New Physics Results from the FASER Experiment

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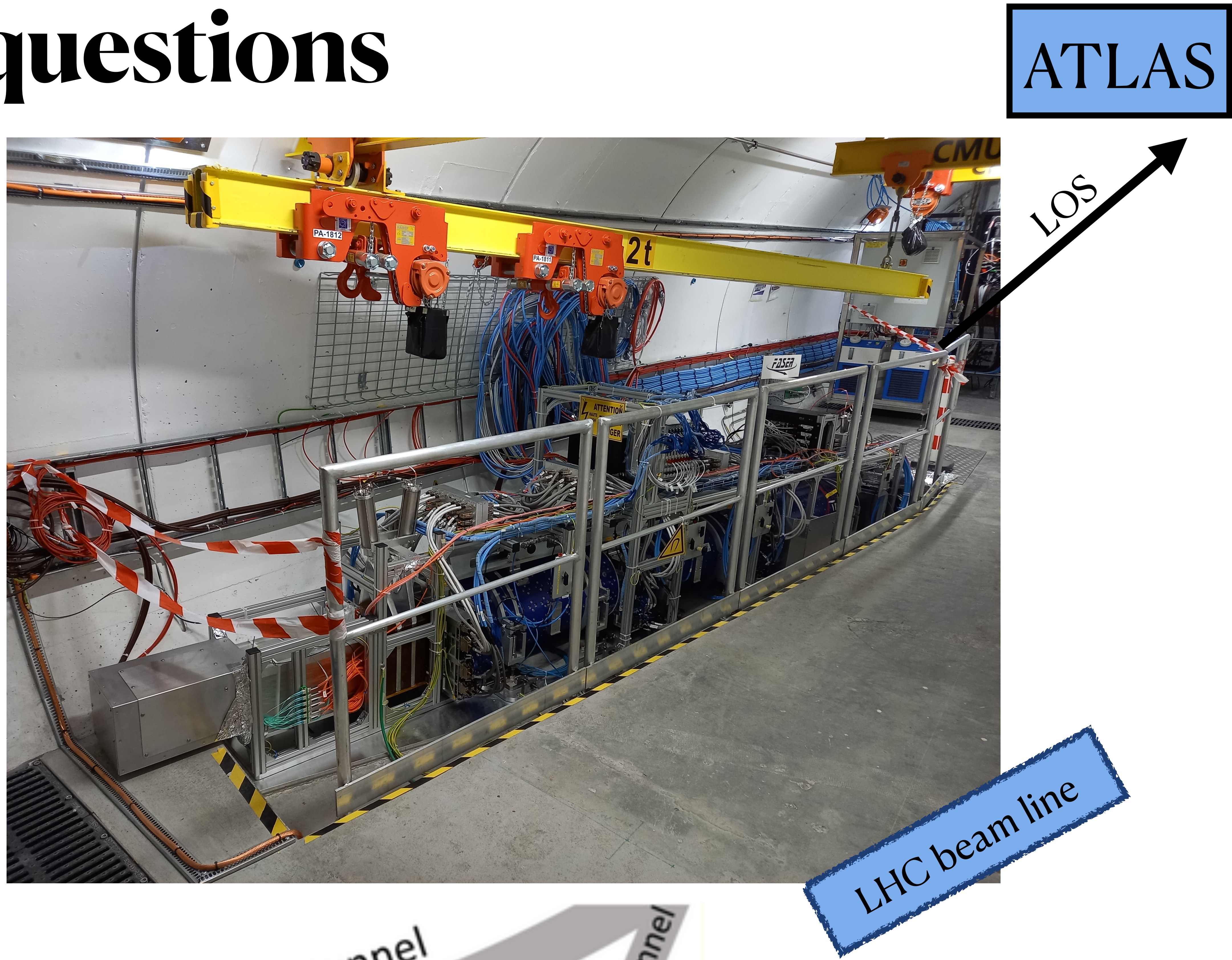
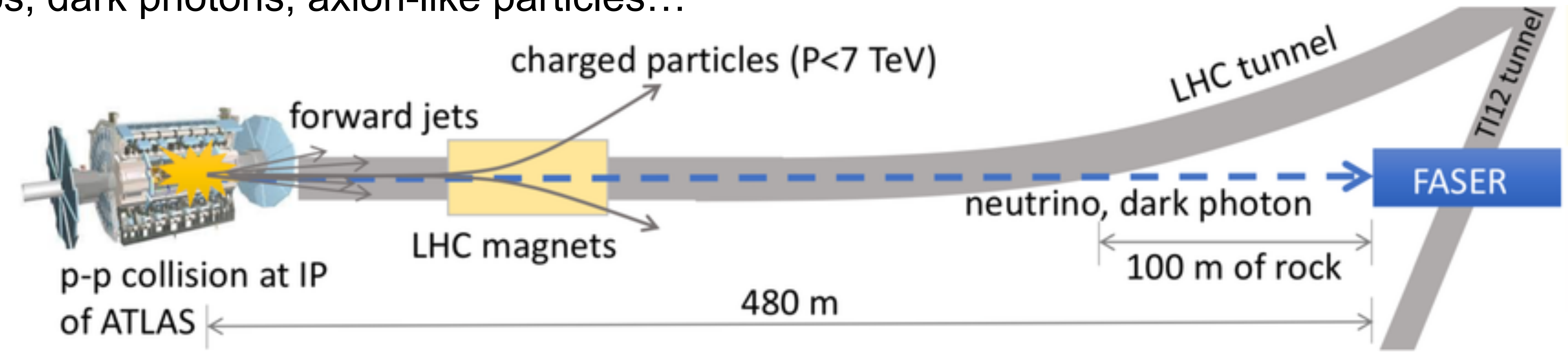
The FASER Detector

FASER - all the “w” questions

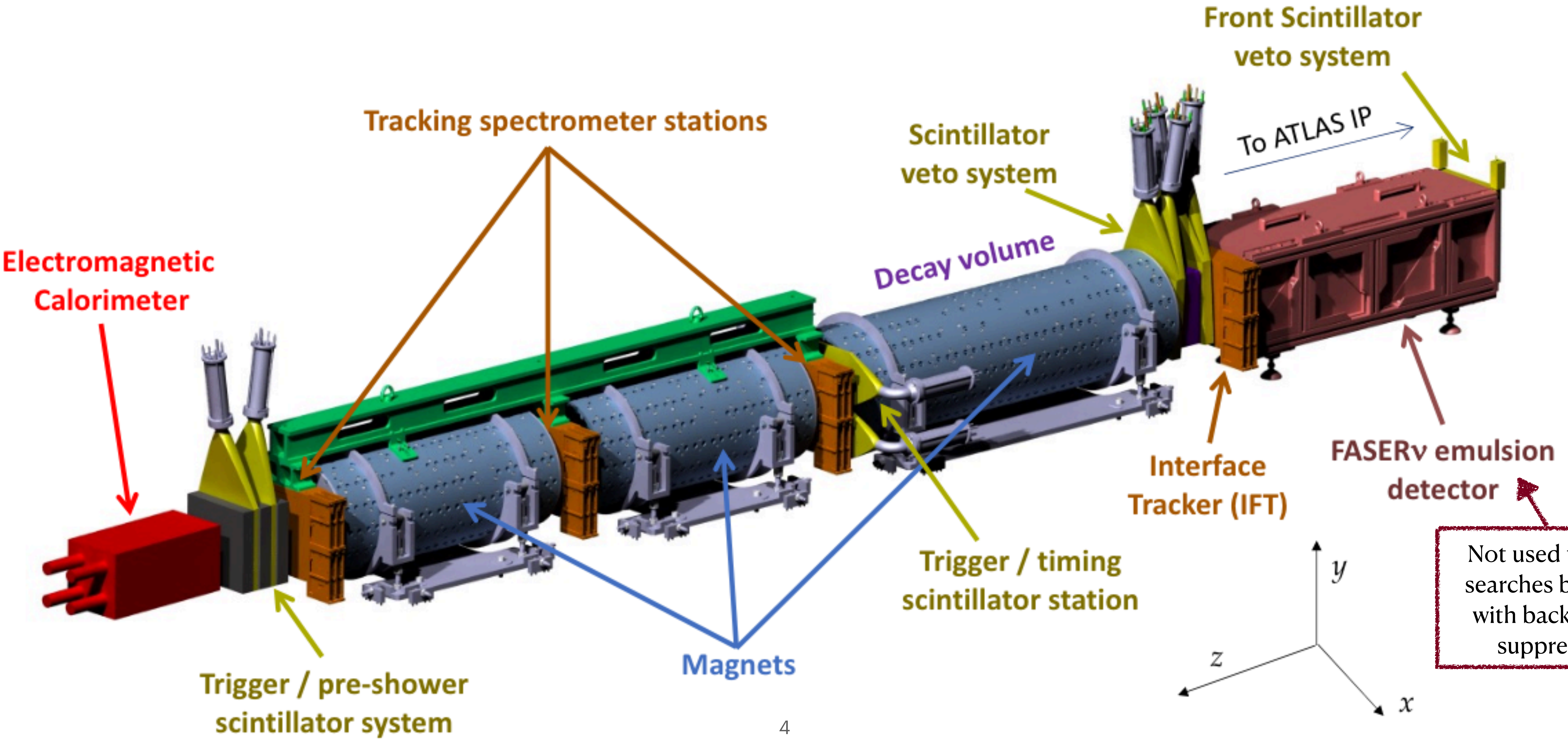
- **What/When/Who**: ForwArd Search ExpeRiment
  - Built between 2019 and 2021
  - Relatively small collaboration ~100 members from 27 institutions
- **Where**: Located 480 m from the ATLAS pp collision point
  - Aligned with ATLAS collision axis line of sight (LOS)
  - Receives very forward decay products (including neutrinos!) from ATLAS
  - Benefits - shielded by 100 m of rock
- **Why**: Designed to search for light, weakly interacting long-lived particles (LLPs)
  - Neutrinos, dark photons, axion-like particles…





arXiv 2207.11427

The FASER detector

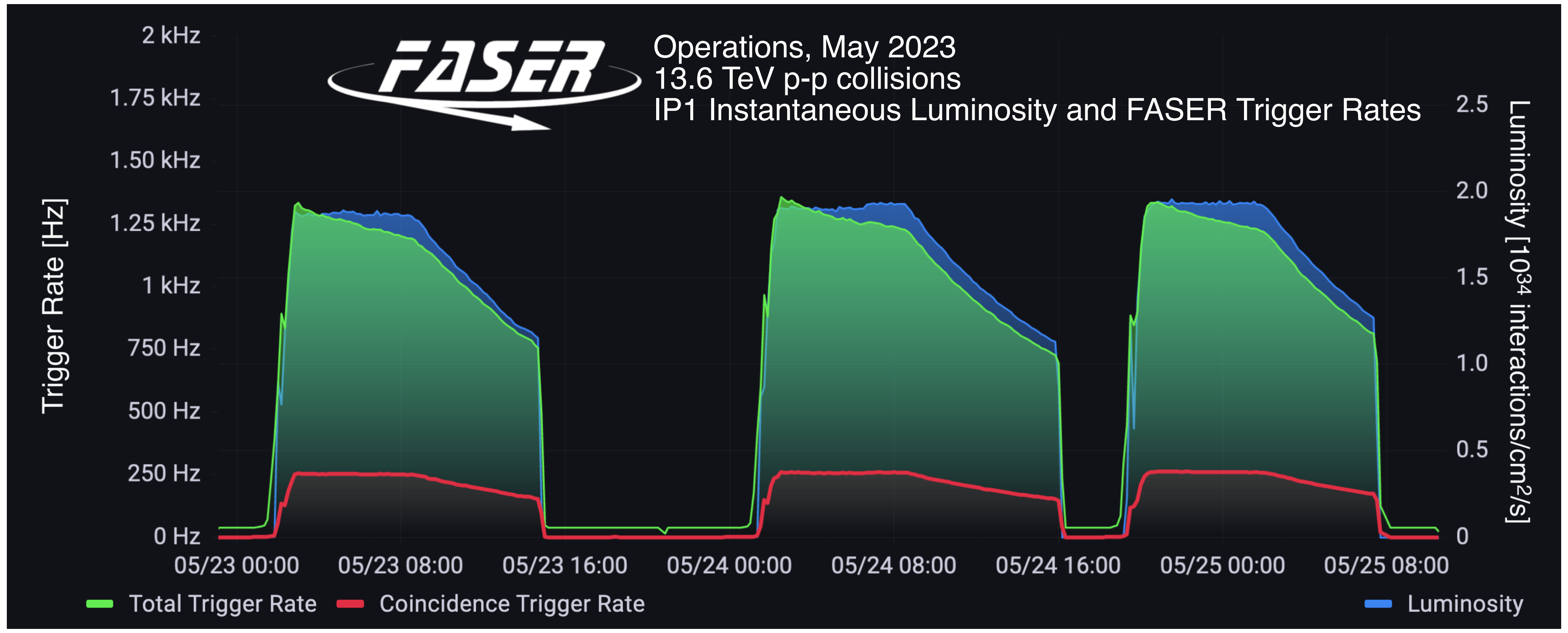


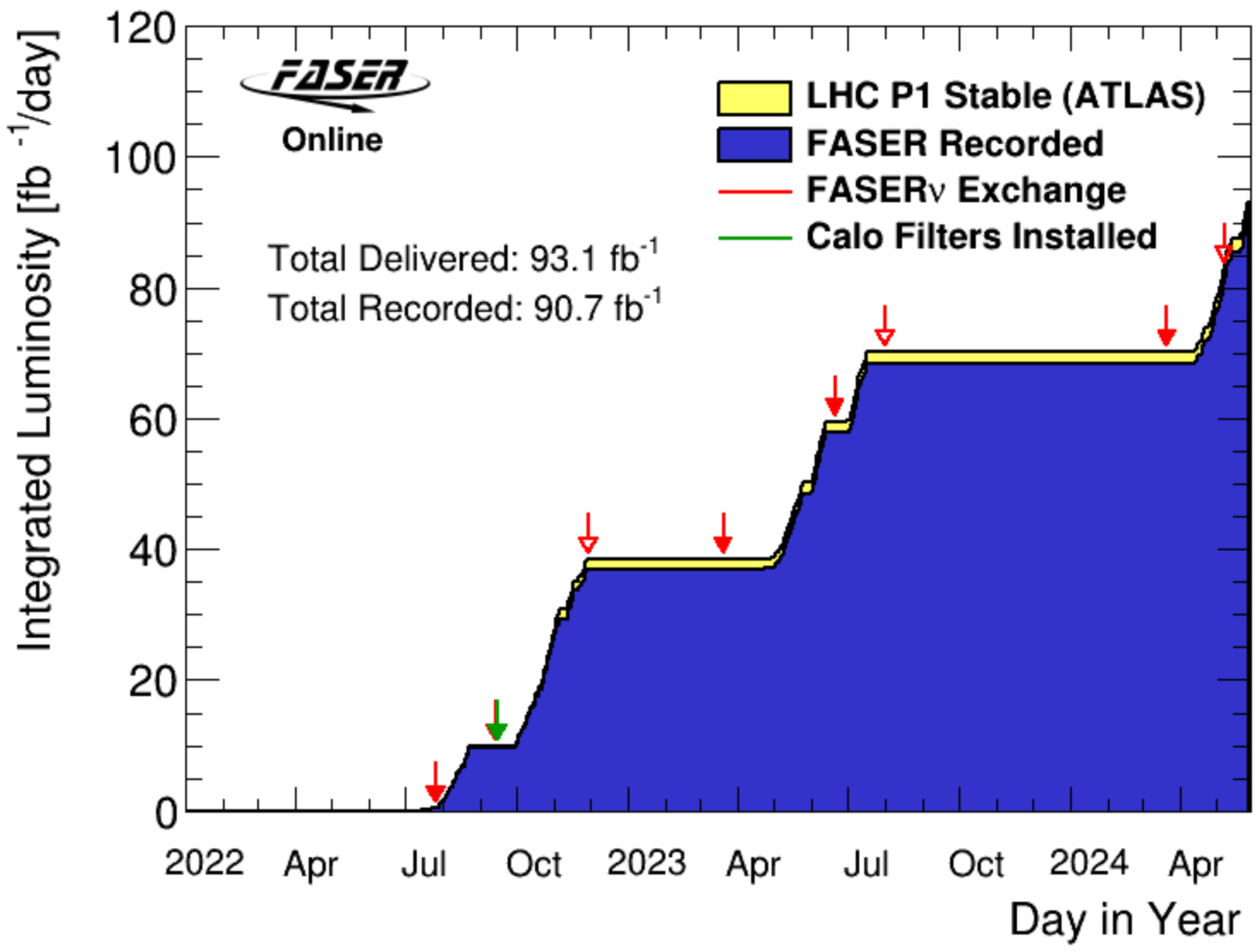
Not used for BSM searches but helps with background suppression

arXiv 2207.11427

FASER operations

- FASER running since soon after the start of Run 3 in 2022
- Recently crossed threshold of 100 fb^{-1} delivered to the FASER experiment since start of running!
- FASER deadtime < 3%
- Luminosity information provided by ATLAS



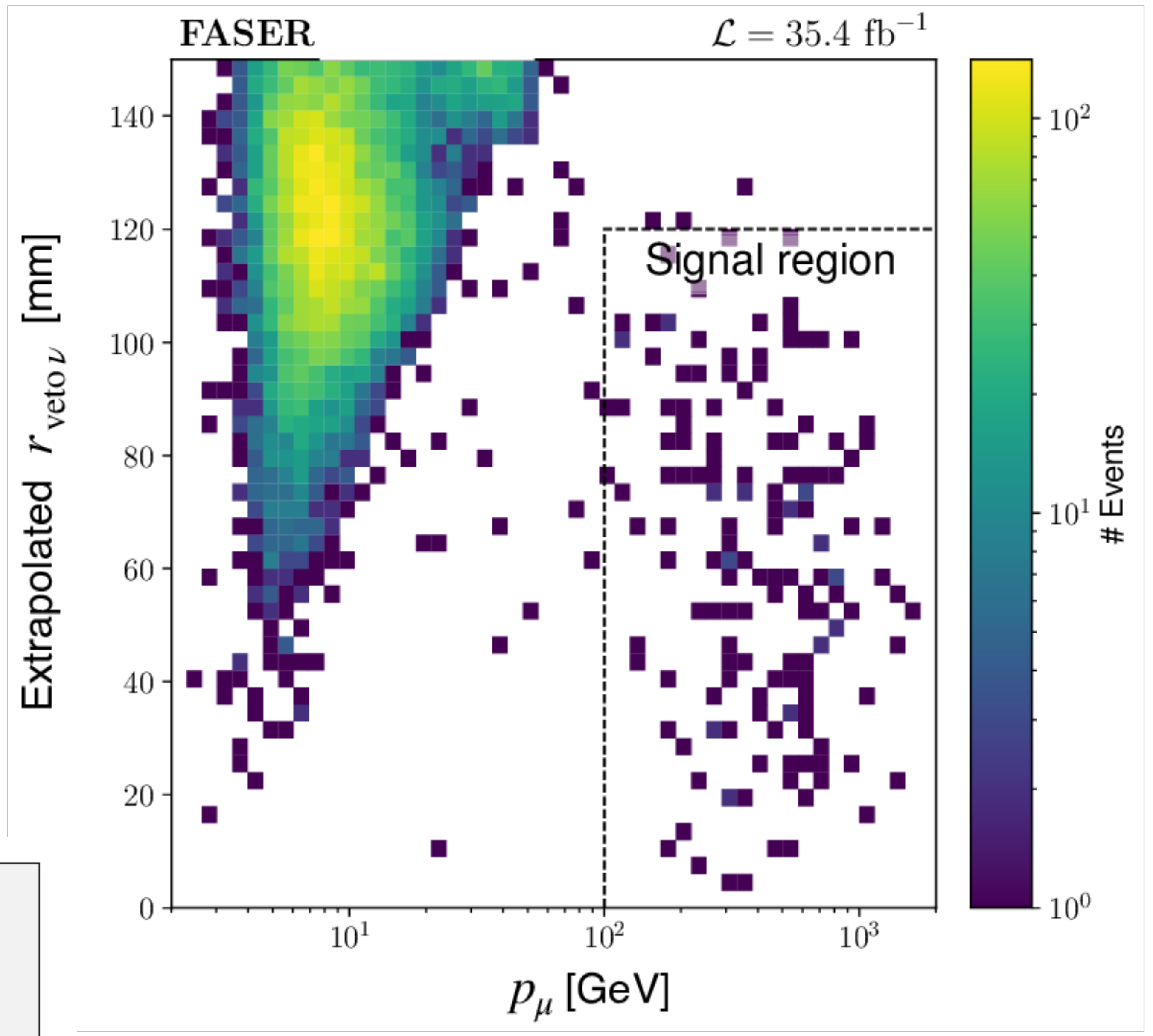


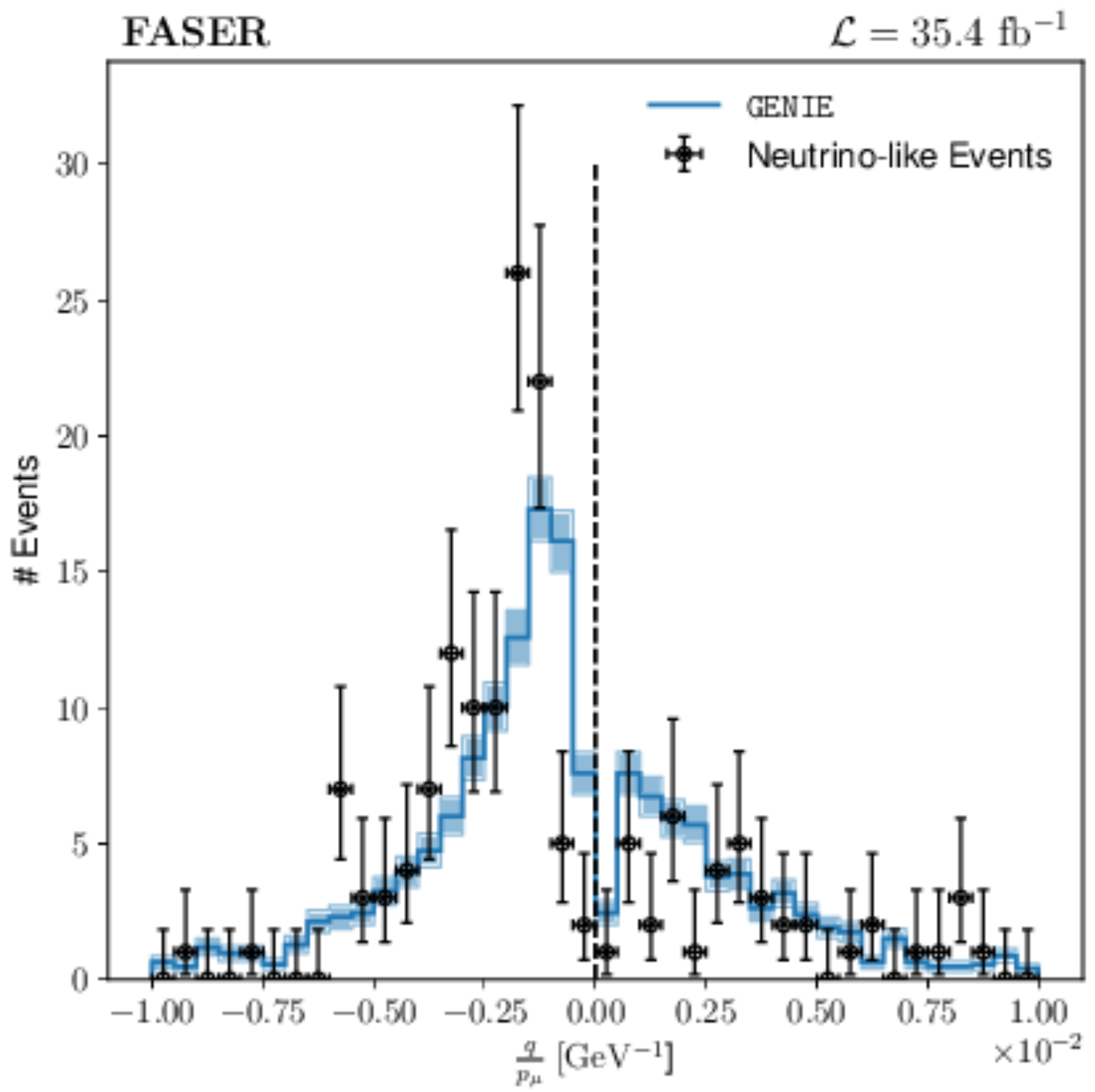
Faser plots

FASER
Neutrino Measurements

Neutrino measurements!

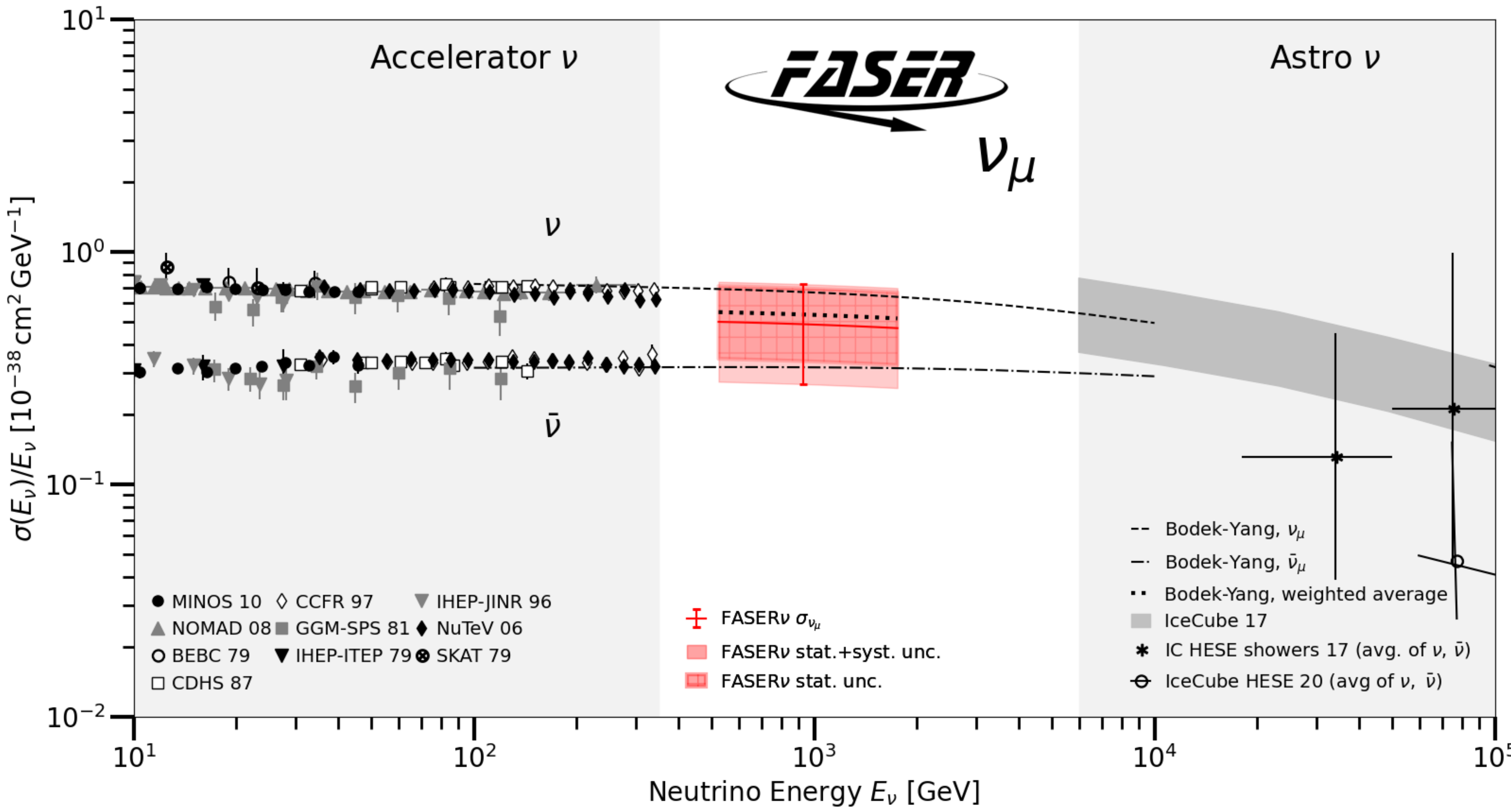
- FASER recently provided first high energy neutrino measurements at a collider
  - Both with FASER (ν_μ) and FASERν emulsion (ν_μ and ν_e)
  - Clear distinction between signal events (ν) and background events
  - Magnetic field allows for q/p measurement showing + and - ν_μ

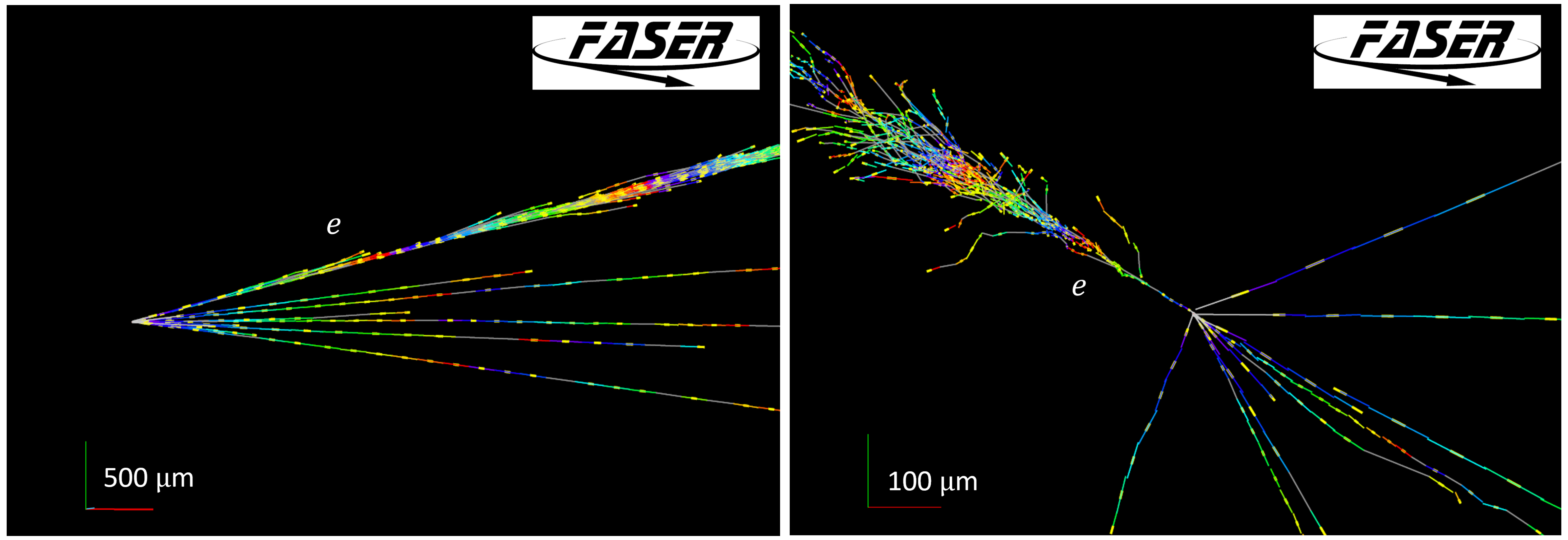




arXiv 2303.14185

arXiv 2403.12520



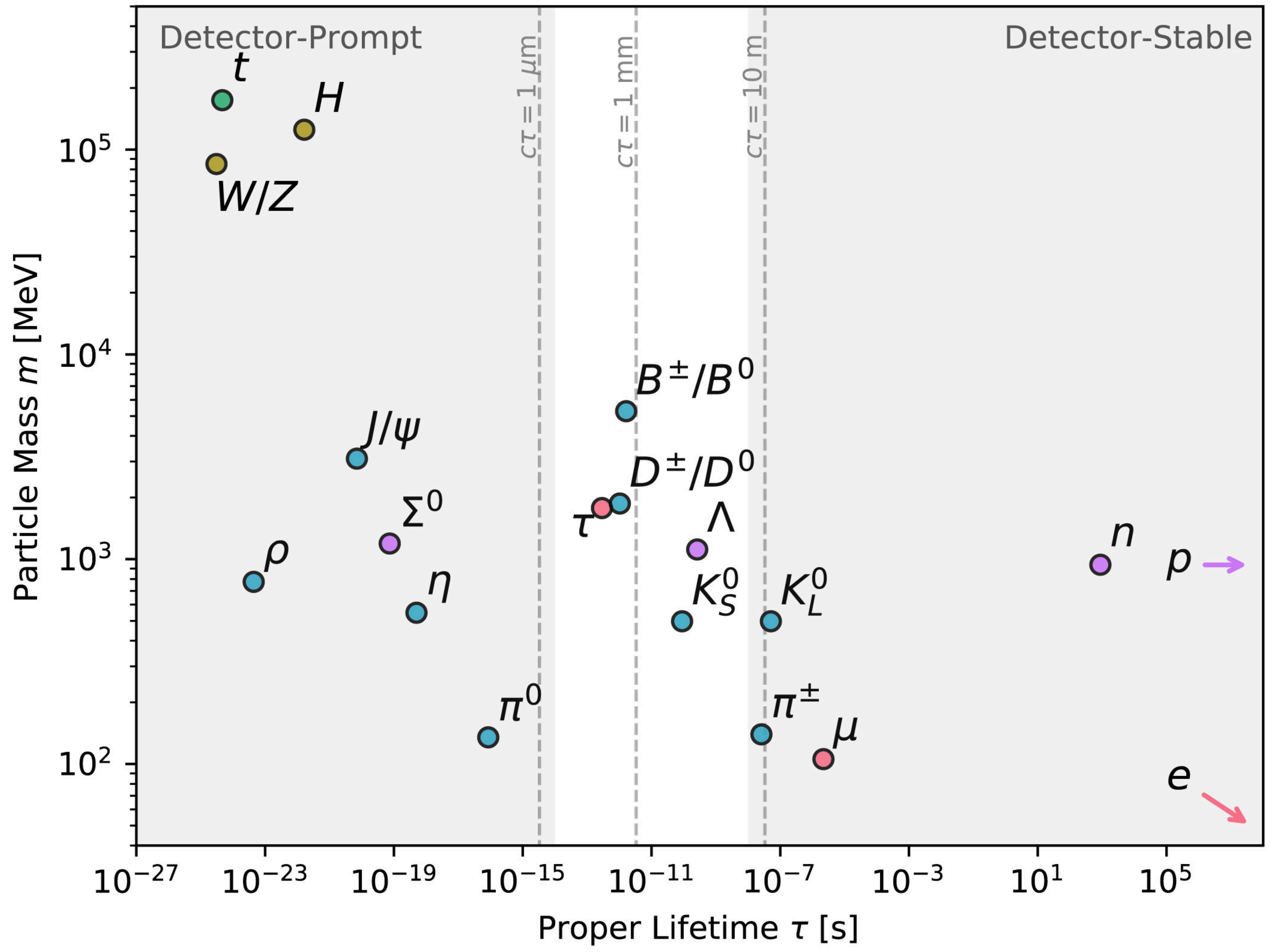


arXiv 403.12520

LLP Searches

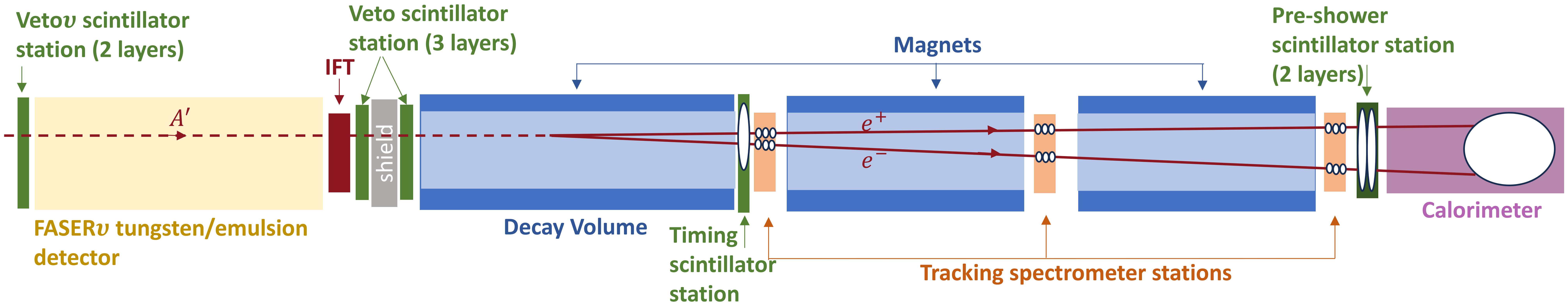
Why care about LLPs?

- No BSM discoveries yet at the LHC :'(
- Many unanswered questions
  - Dark matter · neutrino mass/oscillation · matter/antimatter asymmetry
- Furthermore, many LLPs in the standard model
  - So why not in BSM?
- Many ways to form LLPs - off-shell particles, small phase spaces, small couplings



FASER Search Results

Dark Photon Search



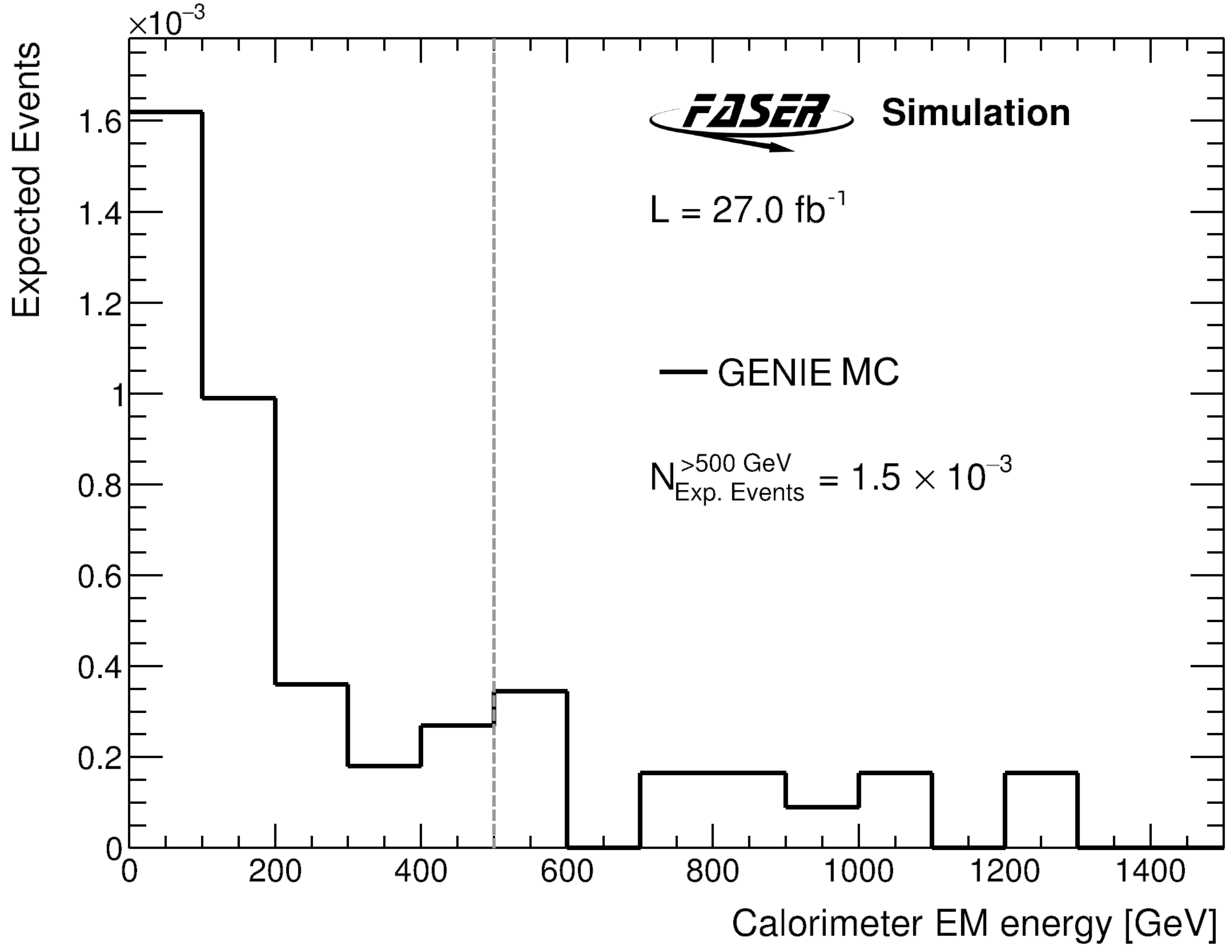
- Search for dark photons using 27 fb^{-1} of 13.6 TeV pp collision data collected in 2022
- A' dark photon and $A'_{B\text{-}L}$ probed in this search
  - A' produced in π^0 decays at the ATLAS IP and travels 480m
    - Travels farther for given lifetime due to (1 TeV) boost of very forward π^0 production
  - Decays in FASER decay volume
    - Only consider decays to electrons
- Expected signature in the detector - nothing in the veto, decay in the decay volume, two close-by tracks, and large energy deposit in the calo

Selection Criteria	Efficiency
No Veto Signal	99.7%
Timing+Preshower Signal	97.9%
$\geq$ 1 good track	91.6%
$=$ 2 good tracks	57.3% *
Track radius $<$ 95 mm	51.8% *
Calo E $>$ 500 GeV	50.8% *

PLB

Dark Photon Search

- Sources of background
  - Neutrinos - main background
    - Estimated through MC samples
  - Neutral hadrons - possible from muon interactions with rock, estimated << 1
  - Veto inefficiency, NCB, large angle muons - determined to be negligible
  - Total estimate 2.3 +/- 2.3 x 10^{-3} events
- Sources of uncertainty

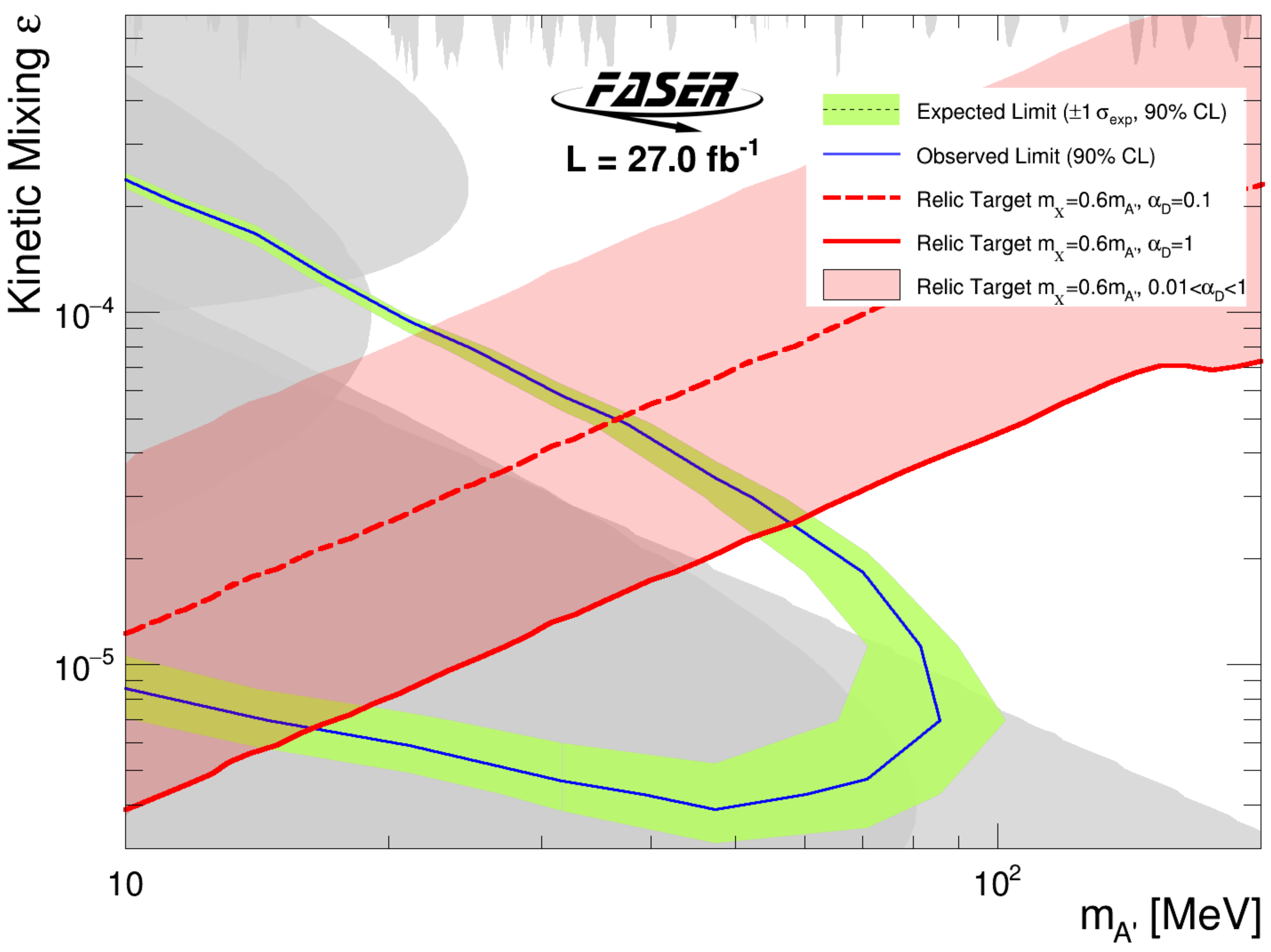


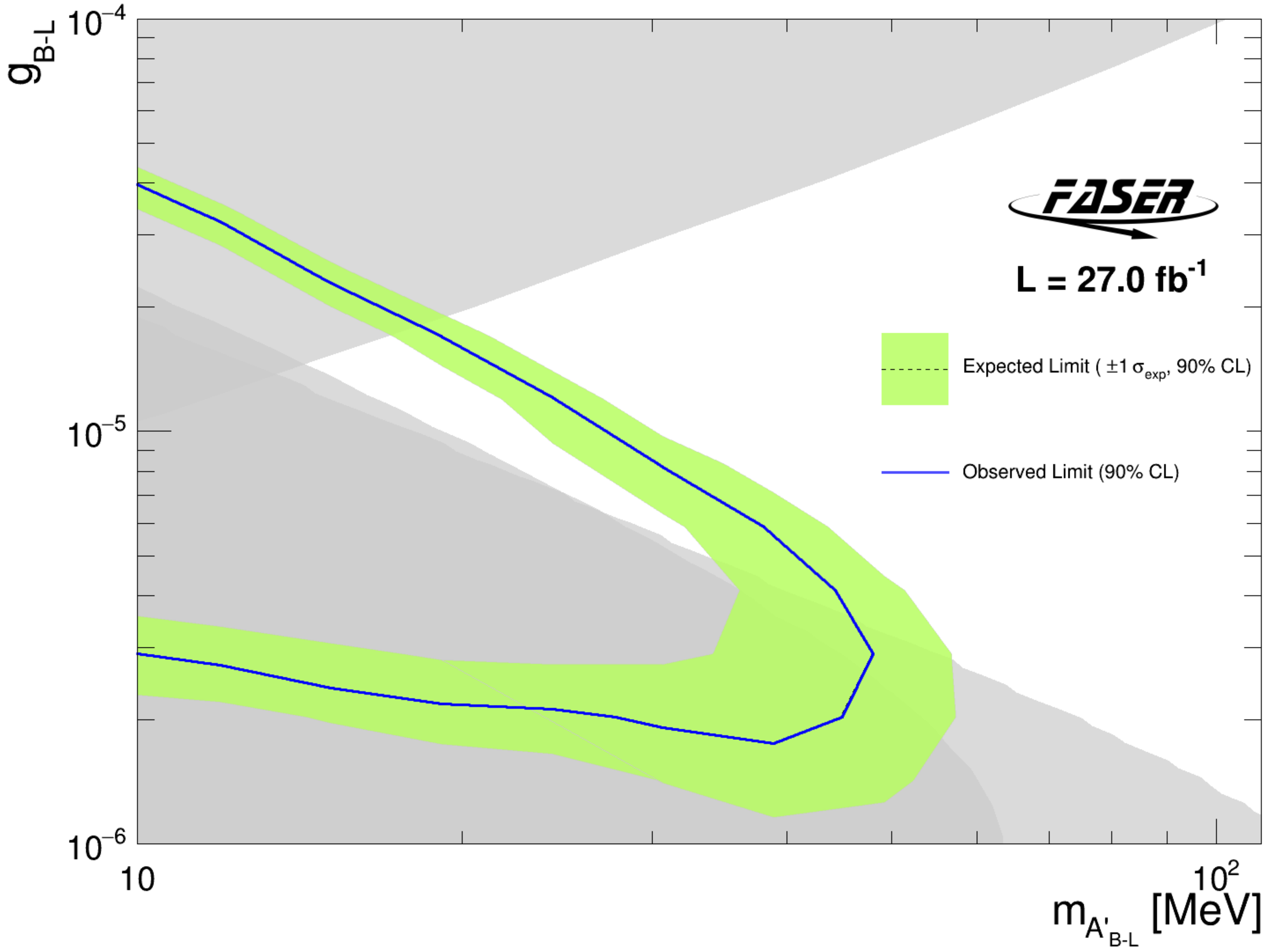
Source	Value	Effect on signal yield
Signal Generator	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
Track Momentum Scale	5%	$<$ 0.5%
Track Momentum Resolution	5%	$<$ 0.5%
Single Track Efficiency	3%	3%
Two-track Efficiency	7%	7%
Calo E scale	6%	0-8% ($<$ 1%)

PLB

Dark Photon Search - Results

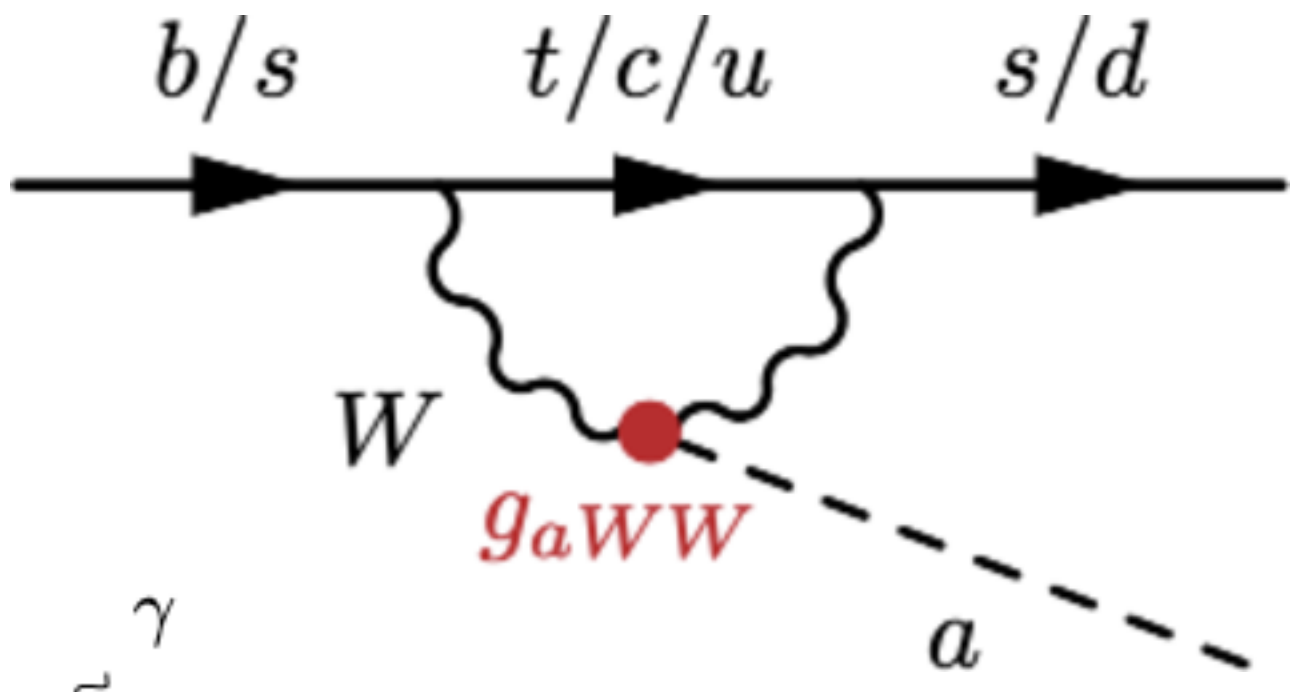
- Zero events observed, consistent with background estimation
- Set limits on A' (dark photon) and $A'_{B\text{-}L}$, with sensitivity in previously un-excluded phase space



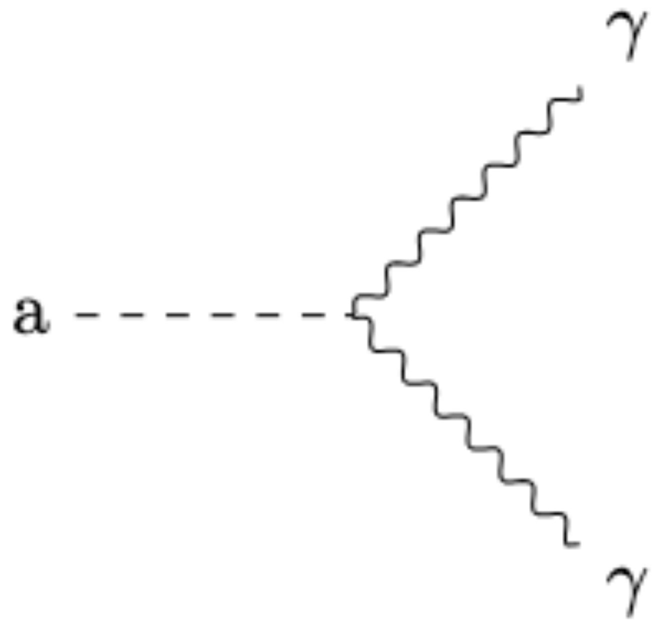


PLB

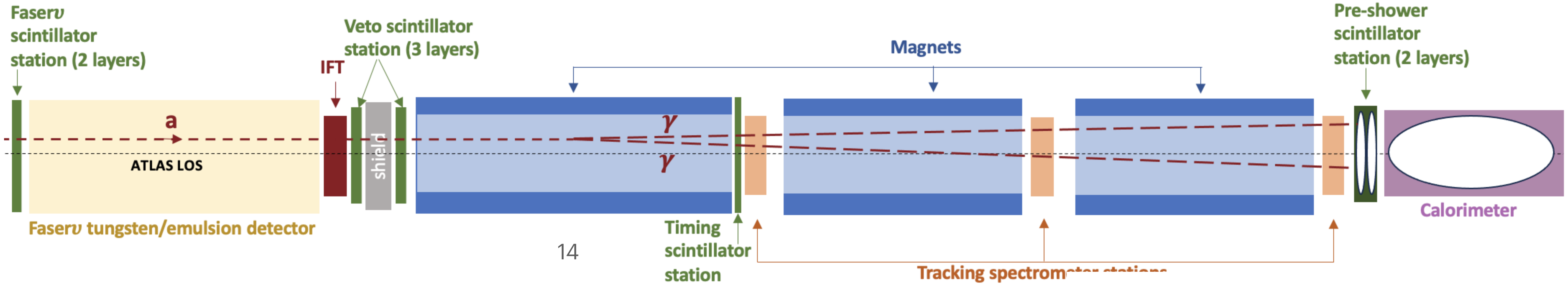
ALPs



- Search for axion-like particles (ALPs) using 57.7 fb^{-1} of pp collision data with 13.6 TeV collected in 2022 *and* 2023
- Focus on coupling with $SU(2)_L$ gauge bosons
  - Predominantly produced by B^0, $B^{+/-}$ decays
  - ALP then decays to two photons
  - With current pre-shower scintillator cannot distinguish between one or two photons



- Detector signature - no activity in the vetoes, ALP is allowed to decay anywhere in the decay or tracker volume, EM-like signal in the pre-shower, and large energy deposit in the calorimeter

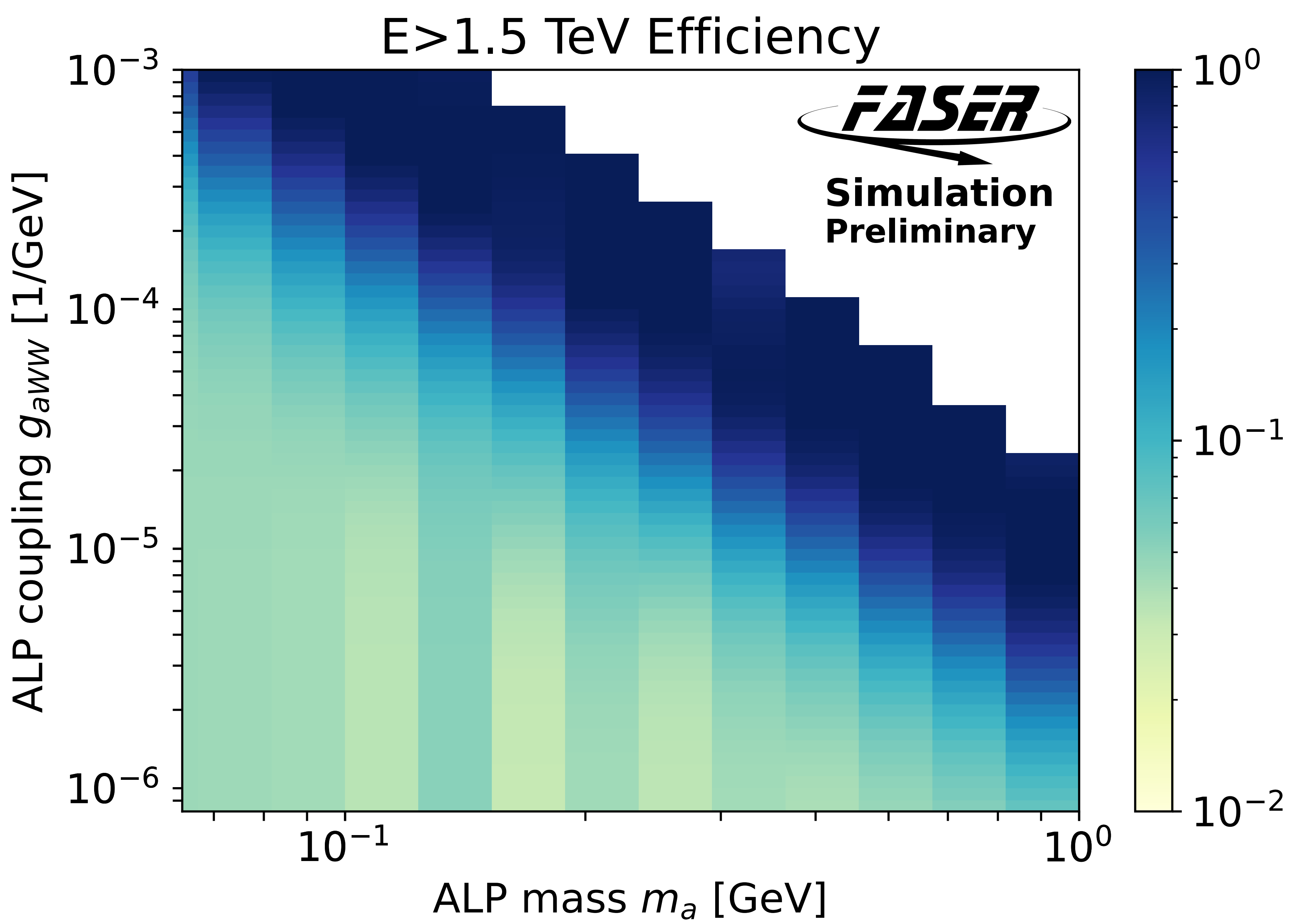


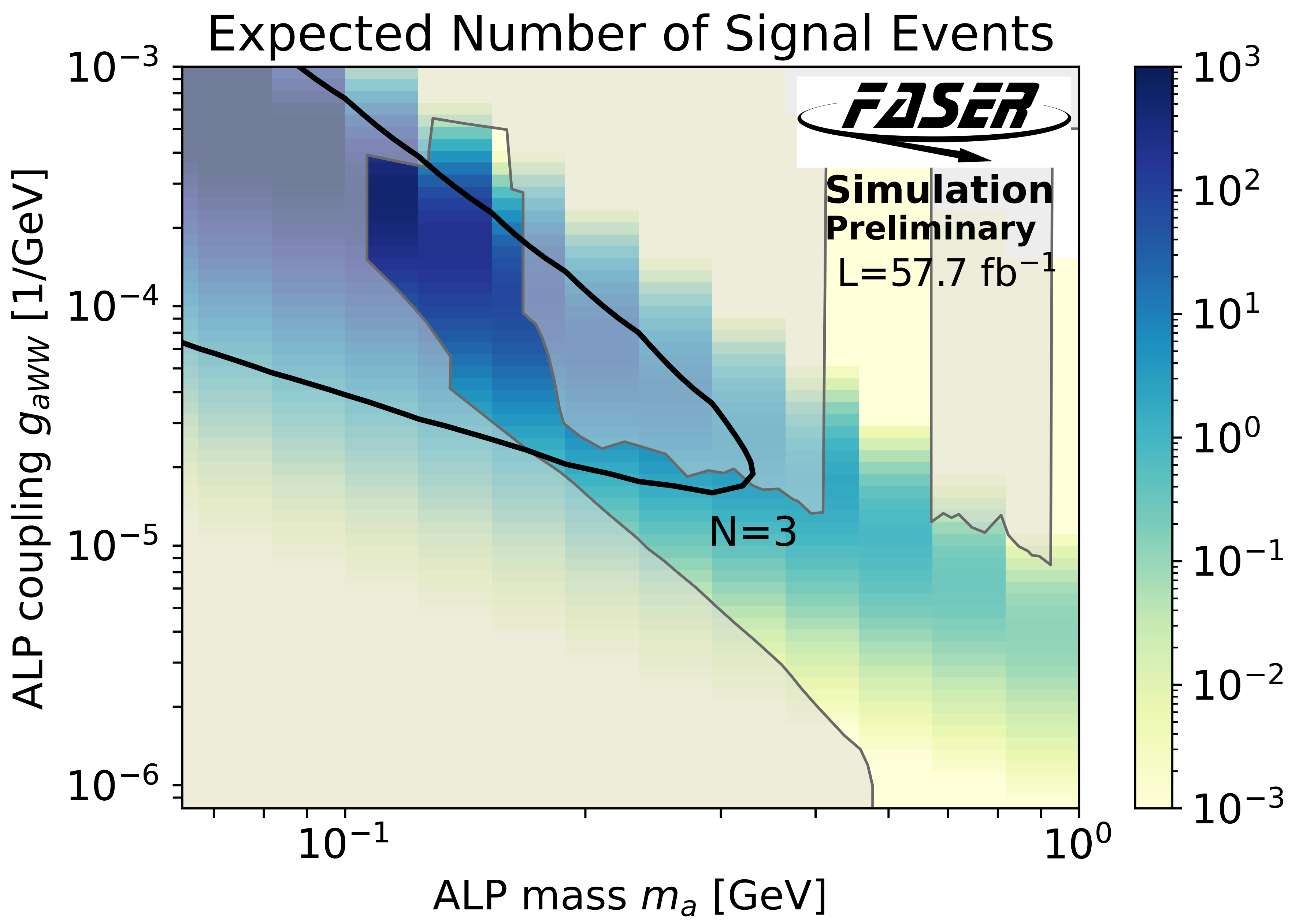
CDS

ALPs - signal selection

- Search region requires
  - ~0 signal in the veto
    - Large preshower ratio of > 4.5
    - Large deposit in the second preshower layer
    - E > 1.5 TeV in the calorimeter
  - Efficiency to select ALPs with E > 1.5 TeV quite high
  - Assuming background free analysis, FASER has sensitivity to see ≤ O(100) events in previously unconstrained regions

Selection	Efficiency	Cum. Efficiency
$m_a = 140$ MeV, $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1}		
Veto Signal nMIP < 0.5	99.6%	99.6%
Timing Scintillator Signal nMIP < 0.5	97.8%	97.4%
Preshower Ratio > 4.5	85.7%	83.5%
Second Preshower nMIP > 10	98.6%	82.3%
Calo $E > 1.5$ TeV	91.6%	75.4%



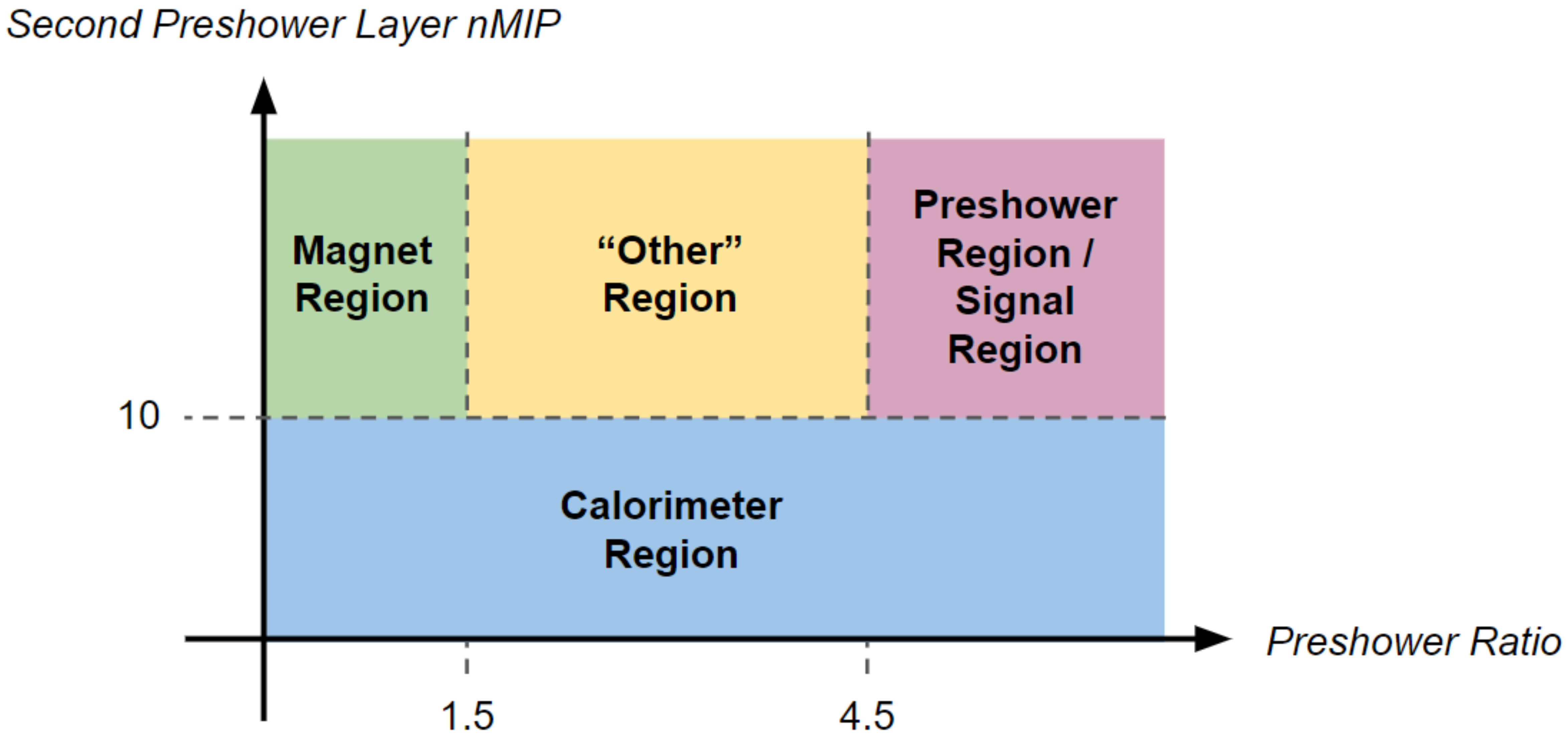


CDS

ALPs - background estimation

- Sources of background
  - Large angle muons, veto inefficiency, neutral hadrons, NCB - negligible
  - Neutrinos - main background
    - Unlike dark photon search, no tracks, also, cannot distinguish the two photons
    - Background estimate based on MC samples
    - Background estimate found to be 0.42 +/- 0.38
- Validation done using control regions in data and MC where neutrinos primarily interact in the
  - Magnet
  - Calorimeter
  - Preshower
  - (Other)

> 1.5 TeV signal region	
Light	$0.23^{+0.01}_{-0.11}$ (flux) $\pm$ 0.11 (exp.) $\pm$ 0.04 (stat.)
Charm	$0.19^{+0.32}_{-0.09}$ (flux) $\pm$ 0.06 (exp.) $\pm$ 0.03 (stat.)
Total	**0.42 $\pm$ 0.38 (90.6%)**

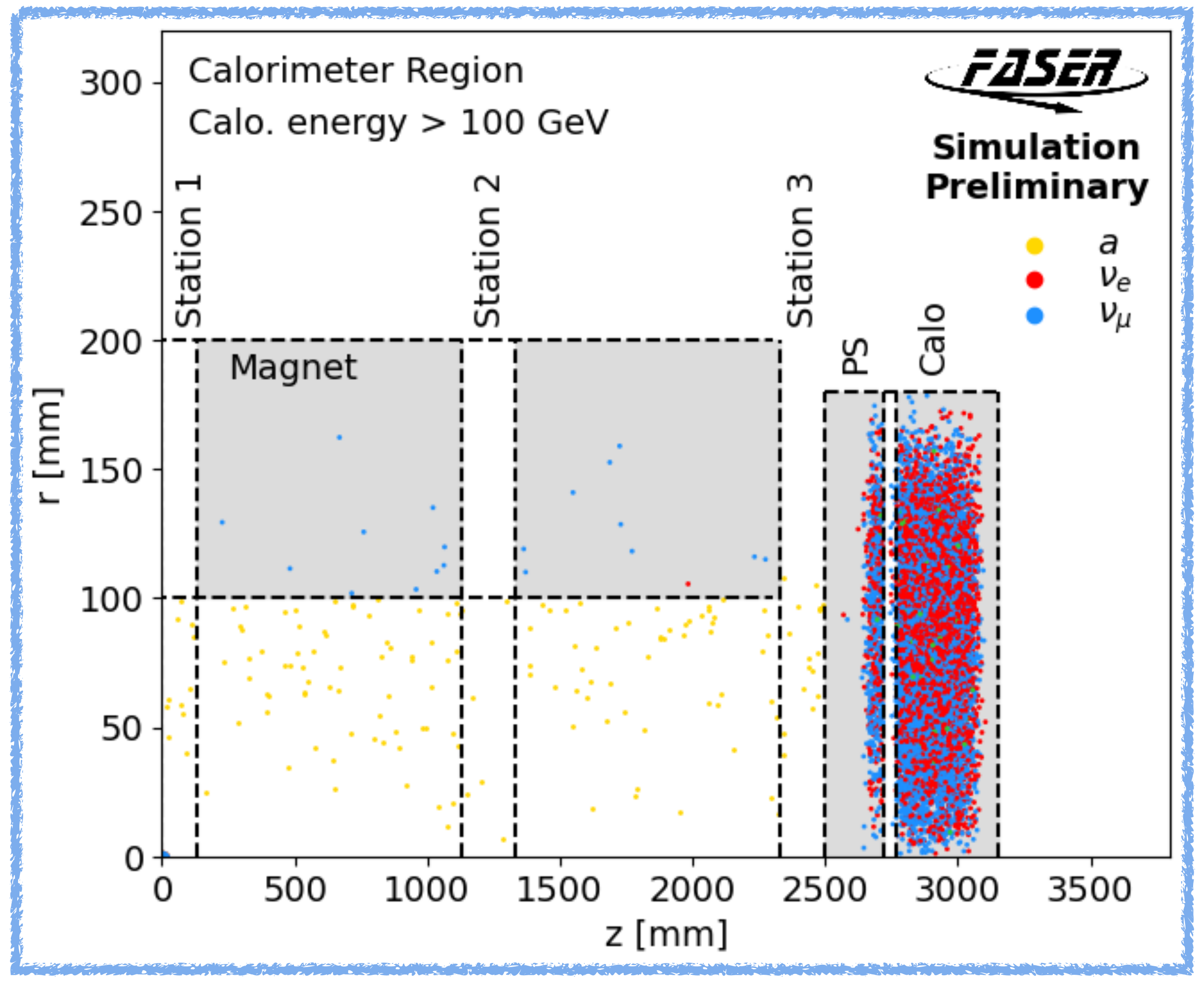


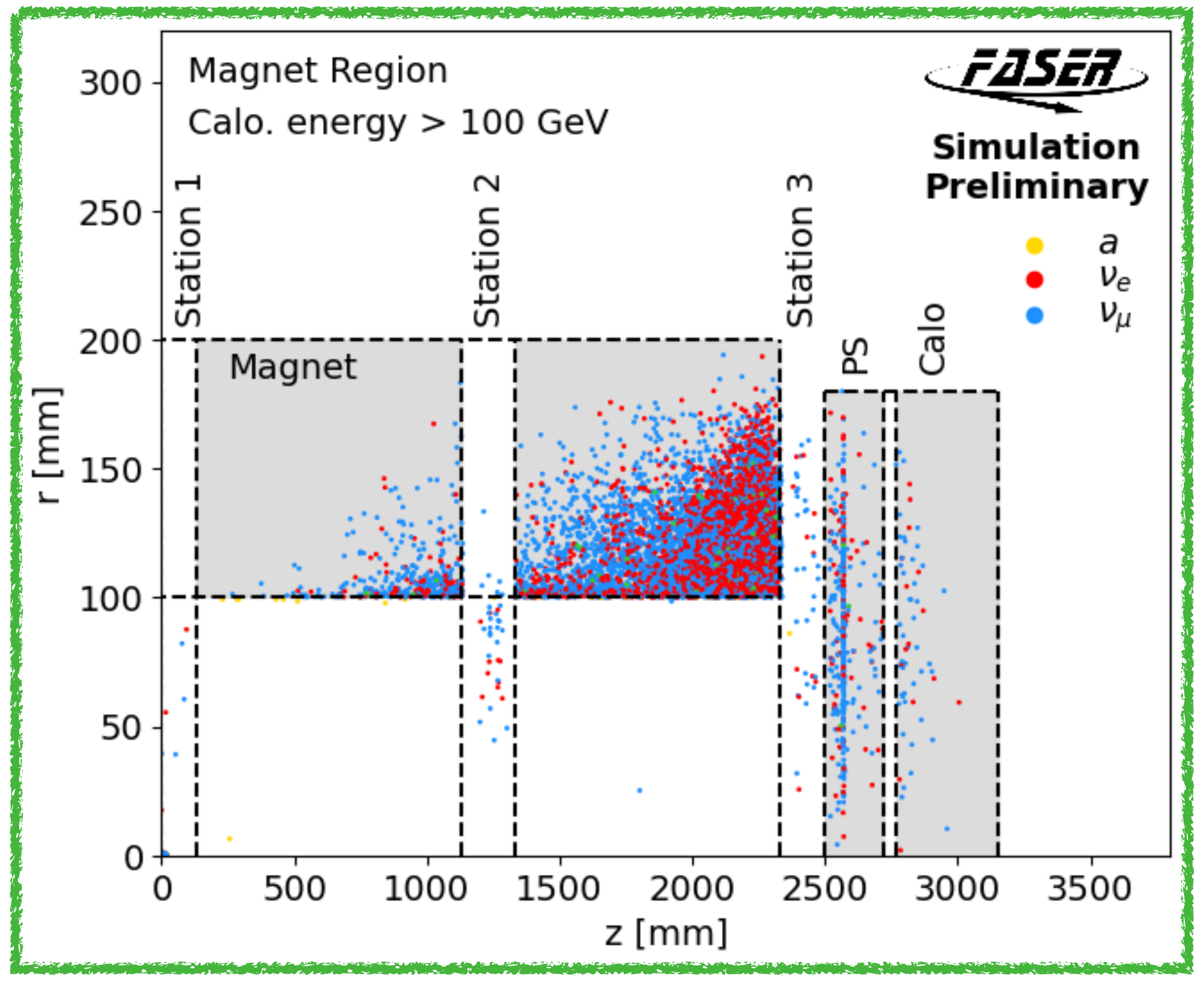
CDS

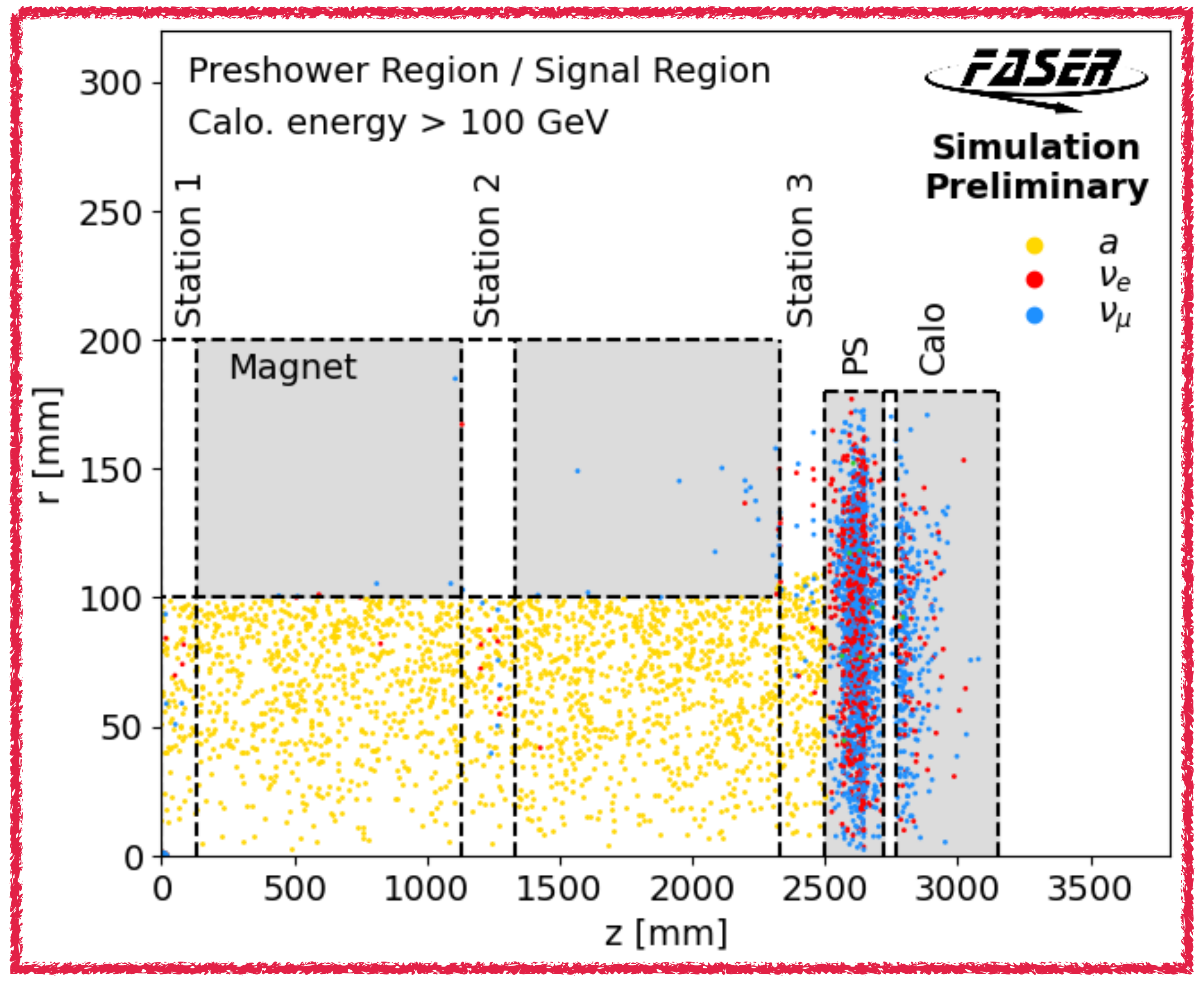
ALPs - background estimation

- Here, ALP vs neutrino type decays shown for the three regions
- High overlap in preshower region
  - Separation from signal comes from high 1.5 TeV requirement
  - Good agreement between predicted and observed

"Other" region	
Light	$17.4^{+1.3}_{-0.8}$ (flux) $\pm$ 2.5 (exp.) $\pm$ 0.3 (stat.)
Charm	$3.9^{+6.0}_{-1.8}$ (flux) $\pm$ 0.5 (exp.) $\pm$ 0.2 (stat.)
Total	**21.3 $\pm$ 6.9 (32.2%)**
Data	**17**







Calorimeter region	
Light	$51.6^{+2.0}_{-3.4}$ (flux) $\pm$ 3.1 (exp.) $\pm$ 0.5 (stat.)
Charm	$11.1^{+19.1}_{-5.1}$ (flux) $\pm$ 0.4 (exp.) $\pm$ 0.3 (stat.)
Total	**62.7 $\pm$ 19.7 (31.4%)**
Data	**74**

Magnet region	
Light	$33.6^{+6.7}_{-3.4}$ (flux) $\pm$ 4.3 (exp.) $\pm$ 0.4 (stat.)
Charm	$9.9^{+16.1}_{-4.6}$ (flux) $\pm$ 0.9 (exp.) $\pm$ 0.2 (stat.)
Total	**43.5 $\pm$ 18.2 (41.9%)**
Data	**34**

Preshower region	
Light	$14.8^{+0.9}_{-1.2}$ (flux) $\pm$ 1.8 (exp.) $\pm$ 0.3 (stat.)
Charm	$3.0^{+4.5}_{-1.4}$ (flux) $\pm$ 0.3 (exp.) $\pm$ 0.1 (stat.)
Total	**17.8 $\pm$ 5.1 (28.8%)**
Data	**15**

CDS

ALPs - systematic uncertainties

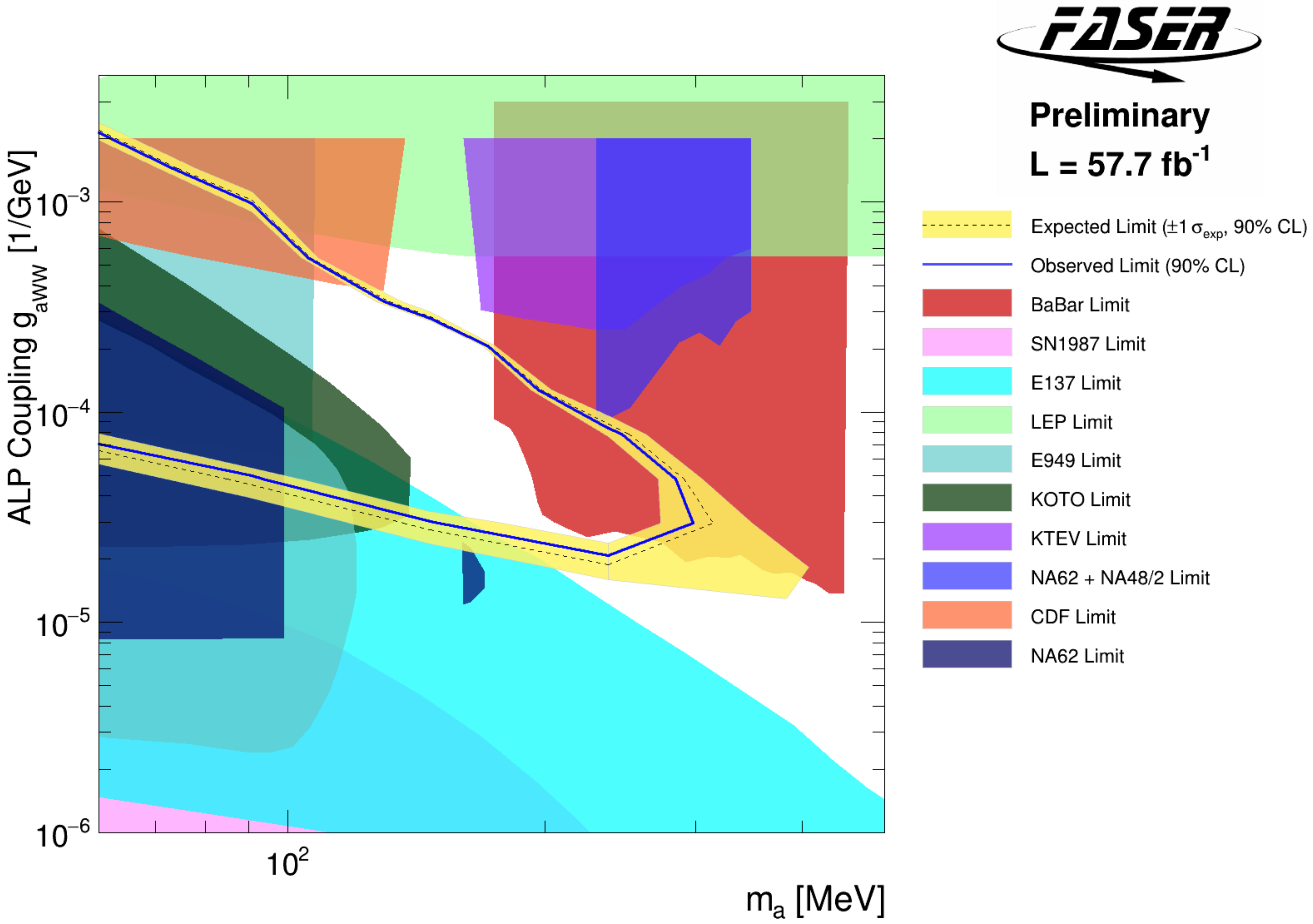
Background uncertainty sources		
0.42	$\pm$	0.32 (flux)
	$\pm$	0.14 (calo. energy)
	$\pm$	0.06 (PS ratio)
	$\pm$	0.02 (PS 1 nMIP)
	$\pm$	0.05 (stat.)
Total: 0.42	$\pm$	**0.38 (90.6%)**

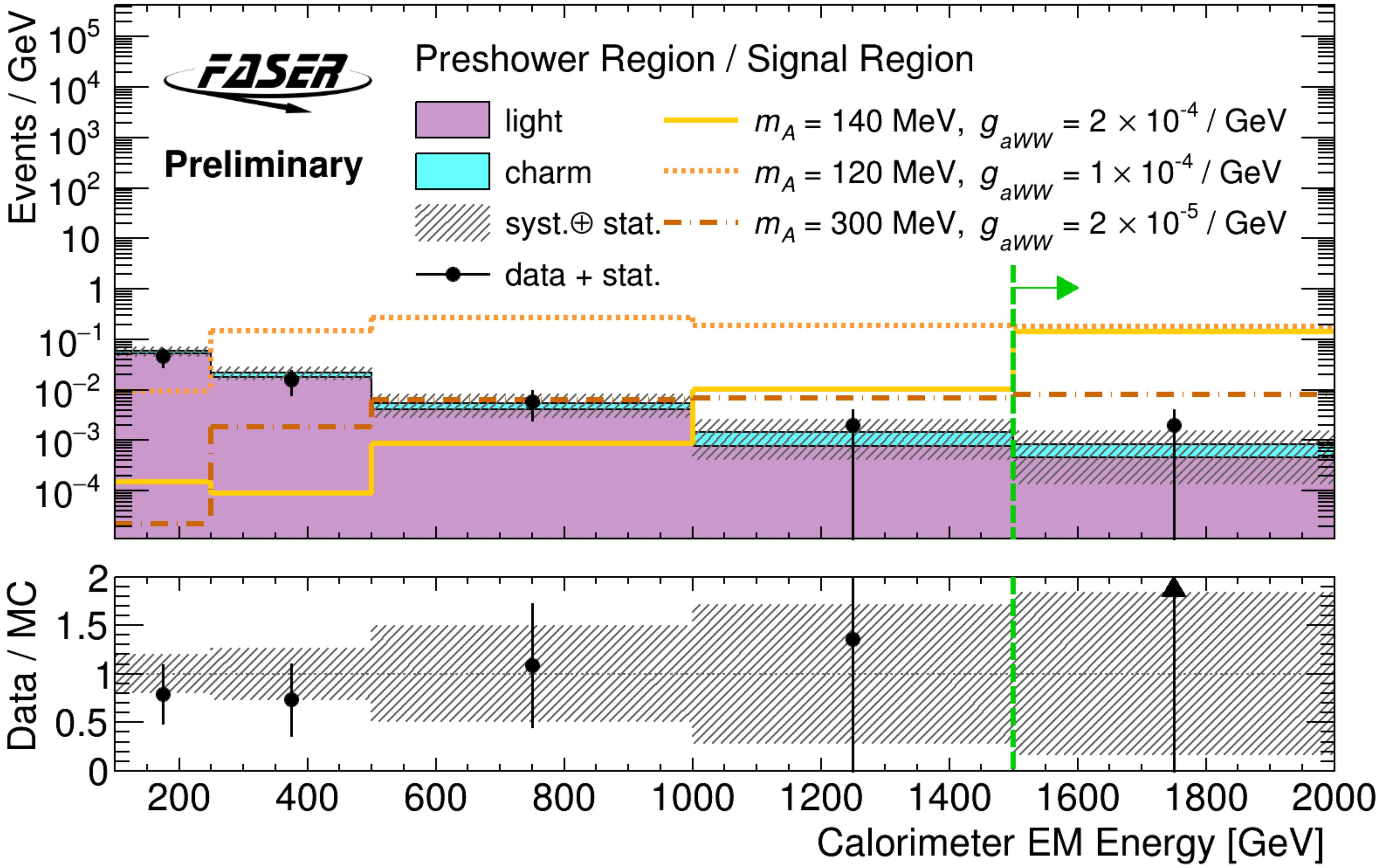
- Several sources of uncertainty from MC stats limitations, modeling of detector response, and theory uncertainties
- Largest source of uncertainty - modeling the flux of SM particles coming from the LHC
  - Envelope of predictions from several generators → uncertainty for particles from light hadron production (validate with LHCf data)
  - NLO Powheg simulation for heavy flavor, large uncertainties from scale variation
  - Impacting both signal efficiency and background estimation

Signal Sample	Flux	Stat.	Luminosity	Calorimeter	Second Preshower Layer	Preshower Ratio
$m_a = 140$ MeV $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1}	59.4%	1.8%	2.2%	3.6%	0.6%	7.9%
$m_a = 120$ MeV $g_{aWW} = 10^{-4}$ GeV^{-1}	57.3%	3.5%	2.2%	16.3%	0.6%	6.9%
$m_a = 300$ MeV $g_{aWW} = 2 \times 10^{-5}$ GeV^{-1}	58.0%	2.9%	2.2%	15.8%	0.6%	8.4%

ALPs - results

- One event observed in the signal region
  - 1.6 TeV in the calo, preshower ratio 9.0, 2nd preshower 146 MIPS
- Observed event could be consistent with signal or background
- One observed event consistent with background prediction - limits set at 90% CL





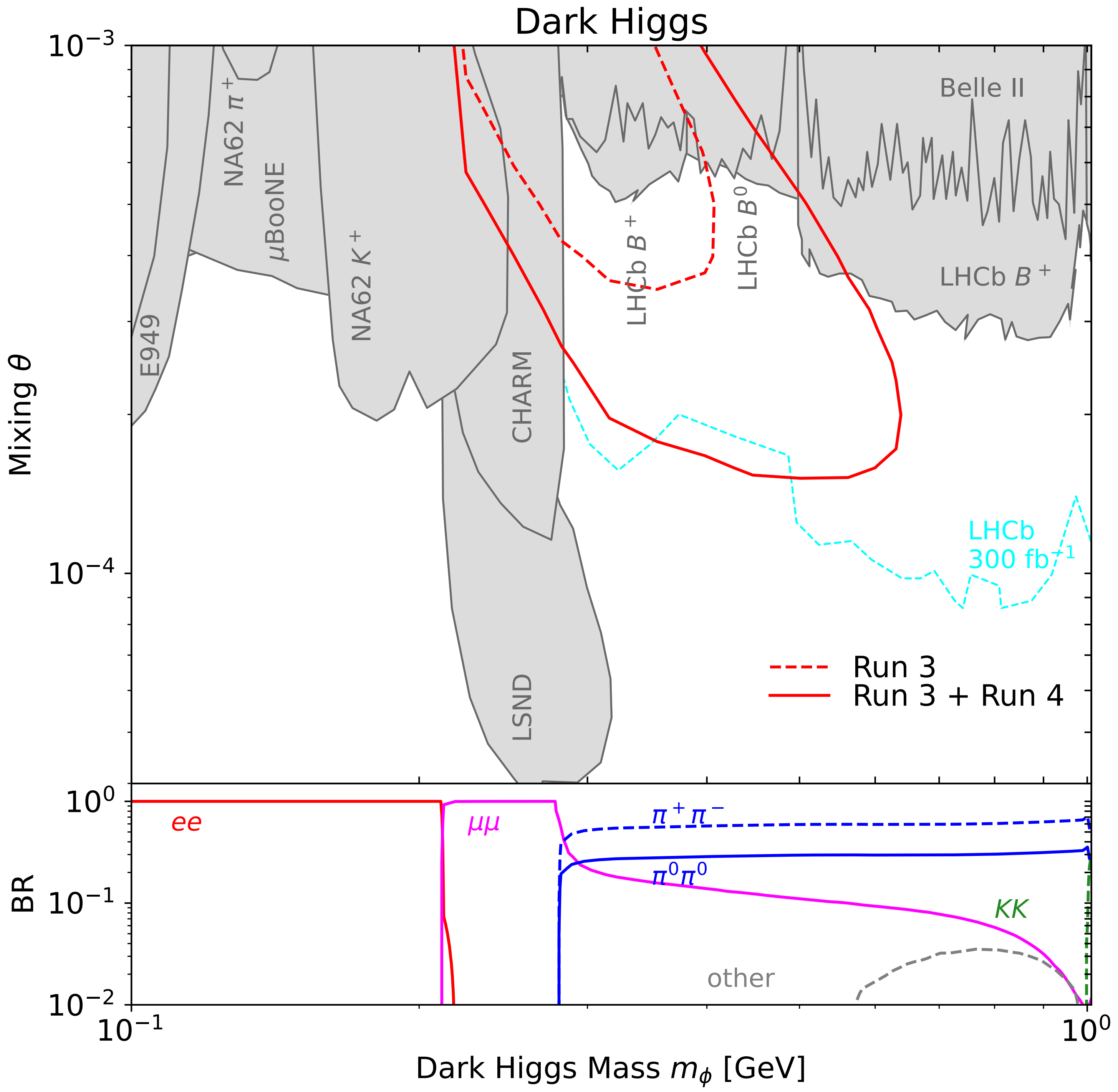
- Sensitivity from FASER in previously unconstrained parameter space - ALP mass 100 to 250 MeV and couplings ranging from 3×10^{-5} to 5×10^{-4} GeV^{-1}
- Reinterpretations underway for other ALP models

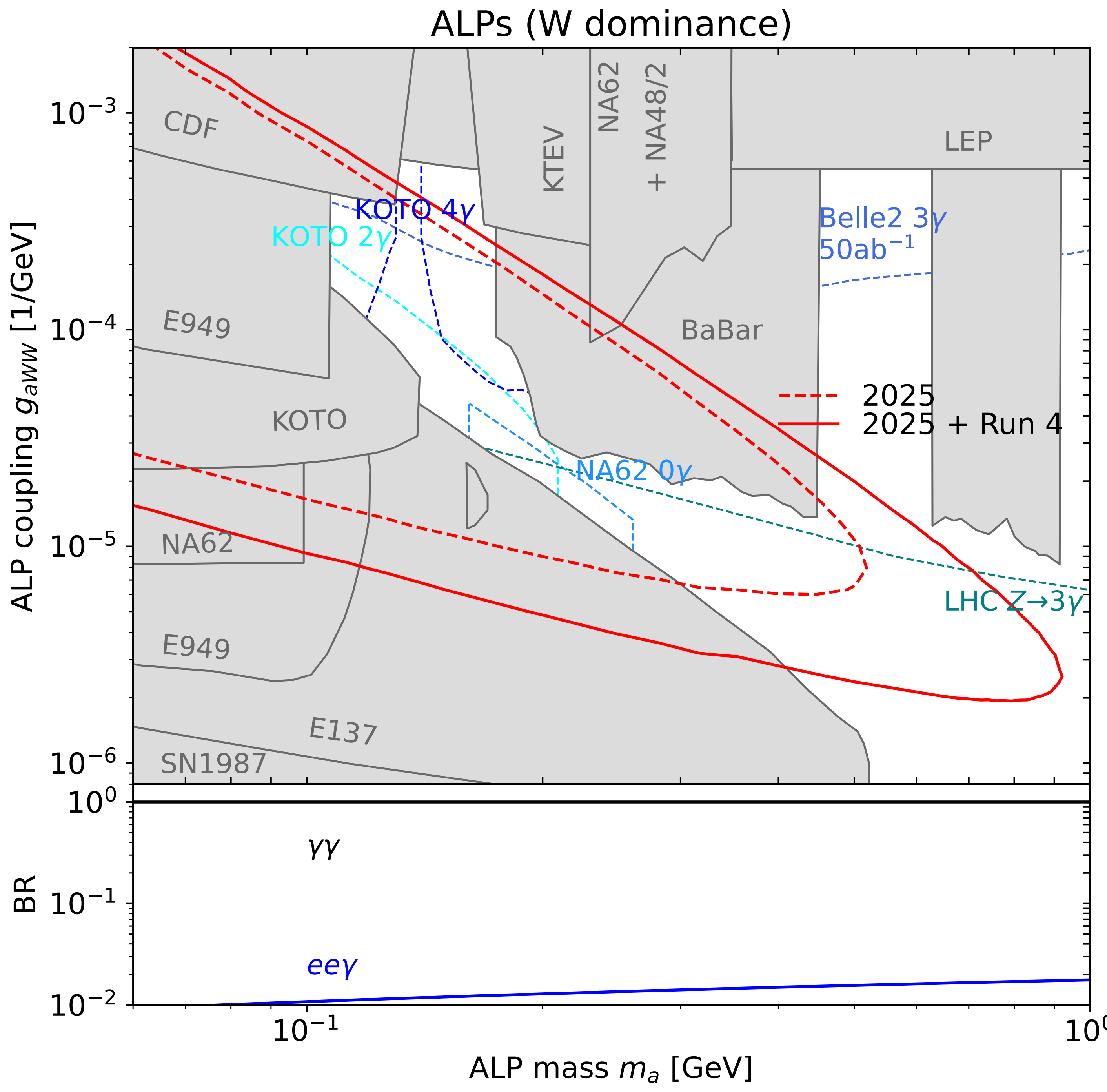
CDS

Moving Forward

Future planning

- Already interesting results from the first two years of FASER run time
  - Including first high energy collider neutrino observations!
- Planned pre-shower upgrade by next year
  - Would significantly improve ALP result
    - Improve rejection of neutrino background
- FASER approved for HL-LHC running (Run 4)
  - Projections for ALPs and Dark Higgs searches for Run 3 (with pre-shower) + Run 4





FASER COLLABORATION

99 collaborators, 27 institutions, 11 countries

International laboratory covered by a cooperation agreement with CERN

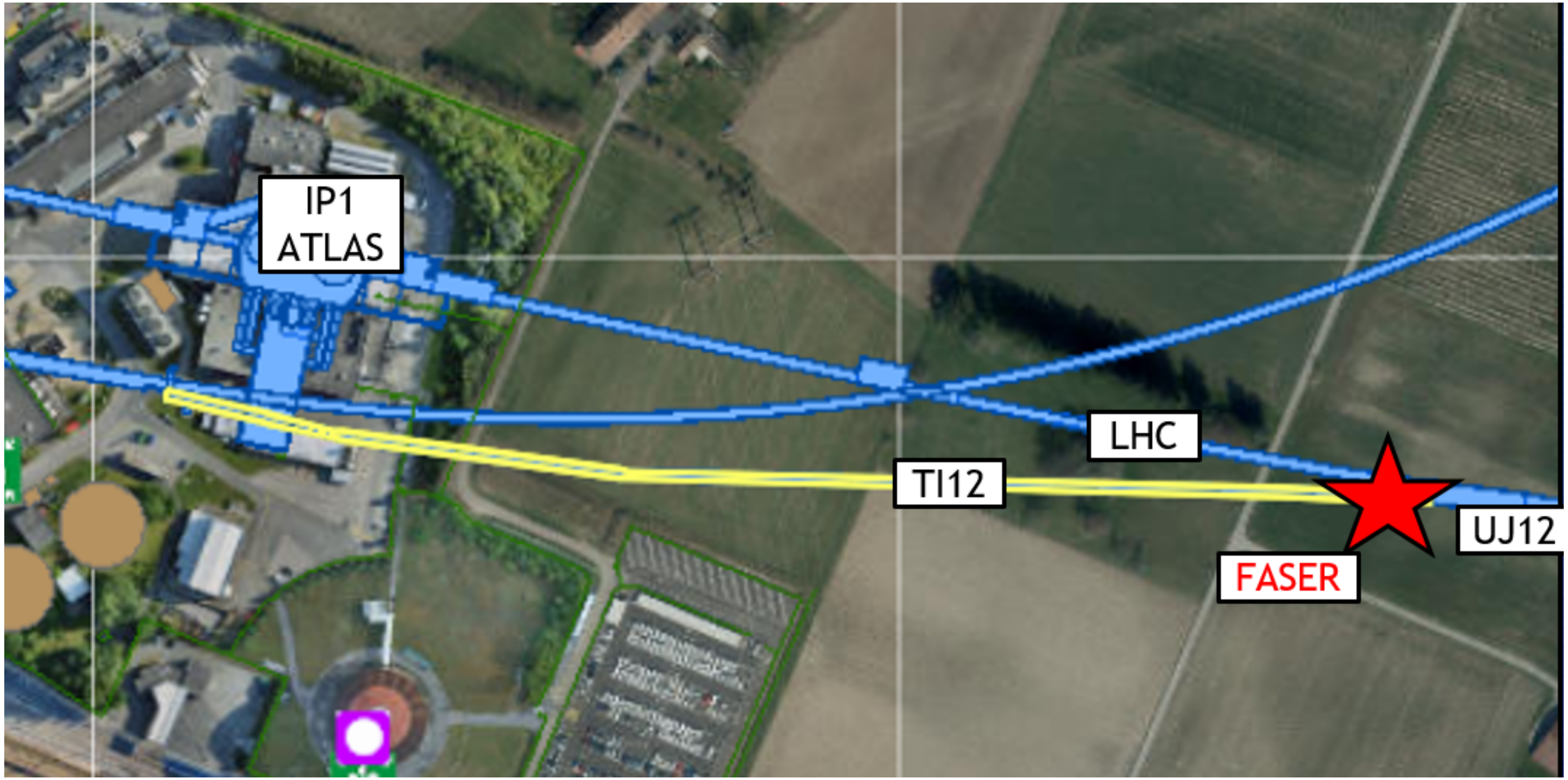
FASER FUNDING

With thanks to

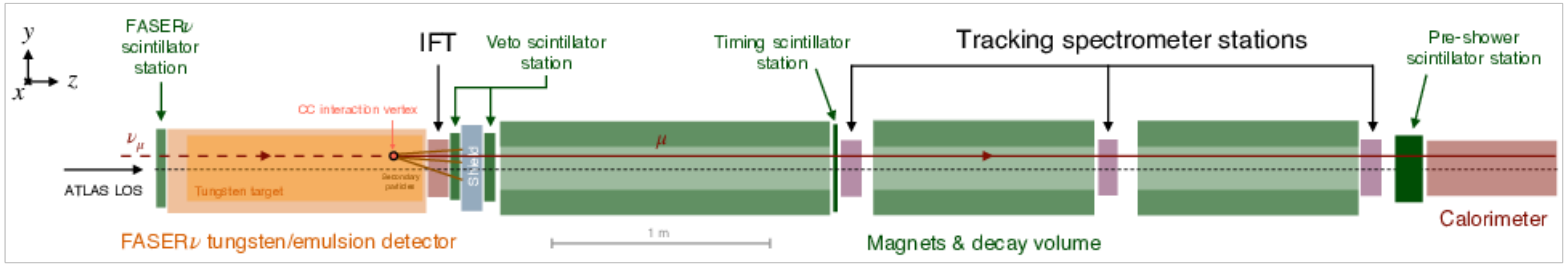
Backup

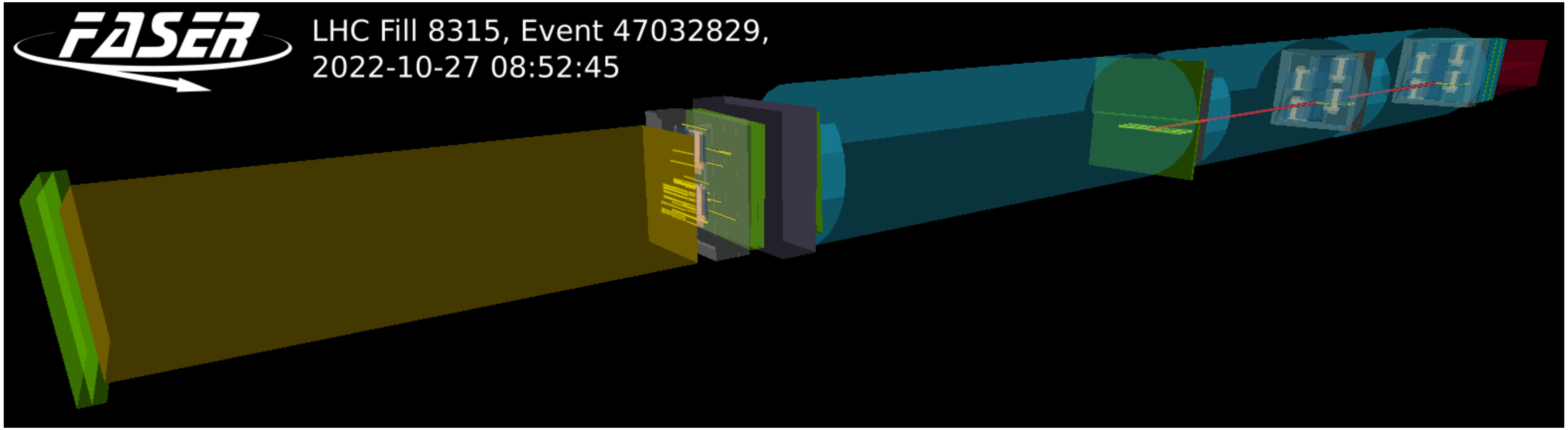
FASER

Map

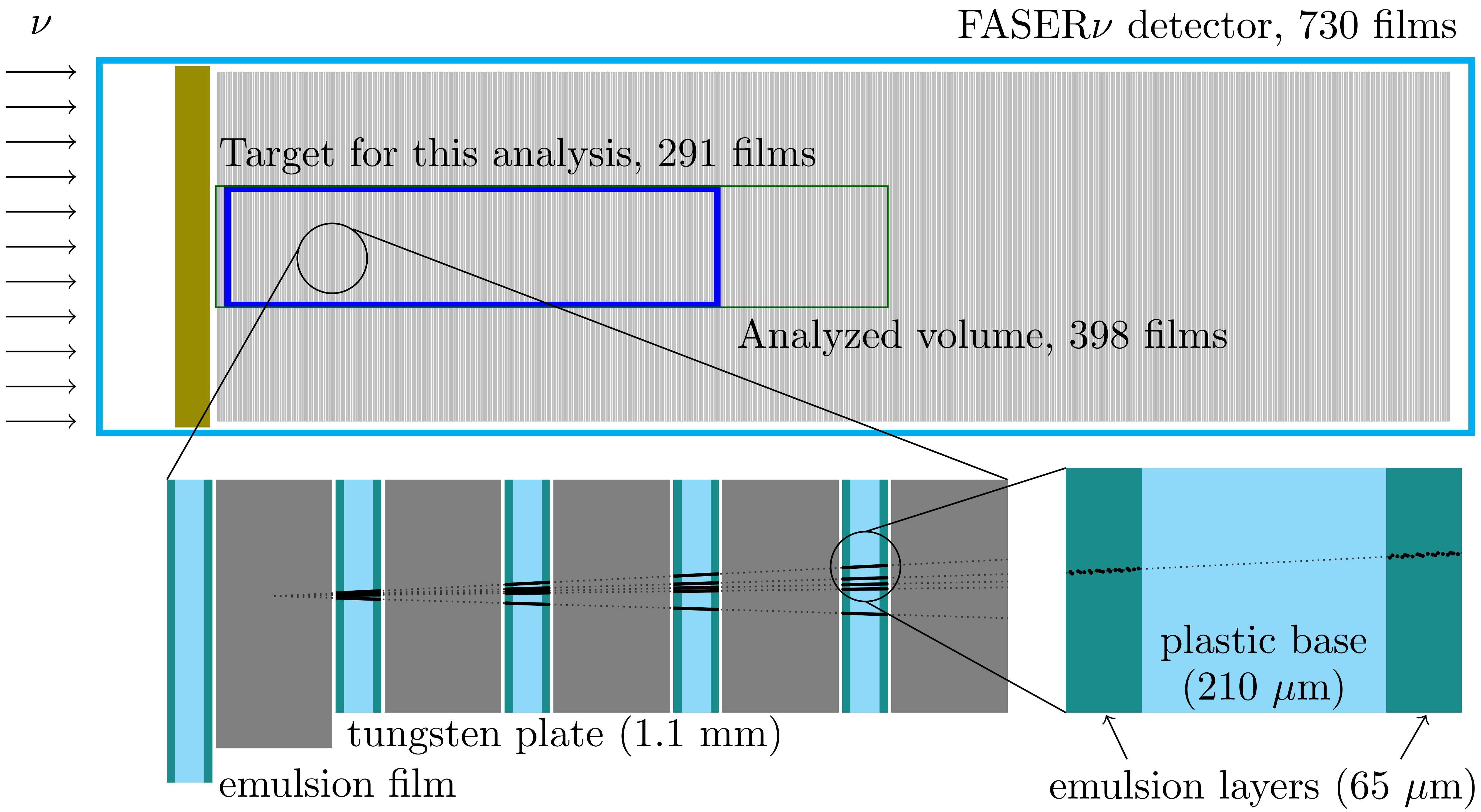


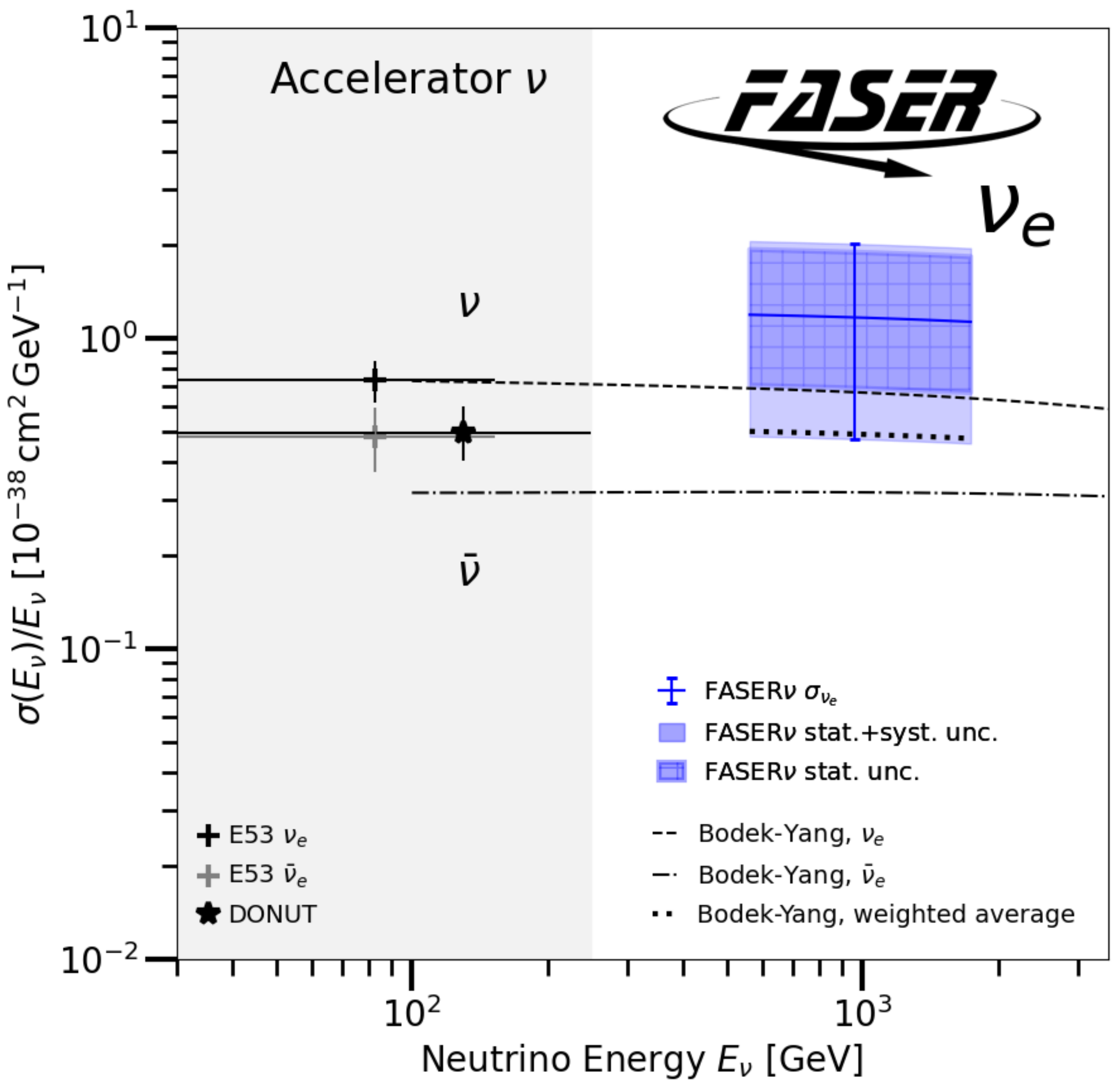
Neutrinos in the electronic detector



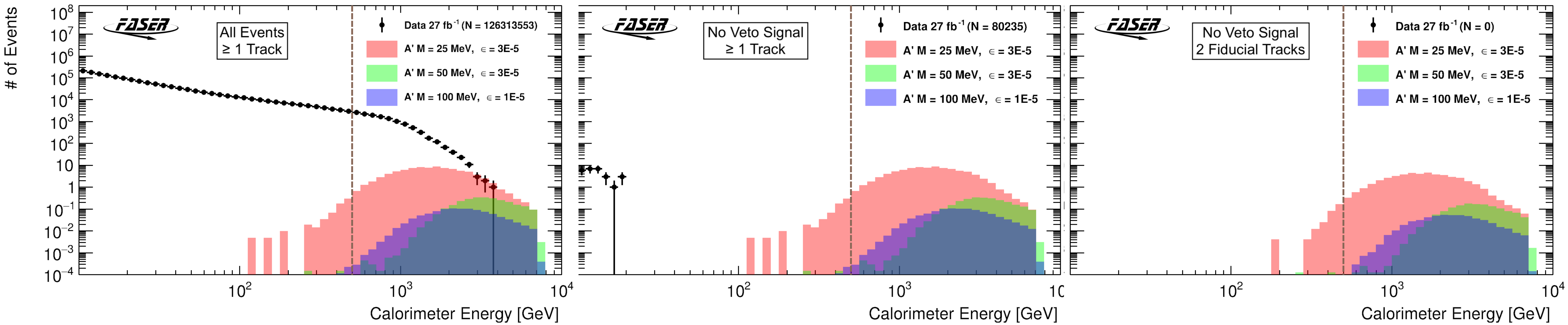


Neutrinos in FASERν





Dark photons



Cut	Data	
	Events	Efficiency
Good collision event	151231009	–
No Veto Signal	1250092	0.827%
Timing + Preshower Signal	332549	0.220%
≥ 1 good track	22224	0.015%
$= 2$ good tracks	0	0.000%
Track radius < 95 mm	0	0.000%
Calo E > 500 GeV	0	0.000%

Background	**Central Value**	**Error (%)**
Veto inefficiency	-	-
Non-collision	-	-
Neutral hadrons	0.8×10^{-3}	1.2×10^{-3} (140%)
Neutrinos	1.5×10^{-3}	2.0×10^{-3} (130%)
Total	$\mathbf{2.3 \times 10^{-3}}$	$\mathbf{2.3 \times 10^{-3}}$ **(100%)**

CDS

ALPs

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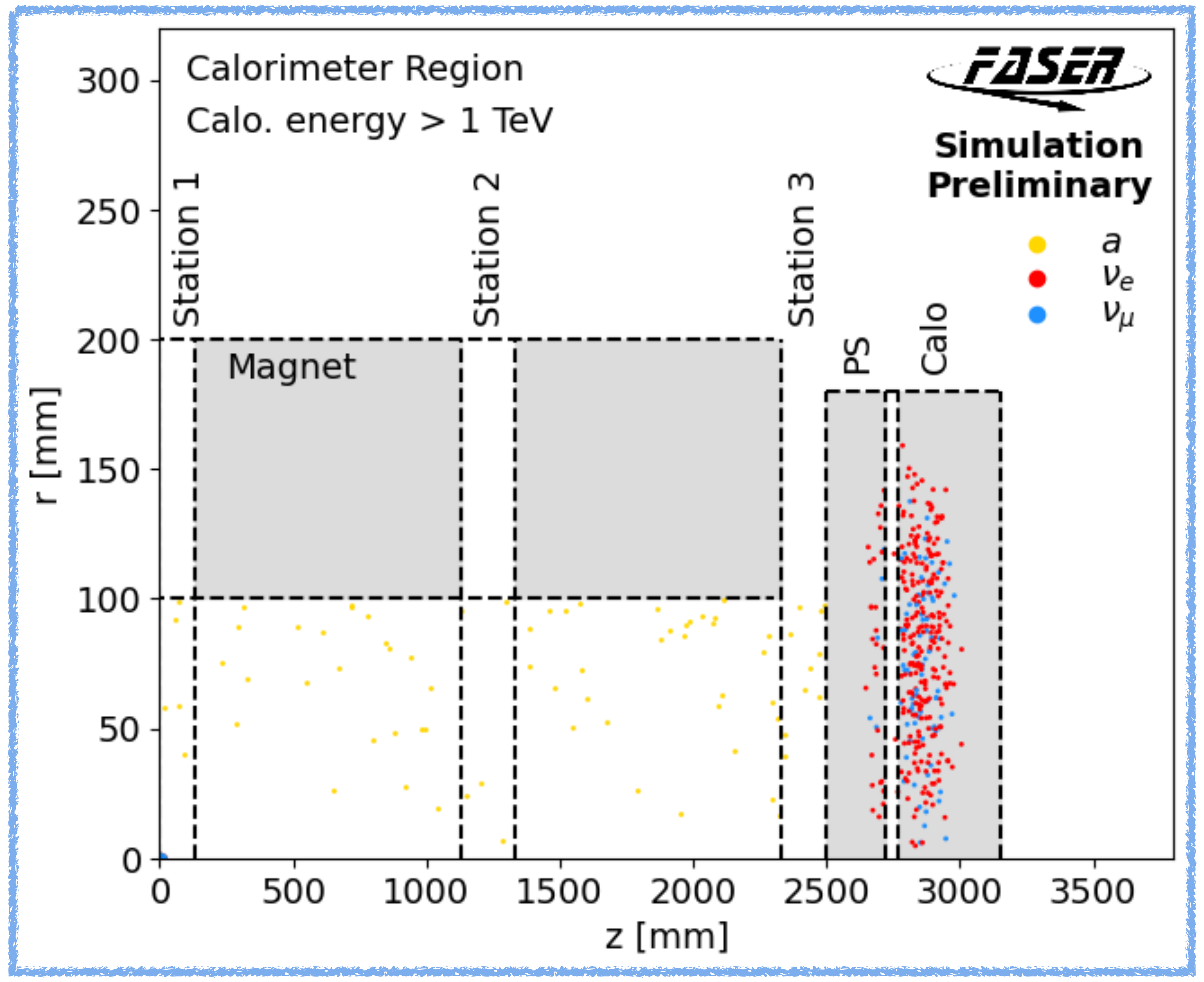
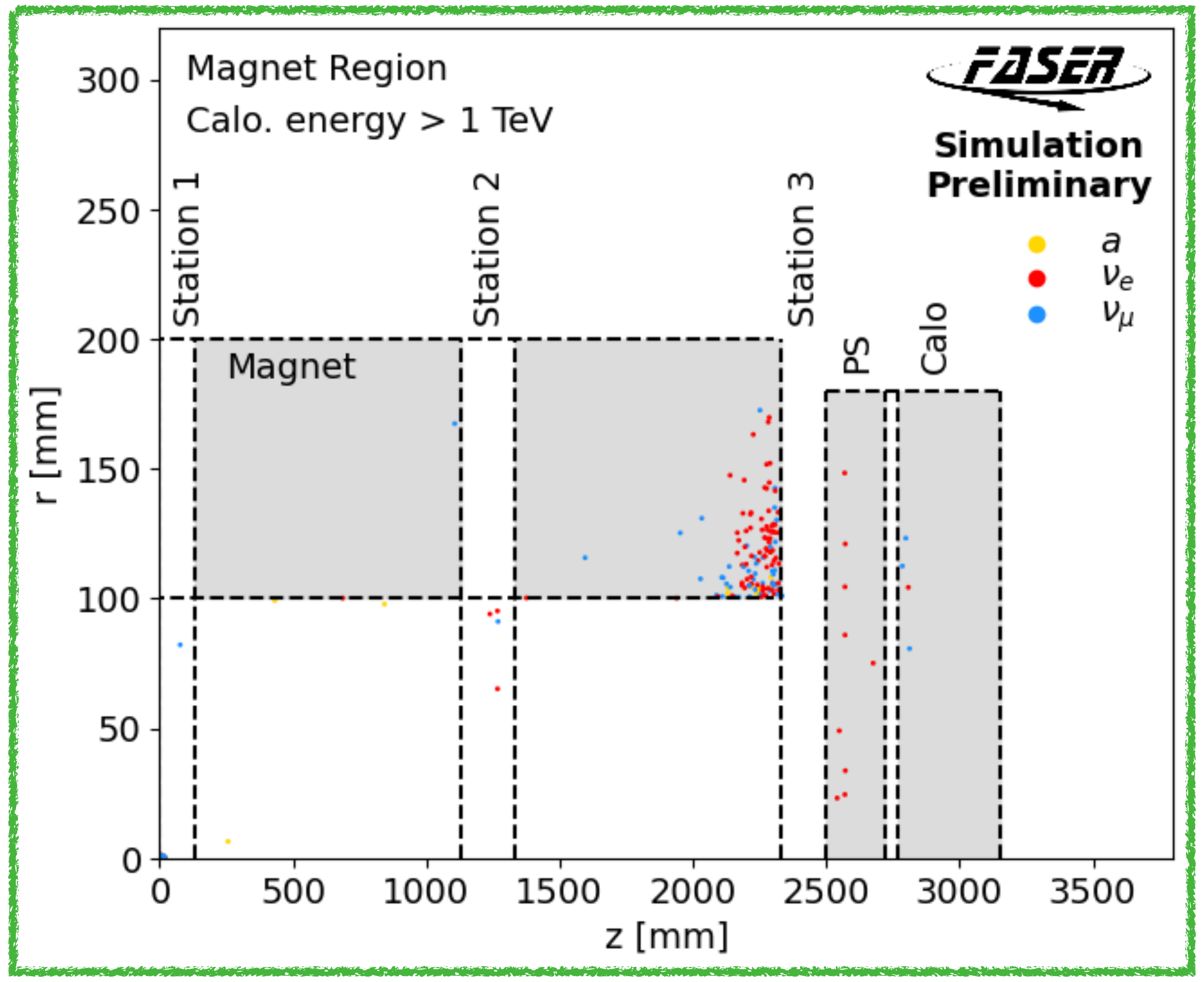
Trigger and Data Quality
Selecting events with calorimeter triggers
Calorimeter timing (> -5 ns and < 10 ns)
Baseline Selection
Veto/VetoNu Scintillator to have no signal (< 0.5 MIPs) Timing Scintillator to have no signal (< 0.5 MIPs)
Signal Region
Preshower Ratio to have EM shower in the Preshower (> 4.5) Second Preshower Layer to have signal (> 10 MIPs) Calorimeter to have a large deposit (> 1.5 TeV)

CDS

ALPs


Calorimeter Region
Calo. energy > 1 TeV
FASER
Simulation Preliminary
Station 1
Station 2
Station 3
PS
Calo
Magnet
a
ν_e
ν_μ
r [mm]
z [mm]


Magnet Region
Calo. energy > 1 TeV
FASER
Simulation Preliminary
Station 1
Station 2
Station 3
PS
Calo
Magnet
a
ν_e
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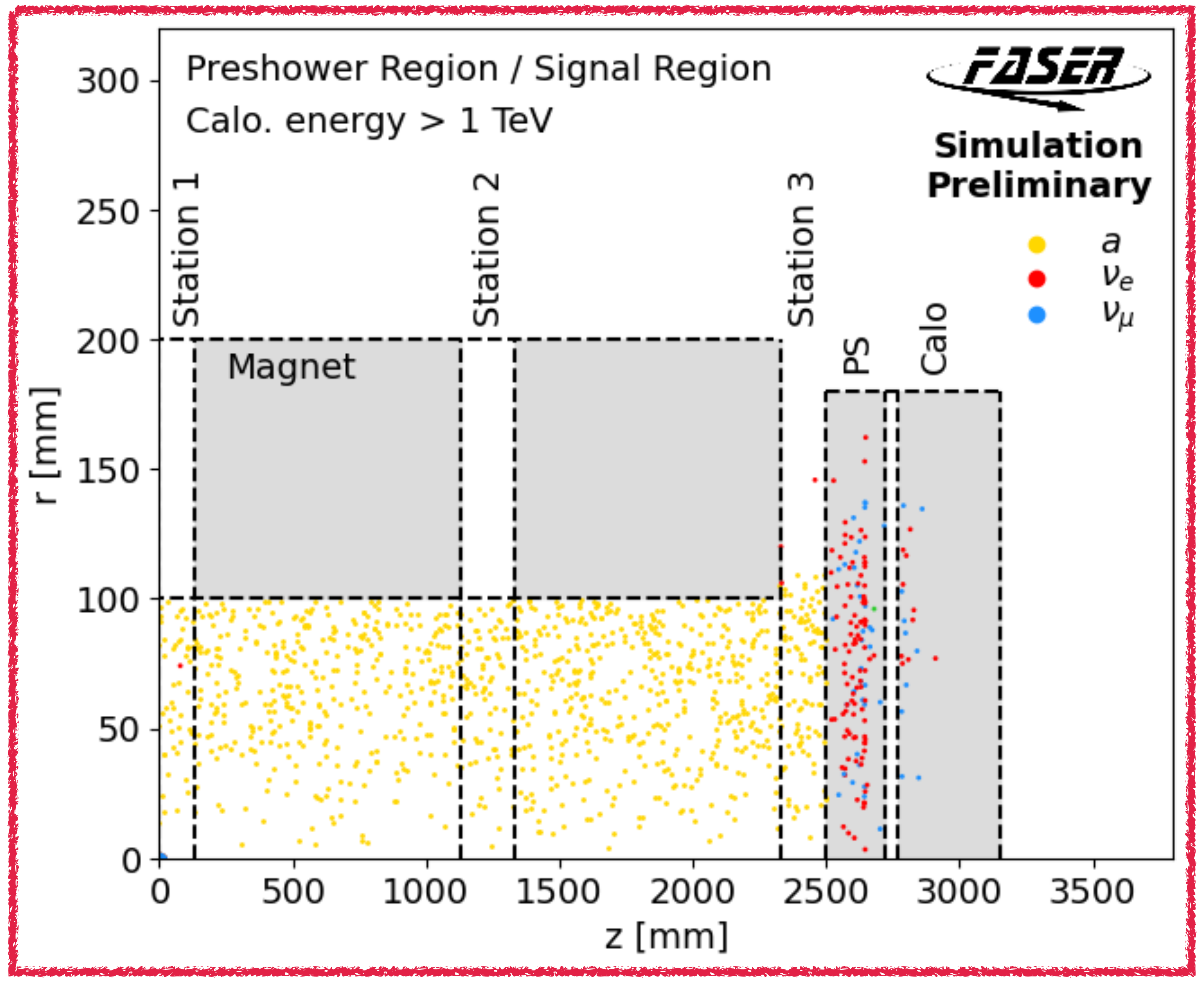
r [mm]
z [mm]


Preshower Region / Signal Region
Calo. energy > 1 TeV
FASER
Simulation Preliminary
Station 1
Station 2
Station 3
PS
Calo
Magnet
a
ν_e
ν_μ
r [mm]
z [mm]

CDS

ALPs

- One observed data event in the ALP search