of higher Fock states

- **Percolation model**
  - Soft sources stronger affected than hard sources with increasing density (multiplicity)

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**F. Fionda**

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**REFERENCES**

Ferreiro, Pajares, PRC86 (2012) 034903  
Kopeliovich et al., PRD88 (2013) 116002
Faster than linear increase observed also in $p_T$ bins

Slope increases with the transverse momentum of J/$\psi$

EMCAL analysis significantly extends the $p_T$ range (up to 30 GeV/c)
Inclusive J/$\psi$ yields vs multiplicity in pp at $\sqrt{s} = 13$ TeV

- **EMCAL** analysis significantly extends the $p_T$ range (up to 30 GeV/$c$)
- **PYTHIA8** calculations qualitatively describe the $p_T$ dependent trends seen in data
- Faster than linear increase observed also in $p_T$ bins
- Slope increases with the transverse momentum of J/$\psi$
High-$p_T$ inclusive charged particles

- Faster than linear increase observed for charged hadrons at high $p_T$
- Similar trend for all hard processes!
- All Monte Carlo models reproduce quite well the results for $p_T > 4$ GeV/c

What about other hard processes?
- Stronger increase with increasing $p_T$
- Qualitatively reproduced by PYTHIA models
Outlook: Multiplicity dependent HF-analyses based on “new” observables
Clear near side peak observed by correlating high-$p_T$ J/$\psi$ ($p_T > 5$ GeV/c) and hadrons with $p_T > 1$ GeV/c

Qualitative good agreement observed with PYTHIA8 simulations

Usage of full Run II statistics (gain of a factor $\sim 100$ expected for $p_T$ (J/$\psi$) > 5 GeV/c) will improve significantly uncertainties allowing finer kinematic scan $\rightarrow$ powerful tool to constraint models!
**D⁰ production vs spherocity**

\[
S₀ \equiv \frac{\pi^2}{4} \min \left( \frac{\sum_i \left| \vec{p}_{T,i} \times \hat{n}_s \right|}{\sum_i \vec{p}_{T,i}} \right)^2
\]

\[p_T \geq 0.15 \text{ GeV/c}, \ |\eta| < 0.8\]

\(n_s\) defined in order to minimize the ratio above (axis of the main scattering)

\[S₀ = \begin{cases} 
0 & \rightarrow \text{“jet-like” events} \\
1 & \rightarrow \text{“isotropic” events}
\end{cases}\]

- **Low multiplicity**
  - Significant improvement expected using Run II statistics
  - More differential studies (both in \(S₀\) and multiplicity) will provide additional constraints for further tuning and/or new model ingredients!

- **High multiplicity**

![Graphs showing D⁰ production vs spherocity](image-url)
Conclusions / Outlook

- Highlights of HF-hadron production measured by ALICE as a function of multiplicity in pp collisions at several $\sqrt{s}$ have been presented:
  - Steep dependence of open and hidden heavy-flavour yields vs multiplicity; similar trend observed for high-$p_T$ light flavour hadrons
  - Steepness increases with the $p_T$ of the particles
  - Models including HF-production in MPI describe qualitatively the observed trends

- Exploit full available statistics of minimum-bias and high-multiplicity triggered events of Run II datasets:
  - usage of finer $p_T / \text{multiplicity}$ bins, significant improvement for statistics-hungry analyses (e.g. non-prompt $J/\psi$)
  - more differential measurements based on new “observables” (e.g. event shape selection using “spherocity”, $J/\psi$-hadron correlations, etc.) will give further insight into HF-production mechanisms
  - more quantitative studies of possible auto-correlation bias effects comparing results based on multiplicity estimators defined in different pseudo-rapidity regions
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Thank you for your attention!
BACK-UP
Intermediate mass region of dielectron pairs ($1.03 < m_{ee} < 2.86$ GeV/c$^2$) dominated by open HF decays

Simultaneous fits of $m_{ee}$ and $p_{T,ee}$, using PYTHIA and POWHEG templates to extract HF cross sections

Different kinematic correlations of heavy-quark pairs in the two generators imply different acceptance for $e^+e^-$ (from HF)

Additional constraints provided for tuning of Monte Carlo in order to reduce model dependence
HF decay muons reconstructed at forward rapidity show faster than linear increase vs multiplicity

Steepness more pronounced at high $p_T$ (not possible to conclude due to large uncertainties)

EPOS calculations underestimate HF decay muon production at high-multiplicity