Enhanced production of Λ_c in proton-proton collisions at the LHC

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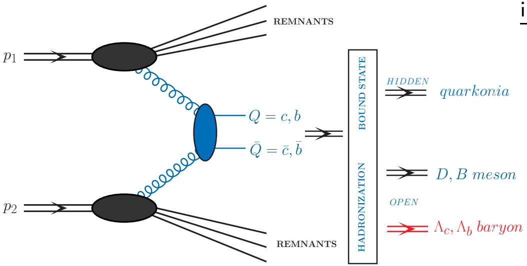
Heavy Flavours at high energies

Heavy-flavours (HF) ⇒ open or hidden charm and beauty ⇒ study of QCD

- among the most important tools in high-energy *pp*, *pA* and *AA* collisions

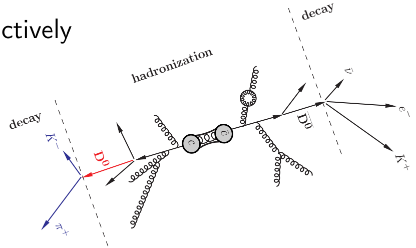


in proton-proton interactions:

- important tests of our understanding of various aspects of QCD quarkonium bound state ⇒ non-perturbative aspects of QCD calculations
- heavy quark mass ⇒ perturbative QCD
- *B* and *D* mesons and/or Λ-baryons ⇒ non-perturbative aspects of hadronization in QCD

Production of HFs is one of the most actively studied topics at the LHC

- **indirect method** ⇒ leptons from semileptonic decays of heavy flavours
- **direct method** ⇒ open heavy mesons
- Λ_c-baryon ⇒ an interesting extension of the standard studies



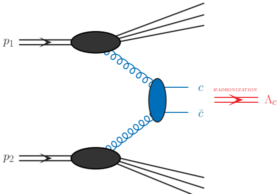
Studies of charm production at the LHC

our last years activity in Heavy Flavours

- model of calculations of charm cross section at high energies:
  k_T-factorization approach $\Rightarrow$ off-shell initial state partons and unintegrated PDFs
  + independent parton fragmentation picture
  - inclusive D meson (transverse momentum and rapidity distributions)
  - $D\bar{D}$-pair production (more exclusive correlation studies)
  - double and triple charm production (multi-parton interactions)
  - charm meson associated with jets
  - inclusive J/ψ-meson (color evaporation model)
  - nonphotonic leptons (semileptonic decays of charm meson)
  - prompt atmospheric neutrino flux (charm in the Earth's atmosphere)

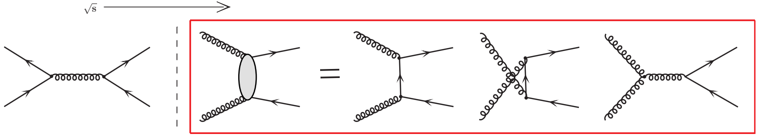
very recently: First measurements of inclusive Λ_c production
in proton-proton scattering at $\sqrt{s} = 7$ TeV

- LHCb data: $2 < y < 4.5$ and $2 < p_T < 8$ GeV
- ALICE data: $|y| < 0.5$ and $1 < p_T < 8$ GeV
- the data sets not fully understood
- reported enhanced production of Λ_c at ALICE and LHCb

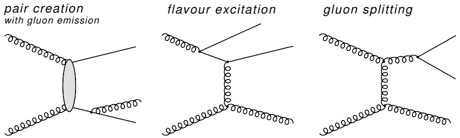


Charm cross section at high energies

- The leading-order (LO) partonic processes for $Q\overline{Q}$ production $\Rightarrow$ gluon-gluon fusion dominant at high energies



- Main classes of the next-to-leading order (NLO) diagrams:



the NLO corrections of a special importance for charm production!

the observables of the interest $\Rightarrow$ single-particle transverse momentum (inclusive spectra)
correlation observables (less inclusive $\Delta\varphi$, M_{inv}, pair p_T)

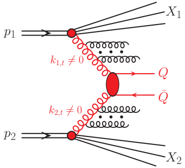
collinear approach:

- stat of the art for single particle spectra at NLO (FONLL, GM-VFNS)
- MC@NLO for correlations
- NNLO not available for charm/bottom

k_T-factorizaton:

- exact kinematics from the very beginning
- correlation observables directly calculable
- some contributions beyond the NLO available (also differentially)

k_T-factorization (high-energy factorization) approach



off-shell initial state partons ⇒

initial transverse momenta explicitly included $k_{1,t}$, $k_{2,t} \neq 0$

- additional hard dynamics coming from transverse momenta of incident partons (virtualities taken into account)
- very efficient for less inclusive studies of kinematical correlations
- more exclusive observables, e.g. pair transverse momentum or azimuthal angle very sensitive to the incident transverse momenta

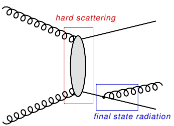
multi-differential cross section:

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \int \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2}$$

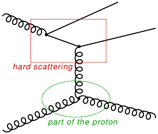
$$\times \quad \delta^2 \left(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t} \right) \mathcal{F}_g(x_1, k_{1,t}^2, \mu)\, \mathcal{F}_g(x_2, k_{2,t}^2, \mu)$$

- $\mathcal{F}_g(x, k_t^2, \mu)$ - (unintegrated) transverse momentum dependent PDFs
- the LO off-shell matrix elements $\overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2}$ available (analytic form)
- the higher-order matrix elements only at tree-level (KaTie Monte Carlo generator)
- part of higher-order (real) corrections effectively included in uPDF

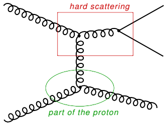
pair creation with gluon emission



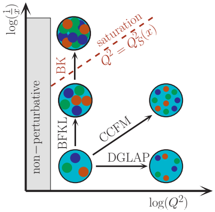
flavour excitation



gluon splitting



Unintegrated parton distribution functions (uPDFs)

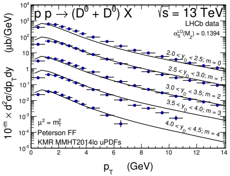


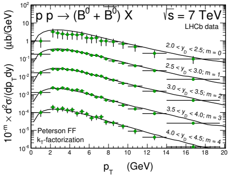
Most popular models:

- H. Jung et al. (CCFM, broad range of x)
- H. Jung et al. (DGLAP + Parton-Branching, broad range of x)
- Kimber-Martin-Ryskin (DGLAP-BFKL, broad range of x)
- Kwieciński-Martin-Staśto (BFKL-DGLAP, rather small x-values)
- Kutak-Staśto, Kutak-Sapeta (BK+saturation, only small x-values)

As a default set: Kimber-Martin-Ryskin (KMR) approach:

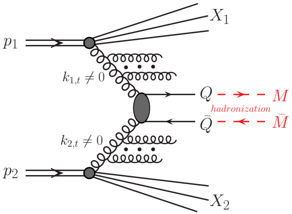
- calculated from collinear PDFs (most up-to-date PDF sets can be used)
- the unique feature: $k_t > \mu$ included as a consequence of angular ordering
  $\Rightarrow$ hard emissions from the uPDF
- in fact, only the KMR model with angular ordering effectively includes real higher-order contributions that correspond, e.g. for charm, to associated production with one (NLO) and two (NNLO) jets (or minijets)





k_T-factorization + KMR uPDF works very well for inclusive open charm and bottom mesons at the LHC (including correlation observables)

Heavy quark to open meson and/or baryon transition



- **independent parton fragmentation** picture $\rightarrow$ phenomenological fragmentation functions from e^+e^- data
- often used for heavy flavours (scale-independent): Peterson et al., Braaten et al., Kartvelishvili et al.
- more up-to-date (scale-dependent): Kneesch et al. (KKKS08) + DGLAP evolution

as a default: We assume the same fragmentation scenario for Λ_c-baryon as for D-meson

- the standard approach:

$$\frac{d\sigma(y, p_t^M)}{dy d^2 p_t^M} \approx \int \frac{D_{Q \to M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dy d^2 p_t^Q} dz$$

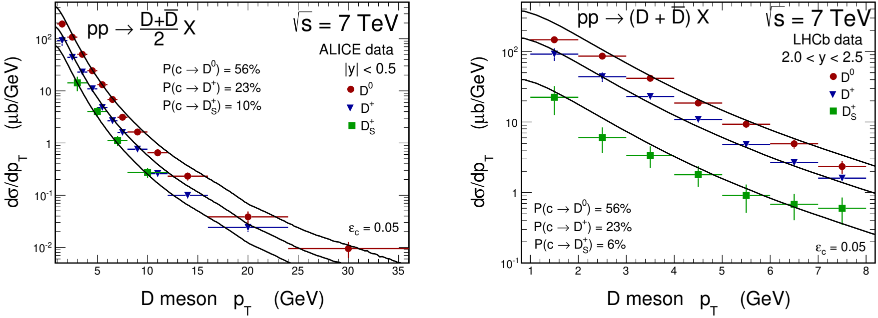
where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0,1)$
approximation: rapidity unchanged in the fragmentation process $\rightarrow y_Q = y_M$
$\Rightarrow$ rescalling of the transverse momentum at a constant rapidity (angle)

- Peterson FF parameter: $\varepsilon_c^{\Lambda_c} = \varepsilon_c^D = 0.05$ (the same shapes of the FFs)
- fragmentation probabilities from different experiments:
$f_{c \to \Lambda_c} = 0.0526 \pm 0.0031$ (e^+e^-), 0.0540 ± 0.0195 (DIS), 0.0639 ± 0.0122 (pp)

D-meson — ALICE and LHCb data

Theoretical computations:

k_T-factorization: $g^*g^* \to c\bar{c}$ + KMR uPDF + Peterson FF for $c \to D$ transition

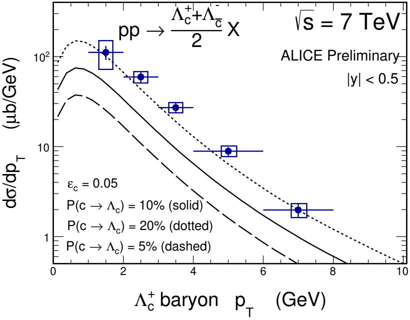


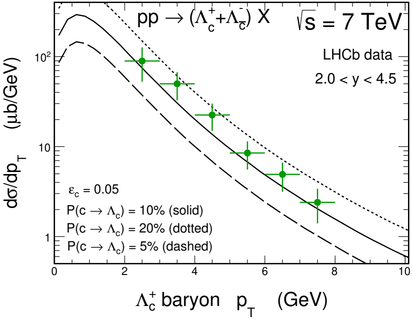
- very good description of the data for the D^0 and D^+ meson with the $f_{c\to D}$ known from the combined analysis of charm-quark fragmentation fraction measurements in the former e^+e^-, ep and pp experiments
- some excess for the D_s-meson
  $\Rightarrow$ we need larger $f_{c\to D_s}$ for the ALICE data than in the case of the LHCb
- we cannot describe both sets of data with the same $f_{c\to D_s}$ but both are consistent with those extracted from other experiments (large uncertainties)

Λ_c-baryon ALICE and LHCb data

Theoretical computations:

k_T-factorization: $g^*g^* \to c\bar{c}$ + KMR uPDF + Peterson FF for $c \to \Lambda$ transition





- the $f_{c\to\Lambda_c} = 0.05$ (typical pre-LHC value) clearly underpredicts both data sets
- the agreement between data and predictions with the increased $f_{c\to\Lambda_c}$ is better
- a visible difference appears in the observed agreement for the midrapidity ALICE and forward LHCb regimes
- the two types of the enhancement: the LHC to the pre-LHC results
  the ALICE to the LHCb results

Λ_c-baryon ALICE and LHCb data

Theoretical computations:

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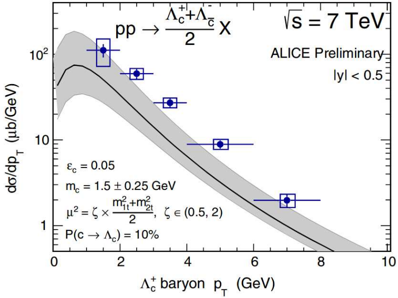
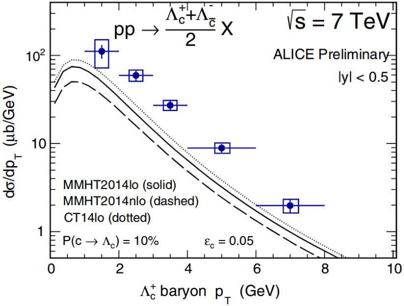


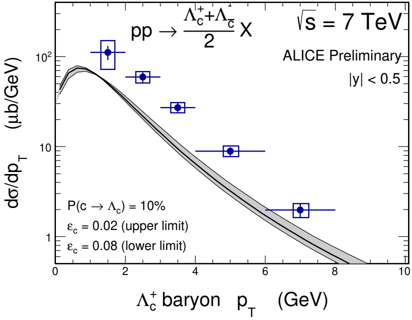


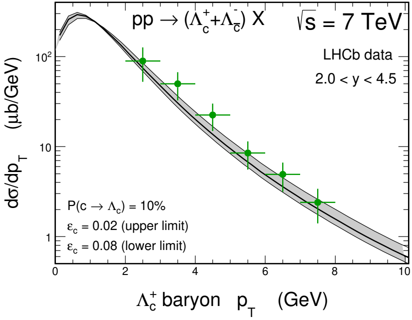
- the uncertainties related to the choice of the perturbative calculation parameters and due to the choice of the gluon collinear PDFs in the calculation of the KMR uPDF
- the upper limit of the uncertainties almost agrees with the ALICE experimental data
- however, this would not be the case for the LHCb data, where already the central value is consistent with the data
- the set of parameters which describes the ALICE data for Λ_c production would also lead to an overestimation of D-meson data
- still, at least the $f_{c \to \Lambda_c} = 0.1$ is needed

Λ_c-baryon — ALICE and LHCb data

Theoretical computations:

k_T-factorization: $g^*g^* \to c\bar{c}$ + KMR uPDF + Peterson FF for $c \to \Lambda$ transition



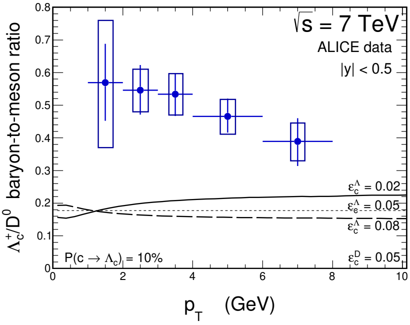


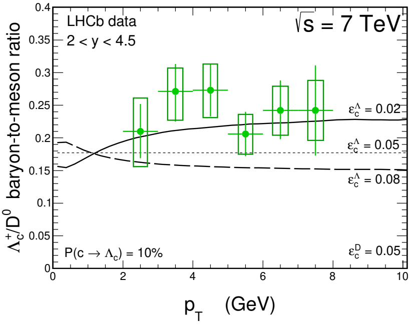
- Can the situation somehow change when the shape of the $c \to \Lambda_c$ fragmentation function is different?
- we modify the ε parameter for the $c \to \Lambda_c$ case
- some uncertainties appear but rather small and do not change the overall picture

Λ_c/D^0 baryon-to-meson ratio ALICE and LHCb data

Theoretical computations:

k_T-factorization: $g^*g^* \to c\bar{c}$ + KMR uPDF + Peterson FF for $c \to \Lambda$ transition



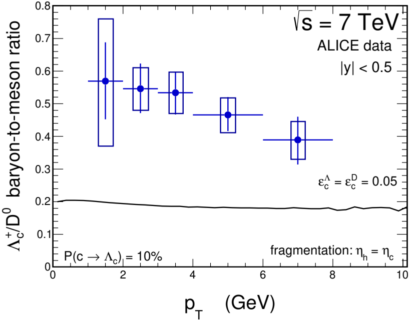


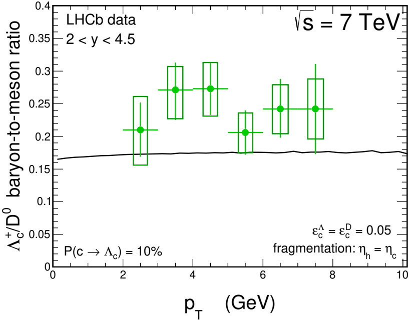
- transverse momentum dependence of the Λ_c/D^0 baryon-to-meson ratio experimentally observed
- from our default set $\Rightarrow$ naturally flat distribution
- some dependence may appear when different fragmentation functions are used for the $c \to \Lambda_c$ and $c \to D$ (different ε-parameters)
- softer (peaked at intermediate-z) FF for the $c \to \Lambda_c$ than for the $c \to D$ suggested by the data

Λ_c/D^0 baryon-to-meson ratio — ALICE and LHCb data

Theoretical computations:

k_T-factorization: $g^*g^* \to c\bar{c}$ + KMR uPDF + Peterson FF for $c \to \Lambda$ transition





- we follow the prescription: $\eta_h = \eta_c$, i.e., we assume that the charmed hadron is emitted in the same direction (in the *pp* cms frame) as the quark/antiquark
- here the energies are rescalled and the masses of the incident parton and final hadron are implicitly taken into account
- some p_T-dependece obtained but almost negligible
- works in the right direction (small-p_T enhanced for ALICE, and lowered for LHCb) but the effect is definately too small

Λ_c/D^0 baryon-to-meson ratio ALICE and LHCb data

Theoretical computations:

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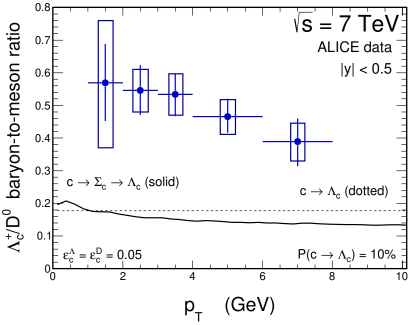

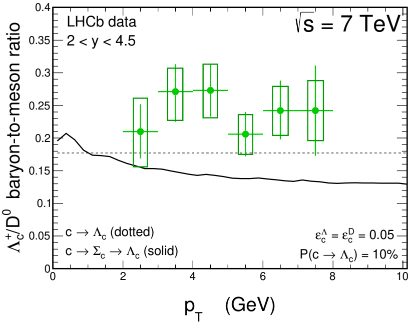

- in principle, Λ_c-baryons do not need to be exclusively directly produced
- they may come from a feed-down mechanism from excited baryonic states (examples of interest are Σ_c baryons both for $J = 1/2$ ($\Sigma_c(2455)$) and $J = 3/2$ ($\Sigma_c(2520)$))
- the feed-down mechanism could modify transverse momentum distributions.
- this mechanism leads to a small enhancement of the Λ_c/D^0 ratio at small transverse momenta, but it also causes it to decrease at larger p_T's

Conclusions

- we found that the fragmentation fraction $f_{c \to \Lambda_c} = 0.1 - 0.15$ describes the recent data from the LHCb but fails to describe the new ALICE data.
- even for LHCb, this number is slightly bigger than the values from the compilation of world results obtained from experimental data on e^+e^-, ep, pp and B meson decays
- although we could agree with the ALICE data using the standard estimation of model uncertainties related to the factorization/renormalization scale, quark mass, and PDF, we were not able to describe simultaneously the ALICE and LHCb Λ_c-baryon data as well as data on D-meson production with the same set of parameters.
- The new data from the ALICE suggests a much bigger $f_{c \to \Lambda_c}$ hadronization fraction than those obtained in other processes and in the recent LHCb measurements.
- The interpretation of the increased fragmentation fraction $f_{c \to \Lambda_c}$ is at present not clear and requires further studies, both on the theoretical and experimental sides

Thank You for attention!