Muon momentum reconstruction in ICARUS-T600 LArTPC via Multiple Scattering

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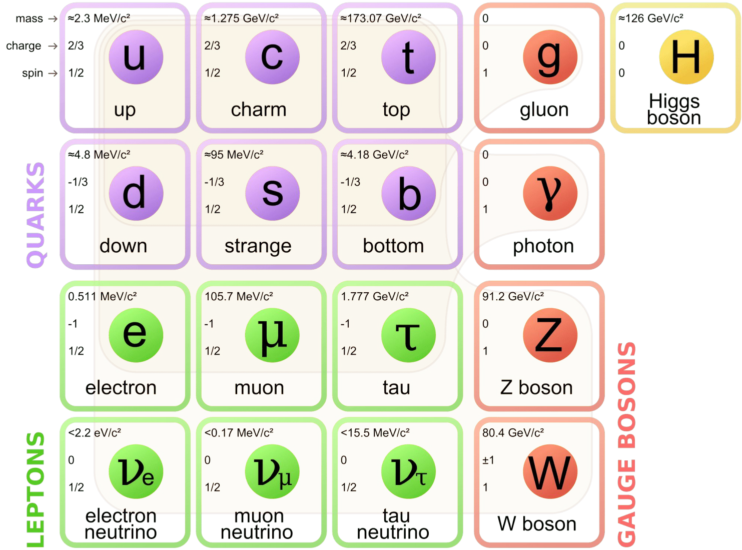
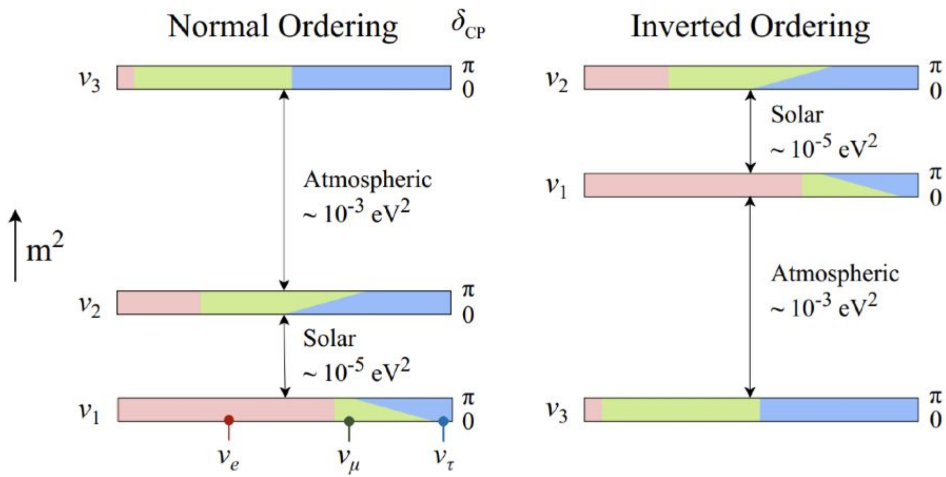
Neutrinos and neutrino oscillations

Standard Model (SM) neutrinos:

- Massless, electrically neutral leptons
- Only weak interaction
- **3 flavor eigenstates**: ν_e, ν_μ, ν_τ





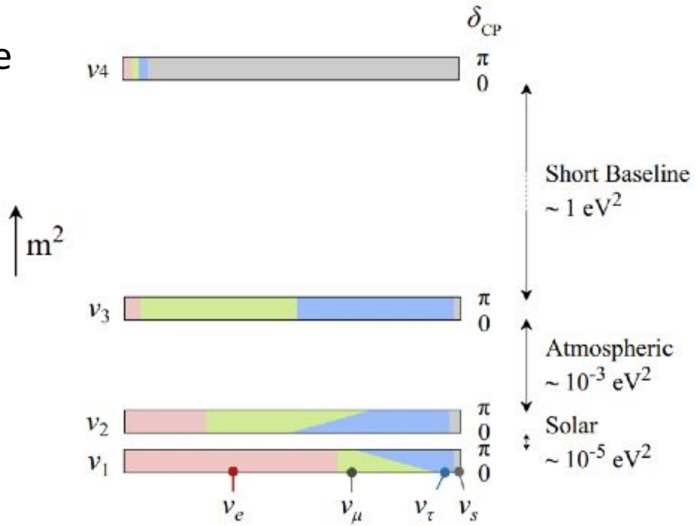
- **Neutrino oscillates** as it propagates through space
- (ν_e, ν_μ, ν_τ) are linear combinations of (ν_1, ν_2, ν_3)

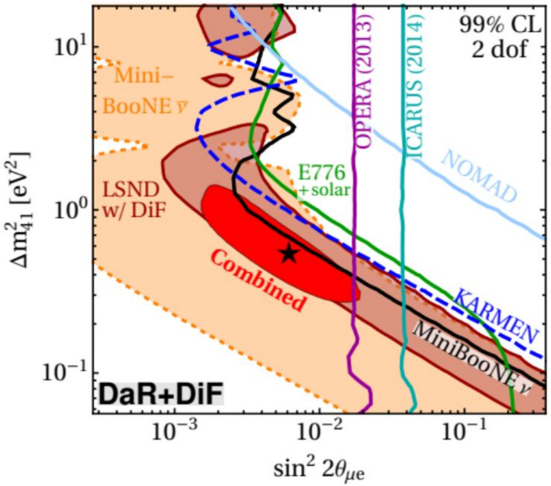
$$|\nu_\alpha\rangle = \sum_{i=1,2,3} U^*_{\alpha i}\,|\nu_i\rangle \qquad |\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i}\,|\nu_\alpha\rangle$$

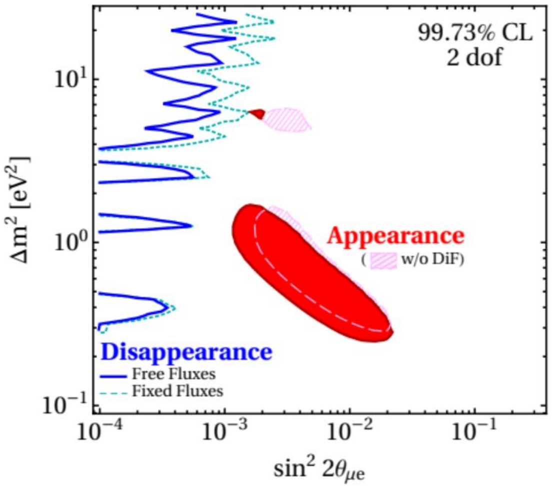
- Direct evidence that **neutrinos have mass**
- Contradicts original minimal SM predictions

Anomalies in oscillation experiments

- **LSND Anomaly**: unexpected excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam
- **Gallium Anomaly**: GALLEX and SAGE with Mega-Curie radioactive source, ν_e observed/predicted = 0.84 ± 0.05 (confirmed by BEST)
- **Reactor Antineutrino Anomaly**: app. deficit wrt expected $\bar{\nu}_e$ flux
- **MiniBooNE Anomaly**: low energy excess of ν_e and $\bar{\nu}_e$
- **Neutrino-4 (Nu-4) Anomaly**: reported signal of $\Delta m^2 \sim 7$ eV^2
- Tension between appearance/disappearance experiments

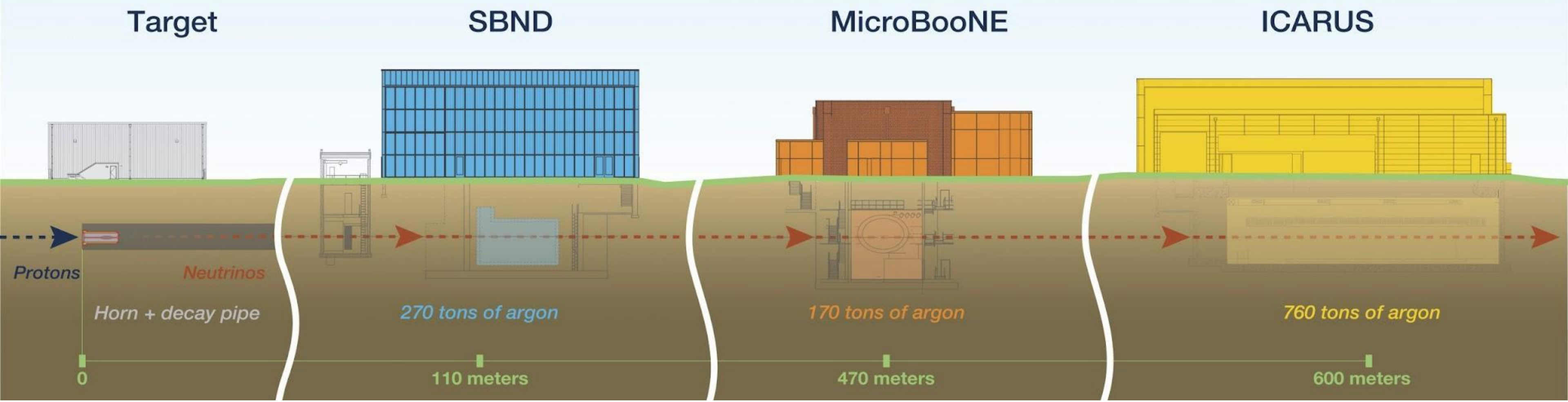






- **4th neutrino (sterile)**: explains observed anomalies through additional oscillations
- Does not interact via weak force
- Much more elusive than active ν
- Mixes with active ν

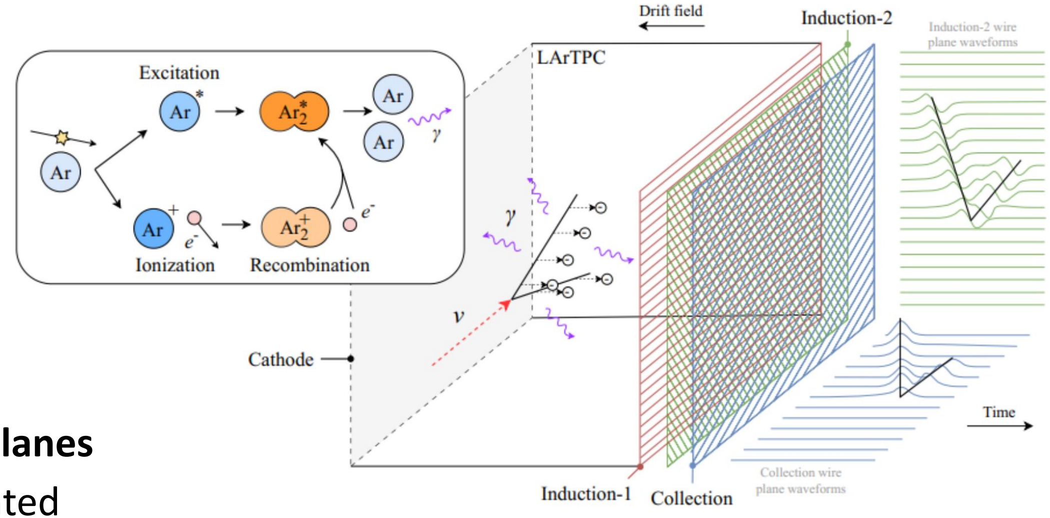
Short-Baseline Neutrino Program at Fermilab

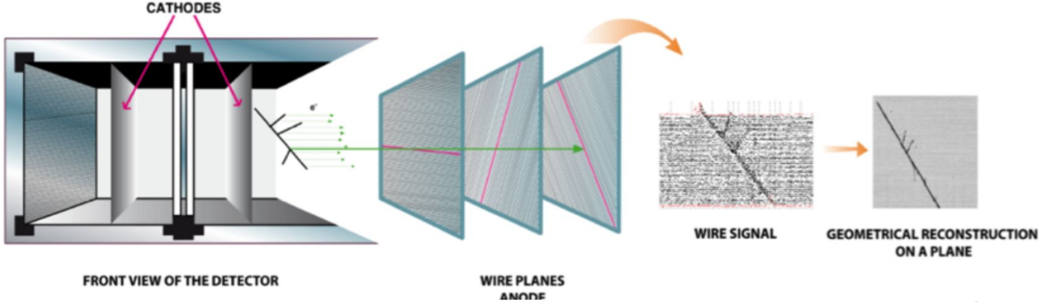


- Investigates ν oscillations at short baselines L/E ~ 1m/MeV
- Booster Neutrino Beam (BNB) + Neutrino at the Main Injector (NuMI, off-axis) *only in ICARUS* at 0-3 GeV
- Confirms or rules out the existence of eV-scale sterile ν
- Measures ν-Ar cross sections (SBN & DUNE programs) + BSM searches
- **3 LArTPC detectors** placed at different baselines along the beam (SBND, MicroBooNE, ICARUS):
  - $\nu_\mu \rightarrow \nu_e$ appearance and ν_μ disappearance comparing ν events at different distances from the source
  - initial ICARUS standalone program (Nu-4): ν_μ disappearance (BNB), ν_e disappearance (NuMI, off-axis)

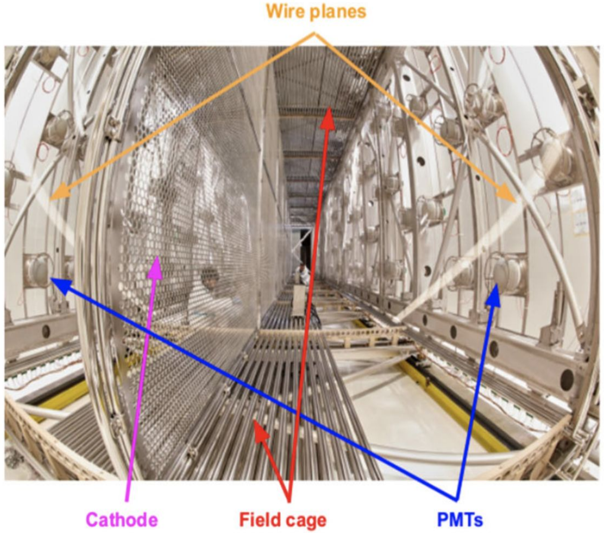
Liquid Argon Time Projection Chamber

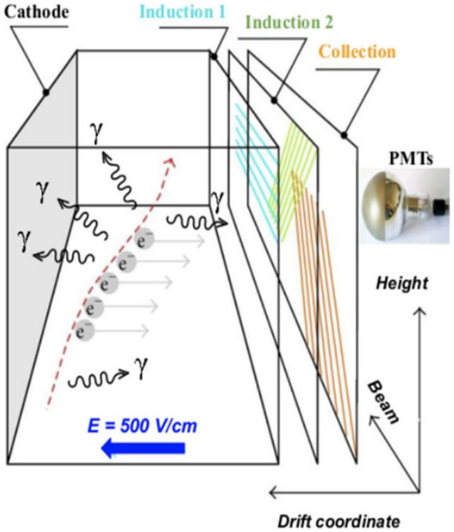
- Accurate 3D spatial reconstruction ($\sim$mm^3 resolution) + calorimetry
- **Liquid Argon** (X_0 = 14 cm): target and detection medium for ν interactions
- ν-Ar interaction: charged particles ionize Argon atoms and create free e- that drift under a uniform electric field
- e- collected by 3 mm-spaced **anode wire planes** (Induction-1, Induction-2, Collection) oriented at different angles (0°, 60°, -60°)
- PMTs detect scintillation light, providing precise timing information



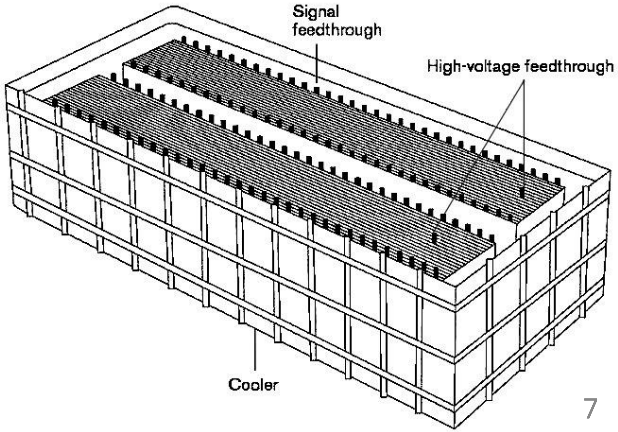


The ICARUS-T600 detector





- Largest and farthest SBN detector
- Originally operated at LNGS
- 760 tons of LAr at 89 K
- 2 adjacent modules (EAST and WEST)
- 2 TPC/module with a central cathode
- **E_{drift} = 500 V/cm** (uniform)
- 360 PMTs TBP-WLS coated



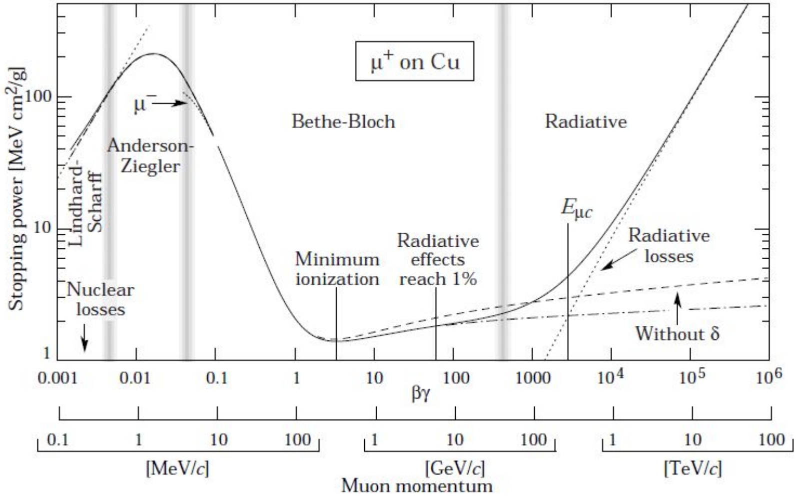
- **Event reconstruction**: multi-step process that transforms raw detector signals into meaningful physics data
- **Main steps**: signal processing, hit finding, pattern recognition and energy reconstruction

Calorimetric energy reconstruction

- Energy of charged particles reconstructed via calorimetry from e- ionization charge collected on TPC wires
- **Energy loss per unit of distance** of a charged particle traversing matter is given by the Bethe-Bloch equation

$$\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = \zeta T_{\max} \left[\ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I_0^2} - 2\beta^2 - \delta(\beta\gamma) \right]$$

where $\zeta = \frac{K}{2} z^2 \frac{Z}{A} \frac{1}{\beta^2 T_{\max}}$ and $T_{\max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / M + (m_e/M)^2}$



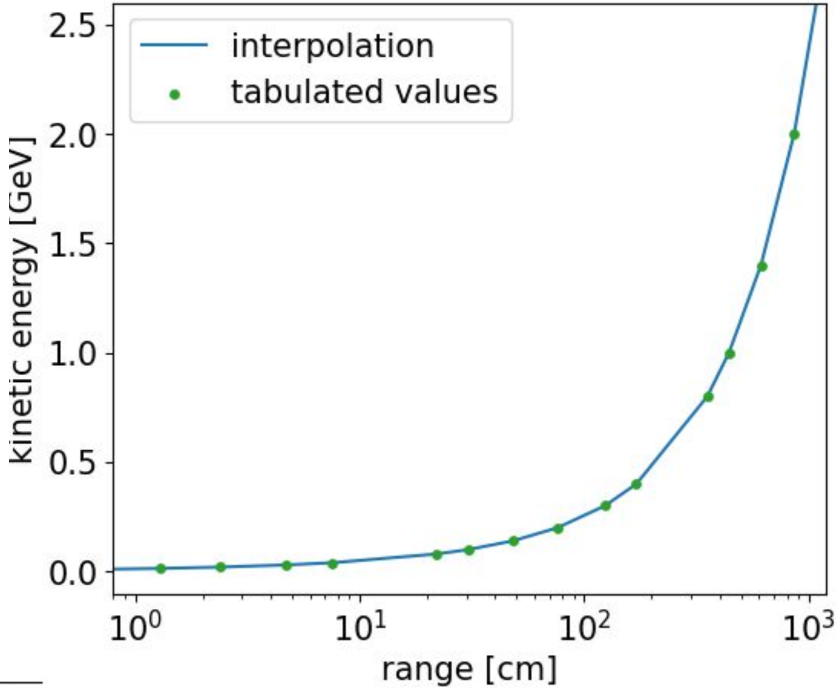
- **dQ/dx correction**: measured dQ/dx is corrected to compensate for signal attenuation along the drift by electronegative impurities that absorb e-, variable electronic gains and induction plane transparency
- **Energy calibration**: converts corrected dQ/dx into dE/dx using parameters such as electronic gain and electron recombination fraction
- **Total energy deposition**: sum of dE/dx multiplied by the pitch of each deposition point

Range-based energy reconstruction

- Relies on the **total length travelled in the detector**
- **Residual range** = distance of a given energy deposit from the track endpoint
- Charged particles slow down due to ionization energy loss as described by Bethe-Bloch equation
- If particles stop inside the detector, kinetic energy K is determined by summing up deposited energy along track
- **Continuous slowing-down approximation (CSDA)**: direct relationship between K and range, leading to an accurate measurement of particle momentum
- Once computed the kinetic energy, the momentum is

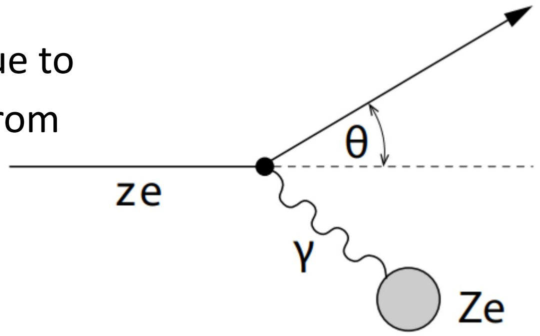
$$p = \sqrt{E^2 - M^2} = \sqrt{(K+M)^2 - M^2} = \sqrt{K^2 + 2KM}$$

○ **Only feasible for fully contained particles!**



Multiple Coulomb Scattering (MCS)

Additional method for estimating momentum of charged particles (muons)
⟶ the only suitable technique for **uncontained muons**



- μ traversing a medium undergoes multiple small-angle deflections due to **Coulomb interactions** with atomic nuclei: overall angular deviation from the initial direction
- For N(scatterings) > 20, θ distribution approximately **Gaussian**
- The standard deviation θ_{MCS} depends on the medium and is inversely proportional to μ momentum
- Empirical approximation: the **Highland formula**

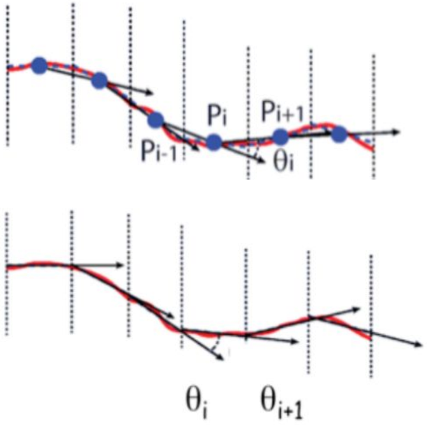
$$\theta_{\mathrm{MCS}} = \frac{S_2}{pc\beta}\sqrt{\frac{X}{X_0}}\left[1 + \varepsilon \ln\left(\frac{X}{X_0}\right)\right]$$

⟶ S_2 = 13.6 MeV and ε = 0.038 empirical coefficients

○ ICARUS: no **B** field ⟶ no momentum measurement via track curvature, but...
2 state-of-the-art MCS-based algorithms allow momentum measurement for uncontained μ

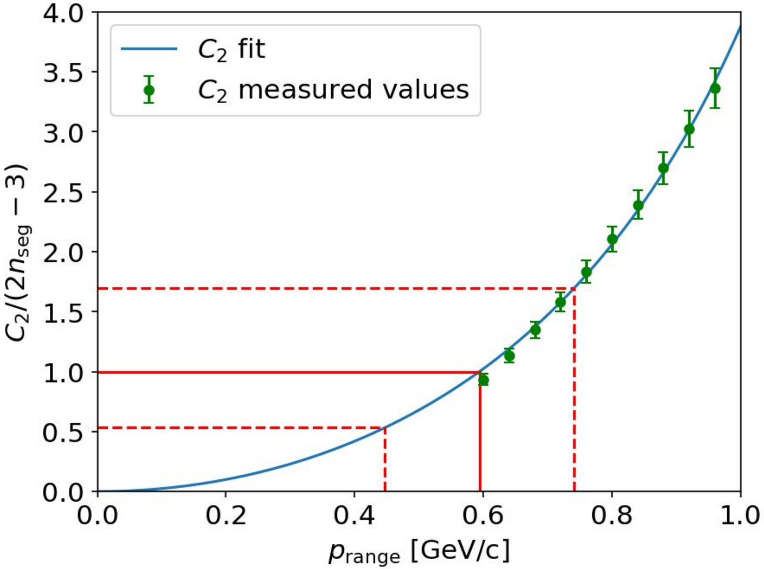
1. The “Gran Sasso” algorithm

- Developed for ICARUS at Gran Sasso National Lab.
- Originally used 2D signal hits only in **Collection view**, I developed an improved approach:
  - **2D** - projected 2D signal hits from the Induction-1, Induction-2, and Collection TPC wire planes
  - **3D** - 3D signal hits reconstructed in the (x, y, z) reference frame
- Divides the μ track into n_{seg} segments and measures deflections between consecutive segments
- Builds χ^2-like function to estimate momentum



- ○ n_{seg} segments of variable length L_{seg} (**$L_{seg} = X_0 = 14$ cm** in this analysis)
- ○ 2 different approaches to compute deflection angles:
  - ○ **polygonal approach:** barycenter of 3 consecutive segments connected by 2 straight lines → θ_{poly} is the difference between their slopes (n_{seg}-2)
  - ○ **linear-fit approach:** 2 consecutive segments are fitted with 2 straight lines → θ_{lin} is the difference between their slopes (n_{seg}-1)
- ○ Ends up with $2n_{seg}$-3 measured deflection angles!

1. The “Gran Sasso” algorithm, cont’d



- ○ **C_2 function** (χ^2-like) compares observed deflections to expectation for a given momentum p
- ○ Best estimate of p_{MCS} obtained by minimizing the discrepancy between observed/expected deflection

$$C_2(p_{\mathrm{MCS}}) = 2n_{\mathrm{seg}} - 3$$

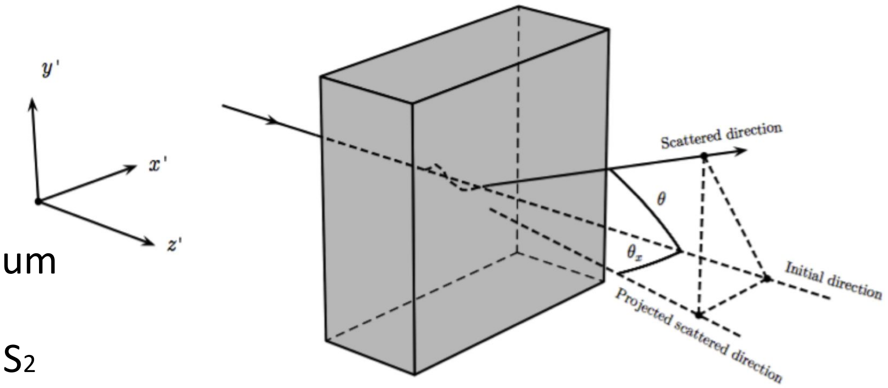
- ○ For p ⟶ p_{MCS} the C_2 function follows the condition

$$\frac{C_2(p)}{2n_{\mathrm{seg}} - 3} = \frac{1}{\alpha + \beta/p^2}$$

- θ_{poly} and θ_{lin}: observed angular deflections
- $\theta_{MCS}(p) \oplus \theta_{err}$: expected angular deflections
- θ_{err} accounts for uncertainty on the drift coordinate, for 2D projected hit points from individual planes
- **Parameter δ_{3P}**: *dispersion wrt local straight-line fit* over 3 consecutive points
- **Parameter σ_{3P}**: *RMS of δ_{3P} distribution*, track-dependent

2. The “MicroBooNE” algorithm

- Originally developed for the MicroBooNE detector
- Only relies on reconstructed **3D signal hits**
- Divides μ track into fixed-length segments $L_{seg} = X_0$
- Only uses linear-fit approach to compute deflections
- **Maximizes a likelihood function** to measure momentum



- Tuning of Highland formula and Highland coefficients S_2
- At higher momenta S_2 asymptotically approaches ~11 MeV
- Momentum-dependent correction factor κ(p) that replaces S_2

$$\theta_{\mathrm{MCS}}(p)\Big|_{X=X_0} = \frac{S_2}{pc\beta} \longrightarrow \theta_{\mathrm{MCS}}(p)\Big|_{X=X_0} = \frac{\kappa(p)}{pc\beta} \quad \text{where } \kappa(p) = \kappa_1 + \frac{\kappa_2}{|p|^2}$$

- For ICARUS: $\kappa_1 = 0.131$ MeV and $\kappa_2 = 10.457$ MeV
- Expected deflections: $\theta_{MCS}(p) \oplus \theta_{err}$ with $\theta_{err} = 10$ mrad

Comparing the two algorithms

	"Gran Sasso" algorithm	*"MicroBoone" algorithm*
Input data format	both 2D and 3D version	only 3D version
Measured deflection	both θ_{poly} and θ_{lin}	only θ_{lin}
Expected deflection	$\theta_{MCS}(p) \oplus \theta_{err}$	$\theta_{MCS}(p) \oplus \theta_{err}$
Highland formula	standard version $\theta_{MCS}(p)$	tuned version $\theta_{MCS}(p)$ with $S_2 \longrightarrow \kappa(p)$
Angular resolution term	variable θ_{err} based on measurement errors along the drift path	fixed θ_{err} = 10 mrad
Segment length	variable, but set at X_0 = 14 cm	fixed $L_{seg} = X_0$ = 14 cm
Statistical method	builds a χ^2-like function	maximizes likelihood function

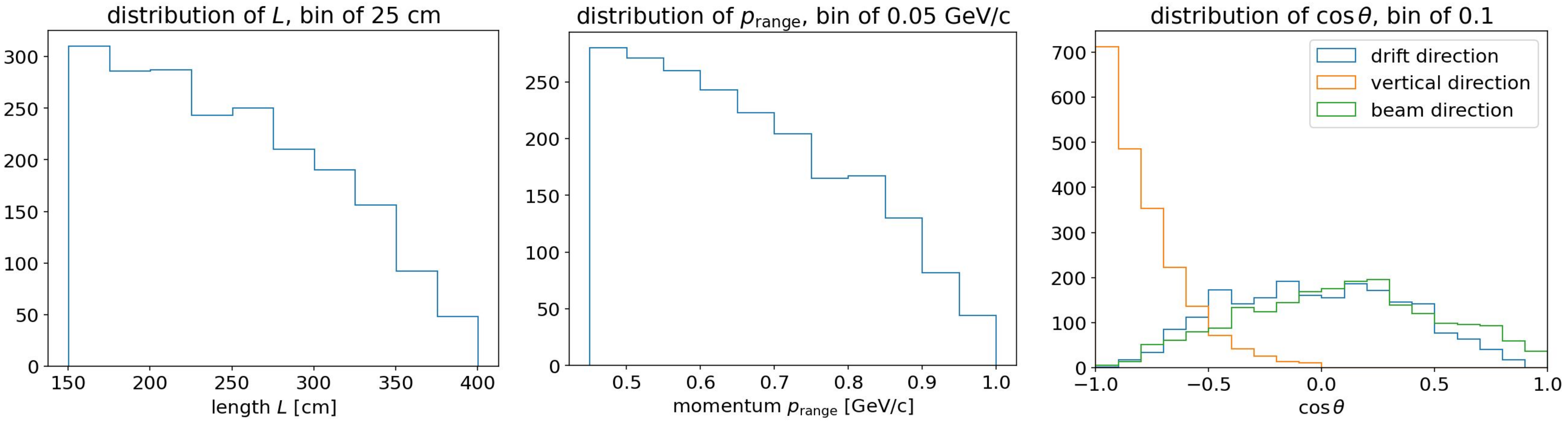
Event selection criteria

- **Use cosmic stopping muons:** range-based momentum p_{range} as benchmark to validate MCS
  - Defined start time t_0 (track position along drift direction) to ensure correct spatial reconstruction
  - L > 40 cm and large ionization deposit near the track endpoint to ensure μ stops inside the detector
  - Reconstructed starting point above ending point (downgoing μ)
- Last 3 angles (~50 cm) excluded to prevent fluctuations near Bragg peak and **mimic uncontained tracks** to avoid overestimation of algorithms performance

total number of tracks (MC sample)	2072
tracks in Induction-1 plane	1786
tracks in Induction-2 plane	1772
tracks in Collection plane	1794
tracks in all planes	1721

total number of tracks (data sample)	2061
tracks in Induction-1 plane	1737
tracks in Induction-2 plane	1630
tracks in Collection plane	1713
tracks in all planes	1519

MC μ tracks sample: sanity checks

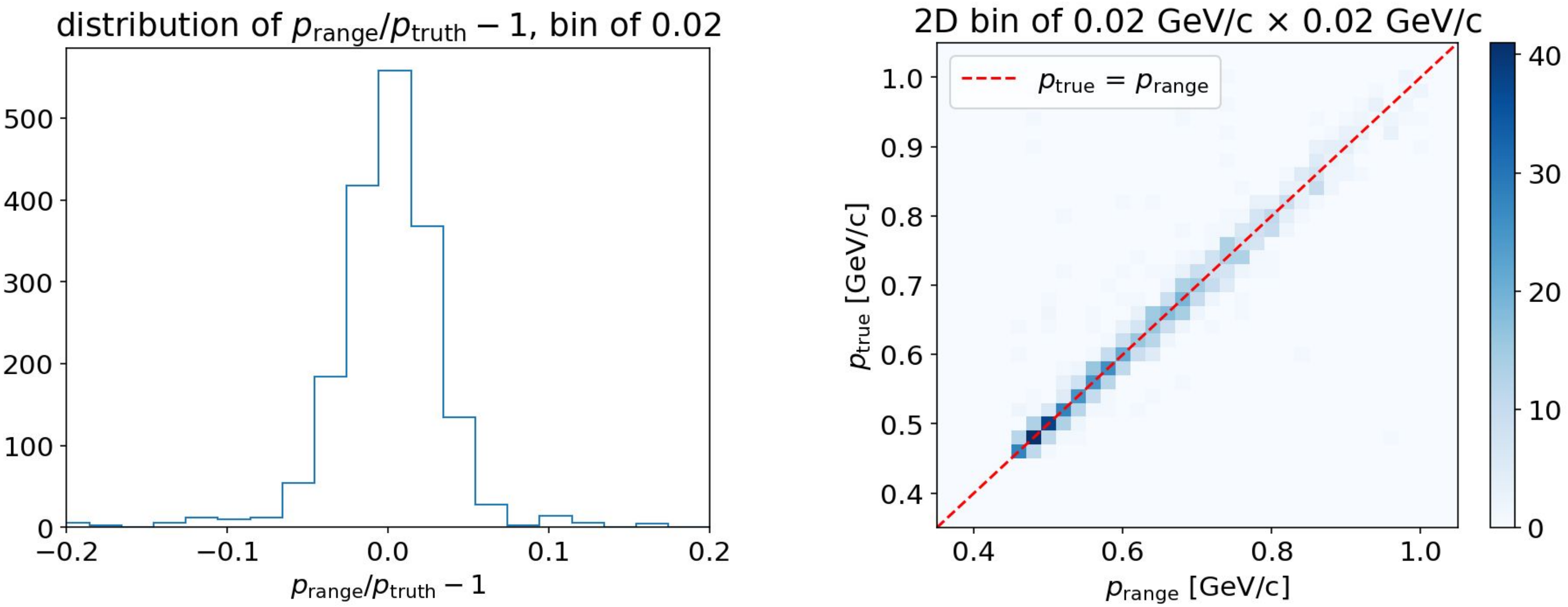

distribution of L, bin of 25 cm

distribution of p_{range}, bin of 0.05 GeV/c

distribution of $\cos\theta$, bin of 0.1

- Sample of **simulated cosmic muons** generated by *CORSIKA*
- Track length: 1.5 m < L < 4.0 m, momentum: 0.45 GeV/c < p_{range} < 1.00 GeV/c
- Low statistics for high L and $p_{range} \longrightarrow 1$ GeV/c
- As expected $\cos\theta_y \longrightarrow -1$ (vertical direction), μ downgoing
- No preferred direction over $\cos\theta_x$ (drift direction) and $\cos\theta_z$ (beam direction)

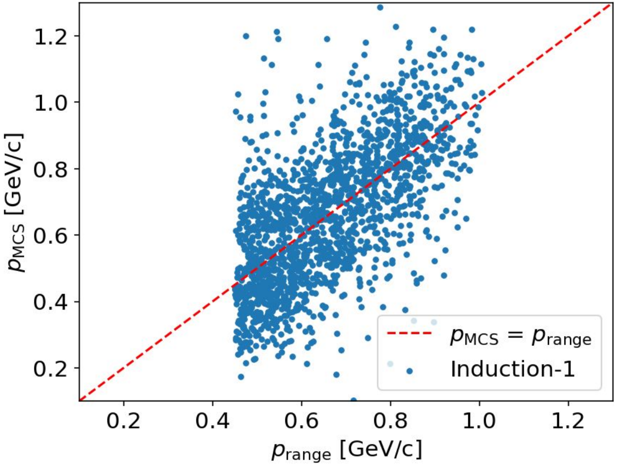
Comparison between true and range momentum

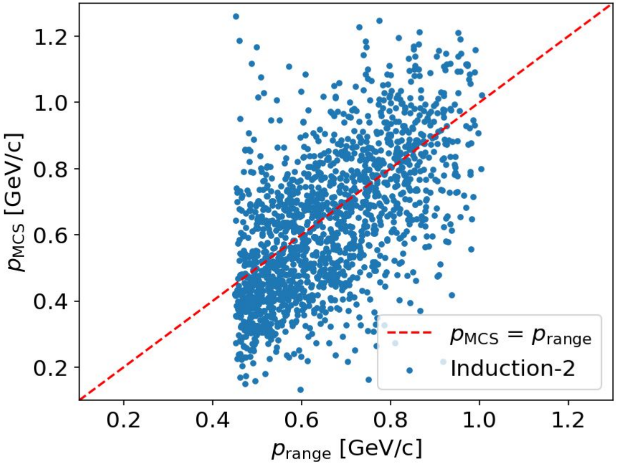


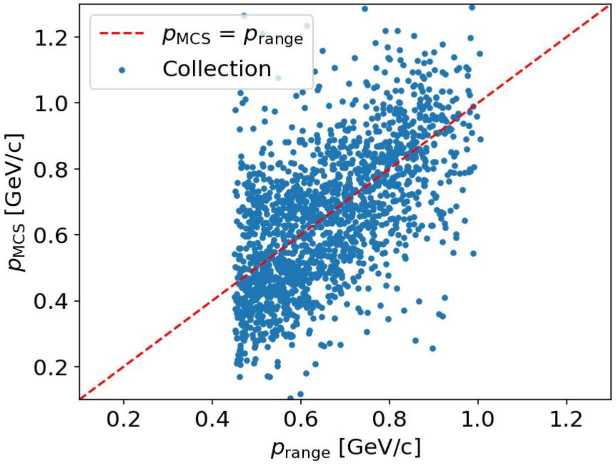
- ○ p_{range}/p_{true} - 1 peaked at zero, resolution ~2%

p_{range} good approximation of p_{true} (only available in MC)

“Gran Sasso” 2D algorithm performance (MC)



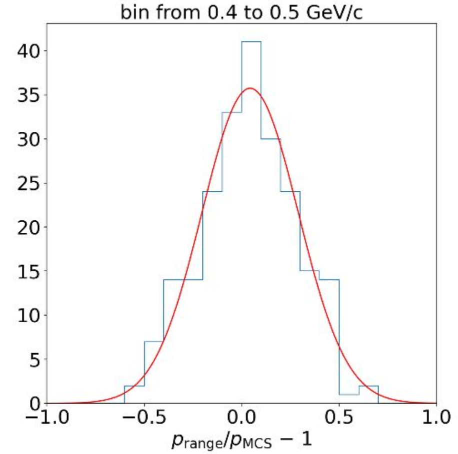


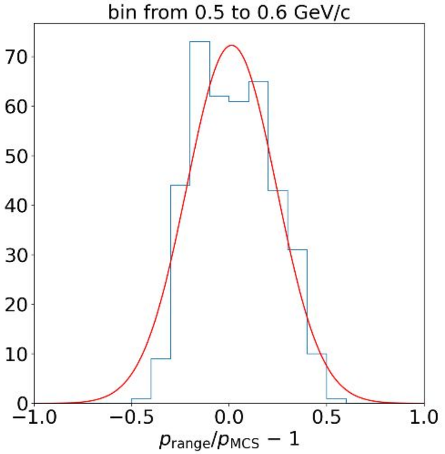


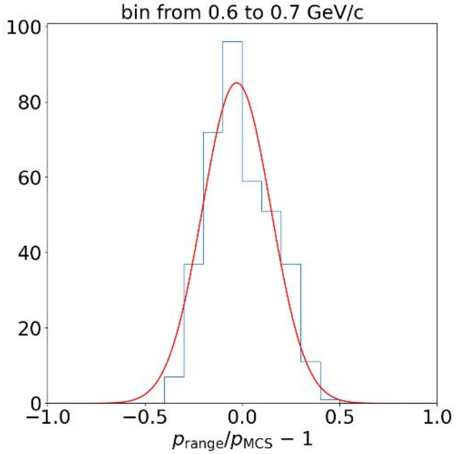
- Performance evaluated by comparing p_{MCS} with p_{range}
- **Algorithm efficiency**
  ε = N(valid p_{MCS})/N(total)
- Valid $p_{MCS} \in (0.1, 1.5)$ GeV/c

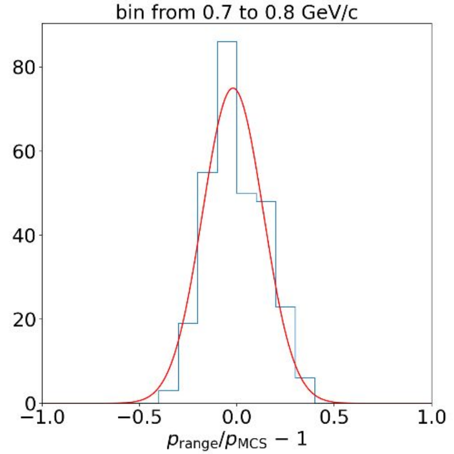
	Induction-1	Induction-2	Collection
total tracks in 2D plane	1786	1772	1794
tracks with valid p_{MCS}	1703	1608	1676
efficiency ε	~95%	~91%	~93%

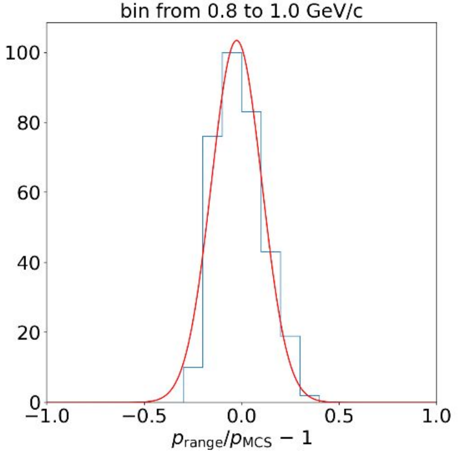
Example of Gaussian fit for each bin (MC)





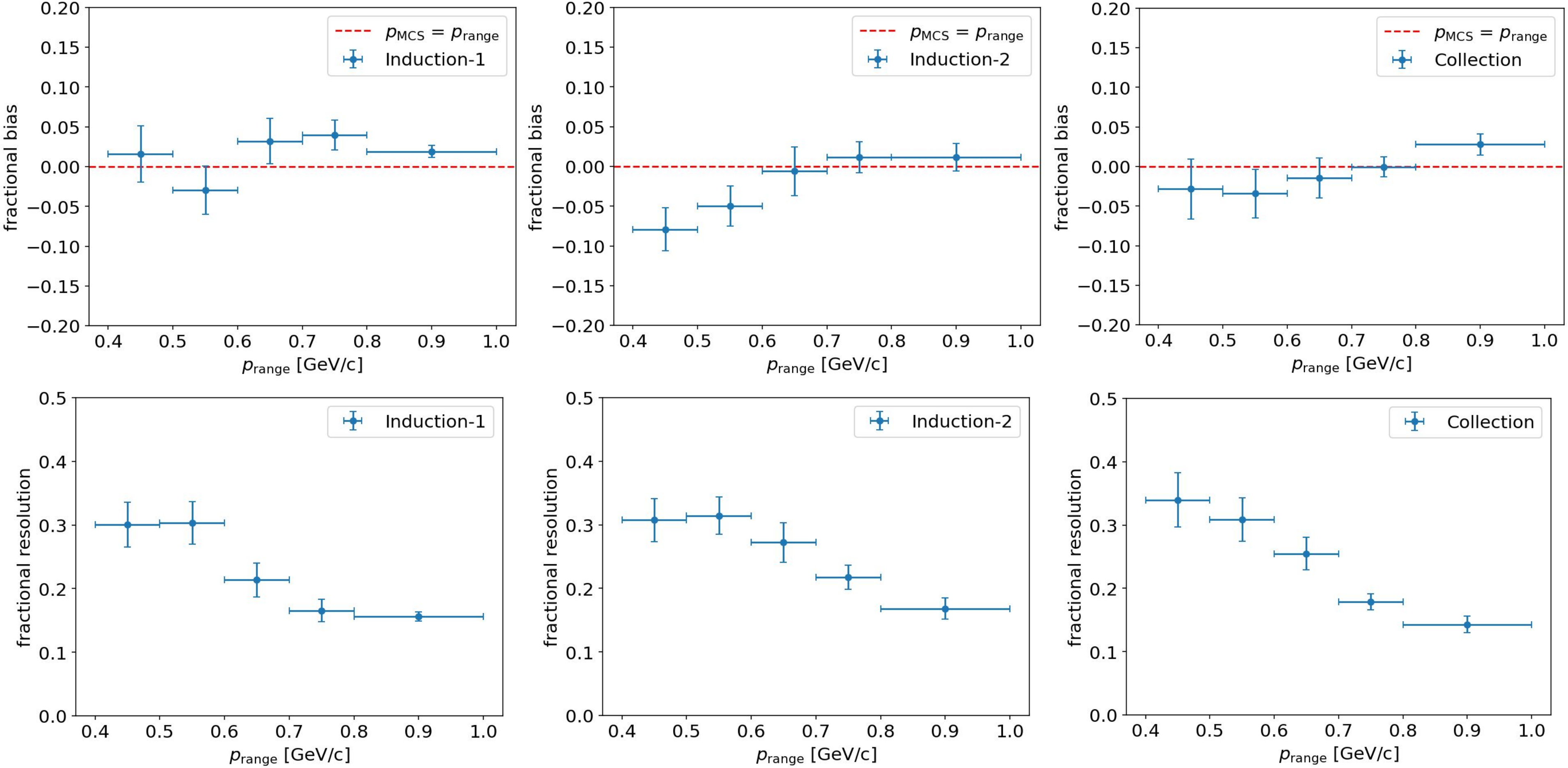






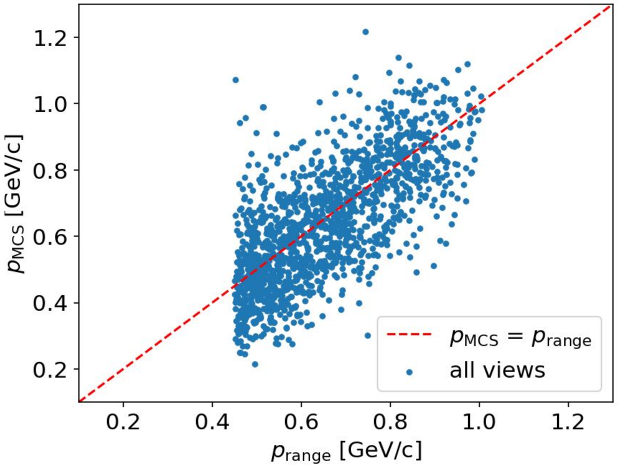
- Dominant error in the $p_{\mathrm{range}}/p_{\mathrm{MCS}}$ ratio from p_{MCS}
- **Gaussian behavior in 1/p** expected (Highland formula)
- Gaussian fit provides mean, stdev ⟶ estimation of **bias and resolution**
- 100 MeV/c momentum bins, except for the last (200 MeV/c) ⟶ low stat

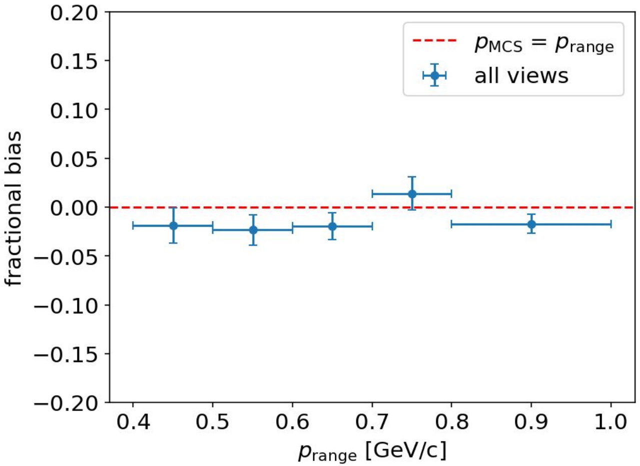
2D views: results (MC)

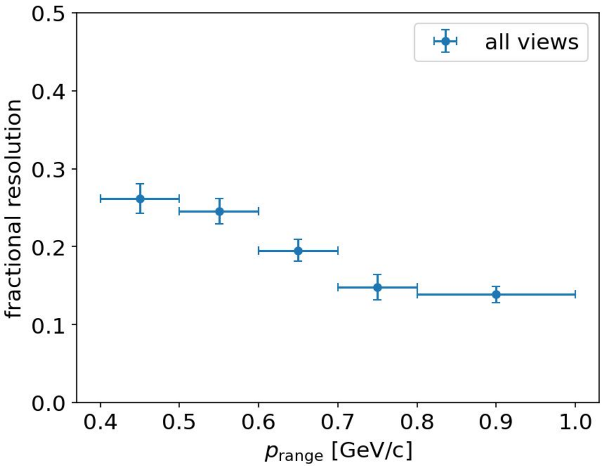


Inductions + Collection: results (MC)

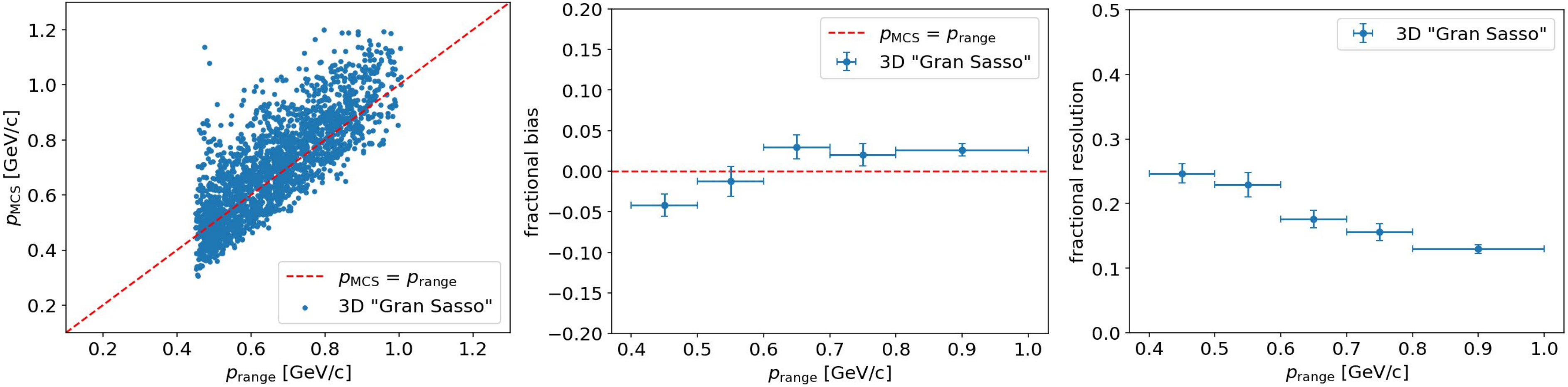
- Collection plane: best signal-to-noise ratio
- Incorporate Induction planes to improve performance and to enhance p_{MCS} reconstruction by reducing uncertainties and mitigating inefficiencies
- 3 possible combinations:
  - **Collection ⊕ Induction-2** = averaging the momenta from both planes
  - **Collection ⊕ Induction-1** = same as above with Induction-1
  - **Collection ⊕ Induction-2 ⊕ Induction-1** = same as above with Induction-2 and Induction-1 ⤵







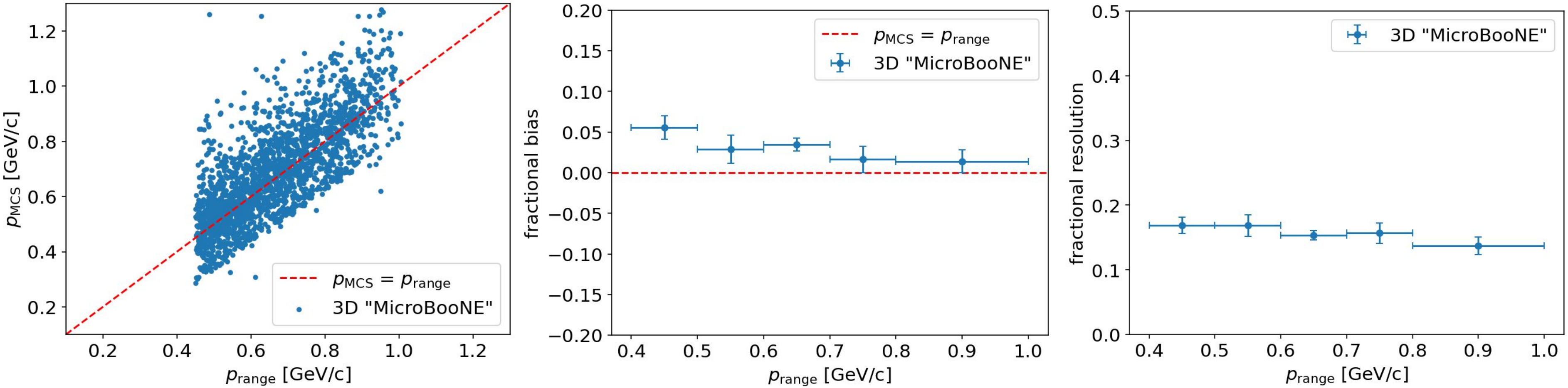
“Gran Sasso” 3D algorithm and summary (MC)



- 2D version (*single view*):
  - Few % agreement between p_{MCS} and p_{range}, slight negative bias at low p in Induction-2
  - Resolution improves from 32% at low p to 16% at high p
- 2D version (*combining different views*):
  - Improves both bias and resolution
- 3D version: performs comparably to the combined 2D views → viable alternative

total tracks in 3D	2072
tracks with valid p_MCS	2036
efficiency ε	~98%

“MicroBooNE” algorithm (MC)

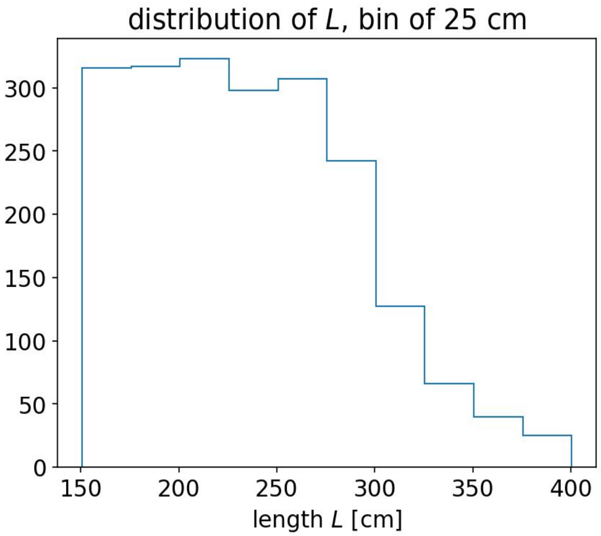


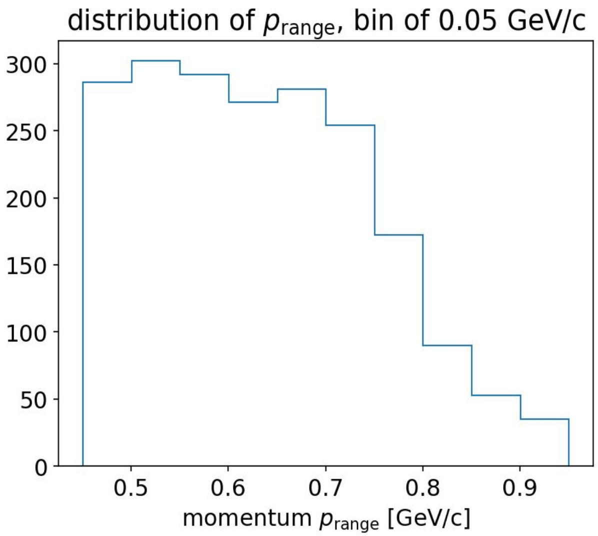
- Small, nearly constant positive bias
- Better resolution at low p

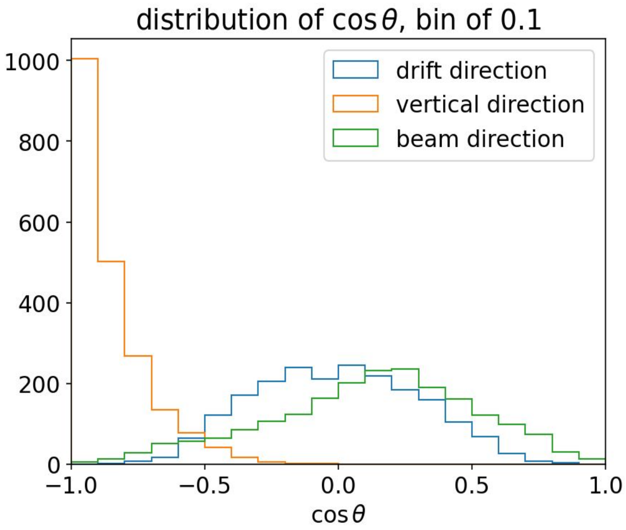
total tracks in 3D	2072
tracks with valid p_MCS	2064
efficiency ε	~100%

We confirm **validity of MCS momentum measurement** for both algorithms!

Real μ tracks sample: sanity checks

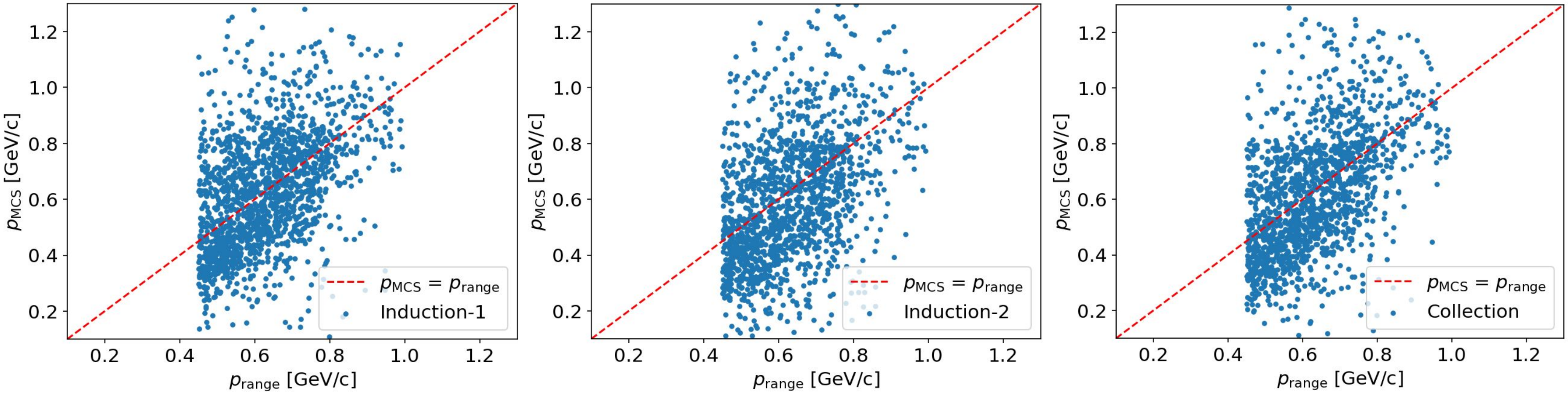

distribution of L, bin of 25 cm


distribution of p_{range}, bin of 0.05 GeV/c


distribution of $\cos\theta$, bin of 0.1

- Sample of **real cosmic muons** from Run-9435 (January 29-30, 2023) PMT-triggered
- Track length: 1.5 m < L < 4.0 m, momentum: 0.45 GeV/c < p_{range} < 1.00 GeV/c
- Low statistics for high L and $p_{\text{range}} \longrightarrow$ 1 GeV/c
- As expected $\cos\theta_y \longrightarrow -1$ (vertical direction), μ downgoing
- No preferred direction over $\cos\theta_x$ (drift direction) and $\cos\theta_z$ (beam direction)

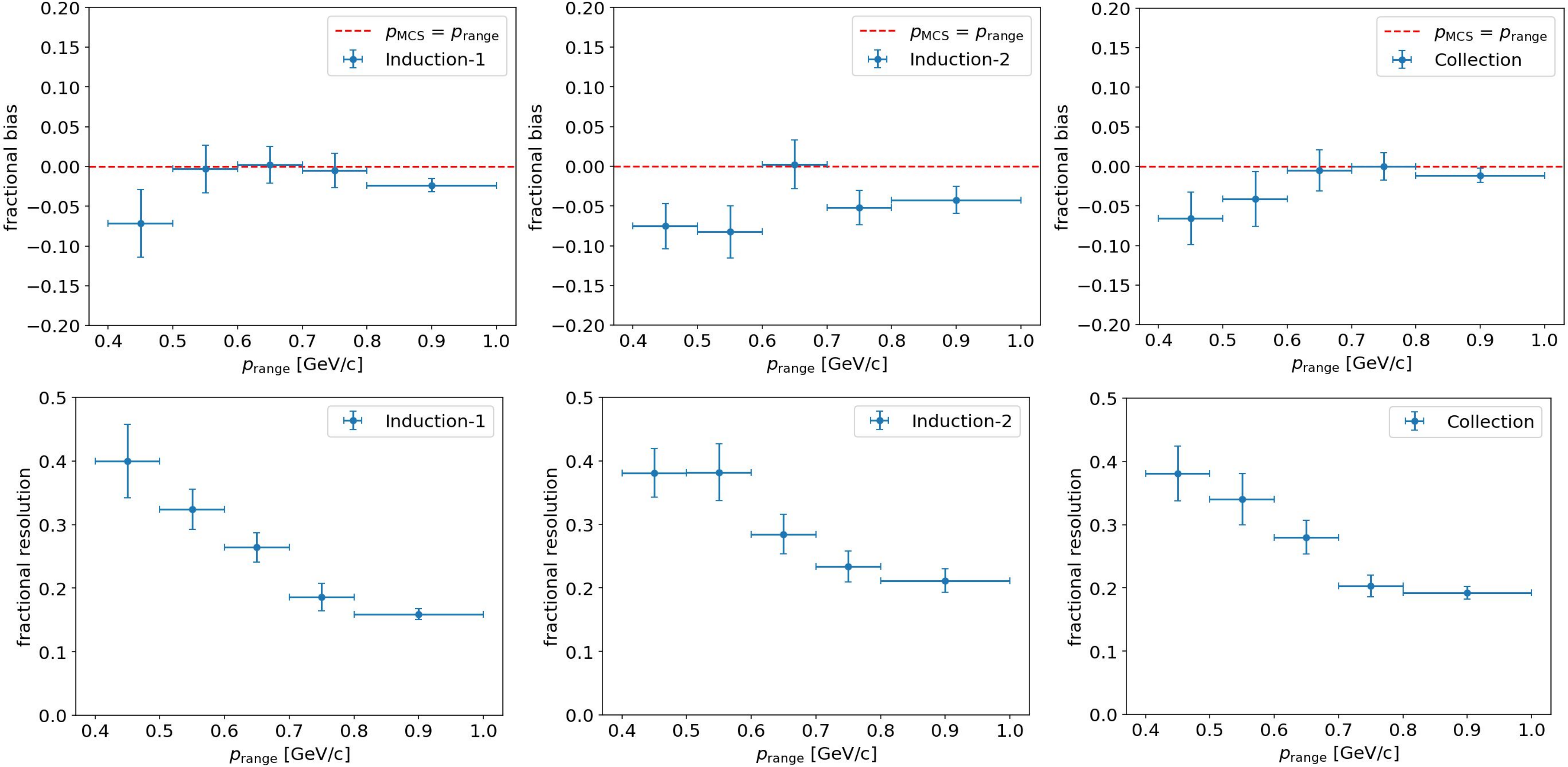
“Gran Sasso” 2D algorithm performance (data)



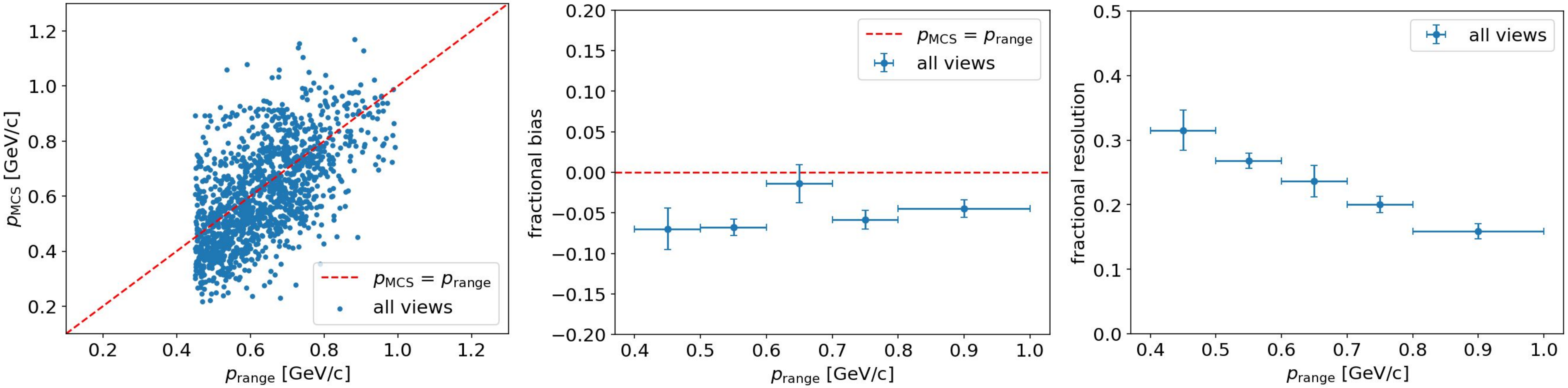
- Performance evaluated by comparing p_{MCS} with p_{range}
- **Algorithm efficiency**
  $\varepsilon = N(\text{valid } p_{\mathrm{MCS}})/N(\text{total})$
- Valid $p_{\mathrm{MCS}} \in (0.1, 1.5)$ GeV/c

	Induction-1	Induction-2	Collection
total tracks in 2D plane	1737	1630	1713
tracks with valid p_{MCS}	1629	1524	1574
efficiency ε	~94%	~93%	~92%

2D views: results (data)

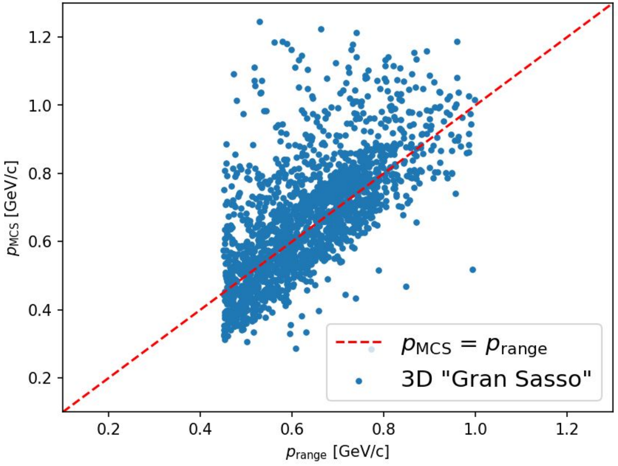


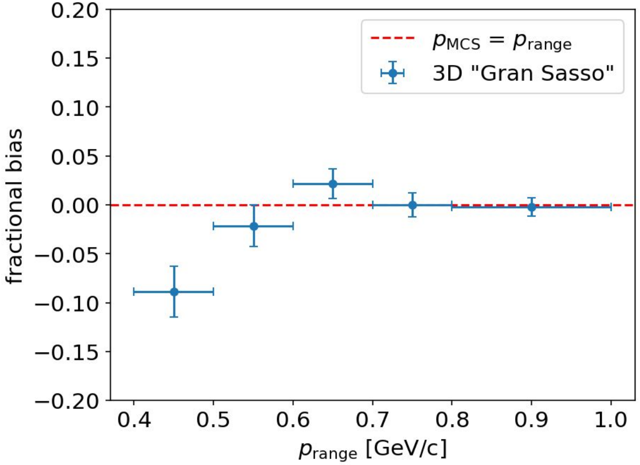
Inductions + Collection: results (data)

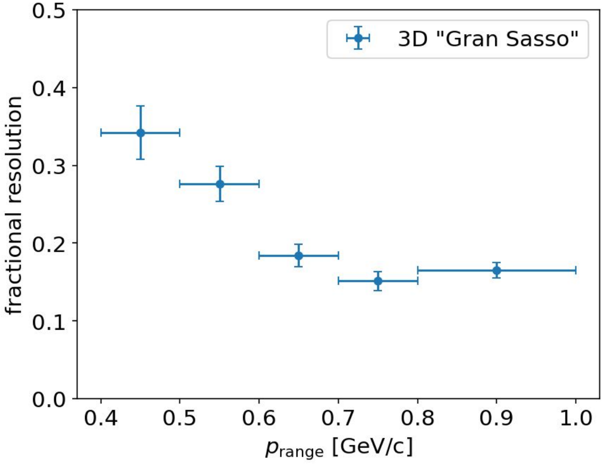


- *Single view*: momentum resolution from 40% at low p to 18% at high p
- *Combining multiple views*:
  - Small negative flat bias, not observed in MC
  - Momentum resolution from 32% at low p to 16% at high p, slightly worse than MC

“Gran Sasso” 3D algorithm and summary (data)



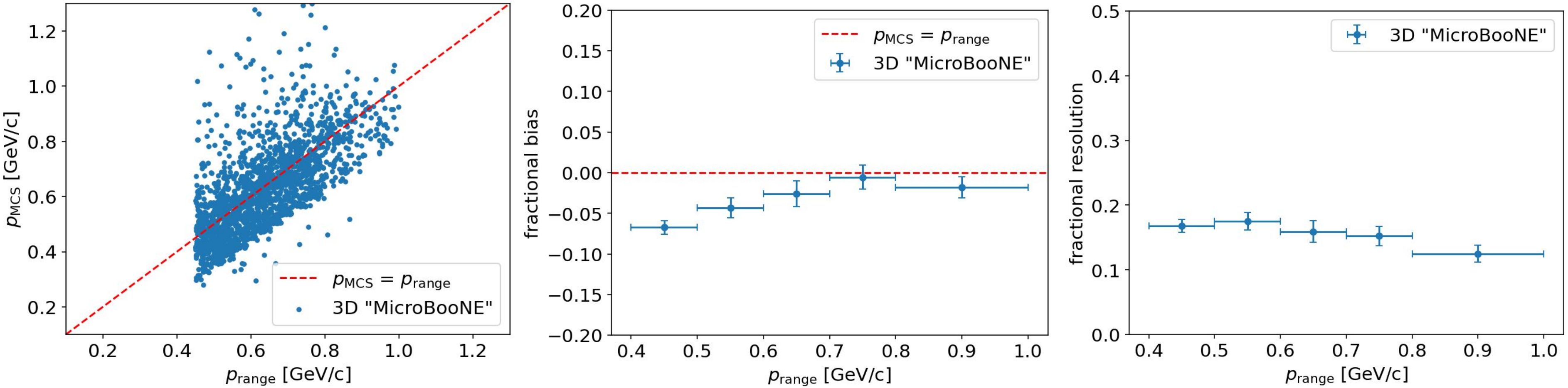




- 3D performs comparably to the combined 2D views
  ⟶ viable alternative
- Small negative bias wrt MC, particularly at low p

total tracks in 3D	2061
tracks with valid p_MCS	1846
efficiency ε	~90%

“MicroBooNE” algorithm (data)



- Small negative bias (in MC small positive bias)
- Resolution ranging from 16% at low p to 14% at high p

total tracks in 3D	2061
tracks with valid p_MCS	1881
efficiency ε	~91%

Conclusion and future perspectives

- “Gran Sasso” and “MicroBooNE” algorithms successfully tested on stopping muons in ICARUS, both in MC simulations and real experimental muon tracks of momentum 0.45 GeV/c < p < 1 GeV/c
- Results confirm that **MCS-based momentum estimation** is a valuable technique, with reasonable agreement between p_{MCS} and p_{range}
- **Future improvements:**
  - Studying performance as a function of track length L rather than just p_{range}, possibly using a fixed length to evaluate the resolution dependence on momentum
  - Tuning the segment length (currently set to 14 cm) to enhance resolution and efficiency
  - Improving MC simulations to incorporate more detector effects, such as some cathode distortions
  - Reject delta rays from the muon track to reduce potential biases

MCS momentum reconstruction **increases the statistics** of ν interaction events

⟶ a factor 2x for BNB and 3x for NuMI ν

crucial for oscillation studies and searches for sterile ν!