Perspectives & Open Problems from Week 1

Paolo Lipari, Hallsie Reno

Proposed paper coming out of the workshop

- Something like "Open questions in heavy quark hadro-production at the intersection of collider and astroparticle physics"
- Big question: do we understand the dynamics of charm (and other heavy flavor) production? How well?
- What are the next steps to make progress?
- Lets discuss this later this morning…

- Monday

  M. Masip *Charm and muons in extensive air showers*

  F. Riehn *Heavy-quark production and further recent developments in SIBYLL*

  T. Pierog *Heavy-quark production and further recent developments in EPOS*

  S. Ostapchenko *Heavy-quark degrees of freedom, and further recent developments in QGSJET*

- Tuesday

  R. Ulrich *Measurements at accelerators particularly useful for High-Energy Astroparticle Physics: from fixed-target experiments to colliders*

  S. Turchikhin *Heavy-flavour production + selected news on forward physics in ATLAS*

  A. Grelli *Heavy-flavour production + selected news on forward physics in ALICE*

  A. Bursche *Heavy-flavour production + selected news on forward physics in LHCb*

- Wednesday

  C. Schwinn *Soft gluon and Coulomb resummation for top-quark pair production at hadron colliders*

  A. Broggio *Resummation techniques for heavy-quark production and Dark Matter annihilation*

- Thursday

  R. Coniglione *The KM3NeT and ANTARES Neutrino Telescopes: capabilities and issues at the highest energies*

  R. Gauld *Neutrino scattering at multi-TeV and PeV energies*

  A. Geiser *Heavy-flavour production in CMS + outlook on a combined treatment of heavy flavour measurements at HERA, LHC and elsewhere*

- Friday

  S. Plätzer *Heavy-flavour treatment in parton showers and (parton shower + hadronization) effects on heavy-quark hadroproduction*

  F. Prino *Phenomenological models of heavy-quark transport in Quark Gluon Plasma*

The LHC data on charm production

Results: visible cross-sections

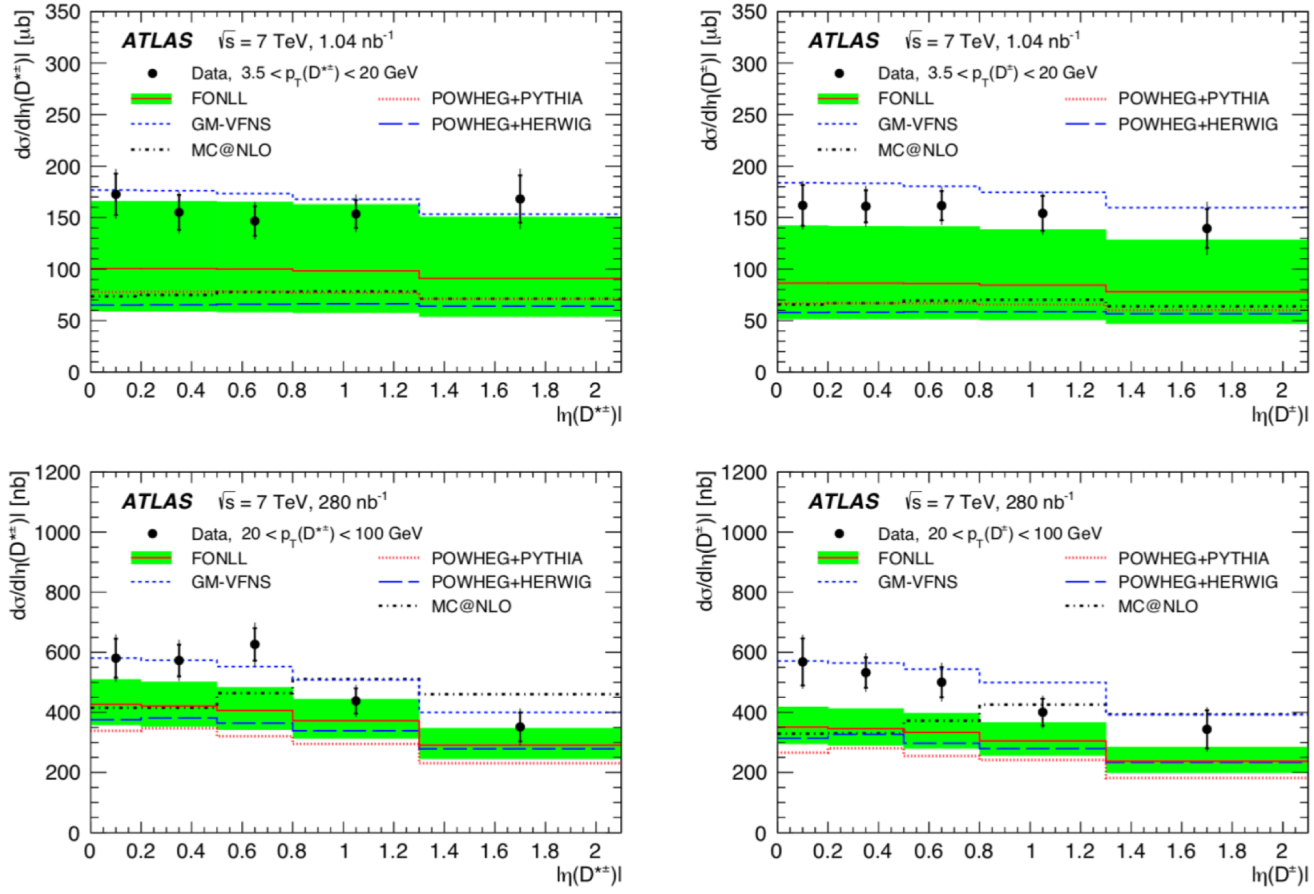
- Visible cross-sections measured:

	$\sigma^{\text{vis}}(D^{*\pm})$		$\sigma^{\text{vis}}(D^{\pm})$		$\sigma^{\text{vis}}(D_s^{*\pm})$	
Range [units]	low-p_T [μb]	high-p_T [nb]	low-p_T [μb]	high-p_T [nb]	low-p_T [μb]	high-p_T [nb]
ATLAS	331 ± 36	988 ± 100	328 ± 34	888 ± 97	160 ± 37	512 ± 104
GM-VFNS	340^{+130}_{-150}	1000^{+120}_{-150}	350^{+150}_{-160}	980^{+120}_{-150}	147^{+54}_{-66}	470^{+56}_{-69}
FONLL	202^{+125}_{-79}	753^{+123}_{-104}	174^{+105}_{-66}	617^{+103}_{-86}	-	-
POWHEG+PYTHIA	158^{+179}_{-85}	600^{+300}_{-180}	134^{+148}_{-70}	480^{+240}_{-130}	62^{+64}_{-31}	225^{+114}_{-69}
POWHEG+HERWIG	137^{+147}_{-72}	690^{+380}_{-160}	121^{+129}_{-64}	580^{+280}_{-140}	51^{+50}_{-25}	268^{+107}_{-62}
MC@NLO	157^{+125}_{-72}	980^{+460}_{-290}	140^{+112}_{-65}	810^{+390}_{-260}	58^{+42}_{-25}	345^{+175}_{-87}

- Statistical and systematics uncertainties generally of the same order
  - Tracking efficiency, luminosity and branching fractions are the main systematics sources
- GM-VFNS approach shows the best description of data
- FONLL and NLO+PS approaches are generally below data, but still consistent within uncertainties

Results: differential cross-sections – η

- GM-VFNS shows again a better description
- MC@NLO predicts a different η shape in the high-p_T range



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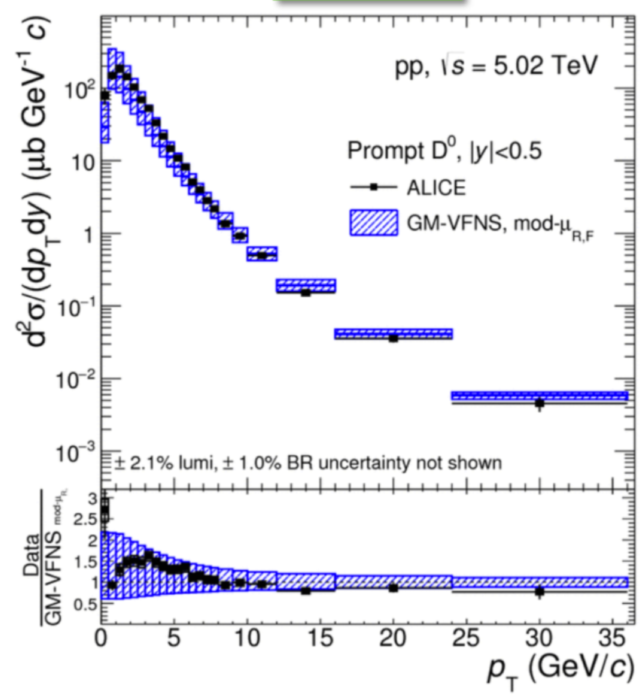
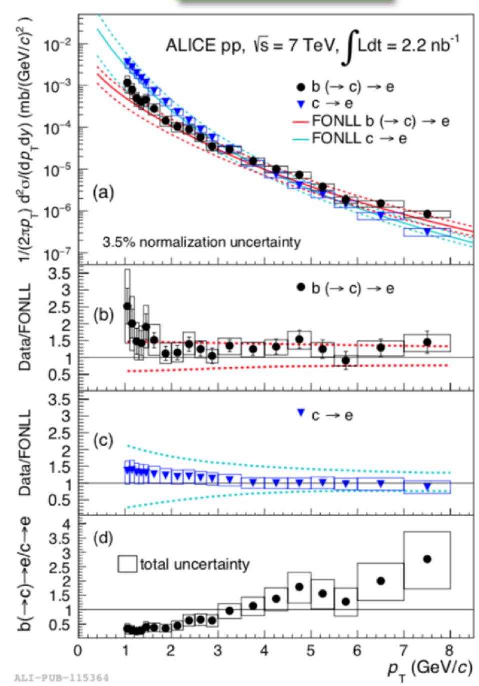
HF production cross-sections at mid-rapidity

D^0 at 5 TeV



HFE at 7 TeV



Phys.Lett. B763 (2016) 507-509

JHEP 1509 (2015) 148

- ☑ We are entering a precison era for the charm measurements in pp collisions.
- ☑ Data points, at few % level precision, start to pose strong constraints for pQCD based models

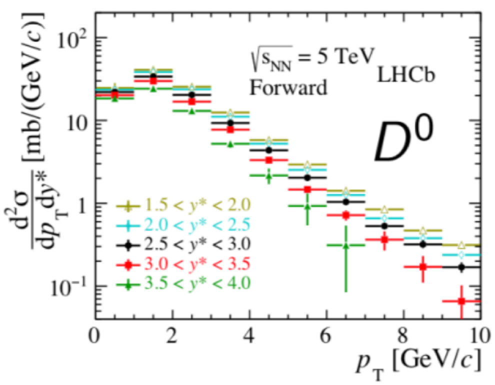
ALICE Coll, Eur.Phys.J. C77 (2017) no.8, 550

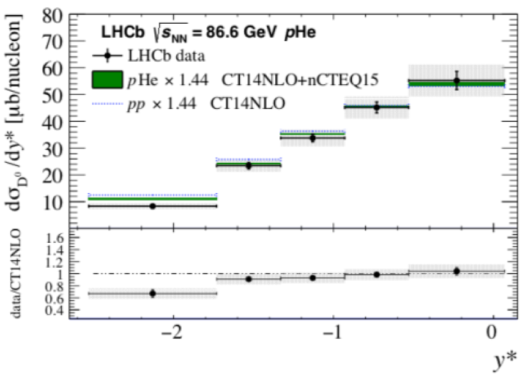
GM-VFNS: (Eur. Phys. J. C72 (2012) 2082

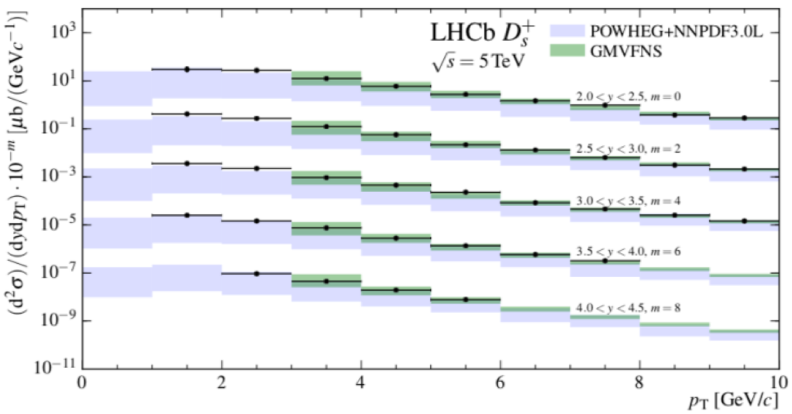
D^0, $D^\pm$, D^*, D_s^+ and Λ_c^+ production

JHEP 10 (2017) 090 , Phys. Rev. Lett. 122 (2019) 132002, JHEP 06 (2017) 147

- production cross section: D^0 5 TeV pPp; D^0, D^+, D_s^+, D^* 5 TeV pp; D^0, D^+, D^*, D_s^+, Λ_c^+ 7 TeV; D^0, D^+, D_s^+, D^* 13 TeV; D^0 86.6 GeV pHe and 110.4 GeV pAr
- production asymmetry: $D^\pm$ 7 TeV $D_s^\pm$ 7 TeV, 8 TeV

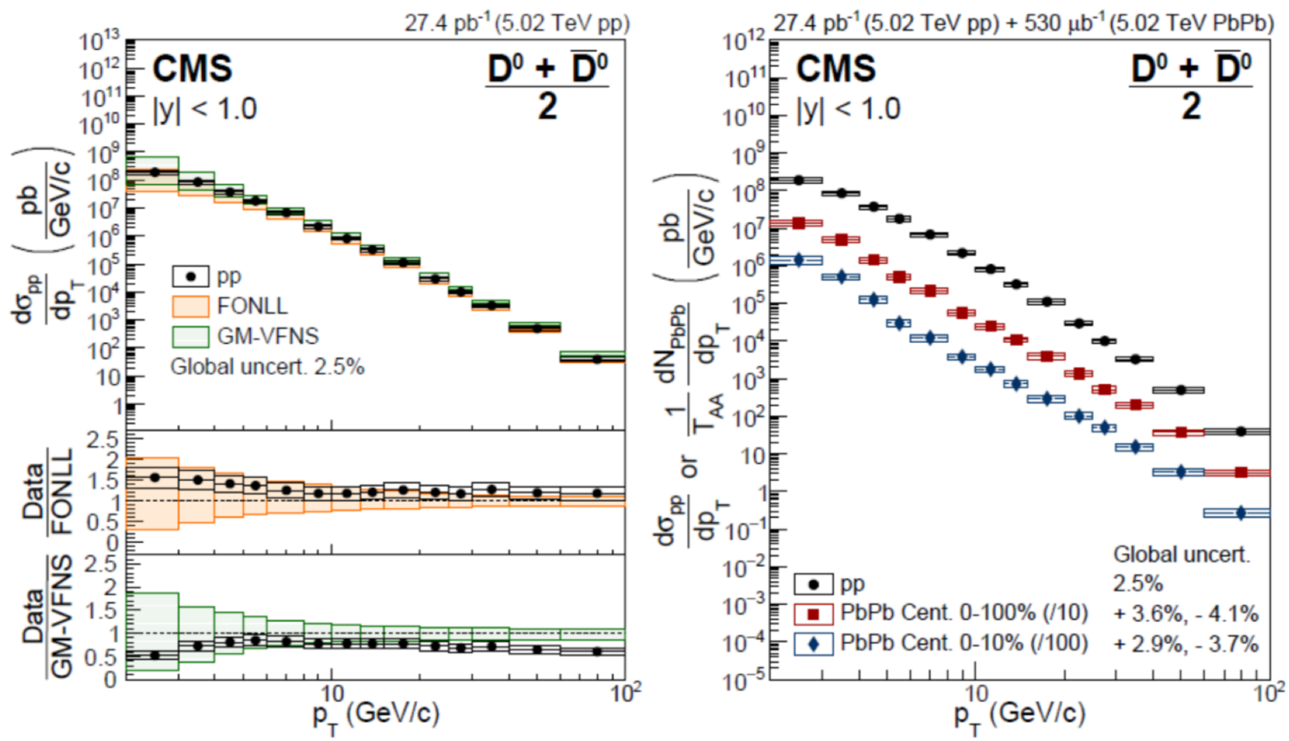






Charm in pp and PbPb @ 5.02 TeV

arXiv:1708.04962 Phys.Lett. B782 (2018)



same conclusions as for ATLAS, ALICE and LHCb results:
data and theory are consistent, but theory unc. >> data unc.

D^0 nuclear modification factor

arXiv:1708.04962 Phys.Lett. B782 (2018)

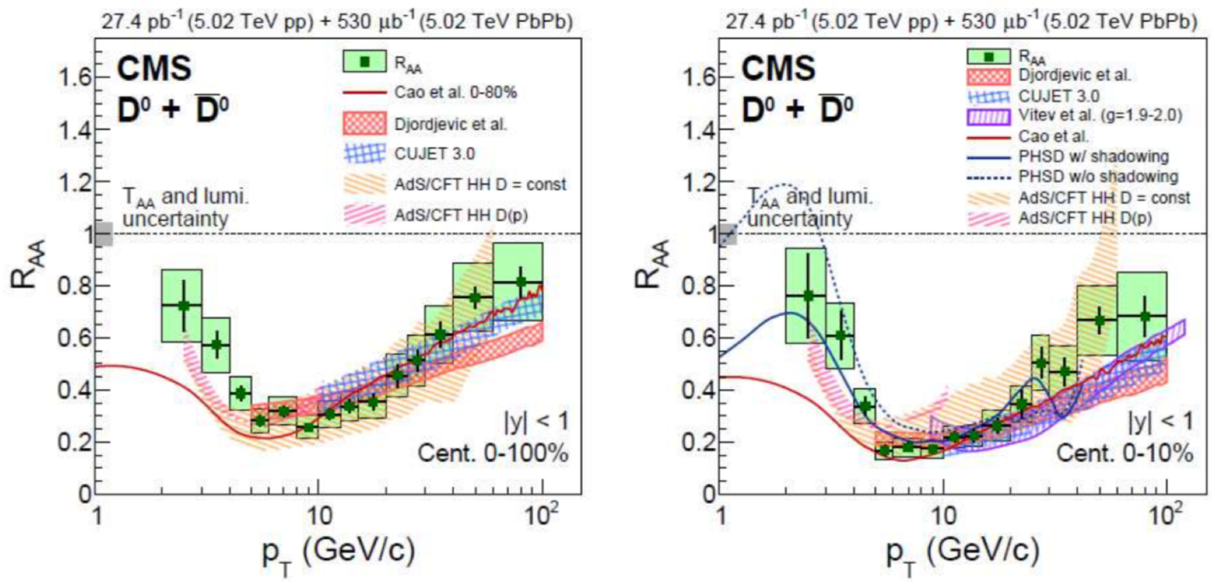
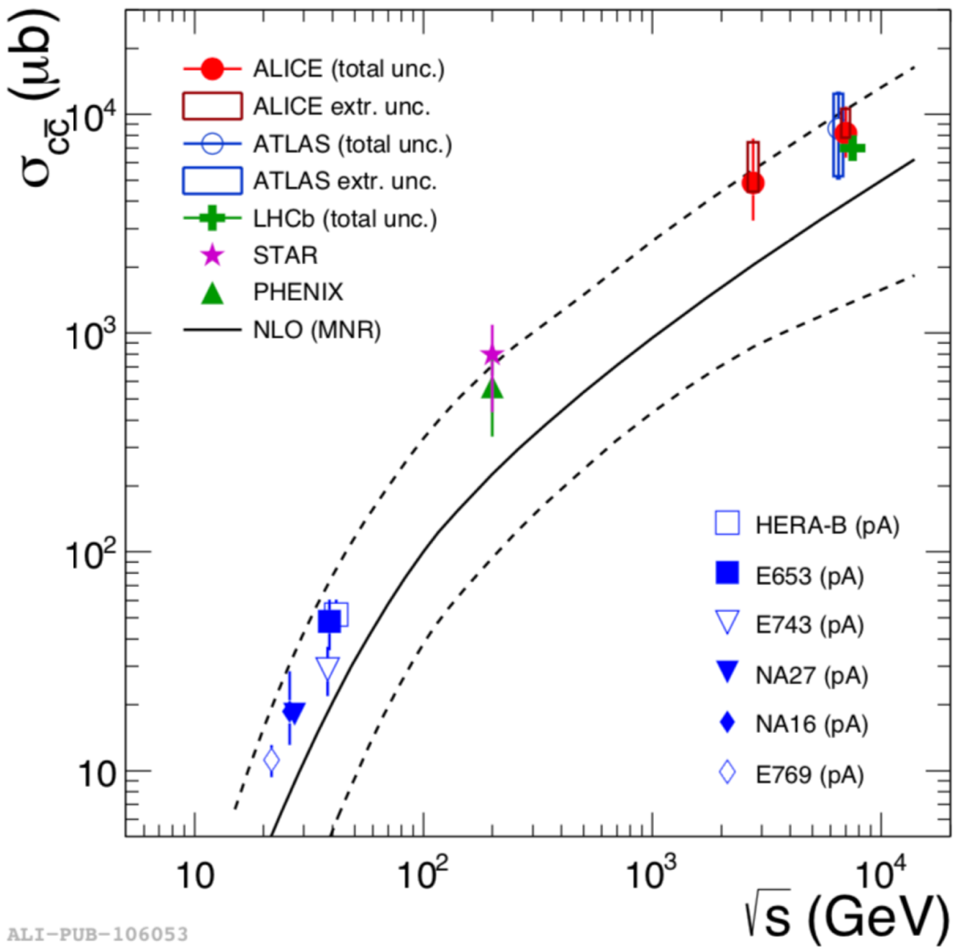


Figure 3: R_{AA} as a function of p_T in the centrality range 0–100% (left) and 0–10% (right). The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty, represented as a grey box at $R_{AA} = 1$, comprises the uncertainties in the integrated luminosity measurement and T_{AA} value. The D^0 R_{AA} values are also compared to calculations from various theoretical models [37–47].

Total charm cross-section

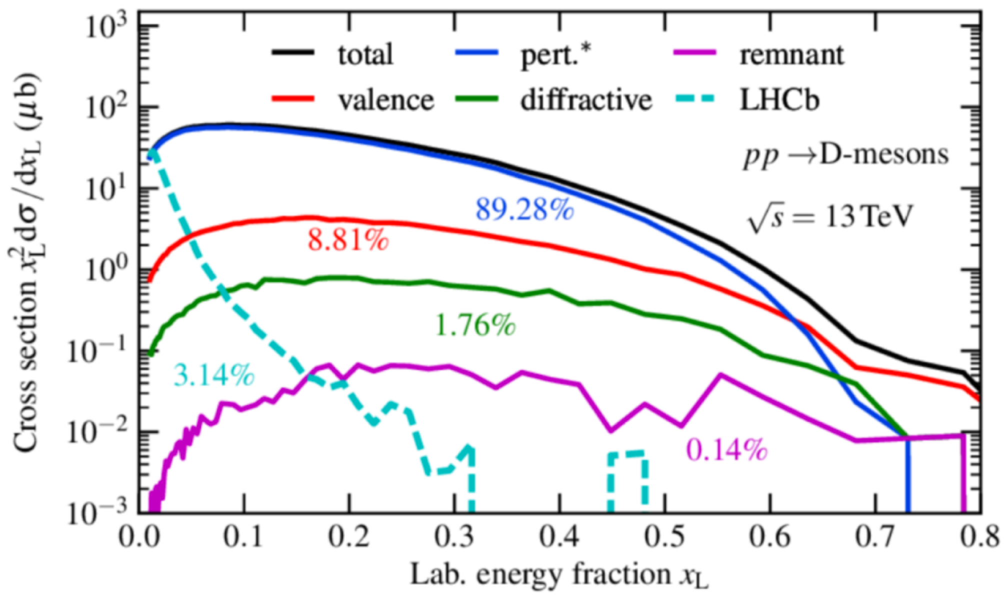


Phasespace coverage

LHCb only covers
small fraction

Source term

$$E_h^{\gamma}\frac{\mathrm{d}N_h}{\mathrm{d}E_h} = F_h$$



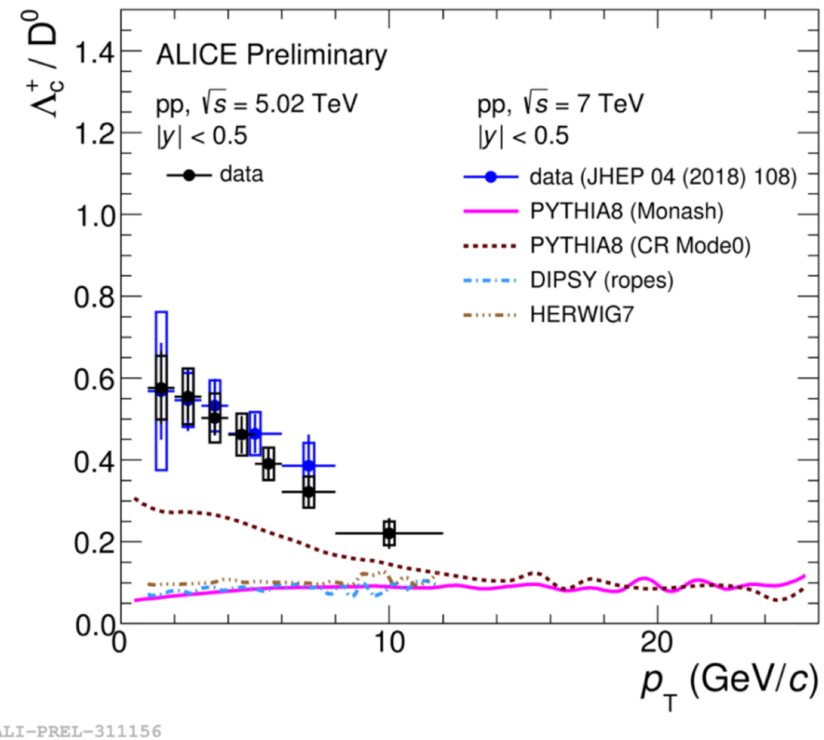
LHC detectors: not so great :(

Felix Riehn

Charmed Baryon Production in Hadronic Interactions.

1. Is there an “anomaly” ?
2. What is its origin ?

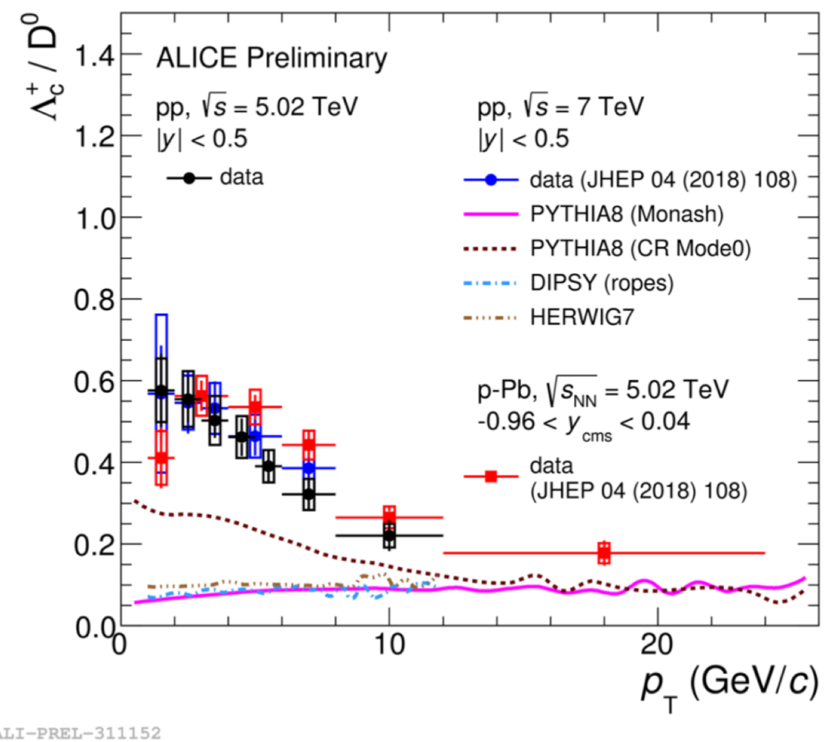
Λ_c production in pp, p-Pb



- Λ_c/D^0 largely understimated by models, only Pythia with CR get the shape but not the magnitude
- Result from HERA, obtained in a similar p_T range, sits in the 0.1-0.2 region. Challenge the universality of the fragmentation functions? Need to measure the z value
- New analysis in pp at 5 TeV largely improves the precision (factor 2 in [1,2] GeV/c) and extends the p_T range

Zeus Collaboration, ArXiv:1306.4862

Λ_c production in pp, p-Pb

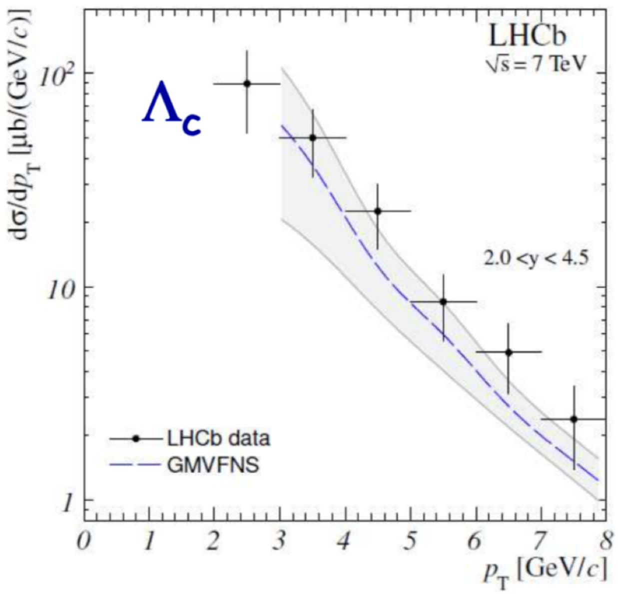


- Λ_c/D^0 largely understimated by models, only Pythia with CR get the shape but not the magnitude
- Result from HERA, obtained in a similar p_T range, sits in the 0.1-0.2 region. Challenge the universality of the fragmentation functions? Need to measure the z value
- New analysis in pp at 5 TeV largely improves the precision (factor 2 in [1,2] GeV/c) and extends the p_T range
- Comparison with p-Pb result shows a similar (?) trend. Need more data to conclude

Zeus Collaboration, ArXiv:1306.4862

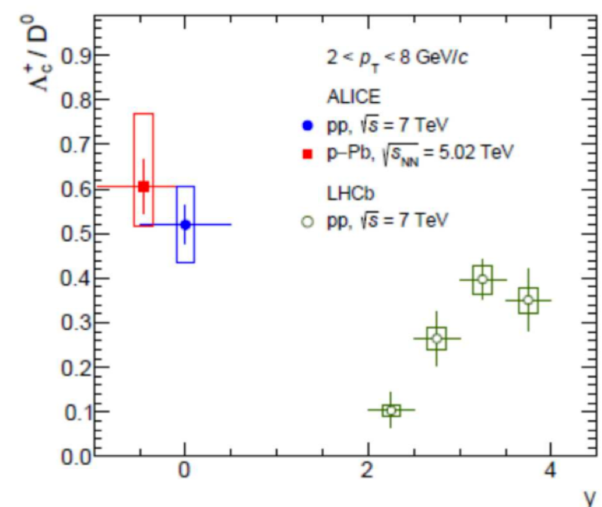
Lambda_c production in LHCb

arXiv:1302.2864, Nucl.Phys. B871 (2013) 1



- consistent with e+e- and ep !

arXiv:1712.09581



inconsistent with ALICE observation of nonuniversality at mid-rapity !?

Λ_c^+ production in pp collisions at $\sqrt{s}$ = 7 TeV and in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE Collaboration*

arXiv:1712.09581

Abstract

The p_T-differential production cross section of prompt Λ_c^+ charmed baryons was measured with the ALICE detector at the Large Hadron Collider (LHC) in pp collisions at $\sqrt{s} = 7$ TeV and in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at midrapidity. The Λ_c^+ and $\overline{\Lambda}_c^-$ were reconstructed in the hadronic decay modes $\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^+ \to pK_S^0$ and in the semileptonic channel $\Lambda_c^+ \to e^+\nu_e\Lambda$ (and charge conjugates). The measured values of the Λ_c^+/D^0 ratio, which is sensitive to the c-quark hadronisation mechanism, and in particular to the production of baryons, are presented and are larger than those measured previously in different colliding systems, centre-of-mass energies, rapidity and p_T intervals, where the Λ_c^+ production process may differ. The results are compared with the expectations obtained from perturbative Quantum Chromodynamics calculations and Monte Carlo event generators. Neither perturbative QCD calculations nor Monte Carlo models reproduce the data, indicating that the fragmentation of heavy-flavour baryons is not well understood. The first measurement at the LHC of the Λ_c^+ nuclear modification factor, R_{pPb}, is also presented. The R_{pPb} is found to be consistent with unity and with that of D mesons within the uncertainties, and consistent with a theoretical calculation that includes cold nuclear matter effects and a calculation that includes charm quark interactions with a deconfined medium.

	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)	Notes
CLEO [43]	$0.119 \pm 0.021 \pm 0.019$	ee	10.55	
ARGUS [42, 98]	0.127 ± 0.031	ee	10.55	
LEP average [80]	$0.113 \pm 0.013 \pm 0.006$	ee	91.2	
ZEUS DIS [51]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep	320	$1 < Q^2 < 1000$ GeV^2, $0 < p_T < 10$ GeV/c, $0.02 < y < 0.7$
ZEUS γp, HERA I [49]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	ep	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\|\eta\| < 1.6$
ZEUS γp, HERA II [50]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	ep	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\|\eta\| < 1.6$

Table 5: Comparison of the Λ_c^+/D^0 ratio as measured in e^+e^- and ep collision systems and at different centre-of-mass energies. Statistical and systematic uncertainties are reported (from references [42, 98] it was not possible to separate systematics and statistical uncertainties). See text for details about how the central values and quoted uncertainties were obtained. When indicated, the rapidity range refers to the centre-of-mass frame.

pp collisions at $\sqrt{s}$ =7 TeV, $|y| < 0.5$, and $1 < p_{\mathrm{T}} < 8$ GeV/c is

$$\left(\frac{\Lambda_{\mathrm{c}}^{+}}{\mathrm{D}^{0}}\right)_{\mathrm{pp}} = 0.543 \pm 0.061\ (\mathrm{stat}) \pm 0.160\ (\mathrm{syst}). \tag{5}$$

In p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02 TeV, $-0.96 < y < 0.04$, and $2 < p_{\mathrm{T}} < 12$ GeV/c the measured baryon-to-meson ratio is

$$\left(\frac{\Lambda_{\mathrm{c}}^{+}}{\mathrm{D}^{0}}\right)_{\mathrm{p\text{–}Pb}} = 0.602 \pm 0.060\ (\mathrm{stat})\ ^{+0.159}_{-0.087}\ (\mathrm{syst}), \tag{6}$$

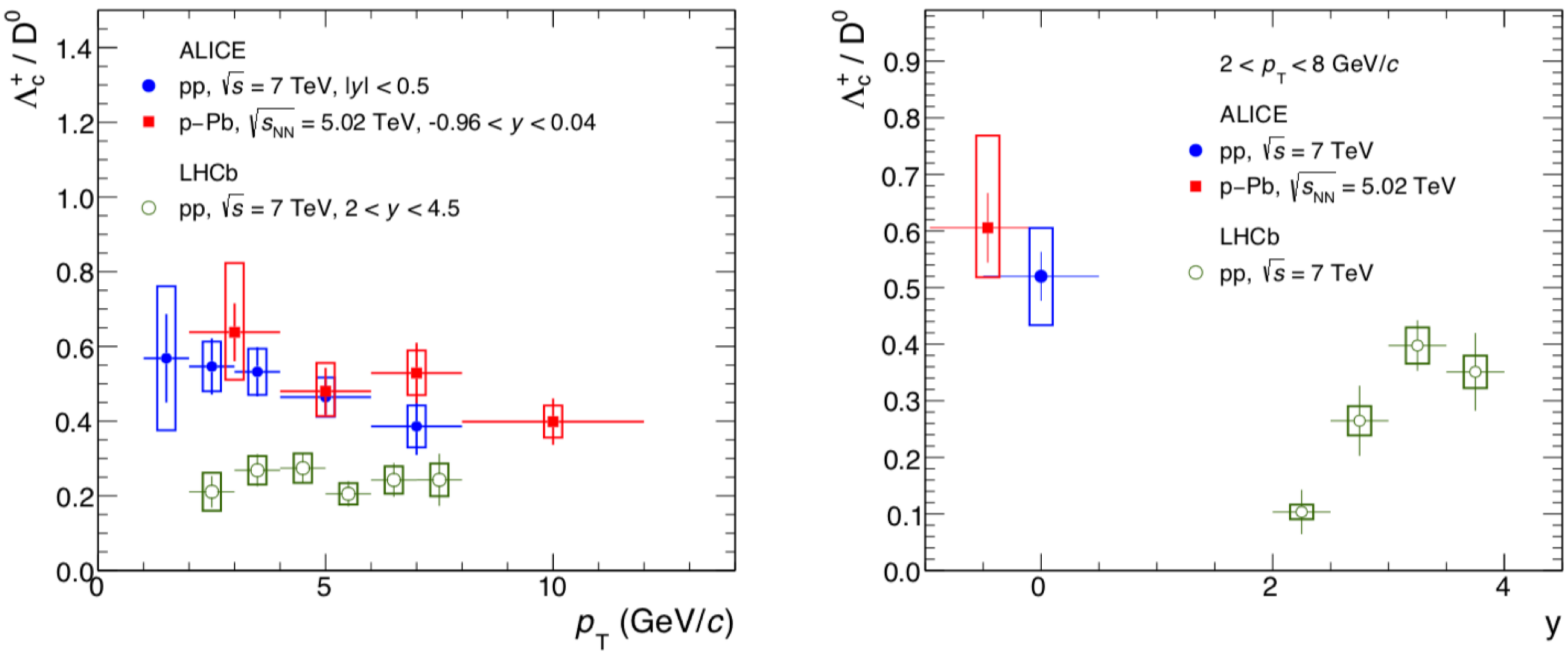


Figure 10: The Λ_c^+/D^0 ratio measured in pp and p–Pb collisions by ALICE, compared with the LHCb measurement [52, 97] as a function of p_T (left) and as a function of y for $2 < p_T < 8$ GeV/c (right).

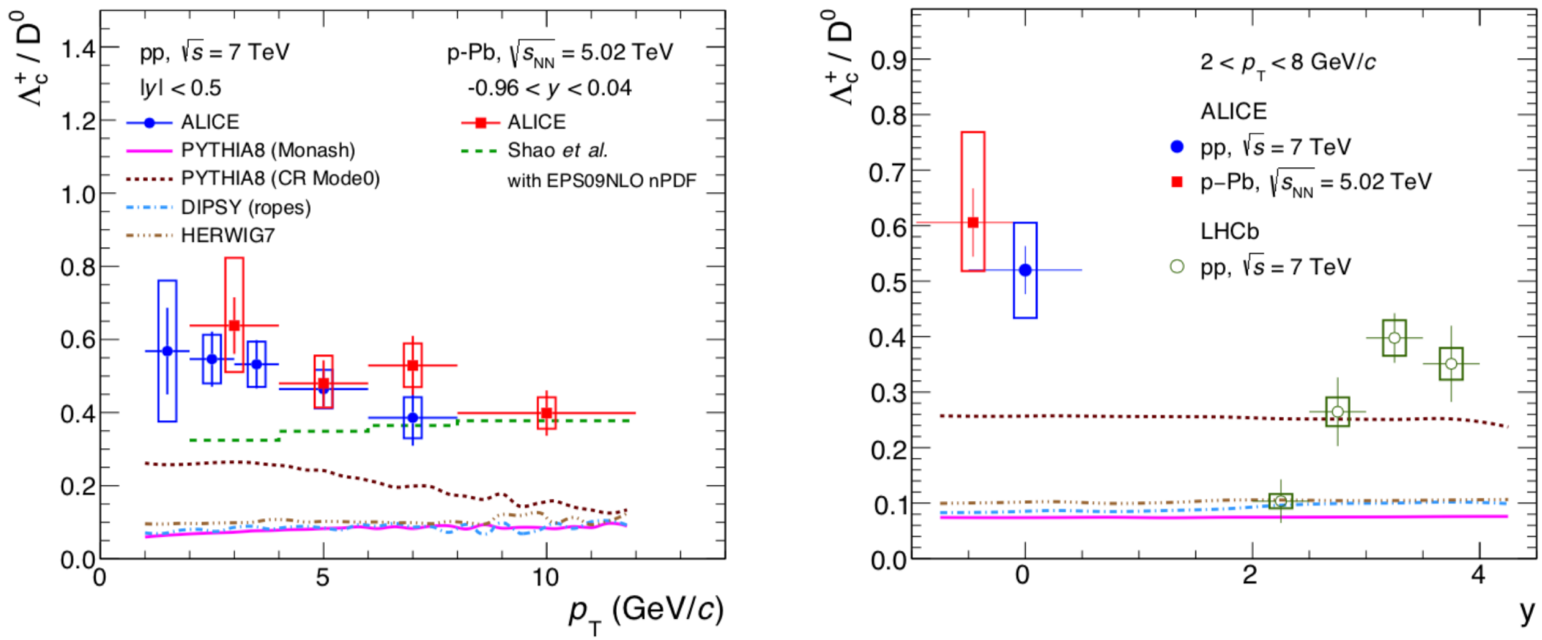
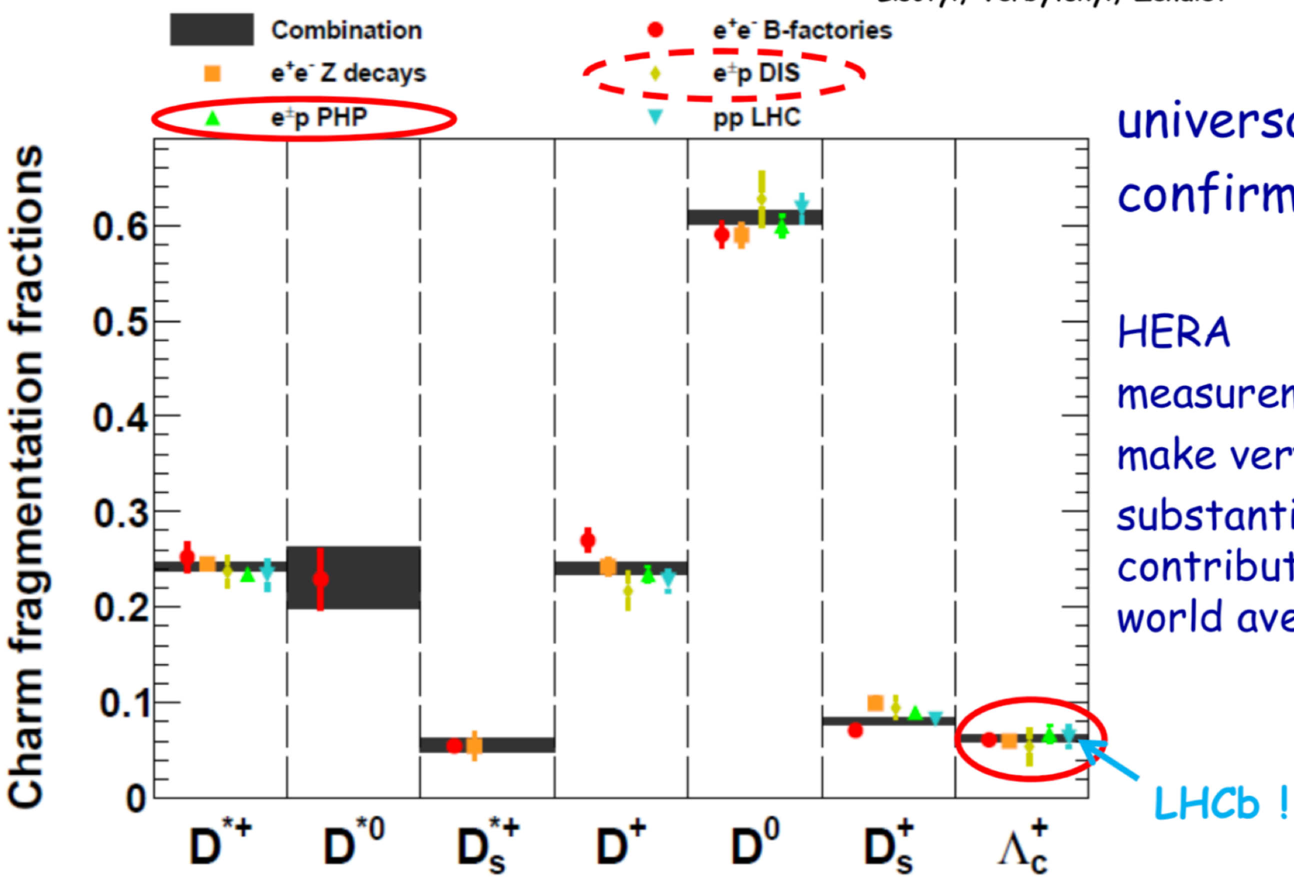


Figure 11: The Λ_c^+/D^0 ratio measured in pp and p–Pb collisions by ALICE as a function of p_T (left) and as a function of y for $2 < p_T < 8$ GeV/c (right). The measurements from pp collisions are compared with different event generators (quoted tunes for PYTHIA and DIPSY taken respectively from [17] and [18]). The p–Pb measurement as a function of p_T is also compared with calculations from Lansberg and Shao [94]. The predictions from event generators as a function of y are also compared with the LHCb measurement [52, 97].

Charm fragmentation fractions

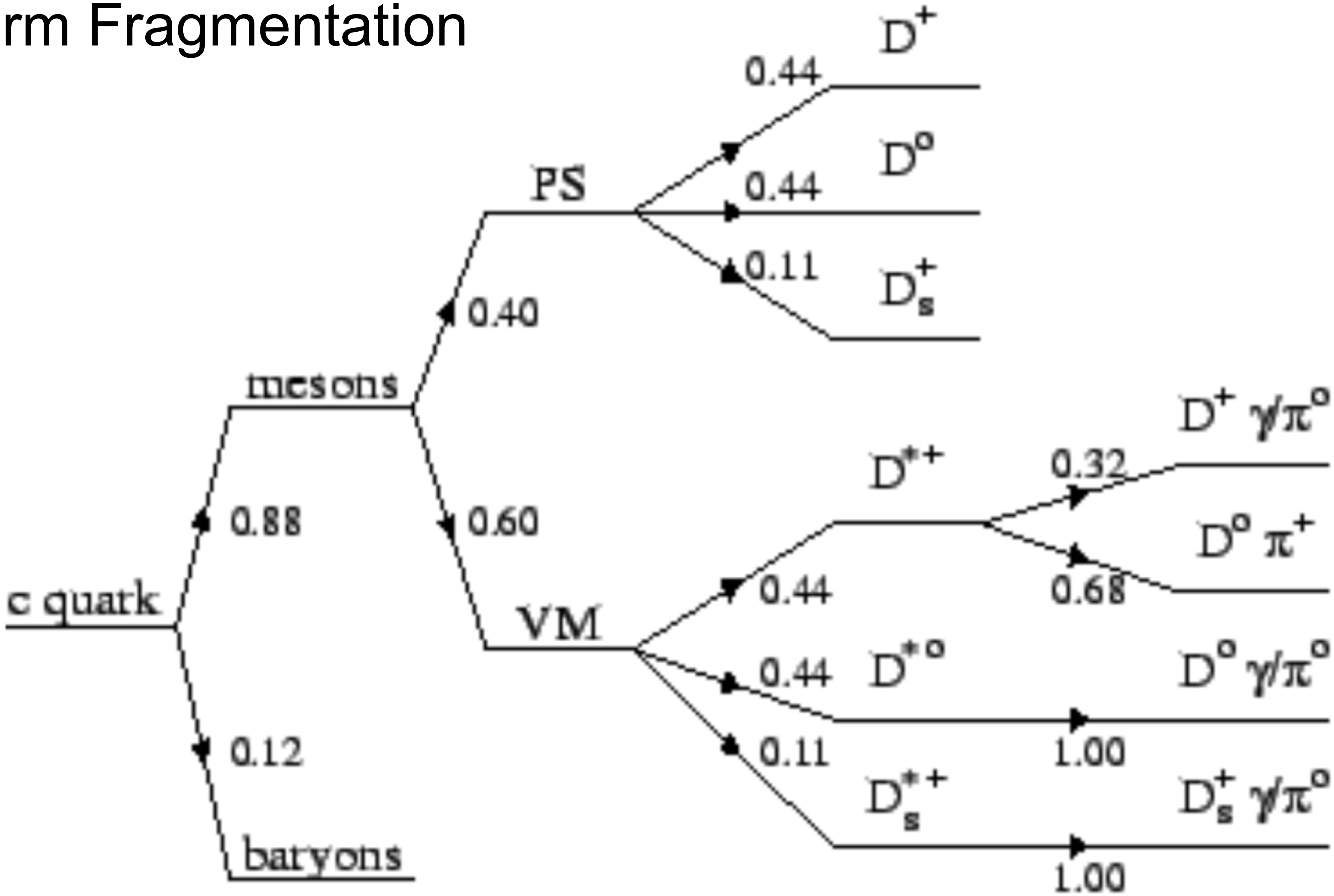
arXiv 1509.01061, EPJC 76 (2016) 397
Lisovyi, Verbytskyi, Zenaiev



universality confirmed

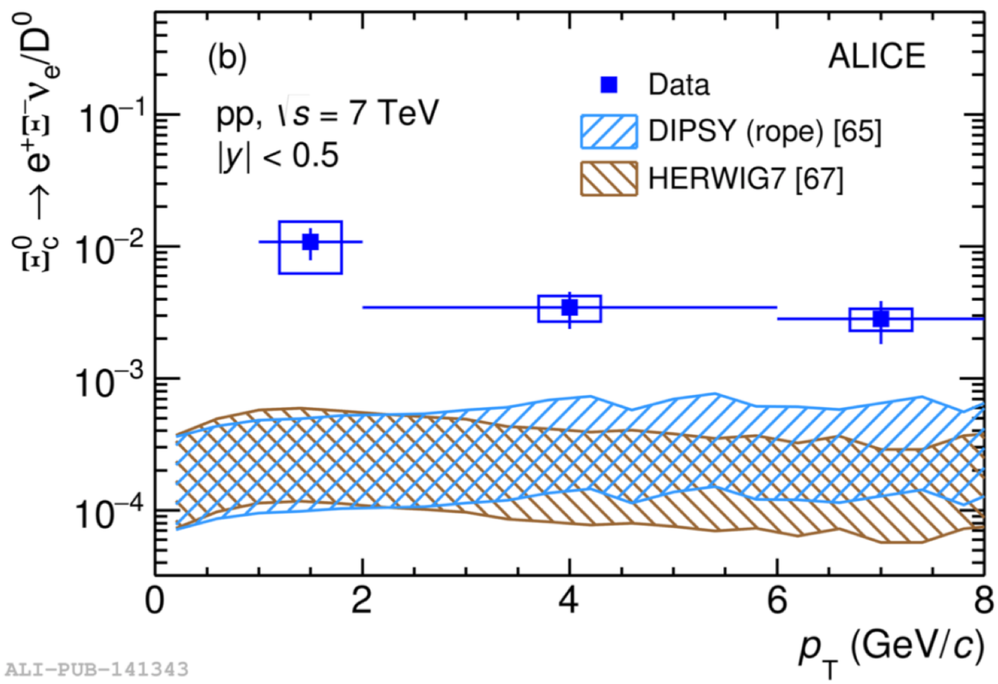
HERA measurements make very substantial contribution to world average

Charm Fragmentation



Ξ_c production in pp

ALICE Coll, Phys.Lett. B781 (2018) 8-19



☑ Ξ_c/D^0 largely understimated by models. Similar situation as for Λ_c

Volume 93B, number 4 PHYSICS LETTERS 30 June 1980

THE INTRINSIC CHARM OF THE PROTON

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and

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Received 22 April 1980

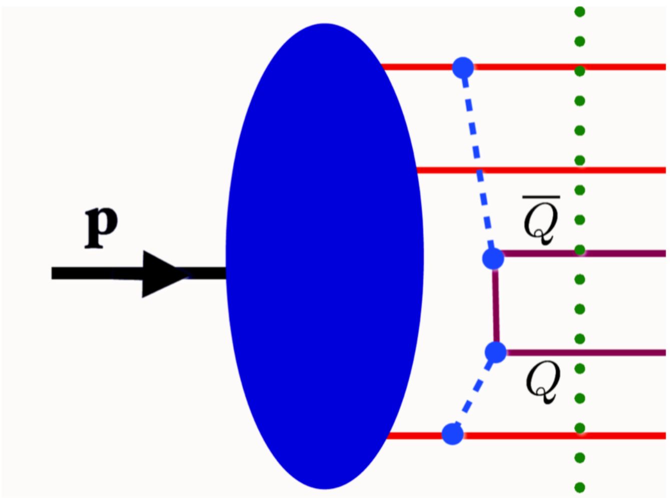


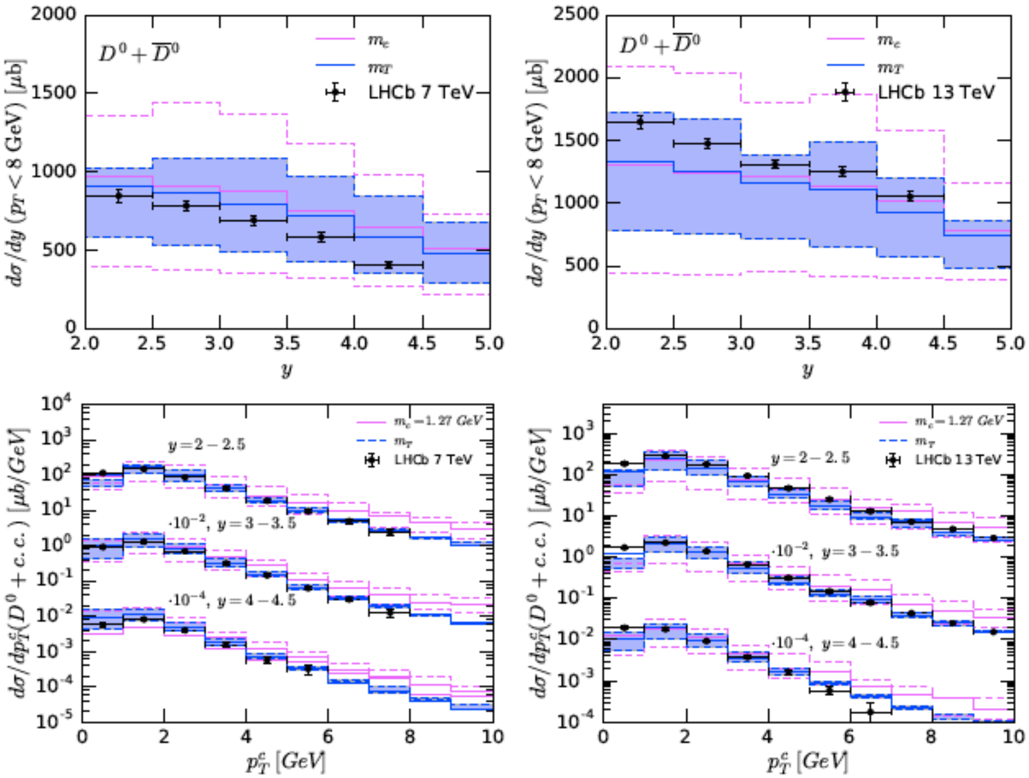
Figure 1: Five-quark Fock state $|uudQ\overline{Q}\rangle$ of the proton and the origin of the intrinsic sea.

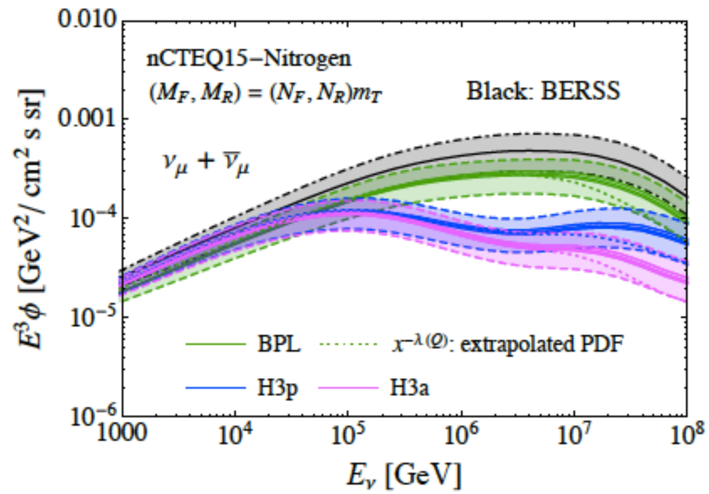
Recent data give unexpectedly large cross-sections for charmed particle production at high x_F in hadron collisions. This may imply that the proton has a non-negligible $uudc\bar{c}$ Fock component. The interesting consequences of such a hypothesis are explored.

- What are the limitations of fragmentation models? The discrepancy of ALICE on Λ_c, is it fragmentation or is it a different dynamics?
- Intrinsic charm – in proton pdfs/baryon-meson fluctuations/c-cbar fluctuations with beam fragmentation to forward charm hadrons.
- What is the definition of intrinsic charm? What is the evidence constraining these models? Ratios of Λ_c /D as a function of pT at ALICE – could this be intrinsic charm, or is this fragmentation? How much room experimentally is there for these effects?

Charm and the prompt atmospheric flux.

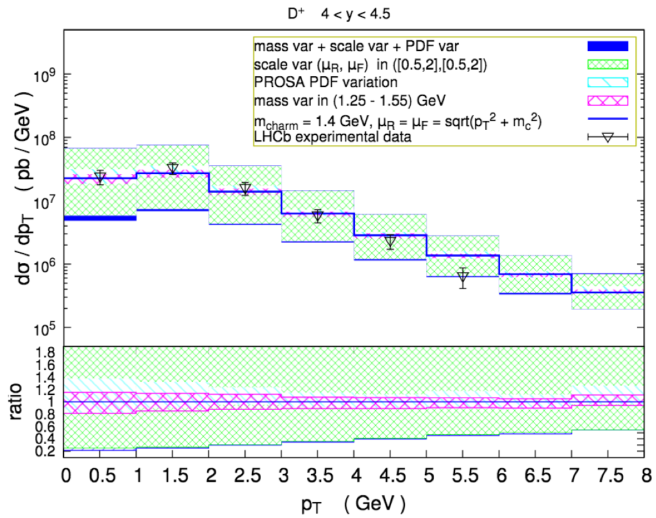
- How do we assess the uncertainty of charm production given what we know from collider measurements given their much small error bars relative to theoretical uncertainties?
  - What is the extrapolation uncertainty to get to the prompt flux, and what if there is a mix of perturbative and non-perturbative contributions?
  - When one optimizes parameters to meet the data, what are the predictions for the atmospheric flux?

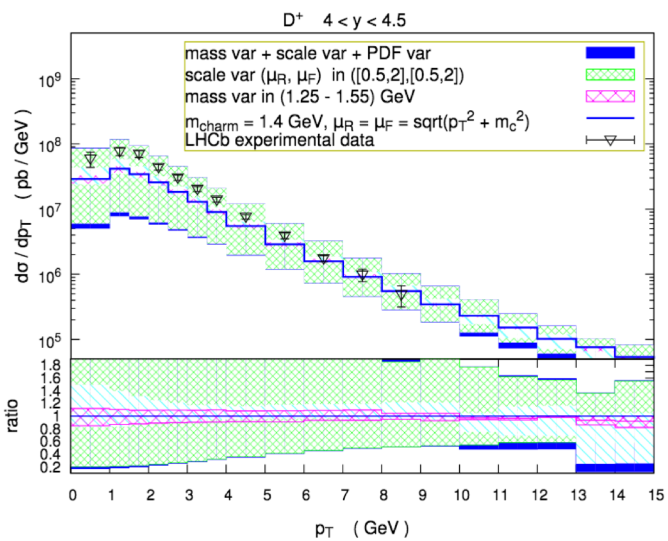


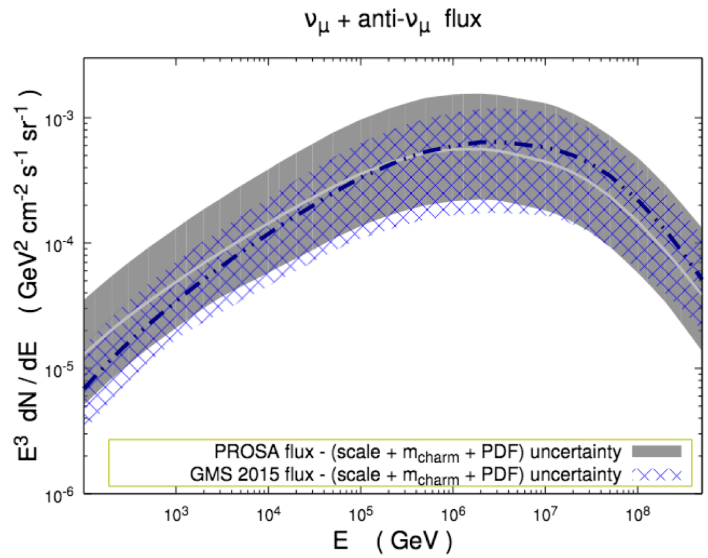


Bhattacharya eta al, JHEP 1506 (2015) 110; Bhattacharya et al., JHEP 1611 (2016) 167

Nuclear corrections to the prompt flux, of order 30%.

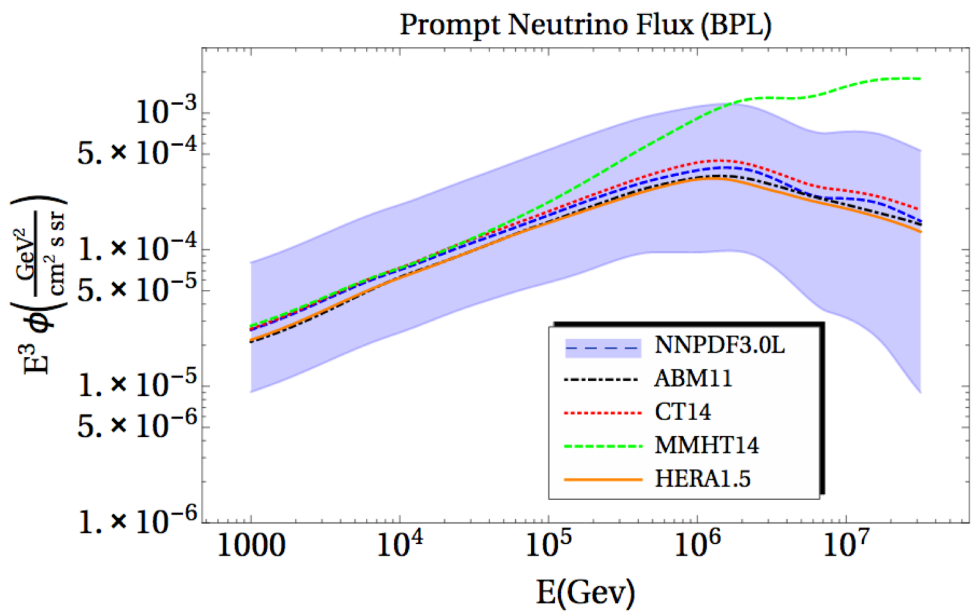






Garzelli et al. (PROSA), JHEP 1705 (2017) 004;
Garzelli, Moch and Sigl, JHEP 1510 (2015) 115.

POWHEGBOX + PYTHIA 6 + PROSA PDFs,
transverse mass, mc=1.4 GeV



Gauld et al., JHEP 1602 (2016) 130

Beginning of talks on detection - we saw potential of KM3Net on this topic (Coniglione).

- How solid is the limit of IceCube on prompt neutrinos?
- What are the IceCube limits on nonperturbative charm production?

Monte Carlo vs single-inclusive evaluations of charm meson distributions NLO QCD, what should be the interplay?

- Can we summarize the strengths and weaknesses of each MC generator? (Talks about SIBYLL by Riehn, EPOS by Pierog, QGSJET by Ostapchenko)?
- There is a need for closer exchange between the MC communities in cosmic ray and collider physics.
- What are the important details of the generators in the shower development?

Monte Carlo / single-inclusive

- How are nuclear effects included? Where do nuclear effects make a difference?

- What are the important details for charm production and how is charm included (or not)?

- HERWIG (Plaetzer) – how showering beyond leading-log is modeled in HERWIG, which introduces kT.

- Transverse momentum effects (TMD, kT factorization) – is this needed for prompt atmospheric flux predictions, correlations of charm with showers?

More Questions:

- Does heavy flavor production have any role in the muon excess problem? (Masip's talk included also photoproduction of muons, prompt electromagnetic decays.)
- Is there anything we can bring from theoretical developments in top production down to charm and b production and other astrophysical applications? (Talks by Schwinn and Broggio.)
- Neutrino cross sections, effects of nuclear PDFs on the cross section (Gauld talk). What are the limits of the nuclear PDF approach in hadronic collisions?
- HERA-LHC-and elsewhere (Geiser). Theory results included (double) triple charm (beyond usual perturbative calculations).
  - Underlying theme of multiple parton interactions, limits of the PDFs.
- Quark Gluon Plasma effects (Prino) – effects should be small for c,b production (Fe-O is similar to peripheral (60-70%) Pb-Pb collisions)

Proposed paper coming out of the workshop

- Something like “Open questions in heavy quark hadro-production at the intersection of collider and astroparticle physics”
- Big question: do we understand the dynamics of charm (and other heavy flavor) production? How well?
- What are the next steps to make progress (in physics)?

- [The next steps to make progress on the paper: Outline this week.]

- What other measurements are important for understanding air showers containing heavy flavor?
- What is the map of important kinematic regions?
- Can cosmic rays/atmospheric neutrinos constrain the theory of heavy flavor production?