Study of charm fragmentation with charm meson and baryon angular correlation measurements with ALICE

Samuele Cattaruzzi*
on behalf of the ALICE Collaboration

*University of Trieste and INFN, Trieste (Italy)
Heavy-flavour hadron production

**Charm quark** mass \( \sim 1.5 \text{ GeV/}c^2 \)
→ produced in **hard parton-parton scattering** processes in hadronic collisions

- pQCD test
- Hadronisation
- Reference for Pb-Pb

Heavy-flavour hadron production cross section calculated by **factorisation approach**:

\[
\frac{d\sigma^H_c}{dp_T}(p_T; \mu_F, \mu_R) = \text{PDF}(x_1, \mu_F) \otimes \text{PDF}(x_2, \mu_F) \otimes \frac{d\sigma^c}{dp_T}(p_T; \mu_F, \mu_R) \otimes D_{c \rightarrow H_c}(z = p_{H_c}/p_c, \mu_F)
\]

- **Parton Distribution Functions**
- **Hard scattering cross section (pQCD)**
- **Fragmentation functions (hadronisation)**

Assumed **universal** across collision systems (ee,..., AA)
Charm baryon-to-meson enhancement in pp collisions

\textbf{p}_T\text{-dependent} enhancement of \( \Lambda_c^+ / D^0 \) ratio in pp w.r.t. \( e^+e^- \)

- **PYTHIA 8 Monash** \((EPJC (2014) 3024)\), with FF tuned on \( e^+e^- \) significantly underestimates the data

- Different hadronisation mechanisms proposed
  - **PYTHIA 8 CR-BLC** \((JHEP 1508 (2015) 003)\)
  - **SHM + RQM** \((PLB 795 (2019) 117-121)\)
  - **POWLANG** \((arXiv:2306.02152)\)

Need to better understand HF hadronisation process

- Baryon-to-meson measurement focuses solely on the charm hadron production

- Further studies can shed light on charm-quark hadronisation by considering also the other particles produced in association to the charm hadron

**LEP average**: \((0.113 \pm 0.013 \pm 0.006)\) \((EPJC 75 (2015) 19)\)

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**ALICE**

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Further characterisation of HF fragmentation

- Additional information from the study of:
  - Azimuthal correlations of HF hadrons with charged particles
    - multi-differential investigation of fragmentation processes
    - characterisation of jet shape and its particle composition
Further characterisation of HF fragmentation

- Additional information from the study of:
  - **Azimuthal correlations** of HF hadrons with charged particles
    - multi-differential investigation of fragmentation processes
    - characterisation of jet shape and its particle composition
  - At **LO** approximation
    - **Near Side (NS)**: fragmentation of the tagged charm quark
    - **Away Side (AS)**: fragmentation of the recoil charm quark
    - **Baseline**: parametrizes the underlying event activity, assumed to be isotropic
  - **NLO** production mechanisms, relevant at the LHC energies, can alter this topology
Further characterisation of HF fragmentation

- Additional information from the study of:
  - Azimuthal correlations of HF hadrons with charged particles
    - multi-differential investigation of fragmentation processes
    - characterisation of jet shape and its particle composition
  - HF tagged jets
    - access to the original parton kinematics
    - constrain the HQ fragmentation function

Longitudinal momentum fraction

\[
\tilde{z}_{||} = \frac{\vec{p}_{\text{ch, jet}} \cdot \vec{p}_{\text{HF}}}{\vec{p}_{\text{ch, jet}} \cdot \vec{p}_{\text{ch, jet}}}
\]
**Near-Side**: description of charm-jet constituents, their momentum and angular displacement w.r.t. the D meson trigger

- **With increasing** $p_T^D$:
  - More energetic charm quarks
    - More phase space to produce other fragments $\rightarrow$ increasing yields
  - Larger heavy quark boost
    - More collimated shower $\rightarrow$ Sharpening of the peak
- No centre-of-mass energy dependence
D-h comparison to model predictions

- Validation of parton-shower models and Monte Carlo generators
  
  ![Graph showing comparison between different models](image)

  - **NS yield:**
    - Larger values at high-$p_T^D$ by **POWHEG+PYTHIA 8 NLO** than **PYTHIA 8**
    - About 10% larger yields for **POWHEG+PYTHIA 8 NLO** w.r.t. **POWHEG+PYTHIA 8 LO**
    - **HERWIG** tends to underestimate the data at low $p_T^D$ and at high $p_{\text{assoc}}$
    - **EPOS** overestimates the results over the whole $p_T$ range

- **PYTHIA 8** and **POWHEG+PYTHIA 8 LO** provide the best description of the measurement
Comparison of the Δφ shape between the $D_s^+$-h (pp @ 13.6 TeV) and non-strange D-h (pp @ 13 TeV) correlation measurements.
Comparison of the $\Delta \phi$ shape between the $D_s^*\text{-}h$ ($pp \text{ at } 13.6 \text{ TeV}$) and non-strange $D\text{-}h$ ($pp \text{ at } 13 \text{ TeV}$) correlation measurements:

- **Away Side (AS): good agreement** over the whole $p_T$ range
Comparison of the $\Delta \phi$ shape between the $D_s^+ - h$ (pp @ 13.6 TeV) and non-strange D-h (pp @ 13 TeV) correlation measurements:

- **Away Side (AS):** good agreement over the whole $p_T$ range
- **Near Side (NS):** significant deviation for low-$p_T$($D$) from non-strange D meson measurement
**NEW!**

**D_{s}^{+}-h correlation comparison with models**

- PYTHIA 8 CR-BLC Mode 0, Mode 2, Mode 3 and Monash provide a reasonably good description of the measured shape of the distribution for $p_{T}(D_{s}^{+}) > 5\, \text{GeV}/c$

- Anyway, significant deviation of the near-side shape from model predictions, in particular for low-$p_{T}(D_{s}^{+})$
**D_{s}^{+} tagged jets**

- Alternative way of probing charm fragmentation into D_{s}^{+}

\[ \frac{z_{ch}}{p_{ch, jet} \cdot \vec{p}_{HF}} \]

**Longitudinal momentum fraction**
**D$_s^*$ tagged jets**

- Alternative way of probing charm fragmentation into D$_s^*$

D$_s^*$-tagged jets vs D$^0$-tagged jets $z_{||}^{ch}$ measurement

$$z_{||} = \frac{\vec{p}_{ch, \ jet} \cdot \vec{p}_{HF}}{\vec{p}_{ch, \ jet} \cdot \vec{p}_{ch, \ jet}}$$

Hint of **harder fragmentation** of charm into D$_s^*$ than D$^0$ in the studied $p_T$ (ch-jet, D$_s^*$) range

Could be a possible explanation of the NS observed difference in the D$_s^*$-h correlation
Λ_c^+-h vs D-h correlation distribution

- Address charm fragmentation to baryons

- From the comparison of the Δφ shape:
  - Good agreement between the Δφ distributions for \( p_T(D, Λ_c^+) > 5 \text{ GeV/c} \)
  - Tendency for an enhancement of both Λ_c^+-h correlation peaks at low-\( p_T(D, Λ_c^+) \) from D-h measurement
Characterisation of $\Lambda_c^+$-h correlation

Possible motivations of the observed difference:

a) Different energy of the charm quark as a consequence of a softer $\Lambda_c^+$ fragmentation

b) Decay of higher mass charm states (SHM+RQM)

c) Hadronisation by coalescence (to be tested with predictions from dedicated models)
Access the charm quark properties if it hadronises to a baryon

\[ \Lambda_c^+ \text{ tagged jets} \]

Longitudinal momentum fraction

\[ z_{||} = \frac{\vec{p}_{\text{ch, jet}} \cdot \vec{p}_{\text{HF}}}{\vec{p}_{\text{ch, jet}} \cdot \vec{p}_{\text{ch, jet}}} \]

Hint of **softer fragmentation** of charm into \( \Lambda_c^+ \) than \( D^0 \) in the studied \( p_T \) (ch-jet, \( \Lambda_c^+ \)) range

In agreement with \( \Lambda_c^+ \)-h results for \( 3 < p_T(\Lambda_c^+) < 5 \) GeV/c

- **PYTHIA 8 CR-BLC Mode 2** in better agreement with data than the **PYTHIA 8 Monash** tune
ALICE has carried out a detailed study of the charm-quark fragmentation through charm meson and baryon angular correlations and charm meson and baryon tagged jet measurements.

**Non-strange D mesons** with jets and correlations:
- $p_T$-differential description of the charm-jet properties
- Fragmentation as in PYTHIA 8 reproduces within uncertainties the measurements

**First $D_s^+ \rightarrow h$ correlation** measurement accessible with pp data at $\sqrt{s}=13.6$ TeV:
- Indications of harder fragmentation from both $D_s^+ \rightarrow h$ and $D_s^+ \rightarrow$-jet
- Observed discrepancy between data and MC generator predictions (PYTHIA 8 CR-BLC)

**Charm-to-baryon fragmentation** accessible with pp data at $\sqrt{s}=13$ TeV:
- Indications of softer fragmentation from both $\Lambda_c^+ \rightarrow h$ and $\Lambda_c^+ \rightarrow$-jet
Summary and outlook

- **ALICE** has carried out a detailed study of the **charm-quark fragmentation** through charm meson and baryon angular correlations and charm meson and baryon tagged jet measurements.

**Further results expected shortly on new Run 3 data samples**

- Measurement of $\Lambda_c^{*-}h$ correlations with **more precision, higher granularity** and **extended $p_T$ reach**

- Address **new observables** (e.g. 2D angular correlations, access to beauty sector via non-prompt D)

Thanks for your attention!
BACKUP SLIDES
**Away-Side**: description of the recoil jet, not necessarily developed by a charm quark

- Similarly as for the NS, with increasing $p_T^{D}$:
  - More energetic parton:
    - Increasing yields
    - Sharpening of the peak
**Λ_c^+ - h correlation comparison with models**

- **Yields:**
  - tensions with PYTHIA8 predictions
  - low-\(p_T(Λ_c^+)\) not correctly reproduced

- **Widths:**
  - generally overestimated, though with large uncertainties

PYTHIA 8 CR-BLC modes, despite predicting the \(Λ_c^+/D^0\) \(p_T\)-dependence, do not describe the differences in the charm-jet...