Charm cross section
for cosmic rays in the atmosphere

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Second LHCb Heavy Ion Workshop: exploring matter with precision charm and beauty production measurements in Heavy Nuclei collisions, Chia Laguna, 4 - 6 September, 2019

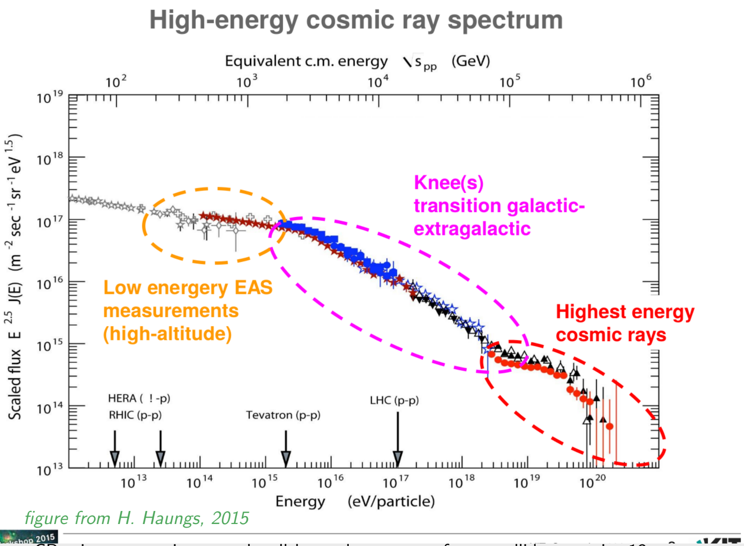
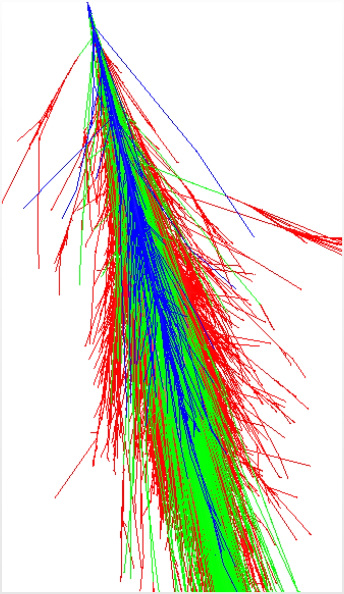


figure from H. Haungs, 2015

∗ CR primary energies extend well beyond present or future collider energies 13 - 100 TeV (GZK cutoff ∼ 300-400 TeV)

∗ present uncertainties on the galactic-to-extragalactic transition and the CR composition at UHE could be (at least partially) addressed by reducing our theoretical uncertainties on hadroproduction.

Extended Air Showers



- Interaction of primary particle (proton, helium, iron ion. . .) with atmosphere
- Ordering parameter: atmospheric depth $X = \int d\vec{r}\,\rho(\vec{r})$ (top to bottom)
- Separate **hadronic interactions** from propagation through atmosphere
- Primary interaction creates pions, kaons, nucleons, Λ. . . which then propagate and interact with other nuclei of the atmosphere or decay
- Heavier hadrons (D. . .) are also created, but do not propagate significantly decaying immediately instead

EAS: open problems

Although Monte Carlo generators for EAS have been tuned to LHC data (which has decreased the differences in their predictions), there is no way to describe simultaneously multiple EAS observables by a unique simulation:

$$< X_{max} >,\ \sigma(X_{max}),\ N_\mu,\ < X^\mu_{max} >$$

$\Rightarrow$ UHE CR composition (that unfortunately is inferred from comparison data/theory, instead of from just data) is still very uncertain !

Solving the composition problem would be important to understand the CR production mechanisms and the present composition uncertainty affects several other observables.

Atmospheric neutrino fluxes

$CR + Air$ interactions:
- AA' interaction approximated as $A\ NA'$ interactions (superposition);
- NA' approximated as $A'\ NN$ interactions: up to which extent is this valid ?

$*$ conventional neutrino flux:

$$NN \rightarrow \pi^{\pm}, K^{\pm} + \mathrm{X} \rightarrow \nu_\mu(\bar{\nu}_\mu) + \mu^{\pm} + \mathrm{X},$$
$$NN \rightarrow K_S^0,\ K_L^0 + \mathrm{X} \rightarrow \pi^{\pm} + e^{\mp} + \nu_e + \mathrm{X}, \quad \pi^{\pm} + \mu^{\mp} + \nu_\mu + \mathrm{X}$$

$*$ prompt neutrino flux:

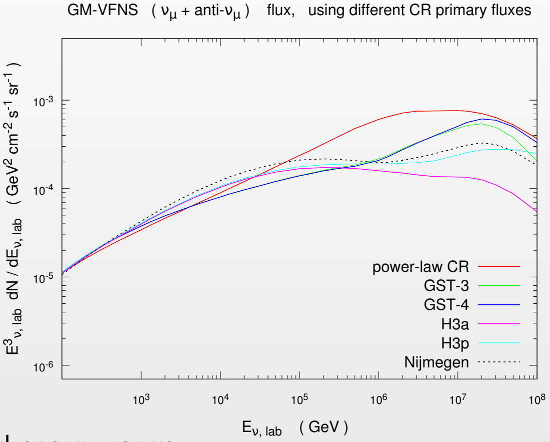
$$NN \rightarrow c, b, \bar{c}, \bar{b} + \mathrm{X} \rightarrow heavy\text{-}hadron + \mathrm{X} \rightarrow \nu(\bar{\nu}) + \mathrm{X}' + \mathrm{X}$$

$c\tau_{0,\,\pi^{\pm}} = 780$ cm, $c\tau_{0,\,K^{\pm}} = 371$ cm, $c\tau_{0,\,D^{\pm}} = 0.031$ cm

Critical energy $\epsilon_h = m_h c^2 h_0\ /\ (\mathrm{c}\ \tau_{0,h}\cos(\theta))$, above which hadron decay probability is suppressed with respect to its interaction probability:

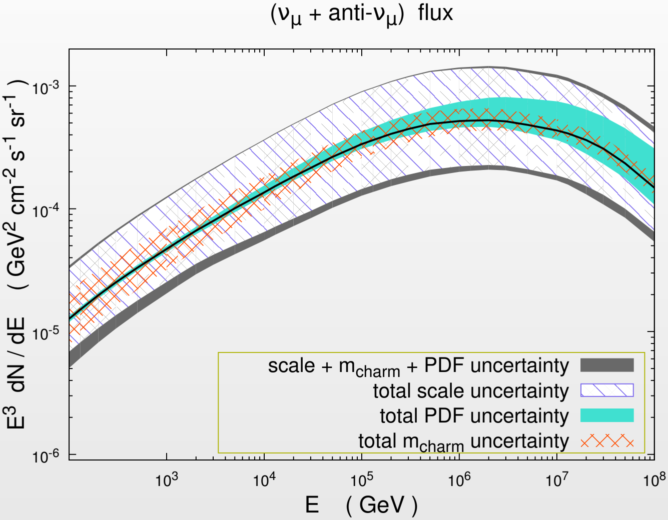
$\epsilon_\pi^{\pm} < \epsilon_K^{\pm} << \epsilon_D \Rightarrow$ conventional flux is suppressed with respect to prompt one, for energies high enough.

Prompt Neutrino Fluxes: uncertainties due to CR composition



- Extended energy range
- Effect of different CR primary flux composition (biggest uncertainties at the largest energies)

PROSA prompt $(\nu_\mu + \bar{\nu}_\mu)$ flux: QCD scale, mass and PDF uncertainties



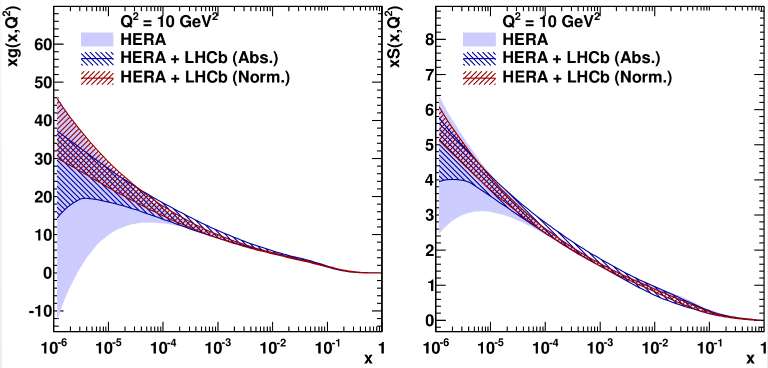
from [arXiv:1611.03815]

Why charm LHCb data matter for these studies ?

- proton PDF fits (from *pp* collisions)
- validation of the theory used to describe charm hadroproduction
- cold and hot nuclear matter effects (in *pA* and *AA* collisions).

PROSA PDF fit [arXiv:1503.04581]

Basic idea: use the data on *D*-meson and *B*-meson hadroproduction at LHCb to constrain PDFs (especially gluon PDFs) at low $x = p_{z,\,parton}/p_{z,\,proton}$ values.

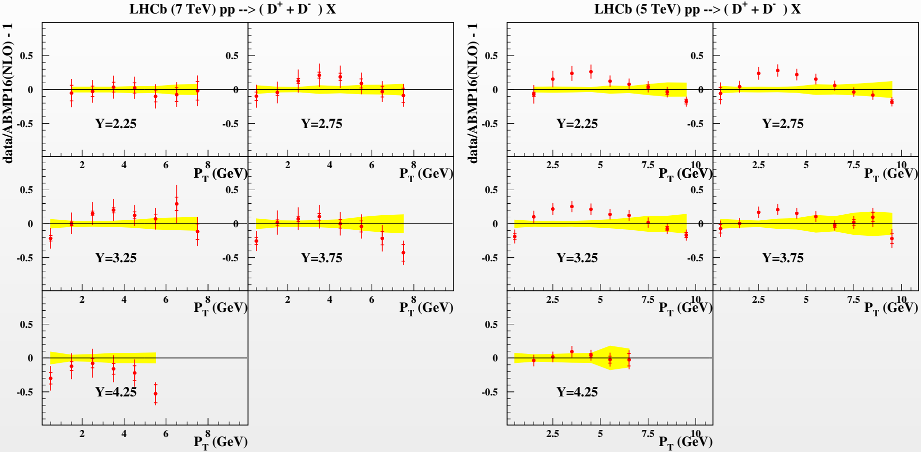


* The gluon and the sea quark distributions are correlated:
  a reduction on the uncertainty of the former propagates to the latter.
* good at "low" x's, but how low shall we go for high-energy astroparticle physics ?
* LHCb data constrains down to $x \sim 10^{-6}$. This is not enough for prompt fluxes at extremely high energies.....

New PROSA PDF fit - spring 2019

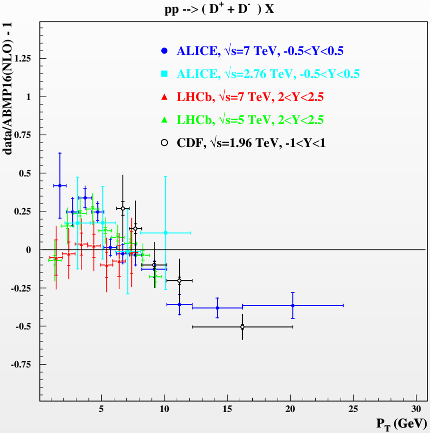
* Not yet allowed to show you by the collaboration!
* Added more LHCb data and even those from other experiments.
* Still compatible within uncertainties with the PROSA 2015 fit.

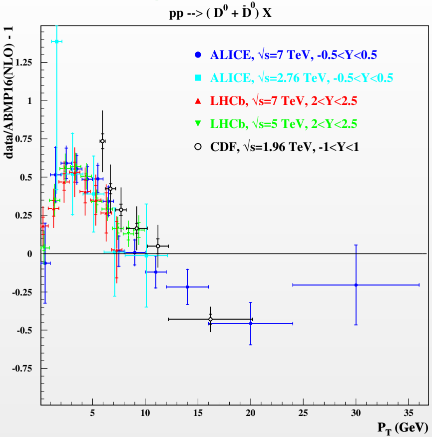
Comparison data/theory for the $pp \to D^{\pm} + X$ LHCb data



$*$ Puzzle: at small rapidities the $D^{\pm}$ data at $\sqrt{s} = 7$ TeV turn out to be described better than those at 5 TeV, whereas we do not expect significant modifications of the physics: are the experimental data at different energies compatible among each other ?

Pulls for the LHCb, ALICE, CDF open-charm data





* Fluctuations for $D^{\pm}$, while a trend is visible for D^0.
* In case of D^0, data at a fixed p_T seem to be reproduced similarly well/bad, indipendently of the $\sqrt{s}$ and of the y probed.
* This implies that the difference in shape between theory predictions and exp. data can not be washed out by modifying PDFs at low x's.

Uncertainties in the heavy-quark content of PDFs

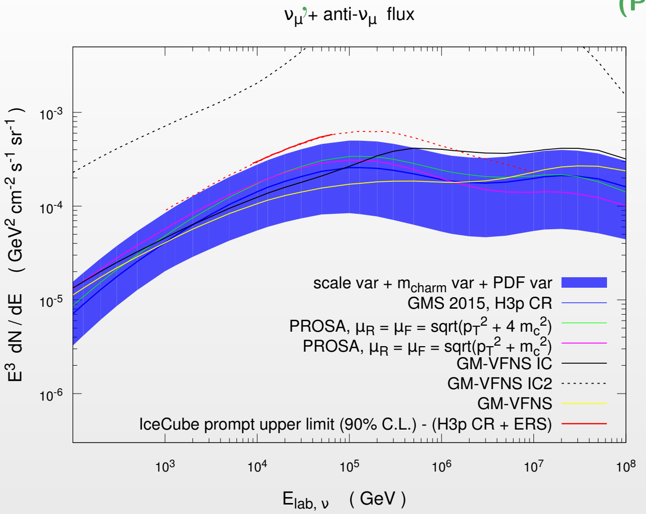
* Ansatz: only extrinsic charm/bottom
  charm and bottom in the nucleon PDFs are radiatively generated:
  - for scales $\mu_F \leq m_c$ ($\mu_F < m_b$) no charm (bottom) in PDFs
  - for scales $\mu_F > m_c$ ($\mu_F > m_b$) charm (bottom) is produced by QCD evolution through $g \to c\bar{c}$ and $c \to gc$ splittings ($g \to b\bar{b}$ and $b \to gb$ splittings)

* Further possibility:
  additional non-perturbative charm and bottom components:
  $\Rightarrow$ Models for intrinsic charm/bottom.

  First claims in favour of a sizable contribution: the interpretation of old experimental data at large x_F.
  However, these data have large errorbars, still compatible with a QCD interpretation not including intrinsic charm (which has also sizable errorbars).
  More striking evidence at near-future LHCb measurements ?

Prompt neutrino fluxes with intrinsic charm

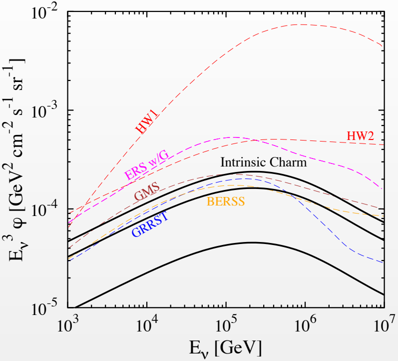
(PRELIMINARY)



Other calculations:

- Halzen and Wille (upper limit somehow compatible with our IC2)
- Laha and Brodsky (smaller upper limit).

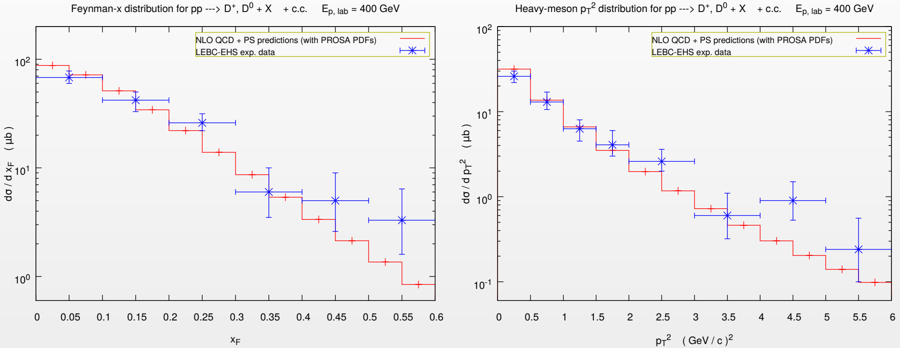
Intrinsic charm and prompt neutrino fluxes



, from [arXiv:1607.08240]

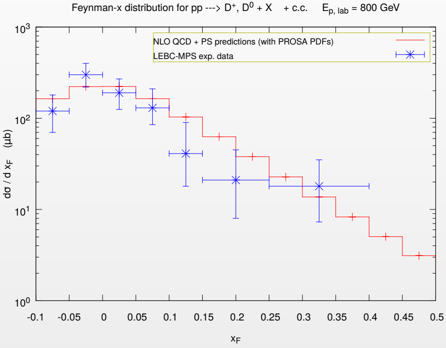
- ∗ Extrinsic heavy-quarks generated by $g \to Q\bar{Q}$ splittings.
- ∗ Intrinsic charm hypothesis testable by LHCb (large x), especially using the fixed-target SMOG apparatus.
- ∗ Further possibility at LHC: investigate $pp \to Zc, \gamma c$.
- ∗ Old results from EMC, ISR, fixed-target experiments (forward Λ_C, asymmetries D - $\bar{D}$, $J/\psi\ J/\psi$).

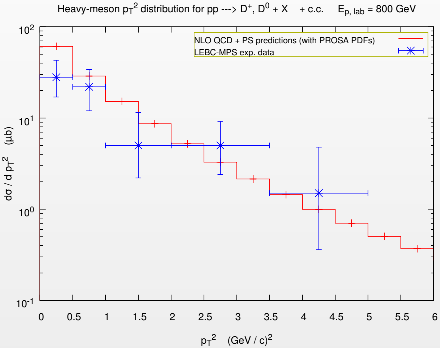
Performances of the PROSA QCD computation of D-meson production w.r.t. LEBC-EHS exp. data



* Fixed target experiment with $E_{p,\,lab} = 400$ GeV.
* Measure relatively large $x_F = p_{z,D}/p_{z,D}^{max}$ (up to $x_F \sim 0.6$) and p_T^2.
* Sizable QCD uncertainty band not included in the plot.

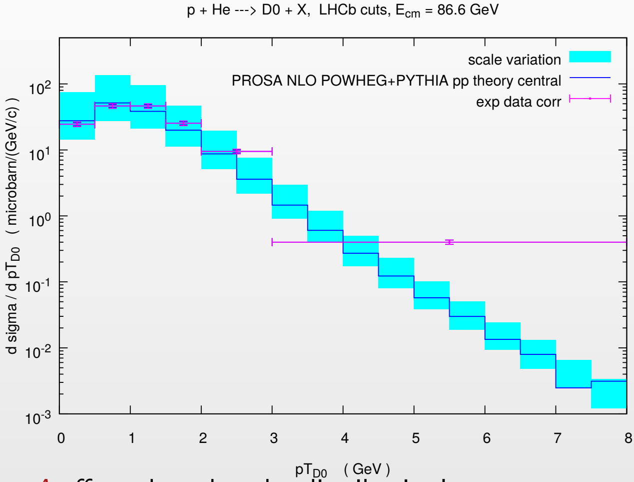
Performances of the PROSA QCD computation of D-meson production w.r.t. LEBC-MPS exp. data





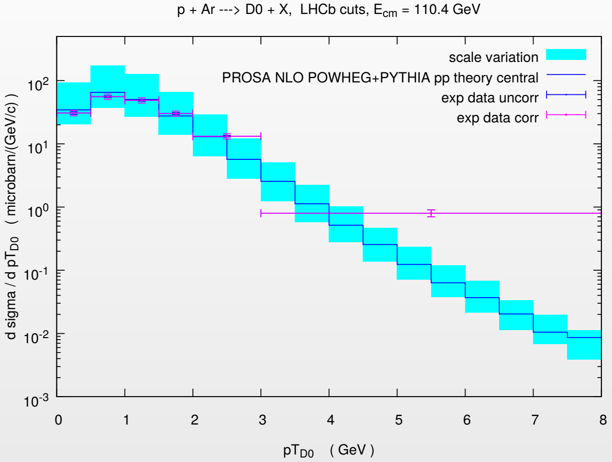
* Fixed target experiment with $E_{lab} = 800$ GeV.
* Measure relatively large x_F (up to $x_F \sim 0.4$).
* Sizable QCD uncertainty band not included in the plot.

Performances of the PROSA QCD computation of D^0-meson production w.r.t. LHCb fixed-target data



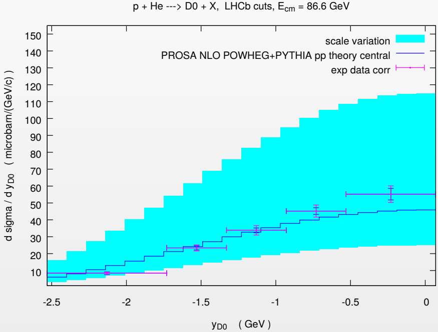
* pA effects broaden the distribution!
* pp theory underestimate the high p_T tails....

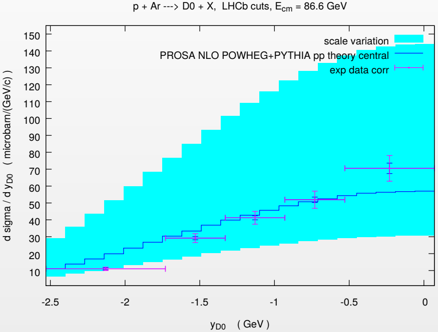
Performances of the PROSA QCD computation of D^0-meson production w.r.t. LHCb fixed-target data



* exp. (p+He) and (p+Ar) similarly enhanced with respect to theory at large p_T: final state effect ?

Performances of the PROSA QCD computation of D^0-meson production w.r.t. LHCb fixed-target data





$\ast$ Big scale uncertainties, especially at large y

$\ast$ Before discussing intrinsic charm, one has to disentangle pA effects: they can enhance distributions at low rapidities.

Performances of the PROSA QCD computation of D^0-meson production w.r.t. LHCb fixed-target data

$*$ Total cross-sections $D_0 + \bar{D}_0$ after LHCb rapidity cuts:
Theory: $\sigma = 76.1 + 116$ (scale) - 35 (scale) microbarn/n
LHCb: $\sigma = 80.8 \pm 2.4 \pm 6.3$ microbarn/n

$*$ Total cross-sections $D_0 + \bar{D}_0$:
Theory: $\sigma = 148.7 + 229$ (scale) - 83 (scale) microbarn
LHCb: $\sigma = 156.0 \pm 13$ microbarn/n

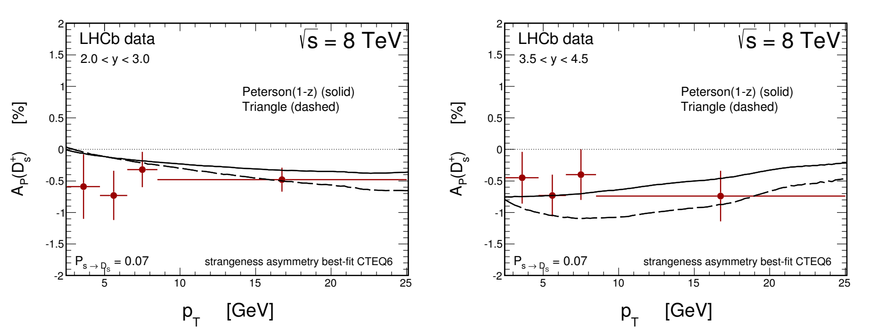
$*$ Total $c\bar{c}$ cross-section:
Theory: $\sigma = 133.8 + 206$ (scale) - 61 (scale) microbarn
LHCb: $\sigma = 288 \pm 24.2 \pm 6.9$ microbarn (??)

Conversion formula:

$$[f(c \to D^0) + f(\bar{c} \to D^0) + f(c \to \bar{D}^0) + f(\bar{c} \to \bar{D}^0)]\sigma(c\bar{c}) = \sigma(D^0 + \bar{D}^0)$$

$$\Rightarrow \qquad 2*0.542*\sigma(c\bar{c}) = \sigma(D^0 + \bar{D}^0)$$

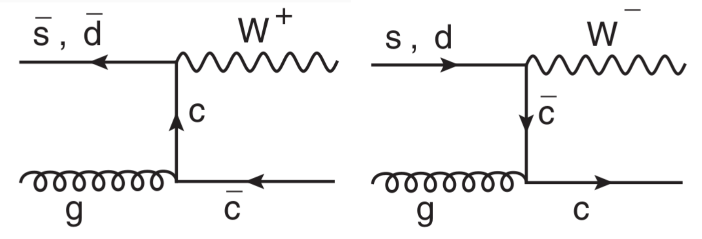
Asymmetries in the production of D_s^+ and D_s^- mesons



from Goncalves et al. [arXiv:1809.05424]

- Hypothesis: the asymmetry observed by LHCb can be due to $s(x) \neq \bar{s}(x)$ in the PDFs.
- Need for even more precise LHCb data!

Wc production and strange quark PDFs

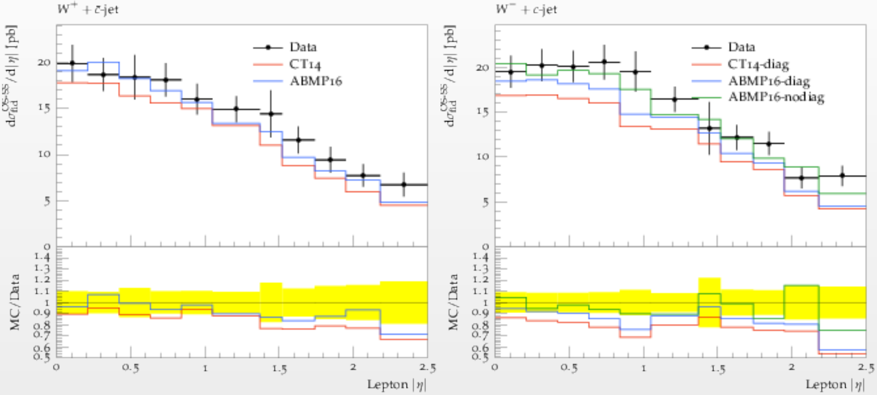


∗ Direct sensitivity to s and $\bar{s}$ PDF!

∗ At NLO new channels open up.

∗ Sensitivity to s PDF in other processes:
− W, Z hadroproduction (indirect),
− charm production in ν-N DIS (direct).

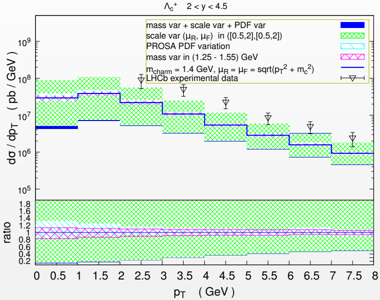
Theory predictions vs. ATLAS experimental data from [arXiv:1402.6263] (PRELIMINARY)



cuts: $W \to l\nu$, $p_{T,c-jet} > 25$ GeV, $\Delta R = 0.4$

To increase the agreement of data on W^- it is essential to include non-diagonal V_{CKM}! In that case no asymmetry is seen.

Forward Λ_c hadroproduction in pp collisions



* LHCb experimental data at $\sqrt{s} = 7$ TeV above the theory bands (differences within 2σ).
* Update of branching ratios and fragmentation fractions needed: big uncertainties on these elements ($\sim 25\%$ and 8%).
* What happens at 13 and 5 TeV ?
* LHCb has measured Λ_c/D^0 ratios in $p - Pb$ collisions.

$\Rightarrow$ Extension to pp would be important for assessing fragmentation/hadronization mechanisms and for testing the intrinsic charm hypothesis.

A rapidity dependence is to be expected/checked.

Conclusions - I

* Heavy-quark hadroproduction investigated by all LHC experiments. LHCb particularly interesting because it explores the “large” rapidities ($2 < y < 4.6$).

* .....but astroparticle experiments explore rapidities even larger.

* Theory predictions on charm and bottom hadroproduction at present have larger uncertainties than the experimental data.

* Dominant uncertainties related to missing higher-orders in pQCD.

* Heavy-quark hadroproduction data useful to constrain PDFs at low and large x's.

* Prompt neutrino flux theory uncertainties reflect the previous ones.