Prompt neutrinos in the forward region at LHC

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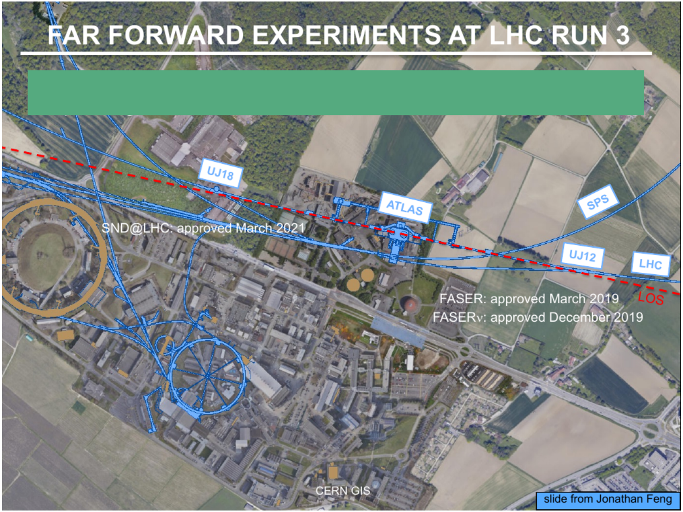
SYSU-PKU Collider Physics forum For Young Scientists

Far-forward neutrinos at LHC



1st direct observation of collider neutrinos with FASER: $n_\nu = 153^{+12}_{-13}$(tot.) of $\nu_\mu + \bar{\nu}_\mu$ at 13.6 TeV. (arXiv:2303.14185)

Forward prompt ν production at $\sqrt{s} = 14$ TeV at LHC

$$p + p \to c \to D_s^{\pm} \to \tau^{\pm} + \nu_\tau(\bar{\nu}_\tau)$$
$$\hookrightarrow \bar{\nu}_\tau(\nu_\tau) + X$$

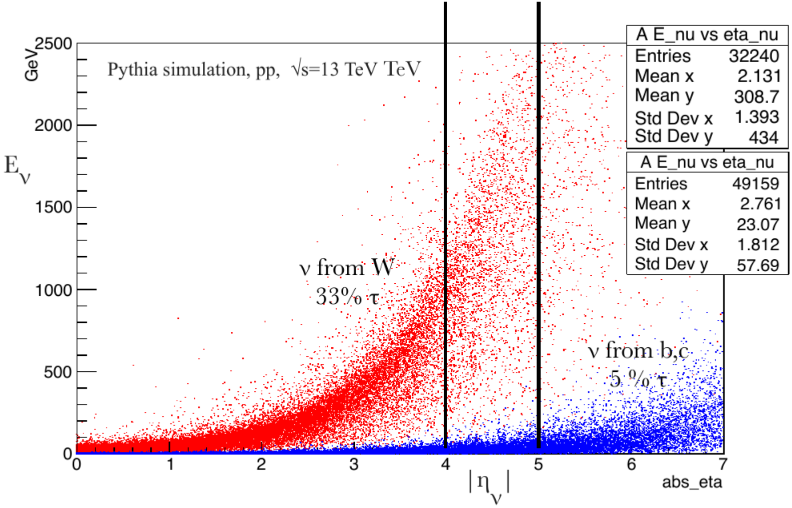
with contributions from $D^{\pm}$, $B^{\pm}$, $B^0(\bar{B}^0)$, $W^{\pm}$ and Z^0 ignored.

$$p + p \to c \to D^{\pm}, D^0, \overline{D}^0, D_s^{\pm}, \Lambda_c^{\pm}$$
$$\to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) + X$$

with other contributions ignored.

- Prompt: ν from heavy hadrons, but not π, K, ...
- $\sigma : \nu_e \approx \nu_\mu$

Neutrinos from W vs. from b,c



(arXiv:1804.04413)

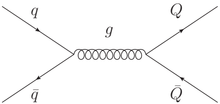
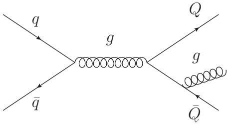
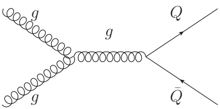
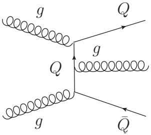
Charm production in perturbative QCD

- pQCD: hard scale $m_c \approx 1.0$ GeV $> \Lambda_{QCD} \approx 200$ MeV, $\alpha_s(m_c) \approx 0.4$.
- Single-particle inclusive differential cross section of the charm quark for the process $H_1 + H_2 \rightarrow c + X$ under collinear factorization framework can be writen as (P. Nason et al., 1989, HVQ program)

$$\left(E\frac{d^3\sigma}{d^3p}\right)_c = \sum_{i,j=q,\bar{q},g} \int dx_1\, dx_2\, f_{i/H_1}(x_1, \mu_F^2) f_{j/H_2}(x_2, \mu_F^2) \left[E\frac{d^3\widehat{\sigma}_{ij}(x_1 P_{H1}, x_2 P_{H2}, p, m^2, \mu_F^2, \mu_R^2)}{d^3p}\right]$$

  - where $q = u, d, s$ and $m_q = 0$ for $n_{lf} = 3$ fixed order calculation;
  - $x-$longitudinal momentum fraction of the parton in the nucleon. For charm quark pair production at $\sqrt{s} = 14$ TeV, $10^{-8} < x < 1$;
  - μ_R-renormalization scale, μ_F-factorization scale;
  - $f_{i/H}(x, \mu_F^2)-$parton distribution function (PDF) [number density], universal; PROSA_2019_FFNS PDFs;
  - $\widehat{\sigma}_{ij}-$parton level hard scattering cross section, process dependent.

Partonic processes upto next-to-leading order pQCD

leading order (α_s^2)	next-to-leading order (α_s^3)
$q + \bar{q} \to Q + \bar{Q}$ 	$q + \bar{q} \to Q + \bar{Q} + g$ 
$g + g \to Q + \bar{Q}$ 	$g + g \to Q + \bar{Q} + g$ 
...	...

Dominated by gg interactions $\Rightarrow$ almost same c and $\bar{c}$ production cross sections, same ν and $\bar{\nu}$ production cross sections.

From charm quarks to charm hadrons to neutrinos

- Introduce intrinsic transverse momentum ($\vec{k}_T$),

$$dx_1 f_{i/p_1}(x_1, \mu_F^2) \to dx_1 \boxed{d^2 k_{T_1} f(\vec{k}_{T_1})} f_{i/p_1}(x_1, \mu_F^2)$$

where

$$f(\vec{k}_T) = \frac{1}{\pi \langle k_T^2 \rangle} \exp\left(-\frac{k_T^2}{\langle k_T^2 \rangle} \right)$$

for forward charm production.

- From charm quark to charm hadron:

$$\left(E\frac{d^3\sigma}{d^3p} \right)_{H_c} = \left(E\frac{d^3\sigma}{d^3p} \right)_c \otimes D_c^{H_c}(z) \text{ with } D_c^{H_c}(z) = \frac{Nz(1-z)^2}{((1-z)^2 + \epsilon z)^2}$$

is the $c \to H_c$ fragmentation function implemented in the colliding parton CM frame with $\vec{p}_{H_c} = z\vec{p}_c$, $0 < z < 1$.

- ν number of events per GeV

$$\frac{dN}{dE_\nu} = \frac{d\sigma(pp \to \nu X)}{dE_\nu} \times \mathscr{L} \times \mathscr{P}_{\rm int}, \text{ with } \mathscr{P}_{\rm int} = \rho_W L_d N_A \frac{\sigma_{\nu W}}{A_W}.$$

Type of uncertainties considered

- Uncertainties from 3-flavour NLO PROSA_2019_FFNS PDFs (default).
- Comparison with CT14nlo_NF3, ABMP16_3_nlo and NNPDF3.1_nlo_pch_as_0118_nf_3 PDF predictions.

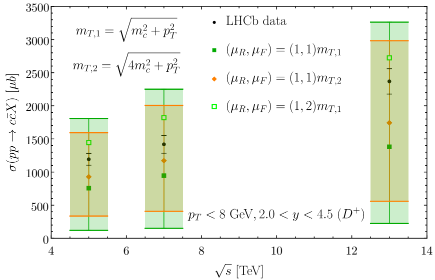
- Fixed order pQCD predictions' scale-choice dependence: $\sigma_c = \sigma_c(\mu_F^2, \mu_R^2) \rightarrow$ used as an estimate of the higher-order uncertainties:

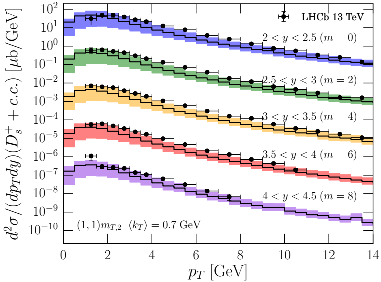
N_R \ N_F	0.5	1.0	2.0	
0.5	✓	✓	×	$\cdot m_{T,2}$
1.0	✓	✓	✓	
2.0	×	✓	✓	

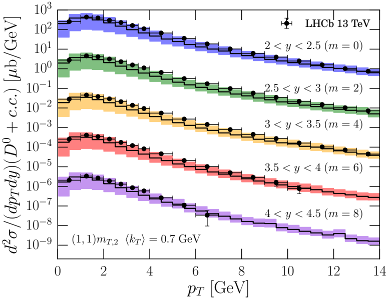
Default: $(\mu_F, \mu_R) = (1,1) m_{T,2} \equiv (1,1)\sqrt{(2m_c)^2 + p_T^2}$ and $\langle k_T \rangle = 0.7$ GeV,

compared to $(\mu_F, \mu_R) = (1,2) m_T \equiv (1,2)\sqrt{m_c^2 + p_T^2}$ and $\langle k_T \rangle = 1.2$ GeV.

Comparison to LHCb data

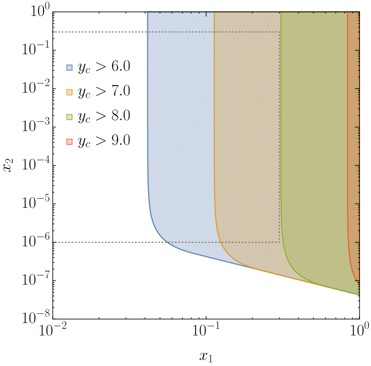


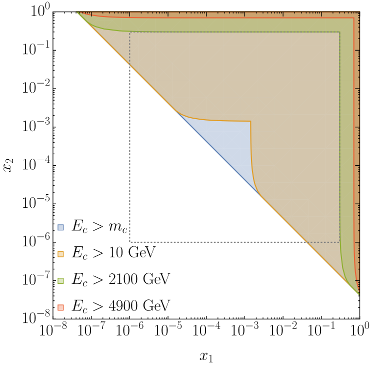




- $\sigma_{\text{theoretical}} < \sigma_{\text{experimental}}$
- $\text{uncer.}_{\text{theoretical}} > \text{uncer.}_{\text{experimental}}$
- Agree, within uncertainty band

(x_1, x_2) region for $y_c > y_{c0}$ or $E_c > E_{c0}$

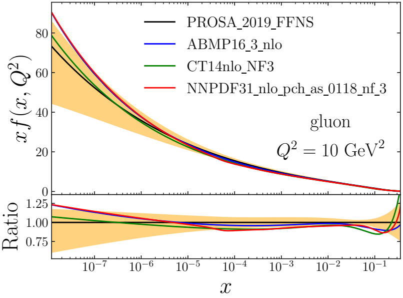




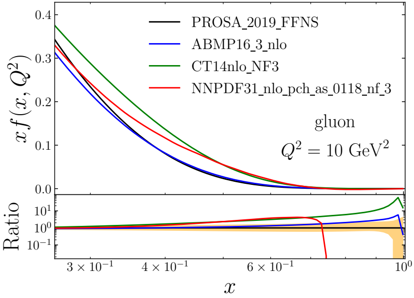
Far-forward (large y and large E) production of charm quarks at large $\sqrt{s}$ involves the product of small-x and large-x PDFs.

Gluon PDFs at $Q^2 = 10$ GeV^2

$x < 0.3$



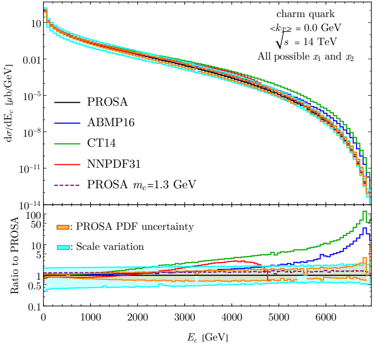
$x > 0.3$



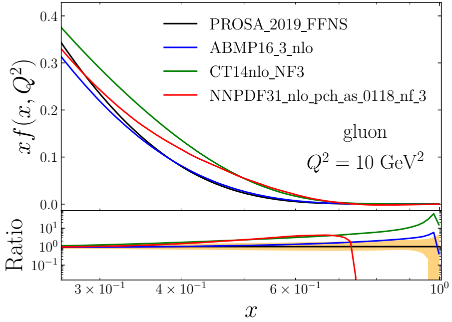
- For $x < 0.3$, the PROSA PDF uncertainty is within $20\% - 30\%$.
- For $x < 0.3$, CT14, ABMP16 and NNPDF3.1 PDFs are within the PROSA uncertainty band.
- For $x > 0.3$, large deviations appear.

Charm quark energy distribution vs. gluon PDF

Energy distribution



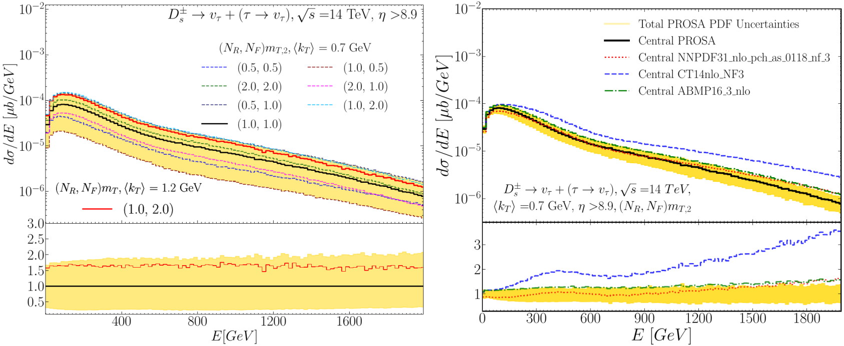
Gluon PDFs ($x > 0.3$)



- Scale undertainty: -70% to $+90\%$.
- PROSA PDF uncertainty: $\pm 20\%$ ($E_c < 500$ GeV) $\Rightarrow$ $\pm 30\%$ ($E_c \sim 2000$ GeV)$\Rightarrow$ 60%.
- Ratios at high energies show a similar behavior.

PDF and scale uncertainties of $\nu_\tau + \bar{\nu}_\tau$ fluxes

Scales | Different PDFs

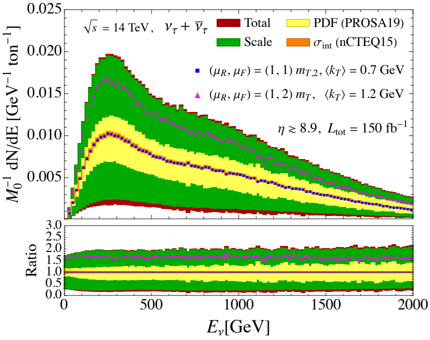


$\eta > 8.9$

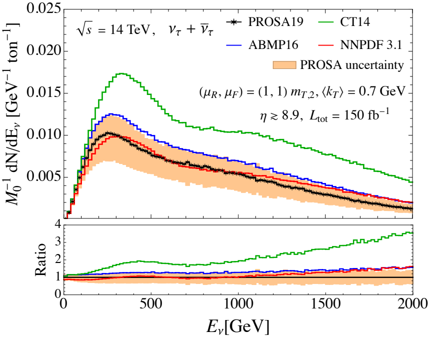
- Scale undertainty: -70% to $+90\%$.
- PROSA PDF undertainty: $\pm 30\%$ ($E_c < 500$ GeV) $\Rightarrow \pm 40\%$ ($E_c \sim 2000$ GeV).
- Deviations already appear at low E_ν: accumulate in $c \to D_s \to \nu_\tau$.

PDF and scale uncertainties of $\nu_\tau + \bar{\nu}_\tau$ CC event numbers

PROSA PDF and scale



Different PDFs

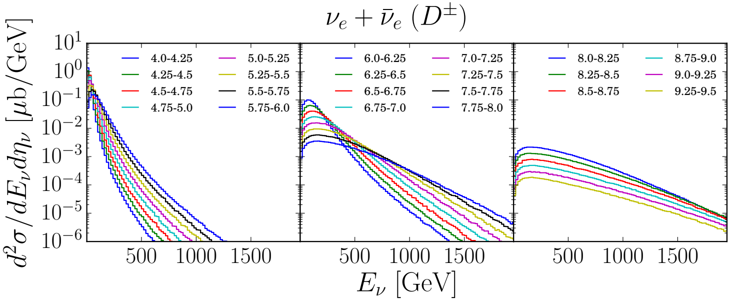


Uncertainty in neutrino CC interaction (nCTEQ15) $< 5\% \ll$ unc. in production.

ν_τ and $\bar{\nu}_\tau$ CC event numbers (FASERν and SND@LHC at run 3)

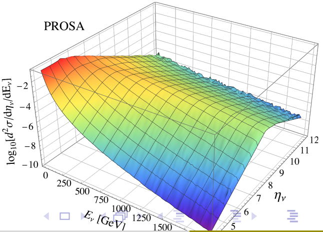
$\mathcal{L} = 150\ \mathrm{fb}^{-1}$	ν_τ	$\bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$		
$(\mu_R,\ \mu_F)$, $\langle k_T \rangle$	(1, 1) $m_{T,2}$, 0.7 GeV					
				scale(u/l)	PDF(u/l)	σ_{int}
SND@LHC $7.2 < \eta_\nu < 8.6$, 830 kg	2.8	1.3	$4.2^{+3.8}_{-3.3}$	+3.7/-3.1	+0.8/-1.2	± 0.1
FASERν $\eta_\nu > 8.9$, 1.2 ton	8.2	3.9	$12.1^{+11.6}_{-9.8}$	+11.3/-9.0	+2.8/-3.9	± 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
SND@LHC $7.2 < \eta_\nu < 8.6$, 830 kg	5.1	2.4	7.5	4.0	6.6	5.0
FASERν $\eta_\nu > 8.9$, 1.2 ton	13.5	6.4	19.9	12.8	23.5	15.6

Double-differential distributions: $d^2\sigma/(dE_\nu d\eta_\nu)$ for experimenters

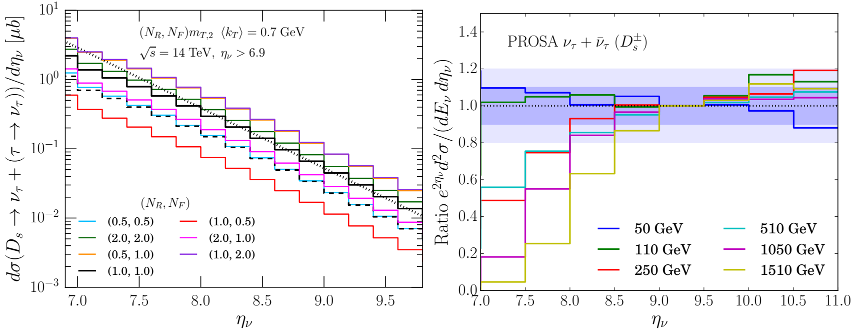


$E_\nu < 2$ TeV,

$\eta_\nu = 4.0 - 12.$



Scaling ($\eta_\nu \gtrsim 8.3$)



$$\frac{d\sigma}{d\eta} \sim e^{-2\eta_\nu}, \;\; f(E_\nu, \eta_\nu) \equiv e^{2\eta_\nu} \frac{d^2\sigma}{dE_\nu d\eta_\nu}$$

with $4\pi \exp(-2\eta_\nu)$ the approximate solid angle of the detector (yield similar numbers of events per unit detector mass for each rapidity range at large enough rapidity)

Summary

- An NLO pQCD evaluation within SM for charm production cross section.
- At large y/η or E, theoretical predictions of neutrino flux rely on PDFs in a combination of very small and large parton-x values.
- ~10 (~5000) $\nu_\tau + \bar{\nu}_\tau$ CC interaction events are expected at run 3 (Forward Physics Facility@HL-LHC).
- Theoretical uncertainties:
  - PROSA PDF uncertainty ($\sim \pm 30\%$)
  - Alternative PDF choices can yield predictions that lie outside the PROSA PDF uncertainty band $\Rightarrow$ constraint on large$-x$ PDFs are needed (LHCb and more forward rapidity measurements?).
  - Scale uncertainties (-70% to 90%) $\Rightarrow$ higher-order corrections are important.
  - Others? fragmentation functions, intrinsic transverse momentum, multiple parton interactions, power corrections, ...
- Implications for theoretical predictions of the prompt atmospheric neutrino flux and/or effect on background evaluations for measurements at neutrino telescopes.

Thanks

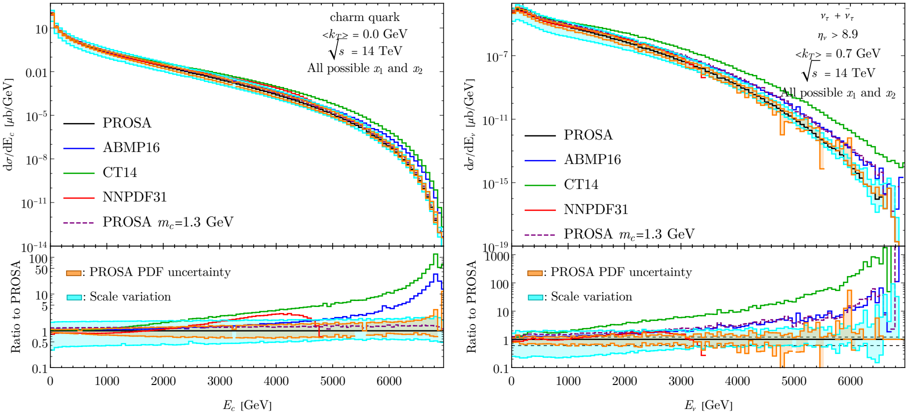
Backup slides

Fixed flavor number scheme (FFNS) PDFs

- PROSA 2019 FFNS PDF
  - 3-flavour ($q = u, d, s$) NLO PDF
  - one central PDF and 40 error PDFs
  - incorporate fits to data on open heavy flavour production from HERA, LHCb and ALICE
- Other 3-flavor NLO PDF sets: CT14, ABMP16 and NNPDF3.1 collaborations

PDF Set	PROSA	CT14nlo_NF3	ABMP16_3_nlo	NNPDF3.1_nlo_nf 3
m_c [GeV]	1.442	1.3	1.376	1.51

Charm quark energy distribution vs. $\nu_\tau + \bar{\nu}_\tau$ energy distribution



The ratios of the deviations show similar behavior.

ν_e, ν_μ, ν_τ@FLARE