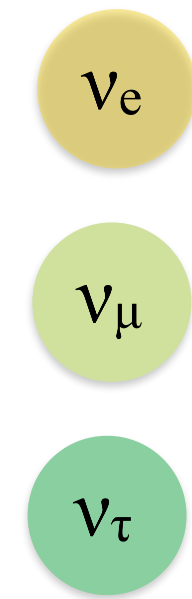
Answering Questions in Neutrino Physics

The Neutrino sector might hint to physics beyond the Standard Model



Neutrino oscillate from one flavour to another

Imposing many questions:

What are the neutrino masses?

β Decay Experiments

Are the neutrinos their own anti particles?

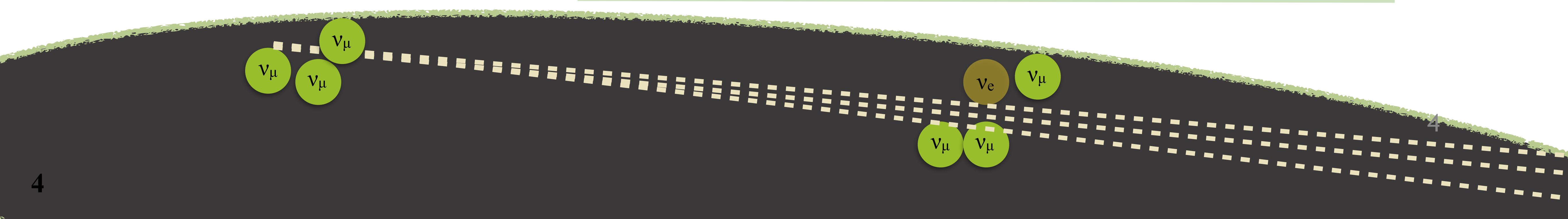
$0\nu\beta\beta$ Decay

Is CP symmetry violated?

Oscillation Experiments

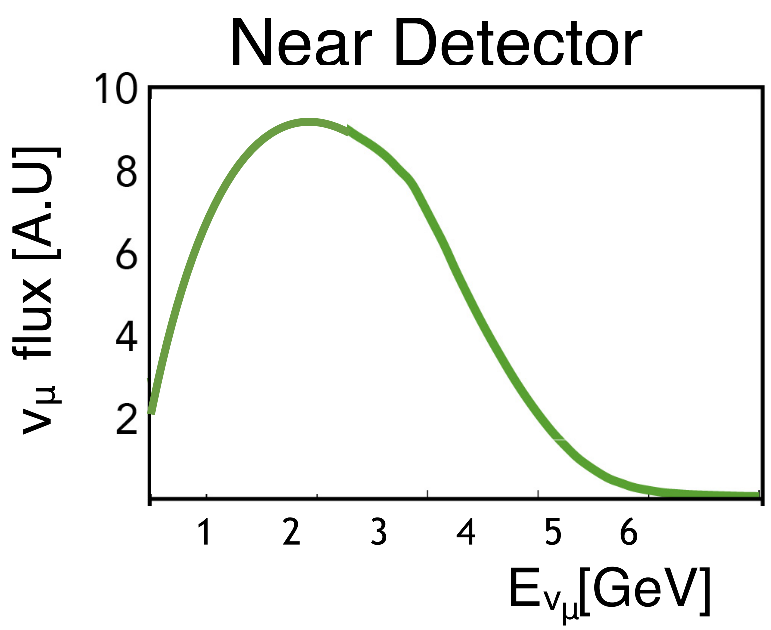
What is their mass ordering?

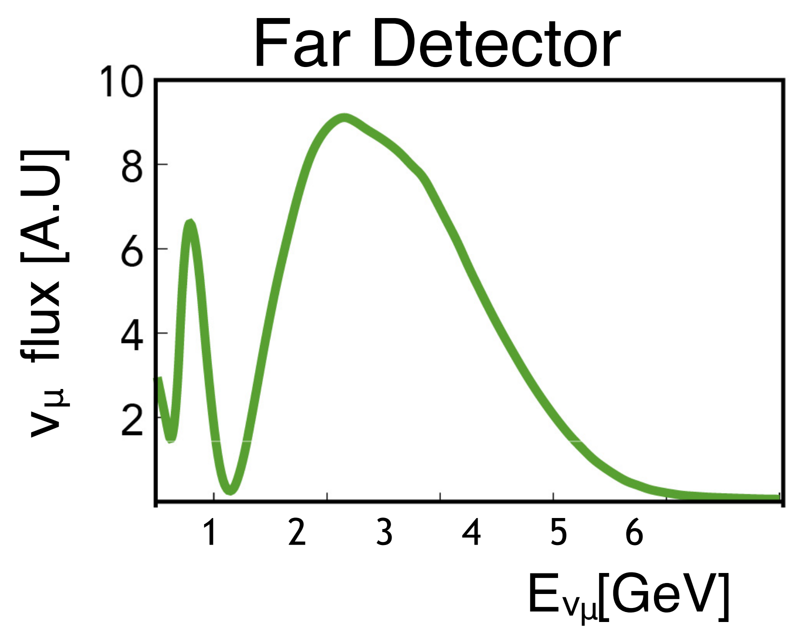
Are there more than the 3 light neutrinos?

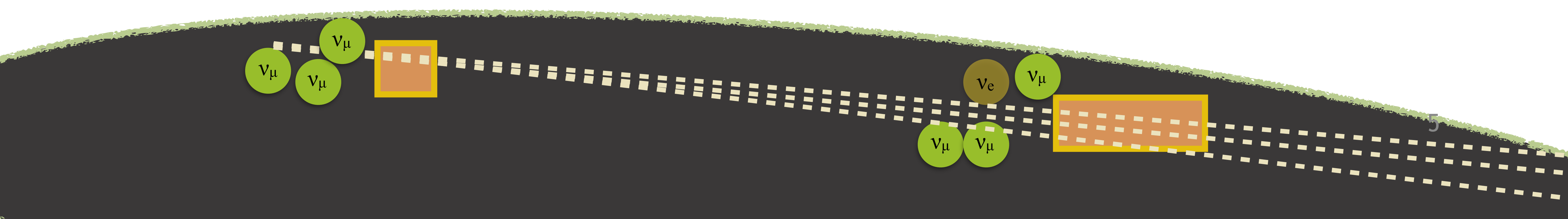


Introduction to Neutrino Oscillations

Oscillation experiments aim to answer the CP nature and the mass ordering of neutrinos as well as search for new physics



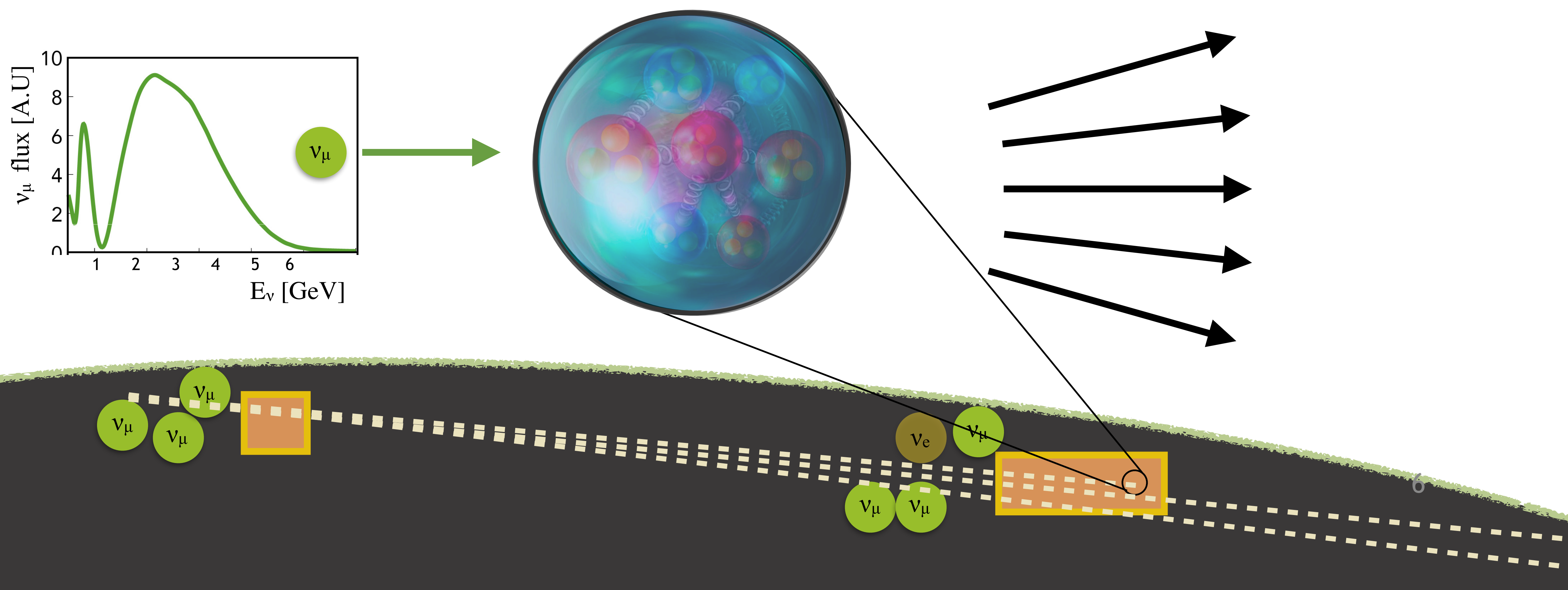




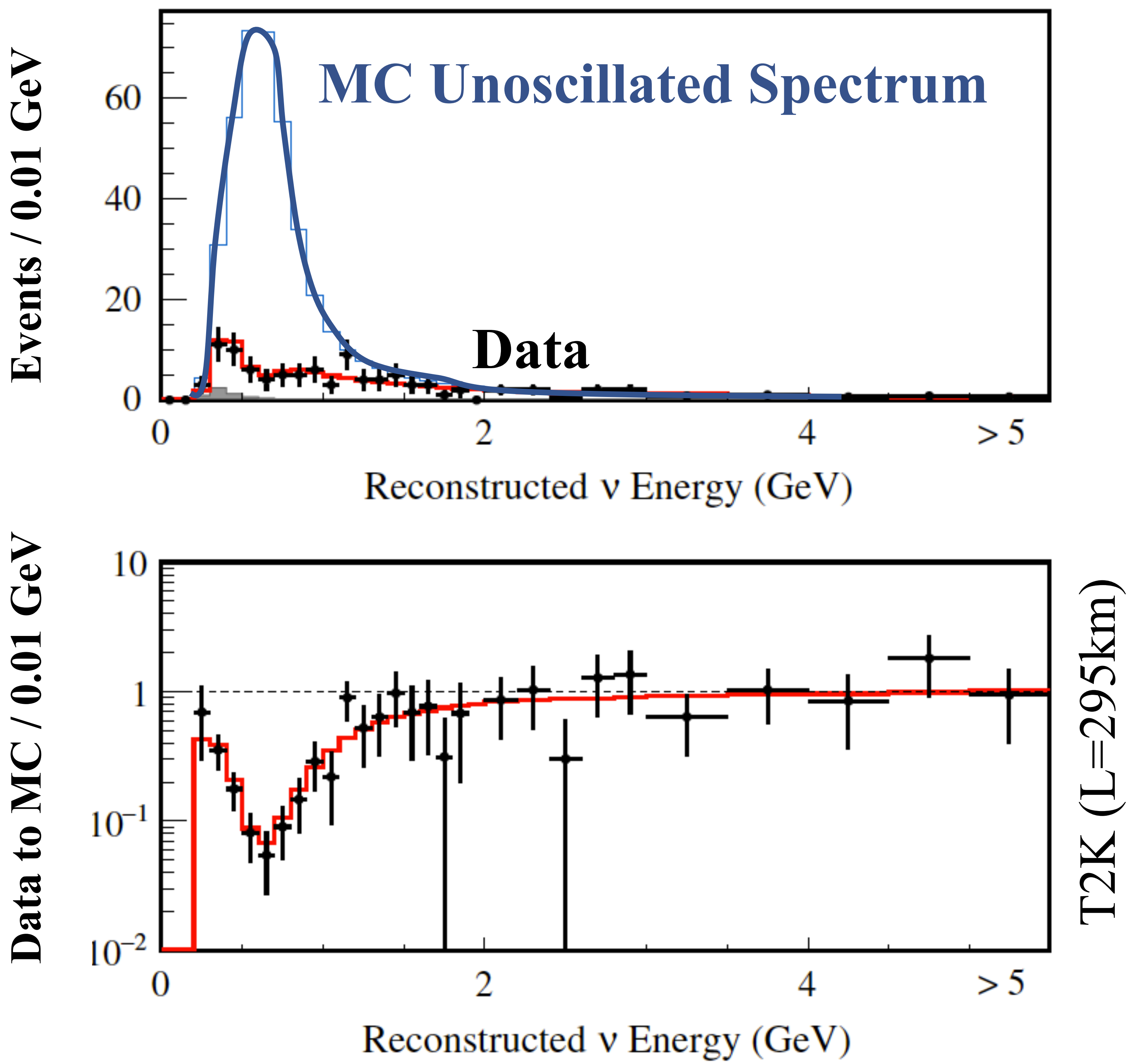
Introduction to Neutrino Oscillations

Incoming true flux | Modelling Input | Measurement

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



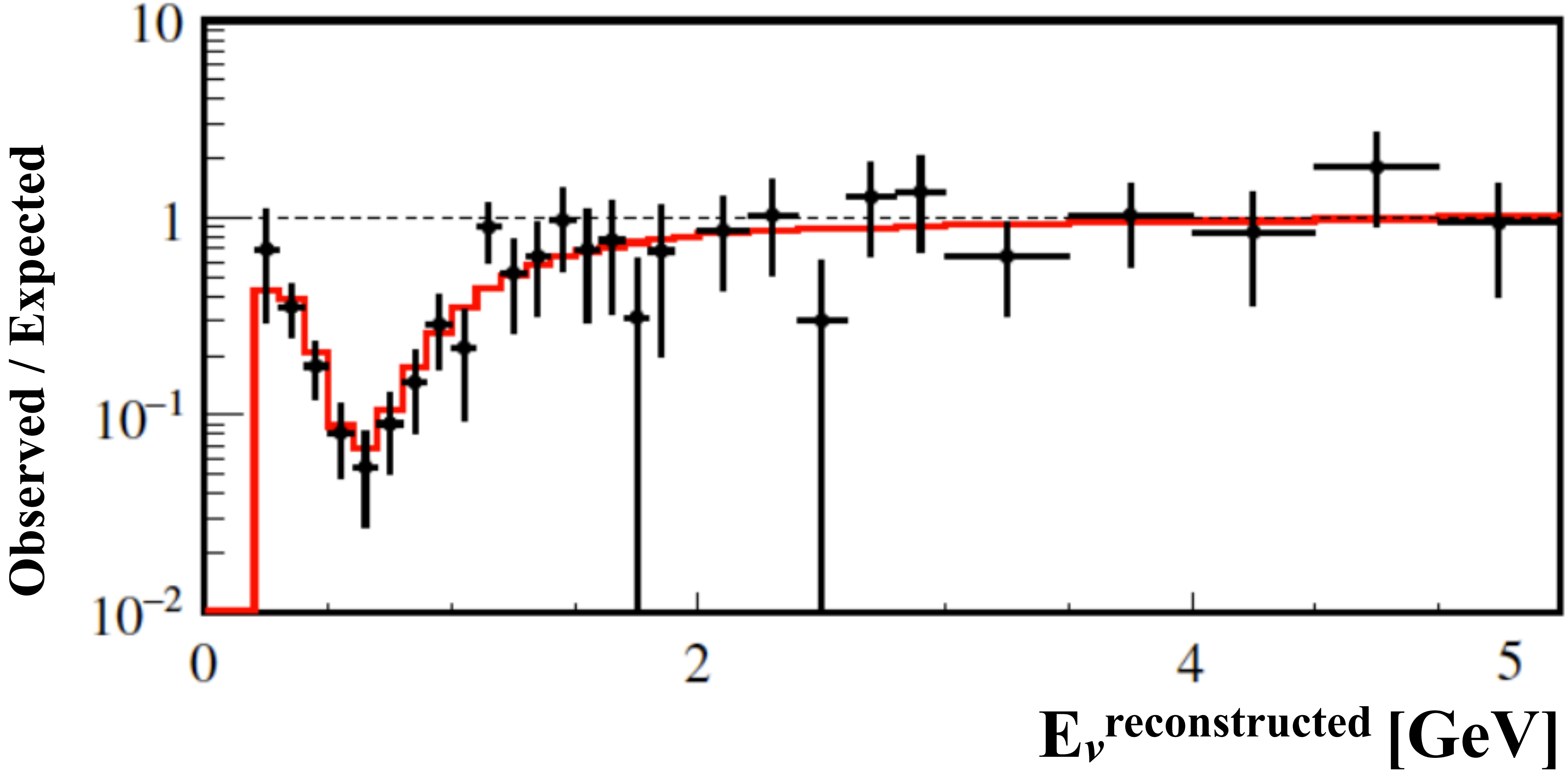
Oscillations Require incoming E_ν Reconstruction



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

Oscillations Require incoming E_ν Reconstruction

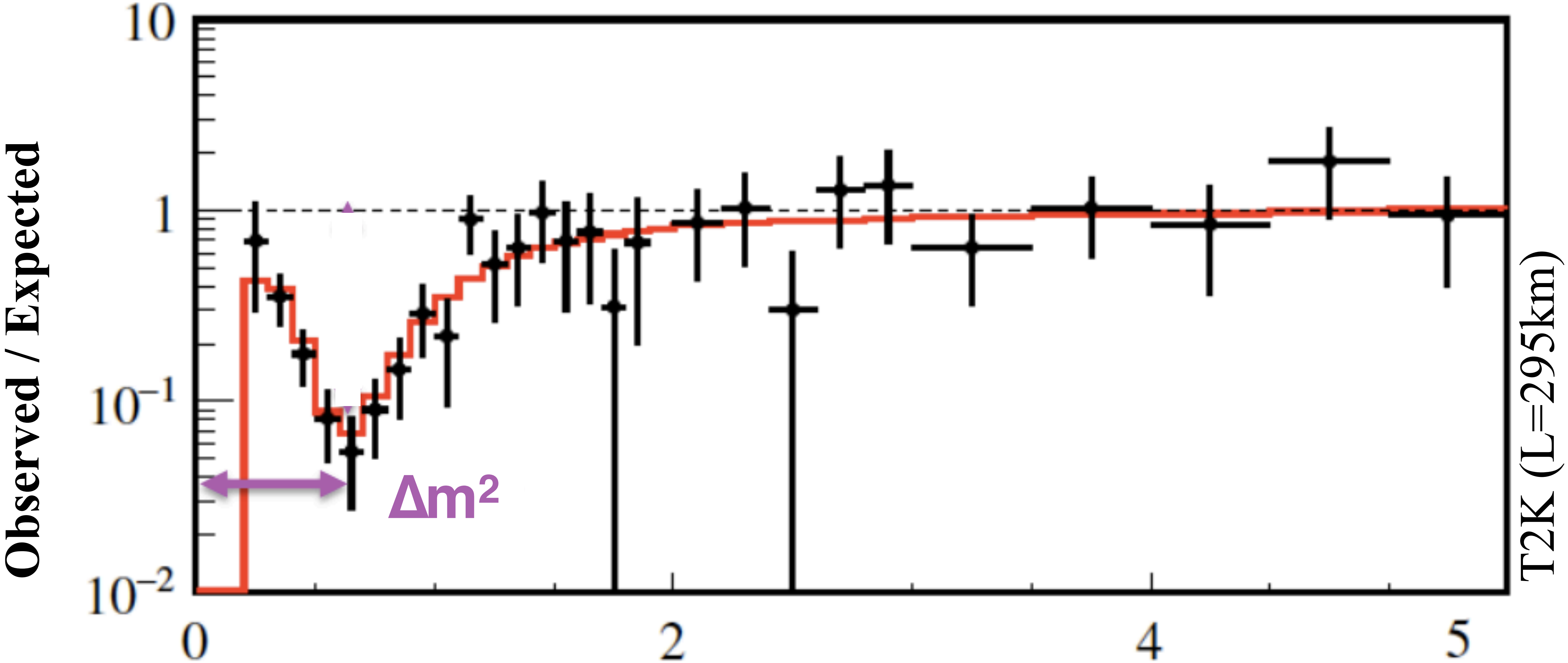
$$P(\nu_\mu \to \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



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

Oscillations Require incoming E_ν Reconstruction

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

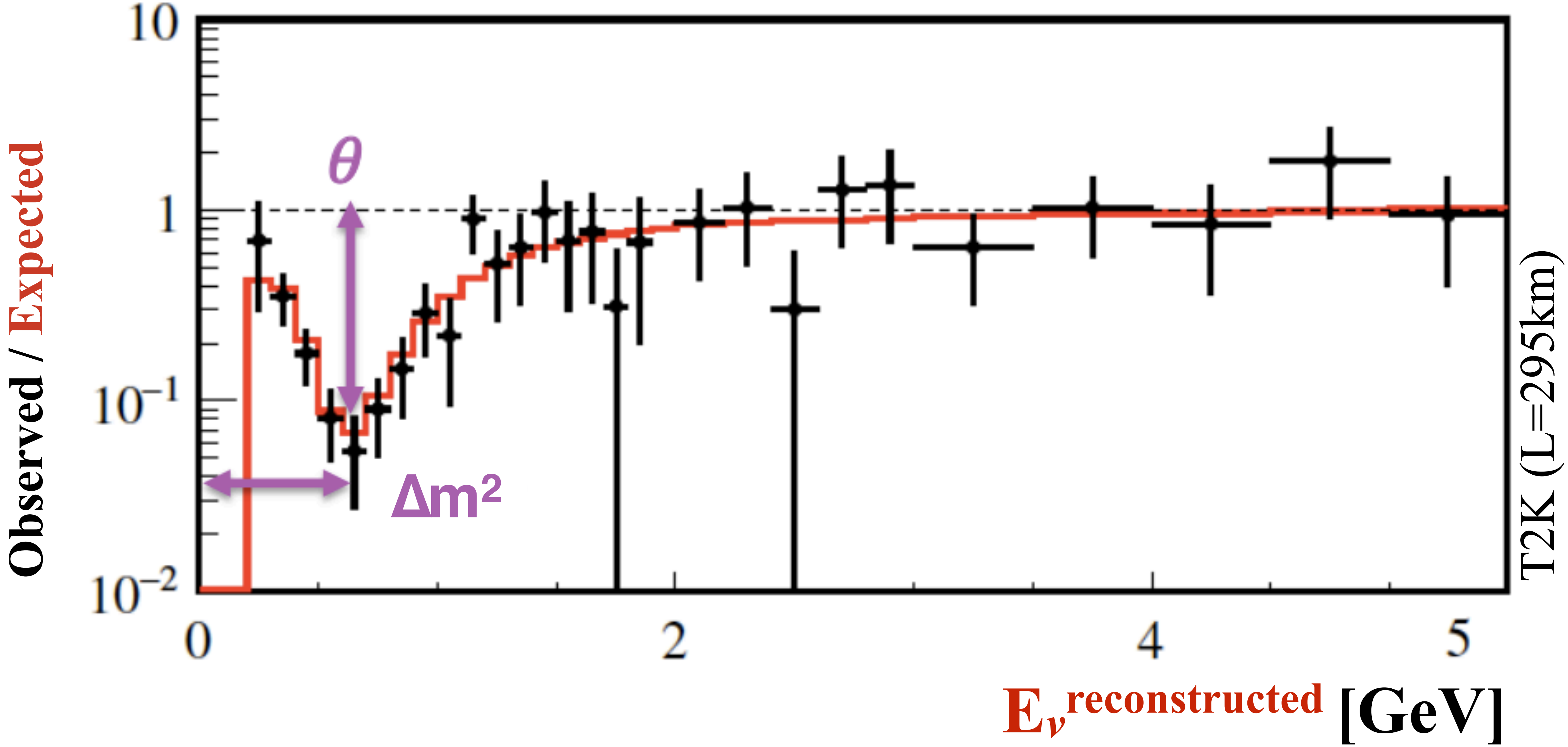


$E_\nu^{reconstructed}$ [GeV]

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

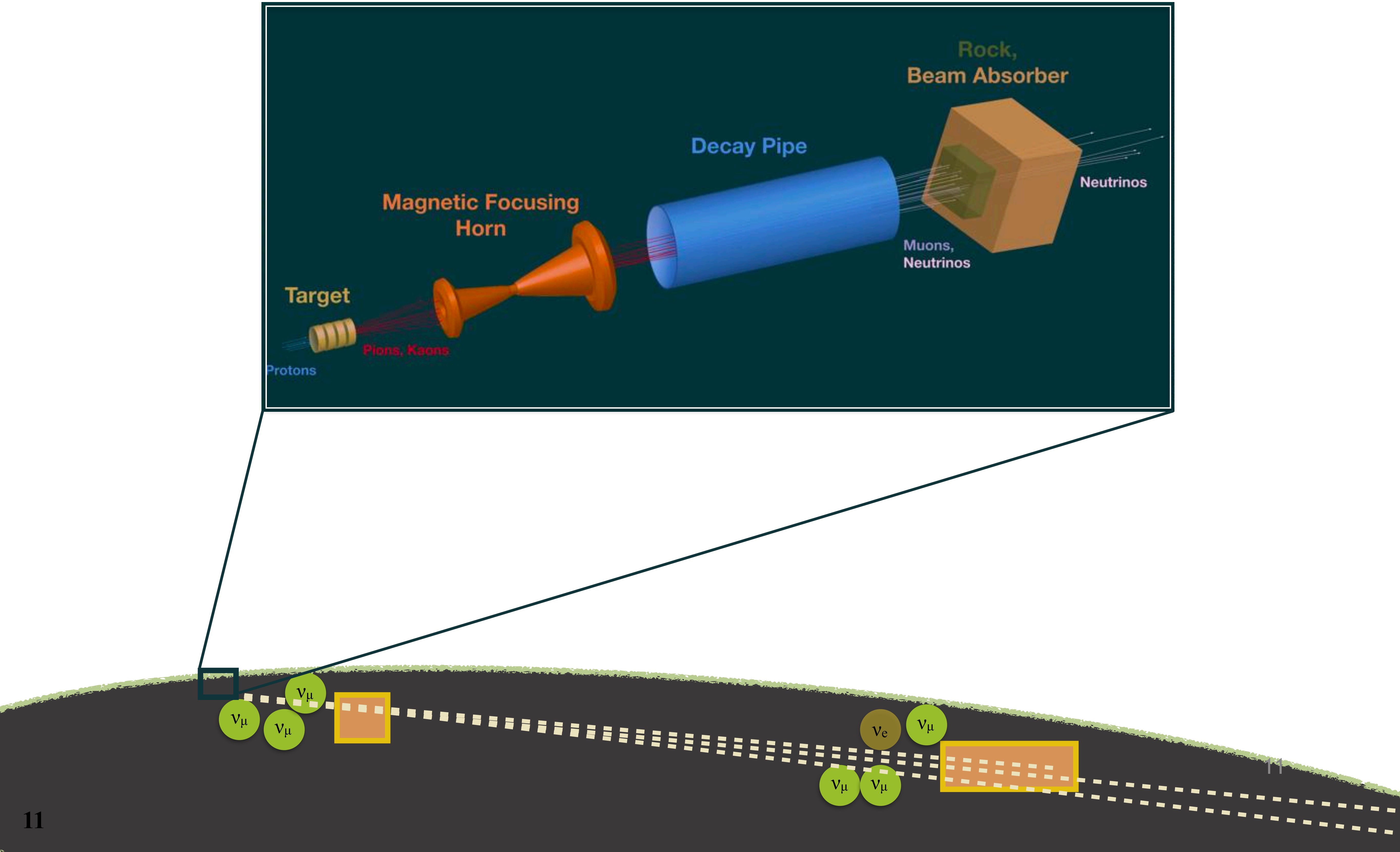
Oscillations Require incoming E_ν Reconstruction

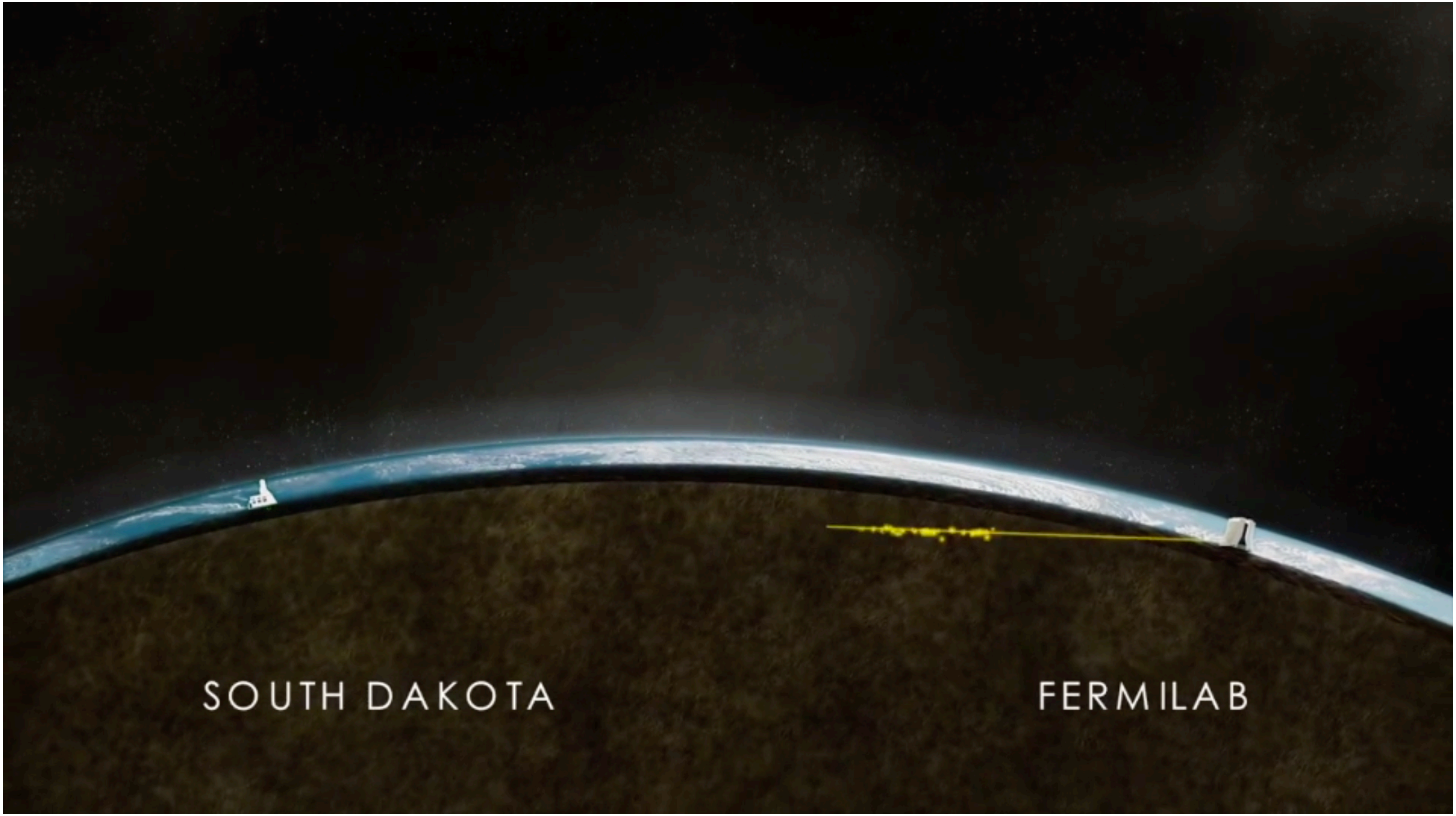
$$P(\nu_\mu \to \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{real}}\right)$$



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

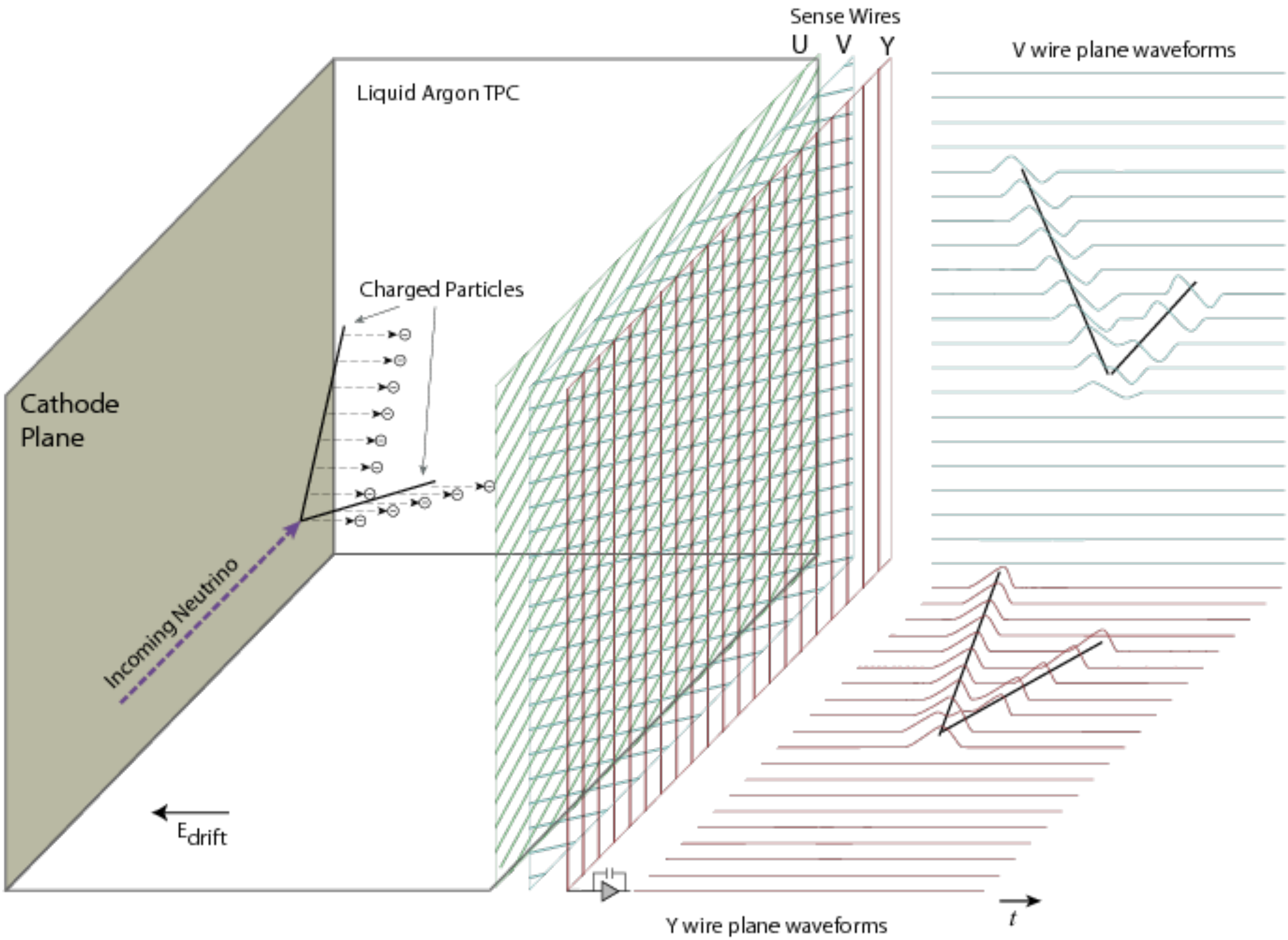
Introduction to Neutrino Oscillations





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

DUNE

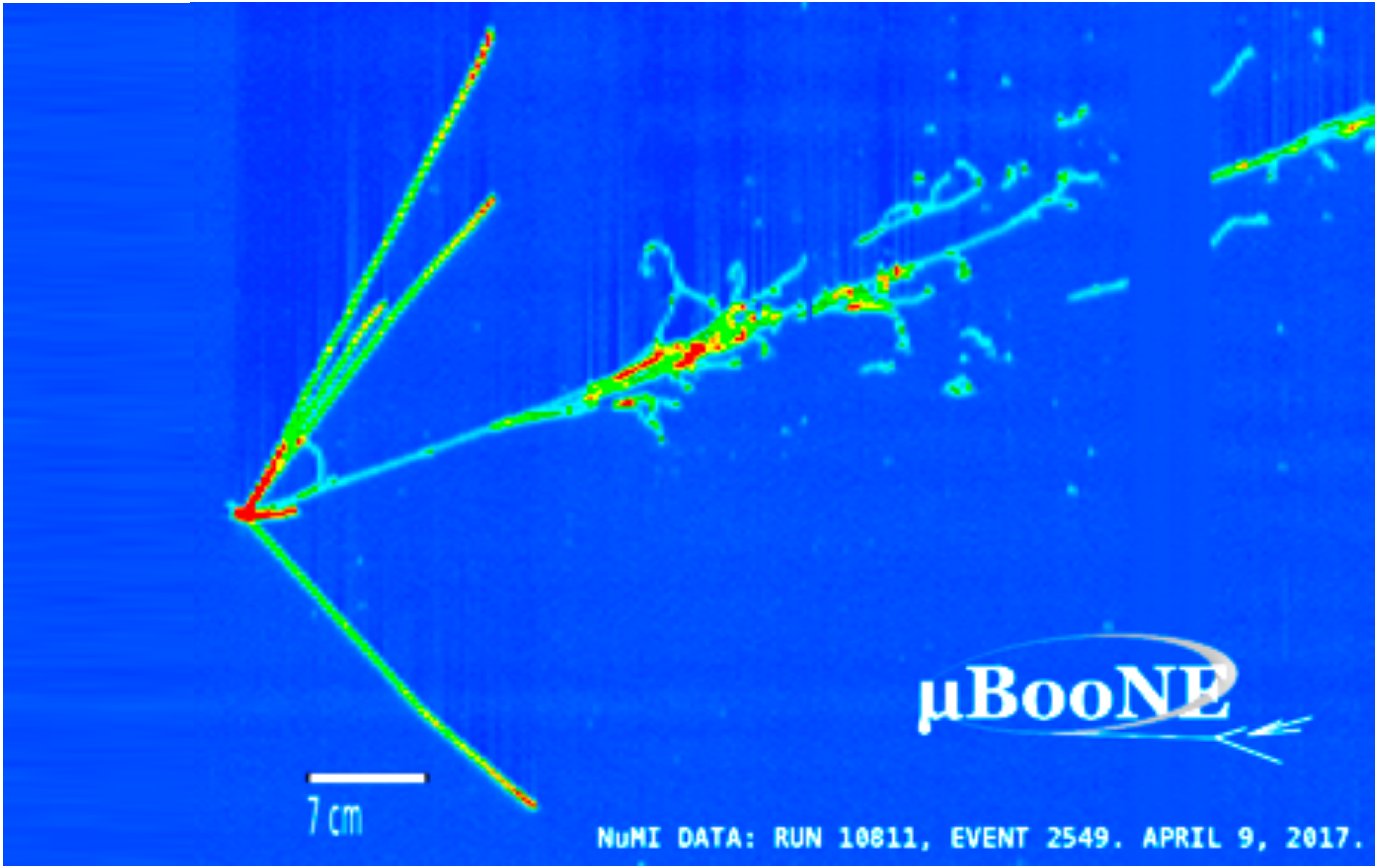


LAr Time Projection Chamber   Active mass : 85 tons

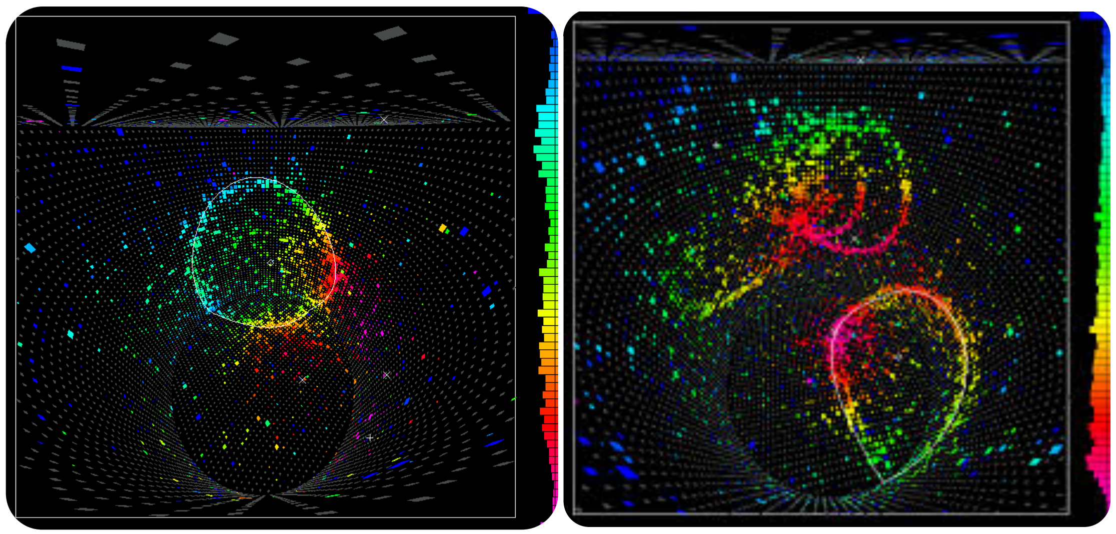
Triggered by PMTs, 3 wire planes with 3 mm spacing

impeccable spatial resolution, calorimetric measurement

μBooNE


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

Incoming Energy Reconstruction

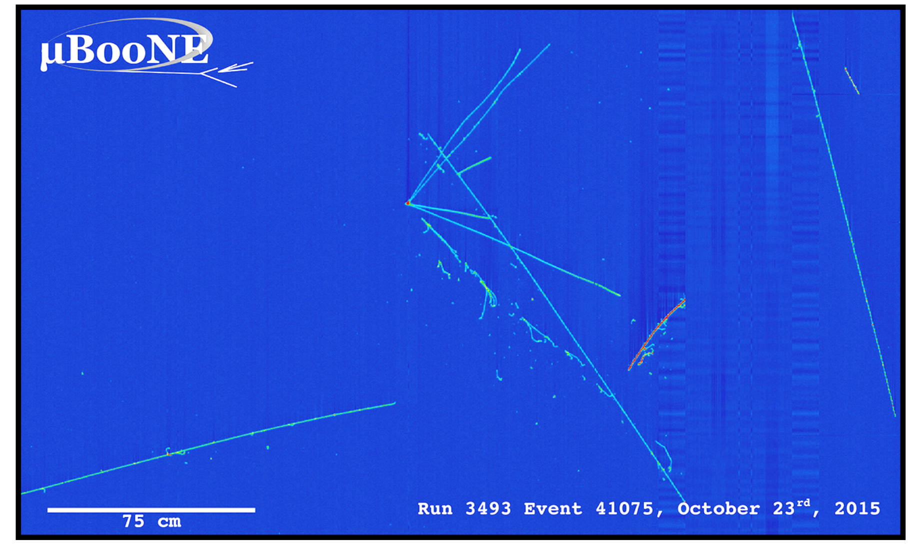


Cherenkov detectors:

Assuming QE interaction

Using lepton only

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



Tracking detectors:

Calorimetric sum

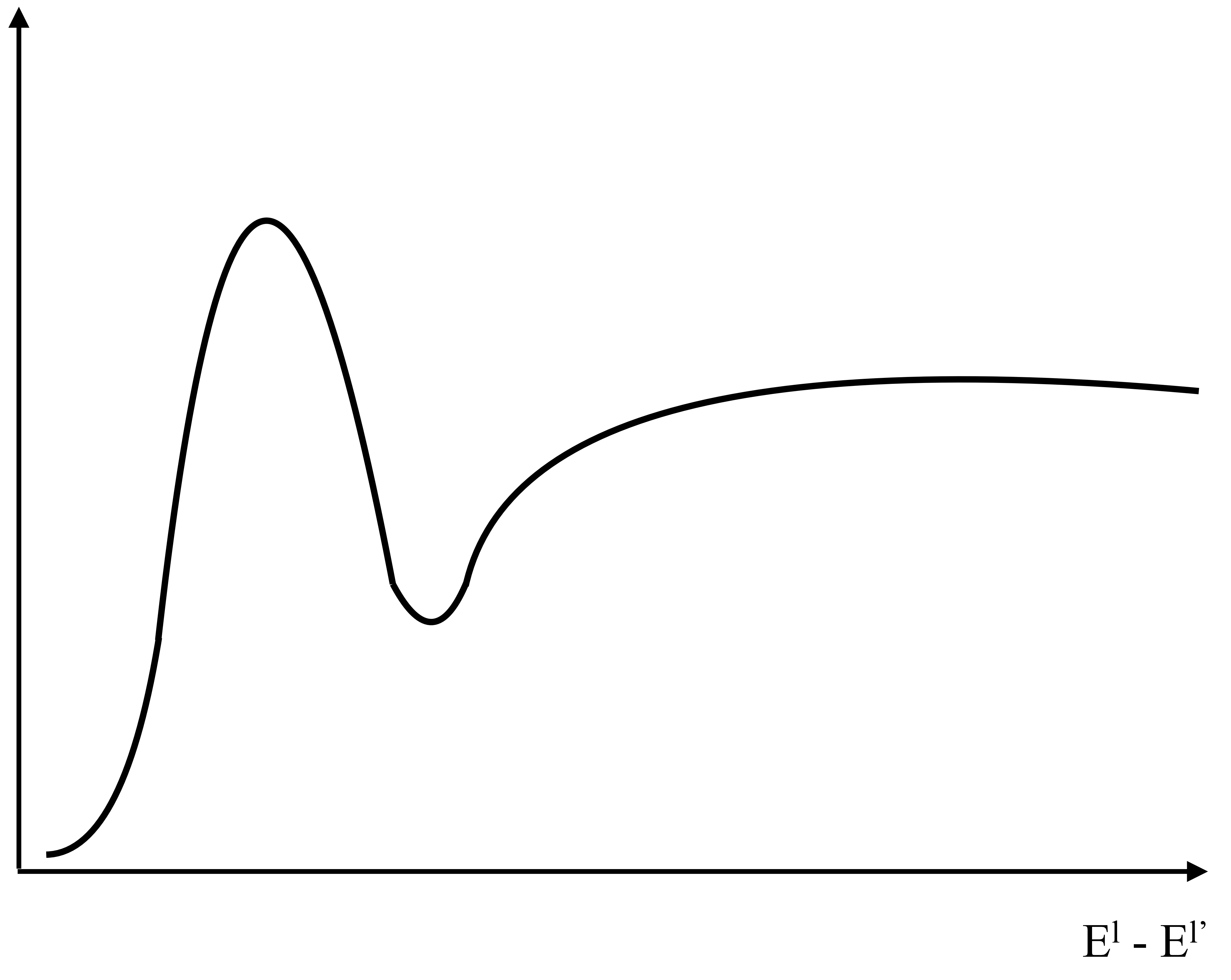
Using All detected particles

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

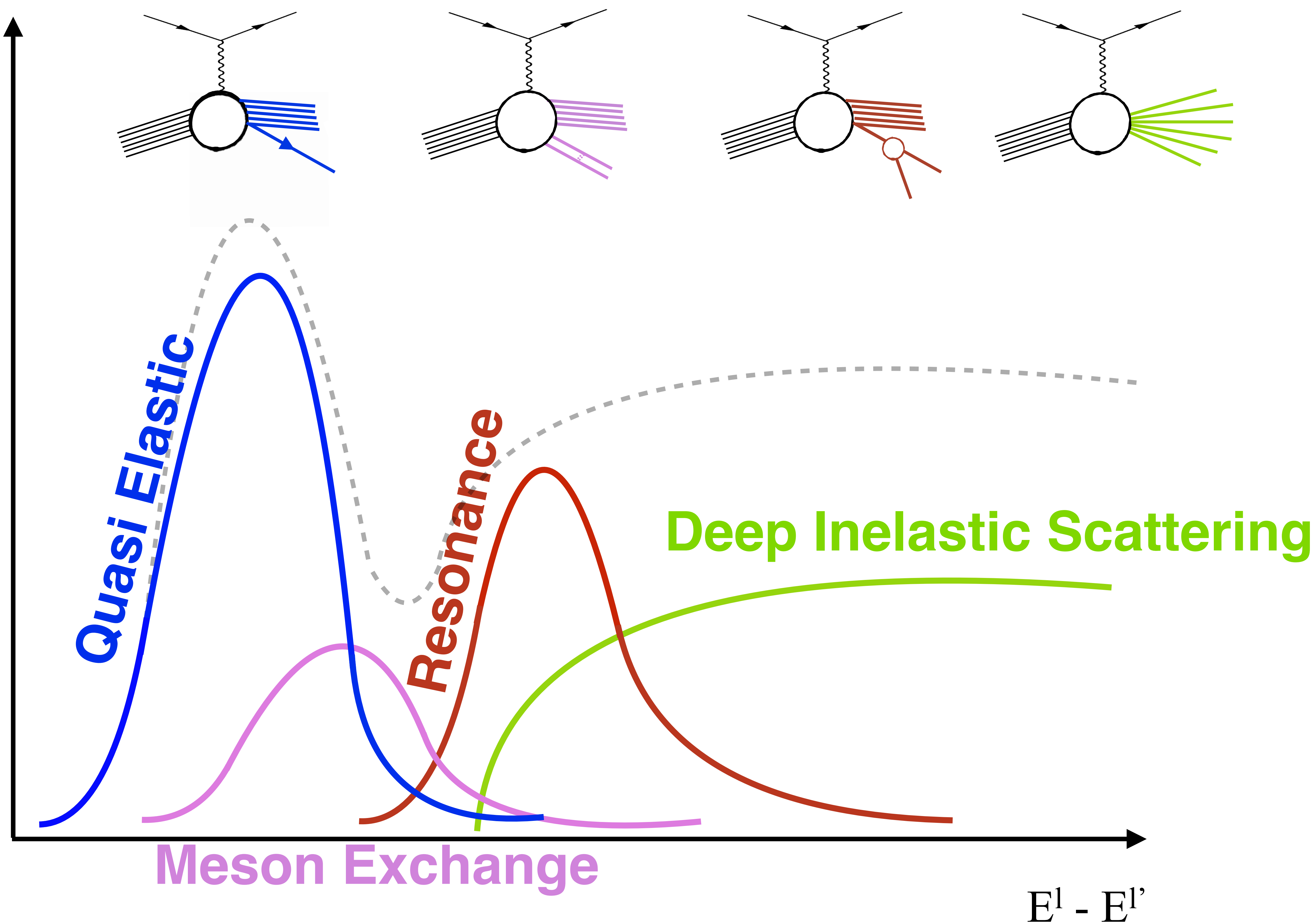
[1p0π]

ϵ is the nucleon separation energy ~ 20 MeV

Lepton-Nucleus Interaction Modelling



E_ν Reco Requires Interaction Modeling



Lepton-Nucleus Interaction Modelling

Neutrino event generators simulating νA interaction

Genie

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more

Using semi-classical / empirical / phenomenological based model

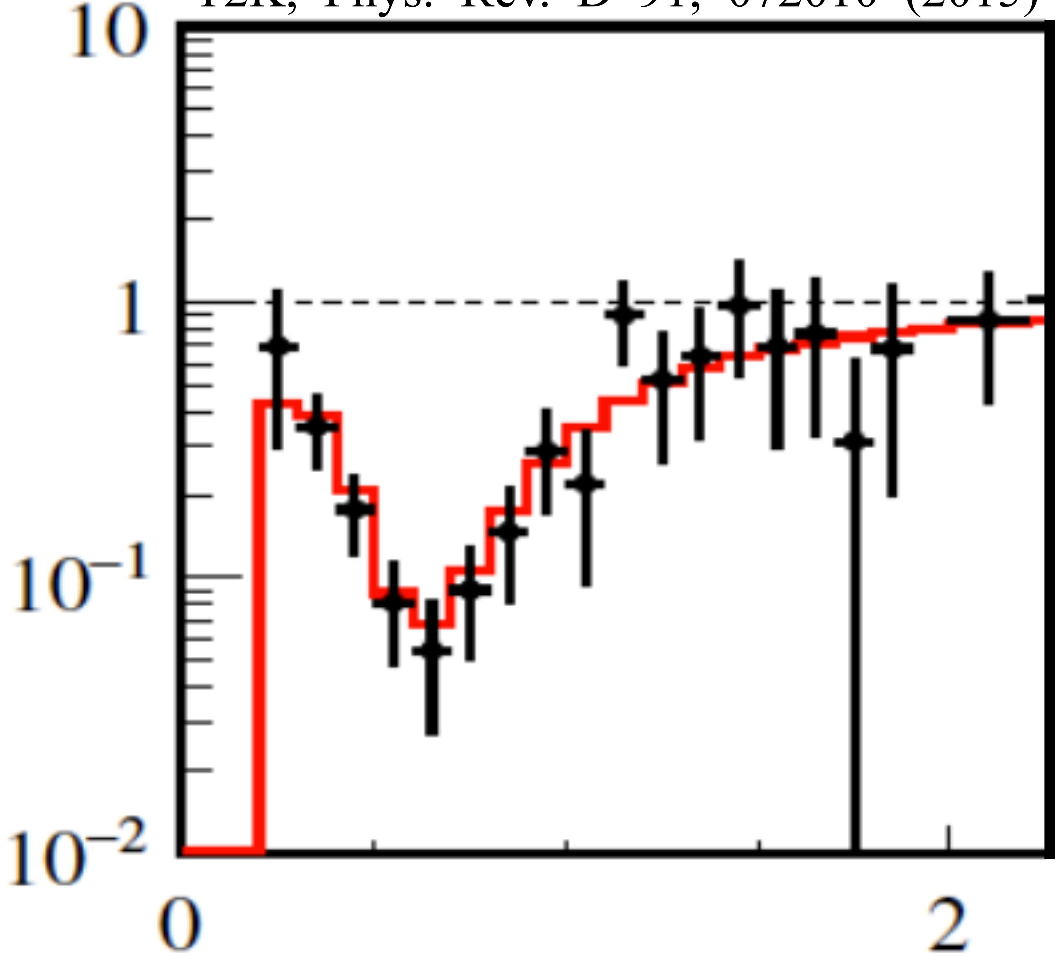
All with many free parameters

Factorisation of

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

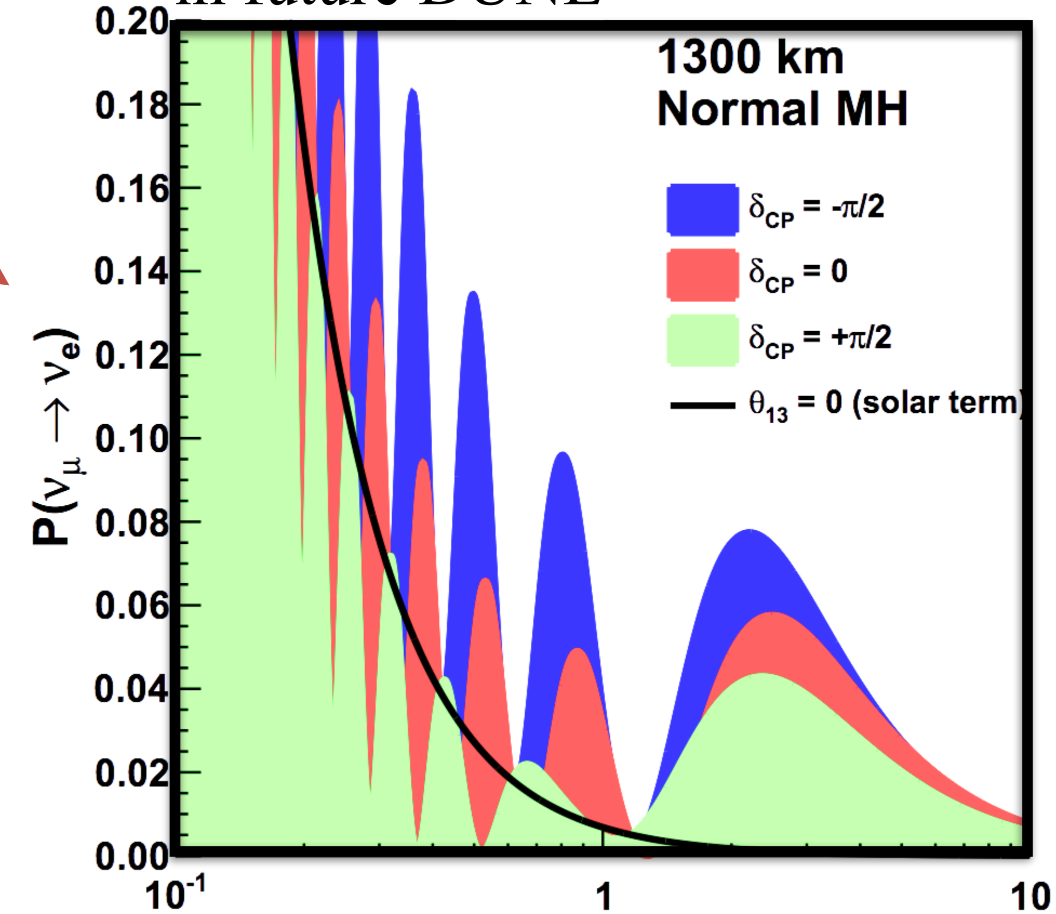
The challenge - next generation high precision

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



Neutrino Energy [GeV]

Simulation of oscillation effects in future DUNE

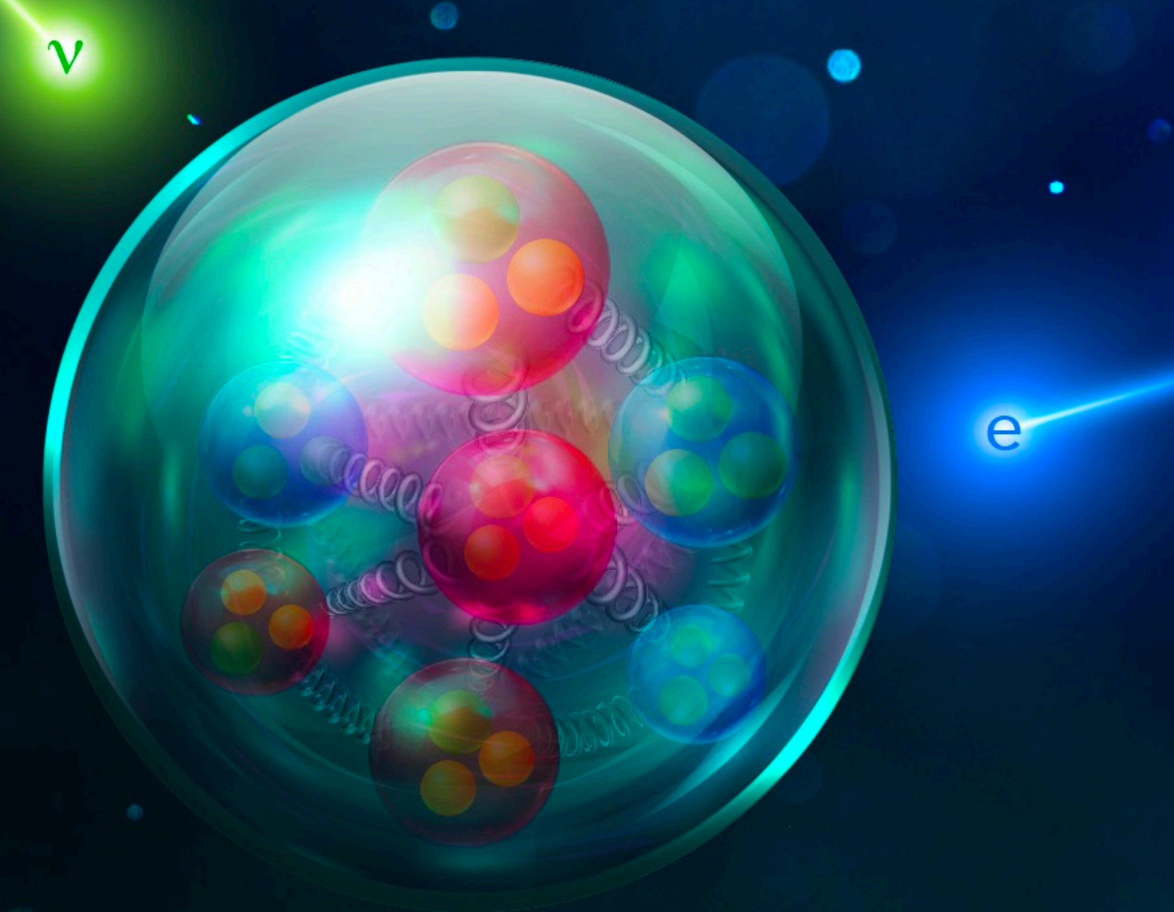


Neutrino Energy [GeV]

Electrons for Neutrinos

Using electron scattering data to reduce neutrino oscillation systematic uncertainties

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

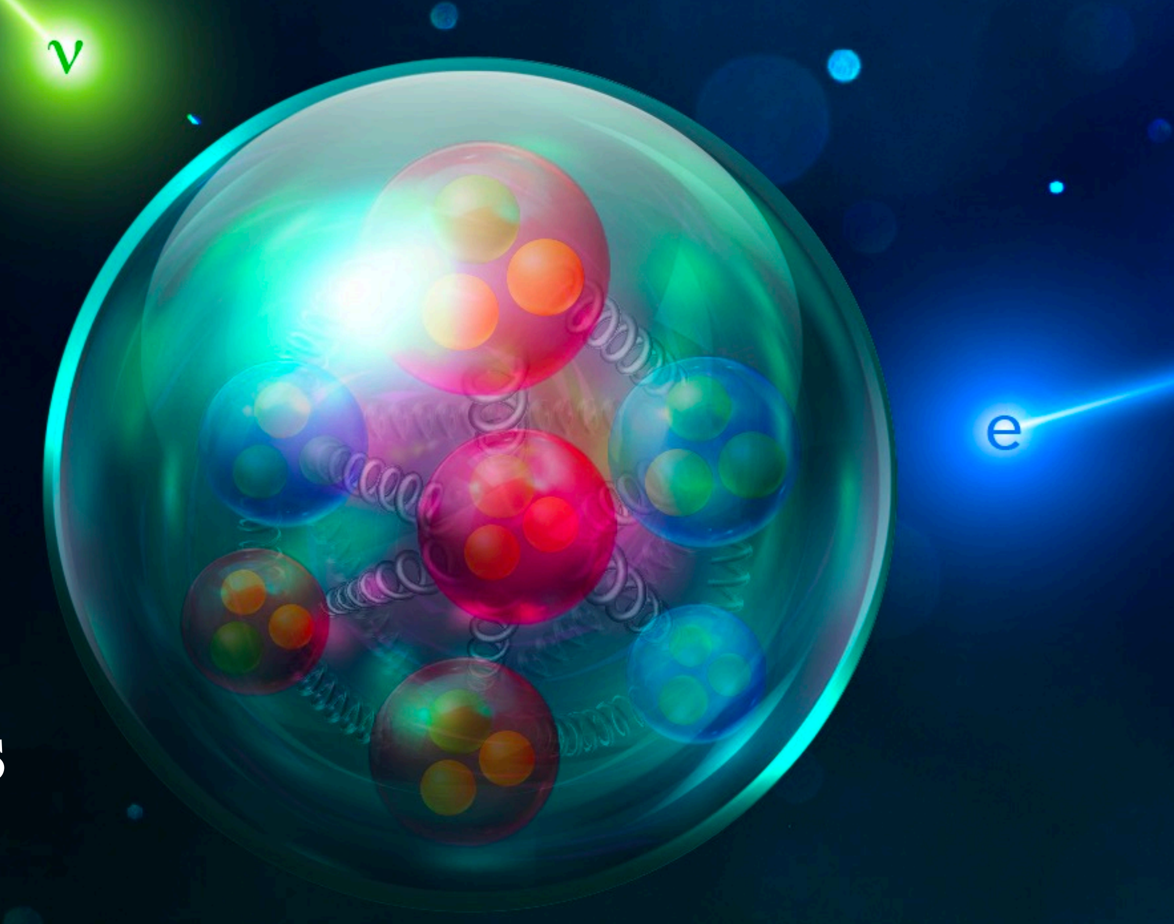


visit: www.e4nu.com

Why electrons?

Electrons and Neutrinos have:

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



Useful to constrain model uncertainties

Why electrons?

Electrons and Neutrinos have:

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

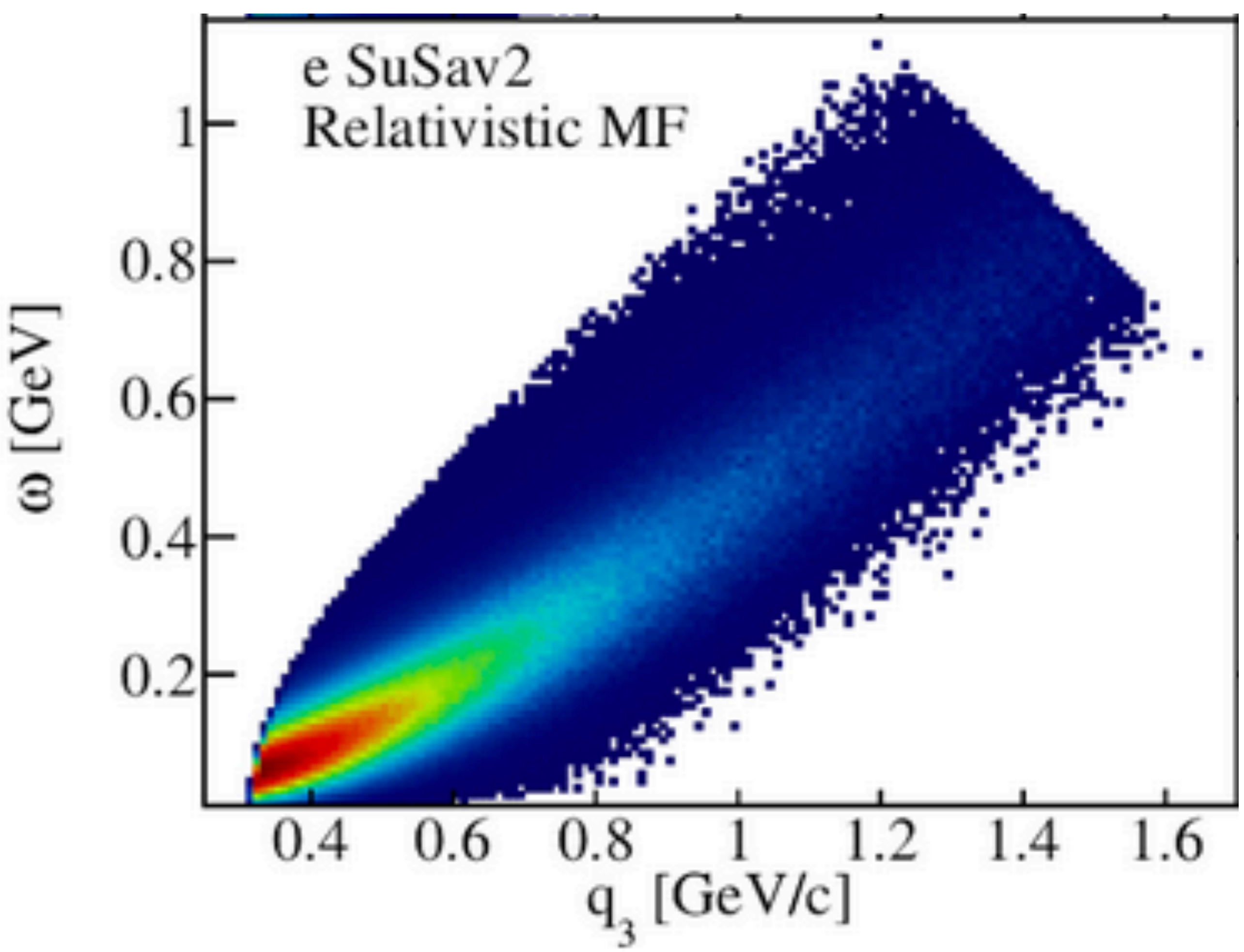
Useful to constrain model uncertainties

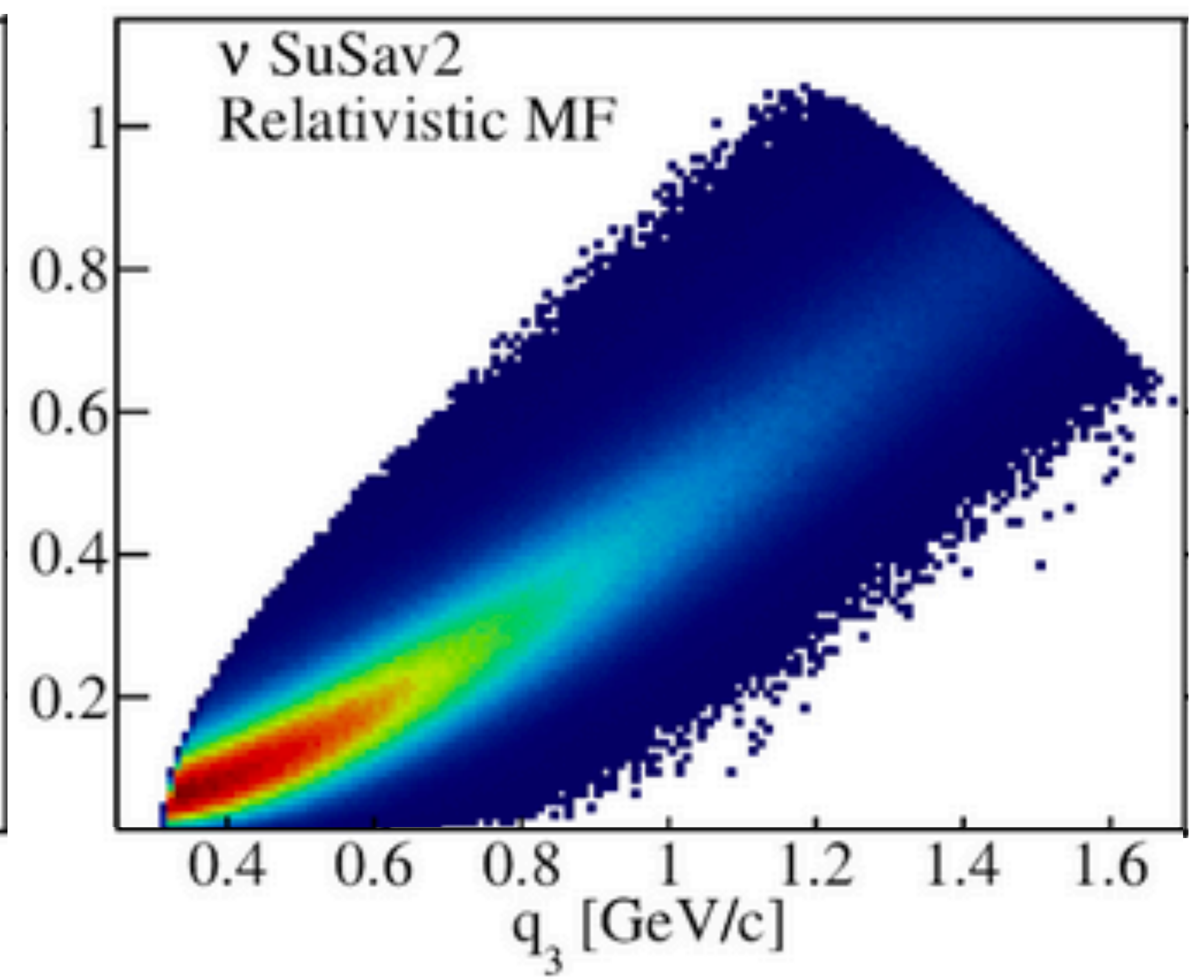
Electron beams have known energy

Useful as a test to incoming lepton energy reconstruction methods

Similar eA and νA Cross sections

Test on 1p0π event selection



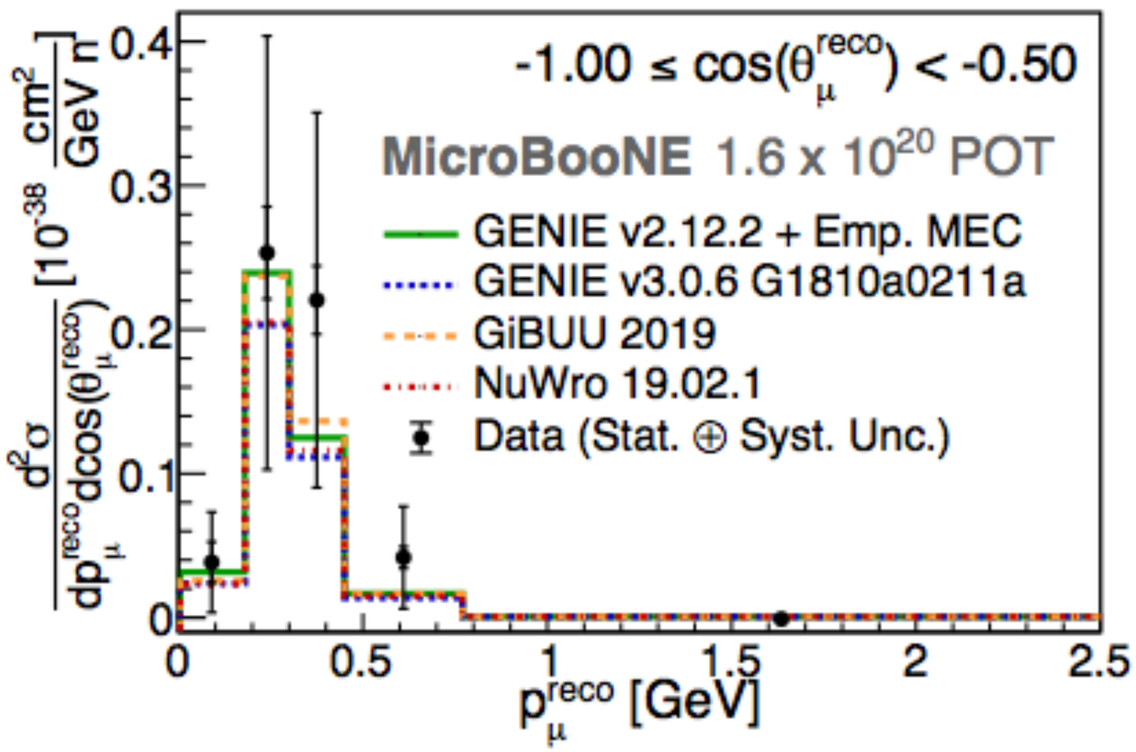


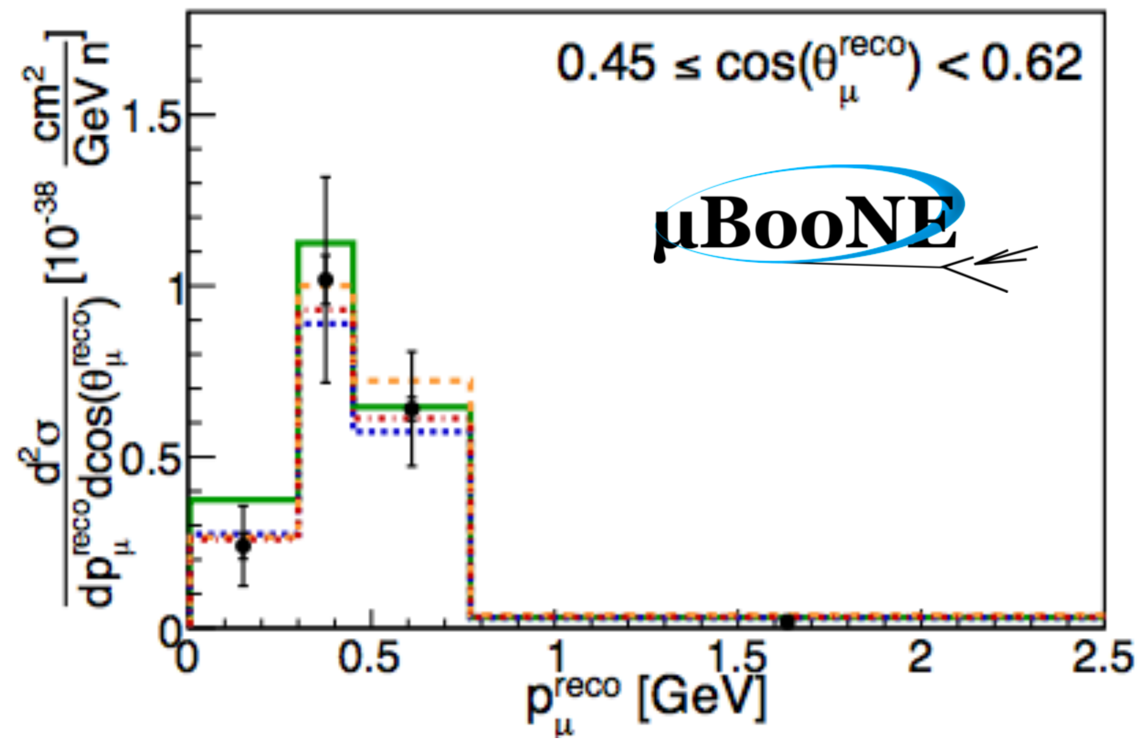
Genie v3.0.6 SuSA

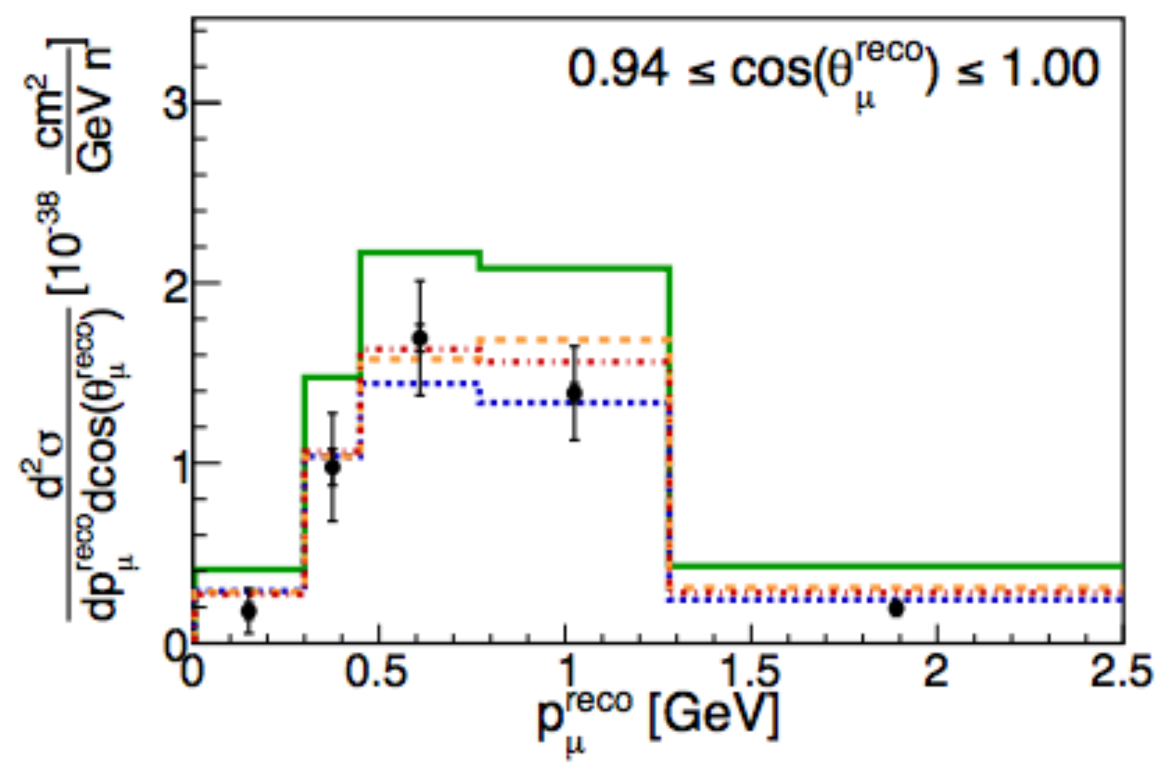
Electron were weighted by $1/Q^4$

Phys.Rev.D 103 (2021) 113003

Inclusive ν data and Generators





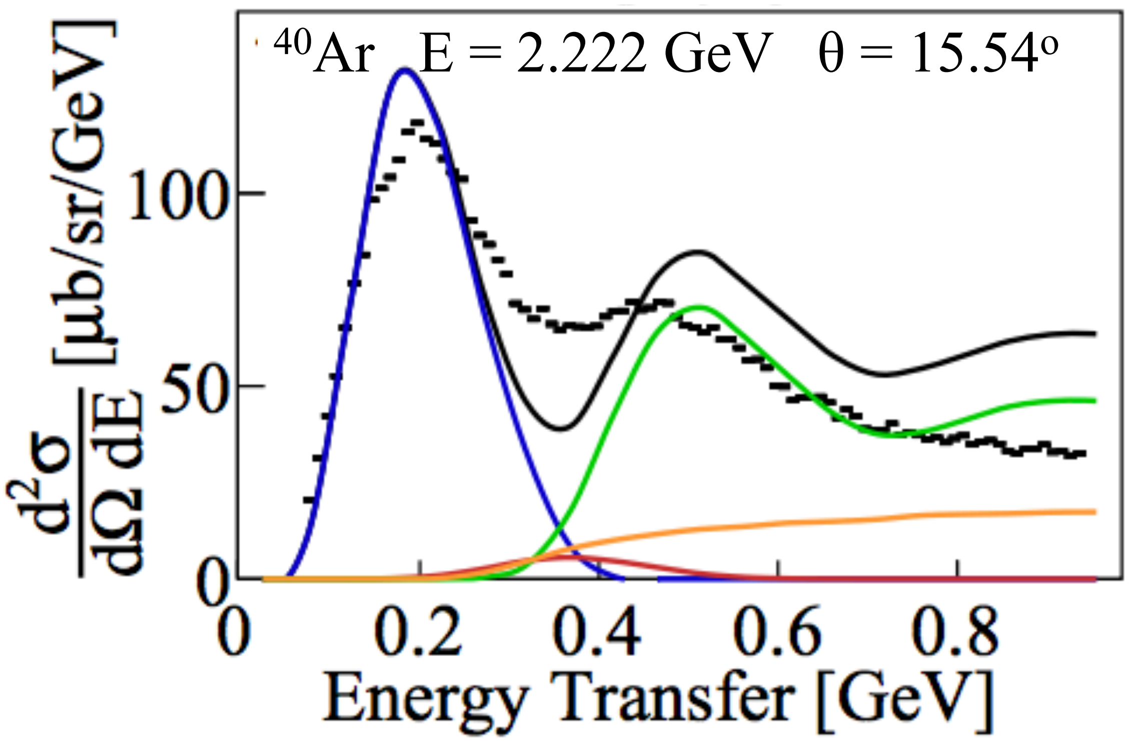


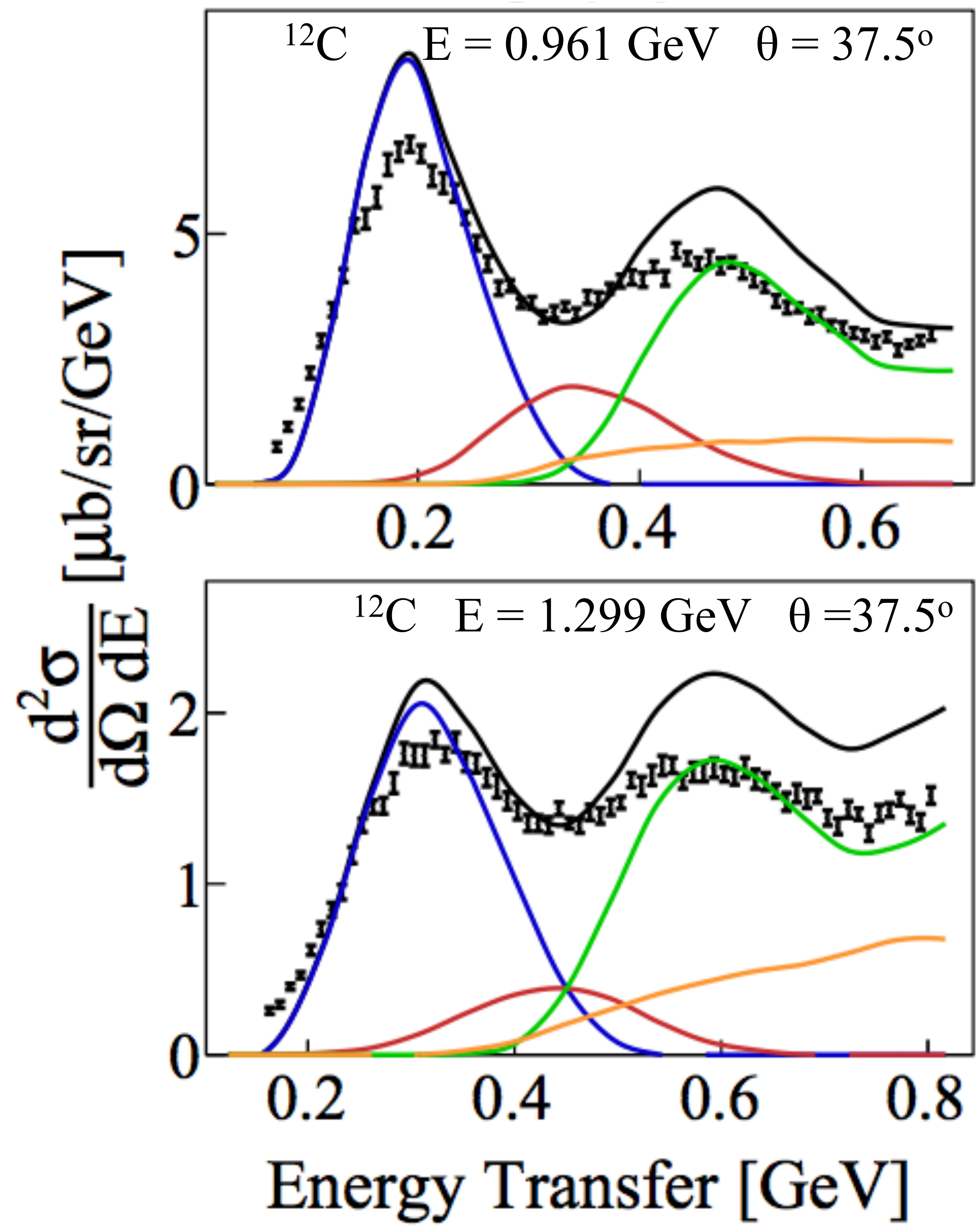
Genie

v3.0.6 tune G18_10a_02_11a

Phys. Rev. Lett. 123, 131801 (2019)

Inclusive e data and generators





Genie

— v3.0.6 tune G18_10a_02_11a

Phys.Rev.D 103 (2021) 113003

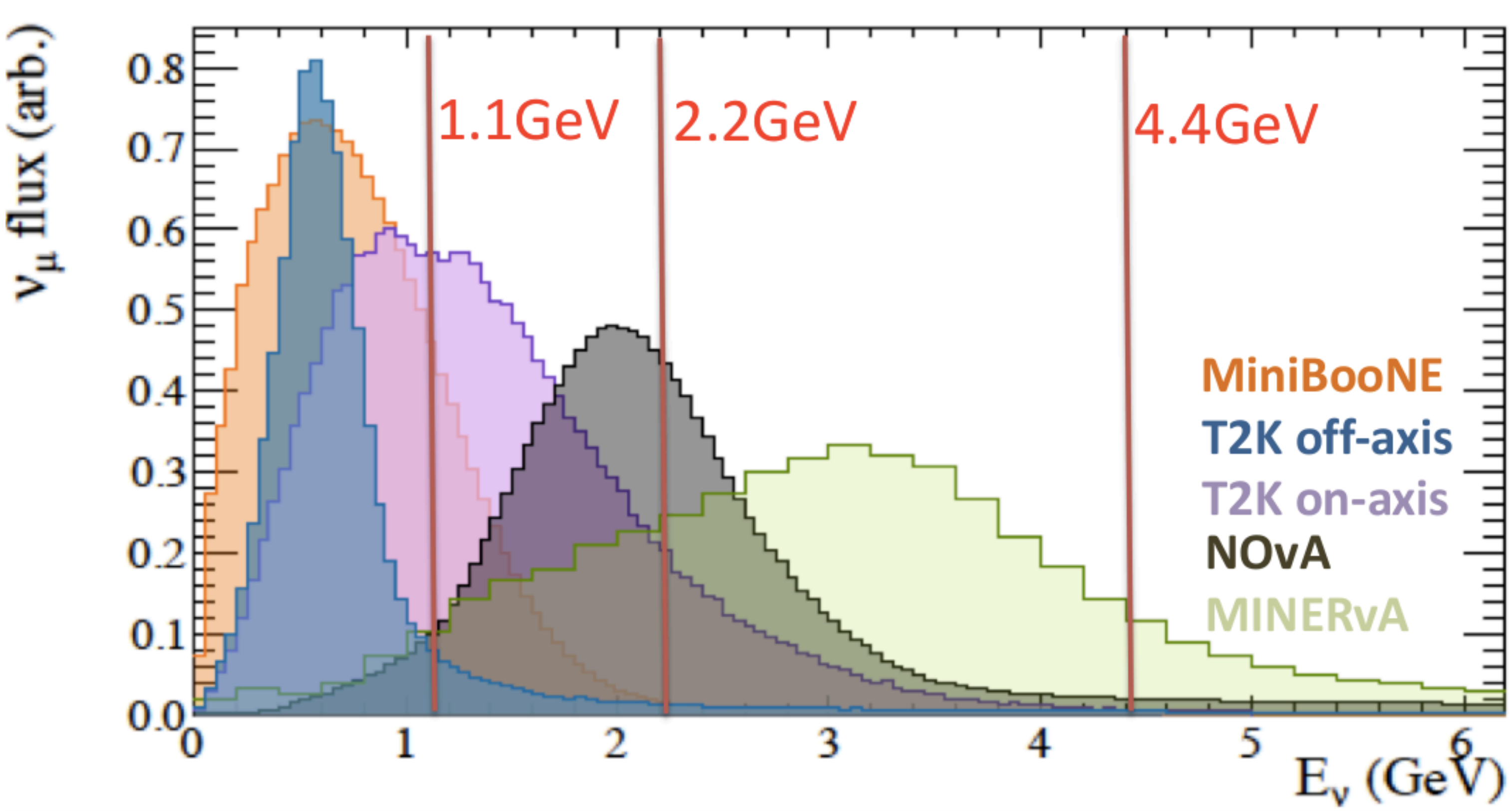
CLAS A(e,e'p) Data E2a

First test of neutrino energy reconstruction with exclusive data!

Targets: ^{4}He, ^{12}C, ^{56}Fe (H$_2$O), (CH), (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

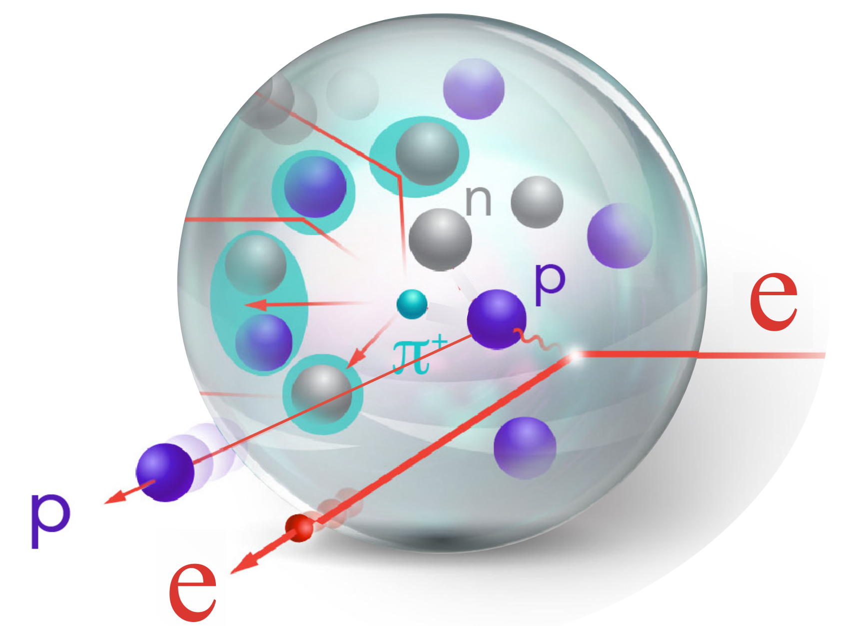
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

no additional hadrons above detection threshold:

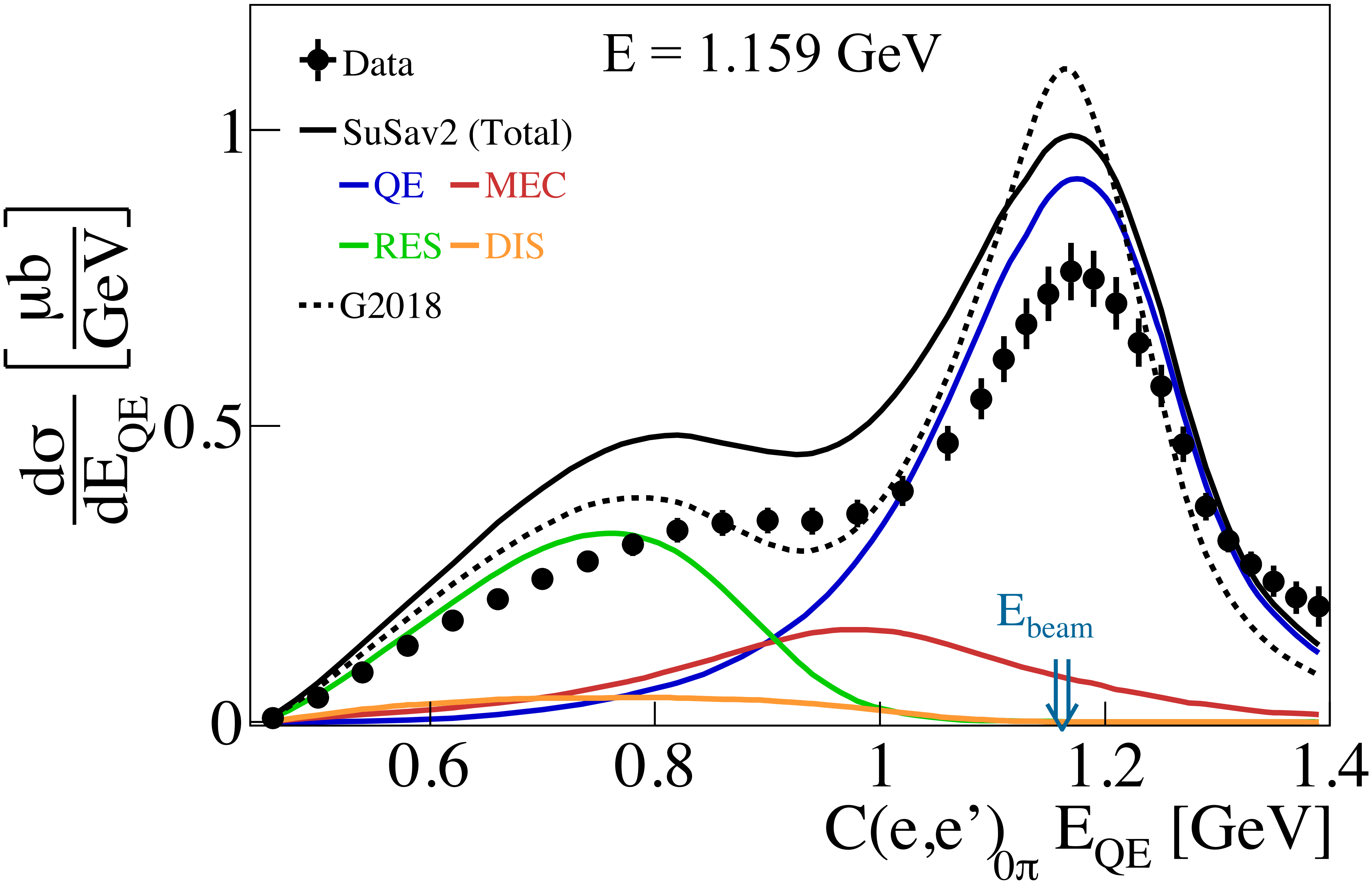
150 MeV/c for $P_{\pi}^{+/-}$

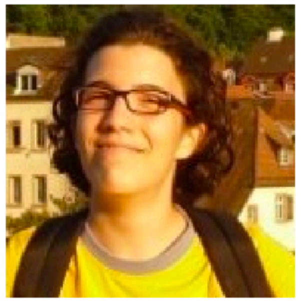
500 MeV/c for P_{π}^{0}



Data

Inclusive Energy Reconstruction





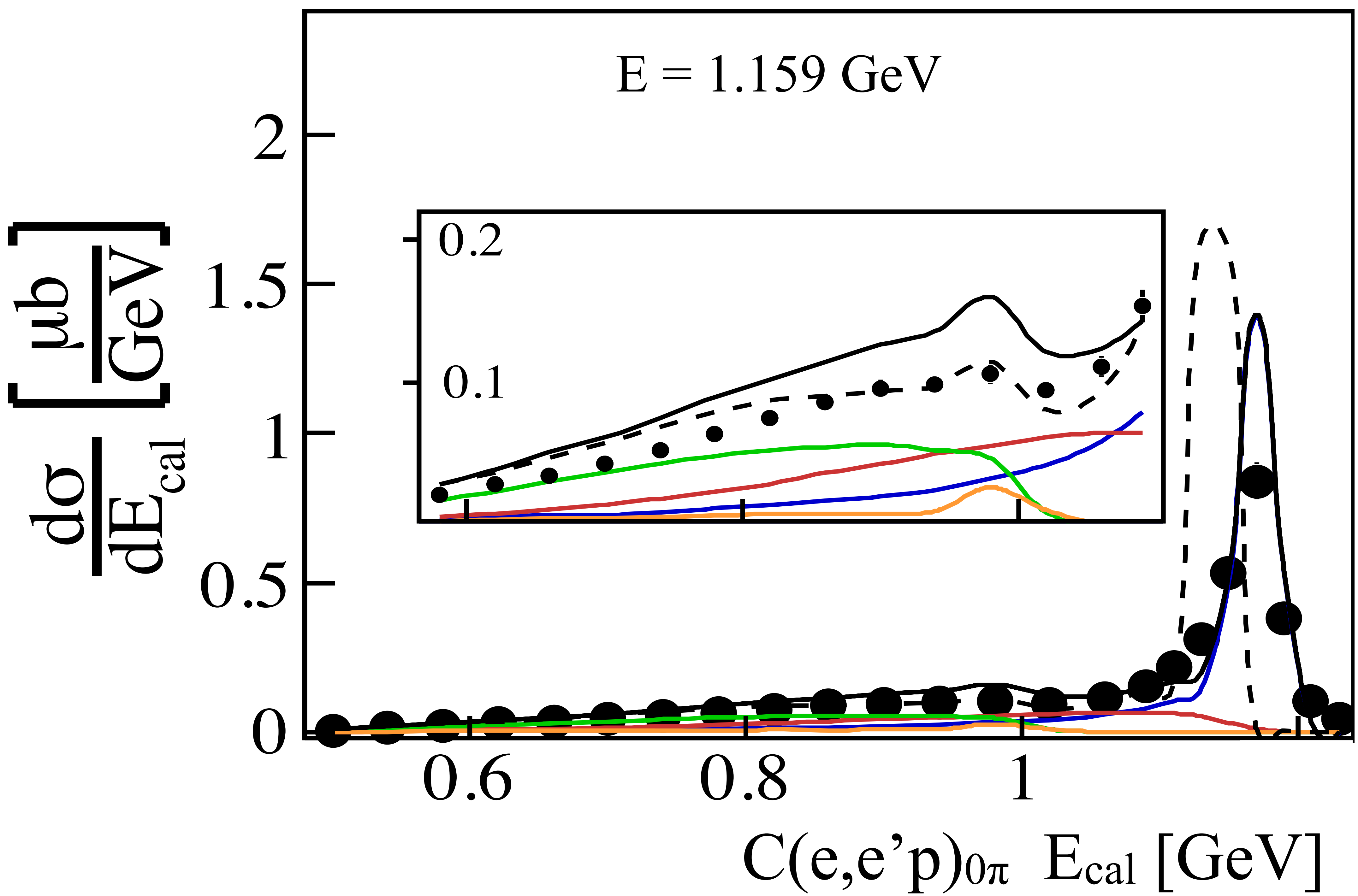
Afroditi Papadopoulou

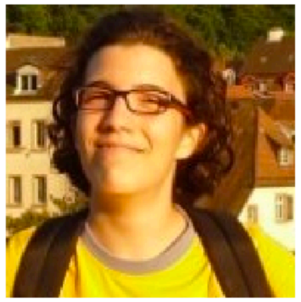
Mariana Khachatryan

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

Nature **599**, 565 (2021)

Reconstructed Calorimetric Energy



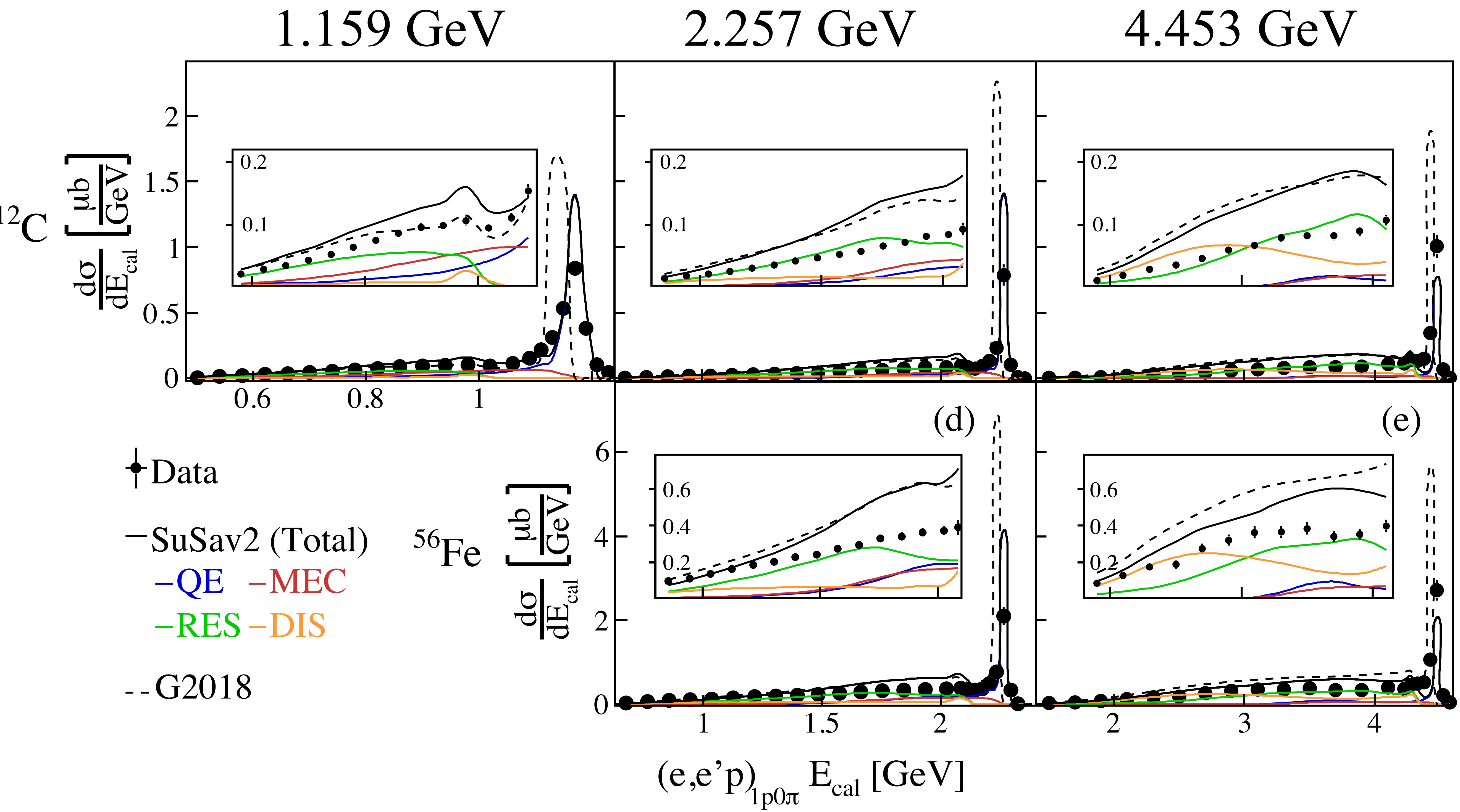


Afroditi Papadopoulou

Mariana Khachatryan

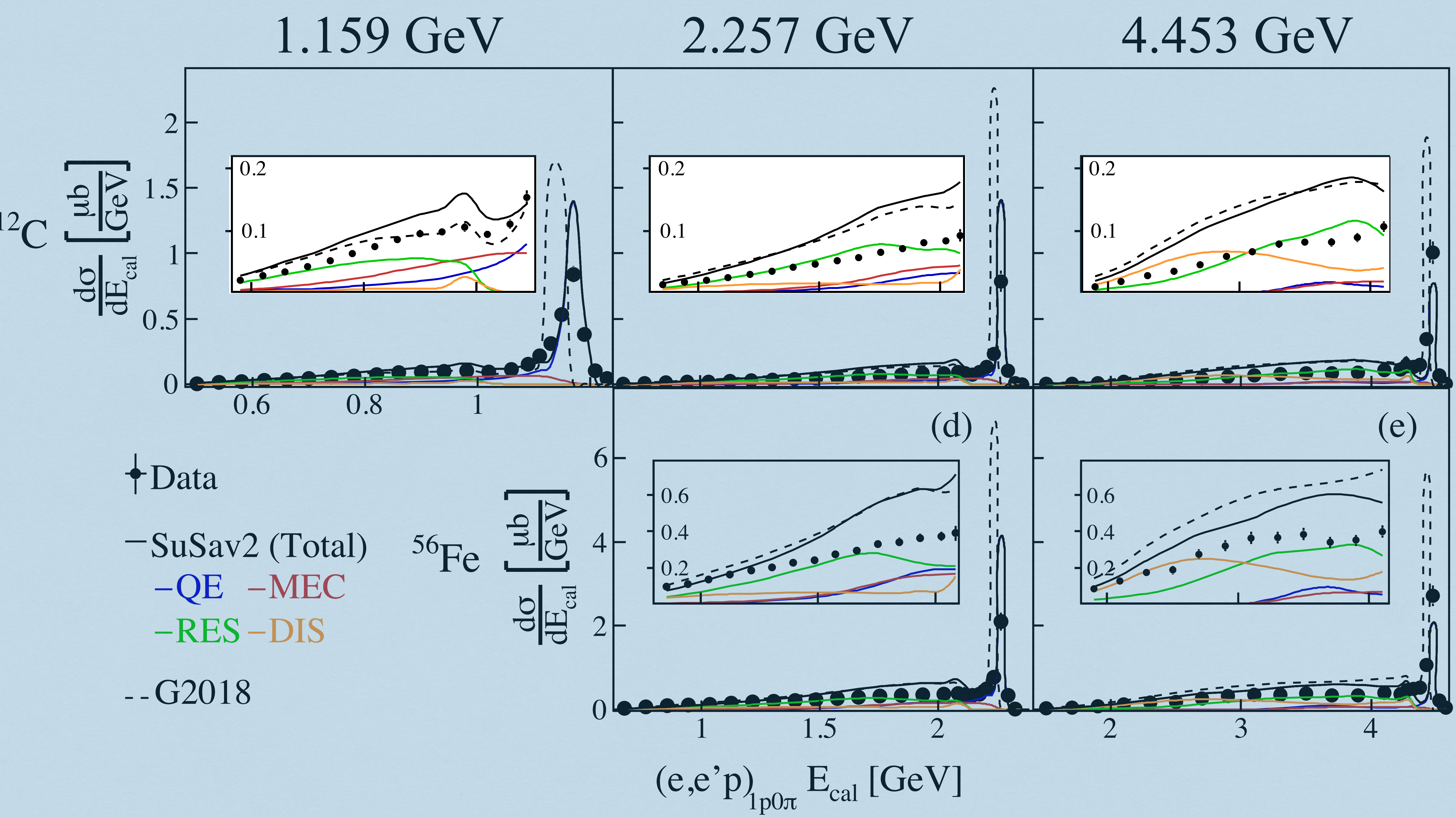
Nature **599**, 565 (2021)

Reconstructed Calorimetric Energy



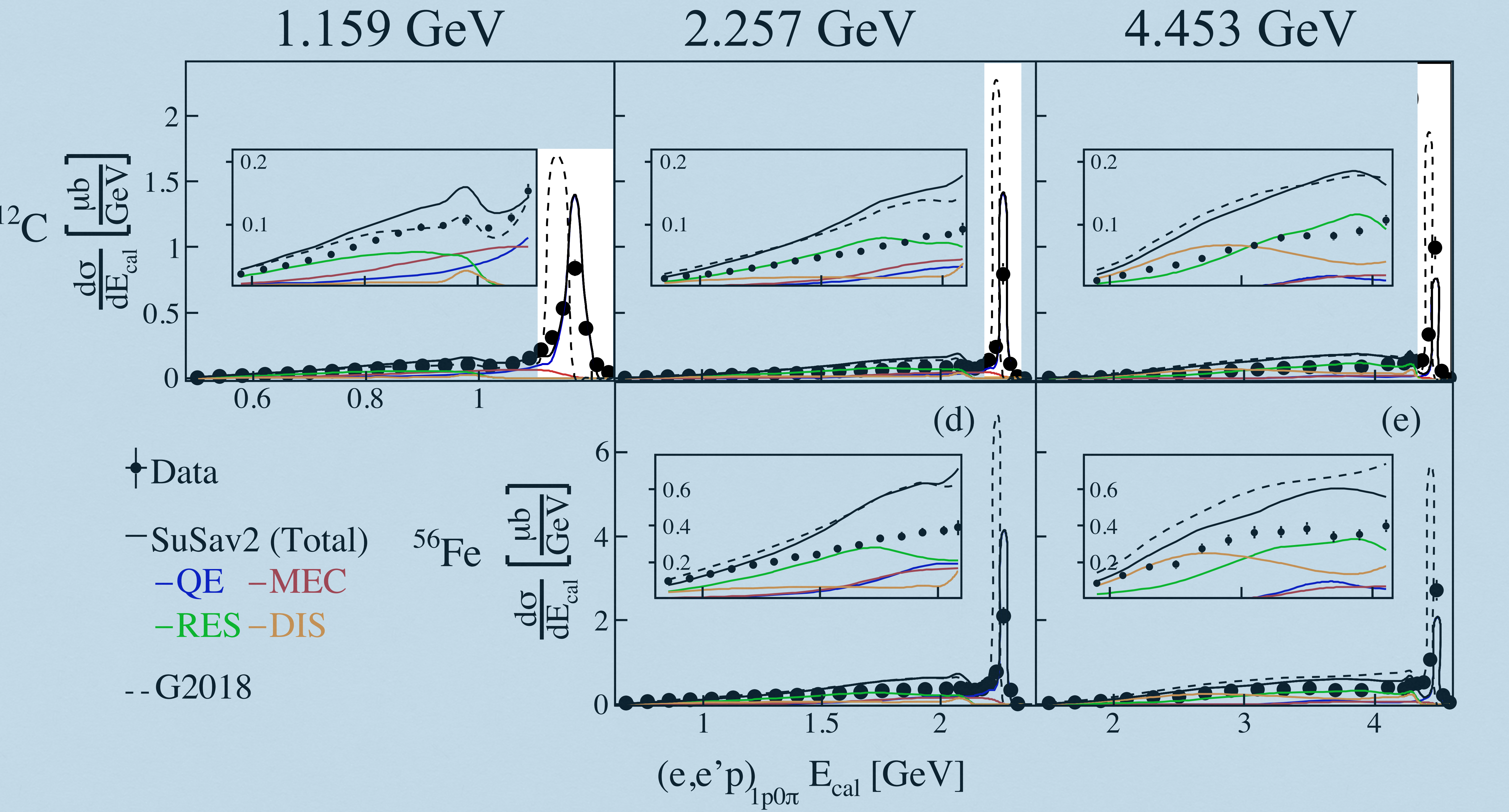
Nature **599**, 565 (2021)

Reconstructed Calorimetric Energy



Nature **599**, 565 (2021)

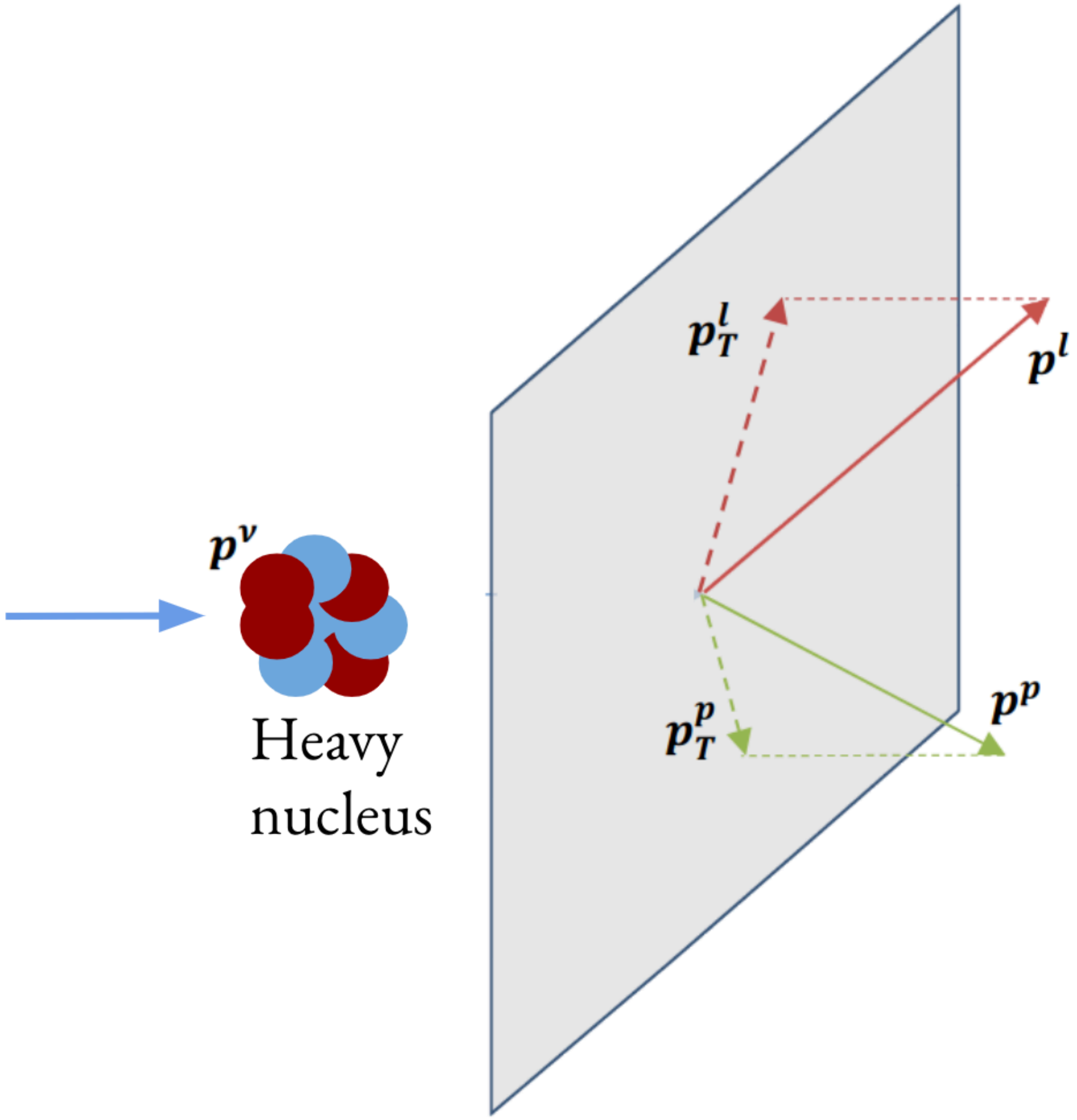
Reconstructed Calorimetric Energy



Nature **599**, 565 (2021)

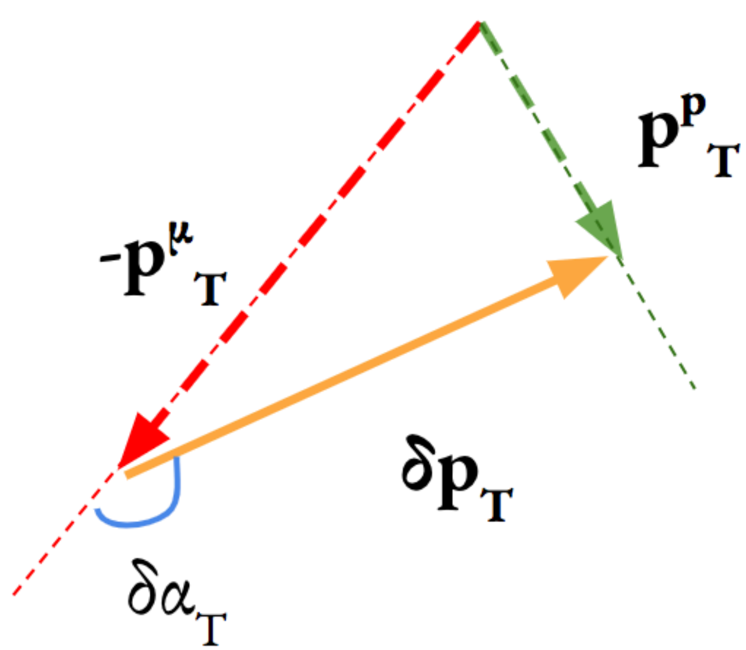
Focusing on different reaction mechanisms

Standard Transverse Variables



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

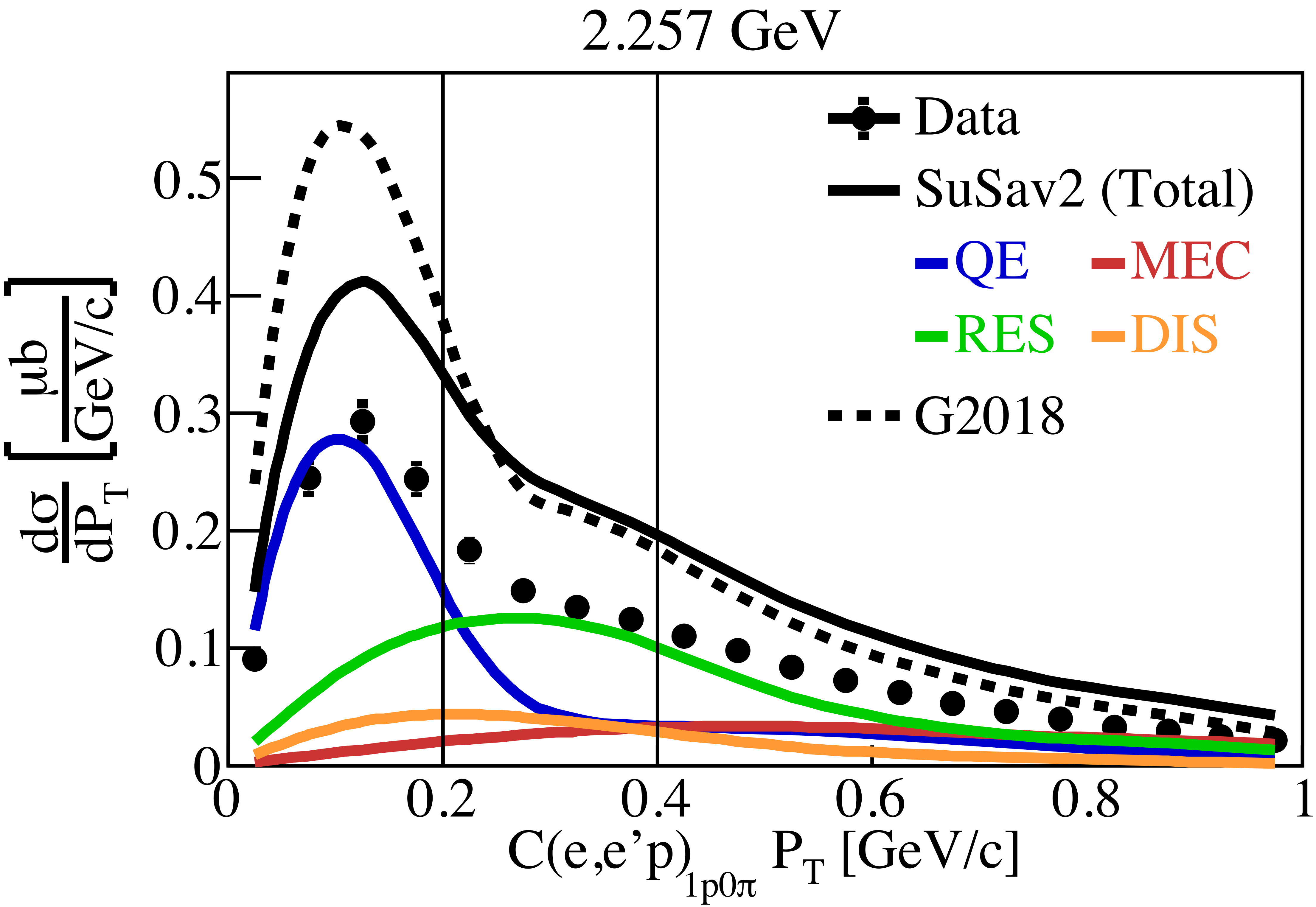
Sensitive to
hit nucleon momentum



$\delta\alpha_\mathrm{T}$

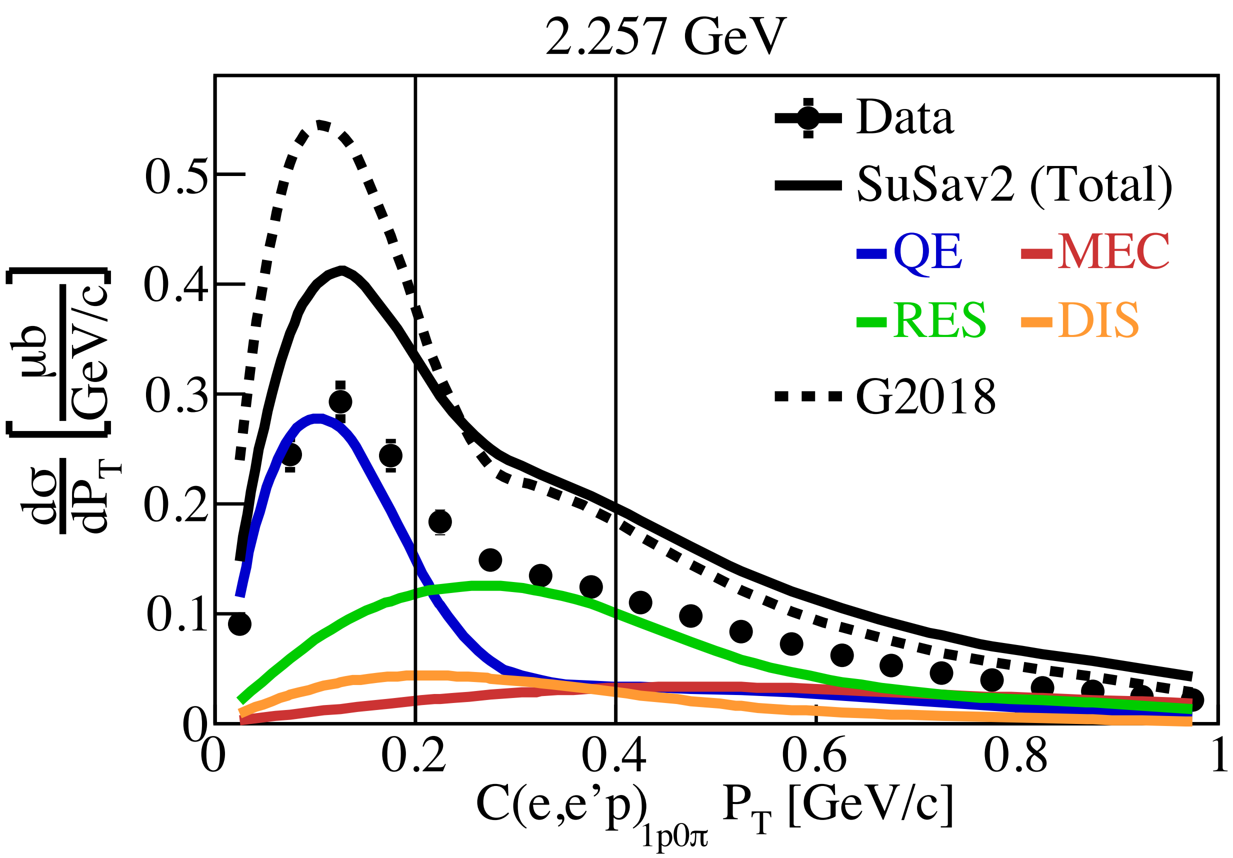
Sensitive to
Final State Interactions

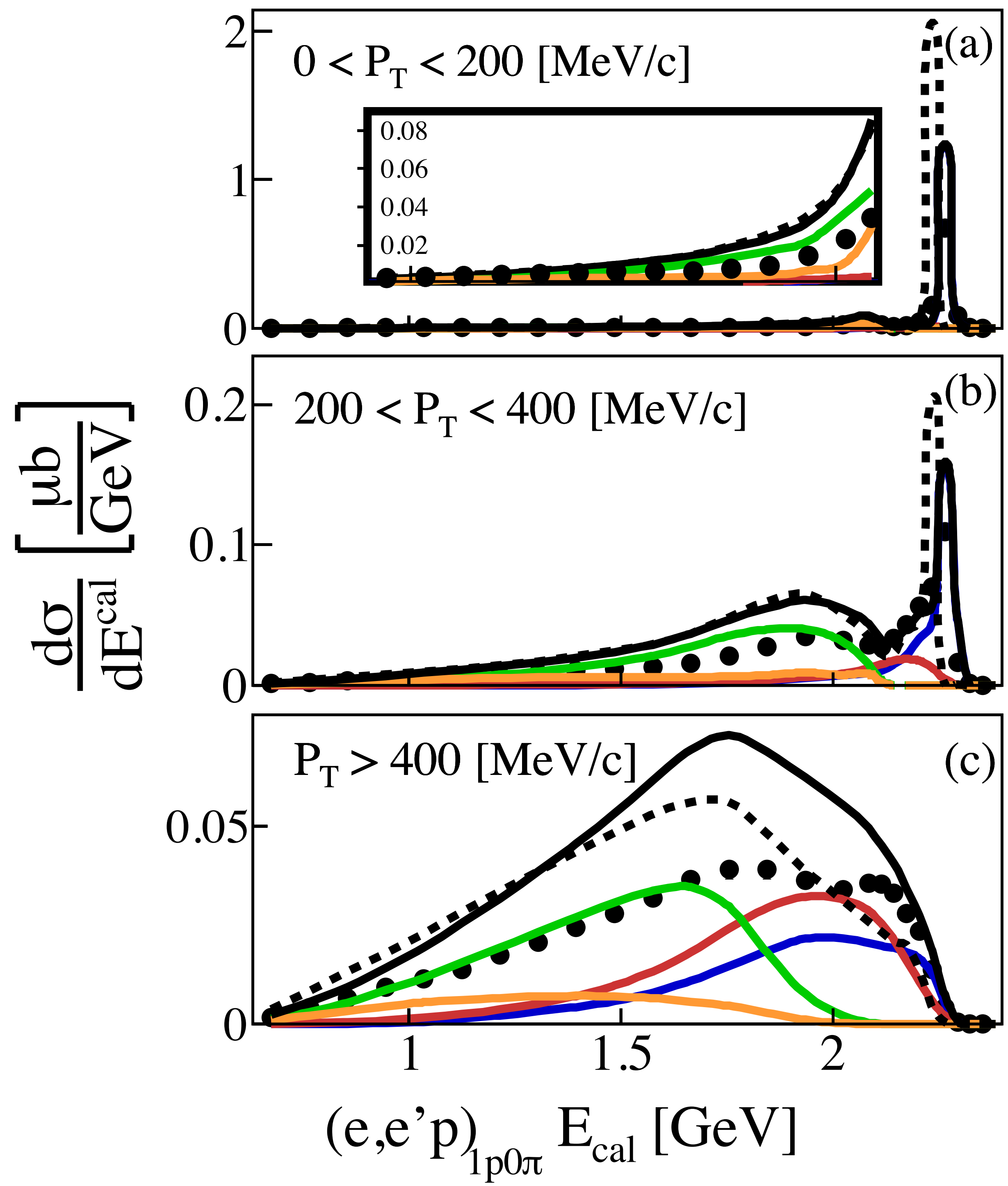
Transverse missing momentum



Nature **599**, 565 (2021)

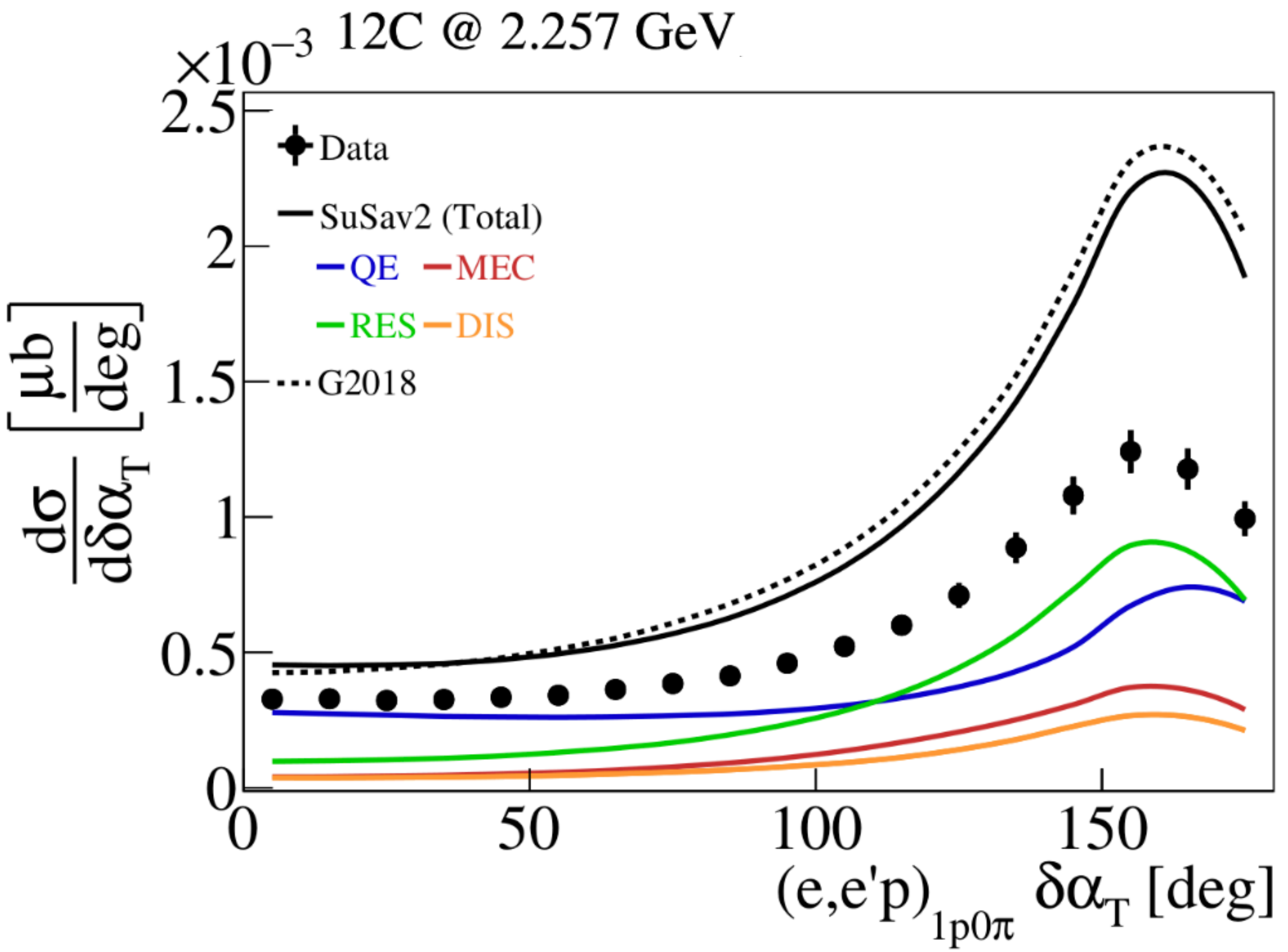
p_T sensitivity to interaction mechanisms



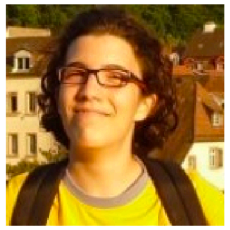


Nature **599**, 565 (2021)

Transverse Kinematic Variables - $\delta\alpha_T$



A. Papadopoulou et al. in preparation



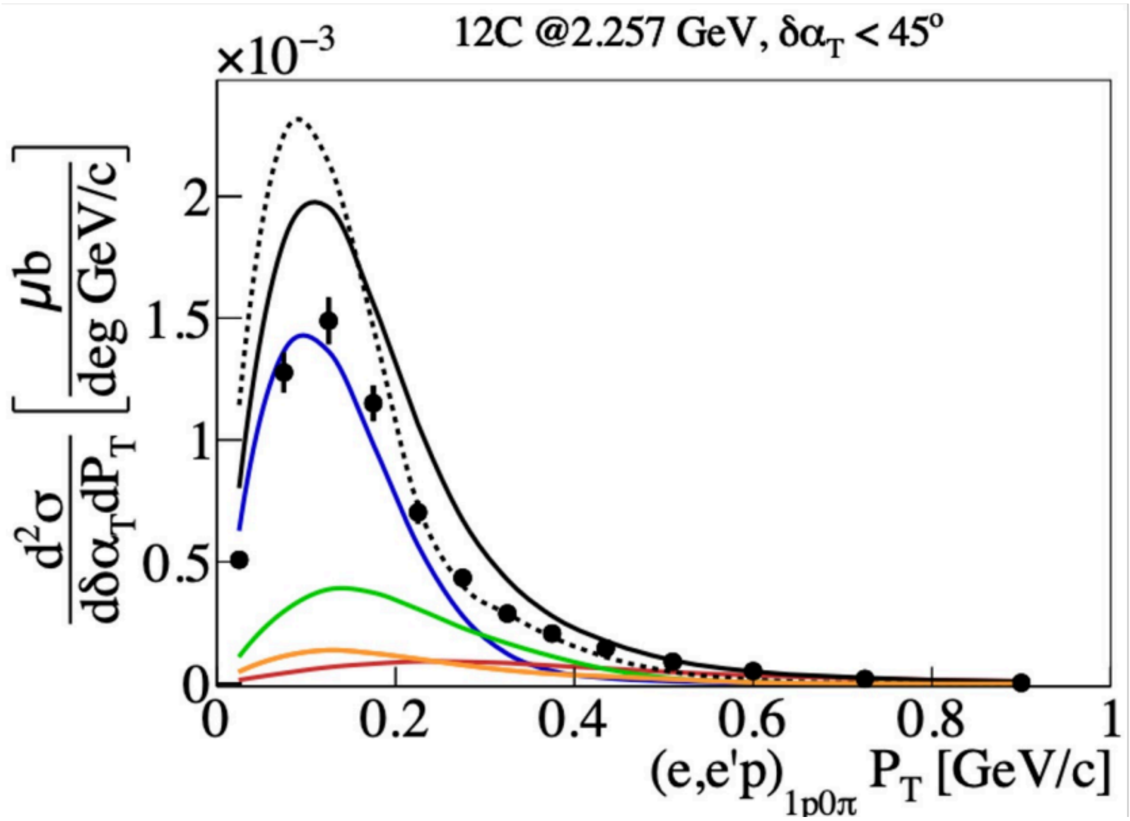
MC vs. (e,e'p) Transverse Variables

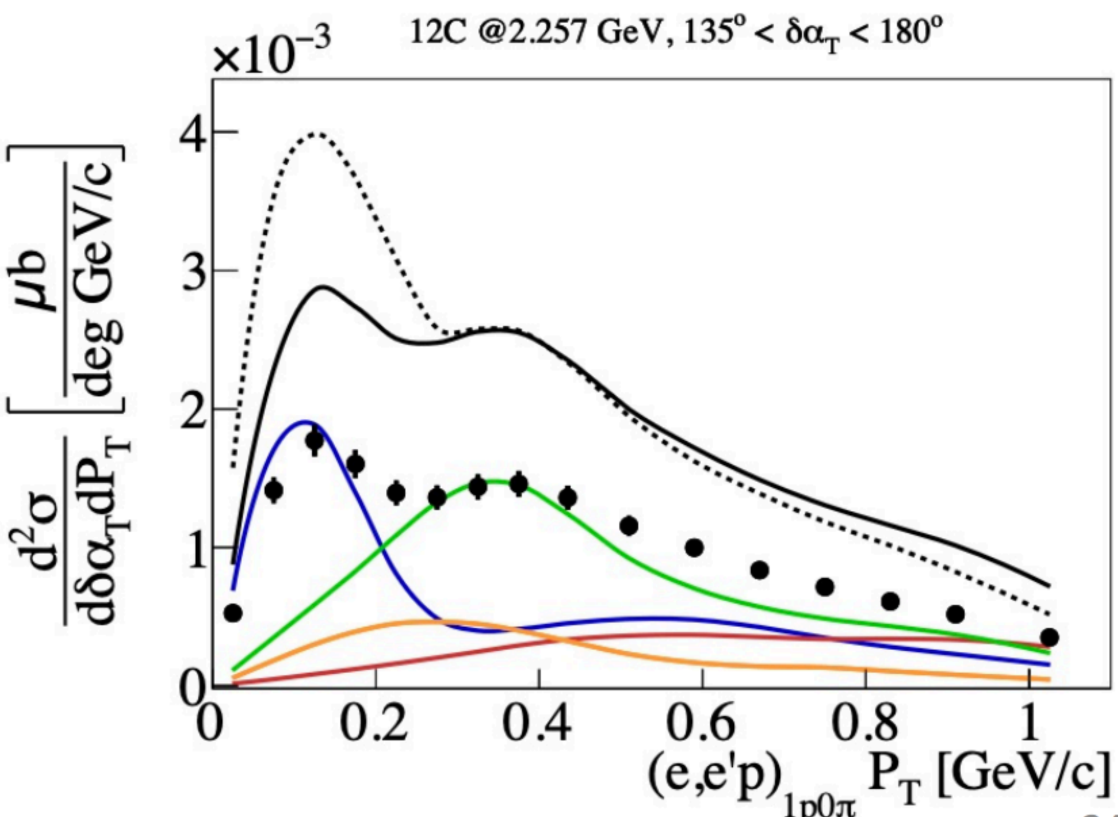
Low αT < 45

QE enhanced region

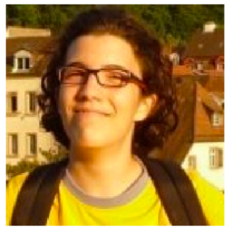
High 135 < αT < 180

Non QE contributions





A. Papadopoulou et al. in preparation



Similarities between e and ν

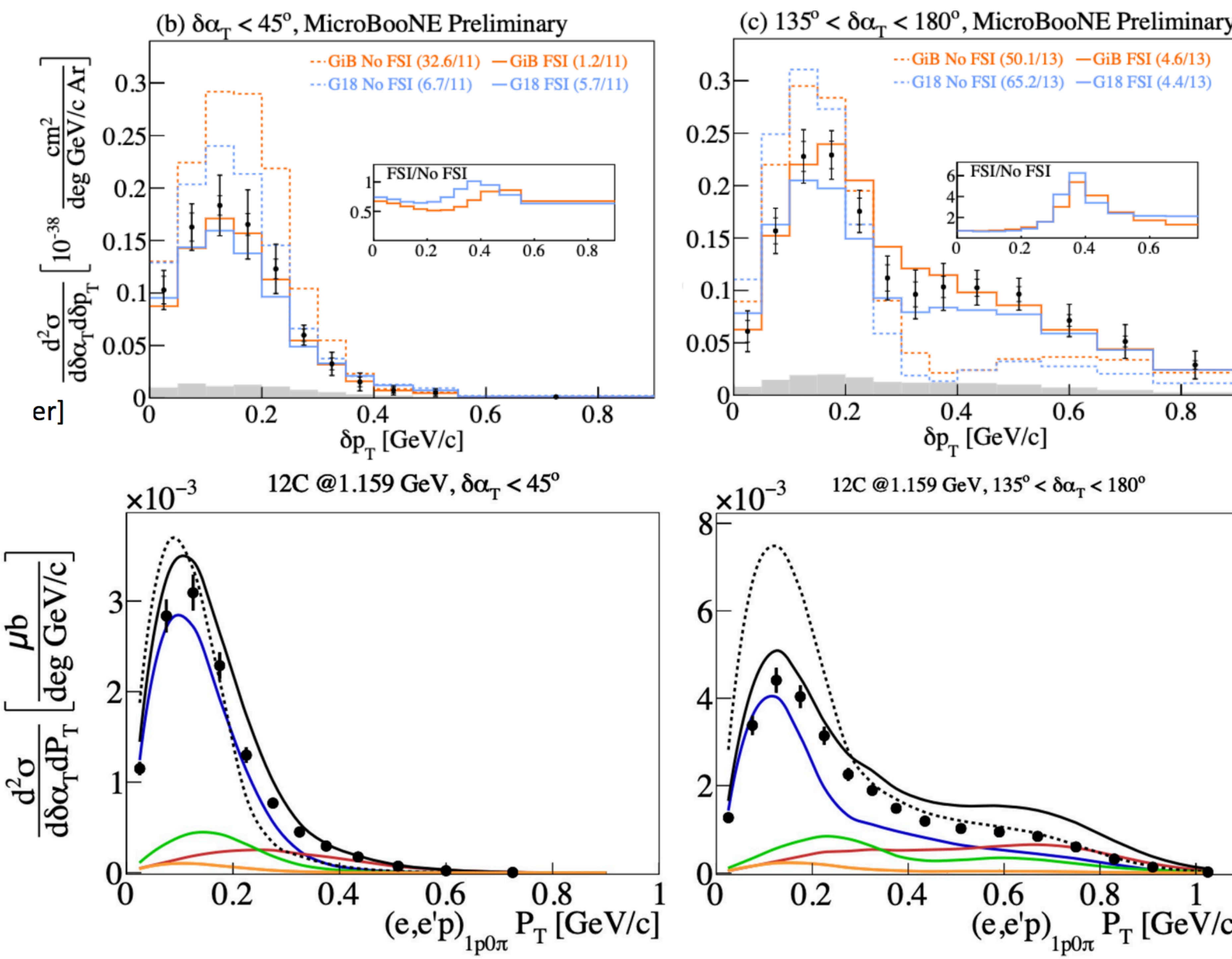
Small $\delta\alpha_T$ Large $\delta\alpha_T$

µBooNE

ν_μ

e4ν

e^-



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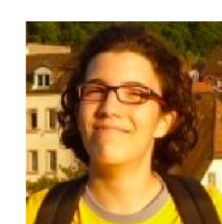
A. Papadopoulou et al. in preparation



Looking forward to new results

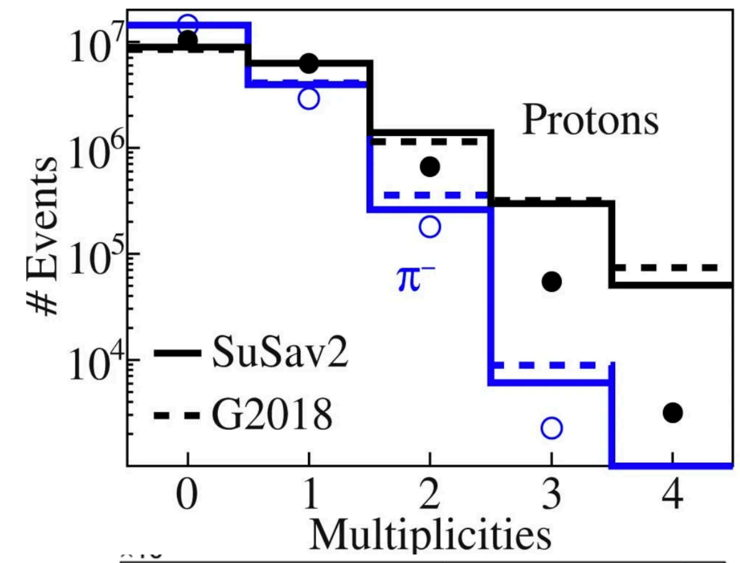
Working on:

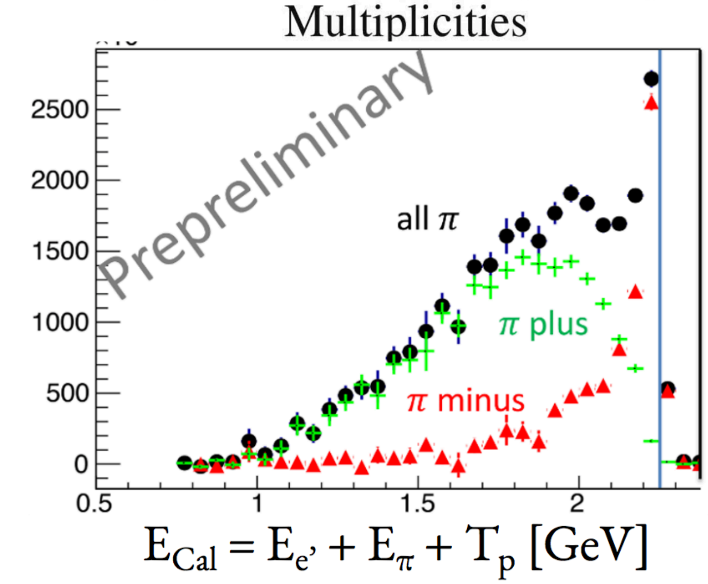
Multi differential analysis

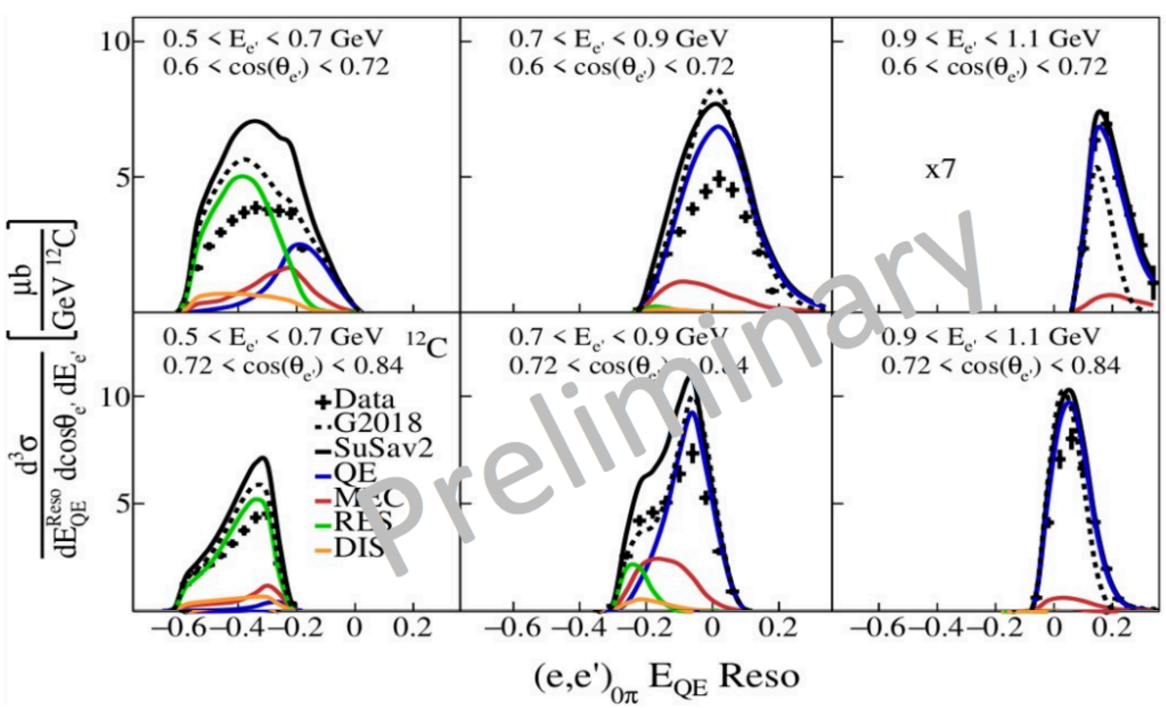
Pion production

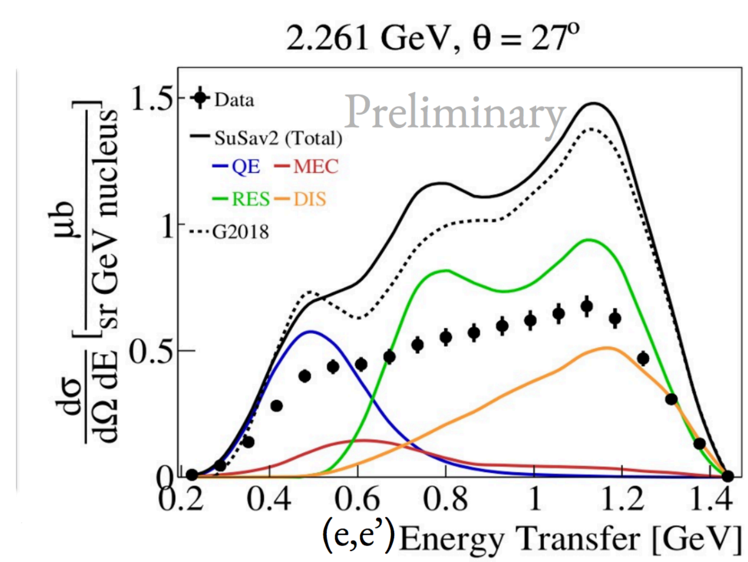
Two nucleon final state

All nuclei and energies









New Data from CLAS12

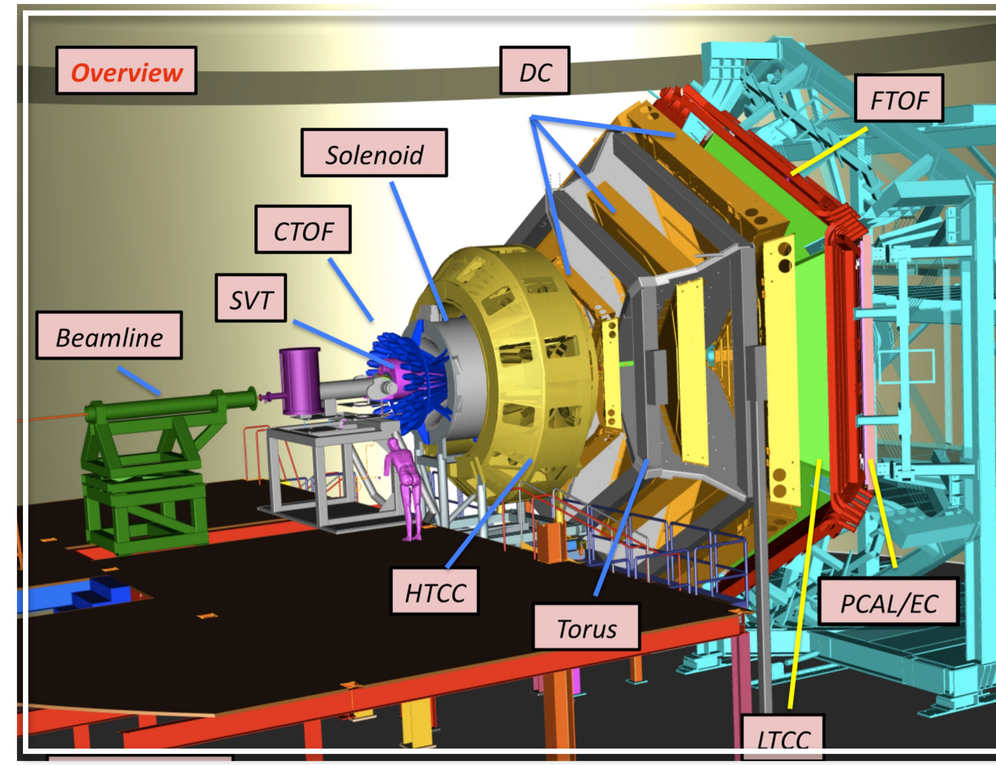
Acceptance down to 5^o $Q^2 > 0.04$ GeV^2

x10 luminosity [10^{35} cm^{-2}s^{-1}]

Keep low threshold, better neutron coverage

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

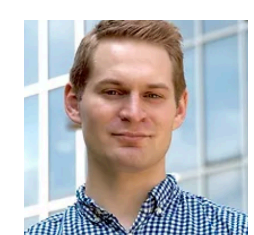
(1,) 2, 4, 6 GeV (relevant for DUNE)



Overwhelming support from:

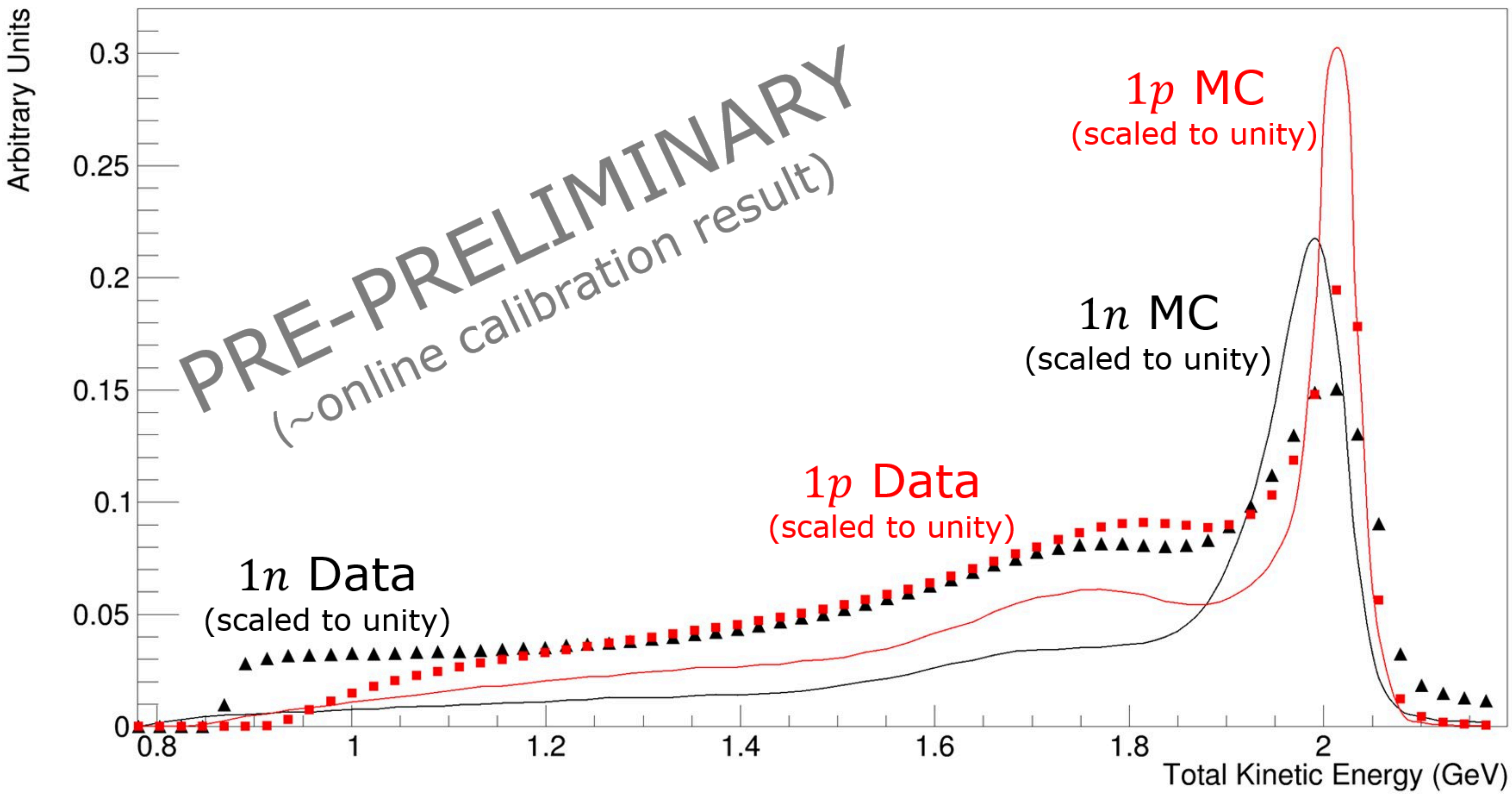
DUNE   ICECUBE SOUTH POLE NEUTRINO OBSERVATORY   Hyper-Kamiokande   T2K   NOvA   MINERvA

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


Justin Estee


Joshua Barrow

Next step RG-M CLAS12



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

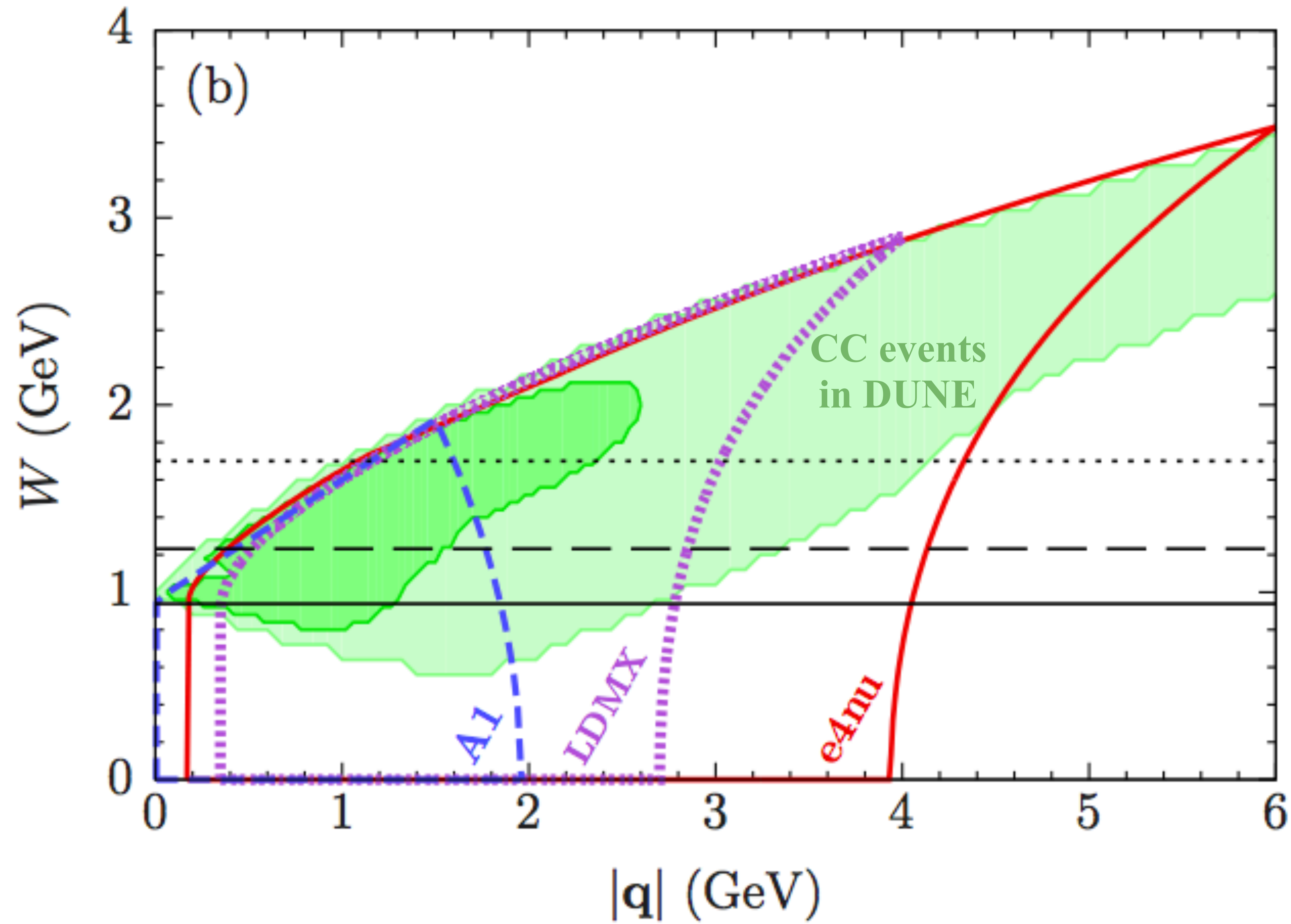
Joshua Barrow

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]

e4nu and DUNE



The e4ν Collaboration

visit www.e4nu.com

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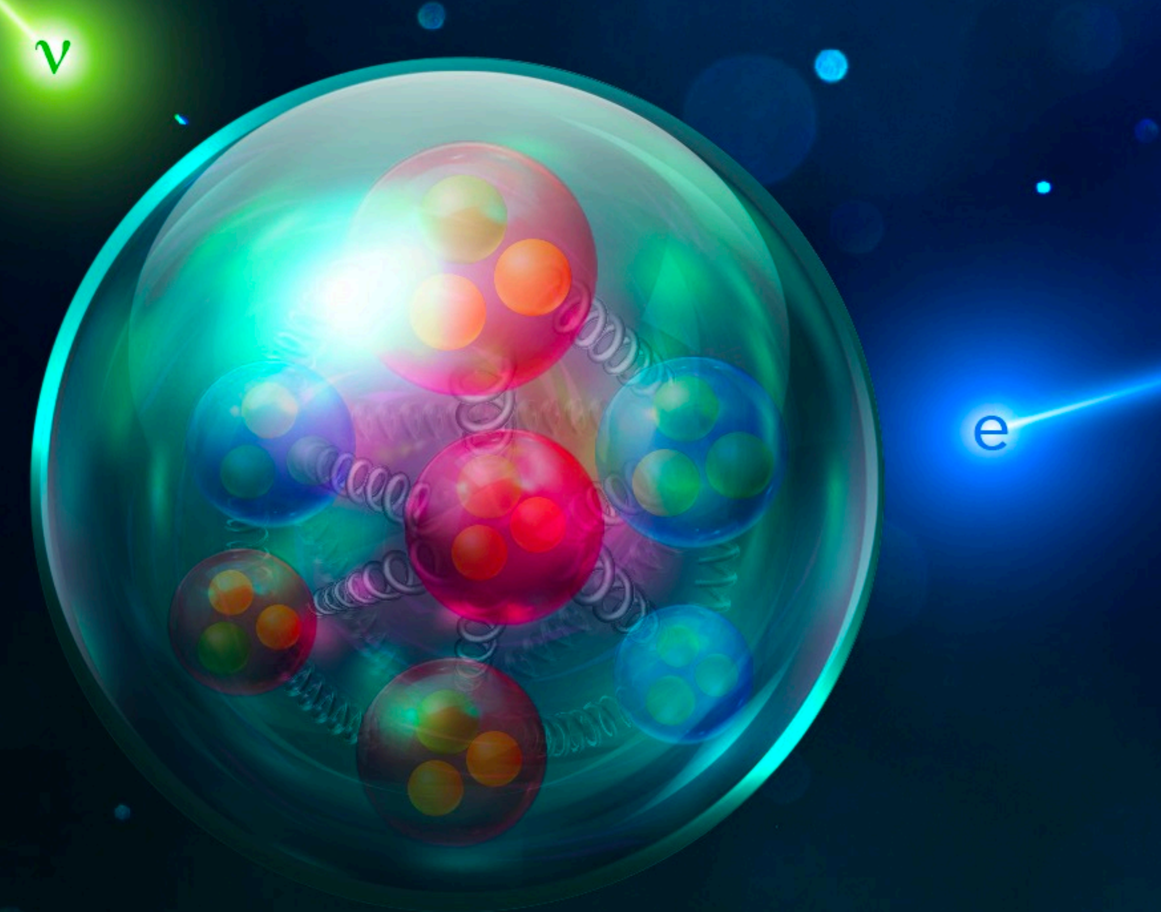
Summary

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

This can limit physics extraction

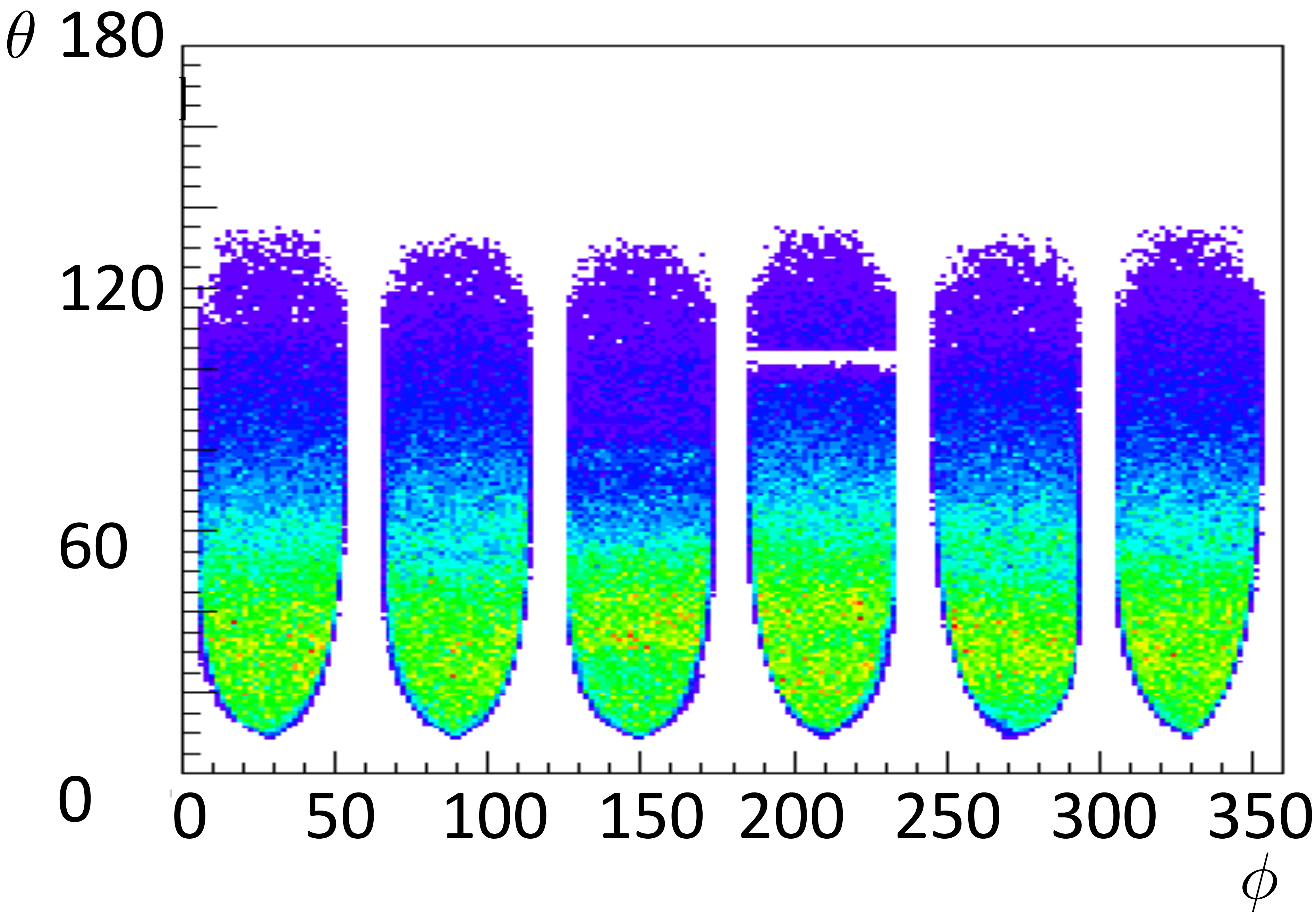
Electron scattering data ~~will help~~ is helping

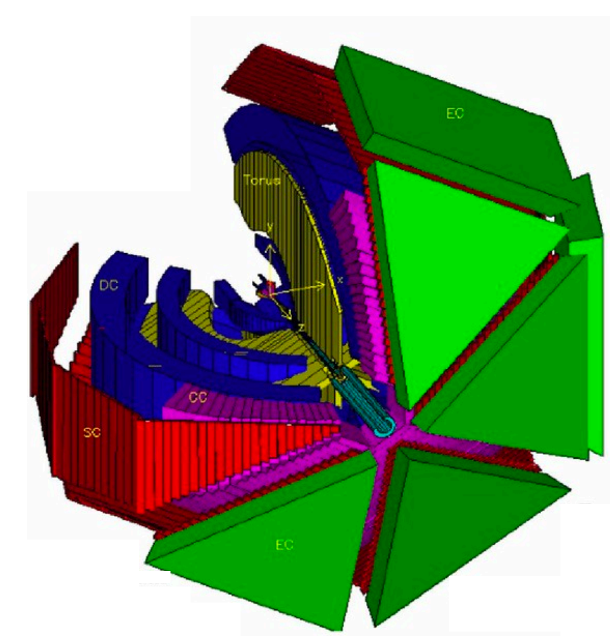
Thank you for your attention

Background Subtraction

Different interaction lead to multi-hadron final states

Gaps can make them loop like QE-like events with outgoing 1μ1p





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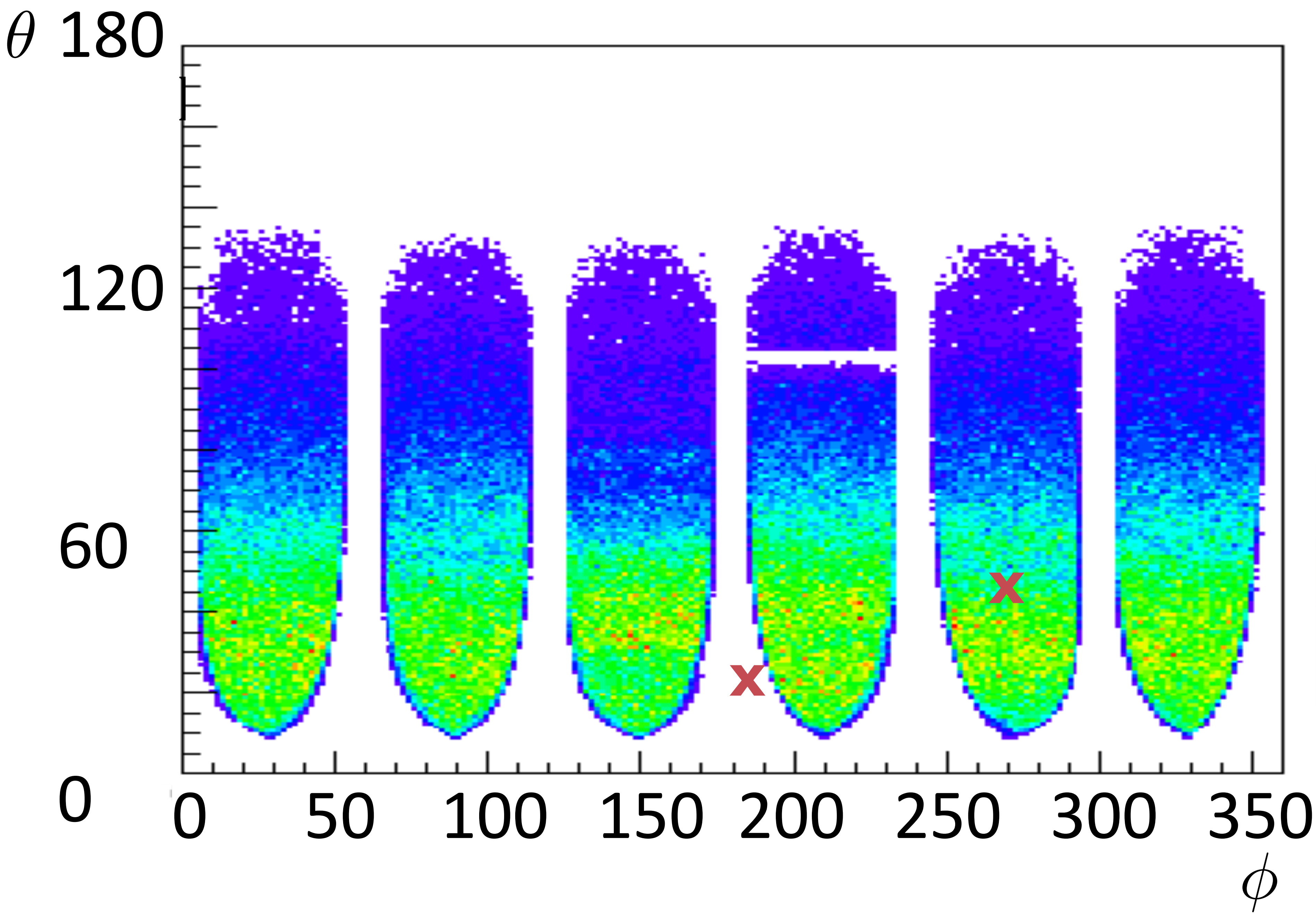
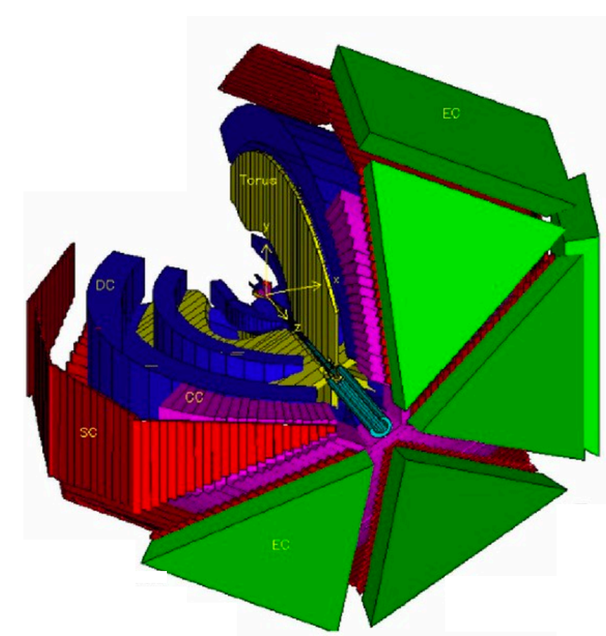
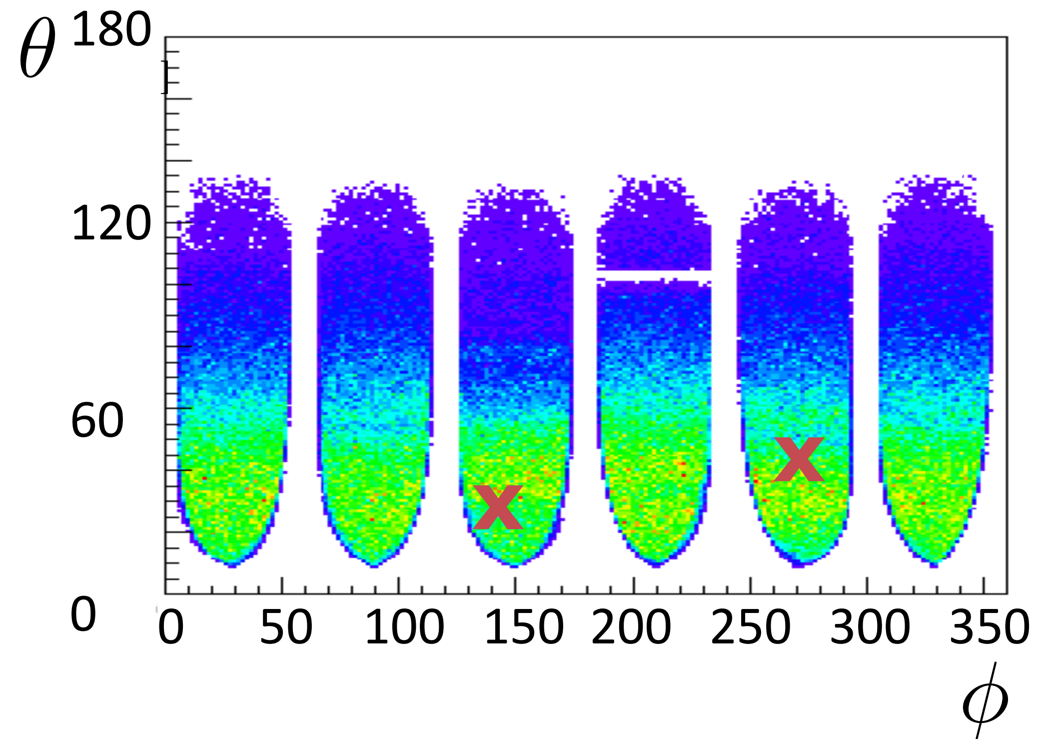
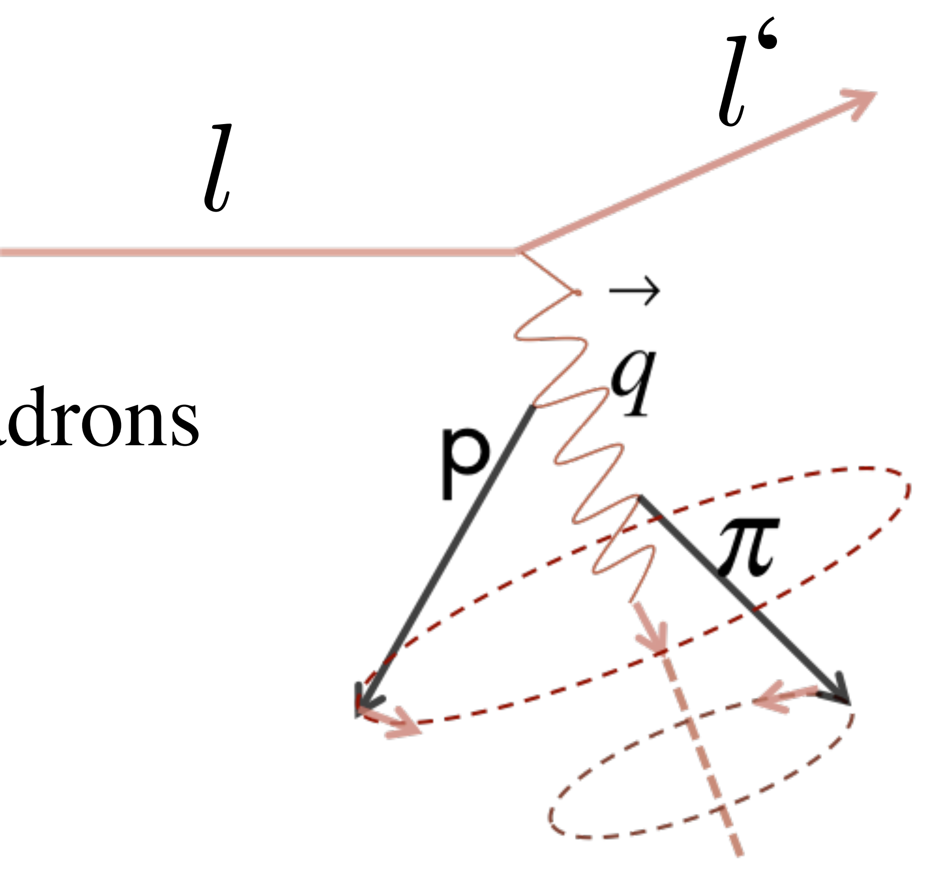




Data Driven Background Subtraction

- Using measured (e,e'pπ) events
- Rotate p,π around **q**
- Determine event acceptance
- Subtract (e,e'pπ) contribution

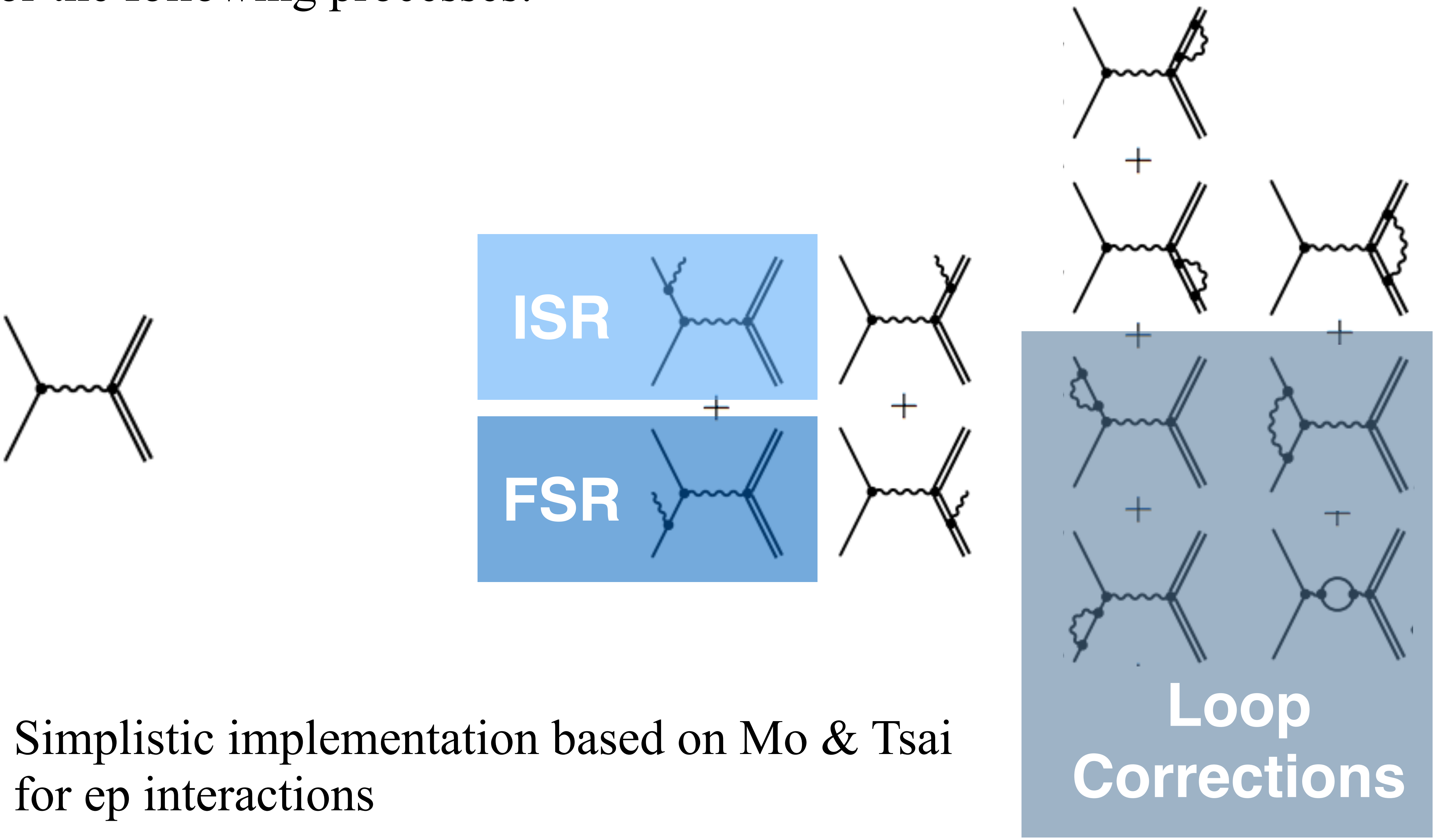




- Same for final states with more than 2 hadrons

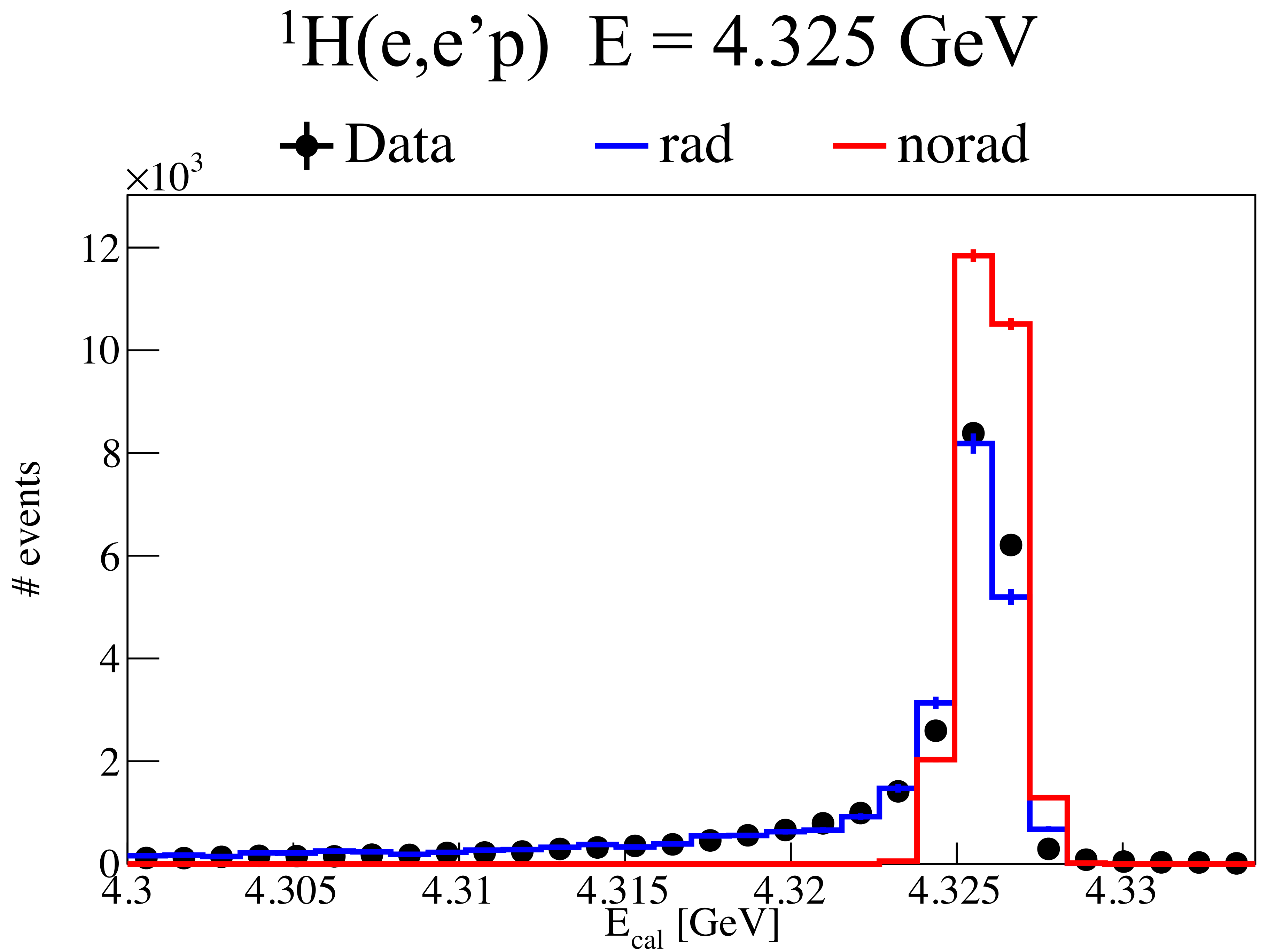
Radiative effects

A first implementation of the radiative corrections to GENIE to account for the following processes:



Simplistic implementation based on Mo & Tsai for ep interactions

Adding radiative effects to GENIE



[Mo and Tsai]

Genie v3.0.6 tune GTEST19