Going Forward: Physics at the FASER Experiment and beyond

Seminar at IJCLab Paris-Orsay / CEA Orsay

Florian Bernlochner (florian.bernlochner@uni-bonn.de)

With kind support of

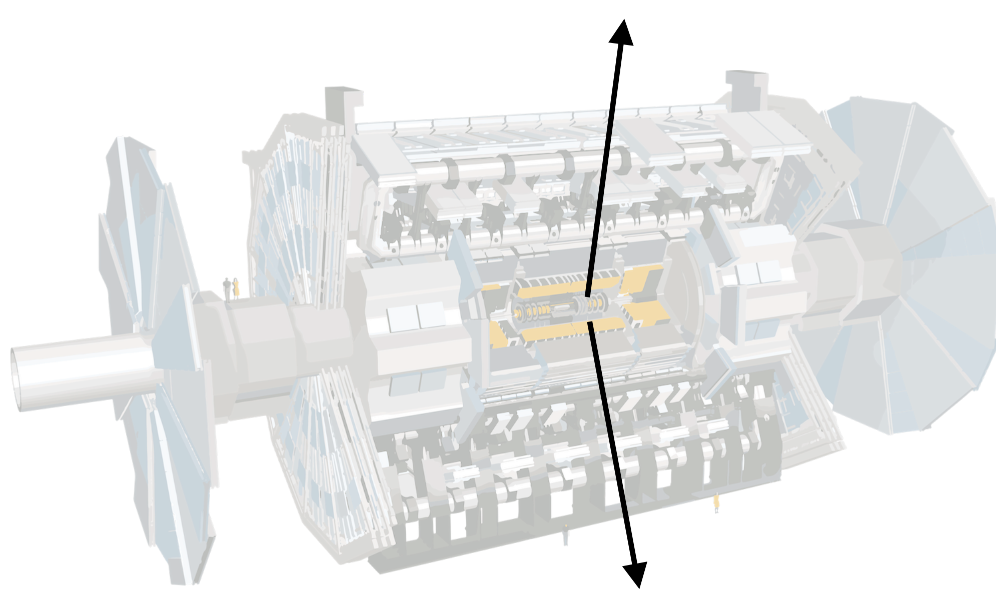
Neutrinos and the long-lifetime frontier

The LHC is the highest energy collider in the world

→ **Its large-scale experiments** were designed to search for **heavy** and **strongly produced** new particles

→ Their design **optimal** to search for **heavy BSM** and probe **SM physics**

SUSY, WIMPs, …



W, Z, top, Higgs

↕ Both produced with **high p_T** (transverse to the beam)

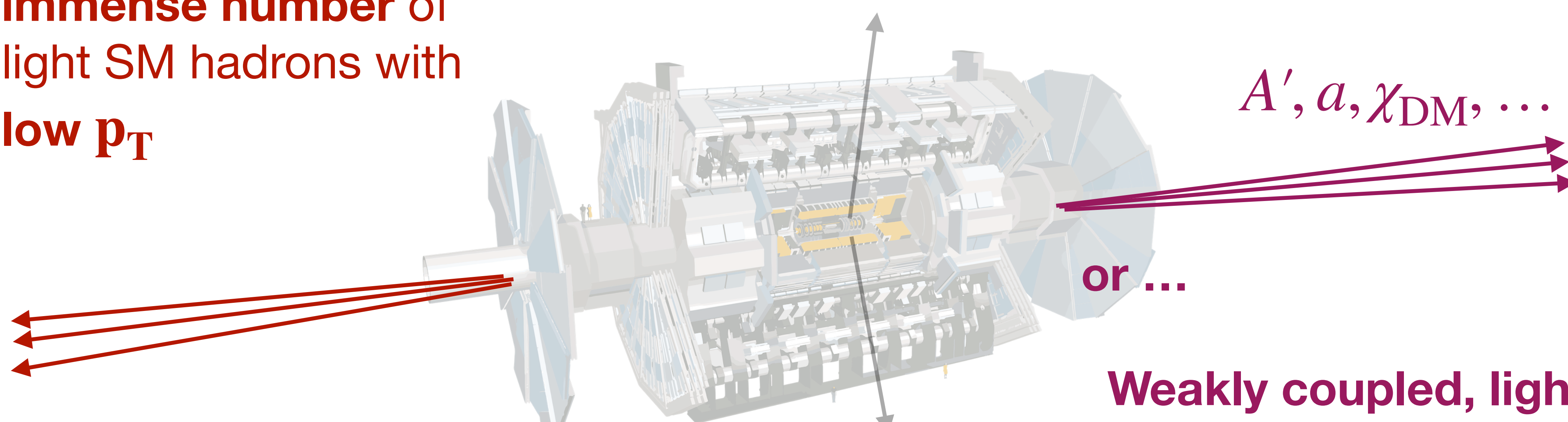
Neutrinos and the long-lifetime frontier

The LHC is the highest energy collider in the world

→ **Its large-scale experiments** were designed to search for **heavy** and **strongly produced** new particles

→ Their design **optimal** to search for **heavy BSM** and probe **SM physics**

But: also produce **immense number** of light SM hadrons with **low p_T**



Neutrinos produced in hadron decays

maybe very rarely produced & long-lived?

Neutrinos and the long-lifetime frontier

The LHC is the highest energy collider in the world

→ **Its large-scale experiments** were designed to search for **heavy** and **strongly produced** new particles

→ Their design **optimal** to search for **heavy BSM** and probe **SM physics**

about **1% of all pions with $E > 10\,\mathrm{GeV}$** are **produced** in the **forward 10[-6]% of solid angle**

→ **small detector** in this region would have **impressive sensitivity**

But: als
immens
light SM
low p_T

$\pi, K, D, D_s, \nu_e, \nu_\mu, \nu_\tau, \ldots$

Neutrinos produced in hadron decays

W, Z, top, Higgs

Weakly coupled, light new particles

maybe very rarely produced & long-lived?

FASER: the **F**orw**A**rd **S**earch **E**xpe**R**iment

FASER : small, inexpensive experiment at LHC with goal to

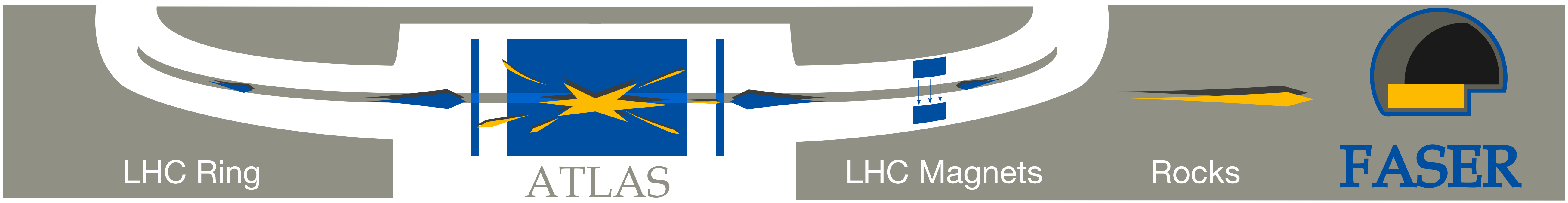
→ **Search long-lived particles (LLPs)**

→ **Study collider Neutrinos**

"Search for Dark Photons with the FASER detector at the LHC", arXiv:2308.05587

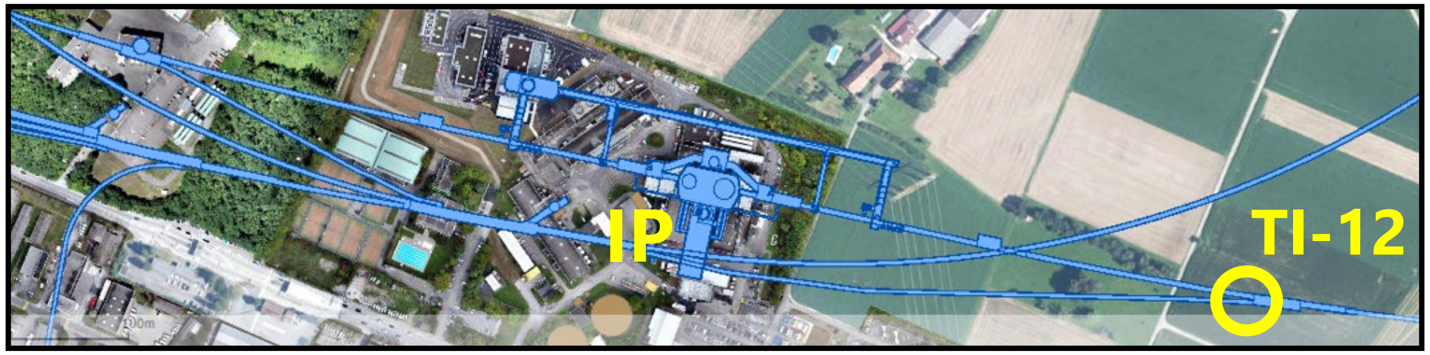
"First Direct Observation of Collider Neutrinos with FASER at the LHC", arXiv:2303.14185

First Emulsion Analysis, https://cds.cern.ch/record/2868284/files/ConferenceNote.pdf



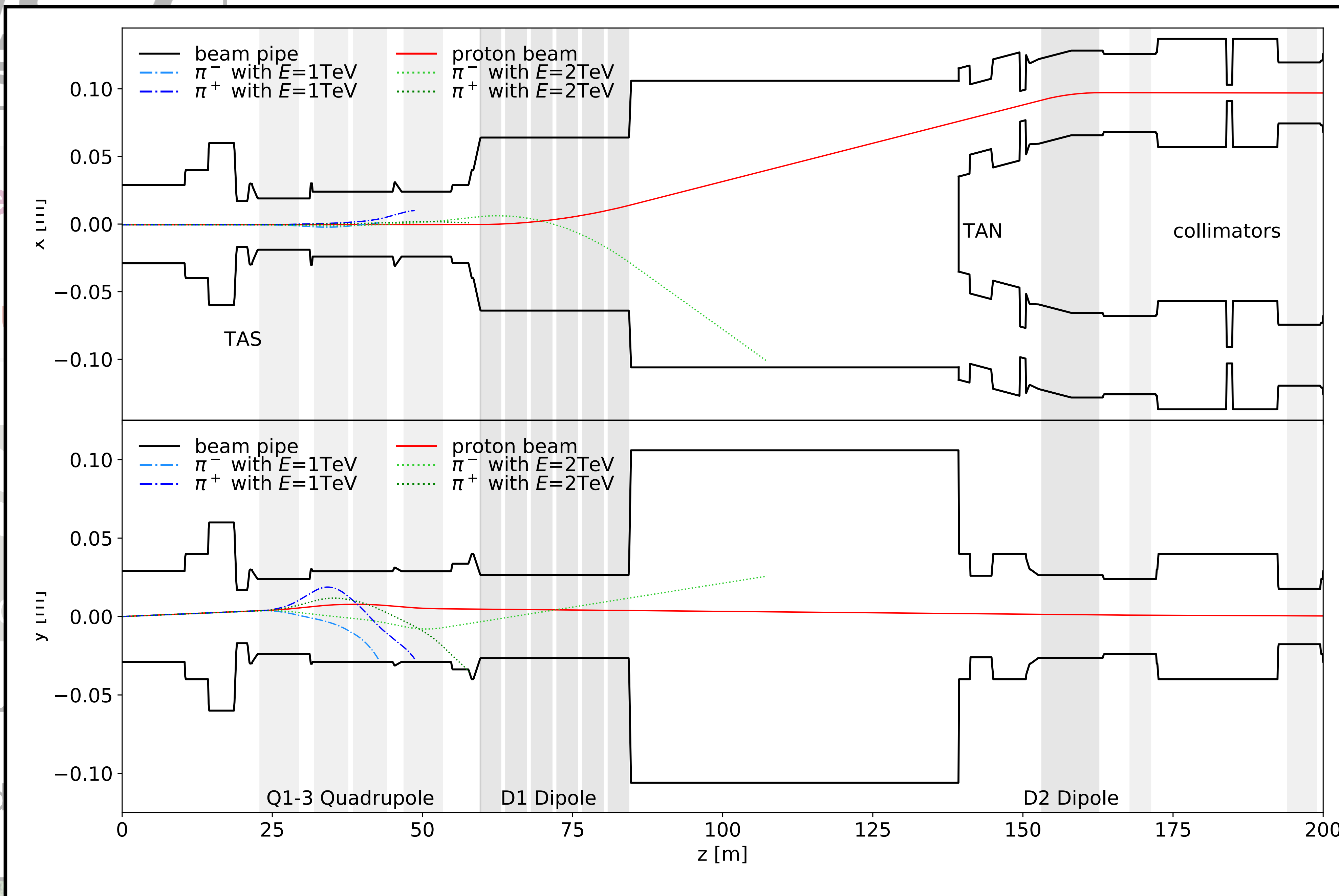
Inside TI-12 tunnel, FASER situated **ca. 500 m downstream** from the **ATLAS** collision point

→ Shielded by **ca. 100 m** rock ; **LHC magnets deflect** charged particles, creates **low bkg.** environment



FASER **aligned** with **ATLAS** line-of-sight (**LOS**) **maximizes neutrino flux**

FASER: the ForwArd Search ExpeRiment



→ Se

→ St

LH

the LHC”,

SER at the LHC”,

ote.pdf

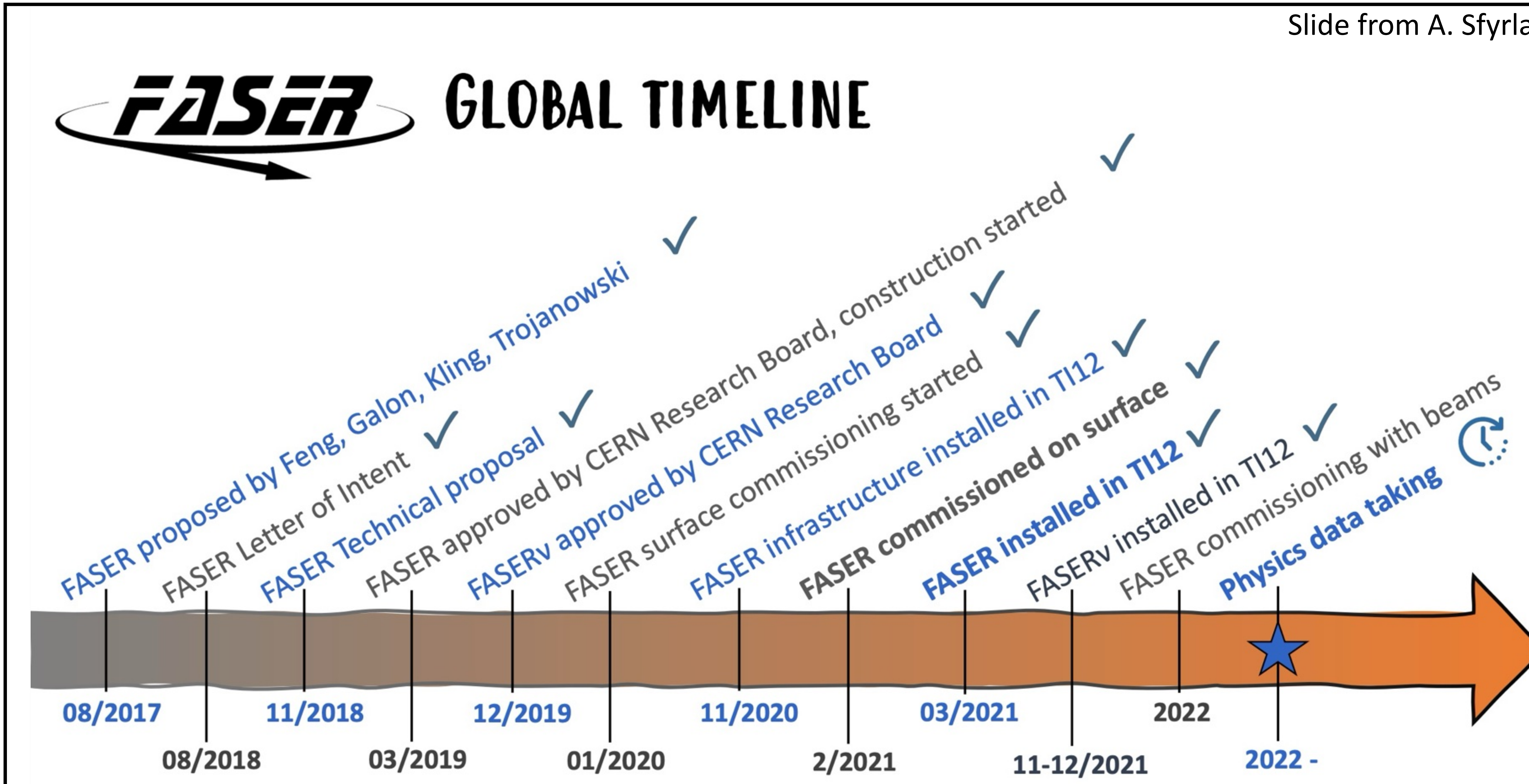
Inside TI-1 ... llision point

→ Shielded ... environment

FASER **aligned** with
ATLAS line-of-sight (**LOS**)
maximizes neutrino flux

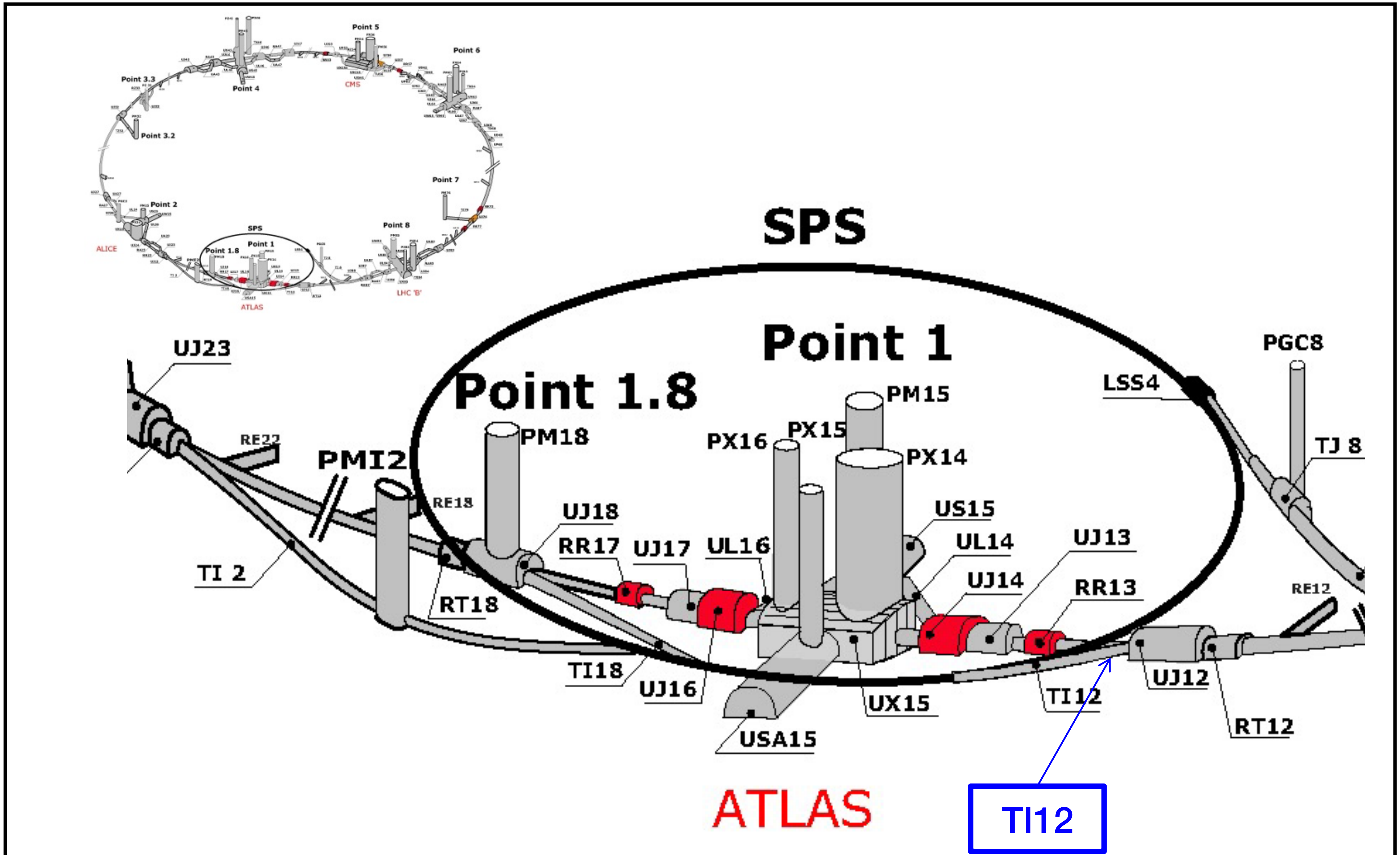
FASER Detector : Global Timeline

From **proposal** to **data taking** in **five** exciting **years :**



Finding the ideal Location : **TI12 tunnel**

Scouting for **real estate** :



→ Aligned with the beam collision axis line-of-sight (LOS), after LHC **has curved away**


TI12: August 2018
Line of sight (LOS) to
ATLAS IP
Needed 50 cm deep trench
to allow 5 m long detector
to be aligned with LOS

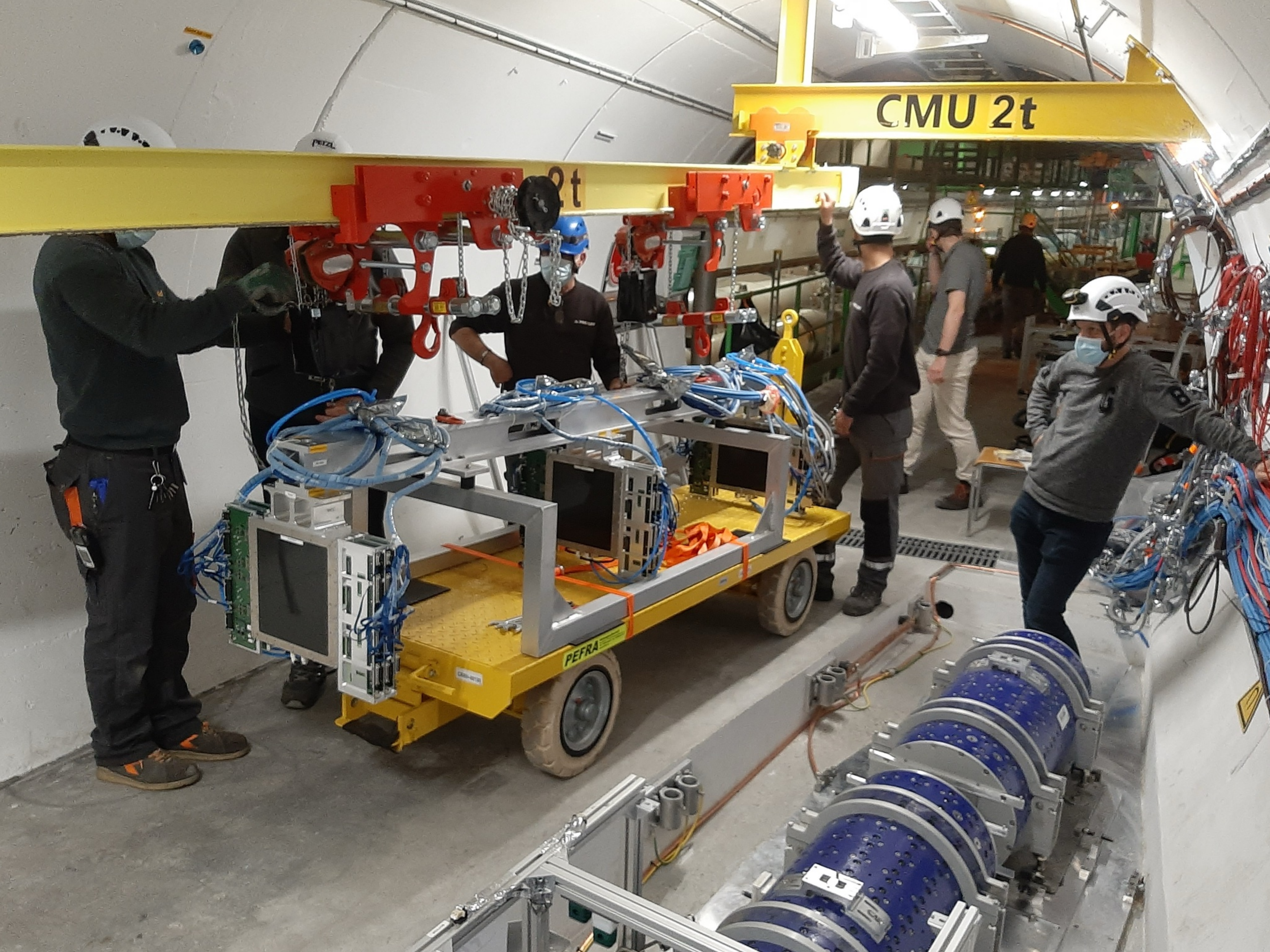

TI12: April 2020
LOS
Needed 50 cm deep trench
to allow 5 m long detector
to be aligned with LOS

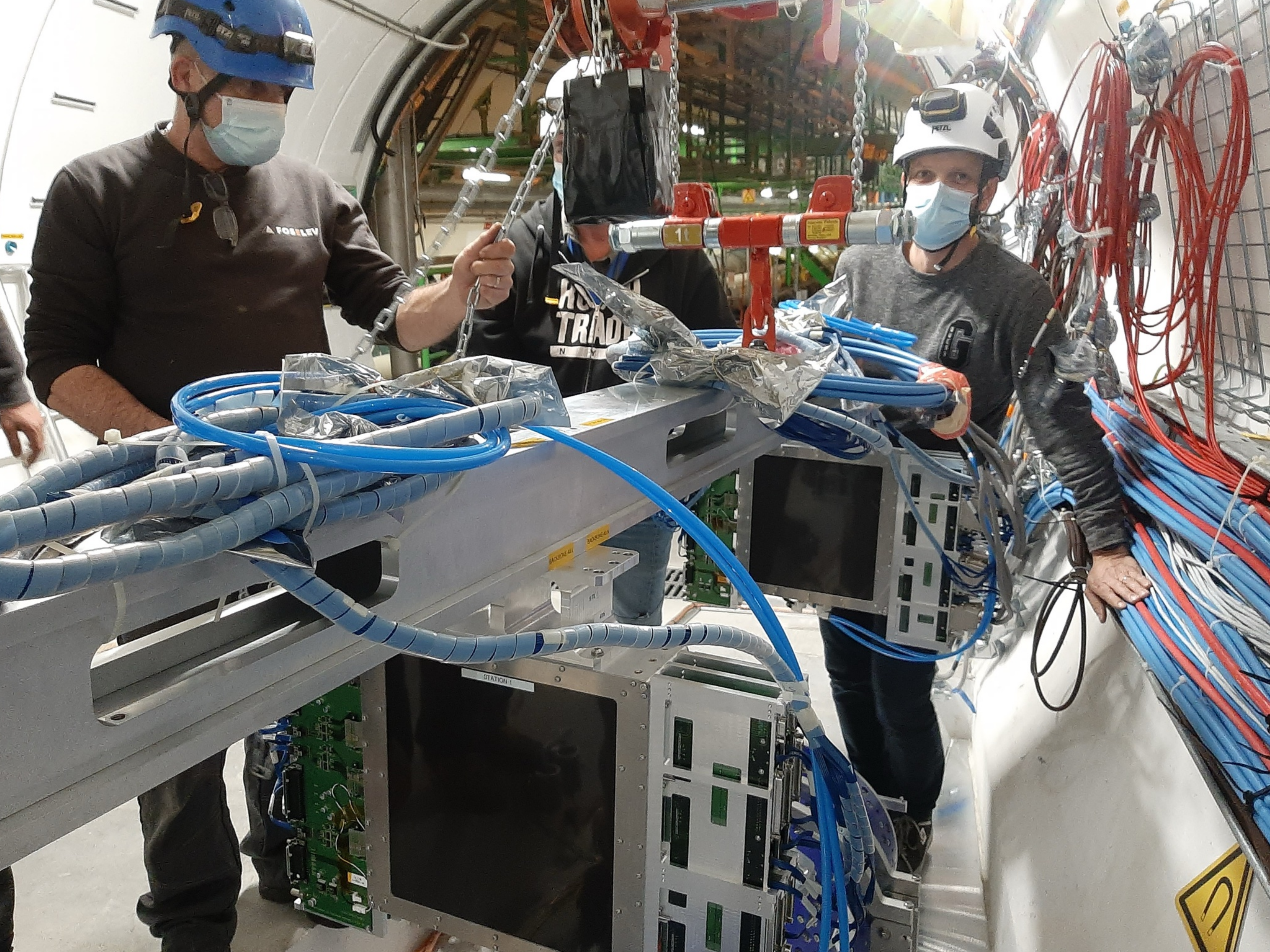
TI12: November 2020

TI12: November 2020

Tracker station installation begins
(built from ATLAS SCT barrel modules)

TI12: March 2021


CMU 2t
2t
PEFRA


STATION 1


PA-1812
PA-1811
2t
FASER
ATTENTION
TI12: April 2021

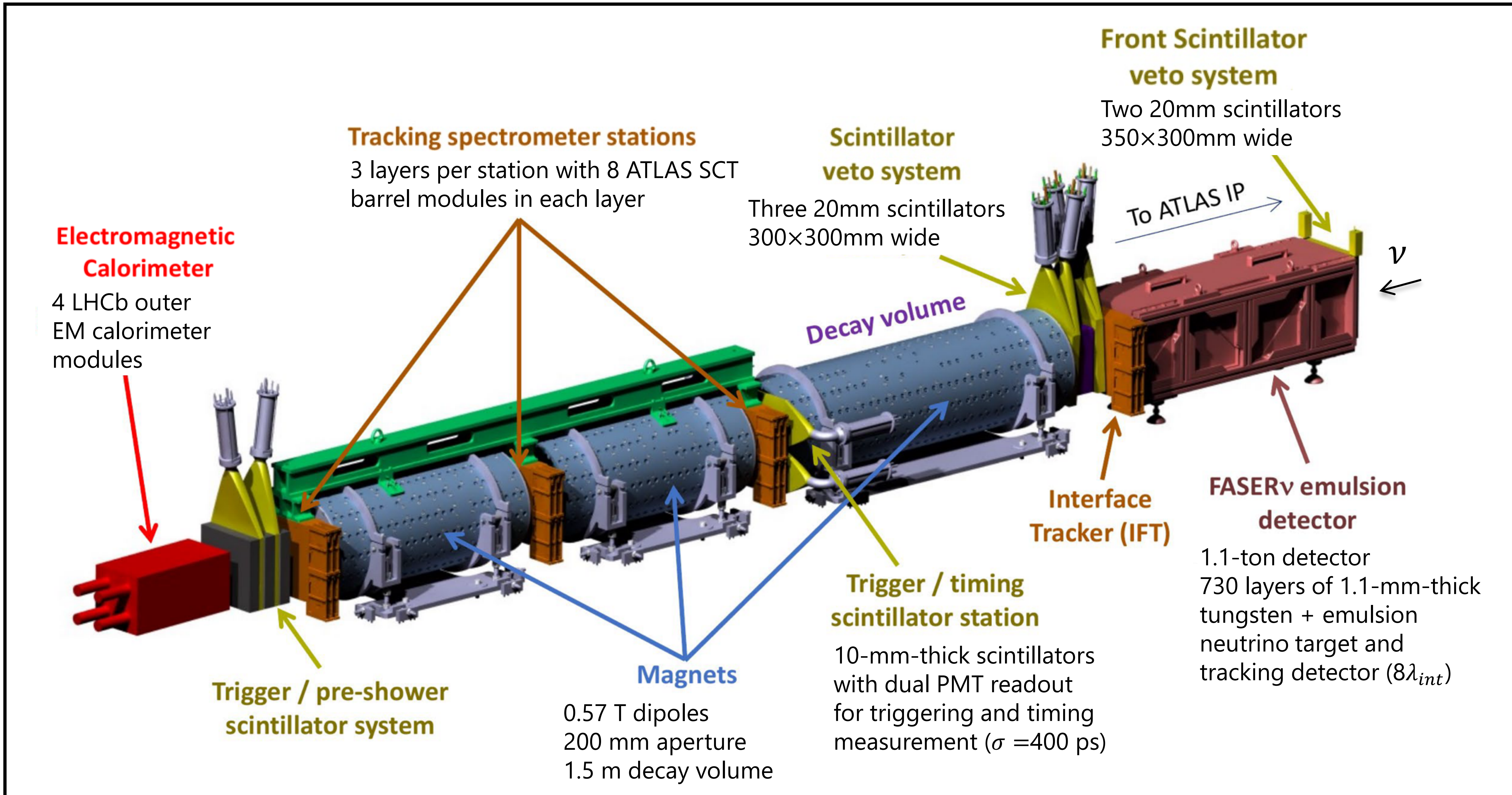
The **FASER** Detector

See "The FASER Detector"
https://arxiv.org/abs/2207.11427

From **front** to **back**:

Neutrino-nucleon cross section increases with energy → even small (1.1 ton) target produces **large number of interactions**

Front Scintillator veto → FASERν → Interface tracker → Scintillator veto system

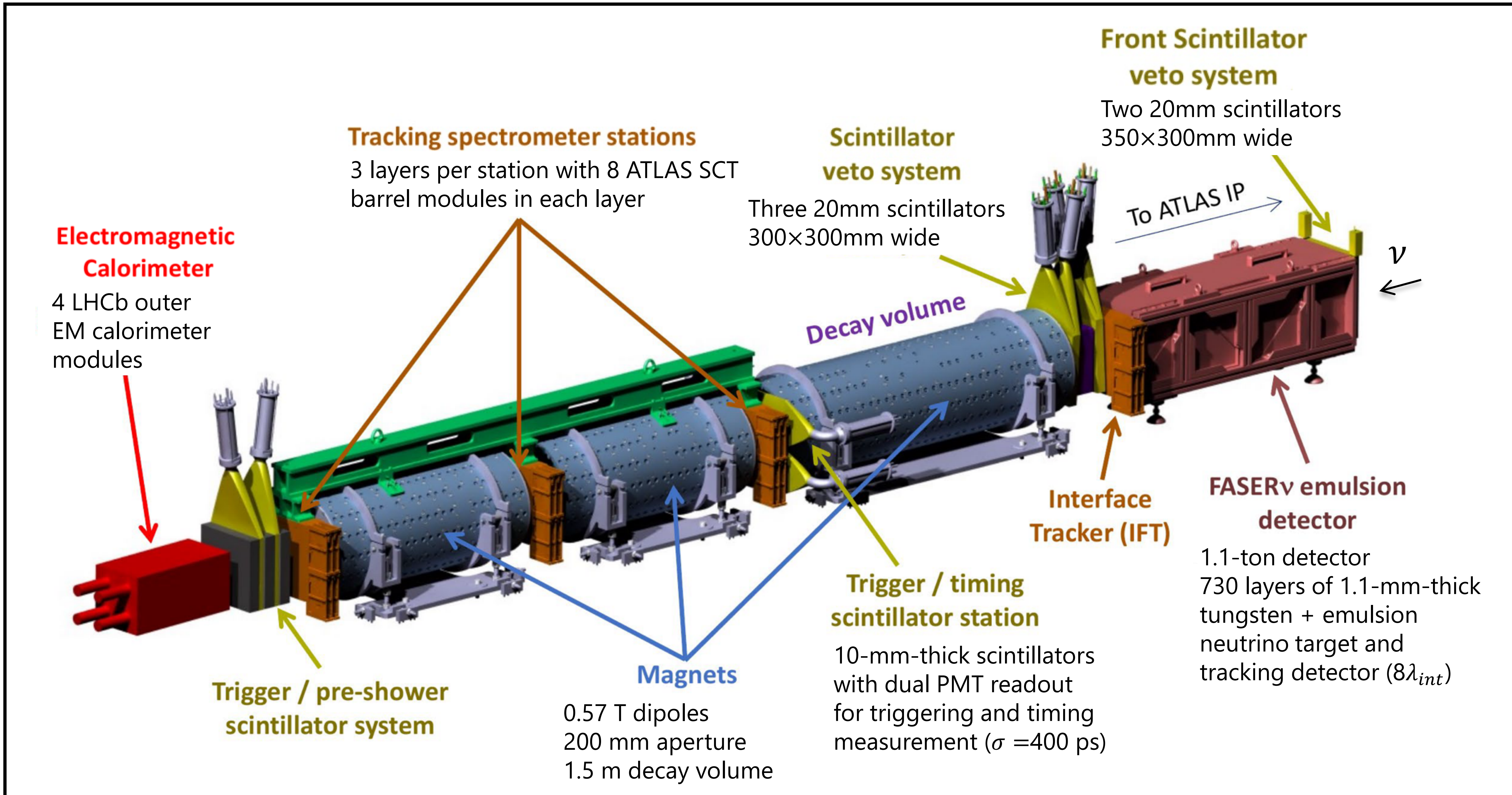


The **FASER** Detector

See "The FASER Detector"
https://arxiv.org/abs/2207.11427

From **front** to **back**:

… Decay Volume in magnetic field → 3 Tracking stations → Electromagnetic cal.



FASER Operations

Continuous and **largely automatic** data taking in 2022 and 2023 :

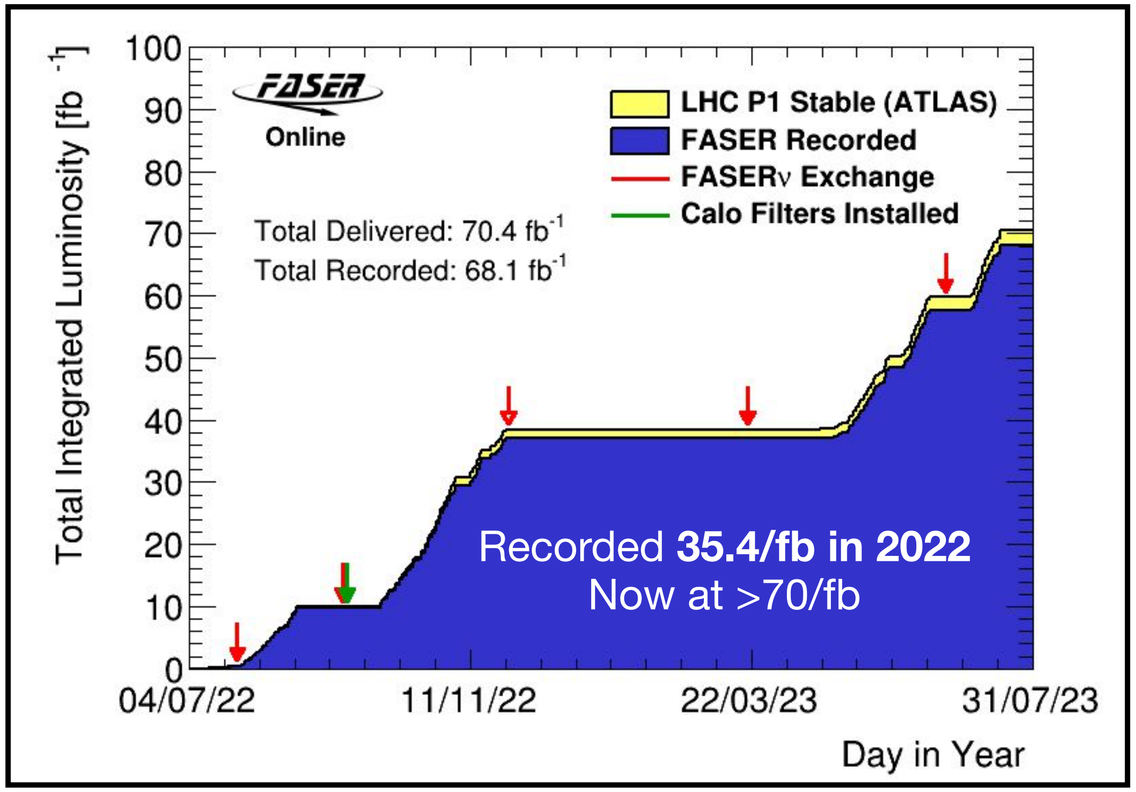
Trigger rate of ~ **1.3 kHz**

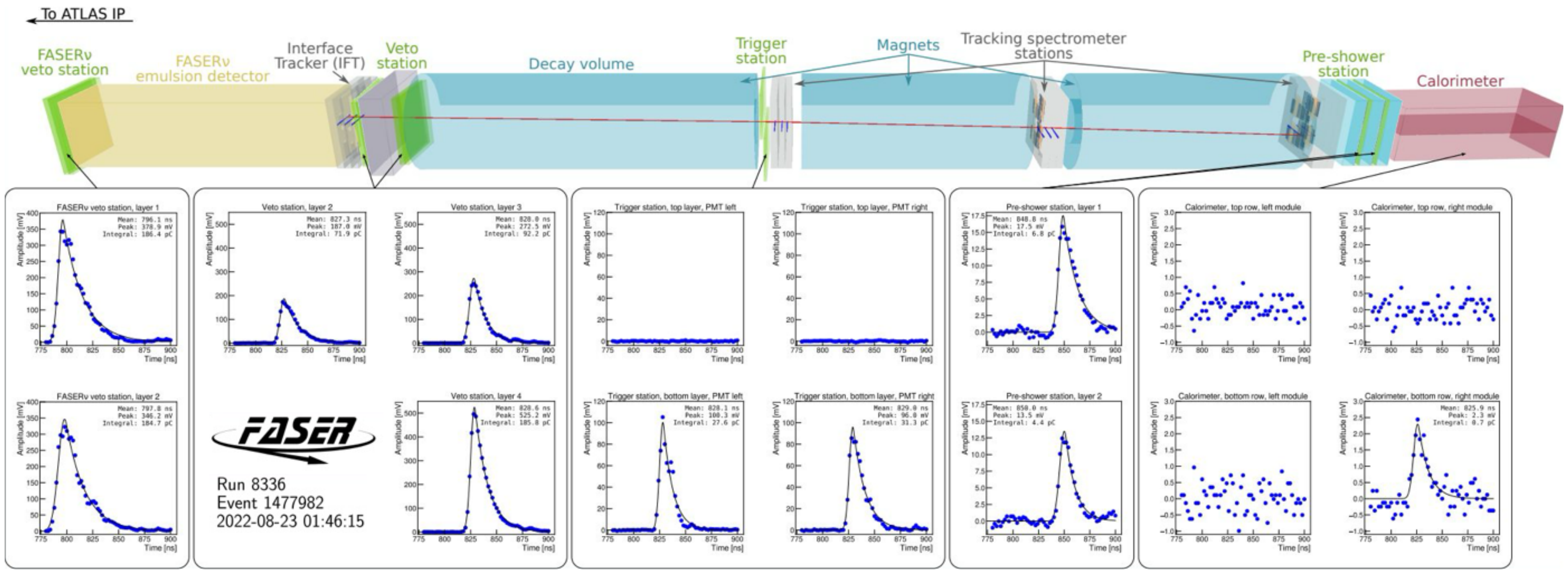
Recorded more than **350 M single** muon events

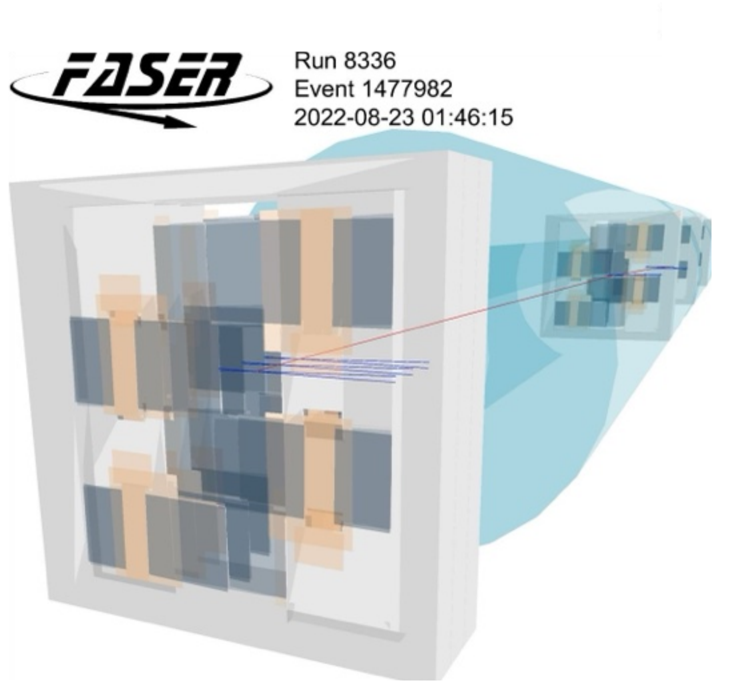
Recorded 96.1% of **delivered** Luminosity :

Limited by DAQ dead-time (1.3%) and instabilities

Dark photon analysis used **27 fb^{-1}**







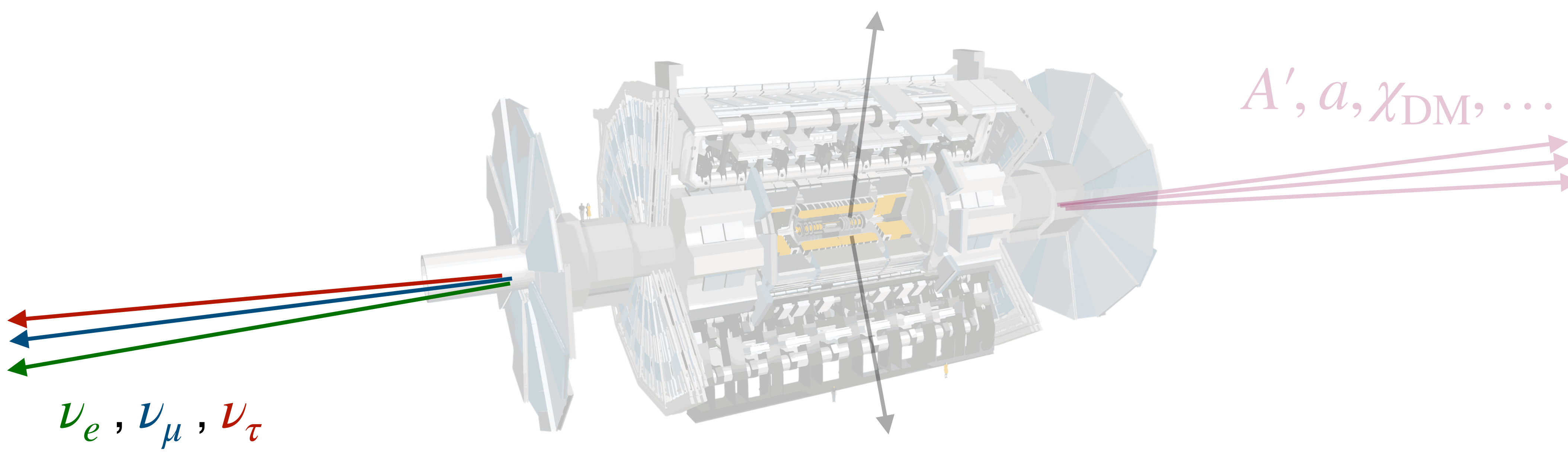
1. νLLPs Searches :-)

“First Direct Observation of Collider Neutrinos with FASER at the LHC”, arXiv:2303.14185

First Emulsion Analysis,
https://cds.cern.ch/record/2868284/files/ConferenceNote.pdf

Why study collider Neutrinos?

Prior FASER, **not a single neutrino** produced in a beam-beam collision has **ever** been **directly detected**



pp-collisions copiously produce neutrinos & anti-neutrinos & at very high energies for which **neutrino interactions are not well studied.**

→ **Energies** in the **range** of **TeV**, highest human-made energies

→ **Neutrino interaction cross section** : $\sigma \sim E_\nu$

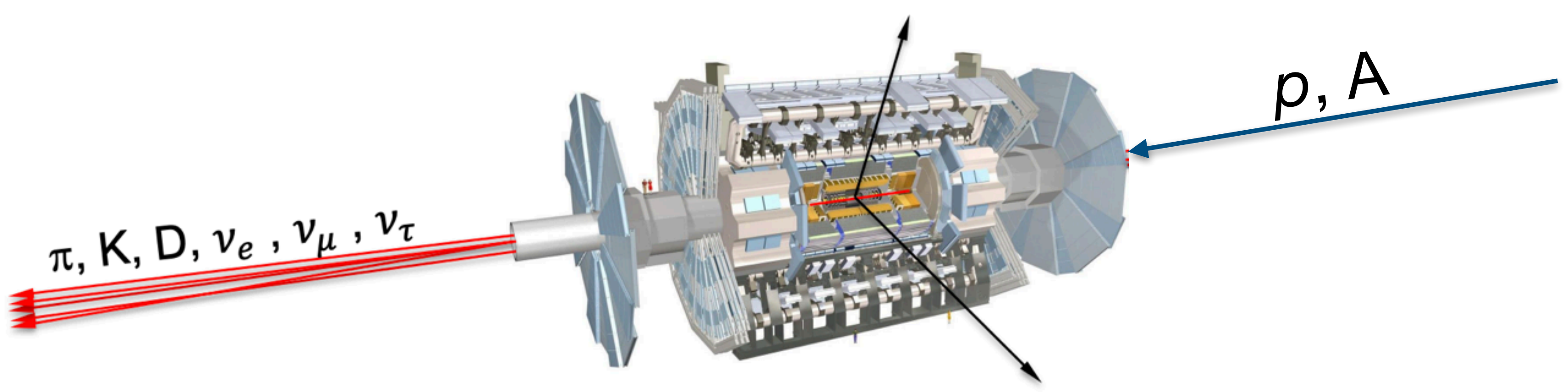
→ **All flavors** are produced : $K \rightarrow \nu_e$, $\pi \rightarrow \nu_\mu$, $D_{(s)} \rightarrow \nu_\tau$

Every time we discover neutrinos from a new source (reactors, the Sun, supernovae, the atmosphere, ...) we learnt something very exciting about not just particle physics, but also cosmology and the Universe.

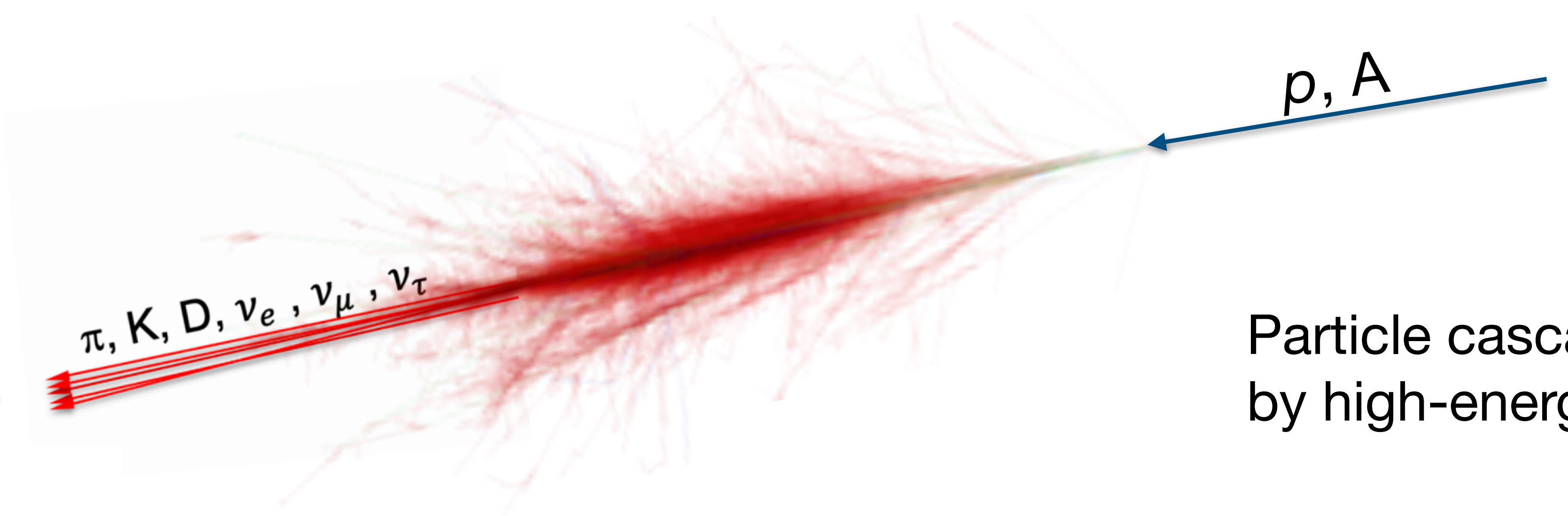
Why study collider Neutrinos?

Forward direction very **relevant** for the simulation and understanding of **extensive air showers** (EAS)

LHC



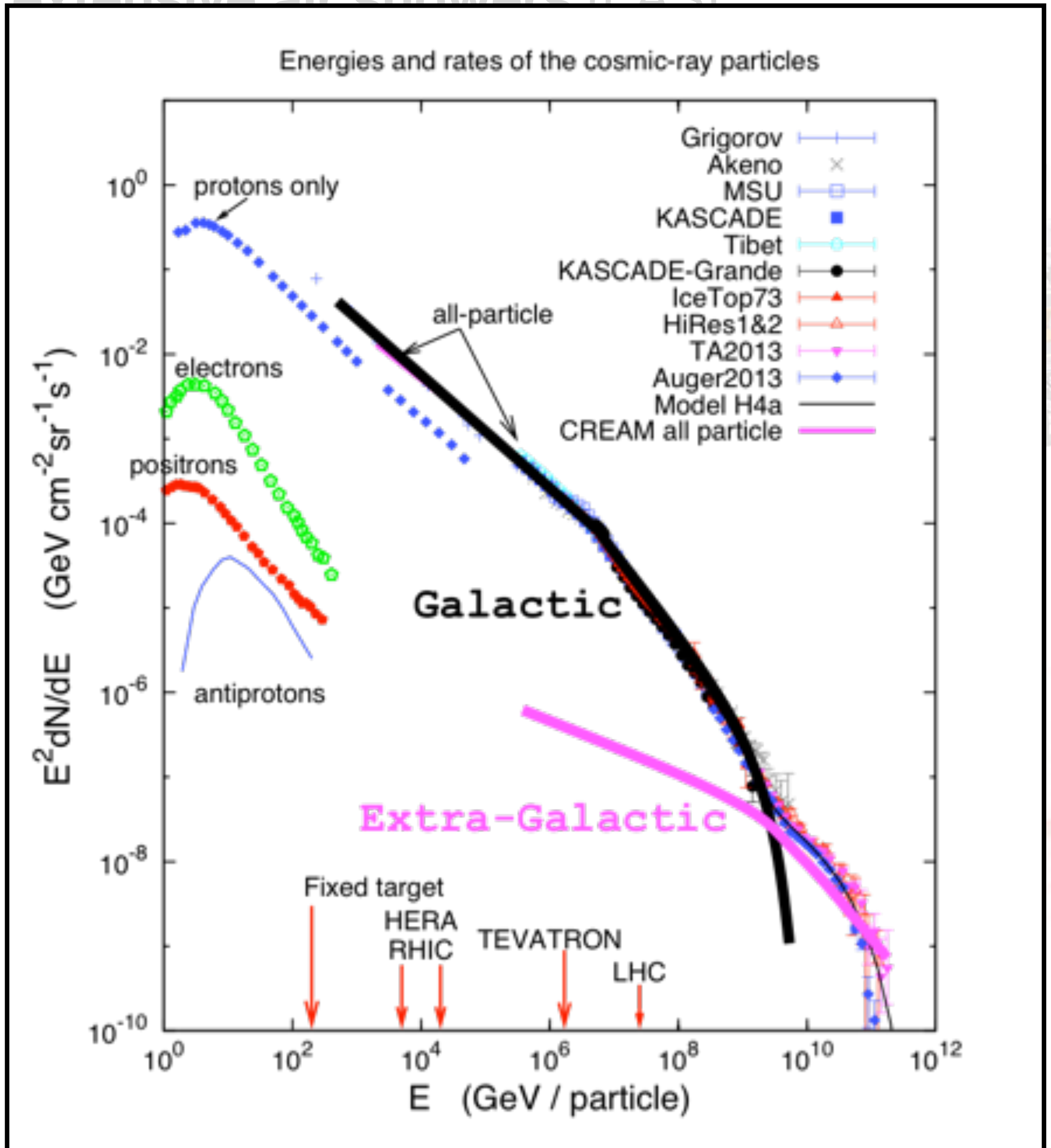
EAS



Particle cascade in EAS initiated by high-energy cosmic ray

Why study collider Neutrinos?

Forward direction very **relevant** for the simulation and understanding of **extensive air showers** (EAS)



Particle cascade in EAS initiated by high-energy cosmic ray

Open question: Mass composition at the highest energies at which extra-galactic sources dominate

Why study collider Neutrinos?

Forward direction very **relevant** for the simulation and understanding of **extensive air showers** (EAS)

Crucial variables to determine mass of primary source :

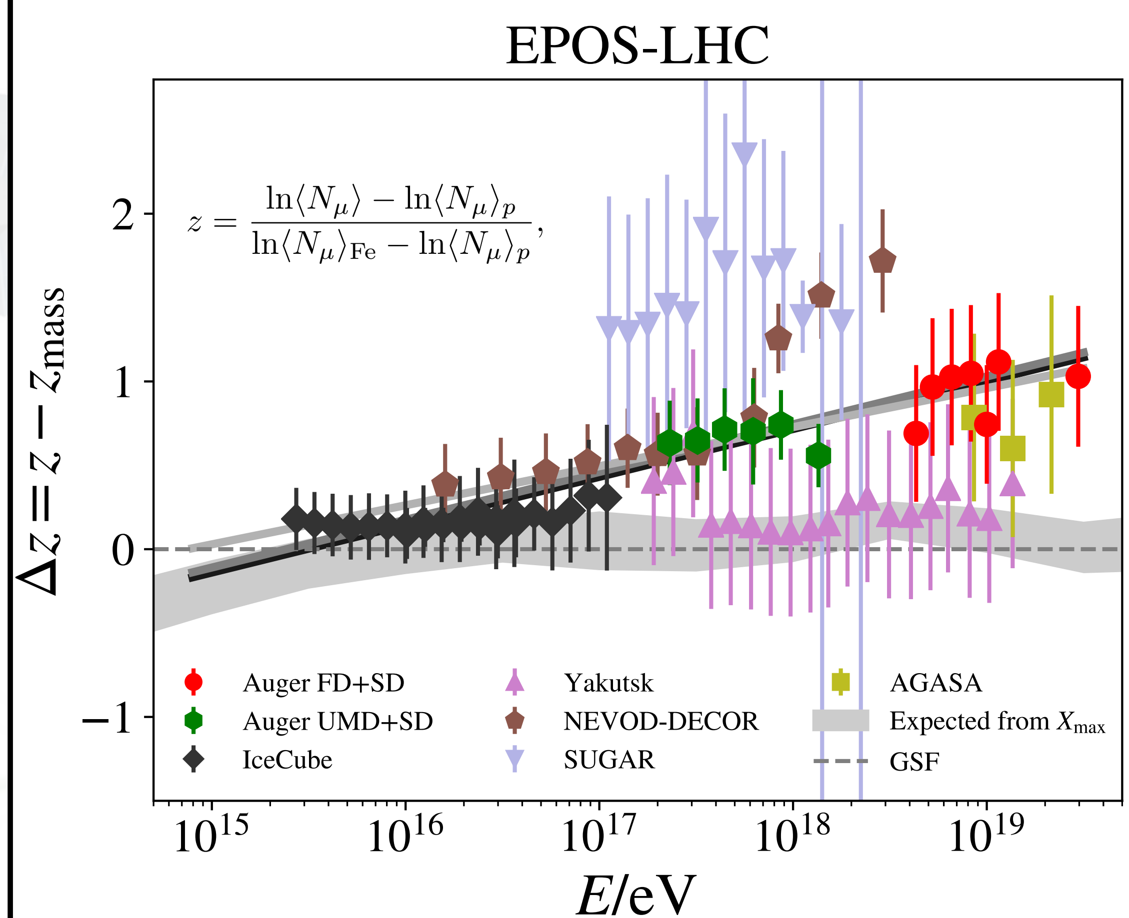
N_μ & $X_{\max}$

(# of muons & depth of shower maximum)

↓

The higher the incident mass, the larger the # of produced muons; better discriminator than $X_{\max}$

Meas. of N_μ contrary to $X_{\max}$ do not rely on fluorescent telescopes (which require moonless nights)

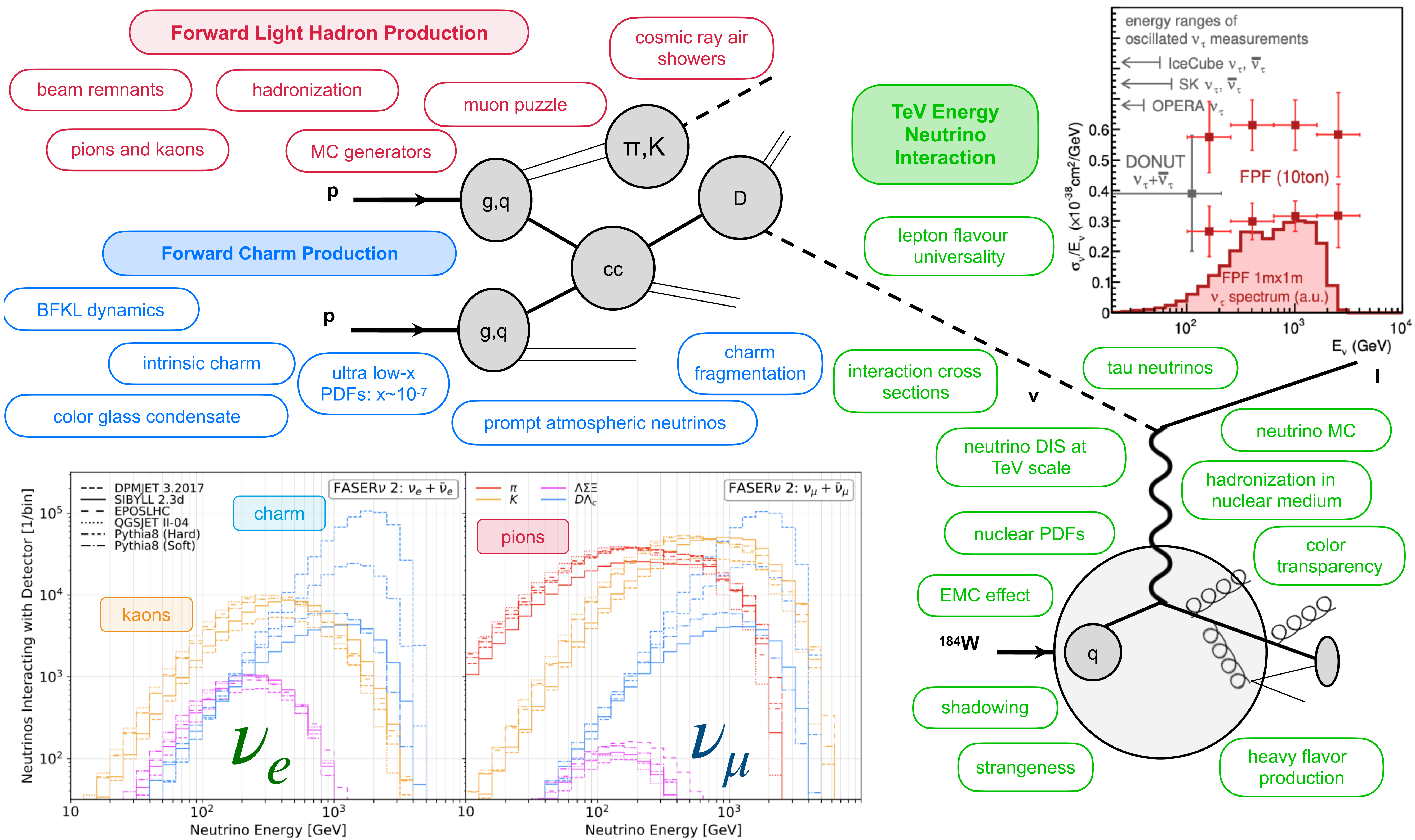


Δz represents difference of measured & inferred number of muons using a given hadronic model

For a better understanding: need to better constrain very forward **strangeness production** → Encoded in E_ν and $\nu_e : \nu_\mu$ ratio.

The big picture:

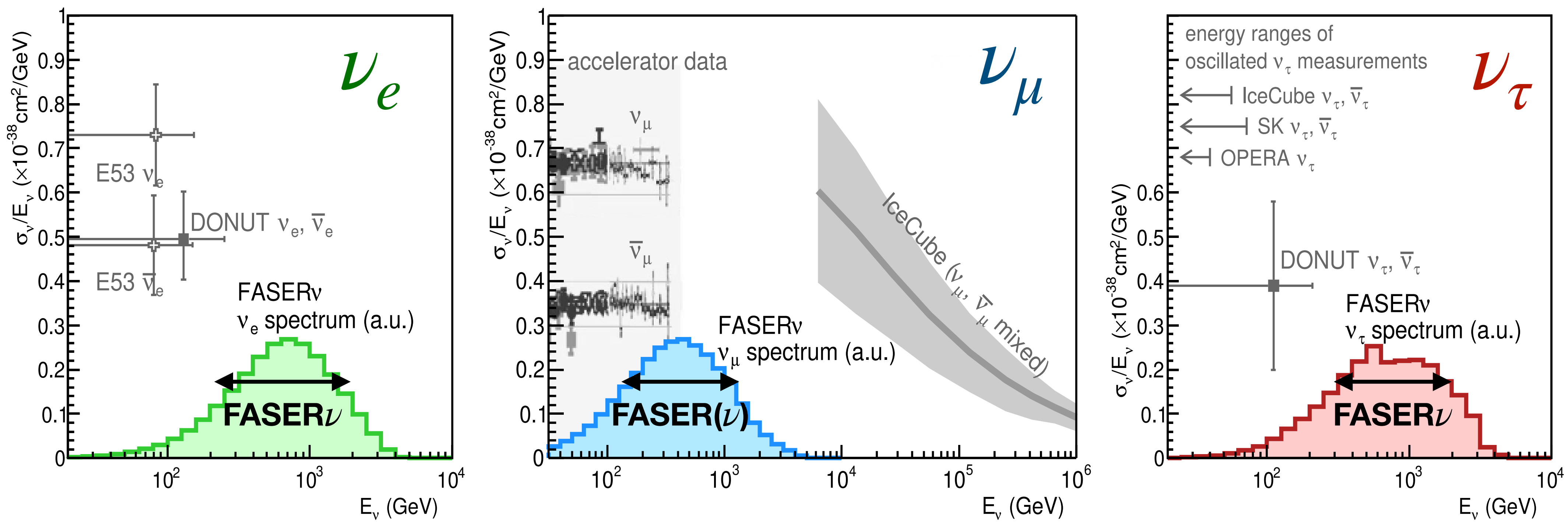
Illustration from arXiv:2305.01715



Why study collider Neutrinos?

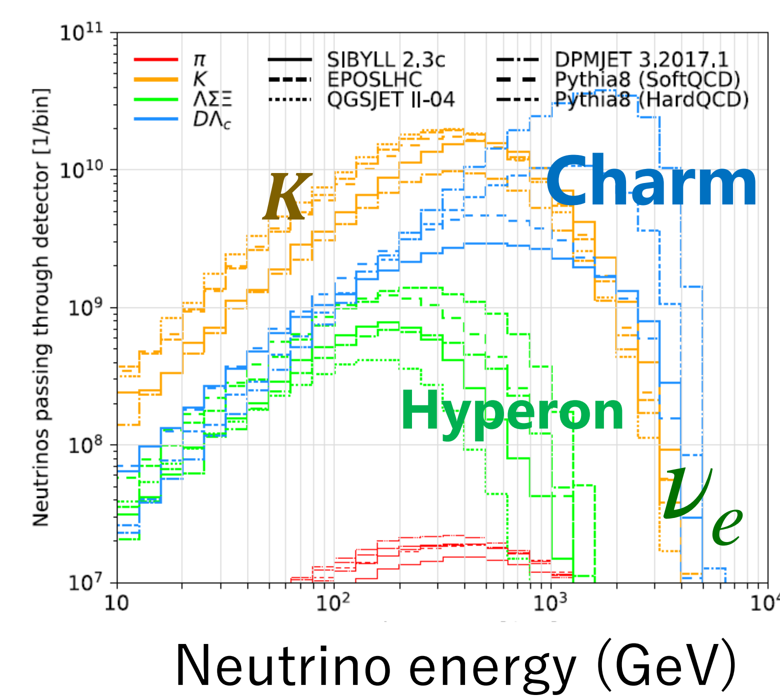
1. **Cross sections** of different neutrino flavors at TeV energies **unexplored**

Neutrino CC interactions with charm $\nu s \rightarrow \ell c$; Nuclear PDFs



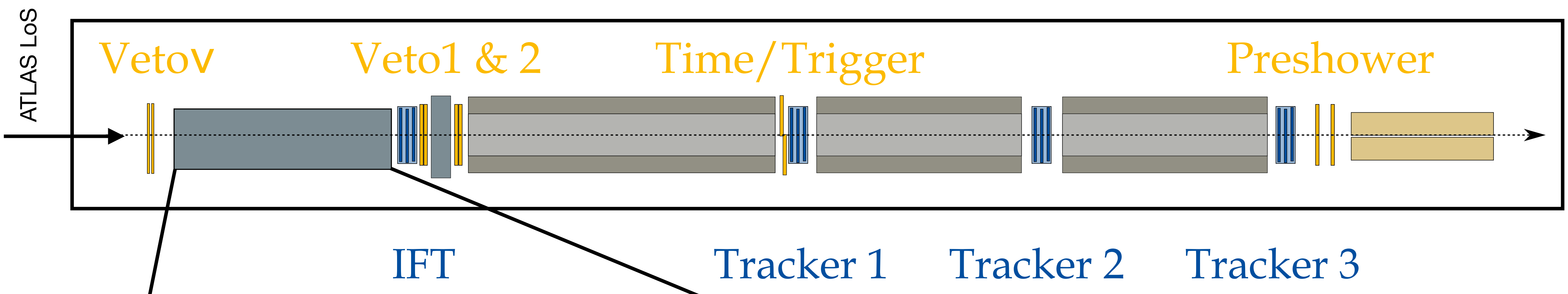
2. **Neutrinos** probe **forward hadron production;** provide **new input for QCD** (though low-x PDFs, charm) **& astroparticle physics** (e.g. atmospheric neutrinos)

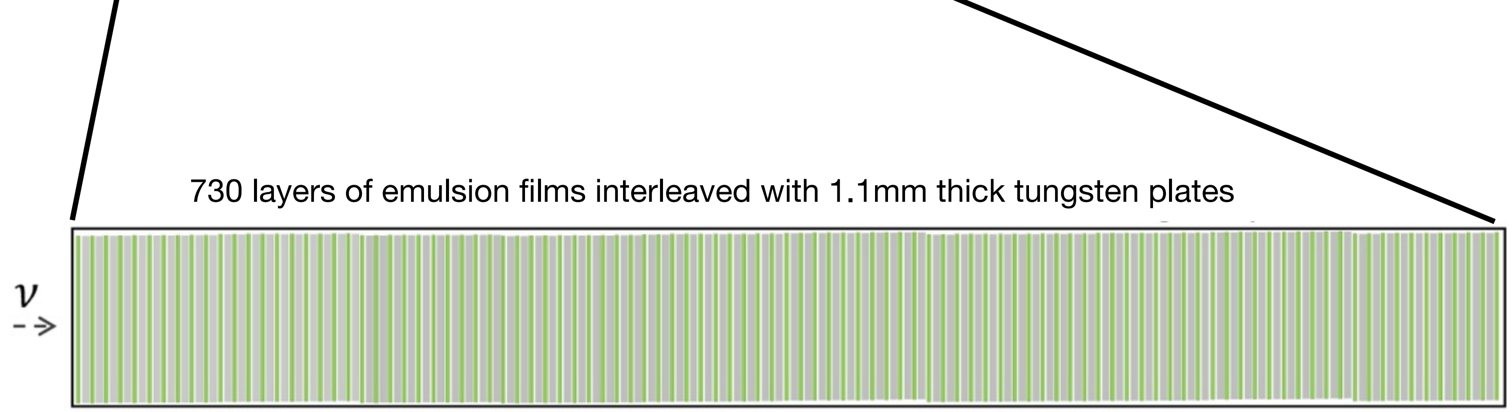
Neutrinos produced in charm important to improve precision of atmospheric neutrino and air-shower measurements



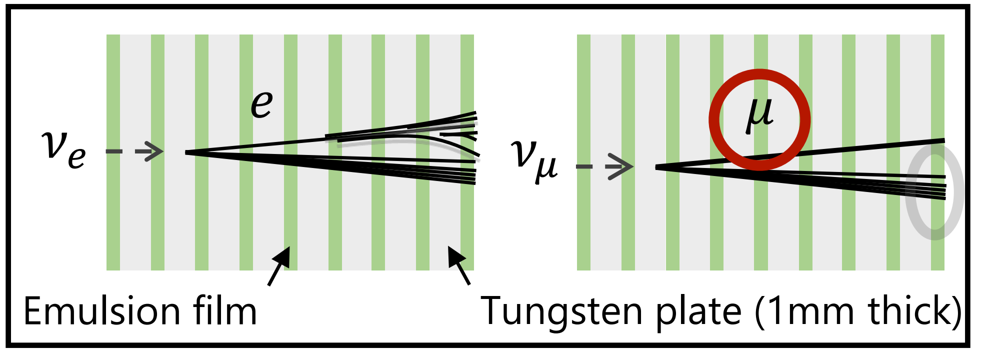
How can FASER study collider Neutrinos?

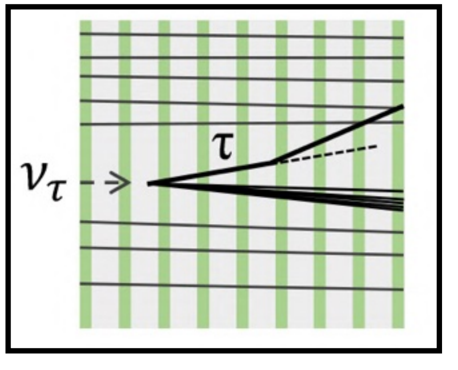
FASER has a **dedicated** emulsion detector (**FASERν**) with **1.1-ton of tungsten**

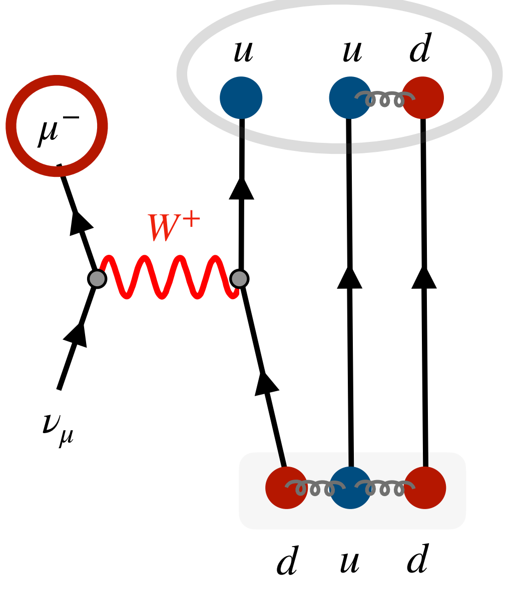




Charged-current (CC) Interactions





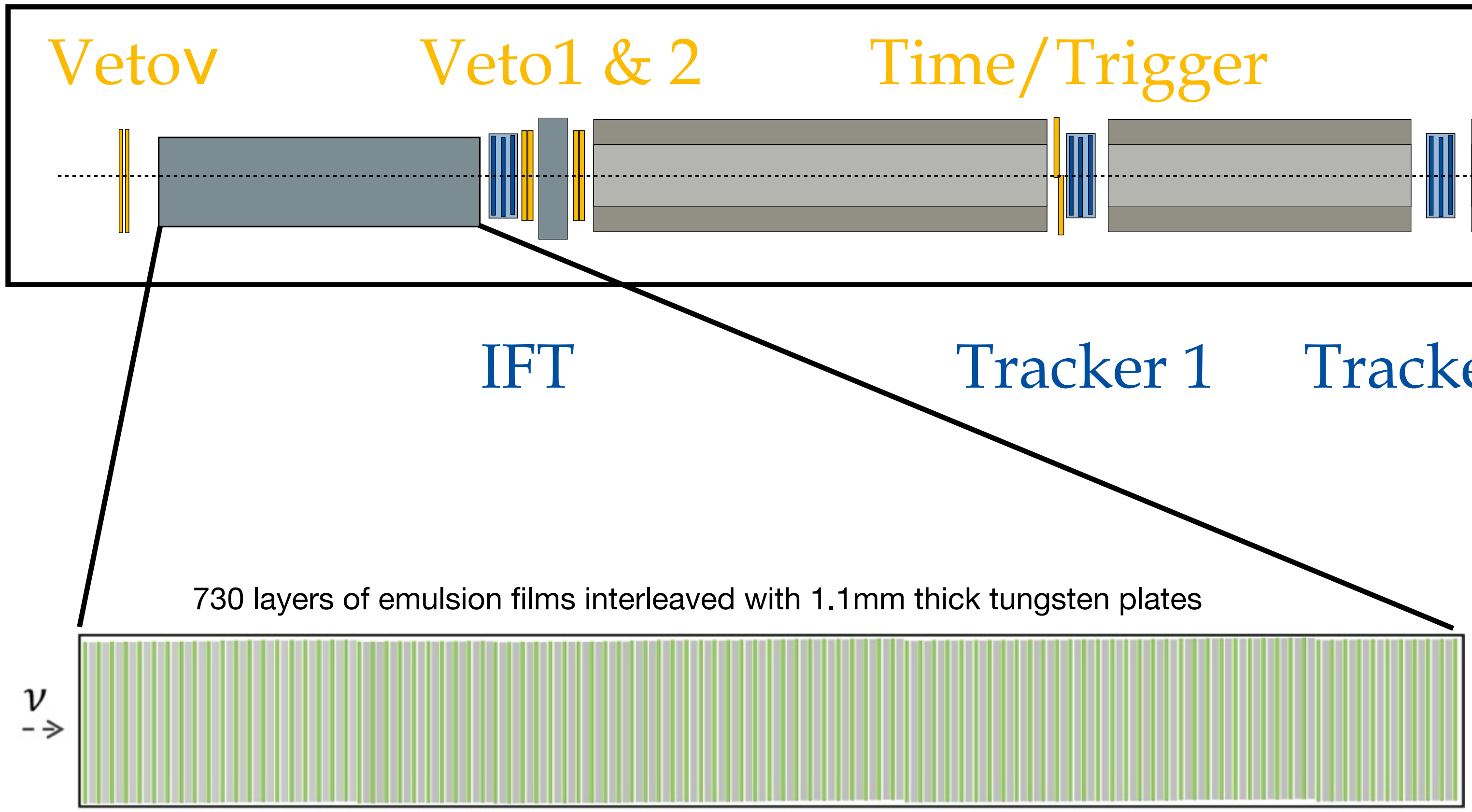


The incoming neutrino transforms the down quark into an up quark and may cause a “spray” of hadronic activity

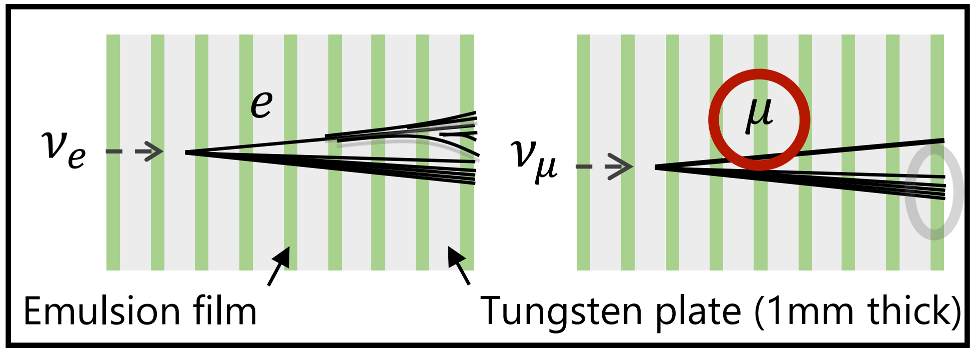
Neutron in the Tungsten target of FASERν

How can FASER study collider Neutrinos?

FASER has a **dedicated** emulsion detector (**FASERν**) with **1.1-ton of tungsten**



Charged-current (CC) Interactions



Two measurement strategies:

1. Use **FASERν** as **target** and **electronic components of FASER to detect CC μ**

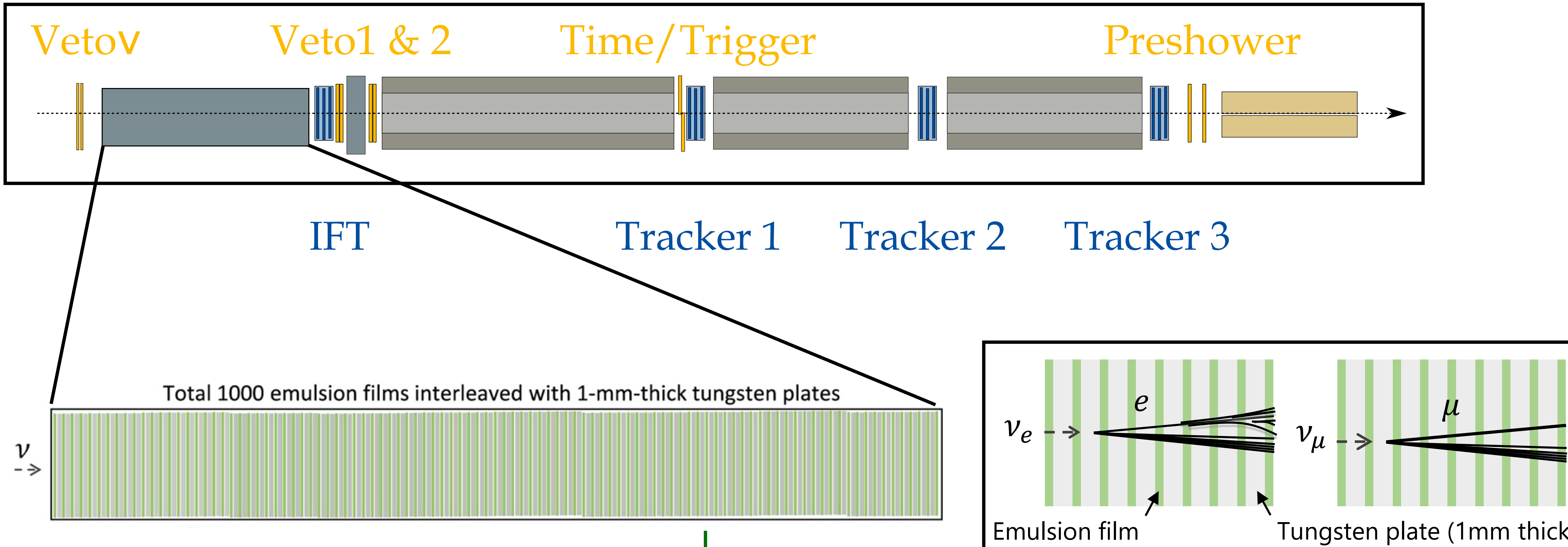
   + : High sensitivity ; can separate ν and $\bar{\nu}$; fast turn-around time

   - : Can only study ν_μ

"Neutrino detection without neutrino detectors: Discovering collider neutrinos at FASER with electronic signals only" by J. Arakawa, J. L. Feng, A. I, F. Kling, M. Waterbury, *Phys.Rev.D* 106 (2022) 5, 052011

How can FASER study collider Neutrinos?

FASER has a **dedicated** emulsion detector (**FASERν**) with **1.1-ton of tungsten**



Two measurement strategies:

2. Scan and analyze **FASERν emulsion films**

 + : Can study all neutrino flavors ; excellent spatial resolution
 - : Time intensive as each film has to be scanned and processed

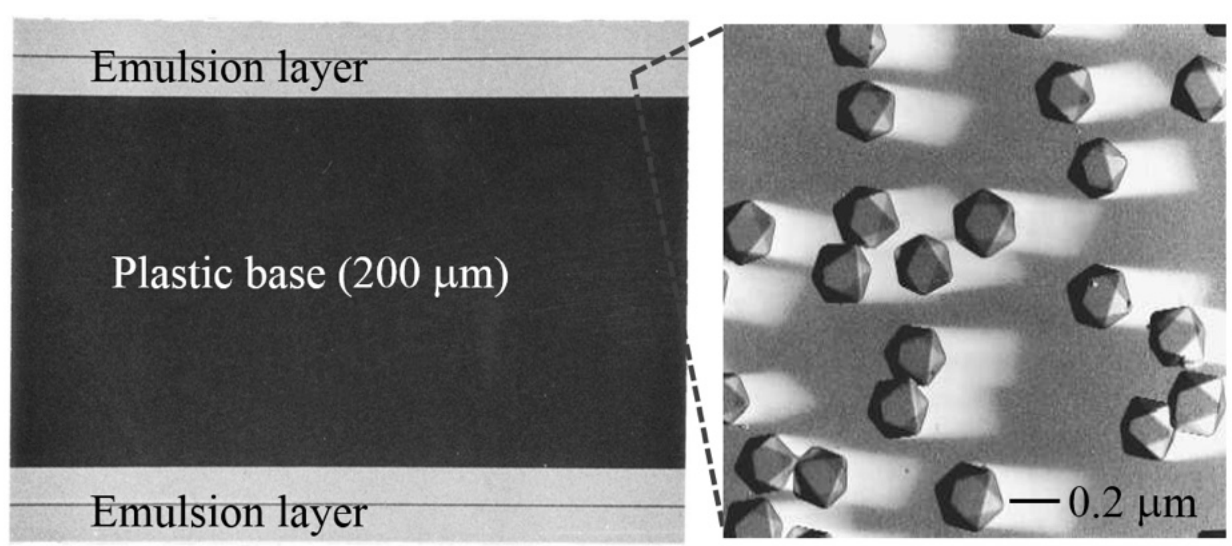
New Summer 2023 **result**!

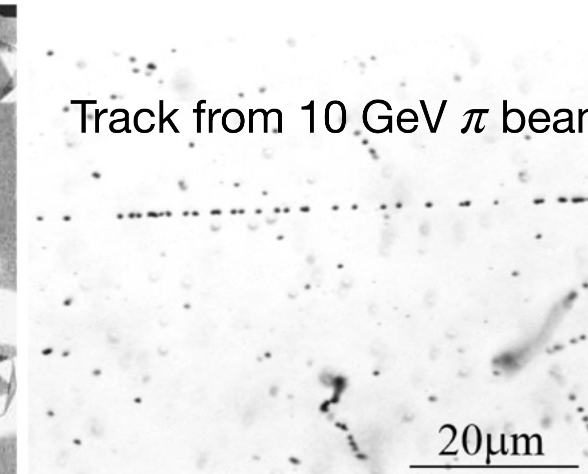
Conference Note: https://cds.cern.ch/record/2868284/files/ConferenceNote.pdf

How can FASER study collider Neutrinos?

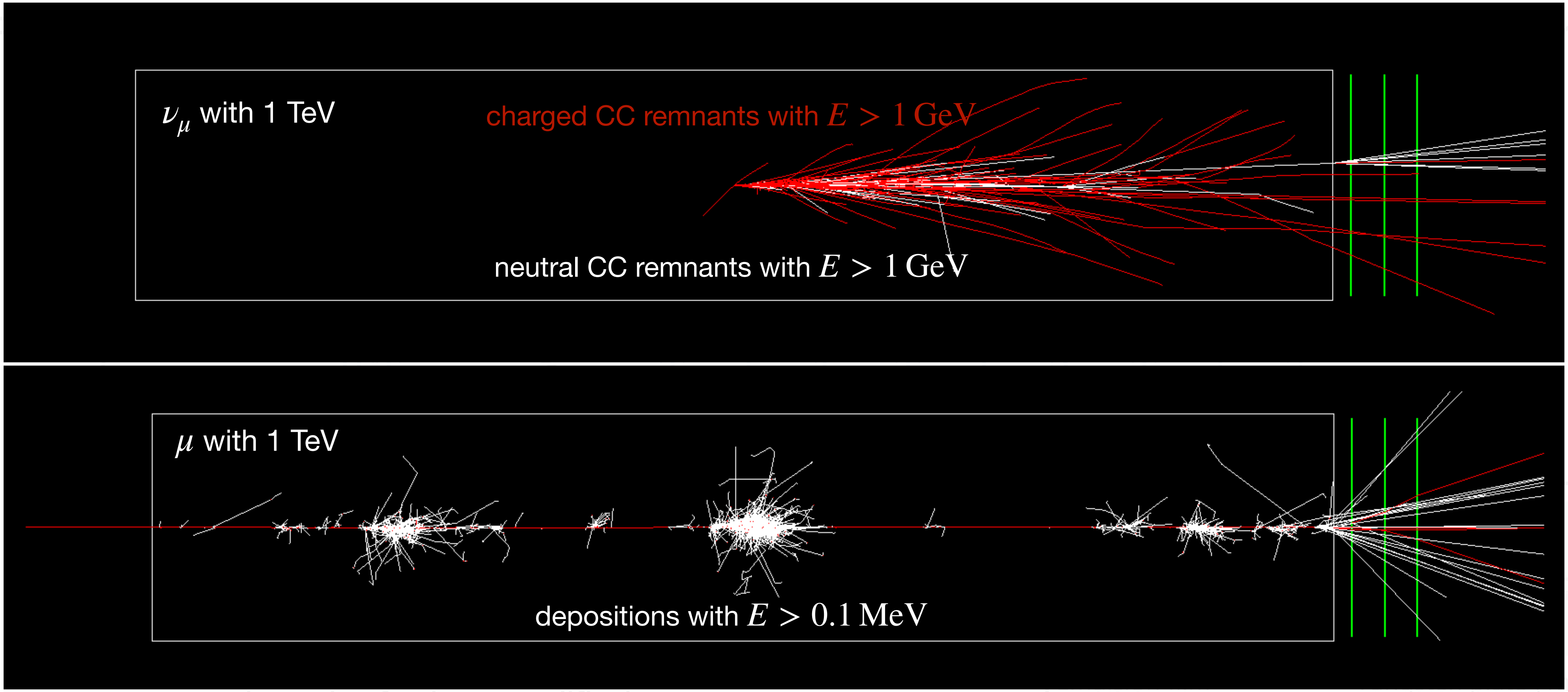
FASER has a **dedicated** emulsion detector (**FASERν**) with **1.1-ton of tungsten**

Silver bromide crystals in a **gelatin substrate**; charged particles cause ionization which is quasi-permanent, and can be further amplified.

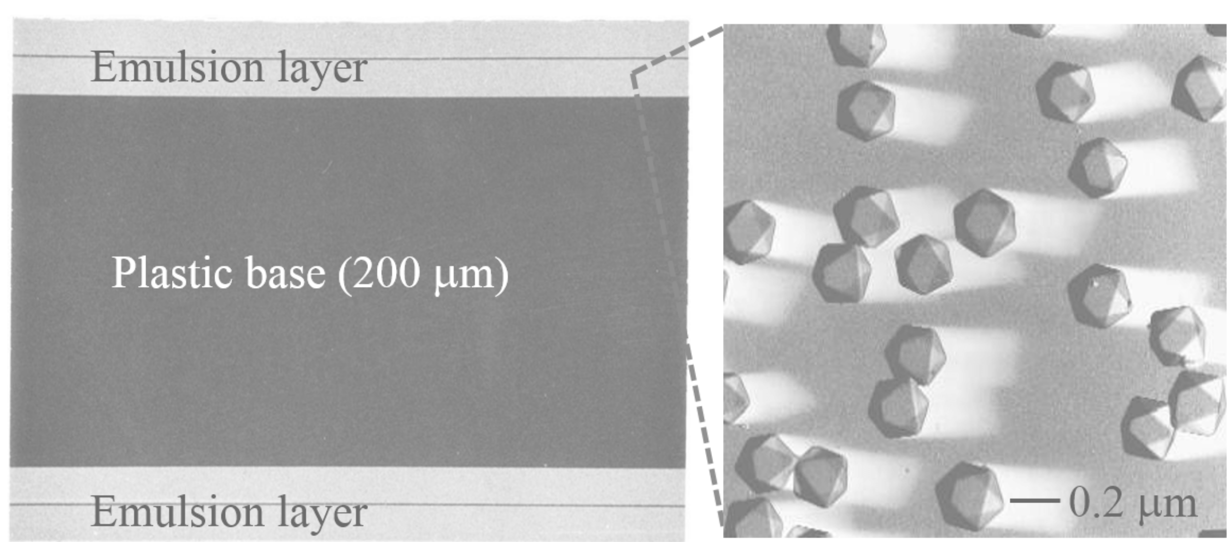


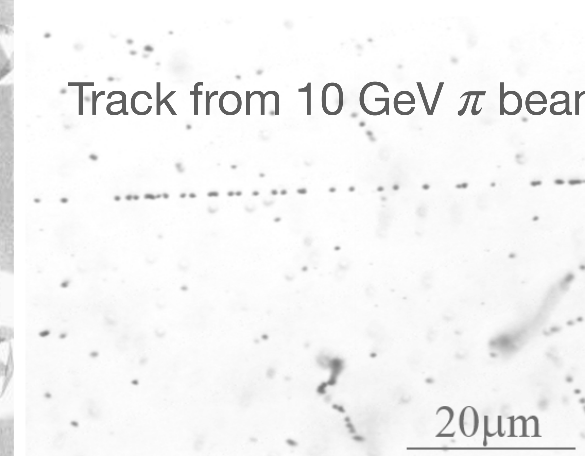


How can FASER study collider Neutrinos?



permanent, and can be further amplified.

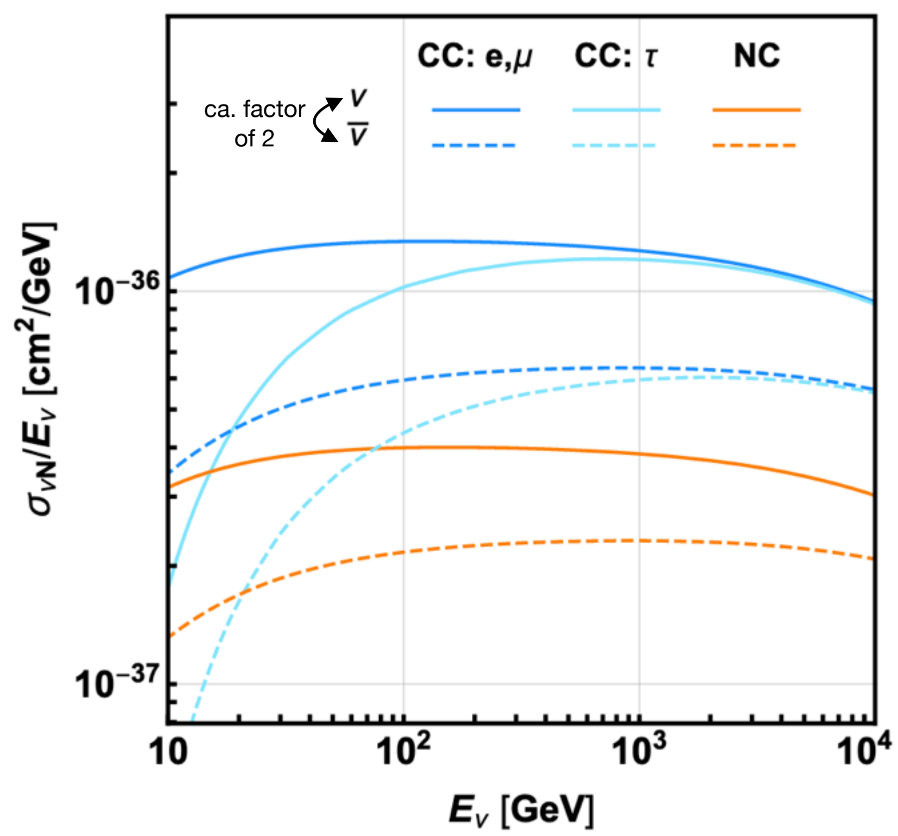


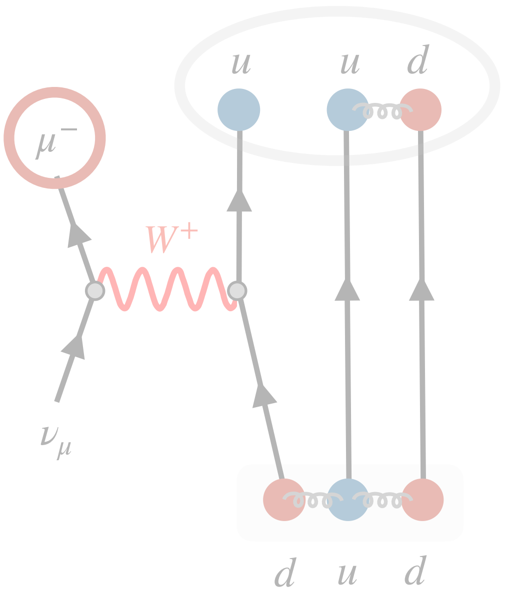


1. First Direct Observation of Collider Neutrinos

for 35.4 fb^{-1}	ν_e	ν_μ	ν_τ
Main source	Kaon decay	Pion decay	Charm decay
# Traversing FASER	$O(10^{10})$	$O(10^{11})$	$O(10^{8})$
# Interactions in FASERν	~200	~1200	~4

Neutrino - Nucleon Cross Section



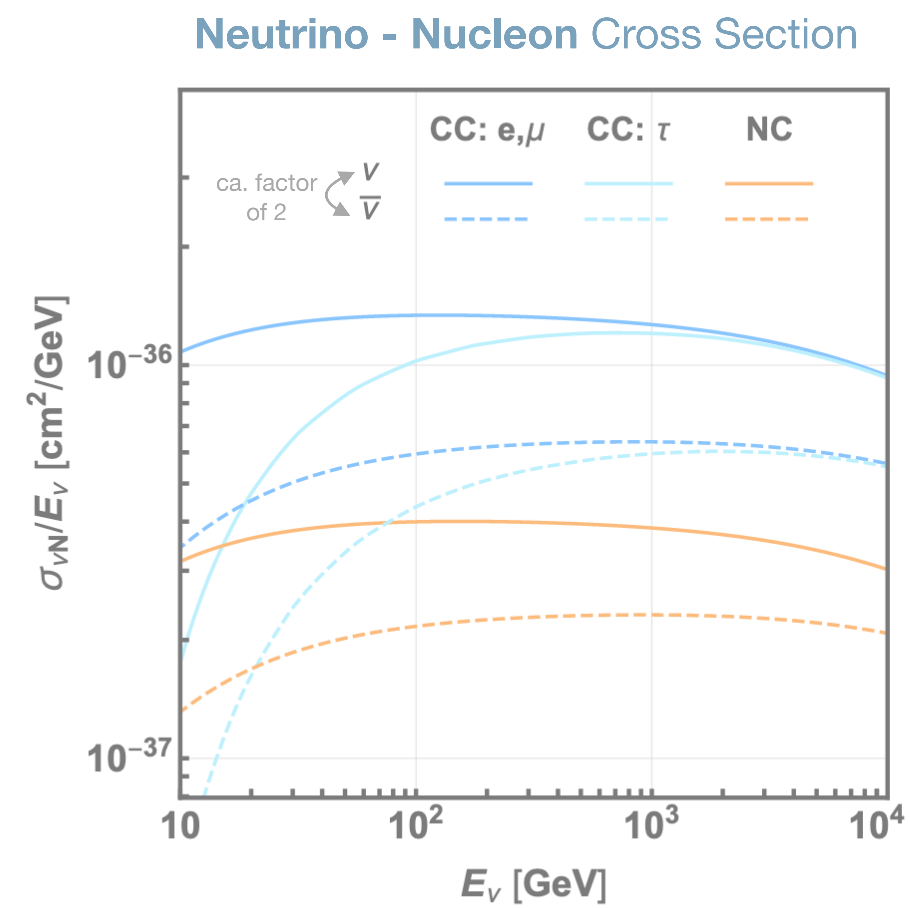


The incoming neutrino transforms the down quark into an up quark and may cause a “spray” of hadronic activity

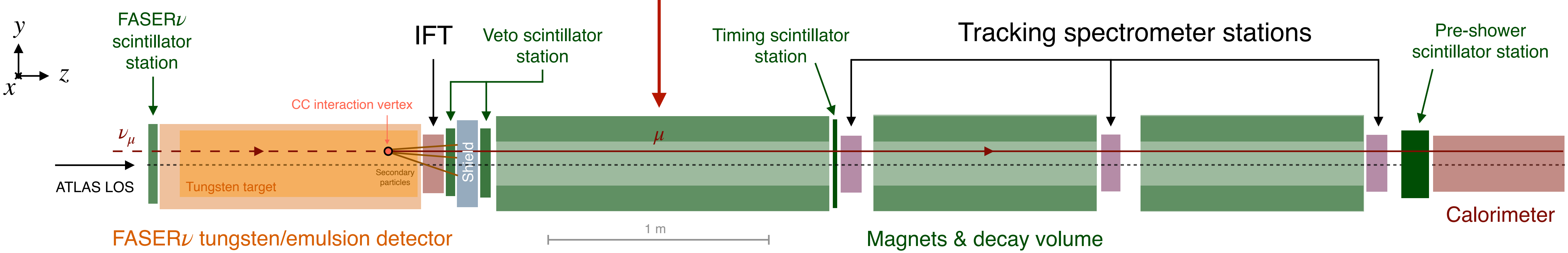
Neutron in the Tungsten target of FASERν

1. First Direct Observation of Collider Neutrinos

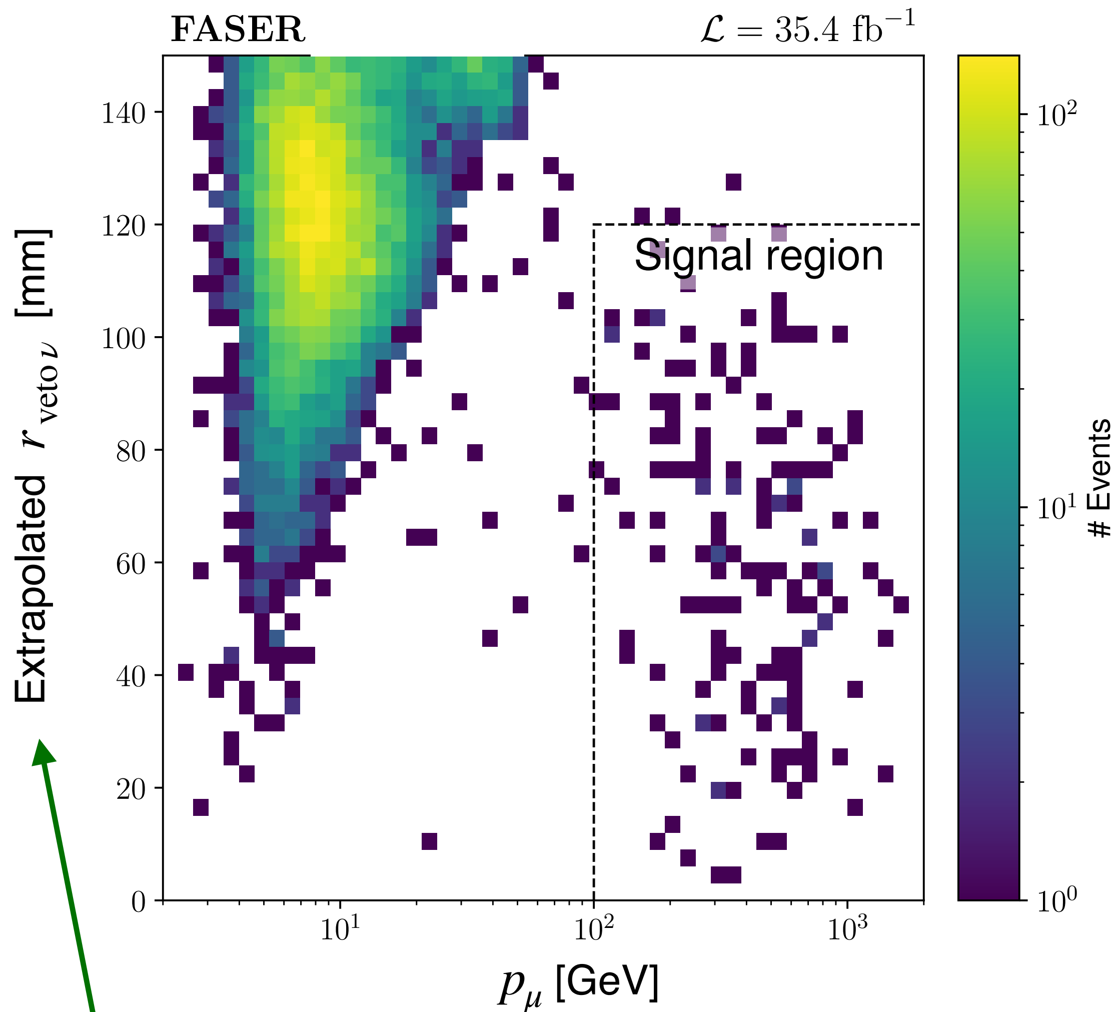
for 35.4 fb^{-1}	ν_e	ν_μ	ν_τ
Main source	Kaon decay	Pion decay	Charm decay
# Traversing FASER	O(10^{10})	O(10^{11})	O(10^{8})
# Interactions in FASERν	~200	~1200	~4



$$\bar{\nu}_\mu + u \rightarrow \mu^+ + d \qquad \nu_\mu + d \rightarrow \mu^- + u$$

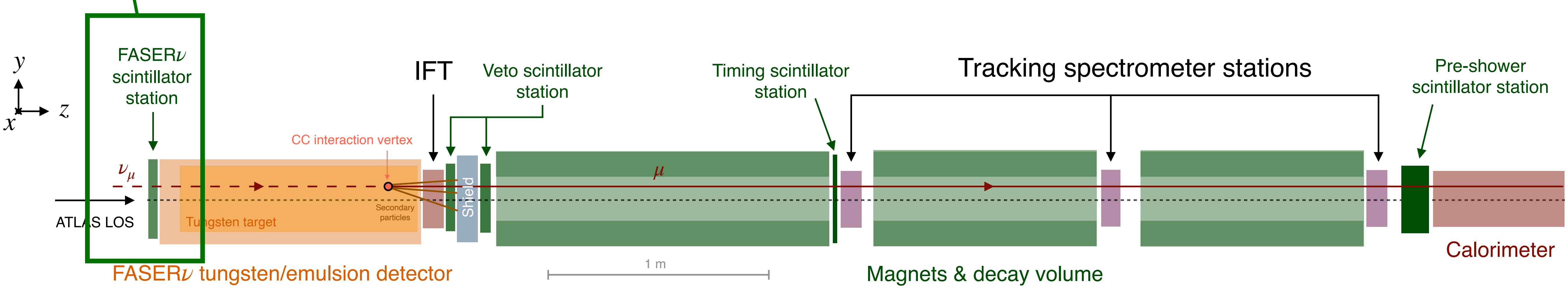


Reconstruct track and **extrapolate back** to the veto station, only select tracks that fall within 120 mm of the center of the station and have $p_\mu > 100\,\mathrm{GeV}$



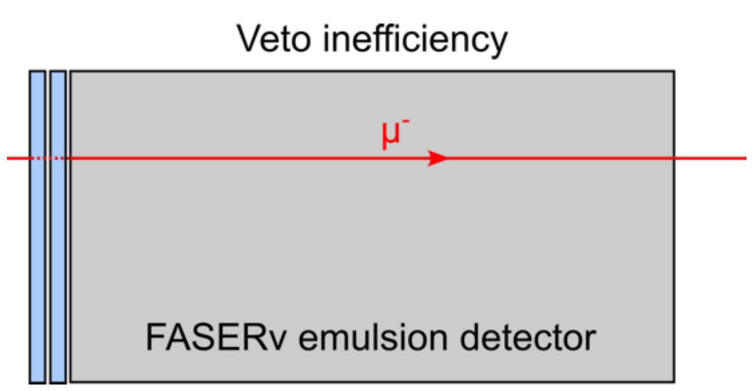
Require **no hits** in the veto station:

Category	Events
Signal	153
n_{10}	4
n_{01}	6
n_2	64’014’695

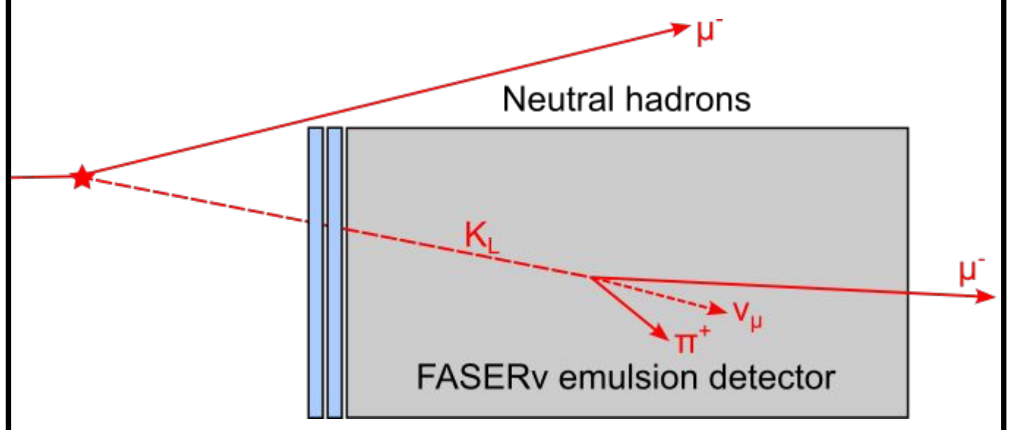


1. First Direct Observation of Collider Neutrinos

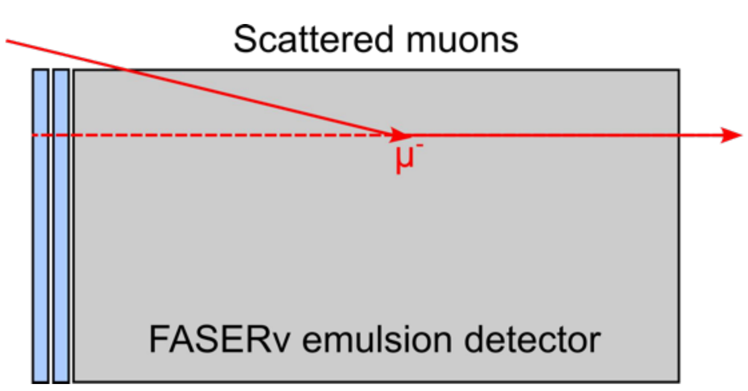
3 Background types :



1) Front-veto inefficiency



2) Background from neutral hadrons



3) Geometric muons

Estimated from hit difference of 1st and 2nd layer of veto

Expect this to be **negligible**, as inefficiency is $\sim 10^{-7}$ **per layer**

Estimated using simulations; most of the expected ca. 300 neutral hadrons with E > 100 GeV absorbed in tungsten

Most parent muons will hit veto

Expect **0.11 +/- 0.06 Events**

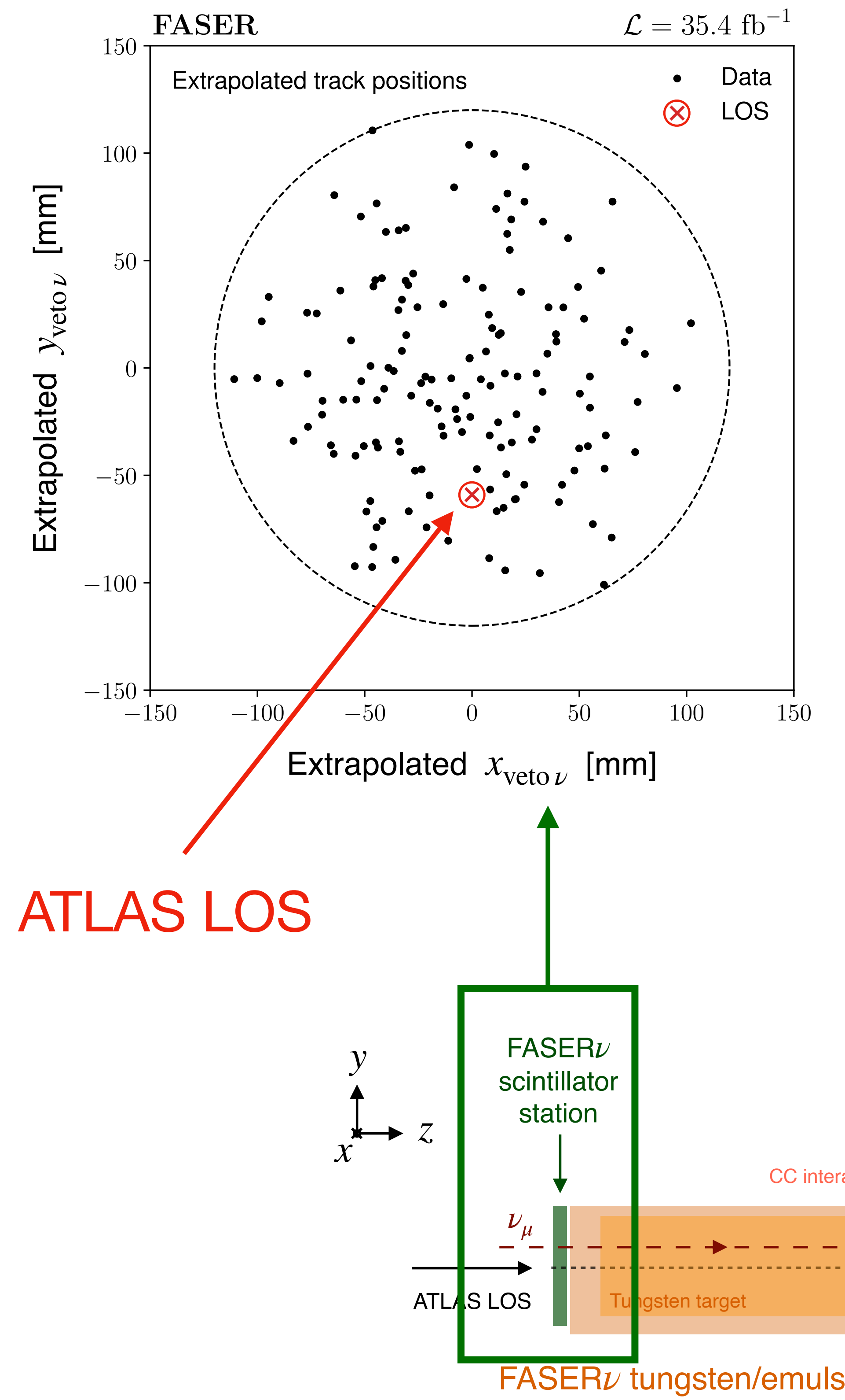
Estimated from control region

Expect **0.08 +/- 1.83 Events**

Observation:

$$n_\nu = 153\,^{+12}_{-13}\,(\text{stat.})\,^{+2}_{-2}\,(\text{bkg.}) = 153\,^{+12}_{-13}\,(\text{tot.})$$

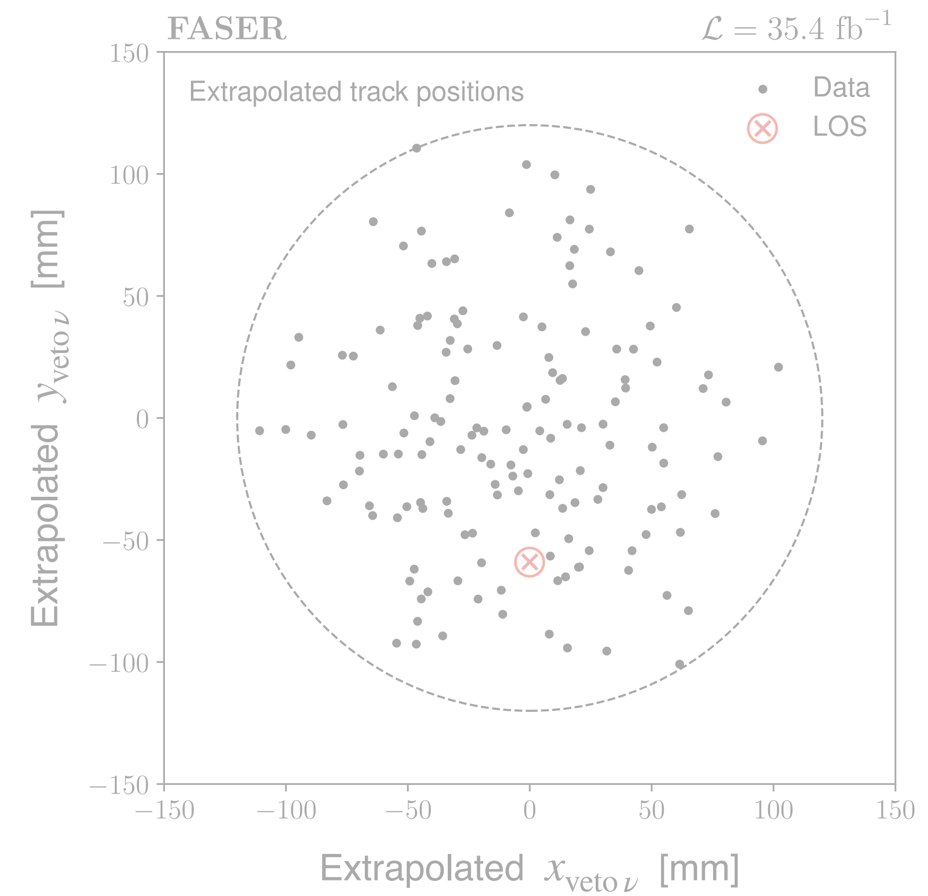
with more than **16 sigma significance**

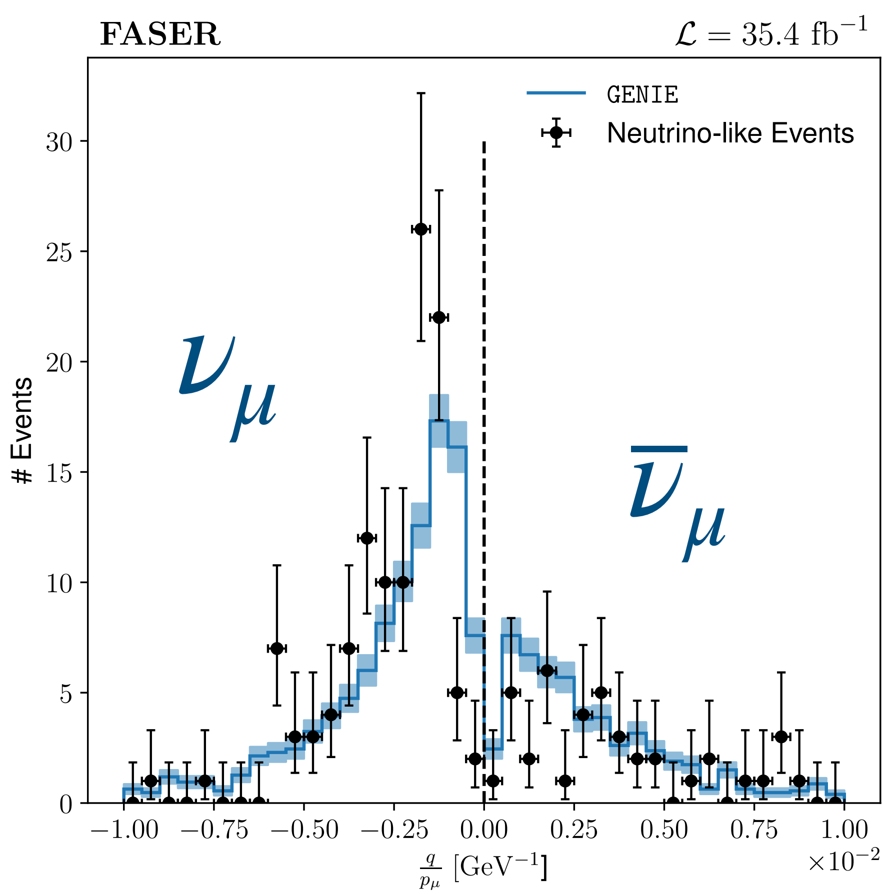


Observation:

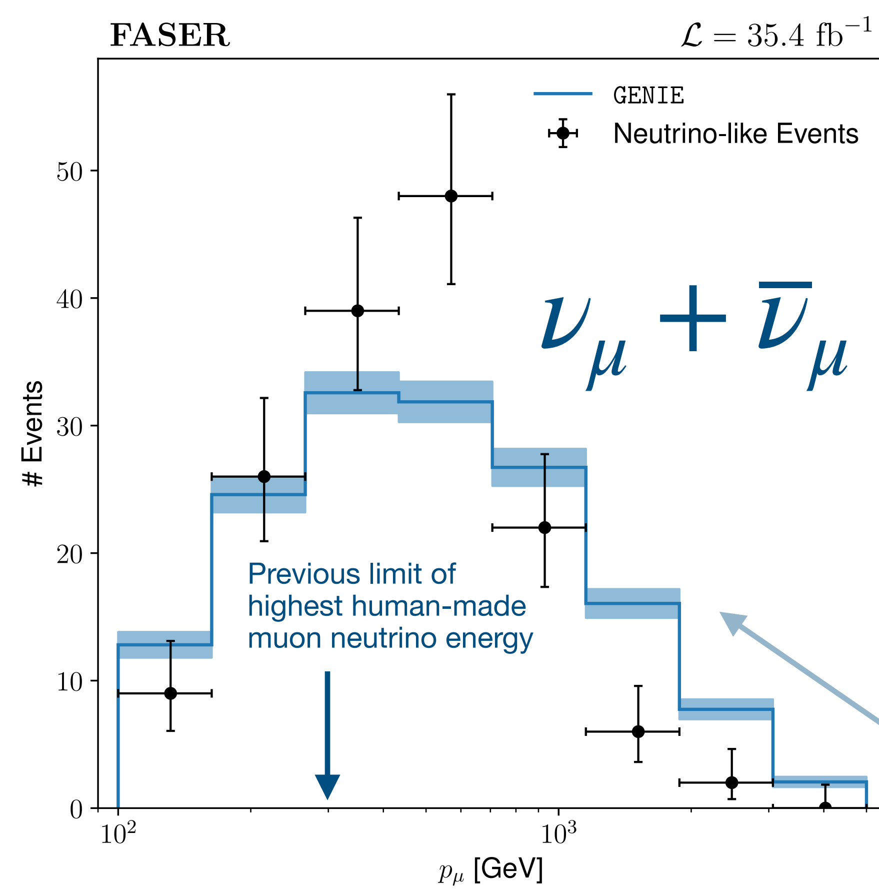
$$n_\nu = 153\,^{+12}_{-13}\,(\text{stat.})\,^{+2}_{-2}\,(\text{bkg.}) = 153\,^{+12}_{-13}\,(\text{tot.})$$

with more than **16 sigma significance**

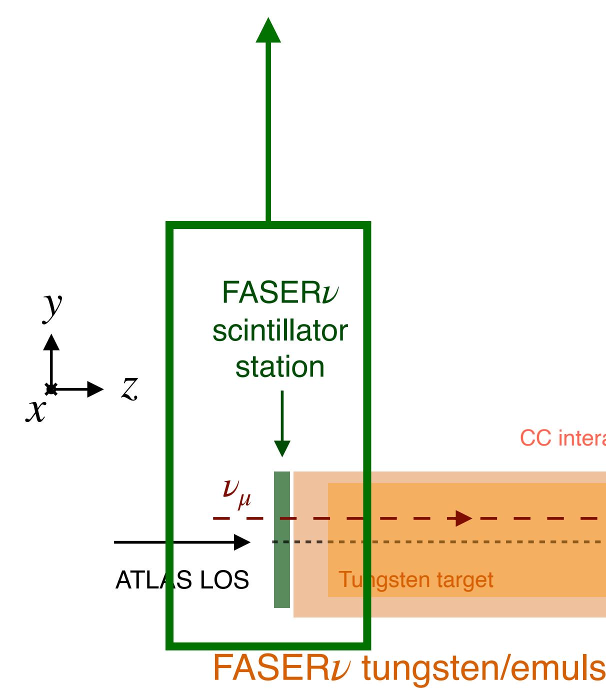




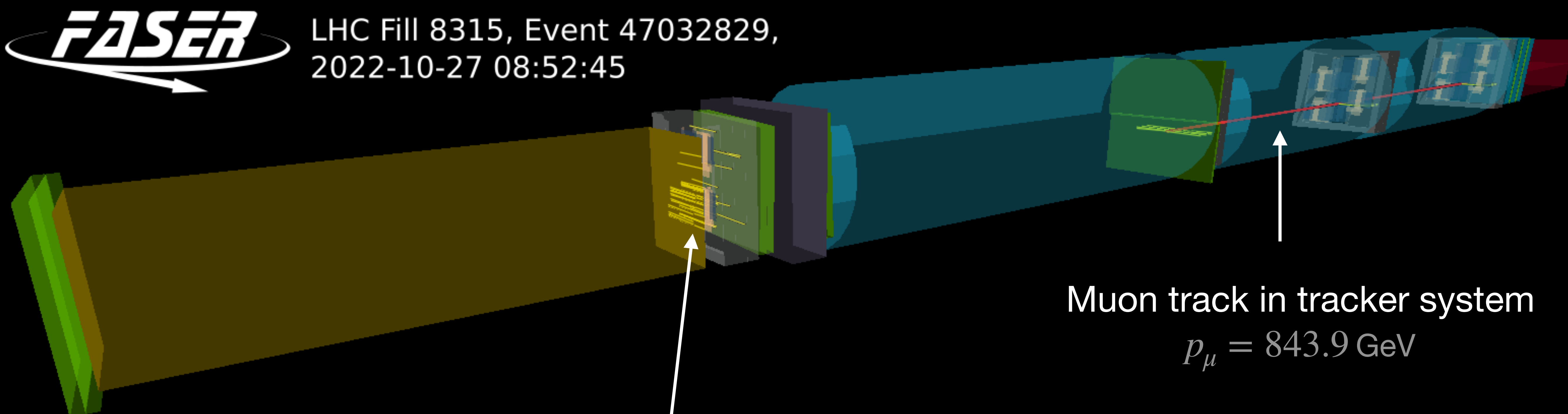
q/p_μ



p_μ



Note that no experimental uncertainties are included on the simulated sample (e.g. assume perfect alignment, no errors on efficiencies, etc.)



Muon track in tracker system
$p_\mu = 843.9$ GeV

Activity in IFT (interface tracker)
from the remnants of the CC interaction
57 clusters

No signal in front veto

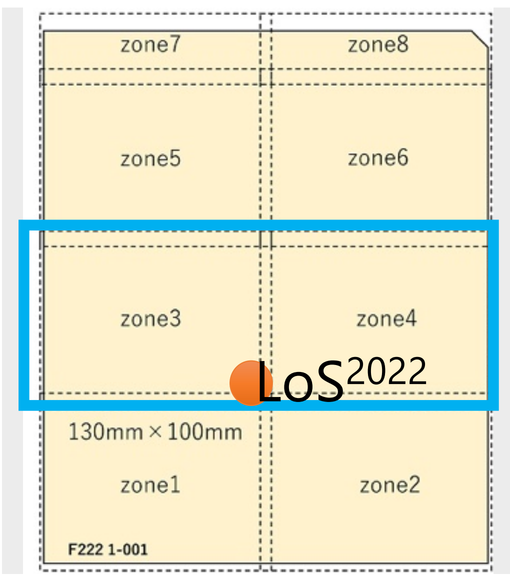
2. First Observation of Collider **Electron**-Neutrinos

Strategy: i) Analyze **150 / 730 films** of the 2022 **2nd module**

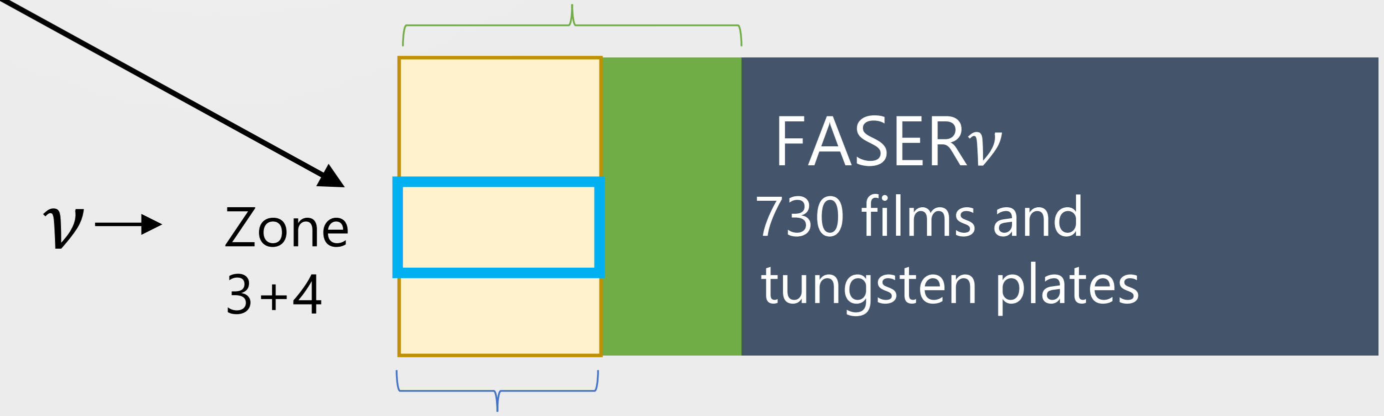
module name	installed period	load	integrated luminosity per module (fb^{-1})
2022 1st module (F221)	Mar 15 - Jul 26	30%	0.4705
2022 2nd module (F222)	Jul 26 - Sep 13	100%	9.523
2022 3rd module (F223)	Sep 13 - Nov 29	100%	28.9082

ii) Focus on region closest to LOS

Front view



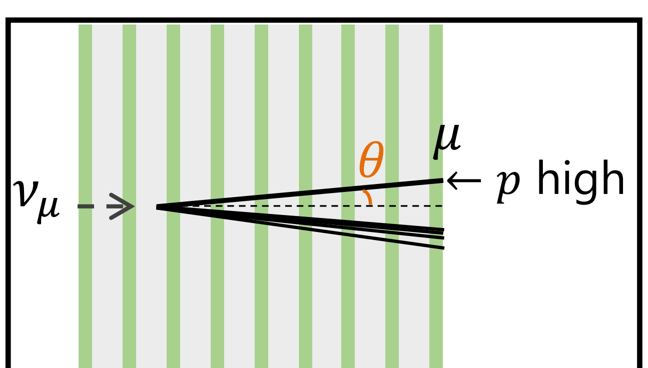
Scanned volume (255 films) (this time)



Target volume for the first analysis (150 tungsten plates)

Target mass (zone 3+4)
$\simeq$ 9 cm x 24 cm x 0.1087 cm x 150 x 19.3 g/cm^3 = 68.0 kg

iii) Signal Signature:



Select events with **at least 5 tracks from common vertex** and **without parent track**, at least 4 tracks closely clustered and with $\theta > 0.28^{\circ}$; require sufficient penetration depth (100 plates)

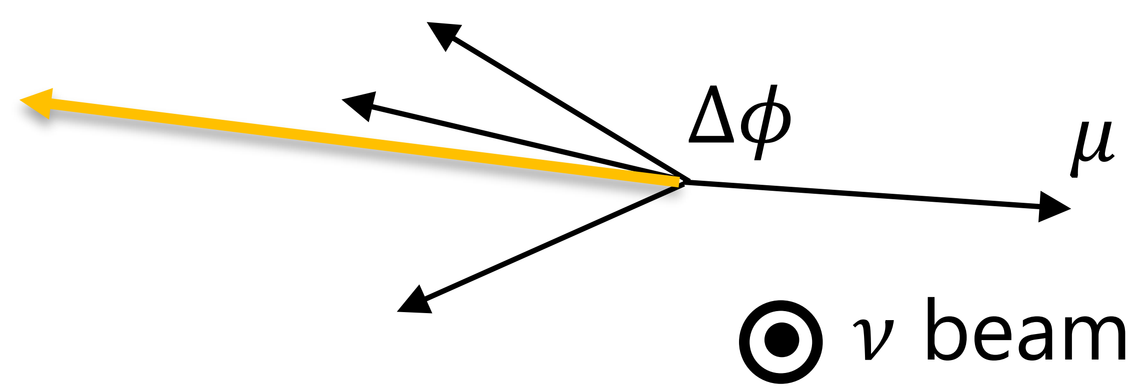
2. First Observation of Collider **Electron**-Neutrinos

iv) Even classification:

ν_μ : long track, no secondary particles

ν_e : short track that produces electromagnetic shower with identifiable maximum

Lepton and CC remnants typically have large $\Delta\phi$ separation (require $\Delta\phi > \frac{\pi}{2}$)



Selection efficiencies: $\nu_e : \sim 23\,\%$ $\nu_\mu : \sim 19\,\%$

(simulated)

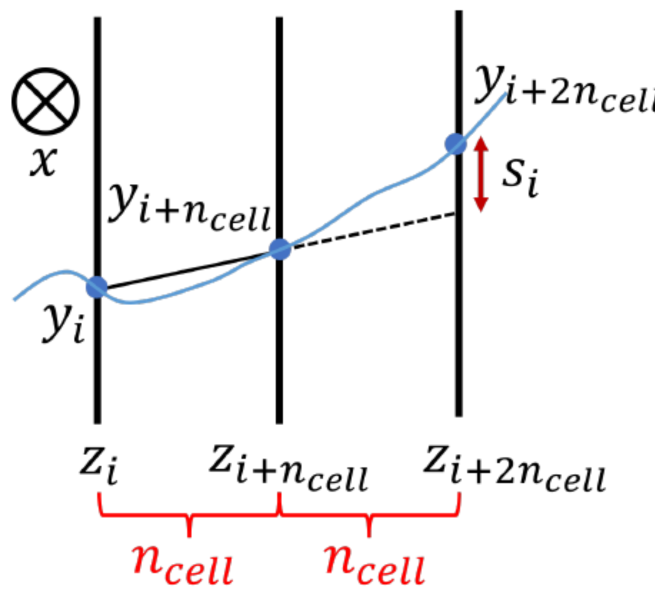
Selection	ν_e CC	ν NC	K_L	n	Λ
	1.000	1.000	1.000	1.000	1.000
Vertex reconstruction	0.516	0.336	0.813	0.803	0.753
E >200 GeV	0.340	0.001	0.000	0.000	0.000
E >200 GeV, tanθ >0.005	0.270	0.001	0.000	0.000	0.000
E >200 GeV, tanθ >0.005. $\Delta\phi$>90deg	0.226	0.000	0.000	0.000	0.000

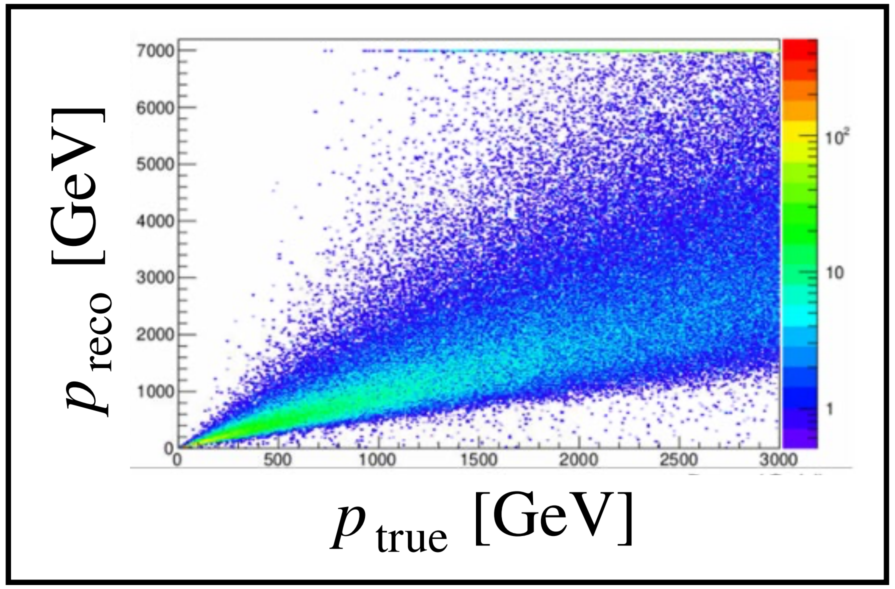
Selection	ν_μ CC	ν NC	K_L	n	Λ
	1.000	1.000	1.000	1.000	1.000
Vertex reconstruction	0.446	0.336	0.813	0.803	0.753
p >200 GeV	0.284	0.071	0.028	0.026	0.018
p >200 GeV, tanθ >0.005	0.236	0.051	0.007	0.013	0.007
p >200 GeV, tanθ >0.005. $\Delta\phi$>90deg	0.192	0.004	0.002	0.006	0.004

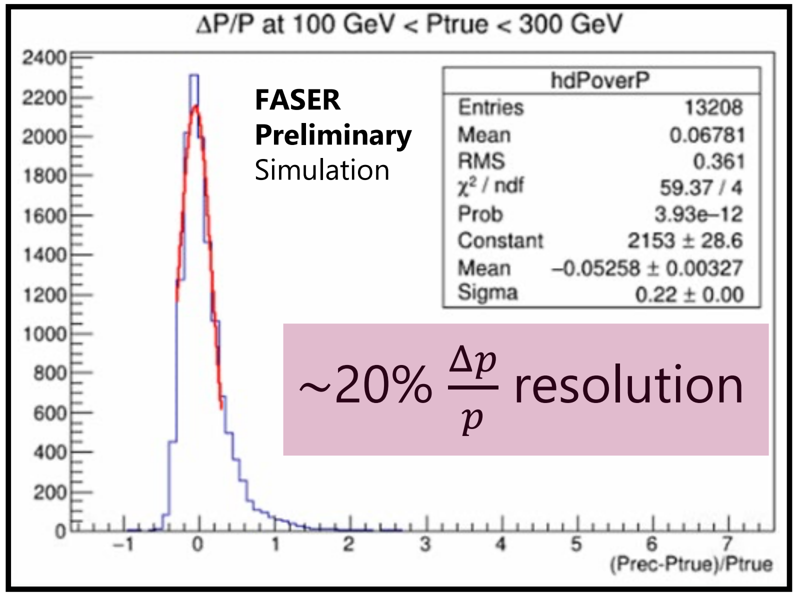
2. First Observation of Collider **Electron**-Neutrinos

Momentum Reconstruction via multiple Coulomb scattering (MCS) method *Nucl. Instrum. Meth. A493 (2002) 45–66.*

Leverages **excellent spatial resolution** of emulsion films ($\sim 0.28\,\mu$m after 100 plates)





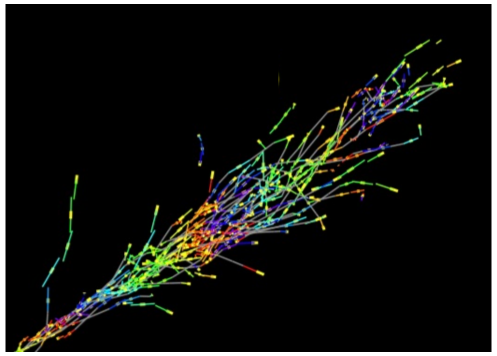


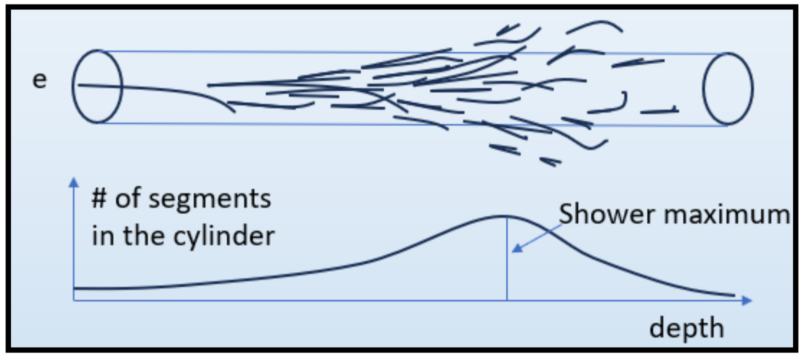
~20% $\frac{\Delta p}{p}$ resolution

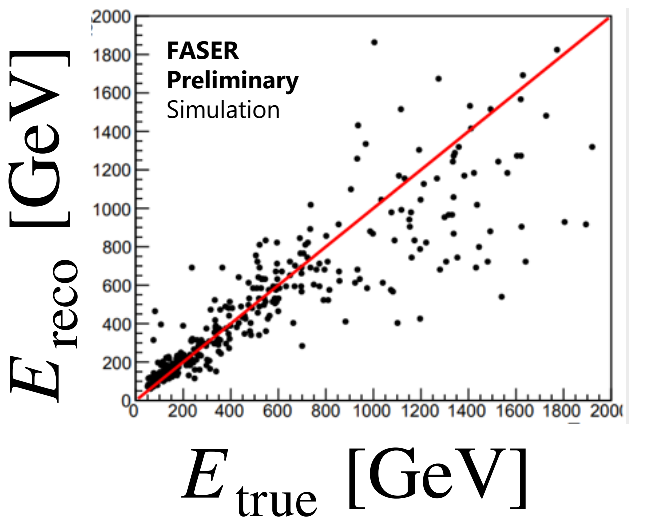
Electron momentum measurement

$\sim 25\,\%\ \Delta E/E$

Use 7 films around shower maximum to estimate electron energy







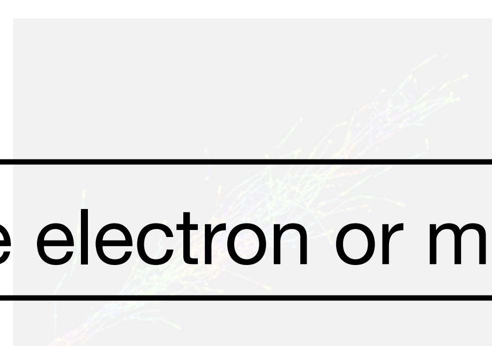
2. First Observation of Collider **Electron**-Neutrinos

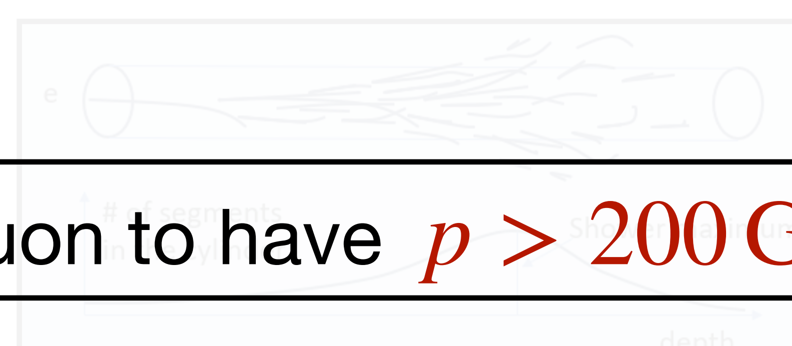
Momentum Reconstruction via multiple Coulomb scattering (MCS) method *Nucl. Instrum. Meth. A493 (2002) 45–66.*

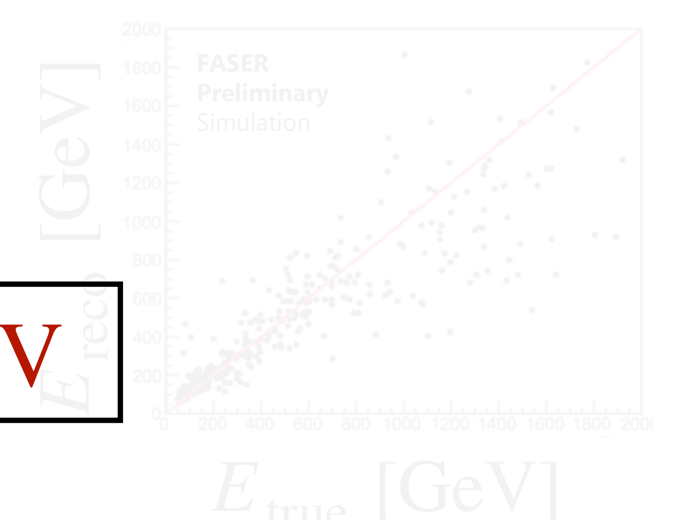
Leverages **excellent spatial resolution** of emulsion films ($\sim 0.28\,\mu$m after 100 plates)

Electron momentum measurement $\sim 25\,\%\ \Delta E/E$

Use 7 films around shower maximum to estimate electron energy



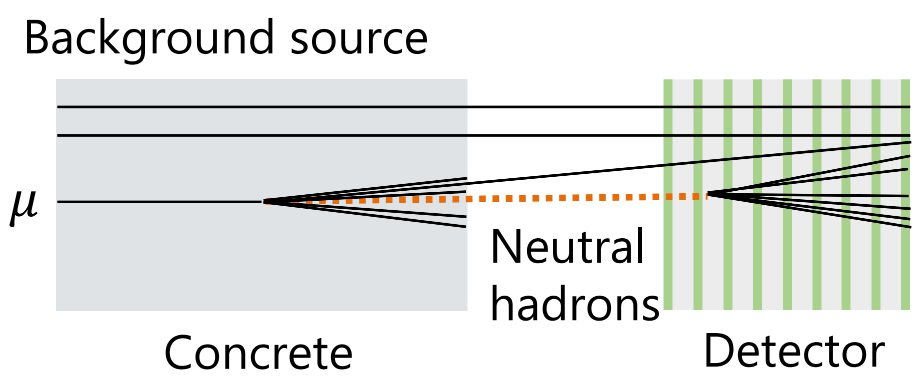




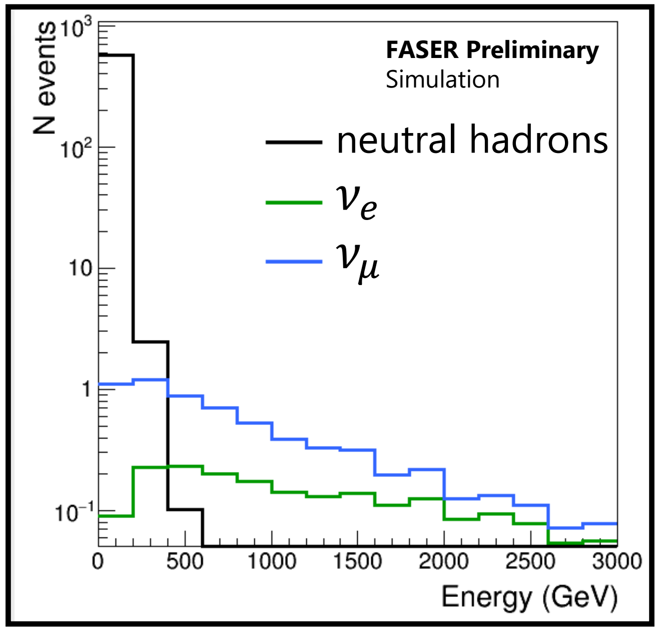
Require electron or muon to have $p > 200\,\mathrm{GeV}$

2. First Observation of Collider **Electron**-Neutrinos

Dominant background: neutral hadrons $K_S, K_L, n, \bar{n}, \Lambda, \bar{\Lambda}$



	Interaction rates of neutral hadrons with E_h >200 GeV in 150 tungsten plates per incident muons
K_S	2.1×10^{-5}
K_L	2.5×10^{-4}
n	2.0×10^{-4}
Λ	2.3×10^{-4}
$\bar{\Lambda}$	3.1×10^{-5}



Estimated from simulation (20 x data sample) with muon energy spectrum from dedicated FLUKA simulation

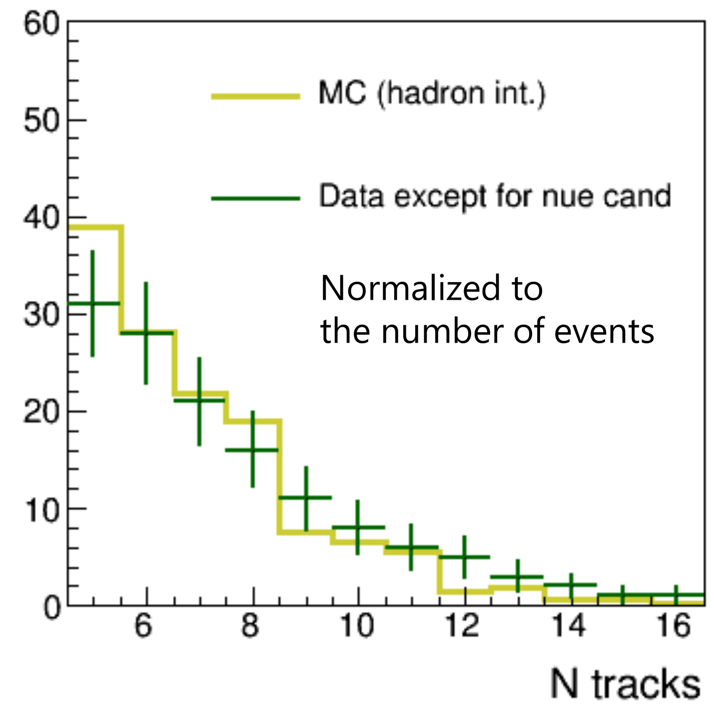
Validation sideband:

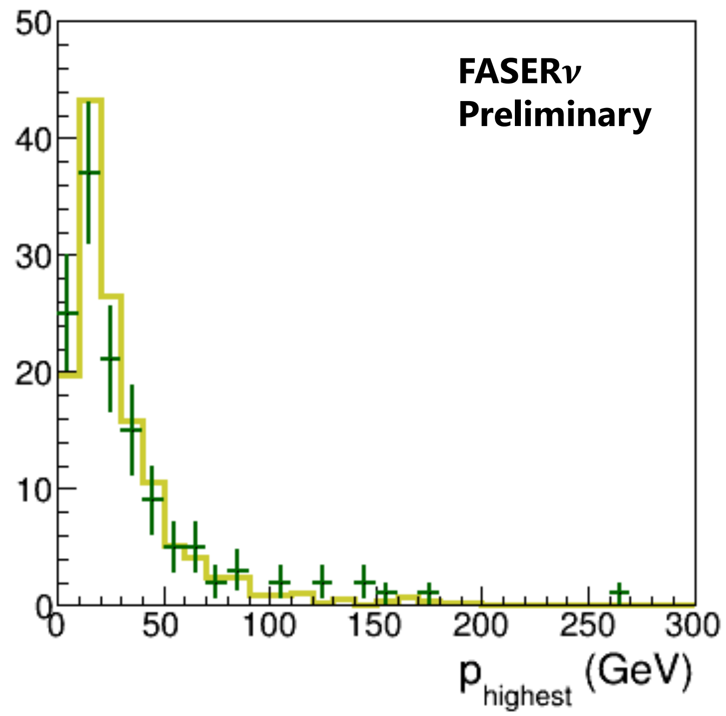
Use Vertices that fail the ν selection

Expectation : 216 vertices from $K_S, K_L, n, \bar{n}, \Lambda, \bar{\Lambda}$

Data : 133 vertices

→ Agreement with simulation within **ca. 50%**





2. First Observation of Collider **Electron**-Neutrinos

7 Signal Candidates :

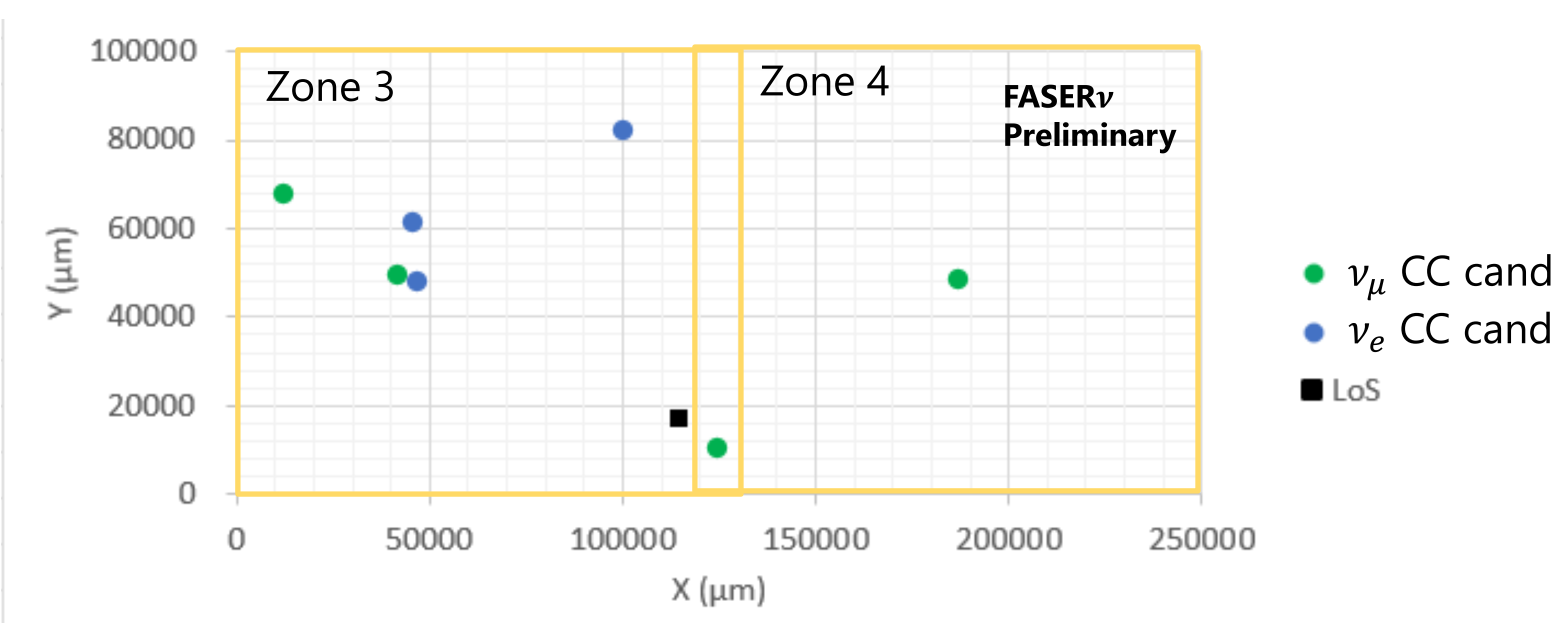
FASERν Preliminary

	Expected background		Expected signal	**Observed**
	Hadron int.	ν NC int.		
ν_e CC	0.002±0.002	-	$1.2^{+4.0}_{-0.6}$	3
ν_μ CC	0.32±0.16	0.19±0.15	$4.4^{+4.2}_{-1.4}$	4

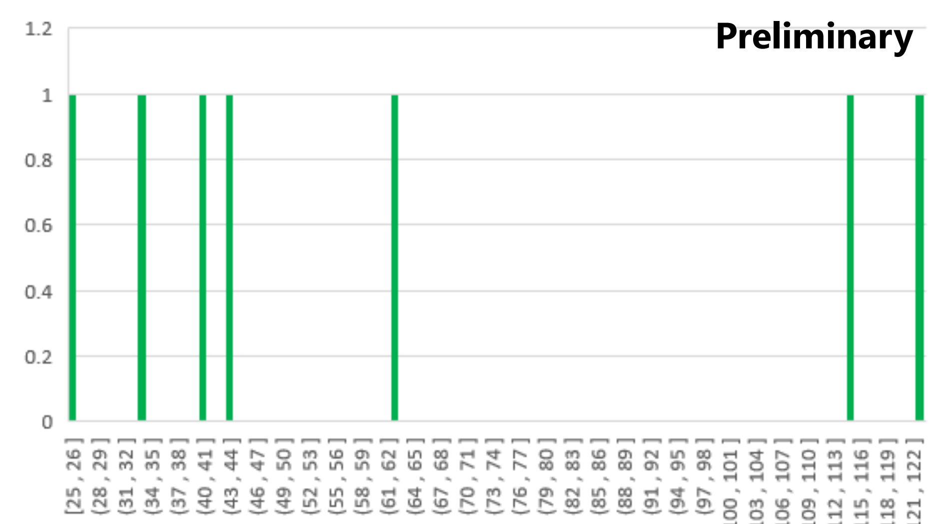
3 Electron-Neutrino candidates observed ; prob. for this to be a background fluctuation

$$\sim 1.6 \times 10^{-7} \rightarrow 5\sigma$$

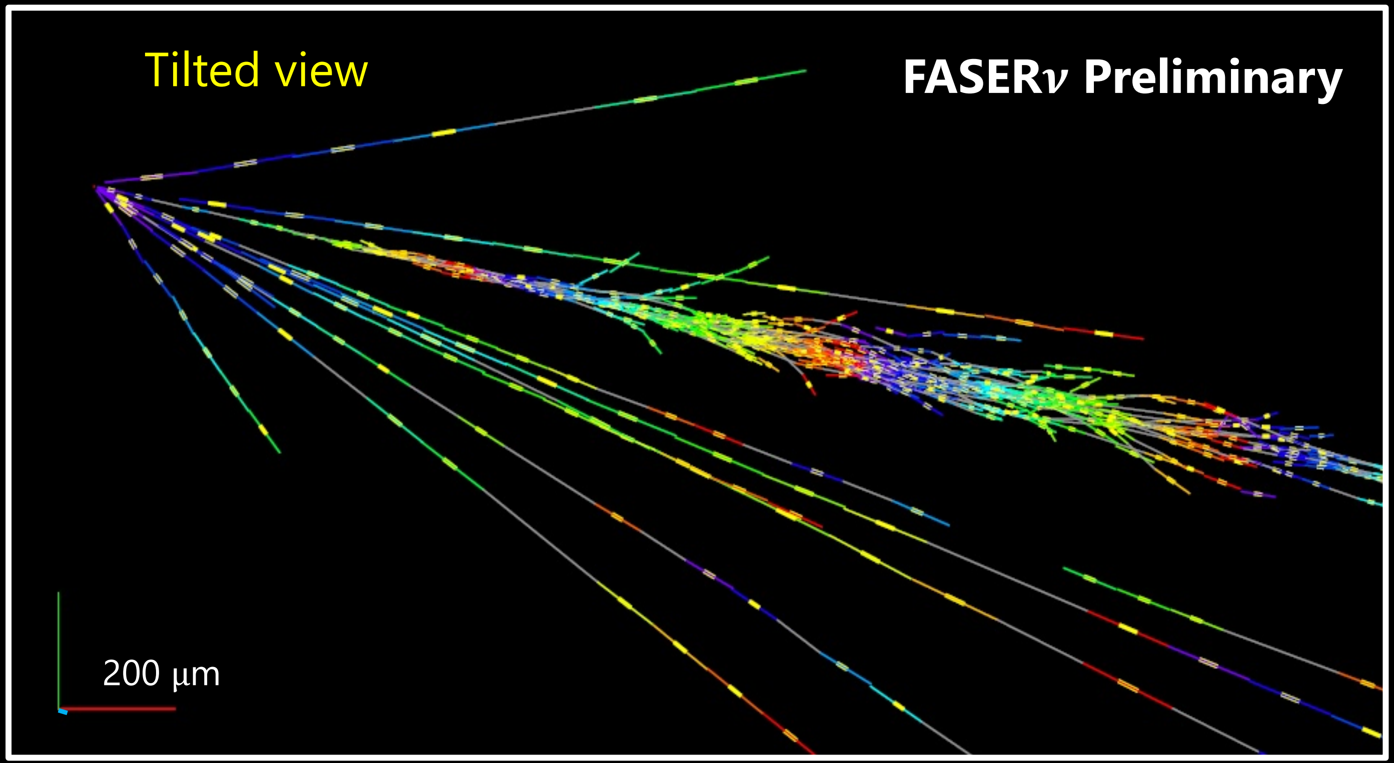
Front view

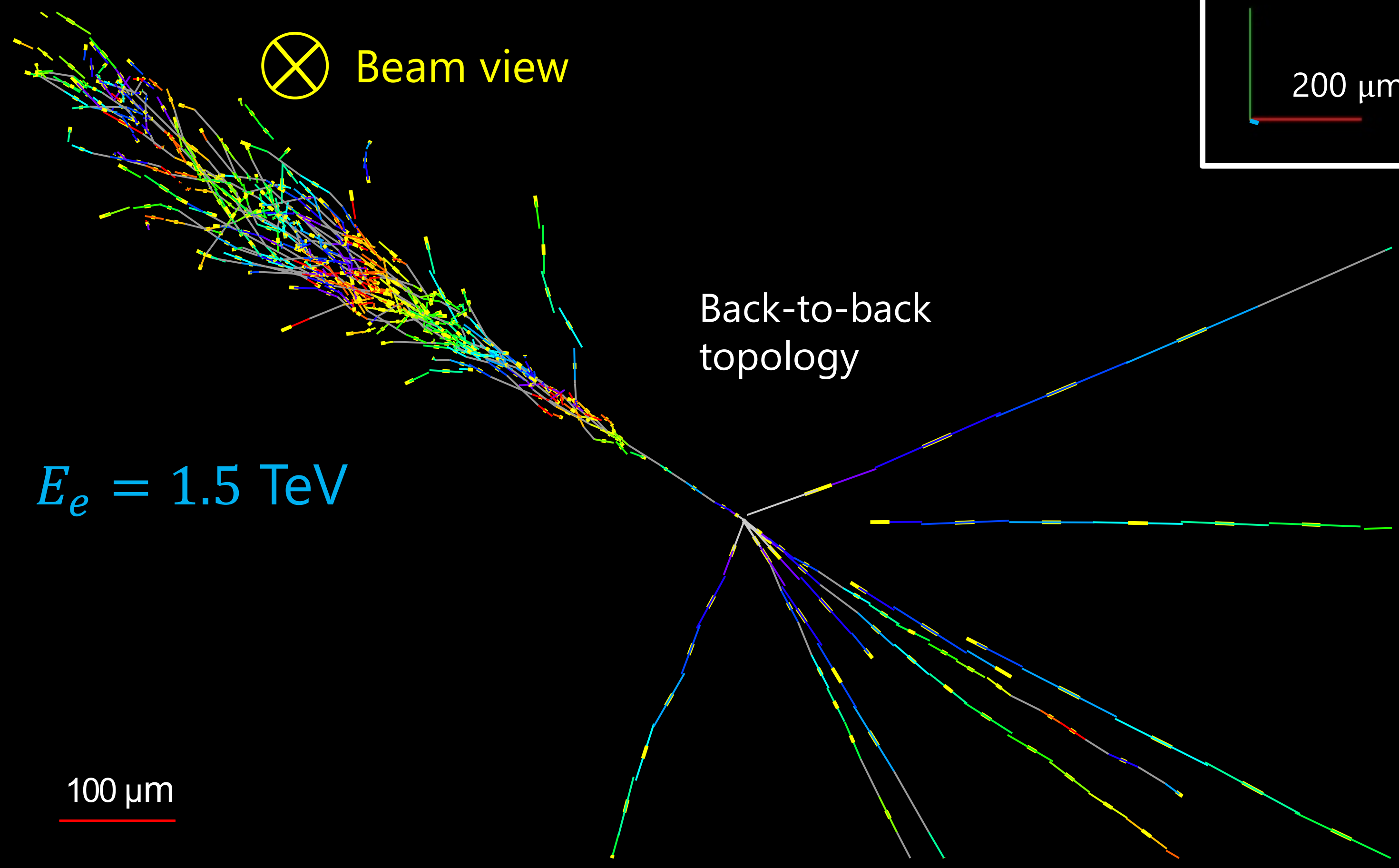


Vertex Plate



New results from FASERν: one of the ν_e CC candidates





- 11 tracks at the vertex, 615 μm inside tungsten
- e-like track from vertex
- Single track for 2 X_0
- Shower max at 7.8 X_0
- 175° between e-like track and others
- $\theta_e = 11$ mrad w.r.t. beam

2. LLPs Searches

"Search for Dark Photons with the FASER detector at the LHC", arXiv:2308.05587

Dark Photons at FASER

Dark Photons neat candidate for "**hidden sector**" extension of SM:

$$\mathscr{L} = \frac{1}{2} m_{A'}^2 A'^2 - \varepsilon e \sum_f q_f A'_\mu \bar{f} \gamma^\mu f$$

Weakly coupled to SM with strength determined by **kinetic mixing** ε

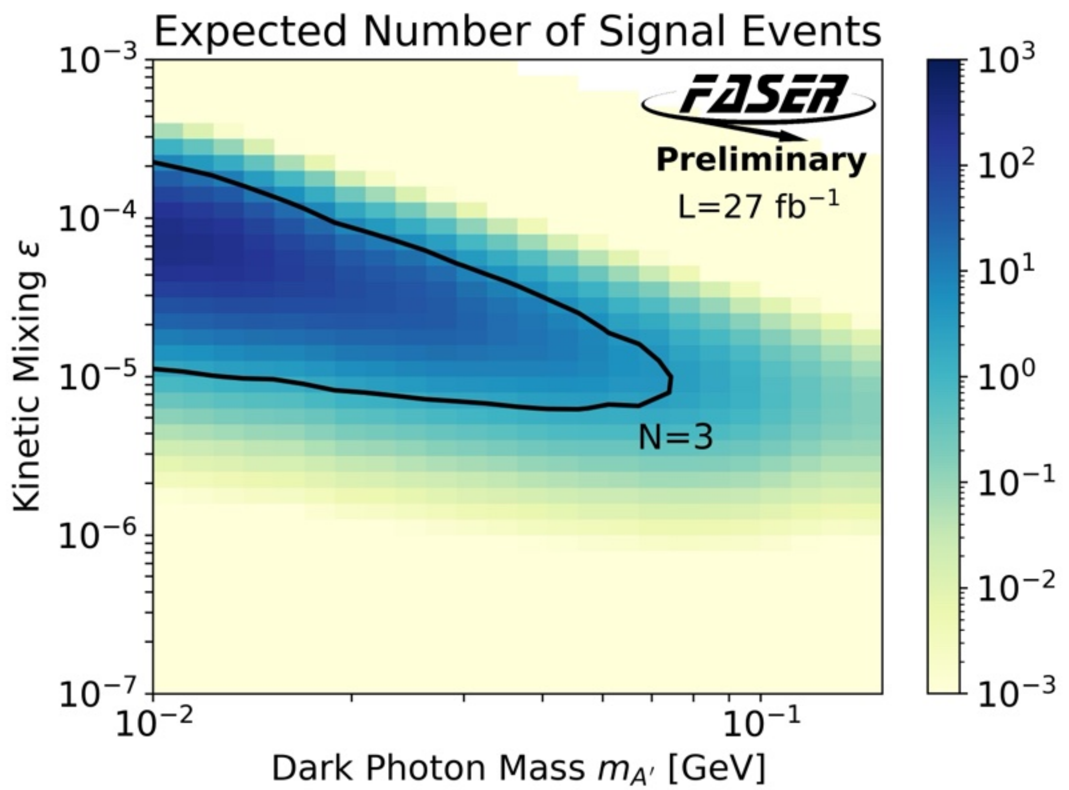
→ FASER sensitive to parameter space of $m_{A'} \sim 10 - 100\,\mathrm{MeV}$ & $\varepsilon \sim 10^{-5} - 10^{-4}$

Dark Photon decay length:

$$L = c\,\beta\,\gamma\,\tau \approx (80\,\mathrm{m}) \left[\frac{10^{-5}}{\varepsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\,\mathrm{MeV}}{m_{A'}}\right]^2$$

$\pi^0 \to A'\gamma$ dominant production mechanism

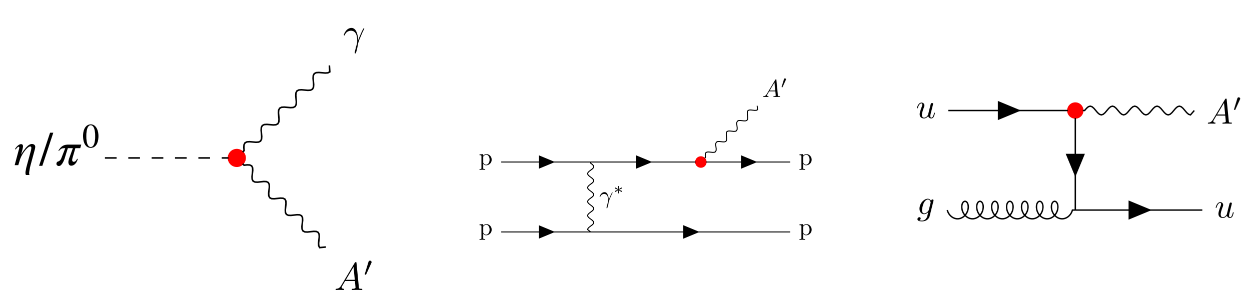
If $m_{A'} < 2m_\mu \to \mathscr{B}(A' \to e^+e^-) \approx 100\,\%$



Dark Photon Modeling

Dark photon signal events modeled using FORESEE [arXiv:2105.07077]

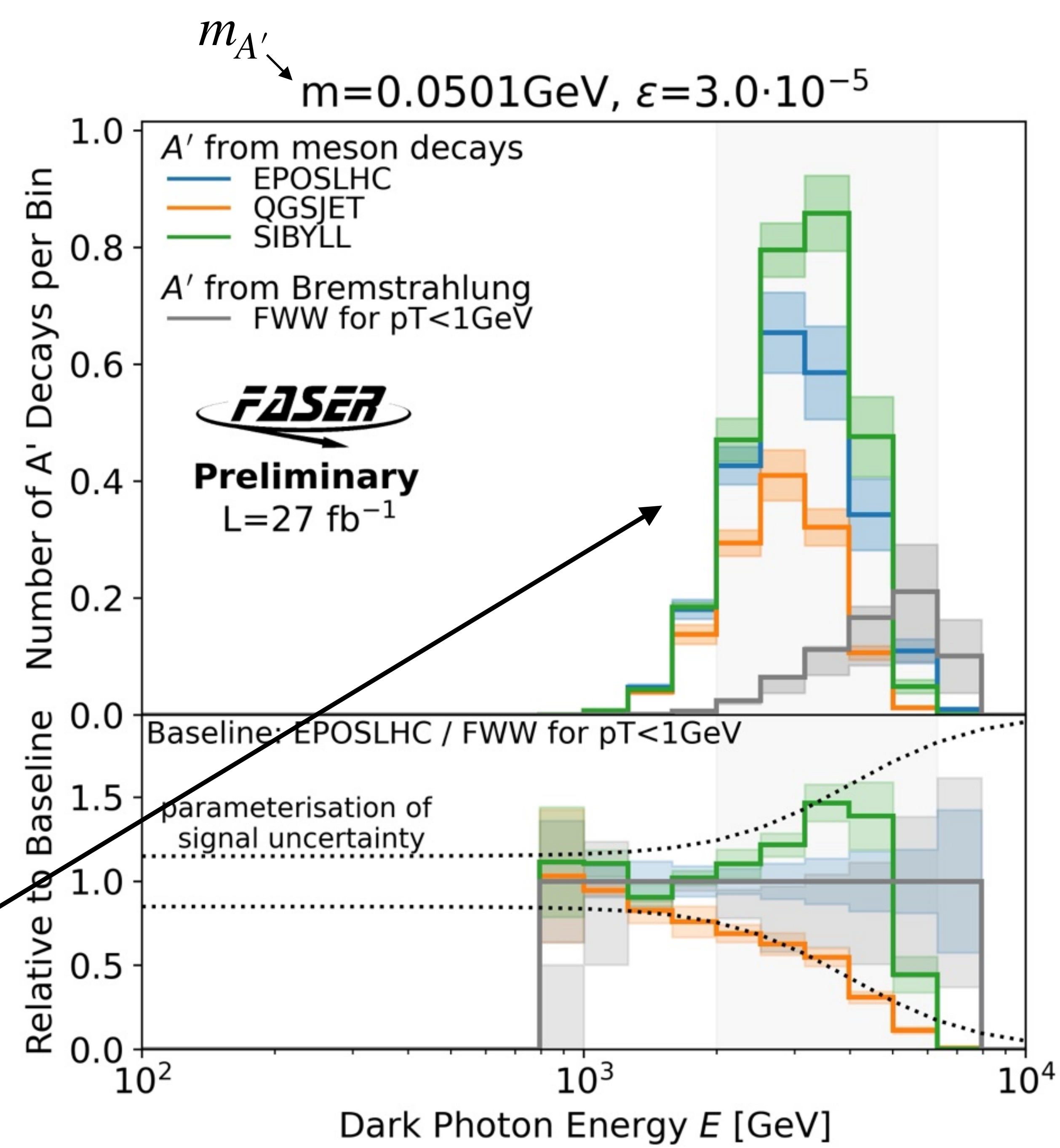
EPOS-LHC used to model **very forward** π^0 and η production and also include sub-dominant **dark-bremstrahlung** contribution ; Drell-Yan and other production modes are negligible.



Systematic uncertainties from signal modeling are dominant contribution:

→ Mainly from poorly known forward hadron production

Use envelope from **EPOS-LHC** and **QGSJET**/**SIBYLL**



Event Selection

Event selection optimized for significance (cut-based) :

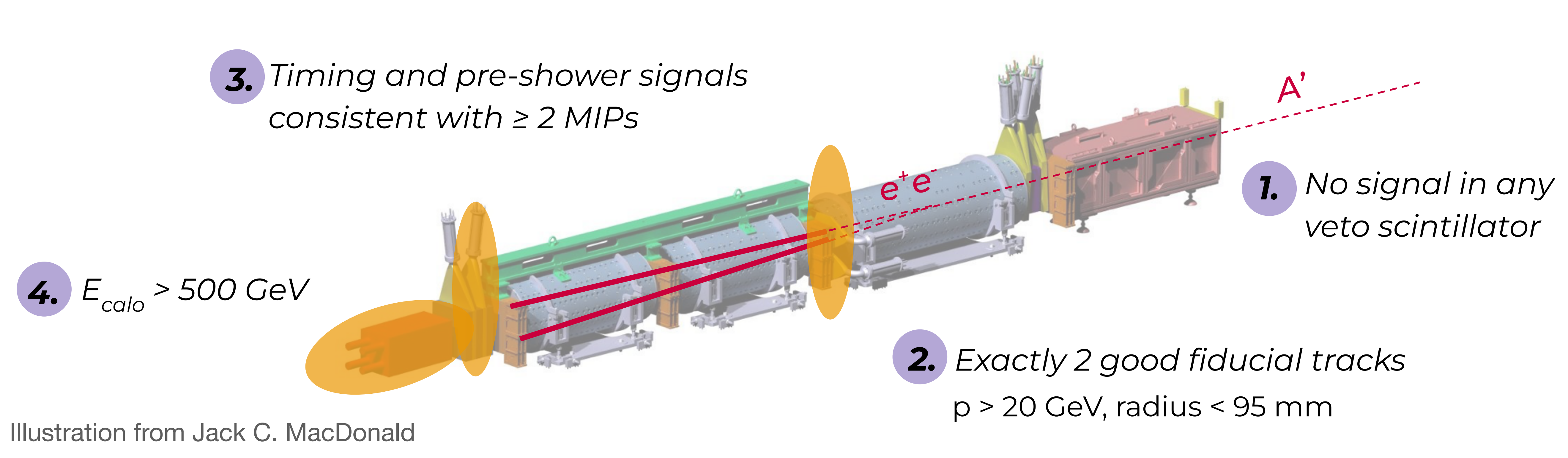
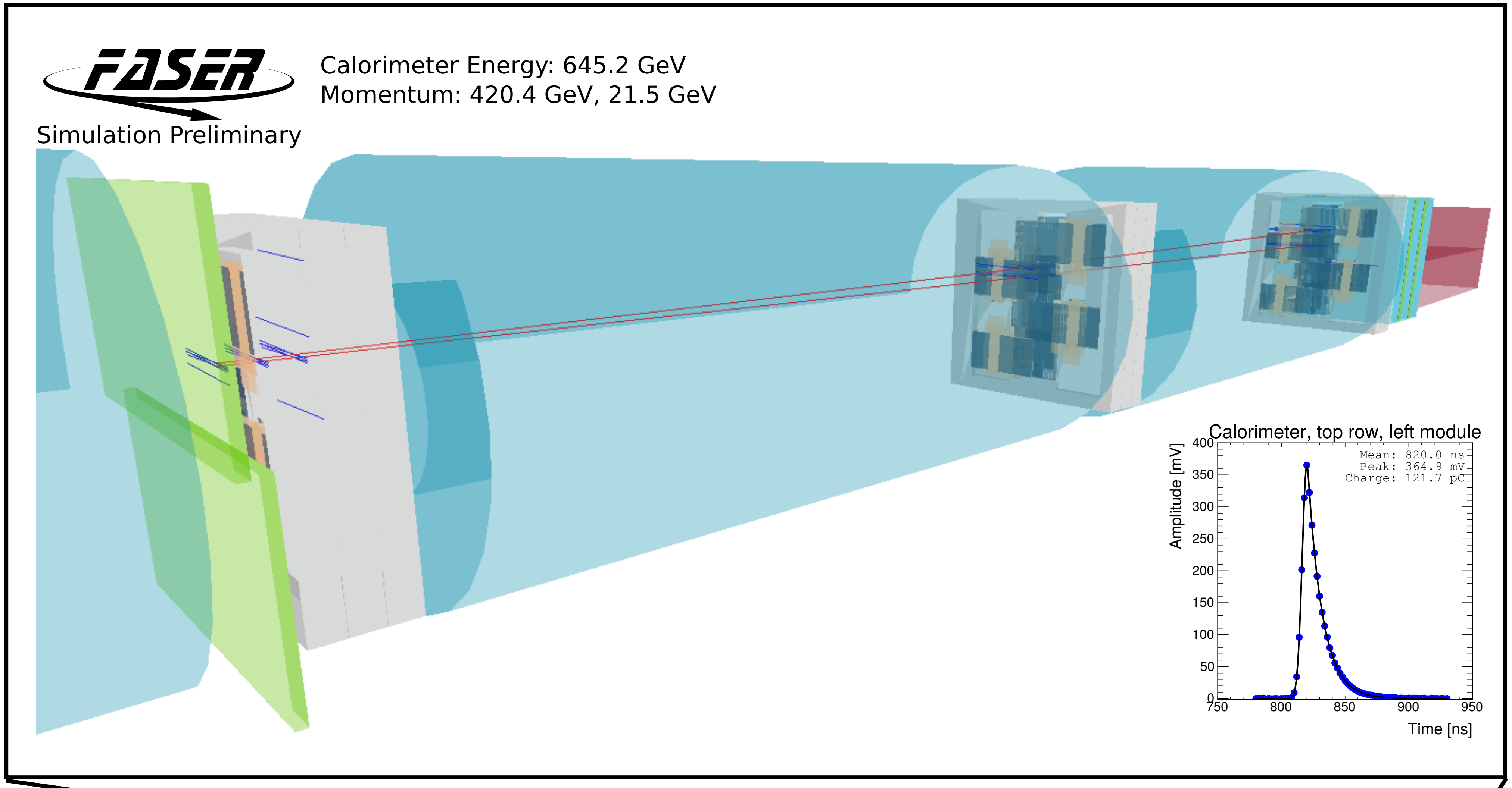


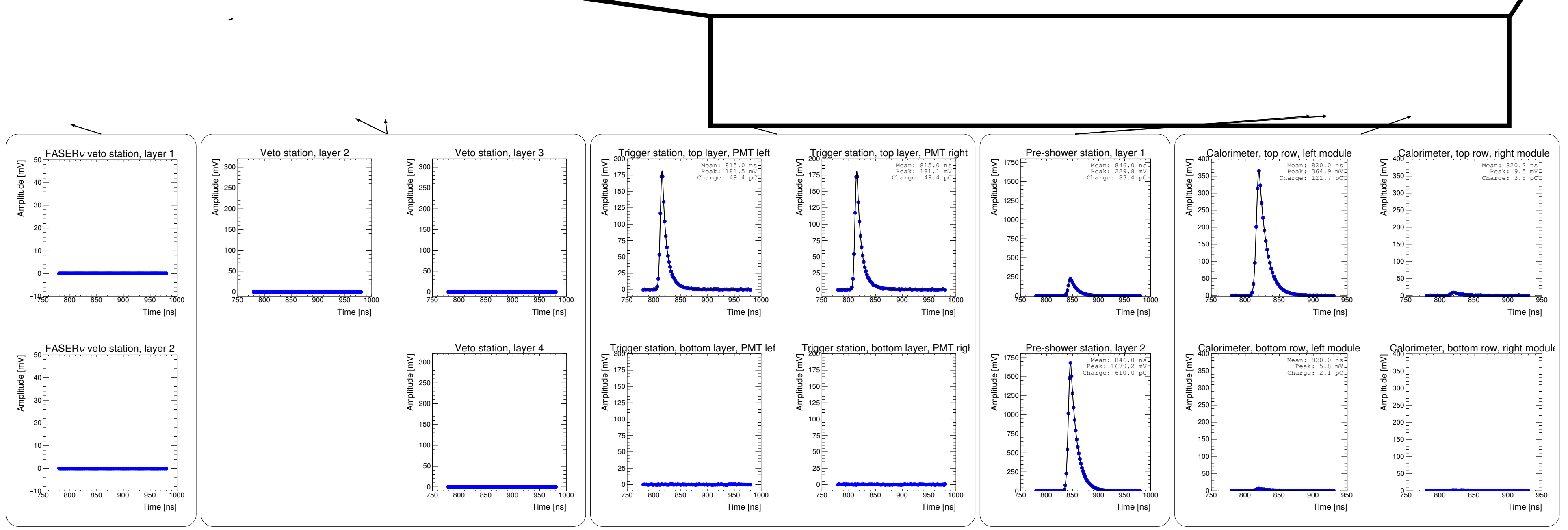
Illustration from Jack C. MacDonald

Require additionally LHC collision events with good quality data ; Analysis cuts optimized fully blinded

→ results in ca. **40% signal efficiency** in FASER $m_{A'} : \varepsilon$ param. space

Simulated dark photon decay in **FASER** :





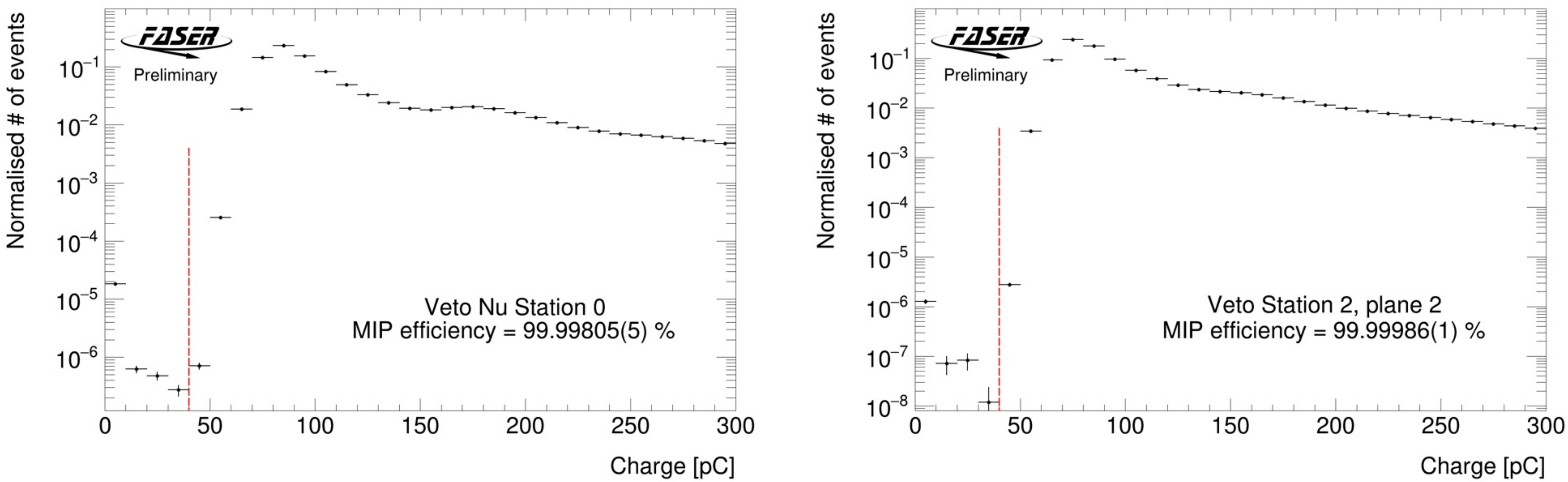
Backgrounds

Various Backgrounds to consider :

1) Veto station inefficiency

Measured layer-by-layer with muon tracks pointing to veto layers

→ **Layer efficiency > 99.9997%**



With **5 layers**, reduced expected 10^8 muons to negligible level and expect

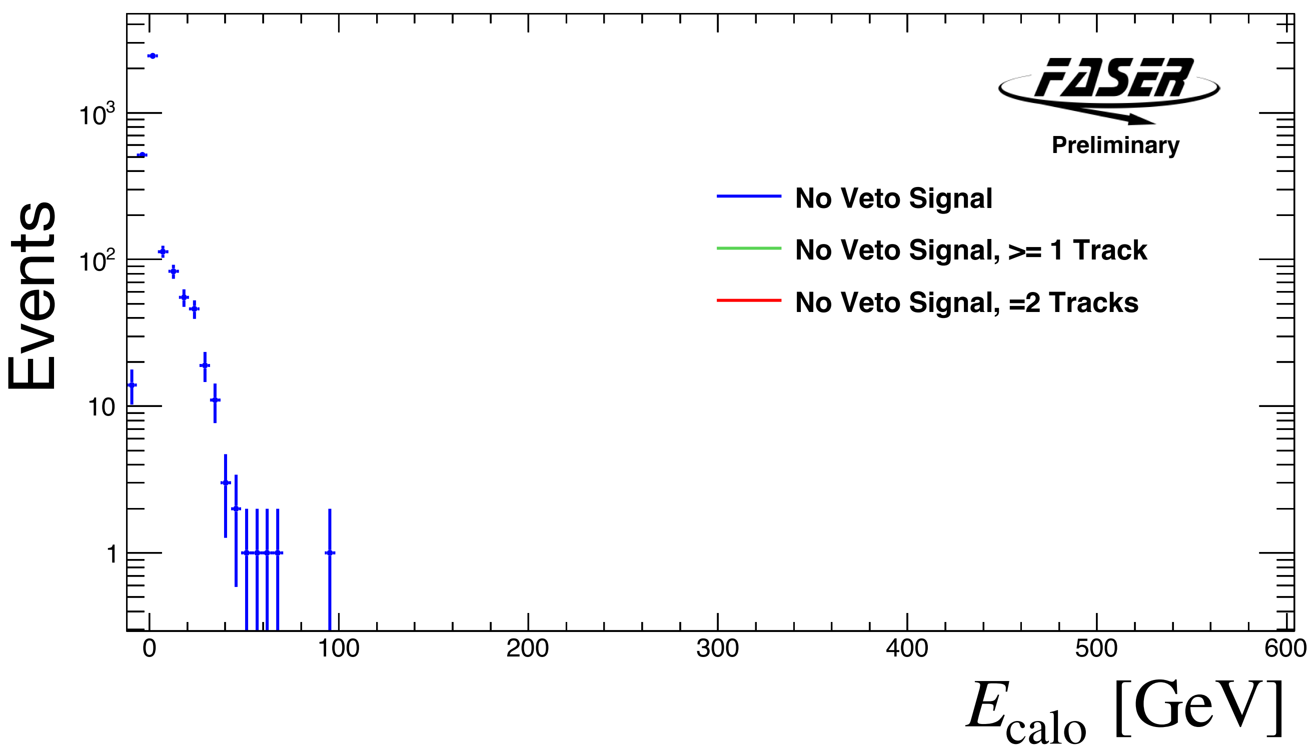
→ **0 background events due to this.**

Backgrounds

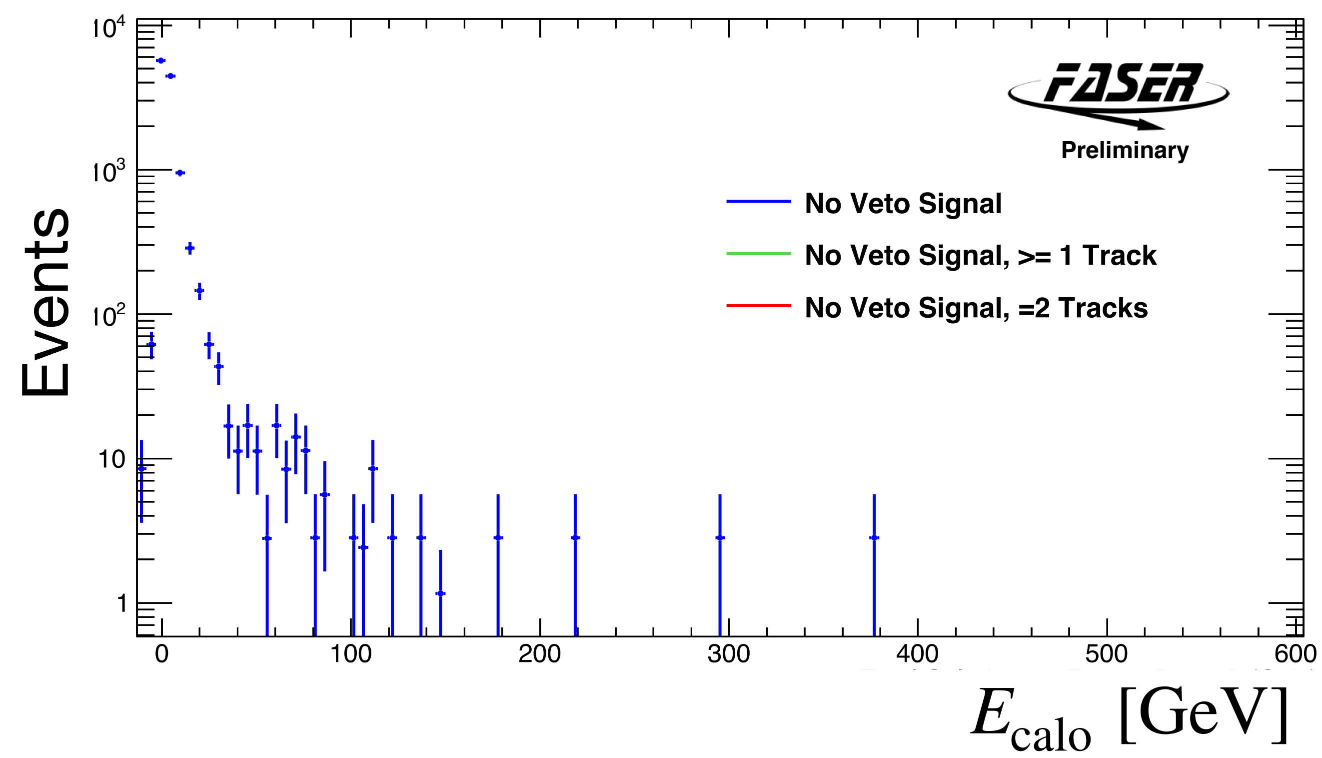
Various Backgrounds to consider :

2) Non-collision backgrounds

Cosmics measured in runs without beam



Nearby beam debris measured in non-colliding bunches



No events observed with 1 or more tracks and $E_{calo} > 500\,\mathrm{GeV}$

→ **0 background events due to this.**

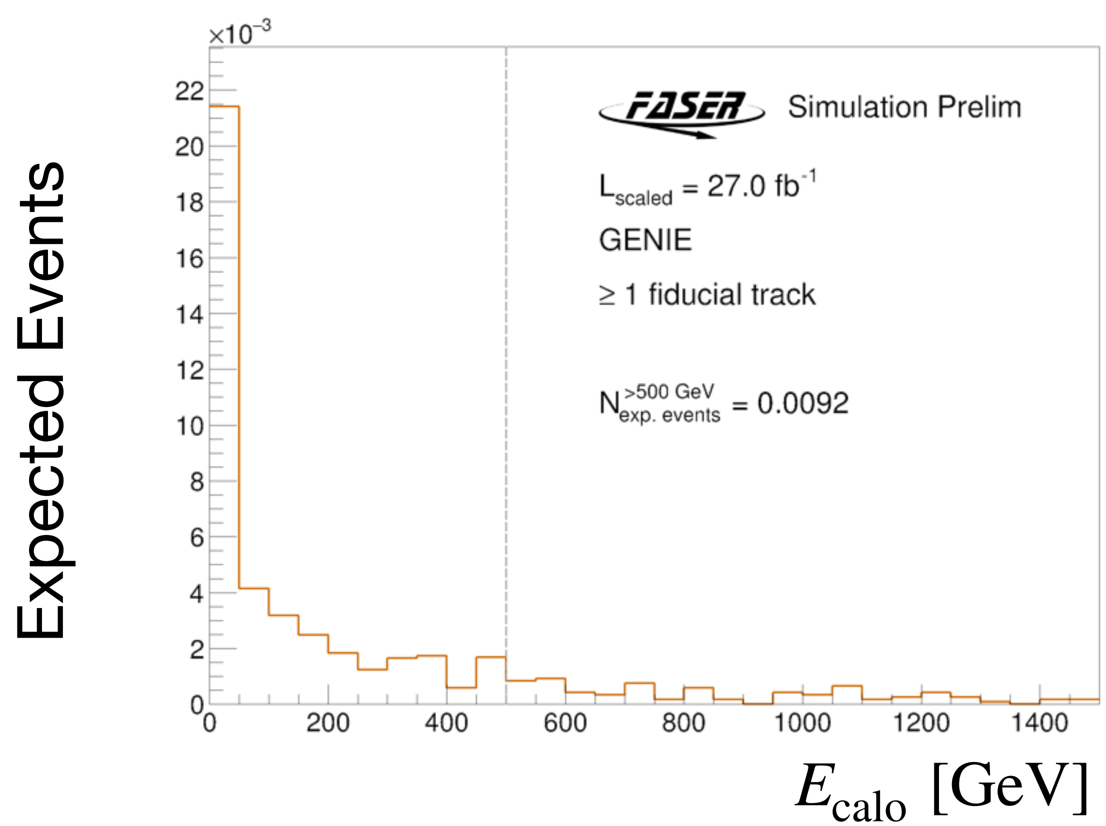
Backgrounds

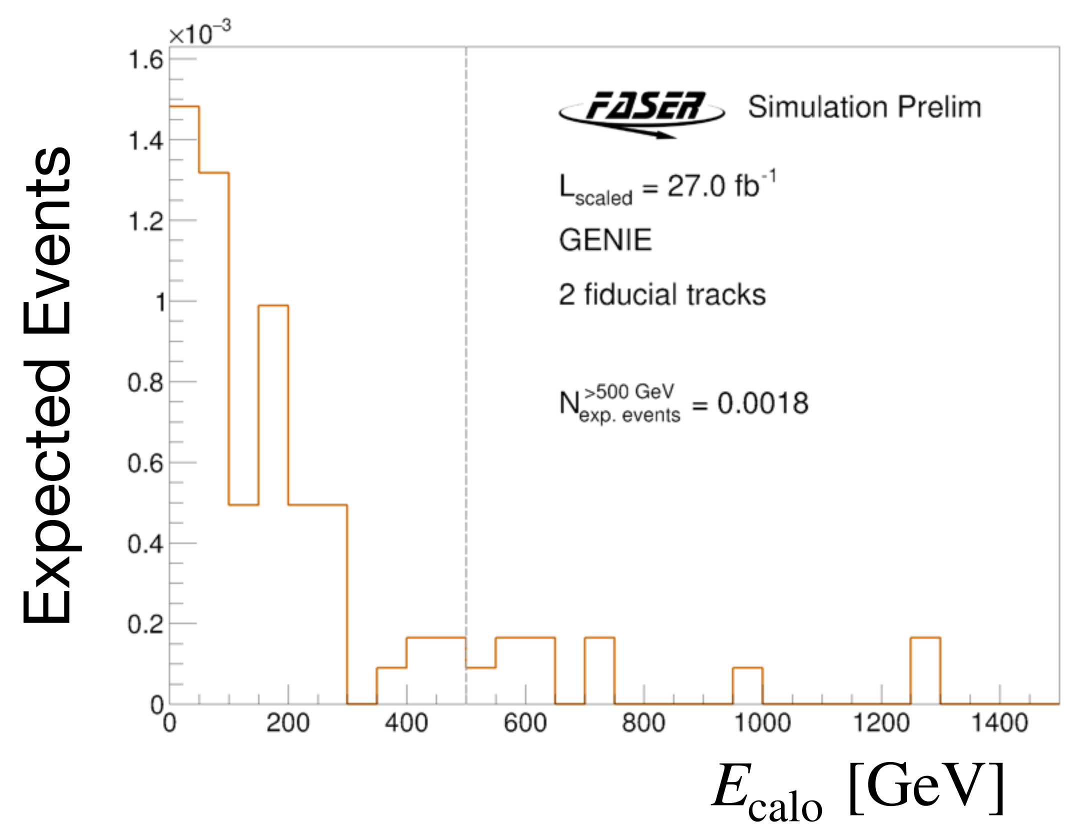
Various Backgrounds to consider :

3) Collider Neutrinos (main background)

We just found them, so time to treat them as a background ;-)

Mostly from interactions in the timing layer ; Estimate their contribution using GENIE simulation and incorporate uncertainties from flux and interaction modeling





→ 1.5 x 10^{-3} background events due to this.

Backgrounds

Various Backgrounds to consider :

4) Neutral Hadrons

From **upstream muons interacting** with the rock in front of FASER

Heavily suppressed : muon typically continues through FASER what would trigger the veto station; neutral hadron must pass through 8 interaction lengths of material before it decays ; decay products must have high energy

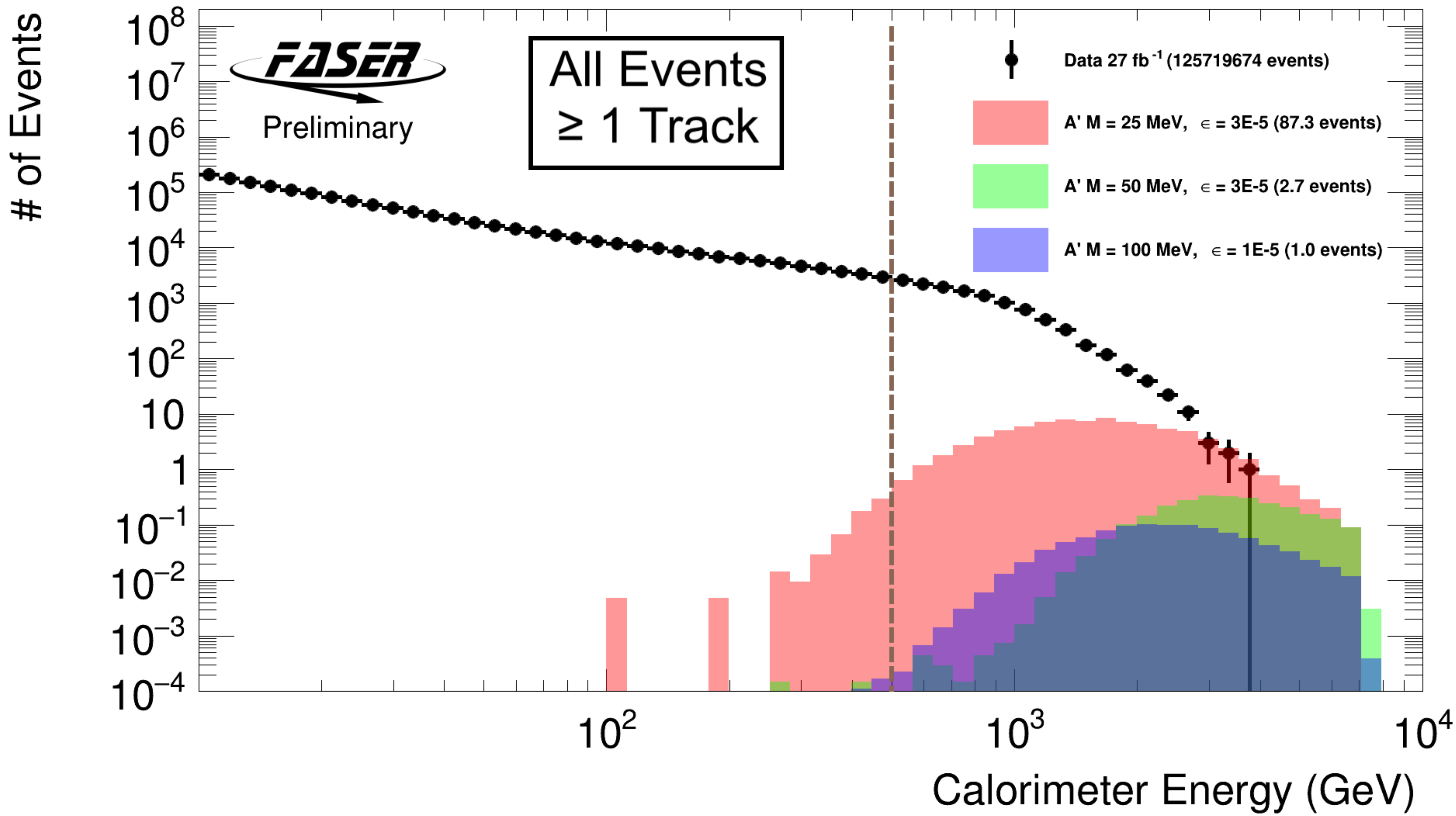
Use sidebands with 2 or 3 tracks and different veto conditions

→ **0.84×10^{-3} background events due to this.**

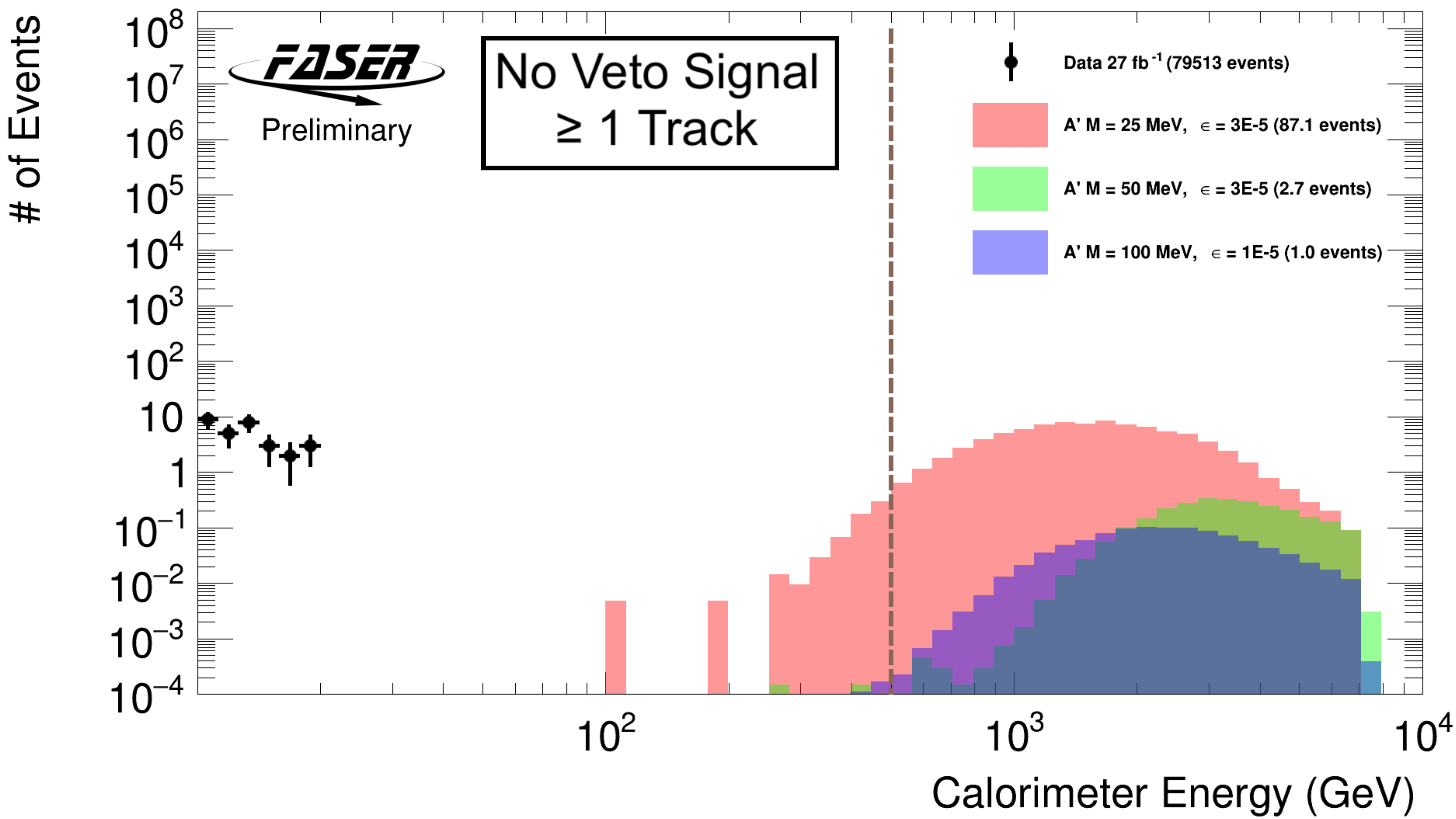
Background Summary:

Background	**Central Value**	**Error (%)**
Background due to veto inefficiency	-	-
Background from neutral hadrons or muons missing veto	0.22×10^{-3}	0.31×10^{-3} (141%)
Neutrino background	1.8×10^{-3}	2.4×10^{-3} (133%)
Non-collision background	-	-
Total	$\mathbf{2.02 \times 10^{-3}}$	$\mathbf{2.4 \times 10^{-3}}$ **(119%)**

Time to unblind

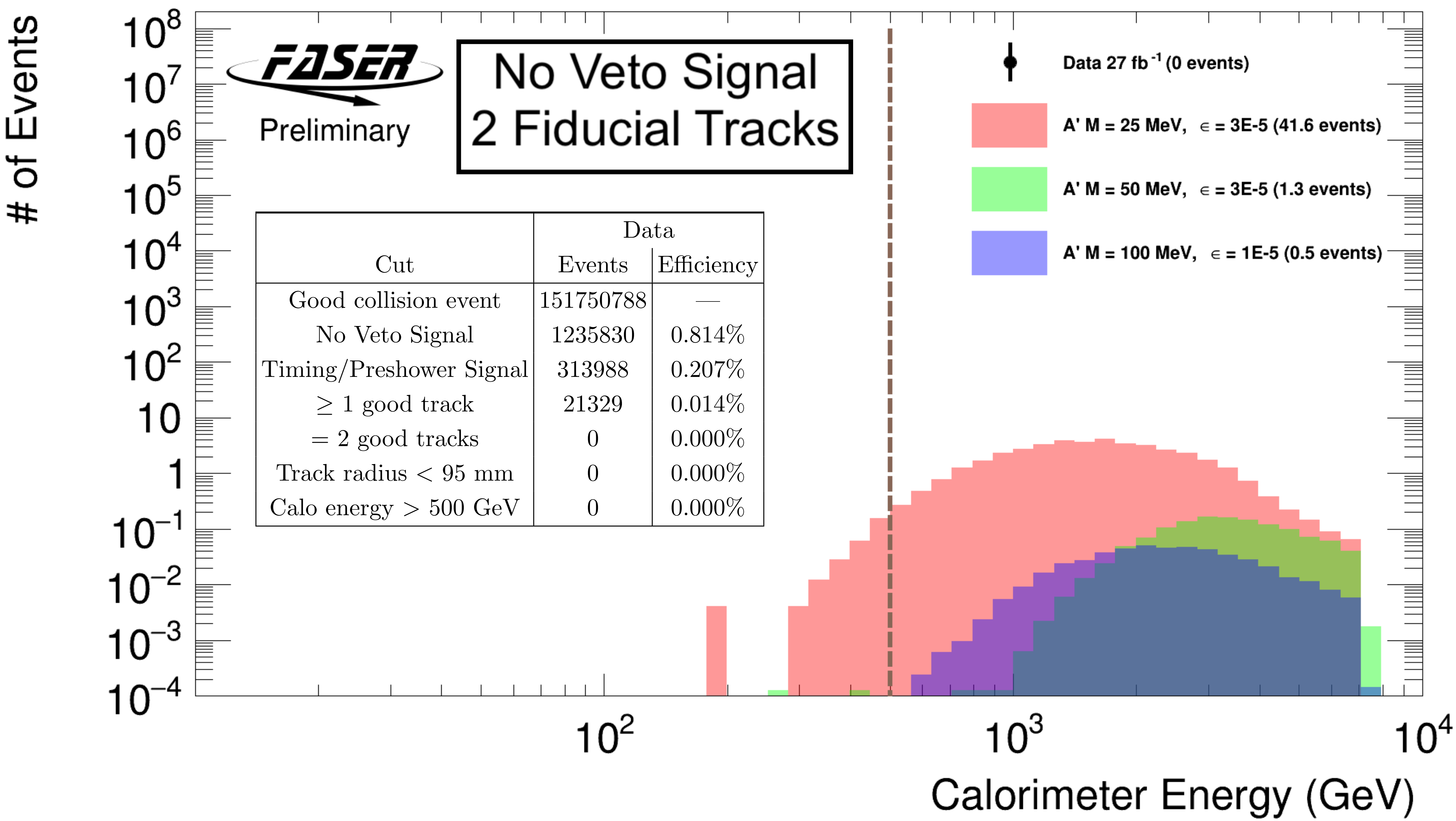


Time to unblind



Time to unblind

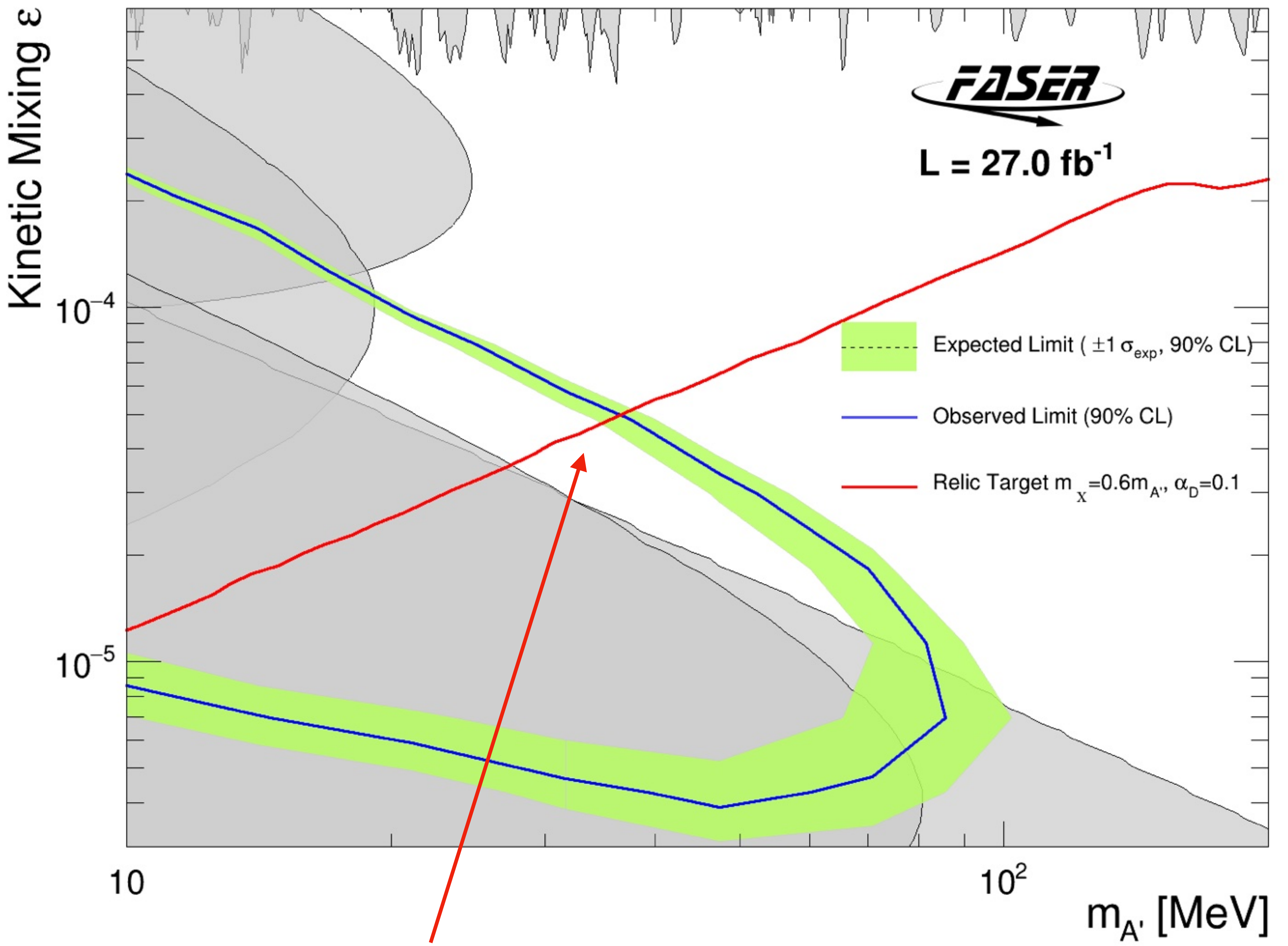
2. *Exactly 2 good fiducial tracks*
p > 20 GeV, radius < 95 mm



Cut	Data	
	Events	Efficiency
Good collision event	151750788	—
No Veto Signal	1235830	0.814%
Timing/Preshower Signal	313988	0.207%
$\geq$ 1 good track	21329	0.014%
= 2 good tracks	0	0.000%
Track radius < 95 mm	0	0.000%
Calo energy > 500 GeV	0	0.000%

Limit Setting

No events observed in signal region → set 90% CL limit



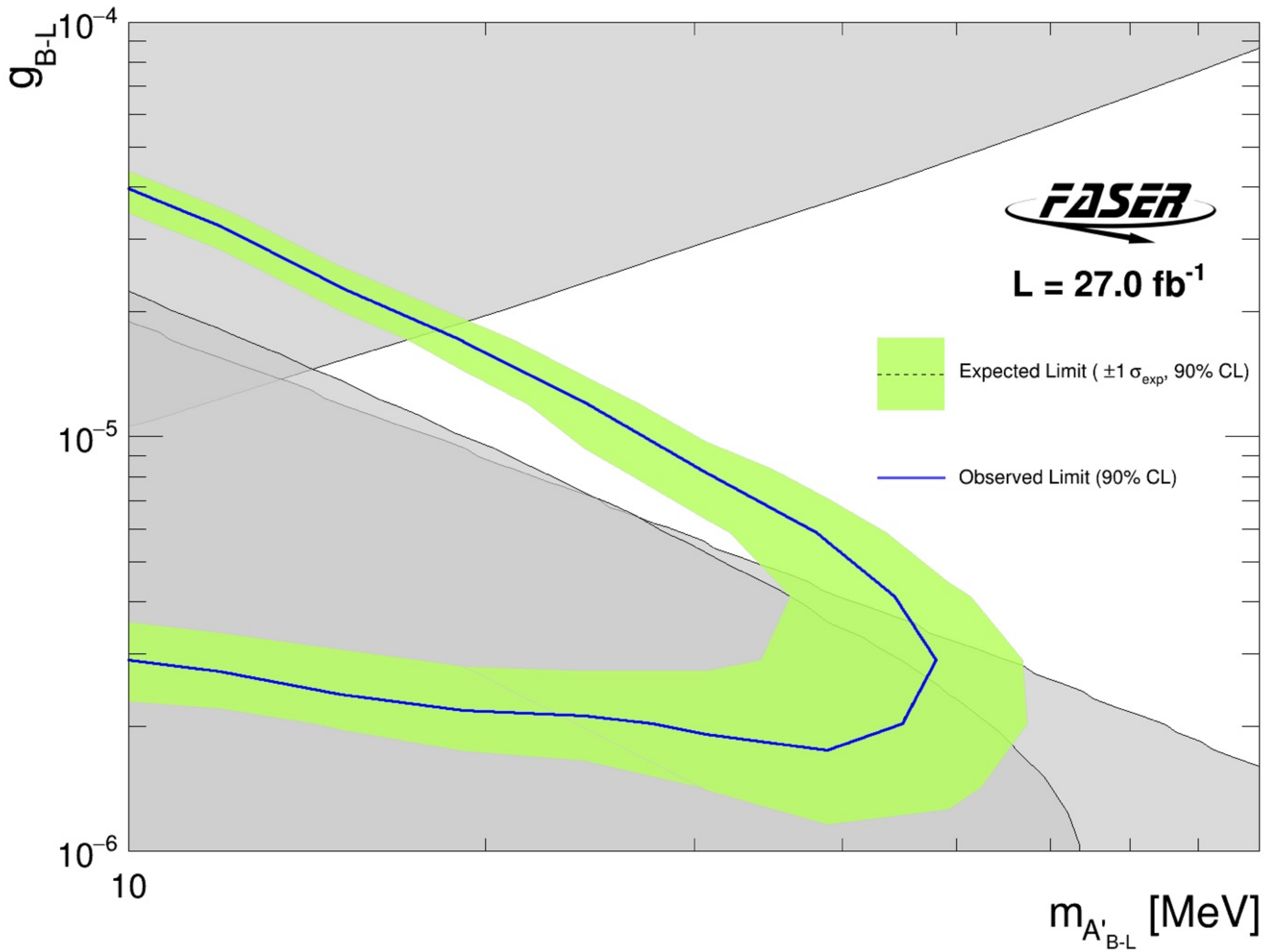
Exclude new region relevant for dark matter thermal relic target

Alternative Model: B-L

$$\frac{1}{2} m^2_{A'_{B-L}} A'^2_{B-L} - g_{B-L} \sum_f Q^f_{B-L} A'^\mu_{B-L} \bar{f} \gamma_\mu f \,,$$

Assume that decay of A'_{B-L} into sterile neutrinos **kinematically forbidden**

A'_{B-L} decay only in electrons and neutrinos with $B(A'_{B-L} \to e^+e^-) \approx 40\%$.



Summary and Outlook

Summary of current Status

FASER **directly observed collider neutrinos** (ν_μ) for the first time (16σ)

"First Direct Observation of Collider Neutrinos with FASER at the LHC" Phys. Rev. Lett. 131, 031801

FASERν **observed collider** ν_e for the first time (5σ)

New Summer 2023 **result**!

Conference Note: https://cds.cern.ch/record/2868284/files/ConferenceNote.pdf

Observations are just the beginning; more studies **underway**

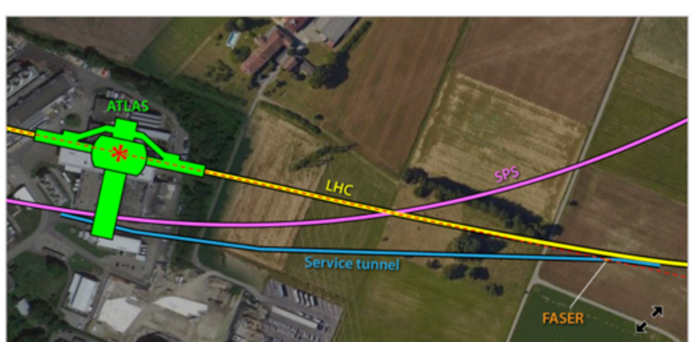
VIEWPOINT

The Dawn of Collider Neutrino Physics

Elizabeth Worcester
Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • *Physics* 16, 113

The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.



Google Earth, imagery (c)2023 Maxar Technologies, map data (c)2023; CERN; adapted by APS/Alan Stonebraker

Figure 1: The Forward Search Experiment (FASER) is installed in a service tunnel that connects the Large Hadron Collider (LHC) and the Super Proton Synchrotron (SPS). Proton collisions at the ATLAS experiment's interaction point (red star) generate beams of ne... Show more

https://physics.aps.org/articles/v16/113

Viewpoint on:
Henso Abreu *et al.* (FASER Collaboration)
Phys. Rev. Lett. **131**, 031801 (2023)

R. Albanese *et al.* (SND@LHC Collaboration)
Phys. Rev. Lett. **131**, 031802 (2023)

The future is forward ;-)

Proposed facility at CERN to host suite of experiments

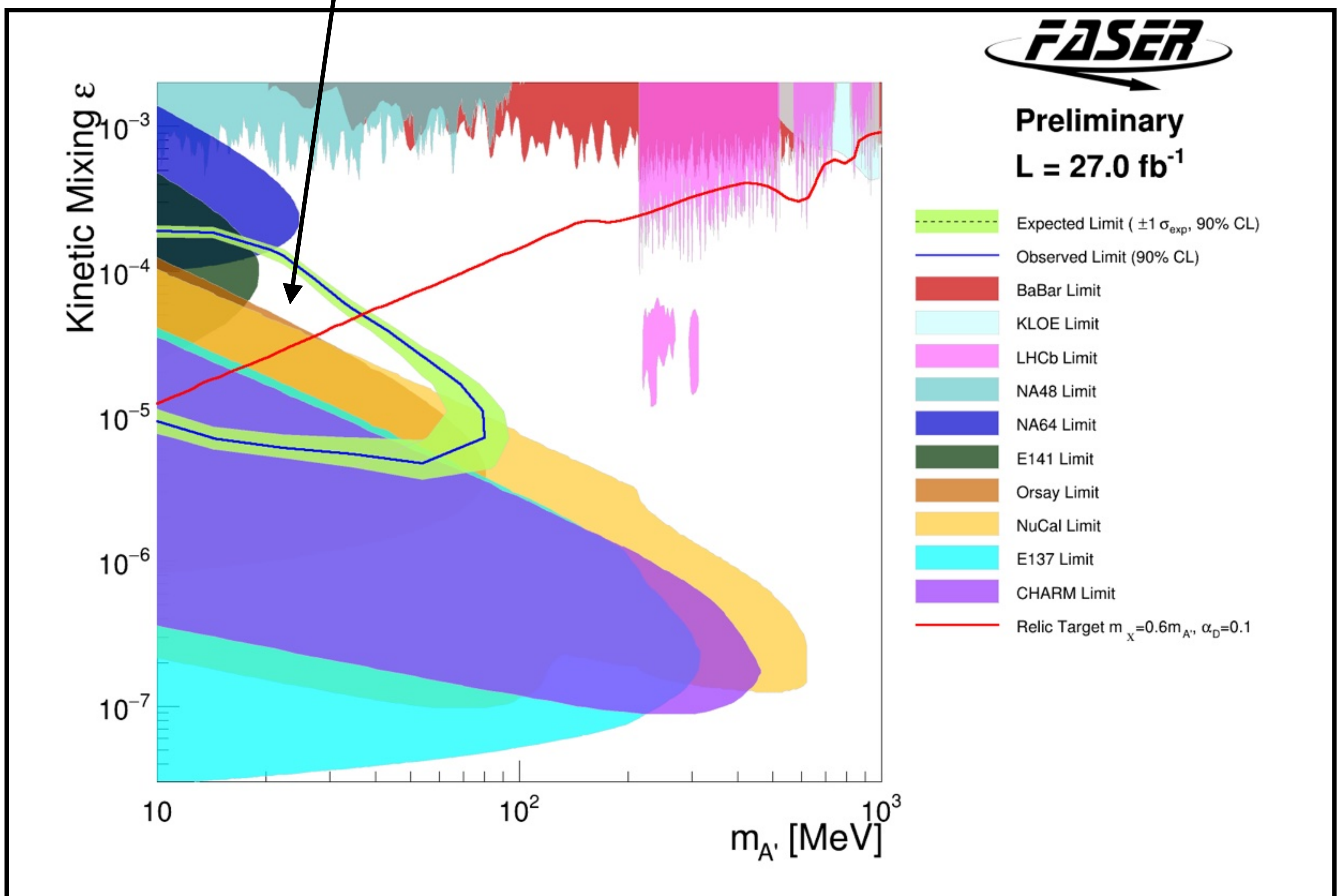
FPF white-paper
https://arxiv.org/abs/2203.05090

Summary of current Status

First FASER limits on dark photon production

“First Results from the Search for Dark Photons with the FASER Detector at the LHC”, https://arxiv.org/abs/2308.05587

We probe **new regions**



We have **40 fb^{-1}** more on disk

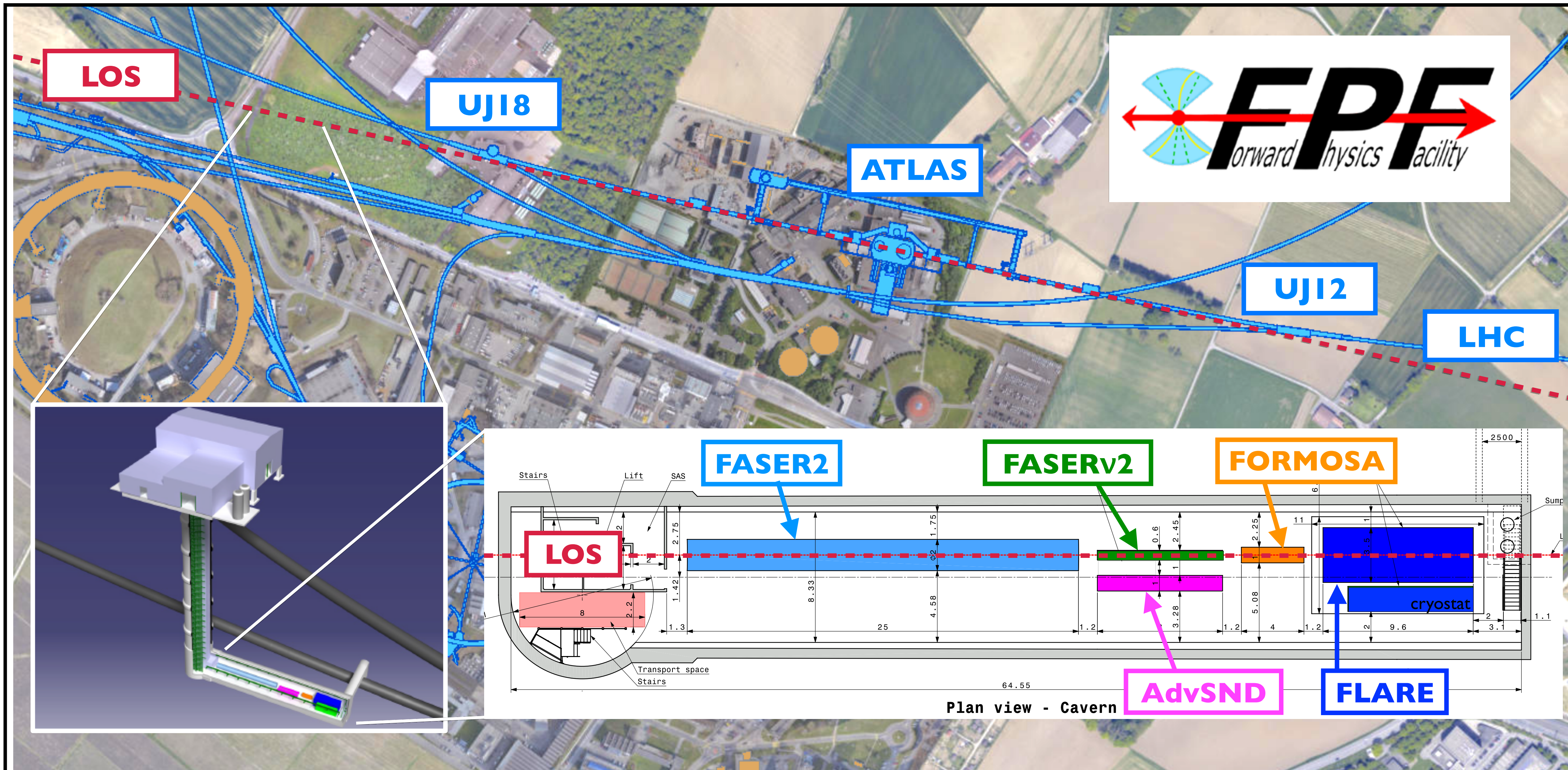
Other **searches** for e.g. ALPs and multiphoton signatures in **preparation**

Stay tuned !

Looking Forward to the FPF

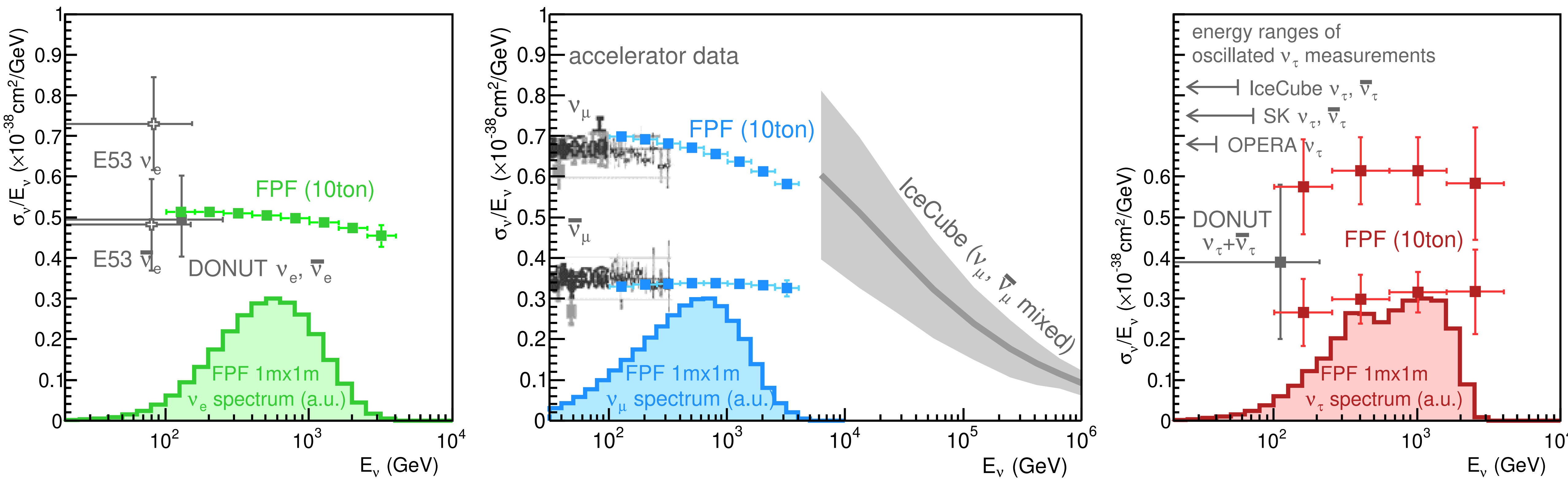
Preferred Location: ca. 620 m west of the ATLAS IP

Cavern dimensions: 65 m long x 8.5 m wide



Looking Forward to Neutrinos

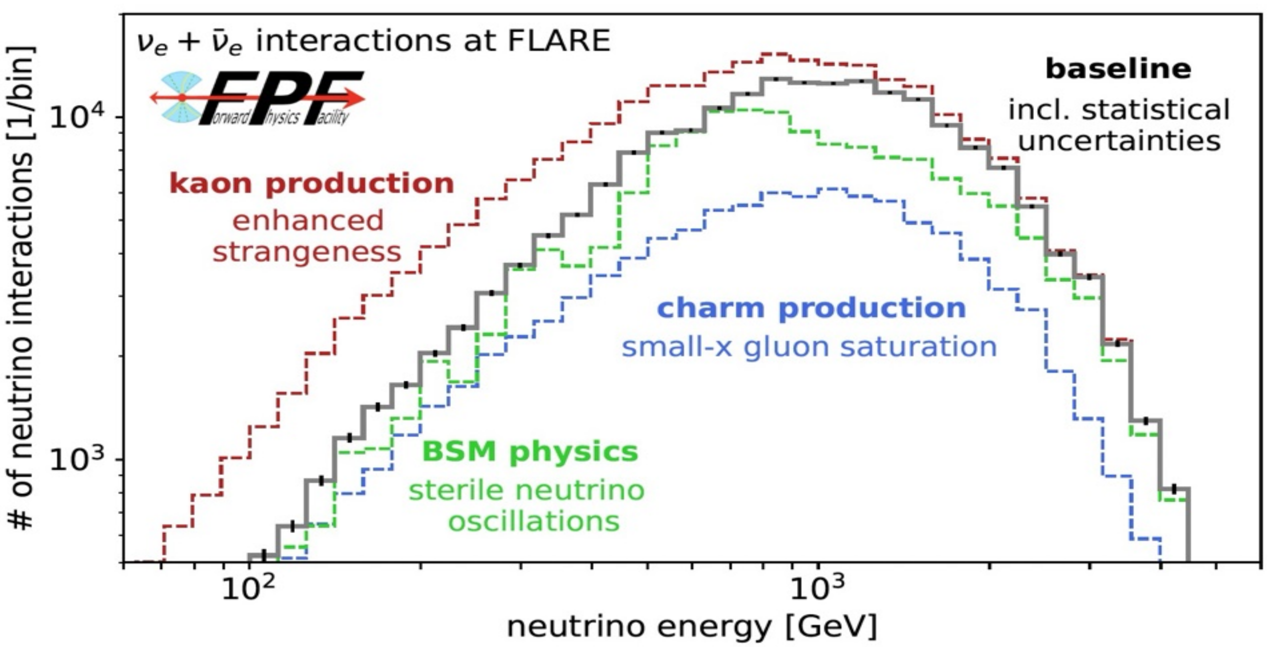
Estimated uncertainties on neutrino flux from FFP :



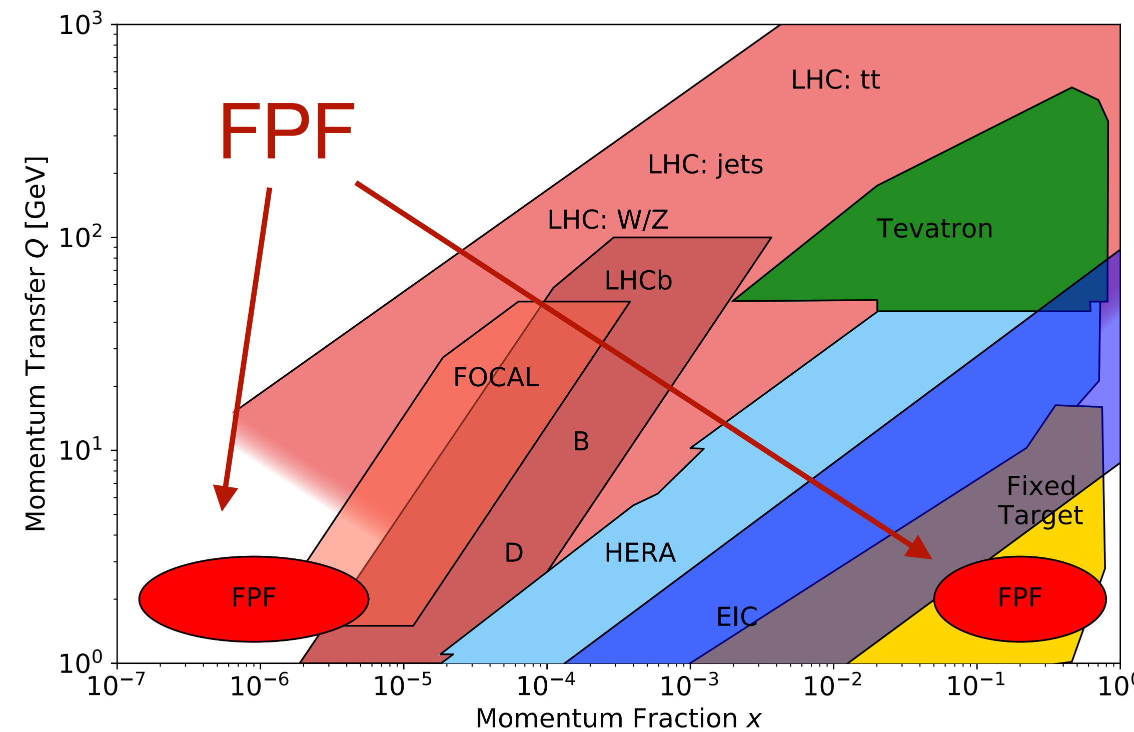
Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

Looking Forward to Neutrinos

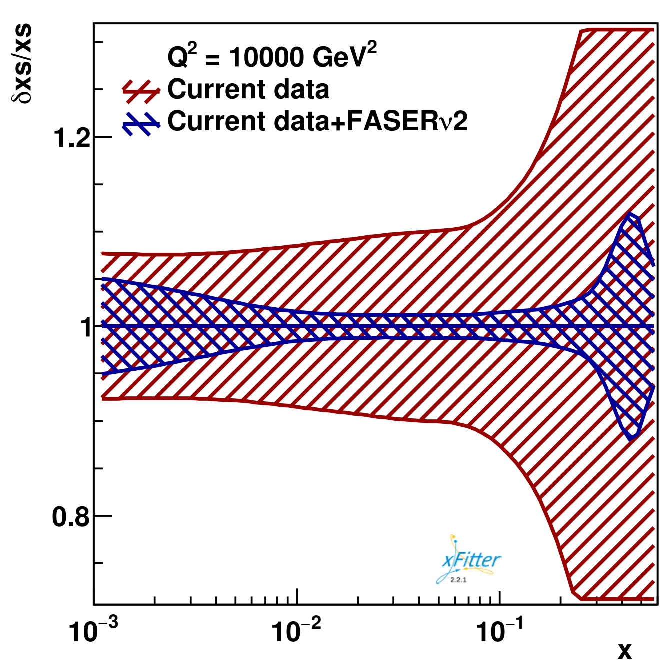
Unique physics reach:



Kinematic coverage in (x, Q) for D-meson prod. in pp collisions



Significant impact on constraining PDFs



w/o FPF

w/ FPF

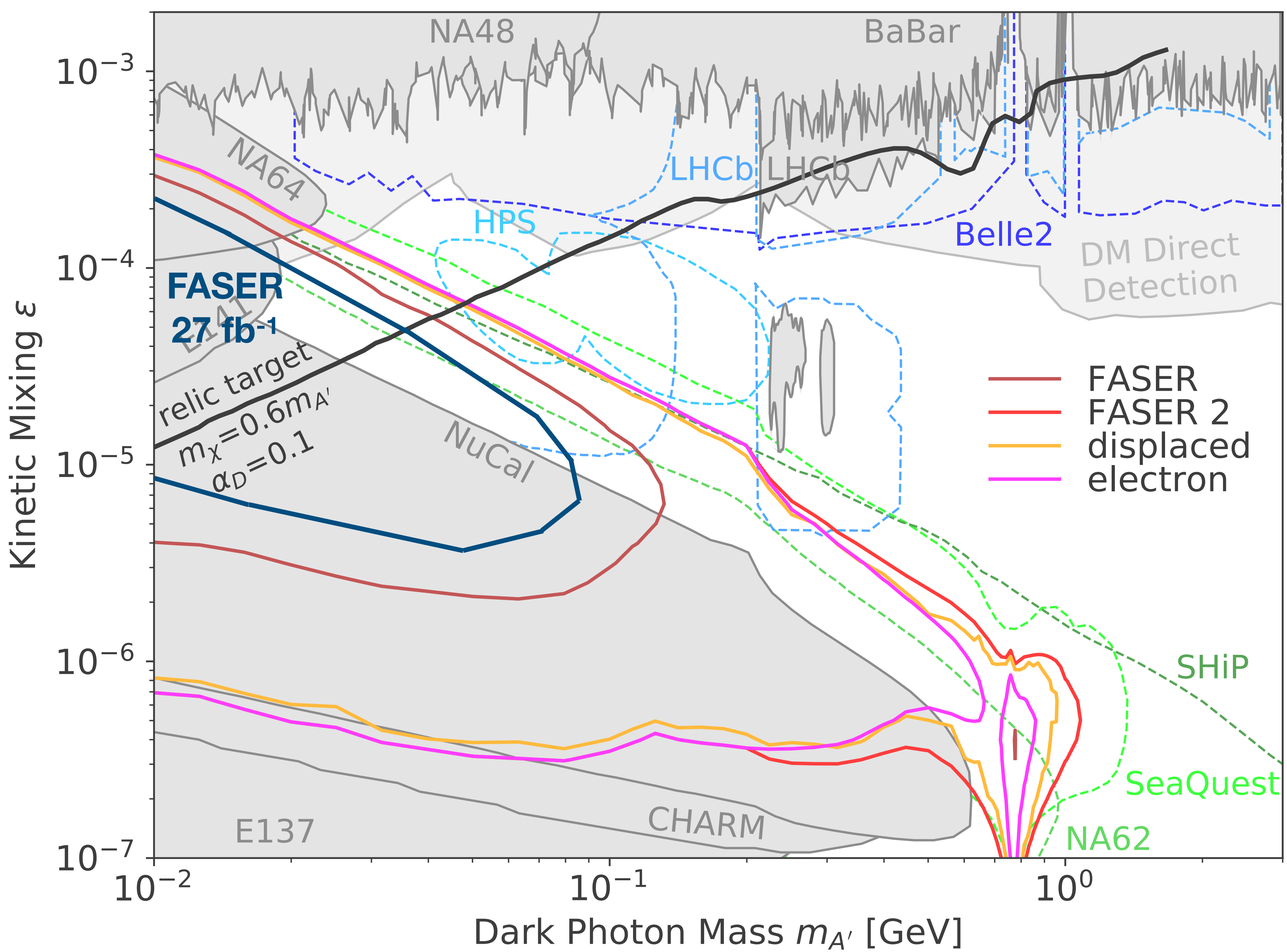
Something to look forward to ;-)

FPF white-paper
https://arxiv.org/abs/2203.05090

https://indico.cern.ch/event/1275380/contributions/5379619/attachments/2662969/4613853/rojo-FPF6-WG1.pdf

Looking Forward to Dark Photons

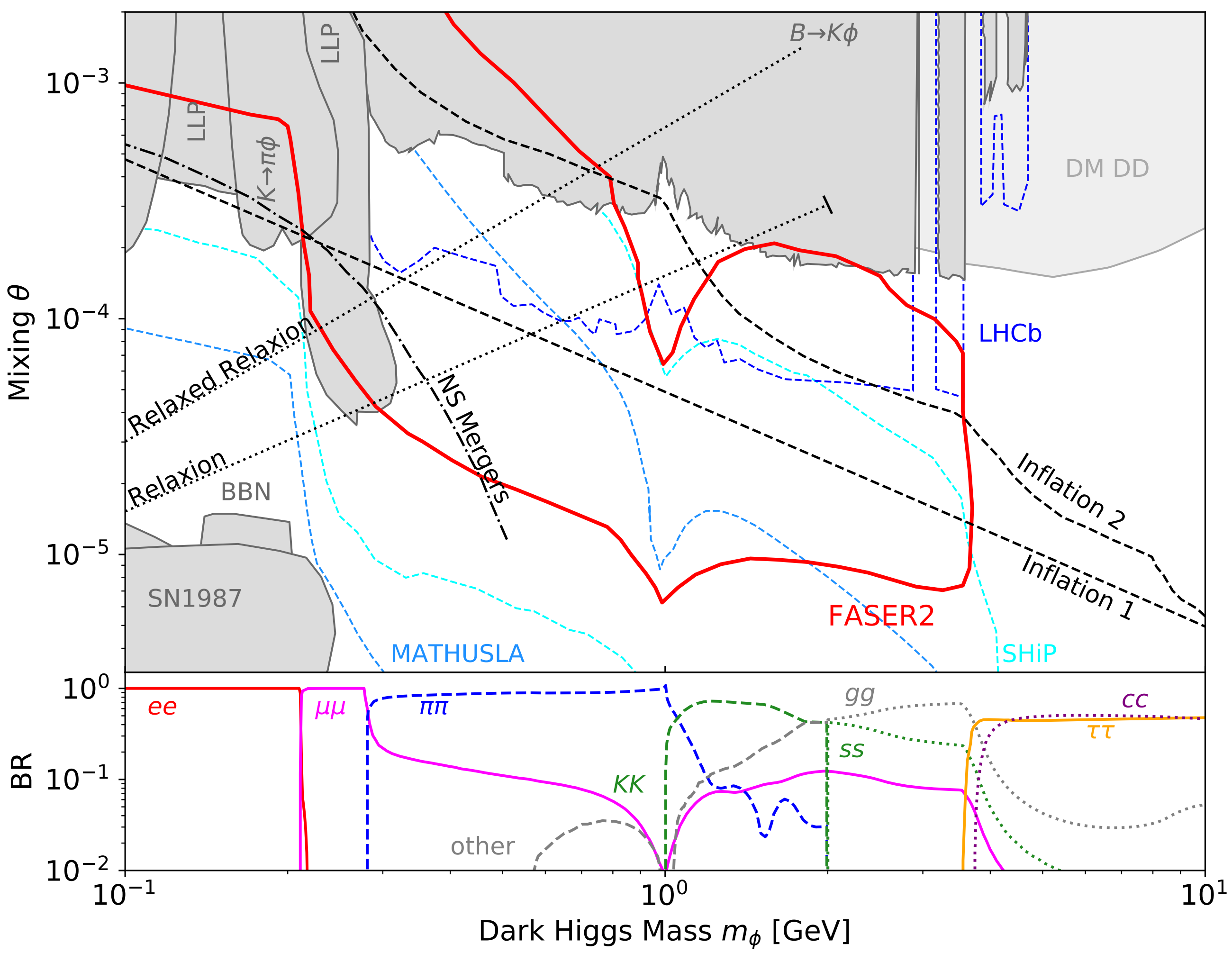
Estimated sensitivities for dark photon signals



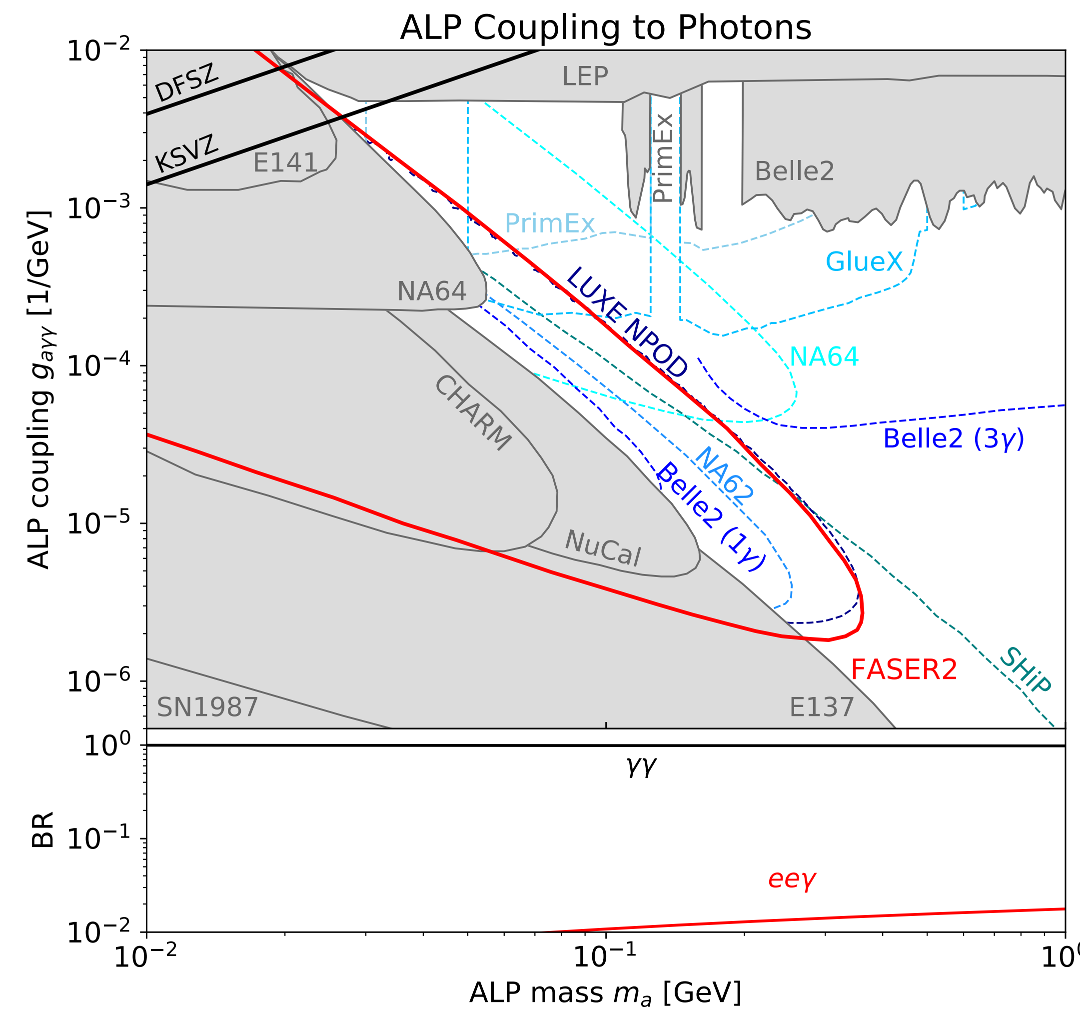
Looking Forward to other LLPs

Sensitive to a plethora of **other models** :

e.g. dark Higgs bosons



ALPs coupling to photons



The FASER Collaboration

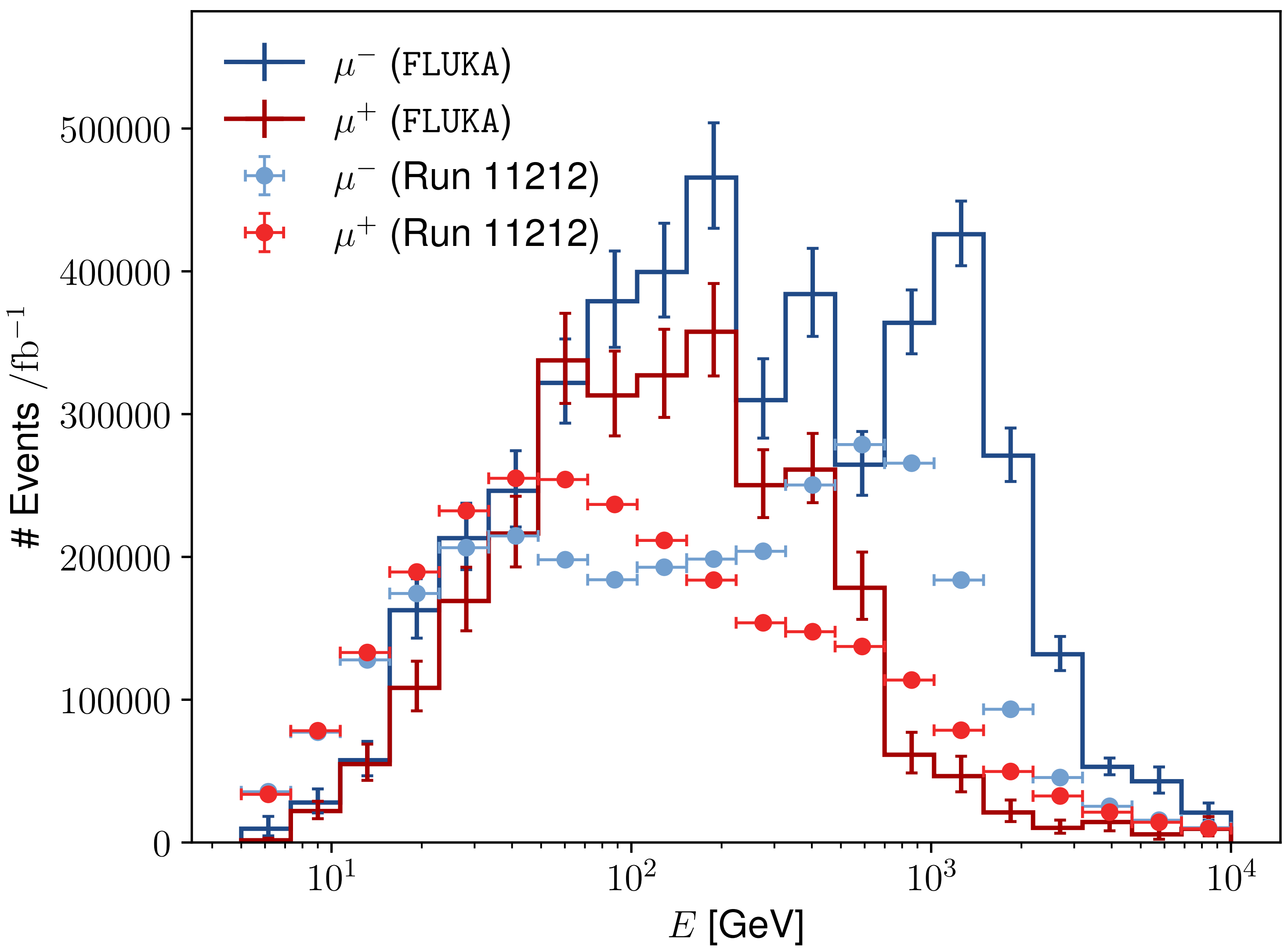
FASER institutions :

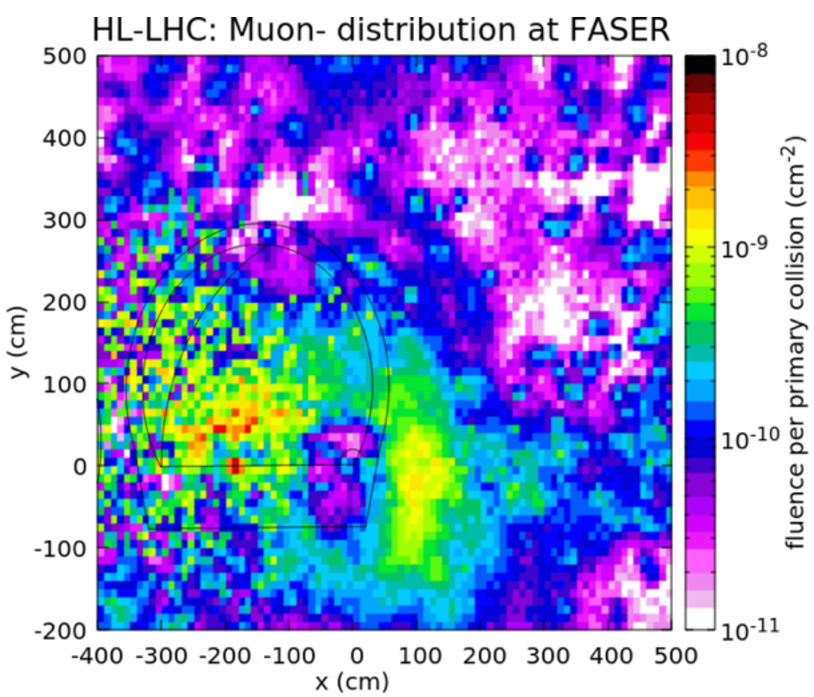
With the kind support of :

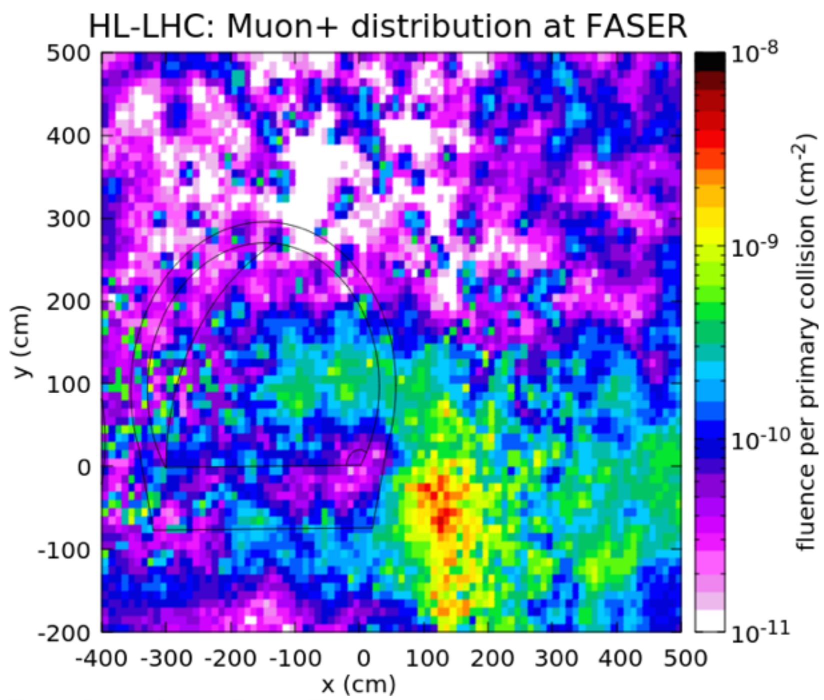
International laboratory covered by a cooperation agreement with CERN

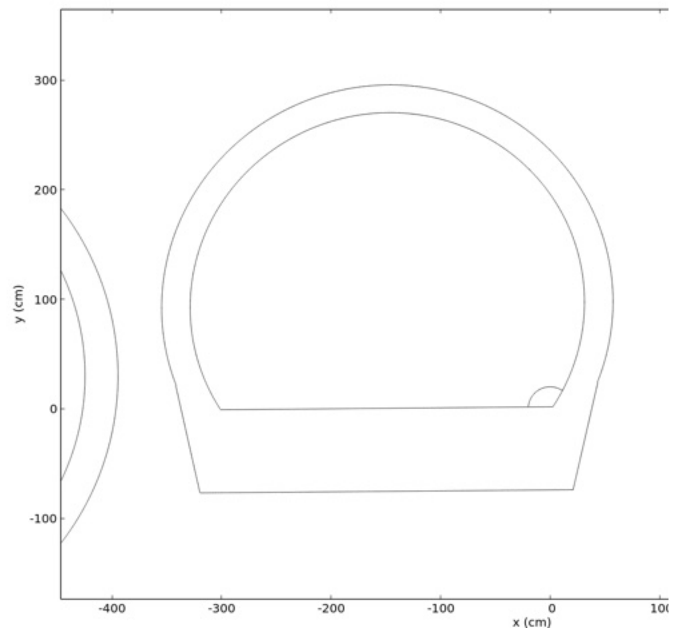
More Information

Muon Energy Spectrum





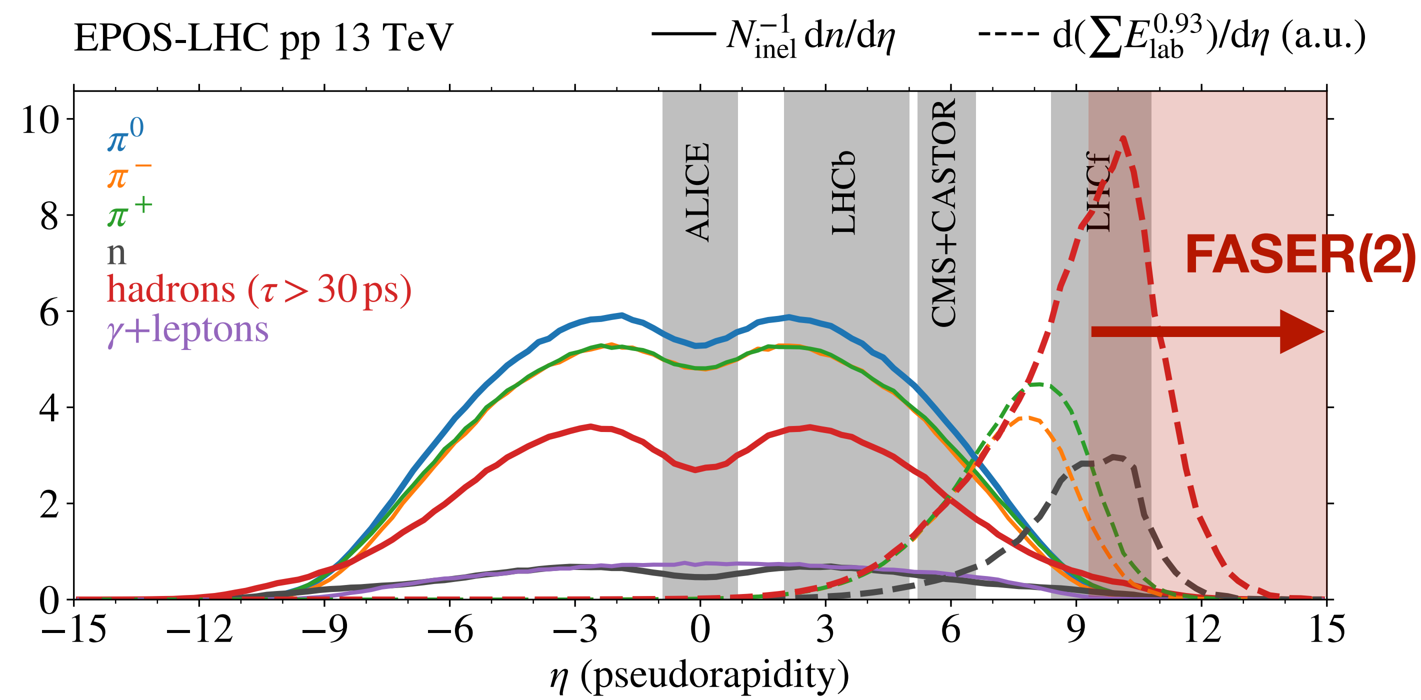




Air showers

Extensive Air Showers (EAS):

- Particle prod. in the far-forward region
- Low momentum transfer
- Non-pert. regime
- Complex particle composition
- Energies range over many orders of magnitudes



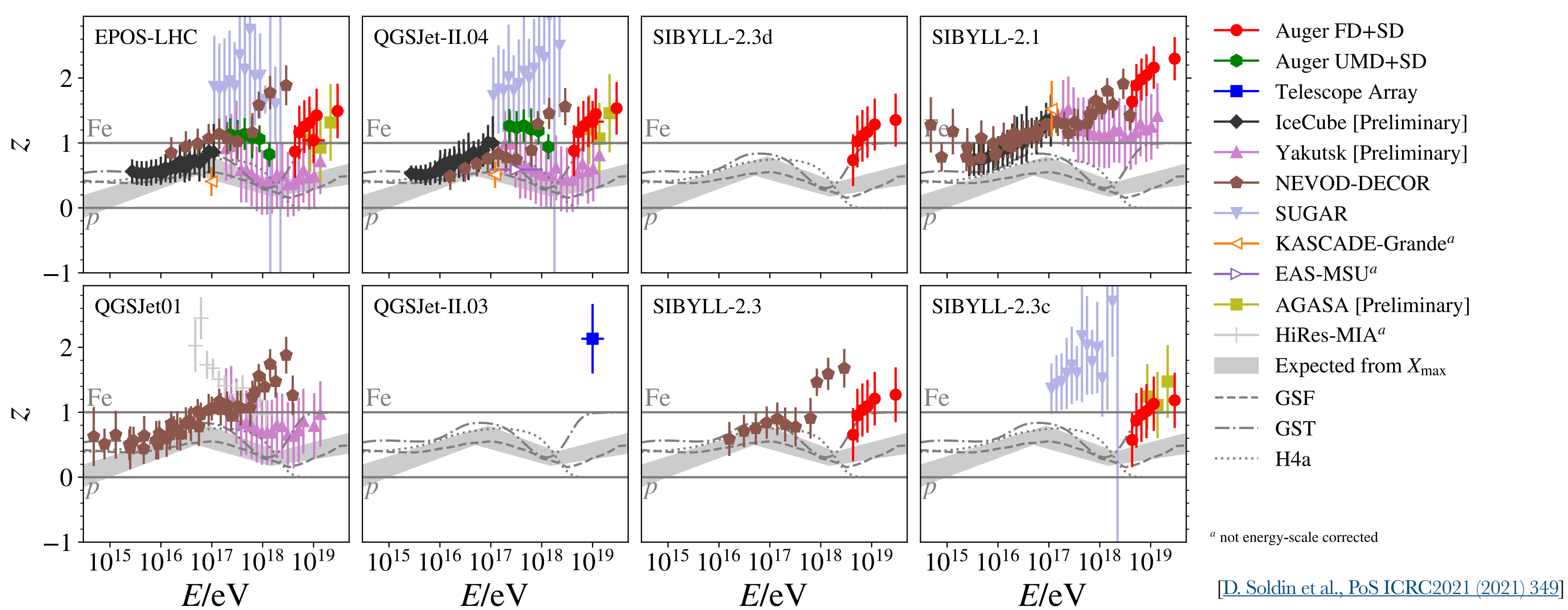
Modeling of particle interactions based on phenomenological models for EAS simulations

FASER & FPF provide **unique laboratory** to test and tune hadronic interaction models

Status: Large discrepancies observed between data & MC

"Muon puzzle"

Strangeness enhancement?

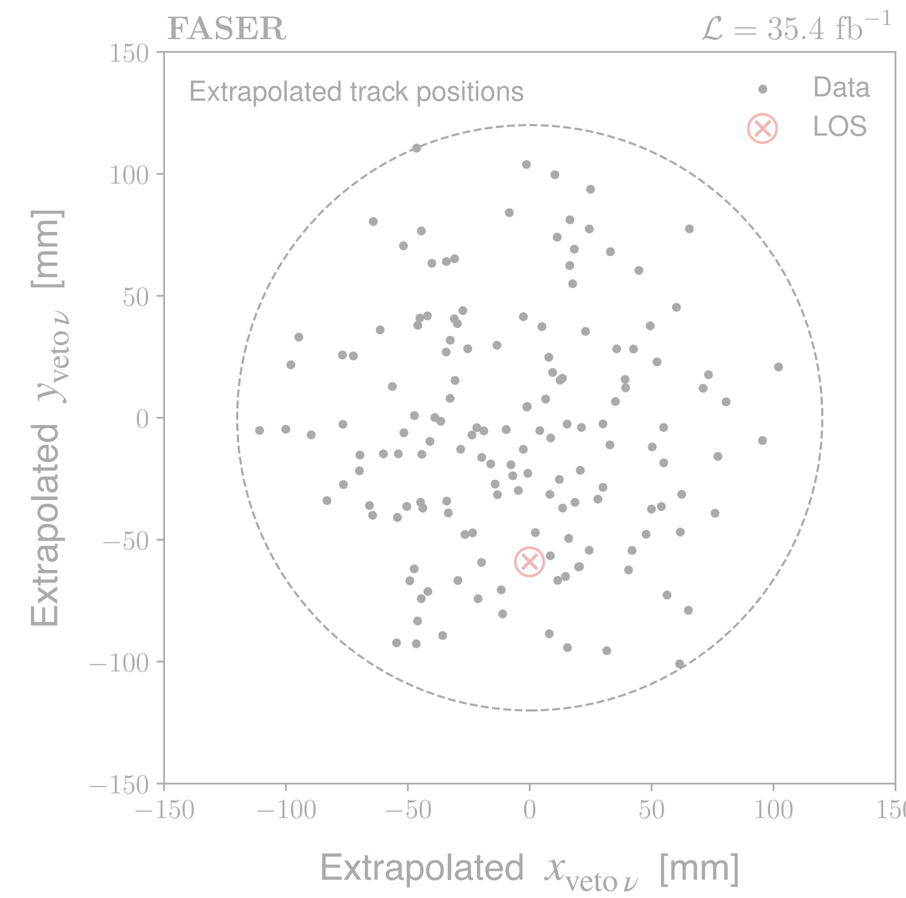


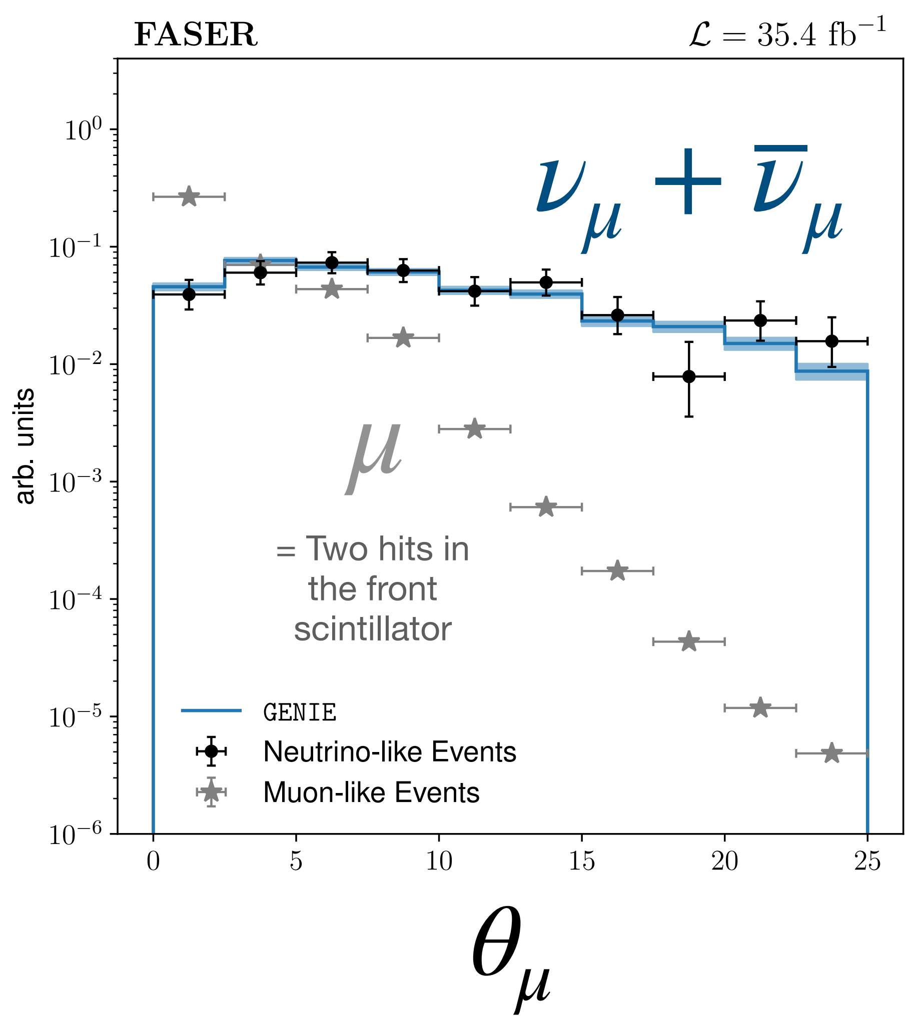
[D. Soldin et al., PoS ICRC2021 (2021) 349]

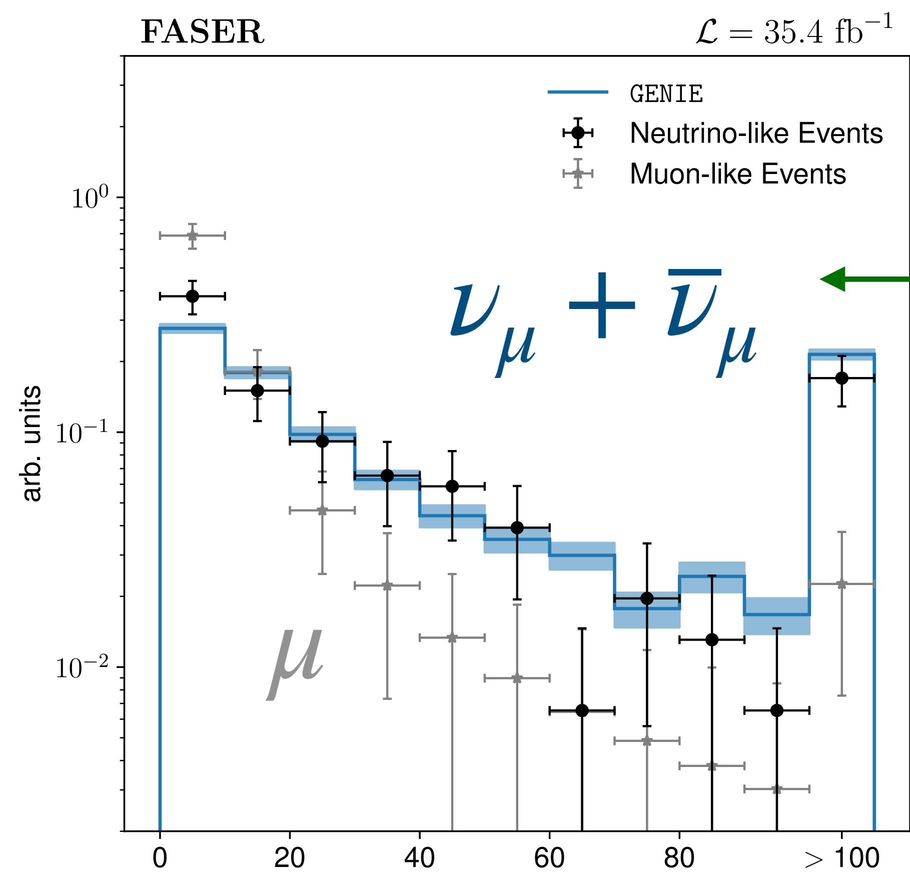
Observation:

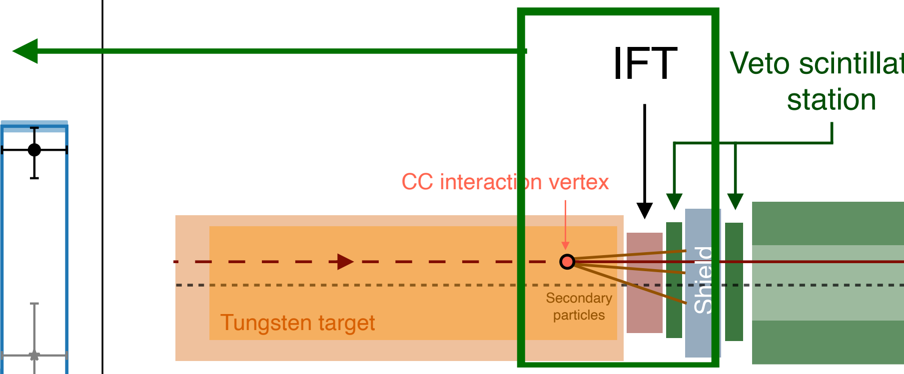
$$n_\nu = 153 \, ^{+12}_{-13} \, (\text{stat.}) \, ^{+2}_{-2} \, (\text{bkg.}) = 153 \, ^{+12}_{-13} \, (\text{tot.})$$

with more than **16 sigma significance**

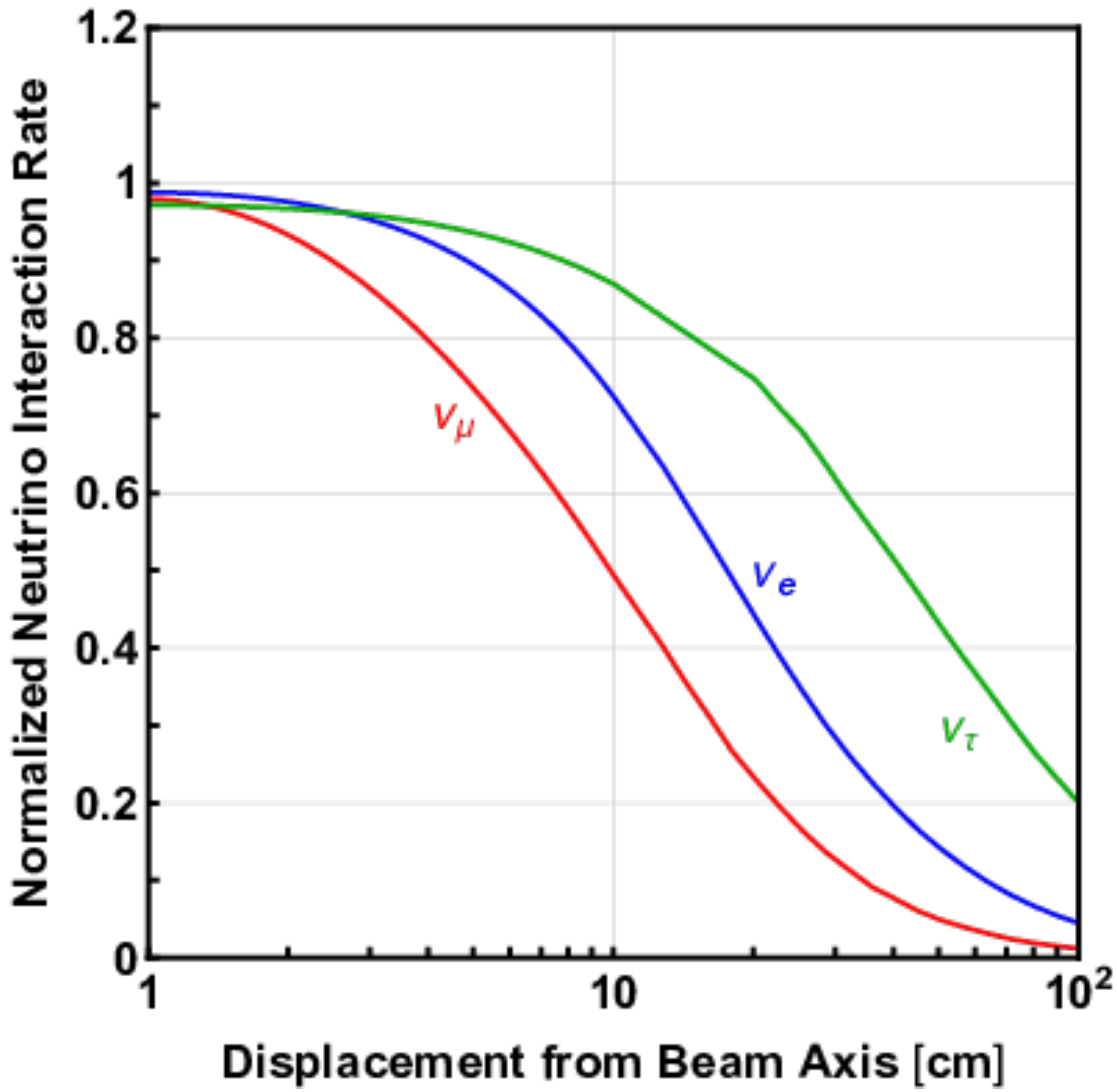




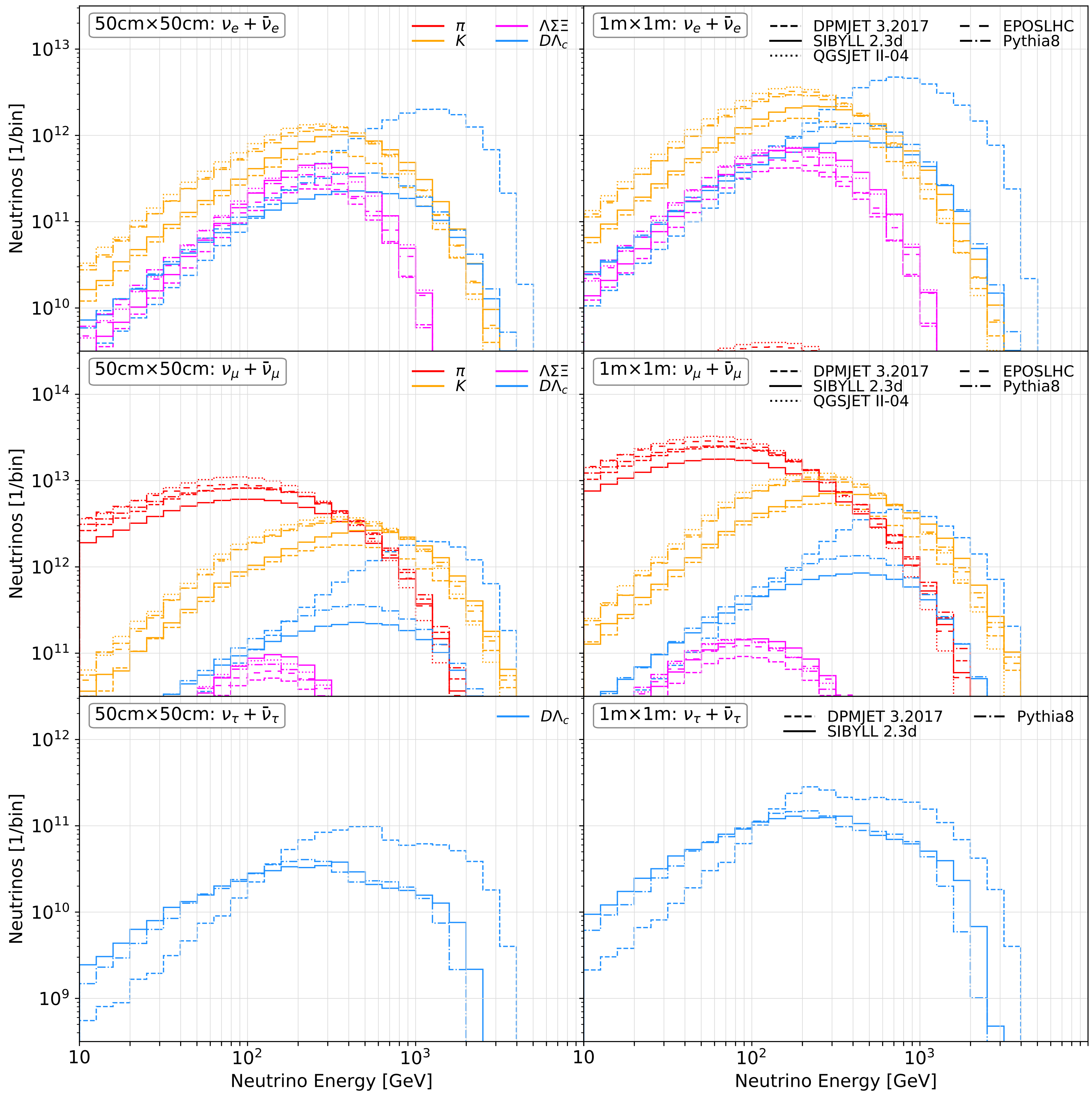




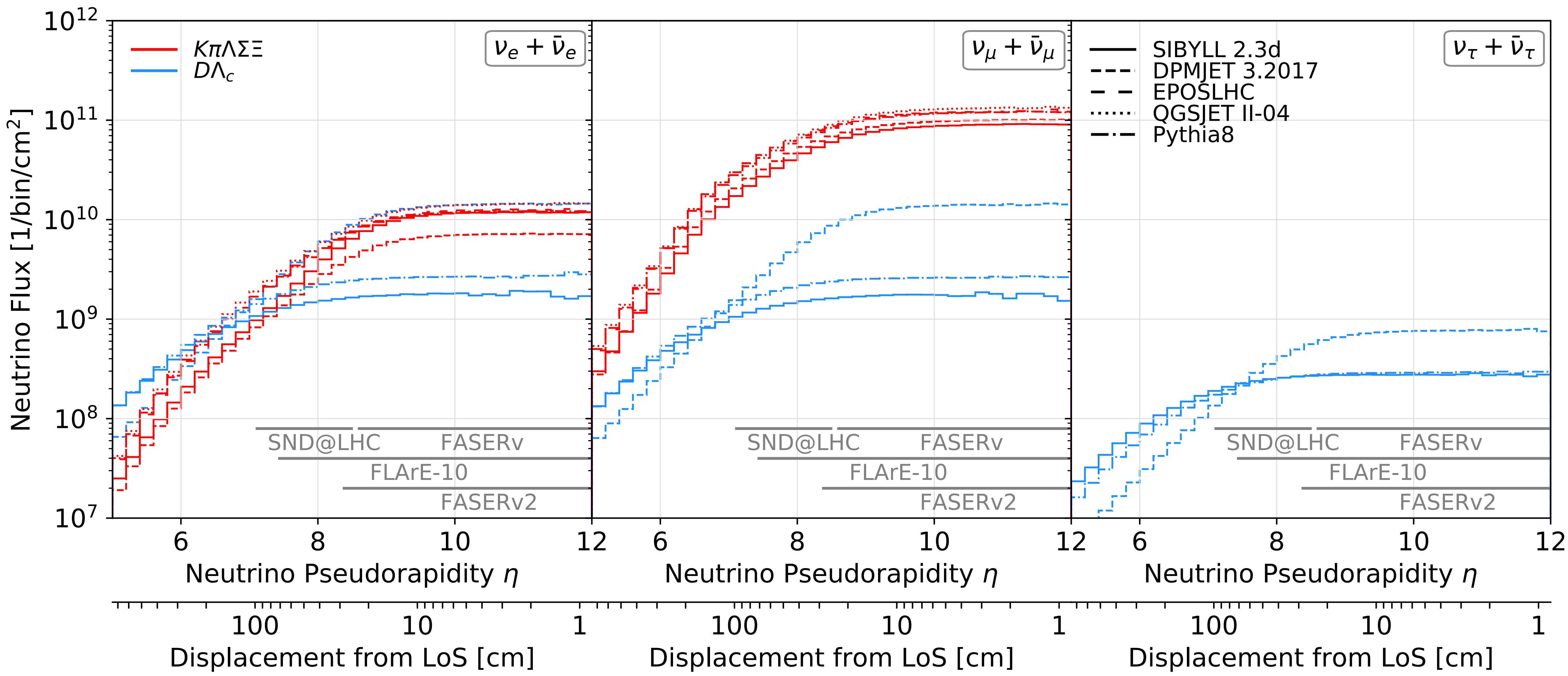
Neutrino flux as a function of beam axis displacement



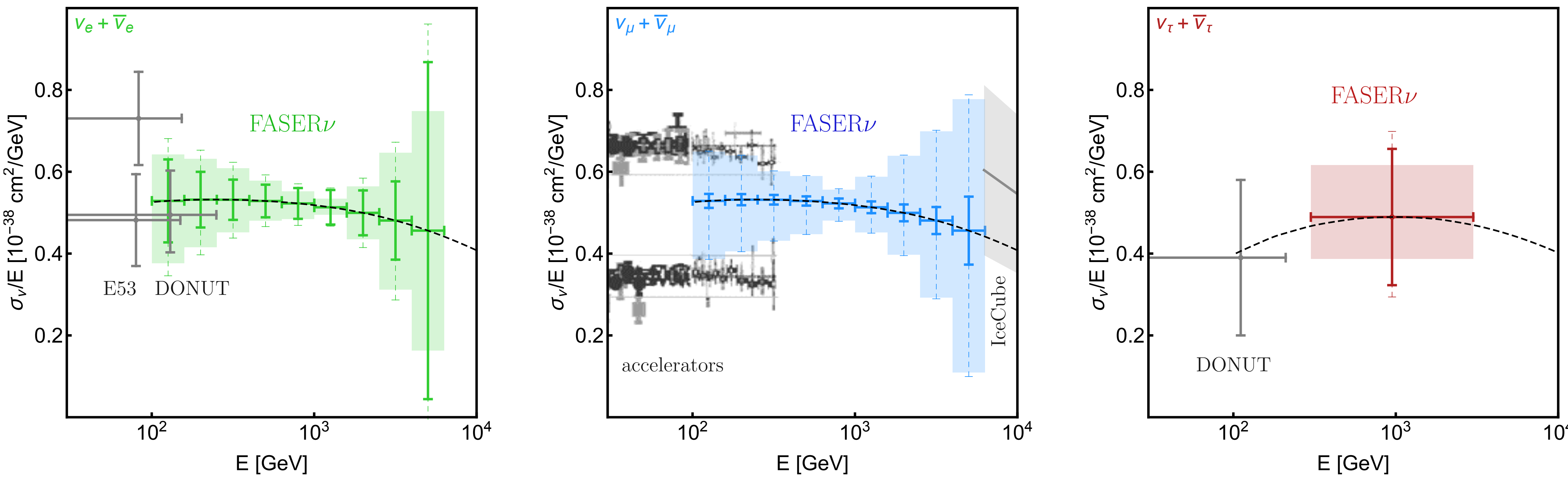
Neutrino Energy Spectrum



Pseudorapidity Coverage of FASER and FFP experiments



Expected Sensitivity after Run 3



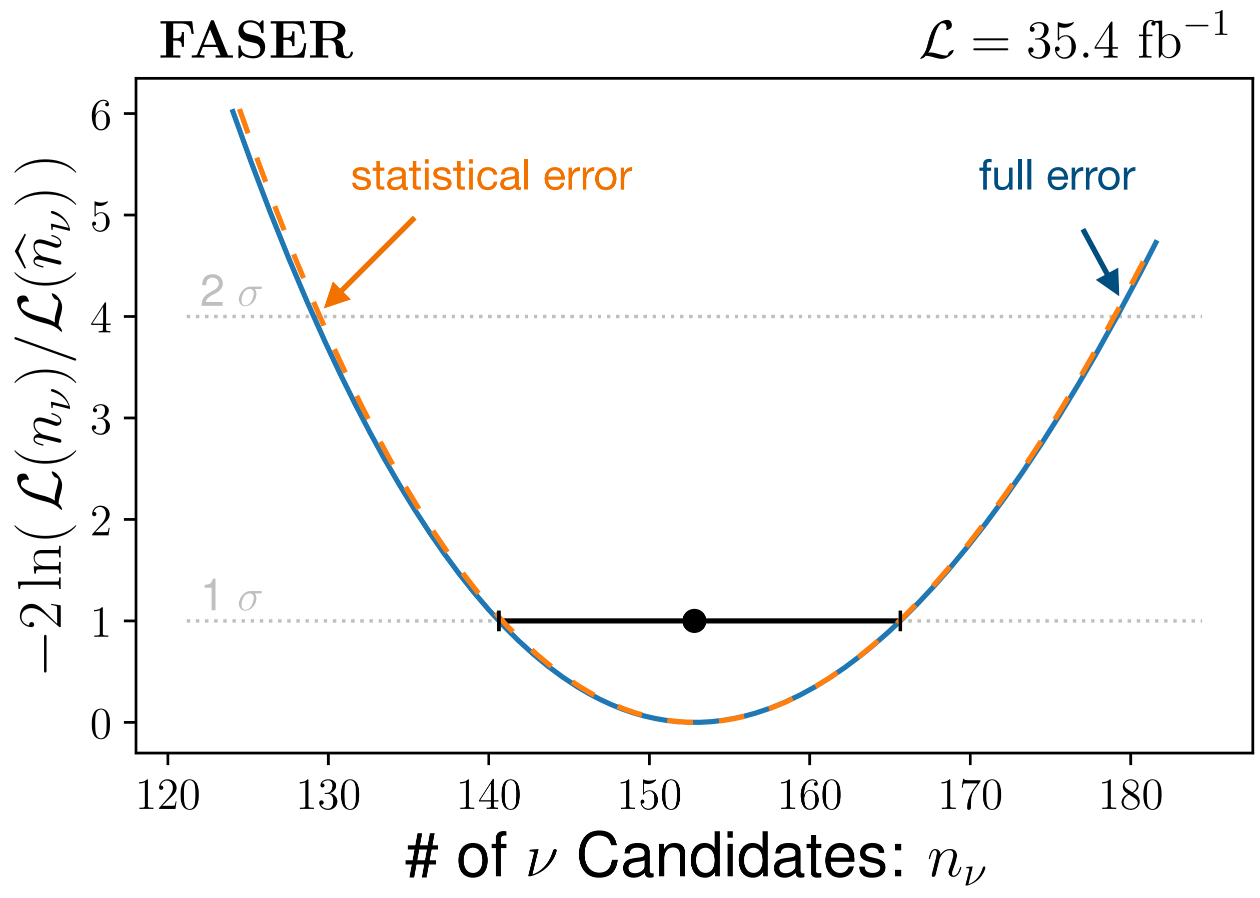
Signal Extraction

Likelihood

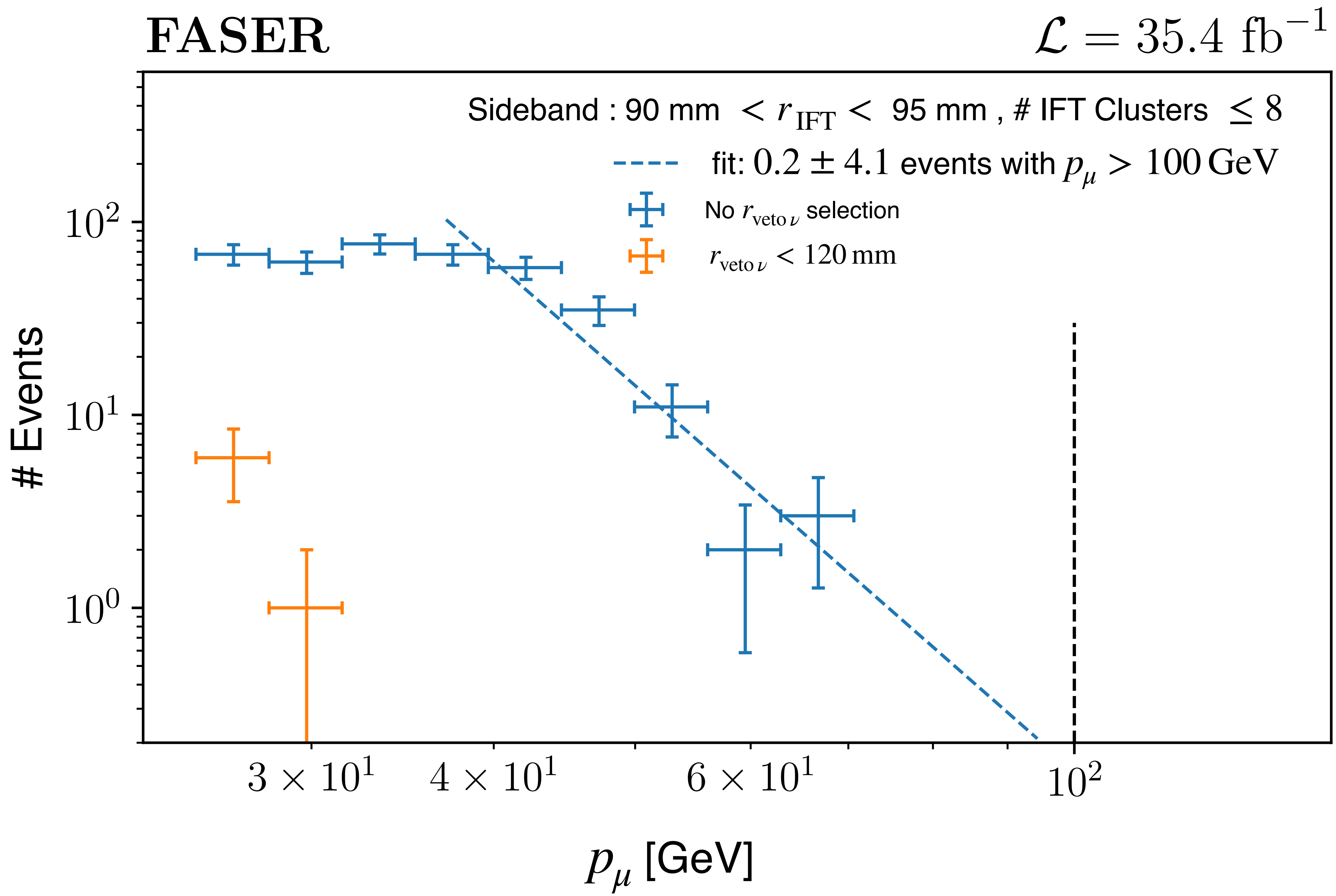
$$\mathcal{L} = \prod_i \mathcal{P}(N_i|n_i) \cdot \prod_j \mathcal{G}_j \, .$$

Test statistics

$$q_0 = \begin{cases} -2\ln\lambda(n_\nu = 0) & \hat{n}_\nu \geq 0 \\ 0 & \hat{n}_\nu < 0 \end{cases}$$



Geometric sideband



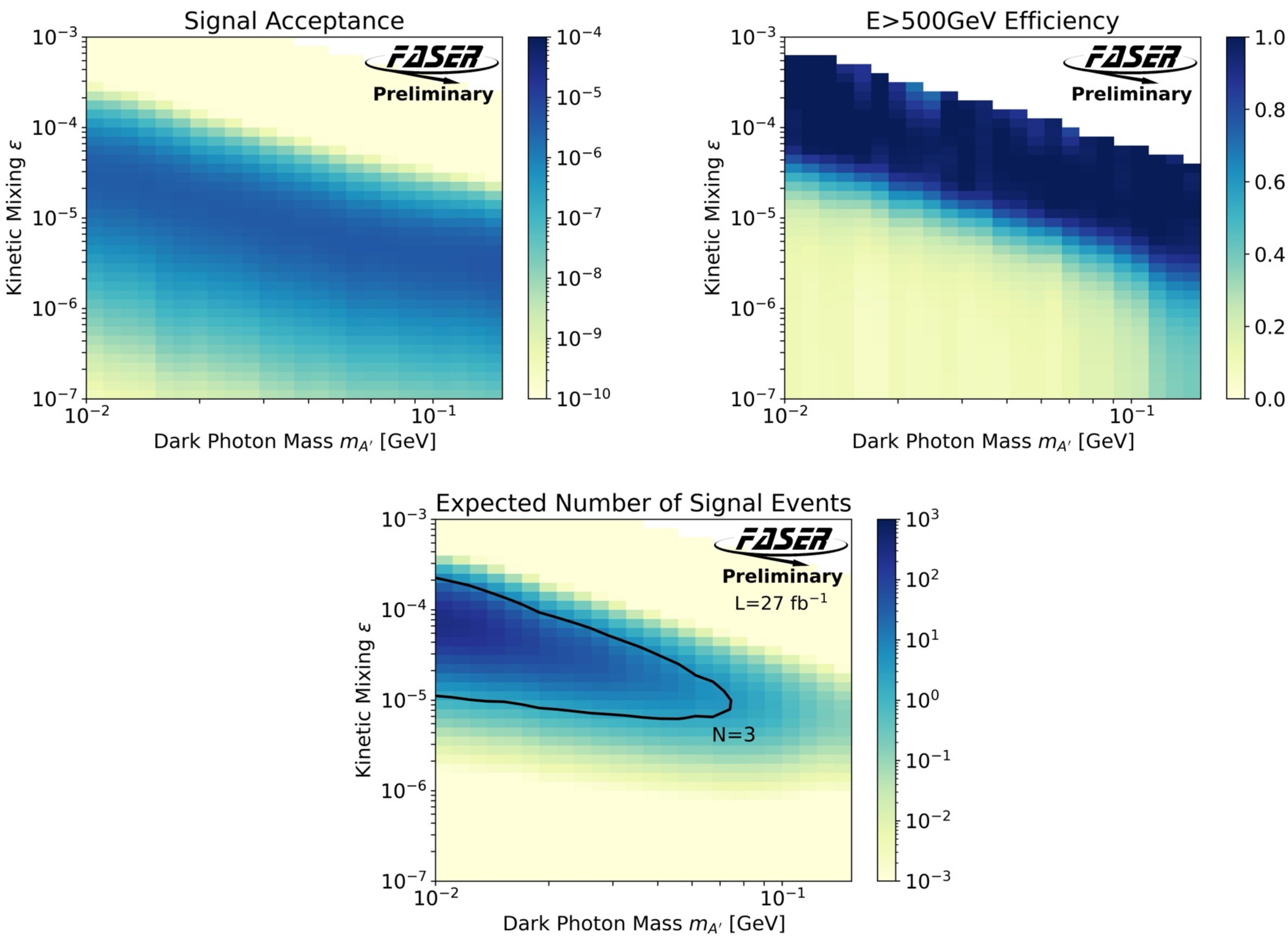
Expected number of neutrino events

Volume	Type	$0 < E_\nu < 500\,\text{GeV}$	$500 < E_\nu < 1000\,\text{GeV}$	$E_\nu > 1000\,\text{GeV}$	$\sum$	$\overline{E}_\nu$ [GeV]
FASERν	ν_μ	359 / 379	239 / 273	291 / 790	890 / 1442	880 / 1376
FASERν	$\bar{\nu}_\mu$	116 / 130	62 / 85	49 / 151	227 / 367	657 / 1028
$r < 95\,\text{mm}$	ν_μ	147 / 154	105 / 118	141 / 375	394 / 647	943 / 1477
$r < 95\,\text{mm}$	$\bar{\nu}_\mu$	48 / 53	28 / 37	23 / 67	99 / 157	687 / 1057

Alignment

Data-driven alignment corrections are applied to the positions and orientations of the modules of the tracking spectrometer stations using a sample of reconstructed muons. In the case of perfect alignment of the FASER tracking detectors, we expect a momentum resolution of 2.1% at 100 GeV, 4.7% at 300 GeV, and 16.4% at 1 TeV. The accuracy of the alignment is validated using a photon conversion sample for momenta up to 250 GeV.

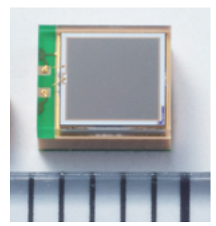
		Efficiency `Genie` [%]	Efficiency data [%]
Timing	colliding BCID good time range	–	100.0
Trigger	triggered by veto, trigger or pre-shower scintillator	–	100.0
FASERν veto station	charge in both layers $< 40\,\mathrm{pC}$	72.5	–
Veto station	charge in both downstream layers $> 40\,\mathrm{pC}$	100.0	98.9
Trigger station	total charge of modules hit by track $> 20\,\mathrm{pC}$	100.0	99.9
Pre-shower station	charge in both layers $> 2.5\,\mathrm{pC}$	99.3	99.9
Calorimeter	charge $> 0.1\,\mathrm{pC}$ for runs without optical filters or with high gain configuration	–	96.1
Tracker	exactly one long track	95.1	99.9
	≥ 12 hits on track	93.7	97.0
	$\chi^2/\mathrm{nDoF} < 15$	91.9	94.3
	$p > 100\,\mathrm{GeV}$	75.8	54.9
	$r < 95\,\mathrm{mm}$ in all tracking stations (extrapolation to IFT)	46.5	56.8
	$r < 120\,\mathrm{mm}$ at FASERν veto scintillator	50.7	62.8
	$\theta < 25\,\mathrm{mrad}$	86.1	95.7
Combined		28.7	34.2



Signal Acceptance
FASER
Preliminary
Kinetic Mixing ε
Dark Photon Mass $m_{A'}$ [GeV]
E>500GeV Efficiency
FASER
Preliminary
Kinetic Mixing ε
Dark Photon Mass $m_{A'}$ [GeV]
Expected Number of Signal Events
FASER
Preliminary
L=27 fb^{-1}
N=3
Kinetic Mixing ε
Dark Photon Mass $m_{A'}$ [GeV]

FPF Experiments

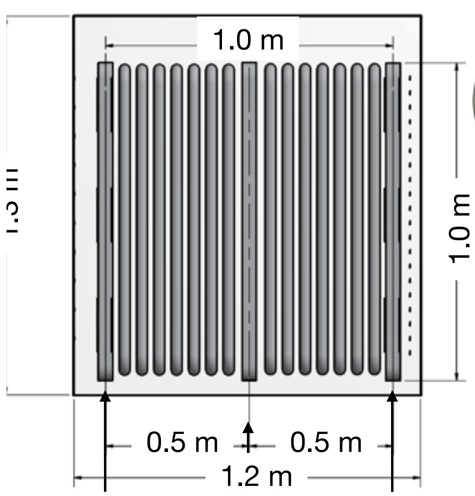
FLArE Detector Preliminary Sketch

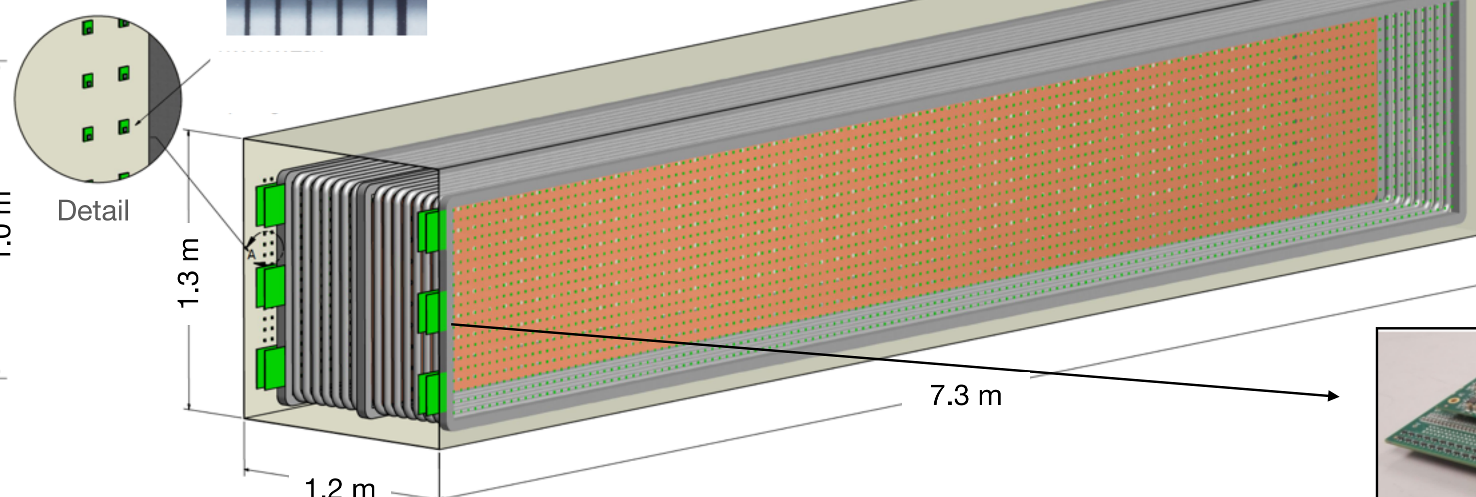


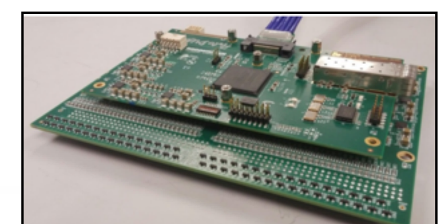
Hamamatsu
S14160 SiPM
6x6 mm
2800 units

Volume	11.5 m^3
LAr	16 ton
LKr	27.5 ton
menbran	0.5 m
heat loss	290 W

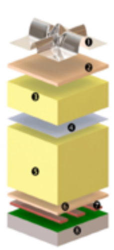
TPC-side view 2



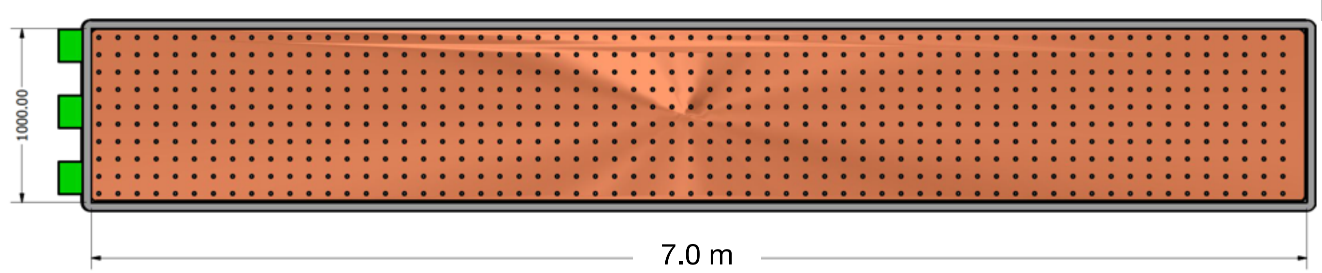




DUNE Front End Motherboard



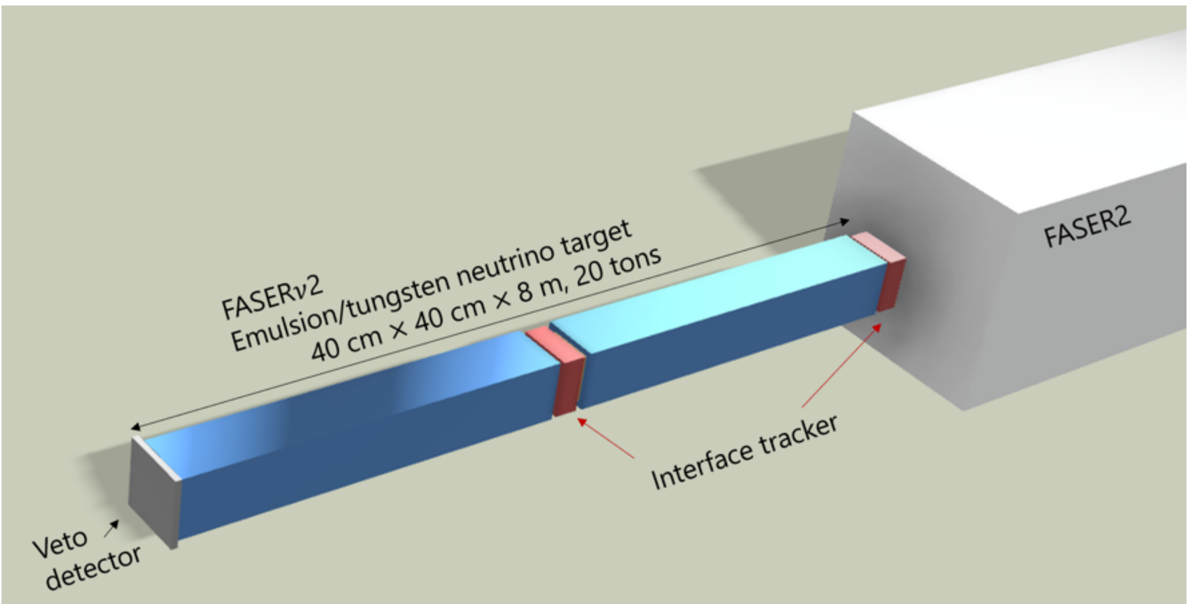
Cryostat Insulation



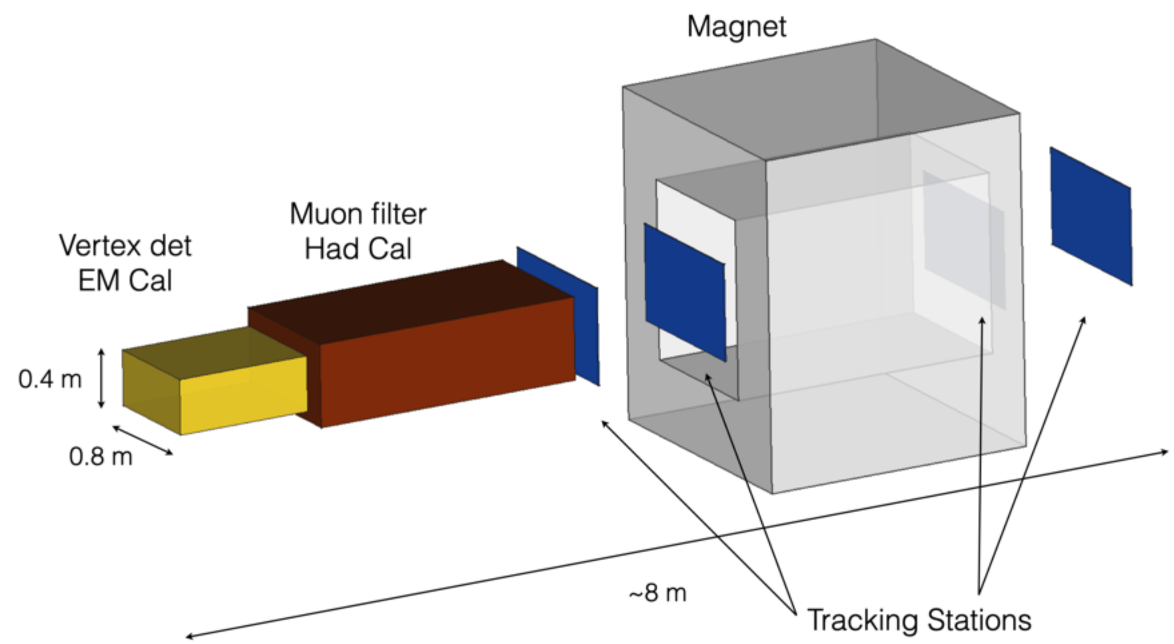
TPC anode plane -side view 1

FPF Experiments

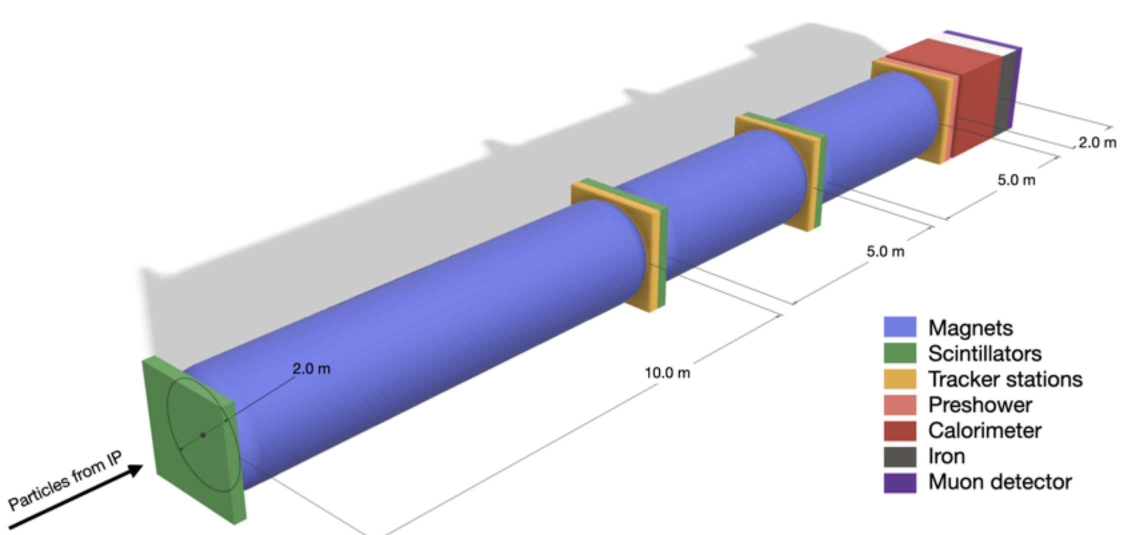
FASERν2



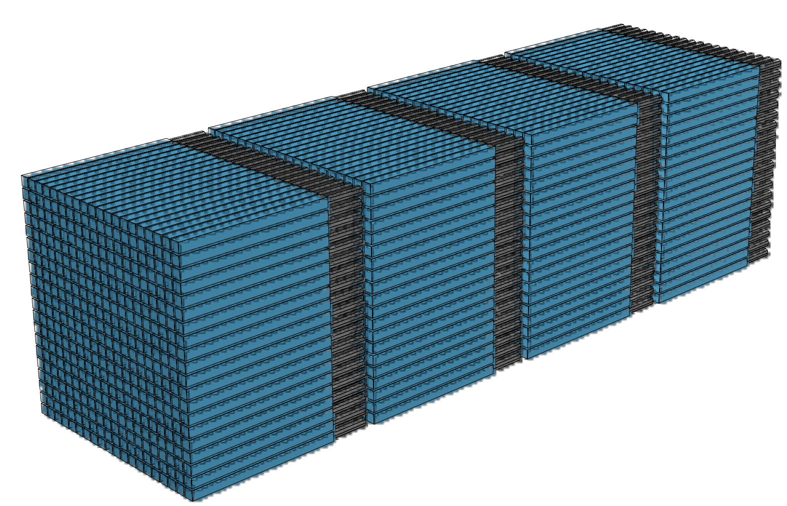
AdvSND



FASER

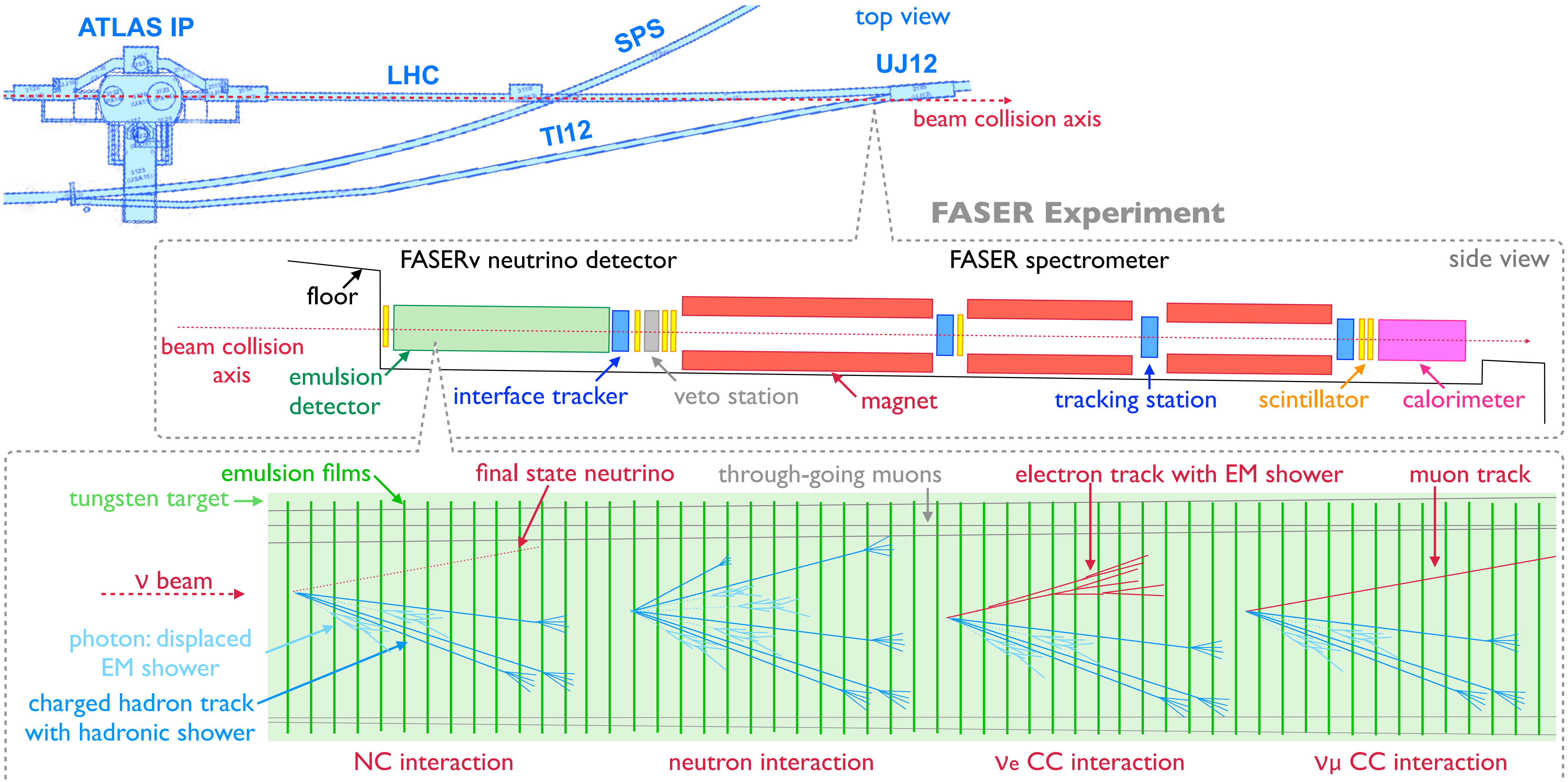


FORMOSA



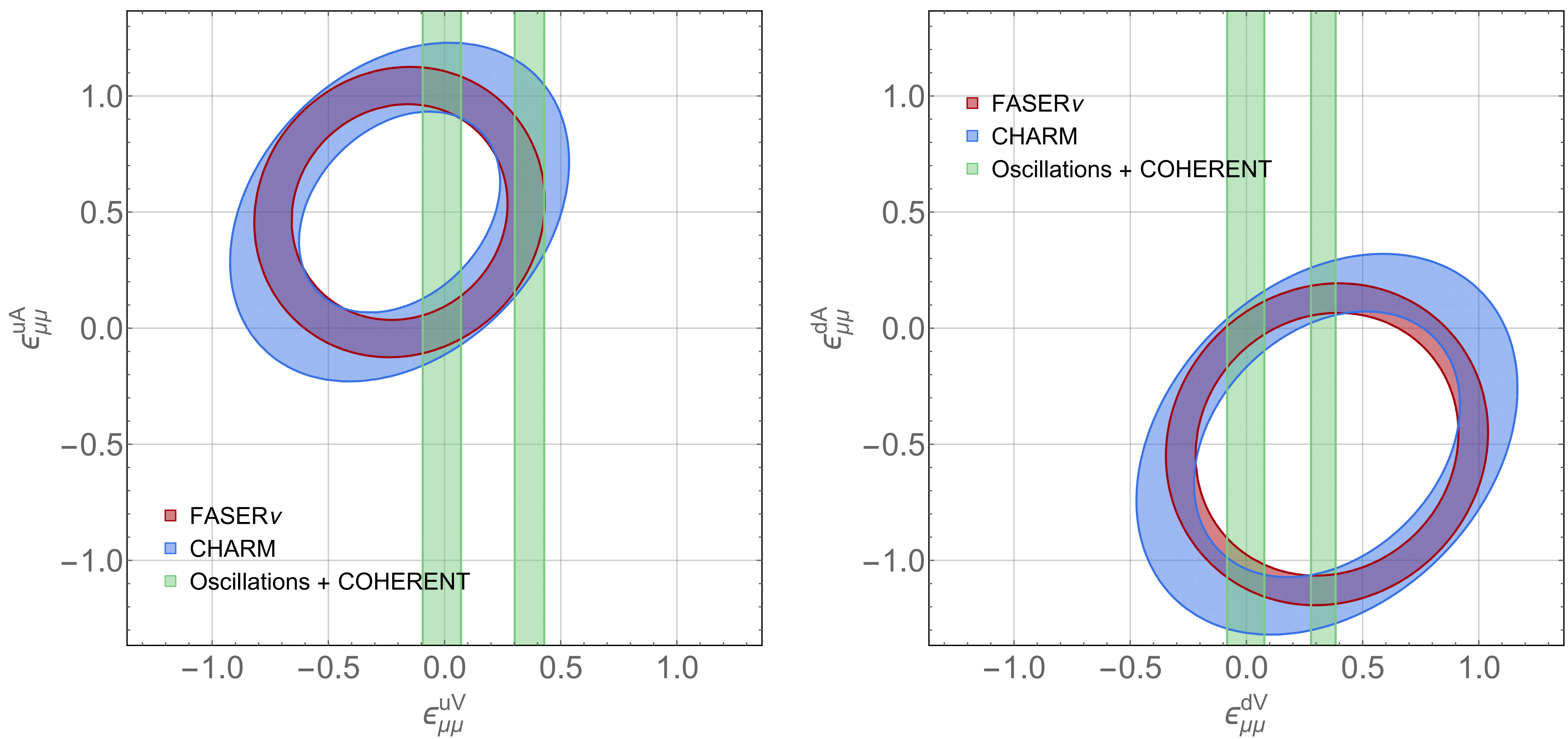
FASER NC Sensitivity

Feasibility explored in https://arxiv.org/pdf/2012.10500.pdf

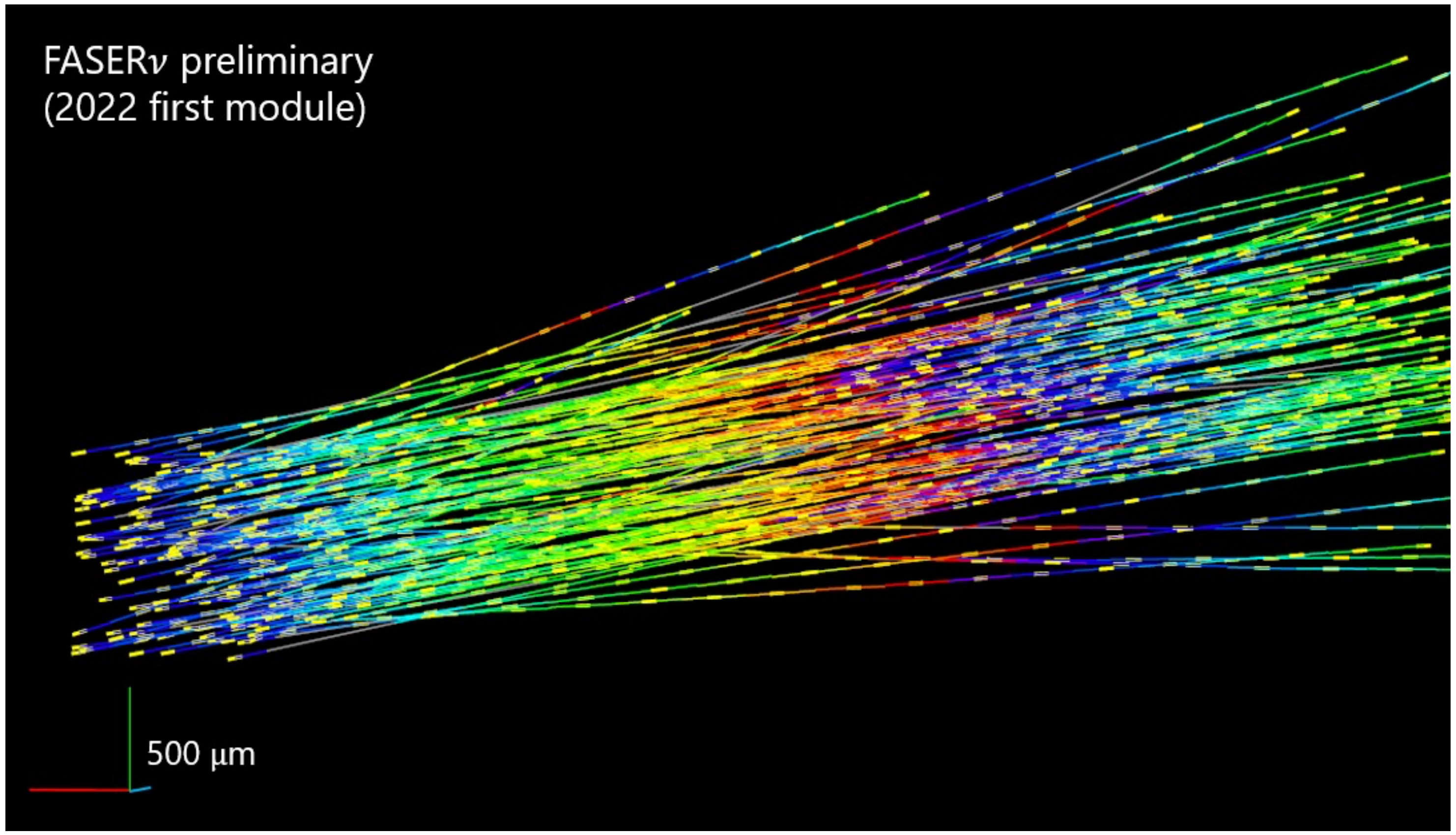


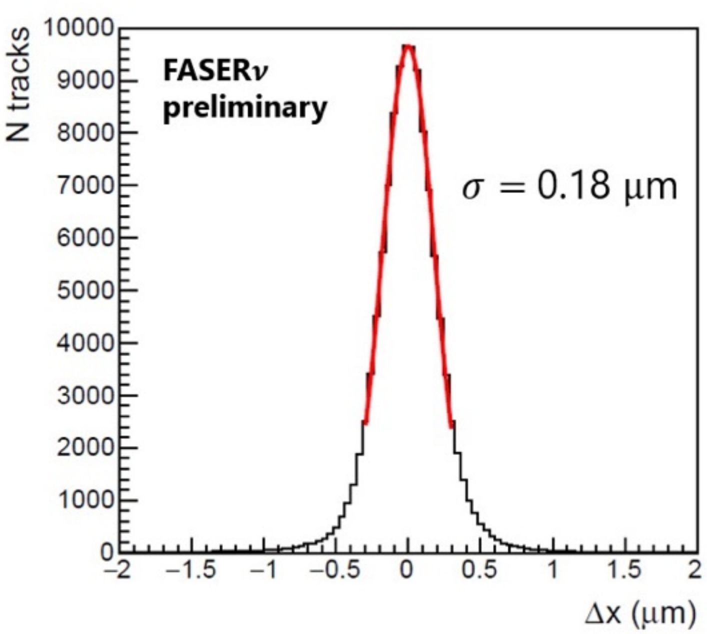
FASER NC Sensitivity

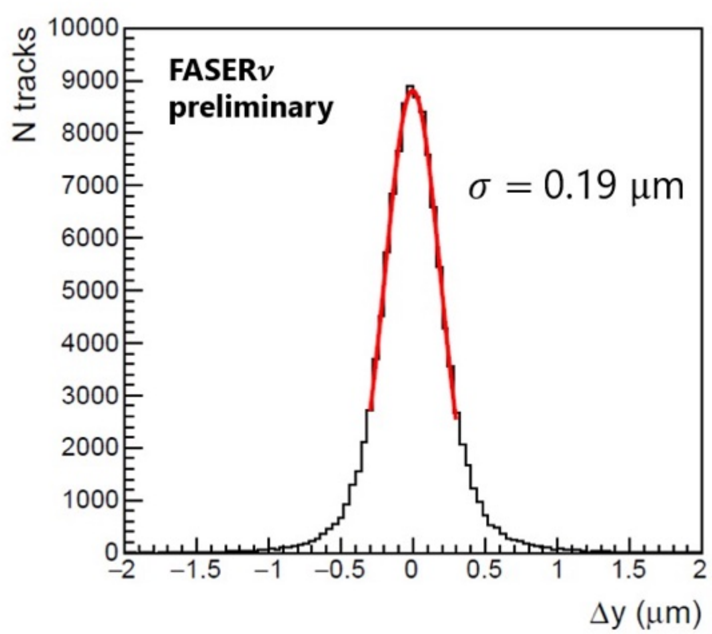
$$\mathcal{L} \supset -\sqrt{2}G_F \sum_{f,\alpha,\beta} [\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta][\epsilon^{f,V}_{\alpha\beta} \bar{f}\gamma_\mu f + \epsilon^{f,A}_{\alpha\beta} \bar{f}\gamma_\mu \gamma^5 f]$$



FASERν Detector Performance







1st **FASERν** detector installed for first 4 weeks of data taking, recording about 0.5/fb of data

Used to commission the assembly, development and scanning reconstruction, analysis chain.

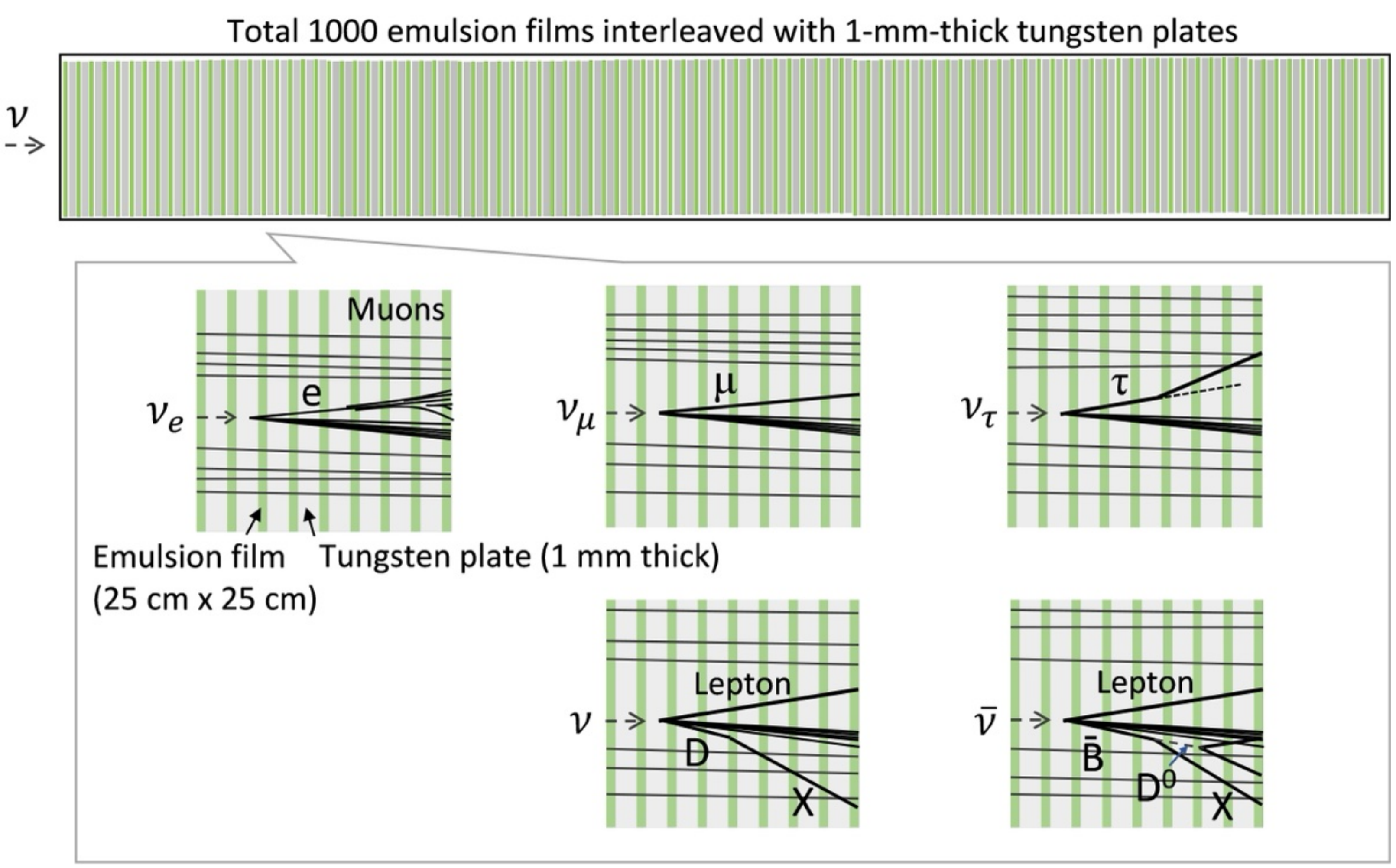
Measured track multiplicity:
ca. 10^4 cm^{-2} / fb^{-1}

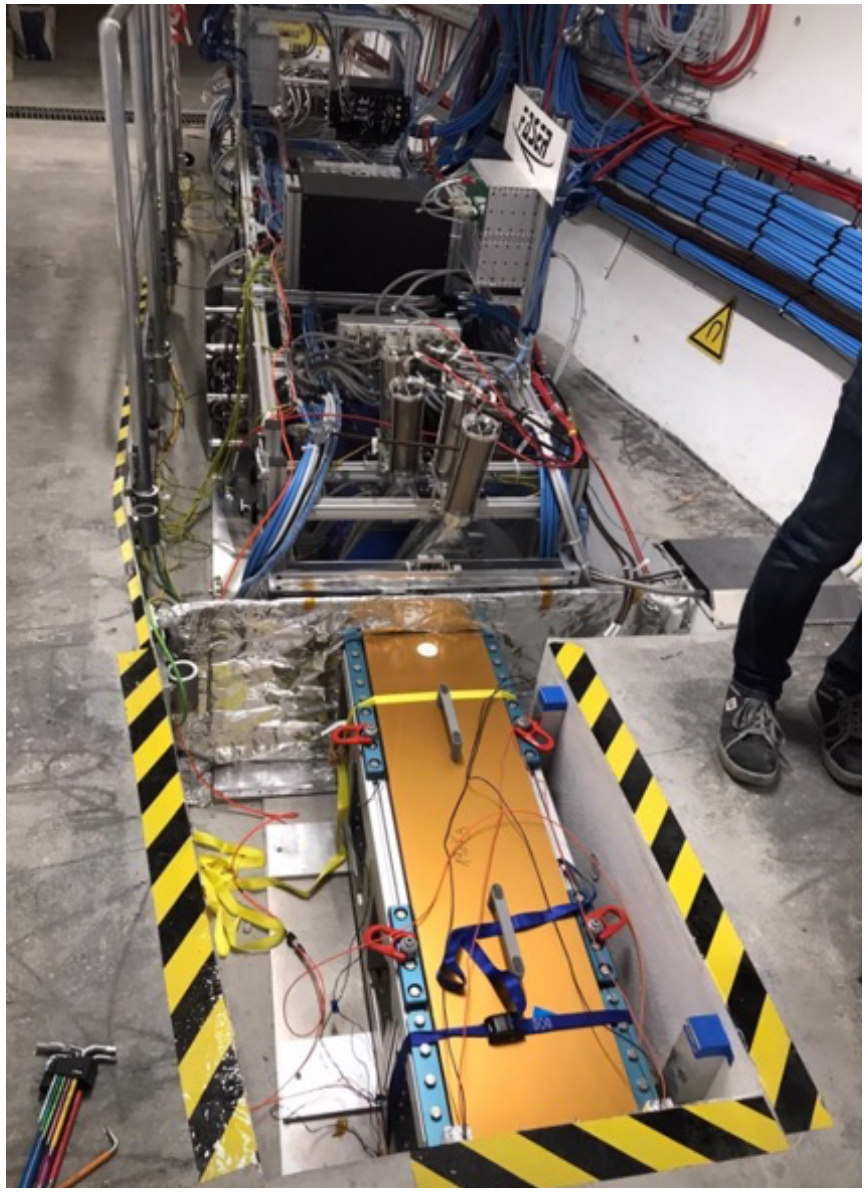
Very good tracking performance.

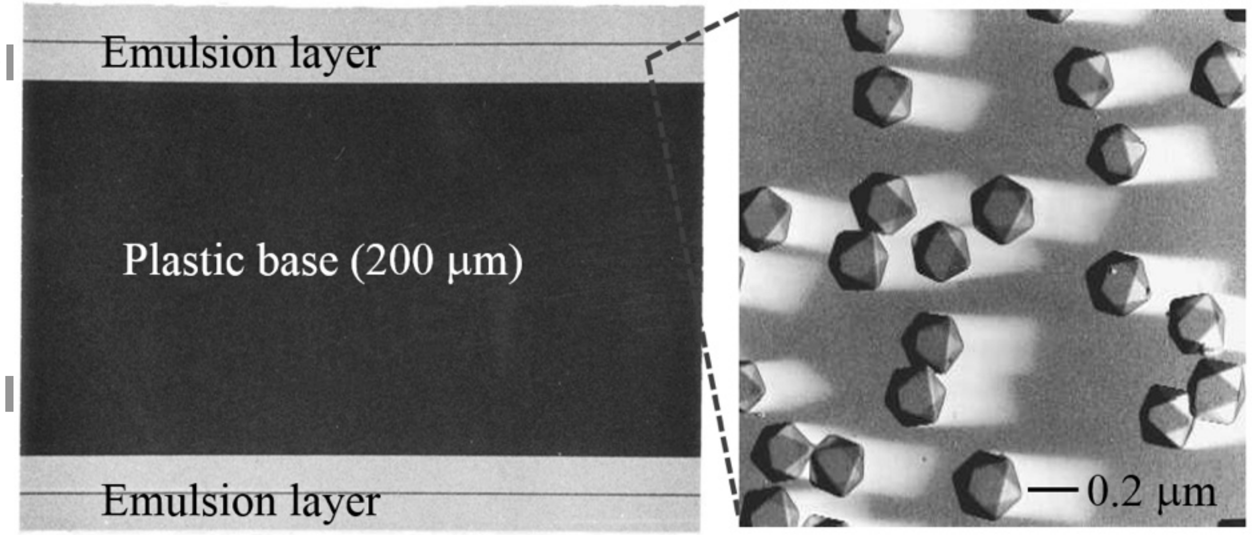
Two other **FASERν** detectors collected ca. **10 and 30/fb** of data with about 2000 neutrino interactions → **Analysis in progress**

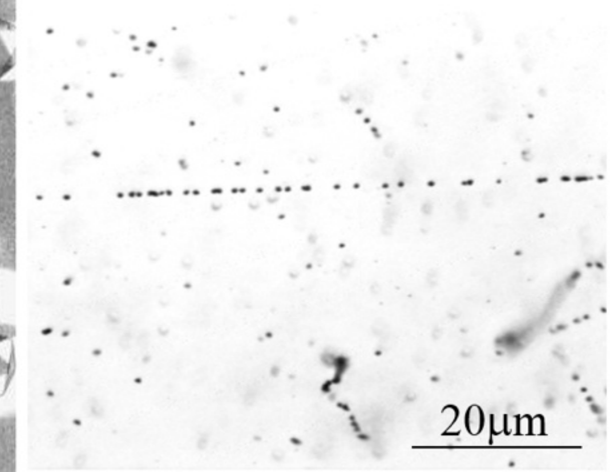
Can **distinguish flavors** using the emulsion films excellent position / angular resolution for charged particles.

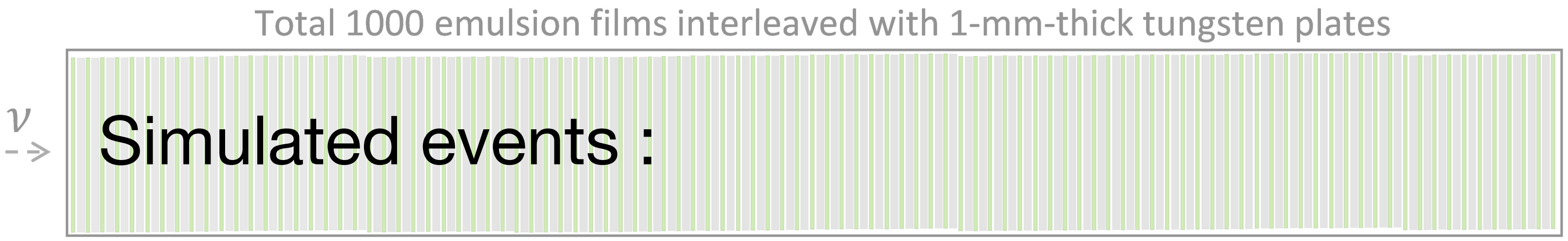
Detector **needs** to be **replaced** every ca. **30/fb** to keep track multiplicity manageable



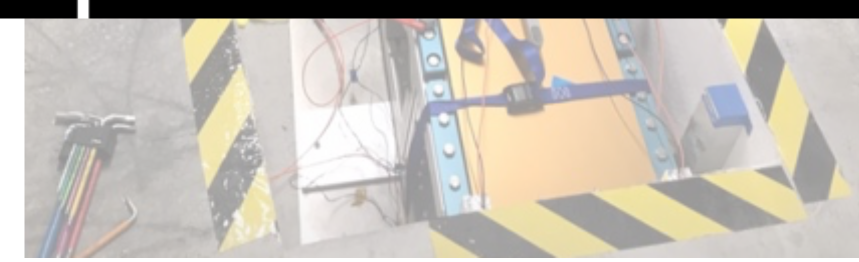


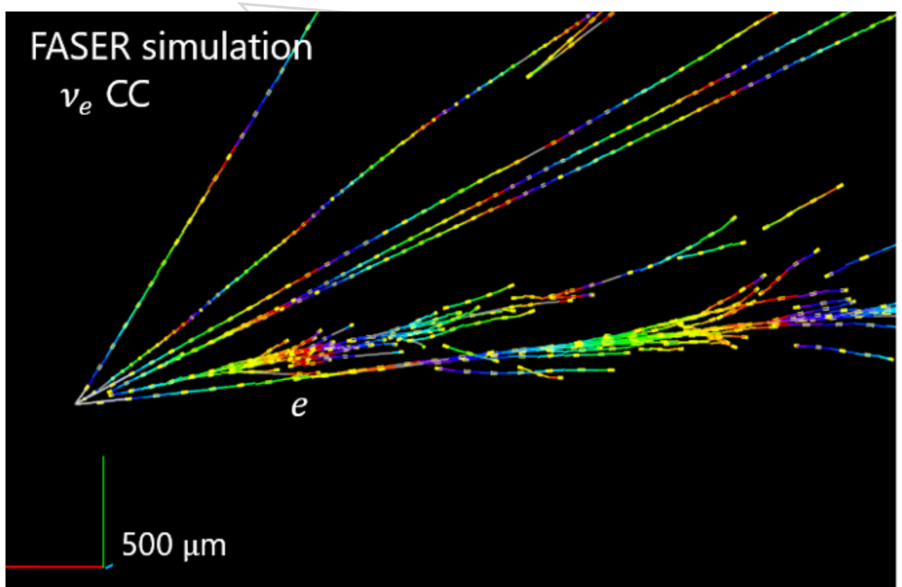


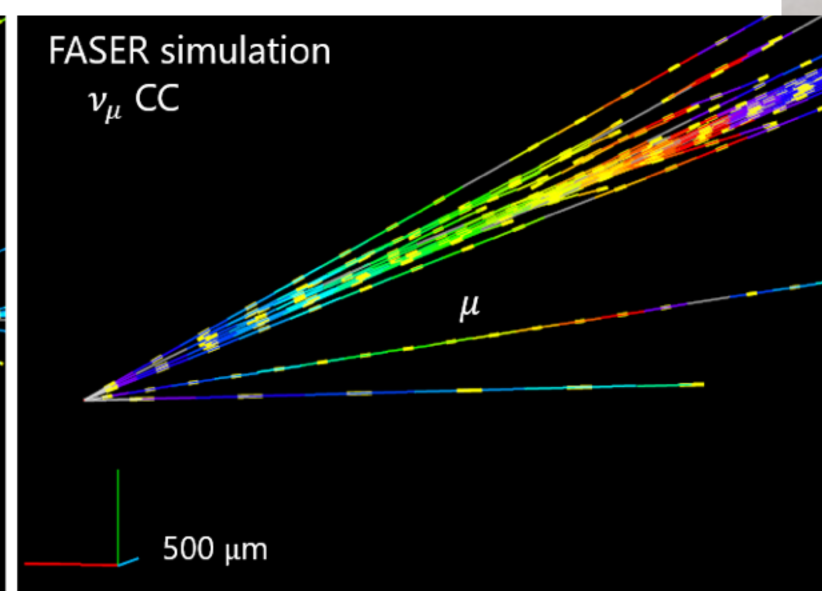


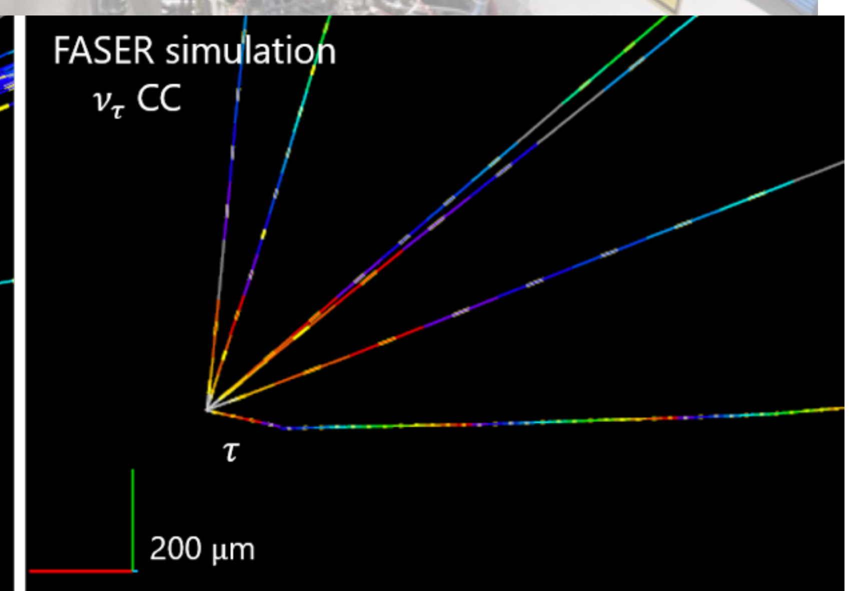


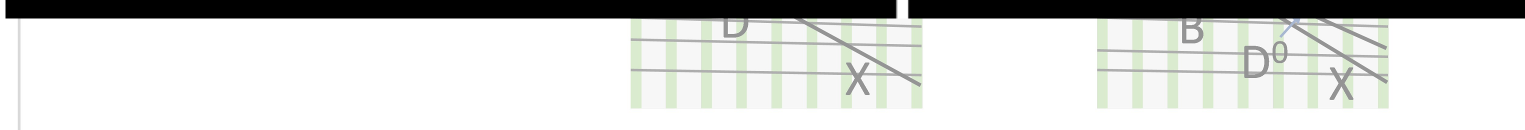
Simulated events :



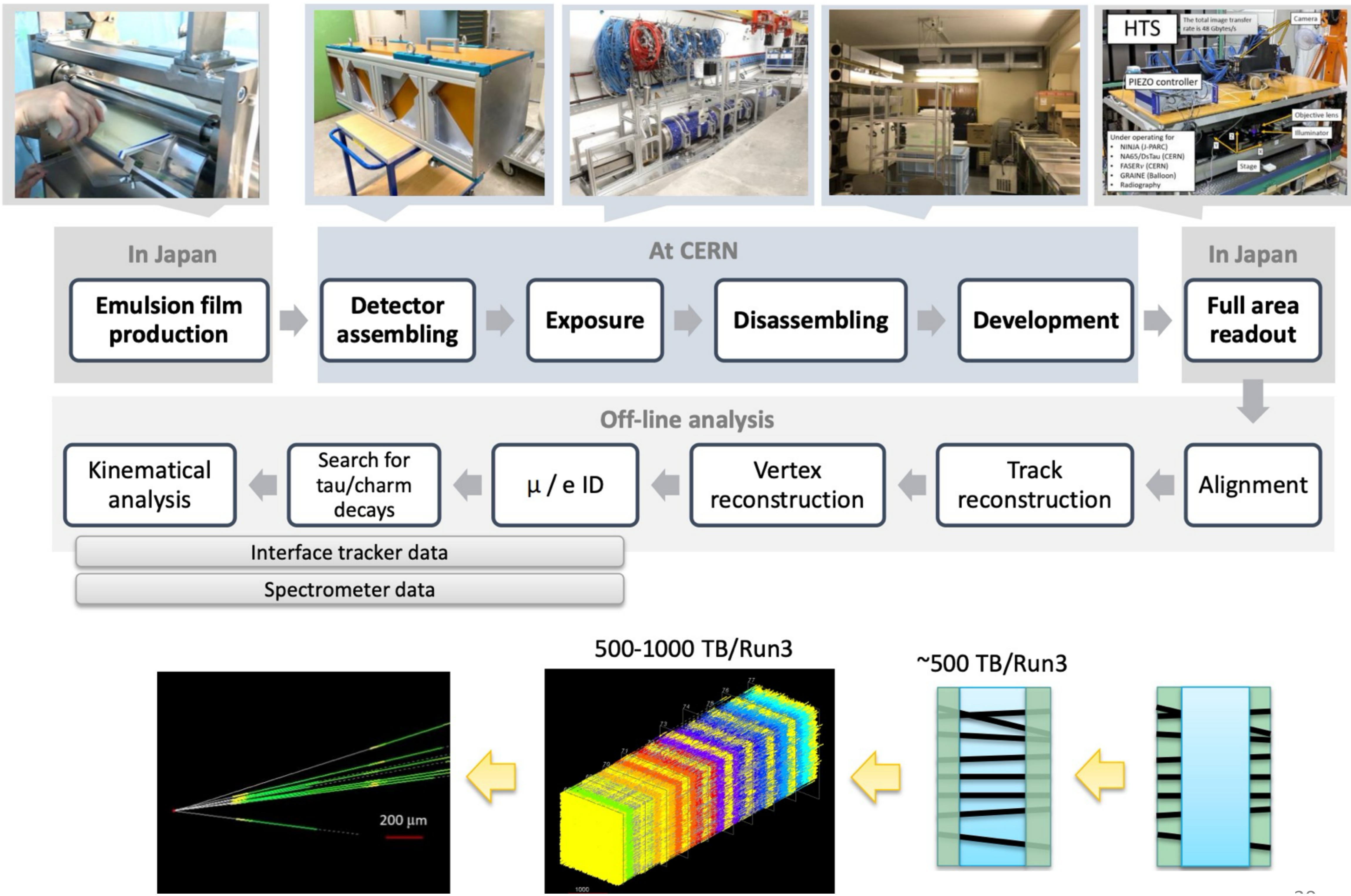








FASERν Workflow



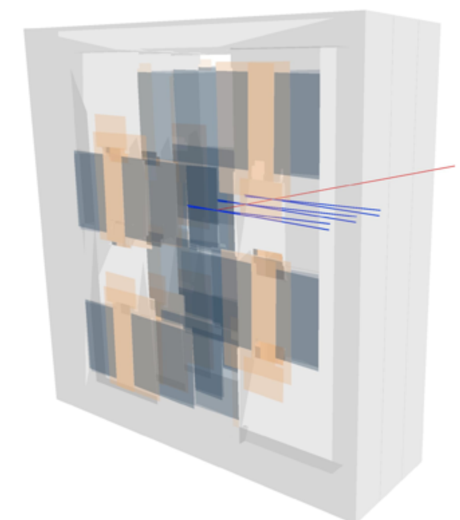
First Collision Muon Event

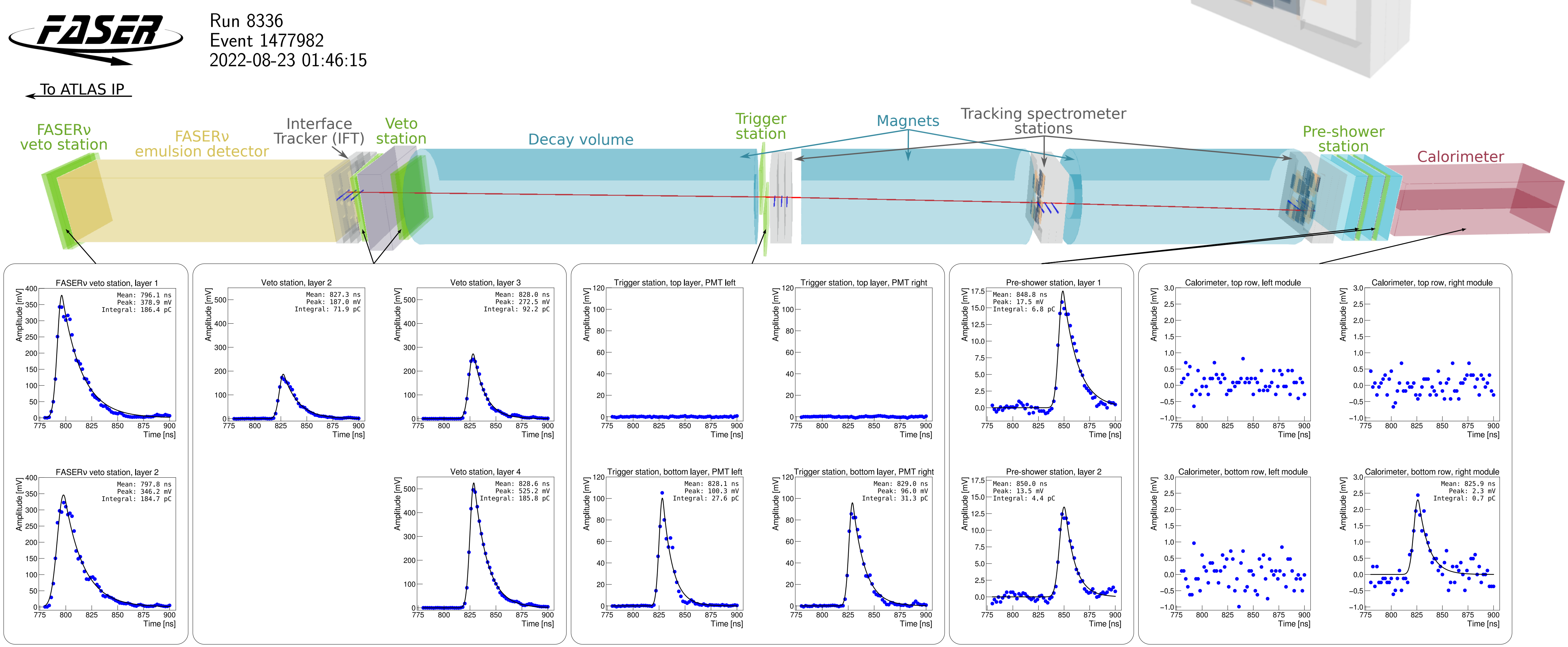
August 23, 2022 @ 01:46 :

1st collision muon traverses FASER with **momentum** of **21.6 GeV**

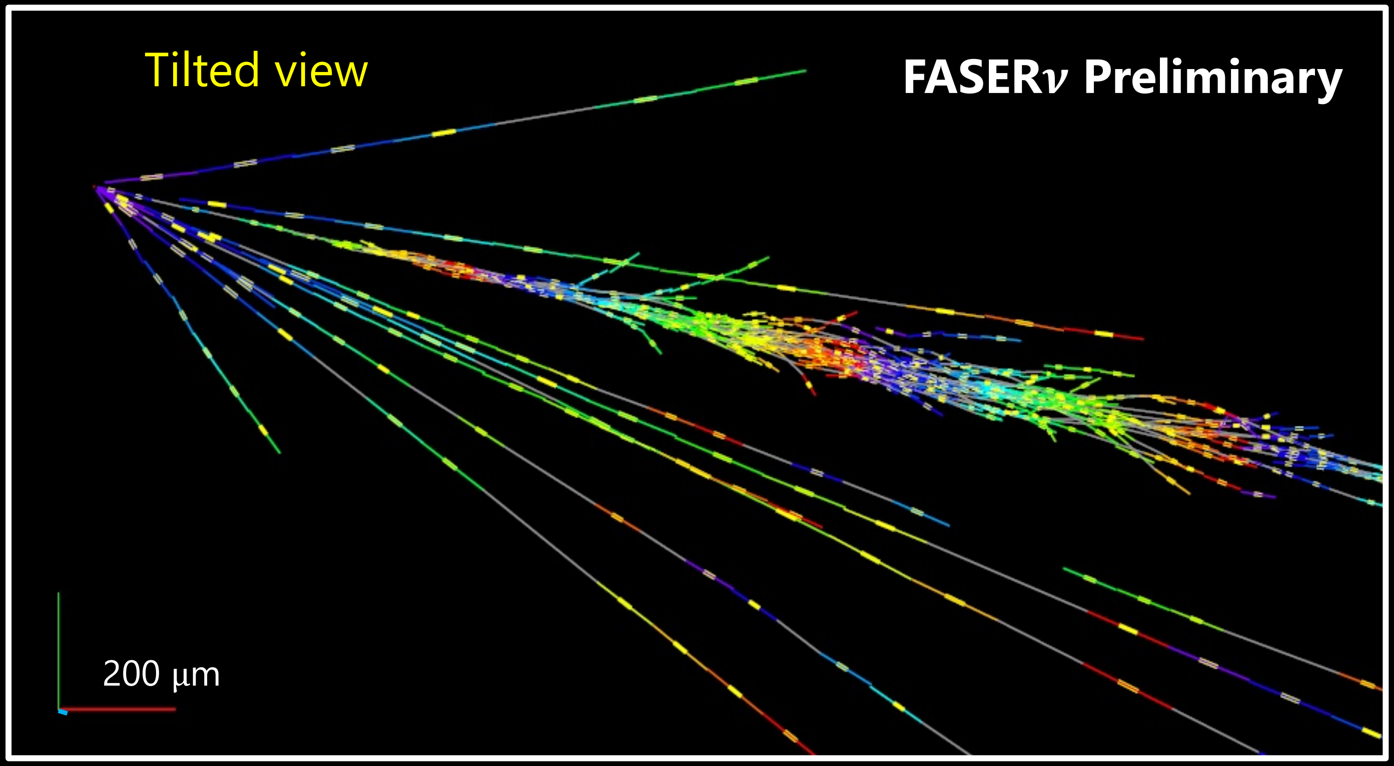
→ Signal consistent with MIP seen in all scintillators and calorimeter

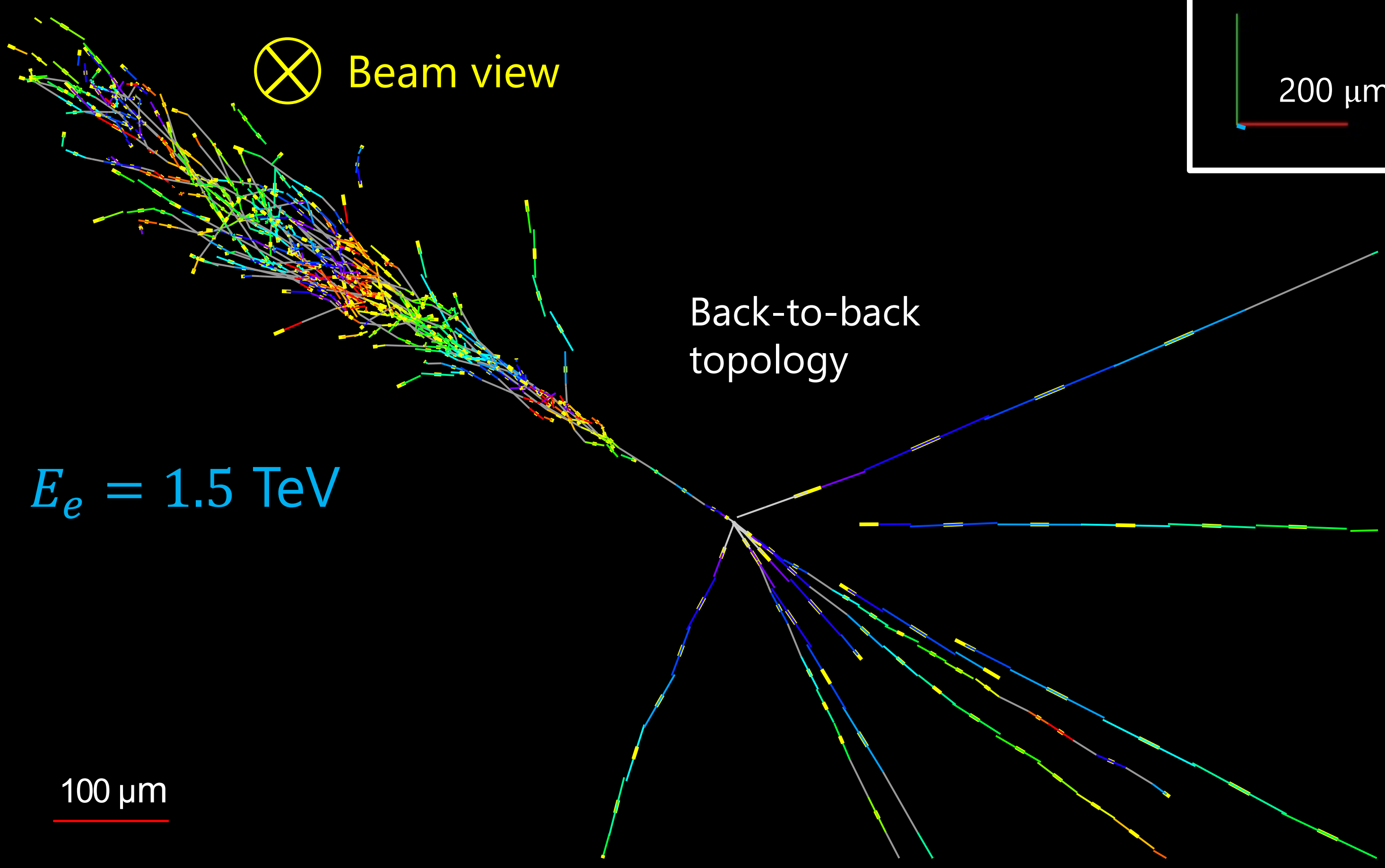
Zoom in 1st tracking station





New results from FASERν: one of the ν_e CC candidates



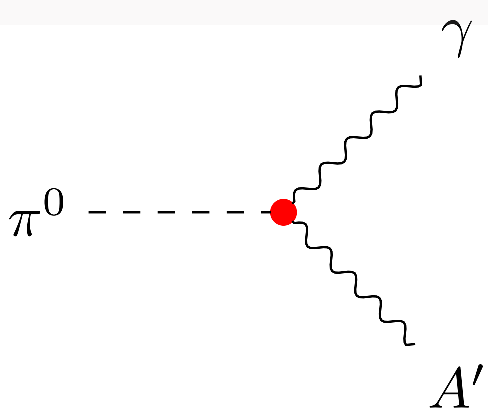


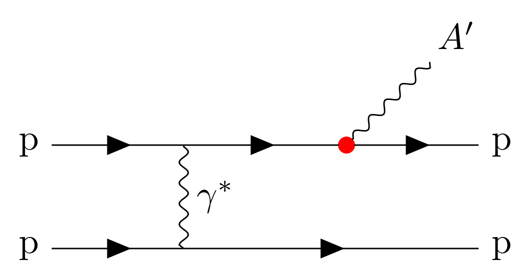
- 11 tracks at the vertex, 615 µm inside tungsten
- e-like track from vertex
- Single track for 2 X_0
- Shower max at 7.8 X_0
- 175° between e-like track and others
- $\theta_e = 11$ mrad w.r.t. beam

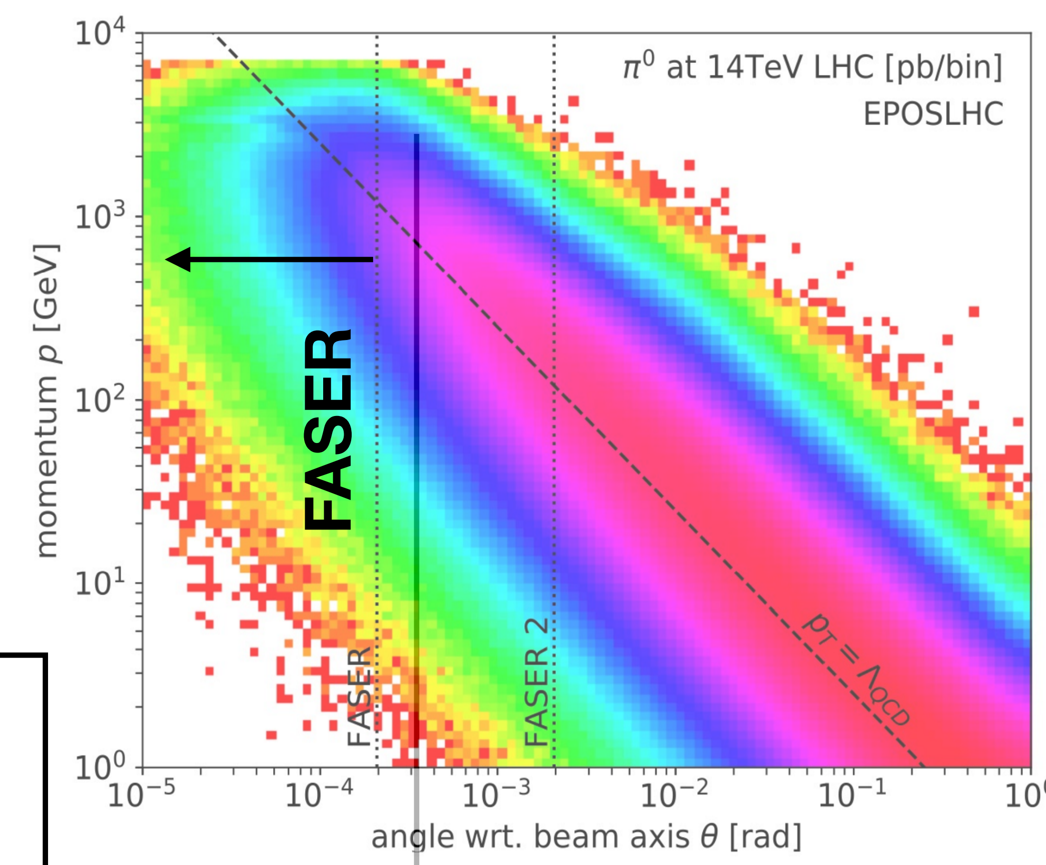
FASER LLP Physics Program :

FASER is sensitive to unprobed coupling / mass regions for **dark photons, ALPs, Neutral Heavy Leptons**

E.g. **Dark Photons** A' are mainly produced in decays of light mesons or via dark Bremsstrahlung







2 Aspects: decay length & angular coverage:

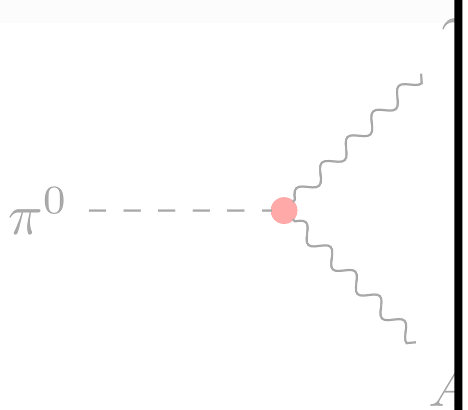
Decay length $\quad \bar{d} = 80\,\mathrm{m} \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{100\,\mathrm{MeV}}{m_{A'}}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right]$

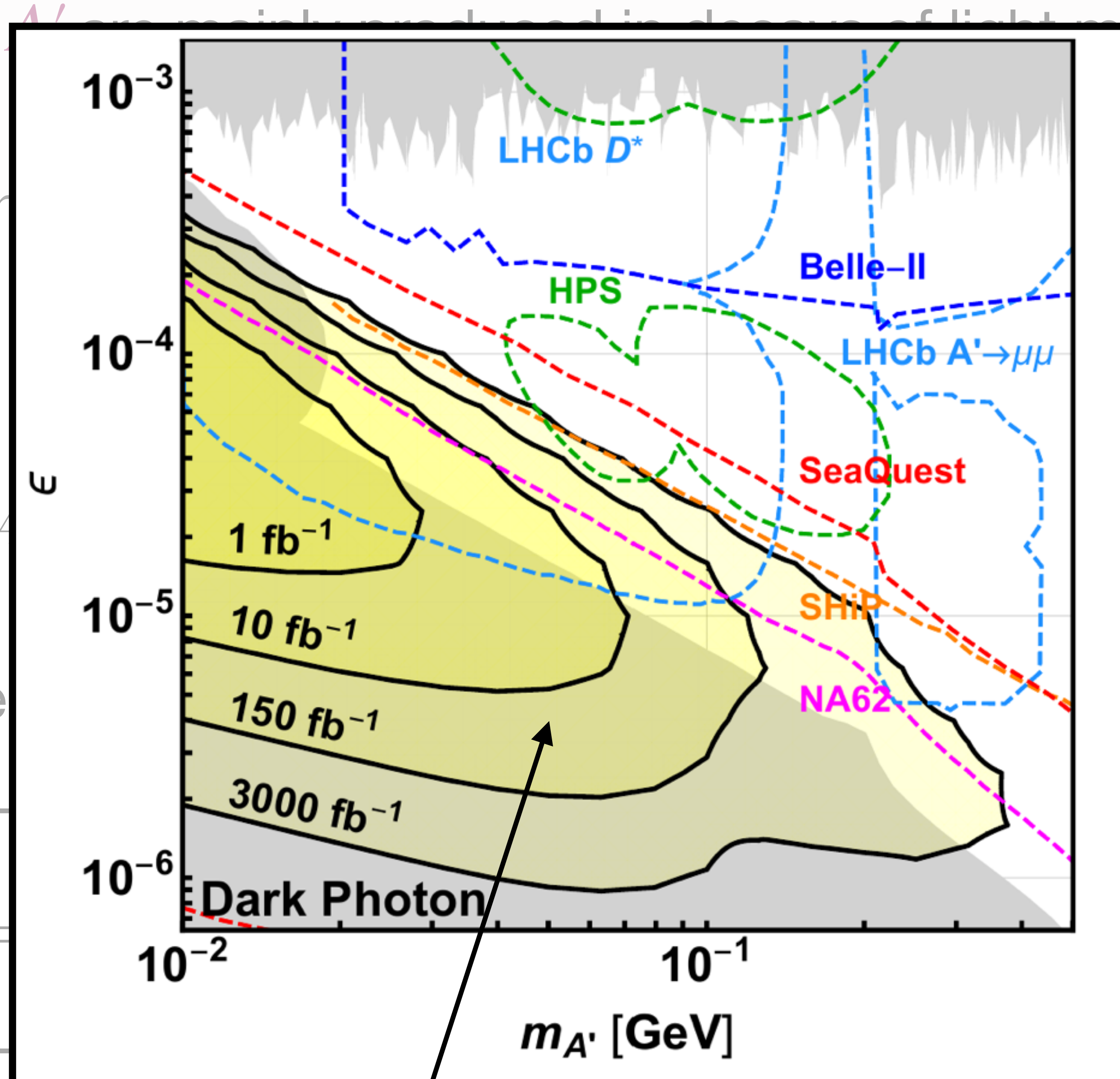
→ With just 10/fb of data FASER can explore new coupling / mass ranges

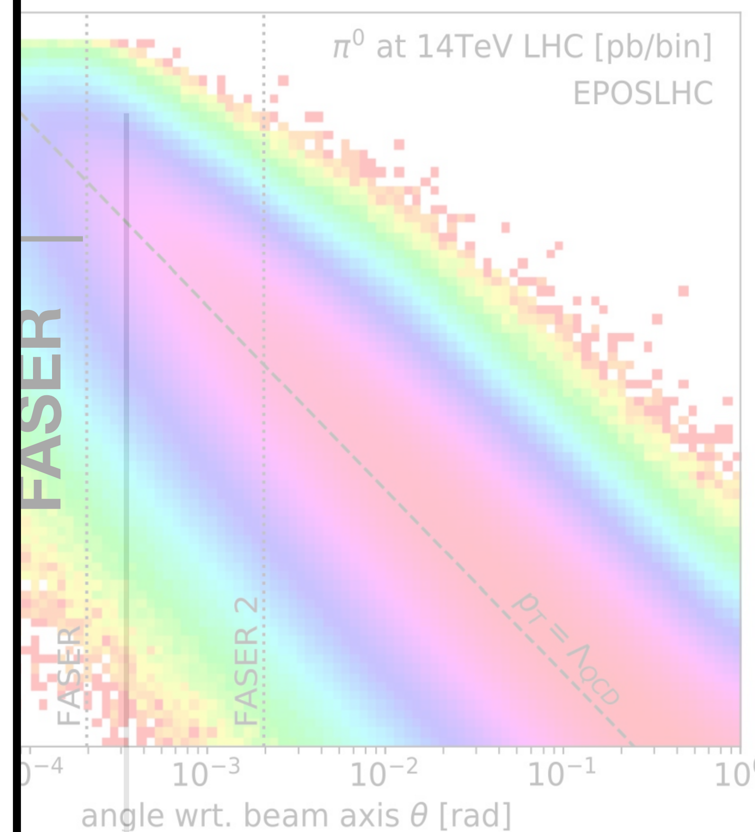
FASER LLP Physics Program :

FASER is sensitive to unprobed coupling / mass regions for **dark photons, ALPs, Neutral Heavy Leptons**

E.g. **Dark Photons** A' are mainly produced in decays of light mesons or via dark Bremsstrahlung







2 Aspects: decay le

Decay length $\bar{d}$ =

→ With just 10/fb of data FASER can explore new coupling / mass ranges