Calorimetry Reconstruction & Particle Id

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Workshop on Calibration and Reconstruction for LArTPC Detectors

11th December 2018

Outline

Motivation: ν energy reconstruction for the precision in oscillation era

PId by technology and energy range

PId methods using calorimetry
- **Bragg peak observation: first proton selection @MicroBooNE**
- **Non-Bragg peak observation**

Motivation: ν energy reconstruction for the precision in oscillation era

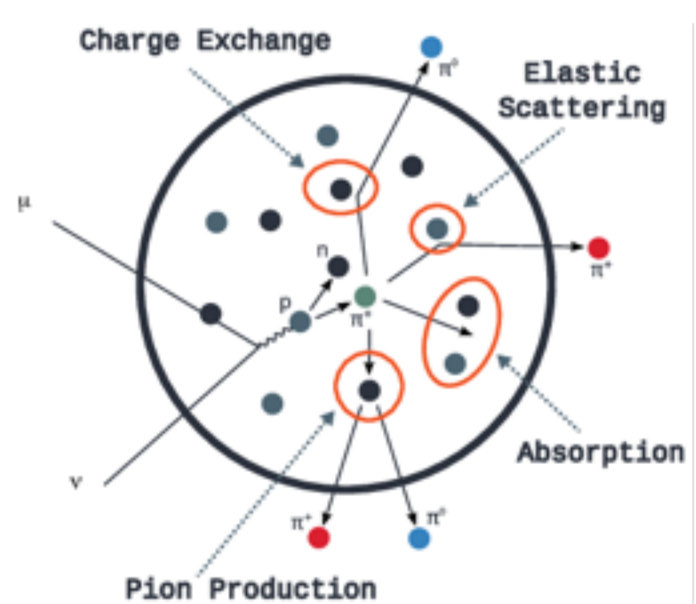
Neutrino energy in an event-by-event basis?

Identification of particles that emerge from the nucleus.
- Model approach (pion-less events assumed as CCQE,…)
- Visible energy

To measure neutrino energy in an accelerator experiment requires particle identification (PId).

Undetected particles, either because they **didn't emerge from the nucleus** or because **they are below the energy detection threshold**, bias our neutrino energy calculation.

- Particles not emerging from the nucleus have to be corrected by the models (theory and MC builders).
- **Lowering energy detection threshold and extending the PId increases our neutrino energy accuracy**. Also provides rich information from exclusive topologies to support theory/MC efforts.



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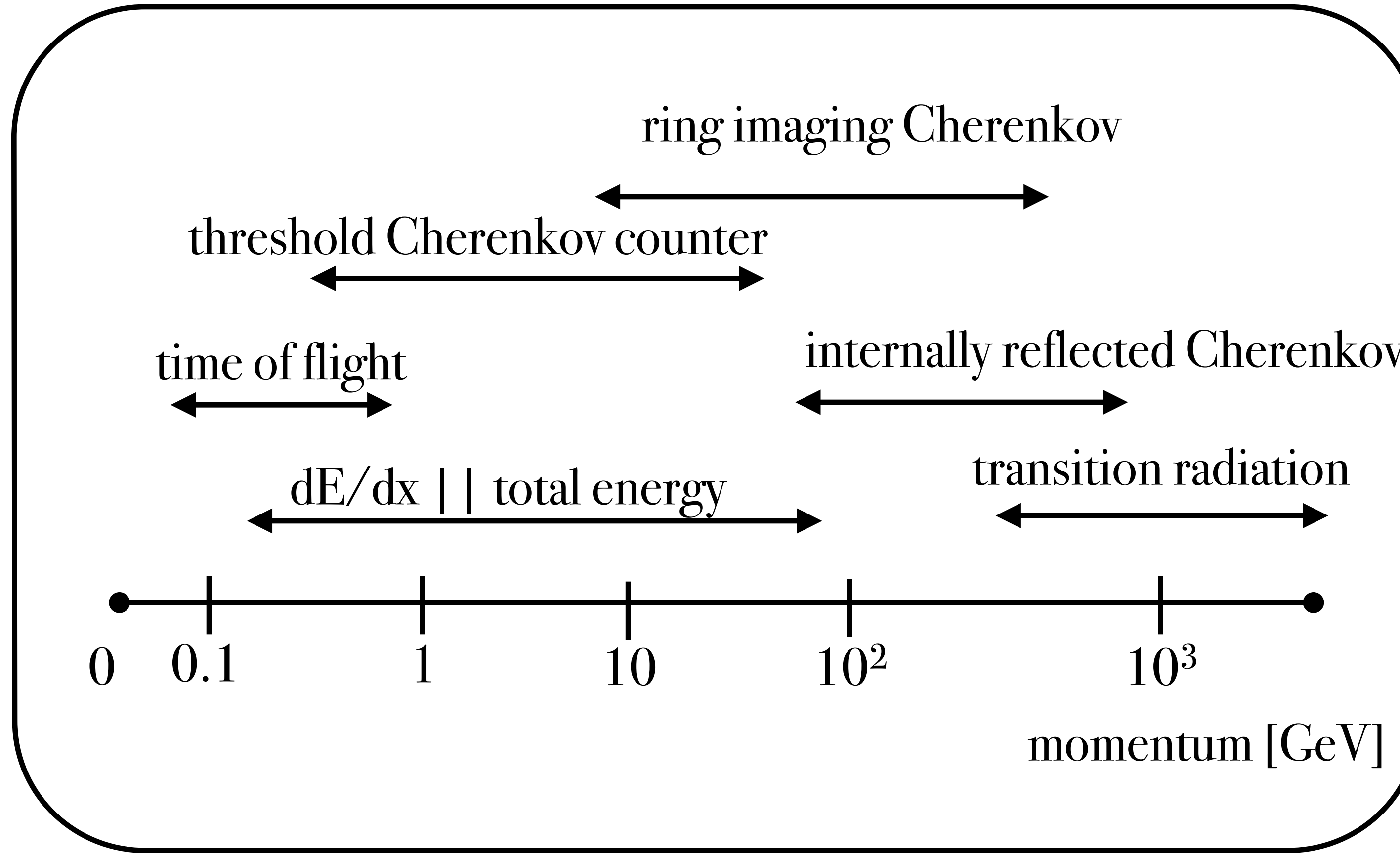


PId for stable particles:

Time-of flight: $\tau \propto 1/\beta$

Cherenkov angle: $\cos\theta = 1/n\beta$

Transition radiation: $\alpha \geq 1000$

Calorimeter:

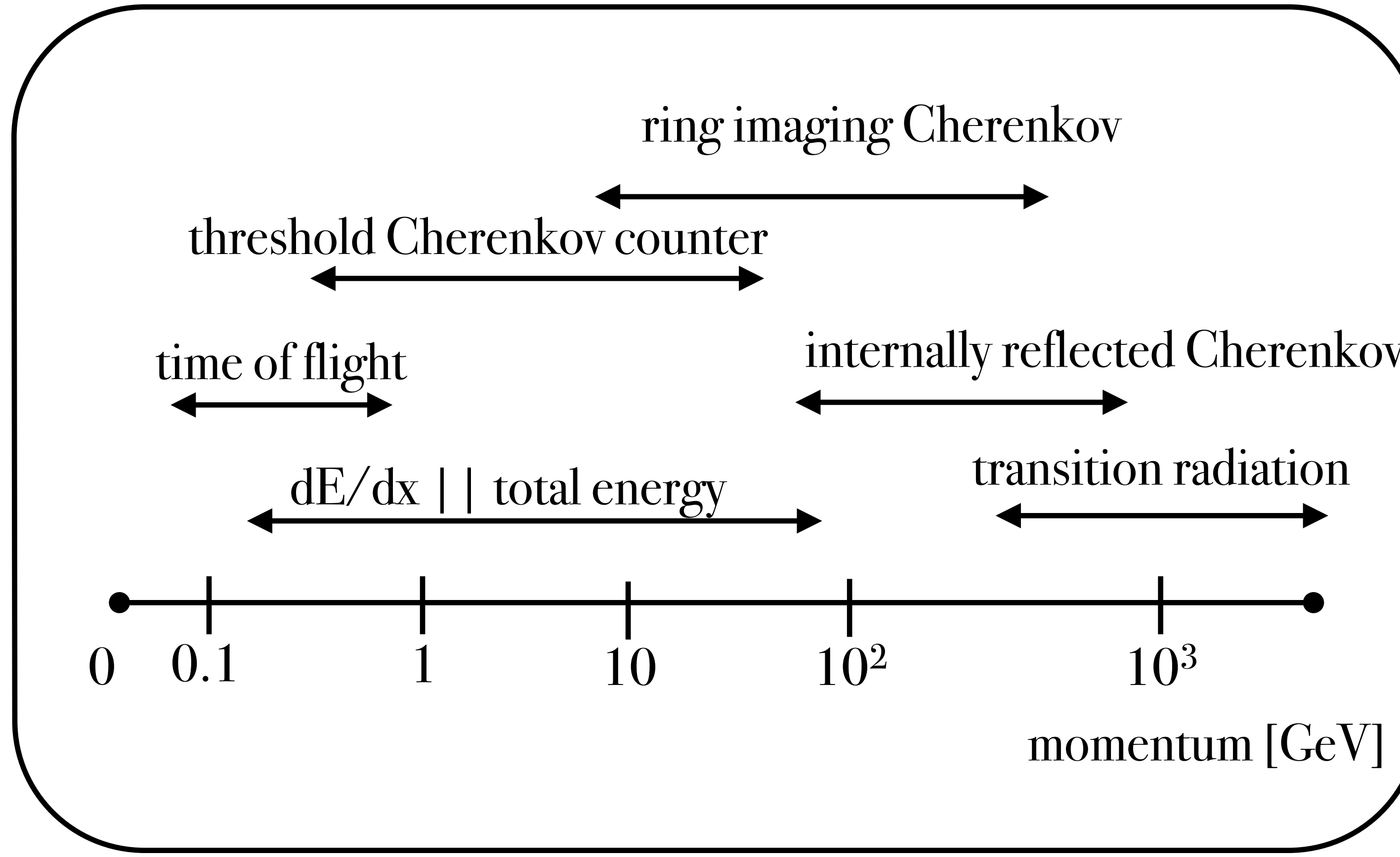
Bethe-Bloch (ionization loss) :

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I\cdot(1-\beta^2)}\right) - \beta^2\right]$$

Total energy: $E = \gamma m_0 c^2$

PId for unstable particles: determination of the 4-vector of all decay products to calculate the **invariant mass of the final state** and identify the original particle.

PId by technology and energy range



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focus of this talk

PId for unstable particles: determination of the 4-vector of all decay products to calculate the **invariant mass of the final state** and identify the original particle.

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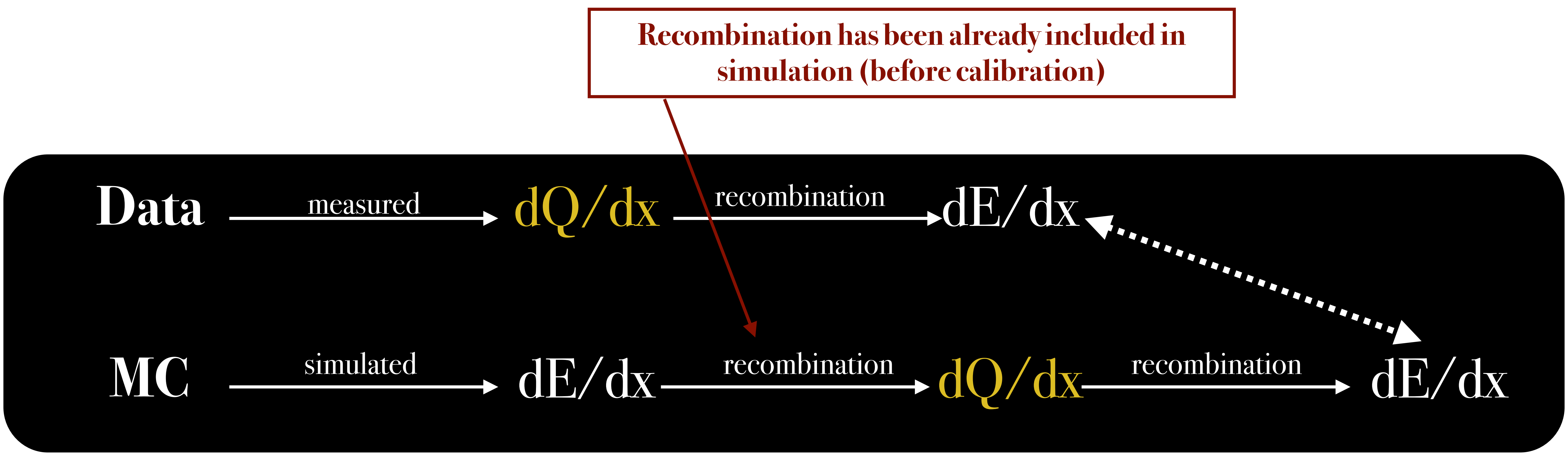
PId methods using calorimetry

In LArTPC we can use **ionization charge to measure the energy loss**. One of the main problems is the **recombination of electron-ion pairs** which has to be accounted for (see Bruce Baller's talk yesterday).

One challenge is the *circularity* of the problem:

Recombination is parametrized by energy deposit ☞ require measurement of MIP (minimum ionizing particles) and HIP (highly ionizing particles).

We need a PId method prior to have an accurate final calorimetry calibration.



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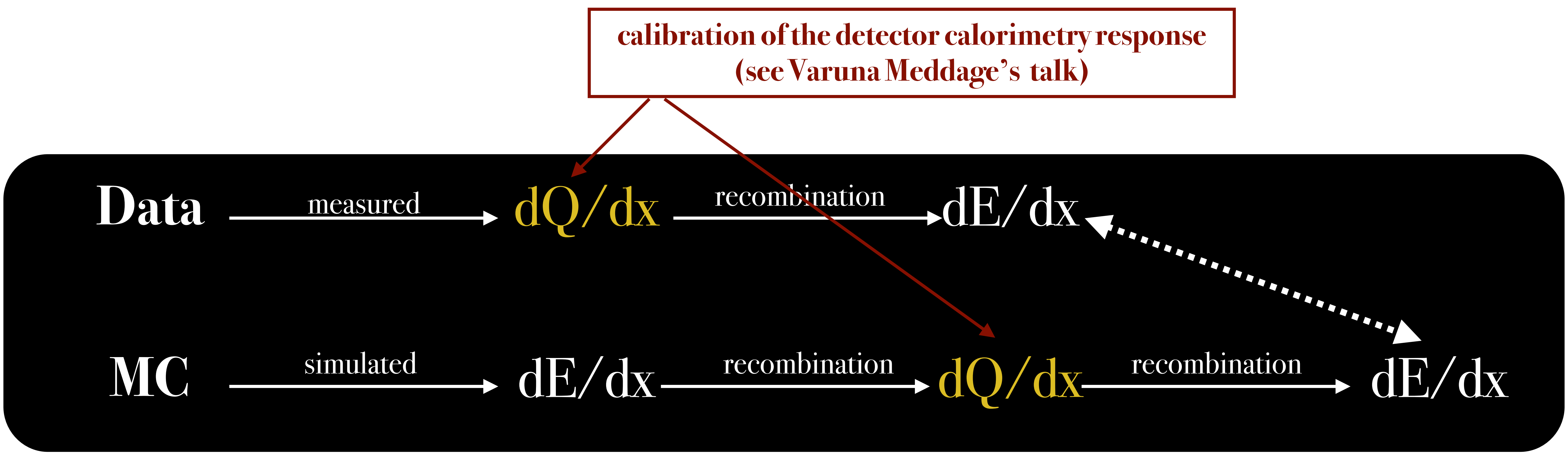

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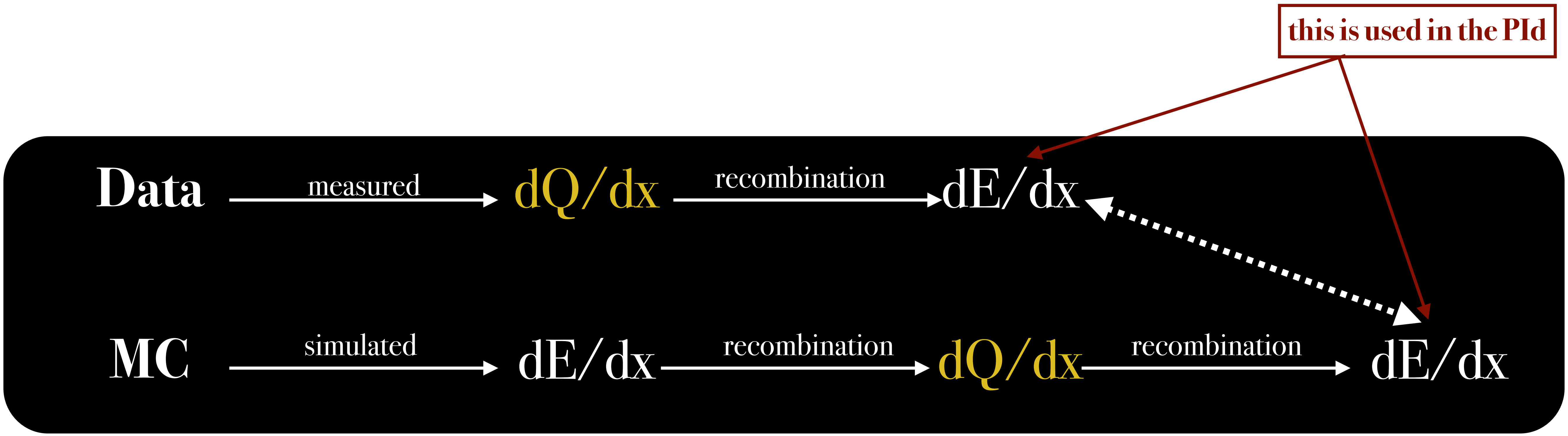


PId methods using calorimetry

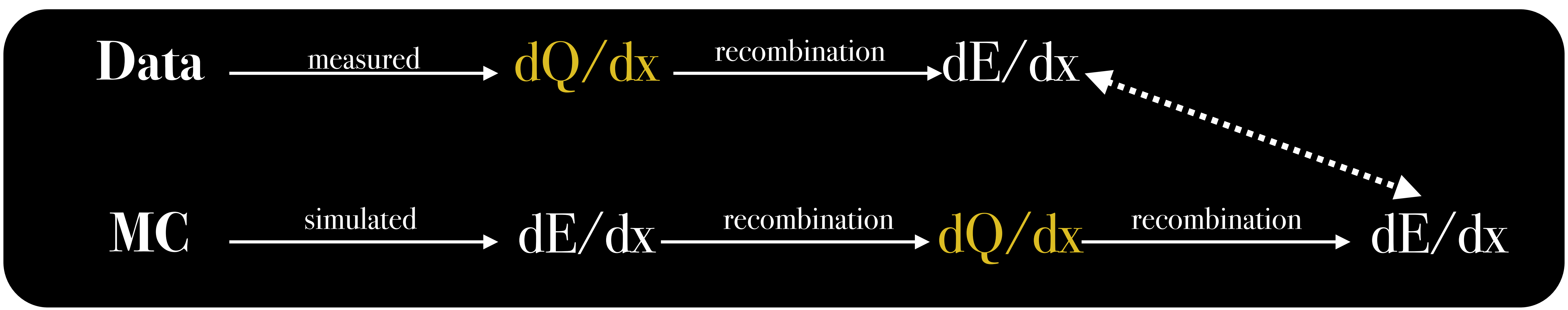
Recombination can be measured from data using residual range to reconstruct dEdx:

$dE/dx = A * R^b$
R: residual range range (distance of a given hit to the last hit)
A:17 (for protons)
b=-0.42

(From ArgoNeuT studies: arXiv:1306.1712. A.K.A. <u>Bruce Baller's formula</u>, *theoretical dE/dx*)

Recombination is obtained by subtracting dependencies **$dQ/dx \propto dE/dx$** (non-linear, see Bruce's description of Birk's law & Box model.)

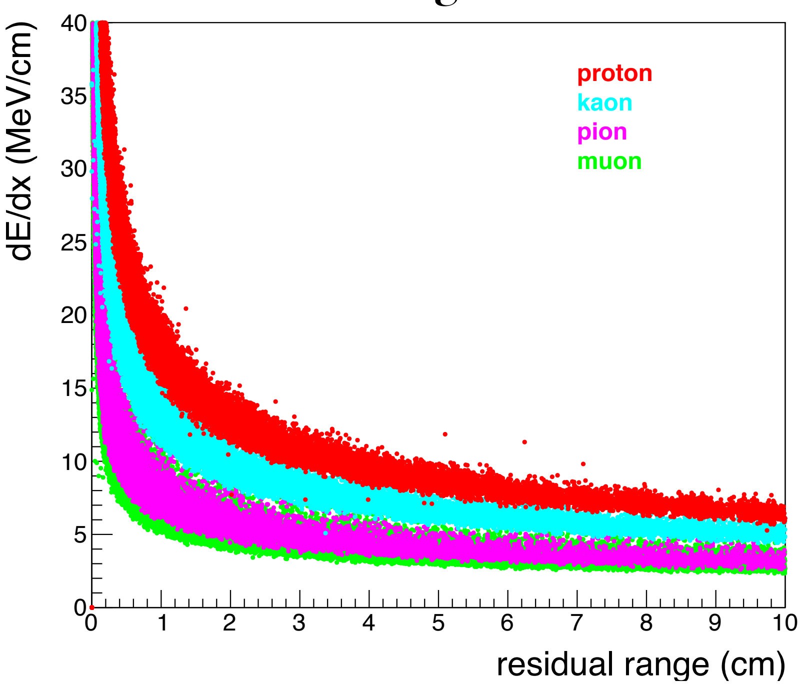
The measurement relies on the E-field simulation and dQ/dx calibration.



Bragg peak observation: first proton selection @MicroBooNE

While the Bragg peak observation is not a requirement to build a PId method based on calorimetry, it performs a **neat selection of non-interacted protons**. Thus, an **excellent selection for recombination studies** and gives a nice **sample of proton-based neutrino topologies** which are relevant for MicroBooNE/SBN main analysis.

Geant4 simulation of dE/dx vs residual range in Ar



Method developed by Tingjun Yang and used in ArgoNeuT.

$$PID = \chi^2_{proton}/ndof = \sum_{hit}\left(\frac{(dE/dx_{measured} - dE/dx_{theory})}{\sigma_{dE/dx}}\right)^2/ndof$$

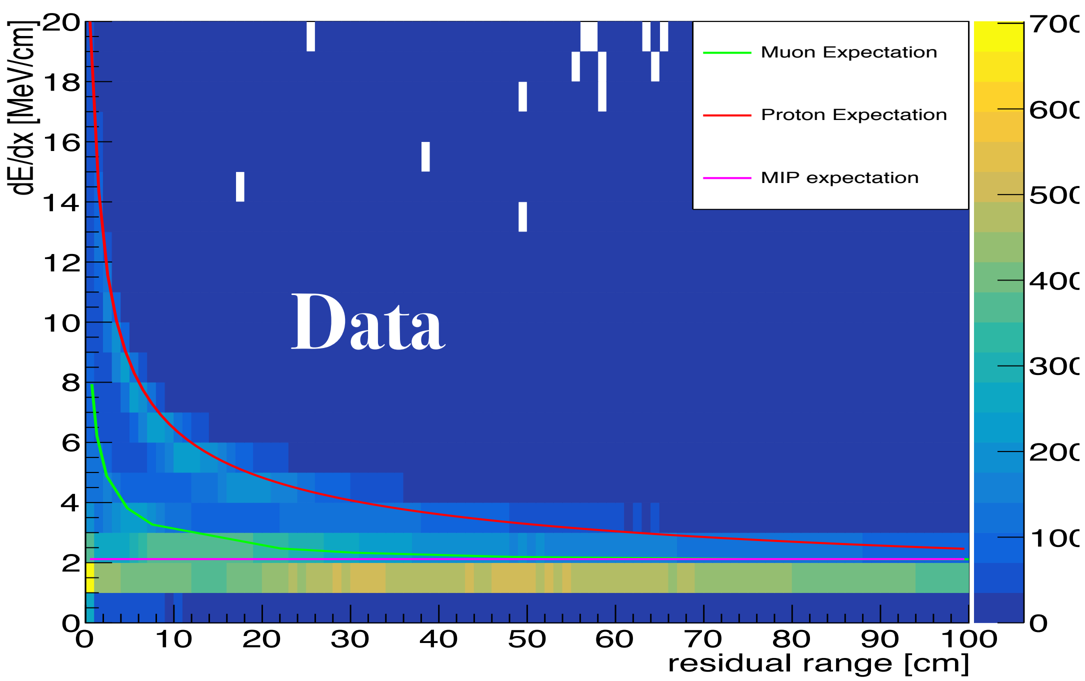
ndof : number of hits in collection plane.

We exclude the first and last hit of each track to avoid any mis-reconstructed residual range.

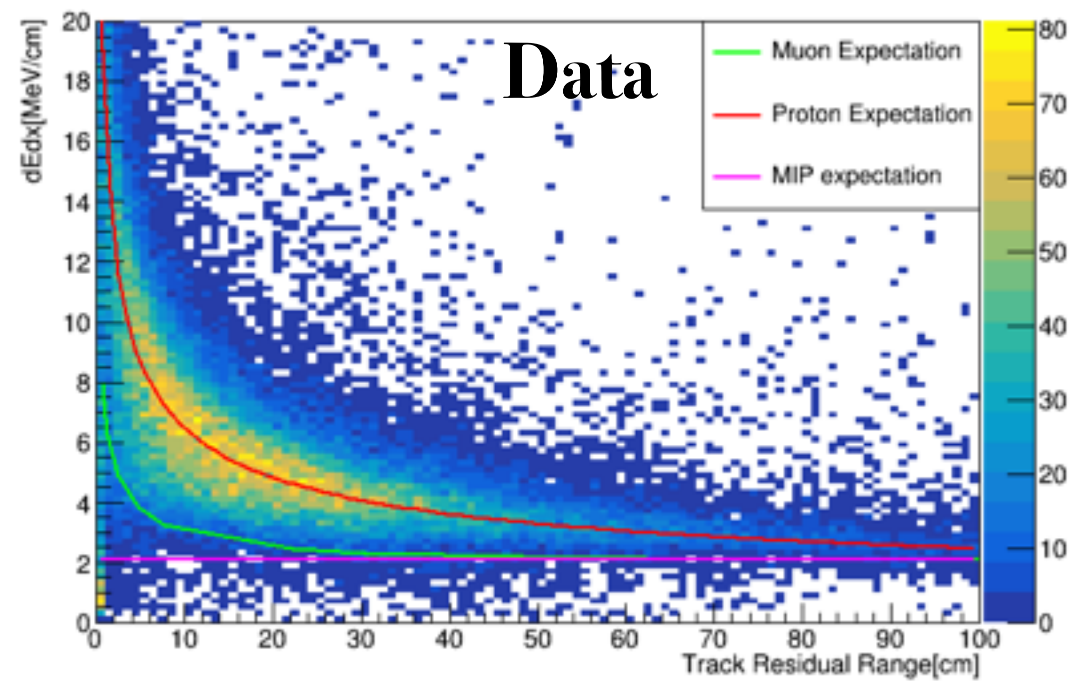
At the moment, we require 5 hits, thus, 3 hits minimum are used per track (ArgoNeuT required 2 hits).

Bragg peak observation: first proton selection @MicroBooNE

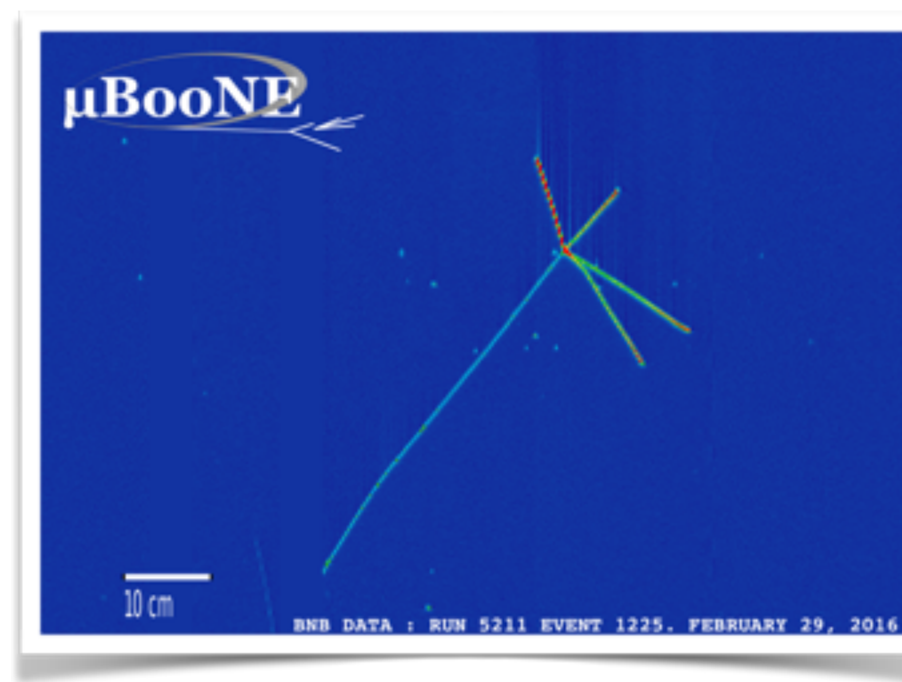
All tracks within ν_μ CC sample



Selected protons in ν_μ CC sample



Proton enhanced sample	Before PID requirement	After PID	relative efficiency after PID requirement
true μ	18.7%	2.0%	
true proton	64.5%	92.6%	85.2%
other	16.8%	5.4%	

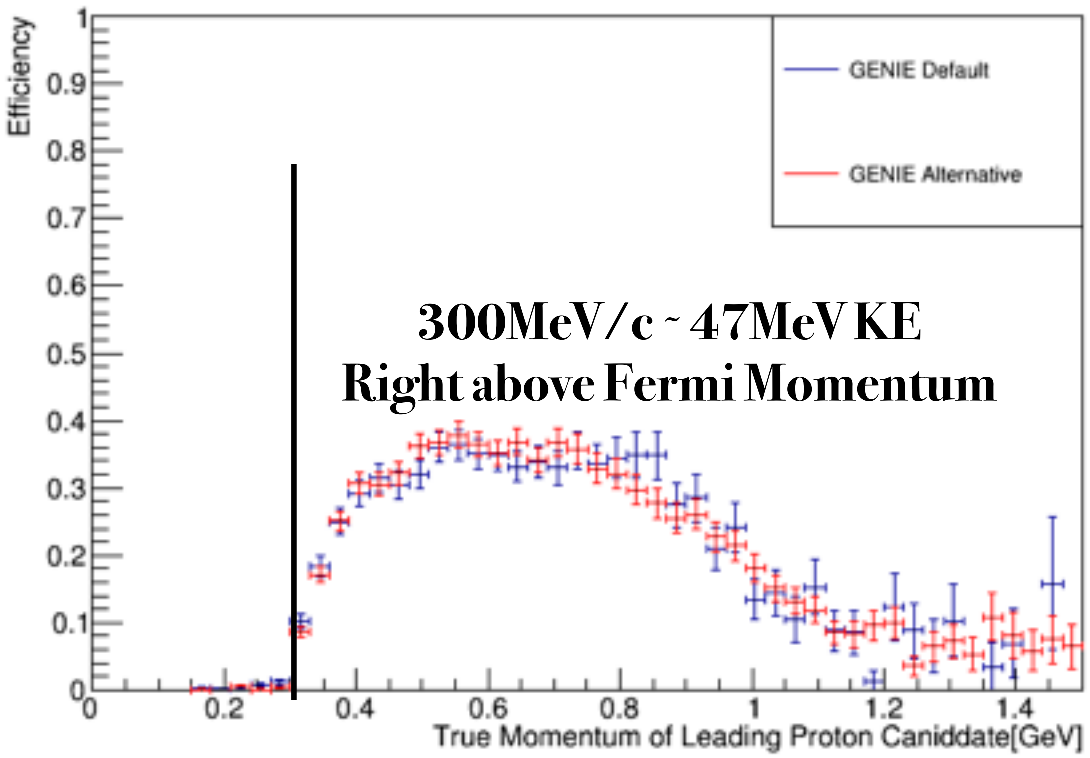


Excellent PId discriminator!

Used for recombination studies at MicroBooNE.

Used for the ν_μ CCNProton and ν_μ CC2Proton analyses presented at NuINT2018.

Bragg peak observation: first proton selection @MicroBooNE



The current proton threshold corresponds to the limit on the method:
at least 5 collection hits= 5x3mm (wire distance)= **1.5cm**

We can go lower to the current threshold (up to ~20MeV in proton KE)

Ongoing studies to lower the proton threshold:

- Introducing the **use of induction planes** in calorimetry (new 2D deconvolution signal processing)
- **Merged tracks recovering**. Sometimes corresponds to 'partially' merged tracks.
- Recovering (correcting) **first/last hit residual range**. At the moment we are identifying MIP vs HIP. To miss last hit can mis-identify a proton as a kaon (see Bruce's talk yesterday). Recover last hit is crucial.

Non-Bragg peak observation

Methods not using Bragg peak observation can be used for:

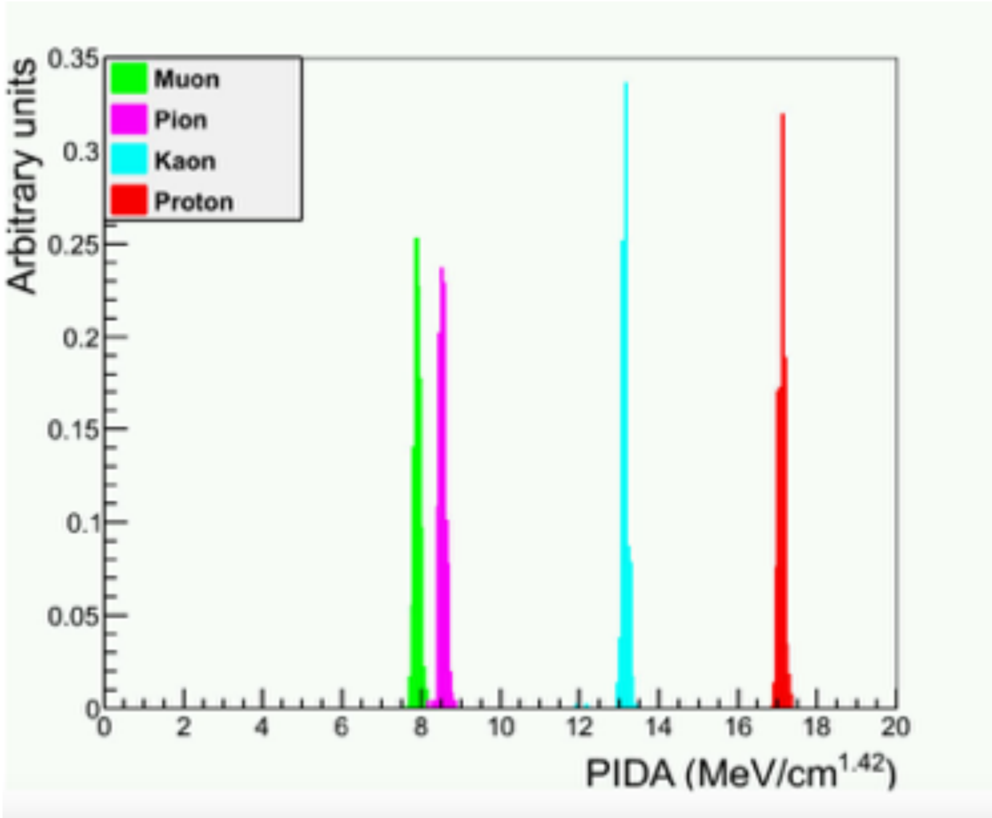
- **Uncontained tracks**
- **Interacted particles**
- **Short tracks** (when resolution in residual range is poor)

They use dE/dx information as well but less *detailed* (averaged). Three examples:

- **PIDA**. From Bruce Baller in ArgoNeuT.
- **Pull method**. From the FGD detectors at ND280-T2K.
- **Likelihood method**. From the TPCs detectors at ND280-T2K.

Non-Bragg peak observation

PIDA. From Bruce Baller in ArgoNeuT (LArTPC). arXiv:1306.1712



PIDA= $\langle dE/dx_i * R_i^{0.42} \rangle$

Excellent PId. Works better for stopping particles (initial design).
Plot shows distributions without smearing due to reconstruction (ideal). <u>In real data these peaks are more smeared</u> distributed and **muon/pion discrimination has not been proven** which will depend on the dE/dx resolution.
Similar as the χ^2 method, PIDA excludes first and last hit.

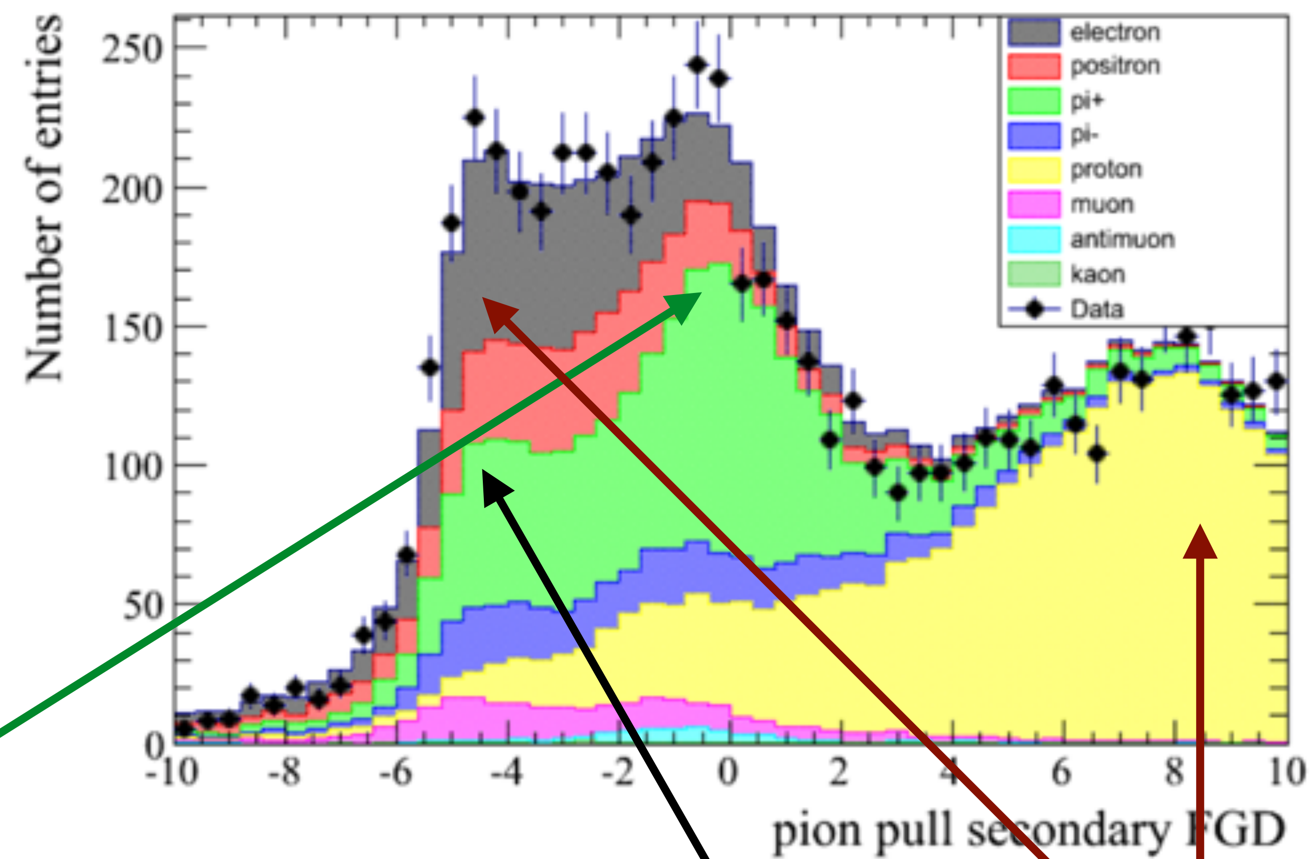
Non-Bragg peak observation

From R. Castillo Fernandez thesis.

Pull method. From the FGD (CH scintillator) detectors at ND280-T2K.

C_T= <dE/dx>$_{\text{truncated mean (70\%)}}$

$$\delta_\alpha = \frac{C_T^{measured} - C_T^\alpha}{\sigma^\alpha}$$



Particle has to be centered at 0. Otherwise most probably corresponds to a broken track or impurity.

Useful for cases of low resolution in calorimetry. Roughly similar to PIDA in concept.
Used in the T2K near detector analysis constraints for oscillation measurements. Goal: enhancing short pions (not reaching the TPC).

Non-Bragg peak observation

From R. Castillo Fernandez thesis.

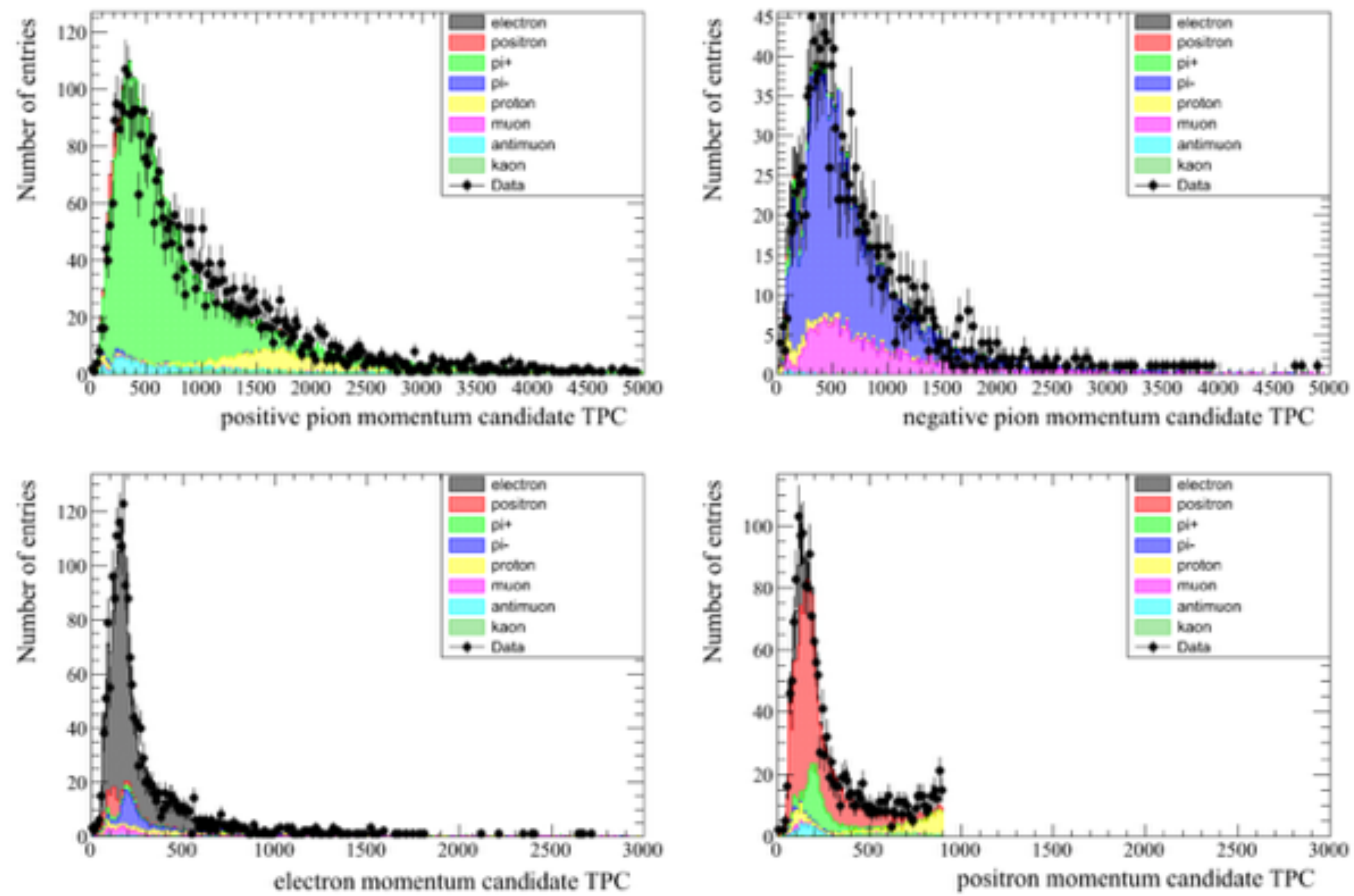
Likelihood method. From the TPCs detectors (argon gas) at ND280-T2K.

$$L_i = \frac{e^{-\delta_i^2}}{\Sigma_l e^{-\delta_l^2}}$$

(δ= pull, previous slide definition)

$$P_i = \frac{L_i}{\Sigma_l L_l}$$

$$L_{MIP} = \frac{L_\mu + L_\pi}{1 - L_p}$$

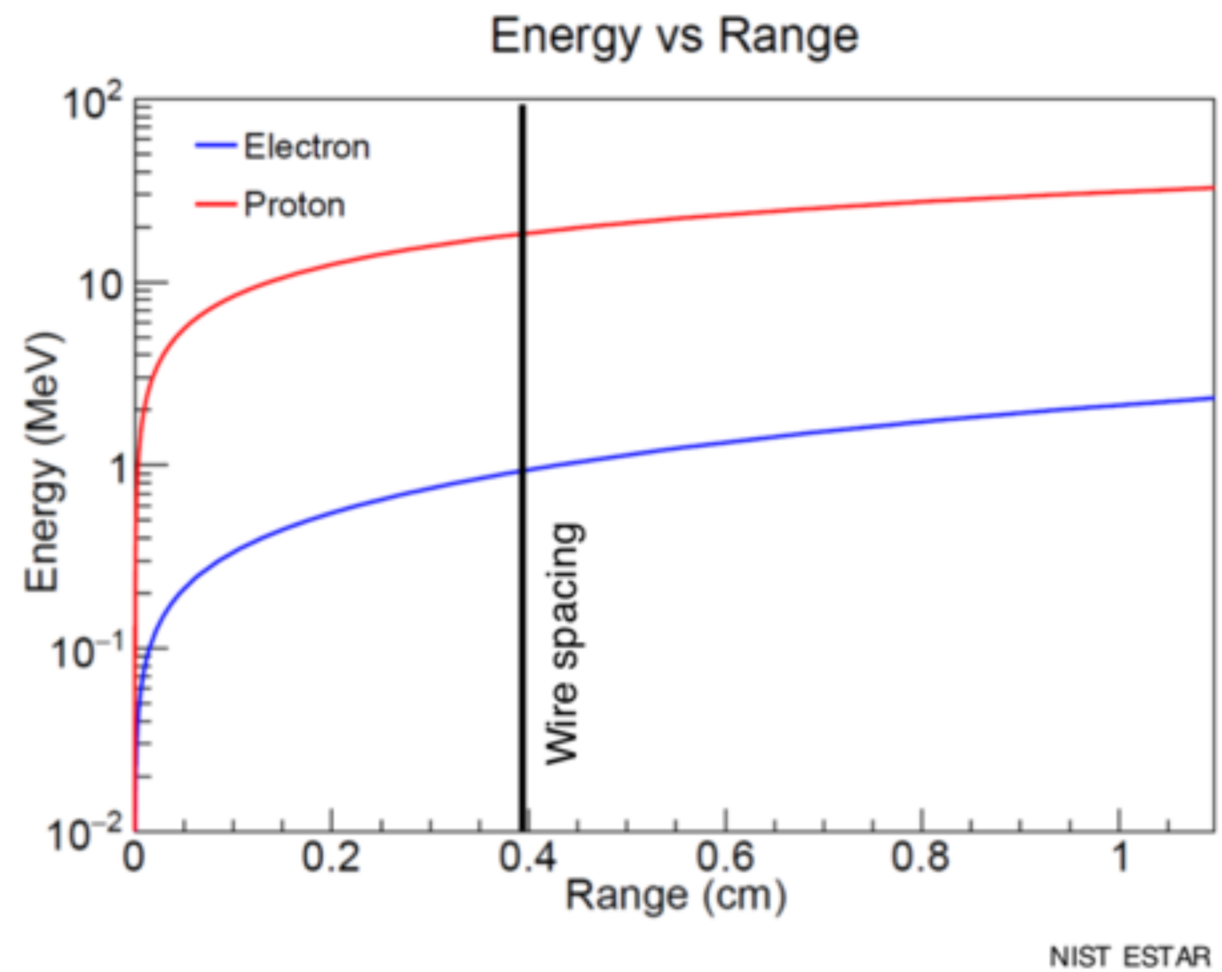


Excellent PID, pion/proton start to show problems ~1.5GeV. Positron/proton includes kinematics cut to reduce proton contamination, non high energy positrons allowed, for T2K this was a negligible inefficiency. Basically means that **for MIPs>1GeV separation wrt protons is harder**.

Used in the T2K near detector analysis constraints for oscillation measurements. Goal: enhancing muon/pions/electrons/positrons.

Non-Bragg peak observation

Heads up! Remember when ArgoNeuT reconstructed MeV scale photons? Guess what…



Plots stolen to O. Paramara.
See Ivan Lepetic talk this session!

Non-Bragg peak observation

Heads up! Remember when ArgoNeuT reconstructed MeV scale photons? Guess what…

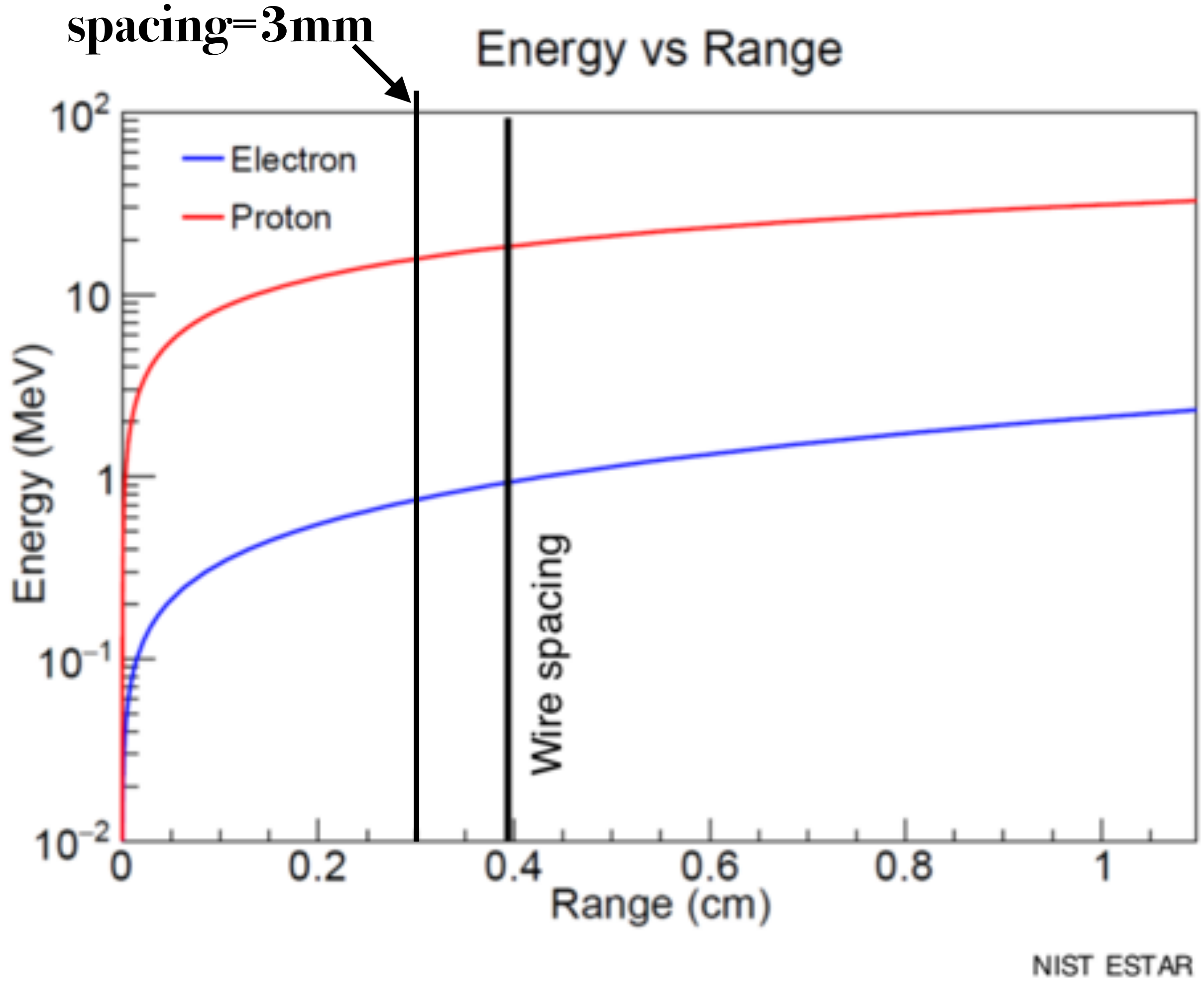
Lowering proton threshold

Let's play the opposite game:
lower limit @1.2 MeV.

Valid path for study on **specific ν_μ CC topologies**:
ν_μ CC2P, ν_μ CCπ^+ with proton in final state,…

Requires: clean muon vtx, exact number of hadrons and no showers.

MicroBooNE wire spacing=3mm



Requiring a muon and and check for additional hit coming out of vertex.
To do this, **we need a very good simulation and calibration**.

Plots stolen to O. Paramara.
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Summary

Detector design and particle identification techniques should cover the energy scope of the experiment.

Calorimetry has been proven to effective for low energetic particles (from few MeV to few GeV).

Current threshold in MicroBooNE is 47MeV KE for protons, we can go lower up to ~20 MeV KE (wire distance limits). Note: **ArgoNeuT recently show us how to do it!**

Calibrating LArTPC accurately is crucial to rely in the PId method. **Recombination becomes a circular problem with proton selection, a PId method selecting HIP with Bragg peak is very useful.**

PId methods presented:

1. Effective methods for tracks with observed Bragg peak are available.
2. For cases where Bragg peak is not observed (interacted, exiting or too short tracks), other methods can be exploited and are presented here.

Discussion

No time to discuss **electron/γ separation** in this talk. However, the principle is the same as (2): averaging dE/dx ☞ See next talks today by Rory Fitzpatrick (shower electron/γ discrimination) and Ivan Lepetic (low energy γ reconstruction).

Additional complication @DUNE:

- **Exiting tracks for near detector or interacting particles** ☞ need to exploit more non-Bragg peak approaches.

- **Contribution of DIS** (muons and pions with the same electric charge per event) **will decrease effectivity of magnets at near detector**.

    - **Muon/pion discrimination**. Cannot be achieved by calorimetry, topological approaches are crucial (PId in secondary particles):
        - scattering and decay topologies (useful for contained tracks)
        - possibility of using delta rays to discriminate muon/pion (due to the high energy). Necessary to exploit for exiting tracks.

BACKUP

PId methods using calorimetry

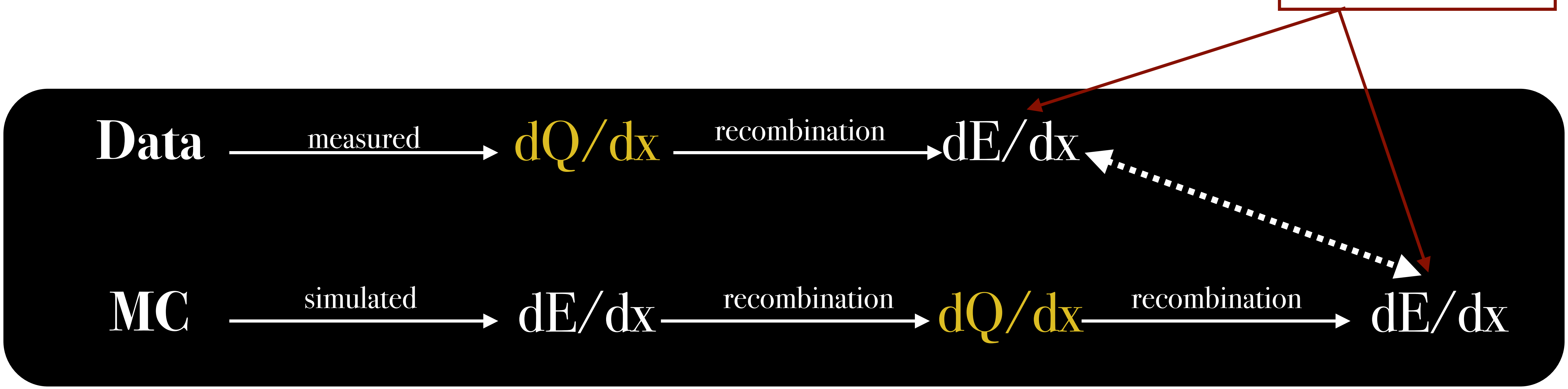
In MicroBooNE (as most of the LArTPC detectors) **protons are fully contained in the TPC**.

We use protons, from neutrino candidate events, which are required to be fully contained in a fiducial volume in the TPC and selected with a χ^2 method (see later) for **PId which only considers the shape of Bethe-Bloch** distributions. The χ^2 method is simple and does not involves definition of observables which may hide underlying issues in calorimetry as different smearing in data/MC for the dE/dx.

To simulate a LArTPC is not easy. Better to keep details visible for depth understanding of the detector, design improved strategies to exploit the full potential and prevent anomalies in simulation.

The PId, performs better agreement data/MC after recombination is corrected. However, selected proton candidates in data remains the same after recombination correction, which is an indication of the robustness of the PId method used.

this is used in the PId



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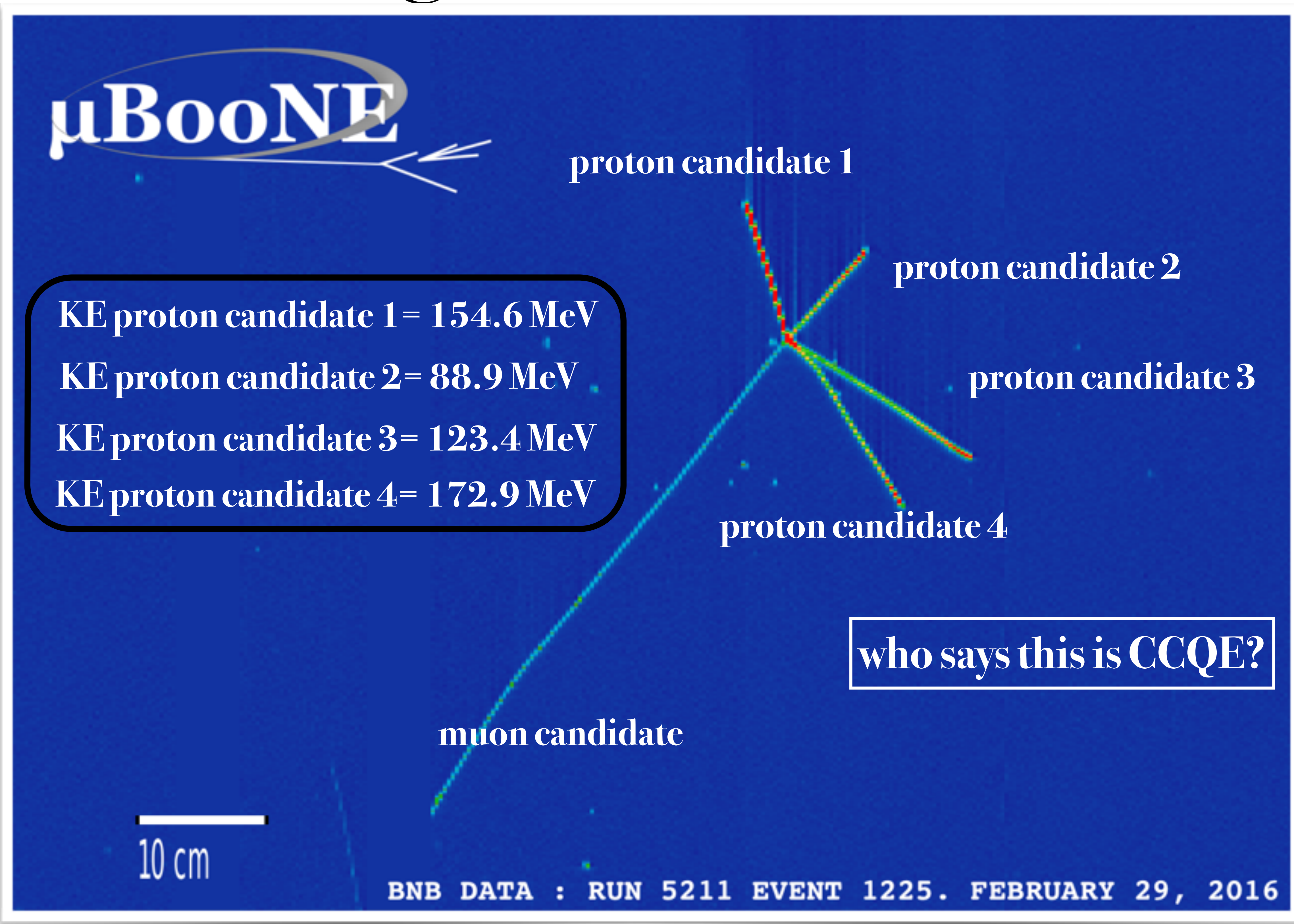

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