Anti-Electron Neutrinos at High-Energy Neutrino Experiments: Identification Strategies and Physics Potential

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Forward neutrinos at the LHC

- The *pp* collisions at the LHC produce *forward hadrons*, decaying to neutrinos
  - Highly collimated beam tangential to the collider ring
  - These neutrinos are never observed by the central experiments
  - Similarly, possible long-lived particles that are unobserved at the IP
  - Dominantly $\pi^{+/-}$ (ν_μ, $\bar{\nu}_\mu$), $K^{+/-}$ (ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$), D (ν_τ, $\bar{\nu}_\tau$, ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$)
  - Λ_0 **hyperons** could be the next most important; no significant $\bar{\Lambda}_0$ contribution
- Problem: undetermined remainder of ν_e+$\bar{\nu}_e$ could be a mixture of K^0 and Λ_0
- Resolving hadron spectra helps understand forward strangeness & cosmic rays

$$K^0_{S/L} \sim \frac{1}{\sqrt{2}}(d\bar{s} \pm s\bar{d})$$

$$\swarrow \qquad \searrow$$

$$\pi^+ + e^- + \bar{\nu}_e \qquad \pi^- + e^+ + \nu_e$$

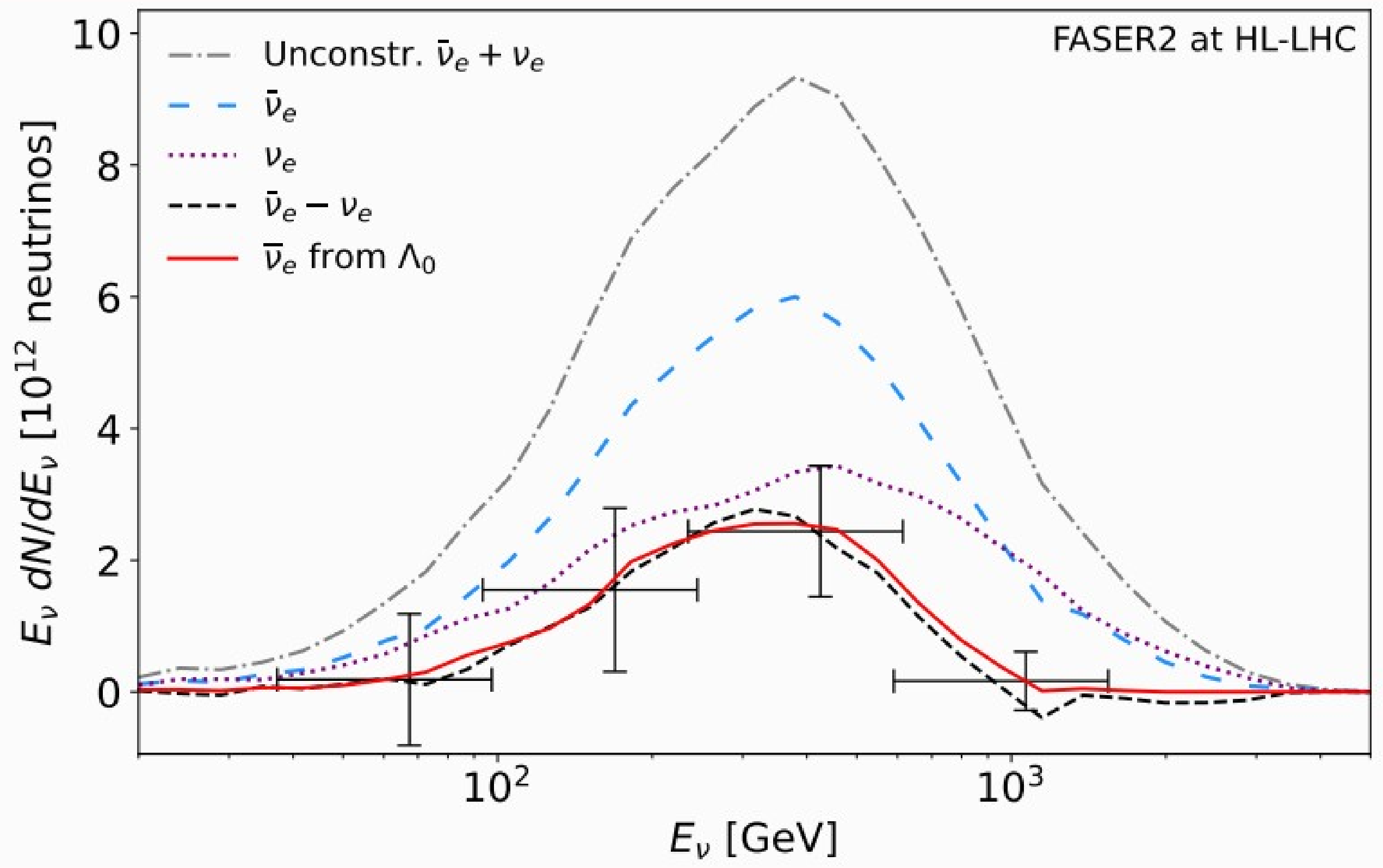
Decays equally to $\bar{\nu}_e$/ν_e

$$\Lambda_0 \sim uds, \quad s \to u \implies \Lambda_0 \to p + e^- + \bar{\nu}_e$$

Only decays to $\bar{\nu}_e$

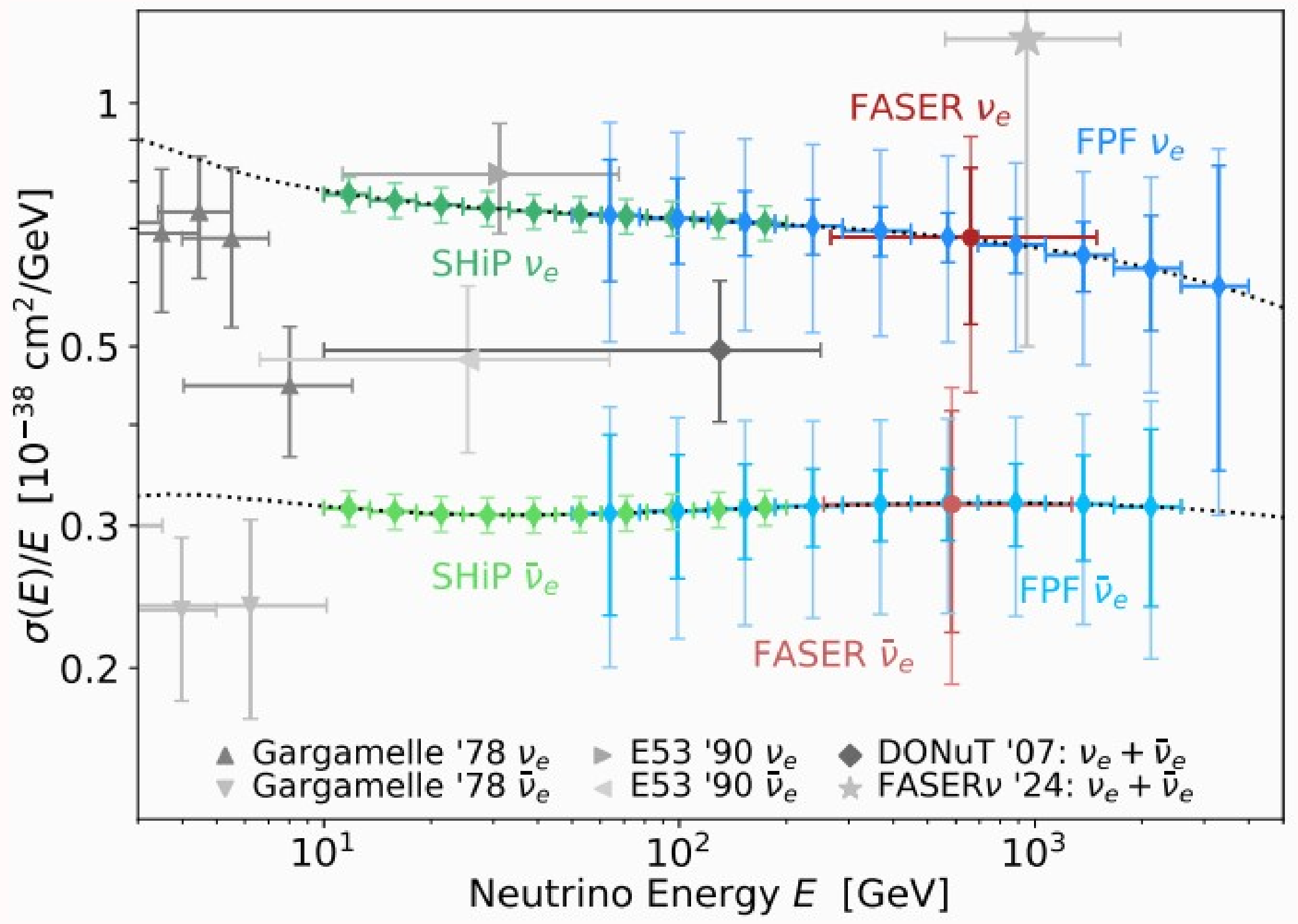
Difference $\bar{\nu}_e$ – ν_e = good proxy for Λ_0 number

- FASER can measure this with the proposed auxiliary detector!
- FASER2 @ FPF: potential for differential measurements



Enables first separate ν_e & $\bar{\nu}_e$ cross section measurements at LHC energies

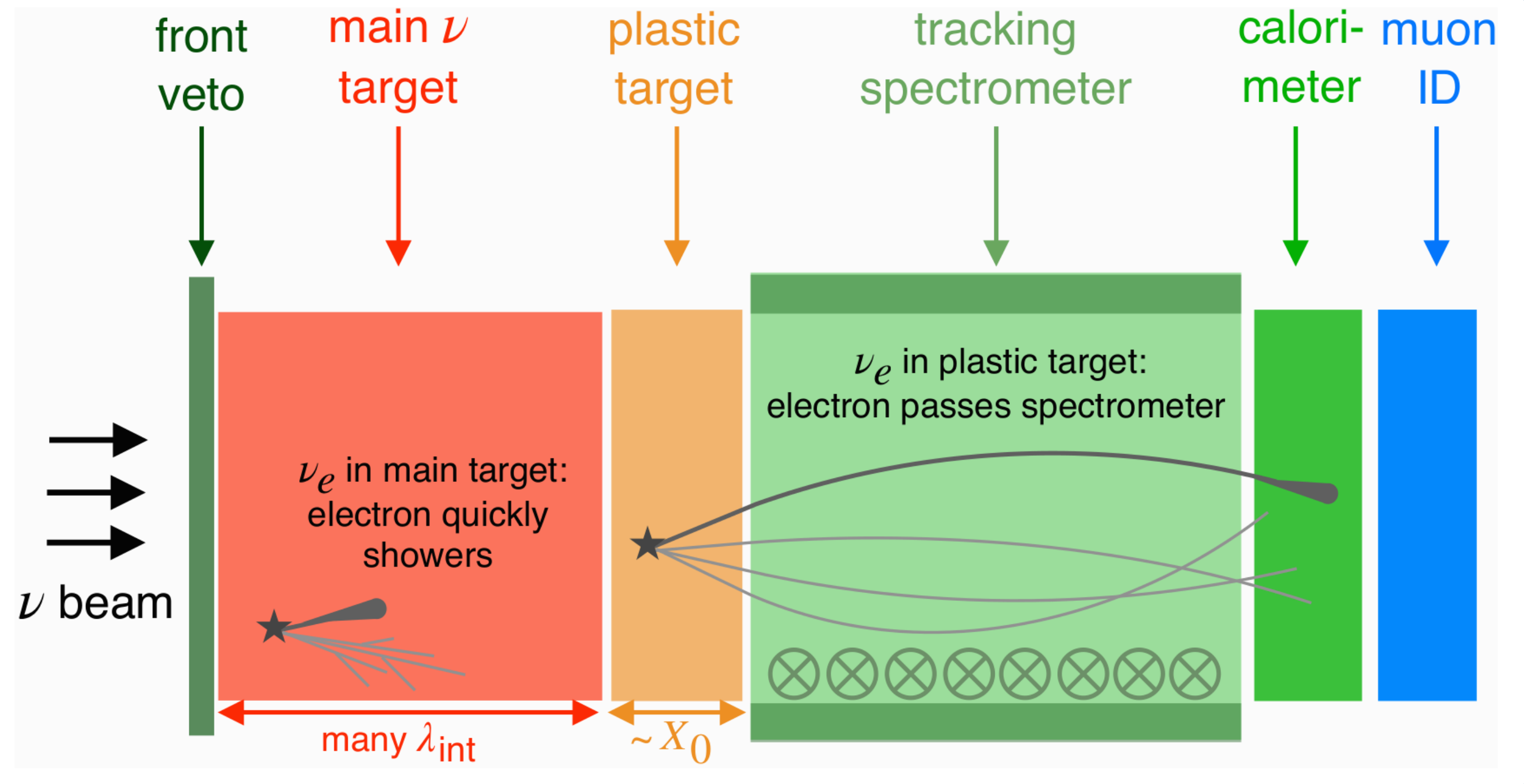
	main detector		plastic target		
	mass	$\nu_e + \bar{\nu}_e$	mass	ν_e	$\bar{\nu}_e$
FASER	1.2 ton	4.9k	6.5 kg	21	11
FPF	20 ton	210k	600 kg	1120	525



The proposed detector

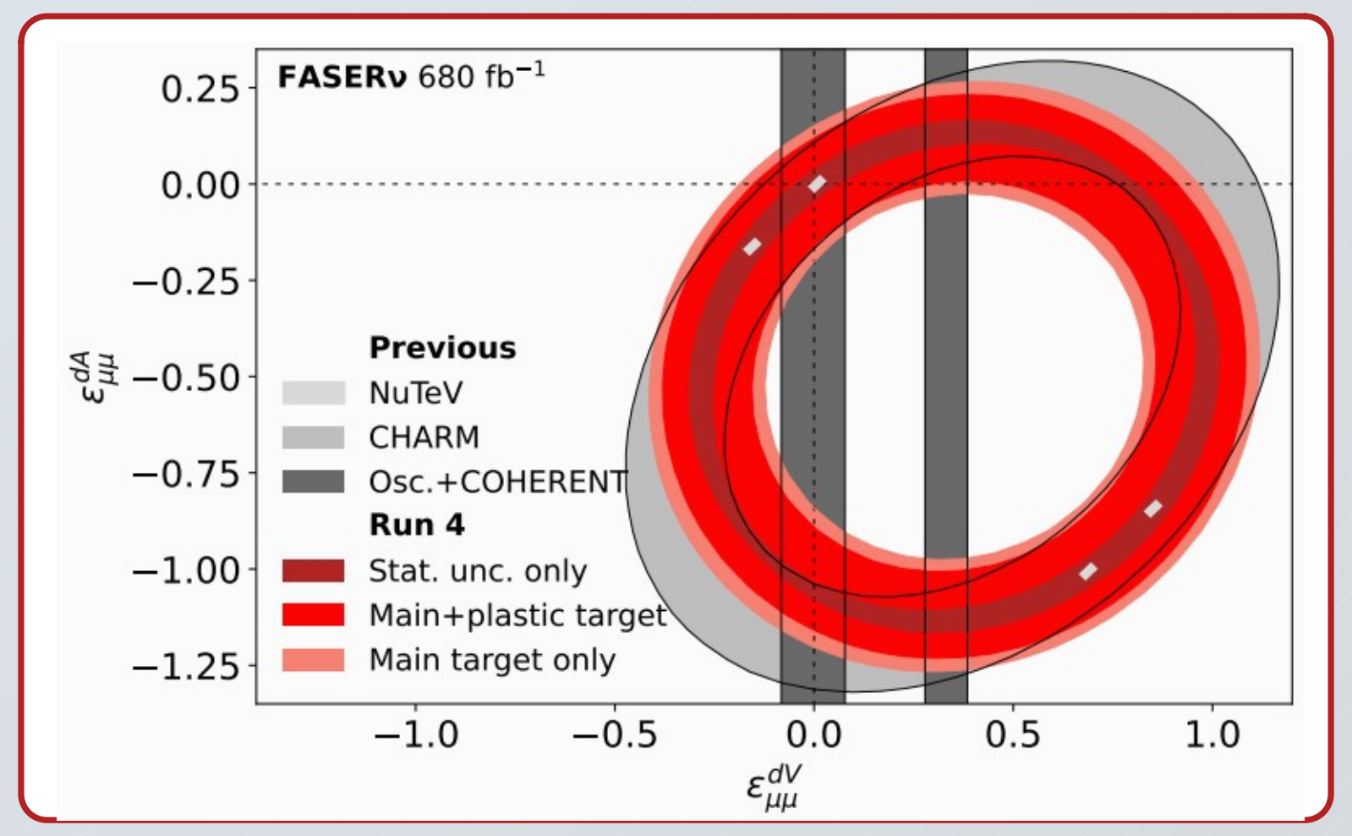
Prototype @ FASER!

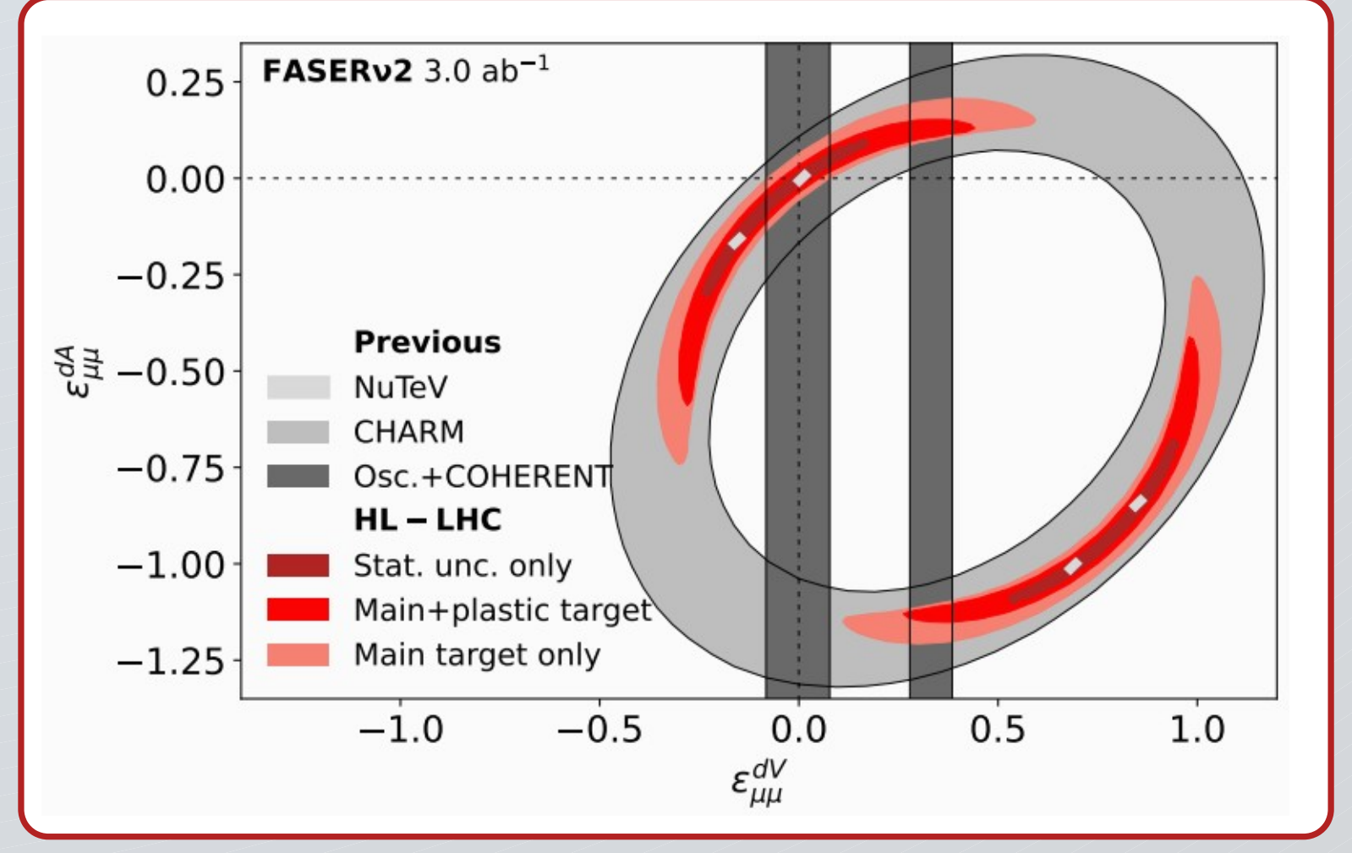
- Existing detectors: excellent ν_μ, $\bar{\nu}_\mu$ identification in CCDIS
- Distinguishing ν_e, $\bar{\nu}_e$ nearly impossible
  - Electrons/positrons shower quickly, not reaching spectrometer
  - Exception: interactions in last radiation length X_0
- Interaction rate proportional to $\rho X_0[1-\exp(-L/X_0)]$
  - Use low-Z materials: graphite / plastic
  - Sufficiently small thickness vs radiation length for electrons to escape
- 20 cm thick plastic scintillator target
- Transverse area equal to spectrometer aperture
- Can be installed at FASER or Forward Physics Facility (FPF)

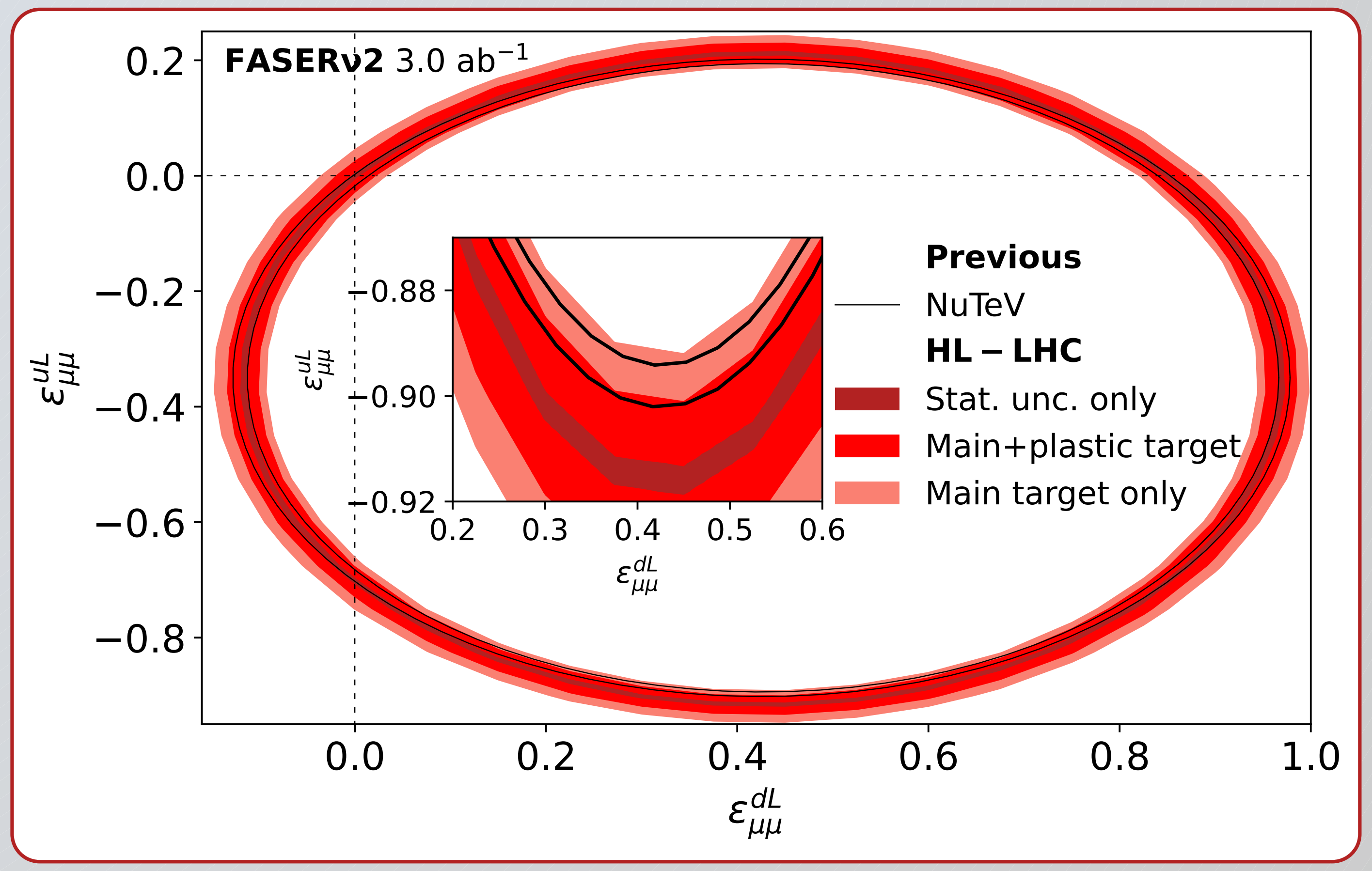


Constraining Non-Standard Interactions (NSI)

- Uncertainty in $\bar{\nu}_e$+ν_e flux important systematic for NC interactions
- NSI modifies NC spectrum vs CC expectation
  - **Without the detector**: unconstrained $\bar{\nu}_e$+ν_e could be all K_0 or all Λ_0
    - Two extremal spectrum shapes
    - Normalize by well-constrained $\bar{\nu}_e$+ν_e CC rate
  - **With the detector**: lower/upper uncertainties for the number of Λ_0
    - Decreased uncertainty envelope
- Stringent constraints from NuTeV
  - u and d quark coefficients varied simultaneously, left- and right-handed coefficients
  - FASER / FPF bounds on vector vs axial-vector couplings, translate to NuTeV variables
- FPF complements the NuTeV result, if proposed detector included
  - Mild shape differences of the elliptical constraint bands
  - Benefits from differences in target neutron and proton numbers

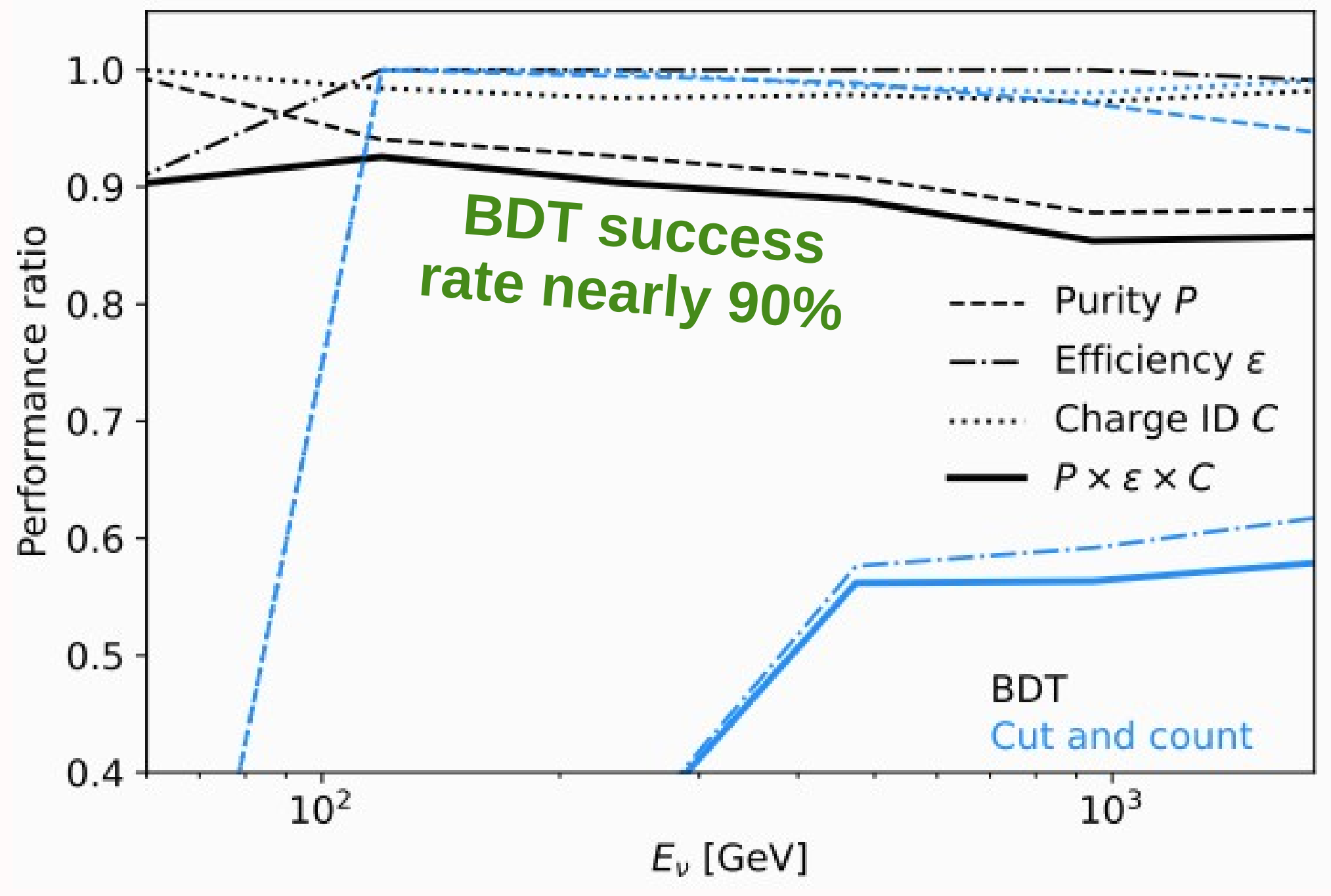






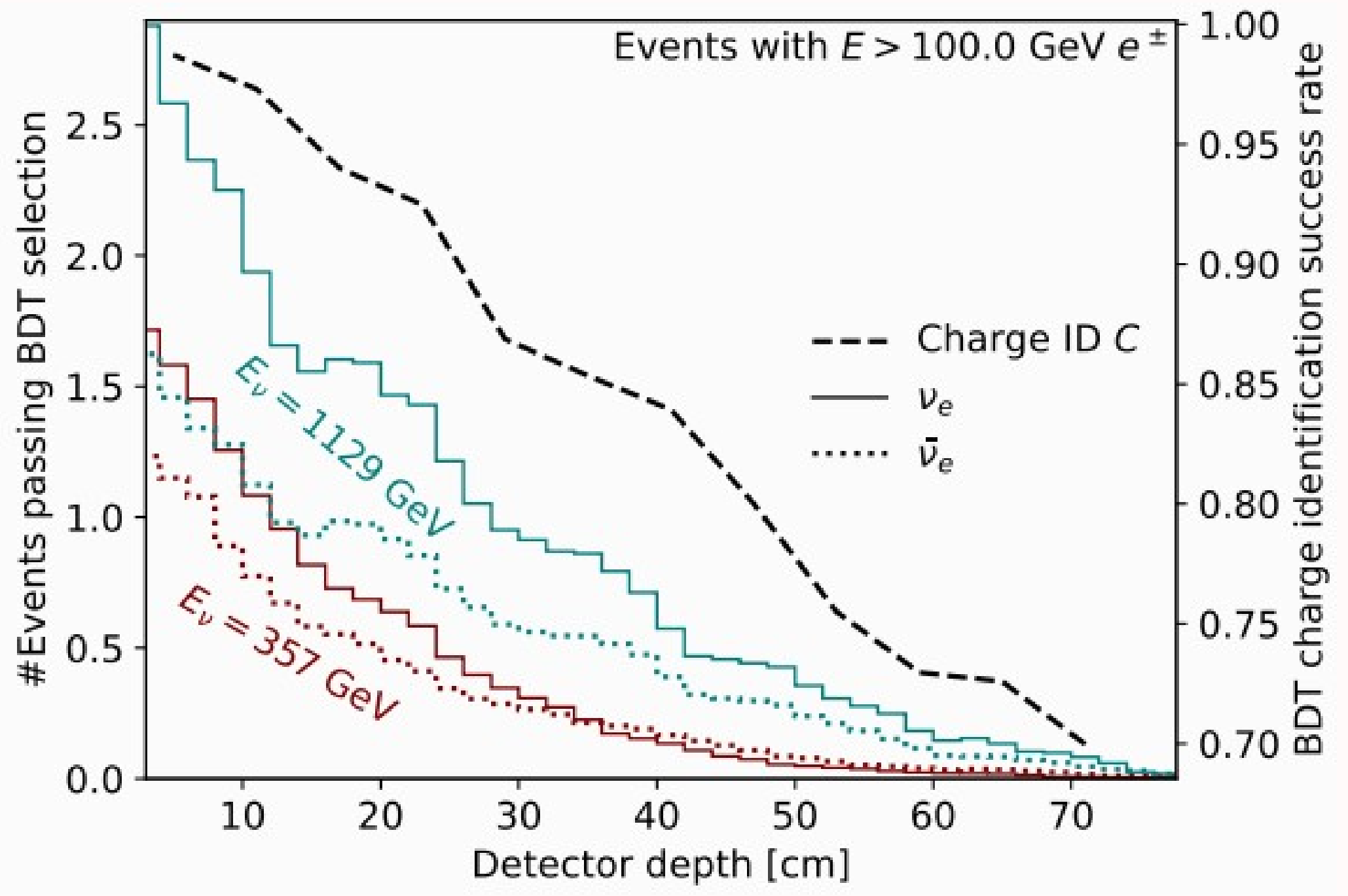
Signal identification with machine learning

- NC or μ neutrino CC events produce similar signatures
- Electrons undergo showering and radiate photons pair producing further electrons
  - The leading lepton may not be the original one, and possibly have different sign
- Simple cut-and-count analysis on simulated events already shows good preservation of signal events, while removing most backgrounds



Improve performance with boosted decision tree (BDT)

Cut	ν_eCC	$\overline{\nu}_e$CC	ν_μCC	NC
No cuts	1120	525	8298	243
$E_\mu < 20$ GeV	1111	520	34	235
$E_{\text{EM}}/E_{\text{Tot}} > 40\%$	984	490	22	144
$E_{e^\pm}/E_{\text{EM}} > 25\%$	856	434	15	73
$E_{e^\pm} > 100$ GeV	612	332	1	19
BDT	1075	515	13	112



- Additional features vs cut-and-count:
  - Vertex position
  - Energy charged tracks
  - Total charge of E > 100 GeV electrons
  - Leading lepton angle vs z-axis
  - Standard deviation & maximum of the angles of all EM tracks vs leading lepton, characterizing EM shower spread
- Estimate E_ν resolution via regression BDT
  - Train to reconstruct incoming E_ν in electron (anti-)neutrino CC events
  - Relative standard error $\delta E_\nu / E_\nu < 30\%$

Depth optimization

- Deeper detectors increase statistics, but performance decreases
- Diminishing returns for depths > 50 cm

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