CETUP* 2023

Neutrinos at a Forward Physics Facility: Production, Interactions and Astroparticle Physics Connections

Hallsie Reno

University of Iowa*

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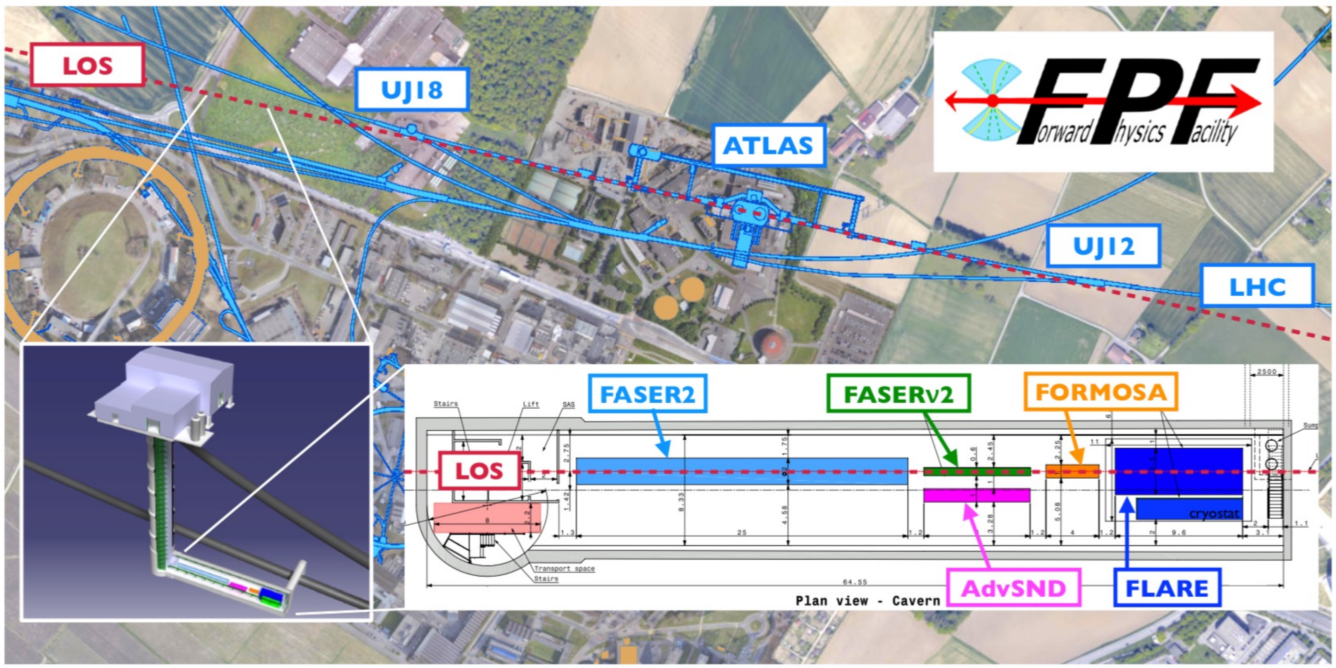
Purpose-built Forward Physics Facility

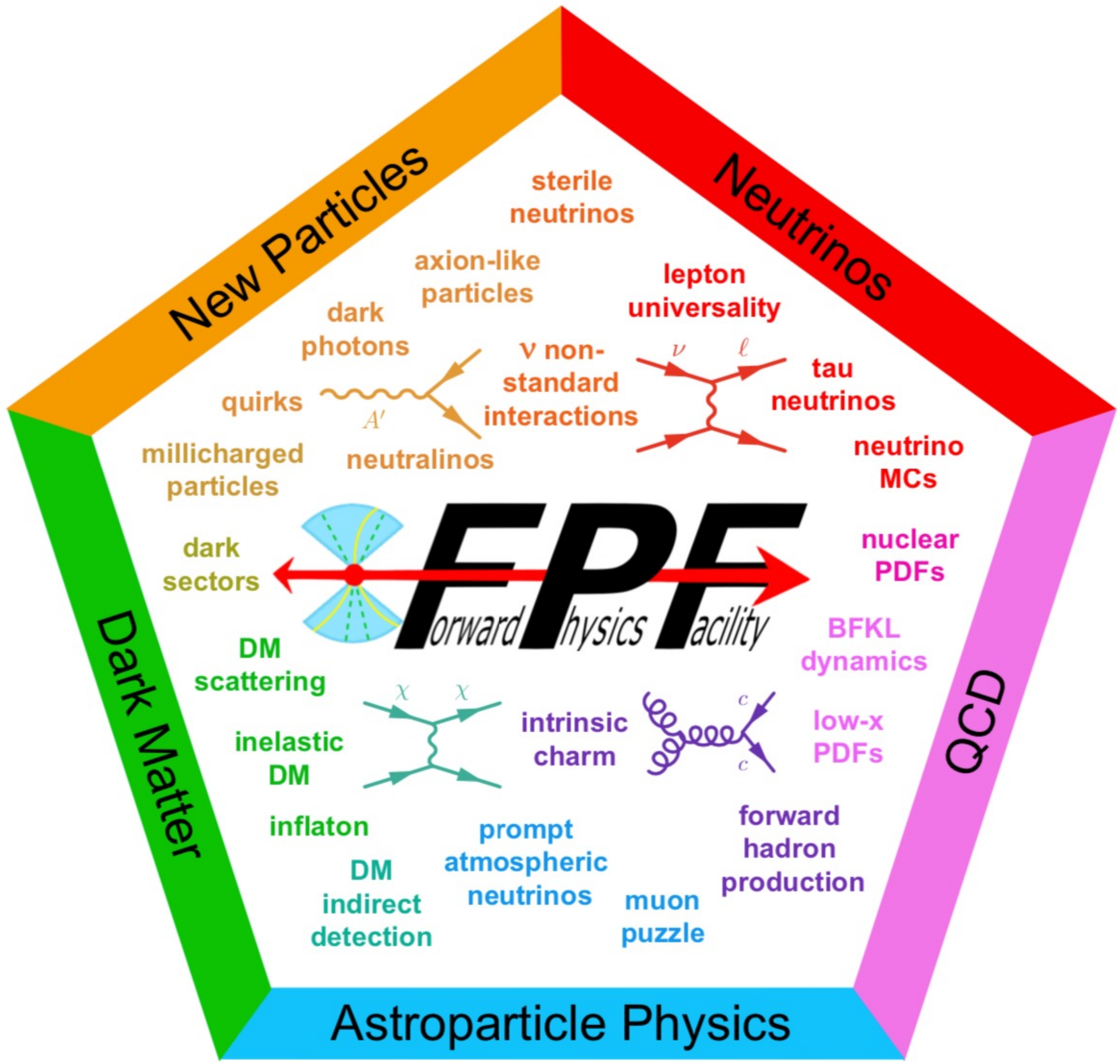
Underground facility ~620 m far forward from the ATLAS IP, shielded by concrete and rock. FPF experiments to detect $\sim 10^6$ neutrino interactions, energies up to a few TeV.



Detectors designed for Standard Model and BSM Physics.

Neutrino detection at FASERv2, AdvSND and FLArE.

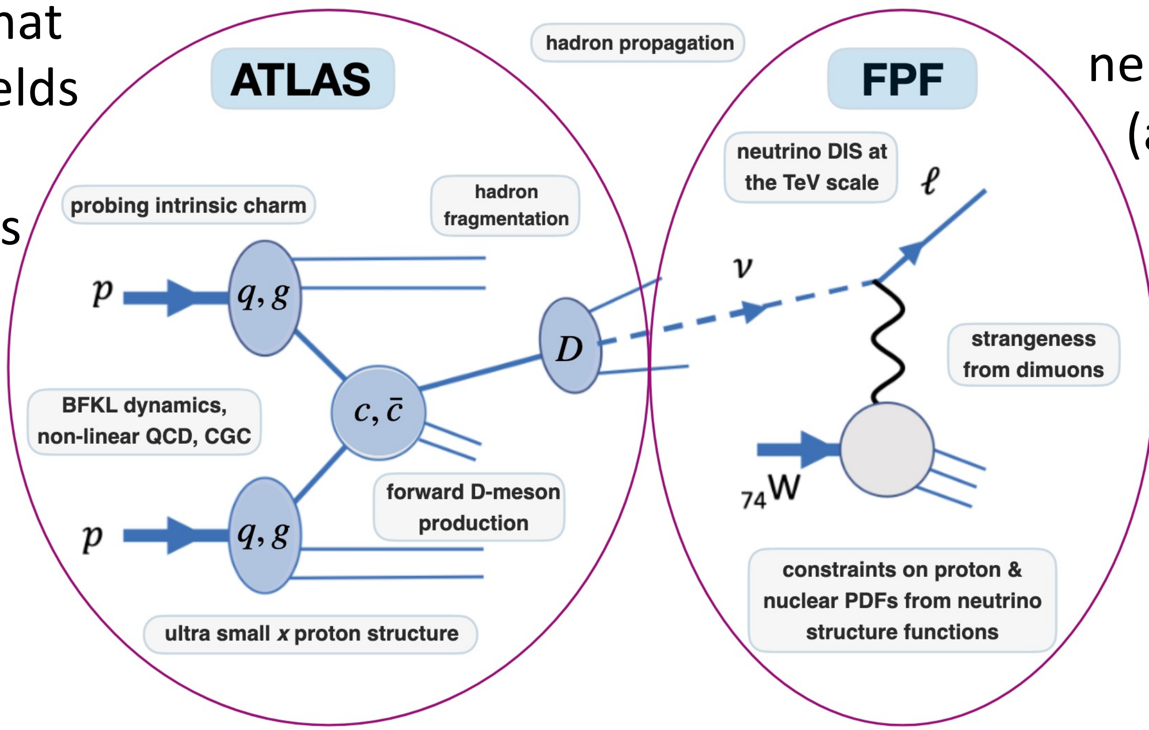
White paper: Feng et al. (Kelly, Pandey, Denton, Jana, Chauhan and others), *Phys.G* 50 (2023) 030501



https://indico.cern.ch/event/1296658/ Forward Physics Theory Workshop hybrid Sept 18-19 @ CERN. In person? Register by July 31.

Collider neutrinos: pp and νA collisions

hadron production that ultimately yields neutrinos of all 3 flavors



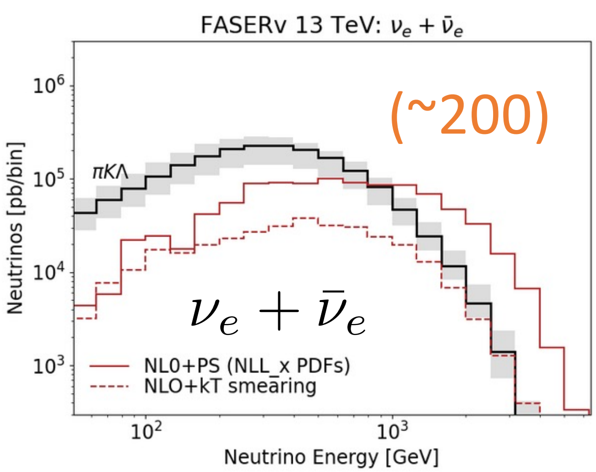
neutrino interactions (all 3 flavors, from different hadron sources) on nuclear targets

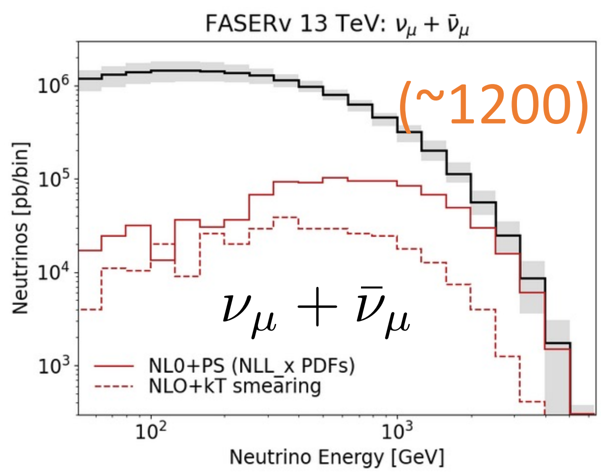
Neutrinos as proxies for hadron production at LHC

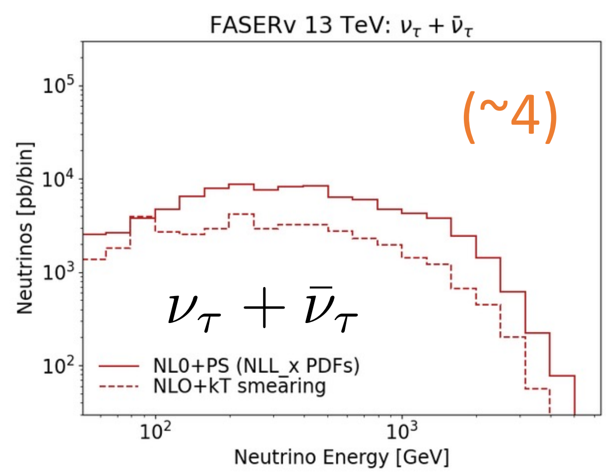
Interacting at FASERν (35 fb^{-1}) that will extend to 150 fb^{-1} in Run3

Interacting at 10-ton detector at FPF (3000 fb^{-1})

~10^5 ~10^6 ~10^3



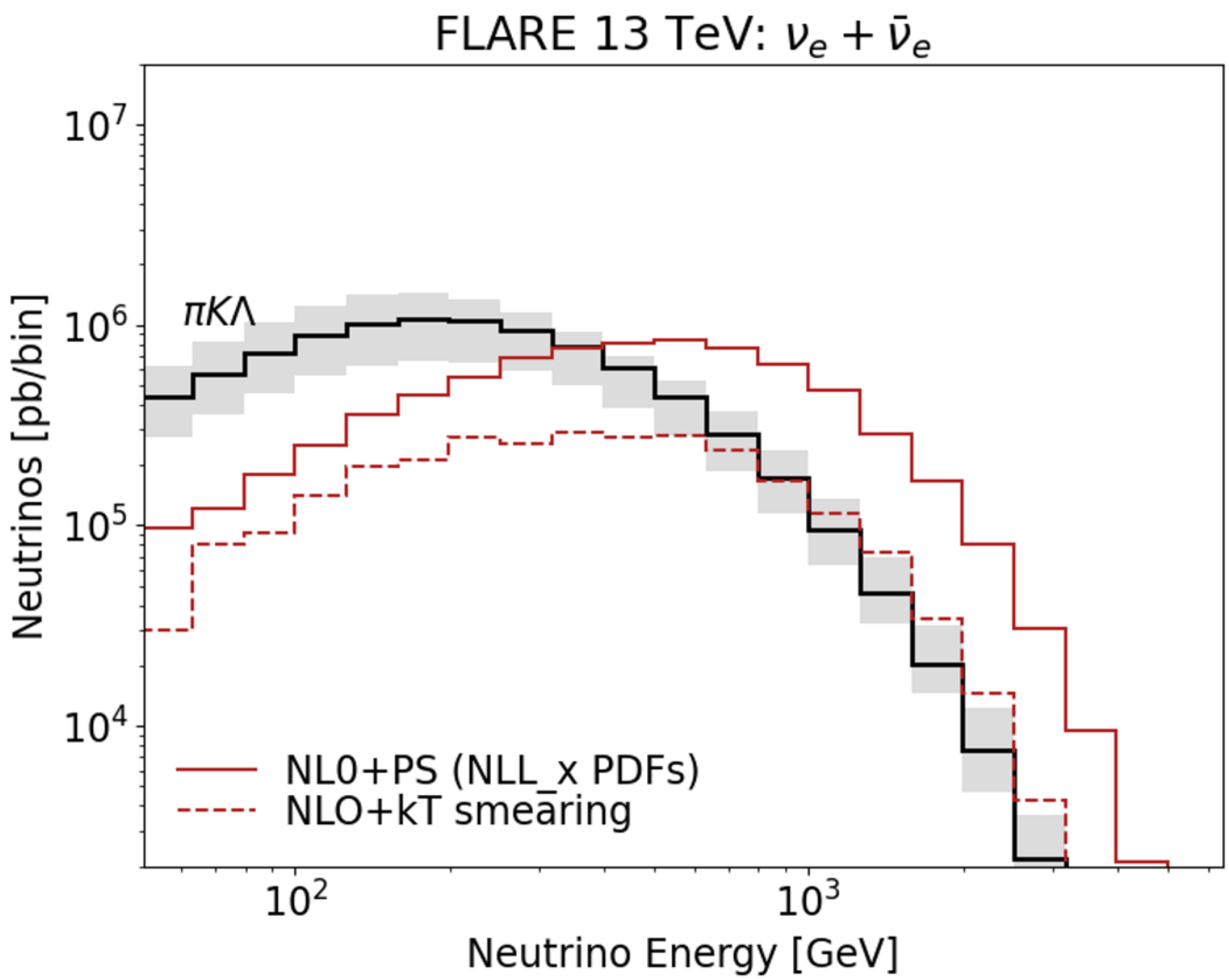




HE charm, plus kaons. HE charm, lots of pions. All from charm.

Charm contributions: Jeong, Bai, MHR (similar to Bai, Diwan, Garzelli et al, 2112.11605,2203.07212) NLO+kT smearing; L. Buonocore and L. Rottoli, in preparation (2023) NLO+PS (NLL_x PDFs);
Light meson contributions: see e.g., Kling & Nevay, Phys.Rev.D 104 (2021) 113008

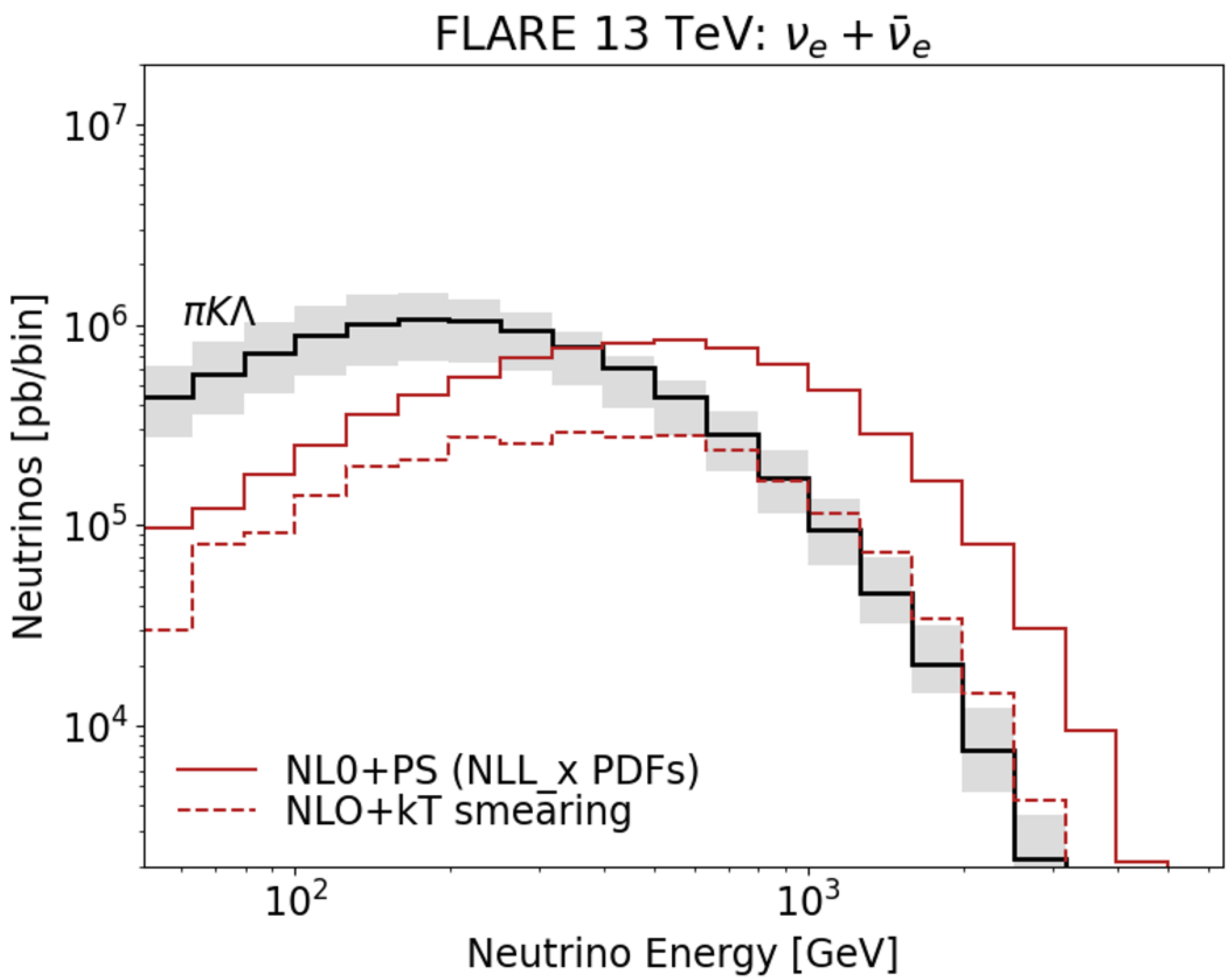
Neutrino flux example



light mesons and baryons

charm contributions (2 calculations)

Neutrino flux example



Uncertainties from:

- small-x
- m_c close to 1 GeV (QCD)
- non-perturbative effects
- new kinematic region
- very forward – factorization & fragmentation

New kinematic range

Run 3: 150 fb^{-1} at 480 m from ATLAS IP
Faserν with front surface 25cm x 25cm, $\eta > 8.5$
SND@LHC off axis, front surface 39cm x 39cm, $8.5 > \eta > 7$

High Luminosity: 3000 fb^{-1} with FPF at 620 m from ATLAS IP
FASERν2, $\eta > 8.7$
AdvSND (in FPF), $8.4 > \eta > 7.2$
FLArE, $\eta > 7.8$

FPF

AdvSND (“near”) in range $4 < \eta < 5$

pseudorapidity

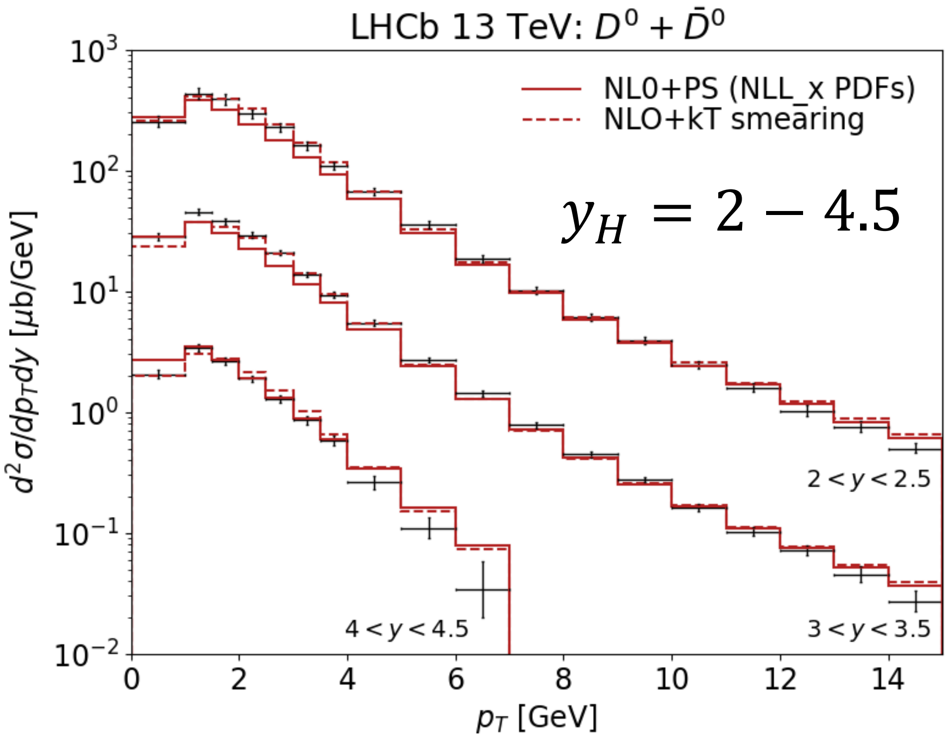
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

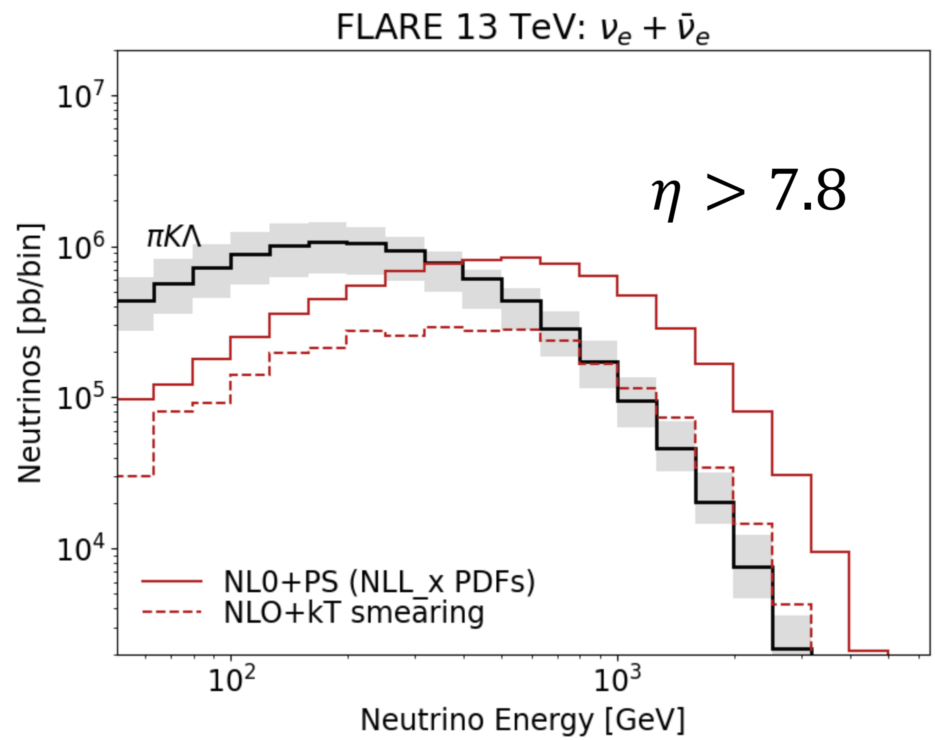
θ	η
0°	∞
0.1°	7.04
0.5°	5.43
1°	4.74

rapidity $y \simeq \eta$ for small masses

Strategy: LHCb extrapolated to FPF

<u>Differences</u>: primarily in PDFs, one has NLL_x PDFs sum $\ln(1/x_2)$.

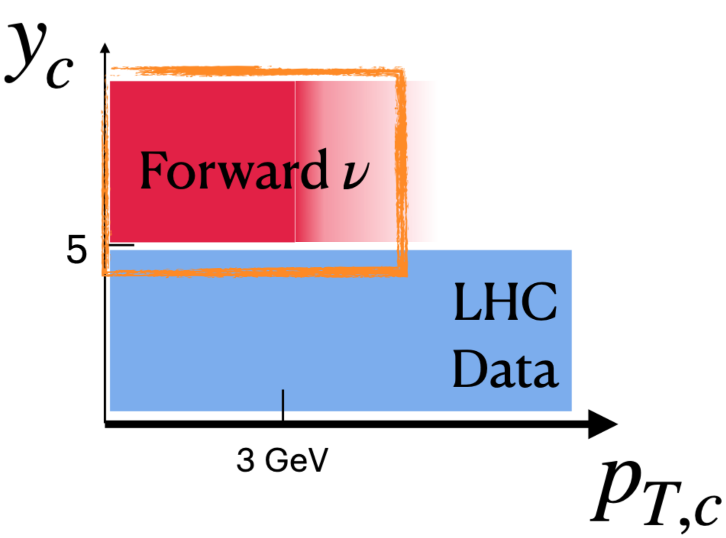




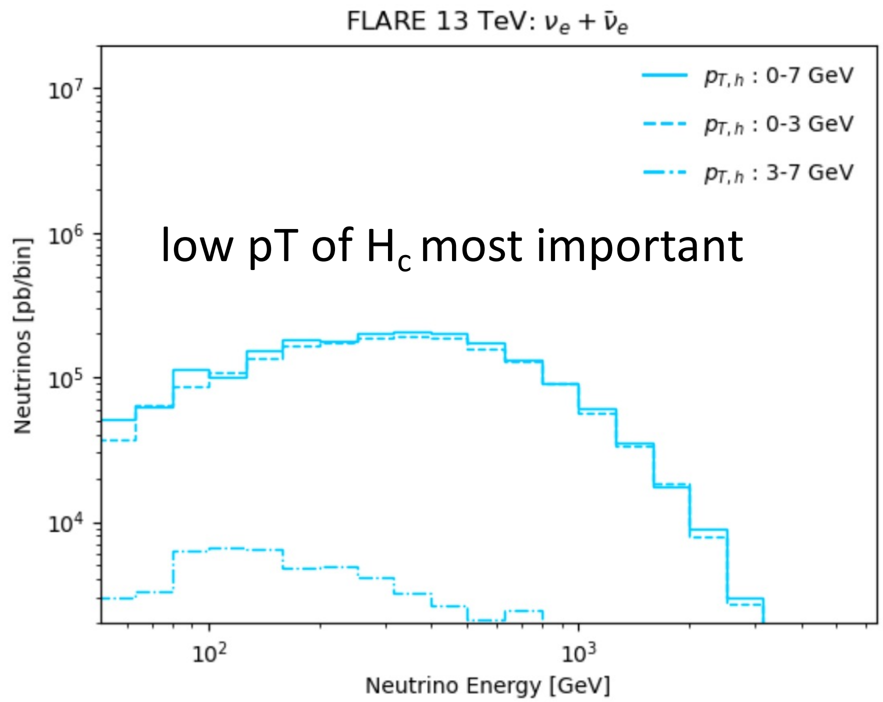
Histograms almost the same for most of LHCb range, much different at FLArE.

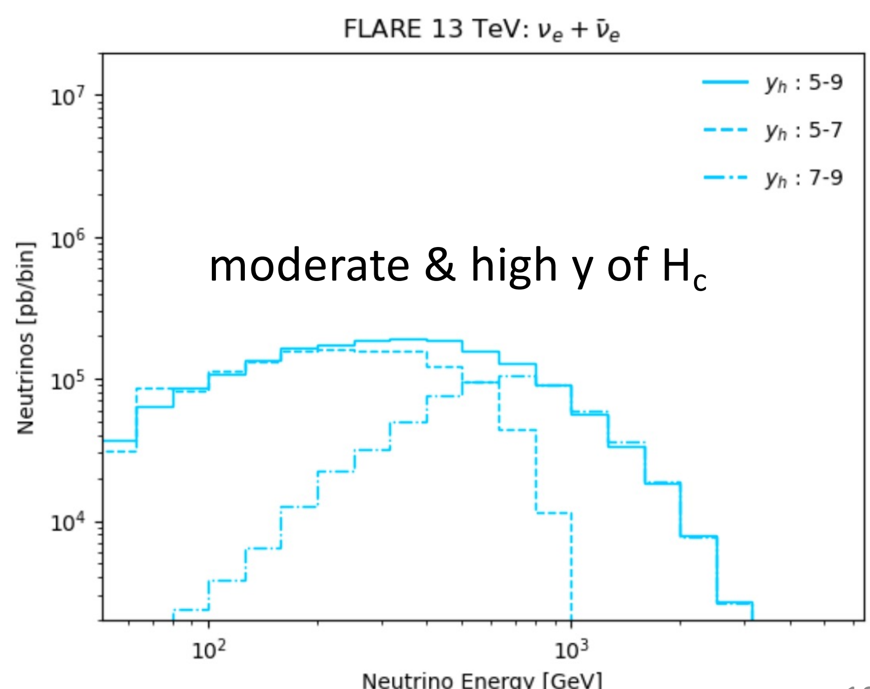
Jeong, Bai, Reno (similar to Bai, Diwan, Garzelli et al, JHEP 06 (2022) 148, JHEAp 34 (2022) 212) NLO+kT smearing; L. Buonocore and L. Rottoli, in preparation (2023) NLO+PS (NLL_x PDFs)

What kinematic region?



B. Chauhan presentation (2023)

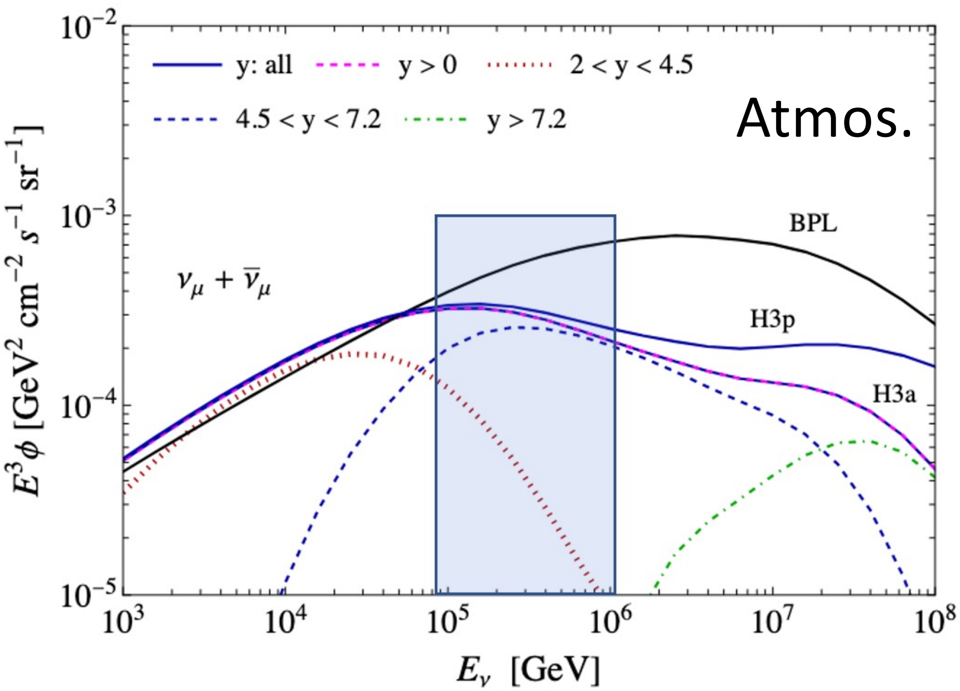


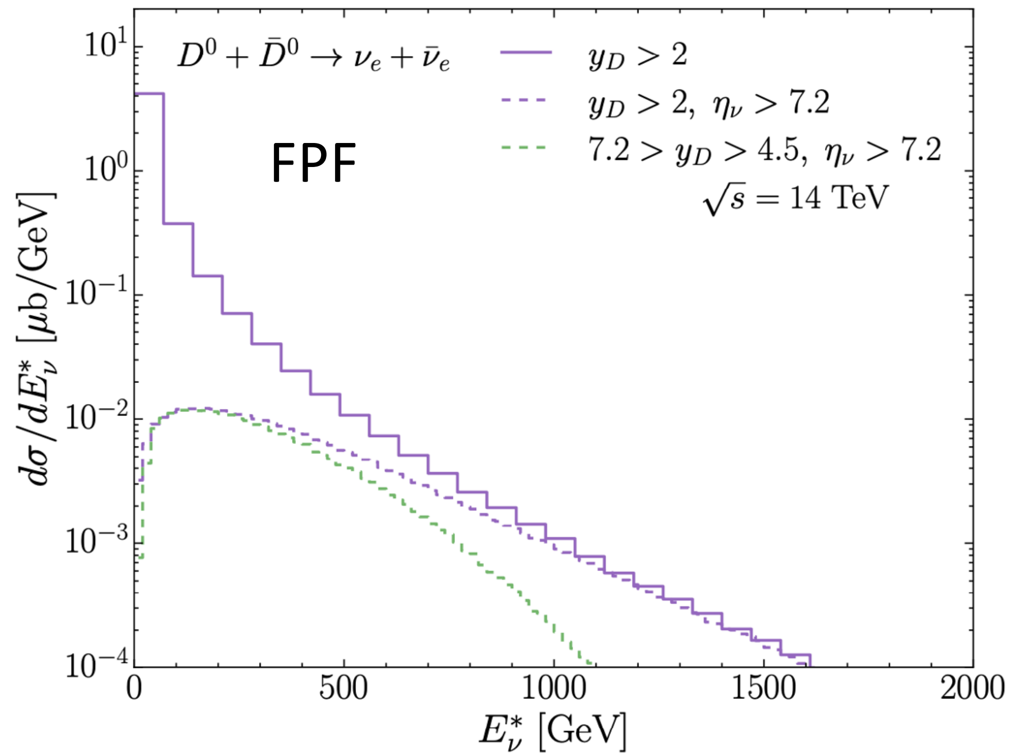


Astroparticle connection: prompt atmospheric neutrinos

From charm hadrons with 4.5<y_C<7.2 in the equivalent collider frame.

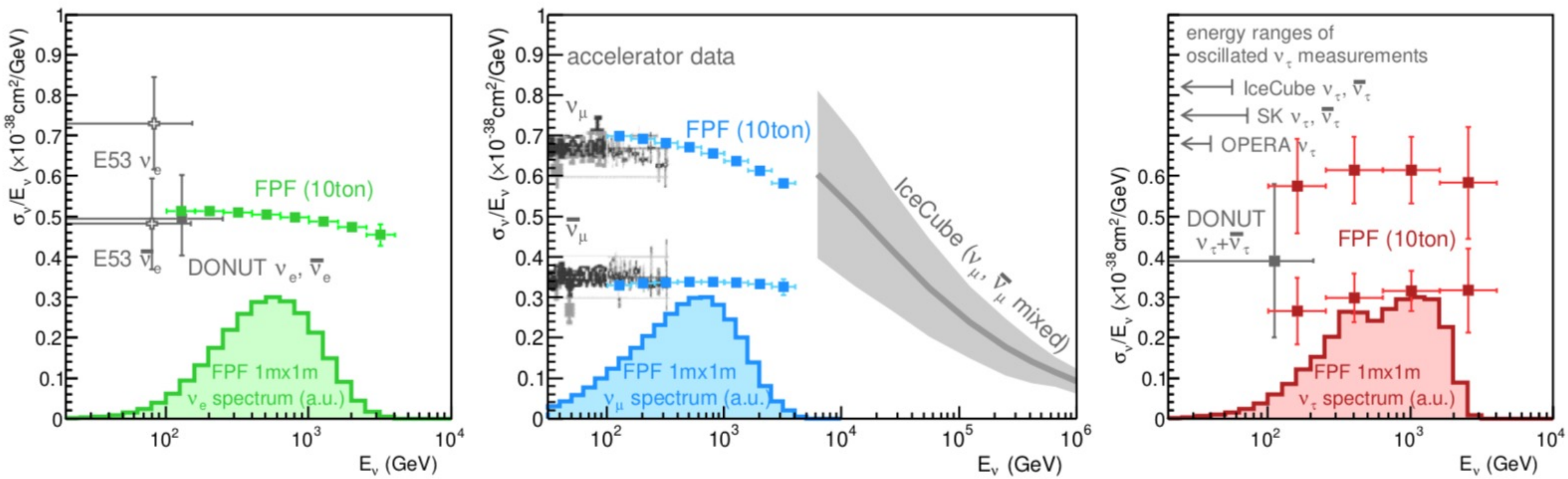
Bai, Diwan, Garzelli, MHR et al, 2112.11605





At FPF: Most $\nu_e + \bar{\nu}_e$ with $E_\nu < 700$ GeV and η_ν>7.2 come from charm mesons with 4.5<*y*<7.2. Direct connection to the prompt atmospheric neutrino flux (from charm).

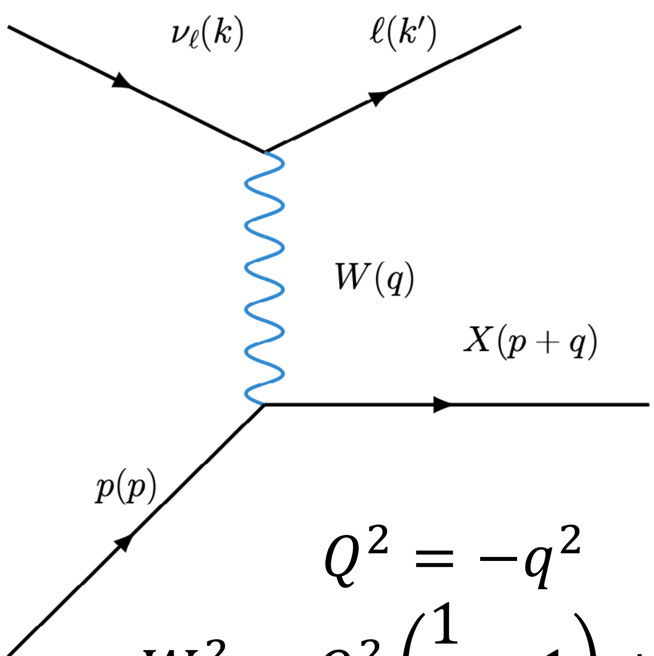
Neutrino CC DIS cross sections



Statistical uncertainty only in figures (from 2203.05090 Feng et al.).

Next: how important is low *Q*, low *W* in the inelastic CC cross section?

Inelastic cross sections: low Q, low W at FPF



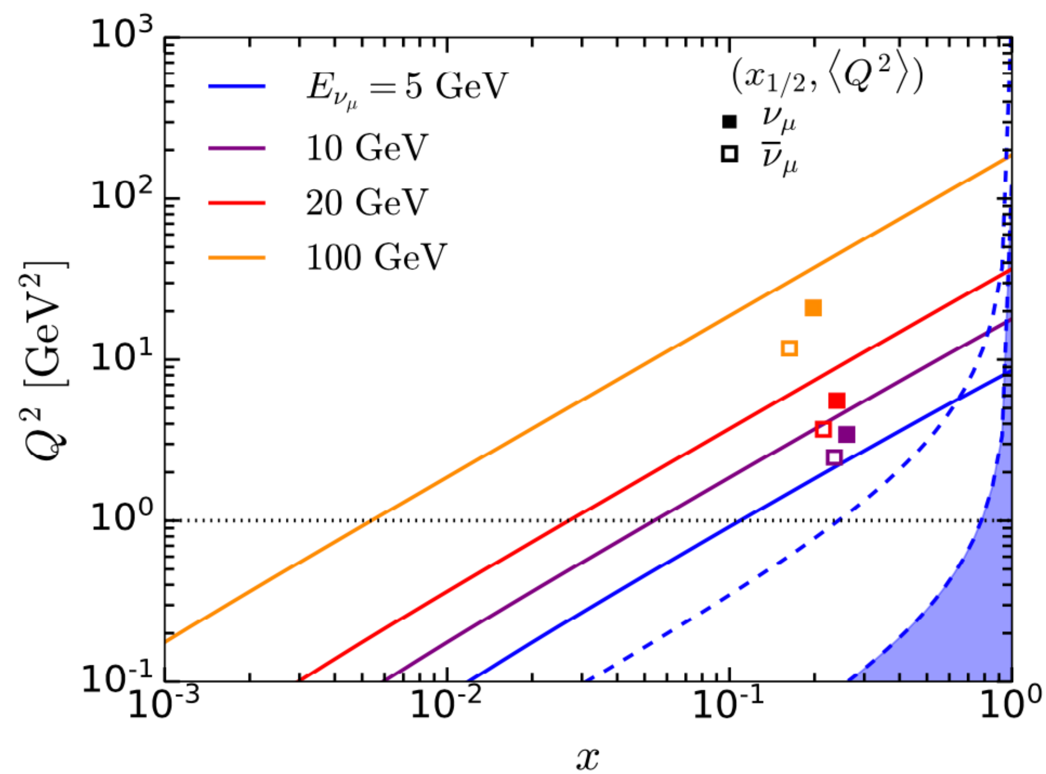
$$Q^2 = -q^2$$

$$W^2 = Q^2\left(\frac{1}{x} - 1\right) + m_N^2$$

$$x = \frac{Q^2}{2p\cdot q}$$

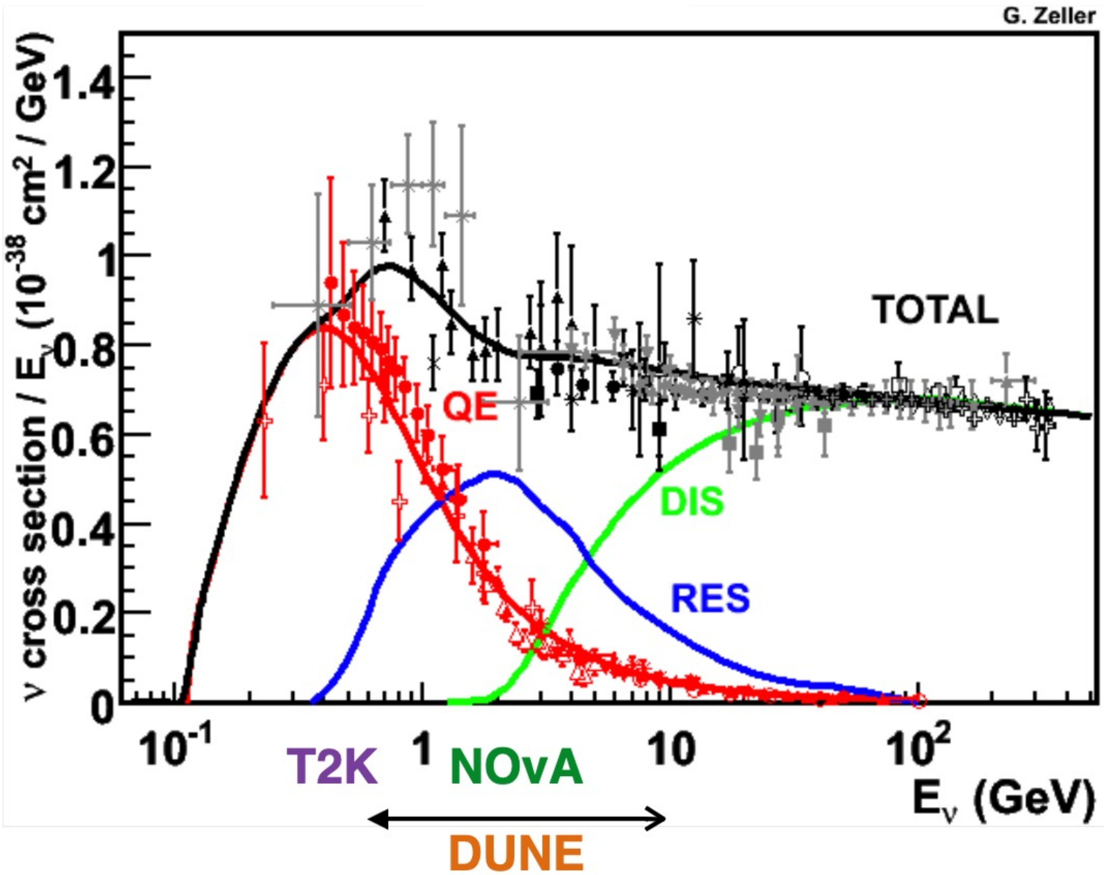
See V. Pandey's talk this week

MHR, *Eur.Phys.J.ST* 230 (2021) 24, 4419-4431



shaded: not inelastic
dashed: W= 2 GeV
solid: limit for (x, Q^2)

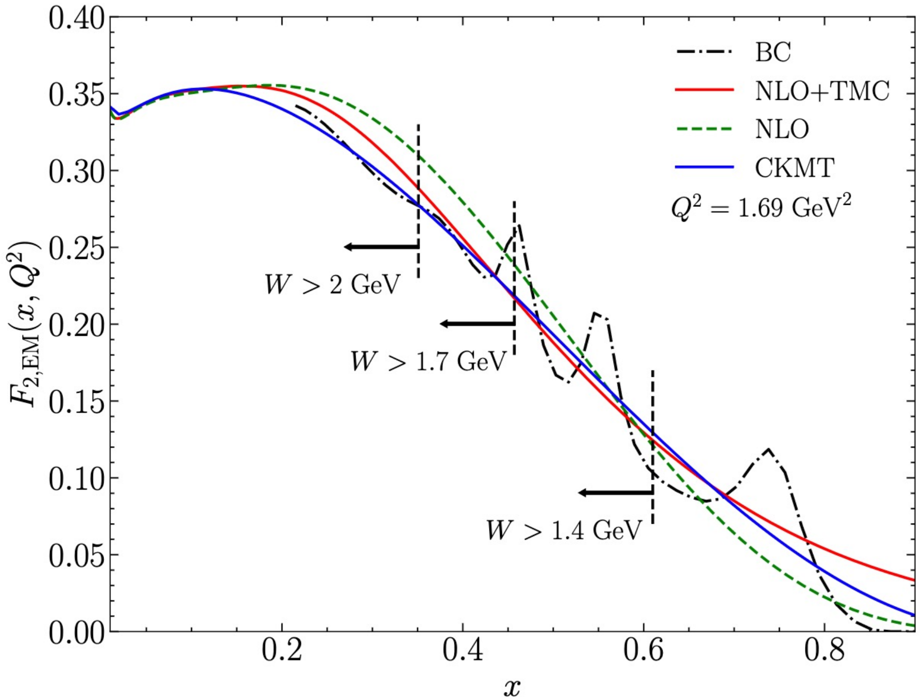
QE, RES, DIS

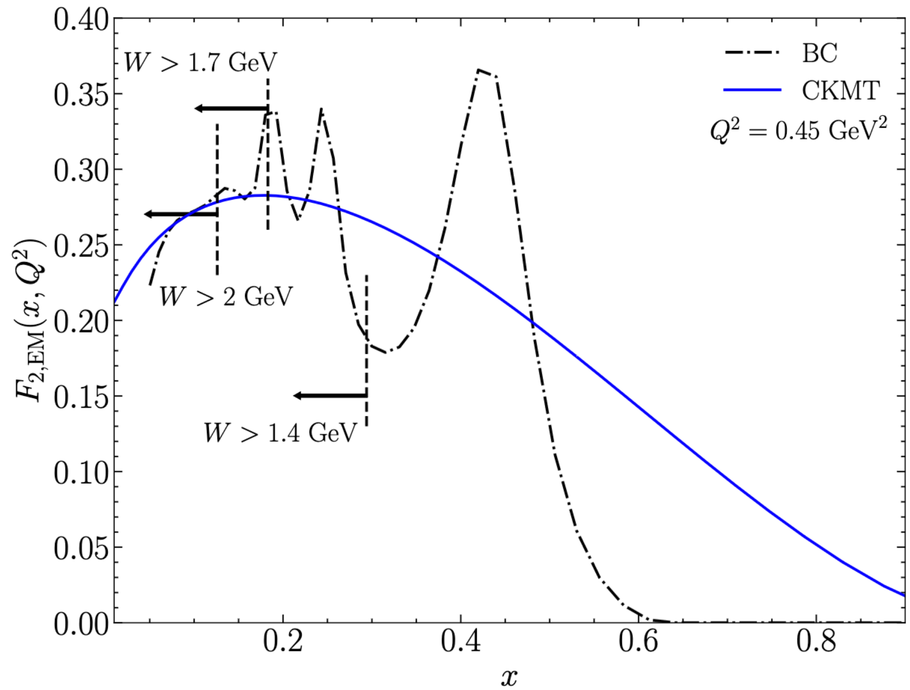


J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

How many resonances in RES? Depends on W_{min}

Structure functions - EM





BC=Bosted, Christy, Phys. Rev. C 81, 055213 (2010) param. of EM data
TMC includes target mass corrections
CKMT= Capella et al. Phys. Lett. B 337, 358 (1994)

CKMT

We use functional form of CKMT adapted to weak structure functions.

$$\sigma_{\gamma p}^{\rm tot}(W^2) = \frac{4\pi^2\alpha_{\rm EM}}{Q^2} F_{2,\rm EM}^{\rm CKMT}(x,Q^2)|_{Q^2\to 0}$$
$$\simeq 4\pi^2\alpha_{\rm EM}\left[\frac{A}{a}\left(\frac{W^2}{a}\right)^{\Delta_0} + \frac{B(1+f)}{b}\left(\frac{W^2}{b}\right)^{\alpha_R-1}\right],$$

Conserved vector current dictates the low Q behavior of structure function for EM.

With Y. S. Jeong, in preparation.

Structure functions – weak

Patch and match at $Q_0^2 = 4\ GeV^2$:

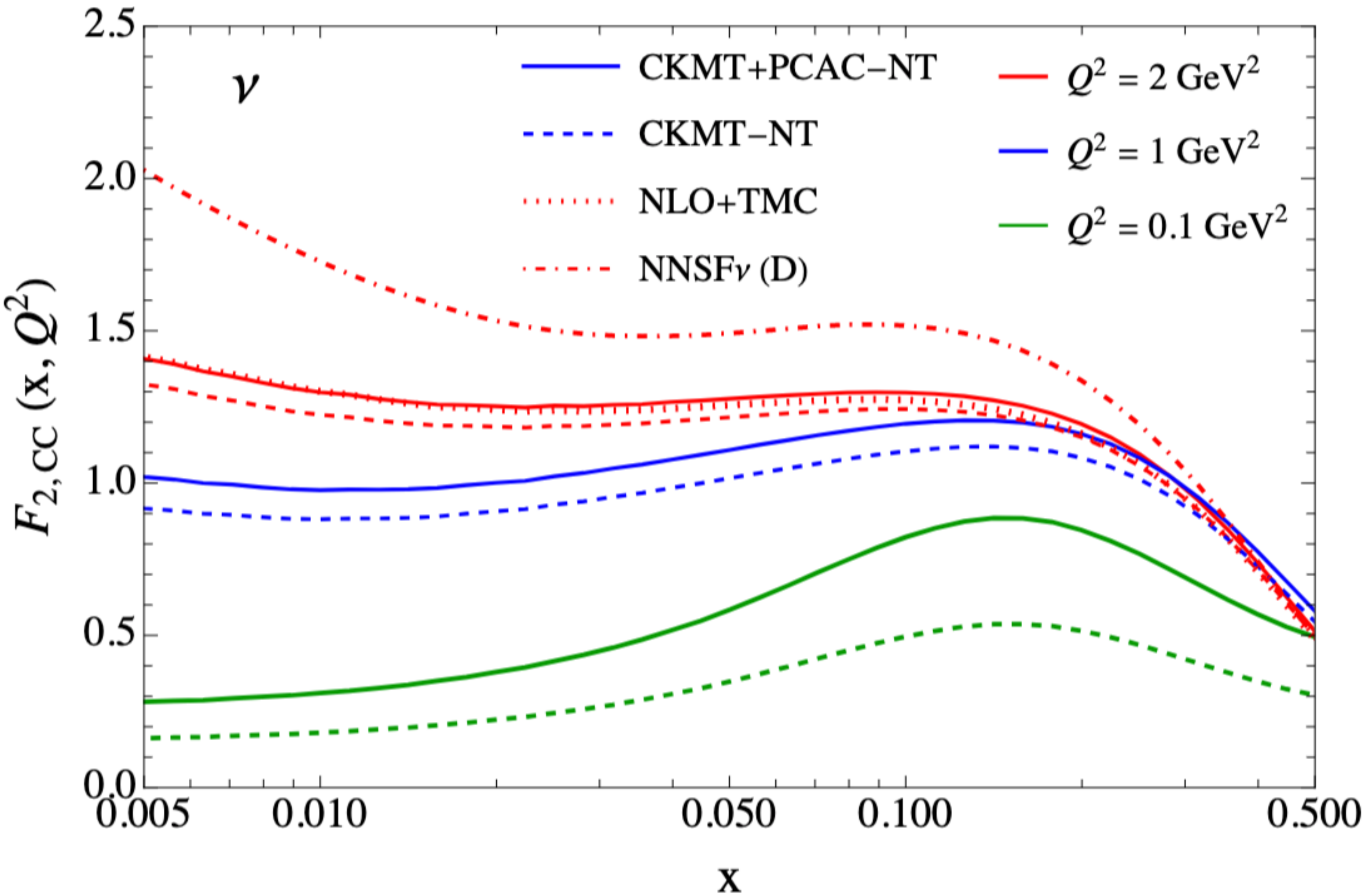
- We use functional form of CKMT adapted to weak structure functions, "valence" and "sea" terms, but same basic structure, matched to NLO+TMC at higher Q^2.
- Add in a PCAC correction, as a first start, matching form of CKMT.
  See Kulagin & Petti, Phys. Rev. D 76, 094023 (2007).
- Compare with Bodek-Yang and NNSFnu structure function inputs.
  See Candido et al., arXiv:2302.08527.
- (We have started with isoscalar nucleons.)

$$F_L^{\rm PCAC} = \frac{f_\pi^2 \sigma_\pi(W^2)}{\pi} f_{\rm PCAC}(Q^2)$$

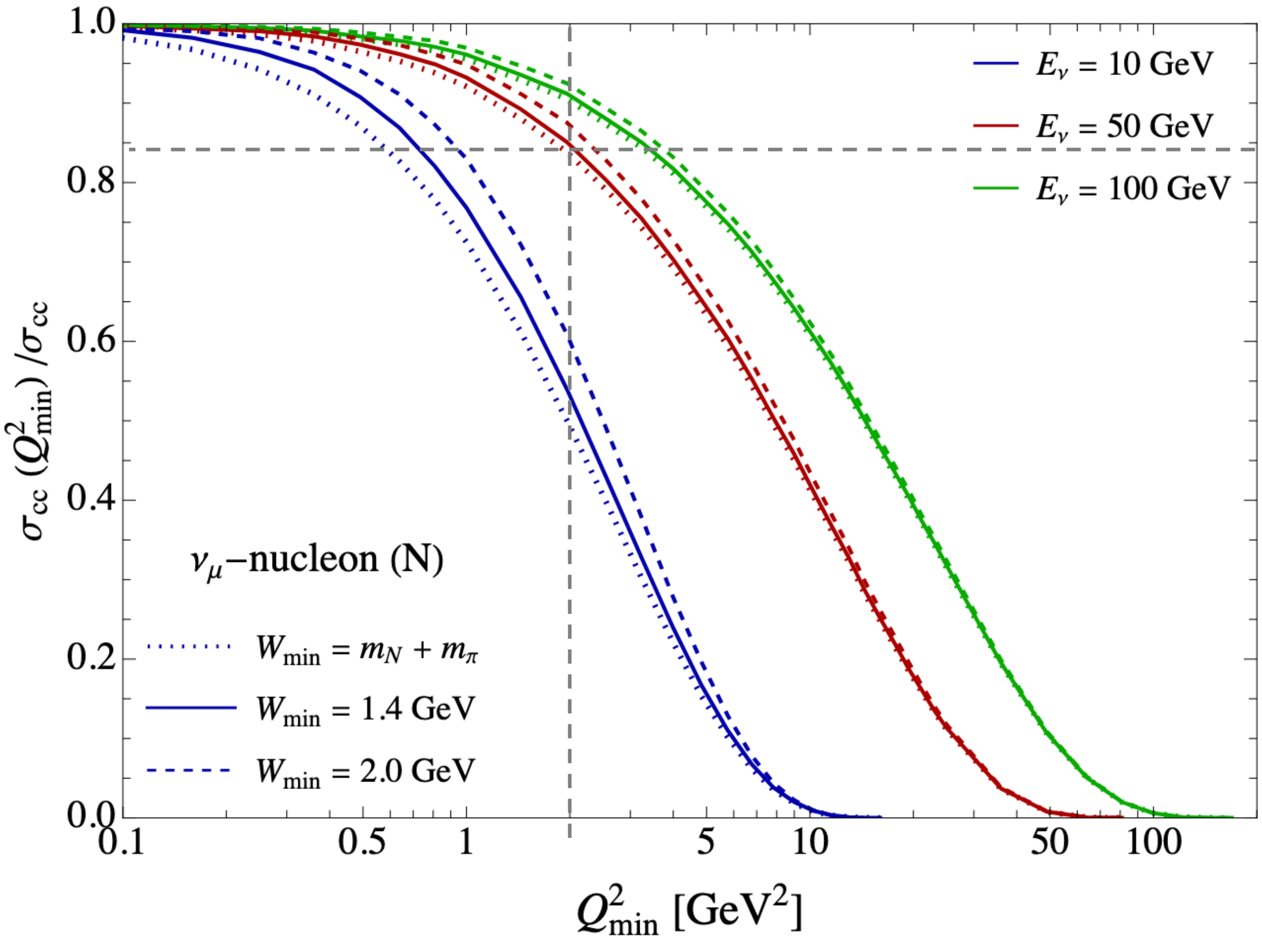
$$f_{\rm PCAC}(Q^2) = \left(1 + \frac{Q^2}{M_{\rm PCAC}^2}\right)^{-2}$$

$$\sigma_\pi \simeq X(W^2)^\epsilon + Y(W^2)^{-\eta_1}$$

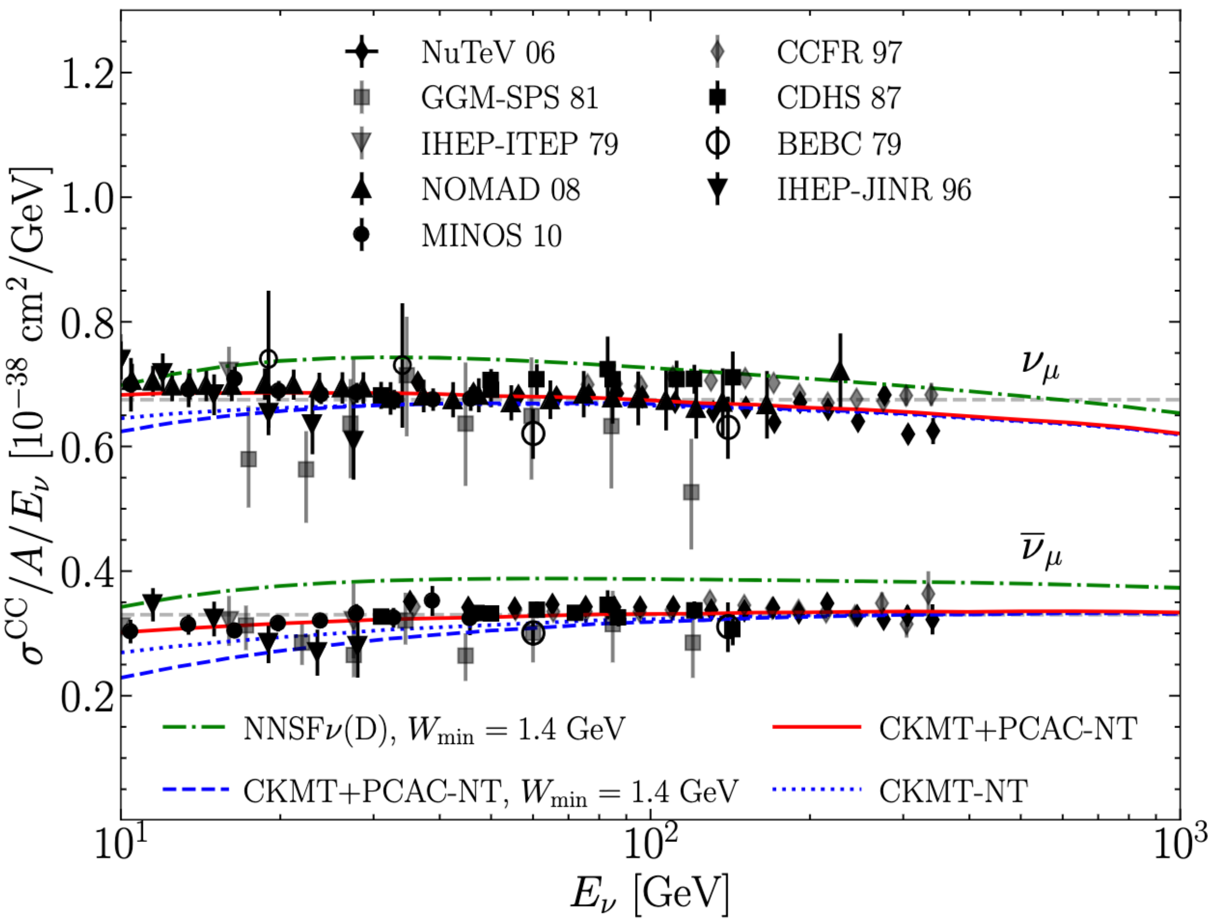
Structure functions – weak



Q^2 dependence of CC cross section



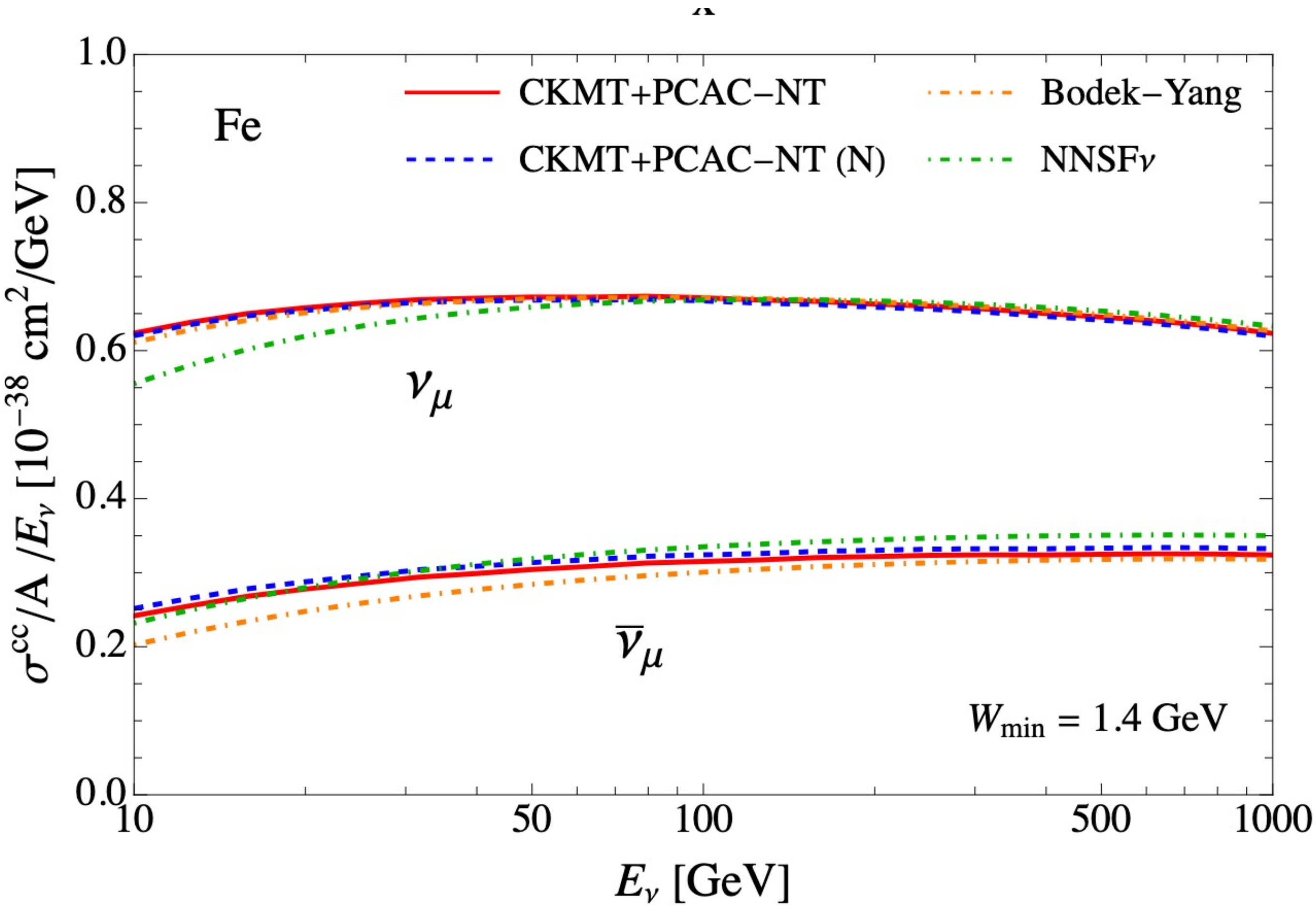
CC cross sections



NNSFnu(D) doesn't have expected low Q behavior, overshoots data.

But, what about nuclear effects?

CC cross section (Fe)



Remarks

- Based on our CKMT+PCAC (patched and matched) extrapolation, the fraction contribution of low *Q*, *W*< 2 GeV for *E*>100 GeV in CC cross section is small (most of the FPF events).
- Even above *W*=2 GeV, modeling low Q structure functions for *E*<100 GeV is useful for FPF experiments (and for DUNE too). There will be 10's of thousands of $\nu_\mu + \bar{\nu}_\mu$ CC events at FPF in the energy range of 50-100 GeV. Thousands in the RES region.
- The NNSFnu structure functions for deuterium don't agree with our inputs. Extrapolation from heavier targets to isoscalar nucleons the problem?
- CKMT+PCAC as implemented can be improved.