$e4\nu$ & $\mu4\nu$

Brightening the Future of Neutrino Oscillation Measurements

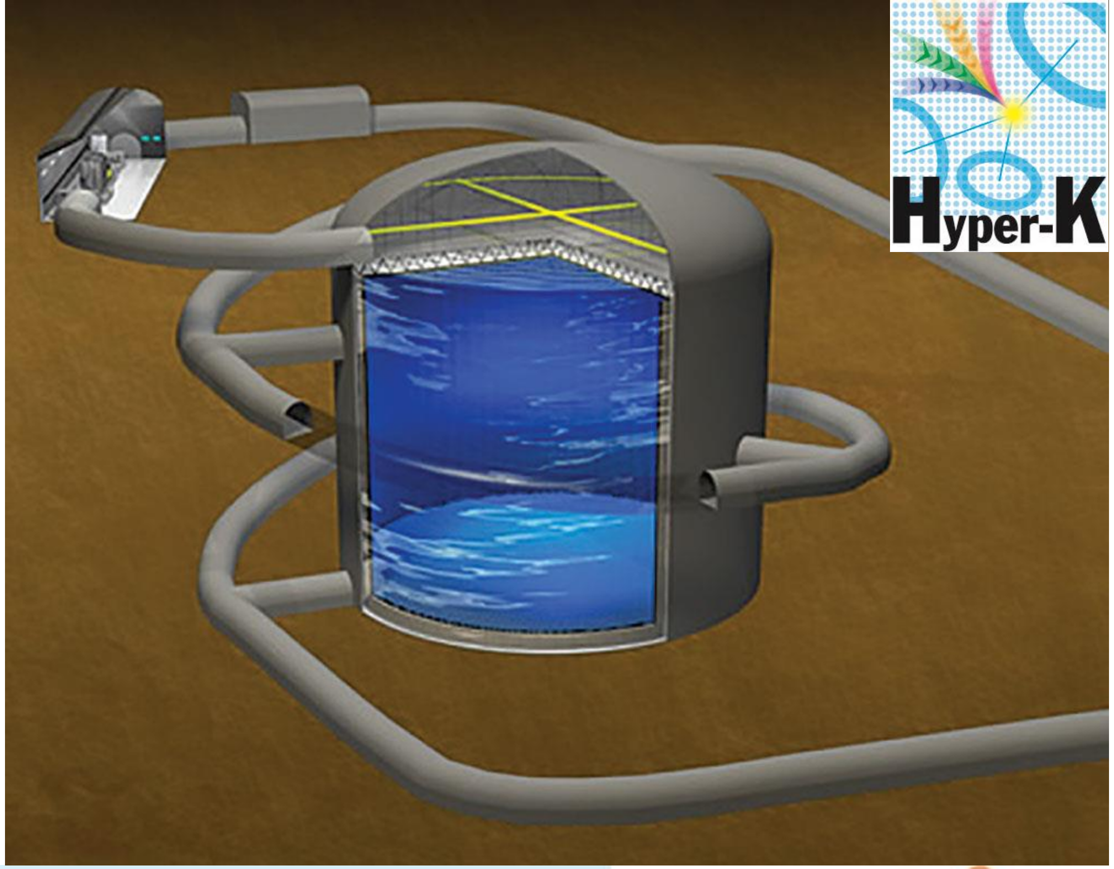
14th Conference on the Intersections of Particle and Nuclear Physics

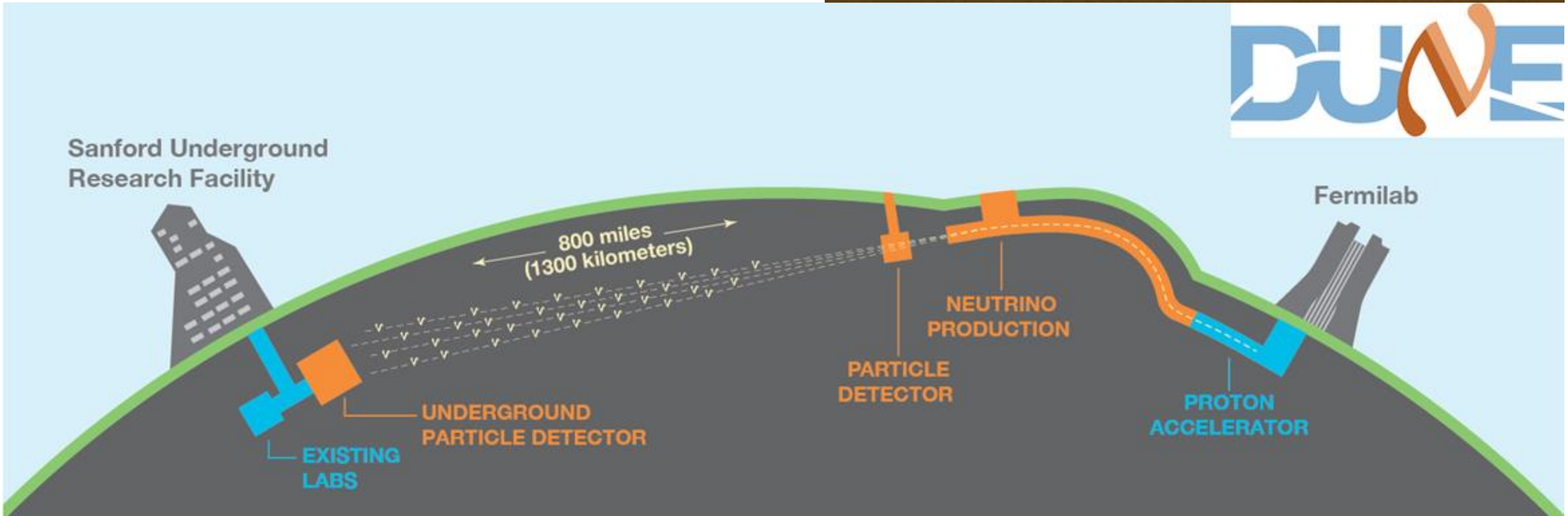
September 1st, 2022

J. L. Barrow
MIT & TAU
Zuckerman Postdoctoral Scholar

Future Experimental ν Physics

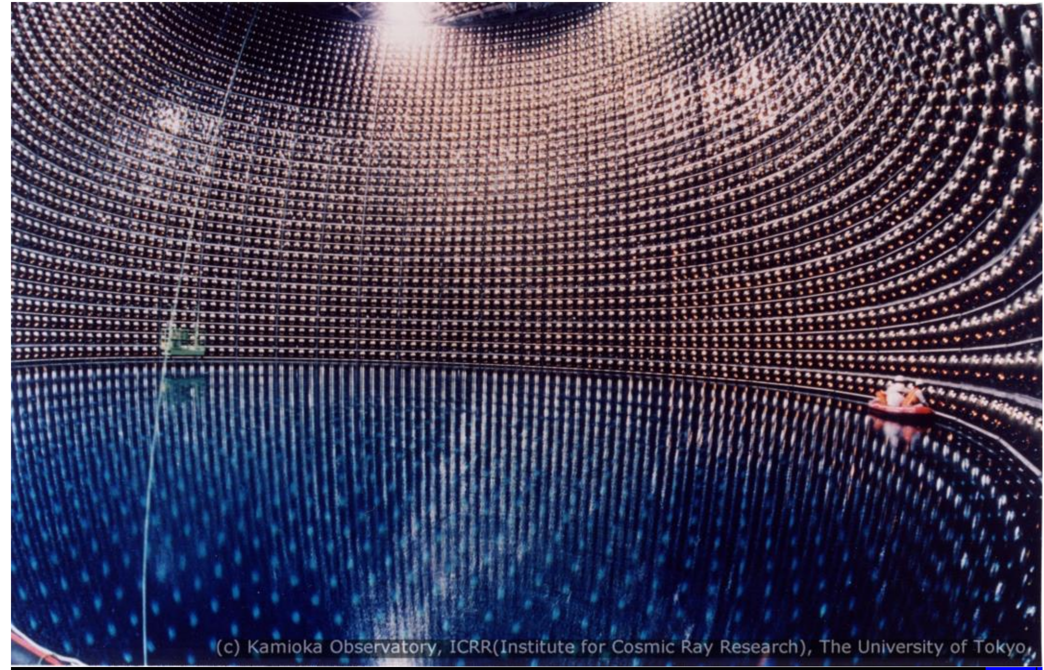
- Goal:
    - Extract ν oscillation parameters
- Implications
    - Leptogenesis, cross sections, τ production, BSM, Non-Standard Interactions
- Challenges
    - Broadband ν spectra
    - Unknown initial ν energy

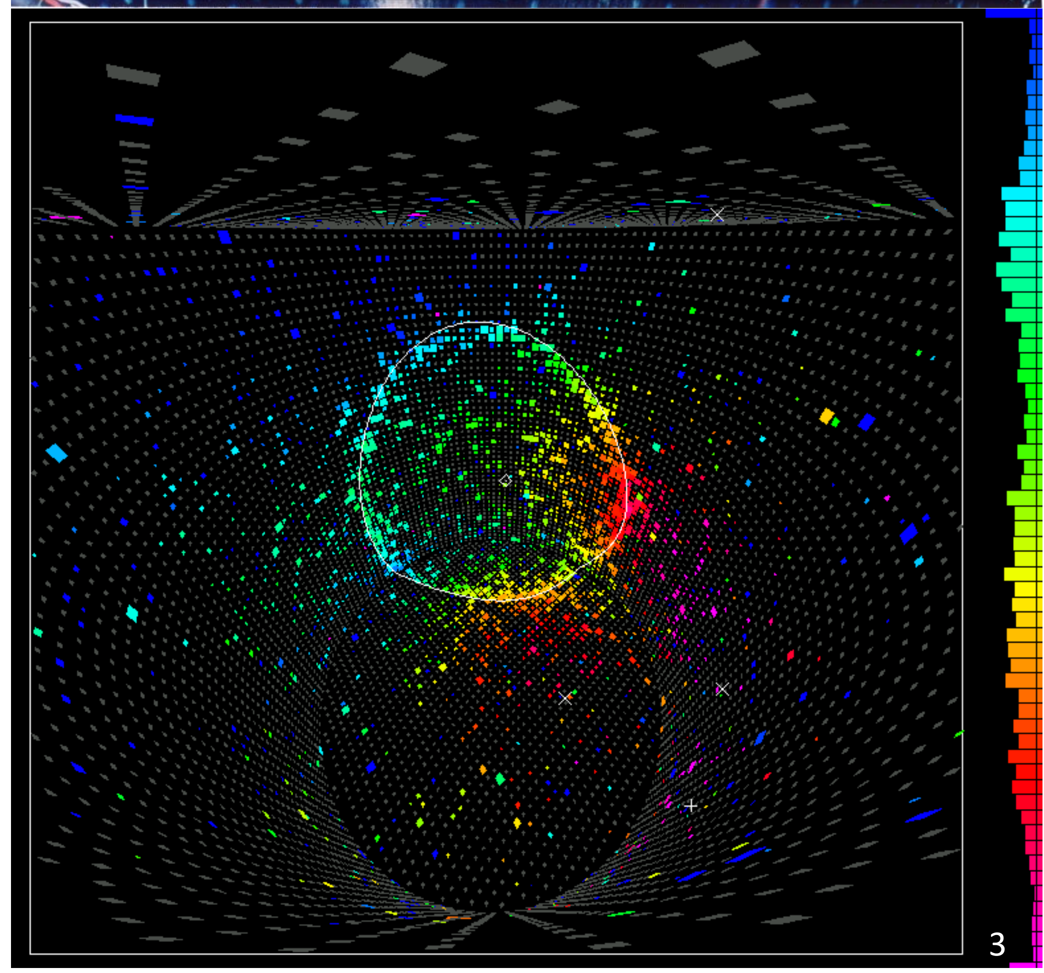




Water Cherenkov Detectors

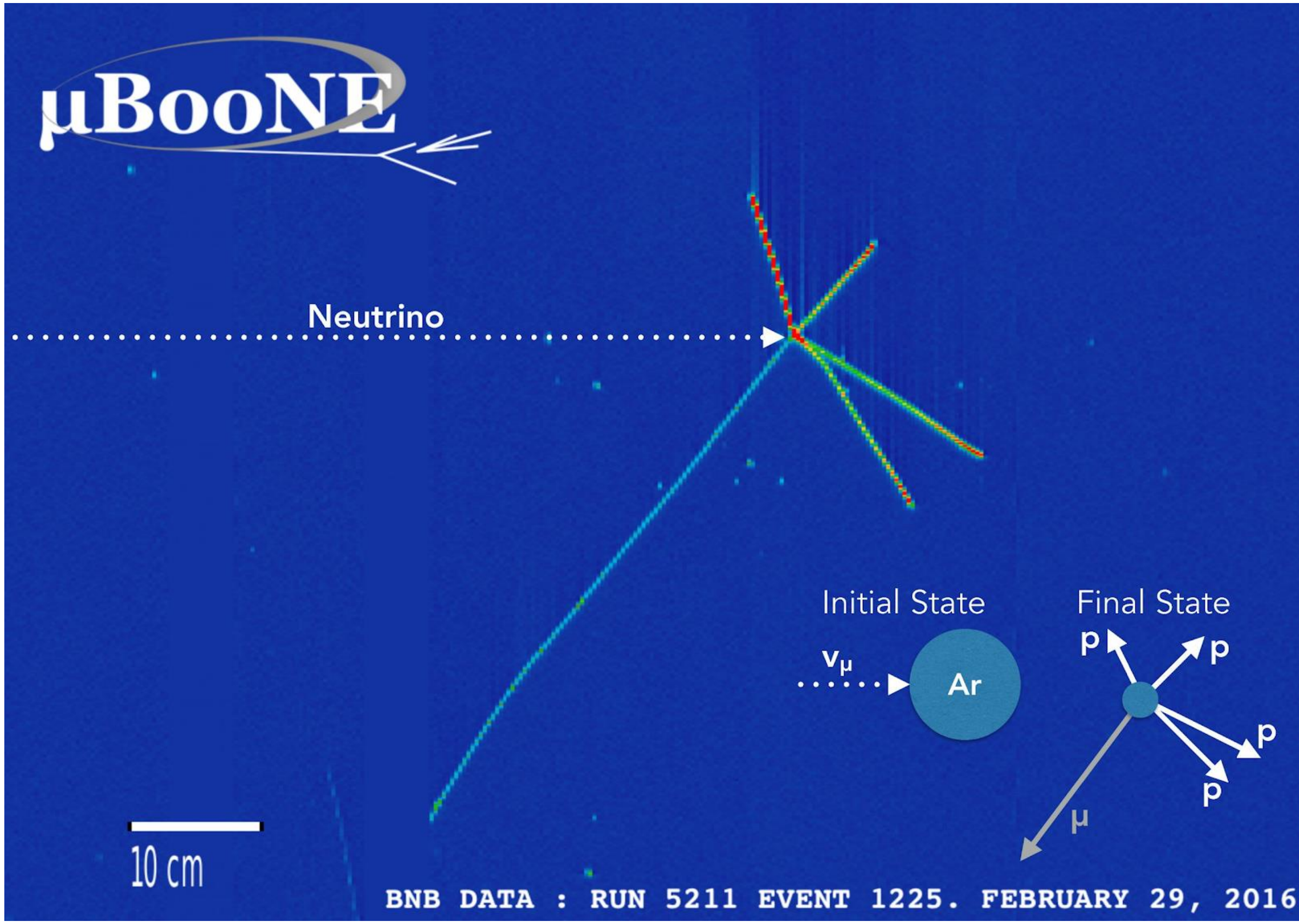
- Super & Hyper-Kamiokande's technology
  - Well understood, battle tested
  - Huge masses, statistics
- Oxygen as main nuclear target
  - "Simple" symmetric nucleus
- Reconstruct particle momenta from Cherenkov rings
  - High proton thresholds
  - Lack of γ/e separation power



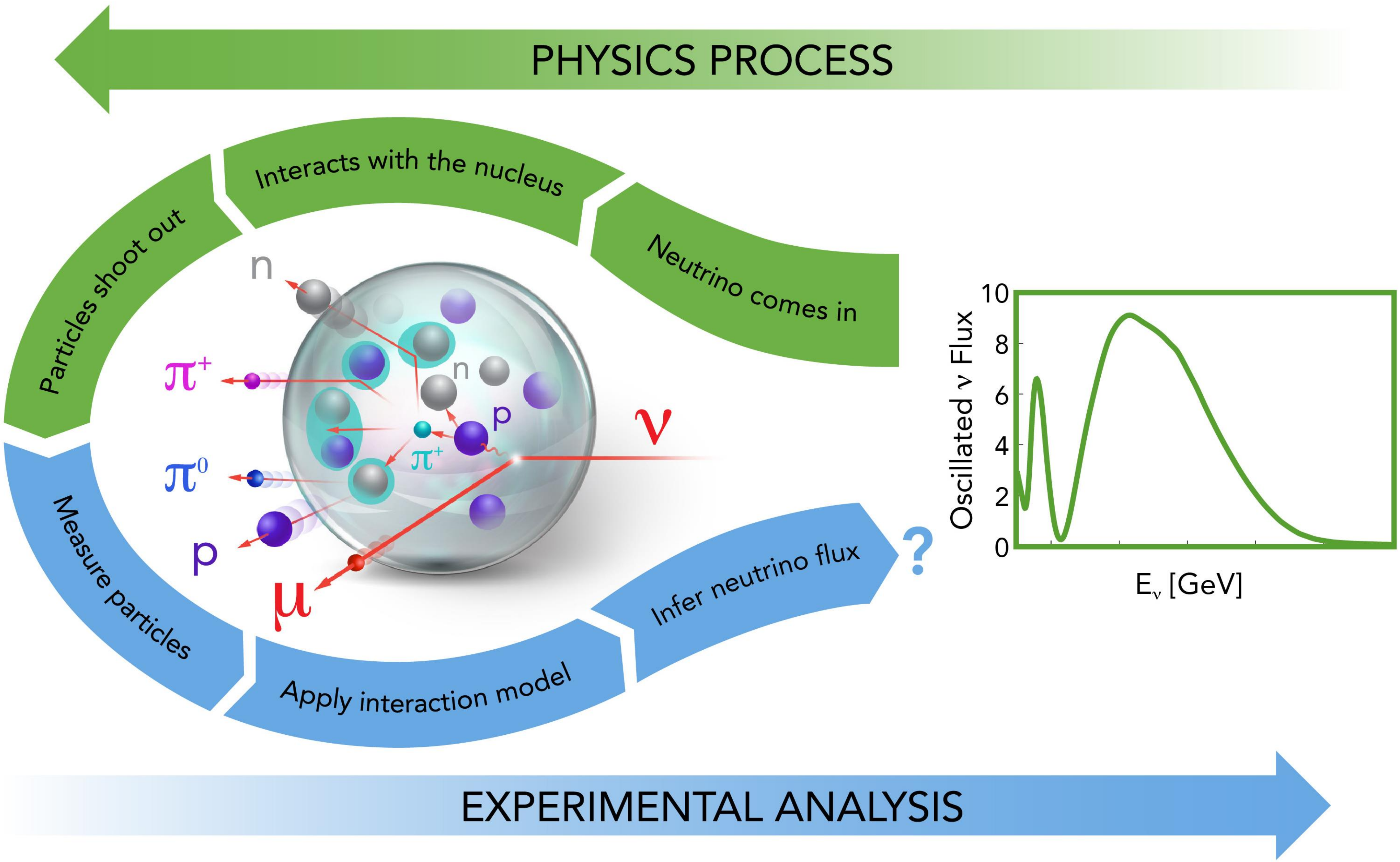


Liquid Argon Time Projection Chambers

- DUNE’s technology
- Argon as target
  - Complex nucleus
- Ionization of LAr for track reconstruction
  - Low proton thresholds
  - $dQ/ds \sim dE/ds$ for calorimetry
  - γ/e separation power



Animation from Bo Yu (BNL)



[Khachatryan, M., Papadopoulou, A., Ashkenazi, A. et al. Nature 599, 565–570 (2021)]

Adapted from A. Ashkenazi and A. Papadopoulou

How Do We Measure Oscillation Parameters?

Measure ν interaction counts in our detectors…
Must use an interaction model to deconvolve the ν flux

$$N_\beta(E_{rec}, L) = \int \Phi_\beta(E_{\text{true}}, L)\,\sigma(E_{\text{true}})\,R_\sigma(E_{\text{true}}, E_{\text{rec}})\,dE$$

measured

ν flux

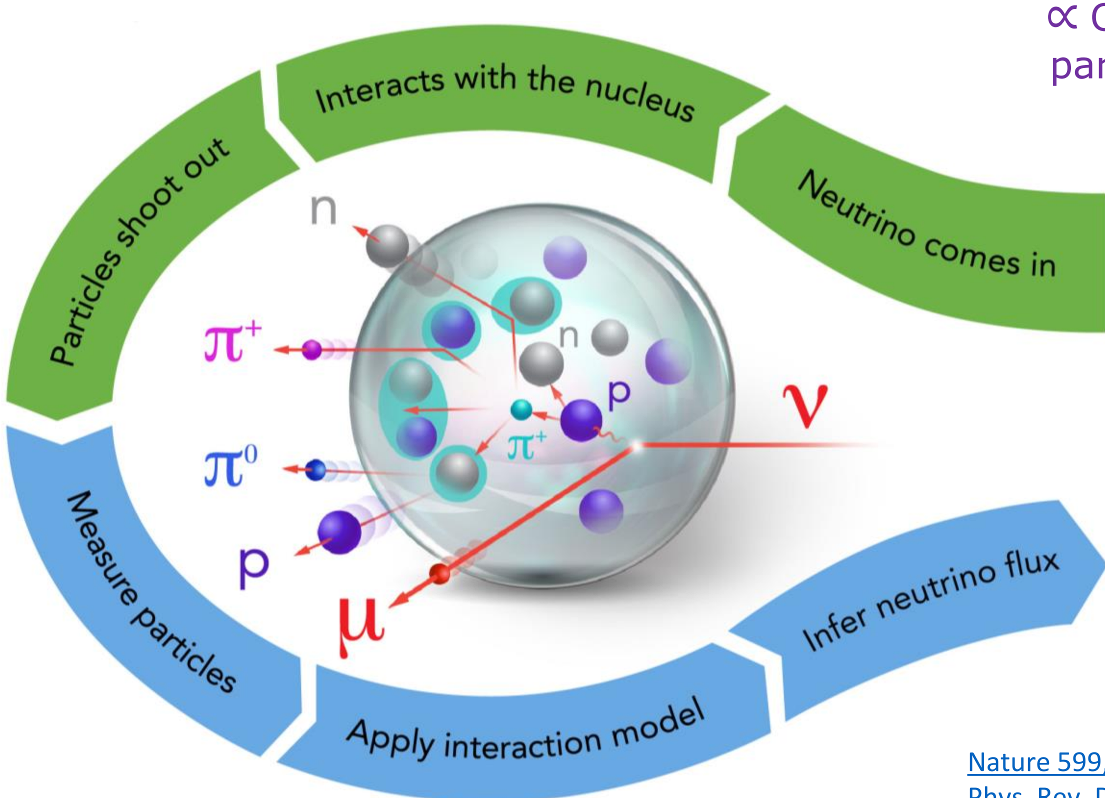
interaction model

Required!

Near detector constraint

$$\Phi_\beta(E, L) \propto P_{\nu_\alpha \to \nu_\beta}(E, L)\,\Phi_\alpha(E, \sim 0)$$

$\propto$ Oscillation parameters!

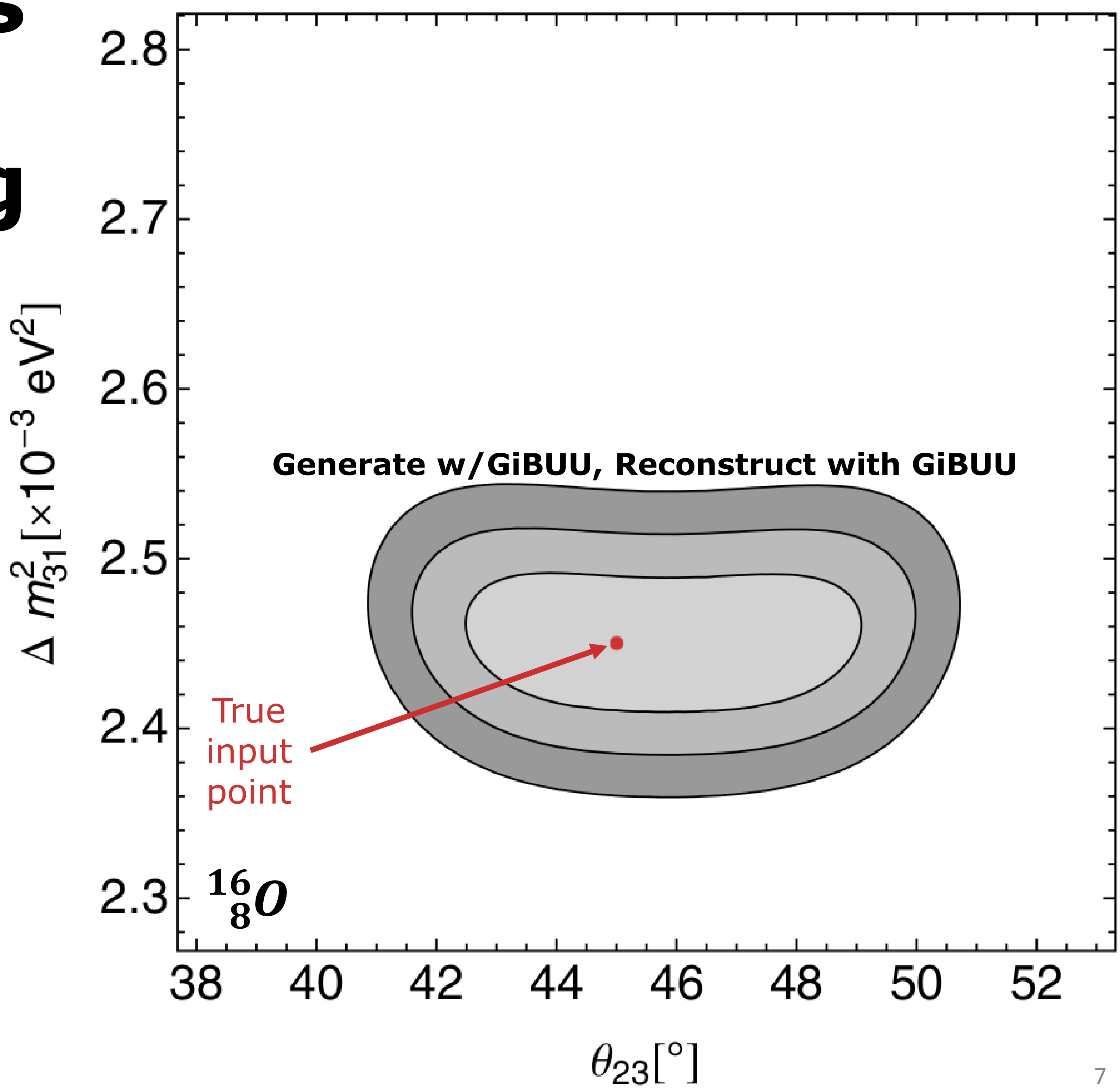


Adapted from A. Ashkenazi and A. Papadopoulou

Nature 599, 565–570 (2021)
Phys. Rev. D 91, 072010 (2015)

Implications of Mismodeling

- Leads to misreconstruction
- Misinterpretations of experimental results!
  - Bad oscillation parameters
  - Fake systematic effects?
  - New physics?

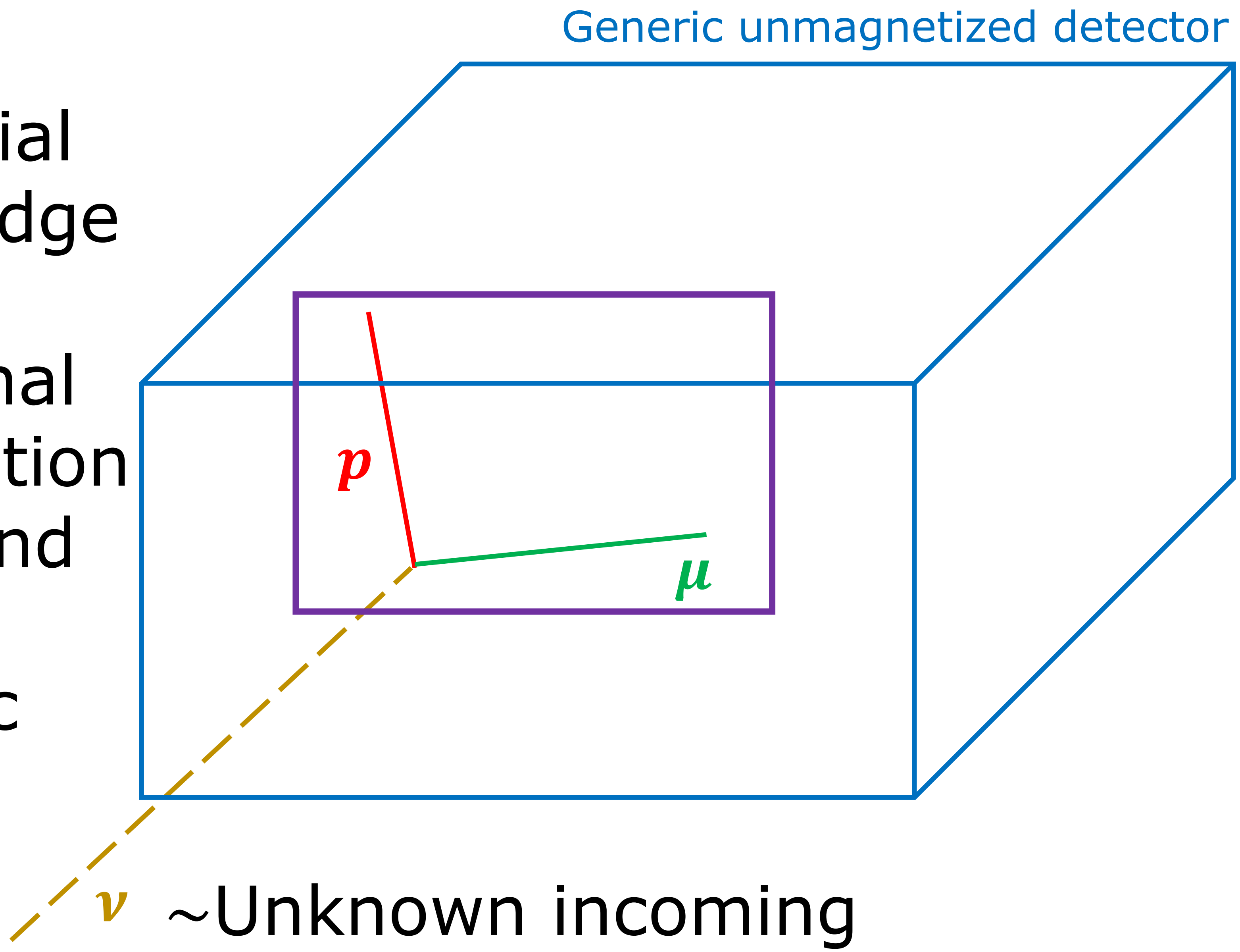


Phys. Rev. D 89, 073015 (2014)

The Charged Lepton Strategy

Must Reconstruct Initial ν Energy

Definitive initial energy knowledge limited by observable final state via ionization calorimetry and range, no magnetic curvature

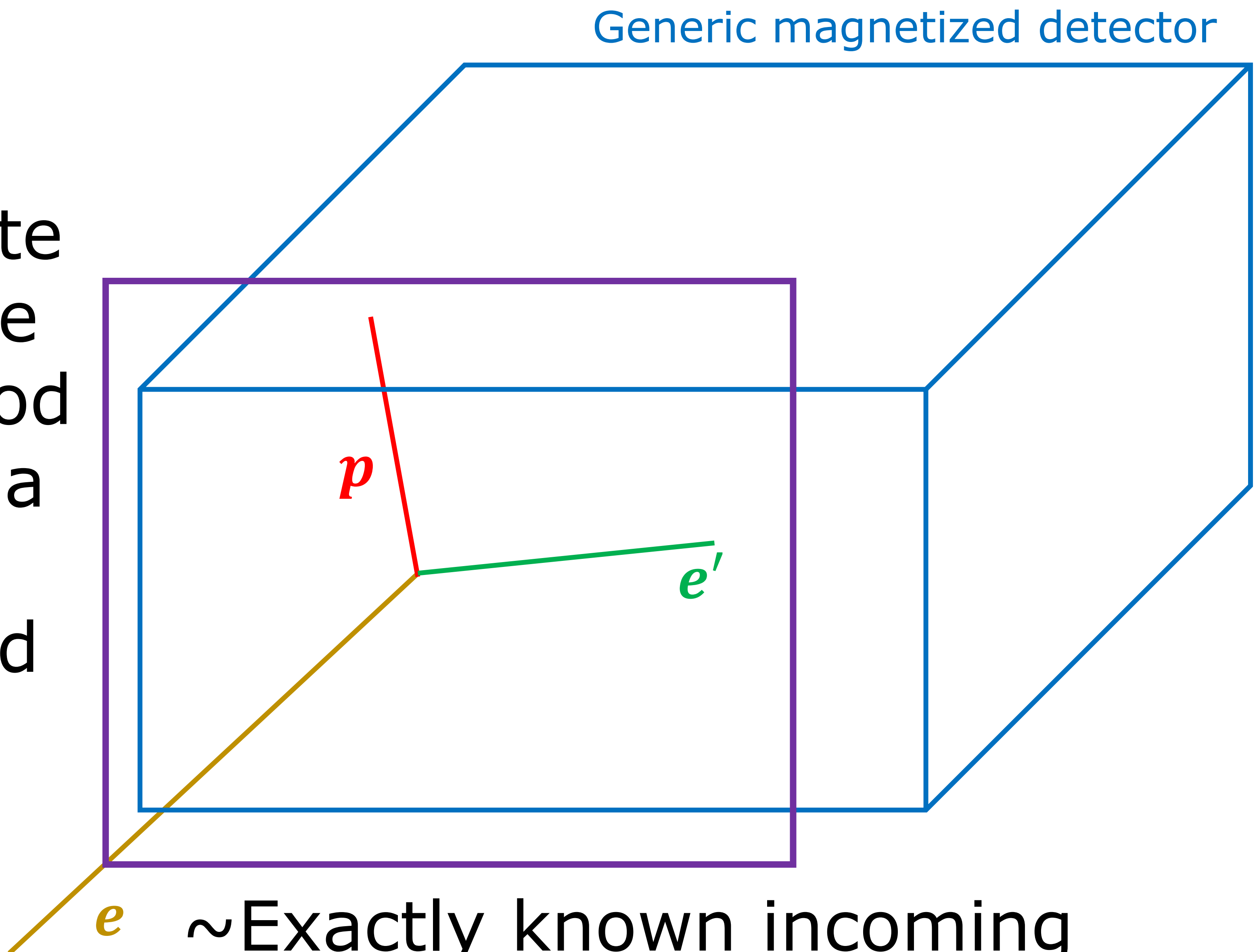


~Unknown incoming neutrino energy

Utilizing Electron Scattering

Identical Topologies with Precision Beams

Most final state particles have well understood kinematics via magnetic curvature and calorimetry

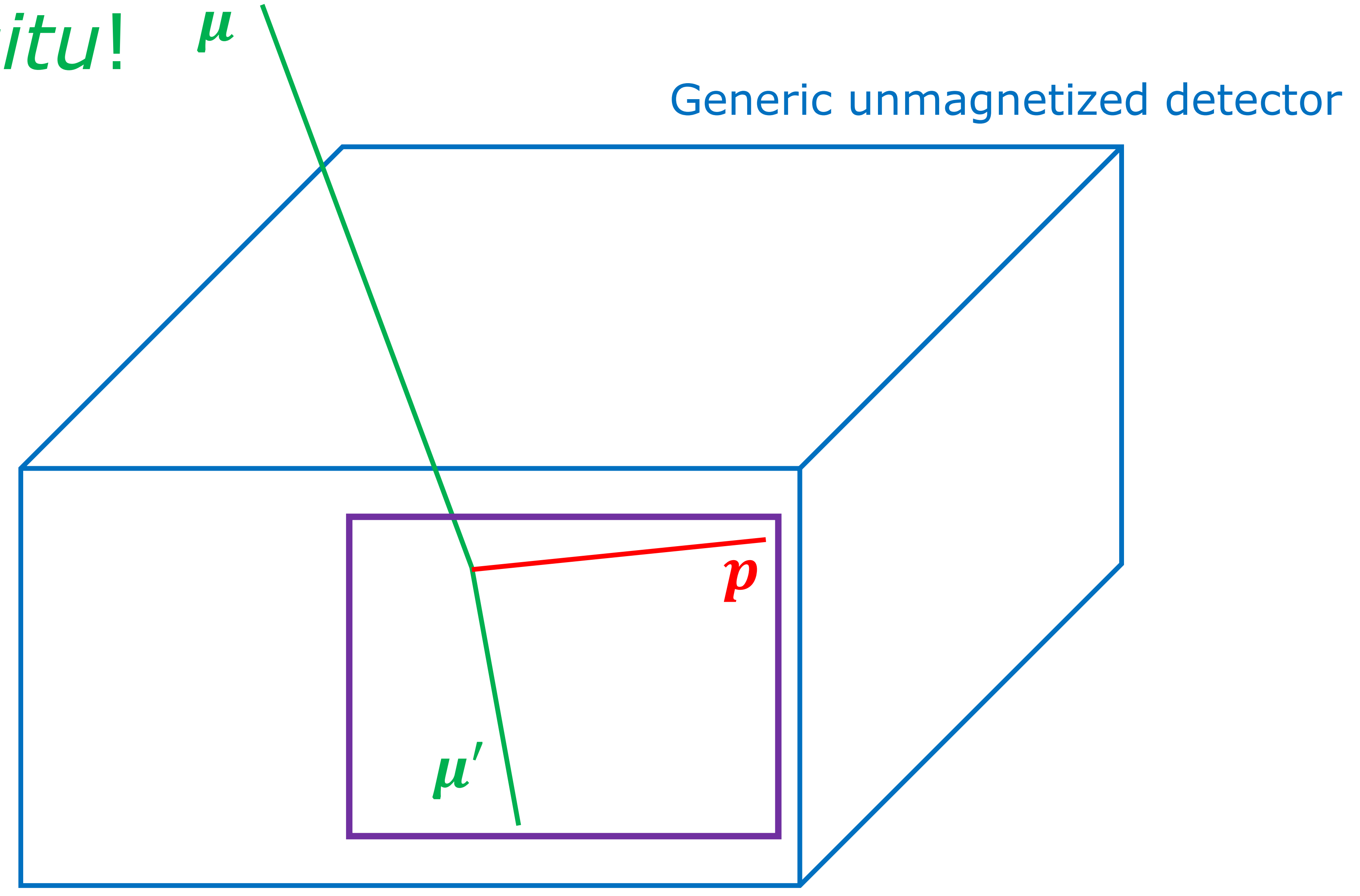


~Exactly known incoming electron energy

Utilizing Cosmic Muon Scattering

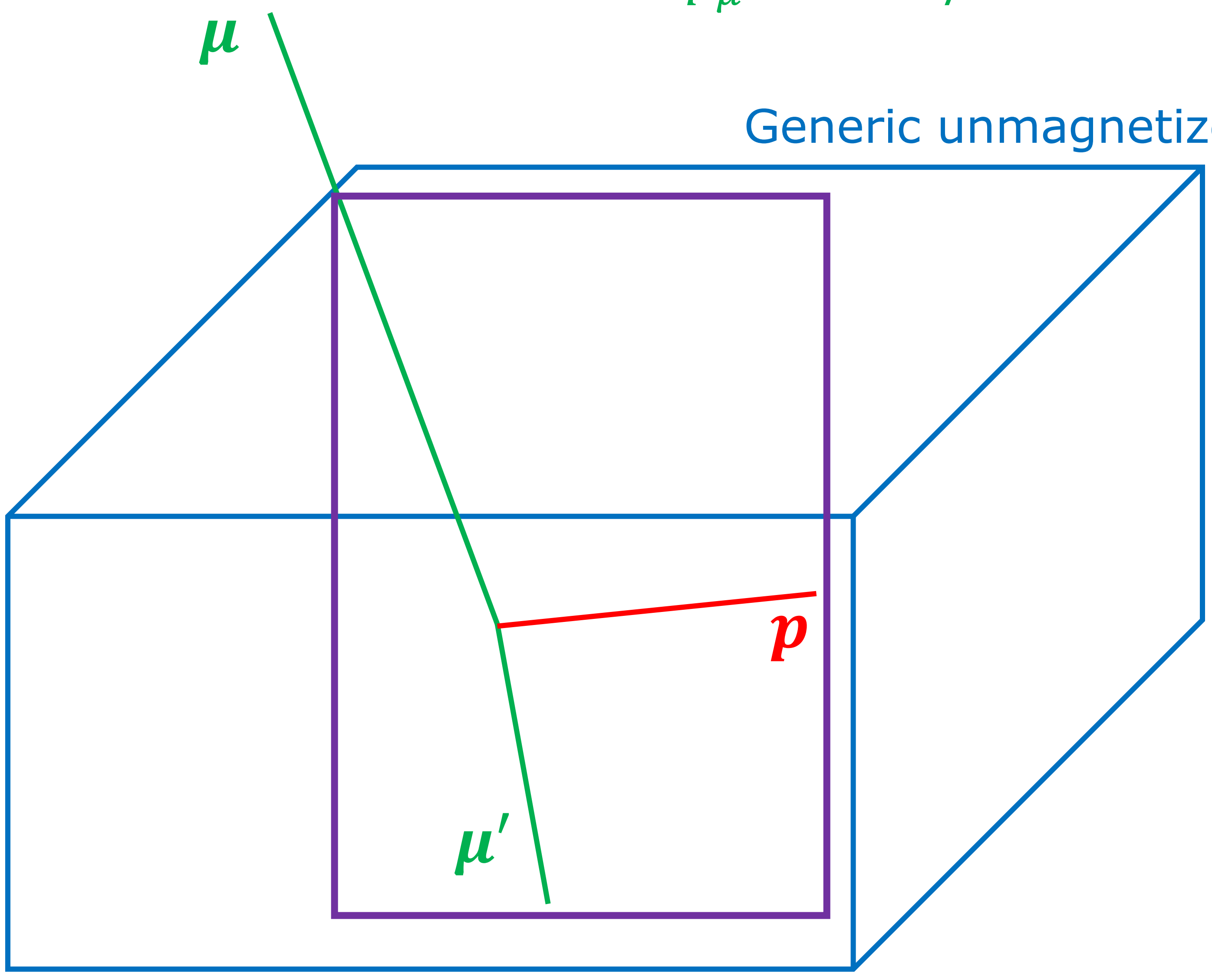
Identical Topologies with Broad Spectra

Use cosmic
$\mu^{\pm}$ *in situ*!



Initial energy knowledge not limited to only “final state” particles

Momentum resolution is
$\sim$11-15% for $p_\mu < 2\mathrm{GeV/c}$

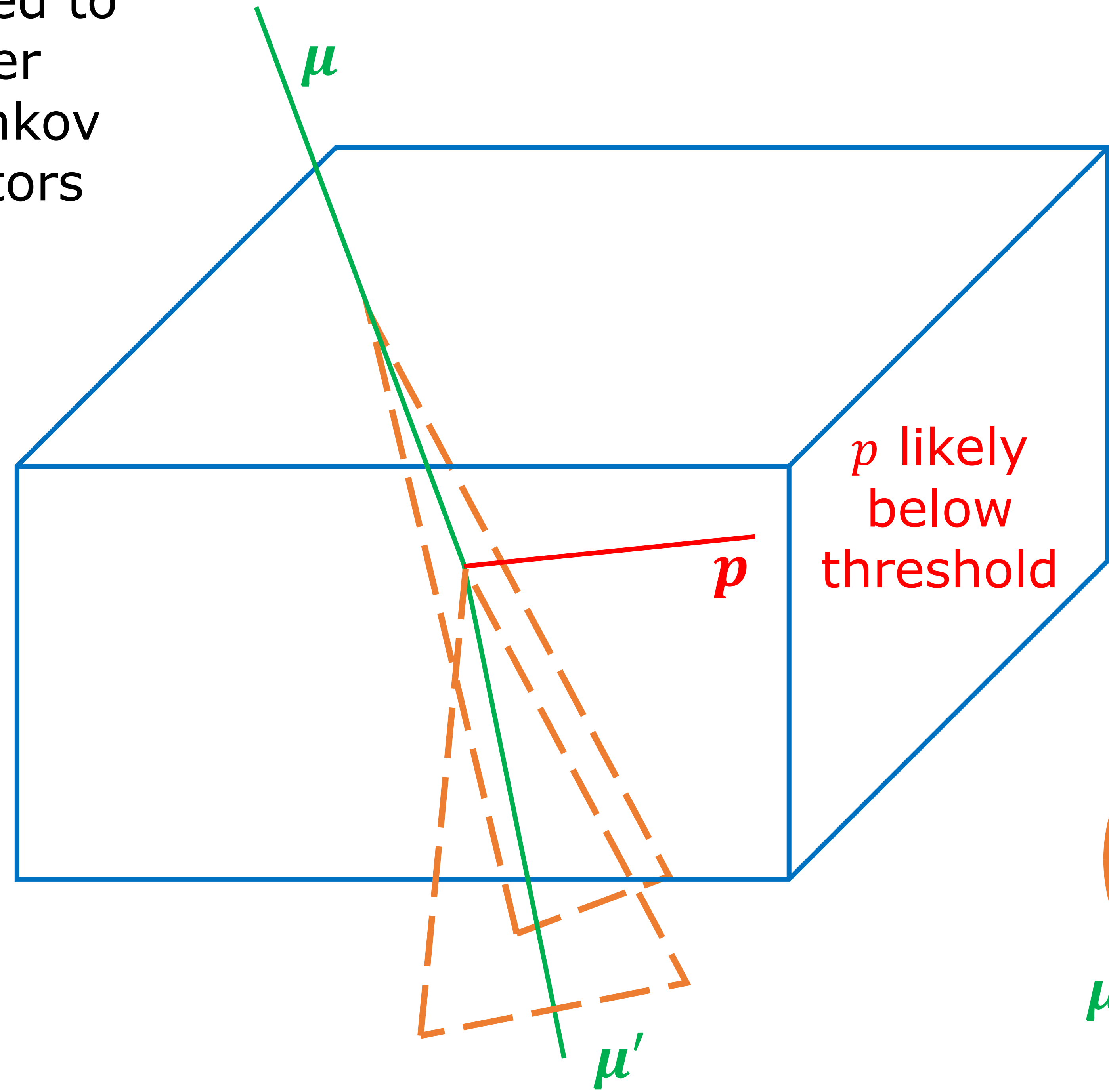


Initial energy knowledge not limited to only “final state” particles

Multiple Coulomb scattering

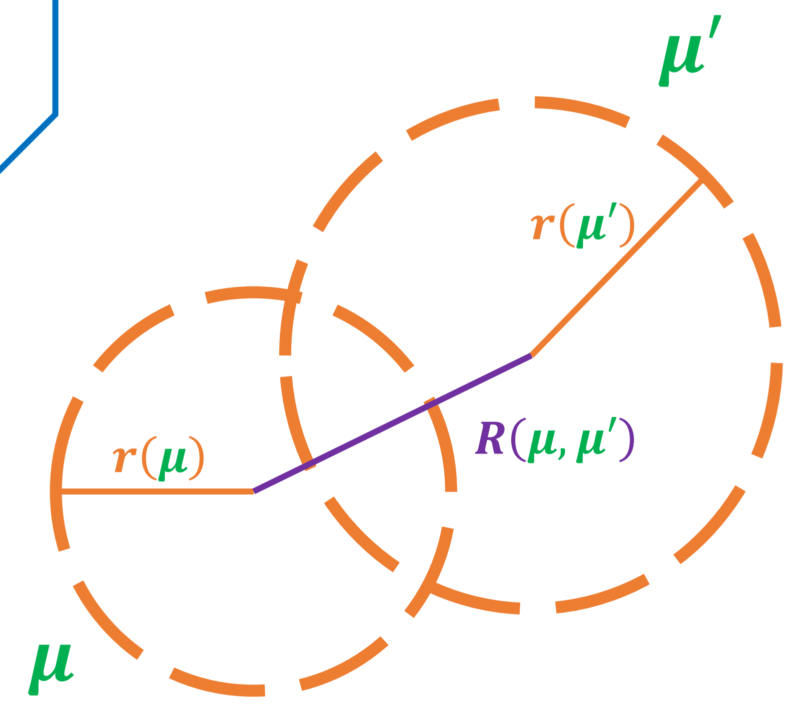
Idea can be extended to Water Cherenkov detectors

Generic Cherenkov detector



$$r(\mu) - r(\mu') \propto \omega$$

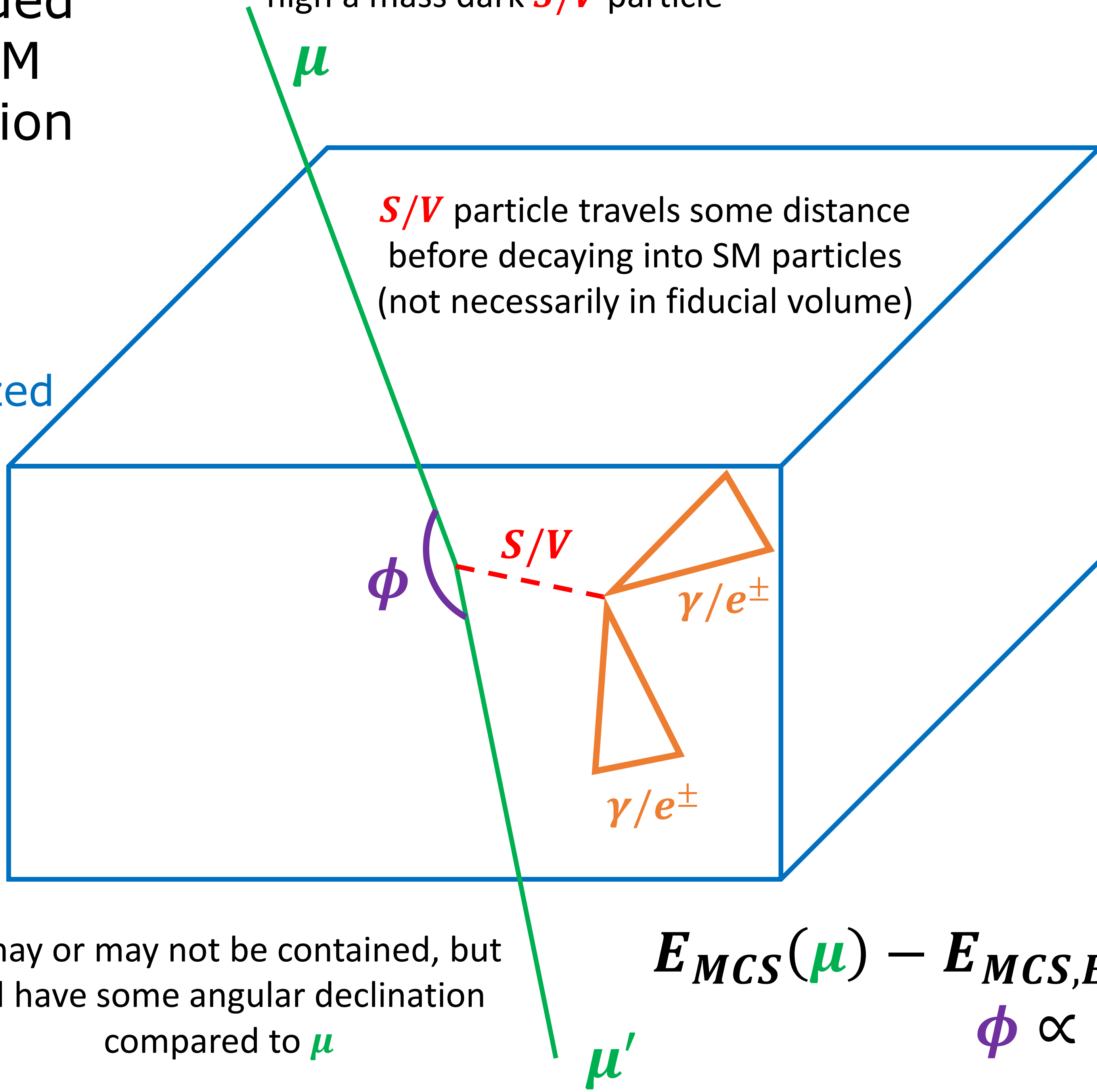
$$R(\mu, \mu') \propto q \propto p_p$$



Idea can be extended for DM detection

μ incident from cosmic flux requires high energy to Bremsstrahlung off high a mass dark S/V particle

Generic unmagnetized detector



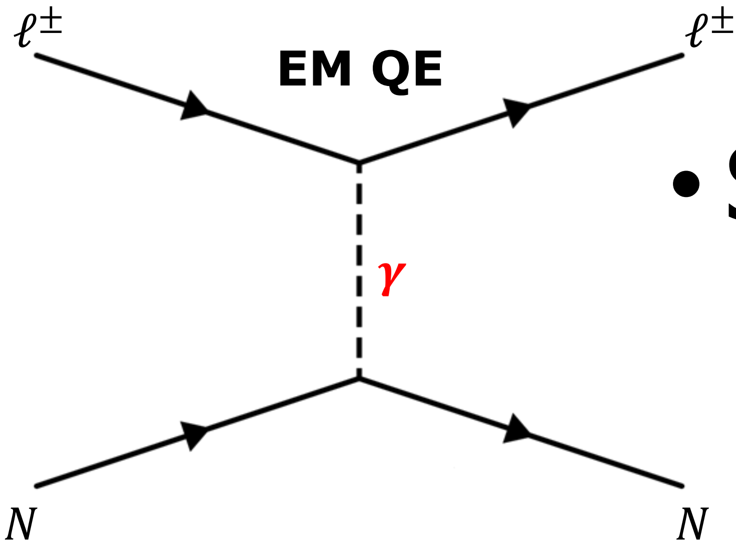
S/V particle travels some distance before decaying into SM particles (not necessarily in fiducial volume)

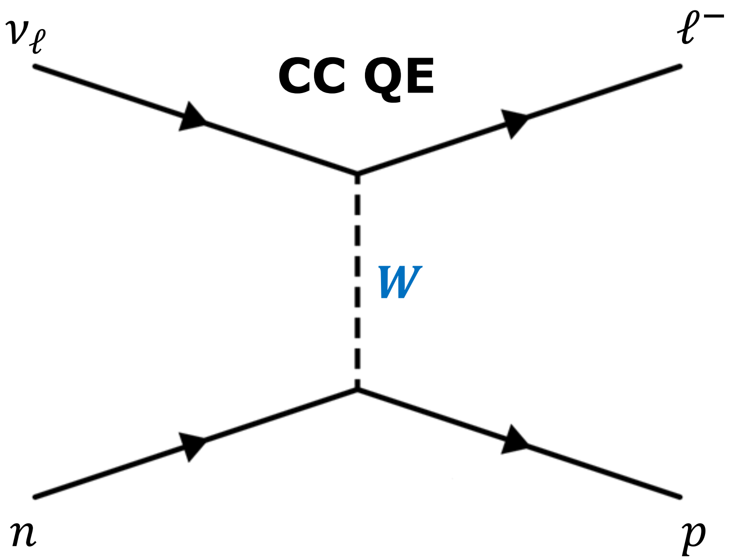
Most general signal: Kinked 2-prong topology with no other activity around the interaction vertex

μ' may or may not be contained, but will have some angular declination compared to μ

$$E_{MCS}(\mu) - E_{MCS,ECal}(\mu') \propto M_{Inv}(S/V)$$
$$\phi \propto q \propto p_{S/V}$$

Why Charged Leptons?





- Similar interactions with nuclei
  - Single boson exchange via
    - **Vector** (V) EM interaction

$$j_\mu^{EM} = \bar{u}\boldsymbol{\gamma^\mu} u$$

- **Vector minus axial vector** ($V - A$) EW CC interaction

$$j_\mu^{EW^\pm} = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\boldsymbol{\gamma^\mu} - \boldsymbol{\gamma^\mu\gamma^5})u$$

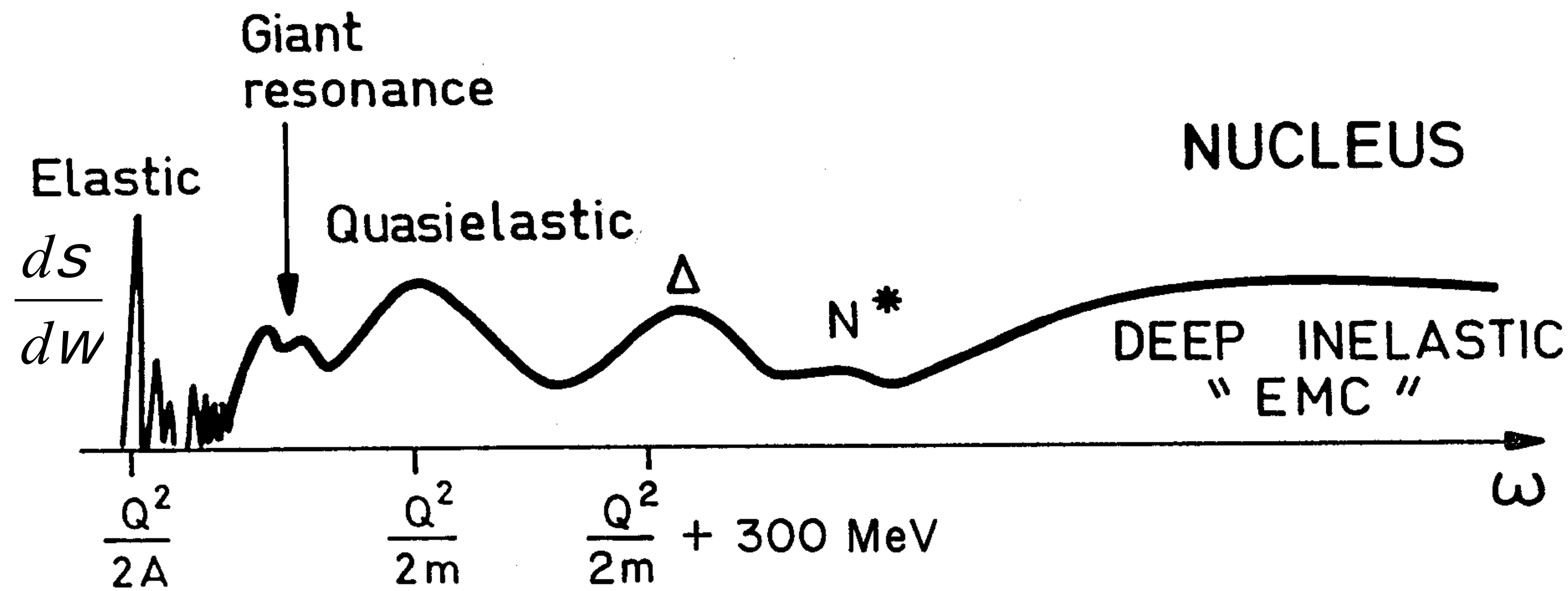
Adapted from L. Weinstein

Phys. Rev. D 103, 113003 (2021)

Improving Discrete Aspects of *Modeling*

$\Longrightarrow \sigma_i(E) R_{\sigma_i}(E, E_{rec})$

- Precision oscillation programs will require many processes to be well modeled



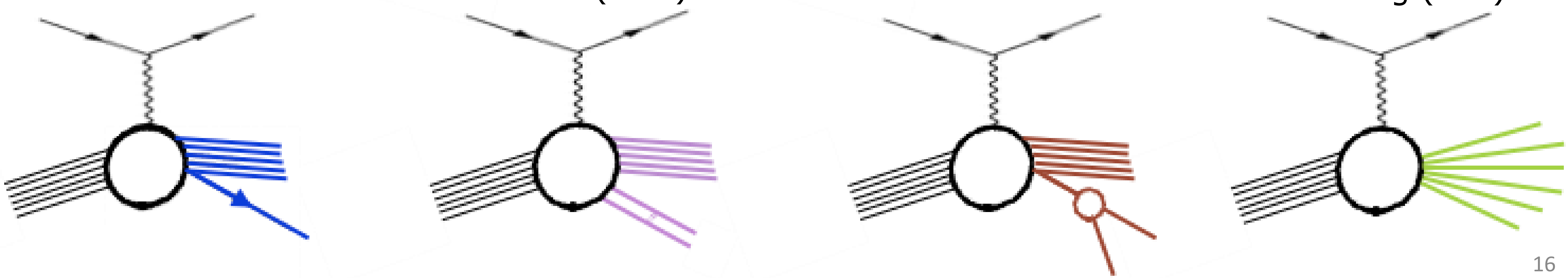
- Need input on all from electron scattering!

Quasielastic (QE)

Meson Exchange Current (MEC)

Resonance (RES)

Deep Inelastic Scattering (DIS)

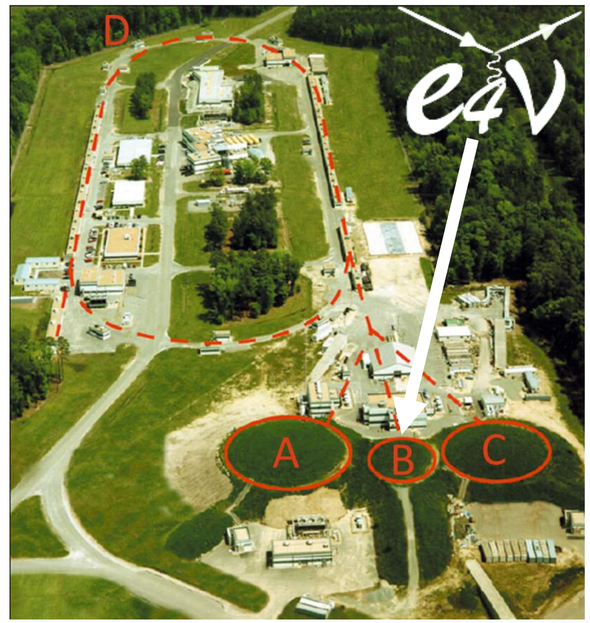


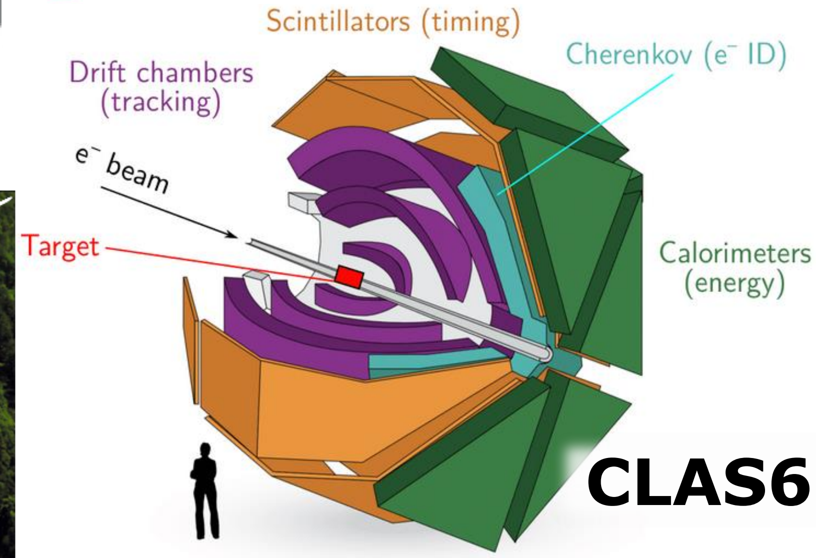
Fermilab

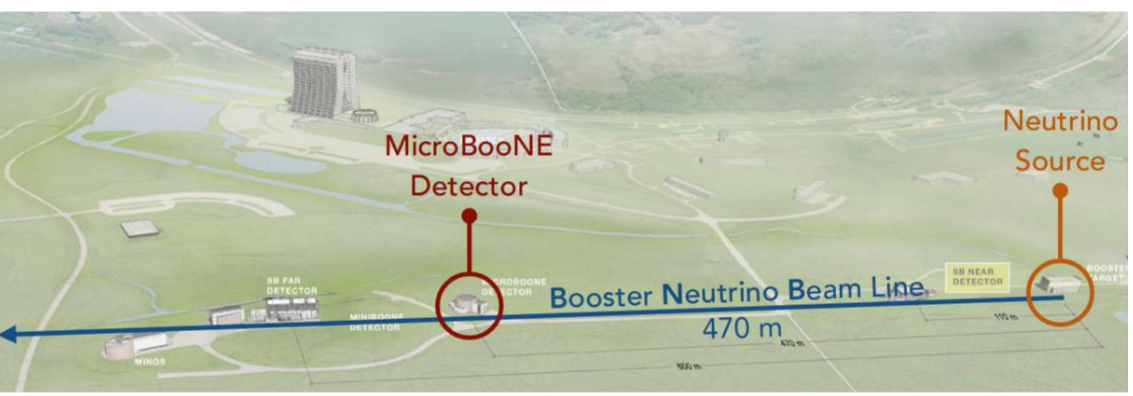
μBooNE

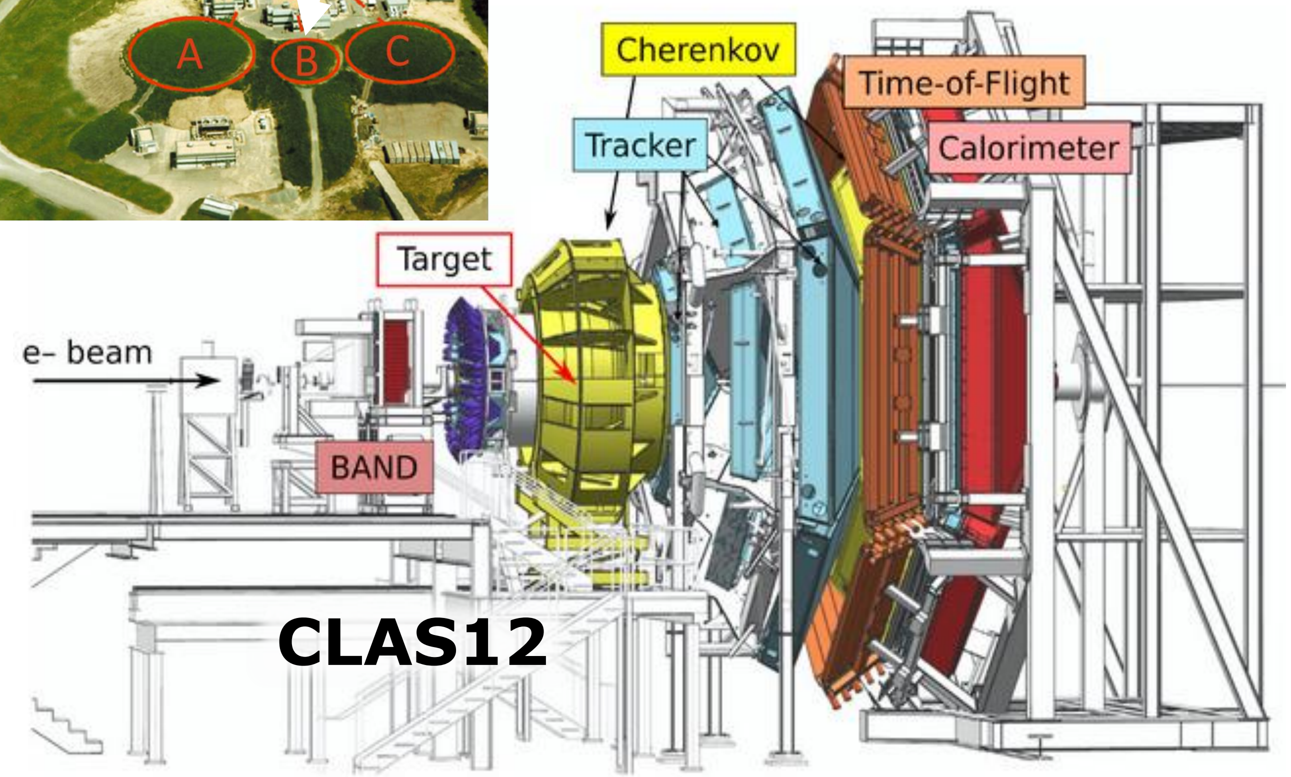
clas

Jefferson Lab









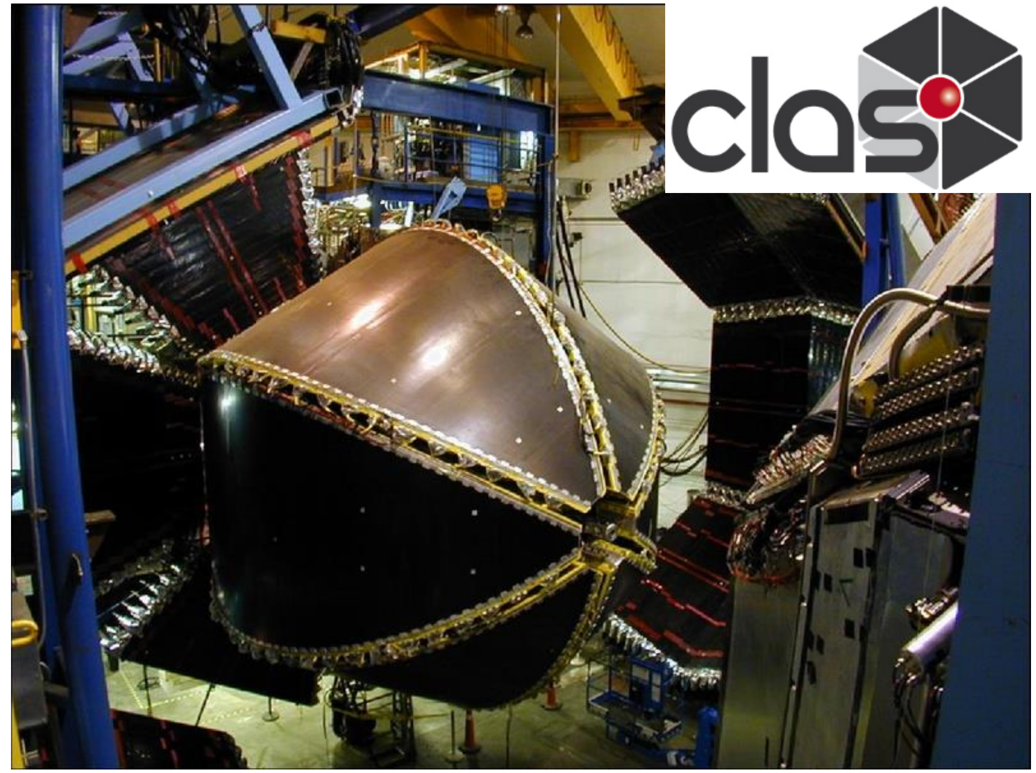
Recent $e4\nu$ Results

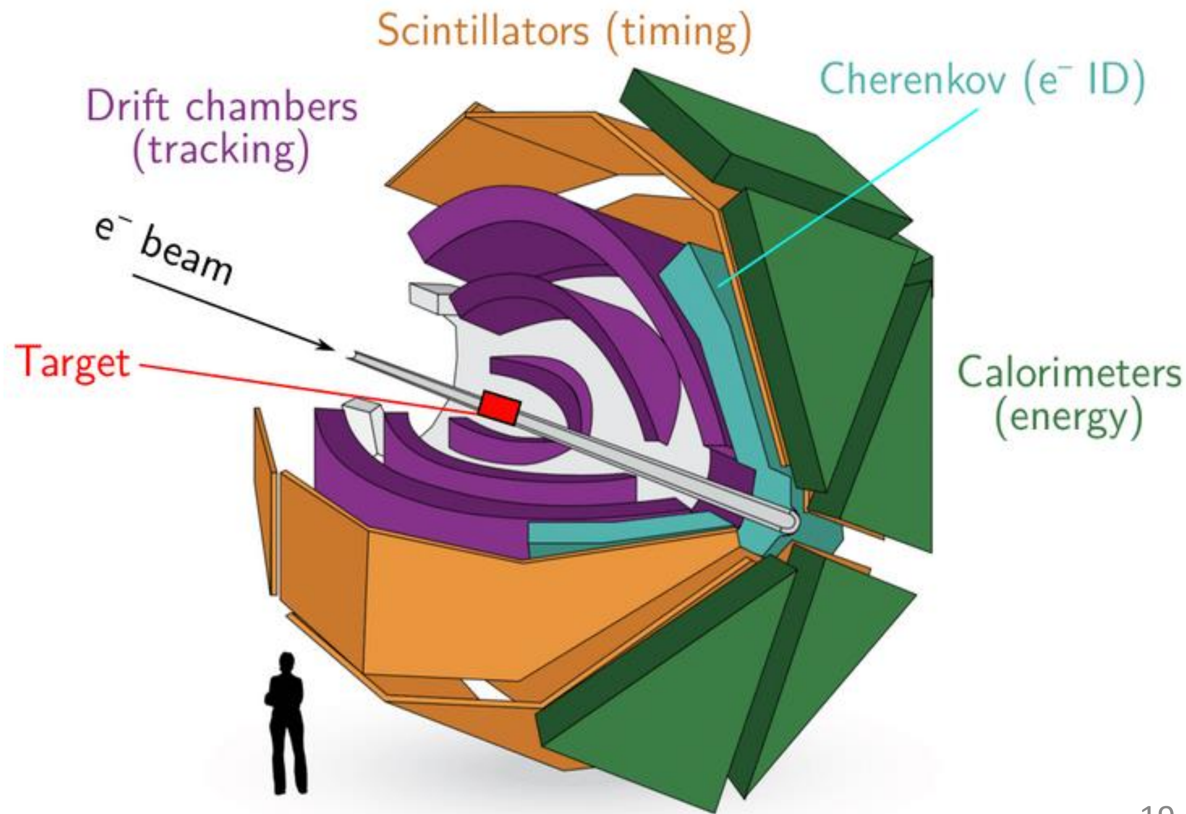
CLAS6 Data Mining

Past CLAS6 data sets used

- Large acceptance: $\theta_e > 15°$
  - "$\sim$50% of 4π" coverage
- Charged particle thresholds similar to ν detectors
- E_e:{1.1,2.2,4.4}GeV
- Targets: $\{\,^4\mathrm{He},\,^{12}\mathrm{C},\,^{56}\mathrm{Fe}\}$

Lead to $e4\nu$'s recent Nature publication on $1p0\pi$



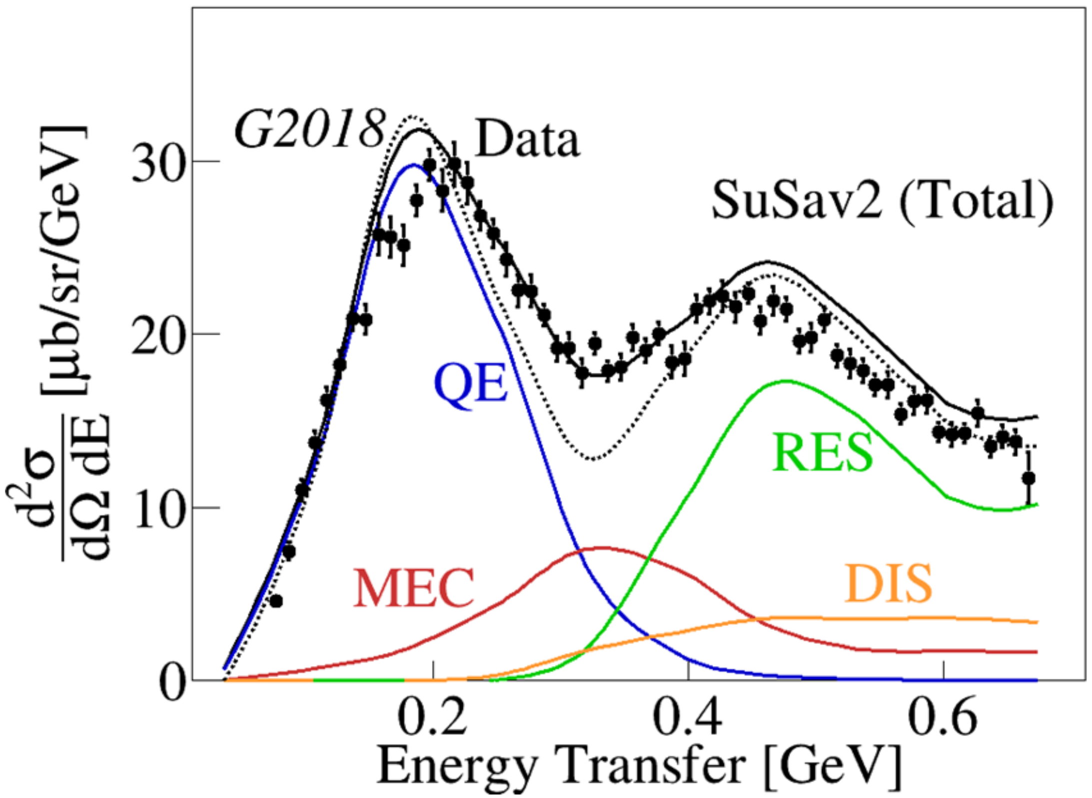


Adapted from A. Papadopoulou

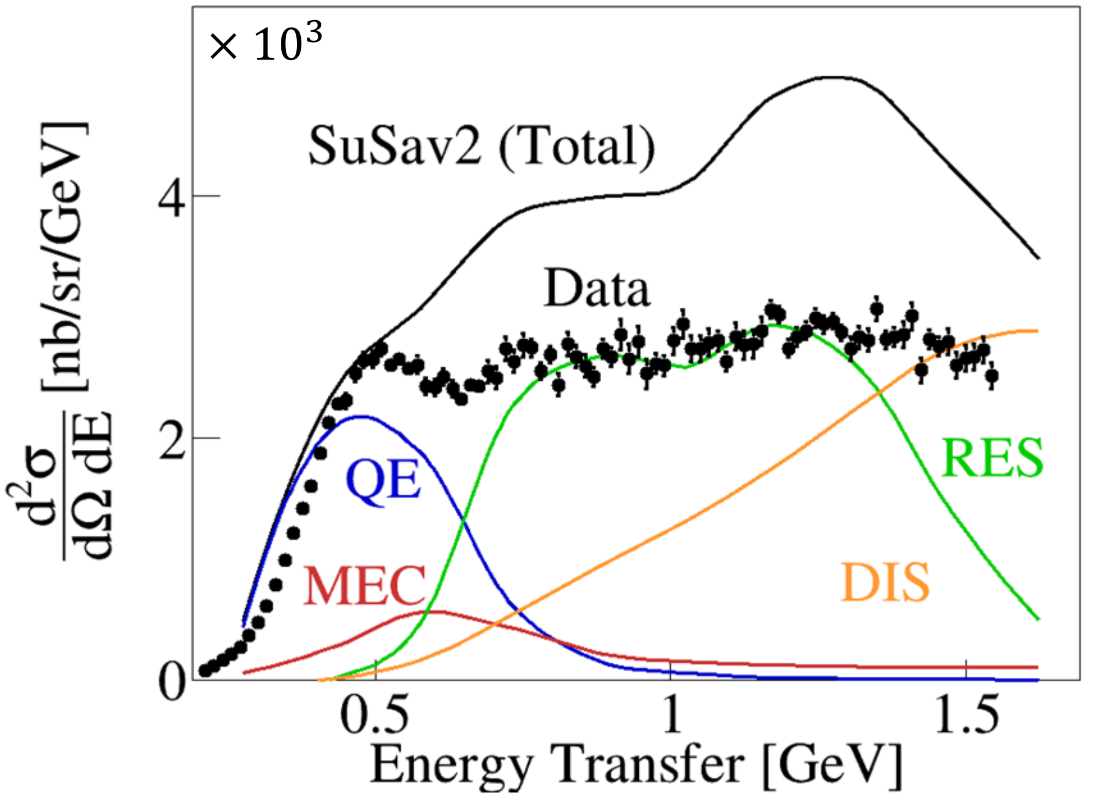
Inclusive $A(e, e')$ Data Comparisons

- Consistent $\{\nu_\ell, \ell\}$ modeling now implemented
  - Can compare to world inclusive QE electron scattering data
  - Any misconstrued behavior here won't work for νs either!
- Much work to do!
  - Must build better models, constrain any free parameters!

Fe(e, e'): 0.961 GeV at 37.5°



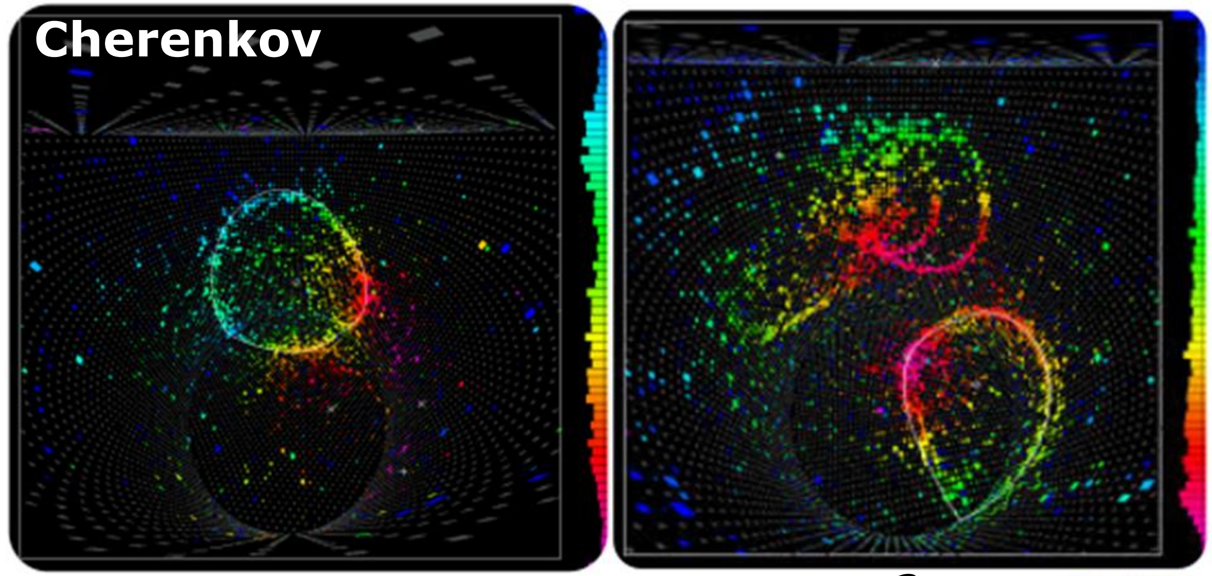
C(e, e'): 3.595 GeV at 16°



Phys. Rev. D 103, 113003 (2021)

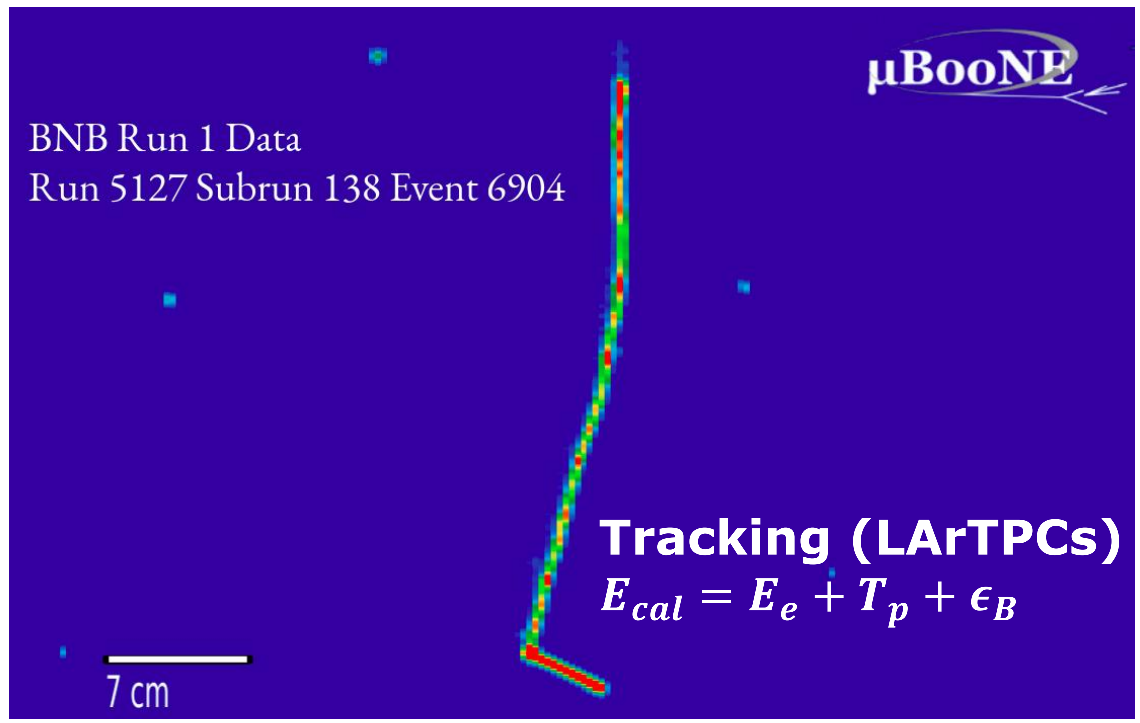
QE-like Energy Reconstruction in ν Experiments

- Goal: reconstruct $E_{\nu,\text{true}}$
- Methodology:
  - Extract E_e like E_ν would be
  - Choose 0π events
  - Weight electron events by $\frac{\sigma_{\nu A}}{\sigma_{eA}} \propto Q^4$, account for propagator



$$E_{QE}^{Ch.} = \frac{2M_N\epsilon_B + 2M_N E_\ell - m_\ell^2}{2(M_N - E_\ell + k_\ell \cos\theta_\ell)}$$

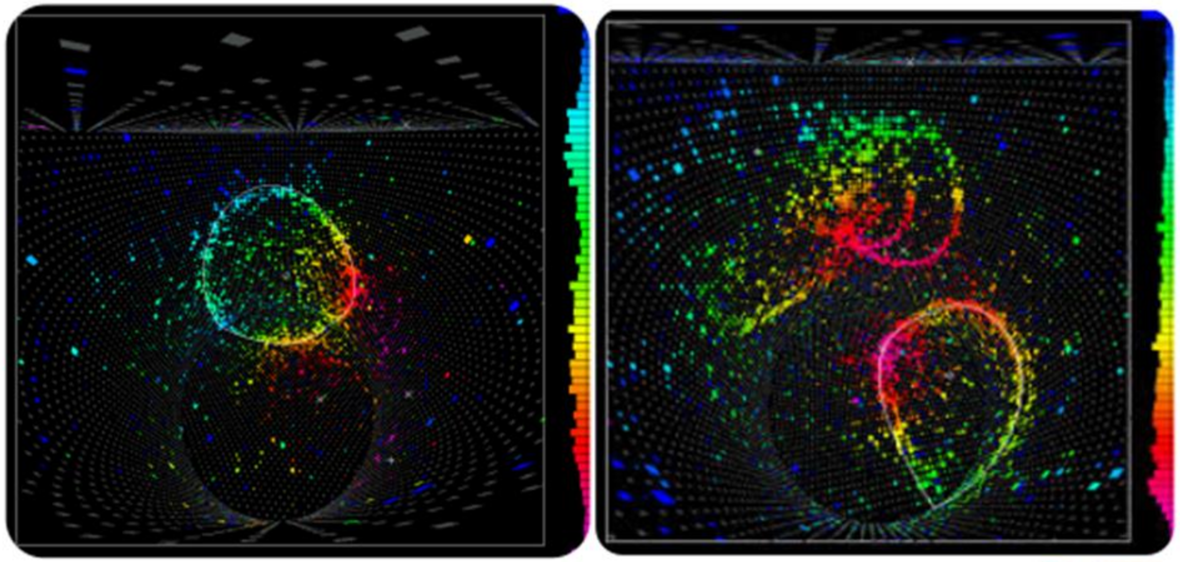
- Detector types play a role
  - May use only lepton variables
  - *…assume pure* QE
  - …others have lower thresholds



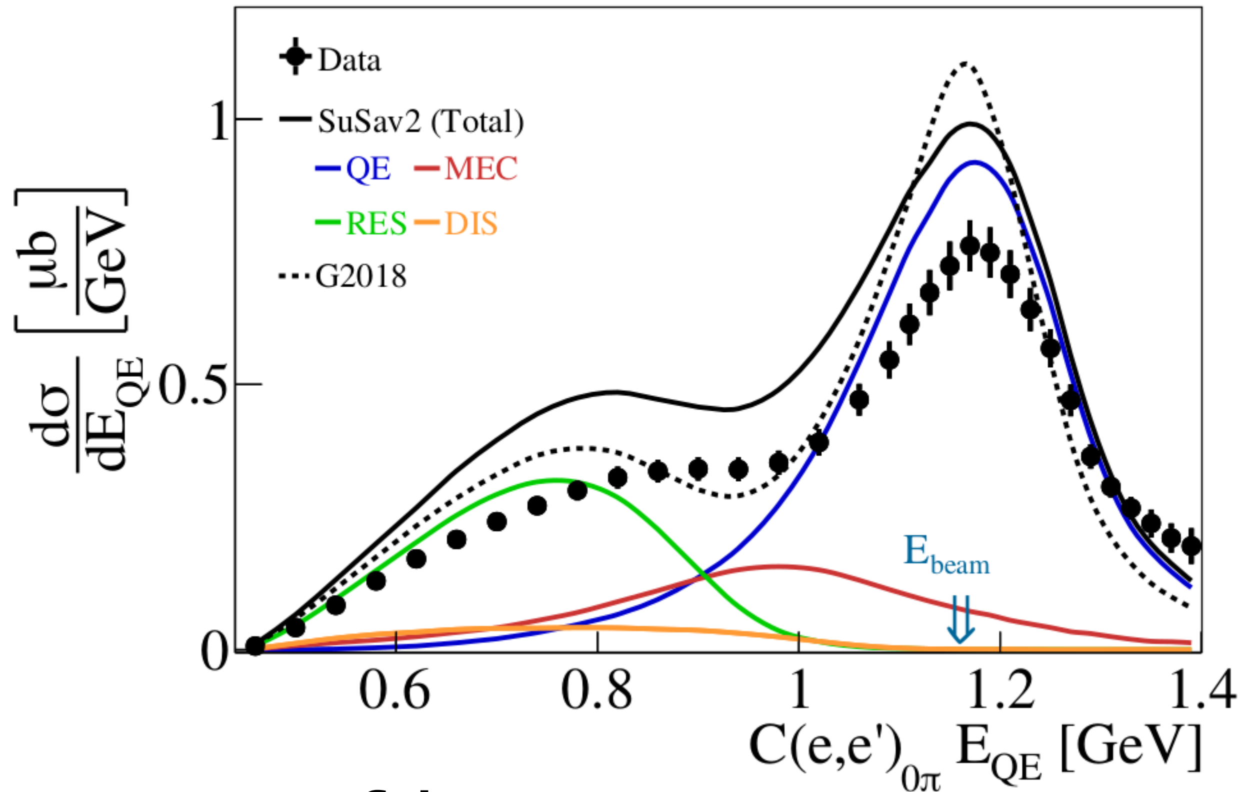
Adapted from L. Weinstein and A. Papadopoulou

Energy Reconstruction Issues

Water Cherenkov Detectors: QE Assumption



$$E_{QE}^{Ch.} = \frac{2M_N\epsilon_B + 2M_N E_\ell - m_\ell^2}{2(M_N - E_\ell + k_\ell \cos\theta_\ell)}$$

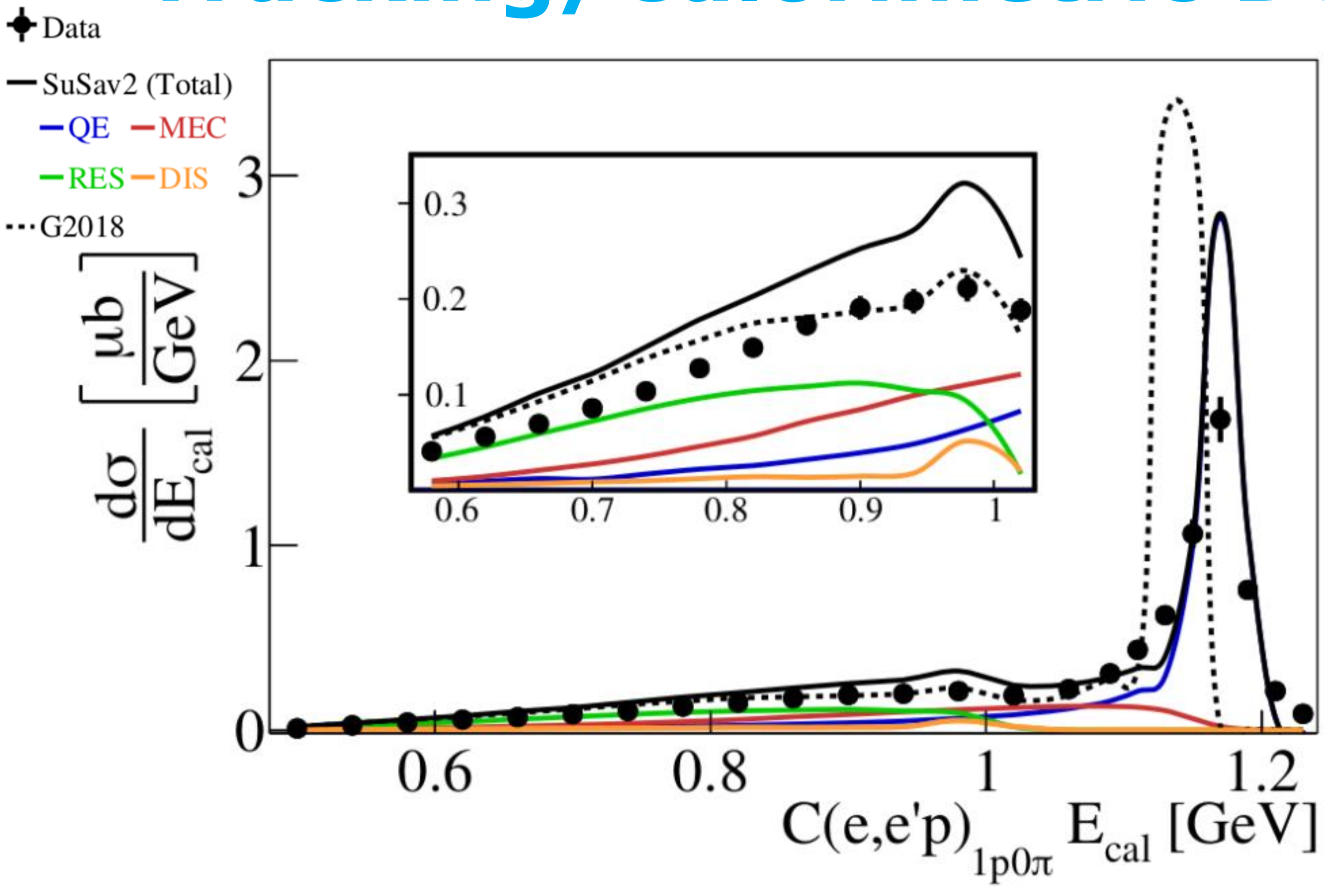


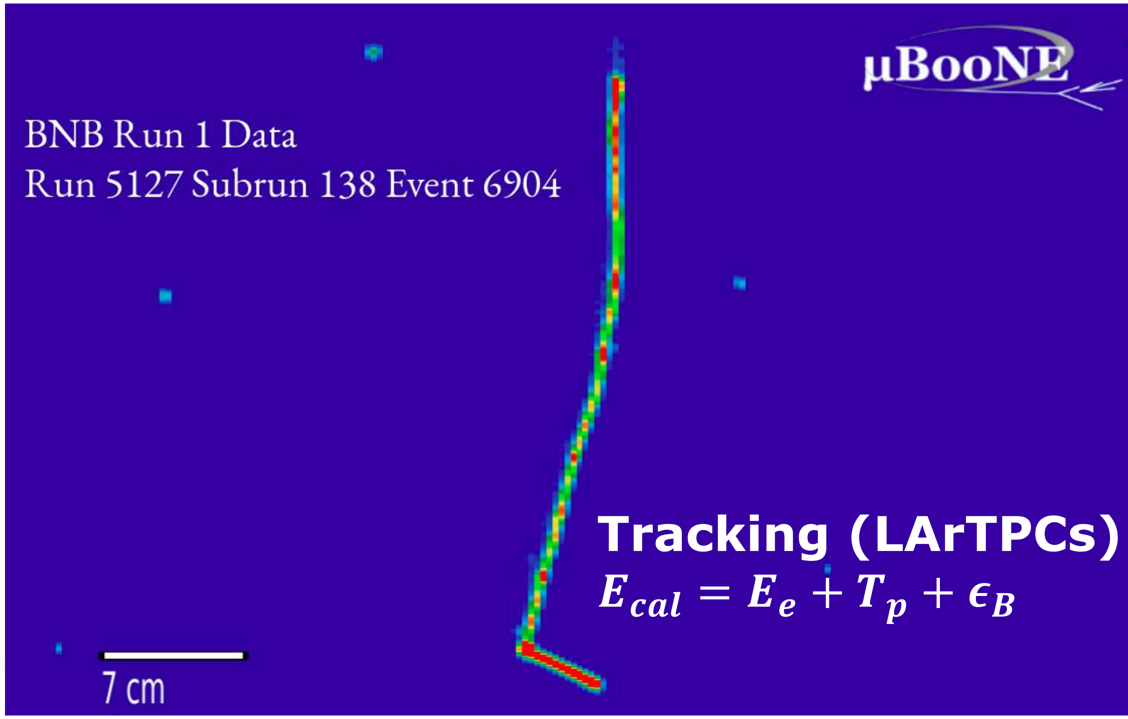
- Generally lacking reconstruction of beam E_e
  - No access to final state baryons (below threshold)
- Strength issues
  - Overestimation of QE peak
  - Overestimation of RES tail

Nature 599, 565–570 (2021)

Energy Reconstruction Issues

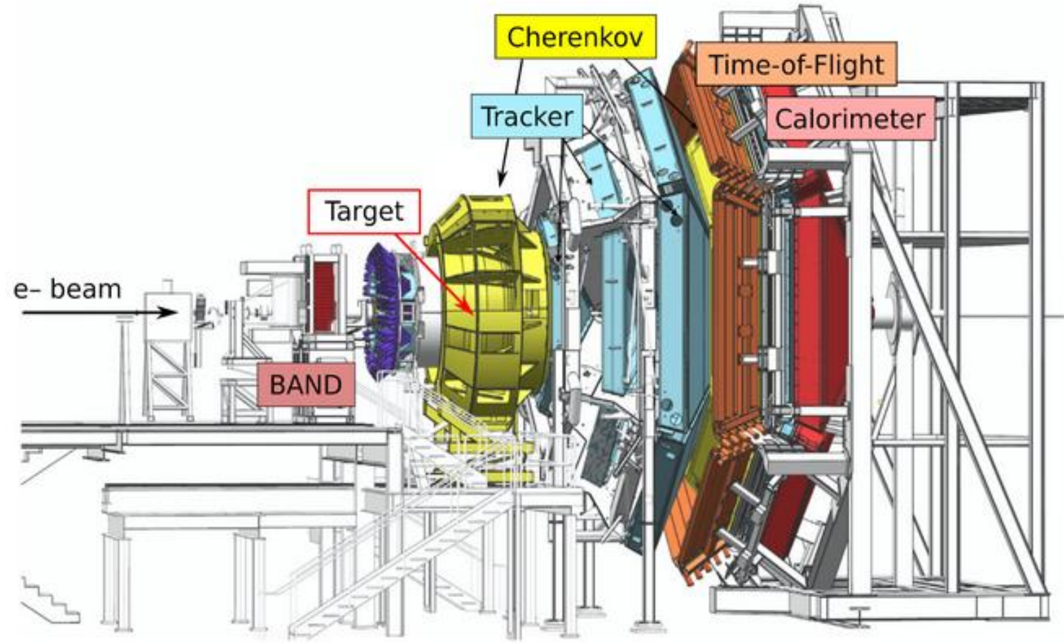
Tracking/Calorimetric Detectors: Summation





- Calorimetric sum over all visible particles (lower thresholds)
  - Better agreement with beam E_e ⟷ QE peak quite narrow
- Relatively consistent behavior for QE-like signals
  - Overestimate of QE peak, tail overshoots due to RES and DIS
- DUNE will rely on more than QE, need RES!

Nature 599, 565–570 (2021)



New Results at CLAS12

Support Letters

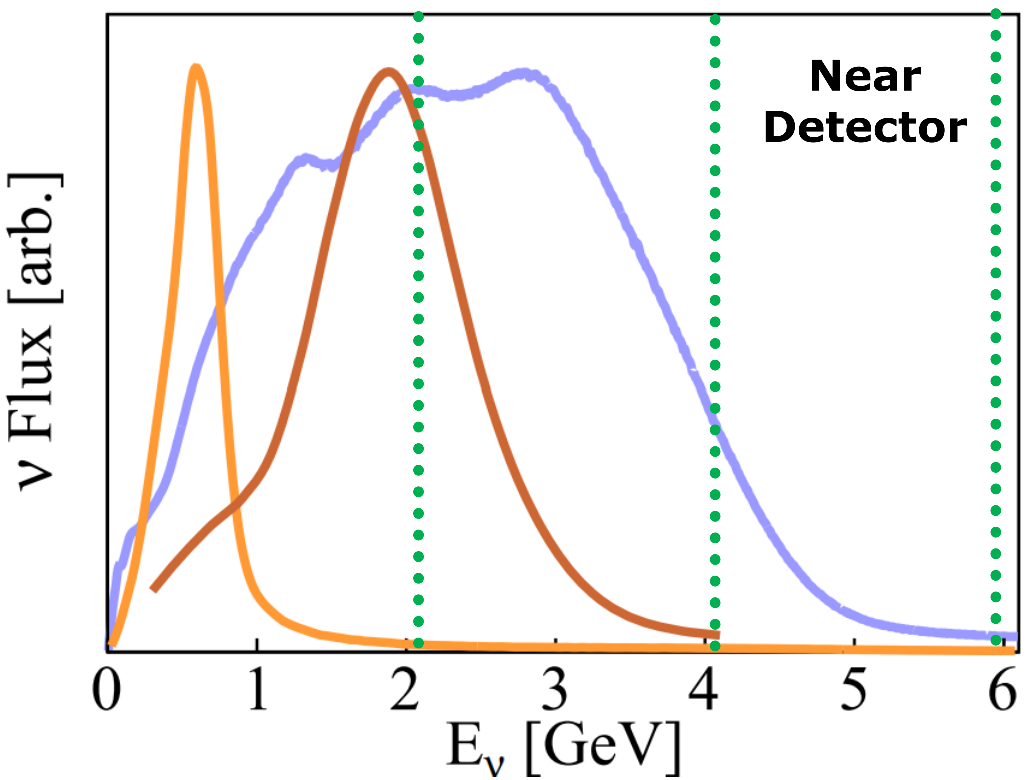
Improvements Over CLAS6

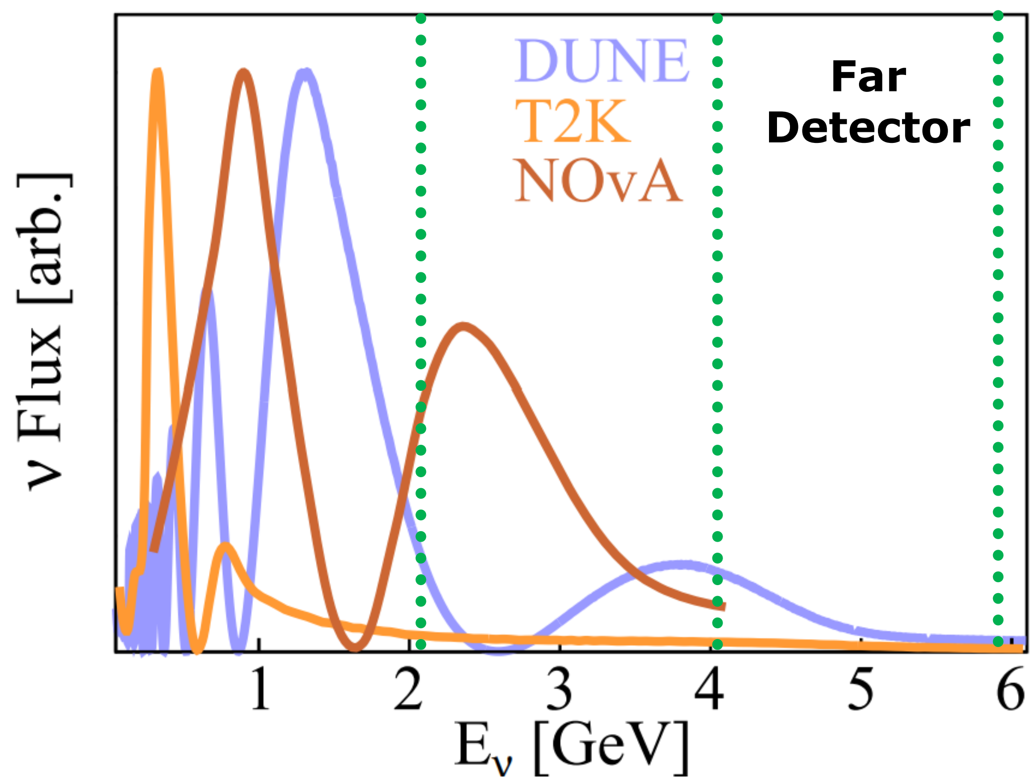
- Monoenergetic beams for {2.1,4.0,6.0}GeV
- ν-relevant targets: {C, Ar, Ca}
- High luminosity (~10X > CLAS6)
- High angular acceptance: $\theta_e > 5°$
  - Access very low Q^2 at lower beam energies
- Good particle identification, lower thresholds + NEUTRONS!

T2K H_2O

NOvA CH

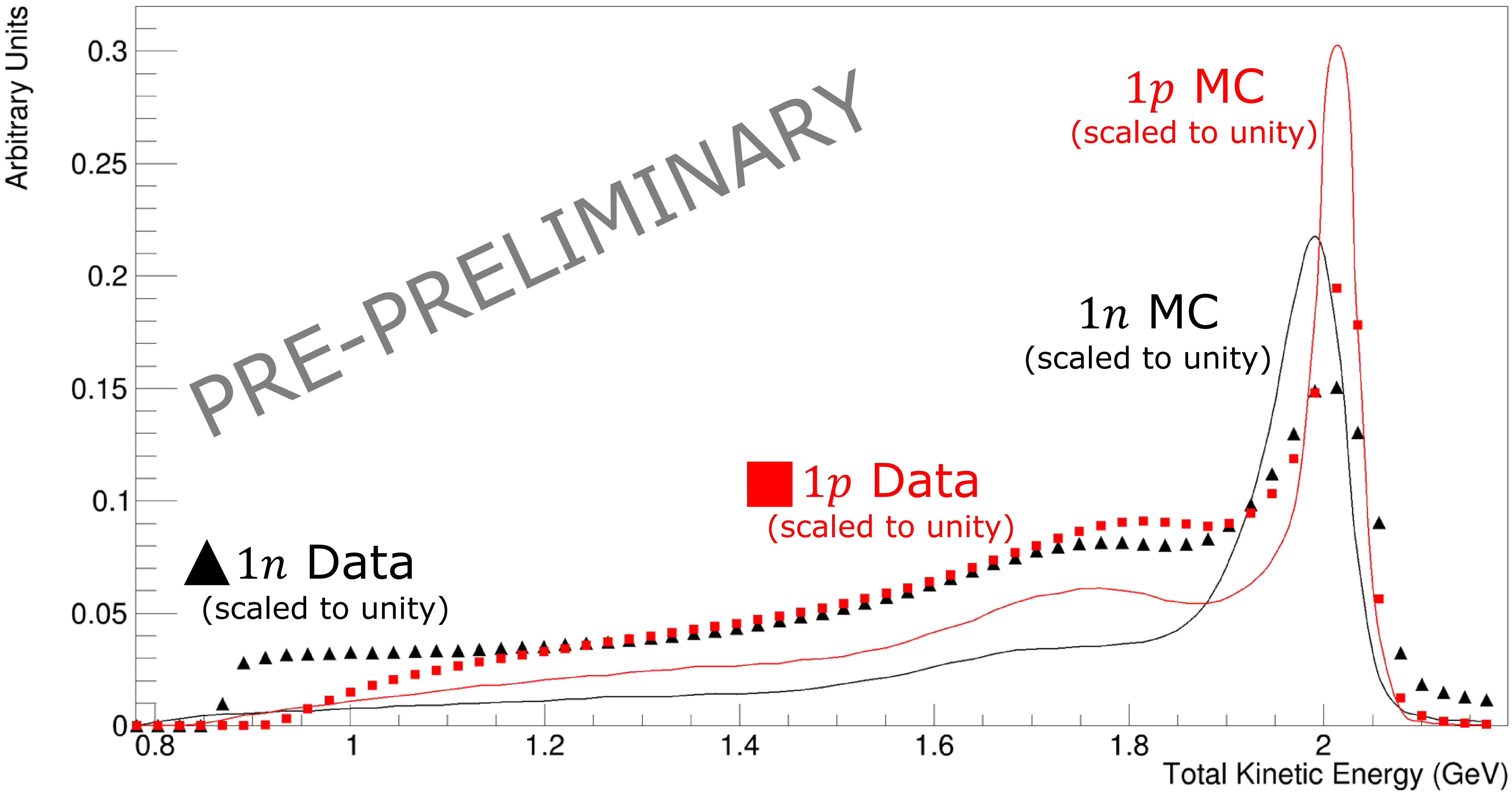
SBN Program, DUNE Ar





Initial Comparisons to Simulation

Showing Unphysical Differences?



Future $e4\nu$ Analyses

- Inclusive double differential cross sections: $\{\mathrm{C}, \mathrm{Ar}, \mathrm{Ca}\}$
  - Access to many angles, many energies, low Q^2
  - Create a new world-level data sets
- Inclusive/Exclusive multidifferential cross sections
- $(e,e'), (e,e'p), \left(e,e'\pi^{\pm}\right), (e,e'p\pi^{-}), (e,e'pp), (e,e'n), (e,e'pn)\ldots$
  - "Traditional" kinematic variable for first GENIE tunings
  - Transverse kinematic variables (FSIs, nuclear models)
- Transparency studies (FSIs)
- Ca/Ar ratios
- Spectral functions, nuclear models

Goals of the μ4ν Initiative

Goals of $\mu 4\nu$

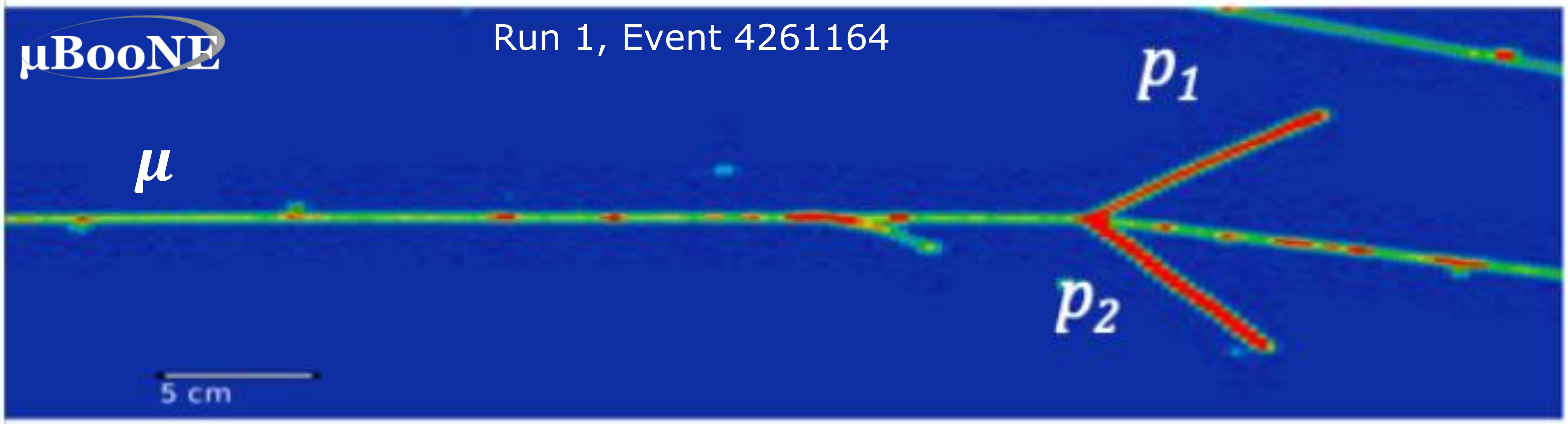
Use cosmic μ interactions (like e!)

Trigger on topologies of interest online

- Utilize low level DAQ outputs ("hits")
- Develop specific trigger algorithms
  - Michel electrons from decays $(\mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \nu_e)$
  - **QE-like proton(s) events ($\boldsymbol{\mu + Ar \rightarrow \mu + Np + X}$)**
  - $n \rightarrow \bar{n}$…

Preselection saves data processing, disk

Courtesy of A. Furmanski

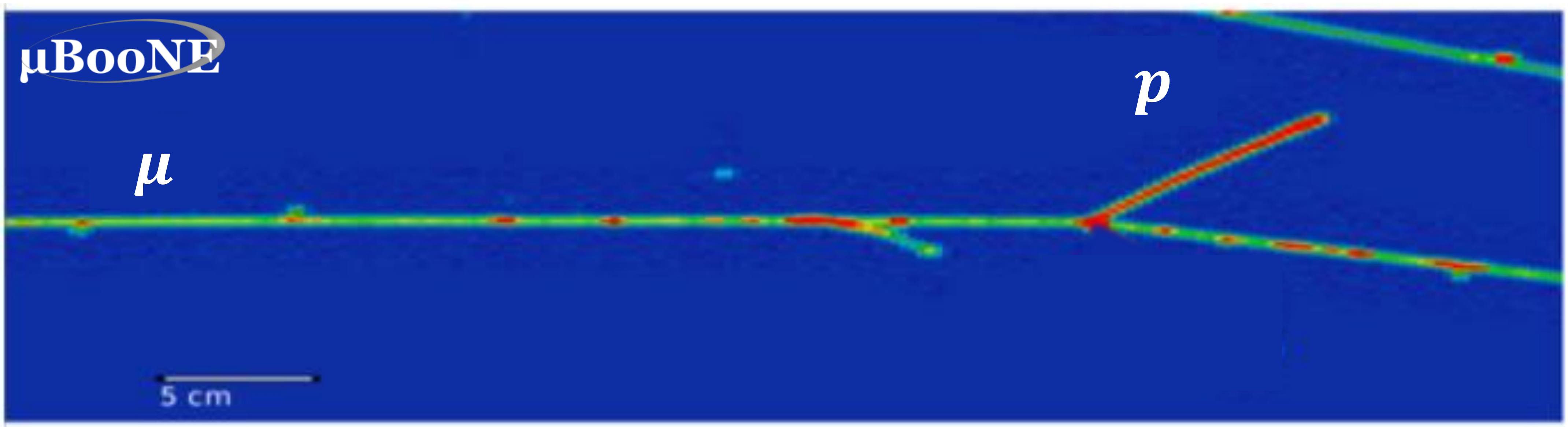


Multiprong (4) QE-like candidate

[Reconstructing cosmic muon scatter events in MicroBooNE]

Courtesy of A. Furmanski

Primary focus



Multiprong (3) QE-like candidate

[Reconstructing cosmic muon scatter events in MicroBooNE]

Potential Ramifications of $\mu 4\nu$ Scattering Studies *In Situ*

Use identical final states between μ and ν probes

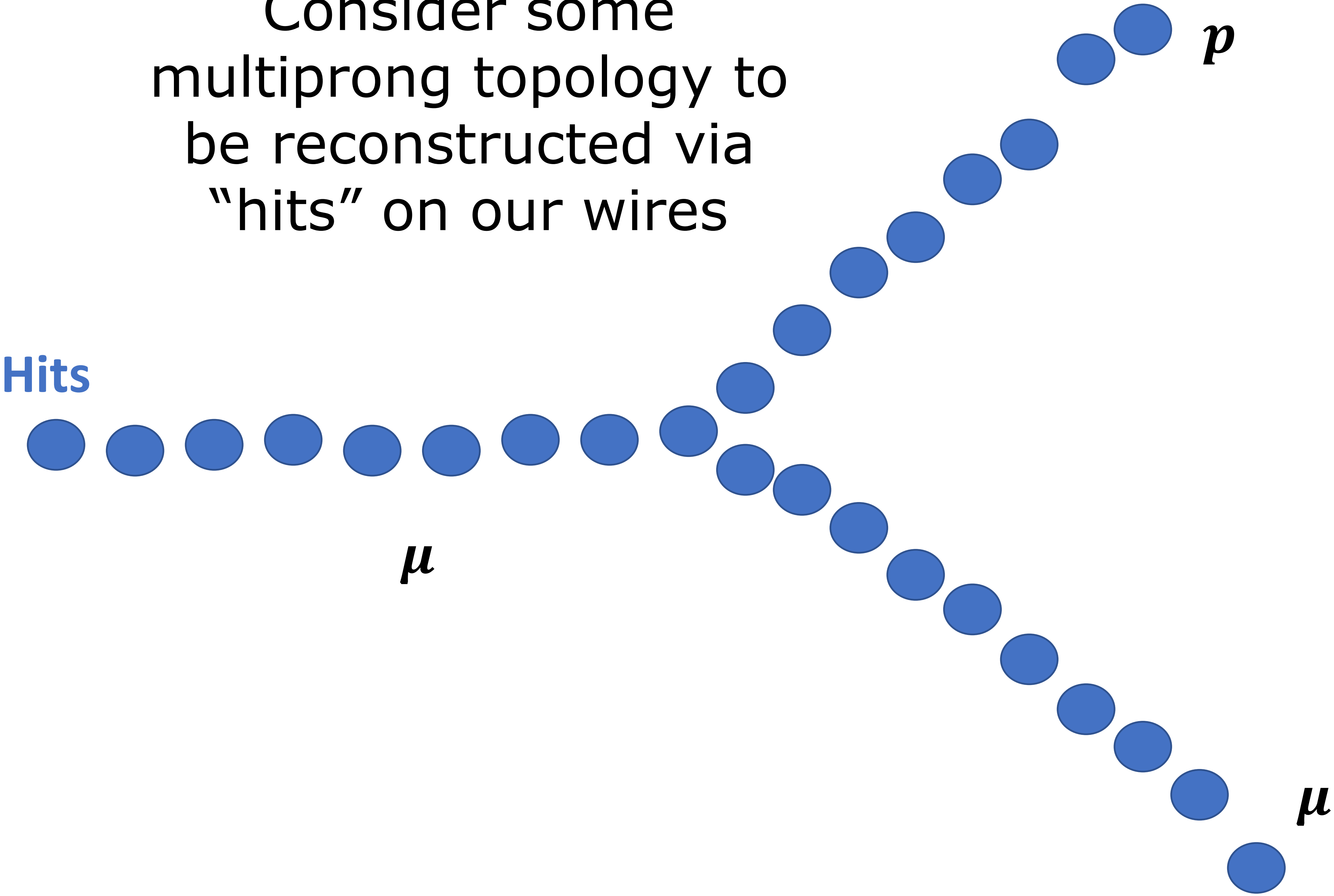
- Reconstructed energy comparisons *in situ*
- Care about energy *just before*/*after* interaction
- Offer online calibration

QE-like candidates offer simplicity

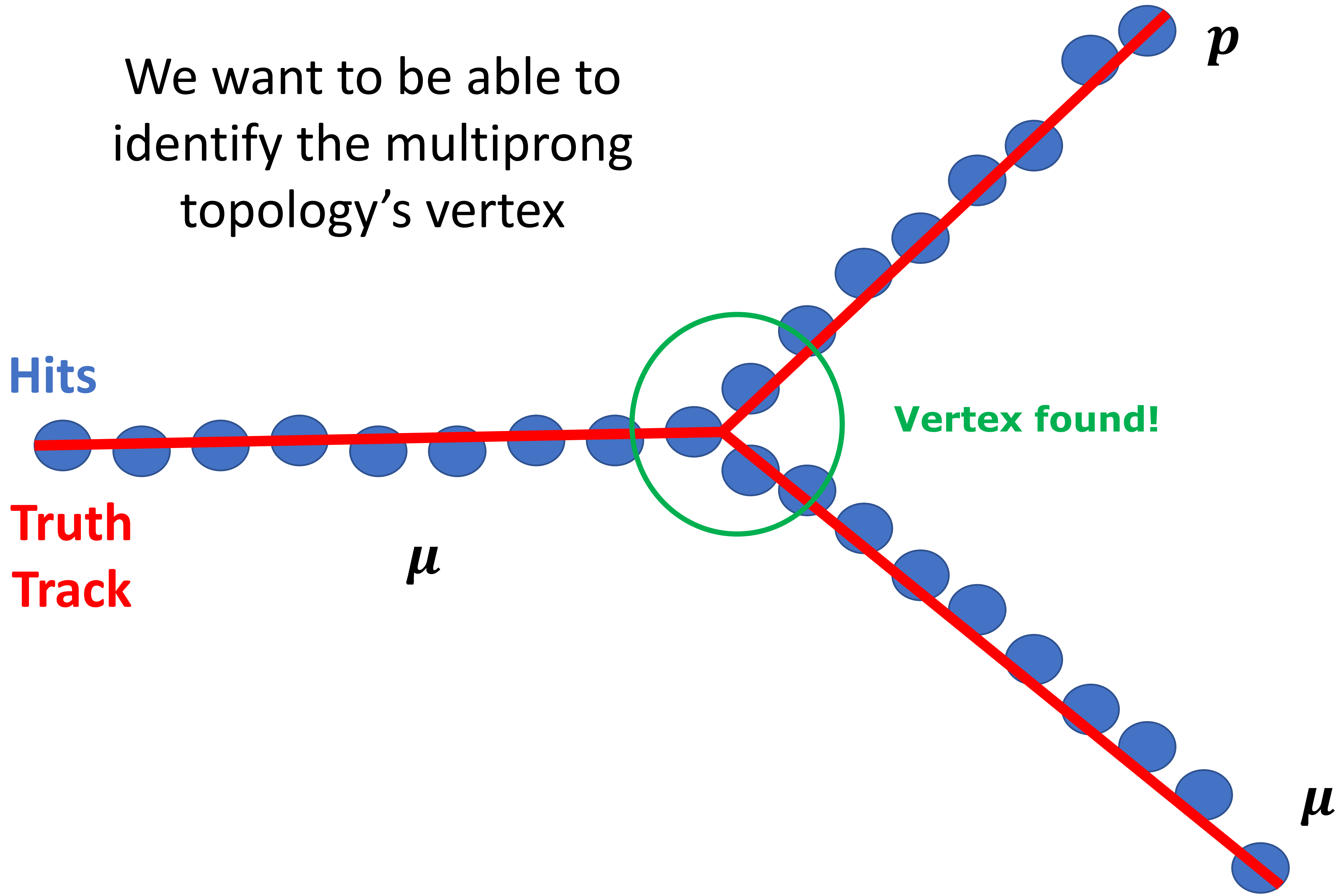
- Better understandings of E reconstruction
- Other topologies possible

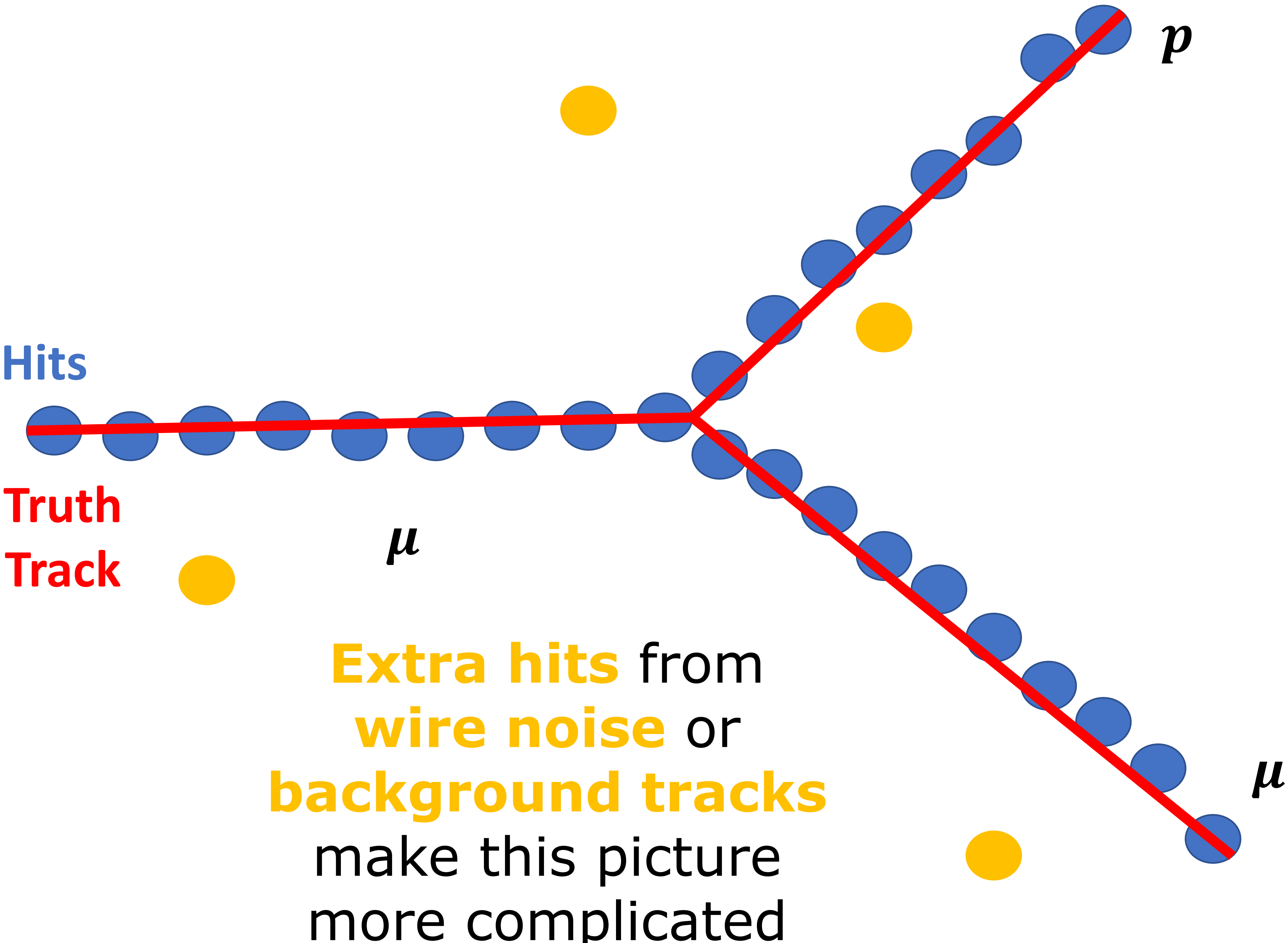
Cosmic $\mu + \mathrm{Ar}$ cross sections (potentially)

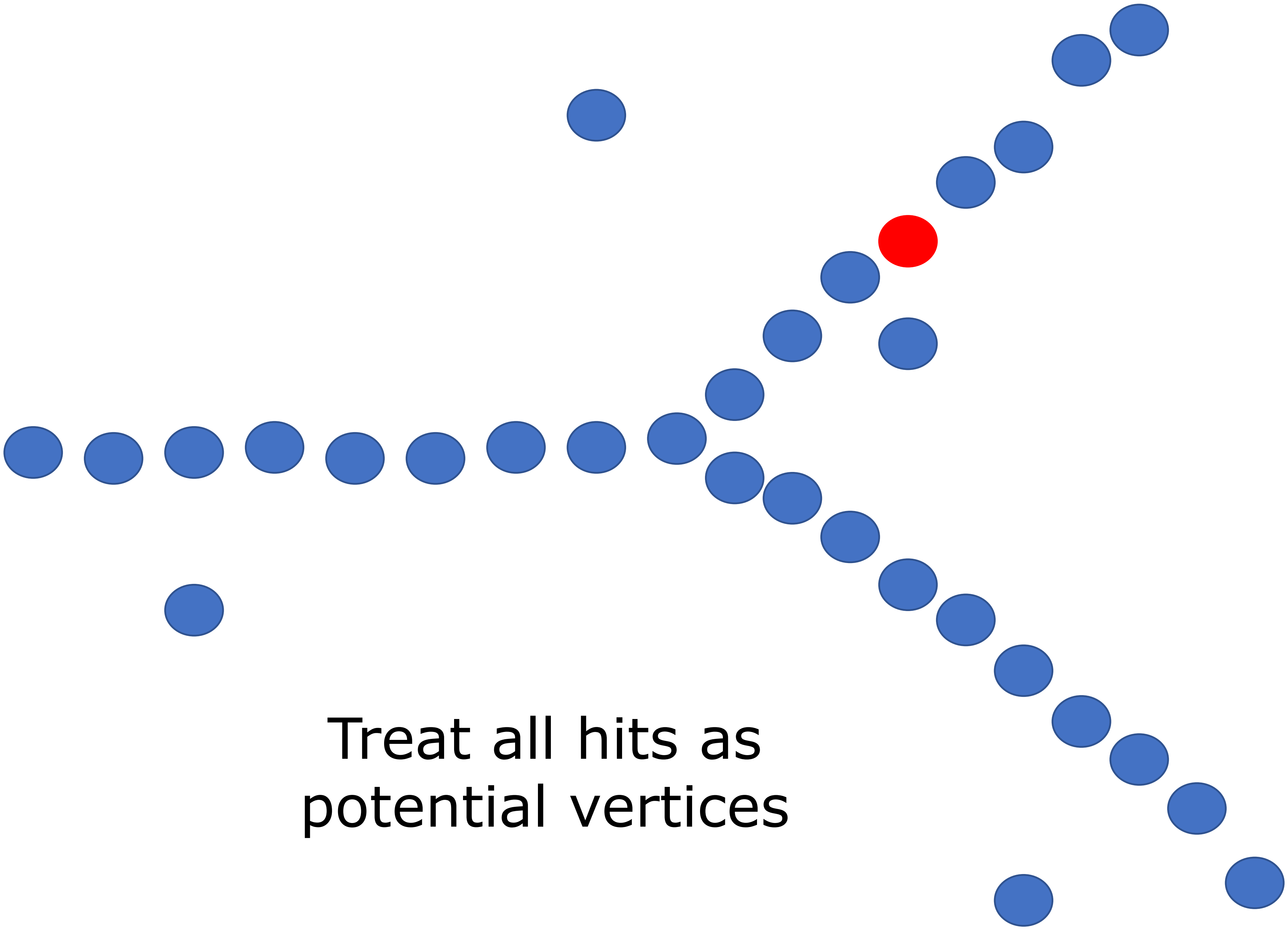
Consider some multiprong topology to be reconstructed via "hits" on our wires



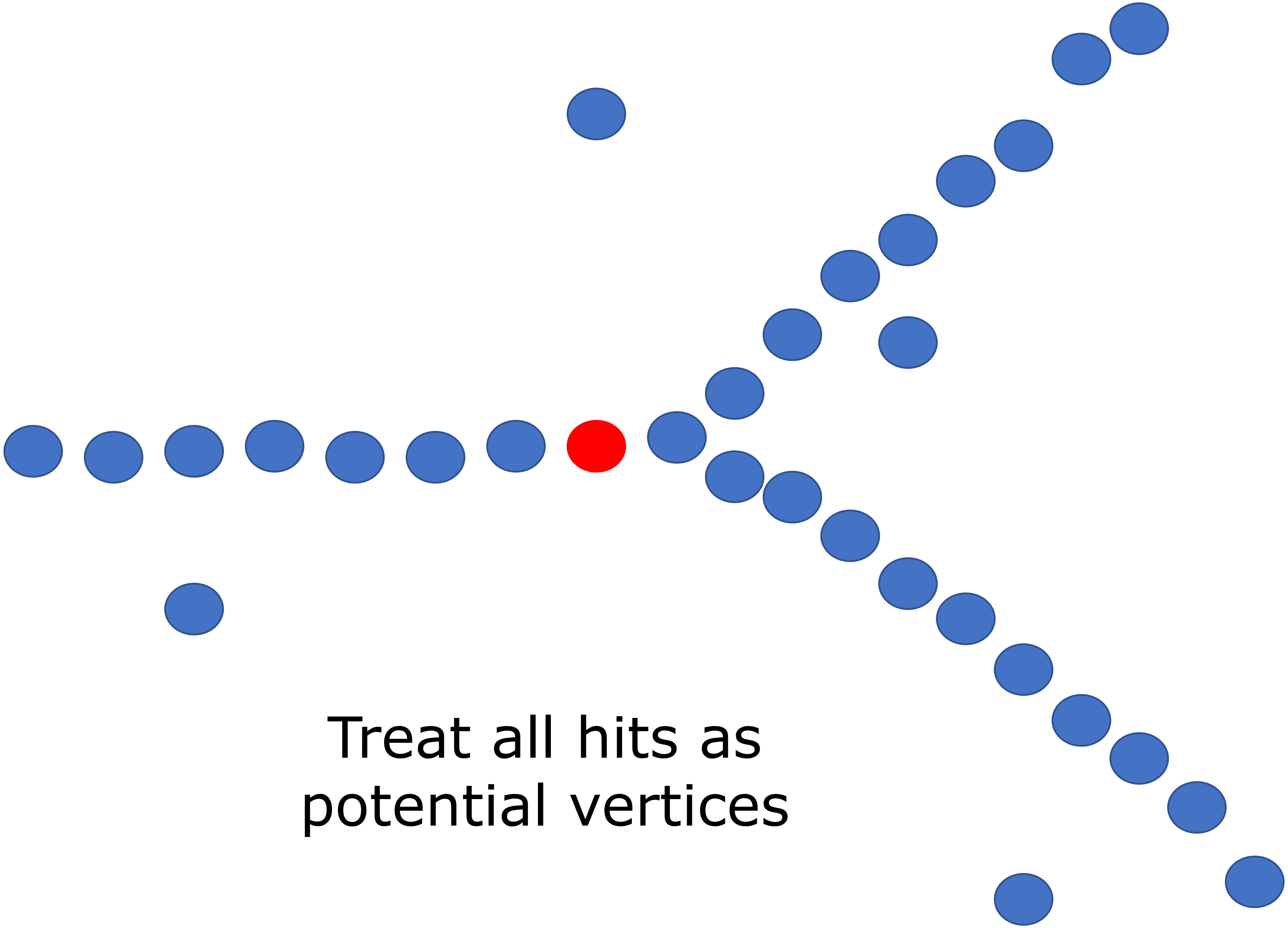
We want to be able to identify the multiprong topology's vertex



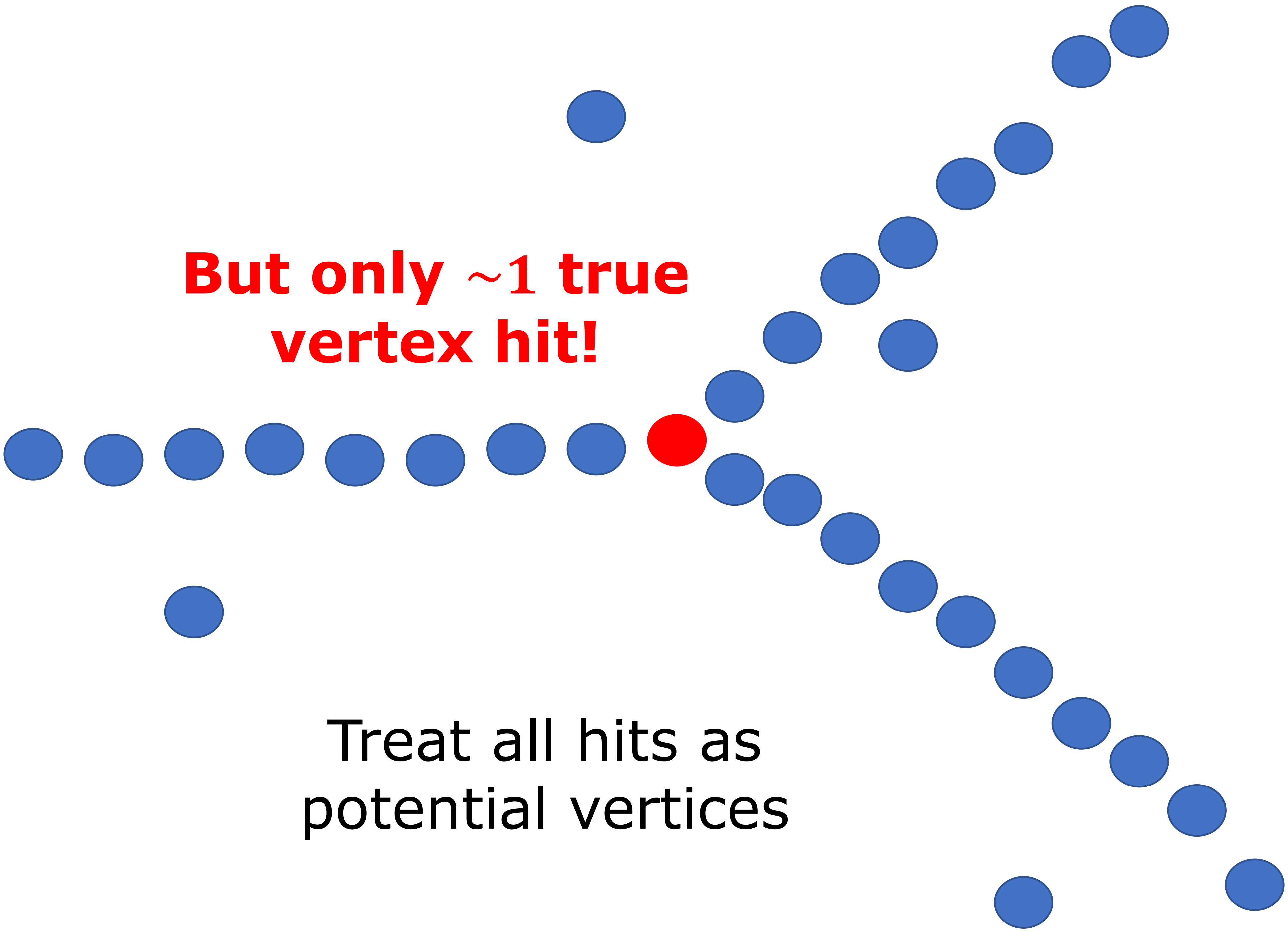

p
Hits
Truth
Track
μ
μ
Extra hits from
wire noise or
background tracks
make this picture
more complicated

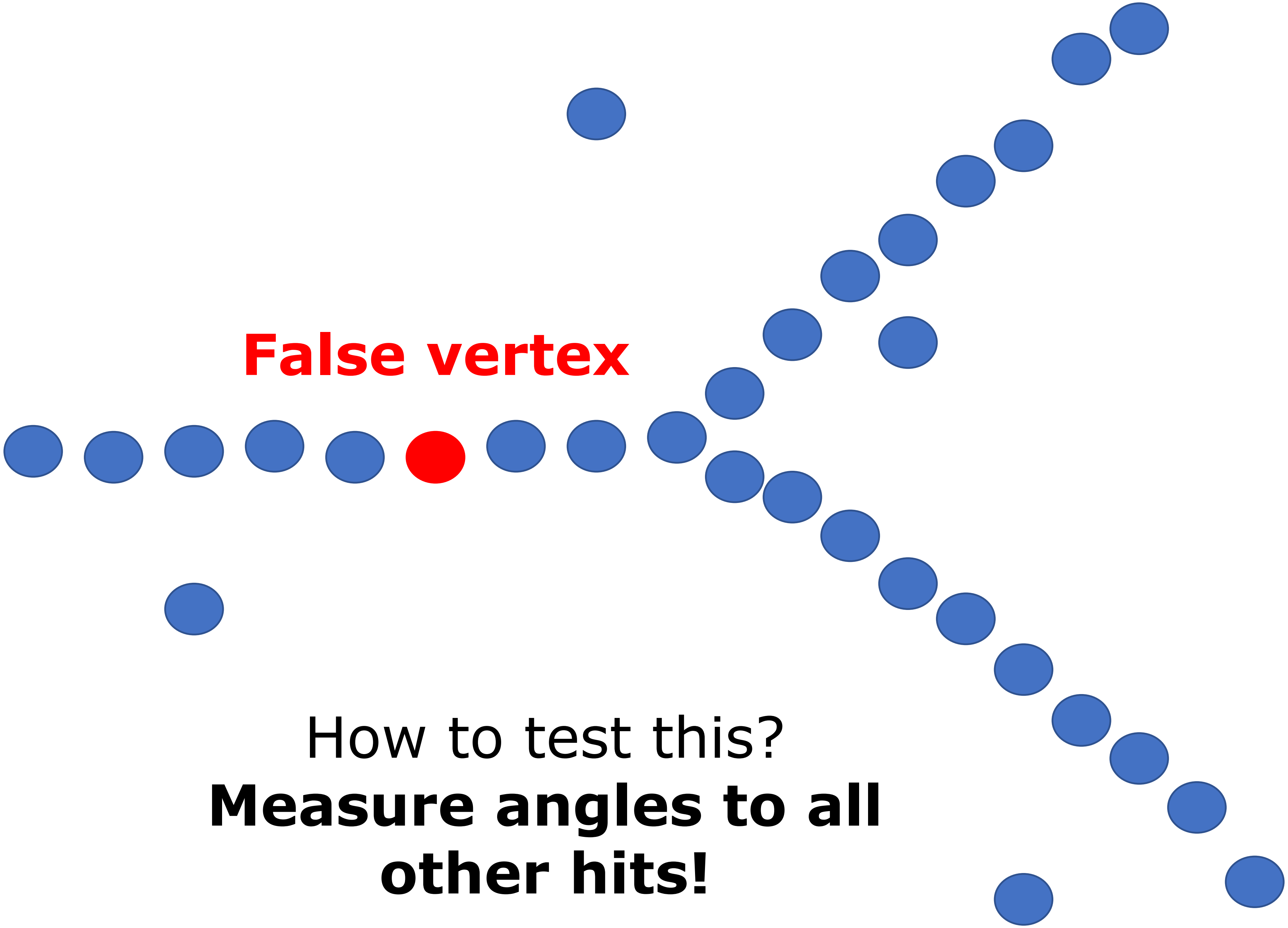


Treat all hits as
potential vertices



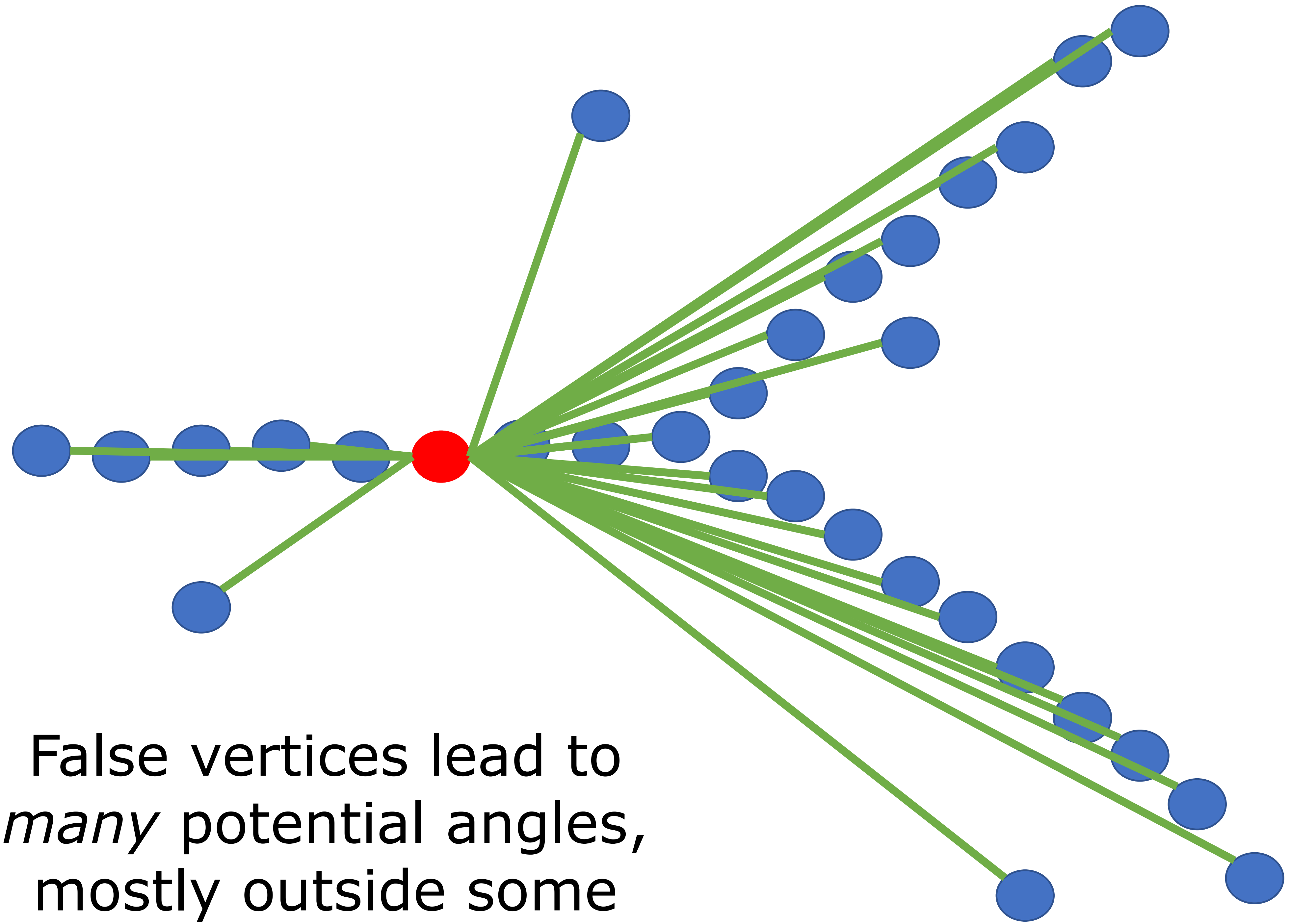
Treat all hits as potential vertices


But only ~1 true vertex hit!
Treat all hits as potential vertices

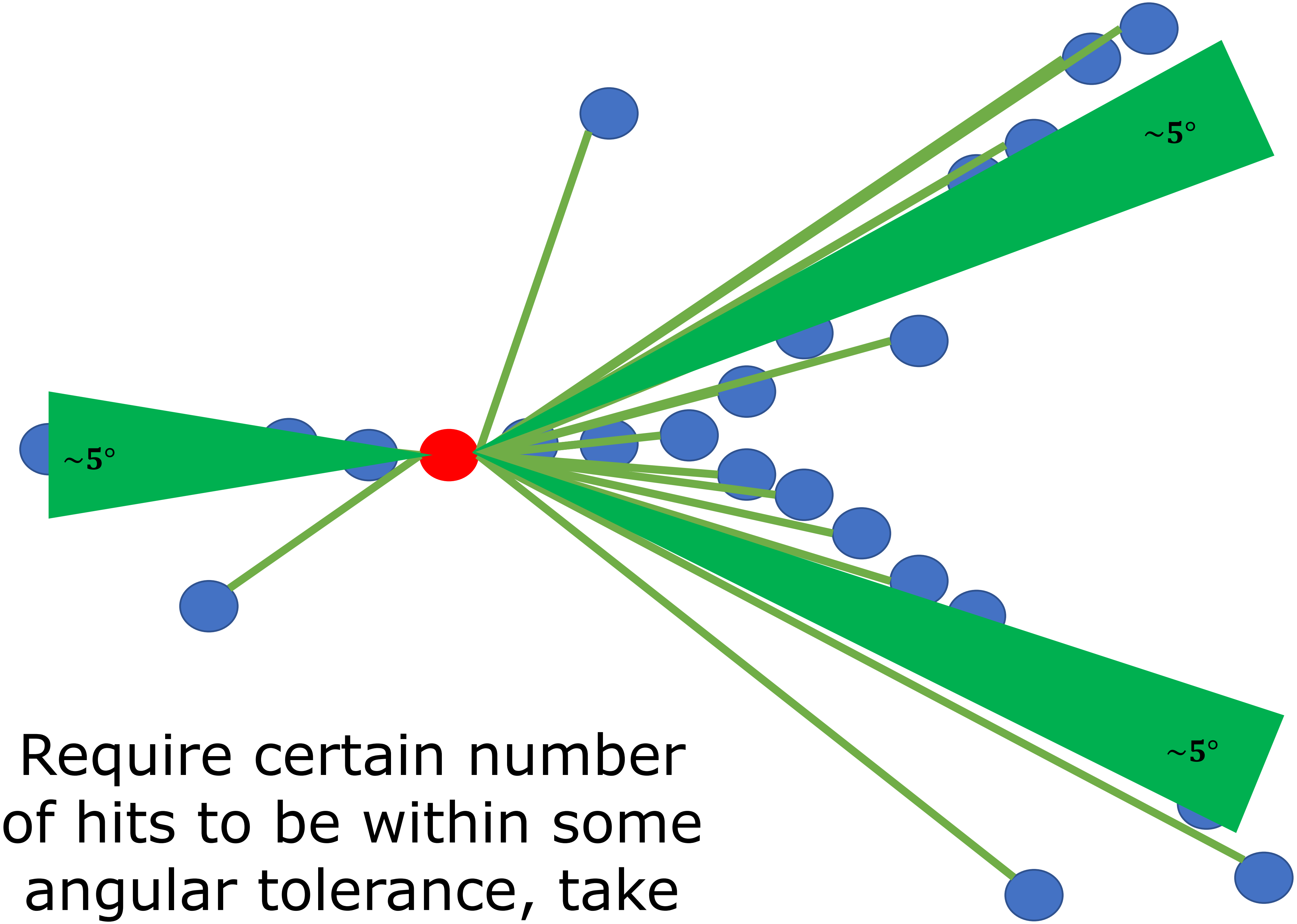


How to test this?

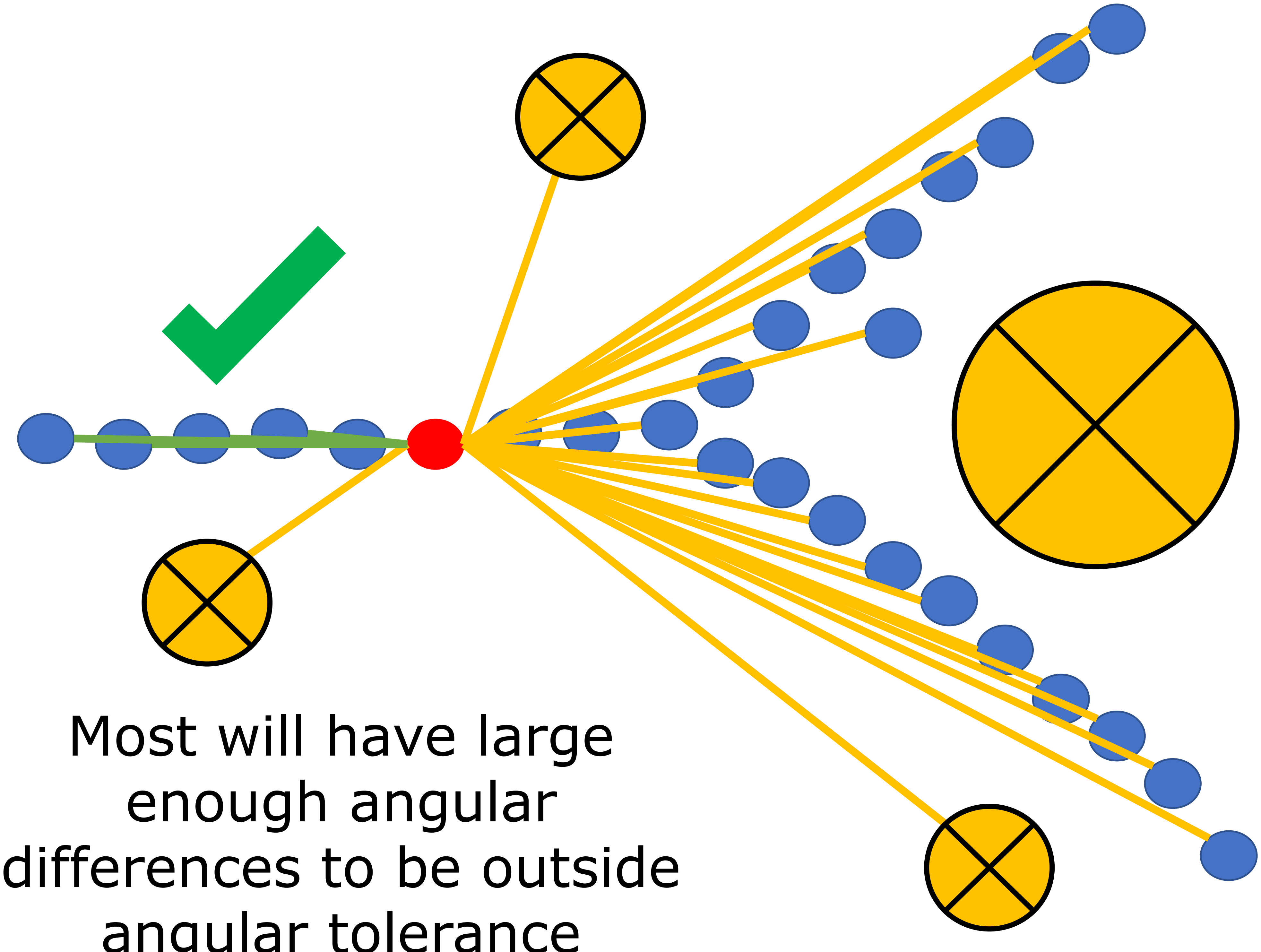
Measure angles to all other hits!



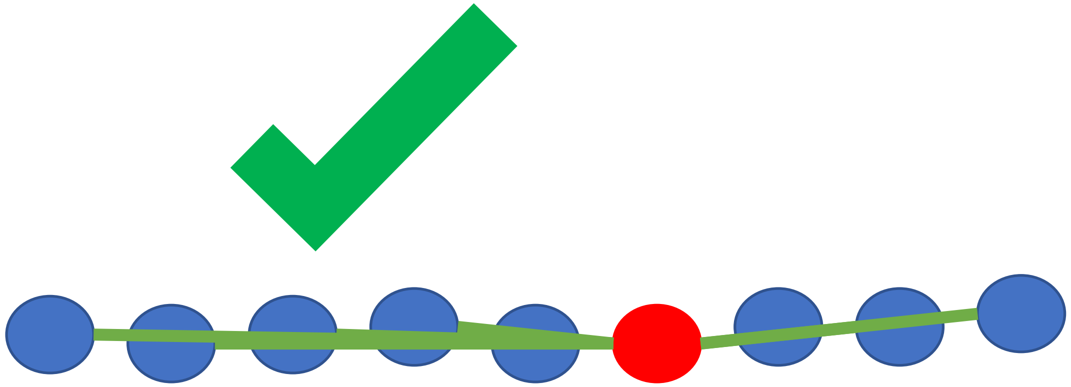
False vertices lead to *many* potential angles, mostly outside some angular tolerance



Require certain number of hits to be within some angular tolerance, take an average

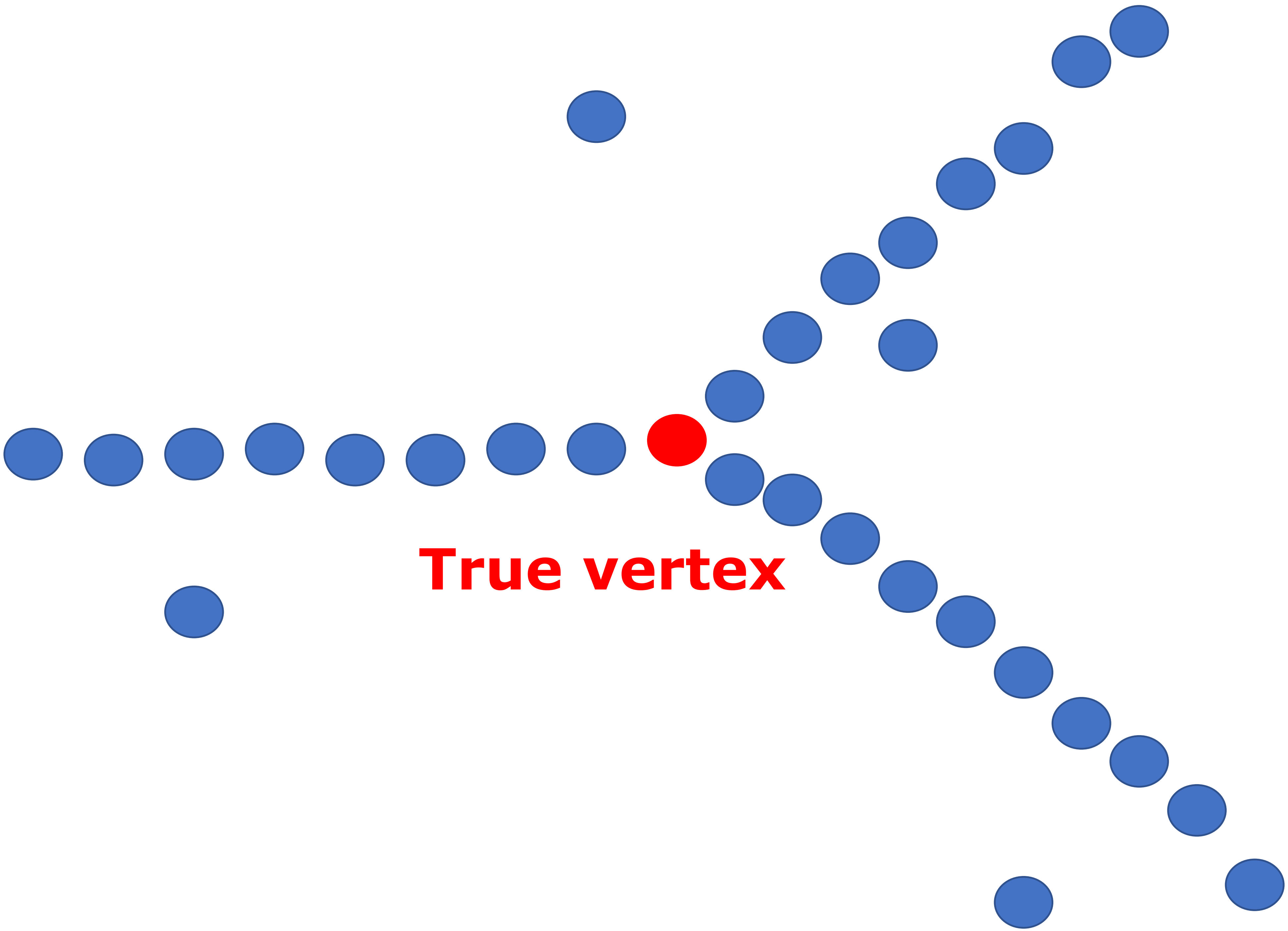


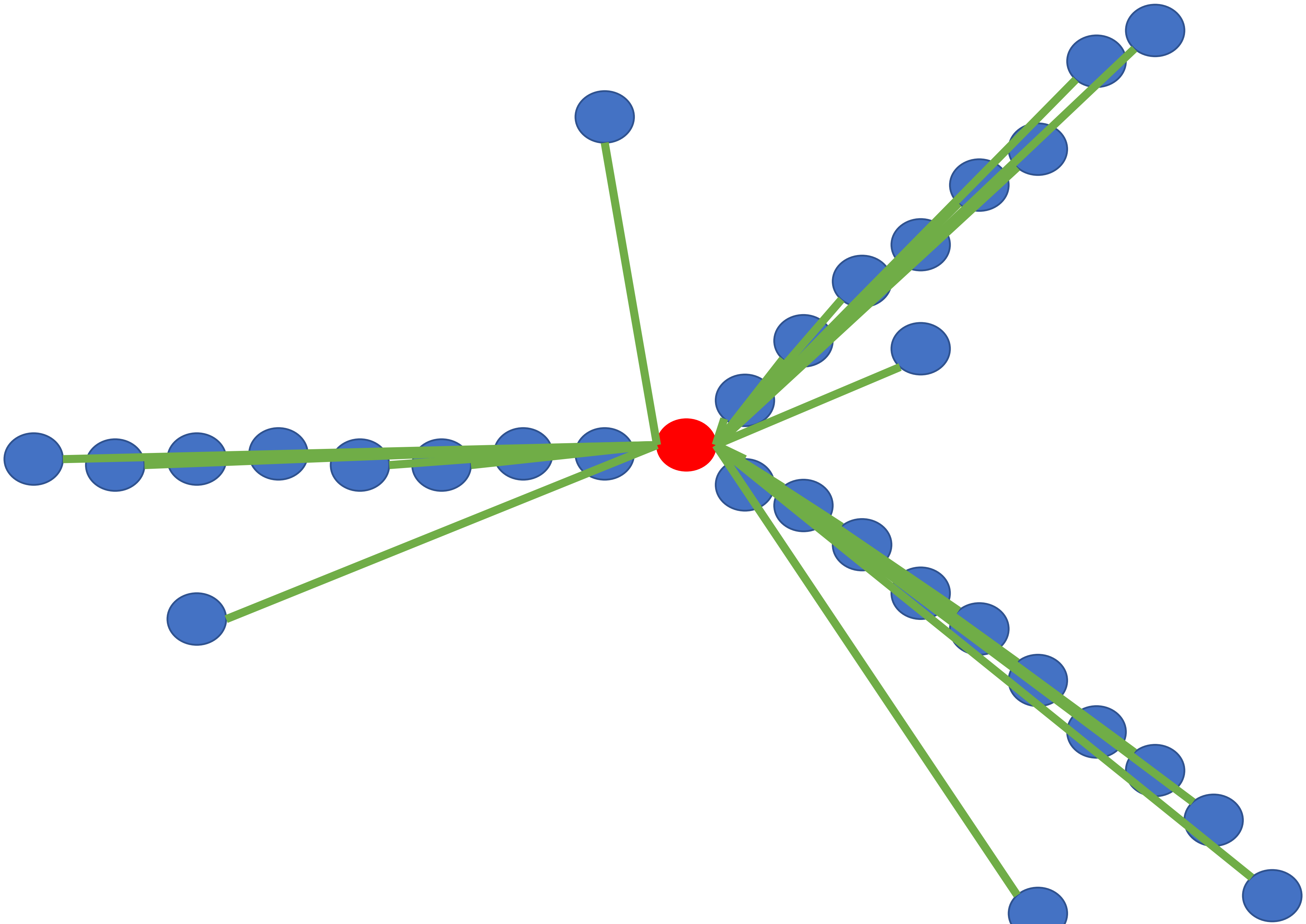
Most will have large enough angular differences to be outside angular tolerance

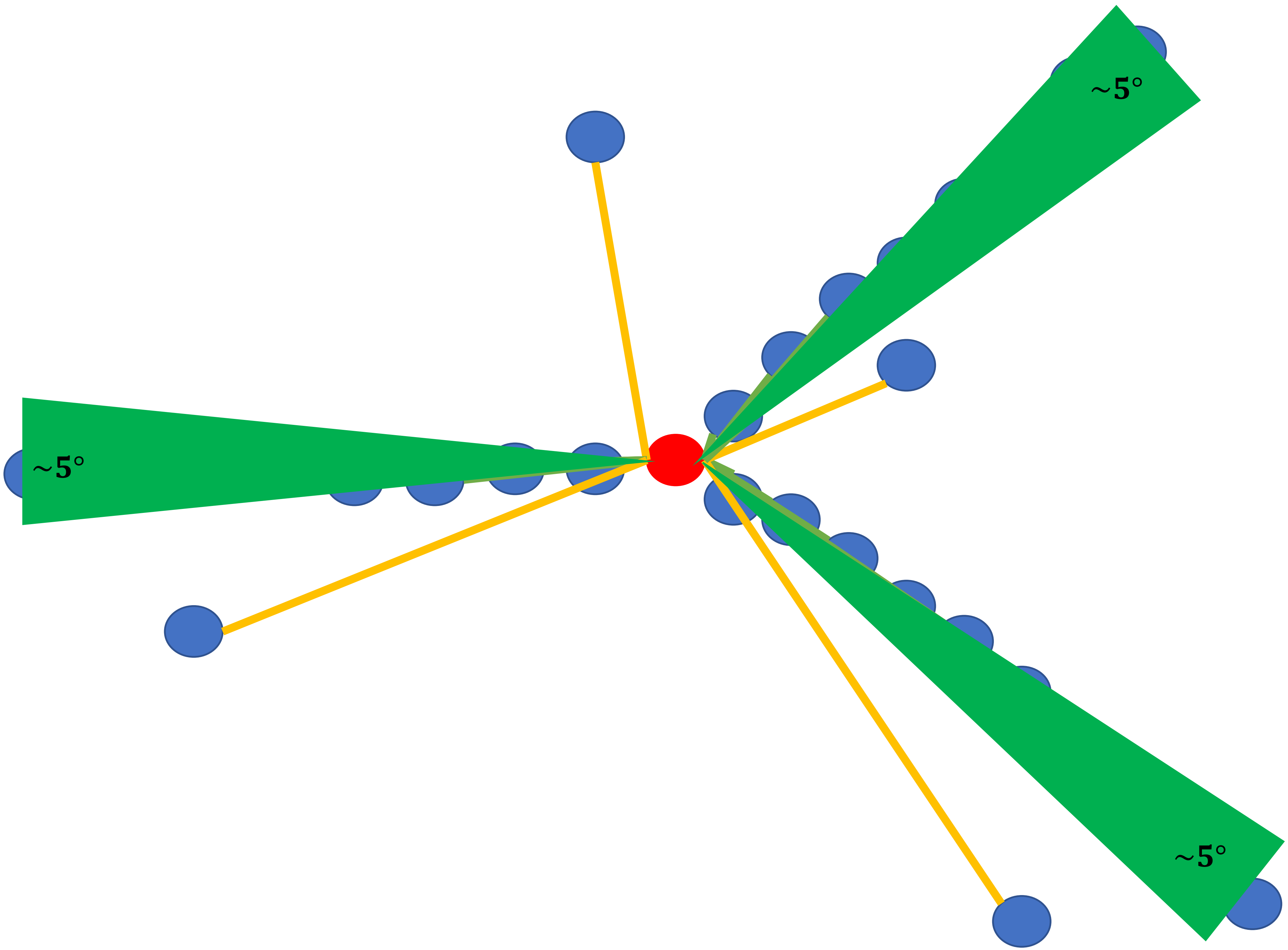


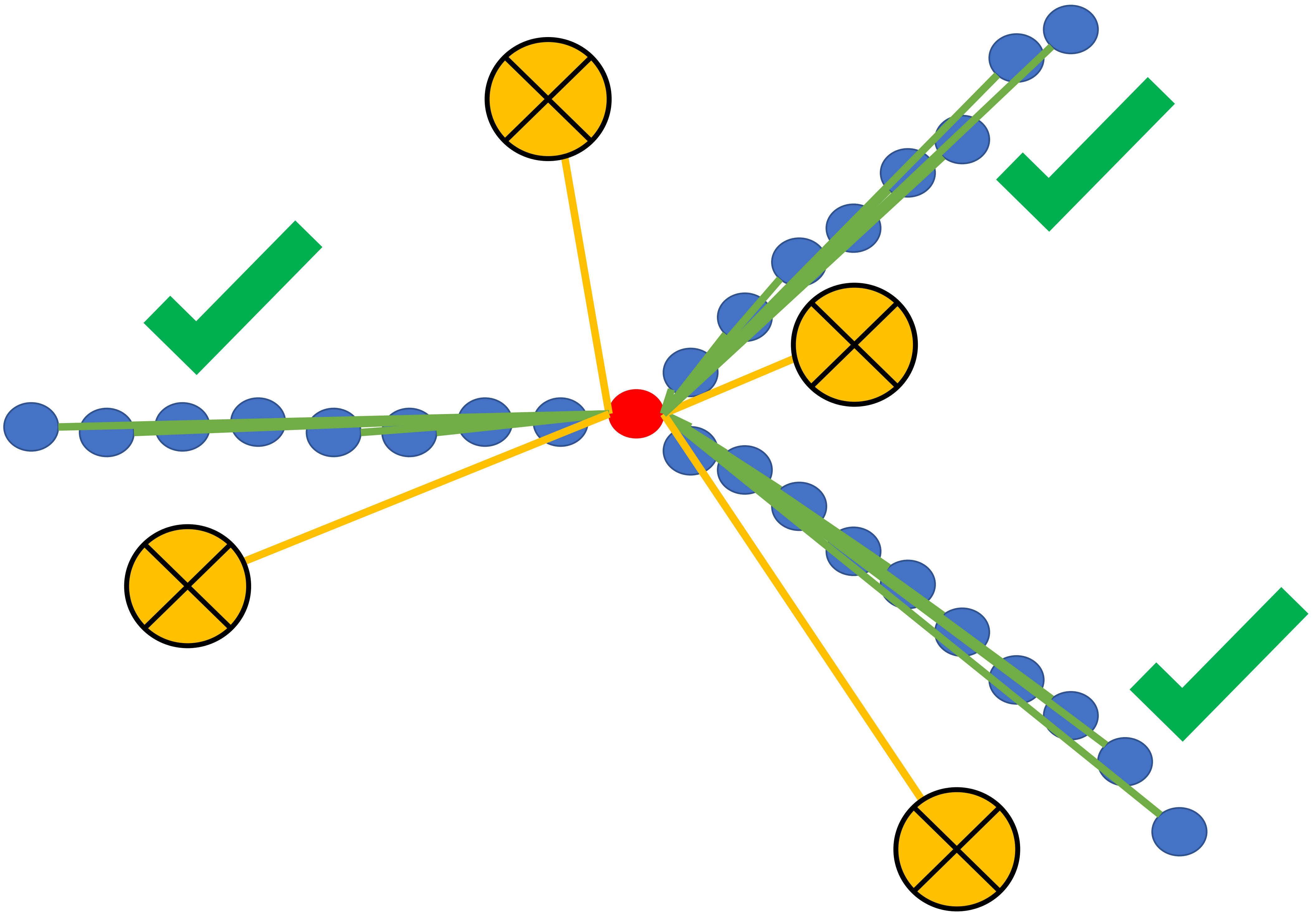
This greatly limits the number of possible tracks of particular angles which can be triggered on

$\rightarrow$ **Require $\geq$ 3 for multiprong!**

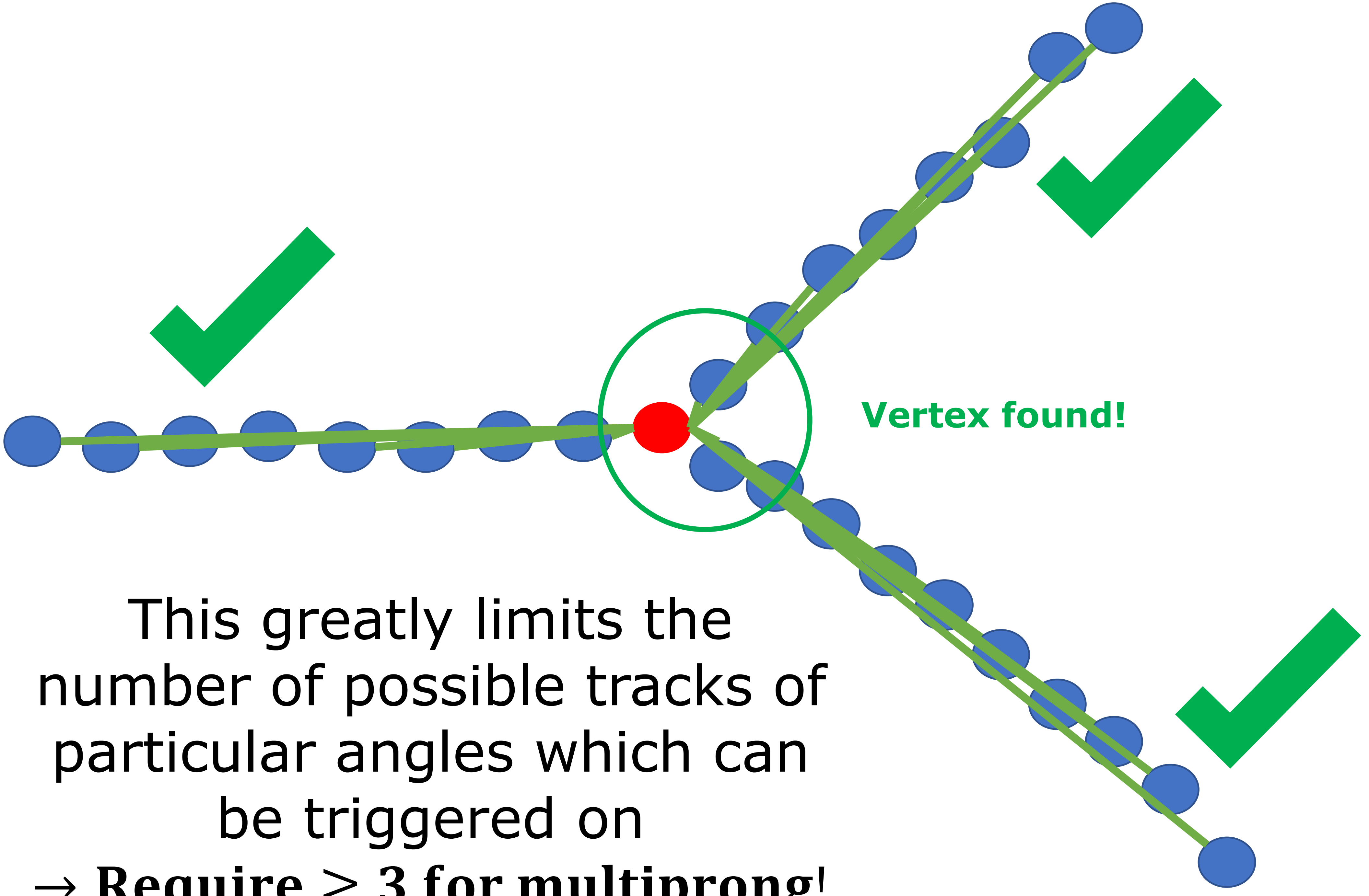

True vertex




~5°
~5°
~5°



Original idea developed in conversation with A. Ashkenazi



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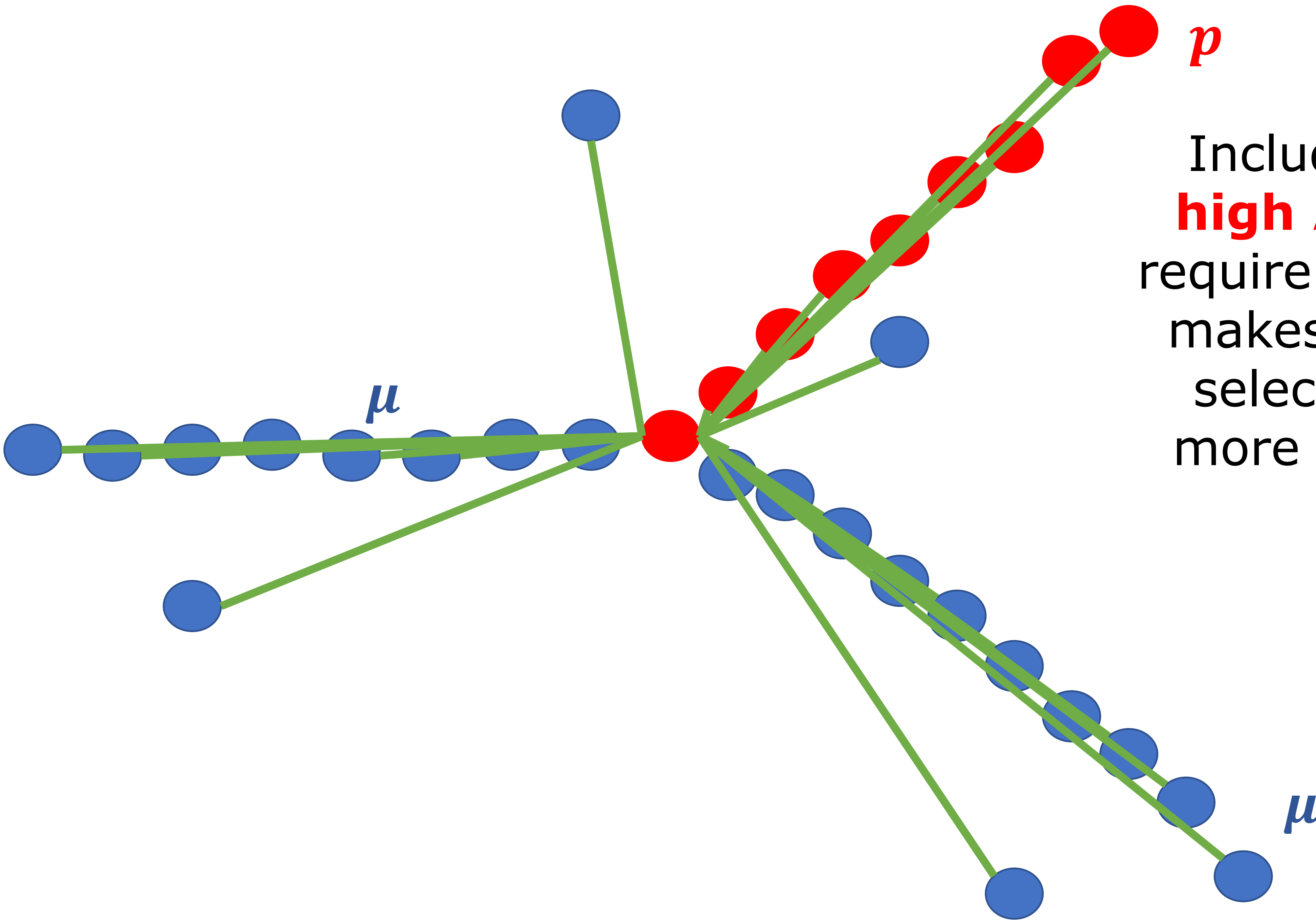


Including **high ADC** requirements makes this selection more pure

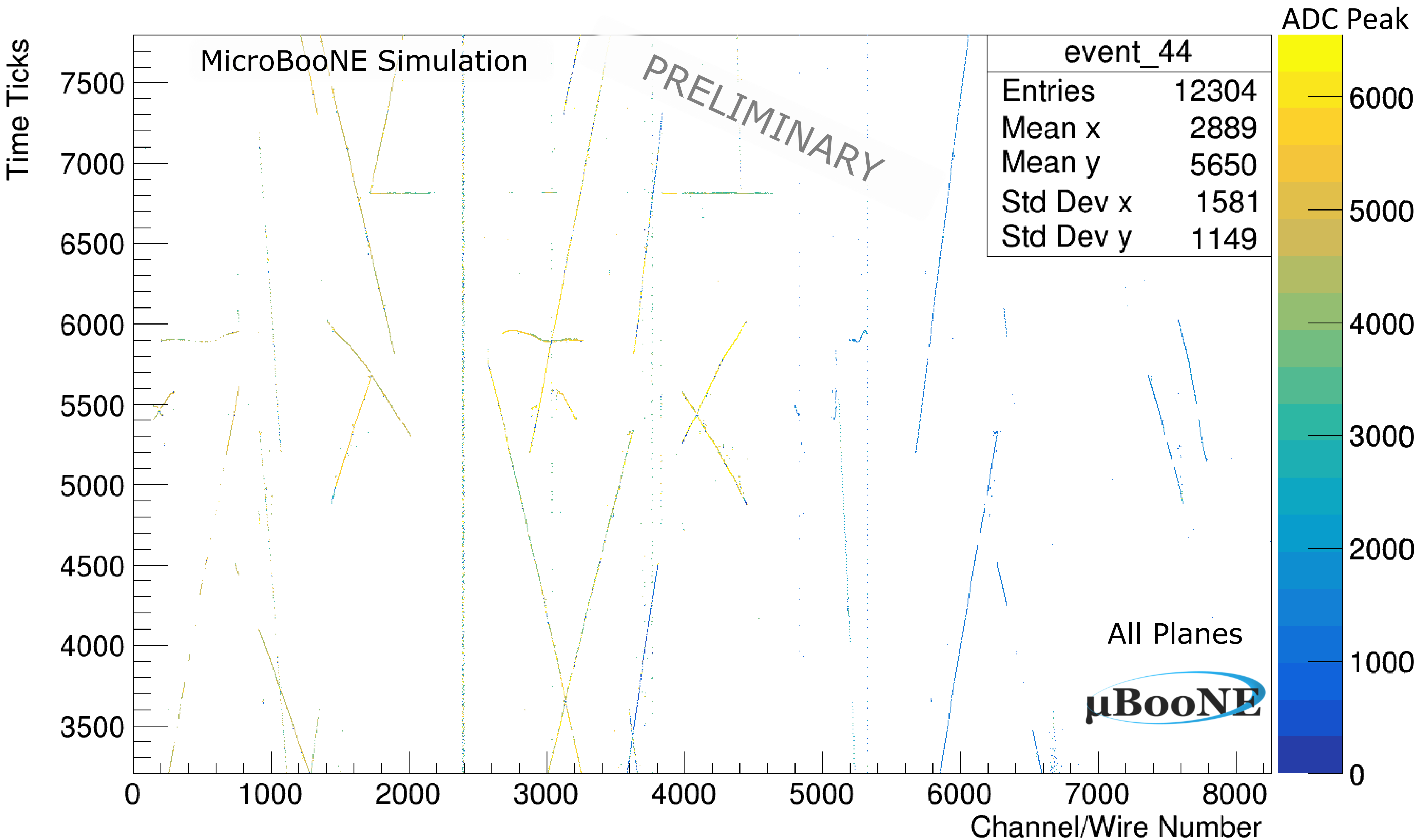
Expected QE-like Data Rates

- QE-like proton ($\mu + \mathrm{Ar} \rightarrow p + \mu + X$) candidates
  - Assume QE EM cross section
- Estimate simulated with cosmic flux:
  - ~ 4000 cosmic μ per second
- $\sim 1\mathrm{Hz}$ true QE interactions above threshold

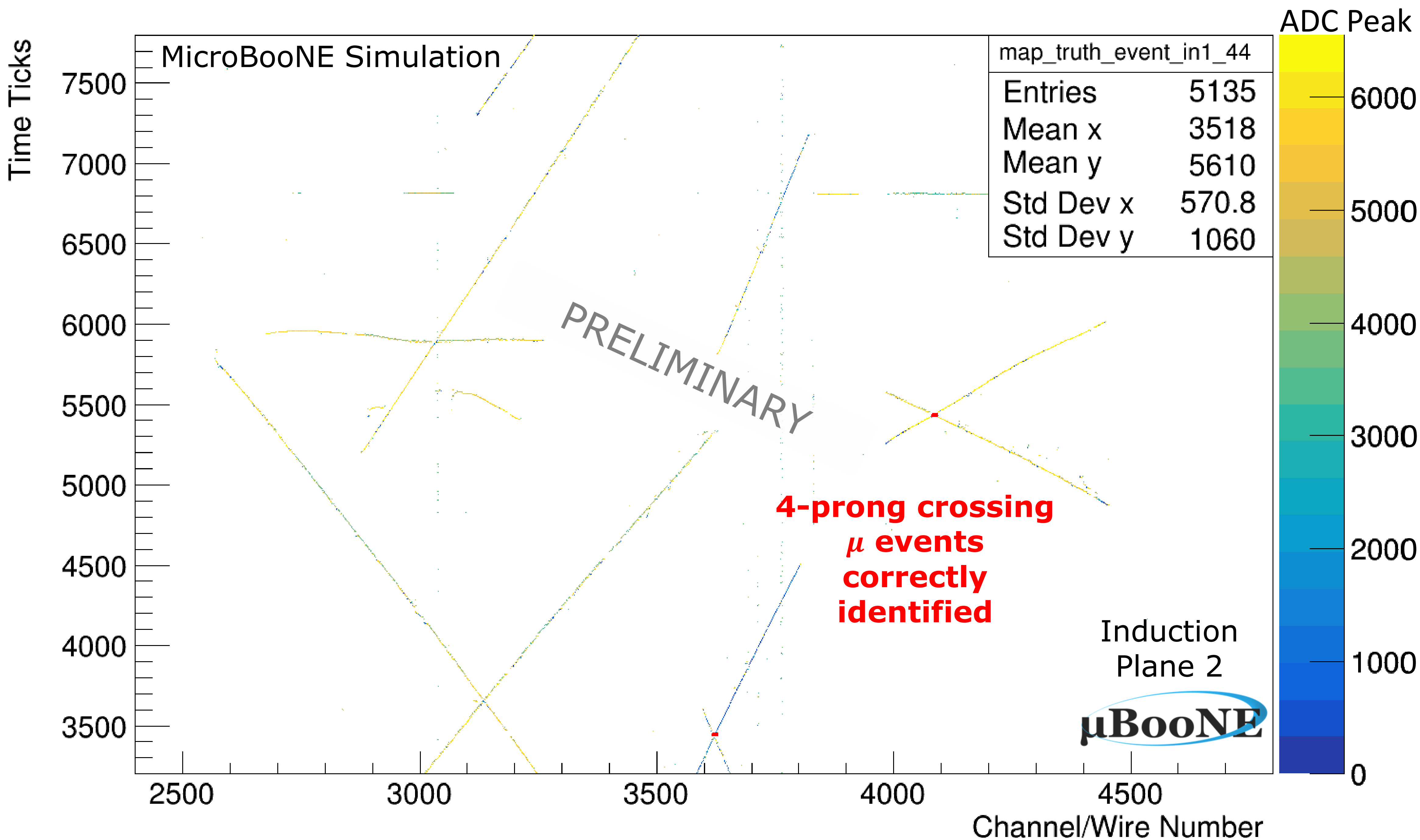
Courtesy of A. Ashkenazi and W. Van De Pontseele

CORSIKA

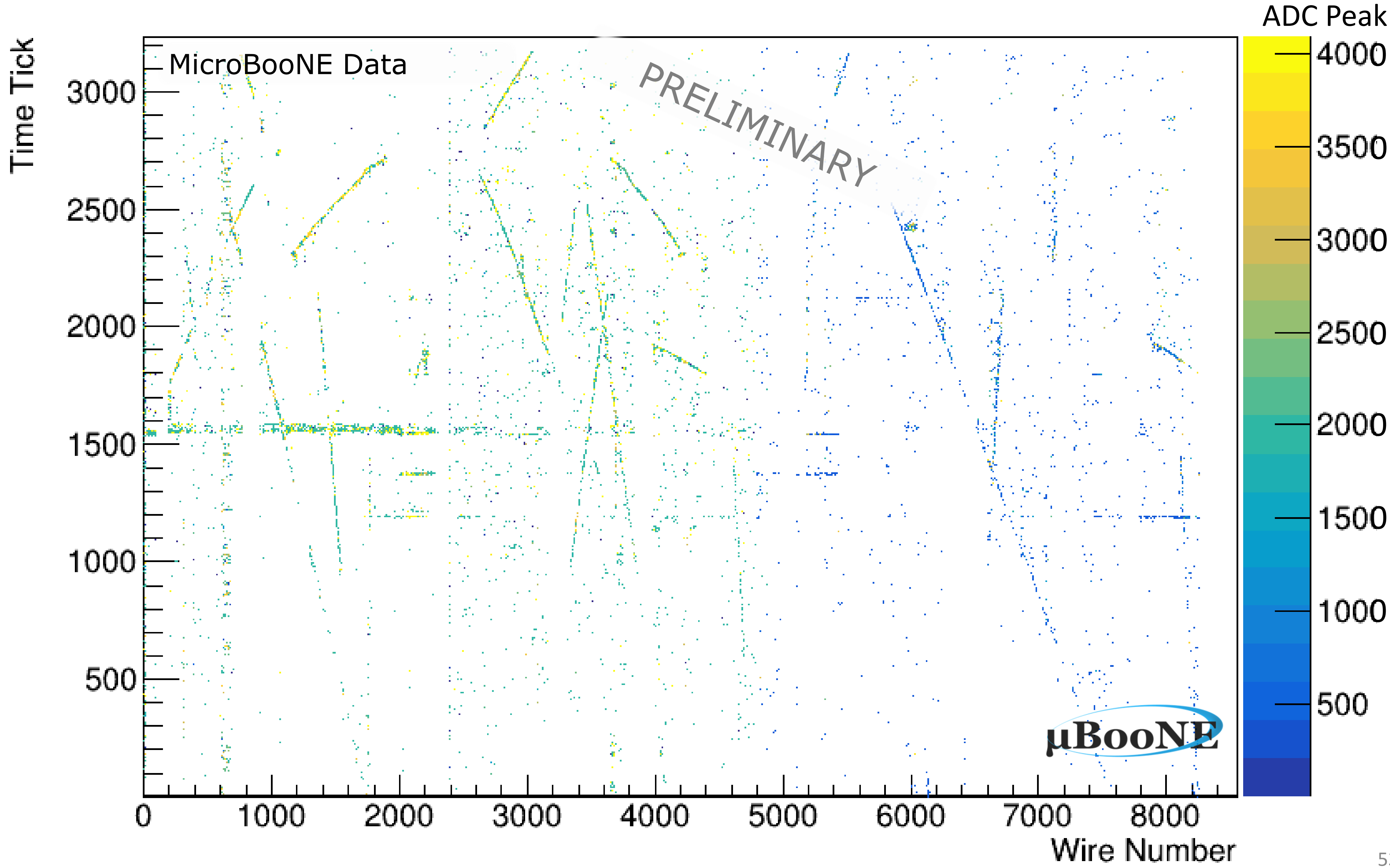
Monte Carlo Data View



Triggering on Multiprong Events in Monte Carlo



Real Data View



Conclusions

- $\ell^{\pm}$ scattering is a powerful proxy to ν interactions
  - e: Well constrained kinematics, systematics
    Plethora of data available for tuning ν event generators
  - $\ell^{\pm}$:Useful for testing energy reconstruction techniques
    Informs interaction model!
    Tune mutual vector part of interactions

- Cosmic μ provide *in situ* opportunities at our detectors
  - Similar final state topologies to ν interactions
  - More kinematic information than initially invisible ν
  - Test each detector's E reconstruction directly!

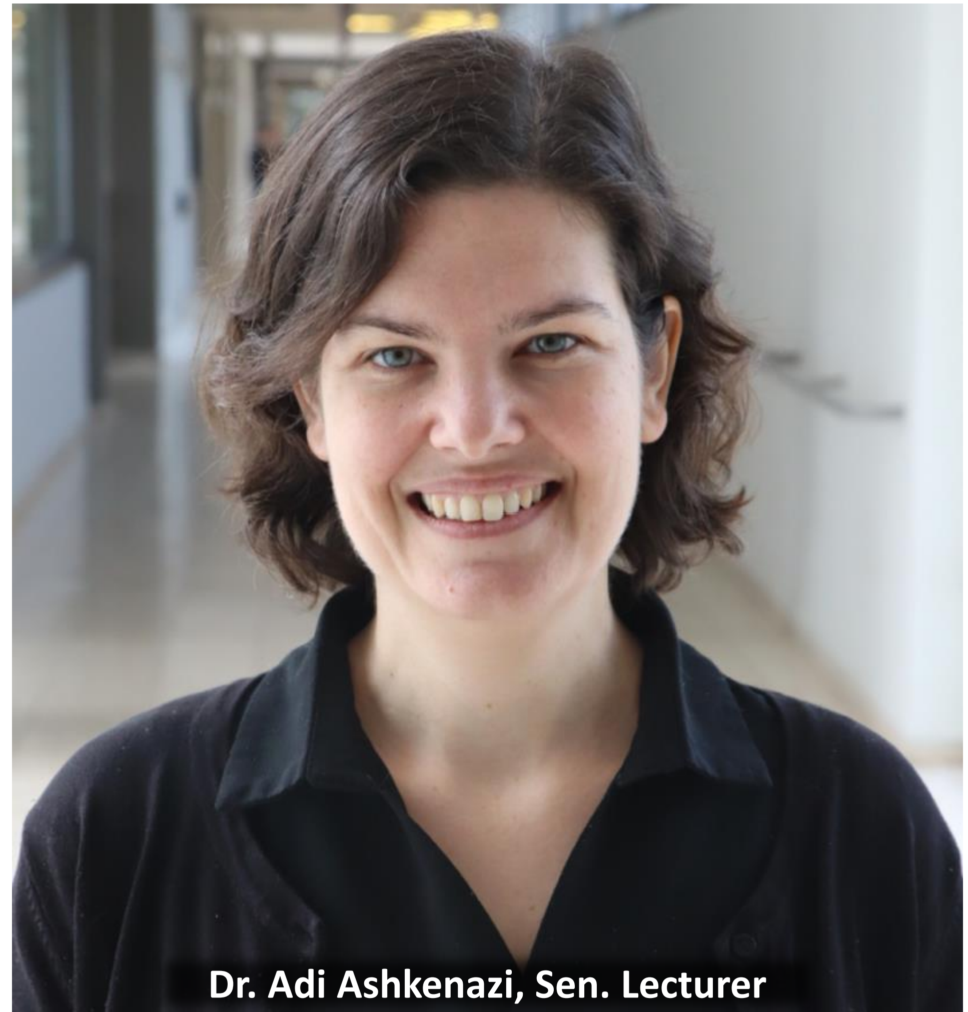
Thanks to the MIT-TAU uB/$e4\nu$ Group!

Thanks to the RGM/$e4\nu$ Group!

Left to right:

- Erin Seroka (GW, GS)
- Larry Weinstein (ODU)
- Axel Schmidt (GW)
- Justin Estee (MIT, PD)
- Sara Ratliff (GW, GS)
- Moi
- Andrew Denniston (MIT, GS)

Thanks to the TAU Group!



Dr. Adi Ashkenazi, Sen. Lecturer

Julia Tena-Vidal, PD

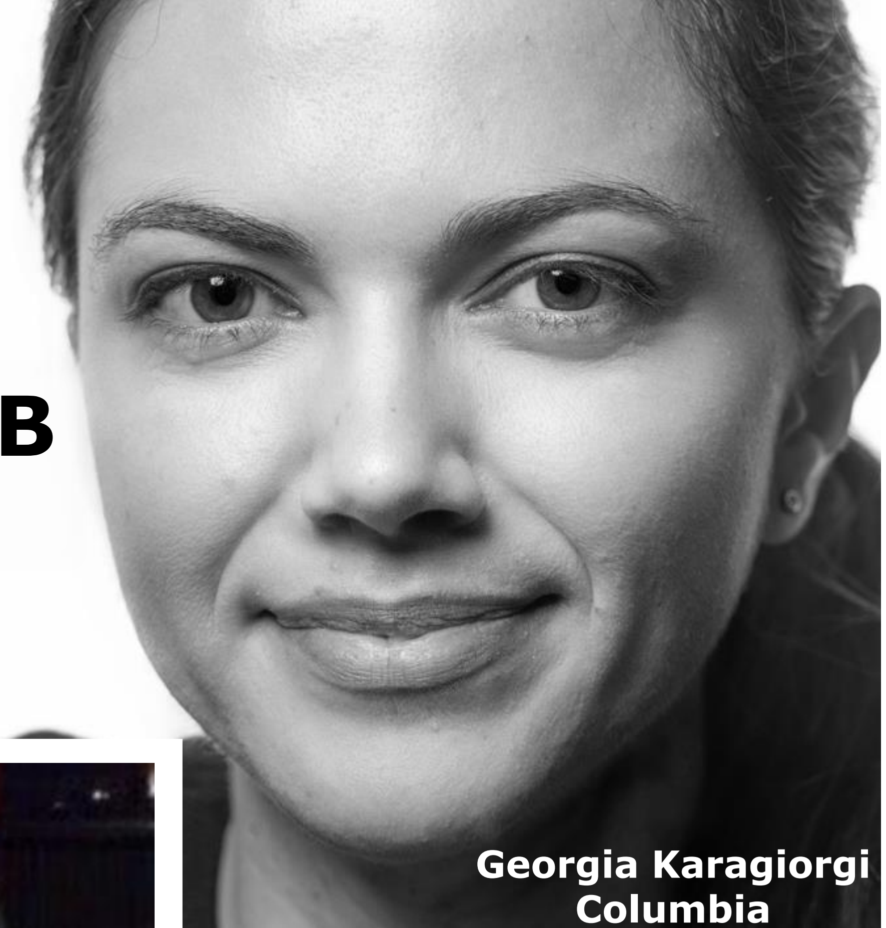
Amir Gruber, UG

Alon Sportes, MS

Matan Goldenberg, MS

Thanks to the uB TP R&D team!

Wes Ketchum
FNAL



Georgia Karagiorgi
Columbia

Daisy Kalra
Columbia

Adi Ashkenazi
TAU

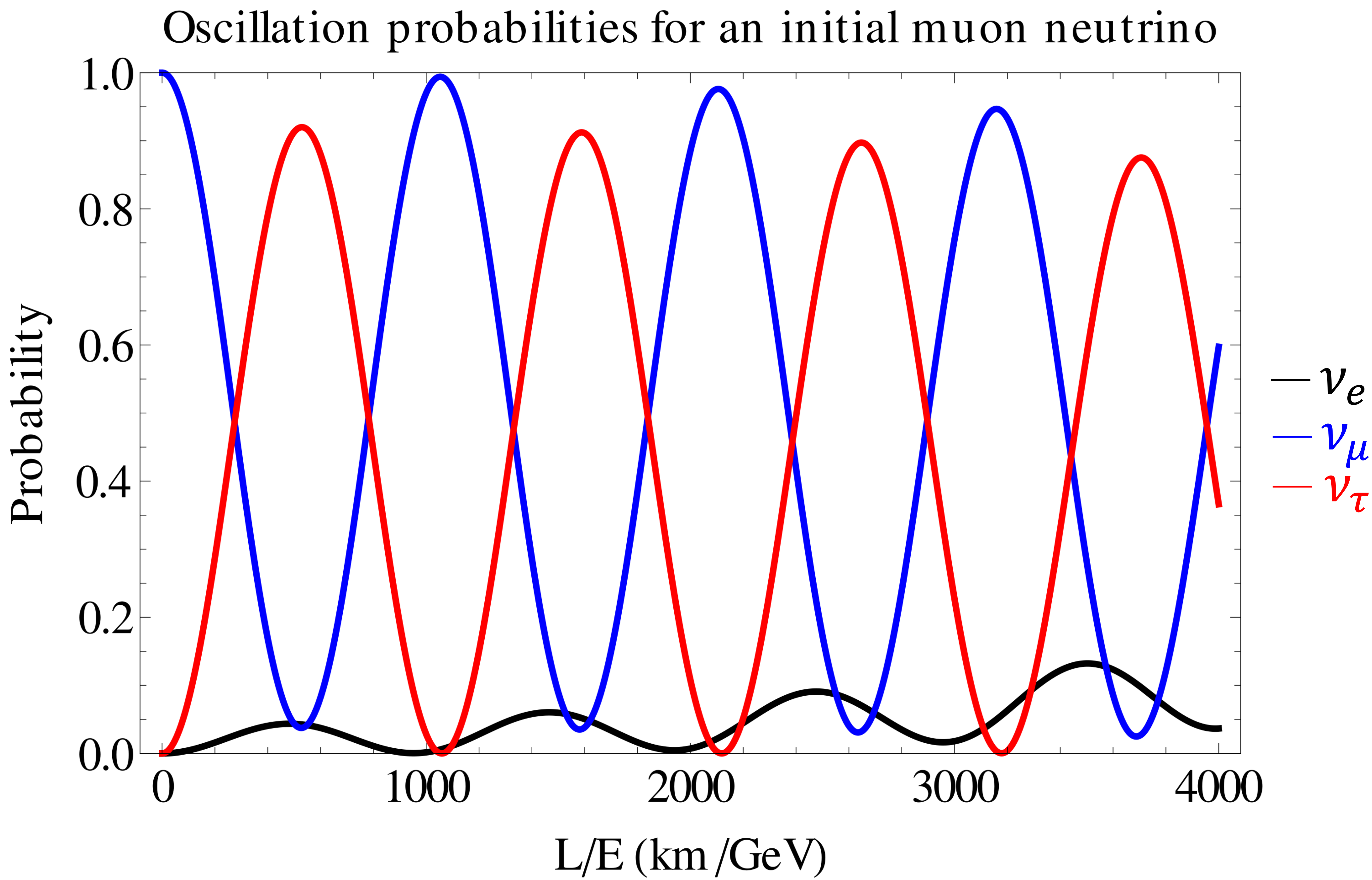
Meghna Bhattacharya
FNAL

Thank-you for your attention!

Questions?

Backup Slides

Neutrino Properties Must Be Understood

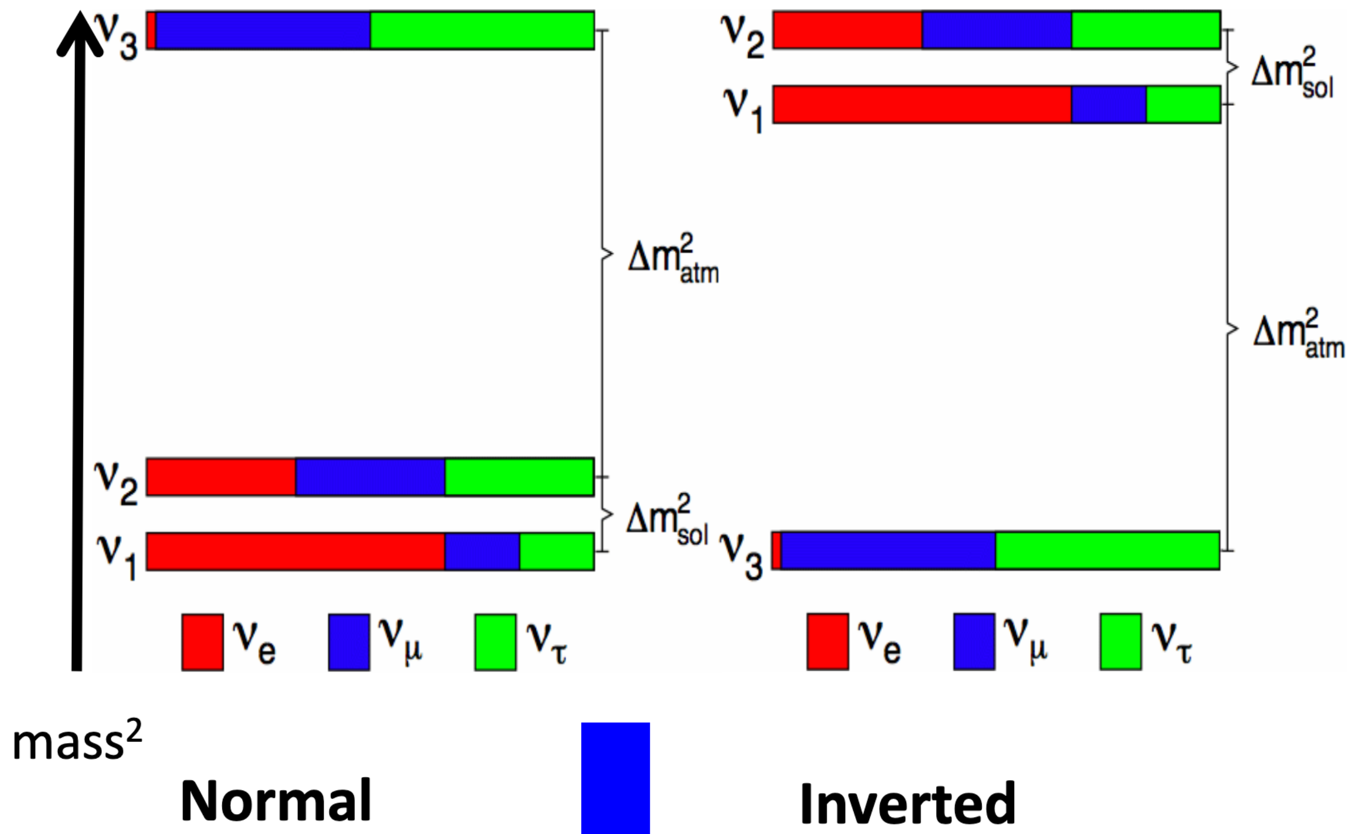


Wiki

Neutrino Properties Must Be Understood

- Evidence of oscillations from solar, atmospheric and many other ν experiments

- Massive states are mixtures of flavor states
  - Three-flavor model parameterized by the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix**



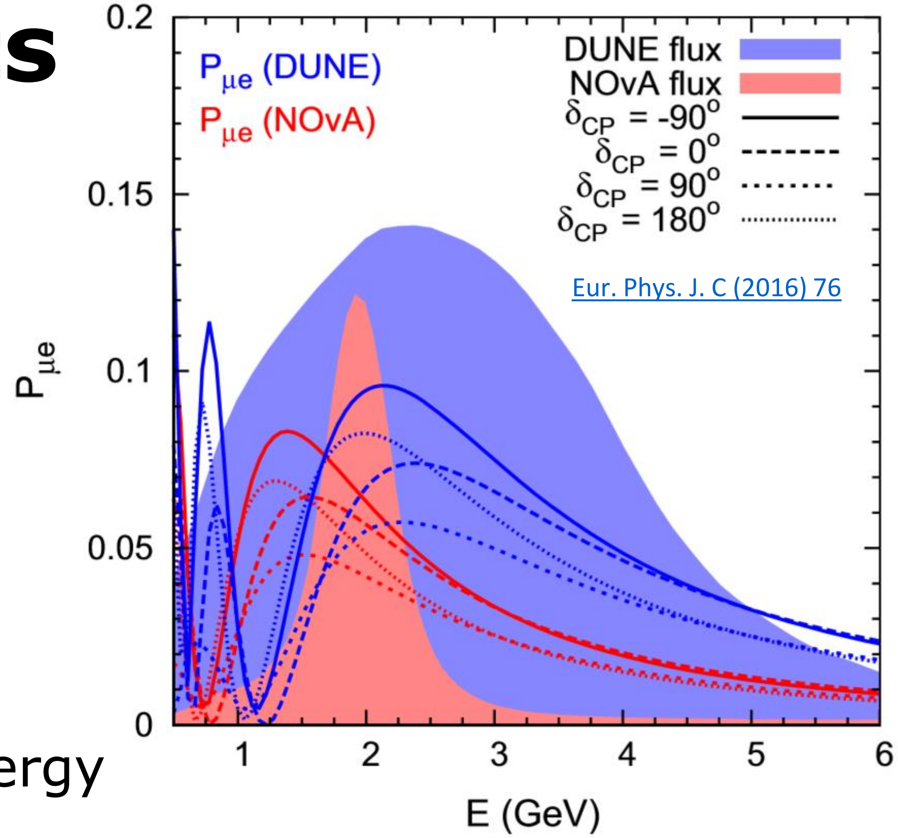
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

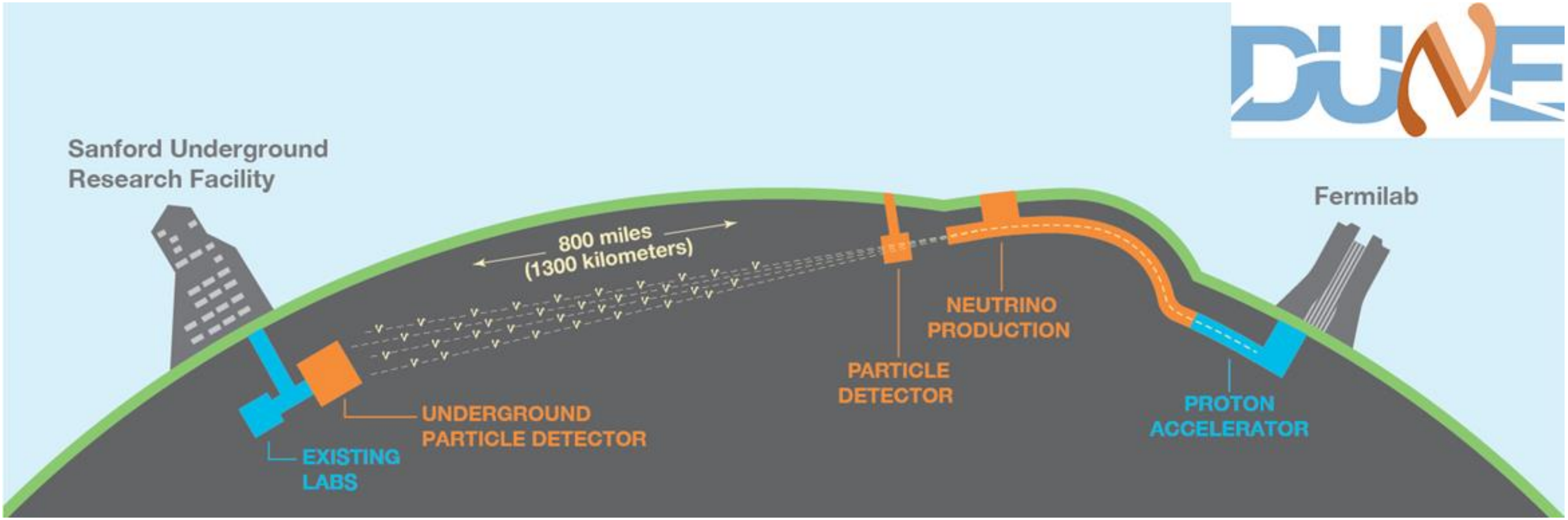
2015 Nobel Prize in Physics

PDG
NuFit
Phys. Rev. Lett. 81, 1562 (1998)
Phys. Rev. Lett. 87, 071301 (2001)
Phys. Rev. Lett. 89, 011301 (2002)

Future Experimental ν Physics

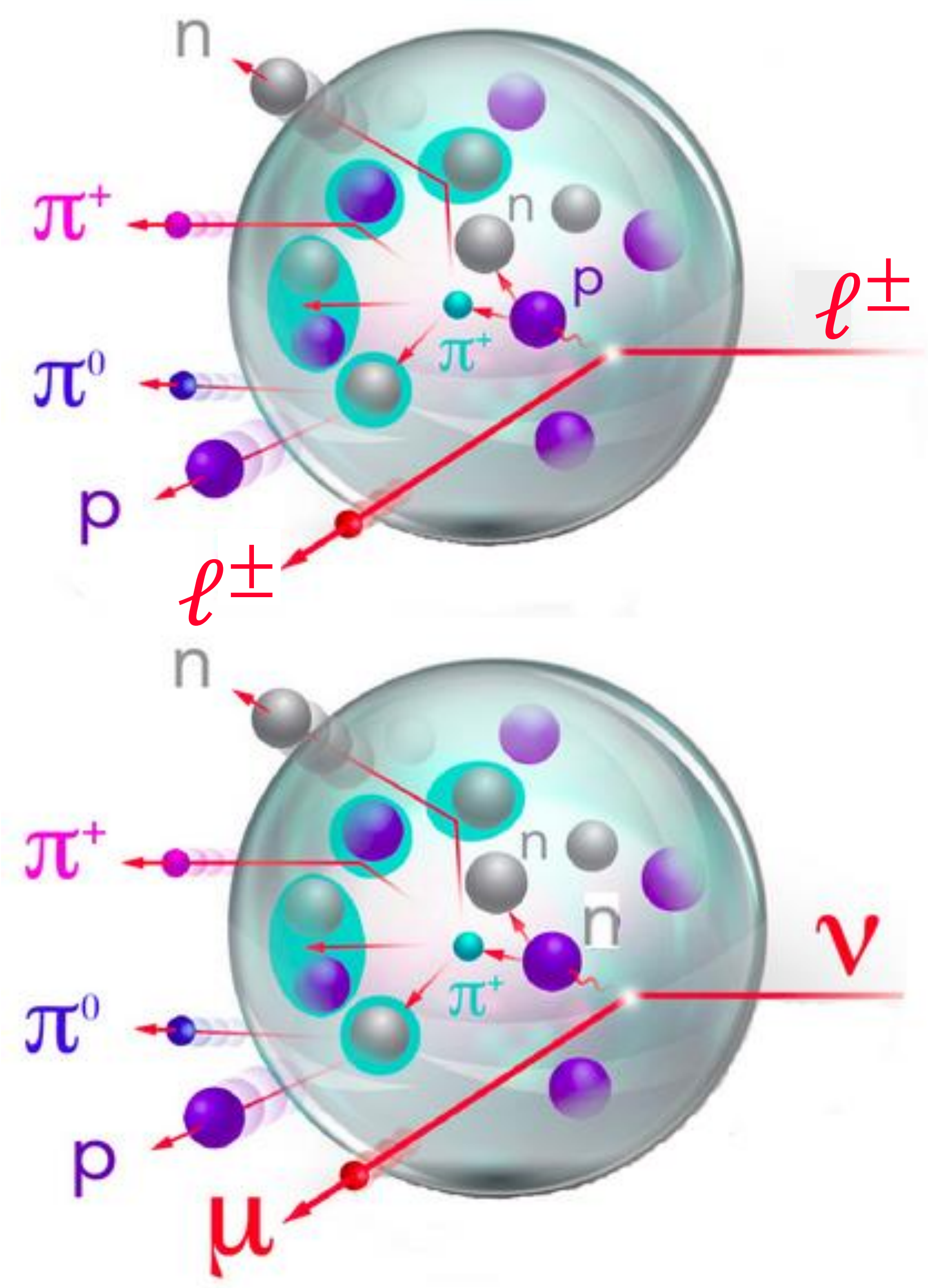
- Goal:
  - Extract ν oscillation parameters
- Implications
  - Leptogenesis, cross sections, τ production, BSM, Non-Standard Interactions
- Challenges
  - Broadband diverging ν beam, unknown initial ν energy





Why Charged Leptons?

- Nuclear physics is effectively identical!
- **Constrain vector part** of all $\{\ell^{\pm}, \nu\}$ interactions!
    - Any model must work for $\ell^{\pm}$ or it won't for ν!
    - Benchmark simulations
    - Improve the vector and nuclear parts' behavior
    - Inform neutrino reconstruction

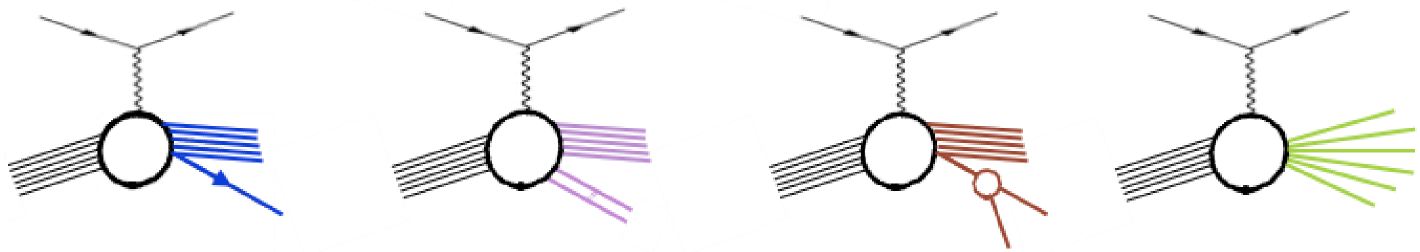


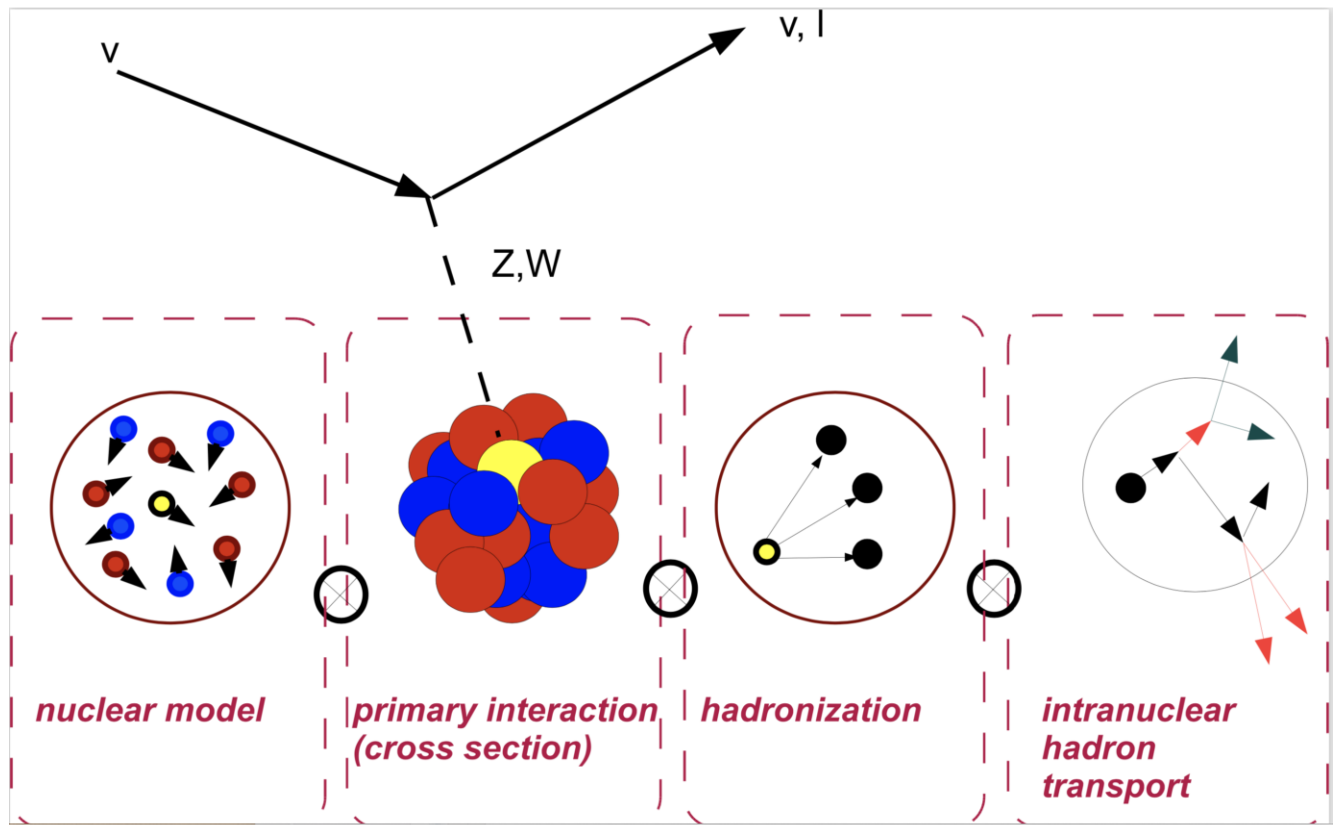
Improving Discrete Aspects of *Modeling*

$$\Longrightarrow \sigma_i(E)R_{\sigma_i}(E,E_{rec})$$

Select observables for analysis with clear usefulness

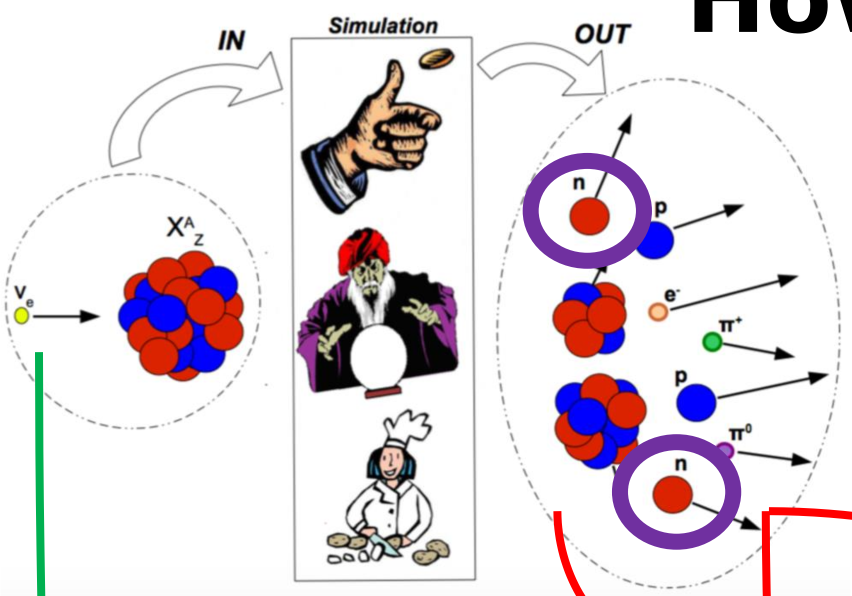
- Allows for "tuning" of models' parameters directly via vector part
- Assumes some factorization



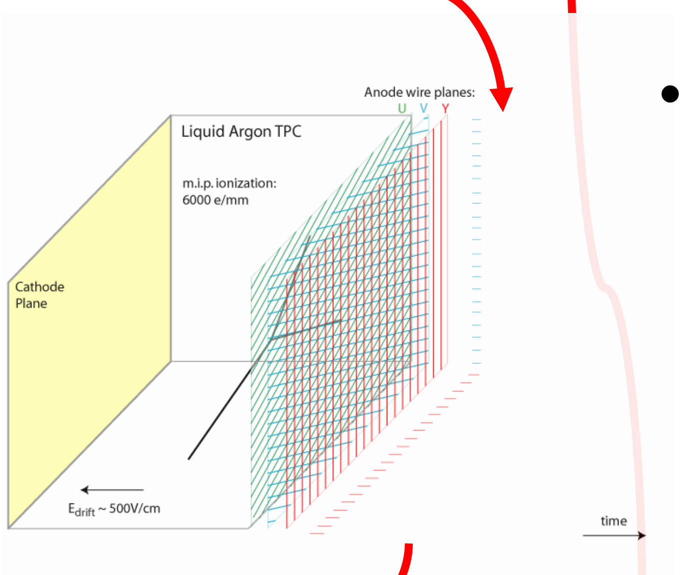


Adapted from C. Andreopoulous

How to inform ν reconstruction?



- Broadband flux is difficult
- Utilize event generators!
  - **Approximate** theory calculations
  - **Produce full final-state predictions**
    - Four-momenta, interaction vertices…

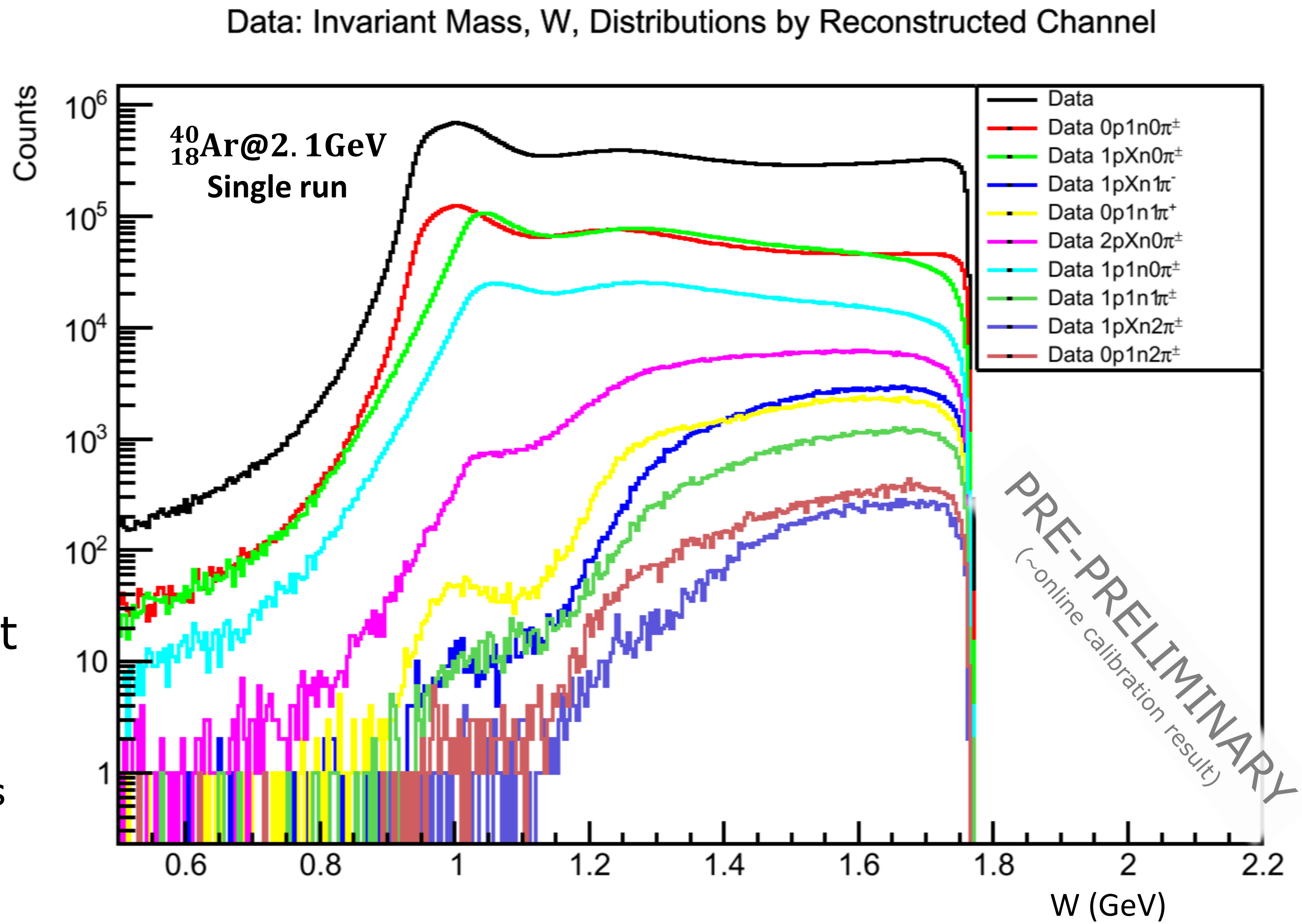


- How to attain $R_{\sigma_i}(E_{\text{true}}, E_{\text{rec}})$?
  - **Expect certain final states, sum energy**
  - Apply particle thresholds
  - Eventually couple w/detector simulation
  - Provide estimates for…
    - **True ν energy reconstruction**
    - Signal efficiency
    - Background estimations
  - Need to study "invisible" particles more!
    - Goal of TAU ν group!

$$\sigma_i(E) R_{\sigma_i}(E, E_{rec})$$

^{40}Ar Counts Look Promising

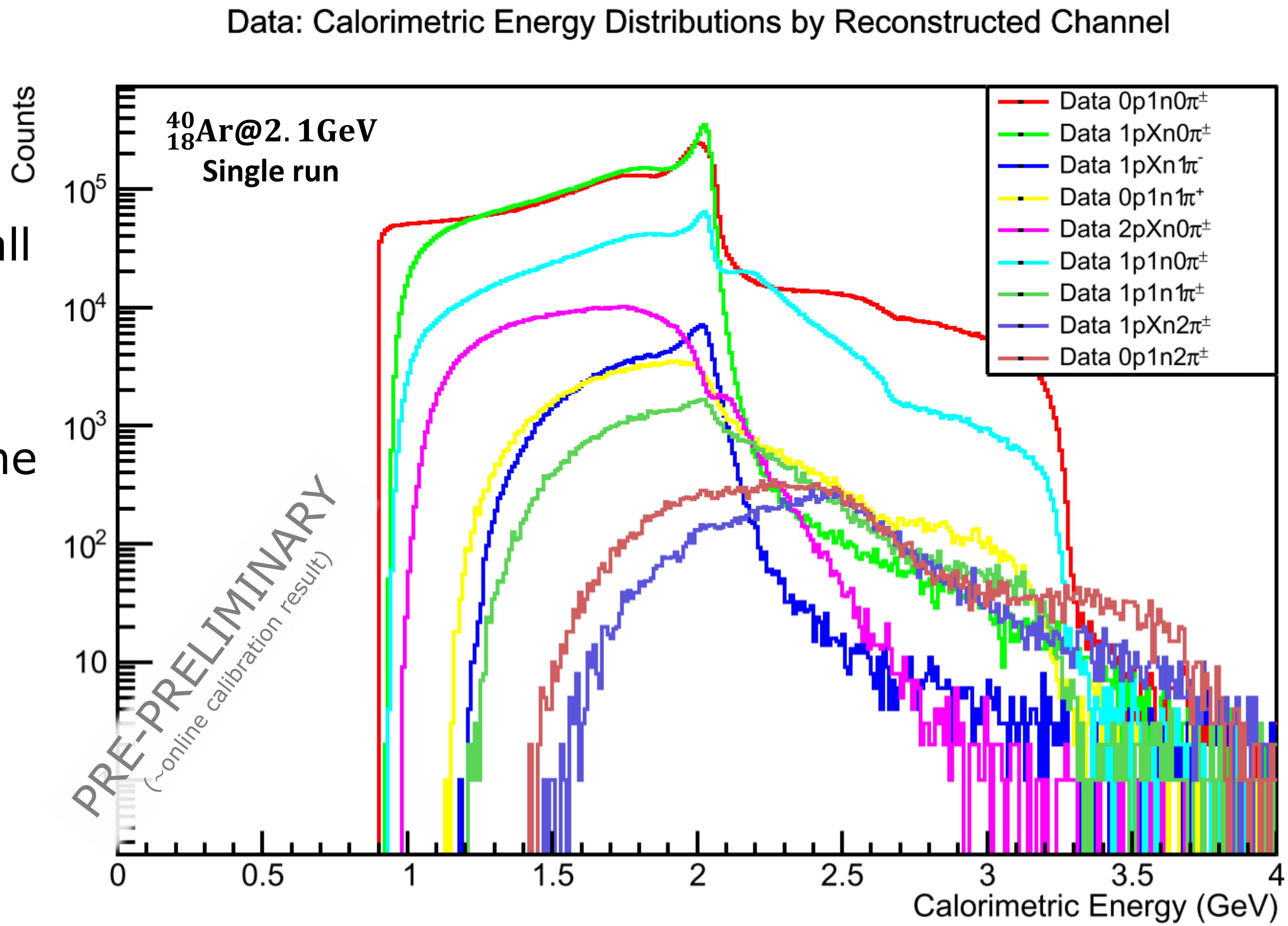
- W approximated off the standing proton
- Shapes are reasonable
- $\sim 5\ \mathrm{MeV}$ bins
  - Statistics look good!
- Problems w/GENIE prevent comparisons at high ω
  - Radiative effects dominate
  - Cut: $\omega \leq 1.2\ \mathrm{GeV}$



Thanks to L. Weinstein and A. Papadopoulou for discussions

^{40}Ar Counts Look Promising

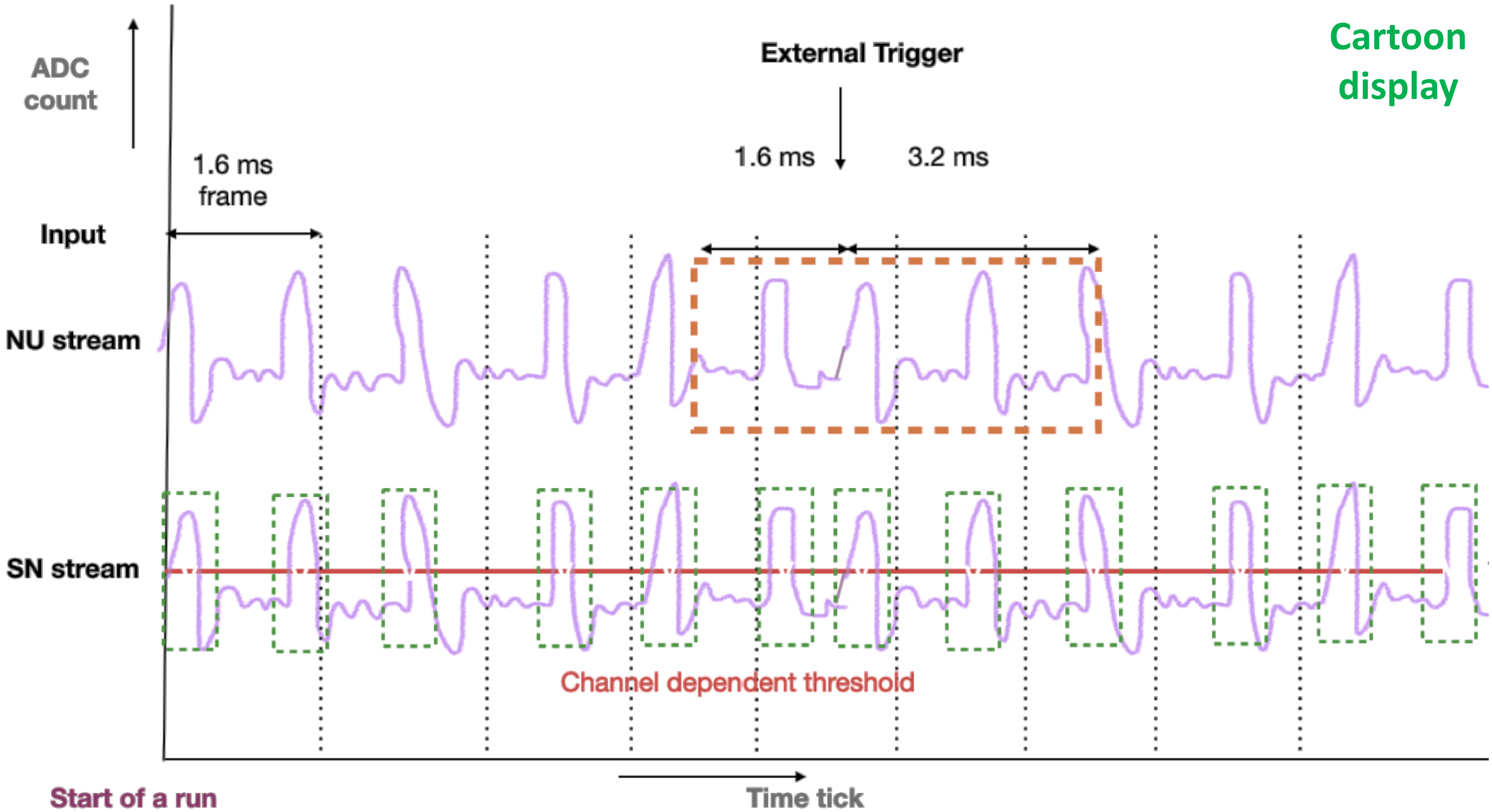
- $\boldsymbol{KE}_{\mathbf{Tot}} + \boldsymbol{m}_{\boldsymbol{\pi}}$ of all particles
- Shapes are ~good up to the beam energy
- ~ 5 MeV bins
  - Statistics look good!



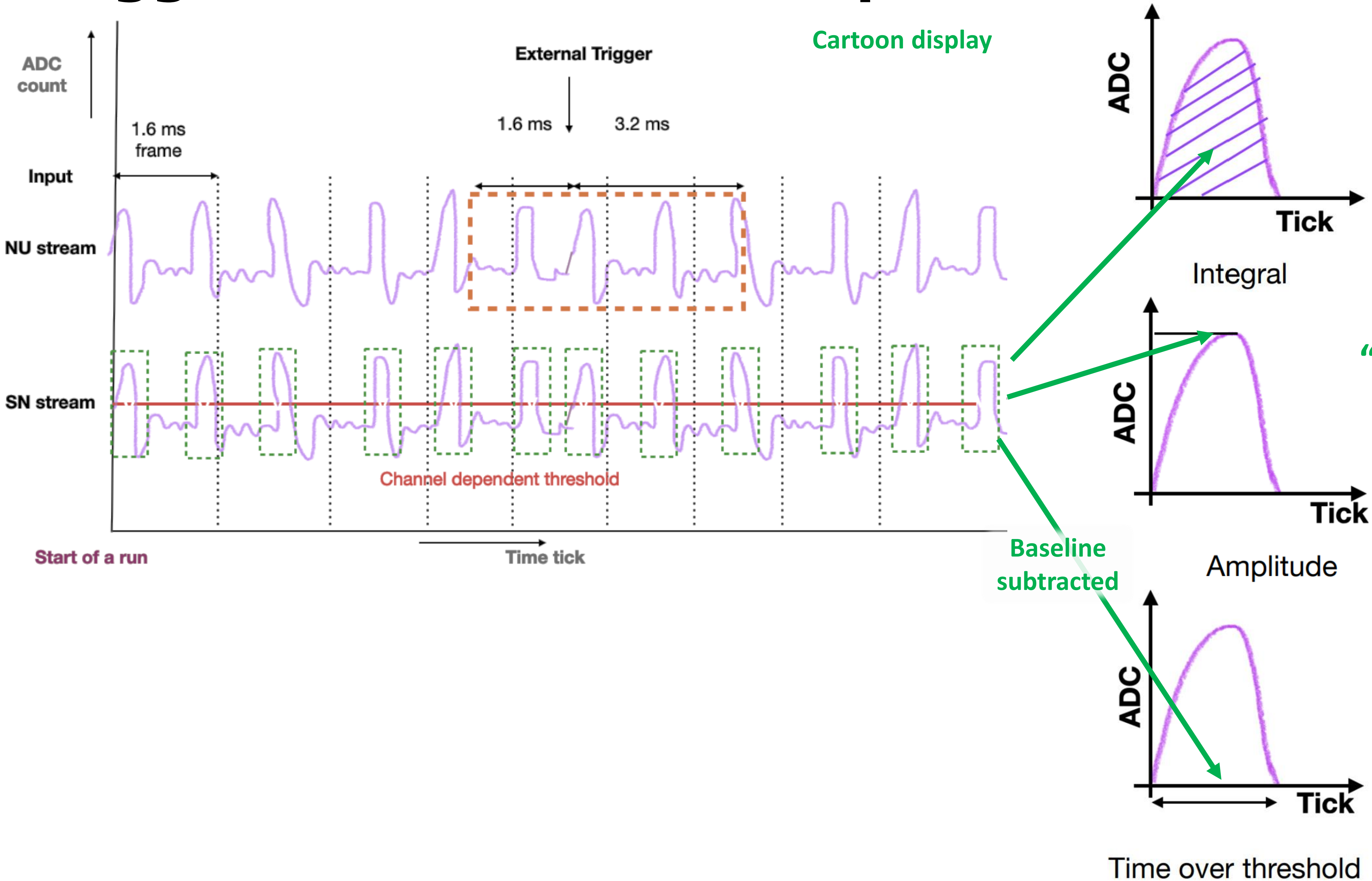
Data Structure

Trigger Primitives

Trigger Primitives from Supernova Stream ROIs



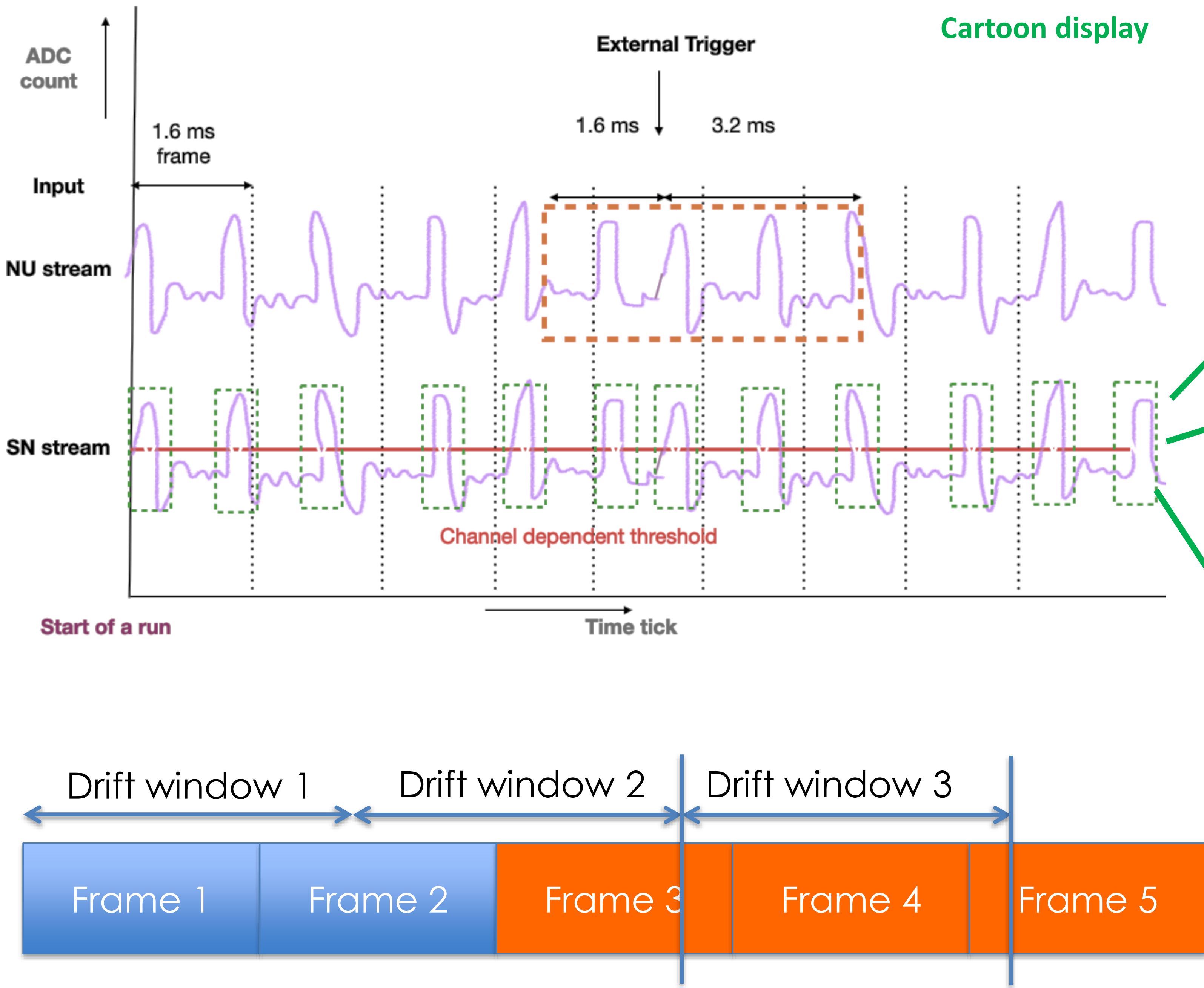
Trigger Primitives from Supernova Stream ROIs

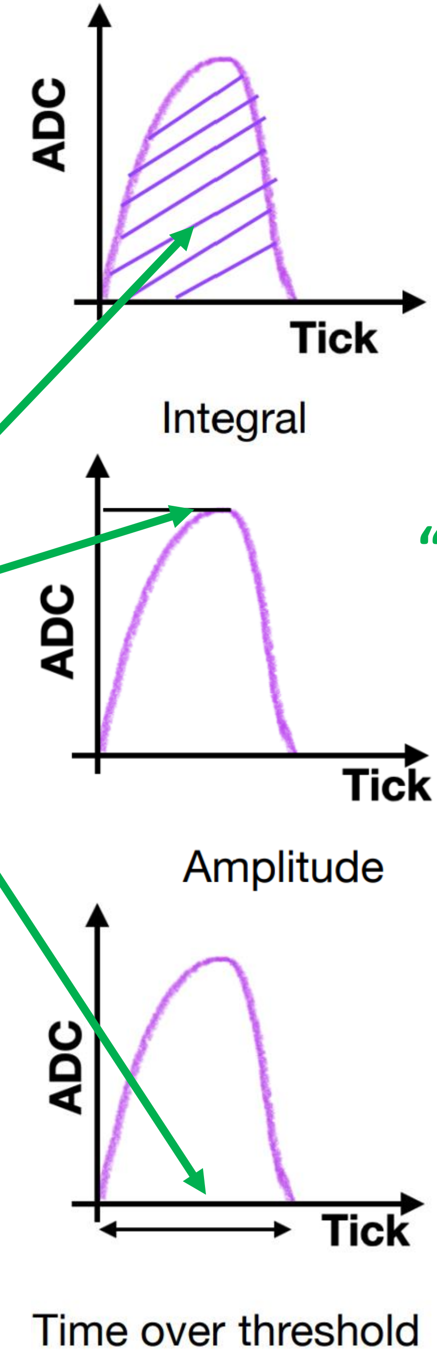


TPs are a "summary" of the region of interest

Courtesy of D. Kalra

Trigger Primitives from Supernova Stream ROIs





TPs are a "summary" of the region of interest

Drift window 3 uses data that span 3 frames

Courtesy of D. Kalra

Trigger Primitive Data Structure

Can now visualize and process Trigger Primitive (TP) objects to create event displays and enter into the trigger algorithms

[SBND TPC Readout Binary Data Format]

Unsorted TP data stream from DAQ

```
struct TriggerPrimitive
{
  uint32_t  chanel
  int64_t   time_start
  uint16_t  adc_integral
  uint16_t  adc_peak
  int32_t   time_over_threshold
};
```

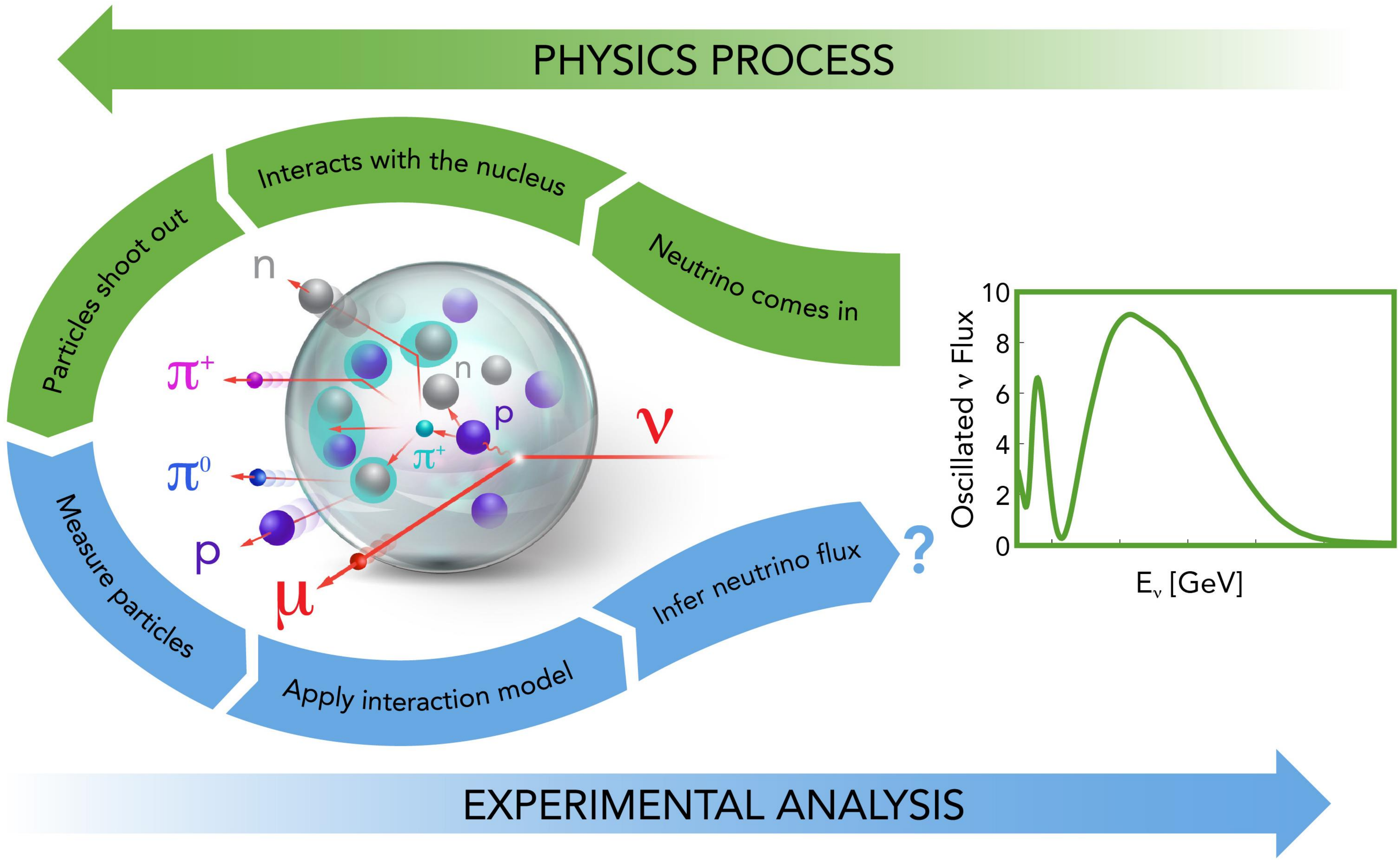
Unsorted TP vector

Ordered TP C++ maps

Multiprong (QE-like $1\mu 1p$) Trigger Philosophy

Multiprong Trigger Design

- Considers “hits” of trigger primitives with locations in time and wire number
  - Time and wire ordering
  - Effectively a “cartesian” plane
- Treat every hit as a potential vertex
  - Consider surrounding hits only to try and find “tracks”
  - Outer box/“radius” of activity
- Transform: semi-*cylindrical* coordinates
  - Use θ to differentiate “tracks” from one another from
  - Consider hits only beyond some distance
    - Prevent non-smooth behavior of angle



[Khachatryan, M., Papadopoulou, A., Ashkenazi, A. et al. Nature 599, 565–570 (2021)]

Adapted from A. Ashkenazi and A. Papadopoulou

How do we measure oscillation parameters?

Measure ν interaction counts in our detectors…
Must use an interaction model to deconvolute the ν flux

$$N_\alpha(E_{rec}, L) = \sum_{i=1}^{\text{Nuclei}} \int \Phi_\alpha(E_{\text{true}}, L)\, \sigma_i(E_{\text{true}}) R_{\sigma_i}(E_{\text{true}}, E_{\text{rec}})\, dE$$

measured

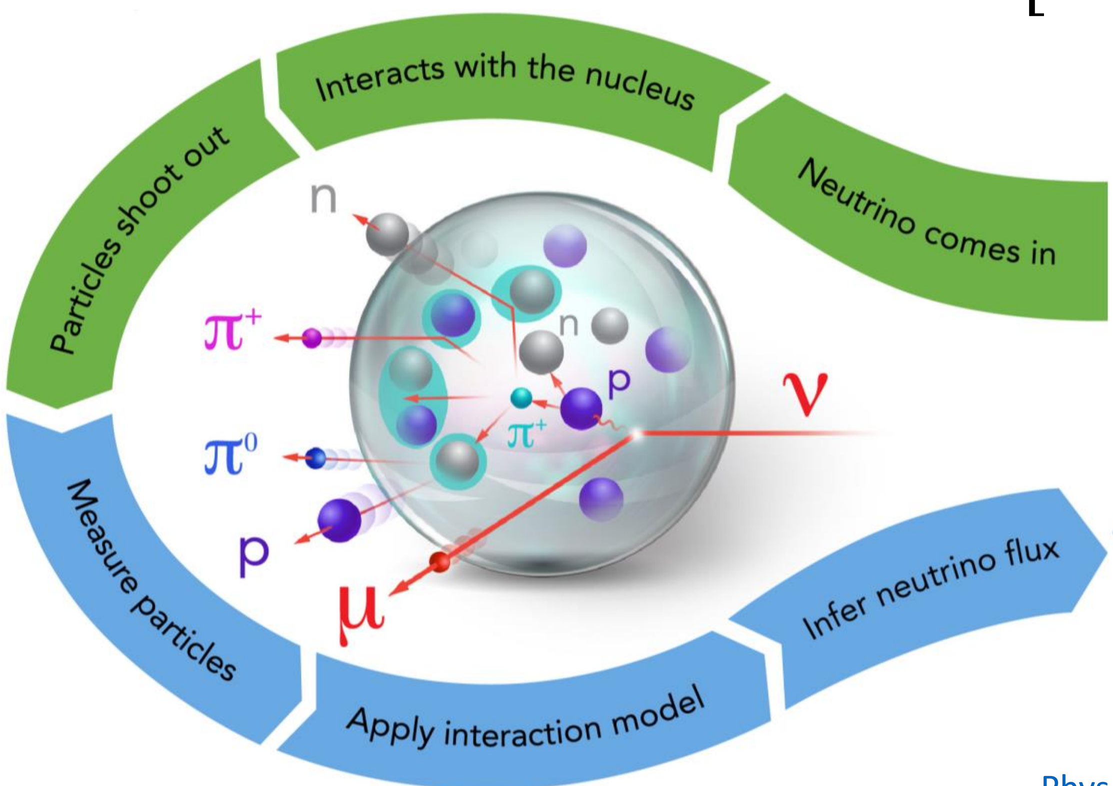
Required! ν flux

interaction model

$$\Phi_\alpha(E, L) \propto \left[1 - P_{\nu_\alpha \to \nu_\beta}(E, L)\right] \Phi_\alpha(E, \sim 0)$$

Near detector constraint

$\propto$ Oscillation parameters!



Adapted from A. Ashkenazi and A. Papadopoulou

Phys. Rev. D 91, 072010 (2015)

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Required!

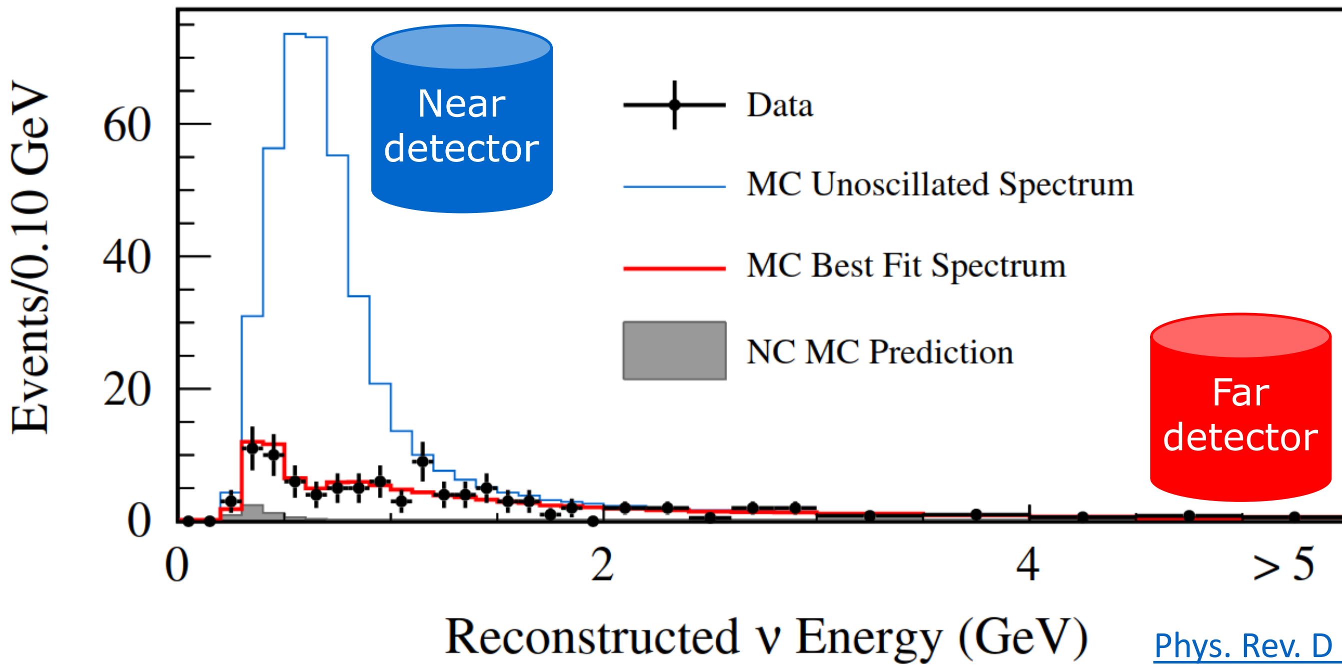
$$N_\alpha(E_{rec}, L) = \sum_{i=1}^{\text{Nuclei}} \int \Phi_\alpha(E_{\text{true}}, L)\,\sigma_i(E_{\text{true}})R_{\sigma_i}(E_{\text{true}}, E_{\text{rec}})dE$$

measured — ν flux — interaction model

$$\Phi_\alpha(E, L) \propto \left[1 - P_{\nu_\alpha \to \nu_\beta}(E, L)\right] \Phi_\alpha(E, \sim 0)$$

$\propto$ Oscillation parameters!

Near detector constraint

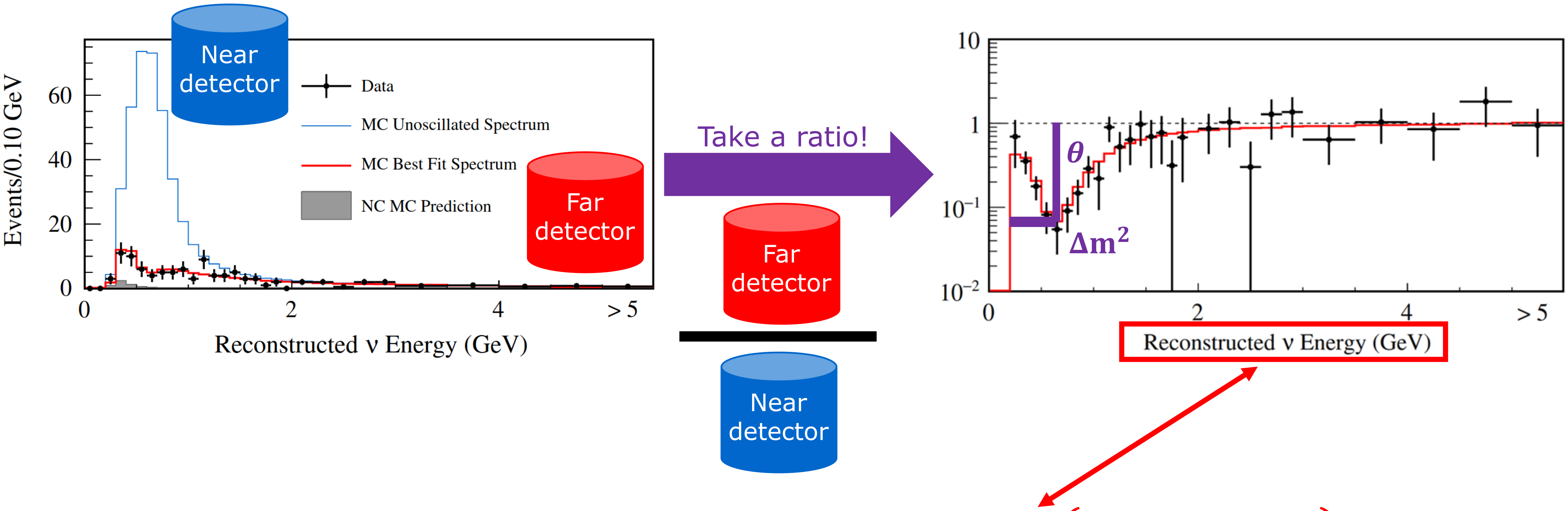


Adapted from A. Papadopoulou

[Phys. Rev. D 91, 072010 (2015)]

How do we measure oscillation parameters?

$$P_{\nu_\alpha \to \nu_\beta}(E_{\text{true}}, L) \approx \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{E_{\text{true}}}\right)$$



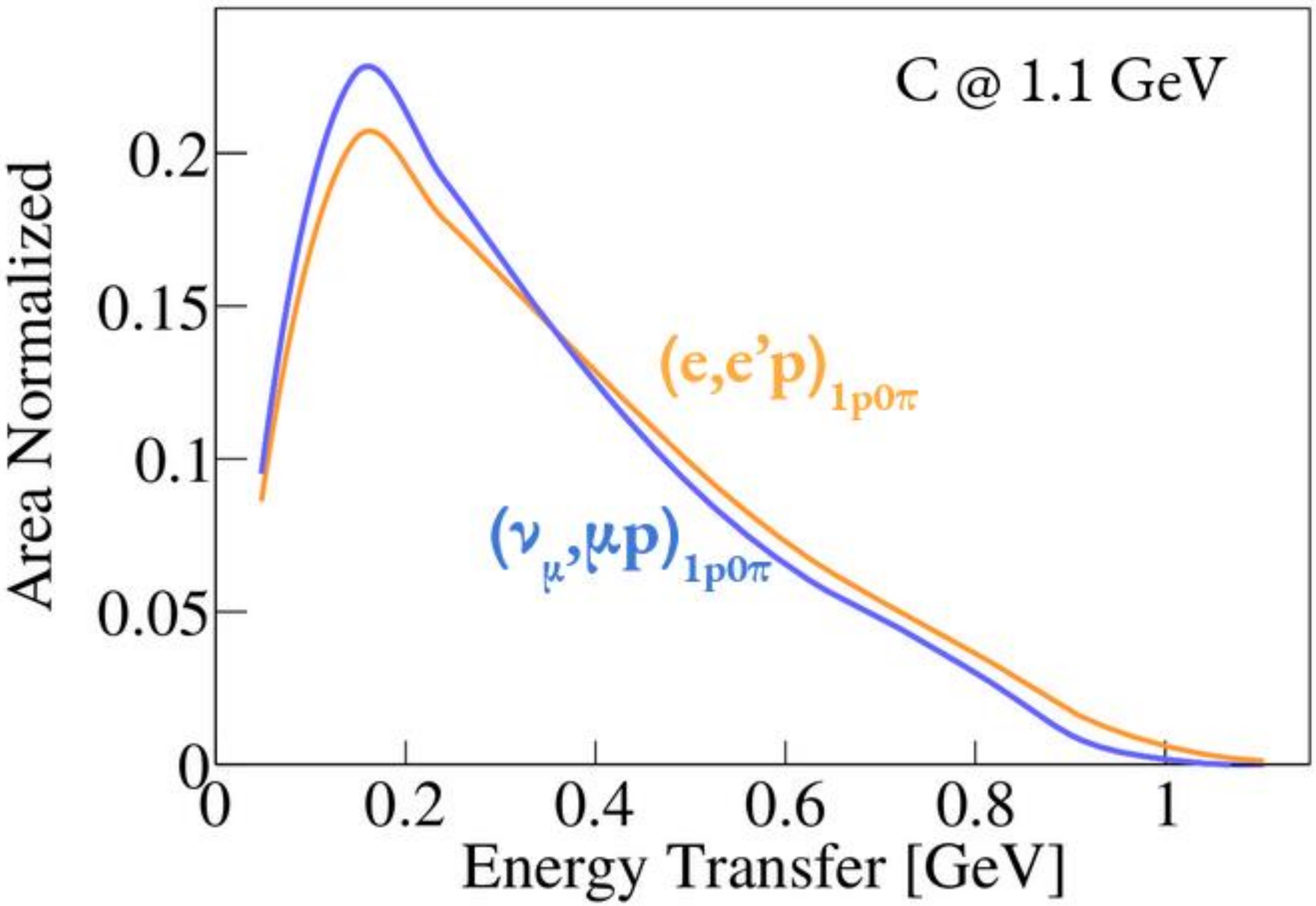
$R_{\sigma_i}(E_{\text{true}}, E_{\text{rec}})$

Adapted from A. Papadopoulou

Phys. Rev. D 91, 072010 (2015)

Adapted from A. Papadopoulou

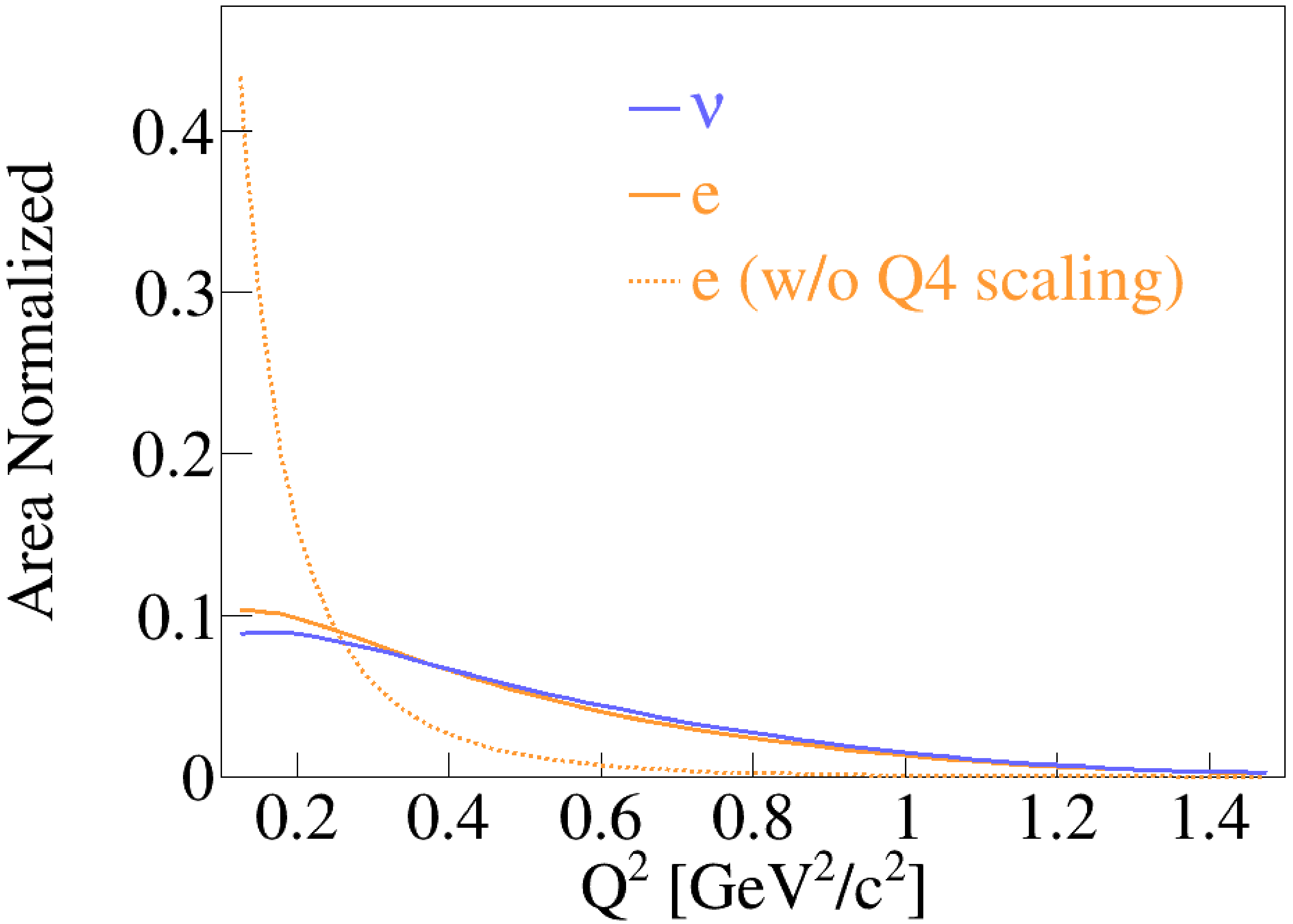
Similarities in Energy Transfers



- Vector part of interaction must be consistent between models
  - **Much effort to make modeling consistent!**
- Can compare by accounting for propagator masses
  - **Scale by Q^4**

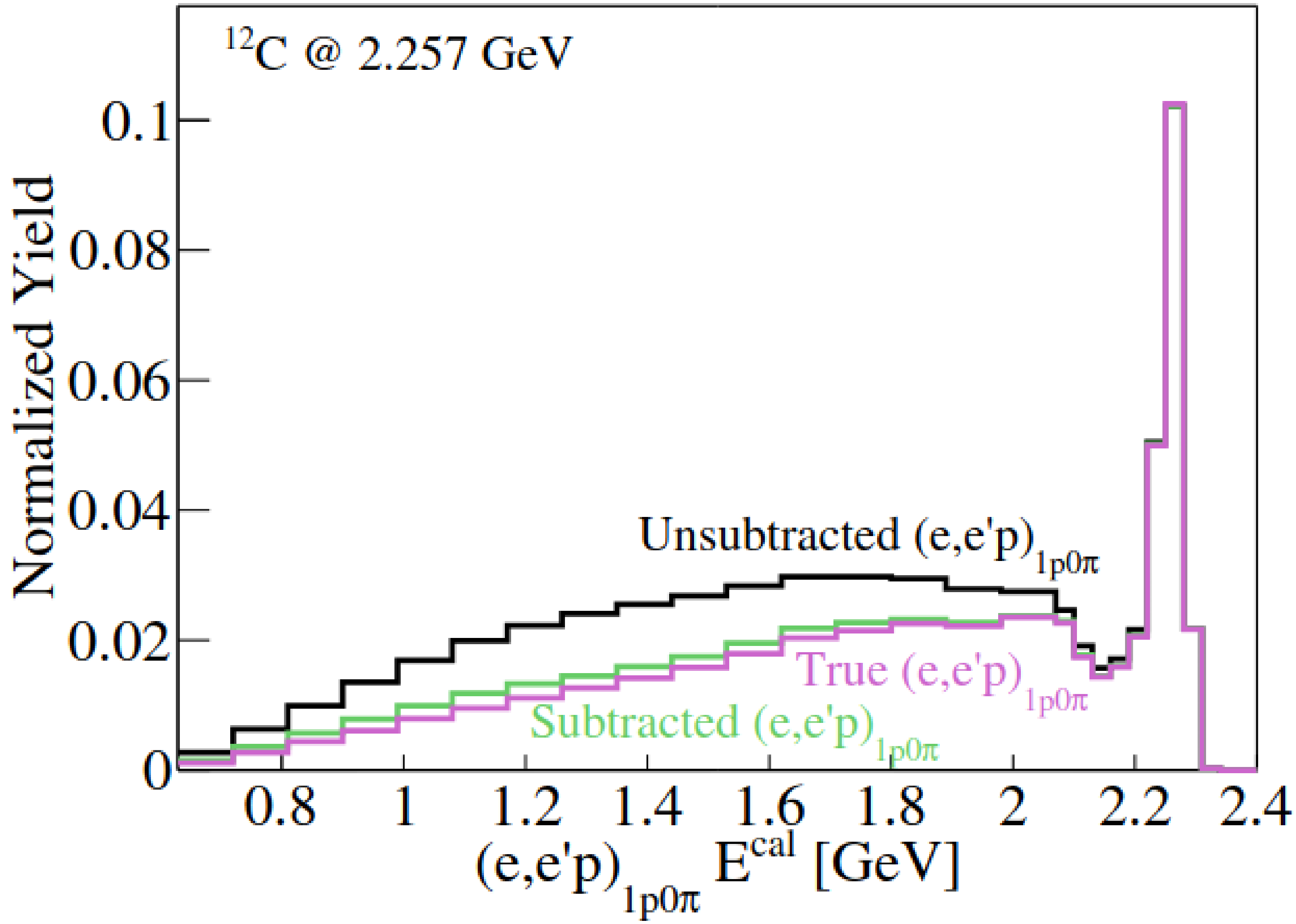
Phys. Rev. D 103, 113003 (2021)

Without Scaling



Data Driven Correction Closure Test

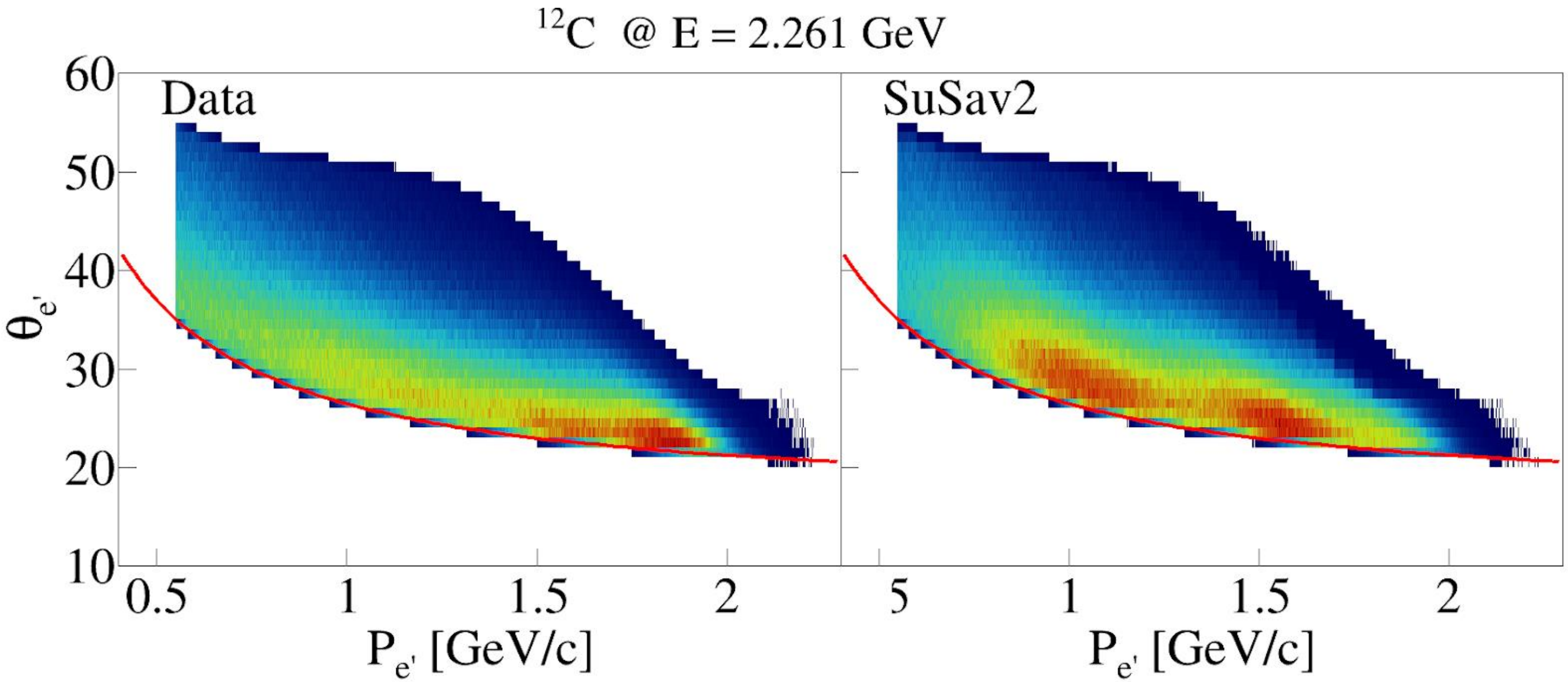
- Use eGENIE files
  - Subtracted & True 1p0π are in good agreement



Well defined signal definition: Min θ_e Cut

@ 1.1 GeV: $\theta = 17 + 7 / P$
@ 2.2 GeV: $\theta = 16 + 10.5 / P$
@ 4.4 GeV: $\theta = 13.5 + 15 / P$
See backup for p / $\pi^{+/-}$ definitions

- We do not acceptance correct below min θ



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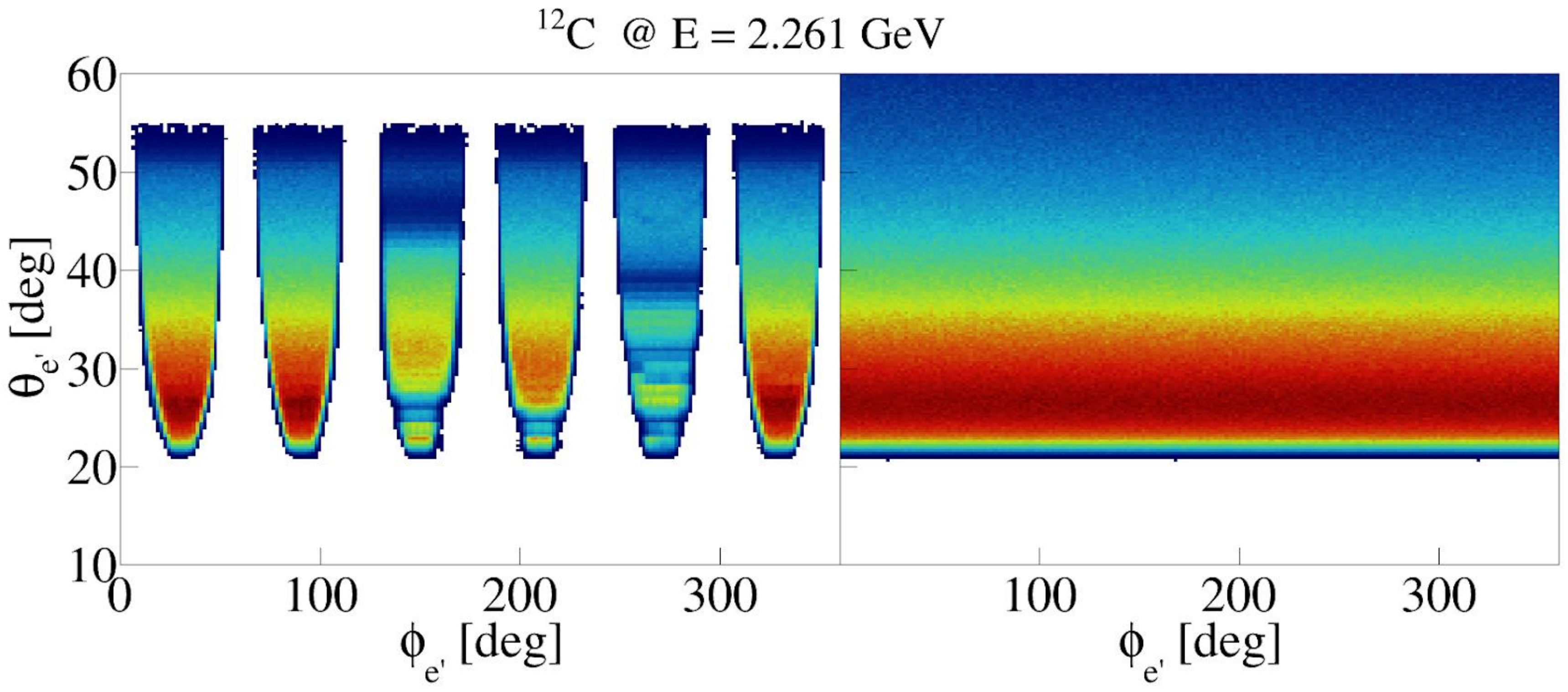
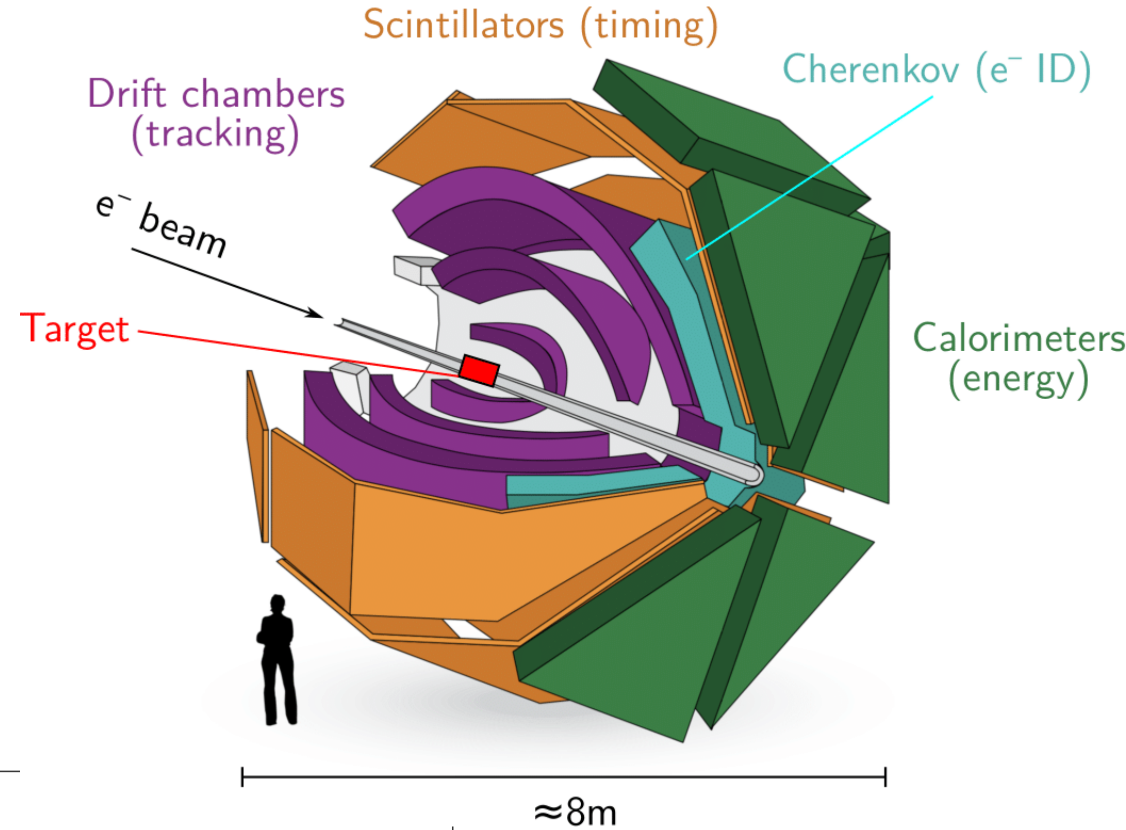
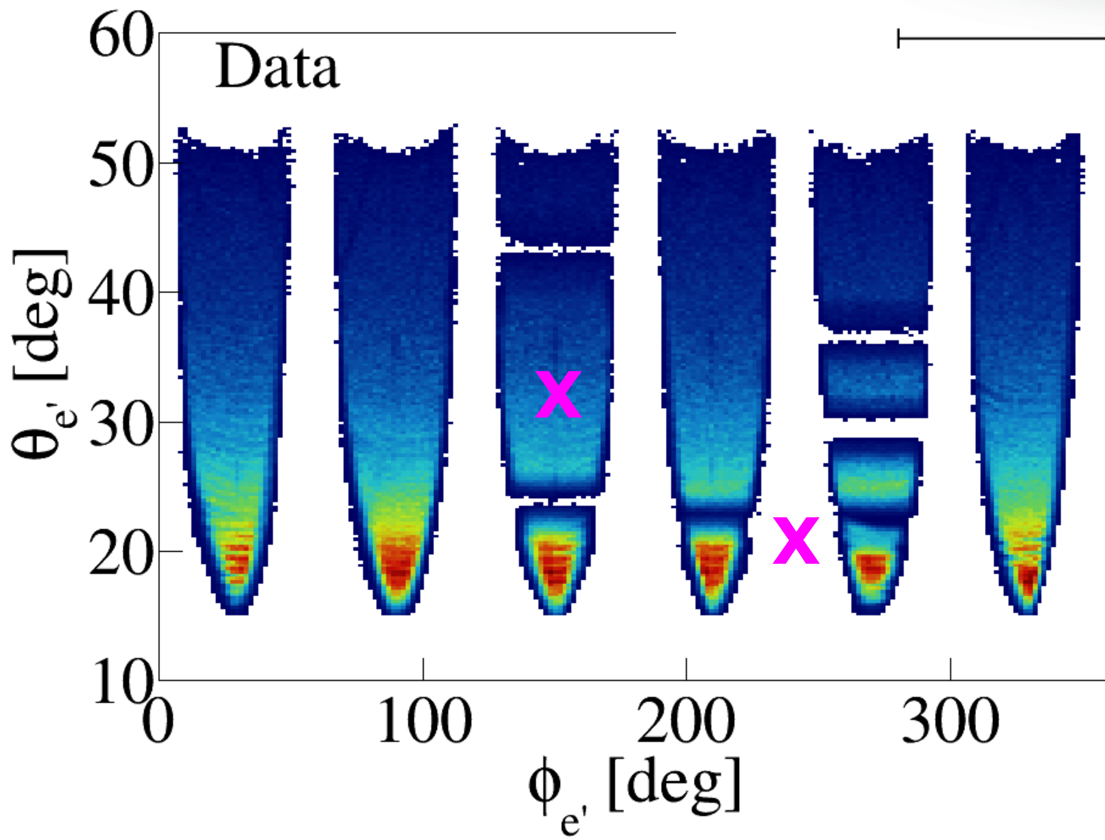


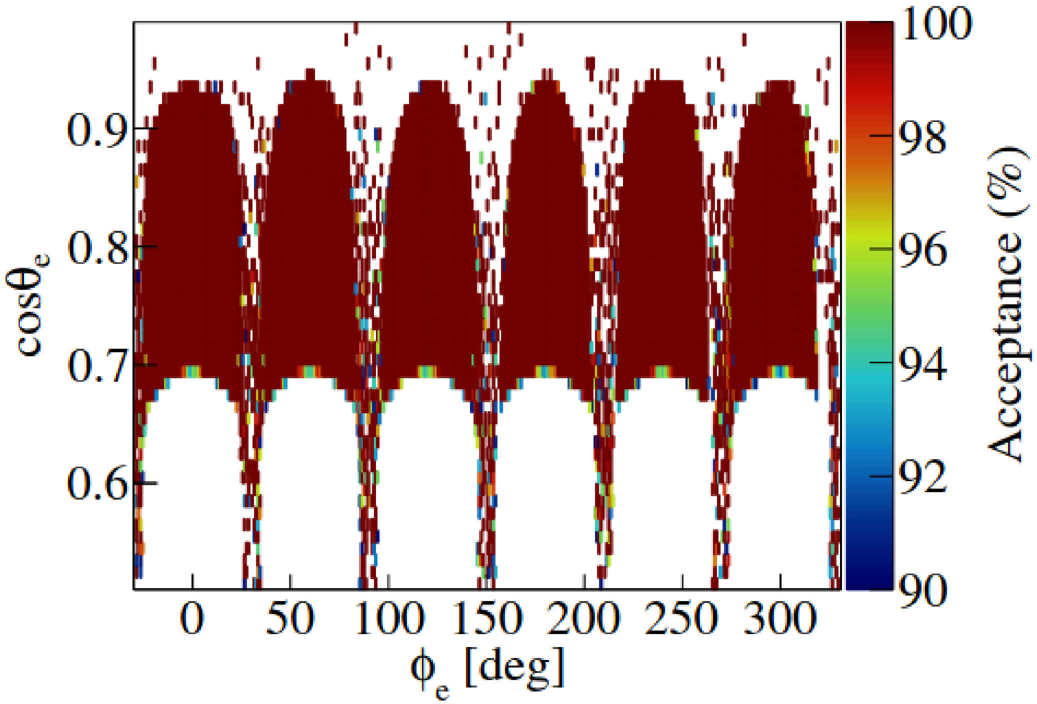
Background Subtraction

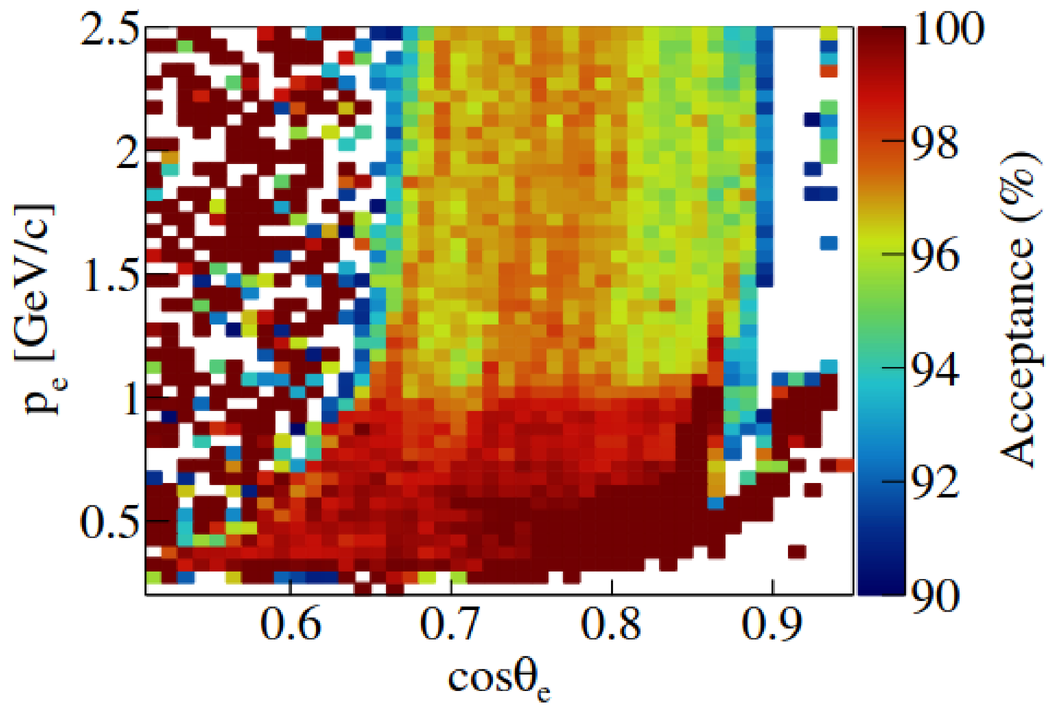
Non-(e,e’p) interactions lead to multi-hadron final states
Gaps can make them look like (e,e’p) events





Acceptance Maps

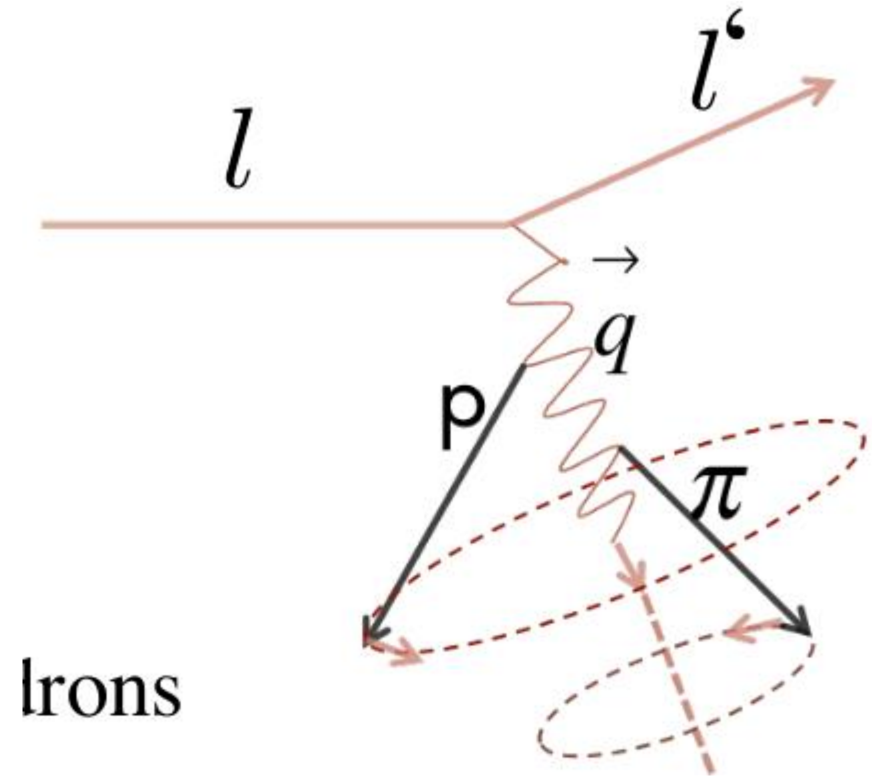




Data Driven Correction

Non-(e,e’p) interactions lead to multi-hadron final states
Gaps make them look like (e,e’p) events

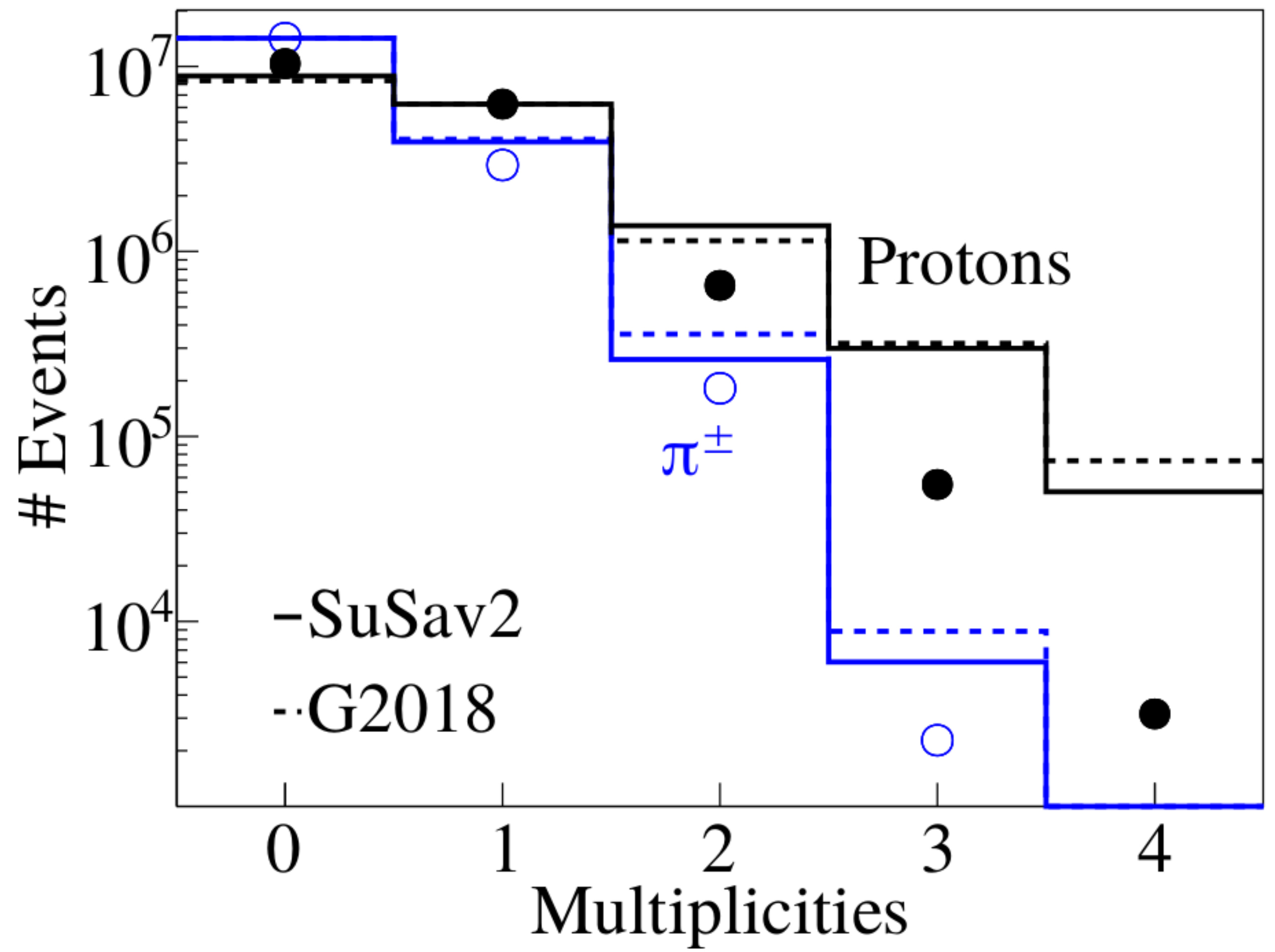
- Use measured (e,e’pπ) events
- Rotate p, π around q to
  determine π detection efficiency
- Subtract undetected (e,e’pπ)
- Repeat for higher hadron multiplicities



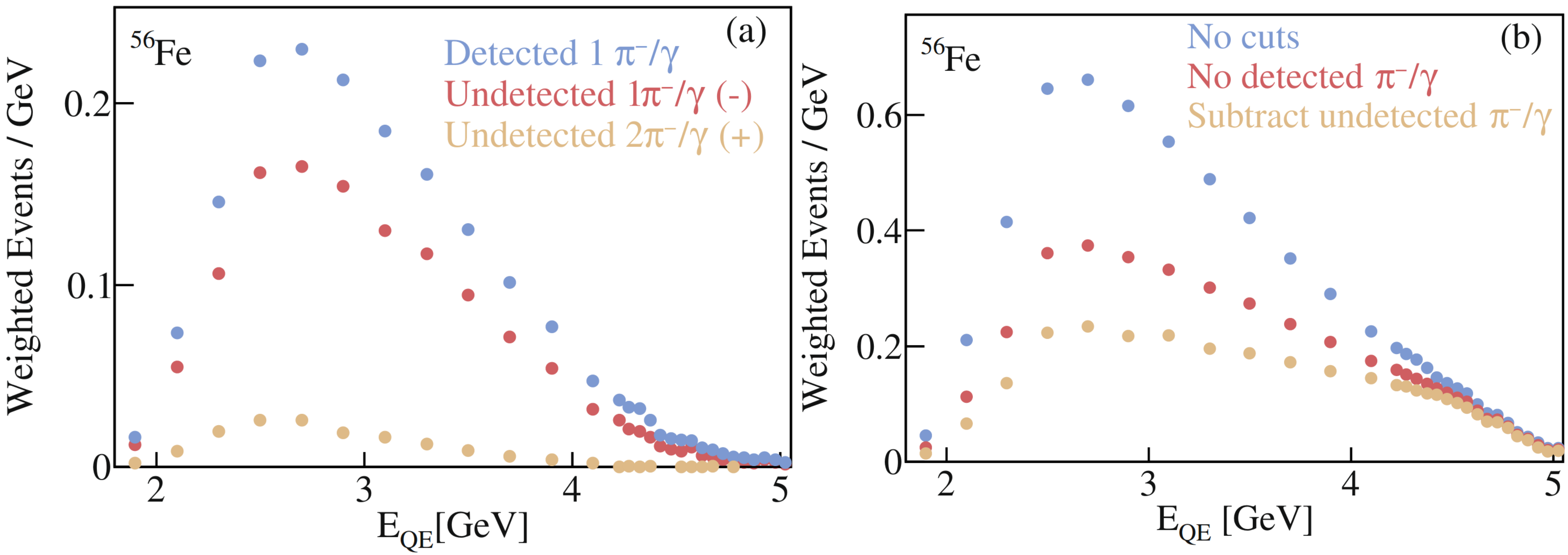
Data Driven Correction

Non-(e,e’p) interactions lead to multi-hadron final states
Gaps can make them look like (e,e’p) events

- Use measured (e,e’pπ) events
- Rotate p, π around q to determine π detection efficiency
- Subtract for undetected (e,e’pπ)
- Repeat for higher hadron multiplicities (2p, 3p, 2p+1π, ...)

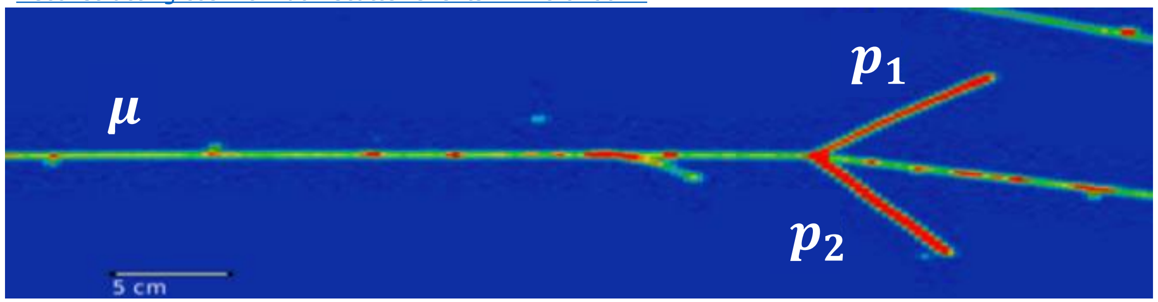


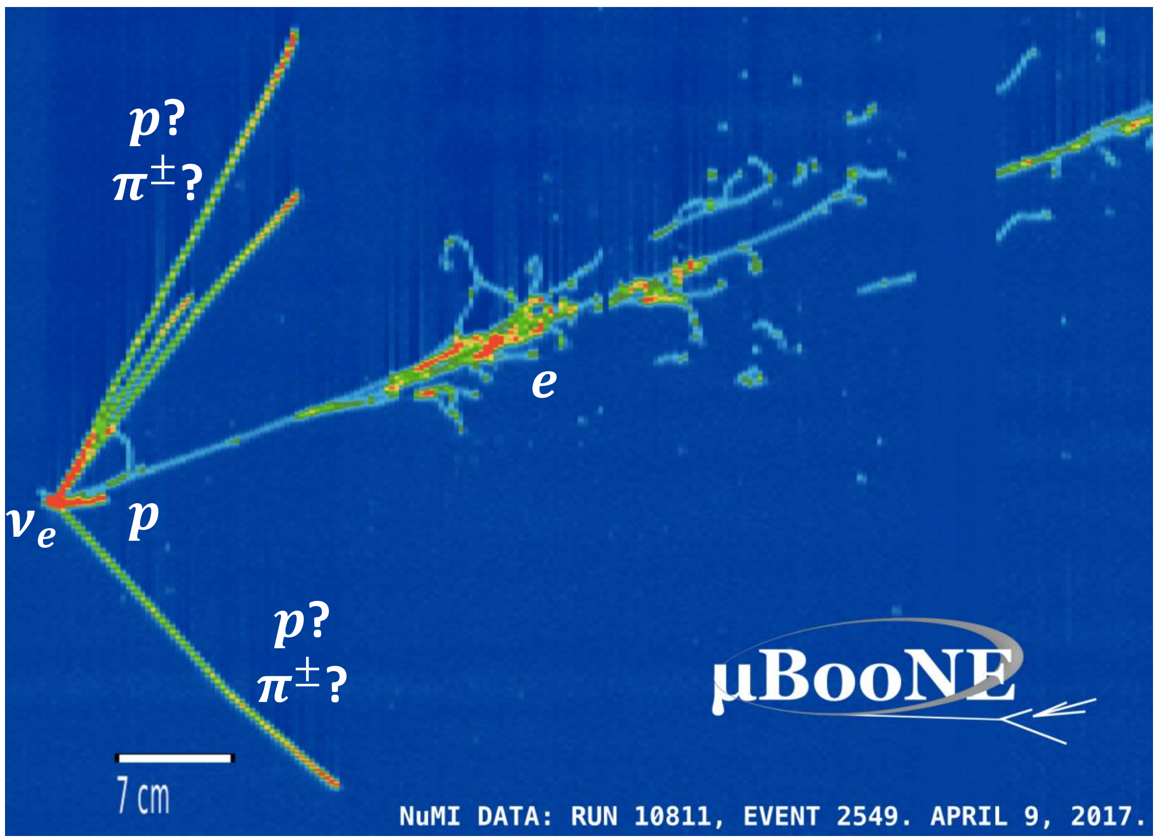
Subtraction Effect

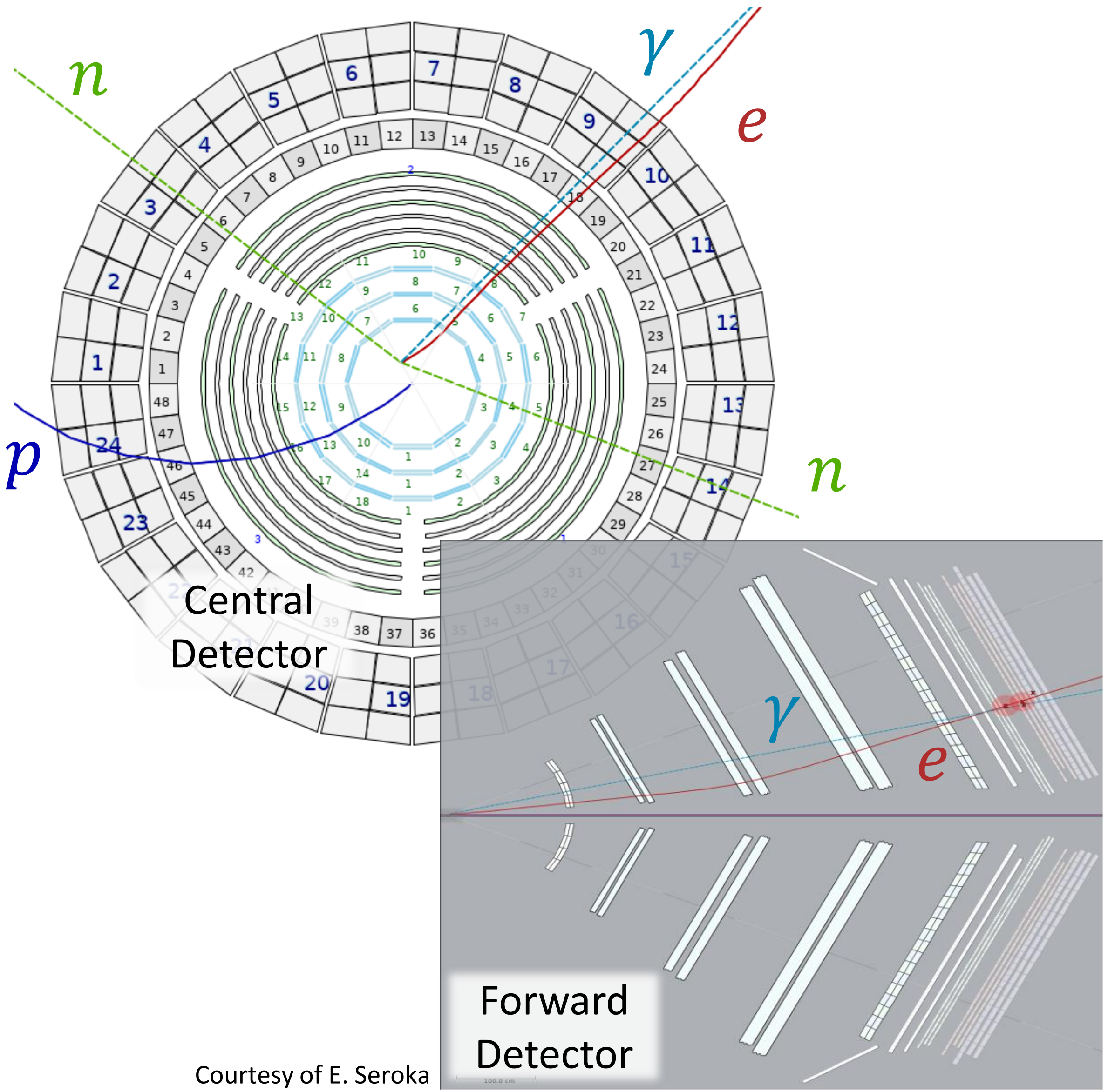


Quality of Detectors

Reconstructing cosmic muon scatter events in MicroBooNE

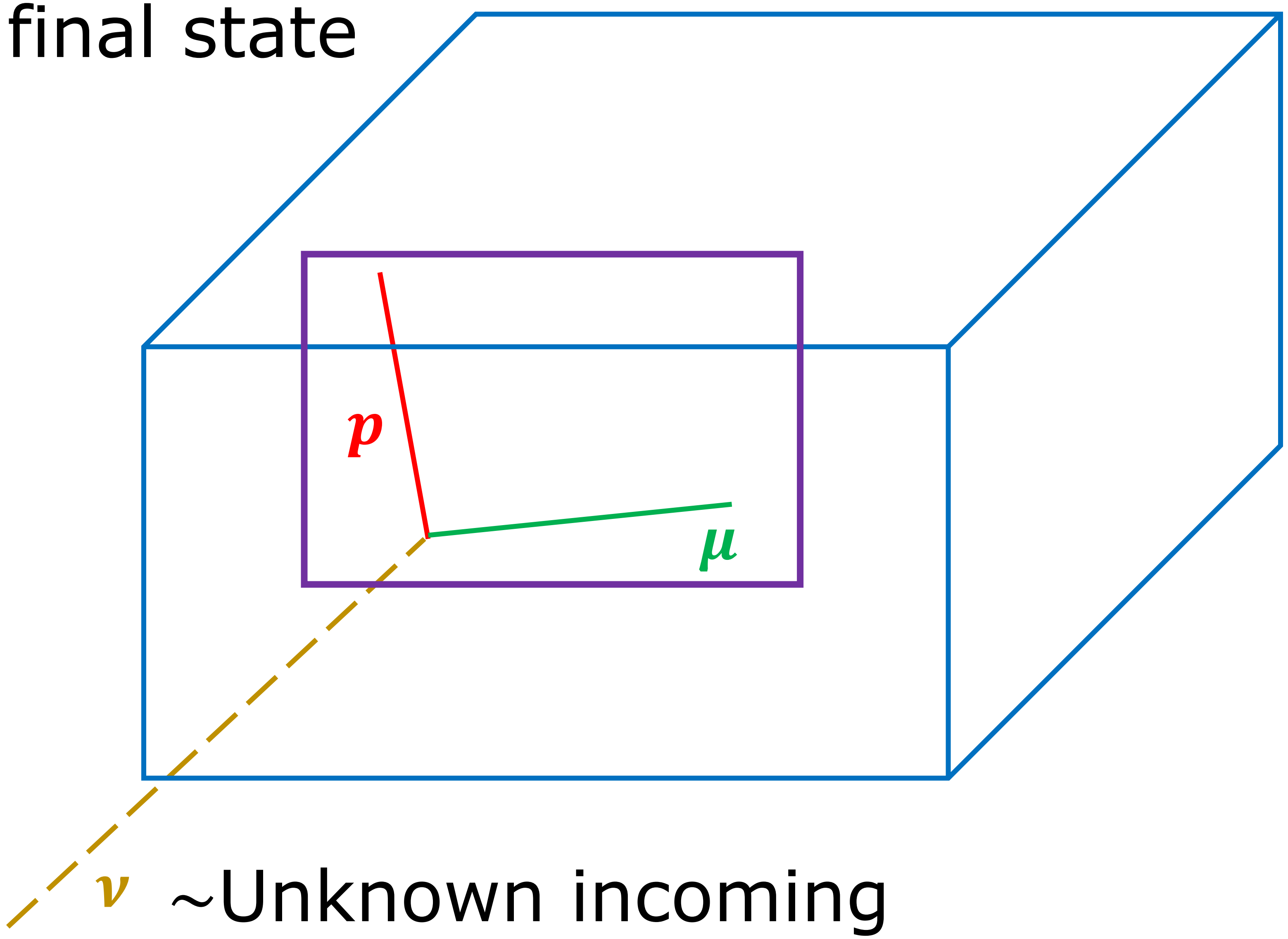






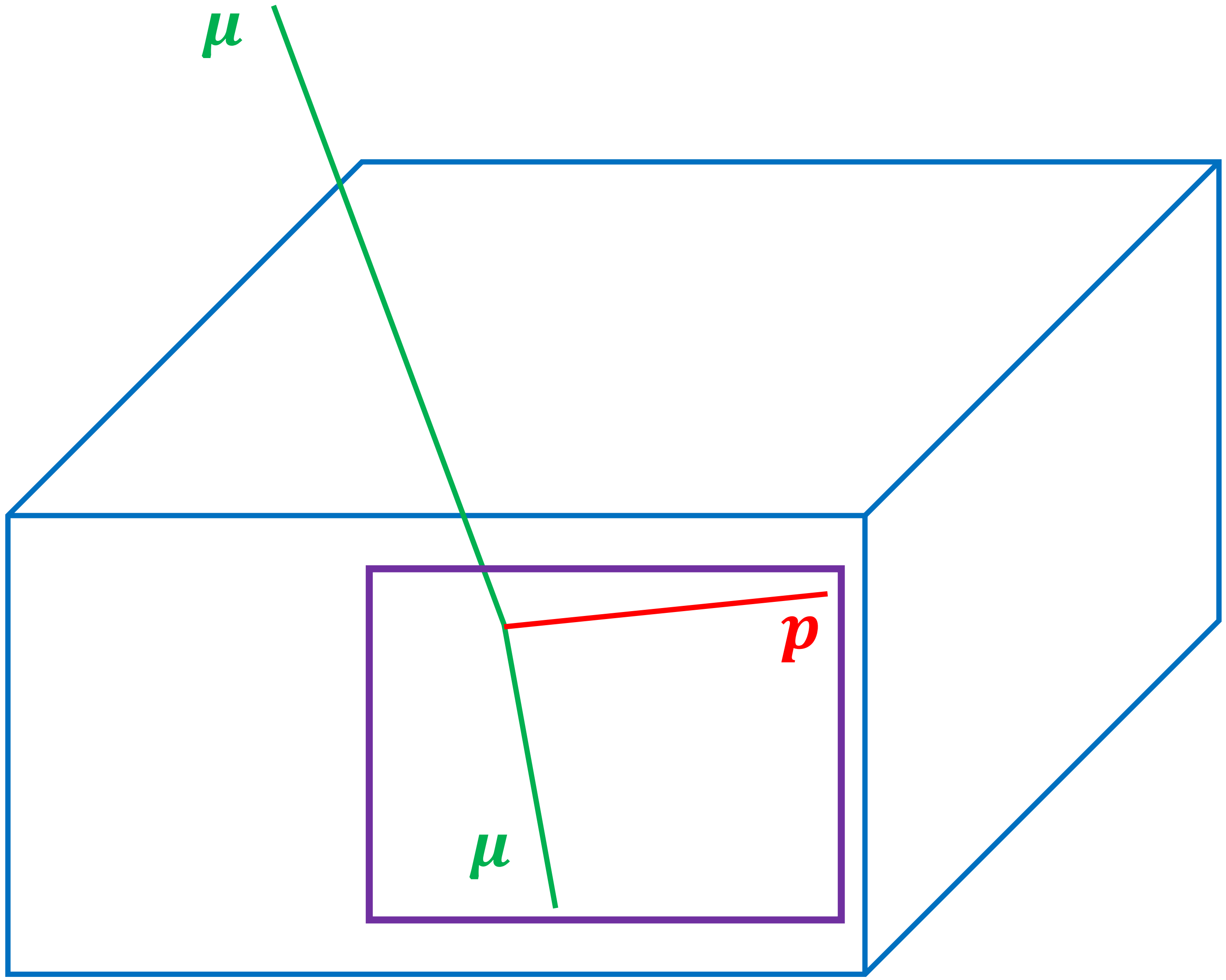
Courtesy of E. Seroka

Definitive initial energy knowledge limited by final state



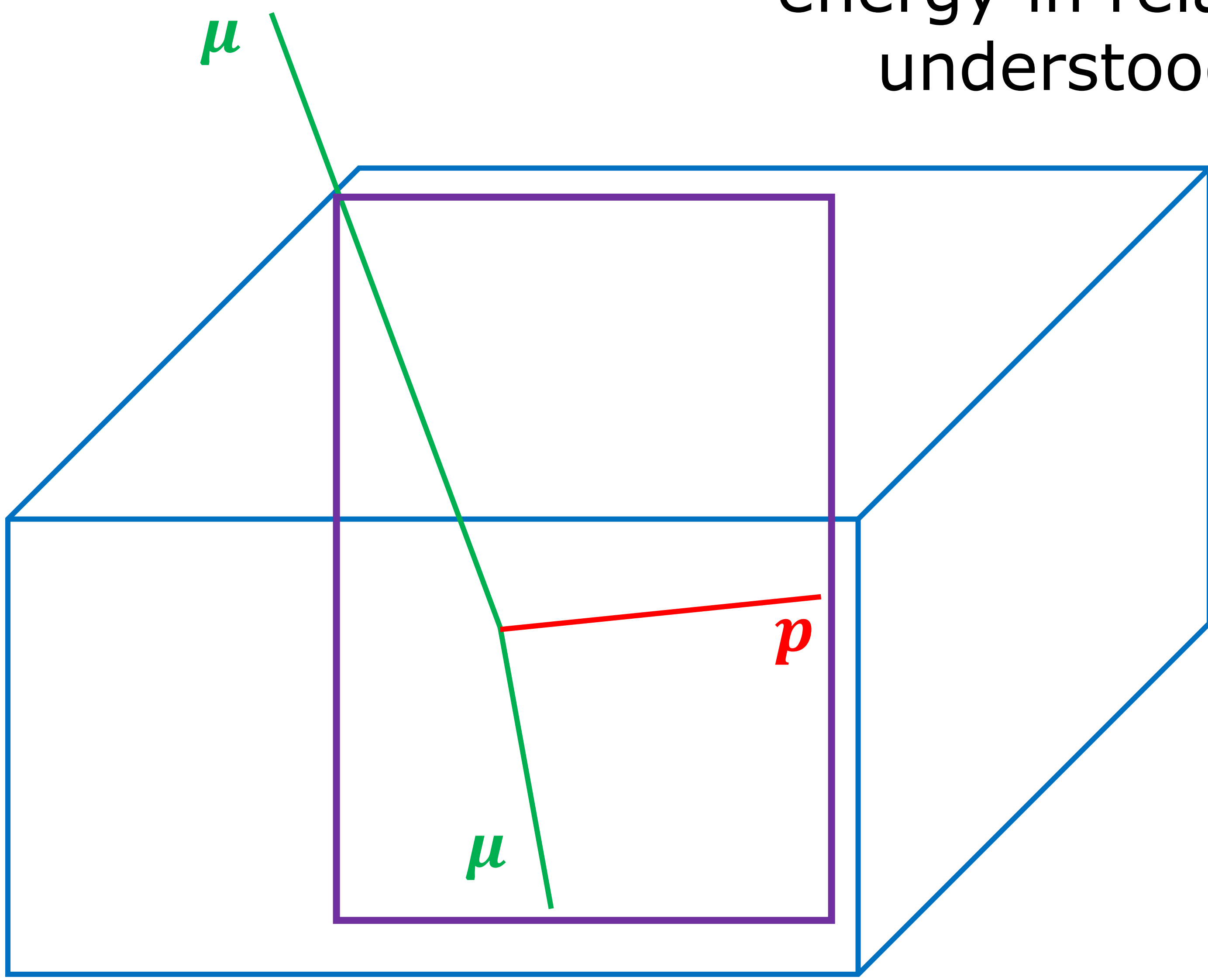
~Unknown incoming neutrino energy

Initial energy knowledge not limited to only "final state" particles



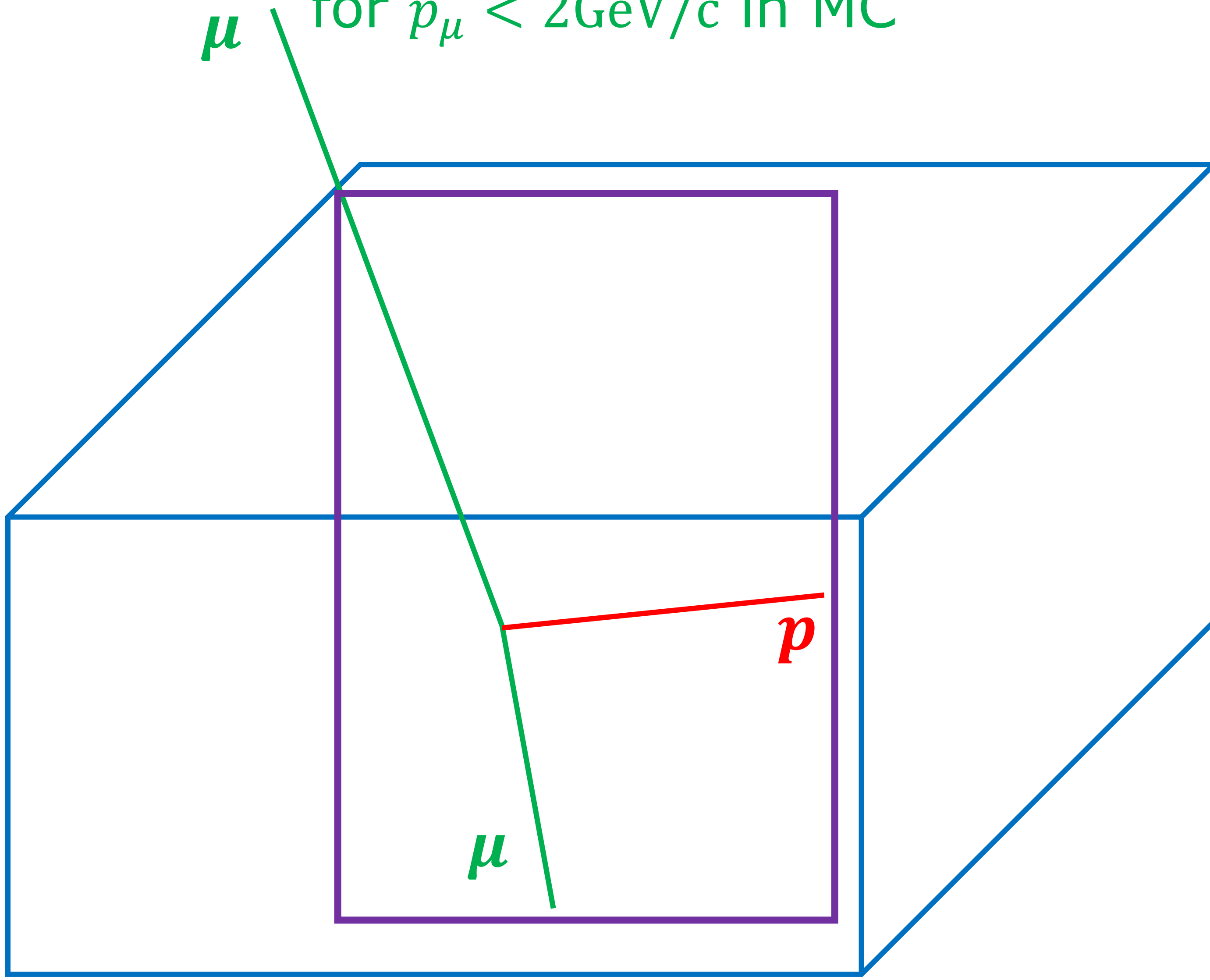
Cosmic muon tracks deposit energy in relatively well understood ways!

Initial energy knowledge not limited to only “final state” particles



MCS momentum resolution is ~11-15% for $p_\mu < 2\mathrm{GeV/c}$ in MC

Initial energy knowledge not limited to only “final state” particles



MCS permits one knowledge of approximate incoming μ energies

MCS improvements

Amir Gruber, TAU UG

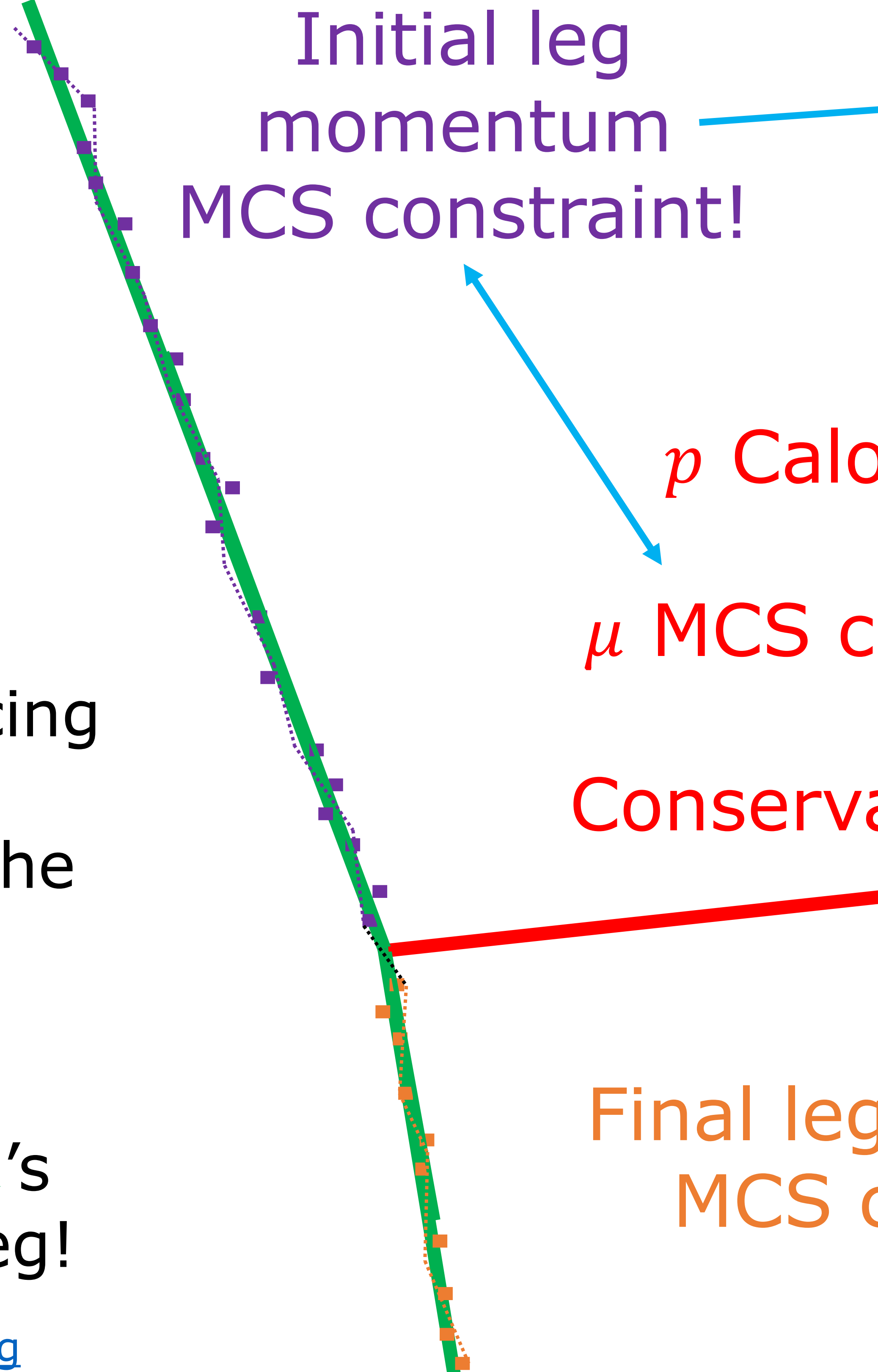
Multiple Coulomb scattering

Cartoon display

MCS relies on elastic-like interactions

Scattering producing small angular deviations over the track

Encodes true energy of the μ's initial and final leg!



Initial leg momentum MCS constraint!

$R_{\sigma_i}(E, E_{rec})$

p Calorimetry

+

μ MCS constraints

+

Conservation Laws

Final leg momentum MCS constraint!

Multiple Coulomb scattering

Many Generators, Many Assumptions

Genie
UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

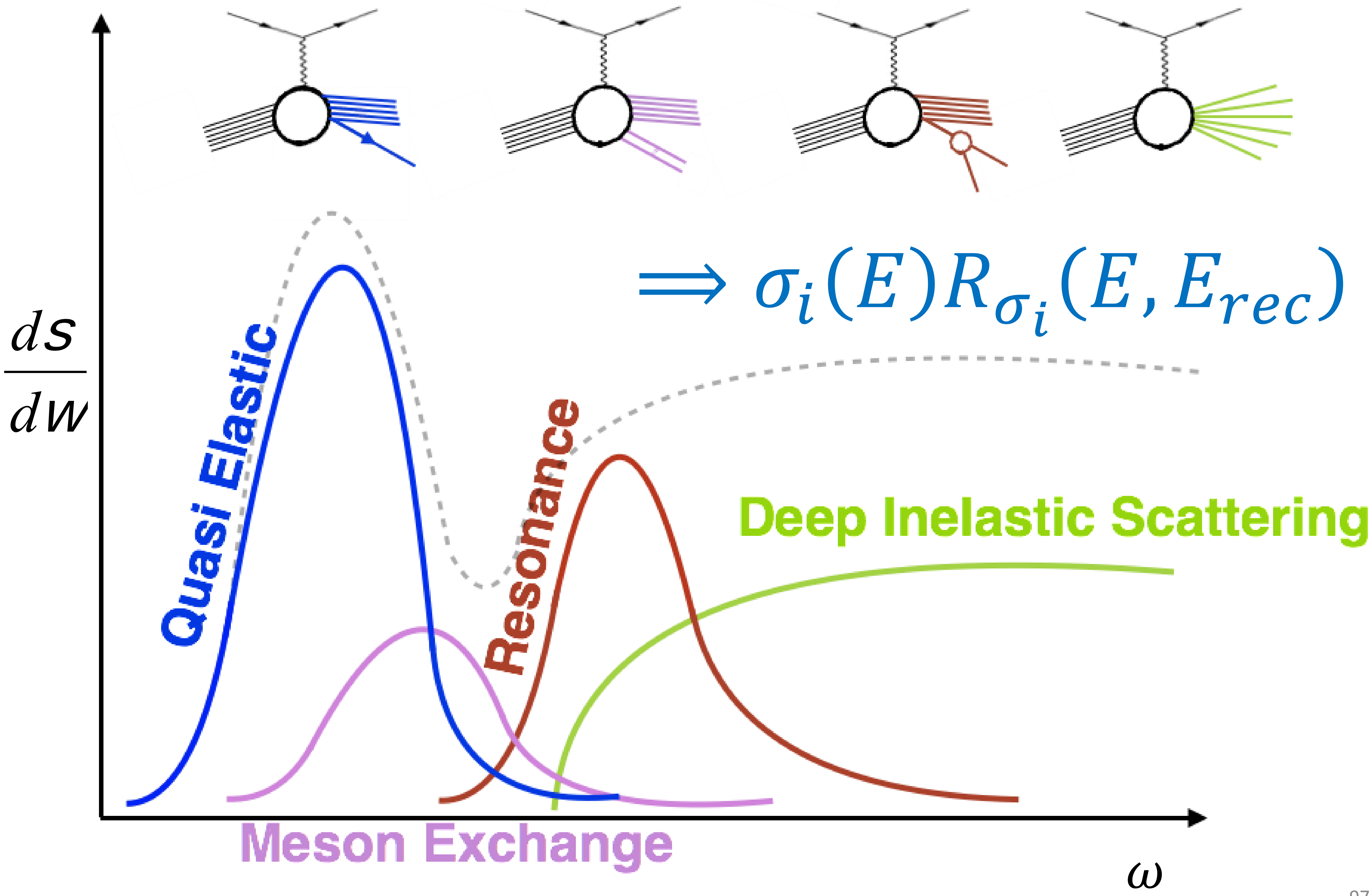
GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

NEUT

NuWro
Wrocław Neutrino Event Generator

Model differences arise from various physics approximations

Assuming different models of Nature ($\sigma_i(E)$) can lead to ill-understanding of $R(E_{true}, E_{rec})$!



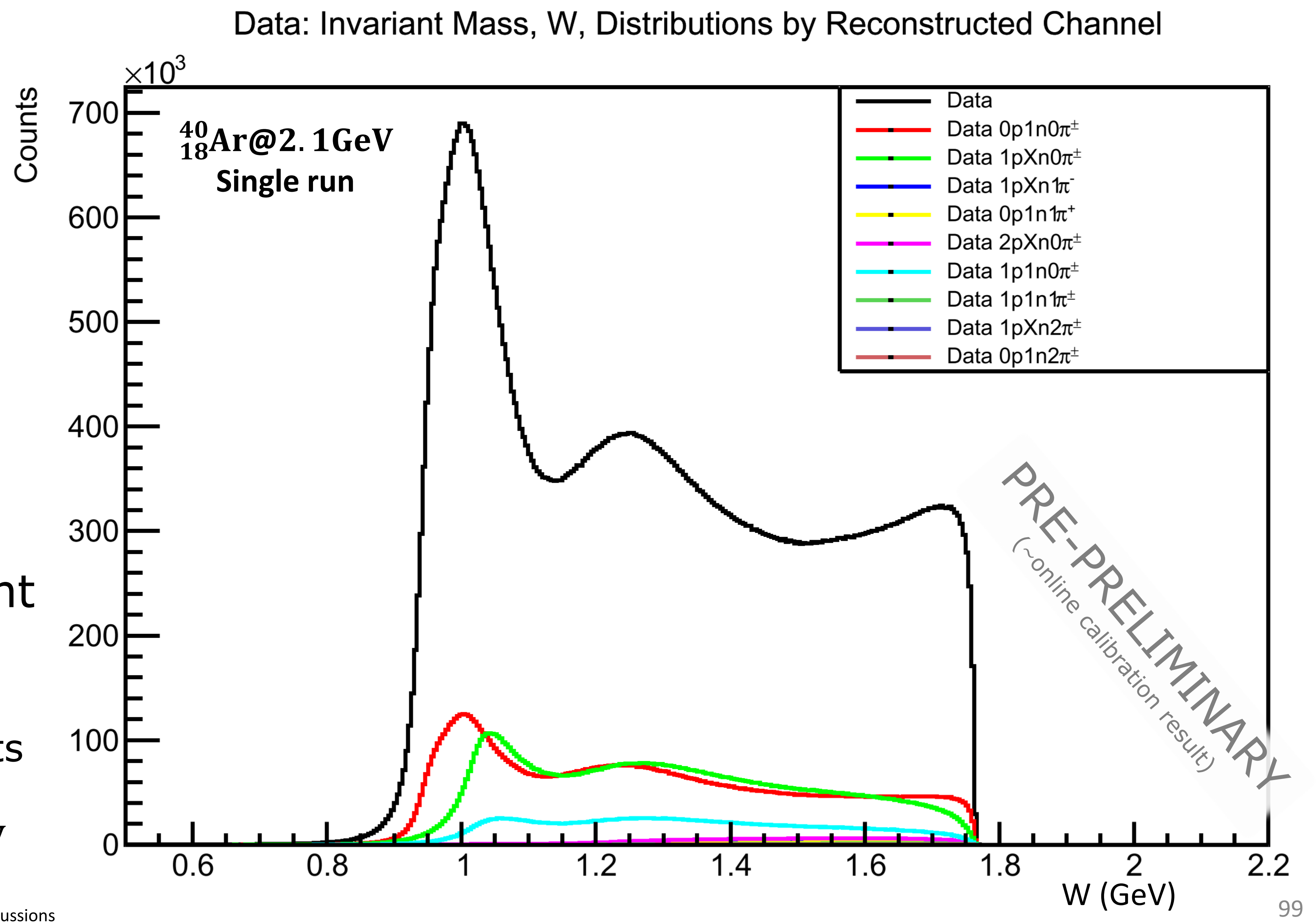
$\frac{ds}{dw}$
$\Longrightarrow \sigma_i(E)R_{\sigma_i}(E, E_{rec})$
Quasi Elastic
Resonance
Deep Inelastic Scattering
Meson Exchange
ω

RGM Data Monitoring: $^{40}\mathrm{Ar}$ Counts Look Promising

Energy (GeV)	Q^2 Threshold	Channels with Expected Counts ($\times 10^6$)				
		$1pXn0\pi^{\pm}$	$2pXn0\pi^{\pm}$	$1pXn1\pi^{-}$	$1pXn2\pi^{\pm}$	$1p1n0\pi^{\pm}$
$\mathbf{2.07}$	$\sim\mathbf{0}$	~ 400	~ 20	~ 7	~ 0.6	~ 100
$\mathbf{4.03}$	$\sim\mathbf{0.3}$	~ 90	~ 20	~ 3	~ 0.6	~ 20
$\mathbf{5.99}$	$\sim\mathbf{0.5}$	~ 20	~ 5	~ 3	~ 2	~ 6

^{40}Ar Counts Look Promising

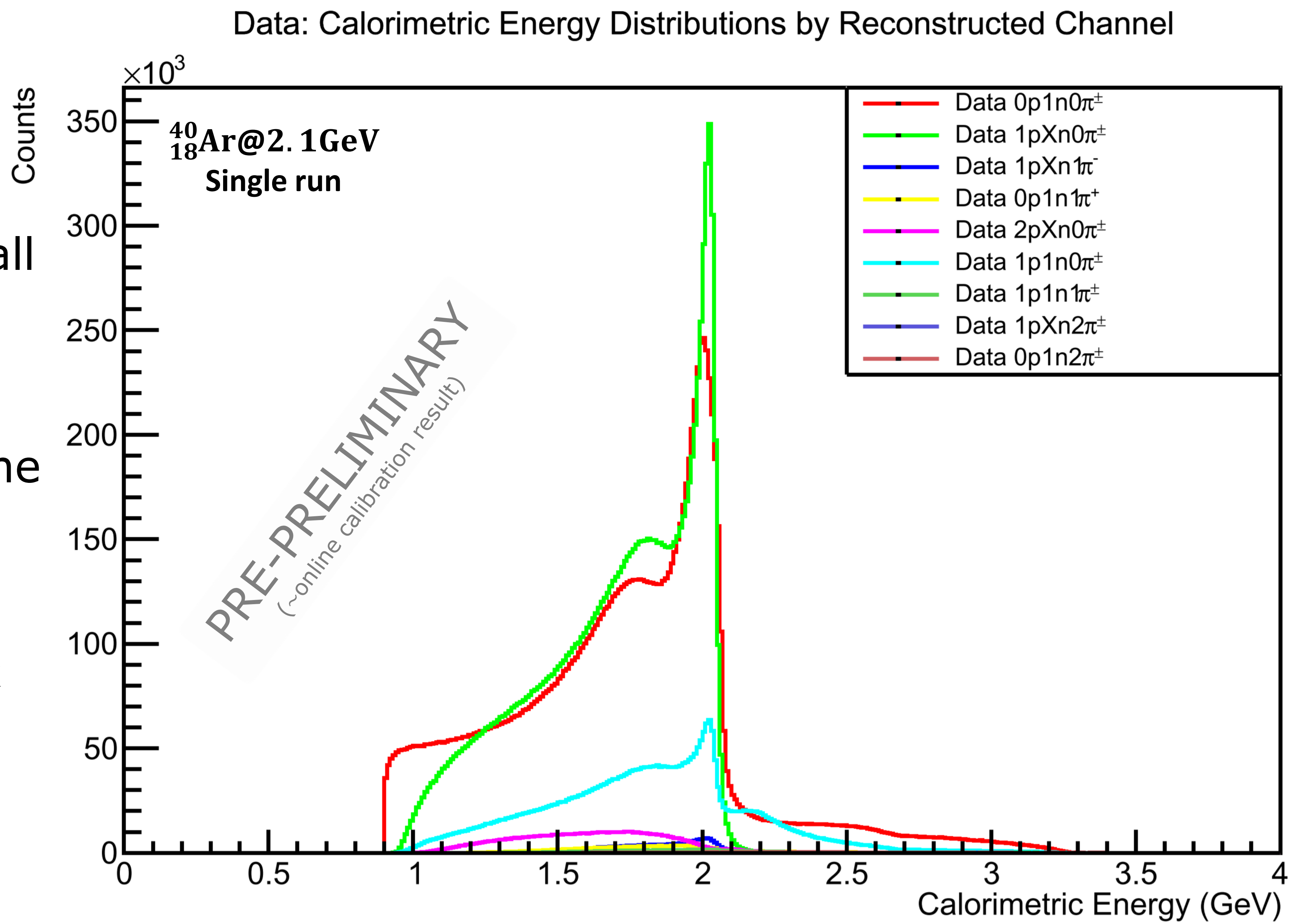
- W approximated off the standing proton
- Shapes are reasonable
- ~ 5 MeV bins
  - Statistics look good!
- Problems w/GENIE prevent comparisons at high ω
  - Radiative effects dominate
  - Cut: $\omega \leq 1.2$ GeV

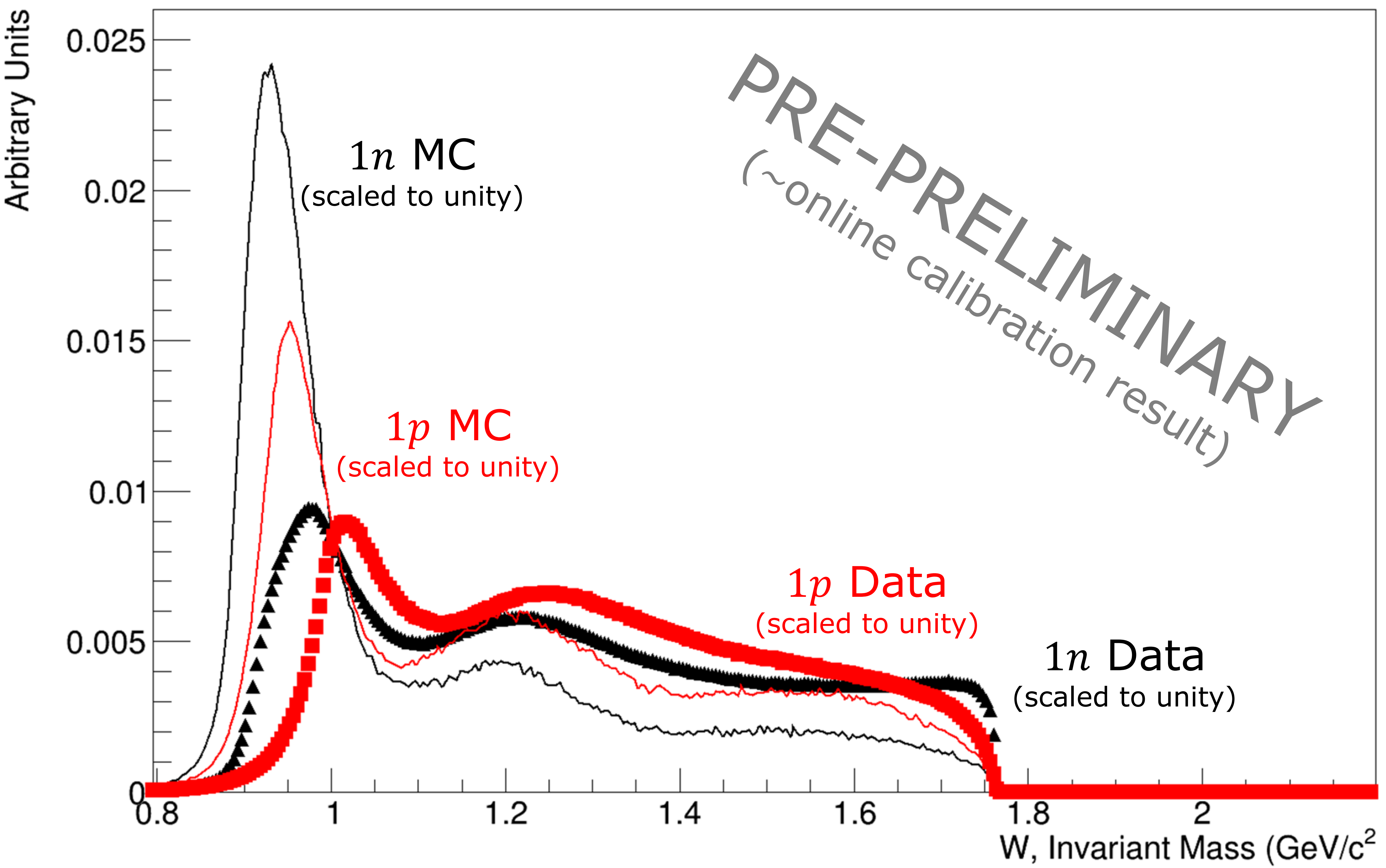


Thanks to L. Weinstein and A. Papadopoulou for discussions

^{40}Ar Counts Look Promising

- $KE_{\mathrm{Tot}} + m_{\pi}$ of all particles
- Shapes are ~good up to the beam energy
- ~ 5 MeV bins
  - Statistics look good!





Arbitrary Units
0.025
0.02
0.015
0.01
0.005
0
0.8
1
1.2
1.4
1.6
1.8
2
W, Invariant Mass (GeV/c^2)
$1n$ MC
(scaled to unity)
$1p$ MC
(scaled to unity)
$1p$ Data
(scaled to unity)
$1n$ Data
(scaled to unity)
PRE-PRELIMINARY
(~online calibration result)

Future $e4\nu$ Analyses

- Inclusive multidifferential cross sections: $\{\mathrm{C}, \mathrm{Ar}, \mathrm{Ca}\}$
  - Access to many angles, many energies, low Q^2
  - Create a new world-level data sets
- Inclusive/Exclusive multidifferential cross sections
- $(\boldsymbol{e}, \boldsymbol{e}')$, $(\boldsymbol{e}, \boldsymbol{e}'\boldsymbol{p})$, $(\boldsymbol{e}, \boldsymbol{e}'\boldsymbol{\pi}^{\pm})$, $(e, e'p\pi^{-})$, $(e, e'pp)$, $(e, e'n)$, $(e, e'pn)$…
  - “Traditional” kinematic variable for first GENIE tunings
  - Transverse kinematic variables (FSIs, nuclear models)
- Transparency studies (FSIs)
- Ca/Ar ratios?
  - Differences, similarities? Useful for ν experiments?
- Spectral functions? Nuclear models?


Alon Sportes


Matan Goldenberg

$e4\nu$@CLAS Summary

- $e4\nu$ is of paramount importance for a successful future ν physics program
  - Proper reconstruction requires excellent nuclear physics modeling
  - Learn from electron scattering!

- CLAS12 and RGM shows great promise in continuing to close these gaps
  - $\{{}^{12}_{6}\mathrm{C}, {}^{40}_{18}\mathrm{Ar}, {}^{40}_{20}\mathrm{Ca}\}$ data galore!
  - Excellent data set for bettering model comparisons!

- CLAS6 data mining analyses continuing!

Today’s Visualizations

Data Words and Format

- TP generation has been implemented on FPGAs for real-time online streaming to trigger implementations
  - However, this hasn't yet worked for MicroBooNE…


```
FFFFFFFF F1E3FFFF F6A8F001 F007F000 F006F000 F000F000 F000F000 117F4792
C000C000 C000C000 C000C000 1180418A C010C1A8 C008C154 C006C822 F1E3FFFF
F6A8F001 F007F000 F006F000 F000F000 F000F000 118041A2 C010CE77 C007CEBE
C005C7F3 1180458A C010C1A8 C008C154 C006C822 F1E3FFFF F6A8F001 F007F000
F006F000 F000F000 F000F000 118045A2 C010CE77 C007CEBE C005C7F3 1180498A
C010C1A8 C008C154 C006C822 F1E3FFFF F6A8F001 F007F000 F006F000 F000F000
F000F000 118049A2 C010CE77 C007CEBE C005C7F3 F1E3FFFF F6A8F001 F007F000
F006F000 F000F000 F000F000 11814193 C016CB5A C002C7B8 C001C201 F1E3FFFF
F6A8F001 F007F000 F006F000 F000F000 F000F000 11814593 C016CB5A C002C7B8
C001C201 F1E3FFFF F6A8F001 F007F000 F006F000 F000F000 F000F000 11814993
```


Courtesy of D. Kalra

Data Words and Format

Beginning of frame	FEM and ADC information for instance ID, number of words						Channel ID
FFFFFFFF	F1E3FFFF	F6A8F001	F007F000	F006F000	F000F000	F000F000	117F4792
C000C000	C000C000	C000C000	1180418A	C010C1A8	C008C154	C006C822	F1E3FFFF
F6A8F001	F007F000	F006F000	F000F000	F000F000	118041A2	C010CE77	C007CEBE
C005C7F3	1180458A	C010C1A8	C008C154	C006C822	F1E3FFFF	F6A8F001	F007F000
F006F000	F000F000	F000F000	118045A2	C010CE77	C007CEBE	C005C7F3	1180498A
C010C1A8	C008C154	C006C822	F1E3FFFF	F6A8F001	F007F000	F006F000	F000F000
F000F000	118049A2	C010CE77	C007CEBE	C005C7F3	F1E3FFFF	F6A8F001	F007F000
F006F000	F000F000	F000F000	11814193	C016CB5A	C002C7B8	C001C201	F1E3FFFF
F6A8F001	F007F000	F006F000	F000F000	F000F000	11814593	C016CB5A	C002C7B8
C001C201	F1E3FFFF	F6A8F001	F007F000	F006F000	F000F000	F000F000	11814993

Courtesy of D. Kalra

Data Words and Format

TP data words:
Integral, amplitude, and time over threshold

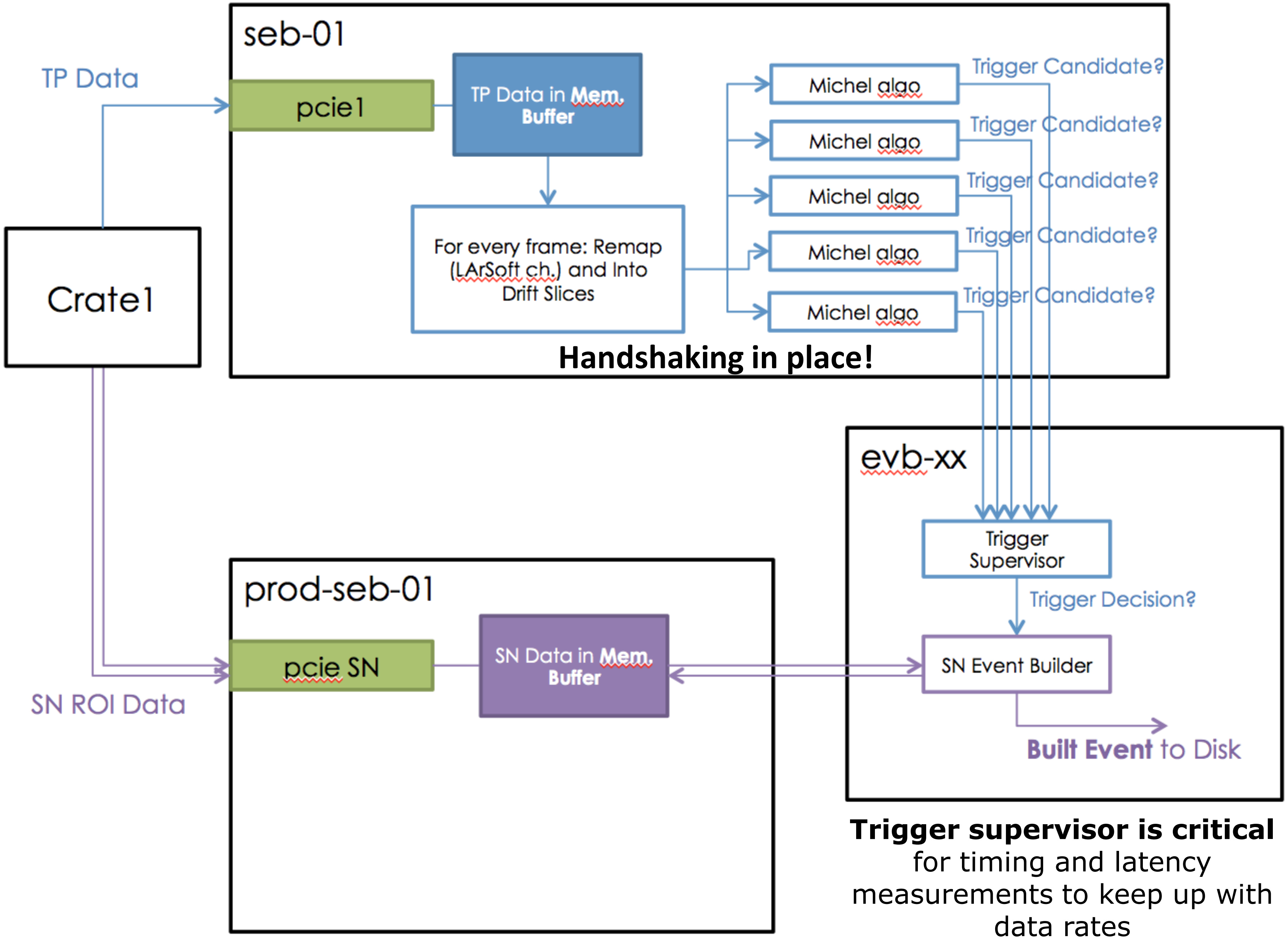
FFFFFFFF	F1E3FFFF	F6A8F001	F007F000	F006F000	F000F000	F000F000	117F4792
C000C000	C000C000	C000C000	1180418A	C010C1A8	C008C154	C006C822	F1E3FFFF
F6A8F001	F007F000	F006F000	F000F000	F000F000	118041A2	C010CE77	C007CEBE
C005C7F3	1180458A	C010C1A8	C008C154	C006C822	F1E3FFFF	F6A8F001	F007F000
F006F000	F000F000	F000F000	118045A2	C010CE77	C007CEBE	C005C7F3	1180498A
C010C1A8	C008C154	C006C822	F1E3FFFF	F6A8F001	F007F000	F006F000	F000F000
F000F000	118049A2	C010CE77	C007CEBE	C005C7F3	F1E3FFFF	F6A8F001	F007F000
F006F000	F000F000	F000F000	11814193	C016CB5A	C002C7B8	C001C201	F1E3FFFF
F6A8F001	F007F000	F006F000	F000F000	F000F000	11814593	C016CB5A	C002C7B8
C001C201	F1E3FFFF	F6A8F001	F007F000	F006F000	F000F000	F000F000	11814993

Courtesy of D. Kalra

Data Acquisition

Modifications to the DAQ for this study

Plans for ~Online Triggering



Trigger supervisor is critical for timing and latency measurements to keep up with data rates

- TP alongside SN streams
- Run on three "new" SEBs
- Collect inputs from many parallel algorithms
- Trigger supervisor sends decision to global DAQ
- Builds event

Courtesy of G. Karagiorgi and the Columbia group; thanks to M. Bhattacharya and W. Ketchum for their trigger supervisor and communications developments

Offline Data Replay

- Online streaming of TPs could not be completed
  - Despite success on MicroBooNE and SBND test stands
- Backup plan in motion…
  - Taken data for *offline replay*
  1. Run over data **without DAQ communications simulation**
     - Assess trigger performances and signal efficiencies
  2. Run over data **<u>with</u> DAQ communications simulation**
     - Assess data throughput, time-dependent trigger decisions in "real-time"

Courtesy of D. Kalra; thanks to M. Kirby and H. Greenlee for their data management expertise and help

Data Taking

Run #	*ADC Value	Huffman Compression
28552, 28554, 28555 (~180")	NOMINAL	OFF
28542 (~150")	10	OFF
28548, 28549, 28564 (~180")	15	OFF
28550, 28551, 28557 (~180")	20	OFF

* Channel thresholds on ~all channels

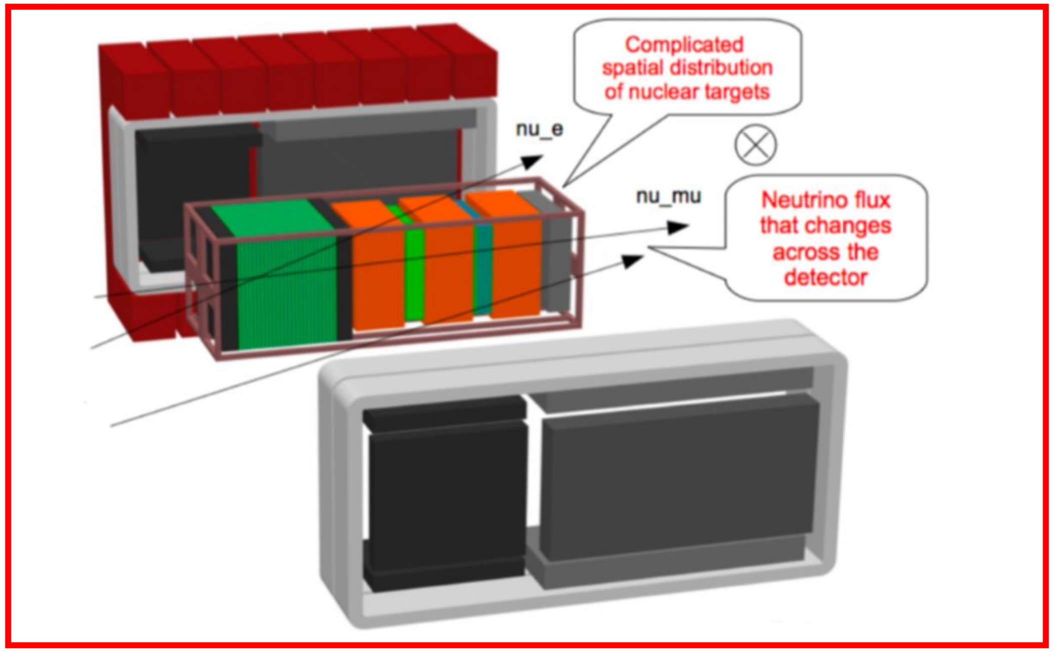
$\mu 4 \nu$@MicroBooNE Summary

- Designed trigger interpreting TP data
  - **QE-like proton**(s) events ($\mu + \mathrm{Ar} \rightarrow \mu + \mathrm{N}p + X$)
  - Uses position and ADC information from TPs
  - Many topological possibilities!

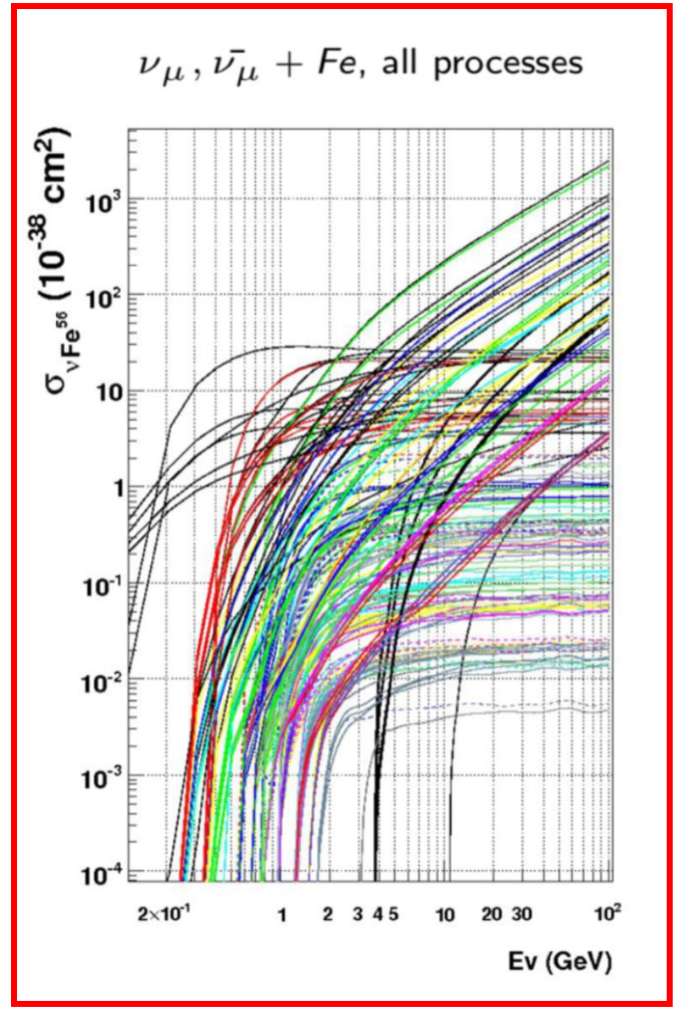
- ~ 12 hours of SN data taken for offline replay
  - Will test trigger efficiencies (run over ~whole data set)
  - Will test data throughput capacity to triggers: “real time”

How do we reconstruct ν interactions?

Propagation of spatially non-uniform, broadband neutrino fluxes through complicated detector geometries (and surrounding dirt, etc.)

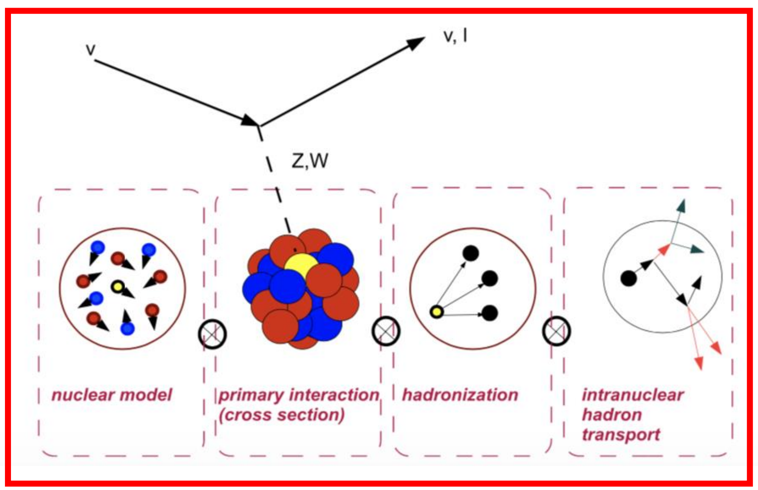


Calculation of total and differential cross sections for all relevant reaction modes, target nuclei, and neutrino energies



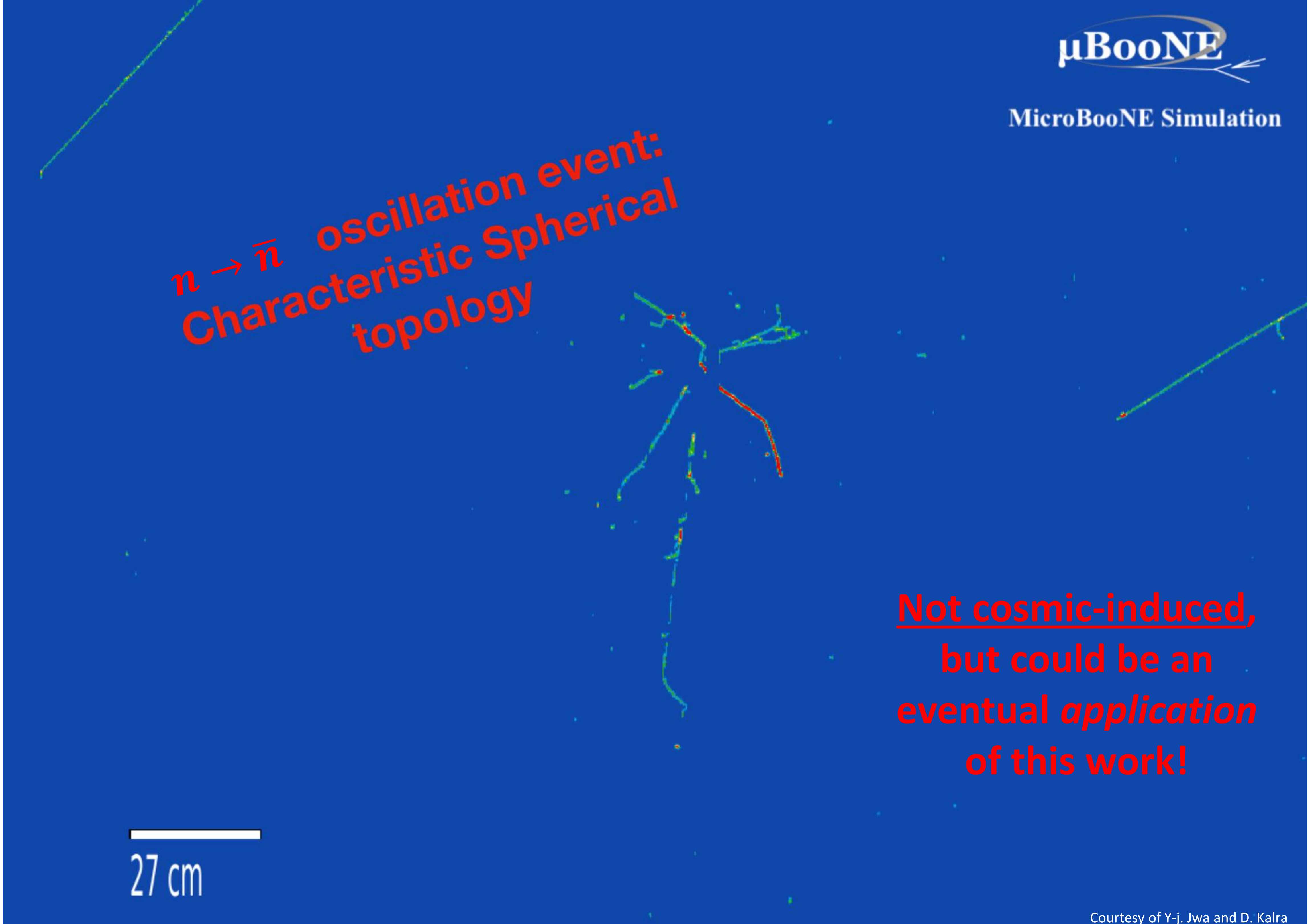
Images by C. Andreopoulos

Account for hadronization, FSI, etc. and pass a vertex position and a full set of 4-momenta for all outgoing particles to the detector simulation



Provide a means of assessing interaction uncertainties that can be propagated into an analysis

Adapted from S. Gardiner


μBooNE
MicroBooNE Simulation
$n \to \bar{n}$ oscillation event:
Characteristic Spherical
topology
Not cosmic-induced,
but could be an
eventual *application*
of this work!
27 cm
Courtesy of Y-j. Jwa and D. Kalra