Charm-baryon production and fragmentation fractions in pp collisions with ALICE

Jinjoo Seo
on behalf of the ALICE Collaboration

2021. 11. 07
Heavy-flavour production

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

- **Initial state**
  Parton distribution function

- **pQCD partonic cross section**

- **Hadronisation by fragmentation**

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

**pp collisions**: Test for pQCD calculations, baseline for nuclear collisions.

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Heavy-flavour production

- Charm fragmentation fraction

\[ f(c \rightarrow H) = \frac{\sigma(H)}{\sum H \sigma(H)} \]

- Measurements in different collision systems and at different energies agree within uncertainties.
  - Support the hypothesis that fragmentation functions are independent of the collision systems?

- Caveat
  - In 2015, only LHCb \( \Lambda_c^+ \) measurement available.
  - Rapidity range: \( 2.0 < y < 4.5 \)


\( \frac{\Lambda_c}{D^0} \) ratio \( \sim 0.1 \) in \( e^+e^- \)
ALICE Detector

**Time Of Flight Detector (TOF)**
- PID via time-of-flight
- $|\eta| < 0.9$

**Time Projection Chamber (TPC)**
- Tracking, PID via $dE/dx$
- $|\eta| < 0.9$

**Inner Tracking System (ITS)**
- Vertexing, tracking
- $|\eta| < 0.9$

**V0 Trigger**
- Event triggering
- $2.8 < \eta < 5.1$ (V0A)
- $-3.7 < \eta < -1.7$ (V0C)

**Time Of Flight Detector (TOF)**
- PID via time-of-flight
- $|\eta| < 0.9$
Charm-hadron in ALICE

- **Data samples (Run 2)**

<table>
<thead>
<tr>
<th>System</th>
<th>Year(s)</th>
<th>$\sqrt{s_{\text{NN}}}$ (TeV)</th>
<th>$L_{\text{int}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>2017</td>
<td>5.02</td>
<td>$\sim$20 nb$^{-1}$</td>
</tr>
<tr>
<td>pp</td>
<td>2016-2018</td>
<td>13</td>
<td>$\sim$32 nb$^{-1}$</td>
</tr>
<tr>
<td>p-Pb</td>
<td>2016</td>
<td>5.02</td>
<td>$\sim$0.3 nb$^{-1}$</td>
</tr>
</tbody>
</table>

- **Hadronic decay**
  - $D^0 \rightarrow K^-\pi^+$
  - $D^+ \rightarrow K^-\pi^+\pi^+$
  - $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$
  - $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$
  - $\Lambda_c^+ \rightarrow pK^-\pi^+$ & $\Lambda_c^+ \rightarrow pK^0_S$
  - $\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^-$
  - $\Xi_c^0 \rightarrow \Xi^-\pi^+$
  - $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$
  - $\Omega_c^0 \rightarrow \Omega^-\pi^+$

- **Semileptonic decay**
  - $\Lambda_c^+ \rightarrow \Lambda e^+\nu_e$
  - $\Xi_c^0 \rightarrow \Xi^-e^+\nu_e$
Comparison of $p_T$-differential production cross section of D meson with models

- **FONLL**: Fixed Order with Next to Leading Log resummation [JHEP (2012) 137]

  $\Rightarrow$ NLO pQCD calculation with fragmentation functions from $e^+e^-$ can describe the charm-meson production!
$\Lambda_c^+$ measurements in ALICE

- $\Lambda_c^+/D^0$ in pp collisions at 5.02 TeV and 13 TeV
- **PYTHIA 8, Monash**: Colour reconnection between partons from different multi-parton interactions.
- Predict baryon enhancement
  - **PYTHIA 8, CR-BLC**: CR with Junction connection topologies enhance baryon formation.

![Graph showing $\Lambda_c^+/D^0$ measurements in pp collisions at 5.02 TeV and 13 TeV](image)

**References**
- PYTHIA 8 Monash (EPJC 74 (2014) 3024)
- PYTHIA 8 CR-BLC (JHEP 08 (2015) 003)
- Catania (arXiv:2012.12001)
- SHM (PLB 795 (2019) 117-121)
- RQM (PRD 84 (2011) 014025)
- QCM (EPJC 78 no.4, (2018) 344)
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- **Predict baryon enhancement**
  - **PYTHIA 8, CR-BLC**: CR with Junction connection topologies enhance baryon formation.
  - **SHM + RQM**: Consider additional excited charm baryon states expected by the RQM.

*Statistical Hadronisation Model (SHM) + additional baryon states*
- **PDG**: 5 \( \Lambda_c \) (I=0), 3 \( \Sigma_c \) (I=1), 8 \( \Xi_c \) (I=1/2), 2 \( \Omega_c \) (I=0)
- **RQM (Relativistic Quark Model)**: Add 18 \( \Lambda_c \), 42 \( \Sigma_c \), 62 \( \Xi_c \), 34 \( \Omega_c \)

**ALICE** | \( |y| < 0.5 \)

- **pp, \( \sqrt{s} = 5 \text{ TeV} \)**
- **pp, \( \sqrt{s} = 13 \text{ TeV} \)**

**PYTHIA 8 Monash**
- (EPJC 74 (2014) 3024)

**PYTHIA 8 CR-BLC**
- (JHEP 08 (2015) 003)

**Catania**
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$\Lambda^+_c$ measurements in ALICE

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    - PYTHIA 8, CR-BLC: CR with Junction connection topologies enhance baryon formation.
  - SHM + RQM: Consider additional excited charm baryon states expected by the RQM.
  - Catania: Hadronisation via vacuum fragmentation + coalescence of charm quark with light quarks in a hot QCD matter.
  - QCM: Combination of charm quarks with co-moving light quarks

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$\Lambda^+_c$ measurements in ALICE

- $\Lambda^+_c$ down to $p_T = 0$ in p-Pb collisions
- $\Lambda^+_c/D^0$: larger in $3 < p_T < 8$ GeV/c and a lower in $p_T < 2$ GeV/c in p-Pb collisions with respect to pp collisions.
- $R_{pPb}$: Systematically above unity in $p_T > 2$ GeV/c, below unity in $p_T < 2$ GeV/c.
- Significant suppression for the $\Lambda^+_c$ baryon in p-Pb collisions in $p_T < 2$ GeV/c

Possible modification due to radial flow or hadronisation mechanisms

\( \Lambda_c^+ \) measurements in ALICE

- \( \Lambda_c^+ \) down to 0 in p-Pb collisions
- POWHEG+PYTHIA6: CNM effect + PYTHIA 6 Parton shower + EPPS16 parameterization for PDFs.
- POWLANG: Hot deconfined medium in p-Pb collisions.
  - Describe the suppression at low \( p_T \).

\[ \begin{align*}
\text{ALICE} & \quad p-Pb, \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \\
& \quad \Lambda_c^+ (\text{arXiv: 2011.06079}) \\
& \quad \Lambda_c^+, \text{Preliminary} \\
\text{pp, } \sqrt{s} = 5.02 \text{ TeV} & \quad \Lambda_c^+ (\text{arXiv: 2011.06079})
\end{align*} \]

\[ \begin{align*}
\text{ALICE} & \quad p-Pb, \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \\
& \quad D \text{ mesons} \\
& \quad JHEP 1912 (2019) 092, 2019 \\
& \quad D \text{ (average } D^+, D^0, D^-) \\
& \quad \Lambda_c^+ \text{ baryons} \\
& \quad \Lambda_c^+ (\text{arXiv: 2011.06079}) \\
& \quad \Lambda_c^+, \text{Preliminary} \\
& \quad \text{extrapolated pp reference}
\end{align*} \]
**Σ⁺⁺ measurements in ALICE**

- $\Sigma_0^{0,++}/D^0$ and $\Lambda_c^+(\leftarrow \Sigma_0^{0,++})/\Lambda_c^+$ in pp collisions at 13 TeV.
- $\Sigma_0^{0,++}/D^0$ ratio shows remarkable difference between the pp and $e^+e^-$ collisions.
- $\Lambda_c^+(\leftarrow \Sigma_0^{0,++})/\Lambda_c^+$ ratio significantly larger than $e^+e^-$ collisions measurements.
- The larger feed-down from $\Sigma_0^{0,++}$ (~40%) partially explains the $\Lambda_c^+/D^0$ enhancement in pp collisions.

**Graphical Representation**

- ALICE | $|y| < 0.5$ • pp, $\sqrt{s} = 13$ TeV

- PYTHIA 8.243, Monash 2013
- PYTHIA 8.243, CR-BLC:
  - Mode 0
  - Mode 2
  - Mode 3

- SHM+RQM
- Catania
- QCM

- BR uncertainty

**References**

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**$\Sigma_{c}^{0,++}$ measurements in ALICE**

- $\Sigma_{c}^{0,++}/D^{0}$ and $\Lambda_{c}^{+}(\Sigma_{c}^{0,++})/\Lambda_{c}^{+}$ in pp collisions at 13 TeV

- $\Sigma_{c}^{0,++}/D^{0}$ ratio shows remarkable difference between the pp and e$^+e^-$ collisions.

PYTHIA 8 CR-BLC, SHM+RQM, QCM and Catania can describe the $\Lambda_{c}^{+}$ and $\Sigma_{c}^{0,++}$

Do we also understand $\Xi_{c}^{0,+}$ and $\Omega_{c}^{0}$?

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\( \Xi^0_c, + \) measurements in ALICE

- \( \Xi^0_c \) measurements in pp collisions at 13 TeV
  - **PYTHIA 8 Monash, PYTHIA 8 CR tunes, SHM+RQM and QCM**: Significantly underestimate the ratios.
  - **Catania**: Describes better the ratios in the measured \( p_T \) interval.
  - \( \Xi^0_c / \Sigma^0_c \) ratio: **Monash** describes the magnitude.
    - Similar enhancement for \( \Xi^0_c \) and \( \Sigma^0_c \) are shown w.r.t e+e- collisions.

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**Graphs**

**ALICE** pp, \( \sqrt{s} = 13 \text{ TeV} \)
- **\( |y| < 0.5 \)**
- **\( \Xi^0_c / D^0 \)**
- **\( \Xi^+ / D^0 \)**
- **\( \Xi^0_c / D^0 \)**
- **\( \Xi^0_c / \Lambda_c^+ \)**

**PYTHIA 8 Monash (EPJC 74 (2014) 3024)**
**PYTHIA 8 CR Modes (JHEP 08 (2015) 003)**
**SHM (PLB 795 (2019) 117-121)**
**RQM (PRD 84 (2011) 014025)**
**QCM (EPJC 78 no.4, (2018) 344)**
**Catania (arXiv:2012.12001)**
\( \Omega_c^0 \) measurements in ALICE

- **\( \Omega_c^0 \) measurements in pp collisions at 13 TeV**
  - No measurement of  \( \text{BR}(\Omega_c^0 \to \Omega^- \pi^+) \) → A theoretical calculation used to scale the models:  \( (0.51 \pm 0.07)\% \)
  - **PYTHIA 8 Monash, CR-BLC** : Underestimate the measurement.
  - **Catania(w/o res.), QCM** : Underestimate the measurement even though including the coalescence process.
  - **Catania(w/ res.)** : Closer to the measurements considering the additional resonance states.

\[
\text{BR}(\Omega_c^0 \to \Omega^- \pi^+) = (0.51 \pm 0.07)\% \ [\text{EPJC 80, 1066 (2020)}]
\]

\[
\text{BR}(\Omega_c^0 \to \Xi_0^0) = (0.51 \pm 0.07)\% \ [\text{EPJC 80, 1066 (2002)}]
\]

\[
\text{BR}(\Omega_c^0 \to \Omega^- \pi^+) \times \Omega_c^0 / D_0
\]

\[
\text{BR}(\Omega_c^0 \to \Xi_0^0) / \Xi_c^0
\]
$\Omega_c^0$ measurements in ALICE

- $\Omega_c^0$ measurements in pp collisions at 13 TeV
  - No measurement of $\text{BR}(\Omega_c^0 \to \Omega^- \pi^+)$ → A theoretical calculation used to scale the models: $(0.51 \pm 0.07)\%$

- PYTHIA 8 Monash, CR-BLC: Underestimate the measurement.
- Catania (w/o res.): Underestimate the measurement even though including the coalescence process.
- Catania (w/ res.): Closer to the measurements considering the additional resonance states.

We measure now all single charm hadron ground states! Are fragmentation functions universal across colliding systems?
Charm fragmentation fractions

- Charm fragmentation fractions
  - Fragmentation fraction for the $\Xi_c^0$ baryon is measured for the first time.
  - Not counting the contribution of $D^{*+}$, which feeds into the $D^0$ and $D^+$ mesons.

<table>
<thead>
<tr>
<th>$H_c$</th>
<th>$f(c \to H_c)$[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.2}(\text{syst})$</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$17.3 \pm 1.8(\text{stat})^{+1.7}_{-1.9}(\text{syst})$</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$</td>
</tr>
<tr>
<td>$\Lambda_c^+$</td>
<td>$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$</td>
</tr>
<tr>
<td>$\Xi_c^0$</td>
<td>$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$</td>
</tr>
<tr>
<td>$D^{*+}$</td>
<td>$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$</td>
</tr>
</tbody>
</table>

+ $\Xi_c^+$ contribution is considered as $\Xi_c^0$ contribution

- Charm fragmentation fractions are not universal

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Charm production cross section

- **Charm production cross section at the LHC**
  - First measurement of charm production cross section, including all the ground state charm hadron measurements, per unit of rapidity at midrapidity in pp collisions at 5.02 TeV
  
  \[ d\sigma^{c\bar{c}}/dy \big|_{|y|<0.5} = 1165 \pm 44\text{(stat)}^{+134}_{-101}\text{(syst)} \mu b \]

  - According to new measured charm fragmentation fractions, updated charm cross section measurements in pp collisions at 2.76 TeV and 7 TeV are about 40% higher than the previously published results.

  - Charm cross section measurements exploiting updated fragmentation fractions lies at the upper edge of the pQCD calculations.
Summary

- First measurement of $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$ and $\Omega_c^0$ production cross section in pp collisions at 13 TeV.
- First measurement of $\Lambda_c^+$ down to $p_T = 0$ GeV/c in p-Pb collisions at 5.02 TeV.

- Large enhancement of all charm-baryon production in pp collisions w.r.t $e^+e^-$ collisions.
- None of the models describe the enhancement of charm-baryon production rates.
  ✓ Modeling of charm baryons with a strange quark is challenging.
- The charm fragmentation fractions are not universal across colliding systems.

- ALICE is ready for data-taking with Run 3 and Run 4.
  ✓ Higher statistics, better precision and more differential measurements for charm baryons awaiting!
Back up
Charm FF in $e^+e^-$ & ep

• Charm fragmentation fraction
  • Assumption is needed due to lack of knowledge about production of $\Xi_c^{0,+}$ and $\Omega_c^0$
    • $f(c \to \Xi_c^+)/f(c \to \Lambda_c^+)=f(c \to \Xi_c^0)/f(c \to \Lambda_c^+)$
    • $f(s \to \Xi^-)/f(s \to \Lambda)=0.066$
    • $f(c \to \Omega_c^0)/f(c \to \Lambda_c^+)=f(s \to \Omega^+)/f(s \to \Lambda)=0.004$
    • $f(c \to \Omega_c^0)/f(c \to \Xi_c^0)=f(s \to \Omega^-)/f(s \to \Xi^-)=0.062$

• Caveat
  • NO measurement of $\sigma(\Xi_c)$, $\sigma(\Xi_c)$ and $\sigma(\Omega_c)$.
  • In 2015, only LHCb $\Lambda_c^+$ measurement available.
    • Rapidity range : $2.0 < y < 4.5$
Charm hadron/D^0 Ratios

- The ratio of $p_T$ integrated cross sections of the various charm hadrons and D^0 meson
- SHM for charm baryon is sensitive to a hadronisation temperature.

arXiv:2105.06335

ALICE, pp, $\sqrt{s} = 5.02$ TeV
PYTHIA 8: JHEP 08 (2015) 003
Monash 2013
CR Mode 0
CR Mode 2
CR Mode 3

arXiv:2105.06335

ALICE, pp, $\sqrt{s} = 5.02$ TeV
PDG, $T_h = 160$ MeV
RQM, $T_h = 160$ MeV
PDG, $T_h = 170$ MeV
RQM, $T_h = 170$ MeV
• $\Lambda_c^+/D^0$ in pp at 5.02 TeV (ALICE vs CMS)
  
  • ALICE and CMS measurements are consistent.
  
• $\Lambda_c^+/D^0$ in p-Pb at 5.02 TeV (ALICE vs LHCb)
  
  • Suggest an enhancement of the ratio at mid rapidity with respect to forward and backward rapidity.
$\Xi_0^c \rightarrow e^+ \Xi^- \nu_e$

- **Unfolding**
  - Unfolding
    - The $p_T$ of $e\Xi$ pairs is corrected for the missing momentum of the neutrino using unfolding techniques.
    - Convergence of the Bayesian unfolding is achieved after three iterations.

\[ p_T \text{ of } e\Xi \text{ pairs is corrected for the missing momentum of the neutrino using unfolding techniques.} \]

\[ 2 < p_T^{e\Xi} < 12 \text{ GeV/c} \]

\[ M(e\Xi) \text{ (GeV/c}^2) \]

\[ \Xi_0^c \rightarrow \Xi^e \nu_e \text{ and charge conj.} \]

\[ \text{Reconstructed } p_T^{e\Xi} \text{ (GeV/c)} \]

\[ \text{Generated } p_T^{e\Xi} \text{ (GeV/c)} \]
HF baryon enhance mechanism

- **PYTHIA 8 with Colour Reconnection (CR) tunes** [JHEP 08 (2015) 003]
  - Colour reconnection mode with QCD SU(3) algebra + string-length minimization
  - Junction connection topologies enhance baryon formation
  - Mode parameters: string reconnection, connection causality of dipoles, time dilation

- **No CR**
  - Partons created in different MPIs do not interact each other

- **Old CR**
  - CR allowed between partons from different MPIs to minimize the string length
  - Used in Monash tune

- **New CR**
  - Minimization of string length over all possible configurations
  - Enhancement of hadrons
  - Used in CR mode X tunes

- **Diagram**
  - Type II: junction-style reconnection
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- **Statistical Hadronisation Model (SHM) + additional baryon states** [PLB 795 (2019) 117-121]
  - PDG: 5 $\Lambda_c$ (I=0), 3 $\Sigma_c$ (I=1), 8 $\Xi_c$ (I=1/2), 2 $\Omega_c$ (I=0)
  - RQM (Relativistic Quark Model): Add 18 $\Lambda_c$, 42 $\Sigma_c$, 62 $\Xi_c$, 34 $\Omega_c$ [PRD 84 (2011) 014025]

<table>
<thead>
<tr>
<th>$n_i \cdot 10^{-4}$ fm$^{-3}$</th>
<th>$D^0$</th>
<th>$D^+$</th>
<th>$D^{*+}$</th>
<th>$D_s^+$</th>
<th>$\Lambda^+_c$</th>
<th>$\Xi^{+,0}_c$</th>
<th>$\Omega^0_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG(170)</td>
<td>1.161</td>
<td>0.5098</td>
<td>0.5010</td>
<td>0.3165</td>
<td>0.3310</td>
<td>0.0874</td>
<td>0.0064</td>
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<tr>
<td>PDG(160)</td>
<td>0.4996</td>
<td>0.2223</td>
<td>0.2113</td>
<td>0.1311</td>
<td>0.1201</td>
<td>0.0304</td>
<td>0.0021</td>
</tr>
<tr>
<td>RQM(170)</td>
<td>1.161</td>
<td>0.5098</td>
<td>0.5010</td>
<td>0.3165</td>
<td>0.6613</td>
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<tr>
<td>RQM(160)</td>
<td>0.4996</td>
<td>0.2223</td>
<td>0.2113</td>
<td>0.1311</td>
<td>0.2203</td>
<td>0.0391</td>
<td>0.0044</td>
</tr>
</tbody>
</table>
HF baryon enhance mechanism

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  - Combination of charm quarks with co-moving light quarks
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  - Combination of charm quarks with co-moving light quarks

- **Catania model** arXiv:2012.12001
  - Coalescence process of heavy quarks with light quark based on the Wigner formalism + fragmentation process
  - Blast wave parametrization for light quarks spectra, FONLL calculation for heavy quarks spectra
<table>
<thead>
<tr>
<th>Model</th>
<th>HQ production</th>
<th>Medium modelling</th>
<th>Quark-medium interaction</th>
<th>HQ hadronization</th>
<th>Tuning of medium coupling</th>
<th>References</th>
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</thead>
<tbody>
<tr>
<td>BAMPS et.</td>
<td>MC@NLO</td>
<td>3d+1 expansion parton cascade</td>
<td>Transport with Boltzmann rad. + coll.</td>
<td>Frag.</td>
<td>RHIC (then scaled by dN/ dη)</td>
<td><a href="https://arxiv.org/abs/1408.2964">https://arxiv.org/abs/1408.2964</a></td>
</tr>
<tr>
<td>Catania</td>
<td>FONLL EPS09 (NLO) PDF shadowing</td>
<td>2d+1 expansion parton cascade</td>
<td>Transport with Langevin coll. only</td>
<td>Frag. + Rec. (different from TAMU?)</td>
<td>Assume 1-QCD U potential</td>
<td><a href="https://arxiv.org/pdf/1712.00730">https://arxiv.org/pdf/1712.00730</a></td>
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<tr>
<td>LIDO</td>
<td>FONLL EPS09 (NLO) PDF shadowing</td>
<td>2d+1 rel. fluido-dynamics</td>
<td>Transport with Langevin + empirical transport coefficients to capture the non-perturbative part. (Boltzmann)</td>
<td>Frag. + Rec.</td>
<td>Coefficients fixed with Bayesian analysis to LHC D and B results</td>
<td><a href="https://arxiv.org/pdf/1806.08848">https://arxiv.org/pdf/1806.08848</a></td>
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<td><a href="https://arxiv.org/pdf/1908.00451v1">https://arxiv.org/pdf/1908.00451v1</a></td>
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<td>3d+1 expansion (EPOS model)</td>
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<td>Frag. + Rec.</td>
<td>QGP transport coefficients fixed at LHC, adapted for RHIC</td>
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