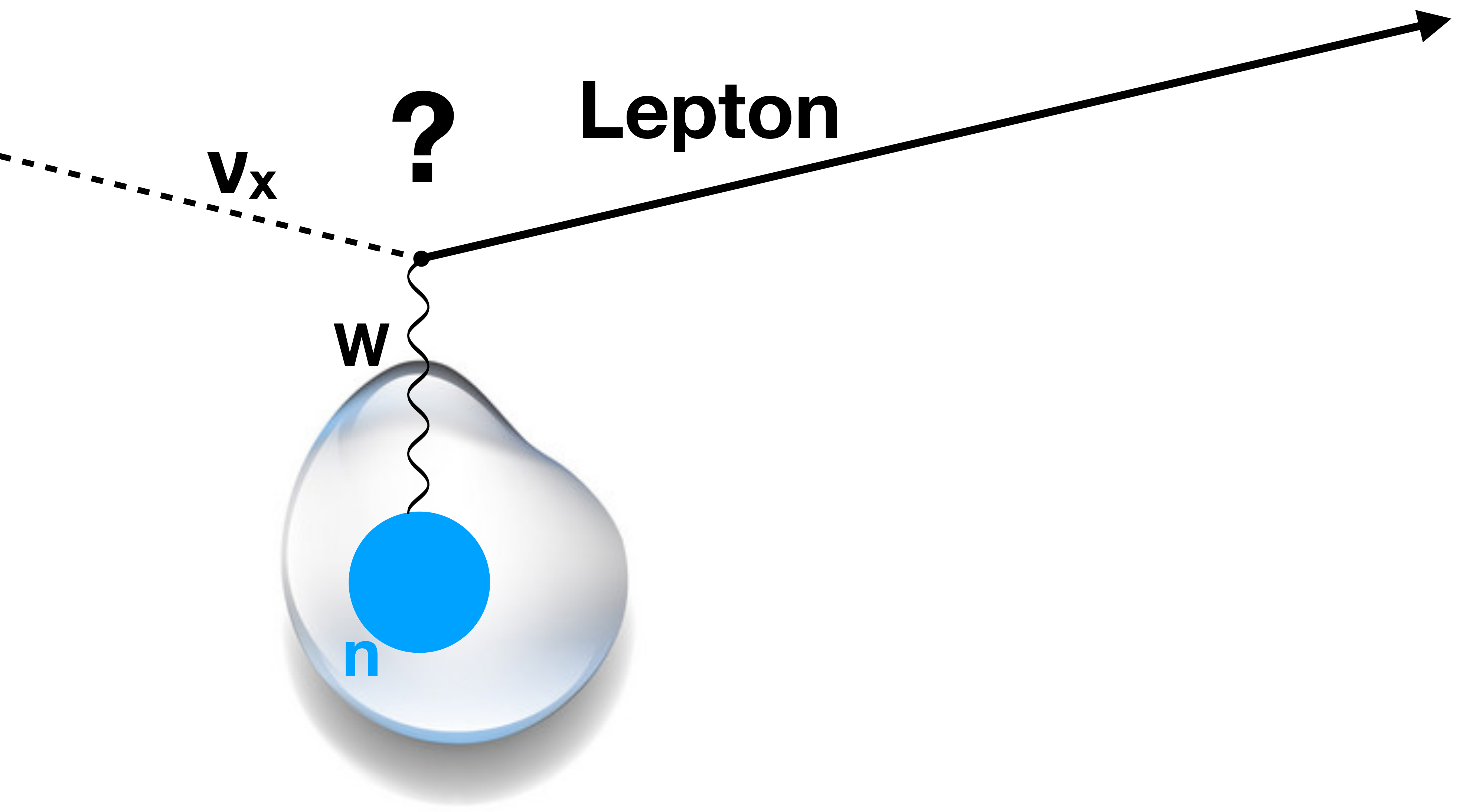
Forward Physics Facility Workshop

Neutrino Interaction Tools for the FPF

Alfonso Garcia

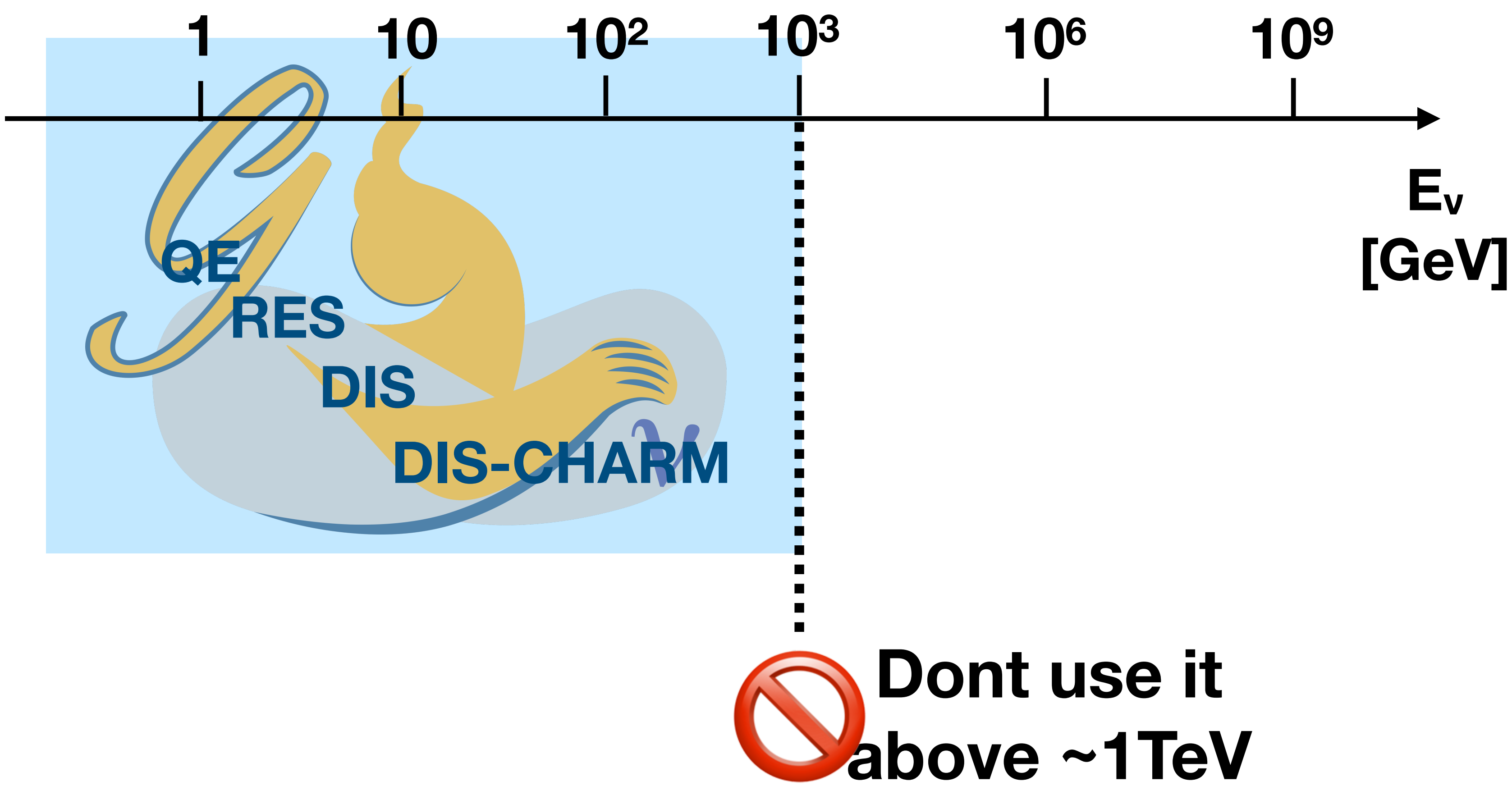
alfonsogarciasoto@fas.harvard.edu

Lepton level



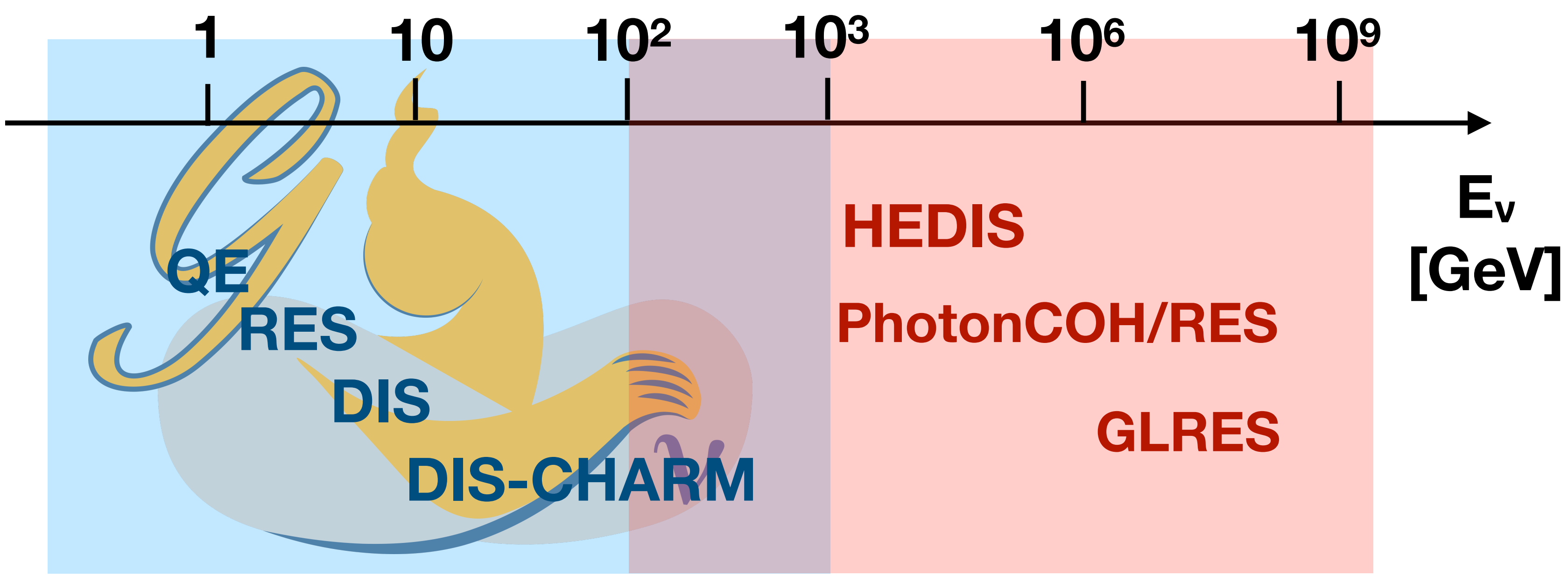
GENIE

- Current status of GENIE in the high energy regime:
  - DIS based on Bodek-Yang model -> optimised for low Q^2.
  - Structure Function = C_{ij} LO⊗PDF LO (GRV98 $Q^2[0.8, 2\cdot10^6]$).
  - Contributions from heavy quarks are not included.



GENIE

- Current status of GENIE in the high energy regime:
  - DIS based on Bodek-Yang model -> optimised for low Q^2.
  - Structure Function = C_{ij} LO⊗PDF LO (GRV98 $Q^2[0.8, 2\cdot10^6]$).
  - Contributions from heavy quarks are not included.



- New extension allows UHE interaction -> HEDIS
  - Newer PDFs with broader Q^2 phase space.
  - Structure Functions = C_{ij} NLO⊗PDF NLO.
  - Account for the heavy quark contributions.

HEDIS

$$F_i\left(x,Q^2\right)=\sum_j^{\text{qrks,gl}}\int_x^1\frac{\mathrm{d}z}{z}f_j\left(z,Q^2\right)C_{i,j}\left(\frac{x}{z},Q^2\right)$$

Parton Density Functions

- Calculated from fit to hadron data.
- Available sets depend on fitted data and formalism.
- Lookup tables (x,Q2) -> LHAPDF

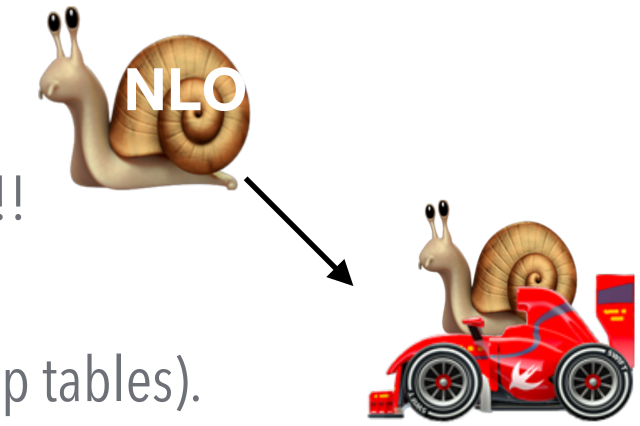
Coefficient functions

- Calculated from Feynman diagrams.
- Depend on order in pQCD.
- Implementation: APFEL.

- Low energy DIS module (Bodek-Yang) use LO Coefficient Functions.
  - Most C_{ij} become zero or delta functions.
  - Structure functions can be computed on the fly -> fast.
- Moving to NLO requires a new approach to compute Structure Functions.

HEDIS

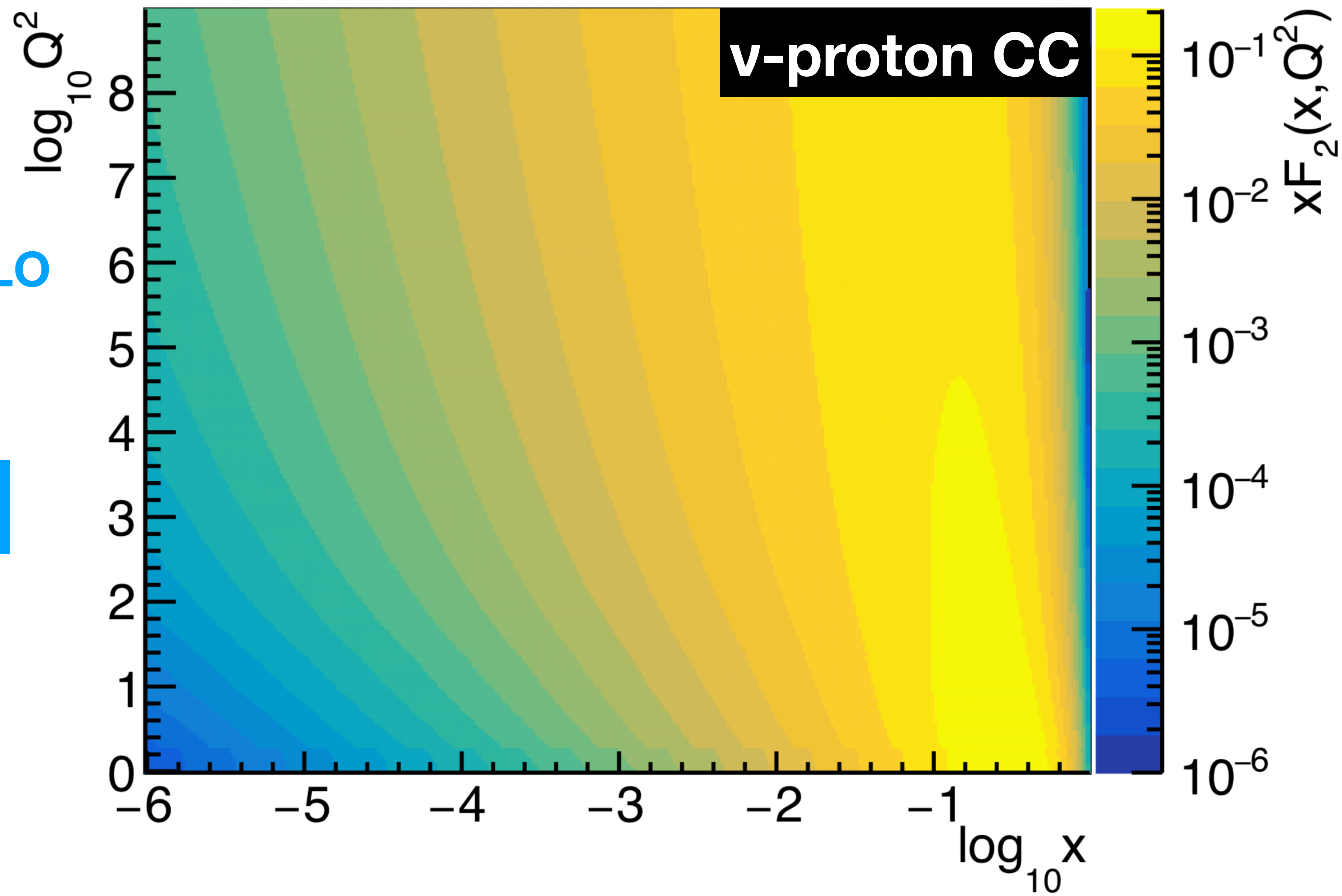
- The key feature:
  - Event generation using NLO Structure Functions!!!
- Solution:
  - Precomputation of the Structure Functions (lookup tables).



$F_i = C_{ij}[NLO] \otimes$ HERAPDF15NLO

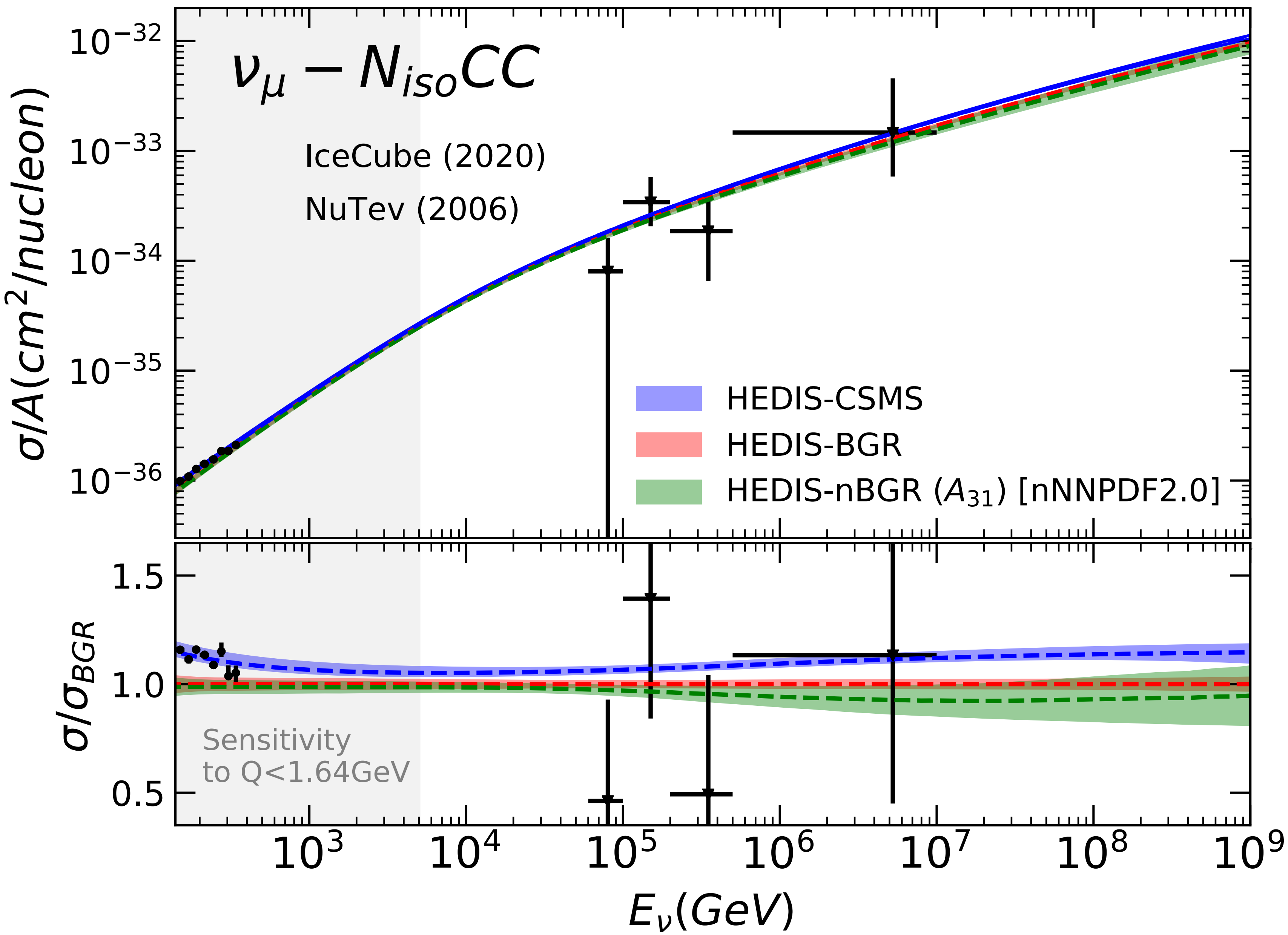
APFEL

LHAPDF6



HEDIS

- Theoreticians showed interested in this package.
- Several experiments will measure neutrino cross sections for E>1TeV in this decade.



DIS

- Generator develop for MINOS
  - Nuclear effects implemented at kinematical level.
  - Reweighting available for some parameters.

$$\xi_w = \frac{2x(Q^2 + {M_f}^2 + B)}{Q^2[1 + \sqrt{1 + (2Mx)^2/Q^2}] + 2Ax},$$

$$\begin{aligned} K_{sea}(Q^2) &= \frac{Q^2}{Q^2 + C_s} \\ K_{valence}(Q^2) &= [1 - G_D^2(Q^2)] \\ &\times \left(\frac{Q^2 + C_{v2}}{Q^2 + C_{v1}}\right) \end{aligned}$$

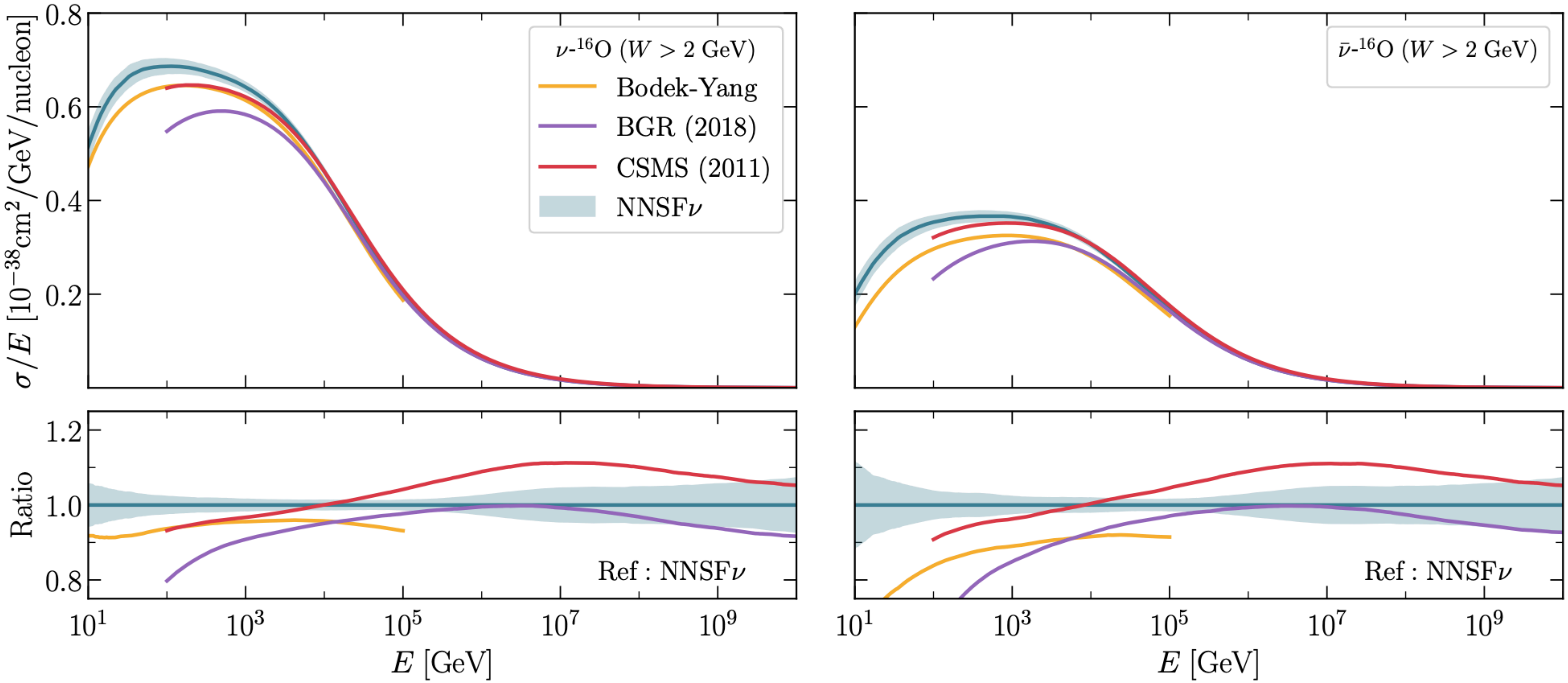
$$F_2(x, Q^2 < 0.8) = K(Q^2) \times F_2(\xi, Q^2 = 8)$$

A 0.538	B 0.305	C_{v2d} 0.255	C_{v2u} 0.189
C_{sea}^{down} 0.621	C_{sea}^{up} 0.363	C_{v1d} 0.202	C_{v1u} 0.291
$C_{sea}^{strange}$ 0.621		$\mathcal{F}_{valence}$ $[1 - G_D^2(Q^2)]$	N 1.015

$x_{A_{HT}^{BY}}$	A_{HT} higher-twist param in BY model scaling variable ξ_w	$\pm 25\%$
$x_{B_{HT}^{BY}}$	B_{HT} higher-twist param in BY model scaling variable ξ_w	$\pm 25\%$
$x_{C_{V1u}^{BY}}$	C_{V1u} u valence GRV98 PDF correction param in BY model	$\pm 30\%$
$x_{C_{V2u}^{BY}}$	C_{V2u} u valence GRV98 PDF correction param in BY model	$\pm 40\%$
x_{CCDIS}	Inclusive CC cross-section normalization factor	
$x_{CC\bar{\nu}/\nu}$	$\bar{\nu}/\nu$ CC ratio	
$x_{DIS-NuclMod}$	DIS nuclear modification (shadowing, anti-shadowing, EMC)	

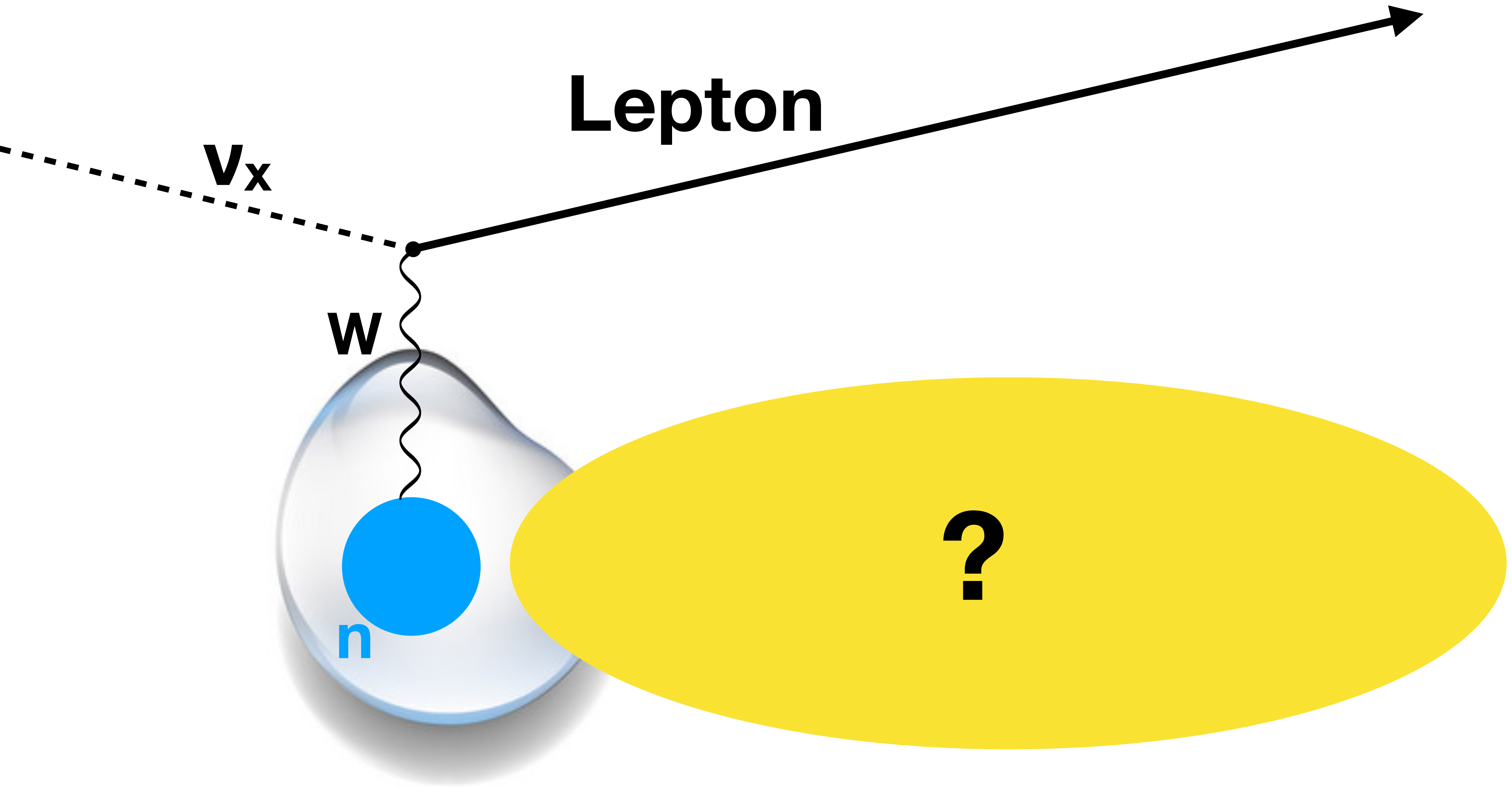
Comparison

- Main points:
  - CSMS overestimates at TeV-PeV (treatment of top quark production).
  - Nuclear effects are relatively small for Oxygen.



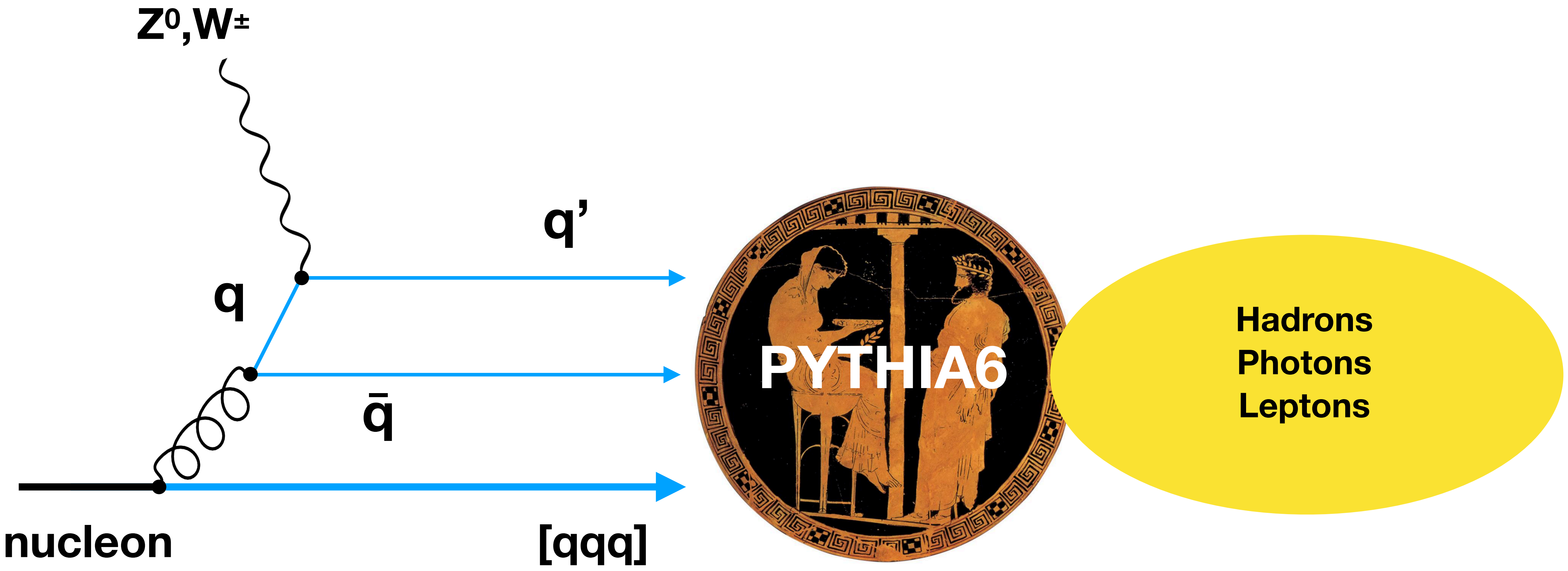
Hadron level

Hadron level



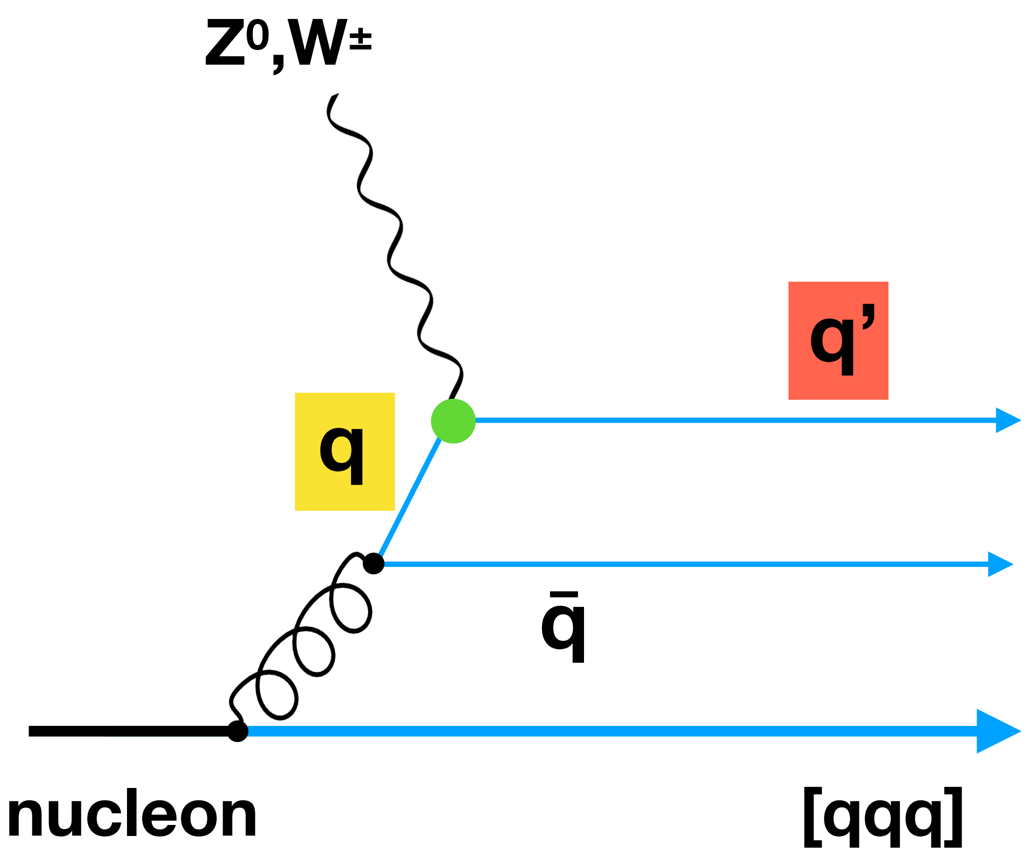
Hadronization-HEDIS

- Quark combination input to PYTHIA6.



Hadronization–HEDIS

- Quark combination input to PYTHIA6.
- Relative contribution from each quark using LO expression.
- Details of hadronic showers not relevant (yet) for neutrino telescopes.

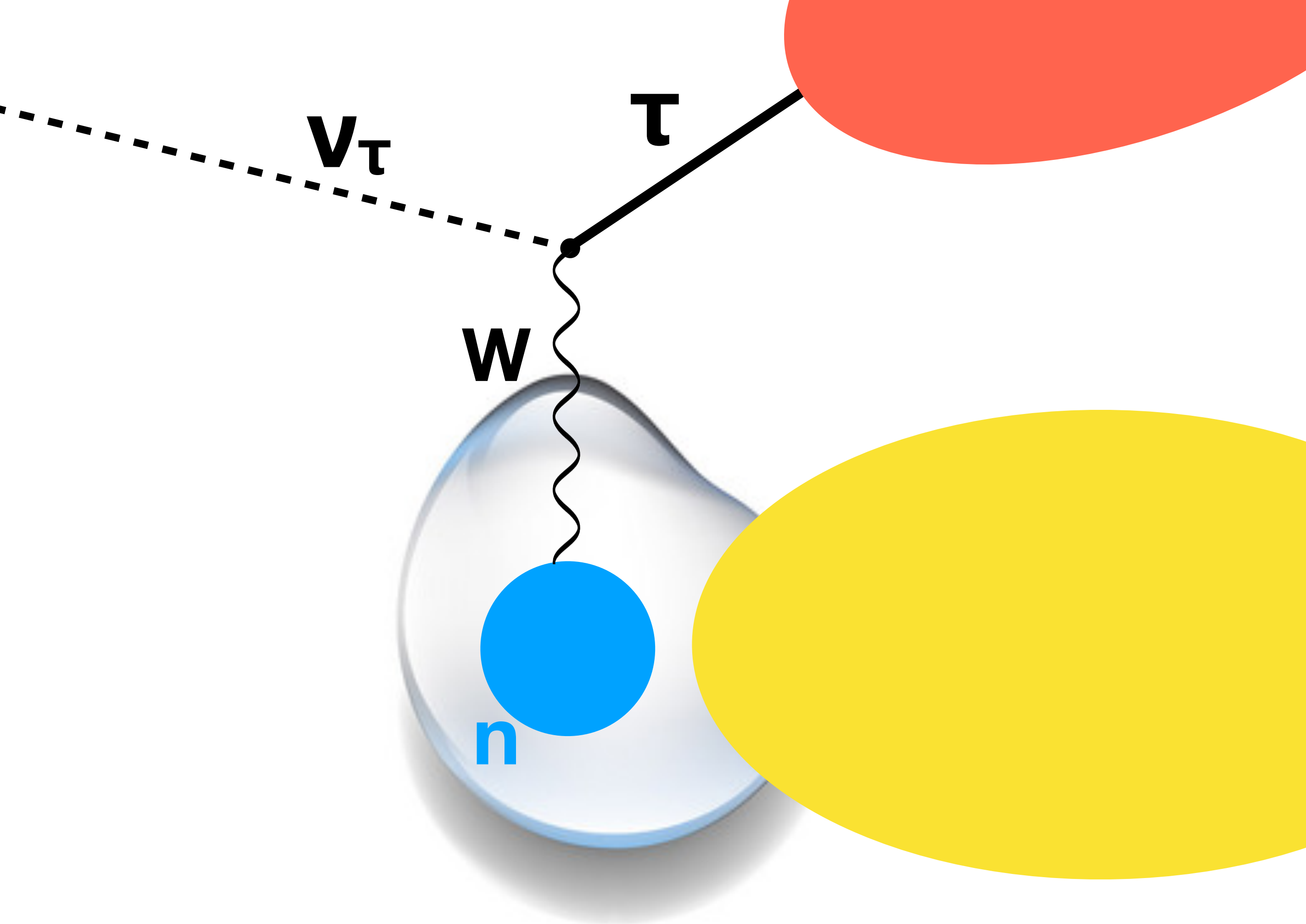


$$F_q \otimes CKM_{q,q'} \otimes Mass_{q'}$$

$$=$$

$$P_{q\rightarrow q'} = \frac{\sigma^{LO}_{q\rightarrow q'}}{\sigma^{LO}}$$

Hadronization–HEDIS



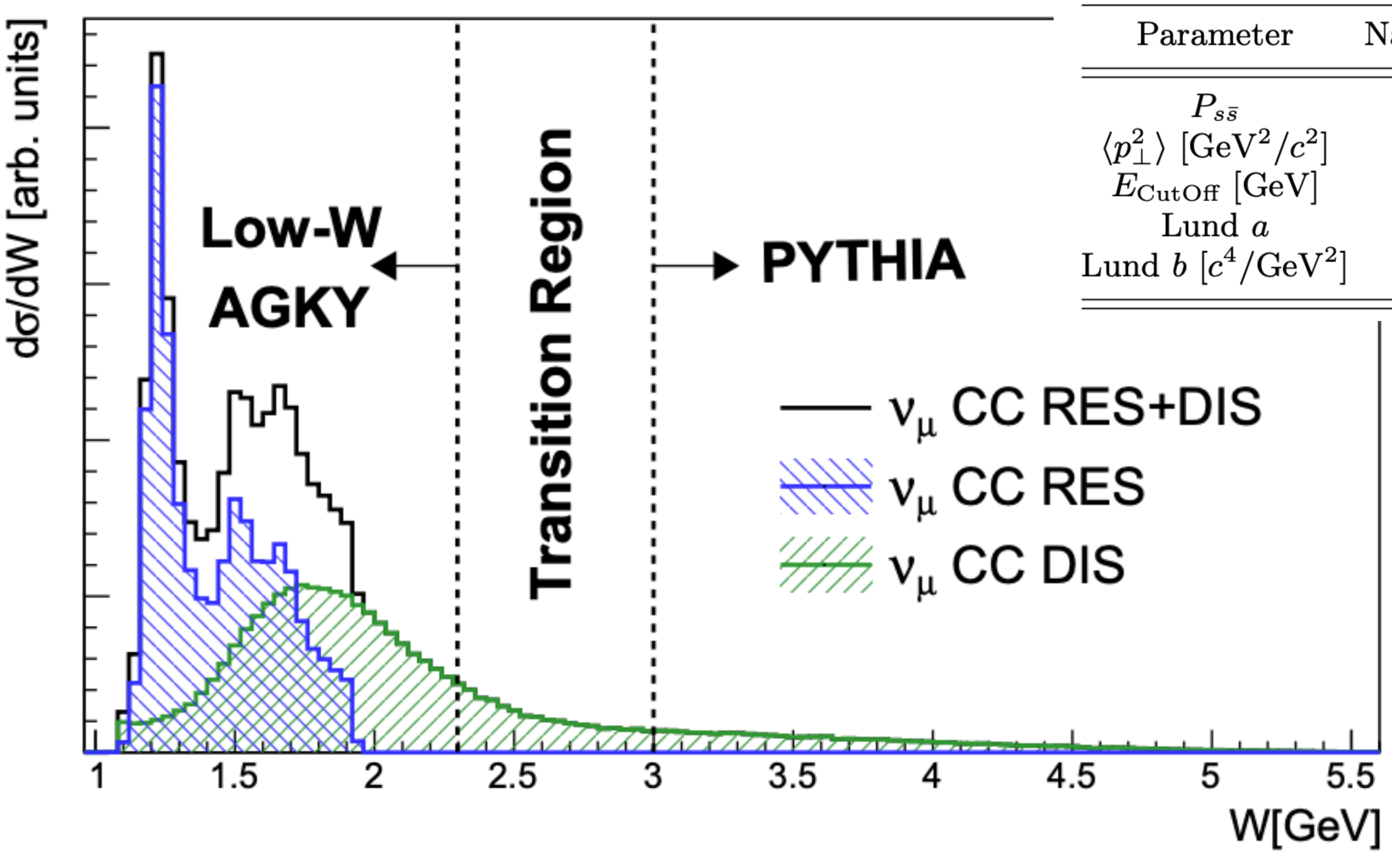

```
--> nu_tau (primary neutrino) E=8360.21
   `-tau- (leading_lepton) E=5554.04
         +-nu_tau E=3297.56 status/id=1/5
         `-rho- E=2256.48 status/id=3/6
              +-pi- E=1290.81 status/id=1/7
              `-pi0 E=965.675 status/id=3/8
                   +-gamma E=890.175
                   `-gamma E=75.4996
--> unnamed state (1000080160) E=14.8951
    +-neutron E=0.922834
    |    `-unnamed state (2000000001) E=2807.09
    |         +-u E=2806.31
    |         |    `-string E=2807.09
    |         |         +-eta E=2243.06
    |         |         |    +-gamma E=1083.88
    |         |         |    `-gamma E=1159.18
    |         |         +-rho+ E=542.988
    |         |         |    +-pi+ E=159.131
    |         |         |    `-pi0 E=383.856
    |         |         |         +-gamma E=243.584
    |         |         |         `-gamma E=140.273
    |         |         +-pi- E=9.73694
    |         |         +-pi0 E=5.21542
    |         |         |    +-gamma E=1.08007
    |         |         |    `-gamma E=4.13535
    |         |         +-omega E=3.59776
    |         |         |    +-gamma E=0.0816192
    |         |         |    `-pi0 E=3.51614
    |         |         |         +-gamma E=3.20452
    |         |         |         `-gamma E=0.311622
    |         |         `-Delta+ E=2.49298
    |         |              +-proton E=2.00807
    |         |              `-pi0 E=0.484947
    |         |                   +-gamma E=0.0471374
    |         |                   `-gamma E=0.437831
    |         `-ud_1 E=0.780469
    `-unnamed state (1000080150) E=13.9722
```

- No PYTHIA running
- No formation zone
- No final state interactions
- **W>2GeV**

Hadronization–DIS

- Hybrid model depending on the W of the interaction.
  - At W>3GeV a PYTHIA tuned version is used.

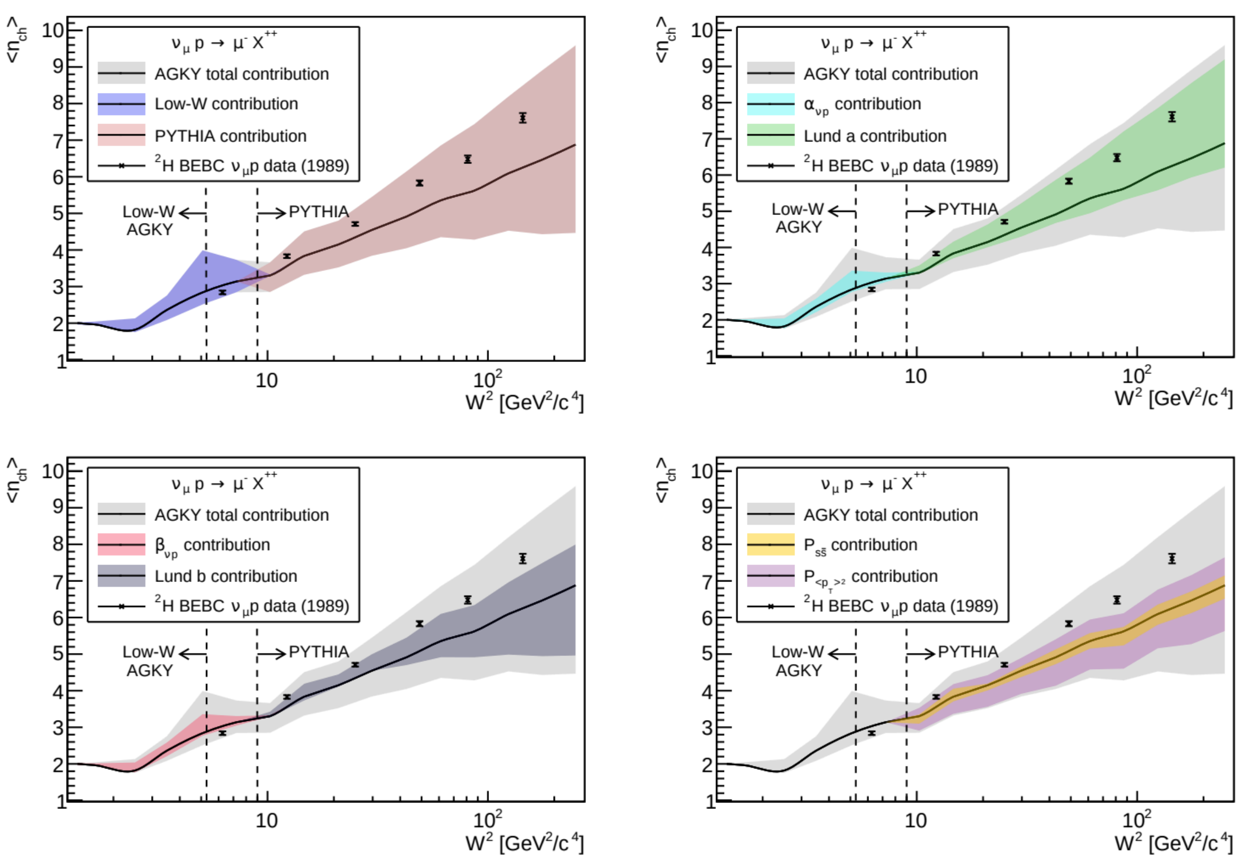
DUNE flux



Parameter	Name in PYTHIA	PYTHIA default	NUX tune	HERMES tune	*2010* GENIE tune
$P_{s\bar{s}}$	PARJ(2)	0.30	0.21	0.25	0.30
$\langle p_\perp^2 \rangle$ [GeV^2/c^2]	PARJ(21)	0.36	0.44	0.42	0.44
E_{CutOff} [GeV]	PARJ(33)	0.80	0.20	0.47	0.20
Lund a	PARJ(41)	0.30	0.30	0.68	0.30
Lund b [c^4/GeV^2]	PARJ(42)	0.58	0.58	0.35	0.58

Hadronization-DIS

- New tuned has been recently developed.



https://arxiv.org/abs/2106.05884

Parameter	GENIE parameter name	*2010* GENIE	Allowed range	*2021* Global Fit	*2021* ^{2}H Fit
		Low-W empirical model			
$\alpha_{\nu p}$	KNO-Alpha-vp	0.40	$[-1.0, 2.0]$	1.1 ± 0.3	1.2 ± 0.4
$\alpha_{\nu n}$	KNO-Alpha-vn	-0.20	$[-1.0, 2.0]$	$1.75^{+0.14}_{-0.11}$	-0.58 ± 0.07
$\alpha_{\bar{\nu} p}$	KNO-Alpha-vbp	0.02	$[-1.0, 2.0]$	$1.32^{+0.16}_{-0.14}$	1.9 ± 0.08
$\alpha_{\bar{\nu} n}$	KNO-Alpha-vbn	0.80	$[-1.0, 2.0]$	1.11 ± 0.09	1.07 ± 0.3
$\beta_{\nu p}$	KNO-Beta-vp	1.42	$[0.0, 2.5]$	0.79 ± 0.15	0.9 ± 0.3
$\beta_{\nu n}$	KNO-Beta-vn	1.42	$[0.0, 2.5]$	0.5 ± 0.1	1.9 ± 0.3
$\beta_{\bar{\nu} p}$	KNO-Beta-vbp	1.28	$[0.0, 2.5]$	0.8 ± 0.1	0.3 ± 0.1
$\beta_{\bar{\nu} n}$	KNO-Beta-vbn	0.95	$[0.0, 2.5]$	$0.88^{+0.09}_{-0.08}$	0.9 ± 0.2
		PYTHIA			
$P_{s\bar{s}}$	PYTHIA-SSBarSuppression	0.30	$[0.0, 1.0]$	0.27 ± 0.04	0.29 ± 0.05
$\langle p_\perp^2 \rangle$ [GeV$^2/c^2$]	PYTHIA-GaussianPt2	0.44	$[0.1, 0.7]$	0.46 ± 0.05	0.43 ± 0.04
E_{CutOff} [GeV]	PYTHIA-RemainingEnergyCutoff	0.20	$[0.0, 1.0]$	0.30 ± 0.04	0.24 ± 0.05
Lund a	PYTHIA-Lunda	0.30	$[0.0, 2.0]$	1.53 ± 0.13	1.85 ± 0.15
Lund b [c^4/GeV^2]	PYTHIA-Lundb	0.58	$[0.0, 1.5]$	1.16 ± 0.09	1.0 ± 0.2
			$\chi^2 =$	87.9/62 DoF	29.5/32 DoF

Formation zone

- DIS includes a formation zone calculation
  - Hadron/nucleon dependent.
  - Reweigh is available

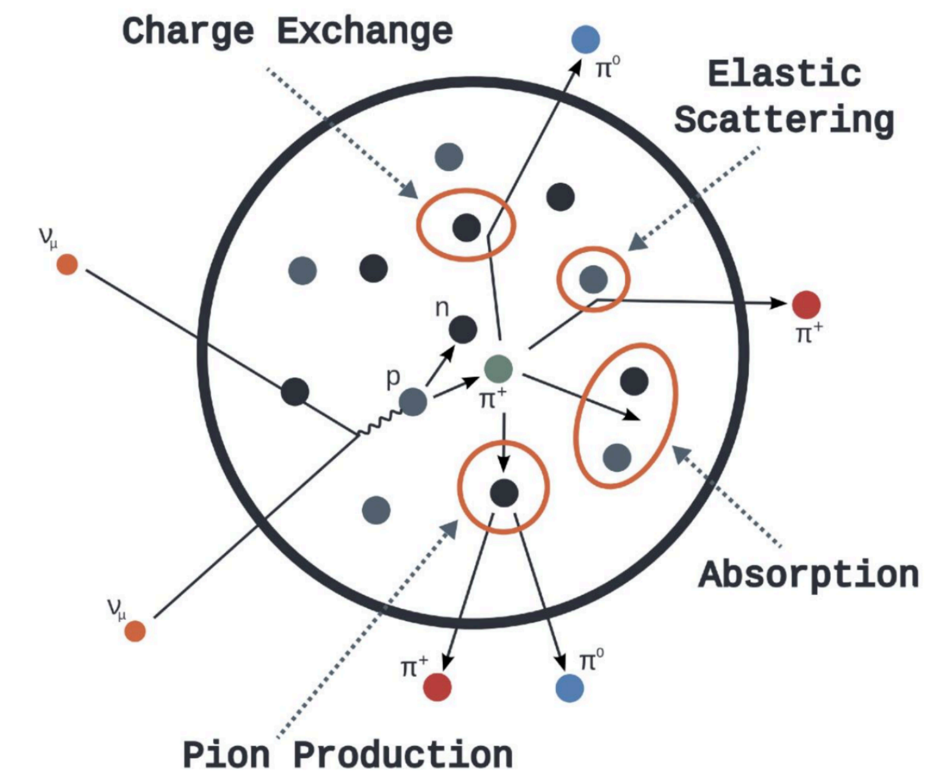
```xml
<!--
     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
     Parameters relevant to formation zone simulation
     - ct0 is the formation time times the speed of light (given in fm)
     - KPt2 is the parameter multiplying pT2 in formation zone calc.
-->
<param type="double" name="FZONE-ct0pion">       0.342    </param>
<param type="double" name="FZONE-ct0nucleon">    2.300    </param>
<param type="double" name="FZONE-KPt2">          0.0      </param>
```

```cpp
//____________________________________________________________________________
double  genie::utils::phys::FormationZone(
   double m, const TLorentzVector & p4,
   const TVector3 & p3hadr, double ct0 /*in fm*/, double K)
{
// m -> hadon mass (on-shell)
// p -> hadron momentum 4-vector (Lab)
// p3hadr -> hadronic-system momentum 3-vector (Lab)

  TVector3 p3  = p4.Vect();            // hadron's: p (px,py,pz)
  double   m2  = m*m;                  //           m^2
  double   P   = p4.P();               //           |p|
  double   Pt  = p3.Pt(p3hadr);        //           pT
  double   Pt2 = Pt*Pt;                //           pT^2
  double   fz  = P*ct0*m/(m2+K*Pt2);   //           formation zone, in fm

  LOG("PhysUtil", pNOTICE)
      << "Formation zone(|P| = " << P << " GeV, Pt = " << Pt
      << " GeV, ct0 = " << ct0 << " fm, K = " << K << ") = " << fz << " fm";

  return fz;
}
```

Final-state interactions

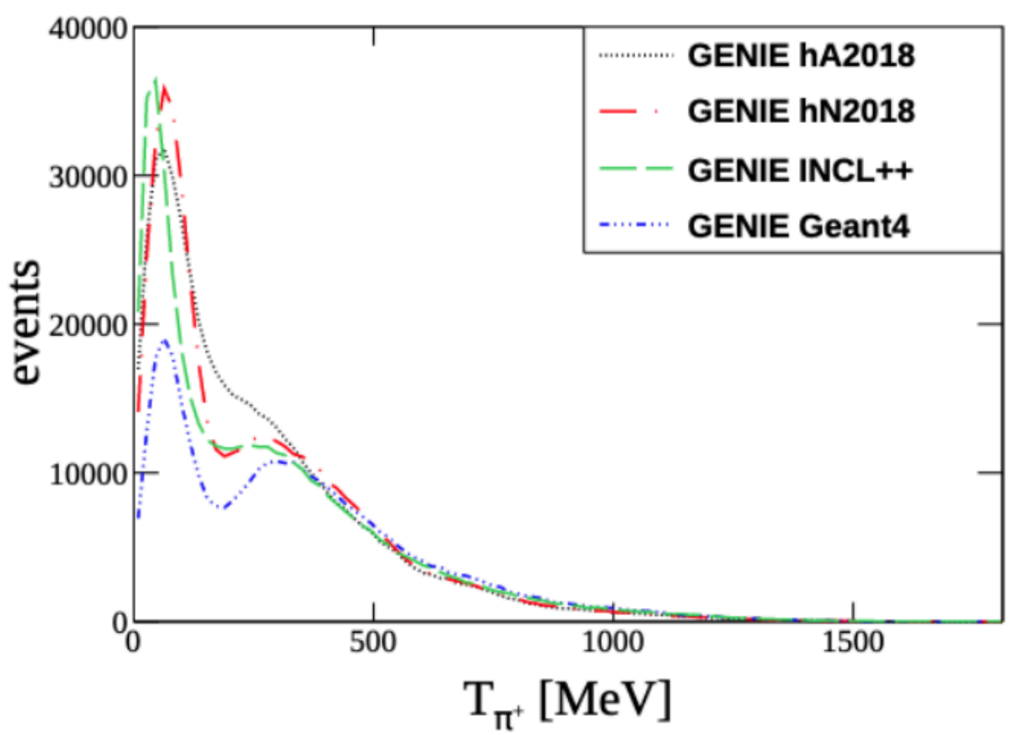
- Based on intranuclear cascade (INC) model.
  - Simple: hA -> For E<1.2GeV
  - Sophisticated: hN -> E>50MeV
  - INCL++
  - GEANT4

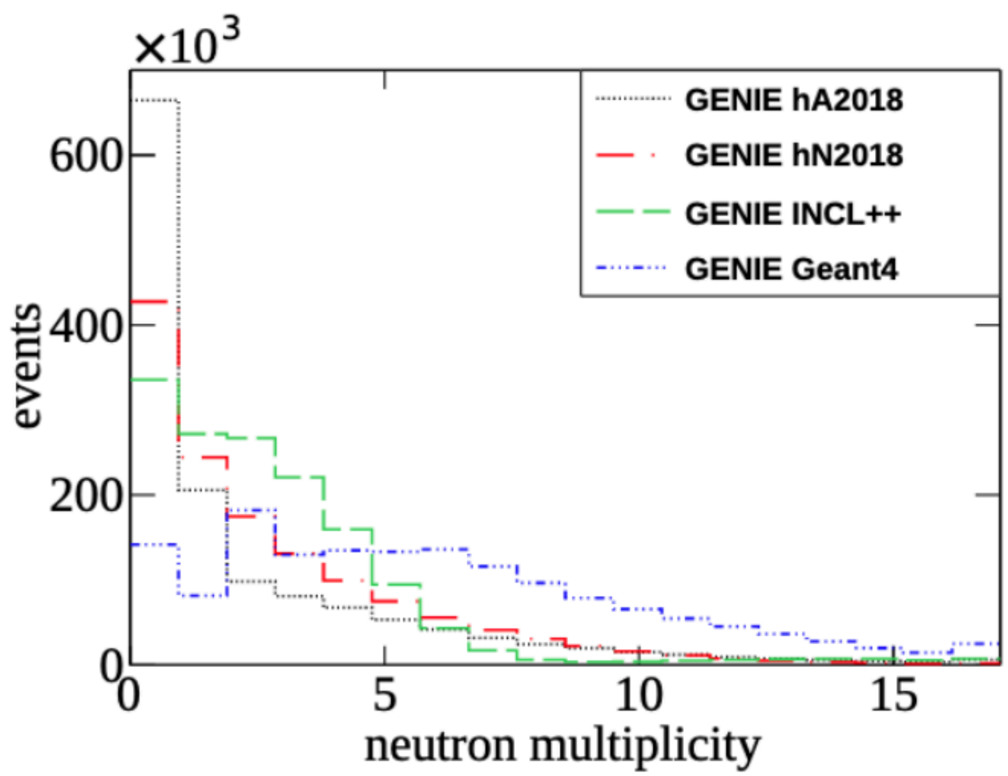
Image: T. Golan



$$\lambda(E,r) = \frac{1}{\sigma_{hN,tot} * \rho(r)}$$

2GeV numu+Ar

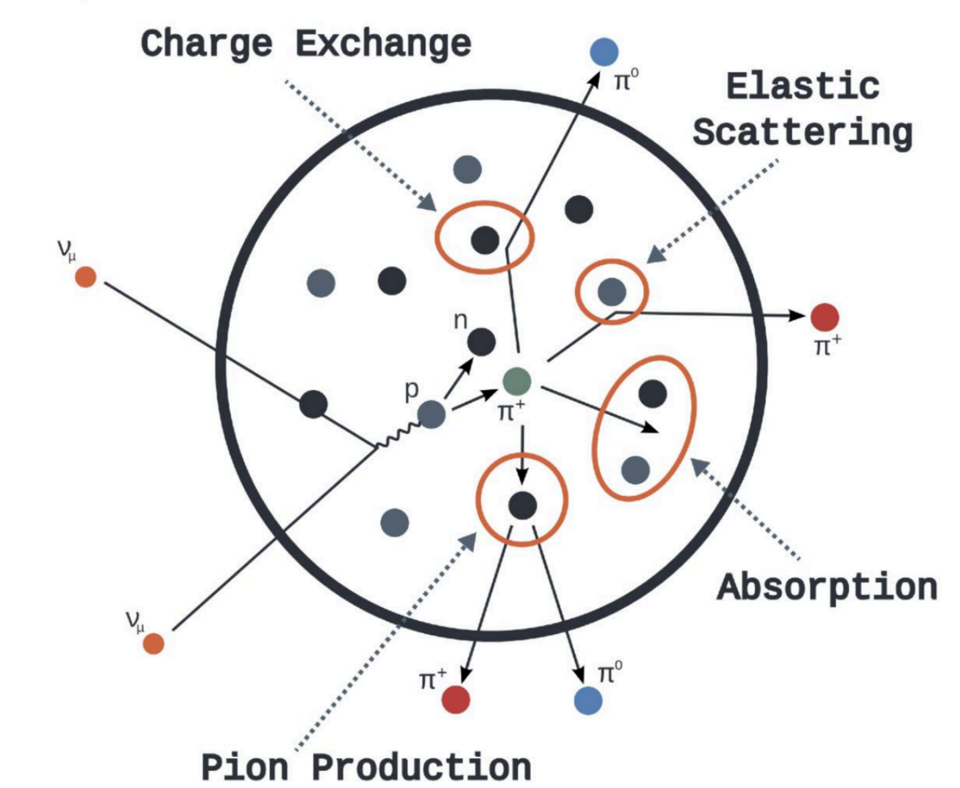




Final-state interactions

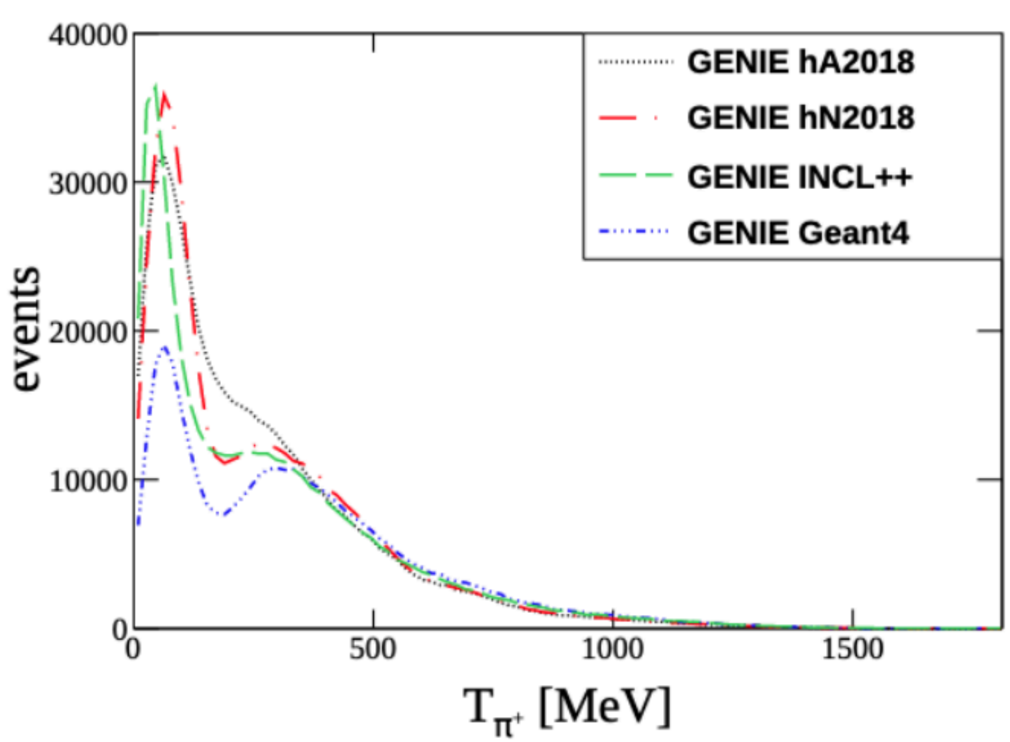
- Based on intranuclear cascade (INC) model.
  - Simple: hA -> For E<1.2GeV
  - Sophisticated: hN -> E>50MeV
  - INCL++
  - GEANT4

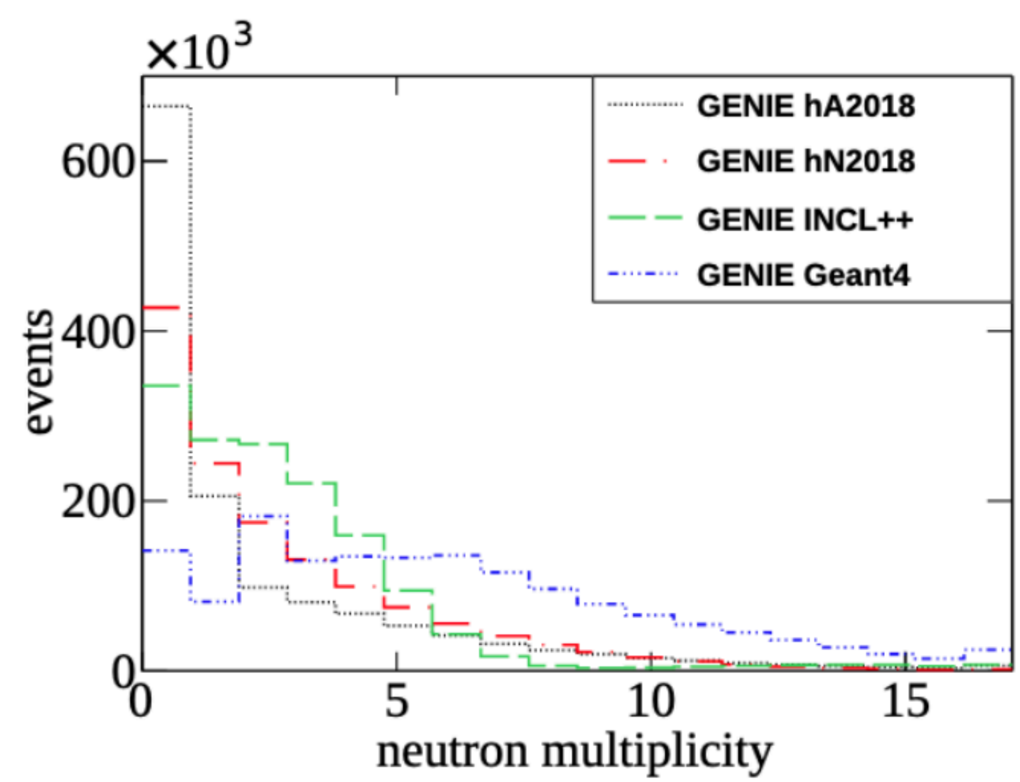
Image: T. Golan



$$\lambda(E, r) = \frac{1}{\sigma_{hN,tot} * \rho(r)}$$

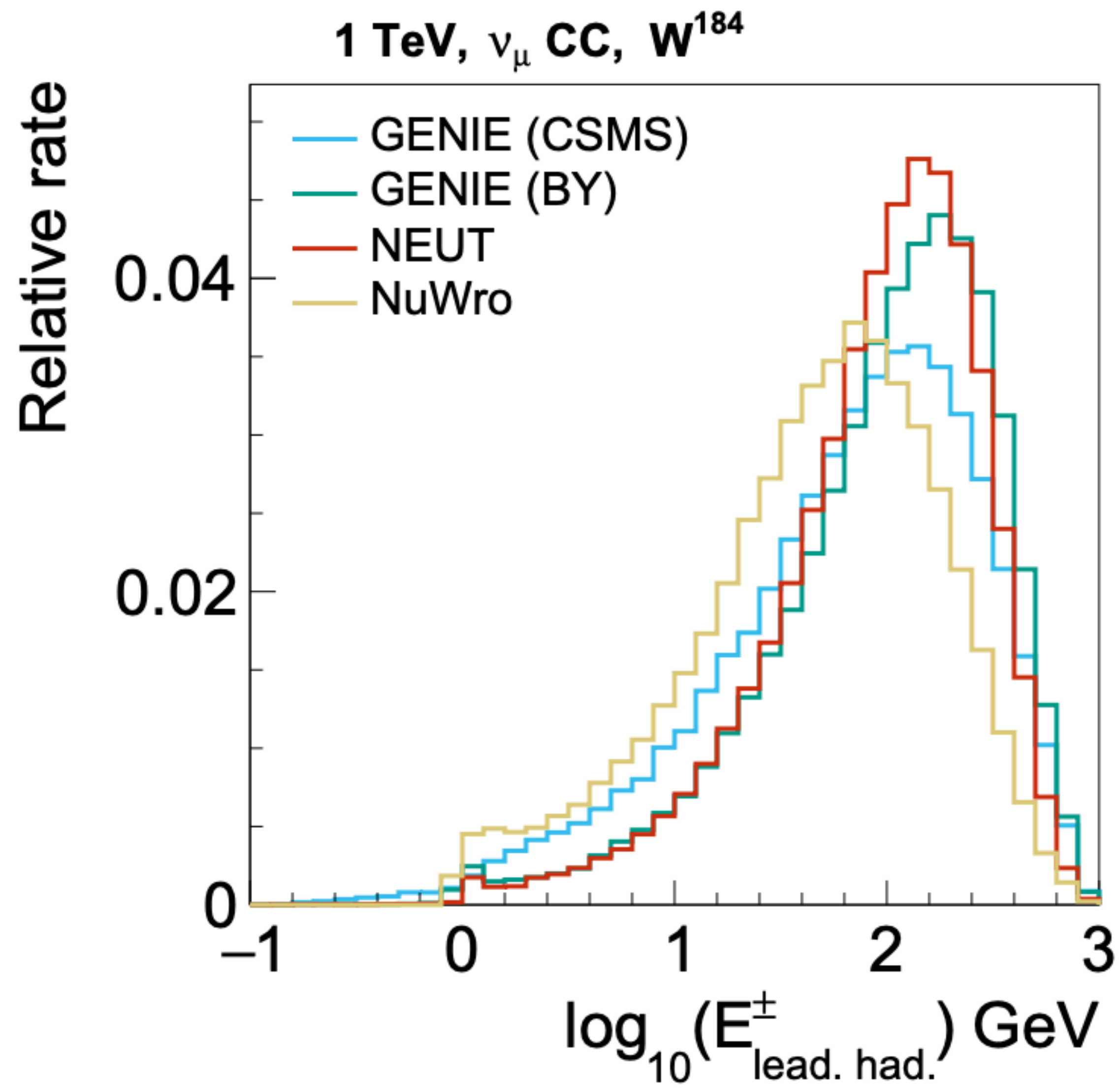
2GeV numu+Ar

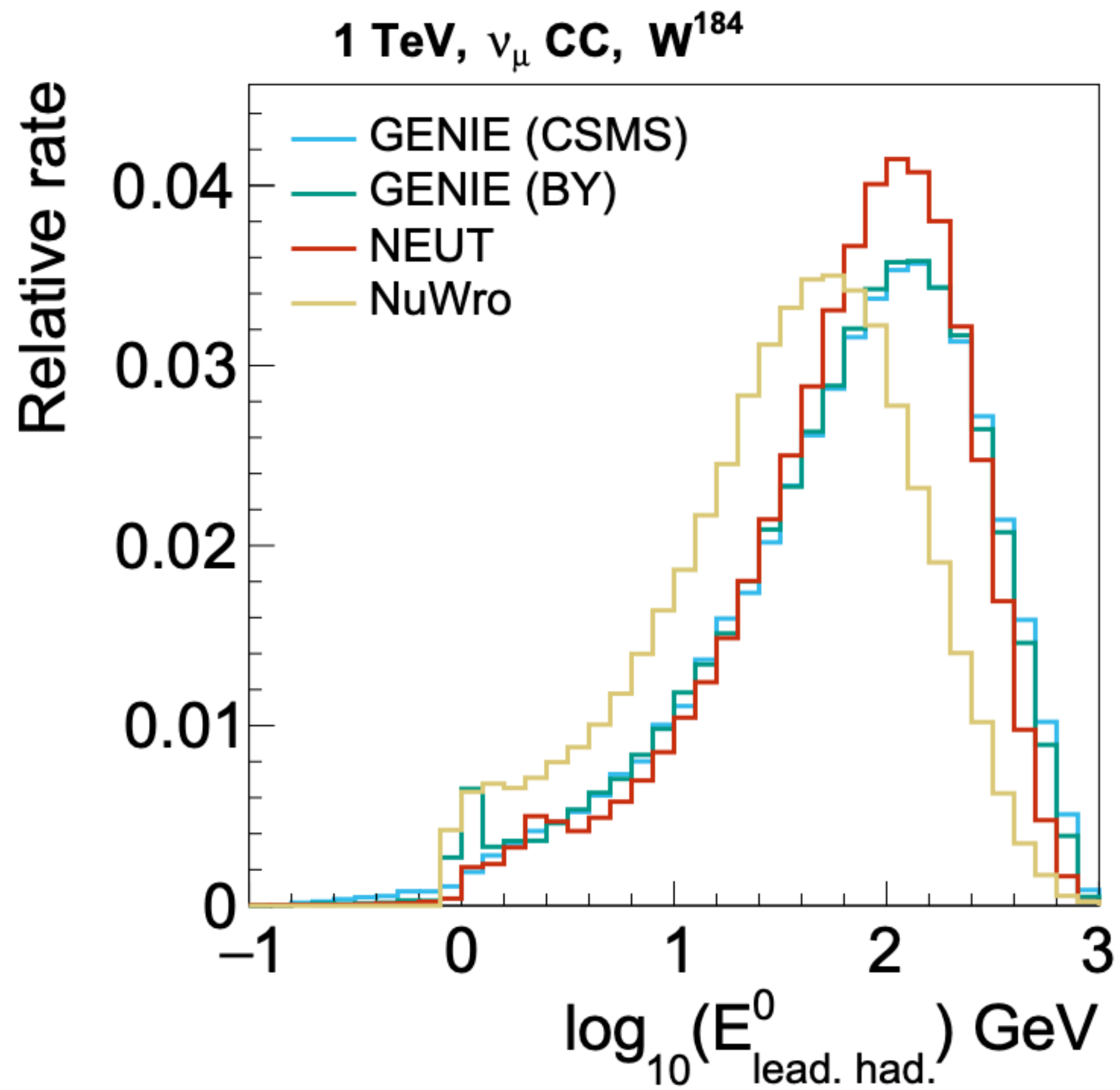




Comparison

- Energy of leading hadrons

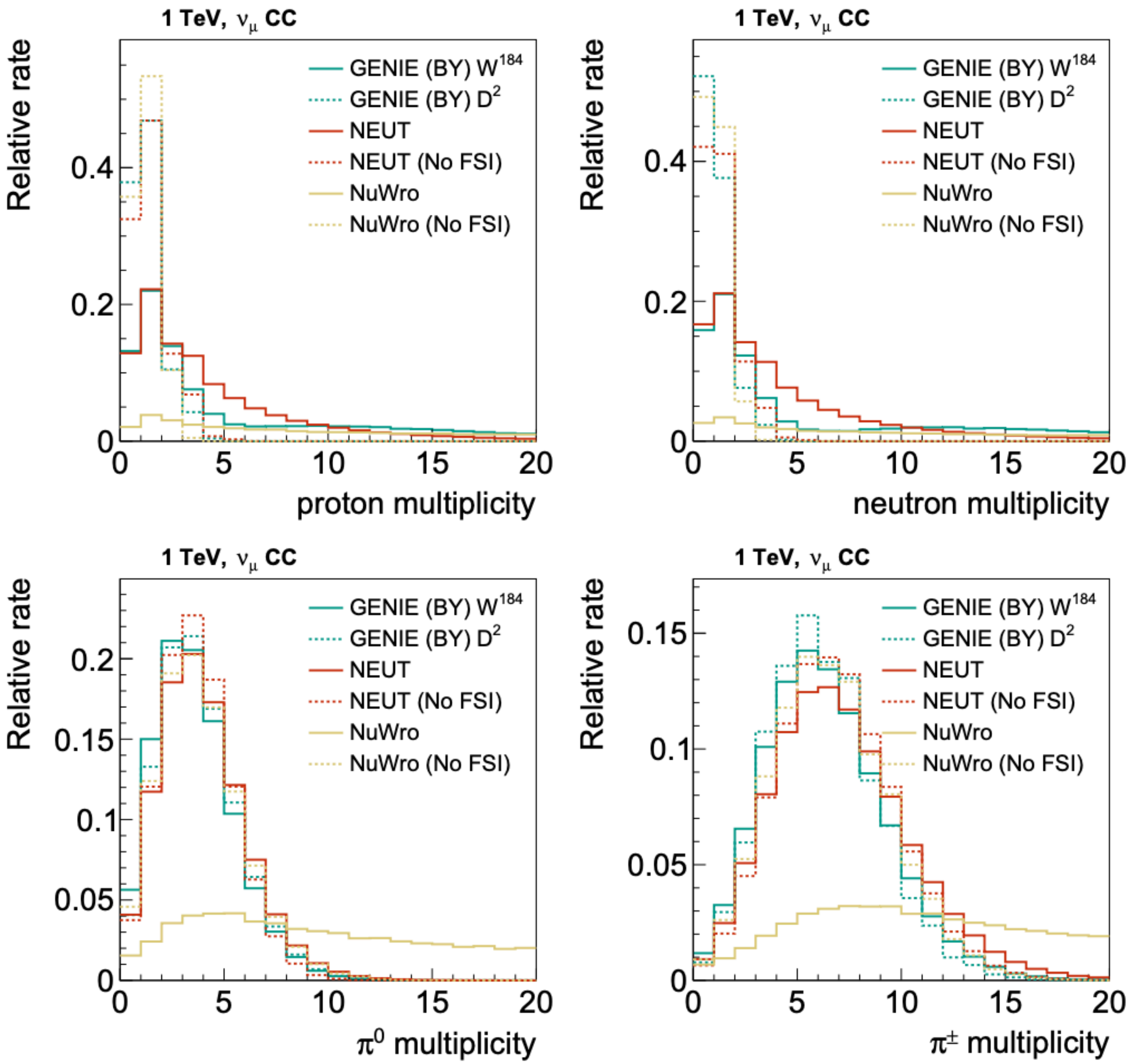




arXiv:2203.05090

Comparison

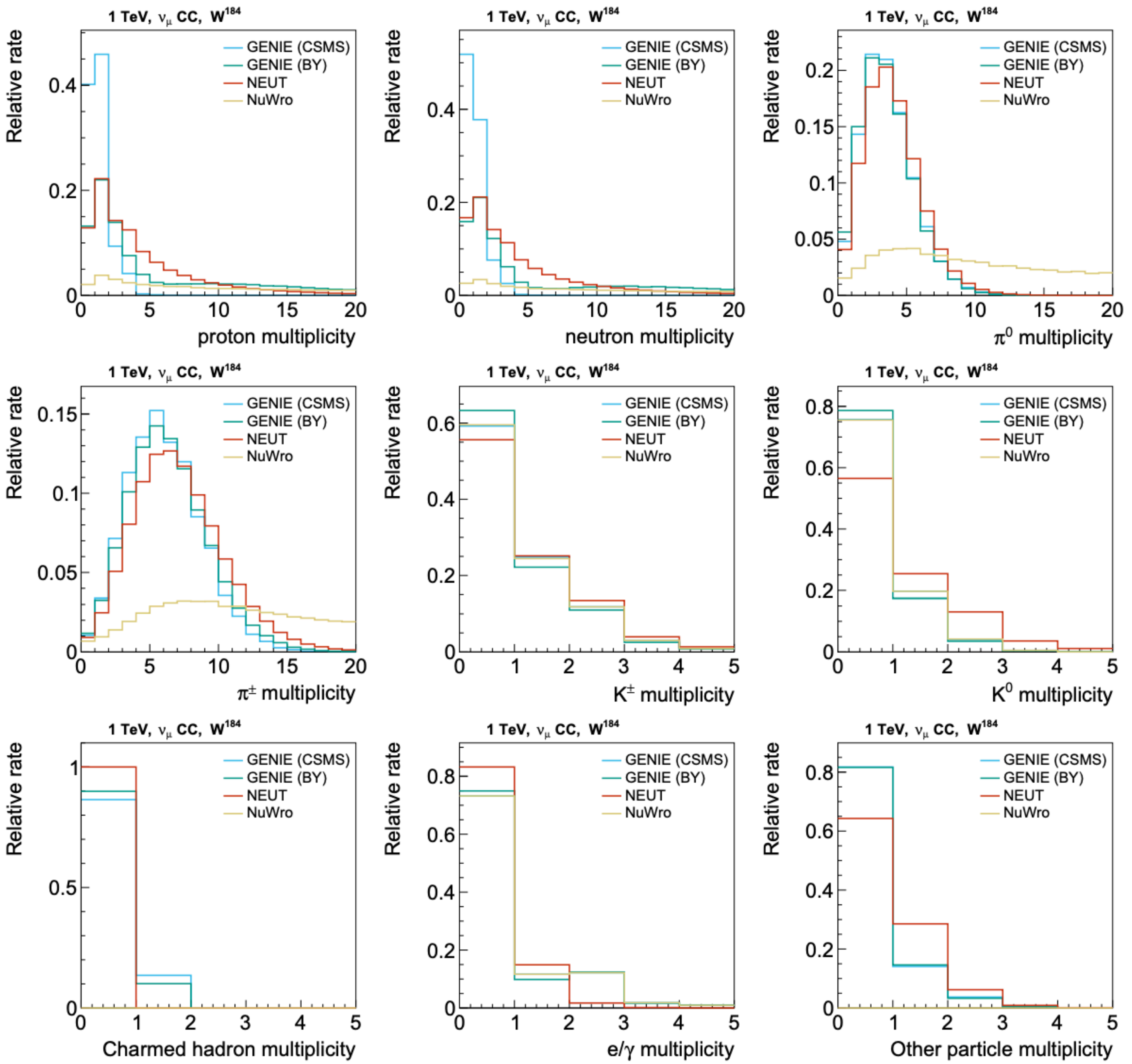
- Hadron multiplicity with/without NSI



arXiv:2203.05090

Comparison

- Hadron multiplicity



arXiv:2203.05090

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101025085.