Electro-nuclear scattering measurements for neutrinos with LDMX

Wes Ketchum (Fermilab) for LDMX collaboration

23rd International Workshop for Neutrinos from Accelerators (NuFact)

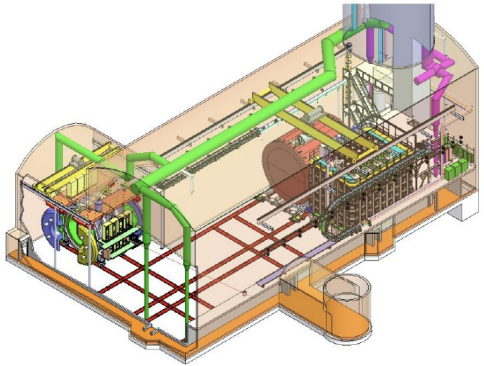
2 August 2022

Neutrino systematic uncertainties

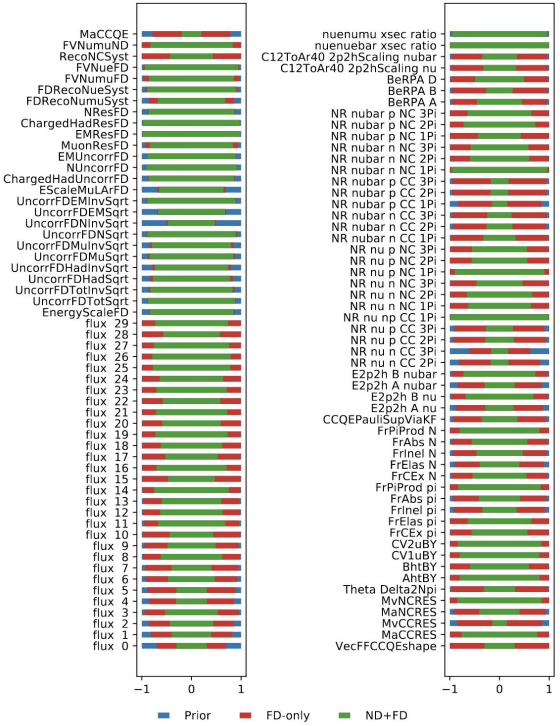
Neutrino oscillation (and other!) measurements require careful control of systematic uncertainties

Typically use a near detector to constrain flux and interaction uncertainties in far detectors

Can be complex: e.g. DUNE-PRISM allows scanning across beam axis to match FD with combination of ND fluxes



DUNE TDR, https://arxiv.org/abs/2002.03005

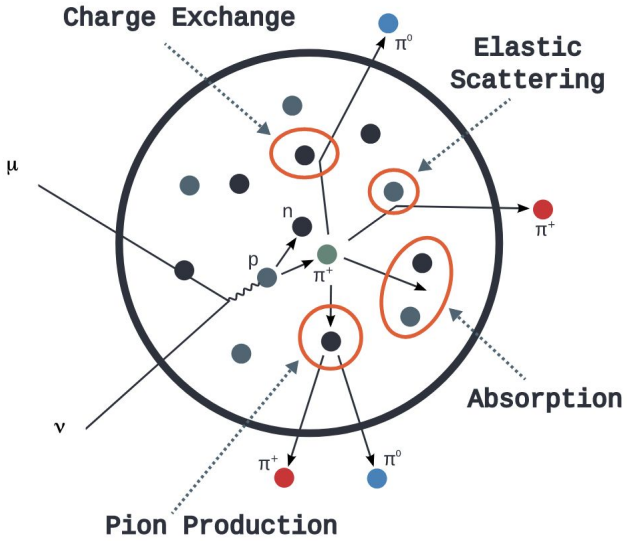


Interaction uncertainties

Neutrino interaction modeling on nuclei in GeV range difficult

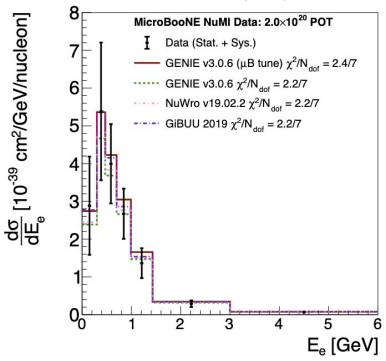
- Must consider wide range of interactions (from QE to DIS)
- Translation of observed final state to initial neutrino energy very difficult
  - Reconstruction of full final state (e.g. neutrons) very difficult
  - Modeling uncertainties in observable final state observable (e.g. FSI)

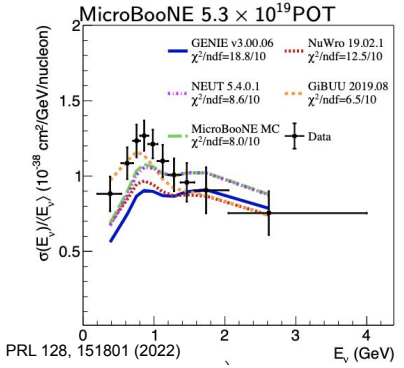
https://arxiv.org/abs/1706.03621



Constraining interaction uncertainties for DUNE

PRD 105, L051102 (2022)





PRL 128, 151801 (2022)

Limited (but growing!) neutrino data on Argon

Future experiments like SBN will continue adding

DUNE near detectors will provide strong constraints

Requires ‘More Capable Near Detector’ to reach full δ_{CP} sensitivity

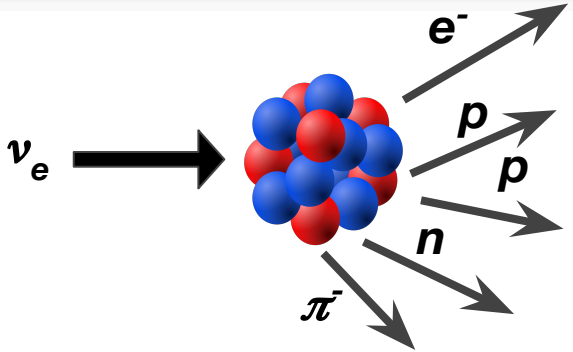
Complex fit including flux and detector systematics

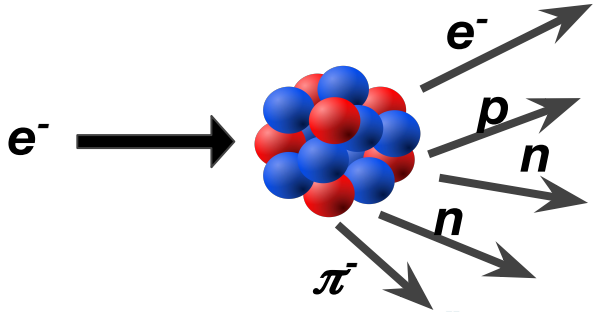
(Not to mention: possible that NDs may see new physics of their own!)

Electron scattering analog

Charged lepton interactions are an important external constraint on neutrino interactions

- Much of the same physics
  - Many identical nuclear effects
- High-statistics datasets
- Initial lepton kinematics are known → allows tests of initial lepton reconstruction





Fermilab

Electron scattering experiments

Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017)	$E_e = 2.222$ GeV $15.5° \leq \theta_e \leq 21.5°$ $-50.0° \leq \theta_p \leq -39.0°$	Ar, Ti Al, C	(e, e') e, p in the final state
e4nu/CLAS (JLab) (Data collected: 1999, 2022)	$E_e = 1, 2, 4, 6$ GeV $\theta_e > 5°$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state
LDMX (SLAC) (Planned)	$E_e = 4.0, 8.0$ GeV $\theta_e < 40°$	W, Ti, Al	(e, e') e, p, n, π, γ in the final state
A1 (MAMI) (Data collected: 2020) (More data planned)	50 MeV $\leq E_e \leq 1.5$ GeV $7° \leq \theta_e \leq 160°$	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles
A1 (eALBA) (Planned)	$E_e = 500$ MeV - few GeV	C, CH Be, Ca	(e, e')

Range of existing and planned electron-scattering datasets

Variety of targets and energies

Detectors with varying capabilities

See Snowmass white paper: https://arxiv.org/abs/2203.06853

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Light Dark Matter eXperiment

Search for light dark matter in electron fixed-target experiment at SLAC LCLS-II

Phase 1: ~4e14 EoT @ 4 GeV,
Phase 2: ~1e16 EoT @ 8 GeV

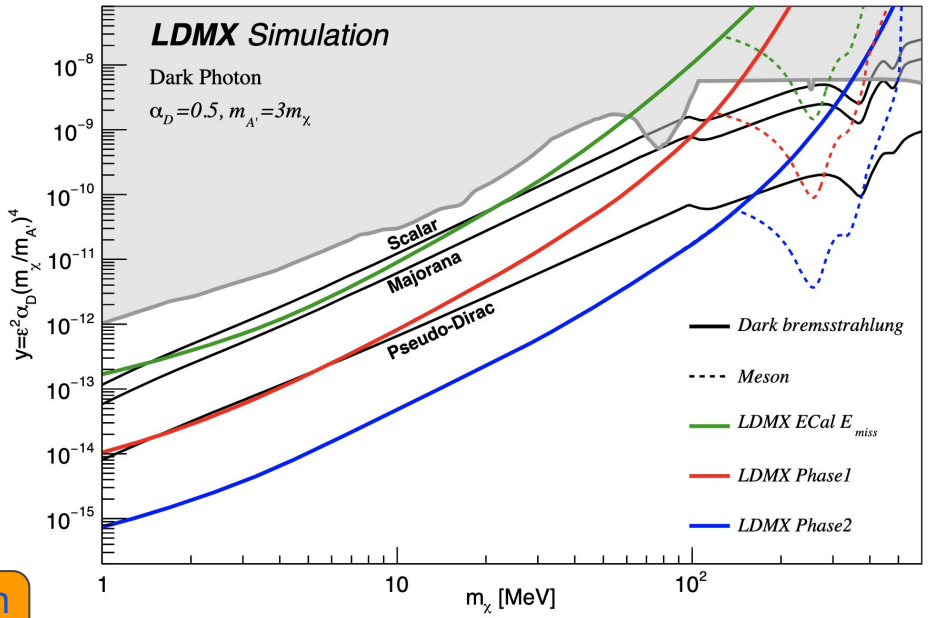
Missing momentum/energy signature

Requires excellent tracking and particle detection in forward regions

< 1 background event achievable → strong sensitivity to light dark matter Candidates

Expecting data 2026

See M. Solt's LDMX Talk in WG4 on Thursday!



https://arxiv.org/abs/2203.08192

LDMX Detector

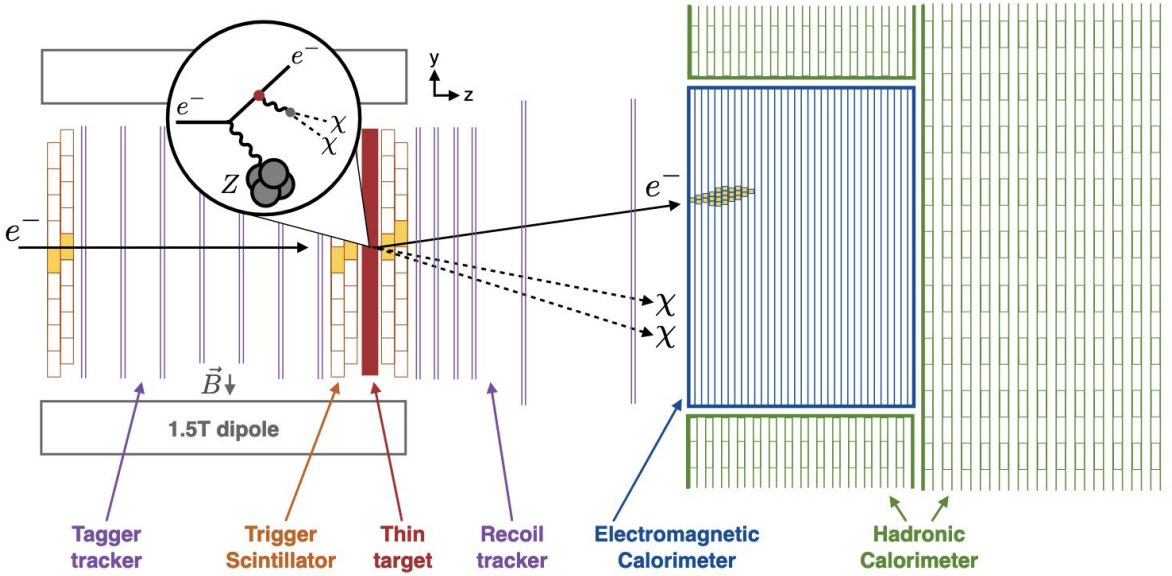
Thin W target (with additional targets e.g. Ti being considered)

Si-strip tagger and recoil electron trackers
→ $p > 50$ MeV sensitivity

High-granularity Si-W ECAL

Fast response →
TS+ECAL form trigger

~17 λ_I sampling HCAL



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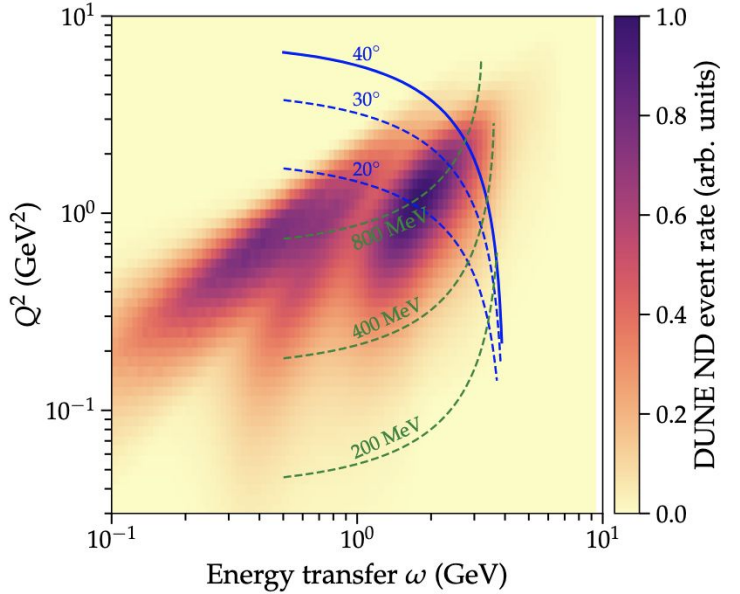
eN Scattering in LDMX

Electro-nuclear scattering in LDMX matches well with phase-space for DUNE

Consider 4 GeV electrons on Ti target

- blue lines: constant recoil electron angle in LDMX
- green lines: constant recoil electron p_T

Ankowski et al., PRD 101, 053004 (2020)



LDMX as part of an eN dataset for neutrinos

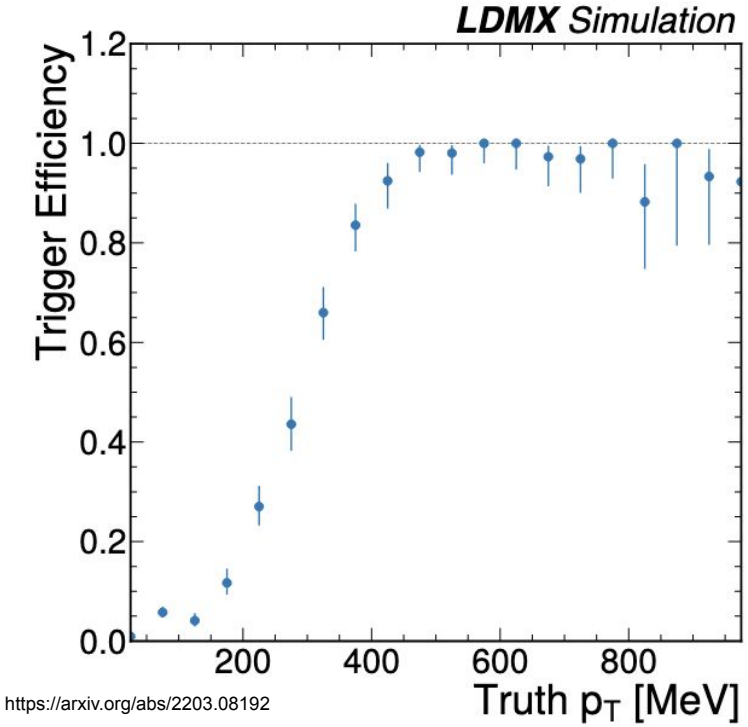
Kinematic reach well-matched to future DUNE oscillation program

- Particularly in RES and DIS region

Excellent coverage and reconstruction for $\theta < 40°$, including for neutral hadrons

→ allows a program of inclusive and exclusive measurements that complement existing/planned experiments

eN Trigger for LDMX



https://arxiv.org/abs/2203.08192

Nominal dark matter trigger insufficient for eN interactions

- Requires large (>2.5 GeV) energy transfer

Newly developed high-p_T trigger algorithm

- Fast reconstruction of energy and cluster position in ECAL
- Correlate to electron position in trigger scintillator to determine p_T
- Further studies to improve rejection of Bremsstrahlung photons

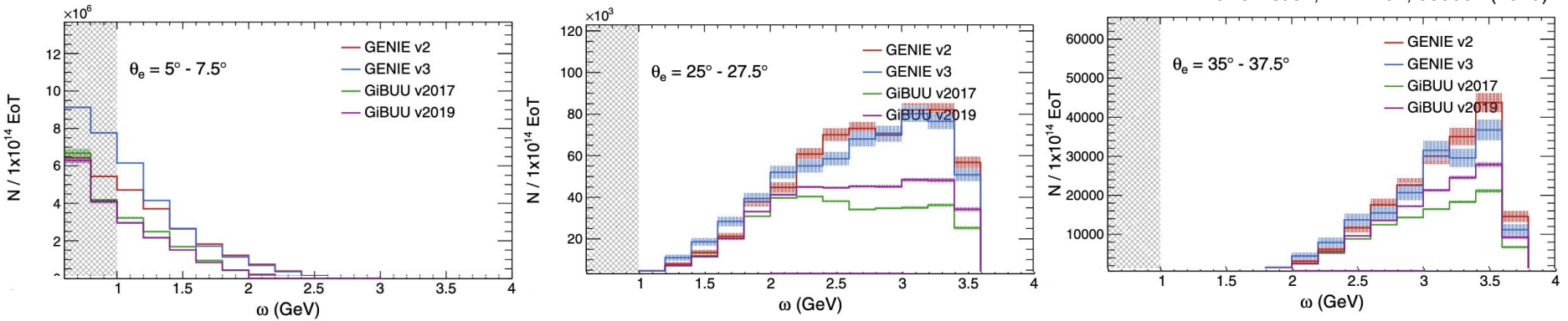
Inclusive Scattering Measurements

Can leverage excellent electron reconstruction and high statistics to make sensitive measurements in 2D/3D/… See studies in Ankowski et al., PRD 101, 053004 (2020)

Note: >200 MeV/c p_T cut applied here

Detector coverage at lower angles, but will require lower-p_T or alternate trigger

Ankowski et al., PRD 101, 053004 (2020)



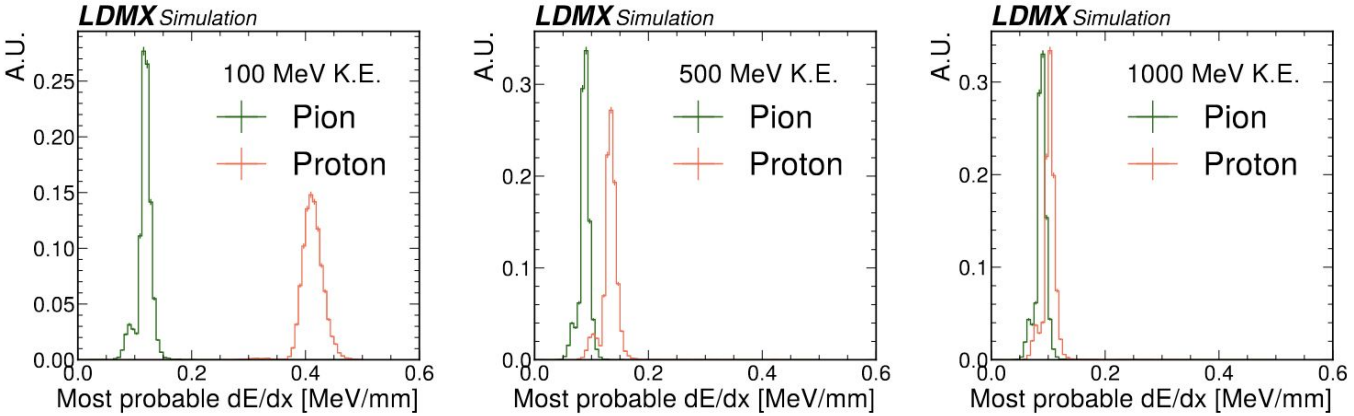
dE/dx measurements in tracker

Separation of protons and charged pions critical for probing interaction models

E.g. QE vs. RES/DIS discrimination, particle multiplicities, FSI studies

Promising early studies of PID using dE/dx in tracker

With (very) simplified model of tracker response, good separation for KE < 500 MeV



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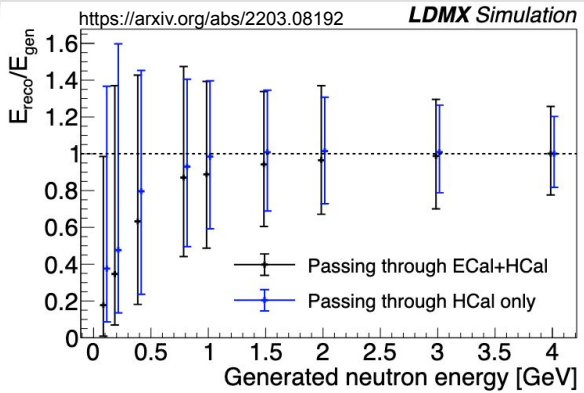
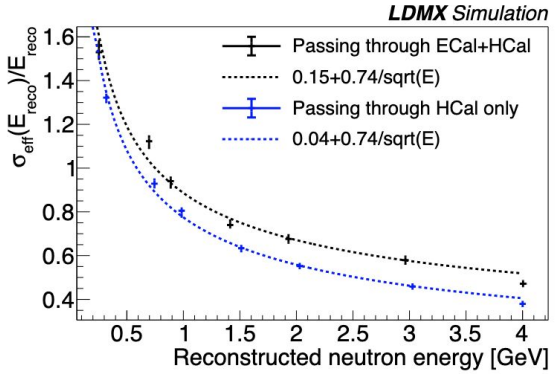
Neutron reconstruction

Primary goal of LDMX HCAL is to veto long-lived neutral hadrons

Effort underway on reconstruction of kinematics of neutrons

- Consider both HCAL and ECAL+HCAL cases, sum energy across calorimeters
- Further work ongoing for shower shape, angular reconstruction





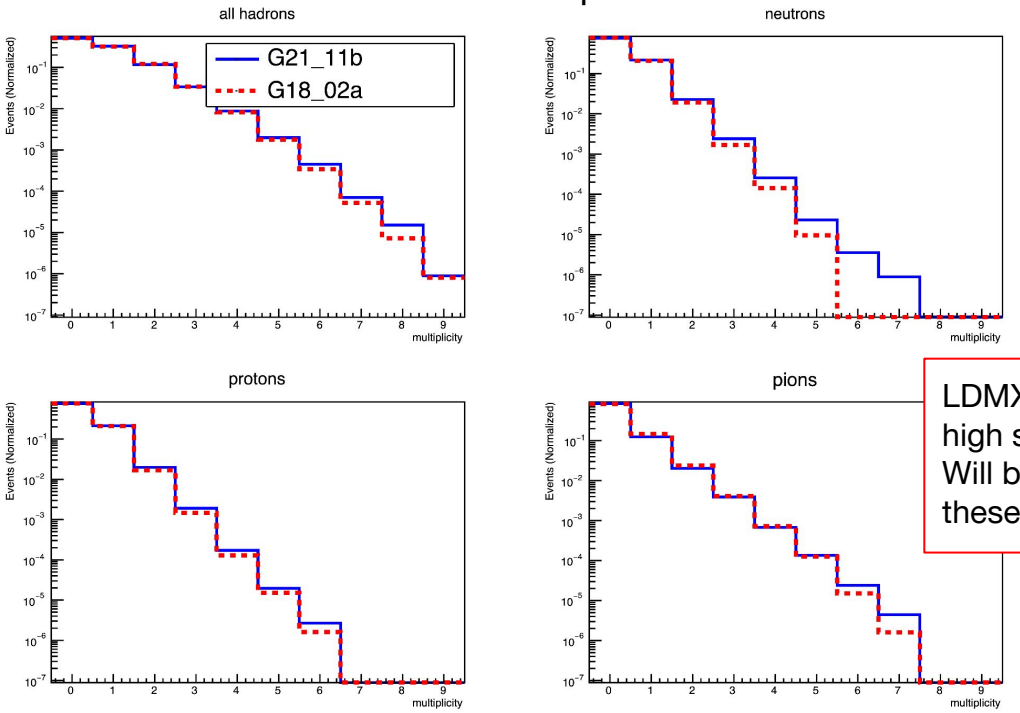
Simulation studies on observables

Through developments, check impact on simulation samples (two GENIE v3.2 tunes)

Apply lepton trigger cuts, and require final-state particles well-reconstructable ($\theta < 40°$)

Still to-do: energy resolution smearing, PID efficiencies, etc.

Particle Multiplicities



LDMX will have very high stats samples! Will be sensitive to these differences.

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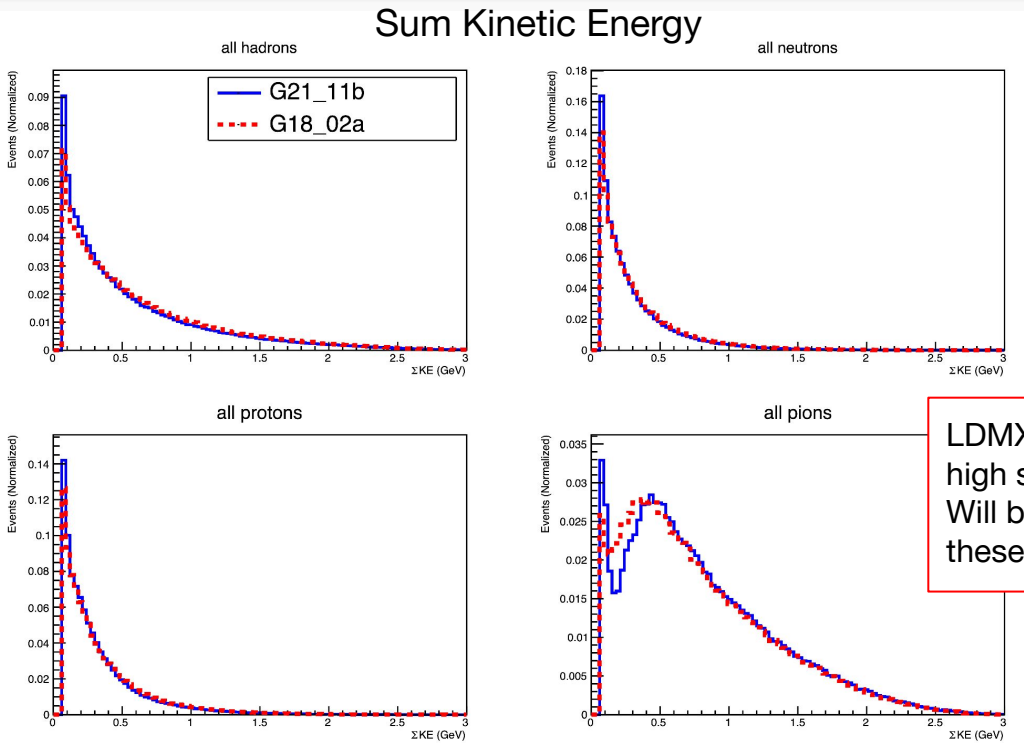

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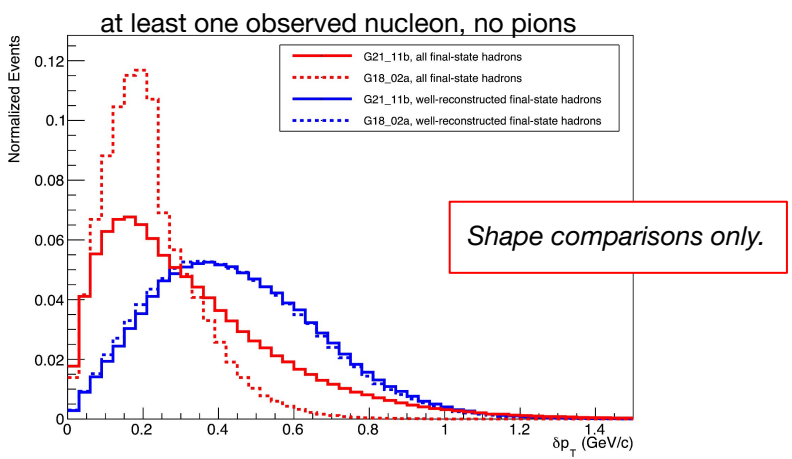
Simulation studies on observables

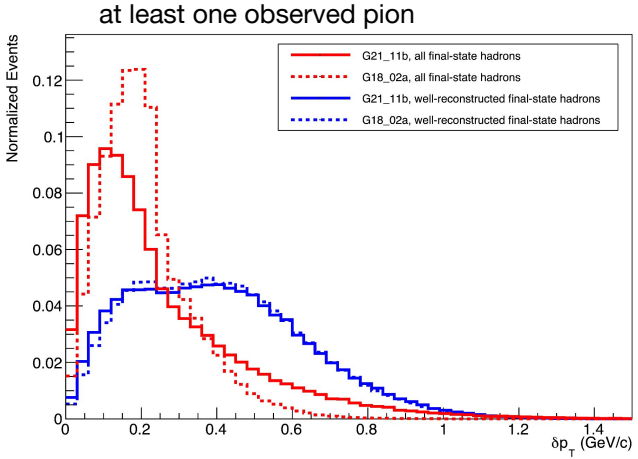
Beginning to look at higher-level observables, e.g. momentum imbalance

Modeling effects of limited detector acceptance will be critical

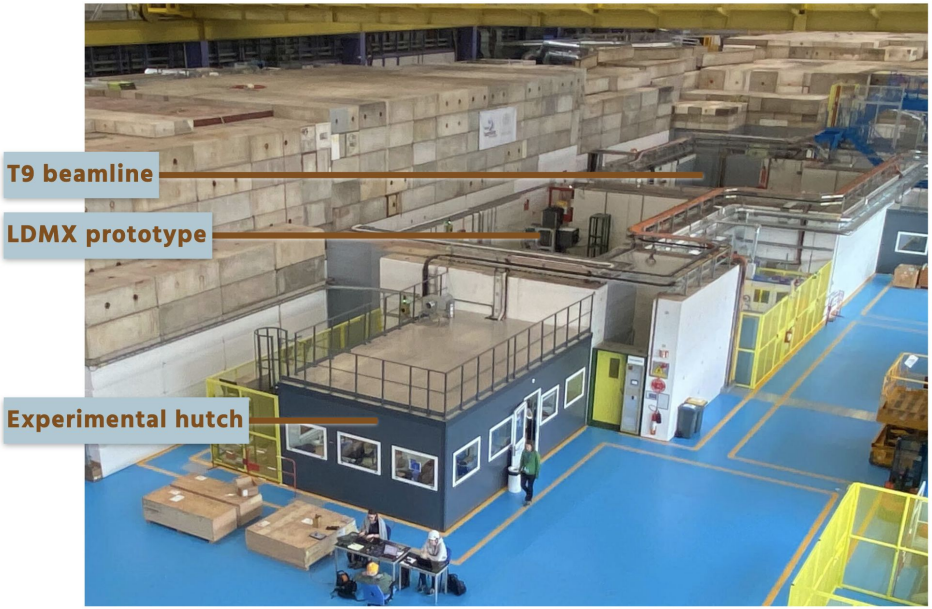
Todo: explore ability to veto additional activity (rather than require good reconstruction)
→ DM detector well-designed for this!



Shape comparisons only.



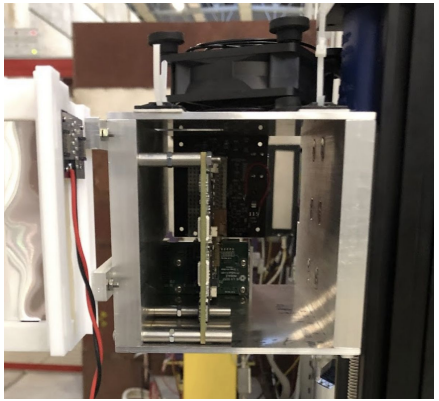
Testbeam at CERN



Testbeam run with trigger scintillator and HCAL prototypes earlier this year

Electrons, muons, pions, 500 MeV - 8 GeV

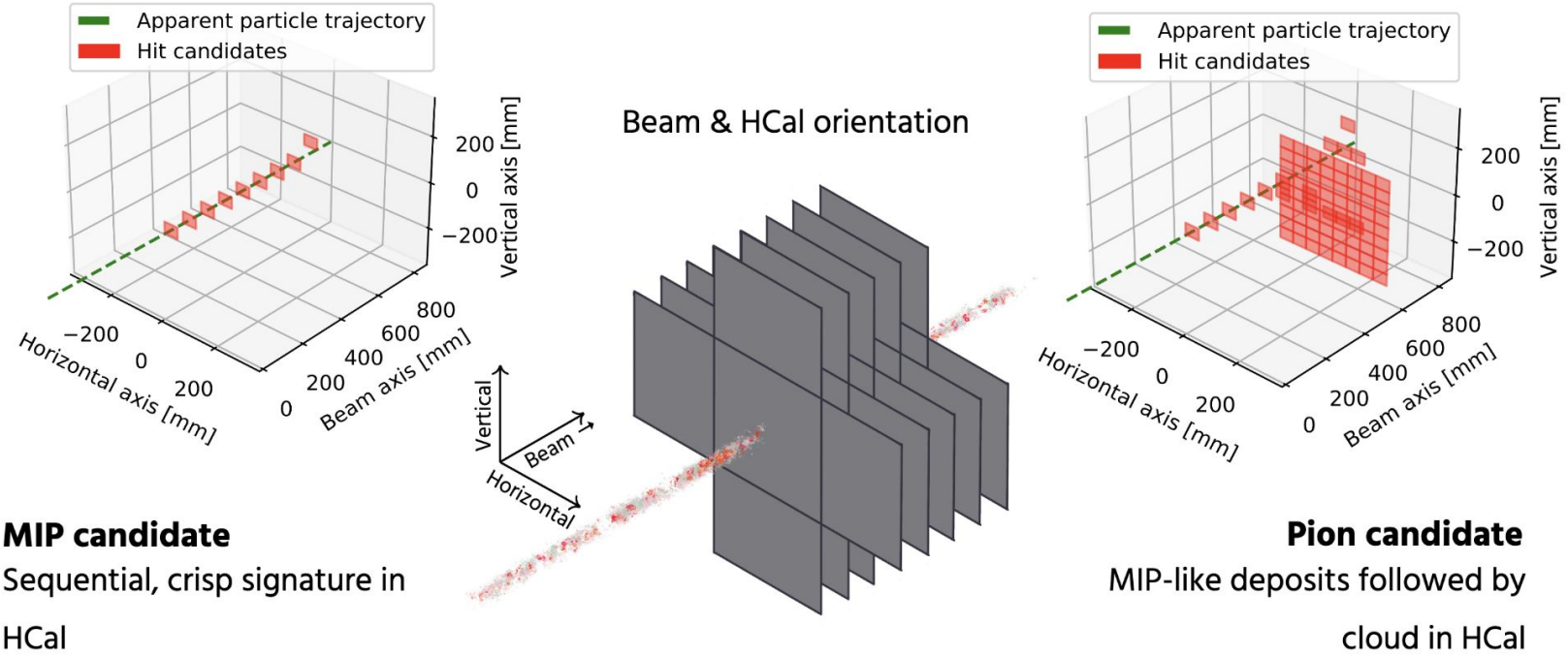
Trigger Scintillator



HCAL Scintillator Bars

See H. Herde's talk at ICHEP for more details!
https://agenda.infn.it/event/28874/contributions/169115/

HCAL response / PID



MIP candidate

Sequential, crisp signature in HCal

Pion candidate

MIP-like deposits followed by cloud in HCal

https://agenda.infn.it/event/28874/contributions/169115/

Future/ongoing studies

Continuing work on improving simulation and reconstruction

- π^0 acceptance, charged particle tracking, ECAL and HCAL clustering
- Understand effects of limited “well-reconstructed” acceptance, ability to veto additional activity

Investigate model comparisons and impact for sensitivity to model parameters

Summary

Electron scattering measurements are an important external constraint on neutrino interaction uncertainties

Proposed LDMX offers unique dataset for eN measurements particularly relevant to DUNE

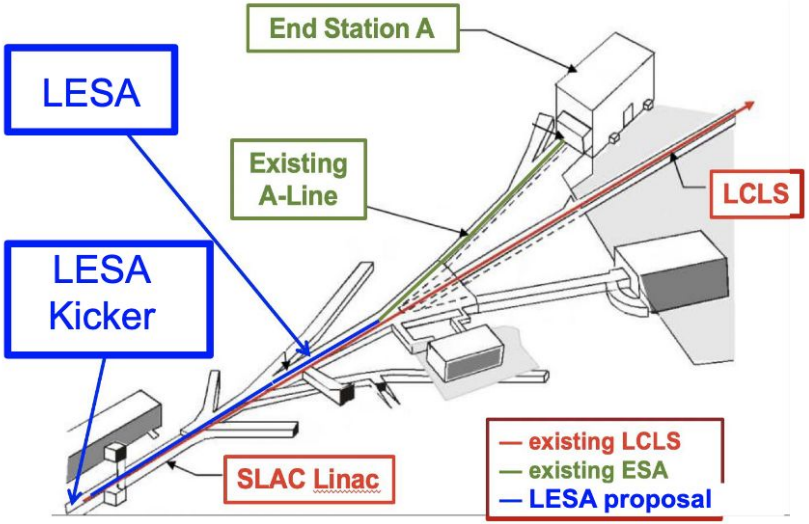
- Leverage dark-matter design for sensitivity to forward particles, particularly neutrons
- Design for feasible eN trigger ($p_T > 400$ MeV/c) in place
- Further work on reconstruction, PID, and event selection/observables ongoing

Thanks!

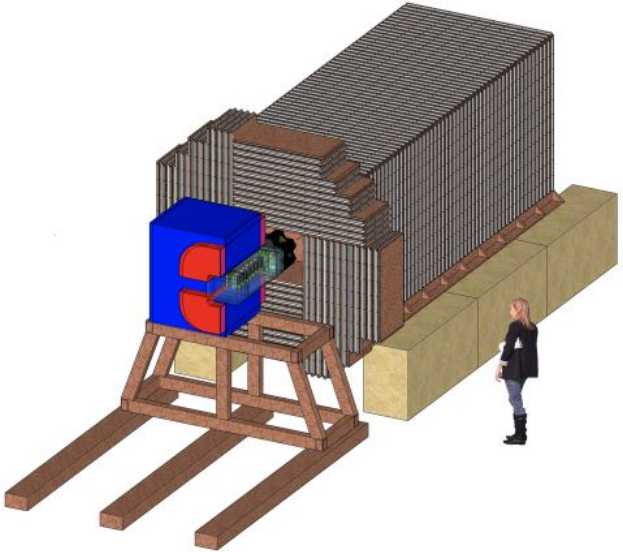

Caltech
Fermilab
LUNDS UNIVERSITET
UNIVERSITY OF MINNESOTA
UCSB
UNIVERSITY OF CALIFORNIA
SANTA BARBARA
SLAC
NATIONAL ACCELERATOR LABORATORY
STANFORD UNIVERSITY
TEXAS TECH UNIVERSITY
UNIVERSITY of VIRGINIA

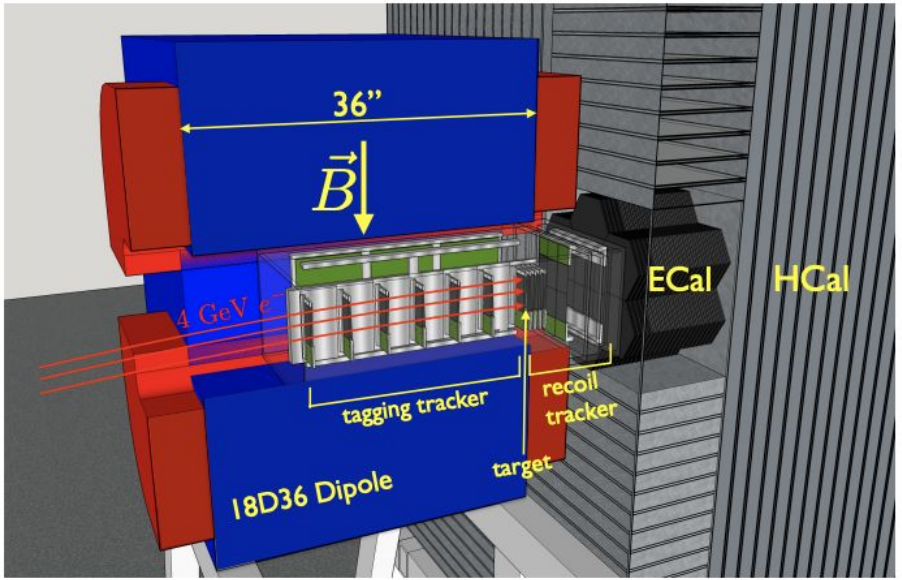
Backups

Beamline

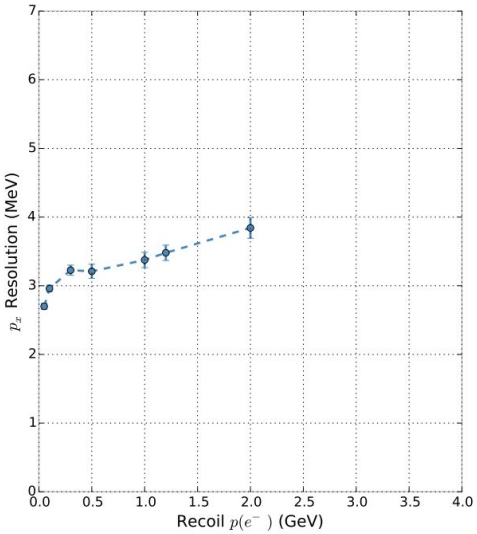

End Station A
LESA
Existing
A-Line
LCLS
LESA
Kicker
SLAC Linac
existing LCLS
existing ESA
LESA proposal

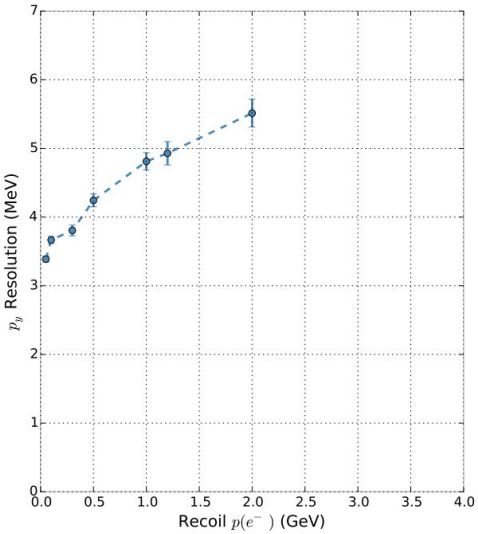
Detector rendering





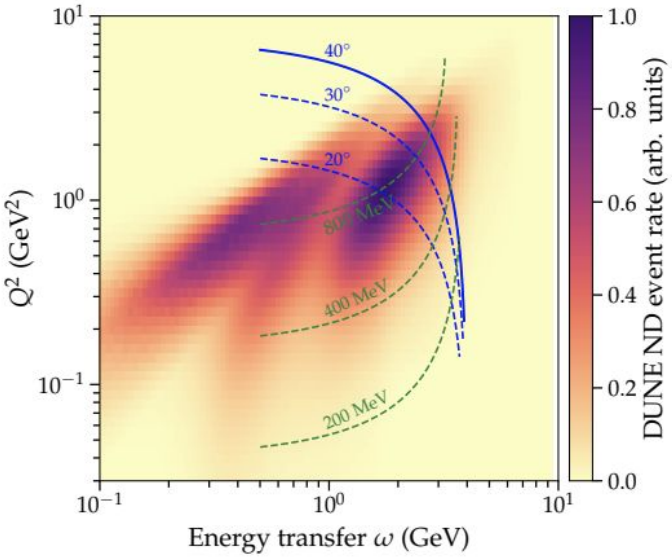
Recoil tracker resolution



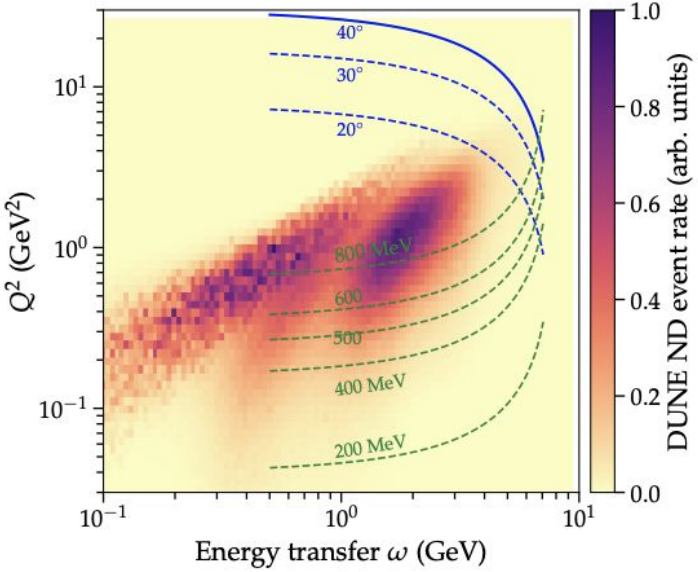


Kinematic overlap with DUNE

4 GeV electrons



8 GeV electrons



GENIE Model Descriptions

Medium Energy GENIE Configurations (100 MeV- 100 GeV)						
Modelling CMC	Ground State	Quasi-elastic	Meson Exchange Current	Resonance	Shallow and Deep Inelastic	Final State Interactions
G18_02a	Relativistic Fermi Gas Model	Llewellyn-Smith QE model	Dytman	Berger-Sehgal	Bodek and Yang Model	hA18 (Effective intranuclear transport model)
G21_11b	Local Fermi Gas Model	SuSAv2	SuSAv2	Berger-Sehgal	Bodek and Yang Model	hN18 (Full intranuclear cascade)