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High-energy Neutrino Generators

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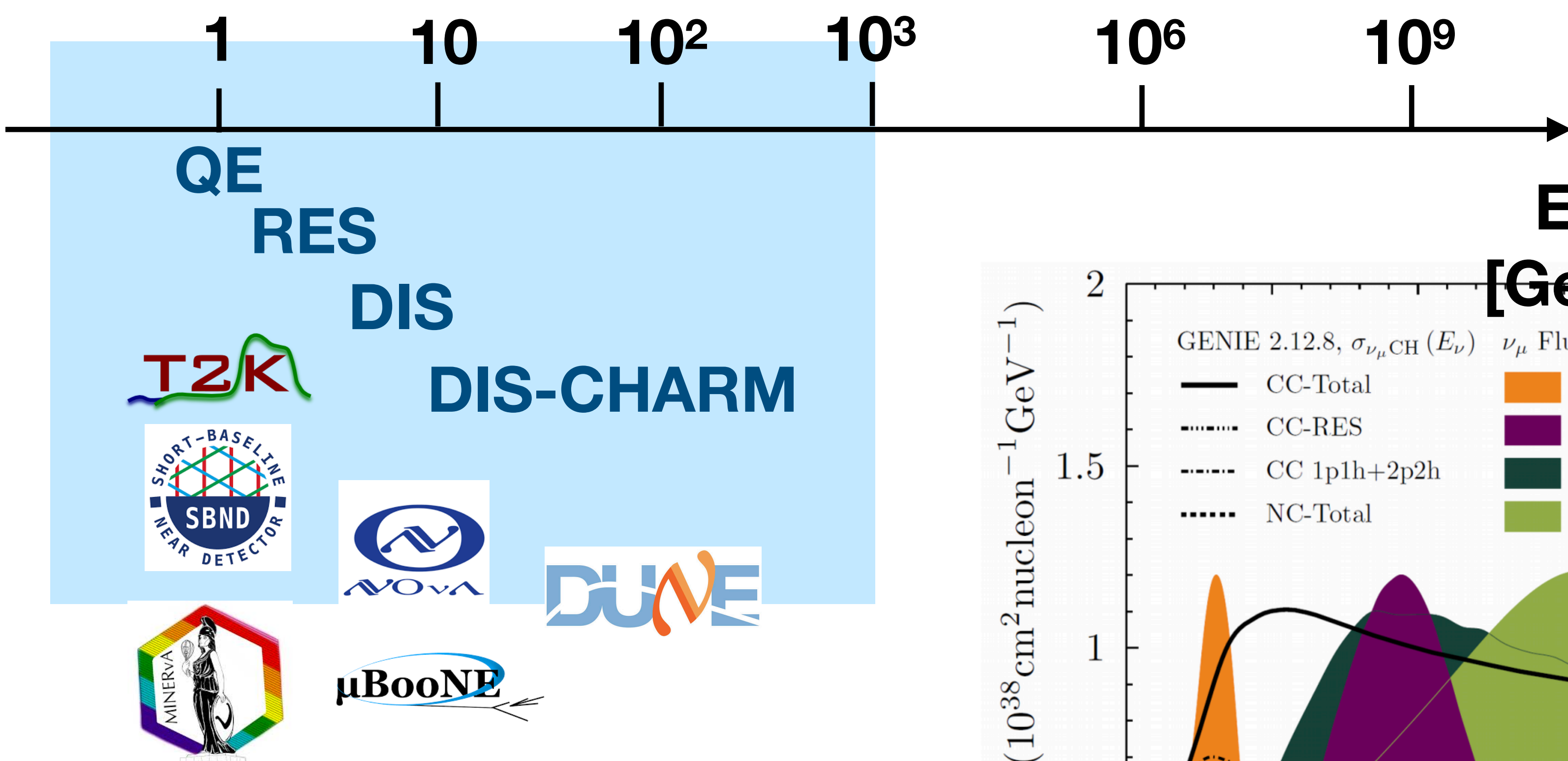
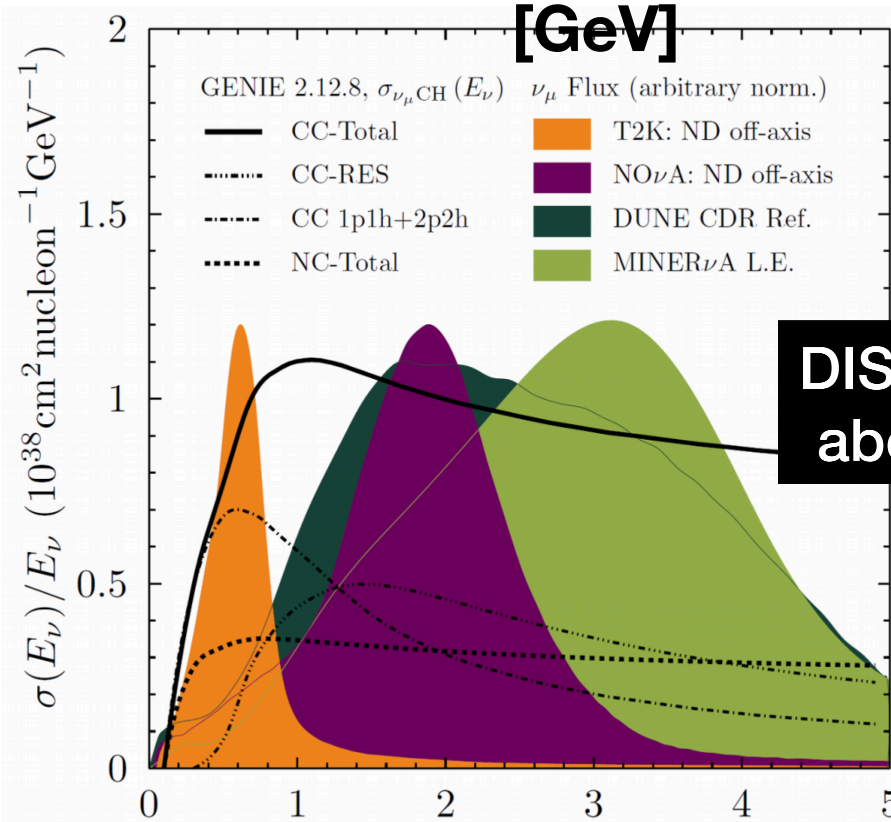
VEGA Valencia Experimental Group of Astroparticles

Different energies -> different needs

- Several frameworks used for long baseline experiments -> GENIE/NuWro/NEUT/GiBUU
  - Tunes -> different models can be implemented.
  - Reweight -> propagate model uncertainties.
  - Relevant in the few GeV regime.





H.Tanaka, TAUP2019

DIS dominates above 10GeV

Different energies -> different needs

- Several frameworks used for long baseline experiments -> GENIE/NuWro/NEUT/GiBUU
  - Tunes -> different models can be implemented.
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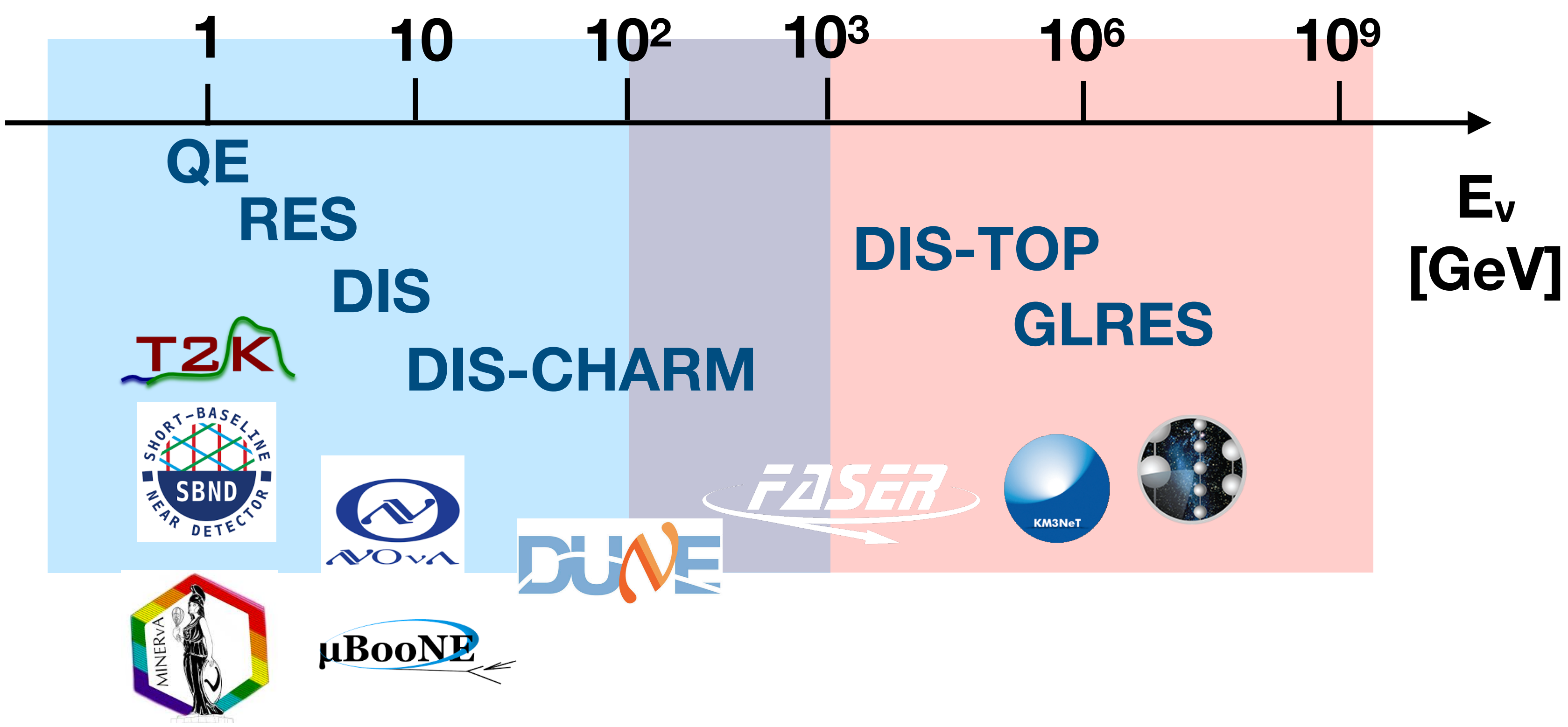
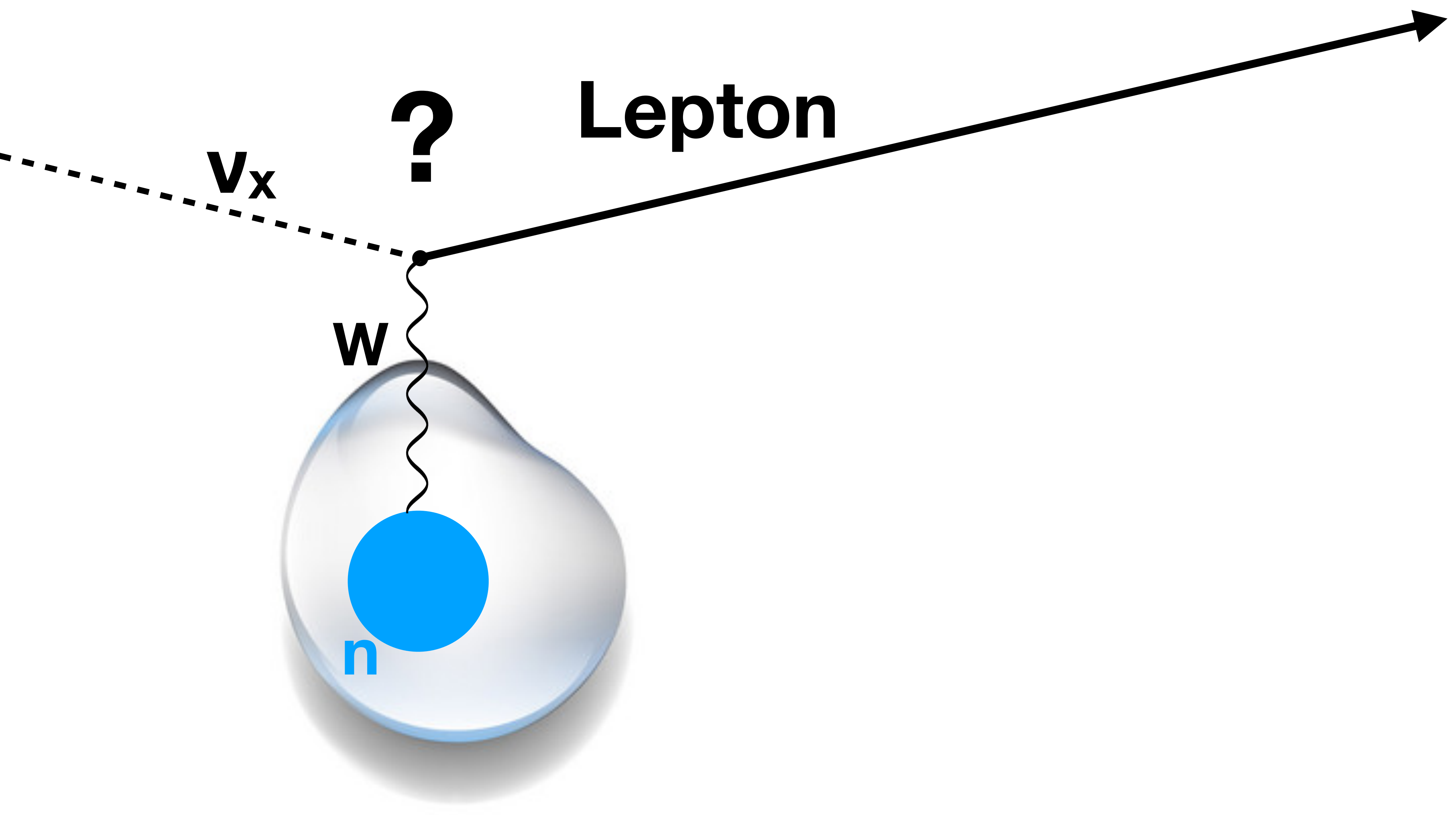


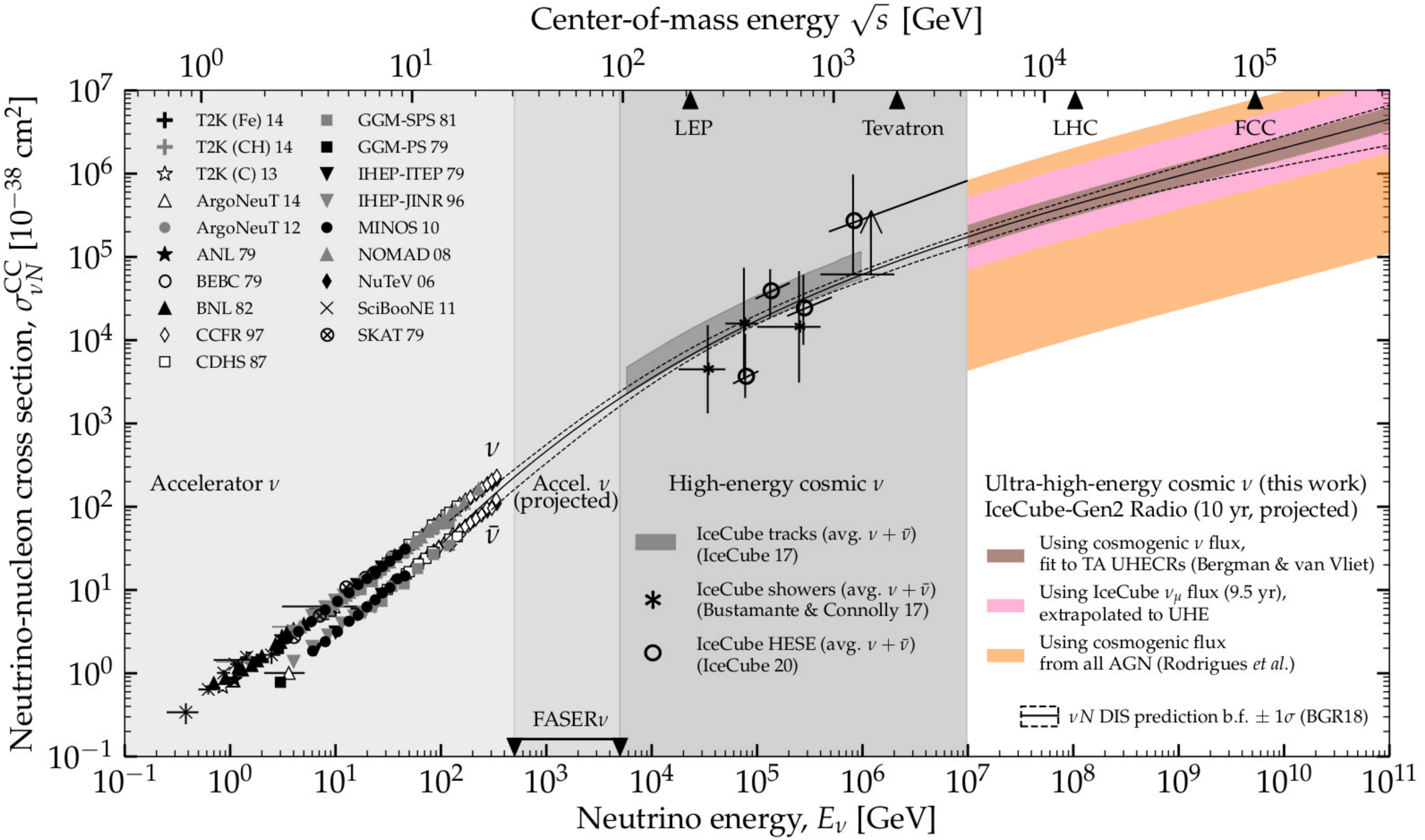
- New community -> neutrino telescopes
  - Mainly focused in the TeV-PeV range.
  - Different requirements wrt LBE.

Lepton level



Available data

- 100GeV-1TeV region very important for studies with atmospheric neutrinos:
  - Precise measurements up to 300GeV (NuTev, NOMAD,etc.).
  - First measurements at E>10TeV from IceCube.
  - Promising prospects from FASERnu in the gap.



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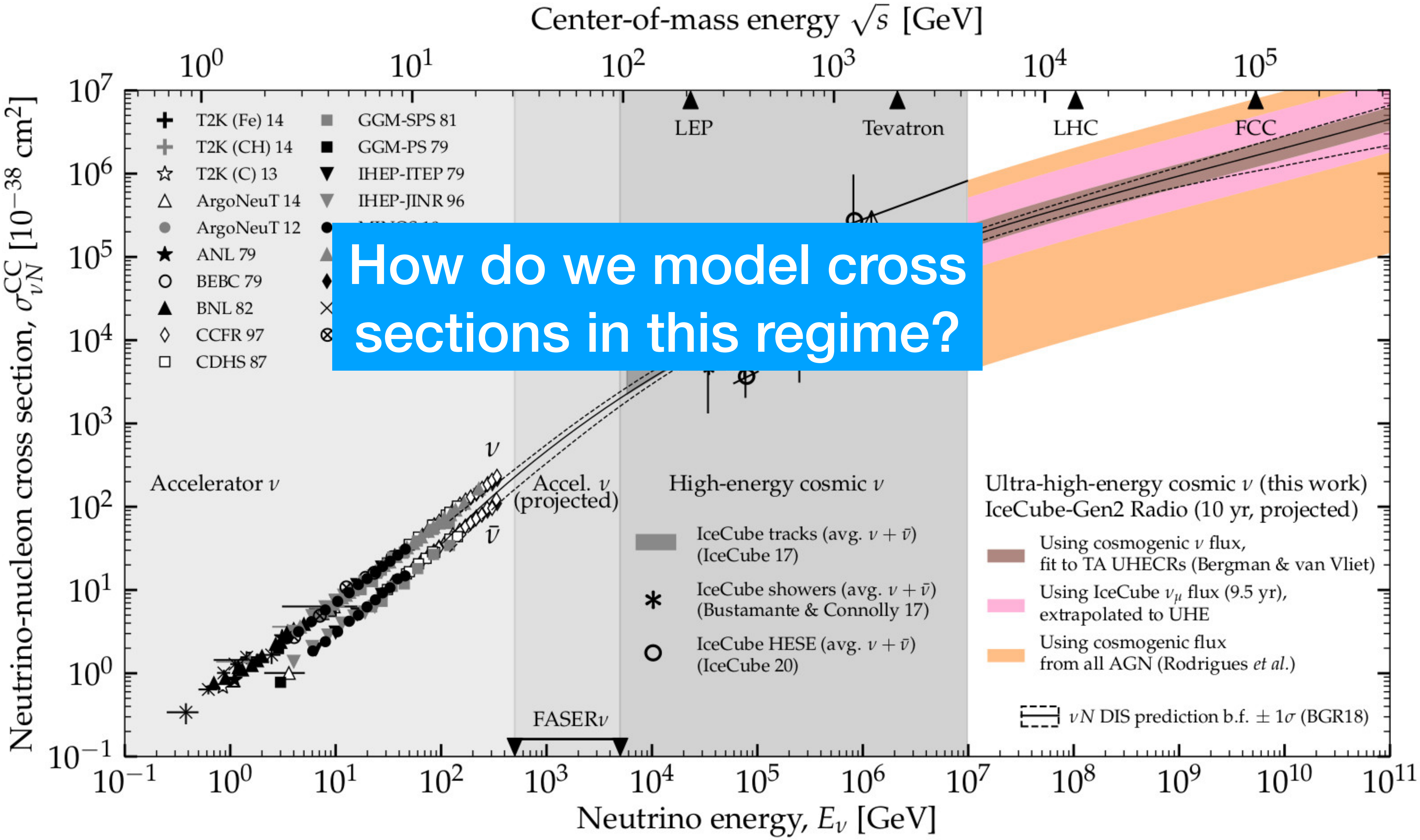
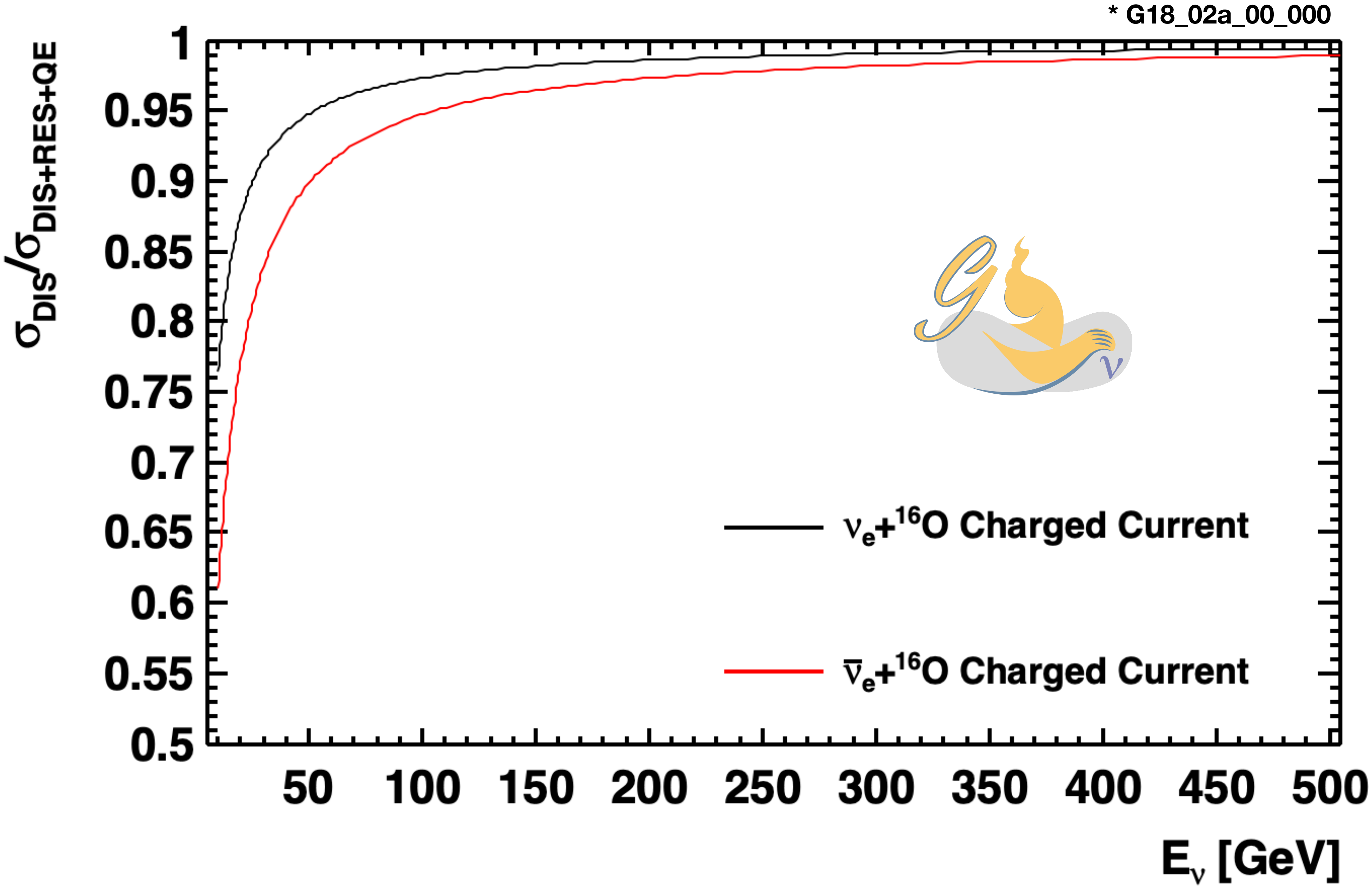


>10GeV

- Above 50GeV non-DIS contribution is <5%.
- Resonant contribution for antineutrinos enhanced.



DIS model

https://arxiv.org/pdf/hep-ph/0107261.pdf

$$\frac{\mathrm{d}\sigma^{\nu,\bar{\nu}}}{\mathrm{d}x\mathrm{d}y} = \frac{G_F^2 M E_\nu}{\pi}\Big[y\Big(xy + \frac{m_l^2}{2E_\nu M}\Big)F_1 + \Big(1 - y - \frac{Mxy}{2E_\nu} - \frac{m_l^2}{4E_\nu^2}\Big)F_2 \pm \Big(xy(1-\frac{y}{2}) - y\frac{m_l^2}{4ME_\nu}\Big)F_3 + \Big(xy\frac{m_l^2}{2ME_\nu} + \frac{m_l^4}{4M^2E_\nu^2}\Big)F_4 - \frac{m_l^2}{2ME_\nu}F_5\Big]$$

- Lepton mass effects relevant for tau production and low energies.
- Structure functions summarise the dynamics of nuclei.

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

Parton Density Functions

- Calculated from fit to hadron data.
- Lookup tables (x,Q2) .

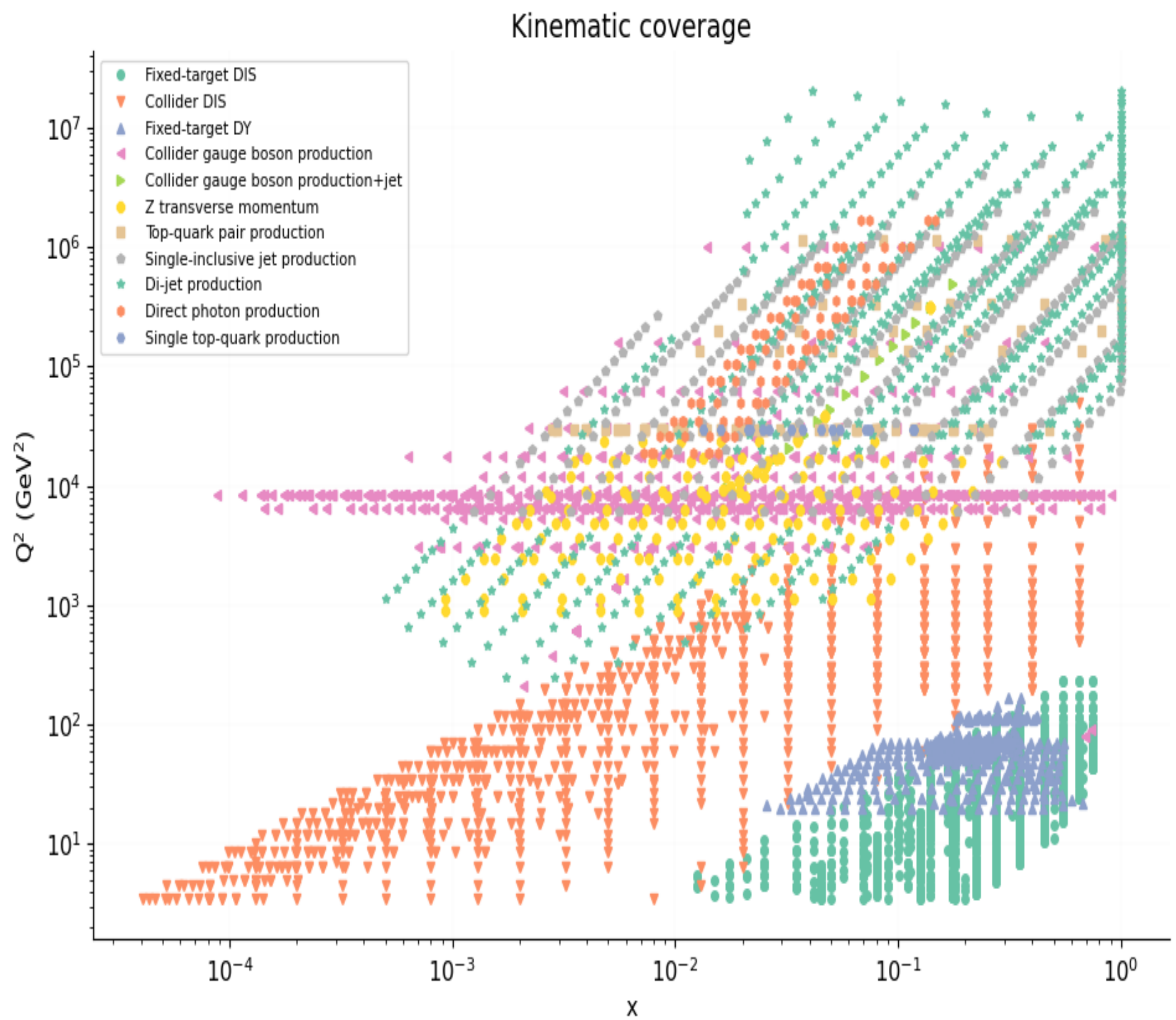
Coefficient functions

- Calculated from Feynman diagrams.
- Depend on order in pQCD.

Phase Space

- Probing different regions of x,Q^2 depending on the energy of the neutrino.

PDFs mainly based on fits to these experiments.



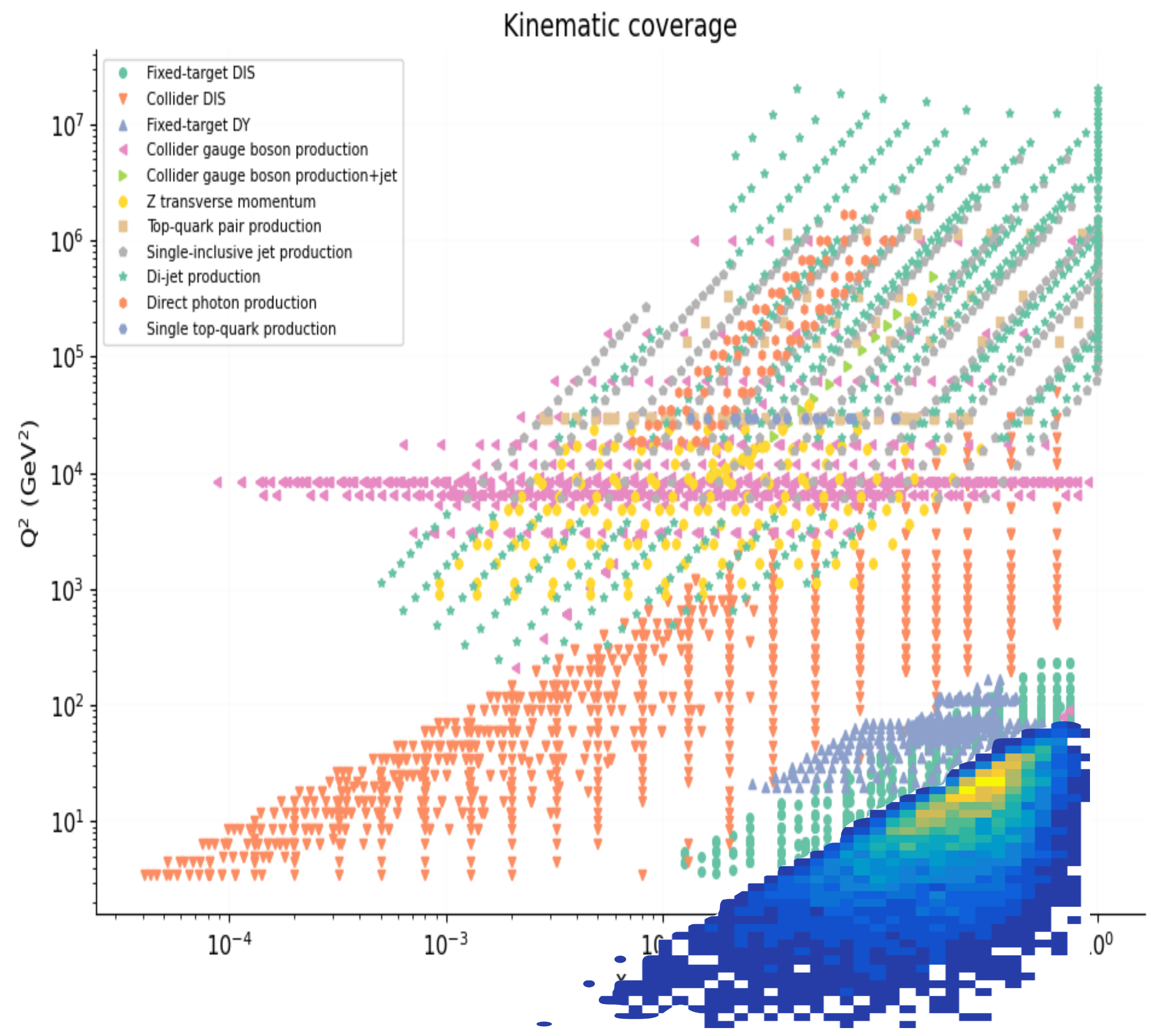
https://nnpdf.mi.infn.it/research/data/

Phase Space

- Probing different regions of x, Q^2 depending on the energy of the neutrino.

Ev = 50GeV

- Low Q2 contributions.
- Double-counting between RES and DIS is important.
- pQCD fails at these energies.
- Non-perturbative QCD corrections.



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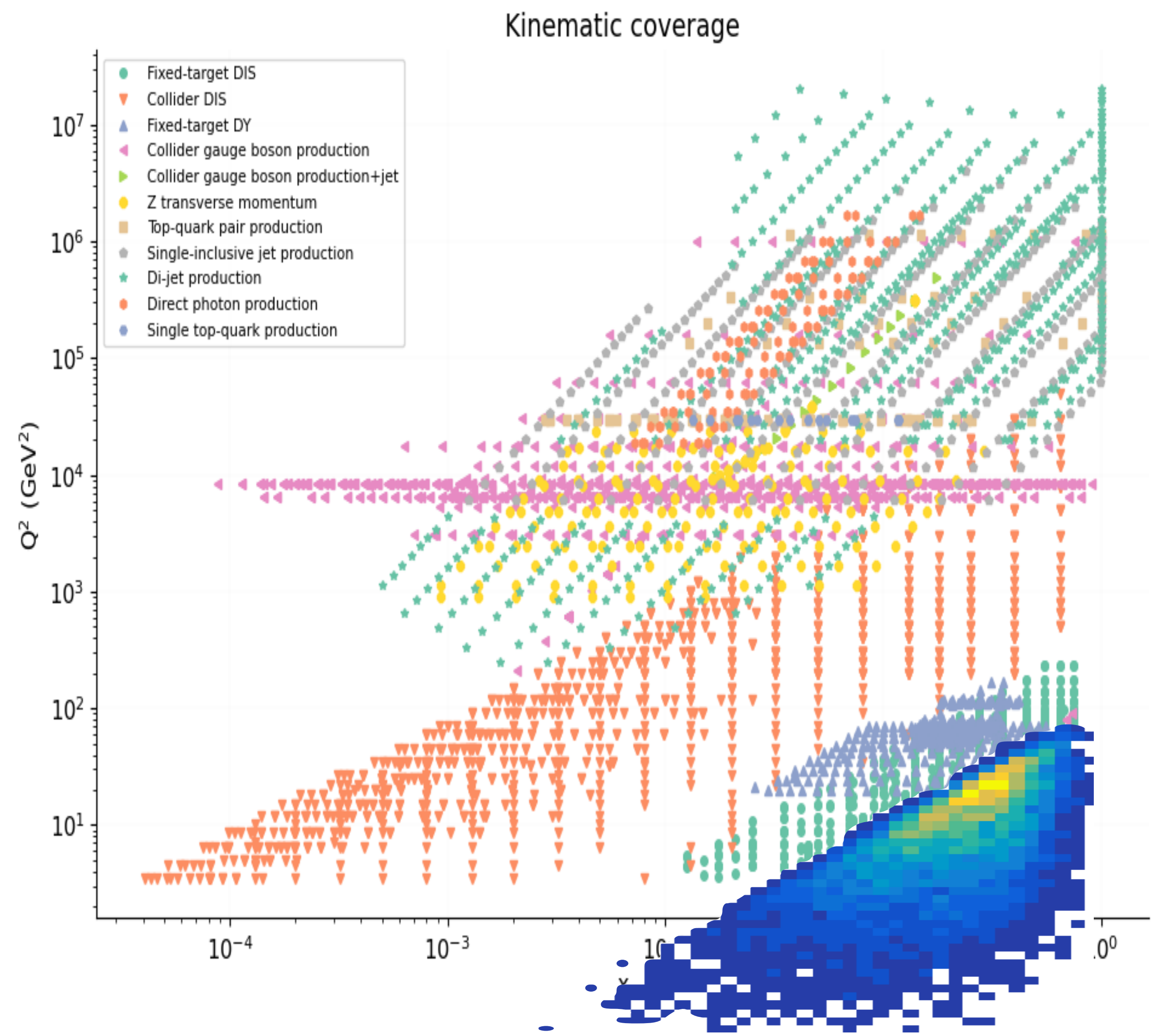
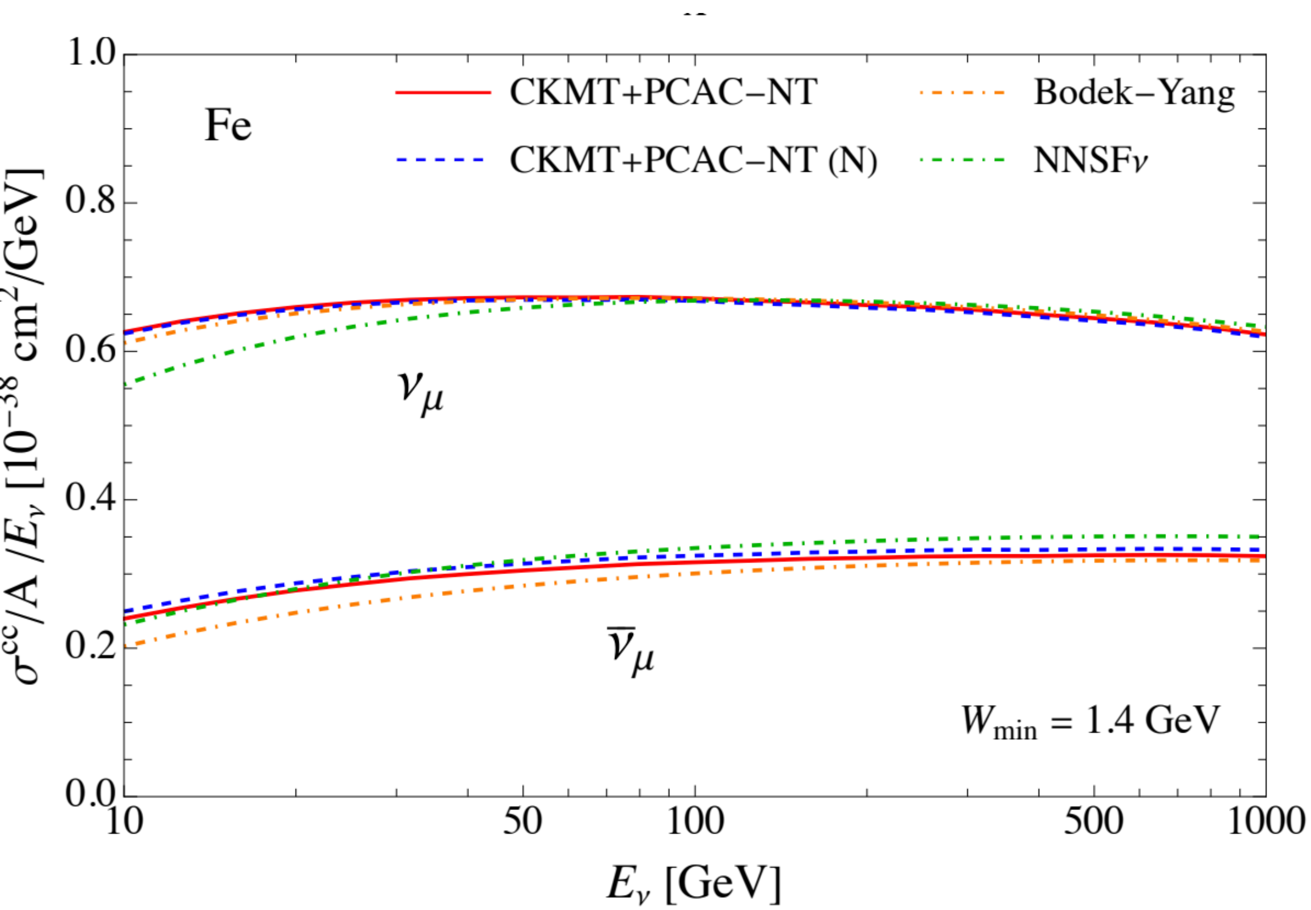
<u>**BODEK-YANG**</u>

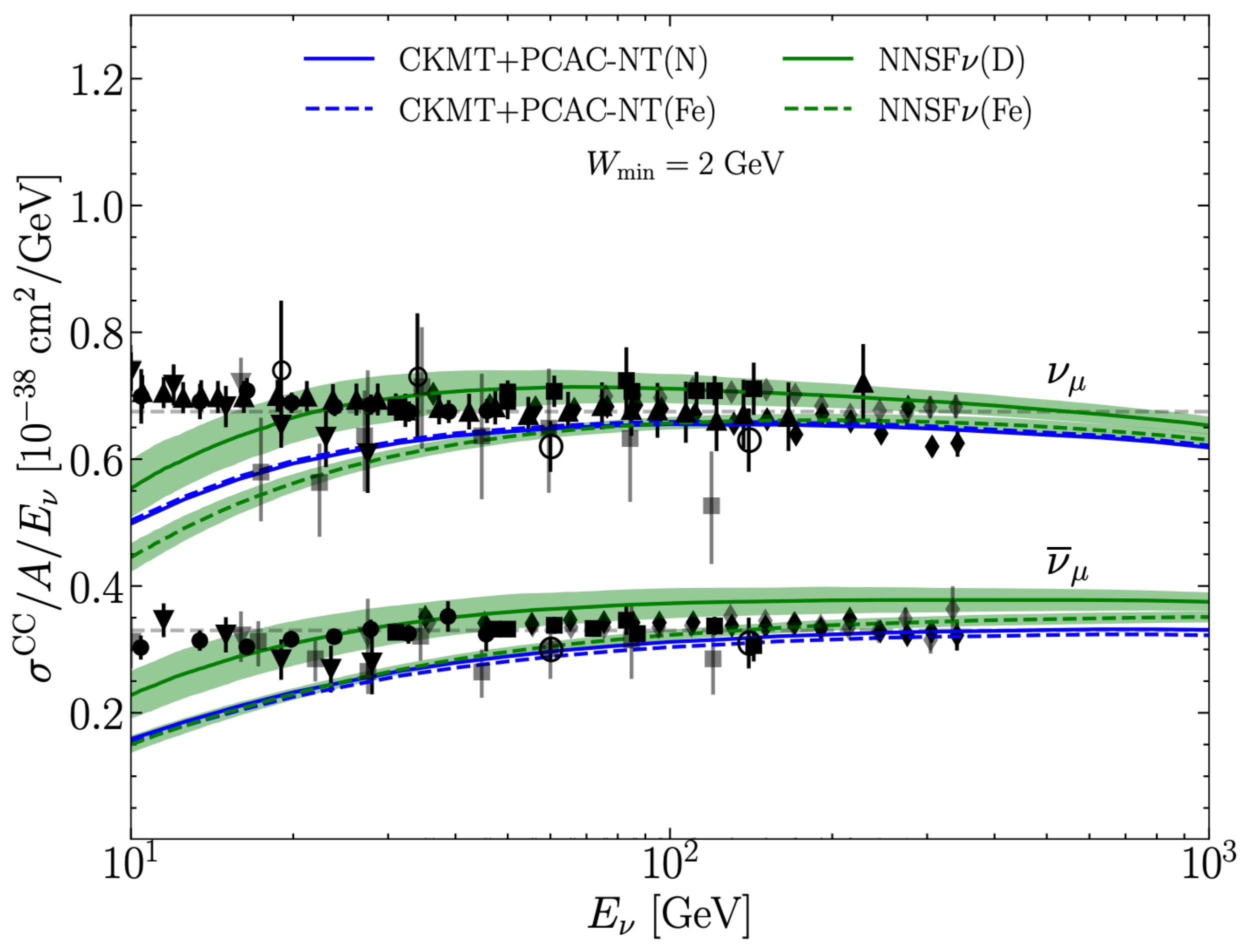
PDF: GRV98lo -> $Q^2_{min} = 0.8\ (GeV/c)^2$



E<1TeV

- New developements to complement the widely used Bodek-Yang model:
  - Efforts to understand nucleat effects at these energies.

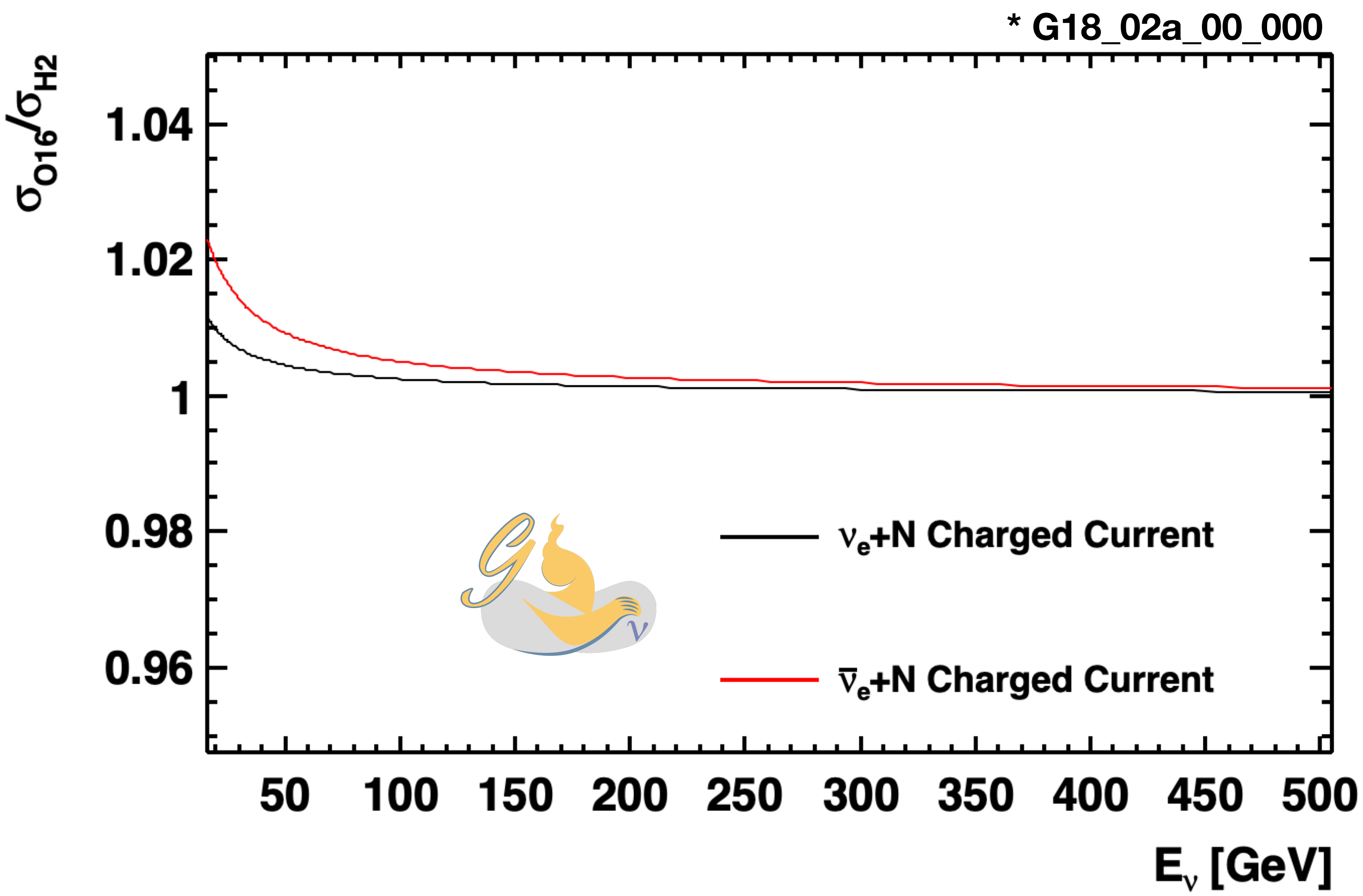


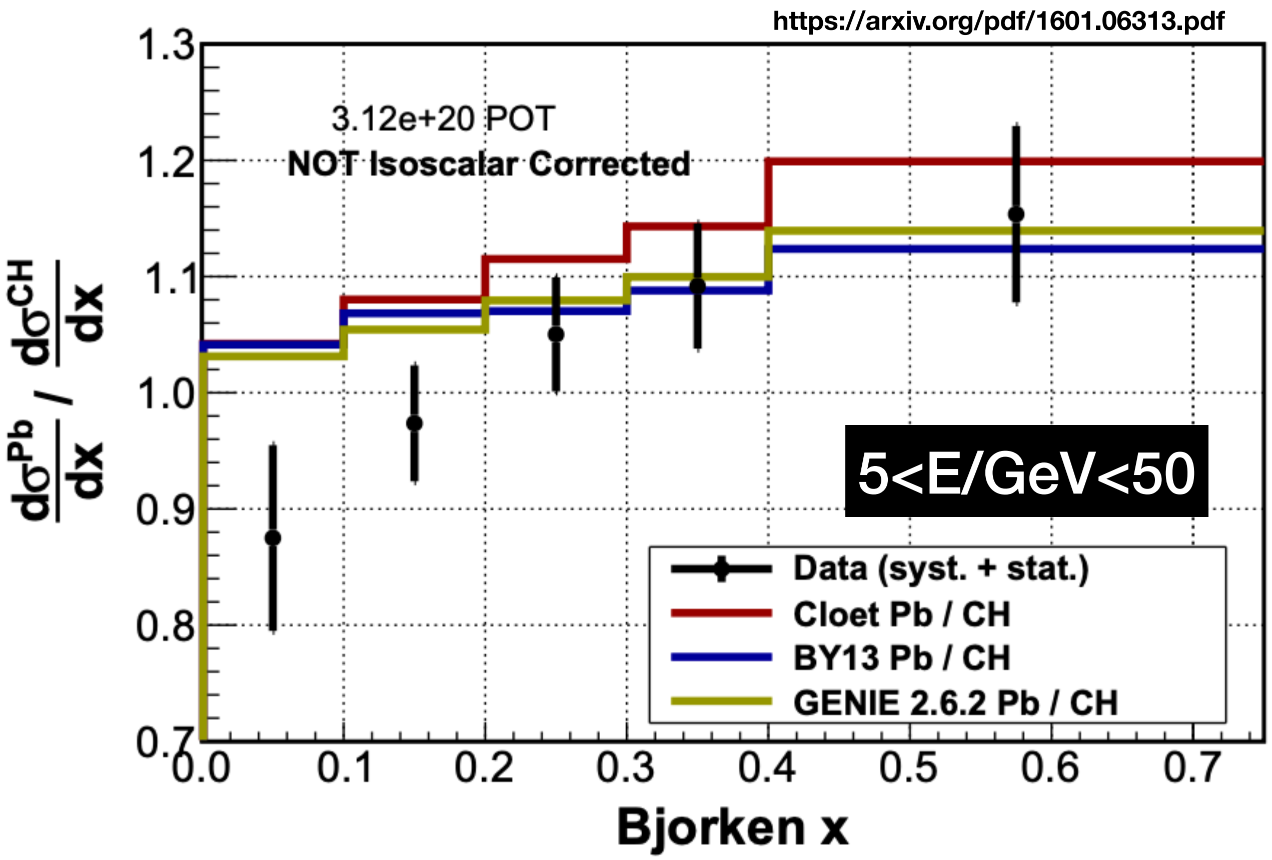


https://arxiv.org/abs/2307.09241

Nuclear effects

- Simple implementation (just nucleon scaling) in neutrino generators.
- Experiments (like Minerva) are showing nuclear effects not modelled.
- Are these effects similar to those observed in charged lepton-nucleon scattering?



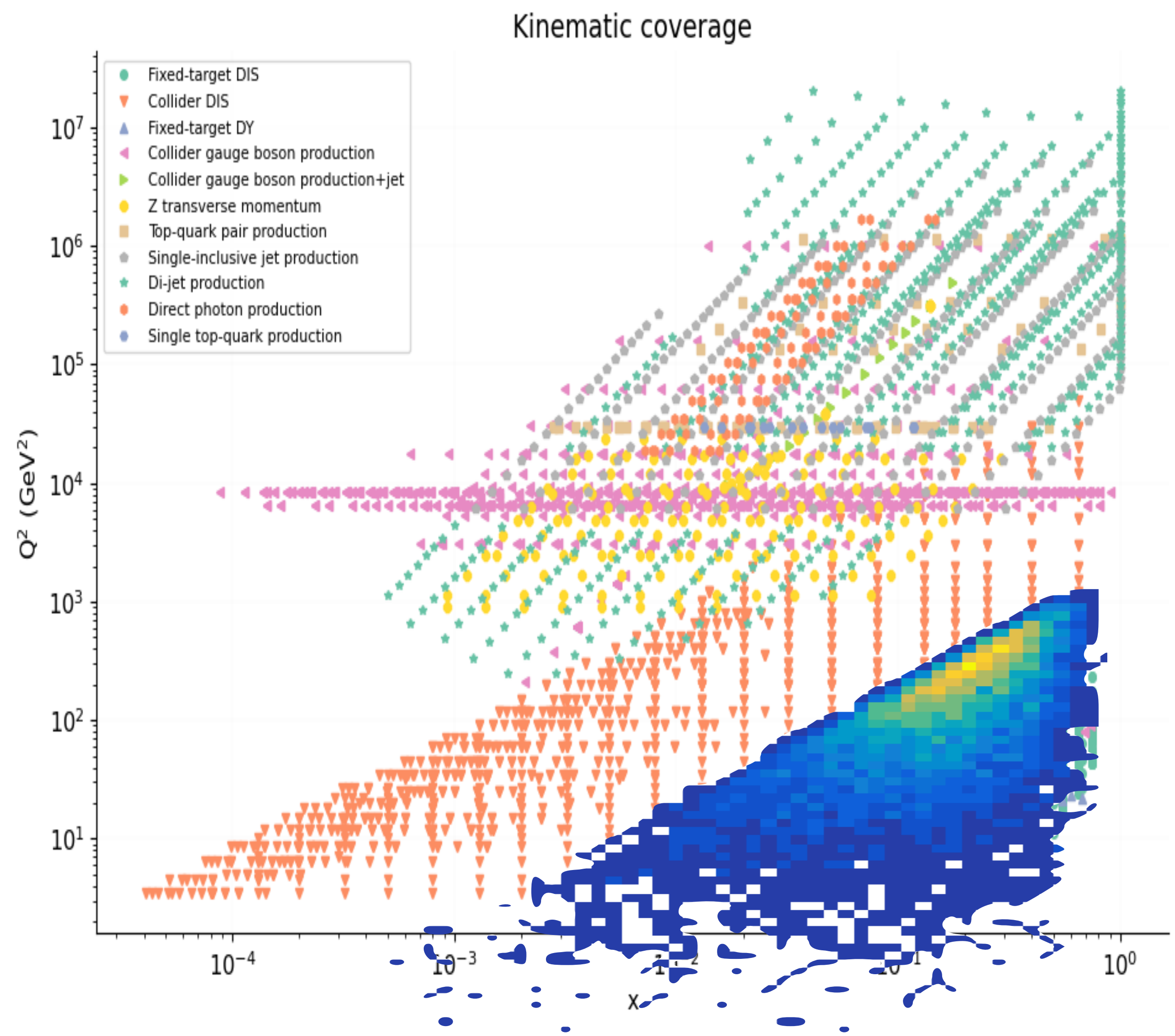


Phase Space

- Probing different regions of x, Q^2 depending on the energy of the neutrino.

Ev = 1TeV

- Medium Q2 contributions.
- pQCD works at these energies.
- Charm production is relevant.



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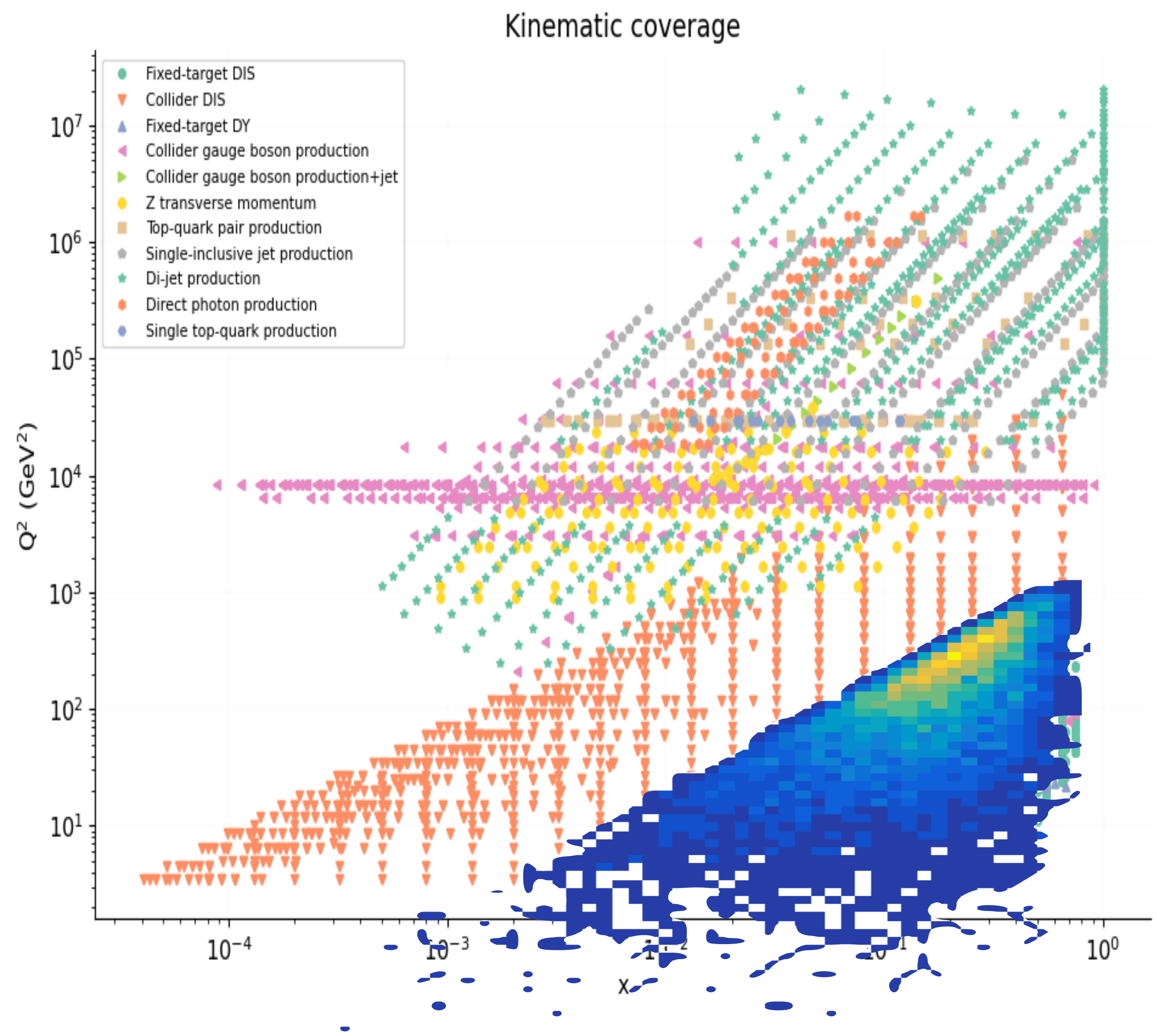
<u>CSMS</u>

PDF: HERAPDF15NLO

Q^2_{min} = 1.0 $(GeV/c)^2$

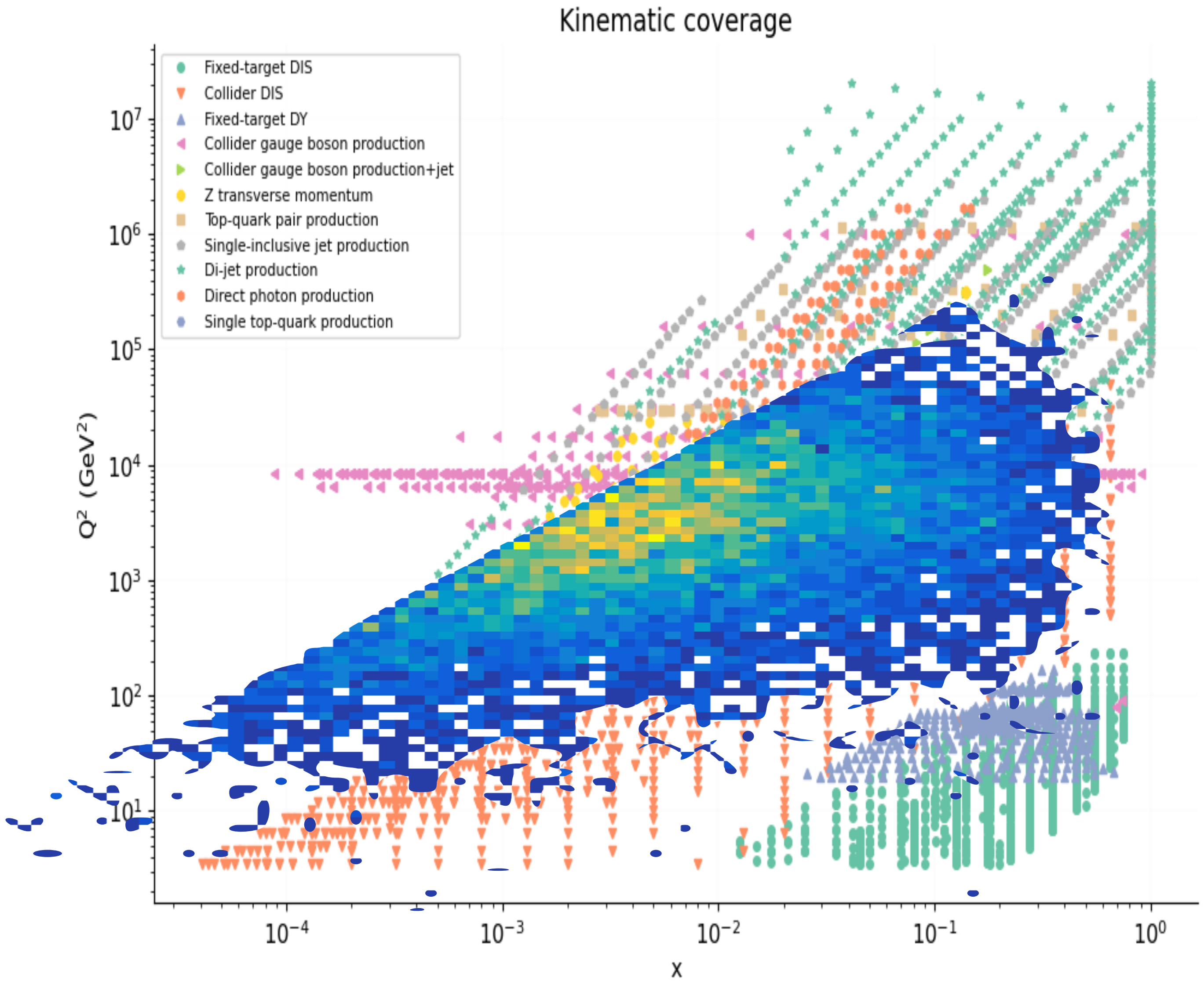


Phase Space

- Probing different regions of x,Q^2 depending on the energy of the neutrino.

Ev = 1PeV

- High Q2 & low x contribution.
- Lack of PDFs data in this regime.
- Top production is relevant.



Phase Space

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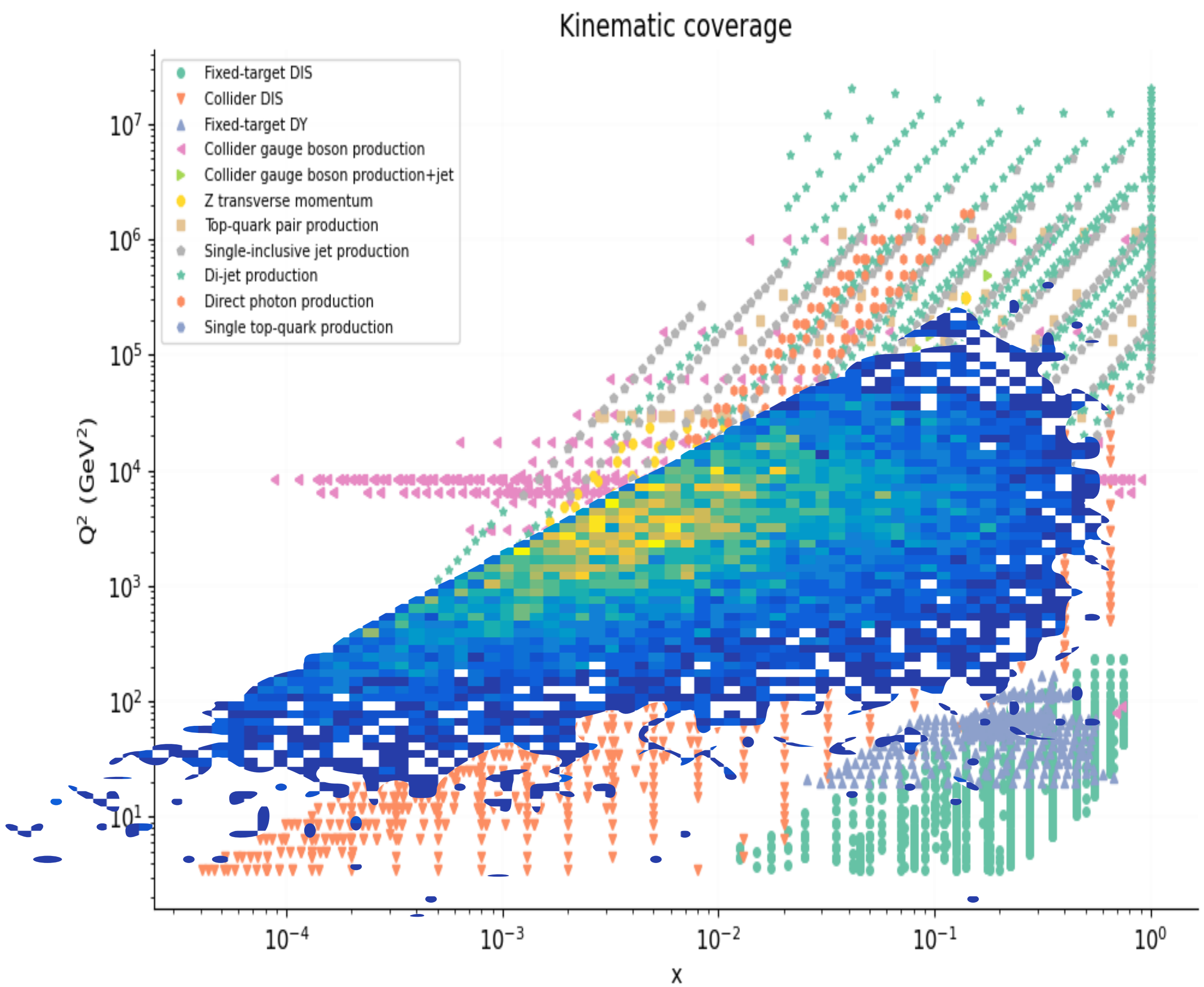
BGR

PDF: HERAPDF15NLO

Q^2_{min} = 2.69 (GeV/c)^2



Phase Space

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- Lack of PDFs data in this regime.
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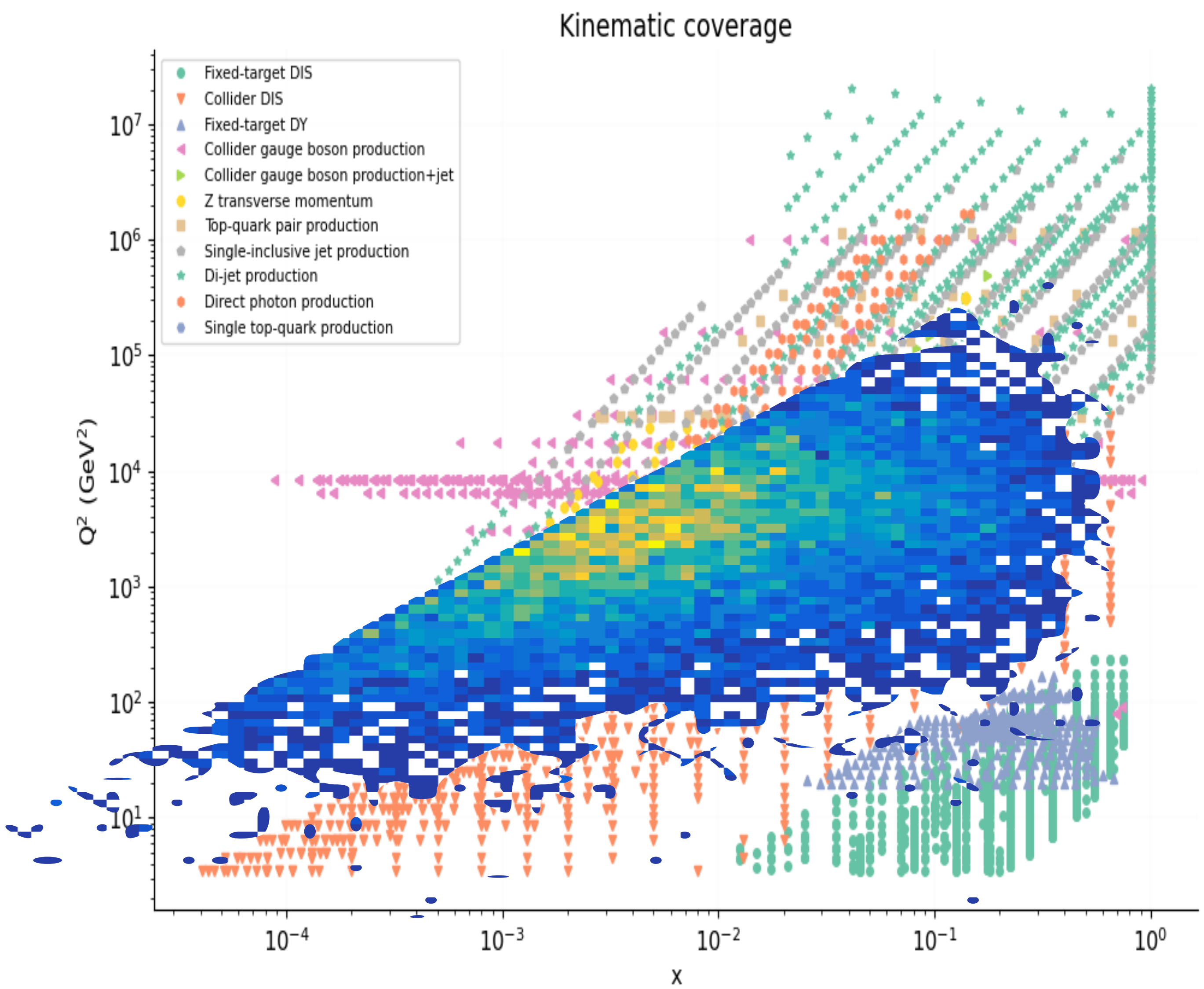
BGR

PDF: HERAPDF15NLO

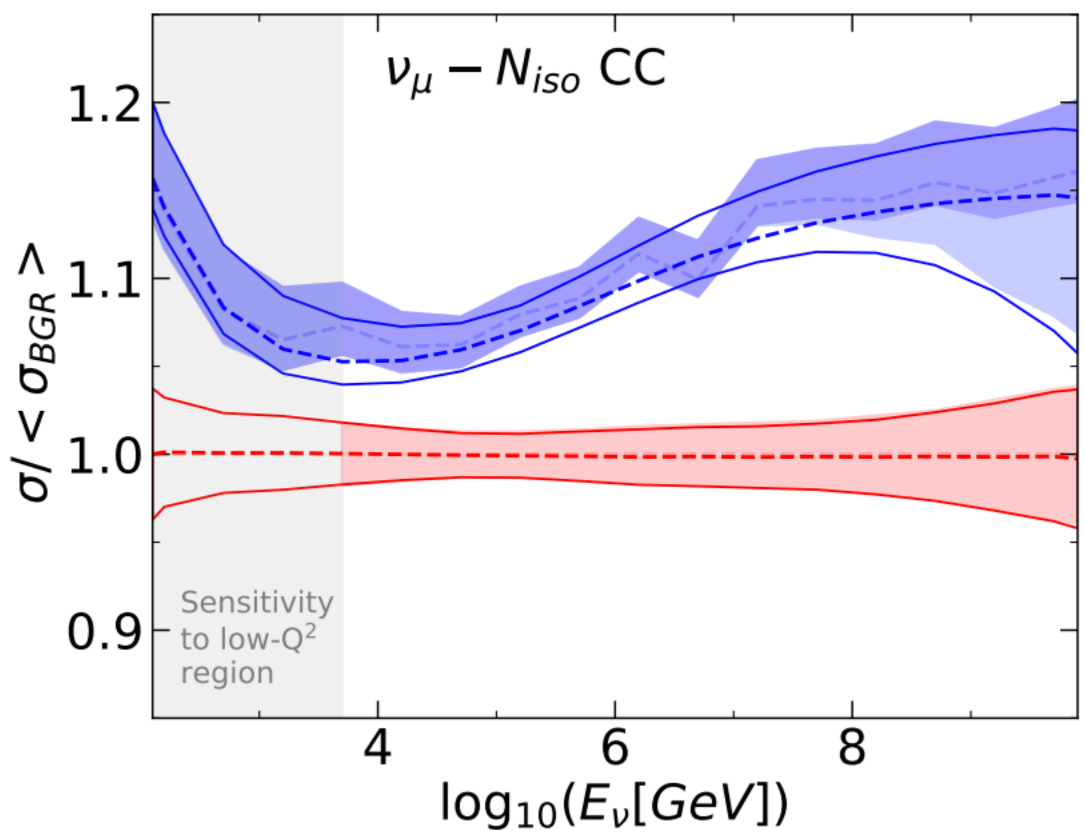
$Q^2_{min} = 2.69\ (GeV/c)^2$

For higher energies very low x contributions are relevant and pQCD breaks down.

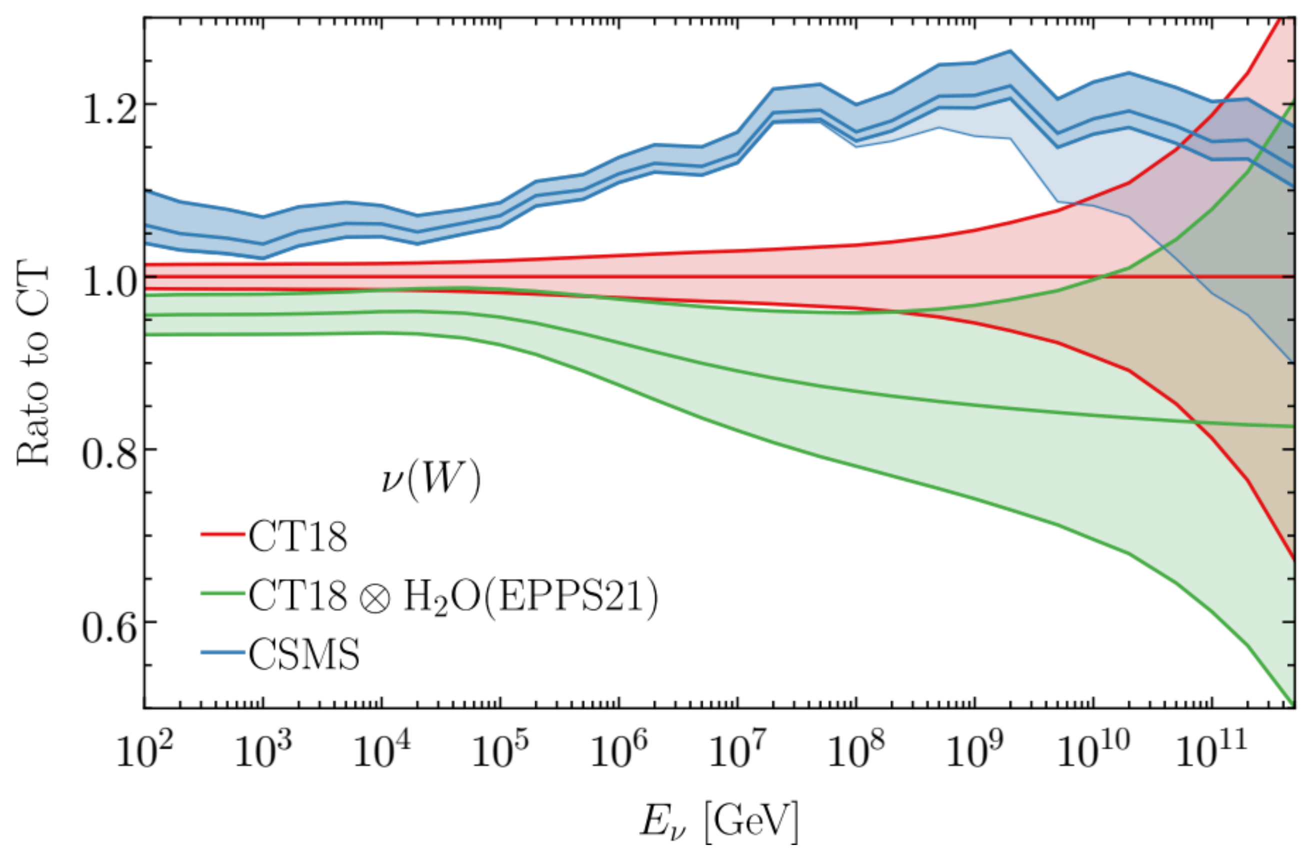


E>1TeV

- Main differences arise from treatment of b->t diagrams and differences in PDF sets.
- Nucleon PDFs show <5% uncertainties



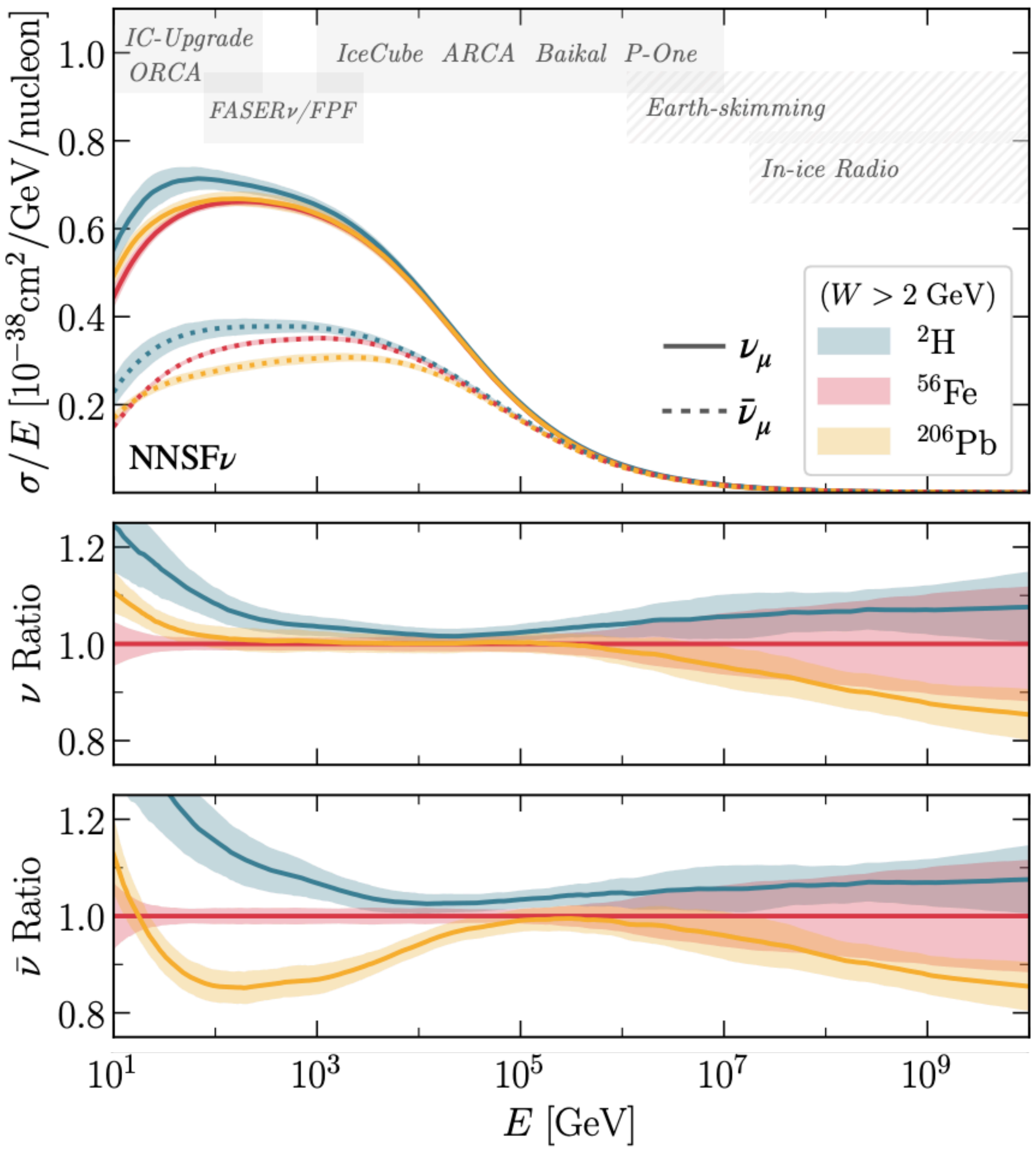
https://arxiv.org/abs/2004.04756

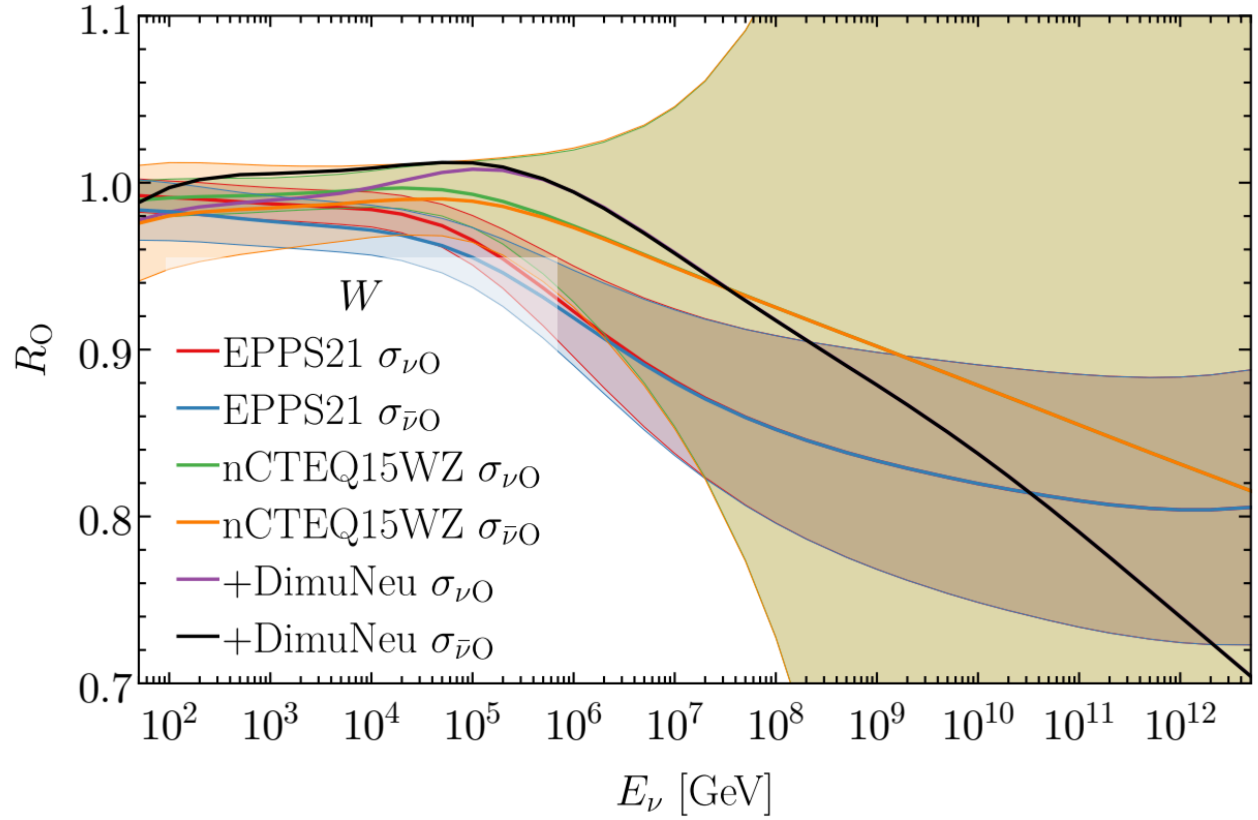


https://arxiv.org/abs/2303.13607

Nuclear effects

- Antishadowing predicted in the TeV range.
- Shadowing start dominating between 100TeV and 1PeV -> large uncertainties

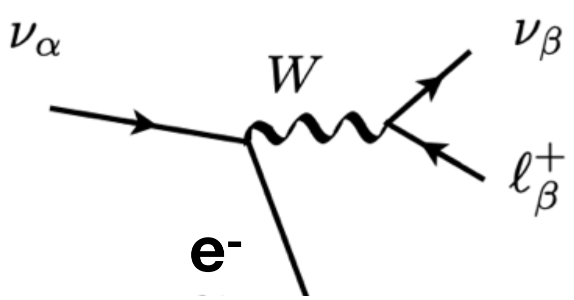


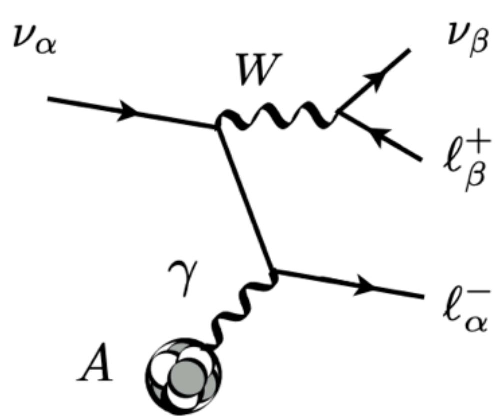


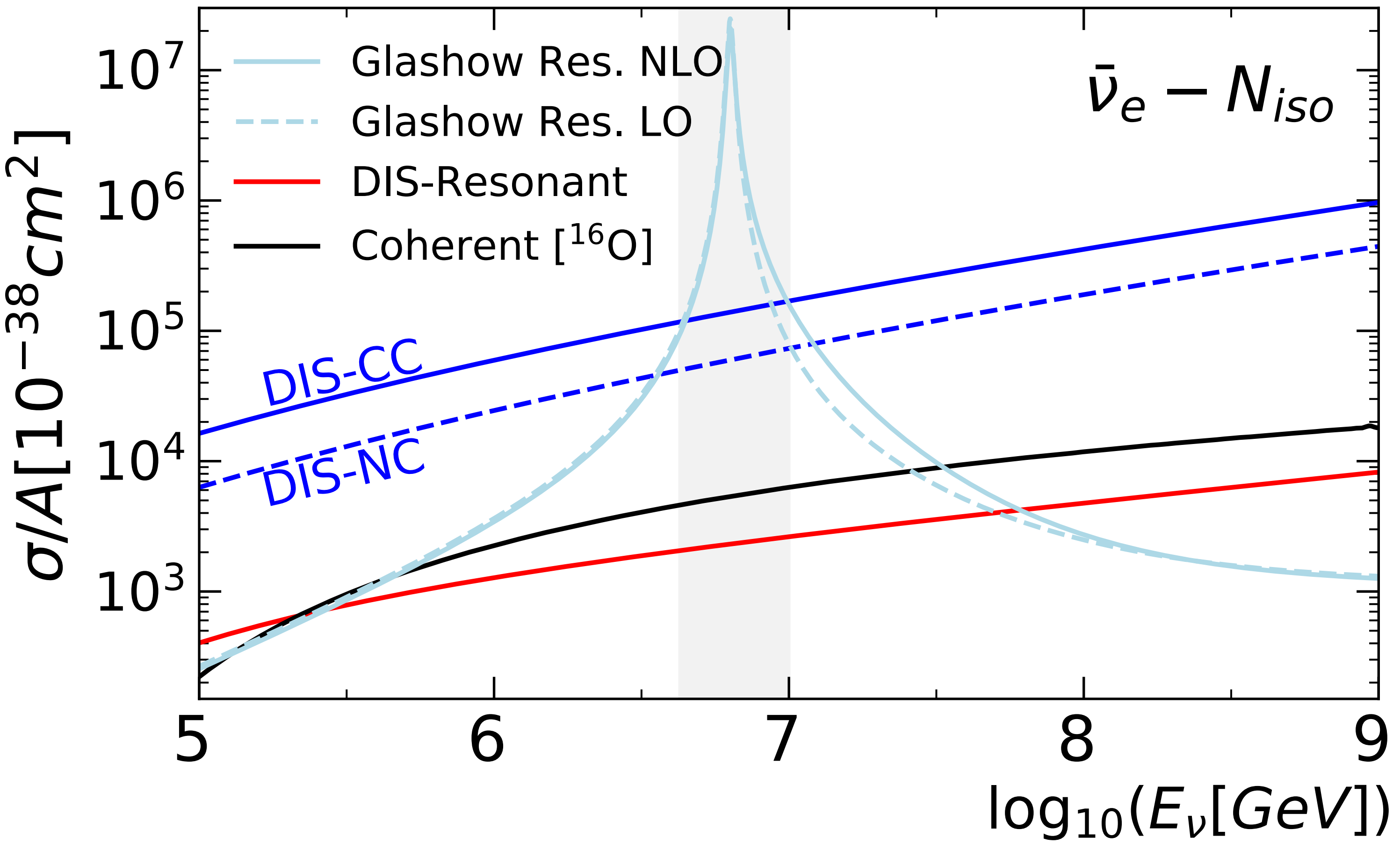
https://arxiv.org/abs/2303.13607

Other processes

- Extension to more "exotic" channels has been implemented.
  - Full kinematics are simulated.





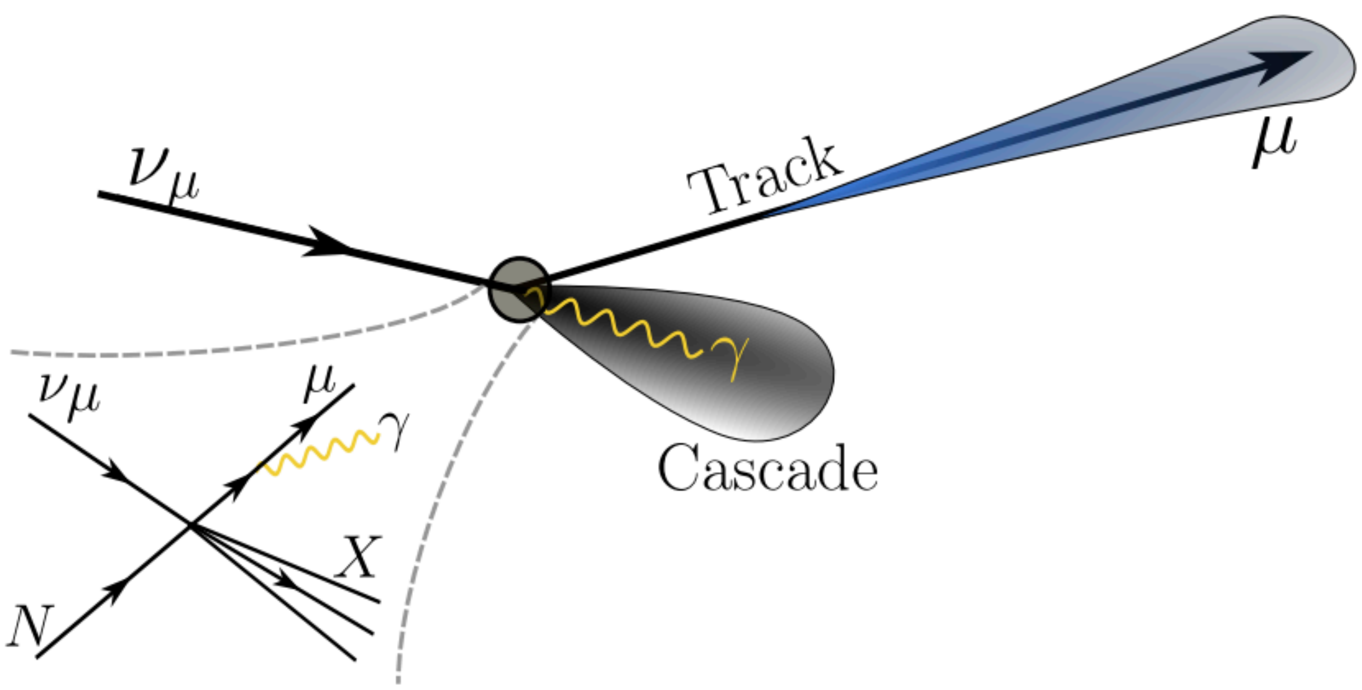


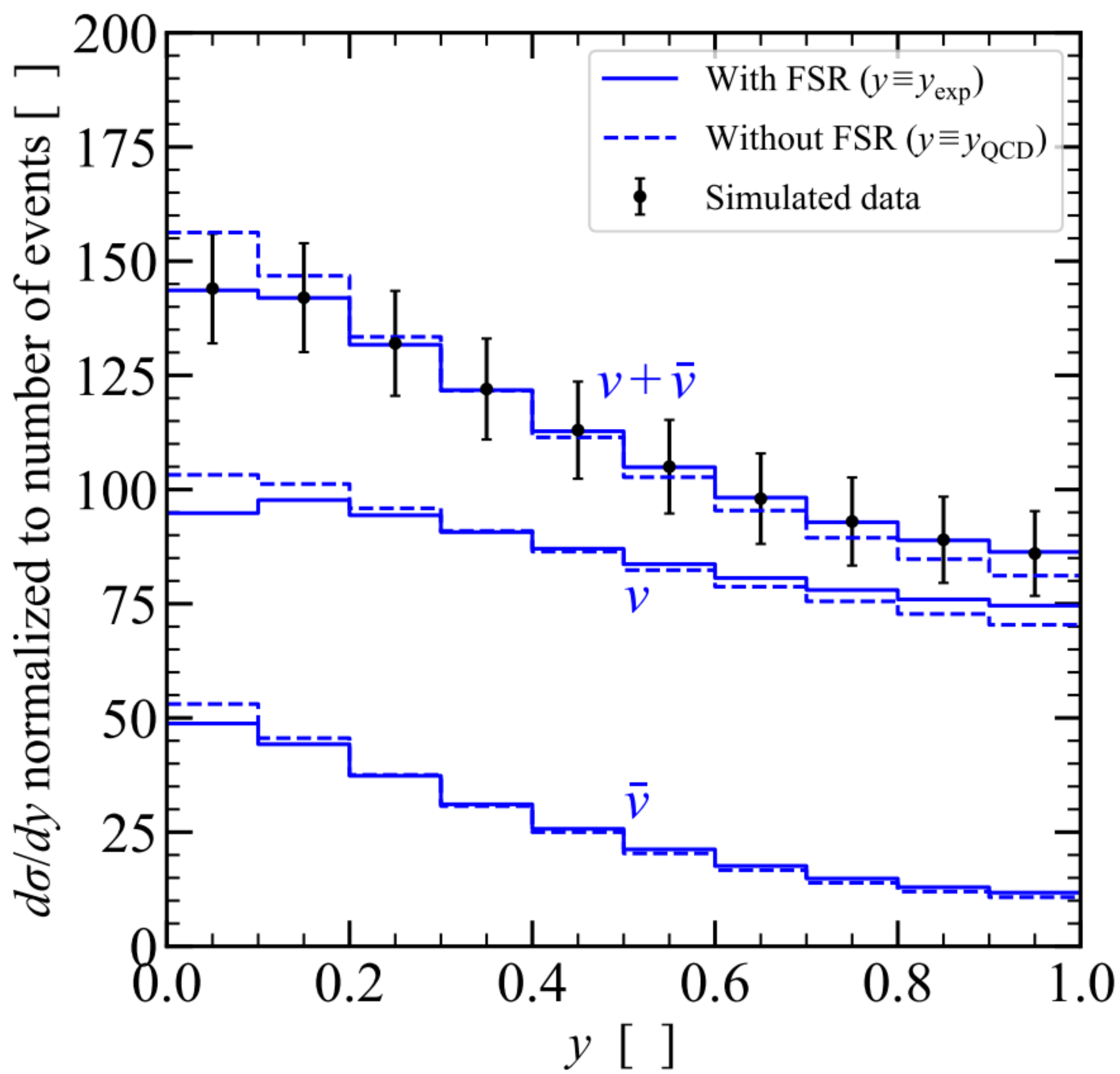
Deep inelastic scattering off quarks and gluons.
Scattering on atomic electrons via the Glashow resonance.
(In)elastic scattering off the photon field of nucleons.
Coherent scattering off the photon field of nuclei.

https://arxiv.org/abs/2004.04756

Final state radiation

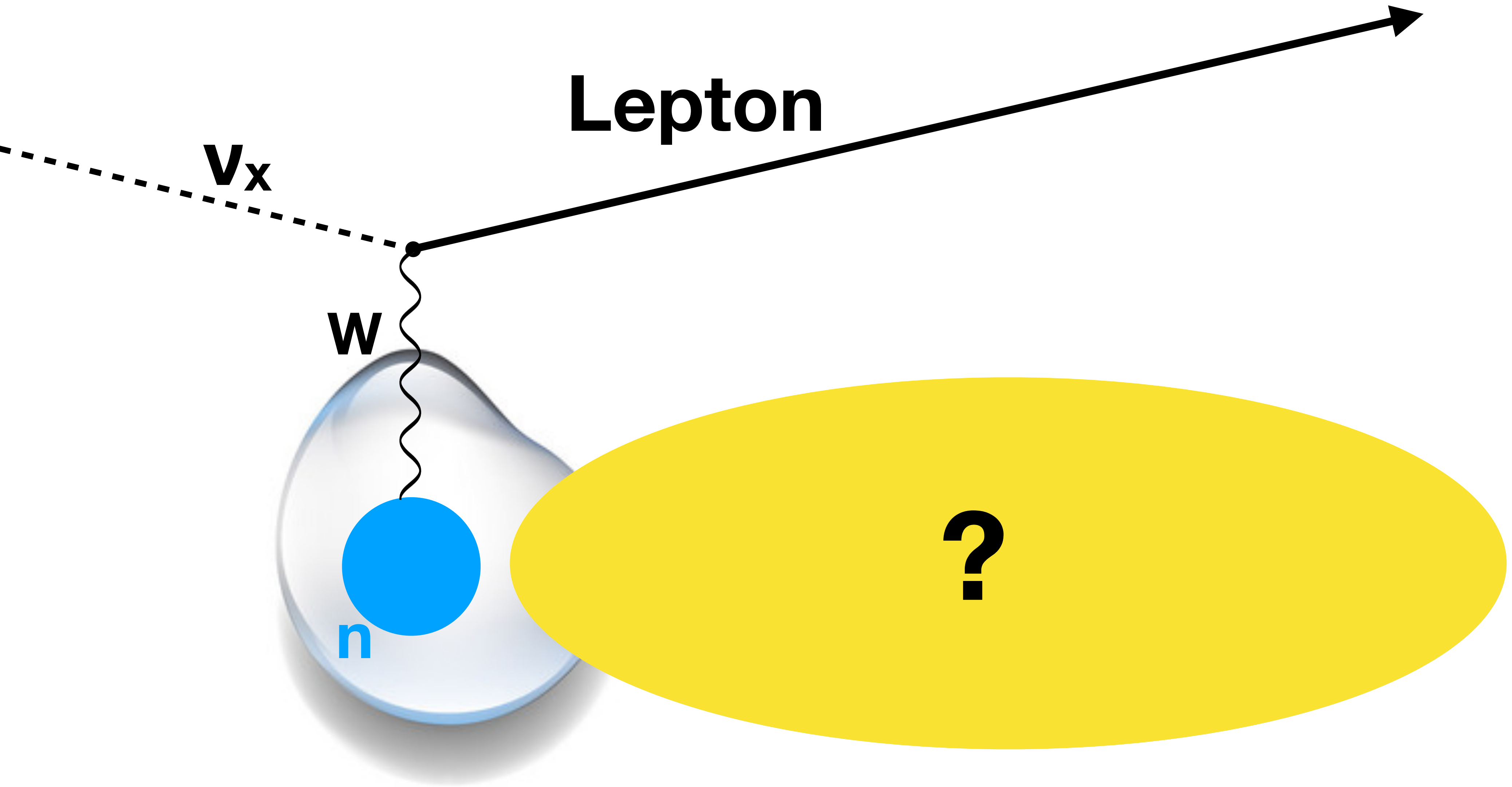
- Prompt internal bremsstrahlung -> not included in current generators
  - Events look more inelastic than currently model -> 2-5% effect.





https://arxiv.org/abs/2403.07984

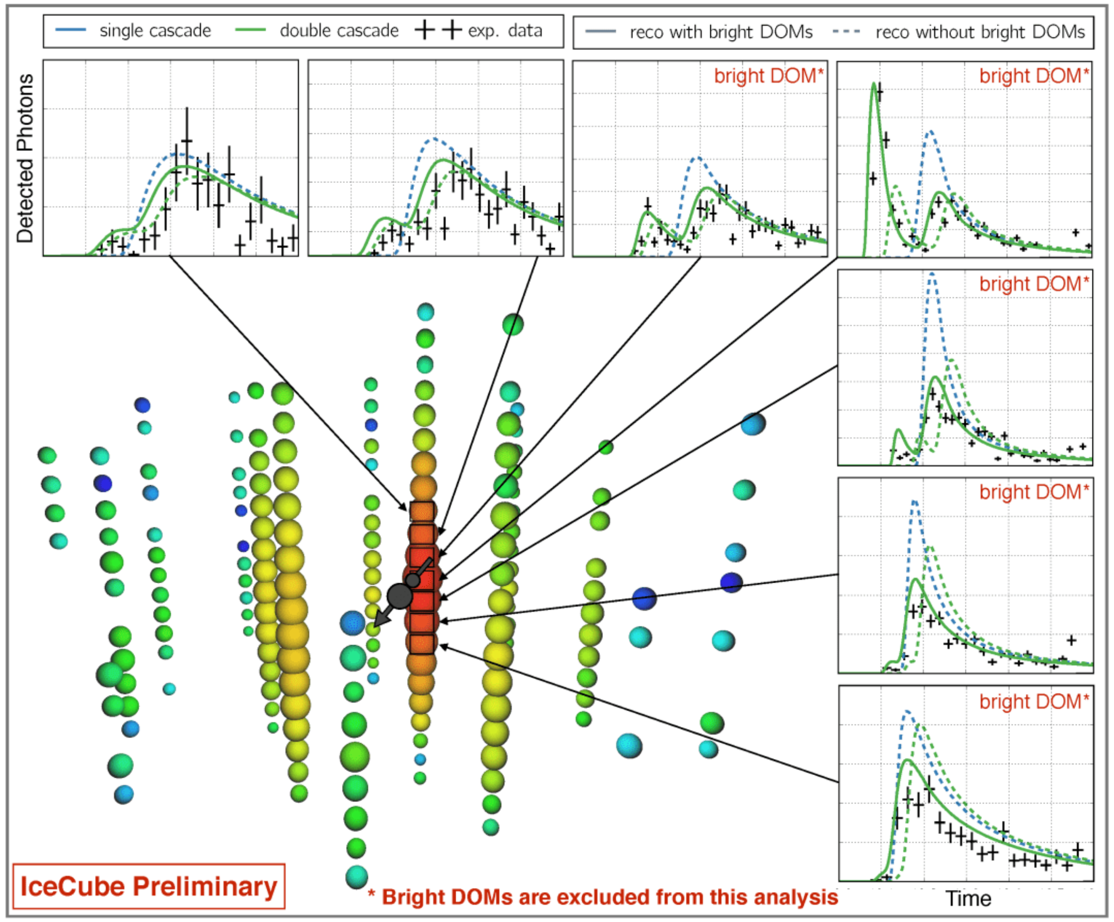
Hadron level



Hadronization

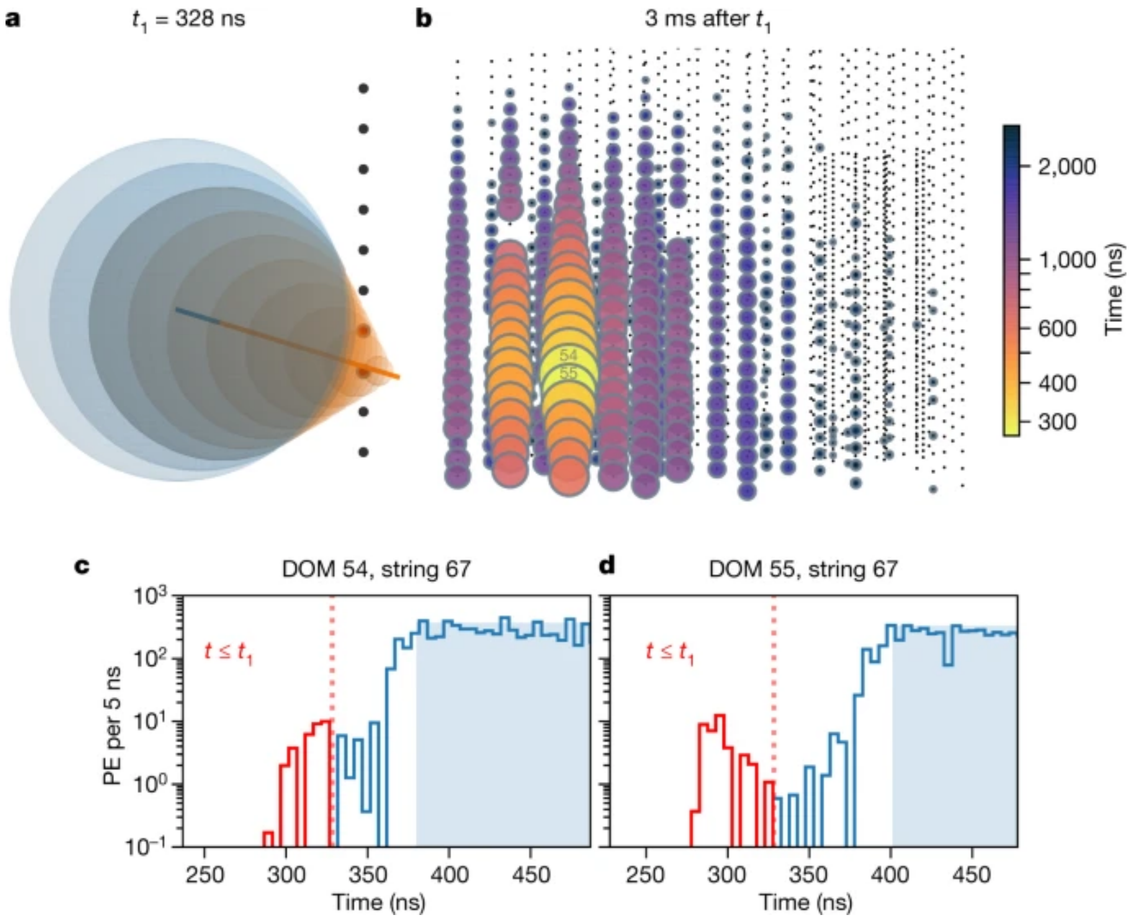
- Historically not the biggest concern for neutrino telescopes
- New developments show that it might not be the case anymore

Tau neutrinos



https://arxiv.org/abs/2011.03561

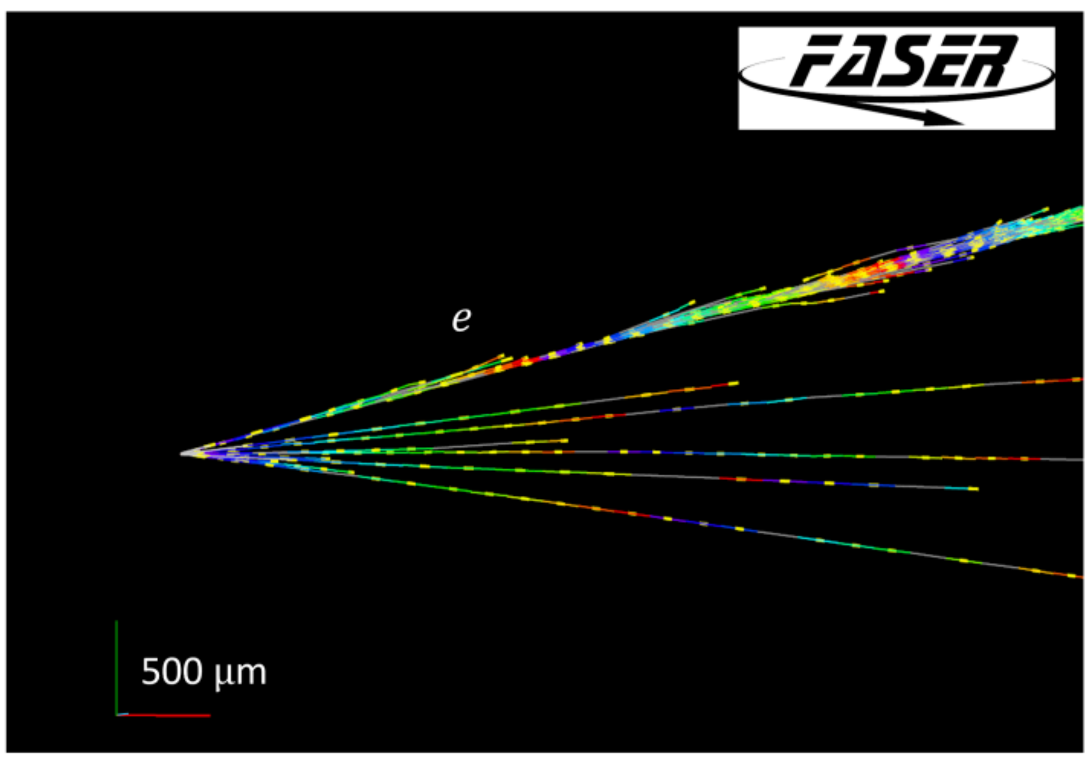
Glashow resonance



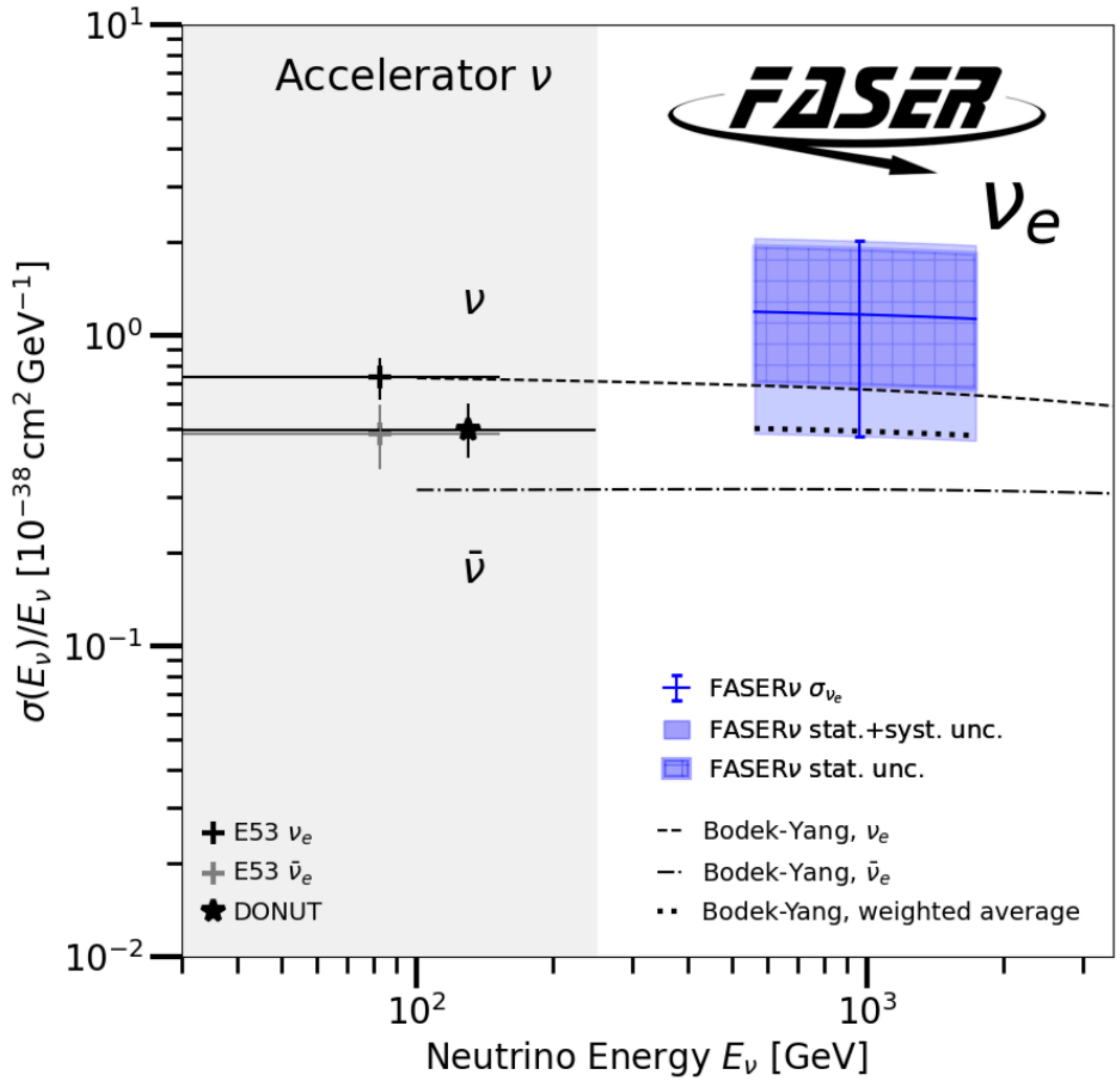
https://arxiv.org/abs/2110.15051

Hadronization

- Forward physics experiments also affected by this
- Activity in the emulsion detector is used to reconstruct the vertex.
- One of the leading systematics in latest analyses.

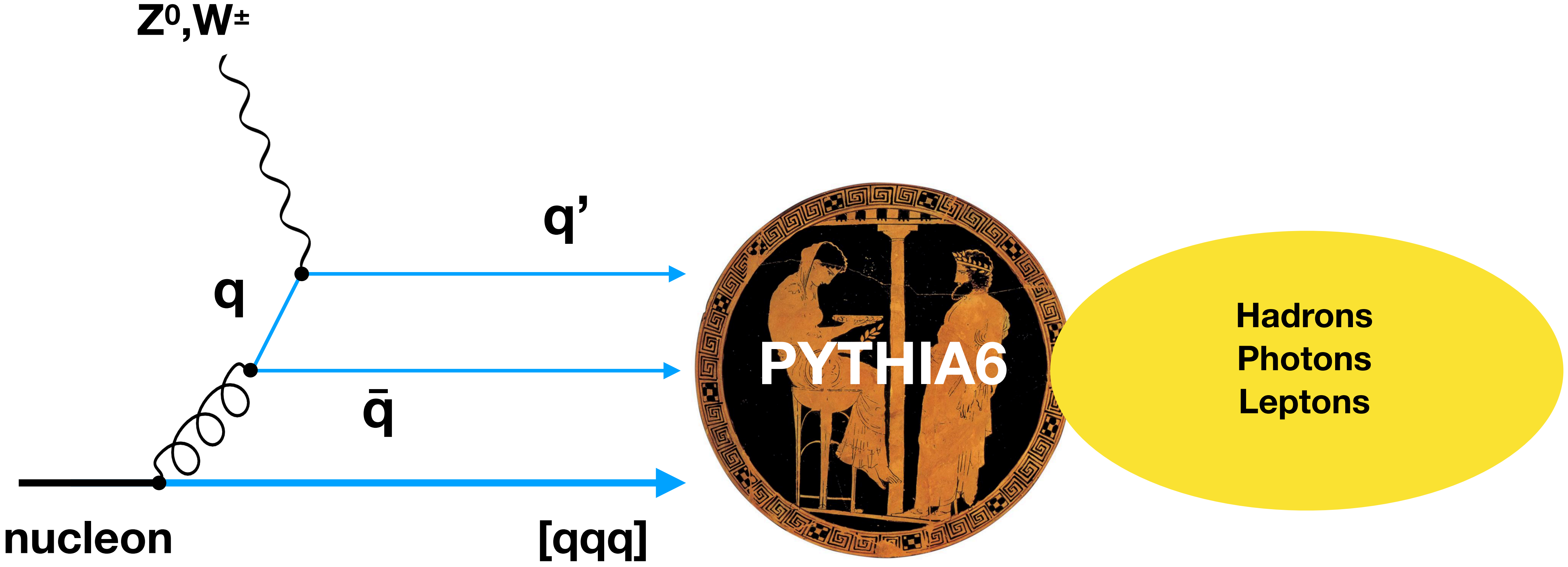


https://arxiv.org/abs/2403.12520



Hadronization

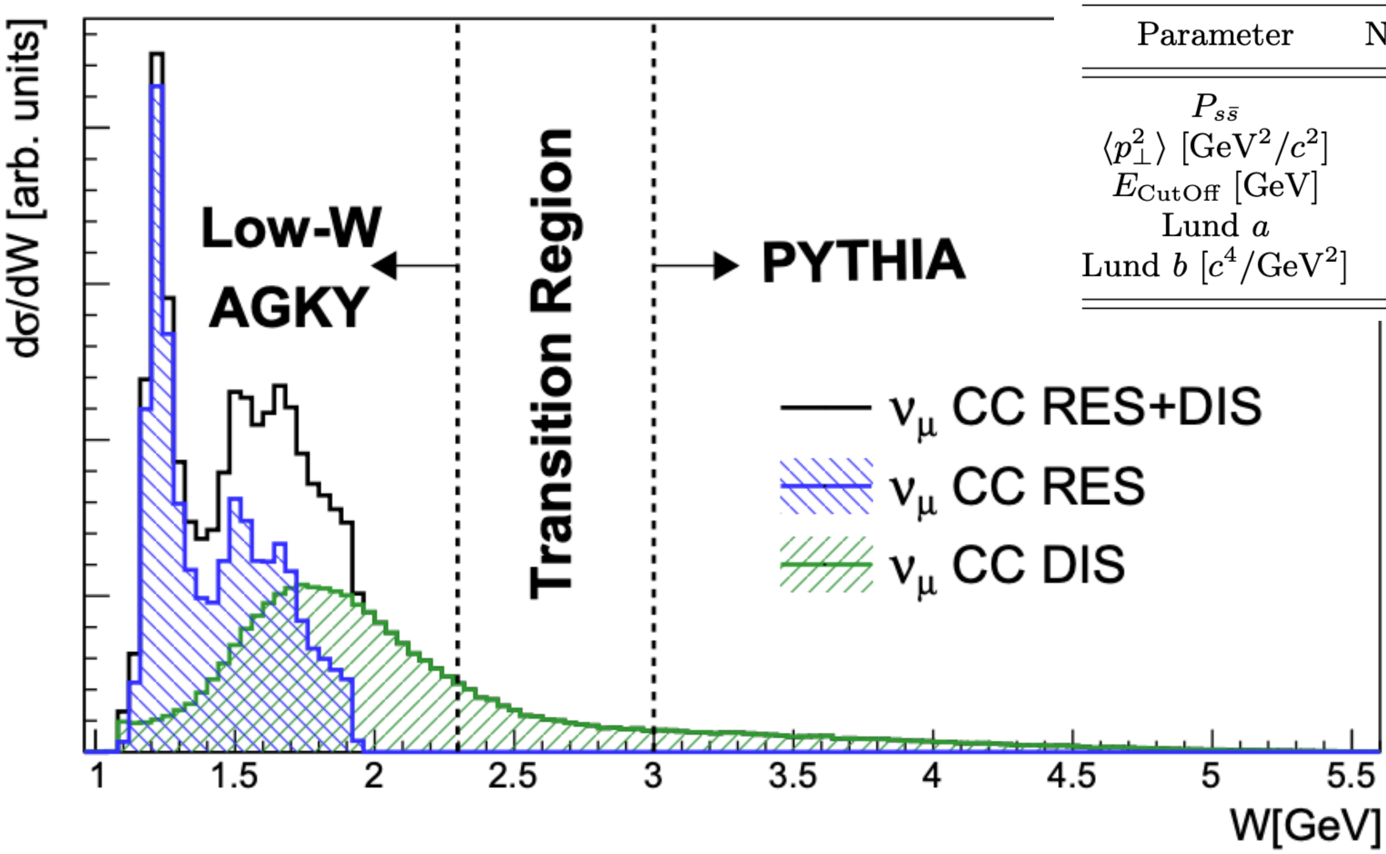
- Quark combination input to PYTHIA6.



Hadronization-DIS

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

DUNE flux

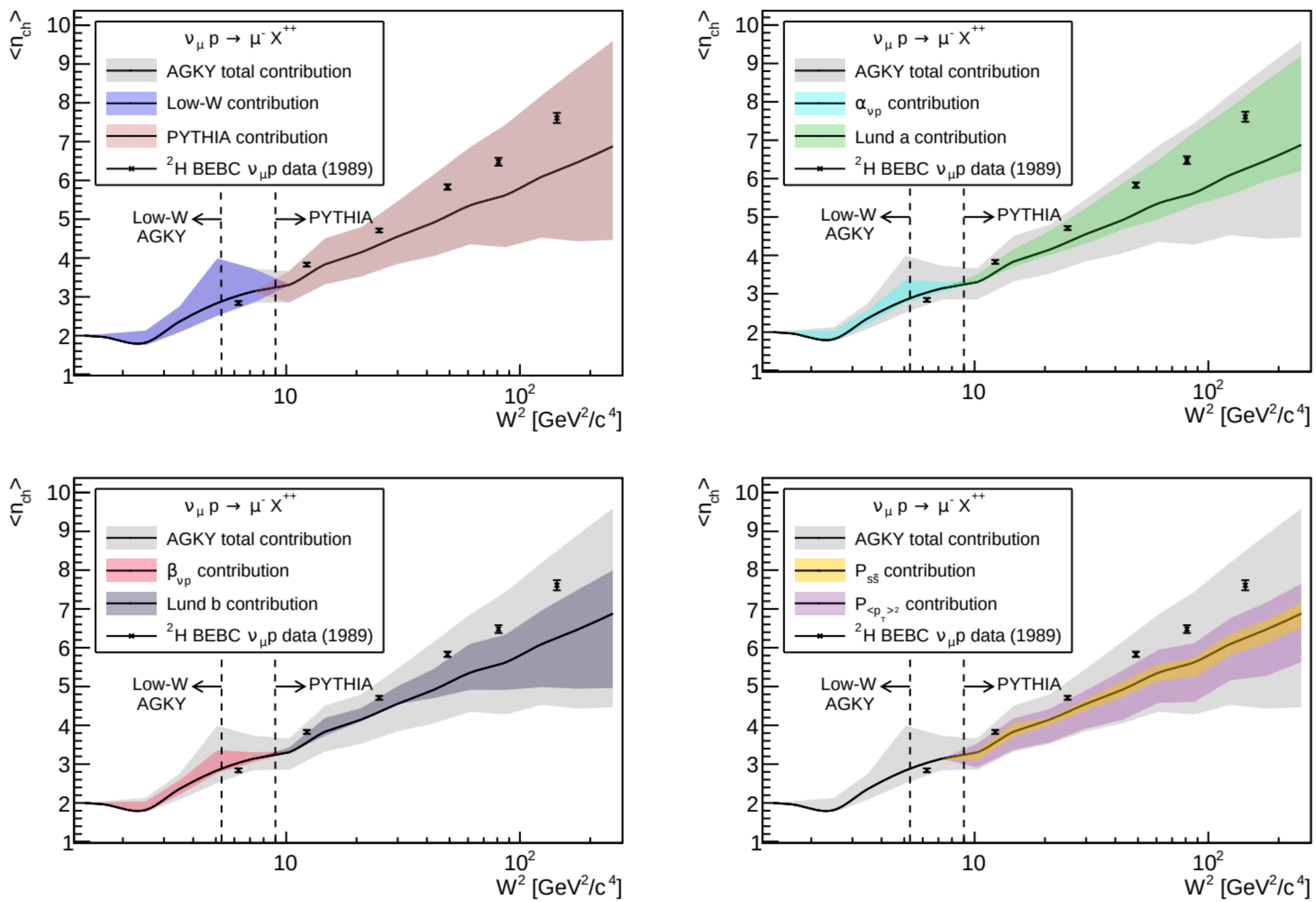


Parameter	Name in PYTHIA	PYTHIA default	NUX tune	HERMES tune	*2010* GENIE tune
$P_{s\bar{s}}$	PARJ(2)	0.30	0.21	0.25	0.30
$\langle p_\perp^2 \rangle$ [GeV^2/c^2]	PARJ(21)	0.36	0.44	0.42	0.44
E_{CutOff} [GeV]	PARJ(33)	0.80	0.20	0.47	0.20
Lund a	PARJ(41)	0.30	0.30	0.68	0.30
Lund b [c^4/GeV^2]	PARJ(42)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

Hadronization-DIS

- New tuned has been recently developed.

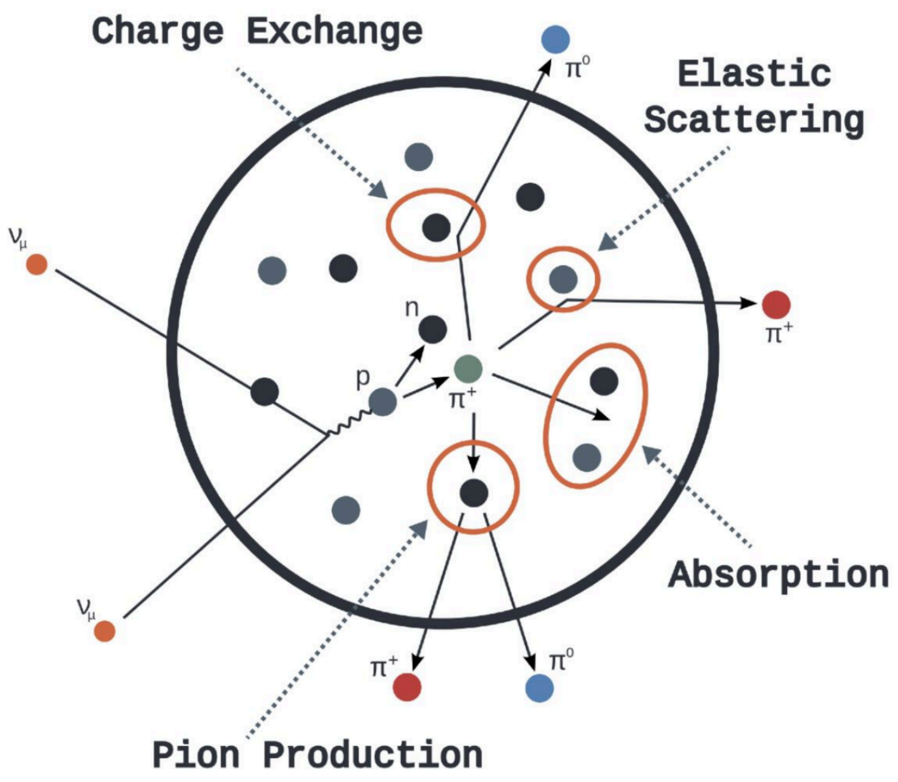
https://arxiv.org/abs/2106.05884



Final-state interactions

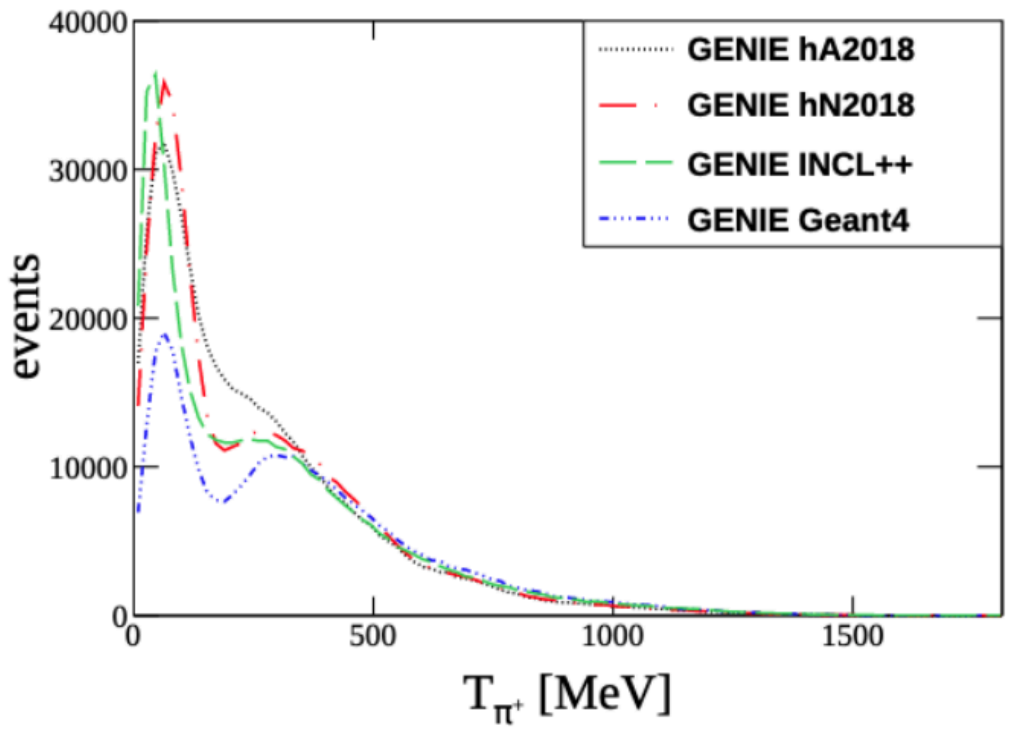
- GENIE -> based on intranuclear cascade (INC) model.
  - Simple: hA -> For E<1.2GeV
  - Sophisticated: hN -> E>50MeV
  - INCL++
  - GEANT4

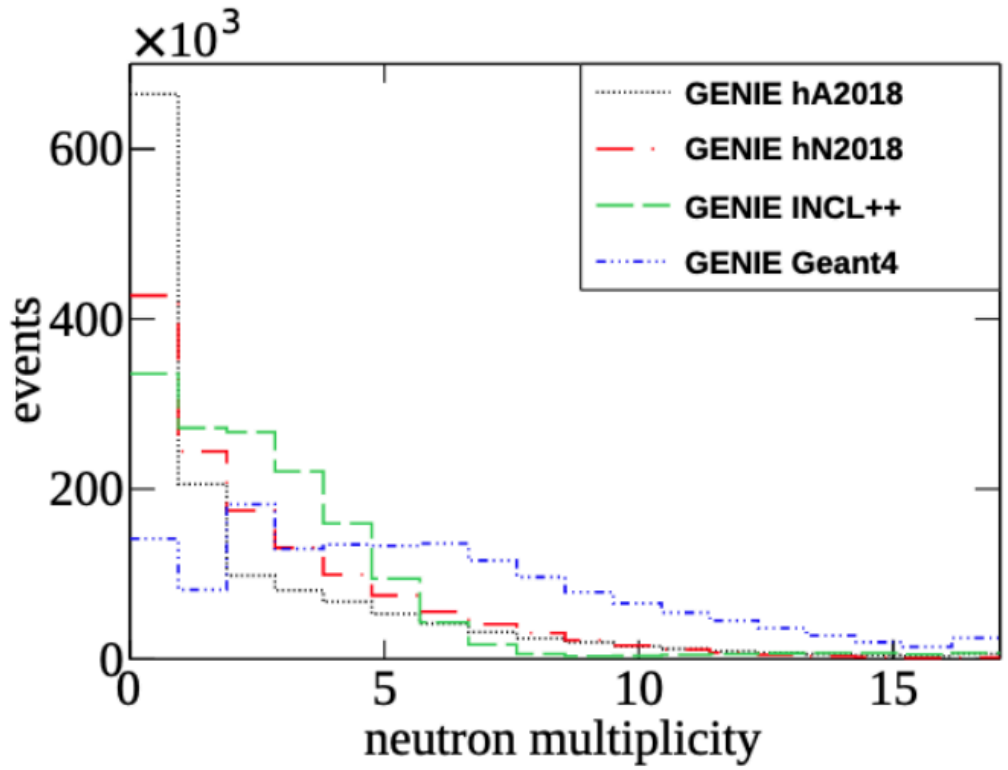
Image: T. Golan



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

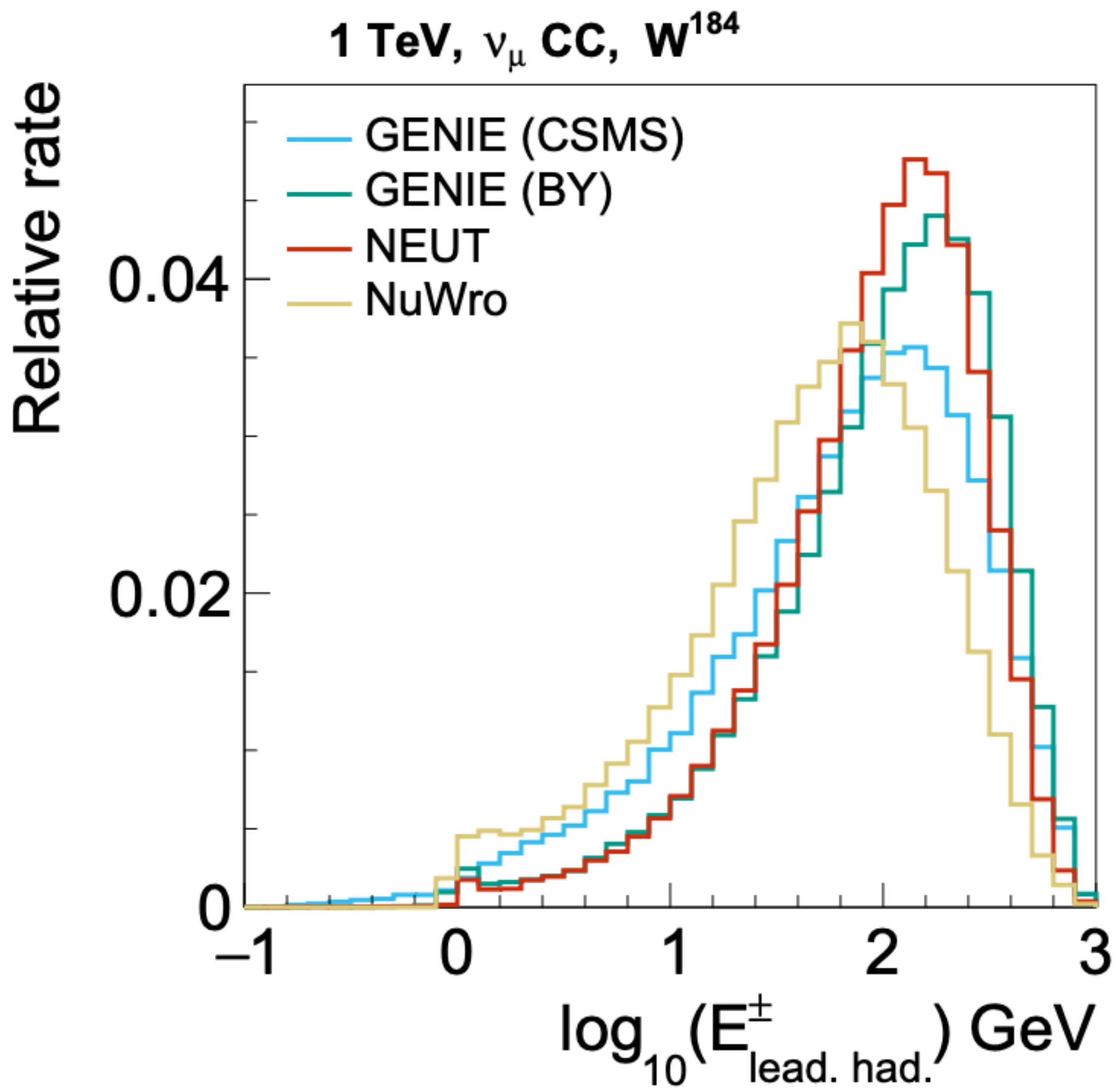
2GeV numu+Ar

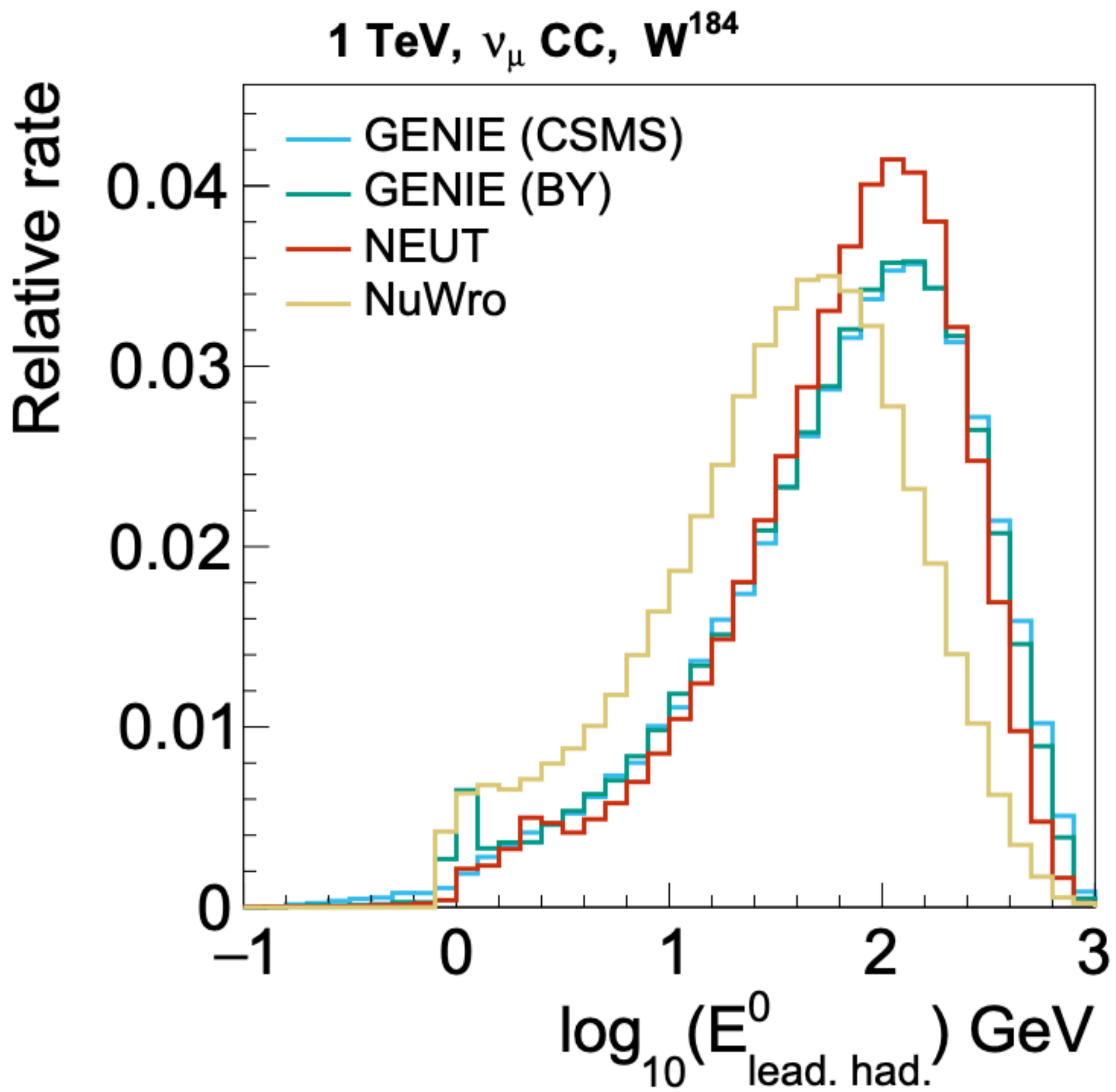




Comparison

- Energy of leading hadrons

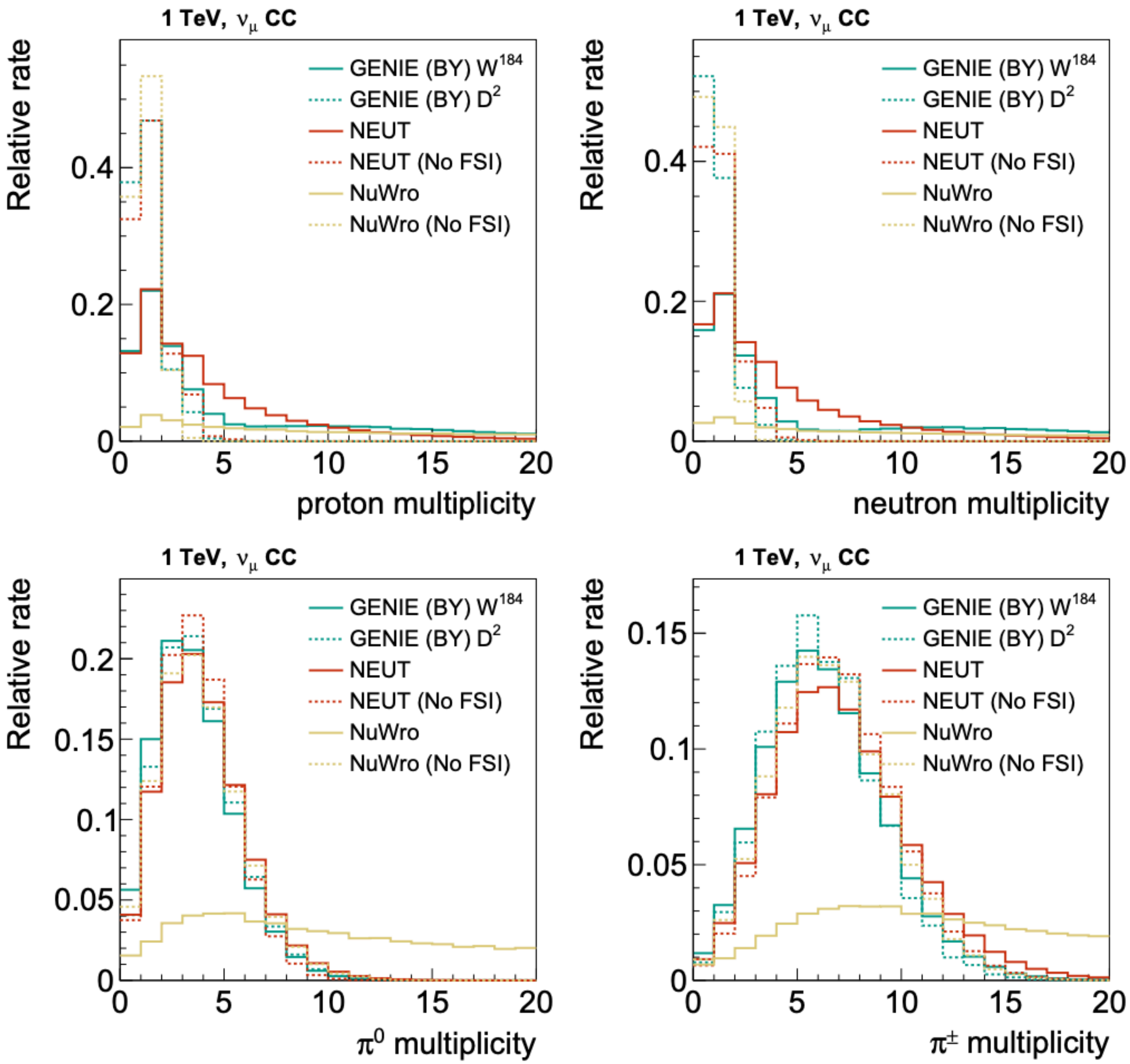




arXiv:2203.05090

Comparison

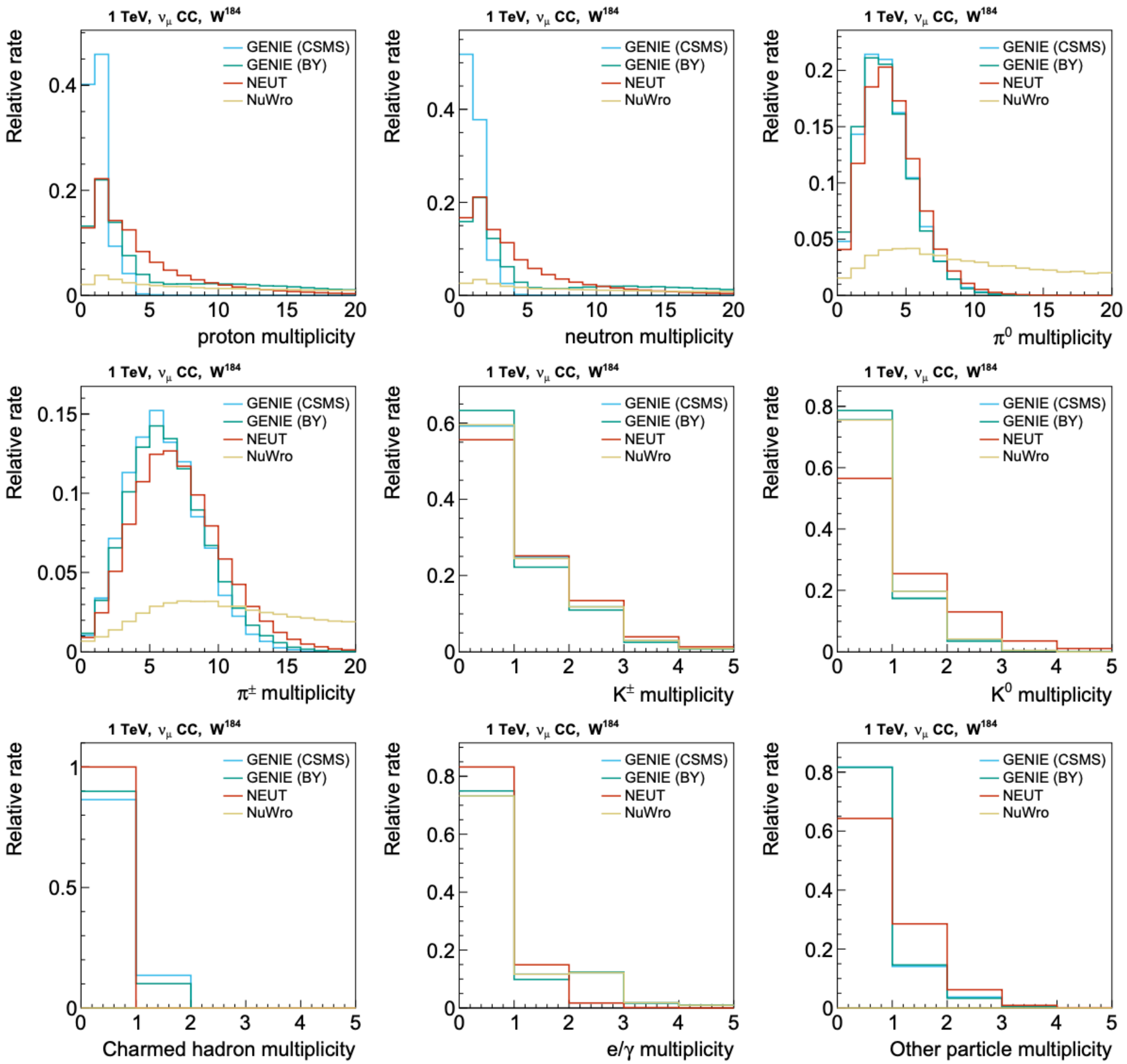
- Hadron multiplicity with/without NSI



arXiv:2203.05090

Comparison

- Hadron multiplicity



arXiv:2203.05090

Conclussions

- High-energy neutrinos are being studied with multiple experiments
- Multiple studies in the latest years trying to improve the modeling of neutrino interactions in this energy regime
- Event generators are incorporating these developments
- … but a lot of work is still required!
  - Incorporate rewiegting tools for nuclear effects
  - Study of hadronization in the regime

Acknowledgements

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