Looking forward to New Physics and Neutrinos with FASER at the LHC

Tomohiro Inada
Tsinghua University

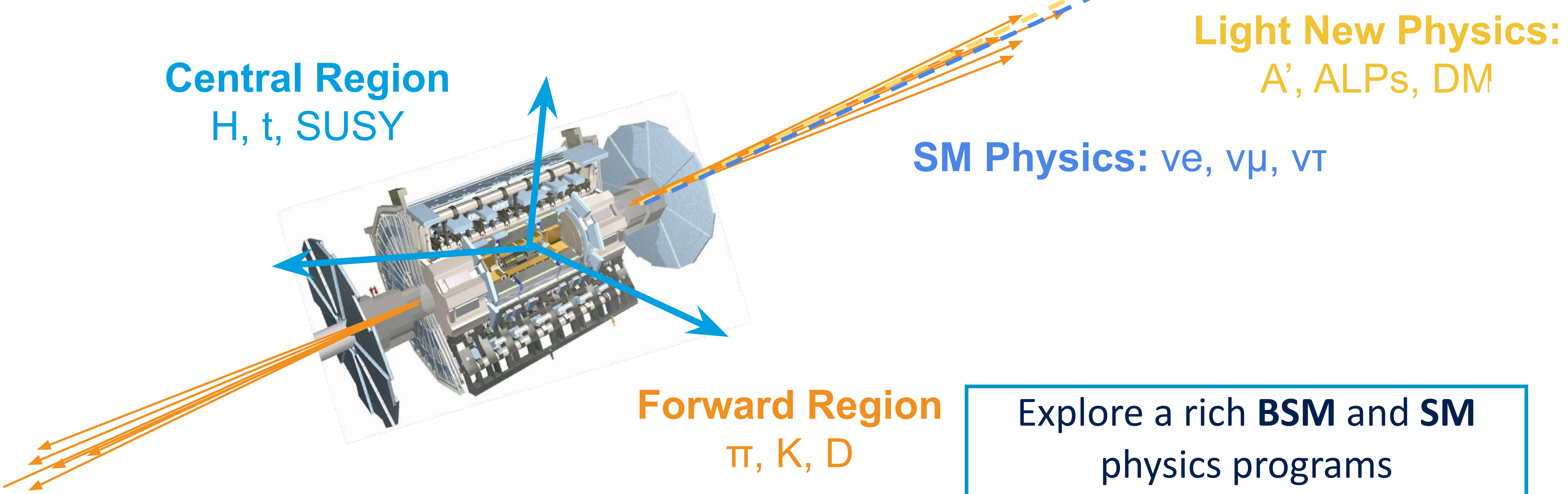
FASER - New experiment at the LHC Run3

FASER has started operation since July 2022

Idea and Motivation

The LHC produces an **intense** and strongly **collimated** beam of highly **energetic** particles in the forward direction.

10^{17} π^0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam



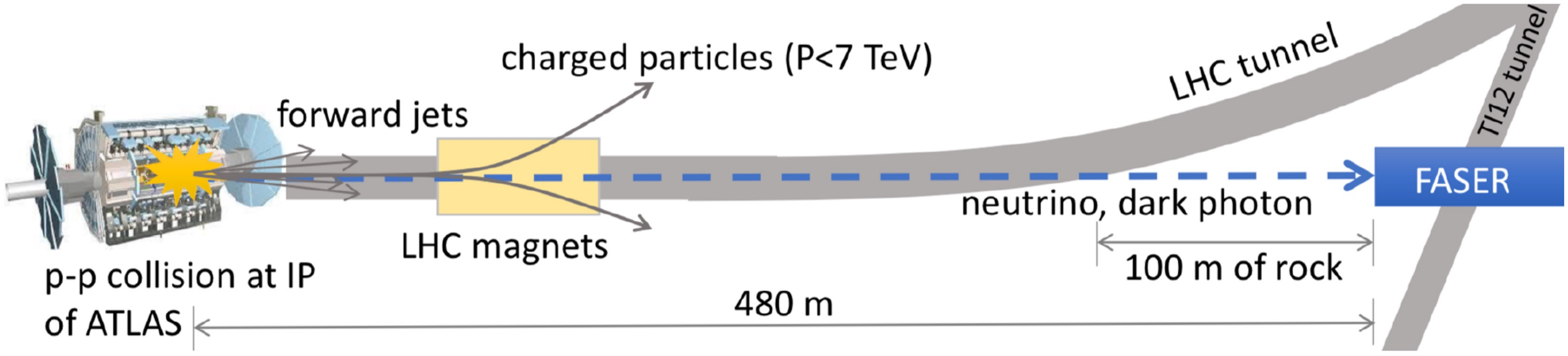
Explore a rich **BSM** and **SM** physics programs
in the far farward region

FASER

- **ForwArd Search ExpeRiment (FASER) at the LHC**
  - Placed **480 m downstream of the ATLAS IP** on the beam axis
  - Started the **operation** from July 2022 (LHC run3)

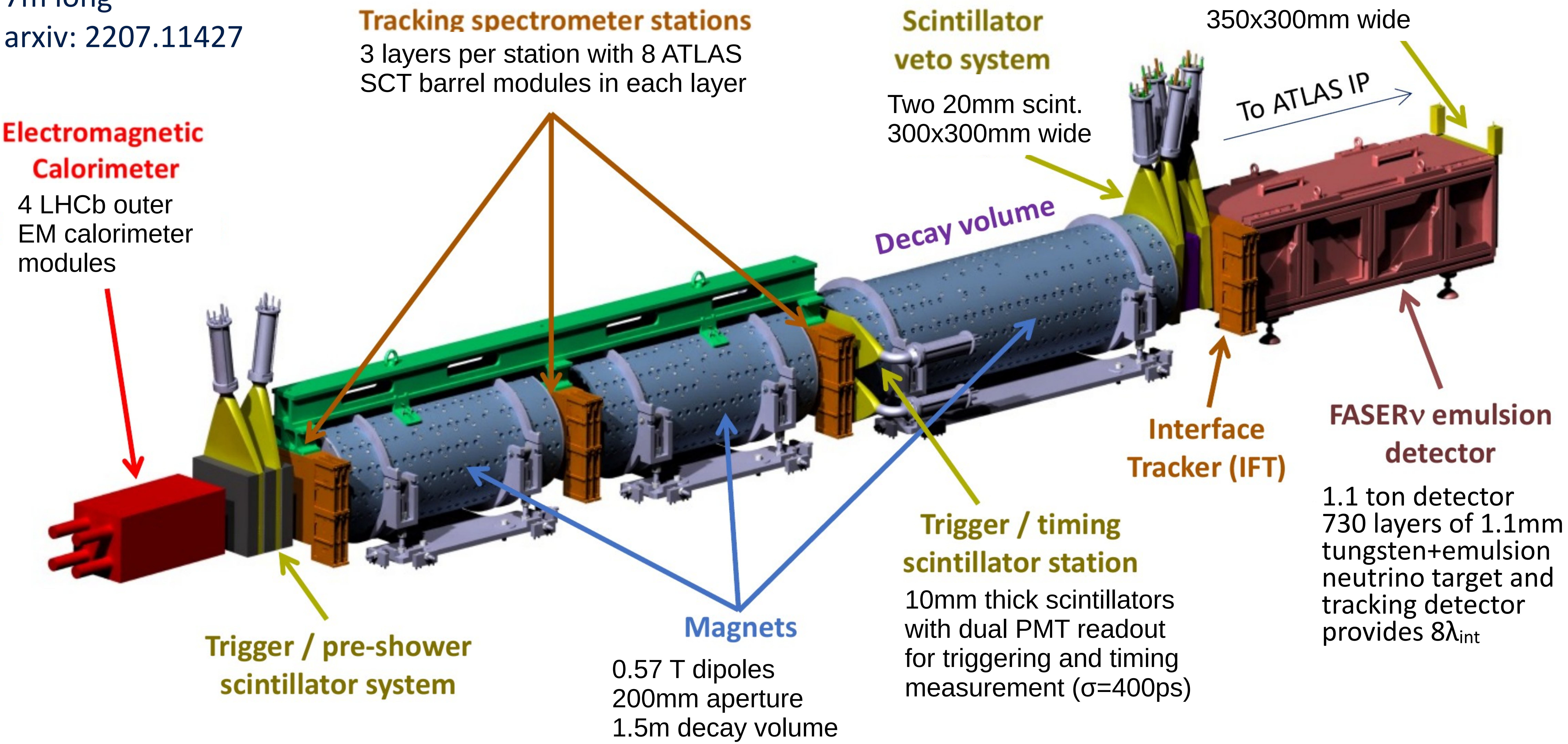
- **Favorable location**
  - **Very low background from collision**
    - **Only high-energy muon** at about 1/cm^2/sec
  - **Low radiation level from the LHC**
    - 4×10^6 1-MeV neutron/cm^2/year

- **Physics motivation**
  - **New long-lived particle searches** in **MeV-GeV masses**
  - **All flavors of neutrinos** at the **TeV-energy frontier**



FASER detector

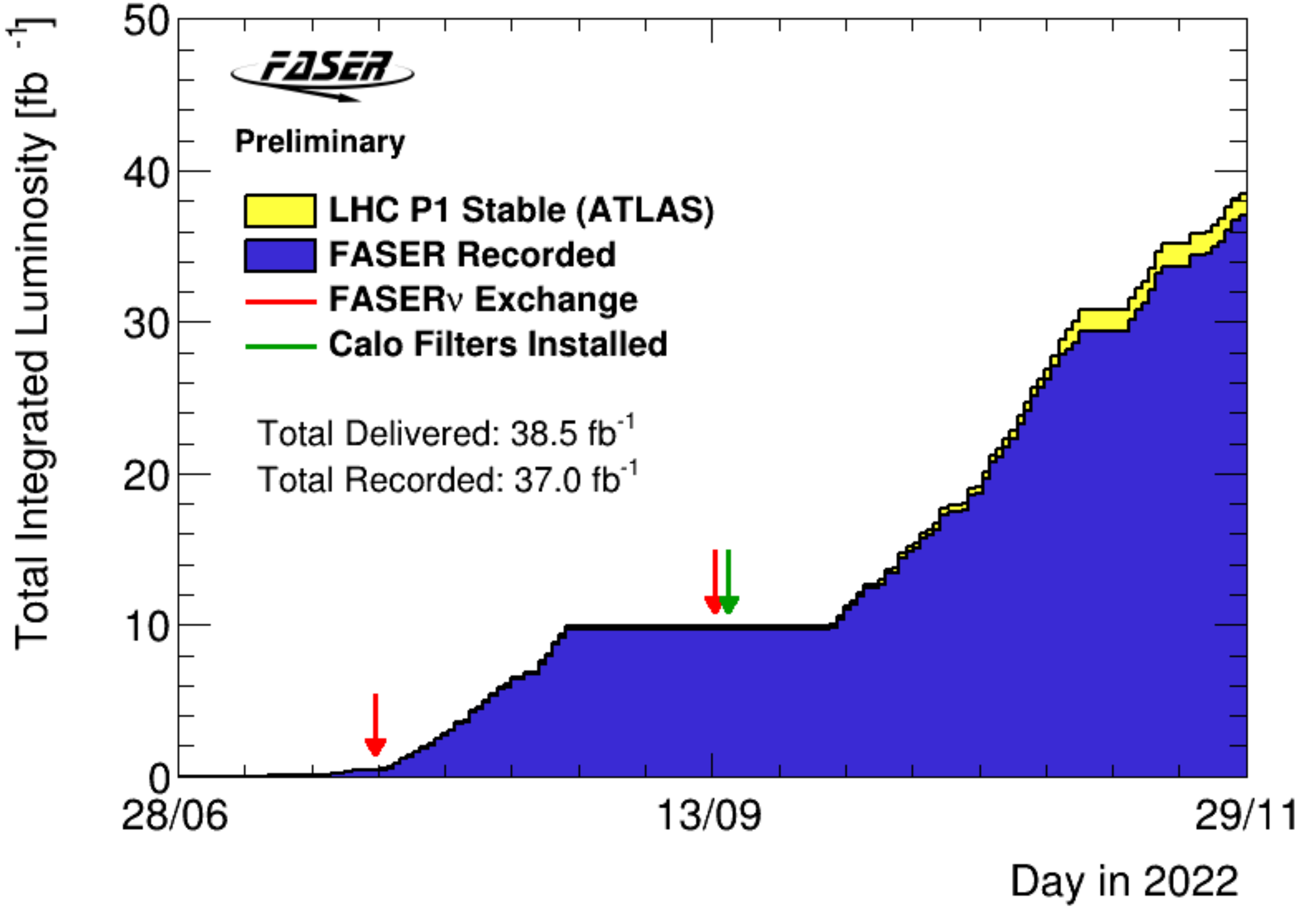
10cm radius
7m long
arxiv: 2207.11427

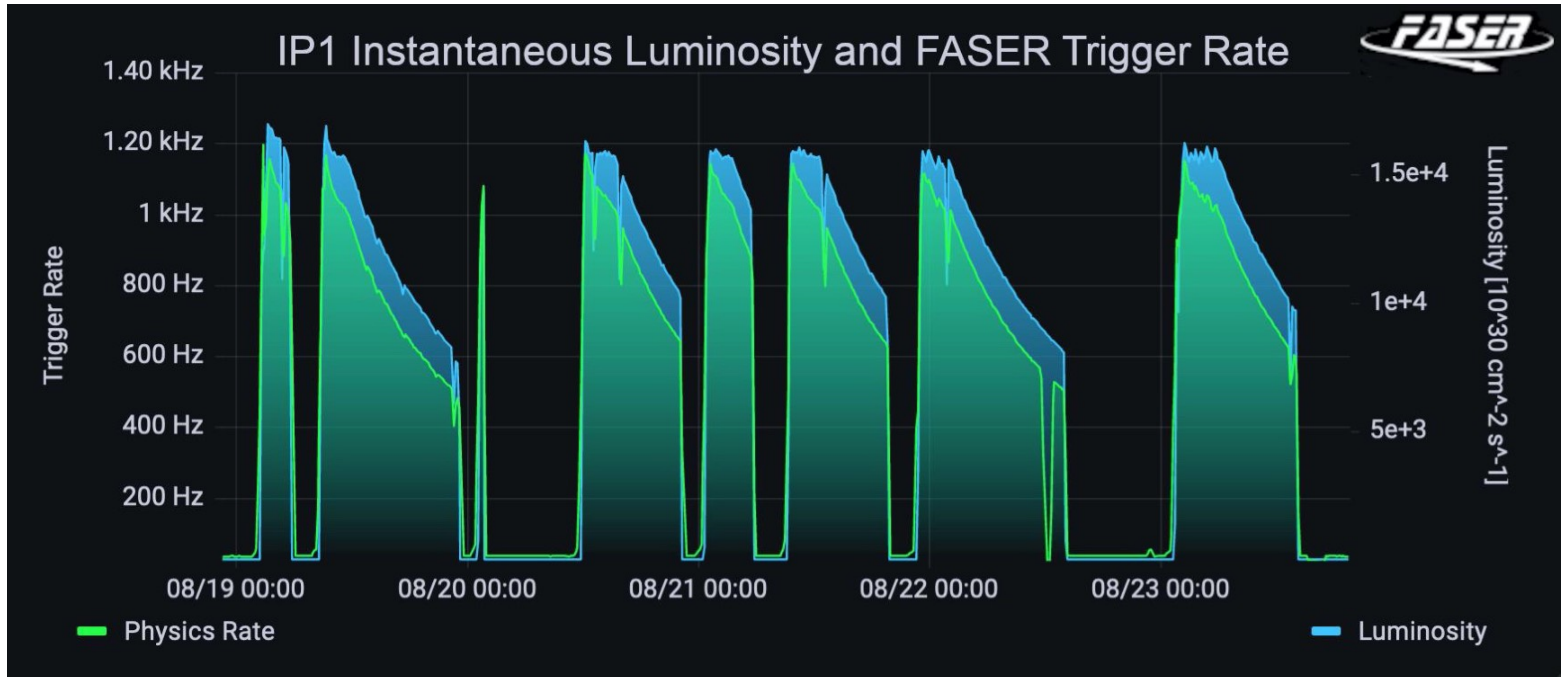


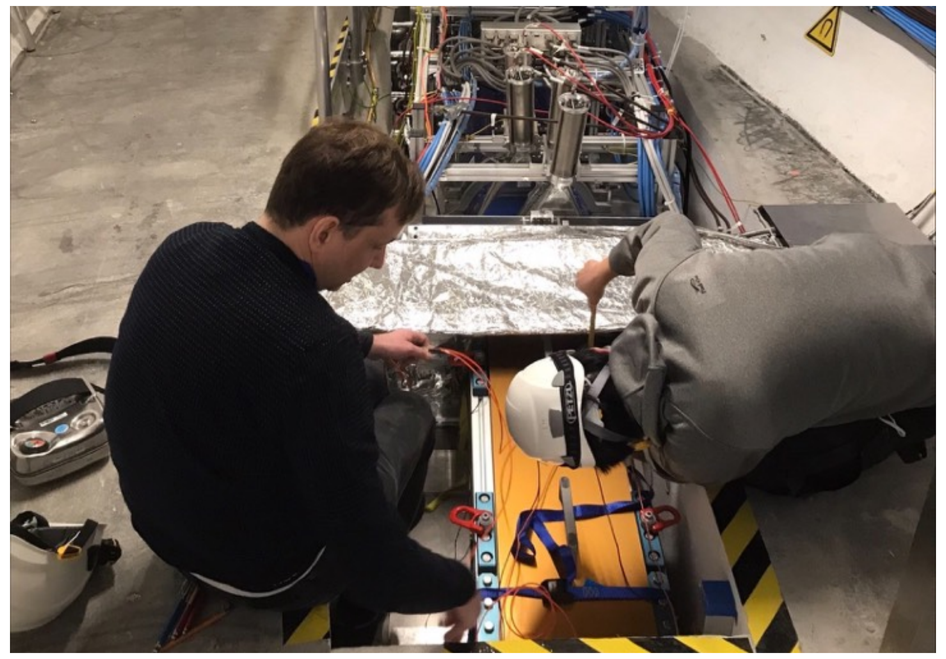
All detector components are successfully installed in T12 in March 2022

FASER Operation

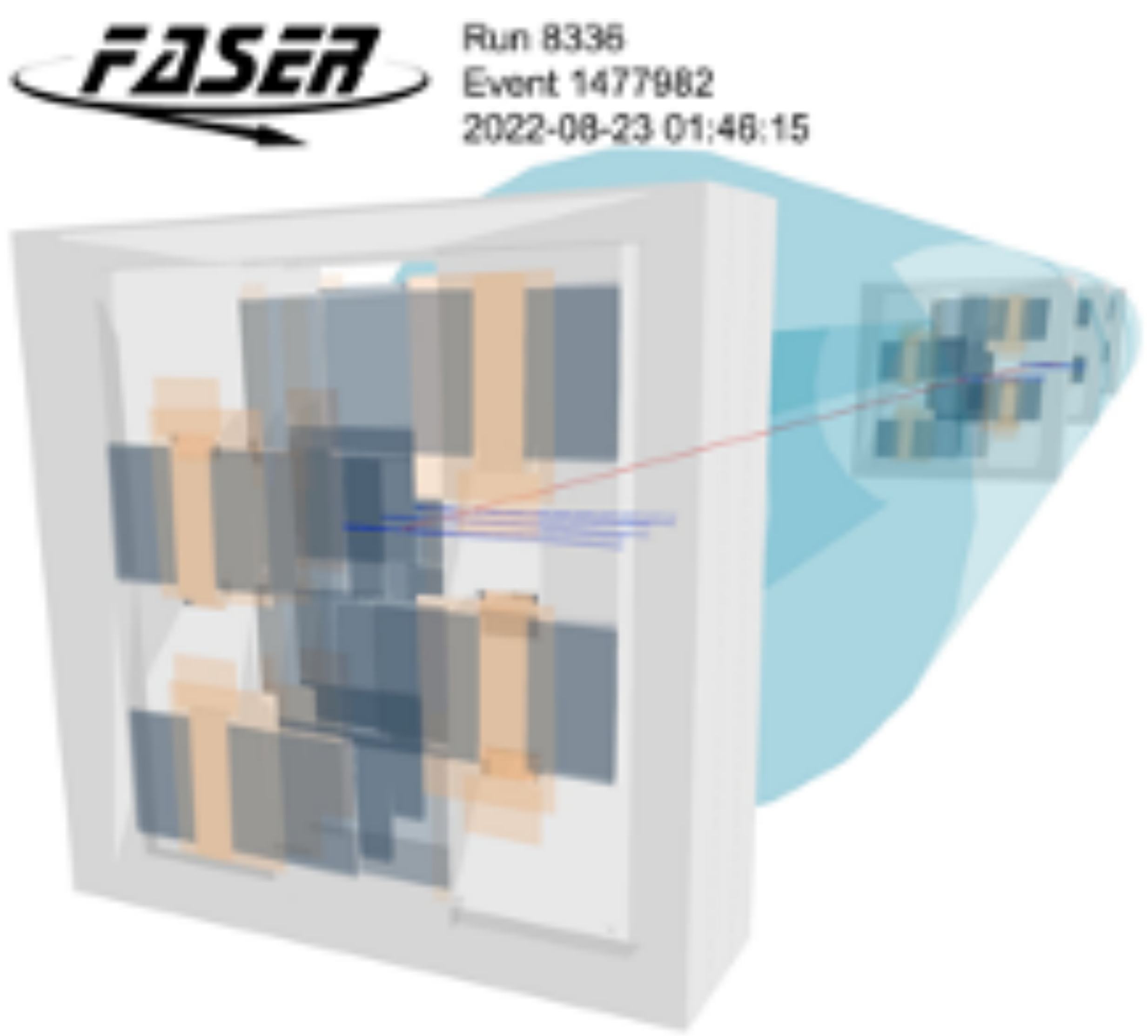
- **Successfully operated during 2022**
  - Continuous and largely automatic data-taking at up to 1.3 kHz
  - Emulsion detector exchanged twice to manage reasonable track density
    - Only for 1st box, partially filled
  - Calorimeter gain was optimized for
    - Low E (<300 GeV) before 2nd exchange
    - High E (up to 3 TeV)



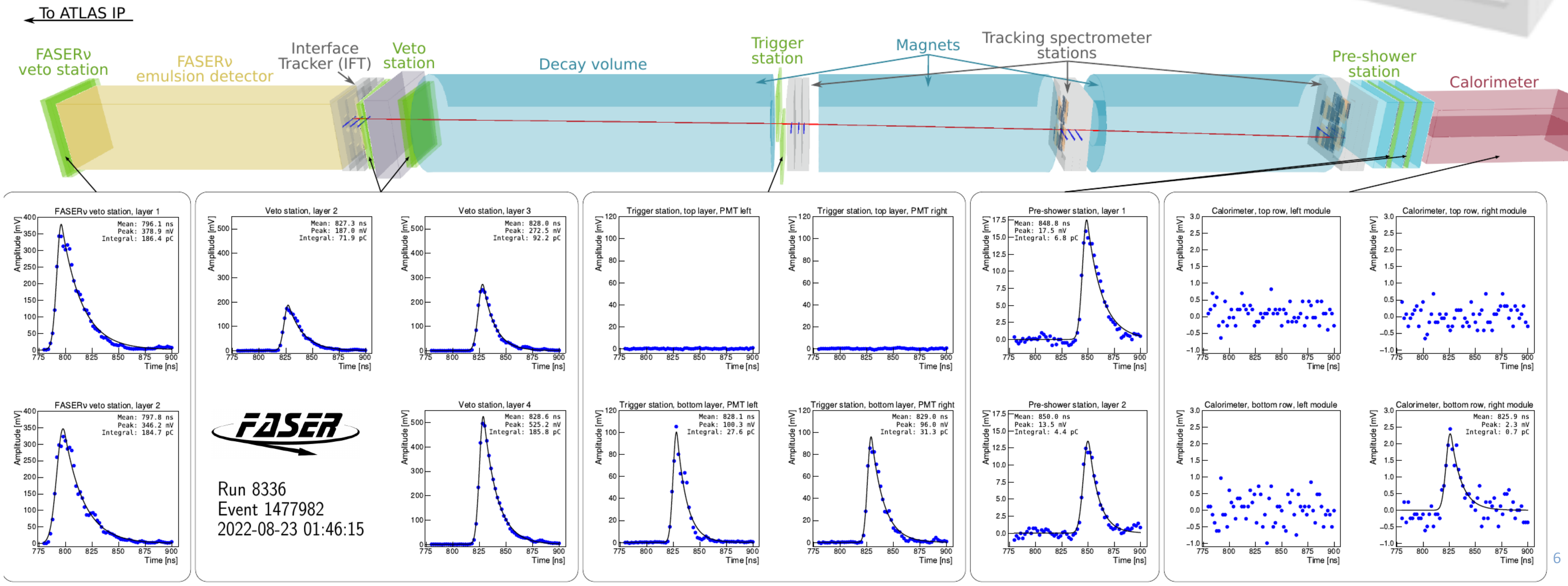




Example Collision Event



- **More than 350M single-muon events recorded**
  - Example:muon leaving track passing through full detector + scintillator deposits consistent with MIP

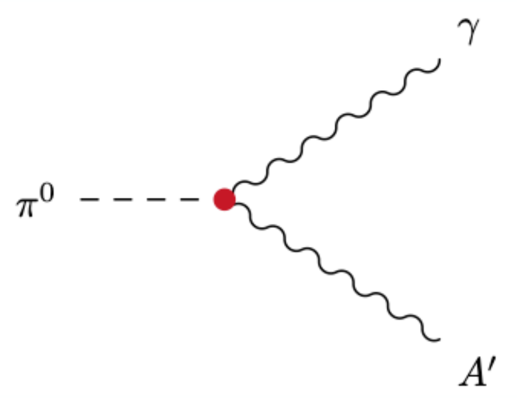


Search for Dark Photons

- **Dark photon**
  - common feature of hidden sector models
  - weakly coupling to SM via kinetic mixing(ε) with SM photon

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f \bar{f} \not{A}' f$$

  - MeV-scale A's produced mainly meson decays



$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$

  - FASER's targeted ε is A', decaying after long distance travel

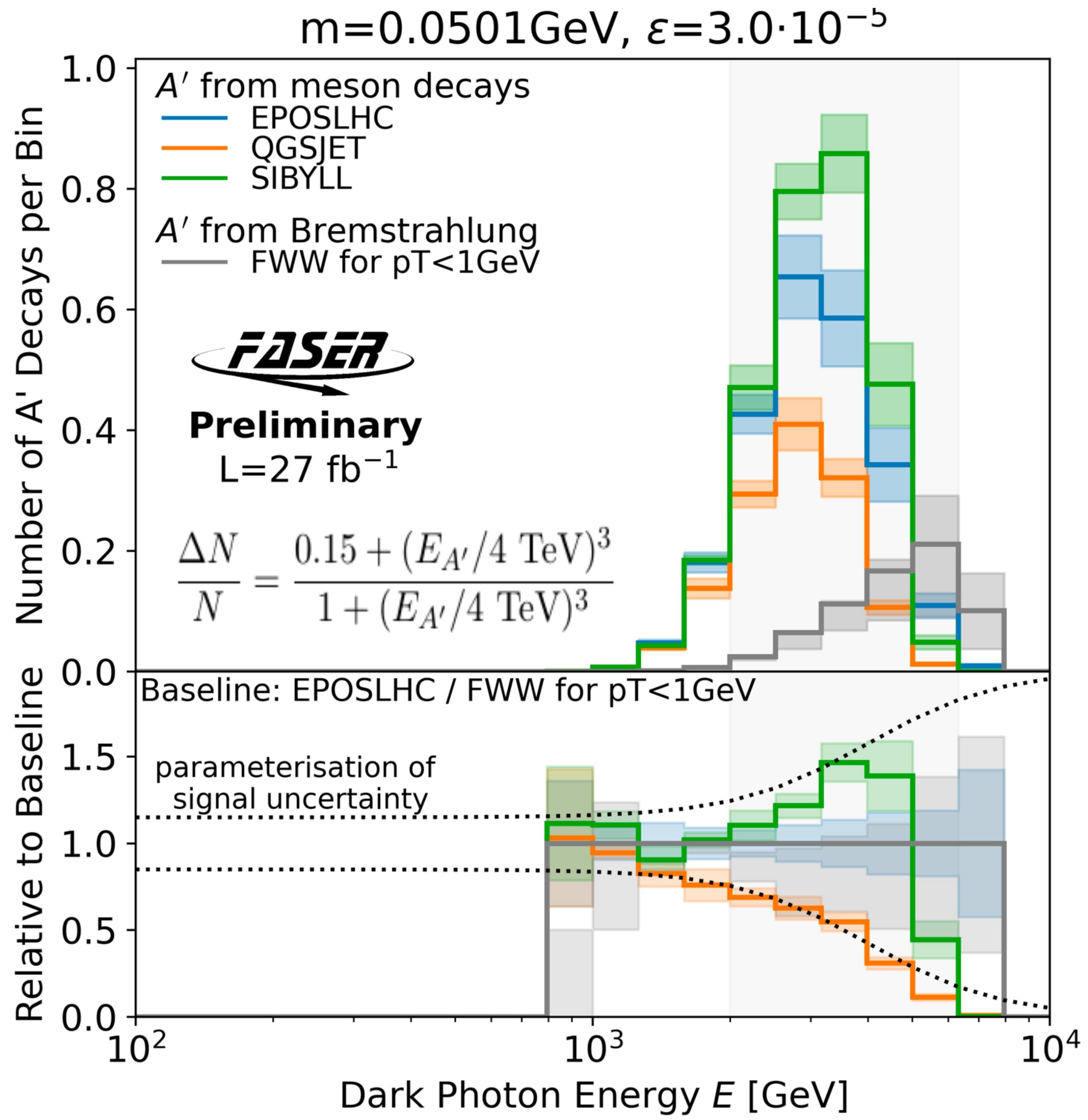
$$\bar{d} = c \frac{1}{\Gamma_{A'}} \gamma_{A'} \beta_{A'} \approx (80\ \mathrm{m})\ B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right]$$

  - Below $2m_\mu$, A' mainly decays to e^+e^- pair

- **A'-> e^+e^- simulated with FORESEE** (F. Kling et al. arXiv:2105.07077)
  - π0 and η visa EPOS-LHC generators

- **Generator uncertainty dominates**
  - Difference to QGSJET/SIBYLL, parameterized vs A' energy
    - Examples: LowE: 15%, 3.5 TeV: 50%, 6.8TeV: 85%

Signal generator uncertainty



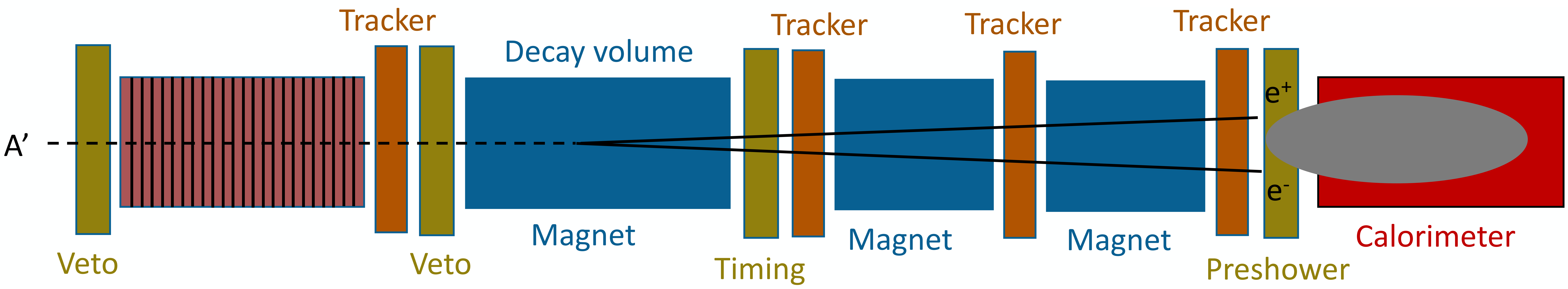
Dark Photon Event Selection

- **Signal:** select **e+e- pairs** appearing in the decay volume
- Simple, robust selection criteria optimized for discovery

Analysis was **blinded for E>100 GeV events without any veto signals**

1. Events in collision crossing, during good physics data period

2. No signal in any of veto scintillators (<40 pC ~ 0.5 MIP)



3. Timing and preshower scintillators consistent with ≥2 MIPs

4. Exactly two good quality tracks with p>20 GeV

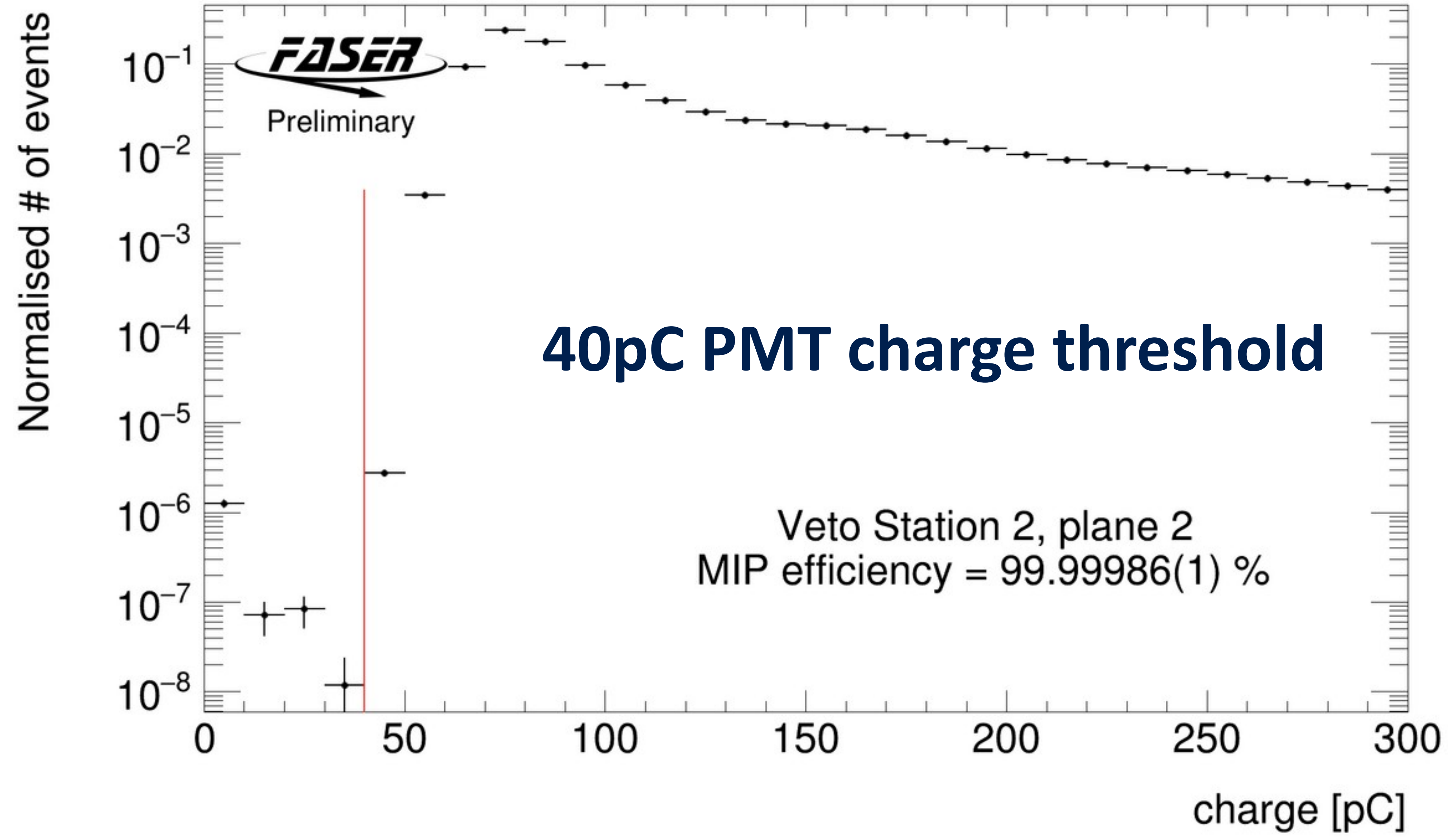
- Both tracks in fiducial tracking volume, r<95mm
- Both tracks extrapolate to r<95mm in veto scintillators

5. Calorimeter E > 500 GeV

Background estimation

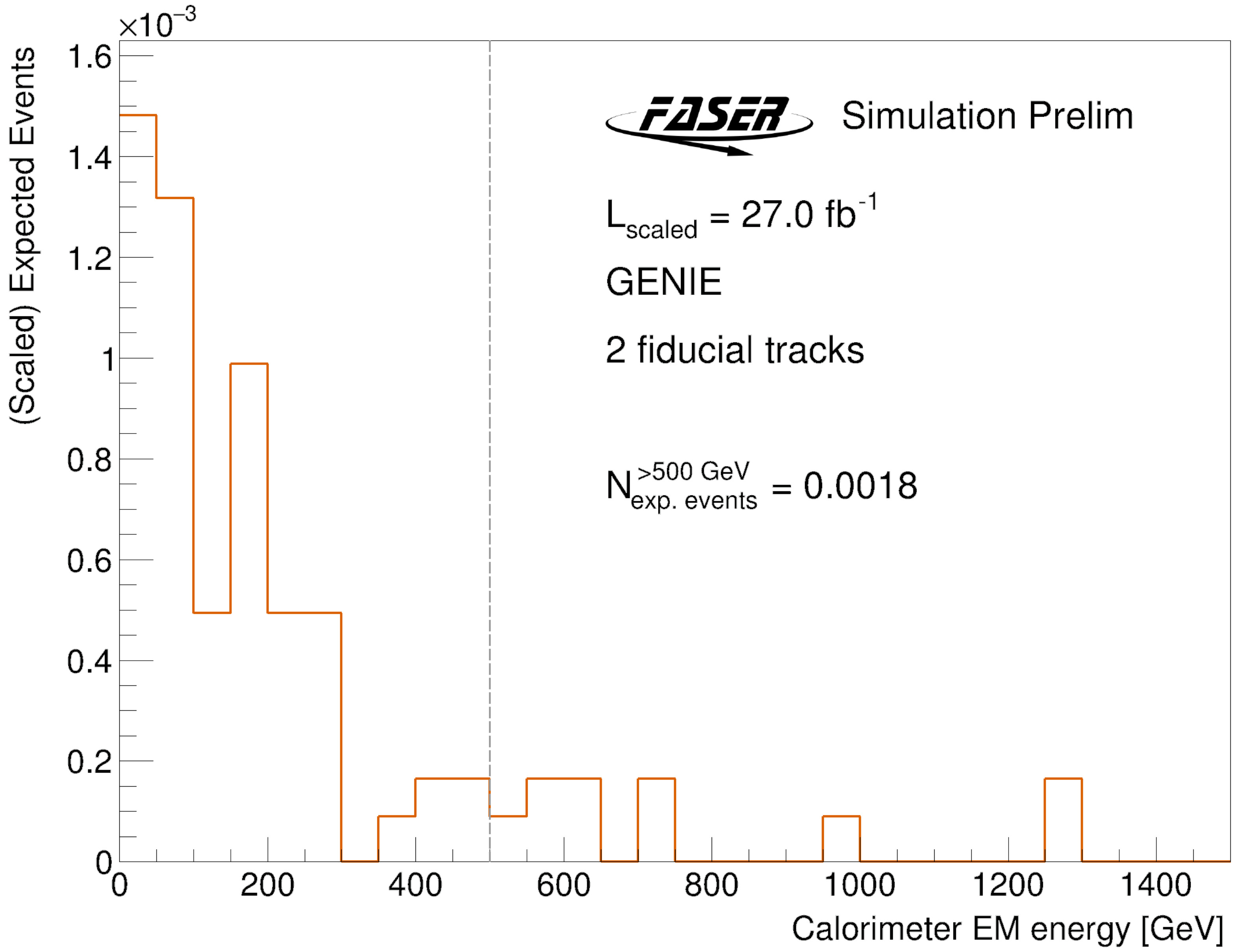
- **Veto inefficiency**

  Can MIP pass through all veto layers undetected?
  - Veto layer scintillators efficiency >99.998%
    - Measured layer-by-layer using muon tracks in trackers pointing back
  - With all layers, even 10^8 muons going through veto produces negligible background even before any other selections applied



- **Neutrino background**

  How often do neutrinos mimic signal?
  - Estimated from Genie simulation ($300ab^{-1}$)
    - Uncertainties from neutrino flux & mismodeling
  - Predicted events with E(calo)>500GeV: **0.0018±0.0024 events**
    - *Largest background in analysis*
  - Background from neutrino induced hadrons upstream found to be negligible

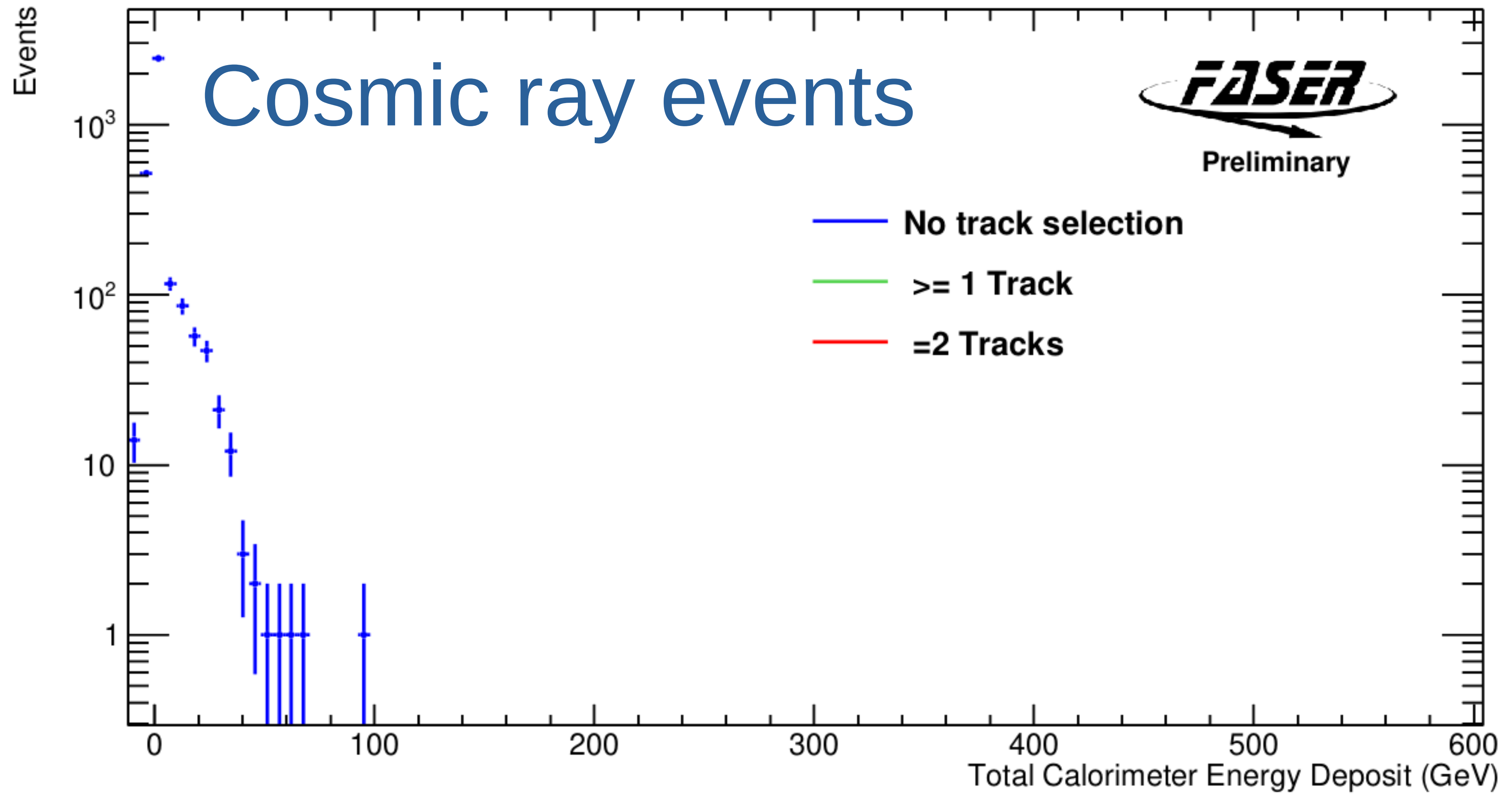


Background estimation

- **Non-collision background**

  Can neutral hadron mimic signal and accompanying muon be missed?

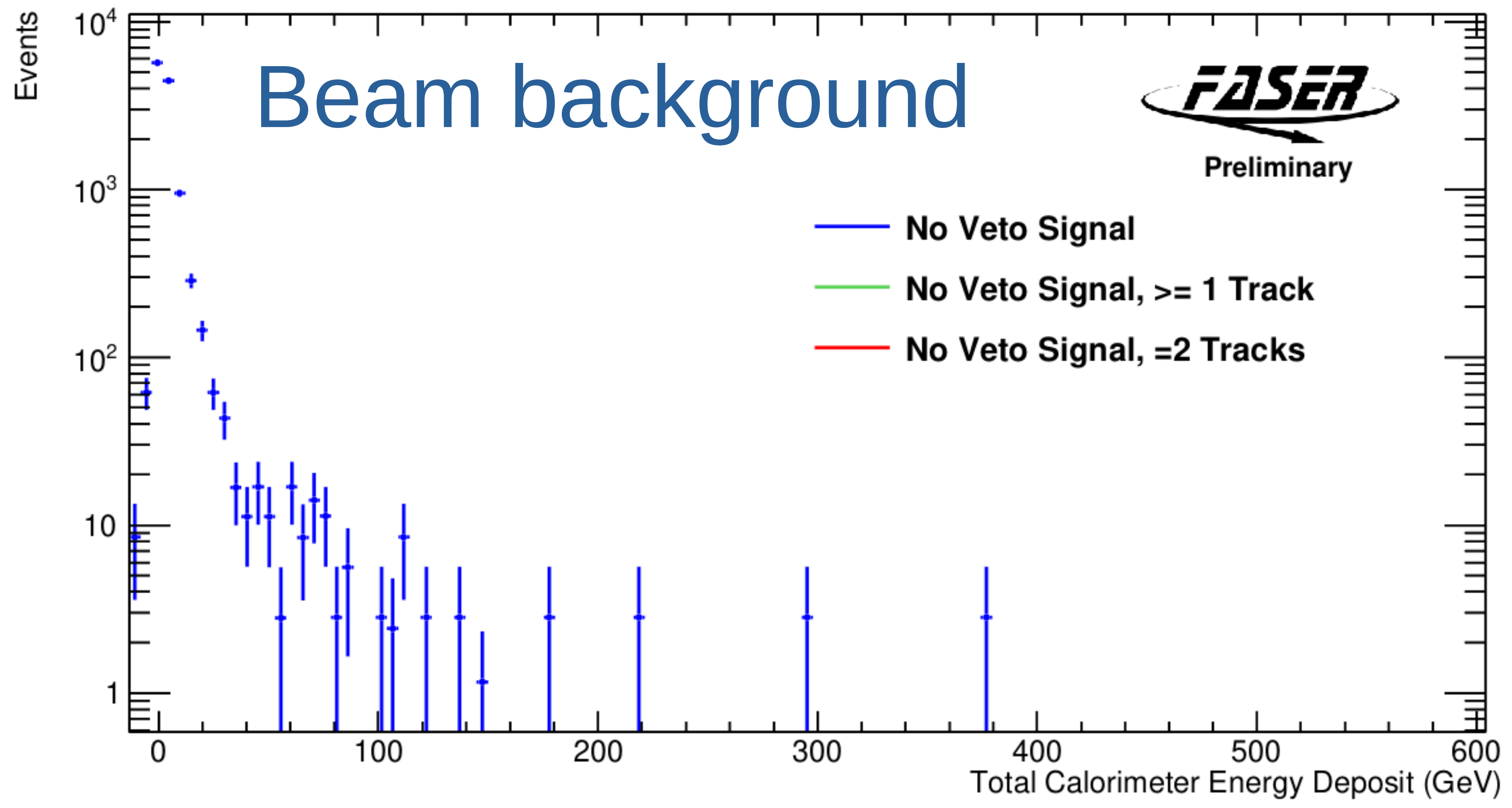
  - Cosmics measured in runs with no beam
  - Near-by beam debris measured in non-colliding bunches
  - No events observed with≥1track or E(calo) > 500 GeV individually



- **Neutral hadrons (e.g. Ks) from upstream muons interacting in decay volume**

  Can neutral hadron mimic signal and accompanying muon be missed?

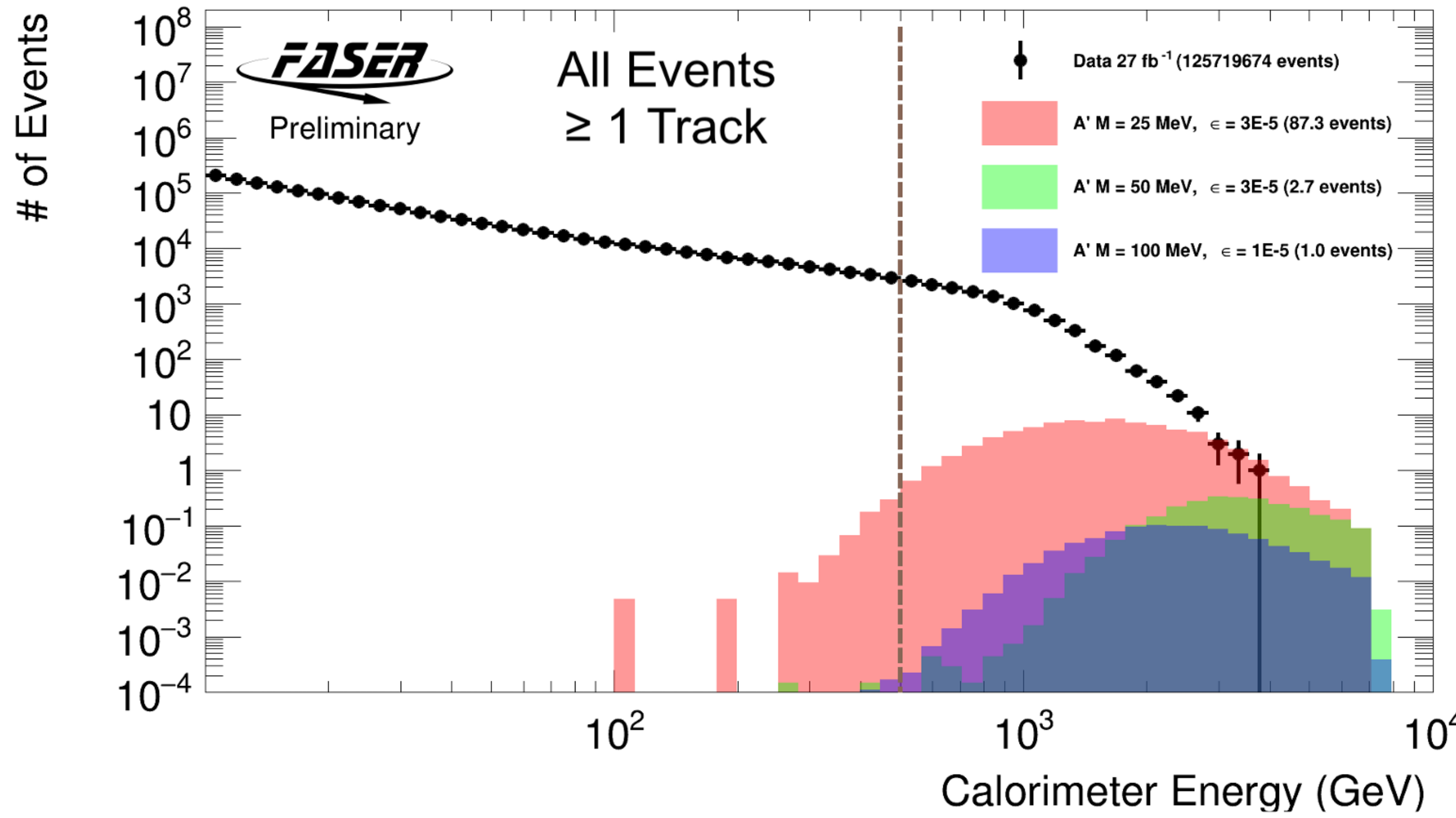
  - Heavily suppressed since
    - Muon nearly always continues after interaction
    - Has to pass though 8 interaction lengths
    - Decay products have to leave E(calo)>500GeV
  - Estimated from lower E events with 2 and 3 tracks and different veto conditions: **$(2.2\pm3.1)\times10^{-4}$ events**

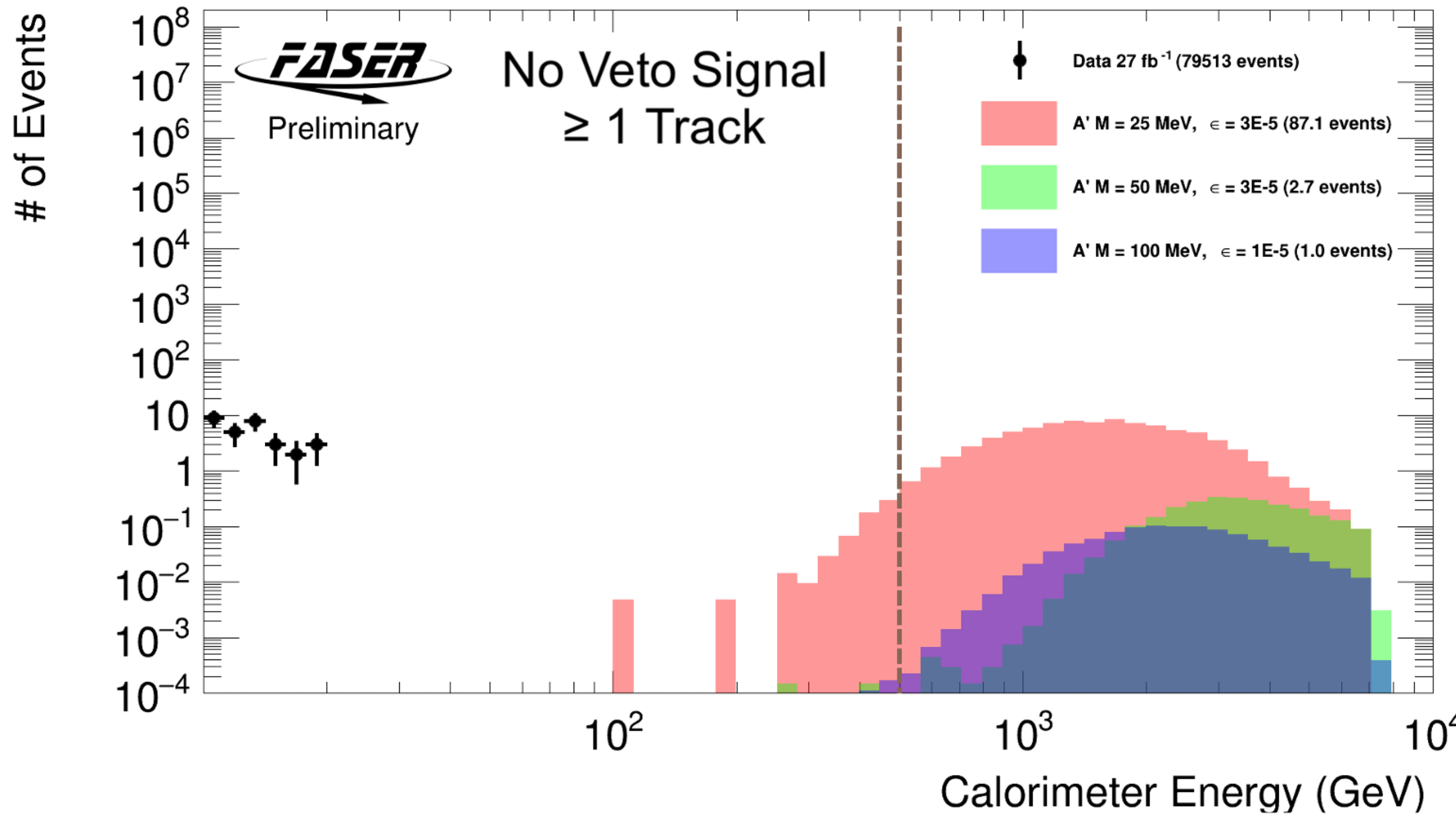


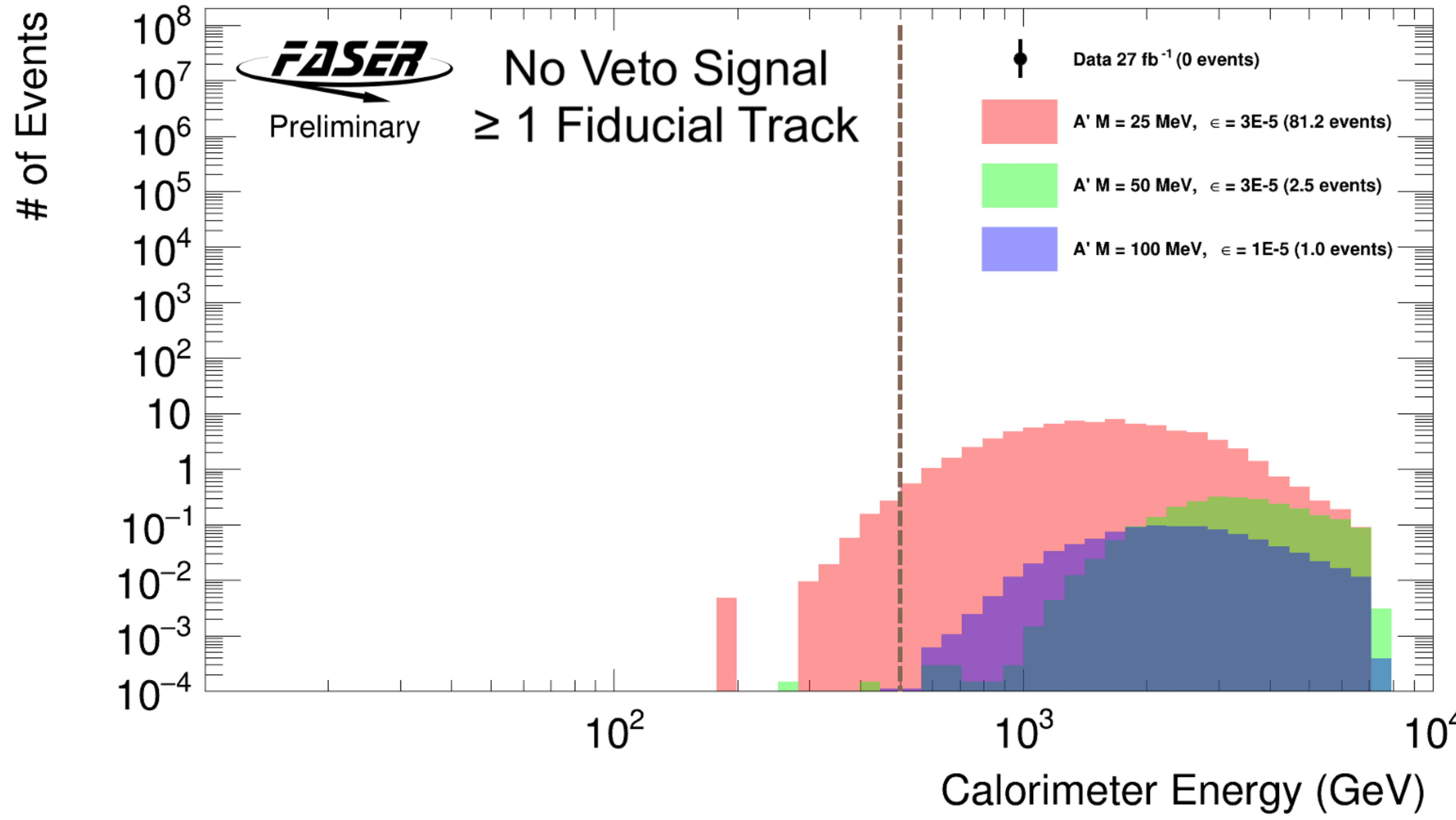
Results

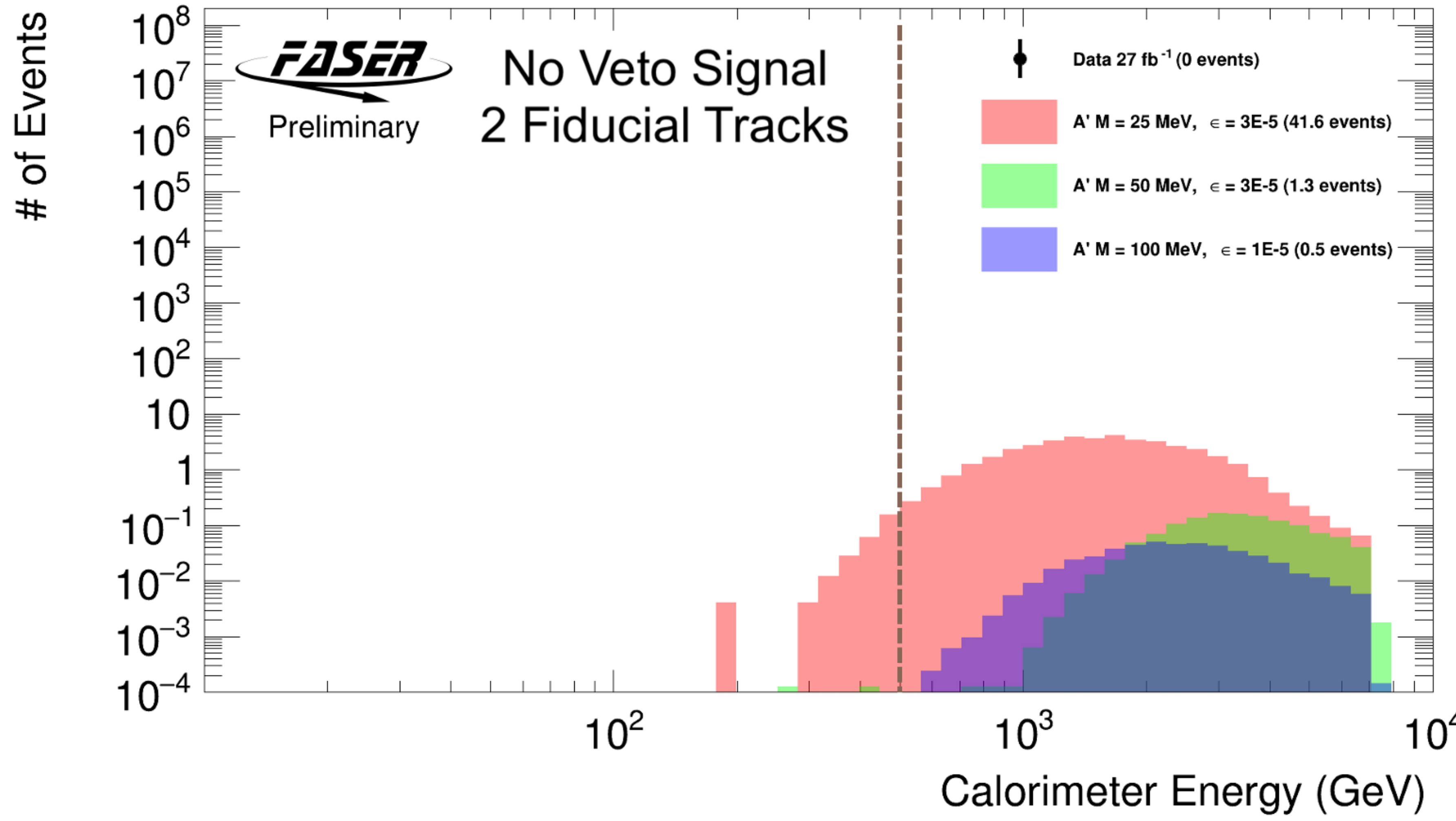
Dark Photon - data

Total background: **0.0020±0.0024 evts**, **No events seen** in unblinded signal region



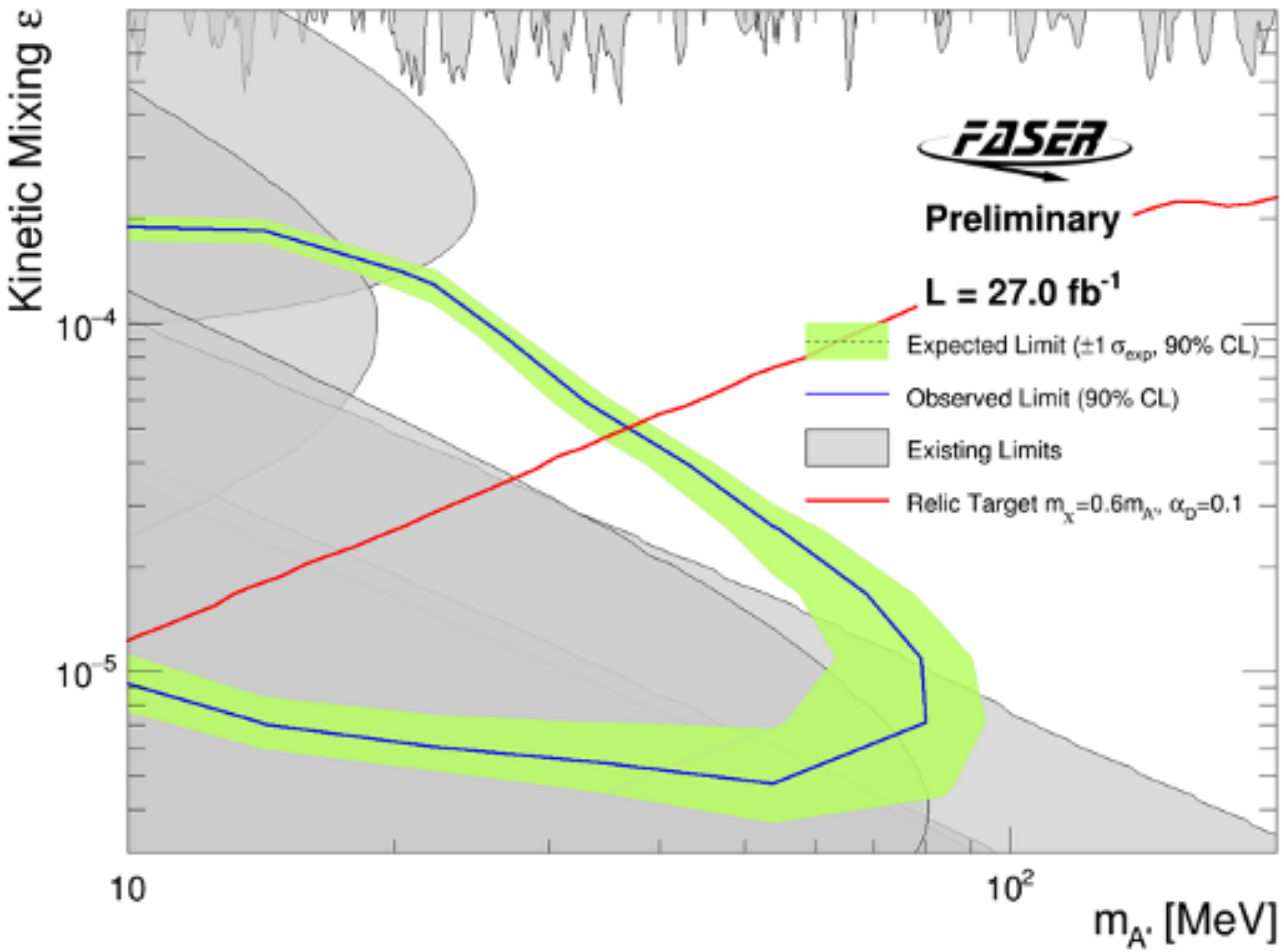






Dark Photon - Exclusion

First Results!



Based on this null results, FASER sets limits in previously **unexplored parameter space**!

- Probing region **interesting from thermal relic target**


Not only the limit…

arXiv > hep-ex > arXiv:2303.14185

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High Energy Physics – Experiment

[Submitted on 24 Mar 2023]

First Direct Observation of Collider Neutrinos with FASER at the LHC

FASER Collaboration: Henso Abreu, John Anders, Claire Antel, Akitaka Ariga, Tomoko Ariga, Jeremy Atkinson, Florian U. Bernlochner, Tobias Blesgen, Tobias Boeckh, Jamie Boyd, Lydia Brenner, Franck Cadoux, David W. Casper, Charlotte Cavanagh, Xin Chen, Andrea Coccaro, Ansh Desai, Sergey Dmitrievsky, Monica D'Onofrio, Yannick Favre, Deion Fellers, Jonathan L. Feng, Carlo Alberto Fenoglio, Didier Ferrere, Stephen Gibson, Sergio Gonzalez-Sevilla, Yuri Gornushkin, Carl Gwilliam, Daiki Hayakawa, Shih-Chieh Hsu, Zhen Hu, Giuseppe Iacobucci, Tomohiro Inada, Sune Jakobsen, Hans Joos, Enrique Kajomovitz, Hiroaki Kawahara, Alex Keyken, Felix Kling, Daniela Köck, Umut Kose, Rafaella Kotitsa, Susanne Kuehn, Helena Lefebvre, Lorne Levinson, Ke Li, Jinfeng Liu, Jack MacDonald, Chiara Magliocca, Fulvio Martinelli, Josh McFayden, Matteo Milanesio, Dimitar Mladenov, Théo Moretti, Magdalena Munker, Mitsuhiro Nakamura, Toshiyuki Nakano, Marzio Nessi, Friedemann Neuhaus, Laurie Nevay, Hidetoshi Otono, Hao Pang, Lorenzo Paolozzi, Brian Petersen, Francesco Pietropaolo, Markus Prim, Michaela Queitsch-Maitland, Filippo Resnati, Hiroki Rokujo, Elisa Ruiz-Choliz, Jorge Sabater-Iglesias, Osamu Sato, Paola Scampoli, Kristof Schmieden, Matthias Schott, Anna Sfyrla, Savannah Shively, Yosuke Takubo, Noshin Tarannum, Ondrej Theiner, Eric Torrence, Serhan Tufanli, Svetlana Vasina, Benedikt Vormwald, Di Wang, Eli Welch, Stefano Zambito

We report the first direct observation of neutrino interactions at a particle collider experiment. Neutrino candidate events are identified in a 13.6 TeV center-of-mass energy pp collision data set of 35.4 fb^{-1} using the active electronic components of the FASER detector at the Large Hadron Collider. The candidates are required to have a track propagating through the entire length of the FASER detector and be consistent with a muon neutrino charged-current interaction. We infer 153^{+12}_{-13} neutrino interactions with a significance of 16 standard deviations above the background-only hypothesis. These events are consistent with the characteristics expected from neutrino interactions in terms of secondary particle production and spatial distribution, and they imply the observation of both neutrinos and anti-neutrinos with an incident neutrino energy of significantly above 200 GeV.

Comments: Submitted to PRL on March 24 2023
Subjects: **High Energy Physics – Experiment (hep-ex)**; High Energy Physics – Phenomenology (hep-ph)
Report number: CERN-EP-2023-056
Cite as: arXiv:2303.14185 **[hep-ex]**
(or arXiv:2303.14185v1 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2303.14185

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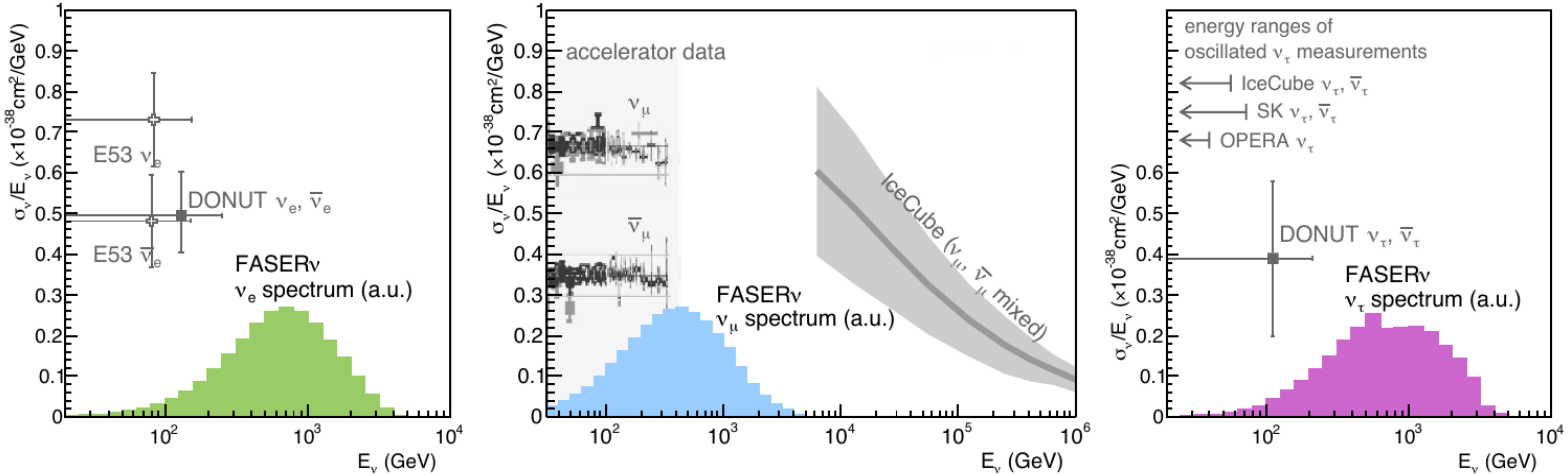
Not only the limit...

Collider neutrino

For 35 fb^{-1}	ν_e	ν_μ	ν_τ
Main source	Kaons	Pions	Charm
# traversing FASERν	~10^{10}	~10^{11}	~10^{8}
# interacting in FASERν	≈200	≈1200	≈4

- **Neutrinos** produced copiously **in decays of forward hadrons**
  - Highly energetic (TeV scale)->high interaction cross-section
- Extends FASER physics program into **SM measurements**
  - Targets measurement of highest energy man-made neutrinos
  - Energy range complementary to existing neutrino experiments
  - **the FASERnu detector** enables to be sensitive to **all-flavors**, in particular, **tau neutrino** is interesting



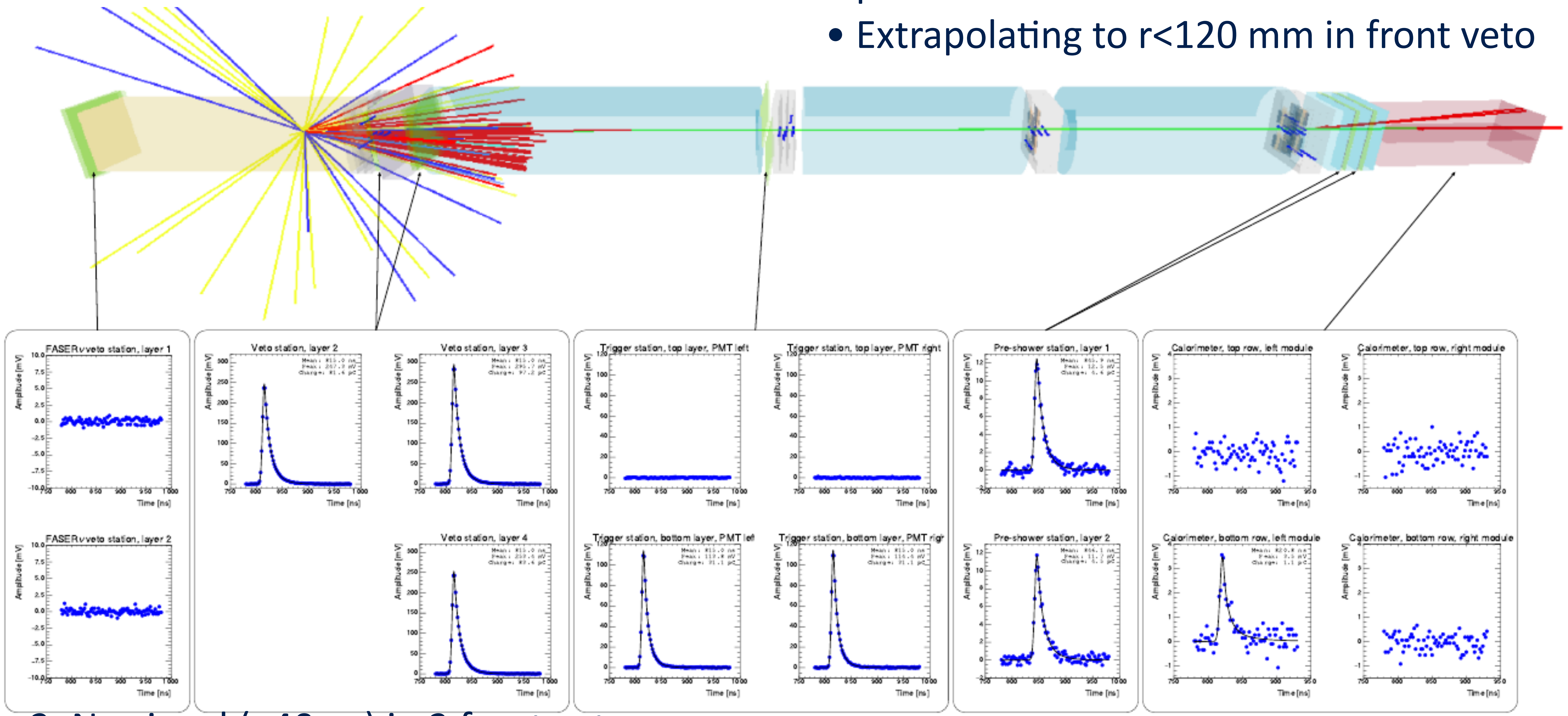
Study at colliders originally proposed by Rújula and Rückl in 1984

Observing Neutrino Candidates in FASER spectrometer

- Try to make a first observation of neutrinos using trackers and veto system
- Signal: **no signal in two front veto** and **one high momentum track** in the rest of detector

1. Good collision events

5. Exactly **1 good fiducial** (r < 95 mm) track
- p_T>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

4. Timing and preshower consistent with ≥1 MIP

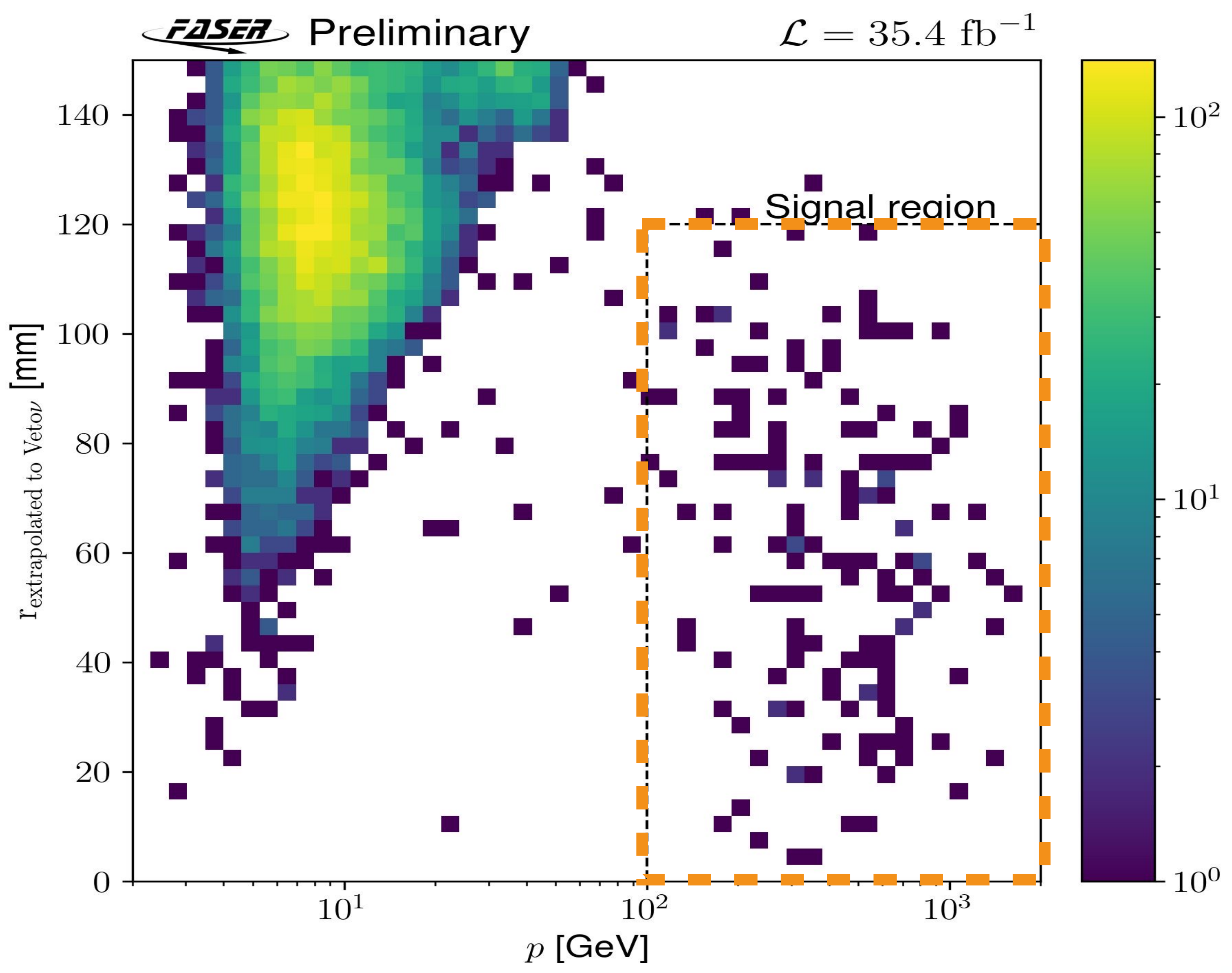
Expect **151 ± 41 events** from **GENIE simulation**

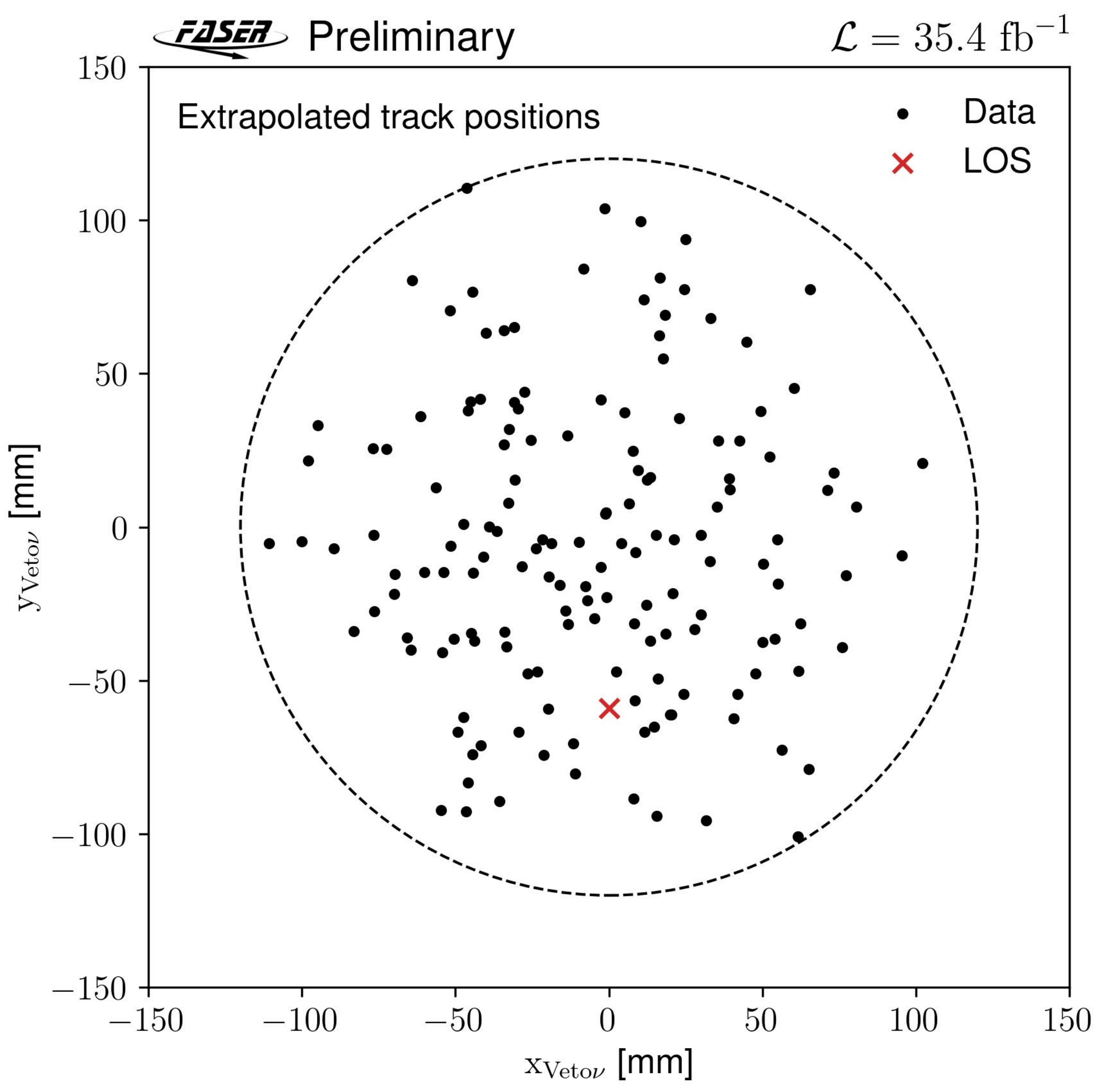
- Uncertainty from DPMJET vs SIBYLL
  - No experimental errors
  - Currently not trying to measure cross section

Neutrino results

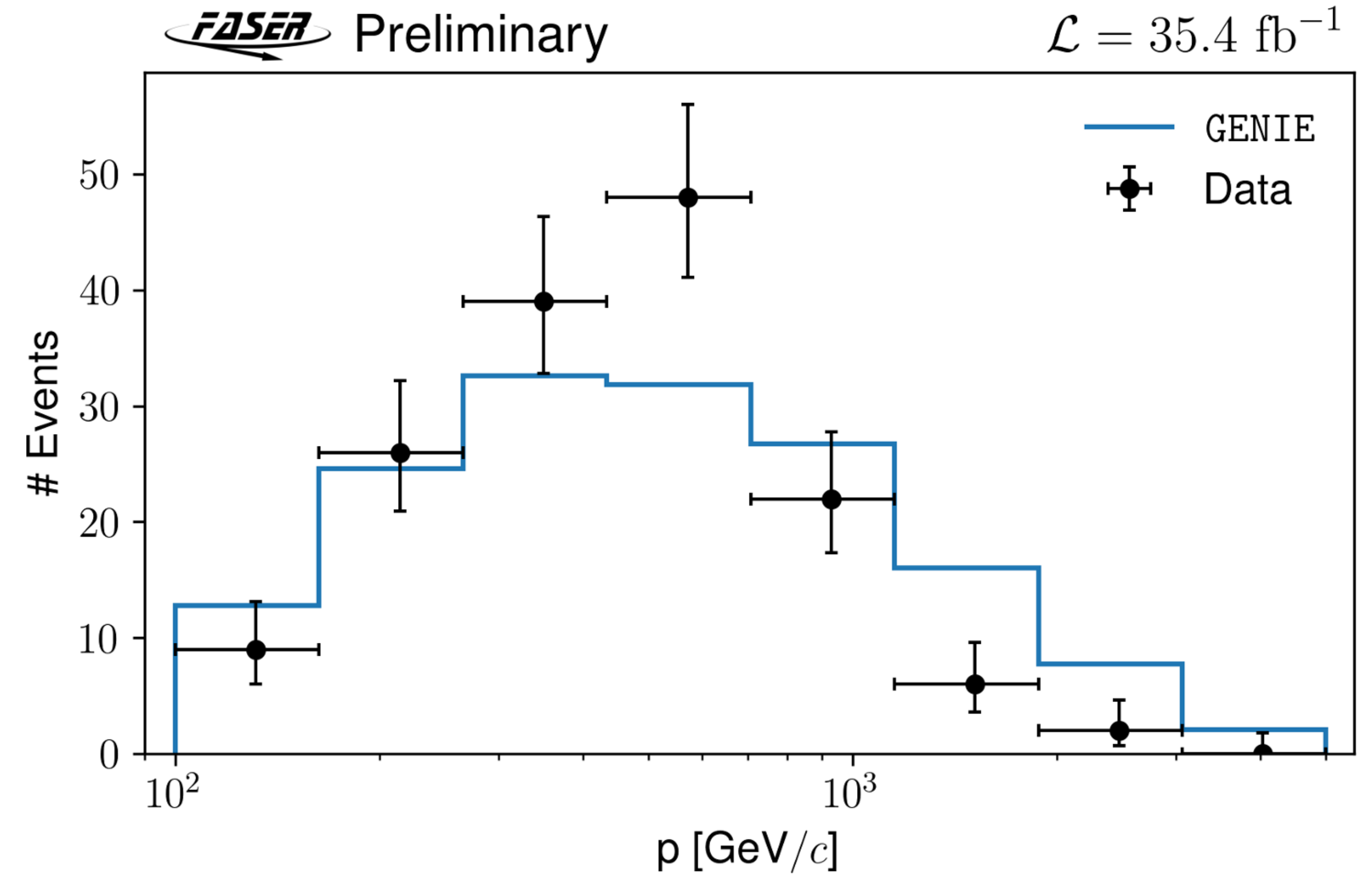
- Upon unblinding find **153 events** with no veto signal
  - Just 10 events with one veto signal
- **First direct detection of collider neutrinos!**
  - **With signal significance of 16σ**
- Candidate neutrino events match expectation from signal
  - Most events have high μ momentum

Candidate	Events
ν enriched Events (Passed all event selection)	153, (151±41, MC)
Events (1 veto signal at the first layer)	4
Events (1 veto signal at the second layer)	6
Events (Veto signals for both layers)	64014695





Track momentum distribution



Note: no acceptance corrections nor any uncertainties in the plot

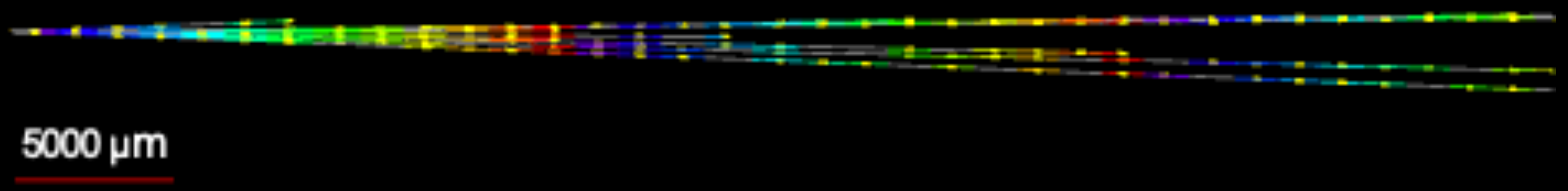
Neutrino Event display

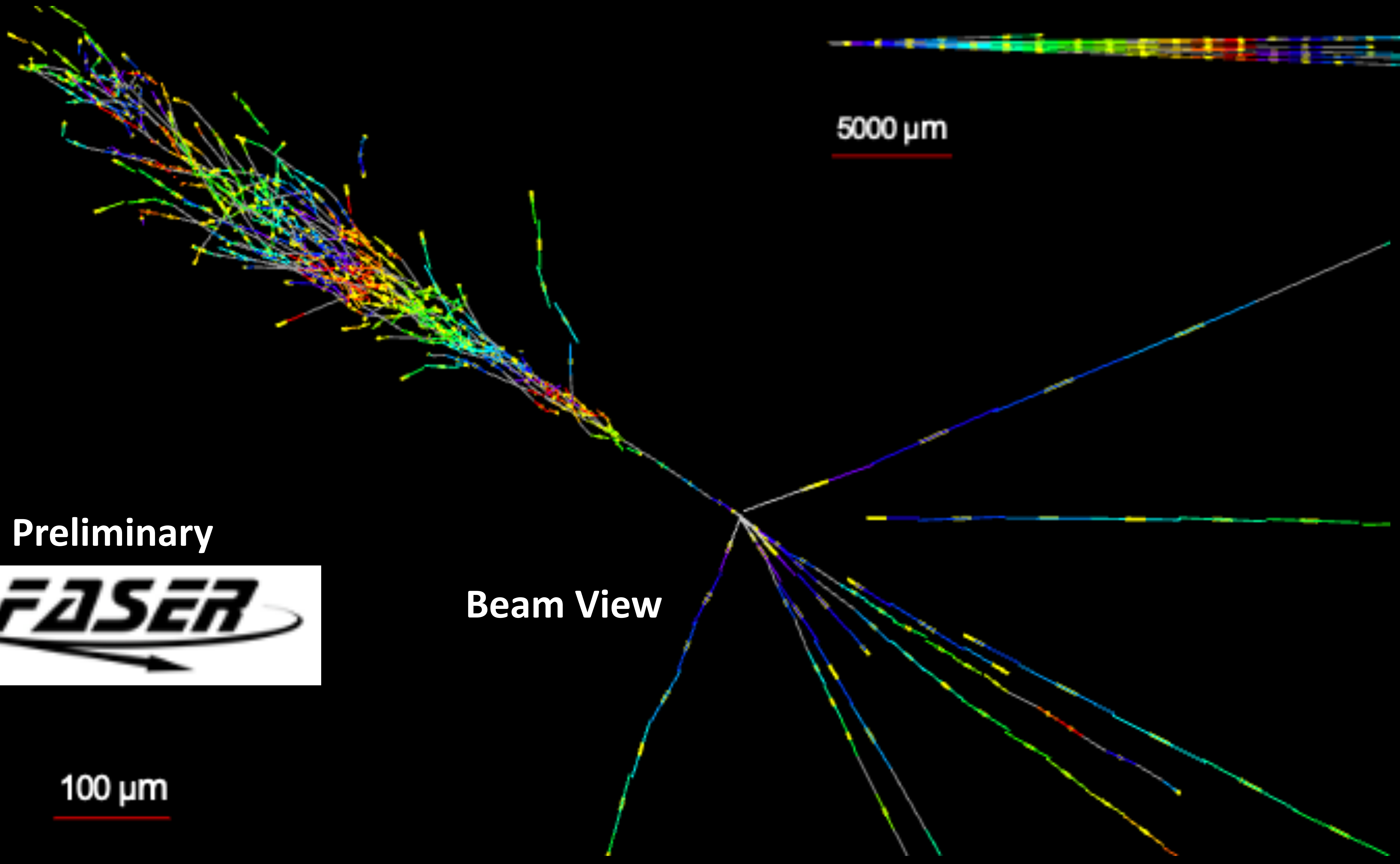
r_{VetoNu}[mm]	$r_{IFT}[mm]$	$r_{Tracker}[mm]$	θ [mrad]	p [GeV]	q	clusters IFT
57.2	55.8	54.6	2.5	843.8	-1	57

Electron Neutrino Event "Candidate"

- **Analysis of FASERν emulsion detector underway**
  - Have multiple candidates including highly ν_e like event

Side View





Beam View

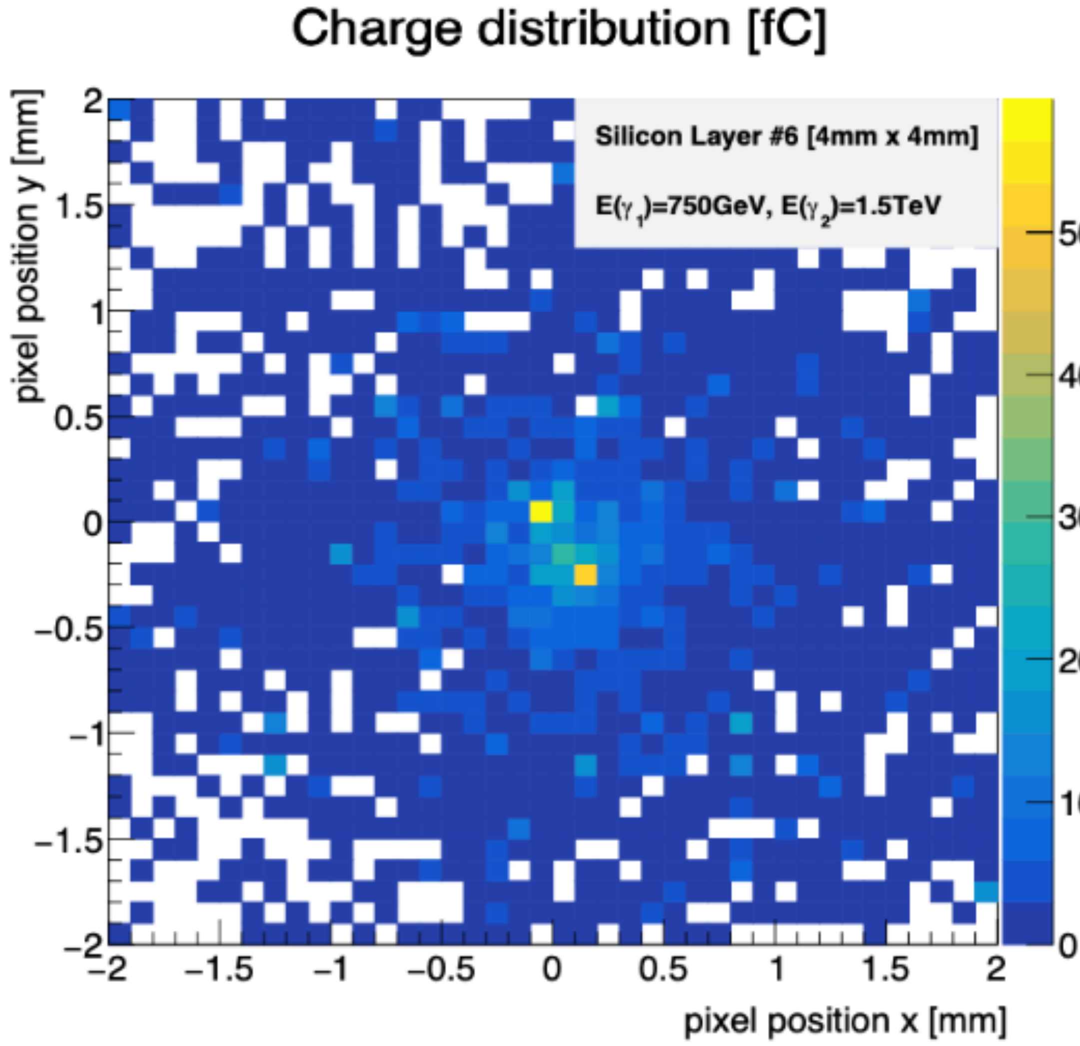
Preliminary

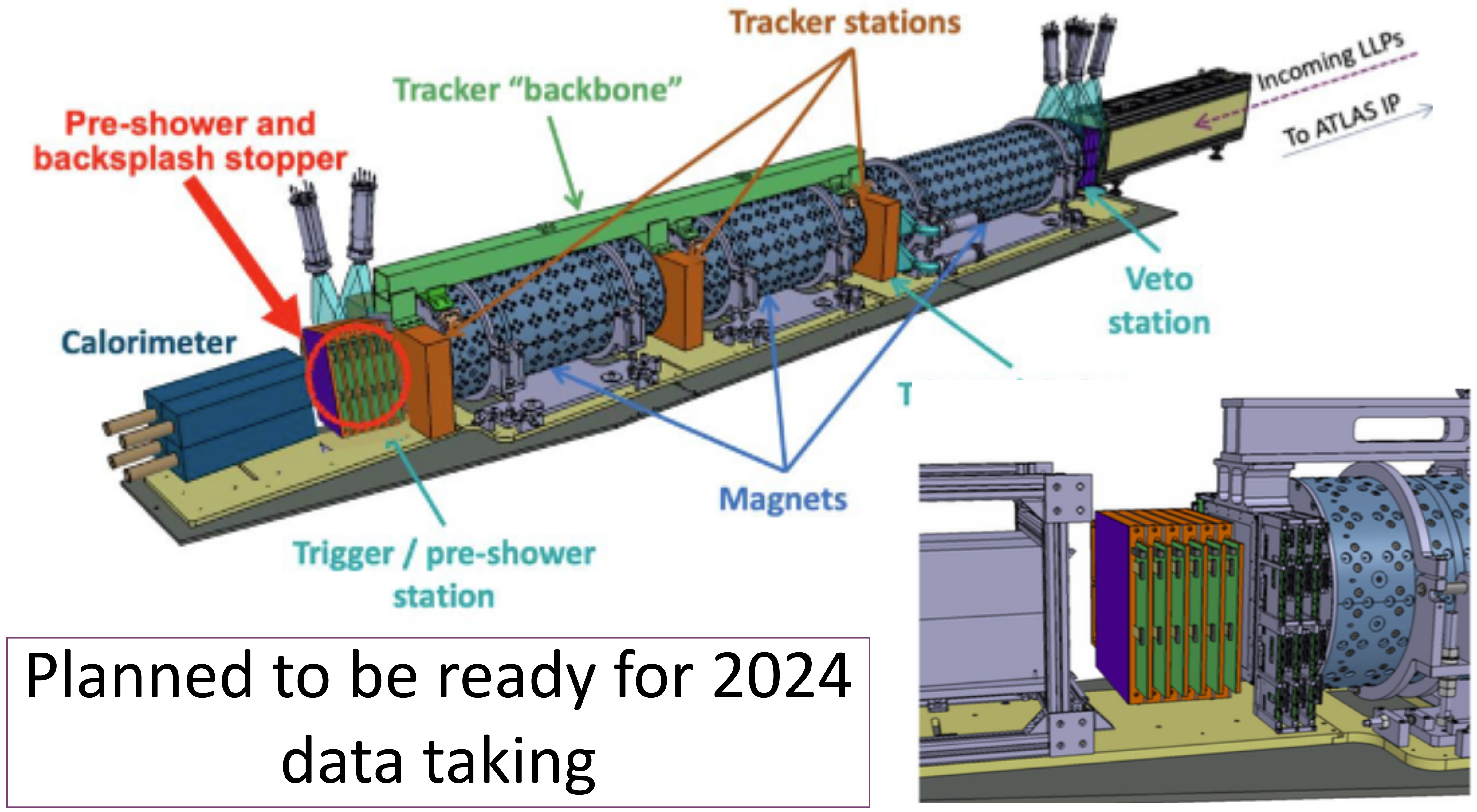
- **Vertex with 11 tracks**
- **e-like track from vertex**
  - Single track for $2X_0$
  - Shower max at $7.8X_0$
  - Θ_c = 11mrad to beam
- **Back-to-back topology**
  - 175° between e & rest

Future upgrade plan for ALPs

- **Upgrade to enable 2-γ physics**
  - enable to measure Axion Like Particles and long live particles decaying into two photons
  - current preshower to be replaced with a high-resolution silicon pre-shower detector using monolithic pixel ASICs
    - hexagonal pixels of 65 µm side

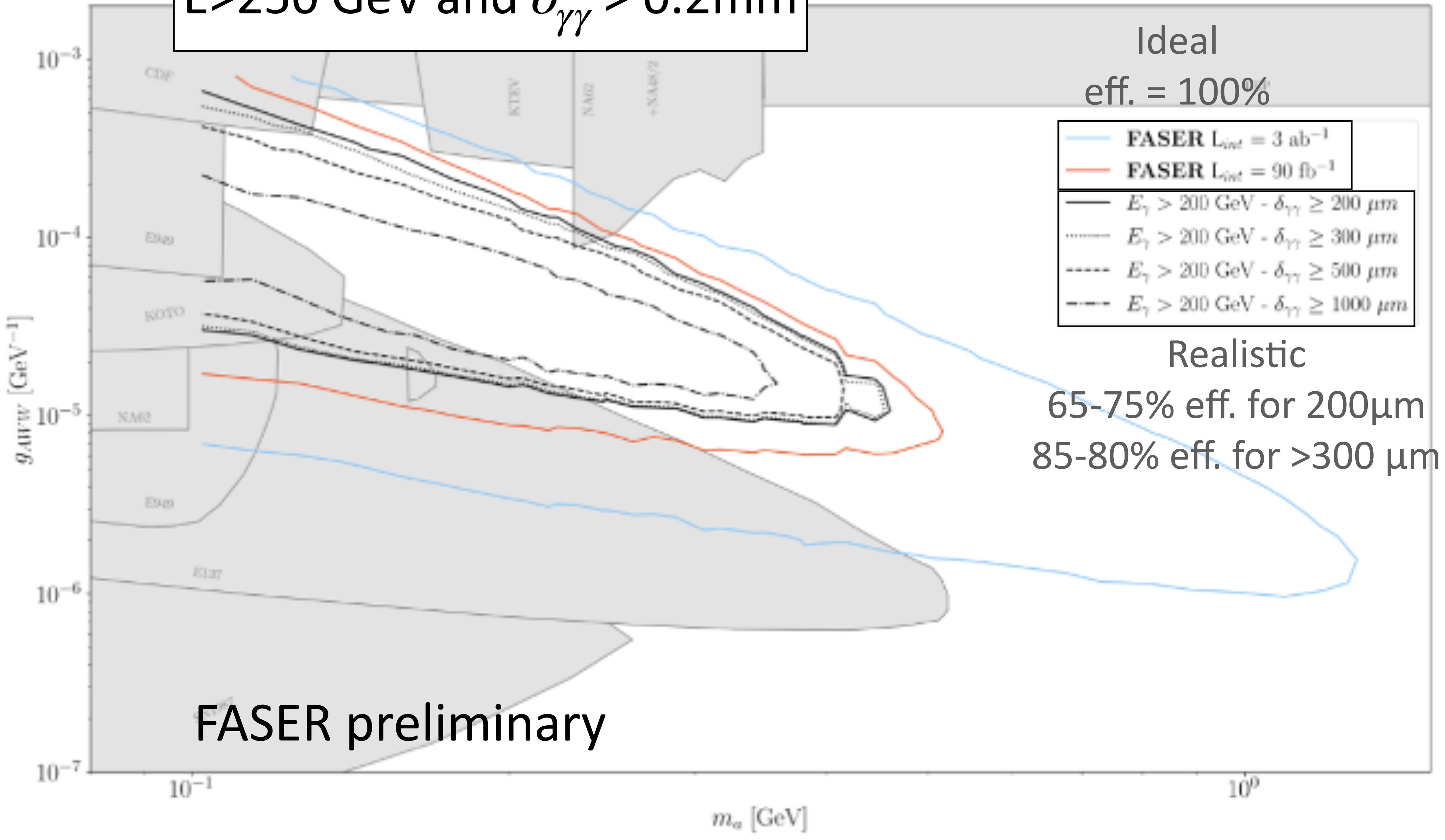
200 µm between two photons
Distinguishable





Planned to be ready for 2024 data taking

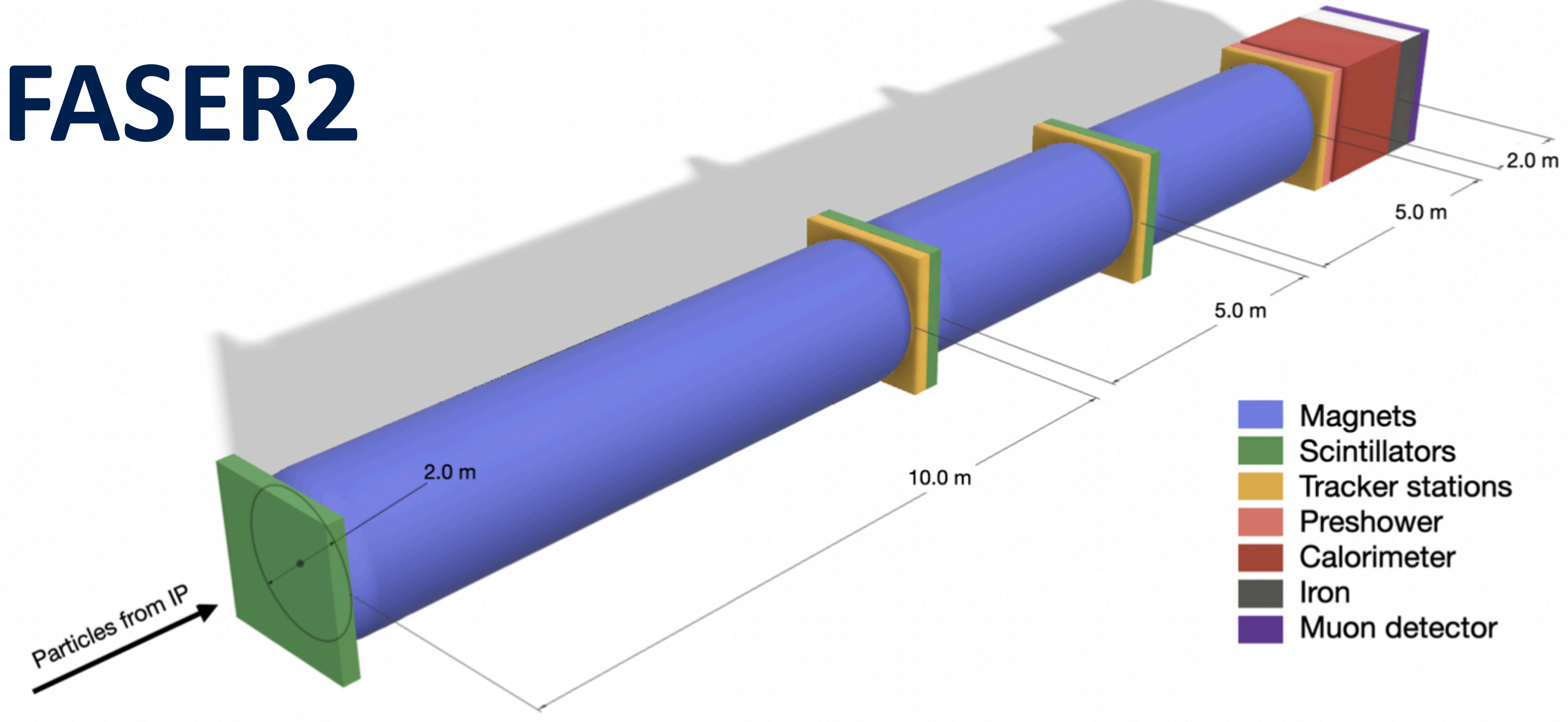
2-photon pairs with
E>250 GeV and $\delta_{\gamma\gamma}$ > 0.2mm

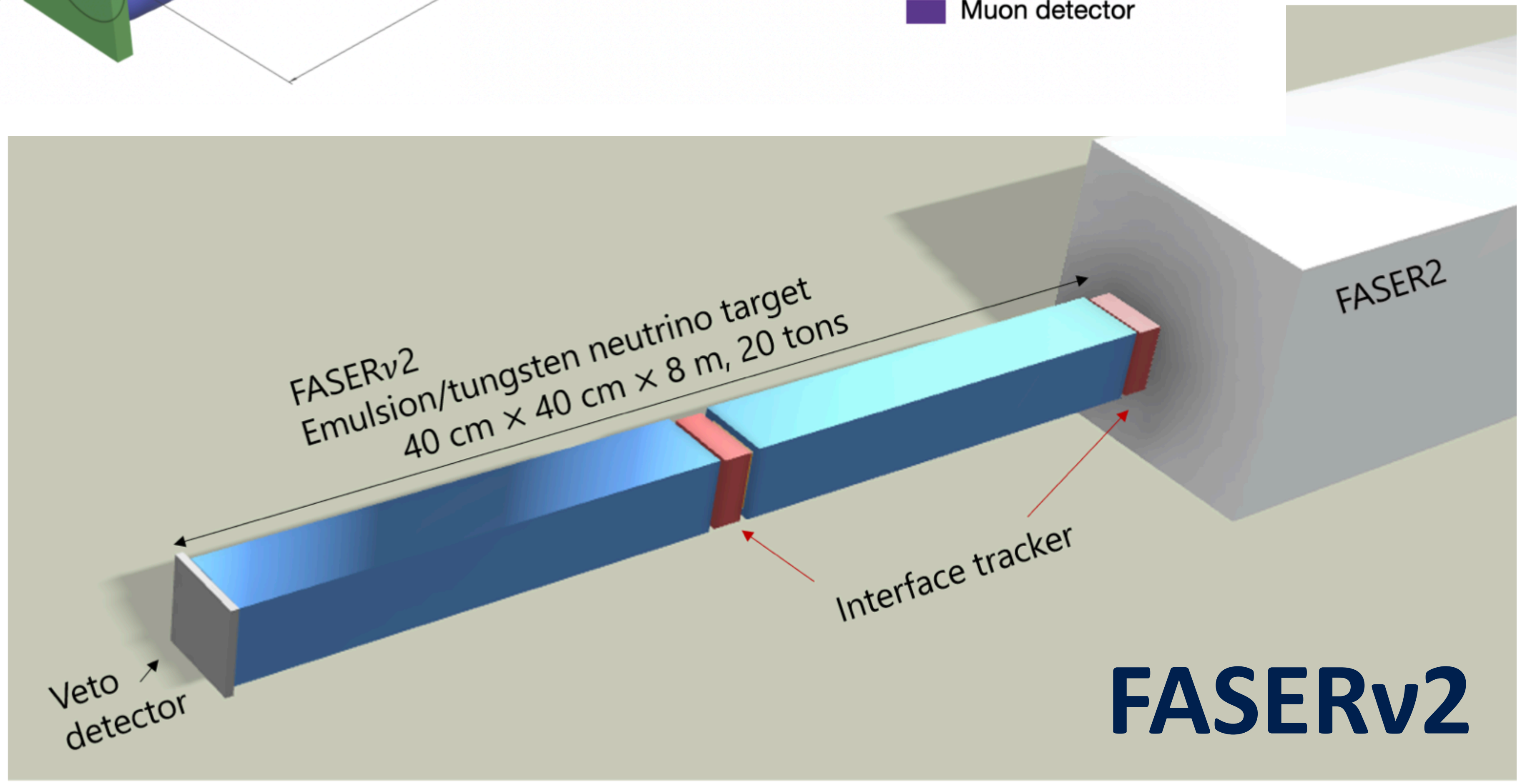


The Forward Physics Facility

In LHC HL-era, it is expected to increase statistics **(×20 Run3, 3000 fb^{-1}) in HL-LHC era**

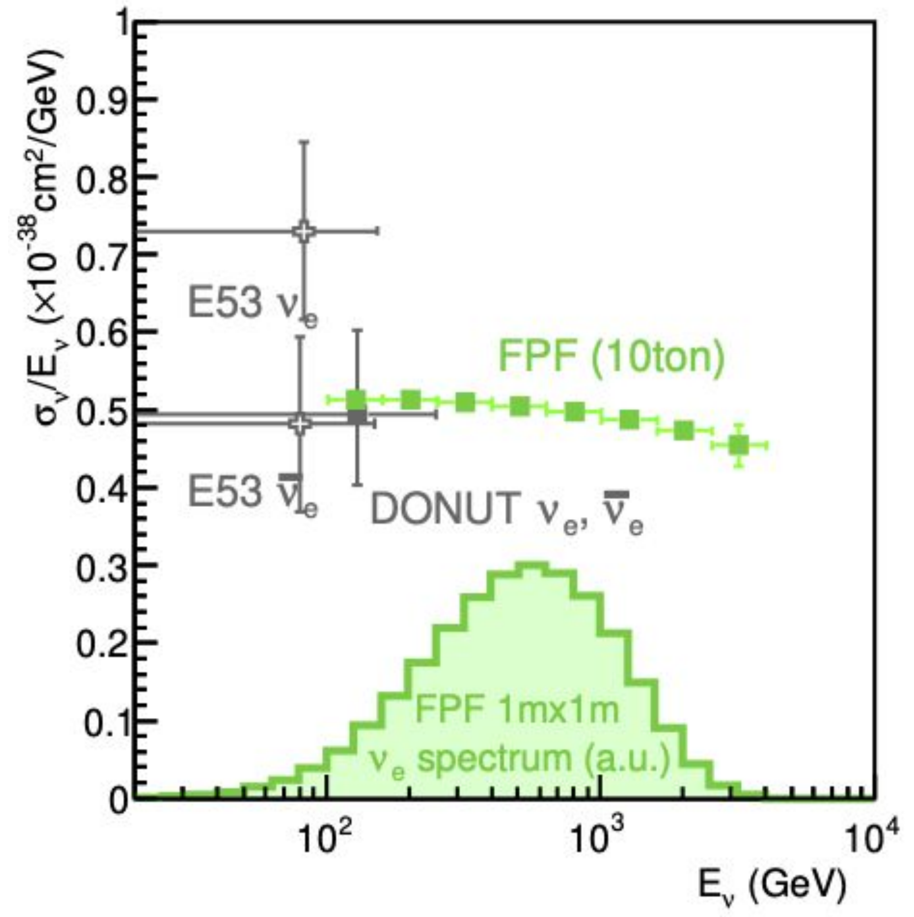
FASER2

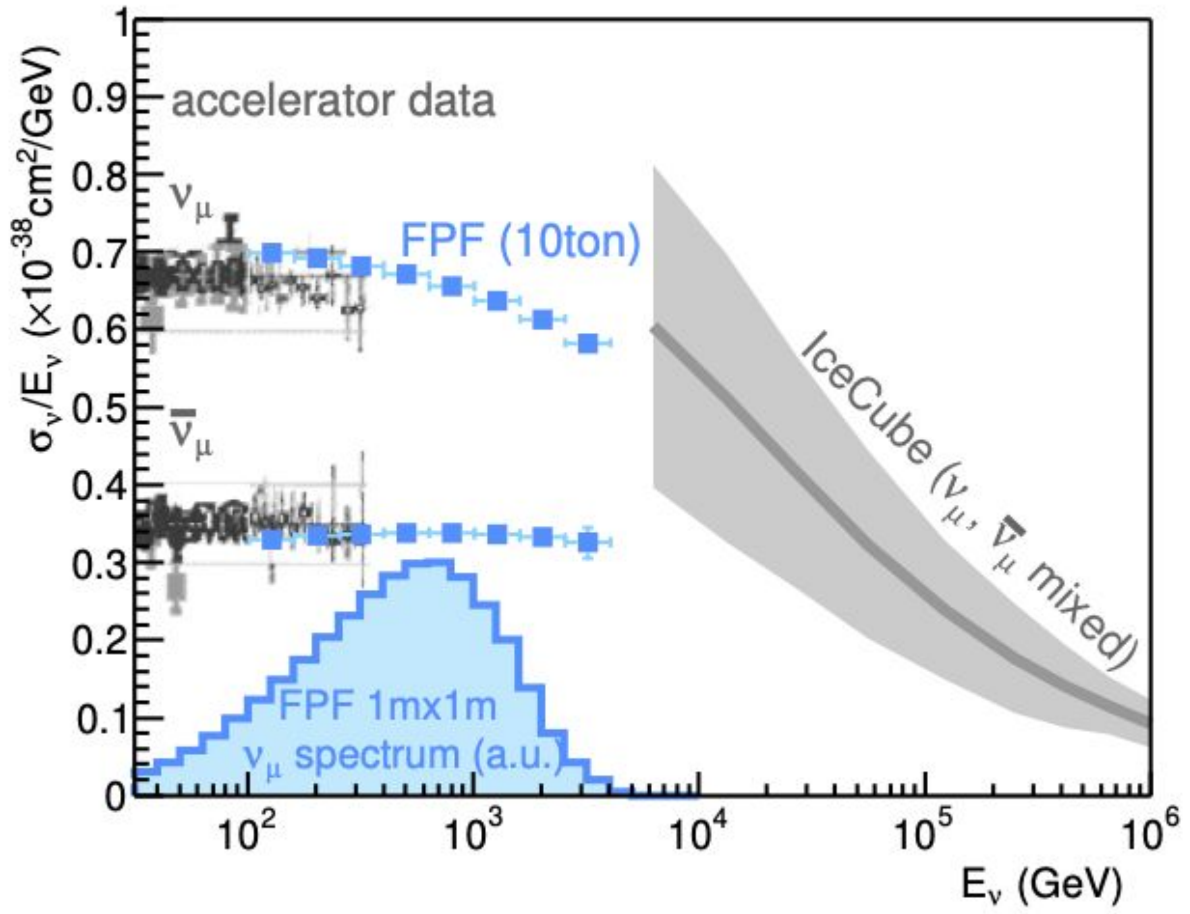


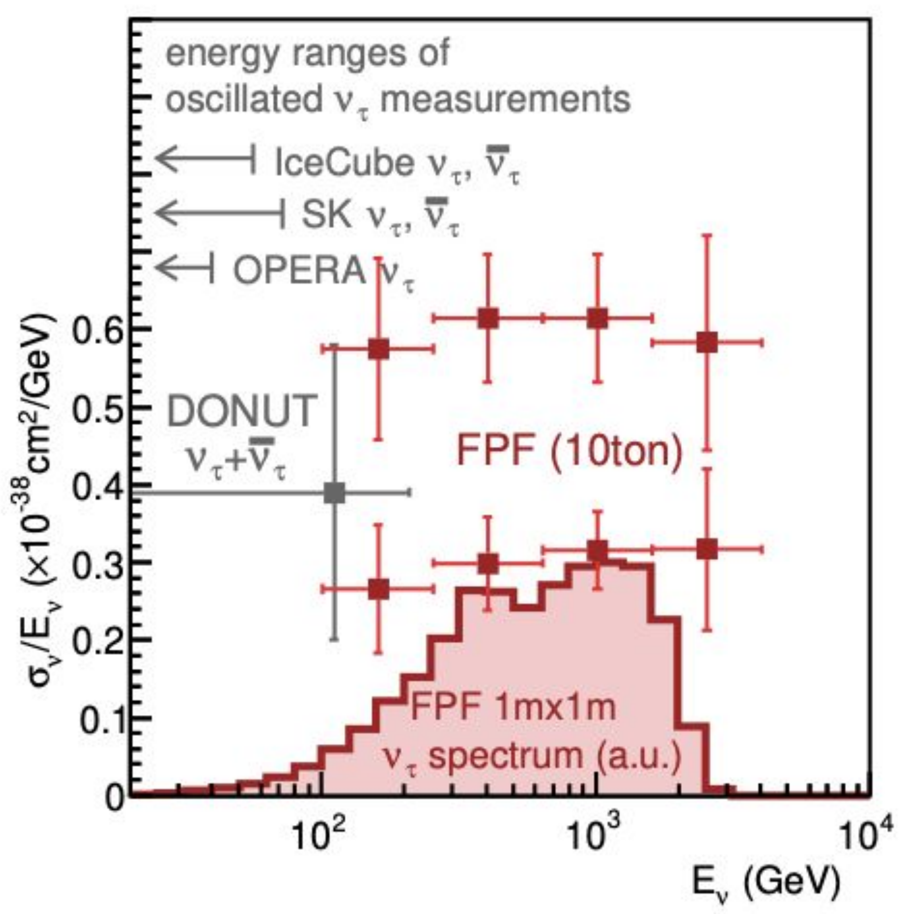


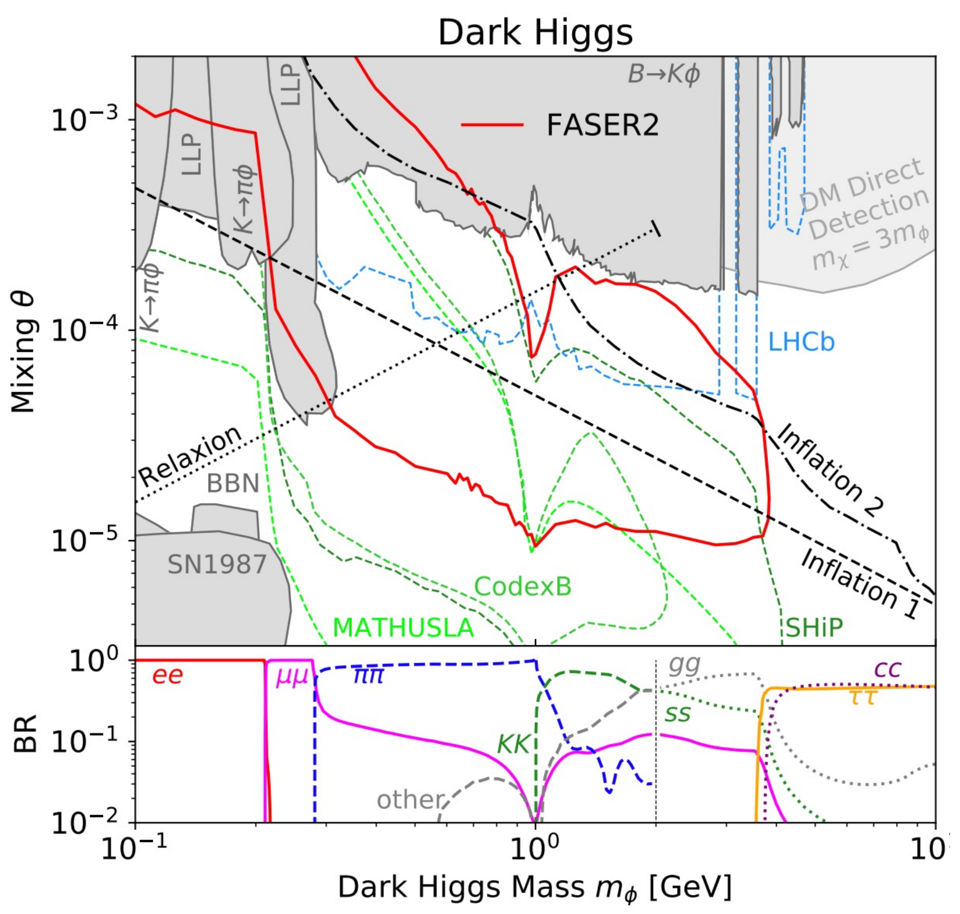
e.g. Expected Neutrino Flux

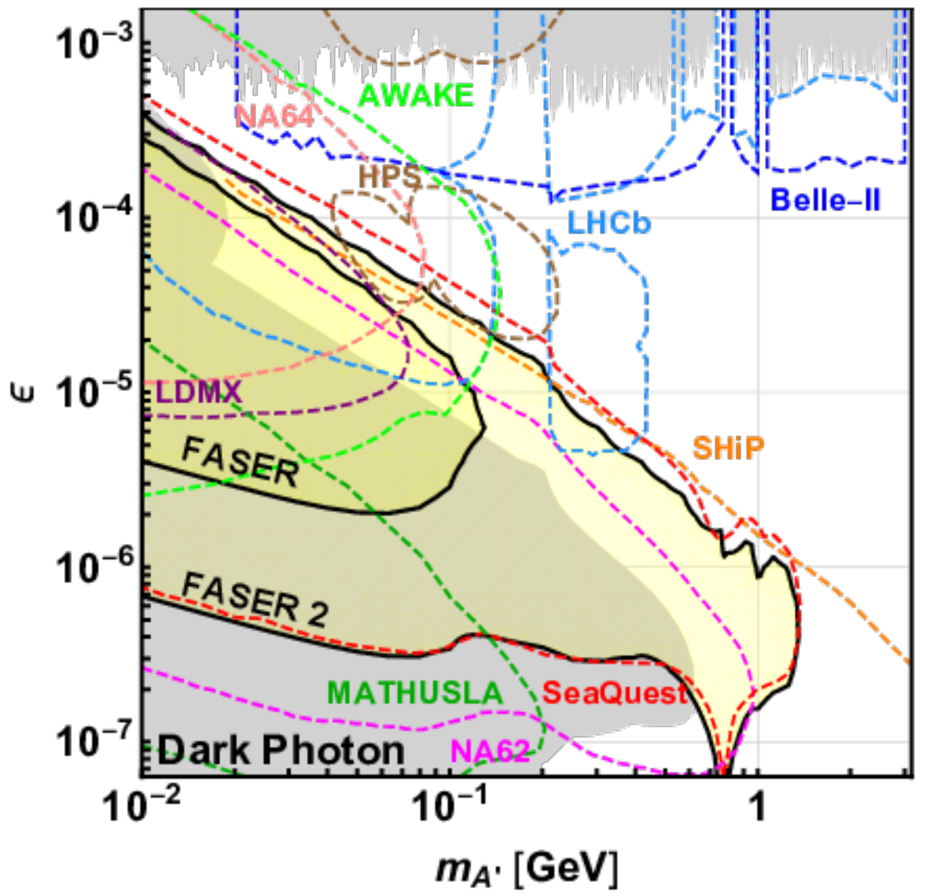
	Detector			Number of CC Interactions		
	Name	Mass	Coverage	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
LHC Run3	FASERν	1 ton	$\eta \gtrsim 8.5$	1.3k / 4.6k	6.1k / 9.1k	21 / 131
	SND@LHC	800kg	$7 < \eta < 8.5$	180 / 500	1k / 1.3k	10 / 22
HL-LHC	FASERν2	20 tons	$\eta \gtrsim 8$	178k / 668k	943k / 1.4M	2.3k / 20k
	FLArE	10 tons	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k
	AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754





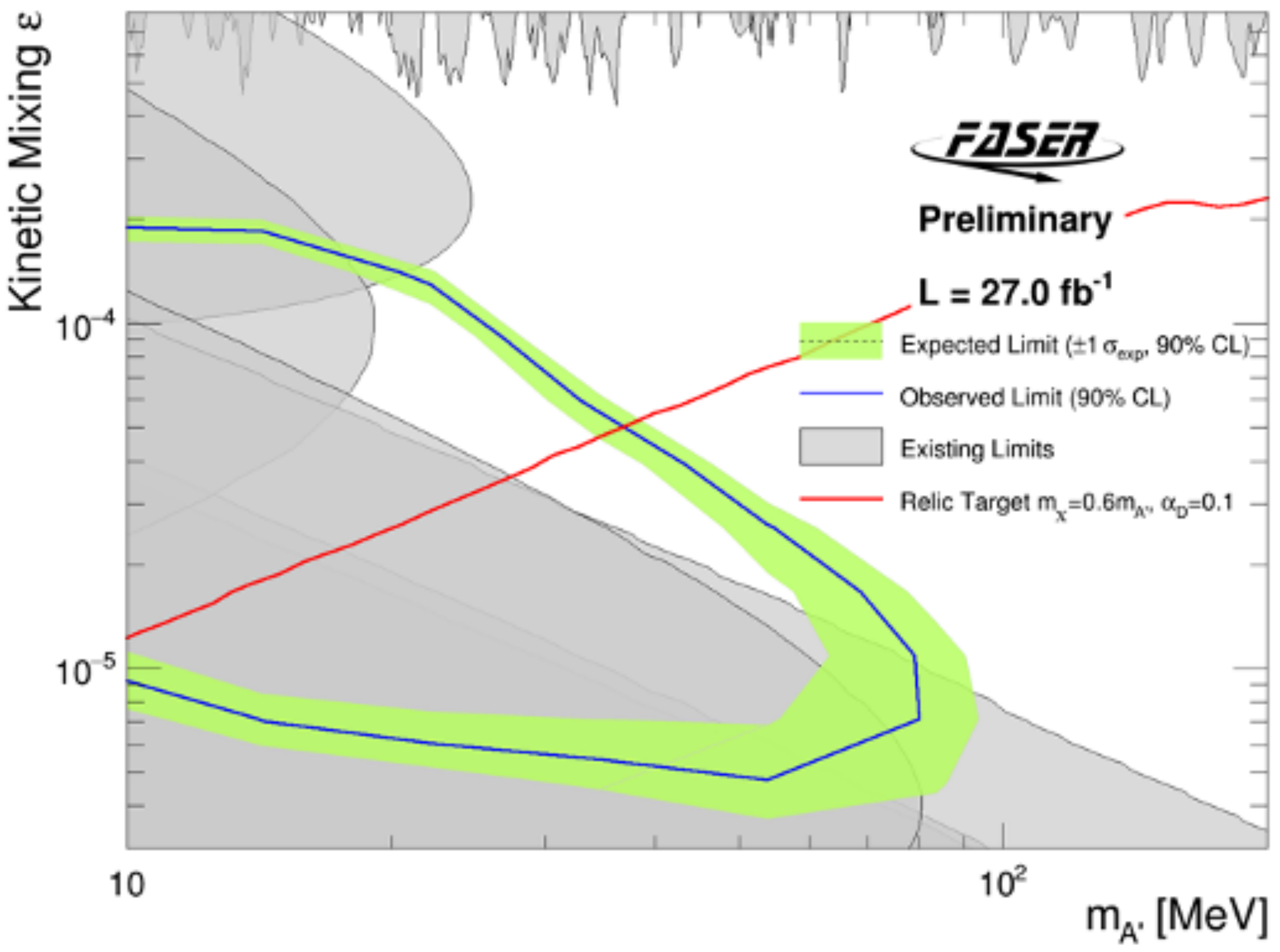






Summary

- FASER successfully took data in first year of Run 3
  - Running with fully functional detector and very good efficiency
- **Excluded A' in region of low mass and kinetic mixing**
  - **Probes new territory in interesting thermal-relic region**
- Reconstructed ~150 νμ CC interactions in spectrometer
  - **First direct detection of collider neutrinos**
    - Opens new window for high-energy ν study
    - arXiv:2303.14185
- **More searches and neutrino measurements** to come with **FASERnu!!**
  - **Flavors, energy spectra** etc
- Up to 10x more data to come during run-3 LHC
- **Upgrade plan for 2-γ from ALPs**
  - With monolithic pixels
- **HL-LHC era, Forward Physics Facility**



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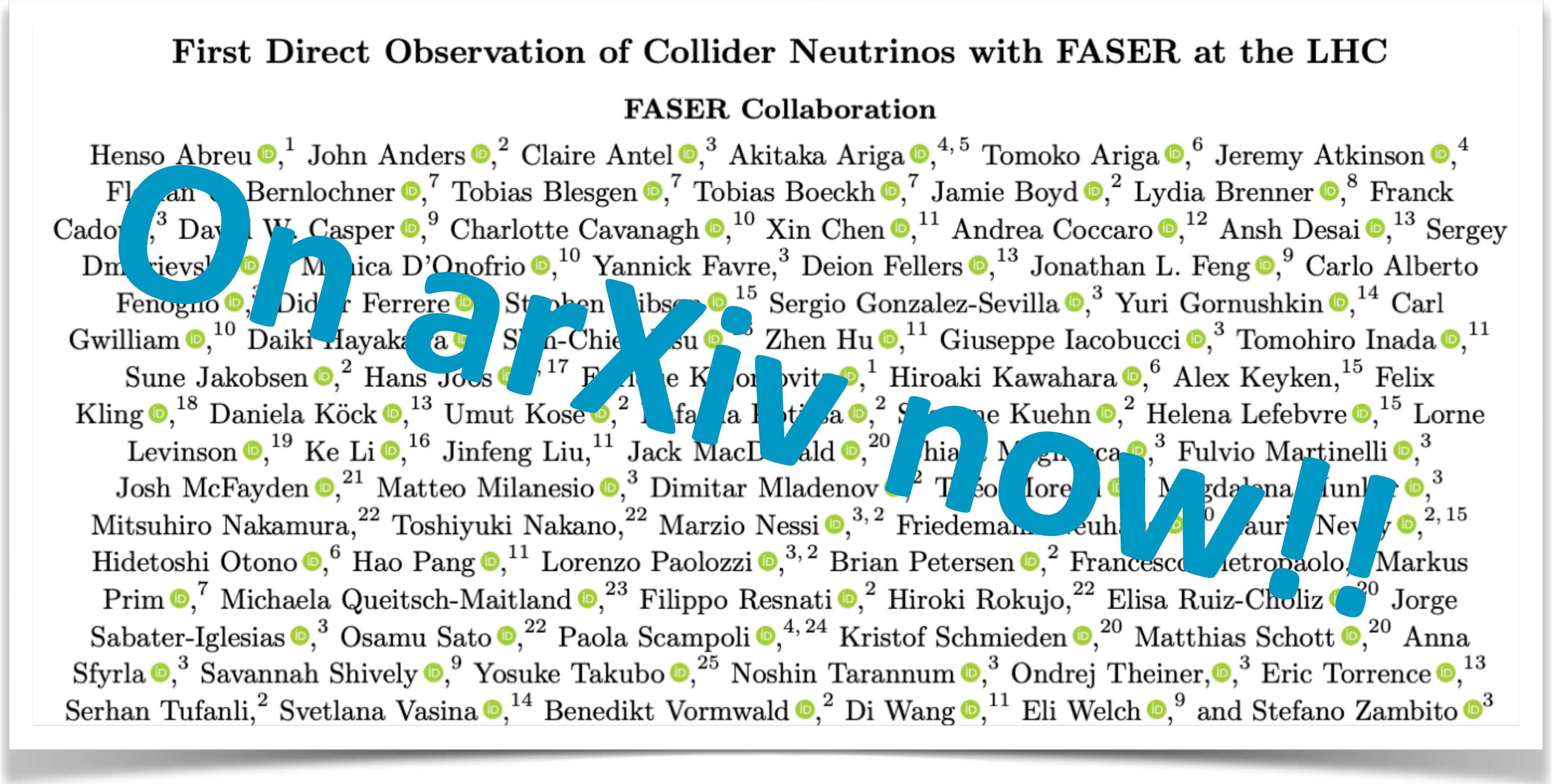
[Submitted on 24 Mar 2023]

First Direct Observation of Collider Neutrinos with FASER at the LHC



First Direct Observation of Collider Neutrinos with FASER at the LHC

FASER Collaboration

Henso Abreu,[1] John Anders,[2] Claire Antel,[3] Akitaka Ariga,[4,5] Tomoko Ariga,[6] Jeremy Atkinson,[4] Fl[illegible] Bernlochner,[7] Tobias Blesgen,[7] Tobias Boeckh,[7] Jamie Boyd,[2] Lydia Brenner,[8] Franck Cado[illegible],[3] Da[illegible] W. Casper,[9] Charlotte Cavanagh,[10] Xin Chen,[11] Andrea Coccaro,[12] Ansh Desai,[13] Sergey Dm[illegible] M[illegible]ica D'Onofrio,[10] Yannick Favre,[3] Deion Fellers,[13] Jonathan L. Feng,[9] Carlo Alberto Fenoglio,[illegible] Did[illegible] Ferrere [illegible] St[illegible] Zhen Hu,[11] Giuseppe Iacobucci,[3] Tomohiro Inada,[11] Sune Jakobsen,[2] Hans Joos [illegible] Hiroaki Kawahara,[6] Alex Keyken,[15] Felix Kling,[18] Daniela Köck,[13] Umut Kose,[2] [illegible] Kuehn,[2] Helena Lefebvre,[15] Lorne Levinson,[19] Ke Li,[16] Jinfeng Liu,[11] Jack MacD[illegible]ald,[20] [illegible],[3] Fulvio Martinelli,[3] Josh McFayden,[21] Matteo Milanesio,[3] Dimitar Mladenov [illegible],[3] Mitsuhiro Nakamura,[22] Toshiyuki Nakano,[22] Marzio Nessi,[3,2] Friedema[illegible],[2,15] Hidetoshi Otono,[6] Hao Pang,[11] Lorenzo Paolozzi,[3,2] Brian Petersen,[2] Francesc[illegible]etropaolo,[illegible] Markus Prim,[7] Michaela Queitsch-Maitland,[23] Filippo Resnati,[2] Hiroki Rokujo,[22] Elisa Ruiz-Choliz,[20] Jorge Sabater-Iglesias,[3] Osamu Sato,[22] Paola Scampoli,[4,24] Kristof Schmieden,[20] Matthias Schott,[20] Anna Sfyrla,[3] Savannah Shively,[9] Yosuke Takubo,[25] Noshin Tarannum,[3] Ondrej Theiner,[3] Eric Torrence,[13] Serhan Tufanli,[2] Svetlana Vasina,[14] Benedikt Vormwald,[2] Di Wang,[11] Eli Welch,[9] and Stefano Zambito[3]

On arXiv now!!

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Dark Photon - Cut Flow

- Data and example signal efficiency as a function of analysis selections
- Note the data column was pre-selected to have at least one reconstructed track (no quality cuts) in the event

Cut	Data		Signal ($\varepsilon = 3 \times 10^{-5}$, $m_{A'} = 25.1\,\mathrm{MeV}$)	
	Events	Efficiency	Events	Efficiency
Good collision event	151750788	—	95.3	99.7%
No Veto Signal	1235830	0.814%	94.0	98.4%
Timing/Preshower Signal	313988	0.207%	93.0	97.3%
≥ 1 good track	21329	0.014%	85.2	89.2%
$= 2$ good tracks	0	0.000%	44.5	46.6%
Track radius < 95 mm	0	0.000%	40.4	42.3%
Calo energy > 500 GeV	0	0.000%	39.7	41.6%

Dark Photon - Systematic Uncertainties

- Complete list of systematic uncertainties and their impact on the signal yield

Source	Value	Effect on signal yield
Theory, Statistics and Luminosity		
Dark photon cross-section	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
Tracking		
Momentum Scale	5%	$< 0.5\%$
Momentum Resolution	5%	$< 0.5\%$
Single Track Efficiency	3%	3%
Two-track Efficiency	15%	15%
Calorimetry		
Calo E scale	6%	0-8% ($< 1\%$)

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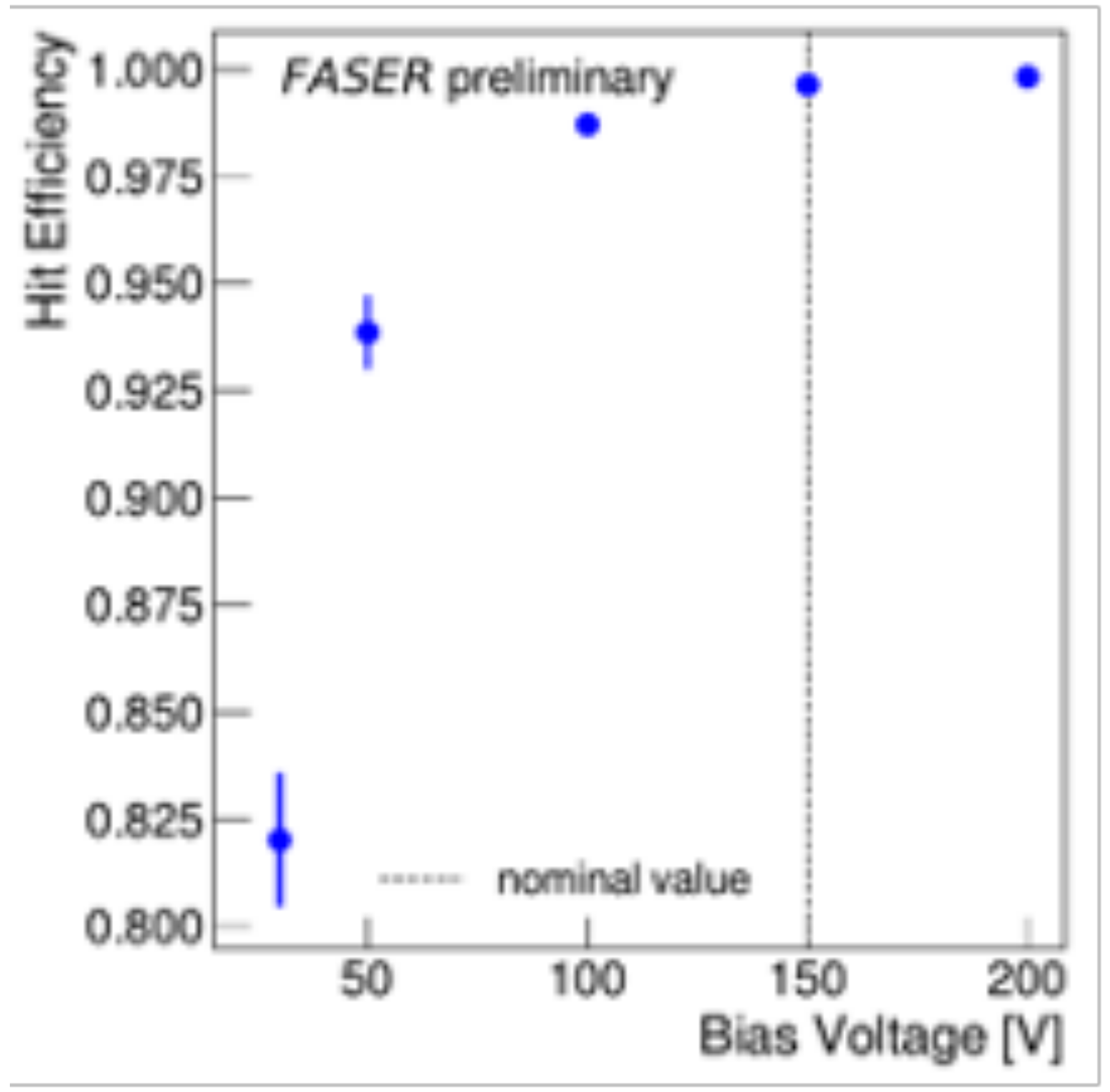
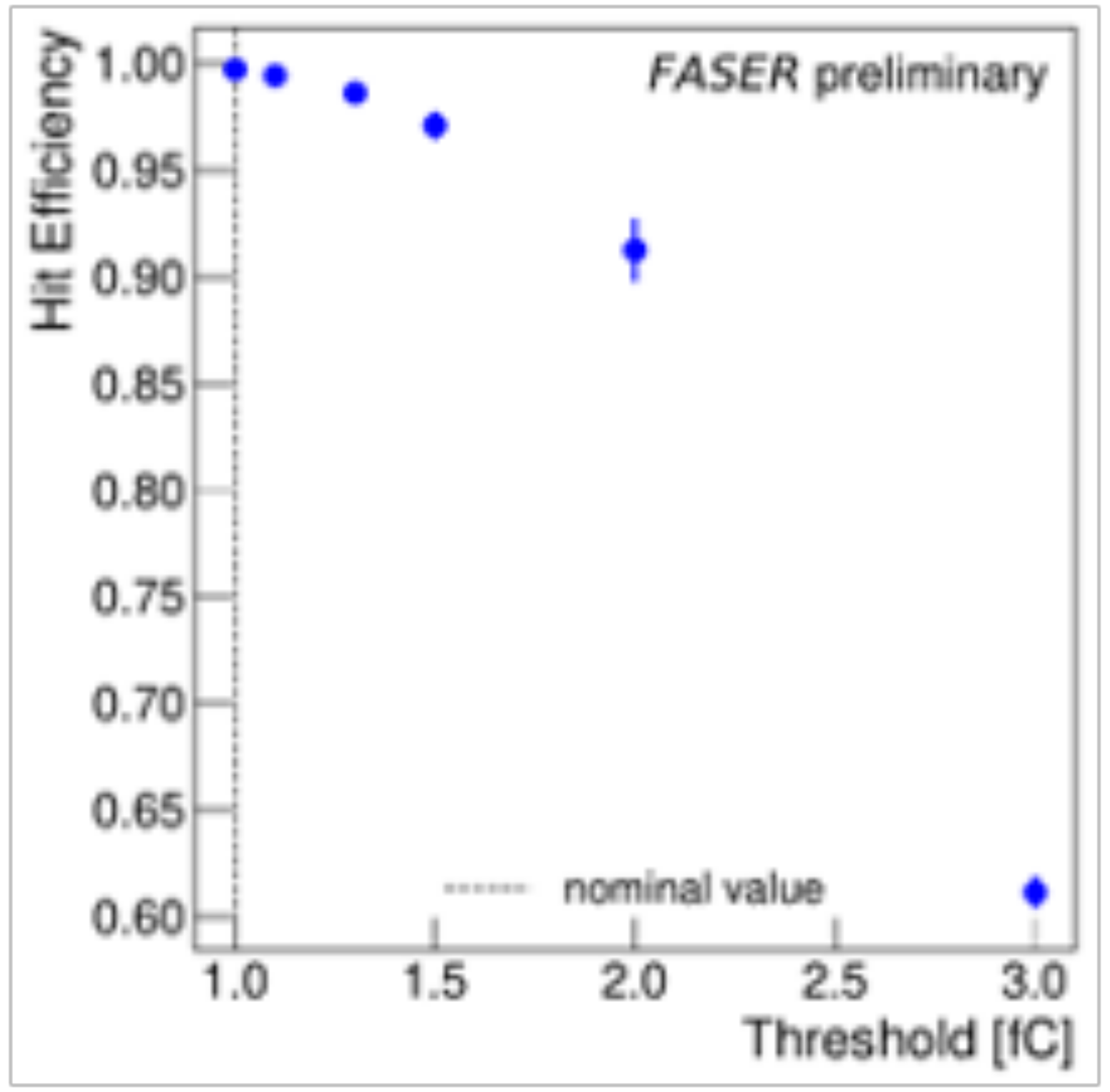
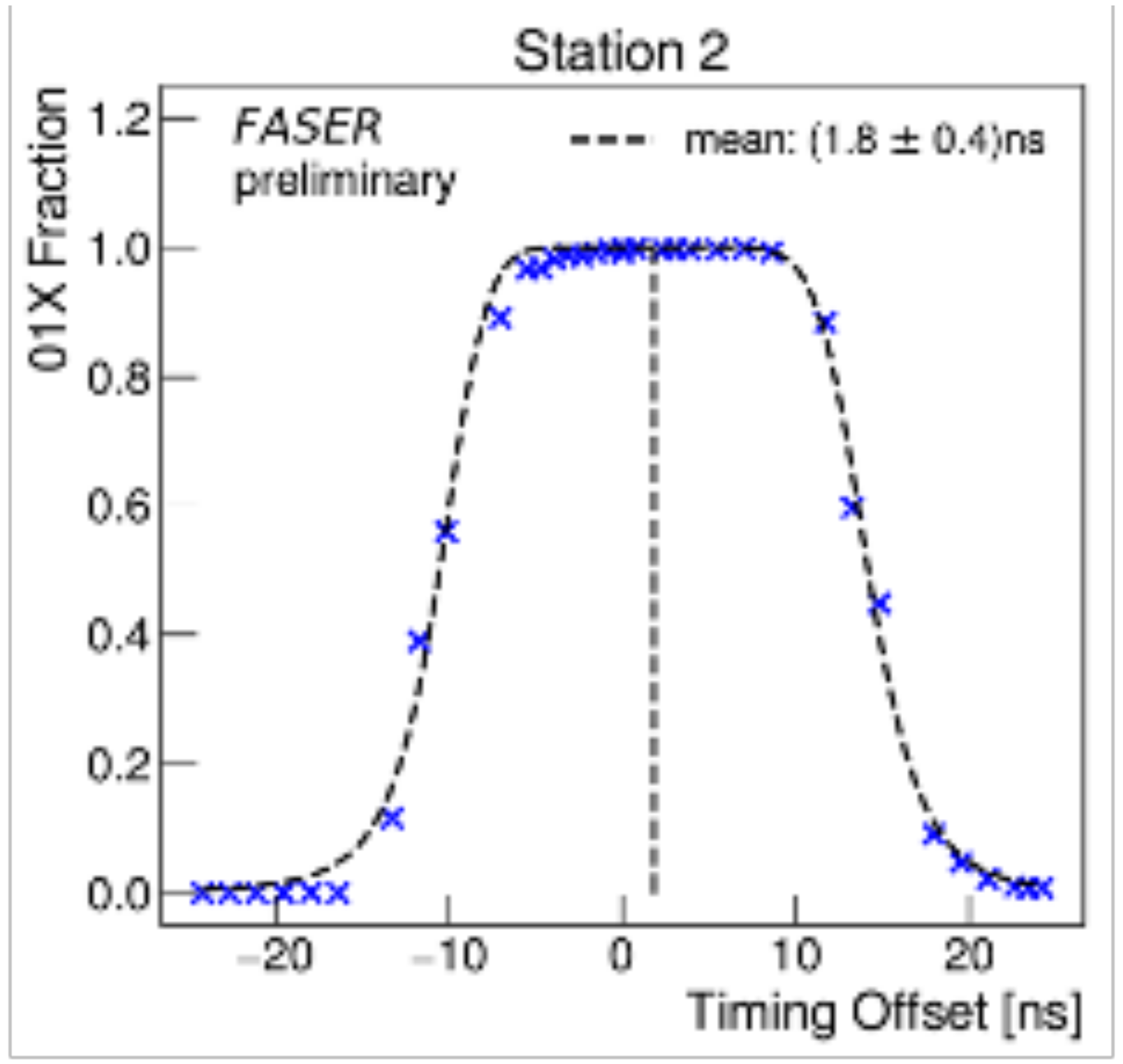
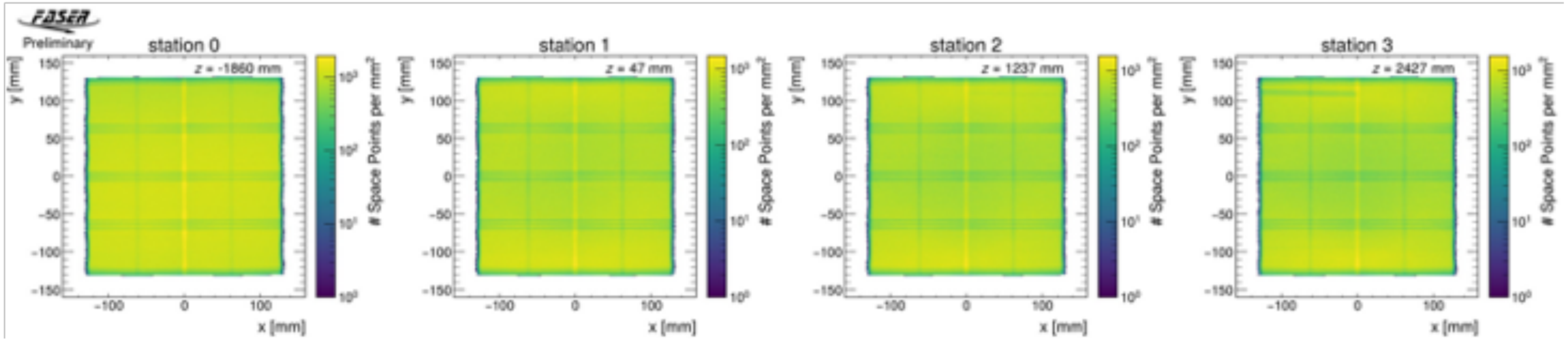
Detector Performance Tracker





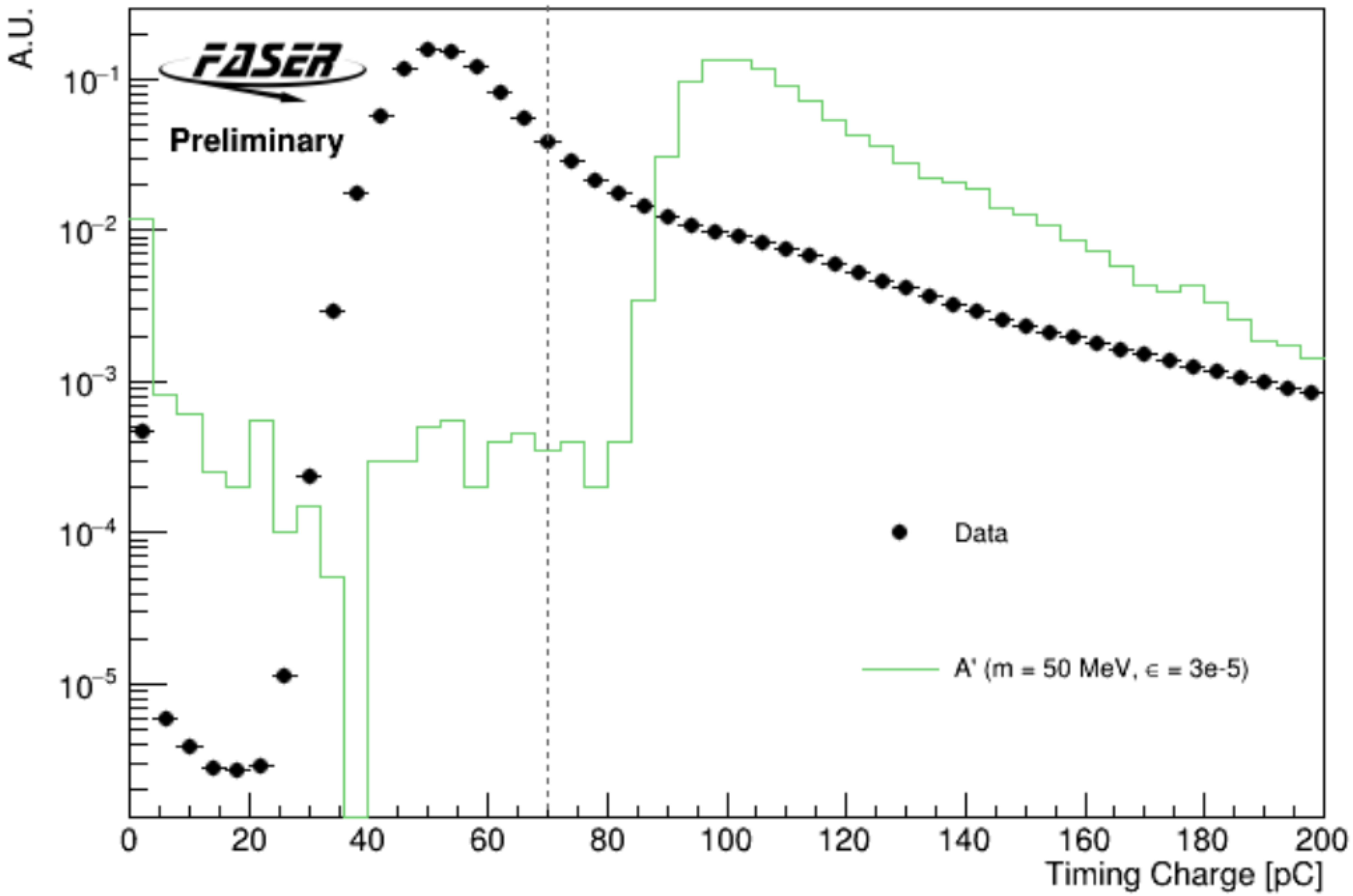




Timing Scintillator Selection

Timing cut of 70 pC is ~100% efficiency for signal

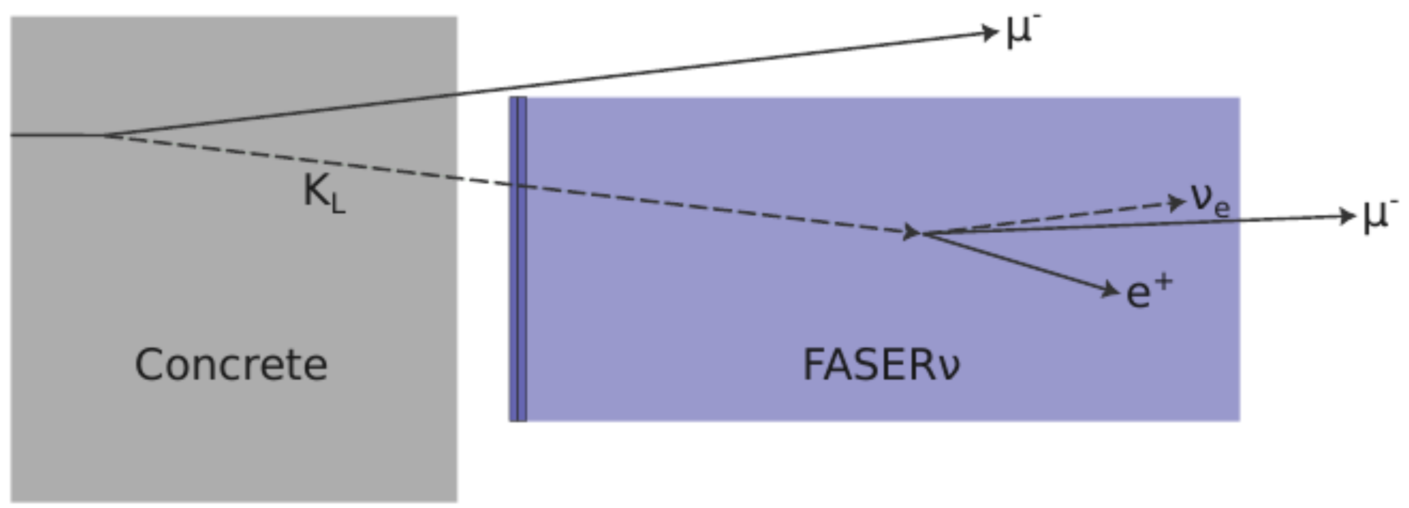
- Supresses a large fraction of data,which are predominantly single-track events



Neutrino background

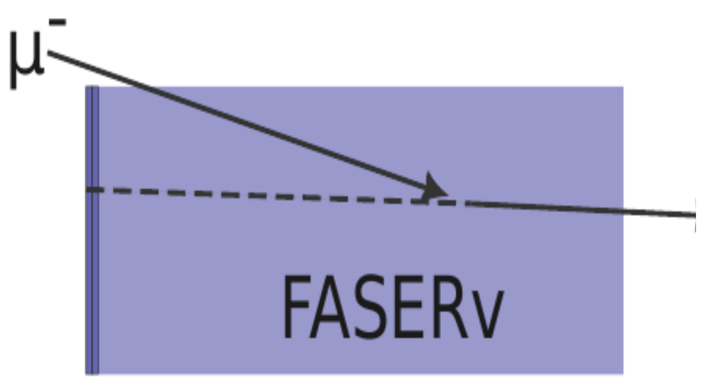
Neutral hadrons estimated from 2-step simulation

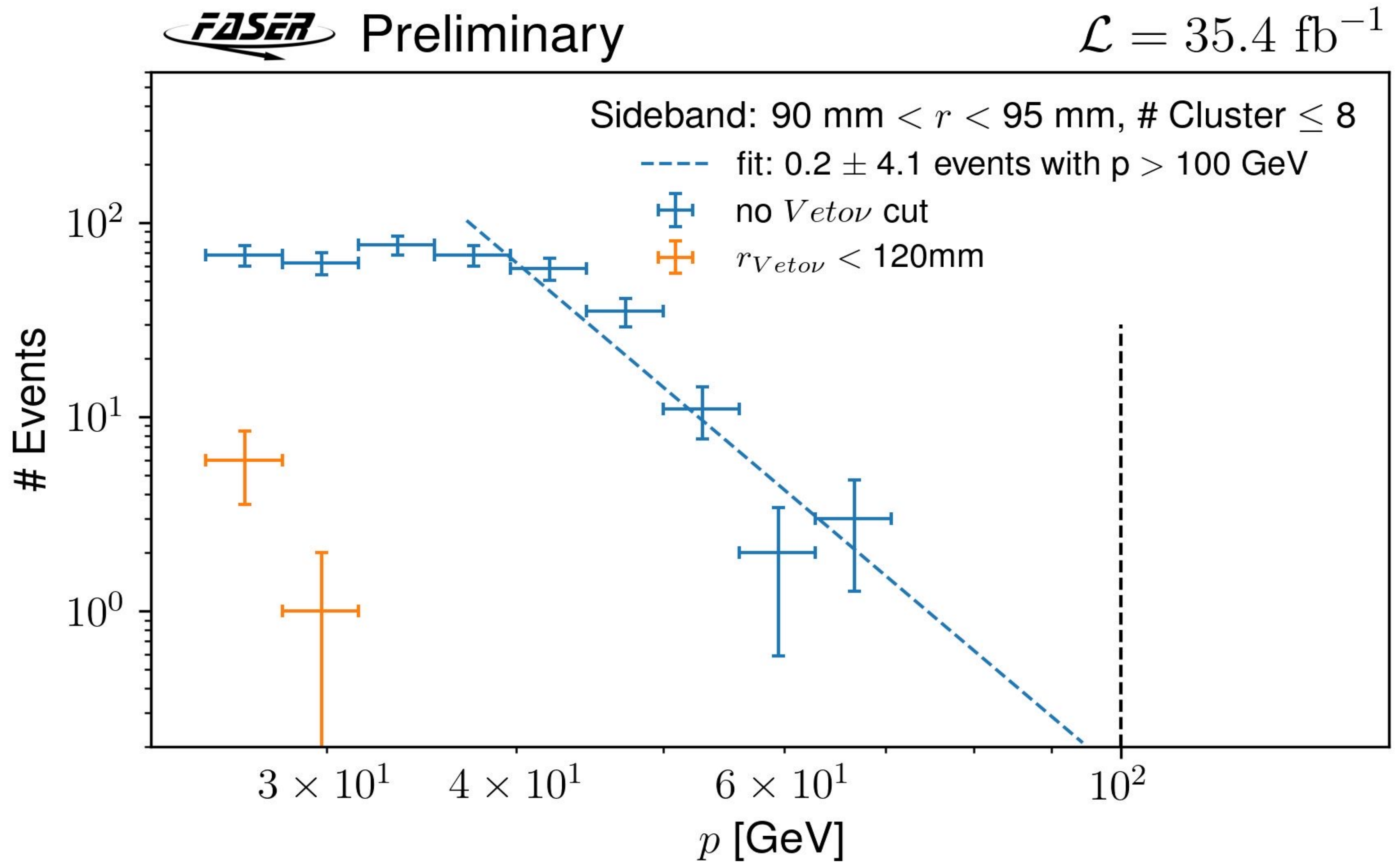
- Expect ~300 neutral hadrons with E>100 GeV reaching FASERν
- Most accompanied by μ but conservatively assume missed
- Estimate fraction of these passing event selection
  - Most are absorbed in tungsten with no high-momentum track
- Predict **N=0.11±0.06** events



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





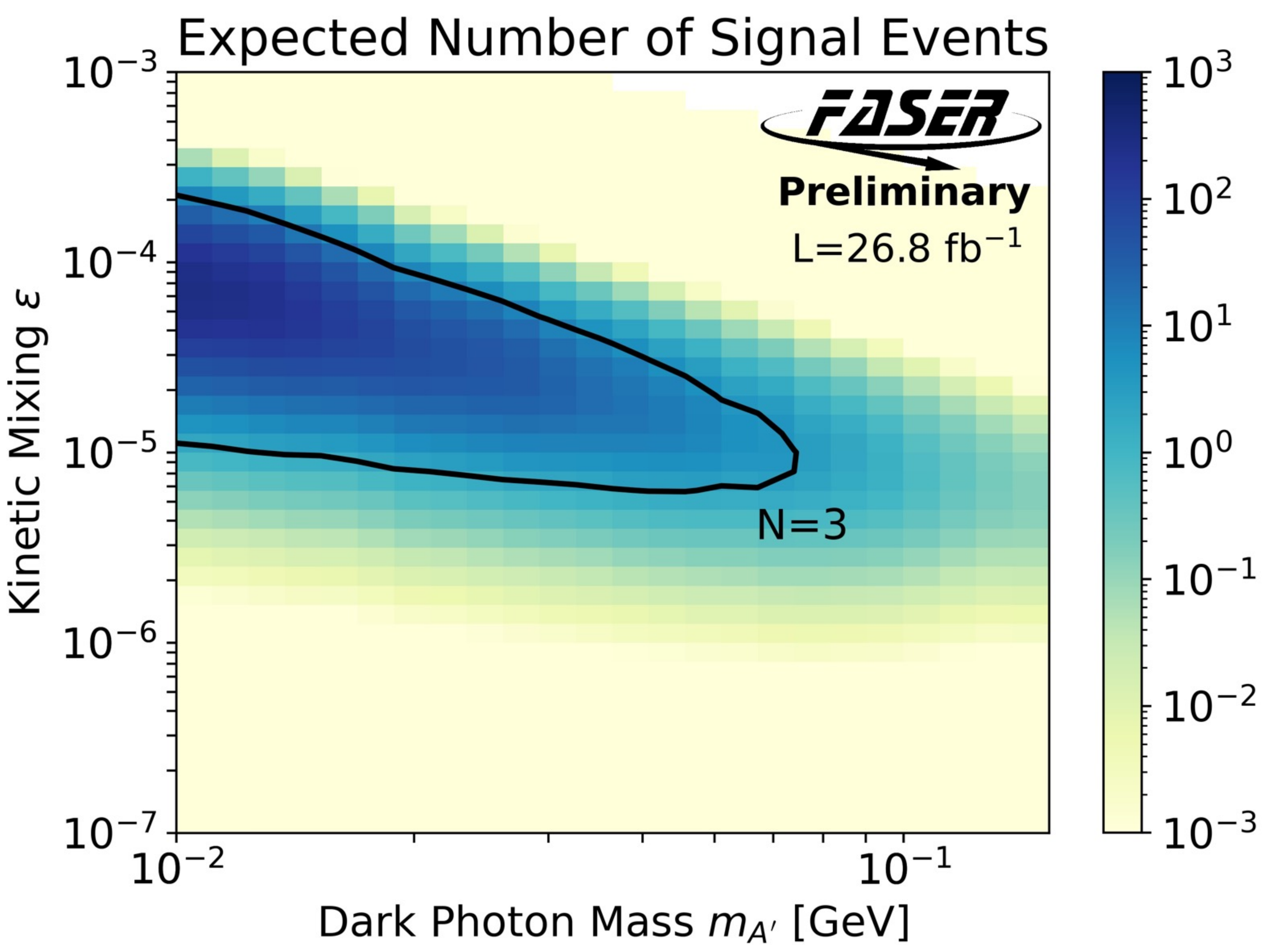
Veto inefficiency estimated from final fit

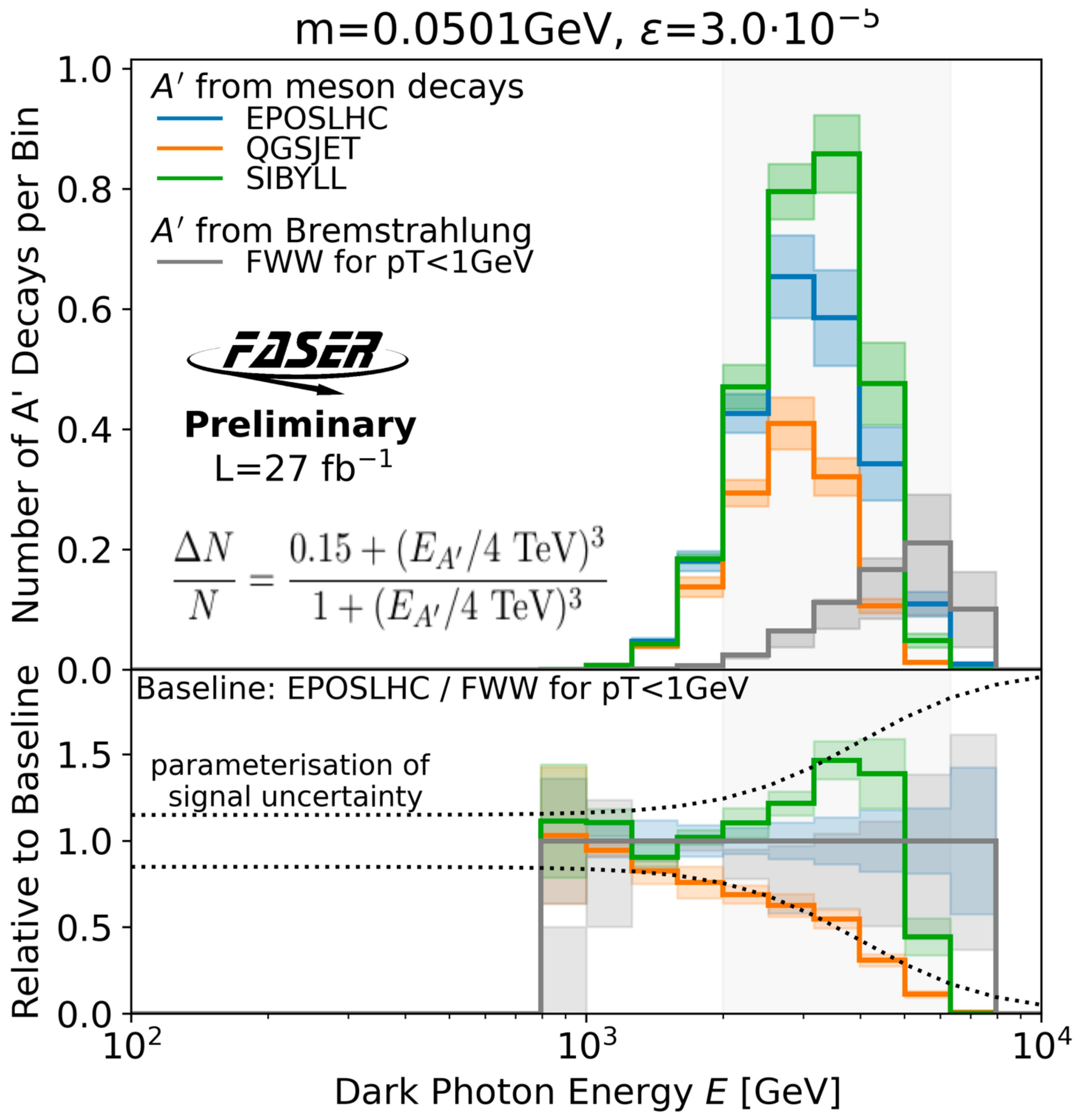
- Fit events with 0 (SR) and also1 (1st or 2nd) or 2 front veto layers firing
- Final negligible background due to very high veto efficiency

Dark Photon Signal

- A’ -> e+e- decays in FASER volume simulated with FORESEE
- π0 and η via EPOS-LHCgenerator
  Generator uncertainty from difference to QGSJET/SIBYLL
- Parameterised based on A’ energy

- **Experimental uncertainties**
  - **Trackingefficiency**
    - 15%forclose-bytracks
      - Estimated from overlay
  - **Calo E scale**
    - 6% at 500GeV
    - Cross-checked withE/p
  - **Momentum scale/resol.**
    - 5%each
    - Negligibleeffect





Neutrinos: fit

- Fit to events with 0, 1 or 2 front veto hits
  - Splitting those were 1 hit is in1st/2nd layer
- Construct likelihood as product of Poissions
- With additional 3 Gaussian constraints for Neutral hadron background, Geometric background and the extrapolation factor

$$\mathcal{L} = \prod_{i}^{4} \mathcal{P}(n_i^{\text{obs}} | \nu_i^{\text{exp}}) \cdot \prod_{j}^{3} \mathcal{G}_j$$

- Determine number of in each category
  - Along with inefficiencies of 2 forward vetos, which are found to be close to expected vals.

Inefficiencies:
$6 / 9 \times 10^{-8}$

1 - p1 = 99.999994(3)%
1 - p2 = 99.999991(4)%

n_0: A neutrino enriched category from events that pass all event selection steps.

n_{10}: Events for which the first layer of the FASERν scintillator produces a charge of >40 pC in the PMT, but no signal with sufficient charge is seen in the second layer.

n_{01}: Analogous events for which more than 40 pC in the PMT was observed in the second layer, but not in the first layer.

n_2: Events for which both layers observe more than 40 pC of charge.

Category	Events	Expectation
n_0	153	$\nu_\nu + \nu_b \cdot p_1 \cdot p_2 + \nu_{\text{had}} + \nu_{\text{geo}} \cdot \eta_{\text{geo}}$
n_{10}	4	$\nu_b \cdot (1 - p_1) \cdot p_2$
n_{01}	6	$\nu_b \cdot p_1 \cdot (1 - p_2)$
n_2	64014695	$\nu_b \cdot (1 - p_1) \cdot (1 - p_2)$