Track Fitting and Kinematics Reconstruction

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Workshop on Calibration and Reconstruction for LArTPC Detector
Dec. 11, 2018

Outline

- I am covering higher level reconstruction topics happening after the pattern recognition (hits→clusters→particle hierarchy) has been completed.

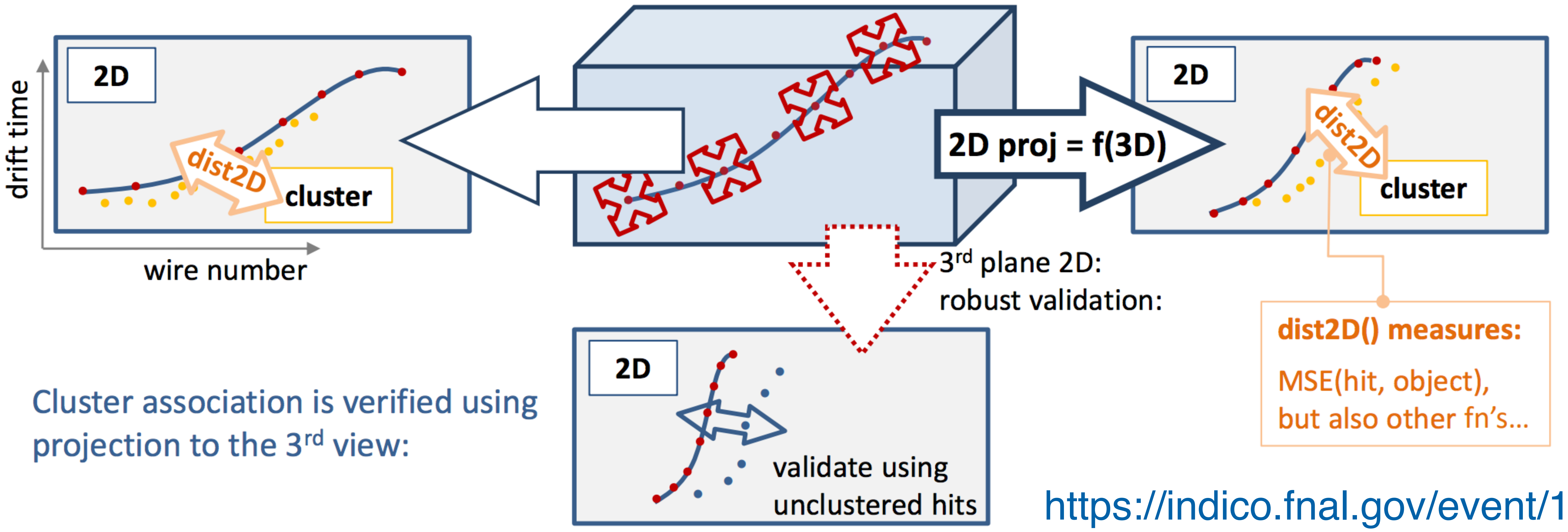
- Fitting tracks in 3D
  - Projection Matching
  - Kalman Filter
- Determining track momentum
  - Range
  - Calorimetry
  - MCS
- Fitting vertices
- Tools to estimate performance in data

Fitting tracks in 3D

Projection Matching Algorithm

- PMA builds the 3D fitted track by minimizing the distance between the 2D fit projections and the track hits in all wire planes simultaneously
  - Can also correct issues with 2D clustering while doing this
  - No need to match hits across planes, each 2D hit has its own 3D position on the trajectory

build 3D (***single track*** or ***full track structures***) to minimize distance the object’s 2D projections to 2D hits



3rd plane 2D:
robust validation:

Cluster association is verified using projection to the 3rd view:

dist2D() measures:

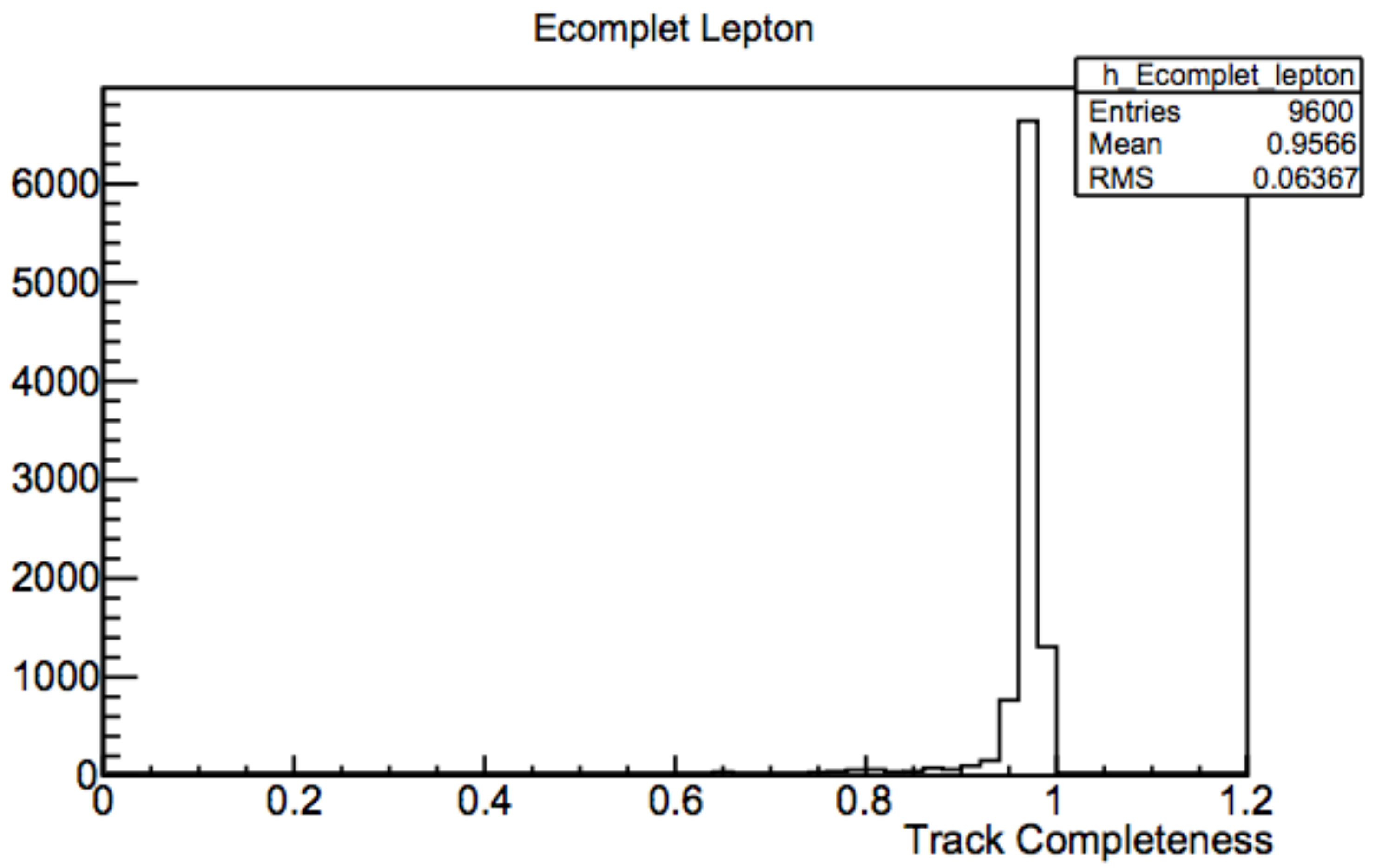
MSE(hit, object),
but also other fn’s…

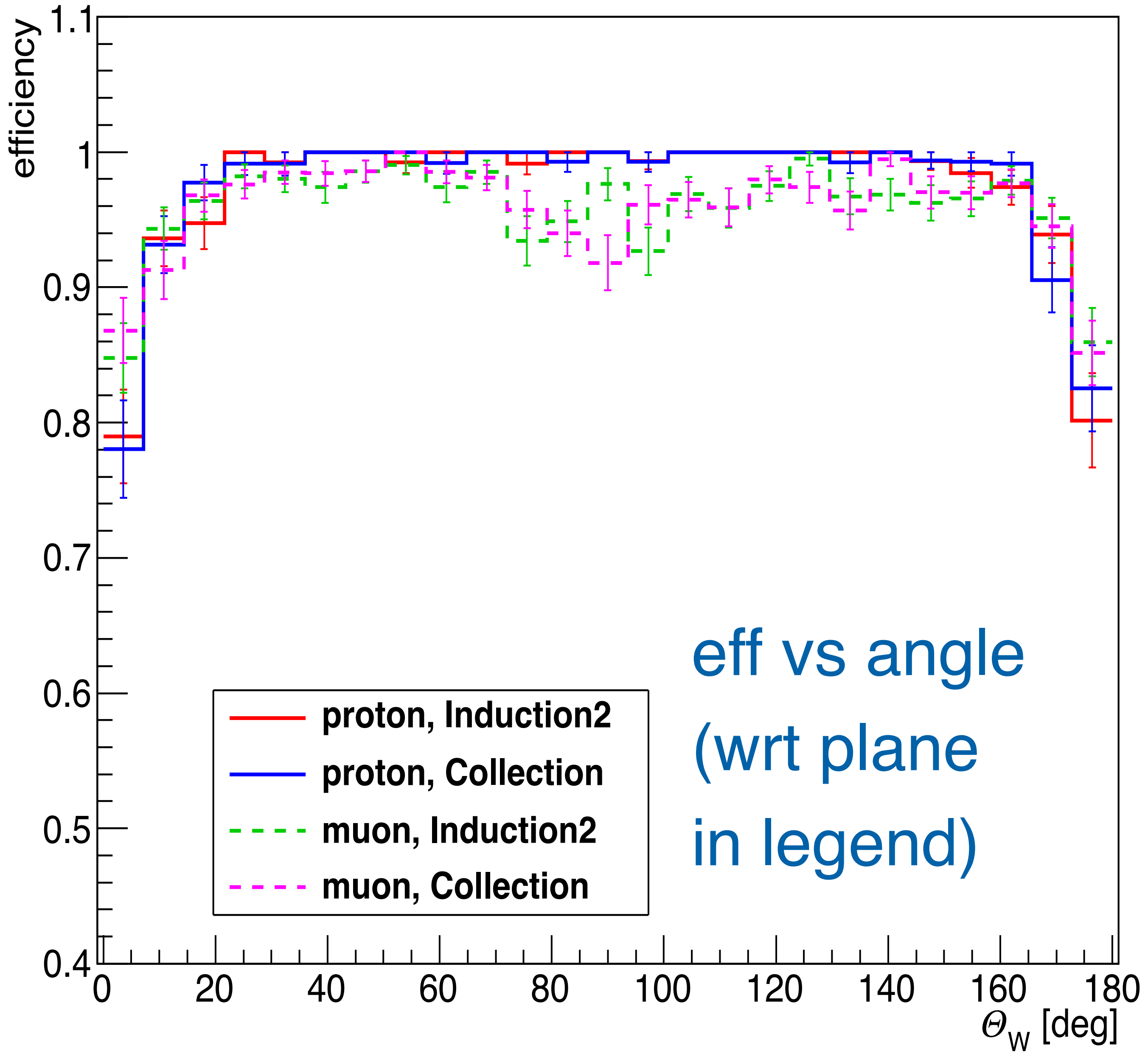
https://indico.fnal.gov/event/10276/session/40/material/slides/1?contribId=62

- Pandora’s fit algorithm has a different implementation, but it is also based on minimizing a distance between the fit projection and the hits on the planes

PMA Performance

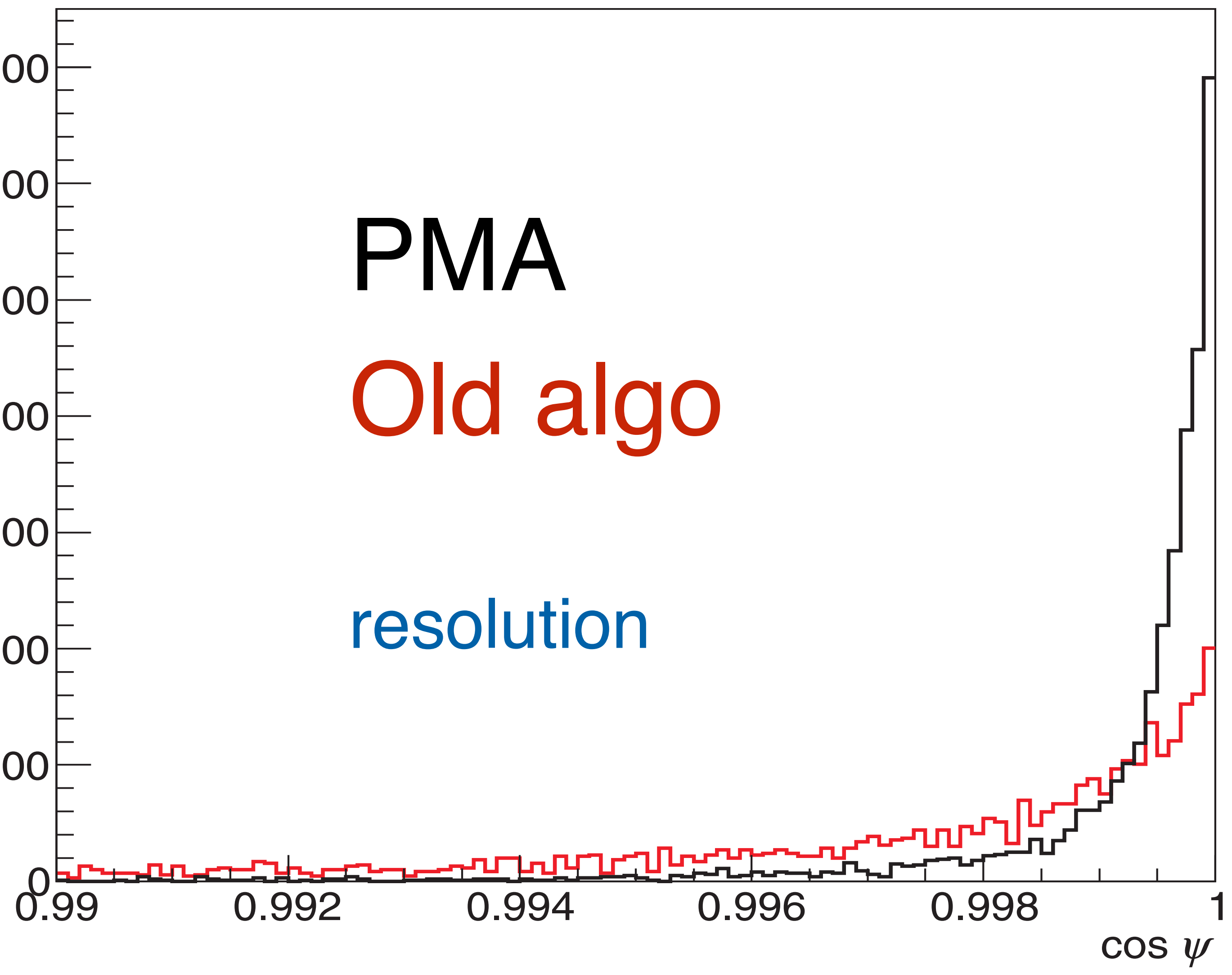
- Results from ICARUS and ProtoDUNE (single phase)
- High efficiency and improved resolution
- Very good completeness and thus length estimation

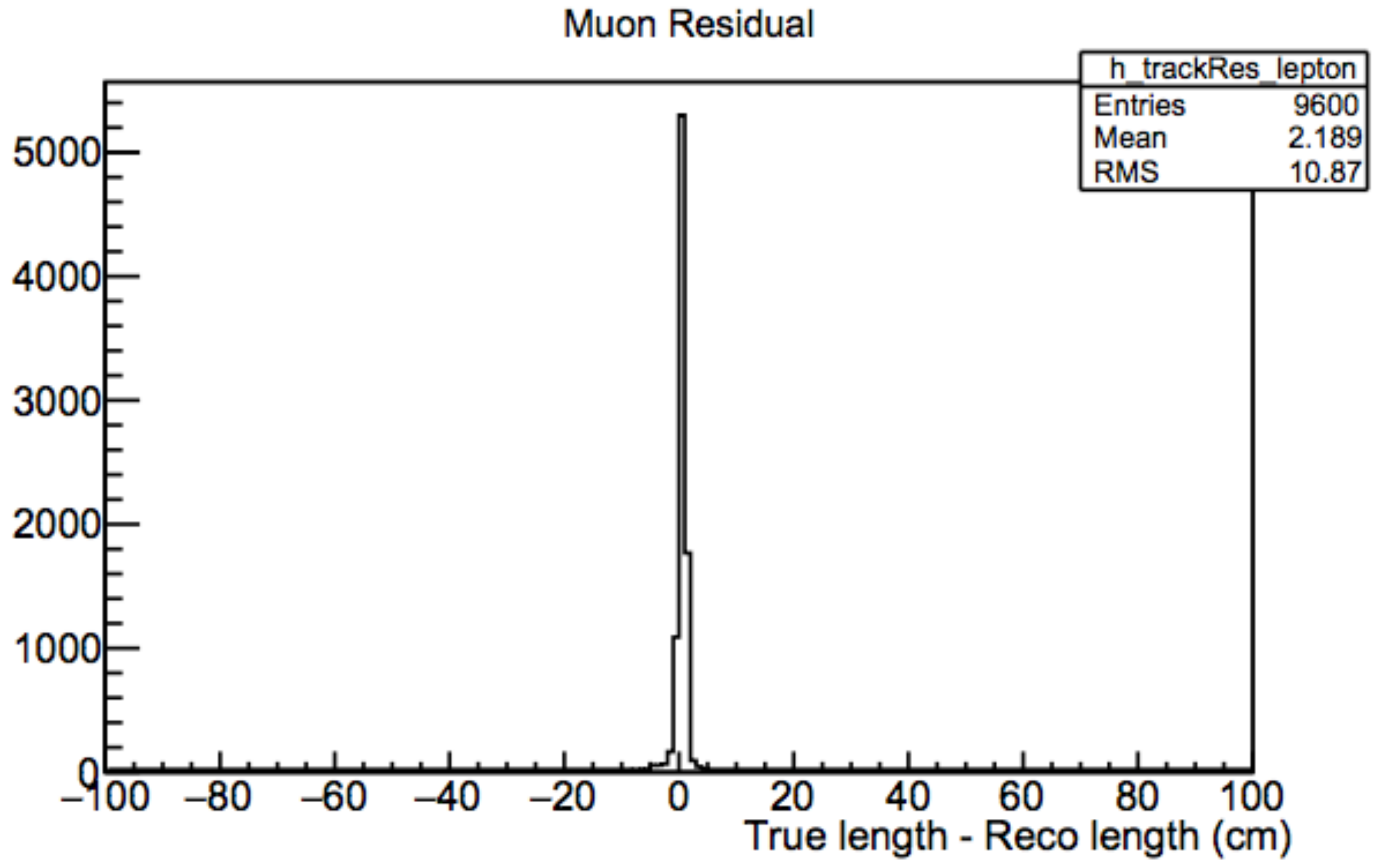




eff vs angle (wrt plane in legend)

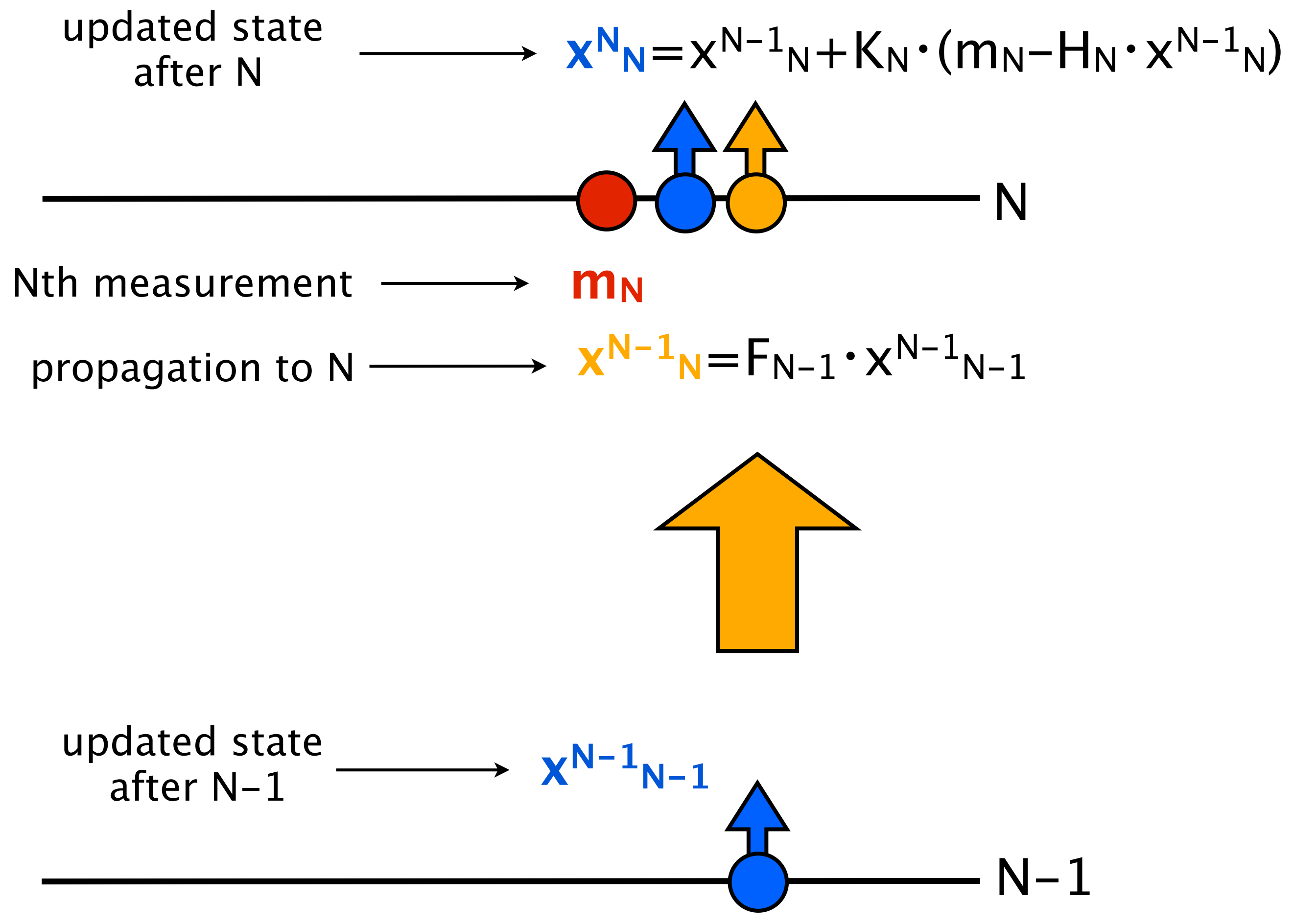
https://arxiv.org/pdf/1210.5089





https://arxiv.org/pdf/1706.07081

Kalman Filter Algorithm



updated state after N → $x^{N}_{N}=x^{N-1}_{N}+K_{N}\cdot(m_{N}-H_{N}\cdot x^{N-1}_{N})$

N

Nth measurement → m_{N}

propagation to N → $x^{N-1}_{N}=F_{N-1}\cdot x^{N-1}_{N-1}$

updated state after N−1 → x^{N-1}_{N-1}

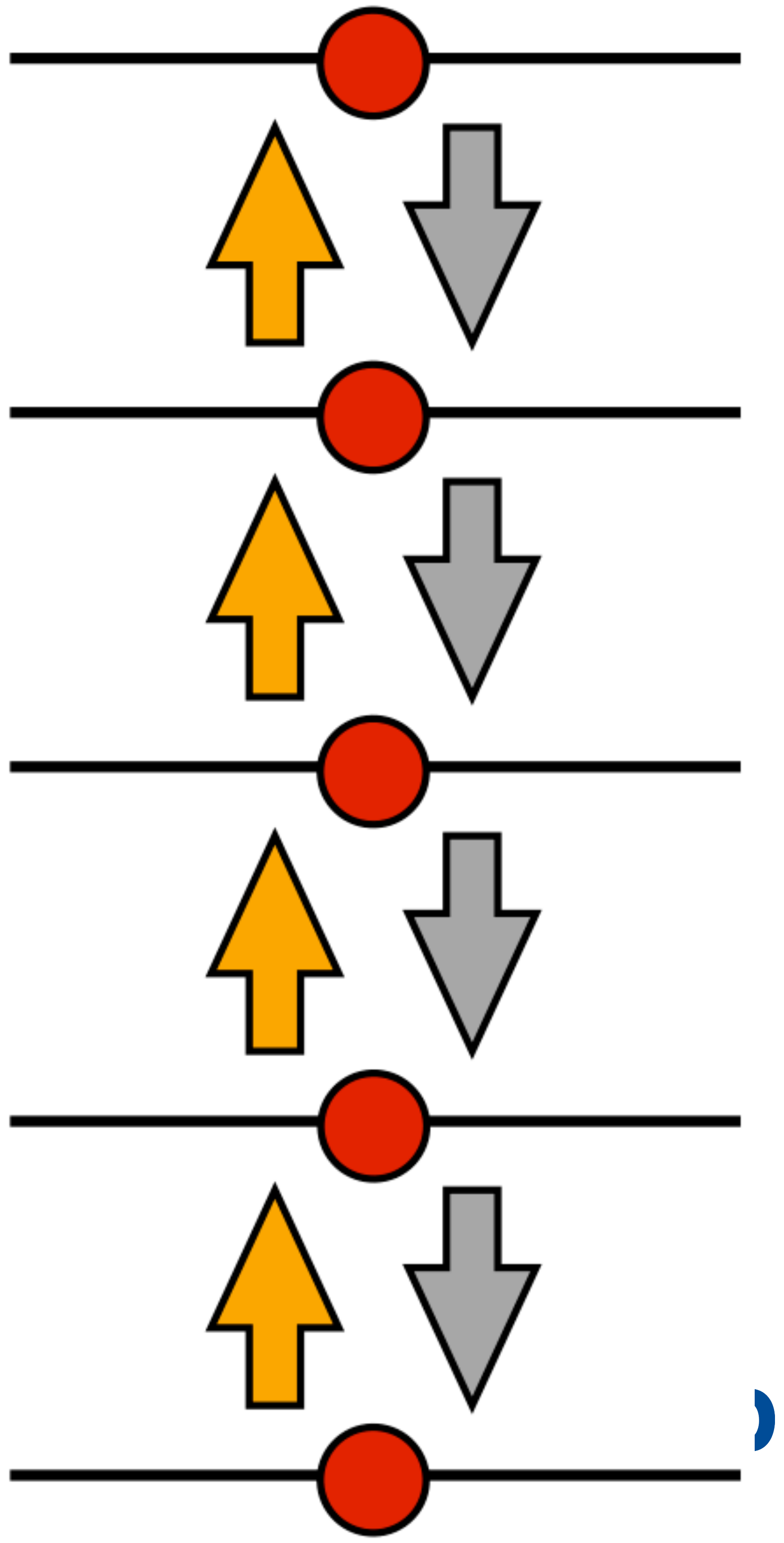
N−1

- Take hits assigned to tracks by pattern reco, fit them with a Kalman Filter

- KF fit is done in two stages:
  - Forward pass: for each hit propagate track to it, update track parameters and covariance
  - Backward “smoothing” pass: as forward but in inverse order, plus combine forward and backward estimates for optimal estimation

- The fit can modify hit sorting of hits across planes and remove spurious hits

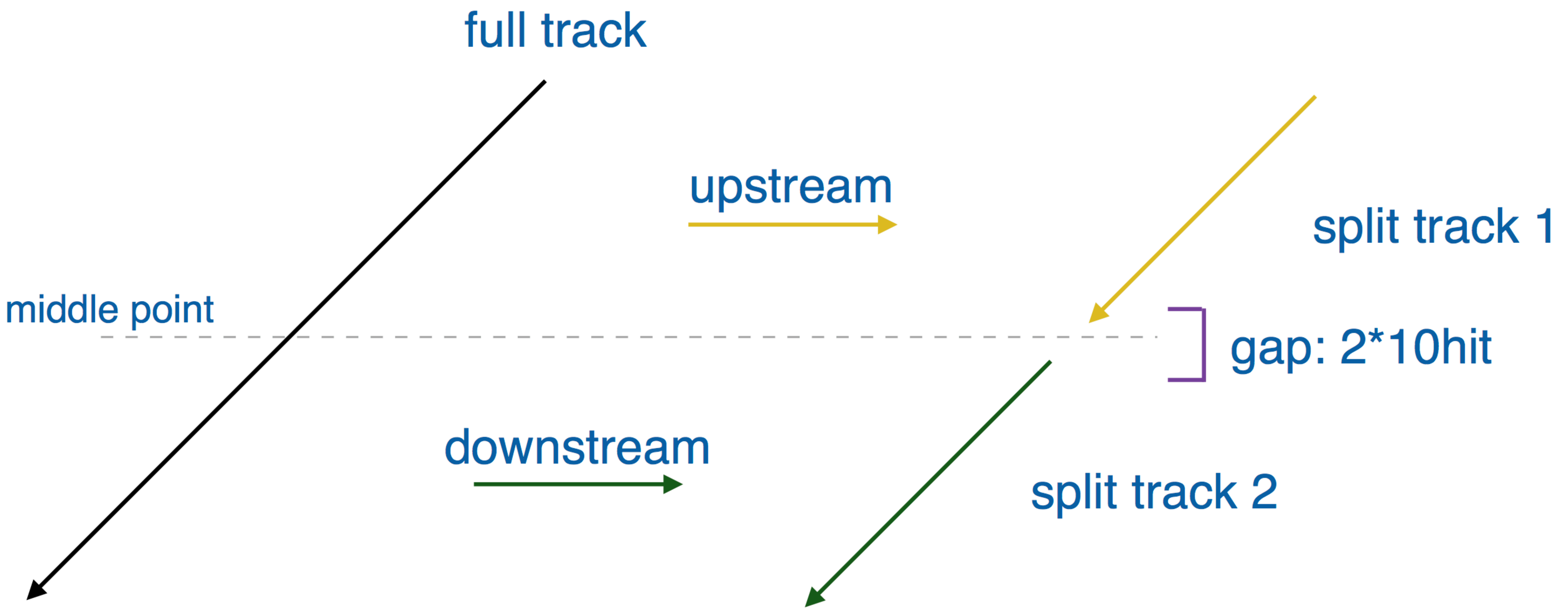
- Output: a ‘fitted’ track, with updated trajectory points, plus covariance matrices, and chi2



Kalman Filter Performance: data-driven method

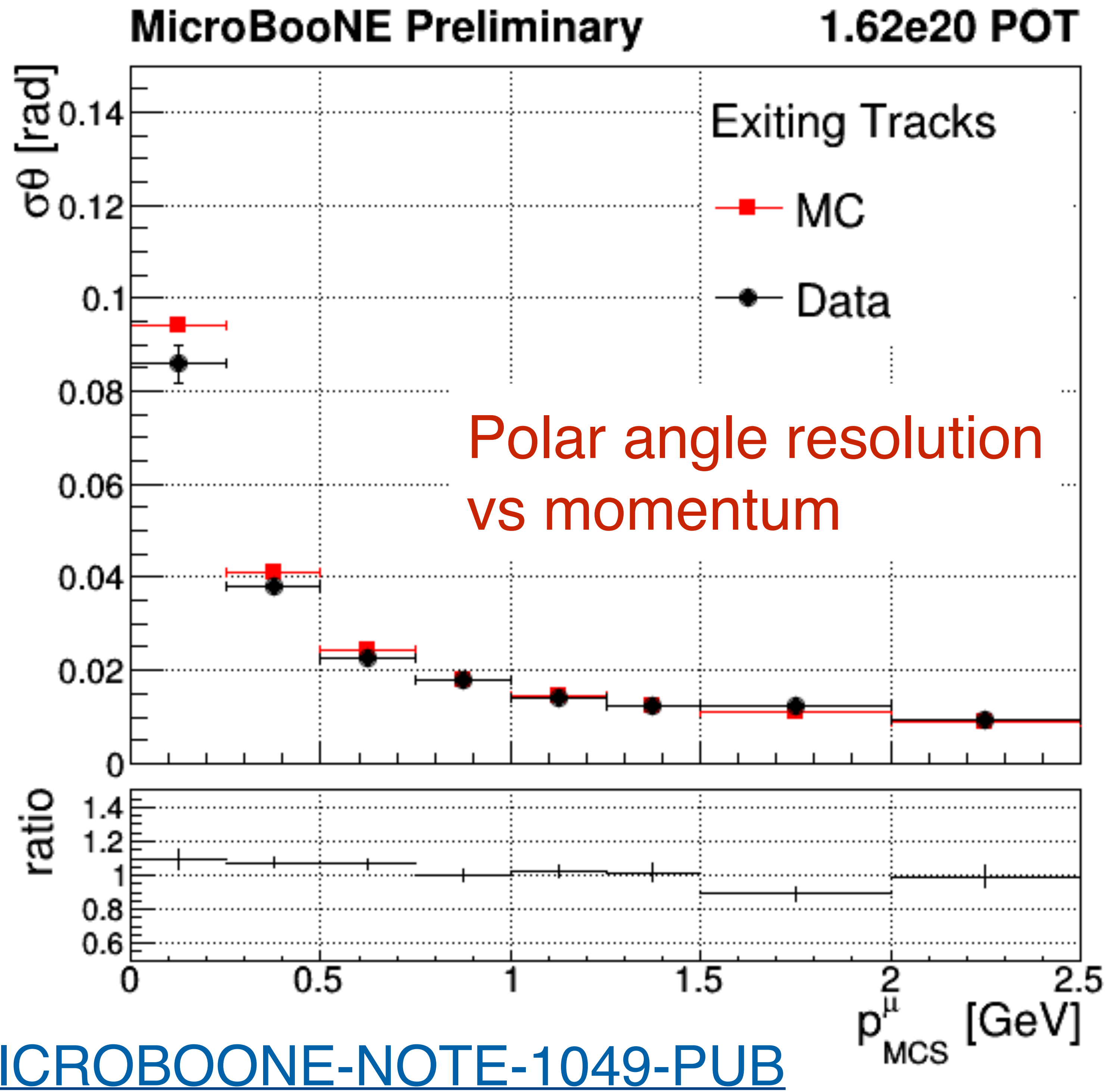
- Split track at middle point, compare parameters from up- and down-stream independent fits
  - resolution at track mid point differs from start but mostly sensitive to same effects (main exception: vertex activity)

- Data-driven resolution:
  - width of $(x_1-x_2)/\sqrt{2}$
    - can be used both on MC and data
- MC-based resolution
  - width of $(x-x_{MC})$
    - can be used only on MC



Kalman Filter Performance: results

- ν_μ CC event selection, consider exiting muon tracks
- Parametrize vs momentum and z position
  - sensitive to scattering and shorted wire regions respectively
- At high momentum achieve position resolution of O(mm) or better
- Resolutions in data well reproduced by MC!
  - typically at <10% level, similar degradation due to dead wires
- Main discrepancy: y position resolution
  - <20% level agreement, driven by induction planes
  - expected to improve with 2D deconvolution signal processing



Polar angle resolution vs momentum

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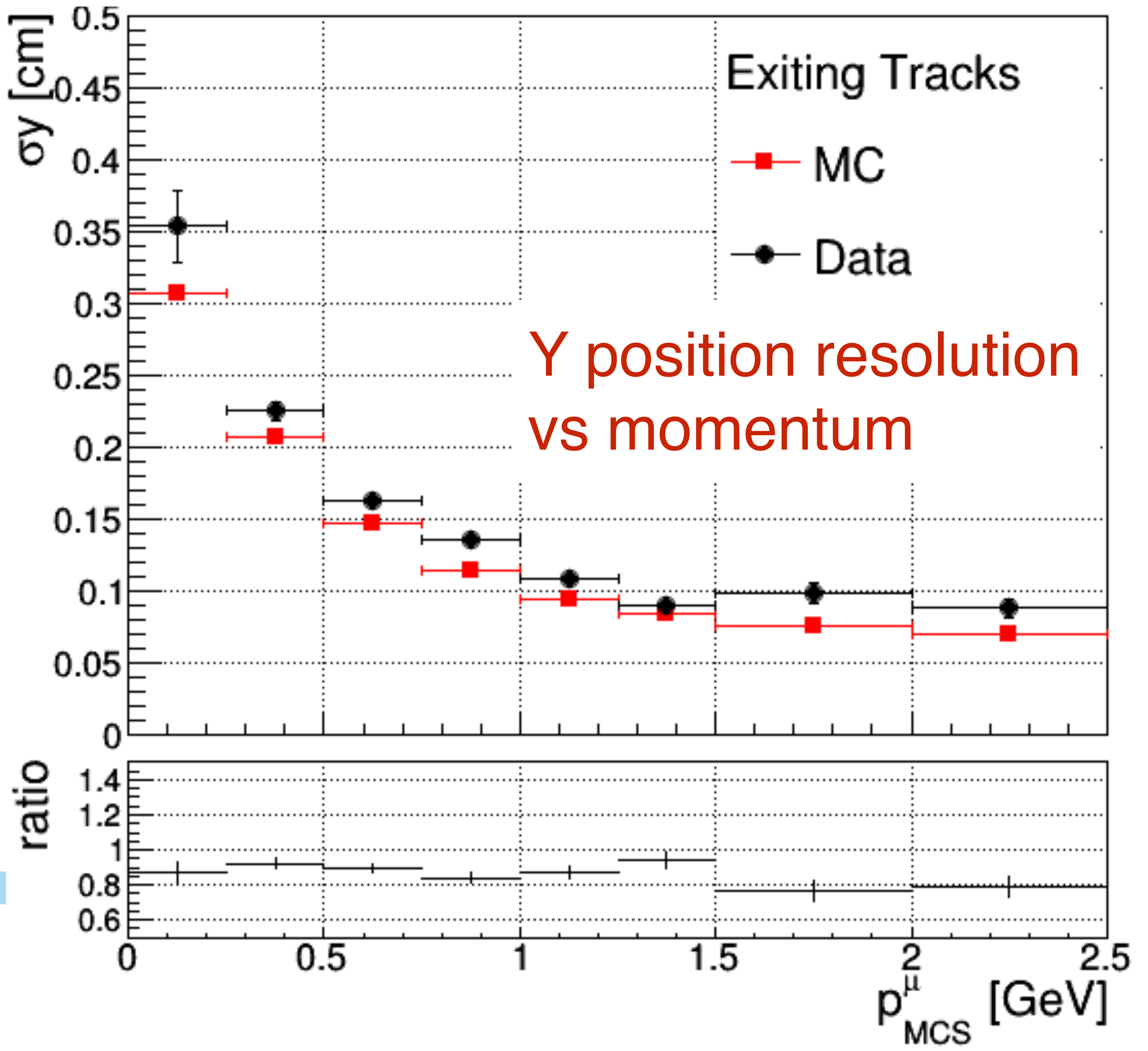


Y position resolution vs momentum

Thoughts about tracks fitters

- Different approaches with different purposes and utilizations

- Projection matching is simple and robust. It processes multiple hits at the same time, and it effectively minimizes distances. Thus it's ideal for estimating the track length. It does not return the covariance matrices so cannot be used for more sophisticated downstream algorithms.
  - Warning: PMA not maintained anymore in LArSoft!!

- Kalman filter relies and (and thus is subject to) various components (hit uncertainty, estimates of PID and initial momentum). Processes hits sequentially, so it's more sensitive to hit issues (e.g. wrong order can result in zigzag patterns). On the other hand it can remove spurious hits and return a purer track (used e.g. in uB calorimetry). It returns full covariance matrices that can be used downstream.

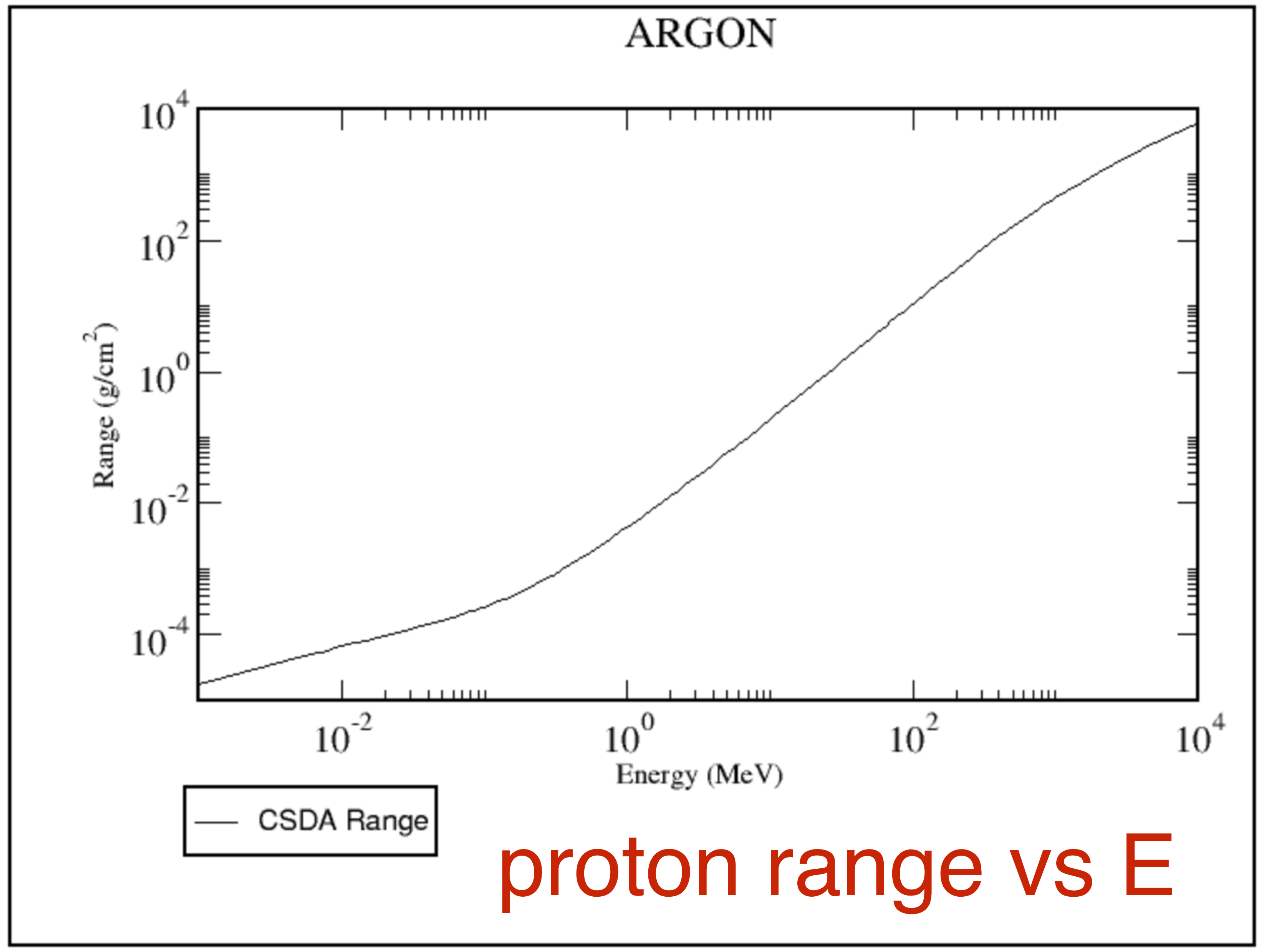
- In my opinion the best approach is to run the Kalman filter on top of PMA/Pandora tracks and use one or the other depending on the goal

- More effort should be put into track fits to showers.
  - better track/shower separation for low energy showers, better reconstruction of the initial electron segment

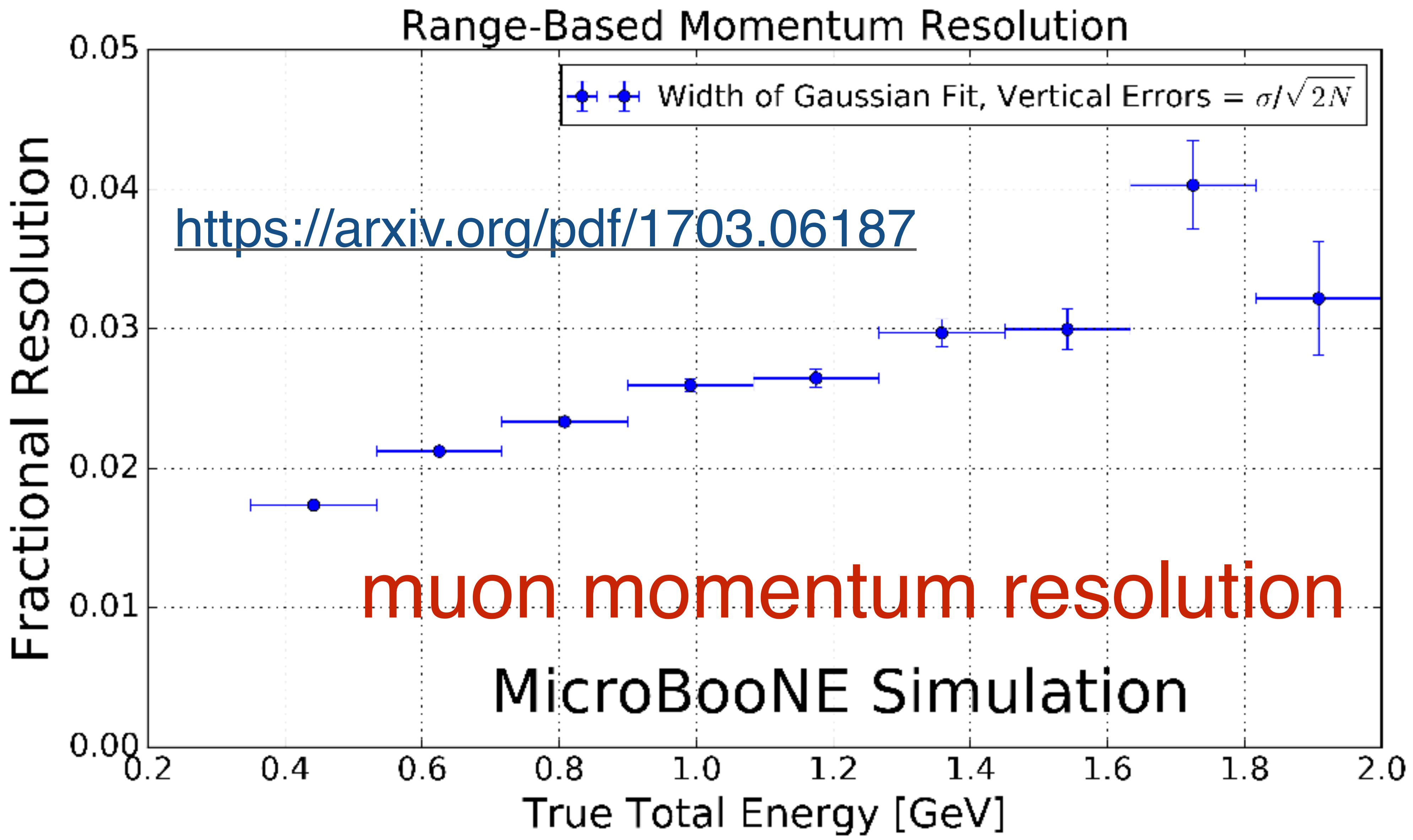
Determining track momentum

Momentum from range

- Look up energy loss on range tables
  - where the rate of energy loss at every point along the track is assumed to be equal to the total stopping power. Energy-loss fluctuations are neglected.
  - Muons from PDG
    - http://pdg.lbl.gov/2018/AtomicNuclearProperties/MUE/muE_liquid_argon.pdf
  - Protons from NIST
    - https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html
  - Discrete tabulated values are interpolated to get a continuous function
- Simplest and most accurate method
  - resolution ≲3%
- LArSoft implementation could be improved:
  - currently limited to muons and protons
  - uncertainties not estimated



proton range vs E



https://arxiv.org/pdf/1703.06187

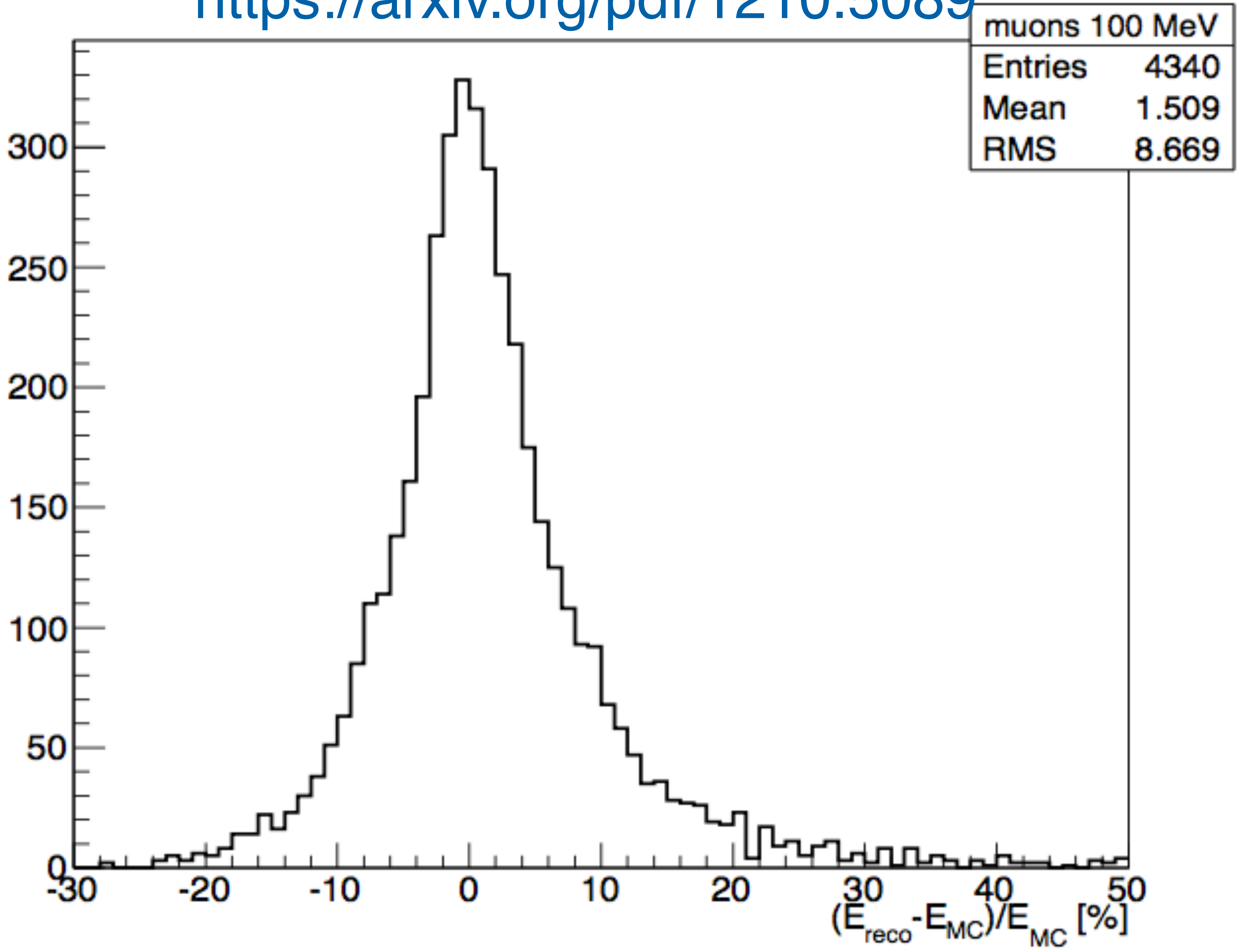
muon momentum resolution

Momentum from calorimetry

- Integrate energy loss dE/dx along track length
- Requires calibrated calorimetry with recombination factor correction
  - need to calibrate not only the MIP region but also the Bragg peak!
- Resolution improves at higher energy (1/√E)

- Not much public documentation
  - Plots on the right are part of the PMA paper (2013) and the MicroBooNE calibration note (2018): σ~10%
- Need a centrally supported version in LArSoft!

https://arxiv.org/pdf/1210.5089



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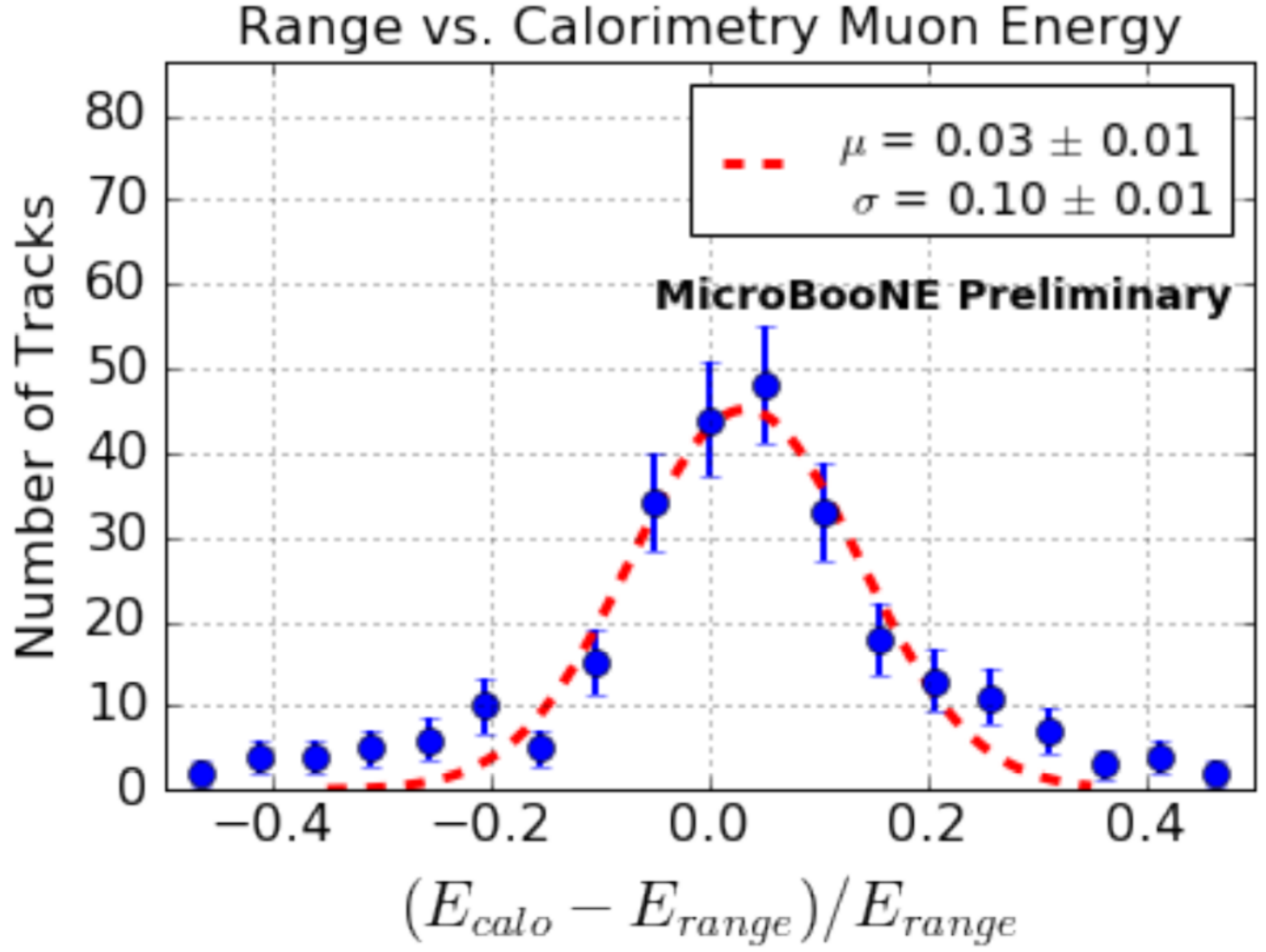
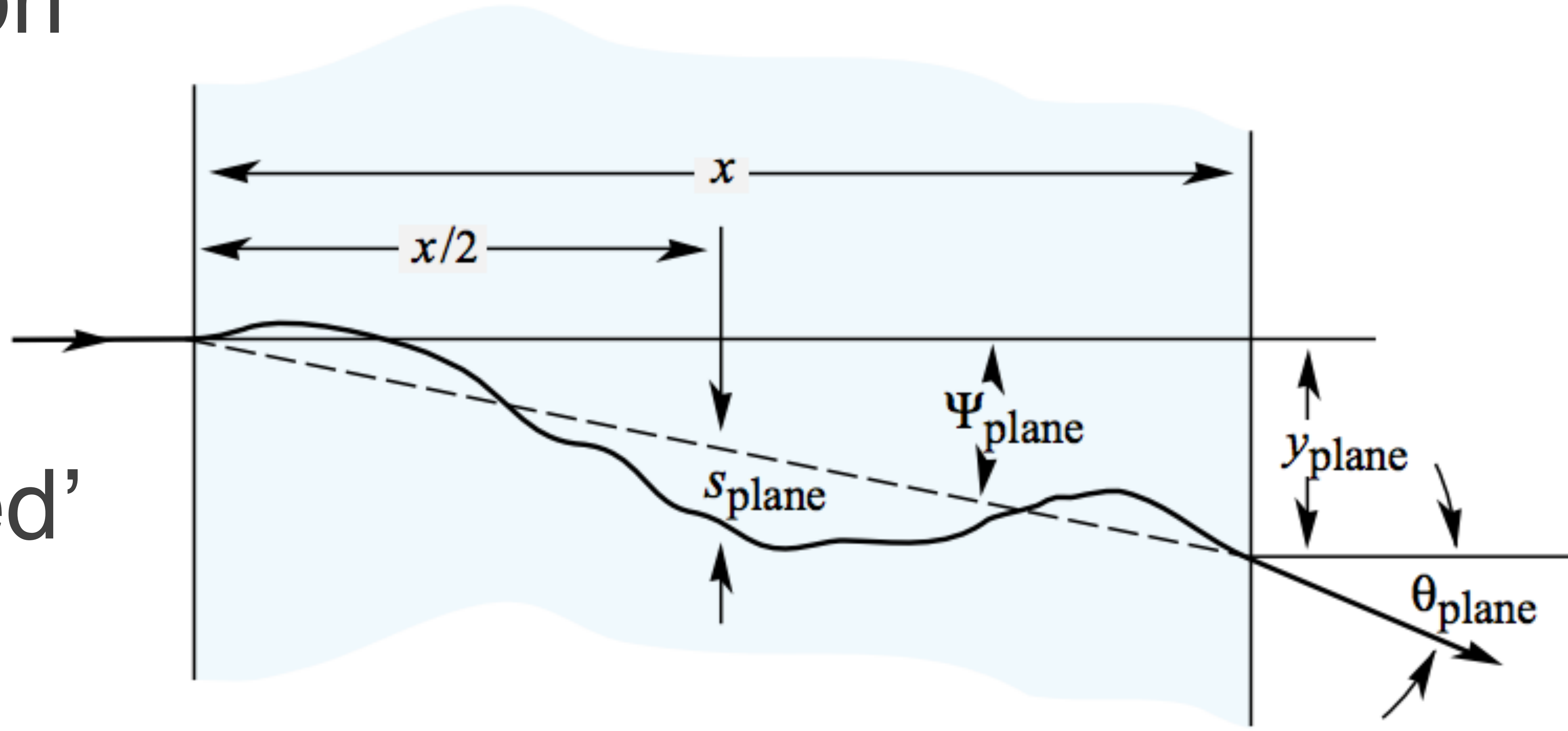


Measuring track momentum with MCS

- The deflections along the particle trajectory due to Multiple Coulomb Scattering depend on the momentum of the particle:

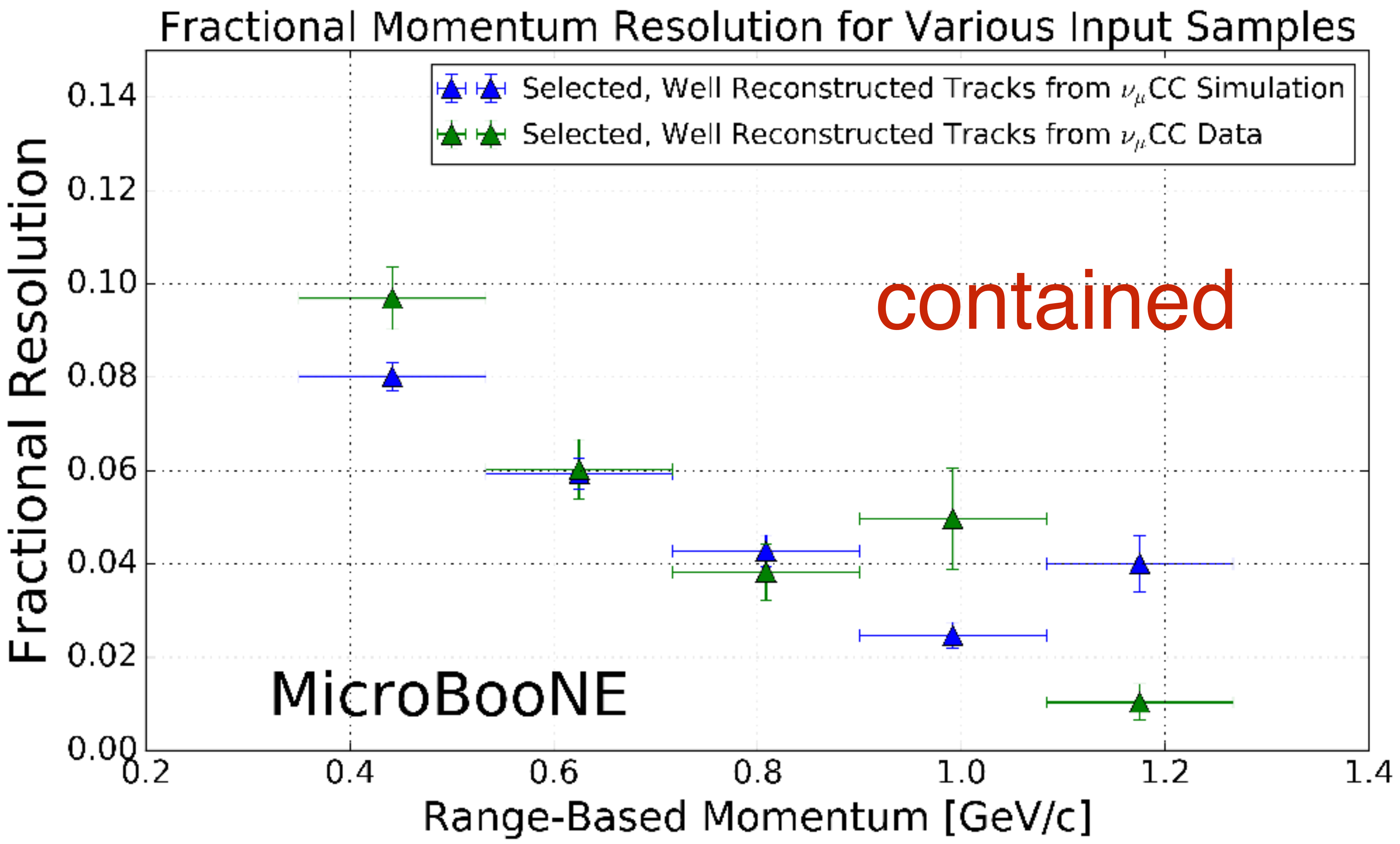
$$\psi_{MCS} = \frac{13.6 MeV/c}{\beta p}\sqrt{\frac{L}{X_0}}\left(1+0.038\ln\frac{L}{X_0}\right),$$



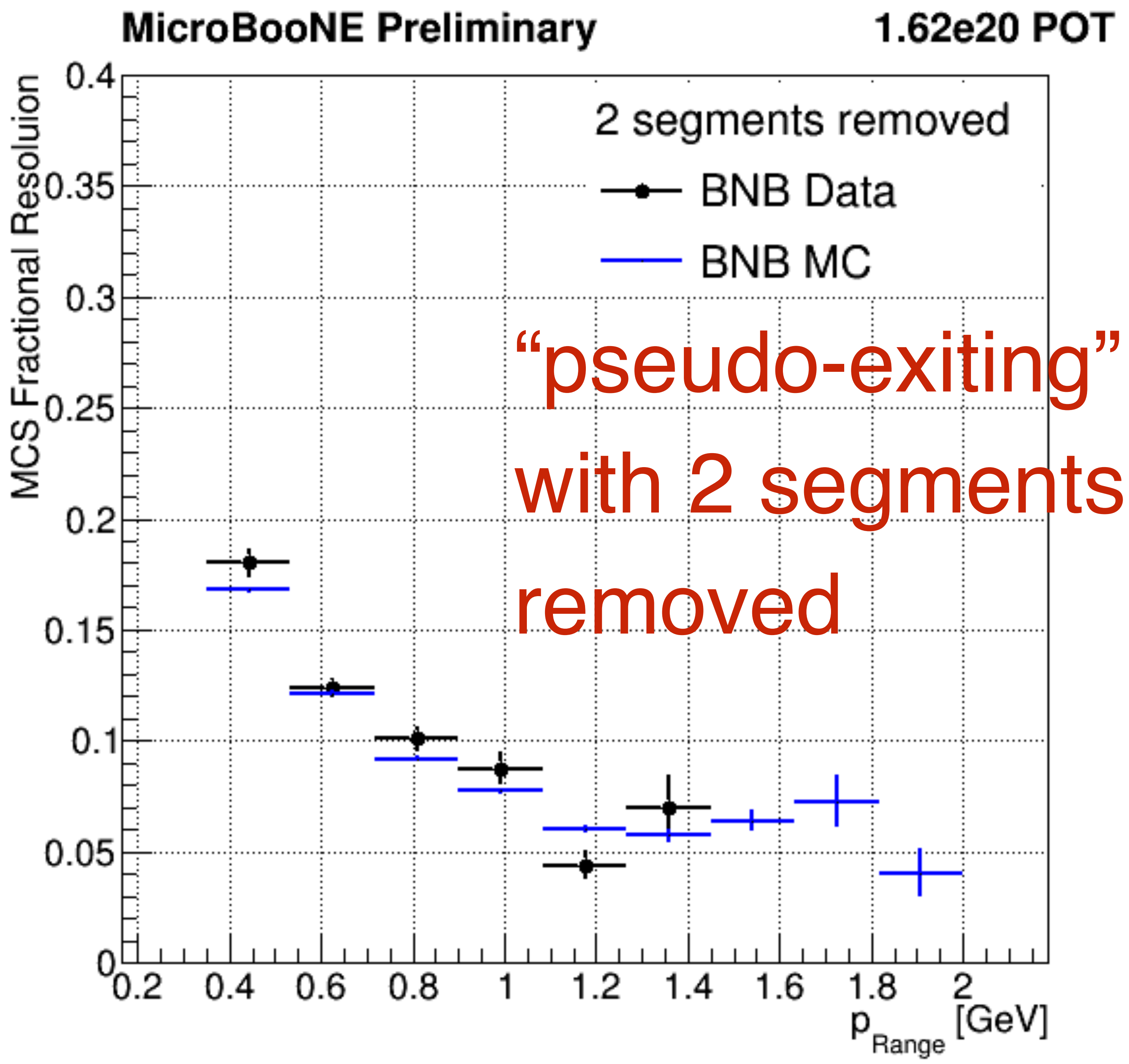
- The Highland formula formula can be ‘inverted’ to estimate the momentum based on the observed scattering angles
- Valid up to p~few GeV, when MCS deflections are comparable to detector resolution
- Two recently published approaches:
  - ICARUS: https://arxiv.org/pdf/1612.07715.pdf
  - MicroBooNE: https://arxiv.org/pdf/1703.06187.pdf

MicroBooNE's approach

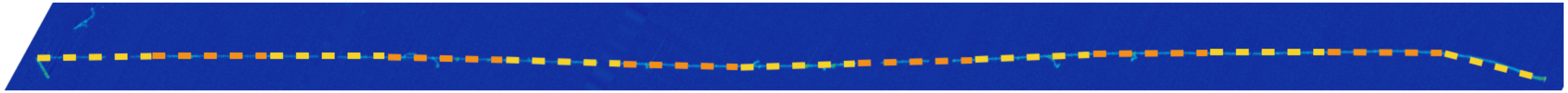
- Likelihood scan in equal steps in momentum from 1 MeV to 7.5 GeV
- Tuned Highland formula for liquid Argon
- Split track in 14 cm long segments, consider angles between consecutive segments
- Momentum at each segment is the initial hypothesis after subtracting the expected energy loss from Bethe-Bloch in the upstream travel distance
- Available in LArSoft
- Validated in data both for contained and "exiting" tracks



contained

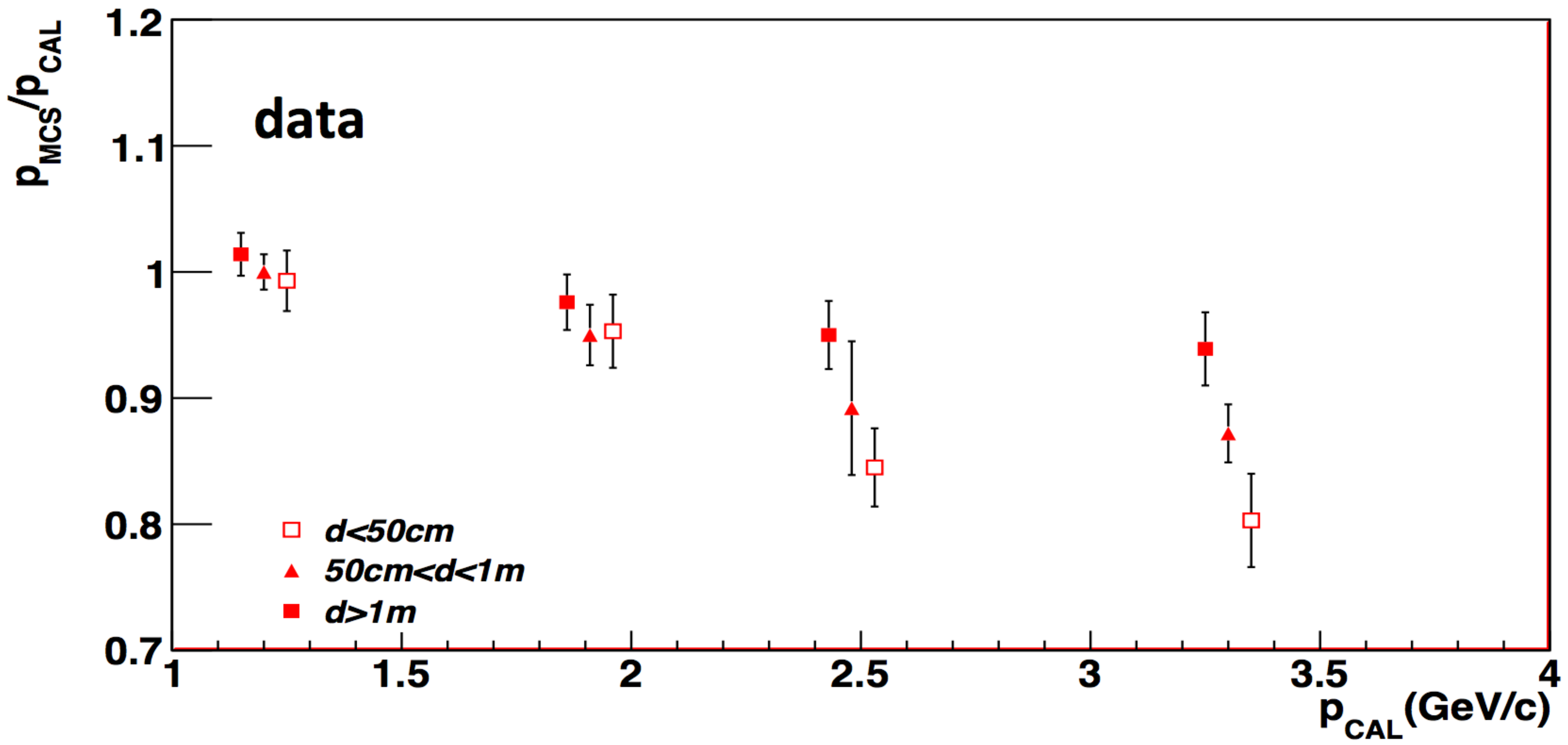


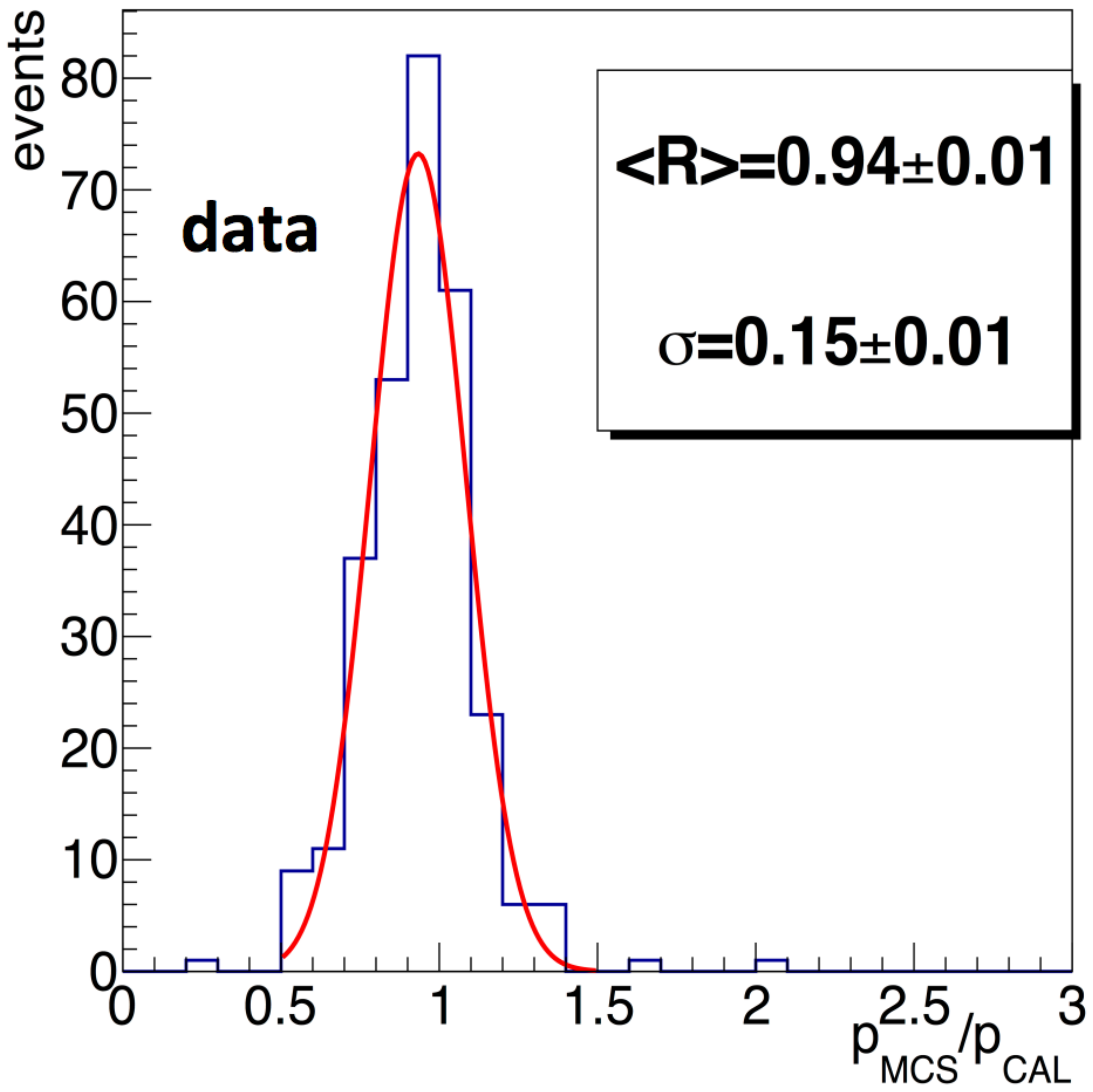
"pseudo-exiting" with 2 segments removed



ICARUS's approach

- 2D angles in collection plane view
- Minimization of a χ^2-like variable
- Split track in 19.2 cm long segments, define angles in two ways
  - from polynomial connecting segment barycenters or from linear fit to each segment
- Momentum at each segment is the initial hypothesis after subtracting the energy loss from calorimetry in the upstream portion of the track
- Detailed study to accounting for know detector distortions
- Validated in data using the first 4m of tracks >5m long
- It would be great to converge on a single MCS algorithm!
- ICARUS also developed a Kalman filter-based algorithm
  - https://arxiv.org/pdf/hep-ex/0606006





Comparing (and combining?) the 3 methods

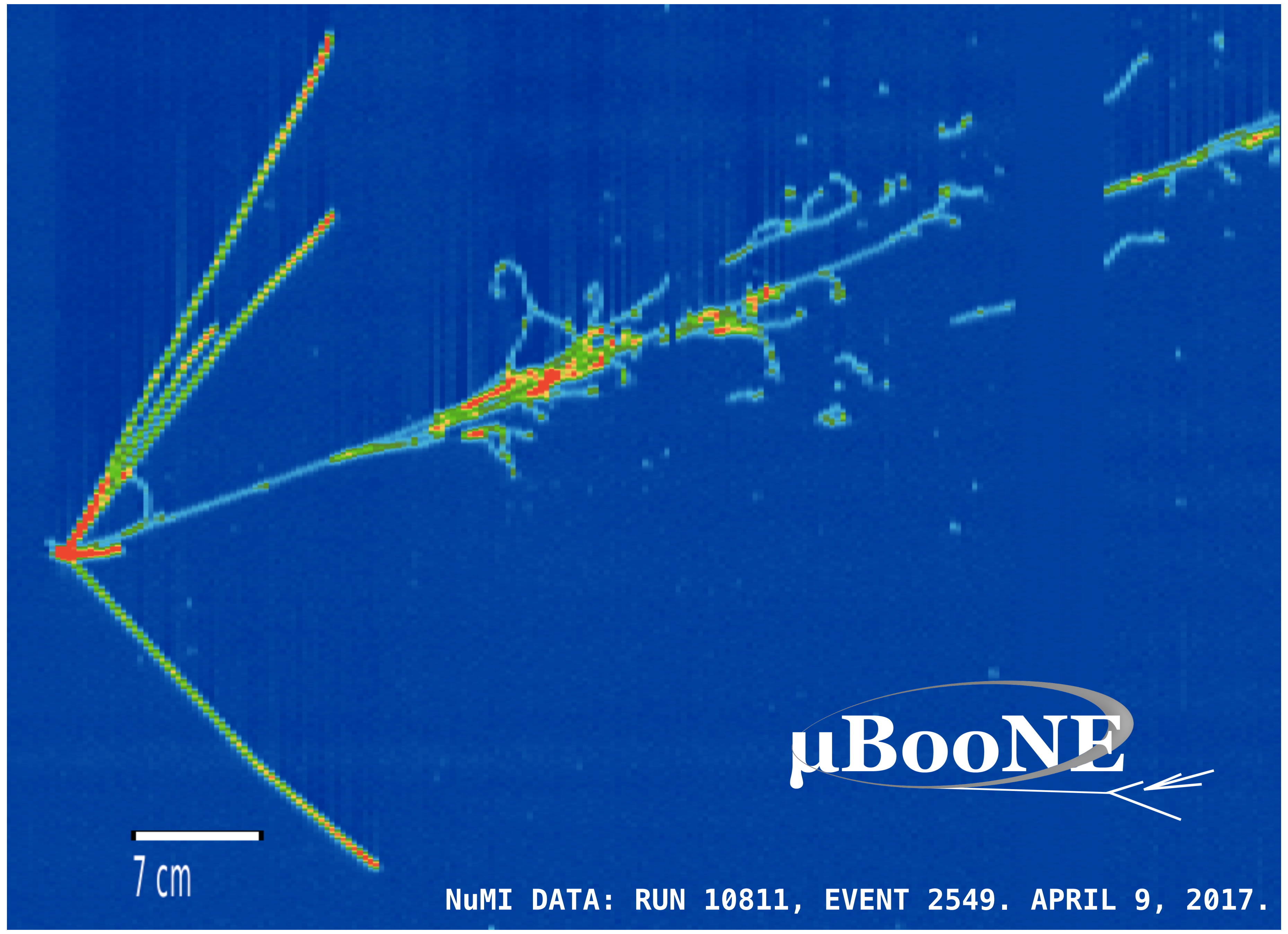
- Range and Calorimetry they require the track to be fully reconstructed, so they are are valid only for contained tracks
- MCS it’s the only method that can be applied both to contained and exiting tracks!

- Possible further developments:
  - The three methods rely on different properties of the track: they can be combined!
  - Range and MCS methods rely on assumption on PID:
    - can the consistency between the momentum estimates be used to complement current PID?
    - can discrepancies wrt Coulomb Scattering expected deflections help tag charge pions?

Fitting vertices

Vertex fitting

- Two vertex fit cases:
  - Vertex position determination used during pattern recognition, used to drive the PR itself
  - Refined vertex position after PR, to re-asses compatibility of objects to the same vertex or to trigger a second-pass reconstruction
- Here we focus on the second case



NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

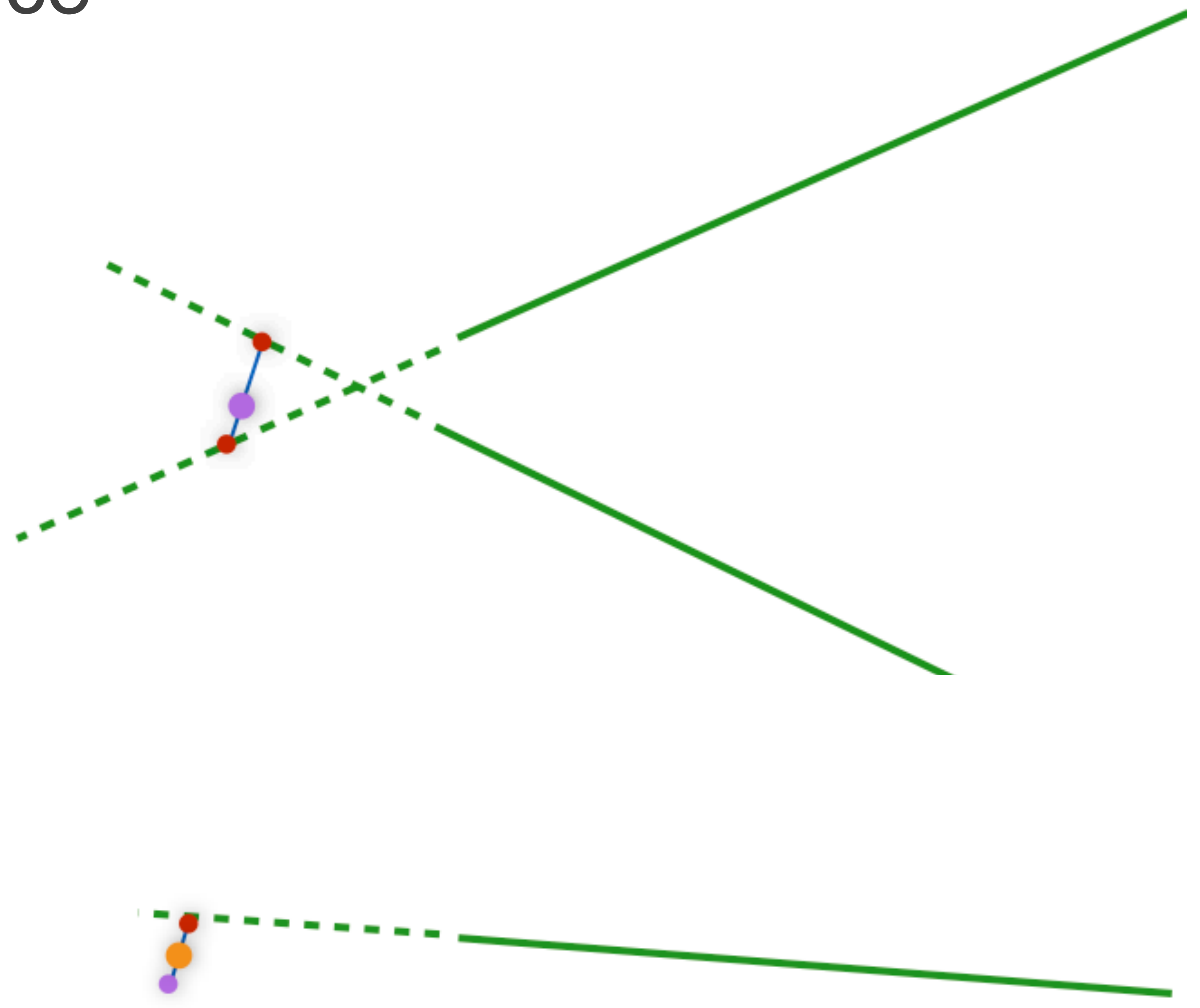
3D Vertex Fits

- Fit of vertex position using track parameters and covariance matrix from Kalman Filter tracks

- First fit two tracks that have closest start position: vertex position from weighted average of closest approach positions along the track directions

- Then consider possible additional tracks, from longest to shortest: update vertex position again with weighted average

- Result is 3D vertex, with fit χ^2 and covariance, and various track-vertex compatibility metrics
  - impact parameter, propagation distance, …



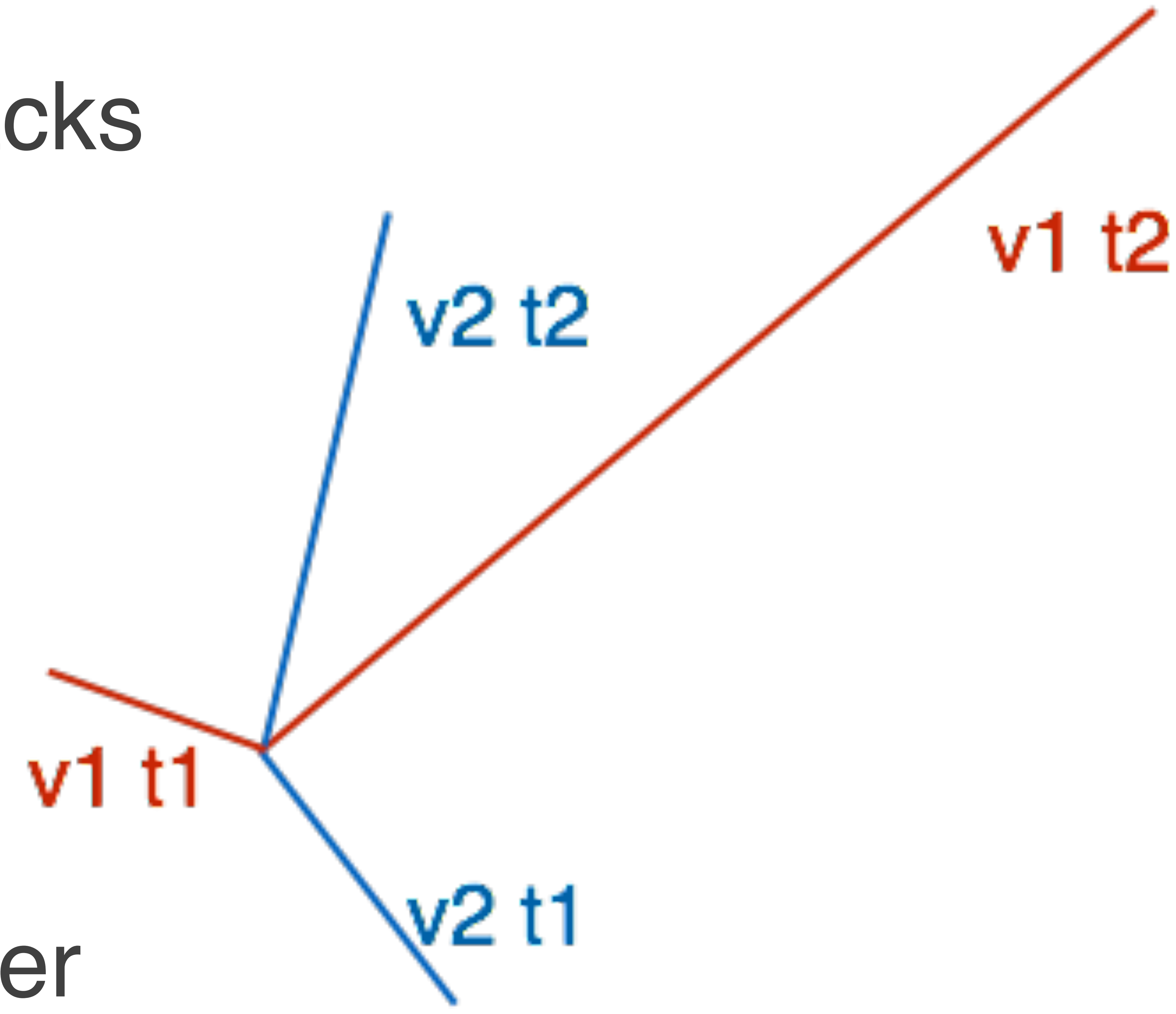
Vertex Fit Performance: data-driven method

- Select vertices from 3D fitter where exactly 4 tracks have been used in the fit

- Split the tracks in two sets:
  - v1: shortest+longest
  - v2: the others

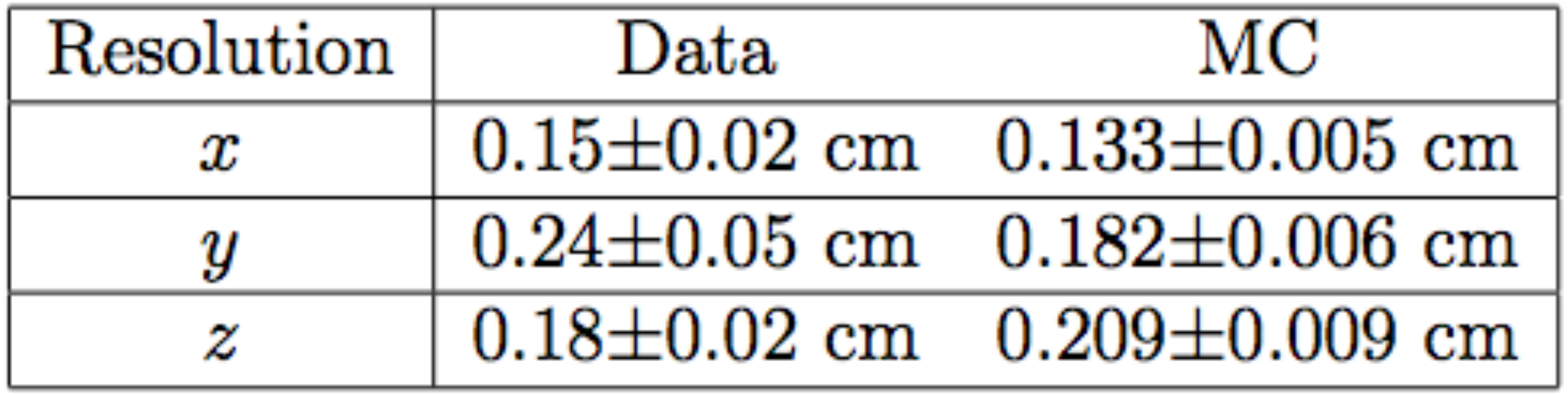
- Refit each track set independently with same fitter

- Extract resolution from comparison of positions from the two split vertices



Vertex Fit Resolution: Results

- Method for vertex resolution on data based on **split track sets** shows good data-MC agreement, but **statistically limited**
- Showing results using open run1 dataset, with very loose event and track selection
  - e.g. tracks with ≥5 hits, >2 cm long
  - **absolute resolution value not optimal due to loose selection**
- To be repeated with more data (also NuMi) to increase stats



Resolution	Data	MC
x	0.15±0.02 cm	0.133±0.005 cm
y	0.24±0.05 cm	0.182±0.006 cm
z	0.18±0.02 cm	0.209±0.009 cm

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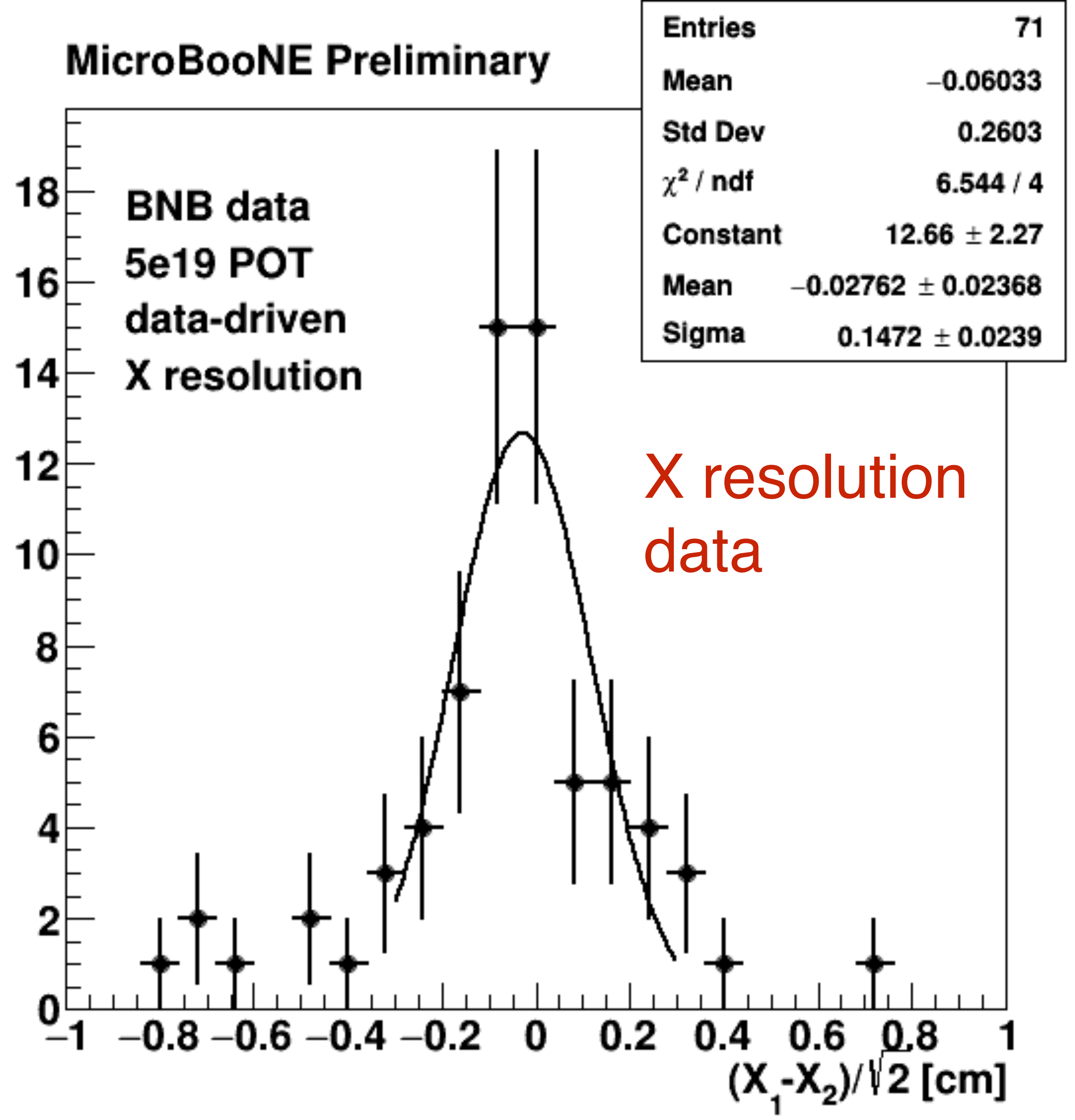
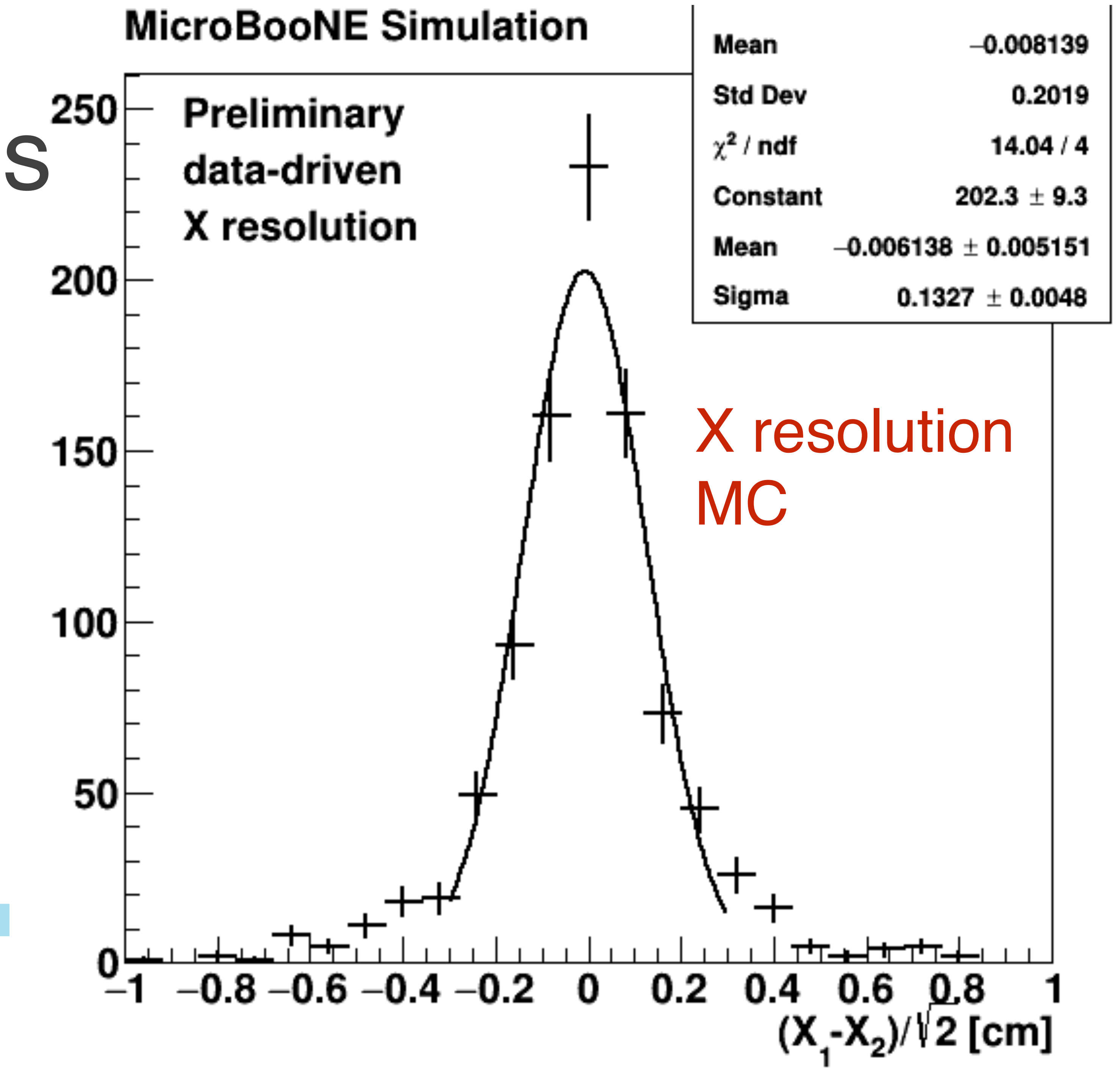


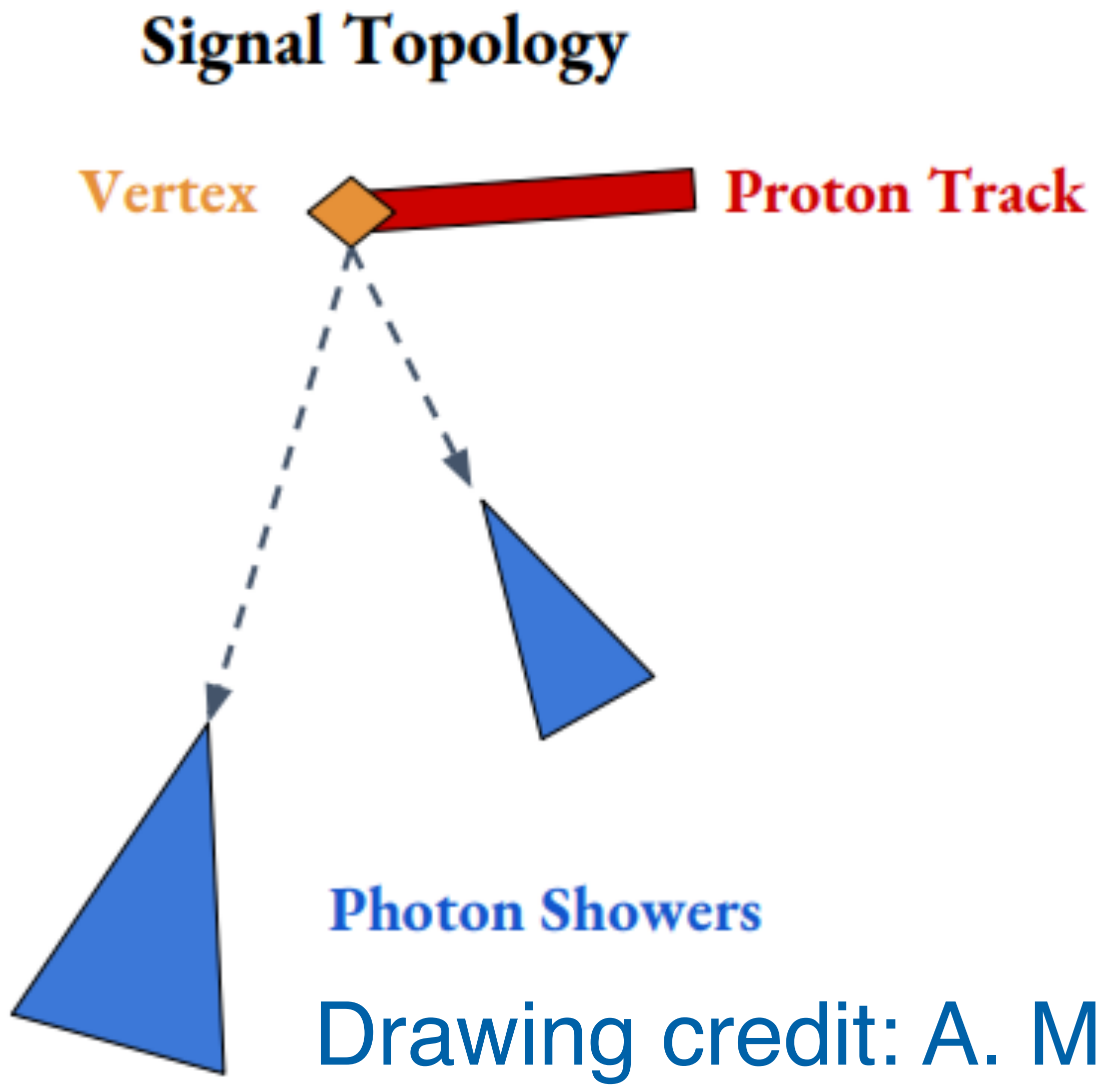
X resolution data



X resolution MC

Vertex Reconstruction for showers

- Similar ideas can be used to associate not just tracks but also showers to the same vertex
- Based on 3 parameters:
  - tmax: maximum distance at which two tracks can be associated
  - bmax: maximum distance the shower is backwards-projected
  - smax: maximum shower impact parameter for a shower
- Shower projection based on PCA fit
- Would be interesting to expand the previous approach to include showers (or fit the initial electron segment as a track)



Drawing credit: A. Mogan

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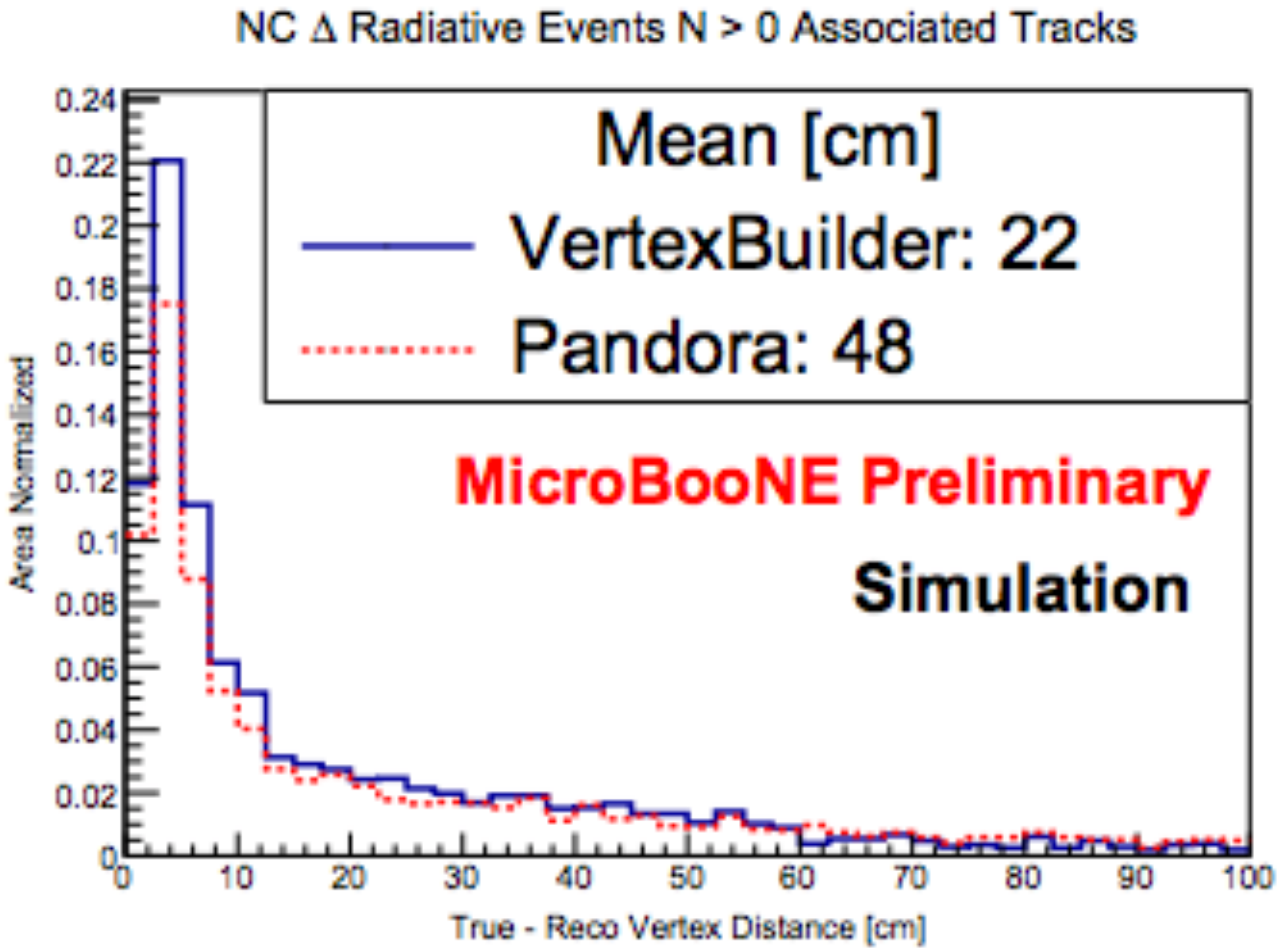


Some comparisons with DUNE CDR

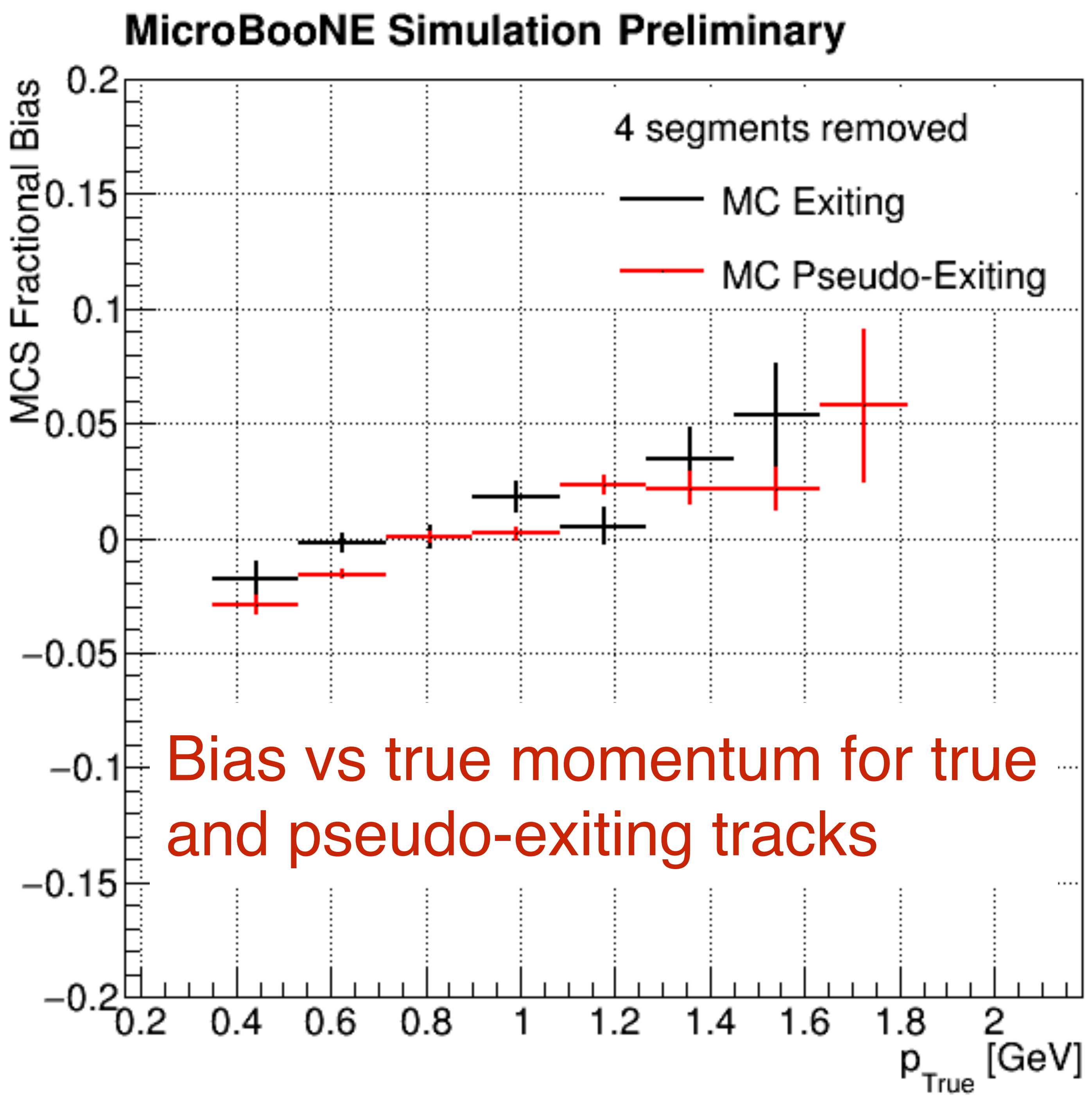
Quantity	CDR value [achieved]	Value measured in data
Muon angular resolution	1 deg (0.017 rad)	0.022 rad ($\sigma_\theta \oplus \sigma_\phi$ for $p>1$ GeV)
Muon contained MCS resolution	18% [18%]	<10%
Muon exiting MCS resolution	30%	15% ($p<2.5$ GeV)
Vertex position resolution	(2.5, 2.5, 2.5) cm [(1.1, 1.4, 1.7) cm]	(0.15, 0.24, 0.18) cm

Backup

MCS exiting tracks: overview of method

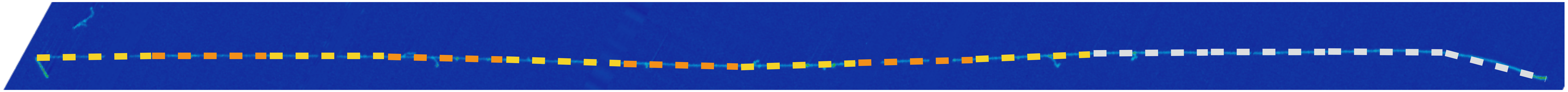
- With contained tracks in data, we compared the MCS to momentum from range. For exiting tracks, what can we compare to?

- Idea: Take long contained tracks and remove N segments from end of track
  - where we tested N=2,4,6
  - can compare to momentum from range for full track
  - main limitation: does not account for TPC edge effects
  - plot demonstrates method validity



Bias vs true momentum for true and pseudo-exiting tracks

Contained track split in segments, last 4 are not considered



Results

- Event selection: ν_μ CC
- Require track length>100 cm

- Overall good data-MC agreement for 2,4, and 6 segments removed
  - **Bias**: <5%
  - **Resolution**: as expected degrades with more segments removed

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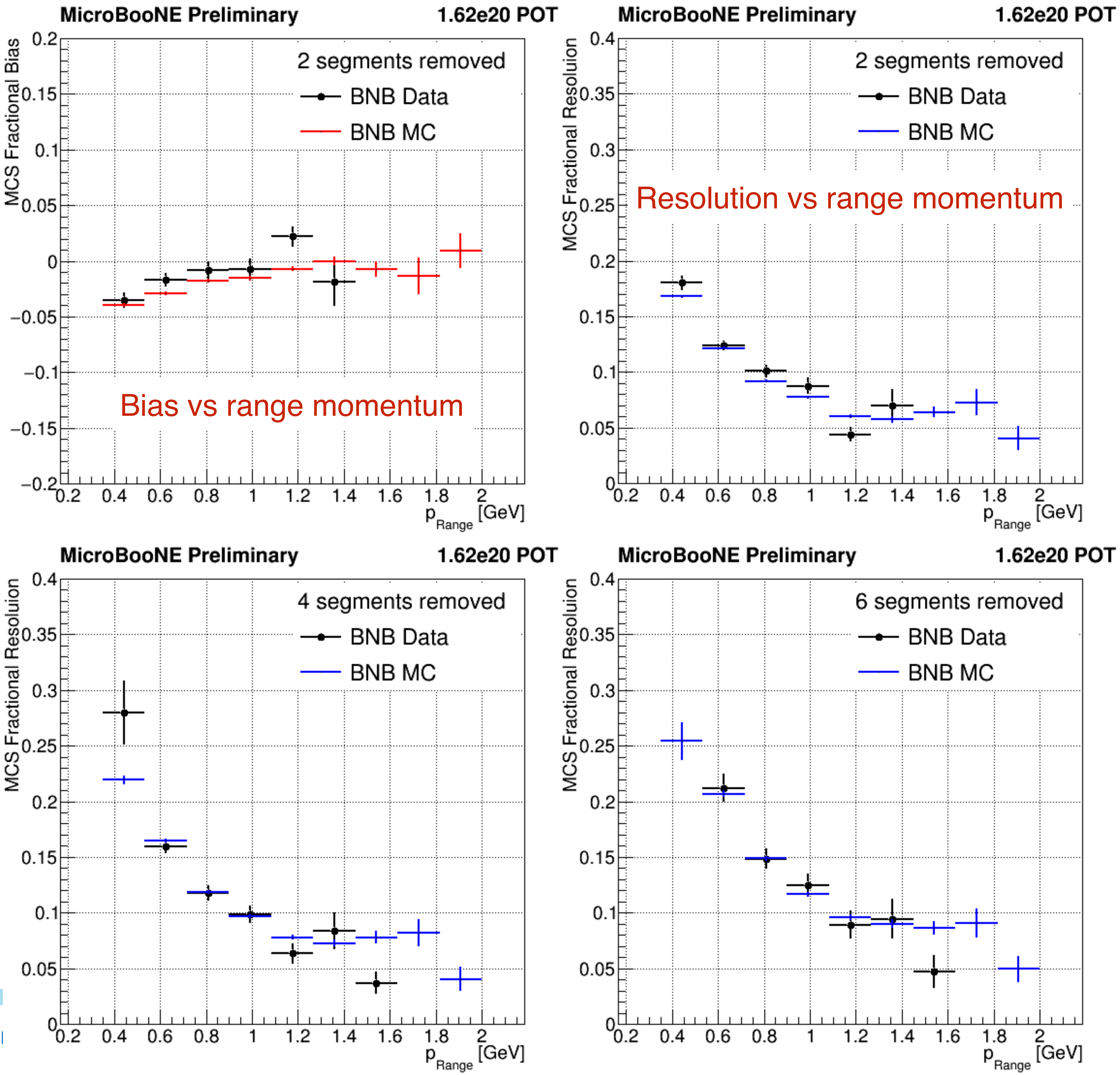

Sources for comparisons with DUNE CDR

Vol II

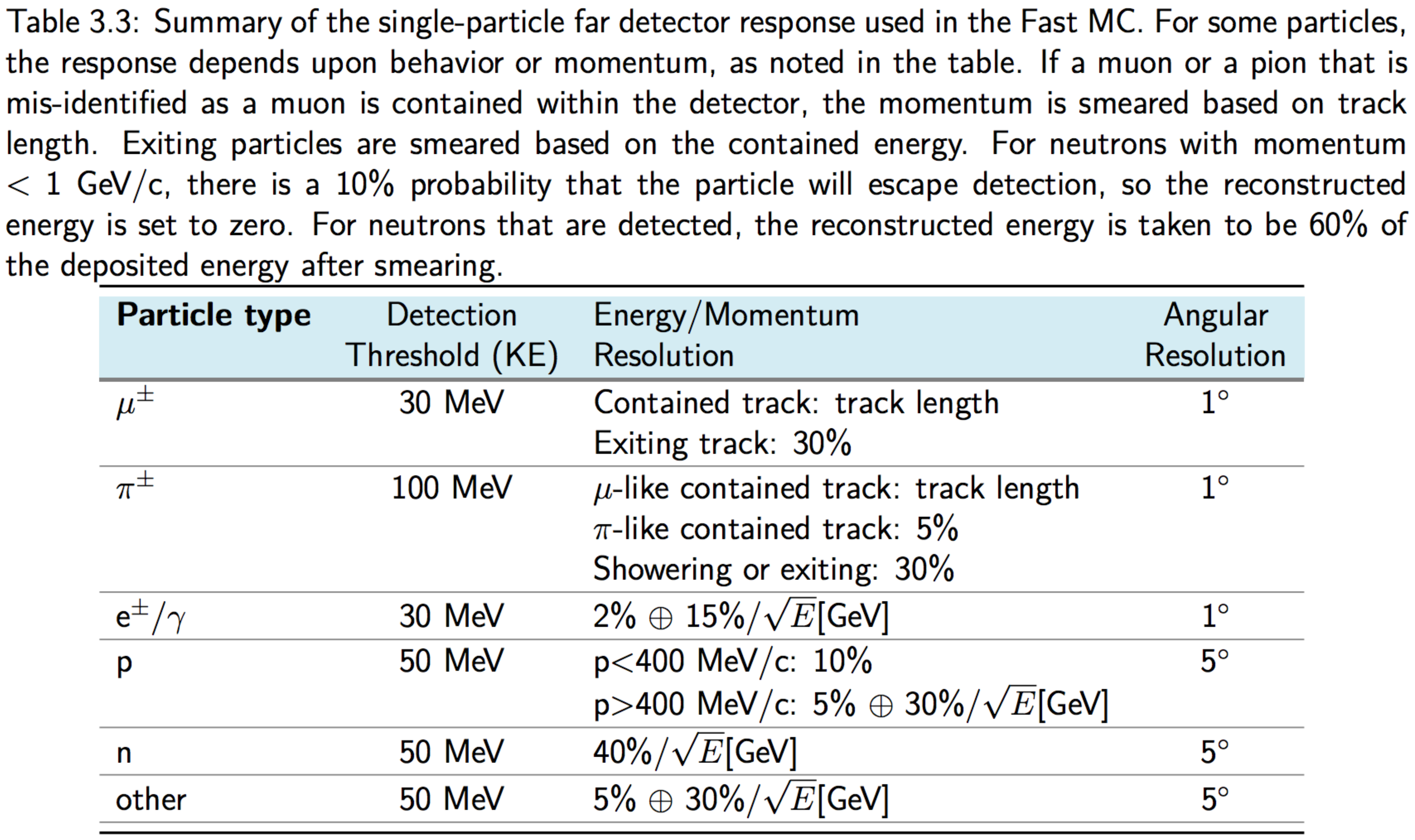

Table 3.3: Summary of the single-particle far detector response used in the Fast MC. For some particles, the response depends upon behavior or momentum, as noted in the table. If a muon or a pion that is mis-identified as a muon is contained within the detector, the momentum is smeared based on track length. Exiting particles are smeared based on the contained energy. For neutrons with momentum $<$ 1 GeV/c, there is a 10% probability that the particle will escape detection, so the reconstructed energy is set to zero. For neutrons that are detected, the reconstructed energy is taken to be 60% of the deposited energy after smearing.

Particle type	Detection Threshold (KE)	Energy/Momentum Resolution	Angular Resolution
$\mu^\pm$	30 MeV	Contained track: track length Exiting track: 30%	1°
$\pi^\pm$	100 MeV	μ-like contained track: track length π-like contained track: 5% Showering or exiting: 30%	1°
e$^\pm/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{E}$[GeV]	1°
p	50 MeV	p<400 MeV/c: 10% p>400 MeV/c: $5\% \oplus 30\%/\sqrt{E}$[GeV]	5°
n	50 MeV	$40\%/\sqrt{E}$[GeV]	5°
other	50 MeV	$5\% \oplus 30\%/\sqrt{E}$[GeV]	5°

http://lbne2-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=10688&filename=DUNE-CDR-physics-volume.pdf&version=10

Vol IV

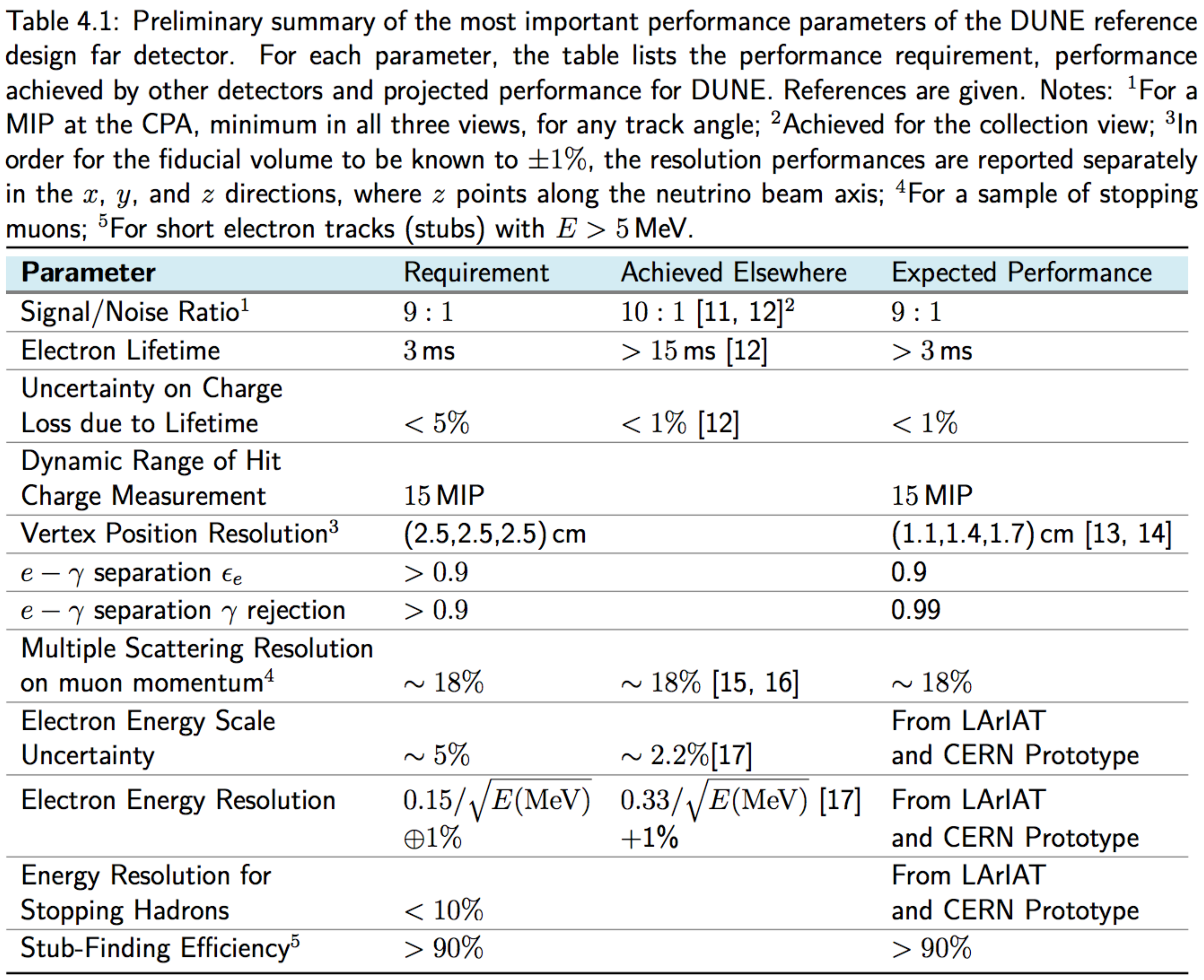

Table 4.1: Preliminary summary of the most important performance parameters of the DUNE reference design far detector. For each parameter, the table lists the performance requirement, performance achieved by other detectors and projected performance for DUNE. References are given. Notes: [1]For a MIP at the CPA, minimum in all three views, for any track angle; [2]Achieved for the collection view; [3]In order for the fiducial volume to be known to $\pm 1\%$, the resolution performances are reported separately in the x, y, and z directions, where z points along the neutrino beam axis; [4]For a sample of stopping muons; [5]For short electron tracks (stubs) with $E > 5$ MeV.

Parameter	Requirement	Achieved Elsewhere	Expected Performance
Signal/Noise Ratio[1]	$9:1$	$10:1$ [11, 12][2]	$9:1$
Electron Lifetime	3 ms	$>$ 15 ms [12]	$>$ 3 ms
Uncertainty on Charge Loss due to Lifetime	$<5\%$	$<1\%$ [12]	$<1\%$
Dynamic Range of Hit Charge Measurement	15 MIP		15 MIP
Vertex Position Resolution[3]	(2.5,2.5,2.5) cm		(1.1,1.4,1.7) cm [13, 14]
$e-\gamma$ separation ϵ_e	>0.9		0.9
$e-\gamma$ separation γ rejection	>0.9		0.99
Multiple Scattering Resolution on muon momentum[4]	$\sim 18\%$	$\sim 18\%$ [15, 16]	$\sim 18\%$
Electron Energy Scale Uncertainty	$\sim 5\%$	$\sim 2.2\%$[17]	From LArIAT and CERN Prototype
Electron Energy Resolution	$0.15/\sqrt{E(\mathrm{MeV})}$ $\oplus 1\%$	$0.33/\sqrt{E(\mathrm{MeV})}$ [17] $+1\%$	From LArIAT and CERN Prototype
Energy Resolution for Stopping Hadrons	$<10\%$		From LArIAT and CERN Prototype
Stub-Finding Efficiency[5]	$>90\%$		$>90\%$

http://docs.dunescience.org/cgi-bin/RetrieveFile?docid=183&filename=cdrvol4.pdf&version=2