FPF White Paper: Neutrino Section Event Generators

Forward Physics Facility Whitepaper: Neutrino Section Draft

VII. Neutrino Physics

A. Neutrino Fluxes
B. Neutrino Cross Sections → Mary Hall Reno

Vishvas Pandey ← C. MC Tools for Neutrino Interactions

D. BSM with Neutrinos → Kevin J. Kelly

UF UNIVERSITY of FLORIDA

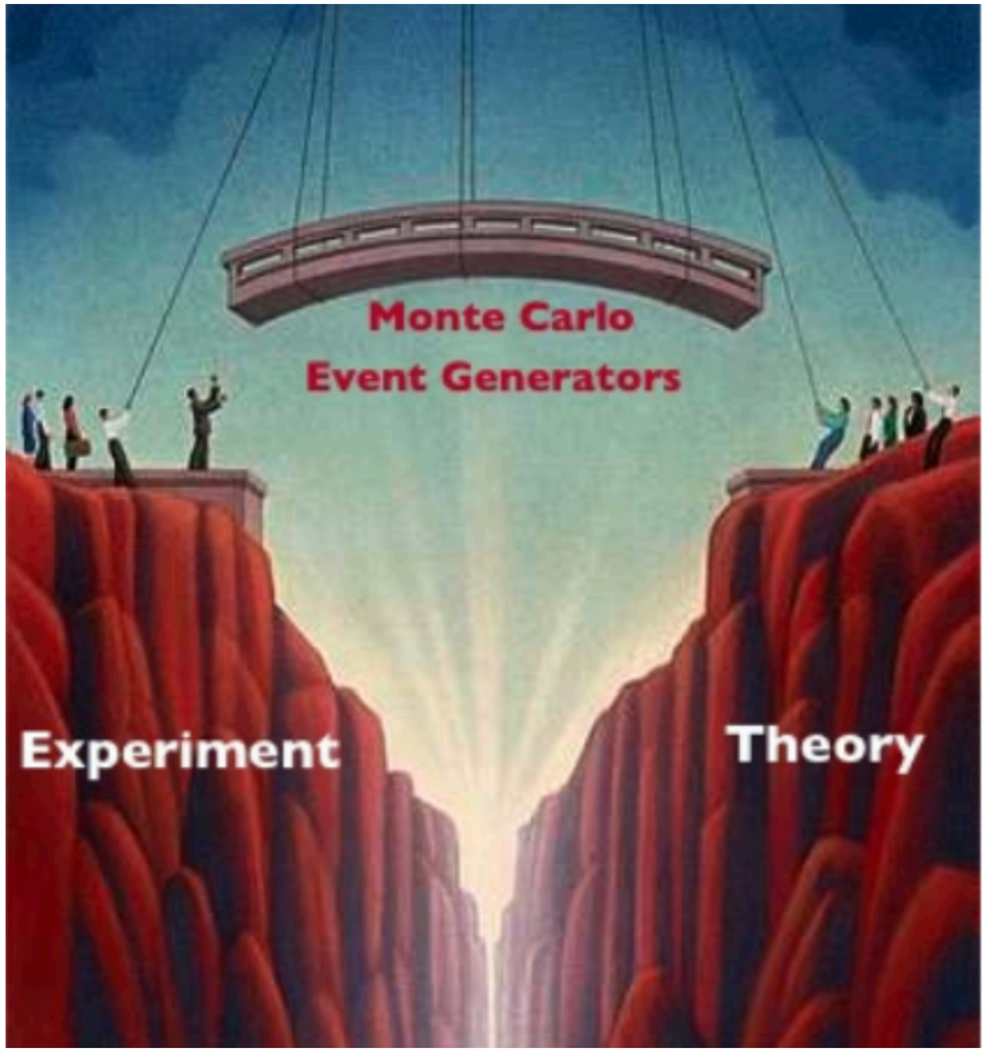
Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

Monte Carlo Event Generators

- MC event generators play key role in experiments: bridge between theory and experiments

- FPF experiments need Neutrino Monte-Carlo generators to predict:
  - neutrino interaction cross section, all final-state particles and their energies
  - for all the current and proposed target material in the detector (tungsten, argon,…)
  - for all three SM neutrino flavors
  - for a broad spectrum of FPF neutrino energies



- Uncertainties associated with the neutrino interactions need to be well controlled for precision neutrino and BSM measurements

Neutrino Monte Carlo Event Generators

■ Widely used Neutrino MC Event Generators:

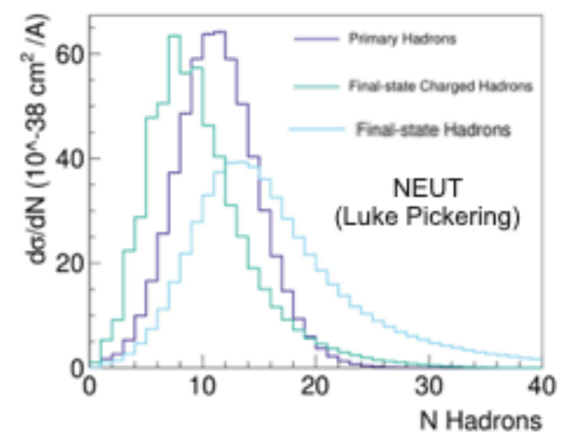
3rd Forward Physics Facility Meeting

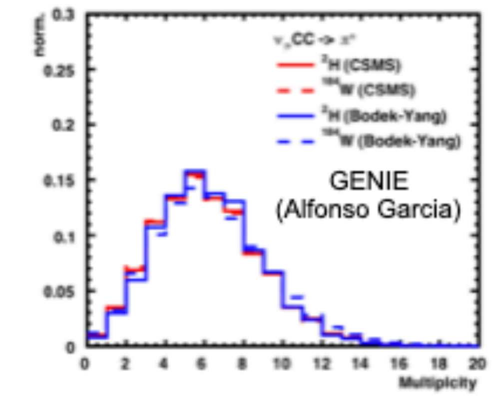
Oct 25 – 26, 2021

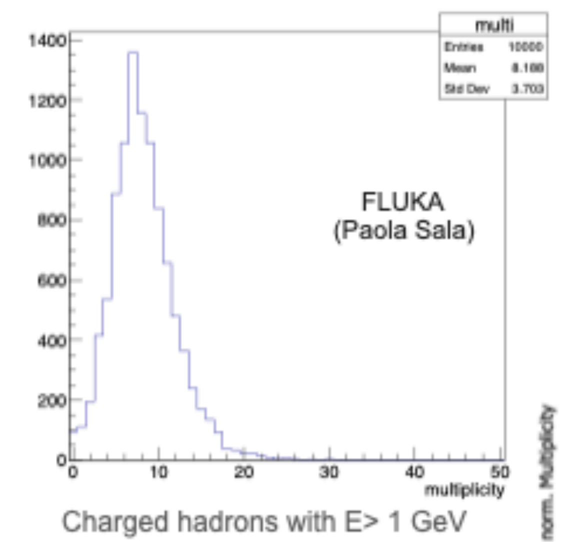
Europe/Zurich timezone

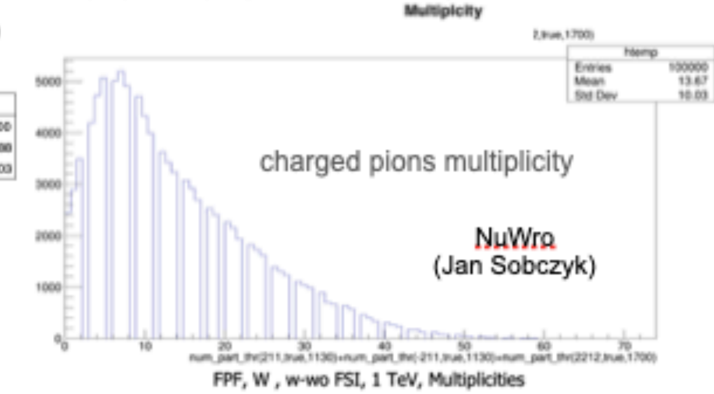
- **Neutrino MC Event Generator Session:**
  https://indico.cern.ch/event/1076733/contributions/4569418/

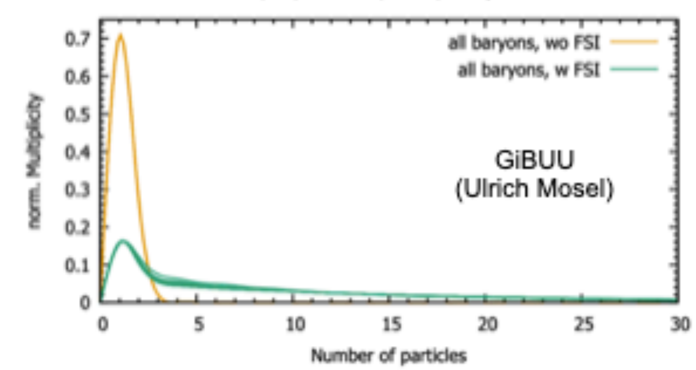
  - **FLUKA**: Paola Sala
  - **GENIE**: Alfonso Garcia Soto
  - **GiBUU**: Ulrich Mosel
  - **NEUT**: Luke Pickering
  - **NuWro**: Jan Sobczyk











- **Dedicated Section in the White Paper**

- **This talk gives a brief summary of these contributions:**
  - Underlying key DIS models
  - Treatment of FSI effects
  - Leading hadron multiplicity and energy distributions

- **Many thanks to generator authors for their contributions to the 3rd FPF meeting and to this white paper!**

NEUT:

Luke Pickering at 3rd FPF Meeting

- Originally written in the 1980s to predict atmospheric neutrino backgrounds for Nucleon Decay Experiments at KamiokaNDE.

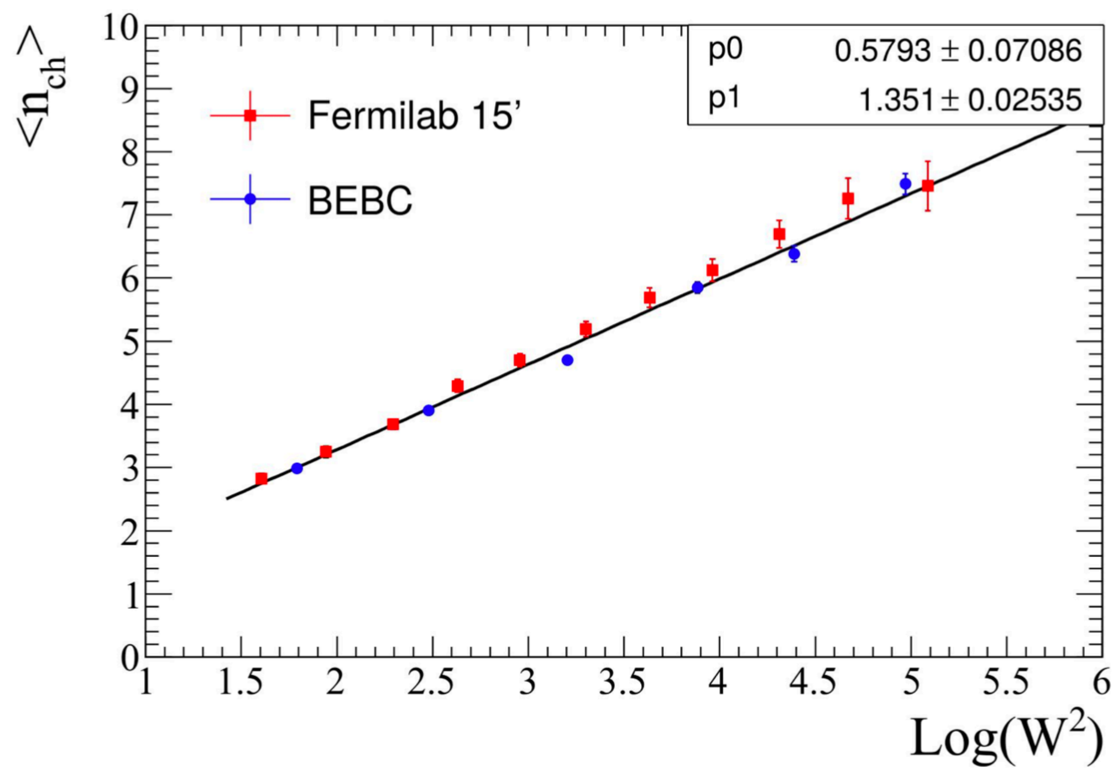
- Development focussed on “few GeV” neutrinos for use in T2K and SK long baseline neutrino oscillation measurements.

DIS Model

- Inclusive cross-section from Bodek-Yang-modified GRV98 PDF set

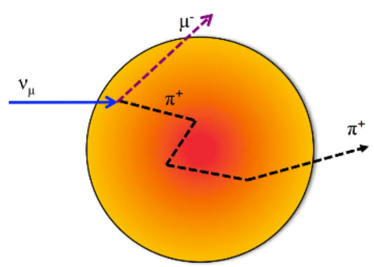
- Fragmentation uses PYTHIA v5.72 included in CERNLIB 2005

- Multiplicity at low energy and W tuned to bubble-chamber data from FNAL and BEBC
  No explicit tuning for higher W



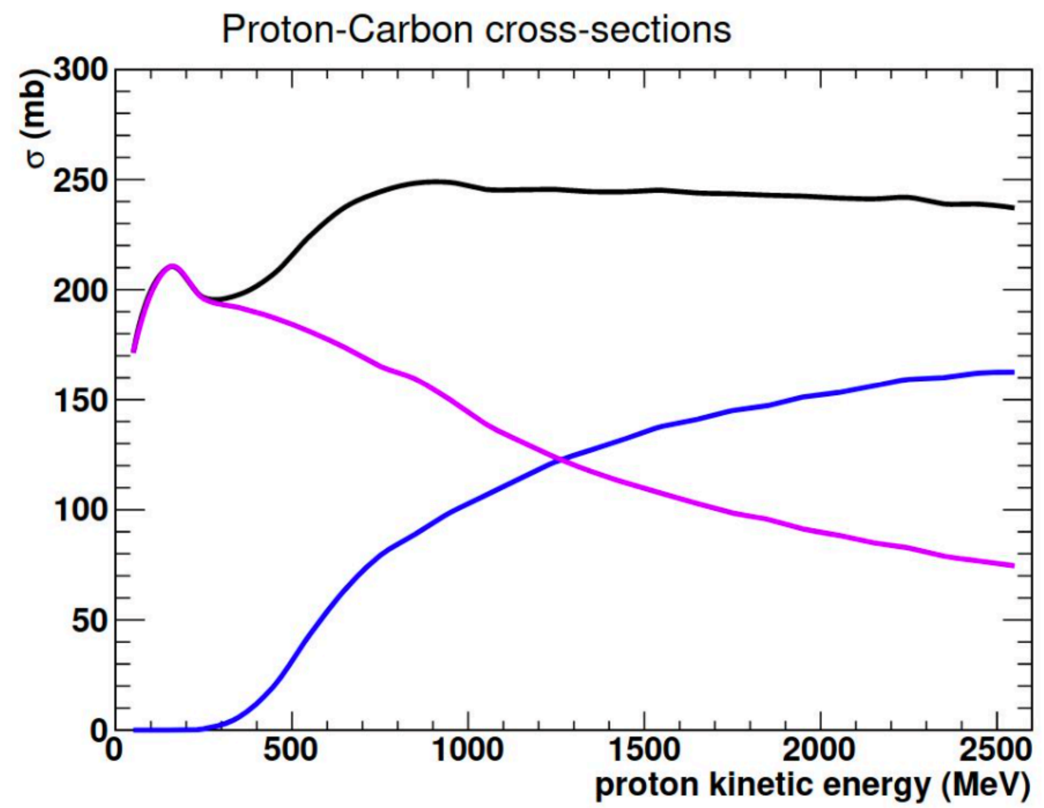
FSI Model

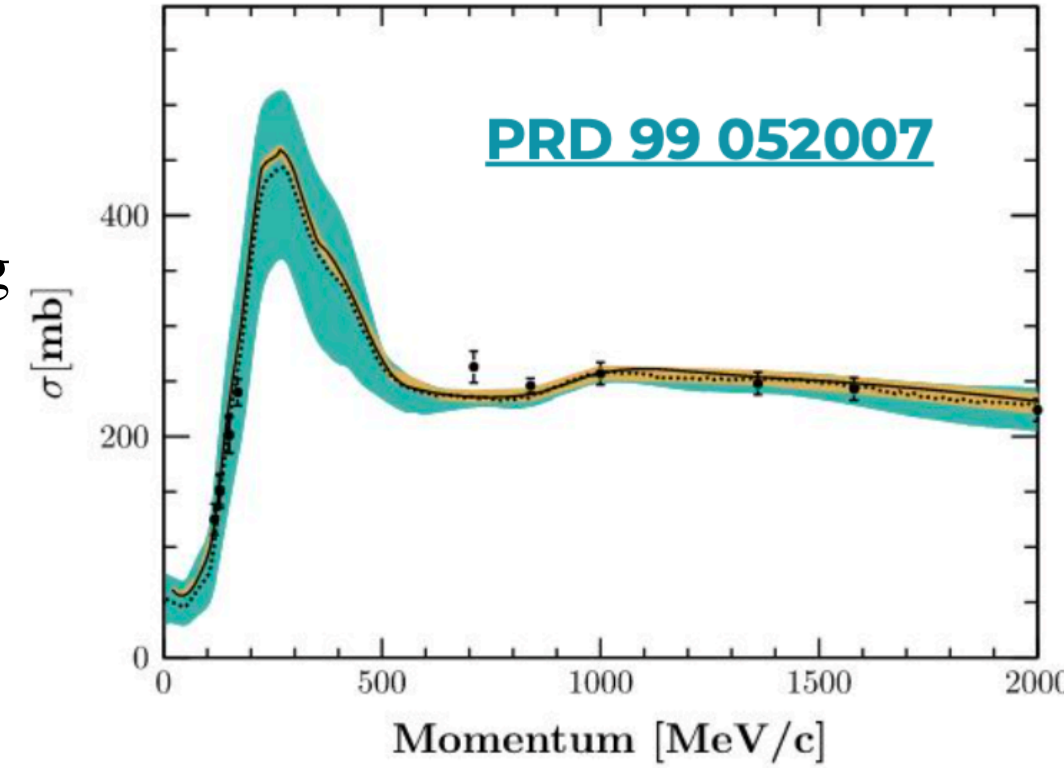
- Semi-classical cascade
  - Hadrons are individually and independently stepped through nuclear volume
  - Interaction probability per 0.2 fm step parameterised by Local Fermi Gas model (charge/nucleon density, nucleon momentum distribution)



- Channels Implemented:
  - Nucleons, pions, kaons, etas, omega
  - Pion model tuned to data: 0.5–2 GeV/c
  - Nucleon cross-sections use Bertini model for $E_N < 3$ GeV

- Includes "formation zone" effects where primary hadrons are stepped away from production point before experiencing cascade



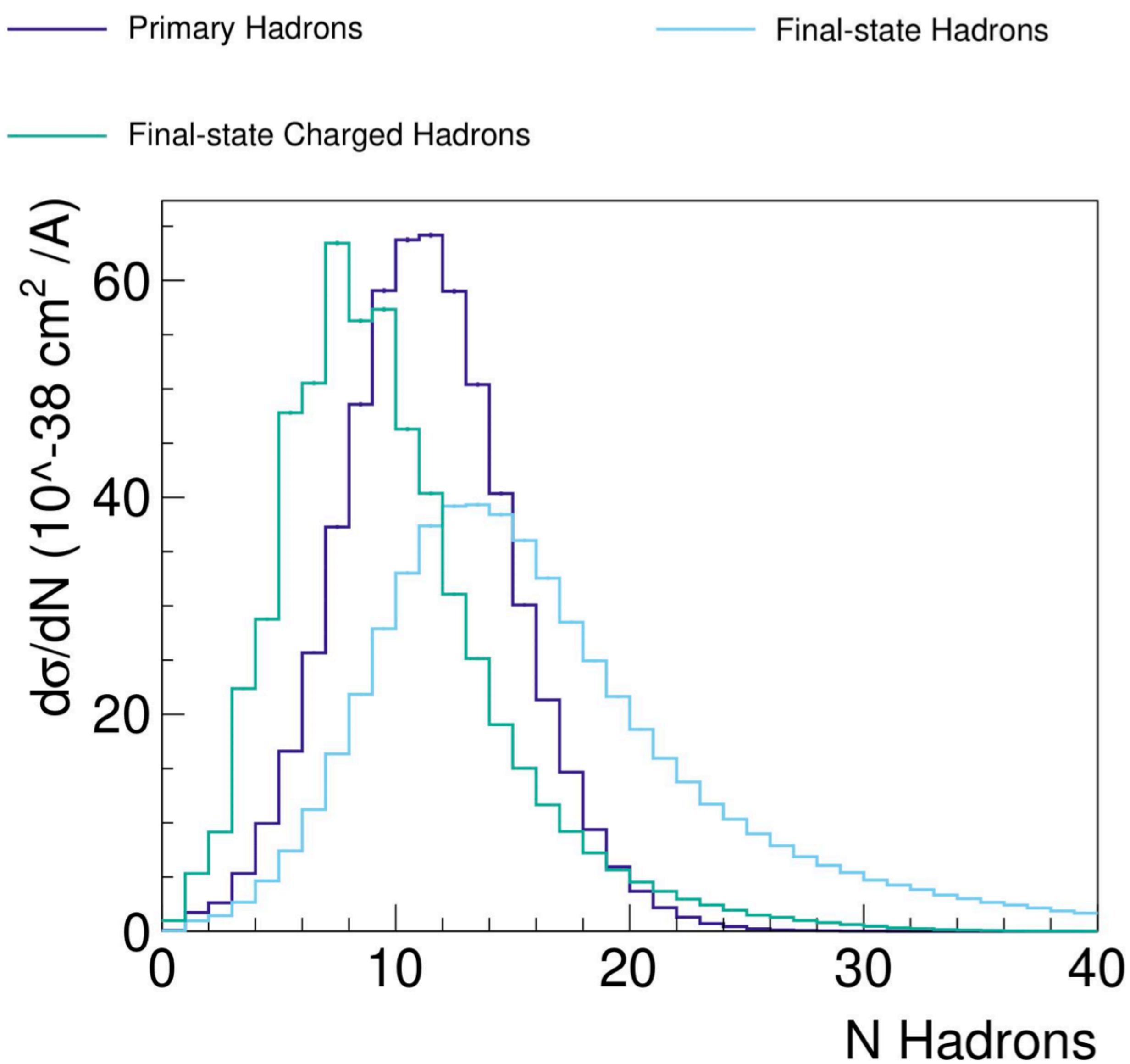


(a) Reactive

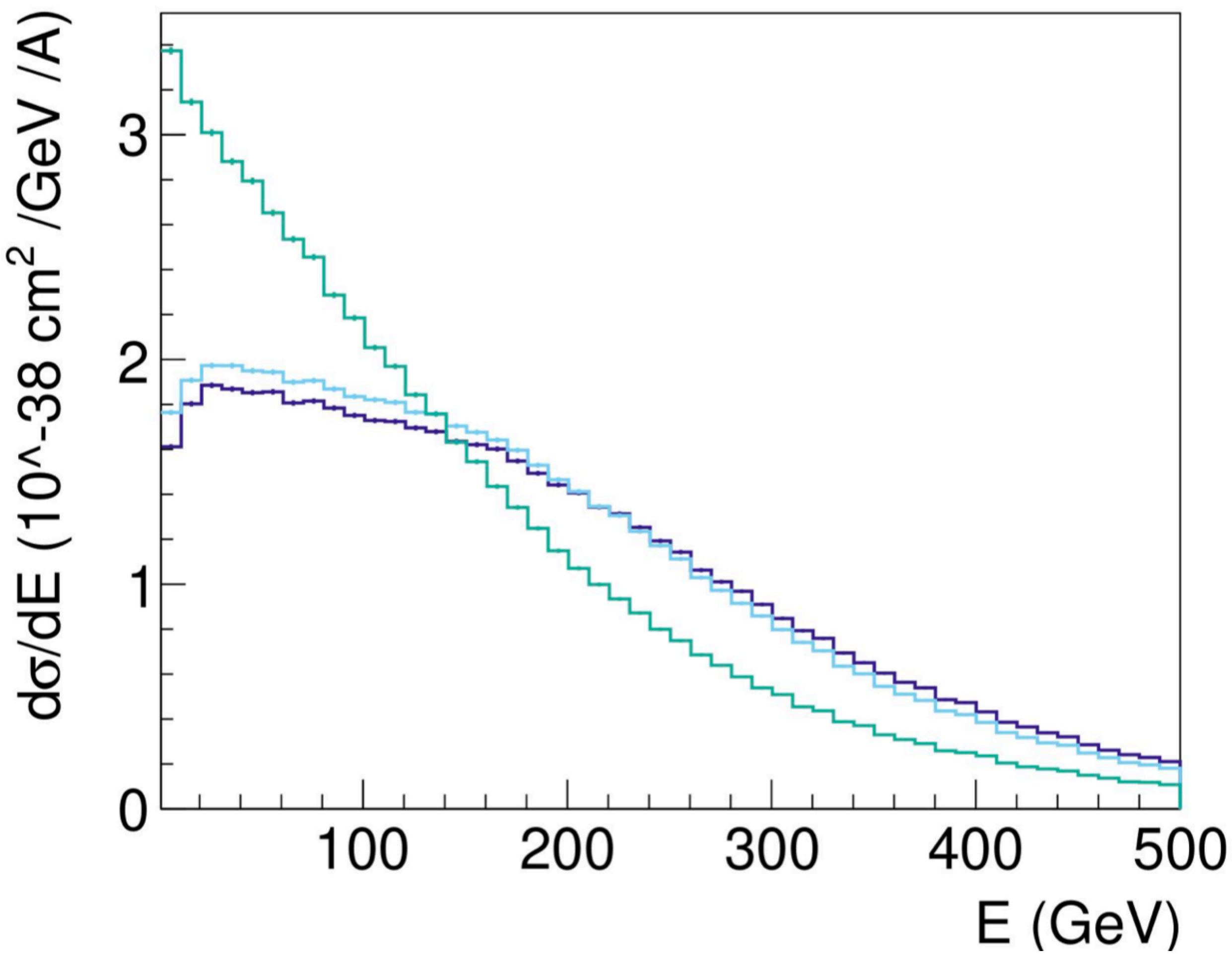
Luke Pickering at 3rd FPF Meeting

1 TeV ν_μ CC Interactions on W target

- **Multiplicity**



- **Leading Hadron Energy**



NuWro:

- Beginning ~ 2005 at Wroclaw University, Poland
- Optimized for ~ 1 GeV neutrinos
- Can handle all kind of targets, neutrino fluxes
- Equipped with detector interface
- Used for numerous comparisons and studies by T2K, MINERvA, MicroBooNE experiments

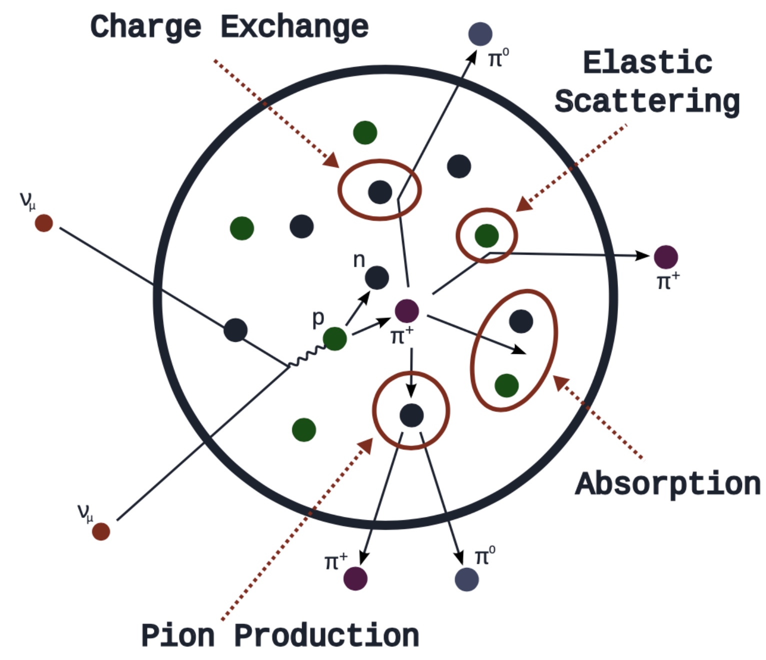
DIS Model

- W > 1.6 GeV
- Inclusive cross sections from Bodek-Yang model
- Hadronization with PYTHIA6 fragmentation functions
- No shadowing, anti-shadowing, EMC nuclear effects
- Some PYTHIA6 parameters adjusted to get better agreement with charged hadron multiplicities data.

NuWro:

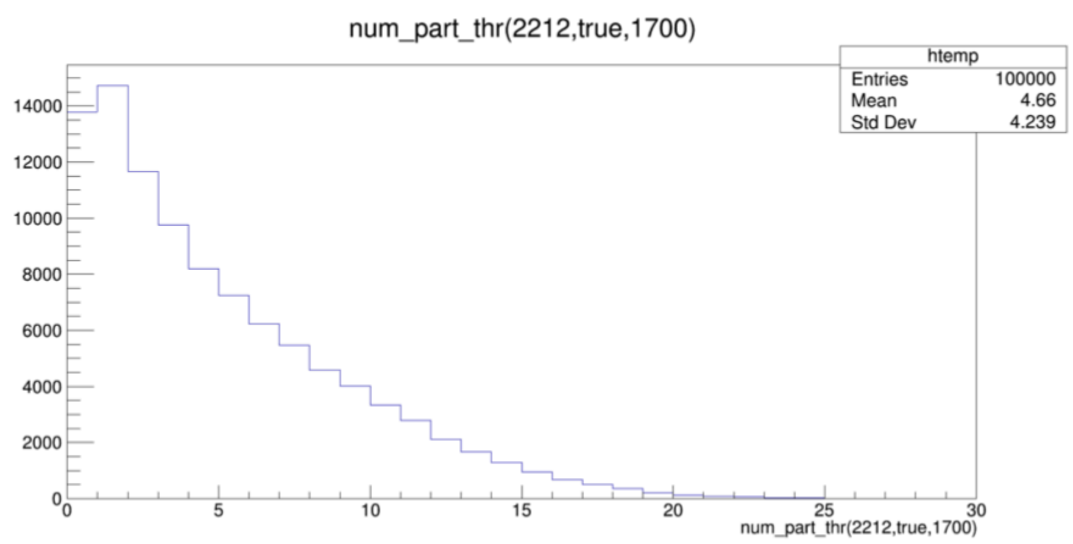
FSI Model

- Intranuclear cascade:
  - Propagates particles through the nuclear medium
  - Semi-classical: includes Pauli blocking, nucleon-nucleon correlation
  - Implemented for nucleons, pions and hyperons
- Formation zone can be switched on and off - it is a major effect.
  - Formation zone (as implemented in NuWro) makes multiplicities much lower (~ order of magnitude)

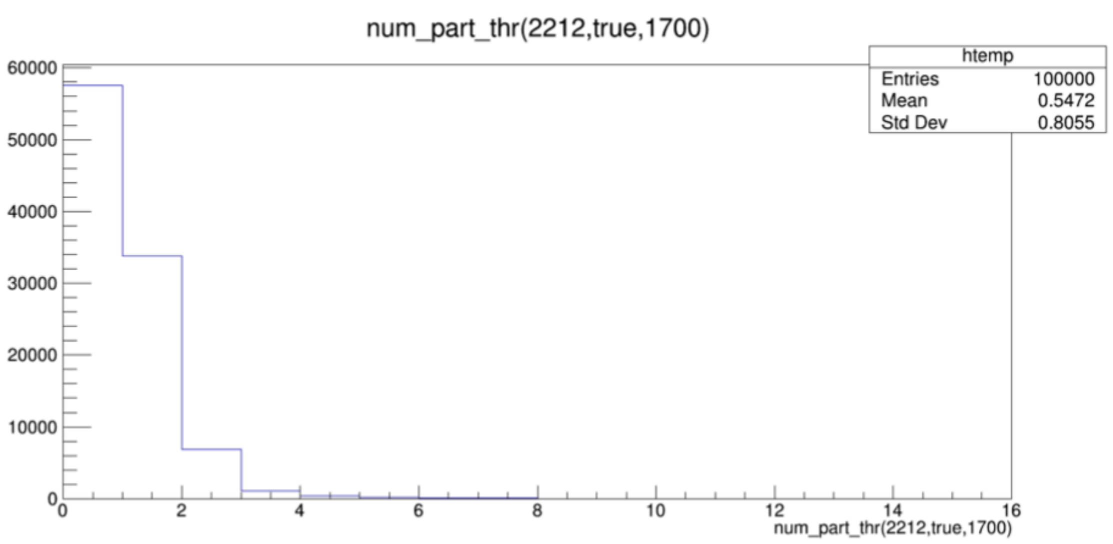


from T. Golan

Multiplicities of protons with kinetic energy above 1 GeV.



Without formation zone.

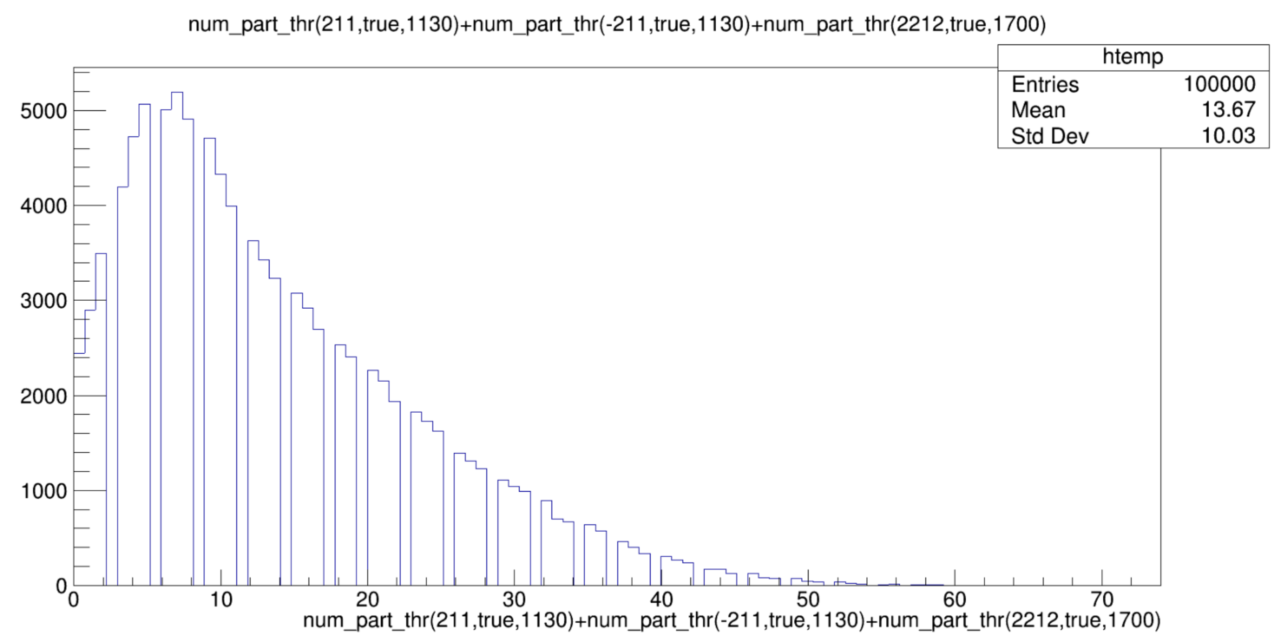


With formation zone.

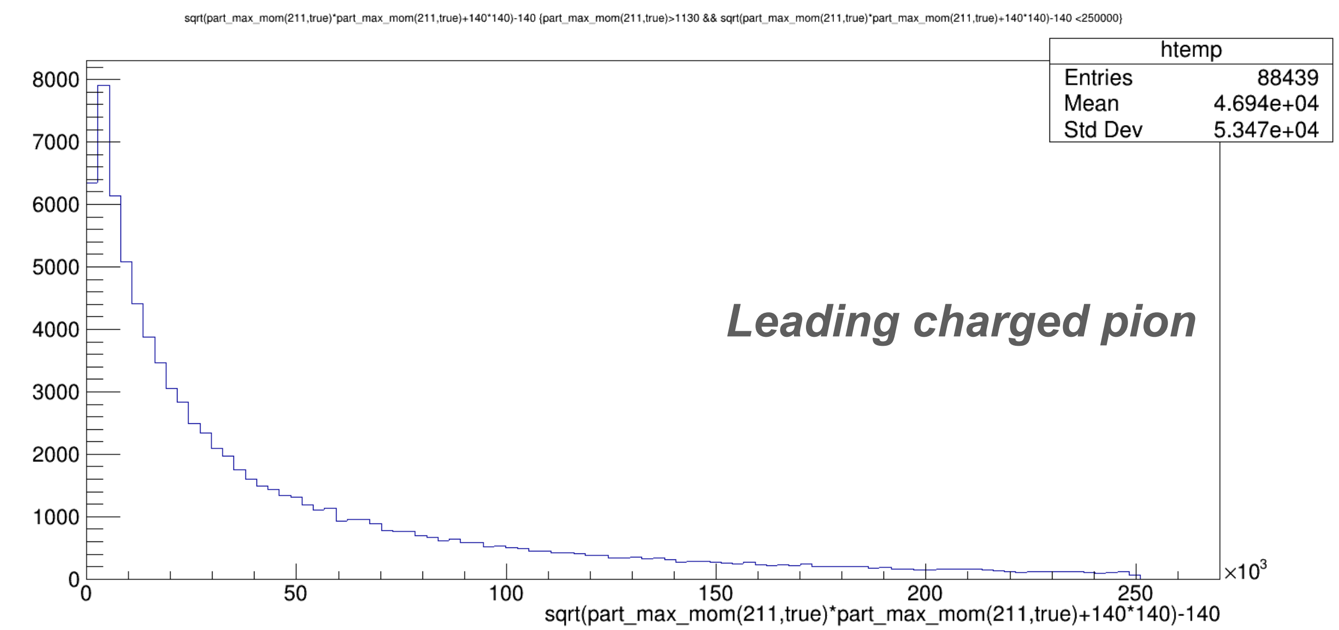
Multiplicity of final state protons is a very good measure of formation zone effects.

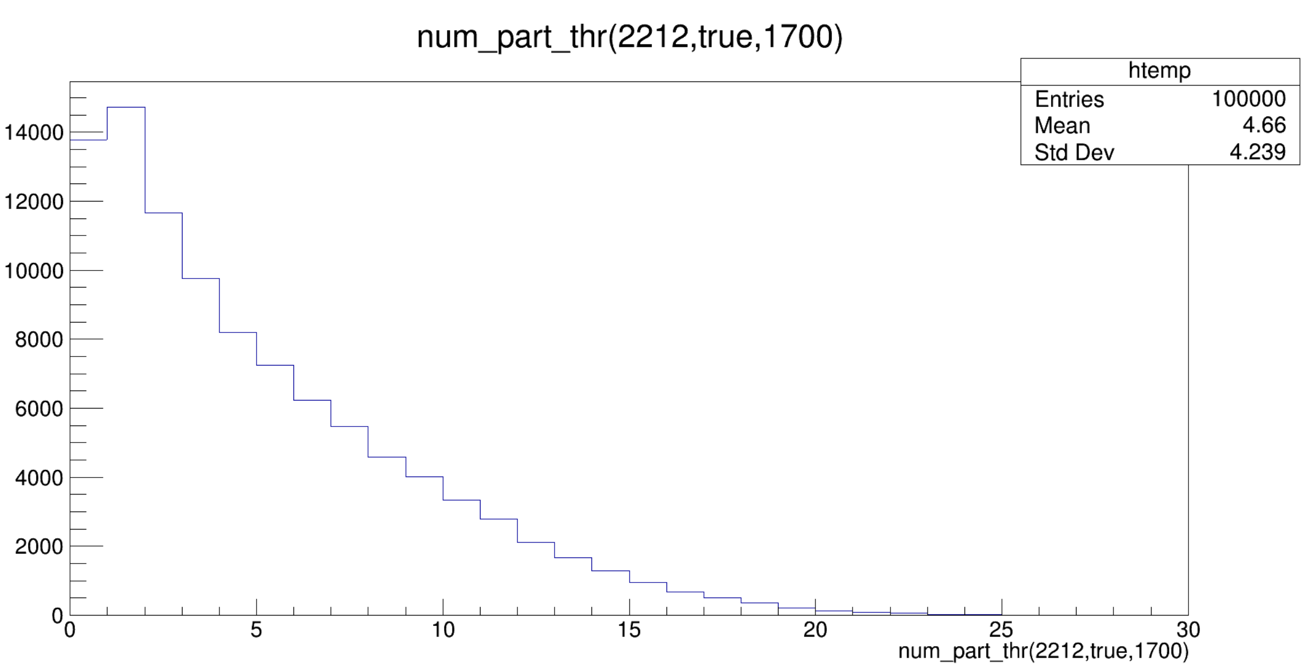
1 TeV ν_μ CC Interactions on W target

- **Multiplicity**
- **Leading Hadron Energy**

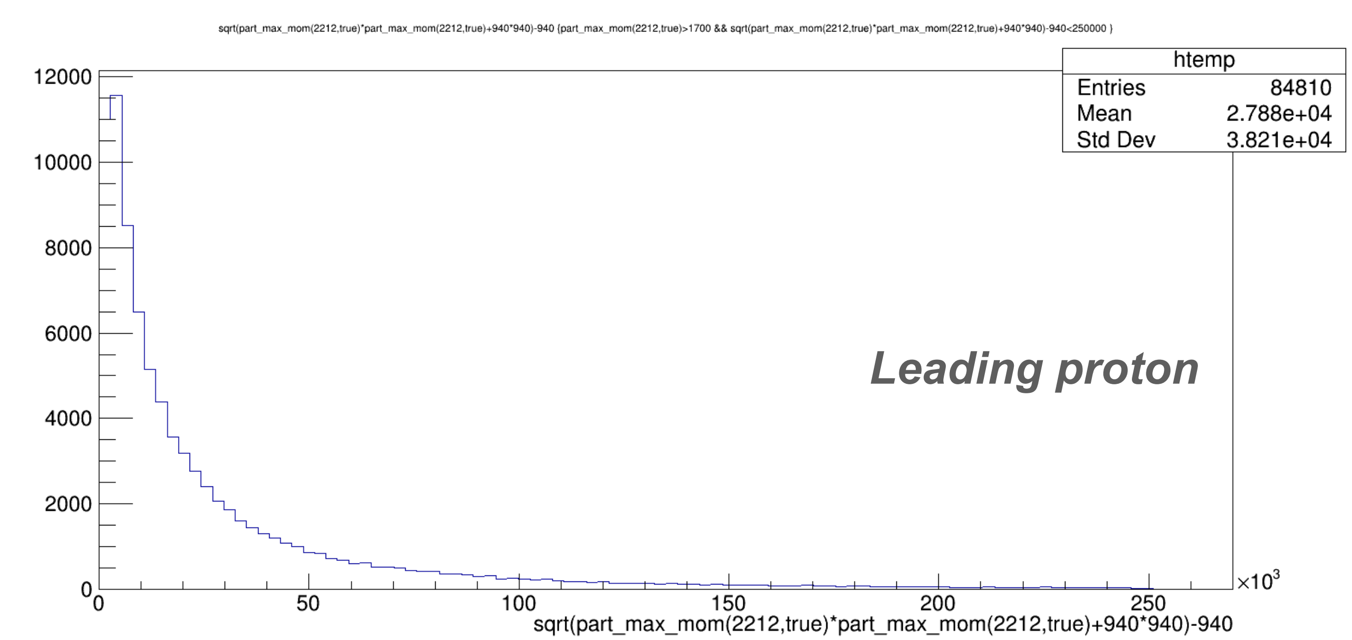


Charged pions multiplicity



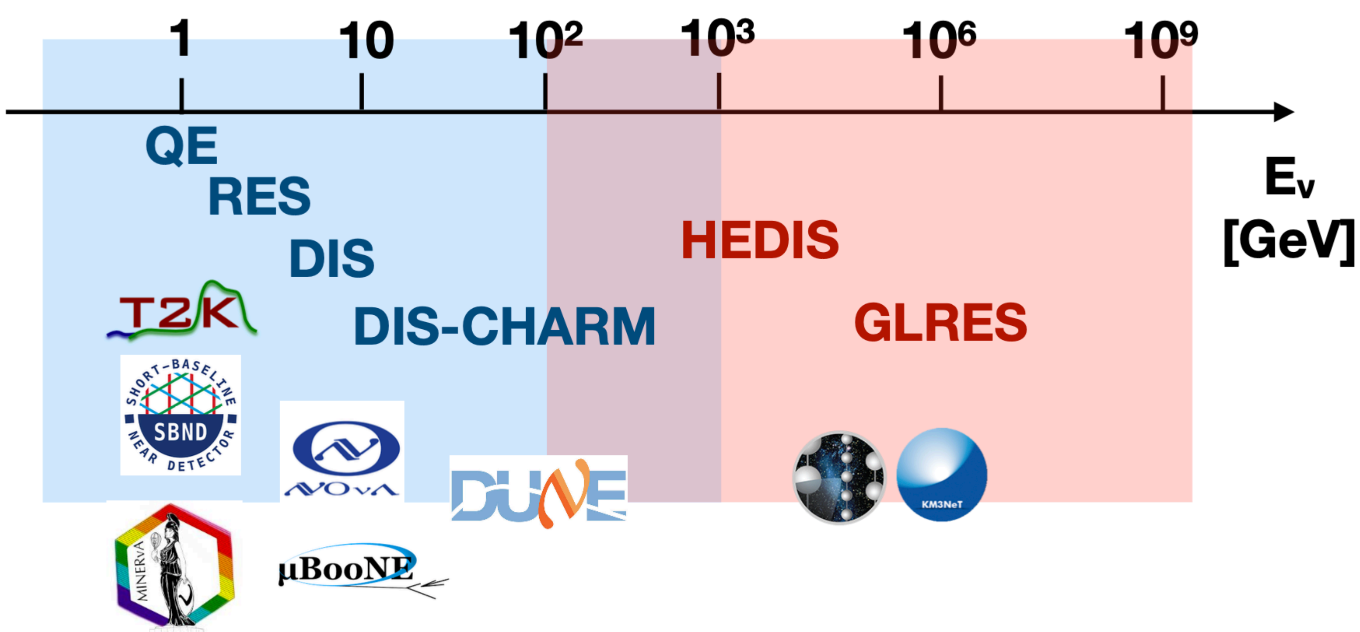


Proton (>1 GeV) multiplicity



GENIE:

- Widely used by long baseline experiments:
  - Tunes -> different models can be implemented.
  - Reweight -> propagate model uncertainties.
  - Relevant in the few GeV regime.
- New community -> neutrino telescopes
  - Mainly focused in the TeV-PeV range.
  - Different requirements wrt LBE.



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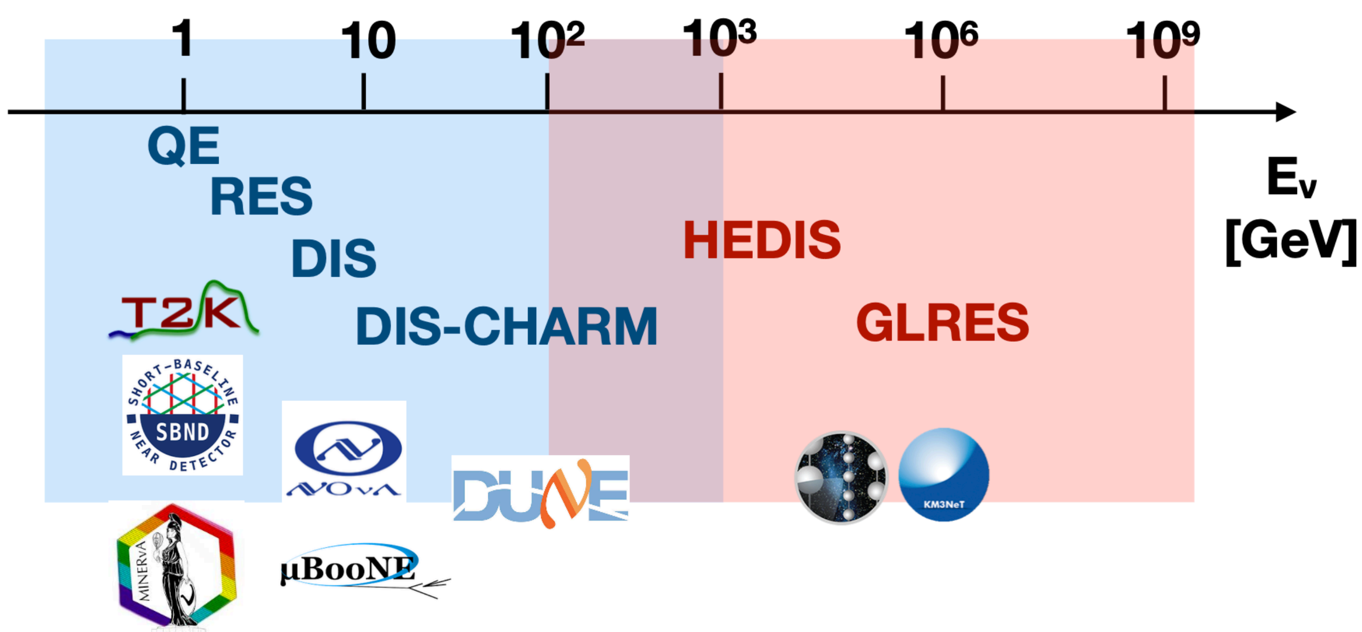
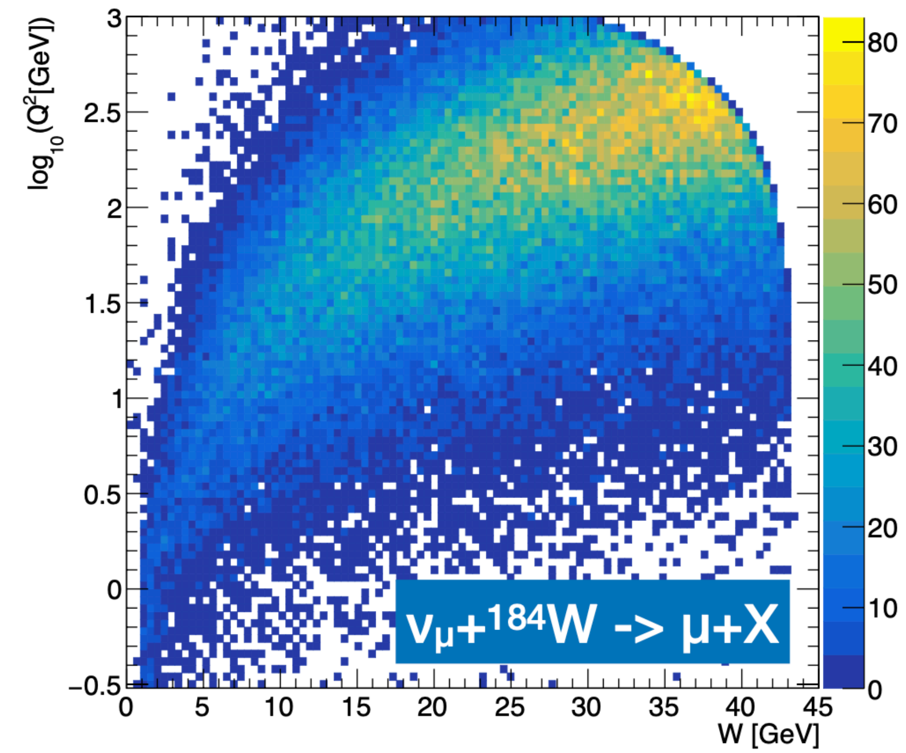
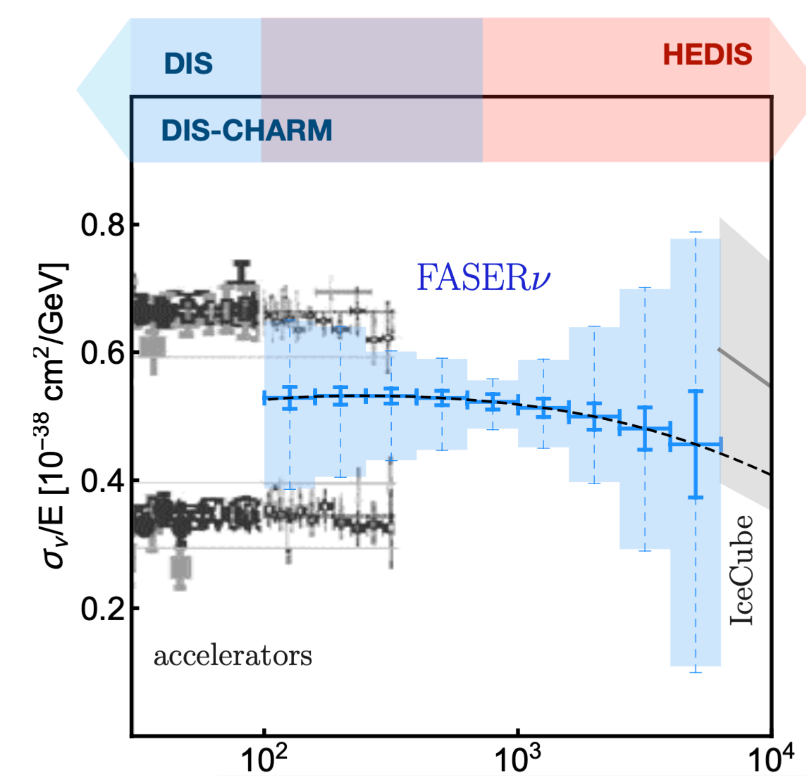




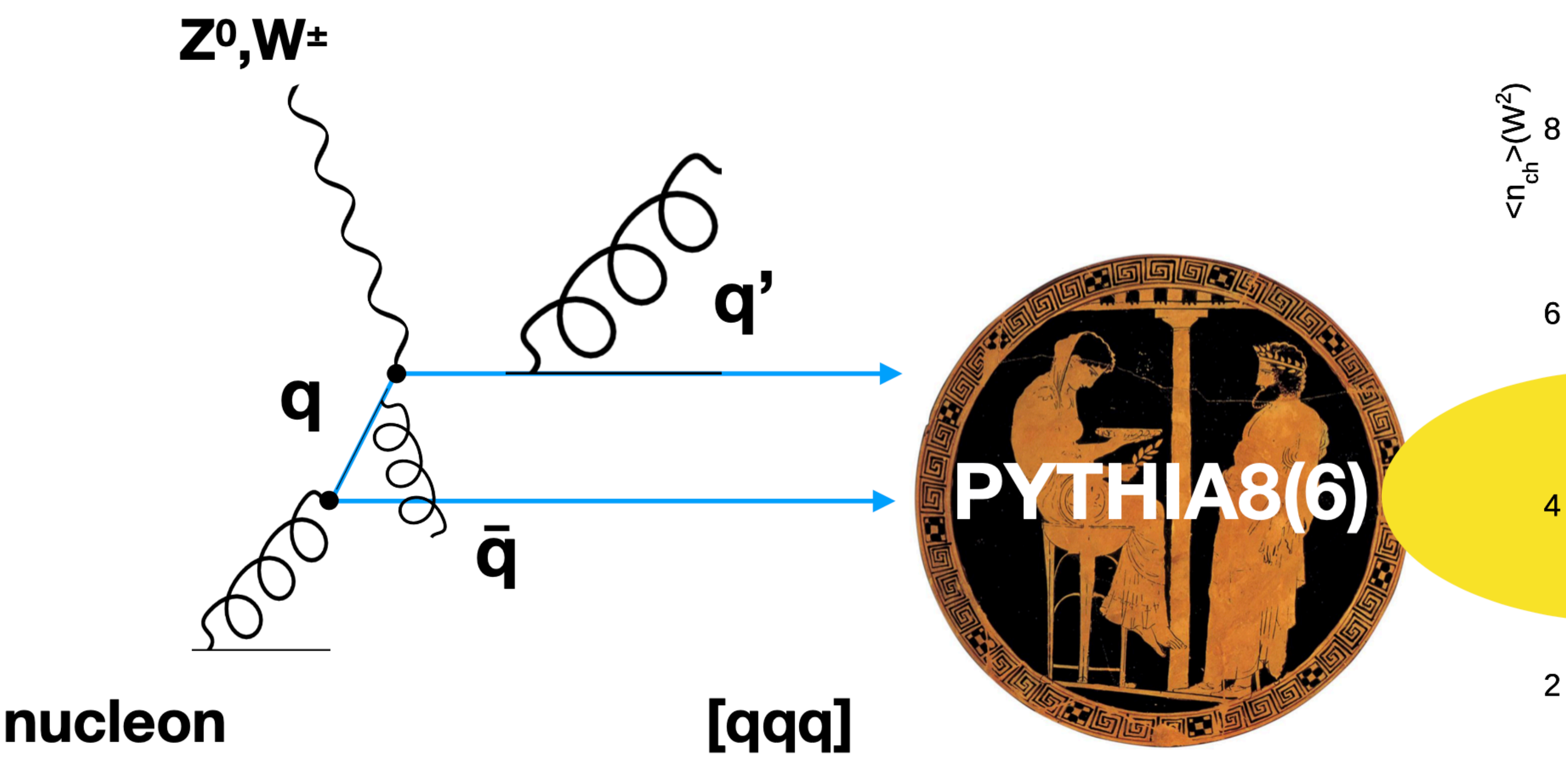
Cross Section Models

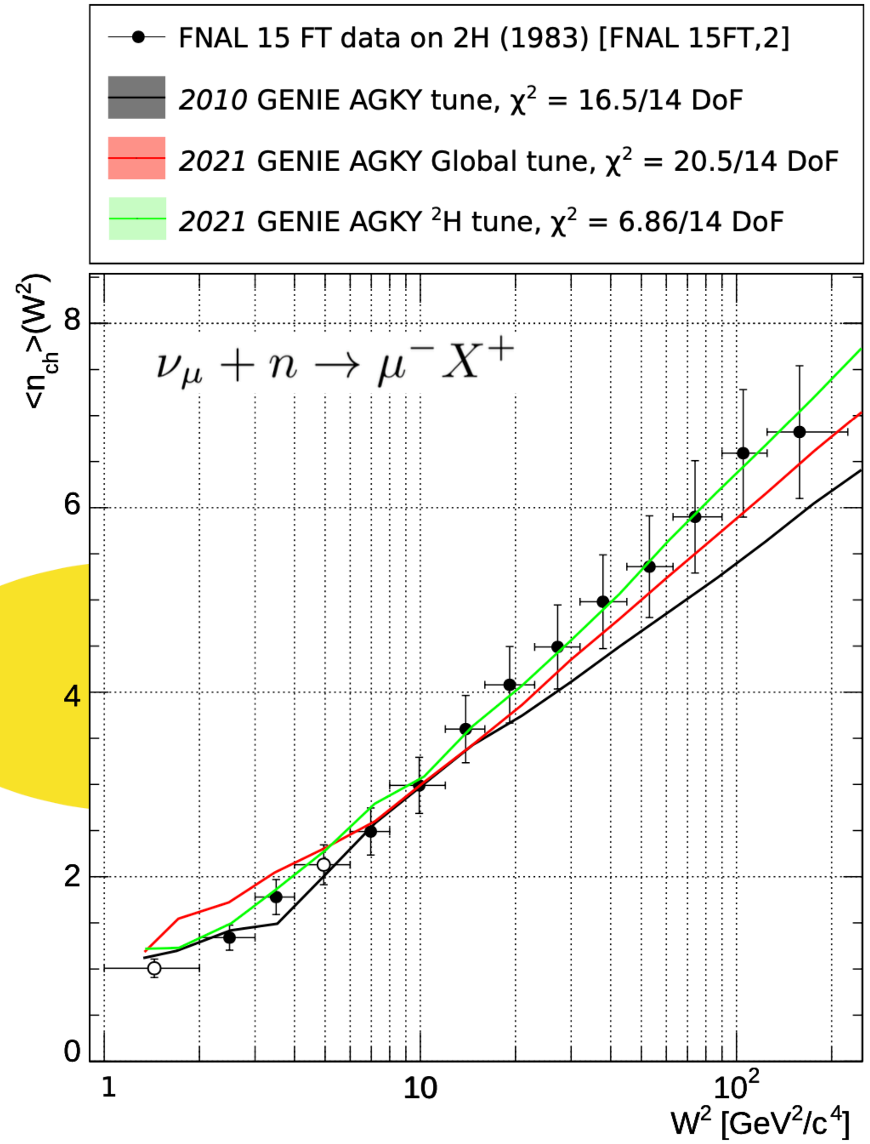
	Model	Structure Function ($C_{ij}\otimes$PDF)
DIS	A. Bodek et al. (2005)	LO⊗LO (GRV98 Q_0^2=0.8)
DIS-CHARM	M. Aivazis et al. (1994)	LO⊗LO (GRV98 Q_0^2=0.8)
HEDIS	A. Cooper et al. (2011) V. Bertone et al. (2018) A. Garcia et al. (2020)	NLO⊗NLO (HERAPDFNLO Q_0^2=1) NLO⊗NLO (NNPDF31LHCb Q_0^2=2.69) NLO⊗NLO (NNPDF31LHCb Q_0^2=2.69)



Hadronization

- Hit and remnant quarks (partonic level) input to PYTHIA for W>3GeV.
  - Thorough camping to understand hadronization at low W.





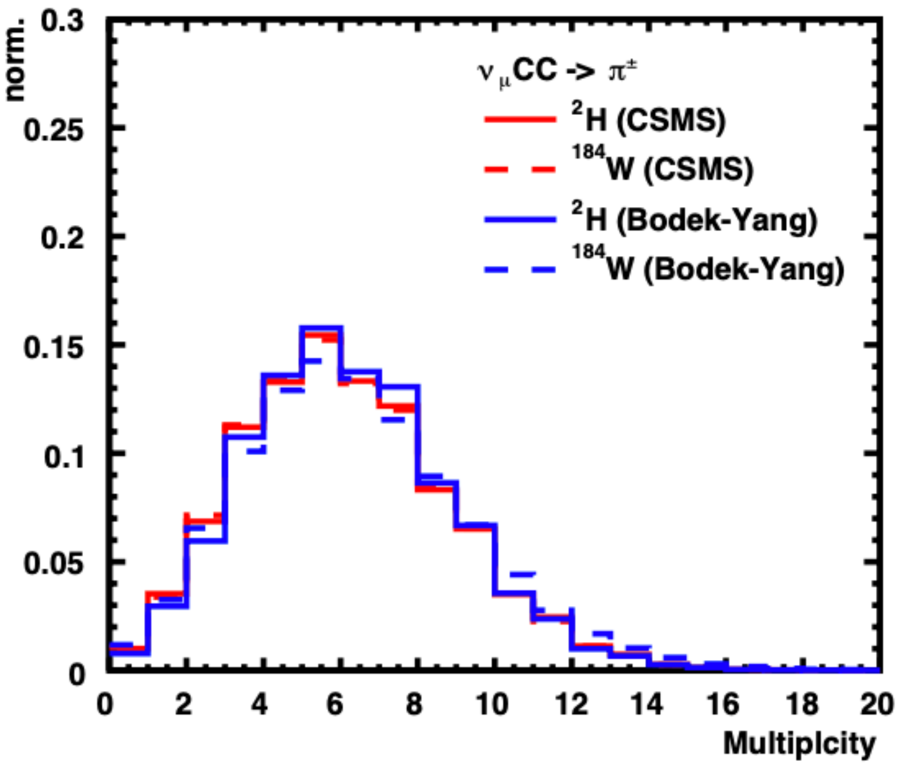
- Several aspects are being currently study:
  - Effect of nucleon and nuclear PDFs.
  - Heavy quark contribution in the Structure Functions.
  - Parton showers using >LO formalism.

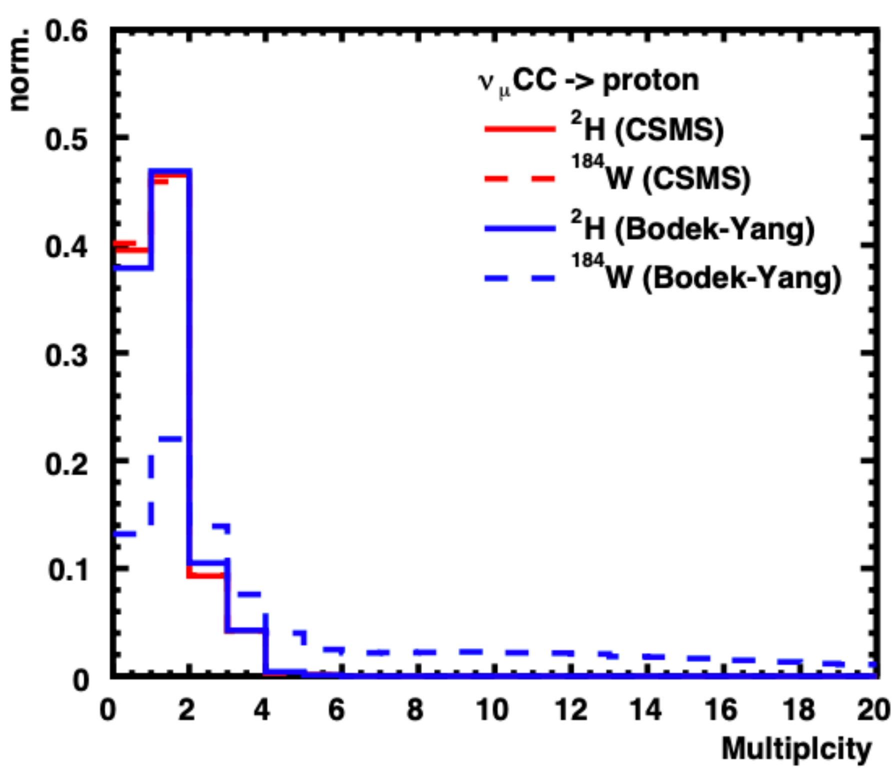
GENIE:

Alfonso Garcia at 3rd FPF Meeting

1 TeV ν_μ CC Interactions on W target

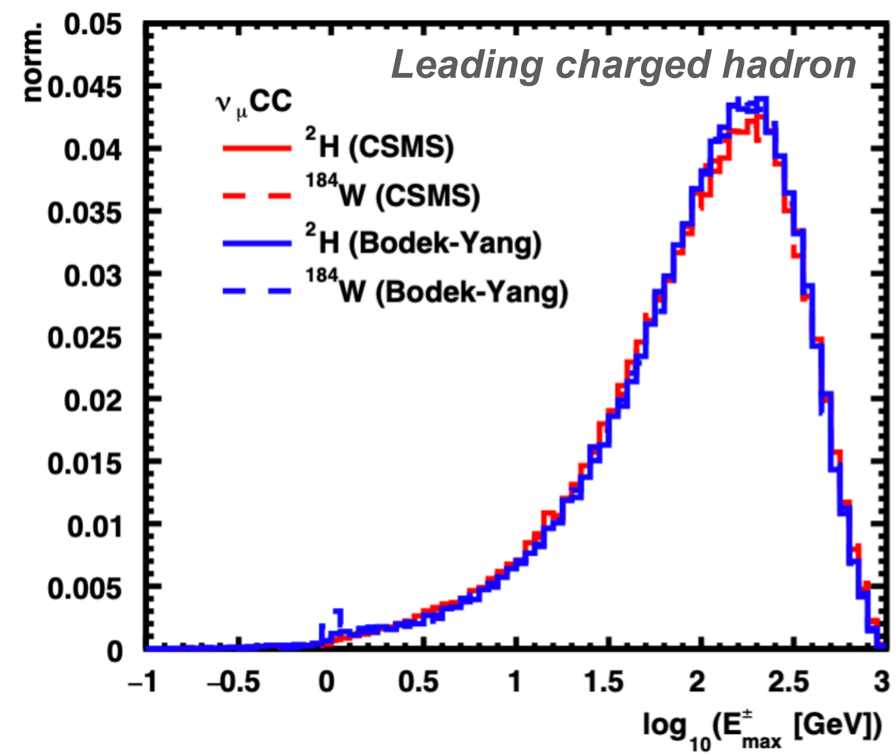
- **Multiplicity**
- **Leading Hadron Energy**

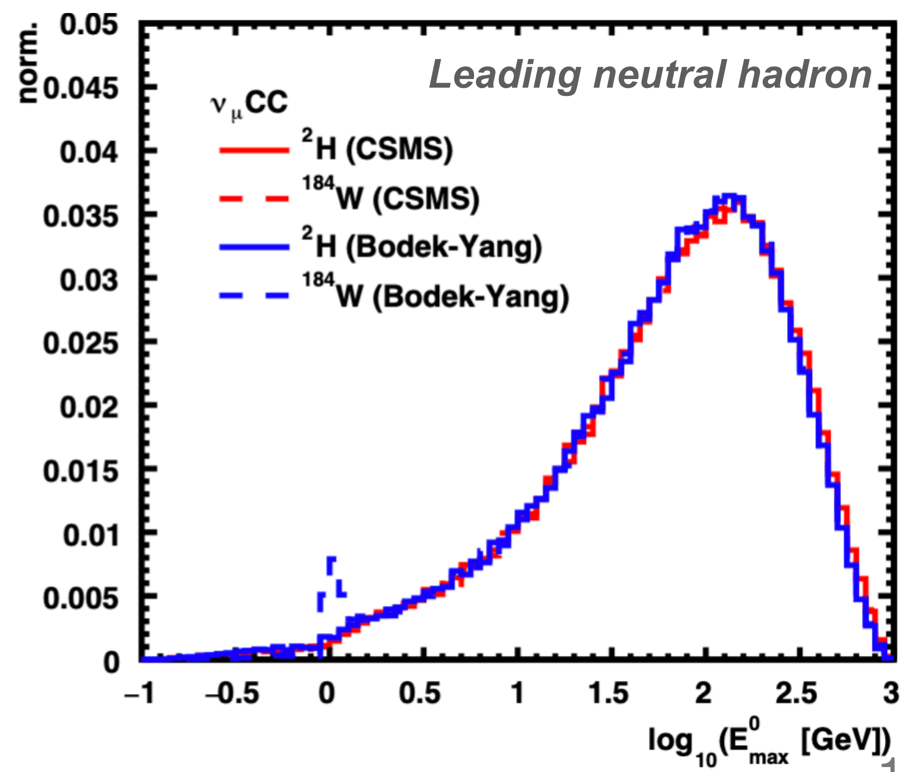




- Bodek-Yang: Default model used by long baseline experiments
  Includes FSI

- CSMS: Default model used by neutrino telescopes

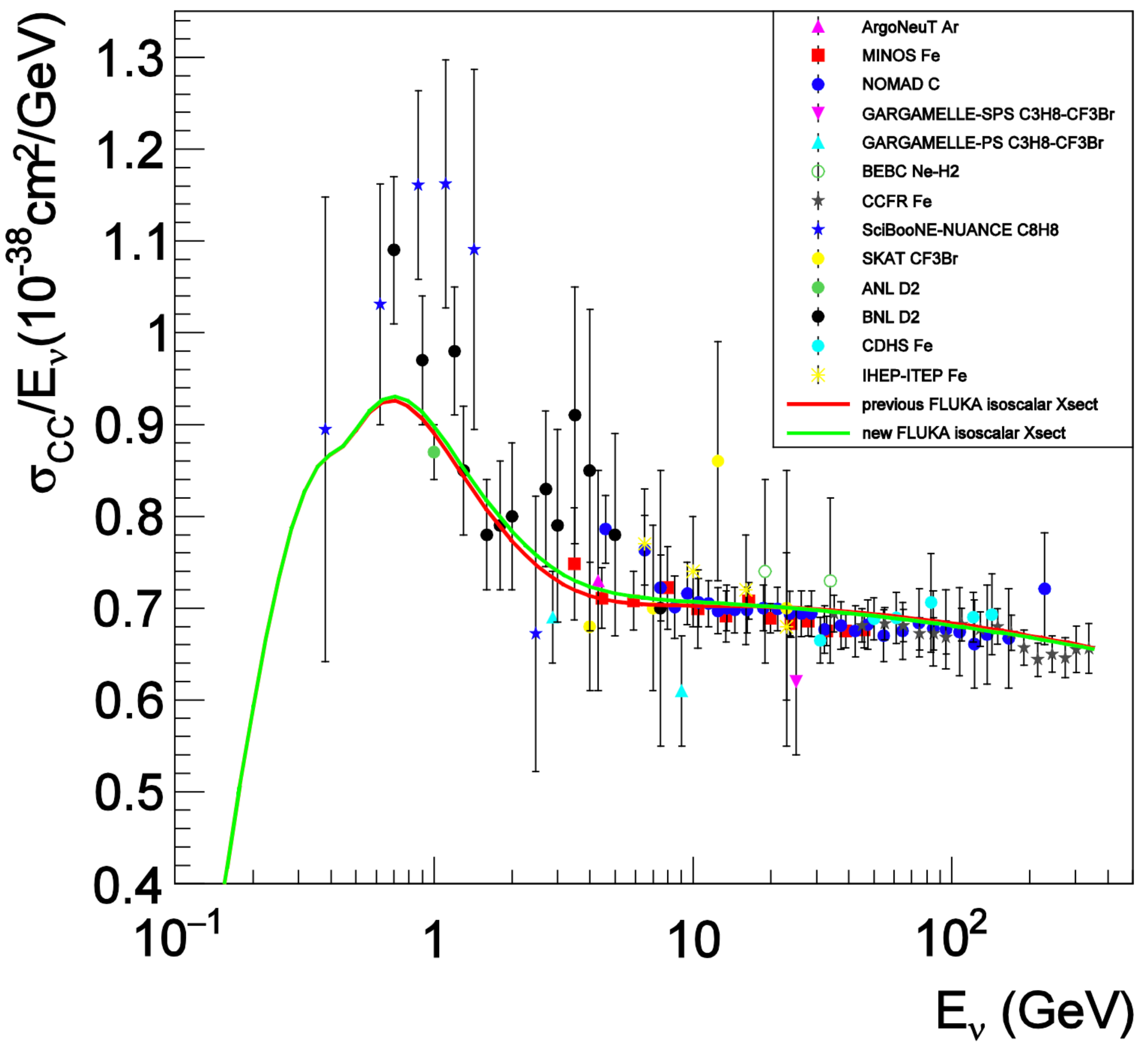




FLUKA:

Paola Sala at 3rd FPF Meeting

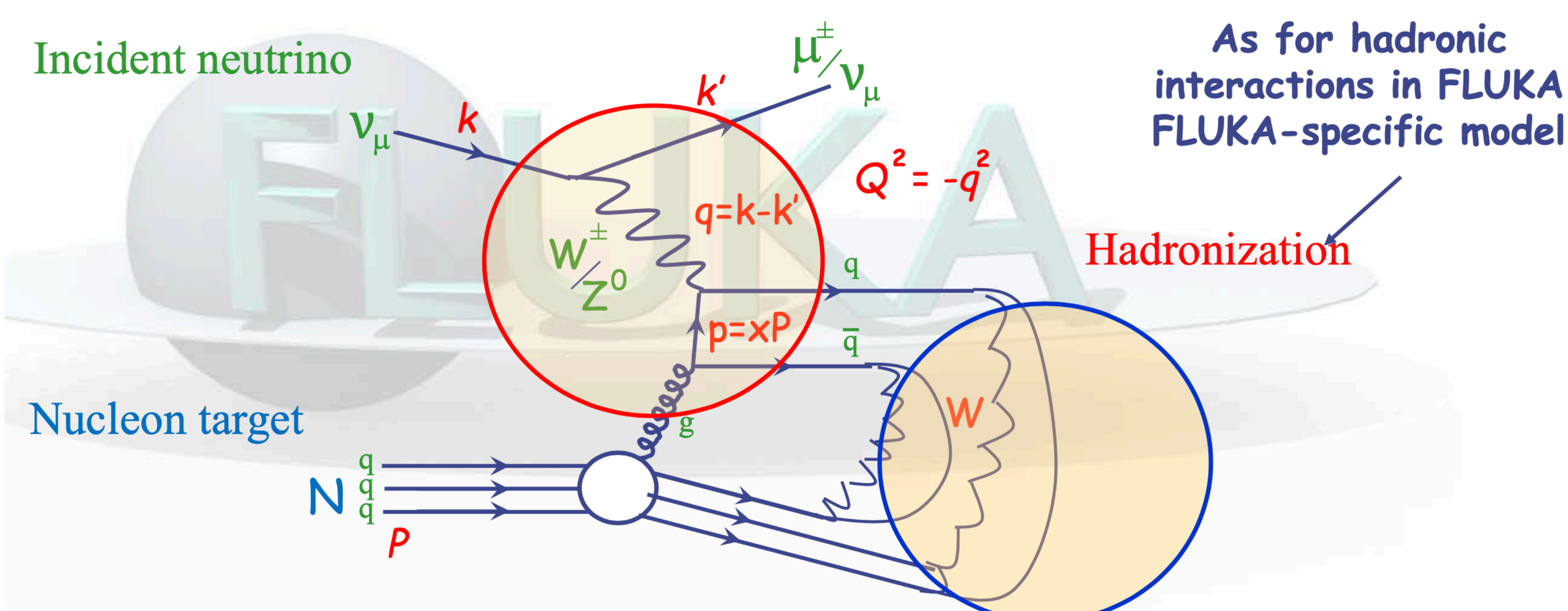
- Generators of neutrino-nucleon interactions: QE, RES, DIS
- Embedded in FLUKA nuclear models for Initial State and Final State effects
- Products of the neutrino interactions can be directly transported in the detector (or other) materials
- Used for all ICARUS simulations/publications



DIS Model

(NUNDIS)

FLUKA hadronization and nuclear interactions work well independently of primary interaction vertex



Hadronization

- Assumes chain universality
- Fragmentation functions from hard processes and e+e− scattering
- Transverse momentum from uncertainty considerations
- Mass effects at low energies (change fragmentation function to account for the need to create real hadrons)
- Chains generated at very low energy→ create single/few resonances
- Chains generated at low energy → **"phase space explosion"** constrained in p_T , including baryons, mesons, resonances.

a special FSI : Formation zone

Naively: "materialization" time (originally proposed by Stodolski).
Qualitative estimate:

In the frame where $p_{||} = 0$

$$\bar{t} = \Delta t \approx \frac{\hbar}{E_T} = \frac{\hbar}{\sqrt{p_T^2 + M^2}}$$

Particle proper time

$$\tau = \frac{M}{E_T}\bar{t} = \frac{\hbar M}{p_T^2 + M^2}$$

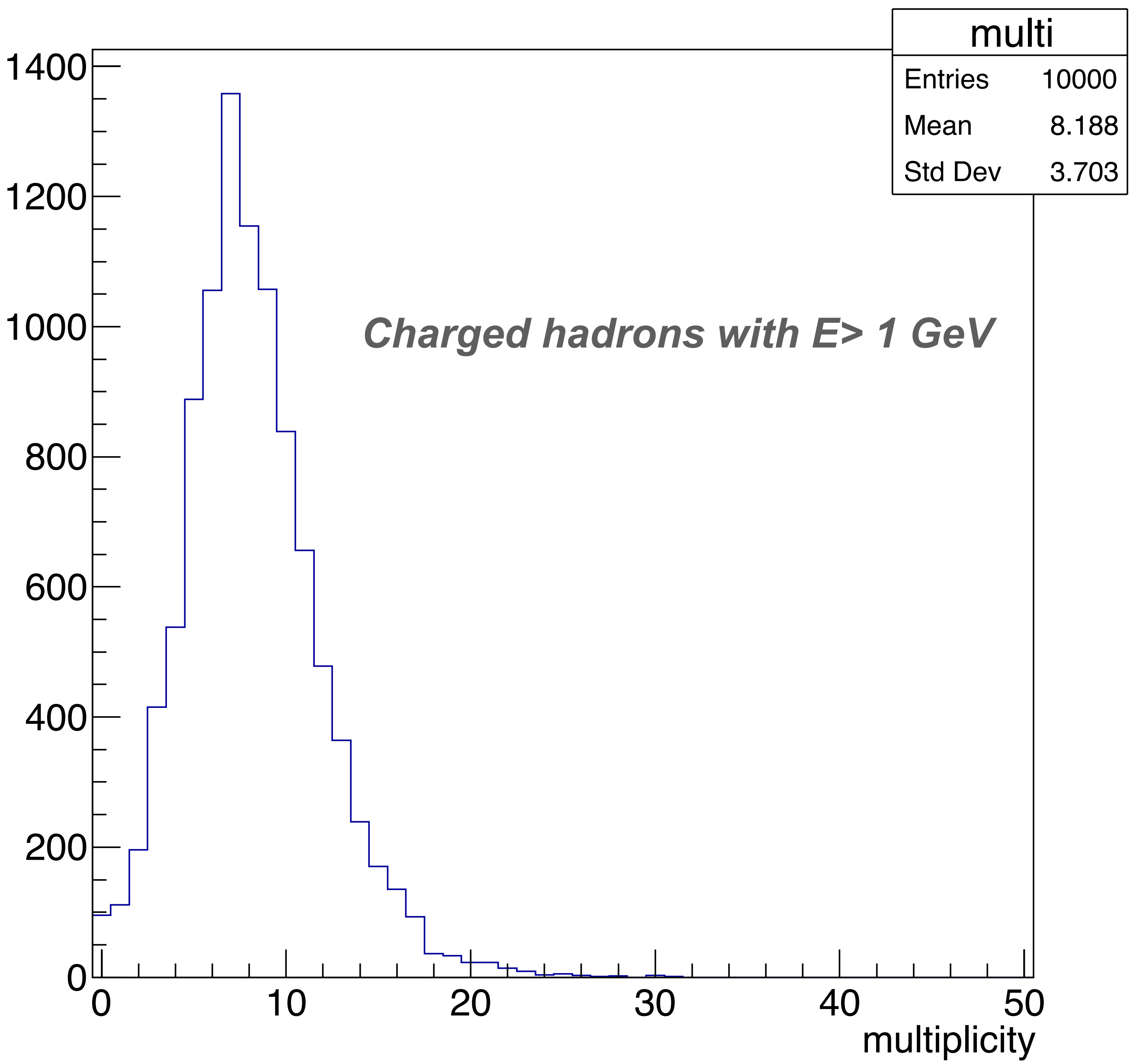
Going to the nucleus system

$$\Delta x_{for} \equiv \beta\, c \cdot t_{lab} \approx \frac{p_{lab}}{E_T}\bar{t} \approx \frac{p_{lab}}{M}\tau = k_{for}\frac{\hbar p_{lab}}{p_T^2 + M^2}$$

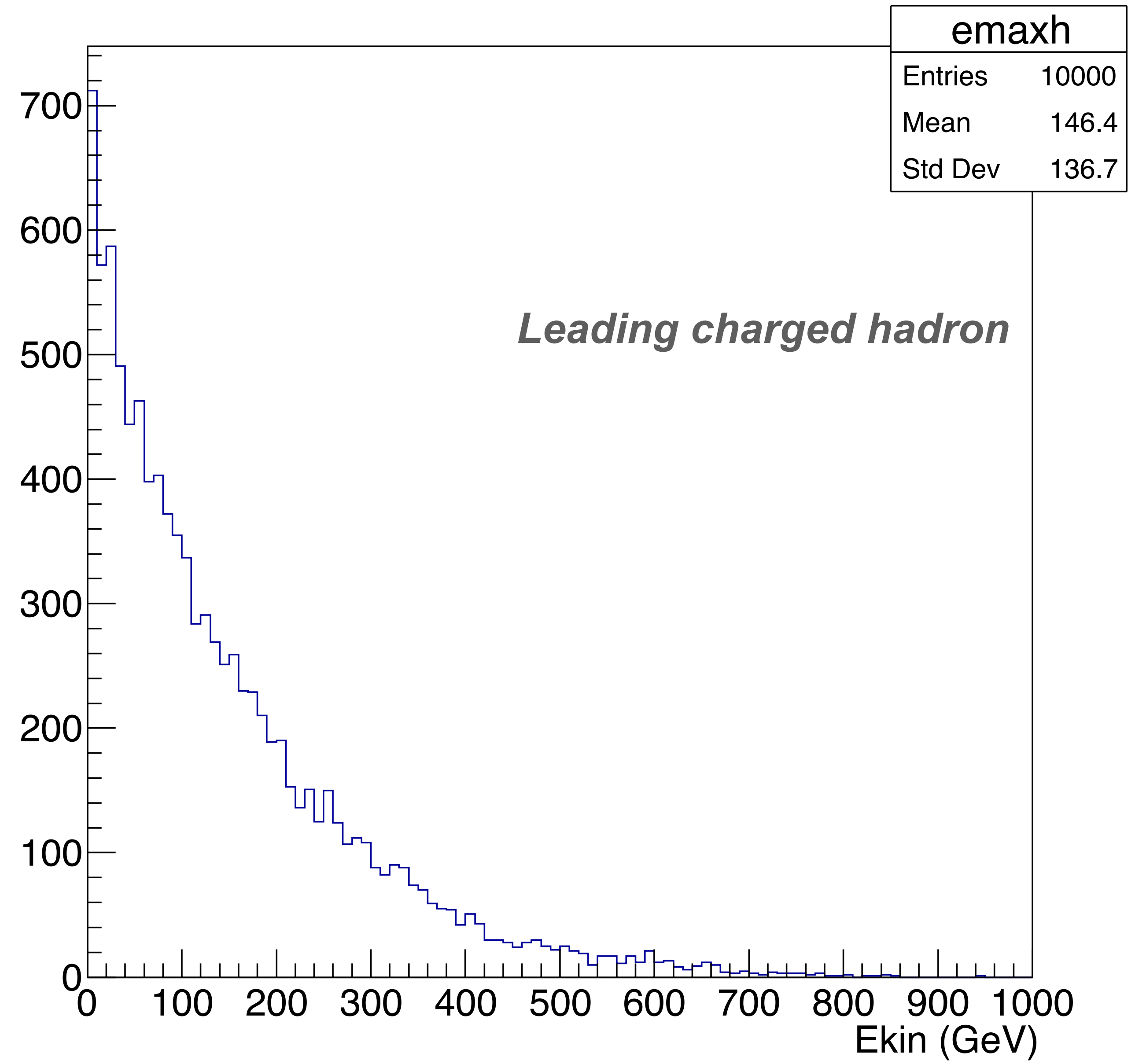
Condition for possible reinteraction inside a nucleus: $\Delta x_{for} \le R_A \approx r_0 A^{\frac{1}{3}}$

1 TeV ν_μ CC Interactions on W target

- **Multiplicity**



- **Leading Hadron Energy**



- Quantum-Kinetic Theory and Event Generator
  based on a BM solution of Kadanoff-Baym equations, allows for off - shell propagation

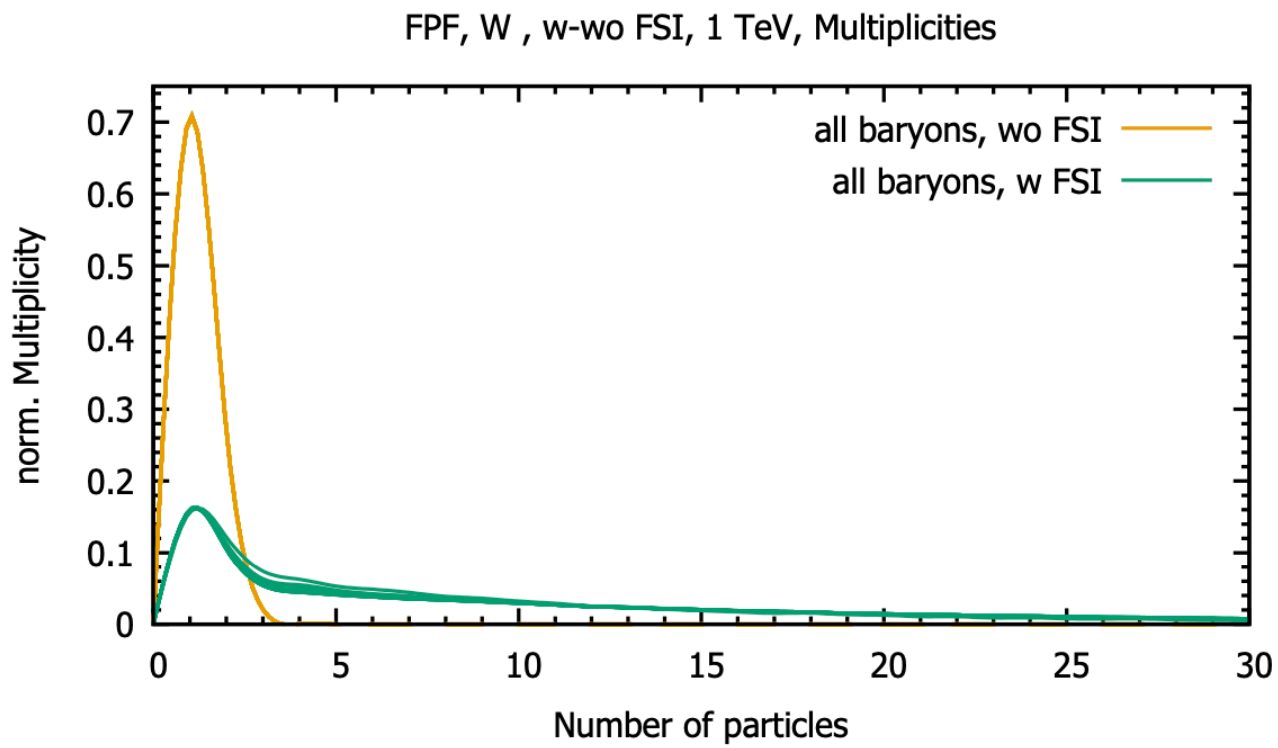
- GiBUU propagates phase-space distributions, not particles

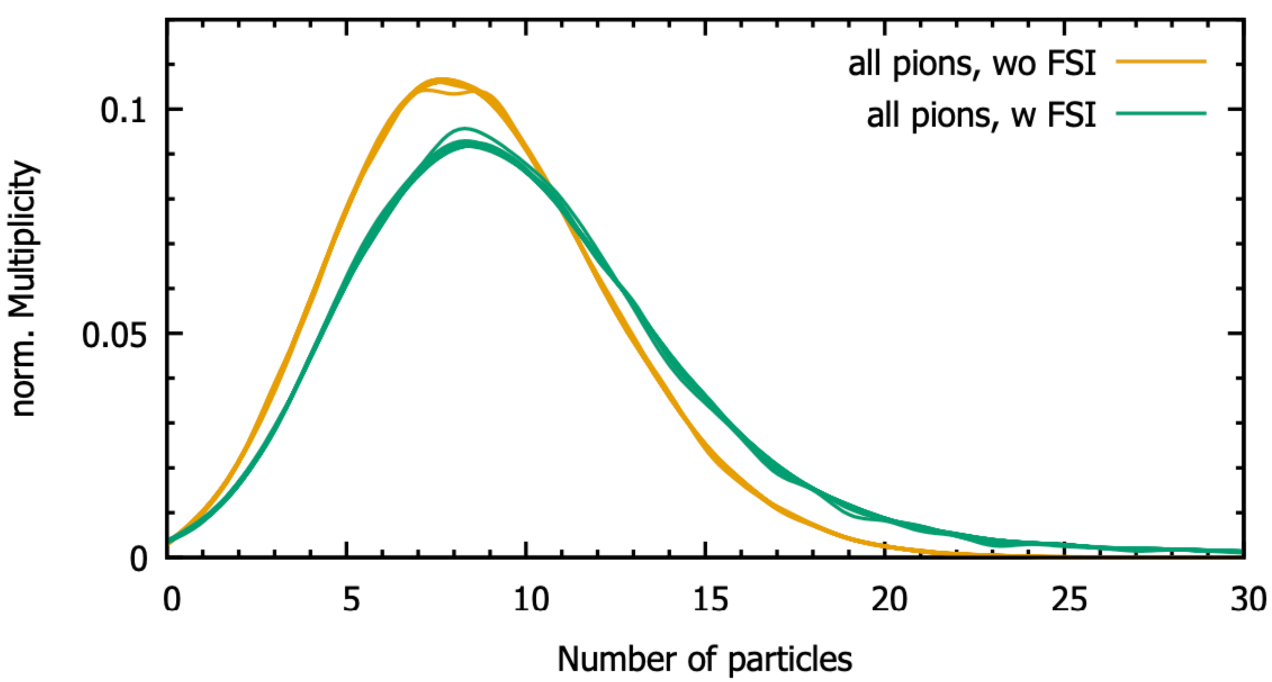
Ingredients

- Initial State Interactions
  - Treats all ISI processes: QE, RES, 2p2h, DIS (switch to DIS = PYTHIA at W ~ 3 GeV)
  - Contains large number of N* resonances and mesons, up to charm
  - Contains modelling of color transparency (Q^2 > 14 GeV^2 for N-N collisions)
- Final State Interactions
  - Fully relativistic, relativistically correct collision criteria for FSI
- Widely tested on
  - heavy-ion reactions (< 20 AGeV), p + A, π + A
  - (e, A) reactions (JLAB: E < 6 GeV, HERMES: 28 GeV, EMC: 230 GeV)
  - (ν, A) reactions (MiniBooNE, T2K, MINERvA)

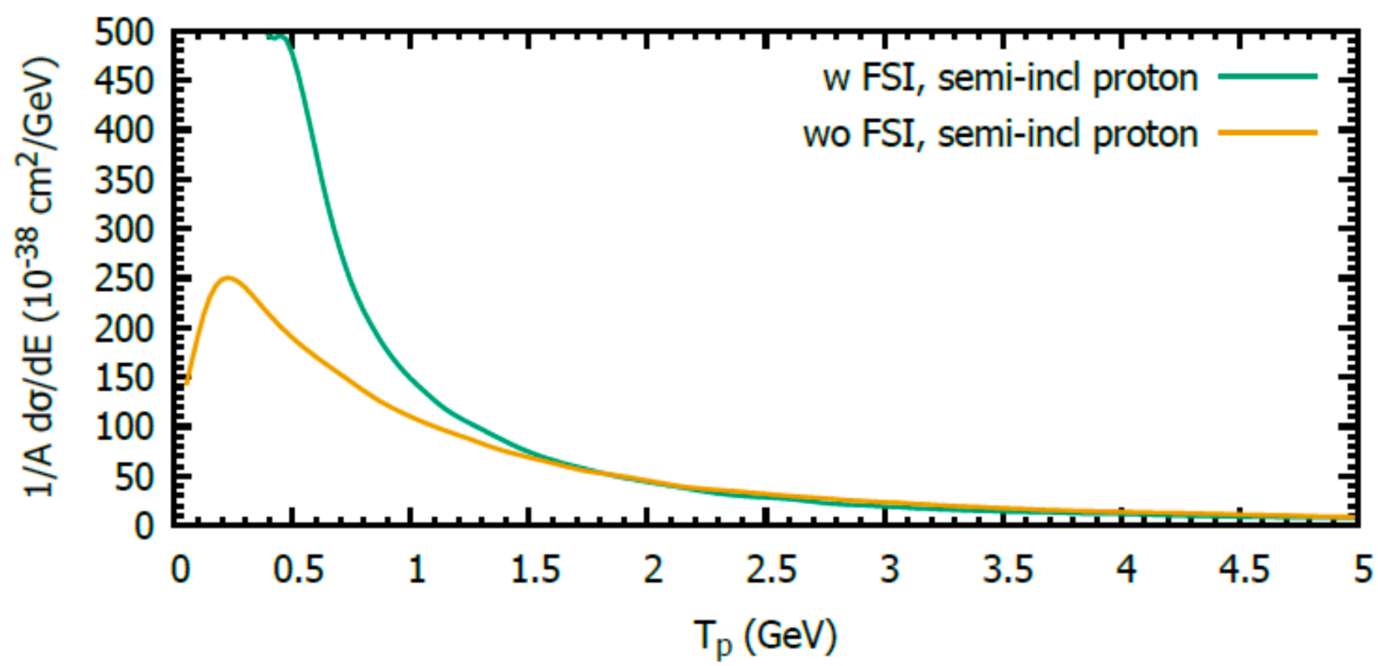
1 TeV ν_μ CC Interactions on W target

- **FSI Effects on Multiplicity**





- **FSI Effects in Energy Spectra**



- FSI sets in below 1.5 GeV kinetic energy

- Consequence of “Avalanche Effect” where initial nucleons collide with others on the way out of the target.

Summary and Outlook

- MC event generators play key role in experiments
- Participation of widely used neutrino Monte-Carlo generators is vital to the success of the FPF
- More details coming in the White Paper, includes comparison between different generator predictions
- **Many thanks to generator authors for their contributions!**

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