Anti-Electron Neutrinos

Identification Strategies and Physics Potential

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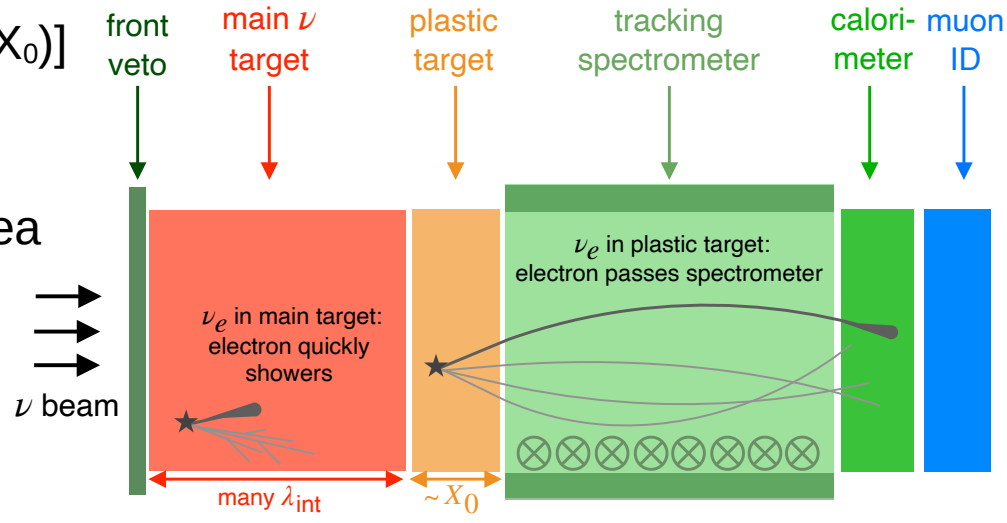
The detector concept

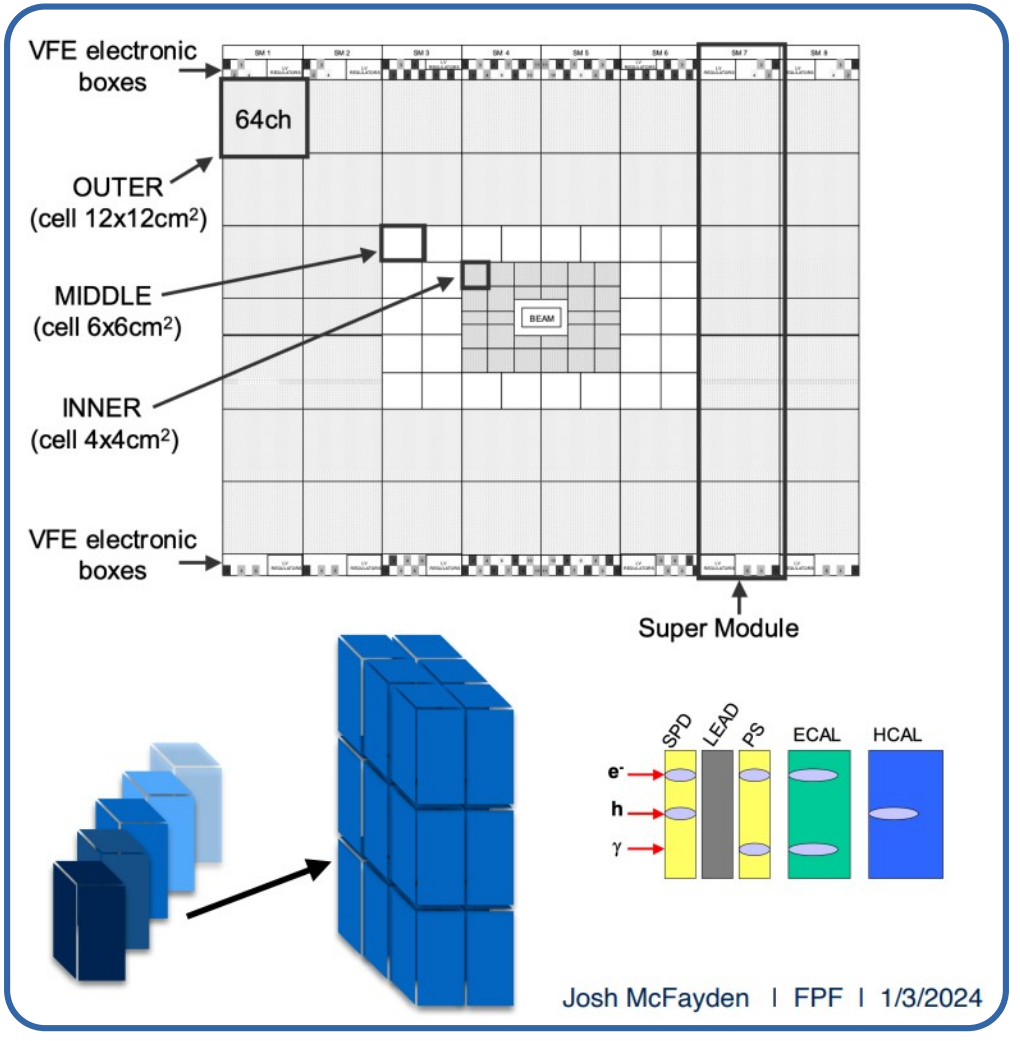
- Existing detectors & ideas have excellent ν_μ, $\bar{\nu}_\mu$ identification in CCDIS events
- Distinguishing ν_e, $\bar{\nu}_e$ nearly impossible, $e^{+/-}$ never makes it to spectrometer
  - Except for interactions in the last radiation length
- Interaction rate proportional to $\rho X_0[1-\exp(-L/X_0)]$
- Use low-Z materials, e.g. graphite / plastic
- Consider a 20 cm thick target, transverse area corresponding to spectrometer aperture

	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



Possible implementations

- Need high enough density to achieve significant number of ν_e interactions
- Small enough thickness vs radiation length for $e^{+/-}$ to escape
- E.g. polyvinyltoluene:
  X_0 = 42.5 cm > proposed 20 cm
- Old LHCb SPD/Preshower detector considered previously. Could rearrange for FASER(2) dimensions, see
  Josh McFayden's slides at FPF7
- Another possibility: FASERCal technology (currently tested), see
  Charlotte Cavanagh's slides at FPF8



Prototype

- Instead of plastic (X_0=40 cm) could use graphite (X_0=20 cm)
- FASER lead shield replaced by a 10 cm graphite block, allowing the proposed detector to be prototyped

Thanks to Jamie Boyd!

Signal identification

- NC or muon neutrino CC events may produce $e^{+/-}$, resembling the signal
- The $e^{+/-}$ undergo showering, radiating photons that pair produce further $e^{+/-}$
  - The leading $e^{+/-}$ may not be the original one, and possibly have different sign
- Simple cut-and-count analysis on P8 generated ν_eCC, ν_μCC and NC events illustrates good preservation of signal events with cuts removing most bg events

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

E_μ = leading muon energy

E_e = leading $e^{+/-}$ energy

E_{EM} = EM energy ($e^{+/-}$ + photons)

E_{Tot} = energy of all visible particles

Signal identification

- NC or muon neutrino CC events may produce $e^{+/-}$, resembling the signal
- The $e^{+/-}$ undergo showering, radiating photons that pair produce further $e^{+/-}$
  - The leading $e^{+/-}$ may not be the original one, and possibly not the best signal
- Simple cut and count analysis on ν_e generated νCC, $\bar{\nu}_e$ CC and NC events indicates good preservation of signal events with cuts removing most bg events
- **A Boosted Decision Tree (BDT) achieves a nearly 90% success rate**

Performance metrics:

- **Purity** = signal/(signal+bg) ratio in events passing cuts
- **Efficiency** = signal after / before cuts
- **Charge ID** = ratio of correctly labeled e^+, e^- vs all signal events passing cuts

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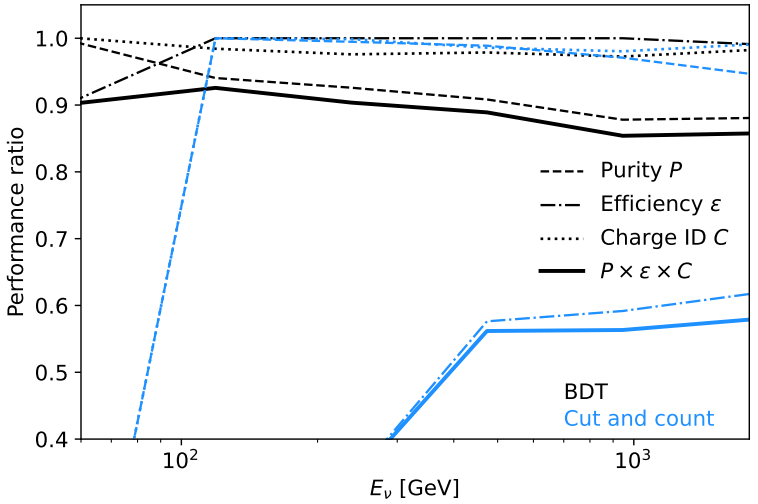
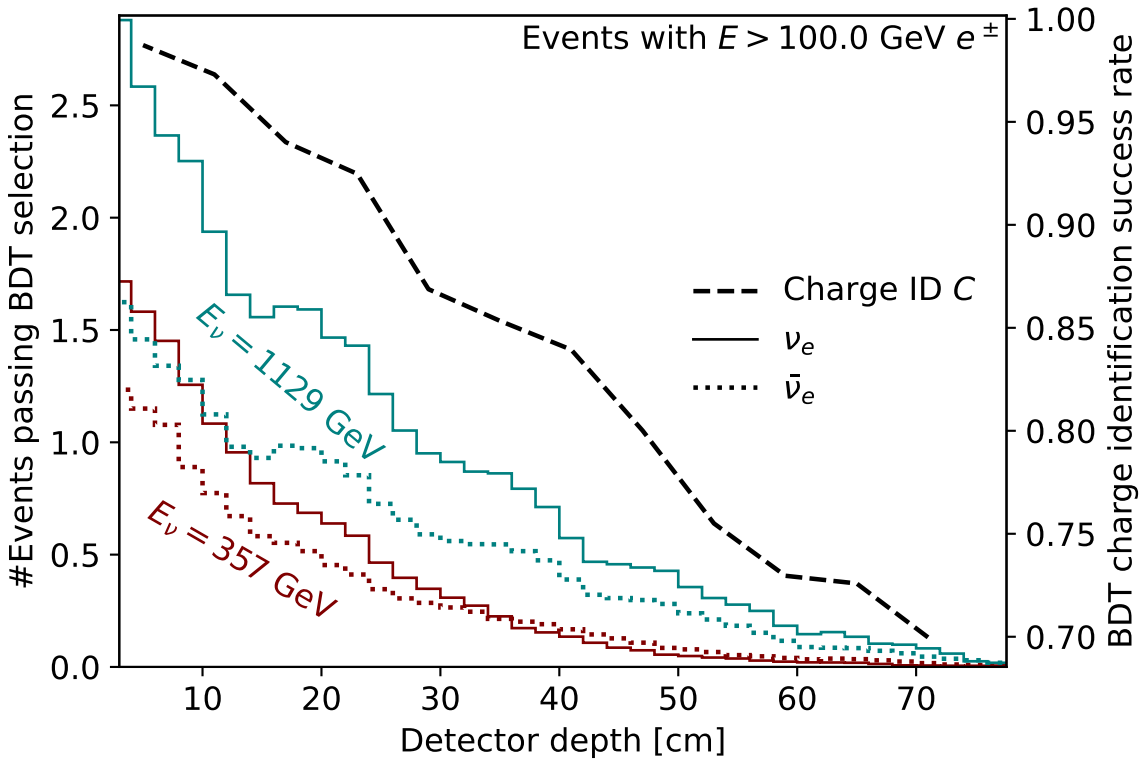
BDT	1075	515	13	112



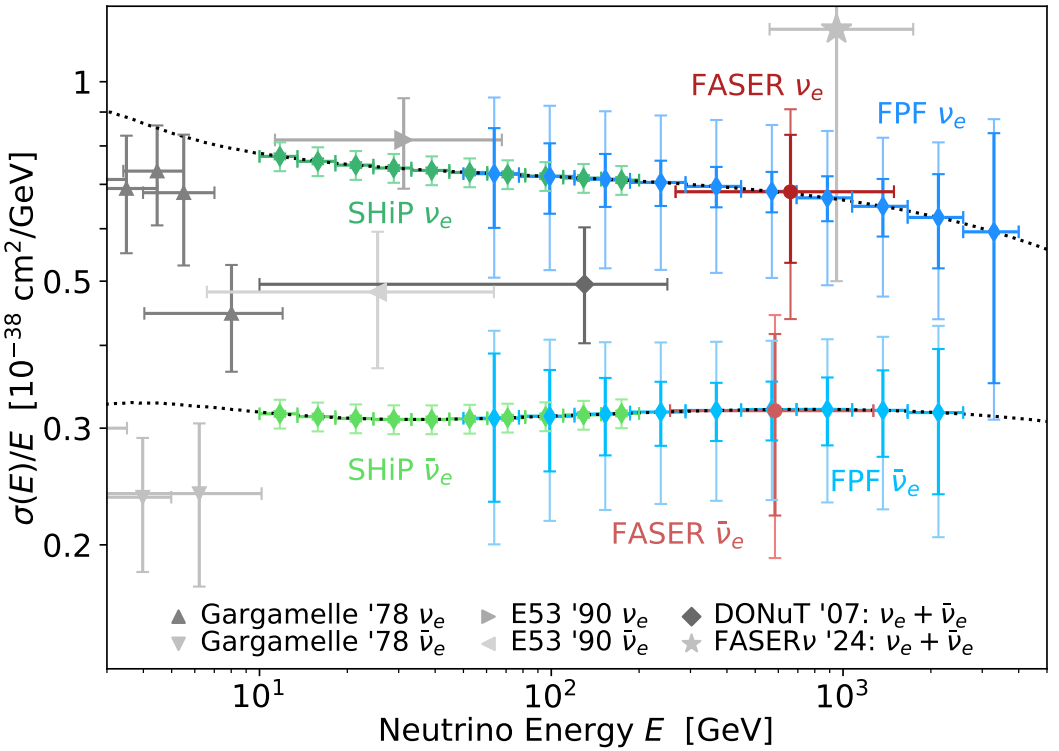
Detector depth optimization

- Space at FASER limited, but could consider deeper detector at FPF
- At different vertex positions z, check:
  - *Left axis*: #events passing BDT selection
  - *Right axis*: associated CID success rate
- Deeper detectors increase statistics, but performance decreases with larger z
- Depths > 50 cm bring diminishing returns



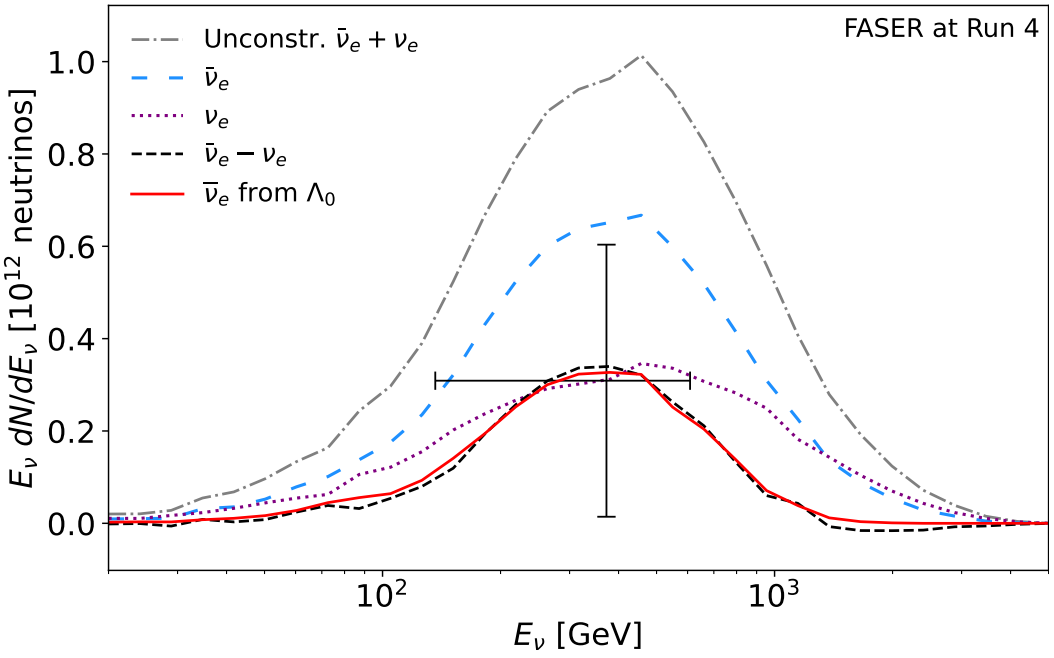
Cross sections

- Possibility for separate ν_e and $\bar{\nu}_e$ CC x-sec measurements, although total #events much below main FASERν
- Previously, only:
  - separate measurements at low E (Gargamelle and E53)
  - Combined measurements at high E (DONuT and FASER)
- Inner error bars: stat unc,
  outer: estimated flux uncertainties
- Dotted: GENIE / Bodek-Yang model



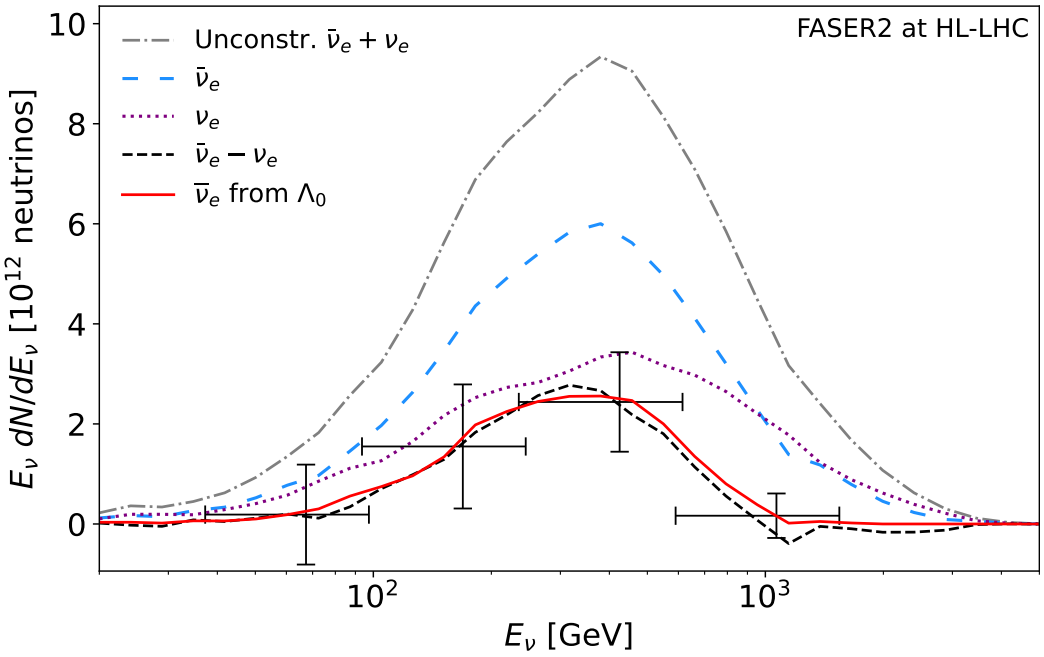
Constraining hyperons
FASERν

- Determine forward hadron distributions to constrain neutrino flux
- Hyperons: understand forward strangeness
  - Connection to astrophysics / CR
- K_0 decays equally to $\bar{\nu}_e/\nu_e$, but Λ_0 only to $\bar{\nu}_e$
- No significant $\bar{\Lambda}_0$ contribution
- The difference $\bar{\nu}_e - \nu_e$ is a good proxy for the number of Λ_0, which FASER can measure with the added detector



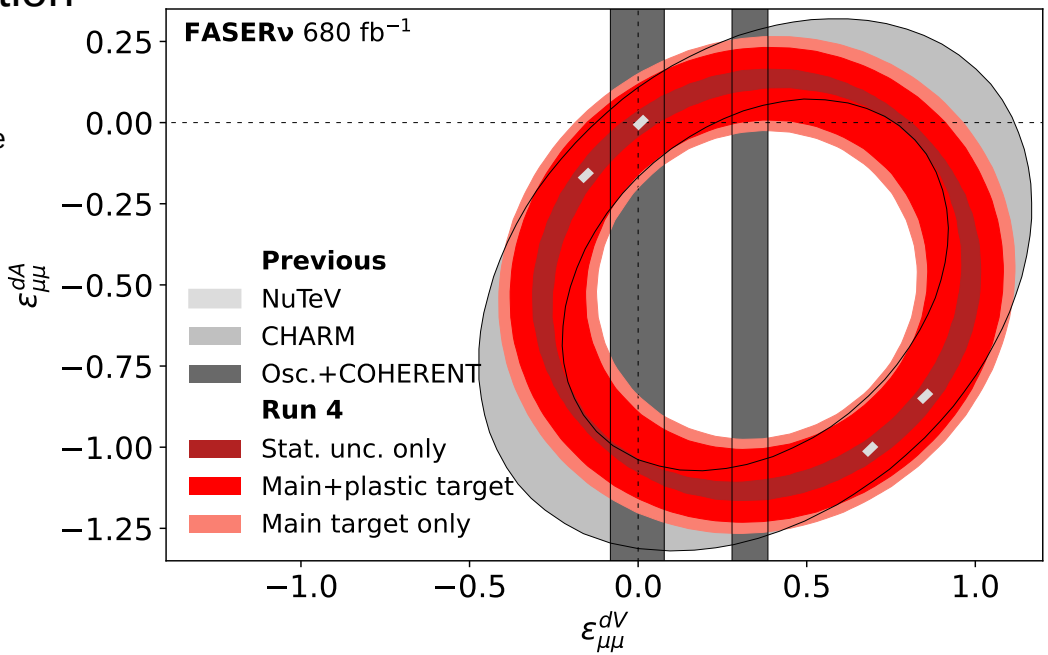
Constraining hyperons
FASERν2

- Determine forward hadron distributions to constrain neutrino flux
- Hyperons: understand forward strangeness
  - Connection to astrophysics / CR
- K_0 decays equally to $\bar{\nu}_e/\nu_e$, but Λ_0 only to $\bar{\nu}_e$
- No significant $\bar{\Lambda}_0$ contribution
- The difference $\bar{\nu}_e - \nu_e$ is a good proxy for the number of Λ_0, which FASER can measure with the added detector
- FASER2 has potential for differential measurements



Non-Standard Interactions

- Uncertainty in $\bar{\nu}_e+\nu_e$ flux important systematic for NC interactions
- Example: constrain NSI with or without the Plastic Scintillator (PS)
- NSI modifies NC spectrum vs CC expectation
  (Subject to flux uncertainties)
  - **Without PS**: unconstrained part of $\bar{\nu}_e+\nu_e$ could be all K_0 or all Λ_0
    - Two extremal spectrum shapes, normalization s.t. well-constrained $\bar{\nu}_e+\nu_e$ CC rate reproduced
  - **With PS**: assume lower/upper uncertainties for the number of Λ_0
    - Decreased uncertainty envelope



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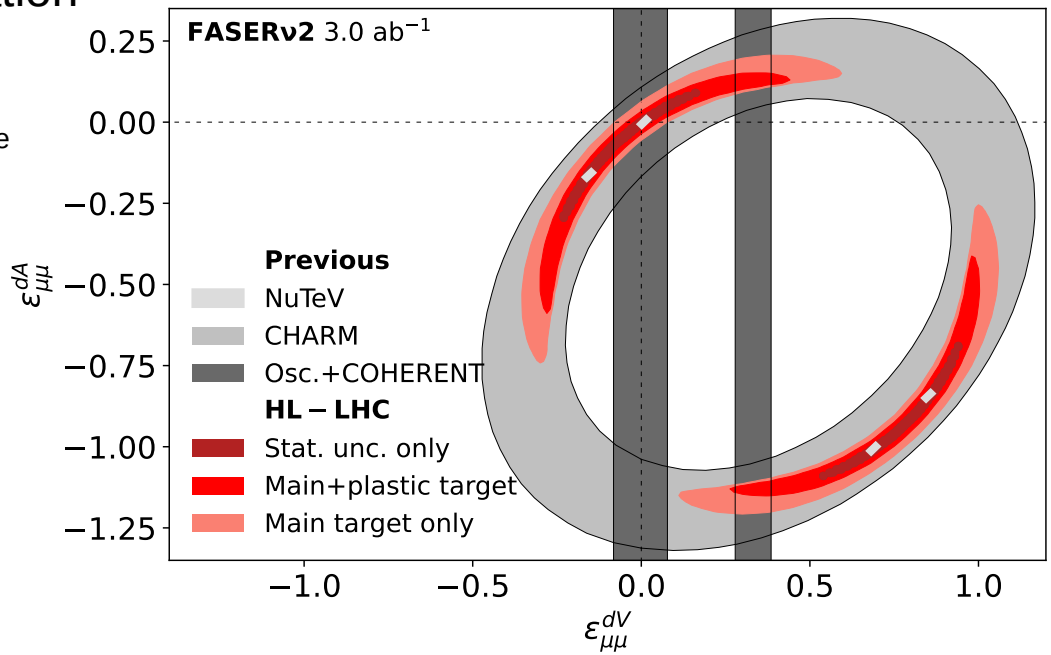
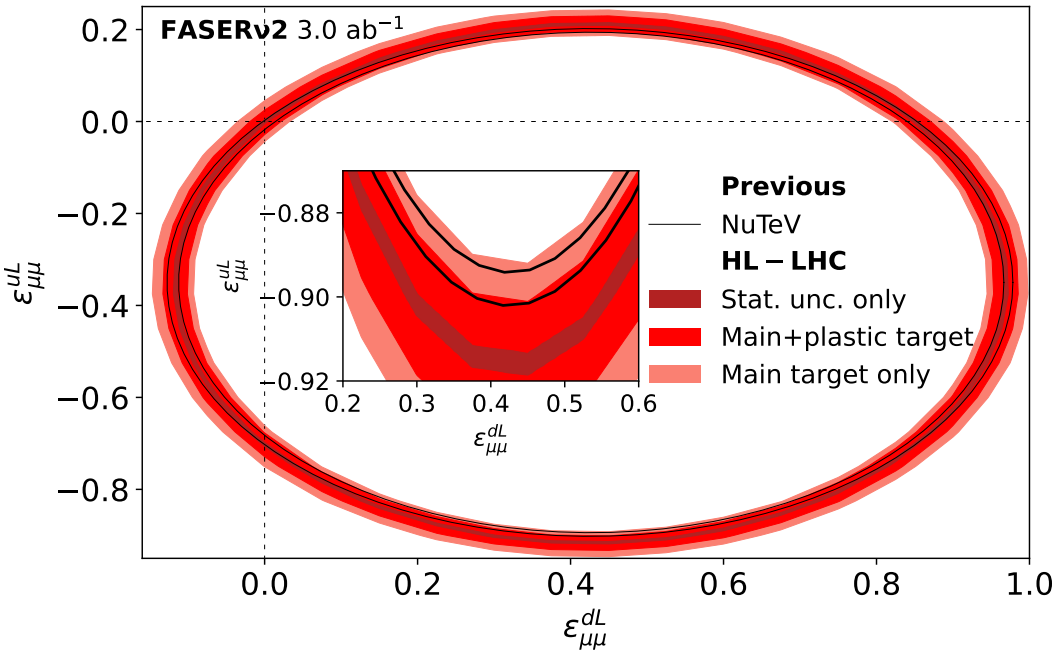
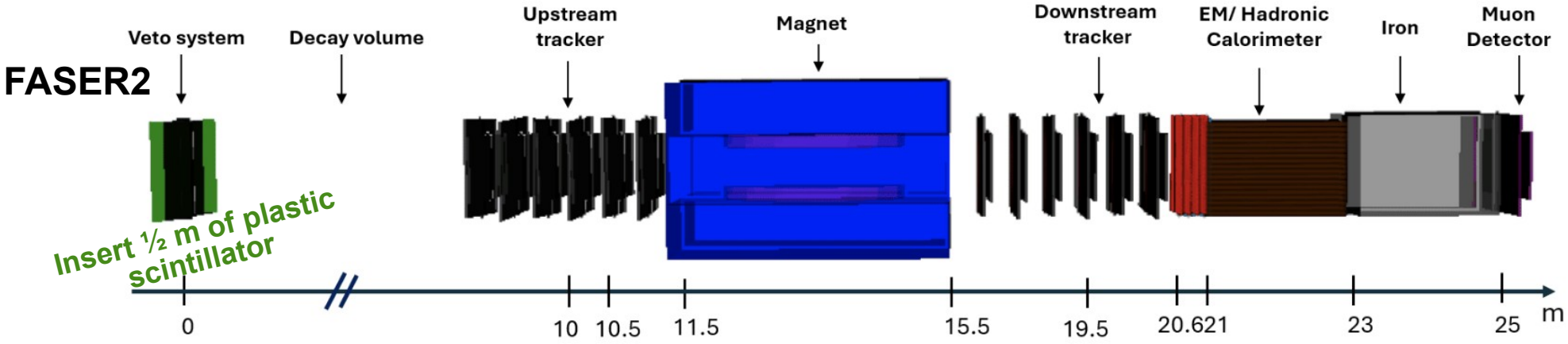


Non-Standard Interactions

- Stringent NuTeV constraints originally given in terms of left- and right-handed coefficients
  - u and d quark coefficients varied simultaneously
- Translate FPF bounds to $\epsilon^{dL}_{\mu\mu}$, $\epsilon^{uL}_{\mu\mu}$
- FPF complements the NuTeV result, if proposed detector included
  - Mild shape differences of the elliptical constraint bands
  - Caused by differences in numbers of neutrons and protons in target



Summary and outlook



- Proposed A simple and cost-effective detector for FASER(2)
- Separate ν_e, $\bar{\nu}_e$ measurements allow constraining hyperons
  - Reduces uncertainty in $\nu_e+\bar{\nu}_e$ flux and NC interaction spectrum
- Potential for a differential measurement of hyperon contribution at FASER2
- Enhanced physics potential illustrated here for NSI in NC interactions

Thanks for your attention!

Backup: EM shower simulation

- Photons & $e^{+/-}$ in P8 sample subjected to showering
- Photons pair produce e^+e^- [PRD 110 (2024) no. 3, 030001]
- Bremsstrahlung: $e^{+/-}$ radiate photons [Rev.Mod.Phys. 71 (1999) 1501-1538, PRD 25 (1982) 1291-1304]
  - Account for Landau-Migdal-Pomeranchuk effect
    - Avoid x=0 singularity in Bremsstrahlung [Dokl.Akad.Nauk SSSR 92 (1953), Dokl.Akad.Nauk.Ser. Fiz. 92 (1953) 735-738, Phys. Rev. 103 (1956) 1811–1820]
- EM shower procession through detector inspired by PENELOPE 2018 code
- Mean Free Path (MFP) λ for a particle of energy E, interaction cross section dσ/dx, from

$$\lambda^{-1}(E) = \frac{1}{X_0}\int_0^1 \frac{d\sigma(E)}{dx}dx$$

  - Pair production: $\lambda = 9/7\ X_0$ as expected
  - Bremsstrahlung: significantly below X_0 => determines length scale for sampling longitudinal step size (exp. distributed)

Backup: BDT analysis details

- Boosted Decision Tree implemented in scikit-learn
- Additional features vs cut-and-count analysis
  - Vertex position (achievable in longitudinally segmented target)
  - Energy of all charged tracks E_{Ch}
  - Total charge of $e^{+/-}$ with energies above 100 GeV
  - Leading $e^{+/-}$ angle w.r.t. line of sight
  - Std.dev. & max. of the angles of all EM tracks vs leading e+/- (characterizes EM shower spread)
- E_ν resolution estimated via regression BDT analysis
  - Features: same observables as BDT analysis above
  - Train BDT to reconstruct incoming E_ν in events classified as ν_eCC or $\bar{\nu}_e$CC
  - Linear dependence between reconstructed / true Eν observed
  - Relative standard error $\delta E_\nu / E_\nu < 30\%$ for reconstruction