FASER and the Forward Physics Facility

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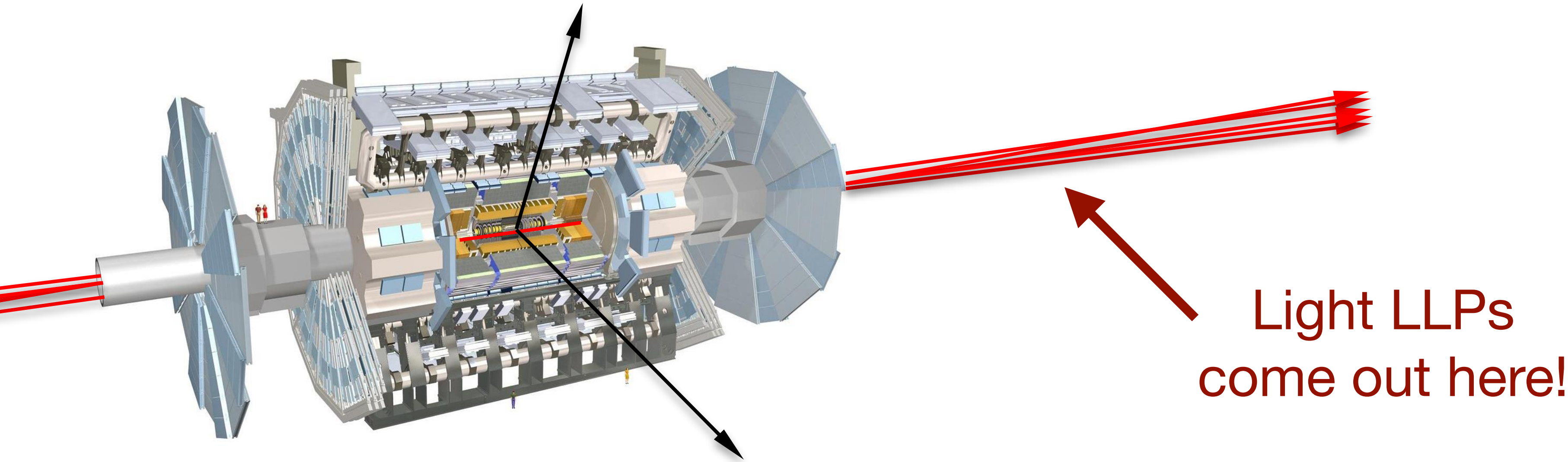
University of Oregon
for the FASER Collaboration

28 March, 2024

Future of HEP: A New Generation, a New Vision

Aspen Center for Physics

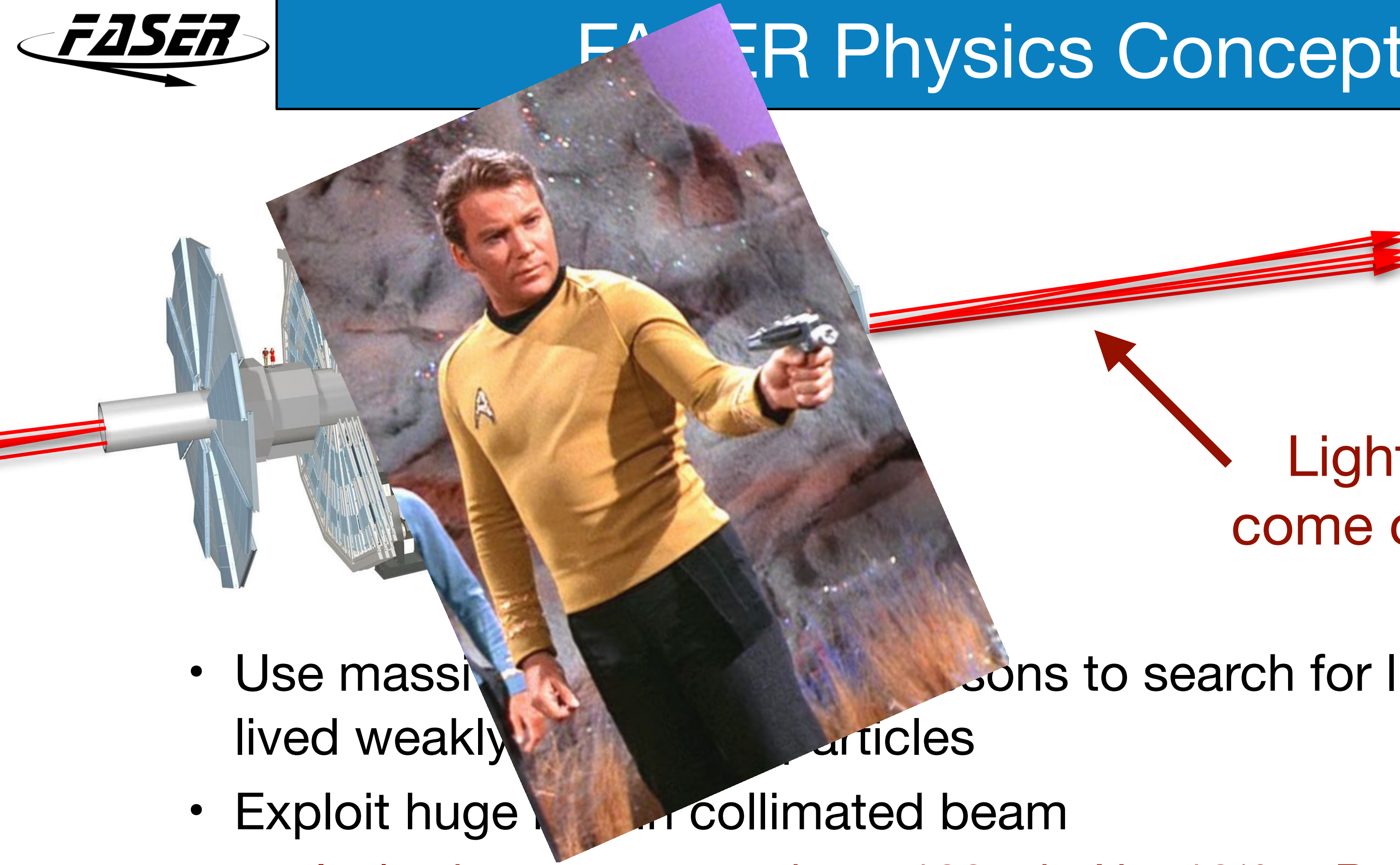
FASER Physics Concept



- Use massive rate of forward mesons to search for light long-lived weakly interacting particles
- Exploit huge rate in collimated beam
  - Inelastic pp cross-section: ~100 mb, N ~ 10^{16} at Run3
  - Very forward production: $\theta \sim \Lambda_{qcd} / E$ ~ mRad
  - Decay length: ~100 m for m ~ 10-100 MeV, $\epsilon \sim 10^{-5}$
- Put small detector on line-of-sight collision axis, probe unexplored territory!

Letter of Intent: CERN-LHCC-2018-030

FA ER Physics Concept



- Use massi… …sons to search for light long-lived weakly… …articles
- Exploit huge … …n collimated beam
  - Inelastic pp cross-section: ~100 mb, N ~ 10^{16} at Run3
  - Very forward production: $\theta \sim \Lambda_{qcd} / E \sim$ mRad
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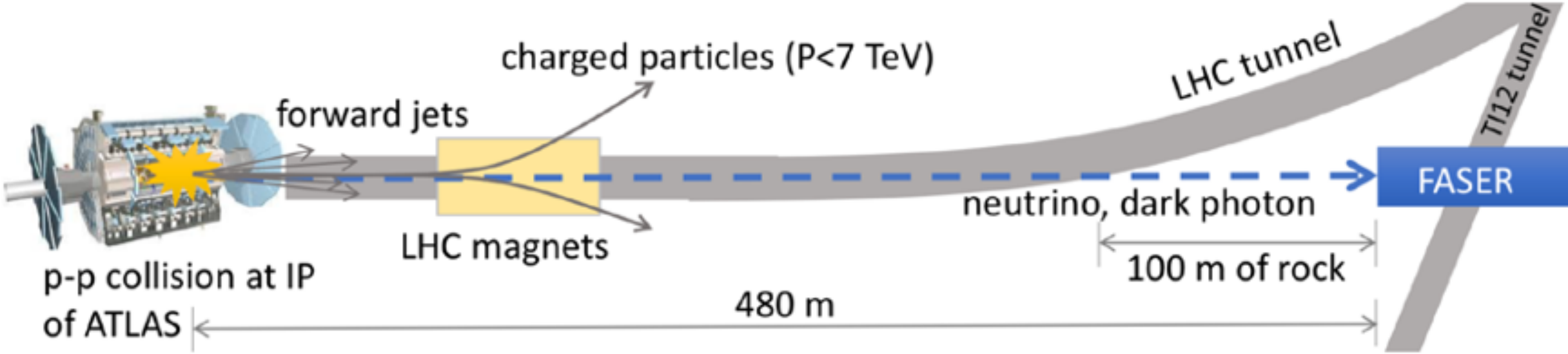
Letter of Intent: [CERN-LHCC-2018-030]

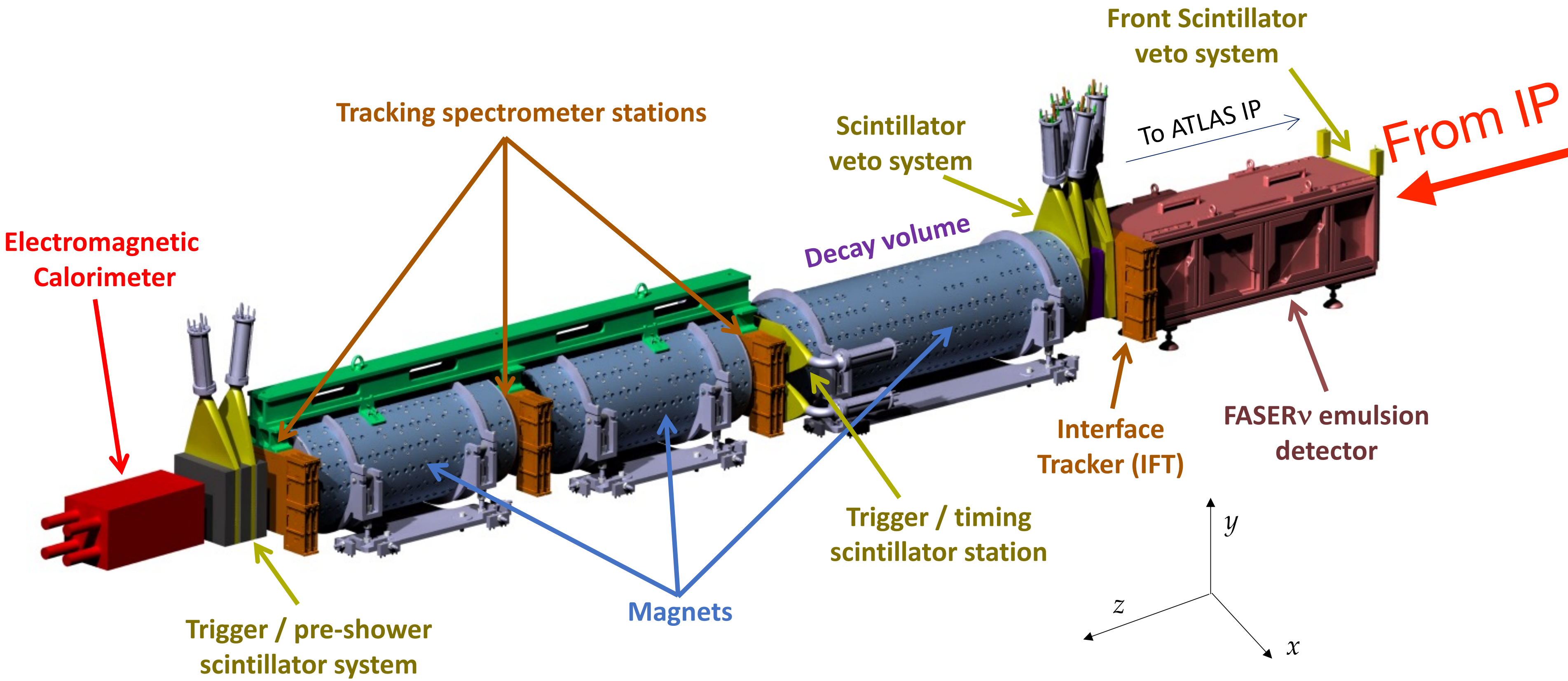
FASER Location



- FASER is 480m away from IP1 on the collision axis
  - 100m of rock shielding before detector
- Designed for a variety of long-lived, weakly interacting particles
  - New physics: Dark Photons, Axion-like particles, …
  - Neutrinos: ν_e, ν_μ, ν_τ
  - Also observe SM muons
- Demonstrates small and cheap experiment
  - Proposed in 2017, installed and taking data in 2021!
  - Currently 96 members, 26 institutions, 10 countries

Tech Proposal: [CERN-LHCC-2018-036]
Physics Prospects: [PRD99 095011 (2019)]

FASER Detector

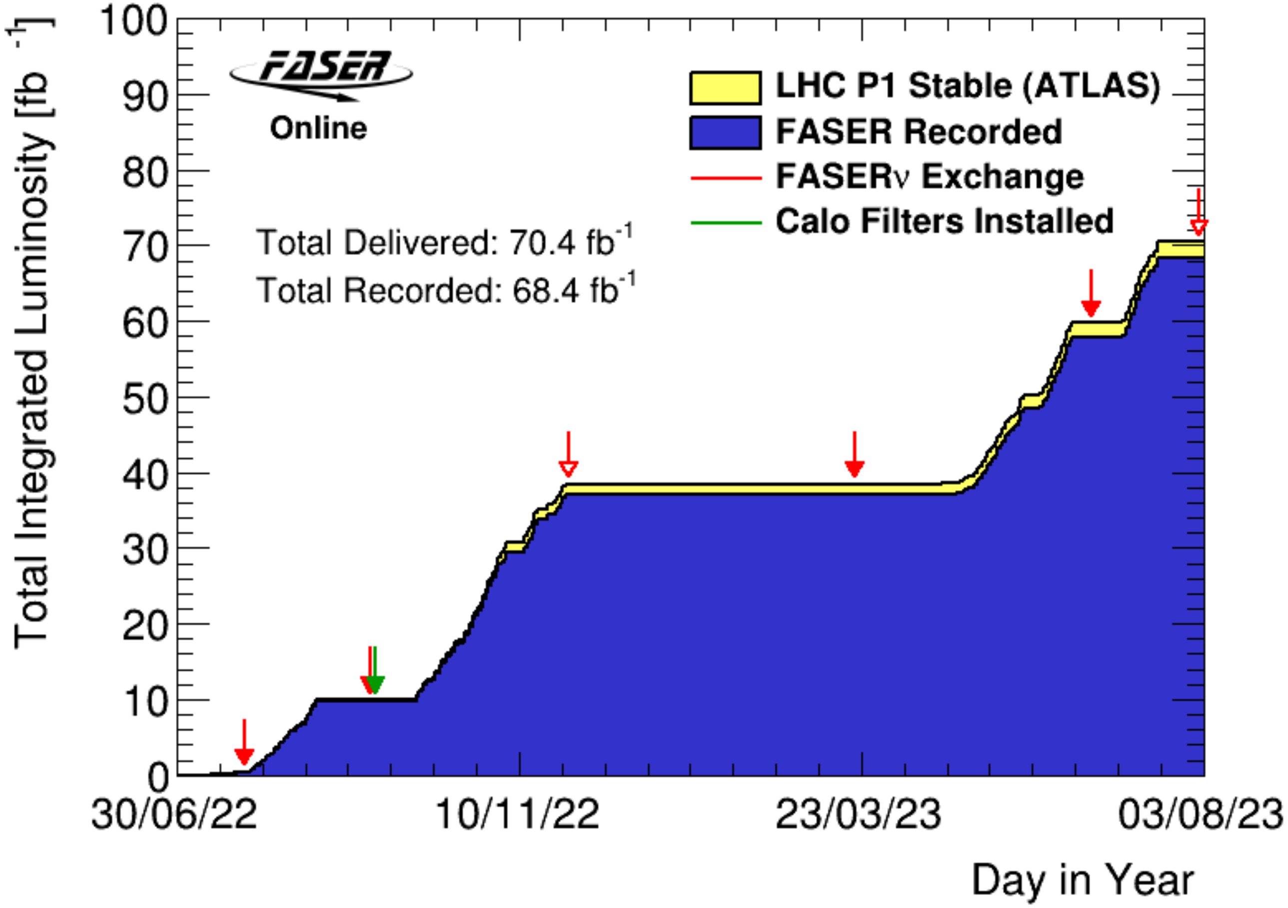


- Detector design constrained by cost, space, and time
- Scintillators w/ PMT readout for veto, trigger, and preshower (particle ID)
- 96 ATLAS SCT modules + 0.6T dipole magnets, r = 10 cm aperture
- 4 LHCb calorimeter modules
- 1.1 Ton Tungsten-emulsion target for additional neutrino sensitivity

Installed in TI12 tunnel

Detector Paper: arXiv: 2207.11427

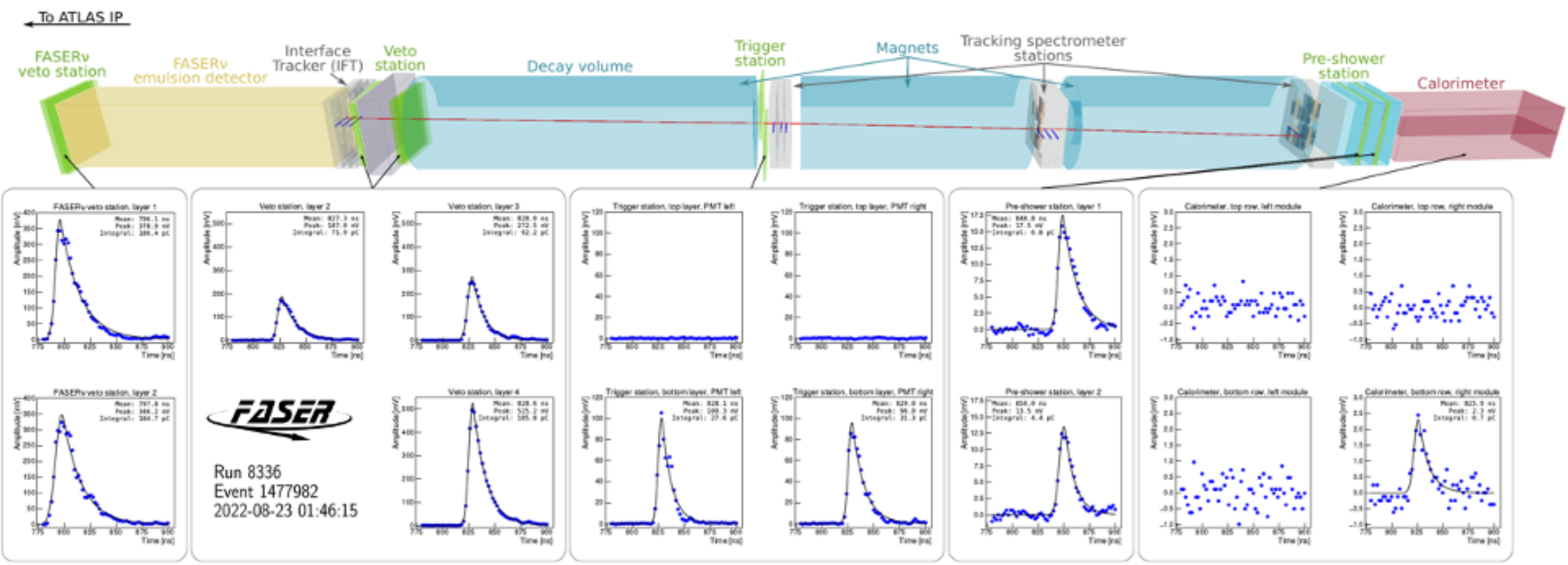
FASER Luminosity



- 4 years from idea to realization
- Installed and commissioned in time for Run3 startup
- Have recorded Run3 data with 97% efficiency

Muons

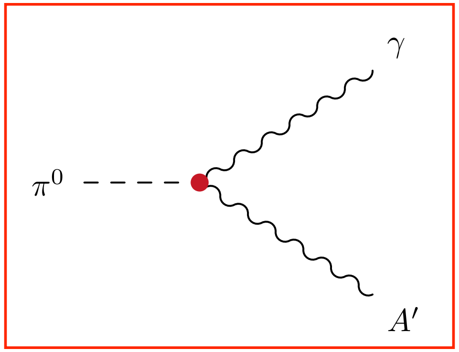
- ~250 Hz of muons from IP1 through r=10 cm dipole aperture (total trigger rate ~1 kHz)
- Rate highly correlated with luminosity (i.e. collisions)
- Important for tracker alignment/performance, calorimeter stability, veto station efficiency measurements, overall monitoring

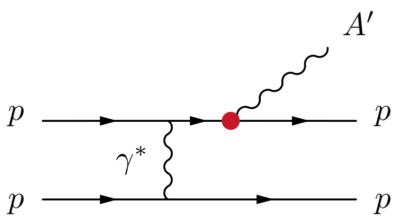


FASER BSM Results

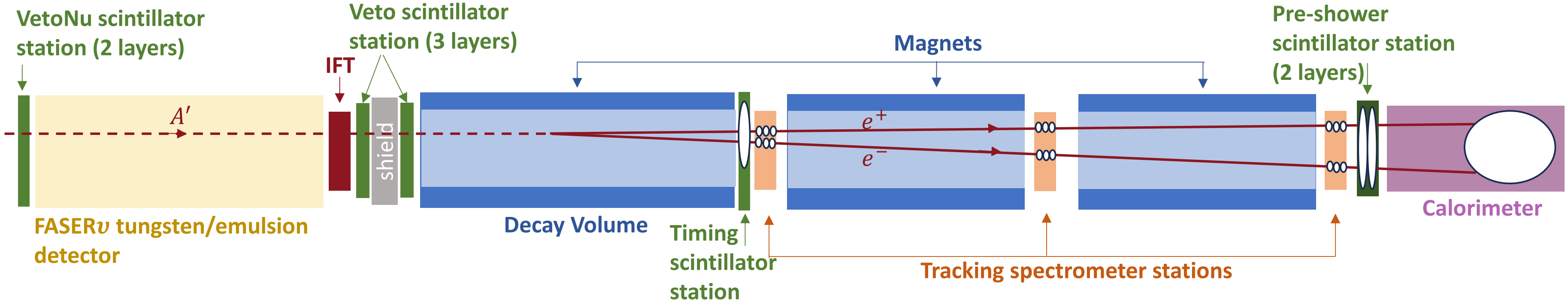
Dark Photons

- U(1) gauge boson, could provide portal to dark sector
  - Produced mainly by light mesons (π^0,η) via kinetic mixing





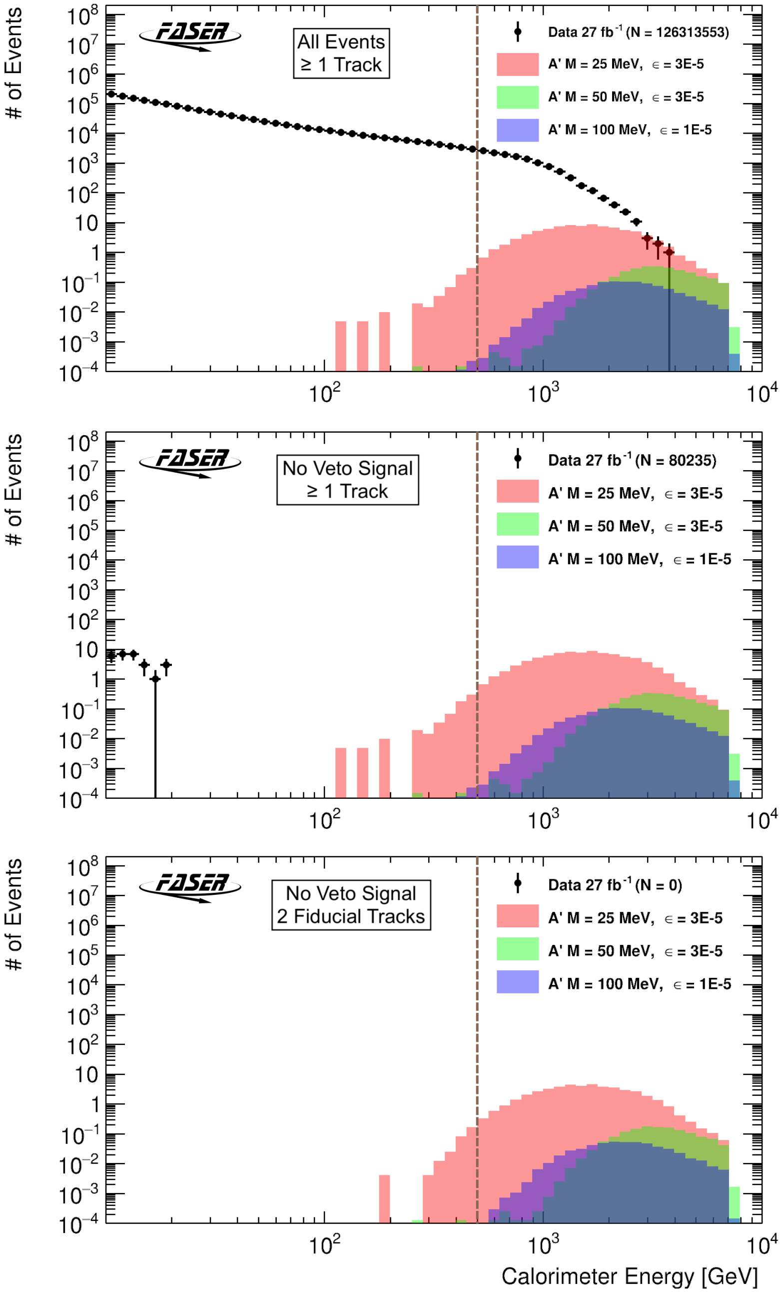
- Observed as A → e^+e^- pair appearing from 'nothing' with ~TeV of energy
  - Must decay in 1.5m decay volume - defines acceptance



Dark Photon Selection

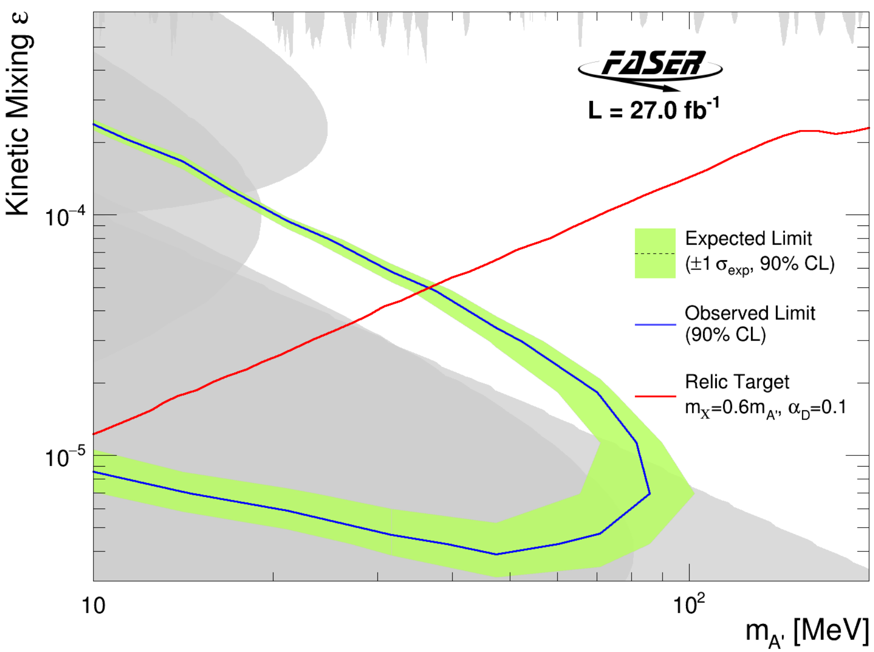
- Selection
  - 2 opposite-sign tracks within fiducial r < 95 mm
  - > 500 GeV in calorimeter
  - Nothing in all 5 veto counters
  - Something in downstream scintillators
  - In time with LHC collision
- Backgrounds Considered
  - Veto inefficiency
  - Neutrino interactions
  - Neutral hadrons
  - Large-angle muons
  - Non-collision / cosmics

All backgrounds found to be very small

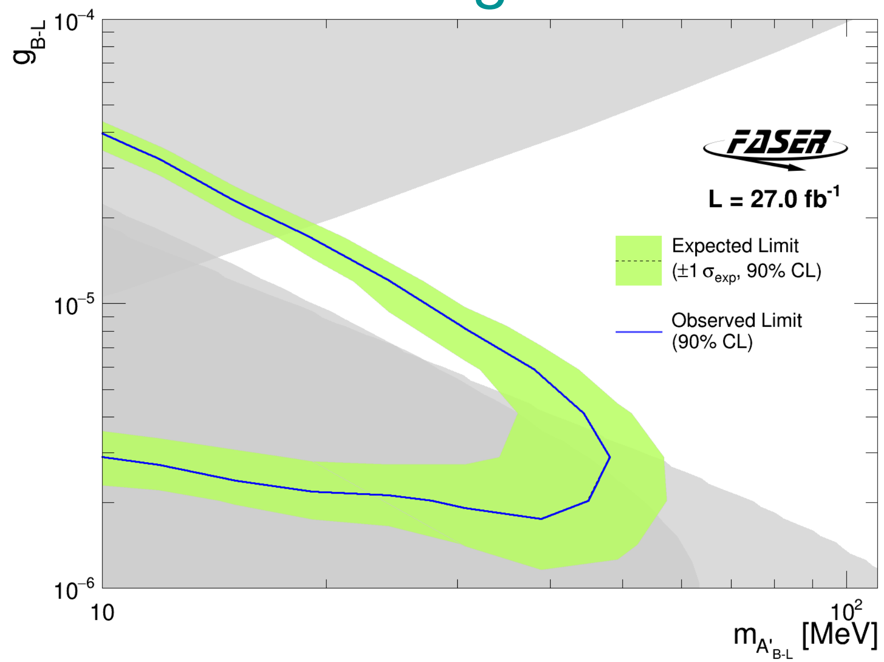


- Observed no events in 27 fb^{-1} from 2022, $(2.3 \pm 2.3) \times 10^{-3}$ background expected → place limits
  - Dark photon and B-L gauge boson models

Dark Photon



B-L Gauge Boson

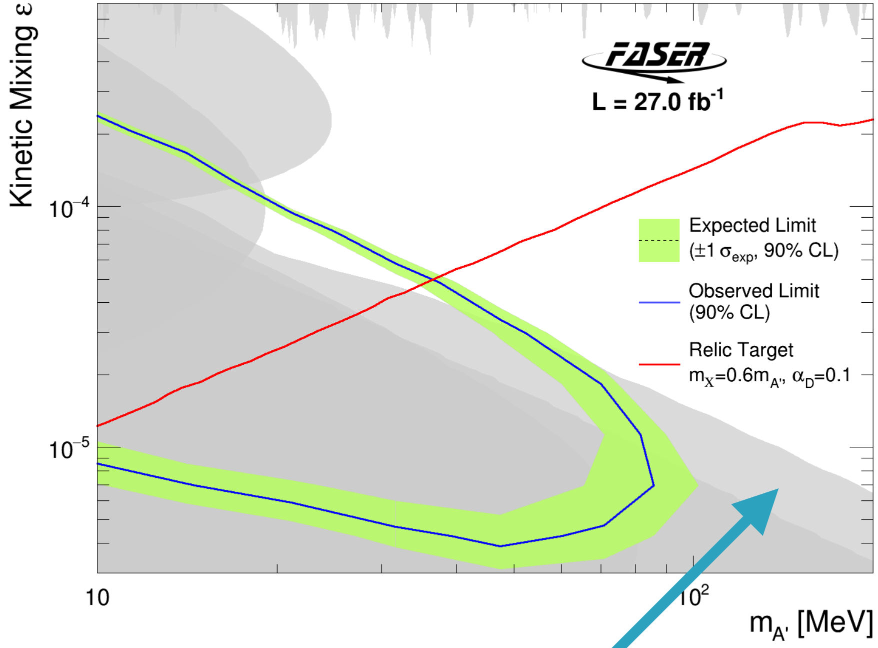


- Same dataset as shown last year, updated and published: [PLB 848 (2024) 138378]

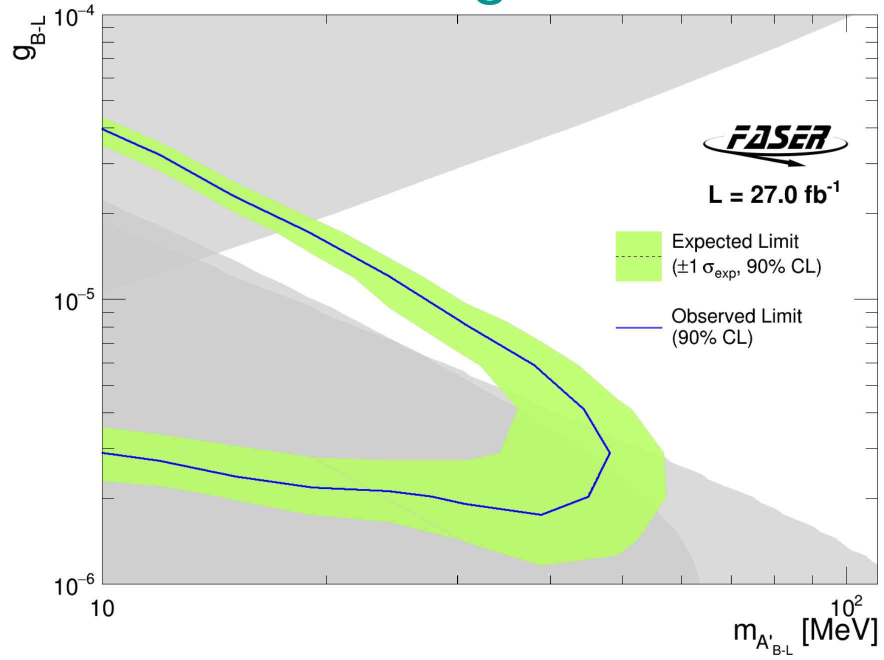
Dark Photon Results

- Observed no events in 27 fb^{-1} from 2022, $(2.3 \pm 2.3) \times 10^{-3}$ background expected → place limits
  - Dark photon and B-L gauge boson models

Dark Photon



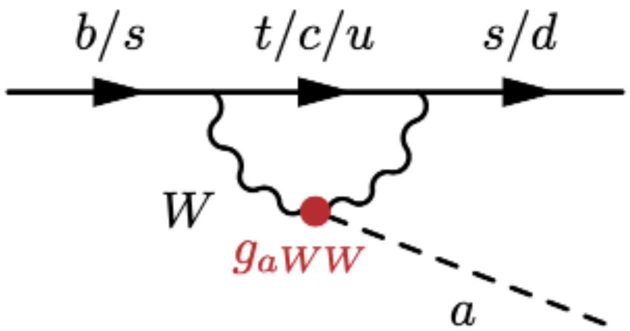
B-L Gauge Boson



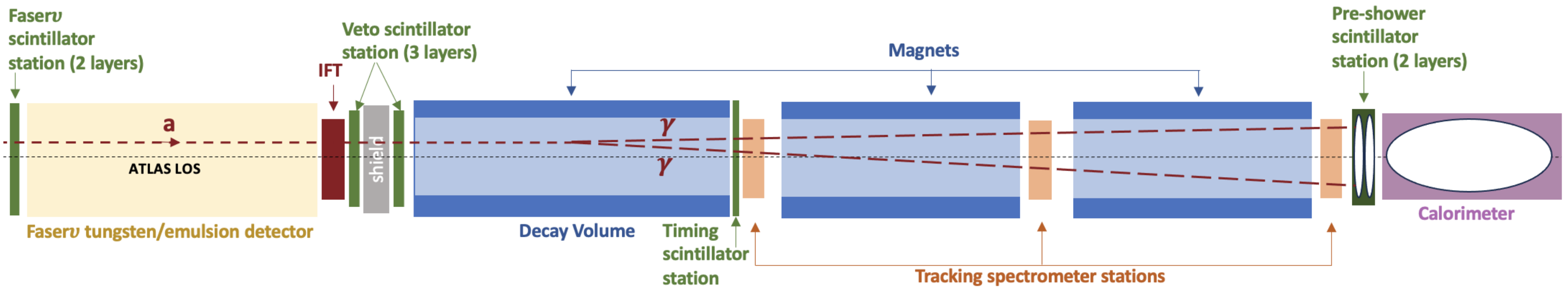
- New NA62 result! [arXiv:2312.12055]

Axion-like Particles - NEW!

- Currently sensitive to axion-like particles (ALPs) coupling to $SU(2)_L$ gauge bosons
  - Mainly produced in B meson decays in our sensitivity range



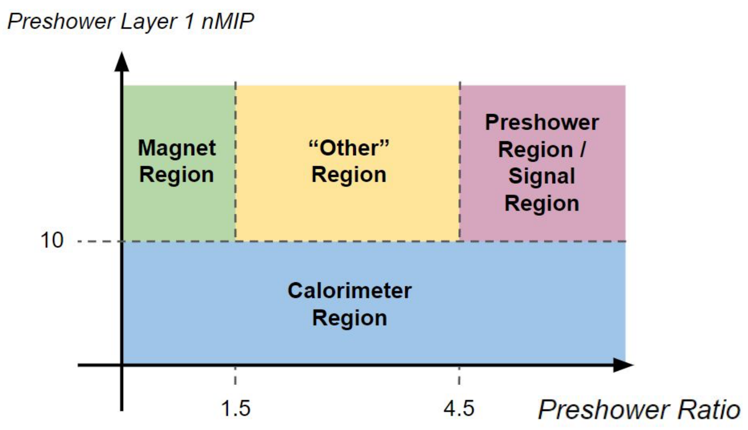
- Observed as a → γγ appearing from 'nothing' with ~TeV of EM energy (can't separate photons)
  - Can decay anywhere in FASER spectrometer volume



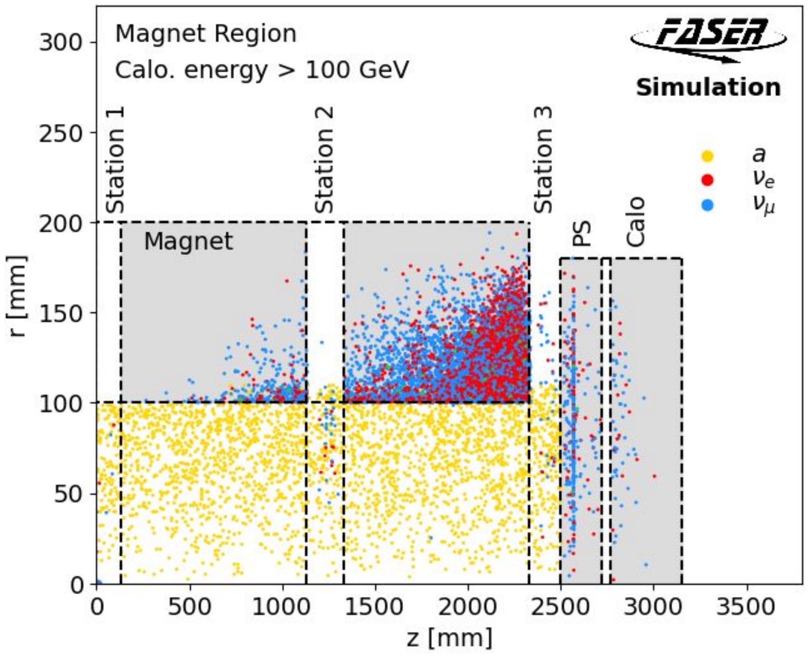
ALPs Selection

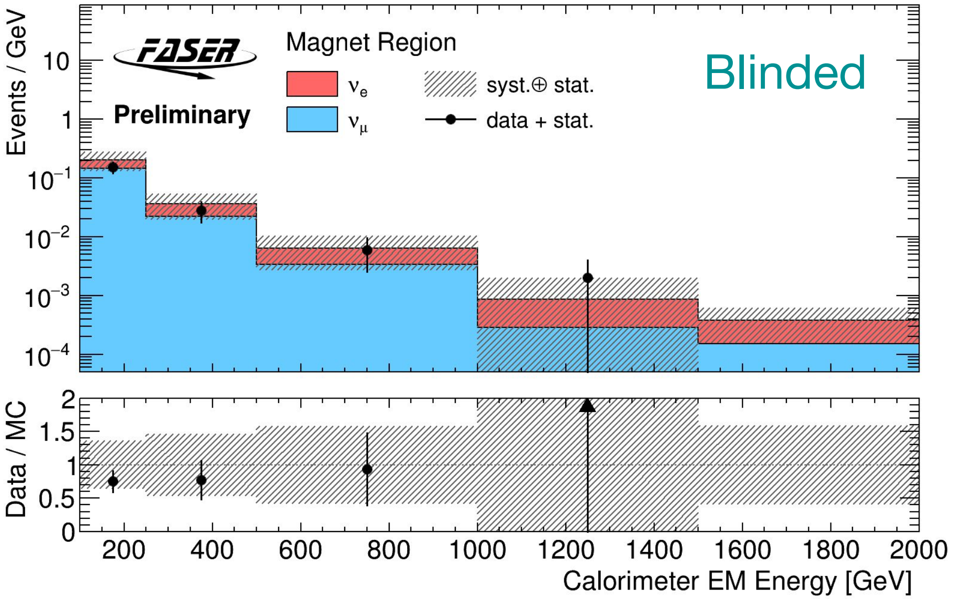
- Significant backgrounds from neutrinos interacting near the calorimeter
  - Require > 1.5 TeV in calorimeter
  - Use control regions to validate neutrino modeling

Neutrino control regions



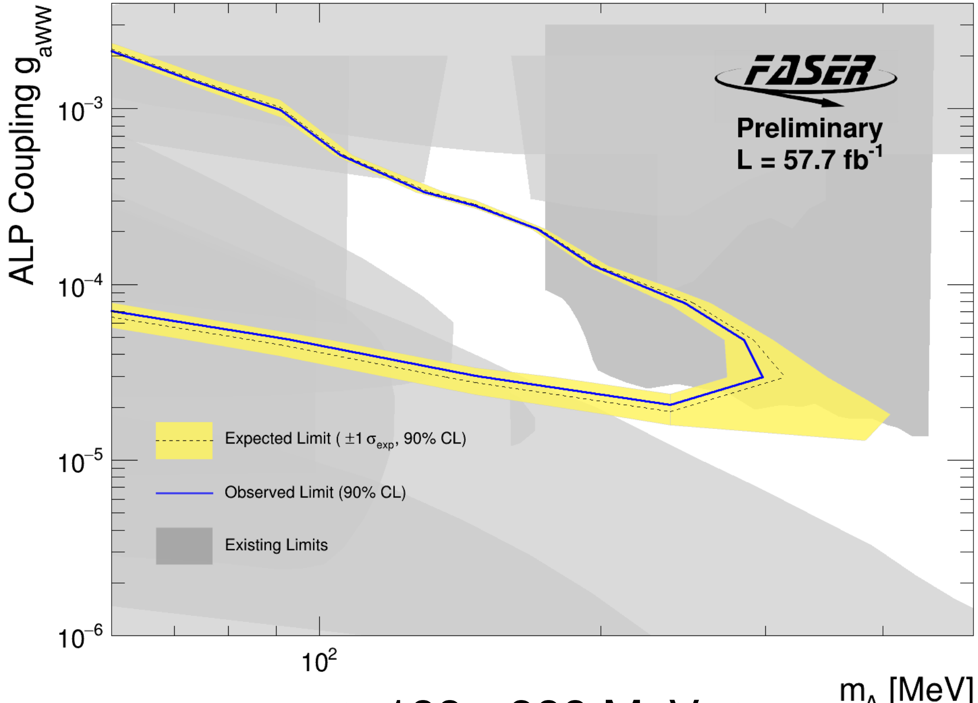
"Magnet" Region, E_{calo} > 100 GeV





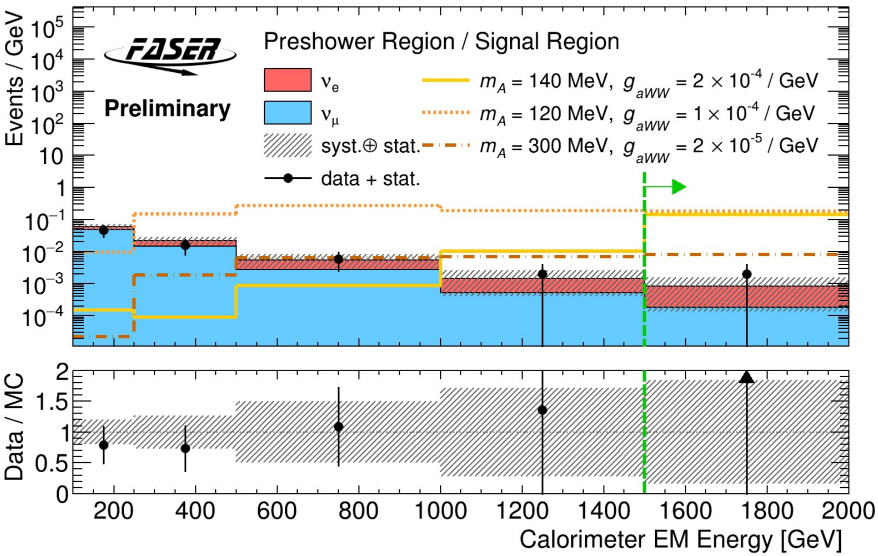
ALPs Results

- Observed 1 event in 58 fb^{-1} after unblinding
- Expecting 0.4 ± 0.4 from CC ν interactions



← 100 - 300 MeV →

Unblinded Signal region



First preliminary result on Axion-like Particles

Documentation here next week:

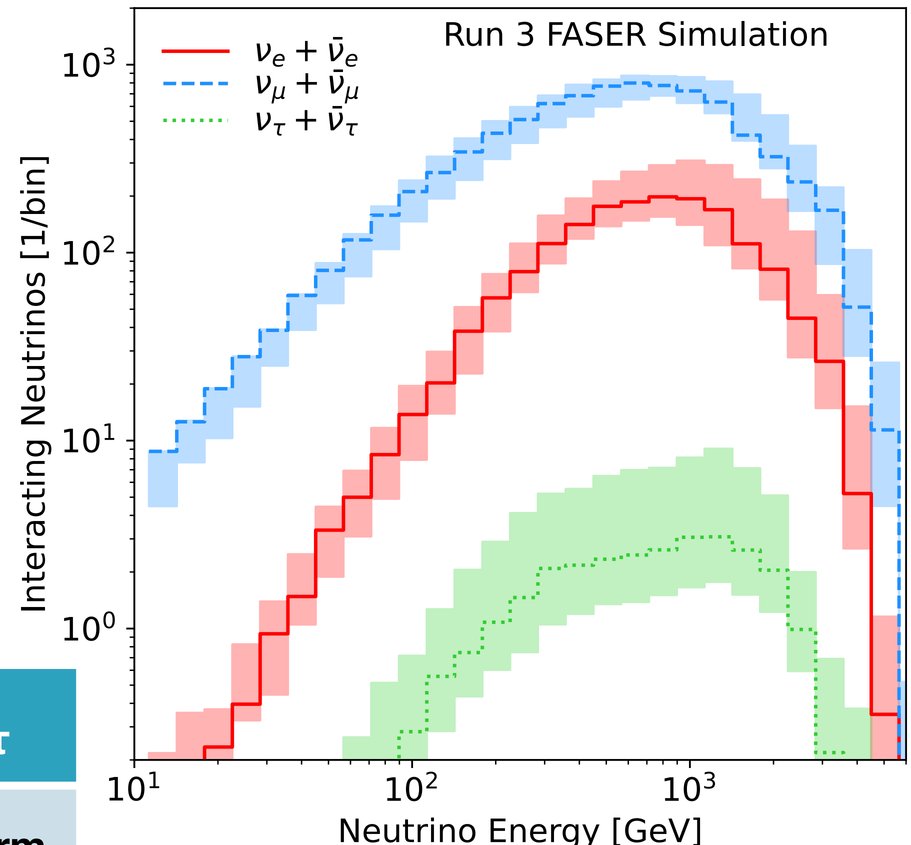
https://faser.web.cern.ch/physics/publications

FASER Neutrino Results

Neutrinos

- Copious production of neutrinos in forward region
- All species produced at ~TeV energy range
- Allows first direct observation of ν from collider

Spectrum of interacting ν



R3: 250 fb^{-1}	ν_μ	ν_e	ν_τ
Primary Source	**Pions**	**Kaons/ Charm**	**Charm**
Traversing FASER	**~10^{12}**	**~10^{11}**	**~10^{9}**
Interacting in FASERnu	**8,500**	**1,700**	**30**

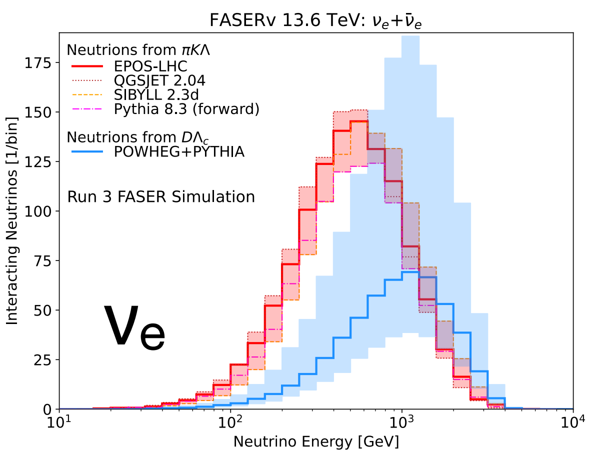
Rate Paper: arXiv: 2402.13318

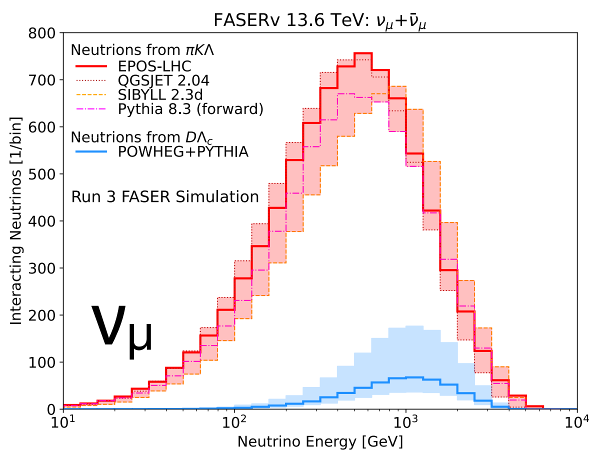
Neutrinos are Interesting

- Measure cross-section in uncovered TeV energy range
  - Highest man-made source, currently unconstrained
- Production rate measures forward hadron production
  - Novel input for PDFs, charm (ν_e) poorly constrained

Considerable interest for Neutrino telescopes, cosmic ray observatories, QCD, and measuring neutrino properties

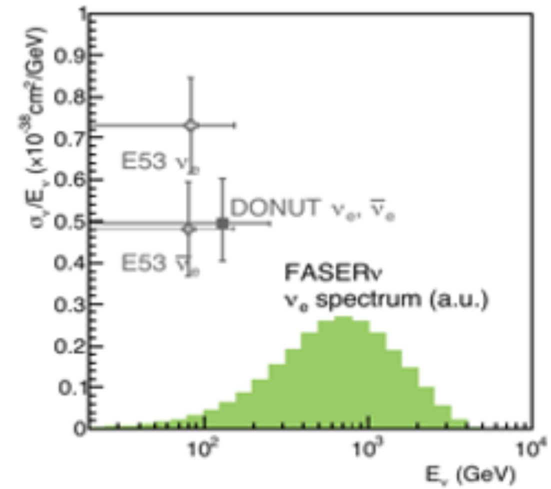
Spectrum of interacting ν





ν from π/K ν from charm

Measured σν



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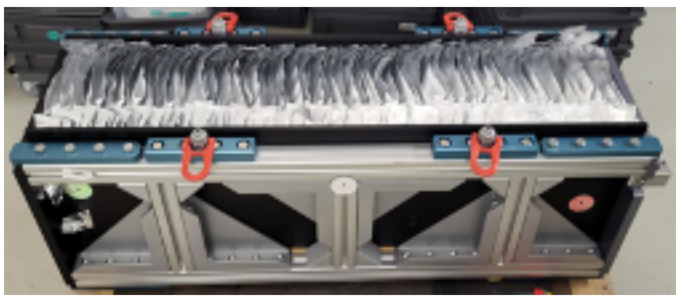
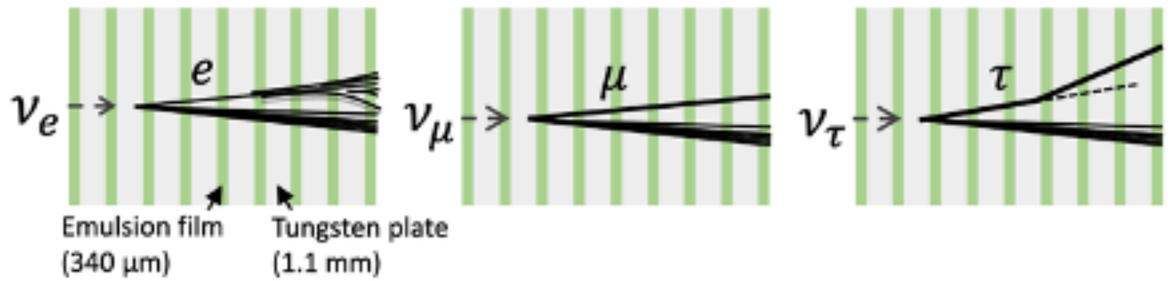
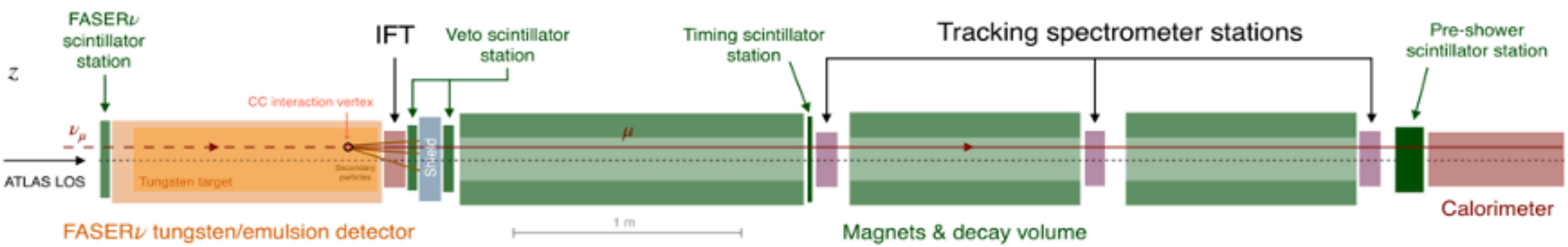
Detecting Neutrinos

- Emulsion detector - FASERnu
  - Sensitive to all 3 species, no charge information
  - 1.1 Ton Tungsten target w/ 730 emulsion planes
  - Exquisite ~300 nm hit resolution

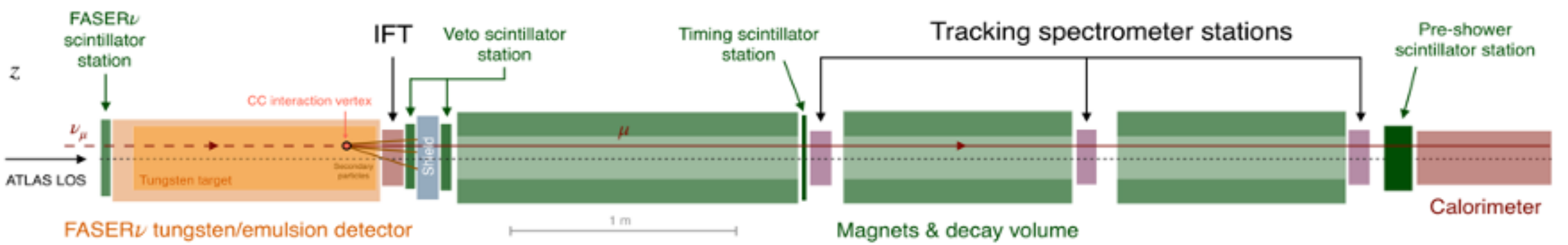


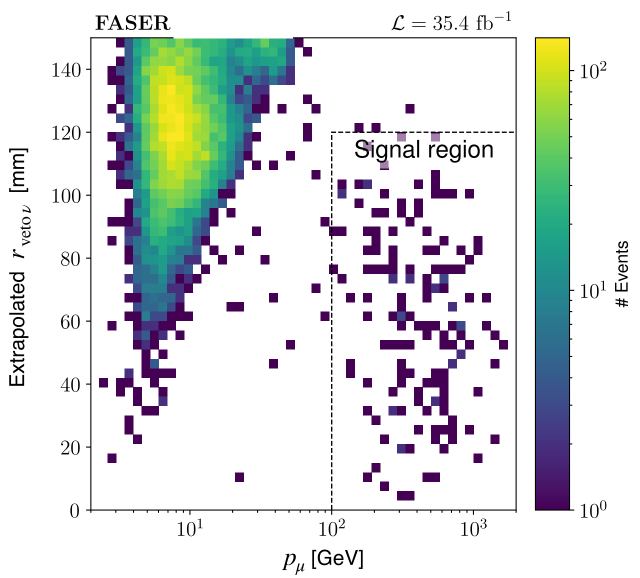


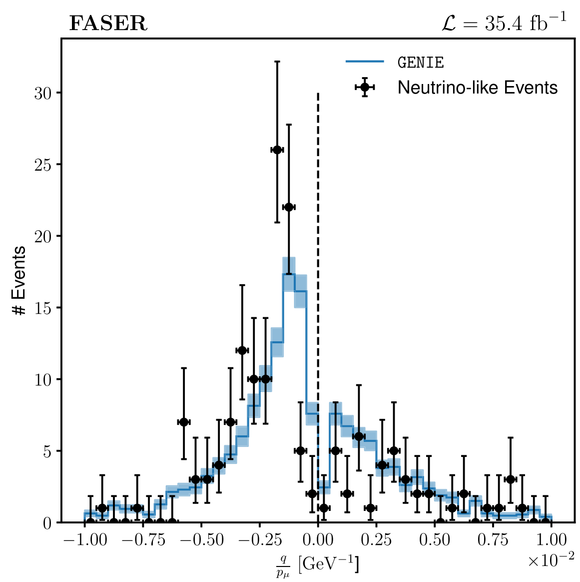
- Electronic detector - FASER
  - Sensitive to muon neutrinos, can separate ν_μ from $\overline{\nu}_\mu$

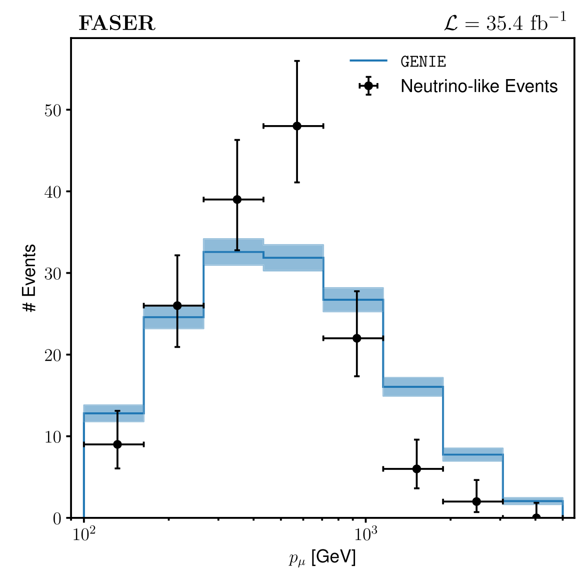


CC Neutrino Observation









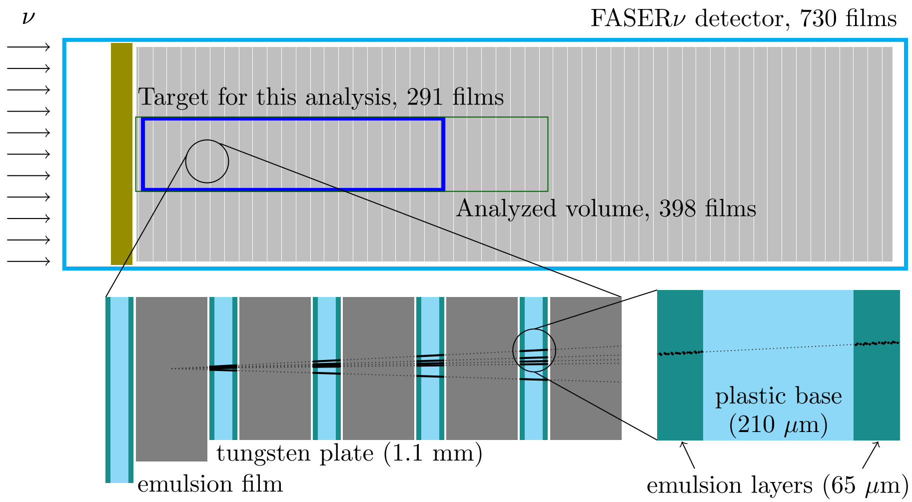
$$n_\nu = 153^{+12}_{-13}(\text{stat})\,^{+2}_{-2}(\text{bkg}) = 153^{+12}_{-13}(\text{tot})$$

(35.4 fb^{-1})

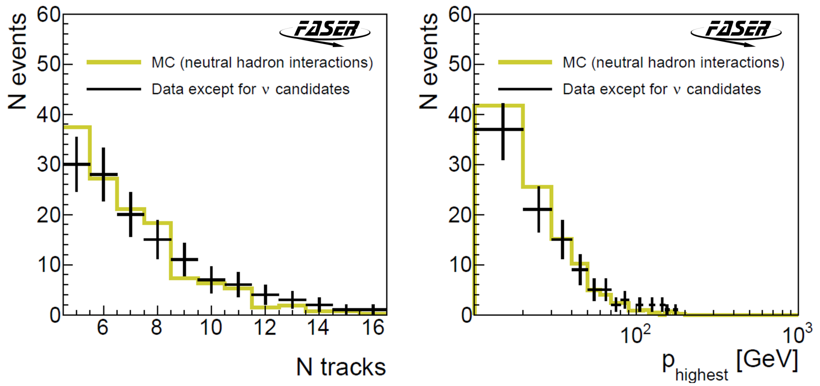
- Small background from neutral hadrons and large-angle muons

PRL 131, 031801 (2023)

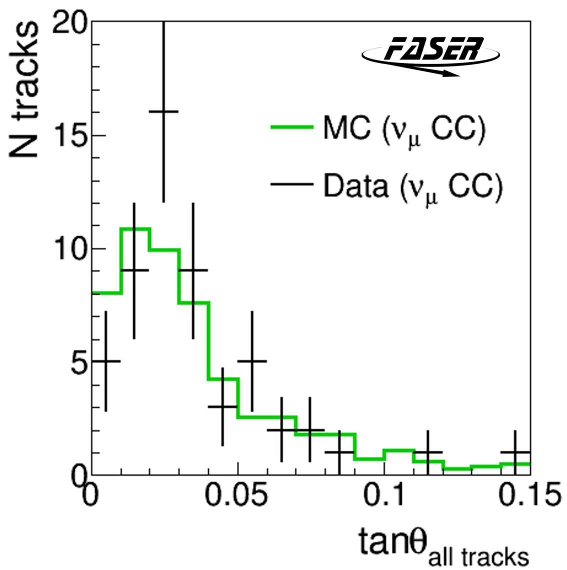
Stay tuned for update!



Neutral Hadrons



Neutrino Candidates



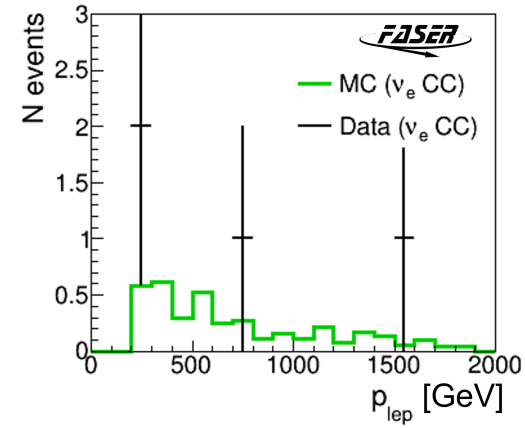
- Analyzed fraction of 1 exposure in 2022 (9.5 fb^{-1})
- Candidate vertices reconstructed and selected from scanning emulsion films (slow)
  - Energy (e) from shower multiplicity
  - Momentum (μ) from multiple scattering RMS
- Backgrounds primarily from neutral hadrons produced in muon interactions is surrounding rock, NC background also evaluated (small)

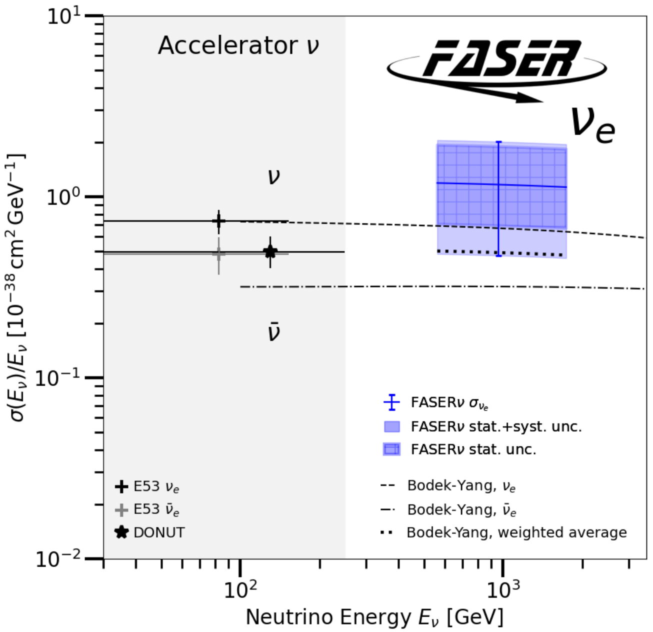
Emulsion Results

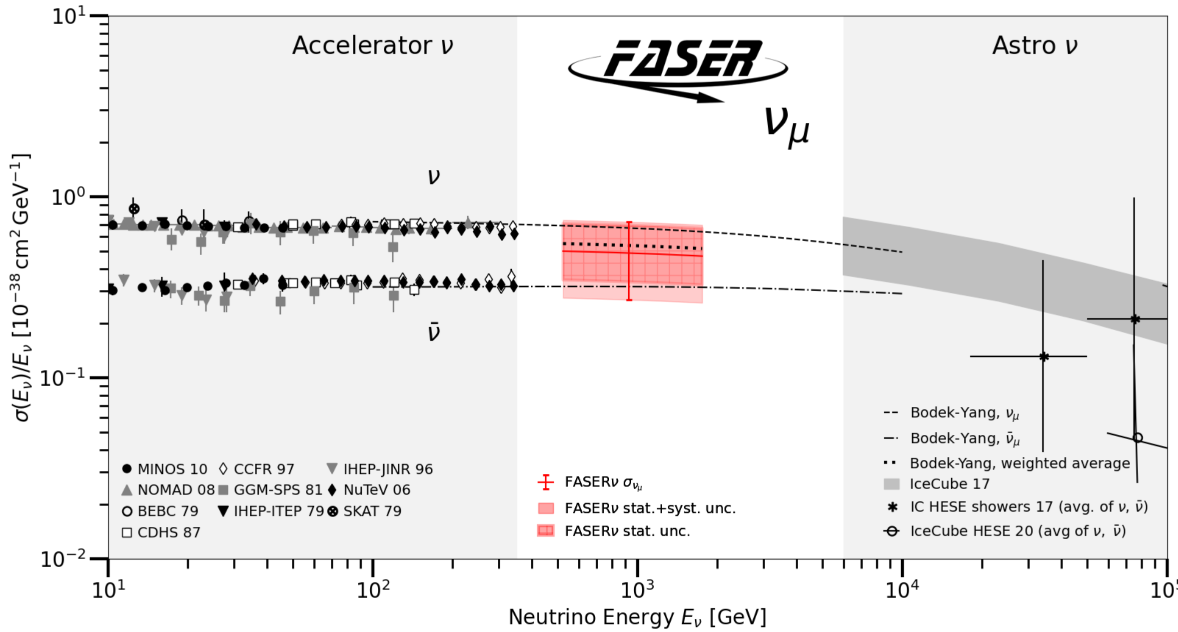
After all vertex selection requirements:

1.5 TeV!

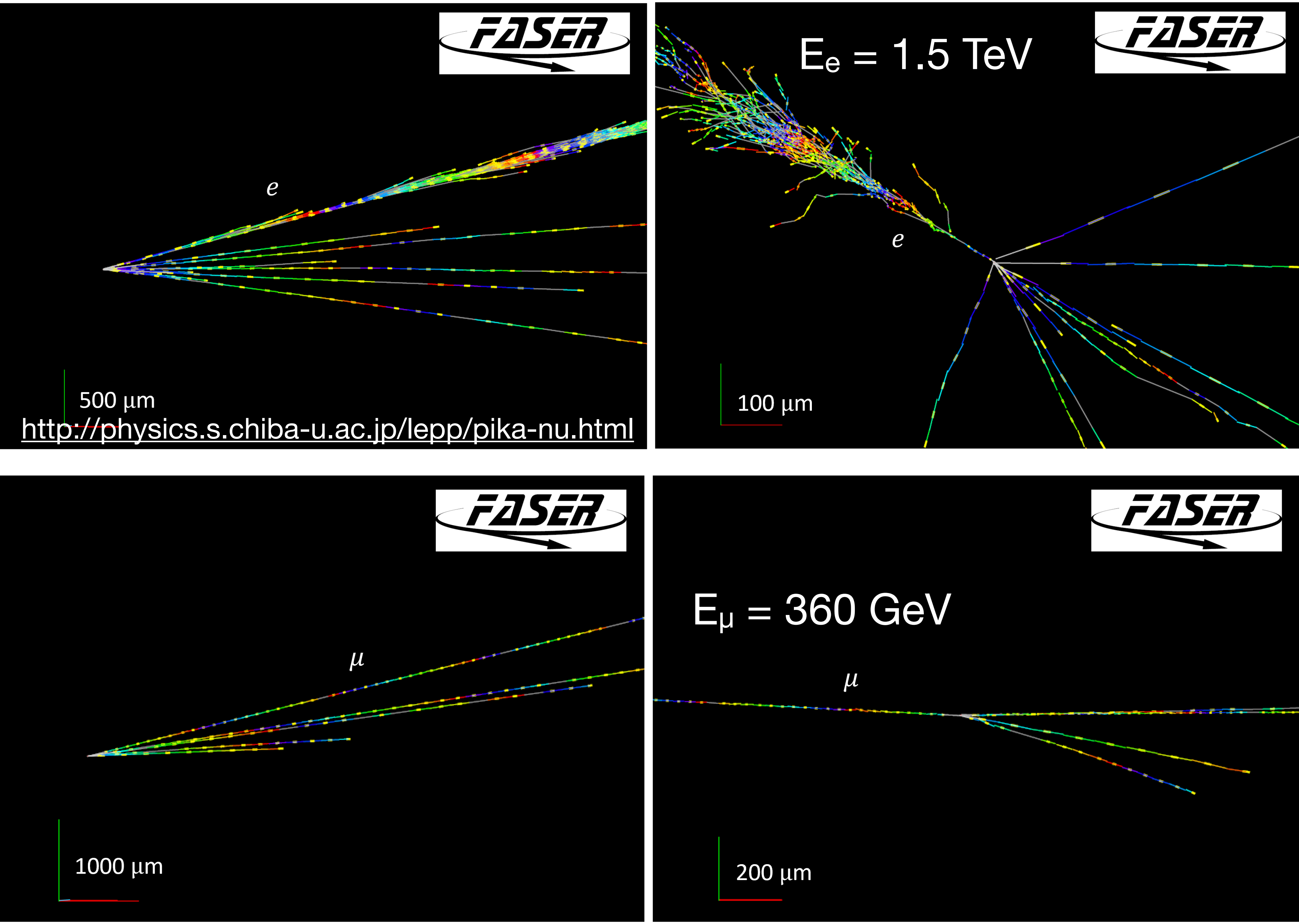
	Obs	Exp	Bgd	Sig
ν_e	4	1.1-3.3	0.025 ± 0.012	5.2 σ
ν_μ	8	6.5-12.4	0.22 ± 0.08	5.7 σ





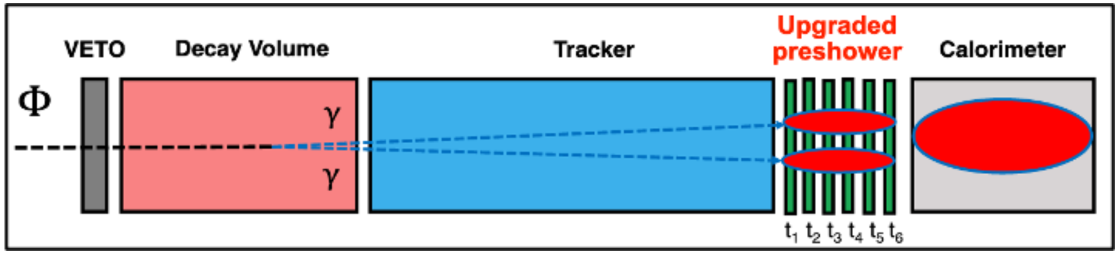


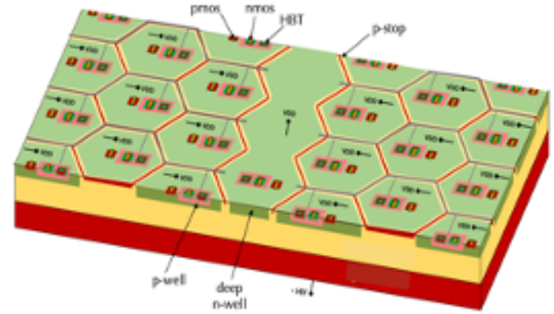
New! arXiv:2403.12520


e
500 µm
http://physics.s.chiba-u.ac.jp/lepp/pika-nu.html
E_e = 1.5 TeV
e
100 µm
µ
1000 µm
E_μ = 360 GeV
µ
200 µm

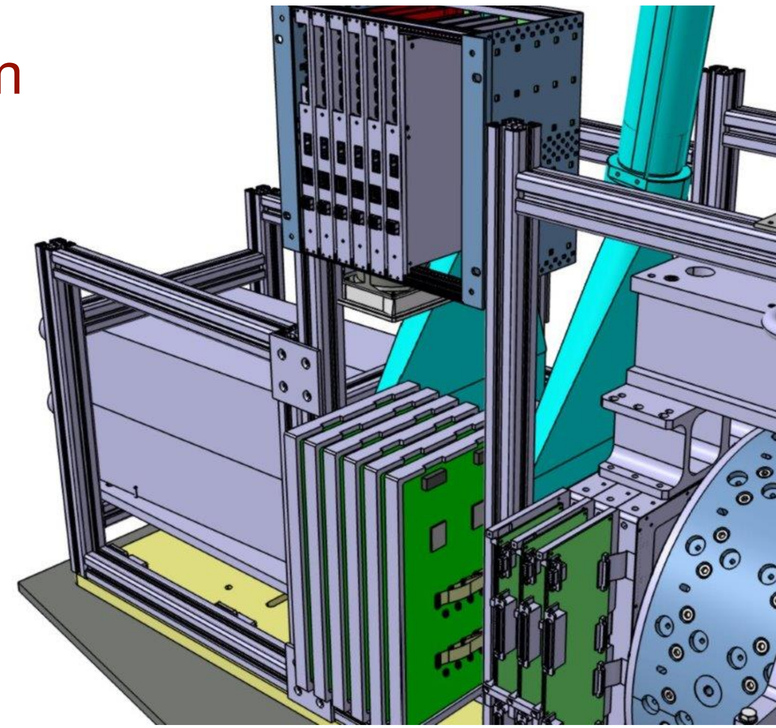
Future Plans

Near Future Plans





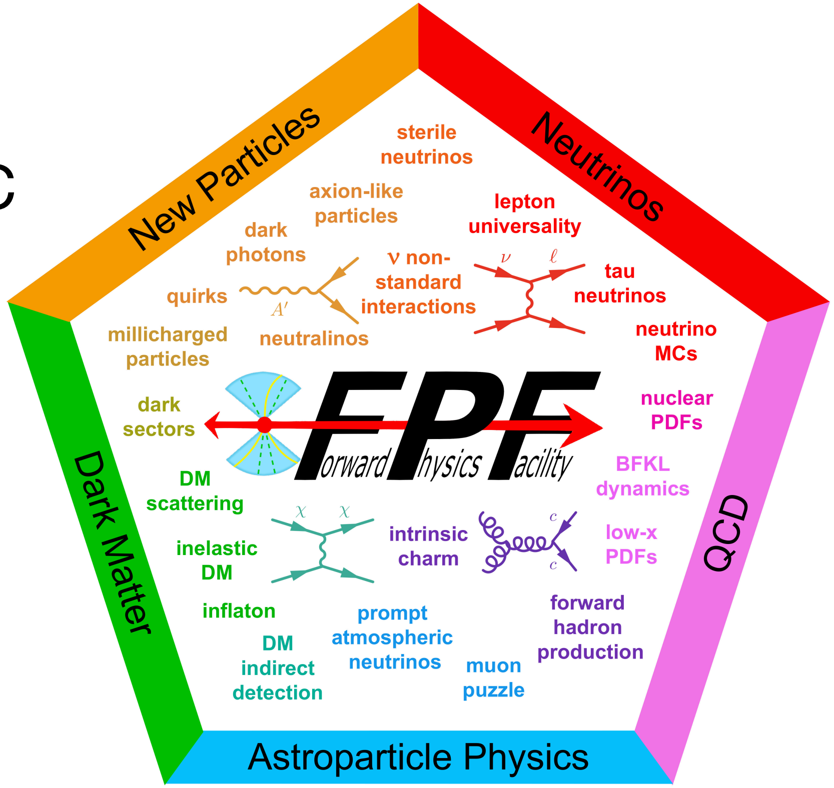
- FASER Preshower upgrade
  - 6 layers of high-granularity Si pixels with W absorber
  - Separate photons at ~200 μm
  - Installed before 2025 (Run3)
- Improve ability to identify 2γ, reject ν backgrounds
- FASER approved for Run4
  - Will record large dataset with upgraded FASER at HL-LHC



Preshower: CERN-LHCC-2022-006 Run4: CERN-LHCC-2023-009

Forward Physics Facility

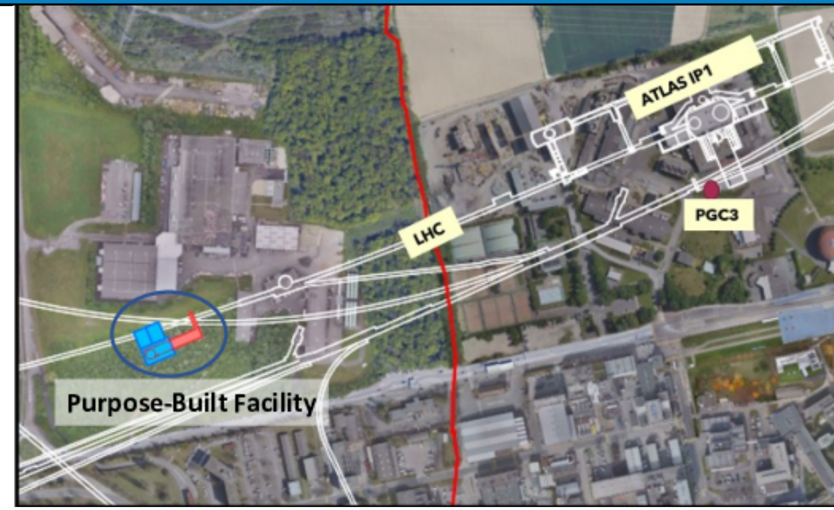
- FPF is a planned project at CERN to build a cavern to house experiments at HL-LHC
- Physics Goals similar to FASER but much improved reach and varied detectors
- Currently Proposed Detectors
  - FASER2 / FASERnu2
  - AdvancedSND - off-axis ν
  - FLArE - LAr TPC for ν
  - FORMOSA - millicharge det.

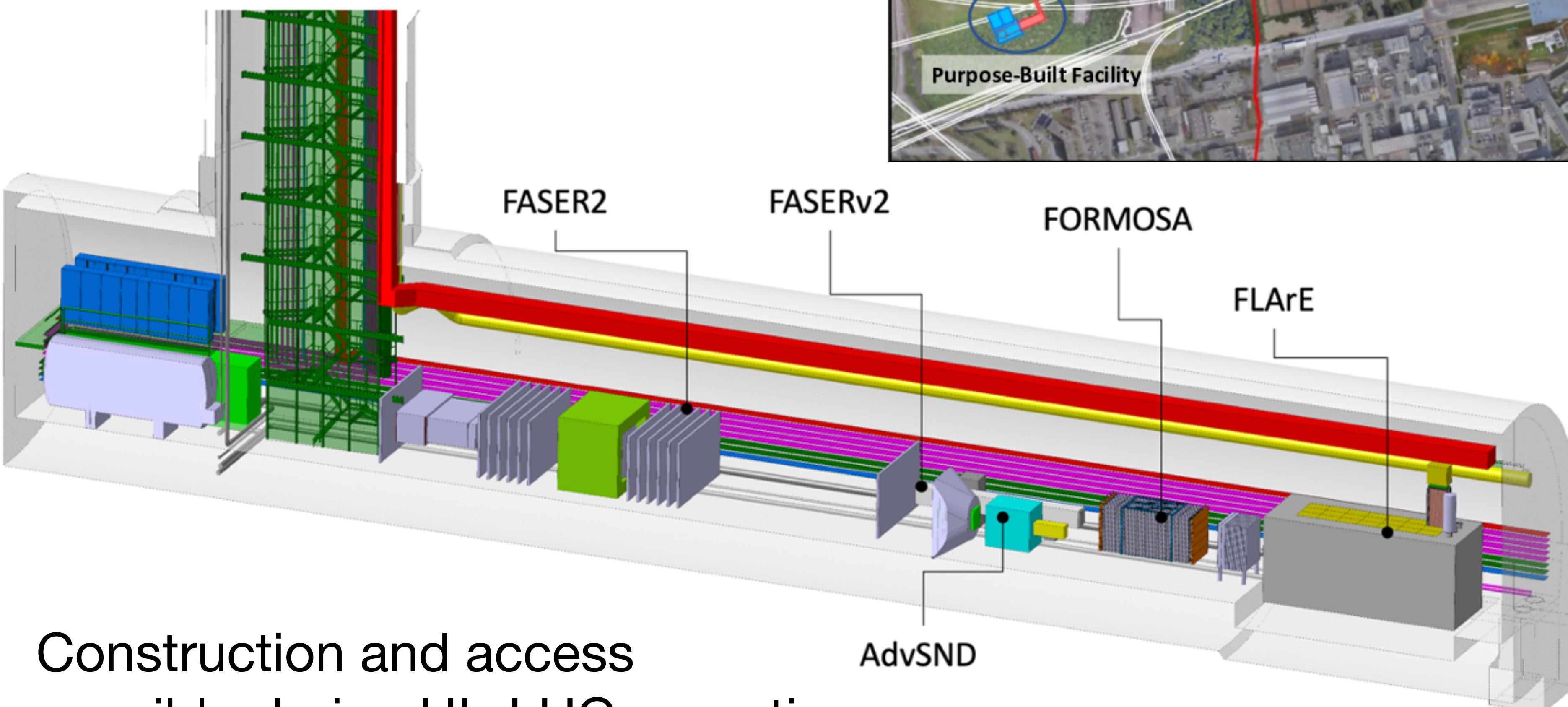


- Community
  - Supported by CERN [Physics Beyond Collider] group, [latest PBC Workshop] this week
  - fpf.web.cern.ch, latest meeting Feb: 7th FPF Meeting

FPF Layout

Dedicated ~65m cavern,
620m from IP1, on the French side

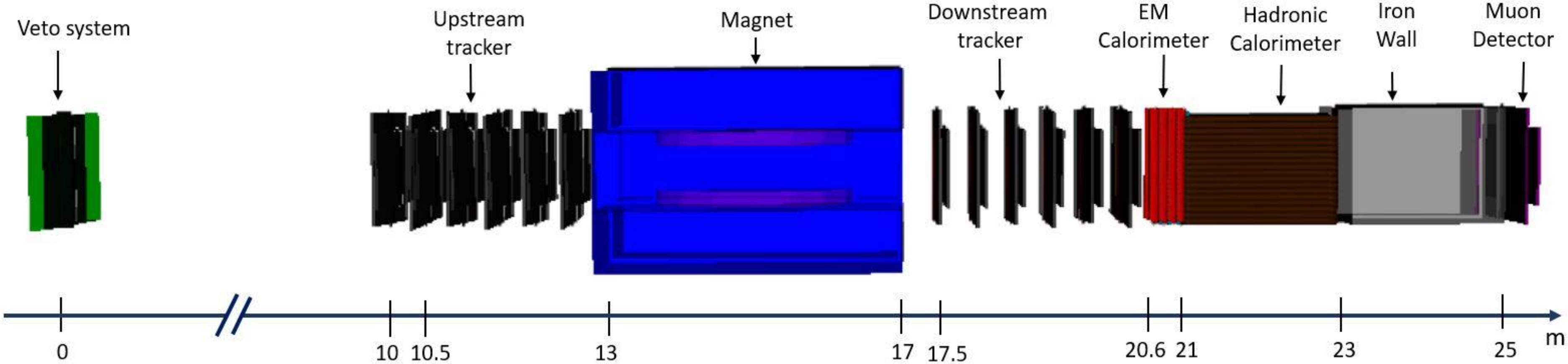




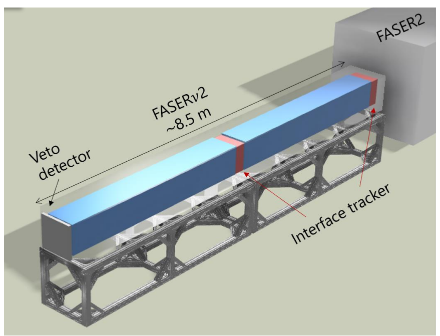
Construction and access
possible during HL-LHC operation

FPF Detectors

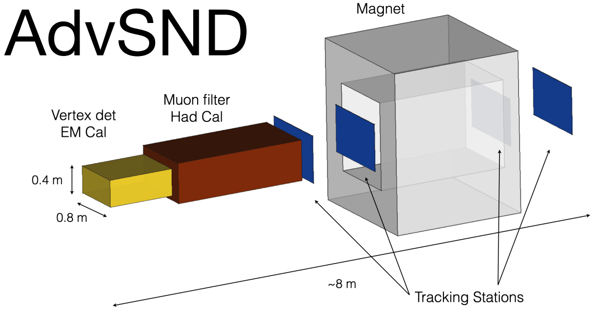
FASER2 Spectrometer - 2-4 Tm field, 3m² aperture



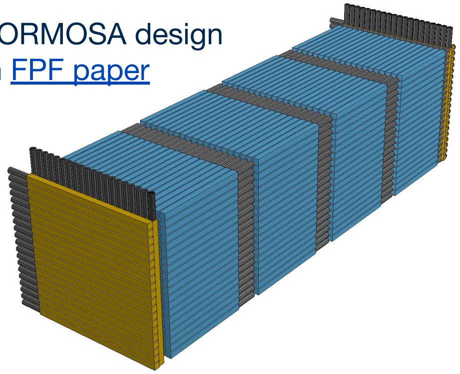
FASERnu2 10-20 tons



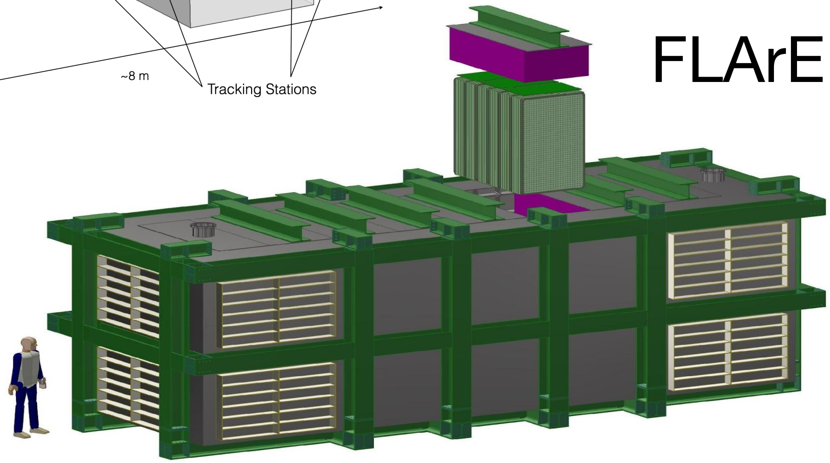
AdvSND



FORMOSA design in [FPF paper]



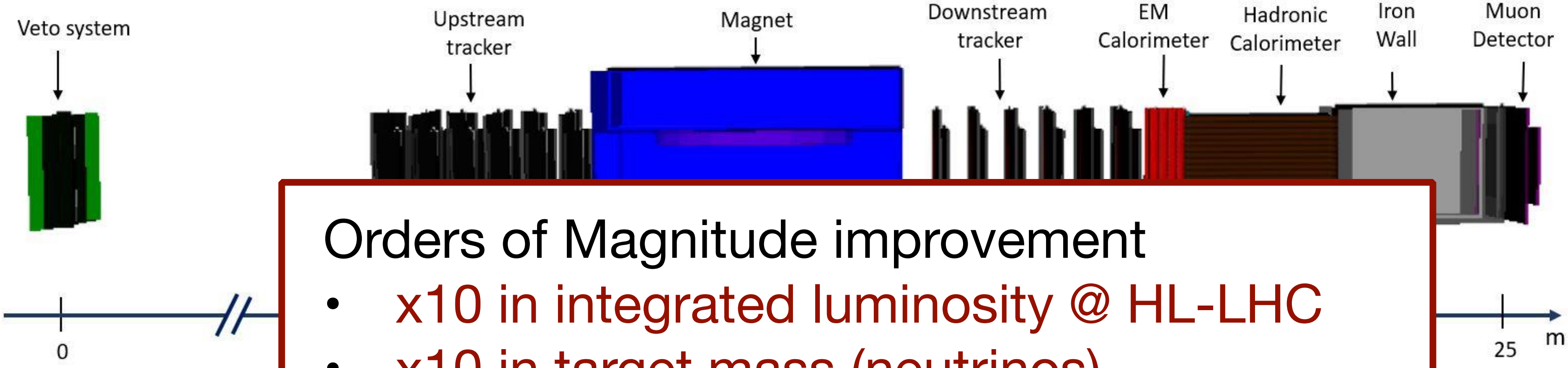
FLArE



Not to scale…

FPF Detectors

FASER2 Spectrometer - 2-4 Tm field, 3m² aperture



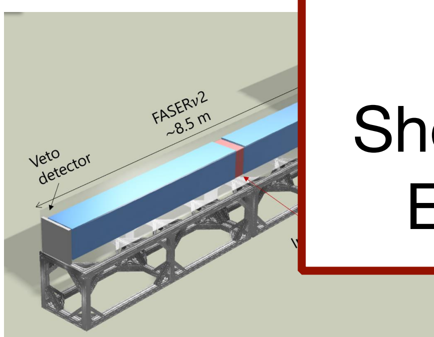
Orders of Magnitude improvement

- x10 in integrated luminosity @ HL-LHC
- x10 in target mass (neutrinos)
- x 1000 in decay volume (searches)

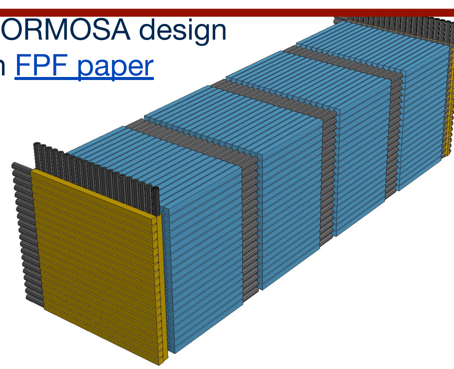
Short-baseline neutrino facility at TeV energy

Expect to detect 1000 neutrinos per day!

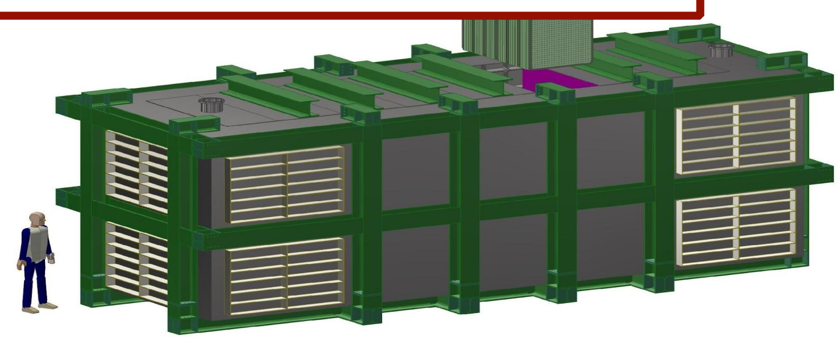
FASERnu2



FORMOSA design
in FPF paper

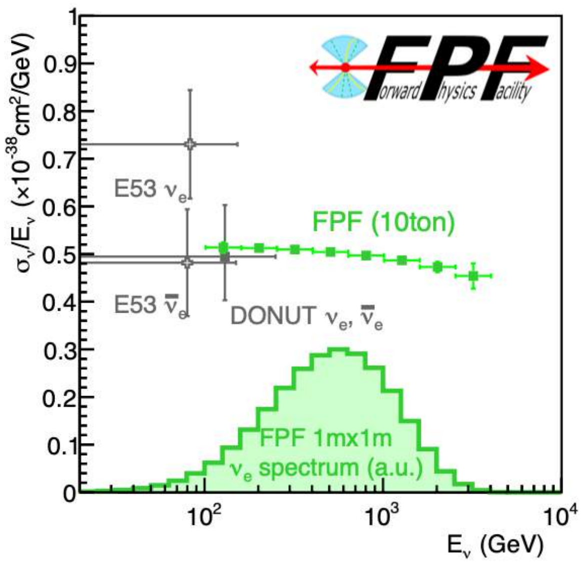


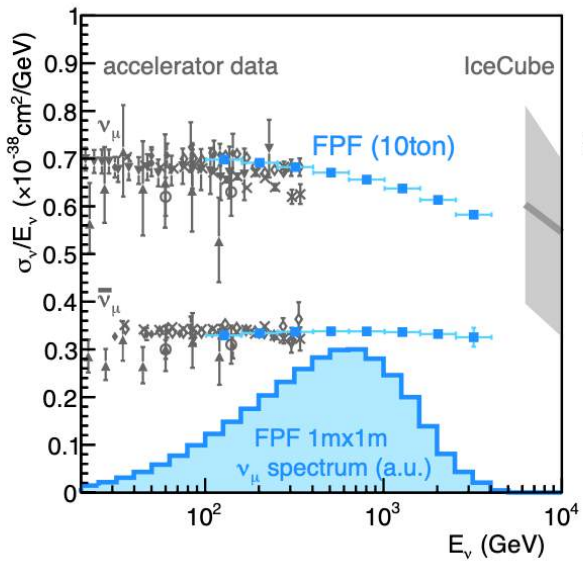
LArE

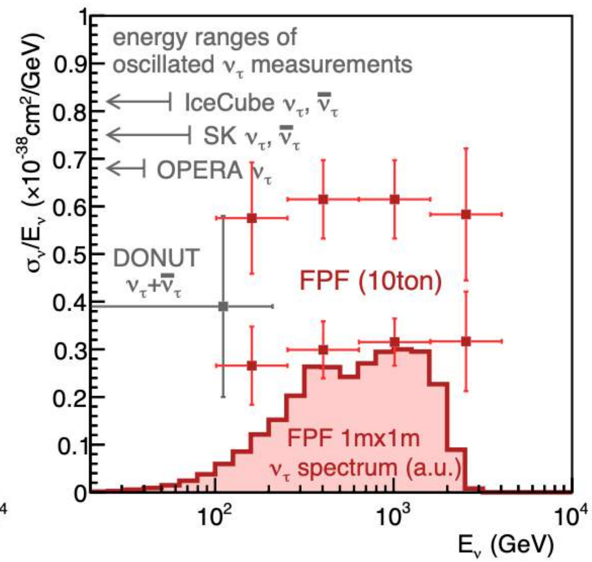


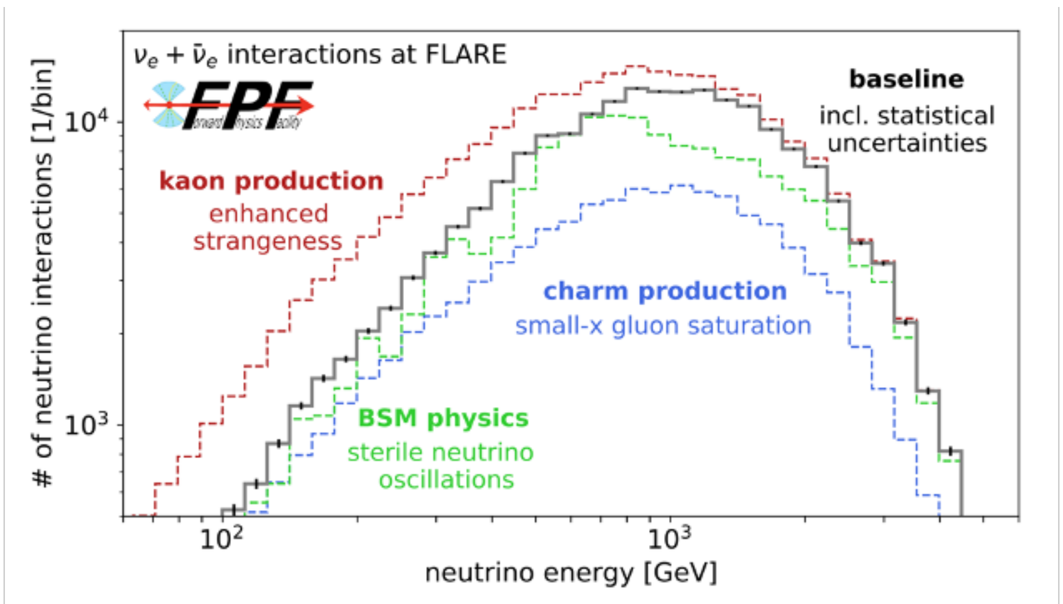
Not to scale…

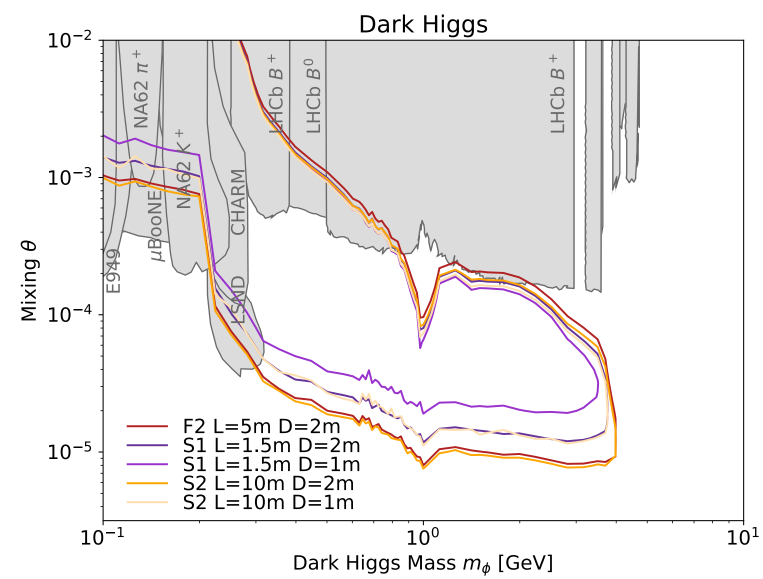
FPF Physics Snapshot





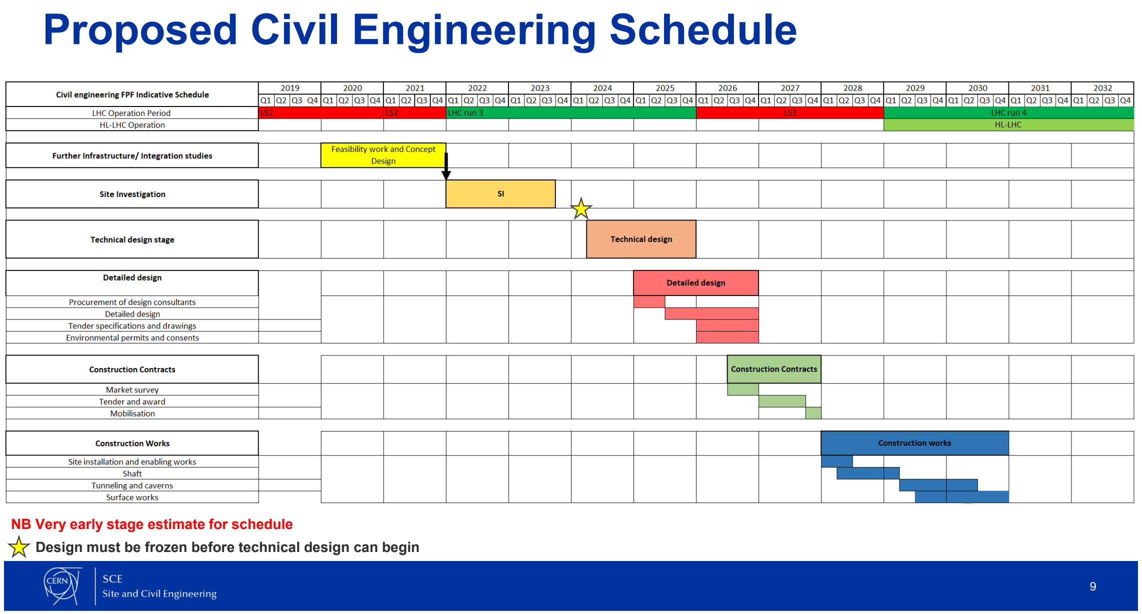


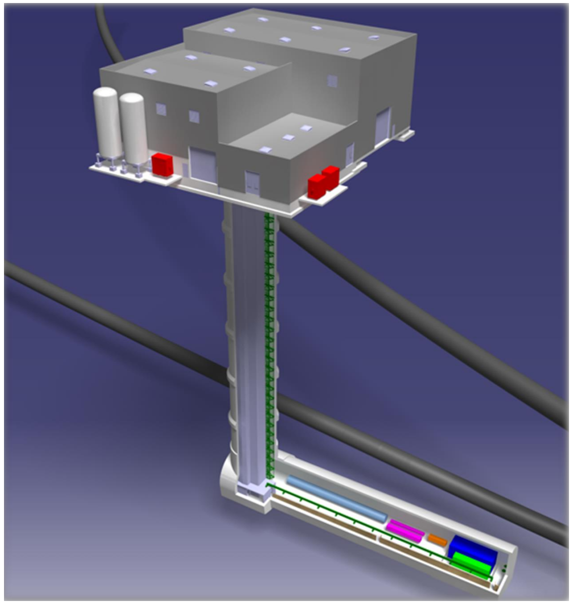




FPF Snowmass report: arXiv:2203.05090

CERN FPF Design Study





- CERN is very serious about FPF
  - Conceptual design ongoing
- Construction doesn't interfere with HL-LHC operations
- Cavern could be ready for experiments by 2031 (mid-Run4)

➢ Core samples

FPF & P5

- FPF Snowmass report: [arXiv:2203.05090]
  - ~200 authors, > 400 pages, 18 working groups
- P5 report did not recommend FPF per-se, but…
  - # Can be considered as part of ASTAE (small expt program) with reduced scope
- Most expensive detector is FLArE
  - Investigating cheaper options, could be built by non-U.S.
- We believe small experiments are important
  - Need discussion with US agencies, ASTAE does not exist yet

Exploring the Quantum Universe

P5 Report

Figure 2 – Construction in Various Budget Scenarios

Draft

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary
Delayed: Recommend construction but delayed to the next decade
Can be considered as part of ASTAE with reduced scope

Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
US Construction Cost >$3B										
on-shore Higgs factory	N	N	N		P	S		P	P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	N	N	N			P		P		
FPF #	N	N	N	P		P		P		

FPF & P5

- FPF Snowmass report: arXiv:2203.05090
  - ~200 authors, > 400 pages, 18 working groups
- P5 report did not recommend FPF per-se, but…
  - # Can be considered as part of ASTAE (small expt program)

5.1.5 – 20-Year Vision & Future Opportunities

The program described in this section consists of a combination of large and small projects and holds great promise for discovery. By the end of this 20-year period we will have ultimate LHC results from the general purpose experiments and a constellation of agile auxiliary experiments. We will also be in the final stages of construction of a Higgs

FPF experiments aim to be part of this future!

Universe

P5 Report

US Construction Cost >$3B

Scenarios	Less	Baseline	More	Science Drivers						
on-shore Higgs factory	N	N	N		P	S		P	P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	N	N	N			P		P		
FPF #	N	N	N	P		P		P		

FASER Collaboration

The FASER Collaboration has 96 members from 26 institutes in 10 countries

CERN
UNIVERSITÉ DE GENÈVE
KYUSHU UNIVERSITY
UC IRVINE

UNIVERSITÄT BERN
Technion Israel Institute of Technology
NAGOYA UNIVERSITY
UNIVERSITY of WASHINGTON

JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
KEK
UNIVERSITY OF OREGON

DESY.
INFN
International laboratory covered by a cooperation agreement with CERN
清華大學 Tsinghua University
ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II
UNIVERSITY OF LIVERPOOL
ZHENGZHOU UNIVERSITY
CHIBA UNIVERSITY
UNIVERSITY OF SUSSEX

Nikhef
UNIVERSITÄT BONN
ETH zürich
MANCHESTER 1824 The University of Manchester

http://faser.web.cern.ch/

FASER Funding

The FASER Collaboration gratefully acknowledges our funding agencies for their support:

HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

Swiss National Science Foundation

NSF

erc

科研費 KAKENHI

Along with the tremendous institutional support from

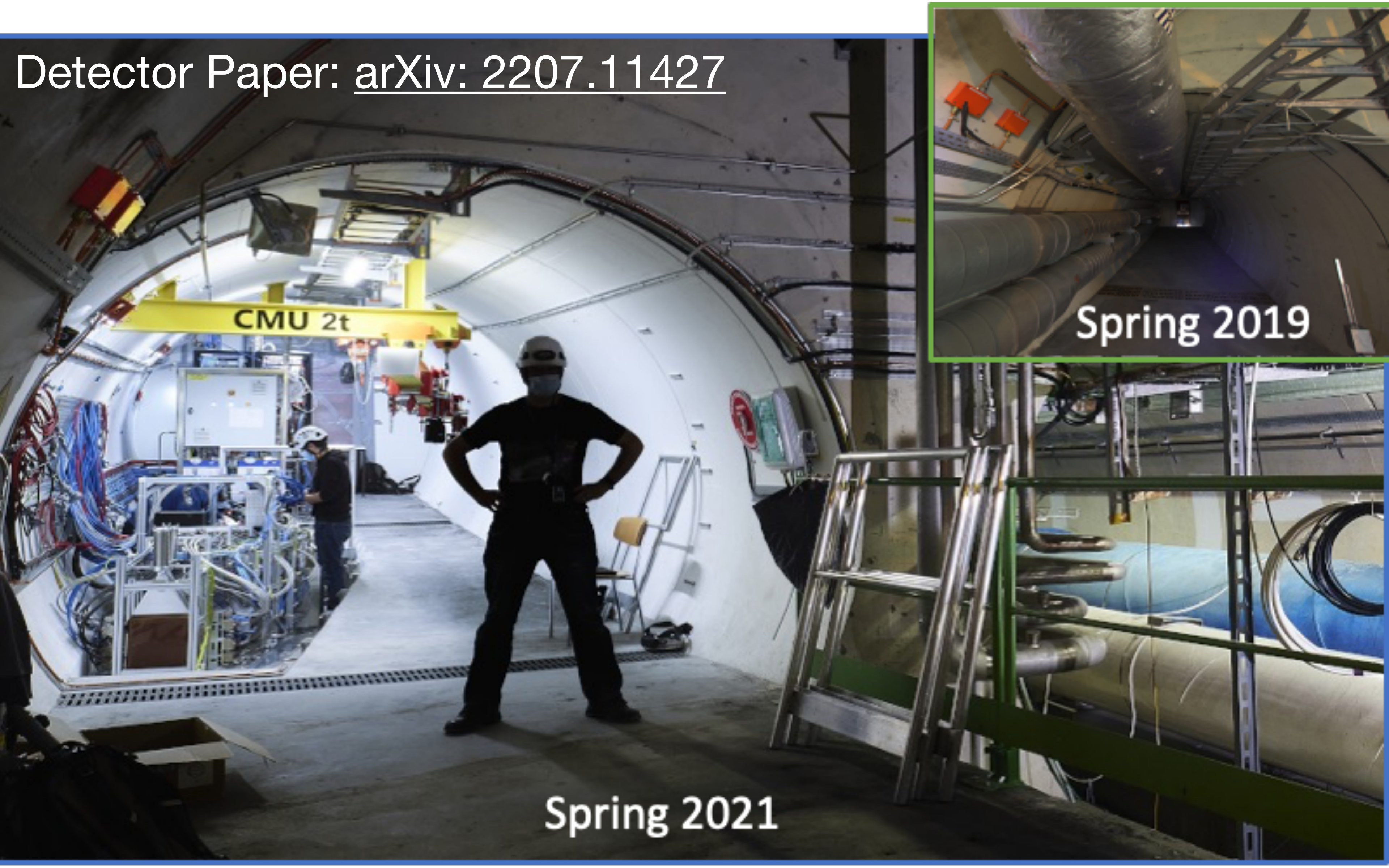
CERN

Conclusions

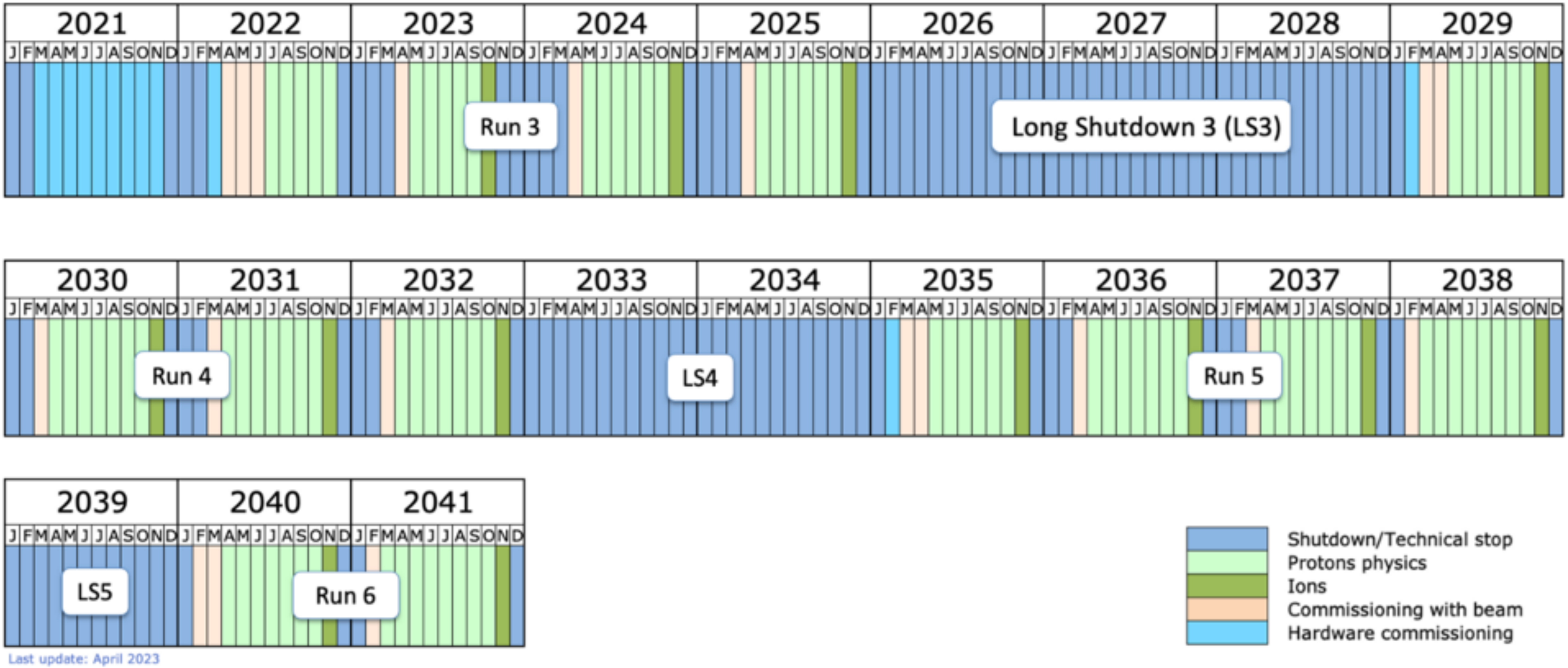
- FASER was installed in time for Run3
- First results on LLP (dark photons, ALPs)
- First cross-section measurement for ν_e and ν_μ
- More physics to come in Run3, including upgrades
- FASER will continue into Run4, pathfinder for future small forward-physics experiments

Believe future is bright with CERN support of FPF
Opportunities for new people to get involved!

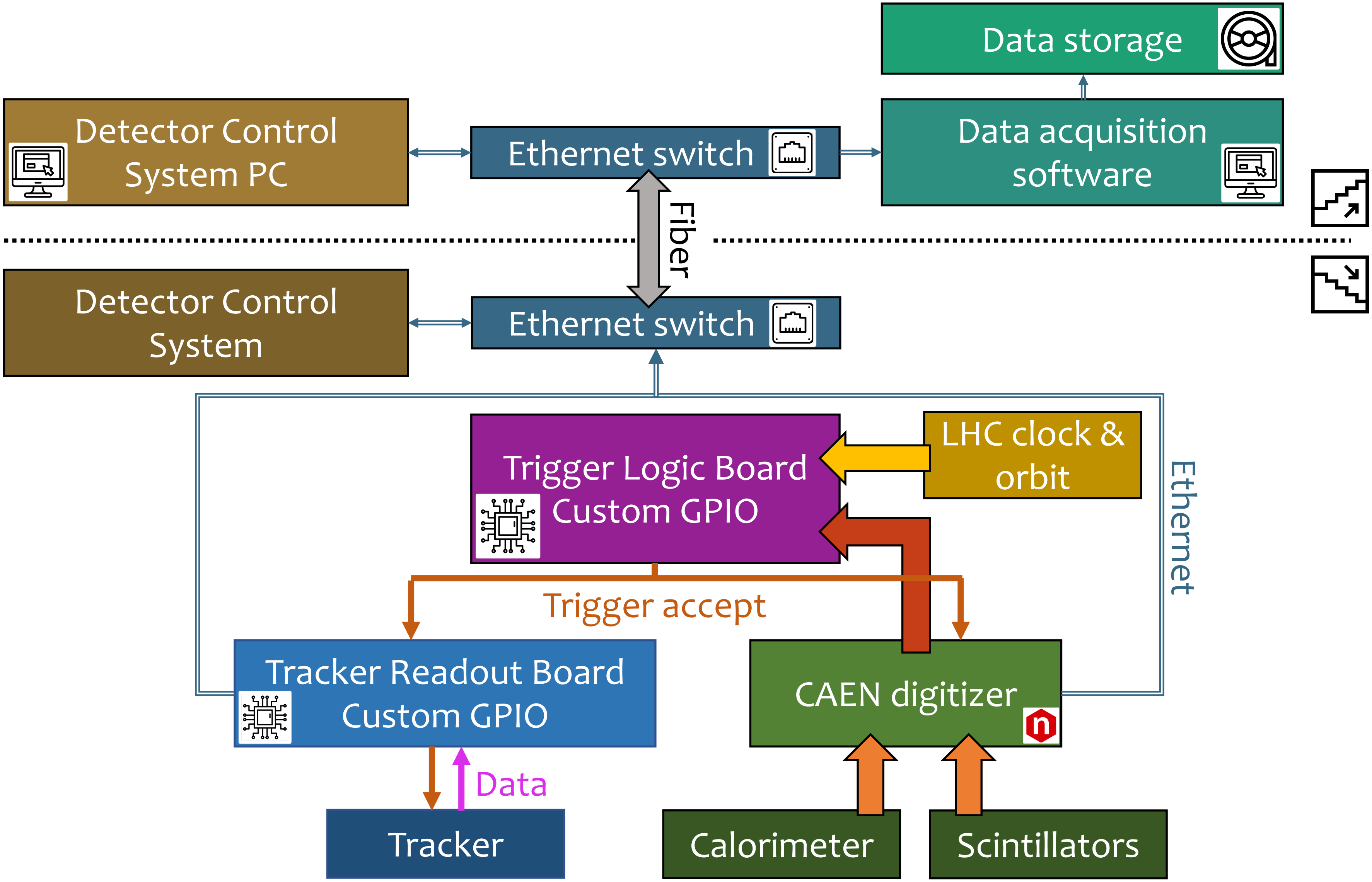
Backup


Detector Paper: arXiv: 2207.11427
CMU 2t
Spring 2019
Spring 2021

LHC Schedule



TDAQ System



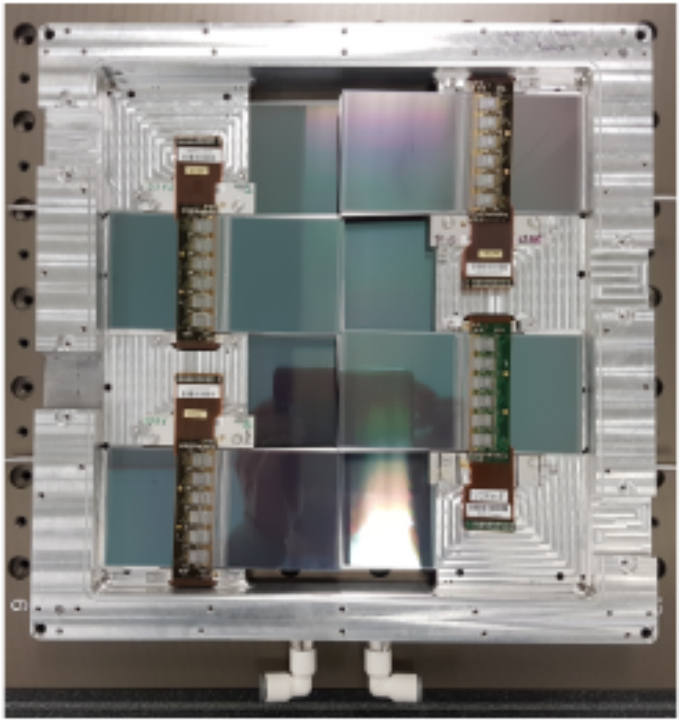
Data storage
Detector Control System PC
Ethernet switch
Data acquisition software
Fiber
Detector Control System
Ethernet switch
Trigger Logic Board Custom GPIO
LHC clock & orbit
Ethernet
Trigger accept
Tracker Readout Board Custom GPIO
CAEN digitizer
Data
Tracker
Calorimeter
Scintillators

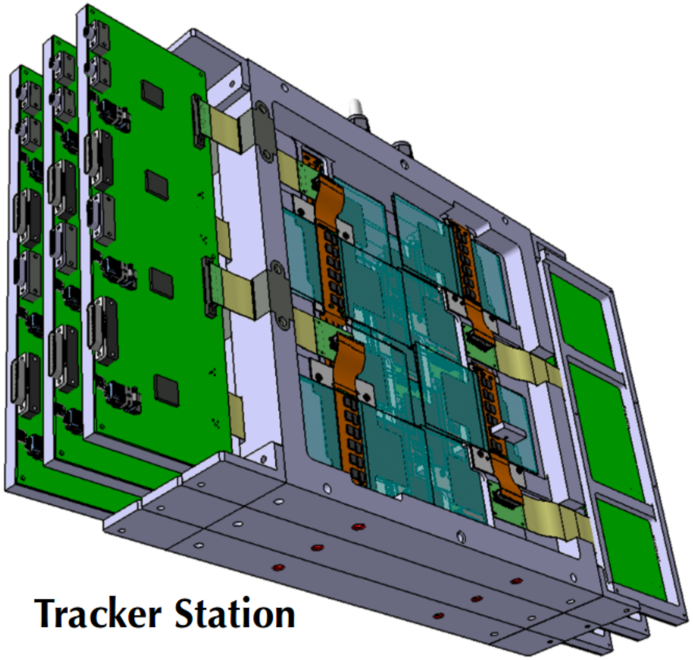
FASER Trigger Rates

Tracker Design

- Need to identify nearby, pair-produced tracks
- 4 tracking planes in 4 stations (12 planes in total)
- Use 96 spare ATLAS SCT modules, 8 per layer
  - 80 μm pitch, 40 mRad stereo angle, 24 cm x 24 cm area
  - 17 μm precision in bending (vertical) plane

Single Layer





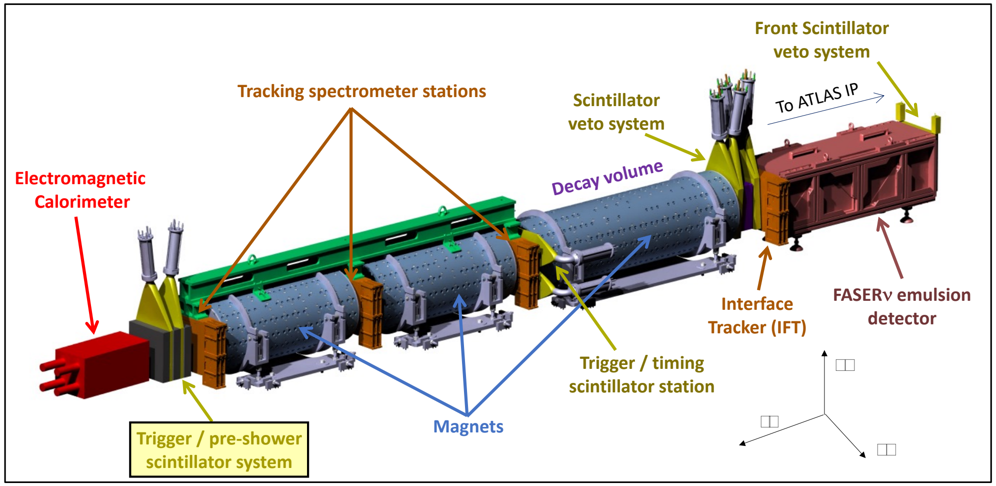
Tracker Station

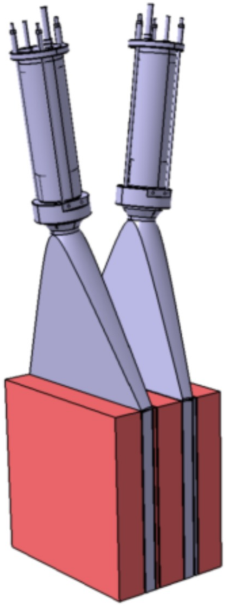
Thanks ATLAS!

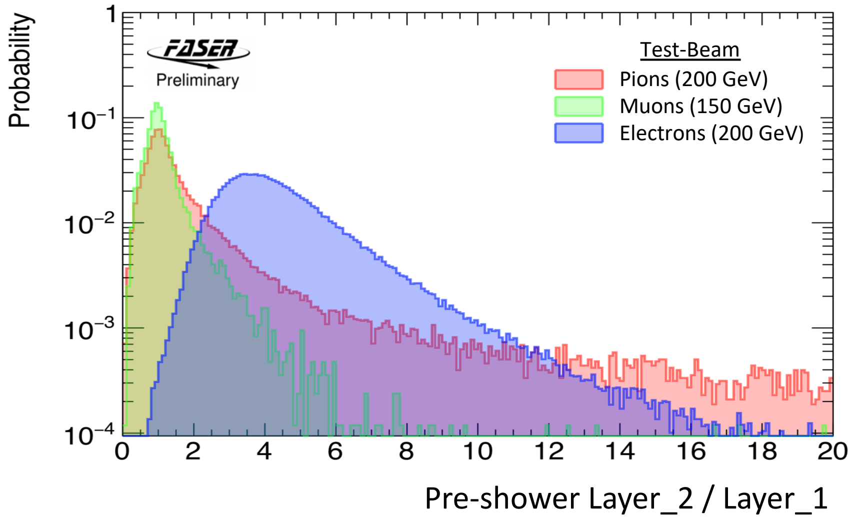
Preshower Detector

Preshower

- Layers of scintillator, tungsten, and porous graphite
- Provides shower depth information
  - Useful for identifying particles







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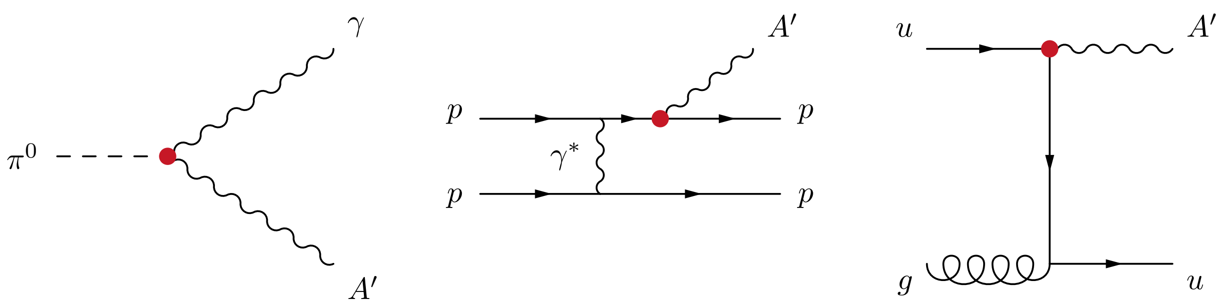
Dark Photon Properties

- Produced in meson decays, e.g.:

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

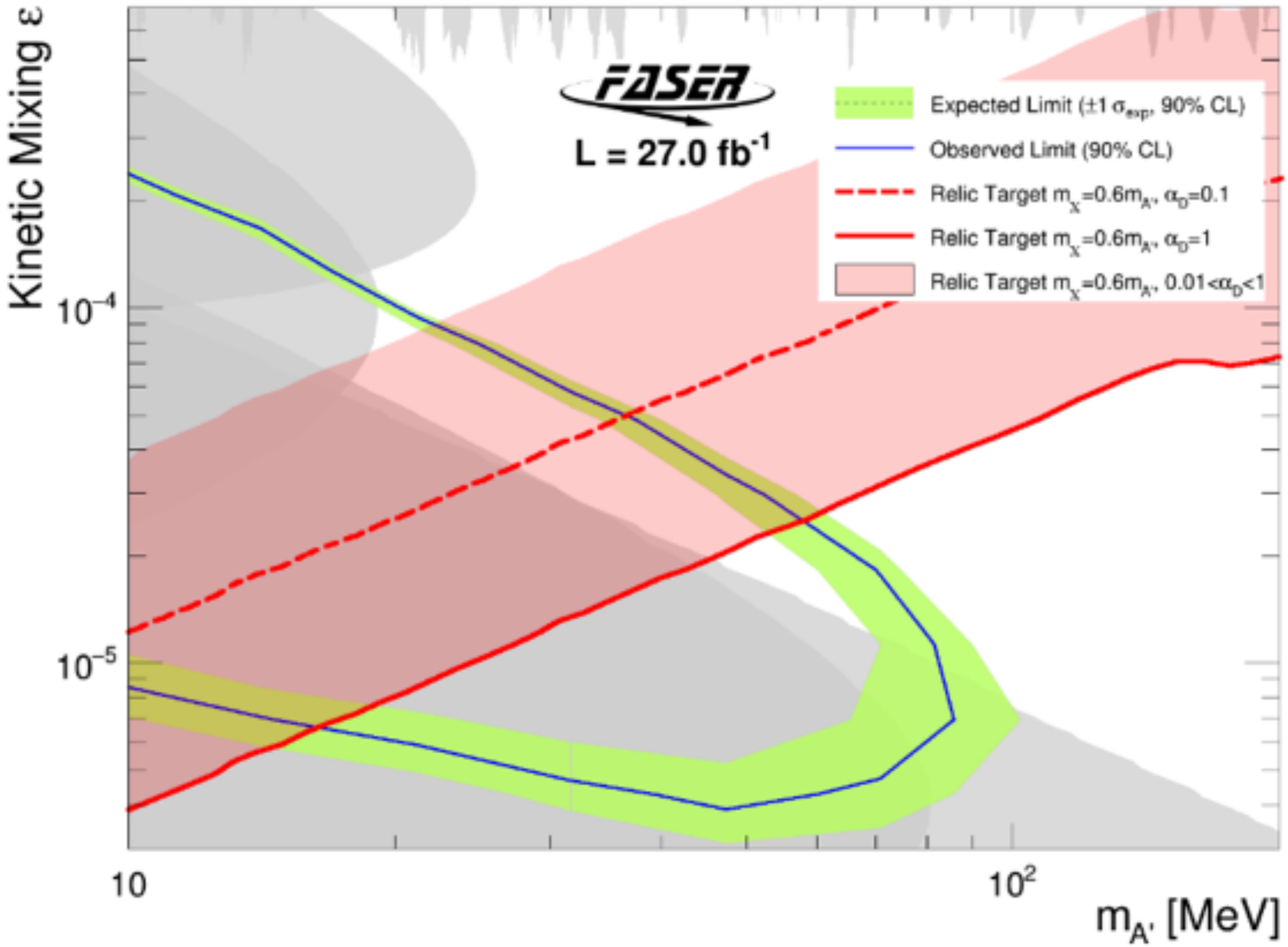
- Other production modes possible

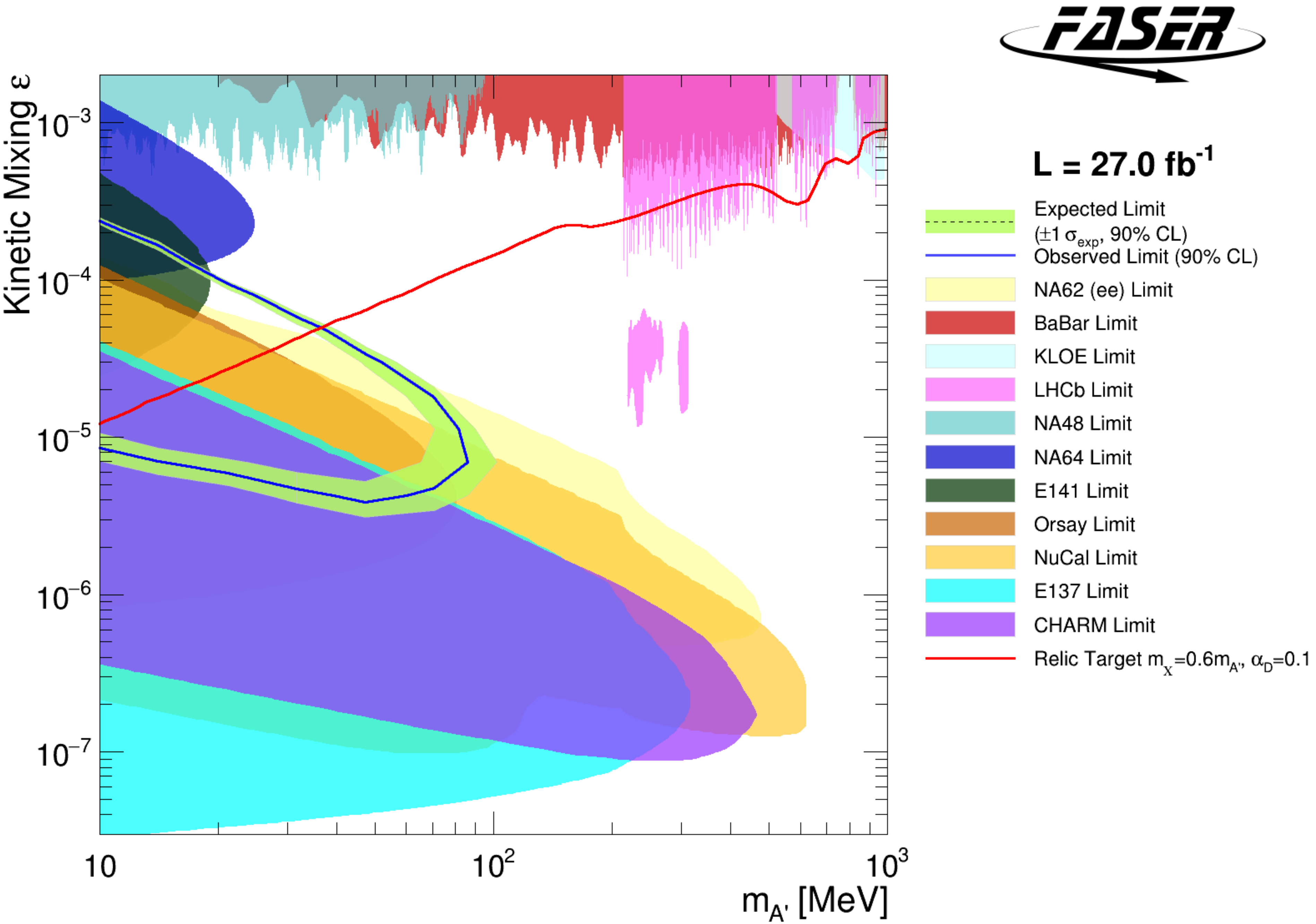


- Long decay length, large boost in forward direction

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

Dark Photon Limit

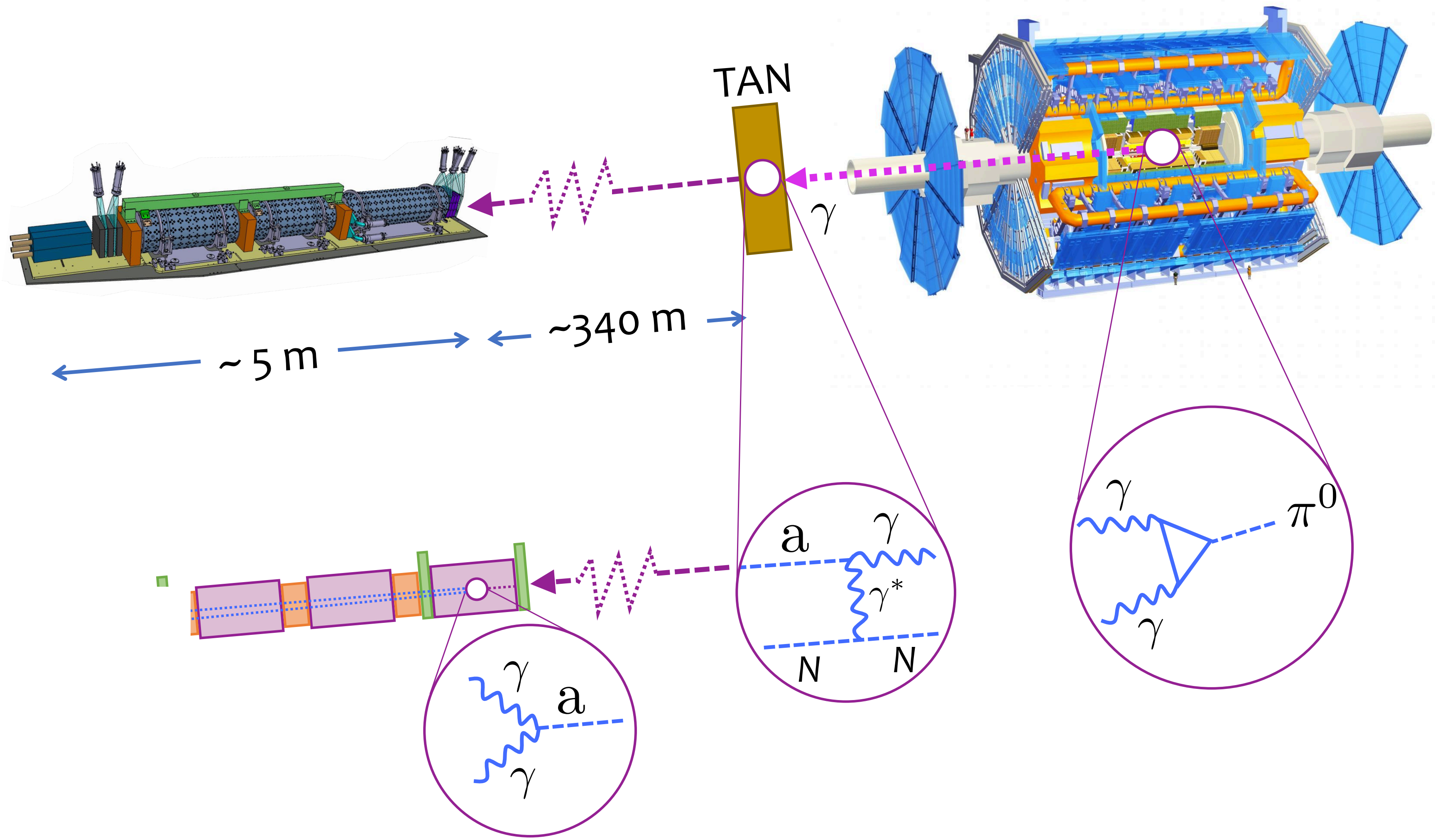




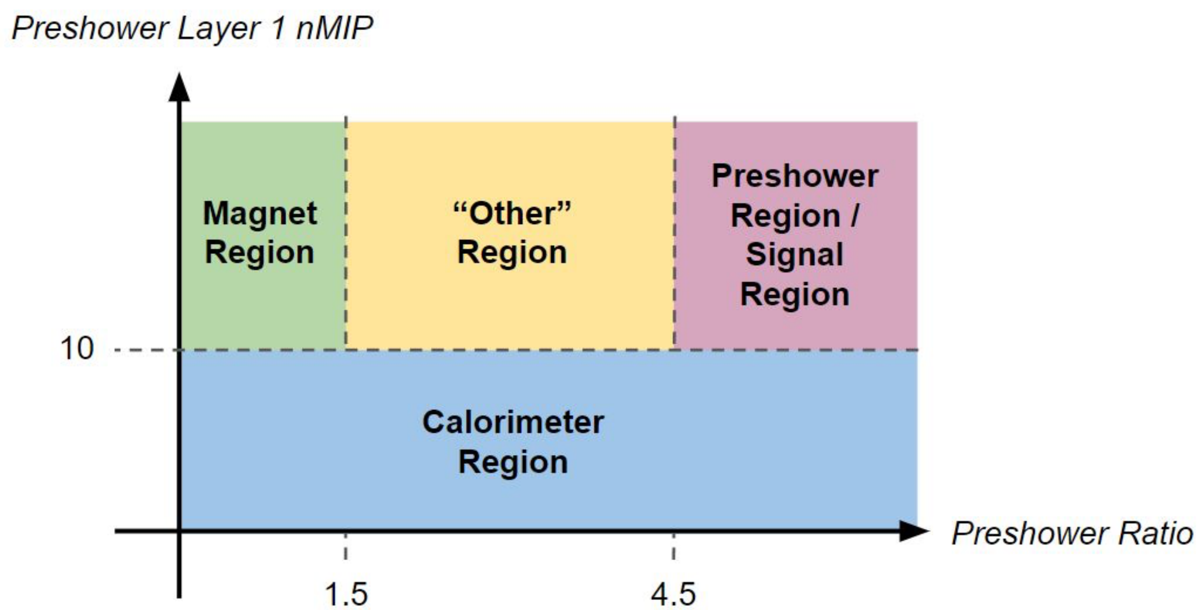
FASER
L = 27.0 fb^{-1}
Expected Limit
(±1 σ_{exp}, 90% CL)
Observed Limit (90% CL)
NA62 (ee) Limit
BaBar Limit
KLOE Limit
LHCb Limit
NA48 Limit
NA64 Limit
E141 Limit
Orsay Limit
NuCal Limit
E137 Limit
CHARM Limit
Relic Target m_χ=0.6$m_{A'}$, α_D=0.1
Kinetic Mixing ε
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10
10^2
10^3
$m_{A'}$ [MeV]

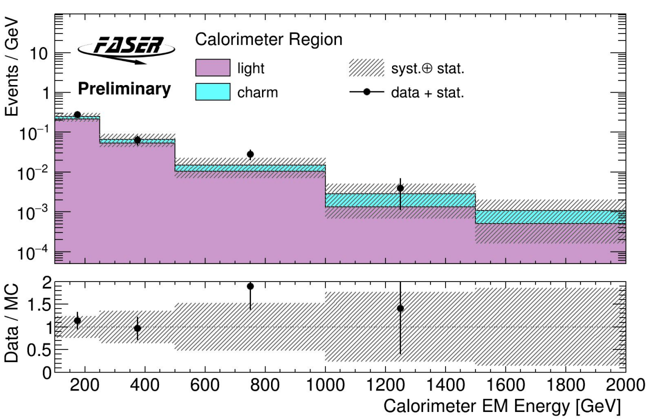
Axion-Like Particles

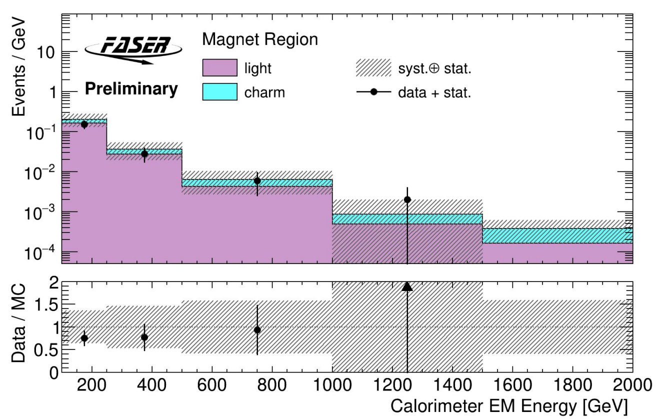
- Produced from photons scattering off TAN
- Observe di-photon final state

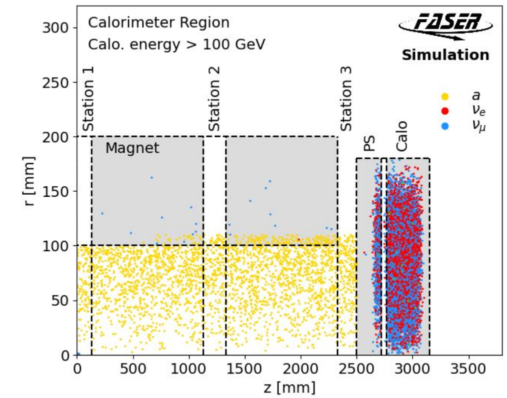


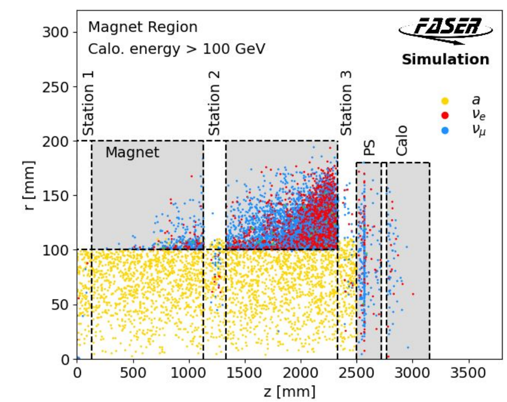
ALPs control regions

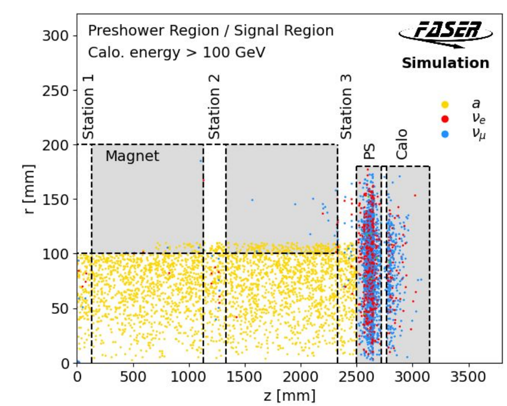




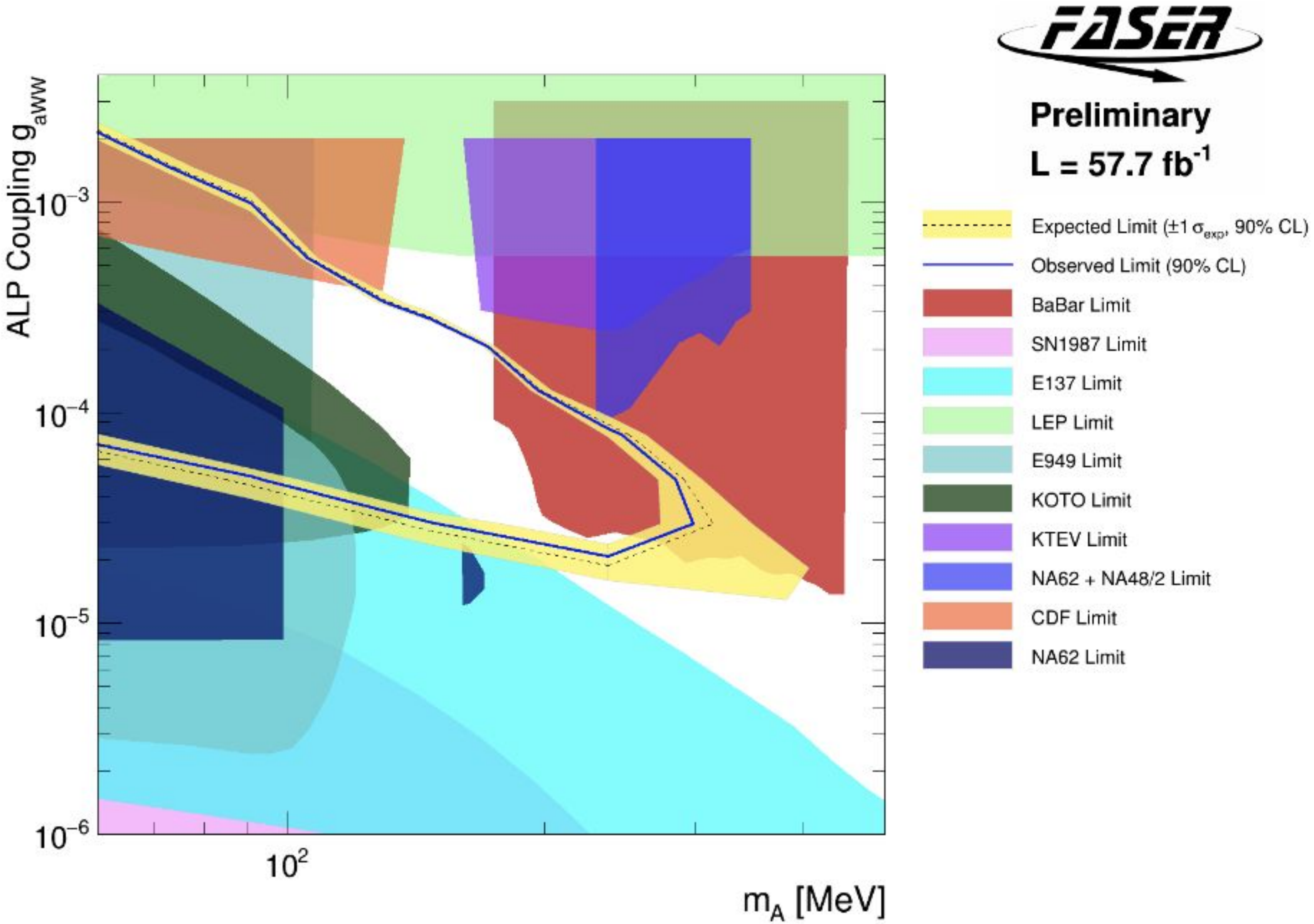






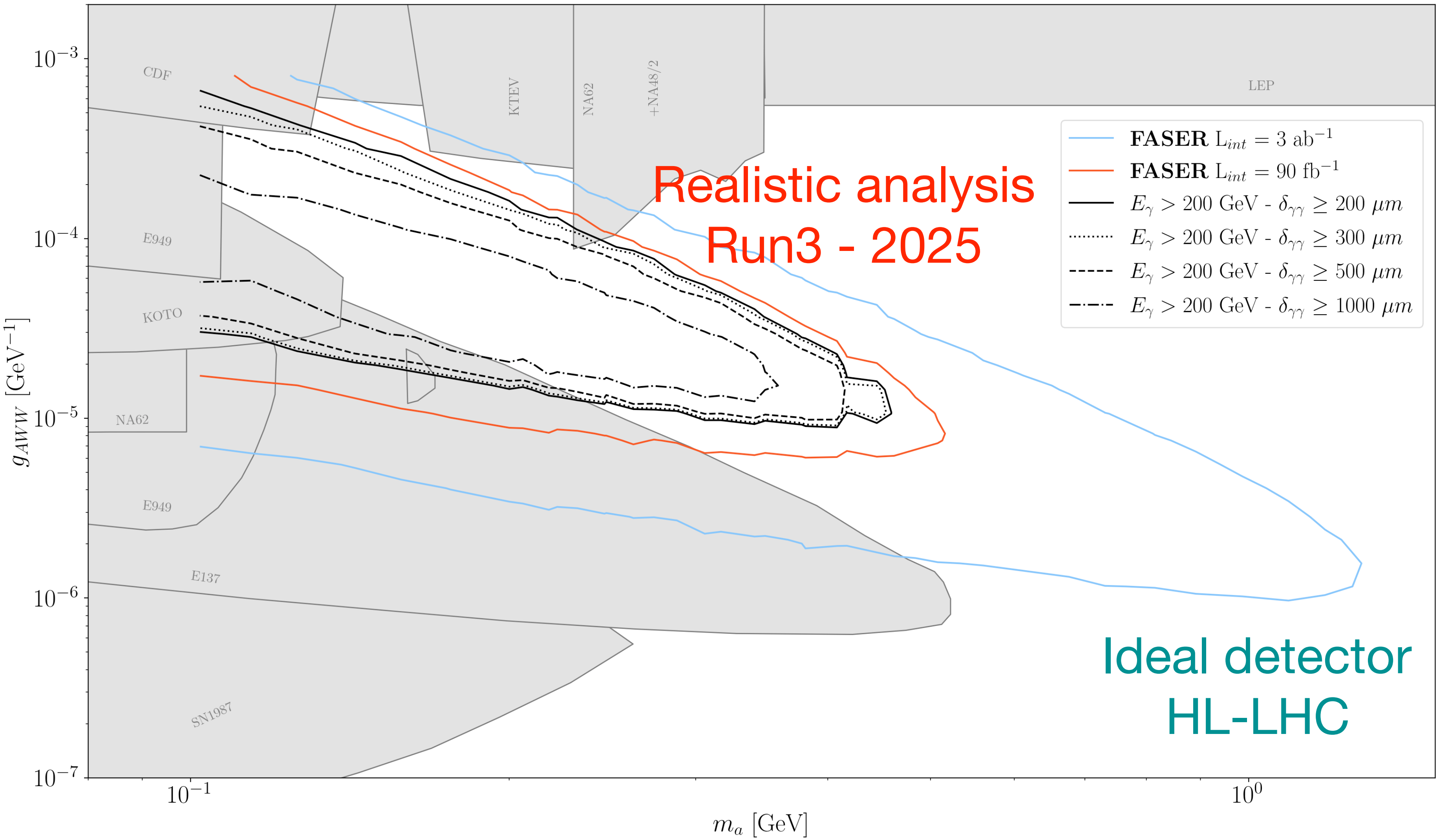


ALPs limits

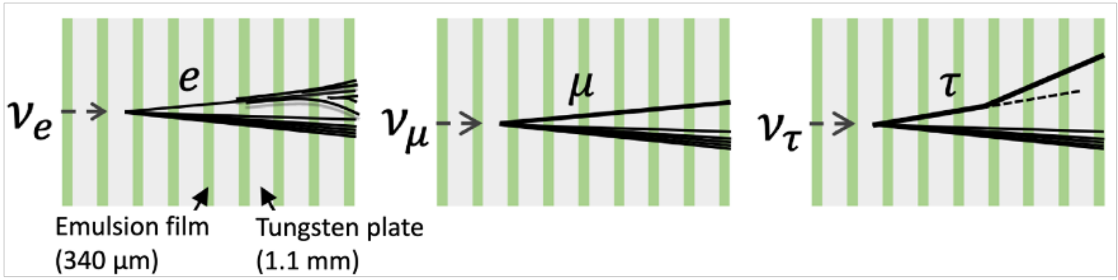


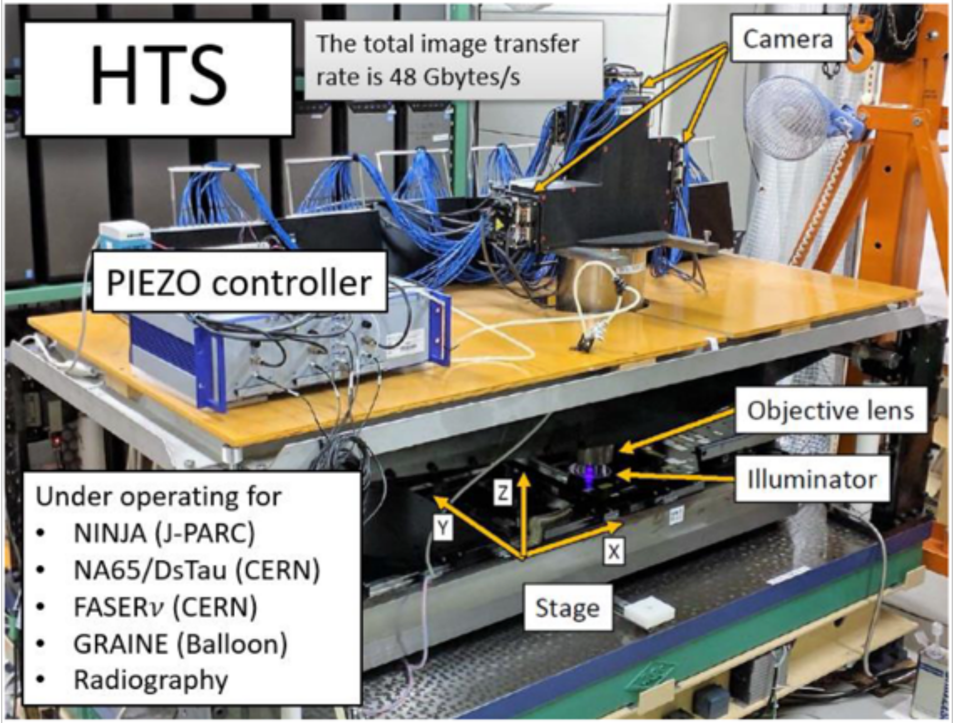
FASER
Preliminary
L = 57.7 fb-1
ALP Coupling g_aWW
10^-3
10^-4
10^-5
10^-6
10^2
m_A [MeV]
Expected Limit (±1 σ_exp, 90% CL)
Observed Limit (90% CL)
BaBar Limit
SN1987 Limit
E137 Limit
LEP Limit
E949 Limit
KOTO Limit
KTEV Limit
NA62 + NA48/2 Limit
CDF Limit
NA62 Limit

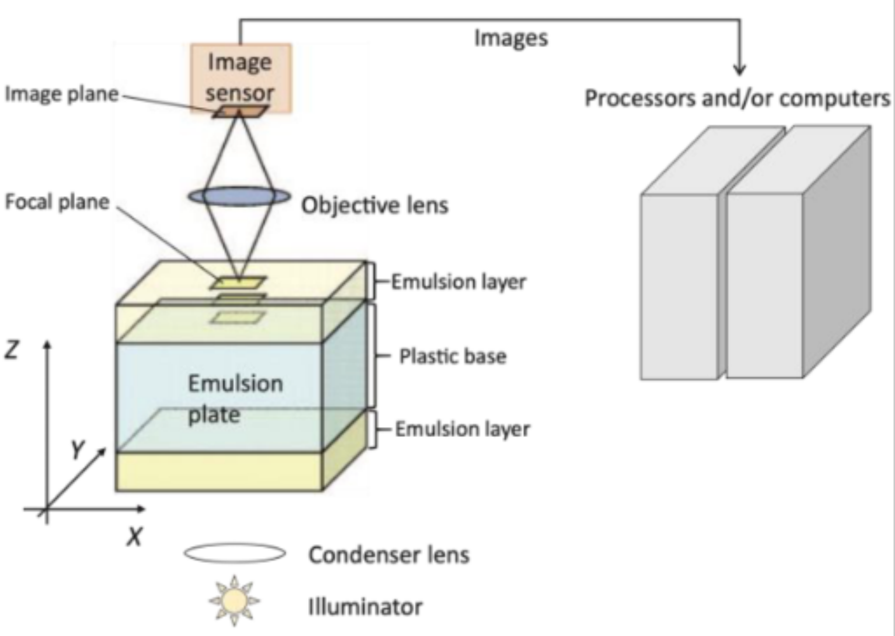
Upgrade ALPs projections



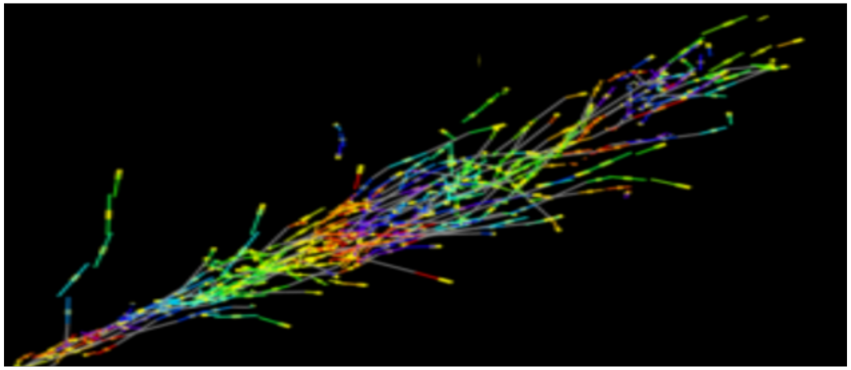
Emulsion Processing

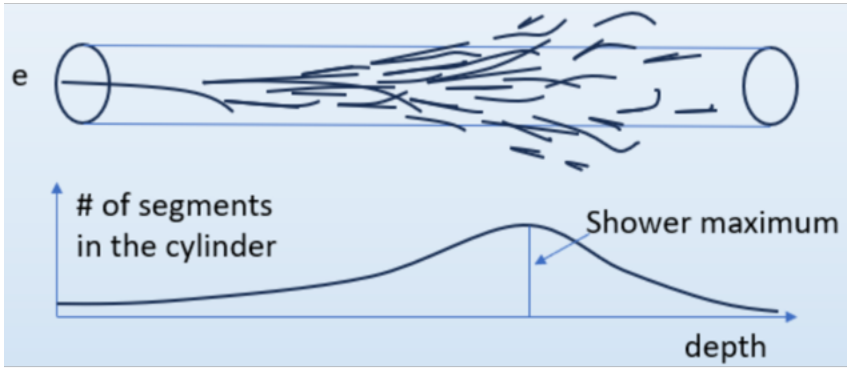


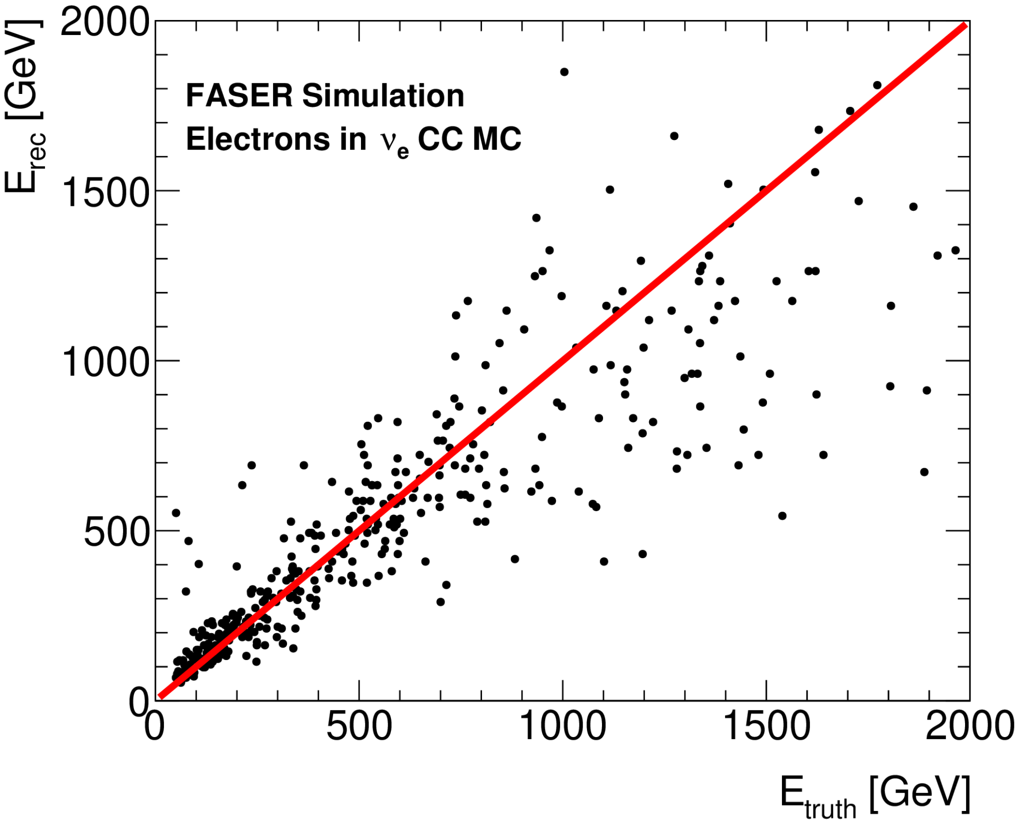




Neutrino Energy



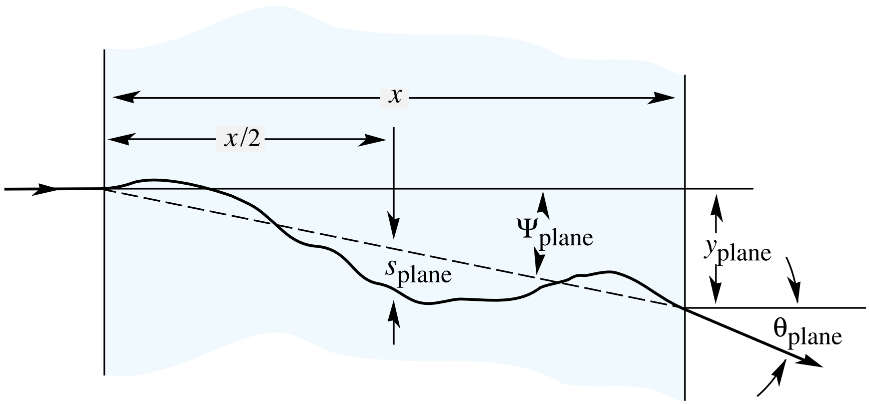


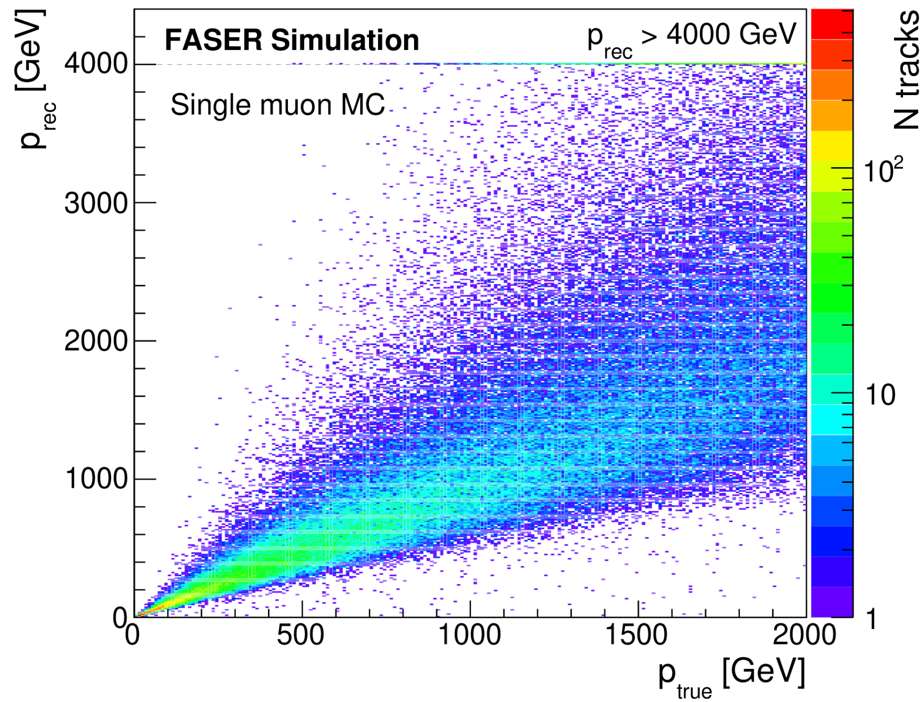


dE/E ~ 25% at 200 GeV, up to 40% at higher E

Neutrino Momentum

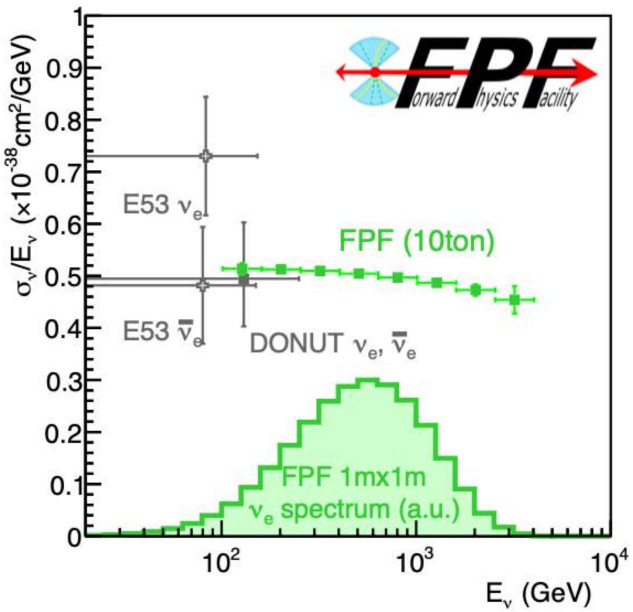
Multiple Coulomb Scattering



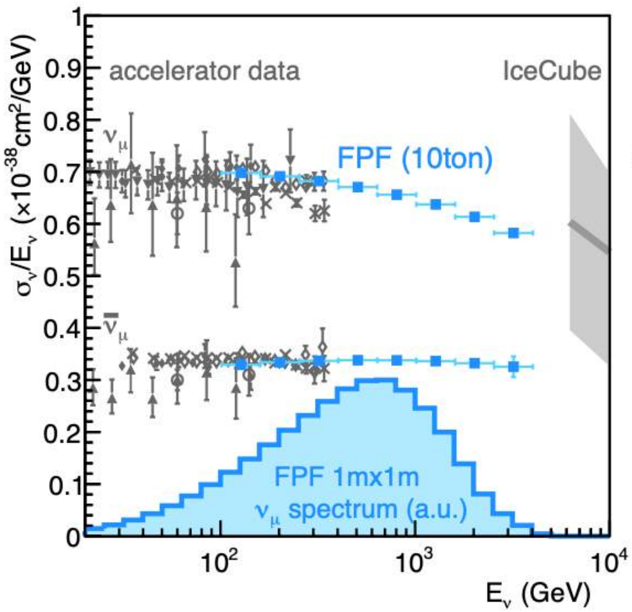


dE/E ~ 30% at 200 GeV, up to 50% at higher p

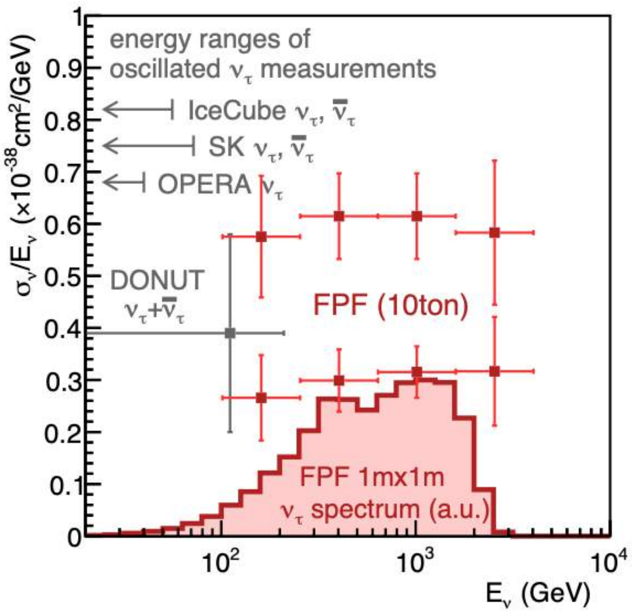
FPF Physics



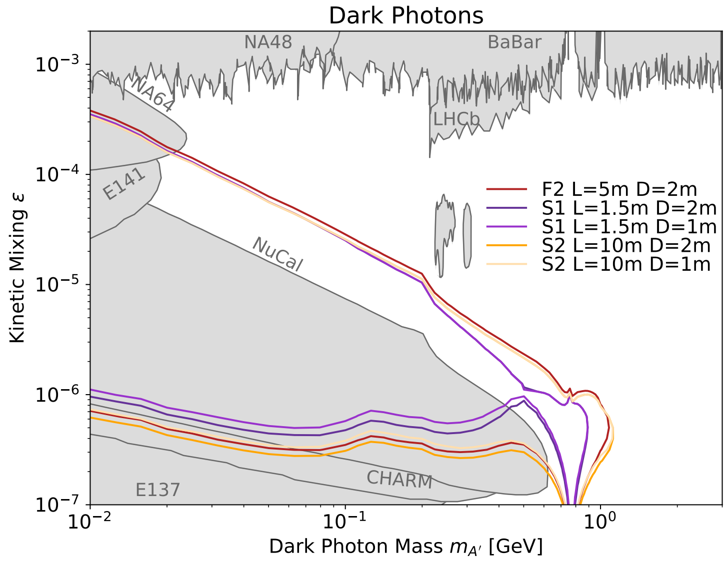
FPF Forward Physics Facility
E53 ν_e
E53 $\bar{\nu}_e$
DONUT ν_e, $\bar{\nu}_e$
FPF (10ton)
FPF 1mx1m
ν_e spectrum (a.u.)
σ_ν/E_ν ($\times10^{-38}$cm^2/GeV)
E_ν (GeV)



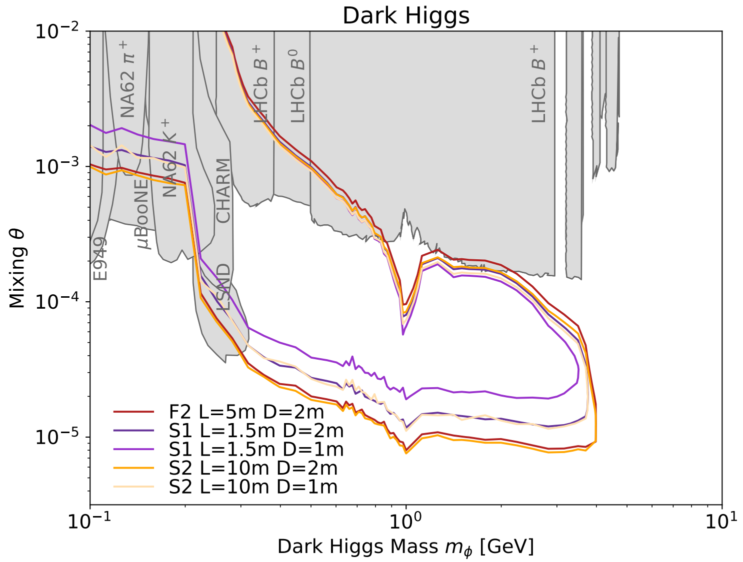
accelerator data
IceCube
ν_μ
$\bar{\nu}_\mu$
FPF (10ton)
FPF 1mx1m
ν_μ spectrum (a.u.)
σ_ν/E_ν ($\times10^{-38}$cm^2/GeV)
E_ν (GeV)



energy ranges of
oscillated ν_τ measurements
IceCube ν_τ, $\bar{\nu}_\tau$
SK ν_τ, $\bar{\nu}_\tau$
OPERA ν_τ
DONUT
$\nu_\tau+\bar{\nu}_\tau$
FPF (10ton)
FPF 1mx1m
ν_τ spectrum (a.u.)
σ_ν/E_ν ($\times10^{-38}$cm^2/GeV)
E_ν (GeV)



Dark Photons
NA48
BaBar
NA64
LHCb
E141
NuCal
CHARM
E137
F2 L=5m D=2m
S1 L=1.5m D=2m
S1 L=1.5m D=1m
S2 L=10m D=2m
S2 L=10m D=1m
Kinetic Mixing ϵ
Dark Photon Mass $m_{A'}$ [GeV]



Dark Higgs
NA62 π^+
NA62 K^+
μBooNE
E949
CHARM
LSND
LHCb B^+
LHCb B^0
LHCb B^+
F2 L=5m D=2m
S1 L=1.5m D=2m
S1 L=1.5m D=1m
S2 L=10m D=2m
S2 L=10m D=1m
Mixing θ
Dark Higgs Mass m_ϕ [GeV]

FPF Neutrino Statistics

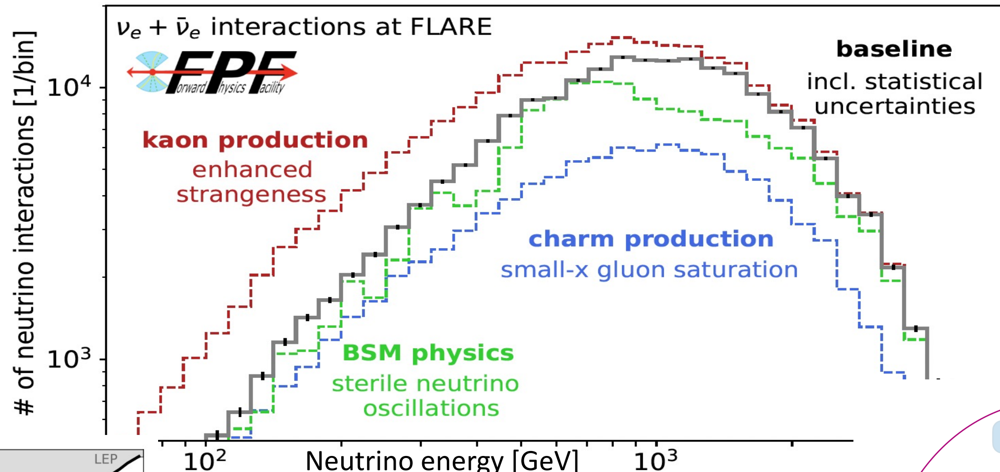
Numbers from: https://arxiv.org/pdf/2203.05090.pdf
Numbers from 2 generators shown (SIBYLL / DPMJET), typically span the range of other generators.

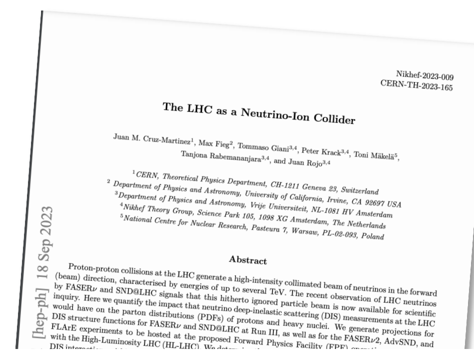
Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 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

Huge increase in number of neutrinos detected with FPF.
Enables broad physics programme.

Forward Physics Facility

- FPF studied in context of PBC for last 3 years
- Strong physics case built up covering searches for new particles, and physics with high energy neutrinos
- New facility allows x10 bigger neutrino detectors, allowing detection of 10^5 ν_e, 10^6 ν_μ, 10^4 ν_τ at highest energies
  - Ultimate exploitation of LHC neutrino beam




Nikhef-2023-009
CERN-TH-2023-165

The LHC as a Neutrino-Ion Collider

Juan M. Cruz-Martinez[1], Max Fieg[2], Tommaso Giani[3,4], Peter Krack[3,4], Toni Mäkelä[5], Tanjona Rabemananjara[3,4], and Juan Rojo[3,4]

[hep-ph] 18 Sep 2023

Abstract