EMMI NQM Seminar

Open Heavy-Flavour production with ALICE at the LHC

Sudhir Pandurang Rode

on behalf of ALICE Collaboration

Indian Institute of Technology Indore, India

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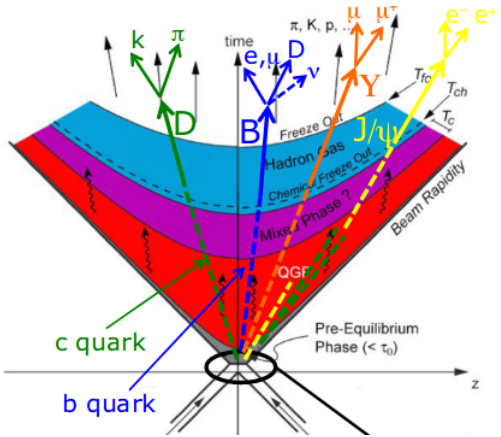
Outline

- Why Heavy-flavour?
- ALICE detector
- Results and discussion
- Summary

Why Heavy flavour ?



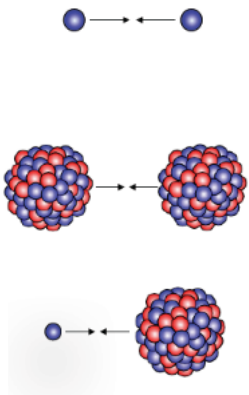
→ Charm and beauty quarks are produced in the initial hard scattering processes at the early stages of the collision.

→ $m_{c,b} \gg$ Quantum ChromoDynamics (QCD) scale parameter ($\Lambda_{QCD} \approx 200$ MeV).

→ Measurement of open heavy flavour via

- Hadronic decay channel
  - $D^0(c\bar{u}) \rightarrow K^- \pi^+$ (BR $\approx 3.88\%$)
  - $D^+(c\bar{d}) \rightarrow K^- \pi^+ \pi^+$ (BR $\approx 9.13\%$)
  - $D^{*+}(c\bar{d}) \rightarrow D^0 (K^-\pi^+) \pi^+$ (BR $\approx 67.7\%$)
  - $D_s^+(c\bar{s}) \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$ (BR $\approx 2.28\%$)
  - $\Lambda_c^+(cud) \rightarrow pK^-K^+\pi^+, pK_s^0$ (BR $\approx 6.23\%$, 1.58%)
- Semi-leptonic decay channel ($B, D \rightarrow e, \mu\nu X$, BR $\rightarrow \approx 10\%$)

Different collision systems at LHC



- **pp collisions**

→ Measure the invariant cross section of different species in pp collisions and provide the required reference for corresponding studies in large systems.

- **Pb-Pb collisions**

→ Study the mass dependent energy loss of quarks in hot QCD medium and participation of heavy quarks in the collective expansion of the system.

- **p-Pb collisions**

→ Study the cold nuclear matter effects.

Nuclear modification factor (R_{AA})

- Definition:

$$R_{\mathrm{AA}} = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}}\rangle \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

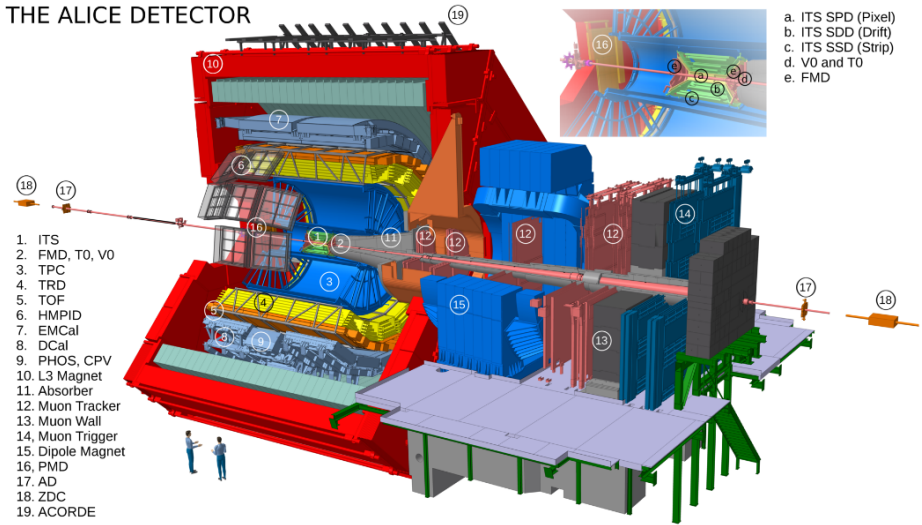
- Quantifies the modification of the momentum distribution in the QCD medium.
- Dead cone effect: expected mass dependent energy loss.

$$\Delta\mathrm{E}(\mathrm{g}) > \Delta\mathrm{E}(\mathrm{u},\mathrm{d},\mathrm{s}) > \Delta\mathrm{E}(\mathrm{c}) > \Delta\mathrm{E}(\mathrm{b}) \quad \text{(Phys. Lett. B 519, (2001) 199)}$$

$$R_{\mathrm{AA}}(\pi) < R_{\mathrm{AA}}(\mathrm{D}) < R_{\mathrm{AA}}(\mathrm{B})$$

- $R_{\mathrm{AA}} = 1$, no medium effect expected.
- $R_{\mathrm{AA}} < 1$, modification or softening of the spectra indicate possible partonic energy loss.

ALICE Detector



ALICE Detector

(Electromagnetic Calorimeter)

EMCal
PID, Trigger
$|\eta| < 0.7$

(Inner Tracking System)

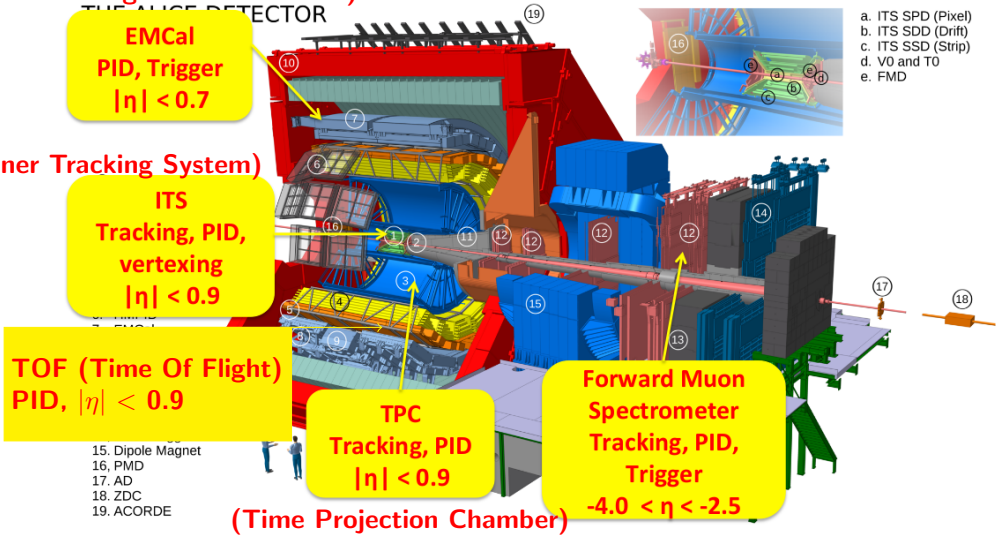
ITS
Tracking, PID,
vertexing
$|\eta| < 0.9$

TOF (Time Of Flight)
PID, $|\eta| < 0.9$

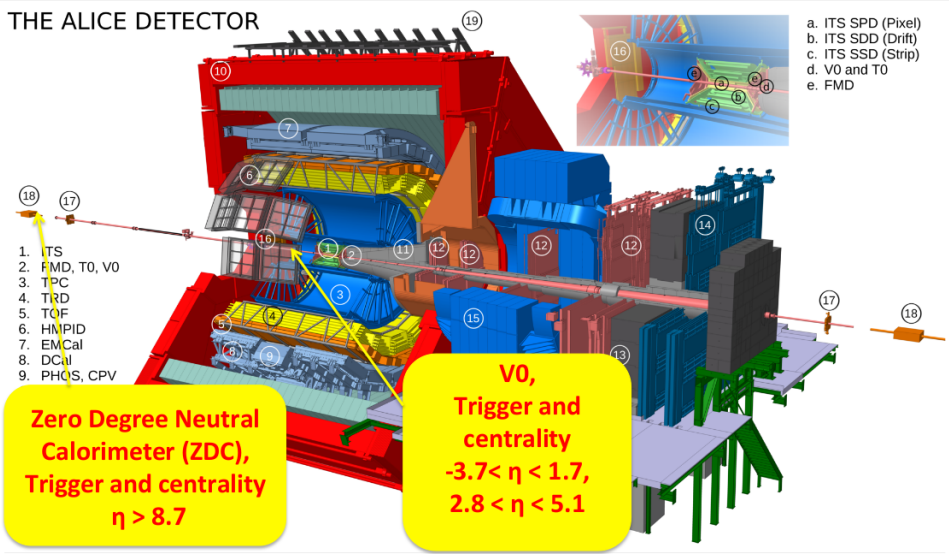
TPC
Tracking, PID
$|\eta| < 0.9$

Forward Muon
Spectrometer
Tracking, PID,
Trigger
$-4.0 < \eta < -2.5$

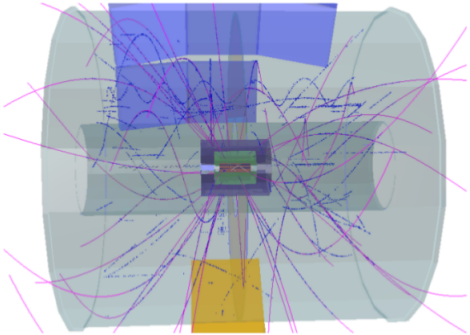
(Time Projection Chamber)



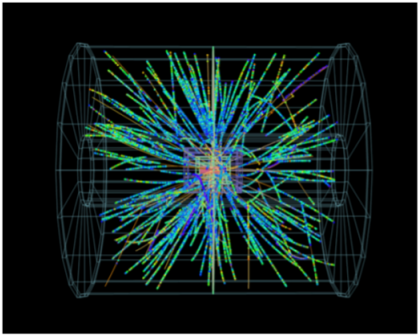
ALICE Detector



pp

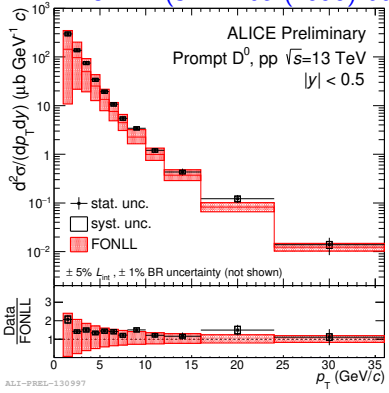


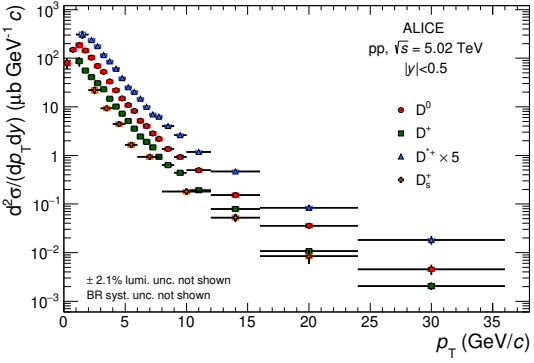
p-Pb



Results: D meson p_{T}-differential cross-sections in pp collisions

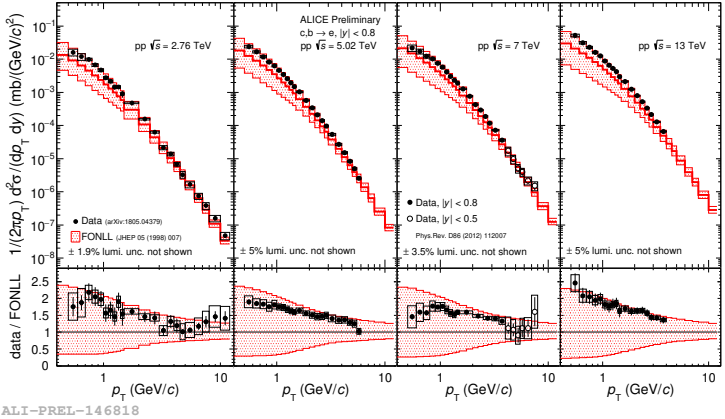
FONLL (JHEP 05 (1998) 007)

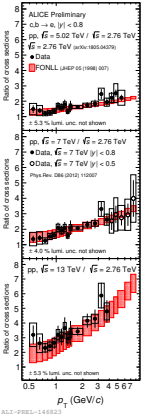




- p_{T}-differential cross-sections are precisely measured for all D mesons.
- Measured cross section of D mesons is in agreement with the FONLL predictions.
- Provide necessary reference for the corresponding measurements in the pA and AA collisions.

Results: p_{T}-differential cross-sections of b,c $\rightarrow$ e in pp collisions

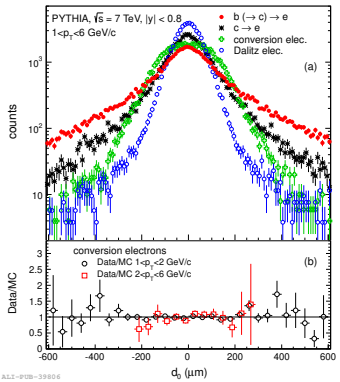


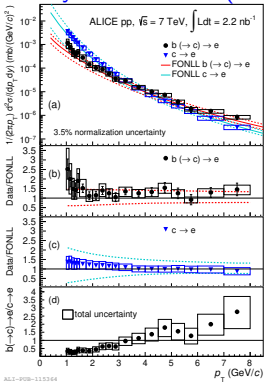


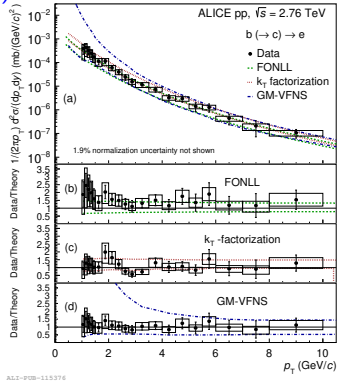
- Measured cross sections of heavy flavour electrons are in agreement with the FONLL predictions and on the upper edge of the FONLL band for all the energies.
- Ratios of the cross-sections at different energies provide better precision for the better comparison.

Results: p_{T}-differential cross-sections of b ($\rightarrow$ c) $\rightarrow$ e in pp collisions

Phys. Lett B763 (2016) 507 - 509



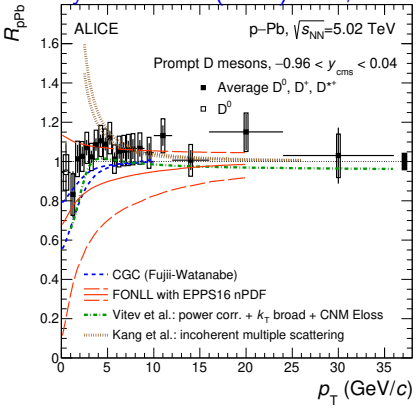


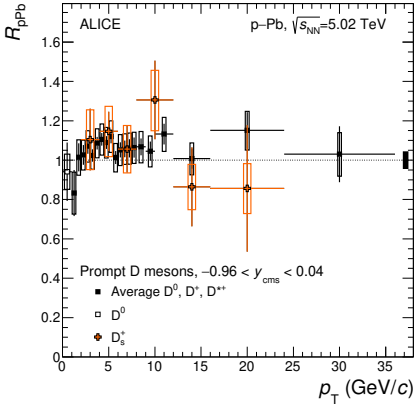


- Electrons from beauty hadron decays are measured by DCA cut method. The b ($\rightarrow$ c) $\rightarrow$ e have larger DCA (Distance of closest approach to the primary vertex) compared to the electron background $\Rightarrow$ cut on the minimum DCA to increase the S/B ratio.
- Measurements used for studying the mass dependent energy loss of the quarks in AA collisions.

$R_{\rm pPb}$ Results: D mesons in p-Pb collisions

Phys.Rev. C94 (2016) no.5, 054908

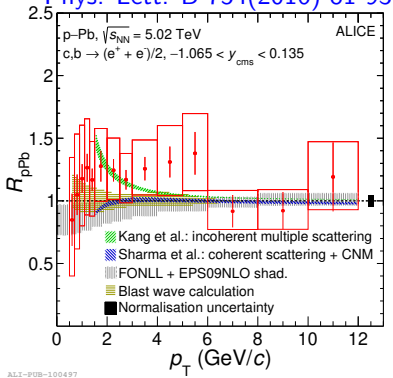




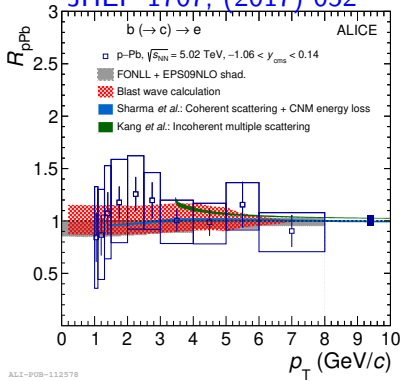
- $R_{\rm pPb}$ of D mesons is compatible with unity in the measured $p_{\rm T}$ range.
- It is also in the compatible with models which include initial-state effects(nPFDs, $k_{\rm T}$ broadening, CNM energy loss, nuclear shadowing and incoherent multiple scattering).

$R_{\rm pPb}$ Results: Electrons from heavy-flavour decays in p-Pb collisions

Phys. Lett. B 754(2016) 81-93

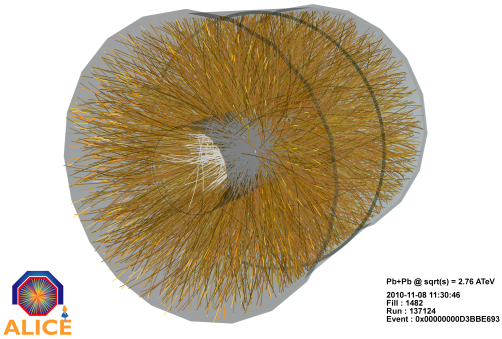


JHEP 1707, (2017) 052

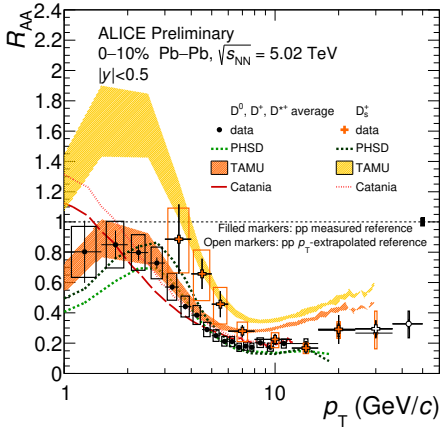


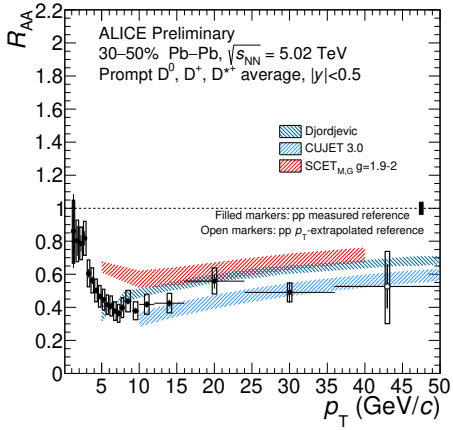
- $R_{\rm pPb}$ of electrons from heavy flavour and beauty hadron decays is consistent with unity in the measured $p_{\rm T}$ range.
- It is also in the agreement with various theoretical predictions which includes initial state effects in the $p_{\rm T}$ range under study.

Pb–Pb


ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

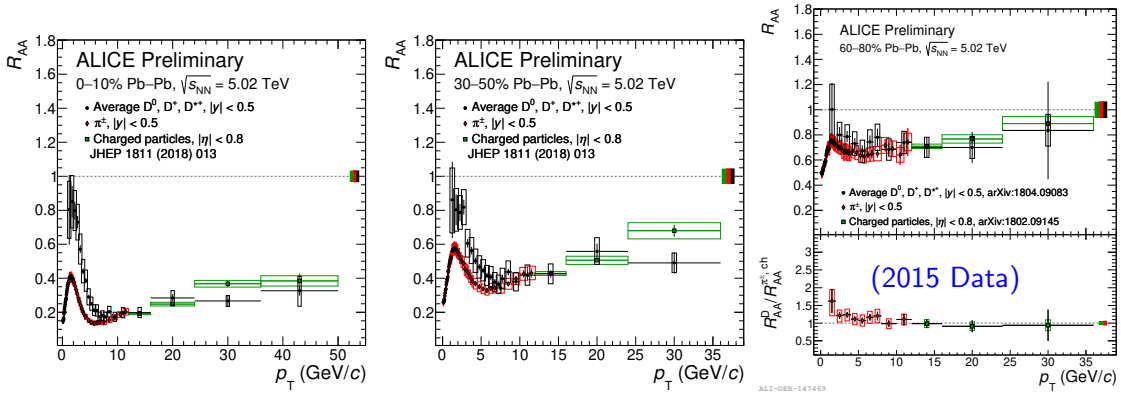
Results: D mesons in Pb-Pb collisions (2018 Data)





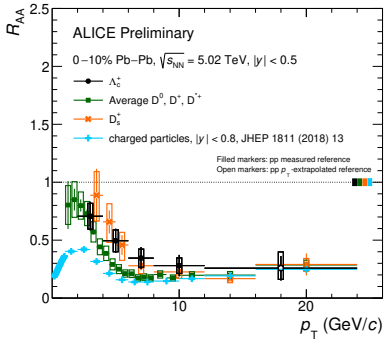
- Nuclear modification factor (R_{AA}) of D mesons is measured in central (0–10%) and most-central central (30–50%) centralities at mid-rapidity.
- R_{AA} is consistent with various transport and pQCD models.

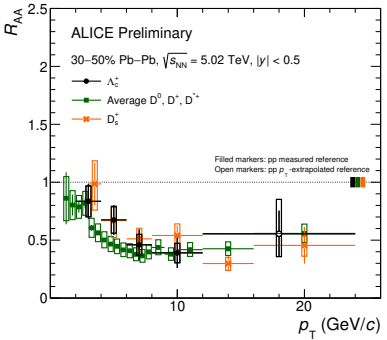
Results: R_{AA} at different centralities in Pb-Pb collisions (2018 Data)



- Measurements are available in different centrality classes.
- Indication of smaller supression of heavy quarks with respect to the light quarks at low/intermediate p_{T}.
- Reduction in the suppression with the centralities.

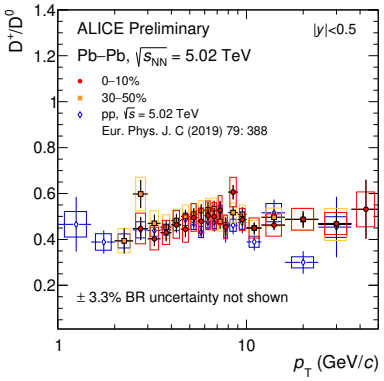
Results: Λ_c^+ baryons in Pb-Pb collisions (2018 Data)

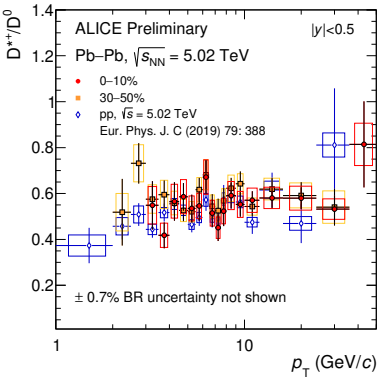




- With 2018 data, statistical uncertainties are significantly reduced.
- Indication of smaller supression of Λ_c^+ ($\Lambda_c^+ \rightarrow$ p K_S^0) with respect to D mesons at low/intermediate p_T.
- Here too, the charged particles hint towards the larger suppression compared to the open heavy flavor hadrons.

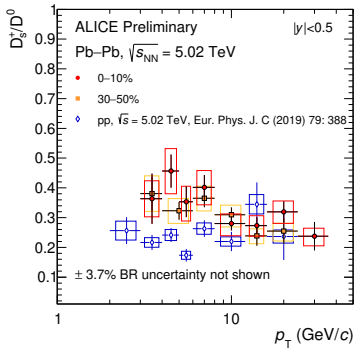
Results: D^+/D^0 and D^{*+}/D^0 ratios in Pb-Pb collisions (2018 Data)

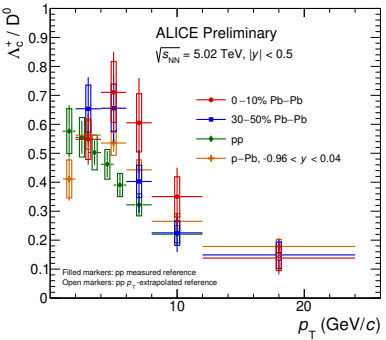




- D^+/D^0 and D^{*+}/D^0: measured at most central and mid-central Pb–Pb collisions.
- Ratios seem to be independent of the collision systems and the centralities with the uncertainties.

Results: $\mathrm{D_s/D^0}$ and $\Lambda_c^+/\mathrm{D^0}$ ratio in Pb-Pb collisions (2018 Data)

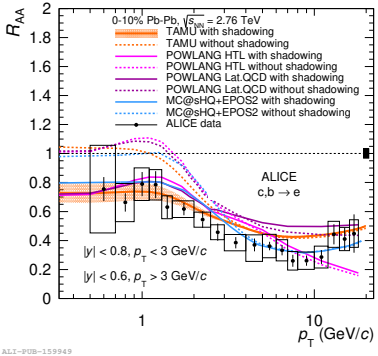


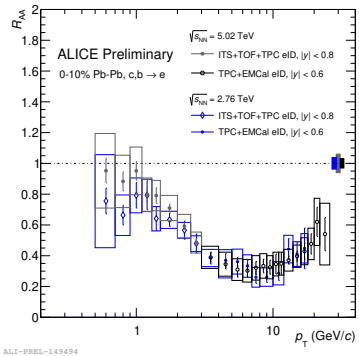


- $\mathrm{D_s/D^0}$: Slight p_T dependence in Pb–Pb in collisions is observed but not so in pp collisions.
- Due to the significant increase in the statistics in 2018, the $\Lambda_c^+/\mathrm{D^0}$ is ratio available in wider p_T range in comparison to 2015 data.
- $\Lambda_c^+/\mathrm{D^0}$: p_T dependence is observed in all the collision systems and in all the centralities (0–10 and 30–50%)

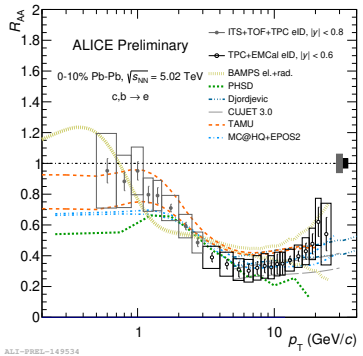
Results: Electrons from heavy-flavour decays in Pb-Pb collisions

Run 1



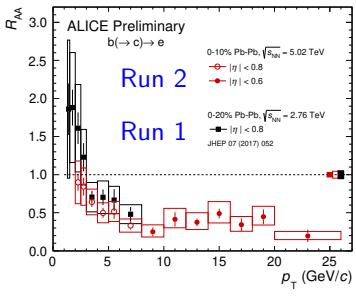


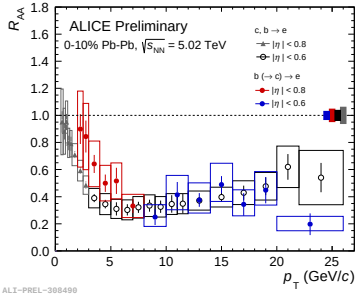
Run 2

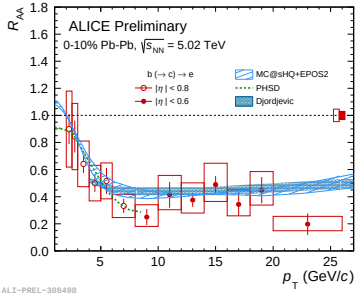


- R_{AA} of electrons from heavy-flavour decays shows good agreement with Run 1 measurement.
- R_{AA} at both energies consistent with various theoretical models that consider radiative and collisional energy loss.

Results: Electrons from beauty decays in Pb-Pb collisions

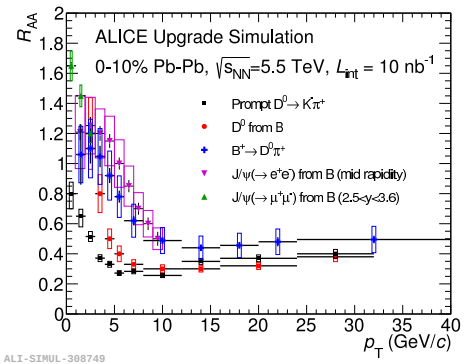


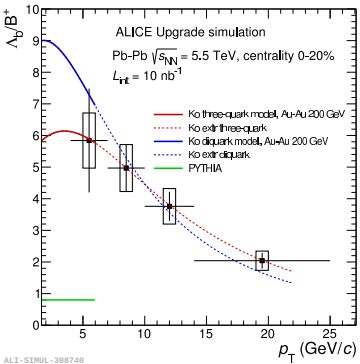




- R_{AA} of electrons from beauty decays shows good agreement with Run 1 measurement.
- Hint of smaller supression of b ($\rightarrow$ c)$\rightarrow$ e with respect to b, c $\rightarrow$ e.
- R_{AA} consistent with models that consider mass-dependent radiative and collisional energy loss.
- Analysis of new pp reference at 5.02 TeV along with 13 TeV is ongoing which would reduce the systematic uncertainties in the R_{AA} measurement and can give more precise results.

What next? → new measurements in Run 3–4





- Simulations of Run 3–4 predicts the R_{AA} of B meson and $\Lambda_{\mathrm{b}}^{+}/\mathrm{B}^{+}$ ratio in central Pb–Pb collisions.
- For the first time, these measurements would be possible after ALICE detector upgrade.

Summary

- Open heavy-flavours are measured in hadronic and semi-electronic channels using the ALICE detector which offers excellent particle identification as well as excellent vertex and track position resolution.
- p_{T}-differential cross sections of open heavy flavours in pp collisions are consistent with the theoretical predictions.
- Nuclear modification factor (R_{pA}) of open heavy-flavours is consistent with unity and agrees with the theoretical prediction which includes initial state effects.
- R_{AA} of Λ_{c} and D mesons are measured with more precision on statistical uncertainties using 2018 data and agrees with model predictions.
- R_{AA} of b ($\rightarrow$ c)$\rightarrow$ e hints at smaller supression with respect to R_{AA} of b, c $\rightarrow$ e at both 2.76 and 5.02 TeV at low/intermediate p_{T} and agrees with the models which consists of mass-dependent radiative and collisional energy losses.

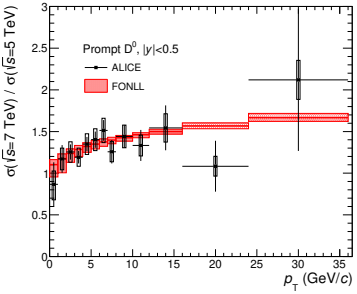
Outlook

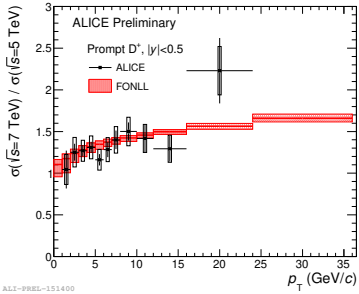
- High multiplicity pp and pA collisions contain very interesting physics and will be important to explore more in that area.
- With the ongoing detector upgrades, the precision on the measurement will considerably increase.
- The improved impact-parameter resolution, together with the improved luminosity of the LHC accelerator complex, will improve the significance of the upcoming measurements.
- Furthermore, first measurements like R_{AA} of B meson and $\Lambda_{\mathrm{b}}^{+}/\mathrm{B}^{+}$ ratio will be possible.

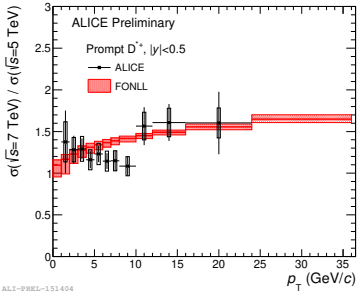
Thank You...

BACK-UP

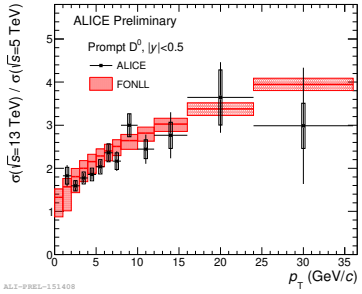
Results: Cross-section ratios in pp collisions (7 TeV/5 TeV)

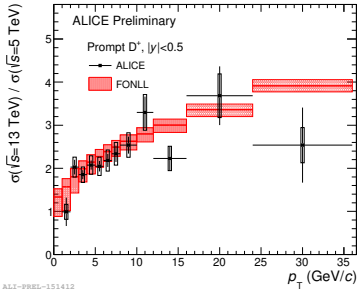


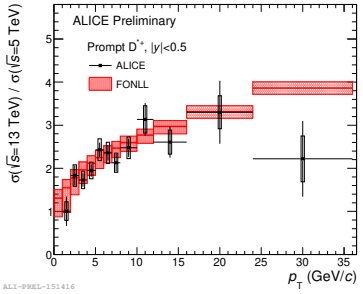




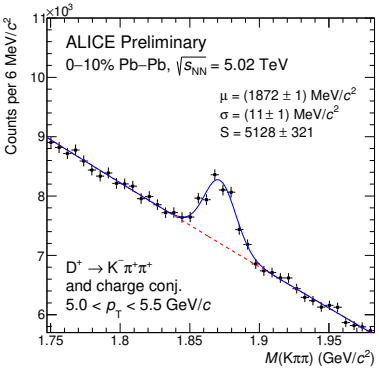
Results: Cross-section ratios in pp collisions (13 TeV/5 TeV)

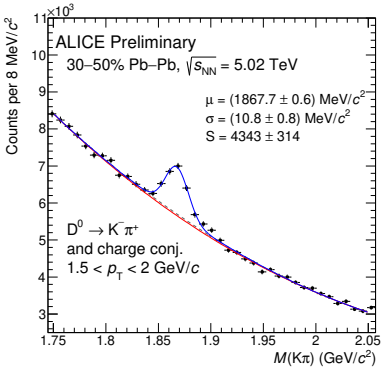




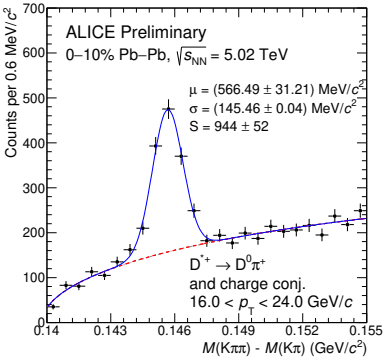


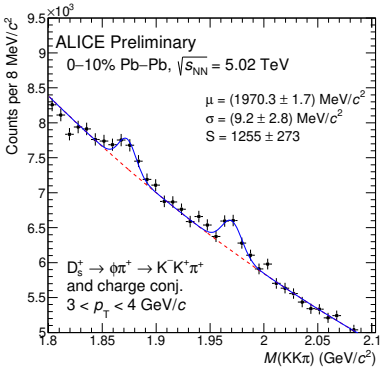
D mesons Invariant mass spectra: Pb–Pb collisions



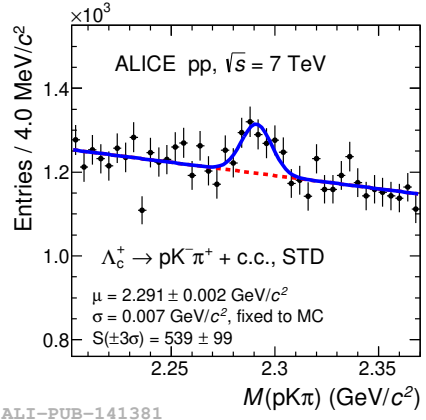


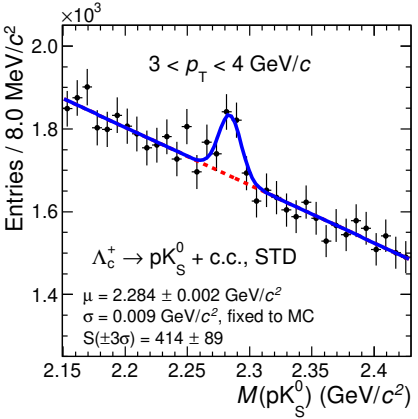
D mesons Invariant mass spectra: Pb–Pb collisions





Λ_c^+ invariant mass spectra





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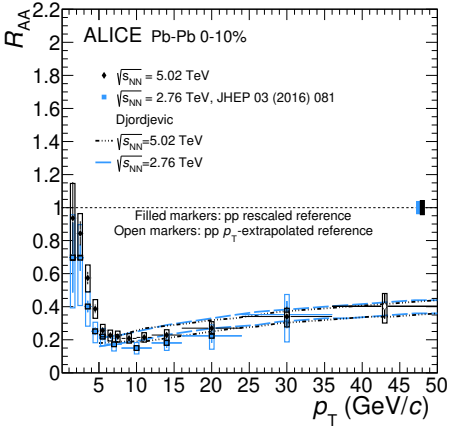
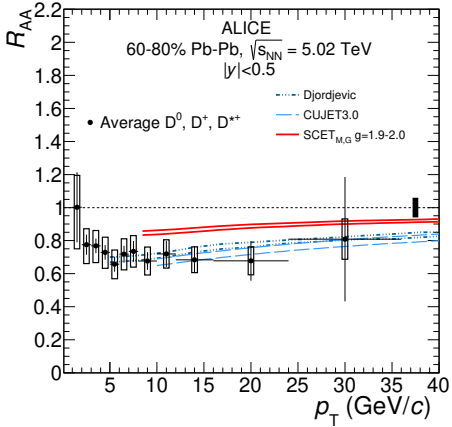
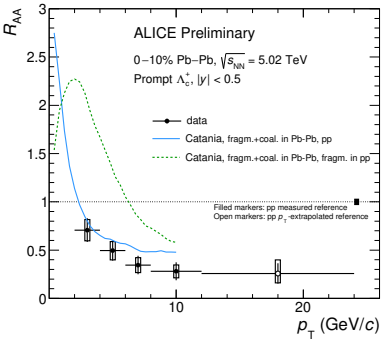
Results: D mesons in Pb-Pb collisions

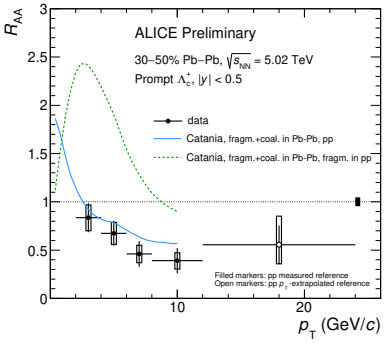




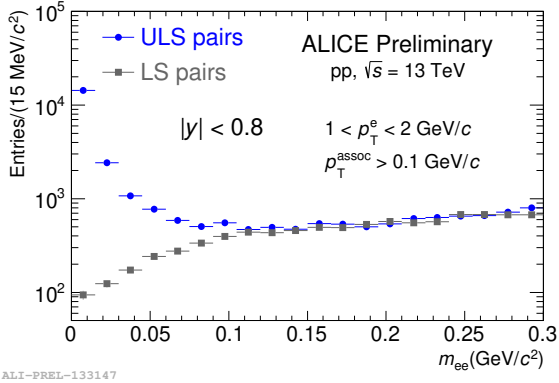
- R_{AA} consistent with various theoretical model.

Results: Λ_c^+ baryons in Pb-Pb collisions (2018 Data)



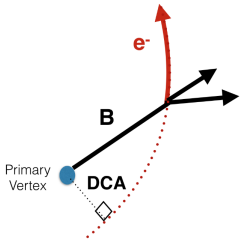


Analysis Strategy: Electrons from heavy quarks via photonic electron tagging method



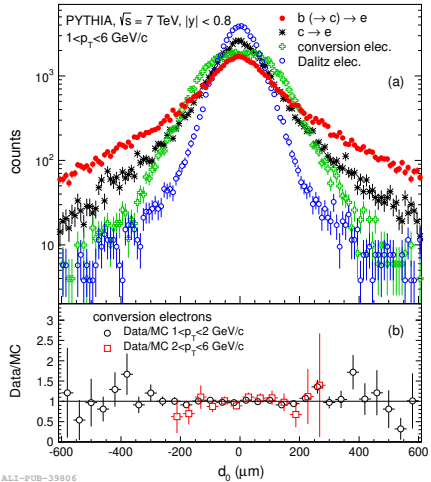
- Electrons from Dalitz decays and photon conversions are the important background sources.
- Heavy-flavour electron yield is obtained by subtraction of photonic background which is estimated using so called Photonic-electron tagging method.
- In this method, the background is created by building invariant mass distribution of like and unlike sign pairs and it is corrected for the tagging efficiency (conditional probability of finding the electron partner in the pair).

Analysis Strategy: Electrons from beauty quarks via DCA cut method



- The b $\rightarrow$ e have larger DCA compared to the electron background $\Rightarrow$ cut on the minimum DCA to increase the S/B ratio.
- In pp and p-Pb collisions, $|\mathrm{DCA}| > [64+780 \times \exp(0.56 p_{\mathrm{T}})]$ (DCA in μm, p_{T} in GeV/c)).

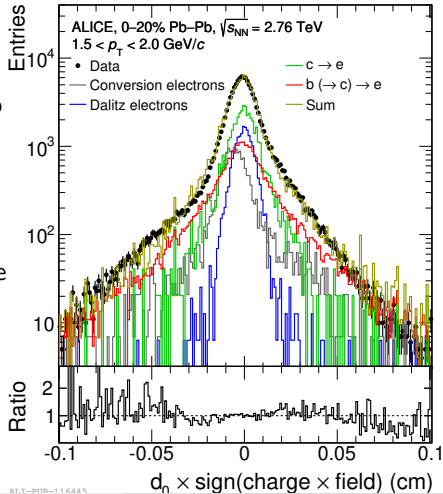
(pp 7 TeV and p-Pb 5.02 TeV)



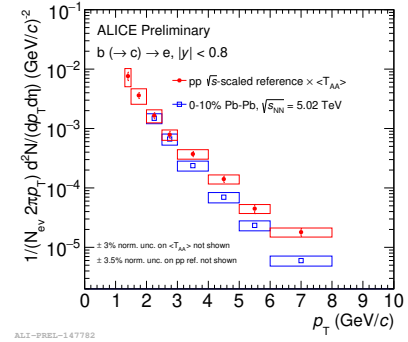
Analysis Strategy: Electrons from beauty quarks via DCA Template fits

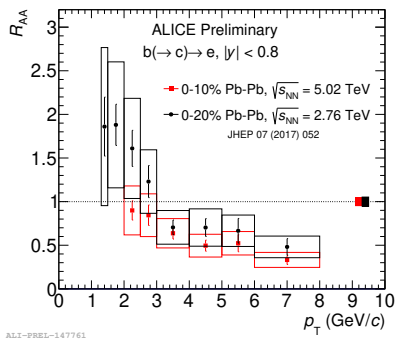
(Pb-Pb 2.76 and 5.02 TeV)

- Low-p_{T} analysis, DCA templates like Dalitz, conversion electrons, c $\rightarrow$ e, and b $\rightarrow$ e obtained using MC and fit to data using a log-likelihood fitting routine.
- High-p_{T} analysis, $\Rightarrow$ just two templates for c $\rightarrow$ e and b $\rightarrow$ e since, Dalitz and conversion electrons are removed using data-driven method along with the hadron contamination.
- DCA templates are further corrected to better match to the data since they are not well reproduced in the Monte Carlo sample.
  - Shift DCA mean and correct resolution using Improver task.
  - Reweight the D and B meson p_{T} spectra.
  - Correct $\Lambda_{\mathrm{c}}/\mathrm{D}^0$, $\mathrm{D}^+/\mathrm{D}^0$, and $\mathrm{D}_{\mathrm{s}}^+/\mathrm{D}^0$ ratios in the charm template based on ALICE measurements.



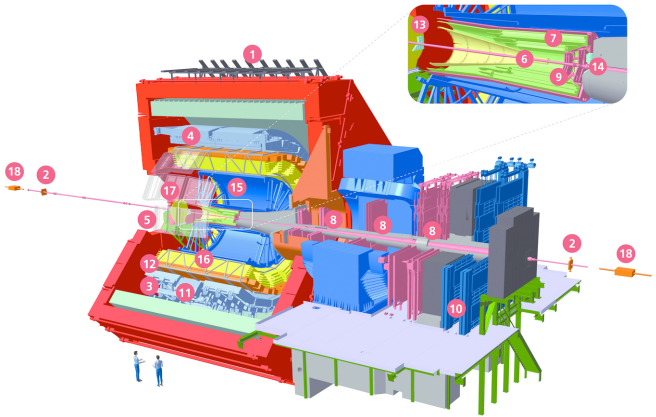
Results: Electrons from beauty quarks in Pb-Pb at 5.02 TeV





- R_{AA} shows good agreement with Run 1 measurement.
- Indication of smaller supression of b ($\rightarrow$ c)$\rightarrow$ e with respect to b, c $\rightarrow$ e at low/intermediate p_{T}.
- The scaled pp reference is used which is obtained from scaling it from 7 TeV using FONLL.
- Analysis of new pp reference is ongoing which would reduce the systematic uncertainties in the R_{AA} measurement and can give more precise results.

ALICE: RUN3



1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter

Models

Kang et al., incoherent multiple scattering: Phys. Lett. B 740, 23 (2015)
Bith inial-state and final-state interaction
Sharma et al., coherent multiple scattering: Phys. Rev. C 80, 054902 (2009)
Energy loss in cold nuclear matter and shadowing
FNOLL + EPOS09NLO: JHEP 9805, 007 (1998) + JHEP 0904, 065 (2009)
Initial state-effects (nuclear shadowing)
Blast-wave calculation: Phys. Lett. B 731, 51 (2014)
Hydrodynamic expansion

MC@sHQ+EPOS2: PR C89 (2014) 014905
Coll+Rad Eloss, recombination, EPOS-expansion

PHSD: PR C92 (2015) 1, 014910, PR C93 (2016) 3, 034906
Parton-Hadron-String Dynamics transport, coalescence

Xu, Cao, Bass: PR C88 (2013) 044907
Langevin with Coll+Rad Eloss, recombination+hydro

SCETM,G NLO: arXiv: 1610.02043
Soft Collinear Effective Theory, Bjorken expansion

Djorkevic: PR C92 (2015) 024918
Coll+Rad Eloss, recombination, finite-size hydro

POWLANG HTL: EPJ C71 (2011) 1666; JP G38 (2011) 124144
Langevin transport, Coll Eloss, recombination, hydrodynamics

AdS/CFT: JHEP 1411 (2014) 017; PR D91 (2015) 8, 085019;
Ads/CFT correspondence, Langevin Eloss + fluctuations, hydro

BAMPS: JP G 38 (2011) 124152; PL B 717 (2012) 430
Boltzmann transport, Coll. Eloss, expansion

TAMU: PL B735 (2014) 445-450
Transport, Coll. Eloss, resonant scatt. and coalescence+hydro

Models

TRANSPORT MODELS	Collisional Energy loss	Radiative Energy loss	Coalescence	Hydro	nPDF
BAMPS + rad. J. Phys. G42 (2015) 115106	✓	✓	✗	✓	✗
LBT arXiv:1703.00822	✓	✓	✓	✓	✓
PHSD PRC 93 (2016) 034906	✓	✓	✓	✓	✓
POWLANG EPJC 75 (2015) 121	✓	✗	✓	✓	✓
TAMU Phys. Lett. B735 (2014) 445	✓	✗	✓	✓	✓
MC@sHQ+EPOS PRC 89 (2014) 014905	✓	✓	✓	✓	✓
pQCD Eloss MODELS	**Collisional Energy loss**	**Radiative Energy loss**	**Coalescence**	**Hydro**	**nPDF**
CUJET3.0 JHEP 02 (2016) 169	✓	✓	✗	✗	✗
Djordevic PRC 92 (2015) 024918	✓	✓	✗	✗	✓
SCET JHEP 03 (2017) 146	✓	✓	✗	✗	✓

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[2] Sharma R, Vitev I and Zhang C, Phys. Rev. C 80, 054902 (2009).
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