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

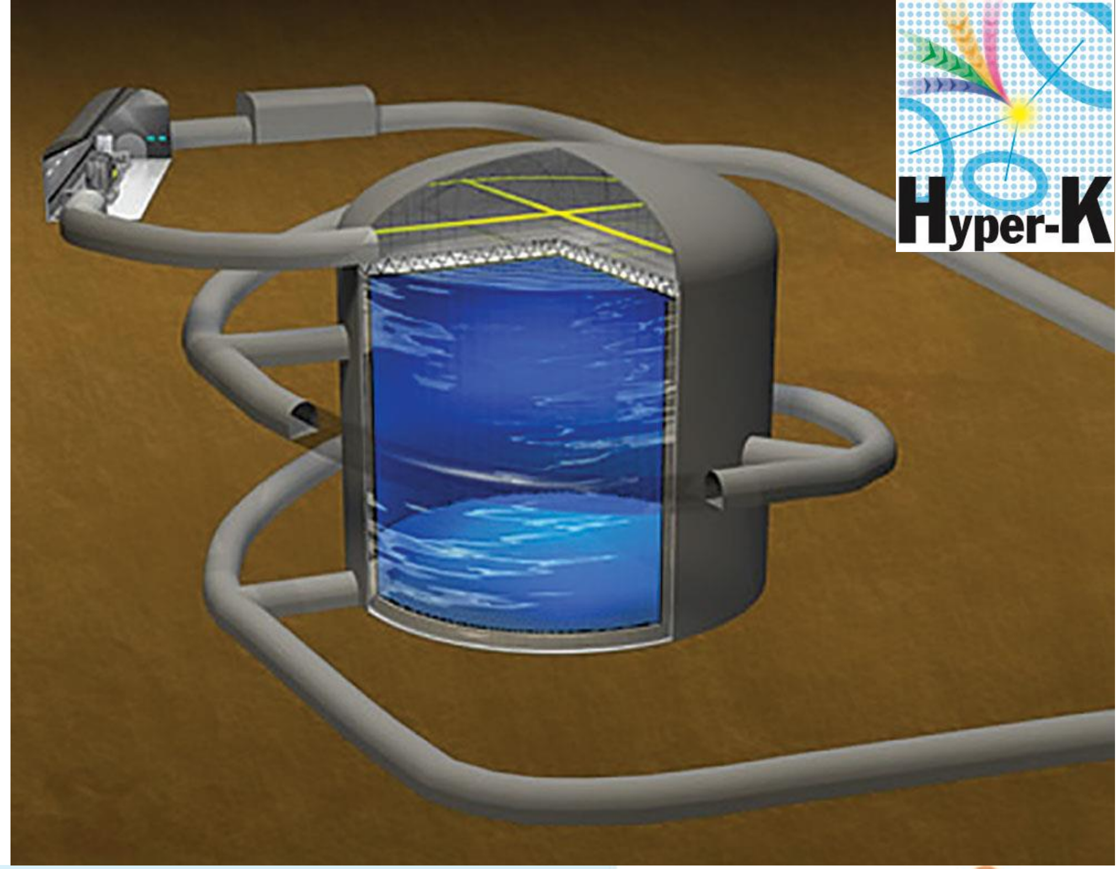
Brightening the Future of Neutrino Oscillation Measurements

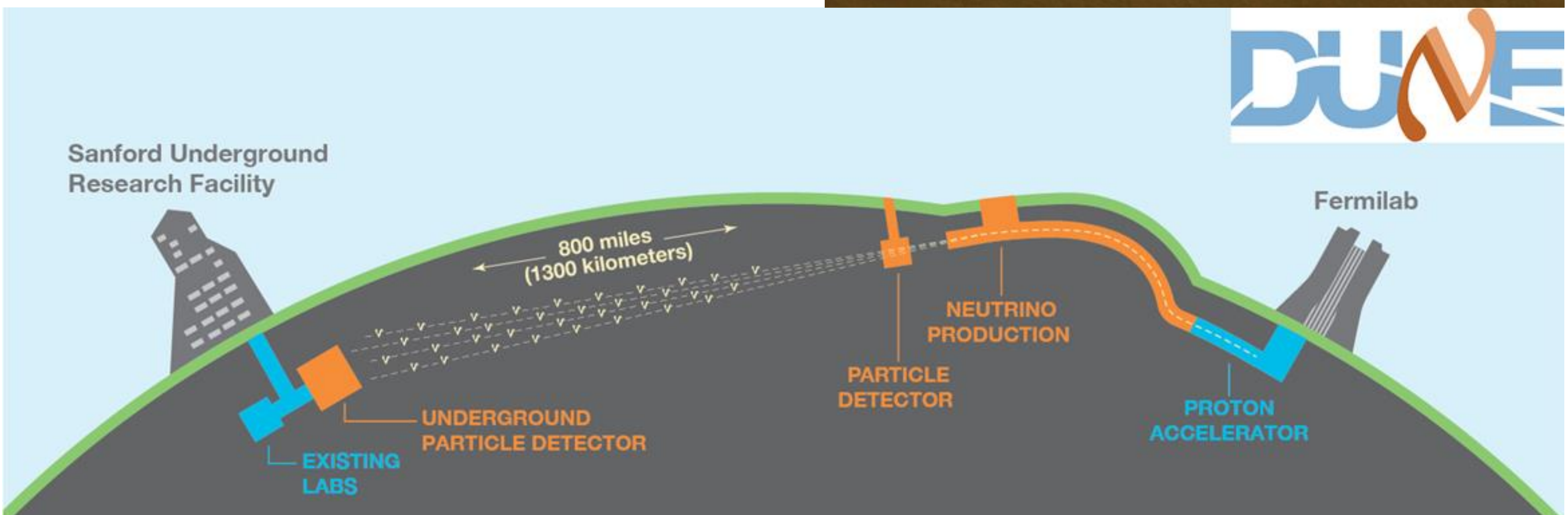
May 25th, 2022
Mitchell Conference on Collider, Dark Matter, and Neutrino Physics

by J. L. Barrow
MIT & TAU
Zuckerman Postdoctoral Scholar

Future Experimental ν Physics

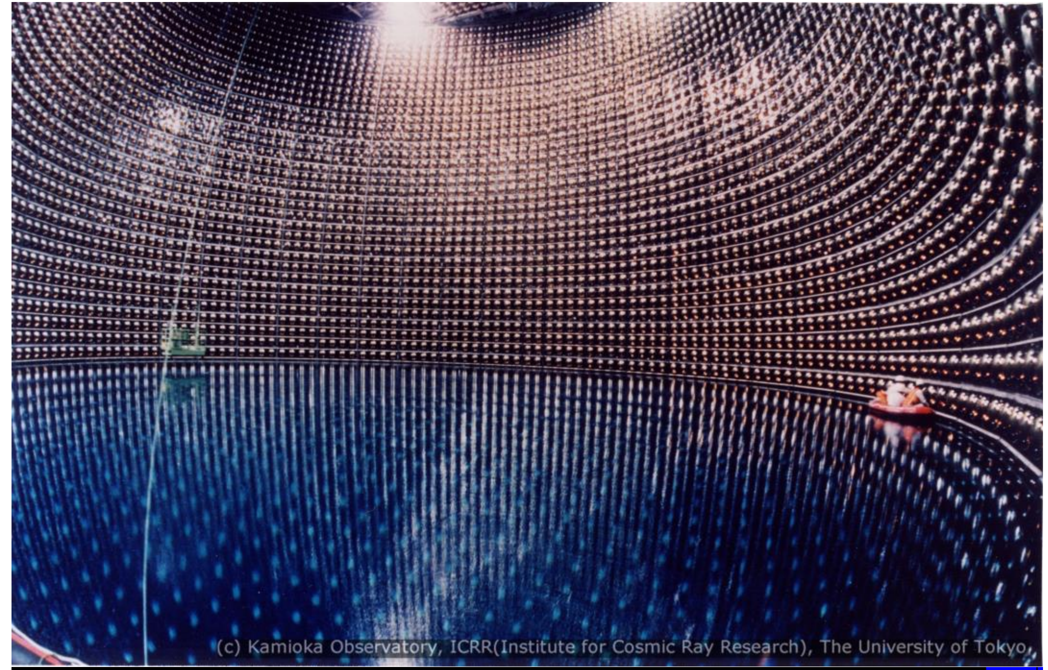
- Goal:
  - Extract ν oscillation parameters
- Implications
  - Leptogenesis, cross sections, τ production, BSM, Non-Standard Interactions
- Challenges
  - Broadband ν spectra
  - Unknown initial ν energy

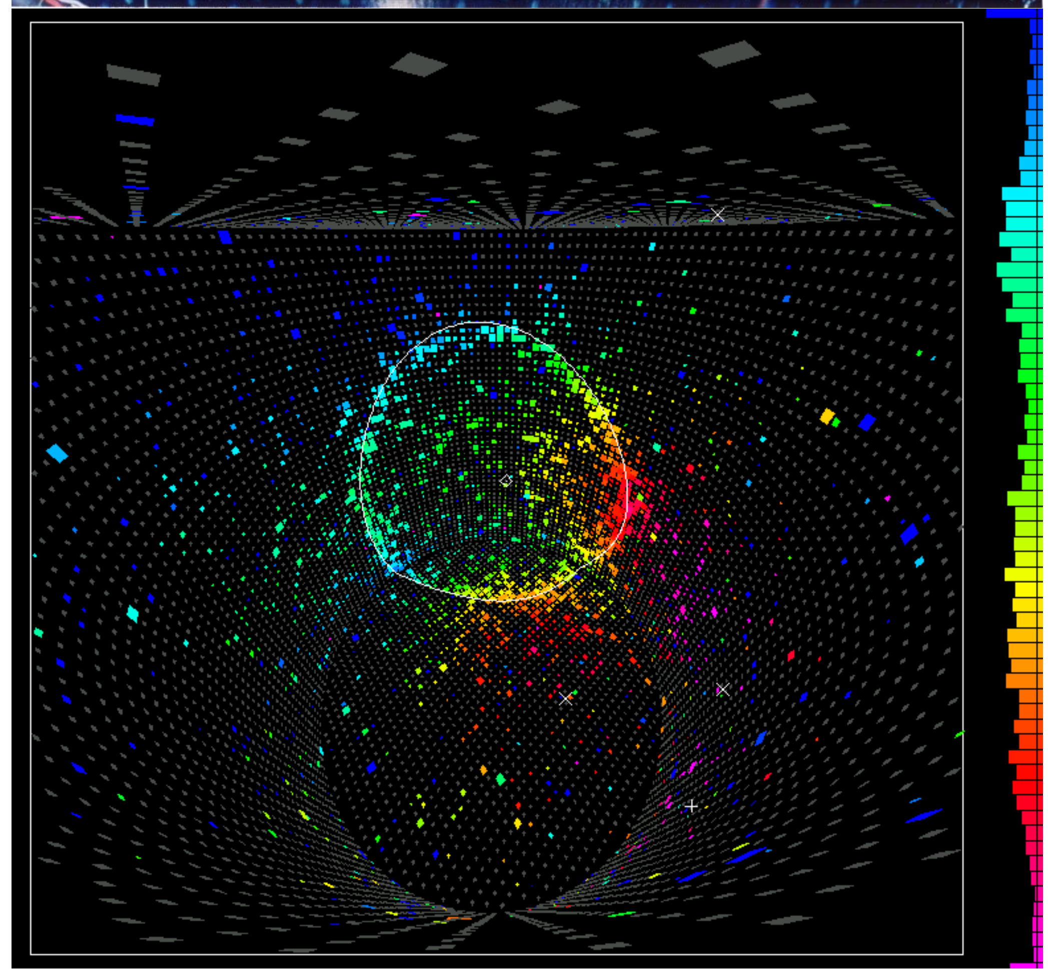




Water Cherenkov Detectors

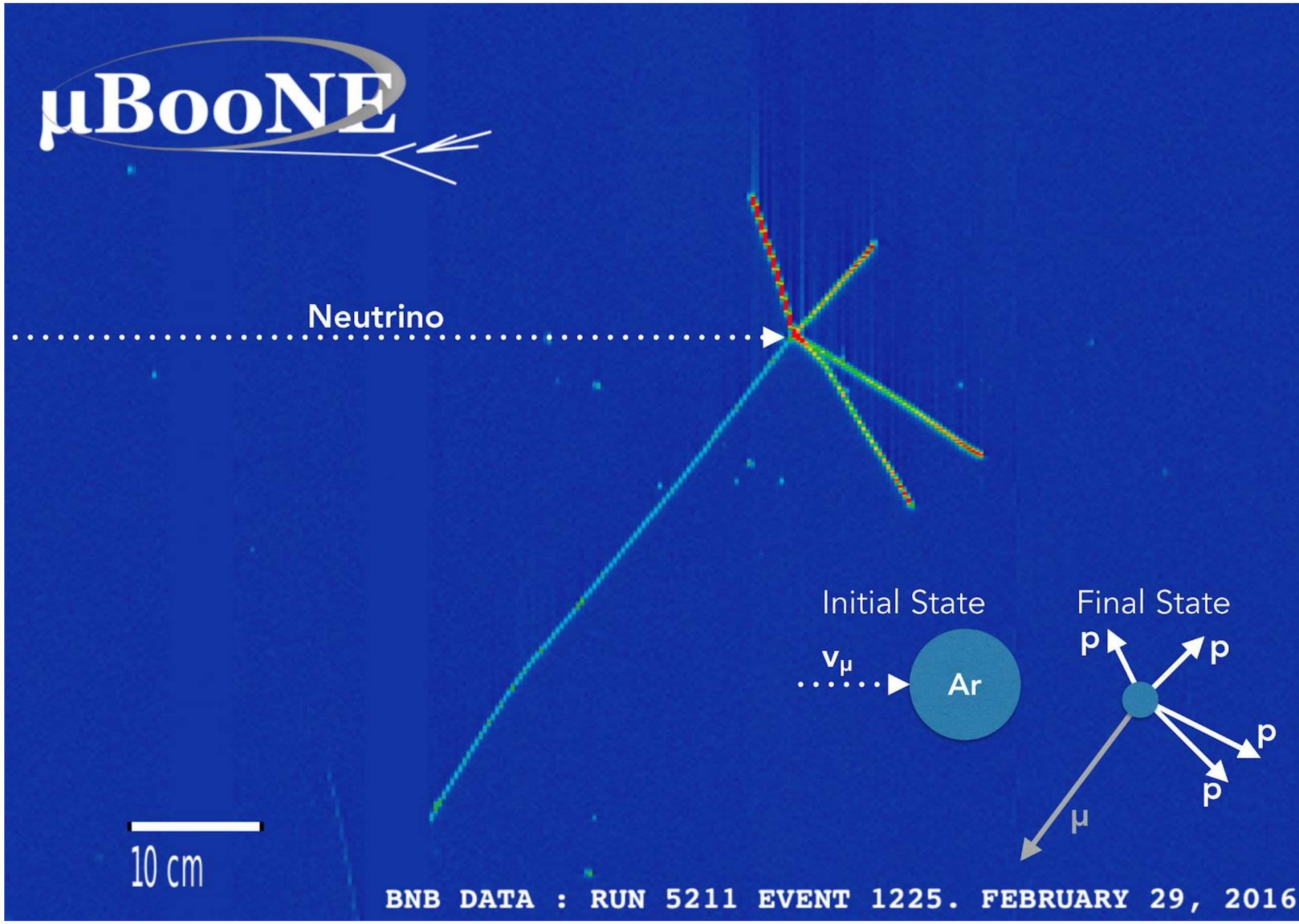
- Super & Hyper-Kamiokande's technology
  - Well understood, battle tested
  - Huge masses, statistics
- Oxygen as nuclear target
  - "Simple" symmetric nucleus
- Reconstruct particle momenta from Cherenkov rings
  - High proton thresholds

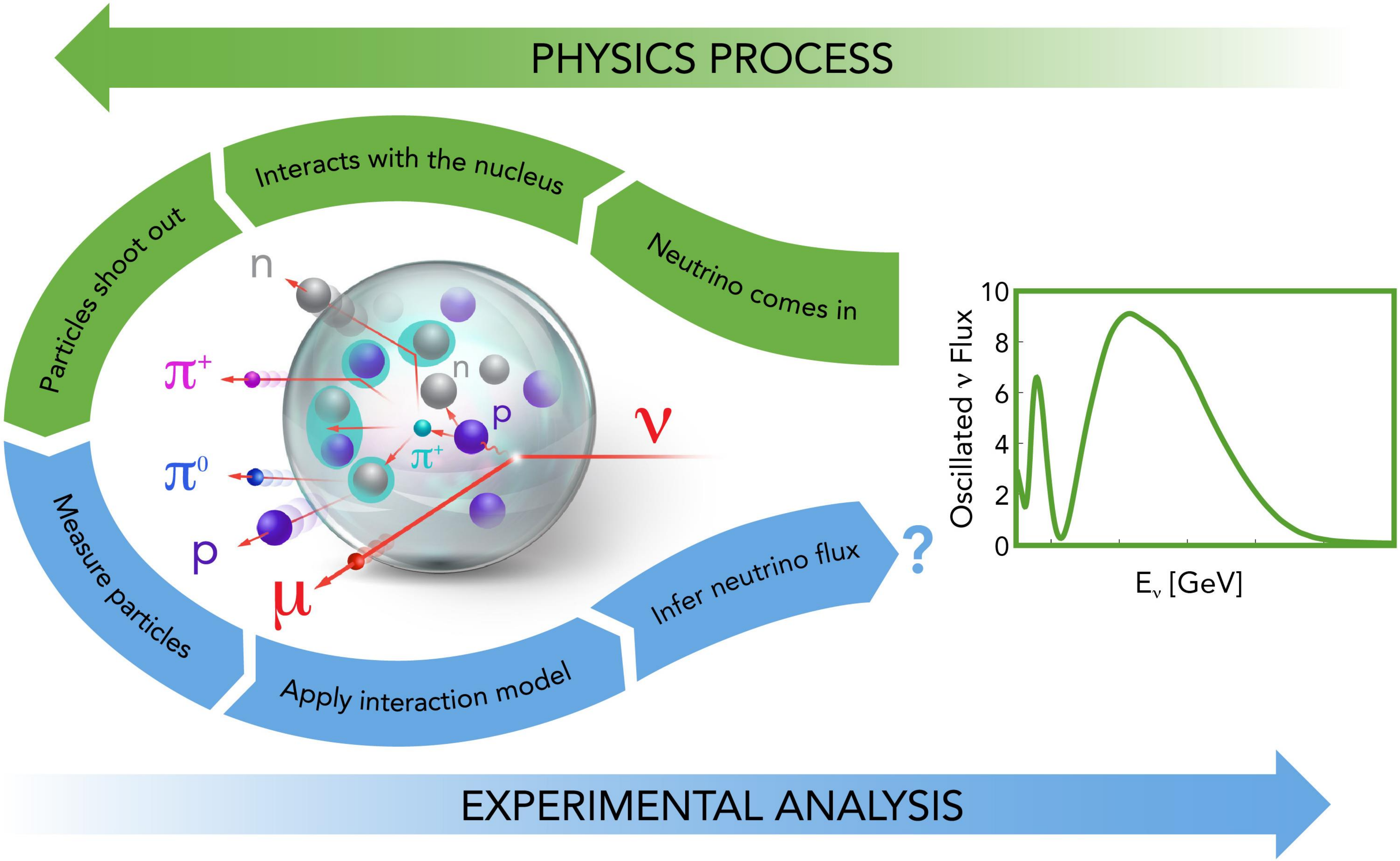




Liquid Argon Time Projection Chambers

- 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





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

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

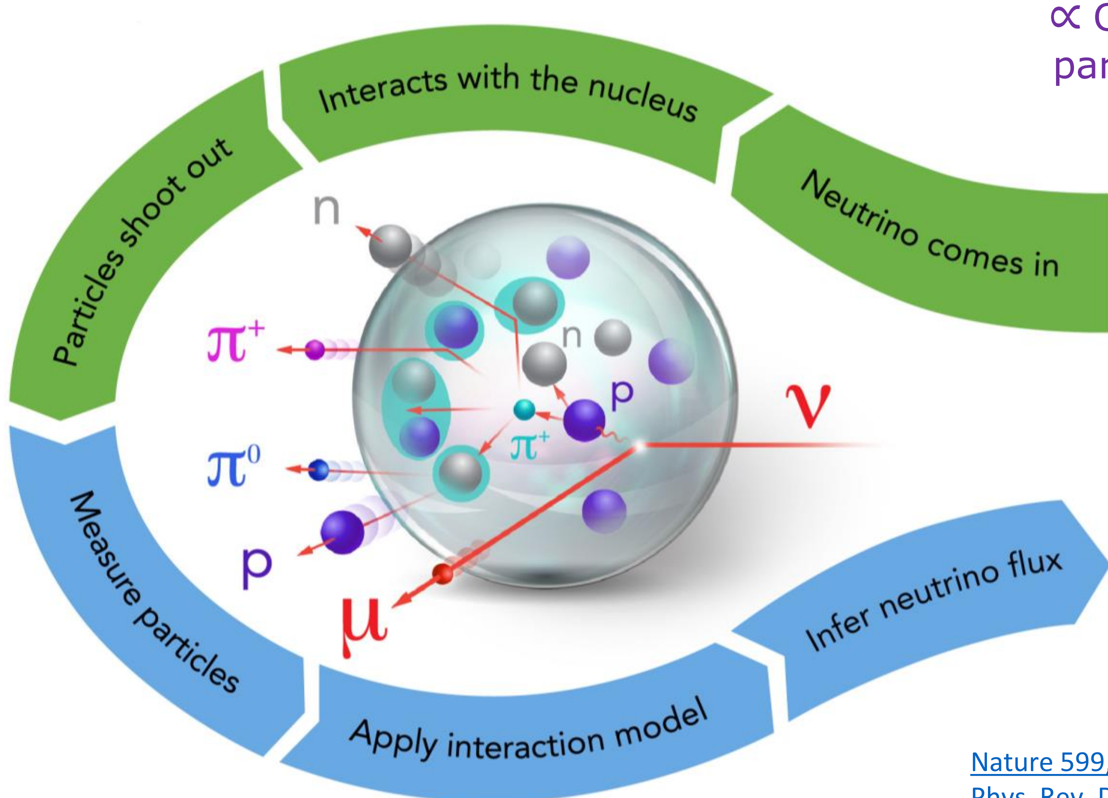
measured — ν flux — interaction model

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!

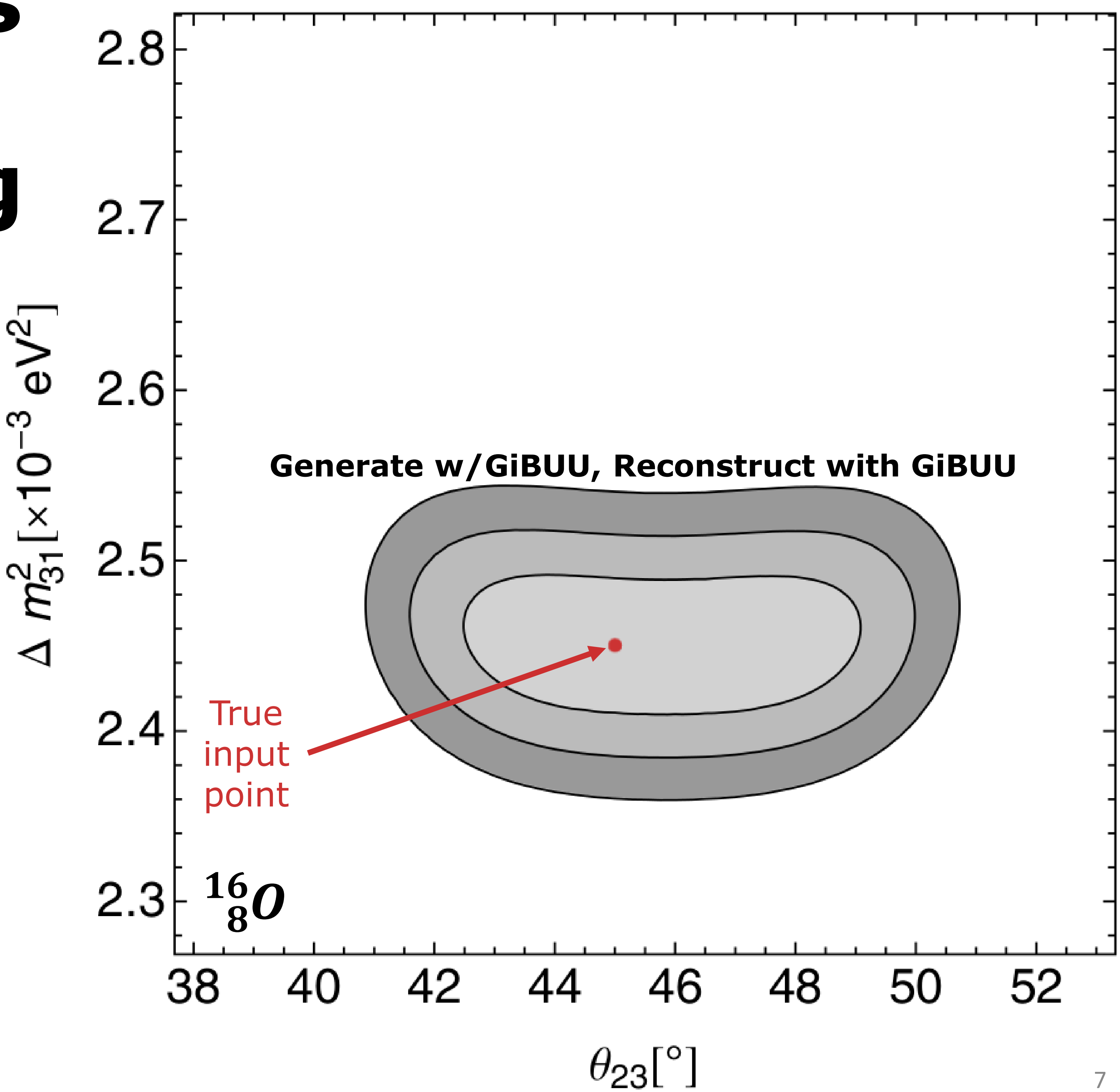


Adapted from A. Ashkenazi and A. Papadopoulou

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?

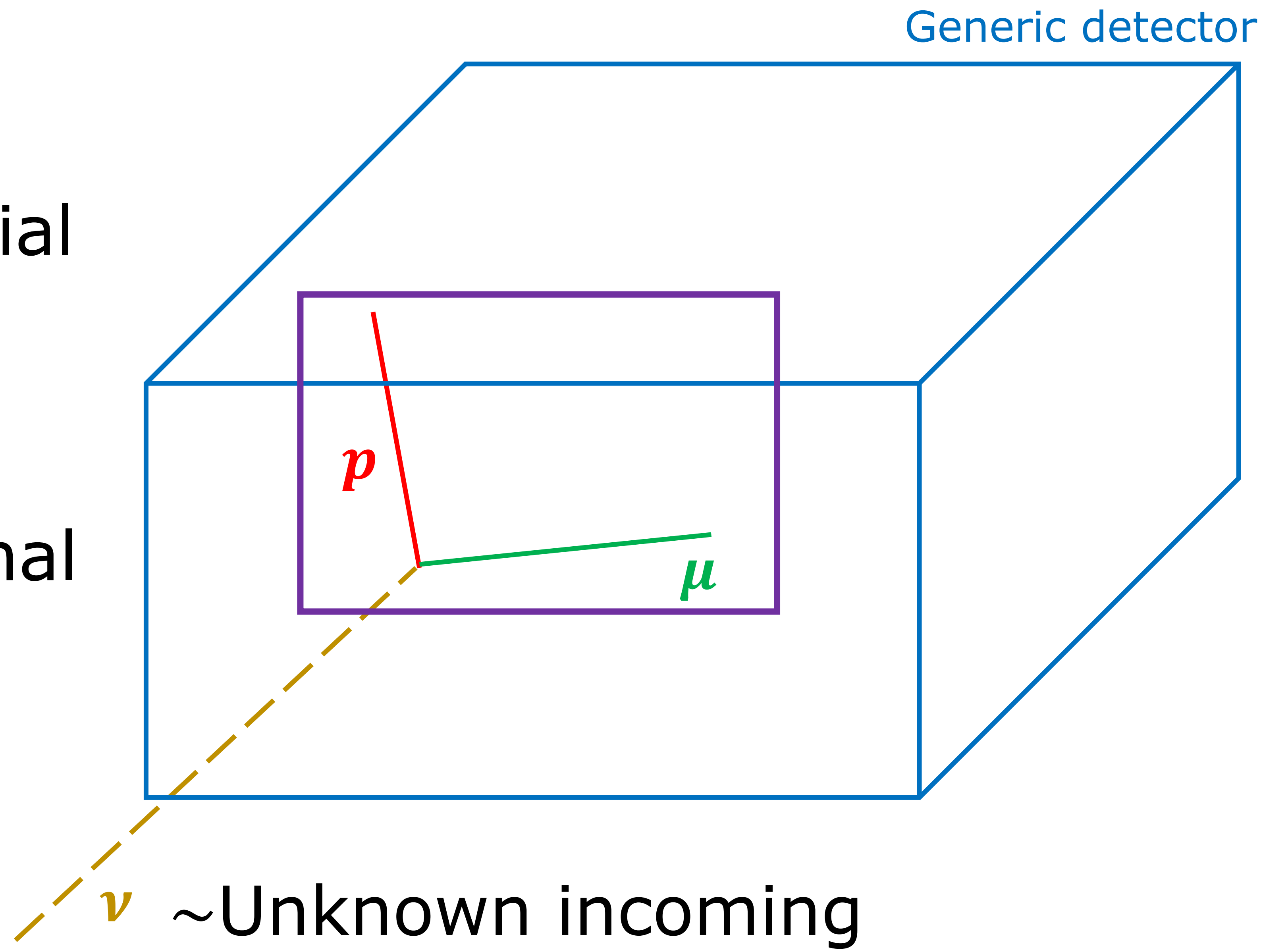


Phys. Rev. D 89, 073015 (2014)

The Charged Lepton Strategy

Must Reconstruct Initial ν Energy

Definitive initial energy knowledge limited by observable final state

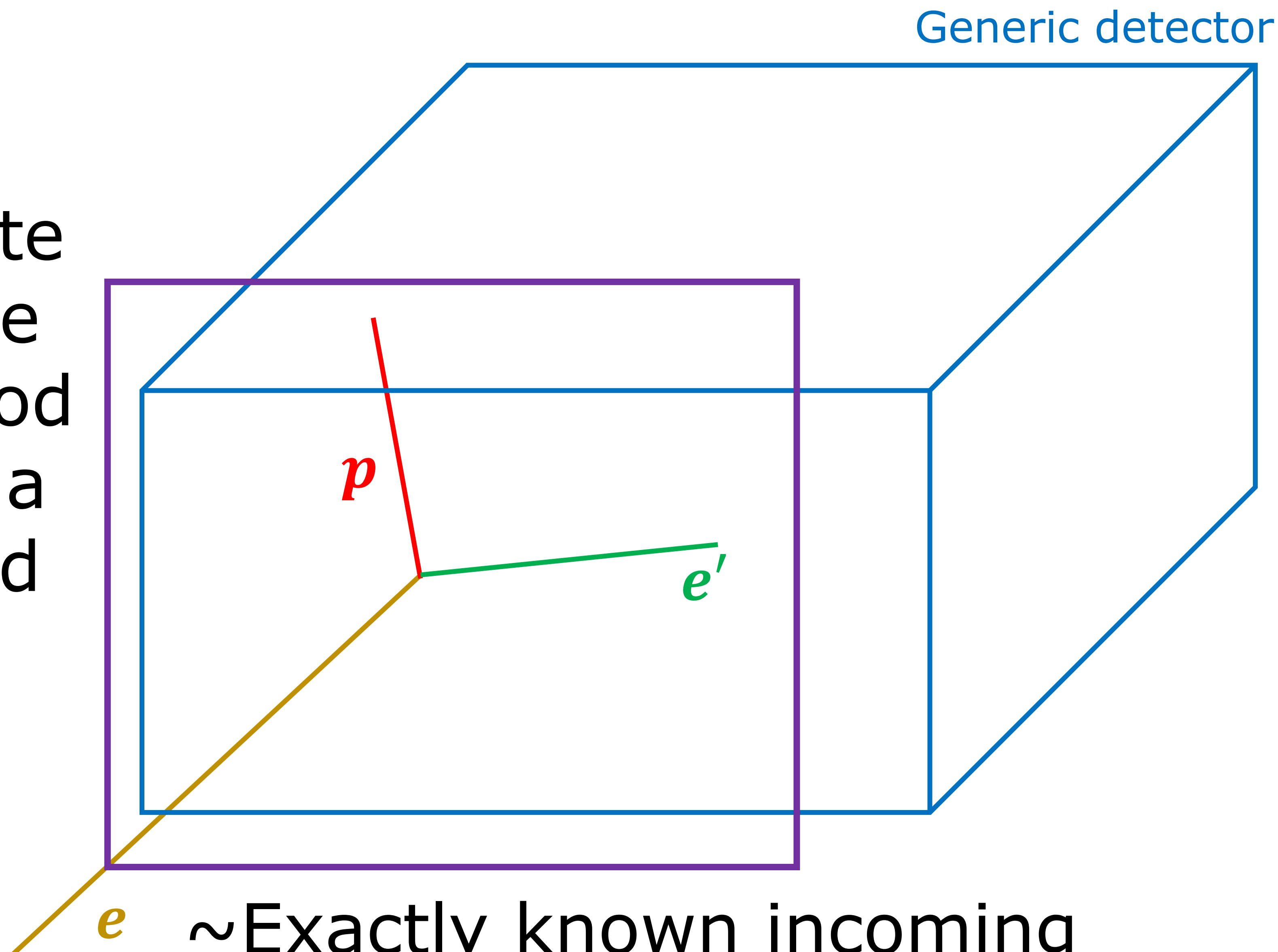


~Unknown incoming neutrino energy

Utilizing Electron Scattering

Identical Topologies with Precision Beams

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



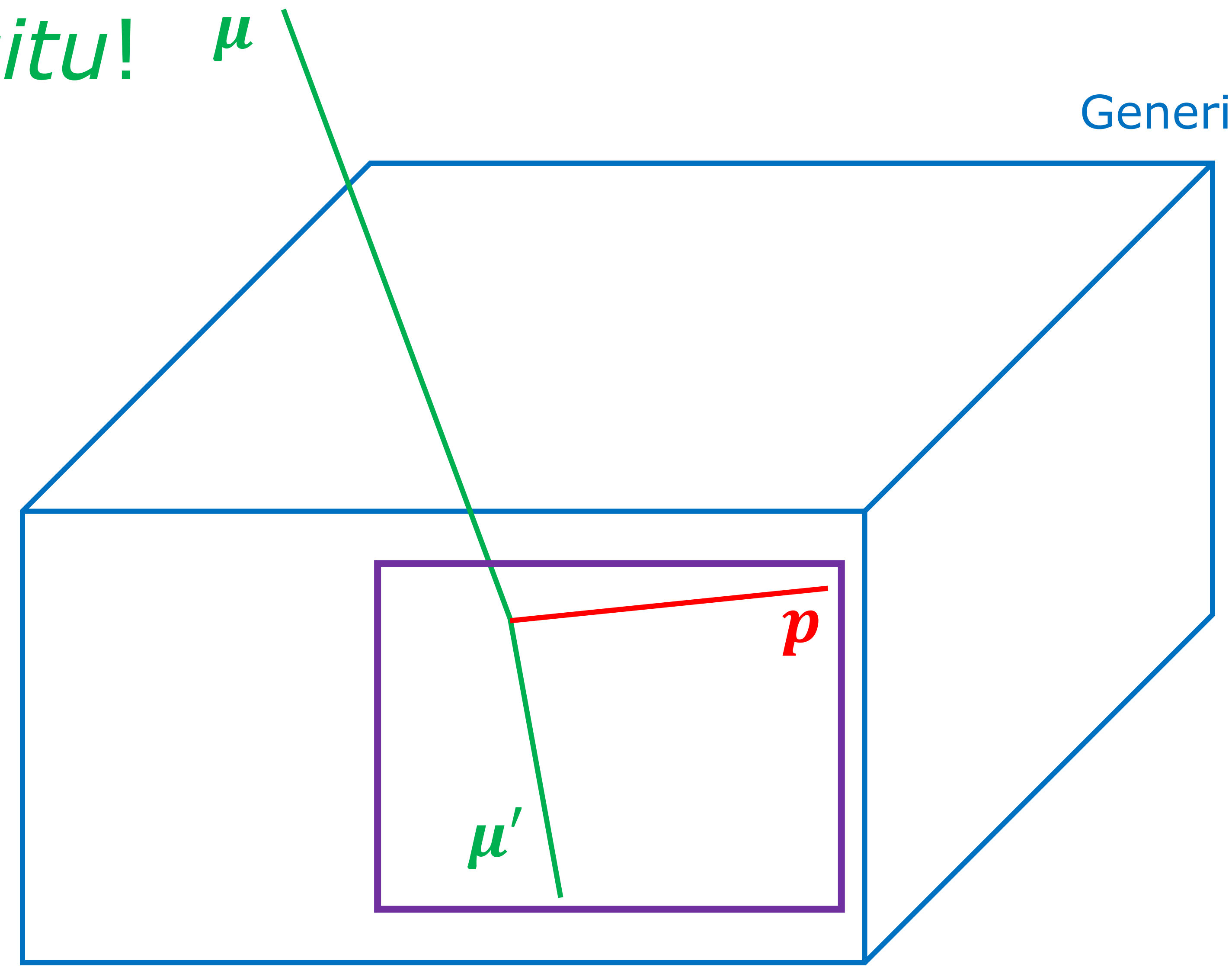
~Exactly known incoming electron energy

Utilizing Cosmic Muon Scattering

Identical Topologies with Broad Spectra

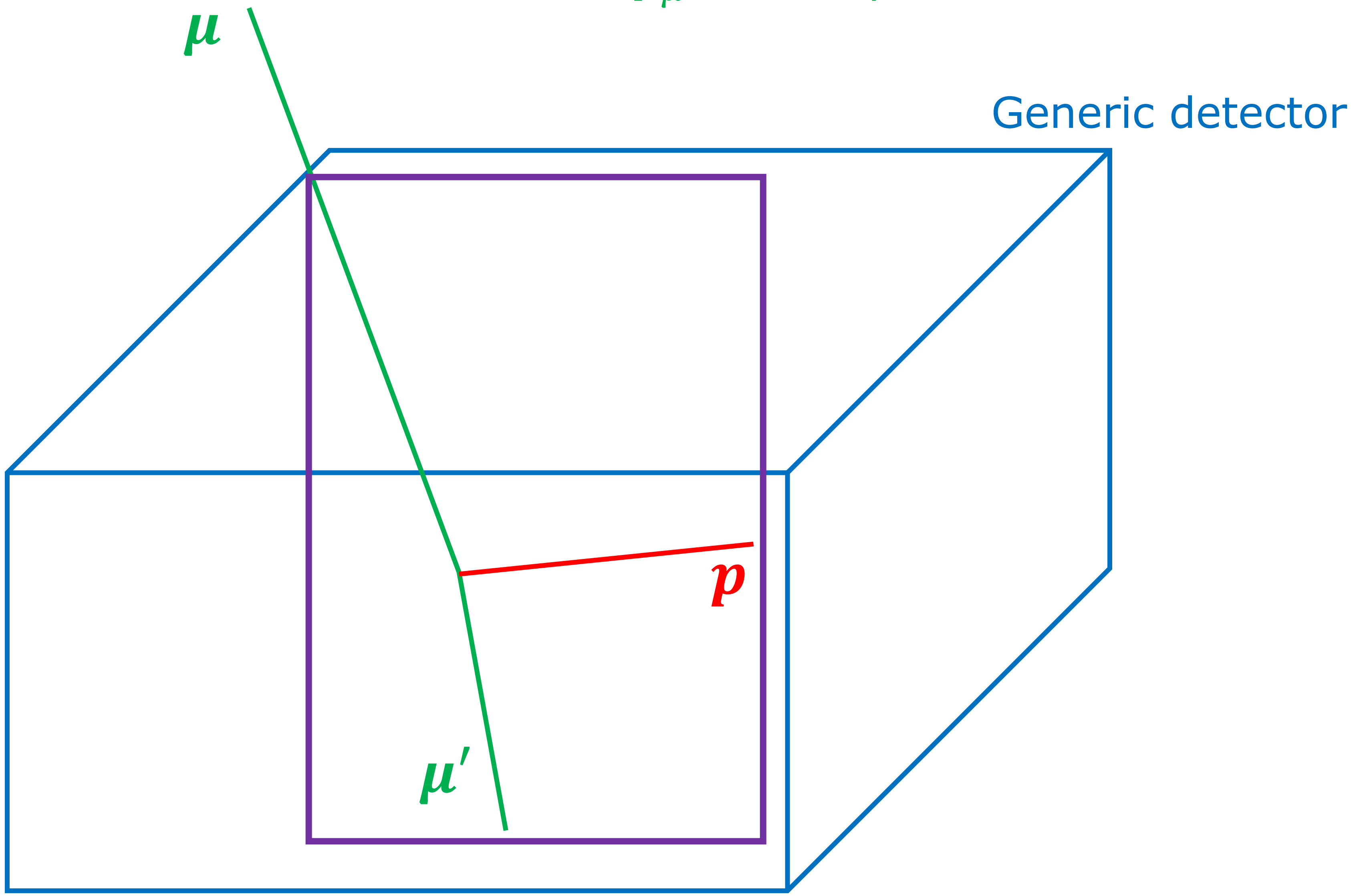
Use cosmic $\mu^{\pm}$ *in situ*!

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



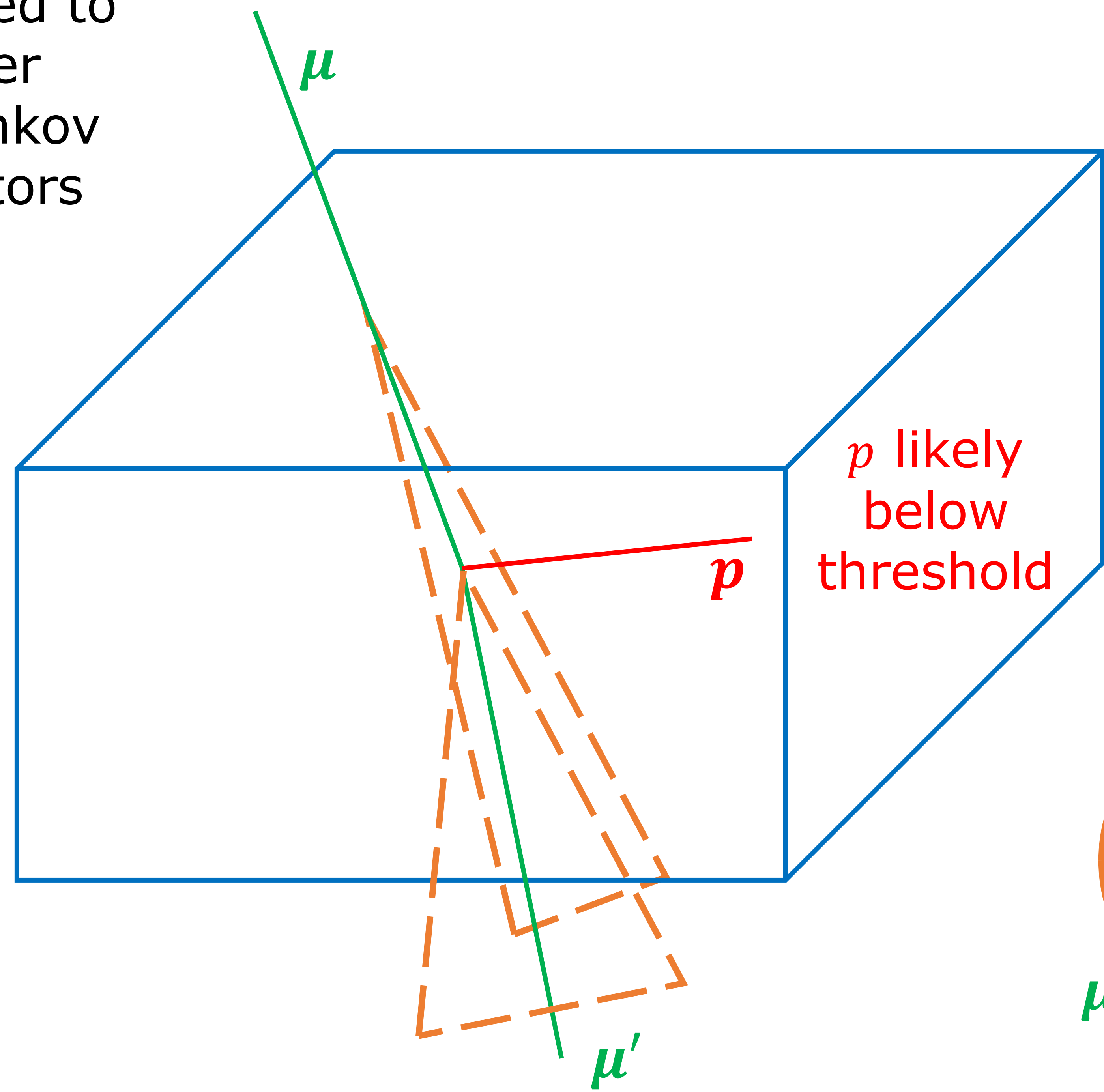
Momentum resolution is
$\sim$11-15% for $p_\mu < 2\mathrm{GeV/c}$

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



Multiple Coulomb scattering

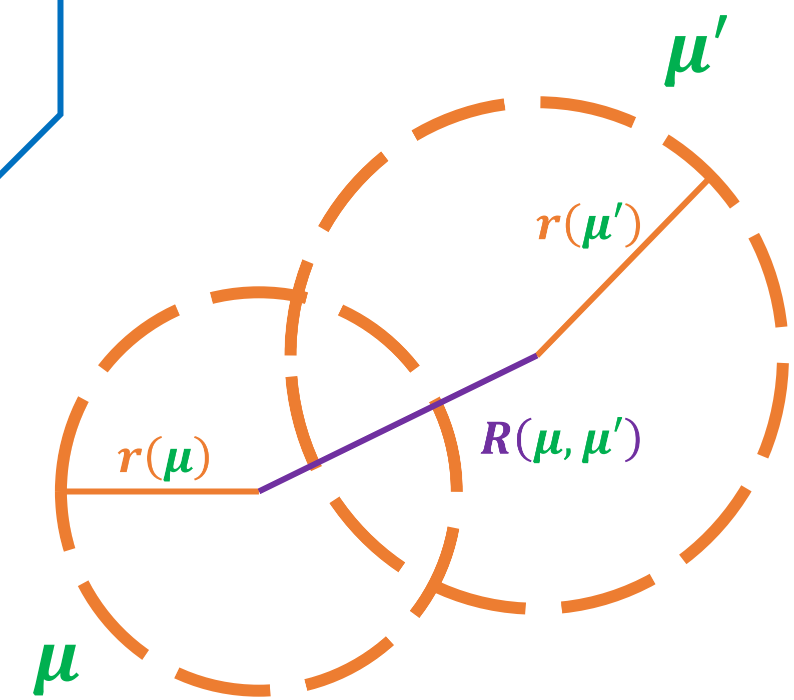
Idea can be extended to Water Cherenkov detectors



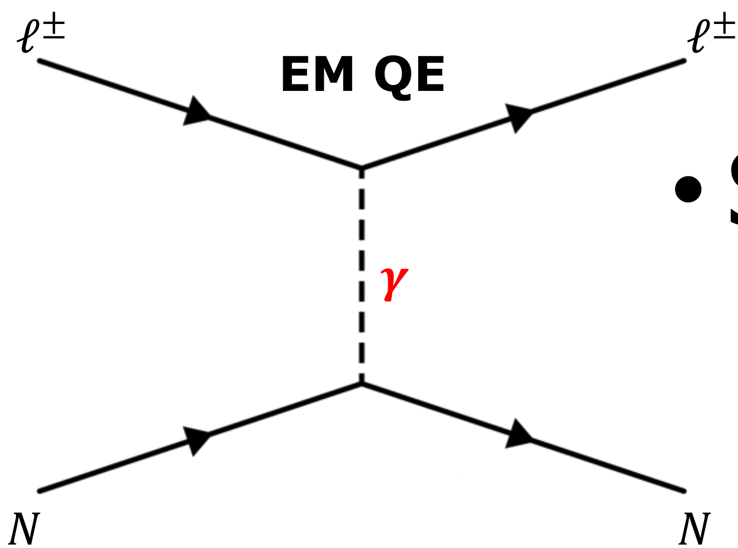
Generic Cherenkov detector

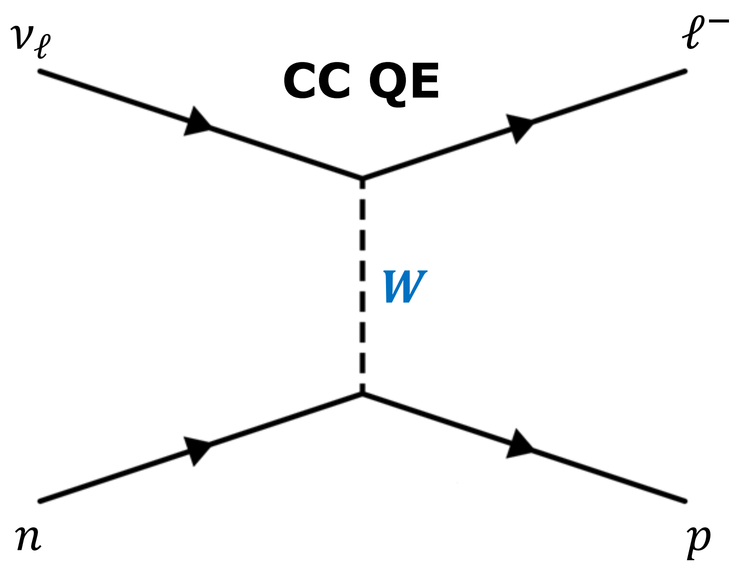
$$r(\mu) - r(\mu') \propto \omega$$

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



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

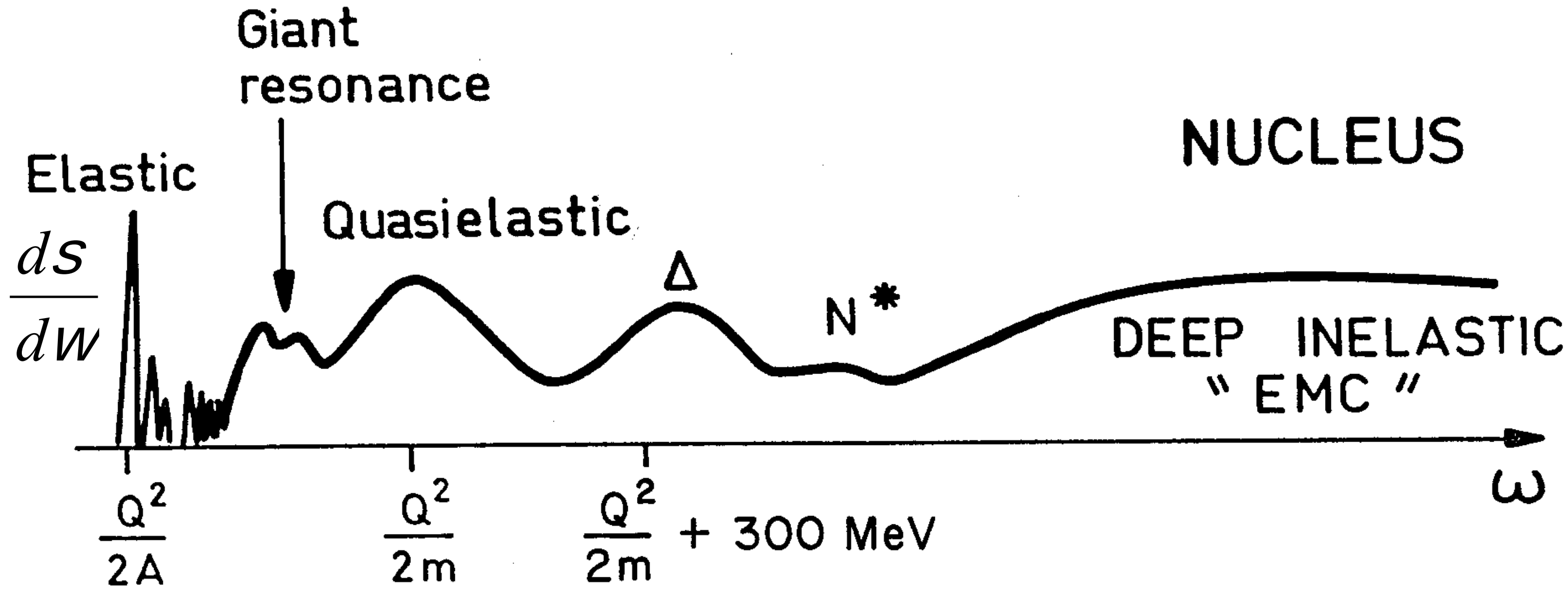
Phys. Rev. D 103, 113003 (2021)

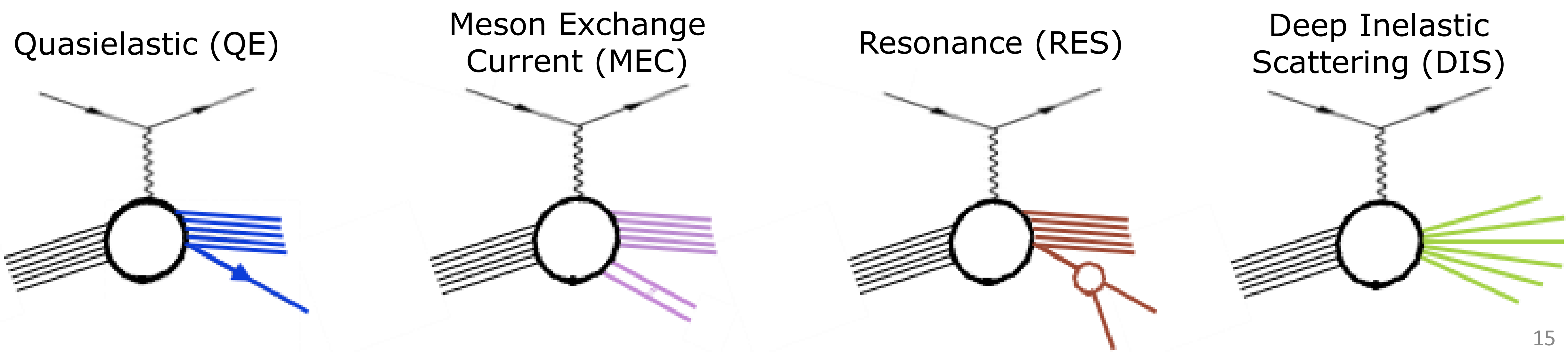
Improving Discrete Aspects of *Modeling*

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

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

- Need input on all from electron scattering!



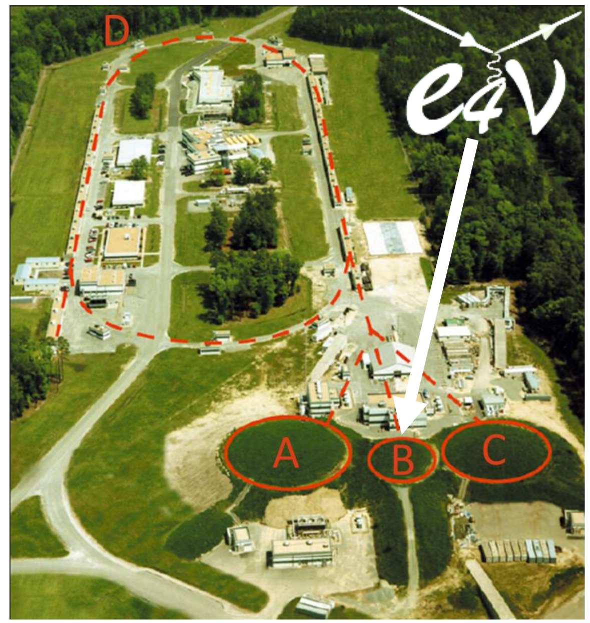


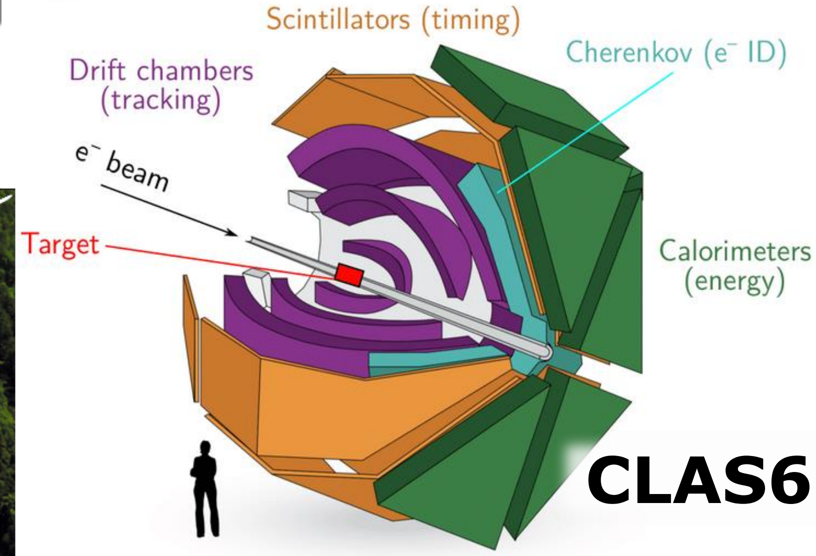
Fermilab

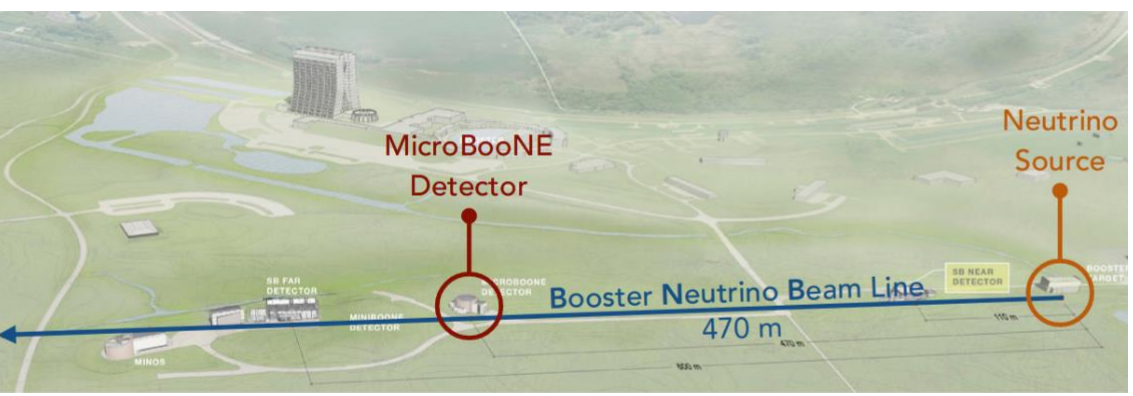
µBooNE

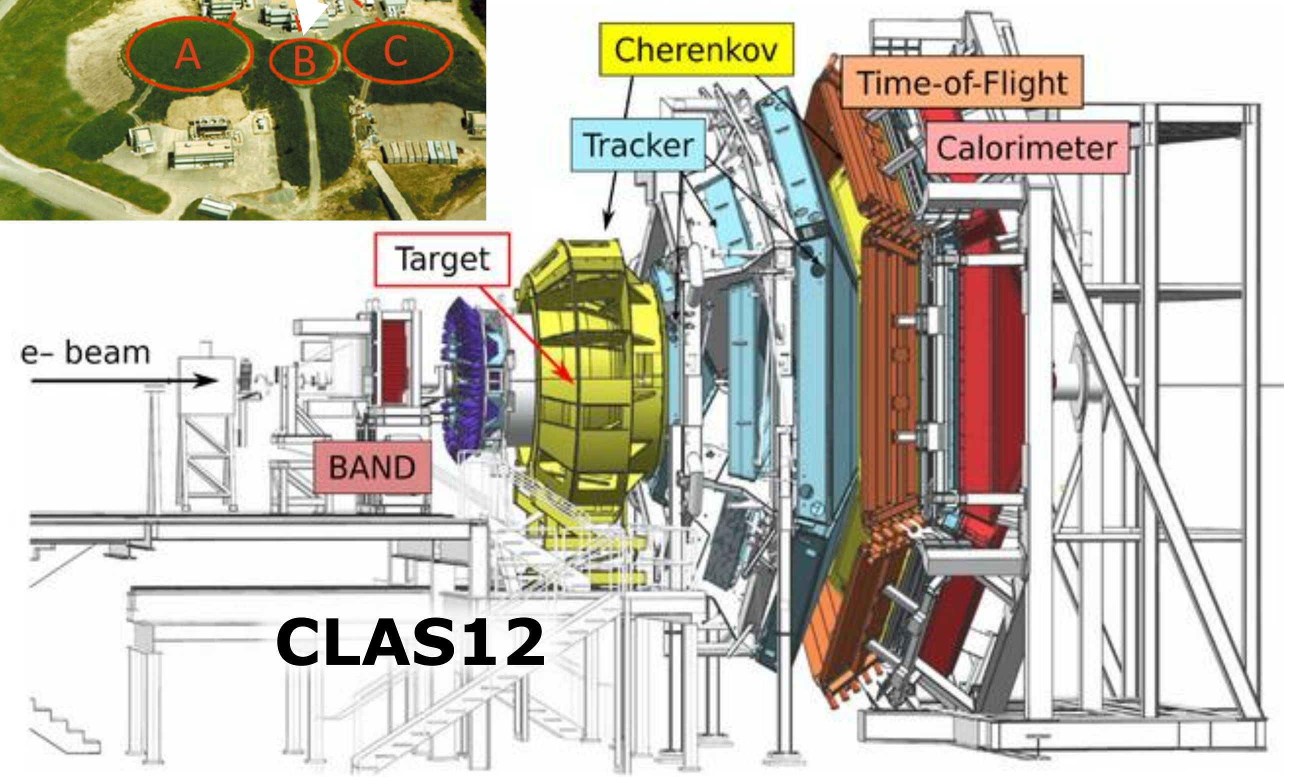
clas

Jefferson Lab









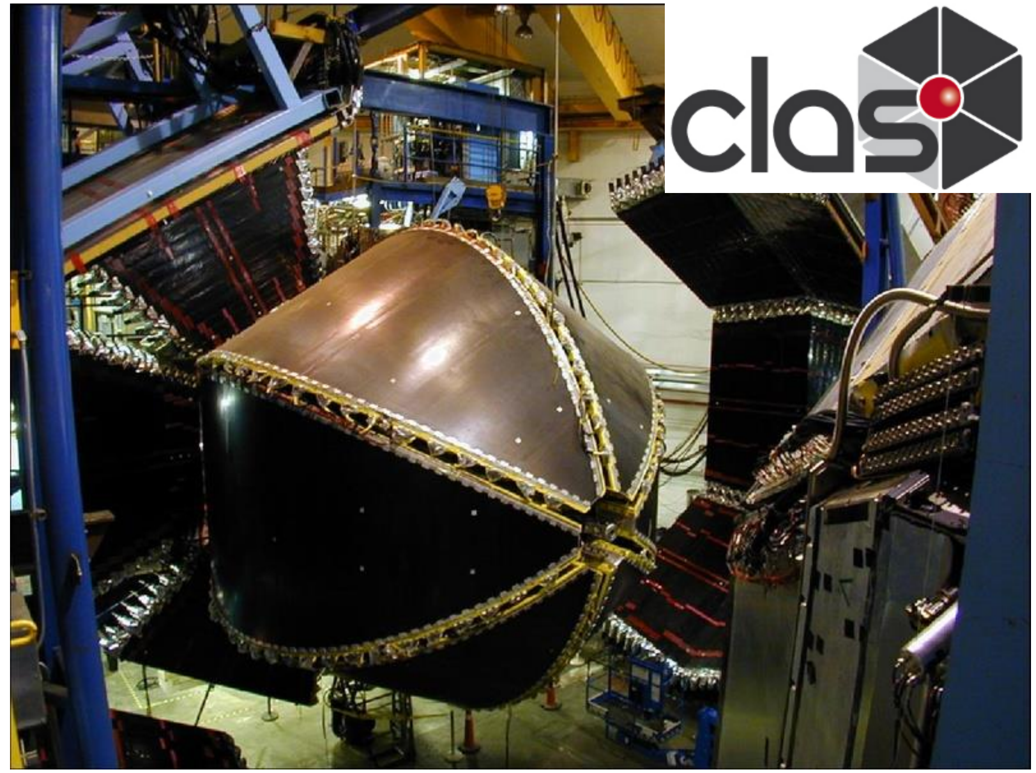
Recent $e4\nu$ Results

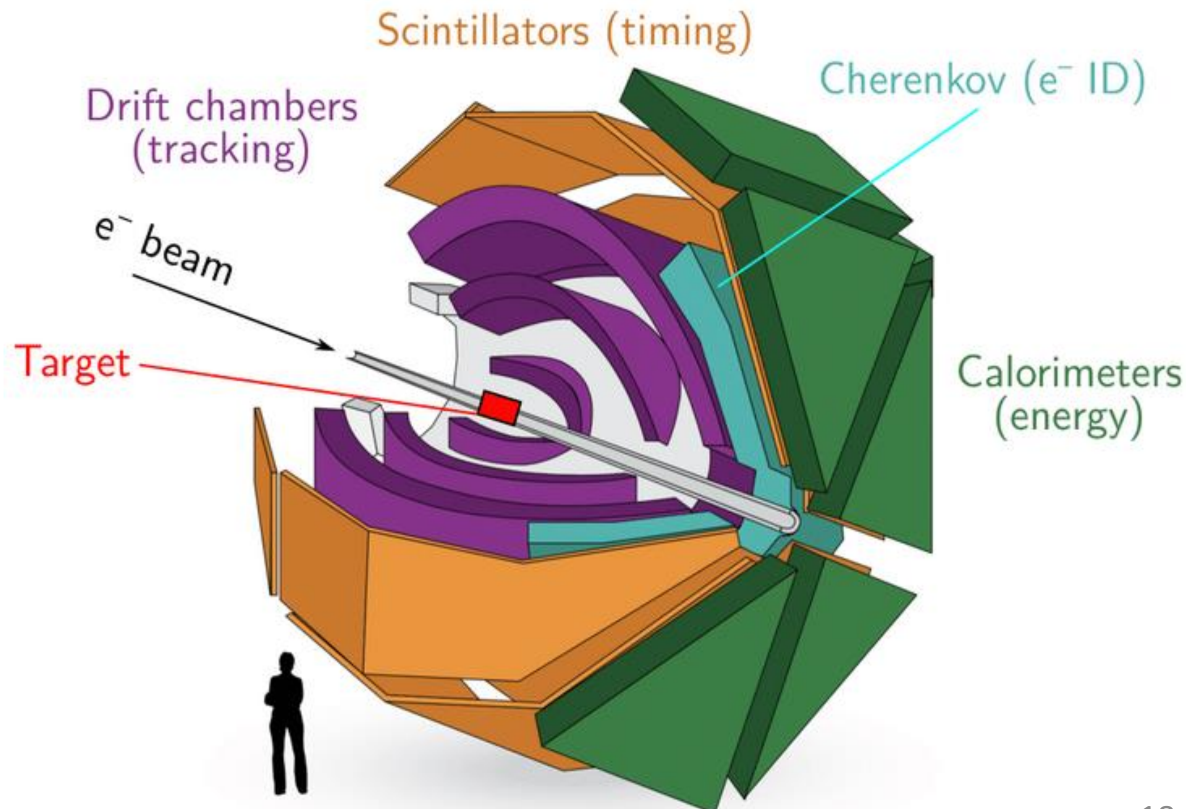
CLAS6 Data Mining

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 $1p0\pi$

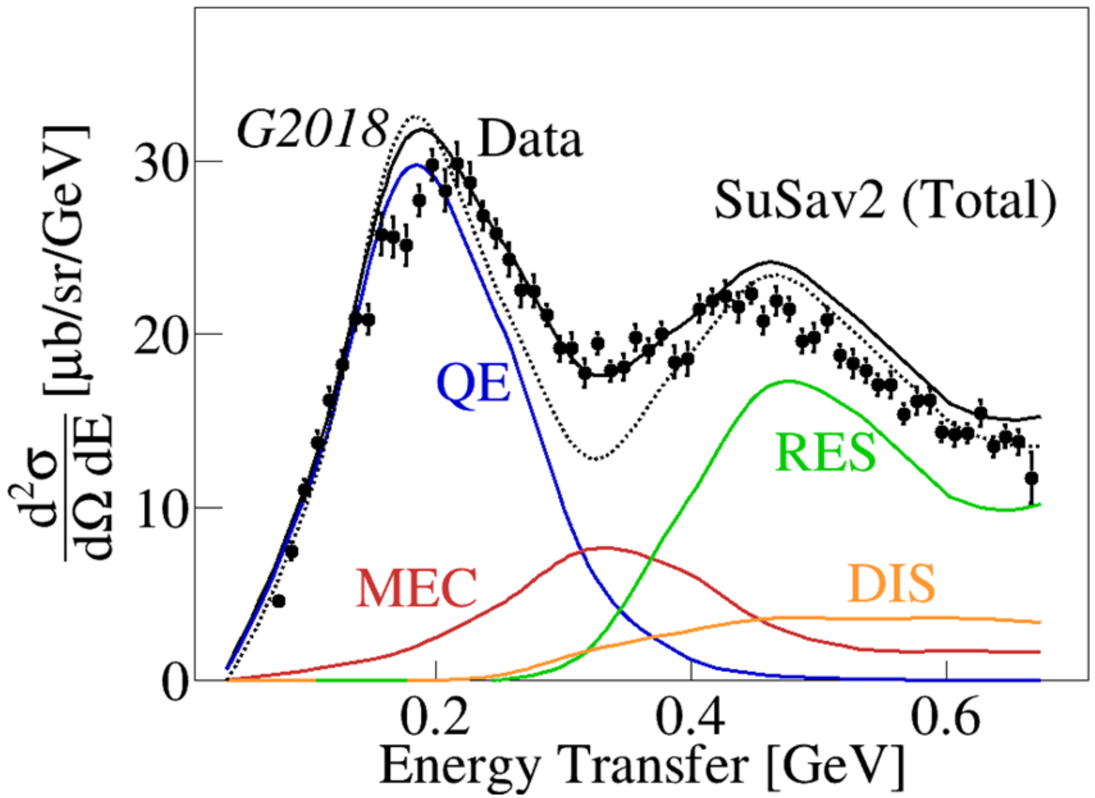




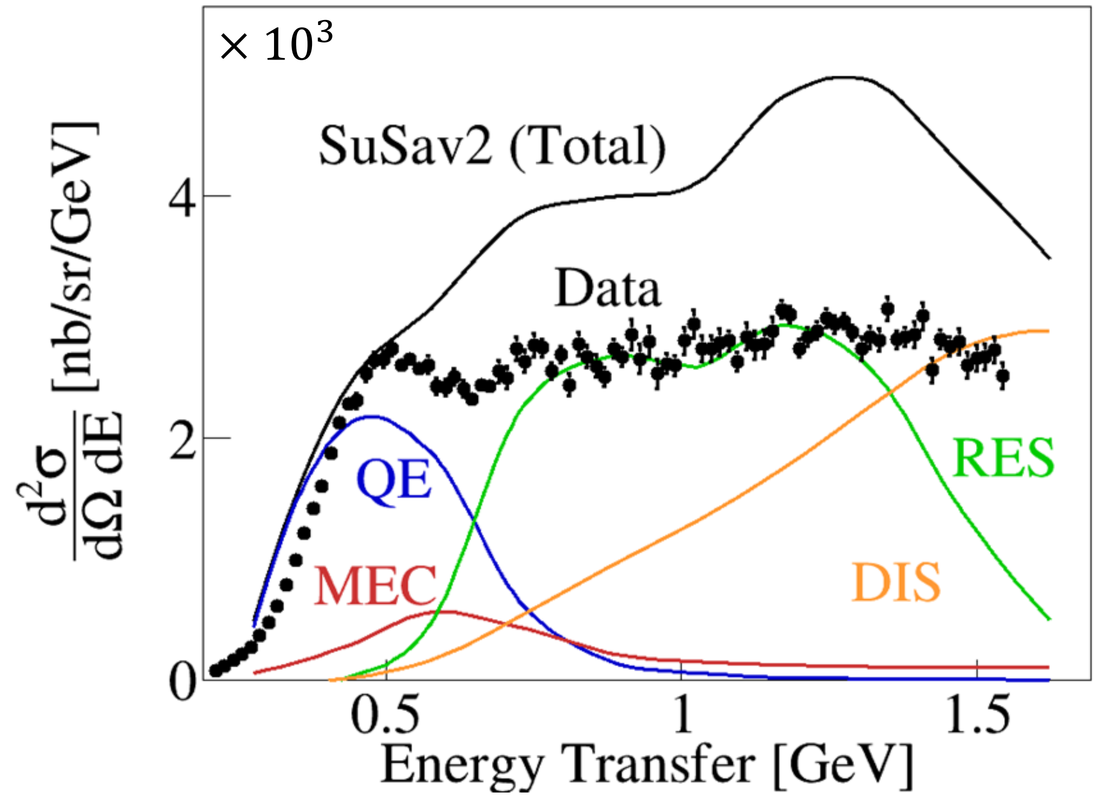
Inclusive $A(e, e')$ Data Comparisons

- 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°



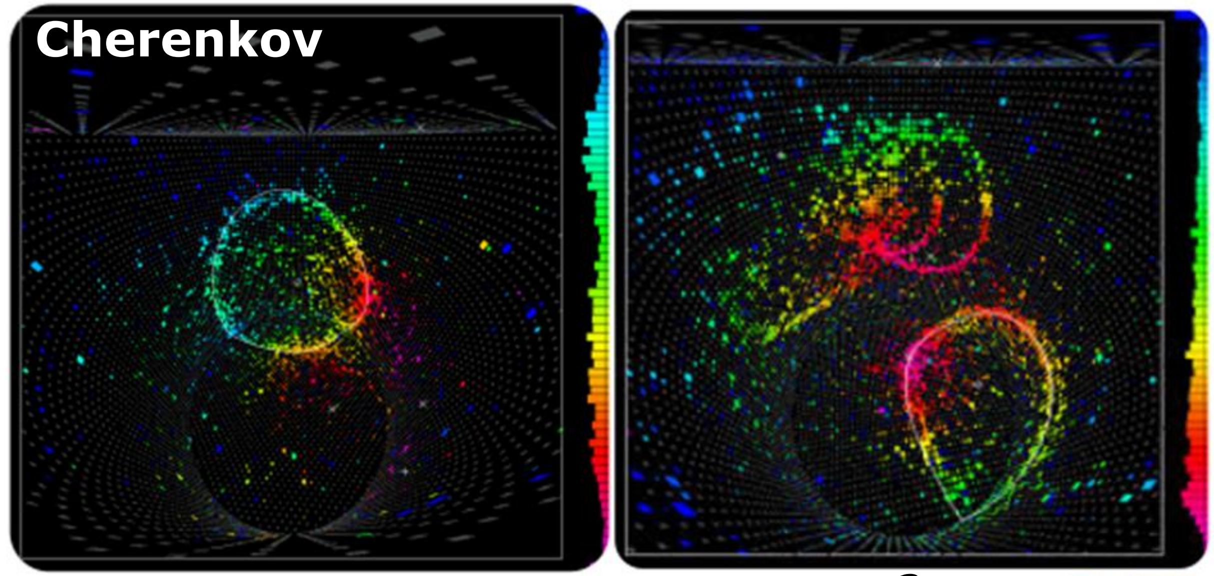
C(e, e'): 3.595 GeV at 16°



Phys. Rev. D 103, 113003 (2021)

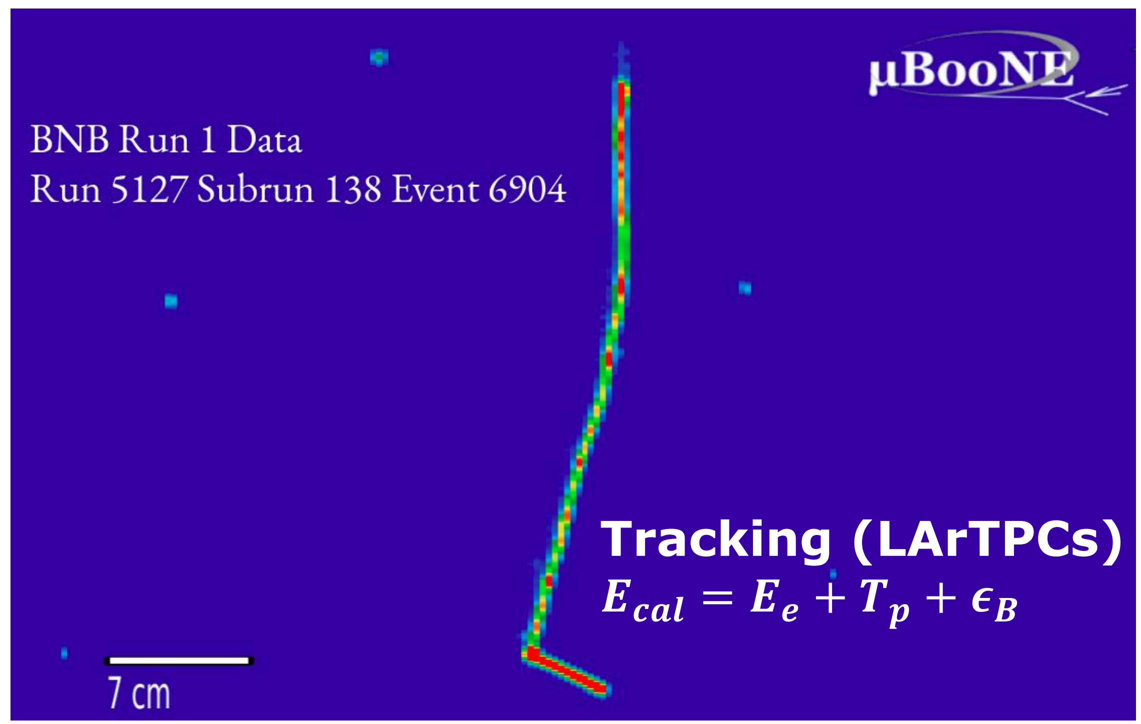
QE-like Energy Reconstruction in ν Experiments

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



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

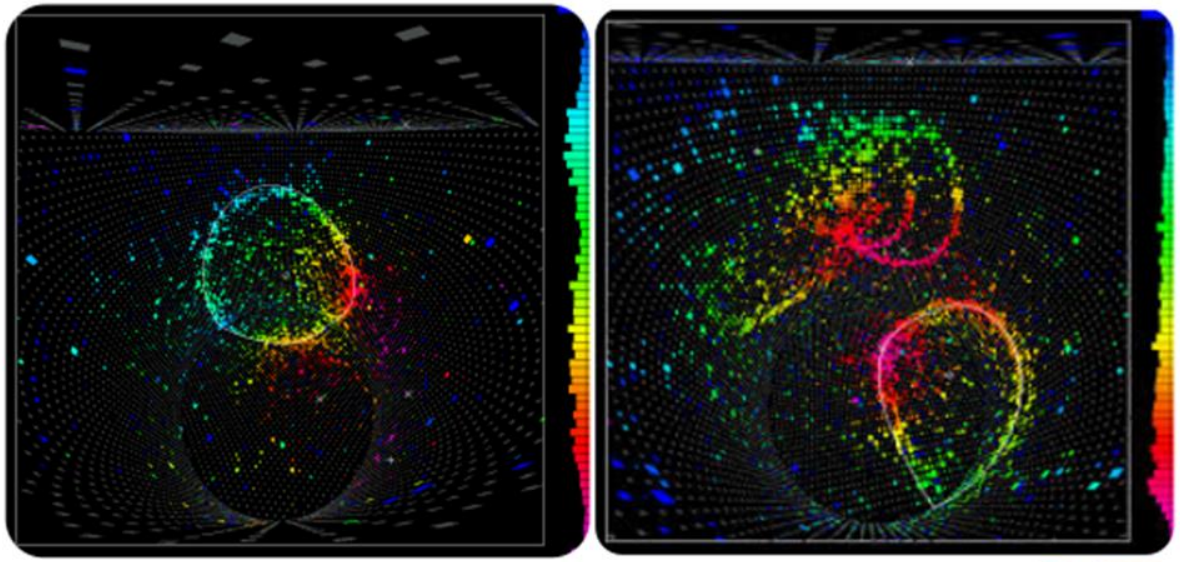
- Detector types play a role
  - May use only lepton variables
  - *…assume pure* QE
  - …others have lower thresholds



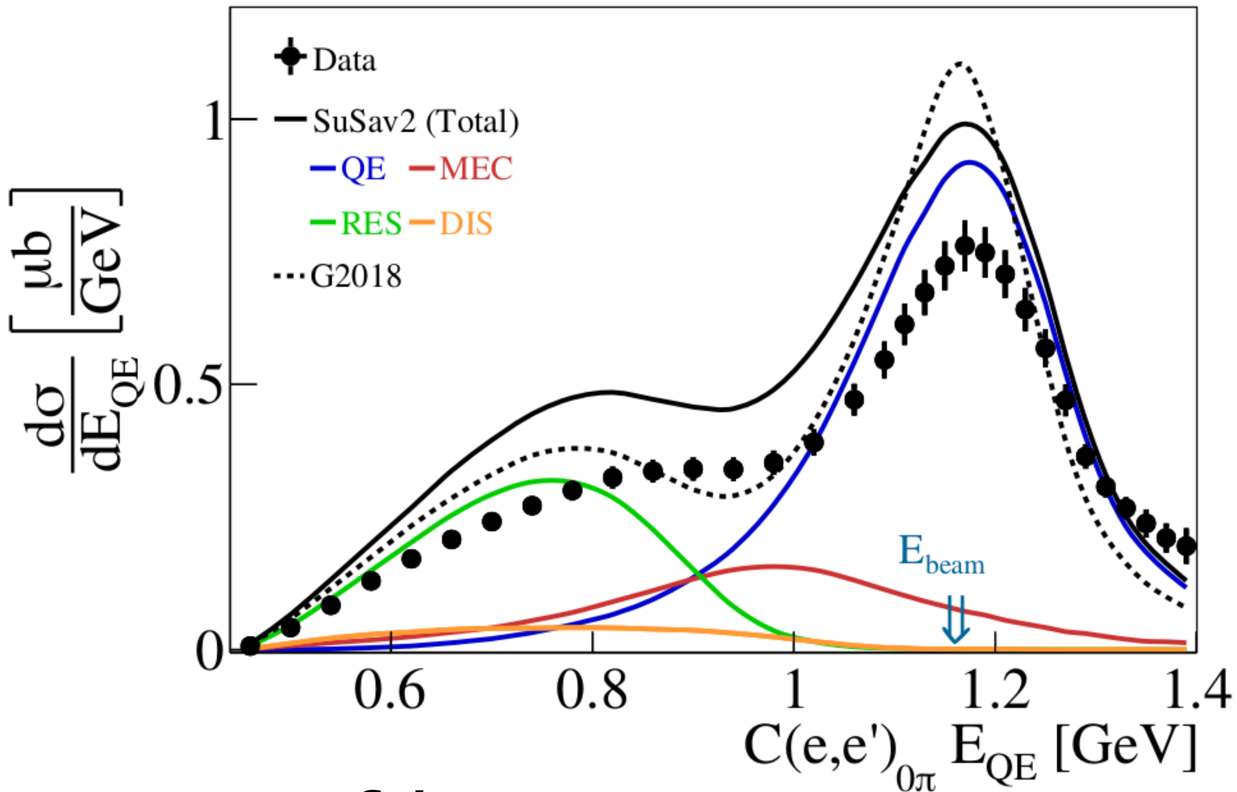
Adapted from L. Weinstein and A. Papadopoulou

Energy Reconstruction Issues

Water Cherenkov Detectors: QE Assumption



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

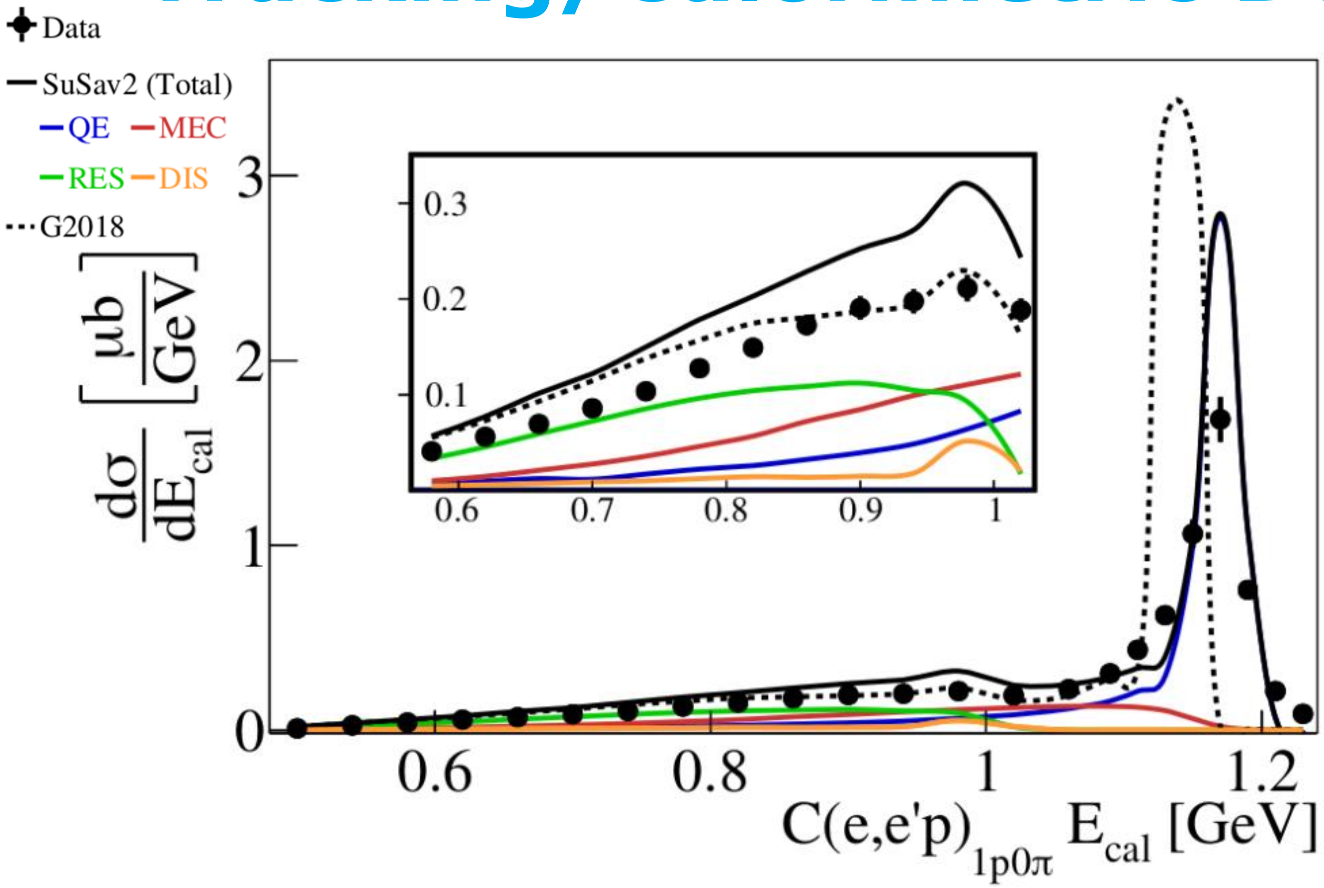


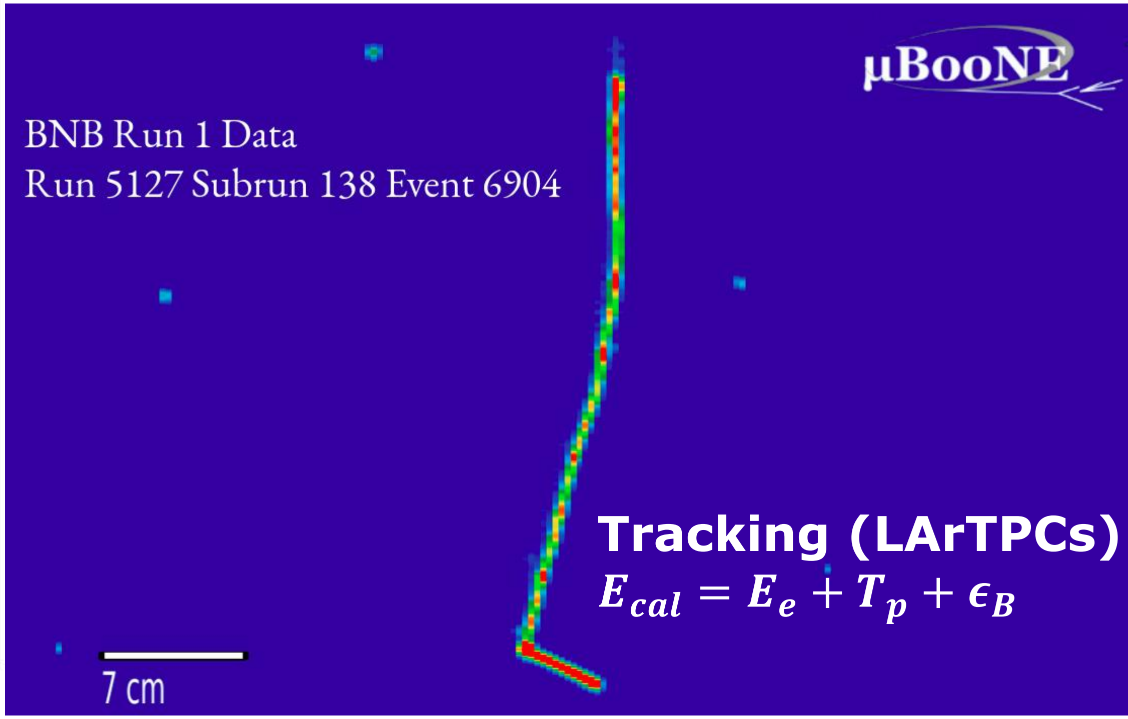
- Generally lacking reconstruction of beam E_e
  - No access to final state baryons (below threshold)
- Strength issues
  - Overestimation of QE peak
  - Overestimation of RES tail

Nature 599, 565–570 (2021)

Energy Reconstruction Issues

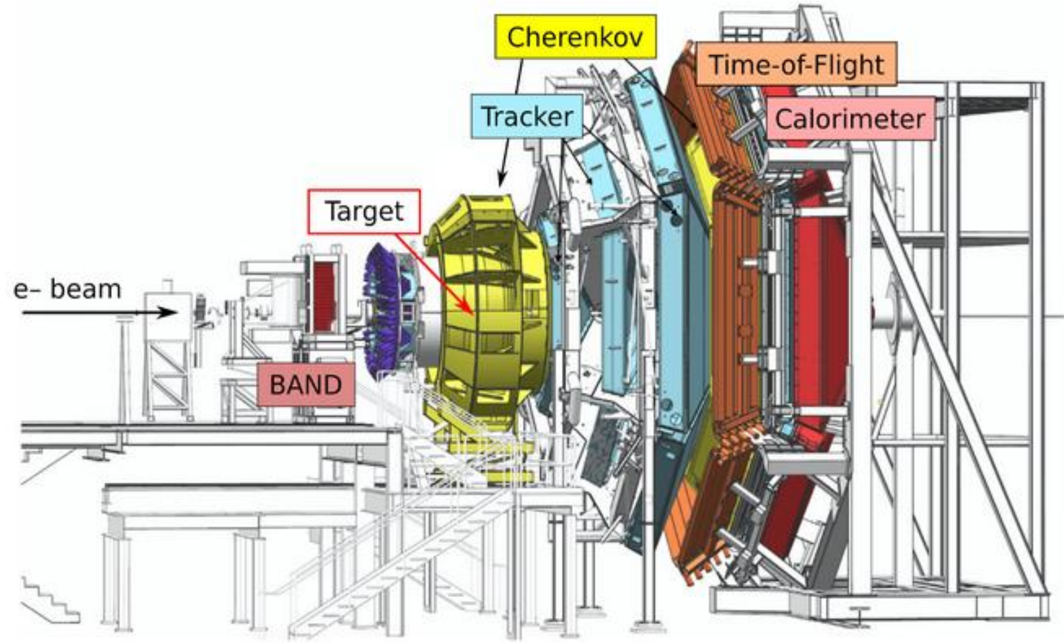
Tracking/Calorimetric Detectors: Summation





- 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

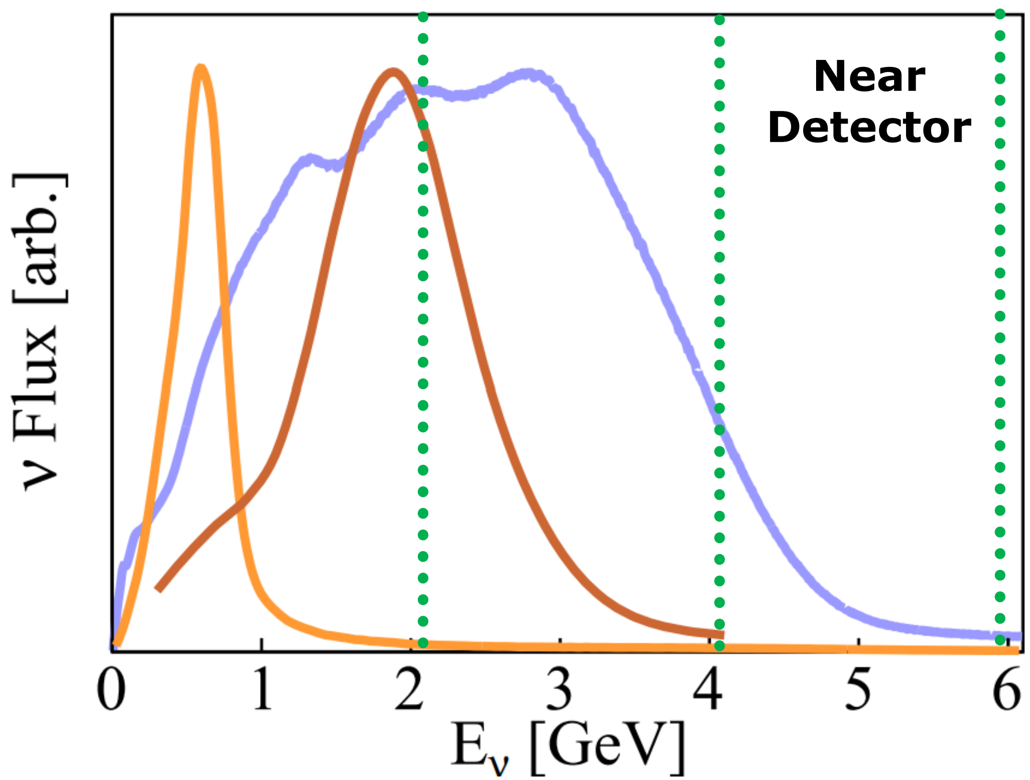
Support Letters

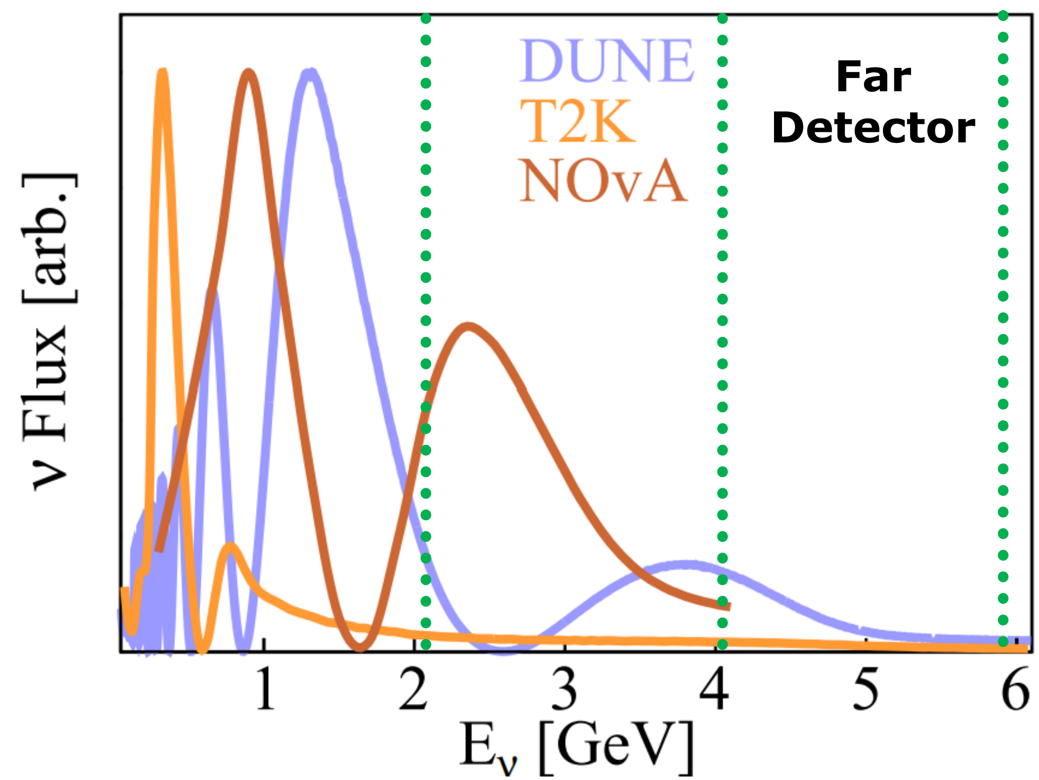
DUNE · IceCube South Pole Neutrino Observatory · Hyper-Kamiokande · T2K · NOvA · MINERvA · Fermilab · GiBUU The Giessen Boltzmann-Uehling-Uhlenbeck Project · Genie · μBooNE

Improvements Over CLAS6

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

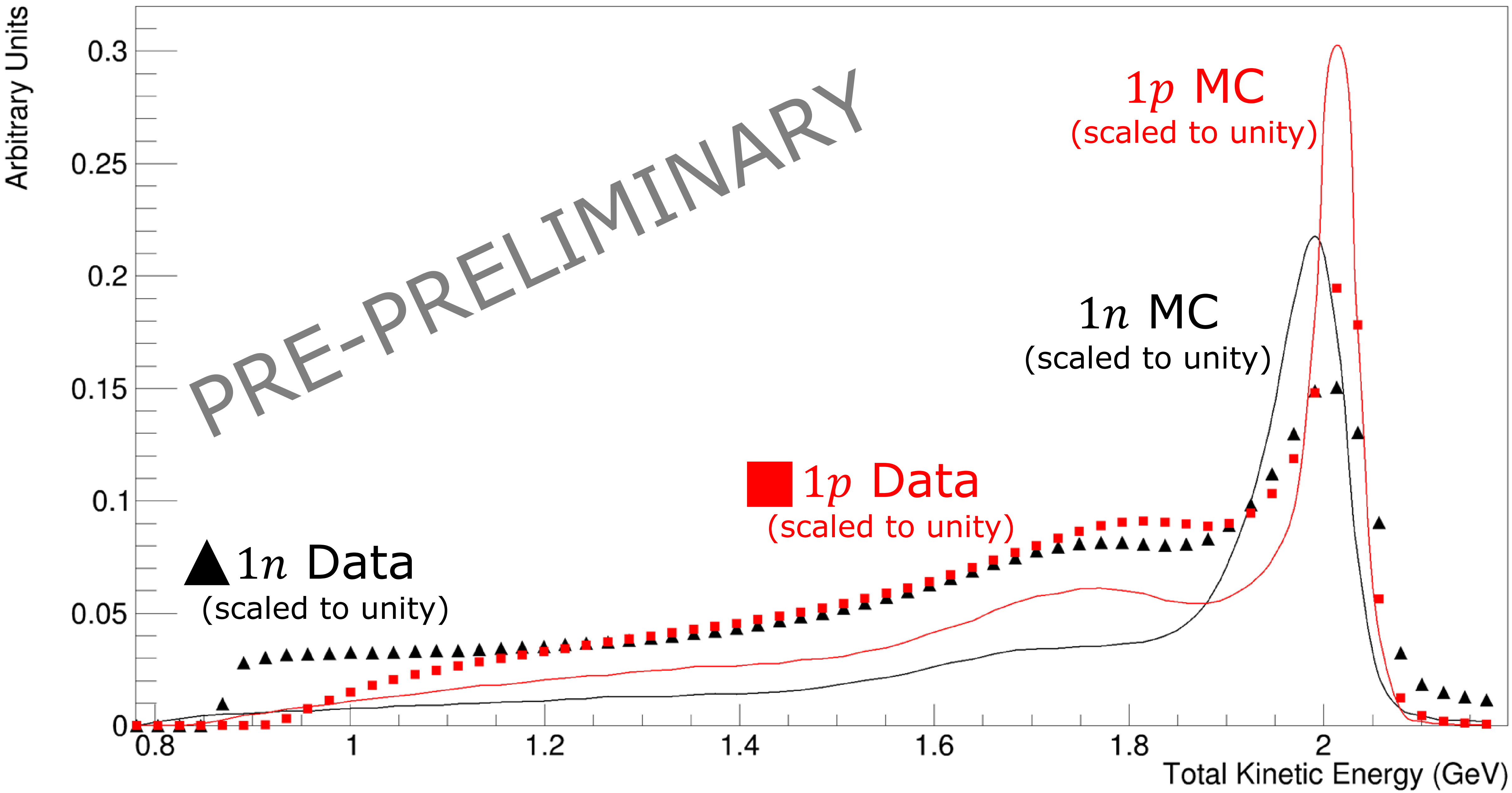
T2K — H_2O
NOvA — CH
SBN Program, DUNE — Ar





Initial Comparisons to Simulation

Showing Unphysical Differences?



Future $e4\nu$ Analyses

- Inclusive 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
- $(e,e'), (e,e'p), \left(e,e'\pi^{\pm}\right), (e,e'p\pi^{-}), (e,e'pp), (e,e'n), (e,e'pn)$...
  - "Traditional" kinematic variable for first GENIE tunings
  - Transverse kinematic variables (FSIs, nuclear models)
- Transparency studies (FSIs)
- Ca/Ar ratios
- Spectral functions, nuclear models

Goals of the μ4ν Initiative

Goals of $\mu 4\nu$

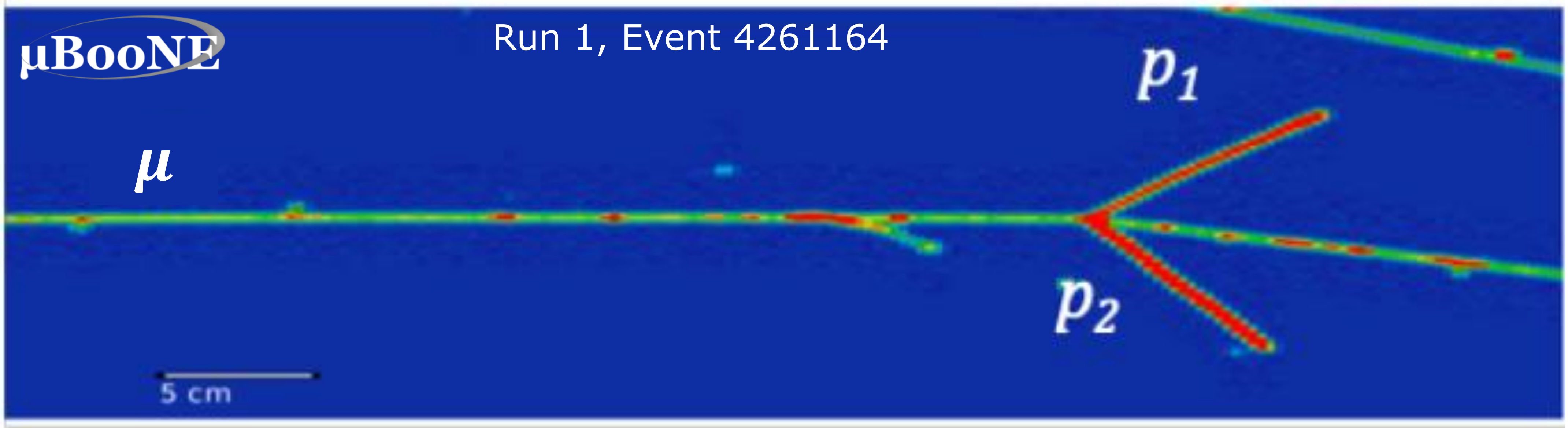
Use cosmic μ interactions (like e!)

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

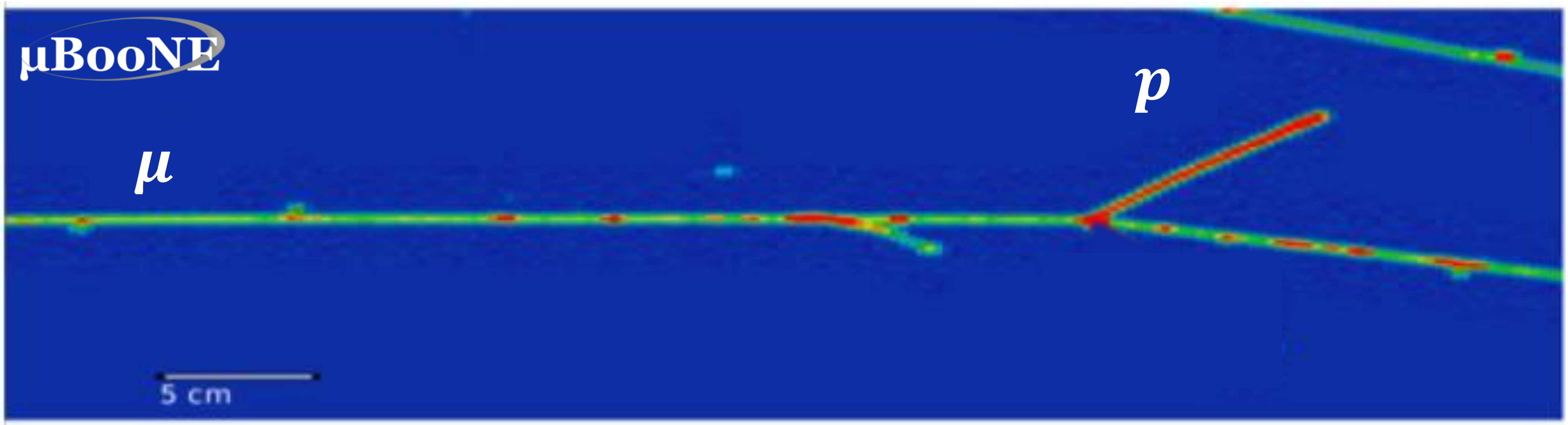
Courtesy of A. Furmanski



Multiprong (4) QE-like candidate

[Reconstructing cosmic muon scatter events in MicroBooNE]

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

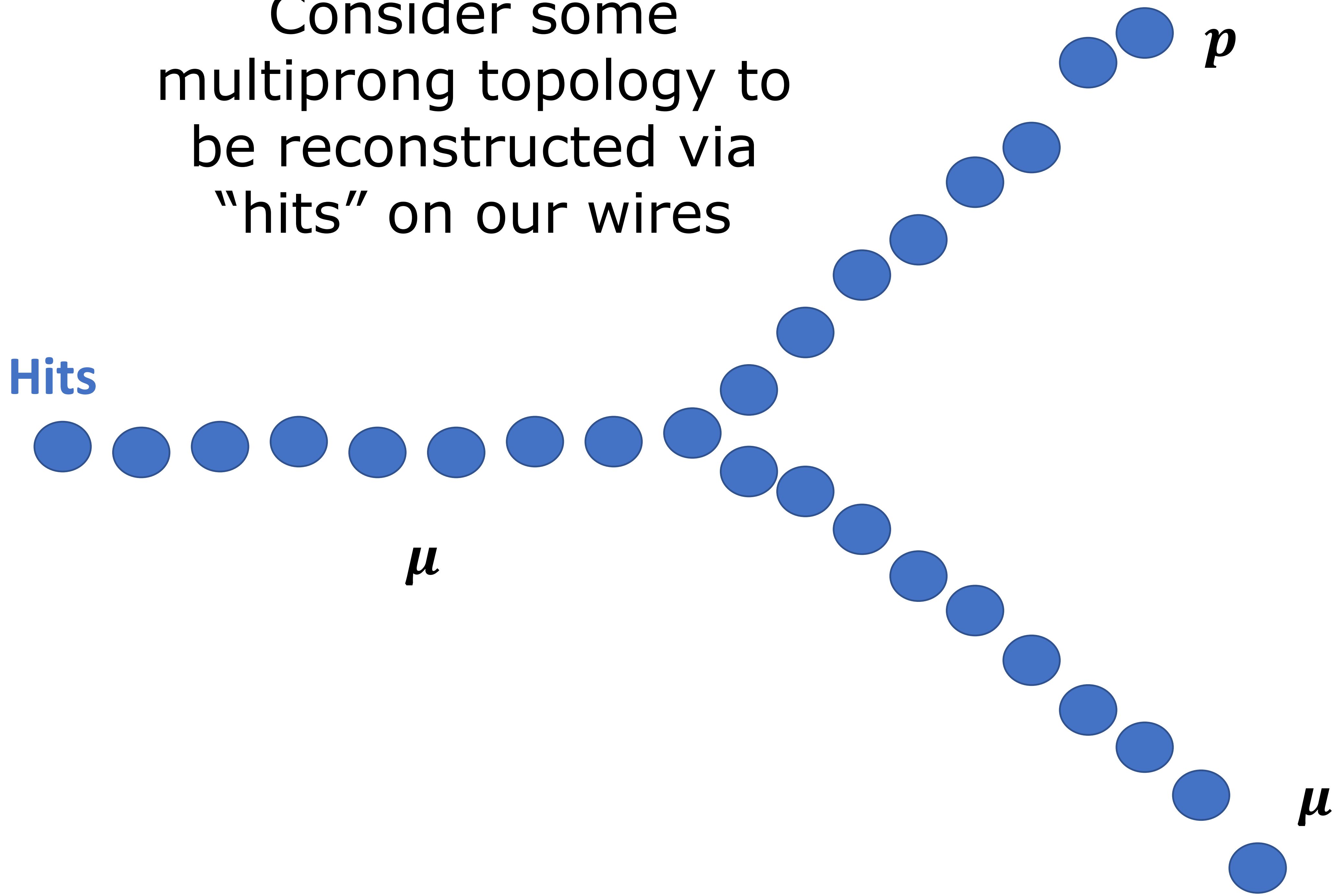
- Reconstructed energy comparisons *in situ*
- Care about energy *just before*/*after* interaction
- Offer online calibration

QE-like candidates offer simplicity

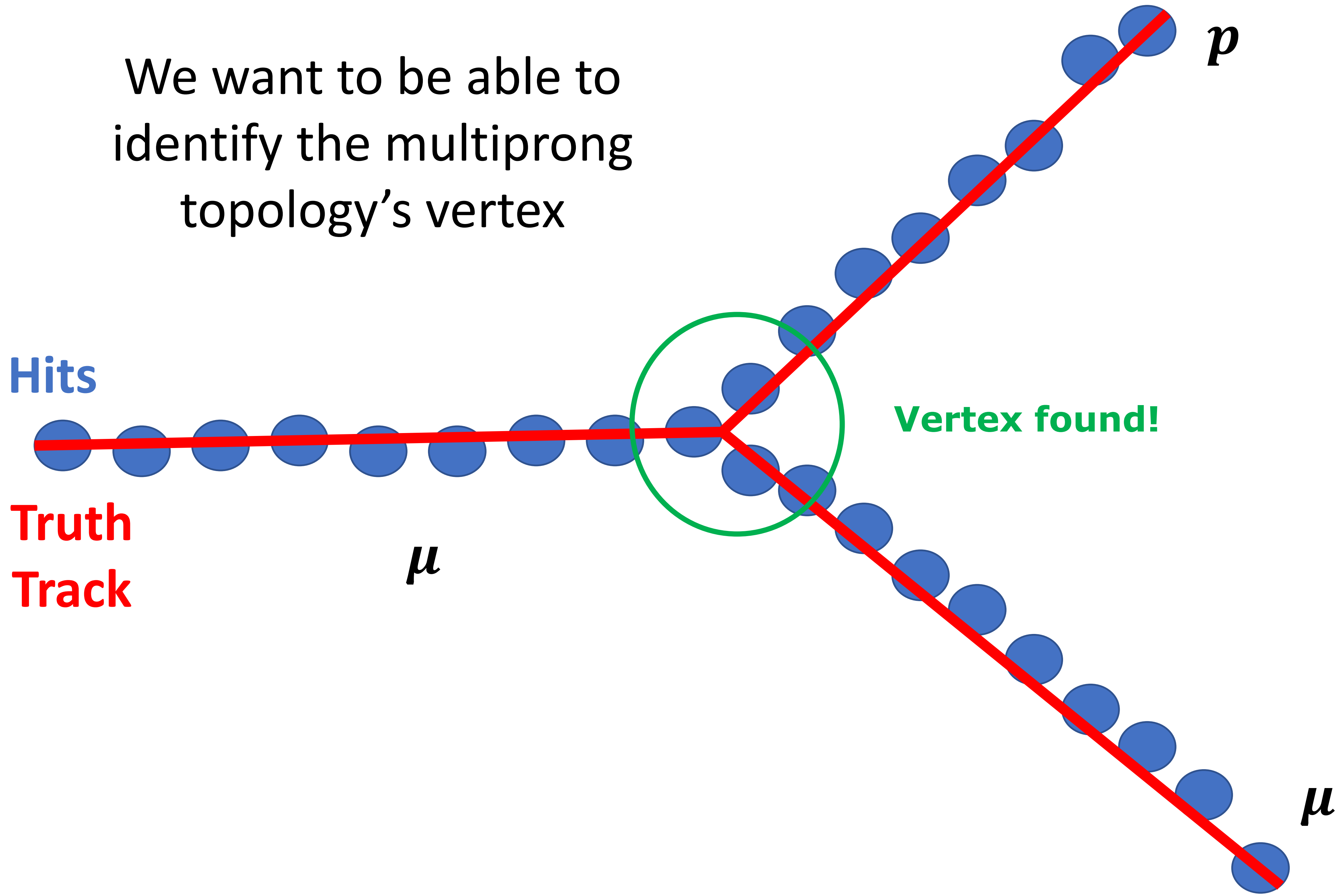
- Better understandings of E reconstruction
- Other topologies possible

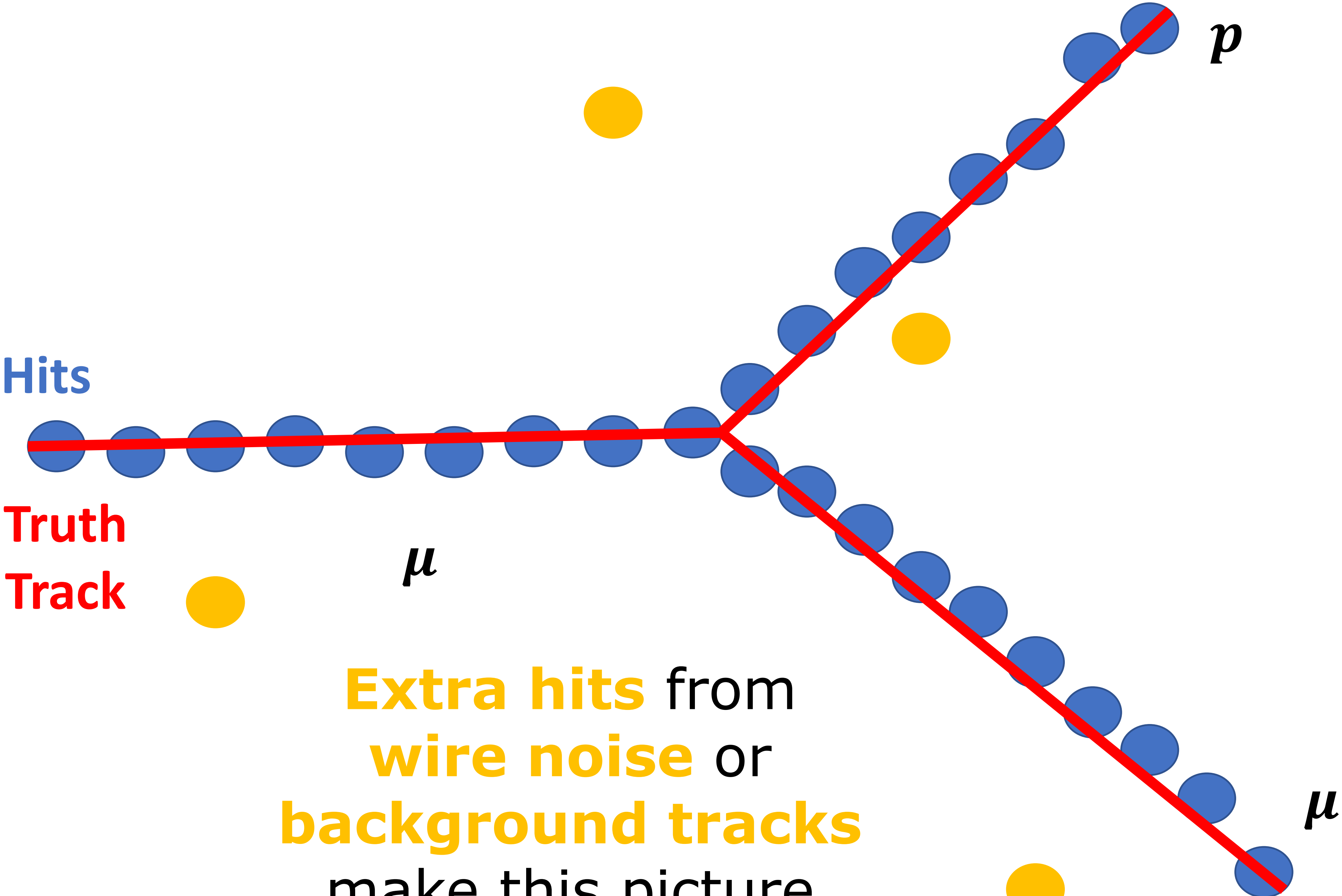
Cosmic $\mu + \mathrm{Ar}$ cross sections (potentially)

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

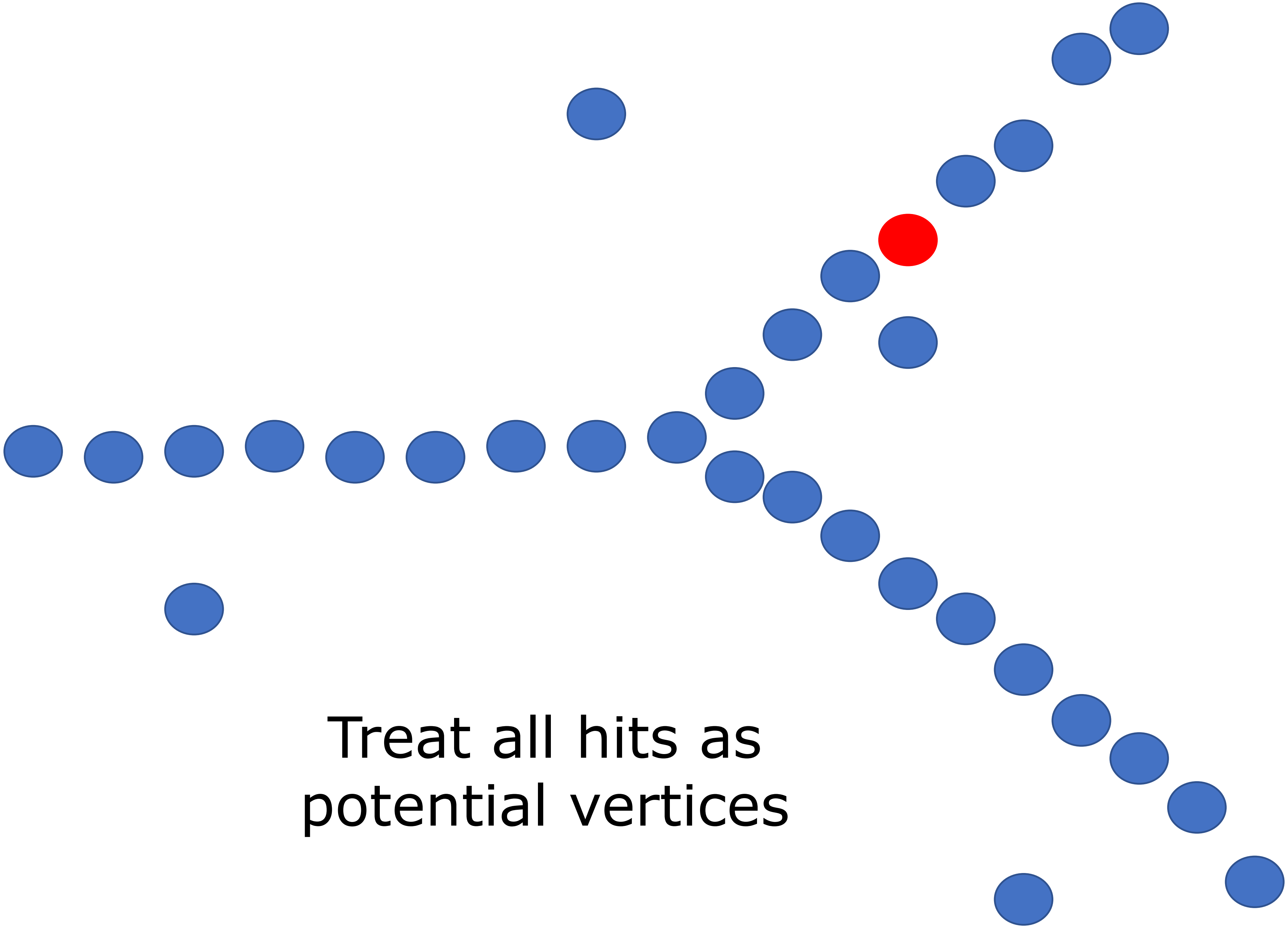


We want to be able to identify the multiprong topology's vertex

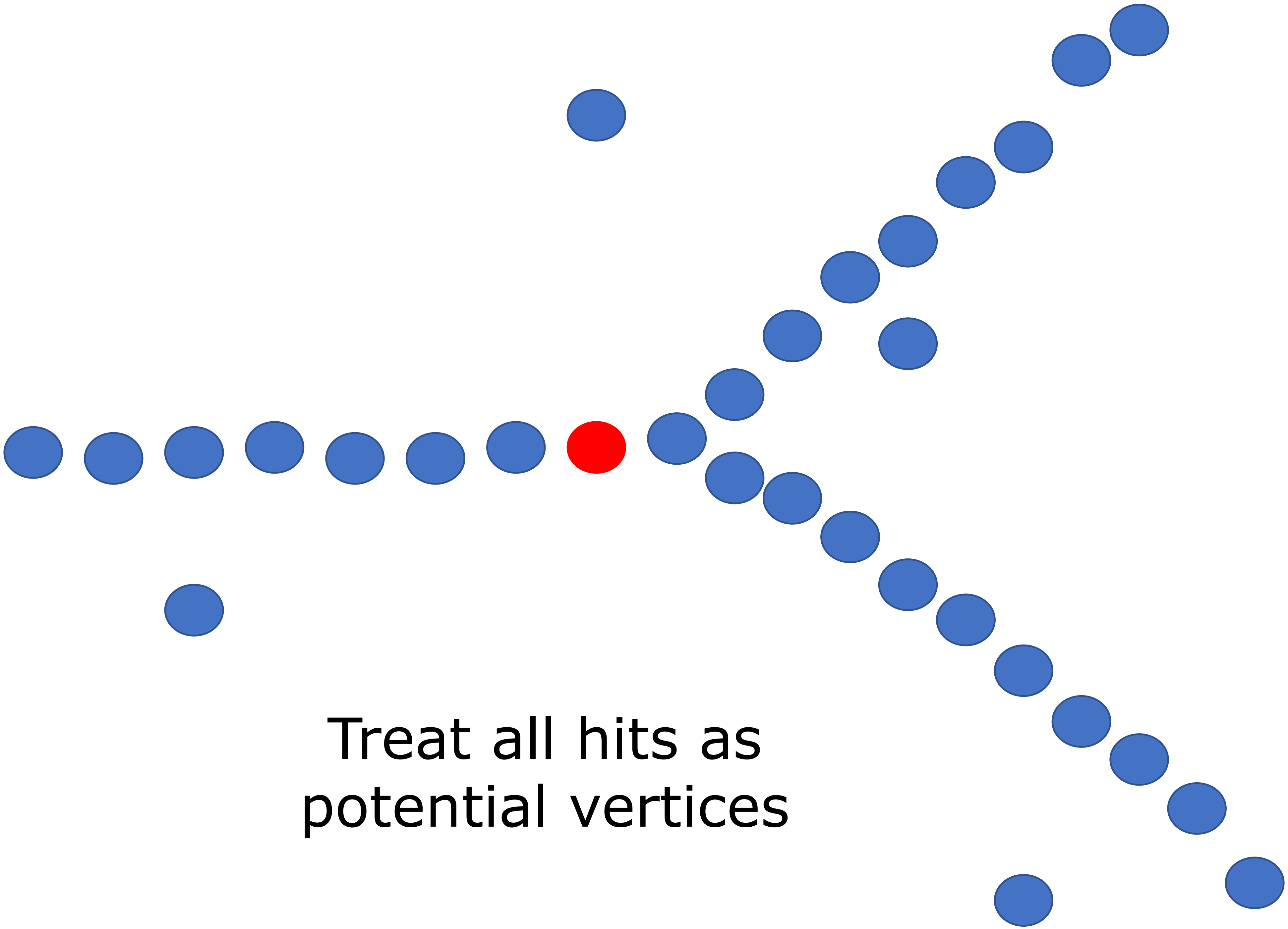




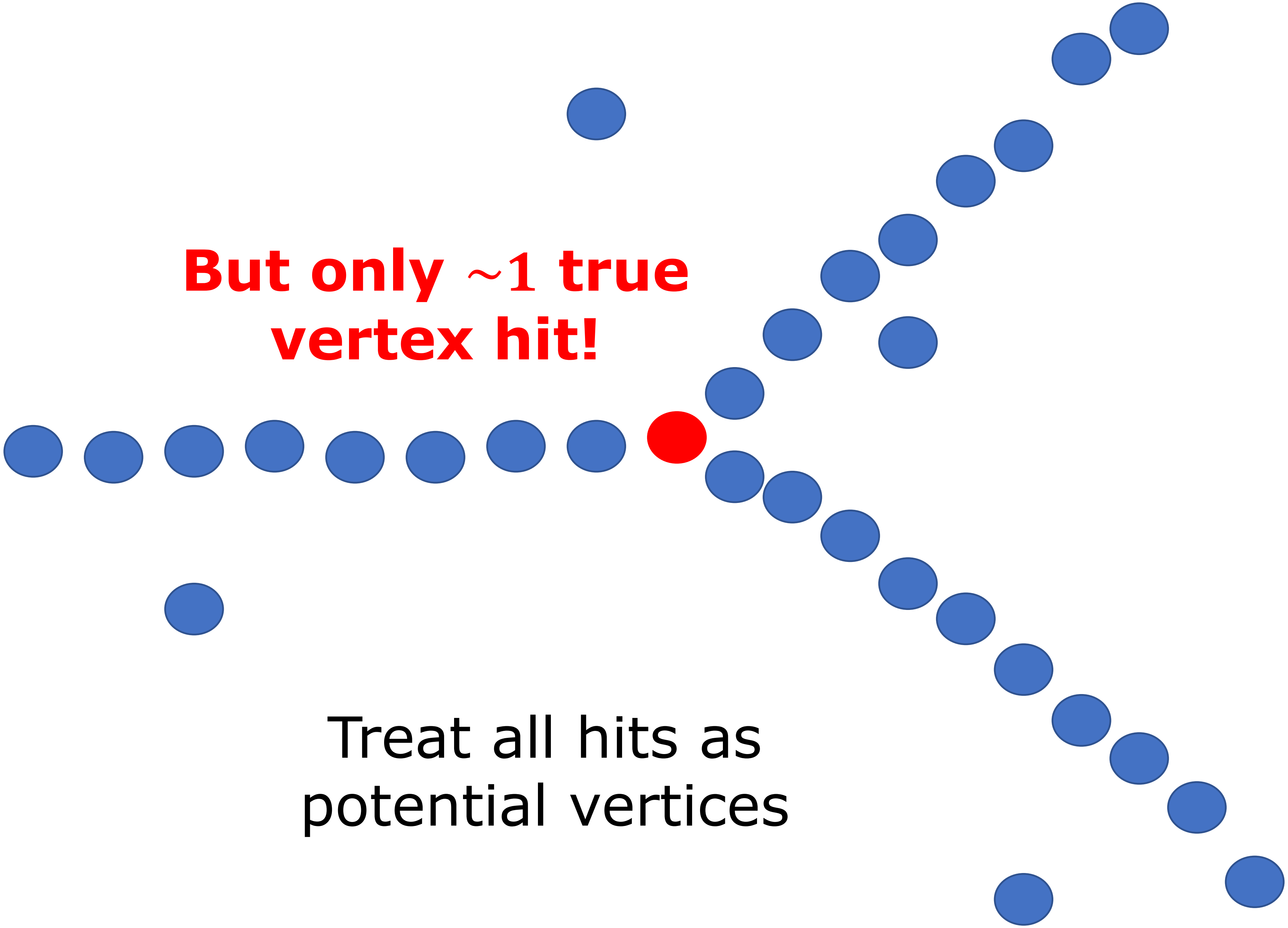
Extra hits from **wire noise** or **background tracks** make this picture more complicated



Treat all hits as potential vertices

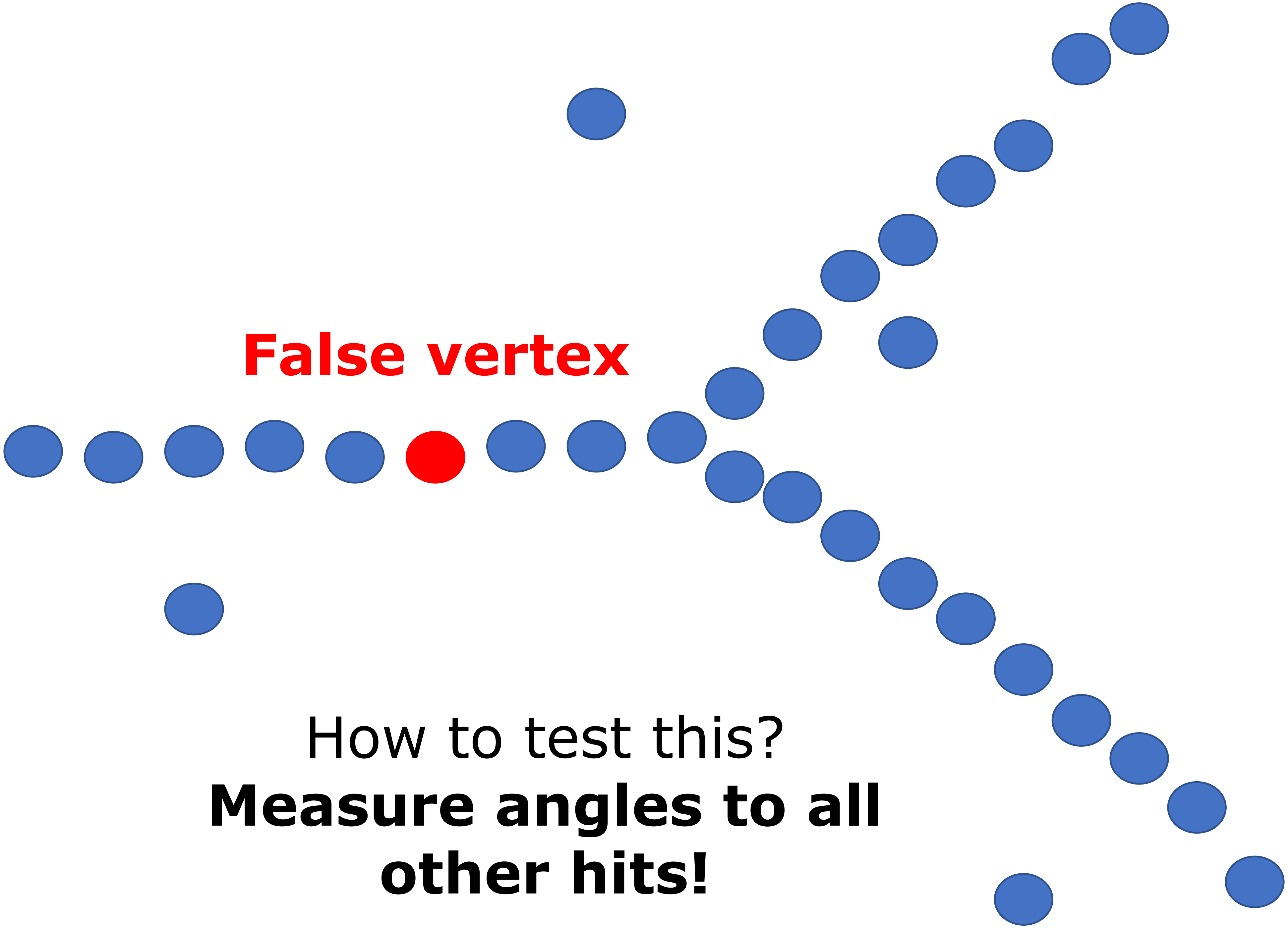


Treat all hits as
potential vertices



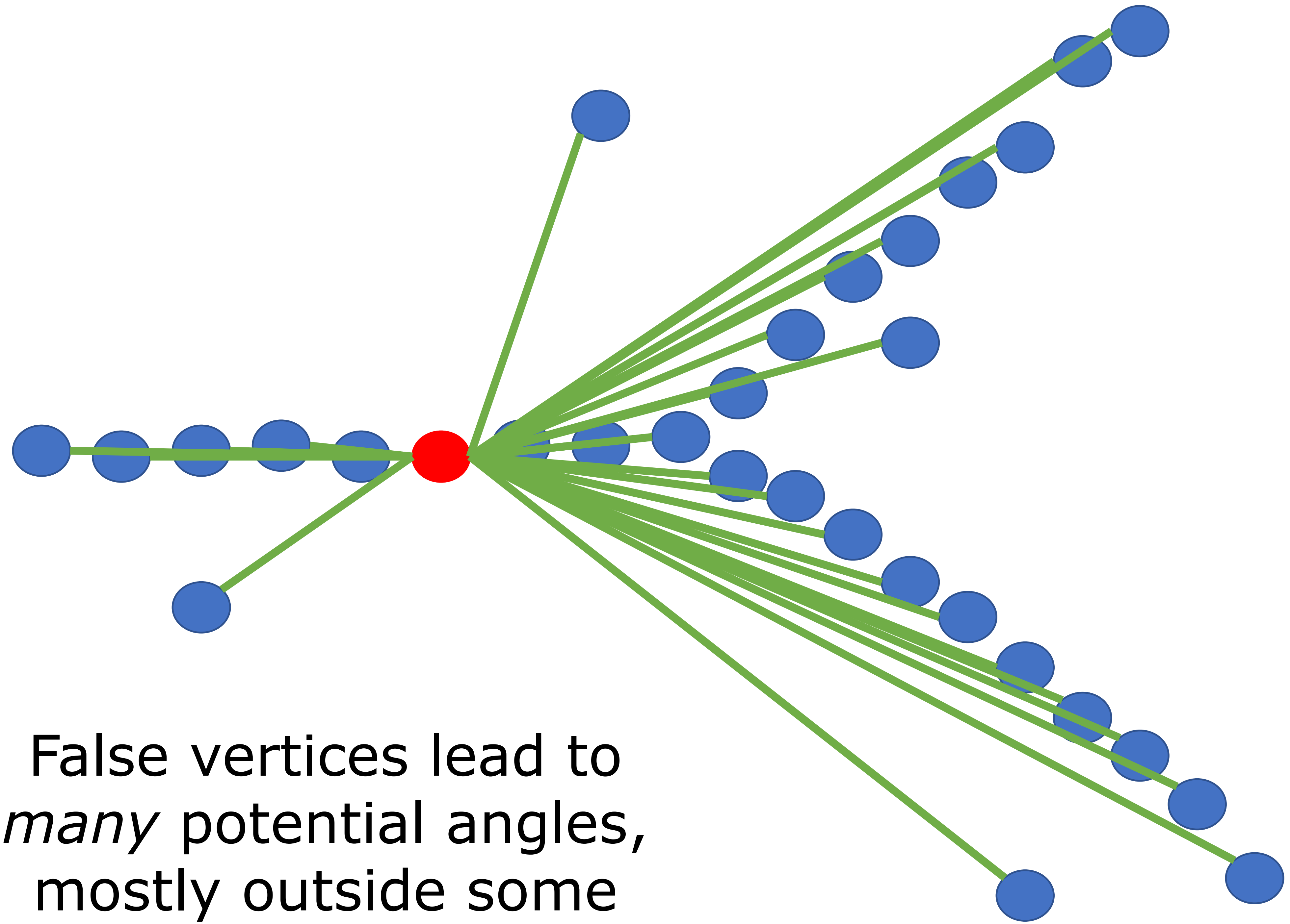
But only ~1 true vertex hit!

Treat all hits as potential vertices

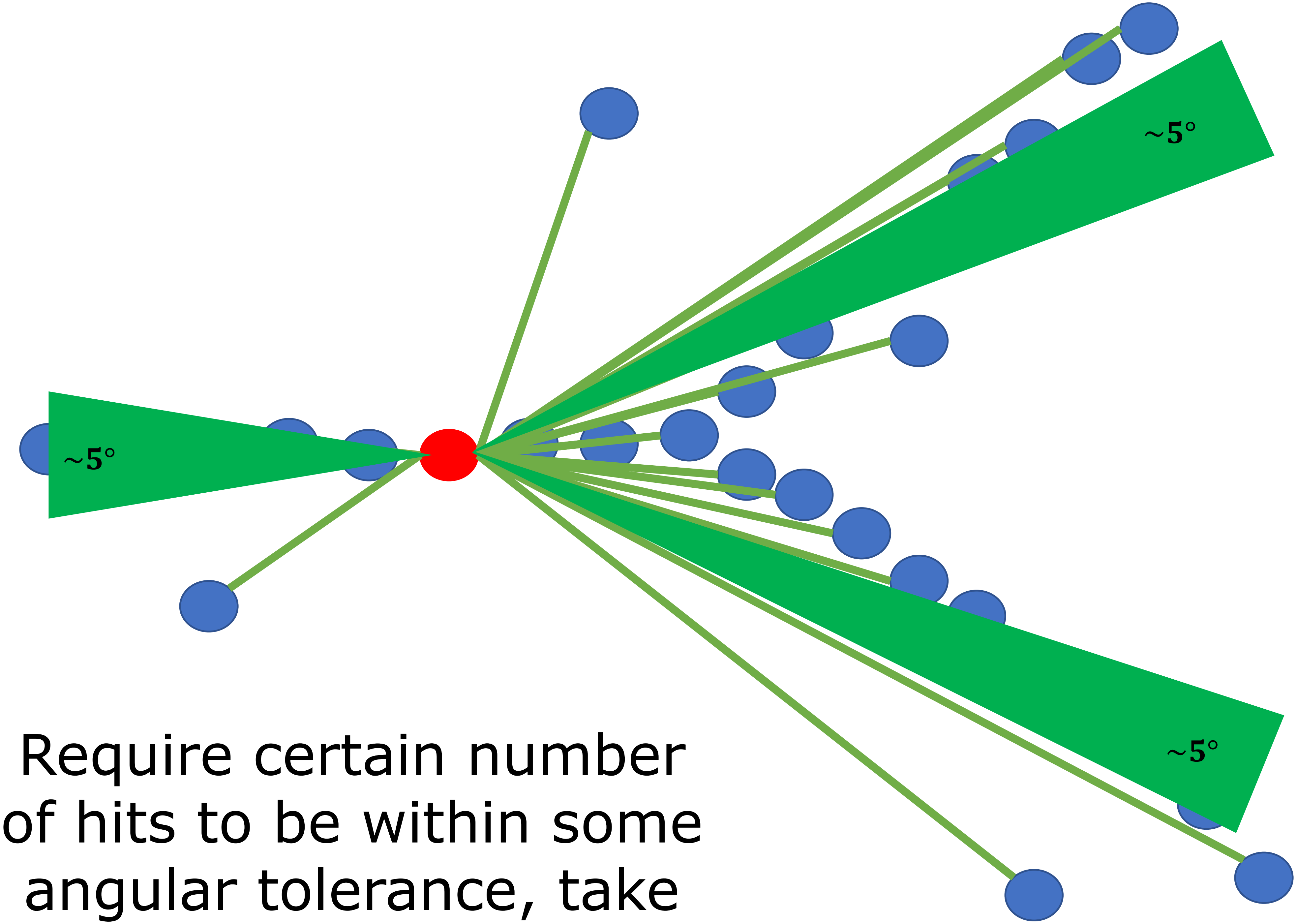


How to test this?

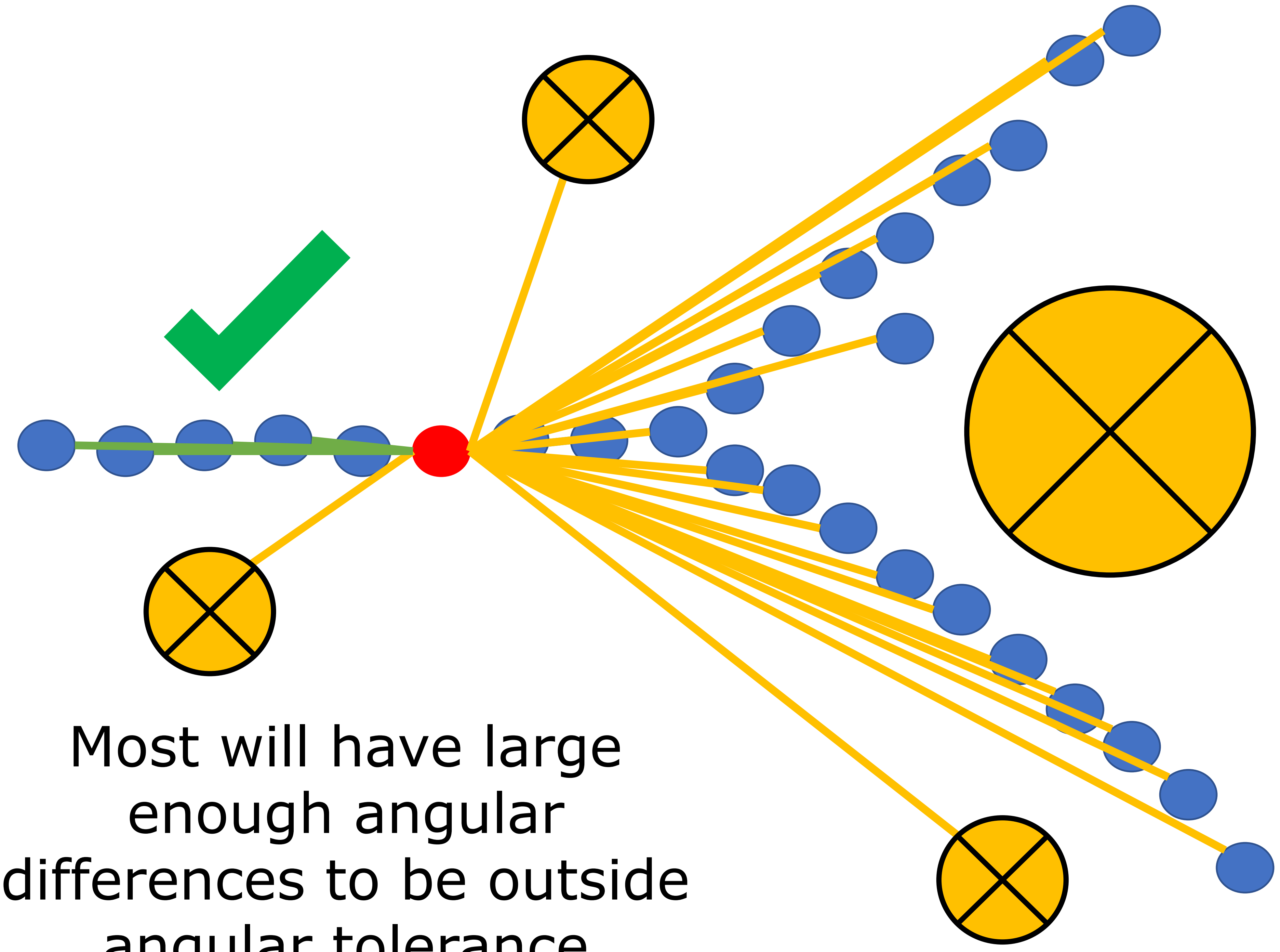
Measure angles to all other hits!



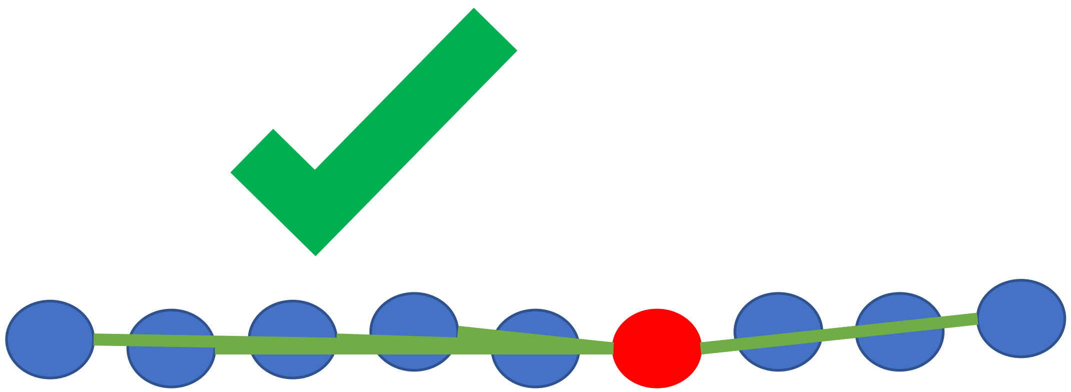
False vertices lead to *many* potential angles, mostly outside some angular tolerance



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

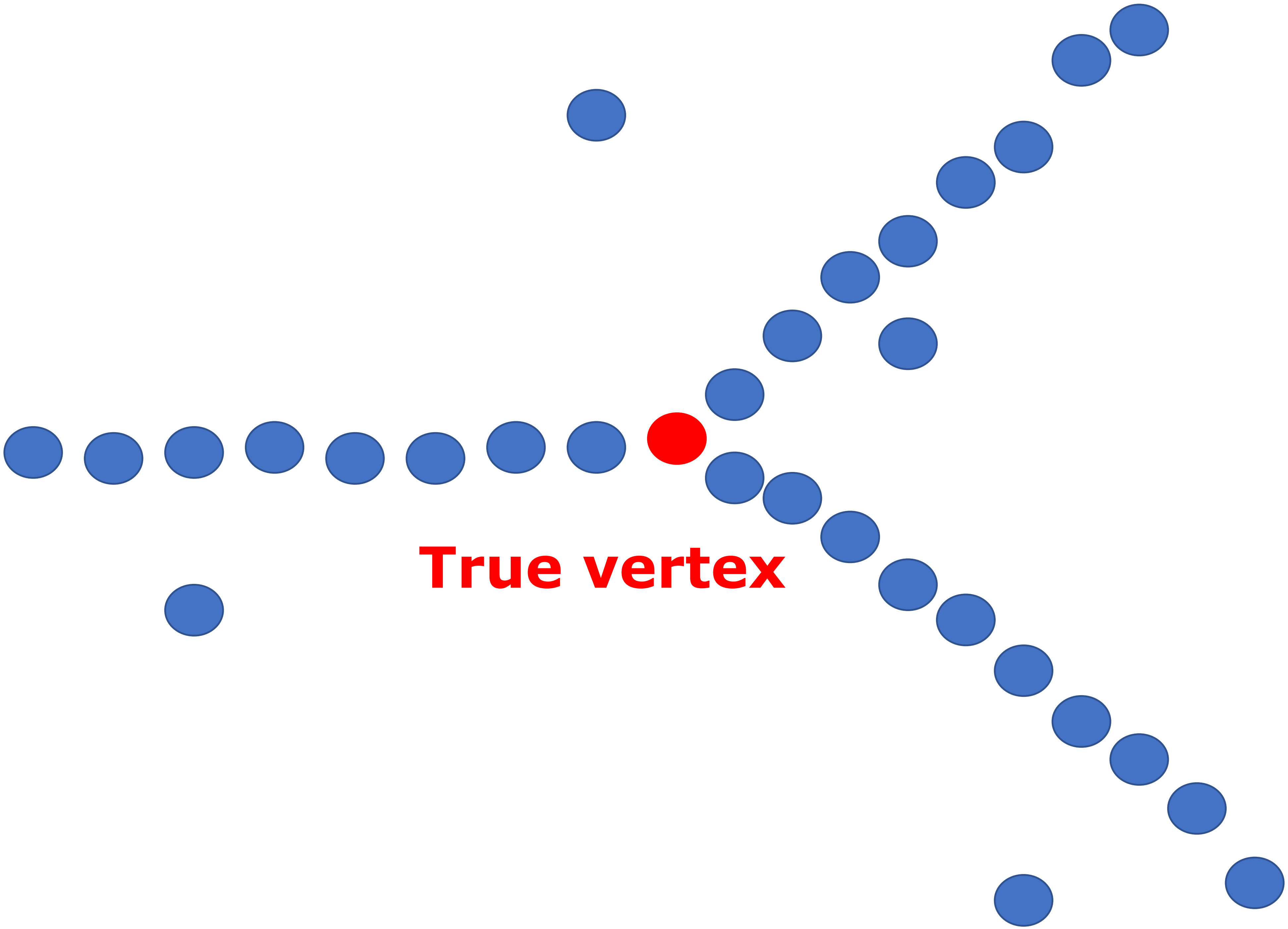


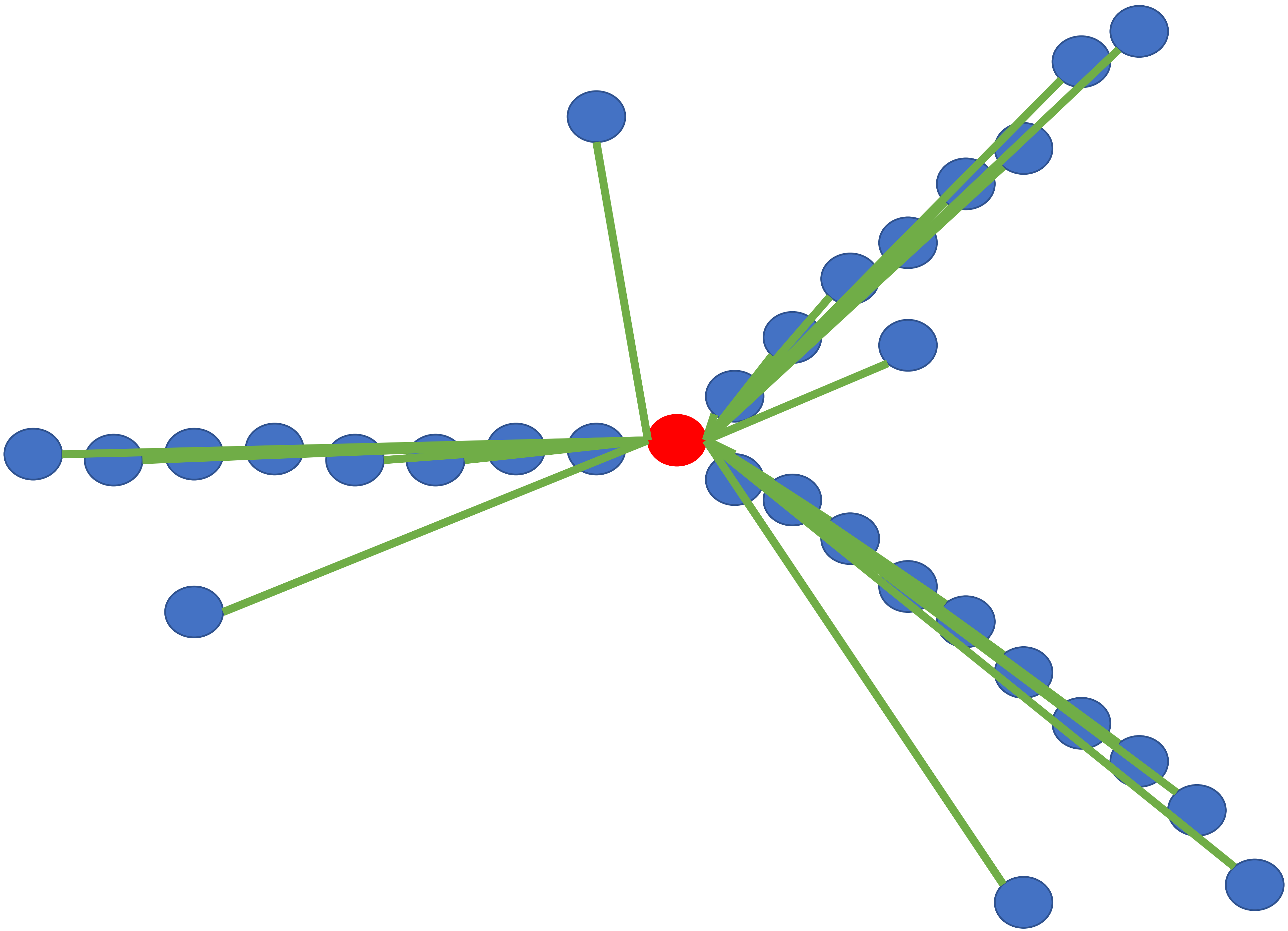
Most will have large enough angular differences to be outside angular tolerance

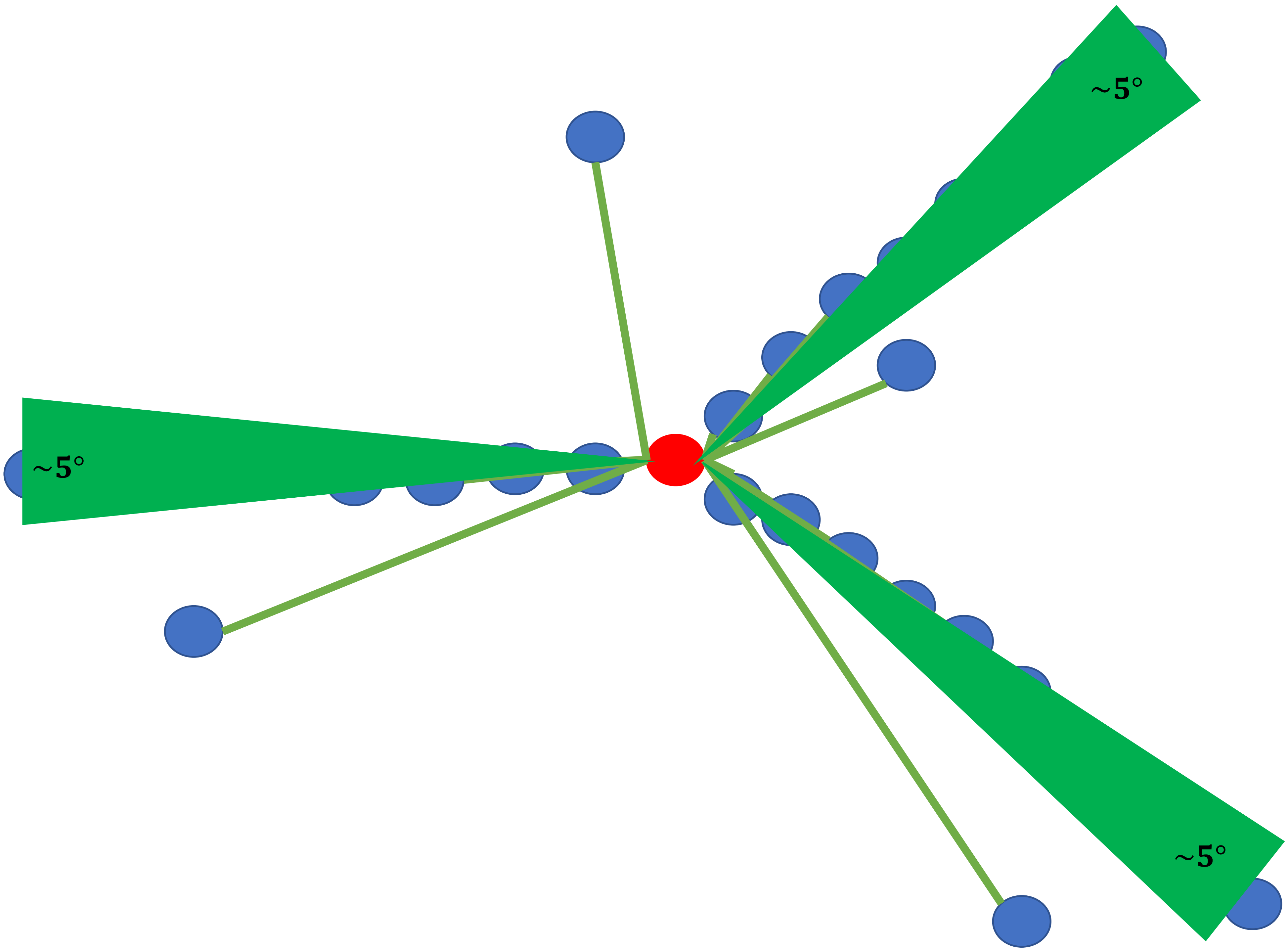


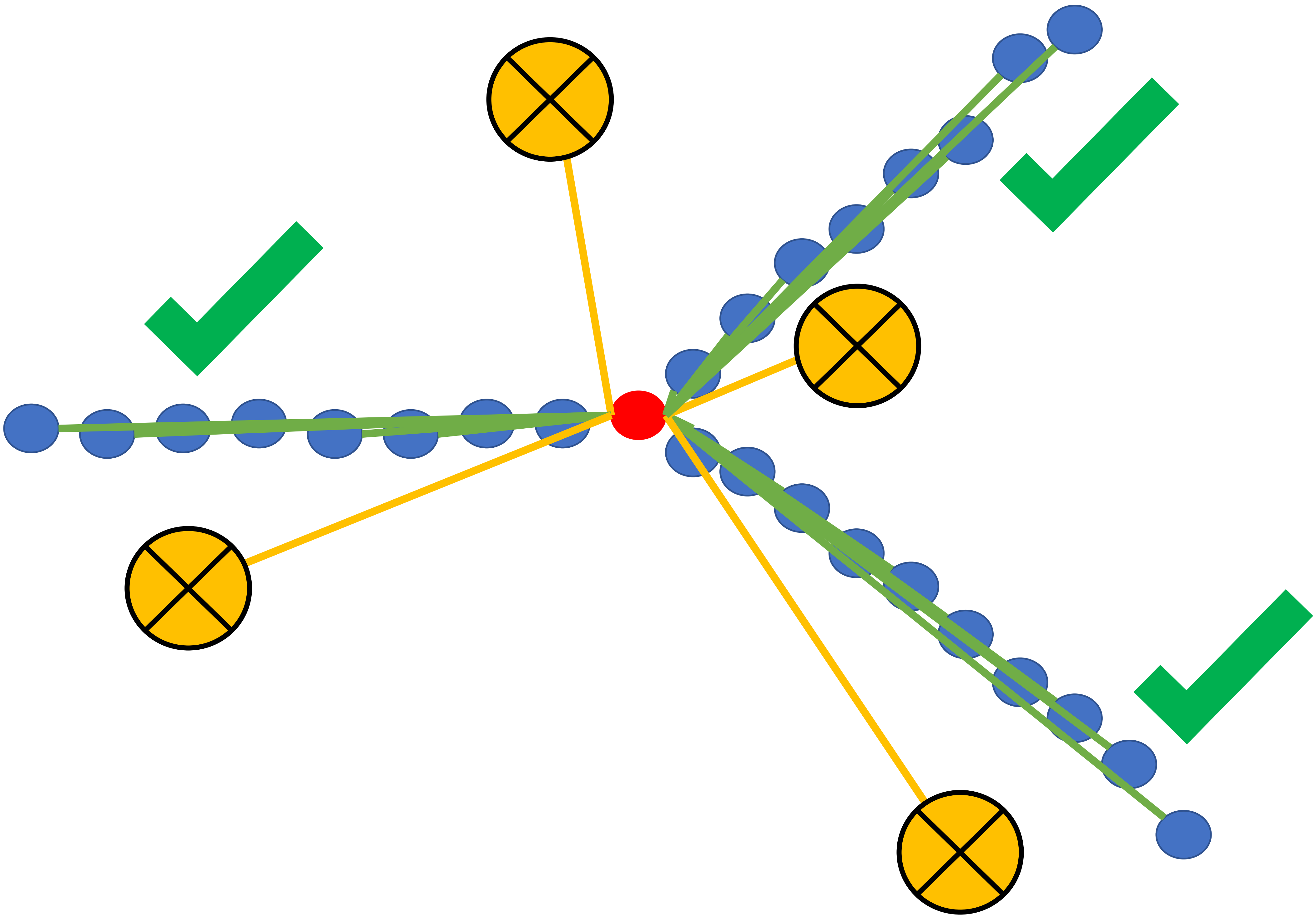
This greatly limits the number of possible tracks of particular angles which can be triggered on

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

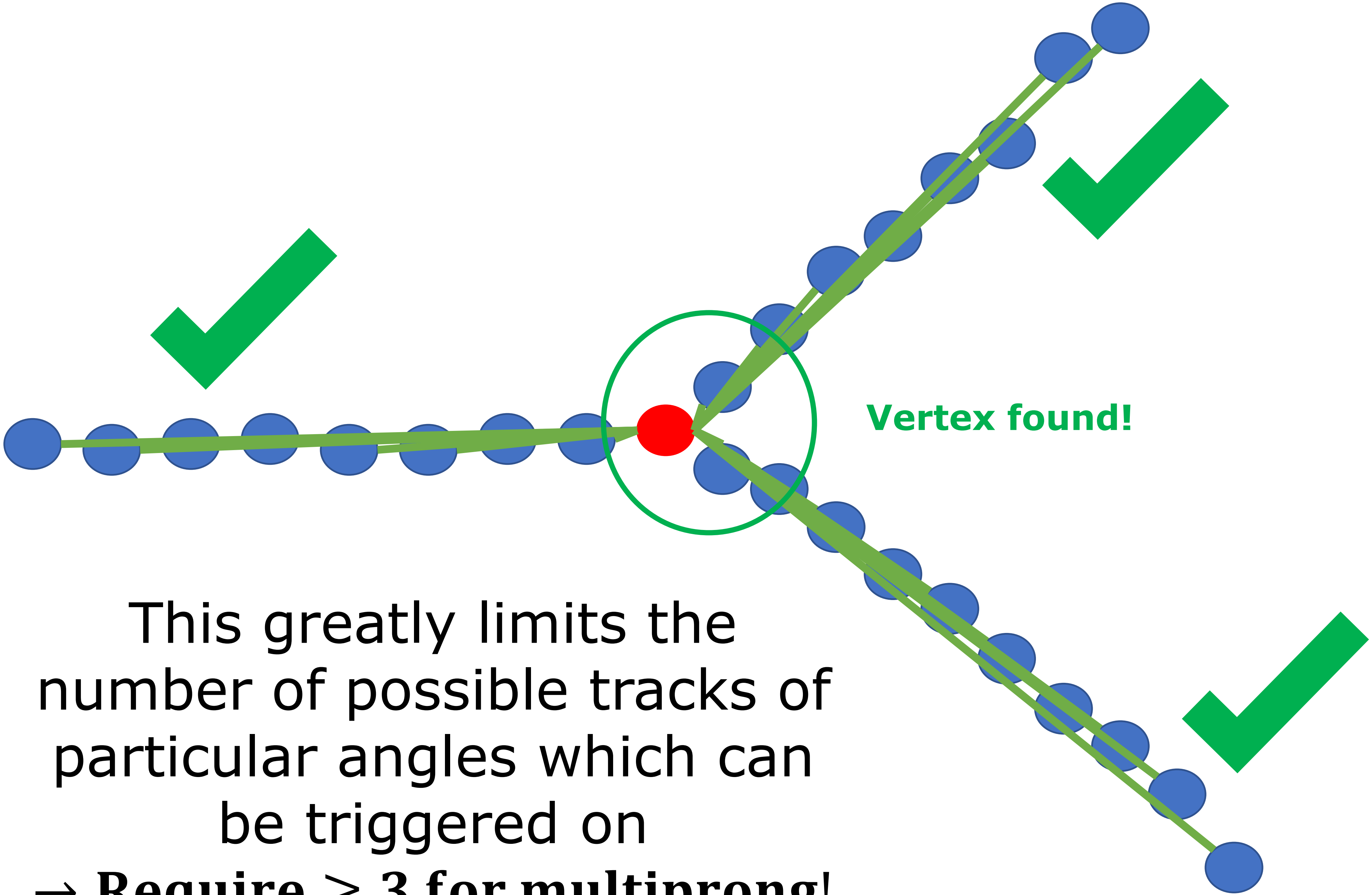

True vertex




~5°
~5°
~5°

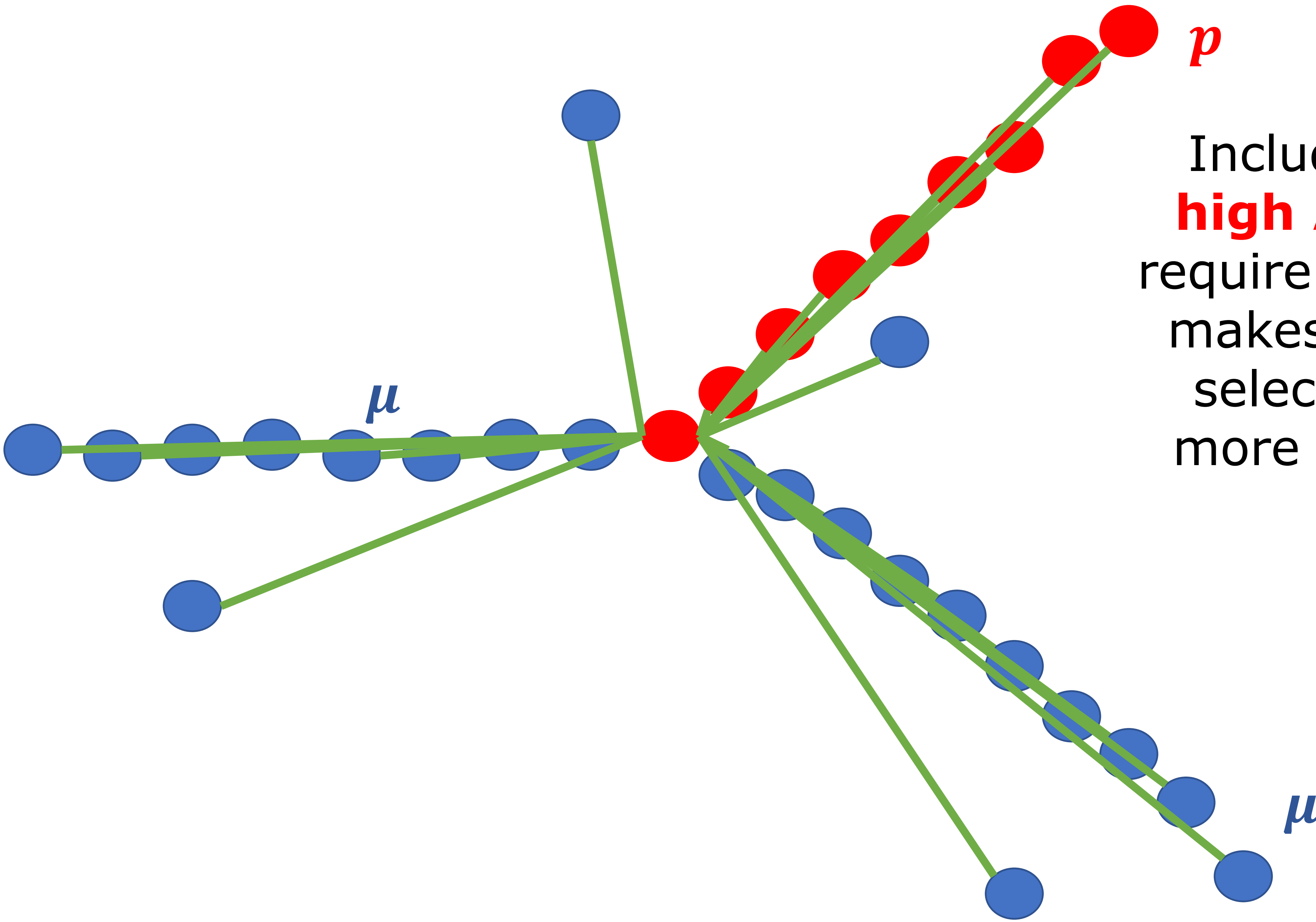


Original idea developed in conversation with A. Ashkenazi



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

→ **Require ≥ 3 for multiprong**!



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

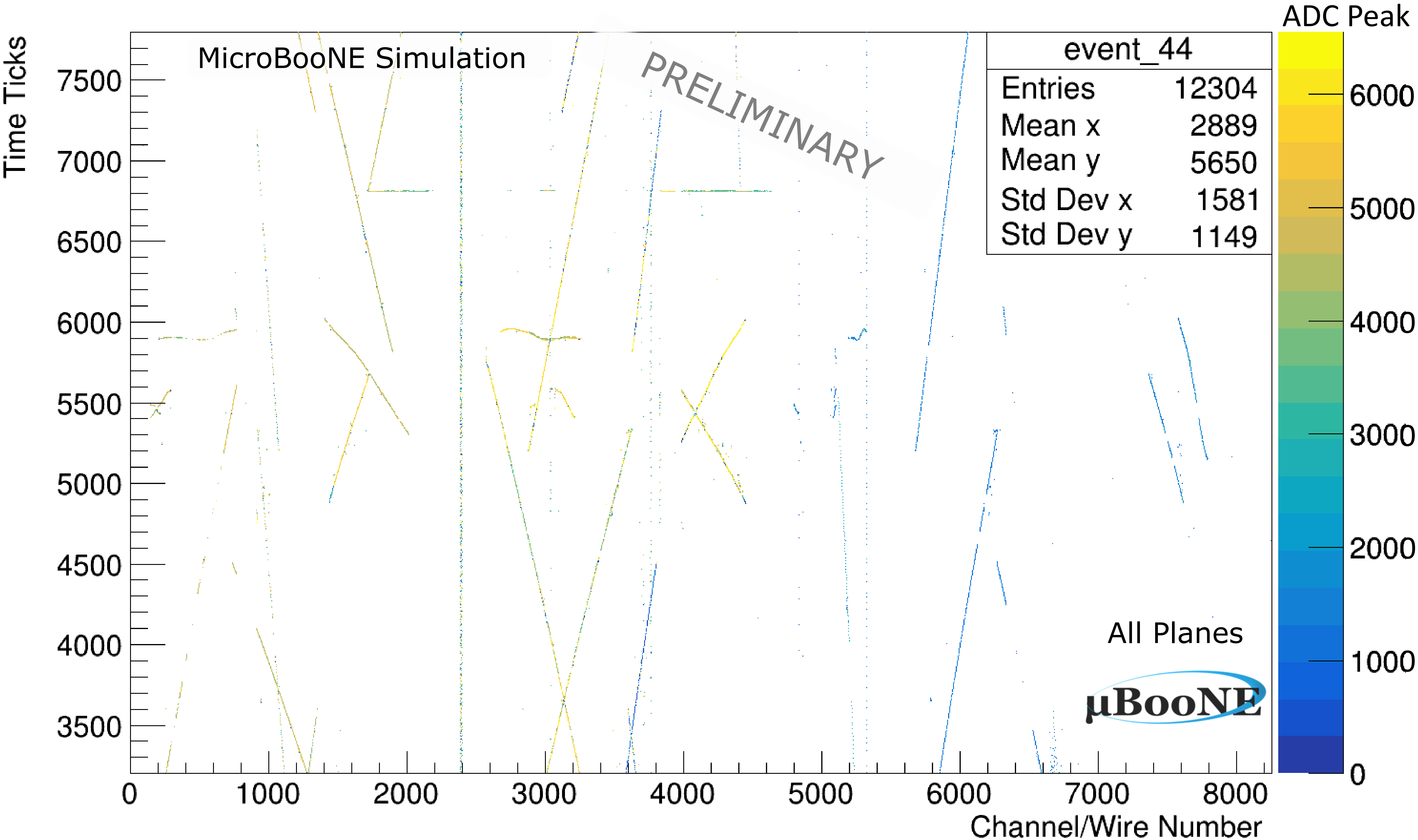
- Estimate simulated with cosmic flux:
  - ~ 4000 cosmic μ per second

- $\sim 1\mathrm{Hz}$ true QE interactions above threshold

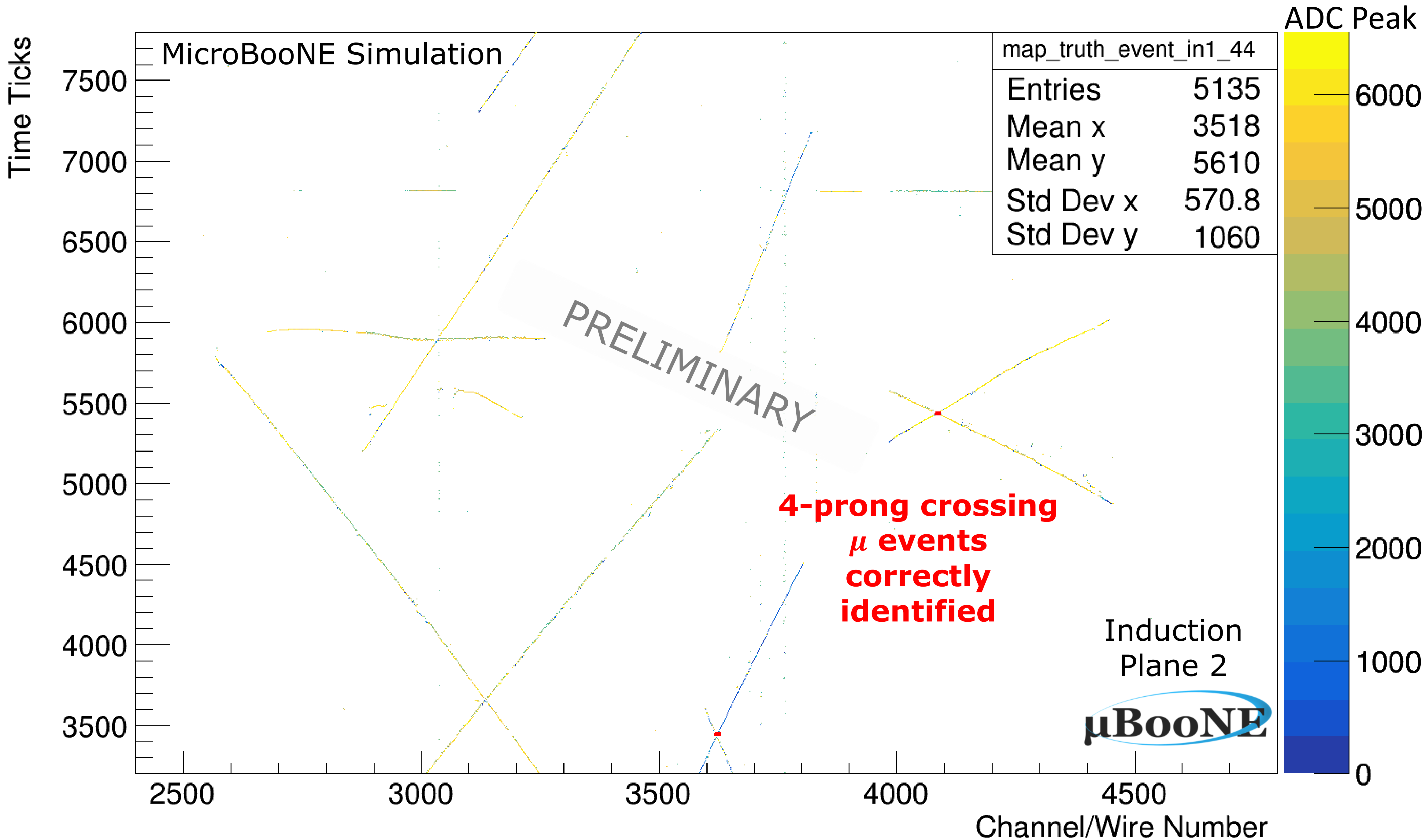
Courtesy of A. Ashkenazi and W. Van De Pontseele

CORSIKA

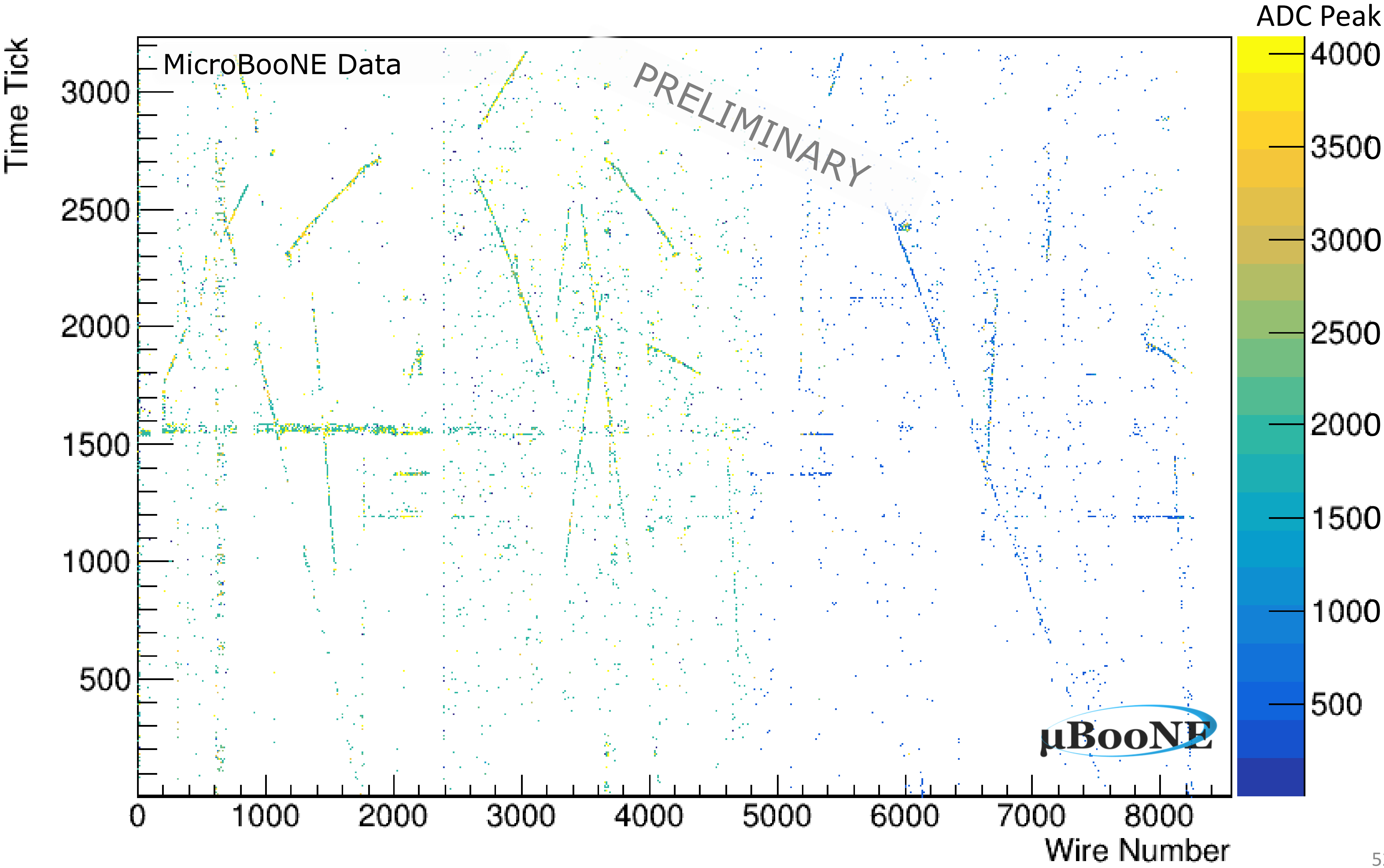
Monte Carlo Data View



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!

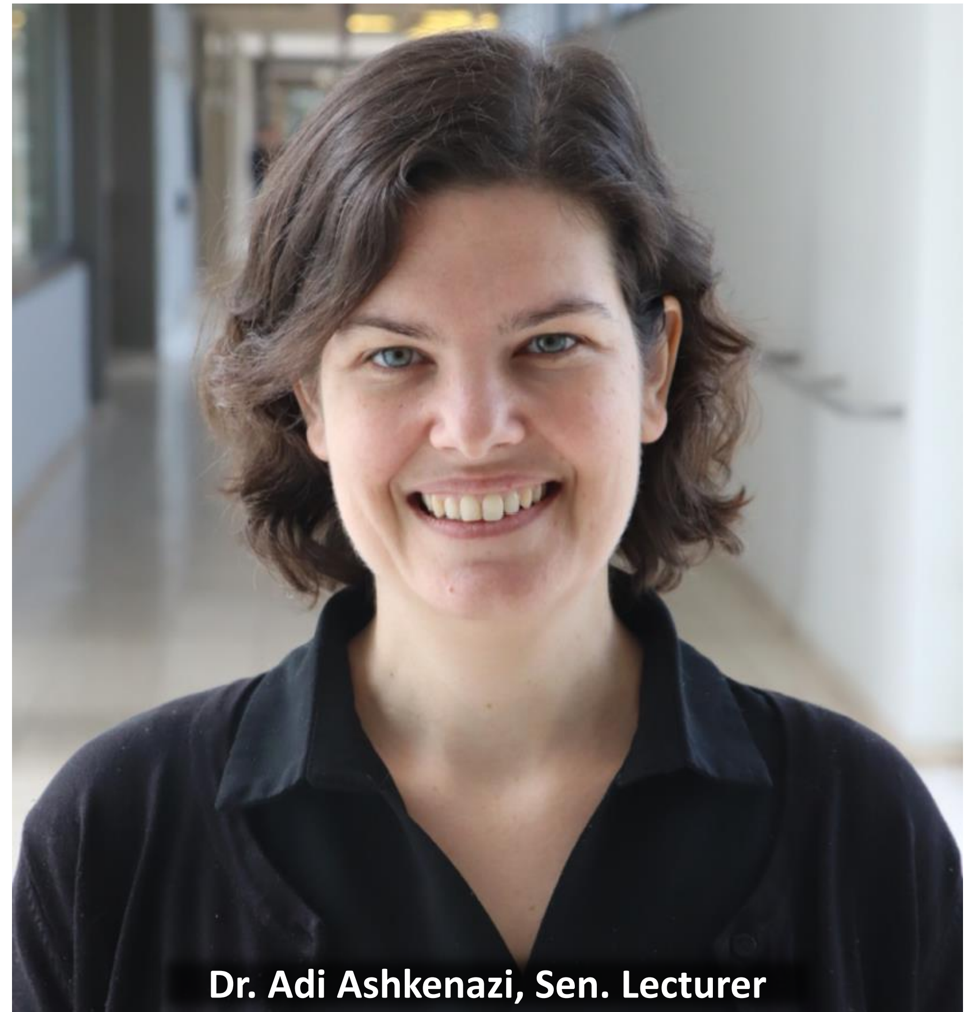
Left to right:

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

μ4ν μBooNE

e4ν clas

Thanks to the TAU Group!



Dr. Adi Ashkenazi, Sen. Lecturer

Josh Barrow, PD

Julia Tena-Vidal, PD

Amir Gruber, UG

Alon Sportes, MS

Matan Goldenberg, MS

Thanks to the uB TP R&D team!

Thank-you for your attention!

Questions?