Heavy-flavour measurements with the ALICE experiment at the LHC

Róbert Vértesi
Wigner Research Centre for Physics
Centre of Excellence of the Hungarian Academy of Sciences
Budapest

vertesi.robert@wigner.mta.hu

This work has been supported by the Hungarian NKFIH/OTKA K 120660 grant and the János Bolyai scholarship of the Hungarian Academy of Sciences
Heavy-flavour (HF) probes

- Heavy quarks are produced early
  \[ \tau_{c,b} \sim \frac{1}{2} m_{c,b} \sim 0.1 \text{ fm} << \tau_{\text{QGP}} \sim 5-10 \text{ fm} \]

- Heavy quarks are (almost) conserved
  \[ m >> T_{\text{QGP}} \ (m_c \sim 1.5 \text{ GeV}, \ m_b \sim 5 \text{ GeV}) \]
  - No flavour changing
  - Negligible thermal production
  \[ \rightarrow \text{Very little production or destruction in the sQGP} \]

Heavy-flavour (HF) probes

- Heavy quarks are produced early
  \[ \tau_{c,b} \sim \frac{1}{2} m_{c,b} \sim 0.1 \text{ fm} \ll \tau_{\text{QGP}} \sim 5\text{-}10 \text{ fm} \]

- Heavy quarks are (almost) conserved
  \[ m >> T_{\text{QGP}} (m_c\sim1.5 \text{ GeV}, m_b\sim5 \text{ GeV}) \]
  - No flavour changing
  - Negligible thermal production
  - Very little production or destruction in the sQGP

- Transport through the whole system
  - Heavy quark kinematics in the sQGP
  - Access to transport properties of the system
  - ...exits the medium also at low momenta
  - Hadronization (fragmentation, coalescence)
  - Heavy vs. light? Charm vs. bottom?
Heavy-flavour (HF) probes

- Heavy quarks are produced early
  \[ \tau_{c,b} \sim \frac{1}{2} m_{c,b} \sim 0.1 \text{ fm} < \tau_{\text{QGP}} \sim 5-10 \text{ fm} \]
  
- Heavy quarks are (almost) conserved
  \[ m \gg T_{\text{QGP}} \quad (m_c \sim 1.5 \text{ GeV}, \quad m_b \sim 5 \text{ GeV}) \]
  - No flavour changing
  - Negligible thermal production
  \[ \rightarrow \text{Very little production or destruction in the sQGP} \]
  
- Transport through the whole system
  - Heavy quark kinematics in the sQGP
  - Access to transport properties of the system
  - ...exits the medium also at low momenta
  - Hadronization (fragmentation, coalescence)
  - Heavy vs. light? Charm vs. bottom?

Penetrating probes down to low momenta!
Experimental access to open HF

- Heavy quarks (c, b) hadronize into mesons (D, B) or baryons (Λc, ...)
- These hadrons later decay weakly into light mesons

- Experimental access:
  - Identification of decay products

Indirect: semileptonic decay

Direct: hadronic channel
Experimental access to open HF

- Heavy quarks (c, b) hadronize into mesons (D, B) or baryons (Λc, ...)
- These hadrons later decay weakly into light mesons

Experimental access:
identification of decay products

Indirect: semi-leptonic decay

- c, b → μ  BR ~ 11%
- c, b → e  BR ~ 11%

Direct: hadronic channel
Heavy quarks (c, b) hadronize into mesons (D, B) or baryons (Λ_c ...)

These hadrons later decay weakly into light mesons

Experimental access:

Identification of decay products

Direct: hadronic channel

- \( D^0 \rightarrow K^- \pi^+ \), BR \( \sim 3.9\% \)
- \( D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+ \), BR \( \sim 2.6\% \)
- \( D^+ \rightarrow K^- \pi^+ \pi^+ \), BR \( \sim 9.5\% \)
- \( D_{S}^{+} \rightarrow \Phi (\rightarrow K^+ K^-) \pi^+ \), BR \( \sim 2.3\% \)
- \( \Lambda_c \rightarrow p K^+ \pi^+ \), BR \( \sim 6.2\% \)
- \( \rightarrow p K_s^0 \), BR \( \sim 1.6\% \)

Indirect: semi-leptonic decay

- \( D^0 \rightarrow K^- \pi^+ \), BR \( \sim 3.9\% \)
- \( D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+ \), BR \( \sim 2.6\% \)
- \( D^+ \rightarrow K^- \pi^+ \pi^+ \), BR \( \sim 9.5\% \)
- \( D_{S}^{+} \rightarrow \Phi (\rightarrow K^+ K^-) \pi^+ \), BR \( \sim 2.3\% \)
- \( \Lambda_c \rightarrow p K^+ \pi^+ \), BR \( \sim 6.2\% \)
- \( \rightarrow p K_s^0 \), BR \( \sim 1.6\% \)
Experimental access to open HF

- Heavy quarks (c, b) hadronize into mesons (D, B) or baryons (Λc, ...)
- These hadrons later decay weakly into light mesons

Experimental access:

- Identification of decay products
- Finding the location of the decay (secondary vertex)

Lifetime of heavy quarks
- $\tau(D) \sim 100-300$ mm
- $\tau(B) \sim 400-500$ mm

Secondary vertex resolution $<100$ mm
A dedicated heavy-ion experiment at the LHC, excellent PID
ALICE

**EMCal**: energy, electron ID

**TPC**: charged-particle tracking, identification

**ITS**: charged-particle tracking, secondary vertex

**TRD**: hadron rejection by transition radiation

**TOF**: identification by precise time of flight

Heavy quark lifetimes:
- $c\tau(D) \sim 100-300\ \mu m$
- $c\tau(B) \sim 400-500\ \mu m$

Secondary vertex resolution: $\sim 100\ \mu m$

**central barrel**: $|\eta|<0.9$

**Muon spectrometer**: forward: $-4<\eta<-2.5$
muon trigger and tracking

A dedicated heavy-ion experiment at the LHC, excellent PID
Heavy flavour in small systems

Production cross sections in pp collisions

- Primary (vacuum) pQCD benchmark
Heavy flavour in small systems

Production cross sections in pp collisions

- Primary (vacuum) pQCD benchmark

HF production vs. event activity

- Interplay between hard and soft processes
- Link between initial and final state
- **Role of collective effects** in small collision systems with high multiplicity? MPI?
Heavy flavour in small systems

Production cross sections in pp collisions
- Primary (vacuum) pQCD benchmark

HF production vs. event activity
- Interplay between hard and soft processes
- Link between initial and final state
- Role of collective effects in small collision systems with high multiplicity? MPI?

Jet and correlation observables
- Fragmentation of charm vs. light quarks
- Properties of jets with charm content
- Contribution of gluon splitting to HF yields
Heavy flavour in small systems

Production cross sections in pp collisions

- Primary (vacuum) pQCD benchmark

HF production vs. event activity

- Interplay between hard and soft processes
- Link between initial and final state
- **Role of collective effects** in small collision systems with high multiplicity? MPI?

Jet and correlation observables

- Fragmentation of charm vs. light quarks
- Properties of jets with charm content
- Contribution of gluon splitting to HF yields

Mesons and baryons

- Tests of fragmentation models
D (charmed) mesons in QCD vacuum

√s=5.02 TeV pp: new, high-precision $D^0$, $D^{*+}$, $D^+$, $D_s^+$ measurements

- $D^0$ down to low momenta ($p_T>0$ GeV/c): no topological cuts, only PID
- New reference for heavy-ion systems (p-Pb and Pb-Pb)

A detailed test of pQCD models

- Data well described by models based on factorization
- Data provide strong restriction for models
HF electrons and muons

- FONLL pQCD describes beauty electrons and beauty/charm ratio
- Agreement for electrons at mid-rapidity and muons at 2.5<\(y<4\)
**D-tagged and b-tagged jets**

- **D-jets** are jets tagged with the reconstruction of $D^0$-mesons at 5, 7 and 13 TeV
- **b-jets** tagged based on impact parameter
- POWHEG(HVQ) + PYTHIA6(Perugia11) describes both adequately
- Strongly restricts models

=> unique opportunity to study flavor-dependent jet properties

*Reference for nuclear modification*
Baryon-to-meson ratio: $\Lambda_c^+ / D^0$, $\Xi_c^0 / D^0$

- $\Xi_c^0 / D^0$ as well as $\Lambda_c^+ / D^0$ are underestimated by models based on ee collisions: Does charm hadronization depend on collision system?
  - PYTHIA8 with string formation beyond leading colour approximation?
    Christiansen, Skands, JHEP 1508 (2015) 003
  - Feed-down from augmented set of charm-baryon states?
    He, Rapp, 1902.08889
  - Detailed measurement of charm baryons provide valuable input for theoretical understanding of HF fragmentation
D-h angular correlations

Near-side peak narrowing with increasing $p_T^D$
Away-side yields increase with $p_T^D$ value
No significant difference between D-h correlation parameters in pp and p-Pb systems
Bio: E. Frajna (ALICE), https://indi.to/tHf8p

- Higher per-trigger yields and baseline for non-prompt D mesons
Higher per-trigger yields and baseline for non-prompt D mesons

Shapes: significantly different at the near side at low $p_T$. 

E Frajna (ALICE), https://indi.to/tHf8p
D-h in PYTHIA: prompt/non-prompt D

- Higher per-trigger yields and baseline for non-prompt D mesons
- Shapes: significantly different at the near side at low $p_T$
- A possibility to statistically separate b and c contributions

E Frajna (ALICE), https://indi.to/tHf8p

E Frajna, R V, Universe 2019 5 (5) 118
D-h in PYTHIA: partonic processes

Partonic processes in PYTHIA 8

- Initial-state radiation
- Final-state radiation
- Multiple-parton interactions
- **Near-side yield**: significant FSR contribution (at higher $p_T^{\text{trigger}}$).
- **Away-side yield**: MPI contribution.
- **Away-side width**: increased by parton-level effects - mainly ISR.
- **Baseline**: contributions of ISR, FSR and MPI effects to underlying event.
Charm fragmentation

- Fragmentation of D mesons
  - Comparison to model POWHEG hvq CT10NLO + PYTHIA6
  - Softer fragmentation in data for low $p_T$
  - Model consistent with data at higher $p_T$
Charm fragmentation

- Fragmentation of D mesons
  - Comparison to model POWHEG hvq CT10NLO + PYTHIA6
  - Softer fragmentation in data for low $p_T$
  - Model consistent with data at higher $p_T$

- $\Lambda_c$-tagged jets at 13 TeV - first measurement at the LHC
  - Exciting prospects for high luminosity LHC run
  - Comparison to models seems to favor PYTHIA with softer settings
Jet structure vs. multiplicity

- PYTHIA8, HIJING++
- Radial structure of light-flavor jets $\psi(N_{ch})$
  - Significantly influenced by multiple-parton interactions

Jet structure vs. multiplicity

- **Radial structure of light-flavor jets** $\psi(N_{ch})$
  - Significantly influenced by **multiple-parton interactions**

- **Multiplicity-scaled jet size measure** $R_{fix}(p_T)$
  - Does not depend on any physical settings for LF (generator, tune, CR/MPI, jet algorithm etc.)

- **PYTHIA8**, **HIJING++**

Jet structure vs. multiplicity

- **PYTHIA8, HIJING++**
- **Radial structure of heavy-flavor jets** $\psi(N_{ch})$
  - Integral structures splitting for the three flavors (lf,c,b)
- **Multiplicity-scaled jet size measure** $R_{fix}(p_T)$
  - Strong dependence of the split on momentum
- **Heavy flavor jet structures sensitive to fragmentation**
Jet structure vs. multiplicity

- PYTHIA8, HIJING++
- Radial structure of heavy-flavor jets $\psi(N_{ch})$
  - Integral structures splitting for the three flavors (lf, c, b)
- Multiplicity-scaled jet size measure $R_{fix}(p_T)$
  - Strong dependence of the split on momentum
- Heavy flavor jet structures sensitive to fragmentation

Flavor-inclusive analysis underway in ALICE 13 TeV pp
Underlying event w/ identified triggers

- PYTHIA8 simulations, 7 TeV pp
- Identify a trigger: $\pi$, $p$, $D$ or $B$
- Examine particle production in underlying event (transverse side)

A. No MPI case
- particle production clearly ordered by flavor of trigger

A Misák, https://indi.to/nSCNc
Underlying event w/ identified triggers

- PYTHIA8 simulations, 7 TeV pp
- Identify a trigger: π, p, D or B
- Examine particle production in underlying event (transverse side)

A. No MPI case:
  - particle production clearly ordered by flavor of trigger

B. No CR case:
  - flavor ordering levelled.
  - Agrees with traditional assumption: UE does not depend on leading hard process
Underlying event w/ identified triggers

- PYTHIA8 simulations, 7 TeV pp
- Identify a trigger: $\pi$, $p$, D or B
- Examine particle production in underlying event (transverse side)

A. No MPI case:
   - particle production clearly ordered by flavor of trigger

B. No CR case:
   - flavor ordering levelled.
   - Agrees with traditional assumption: UE does not depend on leading hard process

C. Physical case (both MPI & CR)
   - Flavor-dependence (re)introduced by color reconnection
   - Similar effect seen in LF & strange

Ortiz, Valencia, Palomo, PRD 99 (2019), 034027
HF fragmentation and underlying event

- Relative effect of **multiple-parton interactions**
  - Near side: flavor-dependent radiation/fragmentation
  - **Transverse side**: LF and HF separated sensitive to color charge effects (quark vs gluon jets)
HF fragmentation and underlying event

- Relative effect of multiple-parton interactions
  - Near side: flavor-dependent radiation/fragmentation
  - Transverse side: LF and HF separated sensitive to color charge effects (quark vs gluon jets)
- Color reconnection: same relative effect in jets and the UE
p-Pb collisions: CNM effects?

- **Nuclear modification**
  - PDF modification: (anti)shadowing, gluon saturation
  - Energy loss in CNM, $k_T$-broadening
  
  *Baseline for hot nuclear effects*
p-Pb collisions: CNM effects?

- **Nuclear modification**
  - PDF modification: (anti)shadowing, gluon saturation
  - Energy loss in CNM, $k_T$-broadening

*Baseline for hot nuclear effects*

- **Multiplicity-dependence?**
  - *Any hot droplets?*

- **Origin of collectivity in small systems?**
  - Disentangle initial and final state effects
HFE in p-Pb collisions

- **HFE production in p-Pb collisions:**
  - No modification w.r.t. pp collisions within uncertainties

- **$Q_{pPb}$ consistent with unity at all centralities**
  - More radial flow in PHENIX d-Au than at the LHC?
- **b-tagged jet cross section and** $R_{ppb}$ **measured for** $10 < p_T < 100$ GeV/c
  - Tagging based on reconstructed secondary vertex
- Data is well described by POWHEG simulations within uncertainties
- $R_{ppb}$ consistent with unity within uncertainties in the measured $p_T$ range
Asymuthal anisotropy in p-Pb

- Collectivity of HFE and HFM in small systems
  - $c,b \rightarrow e$ at mid-rapidity, $c,b \rightarrow \mu$ forward/backward
  - Values of $e$ and $\mu$ $v_2$ comparable with each other within uncertainties
  - Low-$p_T$: comparable to charged hadrons
  - Mid-$p_T$: about half the charged hadron $v_2$
  - Tendency of smaller p-going than Pb-going $v_2$
Heavy ions: hot nuclear effects

- **Nuclear modification**
  
  \[ R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \]

  - **Collisional energy loss**
  - **Energy loss via gluon radiation**
  - Dead cone effect → expected mass ordering:
    \[ \Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \rightarrow R_{AA}^h < R_{AA}^D < R_{AA}^B \]
  - **Color charge effect** (HF is mostly quarks <=> gluon contribution in LF)
  - **Change of fragmentation**: Baryons, jets
Heavy ions: hot nuclear effects

- **Nuclear modification**

\[
R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}
\]

- **Collisional energy loss**
- **Energy loss via gluon radiation**
- **Dead cone effect** → expected mass ordering:
  \[\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \rightarrow ? R_{AA}^h < R_{AA}^D < R_{AA}^B\]
- **Color charge effect** (HF is mostly quarks <-> gluon contribution in LF)
- **Change of fragmentation: Baryons, jets**

- **Collectivity:** strongly coupled medium => substantial \( v_n \)

\[
E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_R)) \right)
\]

\[v_n = \langle \cos(n(\varphi - \Psi_R)) \rangle\]

- **Does heavy flavour flow?**
- **In what stage does it pick up flow?**
  - Does it thermalize with the medium?
  - Do heavy quarks coalesce with flowing light quarks?
Pb-Pb: Suppression of charm

- $D^0$ measurements down to $p_T \sim 0$
- **High-$p_T$:** Suppression pattern similar to light flavor
  - **Mass ordering?** Expected $\Delta E_q > \Delta E_c$ but observed $R_{AA}^h \approx R_{AA}^D$
- **Low-$p_T$:** Charm suppression is significantly weaker than light flavor
  - Coalescence of light and charm quarks?

---

**ALICE Preliminary**

- $0-10\%$ Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV, $|y| < 0.5$
  - $\Lambda_c^+$
  - Average $D^0$, $D^+$, $D^{++}$
  - $D_s^+$
  - Charged particles, $|y| < 0.8$, JHEP 1811 (2018) 13

Filled markers: pp measured reference
Open markers: pp $p_T$-extrapolated reference

**ALICE Preliminary**

- Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- Average $D^0$, $D^+$, $D^{++}$, $|y| < 0.5$
- $0-10\%$
- $30-50\%$
- $60-80\%$ JHEP 10 (2018) 174

Peripheral

Semi-central

Central
Pb-Pb: Suppression of D mesons

- **D⁰** measurements down to $p_T \sim 0$
- **High-**$p_T$: Suppression pattern similar to light flavor
  - Mass ordering? Expected $\Delta E_q > \Delta E_c$ but observed $R_{AA}^h \approx R_{AA}^D$
- **Low-**$p_T$: Charm suppression is significantly weaker than light flavor
  - Coalescence of light and charm quarks?
  - Several models give good description, low discrimination power
Prompt and non-prompt D mesons

- Non-prompt D mesons: access to beauty suppression in Pb-Pb collisions
  - Intermediate $p_T$: non-prompt $D^0$ is less suppressed than prompt $D^0$
Prompt and non-prompt D mesons

- Non-prompt D mesons: access to beauty suppression in Pb-Pb collisions
  - Intermediate $p_T$: non-prompt $D^0$ is less suppressed than prompt $D^0$

- Calculations including flavour dependent energy loss describe it
  - Ratio helps cancel some of the model and data uncertainties
Charm and Beauty - HF electrons

- Significant \((c,b)\rightarrow e\) suppression in Pb-Pb collisions from medium to high \(p_T\)
  - Note: Results in p-Pb collisions are consistent with unity
- Separated beauty-decay electrons hint a weaker b-quark suppression
Significant (c,b)→e suppression in Pb-Pb collisions from medium to high $p_T$
  - Note: Results in p-Pb collisions are consistent with unity

Separated beauty-decay electrons hint a weaker b-quark suppression

Models describe both (c,b)→e and b(→c)→e within uncertainties
  - Difference understood by quark mass dependent energy loss
• Charged baryon/meson ratio $\Lambda_c/D_0$
  • mid-$p_T$: tendency of moderate increase from pp to central Pb-Pb collisions
  • Models include recombination follow the same trend as data
• Hint of baryon to meson enhancement
Heavy-flavor azimuthal anisotropy

- **D mesons flow:** A significant $v_2$ of D mesons is observed at the LHC
  - D-meson $v_2$ is qualitatively similar to **charged particles** $v_2$ at $\sqrt{s_{NN}}=5.02$ TeV

- **Heavy-flavor electrons flow:** A significant $v_2$ observed at the LHC
  - HFE $v_2$ at $\sqrt{s_{NN}}=2.76$ TeV and $\sqrt{s_{NN}}=5.02$ TeV agree within uncertainties
**Azimuthal anisotropy of D: and $R_{AA}$**

### D mesons flow

- A significant $v_2$ of D mesons is observed at the LHC
  - D-meson $v_2$ is qualitatively similar to charged particle $v_2$ at $\sqrt{s_{NN}}=5.02$ TeV
  - Models in which charm picks up flow via recombination or collisional energy loss do better in reproducing $R_{AA}$ and $v_2$ simultaneously

---

$R_{AA}$ and $v_2$ together provide strong constraints on models
Azimuthal anisotropy of HFE: c vs. b

- **HFE:** significant $v_2$ of both the charm and beauty contributions
  - Several models describe HFE $v_2$ (charm and beauty contributions)
  - **Separated beauty-electron contribution** to the $v_2$ qualitatively similar
Summary

QCD vacuum: pp collisions at $\sqrt{s}=5.02, 7, 8$ and $13$ TeV

- *D-meson, HFE, HFM spectra* adequately described by pQCD models
- *HF-tagged jets*: information about fragmentation, model development
- *Charmed baryons*: Unexpected enhancement, recent model explanation
- *Simulation studies*: importance of differential jet and UE measurements
Summary

QCD vacuum: pp collisions at $\sqrt{s}=5.02, 7, 8$ and $13$ TeV
- D-meson, HFE, HFM spectra adequately described by pQCD models
- HF-tagged jets: information about fragmentation, model development
- Charmed baryons: Unexpected enhancement, recent model explanation
- Simulation studies: importance of differential jet and UE measurements

Nuclear modification in p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV
- Nuclear modification by cold nuclear matter
  - $R_{AA}$ consistent with unity at mid-rapidity for D mesons, HFE, b-jets
  - Correlations in pp and pPb are consistent
- Collectivity: substantial HF $v_2$ in small systems: final state effect?
Summary

QCD vacuum: pp collisions at $\sqrt{s}=5.02, 7, 8$ and 13 TeV
- D-meson, HFE, HFM spectra adequately described by pQCD models
- HF-tagged jets: information about fragmentation, model development
- Charmed baryons: Unexpected enhancement, recent model explanation
- Simulation studies: importance of differential jet and UE measurements

Nuclear modification in p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV
- Nuclear modification by cold nuclear matter
  - $R_{AA}$ consistent with unity at mid-rapidity for D mesons, HFE, b-jets
  - Correlations in pp and pPb are consistent
- Collectivity: substantial HF $v_2$ in small systems: final state effect?

Medium effects in Pb-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV
- Energy loss: No ordering in high-$p_T$ suppression: $R_{AA}^{\pi} \approx R_{AA}^{\pi}$
  Ordering at lower $p_T$ ranges: $R_{AA}^{b \rightarrow e} > R_{AA}^{b,c \rightarrow e}$
- Collectivity and coalescence:
  - $R_{AA}$ at low $p_T$ hints coalescence with the flowing medium
  - Significant azimuthal anisotropy $\rightarrow v_2$ & $R_{AA}$ constrain models
  - $\Lambda_c$: HF Barion over meson enhancement hinted by data
- Up to 50 kHz Pb-Pb interaction rate
- Requested Pb-Pb luminosity: 13 nb-1 (50-100x Run2 Pb-Pb)
- Improved tracking efficiency and resolution at low pT
- Detector upgrades: ITS, TPC, MFT, FIT
- Faster, continuous readout
ALICE Upgrade for Run-3 and Run-4

- Up to 50 kHz Pb-Pb interaction rate
- Requested Pb-Pb luminosity: 13 nb⁻¹ (50-100x Run2 Pb-Pb)
- Improved tracking efficiency and resolution at low pT
- Detector upgrades: ITS, TPC, MFT, FIT
- Faster, continuous readout

### ITS upgrade

#### Projected performance

- **Current ITS (data)**
- **Upgraded ITS**

#### Expected precision

- ALICE Upgrade Simulation
- 0-10% Pb-Pb, \( \sqrt{s_{NN}} = 5.5 \text{ TeV} \), \( L_{int} = 10 \text{ nb}^{-1} \)
- \( R_{AA} \) vs. \( p_T \) (GeV/c)
- Various models and data points compared.
Thank you!
### Physics reach after LS2 (2019-20)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current, 0.1 nb⁻¹</th>
<th>Upgrade, 10 nb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_T^{\text{min}}$ (GeV/c)</td>
<td>statistical uncertainty</td>
</tr>
<tr>
<td><strong>Heavy Flavour</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D meson $R_{AA}$</td>
<td>1</td>
<td>10%</td>
</tr>
<tr>
<td>$D_s$ meson $R_{AA}$</td>
<td>4</td>
<td>15%</td>
</tr>
<tr>
<td>D meson from B $R_{AA}$</td>
<td>3</td>
<td>30%</td>
</tr>
<tr>
<td>J/$\psi$ from B $R_{AA}$</td>
<td>1.5</td>
<td>15% ($p_T$-int.)</td>
</tr>
<tr>
<td>$B^+$ yield</td>
<td>not accessible</td>
<td>3</td>
</tr>
<tr>
<td>$\Lambda_c$ $R_{AA}$</td>
<td>not accessible</td>
<td>2</td>
</tr>
<tr>
<td>$\Lambda_c/D^0$ ratio</td>
<td>not accessible</td>
<td>2</td>
</tr>
<tr>
<td>$\Lambda_b$ yield</td>
<td>not accessible</td>
<td>7</td>
</tr>
<tr>
<td>D meson $v_2$ ($v_2 = 0.2$)</td>
<td>1</td>
<td>10%</td>
</tr>
<tr>
<td>$D_s$ meson $v_2$ ($v_2 = 0.2$)</td>
<td>not accessible</td>
<td>$&lt; 2$</td>
</tr>
<tr>
<td>D from B $v_2$ ($v_2 = 0.05$)</td>
<td>not accessible</td>
<td>2</td>
</tr>
<tr>
<td>J/$\psi$ from B $v_2$ ($v_2 = 0.05$)</td>
<td>not accessible</td>
<td>1</td>
</tr>
<tr>
<td>$\Lambda_c$ $v_2$ ($v_2 = 0.15$)</td>
<td>not accessible</td>
<td>3</td>
</tr>
<tr>
<td><strong>Dielectrons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (intermediate mass)</td>
<td>not accessible</td>
<td></td>
</tr>
<tr>
<td>Elliptic flow ($v_2 = 0.1$) [4]</td>
<td>not accessible</td>
<td></td>
</tr>
<tr>
<td>Low-mass spectral function [4]</td>
<td>not accessible</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Hypermolecules</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^3\text{H}$ yield</td>
<td>2</td>
<td>18%</td>
</tr>
</tbody>
</table>

**ALICE ITS upgrade TDR**
ITS performance

- Semiconducting technology
- Resolves secondary vertex

Heavy quark lifetimes:
\[ c \tau(D) \sim 100-300 \text{ mm} \]
\[ c \tau(B) \sim 400-500 \text{ mm} \]

Secondary vertex resolution: \( \sim 100 \text{ mm} \)

Distribution of electron track DCA (distance of closest approach to primary vertex).
MC template fitting allows for statistical separation of charm and beauty contributions.
Recent high-precision measurements in pp at $\sqrt{s}=7$ GeV:
Reference for heavier systems (p-Pb and Pb-Pb)

- $D^0$ at very low $p_T (<1$ GeV/c): PID only,
  no vertex reconstruction or topological cuts
D mesons at different energies (pp)

- D-meson production cross section
- Down to $p_T = 0$ for $D^0$ at 7 TeV
- pQCD calculations describe the data within uncertainties
- data uncertainties much lower than theoretical one
b-jet tagging performance

Secondary vertex method
- $L_{xy}$: projection of decay length on the (x,y) plane
- $L_{xy}/\sigma_{L_{xy}}$: significance of $L_{xy}$
- $\sigma_{vtx}$: secondary vertex dispersion
D-meson production in p-Pb collisions:
No modification w.r.t. pp collisions within uncertainties
- No indication of CNM effects from intermediate to high $p_T$
- Data described by several models containing CNM effects

Hint of $Q_{CP} > 1$ for central collisions (1.5σ at 3<pT< 8 GeV/c)
- similar to light hadrons
- Radial flow? Initial or final-state effect?
Hot effects in p-Pb collisions?

- D-meson production in p-Pb collisions:
  - No modification w.r.t. pp collisions within uncertainties
    - No indication of CNM effects from intermediate to high $p_T$
    - Data described by several models containing CNM effects
  - A model including small-volume QGP formation also describes data (but not favored by)
Heavy-flavour decay muons probe the nPDFs at different $x$ values.

Forward production is consistent with no nuclear modification.

Hint of an enhancement of HF muons at backward rapidity at low $p_T$.

Measurements described by models within uncertainties.
D-meson suppression at high $p_T$ consistent with pions

Understanding: different fragmentation, $p_T$-spectrum shape, color charge effects level out expected ordering

$B \rightarrow J/\psi$ suppression at high $p_T$ is weaker (*note the $|y|$ range*)

Model understanding: different parton masses cause different energy loss in similar kinematic range
Coalescence of strange and charm

- Strangeness enhancement expected to show up in coalescence
- Hint of a weaker $D_s$ suppression than for non-strange D mesons
  - No evidence of centrality-dependence
- Consistent with a strangeness-enhancement scenario with coalescence
**D-h correlations - reconstruction**

\[
\frac{1}{N_{\text{trigger}}} \frac{d^2 N_{\text{assoc}}}{d\Delta \varphi d\Delta \eta}
\]

- **pp and p-Pb collisions at** \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \)
- **charged hadron tracks reconstructed in the ITS and TPC**
- **topological reconstruction of secondary vertexes**
- **D meson raw yields extracted from invariant mass fits in several \( p_T \) intervals**

![Graphs and data plots](https://indico.cern.ch/event/867085/contributions/3656153)

\[
\bar{c}_{\text{inclusive}}(\Delta \varphi, \Delta \eta) = \frac{p_{\text{prim}}(\Delta \varphi)}{S_{\text{peak}}} \left( \frac{C(\Delta \varphi, \Delta \eta)}{M E(\Delta \varphi, \Delta \eta)} \right)_{\text{peaks}} - \frac{B_{\text{peak}}}{B_{\text{sidebands}}} \frac{C(\Delta \varphi, \Delta \eta)}{M E(\Delta \varphi, \Delta \eta)}_{\text{sidebands}}
\]

*E. Frajna (ALICE),
https://indico.cern.ch/event/867085/contributions/3656153*
Near-side and away-side: sensitivity to fragmentation and parton shower
- Best description by POWHEG+PYTHIA6, POWHEG LO +PYTHIA6 and PYTHIA8 & Yields typically underestimated by HERWIG & NLO models predict slightly broader peaks & EPOS3 typically overpredicts the yields.

**PYTHIA6**: LO generator with initial and final state parton shower, Lund string fragmentation.

**PYTHIA8**: also includes multiple-parton interactions and improved colour reconnection description.

**HERWIG 7**: NLO including heavy flavor, cluster hadronisation model, the showering ordering is different from PYTHIA (angular ordering with respect to $p_T$ ordering).

**POWHEG+PYTHIA**: NLO calculation of hard processes, followed by Lund fragmentation.

**POWHEG LO+PYTHIA**: hard process stopped at the LO level, Lund fragmentation.

**EPOS3**: 3D+1 viscous hydrodynamical evolution starting from flux tube initial conditions, which are generated in the Gribov-Regge multiple scattering framework.

**arXiv:1910.14403**

E Frajna (ALICE),
https://indico.cern.ch/event/867085/contributions/3656153
**Comparison to Monte Carlo simulations (away-side)**

**PYTHIA6**: LO generator with initial and final state parton shower, Lund string fragmentation.

**PYTHIA8**: also includes multiple-parton interactions and improved colour reconnection description.

**HERWIG 7**: NLO including heavy flavor, cluster hadronisation model, the showering ordering is different from PYTHIA (angular ordering with respect to $p_T$ ordering).

**POWHEG+PYTHIA**: NLO calculation of hard processes, followed by Lund fragmentation.

**POWHEG LO+PYTHIA**: hard process stopped at the LO level, Lund fragmentation.

**HERWIG 7**: NLO including heavy flavor, cluster hadronisation model, the showering ordering is different from PYTHIA (angular ordering with respect to $p_T$ ordering).

**EPOS3**: 3D+1 viscous hydrodynamical evolution starting from flux tube initial conditions, which are generated in the Gribov-Regge multiple scattering framework.

**Near-side and away-side: sensitivity to fragmentation and parton shower**

- Best description by POWHEG+PYTHIA6, POWHEG LO + PYTHIA6 and PYTHIA8 & Yields typically underestimated by HERWIG & NLO models predict slightly broader peaks & EPOS3 typically overpredicts

- PYTHIA6 (Perugia11) overpredicts both the yields and widths & PYTHIA8 (4C) overpredicts low-$p_T$ yields and widths

---

**arXiv:1910.14403**

E Frajna (ALICE),
https://indico.cern.ch/event/867085/contributions/3656153
Comparision to Monte Carlo simulations (baseline)

**PYTHIA6**: LO generator with initial and final state parton shower, Lund string fragmentation.

**PYTHIA8**: also includes multiple-parton interactions and improved colour reconnection description.

**HERWIG 7**: NLO including heavy flavor, cluster hadronisation model, the showering ordering is different from PYTHIA (angular ordering with respect to \( p_T \) ordering).

**POWHEG+PYTHIA**: NLO calculation of hard processes, followed by Lund fragmentation.

**POWHEG LO+PYTHIA**: hard process stopped at the LO level, Lund fragmentation.

**EPOS3**: 3D+1 viscous hydrodynamical evolution starting from flux tube initial conditions, which are generated in the Gribov-Regge multiple scattering framework.

**Near-side and away-side: sensitivity to fragmentation and parton shower**
- Best description by POWHEG+PYTHIA6, POWHEG LO + PYTHIA6 and PYTHIA8 & Yields typically underestimated by HERWIG & NLO models predict slightly broader peaks & EPOS3 typically overpredicts the yields
- PYTHIA6 (Perugia11) overpredicts both the yields and widths & PYTHIA8 (4C) overpredicts low-\( p_T \) yields and widths

**Baseline: Sensitive to the underlying event**
- \( p_T^{assoc}<1 \text{ GeV} \): best description by PYTHIA
- \( p_T^{assoc}>1 \text{ GeV} \): best description by HERWIG
- POWHEG NLO and LO are the same in all ranges (not trivial since influence expected from NLO charm contributions)

**References**
- arXiv:1910.14403
- E Frajna (ALICE), https://indico.cern.ch/event/867085/contributions/3656153
CORRELATIONS USING PYTHIA 8 - different tunes

- Near side peaks are similarly predicted
- Significantly lower baseline for MonashStar (~20% at max)
- Different underlying events

E Frajna (ALICE),
https://indico.cern.ch/event/867085/contributions/3656153
Different colour reconnection modes

- Mode 0: The MPI-based original Pythia 8 scheme.
- Mode 1: The new QCD based scheme.
- Mode 2: The new gluon-move model.
- Reconnection off.

A tendency for a narrowing of the near-side and away-side peak with increasing $p_T^D$.

An increasing trend of the near-side and away-side yield with increasing $p_T^D$.

Baseline: Other parameters than CR off are mostly the same => difference only in underlying event.

E Frajna (ALICE),
https://indico.cern.ch/event/867085/contributions/3656153
Peterson formula is a fragmentation function for heavy quarks. We use this instead of the Lund formula. For fits to experimental data, better agreement can be obtained.

\[ f(z) = \frac{1}{z^2 (1 - \frac{1}{z} - \frac{e}{1-z})^2} \]

Hint of different trends, but no significant difference between the two models.
Disable the charm quark mass in order to sort the mass cone effect and the color charge effect.

Slight differences at near-side width and yield.

Baseline: Slight difference in underlying event at low $p_T$. 

E Frajna (ALICE), https://indico.cern.ch/event/867085/contributions/3656153
Production vs. multiplicity of D mesons and muons steeper than linear

Same trend for non-prompt (B→)J/Ψ as well as prompt J/Ψ yields

→ No strong flavour dependence

→ Enhancement is likely to be related to c¯c, b¯b production processes, is not strongly influenced by hadronisation
Yields vs. multiplicity in p-Pb: models

- Multiplicity at mid-rapidity: similar enhancement in p-Pb and pp collisions
- Multiplicity at backward rapidity: linear-like, less rapid increase in p-Pb coll.
- EPOS with hydro evolution: qualitatively good description in both cases

Multiplicity at mid-rapidity

Multiplicity at backward rapidity (Pb-going): test auto-correlations