

Neutrinos from charm in the forward region

MH Reno

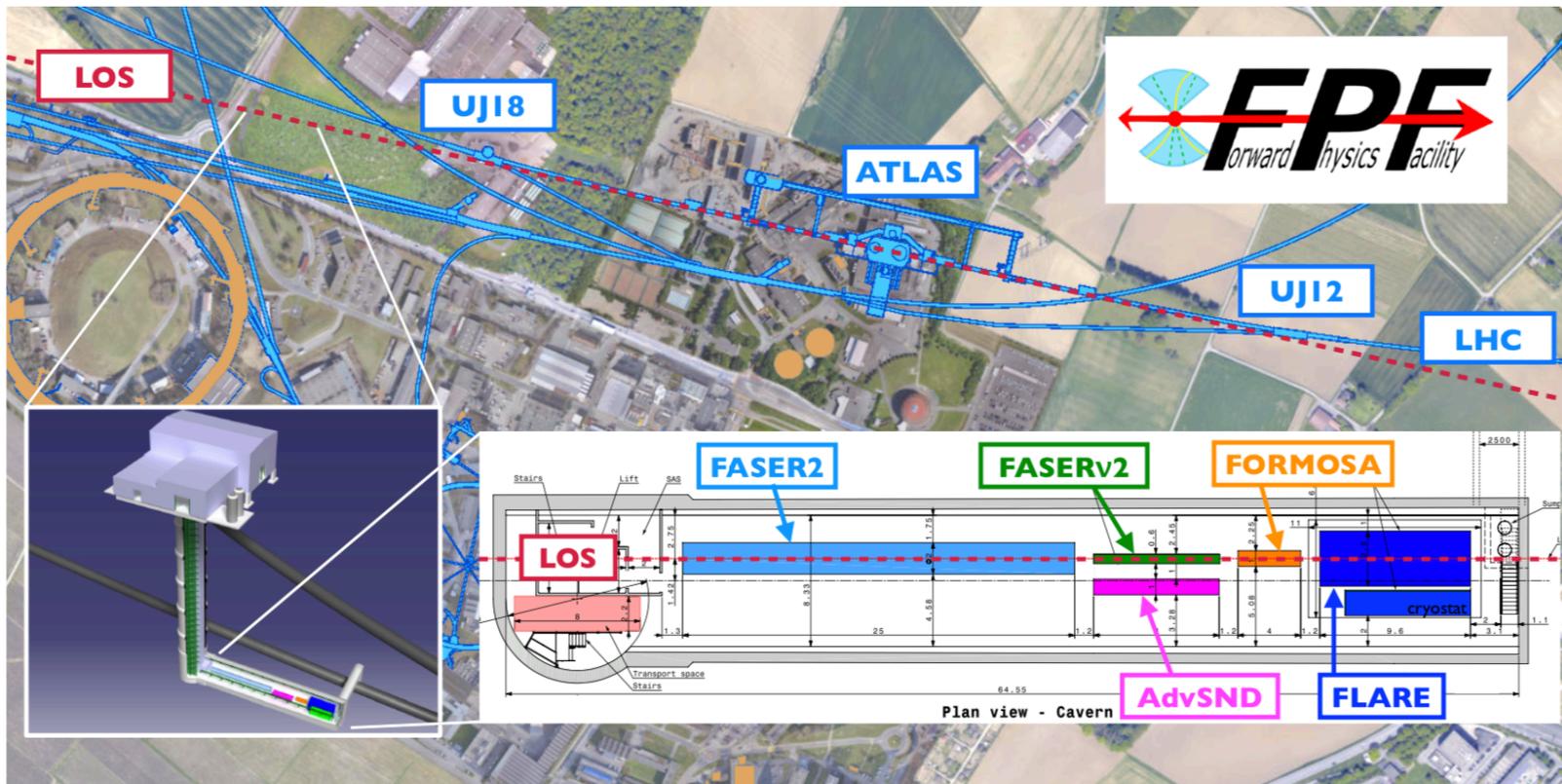
Work by Weidong Bai, Milind Diwan, Maria Vittoria Garzelli, Yu Seon Jeong, Karan Kumar, MHR in

JHEP 06 (2020) 032 [2002.03012], arXiv:2112.11605
and arXiv:2203.07212

Work supported in part by the US DOE.

Purpose-built Forward Physics Facility

Underground facility ~ 620 m far forward from the ATLAS IP, shielded by concrete and rock. FPF experiments to detect $\sim 10^6$ neutrino interactions, energies up to a few TeV.



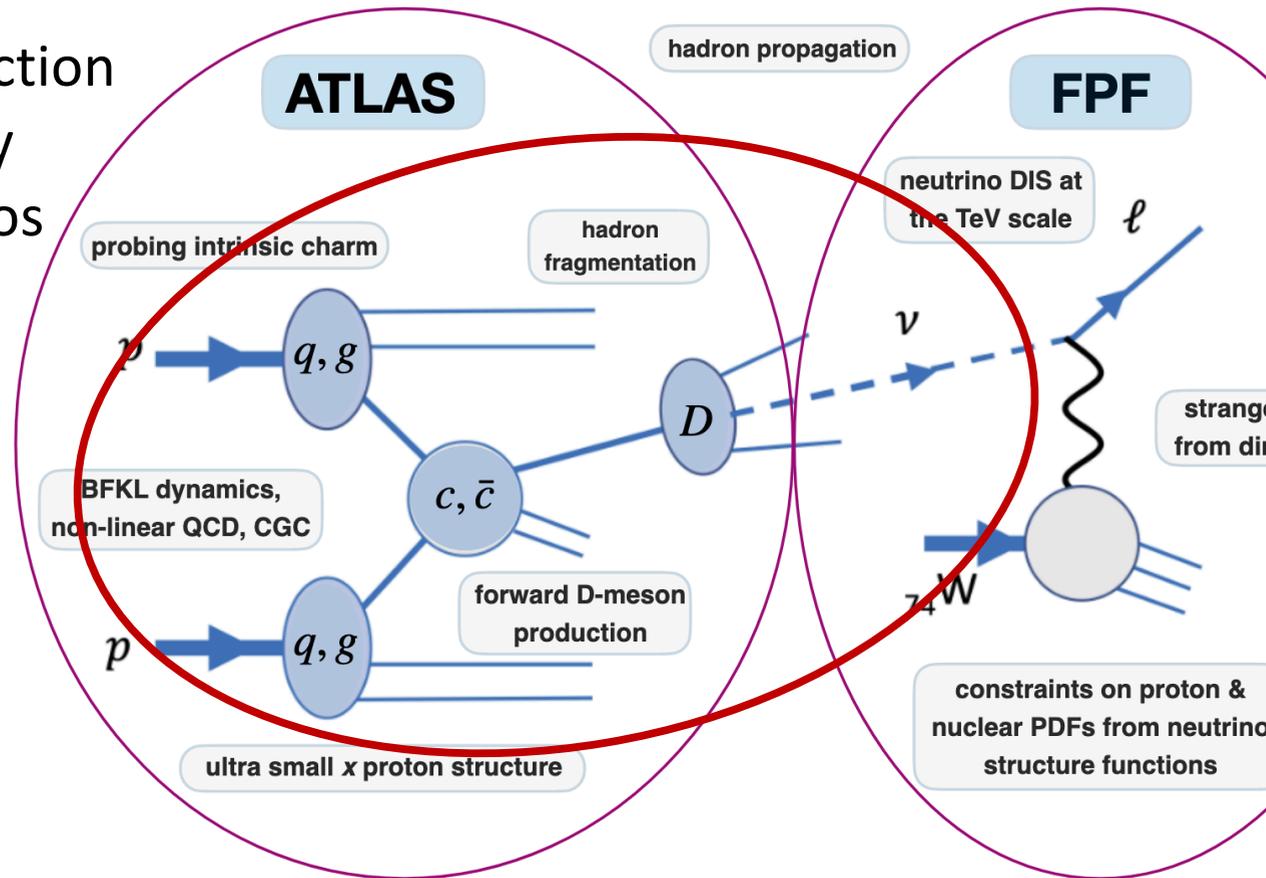
Detectors designed for Standard Model and BSM Physics.

Neutrino detection at FASERv2, AdvSND and FLArE.

FASERv and SND@LHC installation in caverns in Run 3.

QCD in pp and νA collisions

hadron production that ultimately yields neutrinos of all 3 flavors

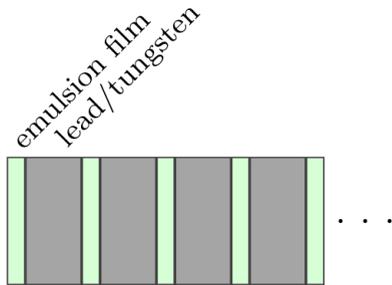


neutrino interactions (all 3 flavors, from different hadron sources) on nuclear targets

- Focus on neutrino production from charm.
 - Tau neutrinos.
 - Electron neutrinos at high energies.
- Regions of parton x .
- PDF uncertainties in the differential cross section for neutrino production.

Phased program of experiments

FASER ν pilot with suitcase-size detector.
 Neutrino candidates, not tau neutrinos, but
 proof of principle.
 FASER, Phys. Rev. D 104 (2021) L091101



29 kg prototype detector, 480 m from interaction
 point, for 12.2 fb⁻¹ in pp collisions at 13 TeV.

Run 3 pp at 14 TeV with 150 fb⁻¹
 FASER ν 1.2 ton, 25 cm x 25cm

on axis, $\eta > 8.5$

SND@LHC 800 kg, 39 cm x 39 cm

off axis, $8.5 > \eta > 7$

480 m from ATLAS IP

High Luminosity

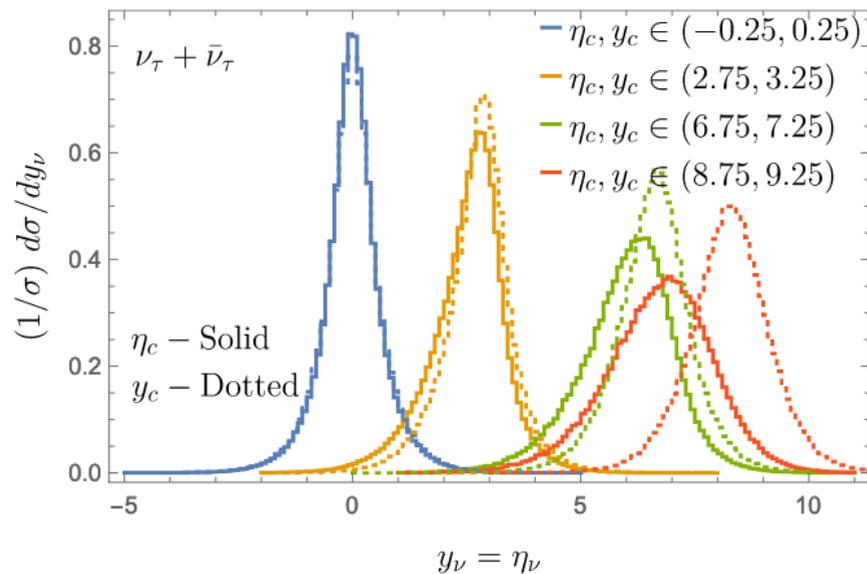
η range
 (HL run):

baseline	UJ12 Alcoves (480 – 521 m)						Purpose Built Facility (617 m)		
	480m			521 m			617 m		
Experiments	FASER ν 2	FLArE		FASER ν 2	FLArE		FASER ν 2	FLArE	
Radius (max)	20 cm	0.5 m	1 m	20 cm	0.5 m	1 m	20 cm	0.5 m	1 m
η_{\min}	8.48	7.56	6.87	8.56	7.64	6.95	8.73	7.81	7.12

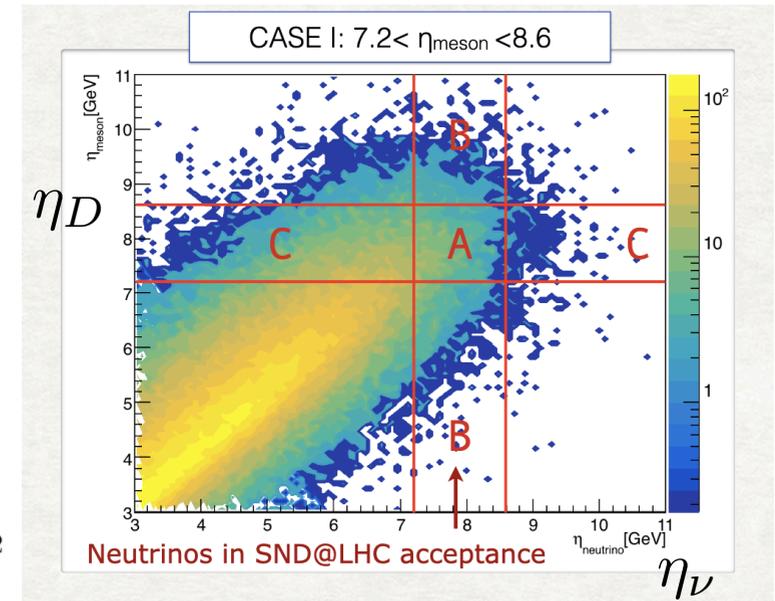
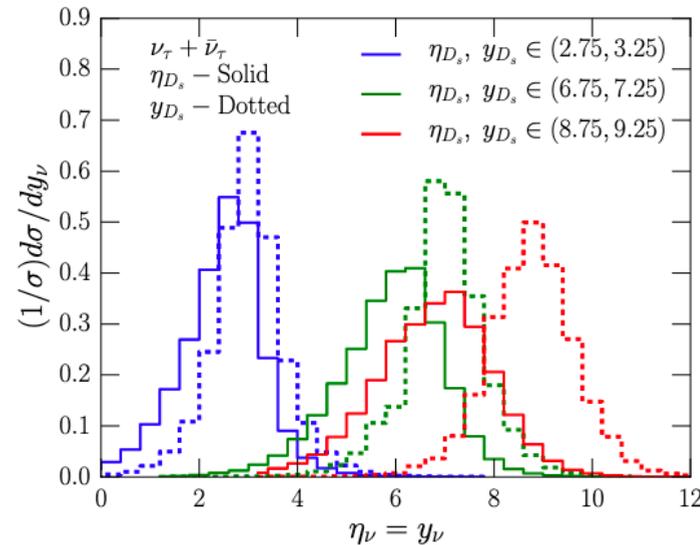
Rapidity/pseudorapidity

spread of neutrino rapidity for restricted charm or meson rapidity/pseudorapidity

charm quark and ν_τ



D_s and ν_τ



Neutrino rapidity correlates better with charm rapidity (dotted) than with charm pseudorapidity (solid) in the forward region. arXiv:2112.11605

A. Di Crescenzo for
SND@LHC, 3rd FPF Meeting

$$\nu_\tau + \bar{\nu}_\tau$$

- D_s decay into $\bar{\nu}_\tau \tau$

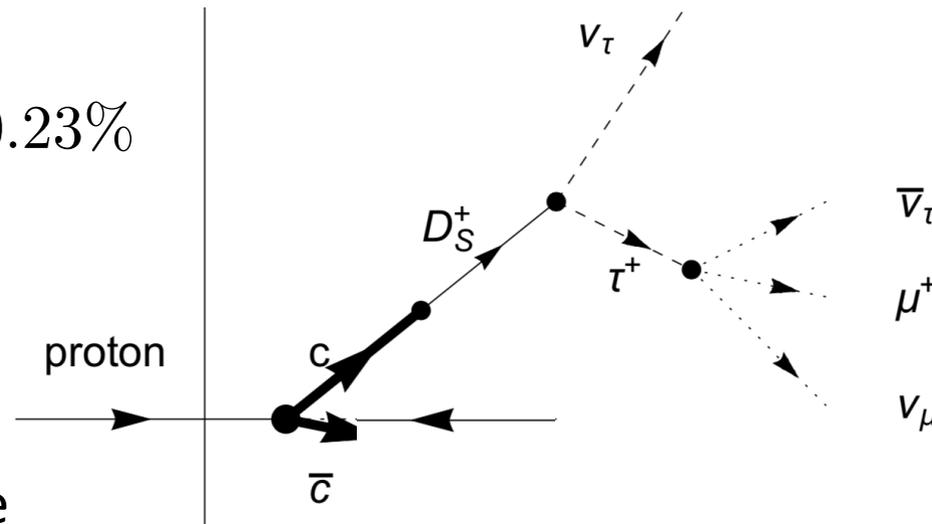
$$B(D_s \rightarrow \bar{\nu}_\tau \tau) = 5.48 \pm 0.23\%$$

- Pion-like decay: prompt

$$D_s^- \rightarrow \bar{\nu}_\tau \tau \rightarrow \bar{\nu}_\tau \nu_\tau X$$

Tau decay also prompt.

- Charm is dominant source of $\nu_\tau + \bar{\nu}_\tau$ - a factor of more than 10 larger than from b-quarks.

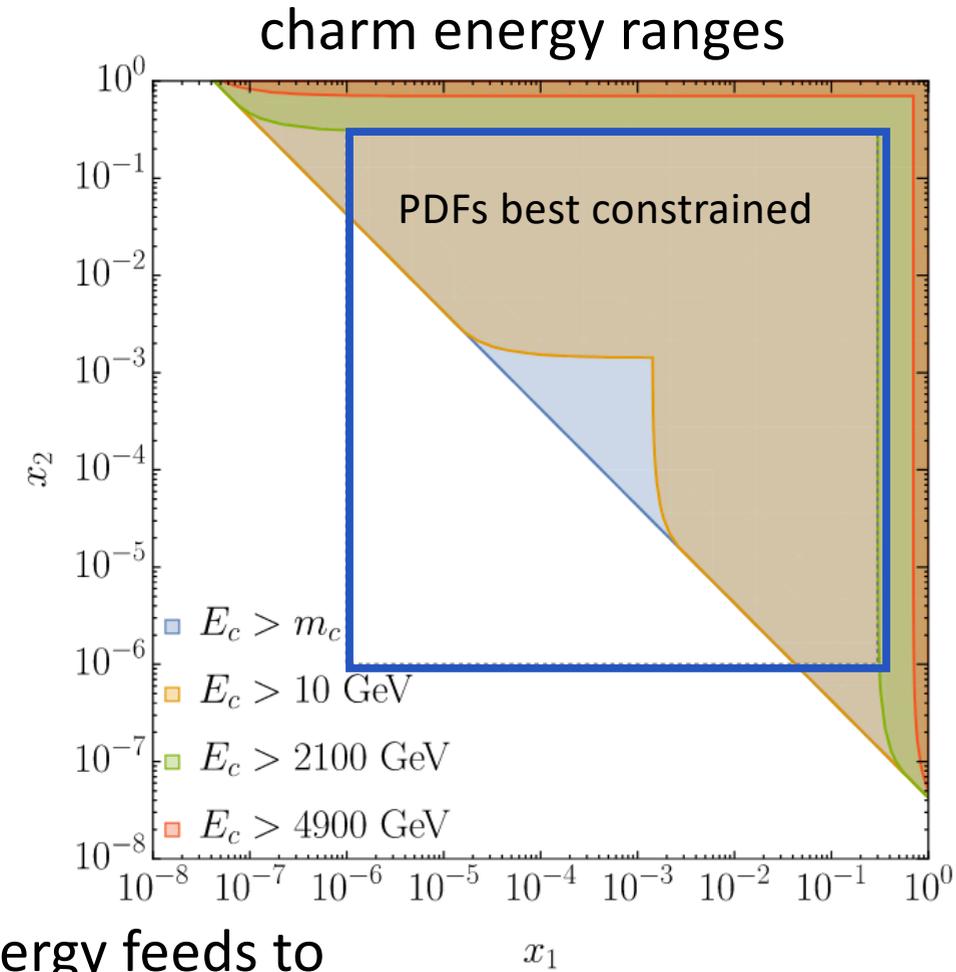
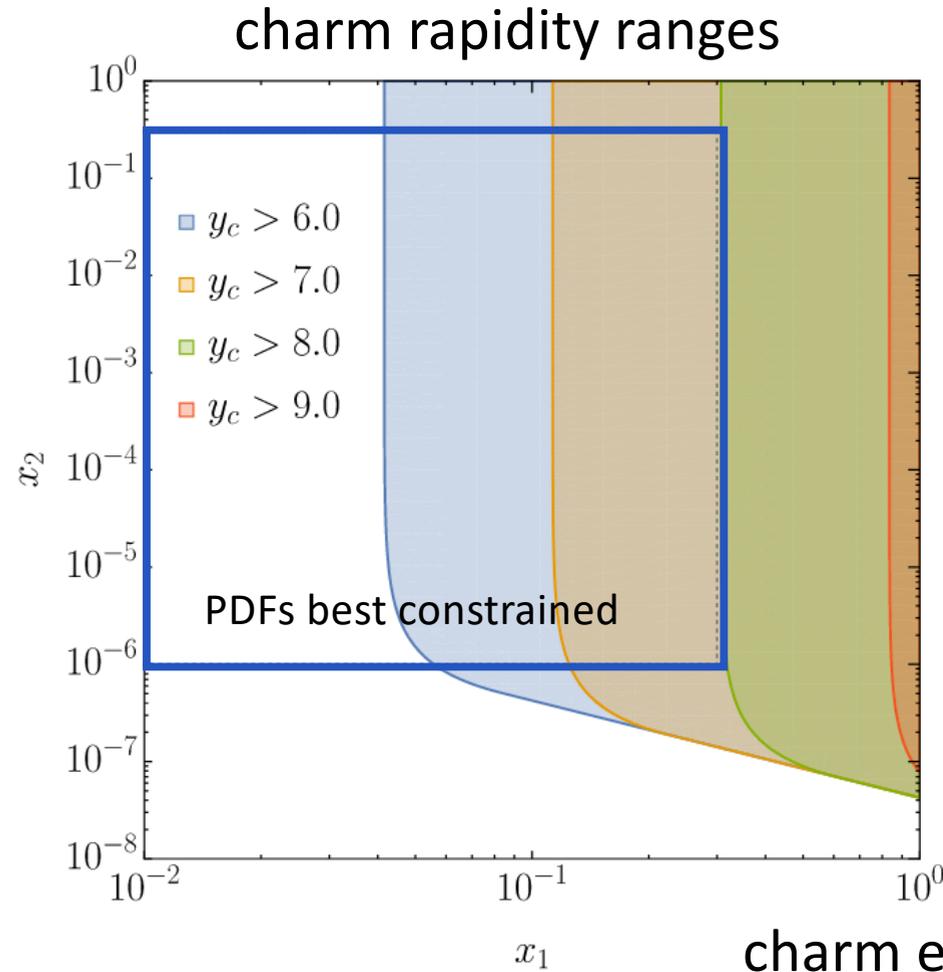


Forward production, $\eta_\nu > 6.9$

NLO pQCD evaluation of inclusive charm production
(Nason, Dawson, Ellis, Nucl. Phys. B327(1988)49)

- PROSA PDFs with scale & PDF uncertainties.
Zenaiev et al, JHEP 04 (2020) 118
- Other PDFs: CT14, NNPDF3.1, ABMP16

Charm pair production: small x and large x PDFs



charm energy feeds to lower neutrino energies

Large x PDFs

Courtesy of the PROSA Collaboration

Data CMS $\sqrt{s} = 8$ TeV
 CMS, Eur. Phys. J. C77 (2017) 459

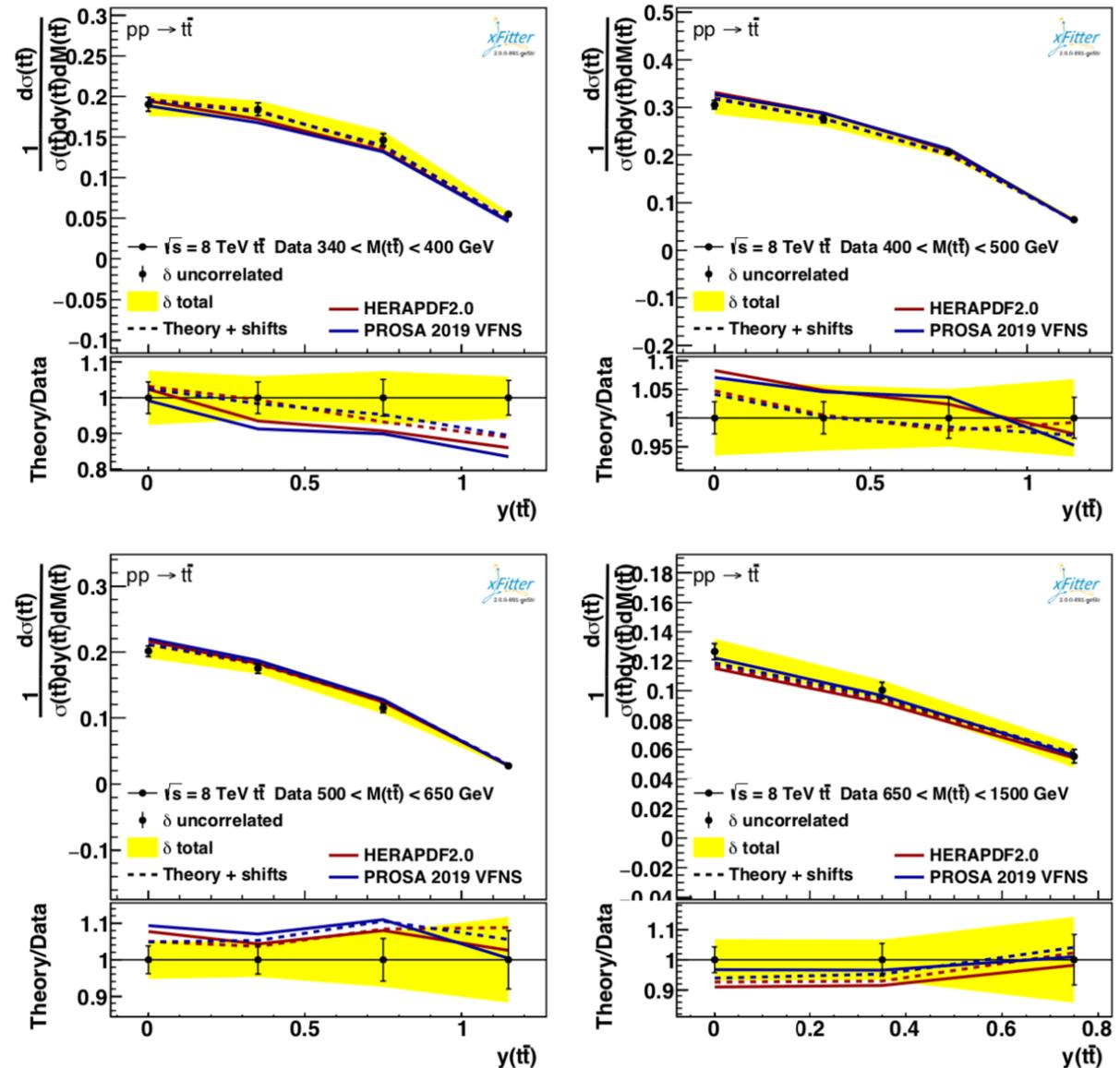
PROSA $\chi^2 = 23/15$

(Compared with HERAPDF2.0 with $\chi^2 = 24/15$ for same comparison.)

Solid lines: standard theory.

Dashed lines: theory corrected for optimal shifts of correlated uncertainties of experimental data.

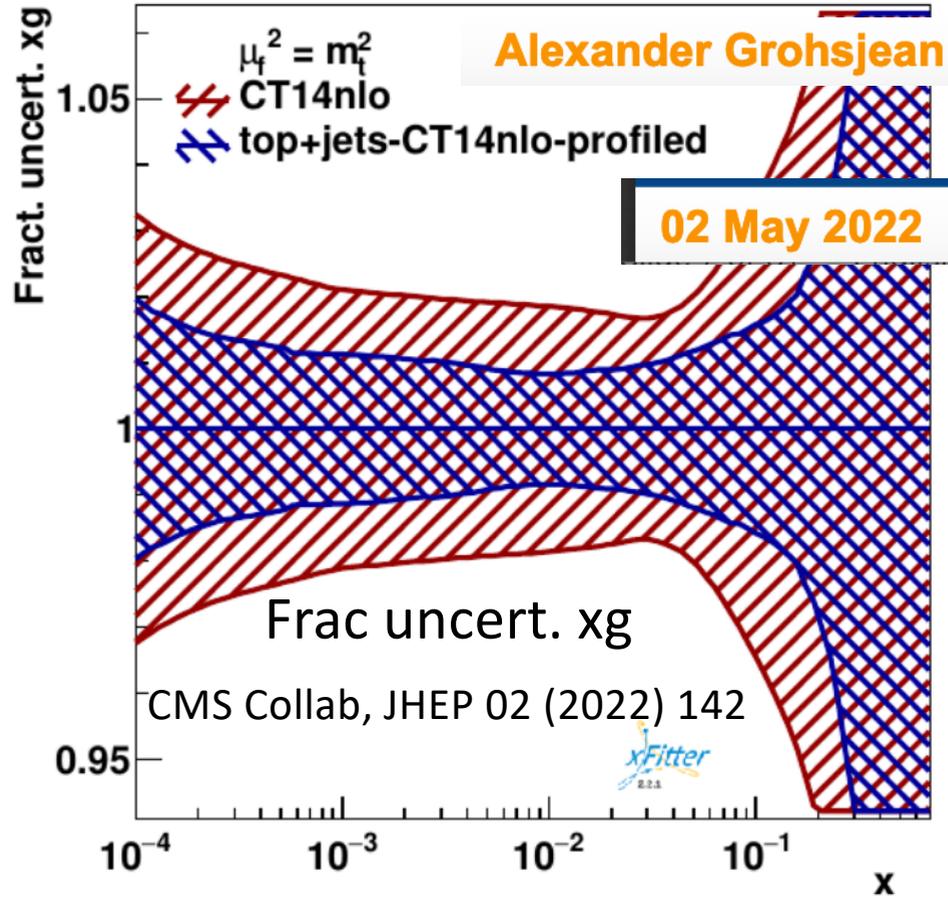
PROSA PDFs vs $y(\bar{t}t)$ in $M(\bar{t}t)$ bins



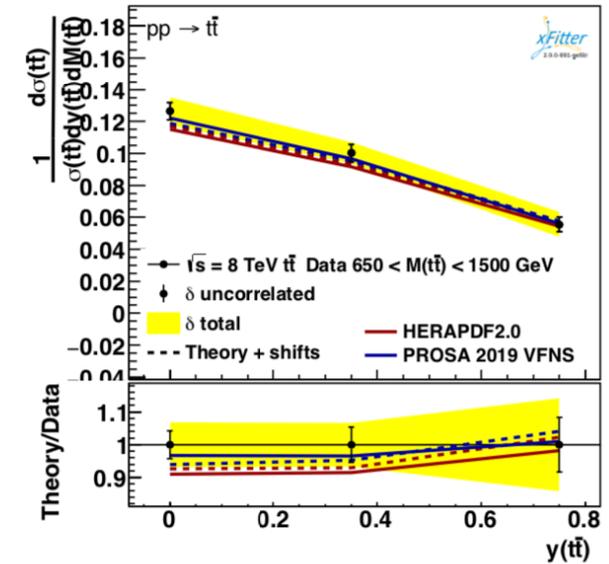
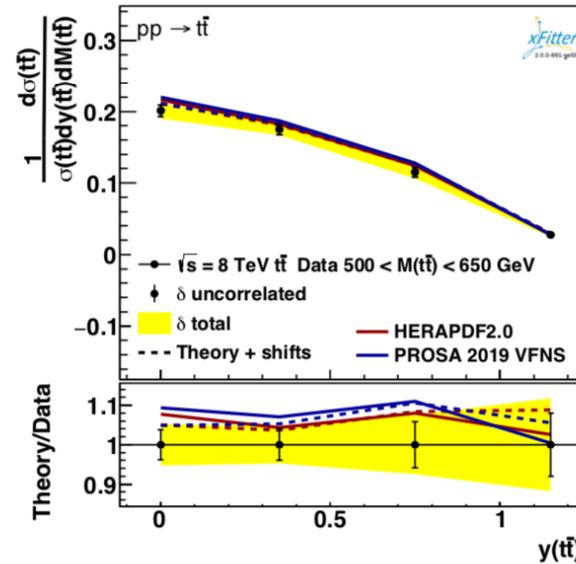
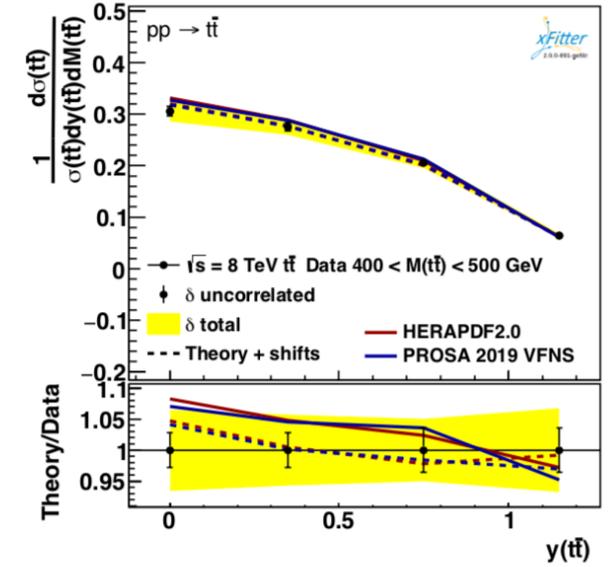
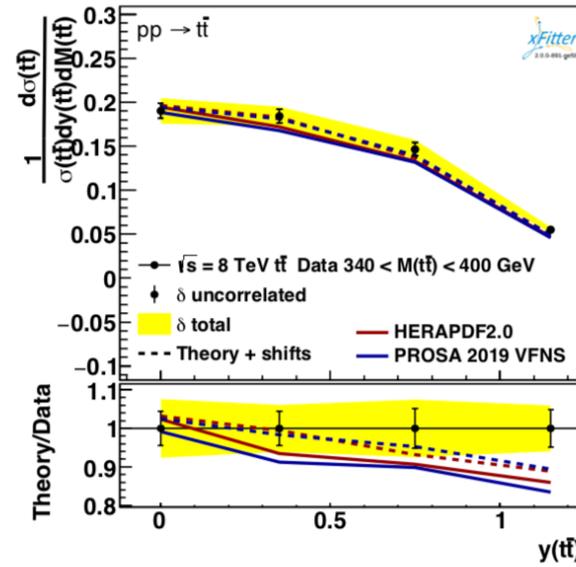
Courtesy of the PROSA Collaboration

Large x PDFs

CMS inclusive jet cross section



DIS 2022, 4 May 2022



MF

Charm pair production

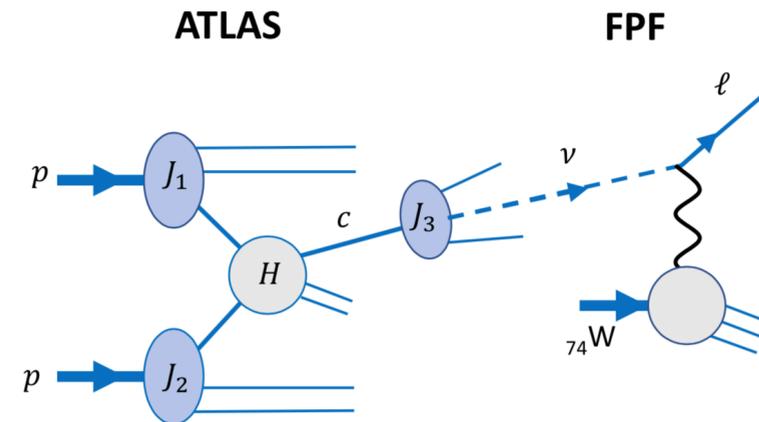
- PROSA 2019 fit to heavy flavor production including LHCb. Zenaiev et al, JHEP 04 (2020) 118. Fits include LHCb and HERA charm production cross sections.

3 flavor PDFs.

- We use LHCb D_s data to (in part) anchor our FPF calculation.

$$\frac{d^2\sigma(\text{NLO})}{dp_T dy} = \int d^2\vec{k}_T \frac{1}{\pi\langle k_T^2 \rangle} \exp[-k_T^2/\langle k_T^2 \rangle] \frac{d^2\sigma(\text{NLO})}{dq_T dy} \Big|_{q_T=|\vec{p}_T-\vec{k}_T|}$$

- Peterson fragmentation to charm mesons.



Short white paper 2109.10905

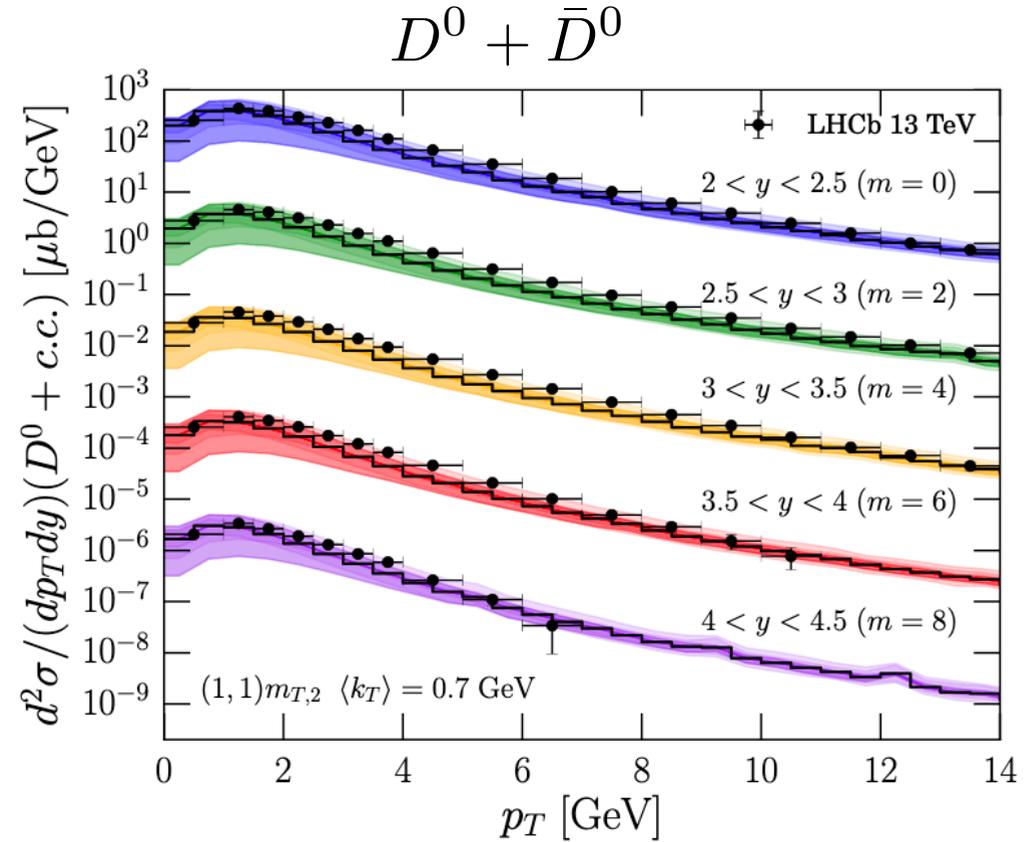
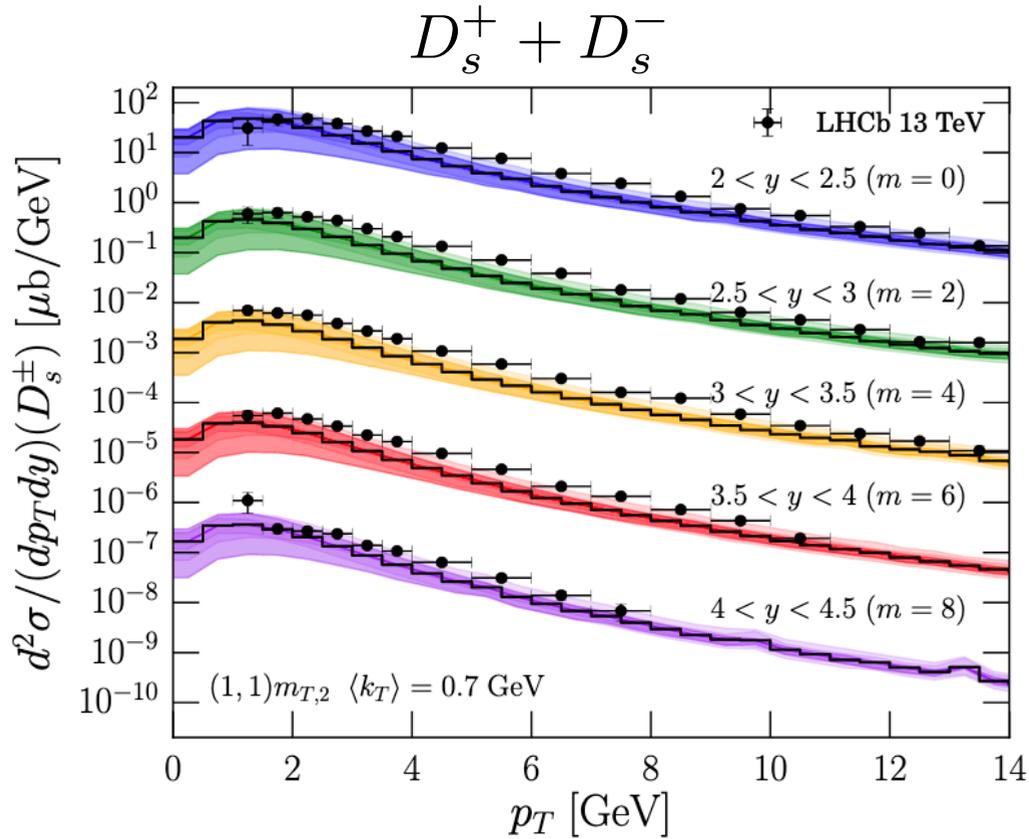
- Intrinsic k_T/ k_T smearing (mimicking higher order effects?)
- Renormalization, factorization scale effects.

D's at LHCb

Gaussian smearing with:

$$\langle k_T \rangle = 0.7 \text{ GeV}$$

similar to POWHEG
+ PYTHIA results



PROSA PDF fits done with $m_{T,2} \equiv \sqrt{(2m_c)^2 + p_T^2}$ also used here. Scale uncertainty band.

D's at LHCb 13 TeV

$$D_s^+ + D_s^-$$

Default (1,1)

Blue solid lines:

$$m_{T,2} \equiv \sqrt{(2m_c)^2 + p_T^2}$$

$$\langle k_T \rangle = 0.7 \text{ GeV}$$

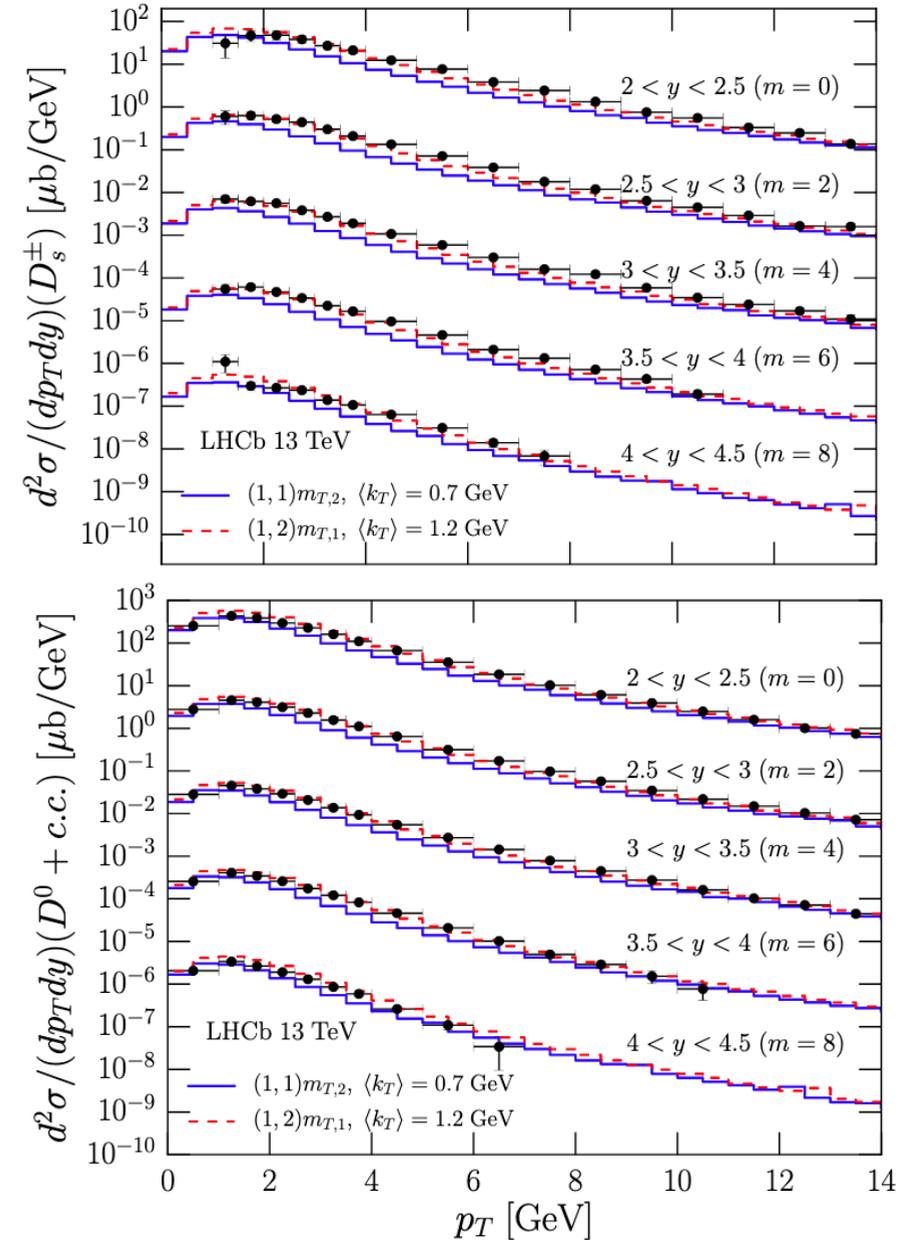
Red dashed lines:

$$m_{T,1} \equiv \sqrt{(m_c)^2 + p_T^2}$$

$$\langle k_T \rangle = 1.2 \text{ GeV}$$

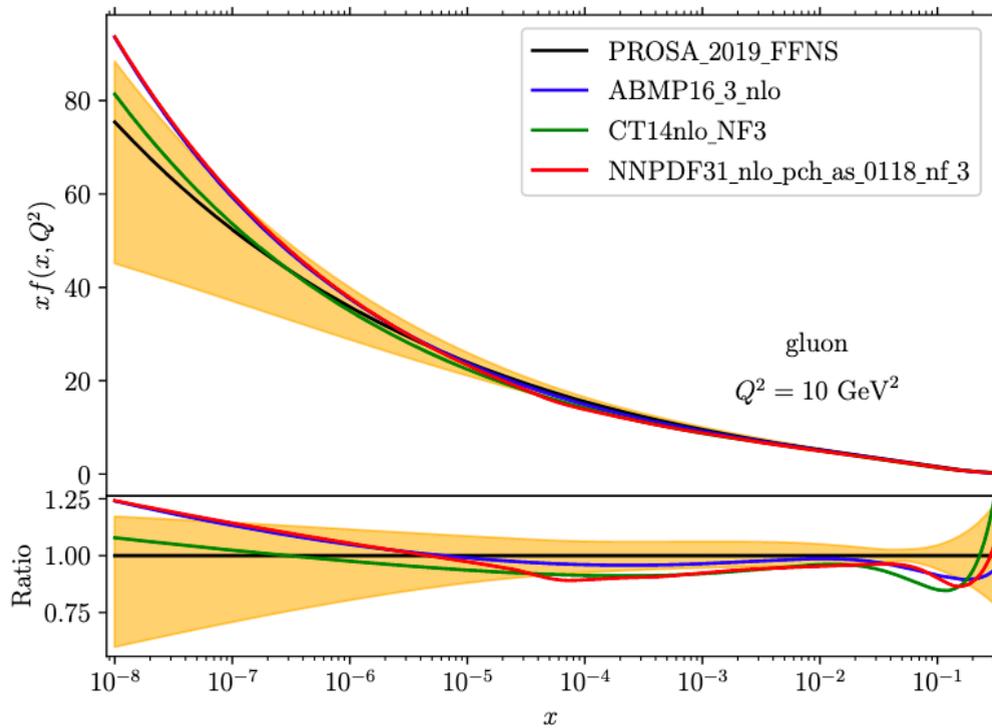
(1,2) factor
for (R,F) scale

$$D^0 + \bar{D}^0$$

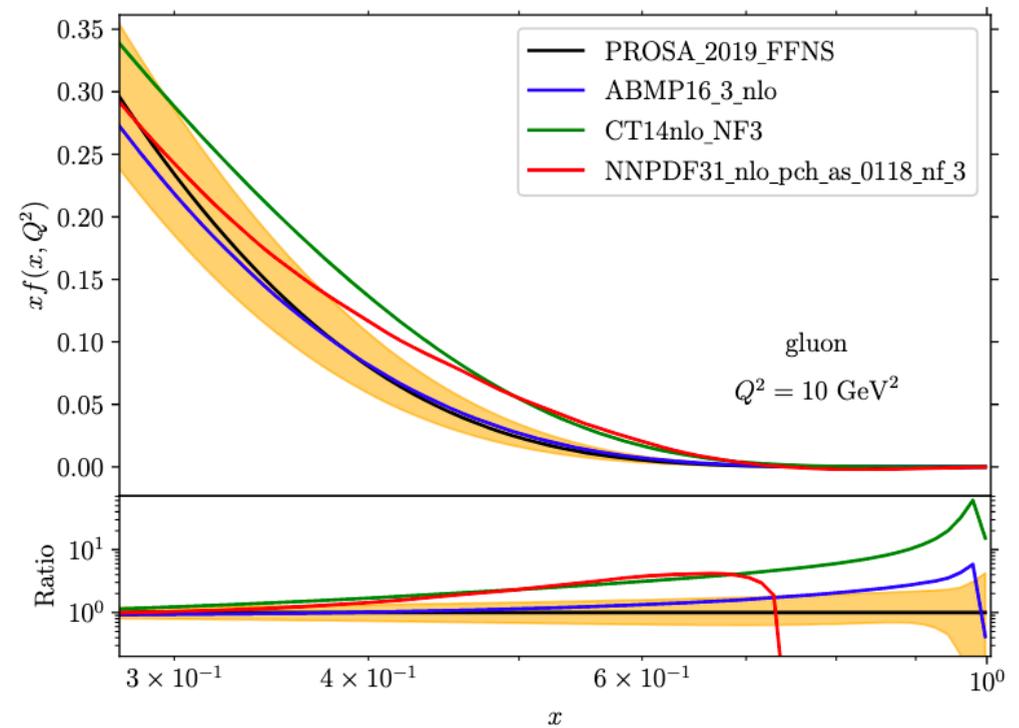


Forward physics: small x and large x PDFs

$xg(x, Q)$

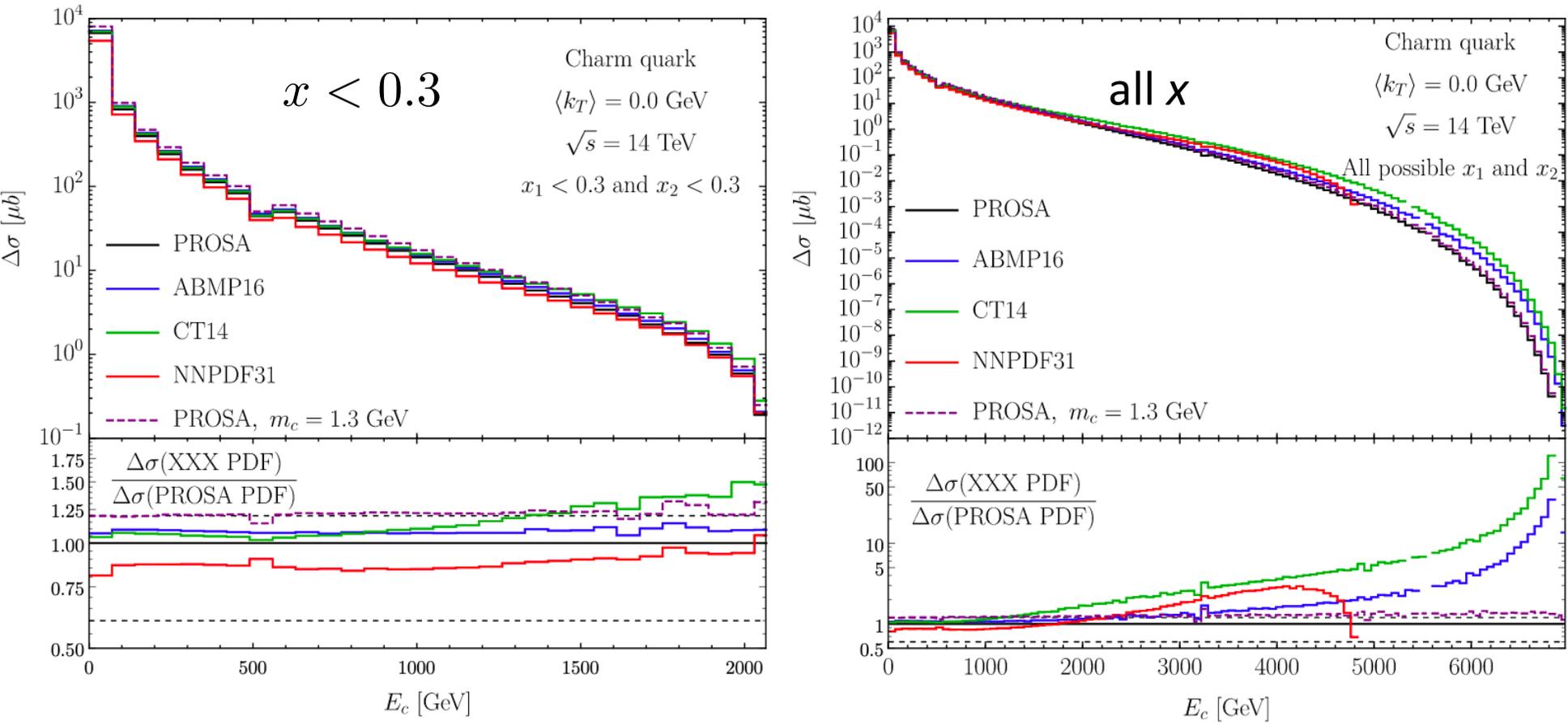


$x < 0.3$



$x > 0.3$

Forward physics: small x and large x PDFs



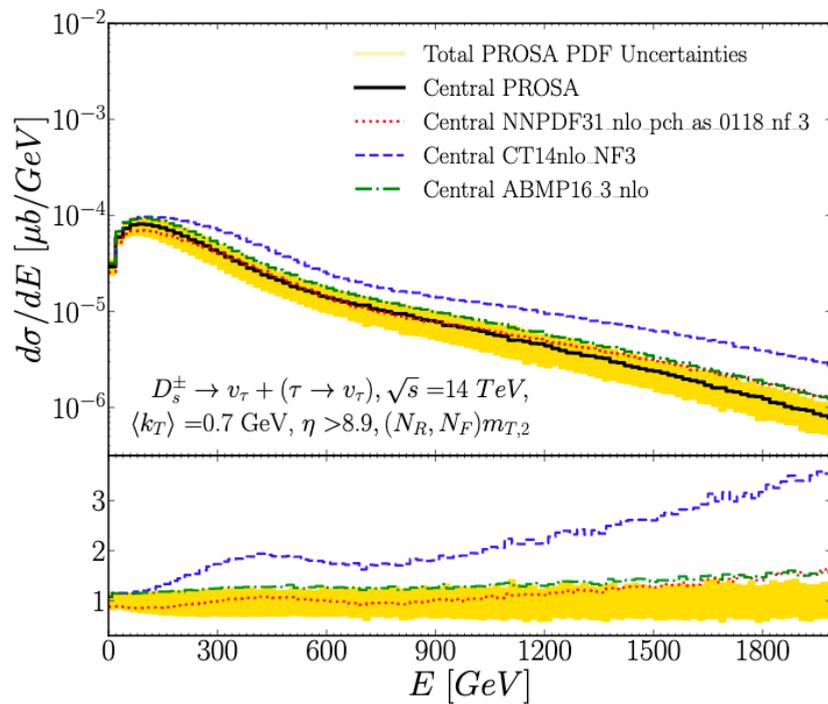
charm quark energy distribution (notice different scales)

Results FASER ν

tau neutrino energy distributions

$$\eta > 8.9$$

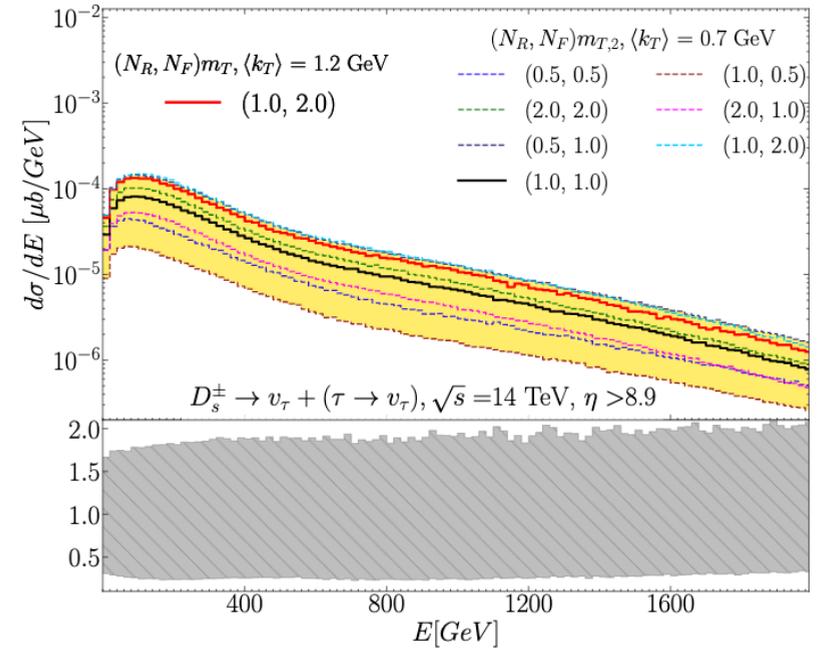
40 PROSA PDFs



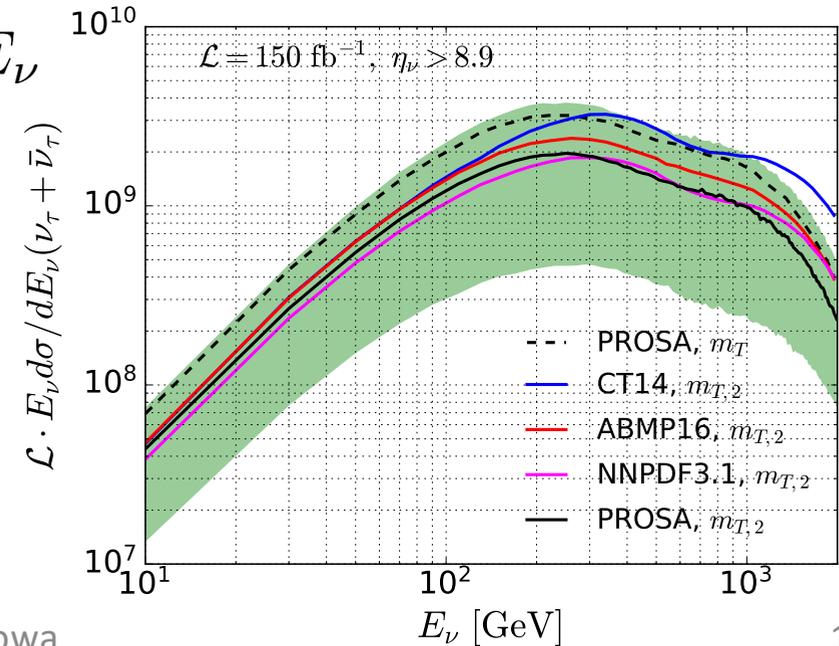
CT14 is outlier

DIS 2022, 4 May 2022

7-point scale variation



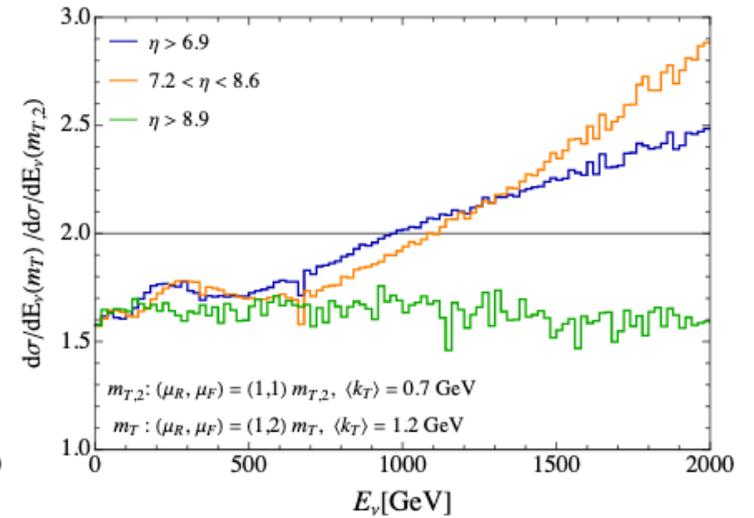
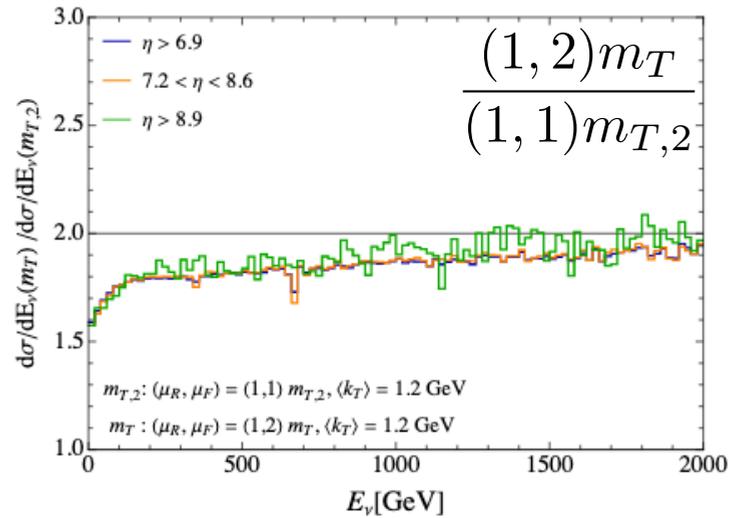
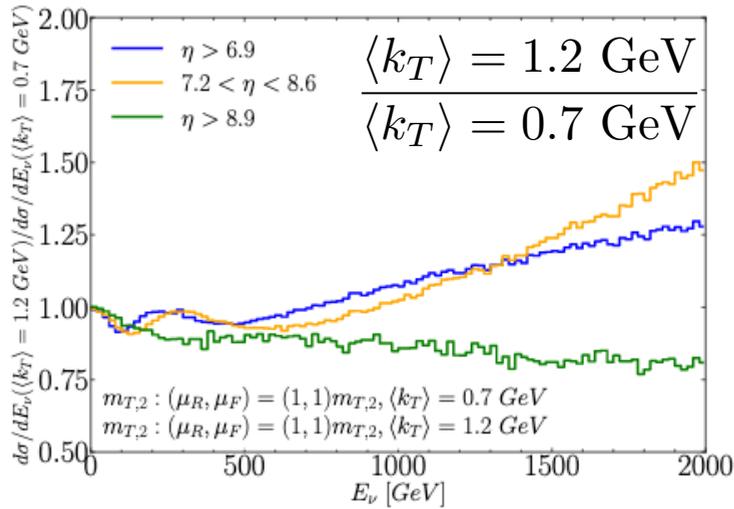
$$\sigma_\nu \sim E_\nu$$



MH Reno, University of Iowa

k_T smearing and scale dependence

tau neutrino energy distribution ratios



- only k_T smearing changed
- increase in high pT tails detectable for smaller η

- only scale choice changed
- largely η_ν independent

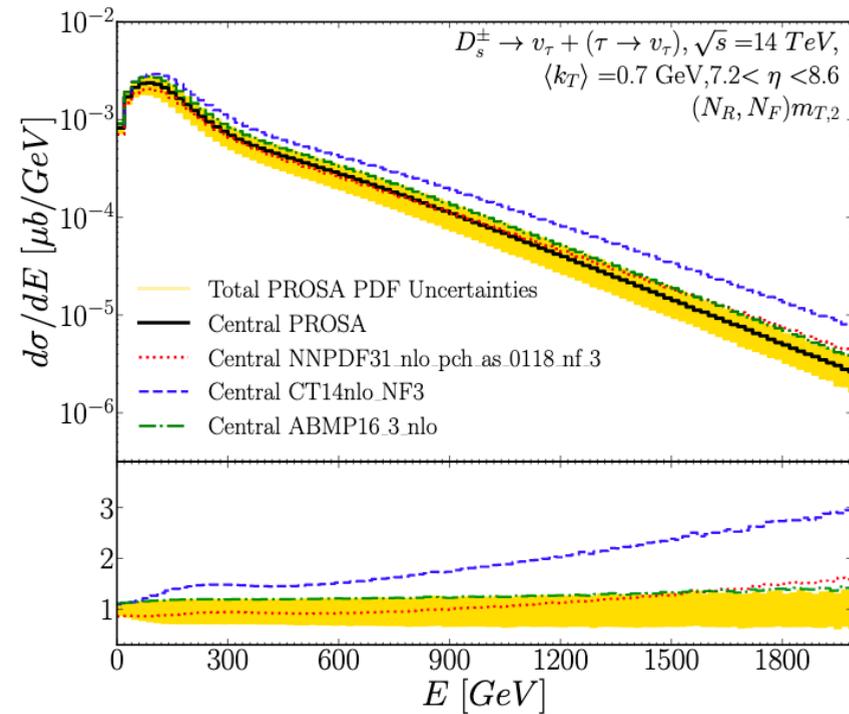
- k_T smearing and scale choice changed

Results SND@LHC

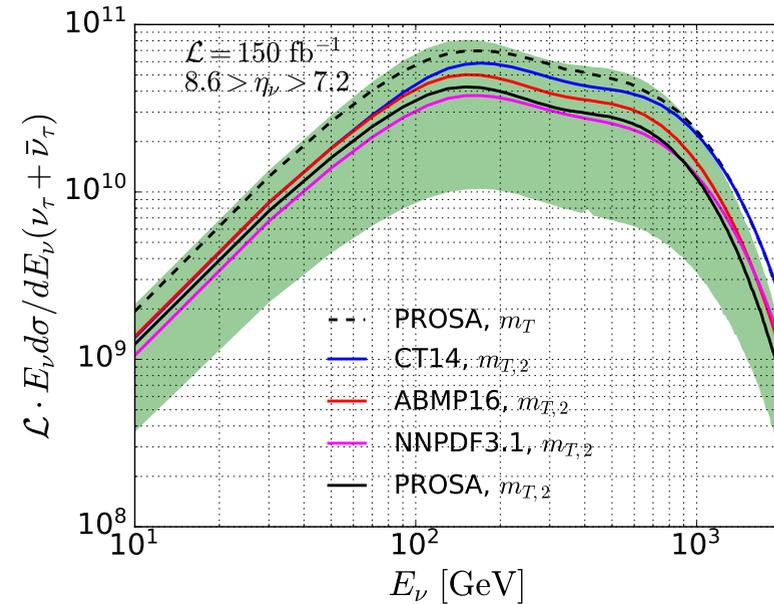
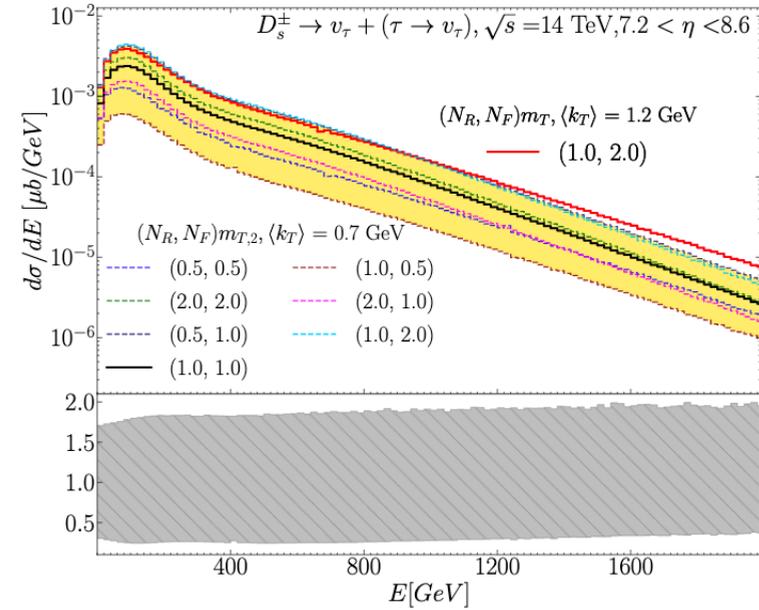
tau neutrino energy distributions

$$8.6 > \eta > 7.2$$

40 PROSA PDFs



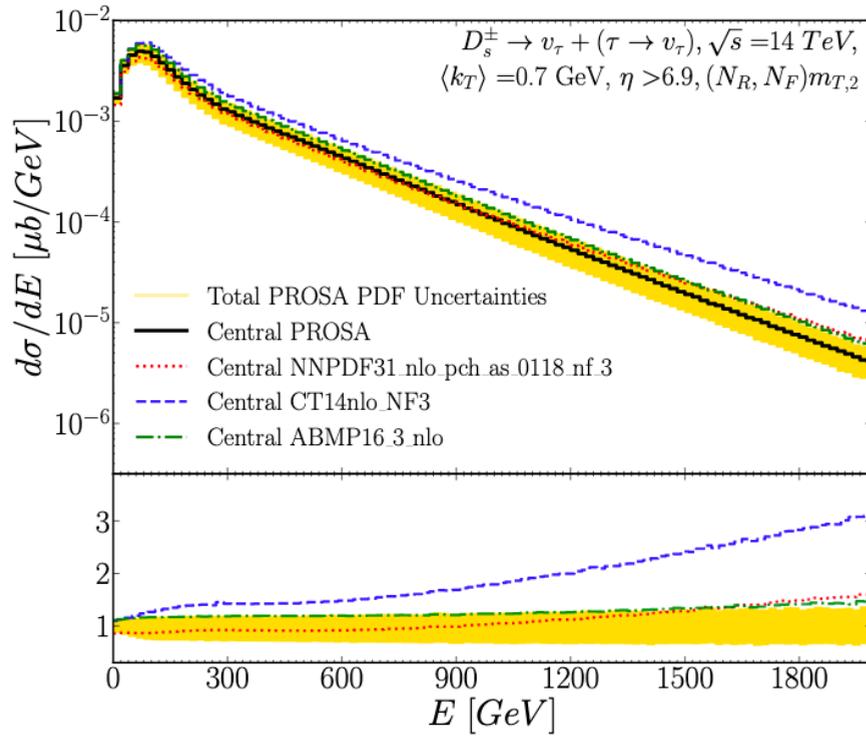
7-point
scale
variation



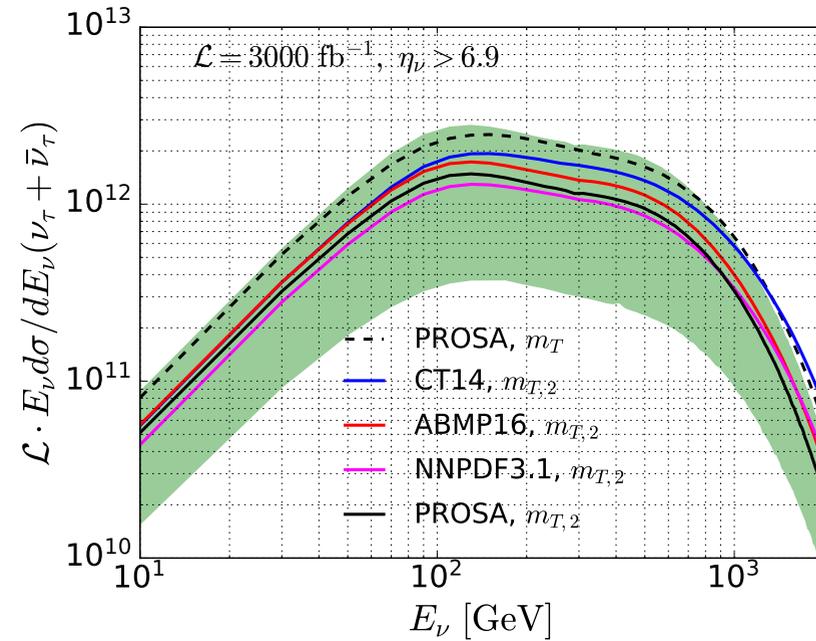
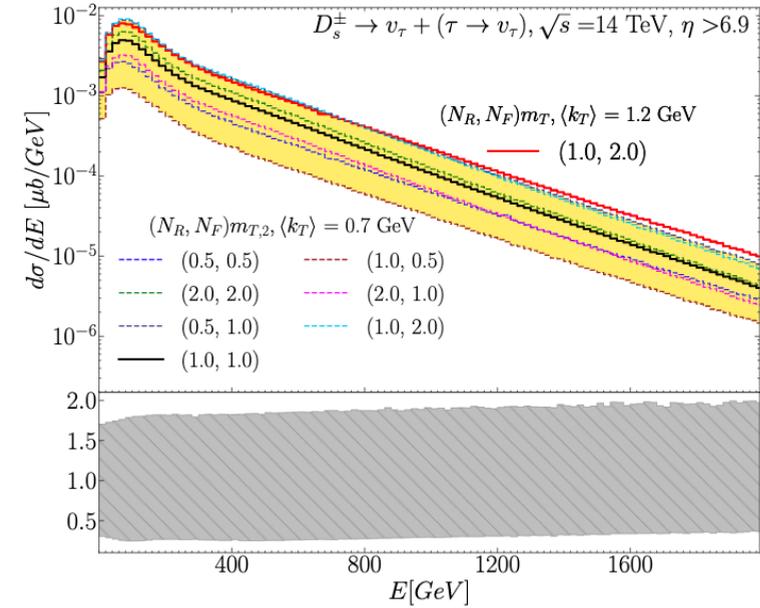
FPF $\eta > 6.9$

tau neutrino energy distributions

40 PROSA PDFs



7-point
scale
variation



$\nu_\tau + \bar{\nu}_\tau$ Events Run 3

$\mathcal{L} = 150 \text{ fb}^{-1}$	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) $m_{T,2}, 0.7 \text{ GeV}$					
				scale(u/l)	PDF(u/l)	σ_{int}
SND@LHC $7.2 < \eta_\nu < 8.6, 830 \text{ kg}$	2.8	1.3	$4.2^{+3.8}_{-3.3}$	+3.7/-3.1	+0.8/-1.2	± 0.1
FASER ν $\eta_\nu > 8.9, 1.2 \text{ ton}$	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) $m_T, 1.2 \text{ GeV}$			(1, 1) $m_{T,2}, 0.7 \text{ GeV}$		
PDF	PROSA FFNS			NNPDF3.1	CT14	ABMP16
SND@LHC $7.2 < \eta_\nu < 8.6, 830 \text{ kg}$	5.1	2.4	7.5	4.0	6.6	5.0
FASER ν $\eta_\nu > 8.9, 1.2 \text{ ton}$	13.5	6.4	19.9	12.8	23.5	15.6

arXiv:2112.11605

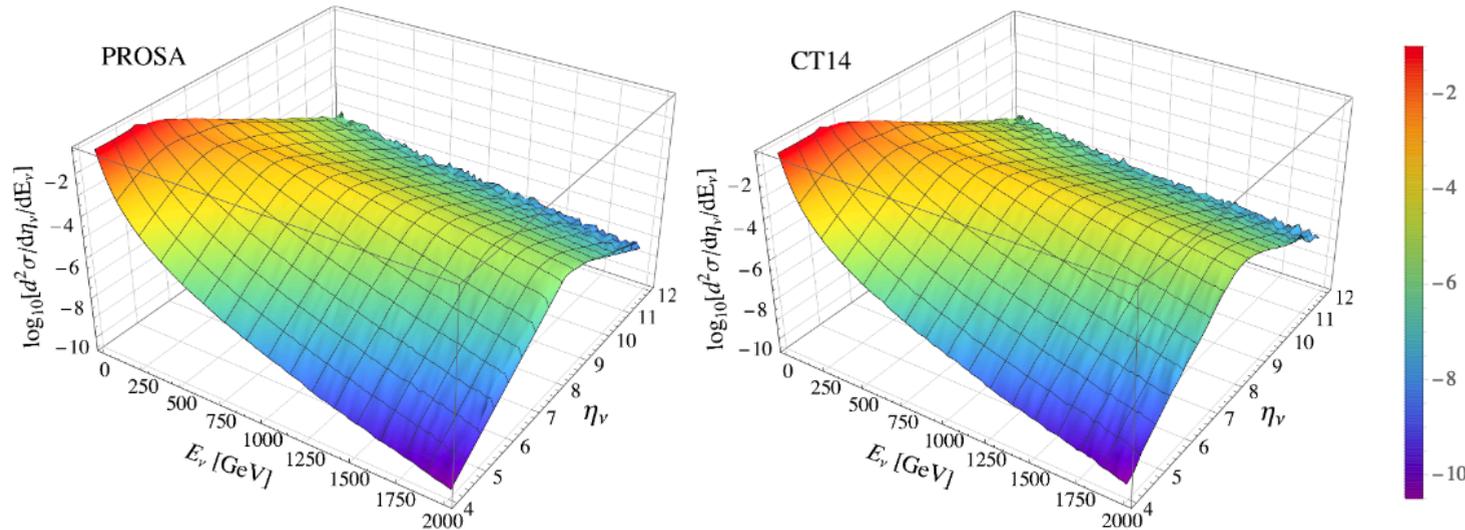
$\nu_\tau + \bar{\nu}_\tau$ Events HL

$\mathcal{L} = 3000 \text{ fb}^{-1}, 1 \text{ m}$	ν_τ	$\bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$		
$(\mu_R, \mu_F), \langle k_T \rangle$	$(1, 1) m_{T,2}, 0.7 \text{ GeV}$					
				scale (u/l)	PDF (u/l)	σ_{int}
$\eta \gtrsim 6.9$	3260	1515	4775^{+4307}_{-3763}	+4205/-3494	+926/-1391	± 112
$(\mu_R, \mu_F), \langle k_T \rangle$	$(1, 2) m_T, 1.2 \text{ GeV}$			$(1, 1) m_{T,2}, 0.7 \text{ GeV}$		
PDF	PROSA FFNS			NNPDF3.1	CT14	ABMP16
$\eta \gtrsim 6.9$	5877	2739	8616	4545	7304	5735

1 m tungsten, namely 60.63 ton

arXiv:2112.11605

Tables of single and double differential distributions



<https://arxiv.org/src/2112.11605v1/anc>

<https://arxiv.org/src/2203.07212v2/anc>

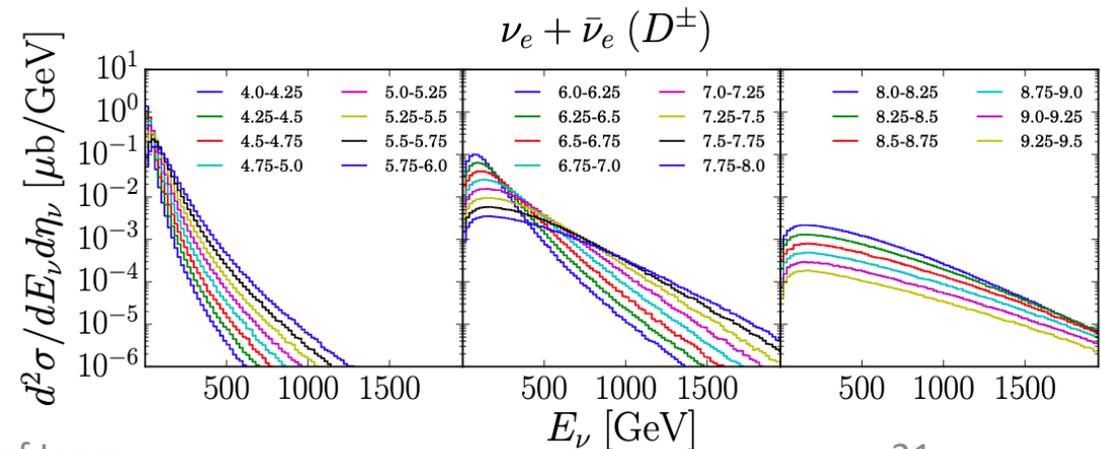
$$\bar{d}\sigma/d\eta_\nu \sim \exp(-2\eta_\nu)$$

$$f(E_\nu, \eta_\nu) \equiv e^{2\eta_\nu} \cdot \frac{d^2\sigma}{dE_\nu d\eta_\nu}$$

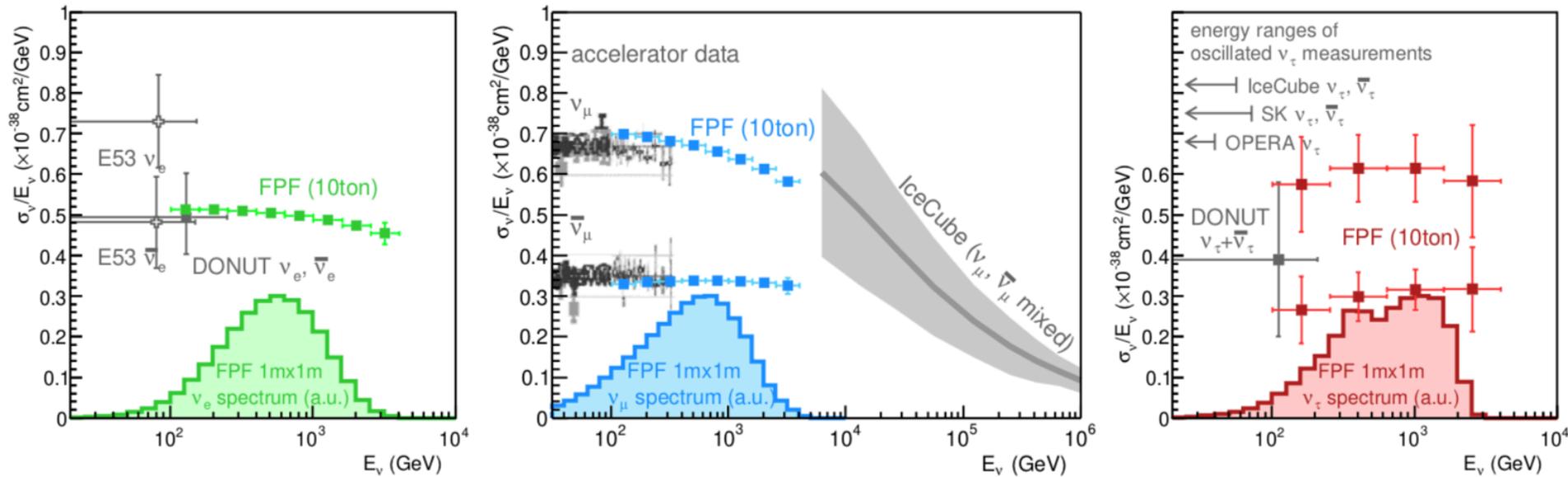
arXiv:2203.07212

For tau neutrino+antineutrino, PROSA and CT14, default scales and k_T .

Scaling behavior in rapidity at high energy.
(See also Kling & Nevay, PRD 104 (2021) 113008)



Neutrino cross sections in new energy range at the FPF



Statistical uncertainty only in figures.

- Neutrinos and antineutrinos. • Many more tau neutrinos!

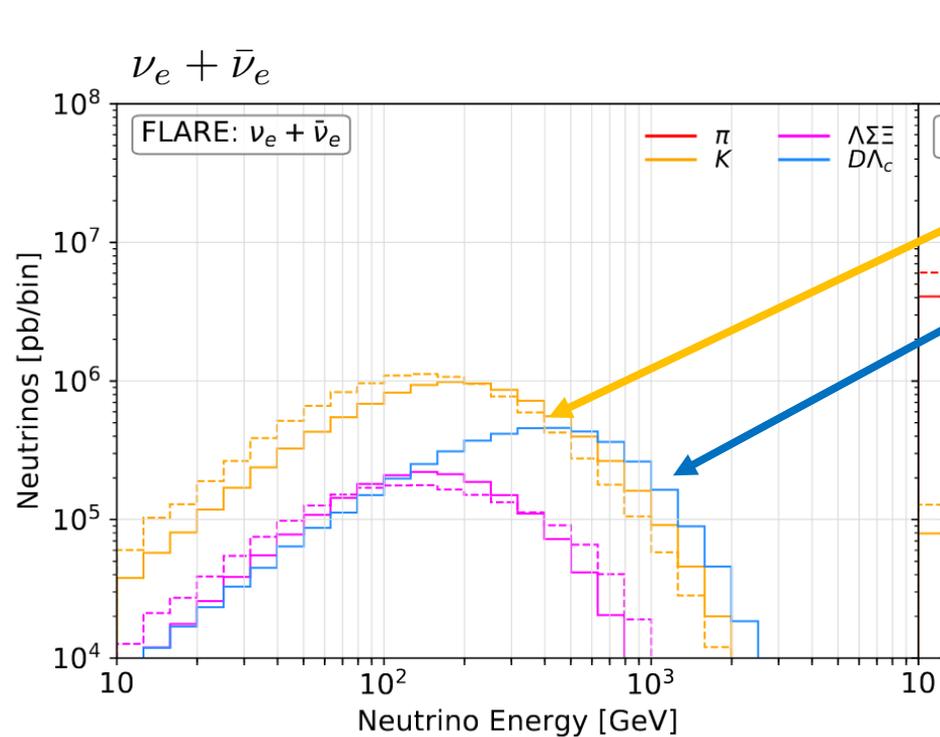
Important to understand systematic uncertainties from QCD in predictions of the flux of neutrinos from the ATLAS interaction point.

Conclusions

- PROSA PDFs are the default PDFs of this work. The PDF uncertainty does not cover the excursions of other PDFs.
- Scale dependences are the largest, total number of events between 0.2-2 times the central prediction. Scale uncertainty band approximately rapidity independent.
- Neutrino energies larger than 1 TeV particularly important for understanding the discrepancies between predictions, as they are sensitive to gluon PDFs for $x > 0.3$.
- Sensitivity in HE neutrino region to kT.
- More work can be done to better understand role of fragmentation, intrinsic transverse momentum, and possibility of intrinsic charm.
- Correlations with high energy $\nu_e + \bar{\nu}_e$ (also from kaons).
- Lower energies, DsTau (NA65) 400 GeV proton beam.

Backup slides

Hadron production and decay to neutrinos

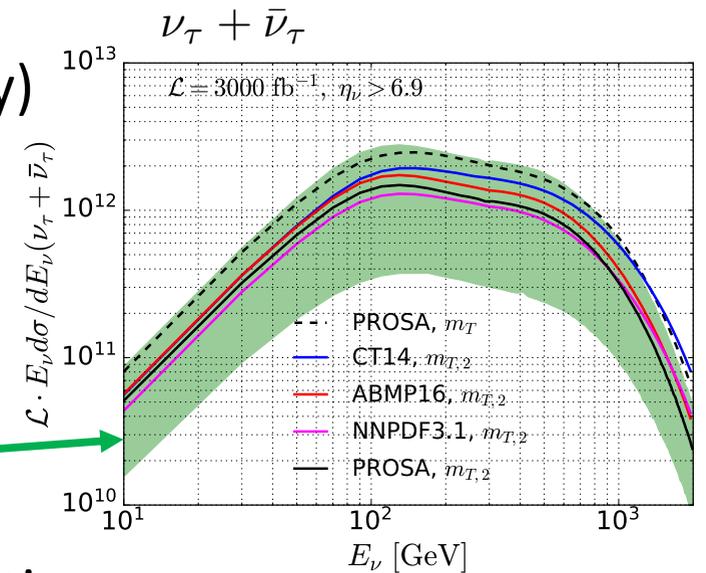


$$\nu_e + \bar{\nu}_e$$

Dominated by
kaons (low and mid energy)
charm (highest energy)

$$\nu_\tau + \bar{\nu}_\tau$$

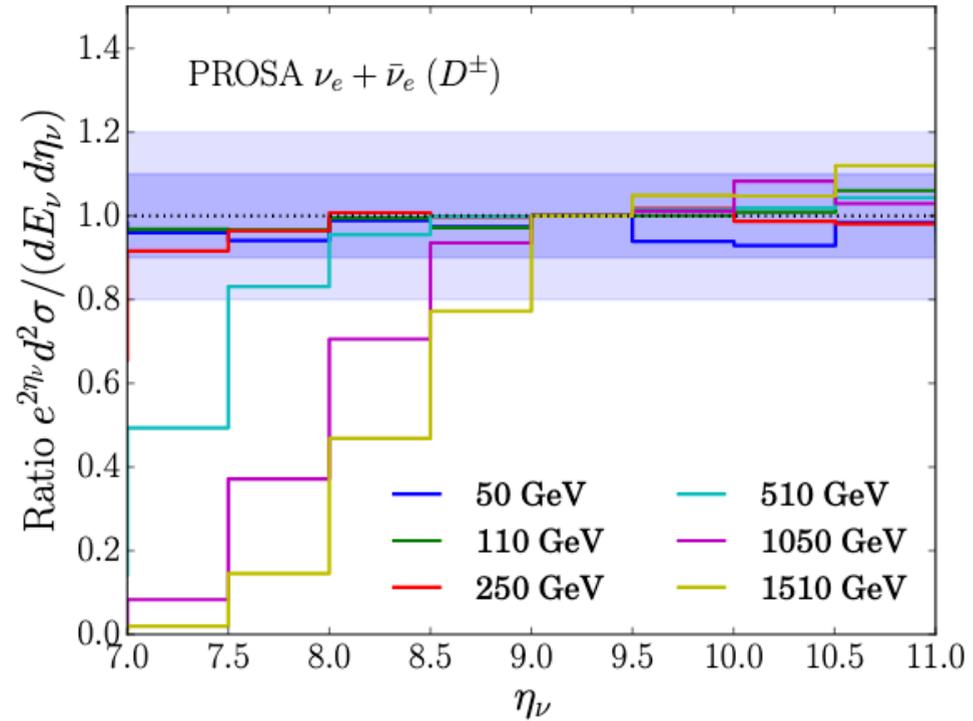
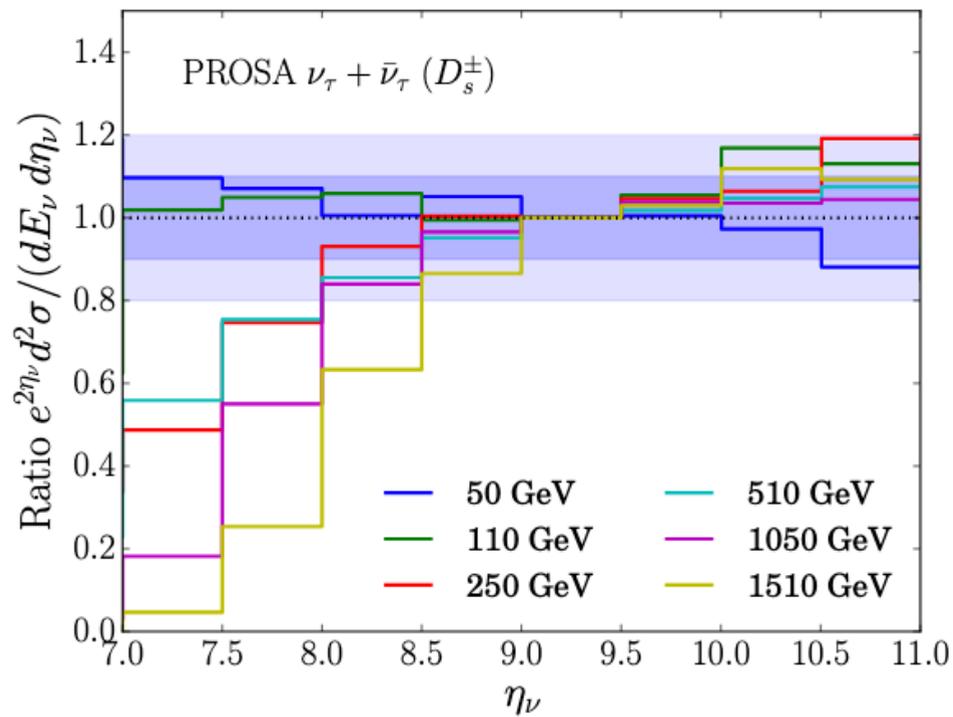
Dominated by
 $D_S^\pm \rightarrow \tau \nu_\tau, \tau \rightarrow \nu_\tau X$



Focus on charm production.
QCD scale m_c , NLO scale dependence.

An example of MC results for neutrinos:
solid histograms show Pythia Monash tune,
dashed histograms show new Pythia tune incl.
CASTOR, TOTEM, ATLAS data.

High energy rapidity scaling behavior



$$f(E_\nu, \eta_\nu) \equiv e^{2\eta_\nu} \cdot \frac{d^2\sigma}{dE_\nu d\eta_\nu}$$

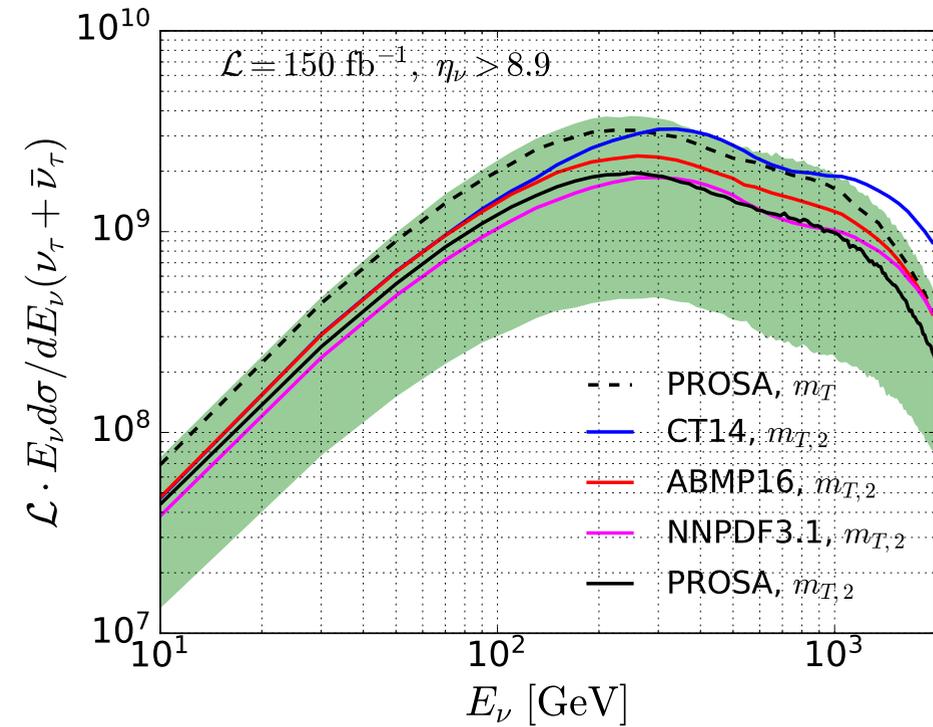
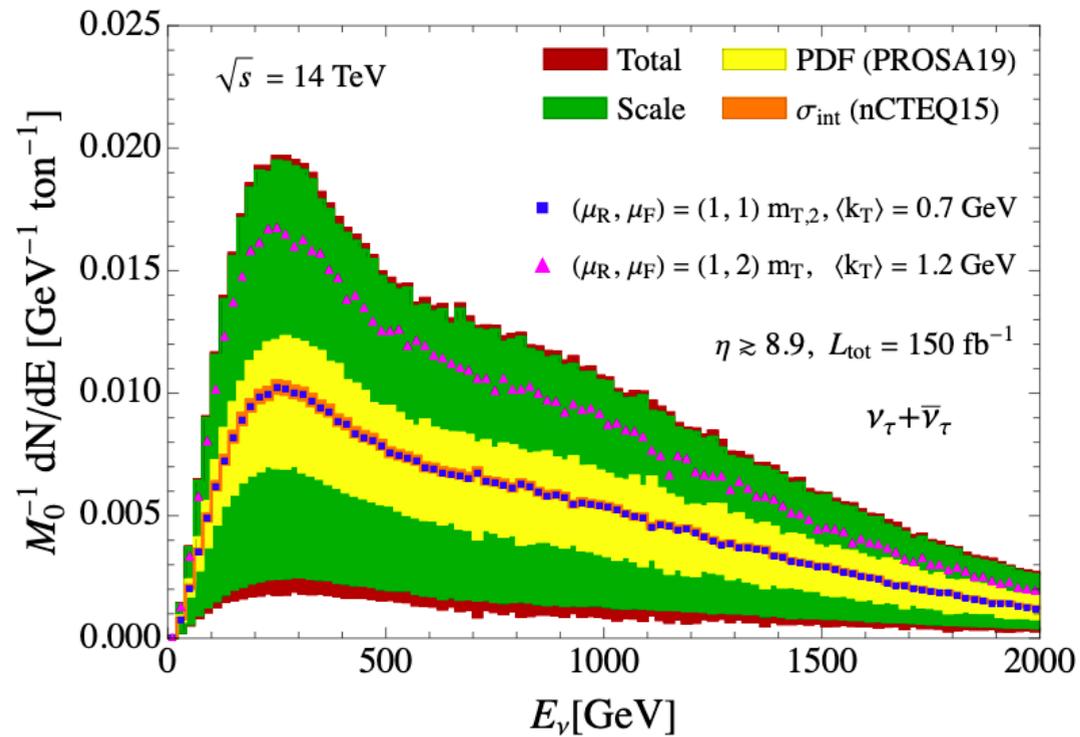
becomes largely independent of η_ν for large enough η_ν

arXiv:2112.11605

Results FASER ν

Events per GeV per ton

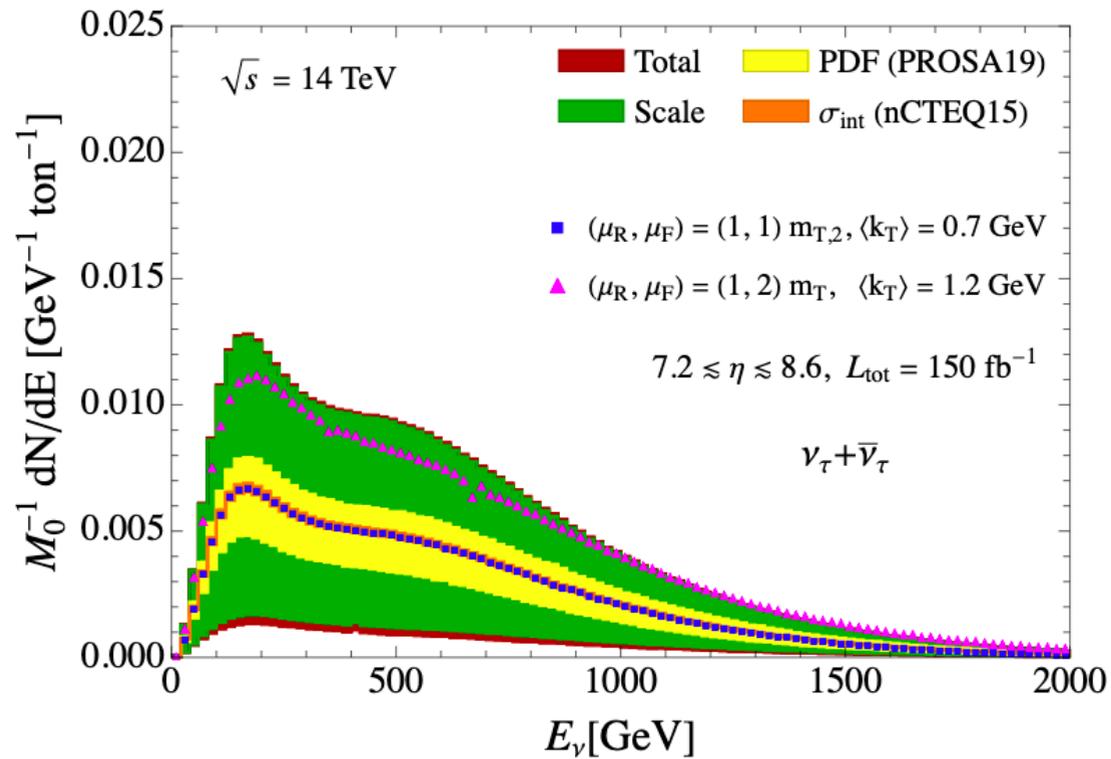
$$\sigma_\nu \sim E_\nu$$



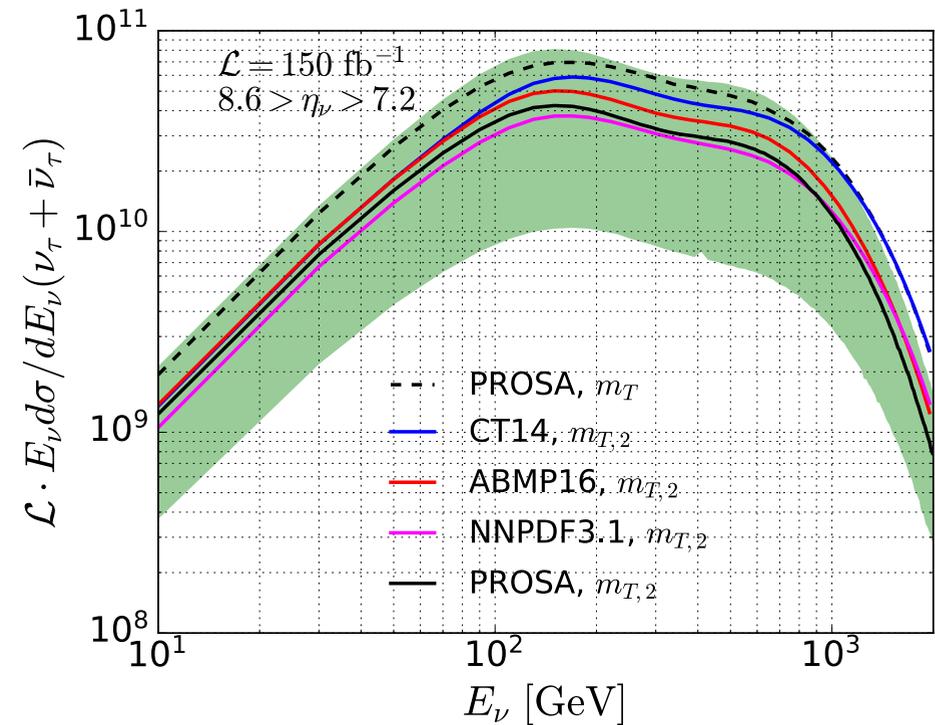
arXiv:2112.11605

Results SND@LHC

Events per GeV per ton



$$\sigma_\nu \sim E_\nu$$

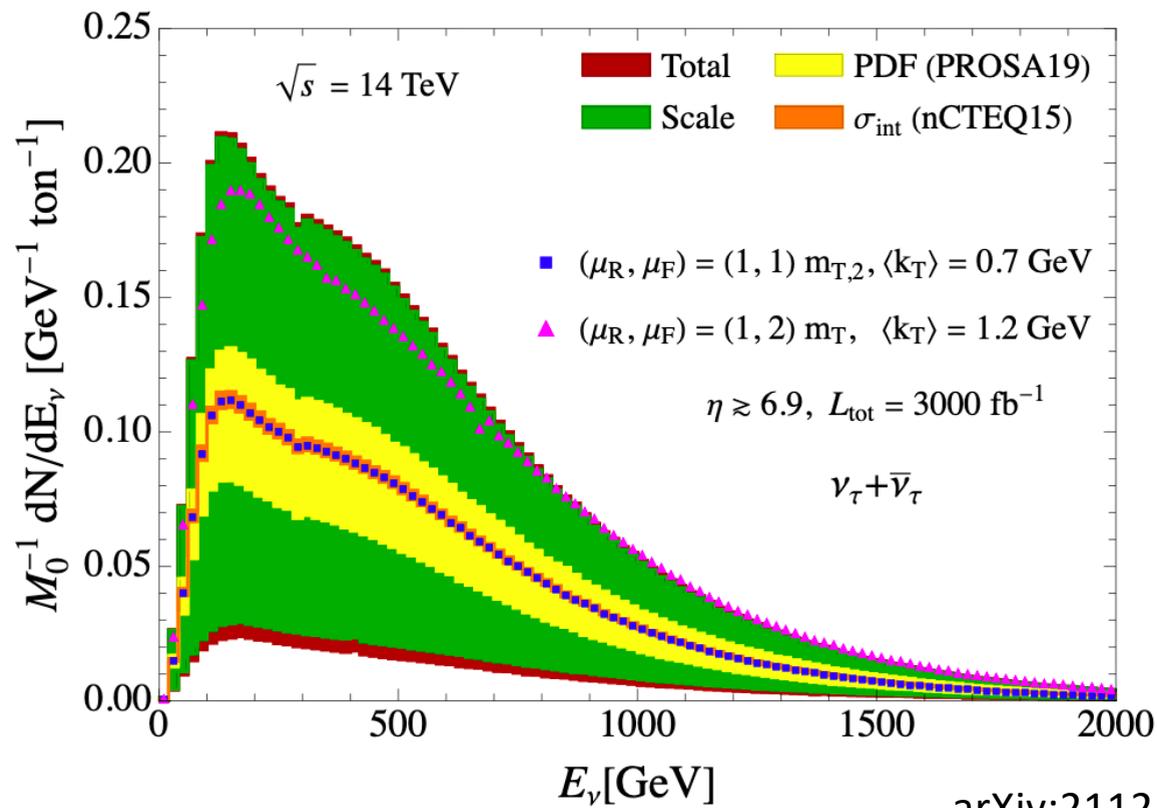


arXiv:2112.11605

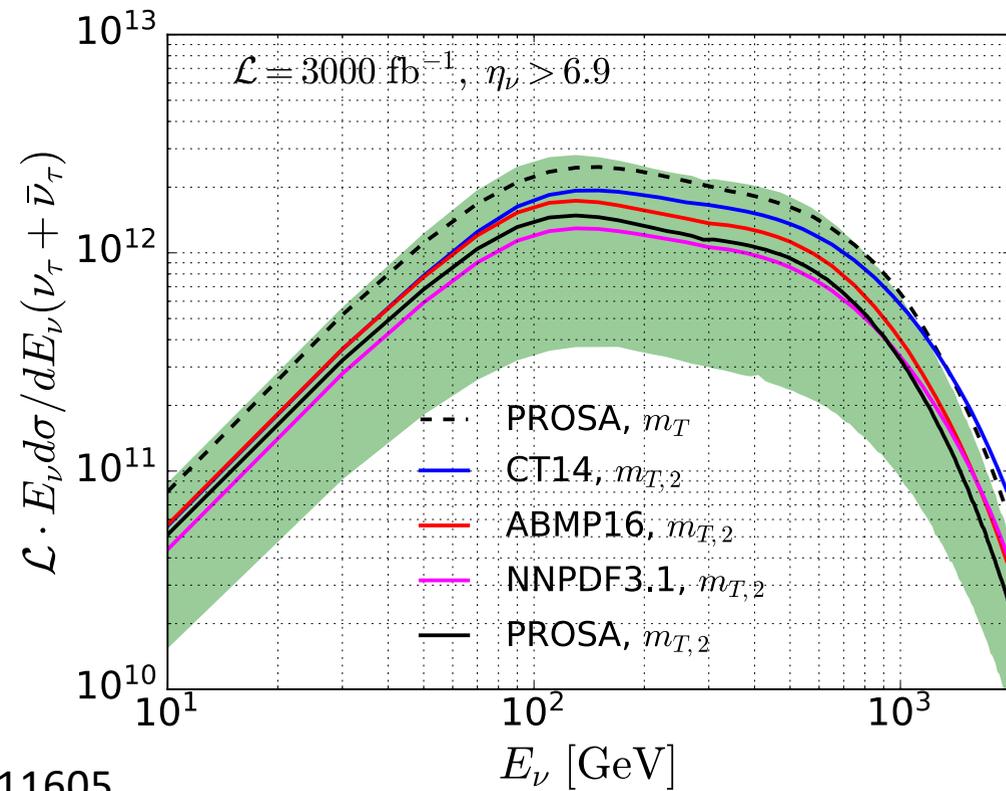
FPF $\eta > 6.9$

Events per GeV per ton

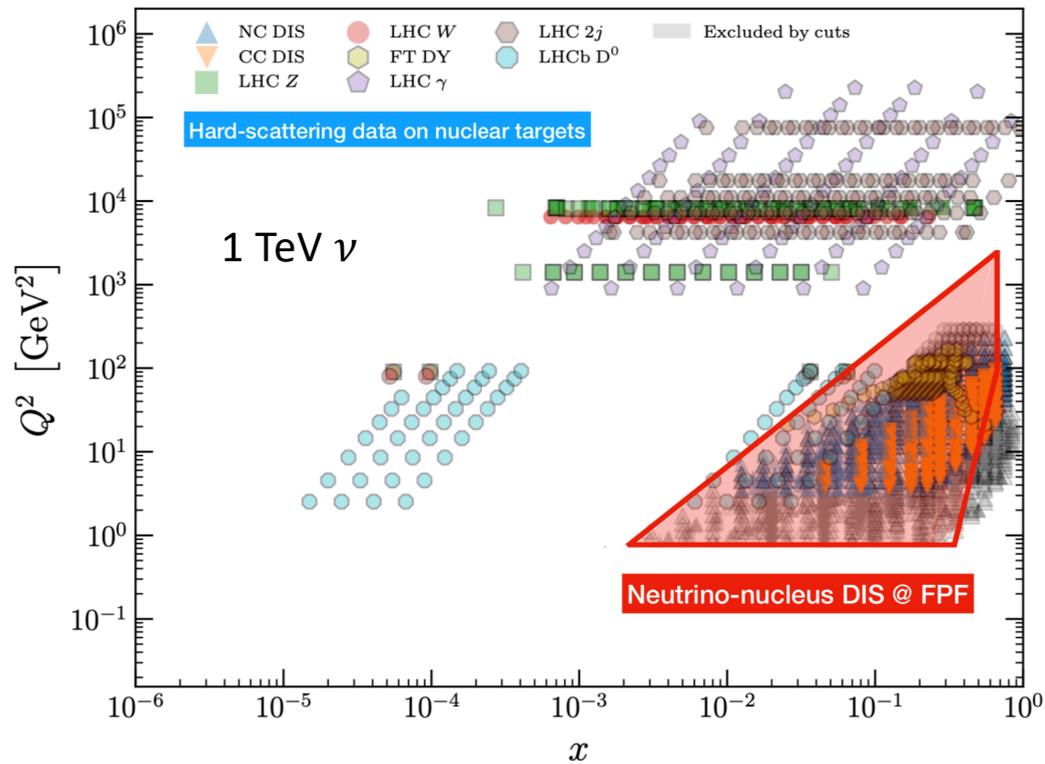
$$\sigma_\nu \sim E_\nu$$



arXiv:2112.11605



QCD in νA collisions



- 10^3 CCQE events in 10-tonne detector.
- Hadronization and final state interactions in DIS.
- Monte Carlo modeling of neutrino interactions.

arXiv:2203.05090

- Extends (x, Q) coverage for nuclear targets.
- Nuclear correction factors for ℓA versus νA , complementary to EIC charged lepton.
- Strange PDF with inclusive DIS and dimuon production, tied to weak boson mass measurements.
- In addition to CC scattering, also NC scattering.
- Low Q , low hadronic invariant mass W control

