# On the reliability of present predictions for tau neutrino fluxes

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mainly on the basis of **[arXiv:2002.03012]** + **work in progress**

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# Introduction: neutrino event rates

* In far forward laboratory experiments *(see talks by F. Kling and A. De Roeck this morning)* we will measure the convolution

$$(\nu \text{ fluxes } \Phi) \times (\nu \text{ cross-sections } \sigma)$$

* Similar situation as in Neutrino Telescopes (e.g. IceCube), but in a laboratory (i.e. more under-control) framework.
* Additionally, with proper instrumentation, we can distinguish $\nu$ and $\bar{\nu}$: not possible in IceCube!
* We can distinguish $\nu$ of different flavour: also possible in IceCube.
* This implies that, counting the number of events,

**A** we can measure $\sigma$'s, assuming that we know $\Phi$'s.

**B** we can measure $\Phi$'s, assuming that we know $\sigma$'s.

....Considering the present uncertainties on $\sigma$'s and $\Phi$'s, I expect that *B* will give us tighter constraints than *A*.

# While waiting for measurements, let's focus on predictions

* DsTau experiment @CERN: can we control $\nu_\tau$ fluxes experimentally ?
  *(see talk by A. De Roeck this morning)*

* Predictions are indeed necessary:
  - in order to understand which physics we can explore
  - in order to optimize the experimental design

* Predictions for fluxes and cross-sections are typically done with separate tools: attention to the consistencies between the two.
  In fact, some parameters are in common between the two calculations...

* Both predictions based on SM theory (including QCD and EW aspects).

* Some BSM aspects might be also incorporated

# Why making $\Phi$ predictions is so difficult ?

* Partly, because we are interested in kinematical regions, where non-pQCD effects may become important.
* Non-pQCD aspects of QCD not in so good control as the pQCD ones:
  - pQCD: clear recipes for calculating $\mathcal{A}$ from a Lagrangian.
  - non-pQCD: realm of phenomenological models
    fits of their parameters to data
    tuning efforts
* Non-pQCD effects occur in every *pp* collision. The experimental cuts adopted in many SM and BSM analyses with the LHC central detectors helps reducing their importance (with respect to the pQCD ones).
* On the other hand, kinematical regions of interest for this talk are only partially explored by LHC central detectors.

*See also talk by Yu Seon Jeong this friday*

# $\nu_\tau$ and $\bar{\nu}_\tau$ fluxes in hadronic collisions

* It is the easiest to predict, because it is dominated by undelying process:
$pp \to c, b, \bar{c}, \bar{b} + X \to heavy - hadron + X' \to \nu(\bar{\nu}) + X'' + X'$
where the decay to neutrino occurs through
$D_s^\pm \to \nu_\tau(\bar{\nu}_\tau) + \tau^\pm$, with further dacay $\tau^\pm \to \nu_\tau(\bar{\nu}_\tau) + X$

* pQCD applicable down to $p_T = 0$ ($m_Q \neq 0$),
but non-pQCD aspects also matter!

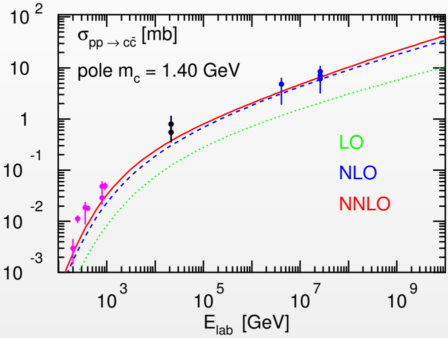
* Heavy flavours decay promptly.

* The point of production of tau neutrinos and taus from $D_s^\pm$ has distance
$d = \gamma c \tau_{D_s} \sim E_{D_s}/m_{D_s} \cdot 150\ \mu\mathrm{m} \sim 1.5$ - $15$ cm for $E_{D_s} = 200$ GeV - 2 TeV.

* Similarly for tau neutrinos from $B^\pm$,
$d = \gamma c \tau_{B^\pm} \sim E_{B^\pm}/m_{B^\pm} \cdot 496\ \mu\mathrm{m} \sim 1.9$ - $19$ cm for $E_{D_s} = 200$ GeV - 2 TeV.

* And for neutrinos from $\tau$ decay,
$d' = \gamma c \tau_\tau = E_\tau/m_\tau \cdot 87.11\ \mu\mathrm{m} \sim 0.98$ - $9.8$ cm.

# $\sigma(pp \to c\bar{c}(+X))$ 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:

# Historical strategies for obtaining predictions

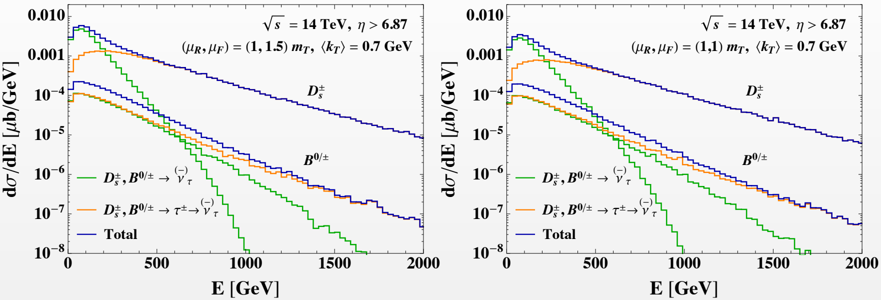
$*$ MC event generators

- Fully exclusive description of events :-)
- One can easily build whicever observable in whichever geometry :-)
- Complex codes, with a long history....:-(
- Accuracy ? :-(
- ....Often used as powerful black-boxes :-|

$*$ $\sigma$ integrators with perturbative and non-perturbative components:

- Often including higher-order $\mathcal{A}$ computed analytically :-)
- Better control of the physics in the calculation :-)
- Less sophisticated description of some non-pQCD effects :-(
- More difficult adaptation to arbitrary observables and geometries :-|

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

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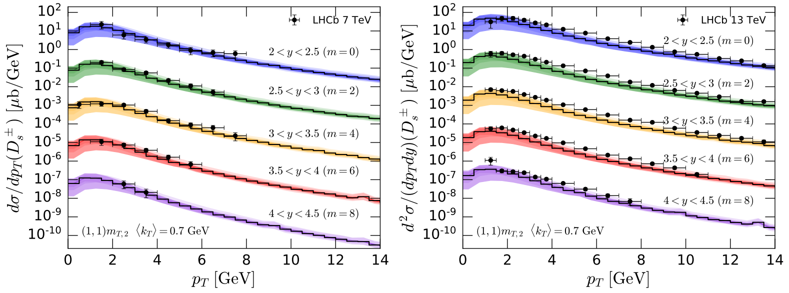
*from W. Bai et al. [arXiv:2002.03012]*

- 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 ?

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

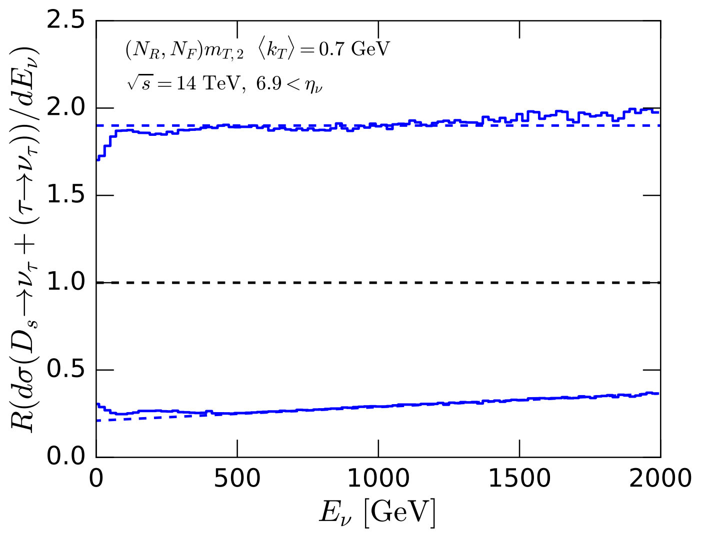



∗ Theory uncertainty due to missing higher orders in pQCD

∗ Experimental data have uncertainty bars much smaller than theory predictions

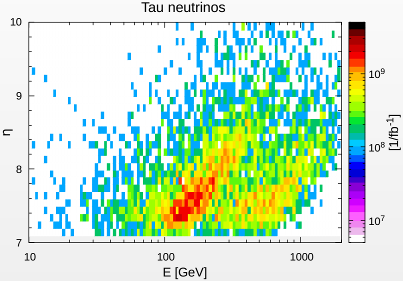
∗ Less precise experimental data (than for other *D*-mesons): $D_s$ data at low $p_T$ are missing!

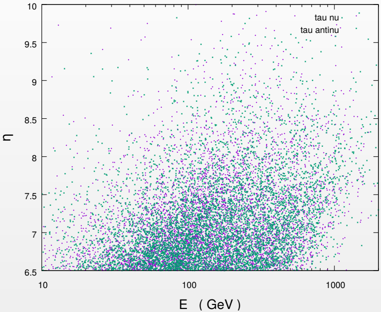
# pQCD uncertainty due to missing higher-orders as a function of $E_{\nu_\tau}$



# $\nu_\tau$ and $\bar{\nu}_\tau$ correlations with MC event generators

## Scatter-plots in $(E, \eta)$ for $\nu_\tau$ and $\bar{\nu}_\tau$ production




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

* Can we distinguish $\nu_\tau$ from direct $D_s \to \nu_\tau$ decay from those from chain $D_s \to \tau \to \nu_\tau$ decay ?

# How to improve $\sigma$ integrators ?

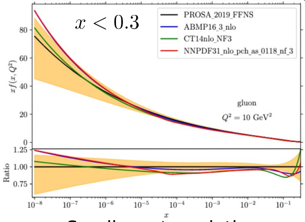
– improving the accuracy of partonic $\sigma$, going beyond NLO.

– incorporating more nonperturbative effects.

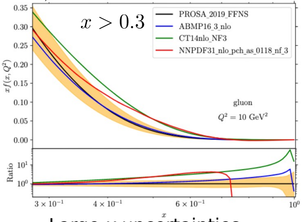
– proceed with the evaluation of further uncertainties, besides the pQCD ones.

# Towards the assessment of PDF-related uncertainties

$xg(x, Q^2)$




Small $x$ extrapolations.



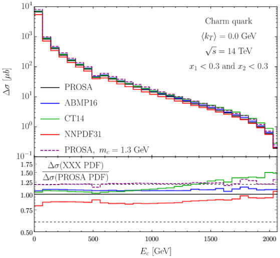

Large $x$ uncertainties.

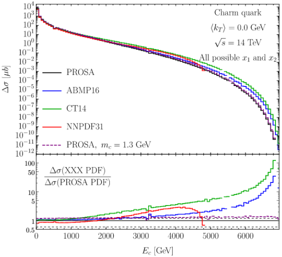
*PDF uncertainties*: PROSA_2019 fit, model & parameterization; ABMP16, CT14,NNPDF3.1

Large $x$ uncertainties translate to large uncertainties at high $E_c$ $(E_D)$ → high $E_\nu$ at FPF.

Neutrino energy spectrum

$$\frac{d\sigma}{dE_c}$$




- Additional large uncertainties due to scale dependence.
- Feature of NLO QCD at scale $\sim m_c$.

*Bai, Diwan, Garzelli, Jeong, Kumar, Reno, in preparation*

# Example of $\nu_\tau$ and $\bar{\nu}_\tau$ event rate calculation

| | $\nu_\tau$ | $\bar{\nu}_\tau$ | $\nu_\tau + \bar{\nu}_\tau$ | $\nu_\tau + \bar{\nu}_\tau$ | | |
|---|---|---|---|---|---|---|
| $(\mu_R,\ \mu_F)$, $\langle k_T \rangle$ | (1, 1) $m_{T,2}$, 0.7 GeV | | | | | |
| | | | | scale (u/l) | PDF (u/l) | $\sigma_{\rm int}$ |
| $\eta \gtrsim 8.9$ | 8.2 | 3.9 | $\mathbf{12.1^{+11.6}_{-9.8}}$ | +11.3/-9.0 | +2.8/-3.9 | $\pm$0.3 |
| $(\mu_R,\ \mu_F)$, $\langle k_T \rangle$ | (1, 2) $m_T$, 1.2 GeV | | | (1, 1) $m_{T,2}$, 0.7 GeV | | |
| PDF | PROSA FFNS | | | NNPDF3.1 | CT14 | ABMP16 |
| $\eta \gtrsim 8.9$ | 13.5 | 6.4 | 19.9 | 12.8 | 23.5 | 15.6 |

**Table:** The charged-current event numbers for tau neutrinos and antineutrinos in 1.2 tons of the tungsten for FASER$\nu$ from $D_s^\pm$ produced in $pp$ collisions at $\sqrt{s} = 14$ TeV and an integrated luminosity $\mathcal{L} = 150$ fb$^{-1}$.

*Bai, Diwan, Garzelli, Jeong, Kumar, Reno, work in progress*

# How to improve MC event generators ?

– Discussion with the authors, in order to go beyond "frozen" sets of parameters. Maybe these "frozen" sets are ok for some application, but it is unclear up to which extent they are the best even for our one.....

– Some of these MC are designed for different applications (e.g. CR EAS). Not automatic that a code designed to work for $pA$ works as well for $pp$. Additionally, there are unresolved issues in CR EAS physics that none of these codes has been able to address.....

– New models for non-pQCD (Forward neutrino experiments are a good motivation to push the authors of MC in this direction)

– New tunes

– Finding a way to account for uncertainties, that goes beyond generator-generator difference.

$\Rightarrow$ Good service for the high-energy astro and HL-LHC community!