From first FASER physics results to searches at the FPF

Far Forwards Physics Meeting
April 4th 2023

Felix Kling

First Results from Moriond!

Dark Photons and Neutrinos

What can we learn from this?

Comparison to Flux Predictions

Some remark on limitations of GENIE.

Hadronization

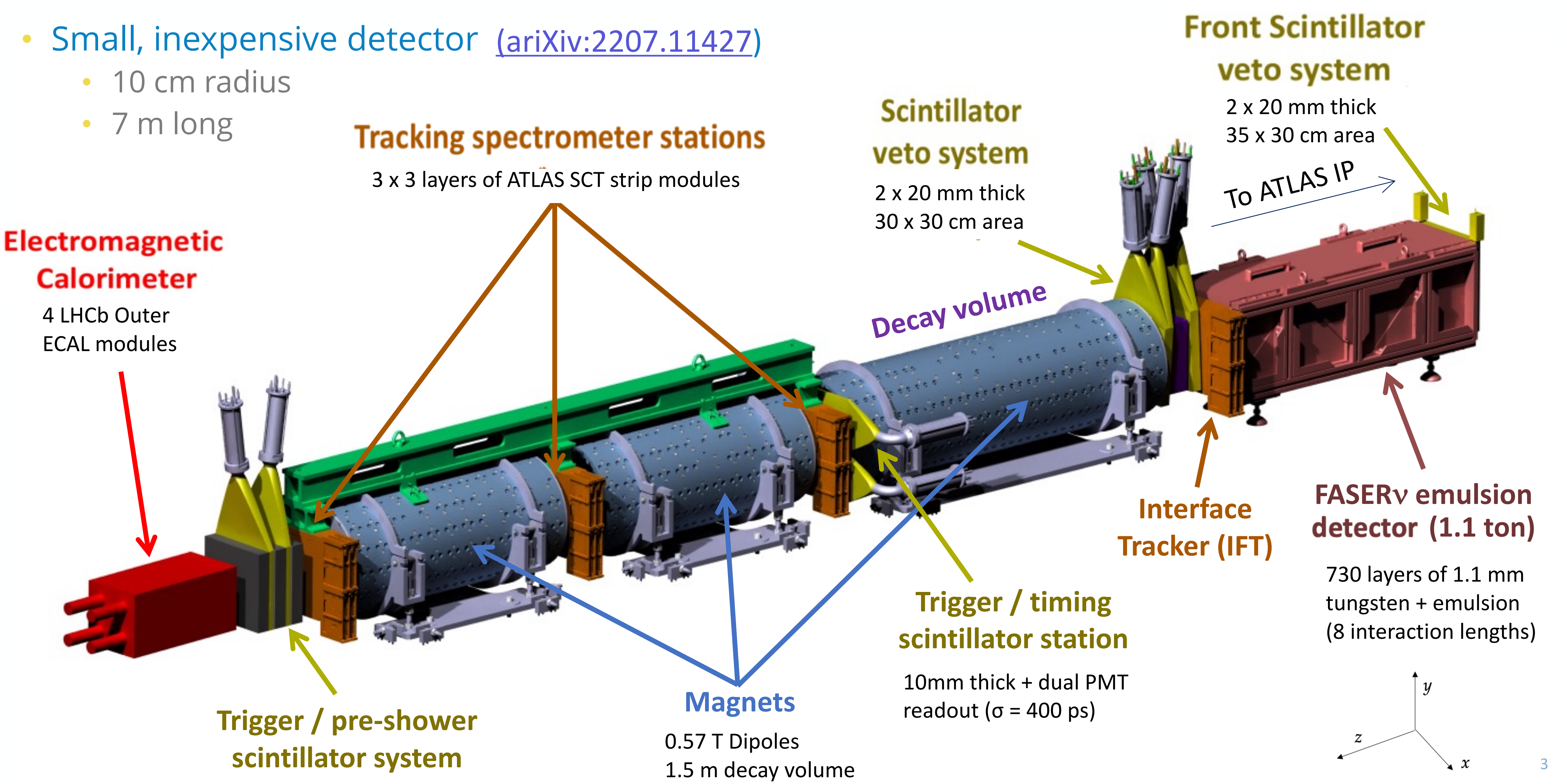
First Results from Moriond!
Dark Photons and Neutrinos

Brian Peterson's (FASER) talk at Moriond EW: slides
Ettore Zaffaroni's (SND) talk at Moriond EW: slides
Carl Gwilliam's talk (FASER) at Moriond QCD: slides
Neutrino Observation (FASER): 2303.14185
Dark Photon Analysis (FASER): CONF NOTE

FASER Experiment

FASER Detector

- Small, inexpensive detector [(ariXiv:2207.11427)]
  - 10 cm radius
  - 7 m long



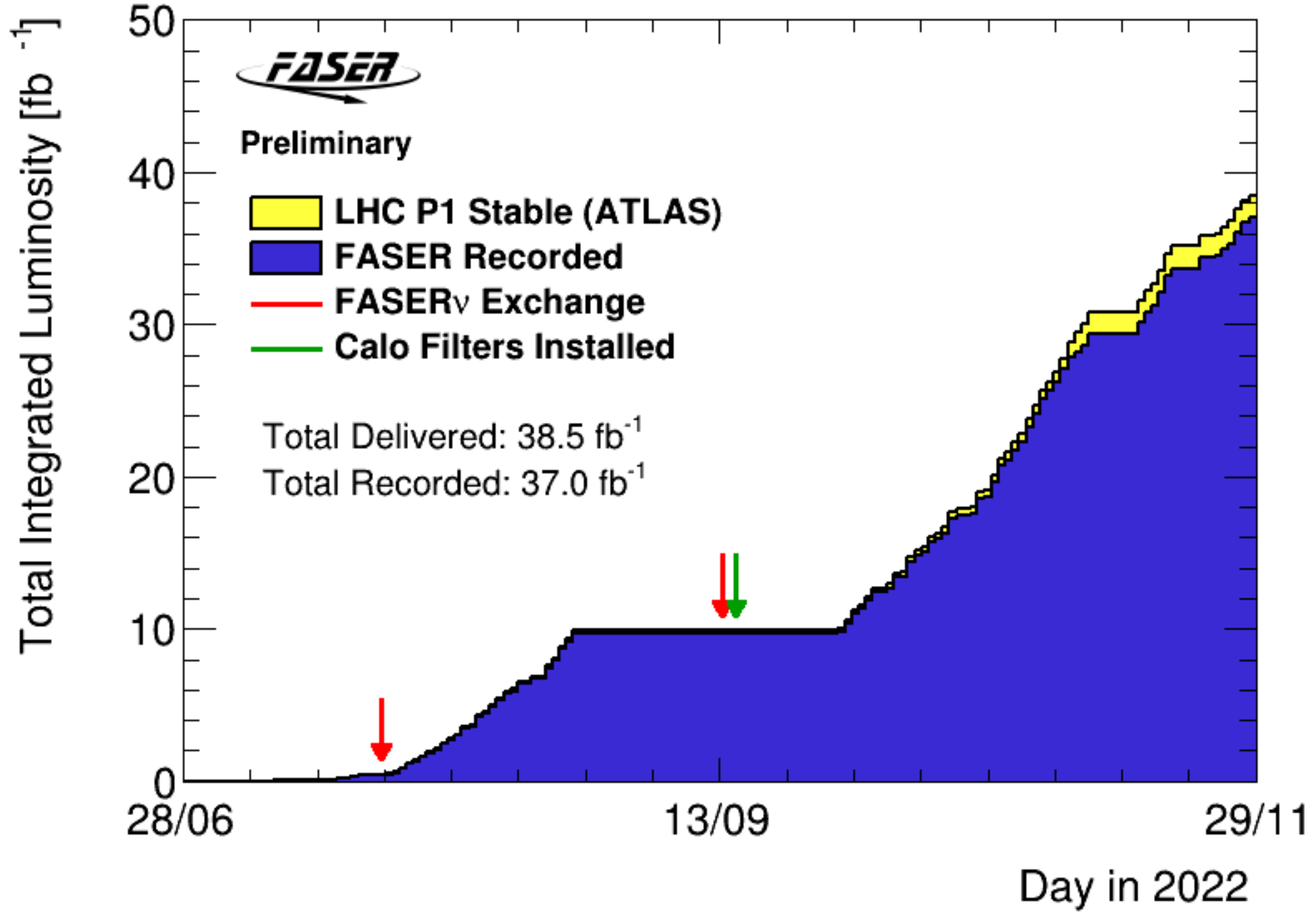
FASER Experiment

- Detector installed between March – Nov 2021, ready for LHC run 3

FASER Experiment

FASER Operations

- Successfully operated throughout 2022
  - Continuous data taking
  - Largely automated
  - Up to 1.3 kHz
- Recorded 96.1% of delivered lumi.
  - DAQ dead-time of 1.3%
  - A couple of DAQ crashes
- Emulsion detector exchanged twice
  - Needed to manage occupancy
  - First box only partially filled
- Calorimeter gain optimised for:
  - Low E (<300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after this exchange

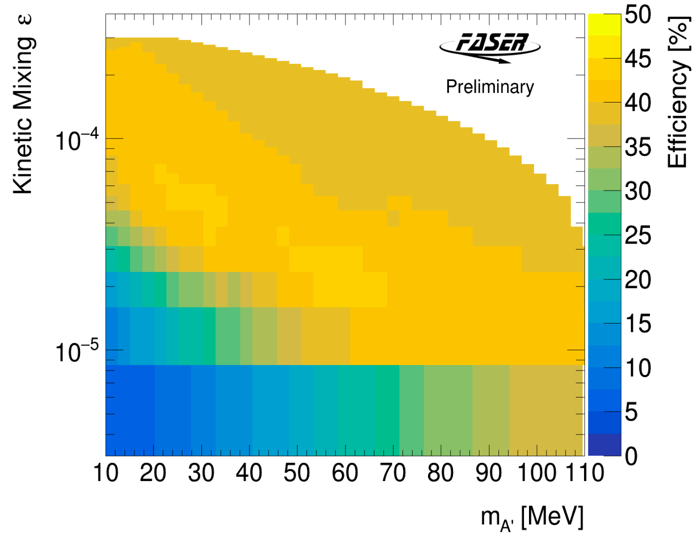


→ Analyses presented use 27.0 fb^{-1} or 35.4 fb^{-1}

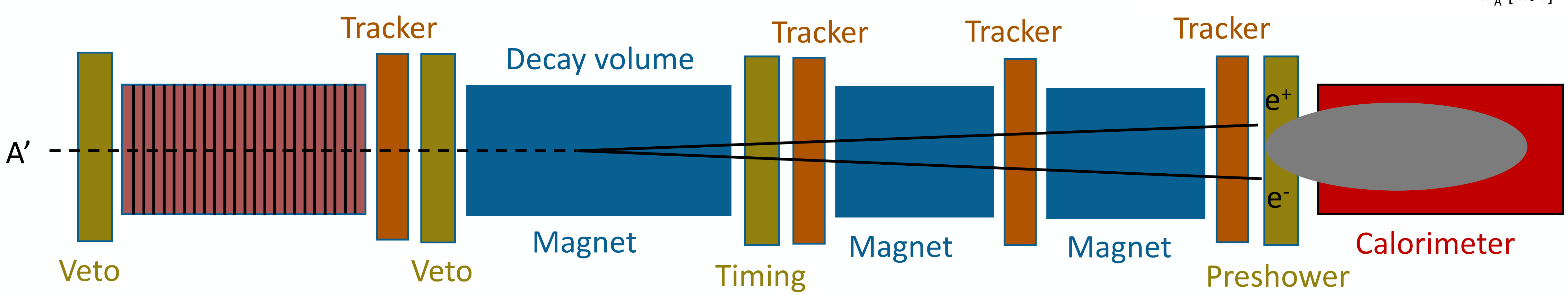
Dark Photon Analysis

Dark Photon Selection

- Simple and robust $A' \rightarrow e^+e^-$ selection, optimised for discovery
  - Blind events with no veto signal and E(calo) > 100 GeV
  - Efficiency of ~40% across region sensitive to



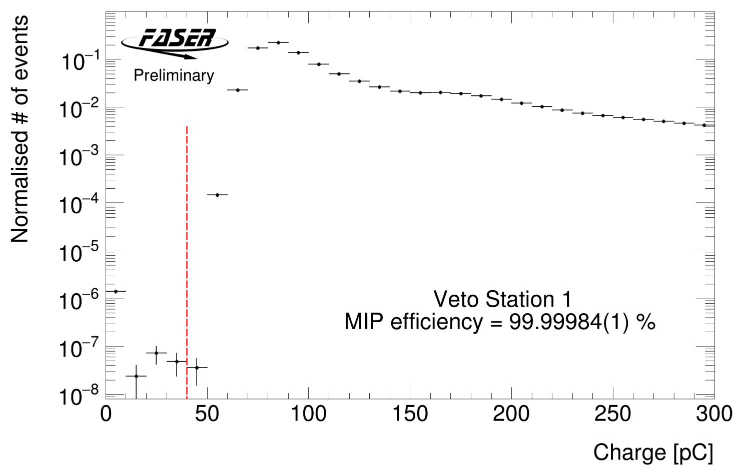
1. Collision event with good data quality
4. Timing and preshower consistent with ≥2 MIPs



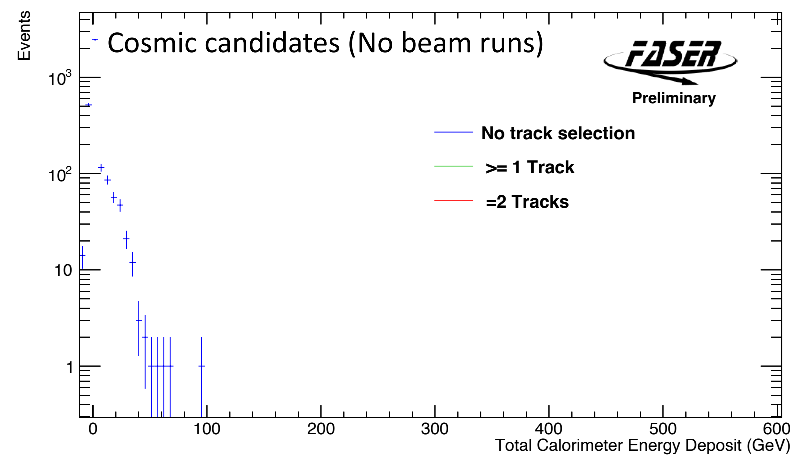
2. No signal (< 40 pC) in any veto scintillator
3. Exactly 2 good fiducial tracks
   - p > 20 GeV and r < 95 mm
   - Extrapolating to r < 95 mm at vetos
5. Calo E > 500 GeV

Dark Photon Backgrounds

- Veto inefficiency
  - Measured layer-by-layer via muons with tracks pointing back to vetos
  - Layer efficiency > 99.998%
  - 5 layers reduce exp. 10^8 muons to negligible level (even before cuts)



- Non-collision backgrounds
  - Cosmics measured in runs with no beam
  - Near-by beam debris measured in non-colliding bunches
  - No events observed with ≥1 track or E(calo) > 500 GeV individually

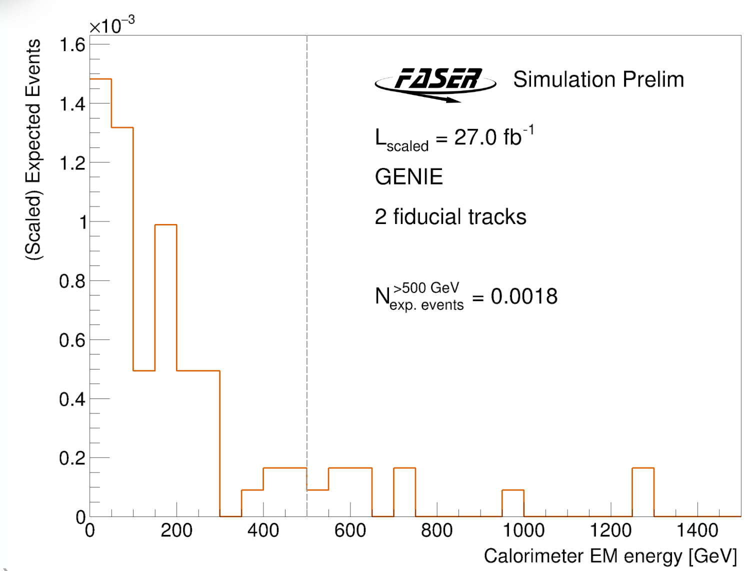


- Main background is from neutrino interactions
  - Primarily coming from vicinity of timing detector
  - Estimated from GENIE simulation (300 ab^{-1})
    - Uncertainties from neutrino flux & mismodelling
  - Predicted events with E(calo) > 500 GeV

$$N = (1.8 \pm 2.4) \times 10^{-3}$$

- Neutral hadrons (e.g. K_S) from upstream muons interacting in rock in front of FASER
  - Heavily suppressed since:
    - Muon nearly always continues after interaction
    - Has to pass through 8 interaction lengths (FASERν)
    - Decay products have to leave E(calo) > 500 GeV
  - Estimated from lower energy events with 2 or 3 tracks and different veto conditions

$$N = (2.2 \pm 3.1) \times 10^{-4}$$

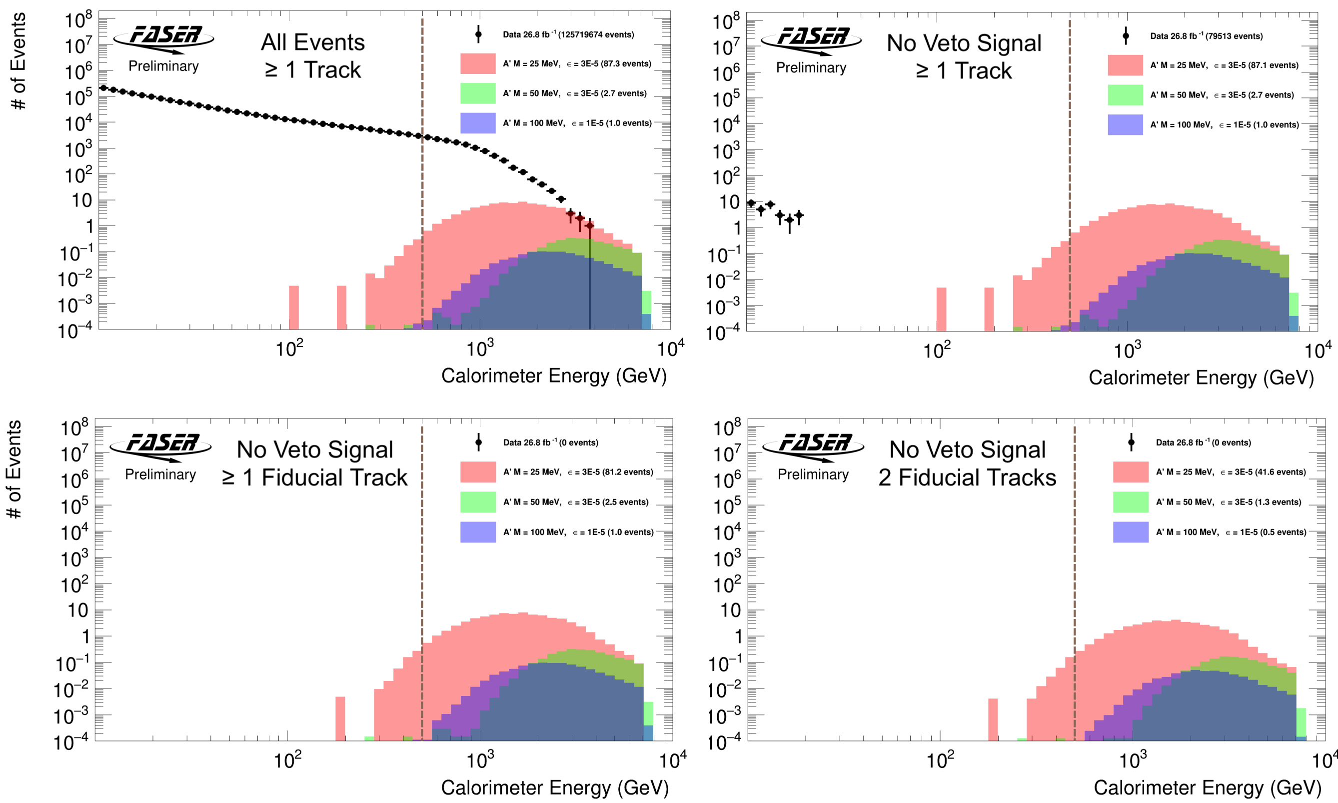


- Total background prediction

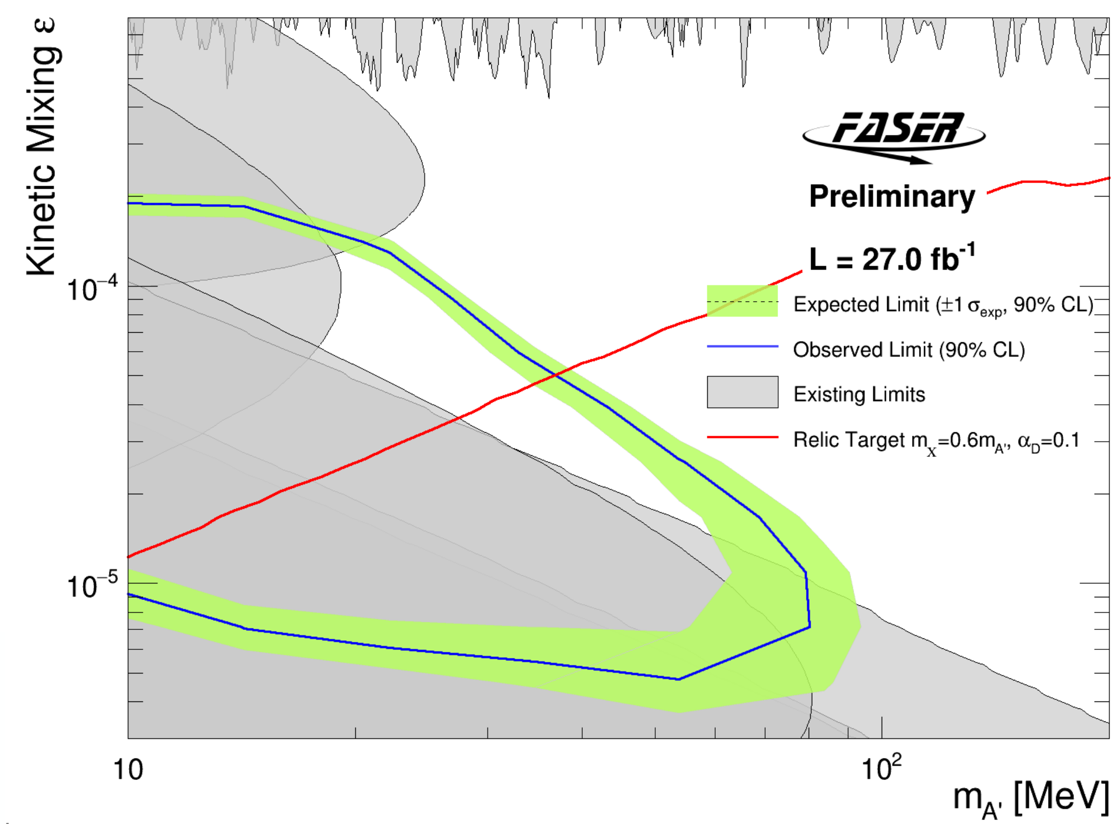
$$N = (2.02 \pm 2.4) \times 10^{-3}$$

Dark Photon Analysis

Dark Photon Results



- No events in unblinded signal region
  - Not even any with ≥1 fiducial track



- Based on this null results, FASER sets limits in previously unexplored parameter space!
  - Probing region interesting from thermal relic target
  - Also taking into account new preliminary NA62 result (see backup)

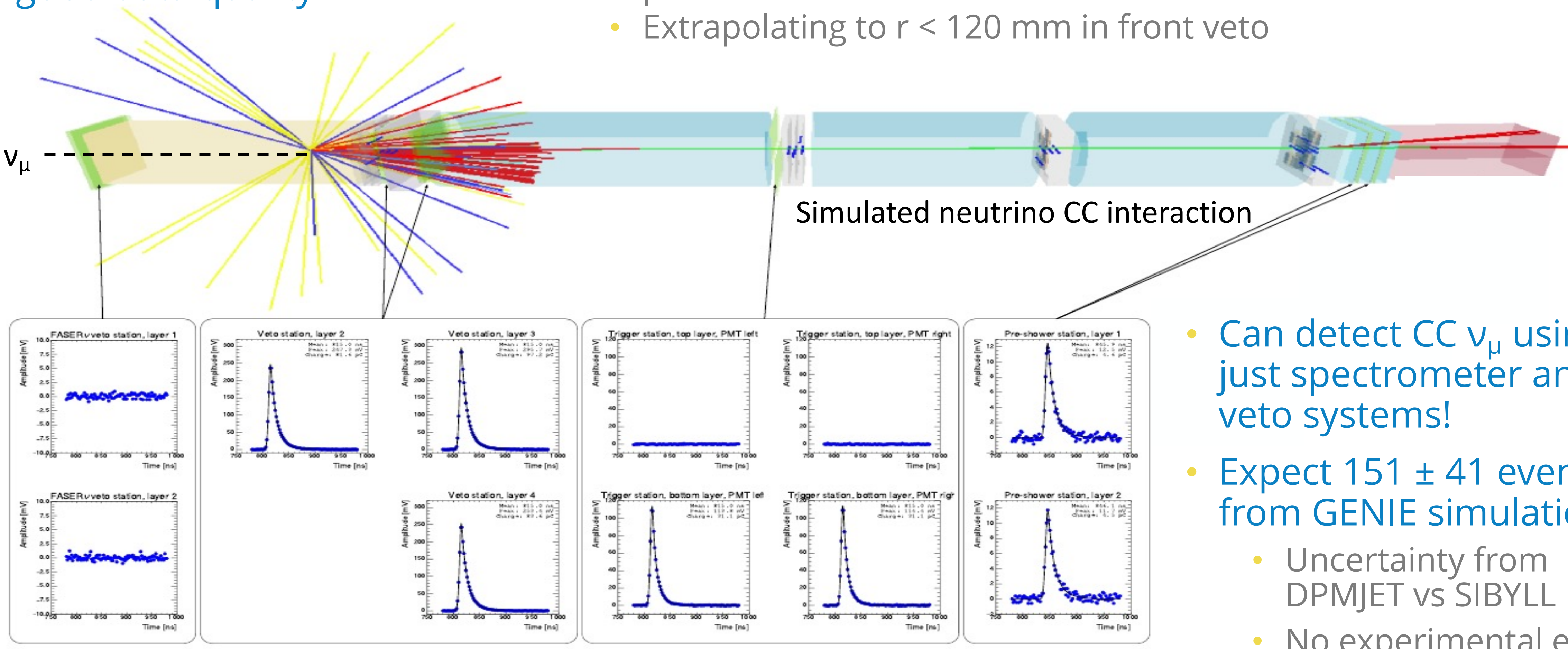
CERN-FASER-CONF-2023-001

Electronic Neutrino Analysis

Observing Neutrino Candidates in FASER

1. Collision event with good data quality

4. Exactly 1 good fiducial (r < 95 mm) track
   - p > 100 GeV and θ < 25 mrad
   - Extrapolating to r < 120 mm in front veto



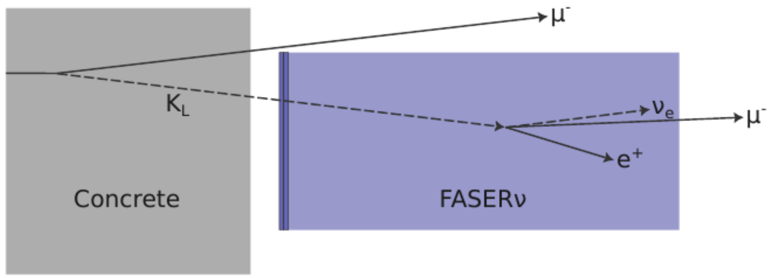
2. No signal (<40 pc) in 2 front vetos
3. Signal (>40 pC) in other 3 vetos
5. Timing and preshower consistent with ≥1 MIP

- Can detect CC ν_μ using just spectrometer and veto systems!
- Expect 151 ± 41 events from GENIE simulation
  - Uncertainty from DPMJET vs SIBYLL
  - No experimental errors
    - Currently not trying to measure cross section

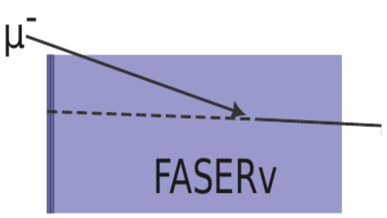
Electronic Neutrino Analysis

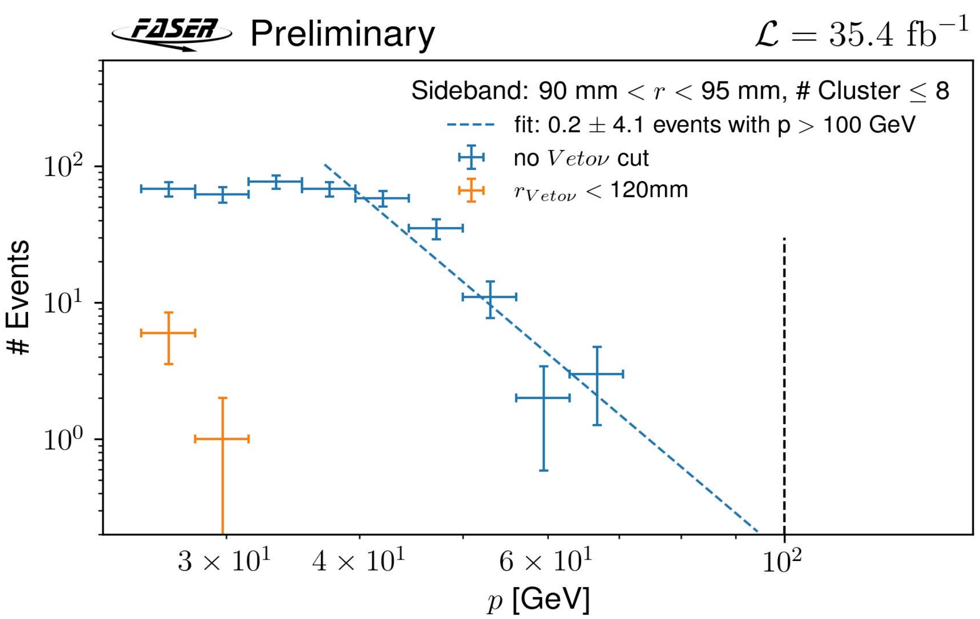
Neutrino Backgrounds

- Neutral hadrons estimated from 2-step simulation
  - Expect ~300 neutral hadrons with E>100 GeV reaching FASERν
    - Most accompanied by μ but conservatively assume missed
  - Estimate fraction of these passing event selection
    - Most are absorbed in tungsten with no high-momentum track
  - Predict N = 0.11 ± 0.06 events



- Scattered muons estimated from data SB
  - Take events w/o front veto radius requirement and single track segment in first tracker station with 90 < r < 95 mm
    - Fit to extrapolate to higher momentum
  - Scale by # events with front veto cut
    - Use MC to extrapolate to signal region
  - Predict N = 0.08 ± 1.83 events
    - Uncertainty from varying selection

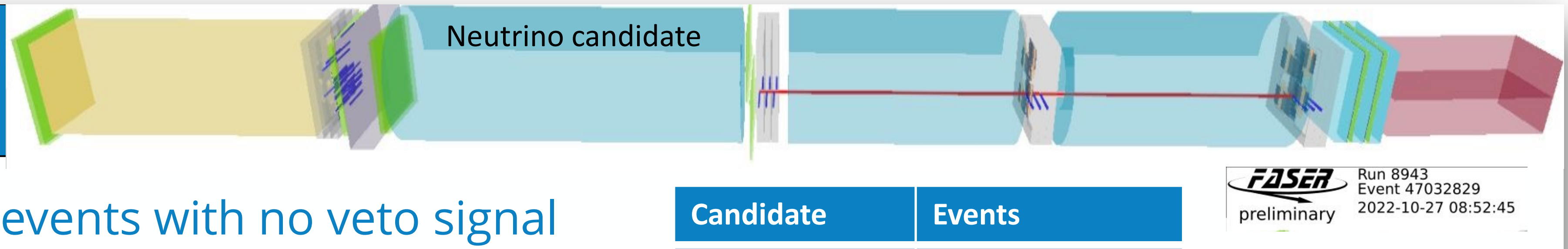




- Veto inefficiency estimated from final fit
  - Fit events with 0 (SR) and also 1 (1st or 2nd) or 2 front veto layers firing
  - Find negligible background due to very high veto efficiency

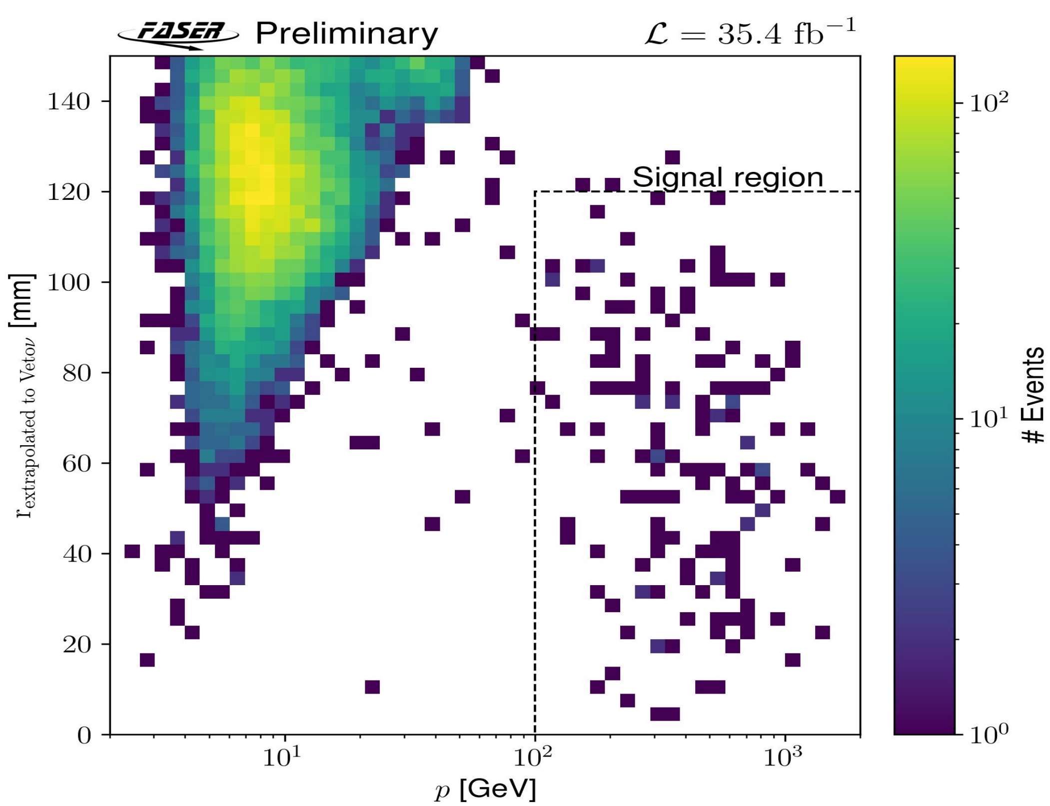
Electronic Neutrino Analysis

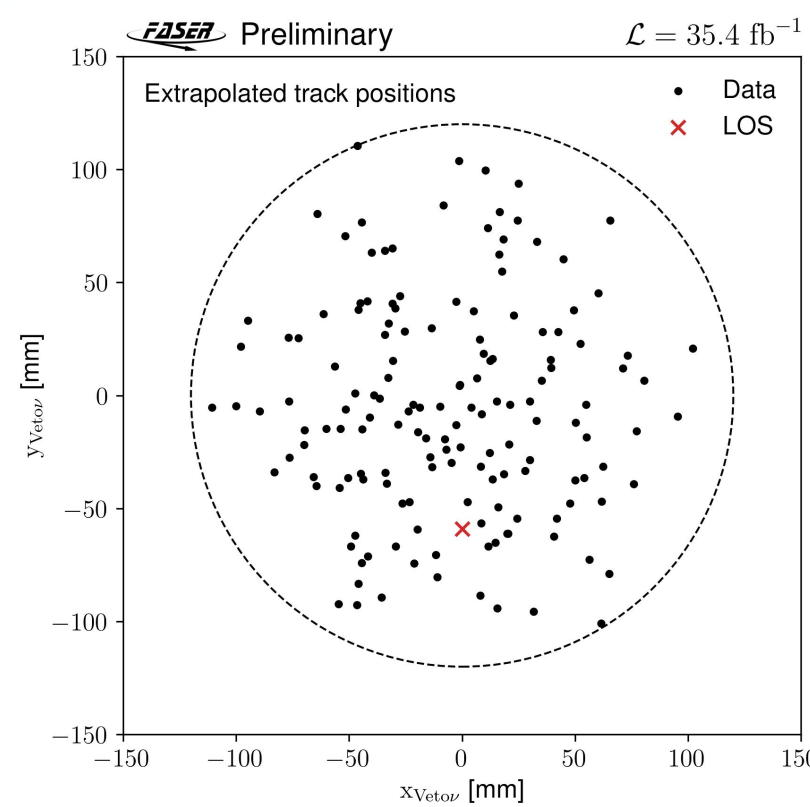
Neutrino Results



- Upon unblinding find 153 events with no veto signal
  - Just 10 events with one veto signal
- First *direct* detection of collider neutrinos!
  - With signal significance of 16σ
  - Submitted to PRL arXiv:2303.14185

Candidate	Events
n_0	153 (151 ± 41)
n_{10}	4
n_{01}	6
n_2	64014695

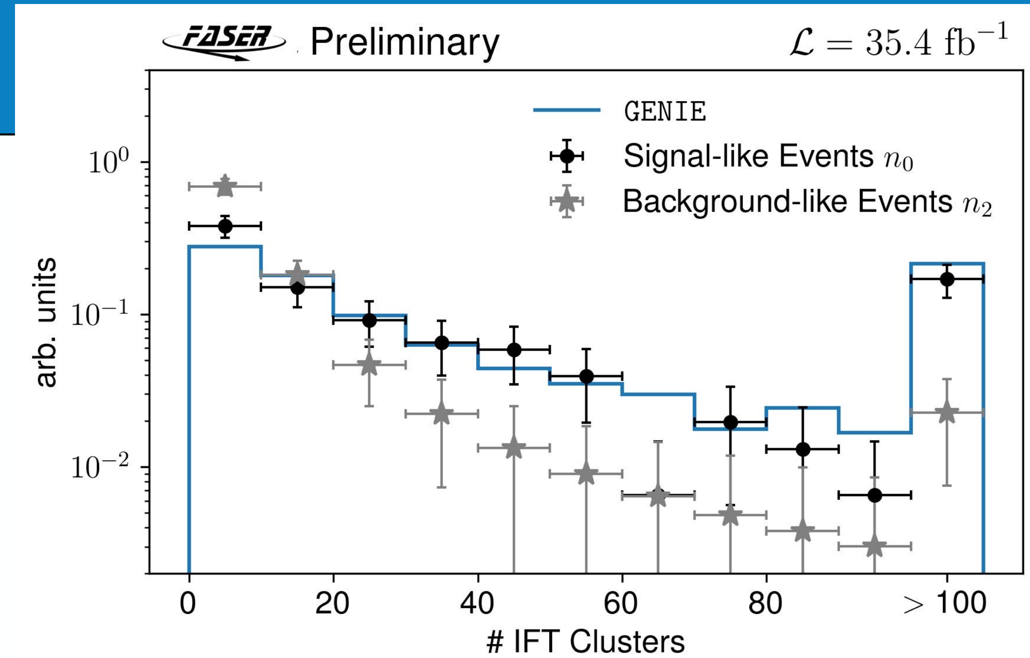


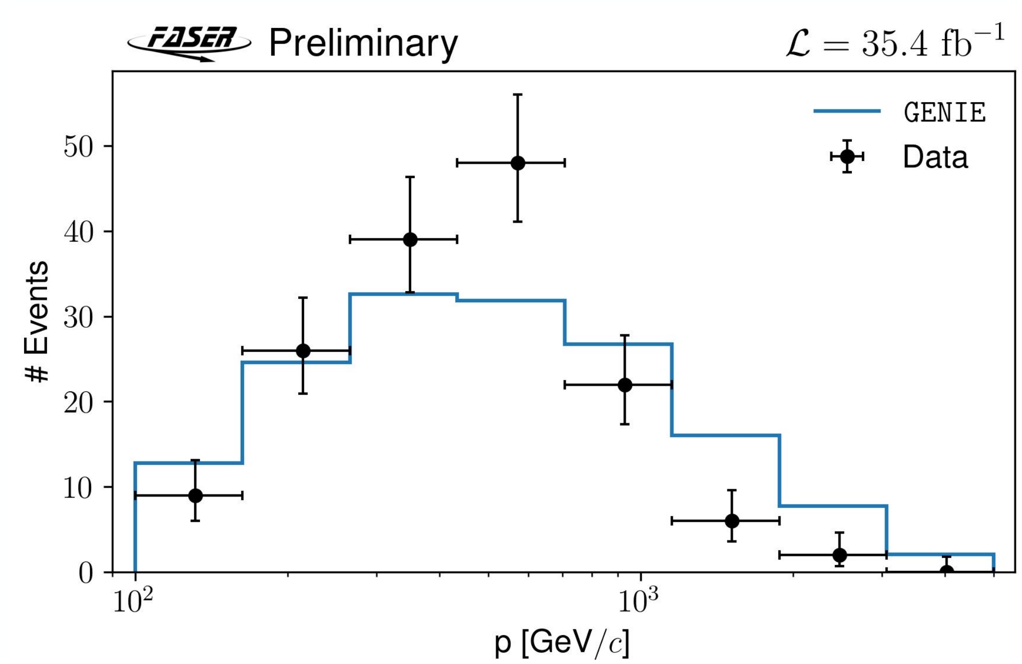


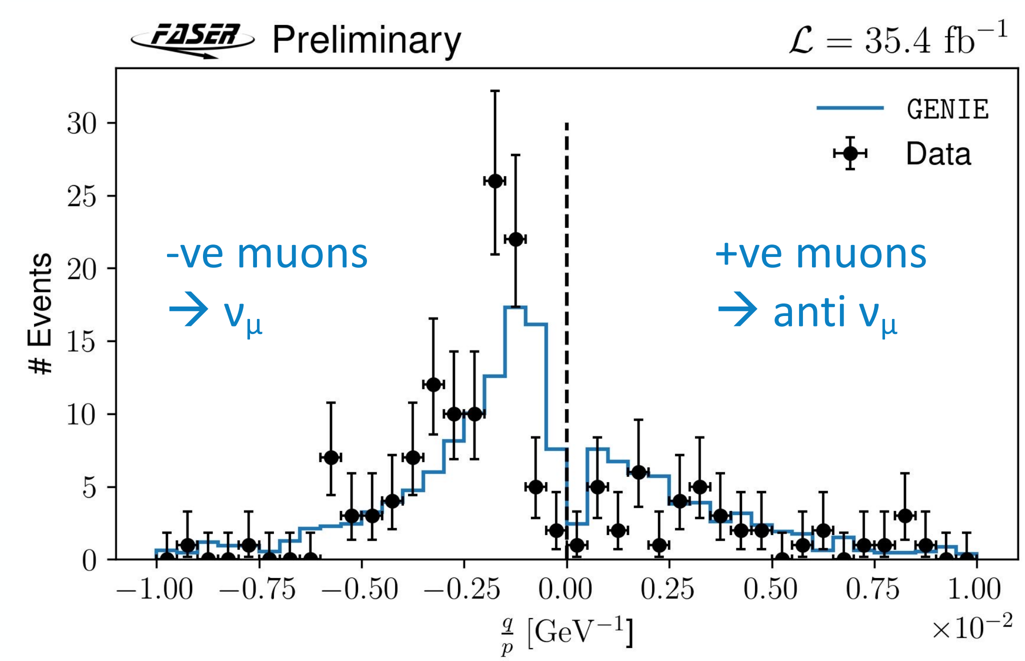
Electronic Neutrino Analysis

Neutrino Characteristics

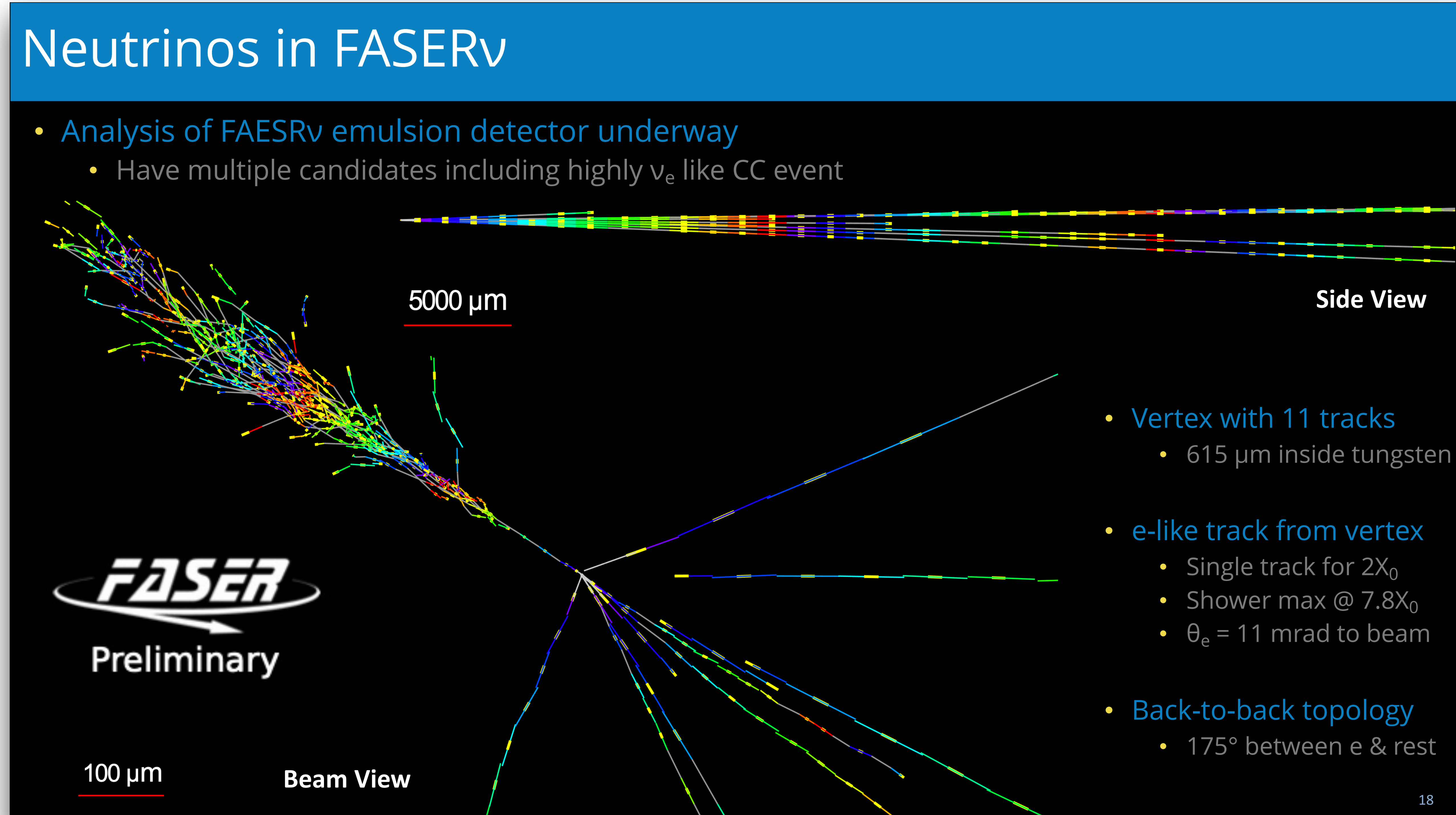
- Candidate neutrino events match expectation from signal
  - High occupancy in front tracker station
  - Most events have high μ momentum
  - More ν_μ than anti- ν_μ
- Note: no acceptance corrections nor any systematic uncertainties in these plots







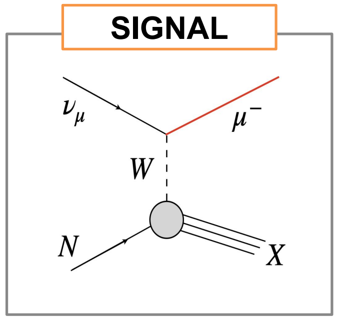
First FASERν Results



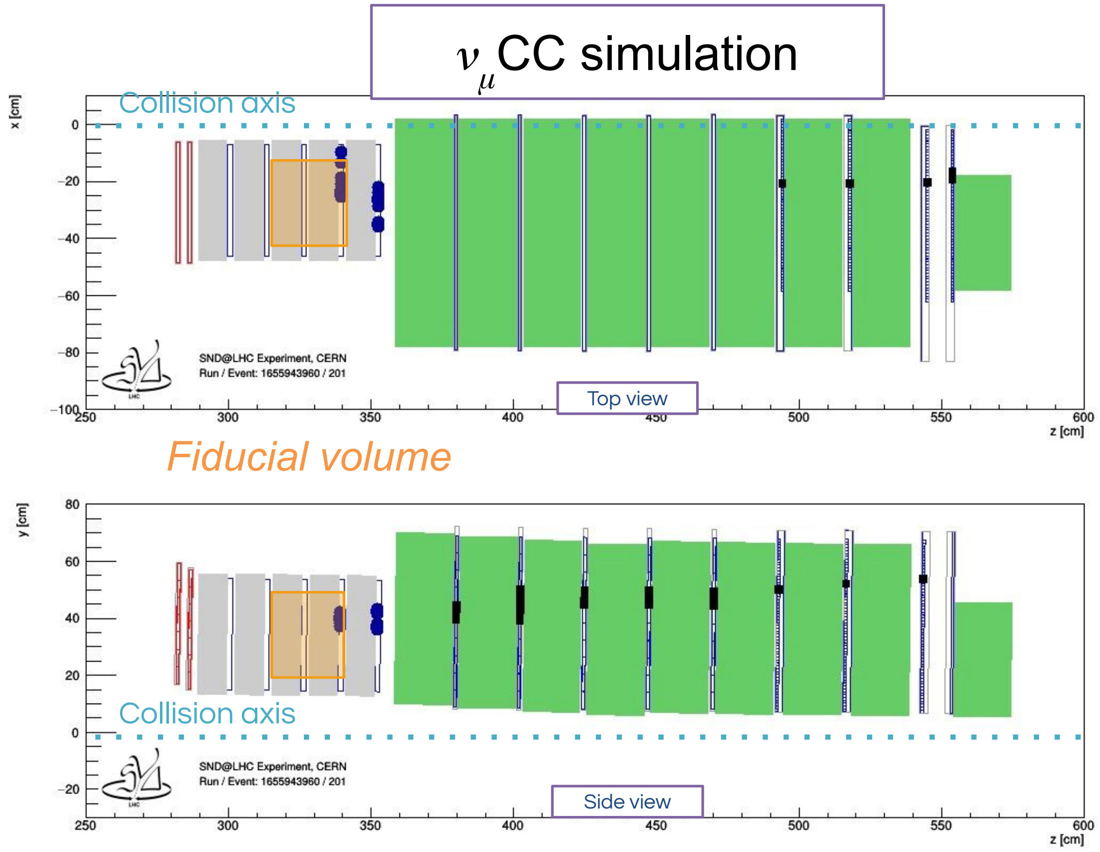
First SND@LHC Results

Neutrino observation with electronic detectors

- Analysis strategy:
  - Full Run 3 **2022 dataset**, 39 fb^{-1}
  - Observe ν_μ **Charged Current** interactions with **electronic detectors only**
  - **Maximise S/B**, counting-based approach
  - ~10^9 muon events: apply **cuts with a strong rejection power** to reach a negligible background level

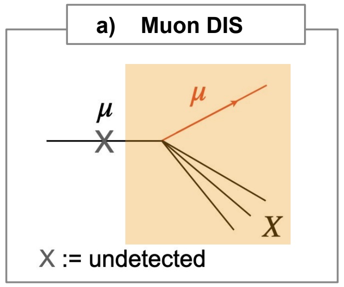


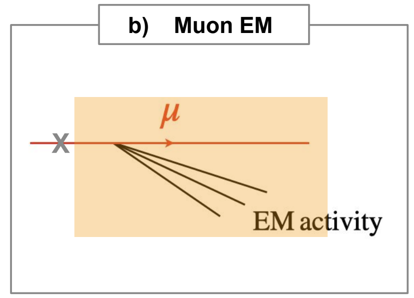
- Signal selection:
  - **Fiducial Volume (1, 2)** cuts
    - Require an event from a **neutral vertex**, located in the 3rd or 4th target wall
    - Select fiducial cross-sectional area to reject entering backgrounds
  - **Neutrino ID** cuts
    - Require large EM activity in SciFi and hadronic activity in the HCAL
    - Event produced upstream (timing)
    - **Muon** reconstructed and **isolated** in the Muon system



Background estimates (I)

SND@LHC PRELIMINARY





:= within SND@LHC acceptance

- Muon induced background
  Number of undetected muons entering the target (2022 Run3 data)

$$N_{\mu}^{bkg} = N_{\mu} \times (1 - \epsilon_{Veto}) \times (1 - \epsilon_{SciFi1}) \times (1 - \epsilon_{SciFi2})$$ ~ 10^{-2} *totally negligible*

Total number of muons in target acceptance — *Veto inefficiency* — *SciFi plane inefficiency*

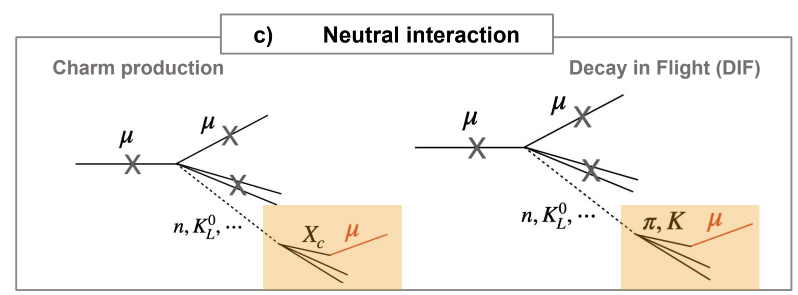
$$N_{\mu} = \frac{28 \times 10^{6}}{fb^{-1}} \times 39\, fb^{-1} = 1.1 \times 10^{9}$$

$$(1 - \epsilon_{Veto}) \times (1 - \epsilon_{SciFi1}) \times (1 - \epsilon_{SciFi2}) \sim 10^{-11}$$

EPFL

Background estimates (II)

SND@LHC PRELIMINARY

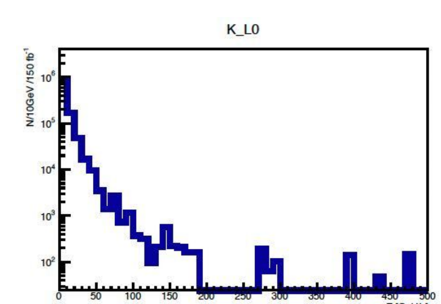


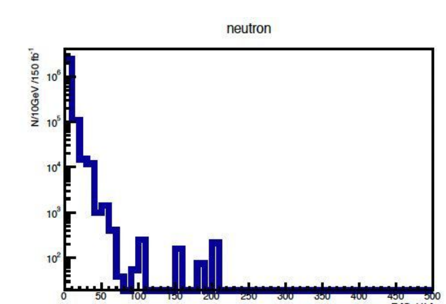
:= within SND@LHC acceptance

- Muon-induced neutral interactions

$$N_{\text{neutrals}}^{\text{bkg}} = N_{\text{neutrals}} \times P_{\text{inel}} \times \epsilon_{\text{sel}}$$

~ 0.12 (K^0_L) + 0.06 (neutrons) **~ 0.2**





Systematic uncertainty estimation is ongoing

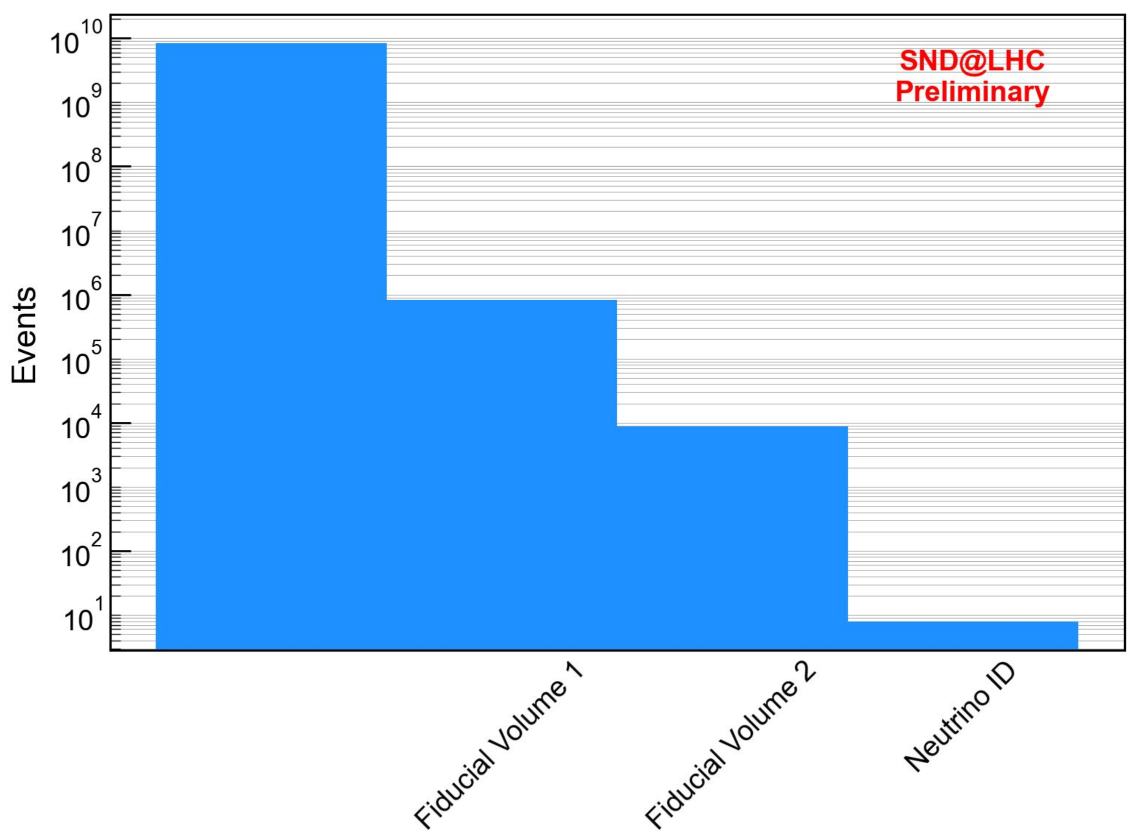
EPFL

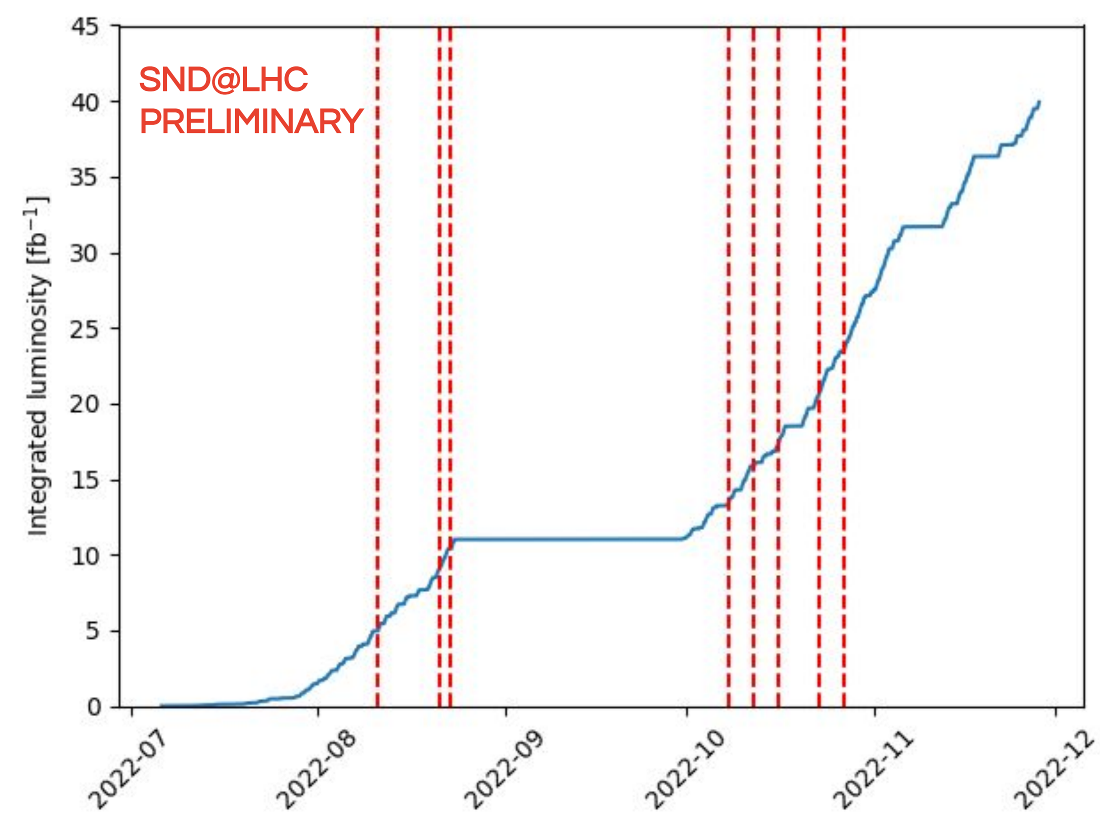
First SND@LHC Results

Observed candidates

SND@LHC PRELIMINARY

- Observed ν_μ **candidates**: 8 (expected 5)
- Preliminary estimate of background yield: 0.2





EPFL

What can we learn from this?

Comparison to Flux Predictions

Neutrino Fluxes

- Expect 151 ± 41 events from GENIE simulation
  - Uncertainty from DPMJET vs SIBYLL
  - No experimental errors
    - Currently not trying to measure cross section

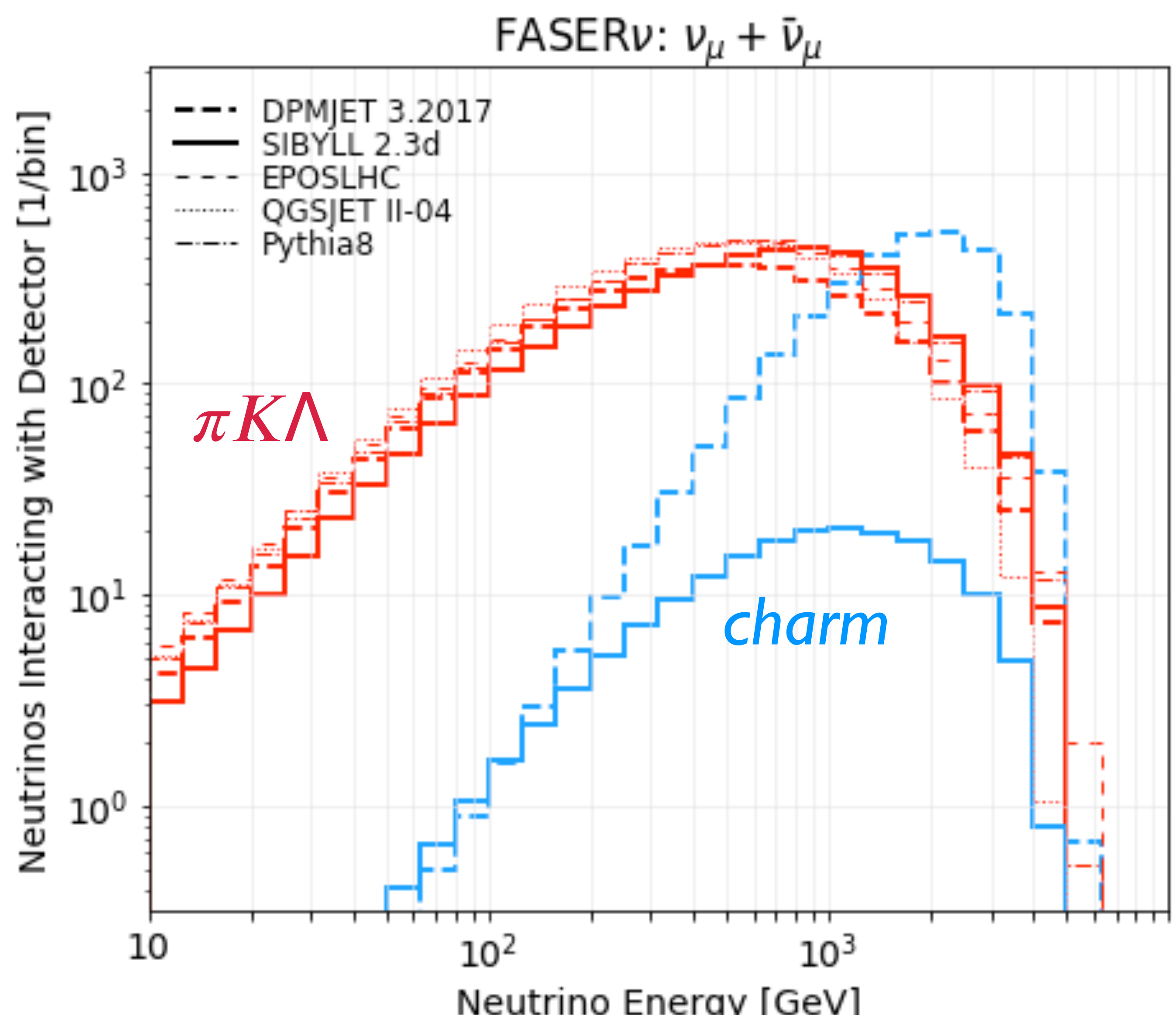
Use neutrino fluxes from 2105.08270

- hadrons from MC generators
- propagation of light hadrons through LHC
- hadron decays into neutrinos
- Large uncertainties from forward charm

Simulation and analysis

- GENIE + Geant4 + cuts
- no experimental uncertainties
  → no flux measurement

So one cannot really say anything, except that it roughly matches expectations.

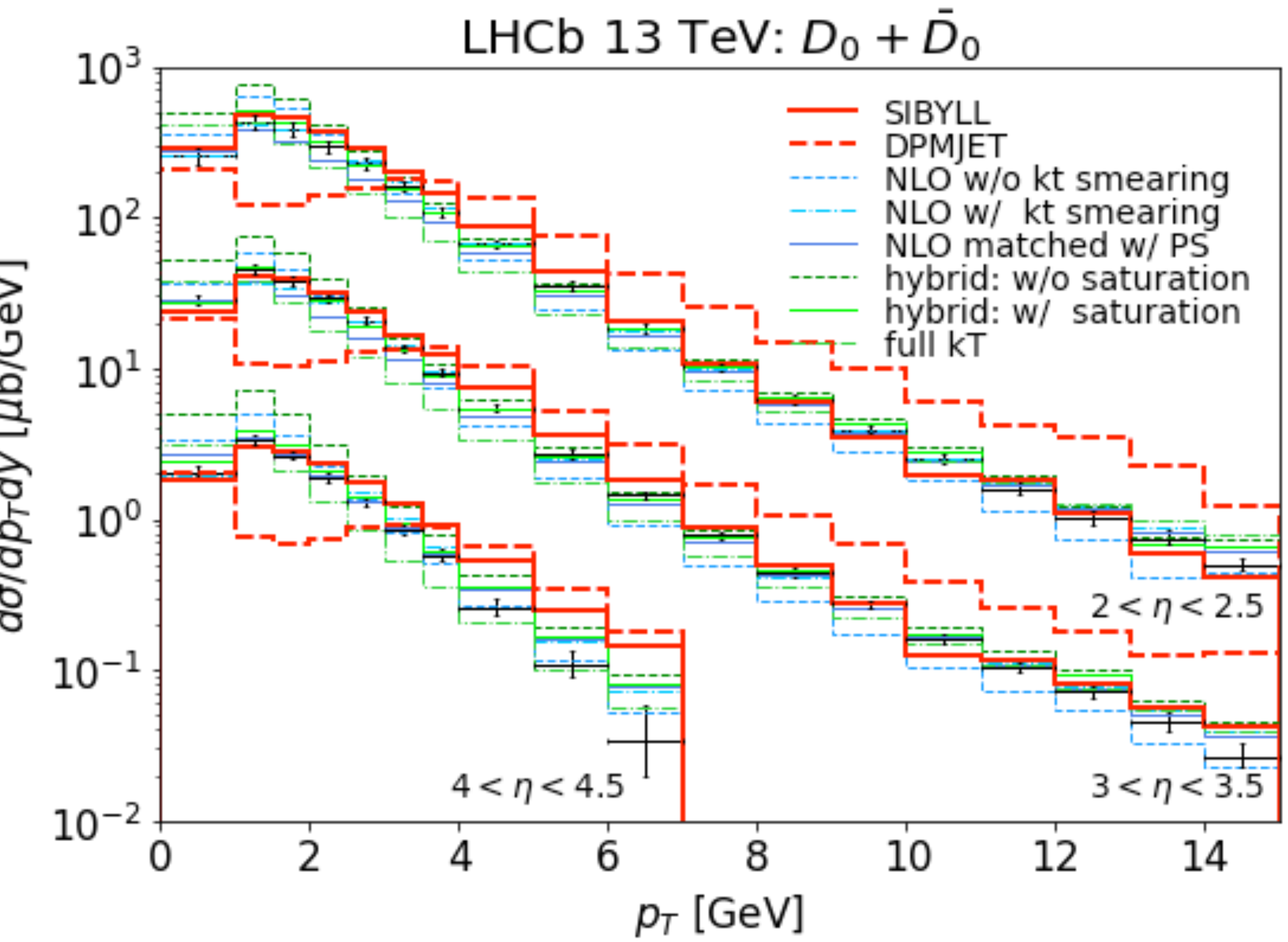


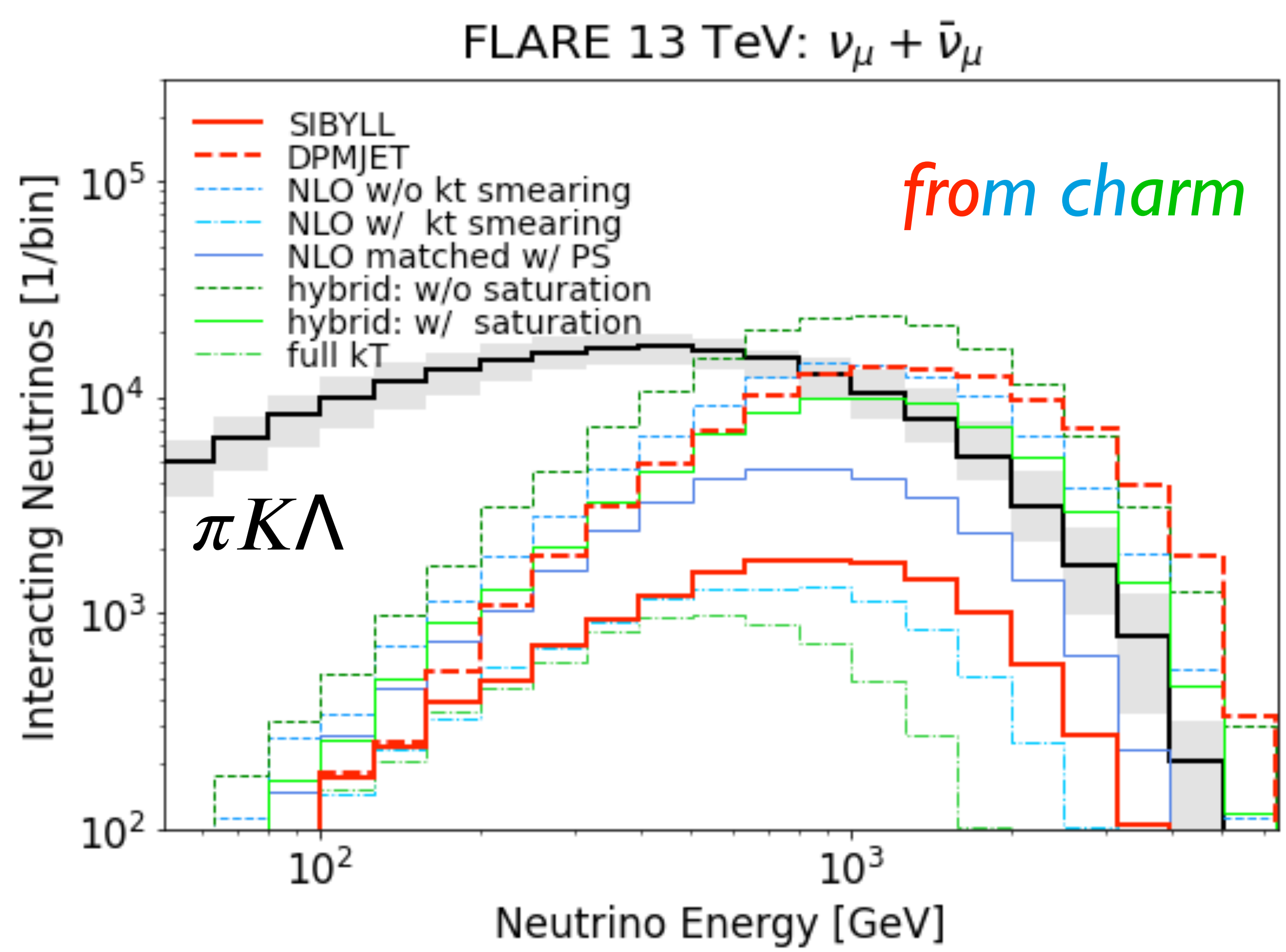
full volume, 150/fb, no efficiencies

Neutrino Fluxes

FPF WG2: forward charm predictions from 5 groups

- different approaches on physics modeling
- predictions span large range
- SIBYLL / DPMJET roughly correspond to minimum/maximum prediction

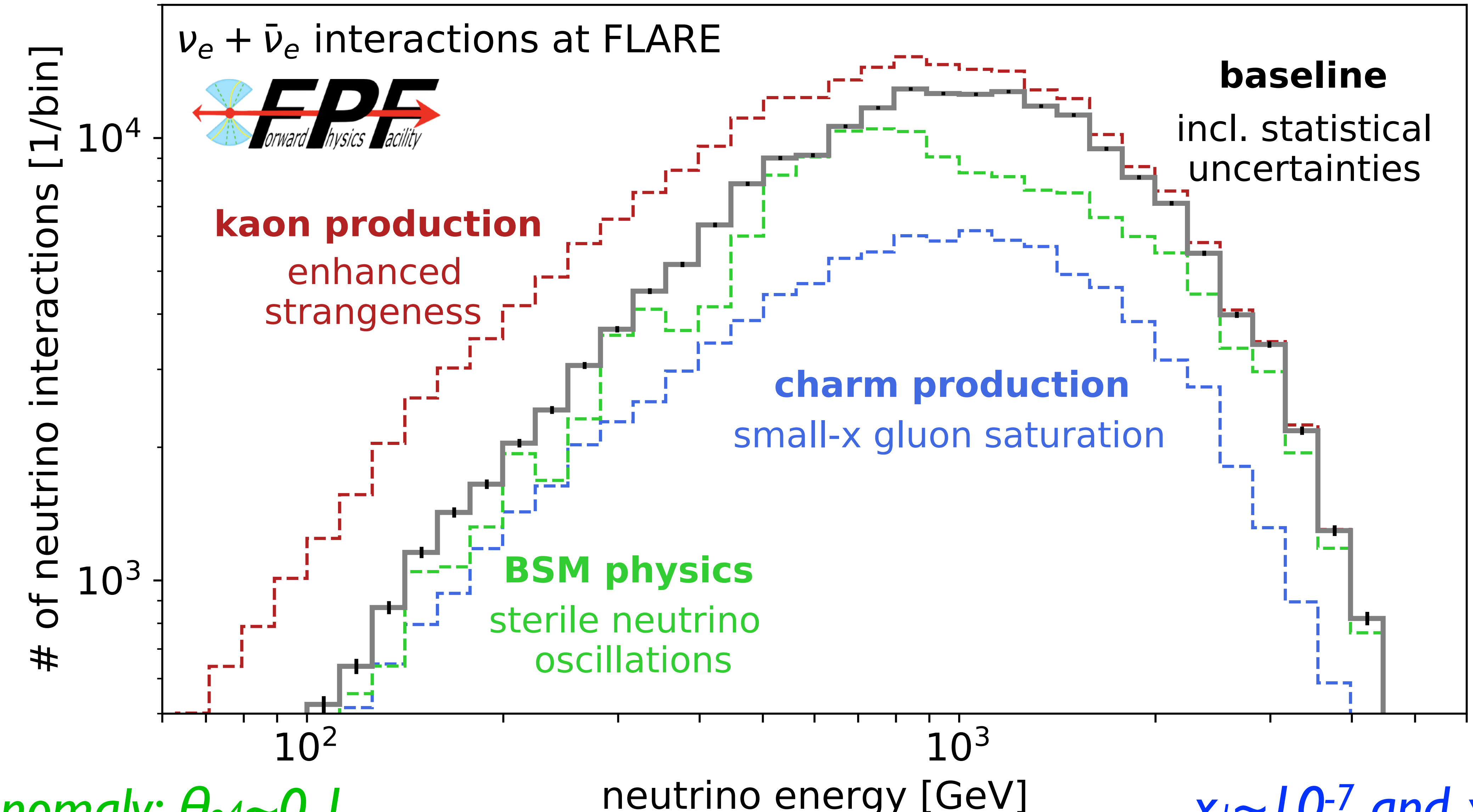




Many thanks to all the contributing groups!

Physics Potential with FLARE

- *CR experiments observe an excess of muons compared to generators*
- *this prevents them from measuring the flux composition and understanding the origin of the cosmic rays*
- *most likely explanation: enhanced forward strangeness at high energies*



Gallium Anomaly: θ_{e4}~0.1

x_1~10^{-7} and x_2~1

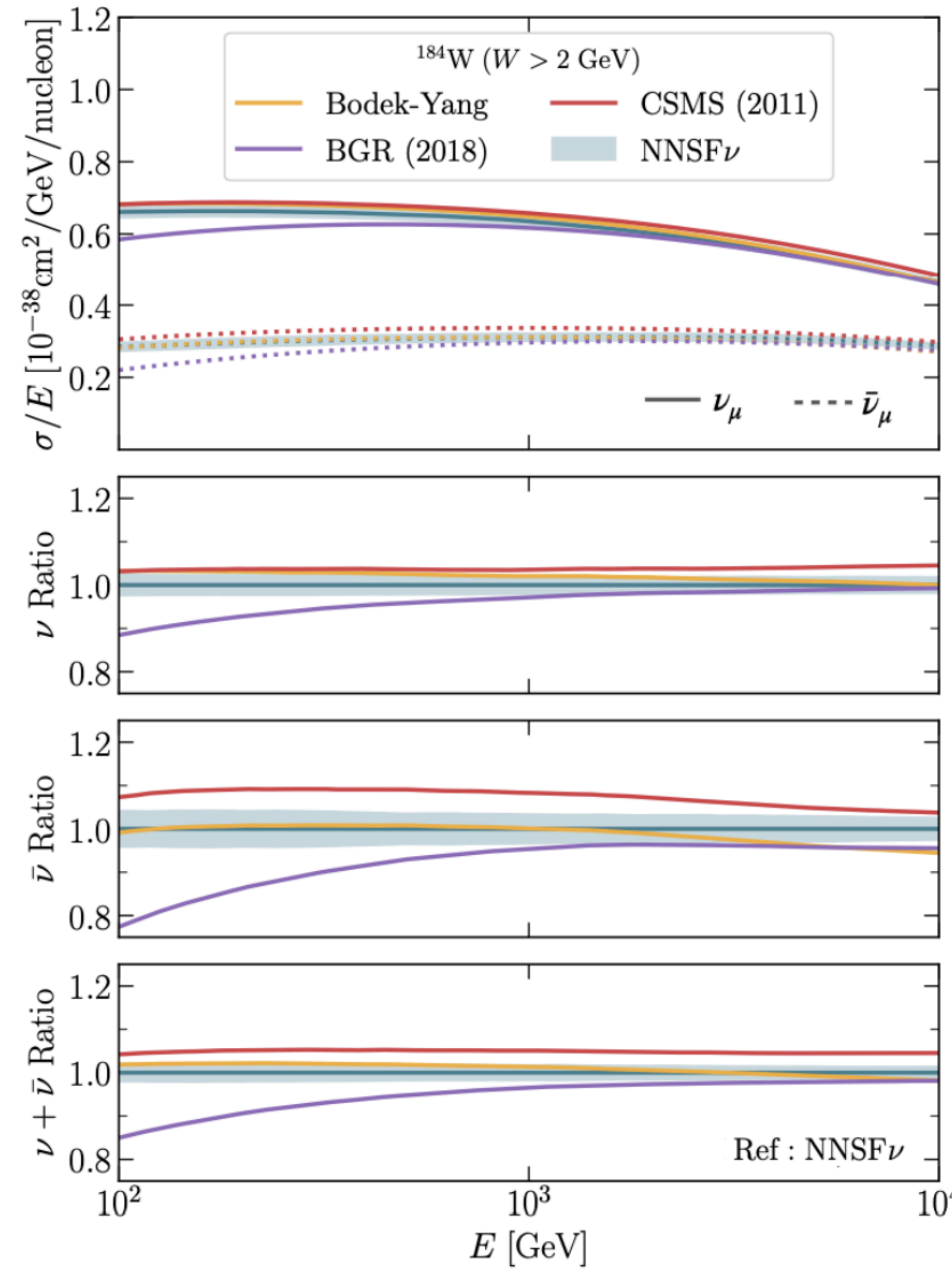
Some remark on limitations of GENIE

Hadronization

Neutrino Interaction Simulation

Last time Juan talked about neutrino interactions

- There are reliable state-of-the-art predictions for differential neutrino cross-sections at FPF energies
- Robust estimate of all relevant sources of experimental and theory uncertainties
- Model-independent determination of nuclear corrections to free-nucleon scattering
- They can be readily used in GENIE by means of the HEDIS package (official GENIE release)

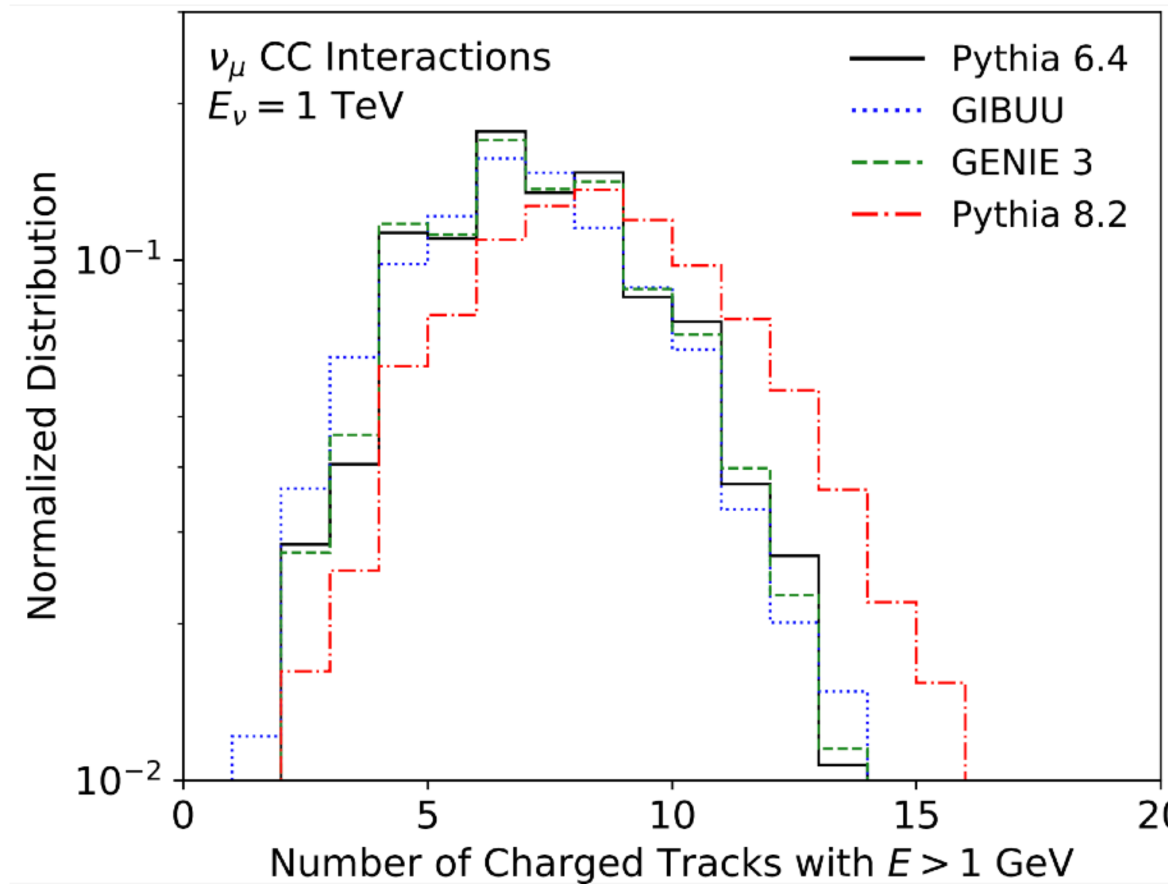


Neutrino Interaction Simulation

Juan mainly covered total rate / leptonic final state.

How about hadronic final state?

- Test: simulate neutrino interactions with GENIE and GIBUU and plot energetic charge particle multiplicity.
- Result: they are the same



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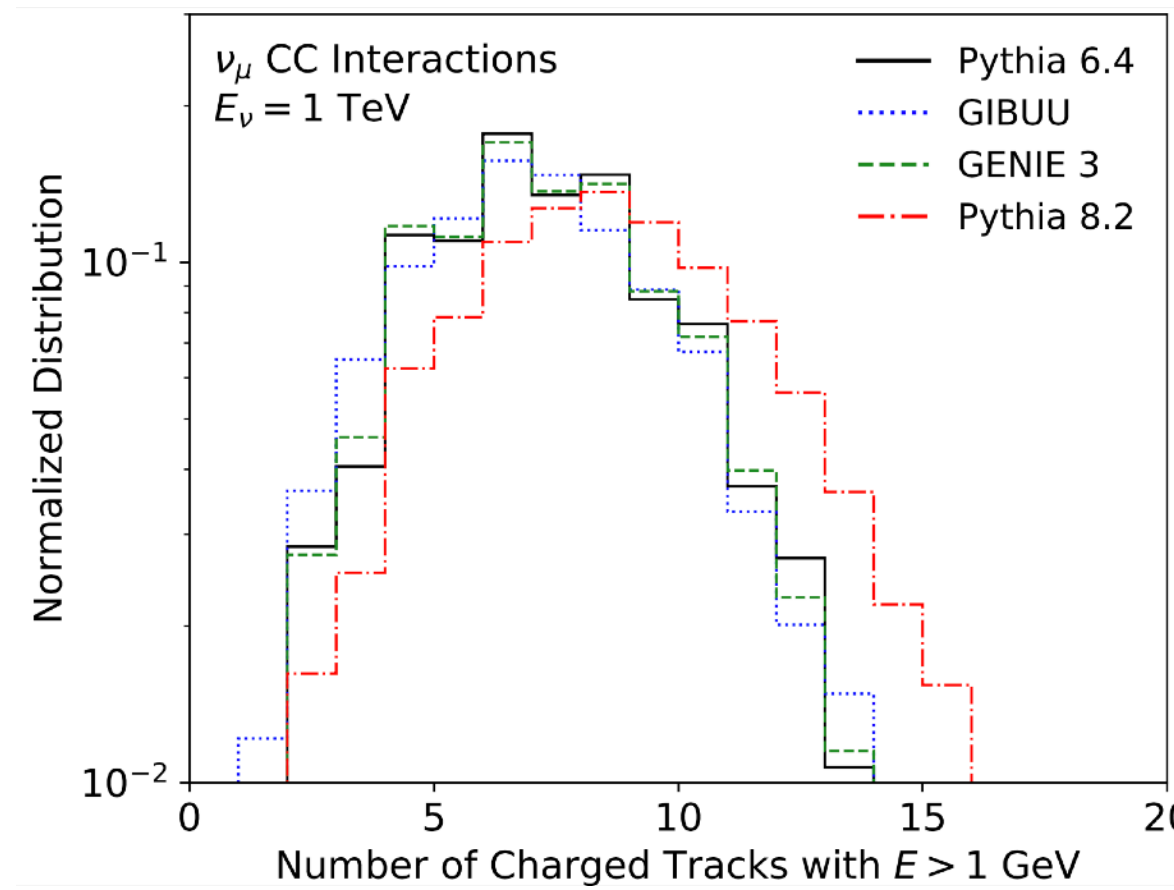
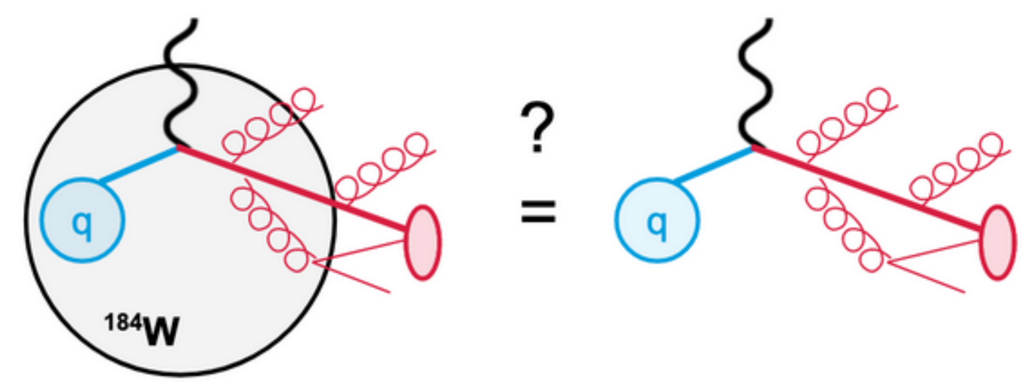


I asked authors about it:

- assumption: hadronization occurs outside nucleus → actually that's a hypothesis, not measured yet
- assumption: partons don't interact with nucleus → that's counterintuitive and most likely wrong

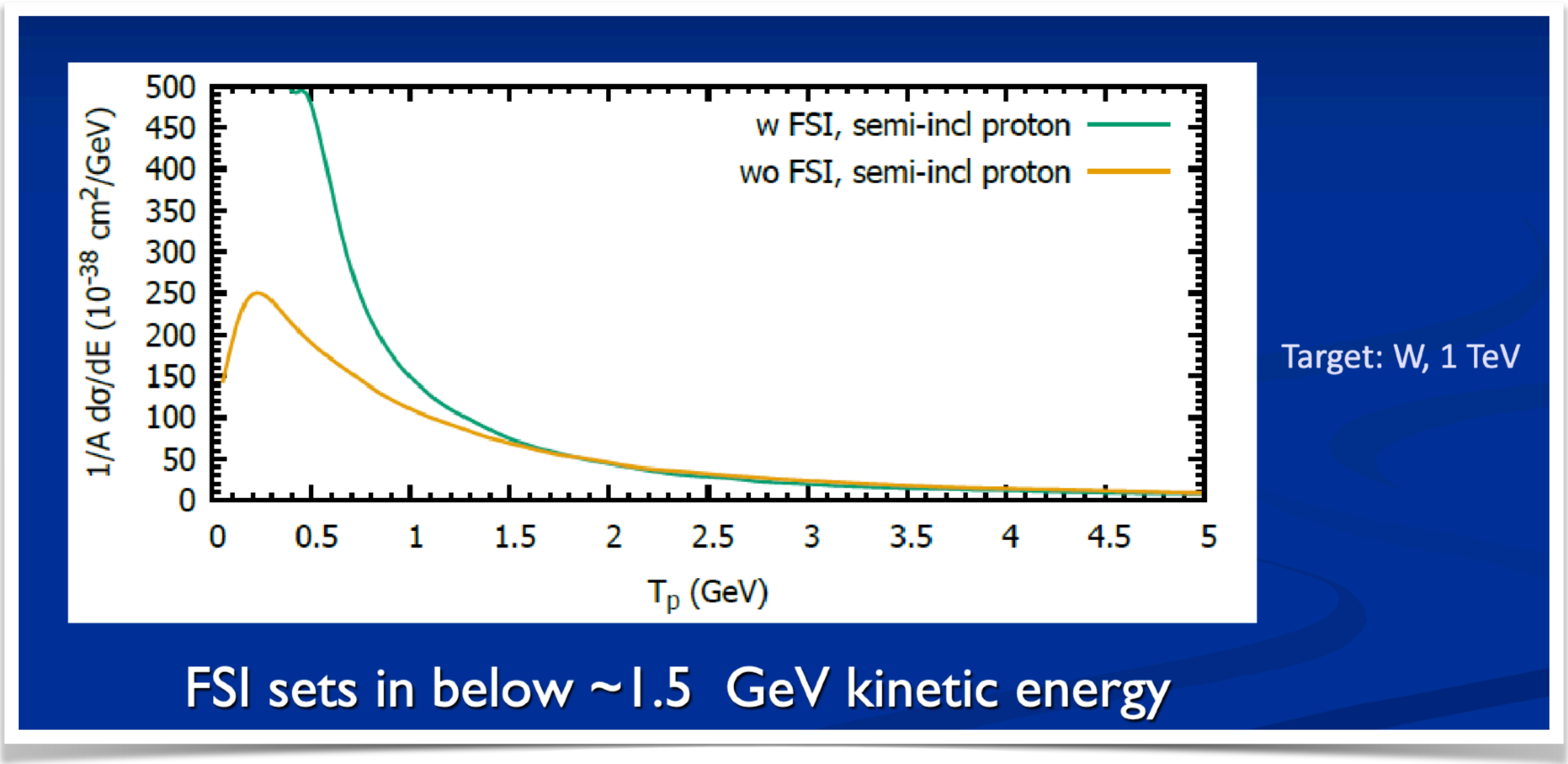


One should be cautious regarding details of hadronic final state.

- Is that important for FLARE
- It's relevant for emulsion experiments (which require >4 tracks)

Neutrino Interaction Simulation

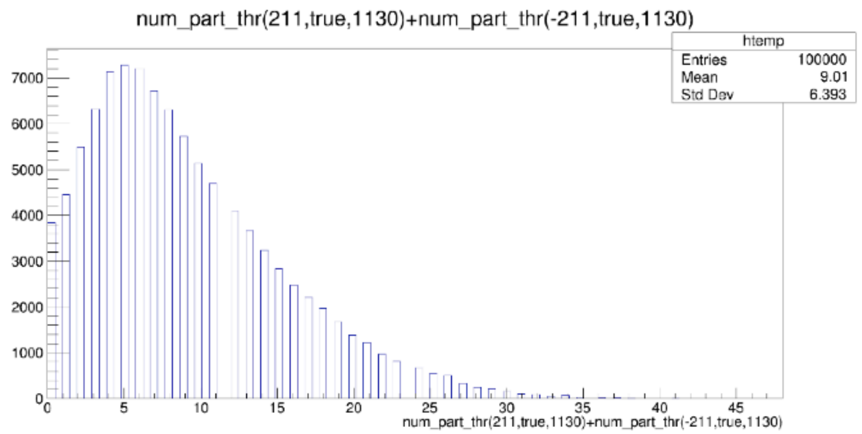
Ulrich Mosel, GIBUU, at FPF3: link



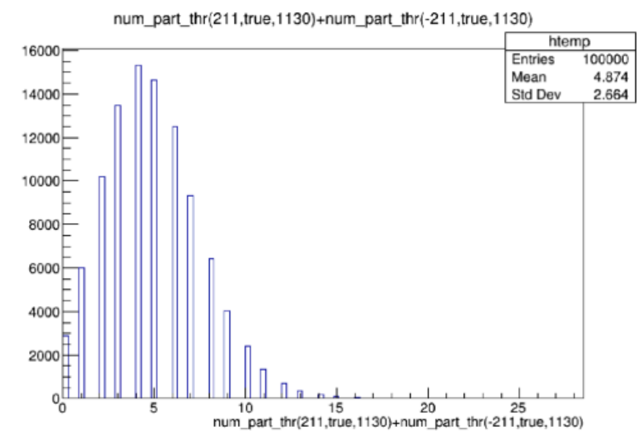
Neutrino Interaction Simulation

Preliminary NuWro results (cont)

Multiplicities of charged pions with kinetic energy above 1 GeV.



Without formation zone.



With formation zone.

Events with $\sim\geq 15$ charged pions carry information about formation zone effects.

Jan T. Sobczyk,
NuWro,
at FPF3 link

3.2.6 Formation zone

The idea of a *formation zone* is implemented and the production positions of hadrons in nucleus are shifted from the initial neutrino interaction position. The implemented model in NEUT is based on SKAT data [44,45]. The production points of the hadrons for those interactions are shifted using the formation length (L_{FZ}), where

$$L_{FZ} = p/\mu^2, \quad (11)$$

p is the momentum of the hadron and $\mu = 0.08(\mathrm{GeV/c^2})$. The actual size of the shift is determined as $L_{FZ} \times (-\log(\mathrm{rand}[0,1])$, where rand[0,1] is a random number from 0 to 1. The distribution of secondary hadron production position is shifted further from the center of the nucleus, the produced position of hadrons shifts to the outer region of the nucleus and thus reduce the probability of FSI.

Neut manual: link