Production of forward neutrinos at the LHC

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with input from
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+ PROSA collaboration

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EF06 meeting - PDF at small x and Forward QCD,
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Ongoing experimental efforts to prepare experiments for measuring forward ν at Run3 LHC

Idea: detectors at a distance of several hundred meters from LHC interaction point, along the tangent to the LHC arc, can intercept an high flux of LHC neutrinos.

Among the others:

- First studies within CMS during 2015
- XSEN letter of intent CERN-LHCC-2019-014 (2019).
- Technical proposal requested by LHC committee not yet submitted.
- Start date ?

In the meanwhile,

- Faserν letter of intent and proposal submitted in 2019 ([arXiv:1908.02310]),
- already approved and financed!
- under construction.
- Data taking probably from the beginning of LHC Run 3.

From hadrons to neutrinos

* neutrino flux from heavy-flavour decay:

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

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 $\tau^\pm \rightarrow \nu_\tau(\bar{\nu}_\tau) + \mathrm{X}$

* neutrino flux from light-flavour decay:

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

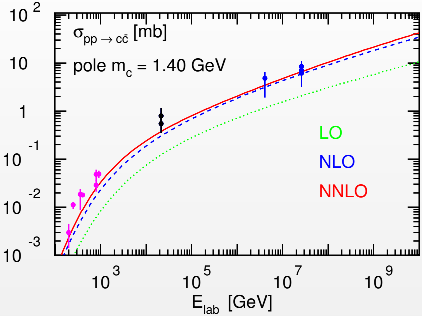
$$pp \quad \rightarrow \quad K_S^0,\ K_L^0 + \mathrm{X} \quad \rightarrow \quad \pi^\pm + \ell^\mp + \nu_\ell + \mathrm{X}$$

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

N.B. other channels of neutrino production occur in the Standard Model,
e.g. W boson and t quark production and leptonic decay,
but they are suppressed with respect to the previous channels.

* In our work we focus especially on neutrino fluxes from heavy-flavour:
$\nu_\tau + \bar{\nu}_\tau$ are mainly produced through this channel.

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



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

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

∗ Assumption: collinear factorization valid on the whole energy range.

∗ Sizable QCD uncertainty bands not included in the figure.

∗ Leading order is not accurate enough for this process:
at NLO new channels open, due to qg interactions.

From parton production to heavy-flavour hadrons

Different descriptions of the transition are possible:

1) Convolution of cross-sections with Fragmentation Functions

2) 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).

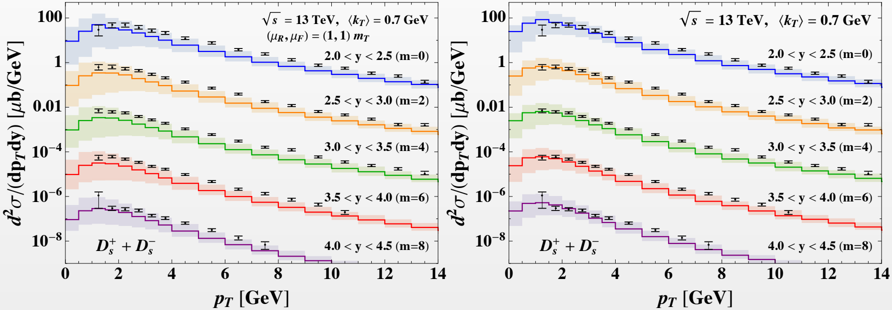
Advantage: fully exclusive event generation, correlations between final state particles/hadrons are kept.

Problem: accuracy not exactly known.

Both methods 1) and 2) used here.

In both cases, additional non-perturbative contribution due to intrinsic $\langle k_T \rangle$, related to the confinement of the initial state partons into hadrons, is added.

$D_s + \bar{D}_s$ production: theory predictions vs. LHCb experimental data



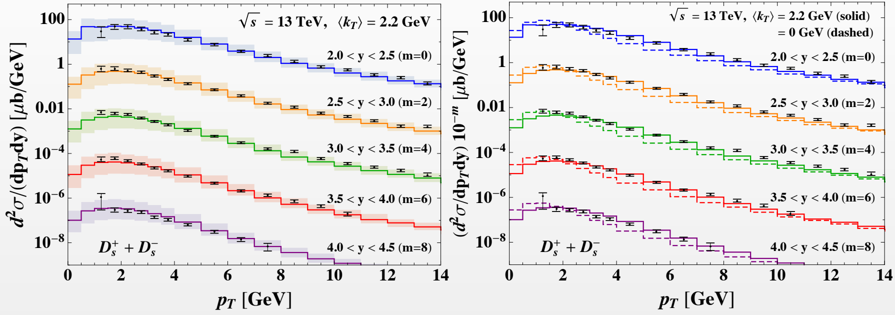
$(\mu_R, \mu_F) = (1, 1)m_T$ $(\mu_R, \mu_F) = (1, 1.5)m_T$

* p_T distributions in different rapidity bins are considered.

* Experimental data have uncertainty bands much smaller than theory predictions.

* The optimization of the choice of the factorization scale plus the effect of an intrinsic $\langle k_T \rangle$ increase the agreement between central predictions and experimental data.

And if we try to fit the LHCb experimental data ?

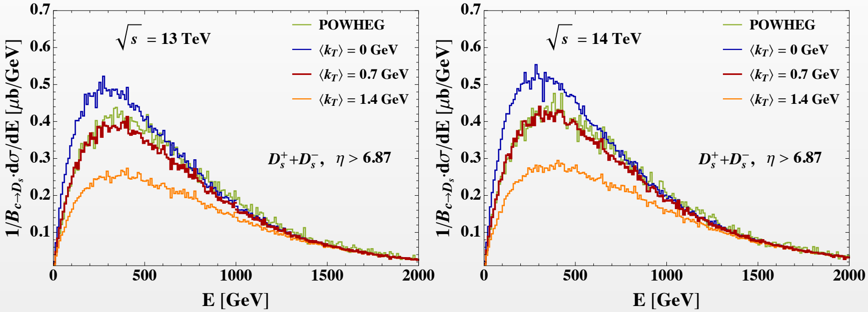


$*$ The "best fit" configuration turns out to correspond to intrinsic $\langle k_T \rangle$ values that are larger than those expected on the basis of other processes.

$*$ This shows that there are other QCD effects that can be approximately reabsorbed in an (intrinsic) $\langle k_T \rangle$ smearing model, which play a role in this process.

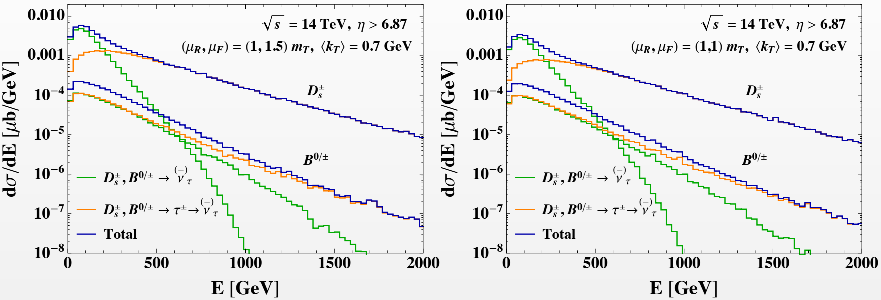
$*$ Part of these effects are expected to be of perturbative origin and another part of non-perturbative origin.

Comparison of $(D_s + \bar{D}_s)$ energy distributions by different theory approaches



* (NLO + FF + $\langle k_T \rangle$) vs. (NLO + Parton Shower + hadronization + built-in $\langle k_T \rangle$), where (Parton Shower + hadronization + built-in $\langle k_T \rangle$) are from PYTHIA.
* Further ongoing studies: sensitivity to different PYTHIA tunes

Energy distribution of forward $\nu_\tau + \bar{\nu}_\tau$



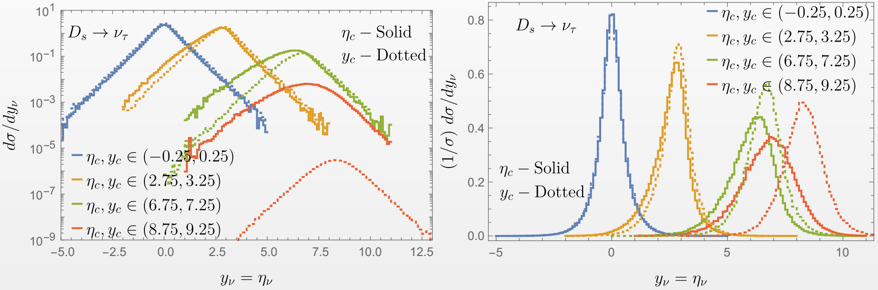
from W. Bai et al. [arXiv:2002.03012]

* direct decay and chain decay contribute to the total in different energy regions

* contributions from B meson decays are one-two order of magnitude smaller than those from D mesons.

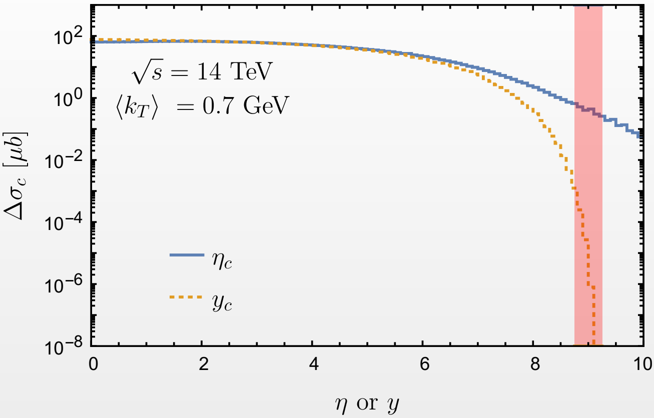
* What are the dominant uncertainties on these distributions ?

$(\nu_\tau + \bar{\nu}_\tau)$ distributions, for various cuts on y or η of charm quark (PRELIMINARY)



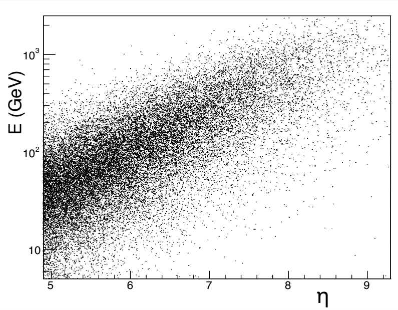
* Absolute and normalized plots
* A cut on charm rapidity $\sim y_c$ produce ν_τ peaked at a similar y_c.
* In the forward region, a cut on charm pseudorapidity η_c produce neutrinos peaked at $\eta_\nu < \eta_c$.

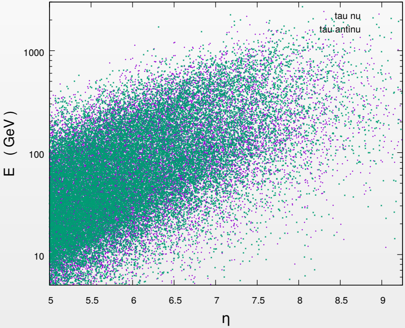
Charm production at large rapidity/pseudorapidity



* For very forward charm production ($\eta_c \gtrsim 7$), cutting on y_c is very different than cutting on η_c.
* charm mass information encoded in y_c (not in η_c): maximum rapidity bound by the mass of the particle.

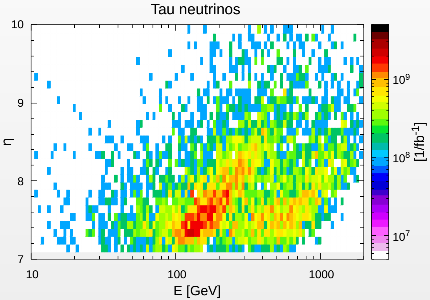
Scatter-plots in (η, E) for heavy-flavour ν and $\bar{\nu}$ production

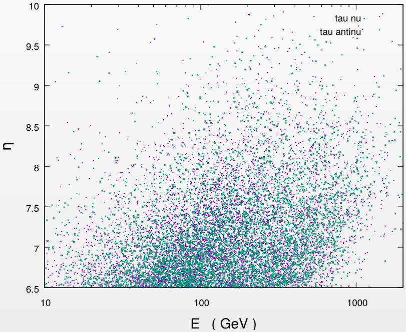




PYTHIA in [arXiv:2004.07821] vs. NLO QCD + PYTHIA (PRELIMINARY).

Scatter-plots in (E, η) for ν_τ and $\bar{\nu}_\tau$ production





DPMJET/FLUKA in [arXiv:2004.07821] vs. NLO QCD + PYTHIA (PRELIMINARY).

Thinking to the future (HL-LHC): Forward-ν facility

Which are the experimental requirements for getting data useful for better understanding/constraining QCD and BSM elements at a Forward-ν facility at HL-LHC ?

Snowmass LoI in preparation:
whoever is interested to contribute to the QCD part,
please contact Felix Kling (`felix@slac.stanford.edu`) or myself.

$\Rightarrow$ Interesting aspects, pointed out by the EF06 conveners:

- disentangling the complementarity of the potential of the Forward-ν facility w.r.t. to detectors at future colliders (LHeC, EIC, FCC.....).
- Would it be useful to have a Forward-ν facility, complementing one of these future experiments ?

Examples of QCD-related physics opportunities at a HL-LHC forward ν facility

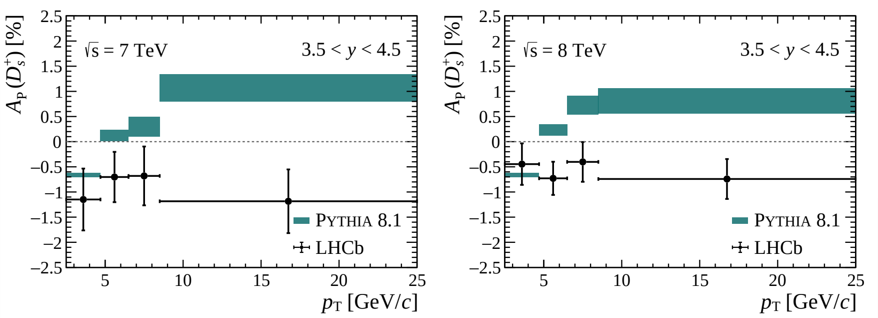
$*$ heavy-flavour production asymmetries

$*$ gluon distribution in proton PDF

$*$ light-quark distributions in nuclear PDFs

$*$ improving QCD predictions for astroparticle physics

D_s^+ - D_s^- asymmetry at LHCb



from LHCb coll. [arXiv:1805.09869]

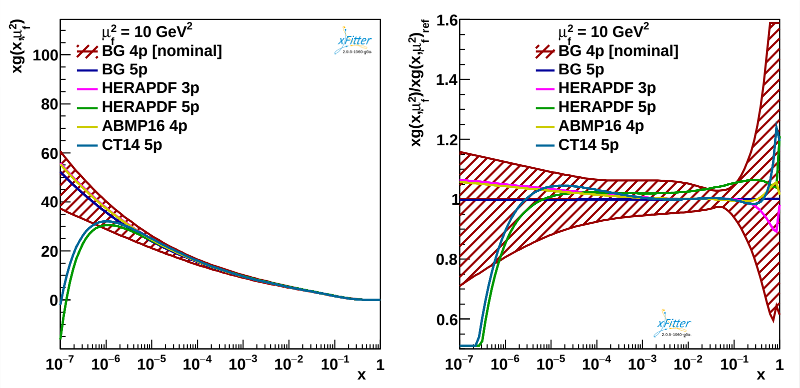
∗ 3σ evidence for an asymmetry of $\sim$ -0.5 %
observed at both $\sqrt{s} = 7$ and 8 TeV: $A_p(D_s^+) = \frac{\sigma(D_s^+) - \sigma(D_s^-)}{\sigma(D_s^+) + \sigma(D_s^-)}$

∗ Waiting for 13 TeV data, is this an hint of $s(x) > \bar{s}(x)$ in the proton ?

∗ Connections with non-universality of fragmentation....

∗ Implications for a Forward ν facility ?

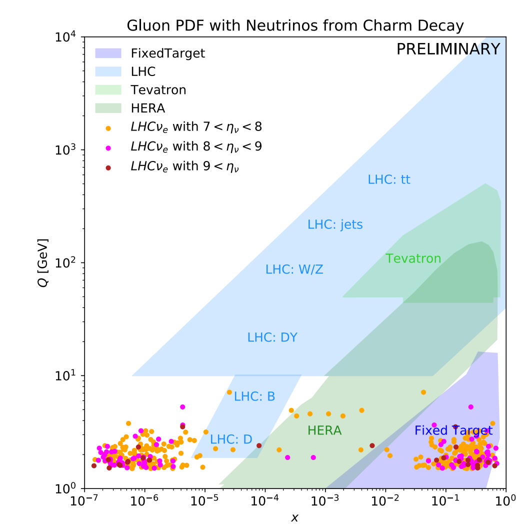
Sensitivity of the low-x gluon to the PDF parameterization employed



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

* Effects of different gluon parameterization in the PROSA 2019 analysis.
* Data on forward D-meson at LHCb constraints g only down to $x \sim 10^{-6}$.

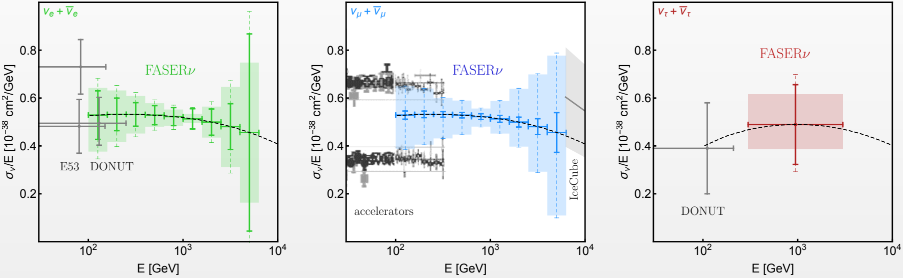
(x, Q) coverage of various experiments for pPDF fits



Very preliminary by F. Kling

Is forward ν production sensitive to saturation ?

Main measurement at a forward ν facility: average ν-induced DIS CC cross-section per (A-weighted) nucleon

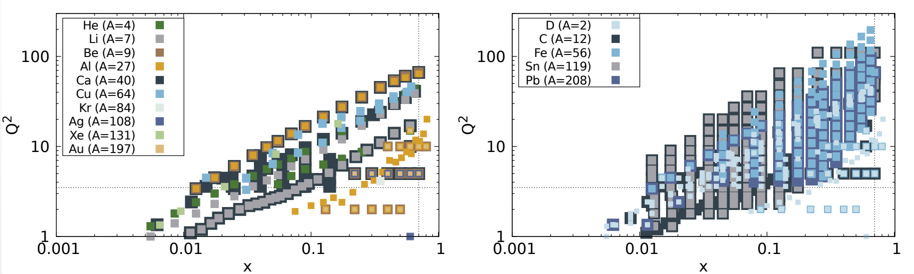


from Faserν collab. [arXiv:1908.02310]

$$\langle \sigma_A \rangle = \frac{\phi_\nu \sigma_{\nu A} + \phi_{\bar{\nu}} \sigma_{\bar{\nu} A}}{\phi_\nu + \phi_{\bar{\nu}}}$$

computed from the number of events that will be observed.
If one is able to control the fluxes (input) one can infer separate precise info on $\sigma_{\nu A}$, $\sigma_{\bar{\nu} A}$ $\Rightarrow$ useful for nuclear PDFs.

(x, Q^2) coverage of fixed-target DIS data for nPDF fits

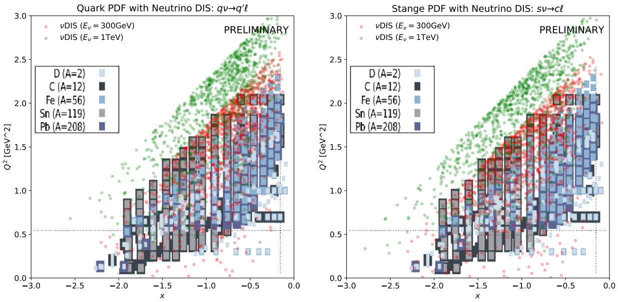


from M. Walt et al. [arXiv:1908.03355]

∗ Inclusive DIS data with charged lepton beams for light and heavy targets.

∗ Data on ν interactions on Fe and Pb targets (CDHSW, CHORUS) also included.

Adding (Q^2,x) coverage of CC DIS induced by ν at a forward ν facility



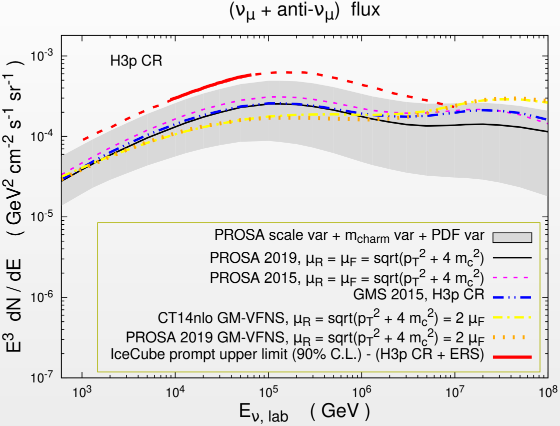
preliminary modifications of previous plot by F. Kling

$*$ Possibility of distinguishing ν_μ and $\bar{\nu}_\mu$ allow for (d, u) flavour decomposition. At LO: $F_2^\nu = 2x(d+s+b+\bar{u}+\bar{c}+\bar{t})$, $F_2^{\bar{\nu}} = 2x(u+c+t+\bar{d}+\bar{s}+\bar{b})$

$*$ Possibility to go beyond the assumption $\bar{u}=\bar{d}=\bar{s}=s$ thanks to charm DIS data.

Prompt neutrino fluxes:

theoretical predictions from [arXiv:1911.13164] 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).

∗ Forward-ν facility can produce data that will help constraining present theoretical uncertainties!

Conclusions

* Experiments active during Run 3 are expected to collect data on forward ν production.

* Snowmass ongoing studies for:
  - understanding QCD requirements which can allow for a proper interpretation of the data of these experiments,
  - unrevealing physics potential of possible extensions of these projects/new Forward-ν facility at HL-LHC.

* Contributions from the Snowmass community are welcome!

Thank you for your attention!