μBooNE

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NEUTRINO INTERACTIONS: WHY WE CARE, HOW TO MEASURE THEM, AND WHAT WE KNOW SO FAR

Kirsty Duffy

UKRI Future Leaders Fellow, University of Oxford

55 cm

Run 3469 Event 53223, Oct

WHO AM I?

- Physics coordinator for the **MicroBooNE** experiment (and before that I was convener of the cross-section physics group). I have also studied neutrino oscillation with the **T2K** and **DUNE** experiments
- Given my background and training:
  - You'll see a lot of MicroBooNE results in this lecture!
  - I'll focus mostly on **accelerator neutrino experiments in the ~GeV region** → because of time we'll largely avoid deep inelastic scattering
  - This will be a **pretty experimental lecture** — more on what we can measure and how than the theory

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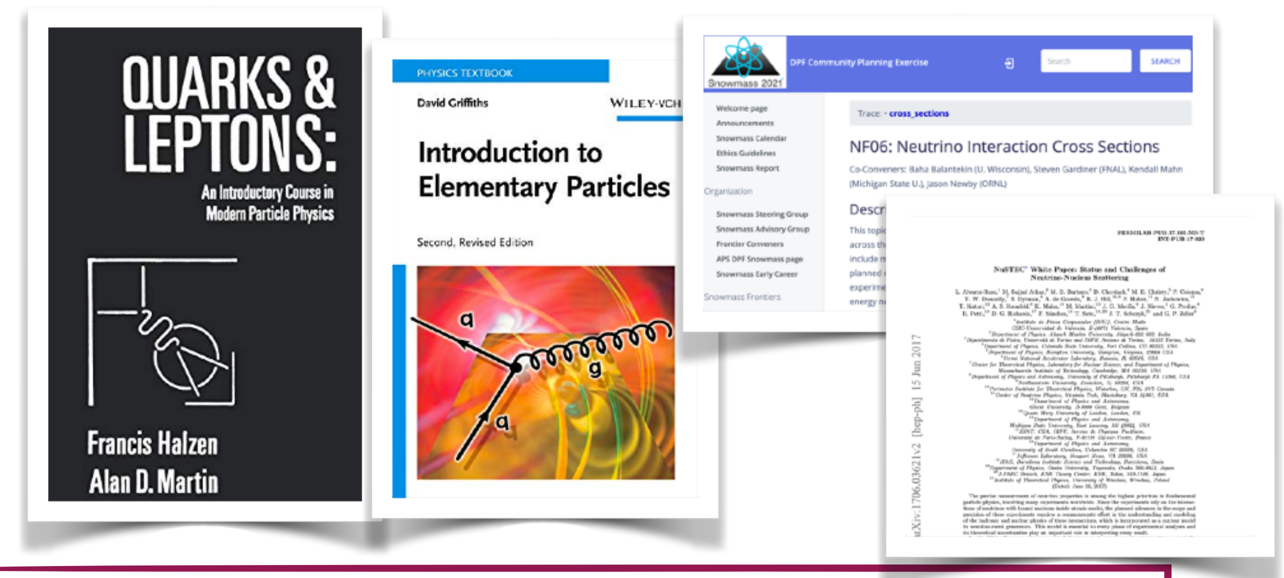
THE GOALS OF THIS LECTURE

- **Discuss neutrino-nucleus interactions…**
  - …why they're **important**
  - …what makes them so **hard to understand**
  - …how we **measure** them
  - …and some of the **experimental measurements** showing what we know so far
- My aim is for you to leave this lecture understanding some of the concepts to the point that you are able to talk to your colleagues about these problems, and understand seminars at the lab

WHAT I WILL NOT COVER

But here are some key words you can google…

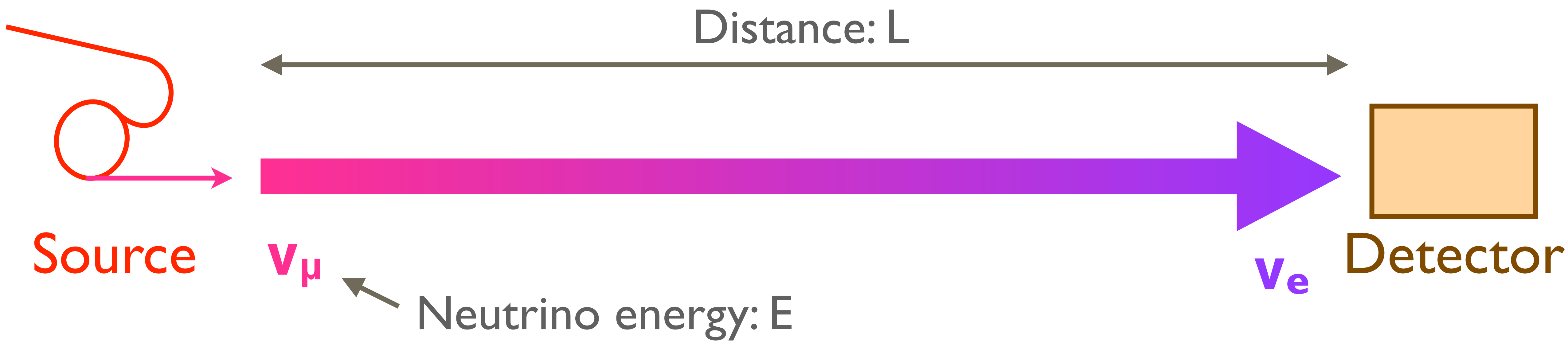
- Most of the maths!
  - A lot of the maths in this area is something you'll cover in grad school or beyond (if you continue in neutrino physics)
  - Today we'll focus on the physical concepts and ideas more than the underlying theory
- Handedness and parity violation in weak interactions
- Electron scattering or high-energy neutrino interactions
- Unfolding (ok, I'll mention this, but it's a much bigger topic than I'm going to have time to go into)



Some references:

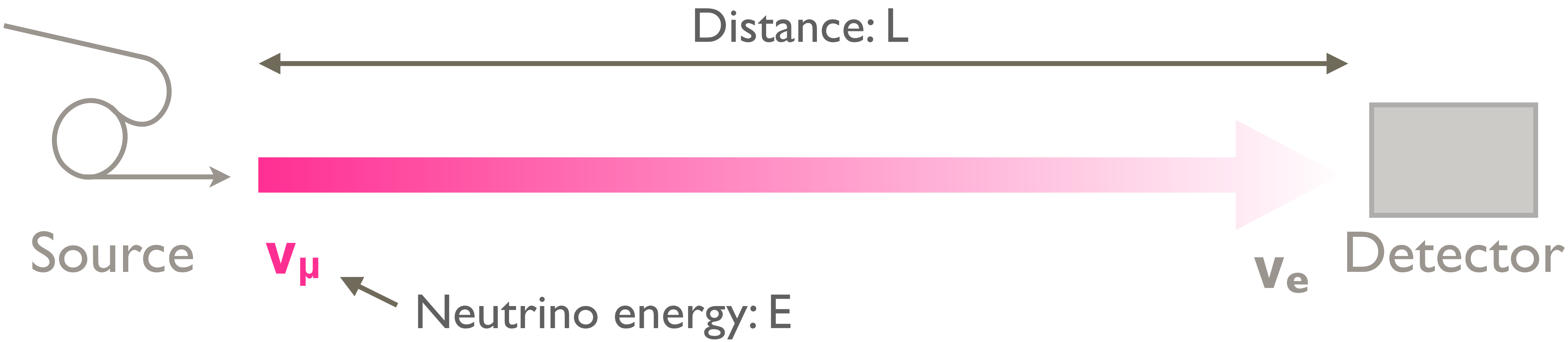
- Halzen and Martin, Quarks and Leptons (textbook)
- Griffiths, Introduction to Elementary Particles (textbook)
- NuSTEC White Paper: Status and Challenges of Neutrino-Nucleus Scattering (as of 2017)
- Review Paper: Progress in measurements of 0.1-10 GeV neutrino scattering and anticipated results from future experiments (from 2018)
- Look at some of the LOIs submitted to Snowmass on the topic of Neutrino Interactions (very current, this year!)

RECAP: NEUTRINO OSCILLATION



Muon neutrino disappearance

Electron neutrino appearance

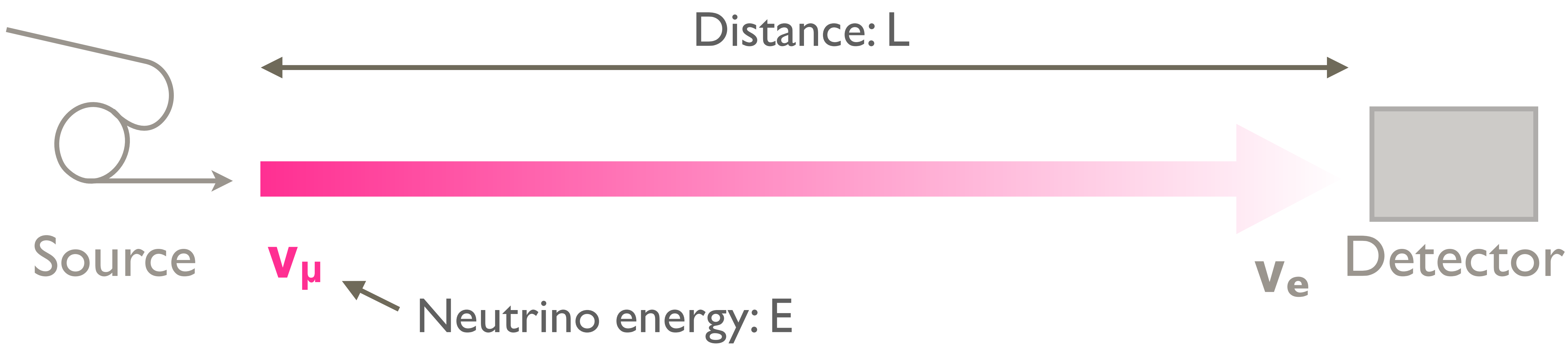


Probability to detect a neutrino of a given flavour **oscillates** as:

$$\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}$$
$$\times\left[1 - \cos^2\theta_{13}\sin^2\theta_{23}\right]\sin^2\frac{\Delta m^2_{32} L}{4E}$$
$$+\,(\text{solar, matter effect terms})$$



Depends on **mixing angles** from the PMNS matrix (appearance probability also depends on δ_{CP})

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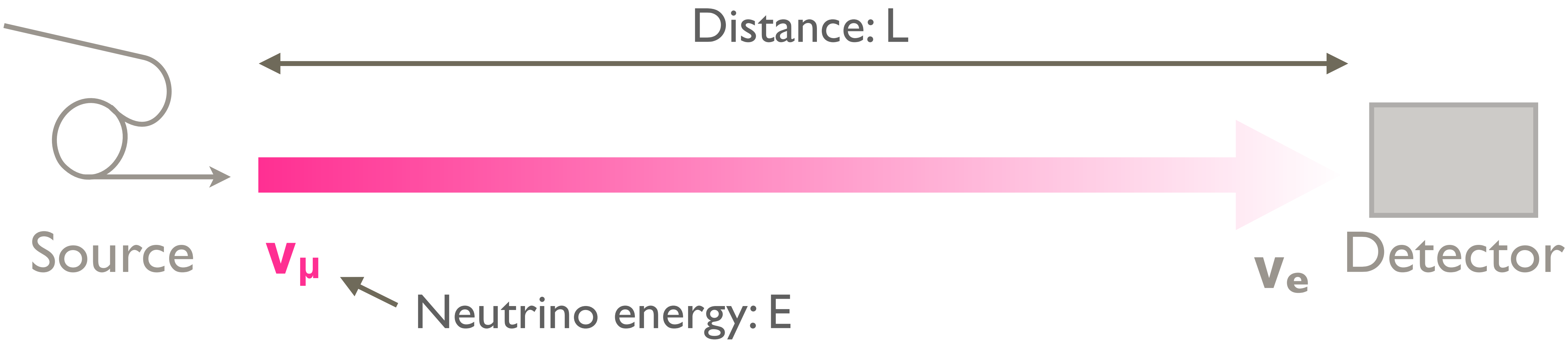
And **mass-squared splittings**



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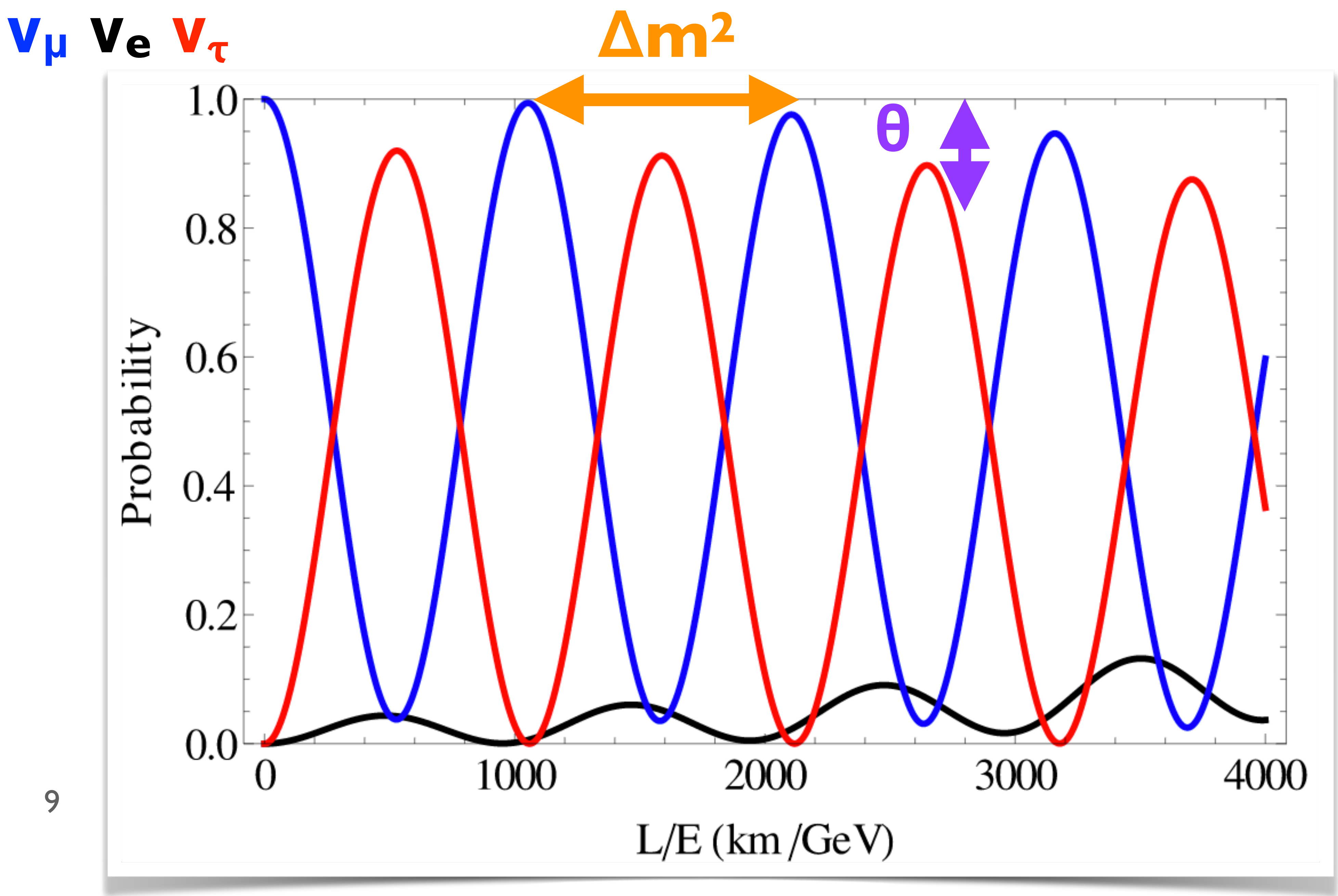
And **mass-squared splittings**

Neutrino oscillation
→ Neutrinos have mass
→ Physics beyond the Standard Model!

RECAP: NEUTRINO OSCILLATION

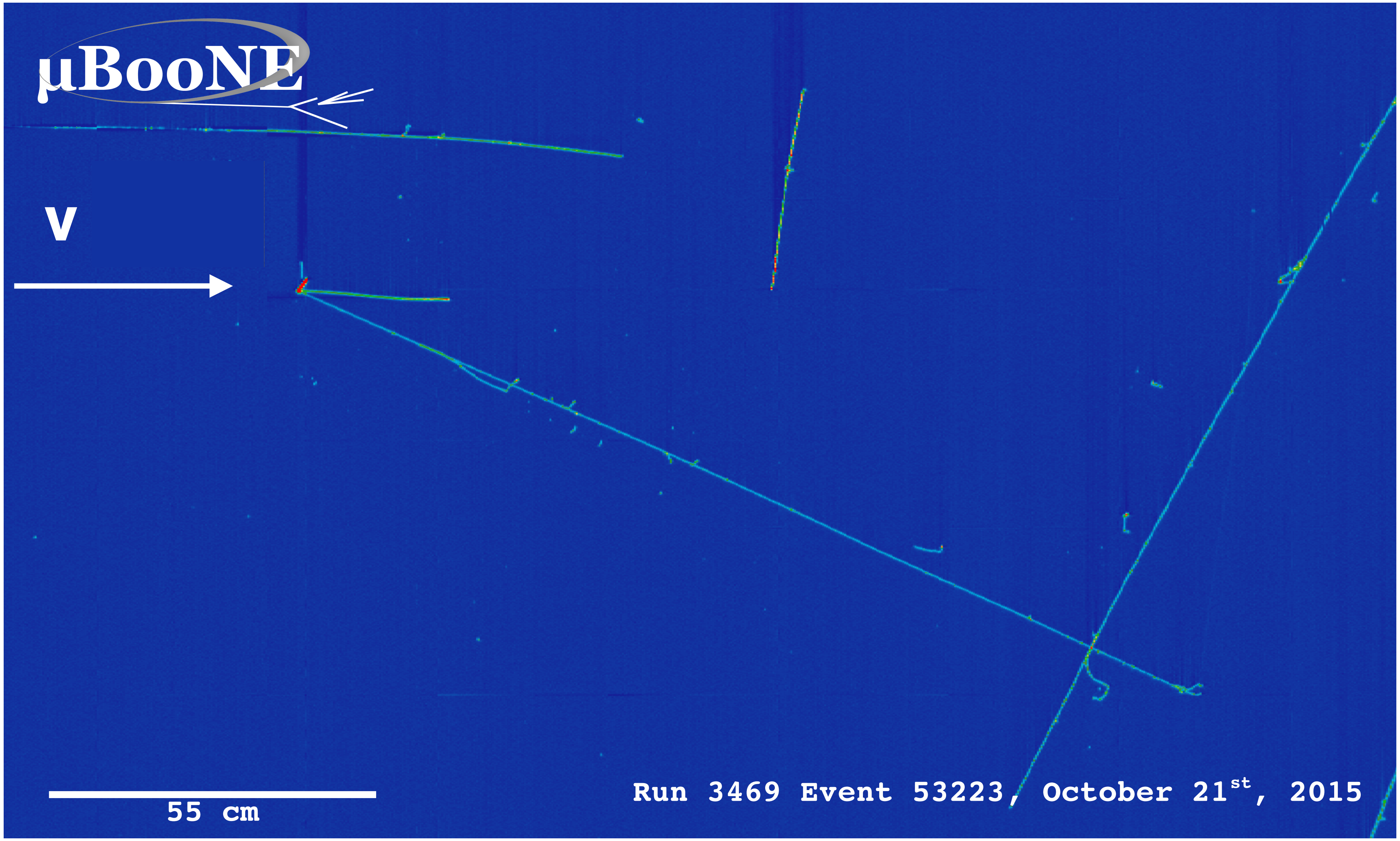


THE PROBLEM

This is what a neutrino looks like in a particle detector:

THE PROBLEM

We can only "see" neutrinos when they interact



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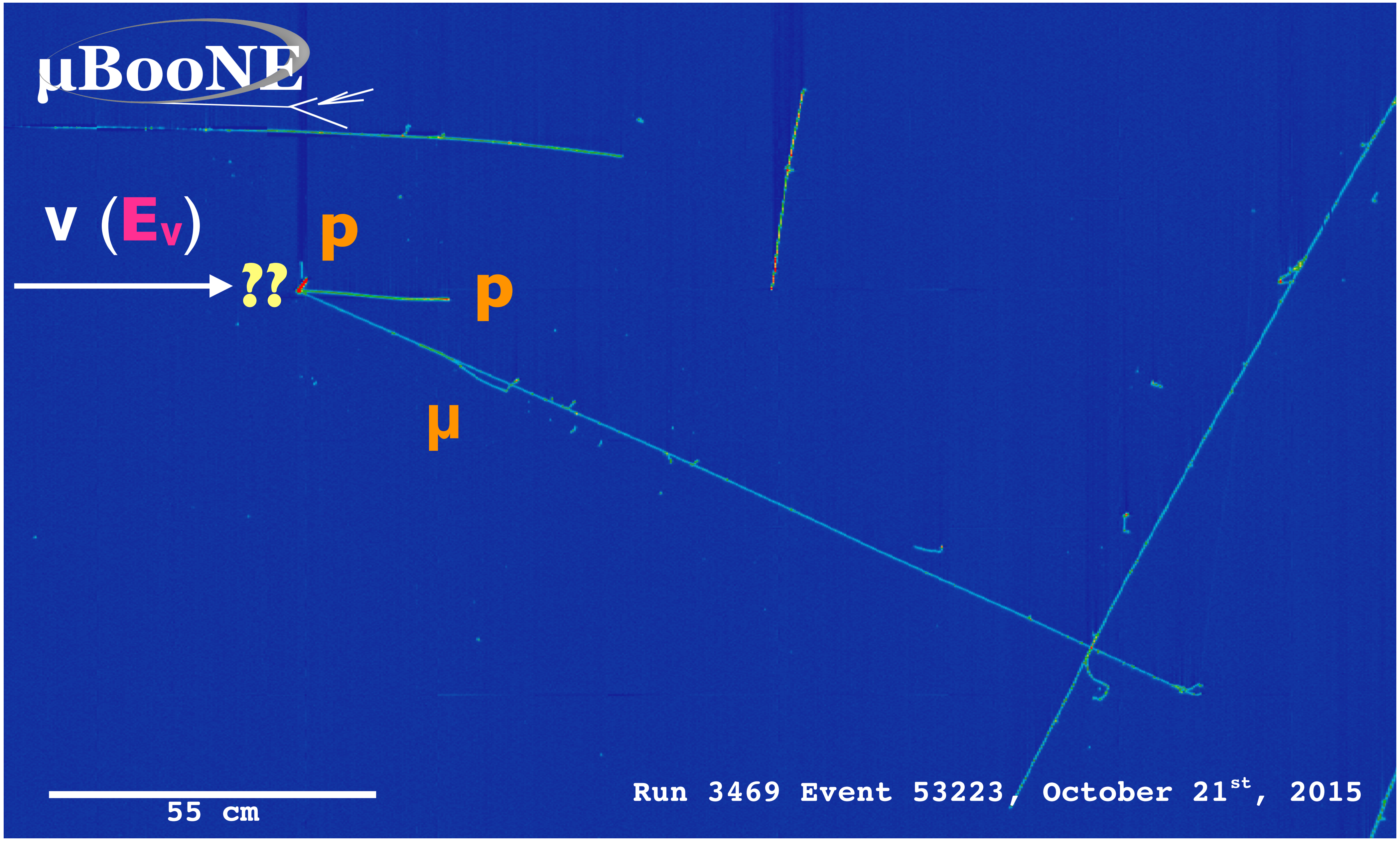

THE PROBLEM

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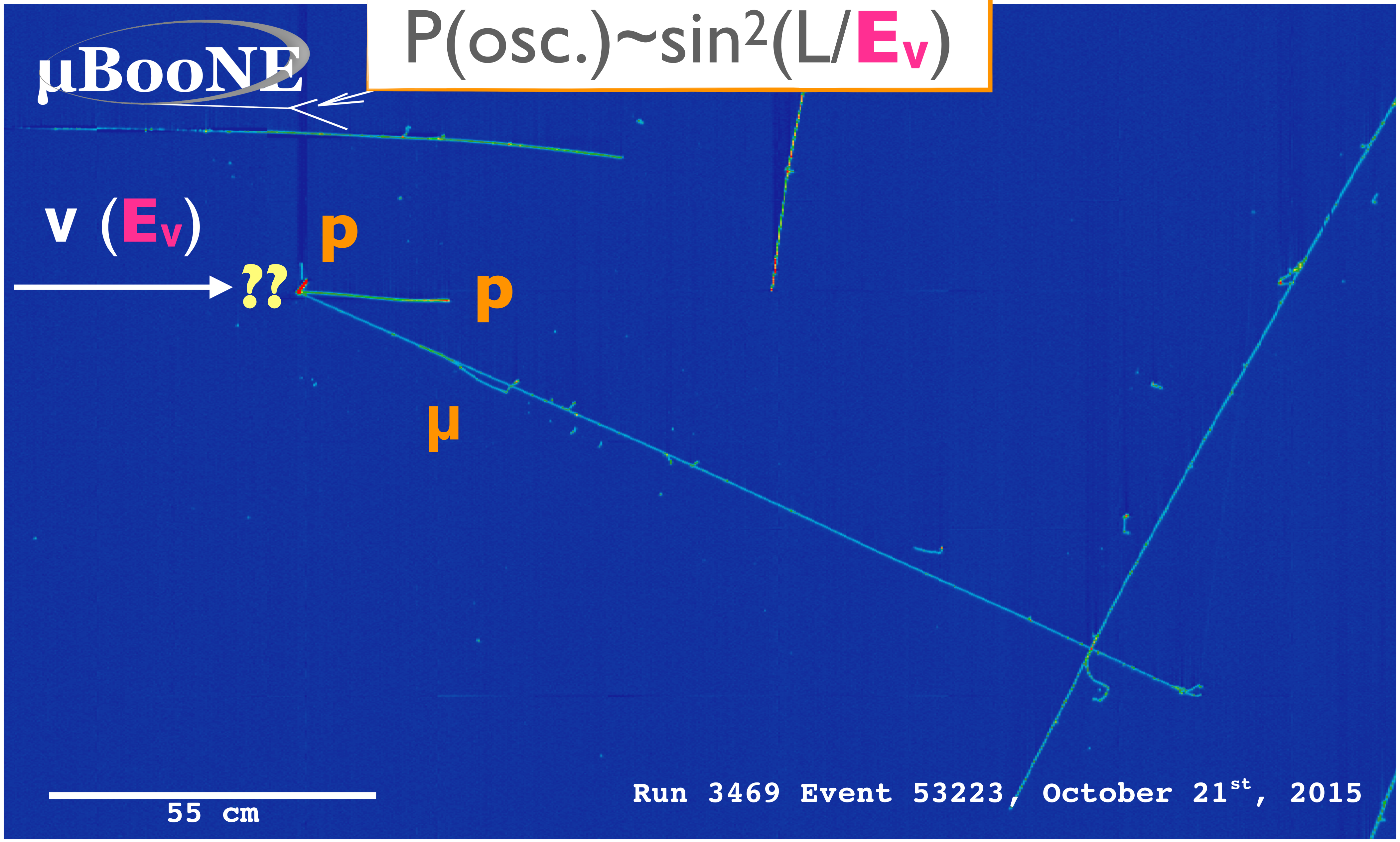
$P(osc.) \sim \sin^2(L/E_\nu)$



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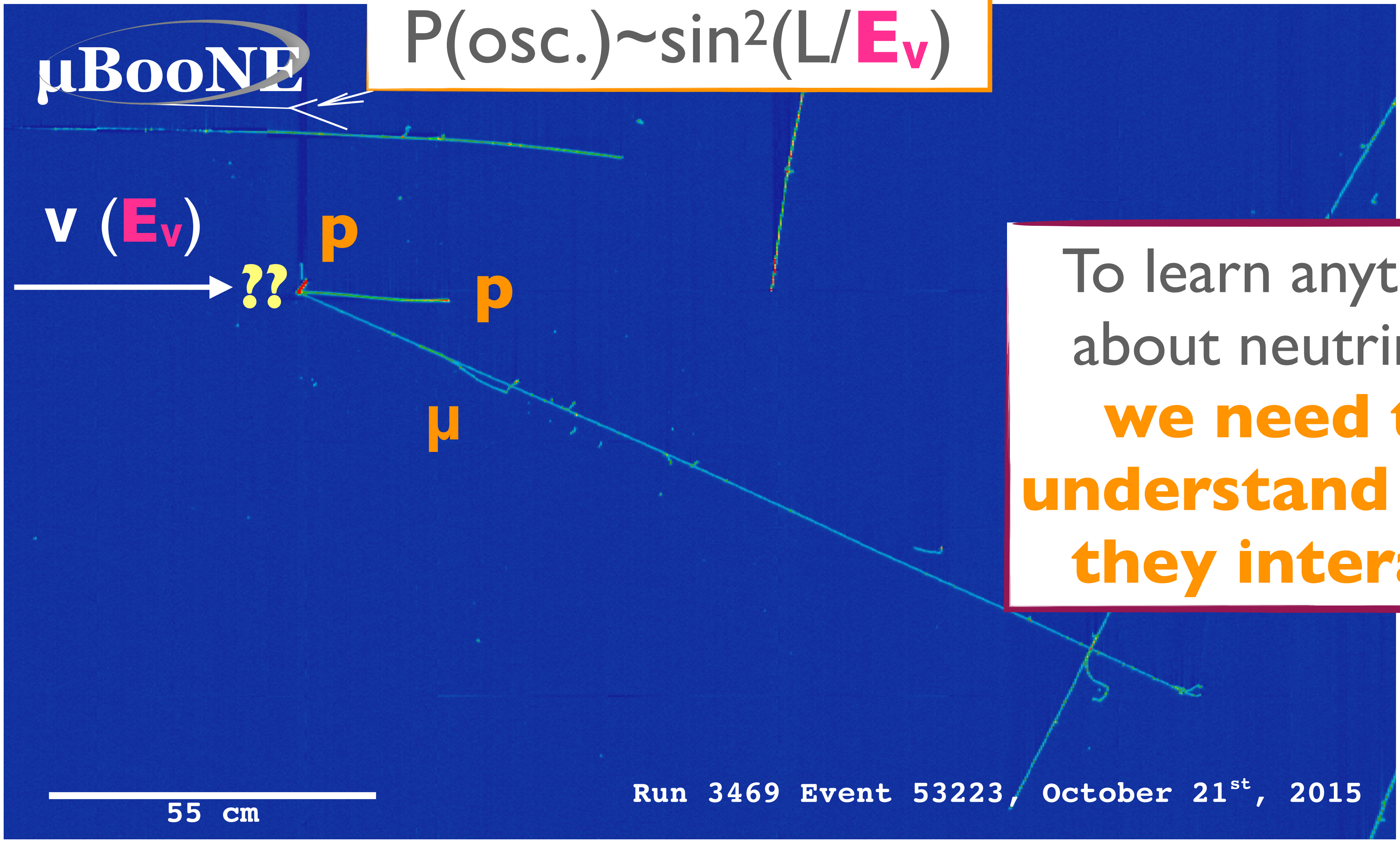
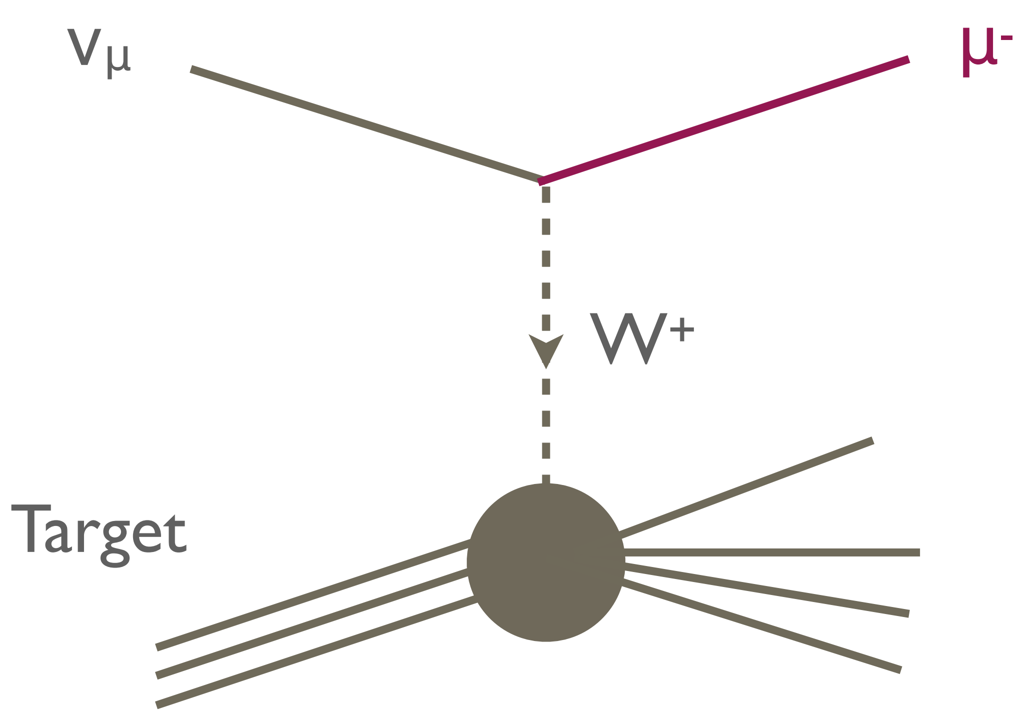


To learn anything about neutrinos, **we need to understand how they interact**

HOW DO NEUTRINOS INTERACT?

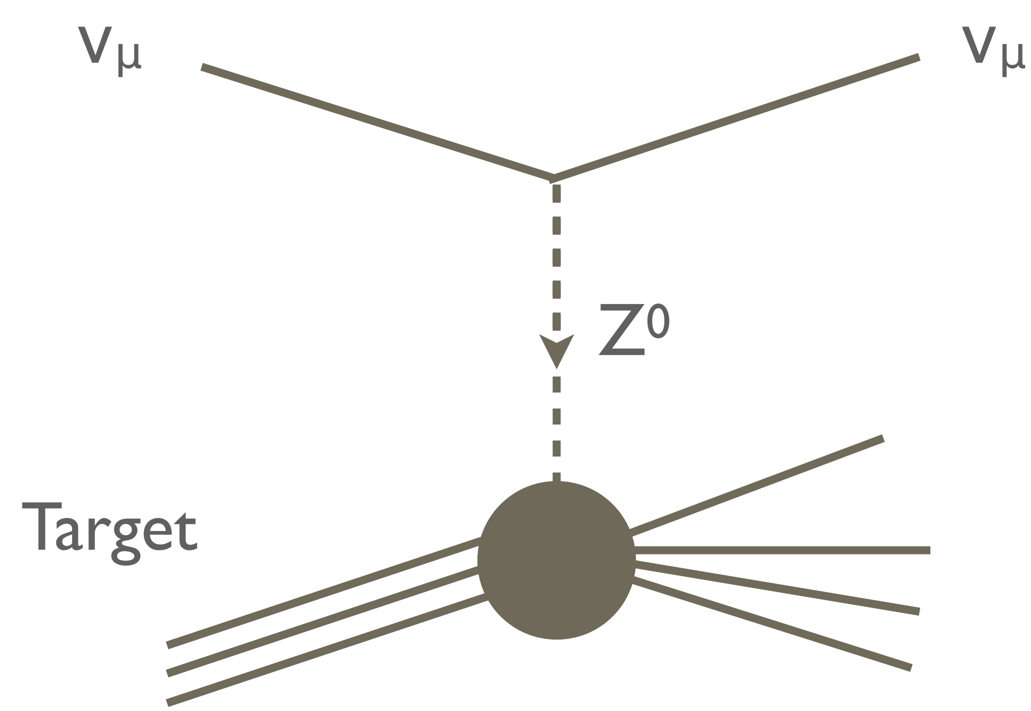
HOW DO NEUTRINOS INTERACT?



Charged-current

→ Exchange of W boson

→ **Lepton produced with same flavour as ν**



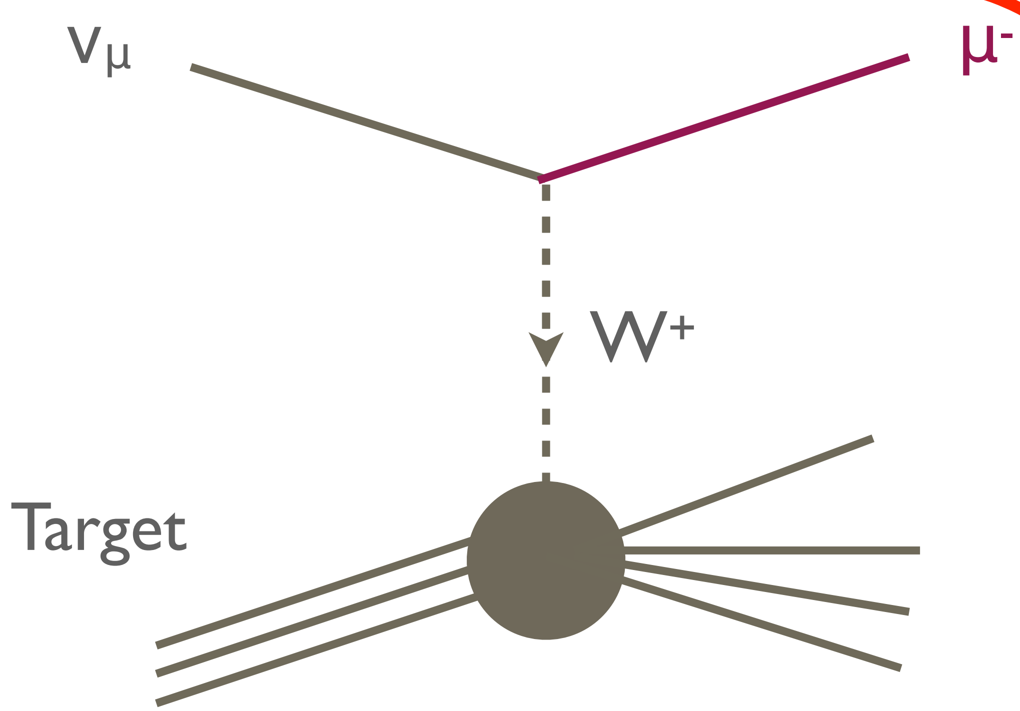
Neutral-current

→ Exchange of Z boson

→ Independent of ν flavour

→ **We will never know the flavour of the original ν!**

HOW DO NEUTRINOS INTERACT?



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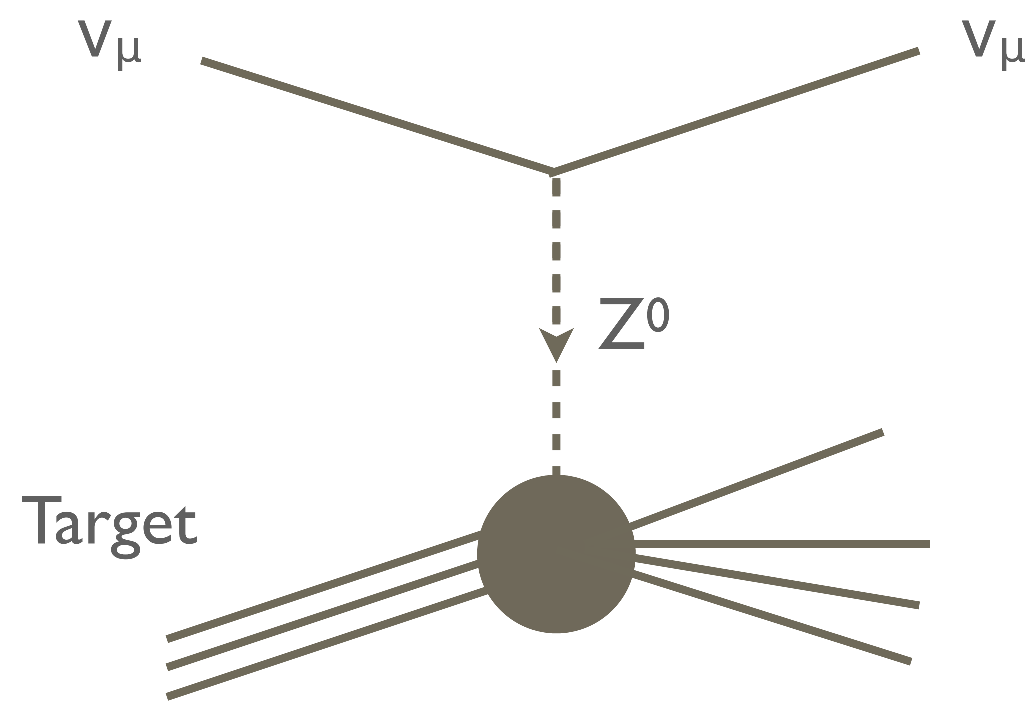


Neutral-current

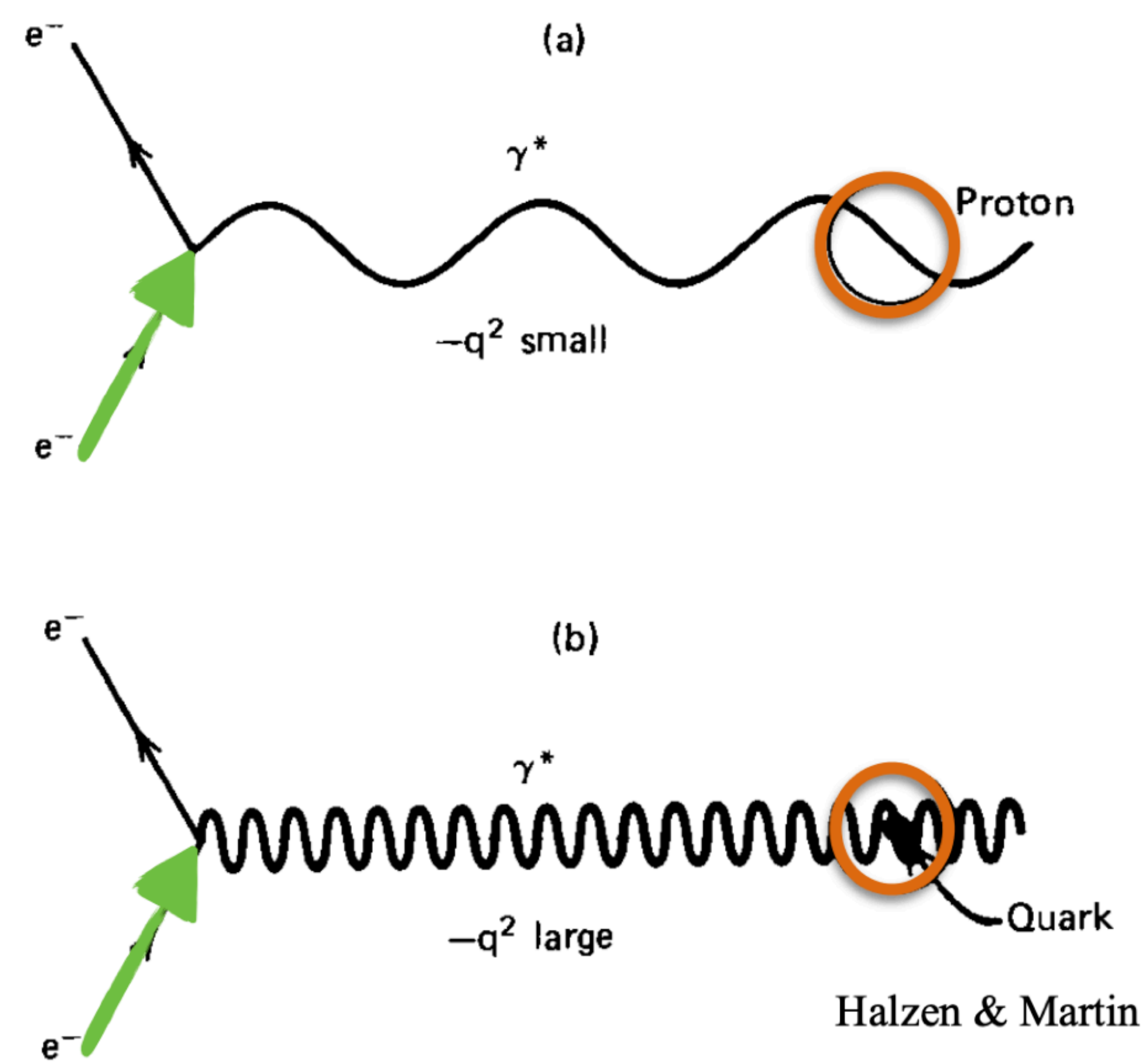
→ Exchange of Z boson

→ Independent of ν flavour

→ **We will never know the flavour of the original ν!**

HOW DO NEUTRINOS INTERACT?

- What the neutrino interacts with depends on the energy of the particle exchanged → "energy transfer", ω
- **Higher energy transfer = smaller de Broglie wavelength = can "see" smaller particles**



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HOW DO NEUTRINOS INTERACT?

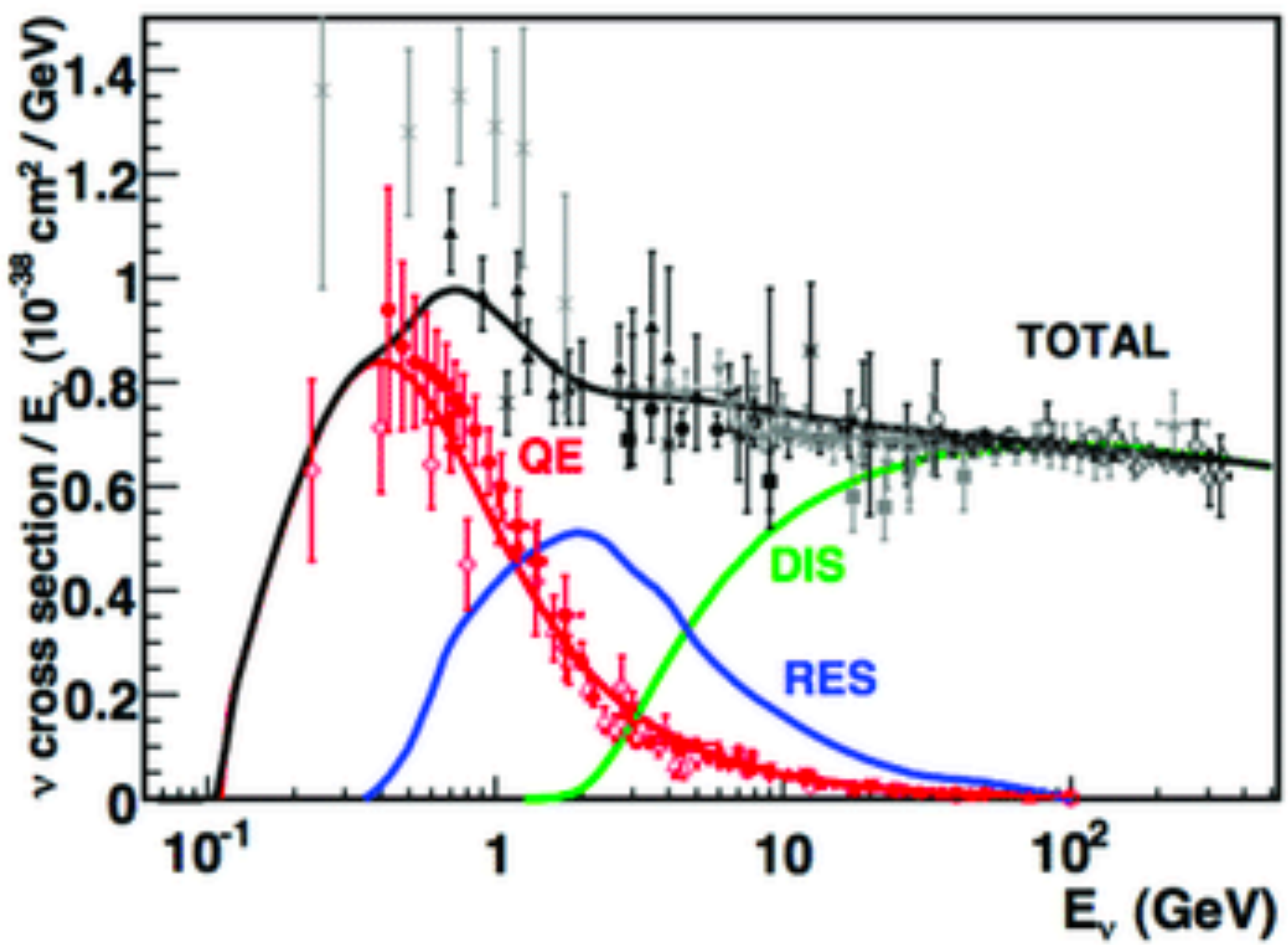
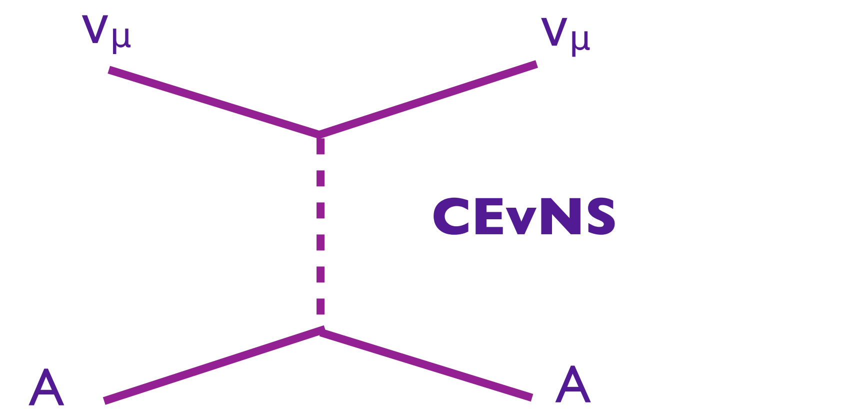
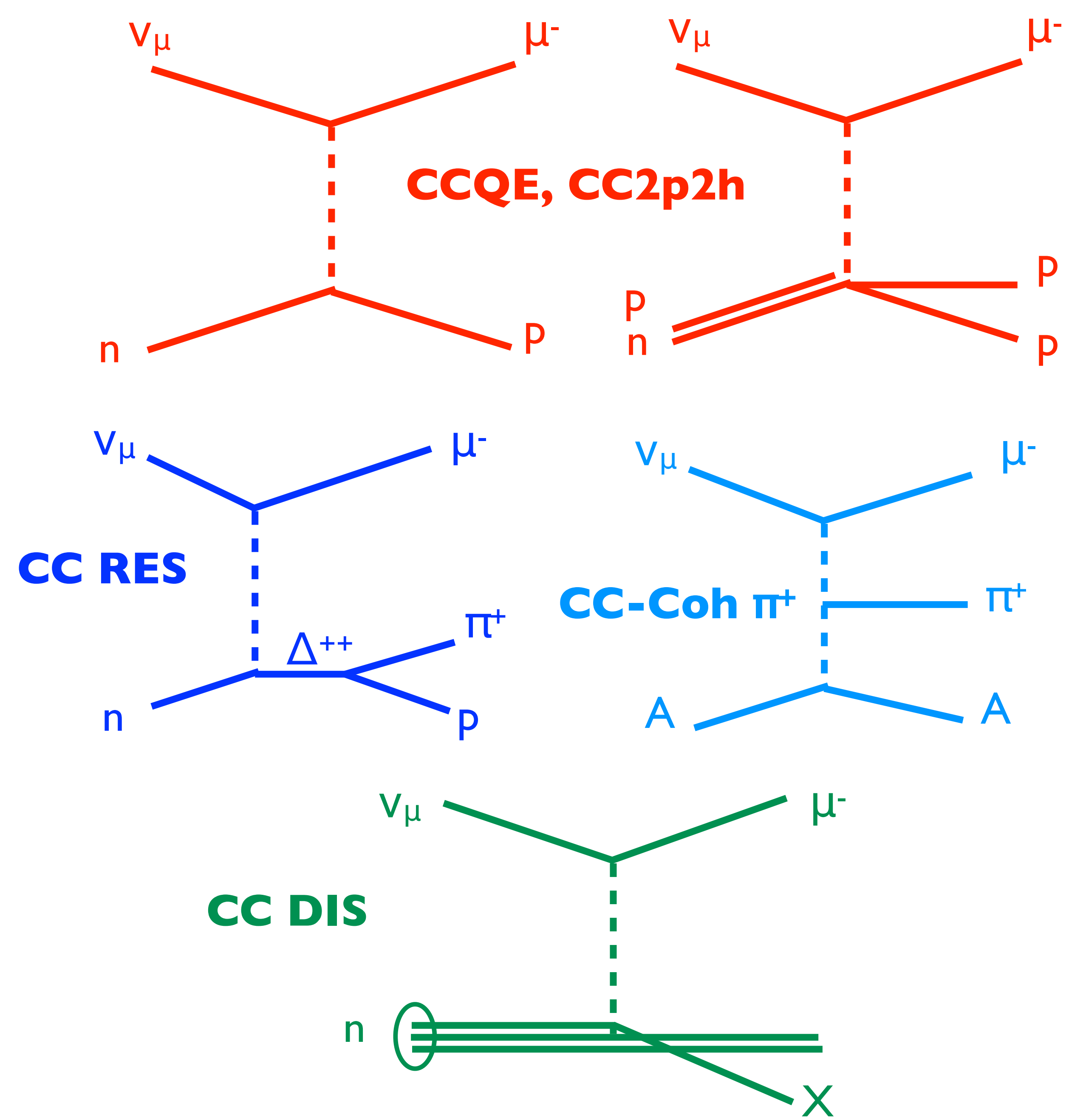


Figure: J.A. Formaggio and G. P. Zeller
Rev. Mod. Phys. 84, 1307 (2012)





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NEUTRINO ENERGY RECONSTRUCTION

$\nu_\mu + n \rightarrow \mu^- + p$

$$E^{QE}_{\nu} = \frac{m_p{}^2 - (m_n - E_b)^2 - m_\mu{}^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

Kinematic

- Assume an interaction type (e.g. CCQE) → if a CCQE interaction with a nucleon at rest, can calculate neutrino energy from lepton kinematics

Advantage:

- Doesn't need hadron reconstruction

Disadvantages:

- Energy is wrong if underlying interaction is wrong (i.e. not CCQE)
- Nuclear effects smear resolution

$\nu_\mu + A \rightarrow \mu^- + X$

$$E_\nu = E_\mu + E_X$$

Calorimetric

- Add up all measured energy from the leptonic and hadronic components

Advantage:

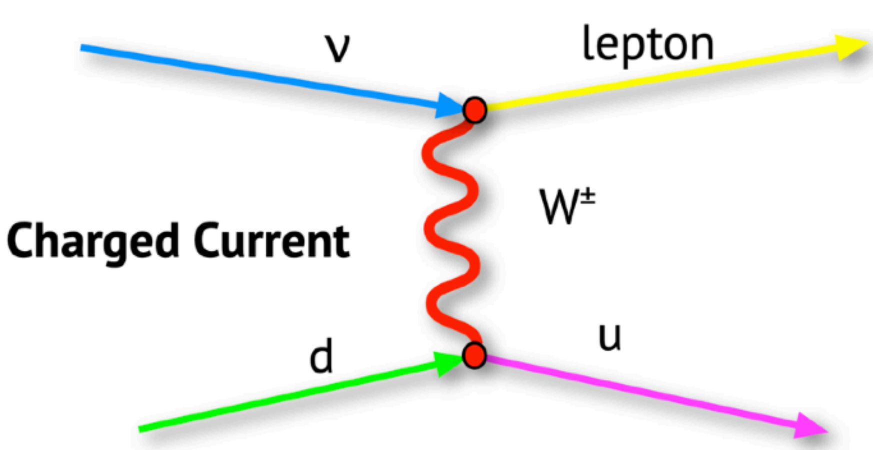
- No a priori assumption about underlying interaction

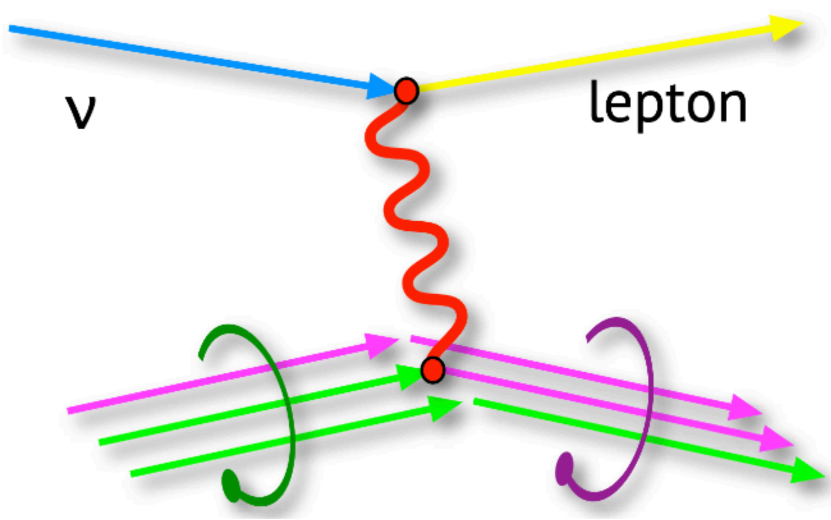
Disadvantages:

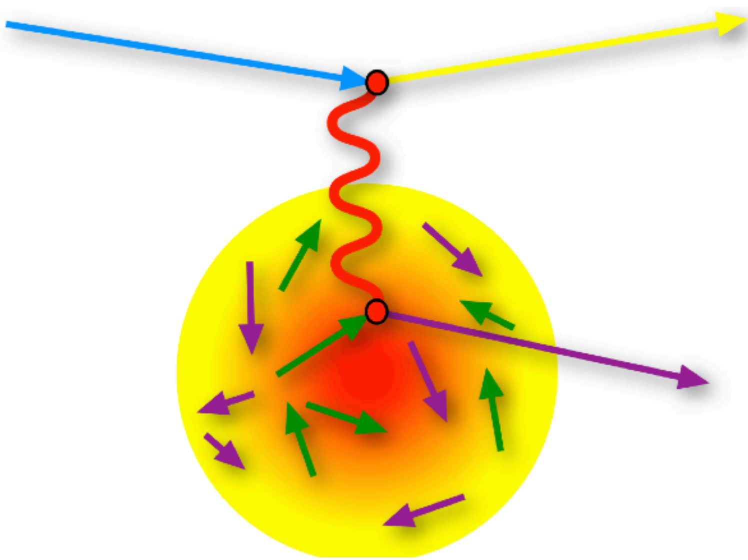
- Relies on hadron reconstruction
- Nuclear effects smear resolution

NUCLEAR EFFECTS: IT'S EVEN MORE COMPLICATED

Interaction with…







Bare fermion
(Grad school) homework problem

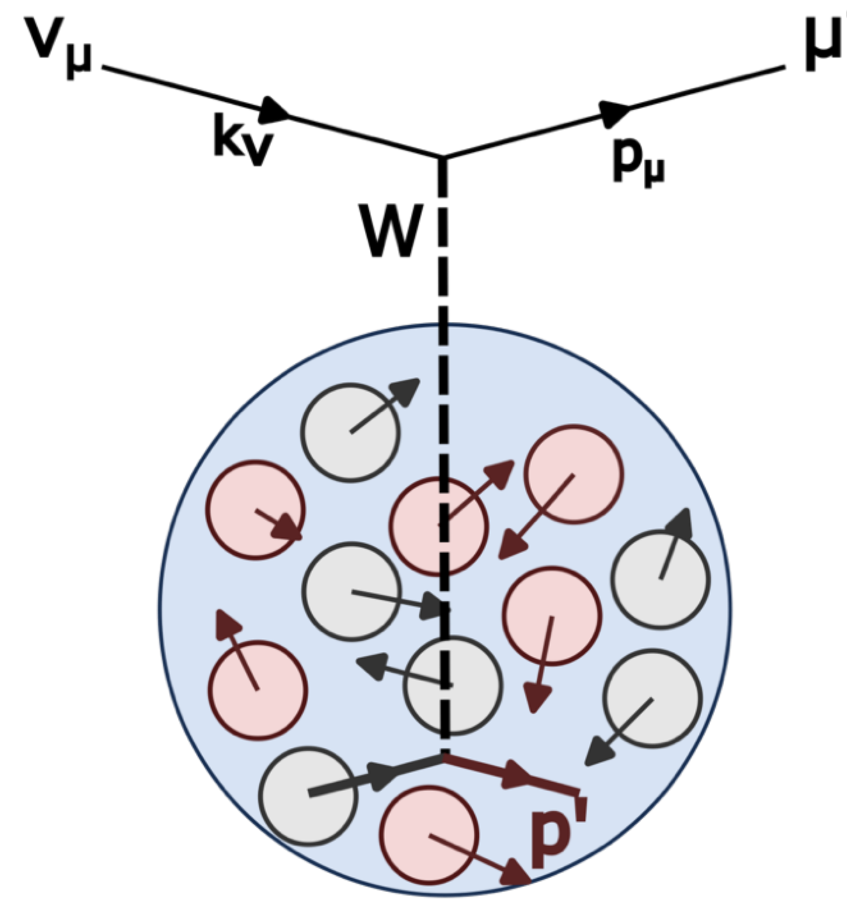
Free nucleon
Parameterise with form factors

Nucleus
What is the initial state?
What escapes the nucleus?

Images: G. Perdue

NUCLEAR EFFECTS: IT'S EVEN MORE COMPLICATED

Image: L. Pickering



The first problem is understanding the **initial state**. That means:

- The nucleon in the interaction is not free or at rest — it is in a nucleus. It experiences some **potential due to other nucleons** and has **some momentum**
- This is deep **nuclear physics**! We have some models for the initial nucleon momentum — some simple, some more sophisticated — but they give different answers and we don't know what's right
- The nucleons can also form **correlated pairs** (or triplets? More?) so then the interaction may not even be with a single nucleon, but with a **correlated state of multiple nucleons** (e.g. 2p2h)

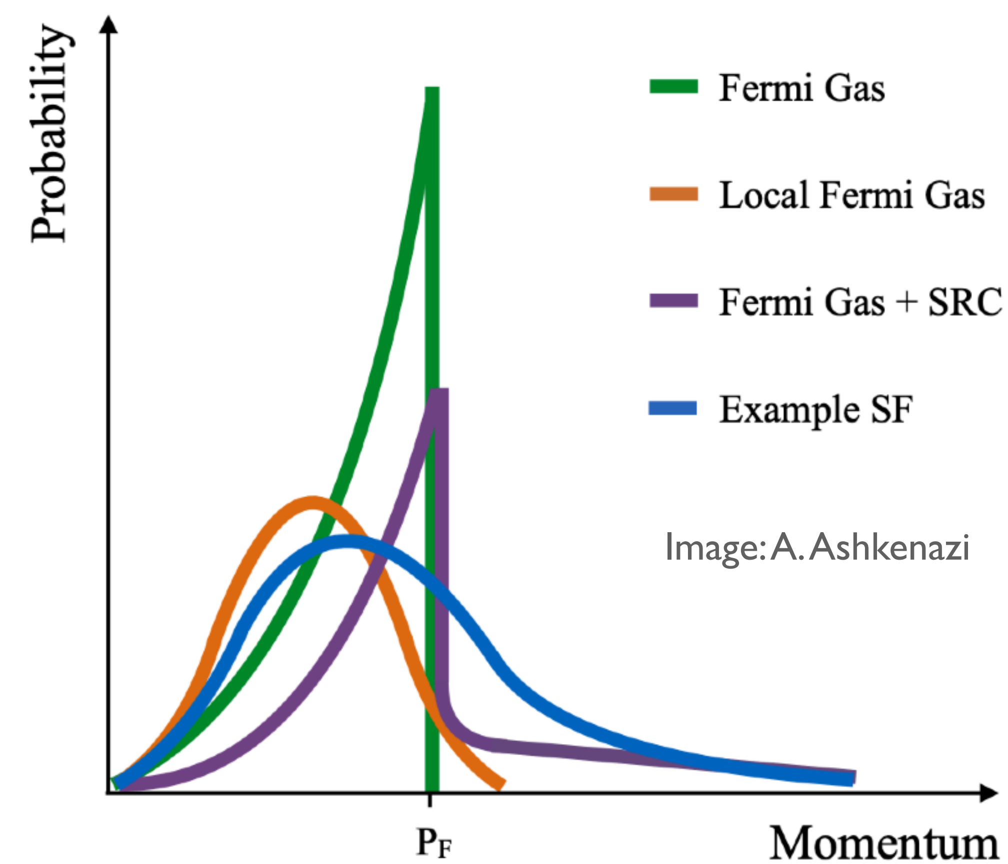


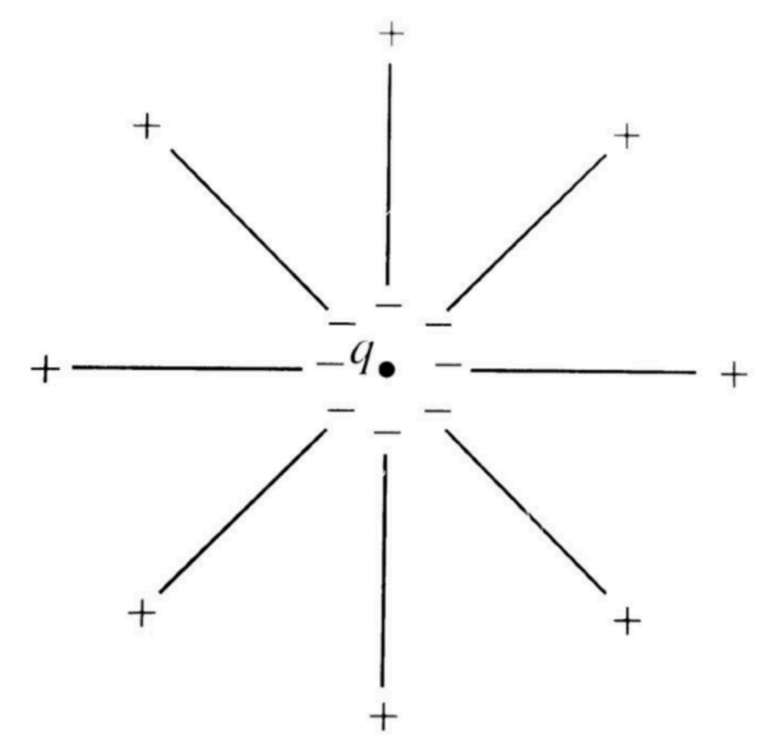
Image: A. Ashkenazi

NUCLEAR EFFECTS: IT'S EVEN MORE COMPLICATED

Griffiths, Introduction to Electrodynamics

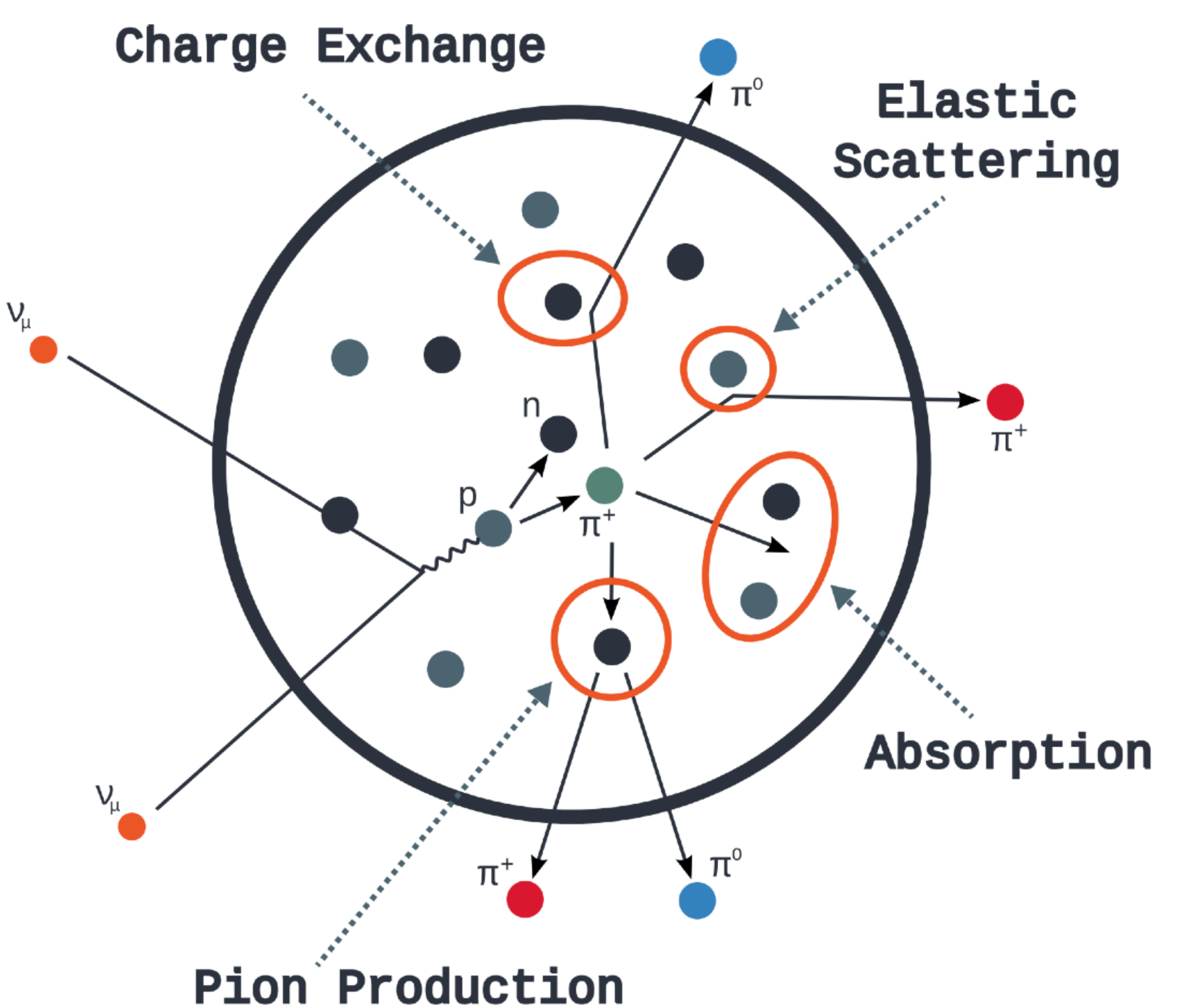
Charge screening in the nuclear medium "RPA"

- Analagous to **screening of electric charge in a dielectric**
- Calculated using **Random Phase Approximation**
- Effect is to **suppress cross section at low energy**, momentum transfer (= **forward-going lepton**)
- Most important for CCQE interactions



NUCLEAR EFFECTS: IT'S EVEN MORE COMPLICATED

Image: T. Golan



Final State Interactions:

Particles may re-interact as they exit nucleus

→ particles can be lost

→ particles you see may not be from neutrino interaction

NUCLEAR EFFECTS: IT'S EVEN MORE COMPLICATED

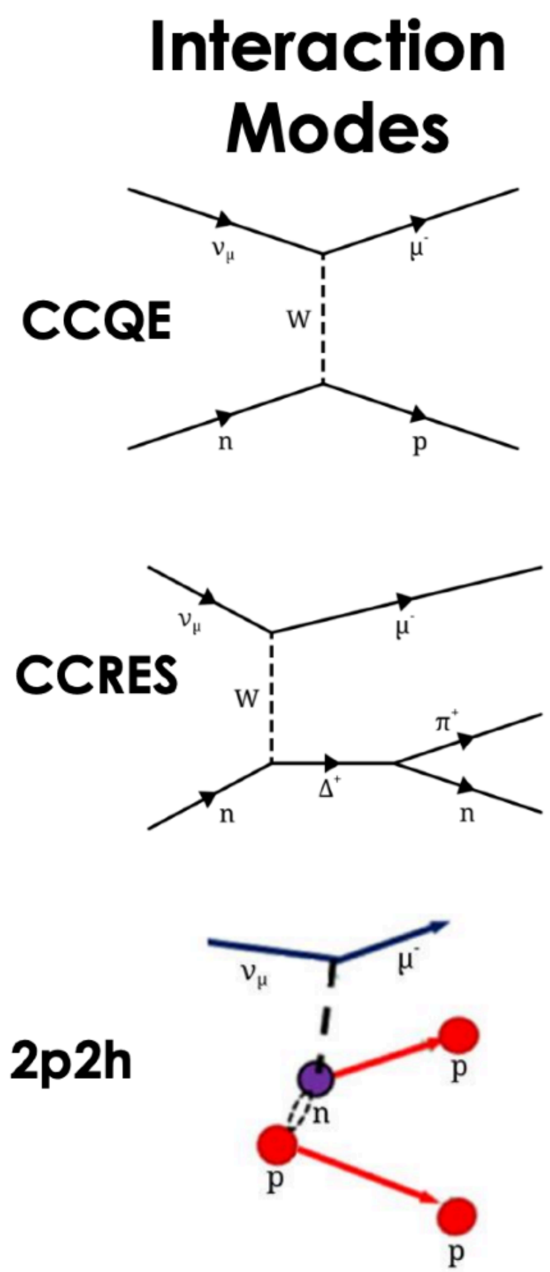
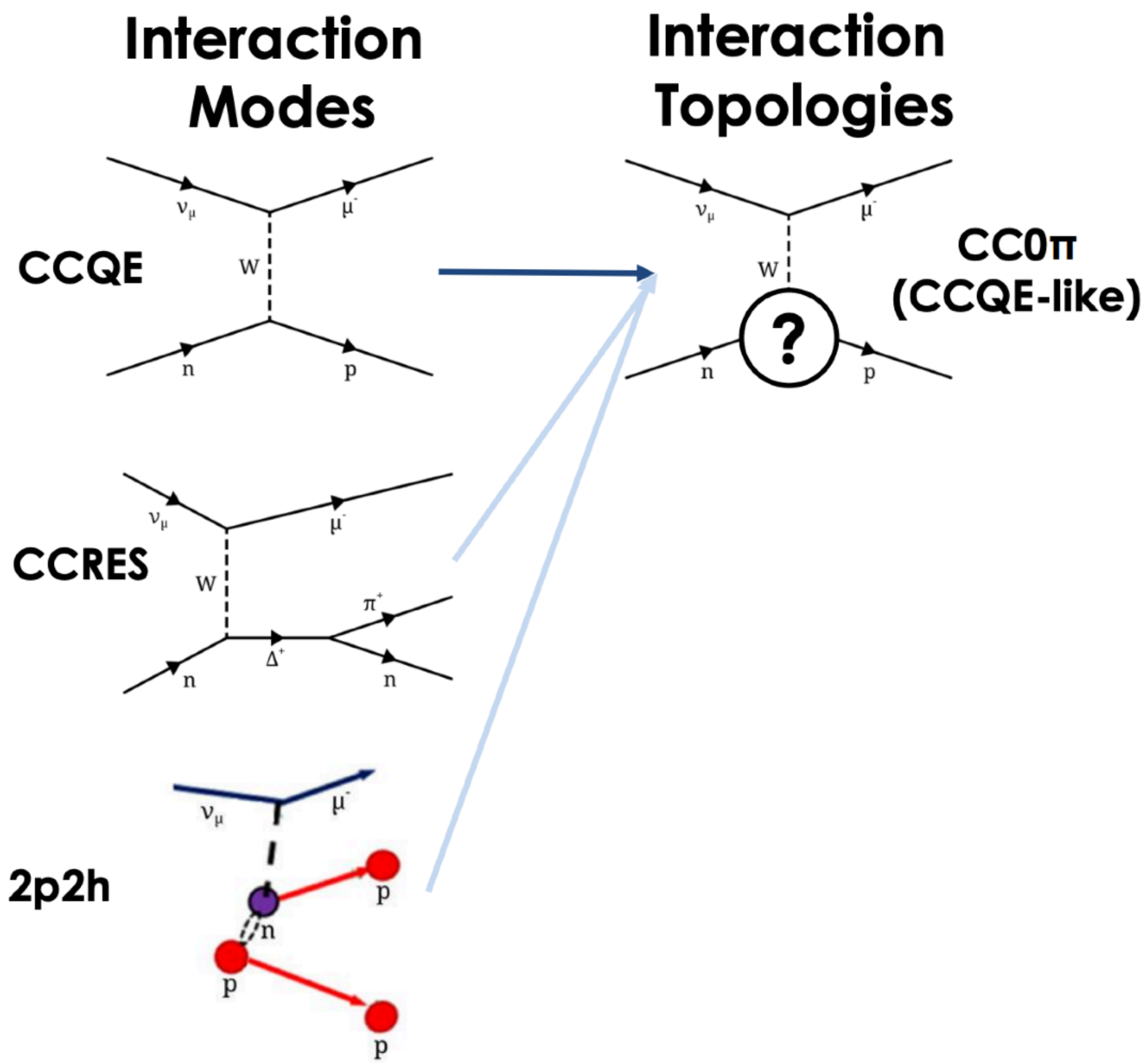


Figure: S. Dolan

NUCLEAR EFFECTS: IT'S EVEN MORE COMPLICATED

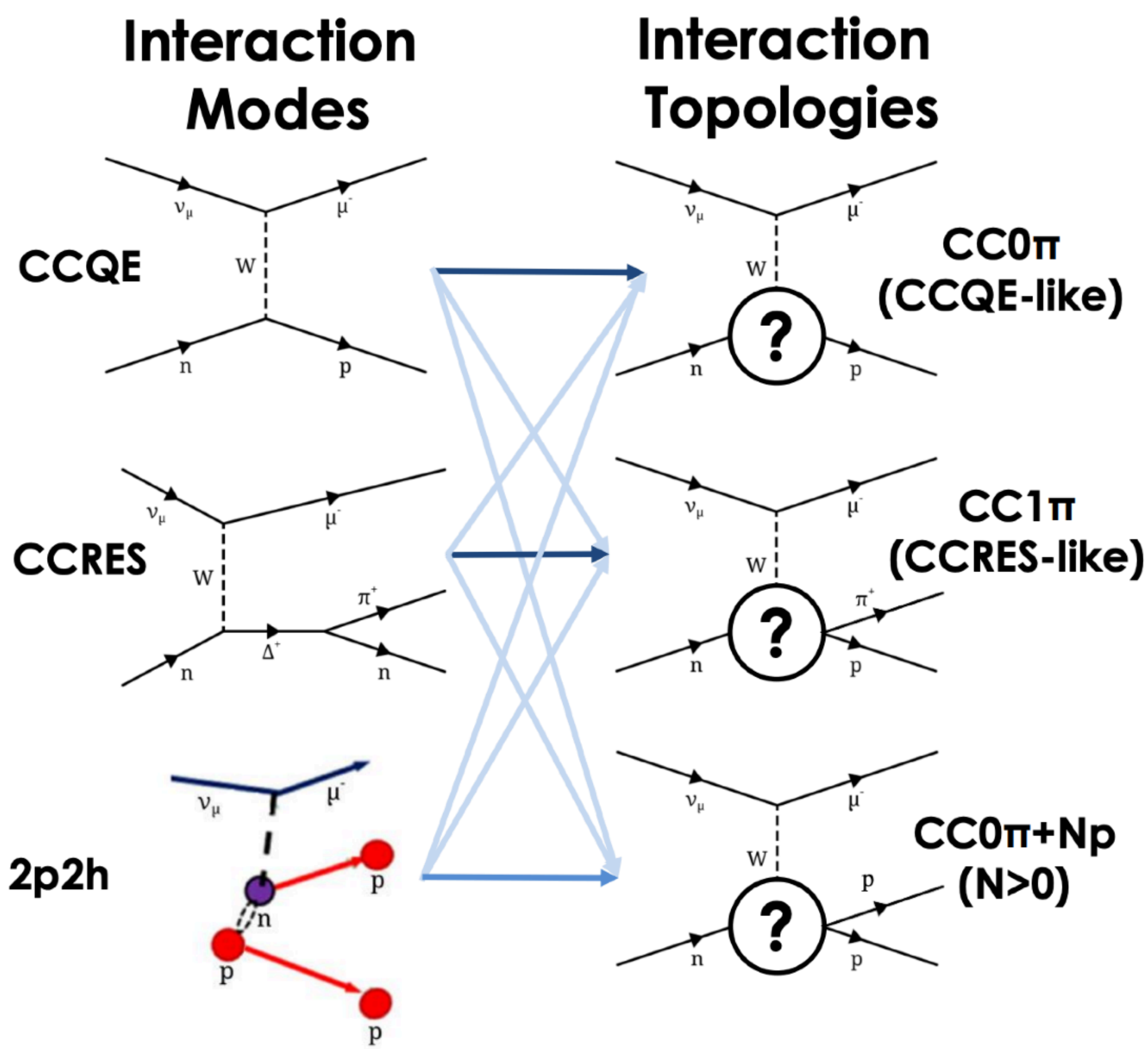


We measure what our detector actually sees

But this contains all sorts of physics!

Figure: S. Dolan

NUCLEAR EFFECTS: IT'S EVEN MORE COMPLICATED



We measure what our detector actually sees

But this contains all sorts of physics!

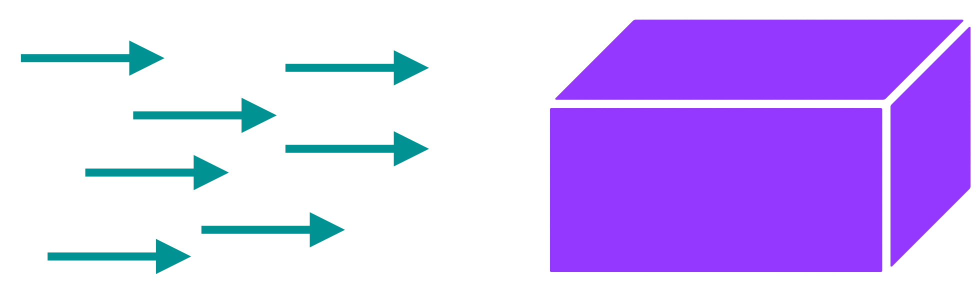
Figure: S. Dolan

HOW TO MEASURE A NEUTRINO INTERACTION CROSS SECTION

WHAT IS A CROSS SECTION?

Think about neutrinos flying at a detector. How many neutrinos will interact?

Flux of incoming neutrinos ϕ



Detector containing number of nuclei T

Number of targets

$$N = \phi T \sigma$$

Number of neutrinos that interact

Cross section

Total flux of incident neutrinos per unit area

WHAT IS A CROSS SECTION?

The cross section is a measure of the probability that a neutrino will interact

$$\sigma = \frac{N}{\phi T}$$

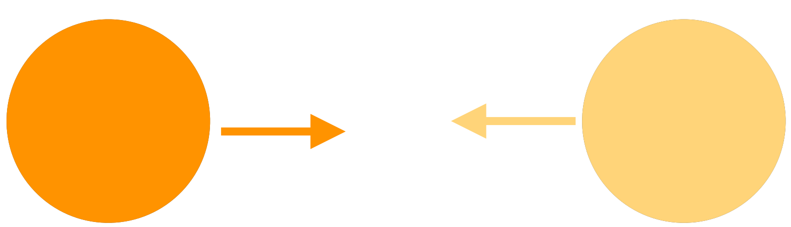
Cross section

Number of neutrinos that interact

Total flux of incident neutrinos per unit area

Number of targets

Classical analogy: think of the literal cross section of two balls that you throw at each other



Larger cross section = more likely to collide

IN PRACTICE:

Total cross section

→ probability for this interaction to happen at all

Number of interactions we measured

$$\sigma = \frac{N_{signal}}{\varepsilon\, \phi\, N_{targets}}$$

Efficiency

→ probability we measure an interaction if it happens

Incoming neutrino flux

Number of targets

IN PRACTICE:

Differential cross section

→ probability for this interaction to happen, in bin i in variable X (e.g at a specific energy or angle)

$$\frac{d\sigma}{dX_i} = \frac{N_{signal,i}}{\varepsilon_i \, \phi \, N_{targets} \, \Delta_i}$$

Number of interactions we measured in bin i

Width of bin i

Efficiency in bin i

→ probability we measure an interaction in bin i if it happens

Incoming neutrino flux

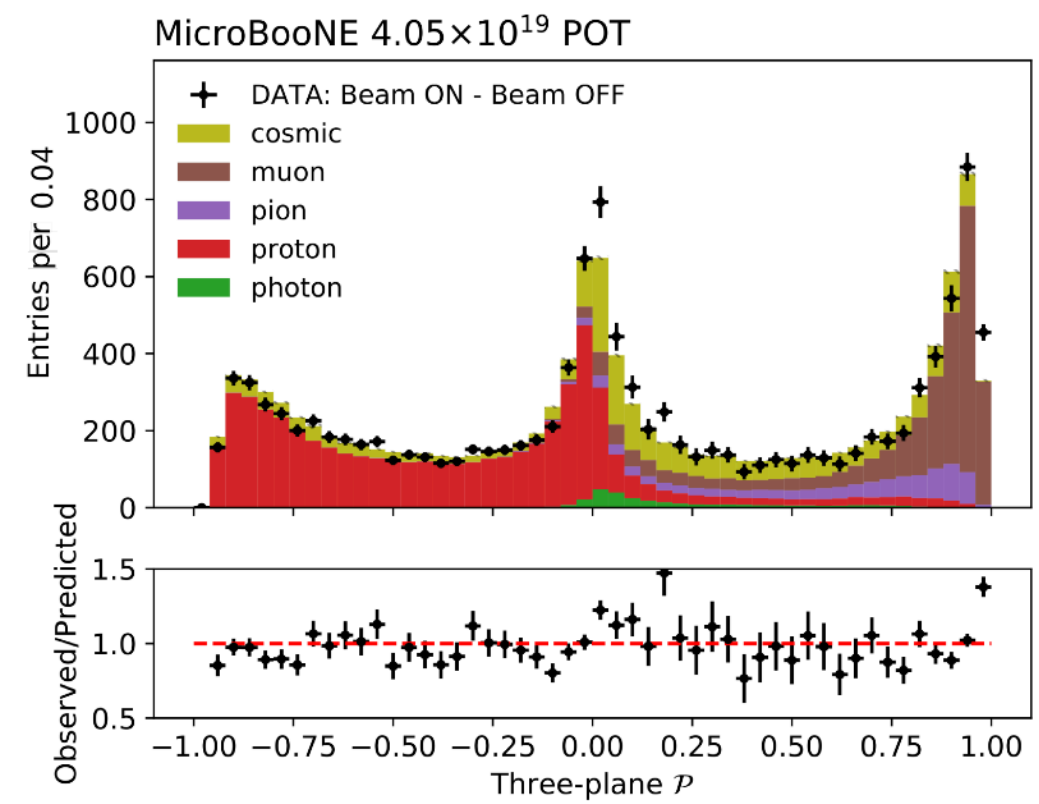
Number of targets

HOW DO WE MEASURE IT?

Number of interactions, $N_{signal,i}$

- Ideally, we'd be able to pick out exactly the type of interactions we want from our data
- But life doesn't work like that! Reconstruction can fail, our algorithms can get confused, and they don't always perfectly identify the particles we want
- So $N_{data,i} = N_{signal,i} + N_{bkg,i}$

JHEP 2021, 153, (2021)



$$\frac{d\sigma}{dX_i} = \frac{N_{data,i} - N_{bkg,i}}{\varepsilon_i \, \phi \, N_{targets} \, \Delta_i}$$

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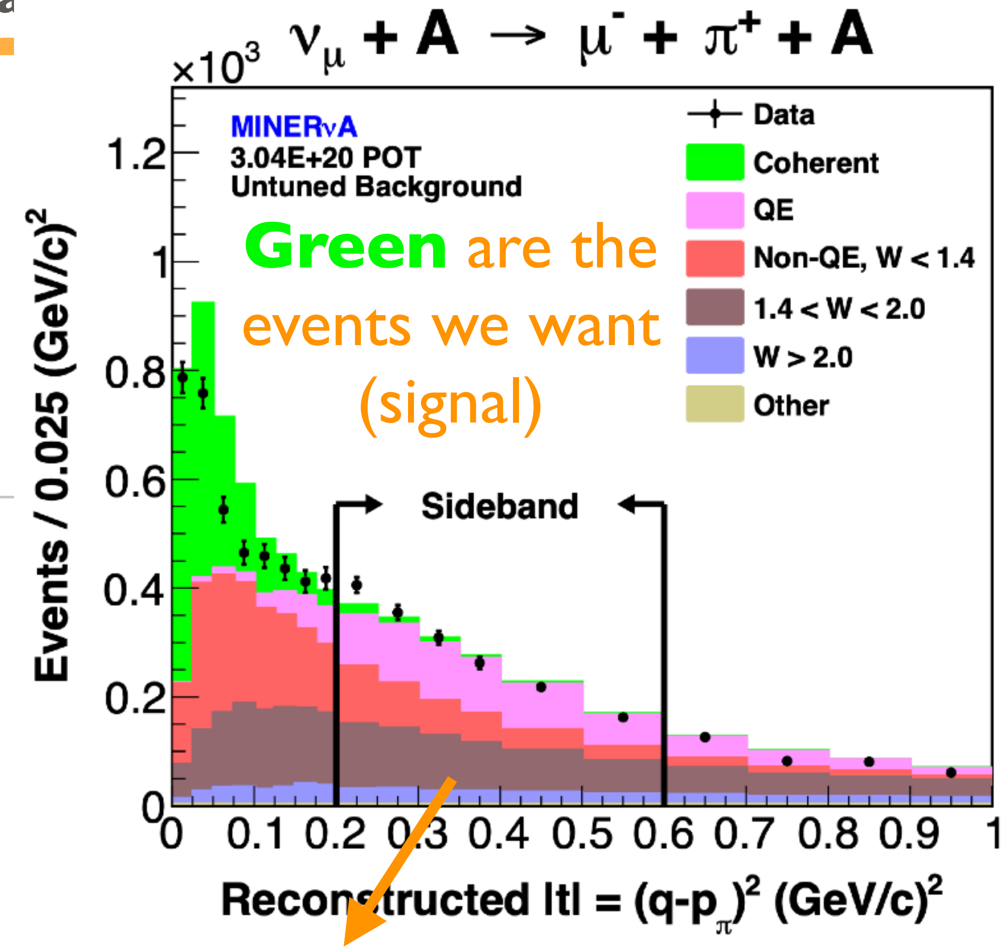
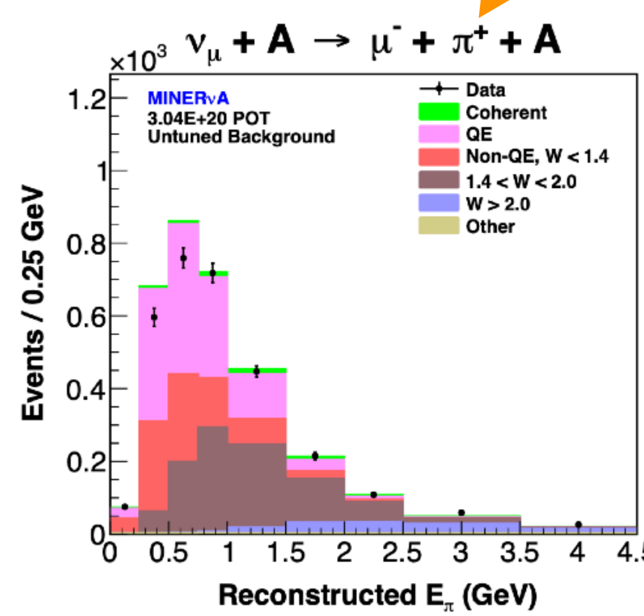
HOW DO WE MEASURE IT?

Estimating the backgrounds, $N_{bkg,i}$

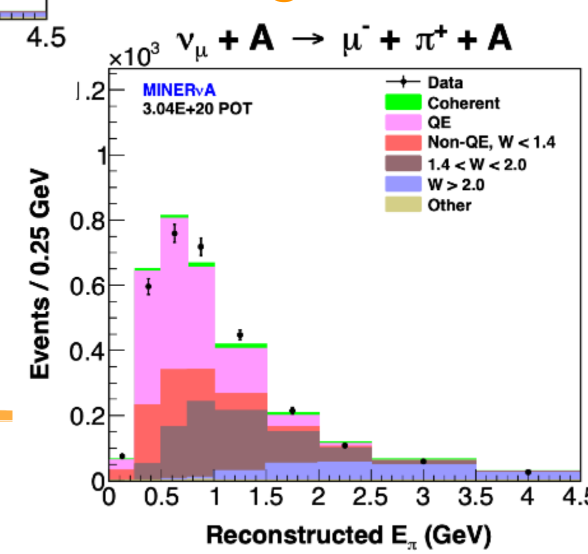
- We have no idea how much of our data events are really signal vs background
- We can estimate it using simulation but (as we'll see later) our simulations aren't always that great…
- We can improve our estimate by trying to select background events in data and fit the simulation to make sure it matches
  → lots of caveats here: need to be confident that the background data you select behaves the same as the background in your signal region





Fit simulation to data in sideband region to get a better estimate of **pink**, **red**, and **brown** backgrounds

After fit



Phys. Rev. D 97, 032014 (2018)

HOW DO WE MEASURE IT?

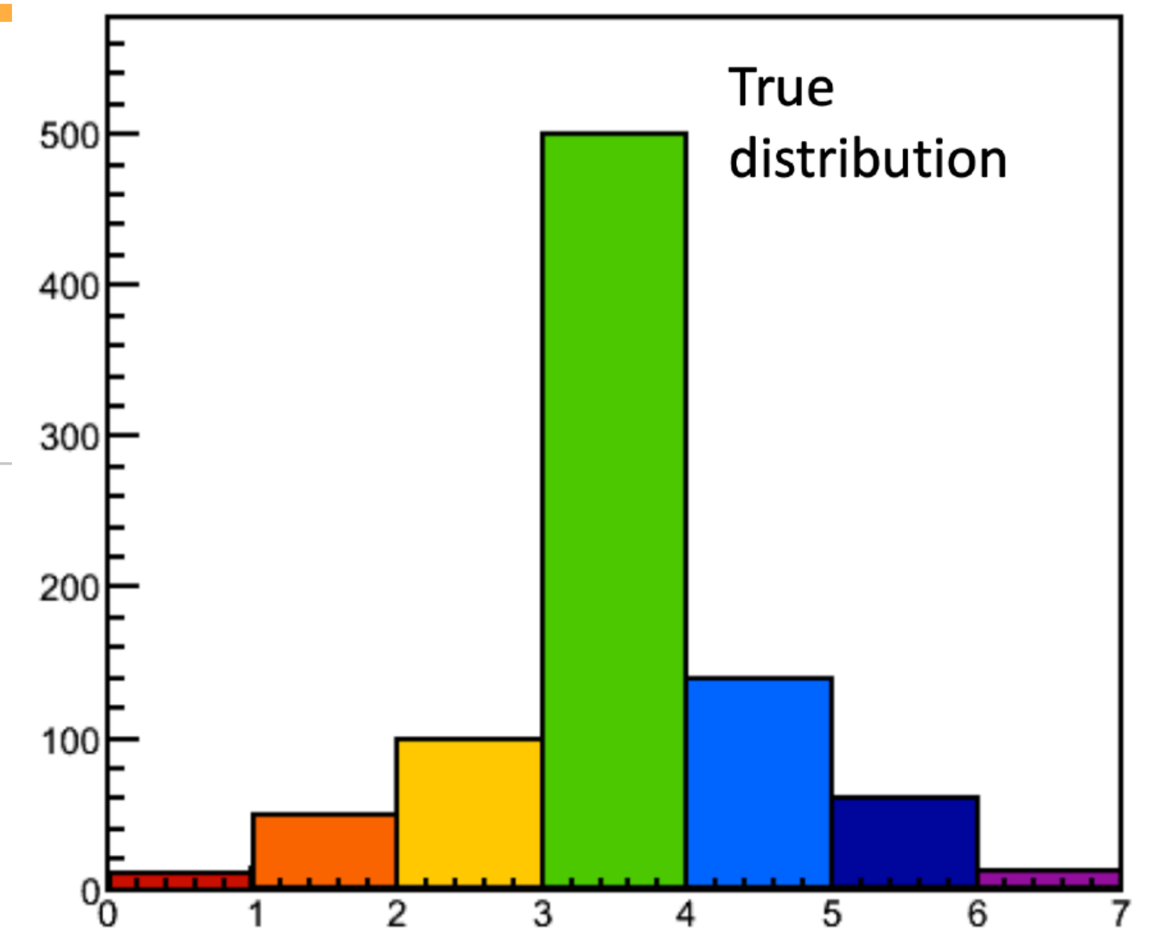
Efficiency

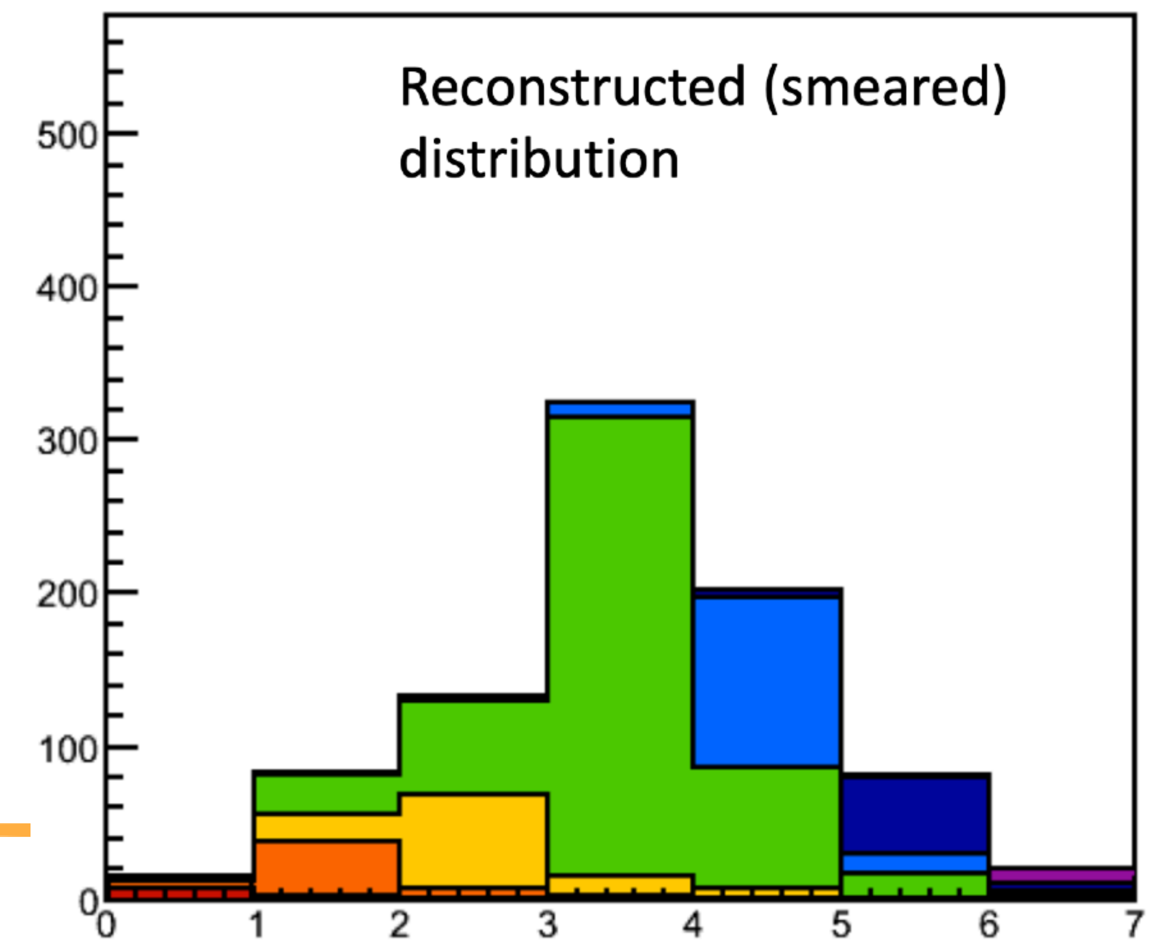
- Scale up the number of events we measure to the number of events we think really happened (e.g. if we think we measure only 10% of events, multiply whatever we measure by 10 to get the "real" value)
- Has to be estimated from simulation
- But we know the models in our simulations are not great!
- This is a problem - can lead to bias in our calculation. Needs to be handled carefully
- Best practice: **try and ensure efficiency is flat** (so the model doesn't have too much impact) **or show it is the same for many different models** (still dangerous: you can't test them all!).

HOW DO WE MEASURE IT?

Unfolding

- We can't measure events with perfect precision, so we will always reconstruct some events into the wrong bin
- Unfolding refers to how we go backwards from the **reconstructed values we measure to the underlying true values**
- E.g. we measure the energy deposited in a detector but we want to report the cross section as a function of the particle's real energy
- Need to estimate relationship from simulation → **can easily lead to bias!**
- Not necessarily a solvable problem. **Many statistical methods** offer different levels of bias and tradeoffs — **hot debate in the community**





Images: M. Betancourt

EVENT GENERATORS

- This is a complicated problem - we can't easily calculate a solution!
- Instead use **Monte Carlo event generators** to predict backgrounds and efficiency
- These **factorise the problem into separate steps** (an approximation - not strictly correct)

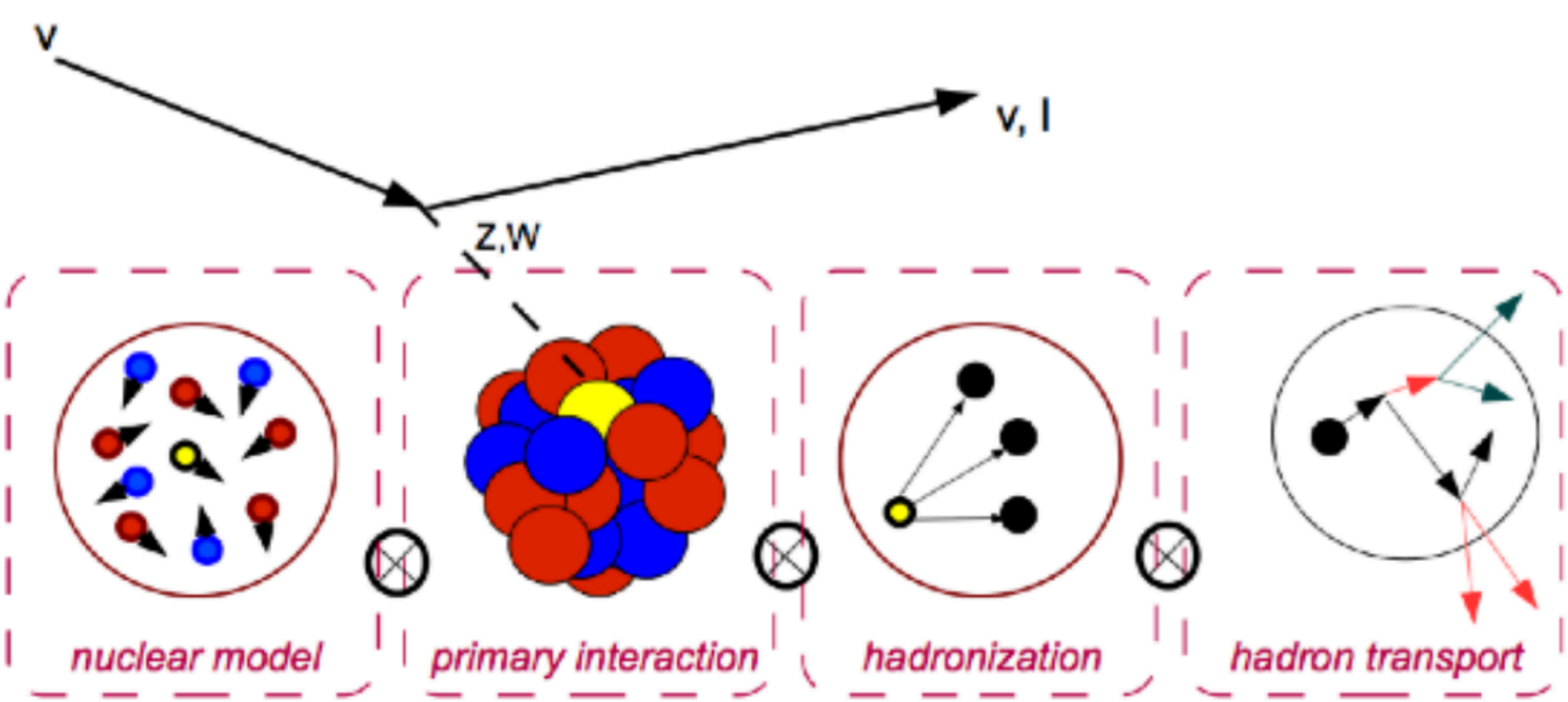


Image: C. Andreopoulos

EVENT GENERATORS

- A number of event generators "on the market"
- Each makes different approximations and assumptions — can produce different predictions even for the same model. **Implementation choices are important**
- Many generators also **tune theoretical models to data** → "effective" models that can match data better but may not be as predictive in other distributions that are also important

SOME EXPERIMENTAL RESULTS

AKA: HOW WE KNOW WHAT WE KNOW
(AND WHAT WE DON'T)

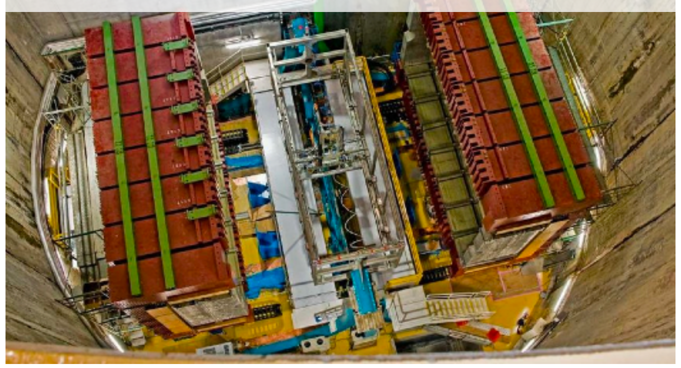
(SOME OF) THE EXPERIMENTS

*** = future experiment**

MINERvA: plastic scintillator

NOvA: liquid scintillator

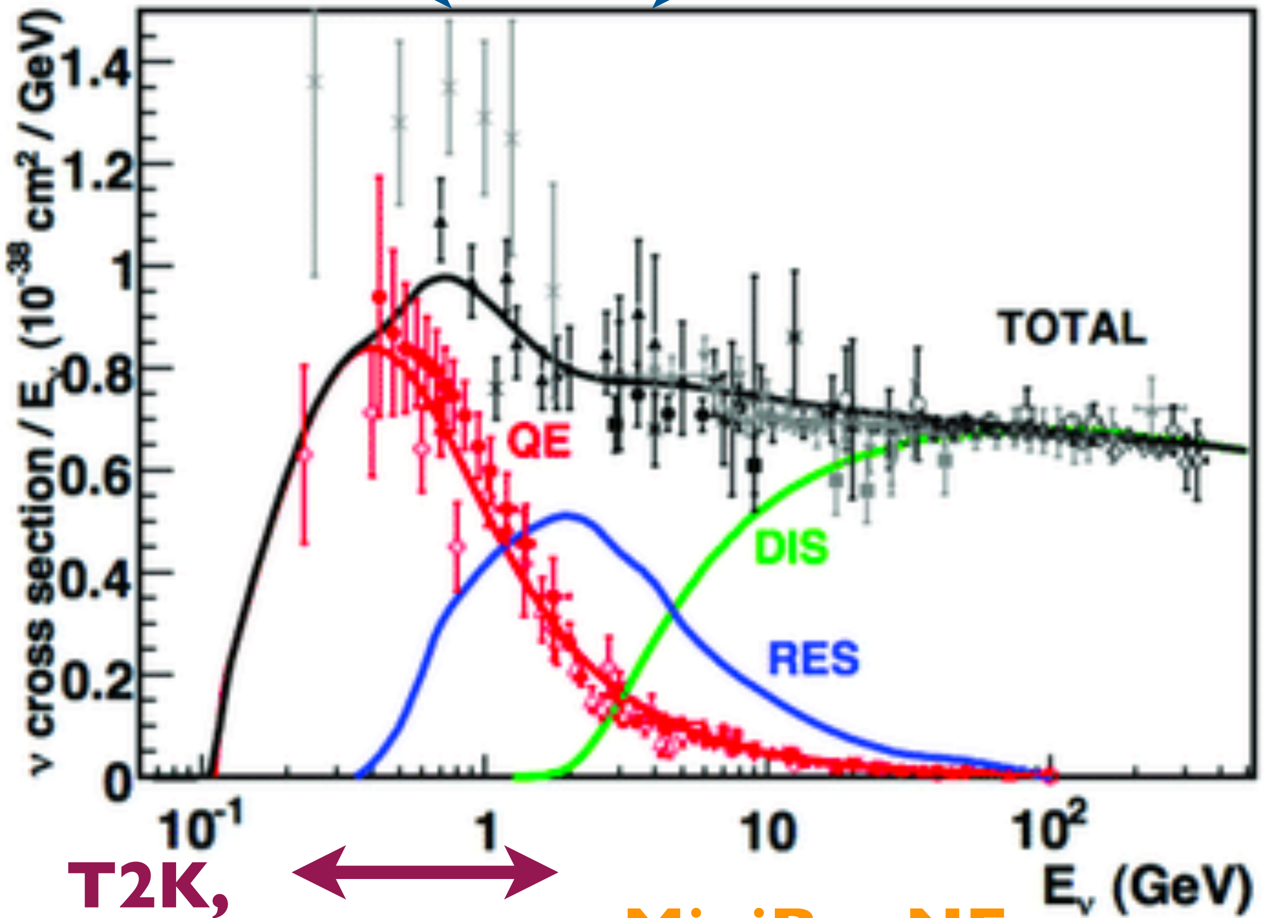
T2K: plastic scintillator, water Cherenkov



NOvA

MINERvA

DUNE*



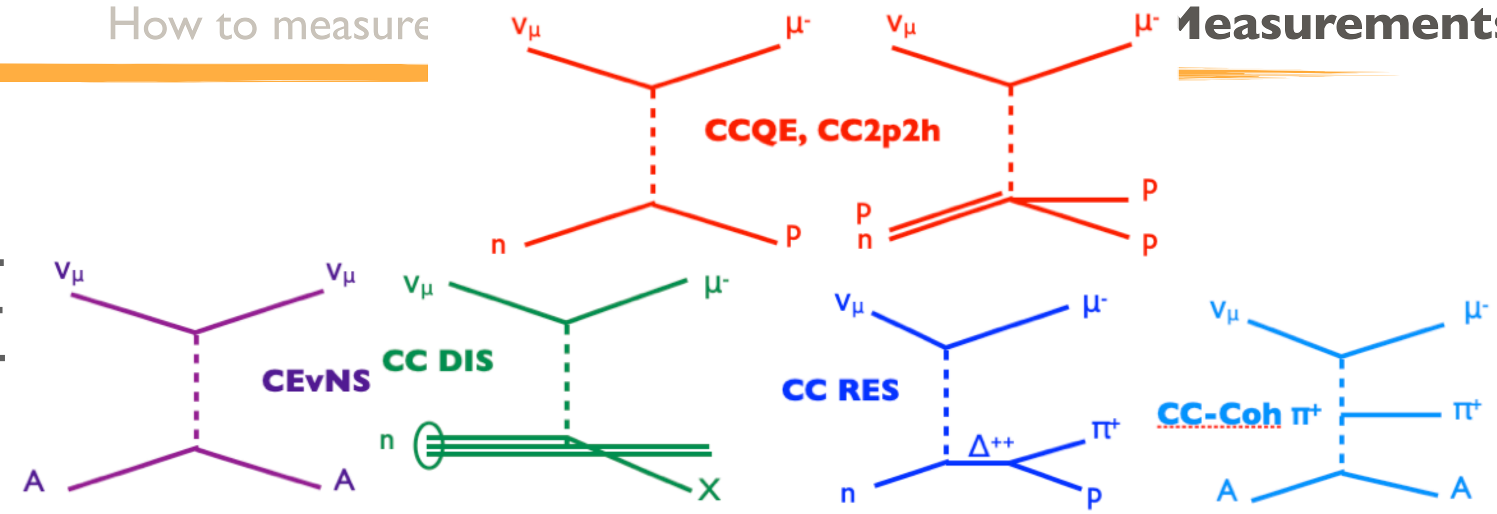
T2K, Hyper-K*

MiniBooNE, MicroBooNE, SBND*

MiniBooNE: liquid scintillator, Cherenkov

MicroBooNE: liquid argon

ν_μ CC INCLUSIVE



- Measure cross-section for **charged-current (CC)** **inclusive** muon neutrino interactions

Outgoing μ^- in final state | …and anything else

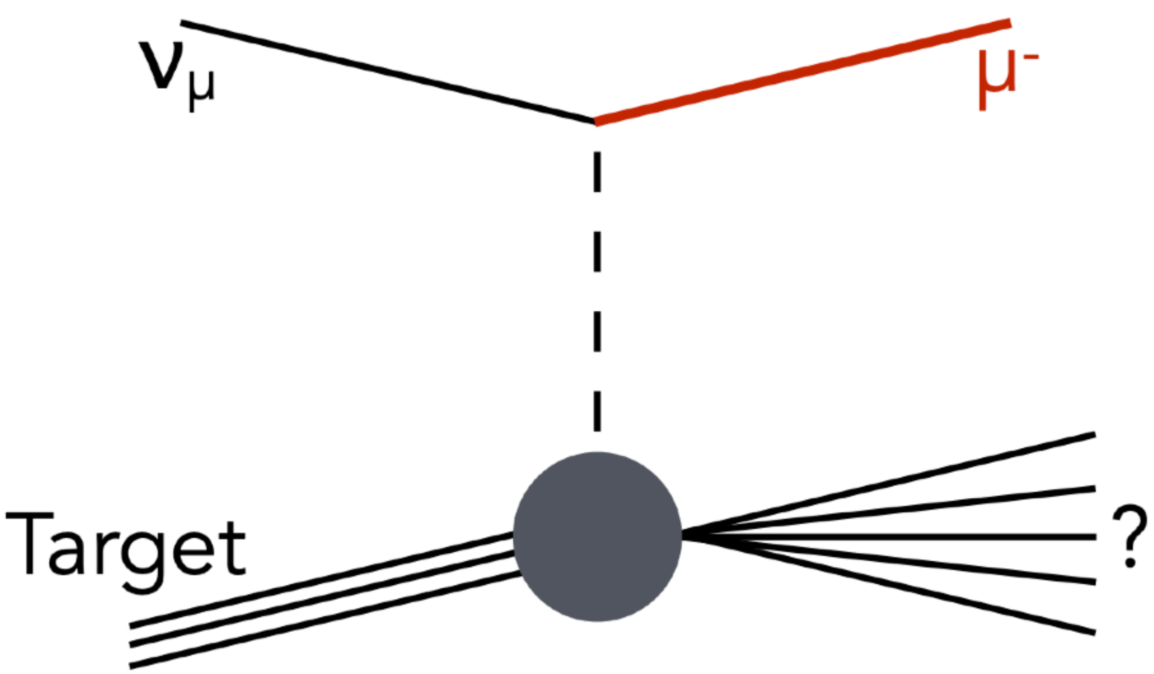
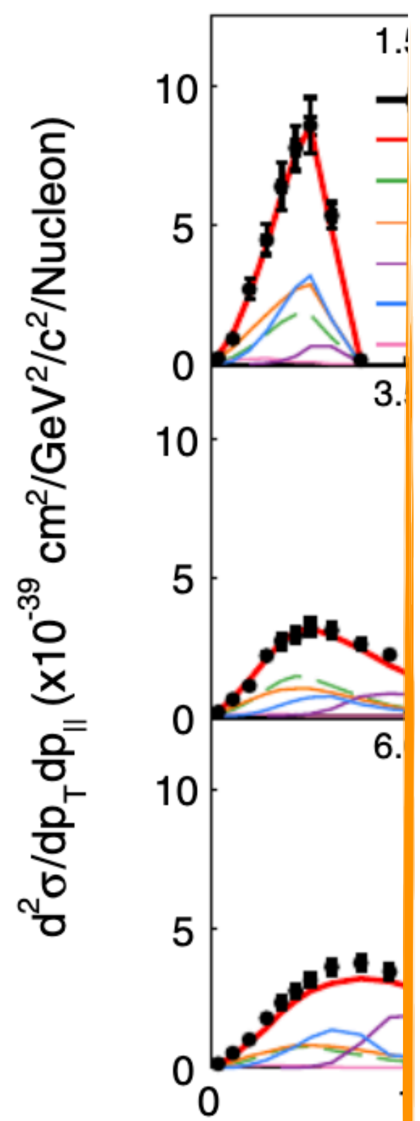


Figure from M. del Tutto

- Large statistics
- Includes many different interaction types — overall test of how well we model all processes

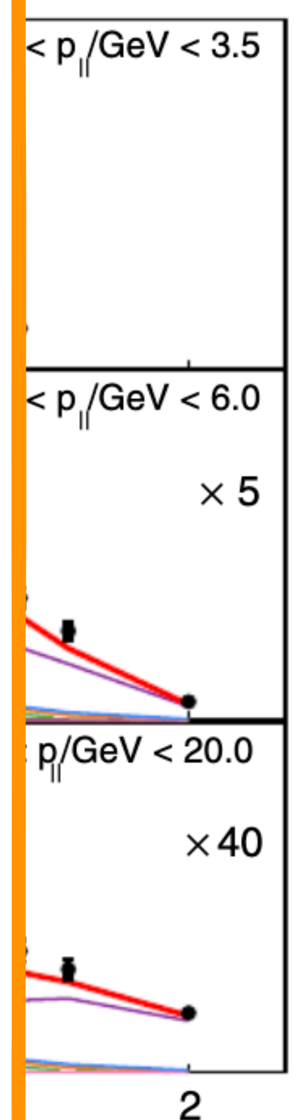
ν_μ CC INCLUSIVE: MINERvA MEASUREMENT



Binned in **muon momentum along two axes**:

- **p_T**: transverse to the incoming neutrino beam
- **$p_{||}$**: parallel to the incoming neutrino beam

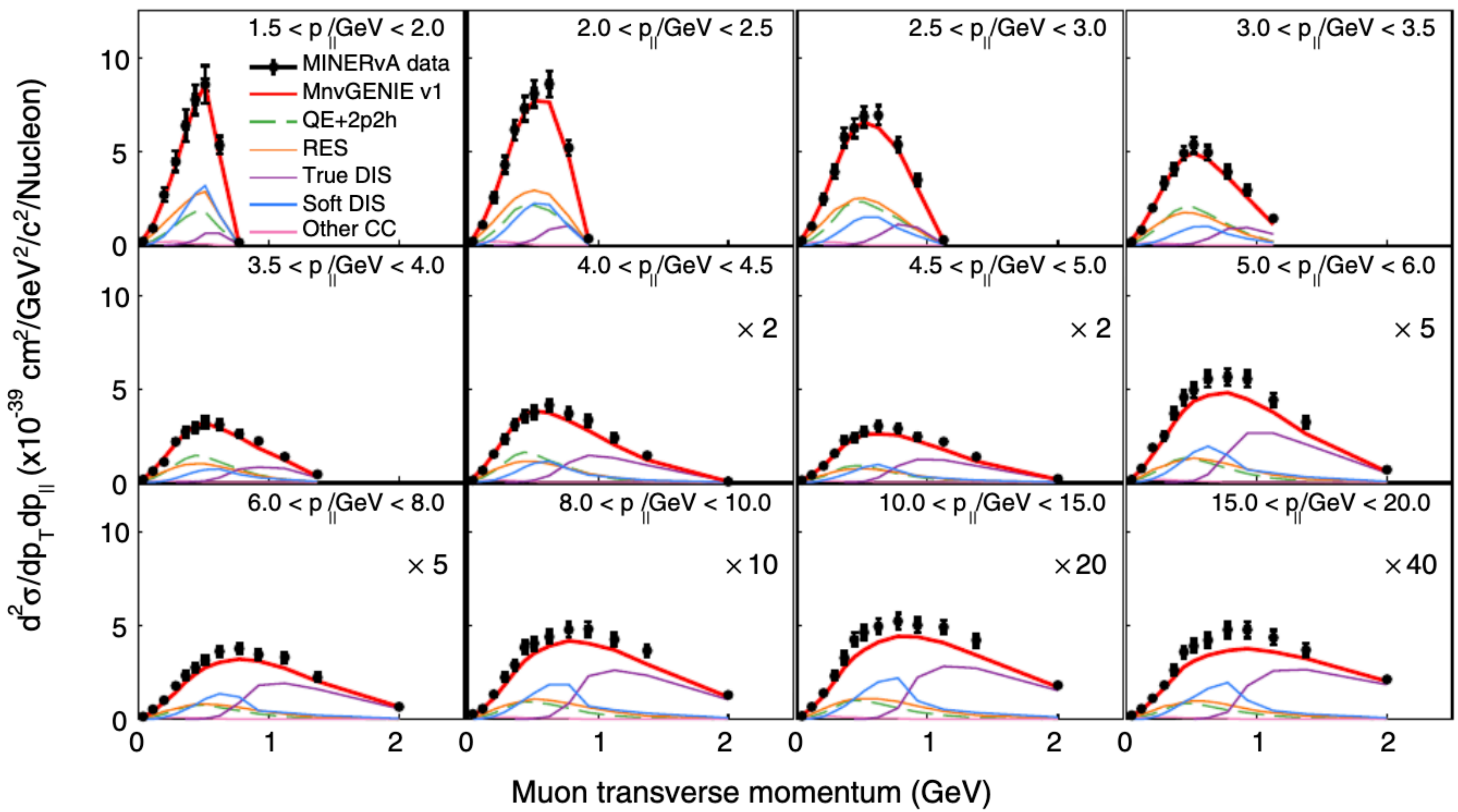
In general, **more bins = more detailed information** but **more work needed to understand efficiency, detector effects**. And you need more data to populate your bins!



μBooNE

ν_μ CC INCLUSIVE: MINERvA MEASUREMENT

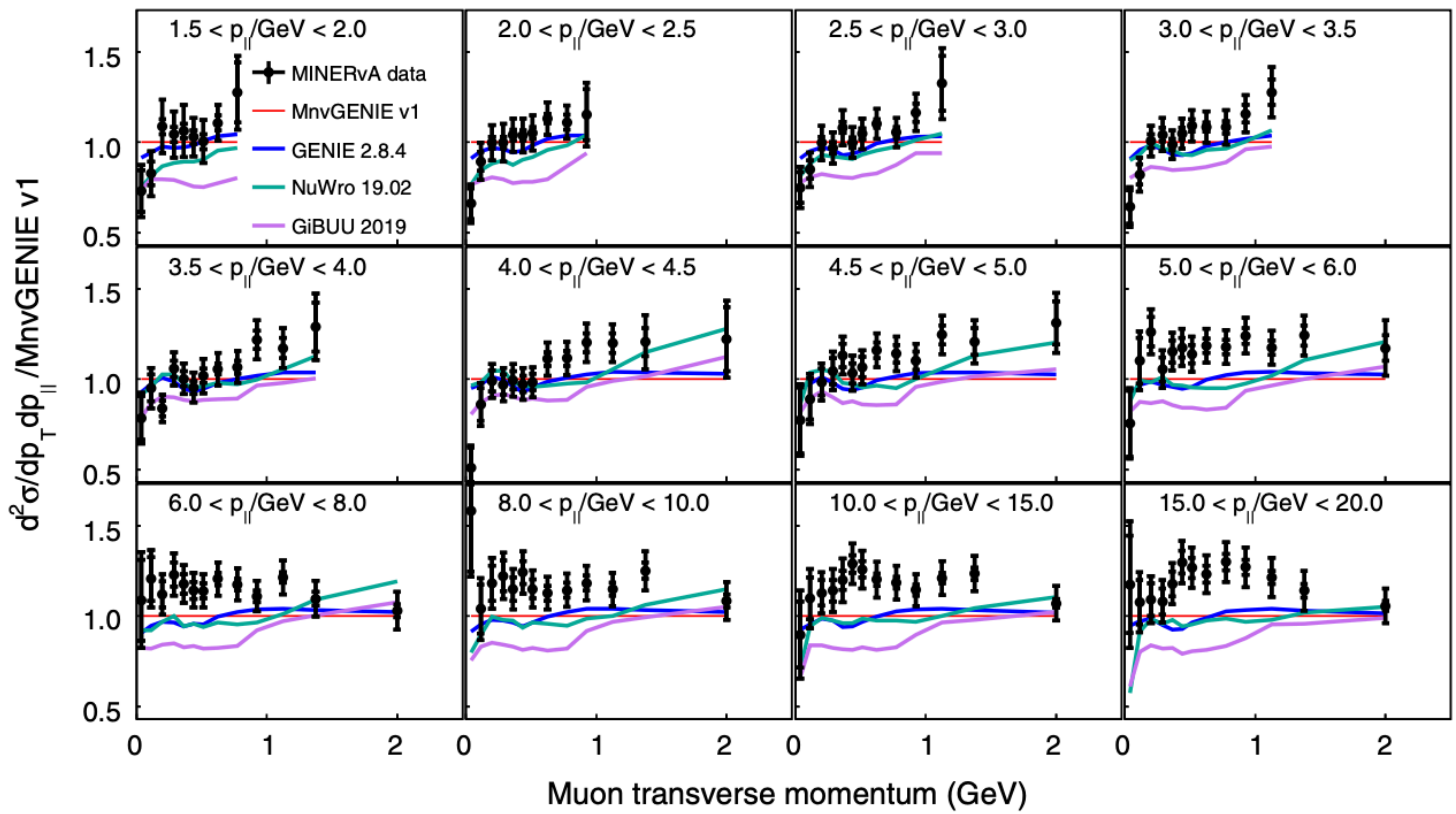
Phys. Rev. D 101, 112007 (2020)



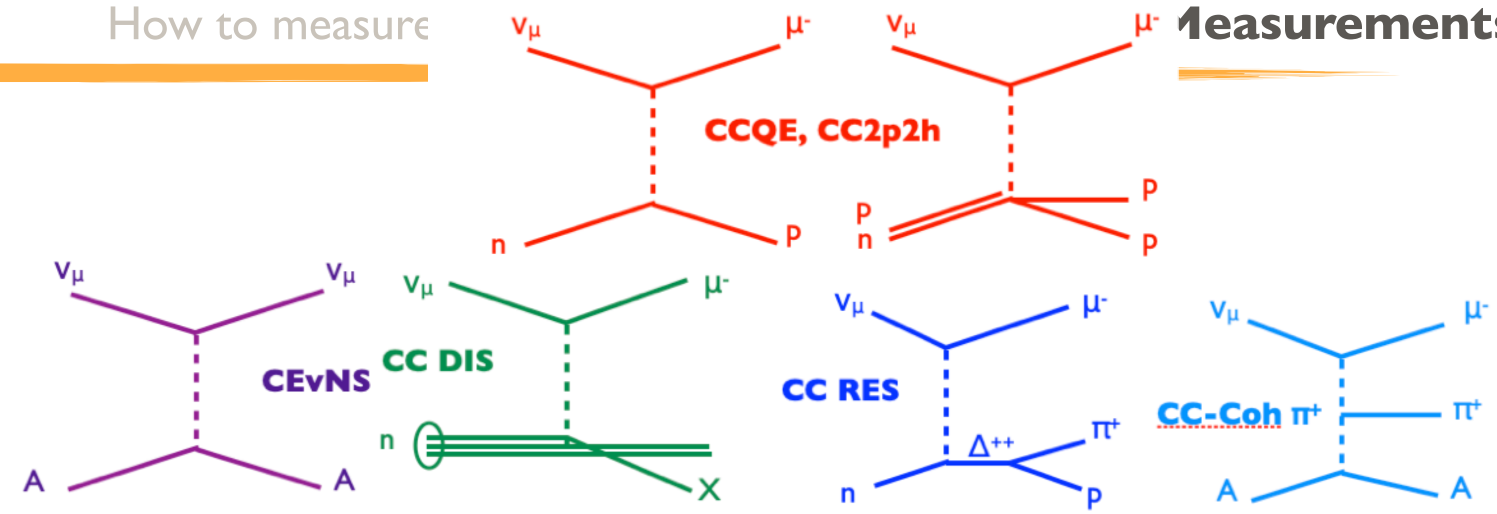
μBooNE

ν_μ CC INCLUSIVE: MINERvA MEASUREMENT

Phys. Rev. D 101, 112007 (2020)



ν_μ CC INCLUSIVE



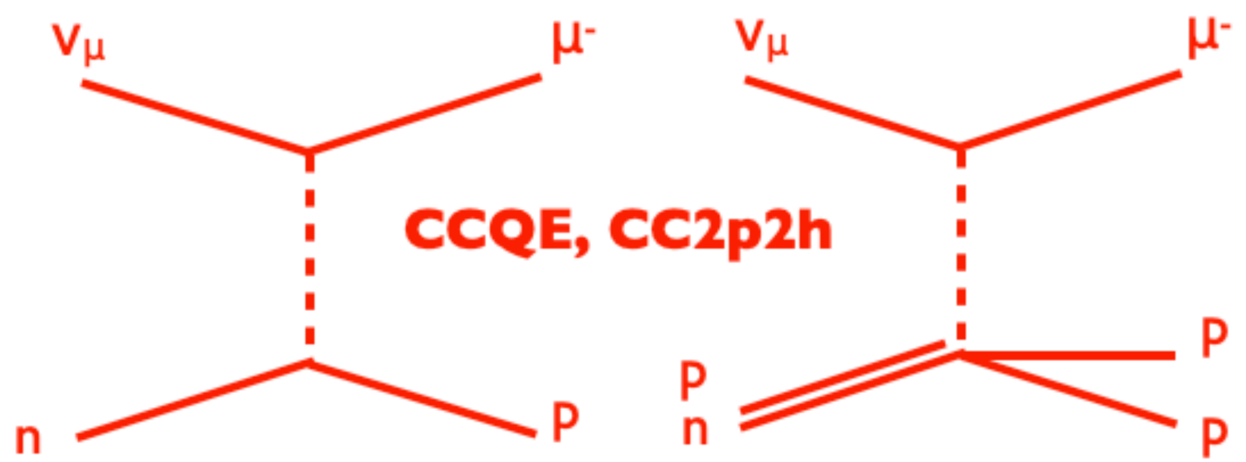
What have we learned?

Models seem generally reasonable, but:

- A more detailed look with MINERvA shows **none of the models really predict their data well**
- **We have a lot to improve!** First step is to look in more detail at **specific types of interactions** to work out where improvements are needed

ν_μ CC0π

- Target **CCQE-like interactions**: look for a visible muon and no visible pions
  - Will also have contributions from e.g. pion production where the pion is absorbed in the nucleus and never leaves



- These interactions are the **"golden channel" for neutrino oscillation at T2K**, and the **dominant interaction type** in many other experiments (e.g. MicroBooNE, SBND, ICARUS, MINERvA low-energy, NOvA) → the fact that they are used so much means they are important to understand well!

- Luckily, CCQE is also the **simplest interaction type** (although nuclear effects won't let us have an easy time…)

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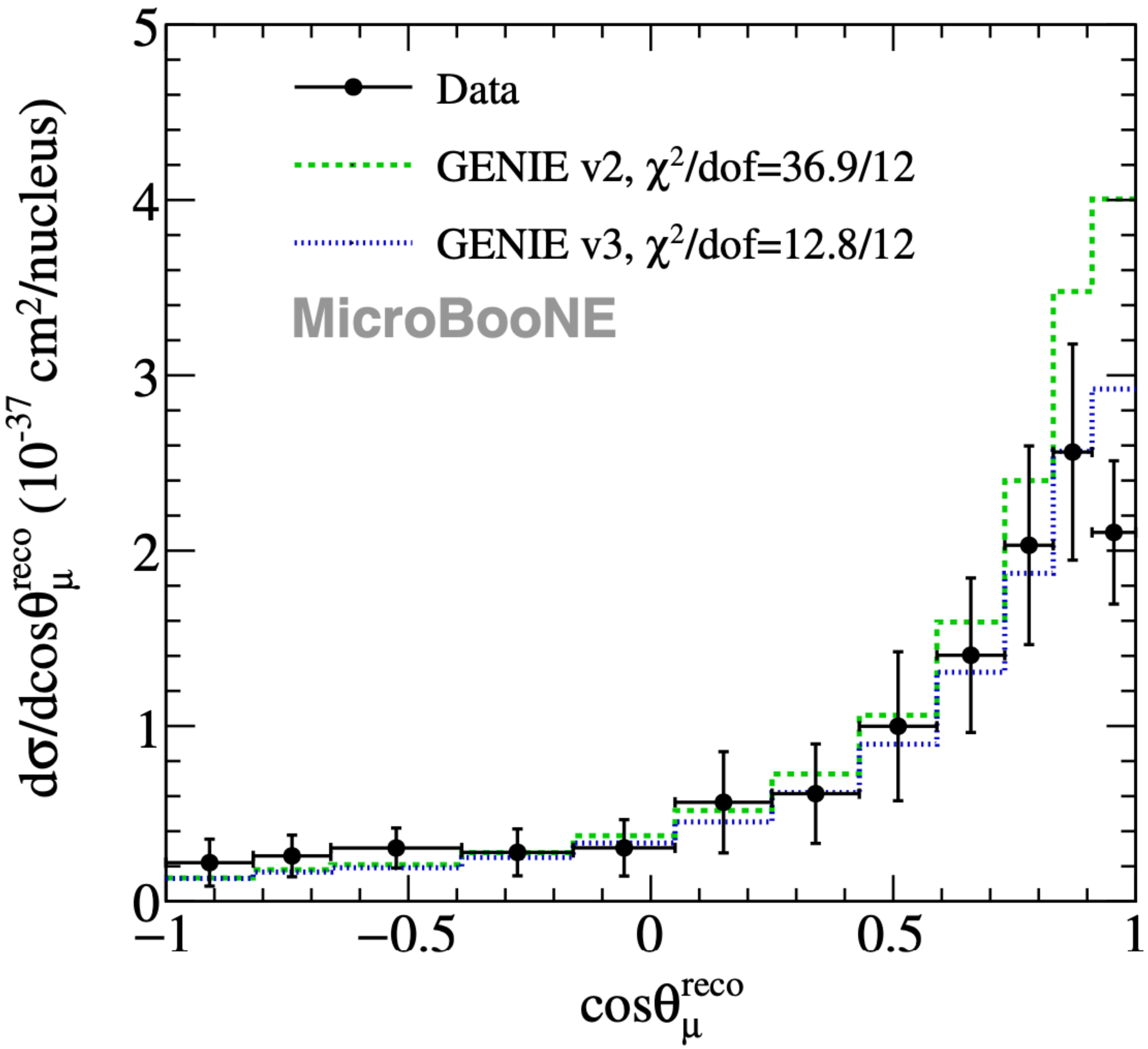
ν_μ CC0πNp: MICROBOONE MEASUREMENT

Phys. Rev. D 102, 112013 (2020)

- Select events with one muon, one or more visible protons, and no pions
- Major difference between green and blue predictions: blue includes RPA corrections → strong evidence that these corrections are needed
- Effect more prominent in MicroBooNE than other experiments because argon is a large nucleus



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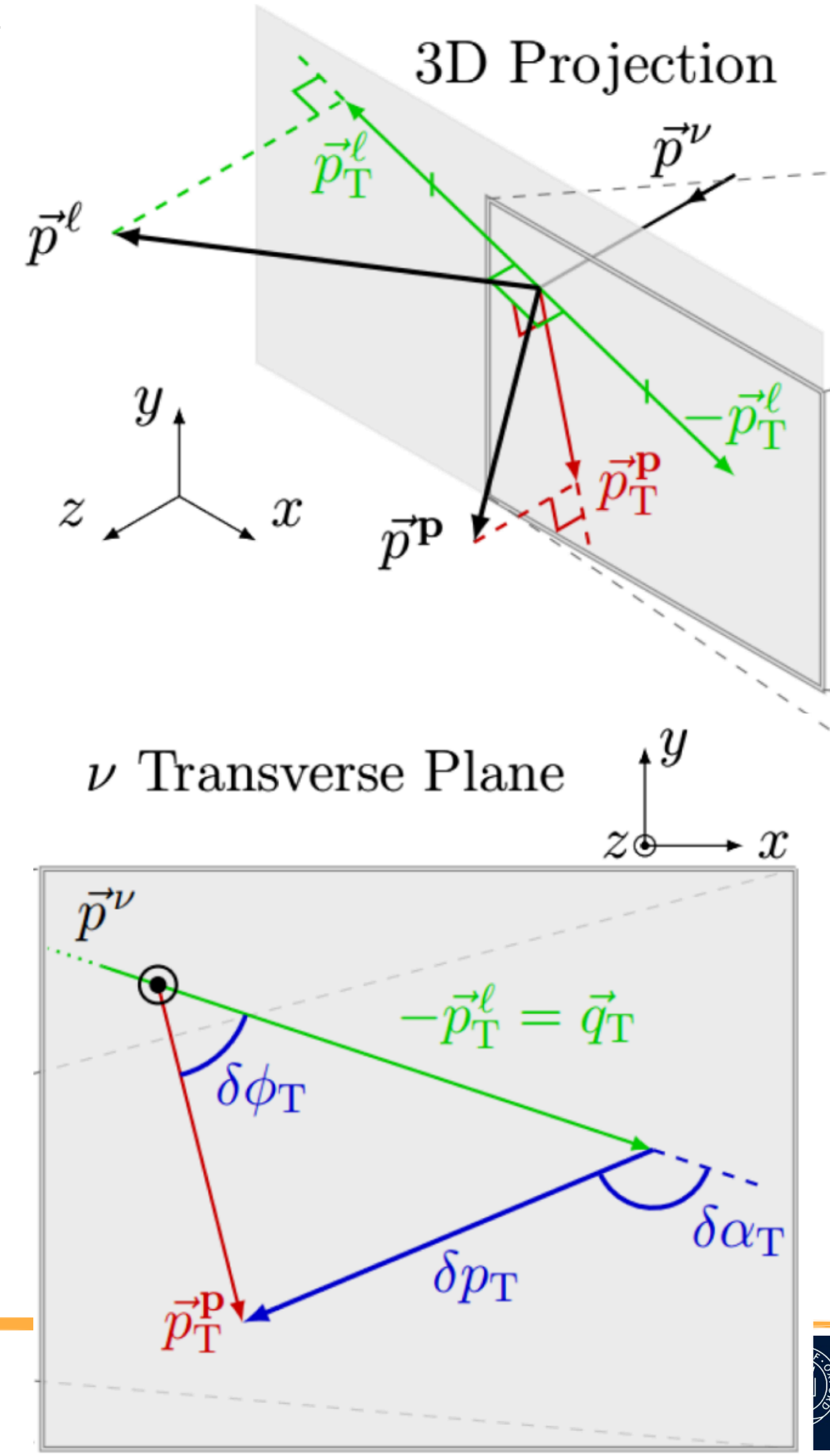
ν_μ CC0πNp: TRANSVERSE VARIABLES (T2K)

- First proposed here: Phys. Rev. C 94, 015503 (2016)
- Used by T2K, MINERvA, MicroBooNE
- Conservation of momentum: pure CCQE interactions will have no transverse imbalance
- Look at different regions in these parameters: start to tease apart the impact of nuclear effects
  - Separate out different interaction processes
  - Separate out initial state effects and final state interactions (FSIs)



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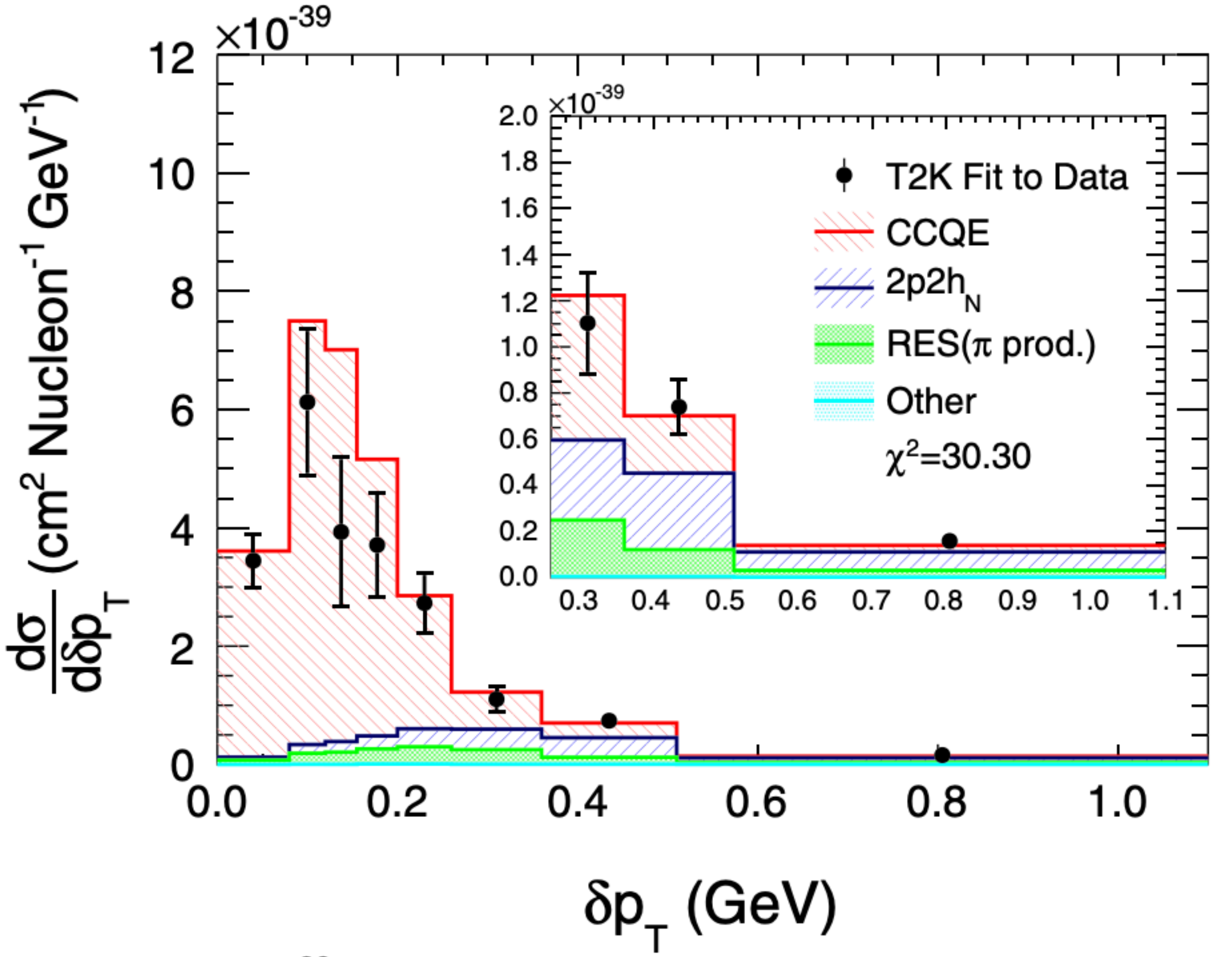
ν_μ CC0πNp: TRANSVERSE VARIABLES (T2K)

Phys. Rev. D 98, 032003 (2018)

- First proposed here: Phys. Rev. C 94, 015503 (2016)
- Used by T2K, MINERvA, MicroBooNE
- Conservation of momentum: pure CCQE interactions will have no transverse imbalance
- Look at different regions in these parameters: start to tease apart the impact of nuclear effects
  - Separate out different interaction processes
  - Separate out initial state effects and final state interactions (FSIs)



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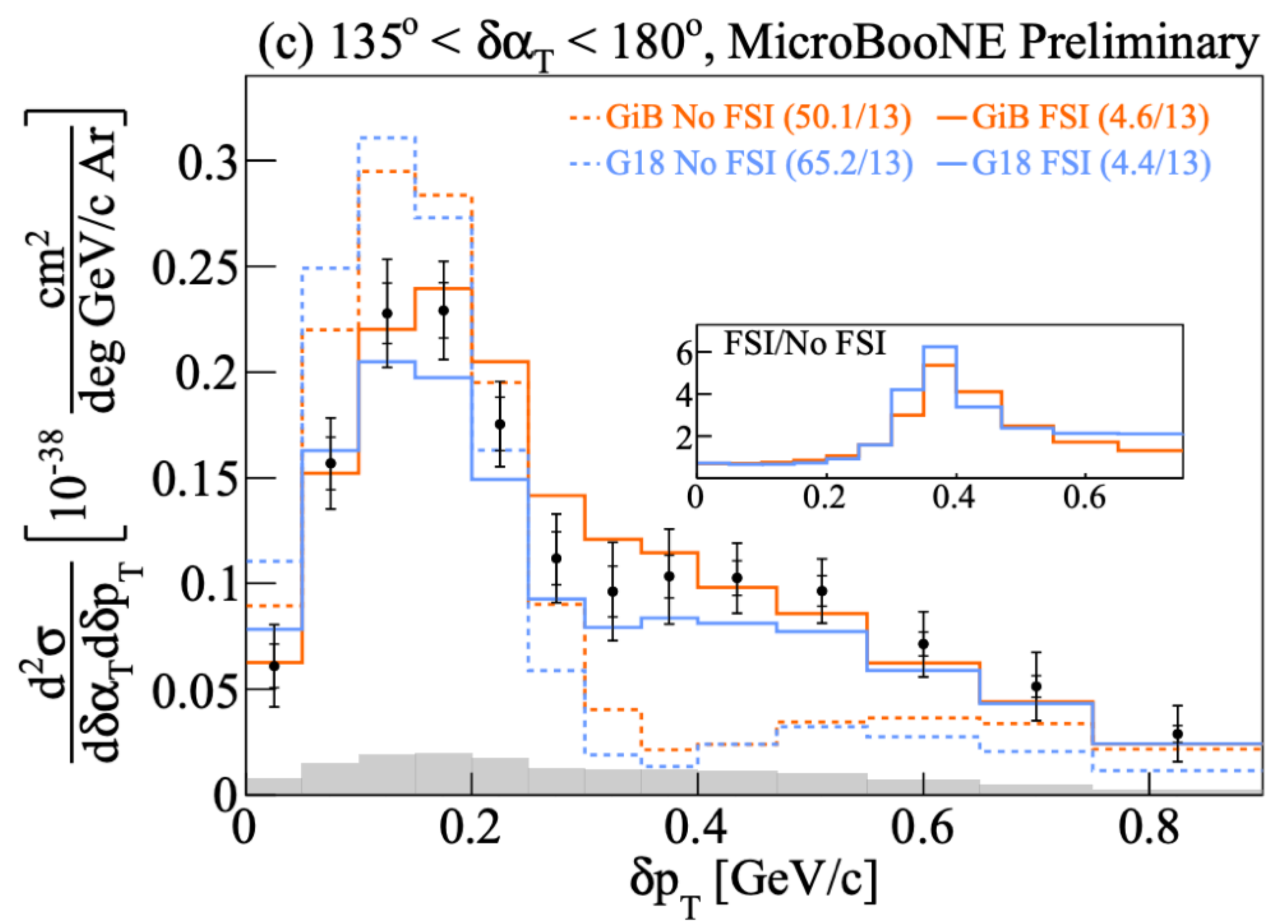
ν_μ CC0πNp: TRANSVERSE VARIABLES (MicroBooNE)

MICROBOONE-NOTE-1108-PUB

- First proposed here: Phys. Rev. C 94, 015503 (2016)
- Used by T2K, MINERvA, MicroBooNE
- Conservation of momentum: pure CCQE interactions will have no transverse imbalance
- Look at different regions in these parameters: start to tease apart the impact of nuclear effects
  - Separate out different interaction processes
  - Separate out initial state effects and final state interactions (FSIs)



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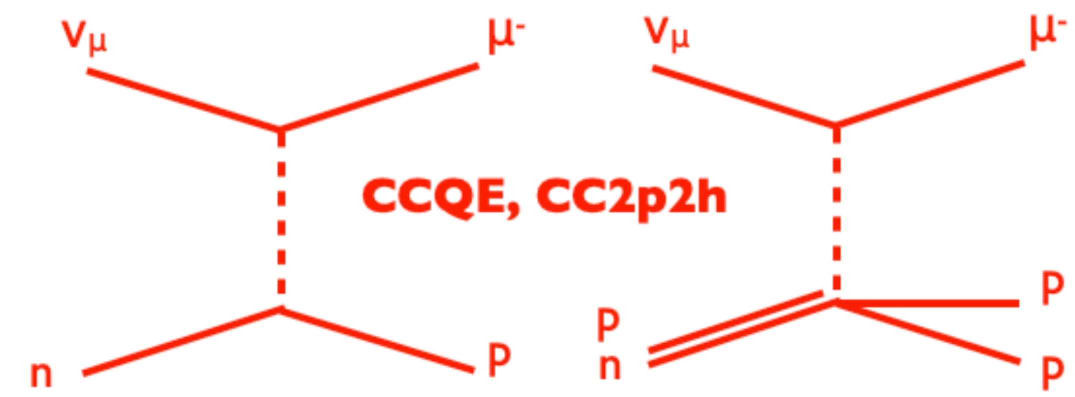
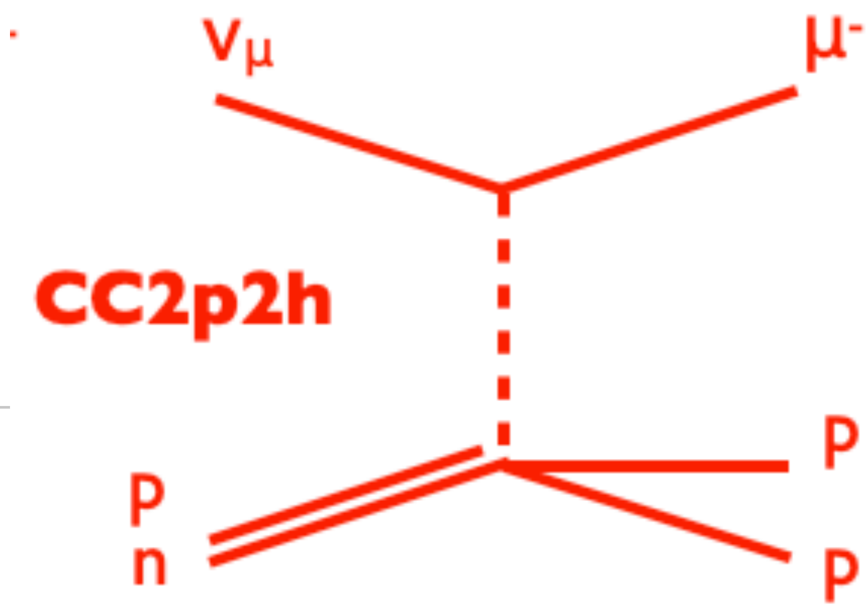
ν_μ CC0π



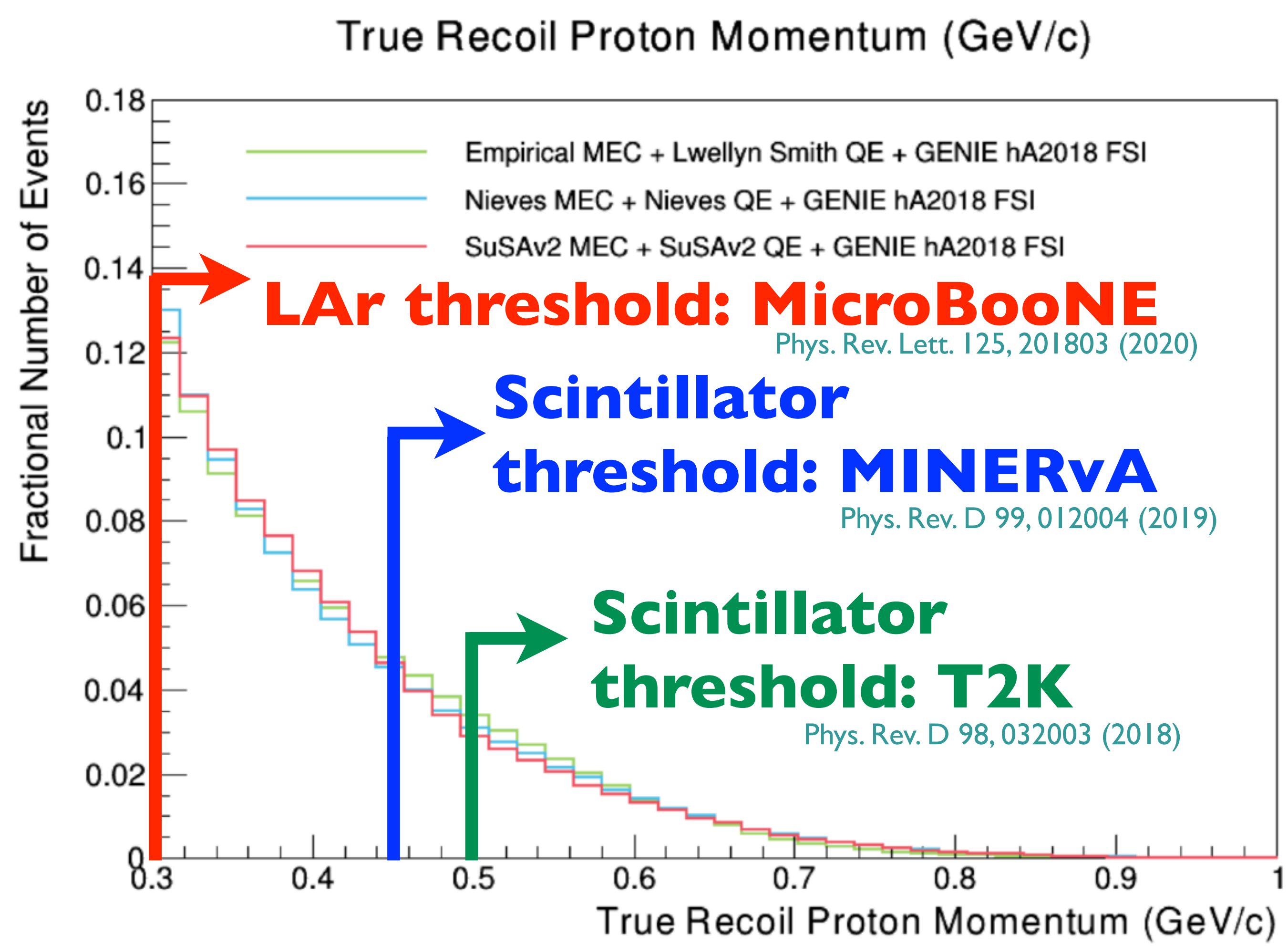
What have we learned?

- Even though the CCQE-like interaction is the simplest possible channel, we still can't predict it perfectly for nuclear targets
- Nuclear effects are important (surprise!)
- We are developing effective techniques to isolate these effects, which means we'll be able to learn more about them in the future

ν_μ CC0π2p



- So far I've basically talked about CC0π interactions as CCQE-like
- But we know **CC2p2h (2 particle, 2 hole) processes are important too**
- Part of the reason I've ignored it so far is many experiments have **high thresholds** such that they can't see the second proton
- But **liquid argon detectors can!**



MICRBOONE-NOTE-1096-PUB

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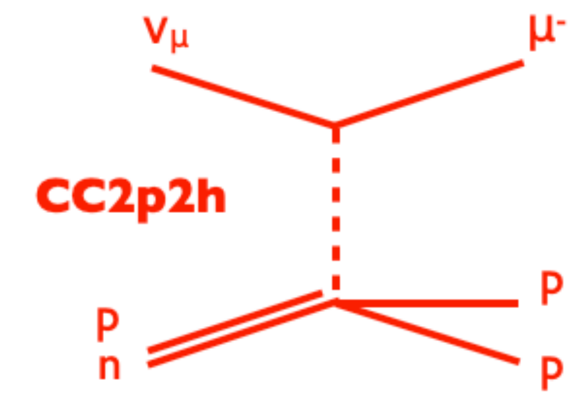
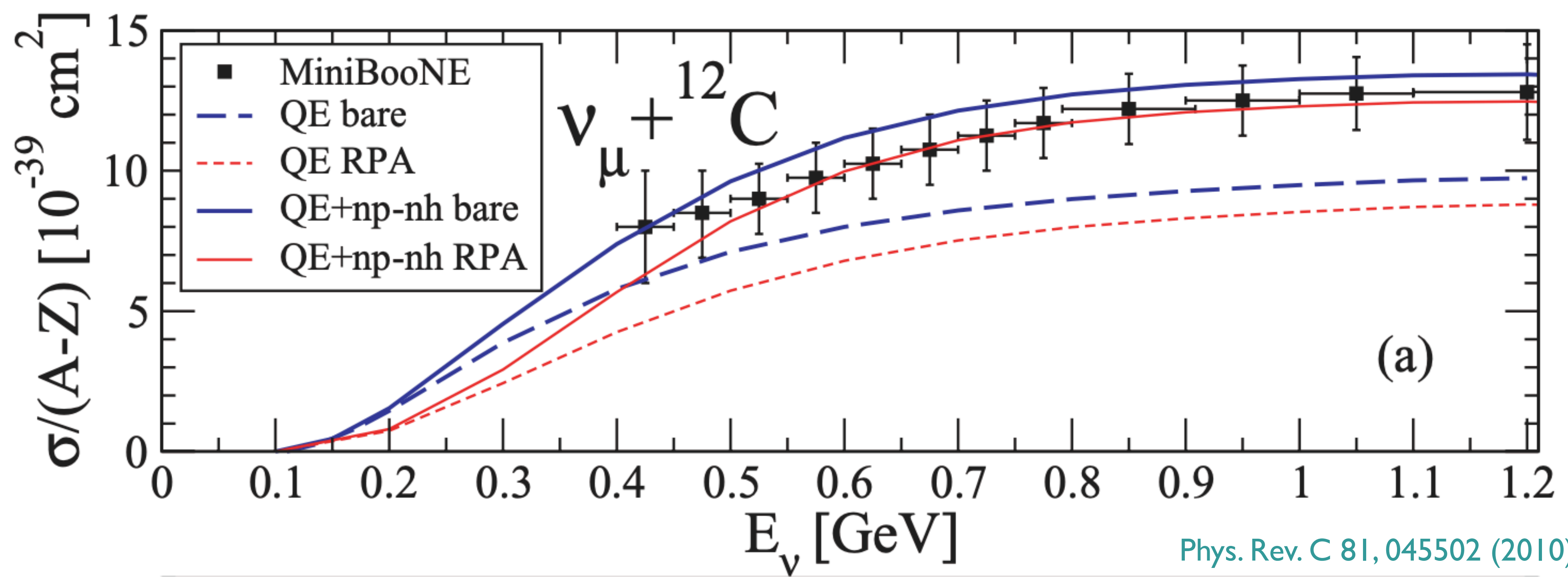
ν_μ CC0π2p



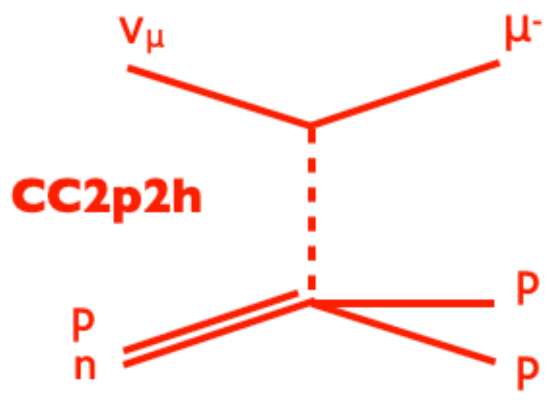
- We did have **strong indirect evidence** for the existence of 2p2h interactions even from experiments that couldn't detect the second proton

- See this data from MiniBooNE, using a CCQE-like selection

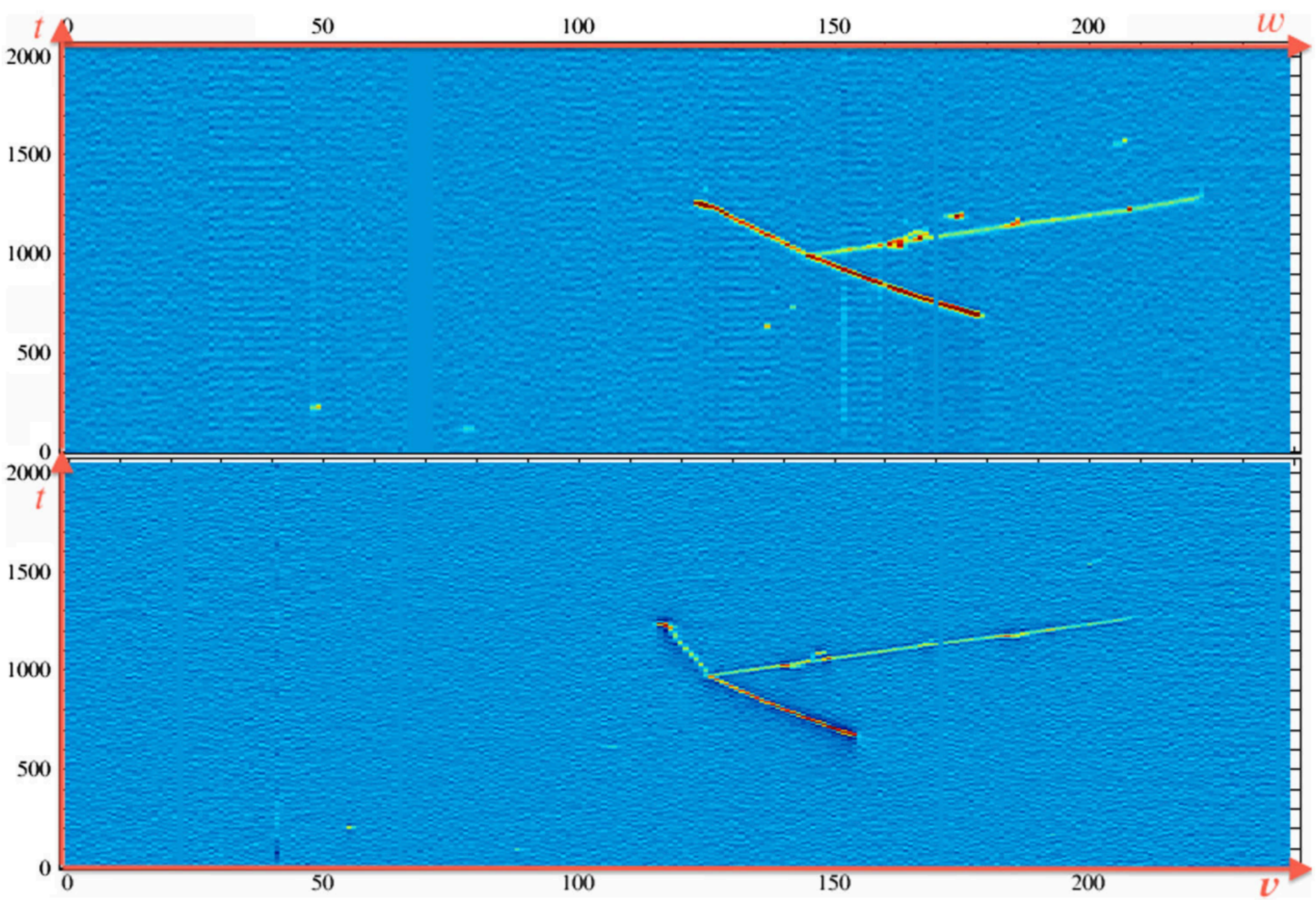


Phys. Rev. C 81, 045502 (2010)

ν_μ CC0π2p: ArgoNeuT MEASUREMENT

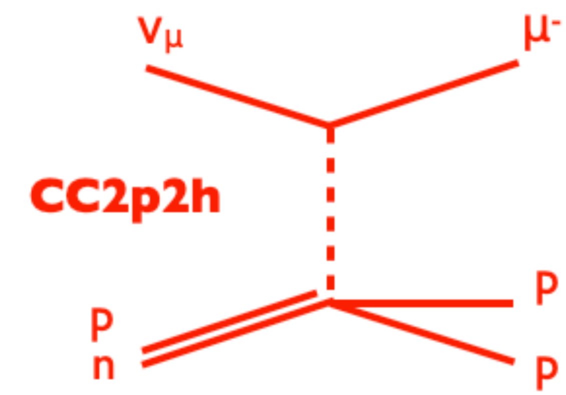


- The ArgoNeut Liquid Argon TPC experiment saw **30 1μ0π2p events**
- Some events showed a specific back-to-back topology that suggests a specific mechanism for **nucleon-nucleon short range correlations in the initial nucleus**

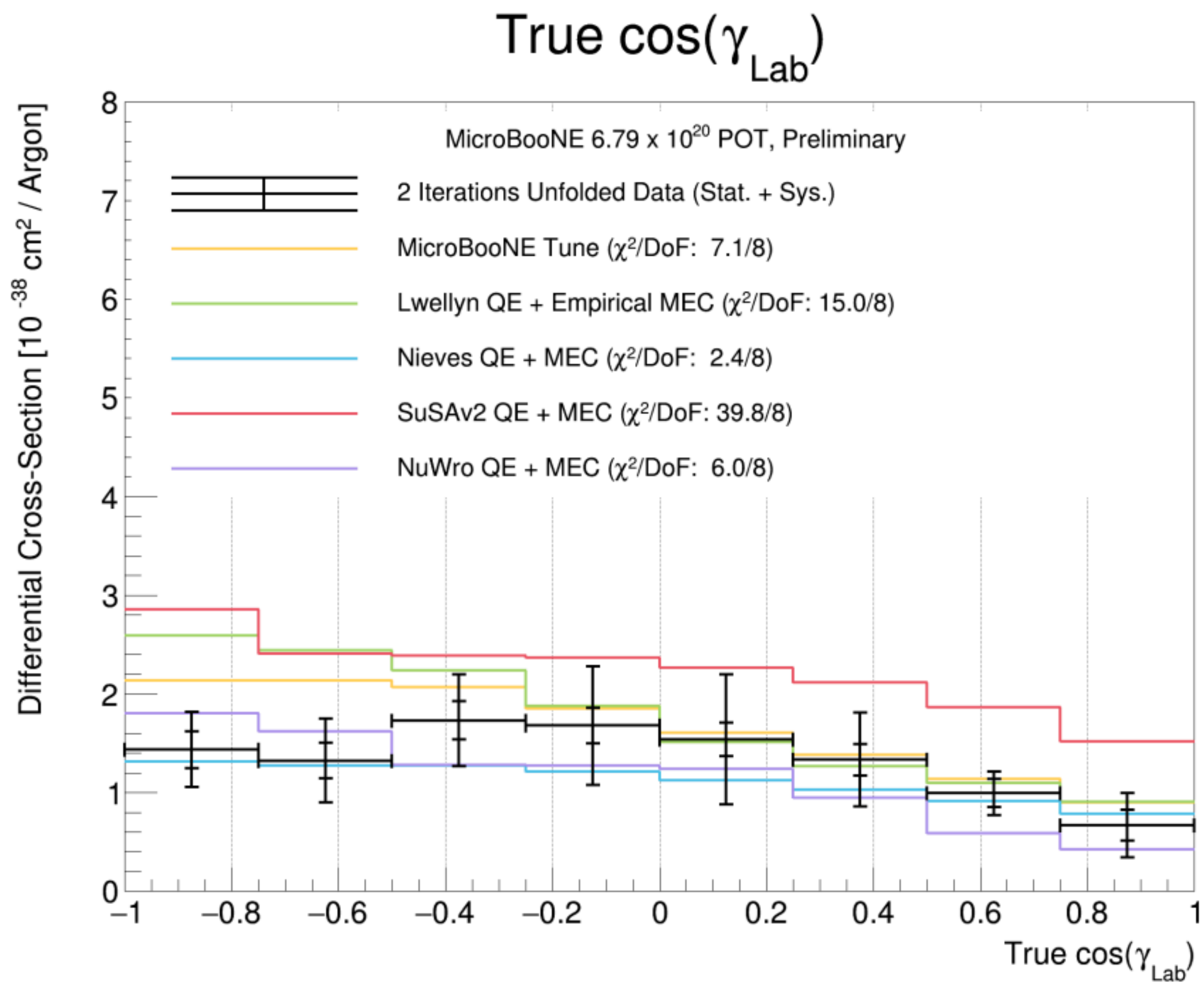


Phys. Rev. D 90, 012008 (2014)

ν_μ CC0π2p: MicroBooNE MEASUREMENT



- MicroBooNE recently released preliminary results showing the **first-ever direct measurement of the 2-proton cross section**
- This is hugely important: **we can learn a lot more from direct measurements** than fitting models to CC0πNp data!



MICROBOONE-NOTE-1117-PUB

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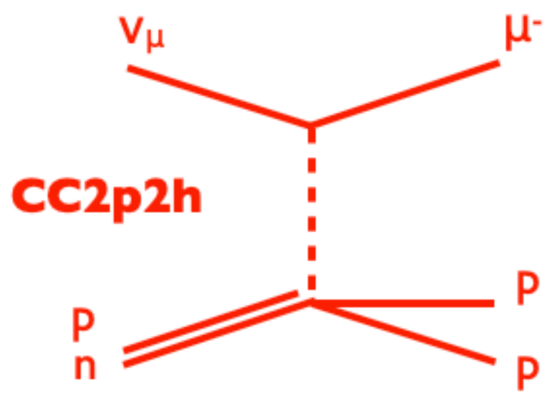
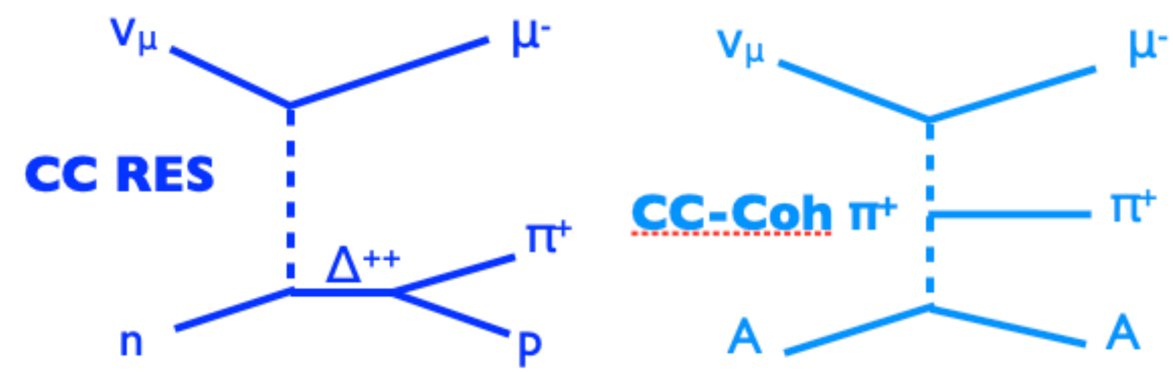
ν_μ CC0π2p



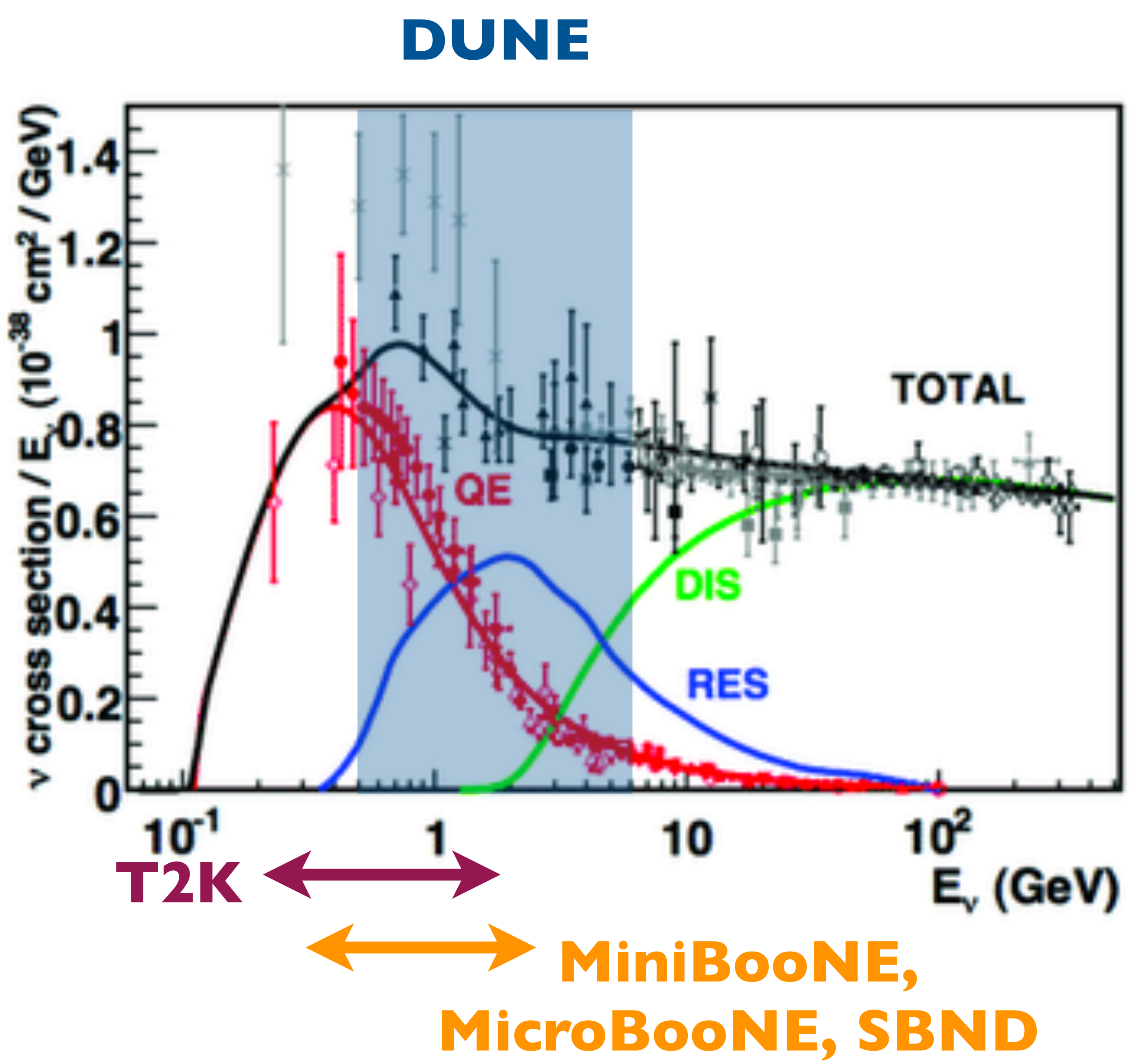
What have we learned?

- Measurements of the CC0π process give strong evidence for the presence of 2p2h interactions → more than just CCQE needed to explain data
- Liquid argon experiments are starting to produce the first ever direct measurements of these processes

PION PRODUCTION

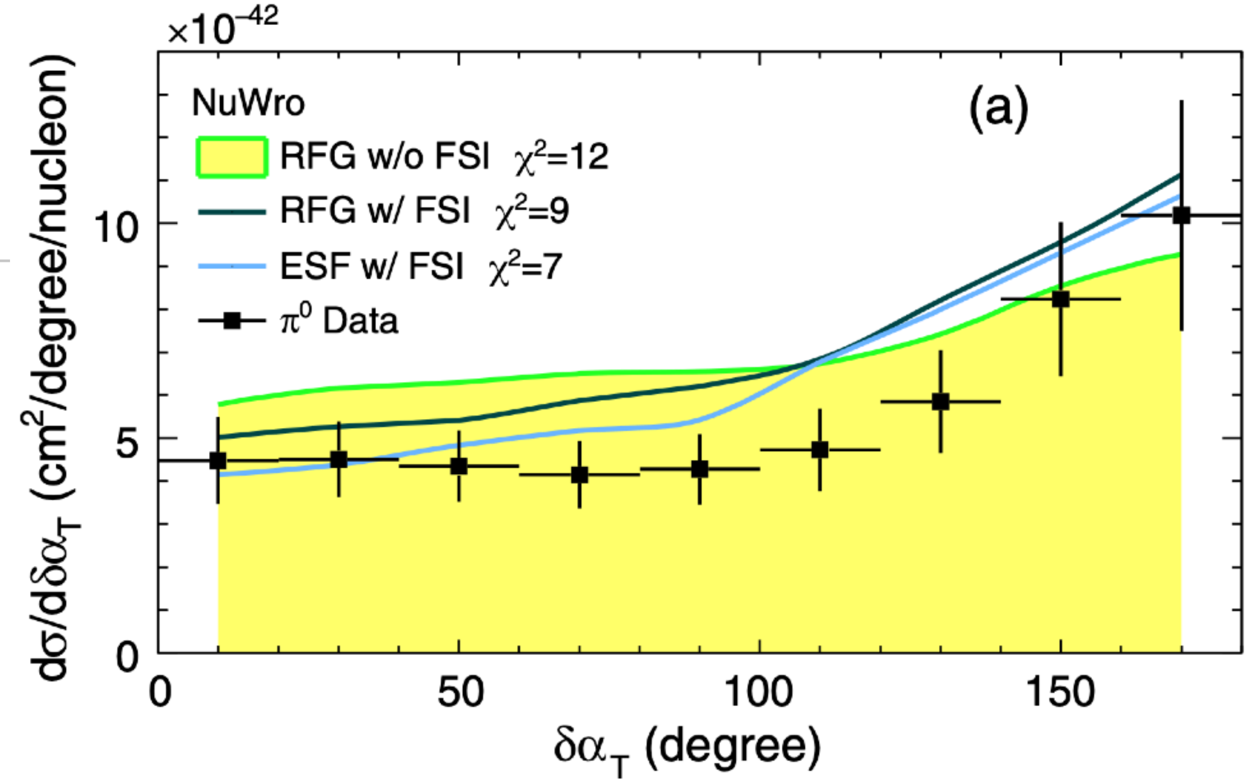


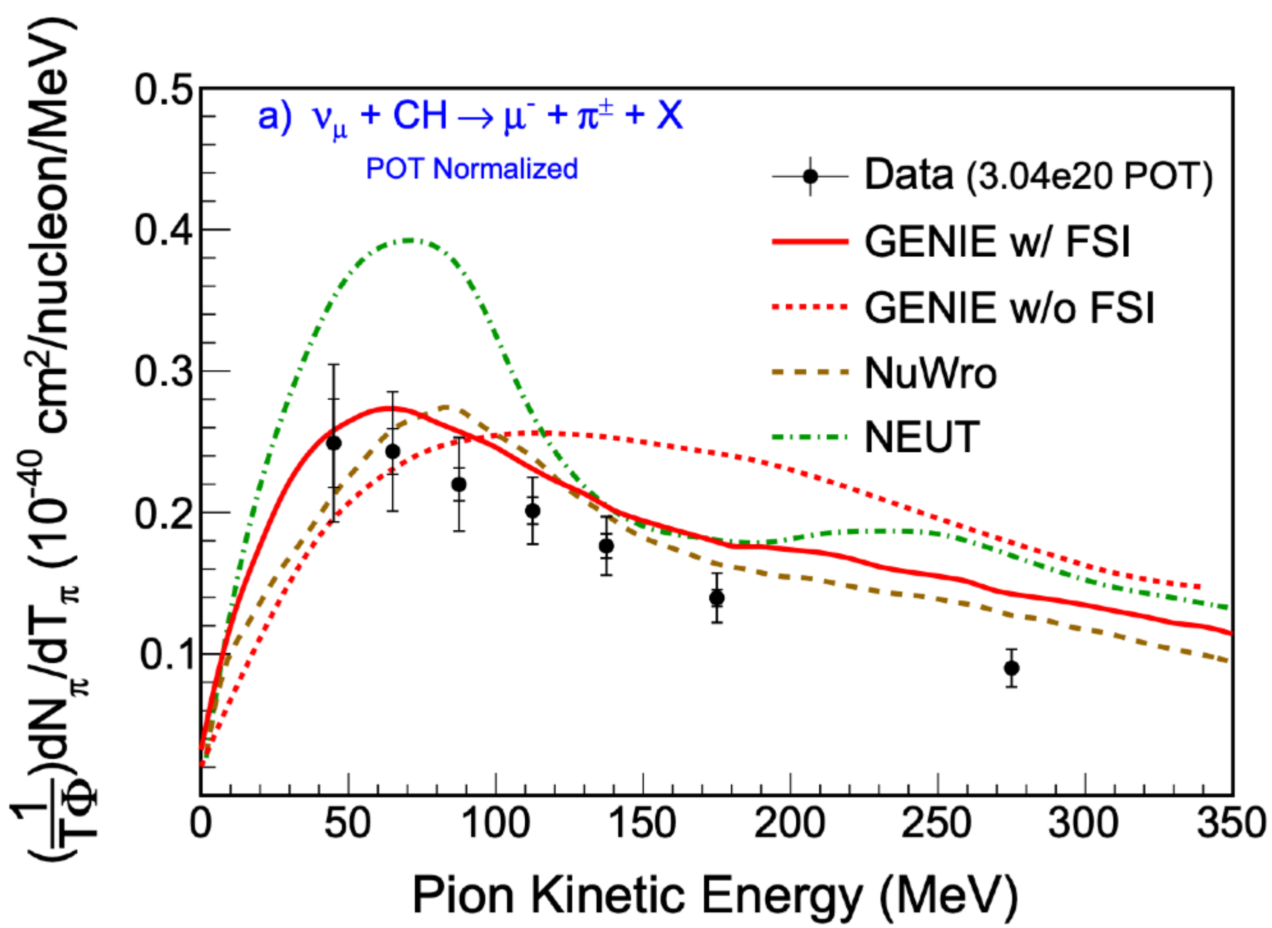
- Most theoretical work recently has been in the CC0π regime
  - → dominant channel for T2K, MiniBooNE, MicroBooNE, and others
- DUNE will operate at higher energies → need a better understanding of **pion production** and **Deep Inelastic Scattering**



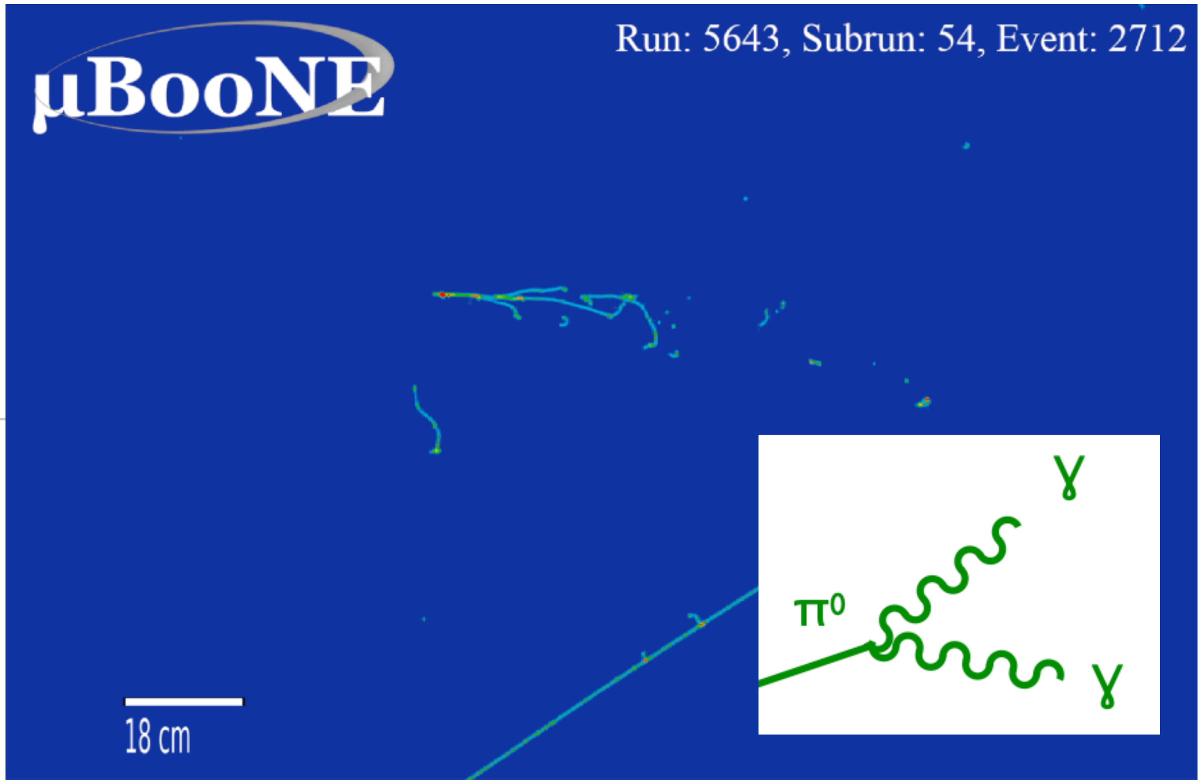
CC π PRODUCTION: MINERνA

- Most pion production models don't fully model nuclear effects or 2p2h interactions (but they should happen) → **a lot of room to improve!**
- MINERvA have studied **transverse variables in CCπ⁰ production** → learn about nuclear effects in these interactions
- Measurements of **CCπ± production** give valuable information too → none of our current models seem sufficient (surprise?)





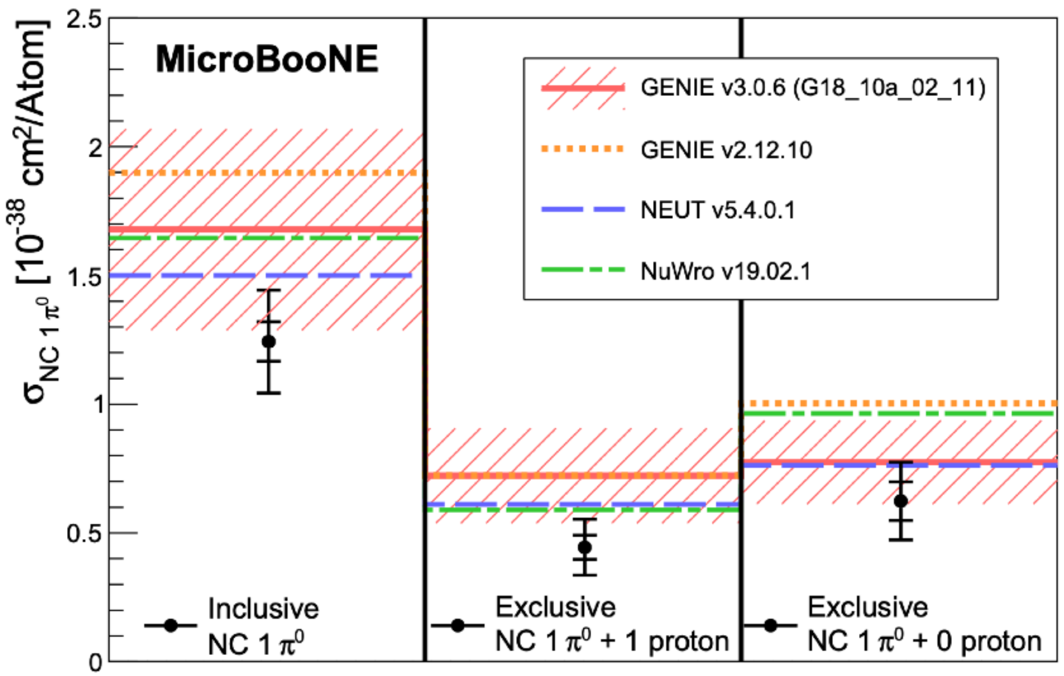
NC π^0 PRODUCTION



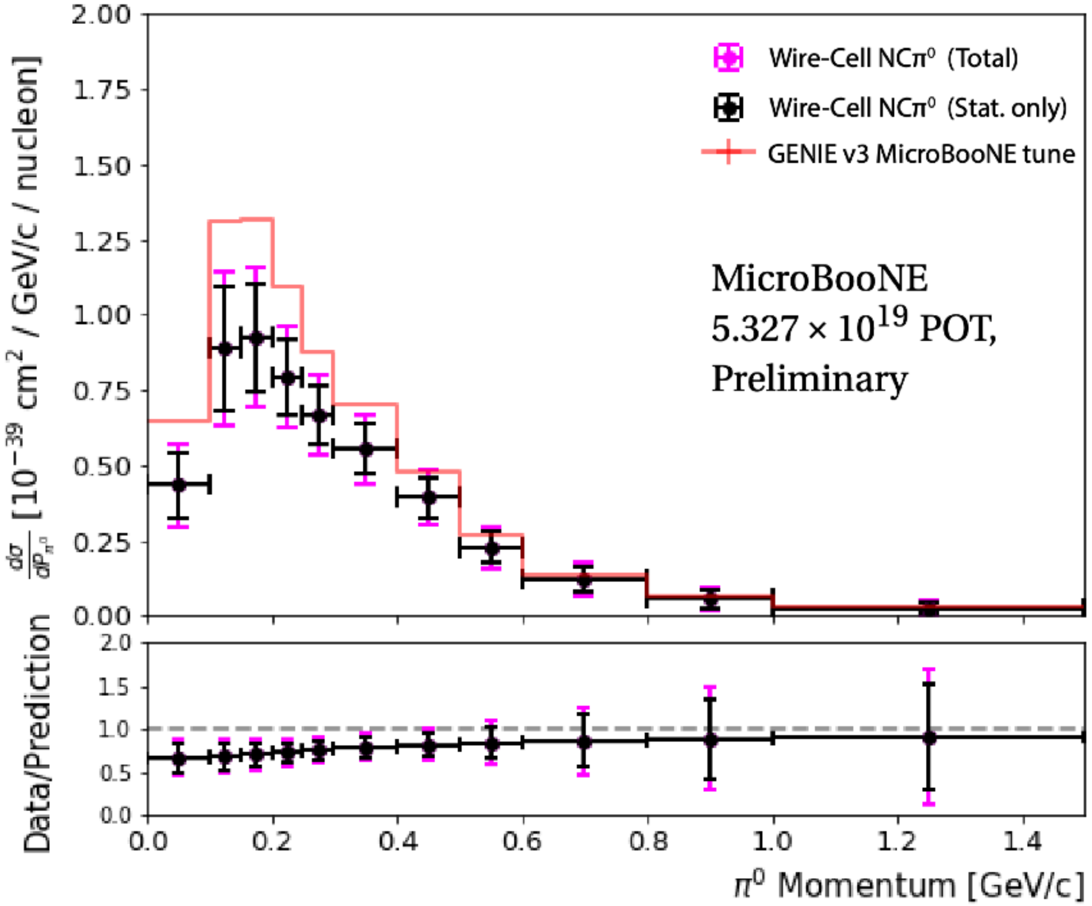
Important background to ν_e searches
→ $\pi^0 \rightarrow \gamma\gamma$ looks like ν_e if one photon missed

So we need to understand this process in detail

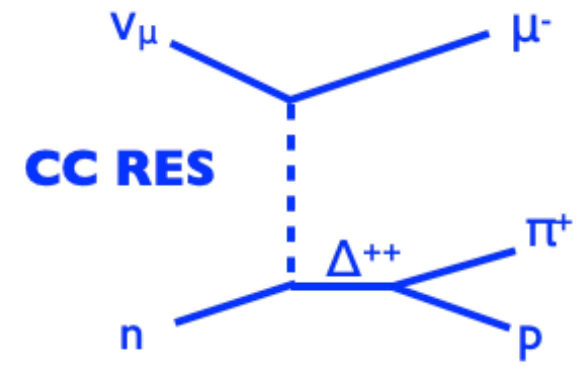
MicroBooNE measurements find models over-predict

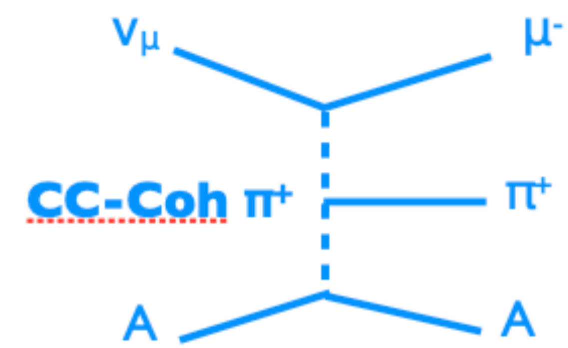


MICROBOONE-NOTE-1111-PUB



PION PRODUCTION



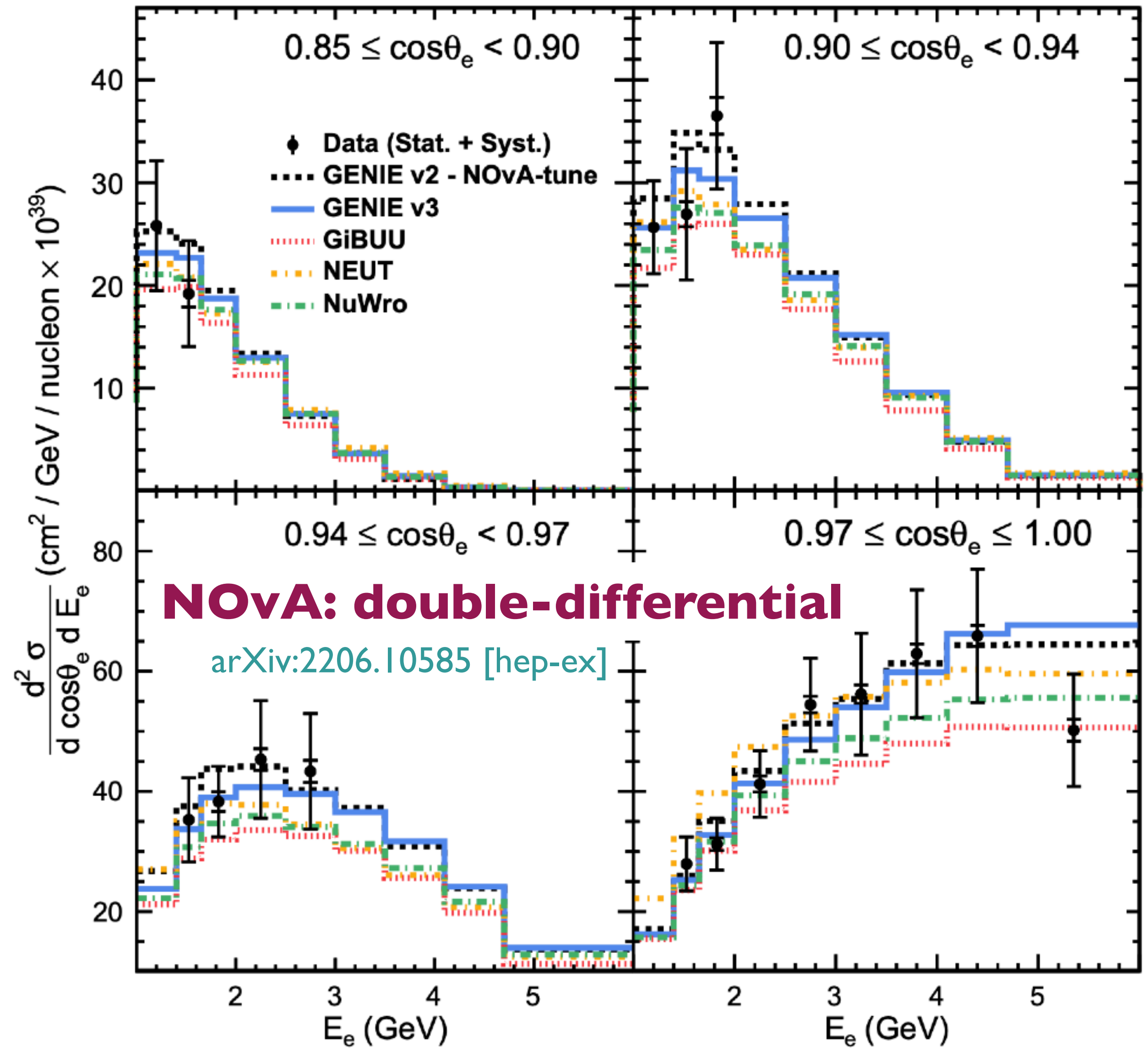


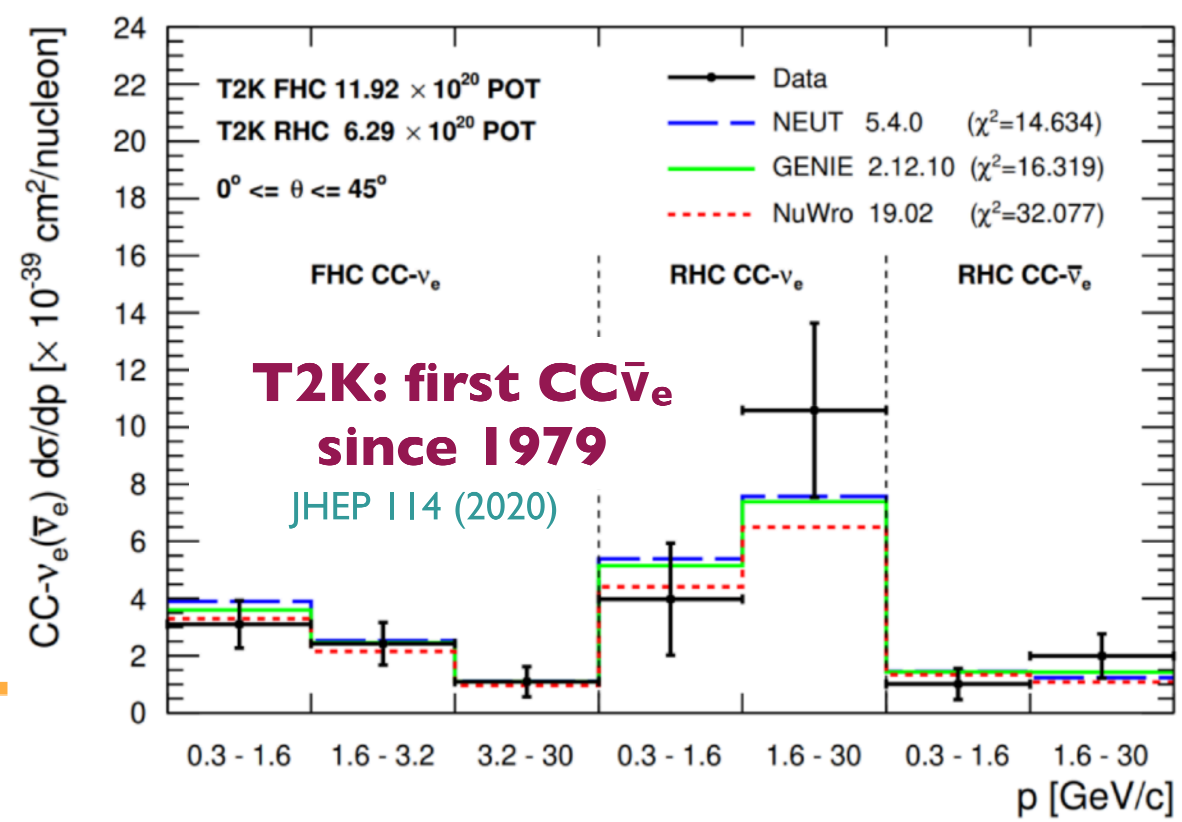
What have we learned?

- Current models are kind of reasonable, but don't describe the data very well
- Not surprising, because there has been less focus on this channel historically
- More data is becoming available → inspire improvements in our understanding before DUNE

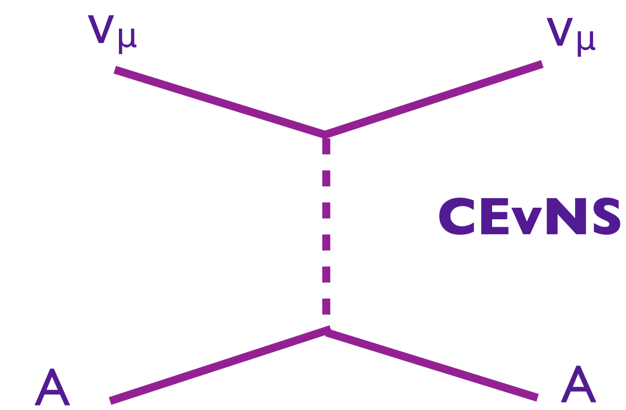
ν_e INTERACTIONS

- Many experiments look for ν_e appearance to measure neutrino oscillation → **must understand ν_e interactions well!**
- But our neutrino beams are ~97%+ ν_μ by design → **hard to study ν_e**, very few measurements
- Mostly we assume **lepton universality**: nuclear effects and interaction probabilities are the same for ν_μ and ν_e (except for e vs μ mass)
- But there are **some direct measurements (and more coming!)**

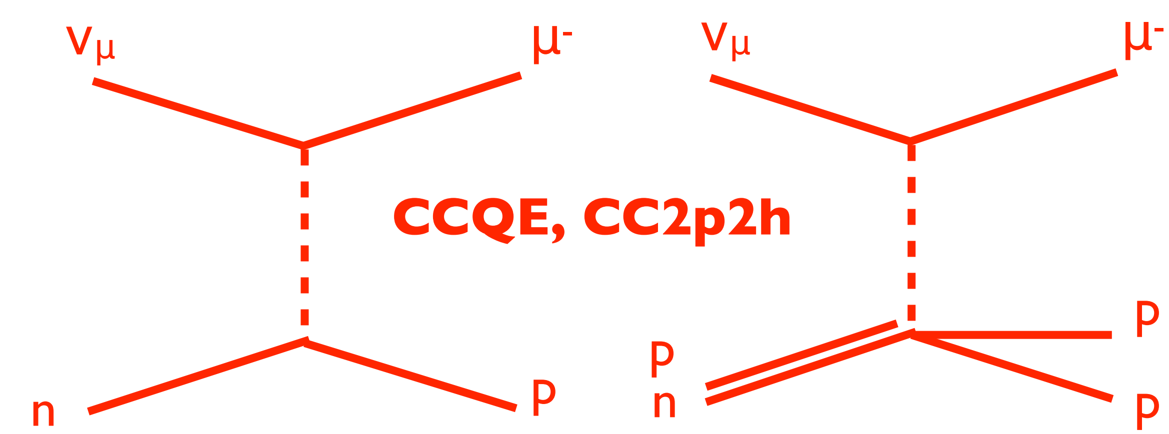


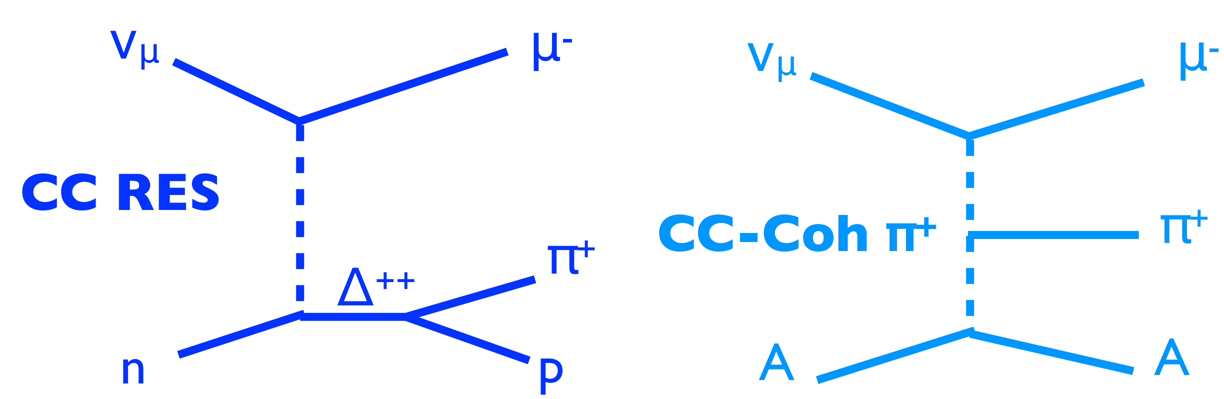


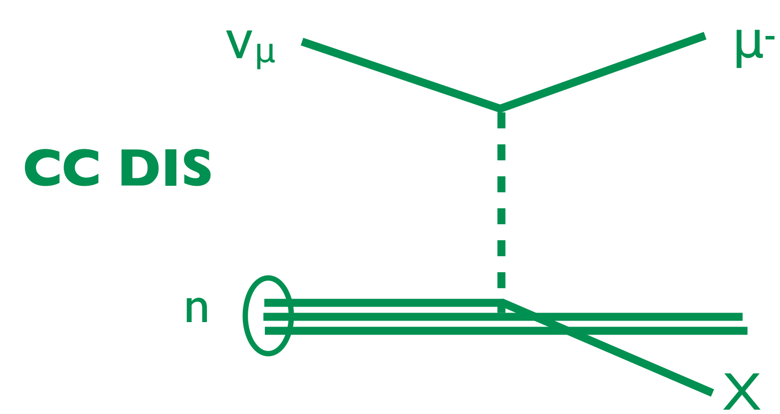
SUMMARY



- In the most positive way possible:
  - **Neutrino interactions are hard!** Our understanding of the nuclear initial state, interaction processes themselves, and final state interactions could all improve
  - **But they're also really important to understand properly** to reduce uncertainty and avoid bias in our measurements of fundamental neutrino properties
  - **There is a lot of work to do and lot of interesting problems to solve** - experimental data is vital to constrain models and gain a better understanding
  - **We're getting there** - join the fun!







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HOW DO WE MEASURE IT?

Incoming neutrino flux

- Most experiments use neutrino beams: measure **Protons On Target (POT)** when beam is running → related to number of neutrinos produced
- Convert into a number of neutrinos per cm^2 **at detector site**
- For example:
  Fermilab BNB O(10^{21}) POT per year
  μBooNE $\phi = 3.15749 \times 10^{10}$ cm^{-2} per year
- Note: this means the cross section we calculate is "flux averaged" → it depends on the flux seen at that specific detector. **Can not directly compare measurements in different neutrino beams!**

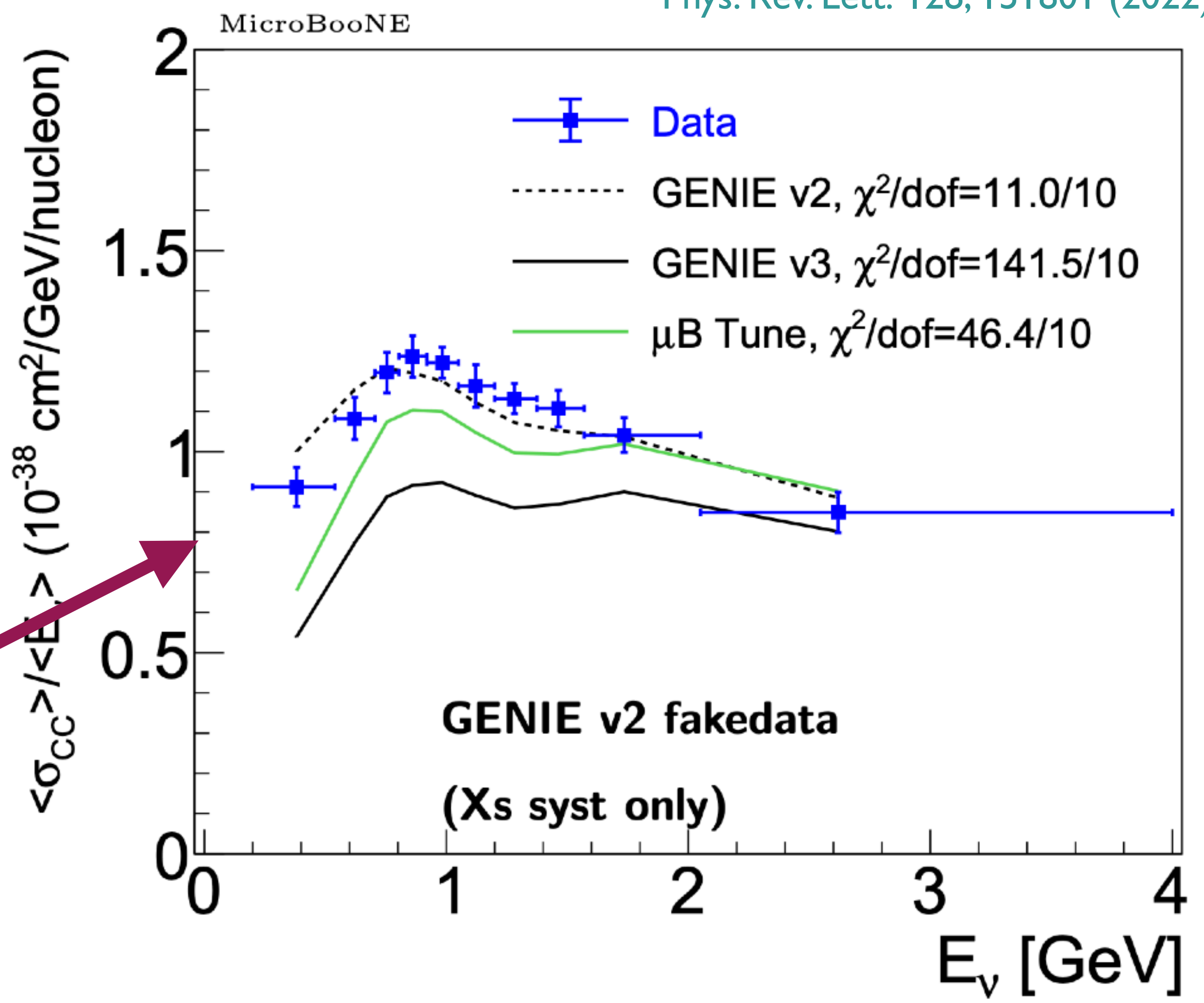
Number of targets

- Regardless of the interaction we are studying, we usually report **cross section per nucleus**
- Calculate number of nuclei from detector mass/volume and density
- For example:
  μBooNE Mass = 85 tonnes
  $N_{nuclei} = \rho_{Ar} V N_A / m_{mol}$
  $= 1.203 \times 10^{30}$

HOW DO WE MEASURE IT?

- Clearly **bias in our result is a big worry**: how can you measure something new if your analysis will only reproduce the model you put in?
- One (popular) way to check for bias: f**ake data tests!**
- Type 1) put in a different model as fake data, calculate the cross section, and **compare to the model to see if you got it right**
- Type 2) use a different model to calculate the data cross section, and **see if you get the same result**

Phys. Rev. Lett. 128, 151801 (2022)



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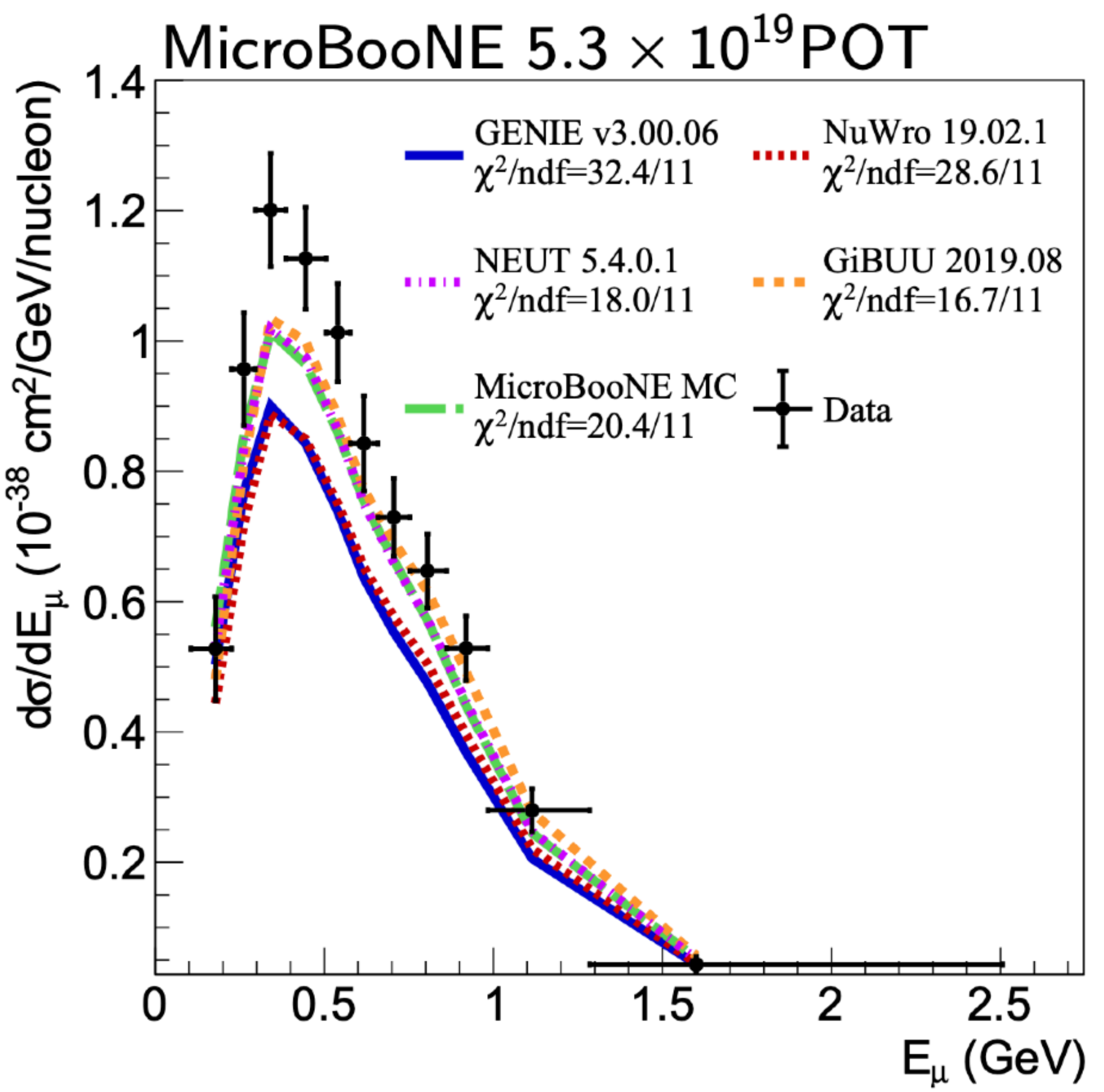
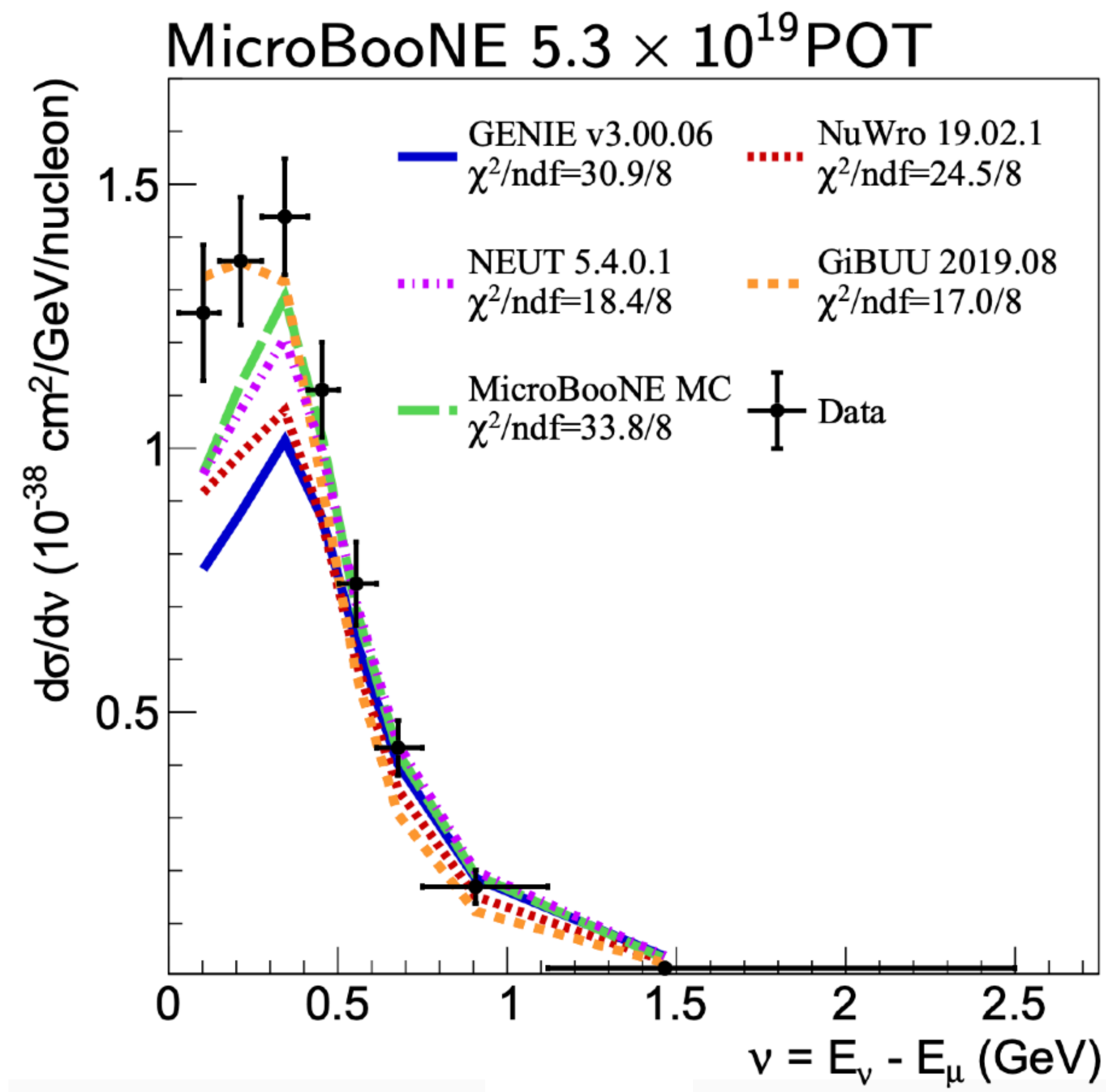
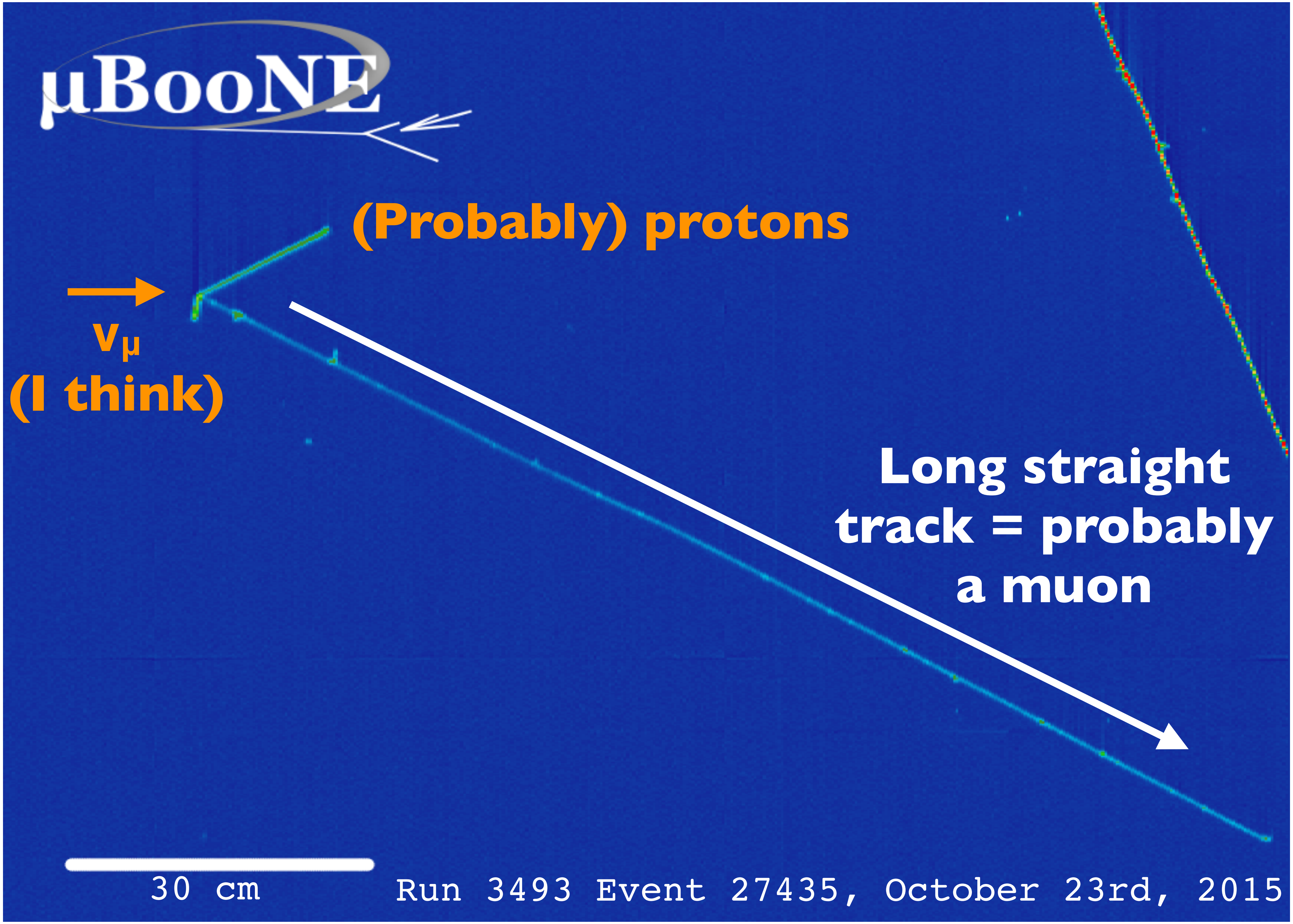
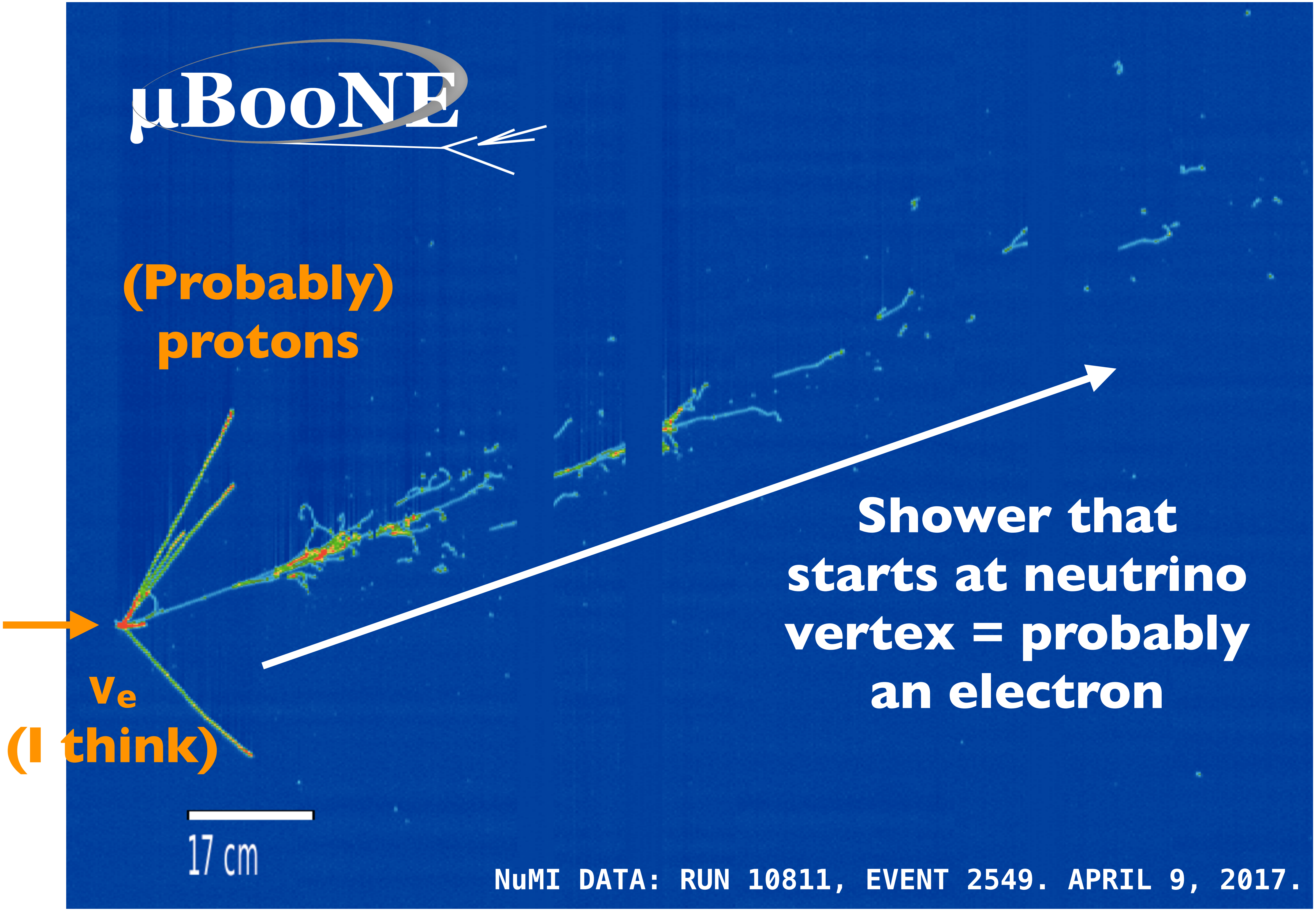
ν_μ CC INCLUSIVE: MicroBooNE MEASUREMENT

Phys. Rev. Lett. 128, 151801 (2022)



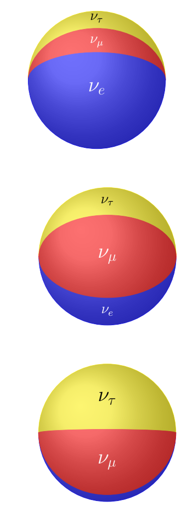



μBooNE
(Probably) protons
ν_μ
(I think)
Long straight
track = probably
a muon
30 cm
Run 3493 Event 27435, October 23rd, 2015


μBooNE
(Probably) protons
ν_e
(I think)
Shower that starts at neutrino vertex = probably an electron
17 cm
NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

RECAP: NEUTRINO OSCILLATION

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



flavour

Interaction

mass

Propagation

PMNS matrix

named after Pontecorvo, Maki, Nakagawa, and Sakata

RECAP: NEUTRINO OSCILLATION

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

flavour

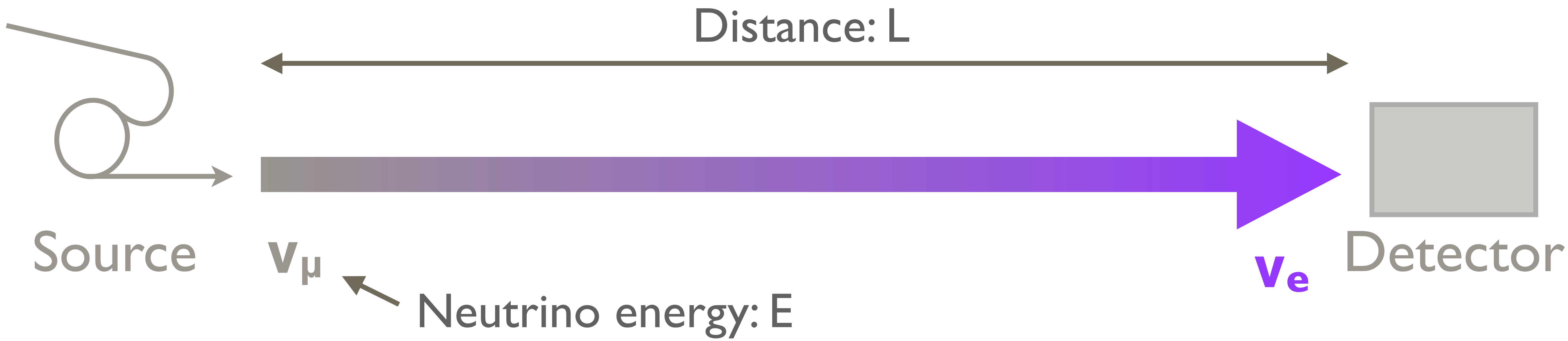
mass

Four free parameters:

Three mixing angles θ_{12}, θ_{23}, θ_{13}

One phase δ_{CP}

Each mixing angle describes mixing between two mass states (3c2 = 3)



Muon neutrino disappearance

Electron neutrino appearance

$\bar{\nu}$ ν

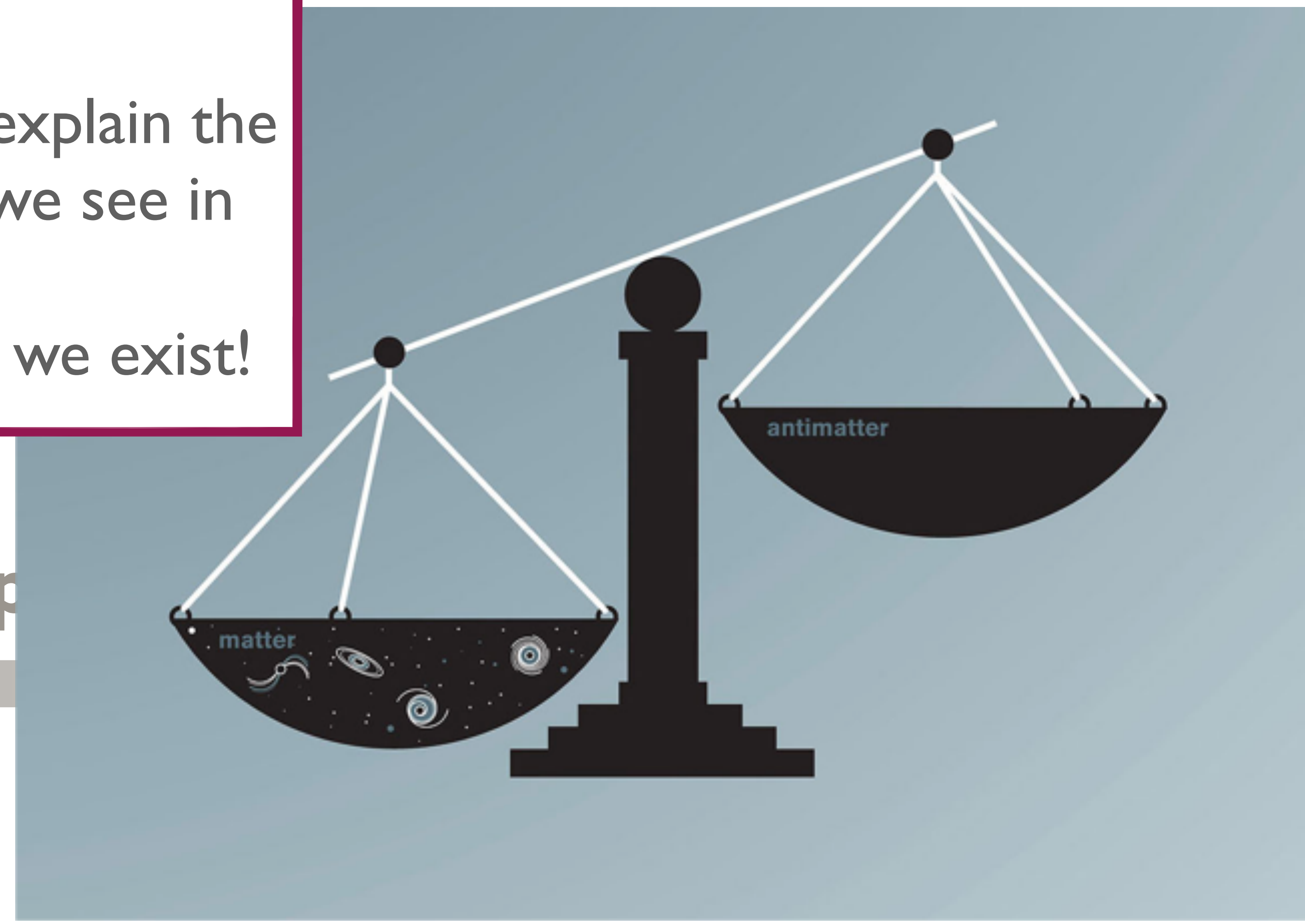
$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \sim \text{something} +/- \text{something else} \times \sin\delta_{CP}$$

Reason #2 why neutrinos are exciting:

CP violation in neutrinos might explain the matter-antimatter asymmetry we see in the universe

→ neutrinos could explain why we exist!

: L



Muon neutrino disapp

Electron neutrino appearance

$\bar{\nu}$ ν

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \sim \text{something} +/- \text{something else} \times \sin\delta_{CP}$$

WHAT IS A CROSS SECTION?

The cross se… …will interact

C… …os that

…ets

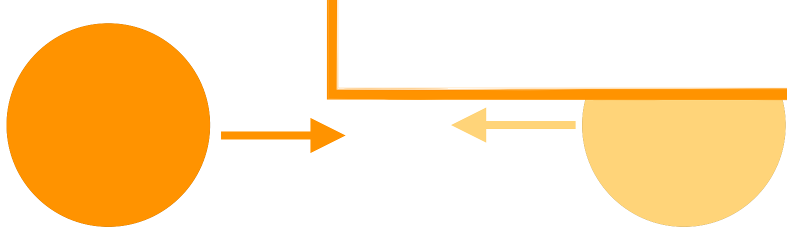
Classical an… …balls that
you throw …

Note: Neutrinos only interact via the weak force, so **cross sections tend to be small**.

At 1 GeV:

$\sigma(\nu N) \sim 10^{-38}\ \mathrm{cm}^2$

$\sigma(pp) \sim 10^{-26}\ \mathrm{cm}^2$



more likely to collide