Neutrino-nucleus interactions and connections to BSM’

Pedro Machado

January, 2022

Neutrino-nucleus interactions and connections to BSM’

Pedro Machado

January, 2022

Outline

We have been talking about the current status of and how to improve our modeling of neutrino-nucleus interactions

In this talk, I would like to take a step back and ask

What physics do we want to do at neutrino experiments?

And what do we need to do this physics?

Fermilab
pmachado@fnal.gov

Outline

We have been talking about the current status of and how to improve our modeling of neutrino-nucleus interactions

In this talk, I would like to take a step back and ask

What physics do we want to do at neutrino experiments?

And what do we need to do this physics?

“Bottom-up” approach: I will present several physics studies and the crucial aspect of neutrino-nucleus interactions that will enable these studies

Hopefully this will motivate further work on specific aspects of neutrino-nucleus interactions

Fermilab
pmachado@fnal.gov

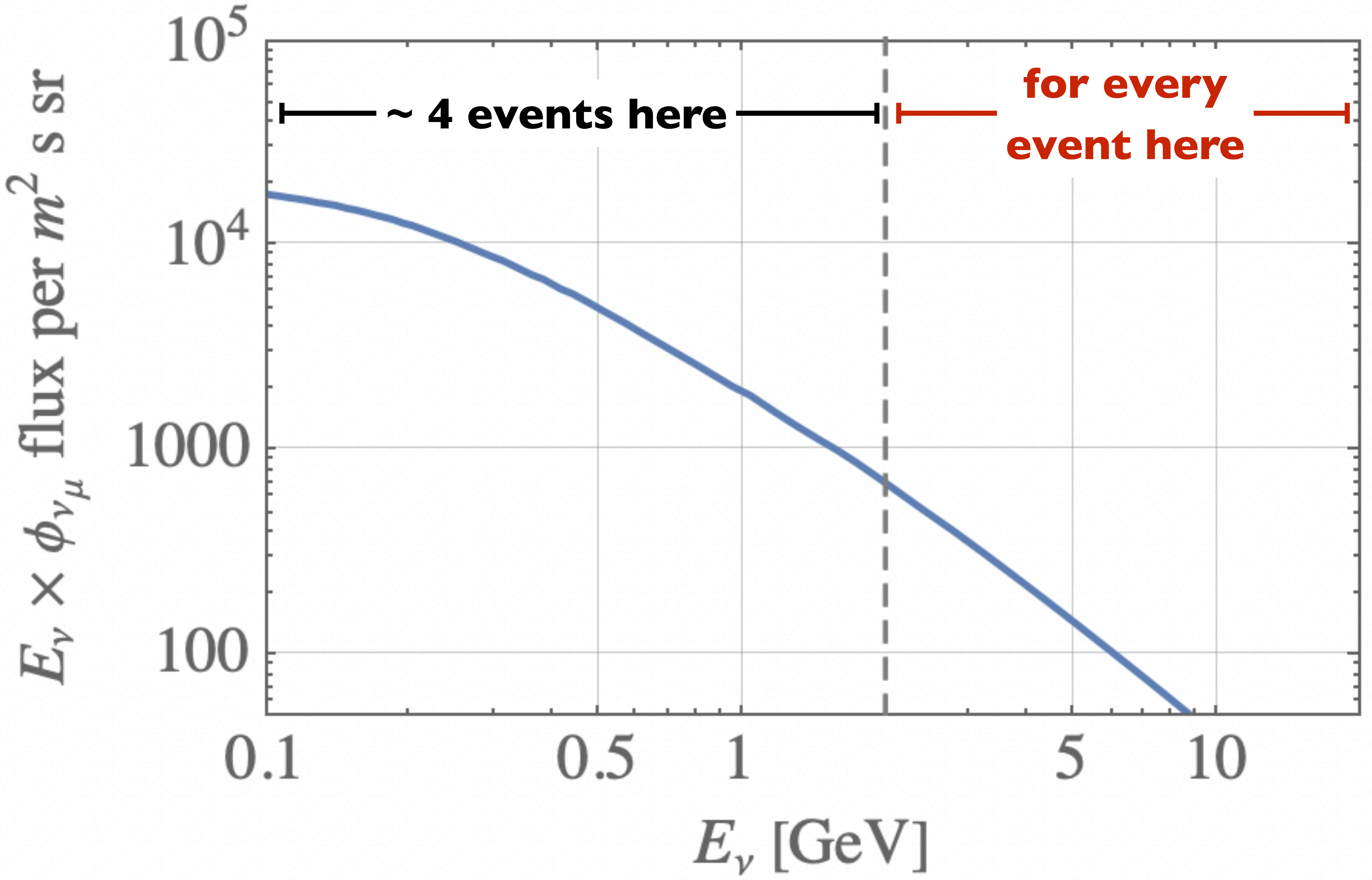
Exclusive cross sections

Why do we care about final state hadrons

pmachado@fnal.gov

Sub-GeV atmospheric neutrinos

Kelly, PM et al Phys.Rev.Lett. 123 (2019) 8, 081801

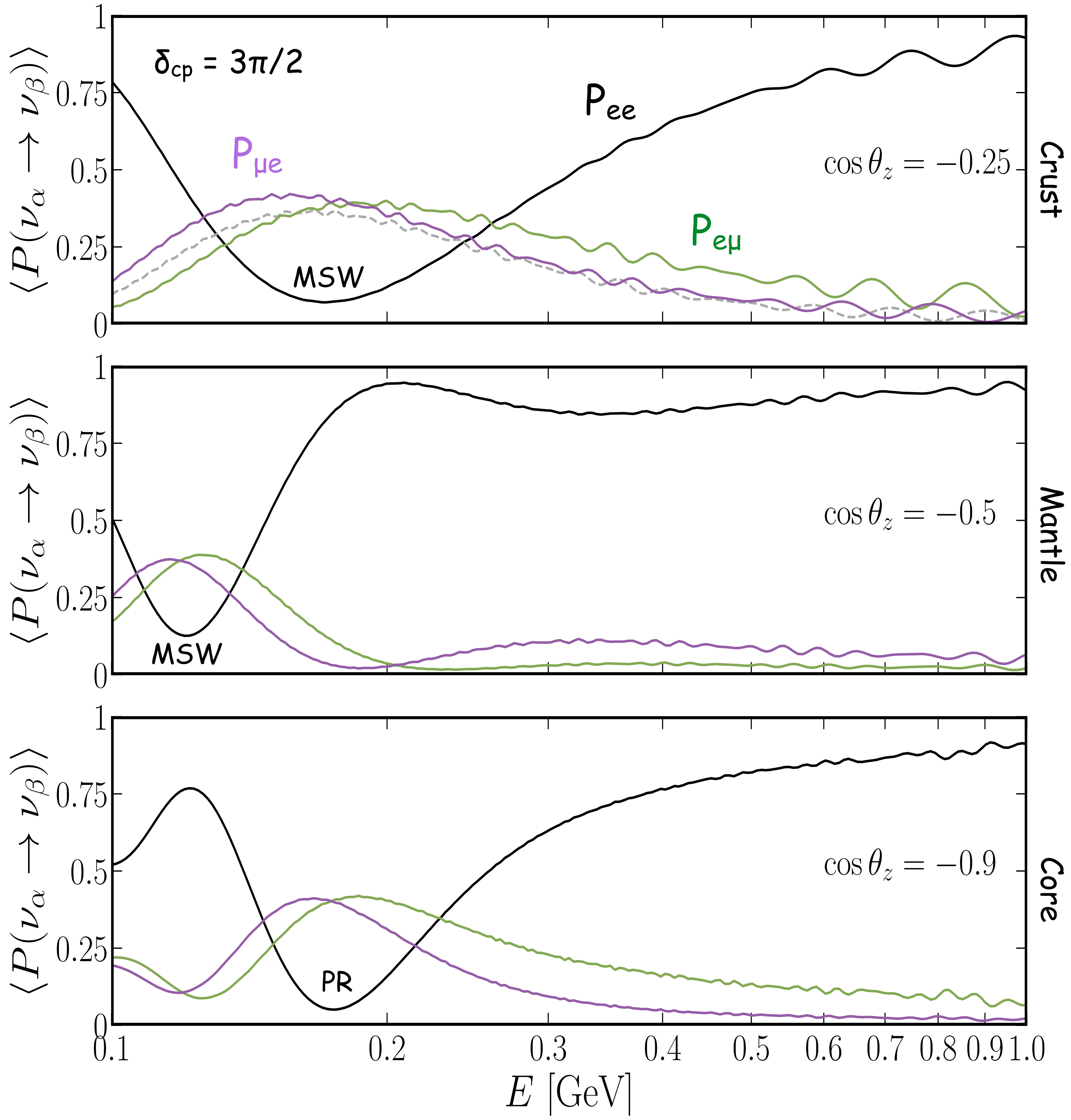


Fermilab
pmachado@fnal.gov

Sub-GeV atmospheric neutrinos

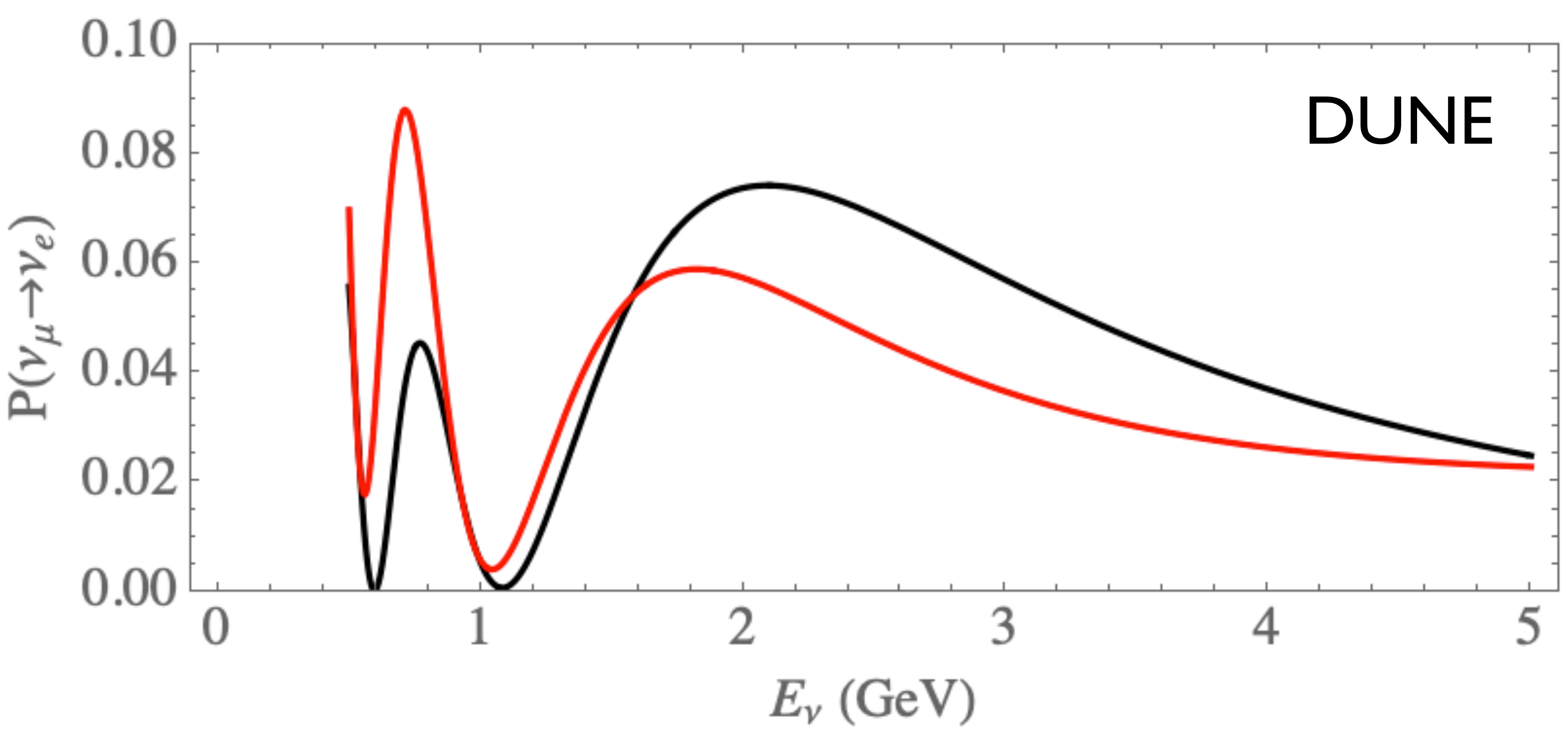
Kelly, PM et al Phys.Rev.Lett. 123 (2019) 8, 081801

Sub-GeV atmospheric neutrinos are one of the richest neutrino samples we have access to.

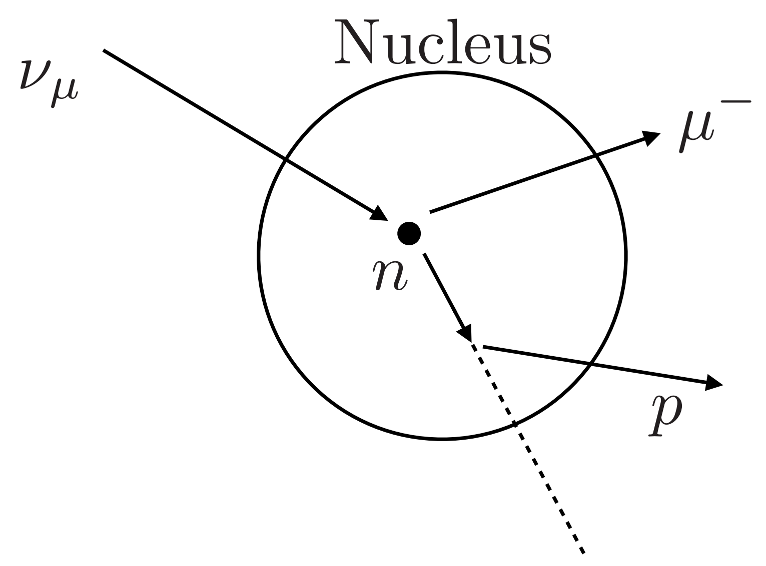


CPV in sub-GeV atmospherics is about 10x larger than in beam neutrinos:

$$P_{CP} = -8J_r \sin\delta_{CP} \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32}$$



But sub-GeV atmospherics are very difficult…



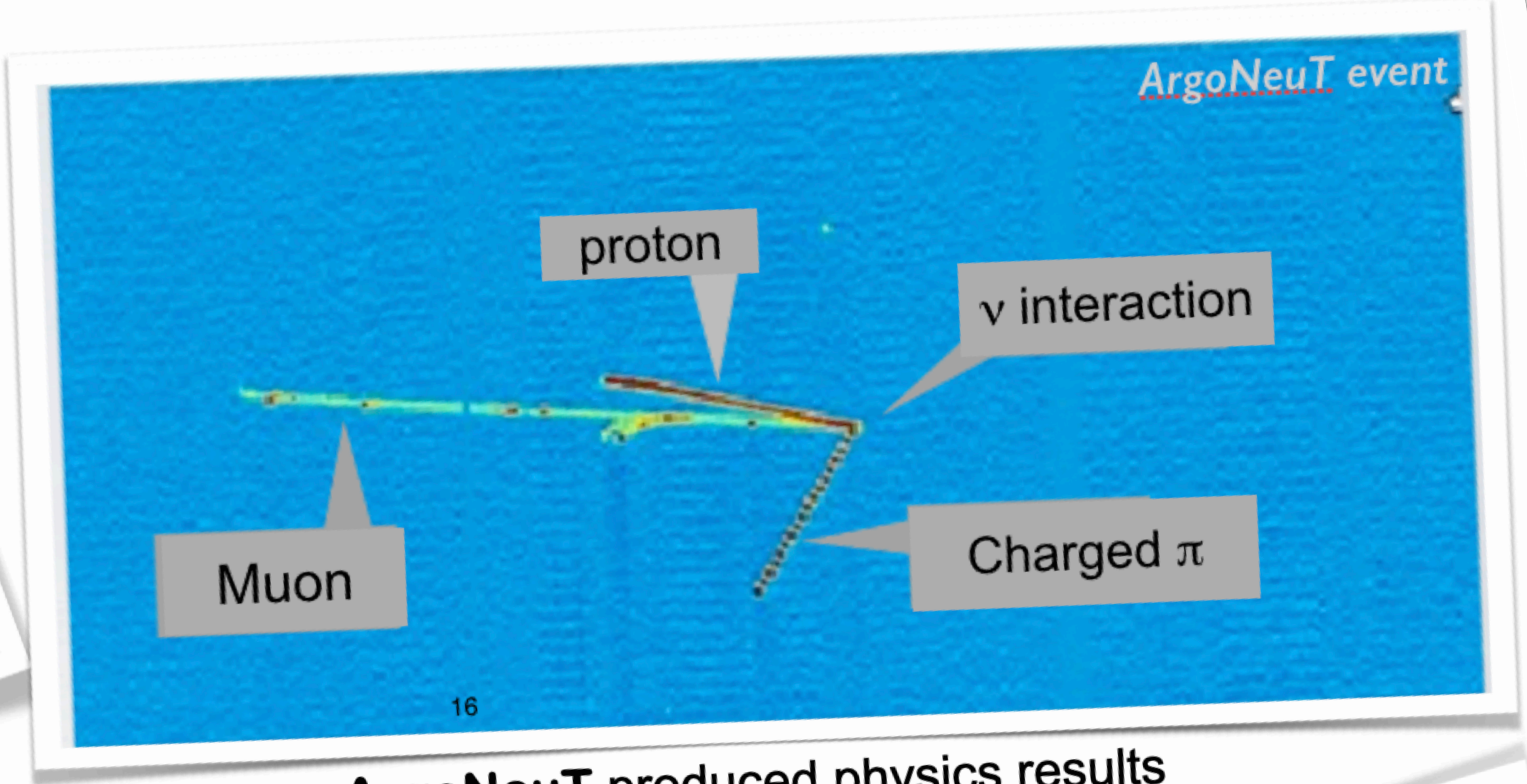
Needs to know neutrino direction

Low E protons are invisible @ Cherenkov detectors

Liquid Argon TPCs can do it!

pmachado@fnal.gov

Why Liquid Argon Time Projection Chamber?



ArgoNeuT produced physics results with a "table-top" size experiment [240 Kg LArTPC]

LAr TPC: Bubble chamber quality of data with added calorimetry

…or LArTPC is "a "colored" bubble chamber" (theorist simplified view!)

Fermilab

slide stolen from O. Palamara

Fermilab
pmachado@fnal.gov

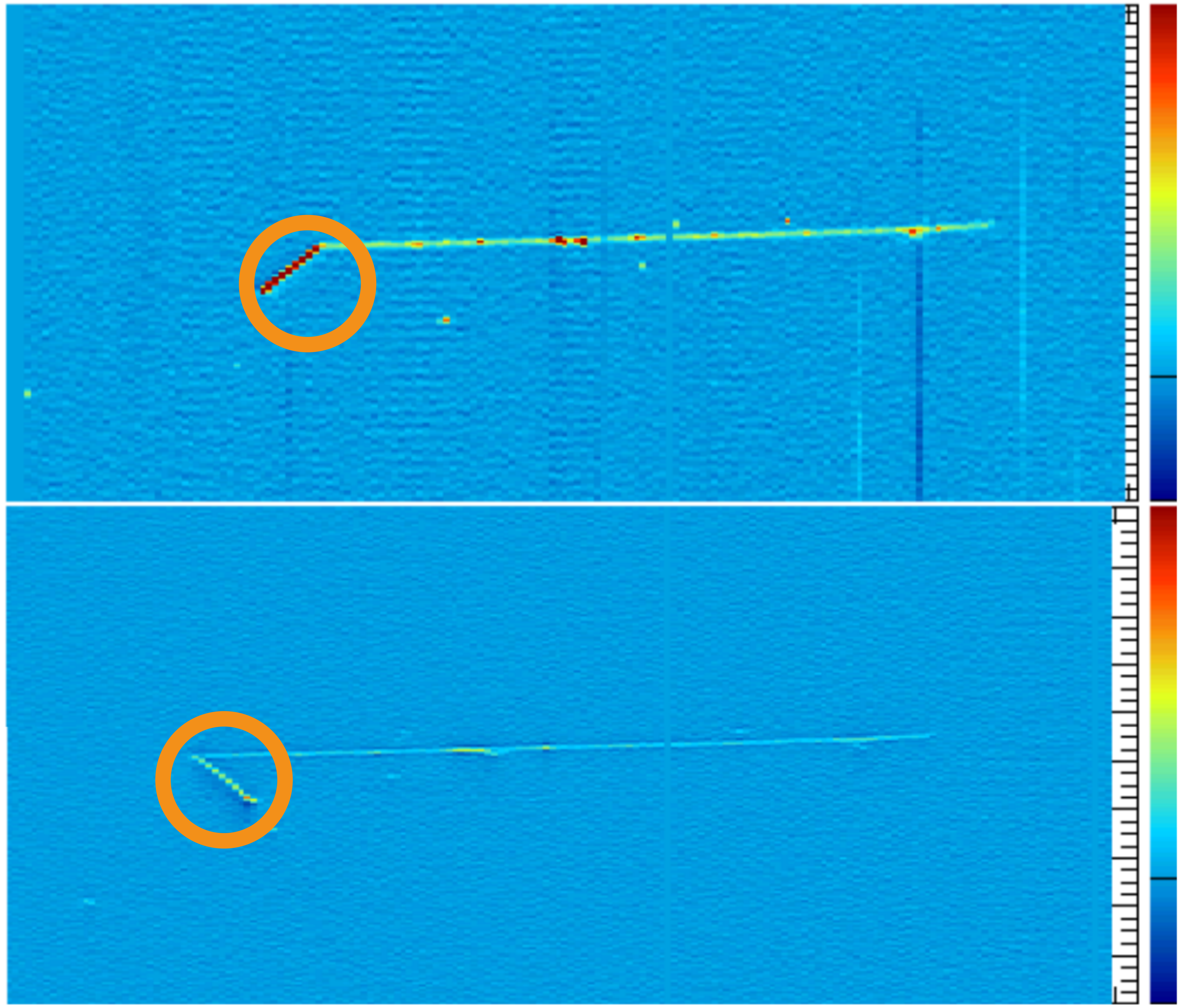
Can we really reconstruct the low energy protons?

What else do we learn from them?

Sub-GeV atmospheric neutrinos

ArgoNeuT demonstrated the LAr capability to detect 21 MeV recoil protons.

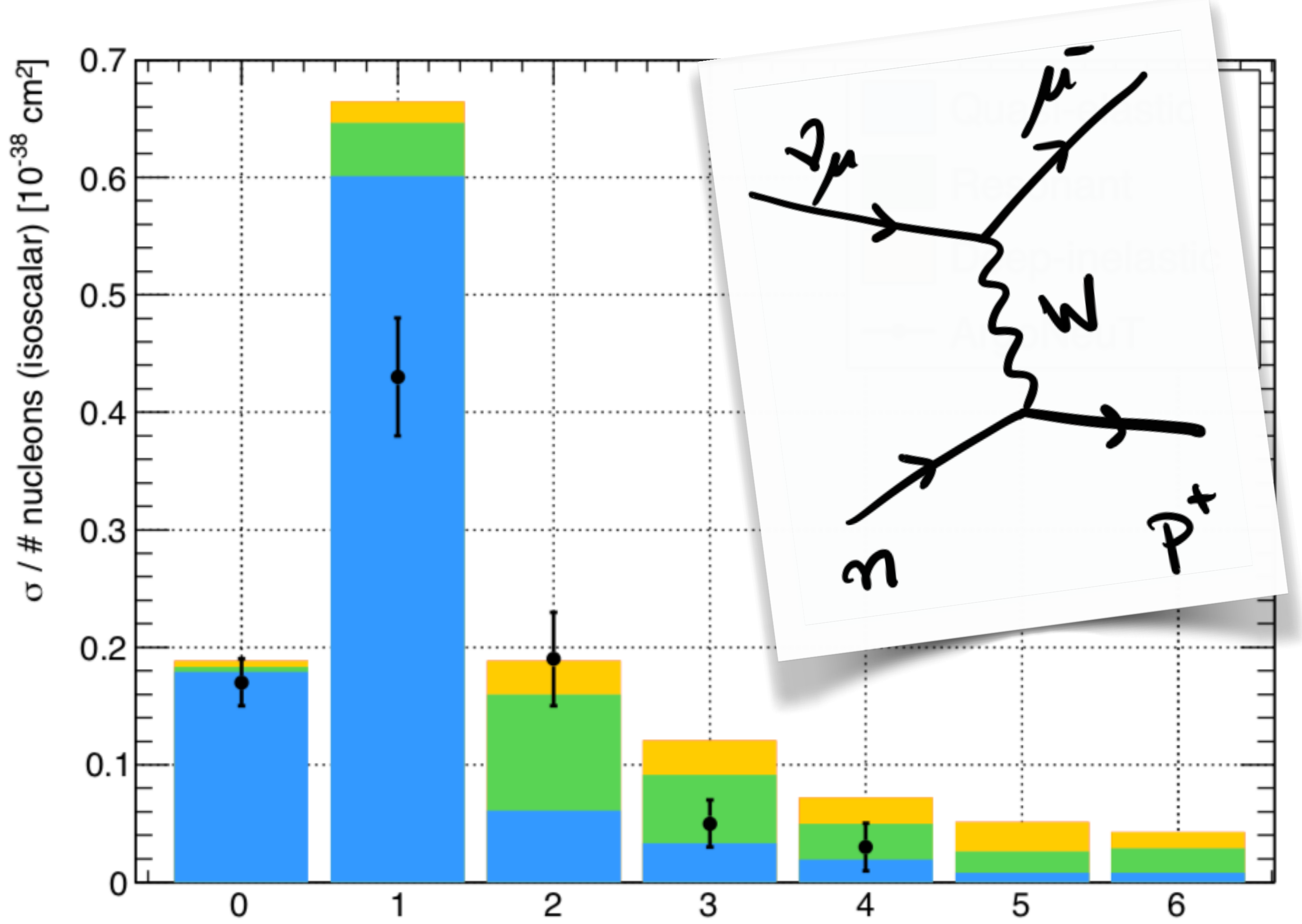
ArgoNeuT 1810.06502



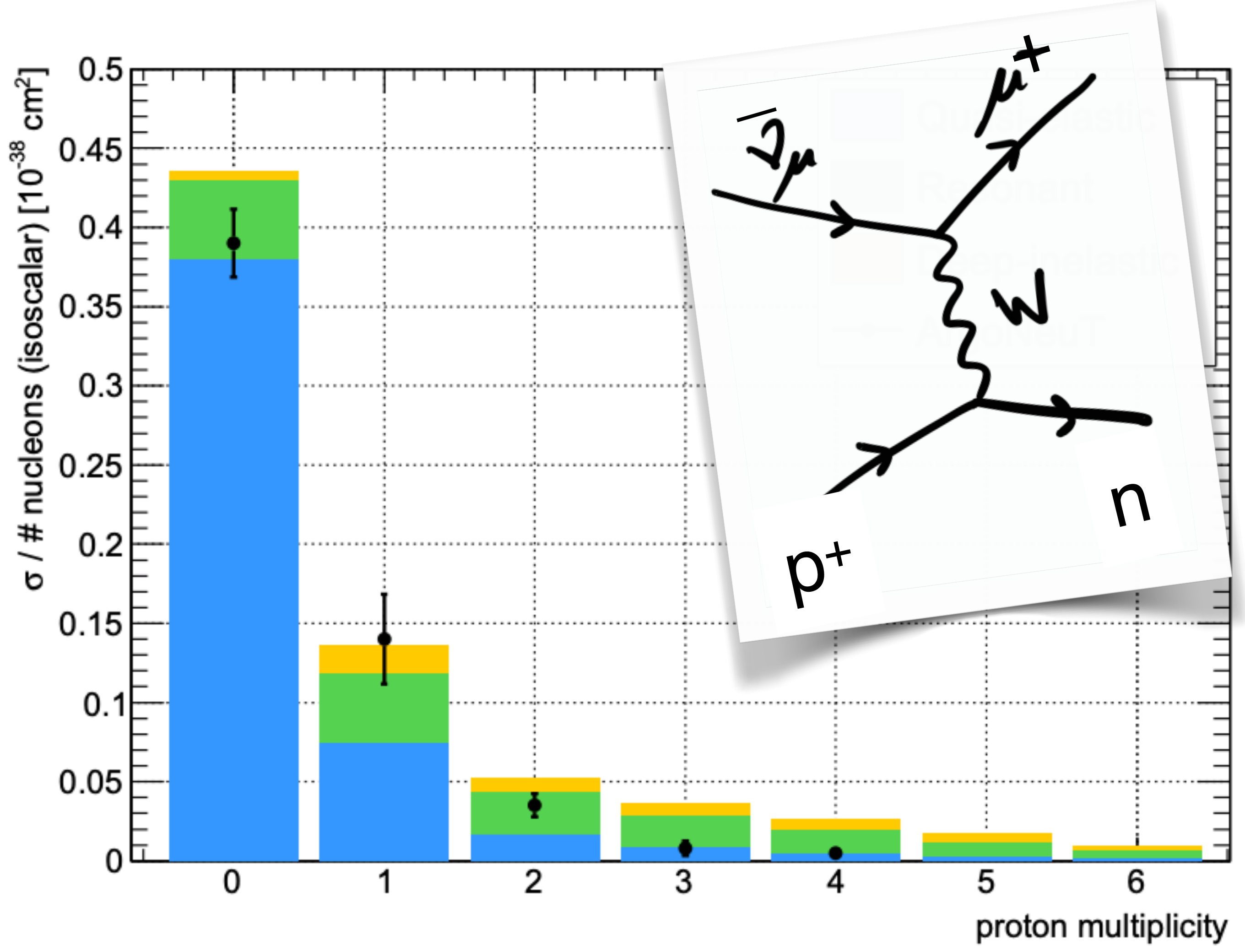
Reconstruct, identify and point.

For comparison, SK can only see protons that emit Cherenkov light, that is, protons with energy above ~ 1.4 GeV

Event topology carries information



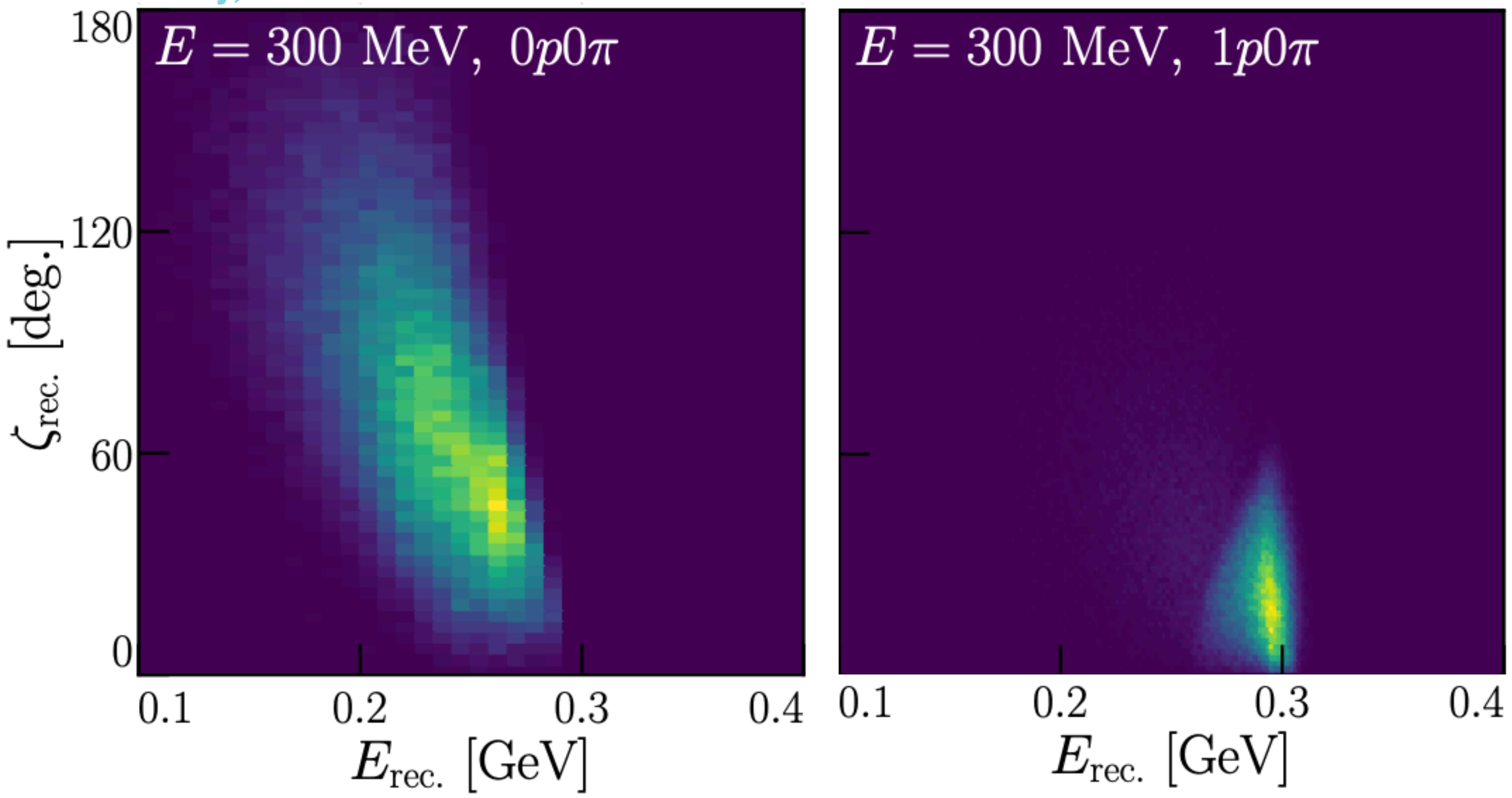
Palamara JPS **12** 010017 (2016)



Fermilab
pmachado@fnal.gov

Sub-GeV atmospheric neutrinos

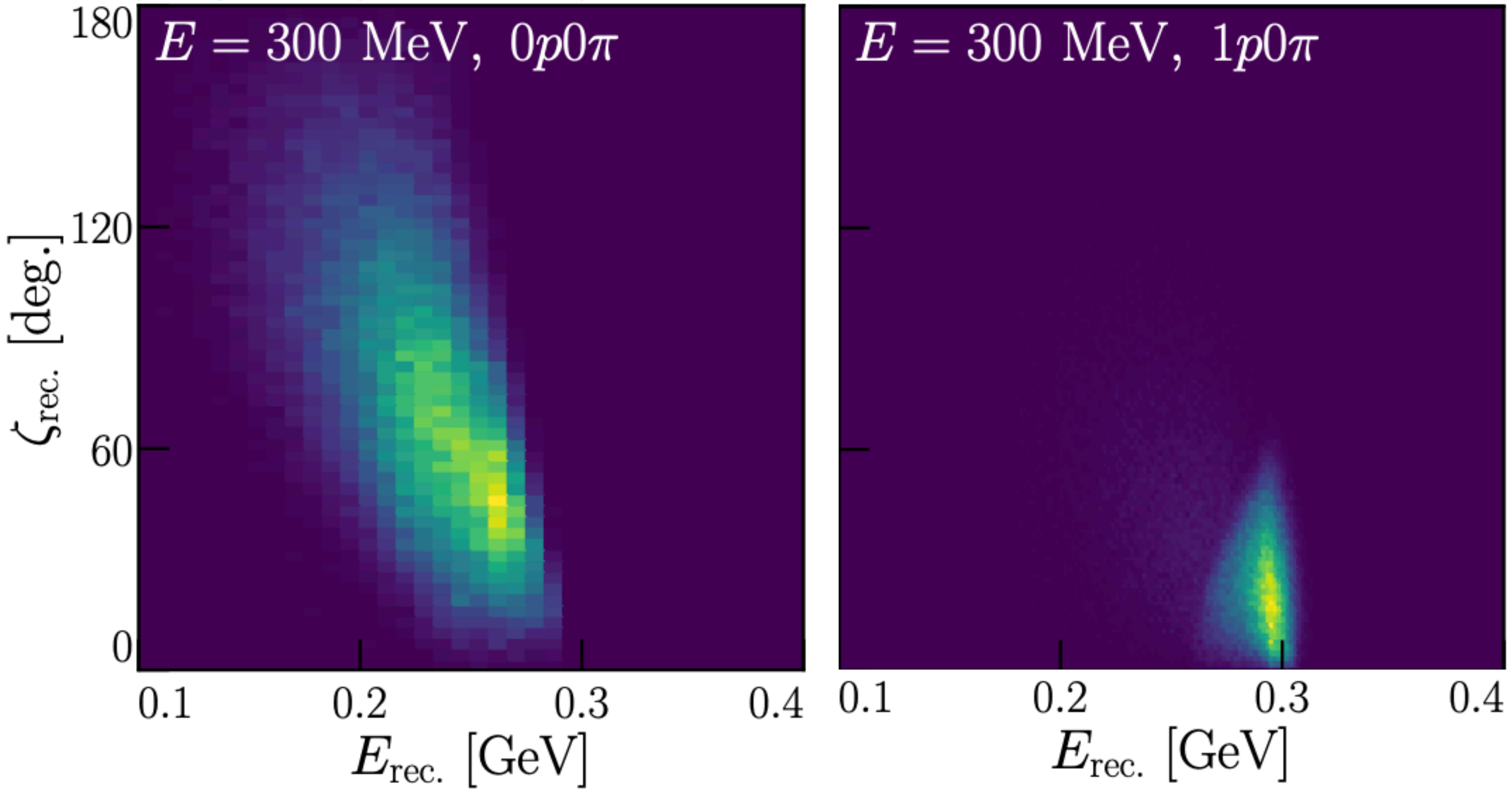
Kelly, PM et al 2110.00003

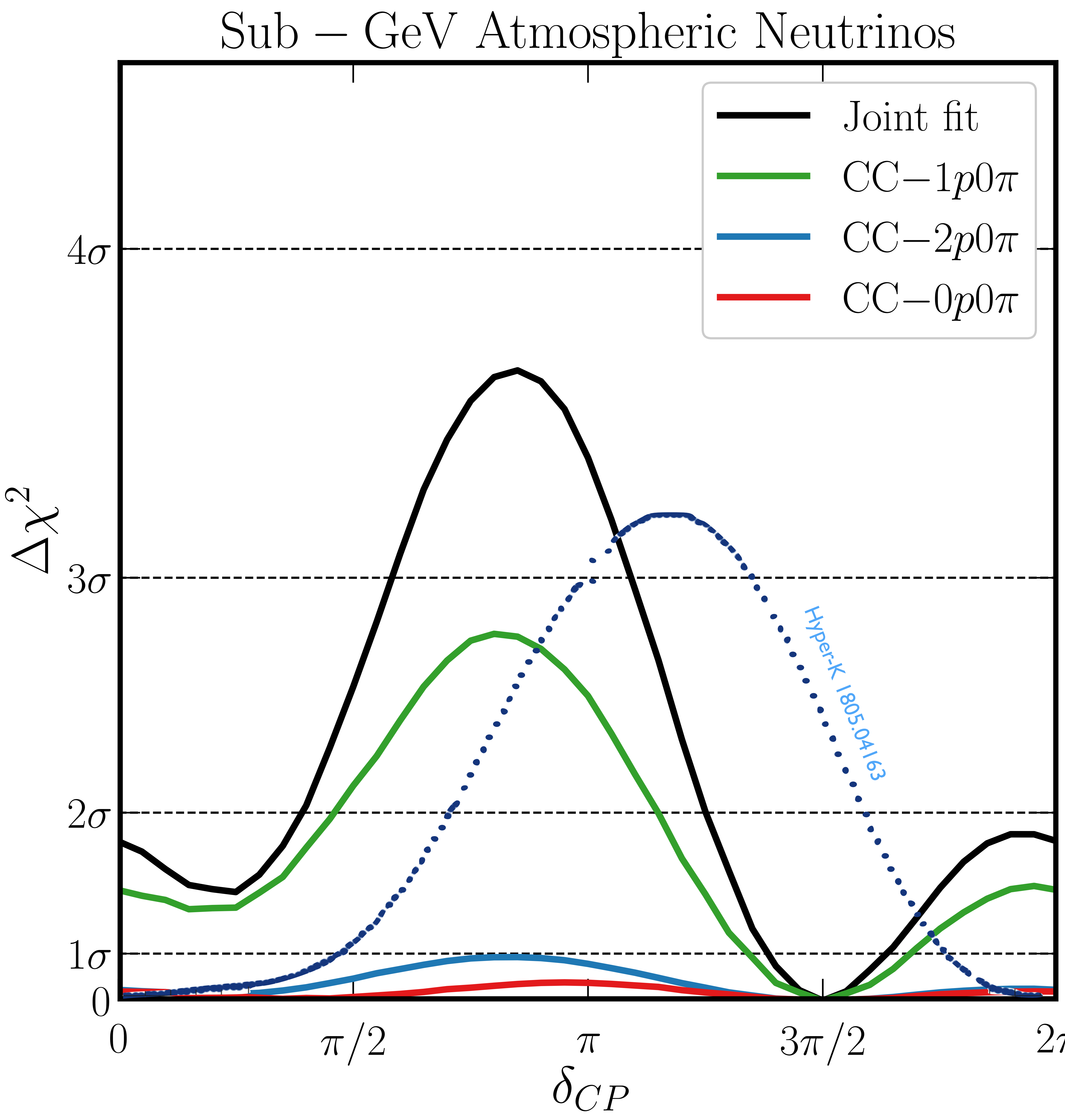


pmachado@fnal.gov

Sub-GeV atmospheric neutrinos

Kelly, PM et al 2110.00003





Kelly, PM et al Phys.Rev.Lett. 123 (2019) 8, 081801

Details:

Simulate neutrino-argon interactions with event generators

Use realistic atmospheric fluxes (Honda et al 1502.03916)

Account for uncertainties of atmospheric neutrino fluxes $\Phi_\alpha(E) = \Phi_{\alpha,0}\, f_\alpha(E) \left(\frac{E}{E_0}\right)^\gamma$

40% normalization, 5% e/μ ratio, 2% nu/nubar ratio, ± 0.2 spectral distortion coefficient

Realistic LArTPC capabilities

Δp = 5%, 5%, 10%, Δθ = 5°, 5°, 10°, for e, μ, p, K_p = 30 MeV

Classify events by final state topology (number of protons)

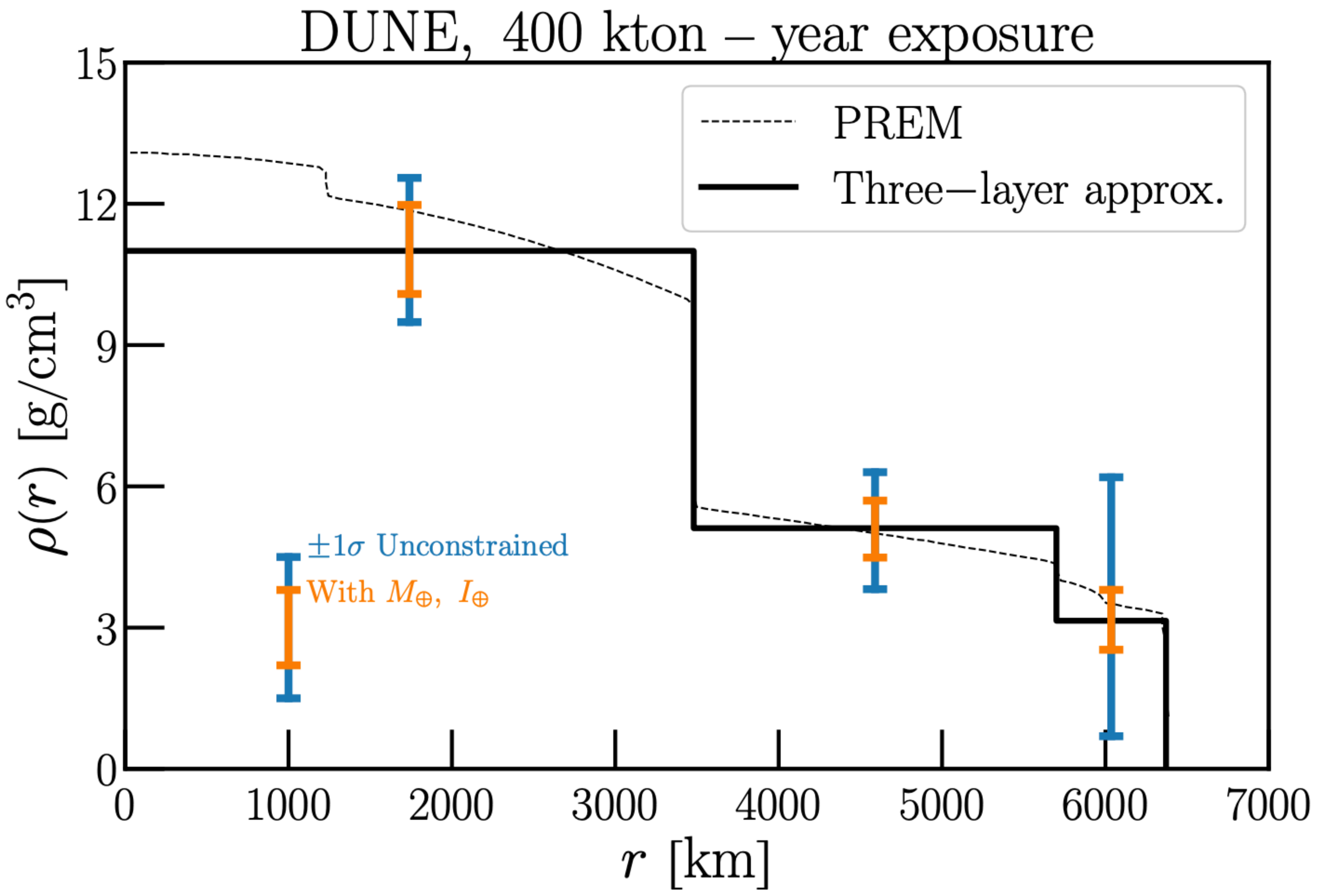
pmachado@fnal.gov

Fermilab

Sub-GeV atmospheric neutrinos

BONUS: Earth tomography

Kelly, PM et al 2110.00003



$$\rho_C = 11.0 \times (1^{+0.088}_{-0.083})\ \mathrm{g/cm^3}$$
core

$$\rho_{LM} = 5.11 \times (1^{+0.12}_{-0.13})\ \mathrm{g/cm^3}$$
lower mantle

$$\rho_{UM} = 3.15 \times (1^{+0.22}_{-0.20})\ \mathrm{g/cm^3}$$
upper mantle

pmachado@fnal.gov

Another example: the low energy excess

Search for Neutrino-Induced Neutral Current Δ Radiative Decay in MicroBooNE and a First Test of the MiniBooNE Low Energy Excess Under a Single-Photon Hypothesis

(The MicroBooNE Collaboration)*

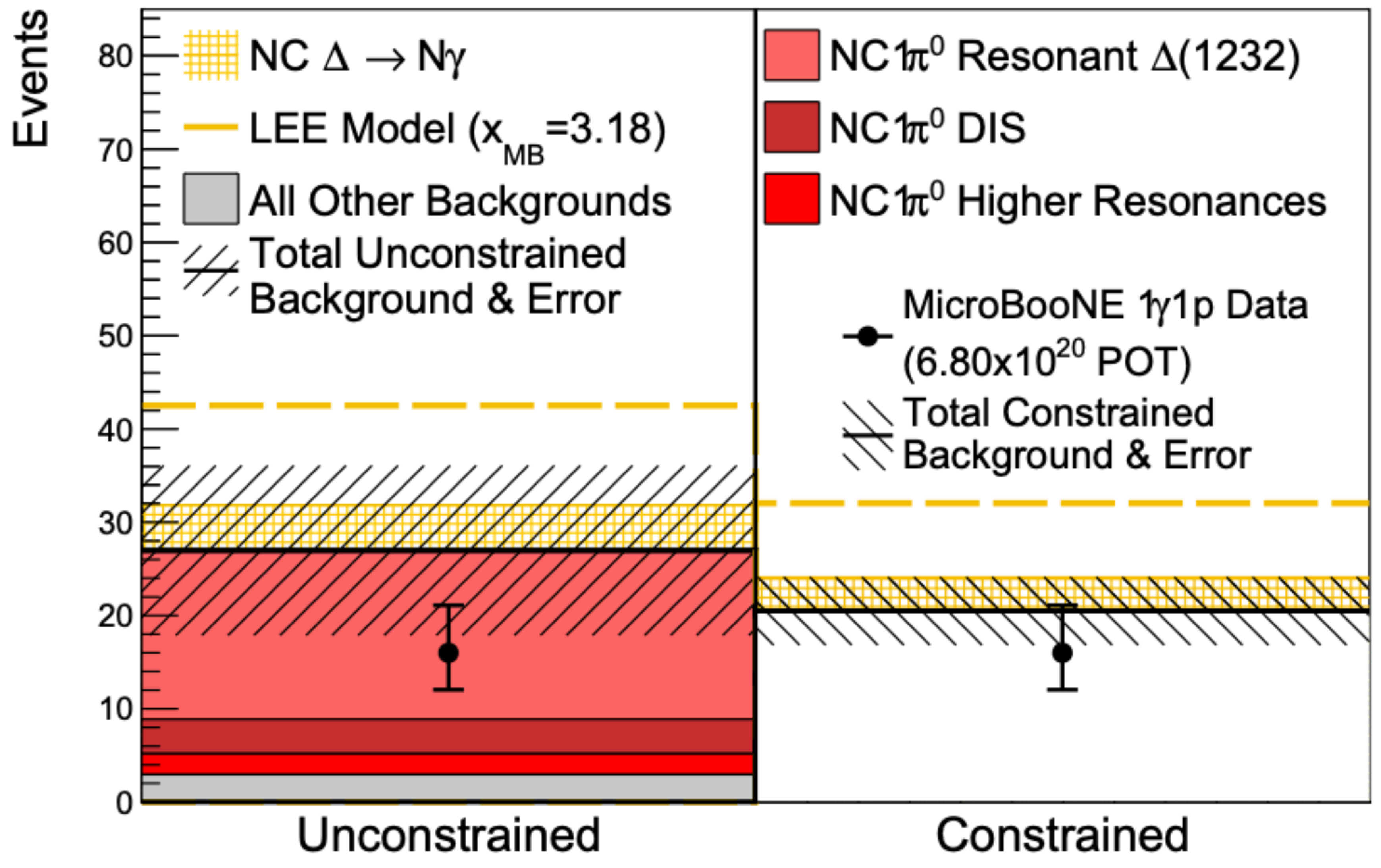
arXiv:2110.00409v1 [hep-ex] 1 Oct 2021

pmachado@fnal.gov

Another example: the low energy excess

Search for Neutrino-Induced Neutral Current Δ Radiative Decay in MicroBooNE and a First Test of the MiniBooNE Low Energy Excess Under a Single-Photon Hypothesis

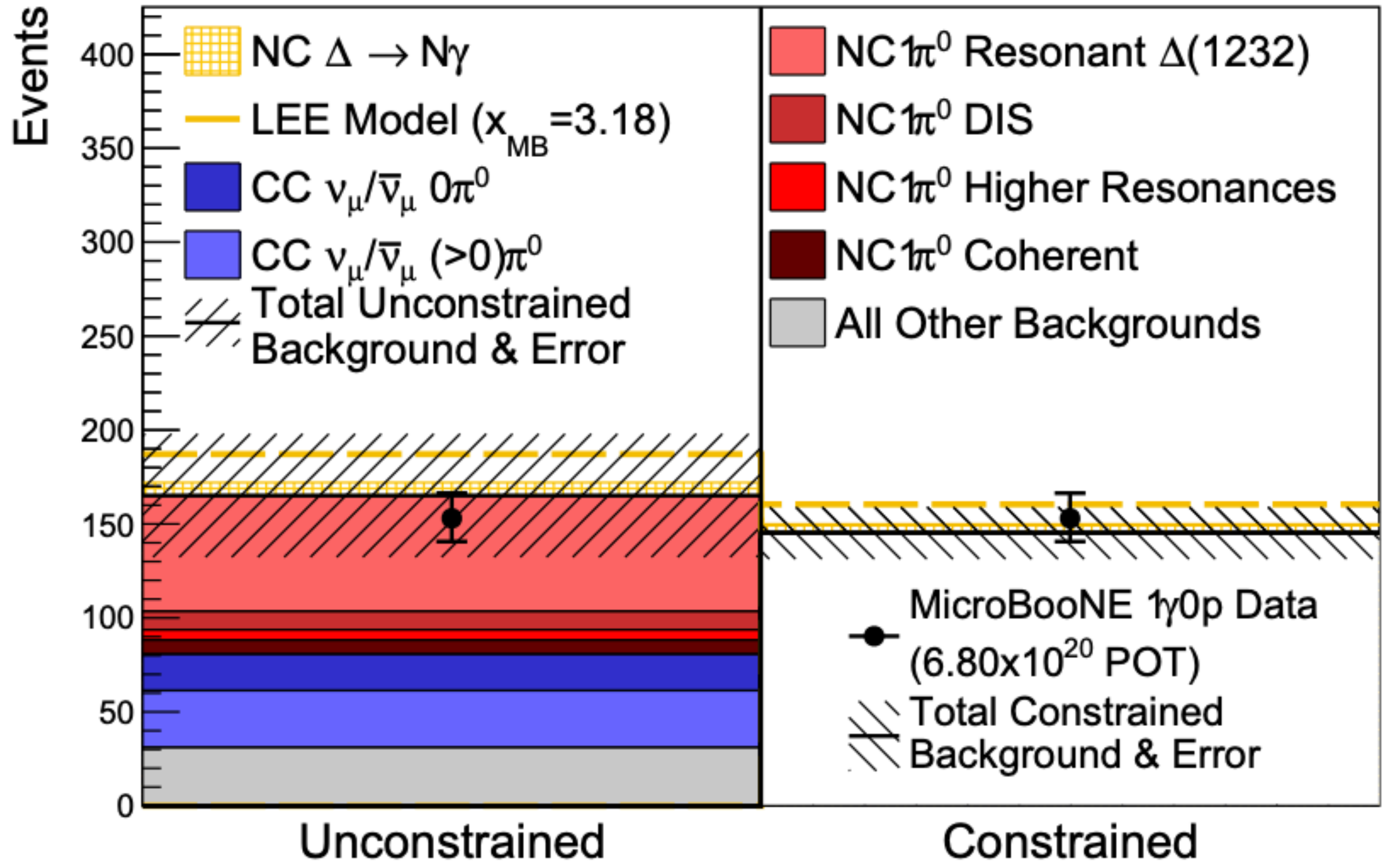
(The MicroBooNE Collaboration)*



(a)

	$1\gamma 1p$	$1\gamma 0p$
Unconstr. bkgd.	27.0 ± 8.1	165.4 ± 31.7
Constr. bkgd.	20.5 ± 3.6	145.1 ± 13.8
NC $\Delta \rightarrow N\gamma$	4.88	6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	15.5	20.1
Data	16	153

Why do you think 1γ0p so worse than 1γ1p??

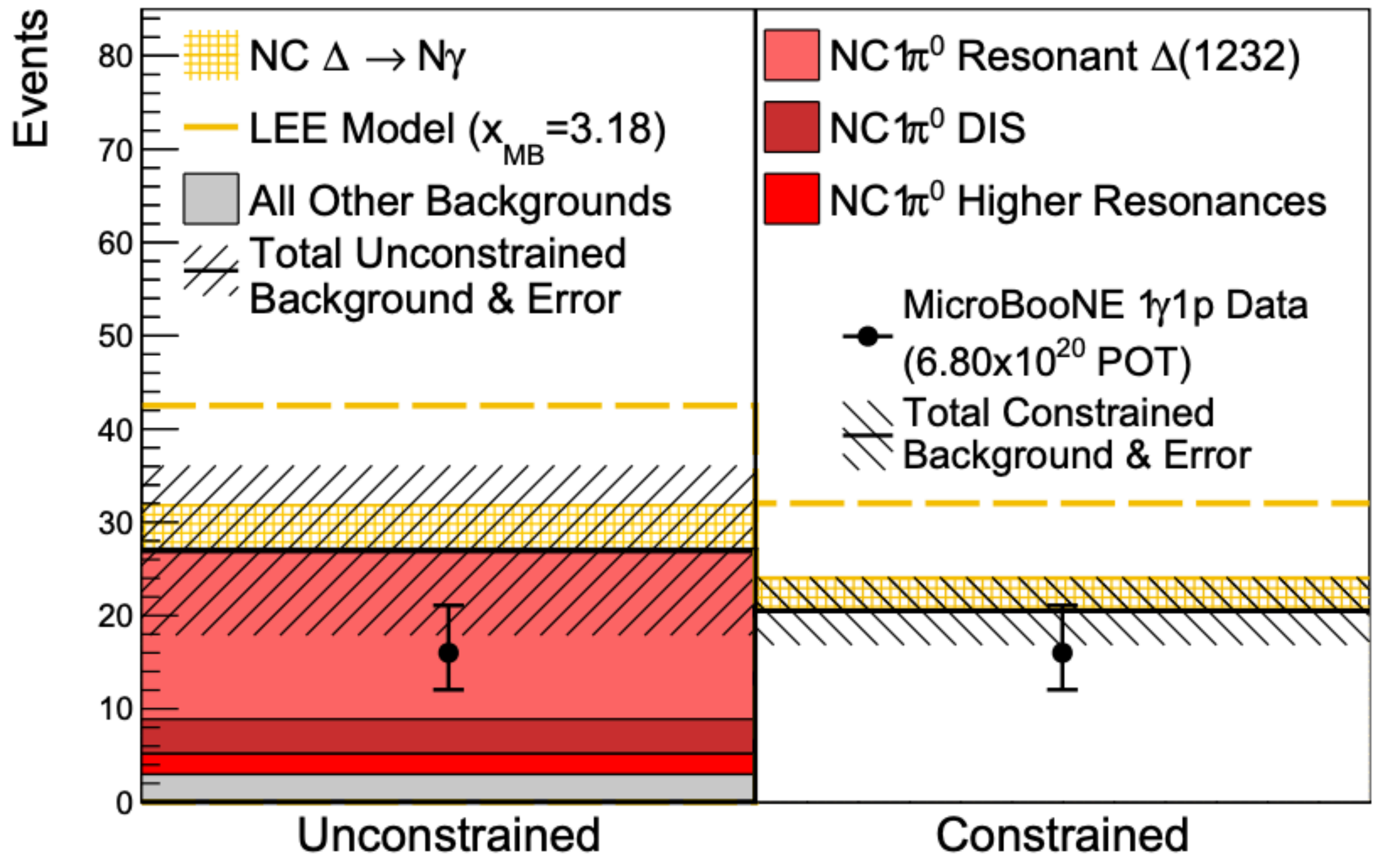


Another example: the low energy excess

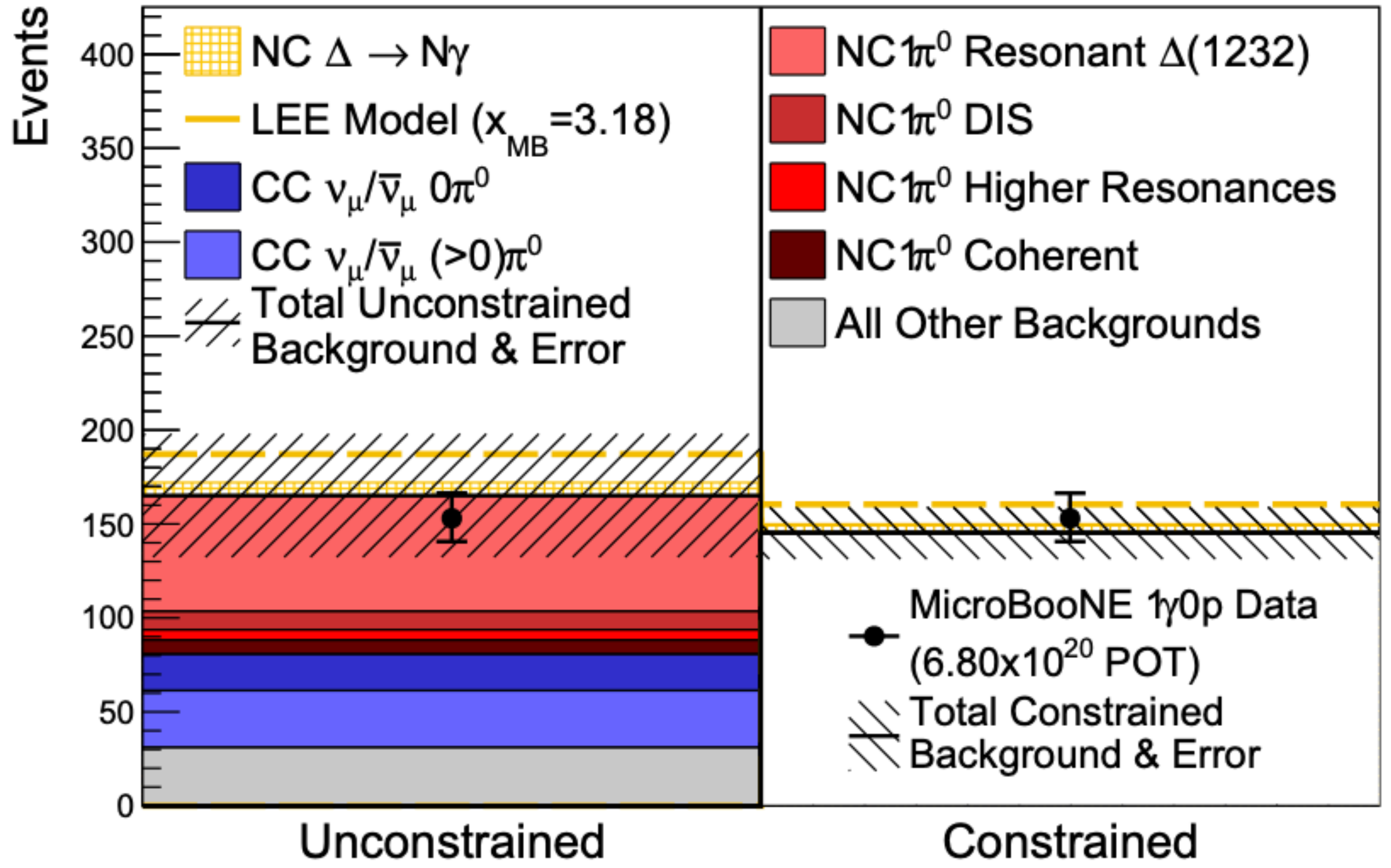
Search for Neutrino-Induced Neutral Current Δ Radiative Decay in MicroBooNE and a First Test of the MiniBooNE Low Energy Excess Under a Single-Photon Hypothesis

(The MicroBooNE Collaboration)*

arXiv:2110.00409v1 [hep-ex] 1 Oct 2021

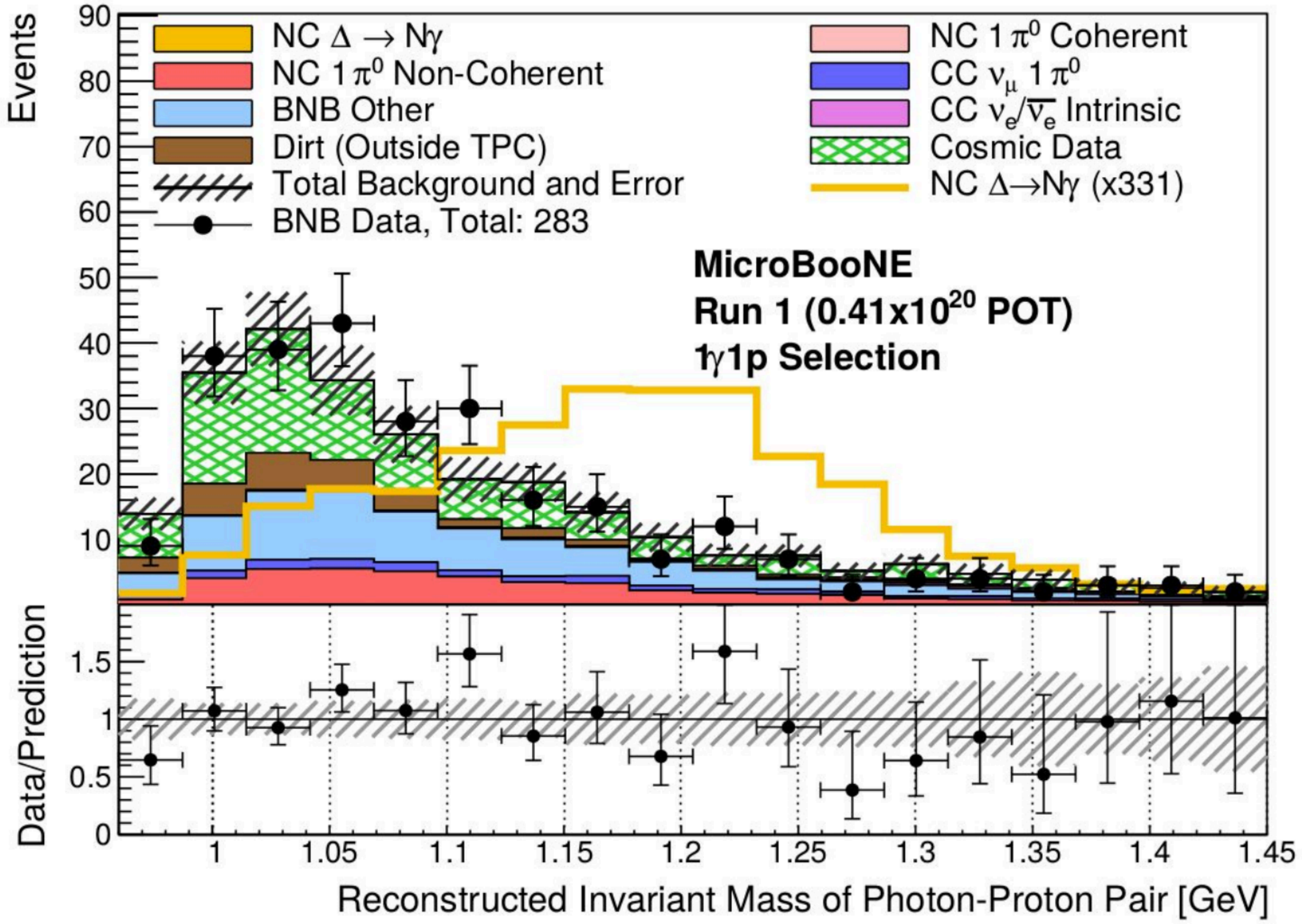


(a)



	$1\gamma 1p$	$1\gamma 0p$
Unconstr. bkgd.	27.0 ± 8.1	165.4 ± 31.7
Constr. bkgd.	20.5 ± 3.6	145.1 ± 13.8
NC $\Delta \to N\gamma$	4.88	6.55
LEE ($x_{\rm MB} = 3.18$)	15.5	20.1
Data	16	153

Why do you think 1γ0p so worse than 1γ1p??



Exclusive cross sections: Why do we care about final state hadrons

Number of protons = nontrivial information (e.g. nu vs antinu)

Background suppression may also depend on number of outgoing protons

We need to properly predict number, energy and direction of outgoing protons

FSIs play an essential role here, initial state of the nucleus is also relevant

pmachado@fnal.gov

Theory Uncertainties

Why do we need to properly estimate them

pmachado@fnal.gov

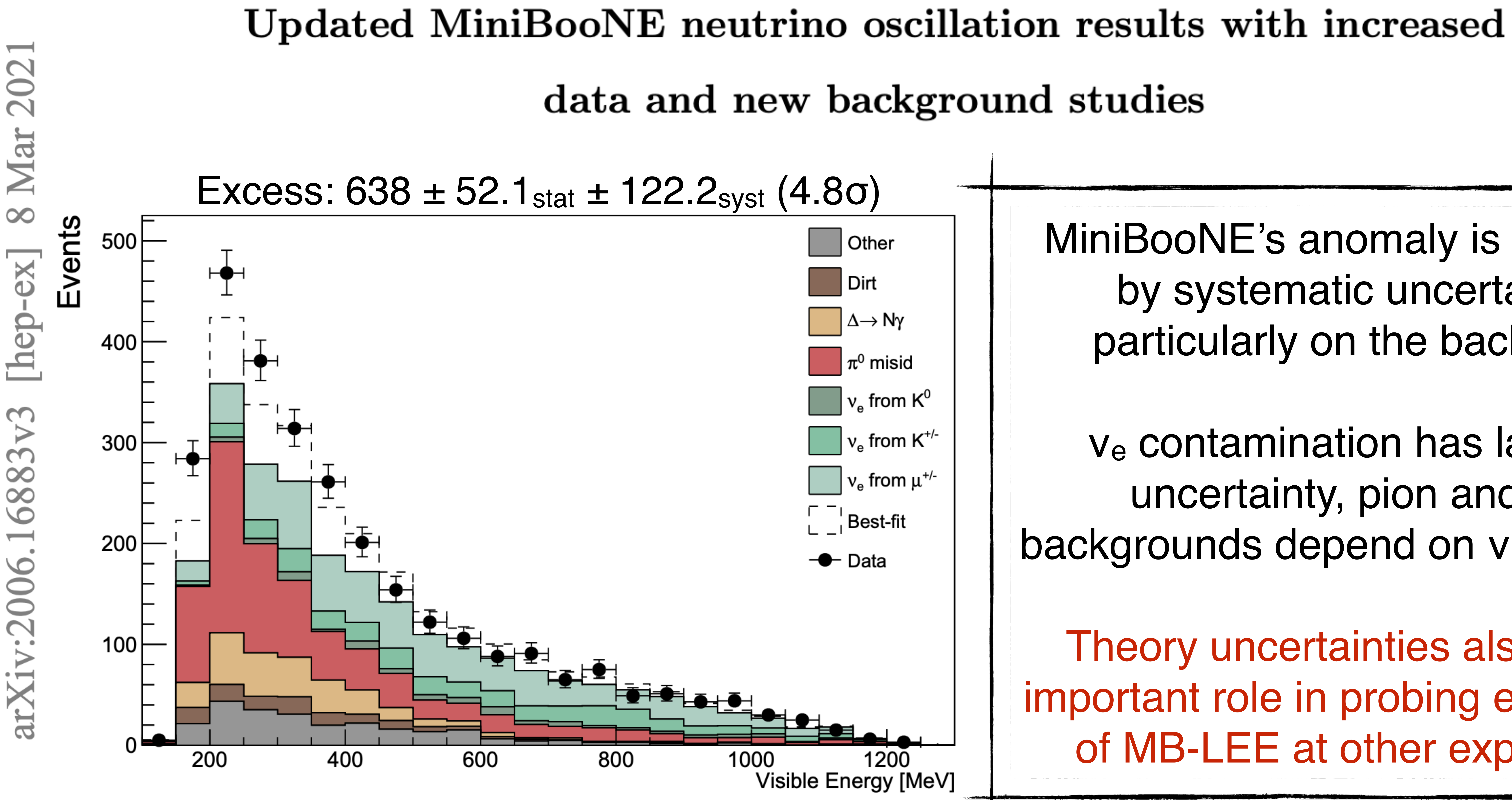
Theory Uncertainties: Why do we need to properly estimate them

Multi-universe approaches somewhat estimate these uncertainties: vary generator/MC parameters and build up some covariance matrix

Near detectors can somewhat mitigate these uncertainties in oscillation studies

But a lot of the physics we want to do does not leverage near-far configuration

Theory Uncertainties: Why do we need to properly estimate them



MiniBooNE's anomaly is dominated by systematic uncertainties, particularly on the background

ν_e contamination has large flux uncertainty, pion and delta backgrounds depend on ν-A modeling

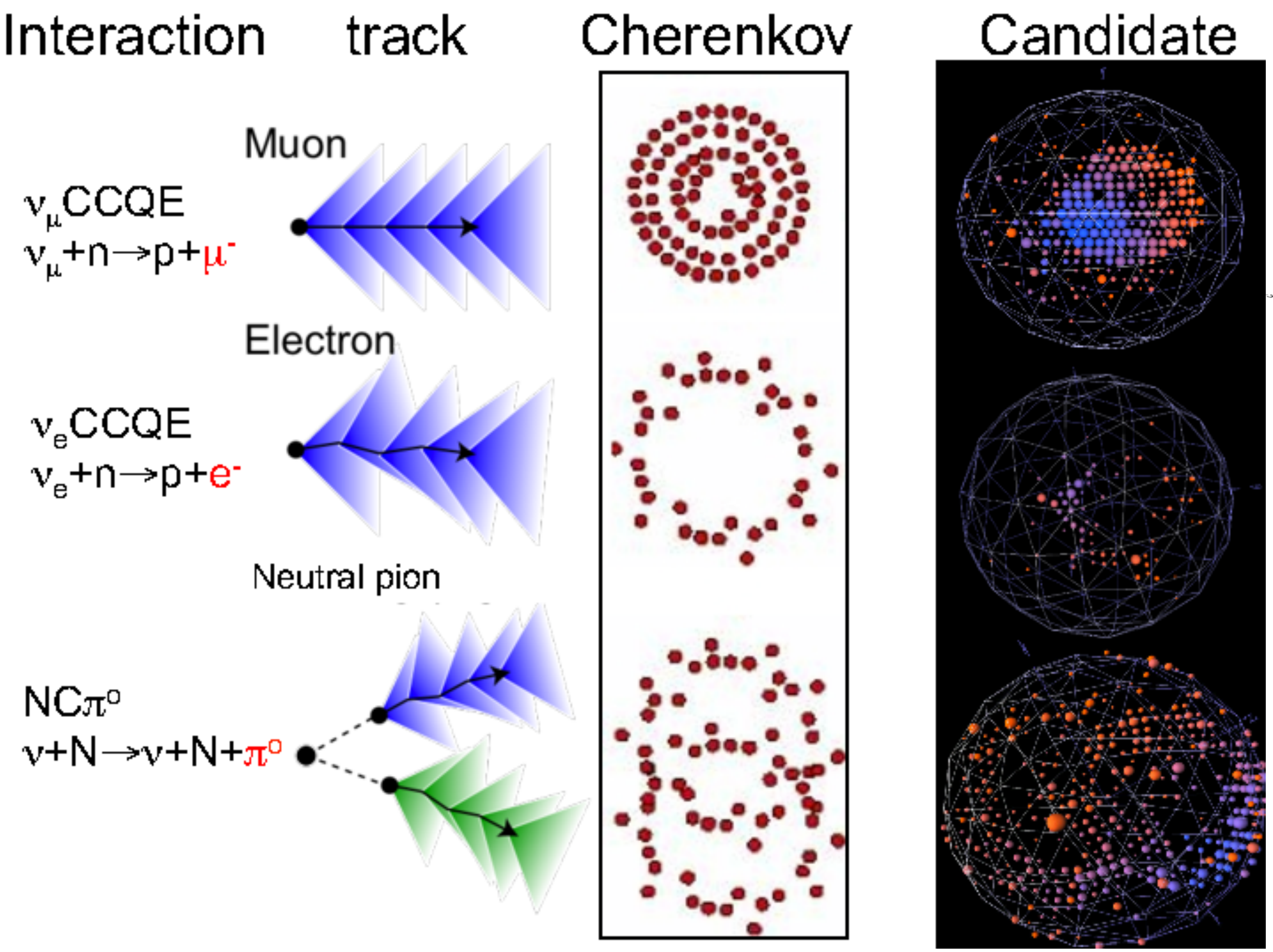
Theory uncertainties also play an important role in probing explanations of MB-LEE at other experiments

pmachado@fnal.gov

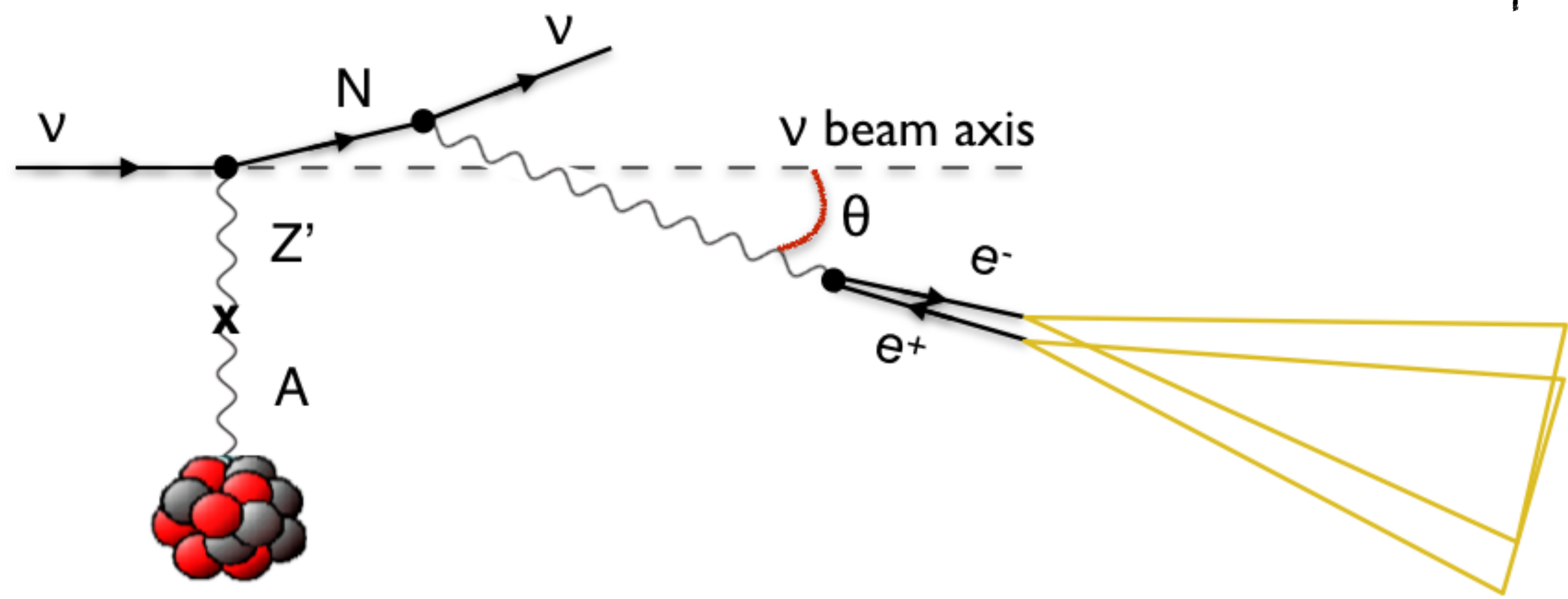
Theory Uncertainties: Why do we need to properly estimate them

arXiv:2006.16883v3 [hep-ex] 8 Mar 2021

Updated MiniBooNE neutrino oscillation results with increased data and new background studies

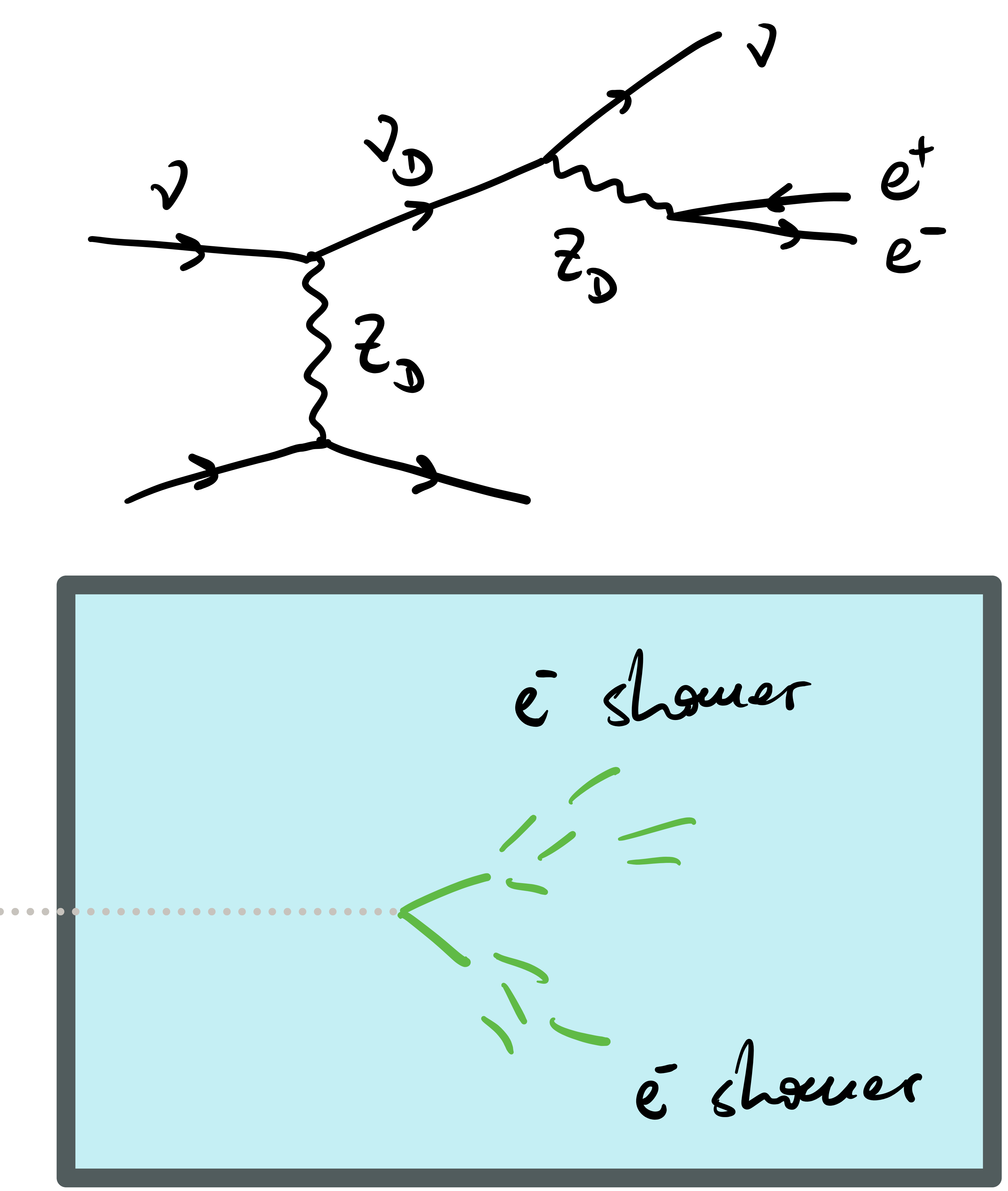


Alternative explanations of the background typically rely on models which lead to collimated e^+e^- pairs or photons

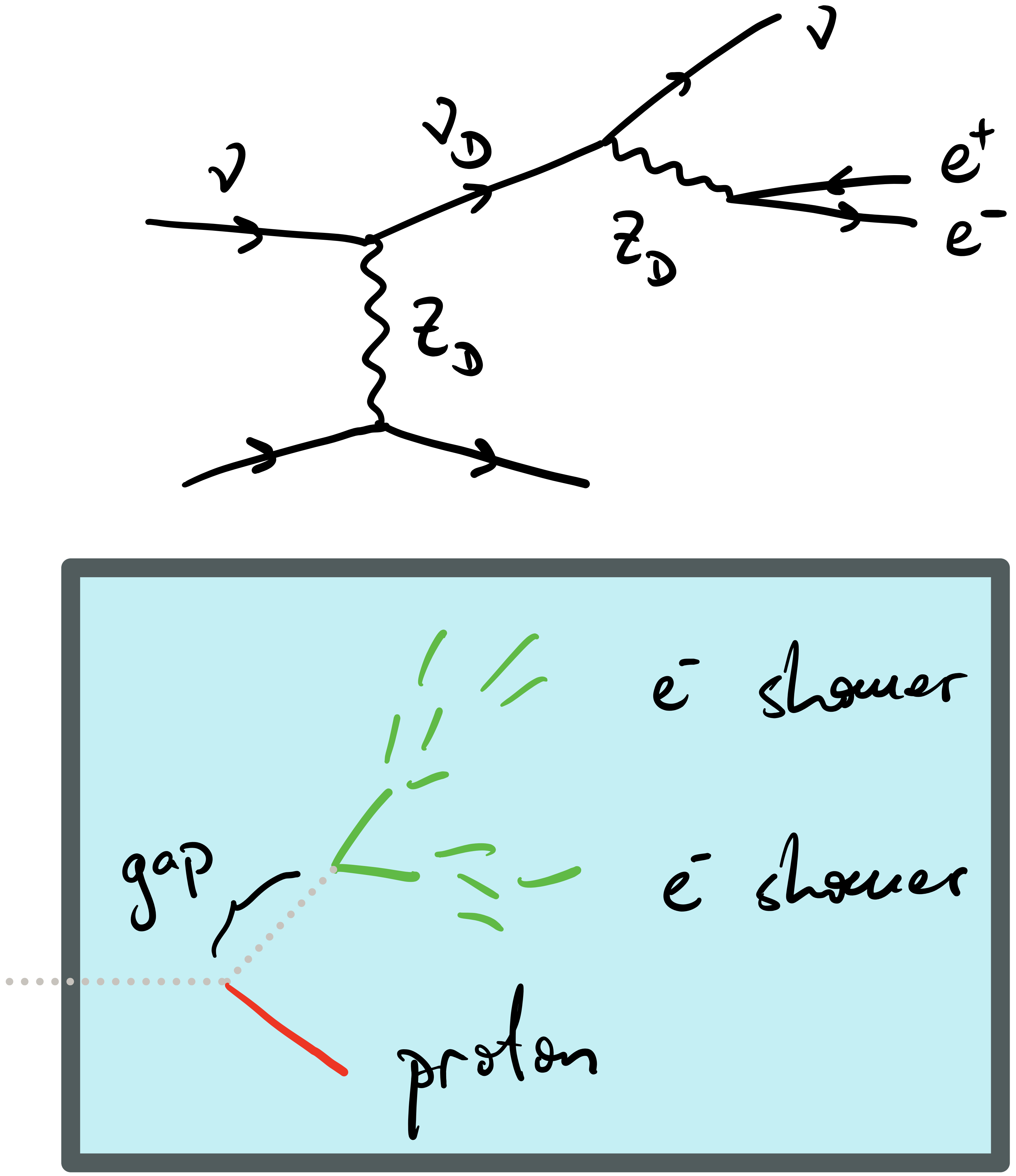


Bertuzzo **PM** et al 1807.09877; Bertuzzo **PM** et al 1808.02500; Arguelles et al 1812.08768; Ballett et al 1808.02915, 1903.07589; Abdullahi et al 2007.11813; Dutta et al 2006.01319; Gninenko 0902.3802, 1201.5194; Vergani et al 2105.06470; Brdar et al 2007.14411; …

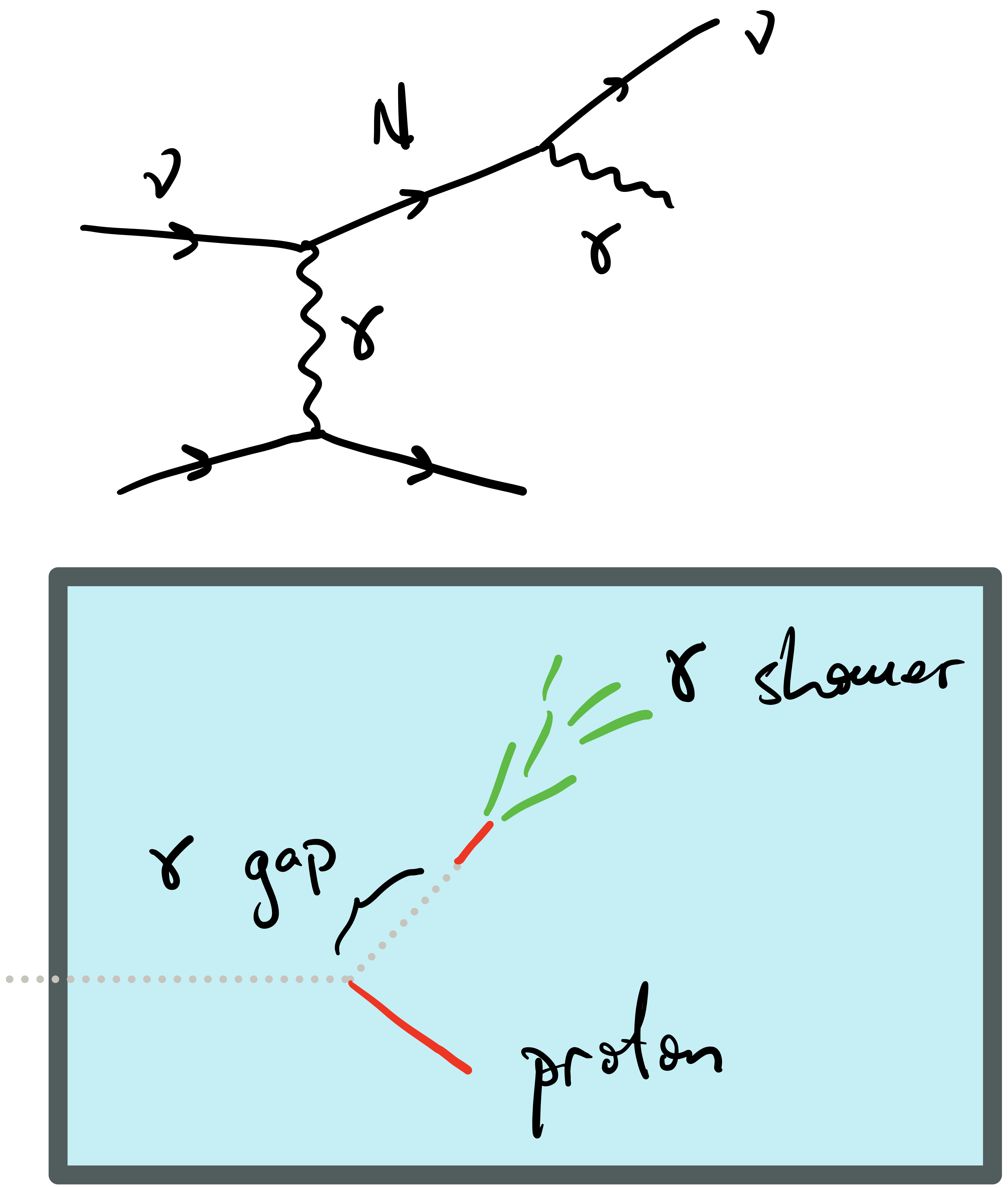
Dark neutrino, light ZD



Dark neutrino, heavy ZD



Transition magnetic moment



pmachado@fnal.gov

Theory Uncertainties: Why do we need to properly estimate them

Backgrounds depend on ν-A modeling, and so do their uncertainties

- Coherent photon production
- π^0 production
- mis-id: low energy μ vs. electron
- mis-id: e/γ separation
- neutrino-nucleus interaction model
- …

Individual uncertainties on each process?

Fermilab
pmachado@fnal.gov

Theory Uncertainties: Why do we need to properly estimate them

Backgrounds depend on ν-A modeling, and so do their uncertainties

- Coherent photon production
- π^0 production
- mis-id: low energy μ vs. electron
- mis-id: e/γ separation
- neutrino-nucleus interaction model
- …

Individual uncertainties on each process?

Without proper background uncertainties, we will need to rely on tunings and side bands

Fermilab
pmachado@fnal.gov

Theory Uncertainties: Why do we need to properly estimate them

Backgrounds depend on ν-A modeling, and so do their uncertainties

- Coherent photon production
- π^0 production
- mis-id: low energy μ vs. electron
- mis-id: e/γ separation
- neutrino-nucleus interaction model
- …

Individual uncertainties on each process?

Nothing against using side bands, but we need to keep in mind that most of the time we use side bands to **extrapolate** the background to the signal region

Without proper background uncertainties, we will need to rely on tunings and side bands

Theory Uncertainties: Why do we need to properly estimate them

With the gigantic statistics that SBN and DUNE will acquire, we can imagine doing a precision physics program in neutrino experiment, but **precision needs proper uncertainties**

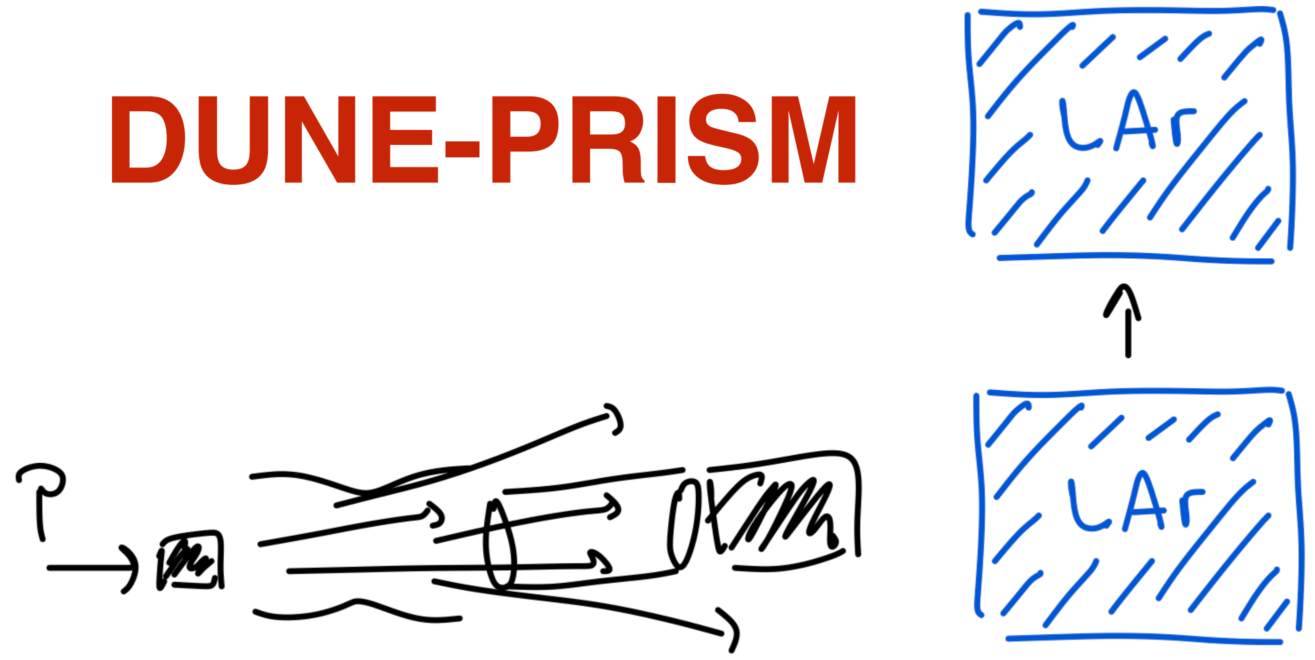
The weak mixing angle at DUNE

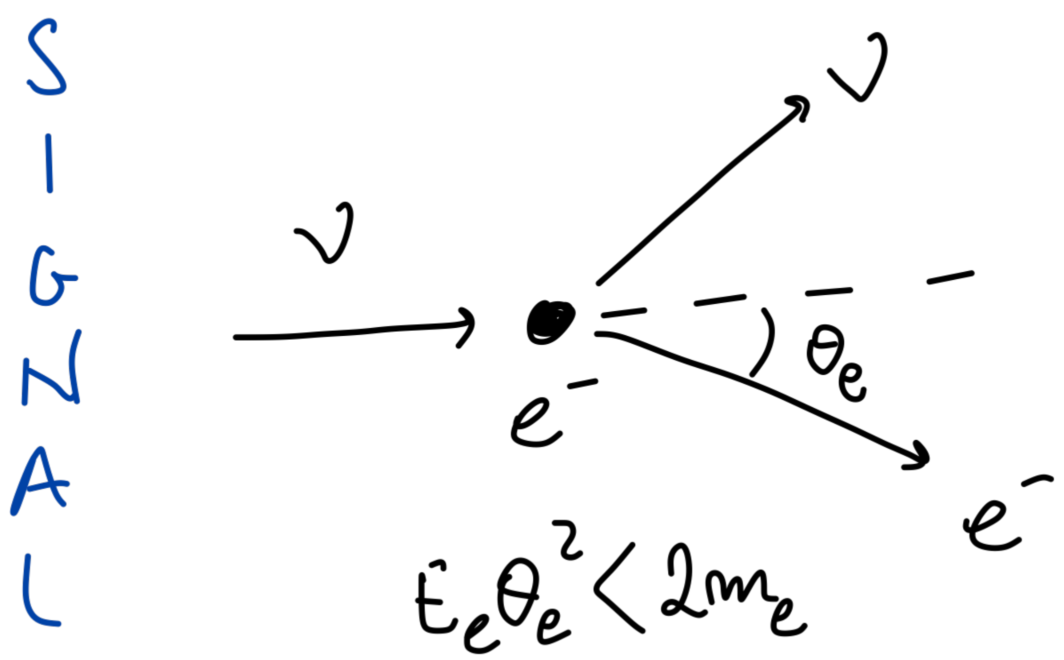
pmachado@fnal.gov

Theory Uncertainties: Why do we need to properly estimate them

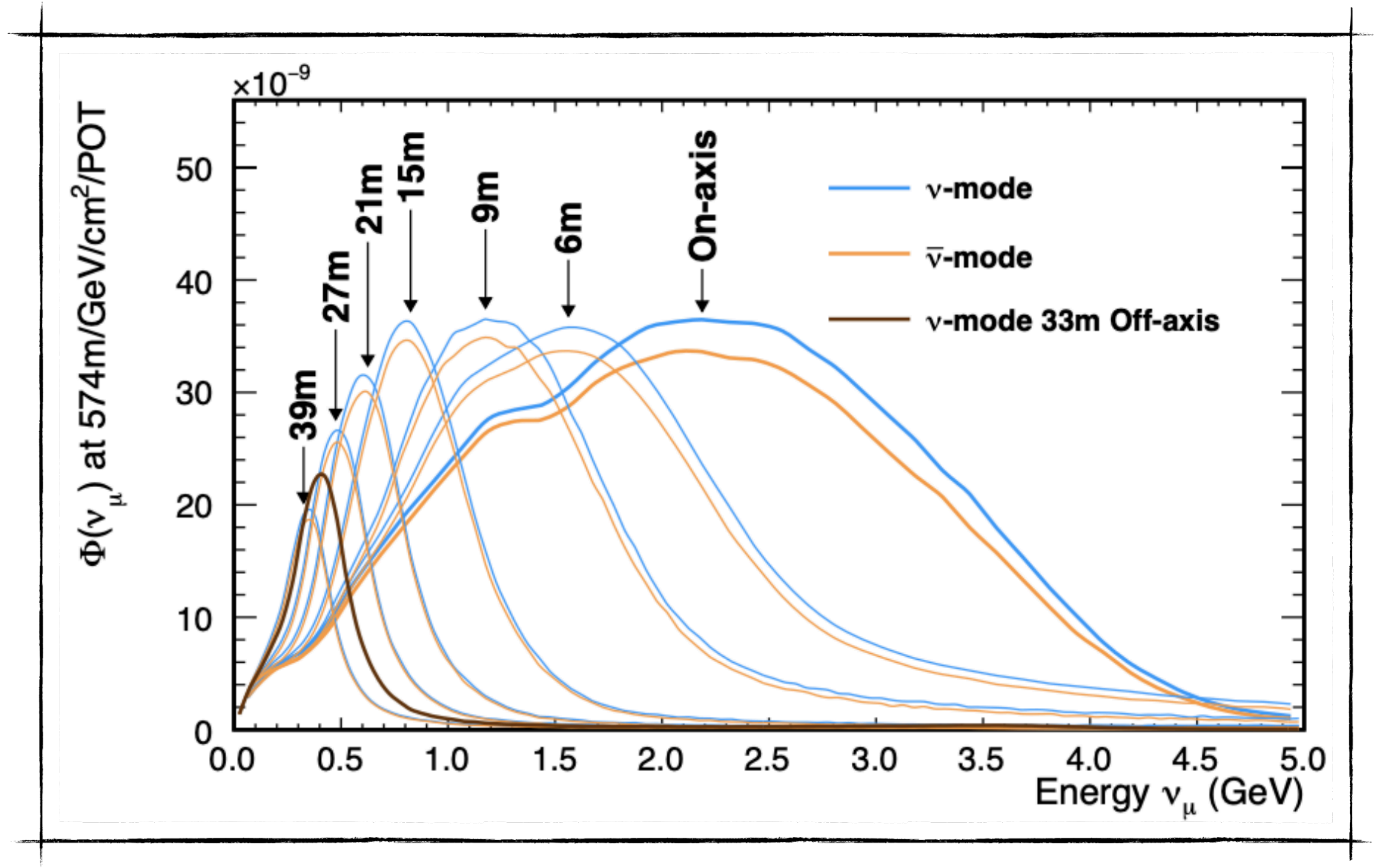
With the gigantic statistics that SBN and DUNE will acquire, we can imagine doing a precision physics program in neutrino experiment, but **precision needs proper uncertainties**

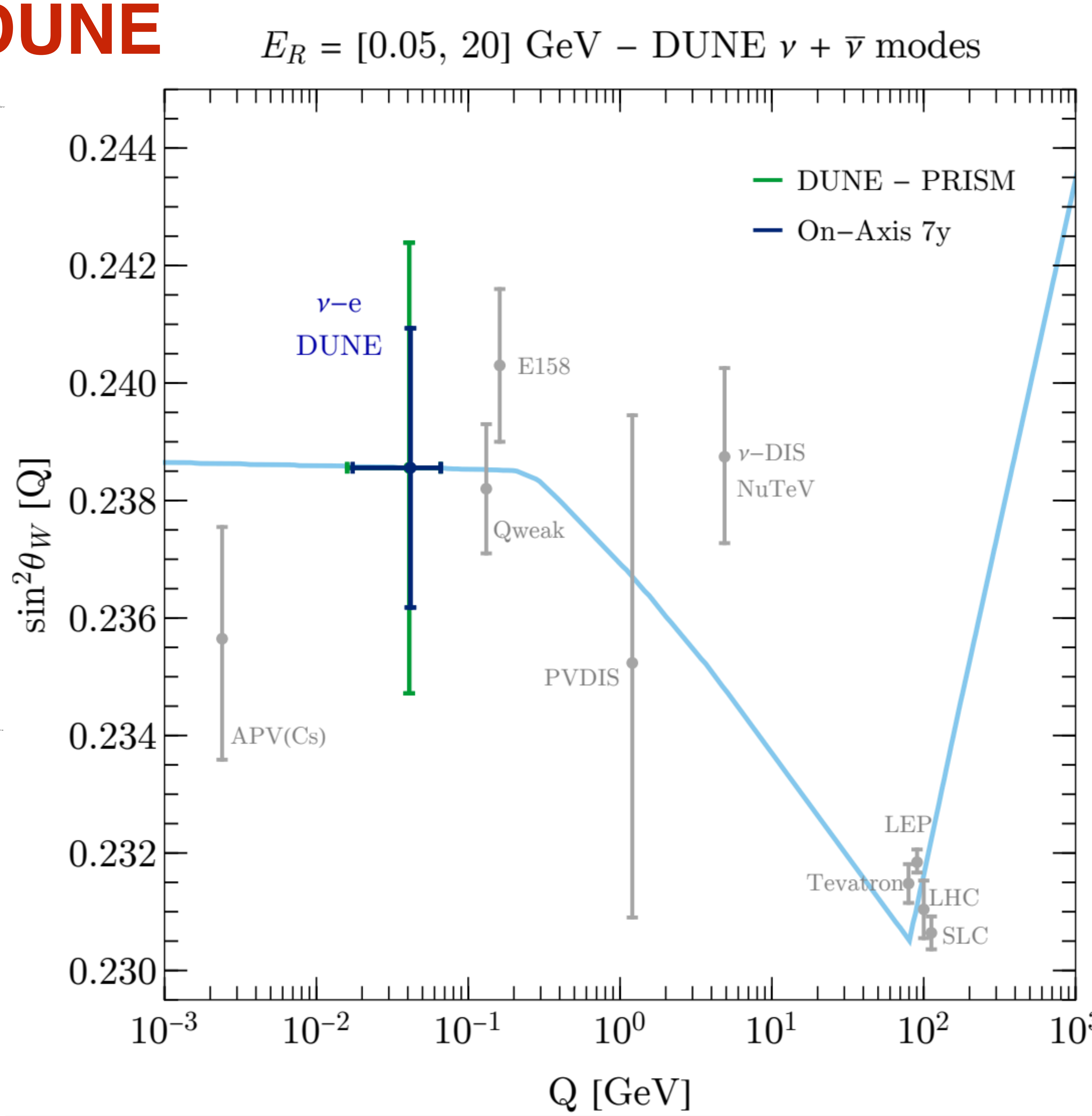
DUNE-PRISM



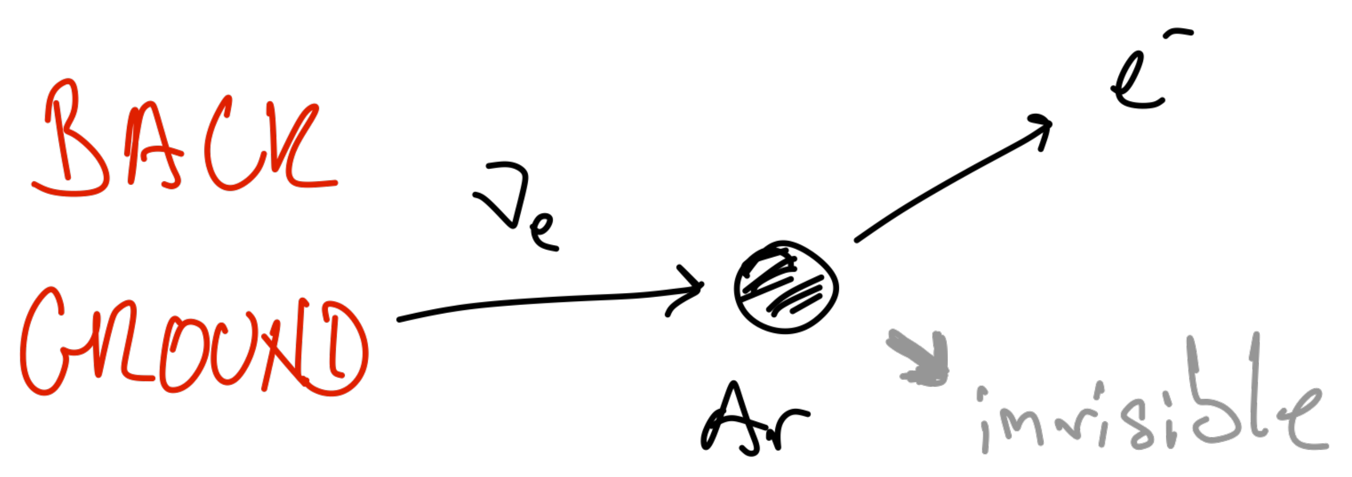


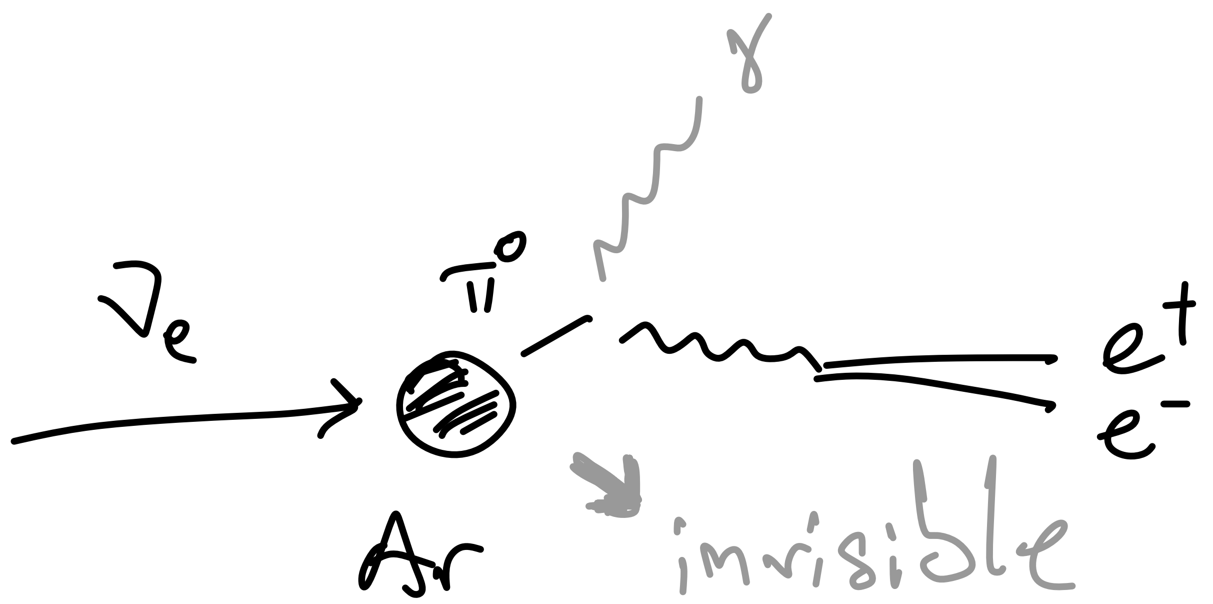
The weak mixing angle at DUNE





de Gouvea M Perez-Gonzalez Tabrizi 1912.06658



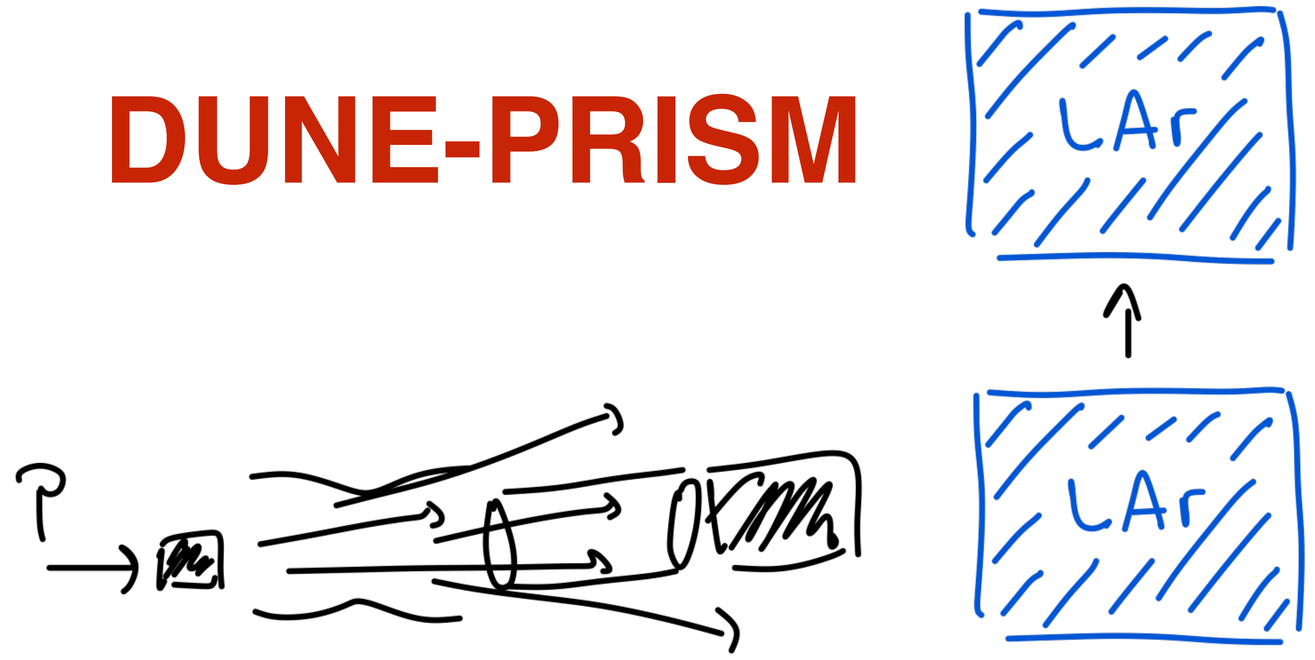


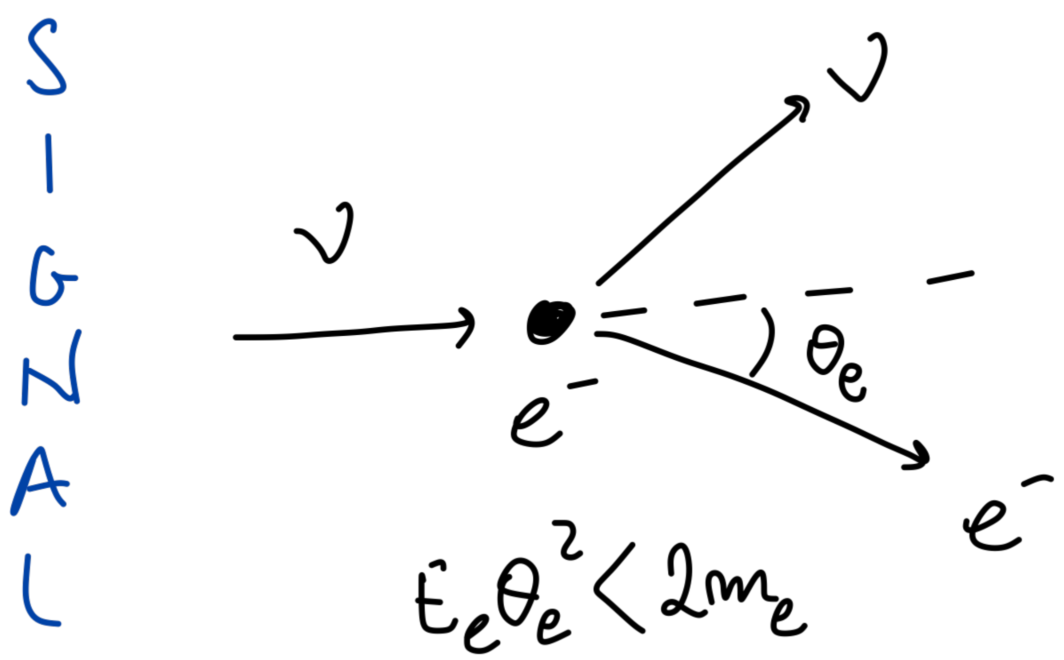
Fermilab
pmachado@fnal.gov

Theory Uncertainties: Why do we need to properly estimate them

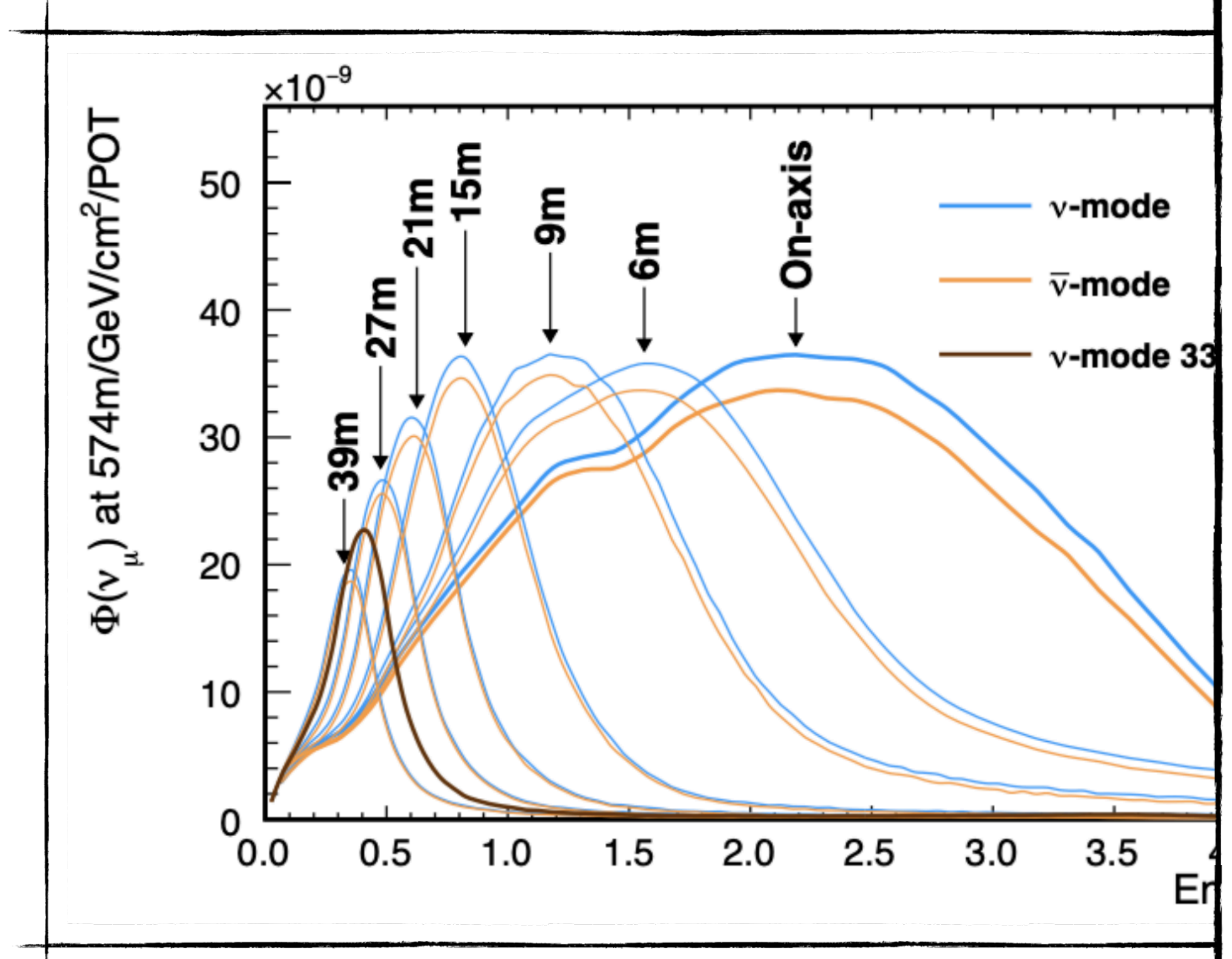
With the gigantic statistics that SBN and DUNE will acquire, we can imagine doing a precision physics program in neutrino experiment, but **pr**

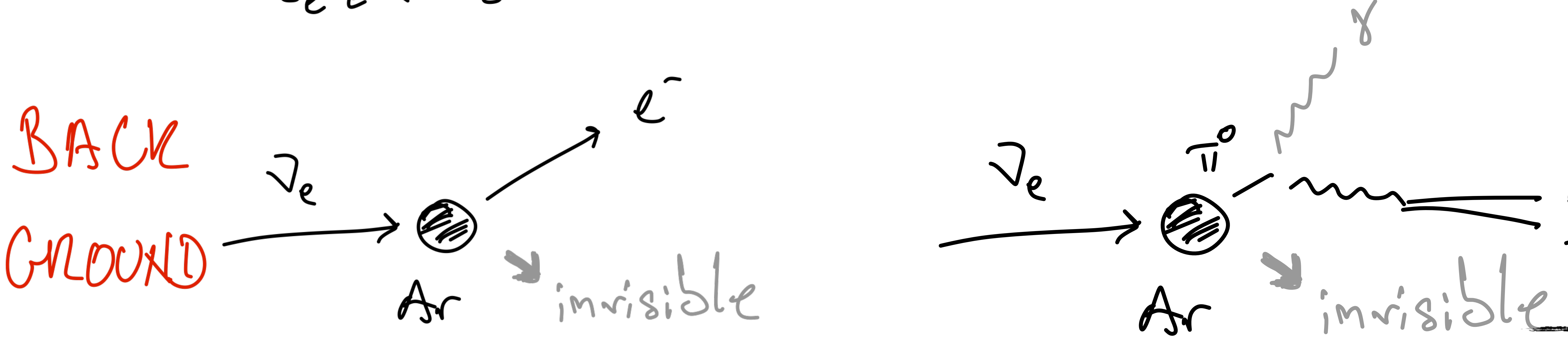
DUNE-PRISM

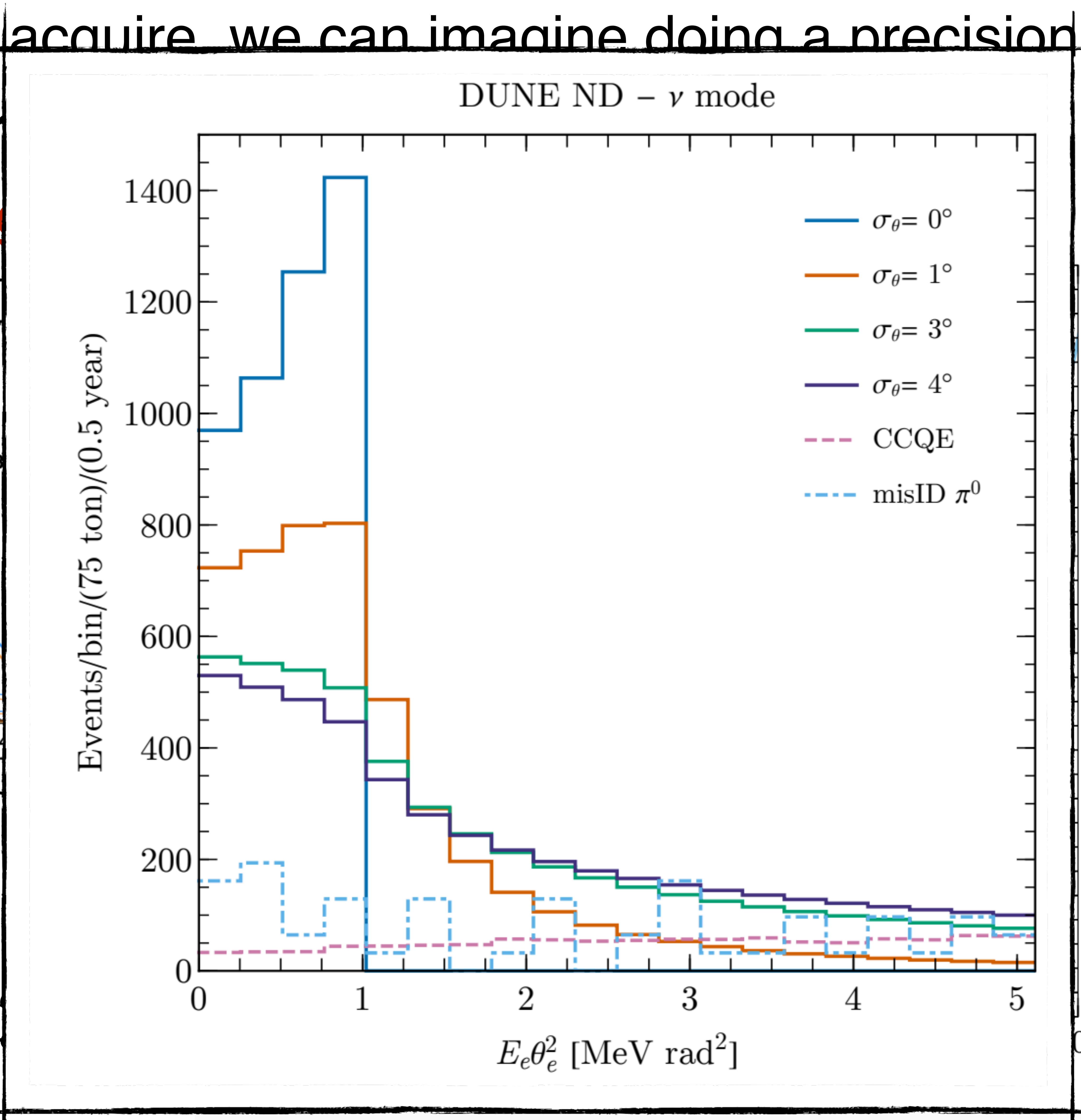




The weak mixing ang







de Gouvea M Perez-Gonzalez Tabrizi 1912.06658

Fermilab
pmachado@fnal.gov

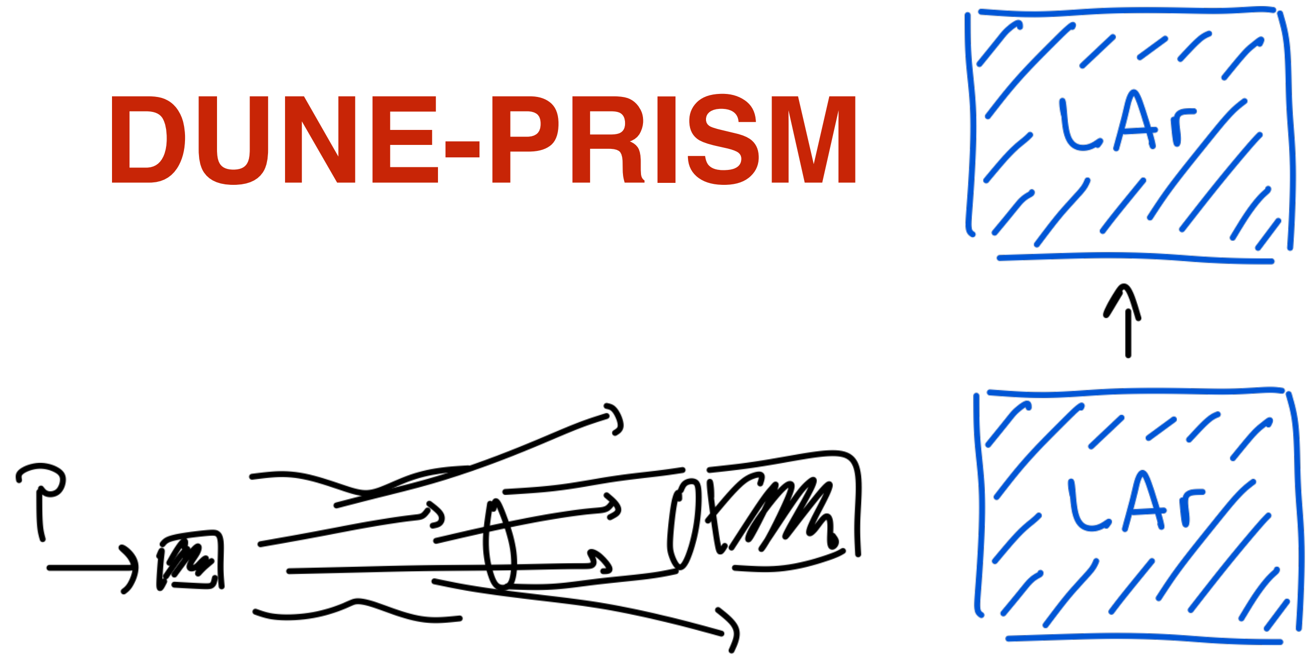
Theory Uncertainties: Why do we need to properly estimate them

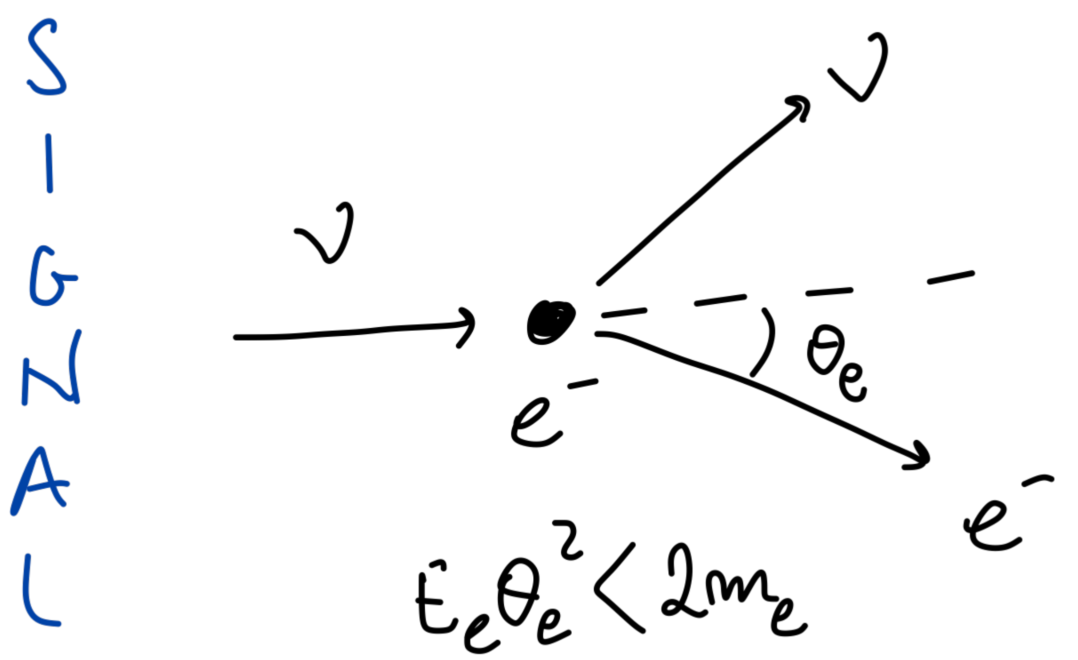
With the gigantic sta… …ne doing a precision physics program in neutrino experiment, but p…

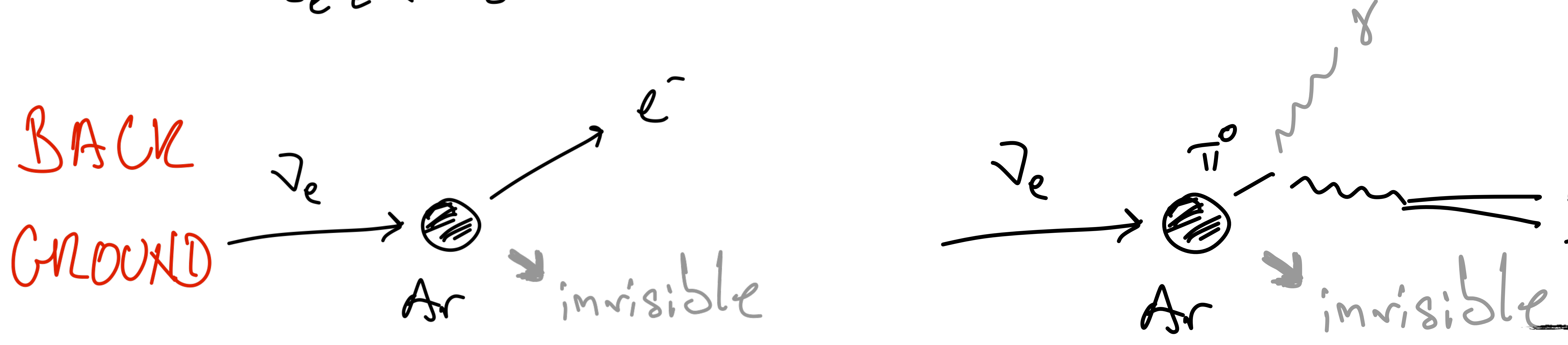
Without proper background uncertainties, we will need to rely on tunings and side bands

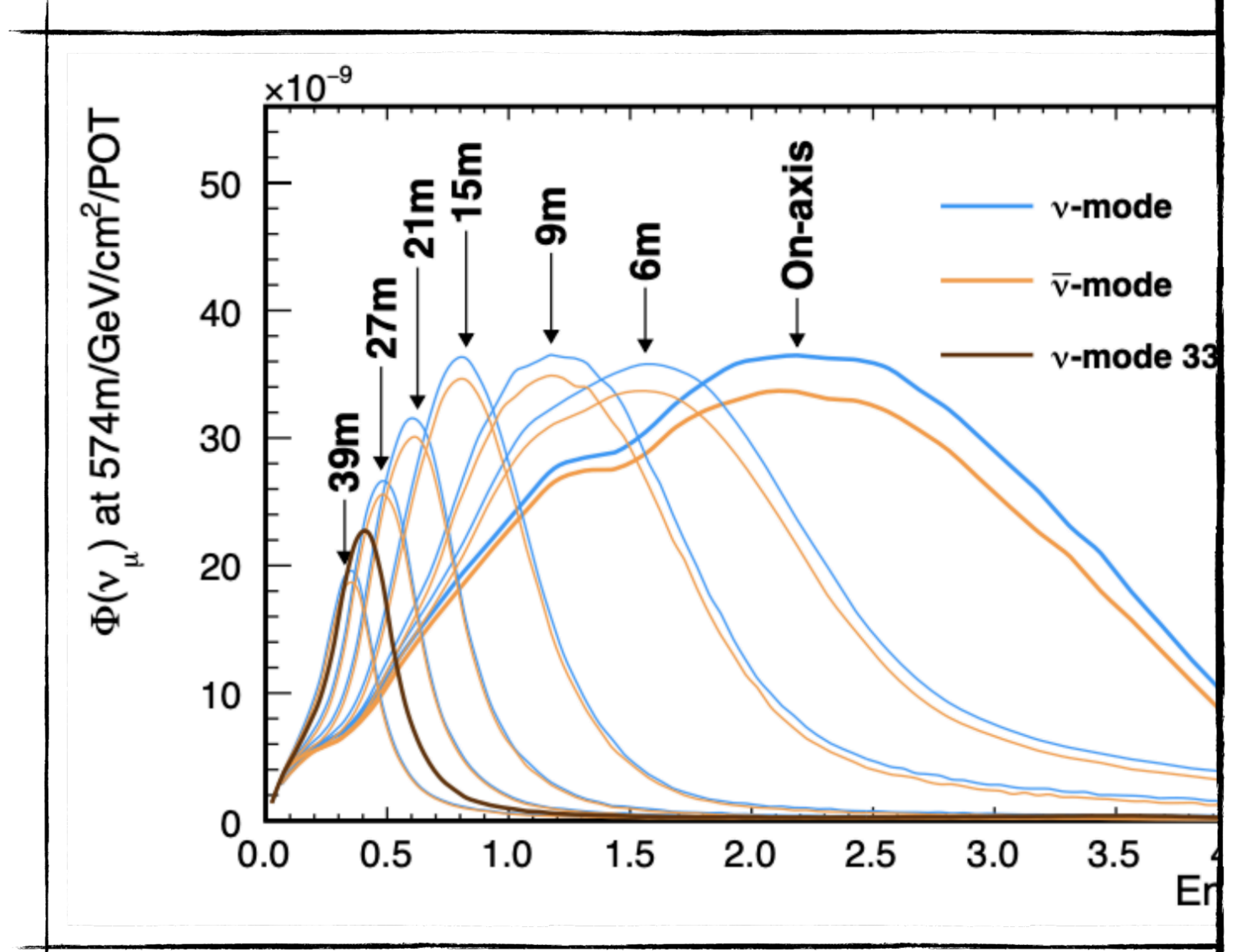
The weak mixing ang…

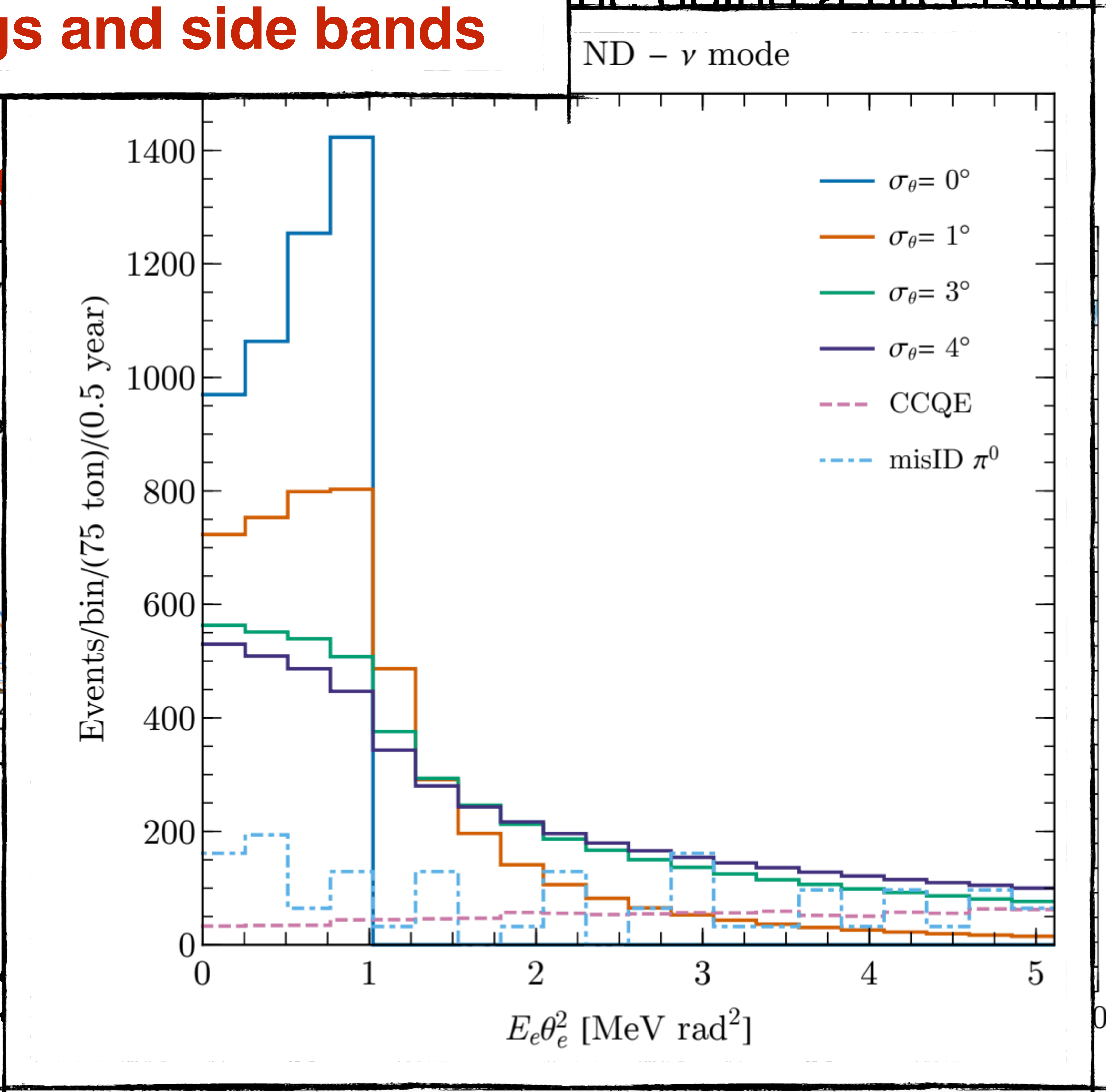
DUNE-PRISM











de Gouvea M Perez-Gonzalez Tabrizi 1912.06658

Proper BSM interface

Why should we avoid stitching things together

pmachado@fnal.gov

Proper BSM interface: Why should we avoid stitching things together

Incorporating BSM scenarios in current neutrino generators may be a daunting task

Many times, things are “stitched together” to speed things up

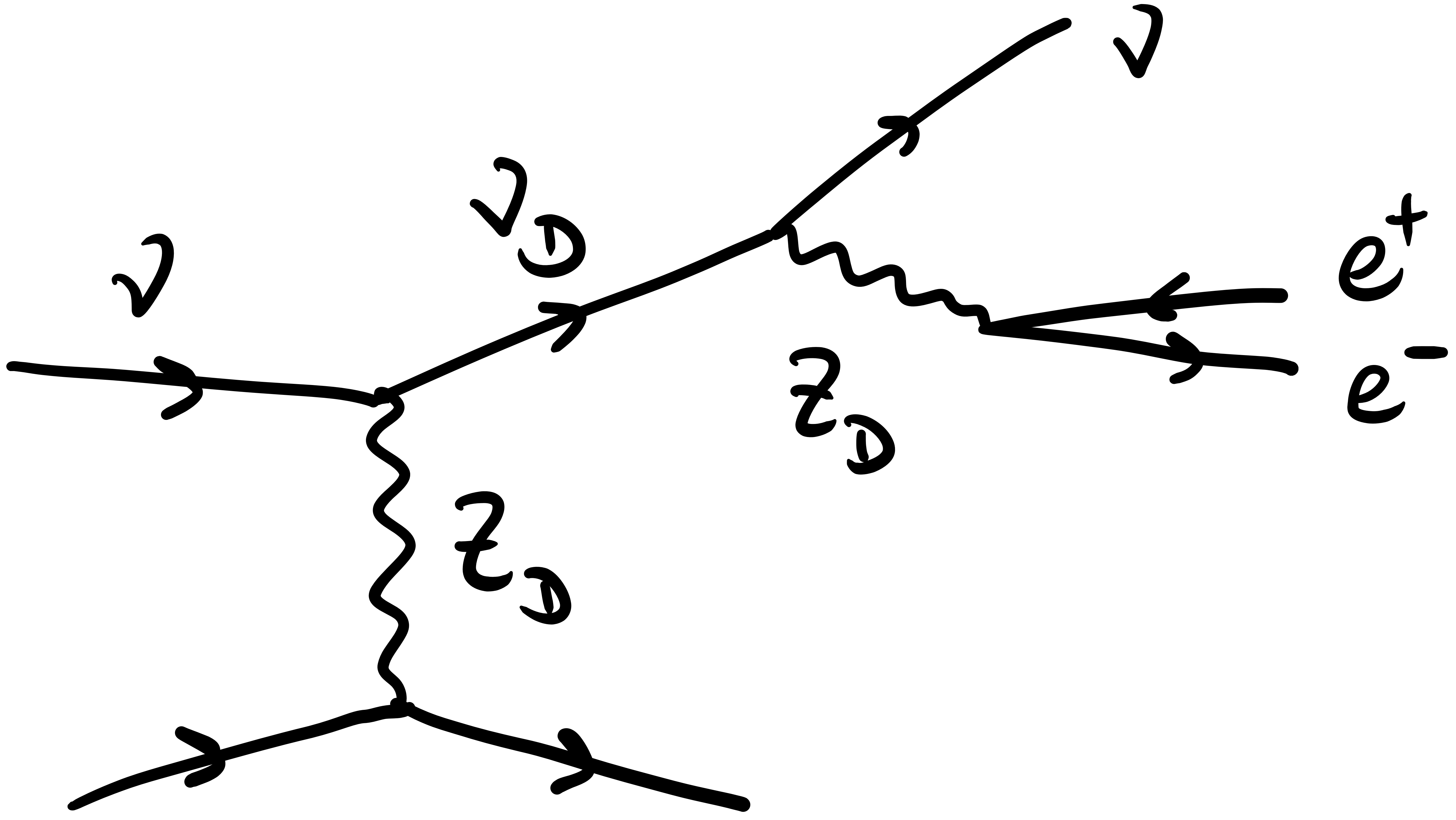
But stitching may incorrectly describe the physics process

Here is what I mean

pmachado@fnal.gov

Proper BSM interface: Why should we avoid stitching things together

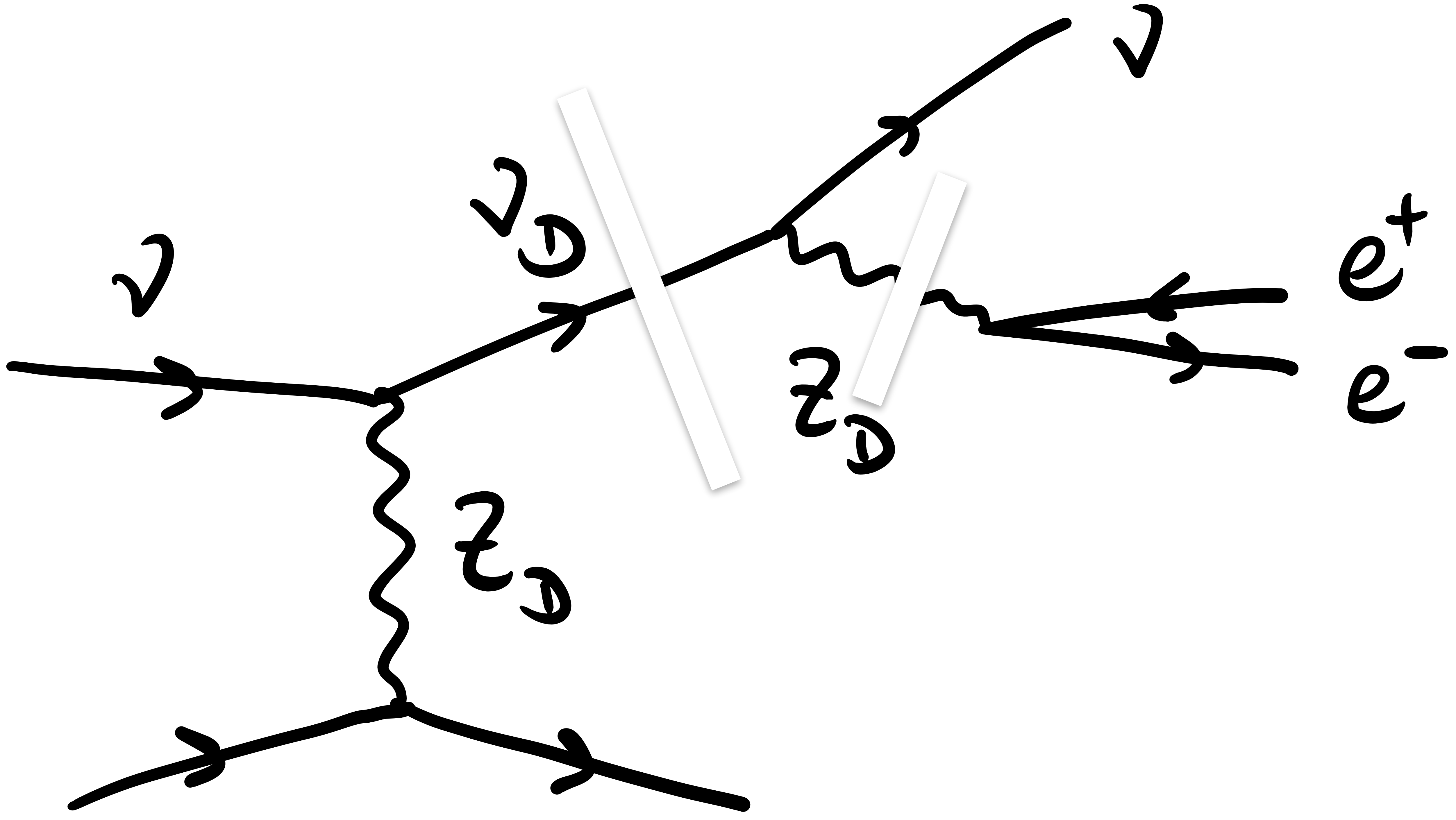
The 2 to 4 scattering can be tricky to simulate



Proper BSM interface: Why should we avoid stitching things together

The 2 to 4 scattering can be tricky to simulate

Break down into 2 to 2, then decay ν_D, then decay Z_D



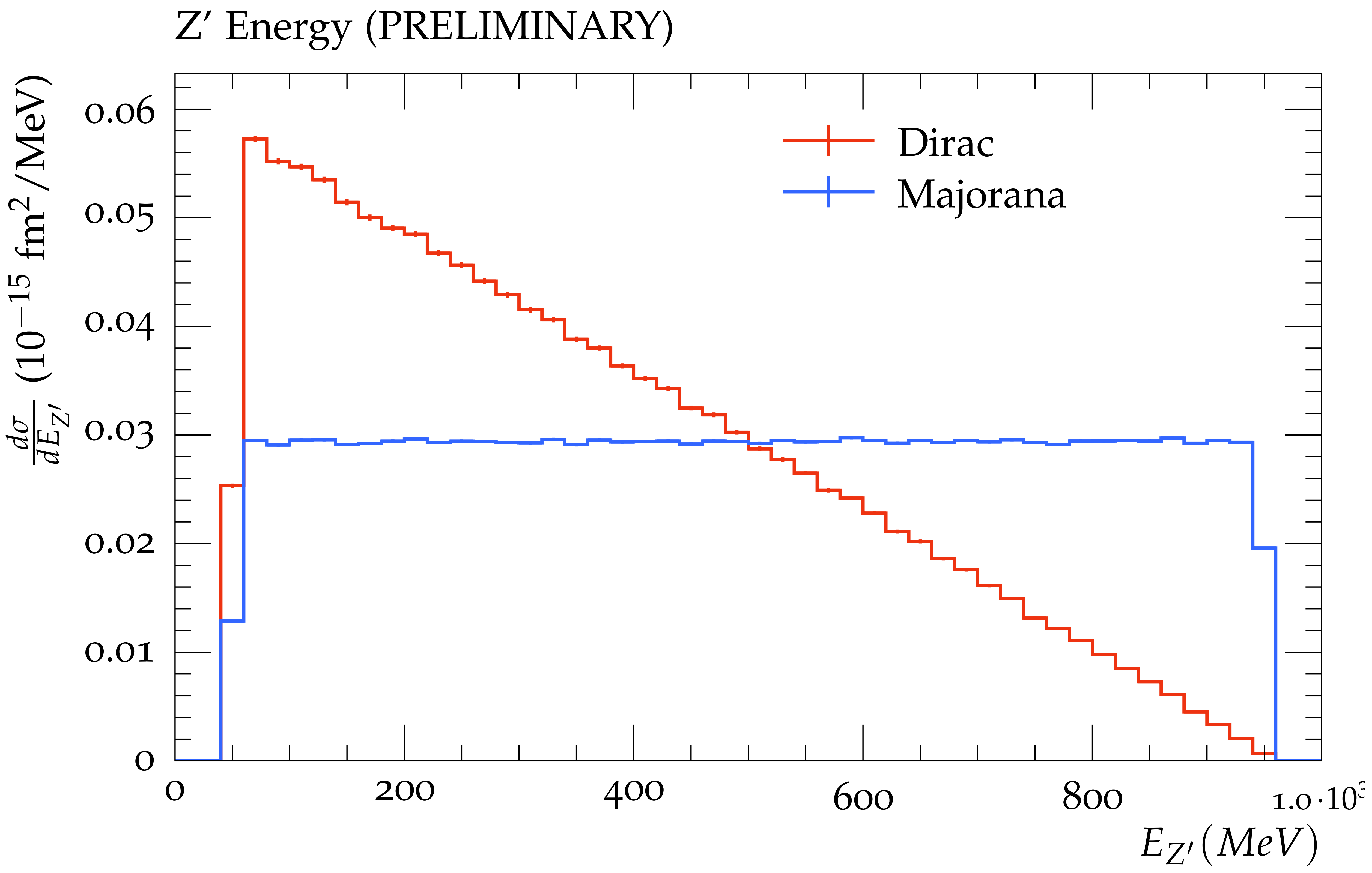
pmachado@fnal.gov

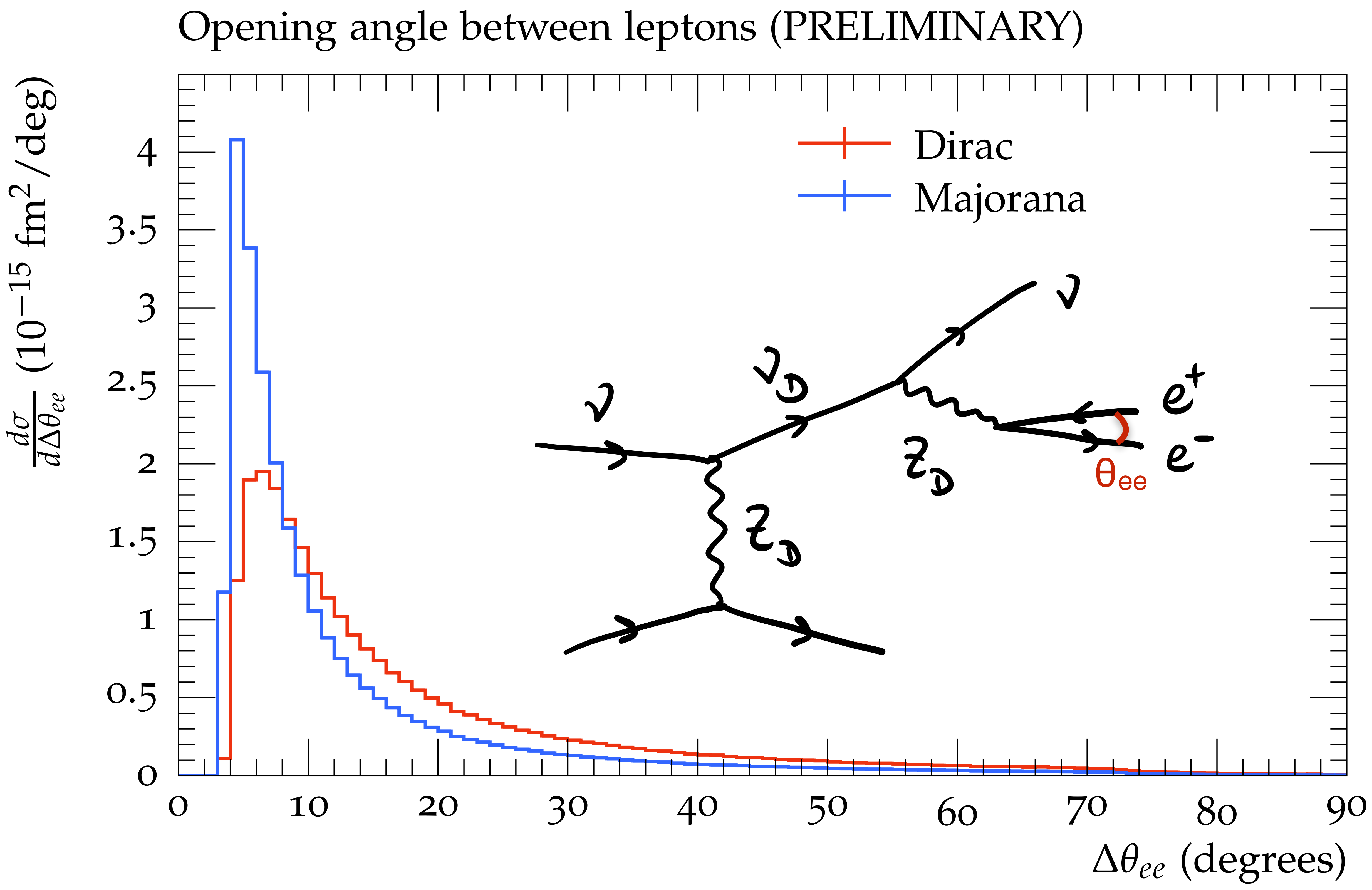
Proper BSM interface: Why should we avoid stitching things together

Spin correlations can be **very important**,

particularly for tau production or BSM physics

*Corrected from Josh's talk: our Lagrangian was missing a P_L in the new interaction

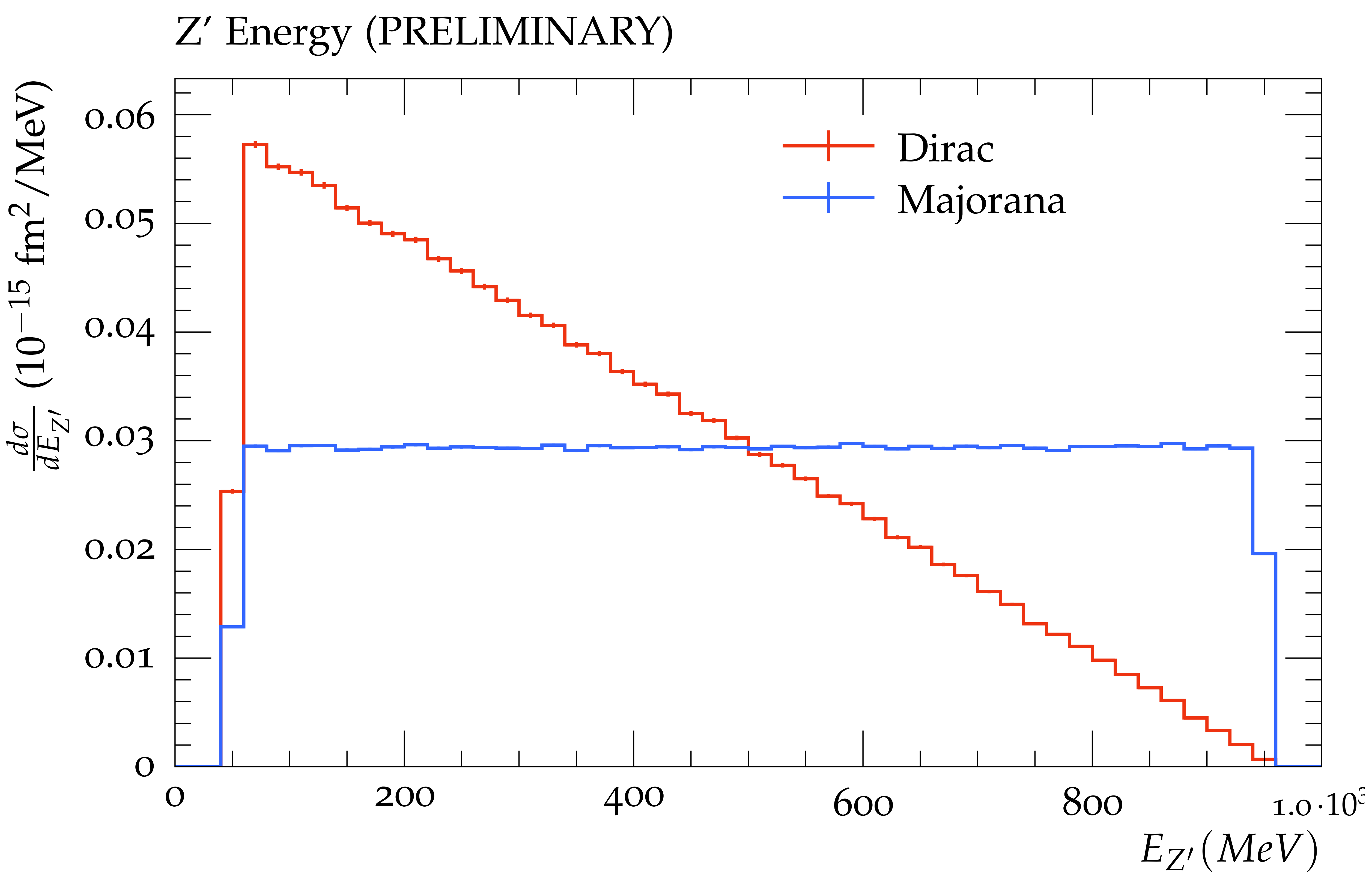


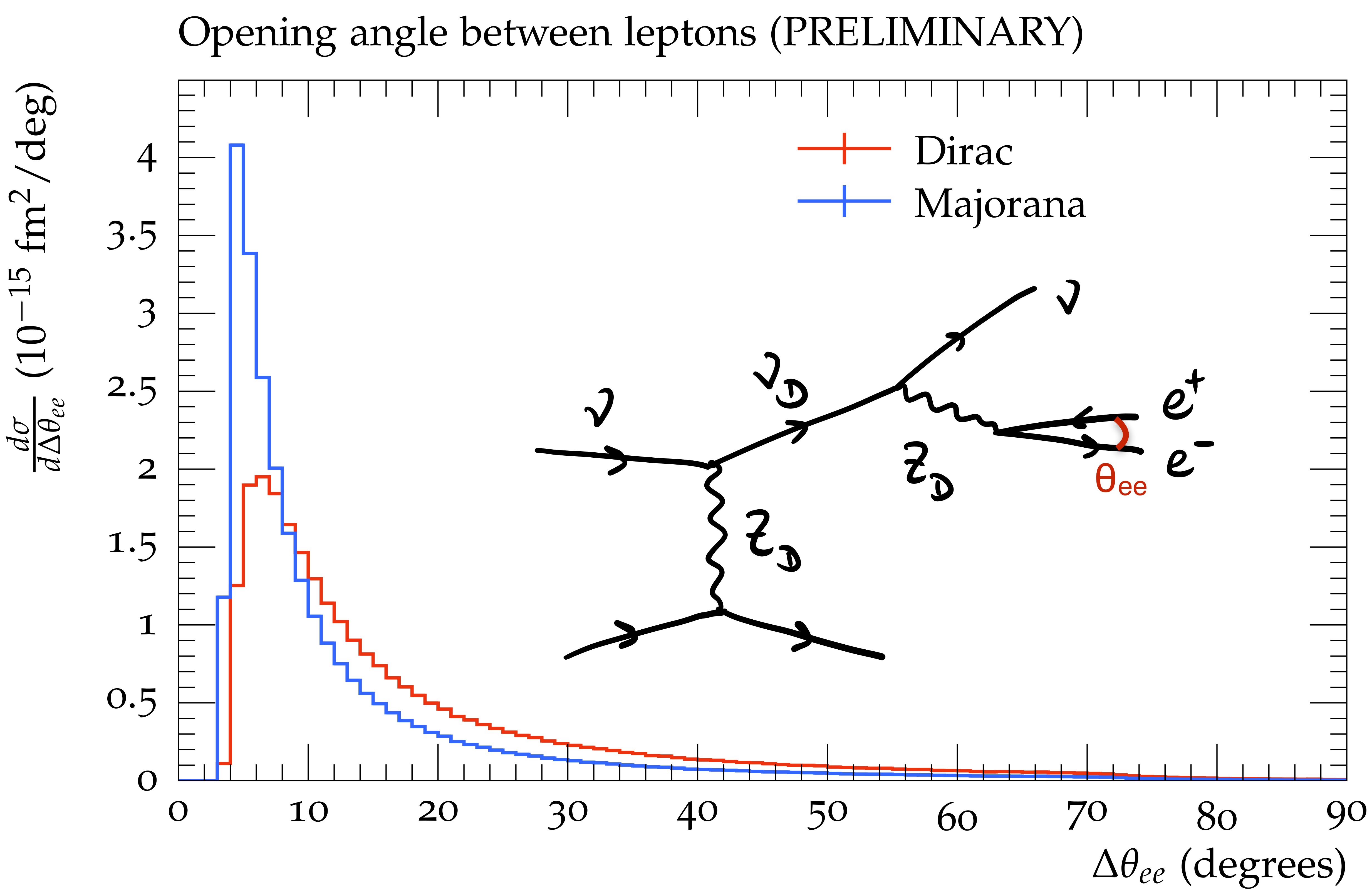


Proper BSM interface: Why should we avoid stitching things together

Spin correlations can induce O(1) effects on certain distributions

This can be avoided by interfacing BSM in generators properly (and tau production)





pmachado@fnal.gov

Tuning of cross sections

See Shirley's talk

Is the tuning procedure robust?
Does it wash away new physics signatures??

Fermilab
pmachado@fnal.gov

How does the ν-A interaction modeling impact new physics searches?

Several other examples

Light dark matter in neutrino experiments

Hidden portal scalars

Heavy neutral leptons

Tau neutrino detection

Millicharged particles

Solar neutrinos in LArTPCs

Neutrino-electron meson resonance production

…

Summary

- **Initial state and FSI:** proton multiplicity is relevant for signal reconstruction (e.g. atmospherics) and background mitigation (e.g. MicroBooNE LEE photon analysis)
- **Theoretical uncertainties:** can play a key role in background estimate and thus in cuts to mitigate these backgrounds; avoid extrapolations from side bands
- **Proper BSM interface:** can correctly account for spin correlations which is particularly important for neutrino beams (since they are 100% polarized)
- **Tuning of cross sections:** wait a few minutes and Shirley will tell you about it

Some reflections

We are living an era of precision neutrino physics

Precision = new opportunities

There is a new trend in neutrino phenomenology which involves leveraging the unique capabilities of neutrino detectors and exploring the model signatures in great detail

This will ultimately lead to a **multi-purpose physics program in neutrino experiments**: precision EW physics, Earth tomography, dark sector connections, dark matter, low-scale neutrino mass models, neutrino electromagnetic properties, …

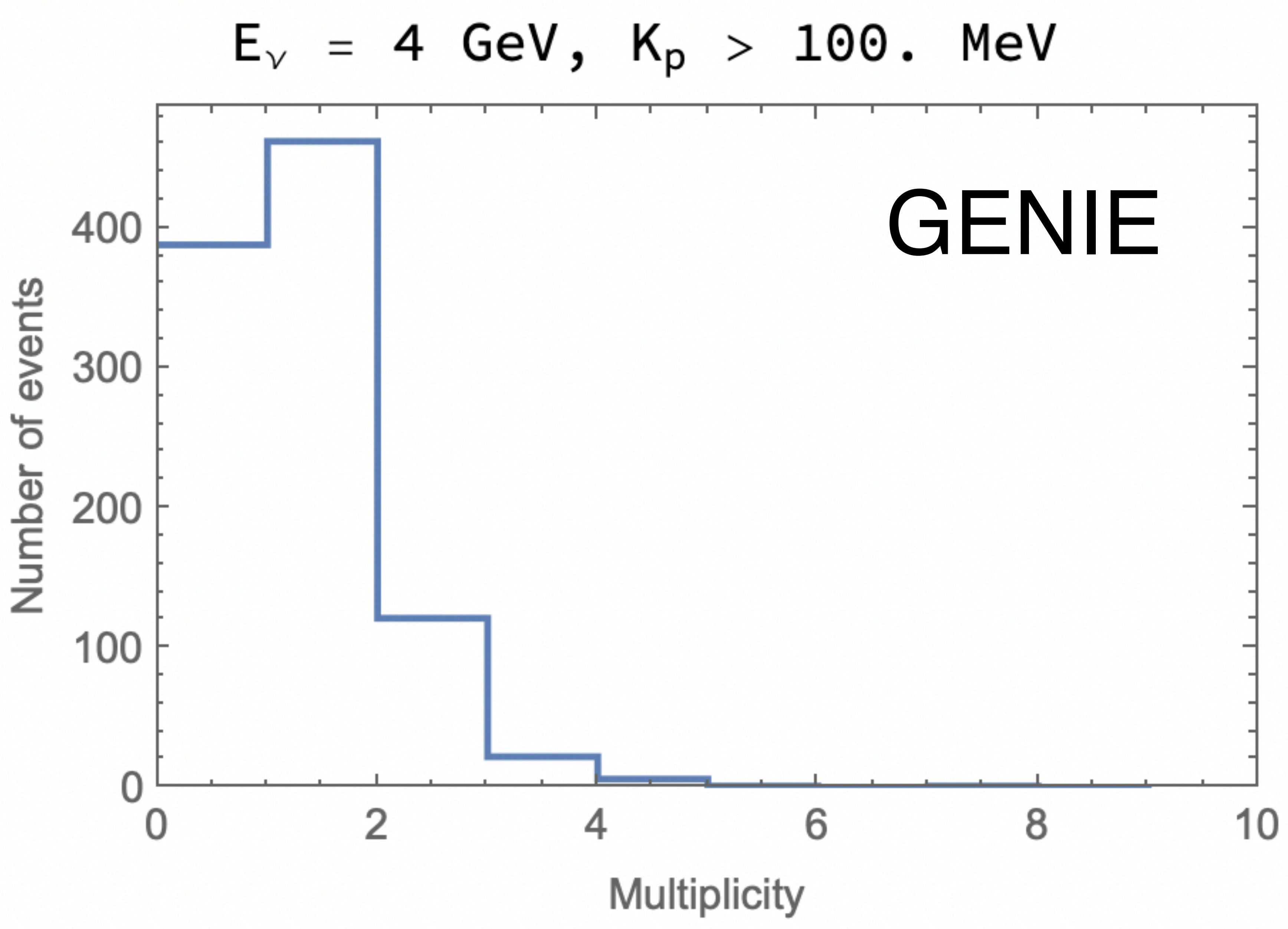
To push neutrino experiments to their fullest and have a rich physics program,
we need to better model neutrino-nucleus interactions

Fermilab
pmachado@fnal.gov

BACKUP

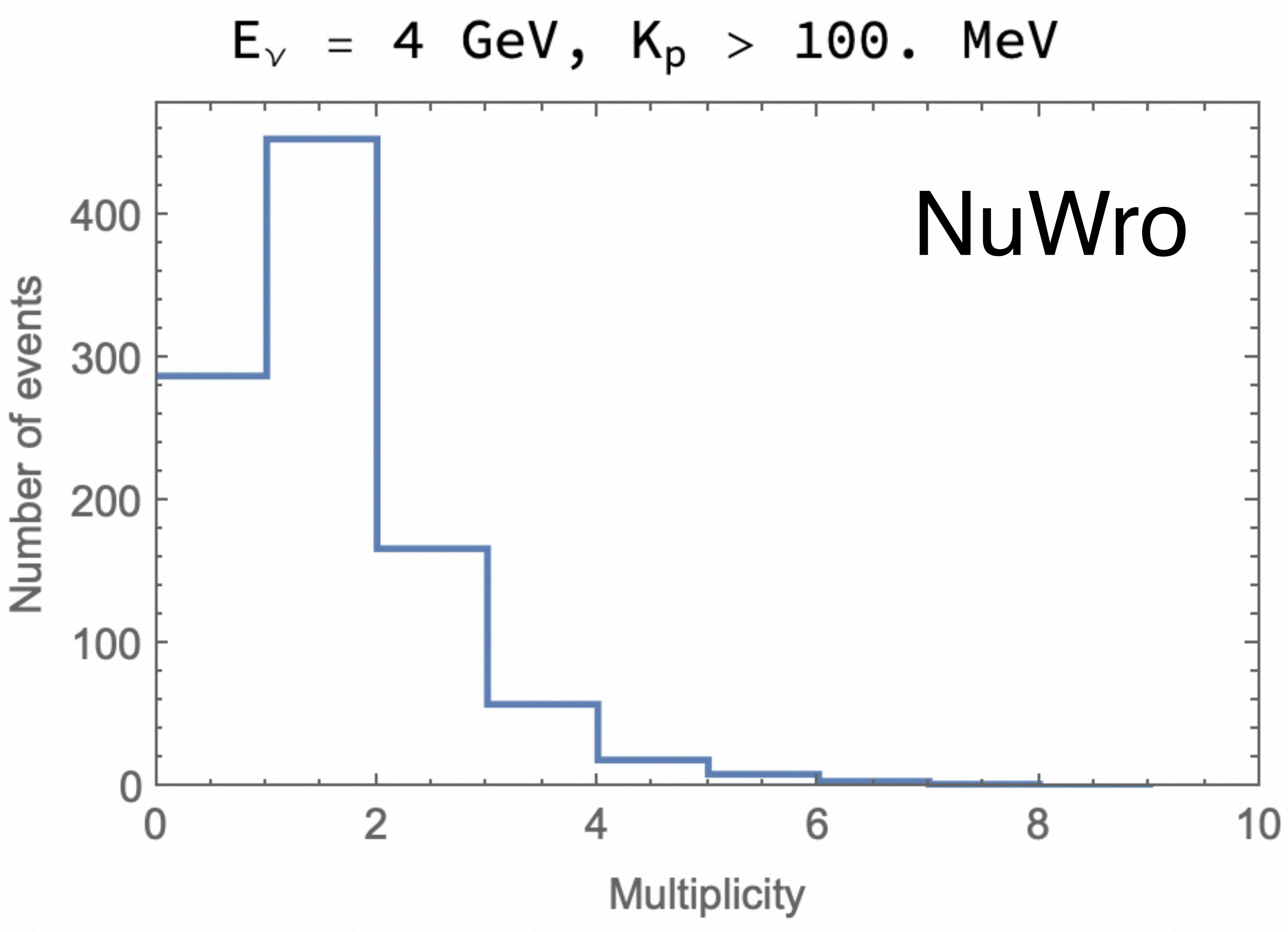
pmachado@fnal.gov

Simple example of proton multiplicity



Multiplicity:

0	=	388
1	=	462
2	=	121
3	=	22
4	=	6
5	=	1
6	=	0
7	=	1
8	=	0
9	=	0



Multiplicity:

0	=	288
1	=	454
2	=	167
3	=	58
4	=	19
5	=	9
6	=	4
7	=	2
8	=	0
9	=	0