Electrons for Neutrinos

Vector Currents in Neutrino and Electron Nuclei Scattering

Physics Beyond the Standard Model Workshop

8/1/22

Adi Ashkenazi

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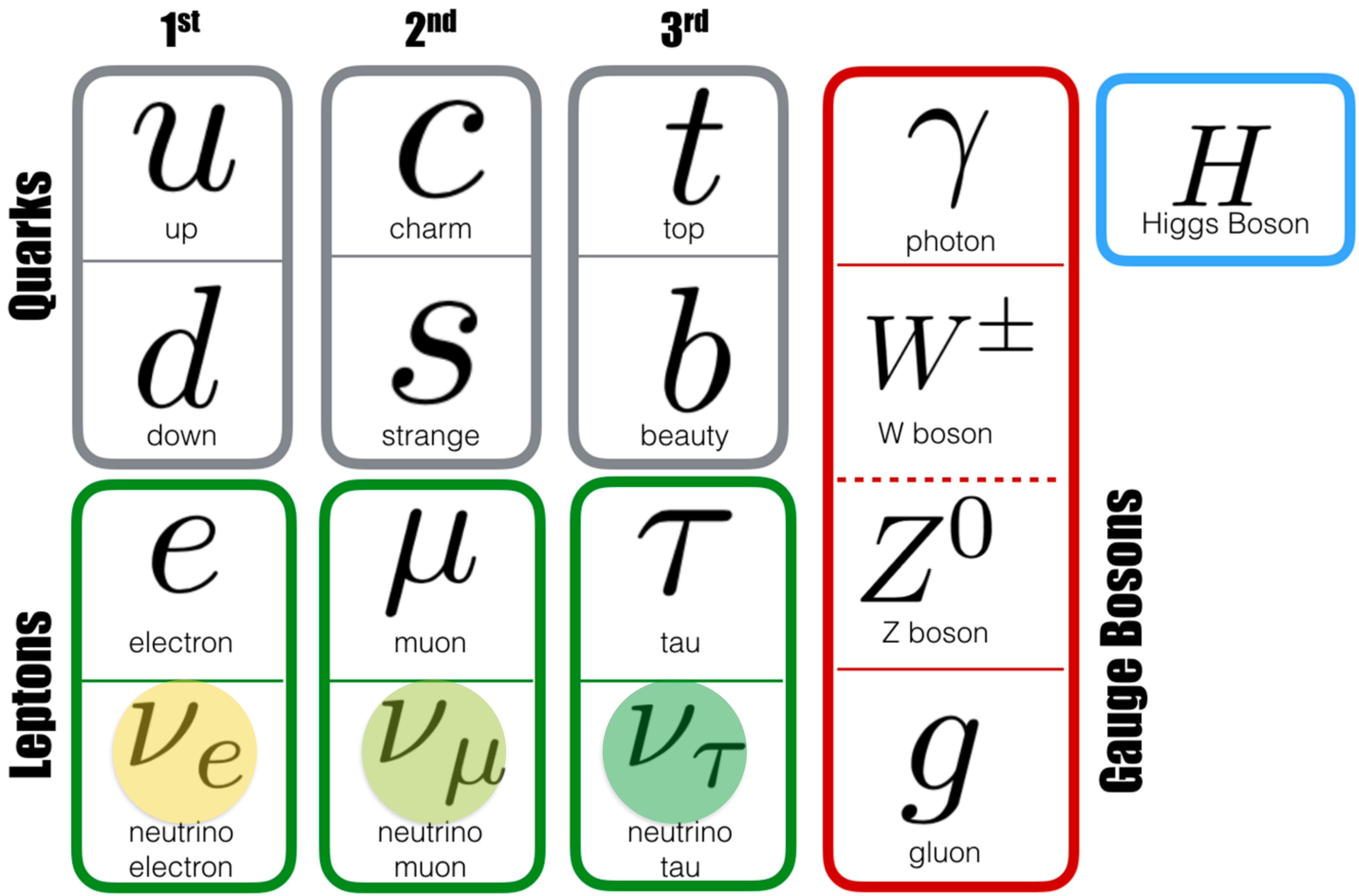
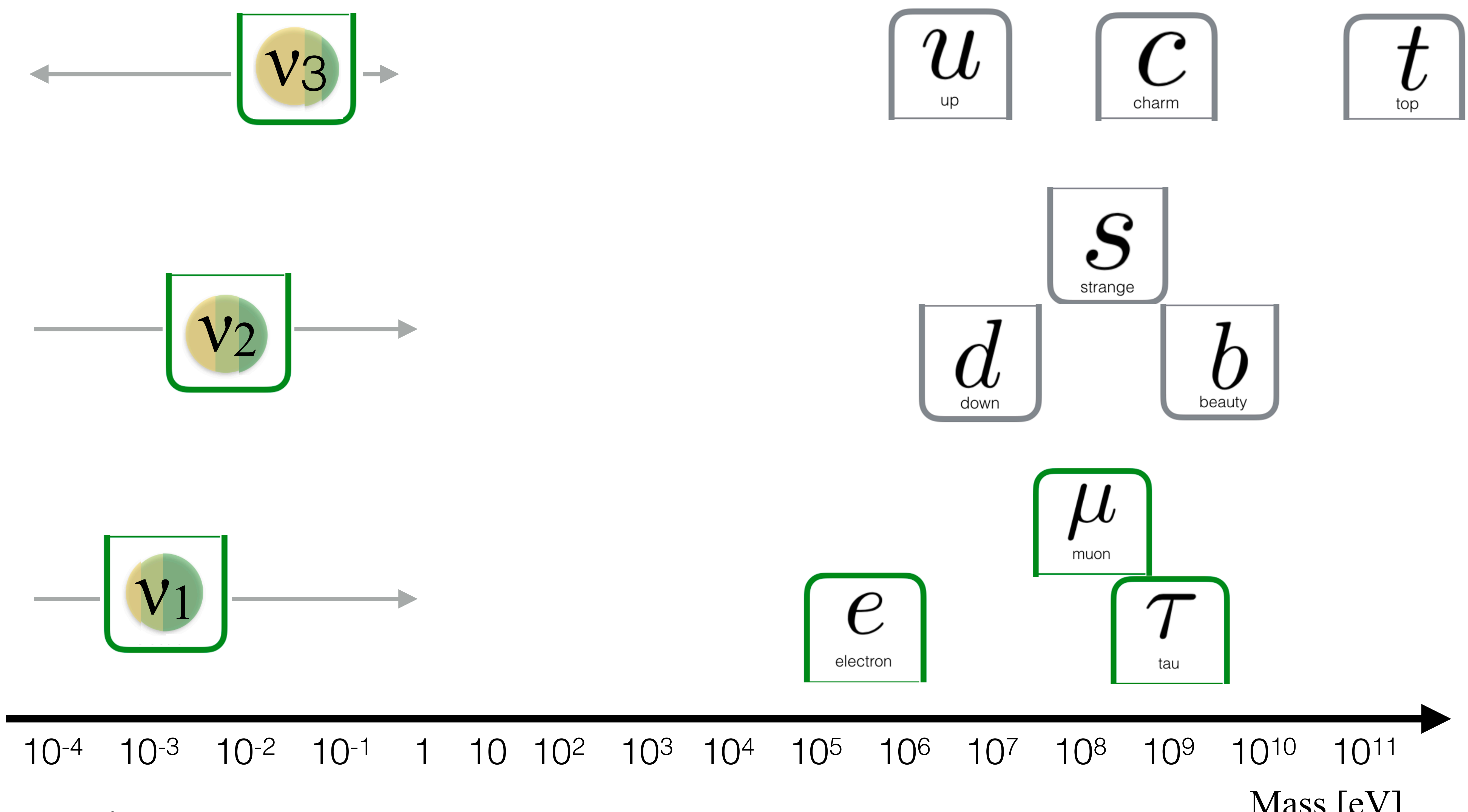
TEL AVIV UNIVERSITY

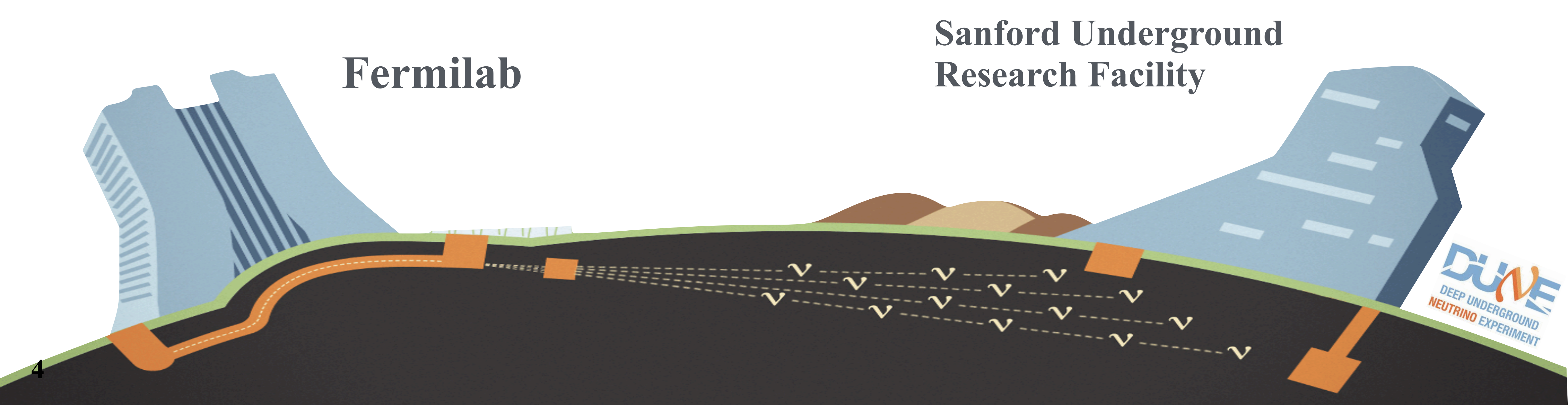
Introduction to Neutrino Oscillations



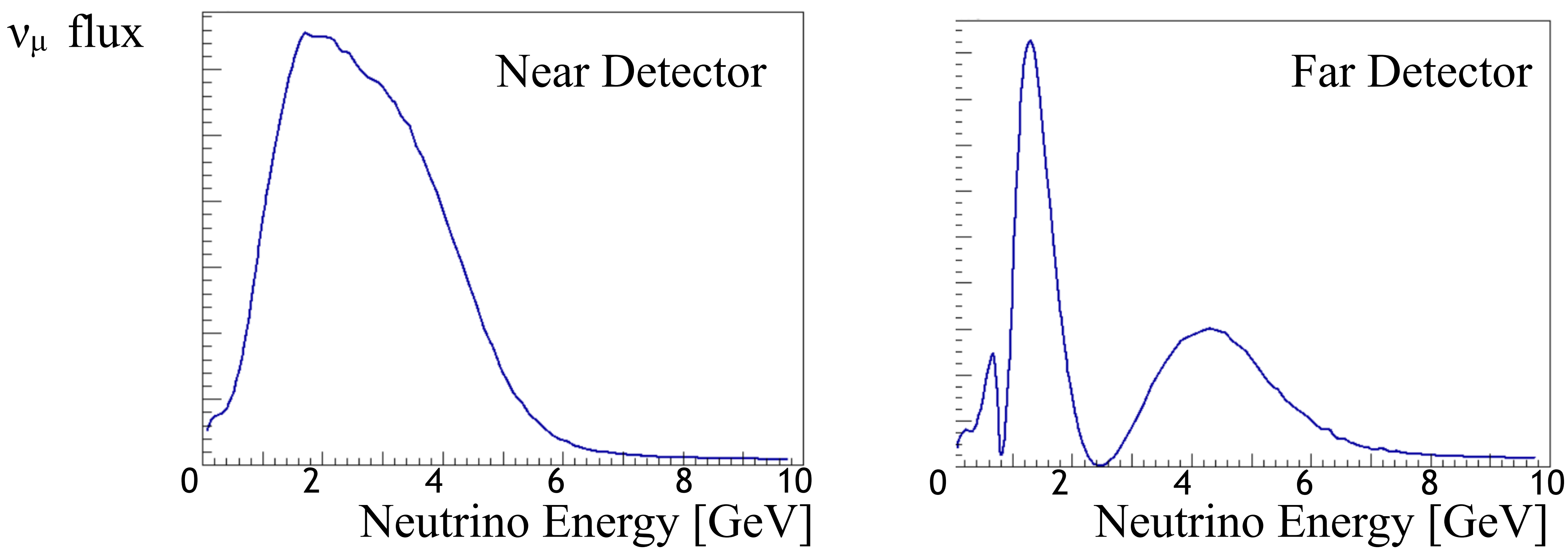
Introduction to Neutrino Oscillations

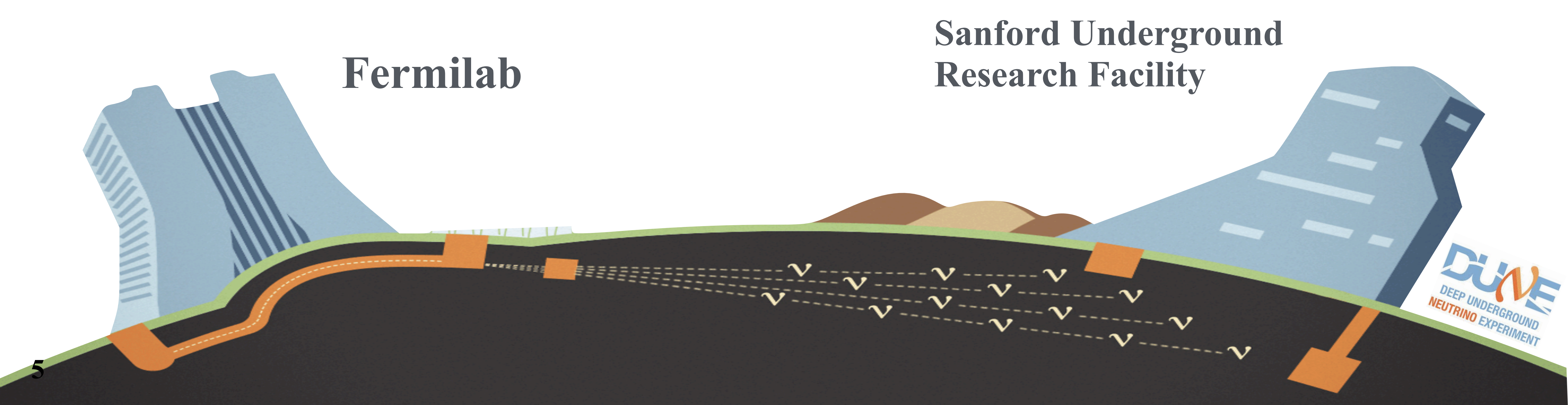


Introduction to Neutrino Oscillations

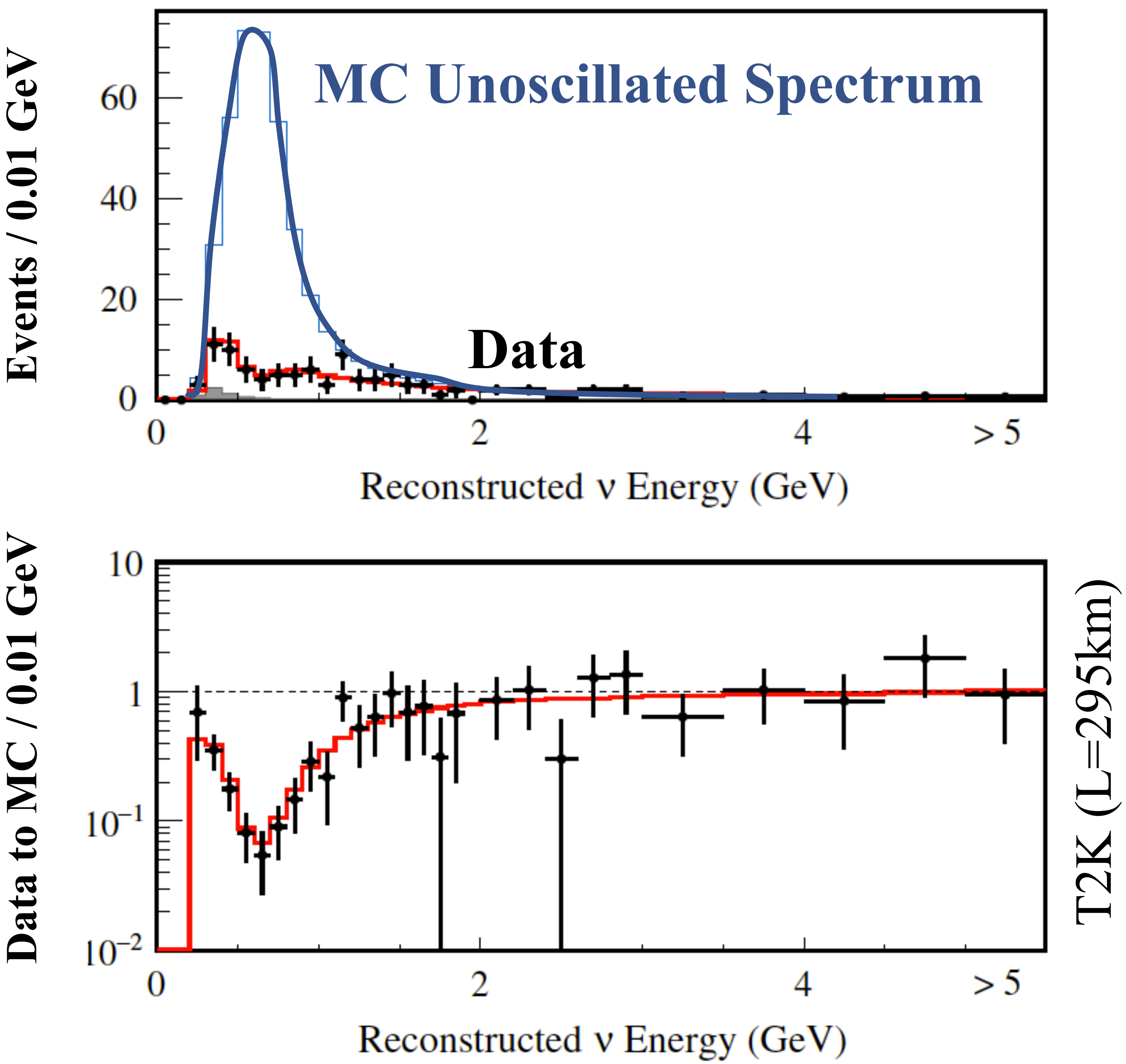


Introduction to Neutrino Oscillations





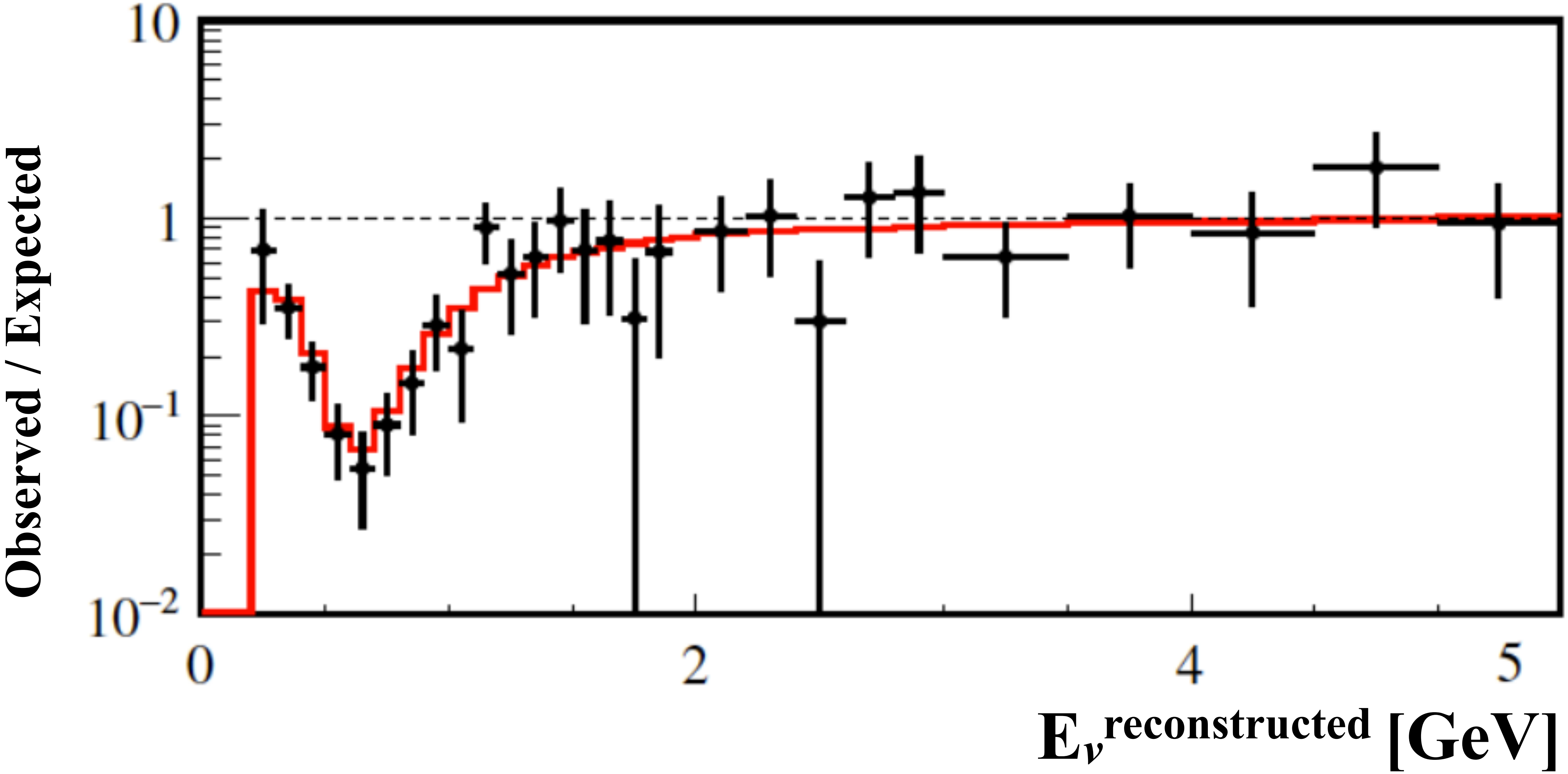
Oscillations Require incoming E_ν Reconstruction



 T2K, Phys. Rev. D 91, 072010 (2015)

Oscillations Require incoming E_ν Reconstruction

$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



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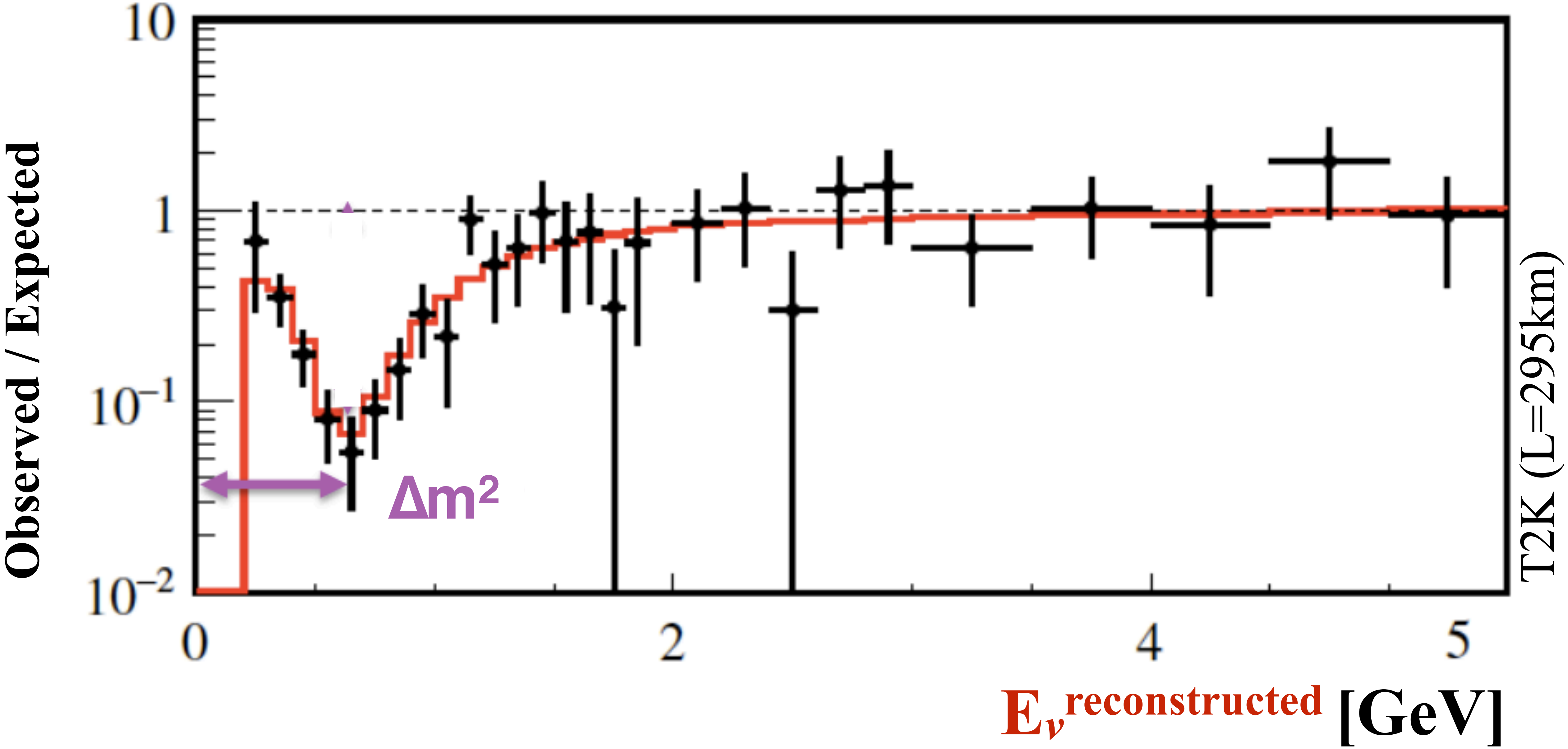
Oscillations Require incoming E_ν Reconstruction

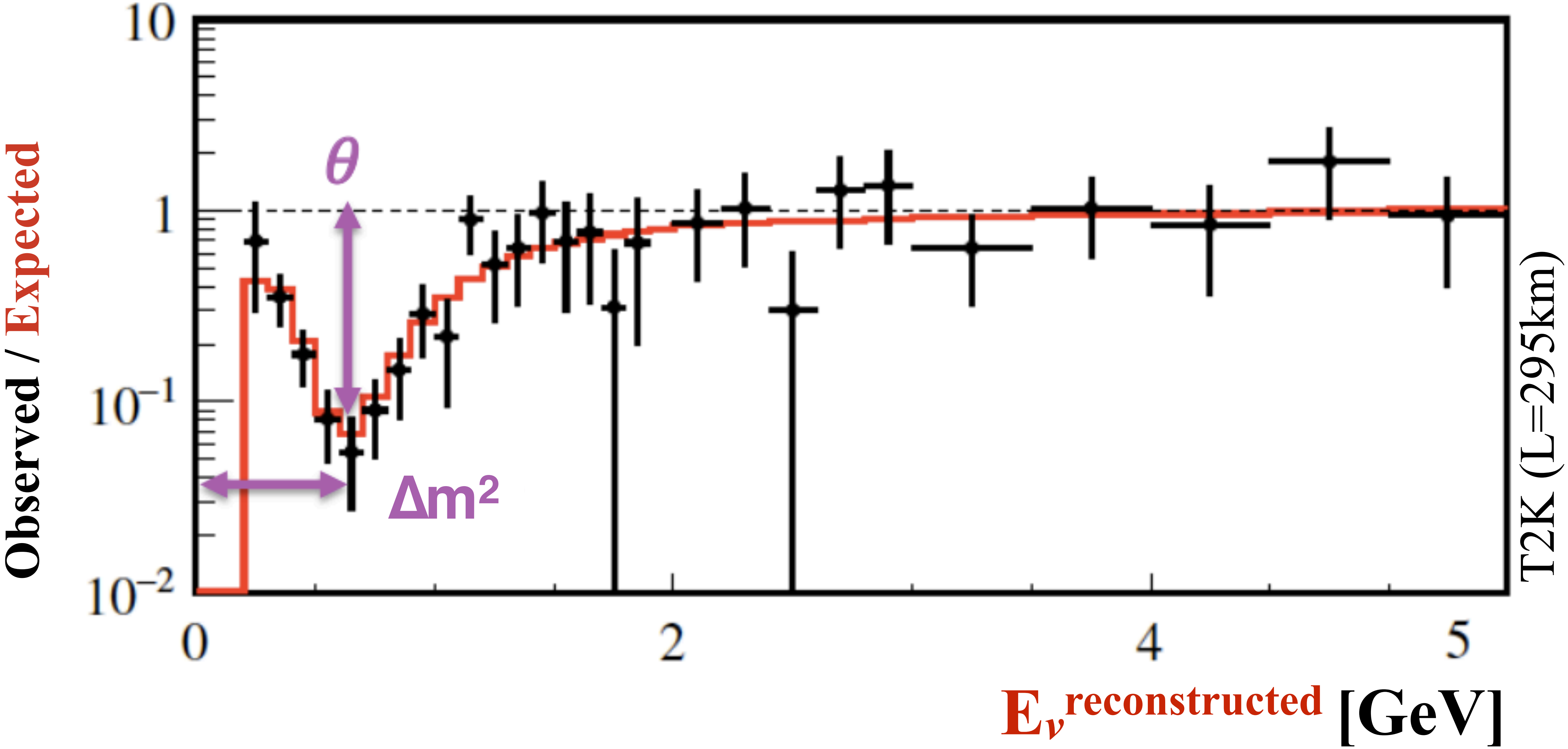
$$P(\nu_\mu \to \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{true}}\right)$$



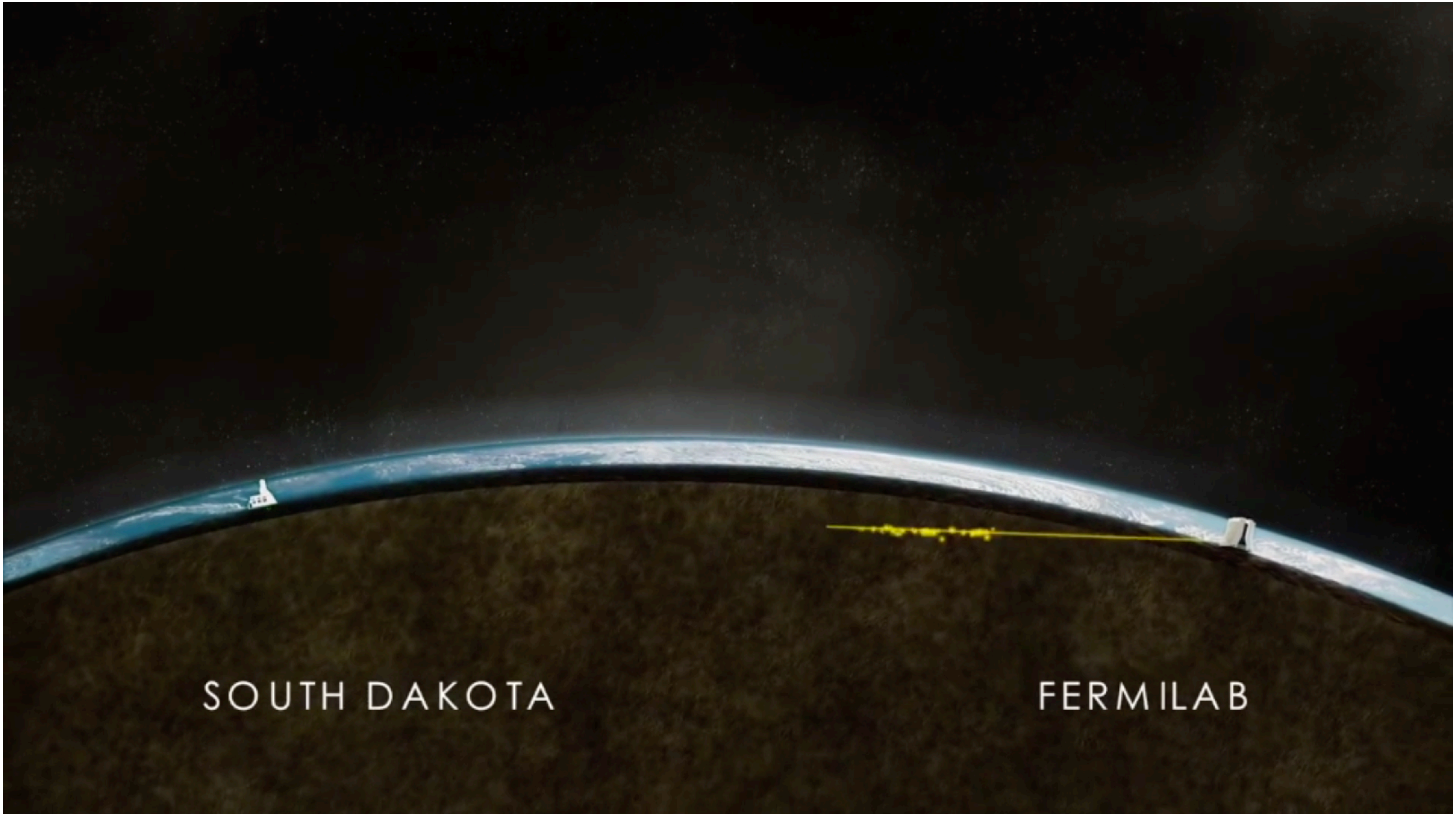
 T2K, Phys. Rev. D 91, 072010 (2015)

Oscillations Require incoming E_ν Reconstruction

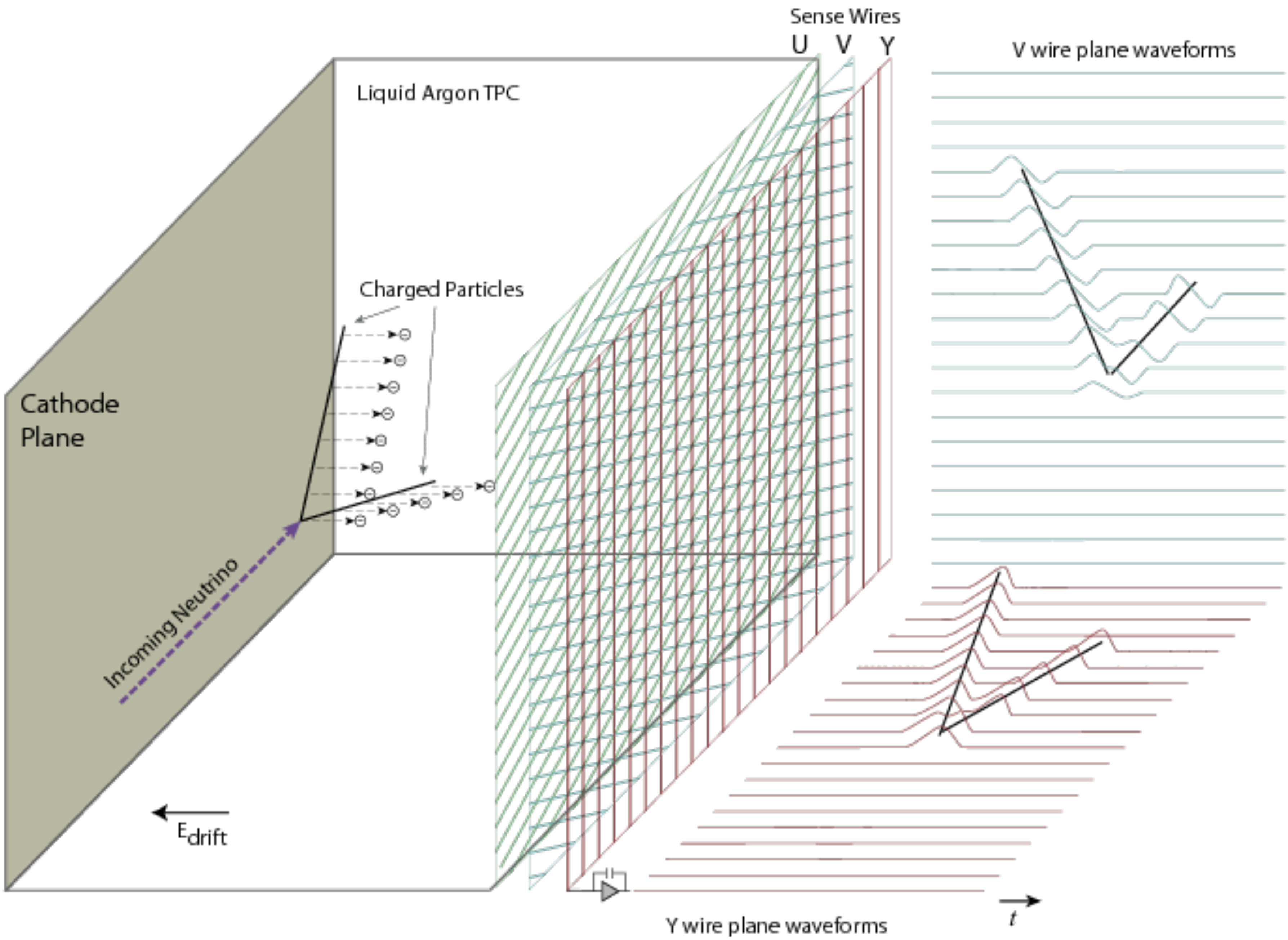
$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{real}}\right)$$



 T2K, Phys. Rev. D 91, 072010 (2015)



Long Baseline 1300 km, active mass ~70 kton
Sensitivity to: $\theta 23$, $\theta 13$, δCP, Mass ordering

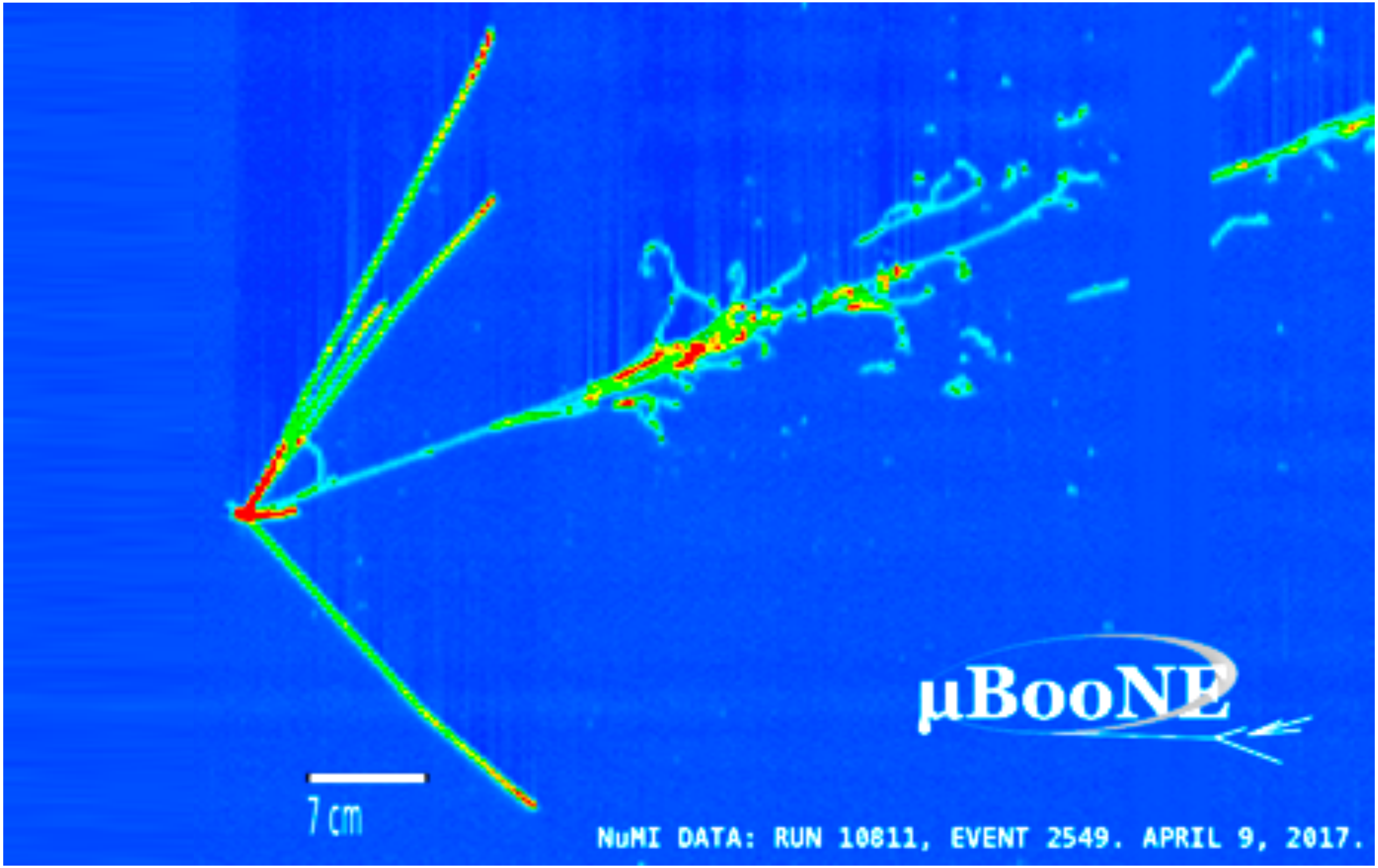


LAr Time Projection Chamber   Active mass : 85 tons

Triggered by PMTs, 3 wire planes with 3 mm spacing

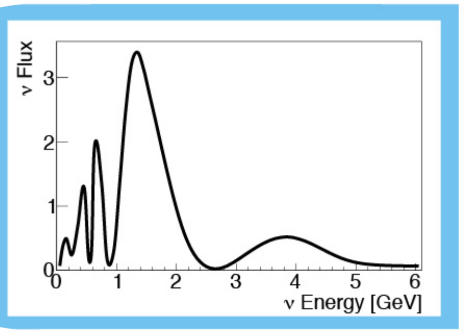
impeccable spatial resolution, calorimetric measurement

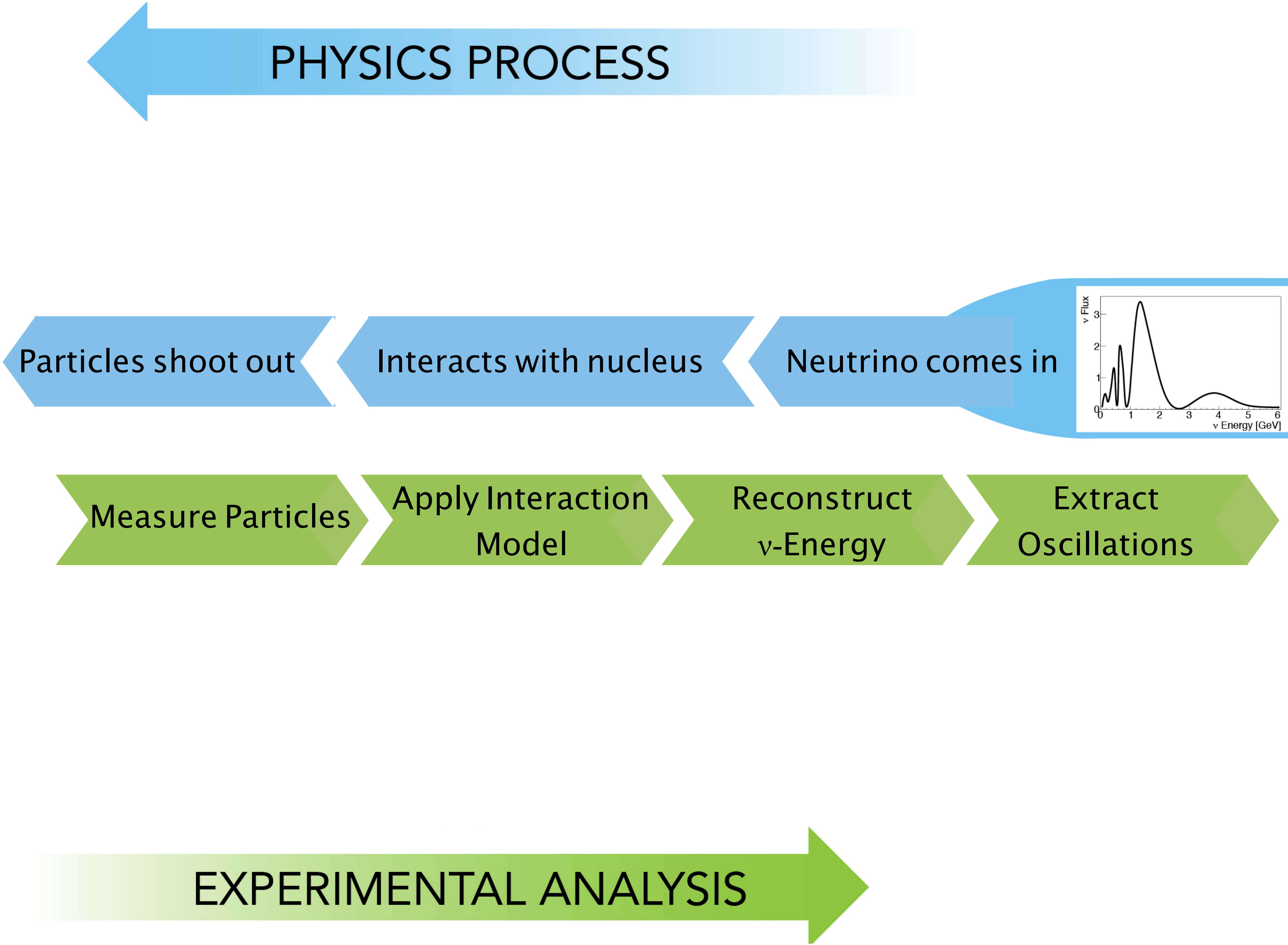
μBooNE

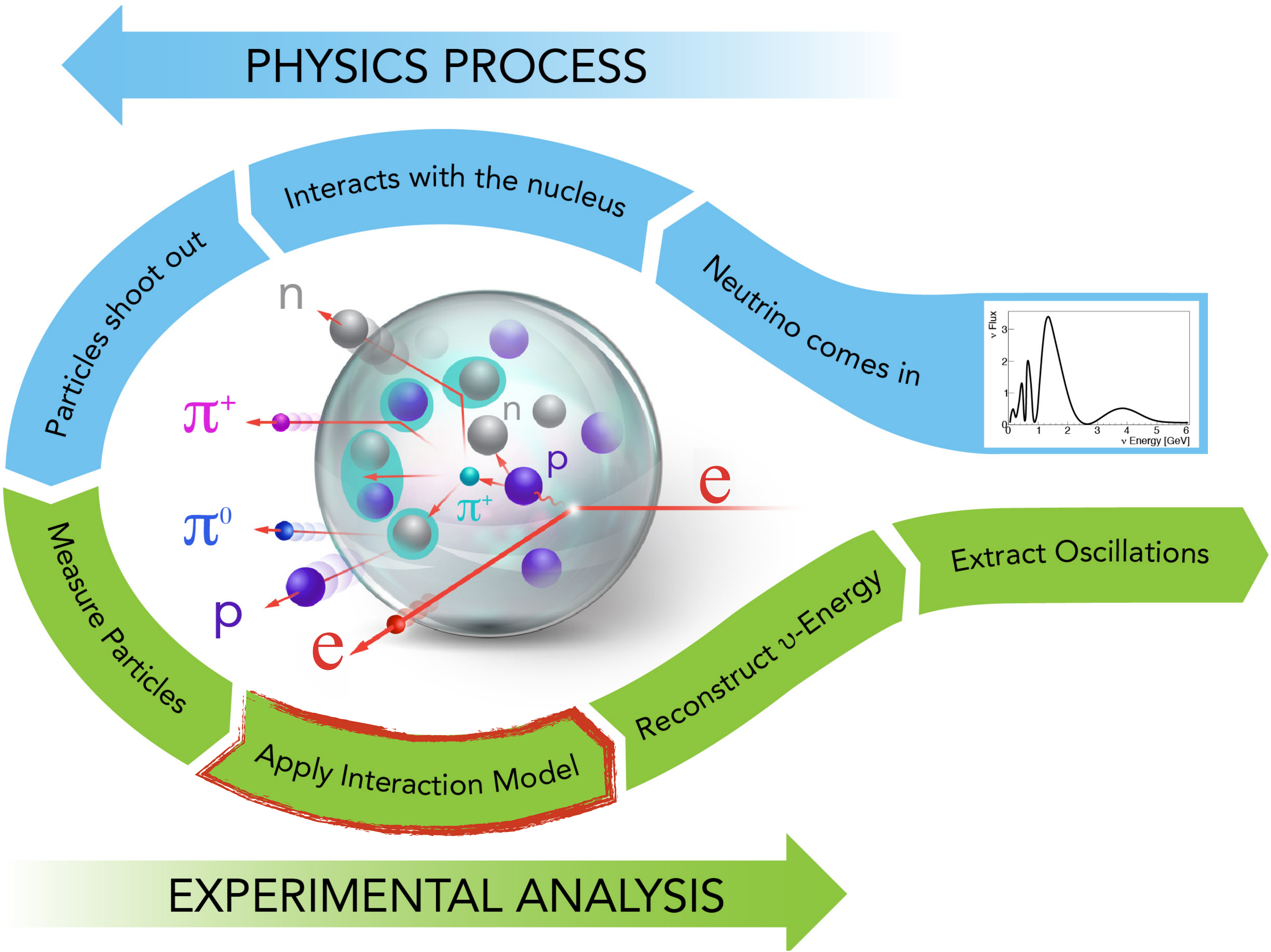

7 cm
μBooNE
NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

PHYSICS PROCESS

Particles shoot out ← Interacts with nucleus ← Neutrino comes in




PHYSICS PROCESS
Particles shoot out
Interacts with nucleus
Neutrino comes in
ν Flux
ν Energy [GeV]
0
1
2
3
4
5
6
Measure Particles
Apply Interaction Model
Reconstruct ν-Energy
Extract Oscillations
EXPERIMENTAL ANALYSIS



PHYSICS PROCESS
Interacts with the nucleus
Particles shoot out
Neutrino comes in
ν Flux
ν Energy [GeV]
n
n
p
p
π+
π+
π0
e
e
Measure Particles
Apply Interaction Model
Reconstruct υ-Energy
Extract Oscillations
EXPERIMENTAL ANALYSIS

The challenge - next generation high precision

$$N(E_{rec}, L) \propto \int \Phi(E, L)\sigma(E) f_\sigma(E, E_{rec}) dE$$

Measurement Incoming true flux Modelling input

The challenge - next generation high precision

$$N(E_{rec}, L) \propto \int \Phi(E, L)\sigma(E) f_{\sigma}(E, E_{rec}) dE$$

Measurement

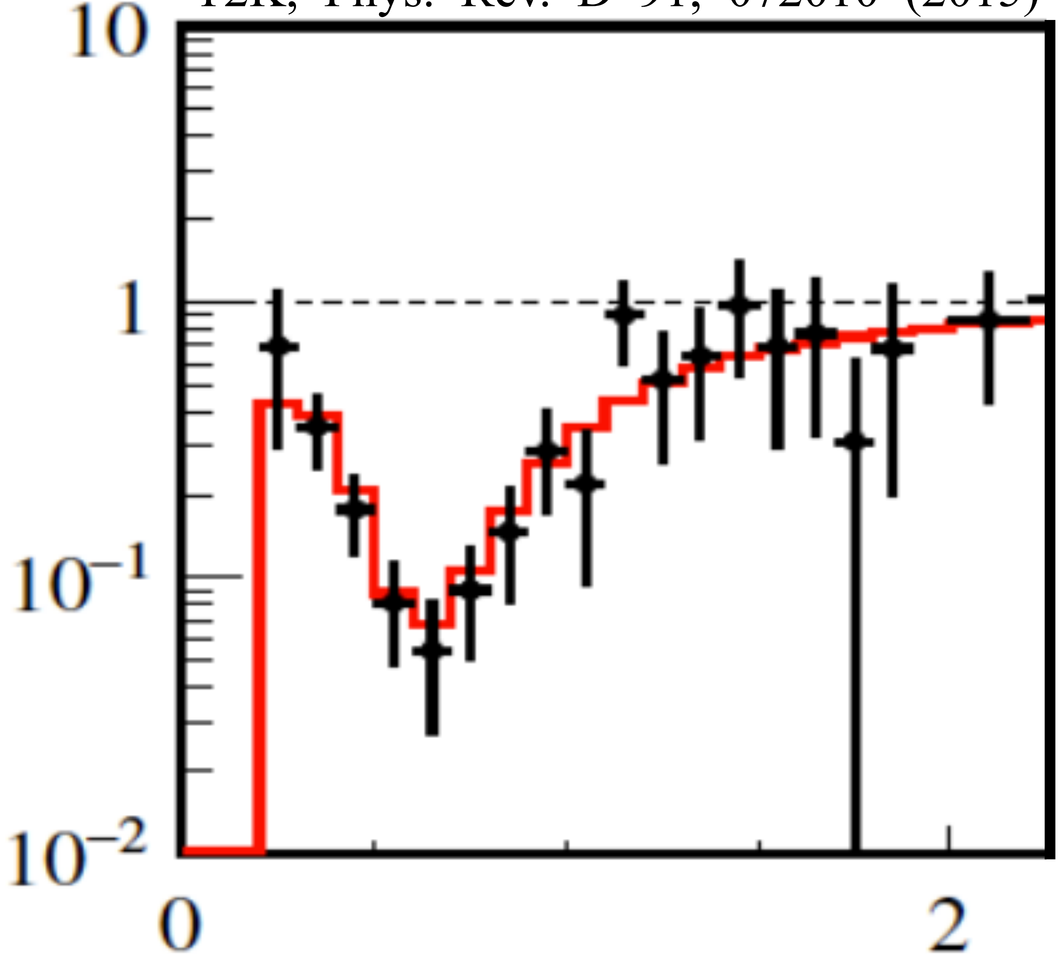
Incoming true flux

Modelling input

- Improve theory
- Use near detector
- Use external constraints
  e scattering

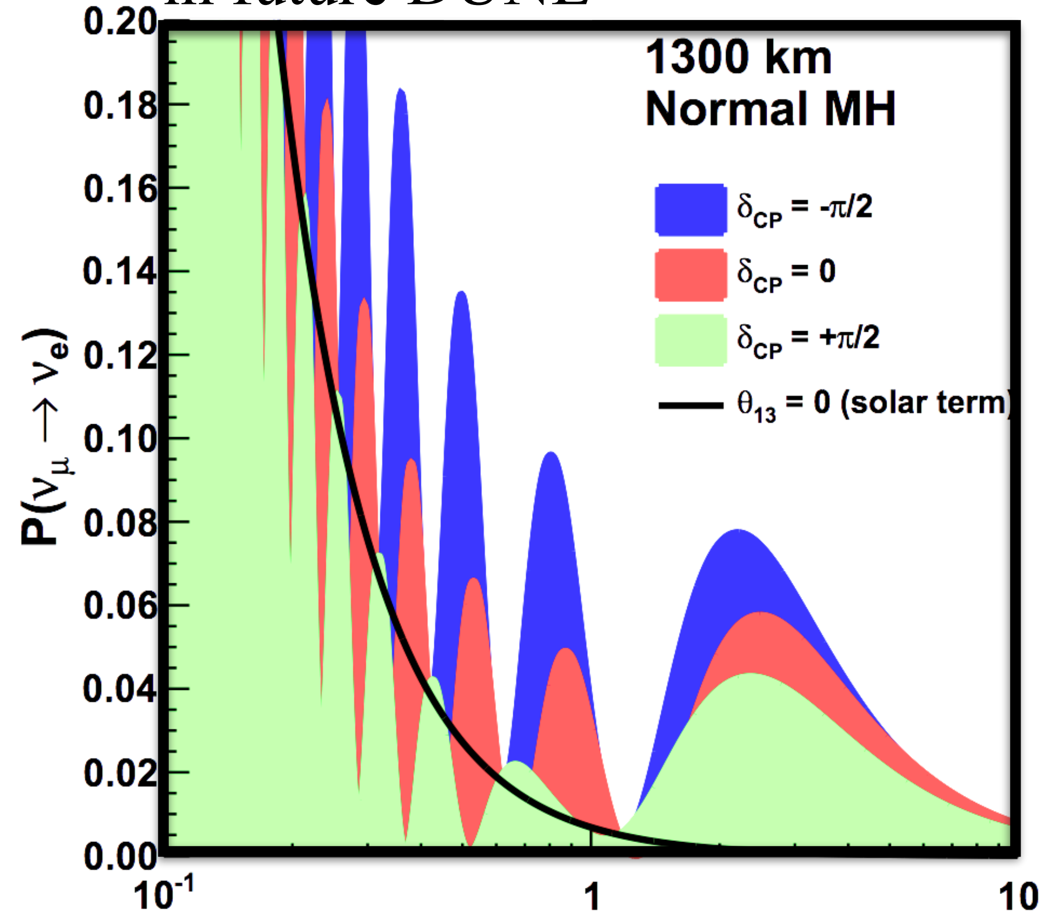
The challenge - next generation high precision

T2K, Phys. Rev. D 91, 072010 (2015)



Neutrino Energy [GeV]

Simulation of oscillation effects in future DUNE

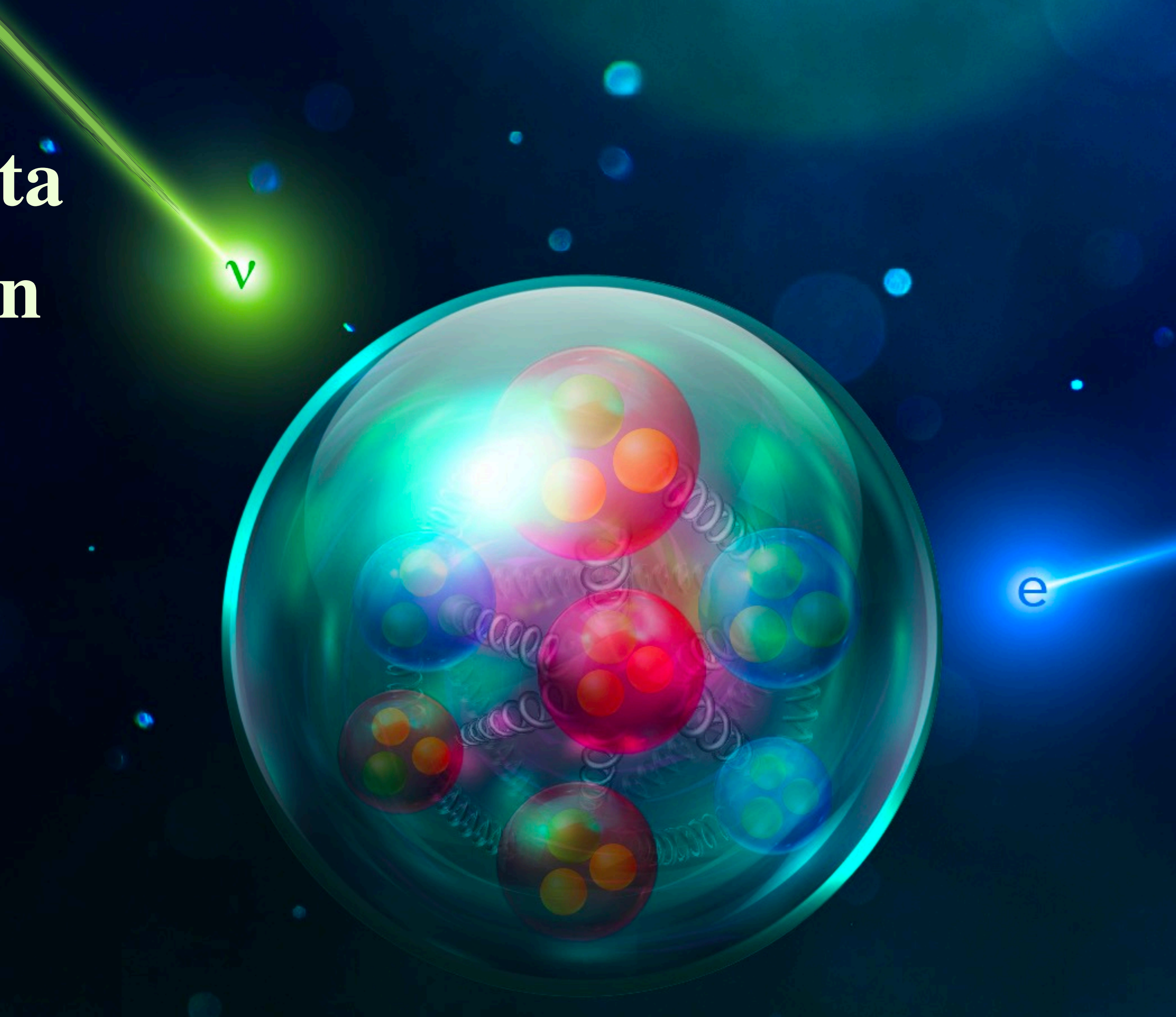


Neutrino Energy [GeV]

Electrons for Neutrinos

Using electron scattering data to reduce neutrino oscillation systematic uncertainties

- **Test neutrino energy reconstruction**
- **Constrain lepton-nucleus interaction models**

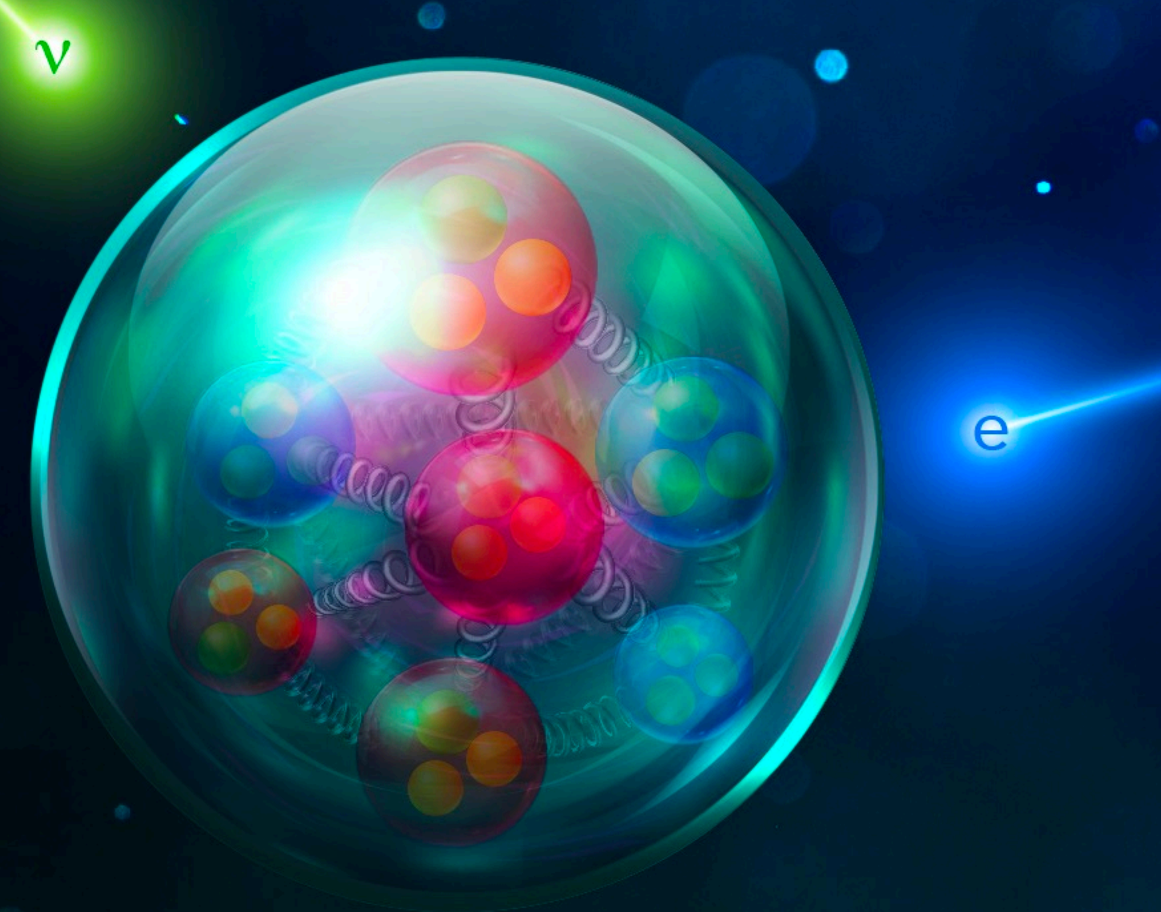


visit: www.e4nu.com

e4ν Why electrons?

Electrons and Neutrinos have:

- **Identical initial nuclear state**
- **Same Final State Interactions**
- **Similar interactions (vector vs. vector + axial)**



Electron beams have known energy

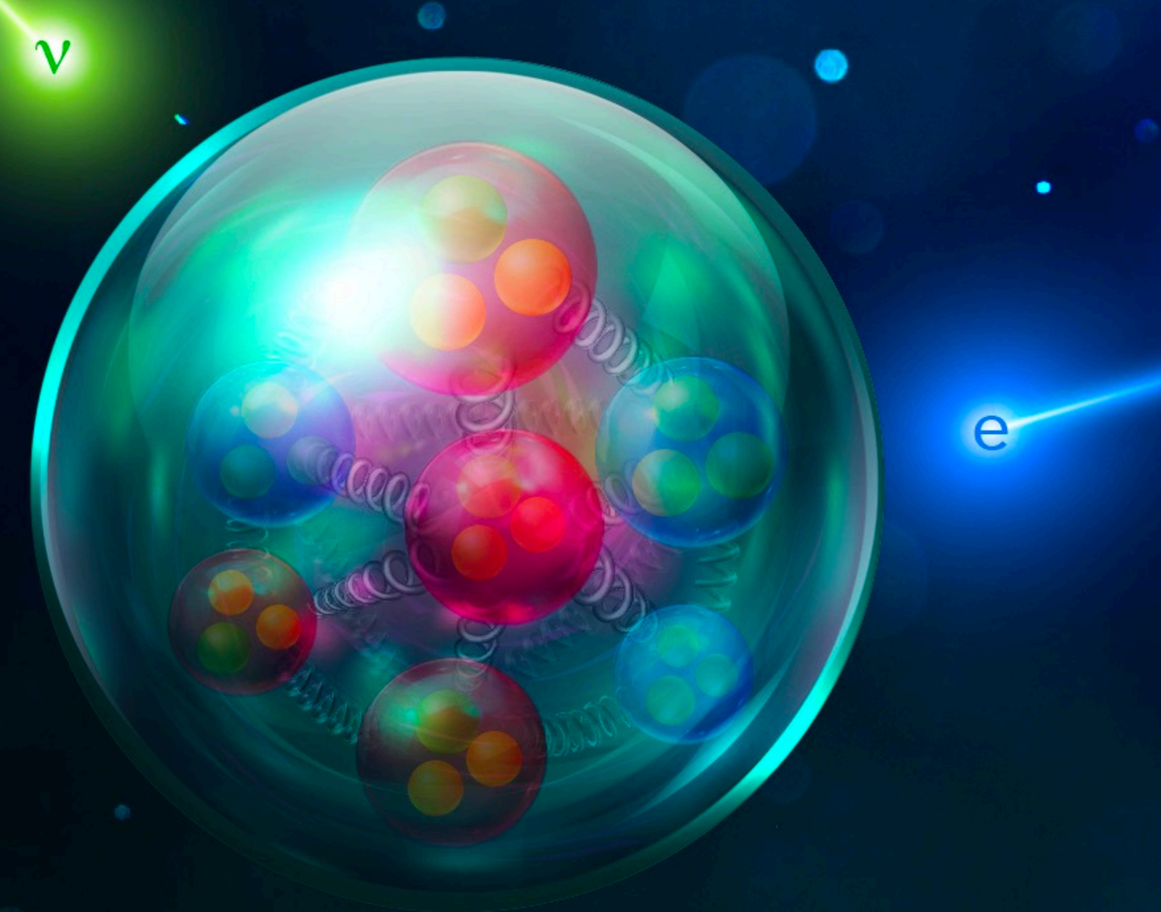
e4ν Collaboration goals

Analyse eA data

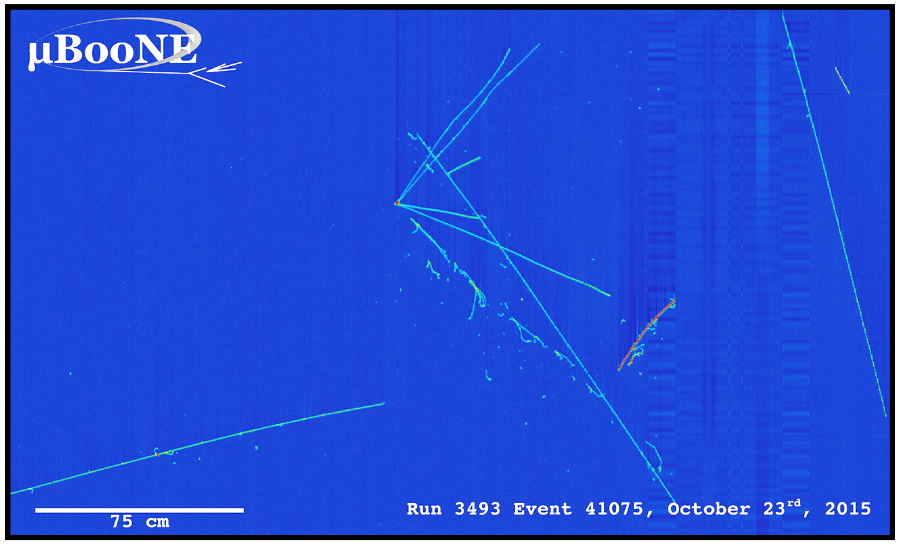
Improve lepton-nucleus models

Tune existing lepton-nucleus models

Determine implications on neutrino oscillations



Incoming Energy Reconstruction



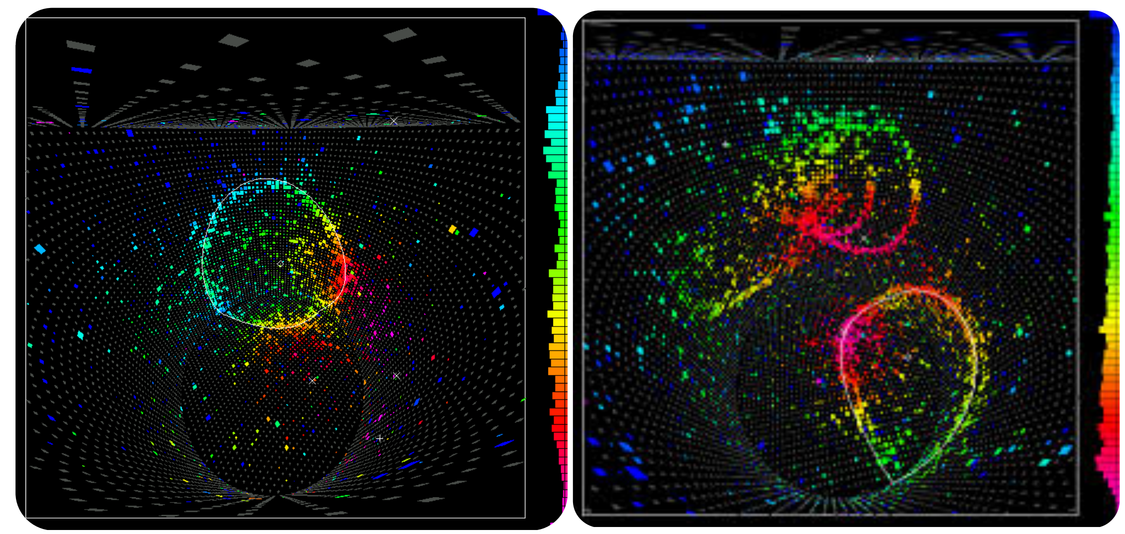
Tracking detectors:

Calorimetric sum

Using All detected particles

$$E_{\text{cal}} = E_l + E_p^{\text{kin}} + \epsilon$$

[1p0π]



Cherenkov detectors:

Assuming QE interaction

Using lepton only

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$

ϵ is the nucleon separation energy ~ 20 MeV

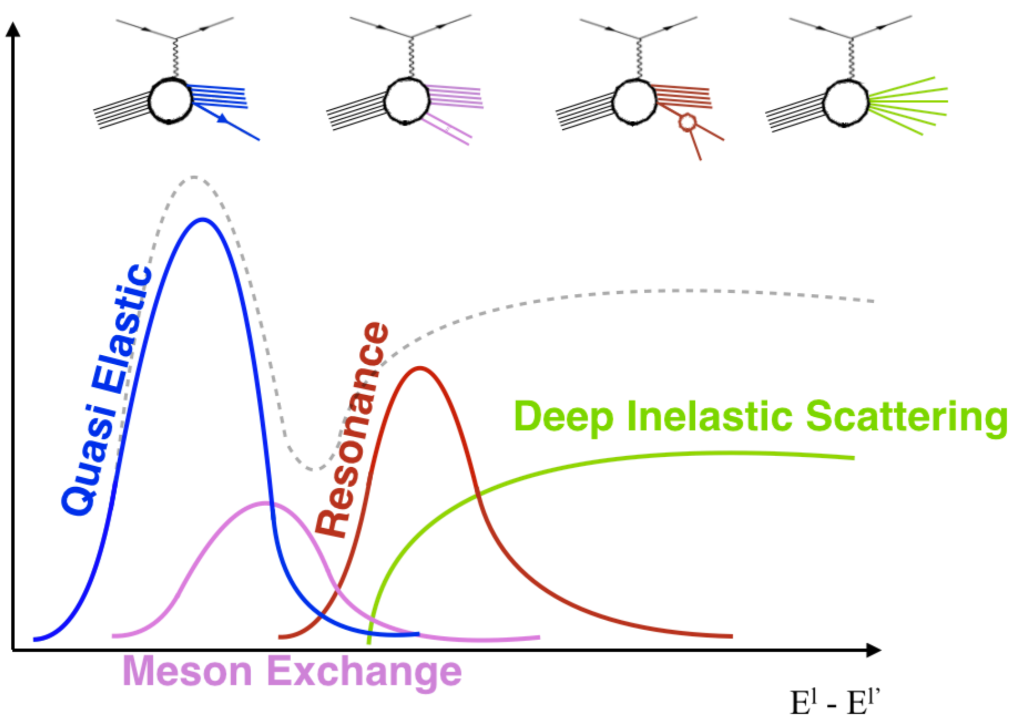
Lepton-Nucleus Interaction Modelling

Neutrino event generators simulating νA interaction

Genie

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more

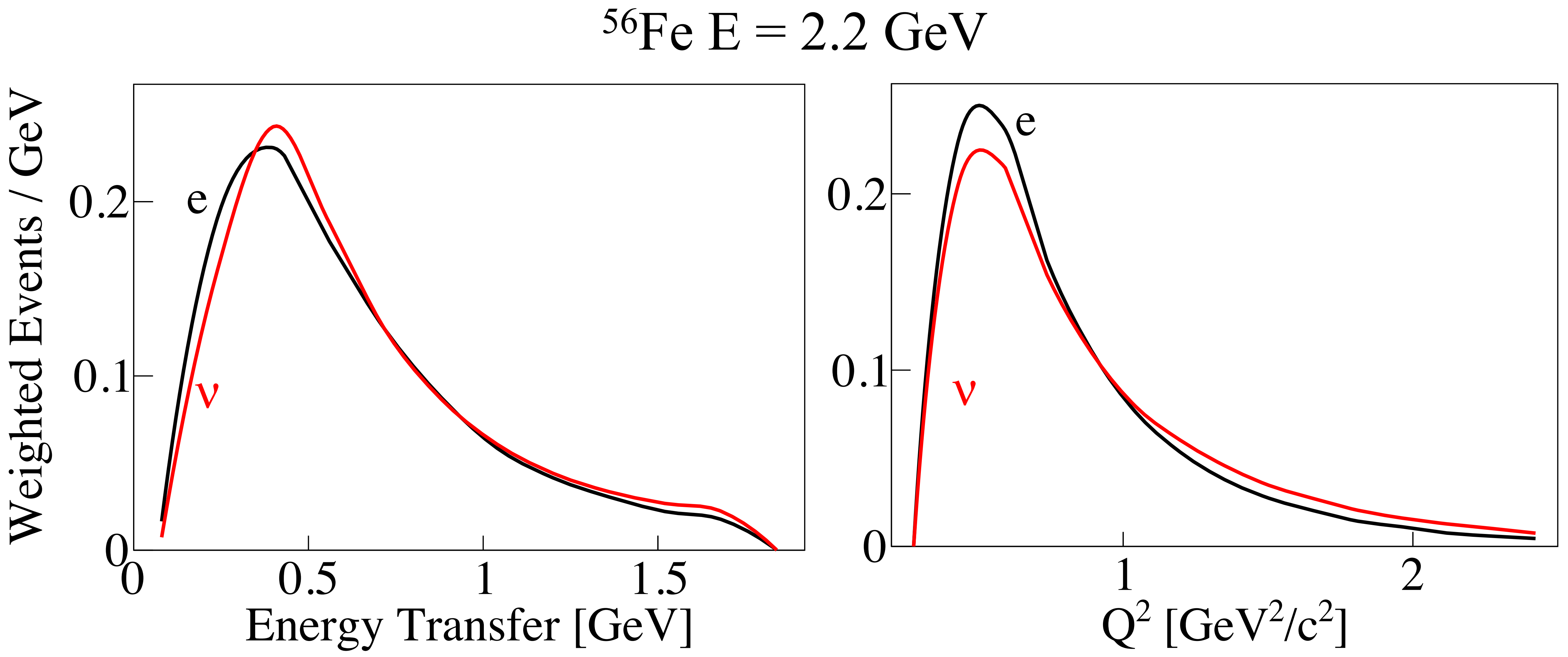


Factorisation of

- Initial state
- Each interaction mechanism separately
- Final State Interactions

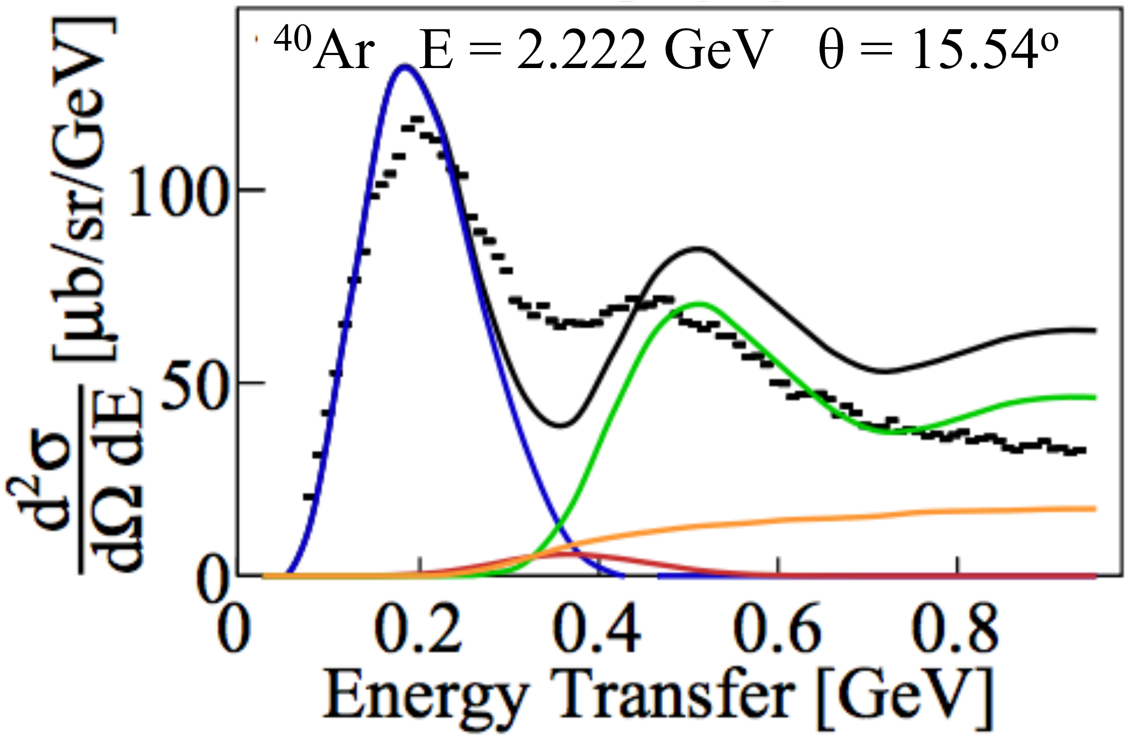
Similar eA and νA Cross sections

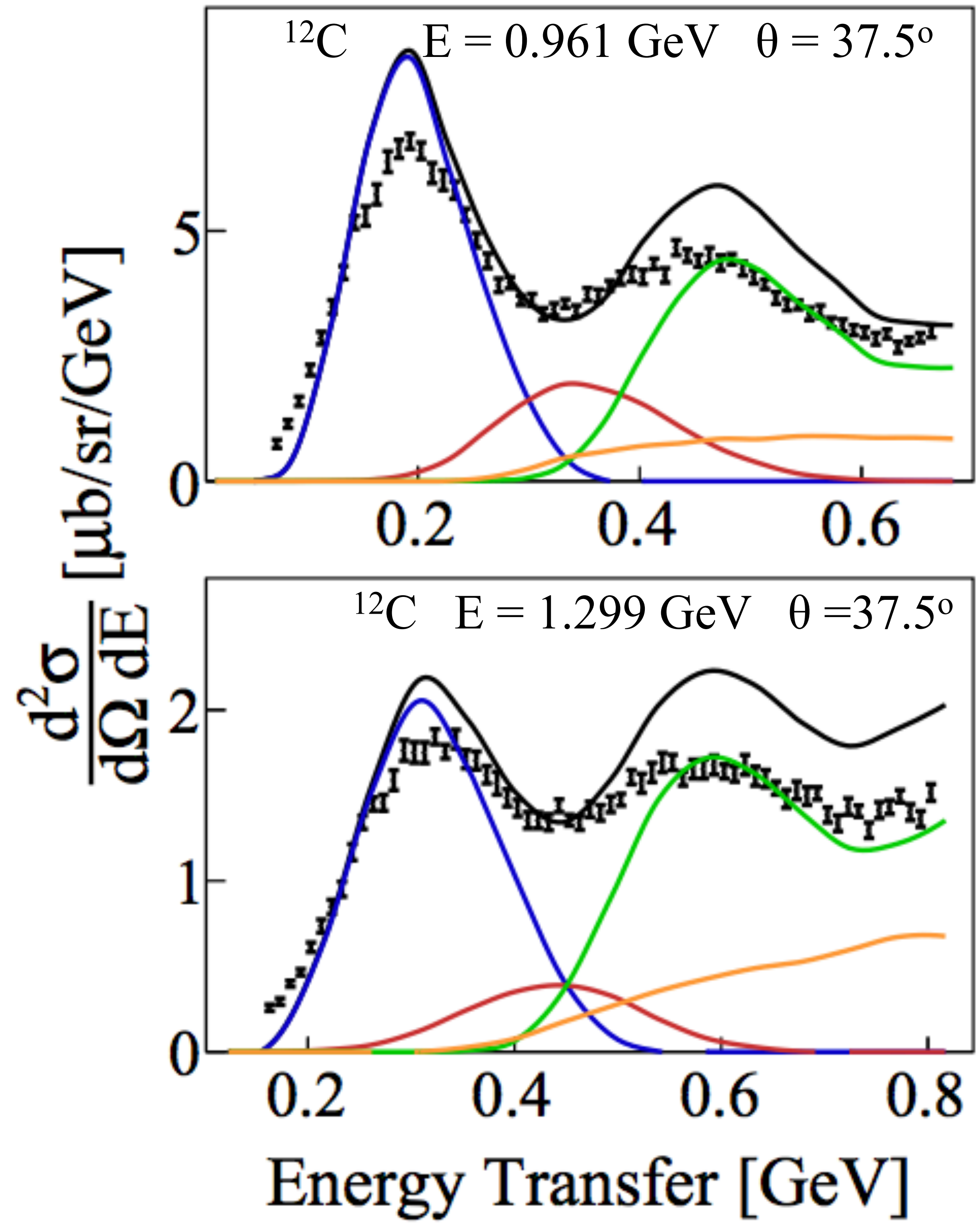
Test on 1p0π event selection



Genie v3.0.6 tune G18_10a_02_11a   Electron were weighted by $1/Q^4$

Inclusive e data and generators





Genie

— v3.0.6 tune G18_10a_02_11a

Phys.Rev.D 103 (2021) 113003

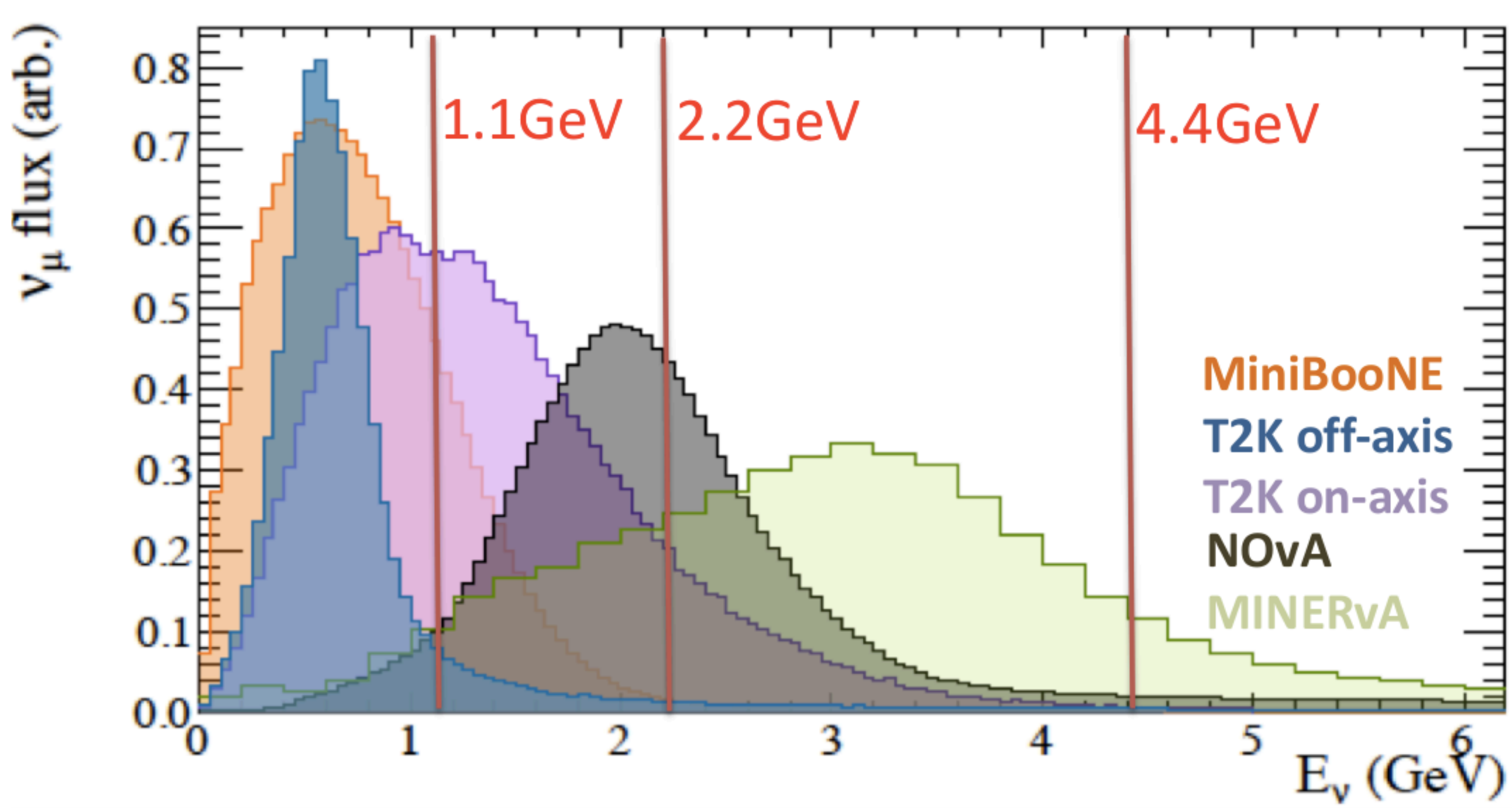
CLAS A(e,e'p) Data E2a

First test of neutrino energy reconstruction with exclusive data!

Targets: ^{4}He, ^{12}C, ^{56}Fe T2K (H_2O), NOvA (CH), DUNE (Ar)

Energies:

1.1, 2.2, 4.4 GeV



Detection thresholds:

300 MeV/c for p

150 MeV/c for $P_{\pi^{+/-}}$

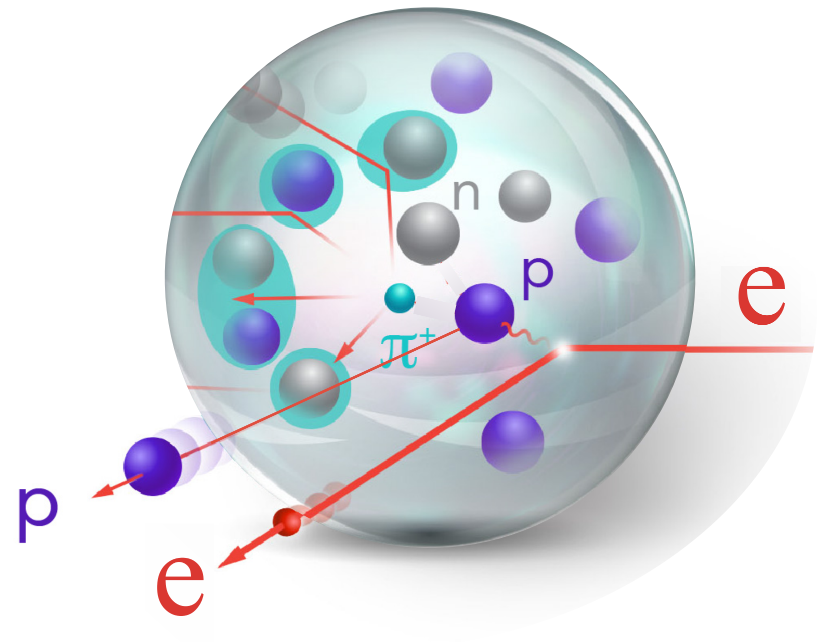
500 MeV/c for P_{π^0}

Comparable to those in ν experiments

1p0π Event Selection

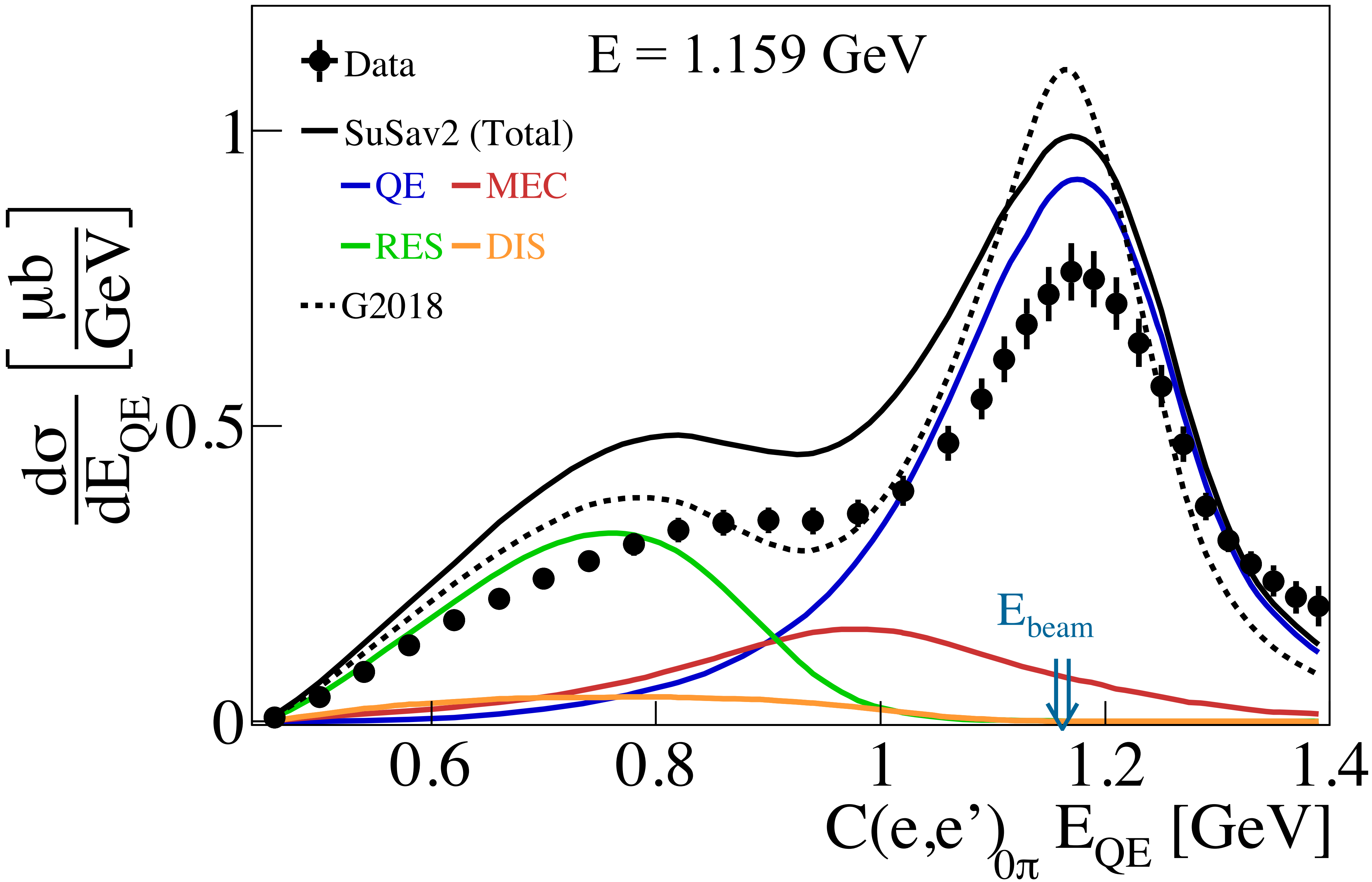
Focus on Quasi Elastic events:

- 1 proton above 300 MeV/c
- no additional hadrons above detection threshold:
  - 150 MeV/c for $P_{\pi}^{+/-}$
  - 500 MeV/c for P_{π}^{0}



e4ν Data

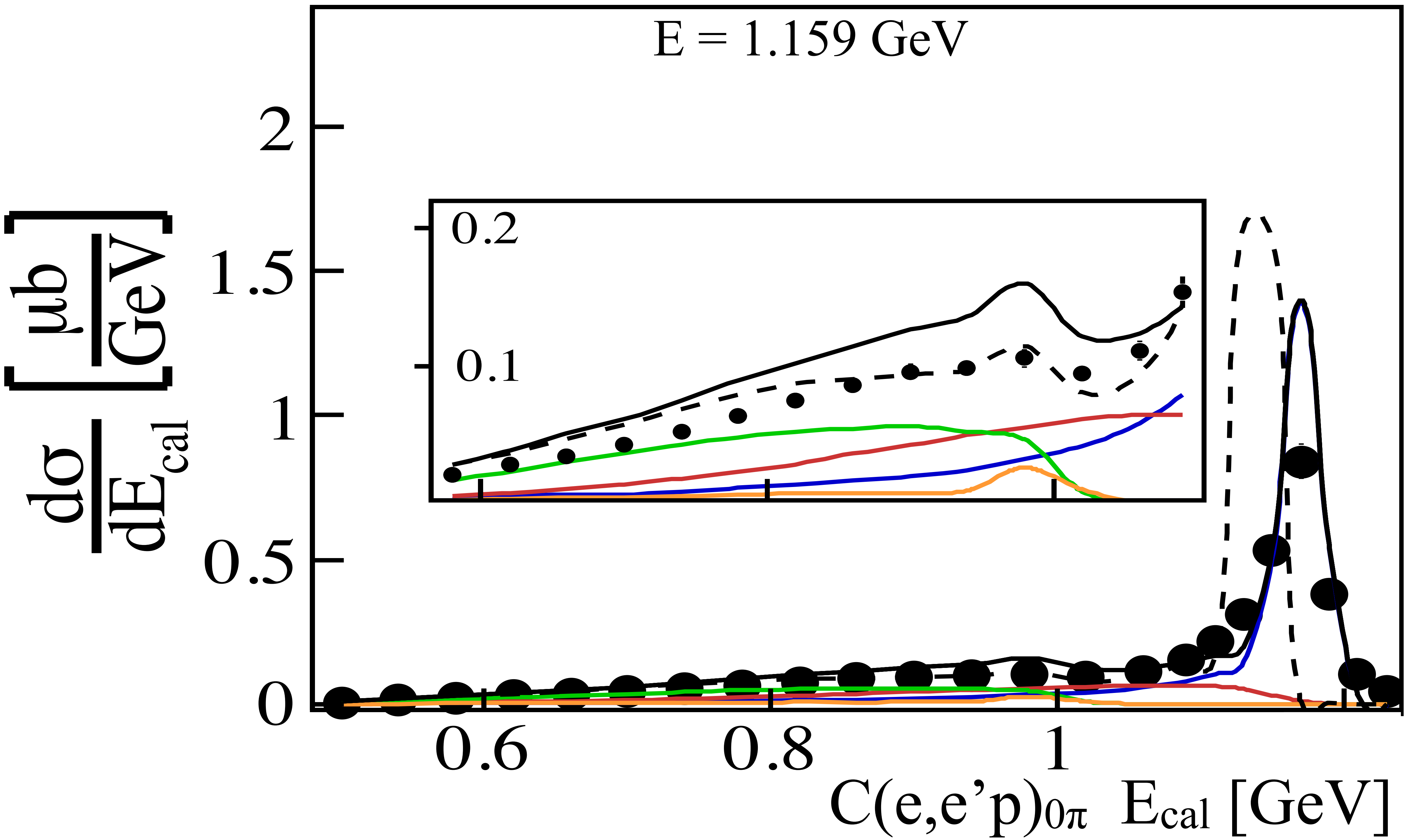
Inclusive Energy Reconstruction



Nature **599**, 565 (2021)

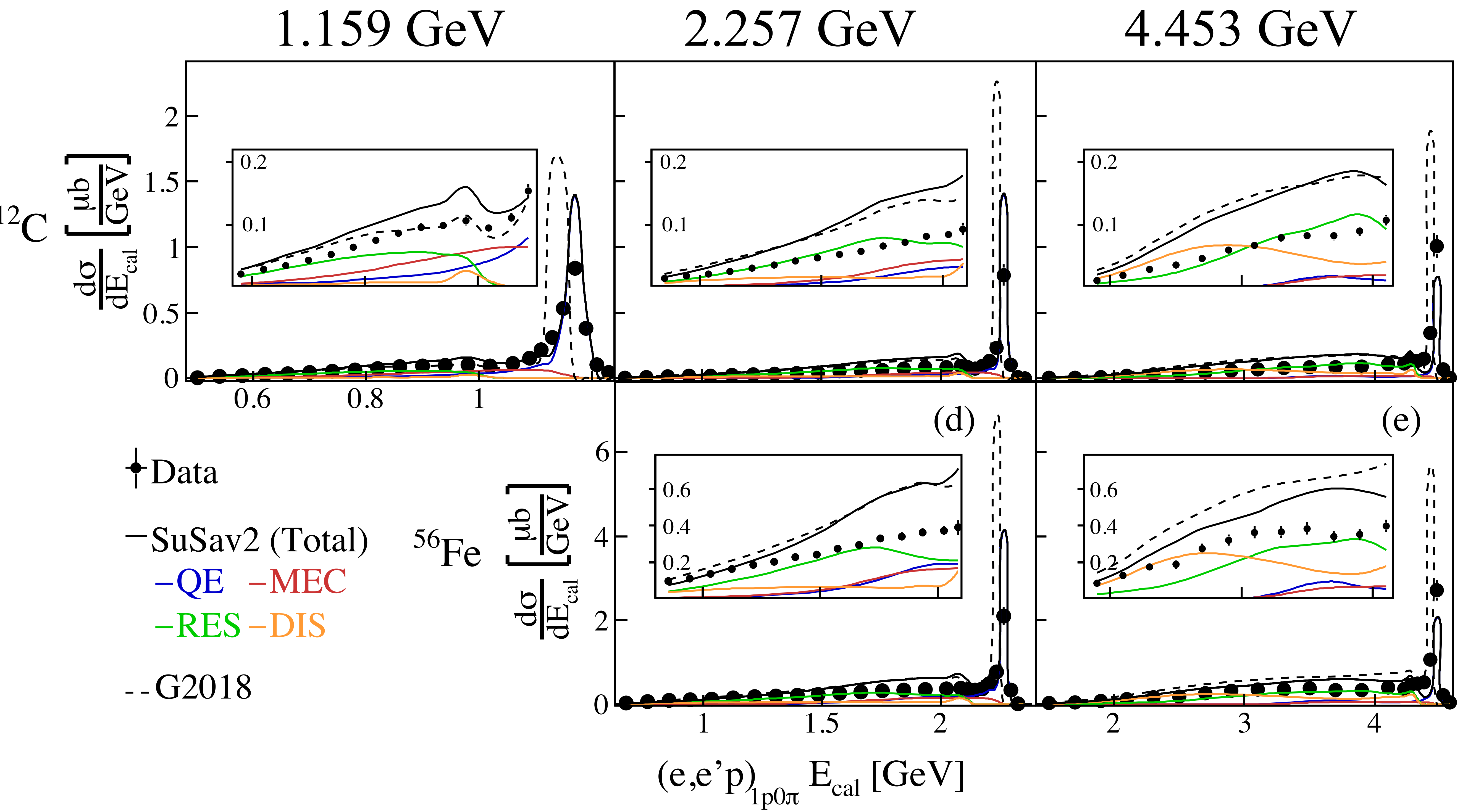
$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$

Reconstructed Calorimetric Energy



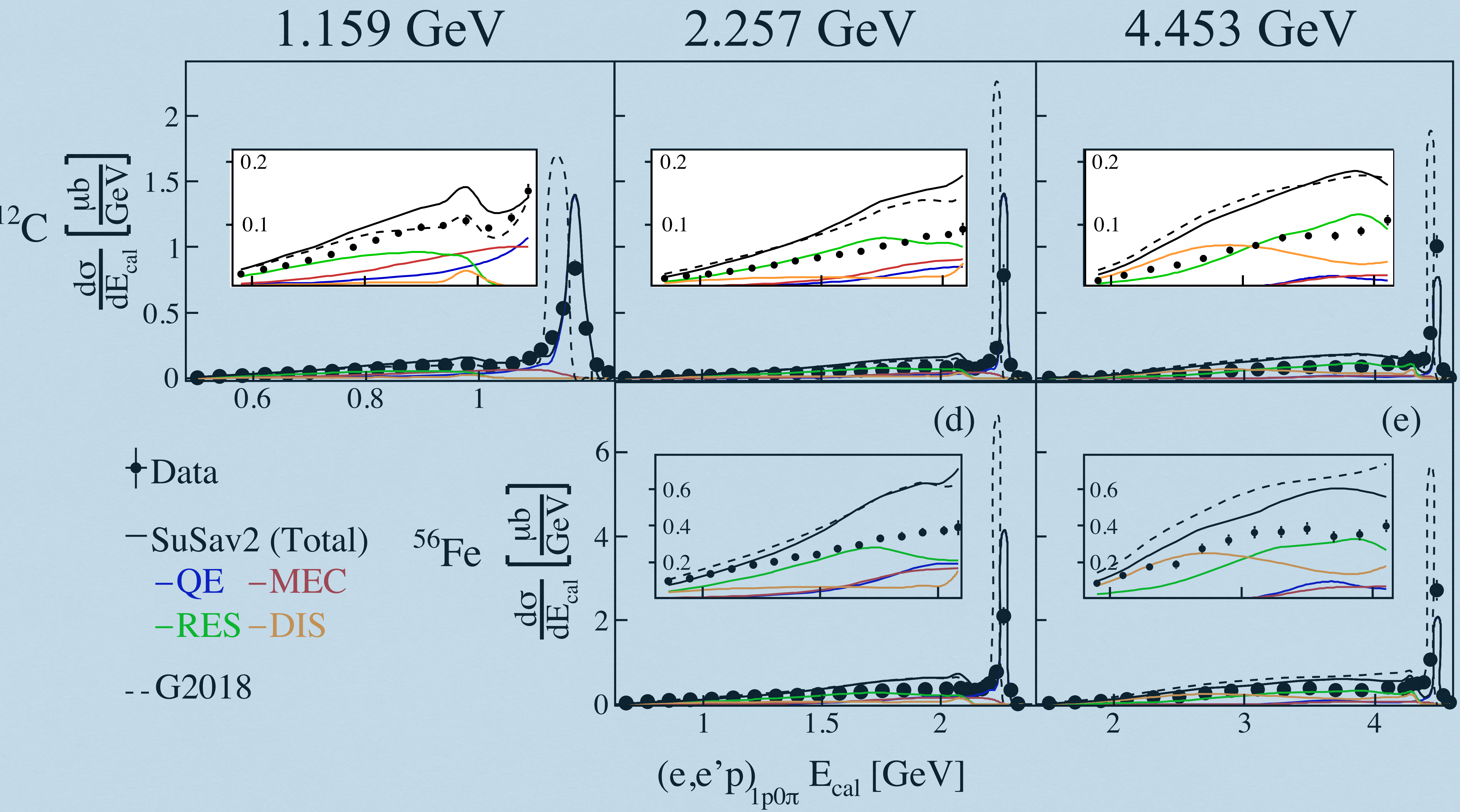
Nature **599**, 565 (2021)

Reconstructed Calorimetric Energy



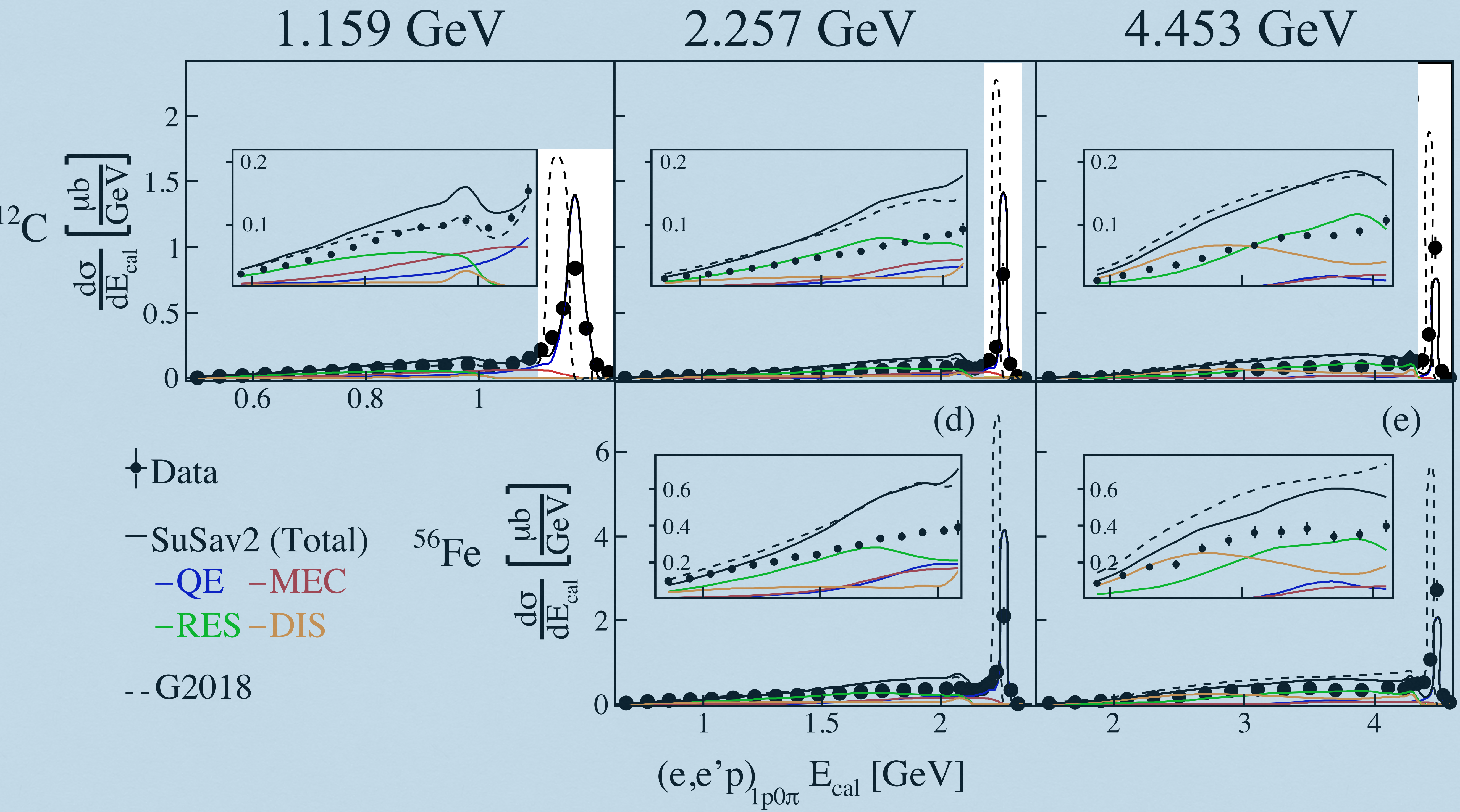
Nature **599**, 565 (2021)

Reconstructed Calorimetric Energy



Nature **599**, 565 (2021)

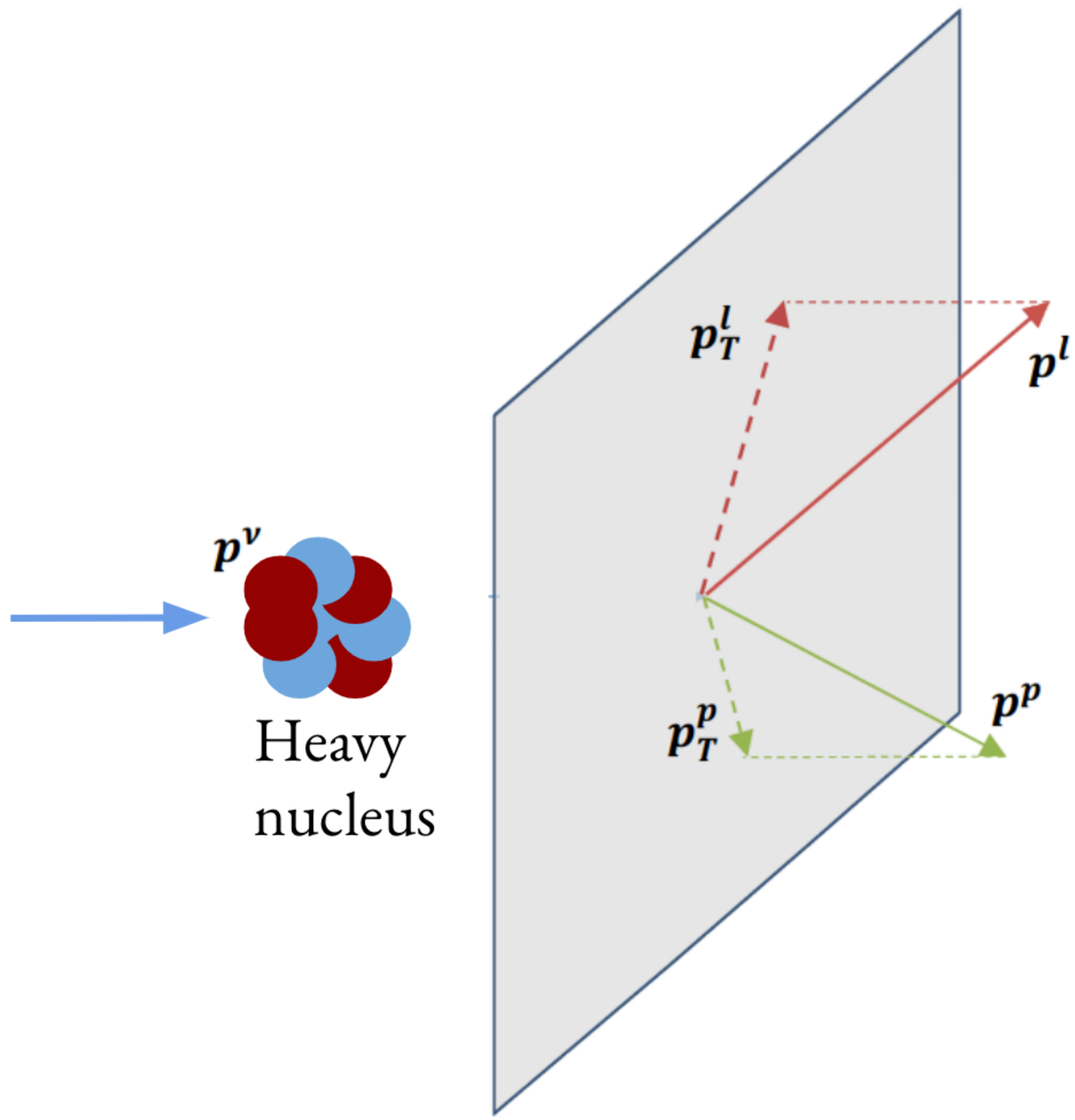
Reconstructed Calorimetric Energy

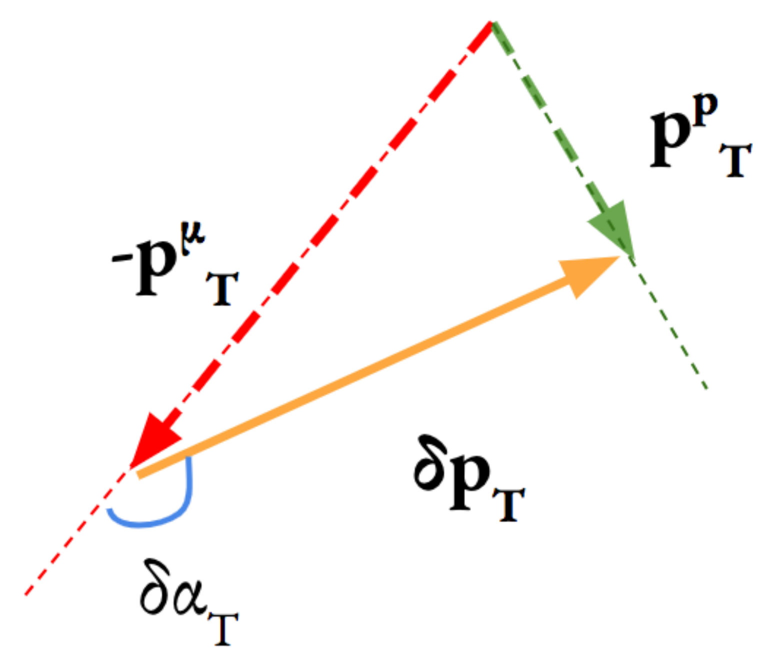


Nature **599**, 565 (2021)

Focusing on different reaction mechanisms

Standard Transverse Variables





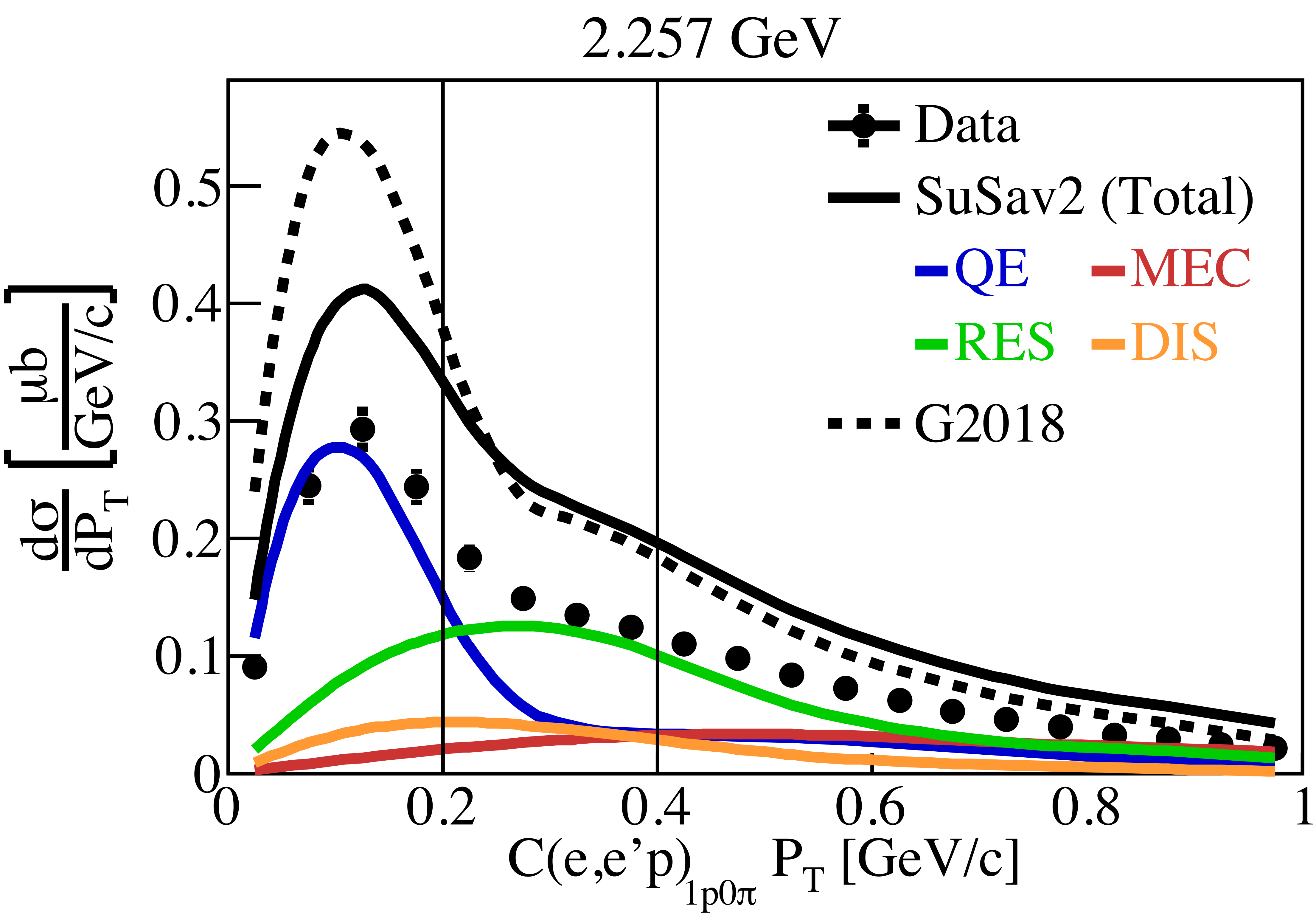
$$\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^{p}$$

Sensitive to
hit nucleon momentum

$\delta\alpha_T$

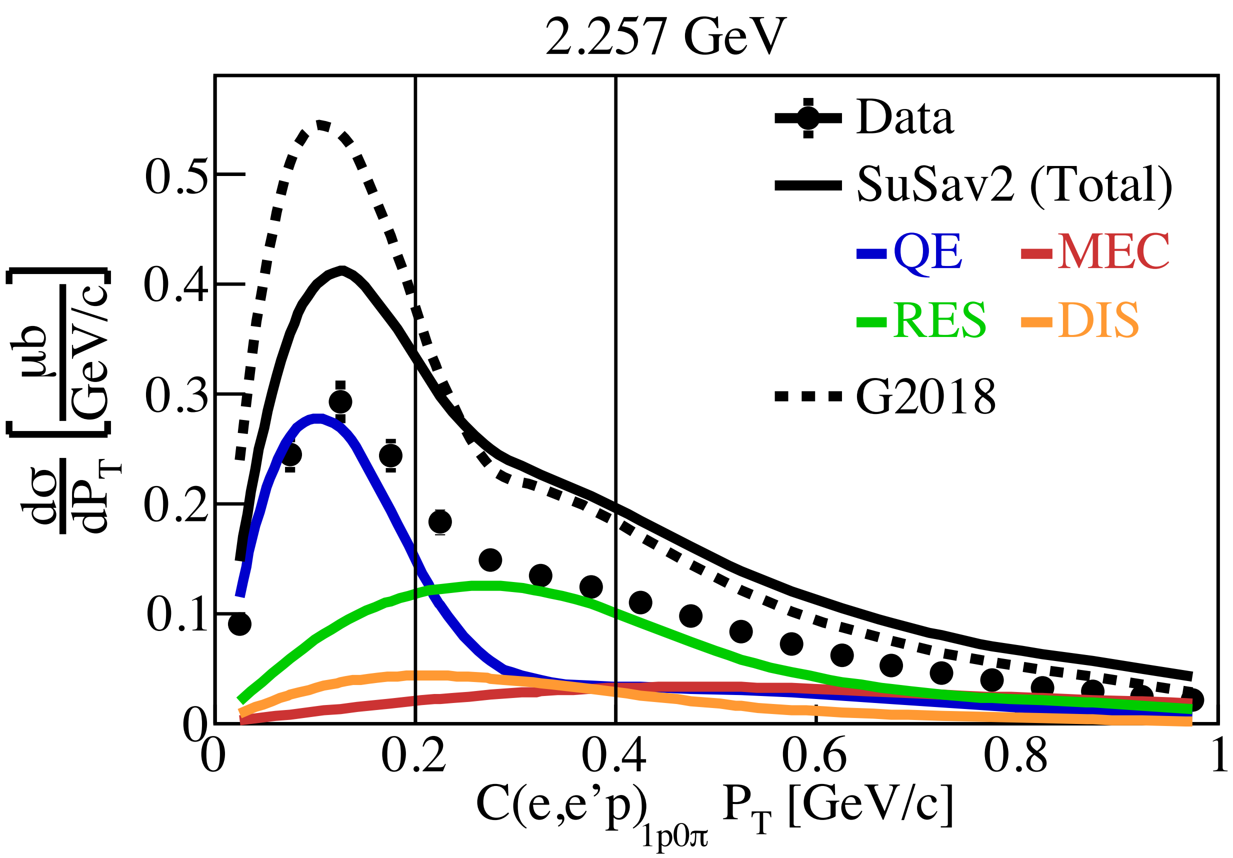
Sensitive to
Final State Interactions

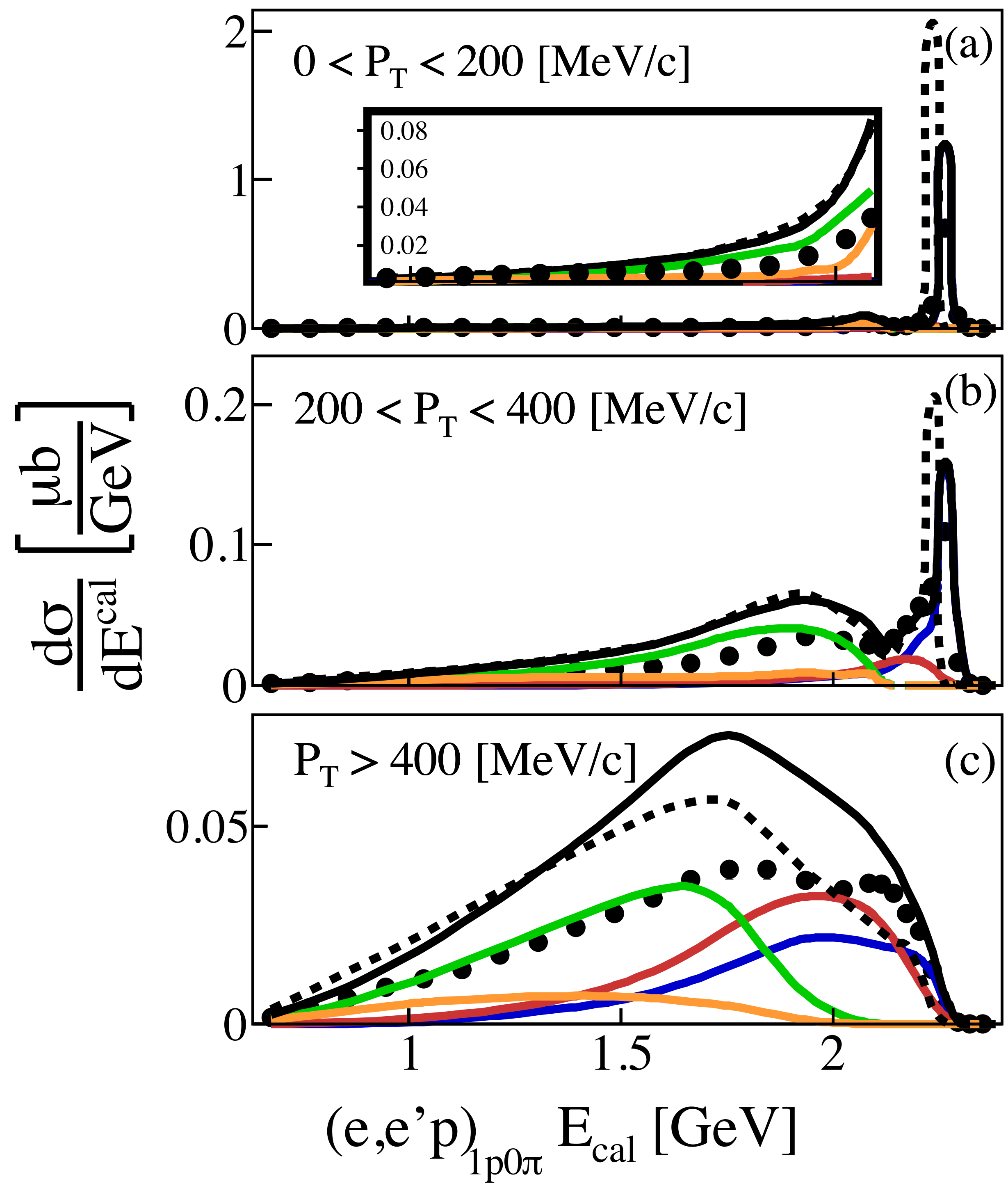
Transverse missing momentum



Nature **599**, 565 (2021)

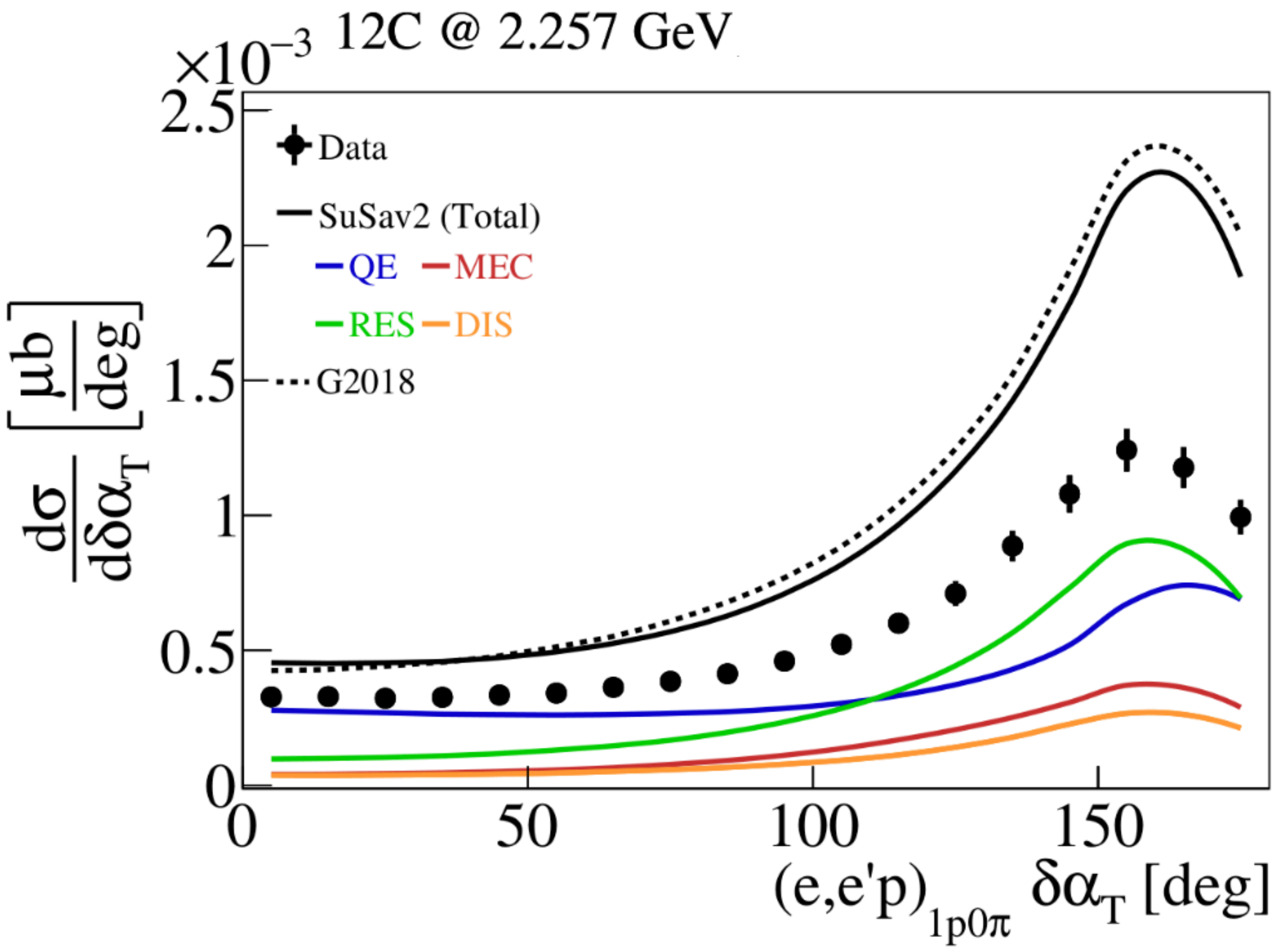
p_T sensitivity to interaction mechanisms





Nature **599**, 565 (2021)

Transverse Kinematic Variables - $\delta\alpha_T$

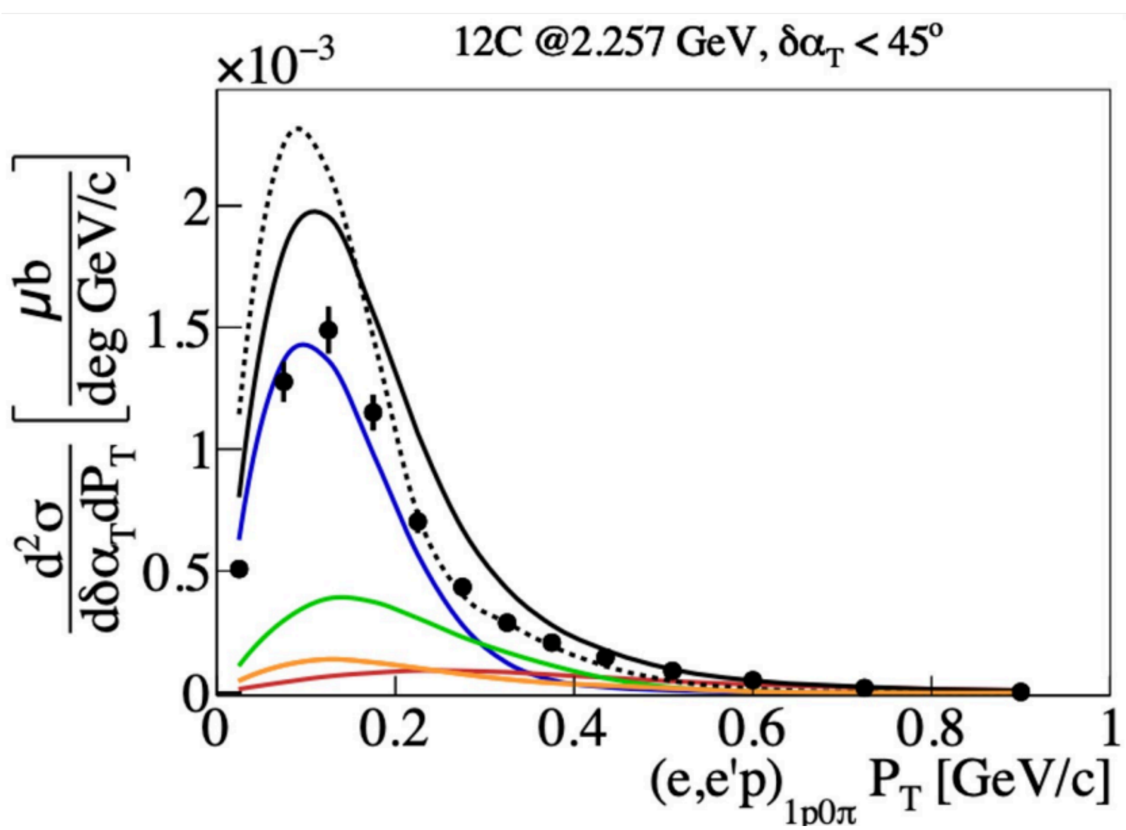


A. Papadopoulou et al. in preparation

MC vs. (e,e'p) Transverse Variables

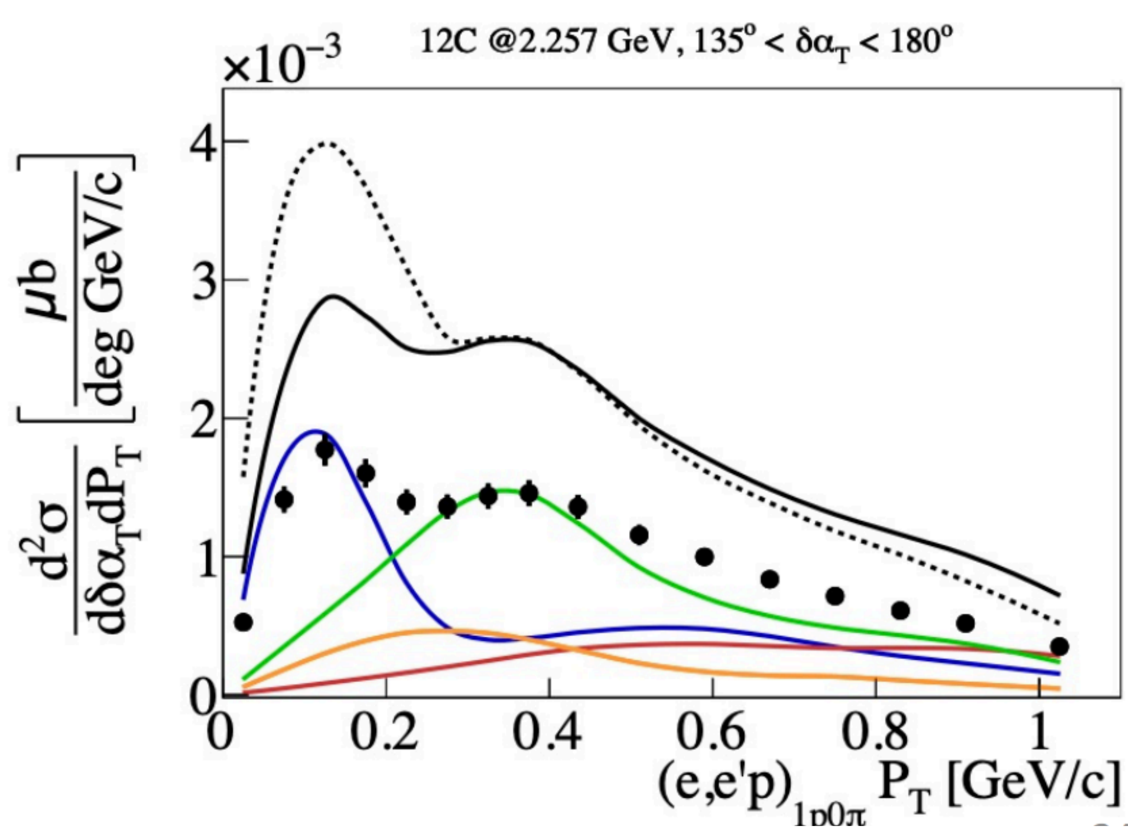
Low αT < 45

QE enhanced region



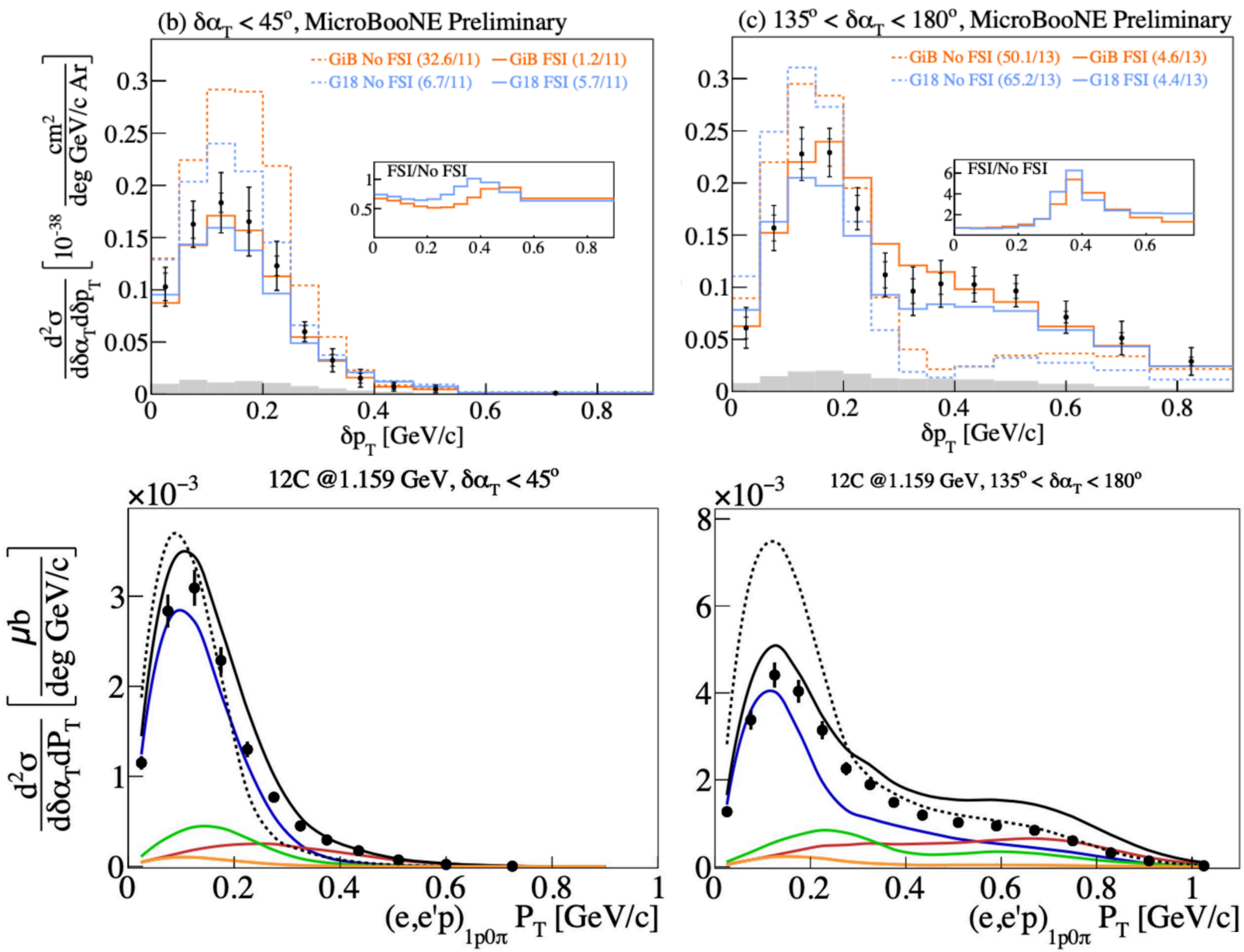
High 135 < αT < 180

Non QE contributions



A. Papadopoulou et al. in preparation

MC vs. (e,e'p) Transverse Variables



A. Papadopoulou et al. in preparation

Looking forward to new results

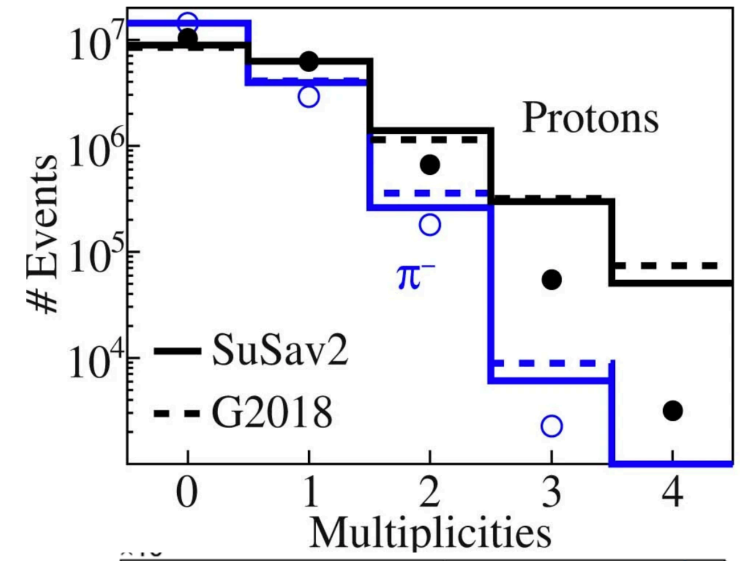
Working on:

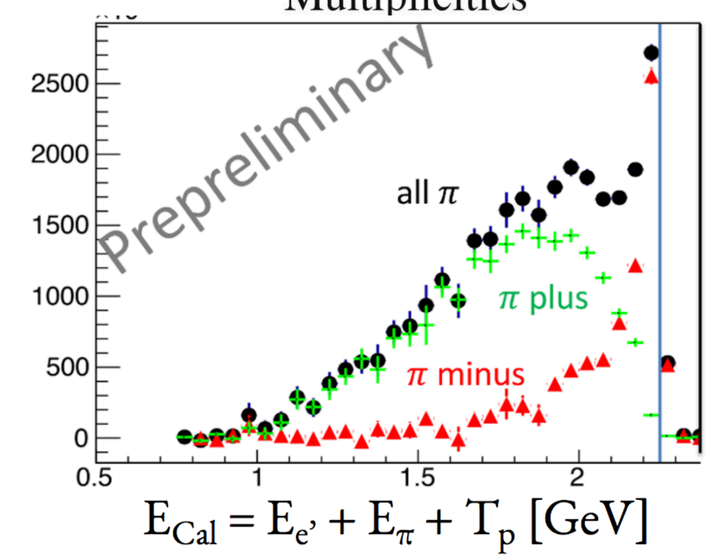
Multi differential analysis

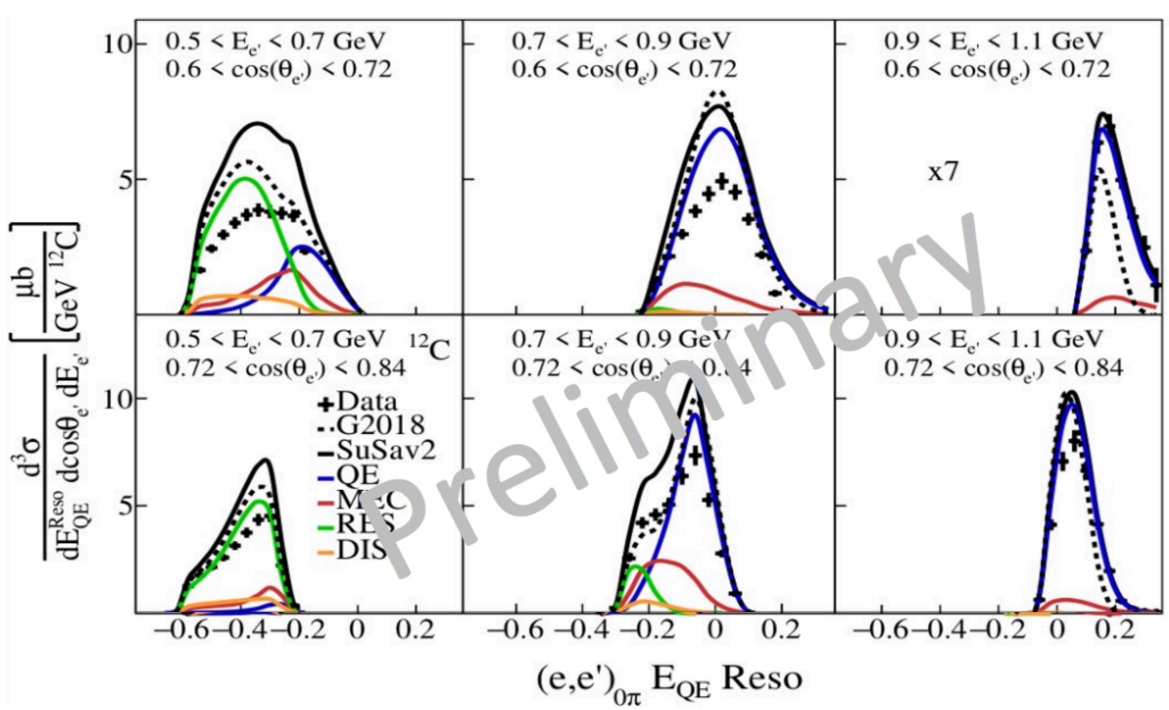
Pion production

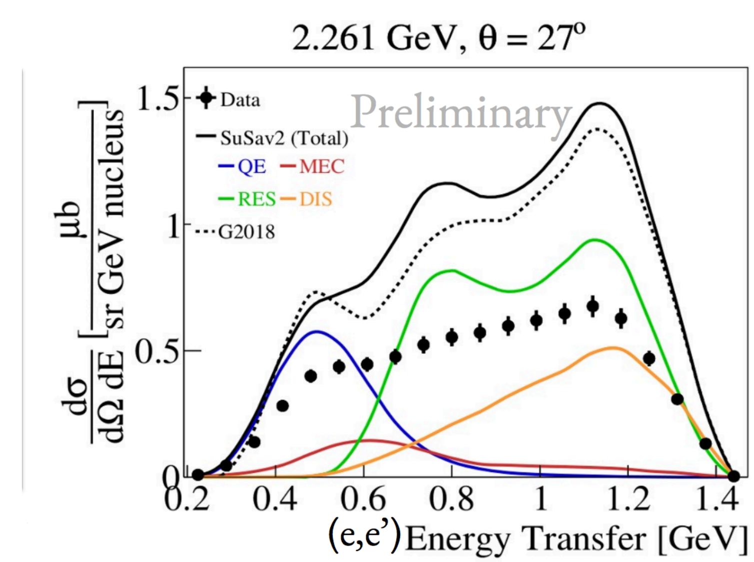
Two nucleon final state

All nuclei and energies

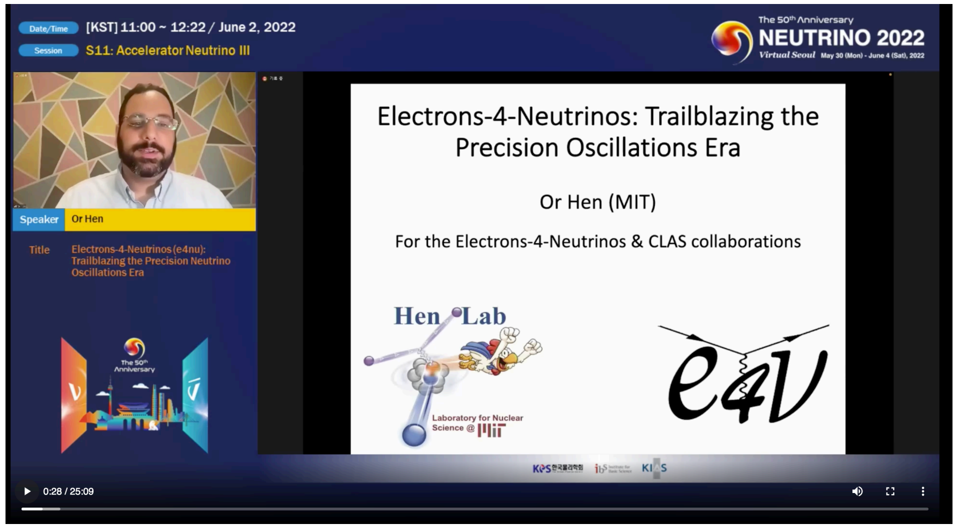


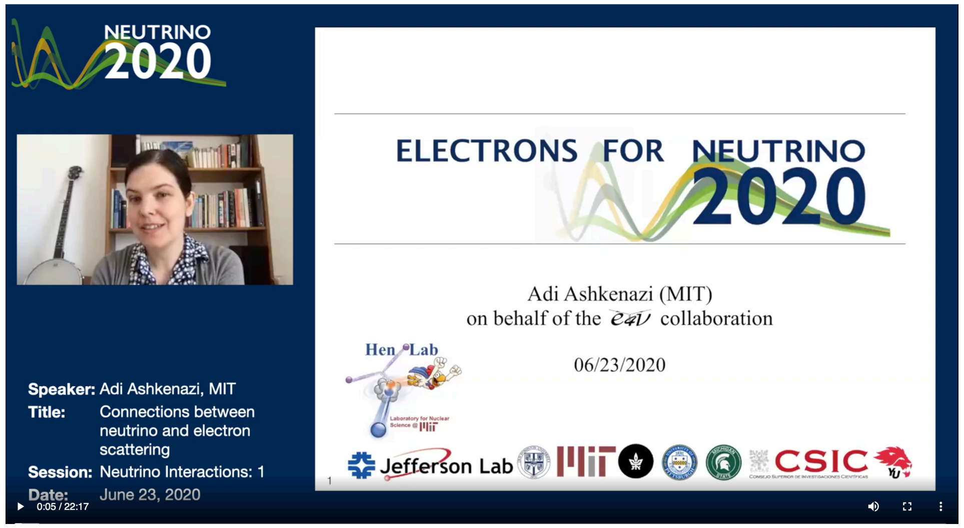


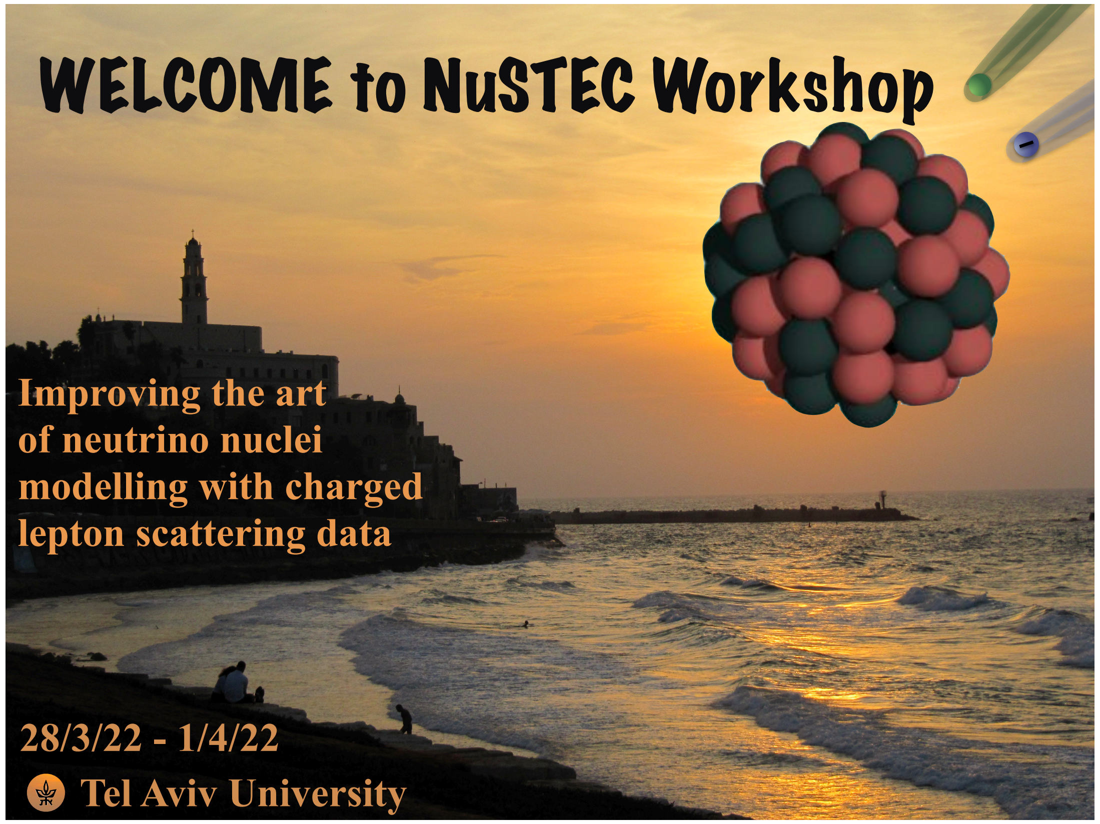




e4ν Impact on the neutrino community



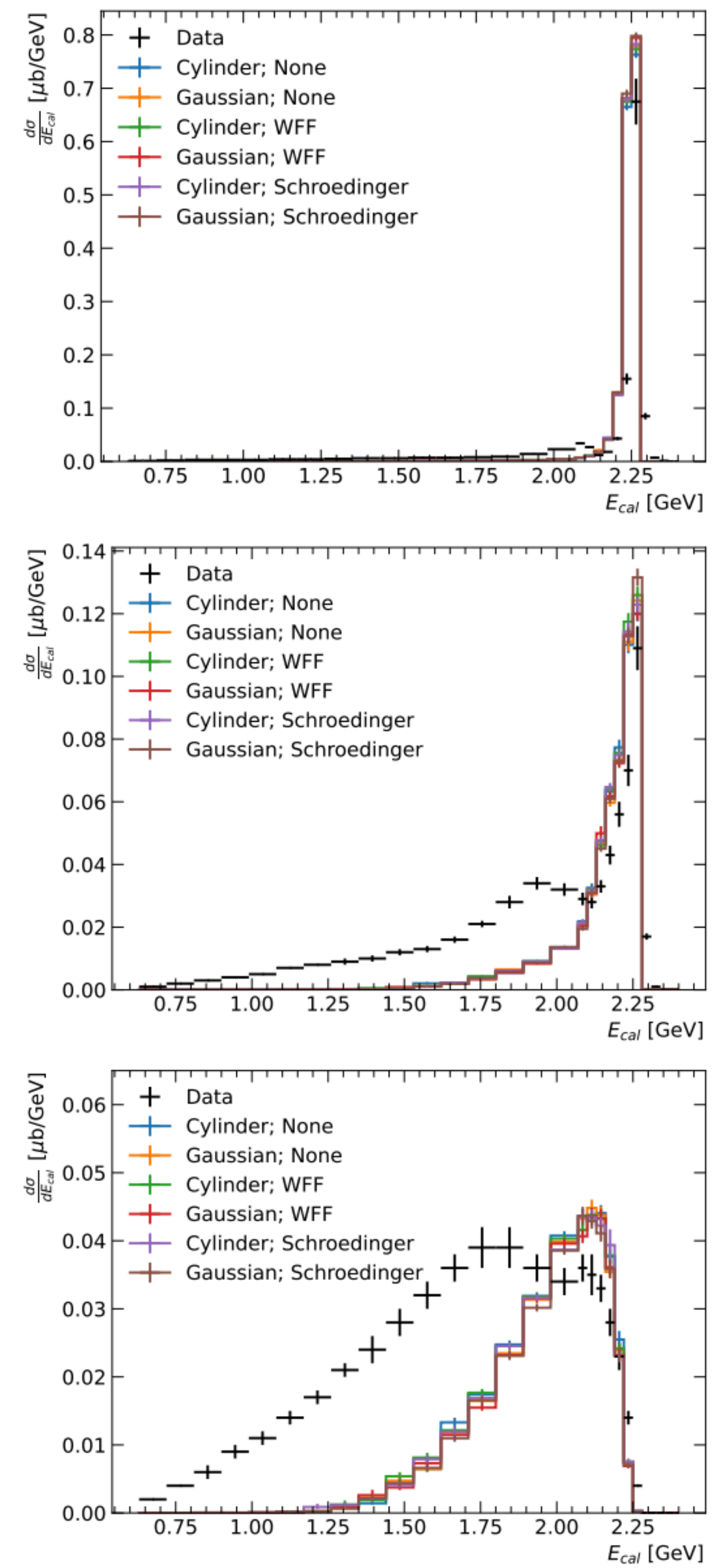




Impact on the neutrino community

Published data available
@ www.e4nu.com

Benchmarking new
models and generators



exp. ACCHILES
Isaacson, Jay, Lovato,
Machado, and Rocco
arXiv: 2205.06378 (2022)

Next step RG-M CLAS12

Better acceptance

Higher luminosity

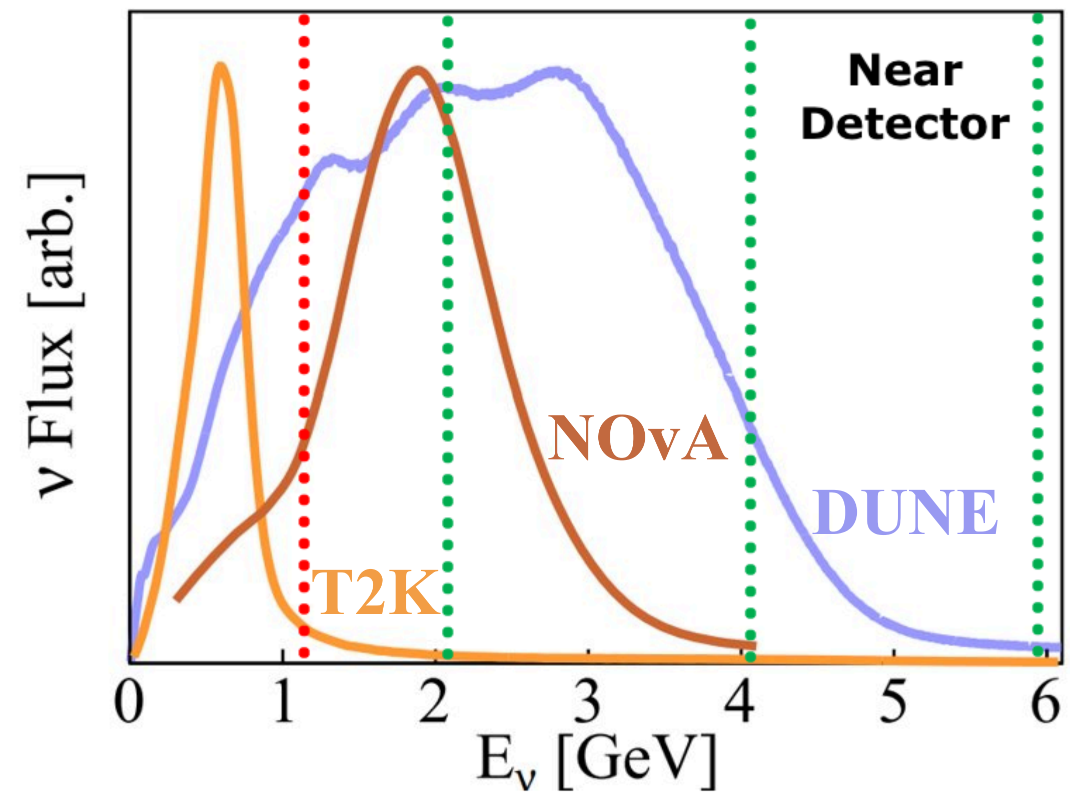
Low detection thresholds

Better neutron coverage

Targets: ^{2}D, ^{4}He, ^{12}C, ^{16}O, ^{40}Ar, ^{120}Sn

1, 2, 4, 6 GeV

First run completed

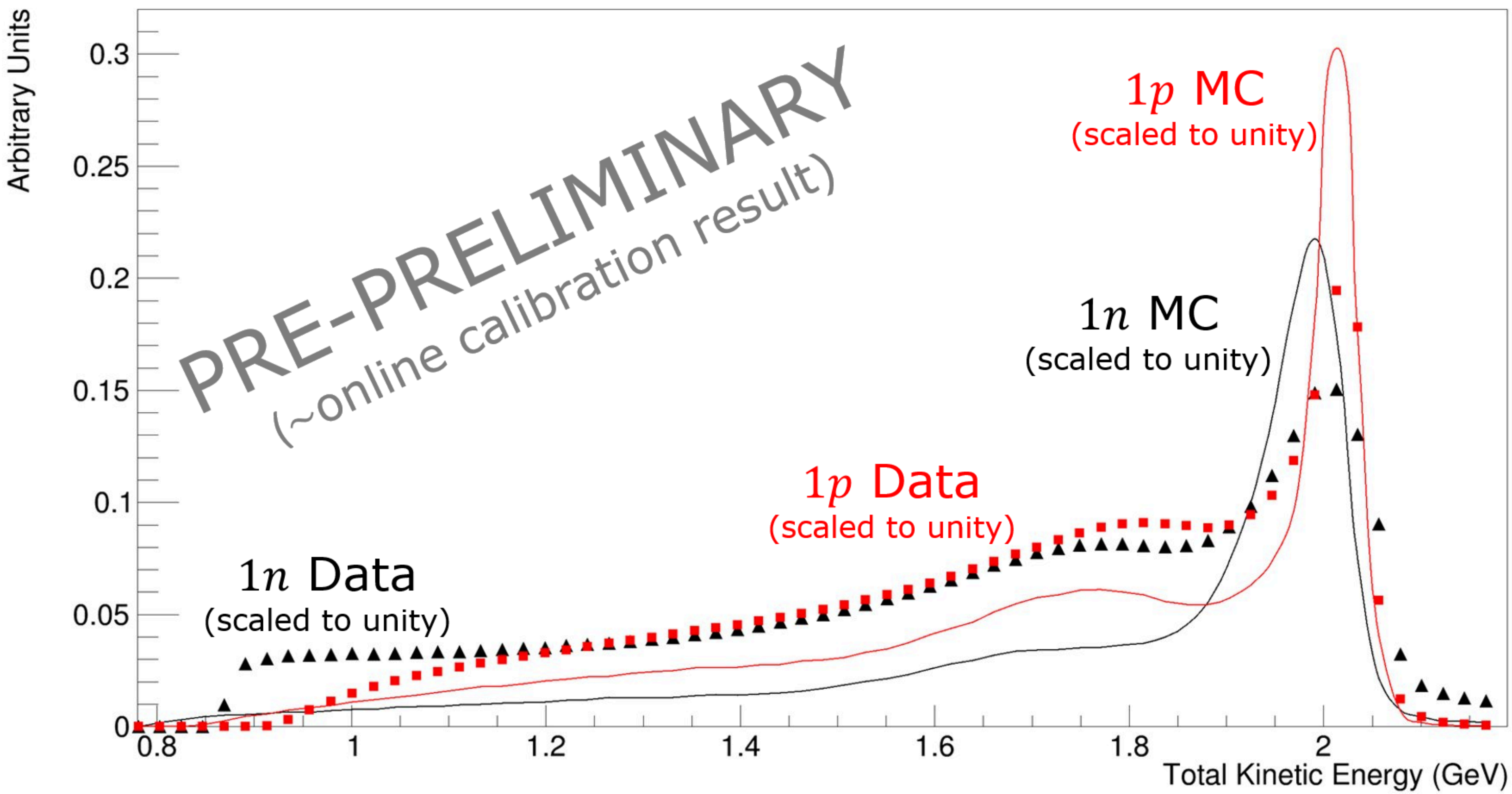


Overwhelming support from:

DUNE, IceCube South Pole Neutrino Observatory, Hyper-Kamiokande, T2K, NOvA, MINERvA

Fermilab, GiBUU The Giessen Boltzmann-Uehling-Uhlenbeck Project, Genie, µBooNE

Next step RG-M CLAS12



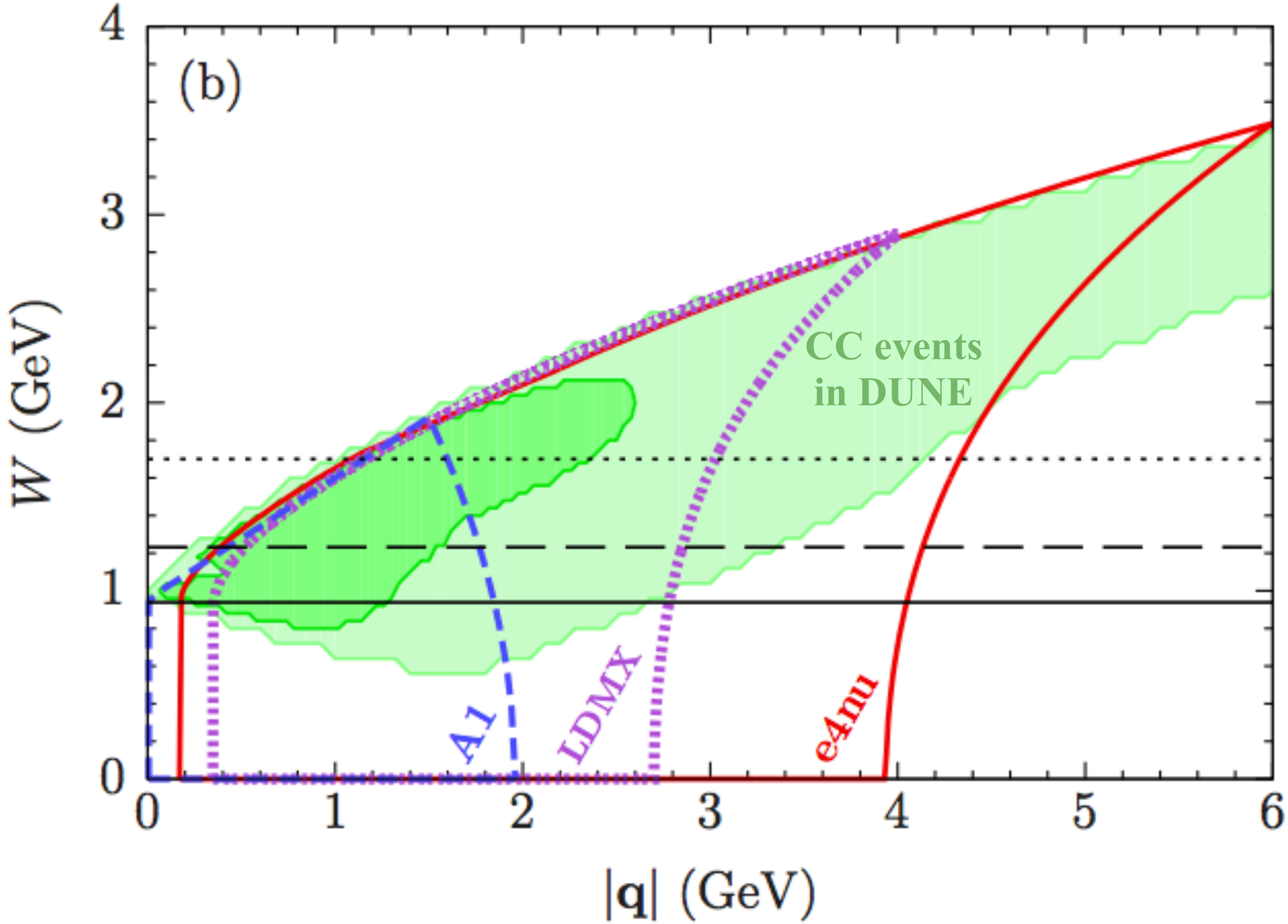
Ar(e,e'N)$_{0\pi}$ Ecal [GeV]

Complementary efforts

Collaborations	Kinematics	Targets	Scattering	Publications
E12-14-012 (JLab) (Data collected: 2017) Jefferson Lab	E_e = 2.222 GeV θ_e = 15.5, 17.5, 20.0, 21.5 θ_p = -39.0, -44.0, -44.5, -47.0 -50.0	Ar, Ti Al, C	(e, e') $(e, e'p)$	Phys. Rev. C **99**, 054608 Phys.Rev.D **105** 112002
e4nu/CLAS (JLab) (Data collected: 1999, 2022) Jefferson Lab	E_e = 1, 2, 4, 6 GeV $\theta_e > 5$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state	Nature **599**, 565 Phys.Rev.D **103** 113003
A1 (MAMI) (Data collected:2020) (More data planned) mami MAINZER MIKROTRON	E_e = 1.6 GeV	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles	
LDMX (SLAC) (Planned) SLAC	E_e = 4.0 GeV $\theta_e < 40$		(e, e') e, p, n, π in the final state	
eALBA (Planned) ALBA	E_e = 500 MeV - few GeV	C, CH Be, Ca	(e, e')	

Adaptation from Proceedings of the US Community Snowmass2021
arXiv:2203.06853v1 [hep-ex]

e4ν and DUNE



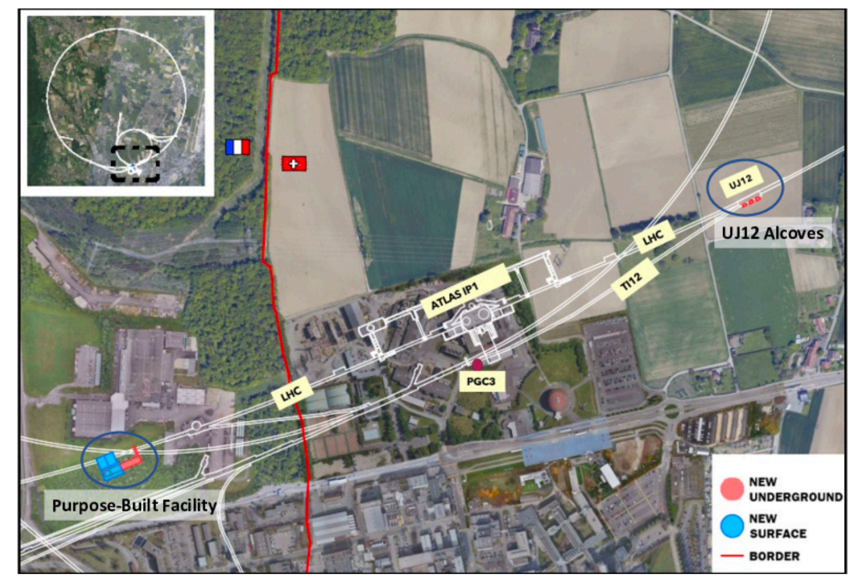
Higher Energies for e4ν

Accelerator based oscillation experiments flux is covered by CLAS12

Better coverage / efficiency will help improve the results

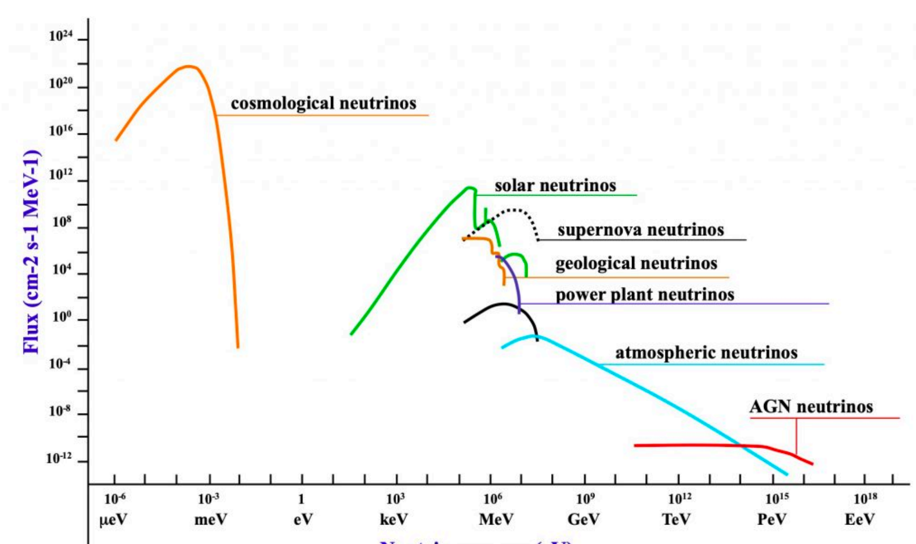
O(10) GeV flux could be relevant to:

Forward Physics Facility @ LHC specifically to the planned FLArE in search for DM, expecting neutrino BG



https://arxiv.org/pdf/2109.10905.pdf

Atmospheric neutrino oscillation experiments



The e4ν Collaboration

visit www.e4nu.com

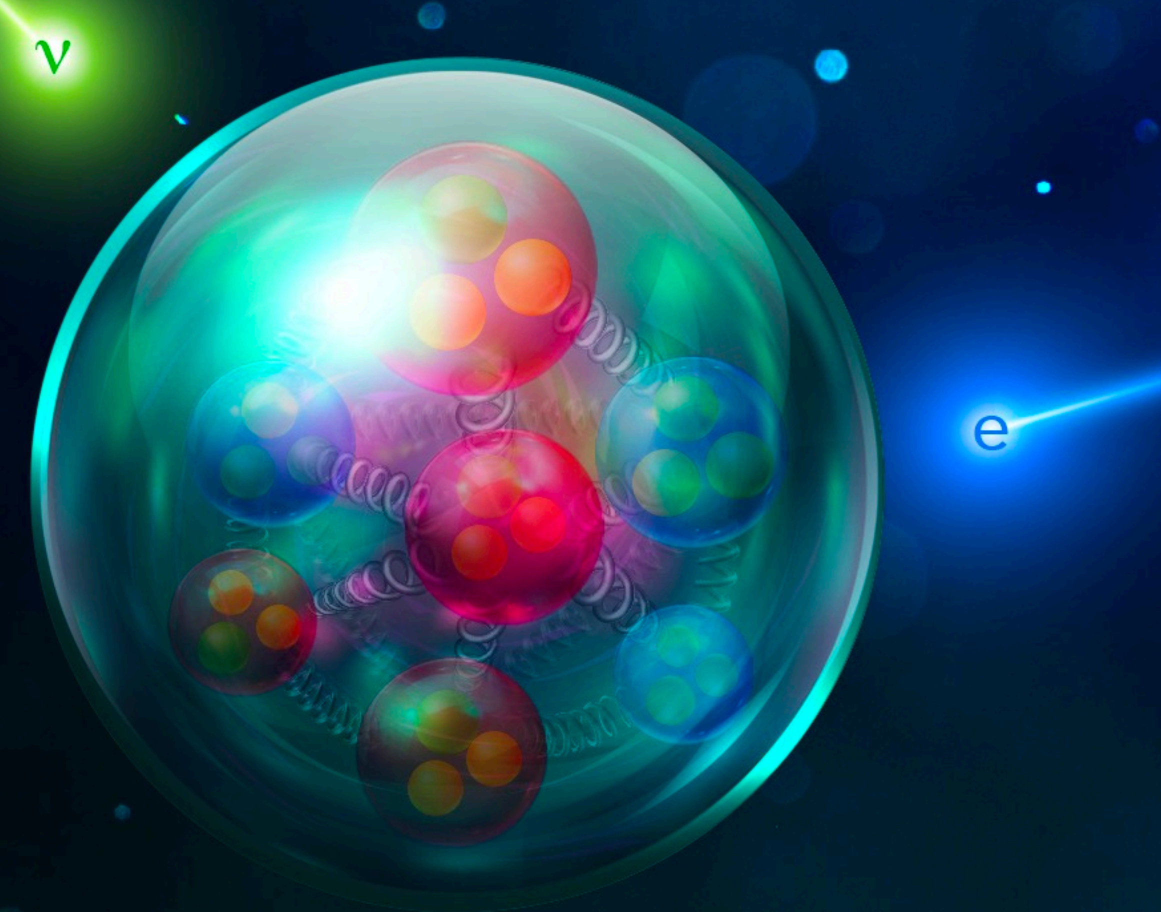
Contact: Minerba betan009@fnal.gov, Adi adishka@tauex.tau.ac.il

νA interaction uncertainties limit oscillation parameters extraction

First use of semi-exclusive eA data to explore νA uncertainties

- Energy reconstruction

- Comparison to event generators



Data/model disagreement even for electron QE-like events

Electron scattering data is helping

Expanding available phase space could contribute to future efforts

Thank you for your attention