

# Constraining Hyperons and Non-Standard Interactions with Anti-Electron Neutrinos

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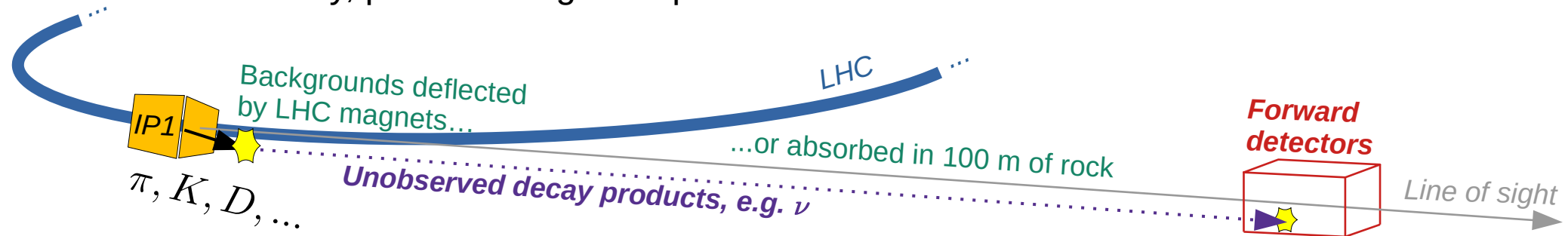
Pittsburgh

May 11 – 13, 2026

**UC Irvine**

# Forward neutrinos and LLPs at the LHC

- The  $pp$  collisions at the LHC produce a myriad of hadrons, decaying weakly 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



- LHC neutrinos first observed by **FASER** and **SND@LHC**!  
**Phys.Rev.Lett. 131 (2023) 3, 3**      **Phys.Rev.Lett. 131 (2023) 3, 031802**
- Collected data since 2022, now preparing for LHC Run 4

# Understanding LHC $\nu$ = Understanding QCD

- Neutrinos at the LHC result from decays of forward hadrons
  - Dominantly  $\pi^{+/-}$  ( $\nu_\mu, \bar{\nu}_\mu$ ),  $K^{+/-}$  ( $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$ ),  $D$  ( $\nu_\tau, \bar{\nu}_\tau, \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$ )
- $\Lambda_0$  **hyperons** could be the next most important; no significant  $\bar{\Lambda}_0$  contribution
- Problem: undetermined remainder of  $\nu_e + \bar{\nu}_e$  could be a mixture of  $K^0$  and  $\Lambda_0$ 
  - Resolving this will help understand forward strangeness, important for cosmic rays

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

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

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

$\downarrow$   
 $\pi^- + e^+ + \nu_e$

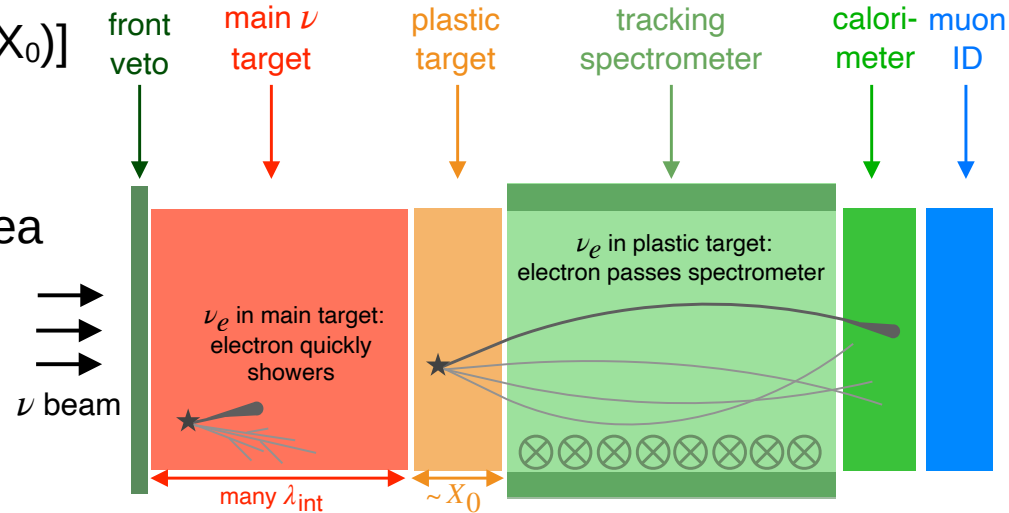
Decays equally to  $\bar{\nu}_e/\nu_e$

- The difference  $\bar{\nu}_e - \nu_e$  is a good proxy for the number of  $\Lambda_0$ 
  - FASER could measure this with a suitable auxiliary detector!

# The detector concept

- Existing detectors & ideas have excellent  $\nu_\mu, \bar{\nu}_\mu$  identification in CCDIS events
- Distinguishing  $\nu_e, \bar{\nu}_e$  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	$\nu_e$	$\bar{\nu}_e$
FASTER	1.2 ton	4.9k	6.5 kg	21	11
FPF	20 ton	210k	600 kg	1120	525



# Prototype

- Need small enough thickness vs radiation length for  $e^{\pm}$  to escape
- Instead of plastic ( $X_0=40$  cm) could use graphite ( $X_0=20$  cm)
- FASER has now replaced a lead shield with a 10 cm graphite block, allowing the proposed detector to be prototyped
- Further possible technologies under development / testing



Figure from J. Boyd, FASER

# 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  $\nu_e$ CC,  $\nu_\mu$ CC and NC events illustrates good preservation of signal events with cuts removing most bg events

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

$E_\mu$  = leading muon energy

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

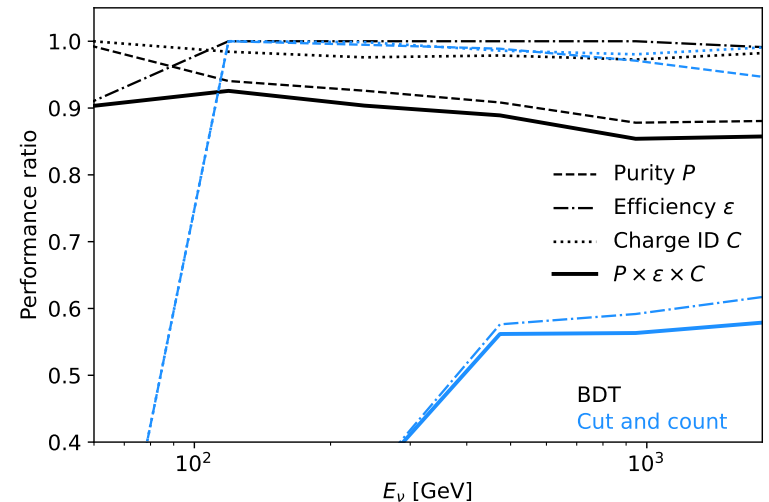
$E_{EM}$  = EM energy ( $e^{+/-}$  + photons)

$E_{Tot}$  = energy of all visible particles

# Signal identification

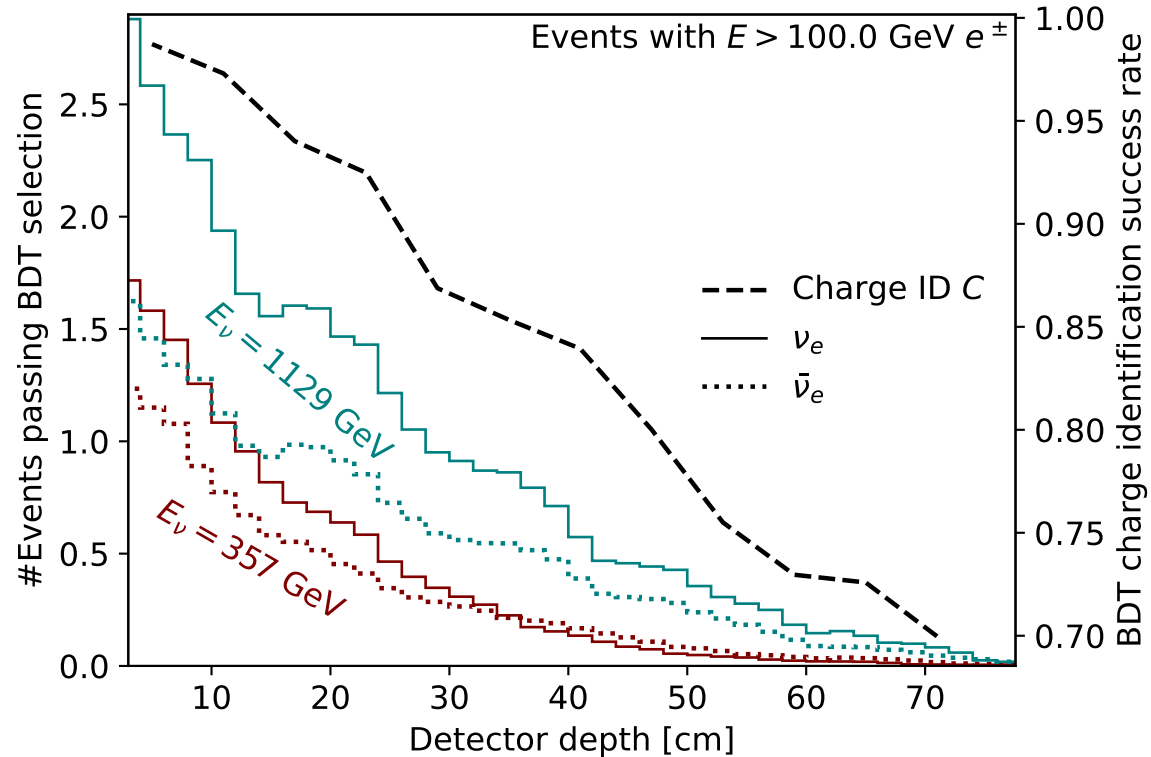
- NC or muon neutrino CC events may produce  $e^{+/-}$ , resembling the signal
- Performance metrics:
  - **Purity** = signal/(signal+bg) ratio in events passing cuts
  - **Efficiency** = signal after / before cuts
  - **Charge ID** = ratio of correctly labeled  $e^+$ ,  $e^-$  vs all signal events passing cuts
- The  $e^{+/-}$  undergo showering, radiating photons that pair produce  $e^+e^-$ 
  - The leading  $e^{+/-}$  may not be the original one, an  $e^+e^-$  pair may be produced
- Simple  $\nu_e$  CC,  $\nu_\mu$  CC,  $\nu_\tau$  CC and  $\bar{\nu}_e$  CC are easily identified by preservation of signal events with cuts removing most bg events
- **A Boosted Decision Tree (BDT) achieves a nearly 90% success rate**

Cut	$\nu_e$ CC	$\bar{\nu}_e$ CC	$\nu_\mu$ CC	NC
No cuts	1120	525	8298	243
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BDT	1075	515	13	112



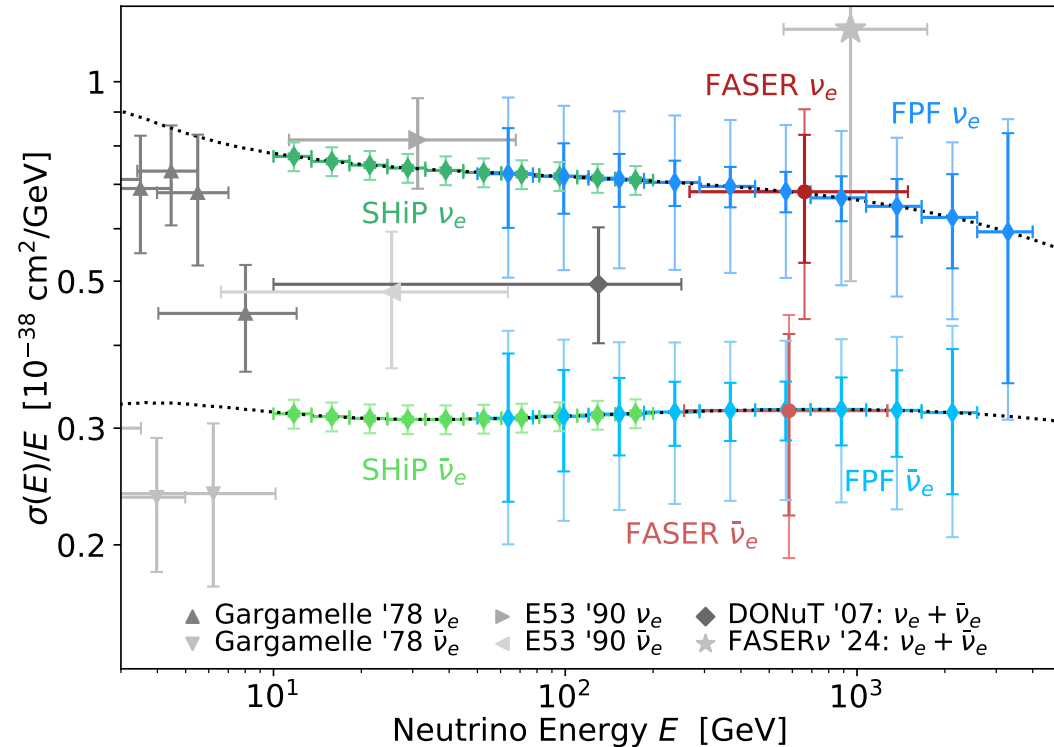
# Detector depth optimization

- 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

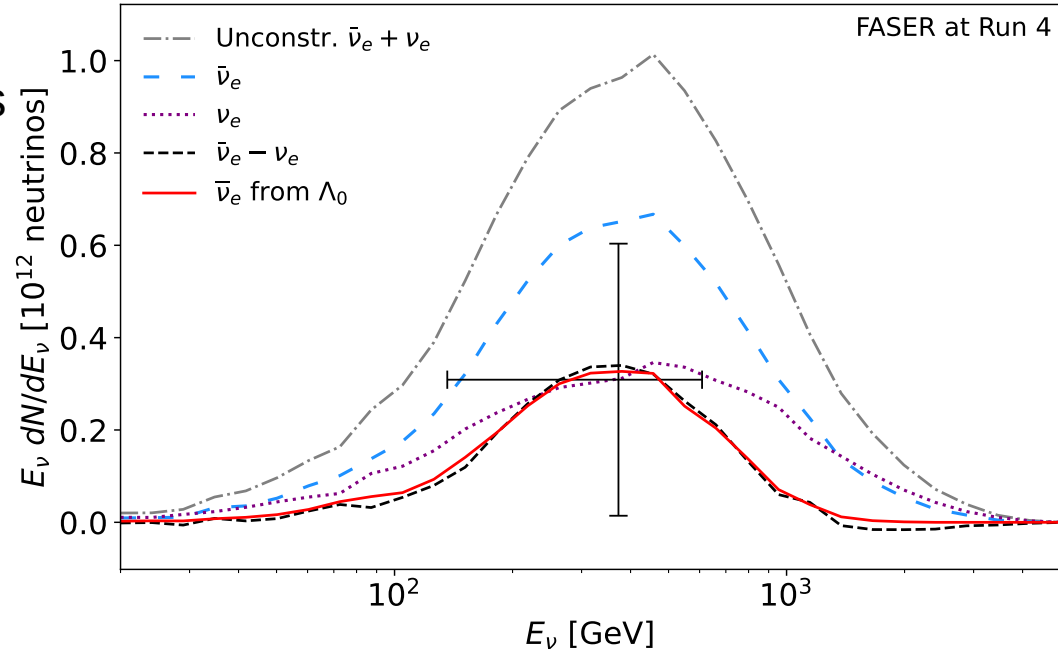
- Possibility for separate  $\nu_e$  and  $\bar{\nu}_e$  CC x-sec measurements, although total #events much below main FASER $\nu$
- Previously, only:
  - separate measurements at low E (Gargamelle and E53)
  - Combined measurements at high E (DONuT and FASER)
- Inner error bars: stat unc, outer: estimated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



# Constraining hyperons

## FASER $\nu$

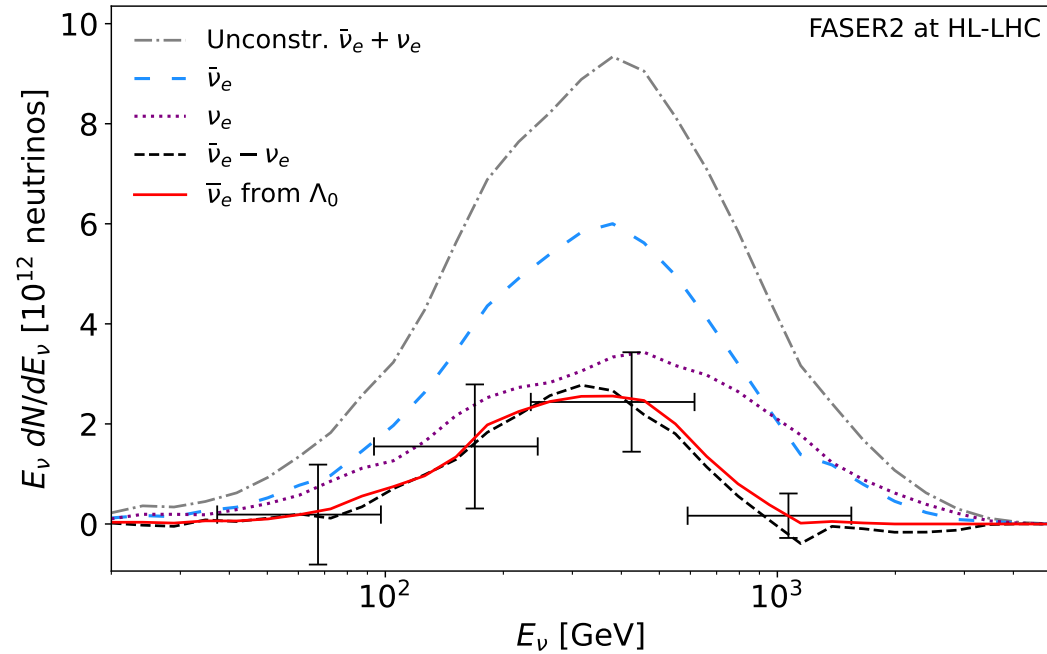
- Determine forward hadron distributions to constrain neutrino flux
- Hyperons: understand forward strangeness
  - Connection to astrophysics / CR
- $K_0$  decays equally to  $\bar{\nu}_e/\nu_e$ , but  $\Lambda_0$  only to  $\bar{\nu}_e$
- No significant  $\bar{\Lambda}_0$  contribution
- The difference  $\bar{\nu}_e - \nu_e$  is a good proxy for the number of  $\Lambda_0$ , which FASER can measure with the added detector



# Constraining hyperons

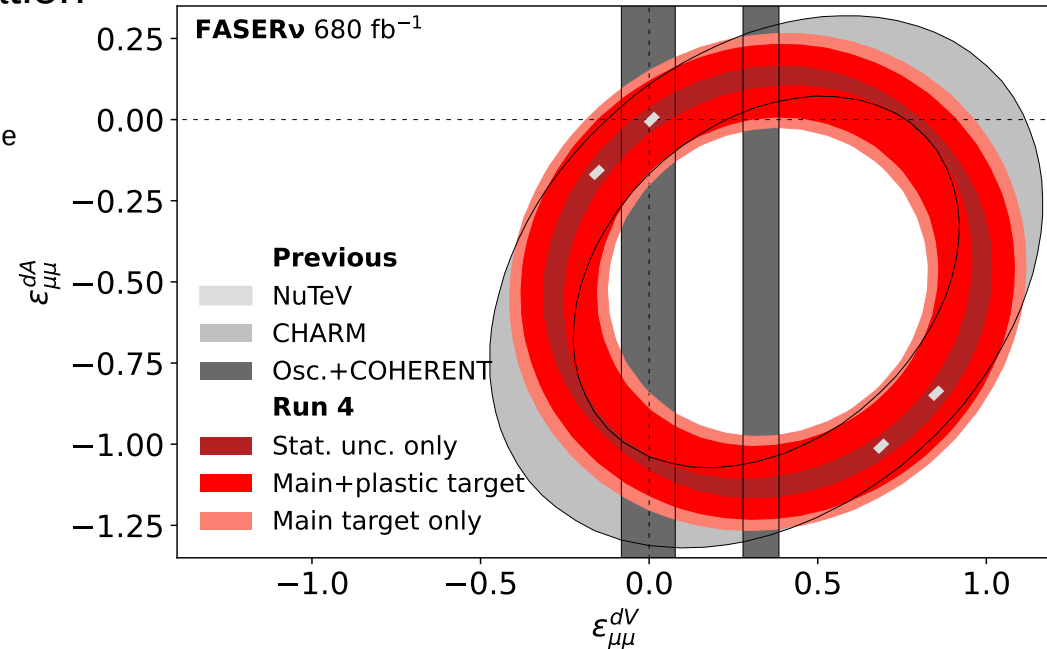
## FASERv2

- 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  $\Lambda_0$  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  $\Lambda_0$ , which FASER can measure with the added detector
- FASER2 has potential for differential measurements



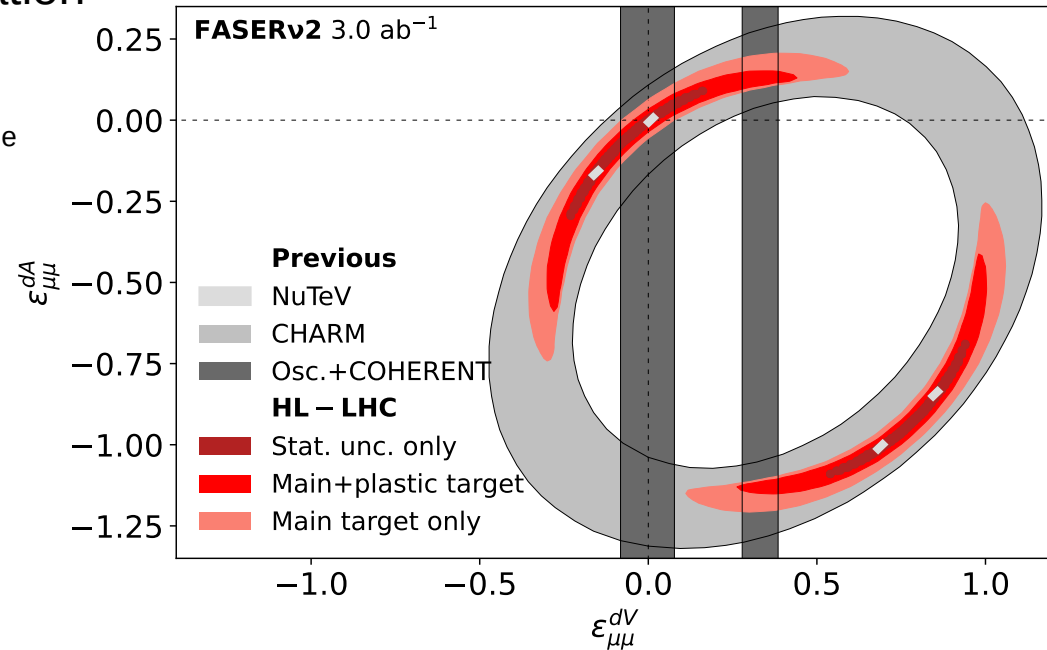
# Non-Standard Interactions

- 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  $\Lambda_0$ 
  - 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  $\Lambda_0$ 
  - Decreased uncertainty envelope



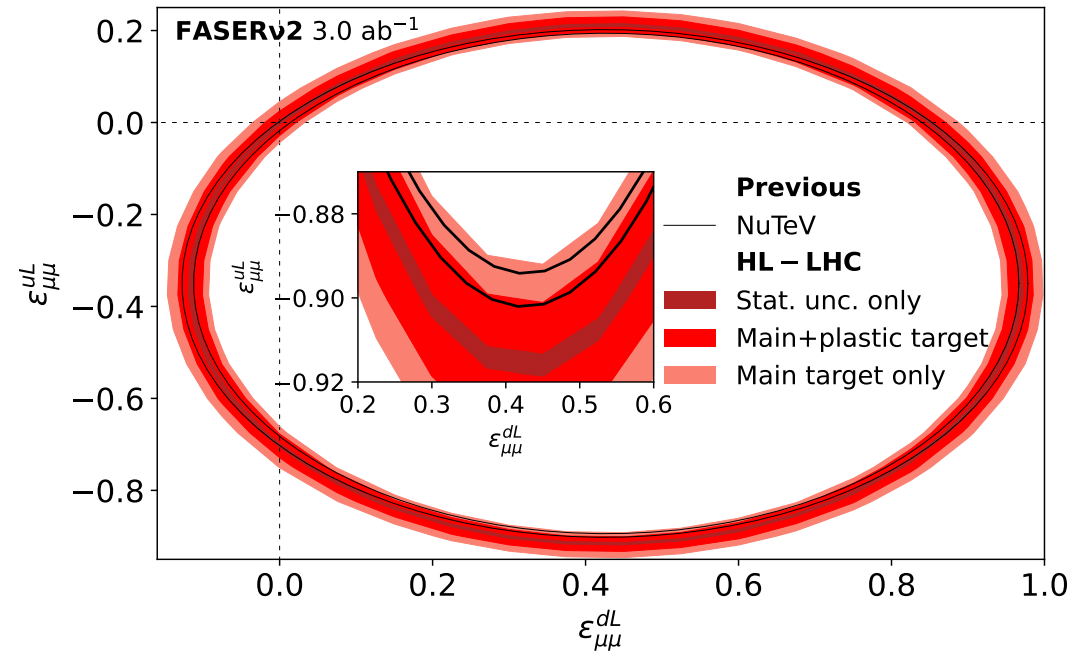
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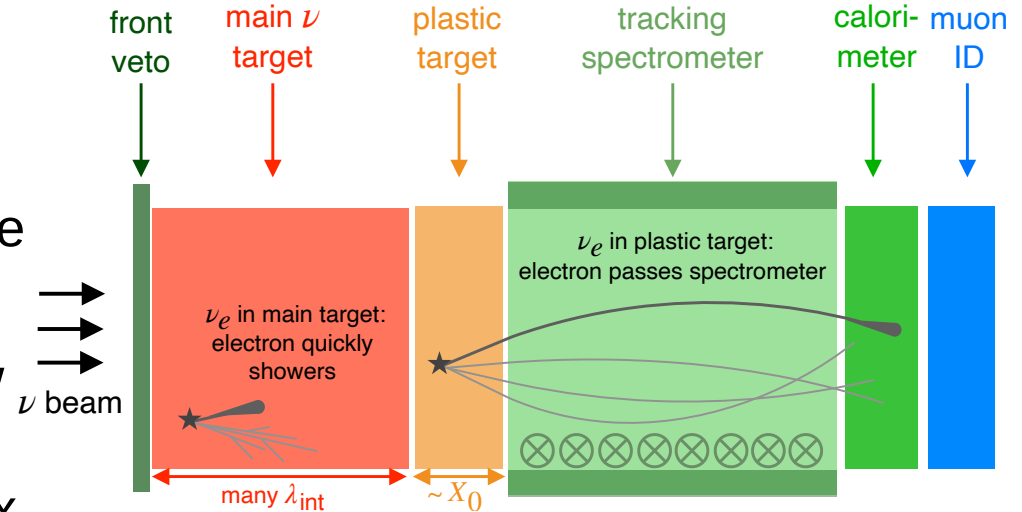
# Non-Standard Interactions

- Stringent NuTeV constraints originally given in terms of left- and right-handed coefficients
  - u and d quark coefficients varied simultaneously
- Translate FPF bounds to  $\epsilon_{\mu\mu}^{dL}$ ,  $\epsilon_{\mu\mu}^{uL}$
- 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  $\nu_e$ ,  $\bar{\nu}_e$  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!**

# 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)  $\lambda$  for a particle of energy  $E$ , interaction cross section  $d\sigma/dx$ , from
  - Pair production:  $\lambda = 9/7 X_0$  as expected
  - Bremsstrahlung: significantly below  $X_0$  => determines length scale for sampling longitudinal step size (exp. distributed)

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

# BDT analysis details

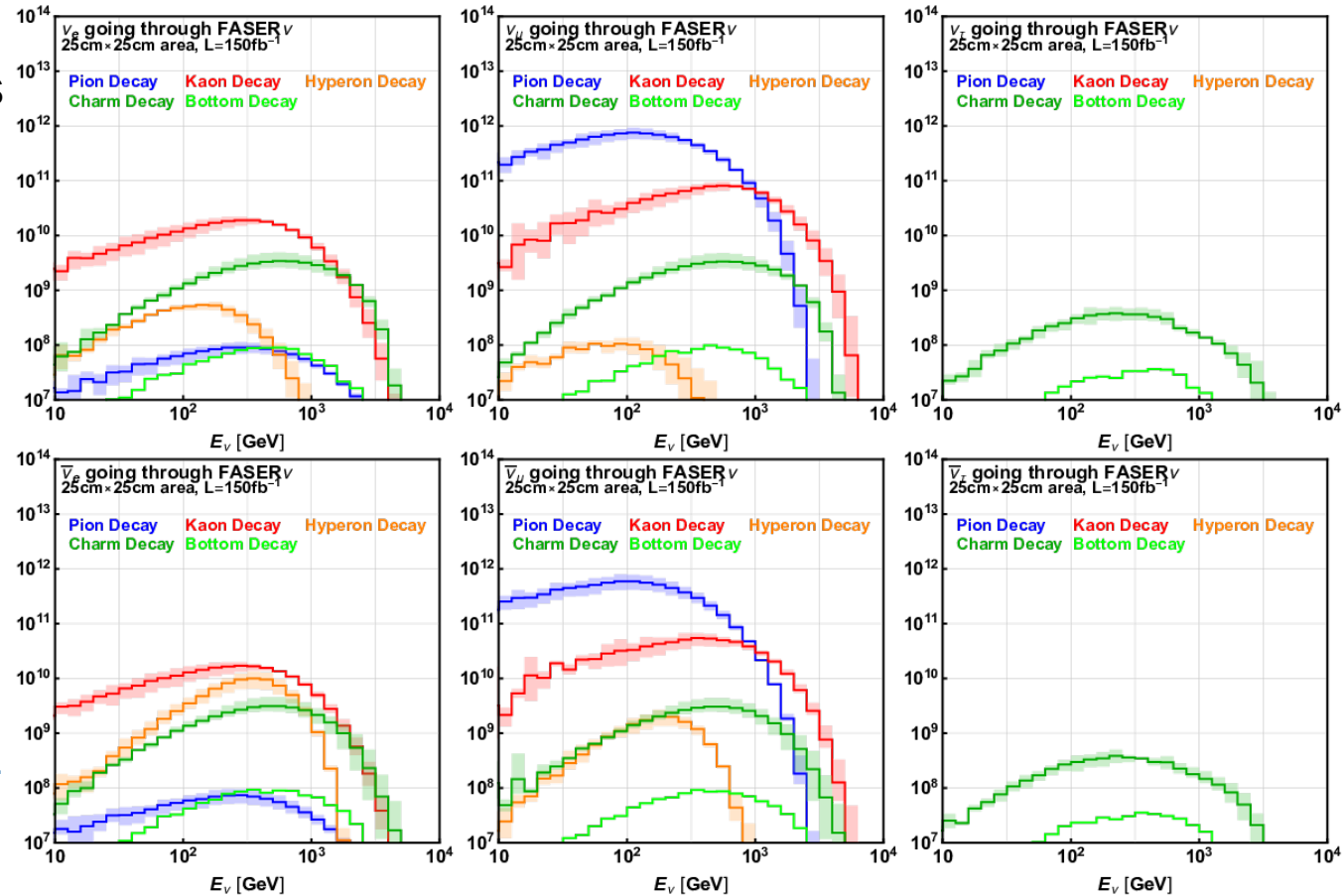
- Boosted Decision Tree implemented in scikit-learn
- Additional features vs cut-and-count analysis
  - Vertex position (achievable in longitudinally segmented target)
  - Energy of all charged tracks  $E_{Ch}$
  - Total charge of  $e^{+/-}$  with energies above 100 GeV
  - Leading  $e^{+/-}$  angle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

# Constraining forward QCD with collider $\nu$

## Forward hadron production

- Different hadrons have characteristic contributions to the  $\nu$  spectra
- Various predictions with very different forward hadron distributions
  - Based on phenomenological models
  - **Constrain using forward neutrino measurements!**

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# Constraining forward QCD with collider $\nu$

## Measurements as a function of energy and rapidity

- Muon neutrinos mainly originate from pions
  - Focused beam
- Tau and high-E electron neutrinos from charmed hadrons
  - More spread out

