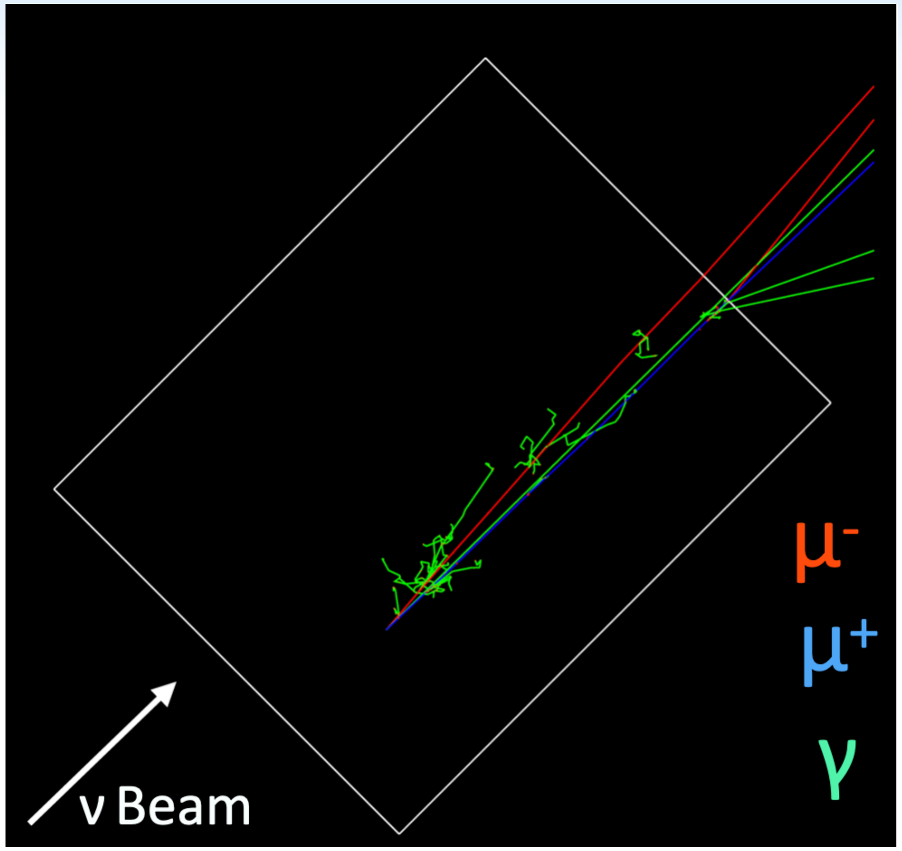
Neutrino Tridents: Experiment

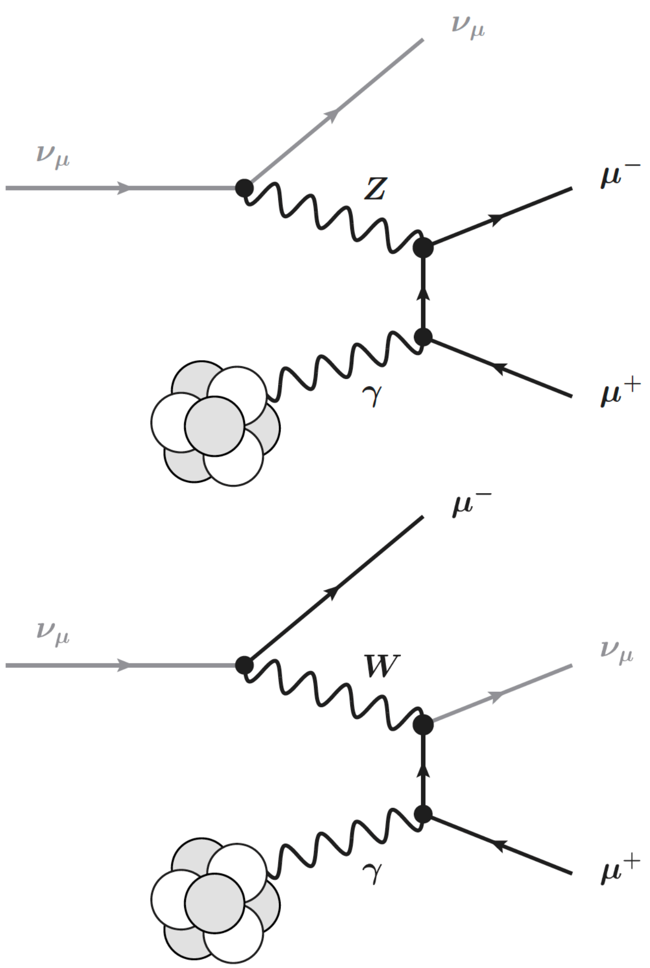


Alex Sousa
for the DUNE BSM/Pheno group

FLArE Far Forward Physics working group meeting
Oct. 4, 2022

Highlights from Wolfgang's Talk

- Only tridents with $\mu^+\mu^-$ in final state have been claimed to be measured so far



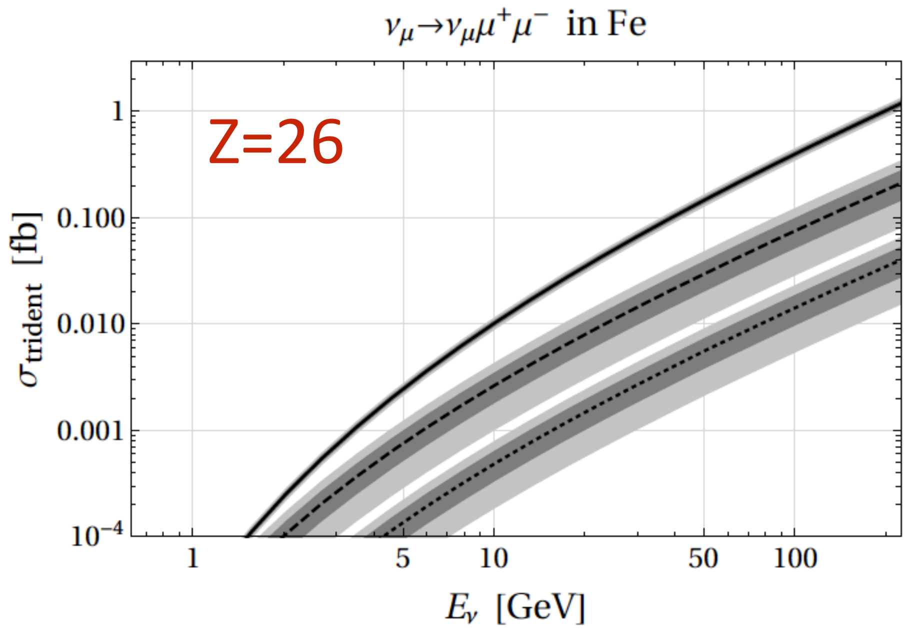
$\nu_\mu \to \nu_\mu \mu^- \mu^+$

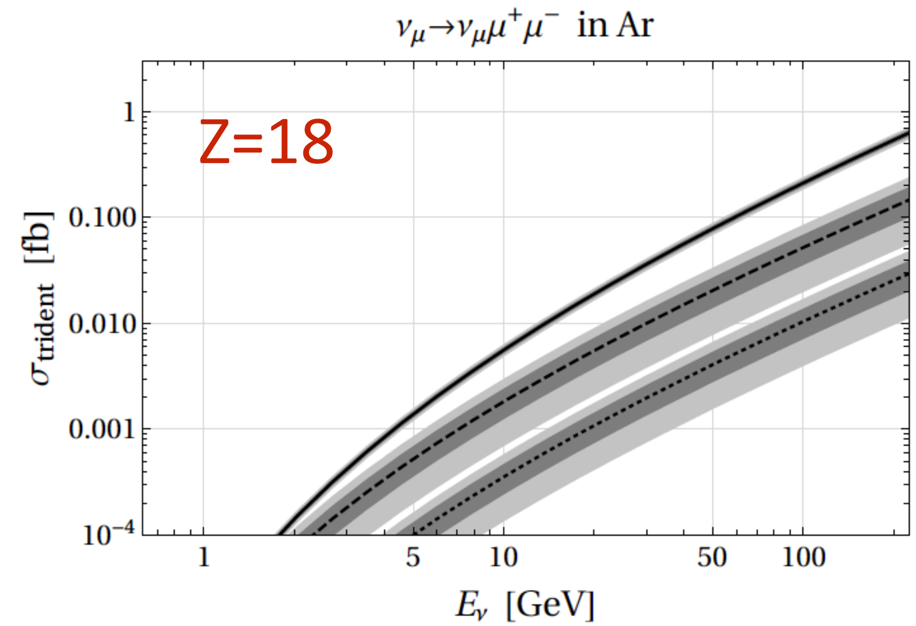
Z and *W* contributions interefere destructively

observation claimed at
CHARM II ('90)
CCFR ('91)

- Production cross section strongly dependent on *Z* and E_ν

$$d\sigma_{\text{coh.}} \propto Z^2 \alpha_{\text{em}}^2 G_F^2 |F_N(q^2)|$$





Existing Expt. Evidence

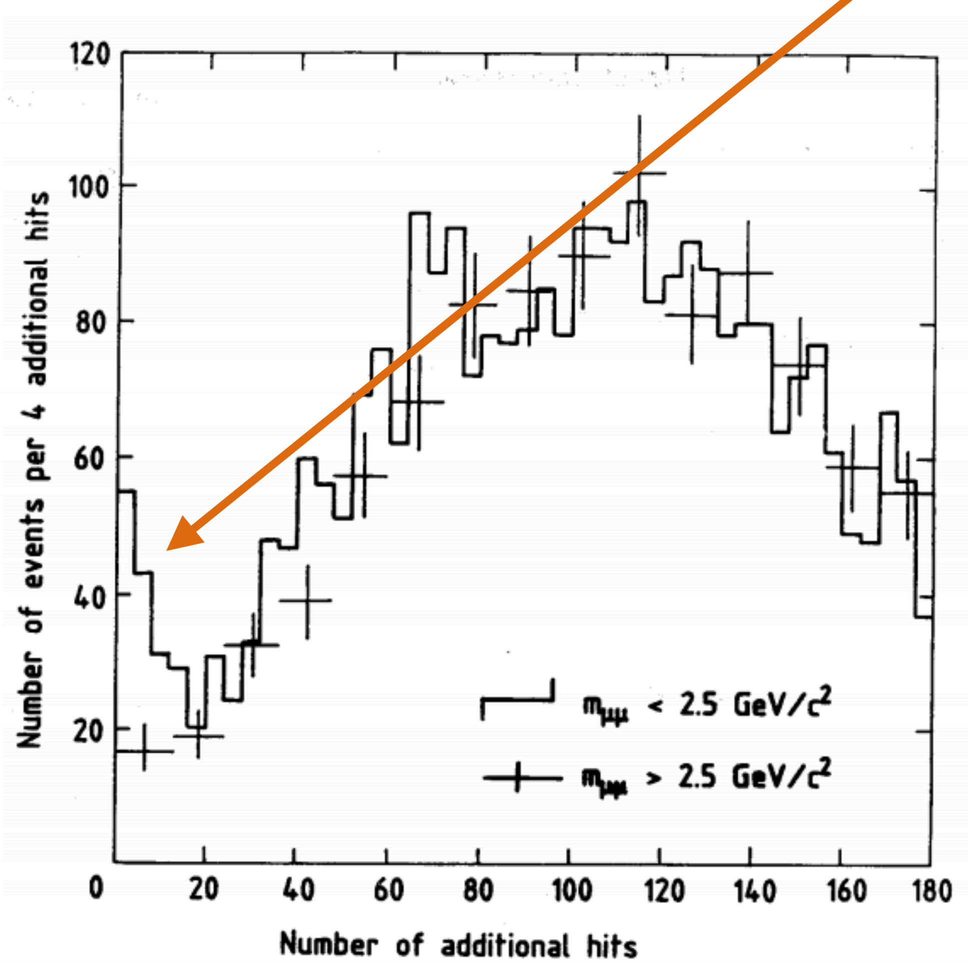
- Very rare process, but there is claimed evidence consistent with SM predictions
- However, NuTEV, which had very favorable conditions to measure tridents, made only a weak claim due to interference from diffractive charm sources not considered by CHARM II and CCFR

CHARM II

$$\langle E_\nu \rangle = 25 \text{ GeV}$$

$$N_{\text{sig}} = 55 \pm 16$$

$$\frac{\sigma_{\text{CHARM-II}}}{\sigma_{\text{SM}}} = 1.58 \pm 0.57$$



first signal claimed at CHARM II: neutrinos with average energy ~ 20 GeV on glass

Phys.Lett. B245, 271 (1990)

$$\sigma_{\text{CHARM II}}/\sigma_{\text{SM}} = 1.58 \pm 0.57$$

similar significance at CCFR: neutrinos with average energy ~ 160 GeV on iron

Phys.Rev.Lett. 66, 3117 (1991)

$$\sigma_{\text{CCFR}}/\sigma_{\text{SM}} = 0.82 \pm 0.28$$

no conclusive signal at NuTeV: neutrinos with average energy ~ 160 GeV on iron

Phys.Rev.D 61, 092001 (2000)

TABLE IV. Parameters from the three parameter fit to the low-E_{HAD} two-muon data.

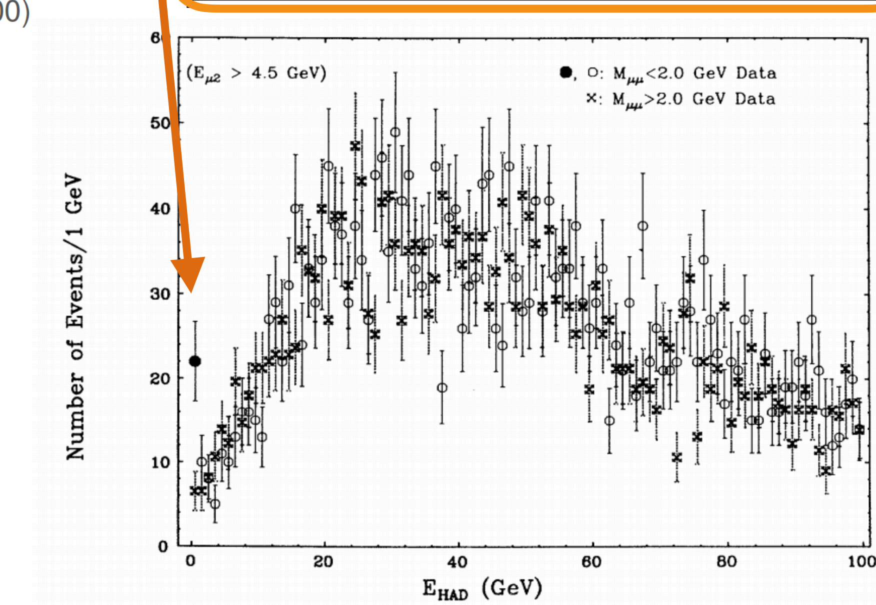
Parameter	Result
DIS	$0.90^{+0.09}_{-0.08}$
Neutrino Tridents	$0.72^{+1.73}_{-0.72}$
Diffractive Charm ($D_S^\pm + D_S^{*\pm}$)	$0.18^{+0.06}_{-0.06}$

CCFR

$$\langle E_\nu \rangle = 160 \text{ GeV}$$

$$N_{\text{sig}} = 37 \pm 12.4$$

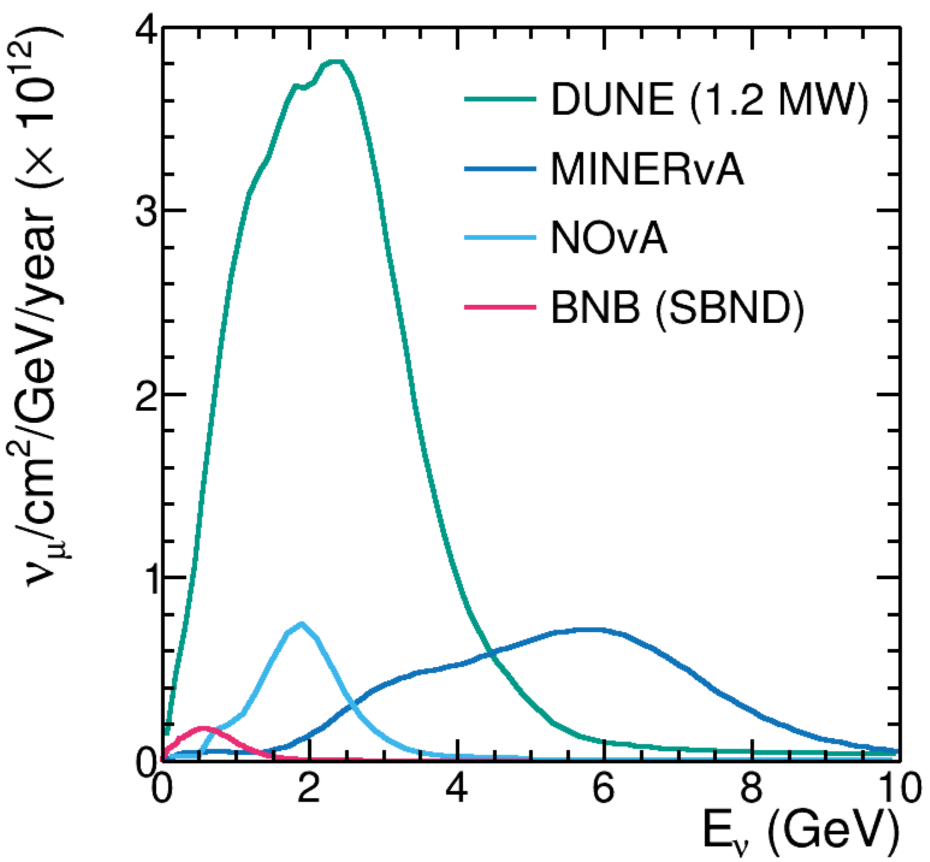
$$\frac{\sigma_{\text{CCFR}}}{\sigma_{\text{SM}}} = 0.82 \pm 0.28$$

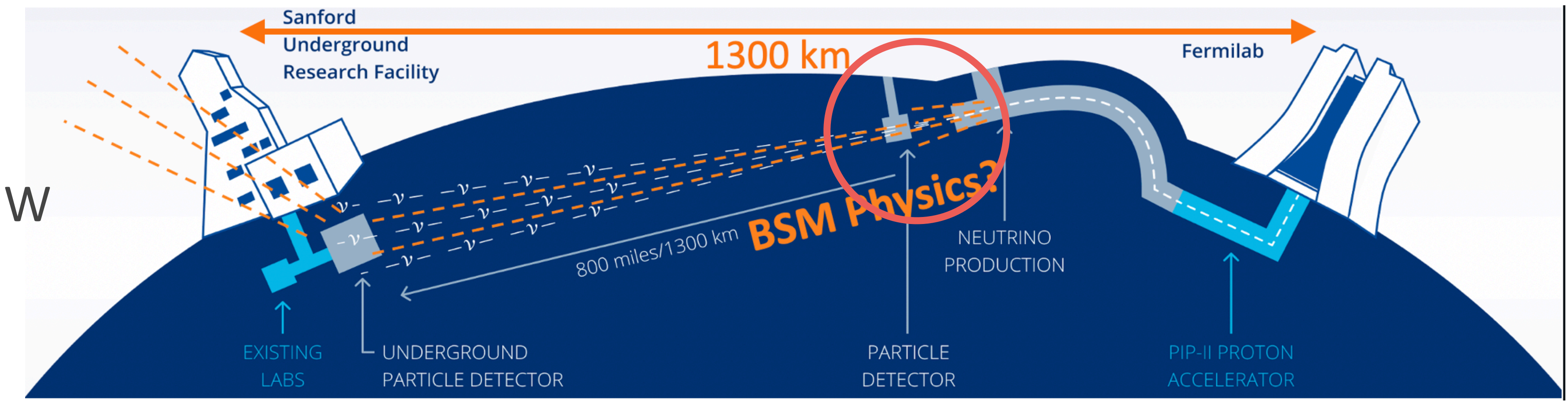


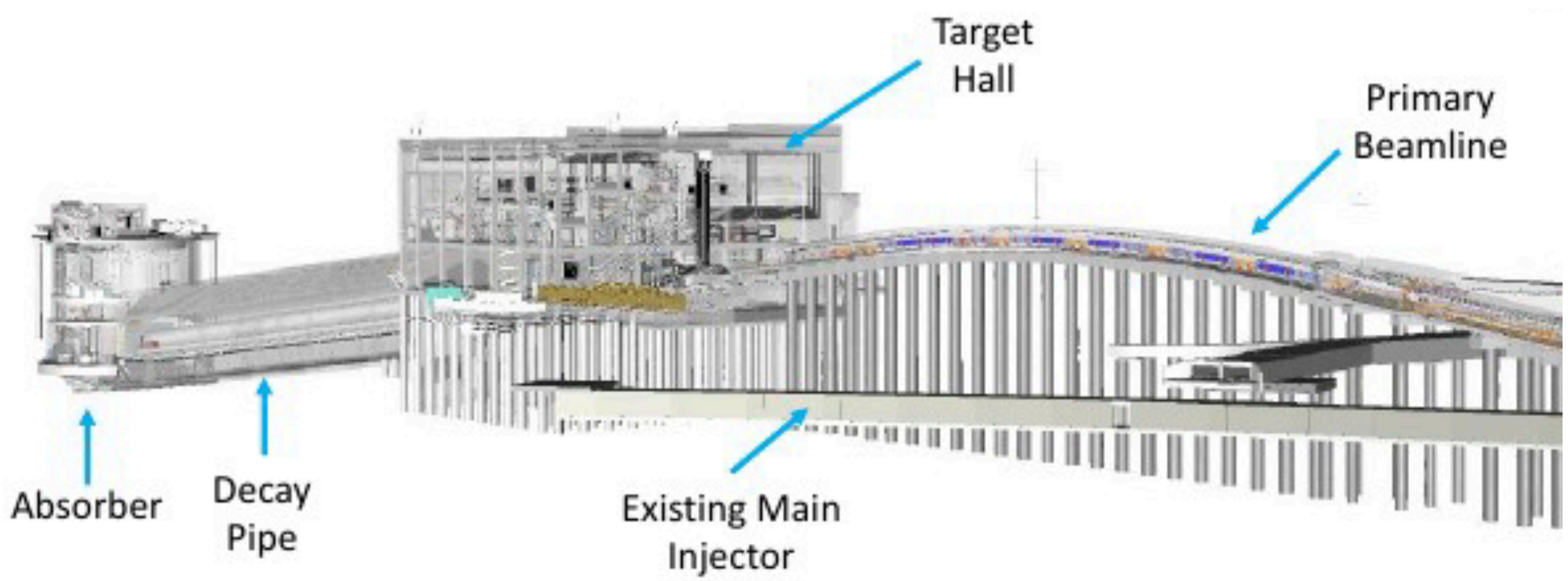
ν Tridents at the DUNE ND

- Large beam neutrino flux at Near Detectors of neutrino experiments enables searches for trident interactions
  - As an example, will go over estimated DUNE sensitivities for trident measurements and potential BSM searches
    - ➡ Altmannshofer, Gori, Martín-Albo, AS, Wallbank, Phys. Rev. D 100, 115029 (2019)
    - ➡ DUNE Collaboration, DUNE FD TDR, Vol. II: DUNE Physics
    - ➡ DUNE Collaboration, Prospects for BSM Physics at DUNE, EPJ C 81, 322 (2021)

- High-intensity wide-band LBNF neutrino beam
  - 1.2 MW upgradeable to 2.4 MW



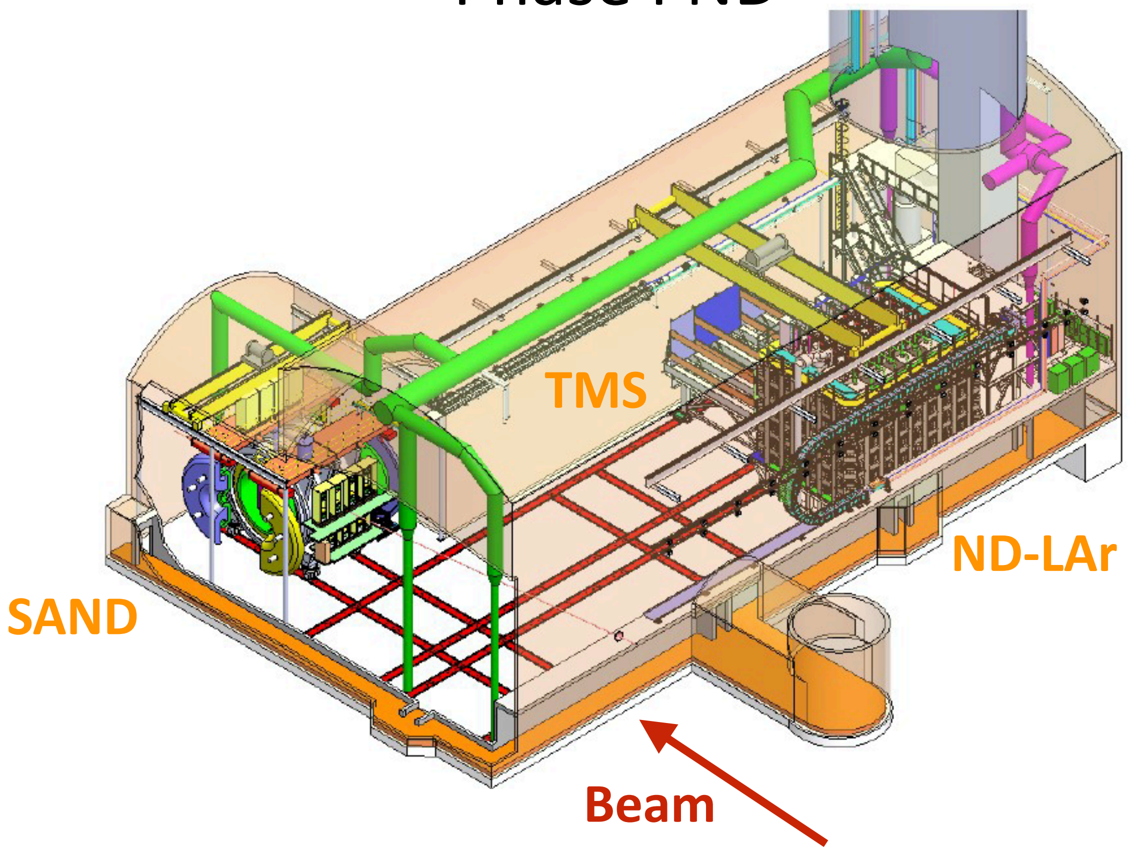




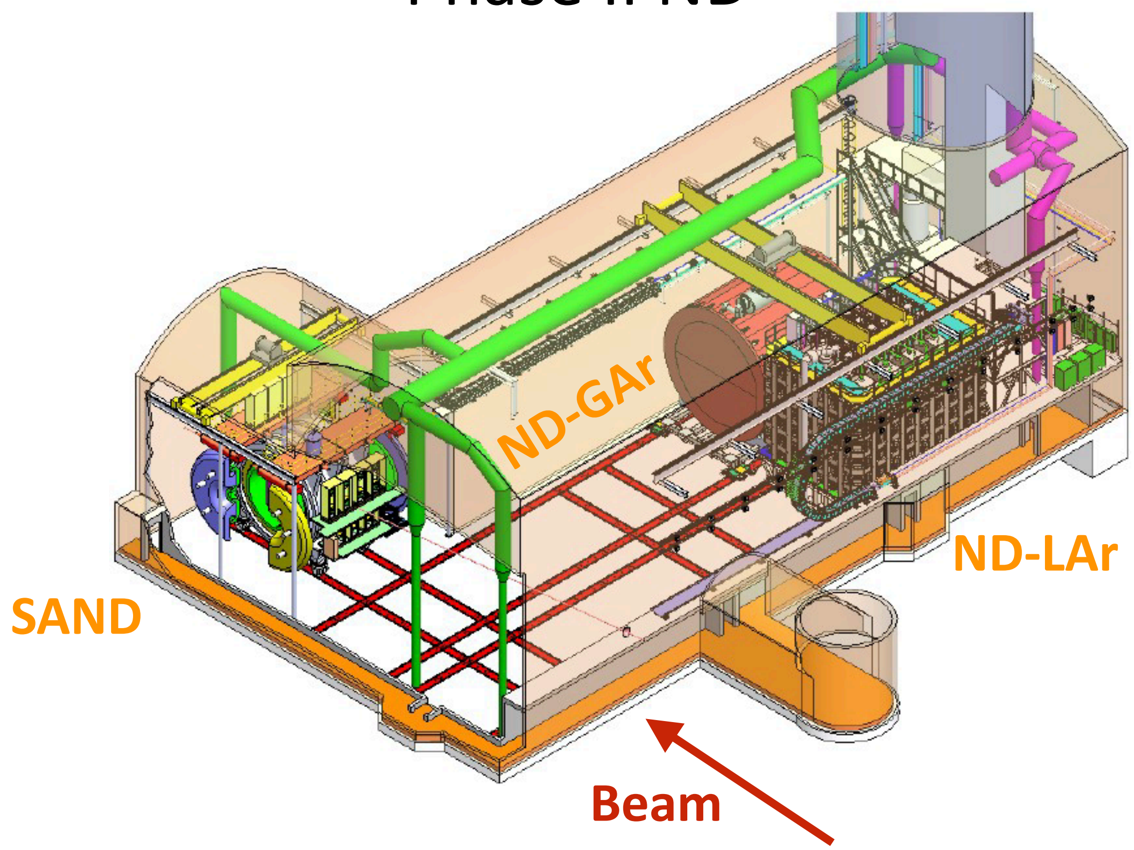
ν Tridents at the DUNE ND

- Highly-capable Near Detector complex
  - 574 m baseline
  - High-Resolution detectors; ND-LAr/ TMS/ND-GAr can move off-axis (PRISM)
- DUNE Phase I presently scheduled to begin beam data taking in 2031, Phase II later in 2030s
- $\mathcal{O}$(10 million/year) neutrino interactions will enable rich non-oscillation physics program

Phase I ND



Phase II ND



- ND-LAr: modular, pixelated LArTPC, primary target, most similar to FD
- TMS (Temp. Muon Spectrometer): magnetized steel/scintillator detector used in Phase I
- ND-GAr: high-pressure gaseous Argon TPC surrounded by ECAL and magnet, to constrain nuclear interaction model and also serve as muon spectrometer during Phase II
- SAND (System for on-Axis Nu Detection): tracker surrounded by ECAL and magnet, on-axis beam monitor

ν Tridents at the DUNE ND

- Experimental setup used in study:
  - Note that only ND-LAr detector was considered

Table 8.1: Beam power configuration assumed for the LBNF neutrino beam.

Energy (GeV)	Beam Power (MW)	Uptime Fraction	POT/year
120	1.2	0.56	1.1×10^{21}

ND Properties	Values
Dimensions	7 m wide, 3 m high, and 5 m long
Dimensions of fiducial volume	6 m wide, 2 m high, and 4 m long
Total mass	147 ton
Fiducial mass	67.2 ton
Distance from target	574 m

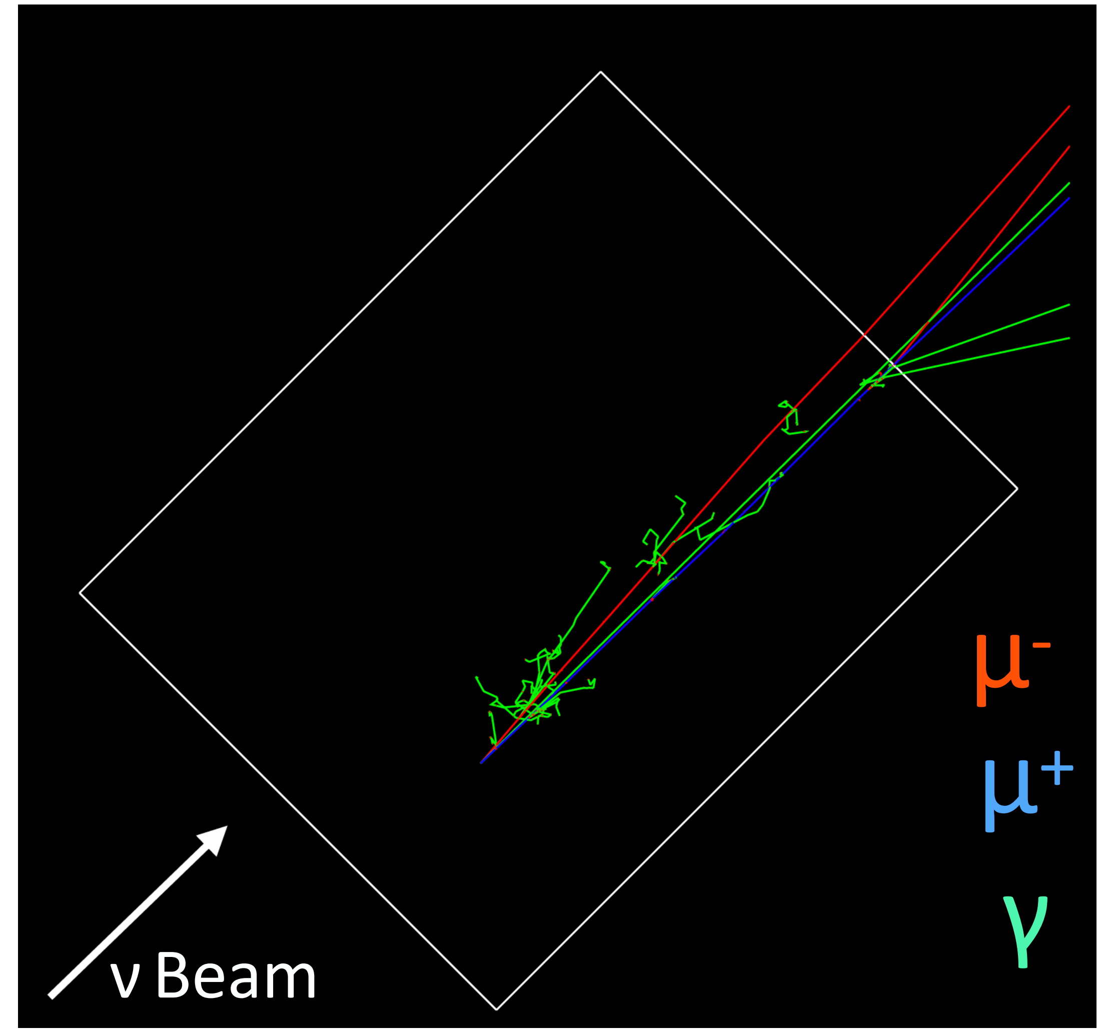


Table 6 Expected number of SM ν_μ and $\bar{\nu}_\mu$-induced trident events at the LArTPC of the DUNE ND per metric ton of argon and year of operation.

Process	Coherent	Incoherent
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	1.17 ± 0.07	0.49 ± 0.15
$\nu_\mu \to \nu_\mu e^+ e^-$	2.84 ± 0.17	0.18 ± 0.06
$\nu_\mu \to \nu_e e^+ \mu^-$	9.8 ± 0.6	1.2 ± 0.4
$\nu_\mu \to \nu_e \mu^+ e^-$	0	0
$\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^+ \mu^-$	0.72 ± 0.04	0.32 ± 0.10
$\bar{\nu}_\mu \to \bar{\nu}_\mu e^+ e^-$	2.21 ± 0.13	0.13 ± 0.04
$\bar{\nu}_\mu \to \bar{\nu}_e e^+ \mu^-$	0	0
$\bar{\nu}_\mu \to \bar{\nu}_e \mu^+ e^-$	7.0 ± 0.4	0.9 ± 0.3

- Trident signal produced with new C++ MC generator code publicly available in Altmannshofer, Gori, Martín-Albo, AS, Wallbank, Phys. Rev. D 100, 115029
  - 4-vectors of trident interactions input into GEANT4-based simulation of ND-LAr detector
- $\mathcal{O}$(100 million) regular neutrino interactions generated using official GENIE/GEANT4 DUNE ND simulation to estimate backgrounds

ν Tridents at the DUNE ND

- Primary background is ν_μ CC interactions with single pion production
  - 38% of GENIE events had a charged lepton and a charged pion in the final state
  - Di-muon events from CC charm production are less than 1% of total bkgnd
  - Signal/background separation through kinematic variables

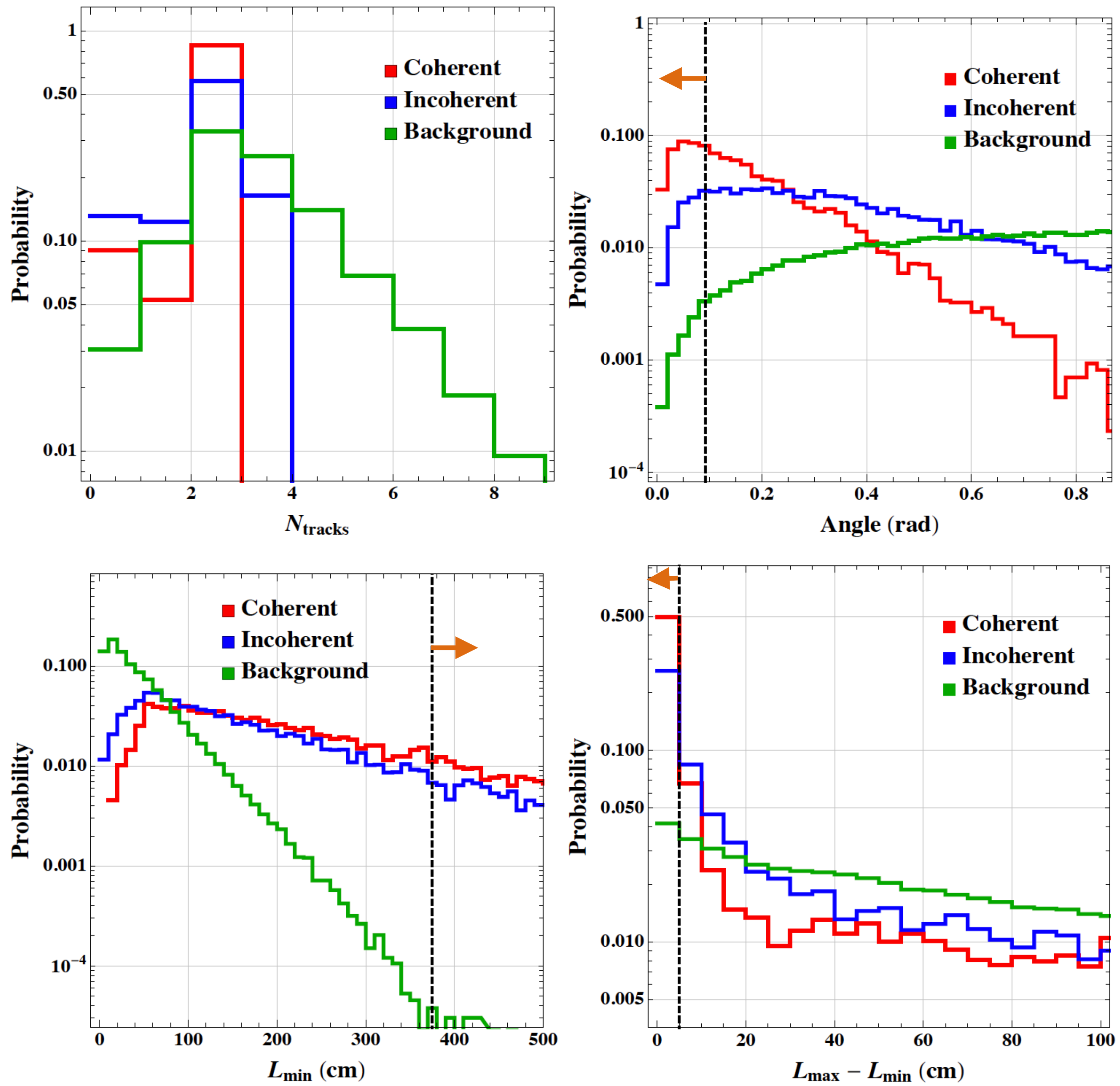
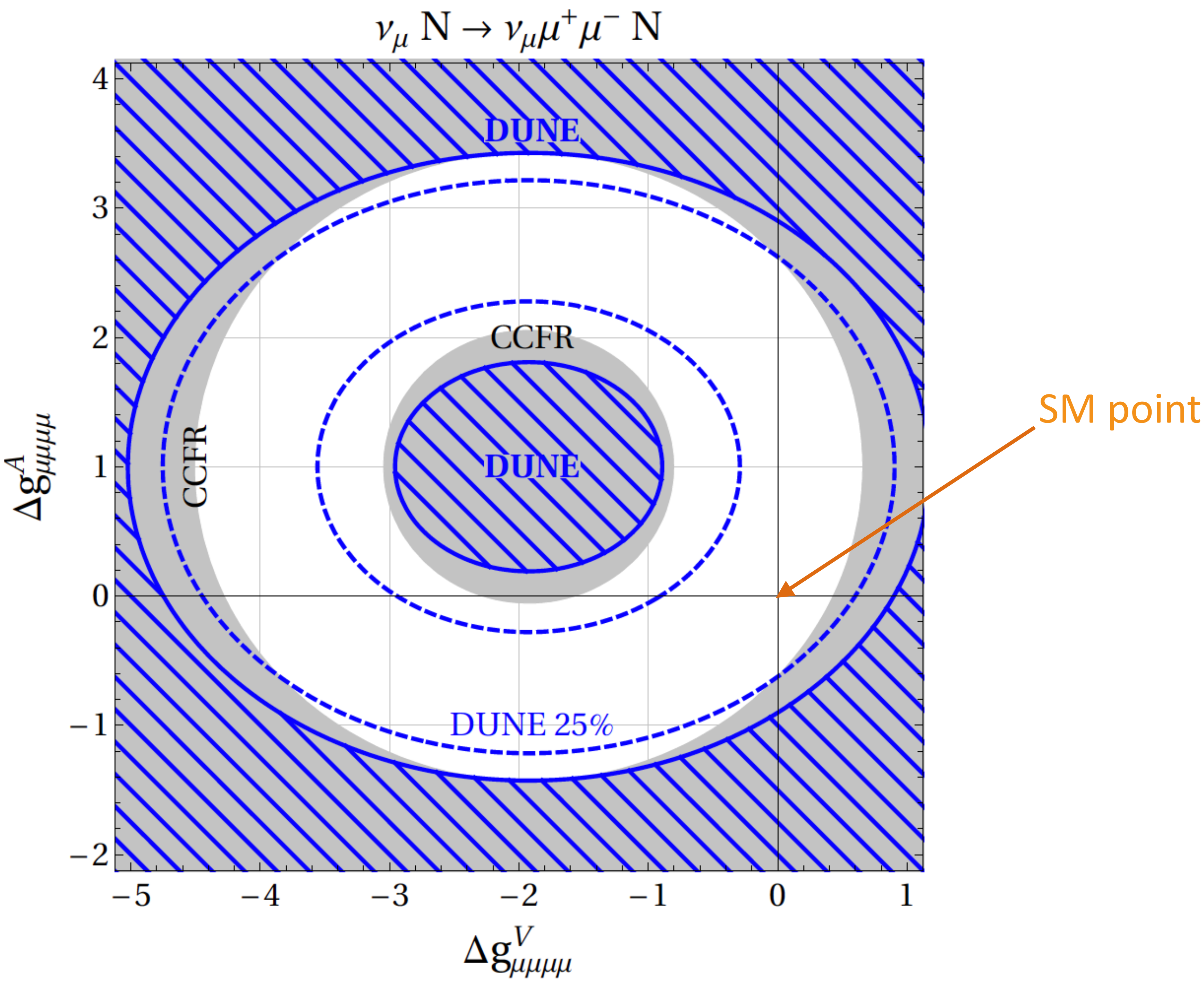


Fig. 15 Event kinematic distributions of signal and background considered for the selection of muonic trident interactions in the ND LArTPC: number of tracks (top left), angle between the two main tracks (top right), length of the shortest track (bottom left), and the difference in length between the two main tracks (bottom right). The dashed, black vertical lines indicate the optimal cut values used in the analysis.

- Achieved 10^7 background rejection!

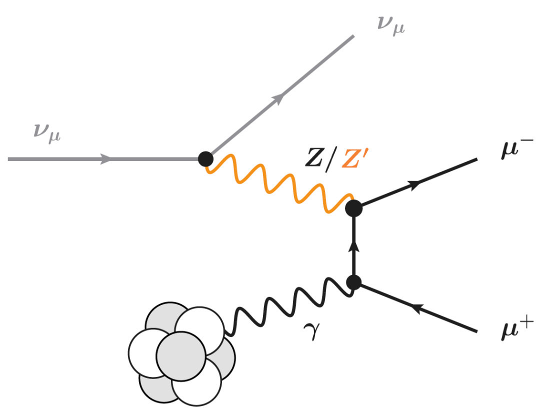
ν Tridents at the DUNE ND

- 95% CL sensitivity to modifications of the vector and axial couplings of muon-neutrinos to muons
  - Assuming ~6 years of ν_μ running or ~3 years each of ν_μ and $\bar{\nu}_\mu$ running
  - Expect to achieve 40% precision in measuring $\mu^+\mu^-$ trident process (comparable to CCFR)
  - Also showing result with 25% precision, which may be achievable through various improvements (3 slides ahead)



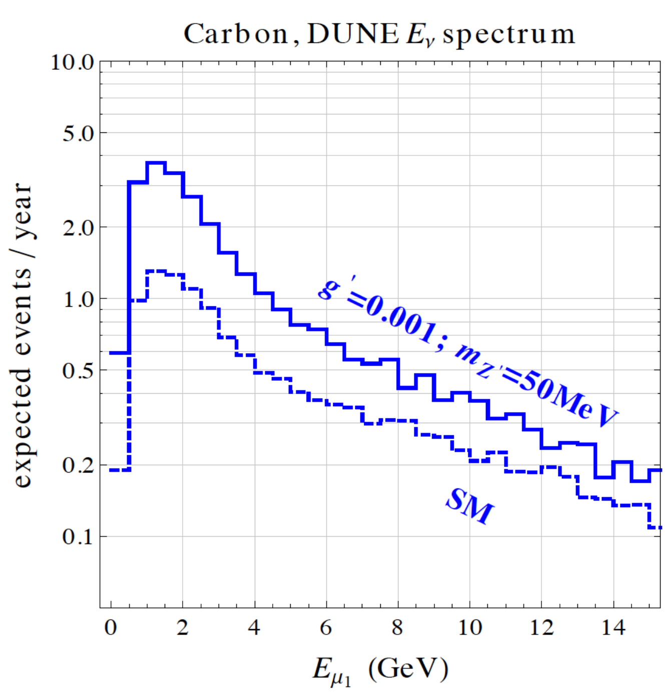
ν Tridents at the DUNE ND

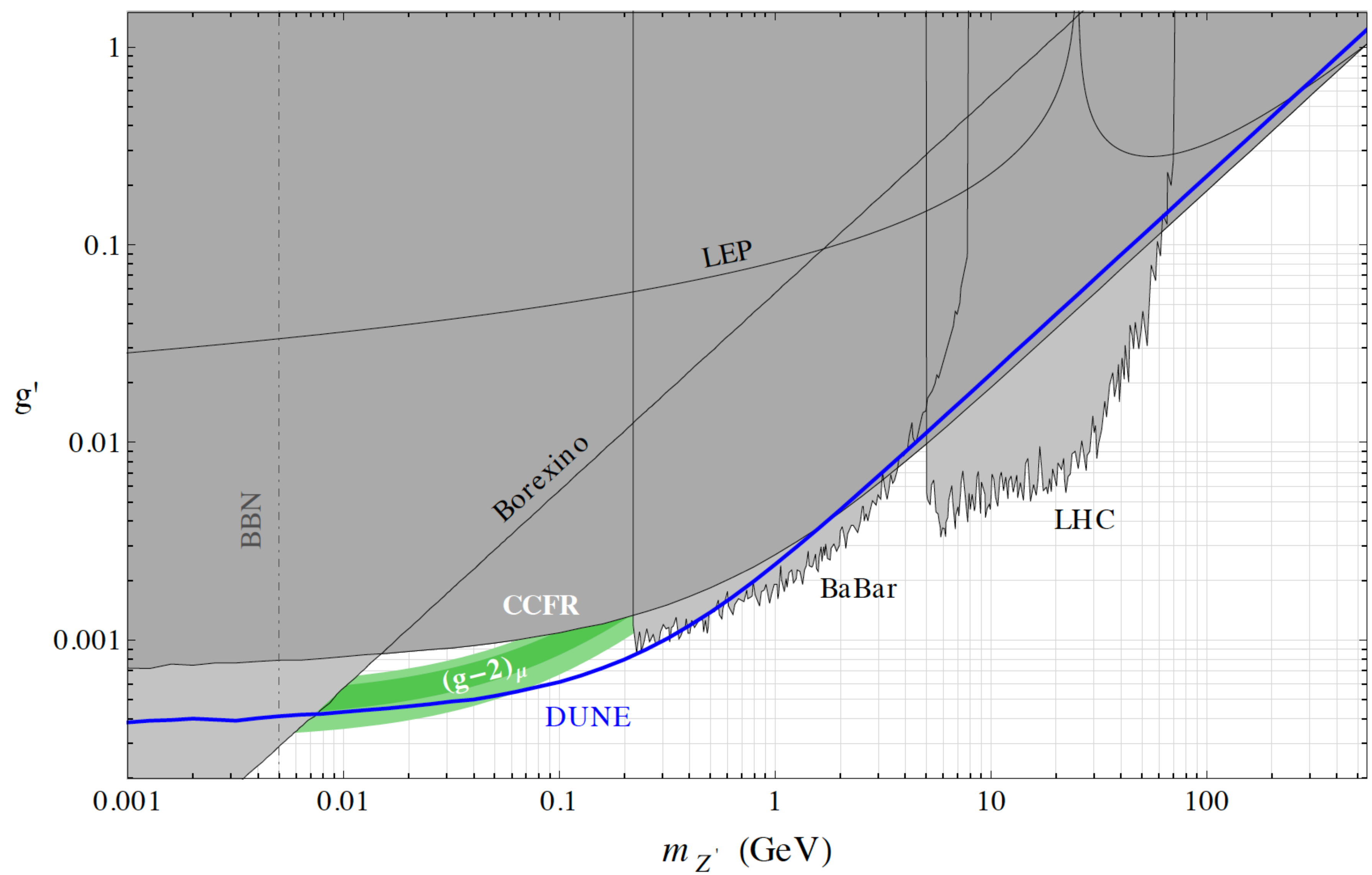
- 95% CL DUNE constraint on g-2 anomaly region for a Z' model based on a gauged L_μ - L_τ global symmetry
  - Z' enhances trident production
  - Assuming ~6 years of ν_μ running or ~3 years each of ν_μ and $\bar{\nu}_\mu$ running
  - Assuming 40% precision in measuring $\mu^+\mu^-$ trident process cross section



$$\frac{\sigma^{\rm DUNE}}{\sigma^{\rm DUNE}_{\rm SM}} \simeq \frac{1.54 + \left(1 + 4s_W^2 + \frac{2v^2(g')^2}{M_{Z'}^2}\right)^2}{1.54 + (1 + 4s_W^2)^2}$$

(for Z' masses $\gtrsim$ few hundred MeV)





ν Tridents at the DUNE ND

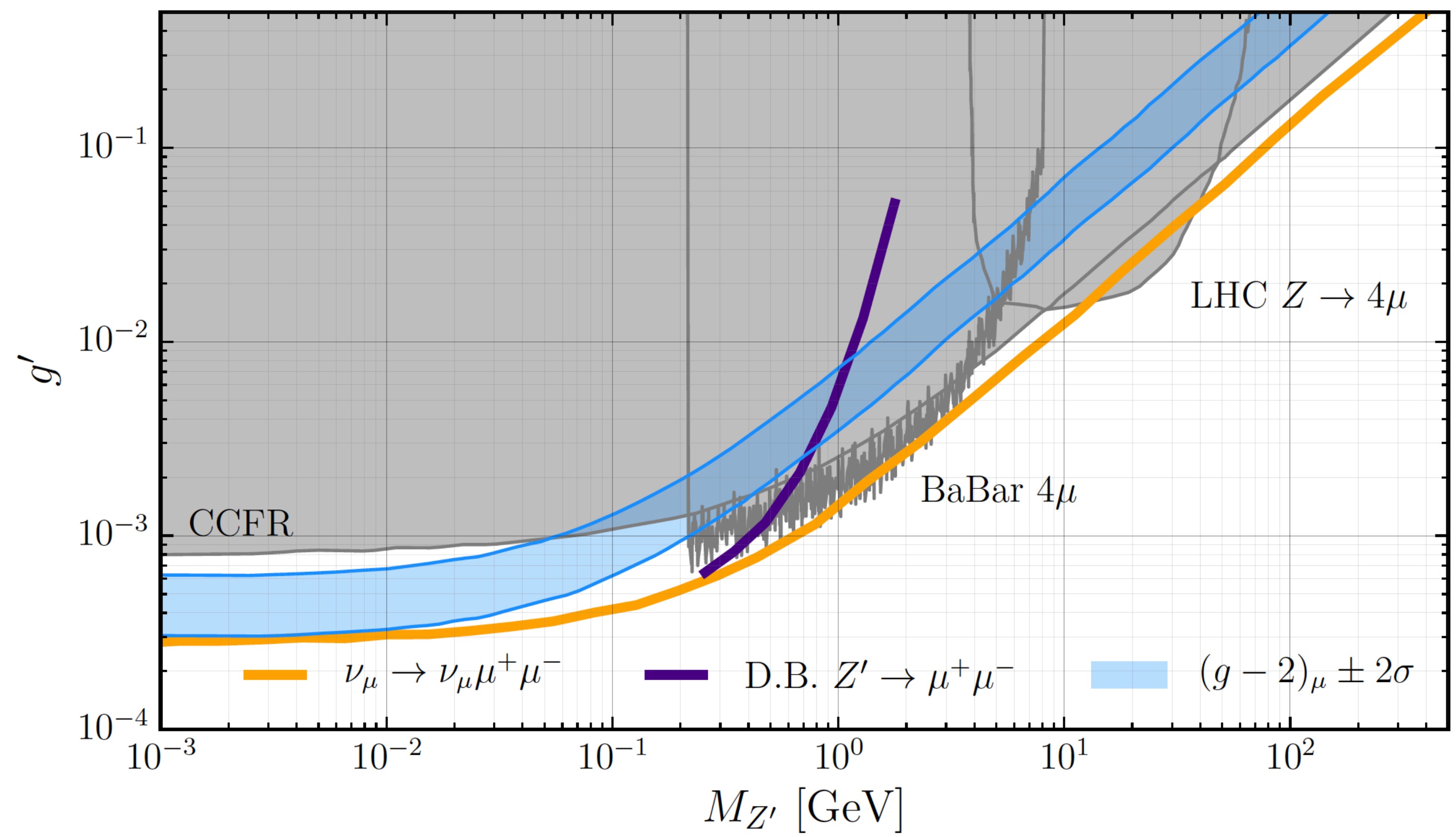
- Constraint from independent study focused on Z' sensitivity:
  - Ballett, Hostert, Pascoli, Perez-Gonzalez, Tabrizi, Funchal, Phys. Rev. D 100, 055012 (2019)

Sensitivity of DUNE ND

$$U(1)_{L_\mu - L_\tau}$$

Enhancement is largest at **lower energies.**

Log sensitive to the Z' mass below 10 MeV.



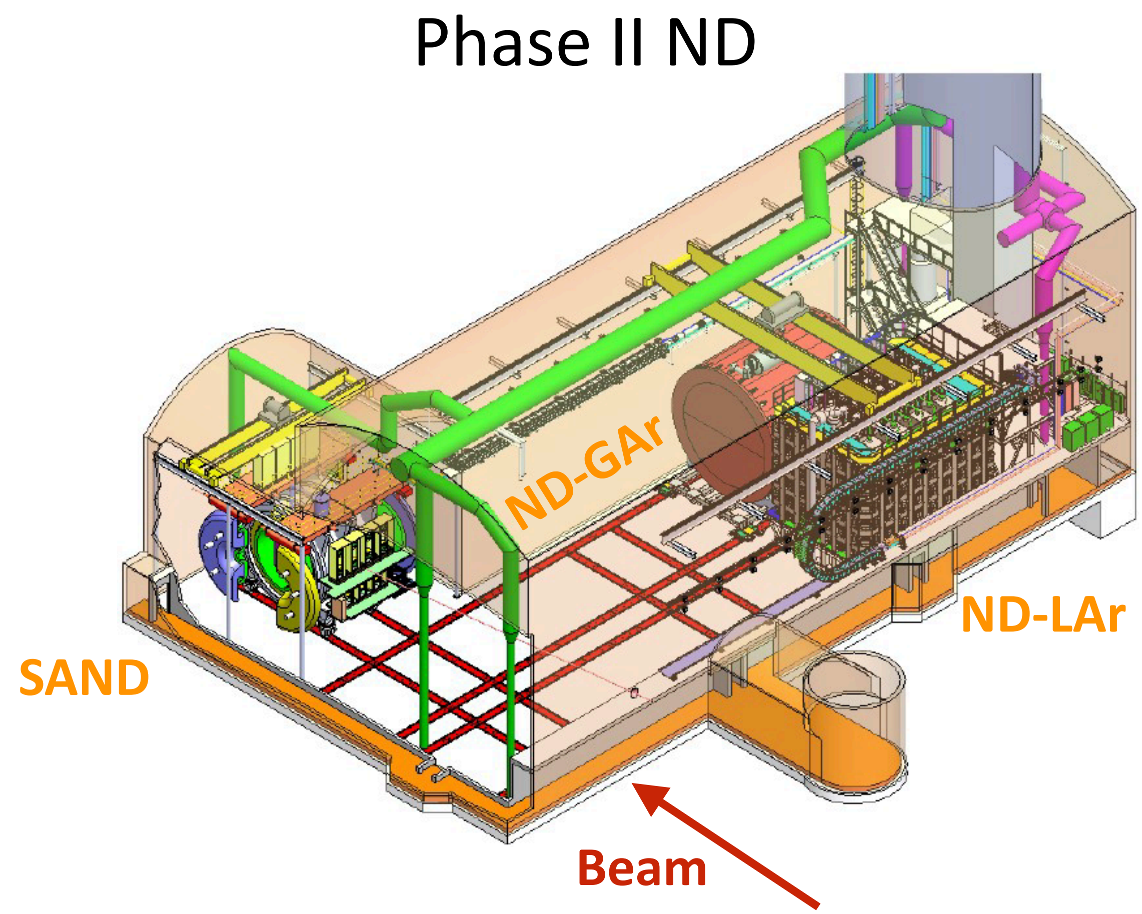
DUNE near detector (25 t) at 90 % C.L.

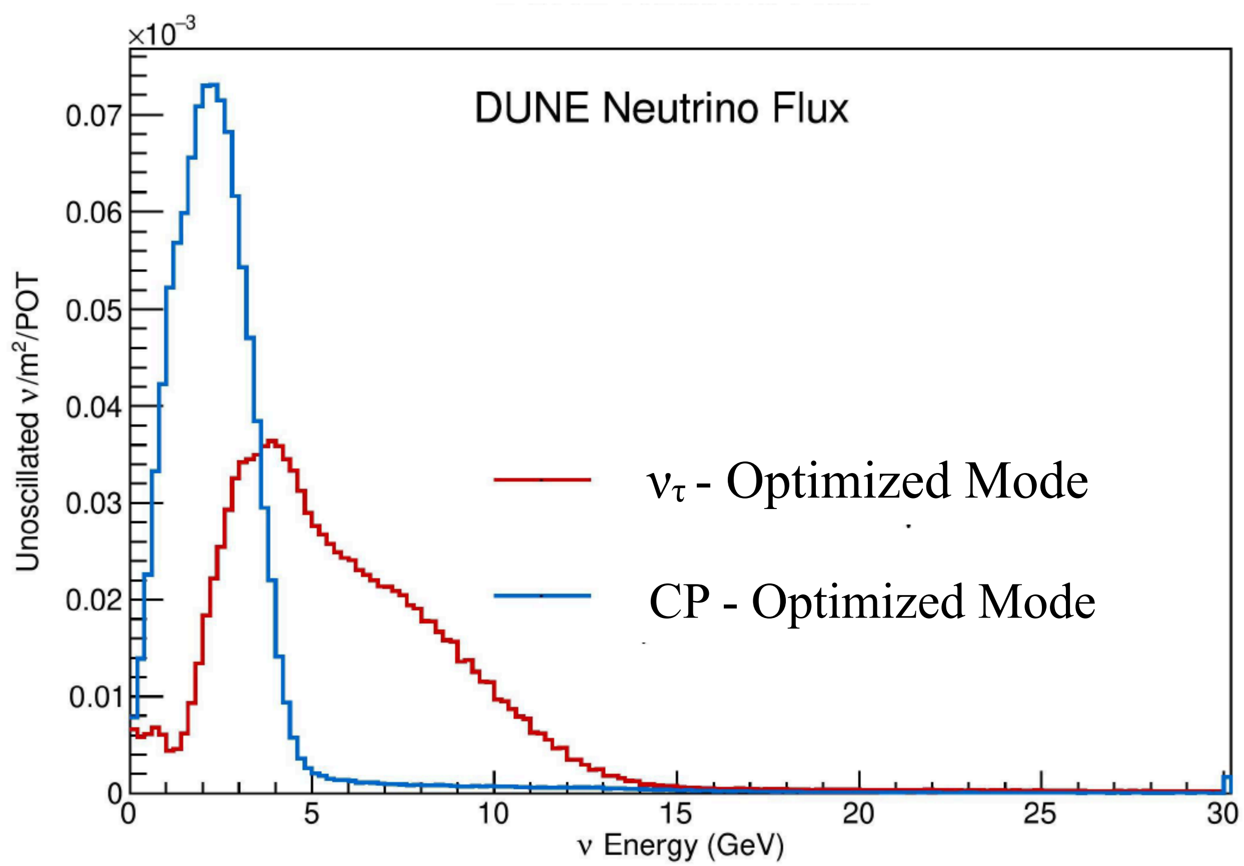
Assume 10% normalisation systematics and no backgrounds.

- Uses smaller ND volume and DUNE CDR flux, assumes no backgrounds. Consistent with our results

ν Tridents at the DUNE ND

- Potential improvements for the DUNE trident analysis
  - Include TMS / ND-GAr in the analysis as magnetized muon spectrometers
    - ➡ Improved background separation from muon charge determination
    - ➡ Extend muon momentum determination to 6 GeV (TMS) or >12 GeV (ND-GAr)
  - Improved selection using machine learning
  - Include SAND as a separate magnetized muon tracker
  - During Phase II, there are prospects for running for a year with a nutau-optimized beam, providing access to higher-energy trident production
  - Probe other trident channels?





- Some of these being studied by Ph.D. student working with DUNE BSM group

ν Tridents at Other NDs

- Total number of ν tridents predicted for expected final experimental exposures, taken from:
  - Ballett, Hostert, Pascoli, Perez-Gonzalez, Tabrizi, Funchal, JHEP 2019, 119 (2019)

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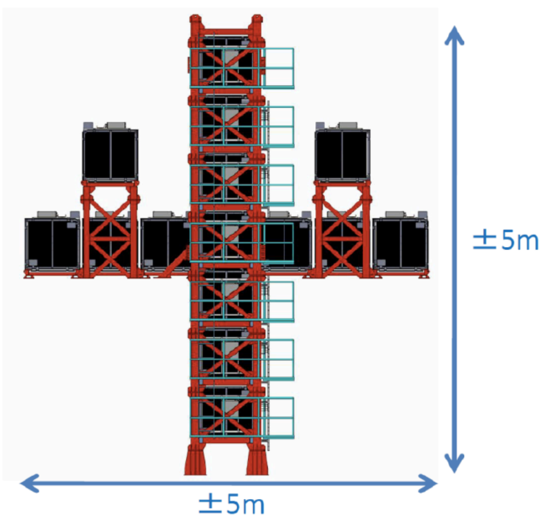
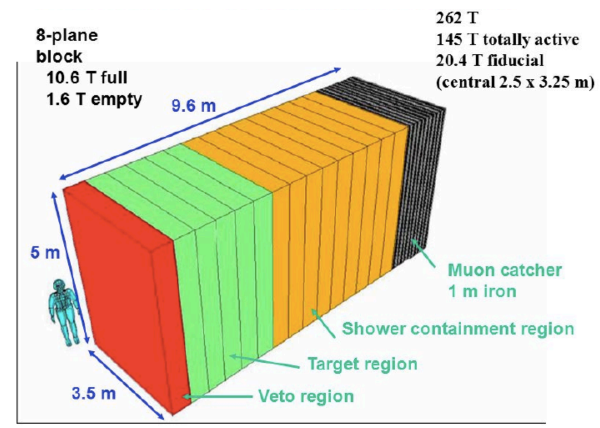
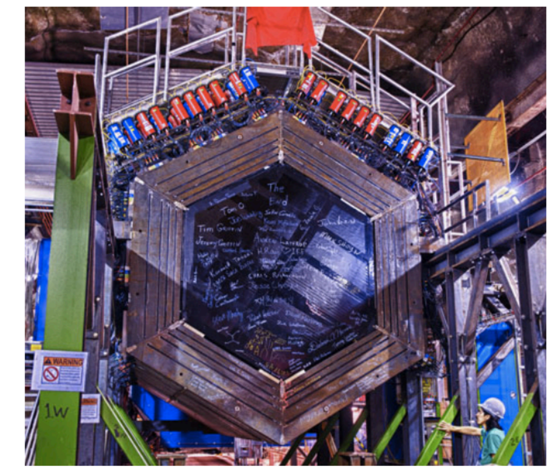






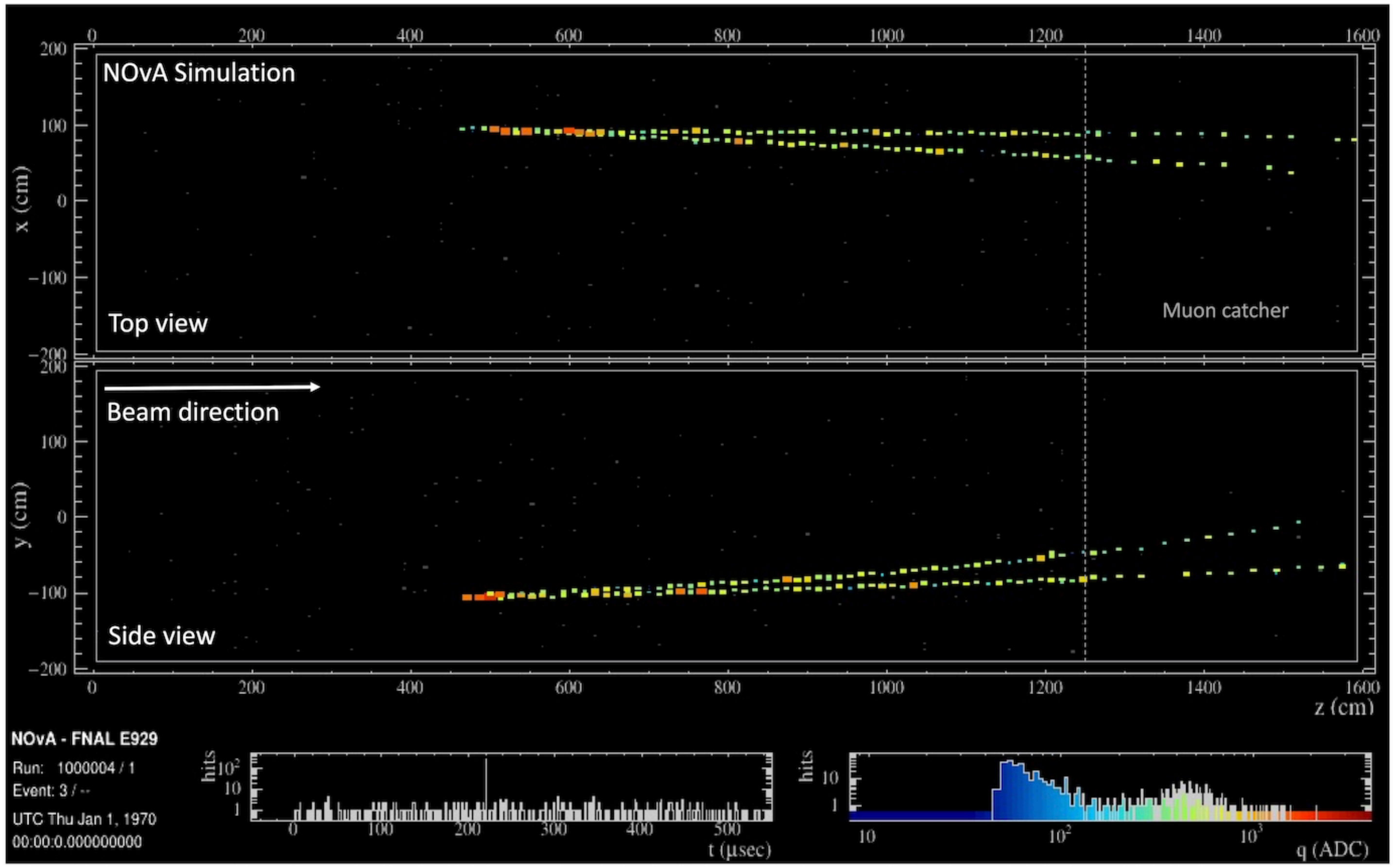
Channel	T2K-I	T2K-II	MINOS	MINOS+	NOνA-I	NOνA-II	MINERνA
Total $e^{\pm}\mu^{\mp}$	563	1444	222 (56)	730	83 (72)	340 (374)	149 (102)
	96	246	46 (11)	151	25 (22)	102 (114)	56 (39)
Total e^+e^-	277	711	61 (15)	62	29 (22)	119 (114)	39 (27)
	24	62	9 (2)	8	4 (4)	16 (21)	10 (7)
Total $\mu^+\mu^-$	30	76	26 (6)	86	9 (9)	37 (47)	18 (13)
	21	54	15 (3)	49	8 (8)	34 (36)	18 (13)

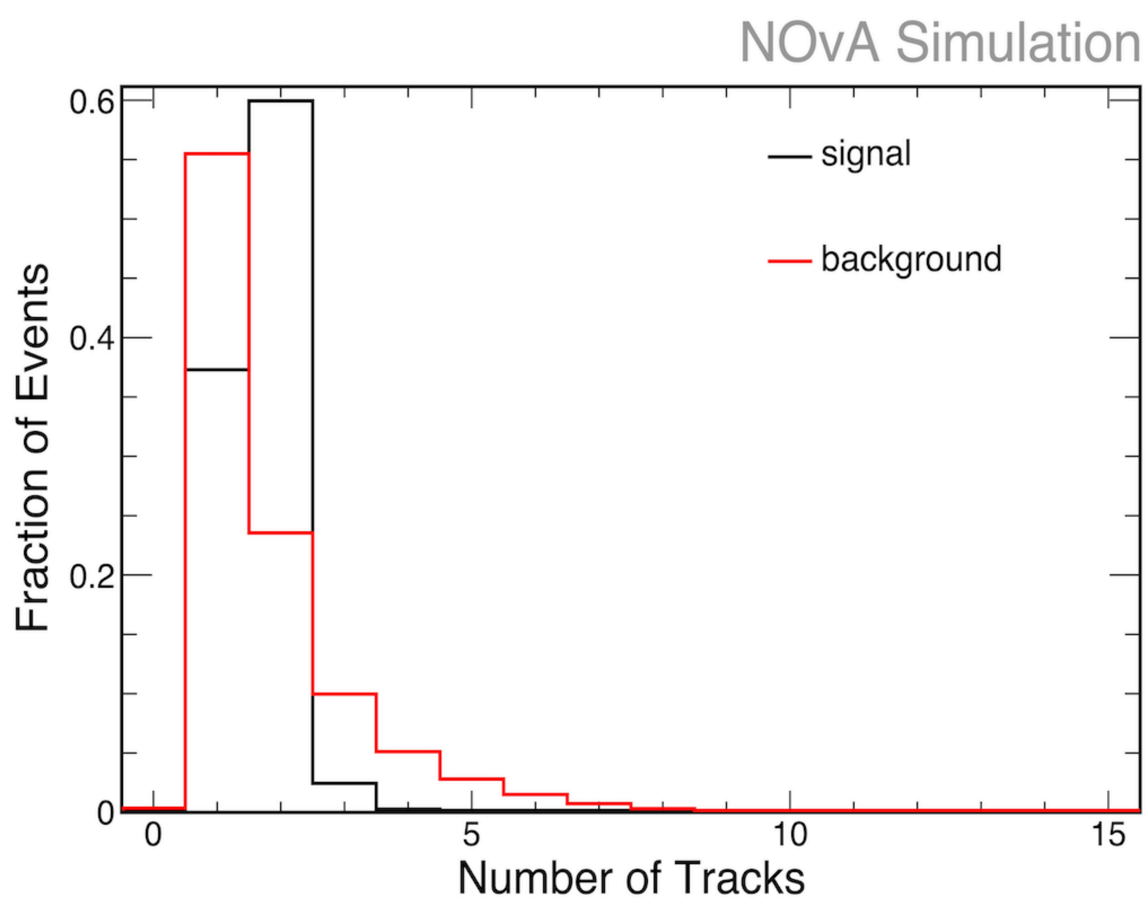
Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

ν Tridents at NOvA ND

- Ongoing analysis, status presented in poster at Neutrino 2022 by Reed Bowles
  - Uses NOvA off-axis beam (narrow-peaked at E_ν = 2 GeV), and 300 ton ND PVC/liquid scintillator (Z~12)
  - With present data set, 23.2x10^{20} POT (neutrino mode) 12.7x10^{20} POT (antineutrino mode), expect 10-20 interactions selectable in each sample

- Trident reconstruction challenging due to the narrow angle between muons
  - ~40% of simulated signal events have only one track reconstructed
  - Can be improved by new reconstruction method being worked on





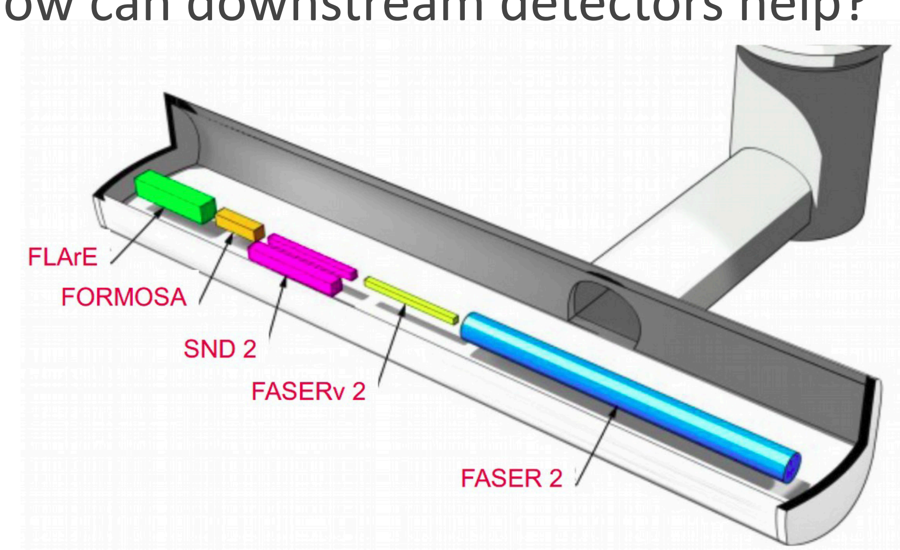
Summary

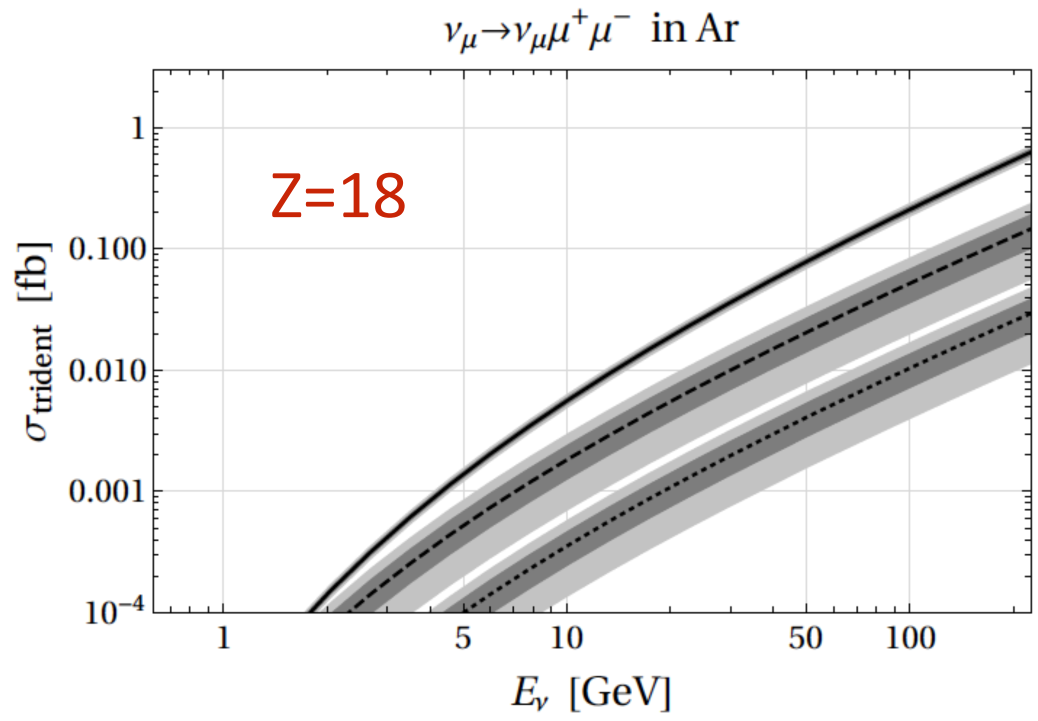
Neutrino tridents produce a distinctive topology of two long tracks in the near detector, distinguishing them from other ν_μ interactions.

NOvA has the potential for a ~30% measurement of neutrino trident production below 20GeV using existing data.

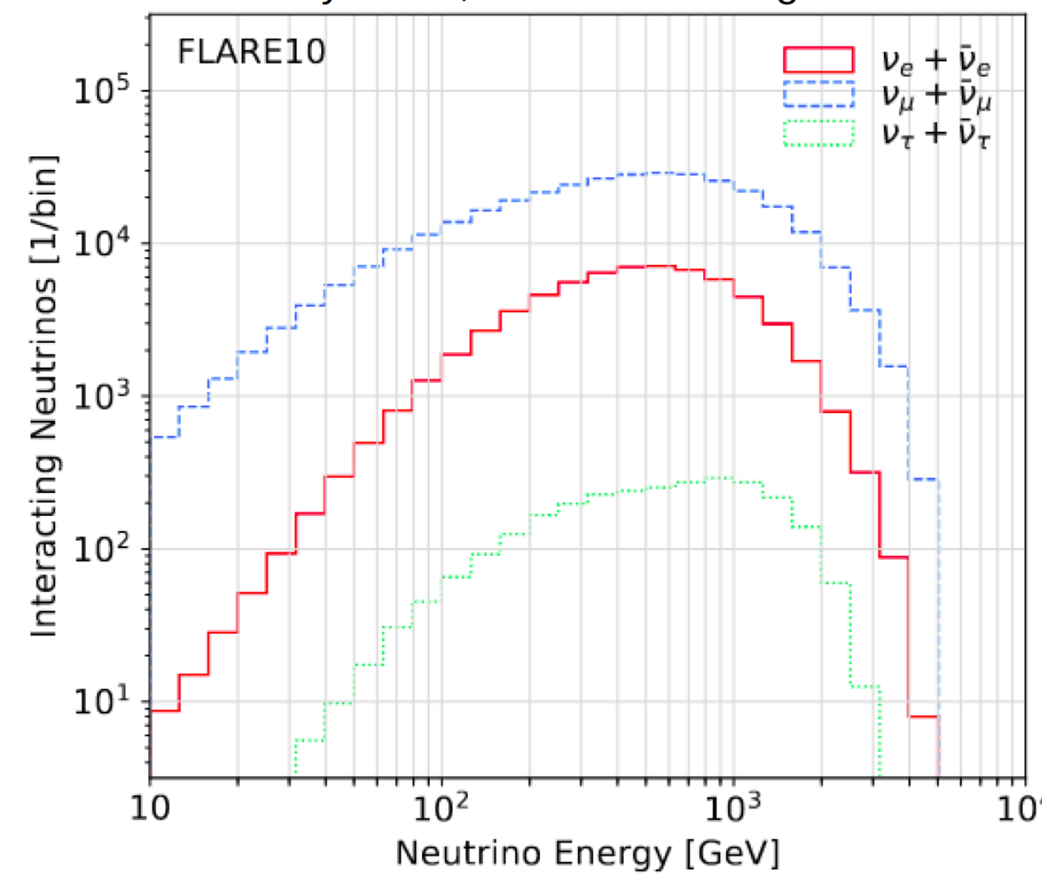
ν Tridents at FLArE?

- Considerations on searches with FLArE
  - 10 ton LAr (Z=18) mass
  - Expected total of ~10^6 ν_μ CC interactions during LHC lifetime
  - Comparatively “large" trident cross sections at these neutrino energies
  - Primary backgrounds from ν_μ CC DIS interactions with 2nd muon from final state hadron decay (charm or π/K)
  - How likely is it that FLArE could be magnetized? (ongoing research on LArTPC magnetization at Fermilab Test Beam Facility)
    - ➡ Dimuon invariant mass for bkgnd rejection
    - ➡ How can downstream detectors help?





Sibyll 2.3d, see also F. Kling 2105.08270

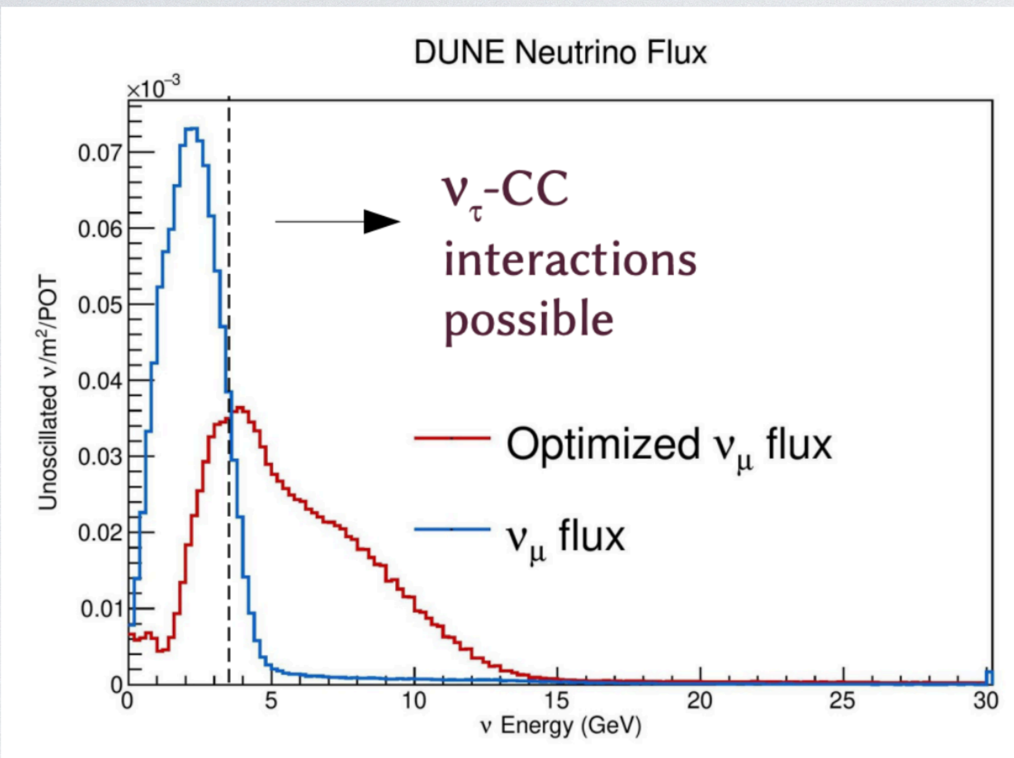


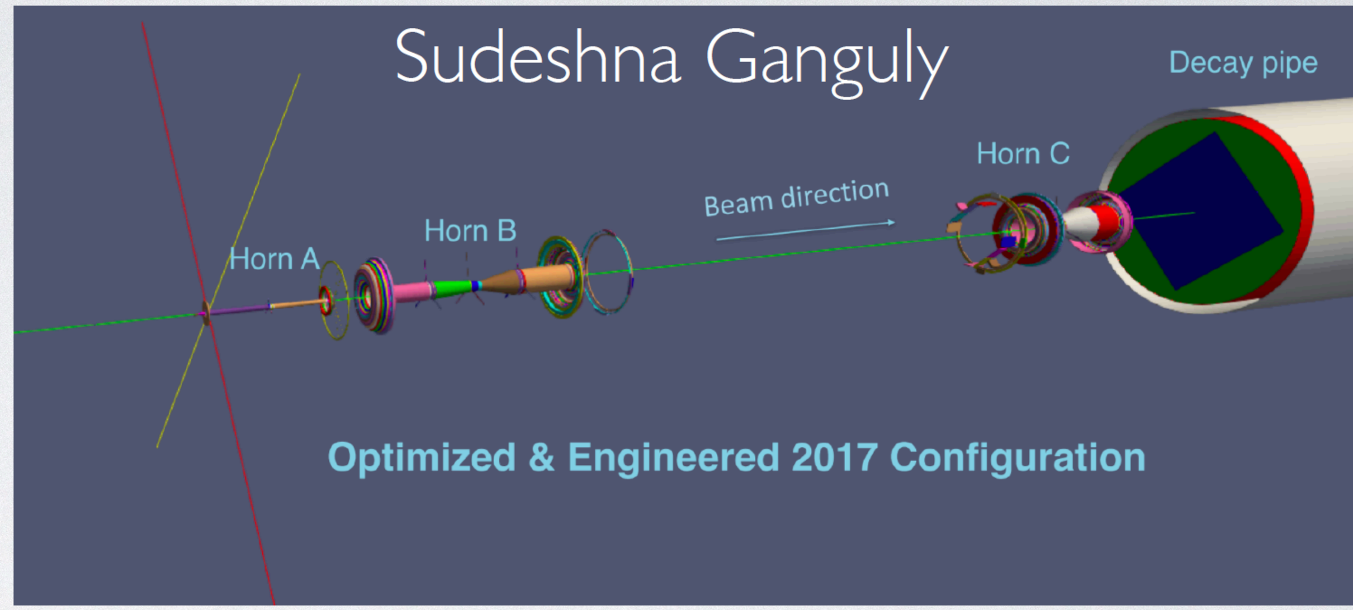
Supplements

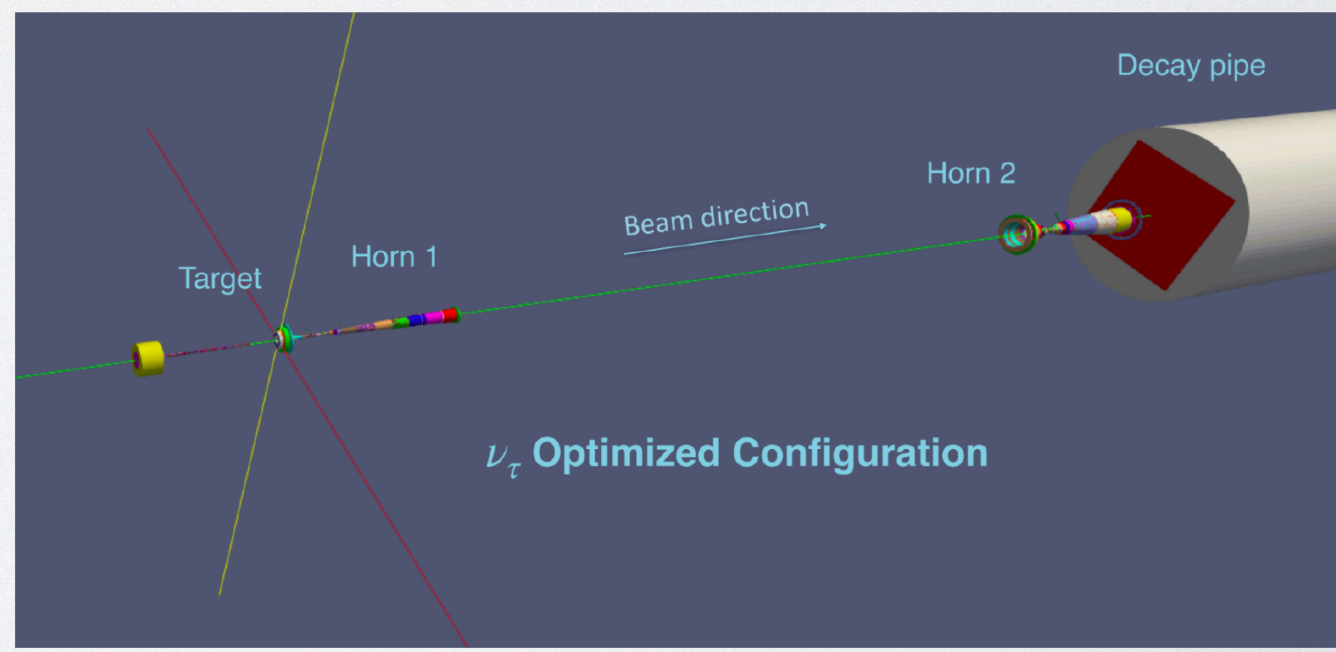
ν_τ-Optimized Beam

Laura Fields, NuTau 2021

FUTURE: DUNE







- Beamline **can be tuned to higher energy** by using two NuMI horns and increasing horn separation
- Fairly **simple optimization**; can probably be improved on, but not dramatically