PDF uncertainties in theoretical predictions for forward ν_τ fluxes at LHC

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

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

$$\bar{\nu}_\tau(\nu_\tau) + X$$

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

From charm quark to forward ν_τ

- Inclusive differential cross section of the charm quark for the process $p + p \to c + X$ under collinear factorization framework calculated at NLO pQCD (up to α_s^3)

$$\left(E\frac{d^3\sigma}{d^3p}\right)_c = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 f_{i/p_1}(x_1, \mu_F^2) f_{j/p_2}(x_2, \mu_F^2) \left[E\frac{d^3\hat{\sigma}_{ij}(x_1P_1, x_2P_2, p, m^2, \mu_F^2, \mu_R^2)}{d^3p}\right]$$

where $4 \times 10^{-8} < x < 1$ for charm quark pair production at $\sqrt{s} = 14$ TeV

- For forward production, introduce intrinsic transverse momentum ($\vec{k}_T$) with

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

and $\langle k_T \rangle = 0.7$ GeV. $\left(\left\langle k_T^2\right\rangle = 4\left\langle k_T\right\rangle^2/\pi\right)$

- Peterson fragmentation function

$$D_c^H(z) = \frac{Nz(1-z)^2}{((1-z)^2 + \epsilon z)^2}$$

for the $c \to D_s$ fragmentation, with $\vec{p}_{D_s} = z\vec{p}_c$, $0 < z < 1$, $\epsilon = 0.008$ and implementation of fragmentation in colliding parton CM frame.

Type of uncertainties considered

- Uncertainties from 3-flavour NLO PROSA_2019_FFNS PDFs.
- 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:

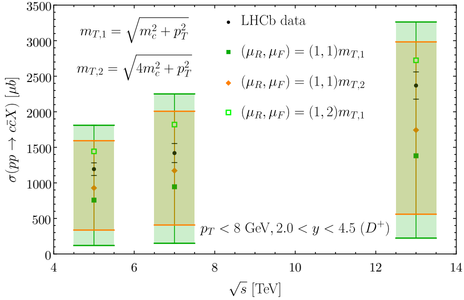
μ_R \ μ_F	0.5	1.0	2.0
0.5	✓	✓	×
1.0	✓	✓	✓
2.0	×	✓	✓

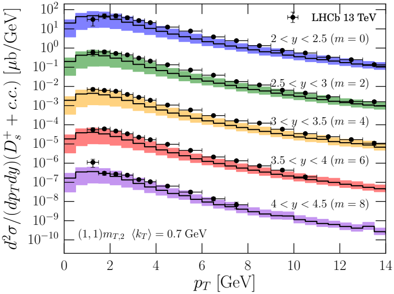
$\cdot m_{T,2}$

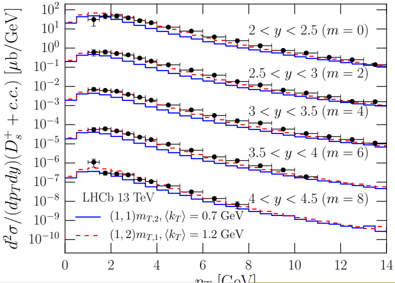
Default: $(\mu_F, \mu_R) = (1,1) m_{T,2} \equiv (1,1)\sqrt{(2m_c)^2 + p_T^2}$ and $\langle k_T \rangle = 0.7$ GeV,

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

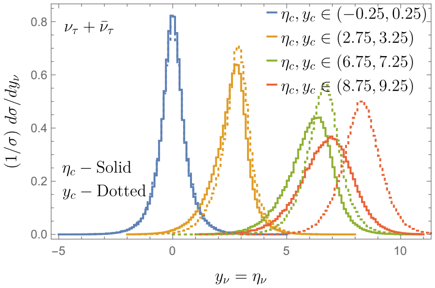


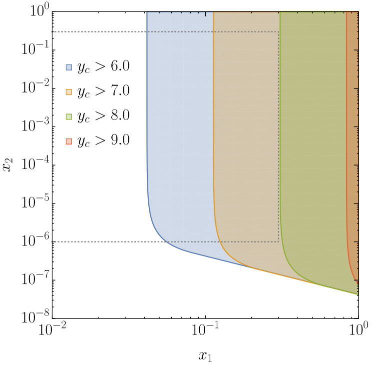




- $\sigma_{theoretical} < \sigma_{experimental}$
- $uncer._{theoretical} > uncer._{experimental}$
- Agree, within uncertainty band

$\eta_\nu = y_\nu$ vs. y_c

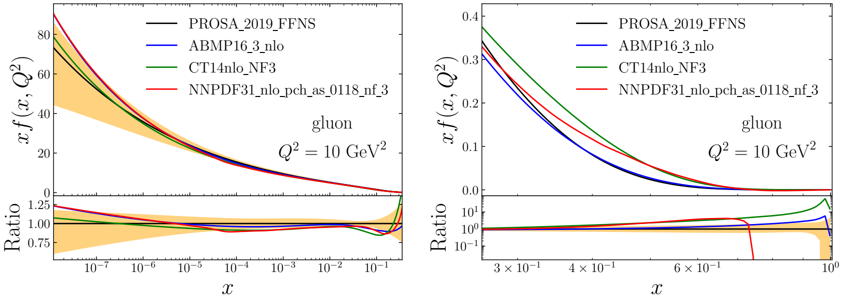




In the forward region:

- Neutrino rapidity correlates better with charm rapidity than with charm pseudorapidity.
- Both small x and large x are involved.

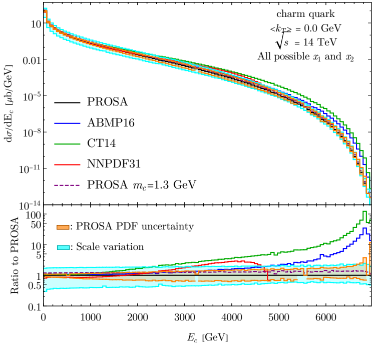
Gluon PDFs w.r.t. PROSA gluon PDF at $Q^2 = 10$ GeV^2



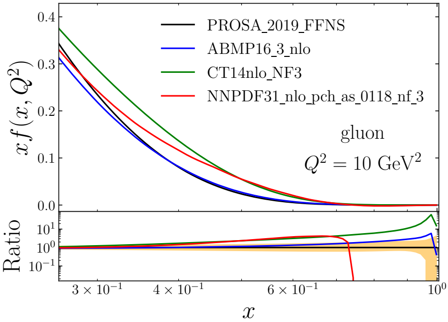
- $gg \to cX$ dominates.
- For $x < 0.3$, the PROSA PDF uncertainty is within $60\% - 120\%$.
- For $x < 0.3$, CT14, ABMP16 and NNPDF3.1 PDFs are within the PROSA uncertainty band.
- For $x > 0.3$, large deviations appear.

Charm quark energy distribution vs. gluon PDF

Energy distribution

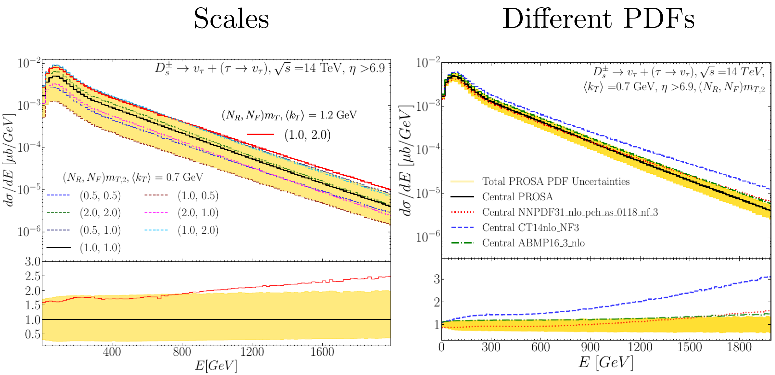


Gluon PDFs ($x > 0.3$)



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

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

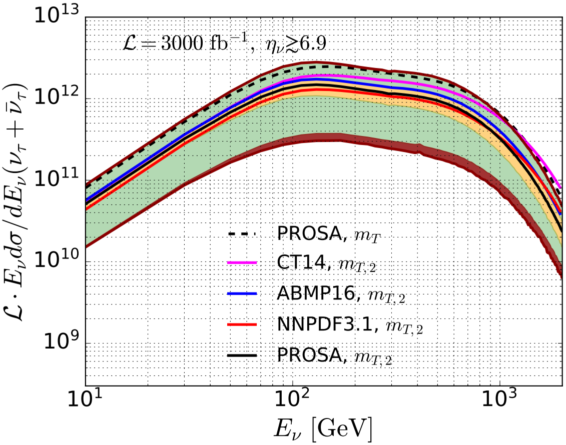


$$\phi_\nu = \mathcal{L}(d\sigma/dE) \text{ with } \mathcal{L} = 3000 \text{ fb}^{-1},\ \eta > 6.9.$$

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

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

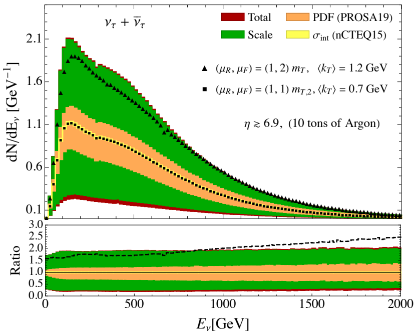
$E\mathcal{L}(d\sigma/dE)$ with $\mathcal{L} = 3000$ fb^{-1}, $\eta > 6.9$.



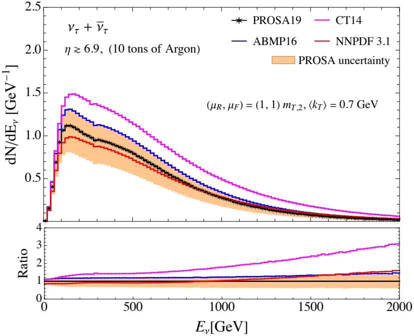
- Scale undertainties dominates except for $E_\nu \gtrsim 1$ TeV.

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

PROSA PDF and scale



Different PDFs



$\eta_\nu > 6.9$ for FLArE 10 tons of Argon detector.

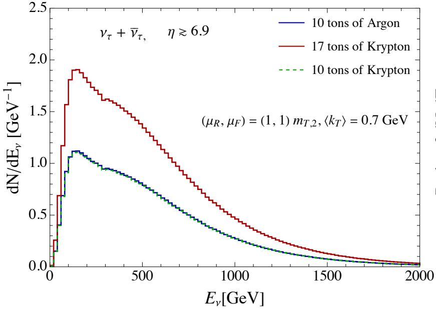
- Uncertainty in neutrino CC interaction (nCTEQ15) $< 5\% \ll$ unc. in production.

ν_τ and $\bar{\nu}_\tau$ CC event numbers for FASERν2 and FLArE

	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}
FASERν2 $\eta_\nu > 8.5$, 20 tons (W)	2296	1088	3384	+3144/-2519	+786/-1089	$\pm$ 77
$\eta_\nu > 6.9$, 10 ton (Ar)	529	257	786	+692/-575	+152/-229	$\pm$11
$(\mu_R,\ \mu_F),\ \langle k_T \rangle$	$(1,\ 2)\ m_T,\ 1.2$ GeV			$(1,\ 1)\ m_{T,2},\ 0.7$ GeV		
PDF	PROSA FFNS			NNPDF3.1	CT14	ABMP16
FASERν2 $\eta_\nu > 8.5$, 20 tons (W)	3808	1804	5612	3552	6492	4338
$\eta_\nu > 6.9$, 10 ton (Ar)	953	465	1418	748	1202	944

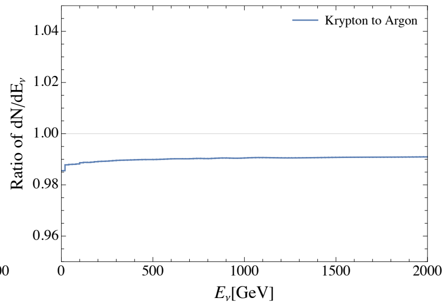
Liquid krypton instead of Argon for FLArE

Same size $(1\,\mathrm{m} \times 1\,\mathrm{m} \times 7\,\mathrm{m})$



$N_{\mathrm{Kr}} \approx 1.7 N_{\mathrm{Ar}}$

Same mass



$N_{\mathrm{Kr}} \approx N_{\mathrm{Ar}}$

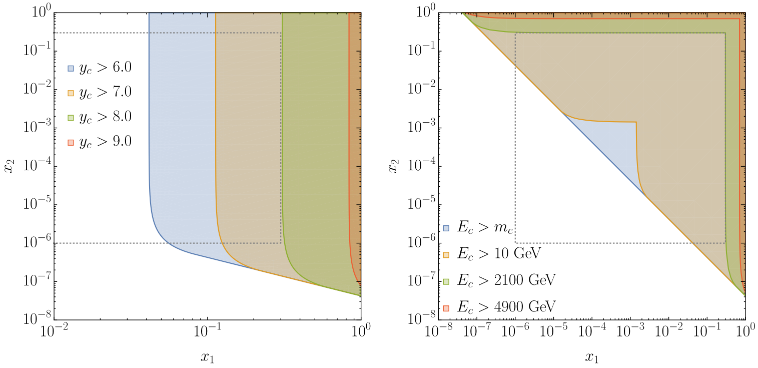
Conclusion

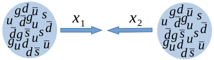
- At large η or E, theoretical predictions of the $\nu_\tau + \bar{\nu}_\tau$ CC DIS event number rely on PDFs in a combination of very small and large parton-x values.
- Hundreds to thousands $\nu_\tau + \bar{\nu}_\tau$ CC interaction events are expected.
- There are theoretical uncertainties:
  - PROSA 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.
  - Scale uncertainties (-70% to 90%) $\Rightarrow$ higher-order corrections are important.

Thanks

Backup slides

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





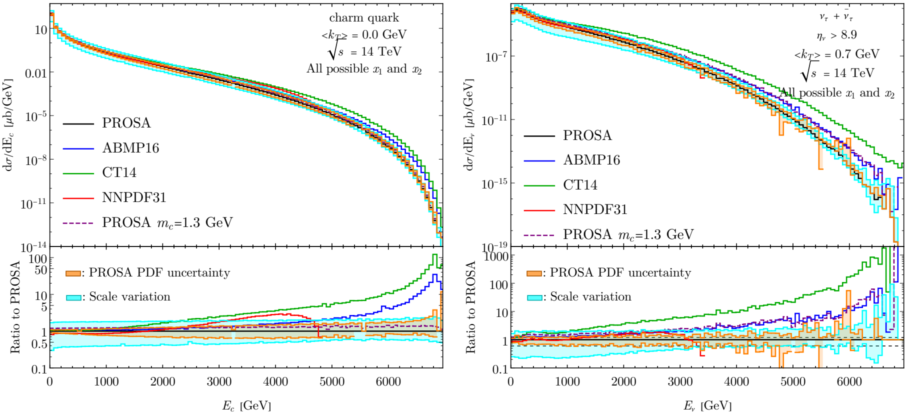
Far-forward (large y and large E) production of charm quarks at large $\sqrt{s}$ involves the product of small-x and large-x PDFs.

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

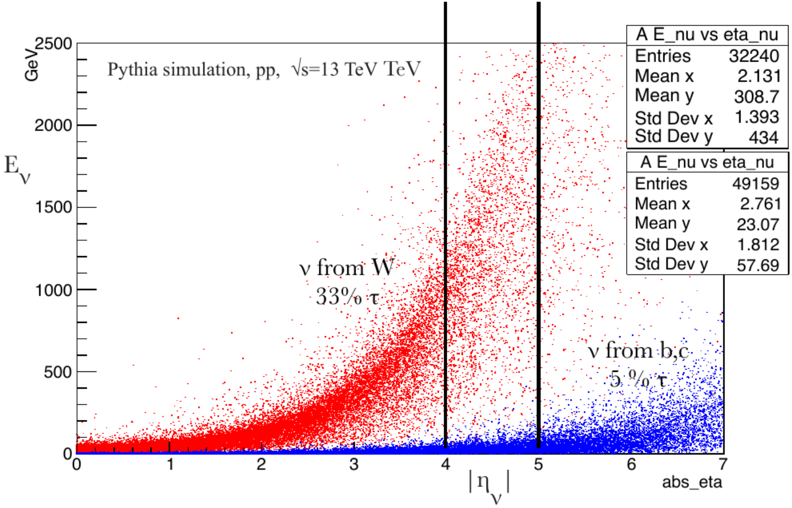
PDF Set	PROSA	CT14nlo_NF3	ABMP16_3_nlo	NNPDF3.1_nlo_nf 3
m_c [GeV]	1.442	1.3	1.376	1.51

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



The ratios of the deviations show similar behavior.

Scatter plot



ν_τ with large y_ν is from D_s with large y_{D_s}