Heavy-quark hadroproduction and prompt neutrino fluxes

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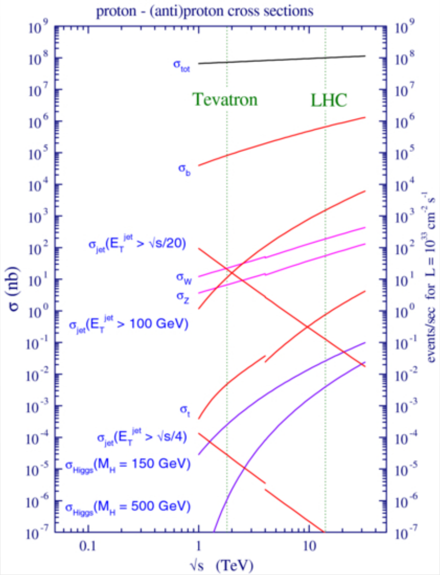
Heavy-flavour hadroproduction at the LHC



∗ huge cross-sections for charm and bottom hadroproduction:

at $\sqrt{S} = 13$ TeV,
$\sigma(pp \to c\bar{c} + X) \sim \mathcal{O}(10mb)$,
$\sigma(pp \to b\bar{b} + X) \sim \mathcal{O}(600\mu b)$,
$\sigma(pp \to t\bar{t} + X) \sim \mathcal{O}(700\text{ pb})$.

∗ Charm, bottom and top hadroproduction are studied by LHCb, ALICE, ATLAS, CMS, in different kinematical regions.

∗ The LHCb experiment allows to probe large rapidities ($2 < y < 4.5$), whereas ATLAS, CMS, ALICE are focused on central region ($|y| < 2.5$).

Heavy-flavour vs. light-flavour hadroproduction

$m_u \sim 2$ MeV, $m_d \sim 5$ MeV, $m_s \sim 100$ MeV
$m_c \sim 1.4$ GeV, $m_b \sim 4.8$ GeV, $m_t \sim 173.3$ GeV

$*\ m_u,\ \ m_d,\ \ m_s << \Lambda_{QCD}$

$\Rightarrow \alpha_S(m_u),\ \ \alpha_S(m_d),\ \ \alpha_S(m_s)\ \ > 1$

$\Rightarrow$ **pQCD** treatment of light-quark hadroproduction is possible **only at large** $p_{T,q}$, complemented by **soft QCD models at low** $p_{T,q}$

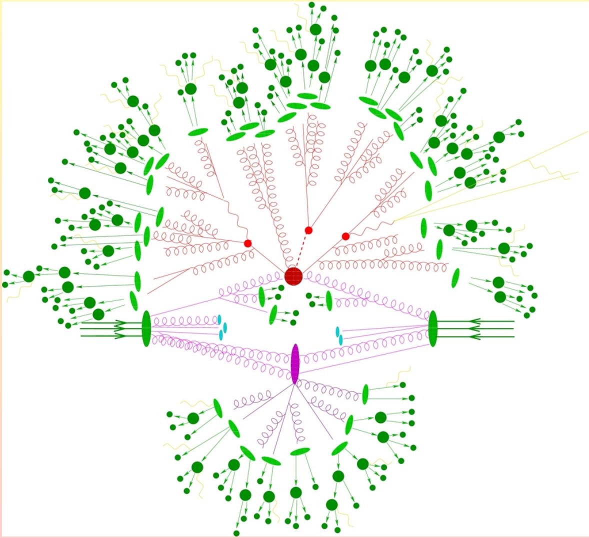
$*\ m_c,\ \ m_b,\ \ m_t >> \Lambda_{QCD}$

$\Rightarrow \alpha_S(m_c),\ \ \alpha_S(m_b),\ \ \alpha_S(m_t) << 1$

$\Rightarrow$ **pQCD** treatment of heavy-quark hadroproduction is justified **even at small** $p_{T,q}$.

$\Rightarrow$ The methods for describing the latter process at colliders can be applied also in astroparticle physics problems.

p-p and p-$\bar{\text{p}}$ collision overview (LHC and Tevatron)



$Q = a\ few\ TeV$

- hard scattering
- parton shower
- QED shower

$\Lambda_{QCD} = 200\ MeV$

- hadronization
- hadron decay
- underlying event
- pile-up (overlap of different collisions).

DECREASING ENERGY SCALE

PERTURBATIVE AND NON-PERTURBATIVE COMPONENTS

QCD collinear factorization for heavy-quark pair hadroproduction

$$d\sigma(N_1 N_2 \to h\bar{h} + X) = \sum_{ab} PDF_a^{N_1}(x_a, \mu_F) PDF_b^{N_2}(x_b, \mu_F) \otimes$$
$$\otimes \; d\hat{\sigma}_{ab \to h\bar{h} + X'}(x_a, x_b, \mu_F, \mu_R, \alpha_S(\mu_R))$$

where

* $x = p^+/P_N^+$ = longitudinal momentum fractions

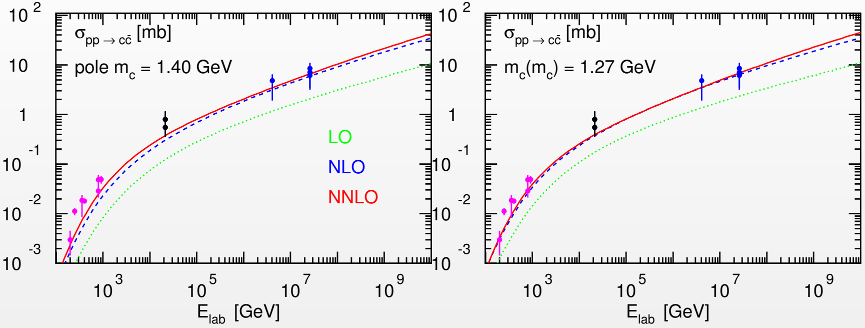
* $PDF_a^{N_1}(x_a, \mu_F)$, $PDF_b^{N_2}(x_b, \mu_F)$ = parton distribution functions (long-distance physics), they absorb infrared collinear singularities uncancelled within the hard-scattering and are universal (process independent).

* $d\hat{\sigma}_{ab \to h\bar{h}}$ = partonic hard-scattering cross-section (short-distance physics), computable by perturbative QCD.

* μ_F = factorization scale: separates long-distance physics (non-perturbative QCD) from short-distance physics (perturbative QCD).

* μ_R = renormalization scale: renormalization eliminates UV divergences, by reabsorbing the divergences in renormalized quantitiesss.

$\sigma(pp \to c\bar{c}(+X))$ at LO, NLO, NNLO QCD



pole mass scheme   running mass scheme

exp data from fixed target exp + colliders (STAR, PHENIX, ALICE, ATLAS, LHCb).

$(E_{lab} = 10^6 \text{ GeV} \sim E_{cm} = 1.37 \text{ TeV})$
$(E_{lab} = 10^8 \text{ GeV} \sim E_{cm} = 13.7 \text{ TeV})$
$(E_{lab} = 10^{10} \text{ GeV} \sim E_{cm} = 137 \text{ TeV})$

$*$ Assumption: collinear factorization valid on the whole energy range.

From heavy quarks to heavy-flavour hadrons

Different descriptions of the transition are possible:

1) fixed-order QCD + Parton Shower + hadronization:
match the fixed-order calculation with a parton-shower algorithm (resummation of part of the logarithms related to partonic collinear emissions on top of the hard-scattering process), followed by hadronization (phenomenological model).

Advantage: fully-differential event generation, correlations between final state particles/hadrons are kept.

Problem: accuracy not exactly defined, it is not an rigorous resummation procedure to all orders in perturbation theory.

2) Convolution of partonic cross-sections with Fragmentation Functions (see the following).

Both methods 1) and 2) used here.

N.B. Top quarks decay before hadronizing, no top hadrons detected.

QCD factorization

for 1-particle inclusive heavy-hadron hadroproduction (valid only in VFNS!)

$$d\sigma(N_1 N_2 \to H + X) = \sum_{abc} PDF_a^{N_1}(x_a, \mu_{F,i}) PDF_b^{N_2}(x_b, \mu_{F,i}) \otimes$$
$$\otimes \; d\hat{\sigma}_{ab \to cX'}(x_a, x_b, z, \mu_{F,i}, \mu_{F,f}, \mu_R, \alpha_S(\mu_R)) \otimes FF_c^H(z, \mu_{F,f})$$

$d\hat{\sigma}$: differential perturbative partonic cross-section,
its m_h dependence, neglected in the ZM-VFNS, is instead kept in the GM-VFNS.

μ_F, μ_R reabsorb IR and UV divergences (truncation of P.T. series).

PDFs: perturbative evolution with factorization scale $\mu_{F,i}$,
non-perturbative dependence on $x{=}p^+/P_N^+$.

FFs: perturbative evolution with factorization scale $\mu_{F,f}$,
non perturbative parameterization in terms of $z = P_H^+/p_c^+$ frequently used.

QCD uncertainties

* $\mu_{F,i}$, $\mu_{F,f}$ and μ_R choice: no univocal recipe.
* Approximate knowledge of heavy-quark masses m_h (SM input parameters).
* Choice of Variable Flavour Number Scheme (several possibilities!)
* PDF (+ $\alpha_S(M_Z)$) fits to experimental data
* FF fits to experimental data

Parton distribution functions (PDFs)

$*$ PDFs encode the partonic content of the hadrons, in terms of quarks and gluons: probability of finding a parton with specific features in a hadron.

$*$ In collinear factorization, PDFs for the distribution of parton i in hadron A are function of two variables:

$$\mathrm{PDF}_{i/A}\,(x,\, Q^2)$$

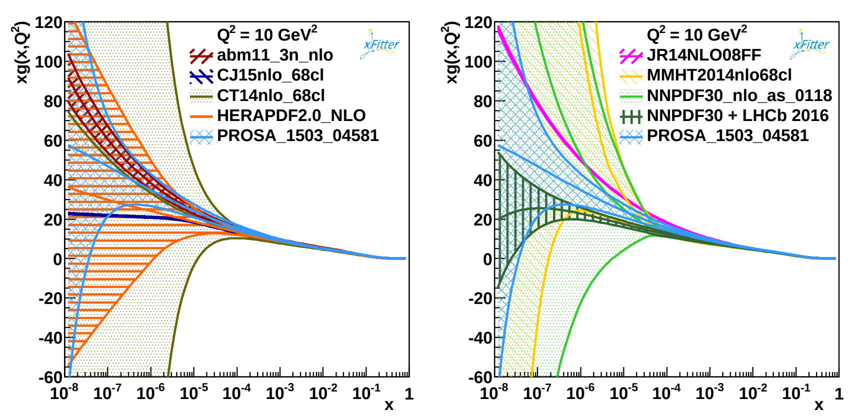
with $i = g,\, u,\, d,\, s,\, c,\, b,\, t,\, \bar{u},\, \bar{d},\, \bar{s},\, \bar{c},\, \bar{b},\, \bar{t}$,
x = fraction of the hadron momentum carried by parton when the hadron is probed in a process with momentum transfer Q^2.

$*$ Evolution of PDFs with Q^2 is determined by DGLAP evolution equations (pQCD).

$*$ Dependence of PDFs on x, instead, has to be determined making fits to experimental data.

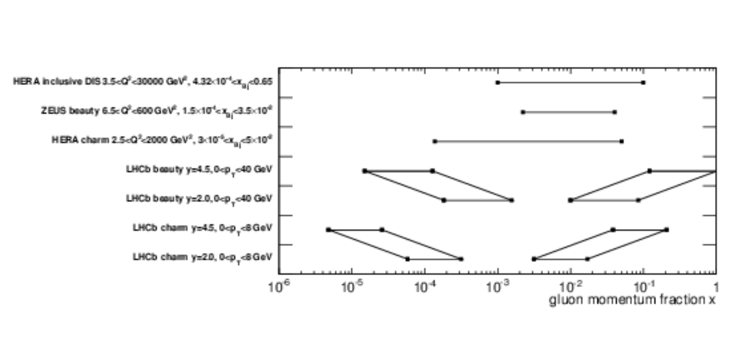
$*$ PDFs encapsulate long-distance physics aspects (non-perturbative).

gluon PDF: comparison between different PDF fits



- PDF non-perturbative dependence on x: fit to experimental data
- The higher are E_{CM} and the most forward is the scattering (y_H large), the lower are the x values probed.

x dependence of PDFs and x coverage of HERA and LHCb experiments



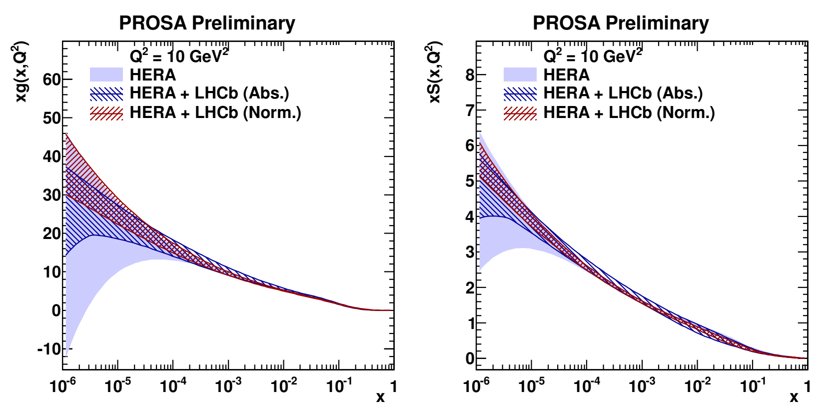
from O. Zenaiev et al. (PROSA collaboration), [arXiv:1503.04581]

- LHCb (p-p) acts as a complementary experiment with respect to HERA (e-p) in order to constrain PDFs.
- Additional constraints come from other LHC experiments.
- At present PDF behaviour in the "extreme" regions (low-x and high-x) is more uncertain than in the intermediate-x range.
- The higher is the energy of a hadronic collision, the higher is the probability that partons in the "extreme" regions participate in it.

PROSA PDF fits:

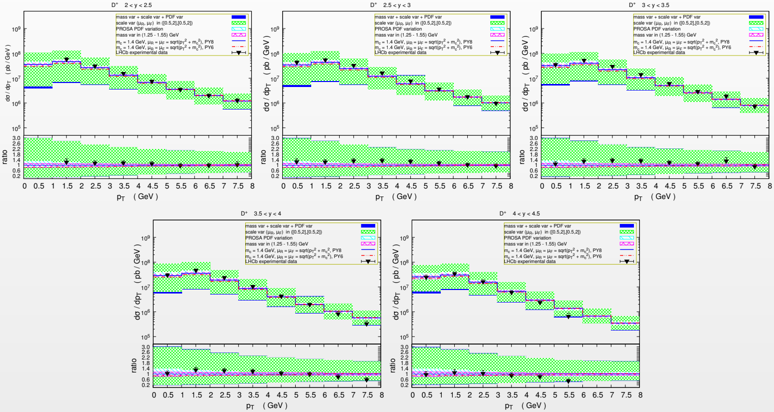
comparison between the three variants of the fit

Basic idea: use the data on *D*-meson and *B*-meson hadroproduction at LHCb to constrain PDFs (especially gluon PDFs) at low x's.



∗ The gluon and the sea quark distributions are correlated:
a reduction on the uncertainty of the former propagates to the latter.

Theory predictions vs. LHCb experimental data on $pp \to D^{\pm} + X$ at $\sqrt{S} = 7$ TeV

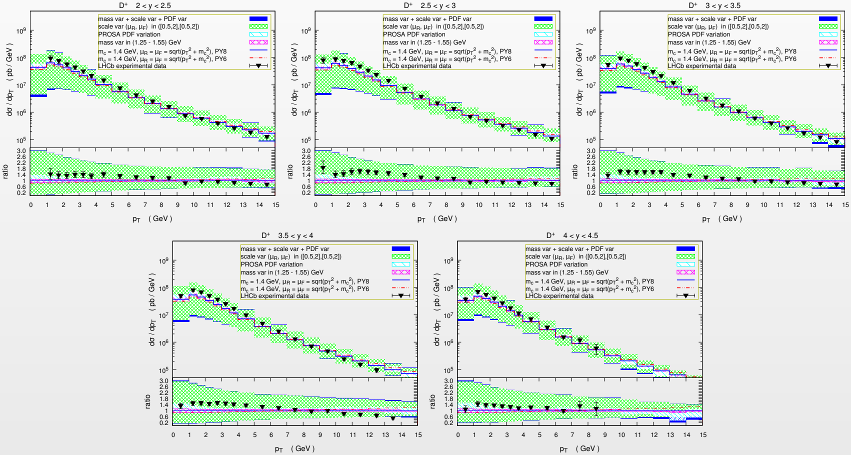


* Here we compare theoretical absolute cross-sections to experimental data, whereas the PROSA PDF fit variant using LHCb data ratios is employed in the predictions.

* Big uncertainties on the theoretical predictions, dominated by μ_R and μ_F scale variations.

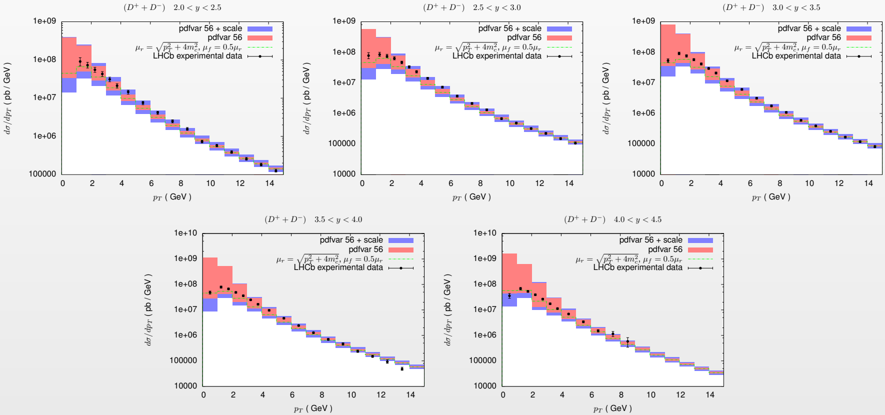
* LHCb coverage: $2 < |y| < 4.5$, but astrophysical data cover larger $|y|$ as well.....

Theory predictions vs. LHCb experimental data on $pp \to D^{\pm} + X$ at $\sqrt{S} = 13$ TeV



These data are not included in the PROSA PDF fit:
experimental data always within the theory uncertainty bands.

How do other PDF fits (CT14nlo), not including LHCb data, behave ? $pp \to D^{\pm} + X$ at LHCb at 13 TeV



* Large PDF uncertainties, increasing at low p_T / large y.

Comparison between theoretical and experimental uncertainties

* For charm hadroproduction, present theory uncertainties look far larger than the experimental ones.

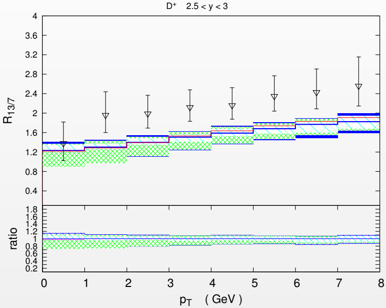
* **Why do we not limit our uncertainty bands to the experimental uncertainty bands ?**

  – Degeneracy: many different modifications in the theory input (charm mass, PDFs, etc....) can lead to a "good agreement" with data. But which modification is the "correct" one ?

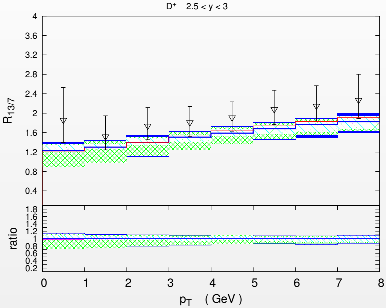
  – QCD theory is not a phenomenological model: predictions coming from first principles as much as possible. The use of phenomenological models is a consequence of our imperfect knowledge of the theory.

  – (Sometimes not only Theories but even) Data can be wrong !

Ratios of theory predictions at different energies vs. LHCb 13/7 experimental data



old (wrong) experimental data



new revised experimental data

* Reduced uncertainties in theoretical ratios (compared to the absolute case).
* Agreement of theory predictions and experimental data improved after last data revision (May 2017).
* Theory predictions from two different independent computations and PDF sets are considered (red line: NLO QCD + NLL GM-VFNS, with CT14nlo PDFs, green/blue bands: NLO QCD + PS + hadronization, with PROSA PDFs).

Why these developments matter ?

Constraining PDFs at low x's is relevant for:

* forward physics and multiple parton interactions, already in the LHC era:
  with increasing precision of the LHC data,
  improving the description of these aspects matters!

* future high-energy colliders: FCC-hh, etc.....
  (see the study in the FCC-hh SM report [arXiv:1607.01831]).

* high-energy astroparticle physics applications:
  - prompt ν fluxes
  - $\nu + \mathrm{N}$ DIS (detection of high-energy neutrinos by VLVνT's)

Atmospheric neutrino fluxes

* conventional neutrino flux:

  $$NN \quad \rightarrow \quad \pi^{\pm}, K^{\pm} + \mathrm{X} \quad \rightarrow \quad \nu_{\mu}(\bar{\nu}_{\mu}) + \mu^{\pm} + \mathrm{X}$$

* prompt neutrino flux:

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

  expected to dominate above $E_{lab,\nu} > 5 \cdot 10^5$ GeV

  heavy-quarks (c, b, $\bar{c}$, $\bar{b}$) produced through:
  1) hard-scattering processes
  2) already in the nucleon PDFs.

Prompt ν fluxes: ingredients of the computation

QCD and astrophysical input:

∗ primary CR flux and composition

∗ Earth atmospheric profile (density and composition)

∗ *N*-Air total inelastic cross-section

∗ *NN* hadroproduction cross-sections for charmed mesons/baryons

∗ cold nuclear matter/QGP effects vs. superposition approximation

Input of a system of coupled differential equations regulating the evolution of particle fluxes in the atmosphere (interaction/decay/(re)generation):

$$\frac{d\phi_j(E_j,X)}{dX} = -\frac{\phi_j(E_j,X)}{\lambda_{j,int}(E_j)} - \frac{\phi_j(E_j,X)}{\lambda_{j,dec}(E_j)} + \\ + \sum_{k\neq j} S^{k\to j}_{prod}(E_j,X) + \sum_{k\neq j} S^{k\to j}_{decay}(E_j,X) + S^{j\to j}_{reg}(E_j,X)$$

Z-moments for heavy-hadron production and decay

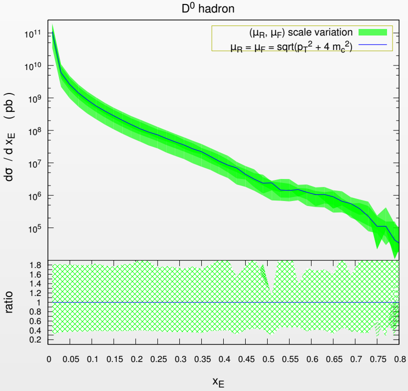
* CR + Air interactions producing heavy hadrons (in particular including charm) parameterized in terms of p-p collisions
* Integration variable: $x_E = E_h/E_p$
* Z-moments for intermediate hadron production:

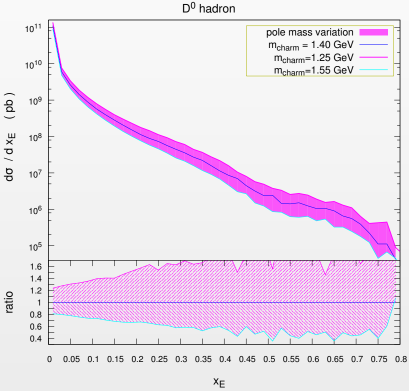
$$Z_{ph}(E_h) = \int_0^1 \frac{dx_E}{x_E} \frac{\phi_p(E_h/x_E)}{\phi_p(E_h)} \frac{A_{air}}{\sigma^{tot,inel}_{p-Air}(E_h)} \frac{d\sigma_{pp\to c\bar{c}\to h+X}}{dx_E}(E_h/x_E)$$

* These hadrons are then decayed semileptonically, producing leptons (+ X)
* Integration variable: $x'_E = E_l/E_h$
* Z-moments for intermediate hadron decay:

$$Z_{hl}(E_l) = \int dx'_E \frac{\phi_h(E_l/x_{E'})}{\phi_h(E_l)} F_{h\to l}(x'_E)$$

$d\sigma(pp \to c\bar{c} \to D^0 + X)/dx_E$: scale and mass uncertainties

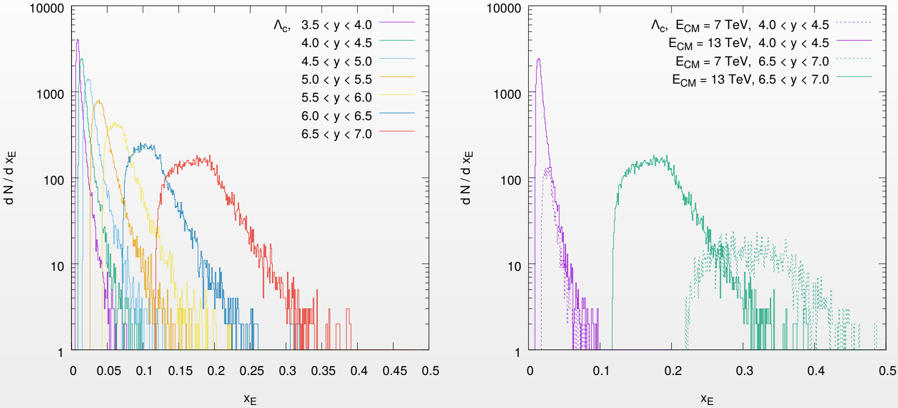




from [arXiv:1507.01570]

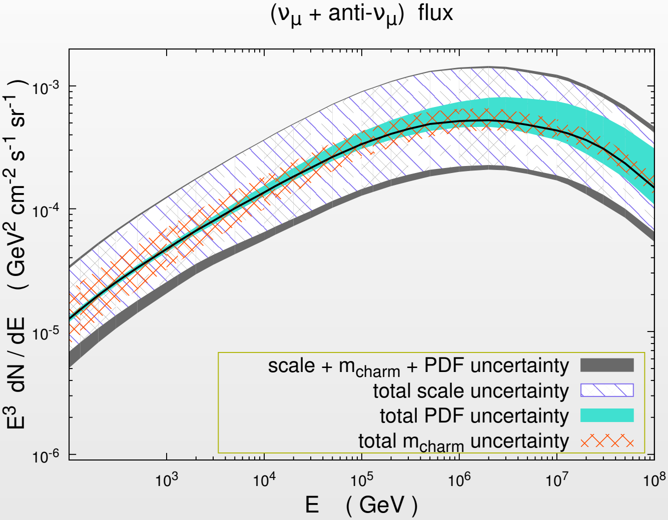
∗ Here plots for *pp* collisions at $E_{p,\,lab} = 10^7$ GeV, shape remains similar at different energies.

Relation between x_E and rapidity y



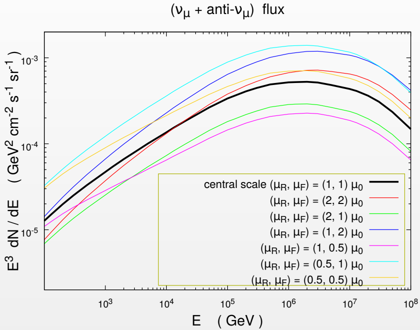
- case of Λ_c considered here, qualitatively similar behaviour for charmed mesons.
- high x_E corresponds to high y (forward particles)
- maximum rapidities y probed at LHCb corresponds to $x_E < 0.15$.

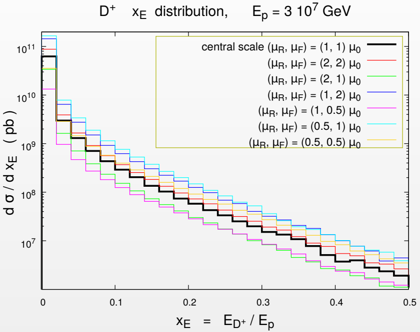
Prompt neutrino fluxes: QCD scale, mass and PDF uncertainties



from [arXiv:1611.03815]

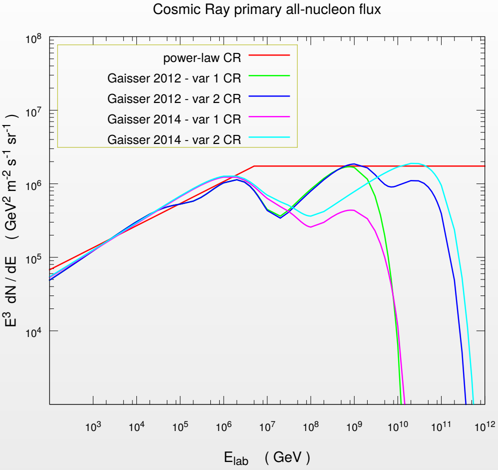
μ_R and μ_F scale uncertainties





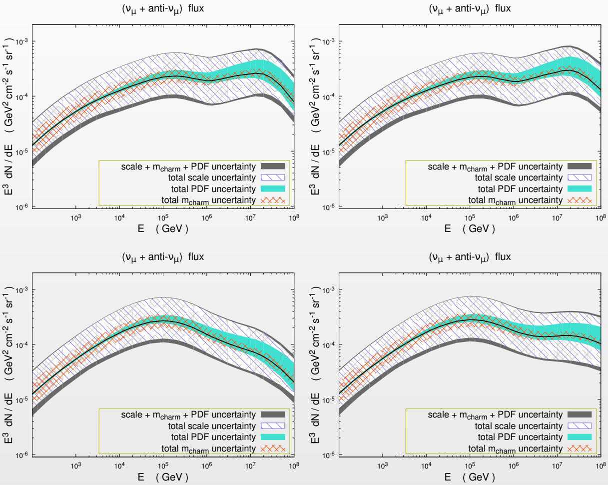
* Scale uncertainties are evaluated by making an envelope over different variations.
* Predictions have a shape uncertainty, not only a normalization uncertainty!

The all-nucleon CR spectra: considered hypotheses



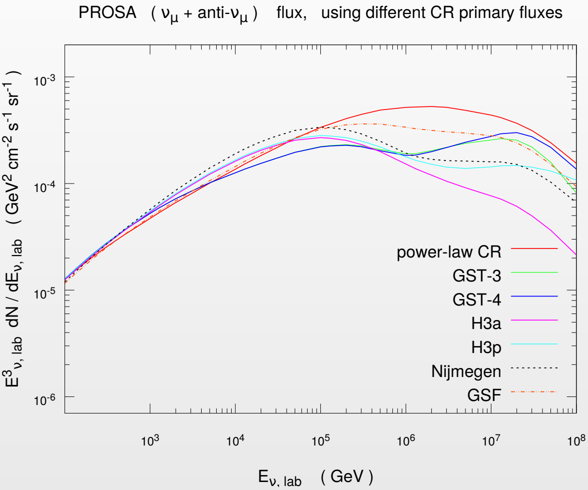
* All-nucleon spectra obtained from all-particles ones under different assumptions as for the CR composition at the highest energies.
* Models with 3 (2 gal + 1 extra-gal) or 4 (2 gal + 2 extra-gal) populations are available.

Prompt ($\nu_\mu + \bar{\nu}_\mu$) fluxes: comparison between theory predictions using different primary CR fluxes



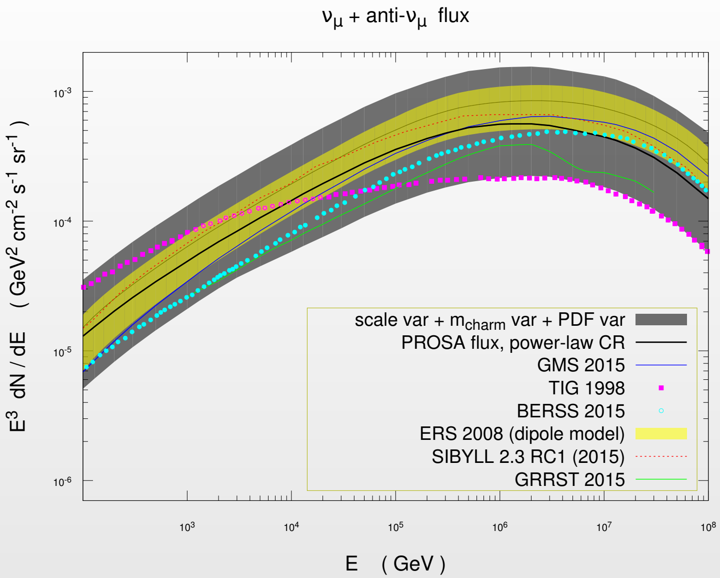
* Each panel corresponds to a different CR primary flux (GST-3, GST-4, H3a, H3p).
* For each panel: μ_R and μ_F scale, PROSA PDF and charm mass uncertainties.

Prompt $(\nu_\mu + \bar{\nu}_\mu)$ fluxes with different CR primary fluxes (PRELIMINARY)



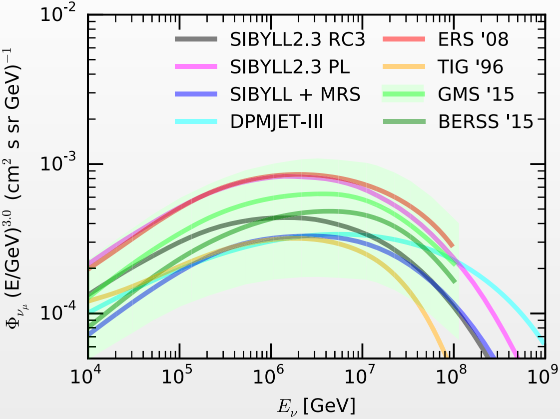
∗ GSF is the newest CR spectrum available by the Gaisser group (ICRC 2017), leading to results similar to the broken power-law case.

Comparison of predictions by different groups



Different predictions compatible within uncertainty band.

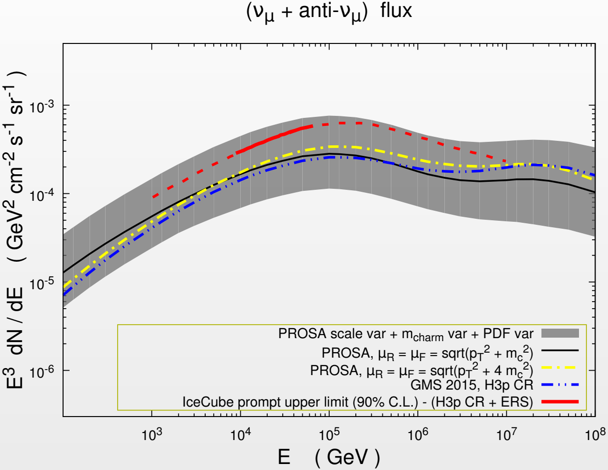
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: comparison with predictions from hadronic models used in EAS physics



from A. Fedynitch, EPJ Web of Conferences 116, 11010 (2016)

All recent central predictions, both those on the basis of pQCD and those on the basis of hadronic models used in EAS physics (like SIBYLL, DPMJET), turn out to lie within our uncertainty band.

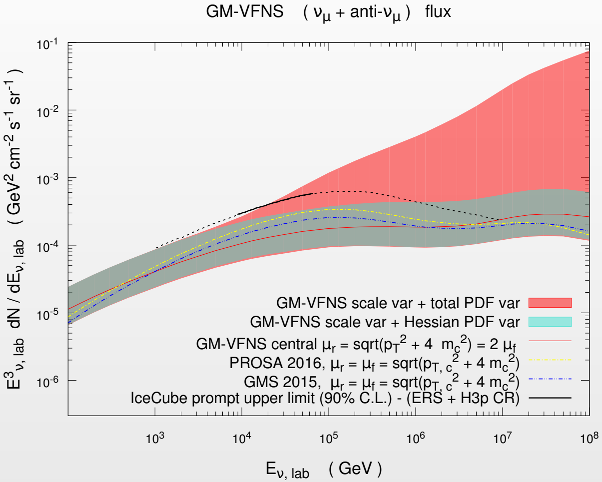
Prompt neutrino fluxes:
theoretical predictions from [arXiv:1611.03815] vs. IceCube upper limits



IceCube upper limit on prompt fluxes from the 6-year analysis of thoroughgoing μ tracks from the Northest Hemisphere [arXiv:1607.08006] assumed the ERS flux as a basis for modelling prompt neutrinos (reweighted to the H3p CR flux).

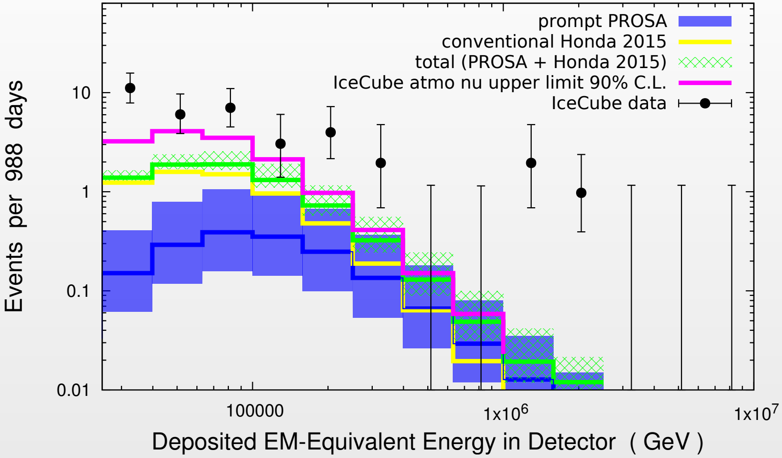
Prompt neutrino fluxes:

theoretical predictions from [arXiv:1705.10386] vs. IceCube upper limits



∗ IceCube results give clear indication that the CT14nlo gluon PDF uncertainties at low x's (see PDF error sets 53-56) are too large!

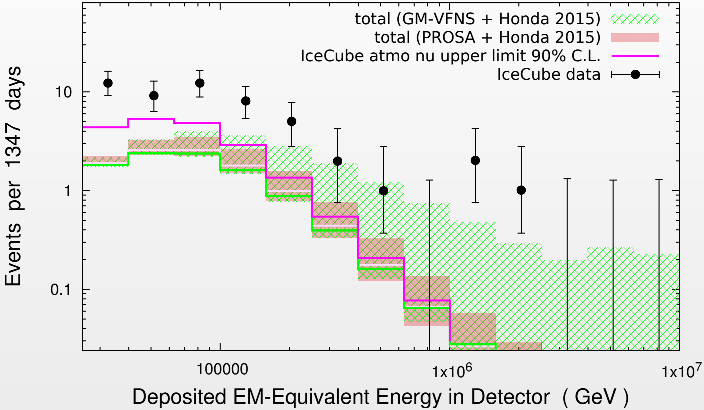
Expected events in IceCube HESE analysis: prompt, conventional and total ($\nu + \bar{\nu}$) components



∗ 3-year analysis,
qualitatively similar results in the 6-year analysis (ICRC 2017).

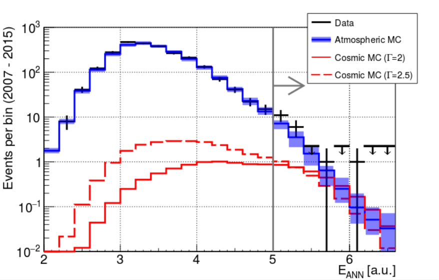
HESE analysis:

theoretical predictions vs. IceCube experimental data

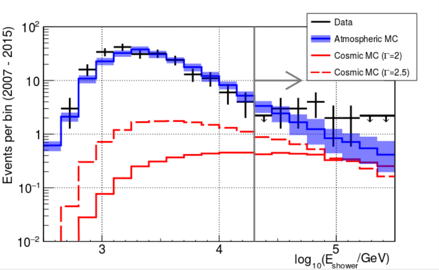


* PROSA 2016 predictions vs GM-VFNS 2017 predictions vs IceCube exp. data
* GM-VFNS 2017 predictions dominated by `CT14nlo` PDF uncertainties.

New results from ANTARES on tracks and showers [arXiv:1711.07212]



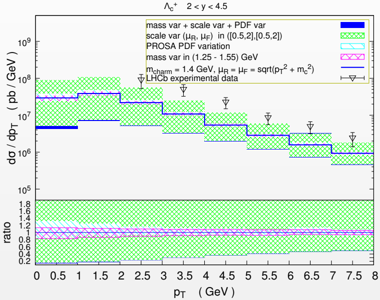
tracks



showers

- ∗ theory predictions for atmospheric flux = Honda + ERS
- ∗ interesting to extend to more recent predictions
- ∗ interesting to compare ANTARES data with IceCube data

Forward Λ_c hadroproduction



* 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 is measuring 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.

Uncertainties in the heavy-quark content of PDFs

$*$ Ansatz: only extrinsic charm/bottom
charm and bottom in the nucleon PDFs are radiatively generated:

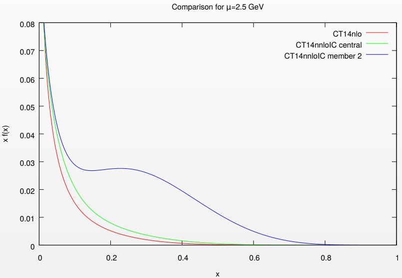
- for scales $\mu_F \leq m_c$ ($\mu_F < m_b$) no charm (bottom) in PDFs
- for scales $\mu_F > m_c$ ($\mu_F > m_b$) charm (bottom) is produced by QCD evolution through $g \to c\bar{c}$ and $c \to gc$ splittings ($g \to b\bar{b}$ and $b \to gb$ splittings)

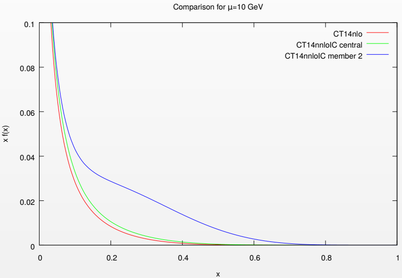
$*$ Further possibility:
additional non-perturbative charm and bottom components:
$\Rightarrow$ Models for intrinsic charm/bottom.

Original motivation: old experimental data at large x_F.
But, no need for intrinsic charm/bottom at LHC
(at least for the observables studied so far).
Possible probe of the (non-)existence of intrinsic charm at LHC:
$pp \to Zc, \gamma c$

Charm component in modern PDFs (CT14)

$\mu_F = 2.5$ GeV $\mu_F = 10$ GeV





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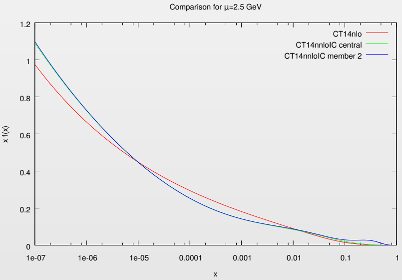
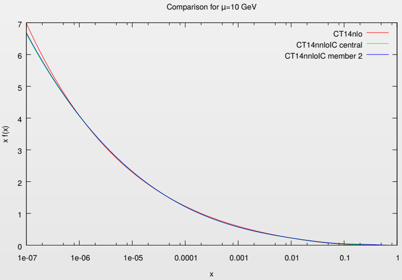
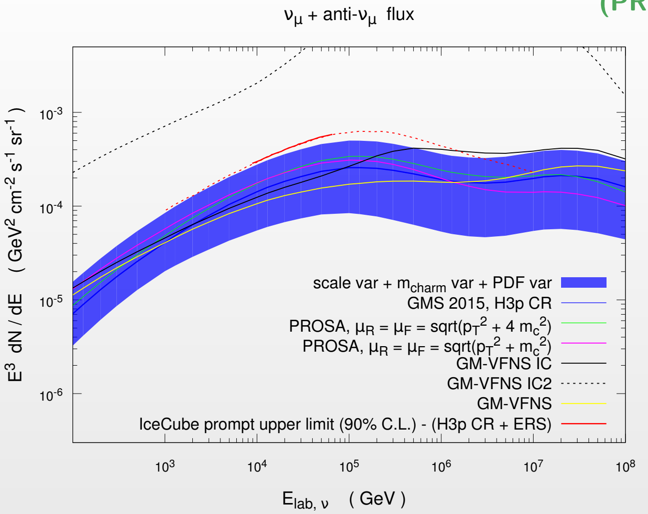




log

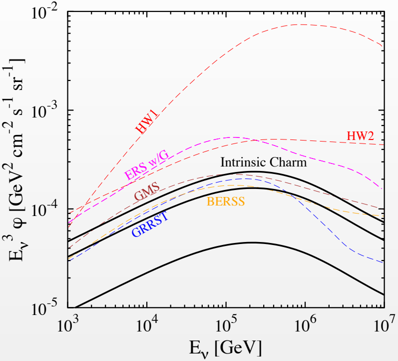
Prompt neutrino fluxes with intrinsic charm

(PRELIMINARY)



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

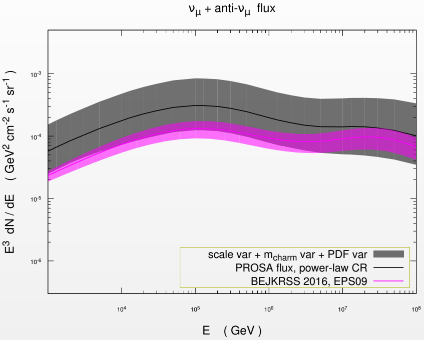
Intrinsic charm and prompt neutrino fluxes

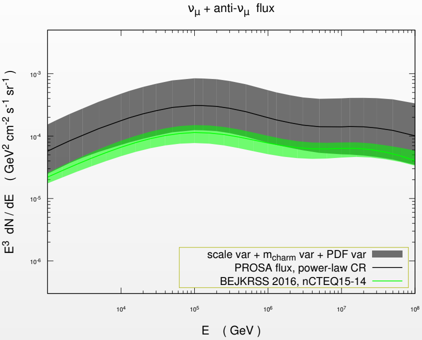


from [arXiv:1607.08240]

* 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: investigate $pp \to Zc$, γc.
* Old results from EMC, ISR, fixed-target experiments (forward Λ_C, asymmetries D - $\bar{D}$, $J/\psi\ J/\psi$).

Nuclear PDFs and prompt neutrino fluxes





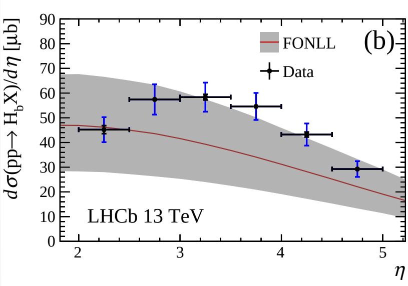
* Bhattacharya et al. 2016, produce predictions by using nuclear PDFs, instead of nucleon PDFs + superposition model
  → their prompt fluxes look suppressed with respect to the older ones.

* However, still compatible with our predictions on the basis of nucleon PDFs + superposition model.

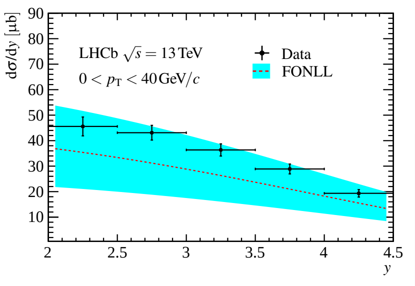
* Uncertainty on nuclear PDF are underestimated: however they can be huge!

Open bottom production at LHCb, $\sqrt{s} = 13$ TeV:

theory vs. experiment



H_b from [arXiv:1612.05140]

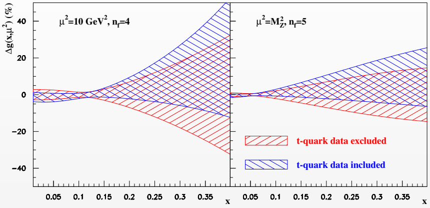


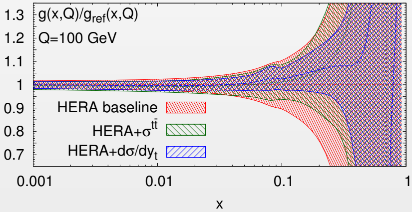
B^+ from [arXiv:1710.04921]

* The corrected data on H_b at 13 TeV exhibit a similar $d\sigma/d\eta$ shape as those at 7 TeV.
* Helpful to have separate results for each H_b (B^+, B^0, B_s^0, Λ_b^0).
* In case of B^+, shape of FONLL predictions more similar to that of data than for H_b.
* We plan cross-checks with further methods (GM-VFNS).

⇒ Important to understand these aspects in order to incorporate bottom hadroproduction and decay in prompt neutrino fluxes.

Top quark measurements and constraints on PDFs





from [arXiv:1611.08609] and from [arXiv:1701.05838]

* Including information on $\sigma^{t\bar{t}}$ and on various differential distributions $d\sigma/dp_{T,t}$, $d\sigma/dy_t$, $d\sigma/dy_{t\bar{t}}$, $d\sigma/dm_{t\bar{t}}$ in PDF fits constrains gluons especially in the region $0.08 < x < 0.5$.

Conclusions

* Heavy-quark hadroproduction investigated by all LHC experiments. LHCb particularly interesting because it explores the "large" rapidities ($2 < y < 4.5$).
* Theory predictions on charm and bottom 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.
* IceCube and future Antares/KM3NeT data can be used to constrain unknown aspects of QCD (e.g. PDFs at low x's and intrinsic charm, difficult to study at colliders).

* A webpage with our most recent predictions is available: `www.desy.de/~lepflux`