Prompt neutrinos and LHC measurements

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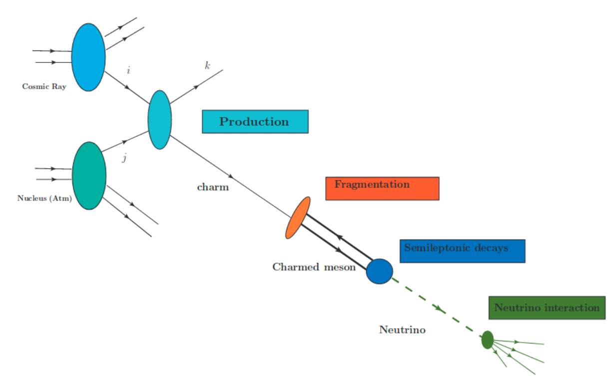
Underlying concept: prompt ν production



from V. Goncalves et al. [arXiv:2103.05503]

$*$ The mechanisms for prompt ν production in the atmosphere (above) is the same as for LHC collisions, except that the latter are induced by *pp* interactions instead of CR + Air (that we in any case approximate as superposition of *pA*, in turn approximated in terms of *pp* and *pn*).

Main sources of neutrino fluxes in the atmosphere ....and at the LHC

Nucleon-Nucleon interactions:

$*$ conventional neutrino flux:

$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + X \rightarrow \pi^{\pm}, K^{\pm} + X' \rightarrow \nu_{\ell}(\bar{\nu}_{\ell}) + \ell^{\pm} + X',$$
$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + X \rightarrow K^0_S,\, K^0_L + X \rightarrow \pi^{\pm} + \ell^{\mp} + \overset{(-)}{\nu}_{\ell} + X$$
$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + X \rightarrow light\ hadron + X' \rightarrow \nu(\bar{\nu}) + X''$$

$*$ prompt neutrino flux:

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

where the decay to neutrino occurs through semileptonic and leptonic decays:

$D^+ \rightarrow e^+ \nu_e X, \quad D^+ \rightarrow \mu^+ \nu_\mu X,$

$D_s^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \tau^{\pm}$, with further decay $\tau^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + X$

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

Specific to the atmosphere:

Critical energy $\epsilon_h = m_h c^2 h_0 \,/\, (c\ \tau_{0,h} \cos(\theta))$, 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, due to finite atmosphere height h_0.

Light flavour vs. heavy flavour

$*$ Light-flavoured hadrons include only light quarks as valence quarks in their composition.

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

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

$\Rightarrow$ Light hadron production at low p_T is dominated by non-perturbative QCD effects.

$*$ Heavy-flavoured hadrons include at least one heavy-quark as valence quark in their composition.

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

$\Rightarrow \alpha_s(m_c), \;\; \alpha_s(m_b), \;\; << 1$

$\Rightarrow$ At a scale $\sim m_Q$, QCD is still perturbative. At the LHC, charm is produced perturbatively (if one neglects possible intrinsic charm contributions) even at low p_T, but non-perturbative effects at such low scales may also play important roles. At the EIC, charm can also be produced by diffraction.

$* \; m_c, \;\; m_b <<$ LHC energies

$\Rightarrow$ Multiscale issues, appearence of large logs.

Heavy-quark production in hadronic collisions

* Heavy quarks are mostly produced in pairs in the Standard Model.
* This process is dominated by QCD effects.

* Collinear factorization theorem is assumed:

$$d\sigma(N_1 N_2 \to Q\bar{Q} + X) = \sum_{ab} PDF_a^{N_1}(x_a, \mu_F^2) \otimes PDF_b^{N_2}(x_b, \mu_F^2) \otimes \otimes \; d\hat{\sigma}_{ab}(x_a, x_b, \mu_F^2, \mu_R^2, \alpha_s(\mu_R^2), m_Q)$$

$d\hat{\sigma}$: differential perturbative partonic hard-scattering cross-section,

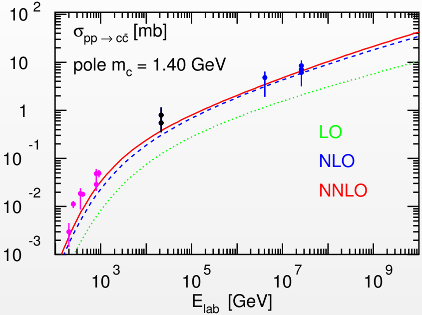
μ_F, μ_R reabsorb IR and UV divergences,

PDFs: perturbative evolution with factorization scale μ_F,
non-perturbative dependence on $x = p^+/P_N^+$.

QCD uncertainties

* μ_F and μ_R choice: no univocal recipe.
* Approximate knowledge of heavy-quark mass values m_Q (SM input parameters).
* Choice of the Flavour Number Scheme (several possibilities).
* PDF (+ $\alpha_S(M_Z)$) fits to experimental data.

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



$(E_{lab} \simeq 400 \text{ GeV} \sim E_{cm} = 27 \text{ GeV})$

$(E_{lab} \simeq 7000 \text{ GeV} \sim E_{cm} = 114.6 \text{ GeV})$

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

data from fixed target exp (E769, LEBC-EHS, LEBC-MPS, HERA-B)
+ colliders (STAR, PHENIX, ALICE, ATLAS, LHCb)
are extrapolated from fiducial measurements.

* LHC fixed-target program make measurements in the region between old fixed-target experiments and RHIC (not covered by other exp.).
* Sizable QCD uncertainty bands not included in the figure.
* Leading order is not accurate enough for this process!

From parton production at NLO 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 soft and collinear emissions on top of the hard-scattering process), followed by hadronization (phenomenological model).

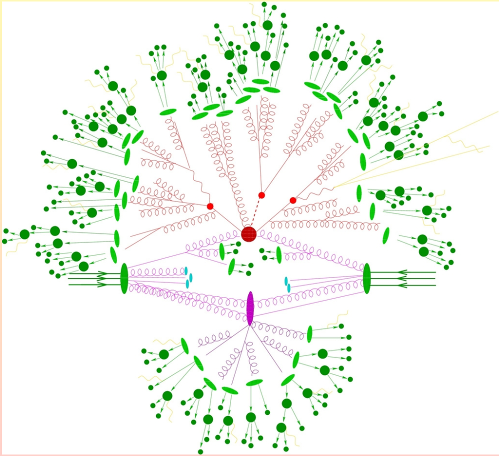
Advantage: fully exclusive event generation, correlations between final state particles/hadrons are kept.

Problem: accuracy not exactly known, differently from the case of conventional analytical resummation procedures to all orders in P. T.

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

Both methods 1) and 2) are used in the following.

p-p and p-$\bar{\mathrm{p}}$ 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).

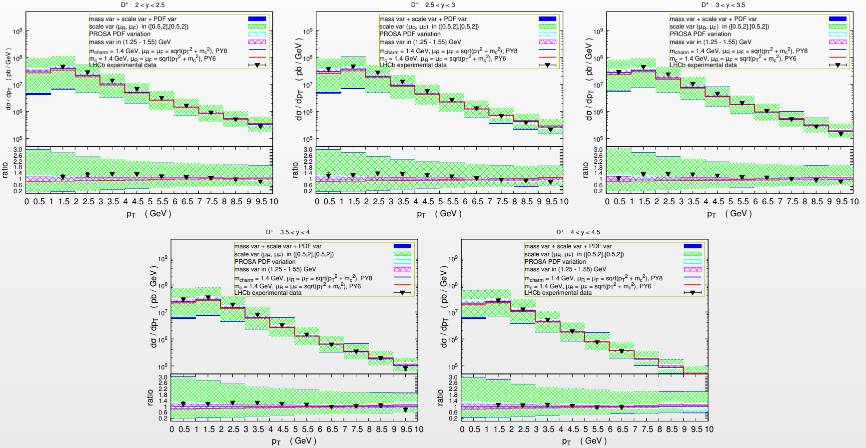
DECREASING ENERGY SCALE

PERTURBATIVE AND NON-PERTURBATIVE COMPONENTS

Monday, December 9, 13

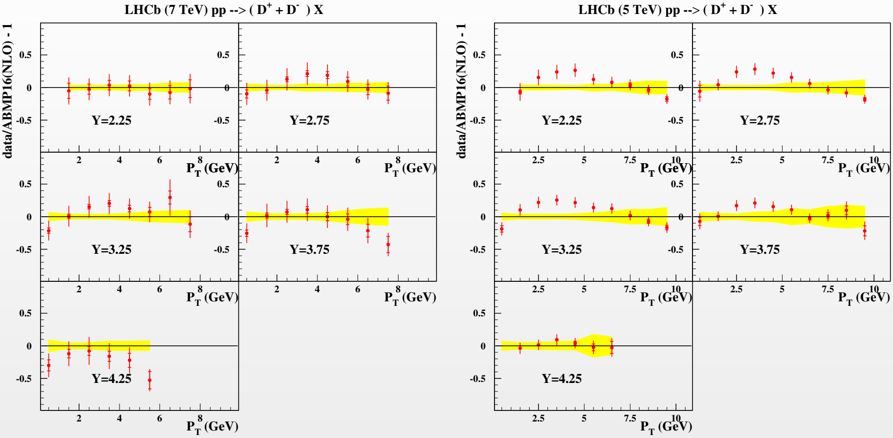
NLO+PS differential σ vs experimental data

for differential cross-sections for $pp \to D^{\pm} + X$ at LHCb at 5 TeV



* agreement theory/experiment within large (μ_R, μ_F) uncertainty bands.
* theory uncertainties much larger than the experimental ones.

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

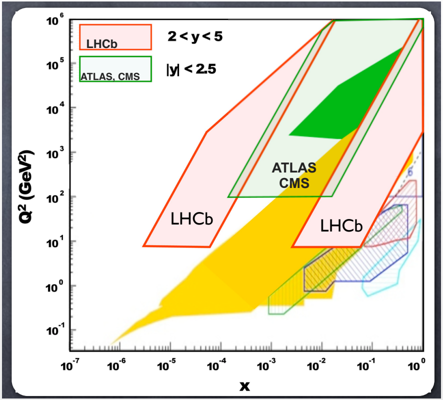


$*$ Puzzle: at small rapidities the $D^{\pm}$ data at $\sqrt{s} = 7$ TeV turn out to be described better than those at 5 TeV, whereas we do not expect significant modifications of the physics: are the experimental data at different energies compatible among each other ?

Further investigations: adding data from other experiments

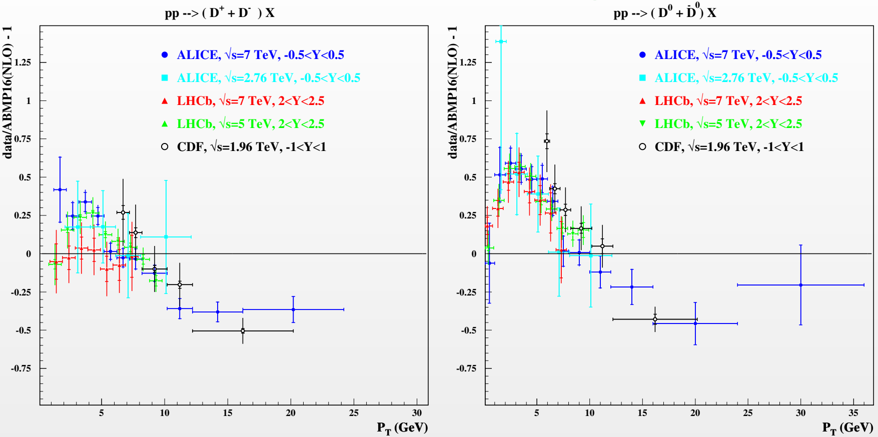
* LHCb open-charm data ($2 < y < 4.5$)
* ATLAS (and CMS) open-charm data ($|y| < 2.5$)
* CDF open-charm data ($|y| < 1$)
* ALICE open-charm data ($|y| < 0.5$)

+ further open-bottom data



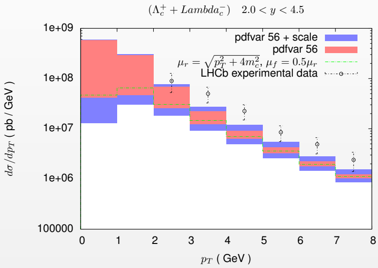
Different experiments span (Q^2, x) regions partially overlapping: good for verifying their compatibility and for cross-checking their theoretical description.

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

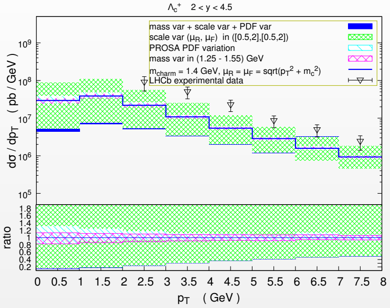


* Fluctuations for $D^{\pm}$, while a trend is visible for D^0.
* In case of D^0, data at a fixed p_T seem to be reproduced similarly well/bad, indipendently of the $\sqrt{s}$ and of the y probed.
* This implies that the difference in shape between theory predictions and exp. data can not be washed out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

Forward Λ_c hadroproduction in pp collisions



GM-VFNS + FF



NLO + PS + had

- ∗ 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.

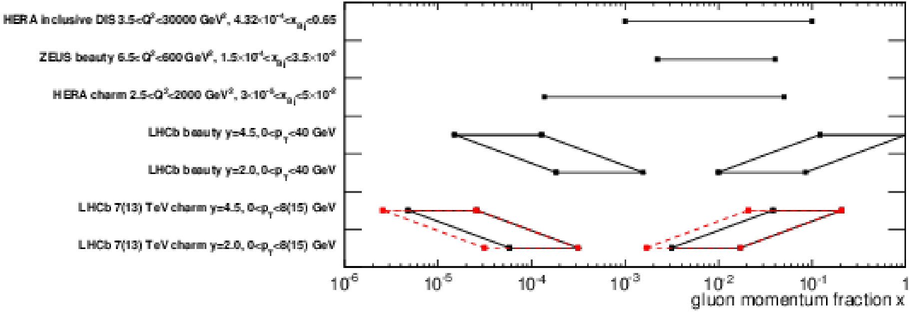
⇒ Extension to *pp* would be important for assessing fragmentation/hadronization mechanisms

- ∗ A rapidity dependence might be expected/should be experimentally checked.

Why improving the description of open heavy-flavour hadroproduction/acquiring more data matters ?

* Constraints of PDFs at low x's, which in turns 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 far-forward LHC experiments: Faserν, SND@LHC, FPF, etc.....
    (see e.g. FPF report [arXiv:2109.10905]).
  - future high-energy colliders: FCC-hh, etc.....
    (see the study in the FCC-hh SM report [arXiv:1607.01831]).
* Fixed-target program at the LHC and constraints of PDFs at large x's.
* high-energy astroparticle physics applications:
  - High Energy Cosmic Ray physics and prompt neutrino fluxes
* disentangling cold and hot nuclear matter effects
  (in pA and AA collisions).

x coverage of HERA and LHCb experiments



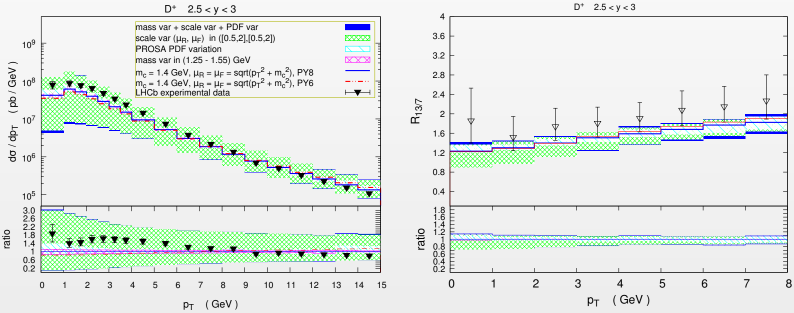
LHCb data allow to cover x regions uncovered by HERA data,
both at low x's (especially open charm data)
and at large x's (especially open bottom data).

For LHCb, LO formula $x_{1,2} = (\sqrt{p_T^2 + m_Q^2}/E_p)\ \exp(\pm y)$ $\Rightarrow$ Larger rapidities of the emitted quark correspond to more extreme x's; large $\sqrt{s} \leftrightarrow$ small x 's

charm production in DIS at EIC extends HERA charm coverage even to $x > 0.1$.

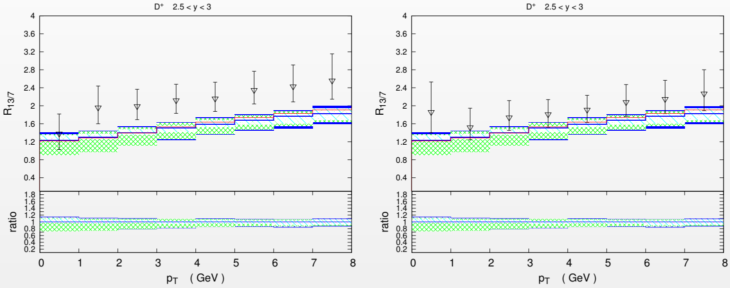
How to use charm production data for inferring other quantities, if scale uncertainties are so big ?

- Issue already seen in the comparison with LHCb data on charmed meson production



- Solution: use ratios.
- When considering LHCb, it is possible to use data in two different rapidity ranges: e.g. ($4 < y < 4.5$) and ($3 < y < 3.5$).
- One can also use ratios of data at two different center-of-mass energies.

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

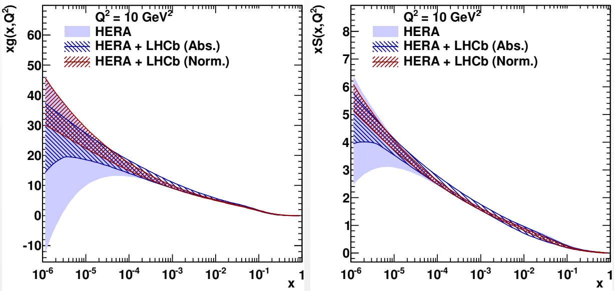


old (wrong) experimental data   experimental data after revision

- ∗ Reduced uncertainties in ratios (compared to the absolute case).
- ∗ Agreement of theory predictions and experimental data improved after last data revision by LHCb (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).

The power of LHCb data ratios in constraining PDFs

PROSA 2015 PDF fit: comparison between three variants
from PROSA collab., EPJC 75 (2015) 471



Three variants of the PDF fit:

1) one with HERA data only (behaviour at low (x, Q^2) driven by parameterization and sum rules);

2) one also including LHCb absolute differential cross-sections;

3) another one with reduced uncertainties: for each fixed LHCb p_T bin, use the ratios of distributions $(d\sigma/dy)/(d\sigma/dy_0)$ considering different rapidity intervals (i.e. normalized to the central bin $3 < y_0 < 3.5$):
in the ratios theoretical uncertainties partly cancel.
Shapes of rapidity distributions are fitted.

PROSA 2015 PDF fit: methodology

* Fit entirely performed with `xFitter` - publicly available framework (see next talk).
* Methodology inspired by the HERAPDF1.0 PDF fit.
* Ab-initio fit. All data (HERA DIS + LHCb open heavy flavour at $\sqrt{s} = 7$ TeV) included from the very beginning.
* NLO QCD predictions for heavy-quark production (FFNS).
* Fragmentation functions: c as measured at HERA [EPJC 59 (2009) 589, JHEP 04 (2009) 082], b as measured at LEP [NPB 566 (2000) 245].
* Fragmentation fractions: combination of LEP and HERA measurements [arXiv:1112.3757]
* m_c^{pole}, m_b^{pole} left as free parameters in the fit.

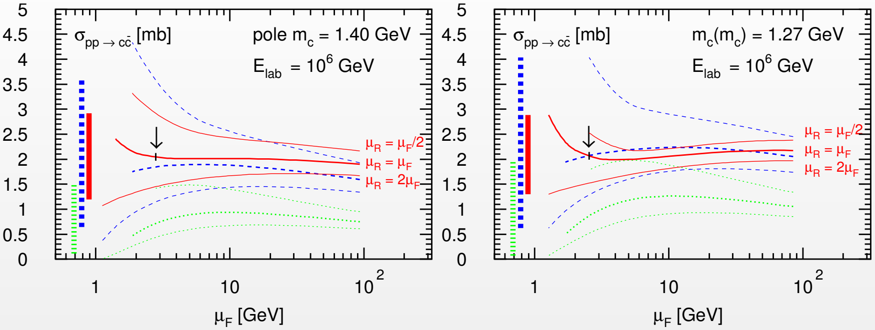
PROSA 2019 PDF fit:

what is new w.r.t. PROSA 2015 ?

* central (μ_R, μ_F) scale choice
* Together with the PDF dependence on x, we fit the values of $m_c(m_c)$ and $m_b(m_b)$ in the MSbar scheme, consistently used for all theoretical predictions at NLO in the FFNS. We find
  $m_c(m_c) = 1.23 \pm 0.03$ (exp) GeV,
  $m_b(m_b) = 3.98 \pm 0.010$ (exp) GeV.
* PDF parameterization modified/extended with additional terms.
* FFNS and VFNS versions

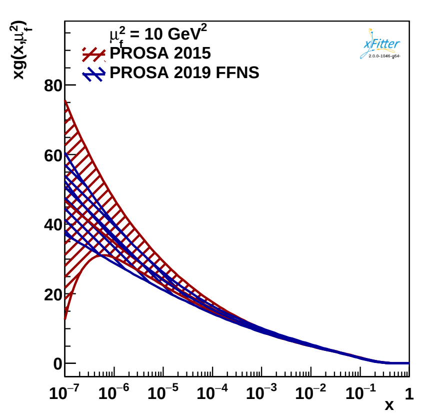
from O. Zenaiev et al., [arXiv:1911.13164]

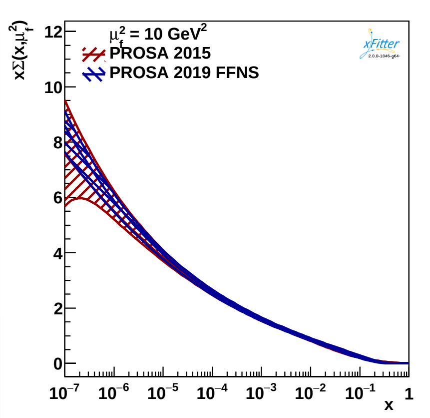
$\sigma(pp \to c\bar{c})$: scale dependence at LO, NLO, NNLO



* Perturbative convergence when mass is renormalized in $\overline{\mathrm{MS}}$ scheme is reached slightly faster than in pole mass scheme.
* Sensitivity to radiative corrections is smaller at a scale $\mu_R \sim \mu_F \sim 2m_c$ than at the scale $\mu_R \sim \mu_F \sim m_c$.
* This translates into a dynamical scale $\sqrt{p_{T,c}^2 + 4m_c^2}$ to better catch dynamics in differential distributions.

PROSA 2019 vs PROSA 2015: gluons & sea quarks





* new gluon and sea quark PDFs consistent with the old ones
* reduced uncertainties for $x < 10^{-4}$

Alternative gluon PDF parameterizations

PROSA19:

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} (1 + F_g \log x),$$

ABMP16:

$$xg(x) = A(1-x)^b x^{a(1+\gamma_1 x)},$$

CT14:

$$xg(x) = A x^{a_1} (1-x)^{a_2} (e_0 (1-y)^2 + e_1 (2y(1-y)) + y^2), y = 2\sqrt{x} - x,$$

HERAPDF2.0 flex. g:

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{25},$$

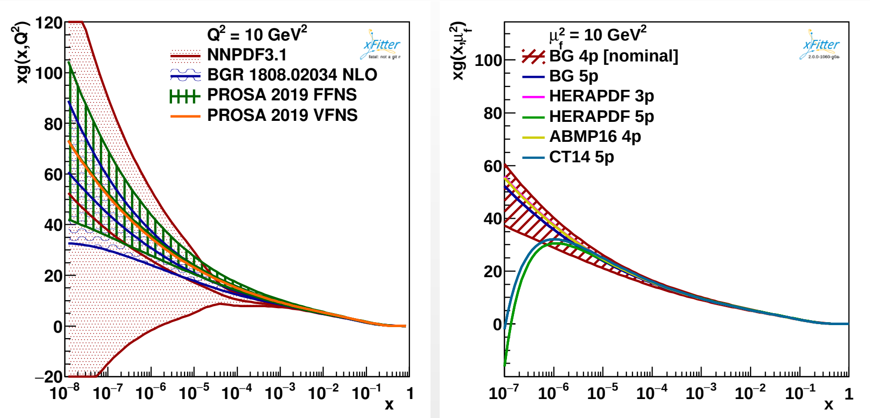
HERAPDF2.0 no flex. g:

$$xg(x) = A_g x^{B_g} (1-x)^{C_g},$$

BG:

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} (1 + F_g \log x + G_g \log^2 x)$$

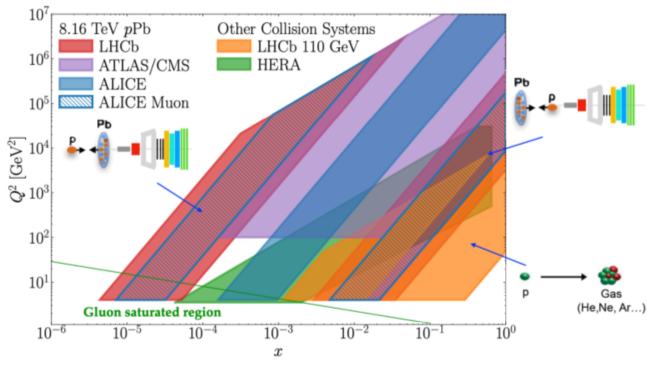
gluon PDF: comparison between different PDF fits, parameterizations



∗ Compatibility of indipendent PDF fits including *D*-meson data.

∗ However, sensitivity to the parameterization, as soon as one exits the region covered by data.

Fixed-target experiments at the LHC: increased large x coverage and sensitivity to nuclear matter eff ects



from LHCb collaboration

∗ LHCb-FT coverage at scale $Q^2 \sim 4$ GeV^2:

$2 \cdot 10^{-4} \lesssim x \lesssim 4 \cdot 10^{-1}$ ⇒ gluon, sea quarks

∗ Light targets: probe NM effects in pA collisions in A range different from Pb

∗ Cold and Hot Nuclear Matter effects (at small x) can be compared by using p or Pb beams impinging on the nuclear targets (He, Ne, Ar, ...).

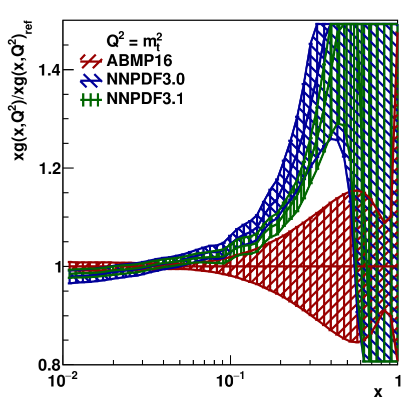
PDF uncertainties at large x

* PDF uncertainties are often estimated by considering a single PDF set.
* However, the differences between different PDF sets might be not covered by the uncertainty of a single set.

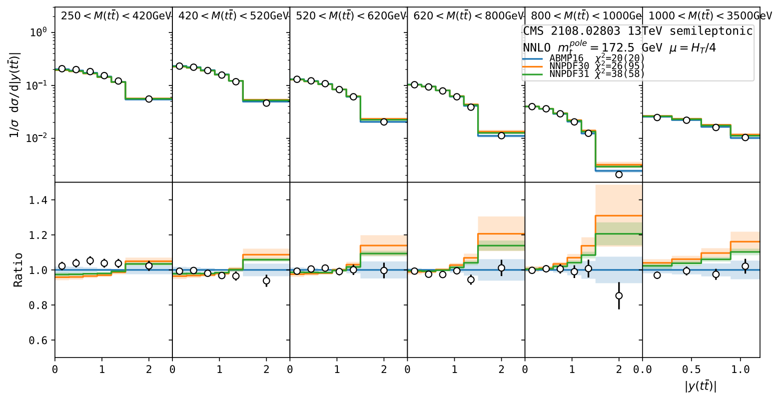
⇒ A more comprehensive estimate would be recommended.

* g PDF at large x play an important role in the predictions.

⇒ data on $t\bar{t} + X$ and jet production at the LHC are important for constraining g PDF in this region.

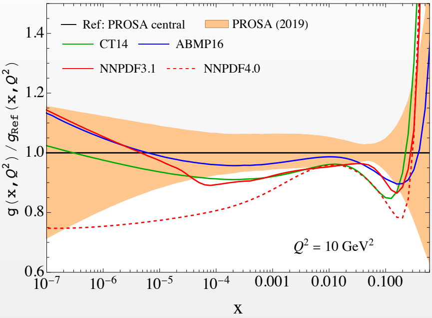


NNLO predictions on $d^2\sigma/dM(t\bar{t})dy(t\bar{t})$ for $t\bar{t}+X$ with different PDF sets vs. experimental data

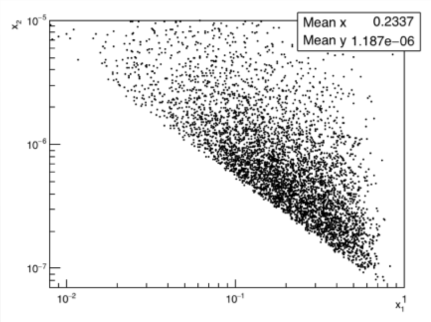


* The NNPDF3.0 central set (default for ATLAS $t\bar{t}b\bar{b}$ predictions) shows a poor description of these data, in the high-energy tails.
* The uncertainty bands, although large, do not encompass data in all bins

PDFs uncertainties at low and large-x and x coverage of forward ν LHC exp.



W. Bai et al., [arXiv:2212.07865]



SND@LHC technical proposal (2021)

∗ Differences in gluon PDFs at large x are not covered by the uncertainties associated to each single PDF set.

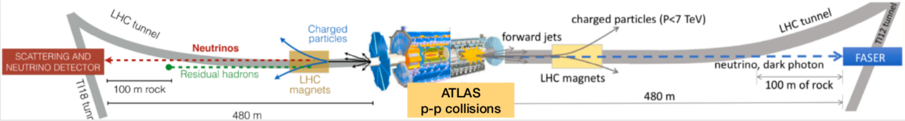
∗ The coverage of forward ν experiments can help constraining PDFs at extreme x-values (actually more extreme than what is needed for atmospheric prompt ν at the PeV scale).

Far-forward LHC experiments

* Various projects to exploit beams of particles produced in the interactions points at the LHC, propagating in the direction tangent to the accelerator arc.

* Let these beams propagating for some distance: some particles will be deviated or stopped, some other will reach the detector.

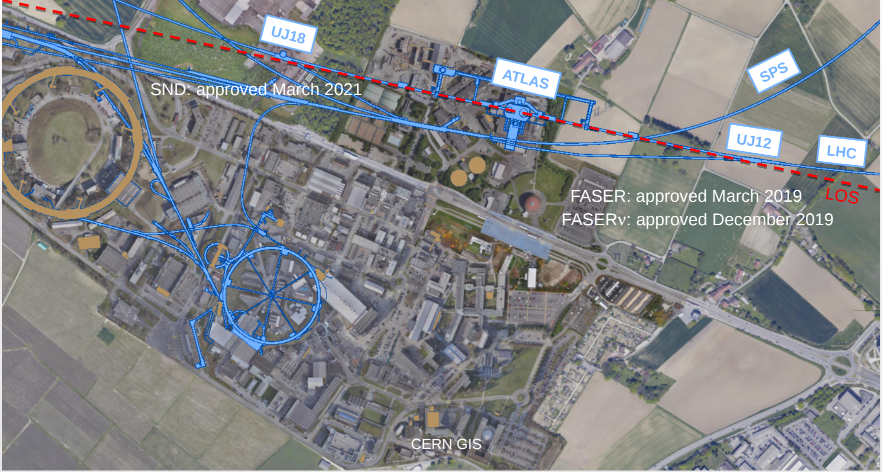
* Pilot experiments, on the tangent to the LHC beam line, at $\sim$ 480 m from ATLAS IP:
  - FASER ($\eta > 9.2$), Faserν ($\eta > 8.5$) and SND@LHC ($7.2 < \eta < 8.4$), all active in taking data during Run 3.



* Detection mechanisms: CC and NC ν and $\bar{\nu}$ induced DIS, DM scatterings on e and A.

FAR FORWARD LHC EXPERIMENTS

The existing caverns UJ12 and UJ18 and adjacent tunnels are good locations for experiments along the LOS: 480 m from ATLAS and shielded from the ATLAS IP by ~100 m of rock.



First observations of far-forward LHC neutrinos

* FASER collab., [arXiv:2105.06197]:

A search for neutrino interactions is presented based on a small emulsion detector installed at the LHC in 2018. We observe the first candidate vertices consistent with neutrino interactions at the LHC. A 2.7σ excess of neutrino-like signal above muon-induced backgrounds is measured. These results demonstrate FASERν's ability to detect neutrinos at the LHC and pave the way for future collider neutrino experiments.

* FASER collab., [arXiv:2303.14185]:

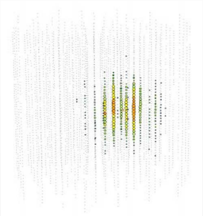
Summary We report the first direct detection of neutrinos produced at a collider experiment using the active electronic components of the FASER detector. We observe 153^{+12}_{-13} neutrino events from CC interactions from ν_μ and $\overline{\nu}_\mu$ taking place in the tungsten-emulsion detector of FASERν. The spatial distribution and properties of the observed signal events are consistent with neutrino interactions, and the chosen analysis strategy does not depend on the quality of the modeling of detector effects in the simulation. For the signal events, the reconstructed charge shows the presence of anti-neutrinos, and the reconstructed momentum implies that neutrino candidates have energies significantly above 200 GeV. This

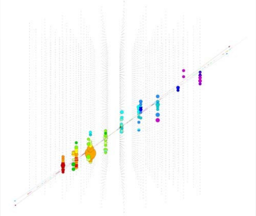
* SND@LHC collab., [arXiv:2305.09383]:

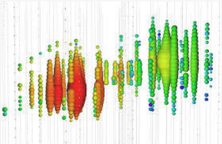
Conclusions - A search for high energy neutrinos originating from *pp* collisions at $\sqrt{s} = 13.6$ TeV is presented using data taken by the electronic detectors of SND@LHC. We observe 8 candidate events consistent with ν_μ CC interactions. Our muon-induced and neutral-hadron backgrounds for the analysed data set amount to $(7.6 \pm 3.1) \times 10^{-2}$ events, which implies an excess of ν_μ CC signal events over the background-only hypothesis of seven standard deviations.

Astroparticle experiments for detecting high-energy neutrinos

$\ast$ Atmospheric neutrinos at ANTARES, IceCube, KM3NeT, Baikal-GVD...
track / shower events from CC and NC $\nu + \bar{\nu}$ induced DIS in ice/water.







- lighter targets for DIS than in far-forward LHC experiments
- these experiments distinguish different flavour (like the LHC ones)
- these experiments do not distinguish ν and $\bar{\nu}$ (differently from LHC ones).
- these experiments do not have a ν and $\bar{\nu}$ pseudorapidity cut (differently from LHC ones).

How to get atmospheric fluxes? From cascade equations to Z-moments [*review in Gaisser, 1990; Lipari, 1993*]

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

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

Under assumption that X dependence of fluxes factorizes from E dependence, analytical approximated solutions in terms of Z-moments:

– Particle Production:

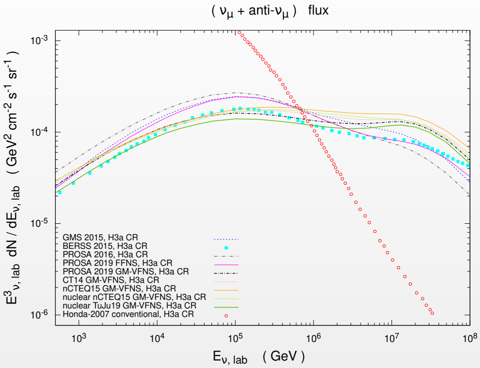
$$S_{prod}^{k\rightarrow j}(E_j,X) = \int_{E_j}^{\infty} dE_k \frac{\phi_k(E_k,X)}{\lambda_k(E_k)} \frac{1}{\sigma_k} \frac{d\sigma_{k\rightarrow j}(E_k,E_j)}{dE_j} \sim \frac{\phi_k(E_j,X)}{\lambda_k(E_j)} Z_{kj}(E_j)$$

– Particle Decay:

$$S_{decay}^{j\rightarrow l}(E_l,X) = \int_{E_l}^{\infty} dE_j \frac{\phi_j(E_j,X)}{\lambda_j(E_j)} \frac{1}{\Gamma_j} \frac{d\Gamma_{j\rightarrow l}(E_j,E_l)}{dE_l} \sim \frac{\phi_j(E_l,X)}{\lambda_j(E_l)} Z_{jl}(E_l)$$

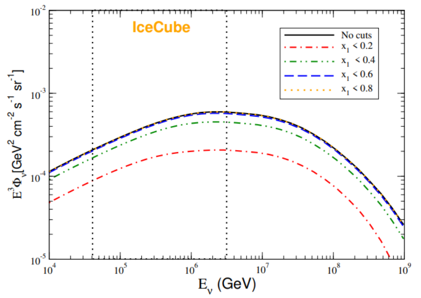
Solutions for $E_j >> E_{crit,j}$ and for $E_j << E_{crit,j}$, respectively, are interpolated geometrically.

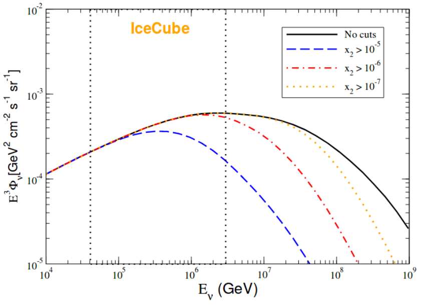
$(\nu_\mu + \bar{\nu}_\mu)$ atmospheric fluxes: conventional $\to$ prompt transition



* Atmospheric ν from solving a system of coupled differential eqs. for the variation of fluxes of different particles as a function of the atmospheric depth.
* Honda-2007 conventional flux reweighted with respect to a more modern CR primary spectrum (H3a).
* central GM-VFNS, PROSA, BERSS and GMS flux predictions all yield to a very similar transition point $E_\nu \sim (6-9) \cdot 10^5$ GeV.
* Transition prompt conventional absent at colliders

Prompt atmospheric ν fluxes, small-x and large-x PDFs





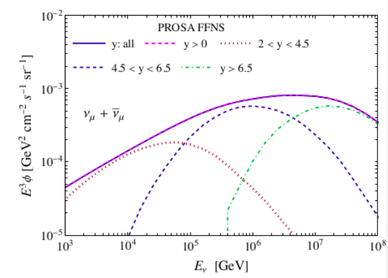
, *from V. Goncalves et al. [arXiv:1708.03775]*

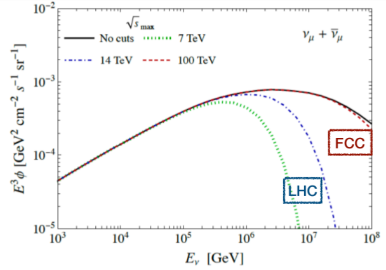
∗ A robust estimate of large x effects is important for determining the normalization of prompt atmospheric neutrino fluxes

∗ Region particularly relevant: $0.2 < x < 0.6$, partly testable through ν experiments at the LHC.

∗ On the other hand, for ν at the PeV scale, knowledge of PDF down to $x > 10^{-6}$ is enough.

Prompt atmospheric ν fluxes and LHC phase-space coverage



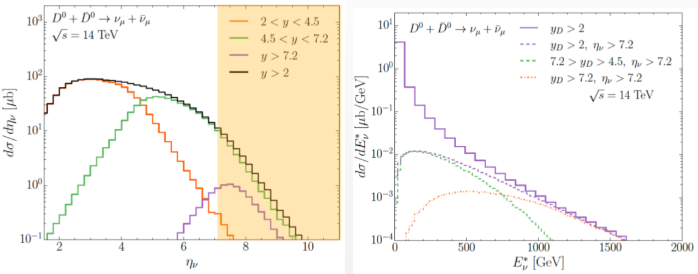


∗ To connect to prompt ν fluxes at the PeV, LHC measurements of charm production should focus on the region $4 < y_c < 7$.

∗ The $\sqrt{s} = 14$ TeV at LHC is in any case a limitation, FCC would be better (see also analysis in V. Goncalves et al, [arXiv:1708.03775]).

∗ Exploring the connection between (E_ν, y_ν) and y_c reveals that there is some kinematic overlap between the heavy-flavour production region explored in far-forward ν experiments at the LHC and in the atmosphere.

Prompt ν fluxes at the LHC



∗ At the LHC, charmed mesons with $4 < y_c < 7$ give rise to neutrino populating a wide rapidity spectrum, with a maximum around $\eta_\nu \sim 5$.

∗ These neutrinos constitutes the majority of neutrinos for $\eta_\nu \gtrsim 7.2$ (region probed by SND@LHC, and at future FPF).

∗ The energy spectrum of these neutrinos is peaked at ~ 100 GeV in CM frame, but extends also to the TeV. For $E_\nu \sim 700$ GeV half neutrinos at the LHC come from charm with $4.5 < y_c < 7.2$, whereas another half come from charm with $y_c > 7.2$. On the other hand, most energetic neutrinos at the LHC come from charmed mesons with higher rapidities.

Wishlist useful measurements LHCb

∗ D-meson and B-meson spectra at 13.6 TeV, 14 TeV.

∗ Re-analysis of 7 TeV data ?

∗ if possible, more p_T bins in the region 0 - 5 GeV

∗ $\Lambda_c^\pm$ double-differential spectra in y, p_T.

∗ Particular focus on $D_s^\pm$ (main source of ν_τ and $\bar{\nu}_\tau$ in far-forward LHC experiments).

∗ Charge asymmetries with better statistics.

∗ All above in pp, pPb, pO standard collider modality
+ SMOG fxixed-target modality using various light targets.

∗ LHCb measurements of DY and $t\bar{t}$-pair production in pp.

∗ Measurements should be accompanied by detailed information concerning systematic uncertainties (correlation matrices).

∗ Further measurements of correlations between D-mesons from c and $\bar{c}$ help to stress-test theory predictions.

Conclusions - prompt neutrinos

* Prompt neutrino fluxes in the atmosphere are a background to neutrinos from far astrophysical sources.

* Theory uncertainties still large and constraints from VLVνT still loose. Computing higher-order corrections is an indispensable ingredient for reducing these uncertainties.

* Synergy LHC-EIC-astroparticle physics

* There is some kinematical overlap between the charm hadron production region explorable in far-forward experiments at the LHC and the one explorable in VLVνT's.

* Atmospheric ν's with $E_{\nu,LAB} \sim \mathcal{O}(\mathrm{PeV})$ mostly come from charm produced within LHC $\sqrt{s}$ in the rapidity range $4.5 < y_c < 7.2$, which in turn produce neutrinos even in the ν rapidity range of the SND@LHC detector $\eta_\nu > 7.2$ and future (like in the FPF).

Thank you for your attention!