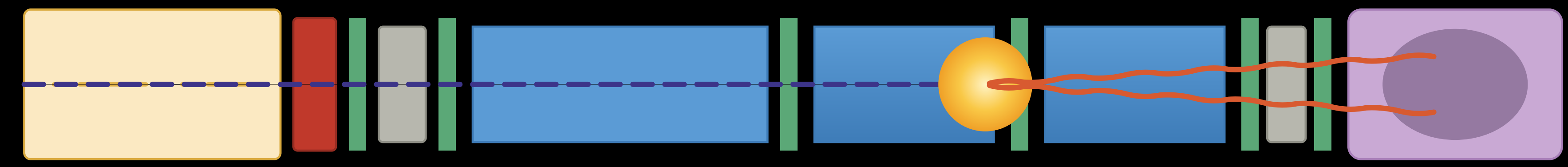
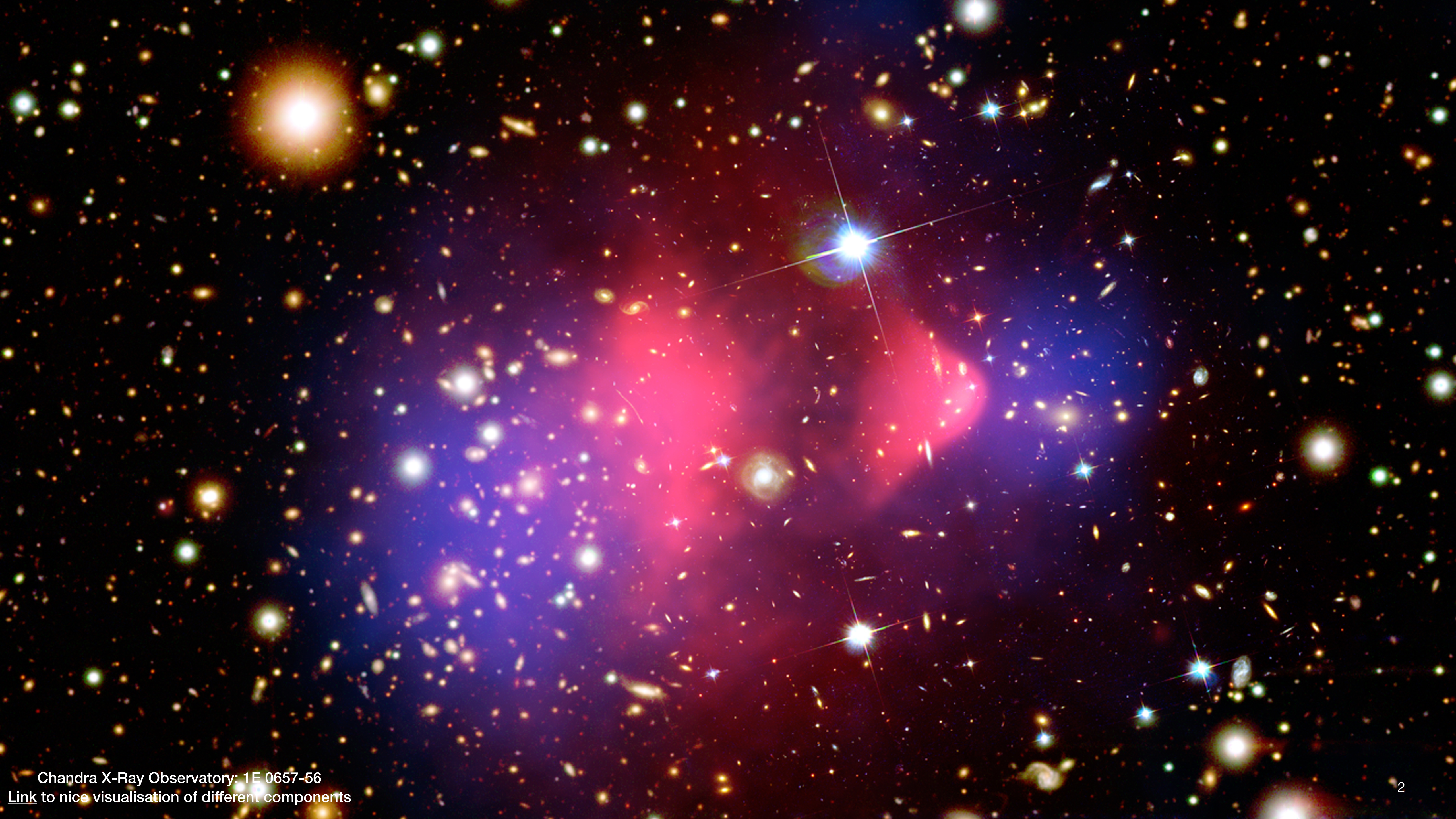
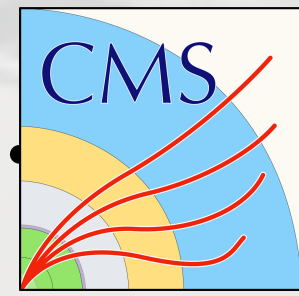


Shining light on
dark matter with the LHC

Daniela Koeck  UNIVERSITY OF
OREGON

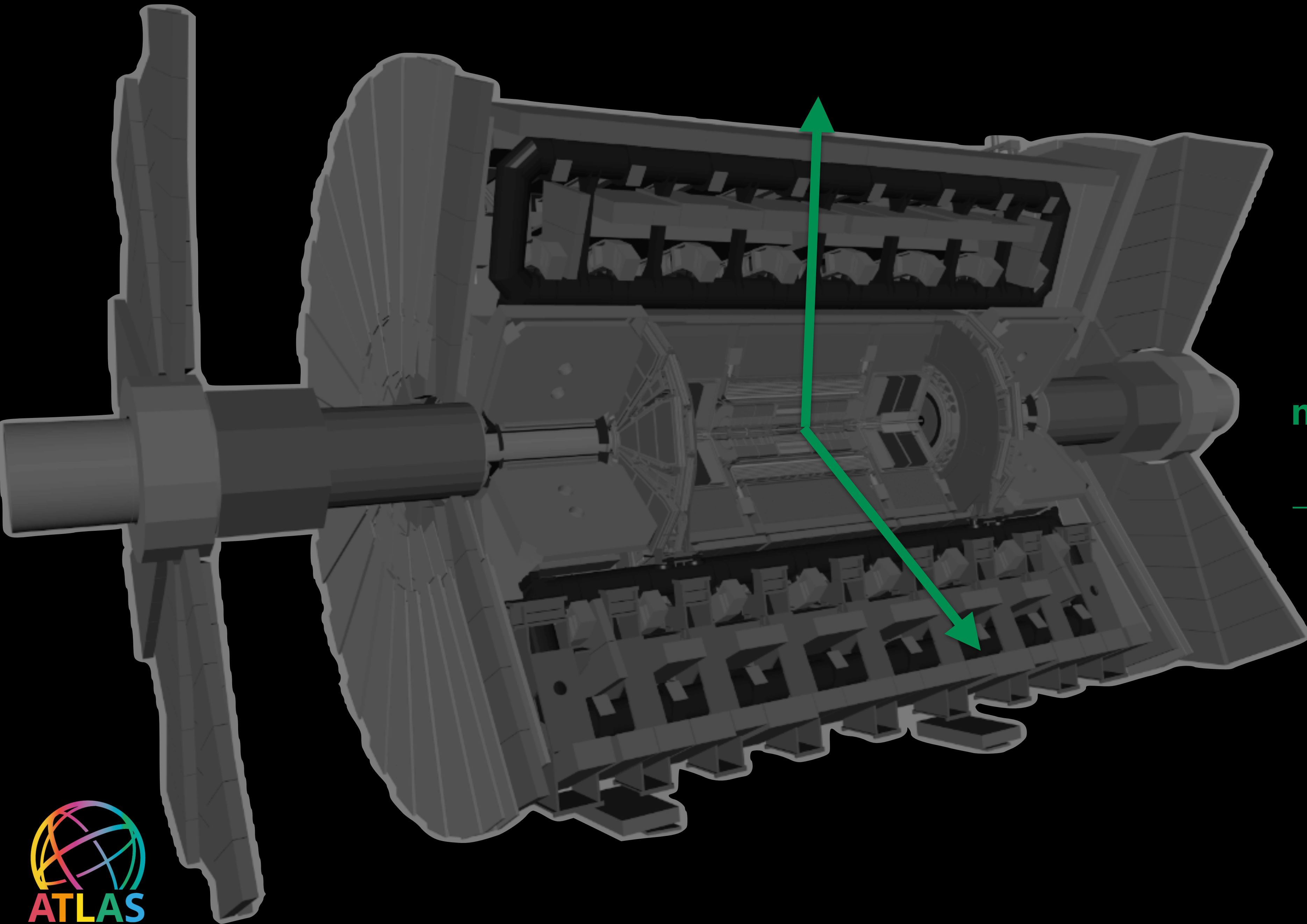






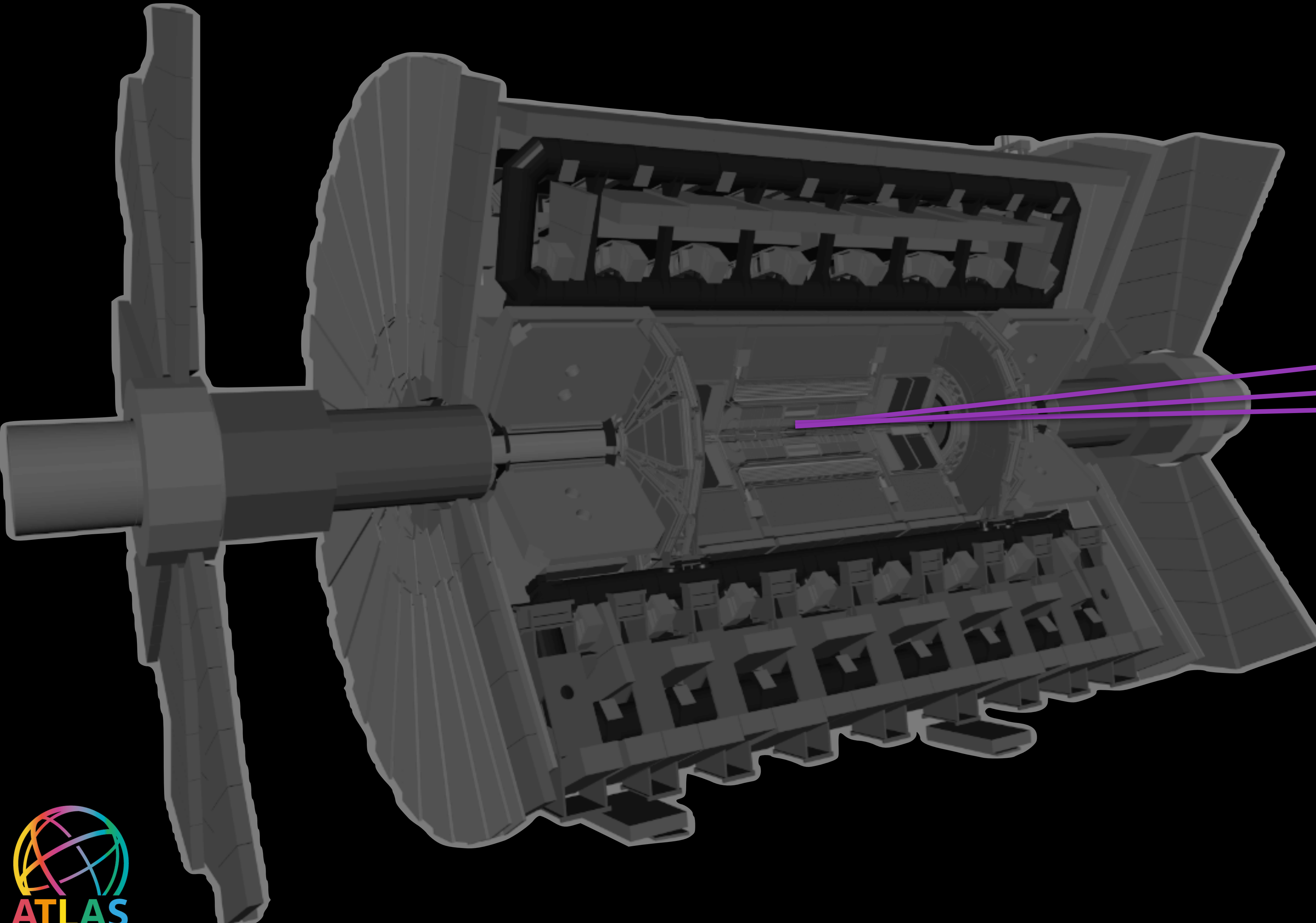
ALICE





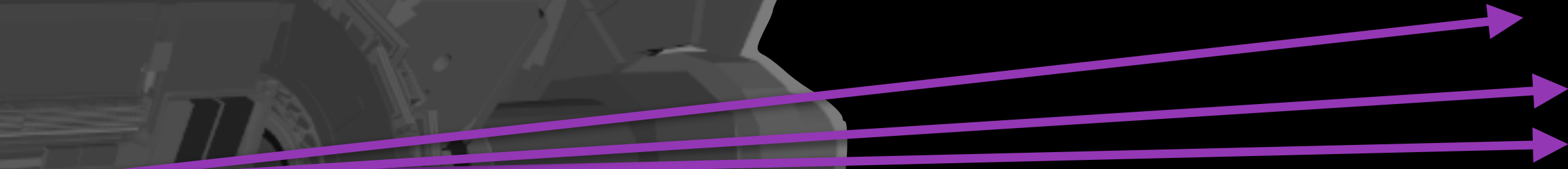
massive particles

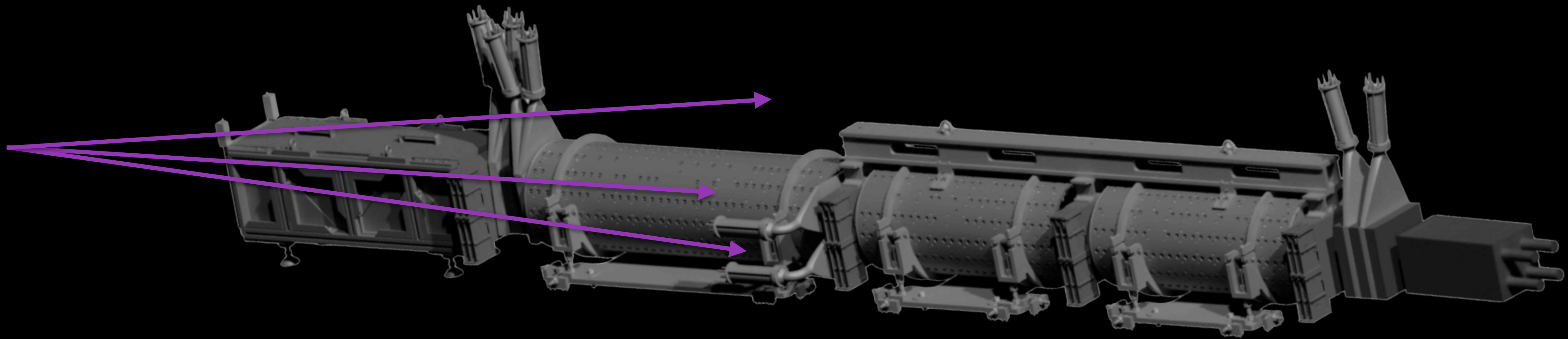
—> transverse momentum



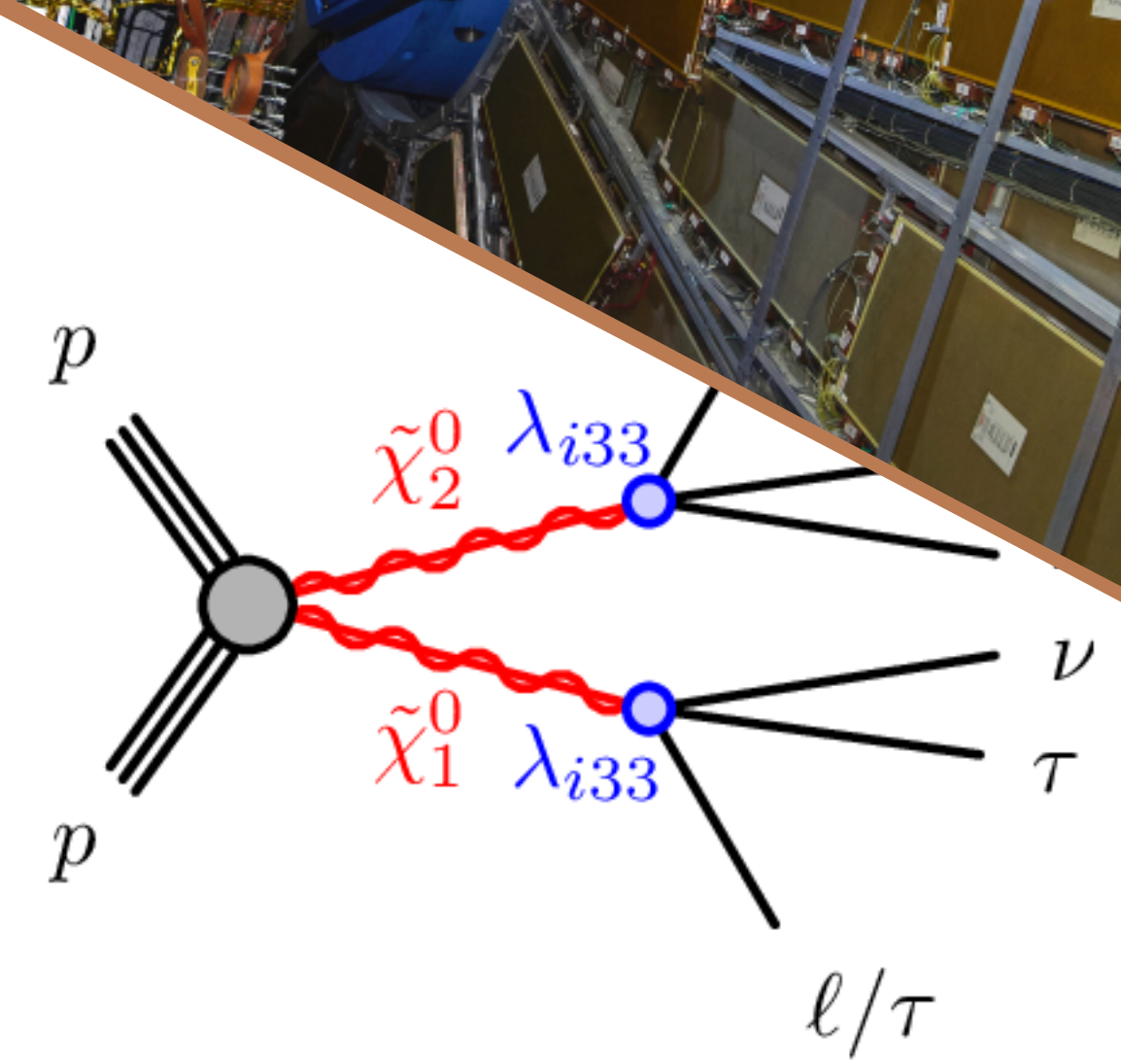
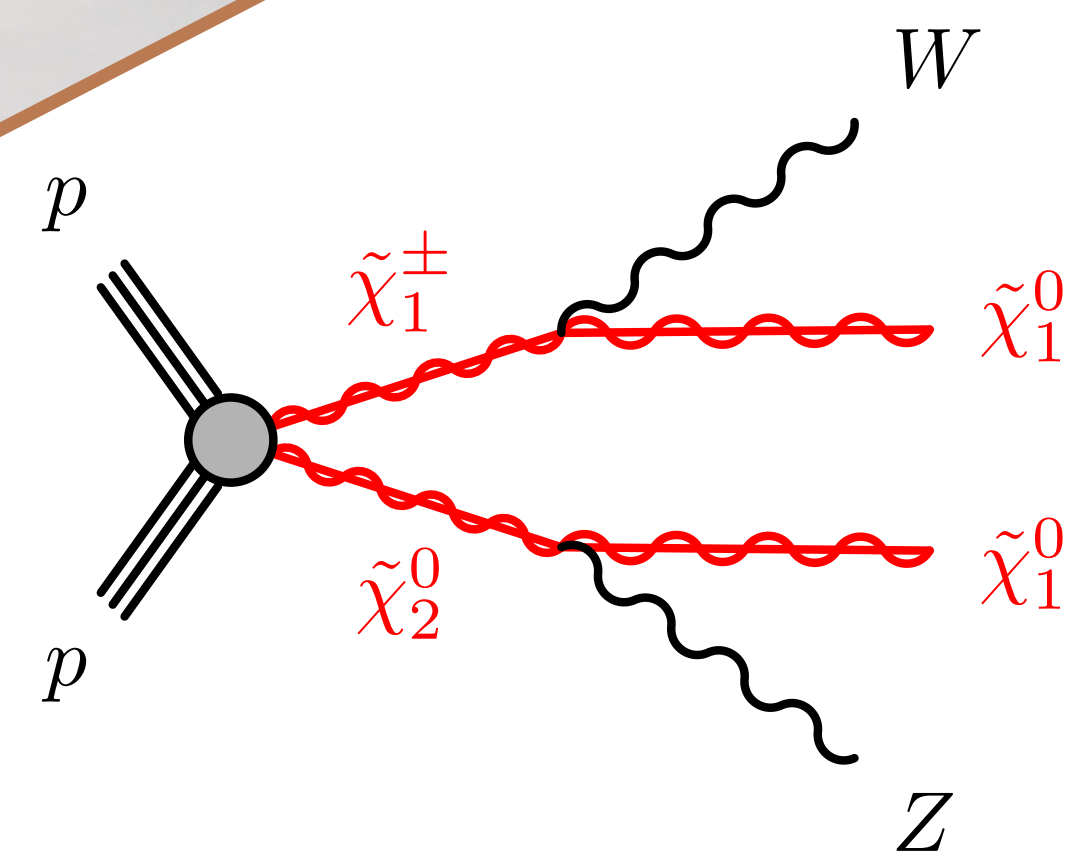
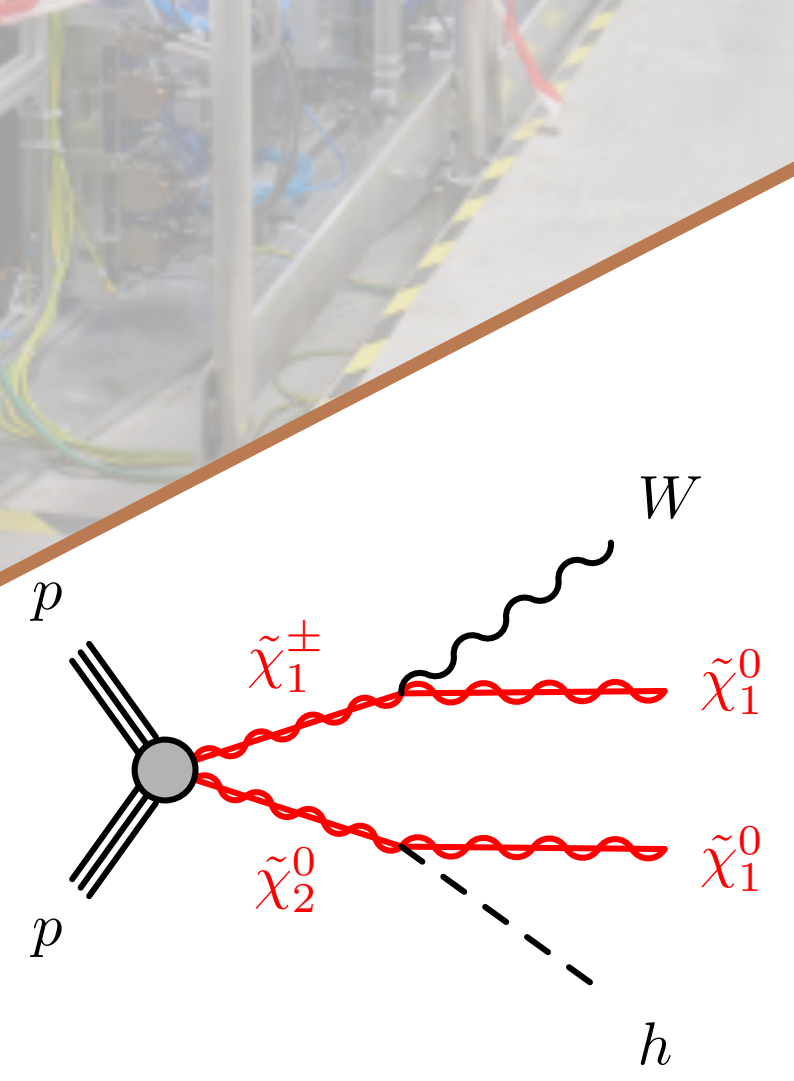
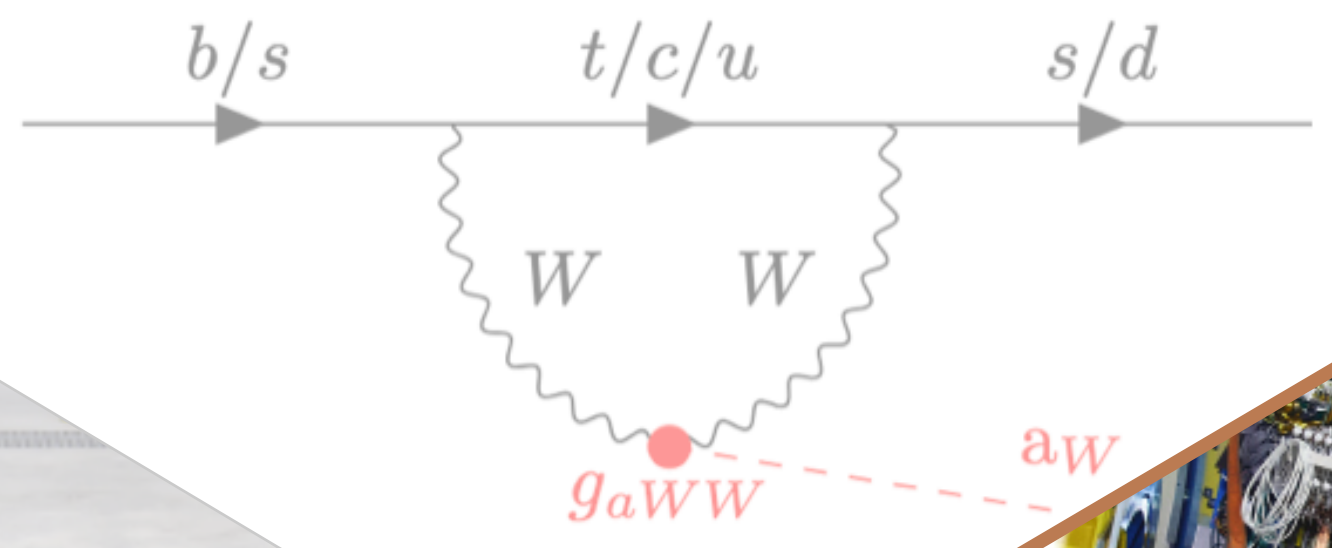
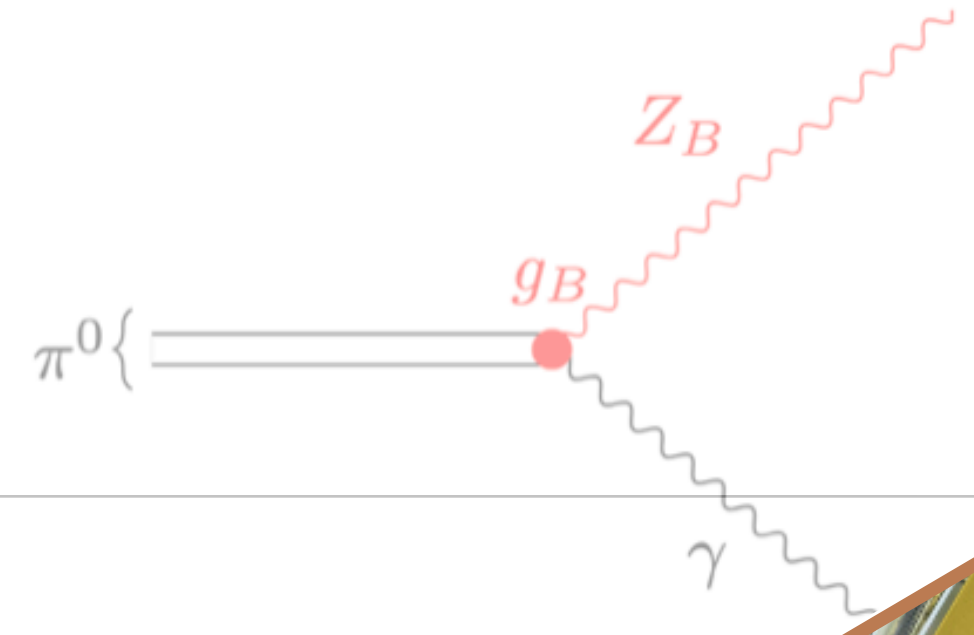
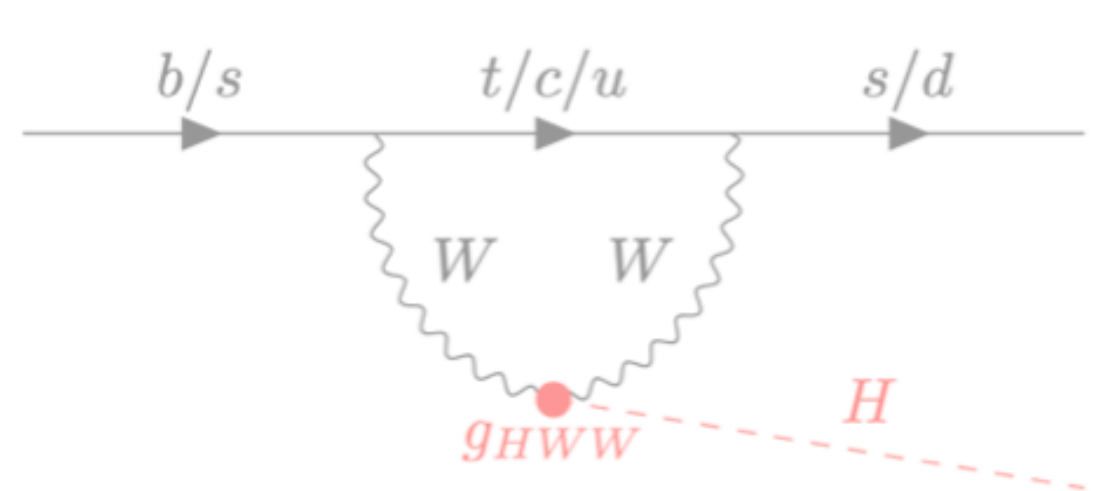
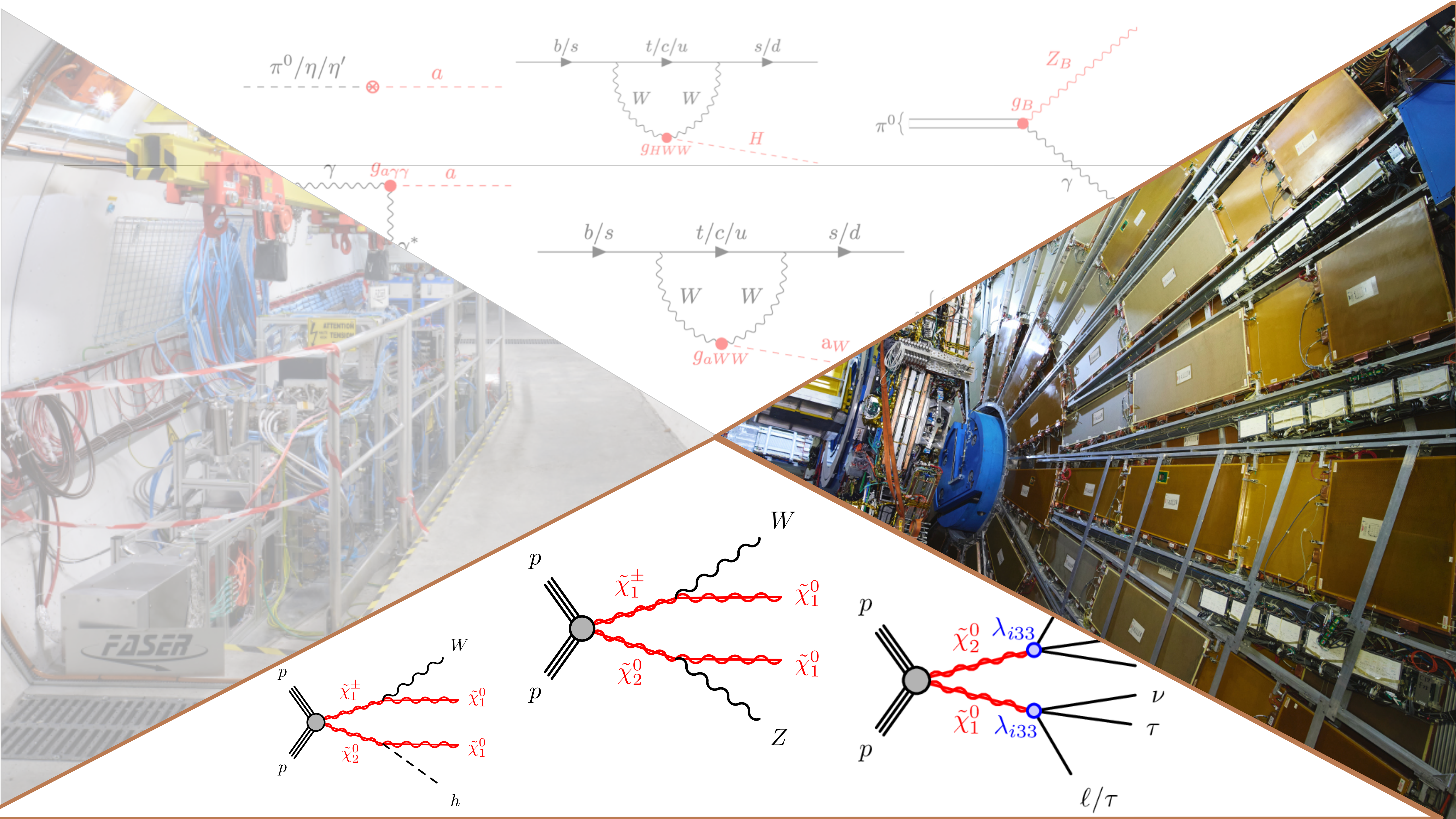
Low transverse momentum

High rate in forward direction

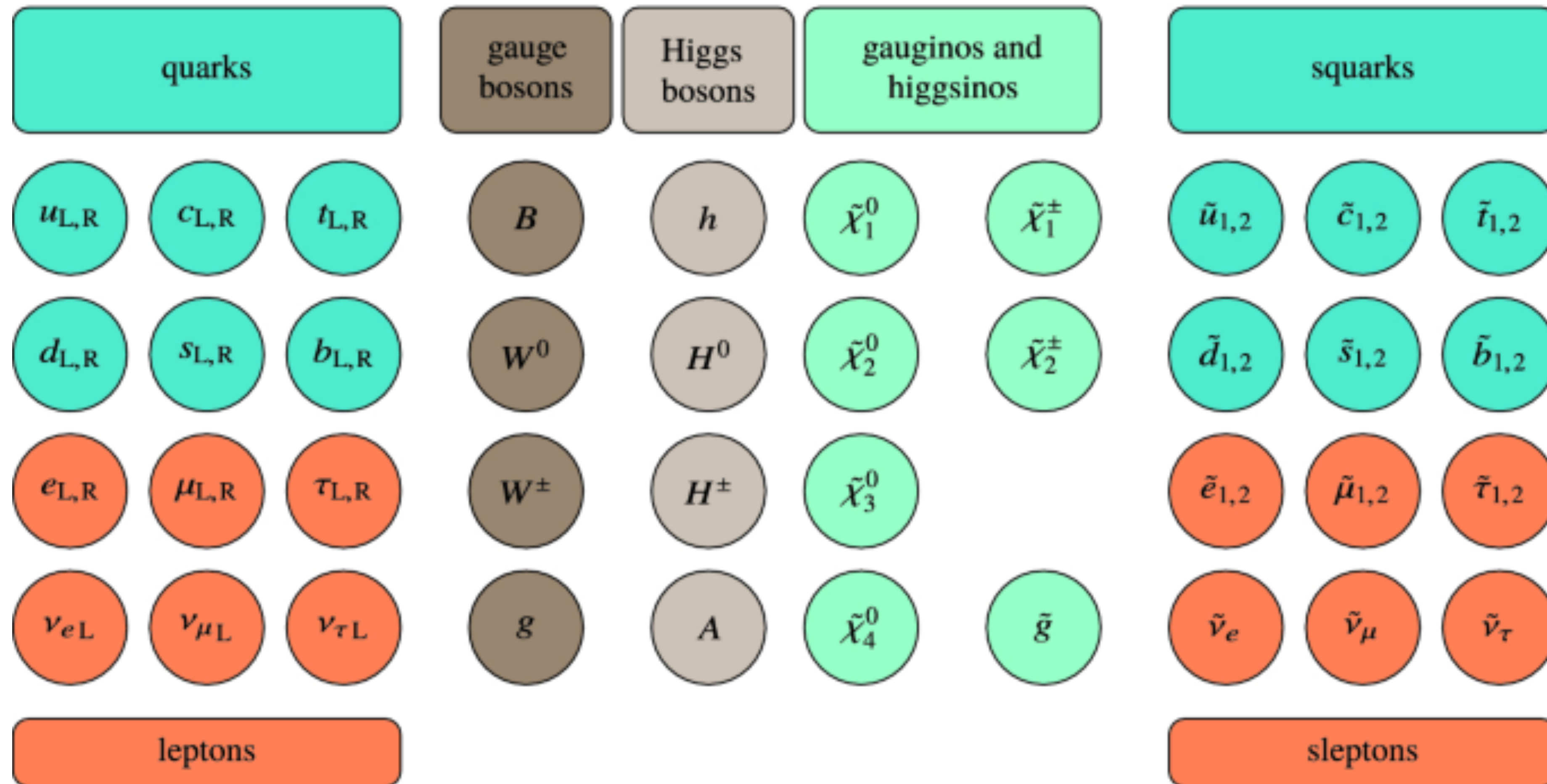




FASER



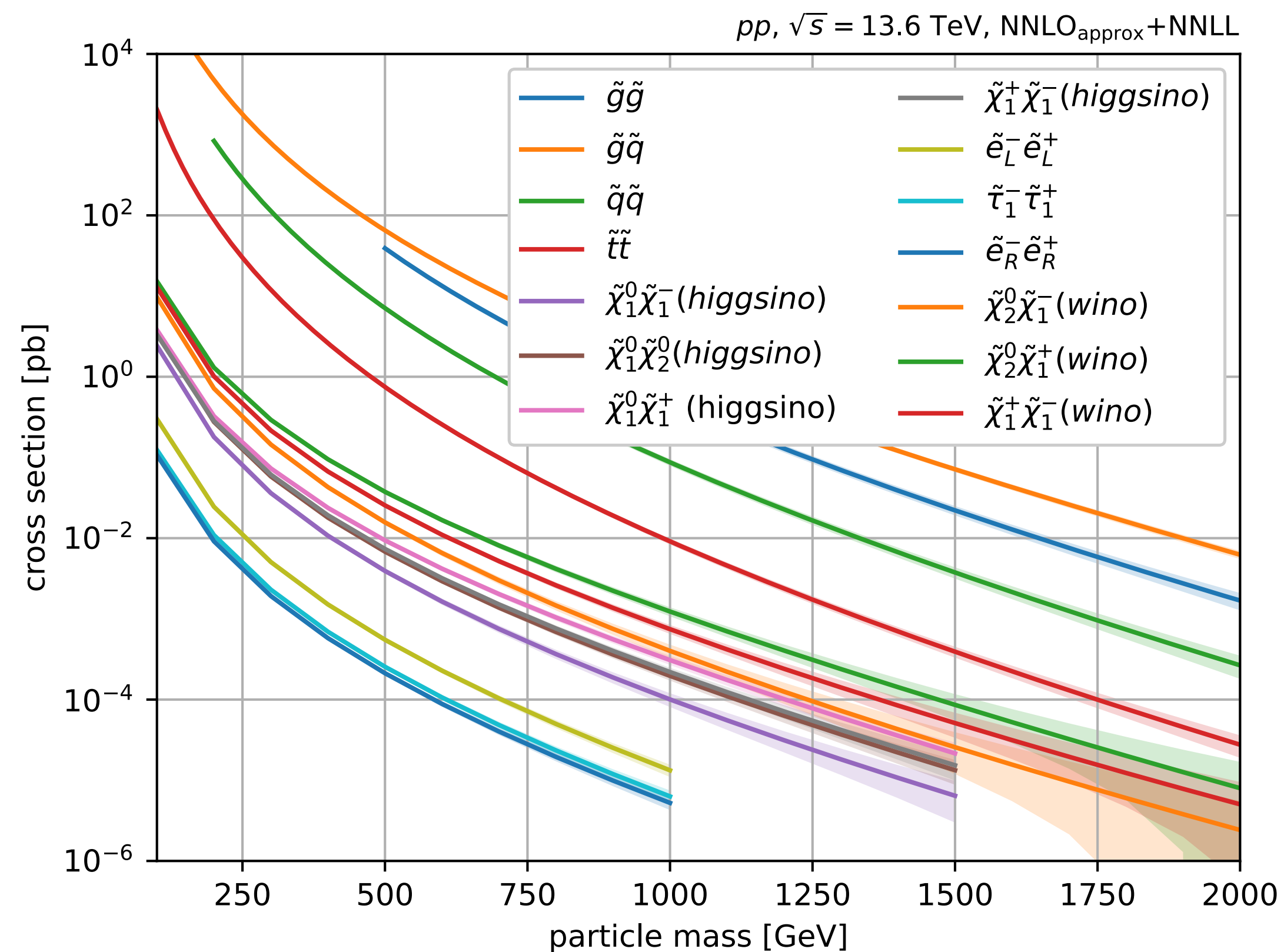
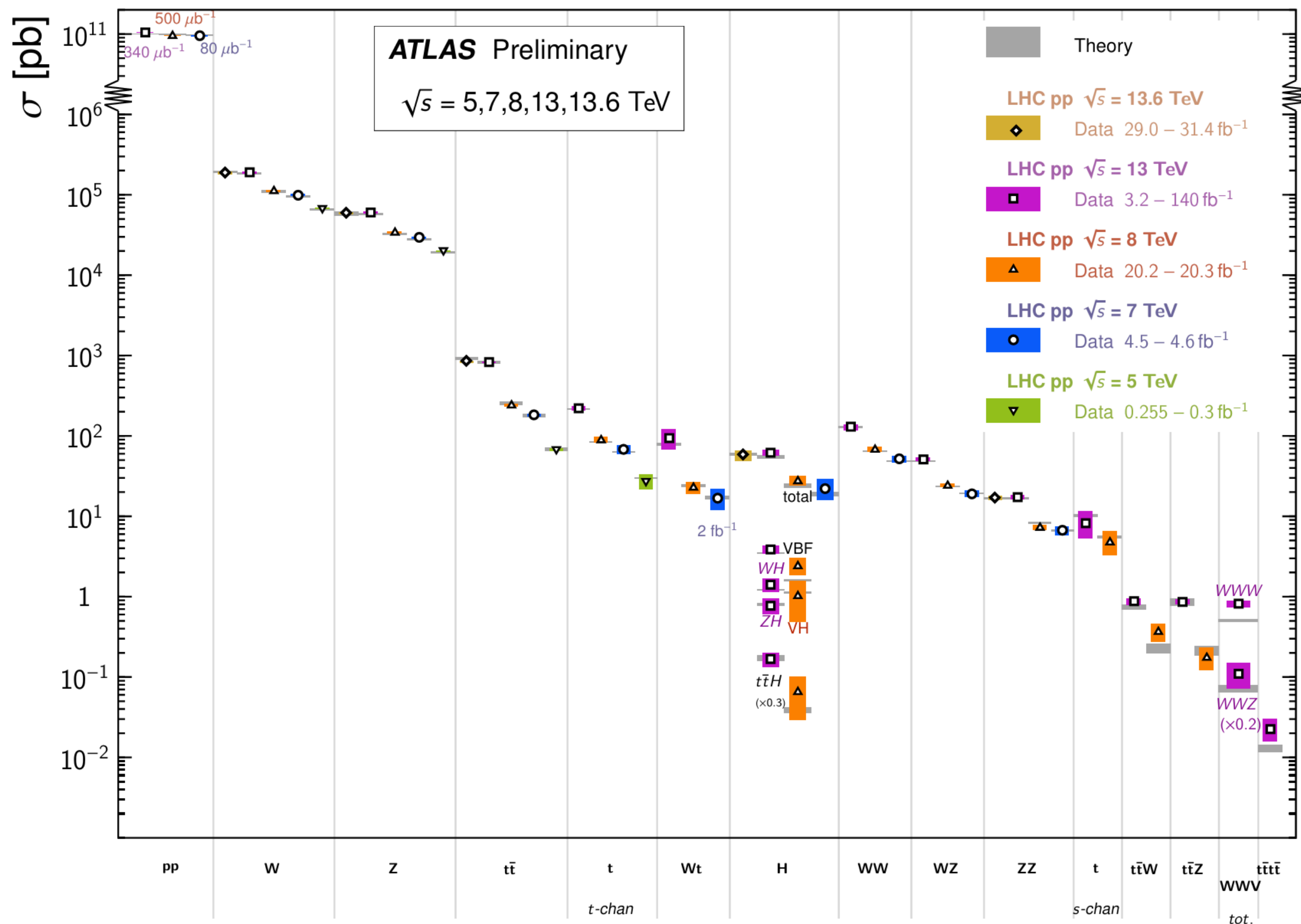
Supersymmetry (SUSY)



What is my research focused on?

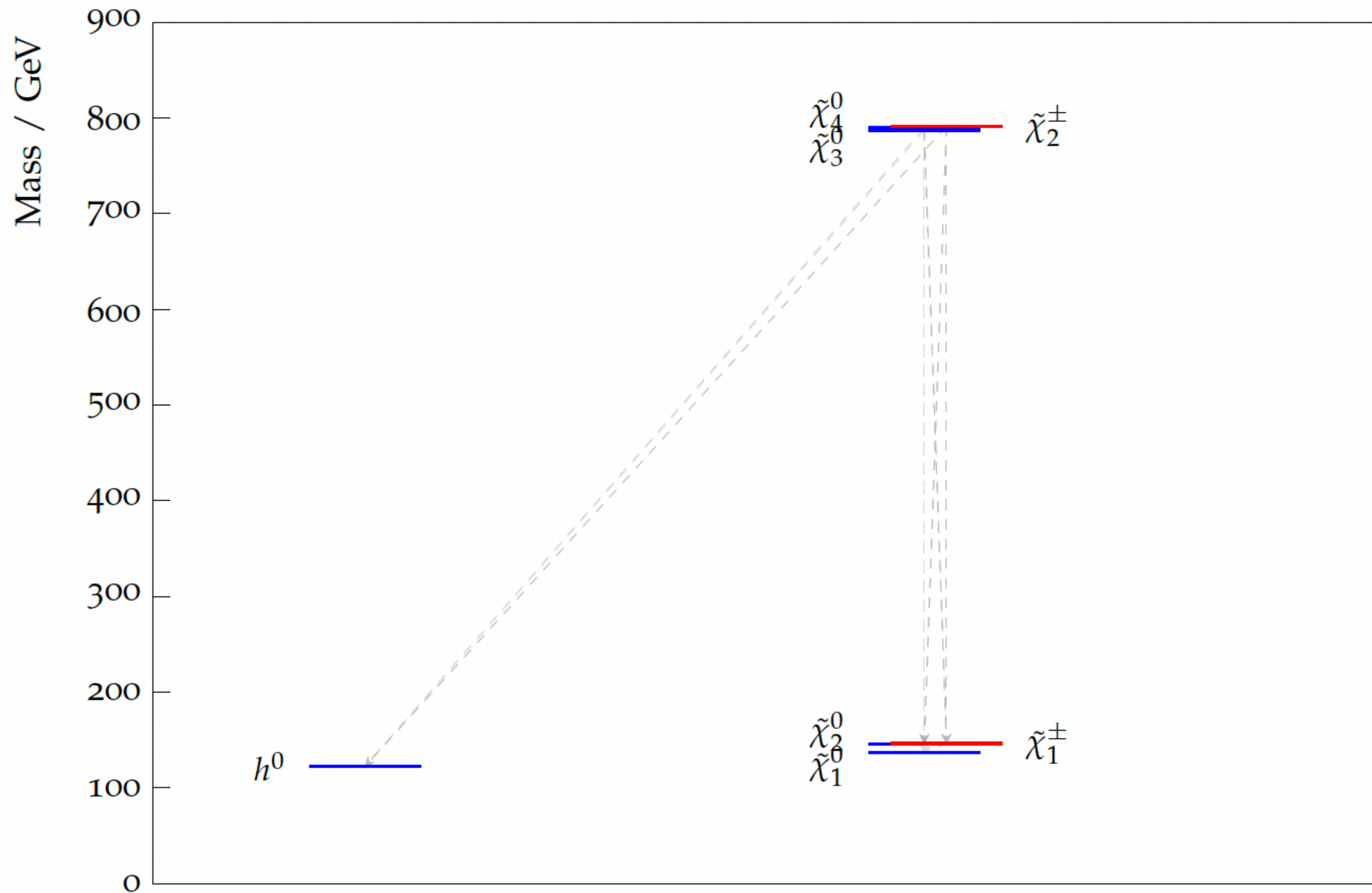
Standard Model Total Production Cross Section Measurements

Status: June 2024



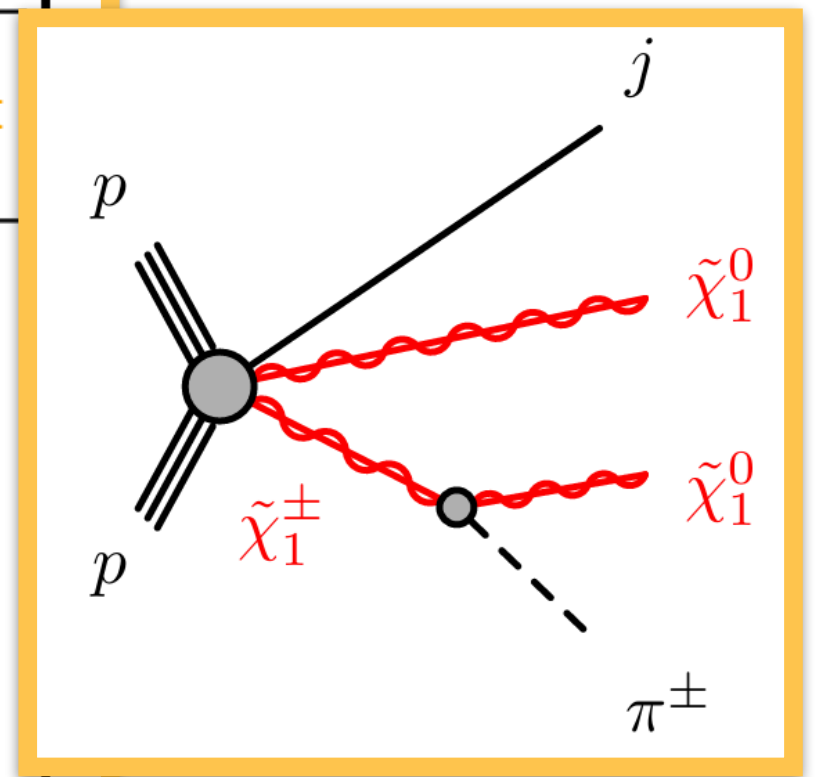
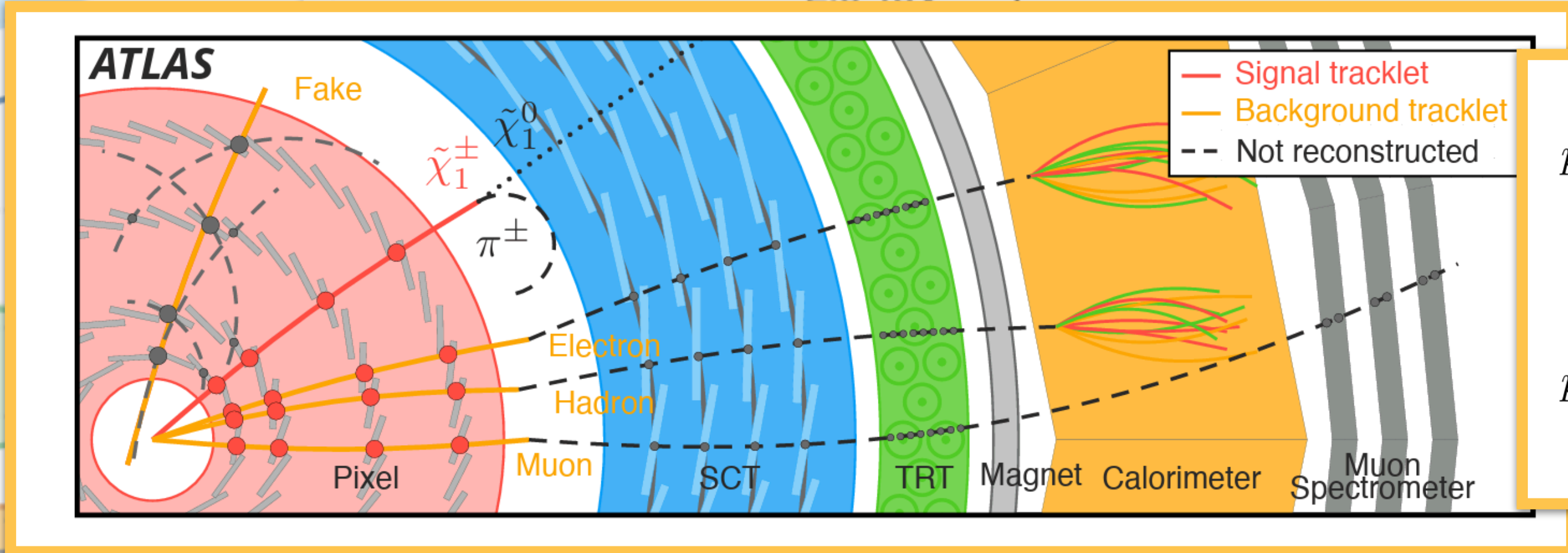
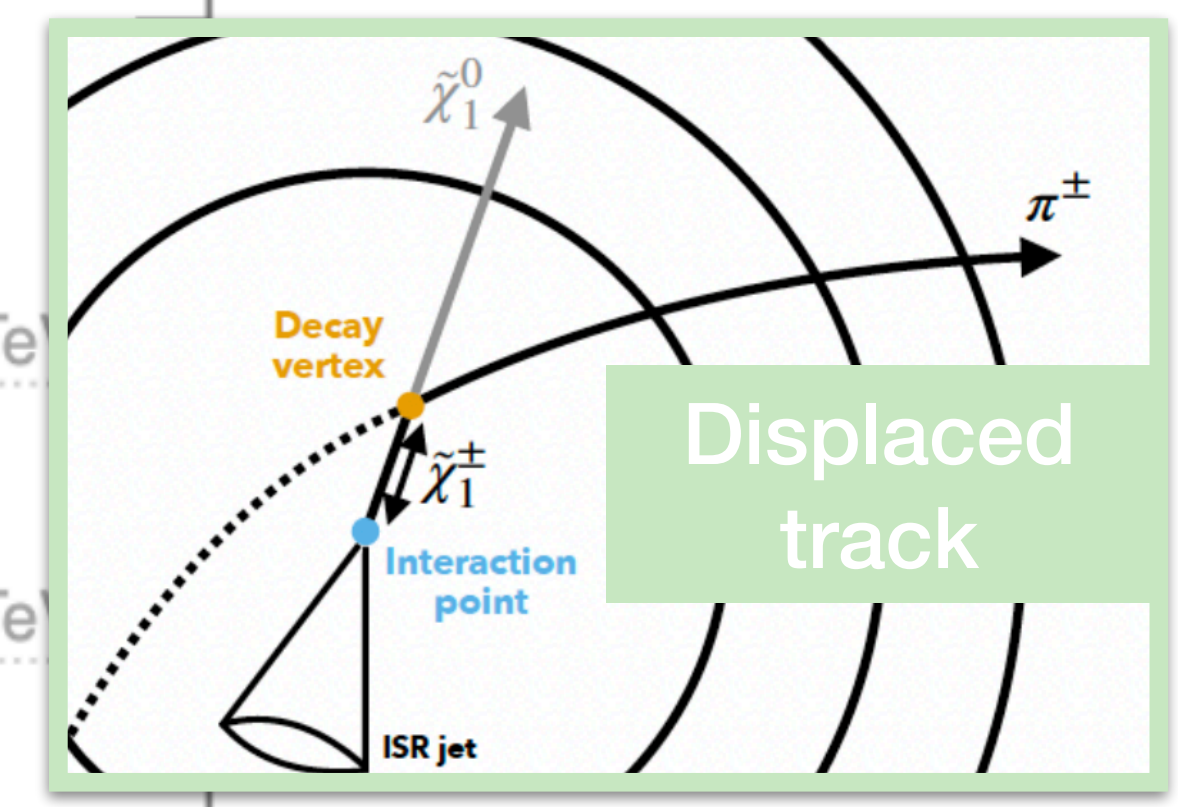
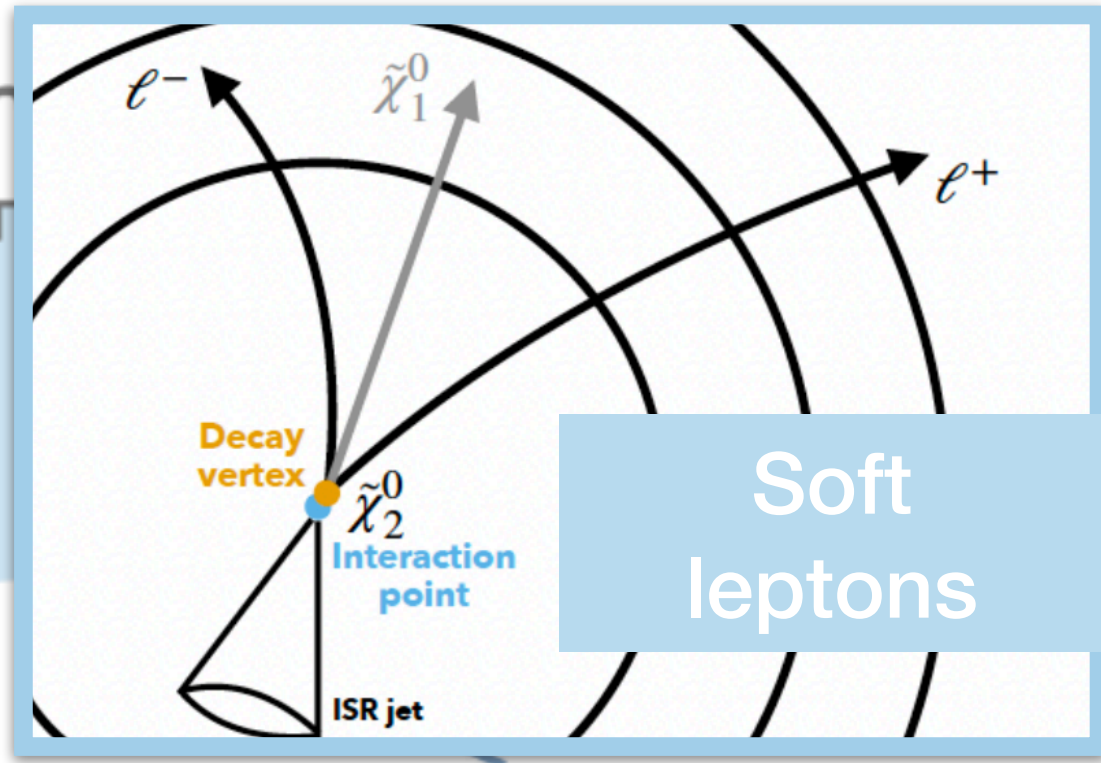
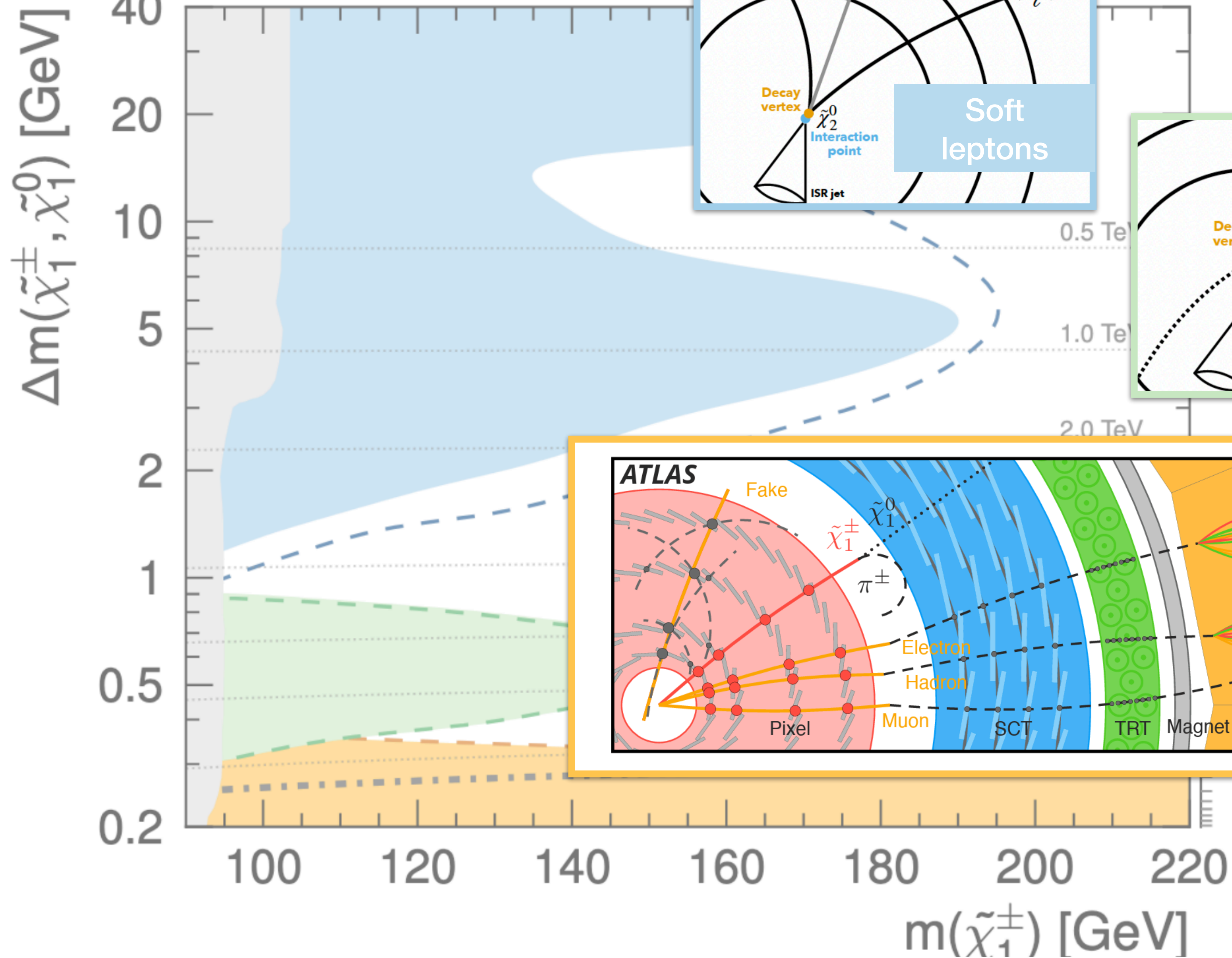
<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections>

Compressed SUSY

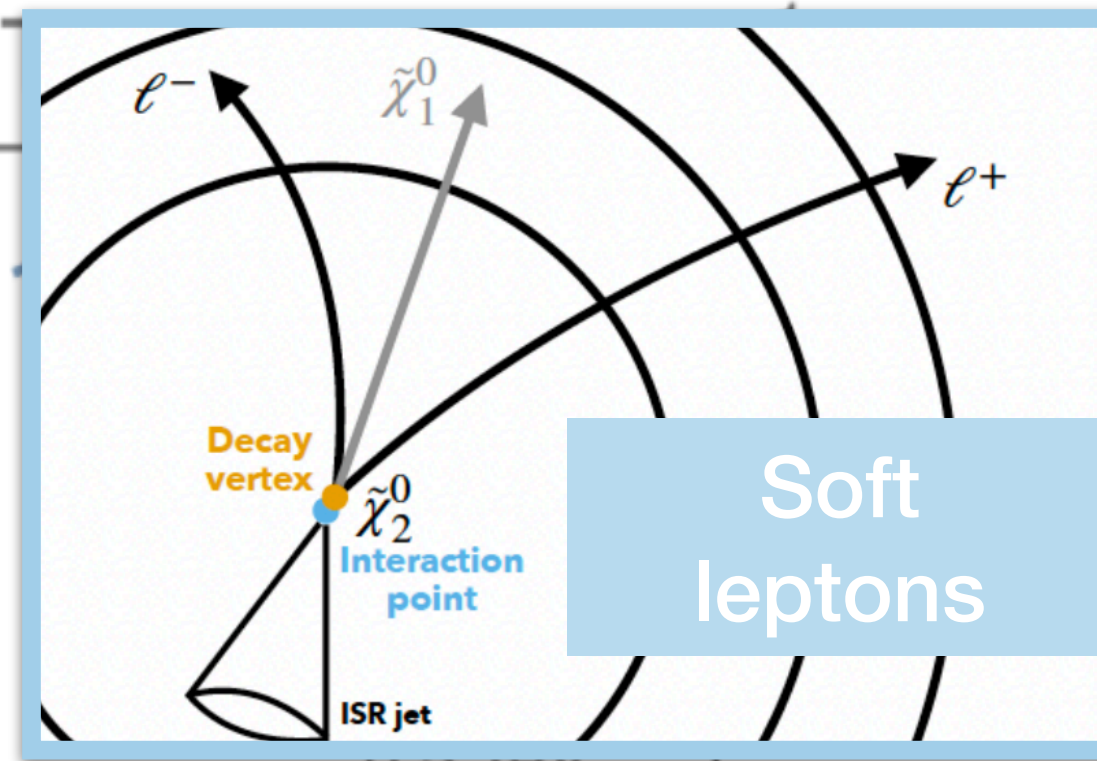
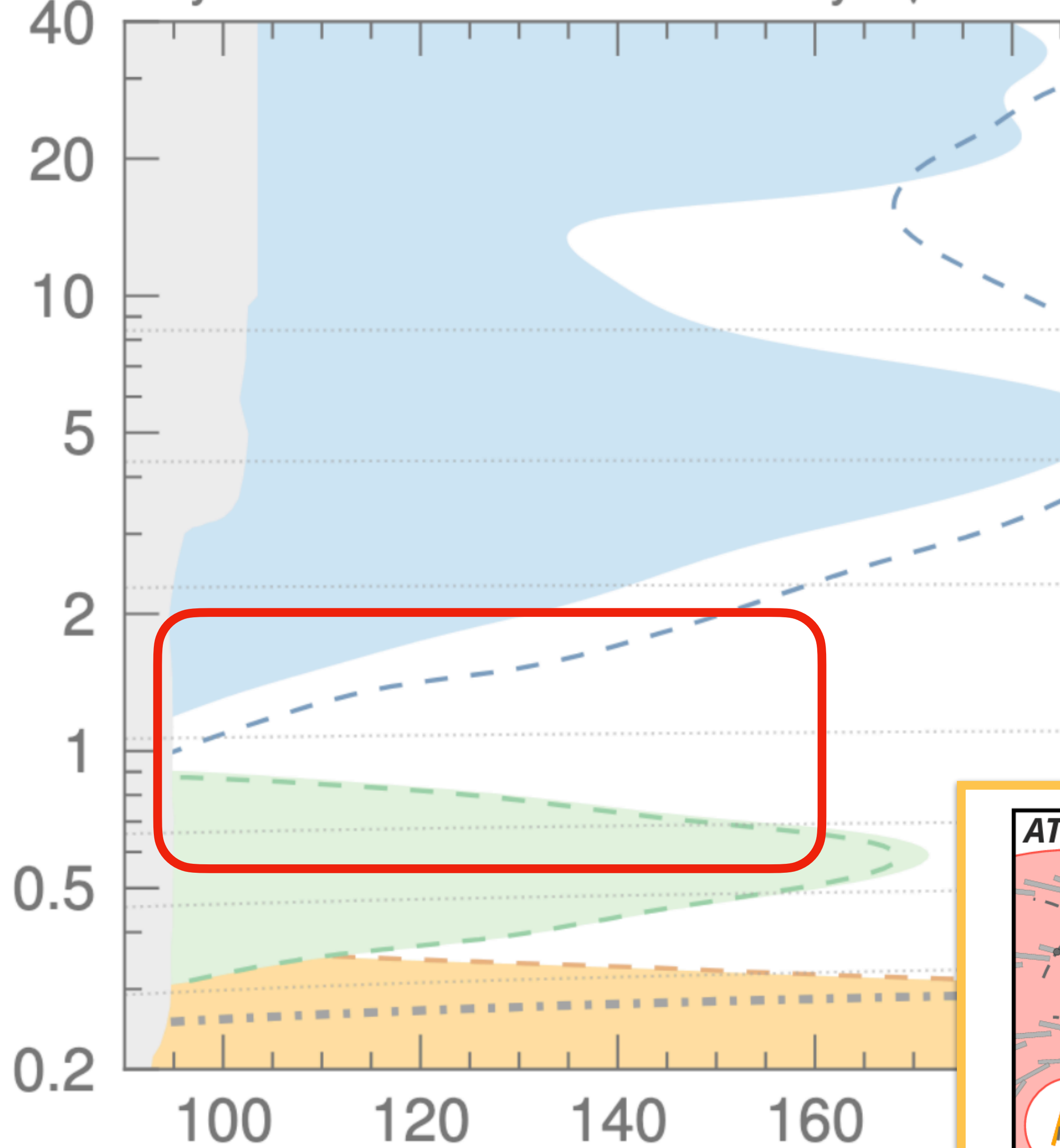


- Low mass difference between gauginos - 'compressed' scenarios
- Higgsinos with close by masses well motivated through Dark Matter & Naturalness
- Not yet excluded by any ATLAS searches and the pMSSM scan
- Excesses at small mass splittings $\sim 10\text{-}20$ GeV observed by ATLAS and CMS

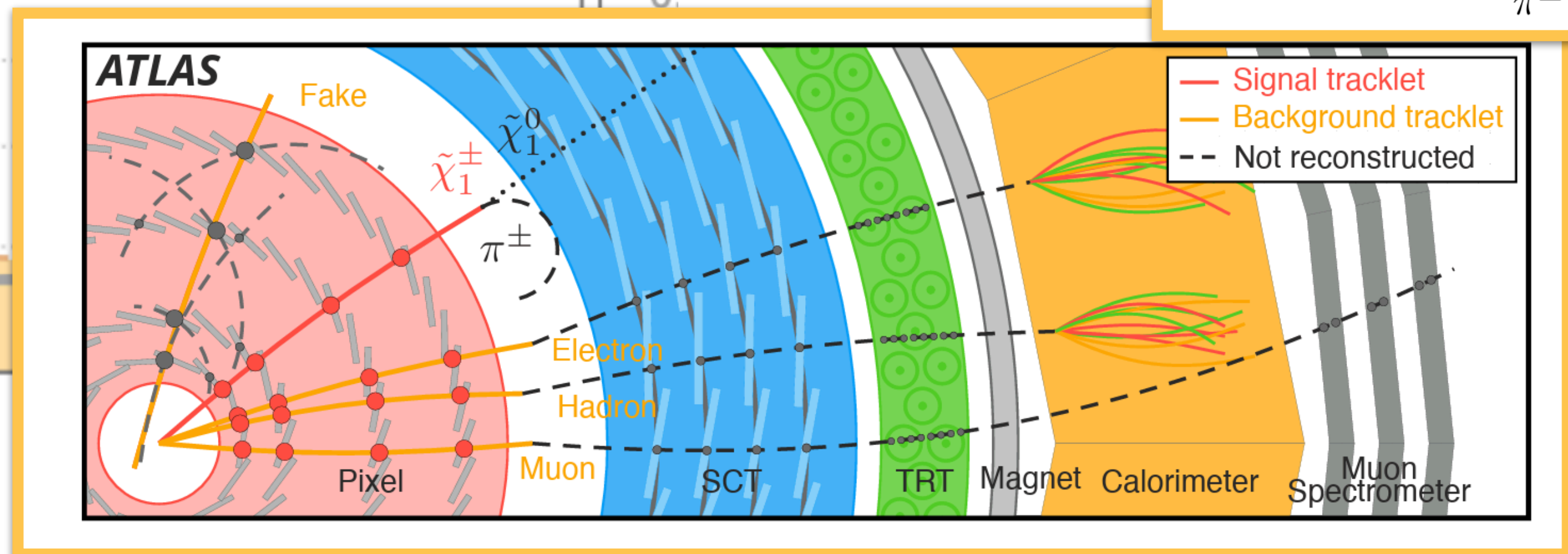
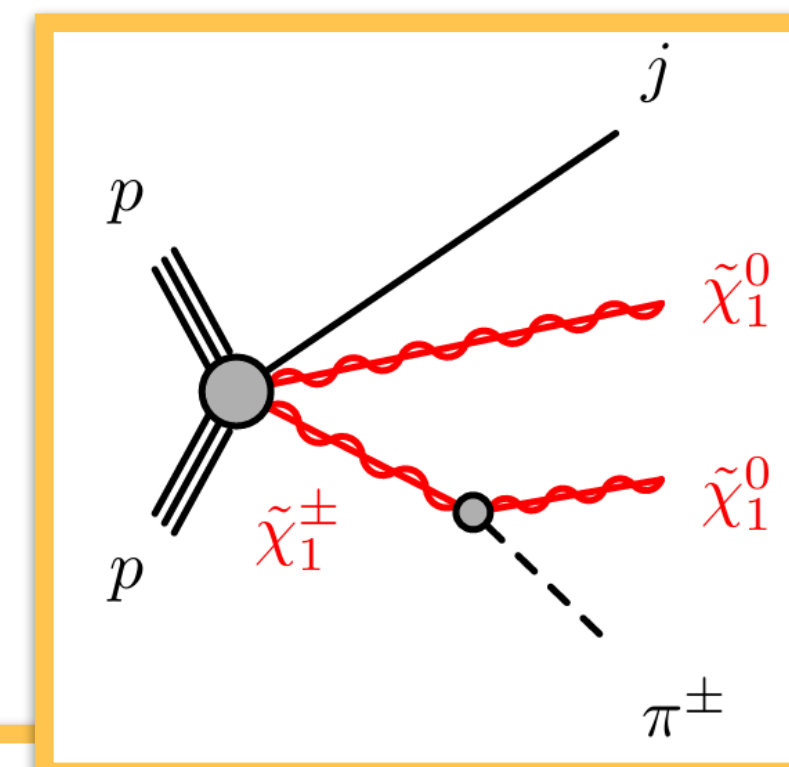
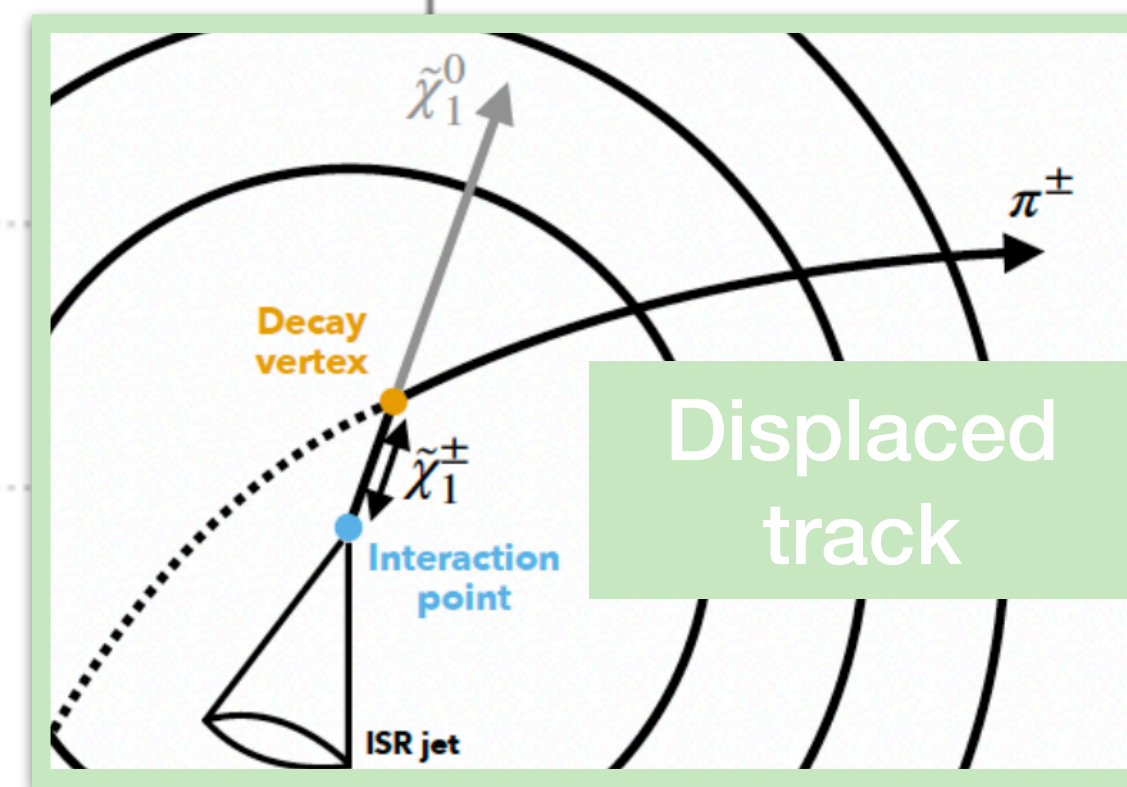
Very quickly changing detector signature



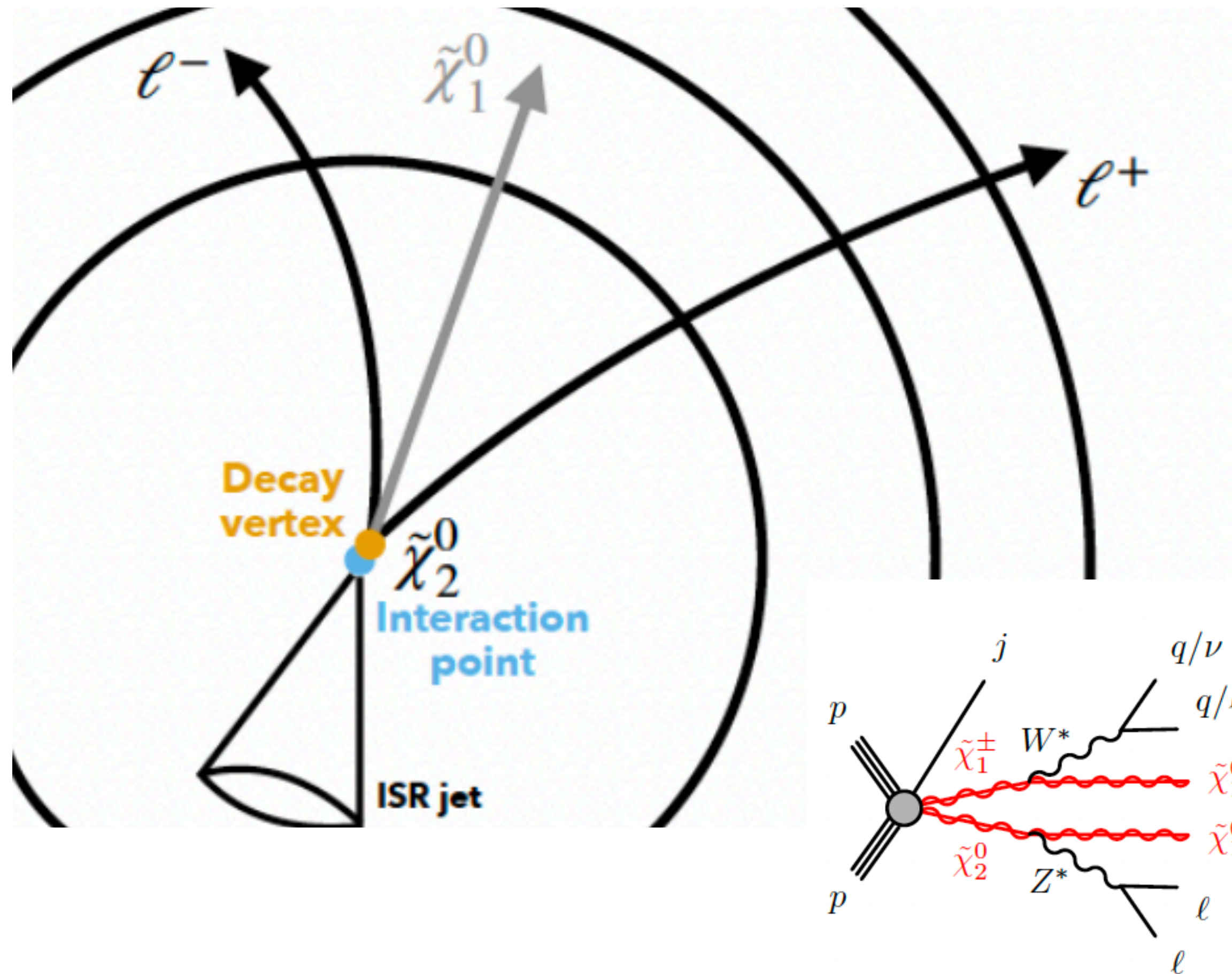
$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ [GeV]



Very quickly changing detector signature

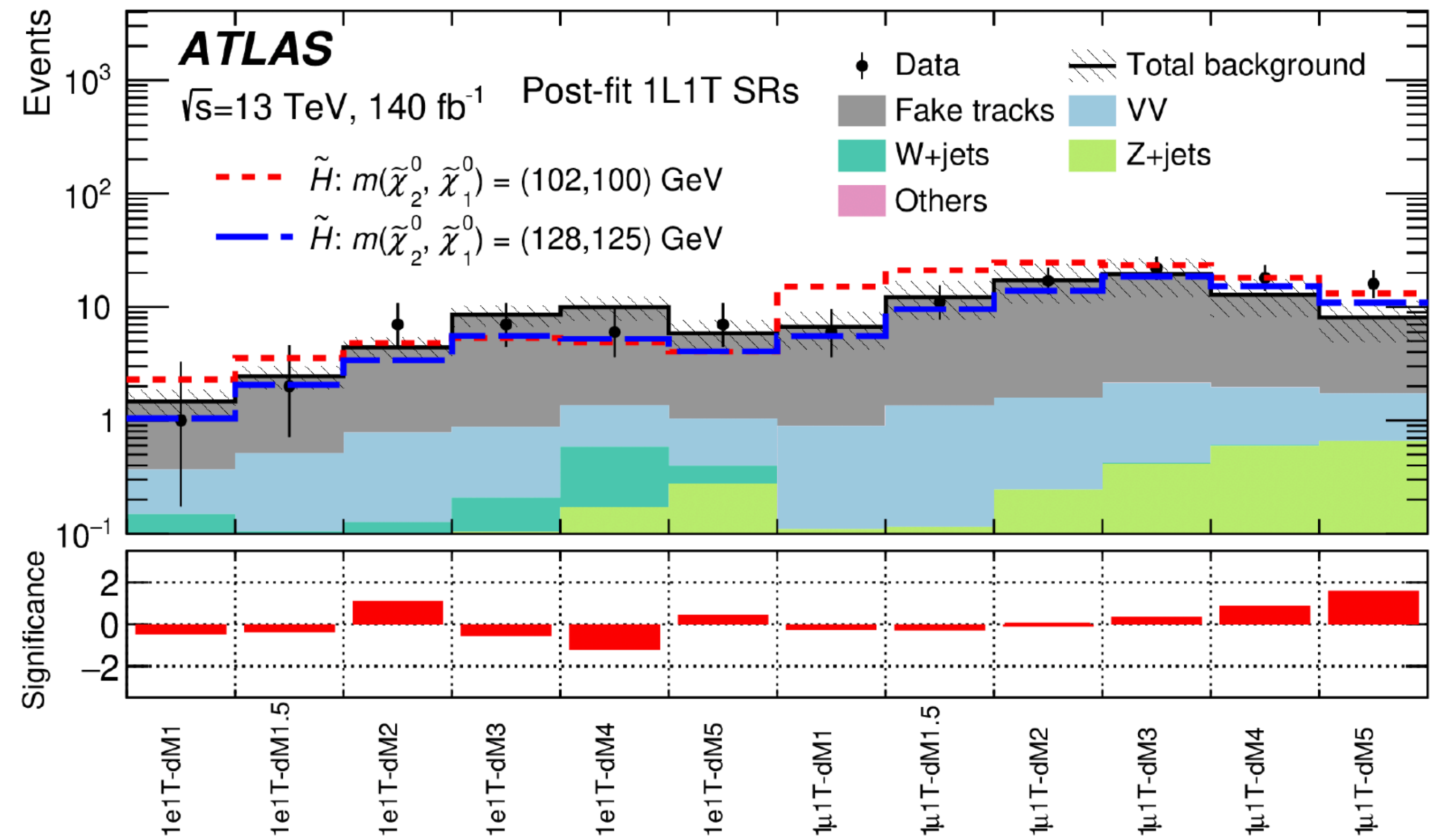
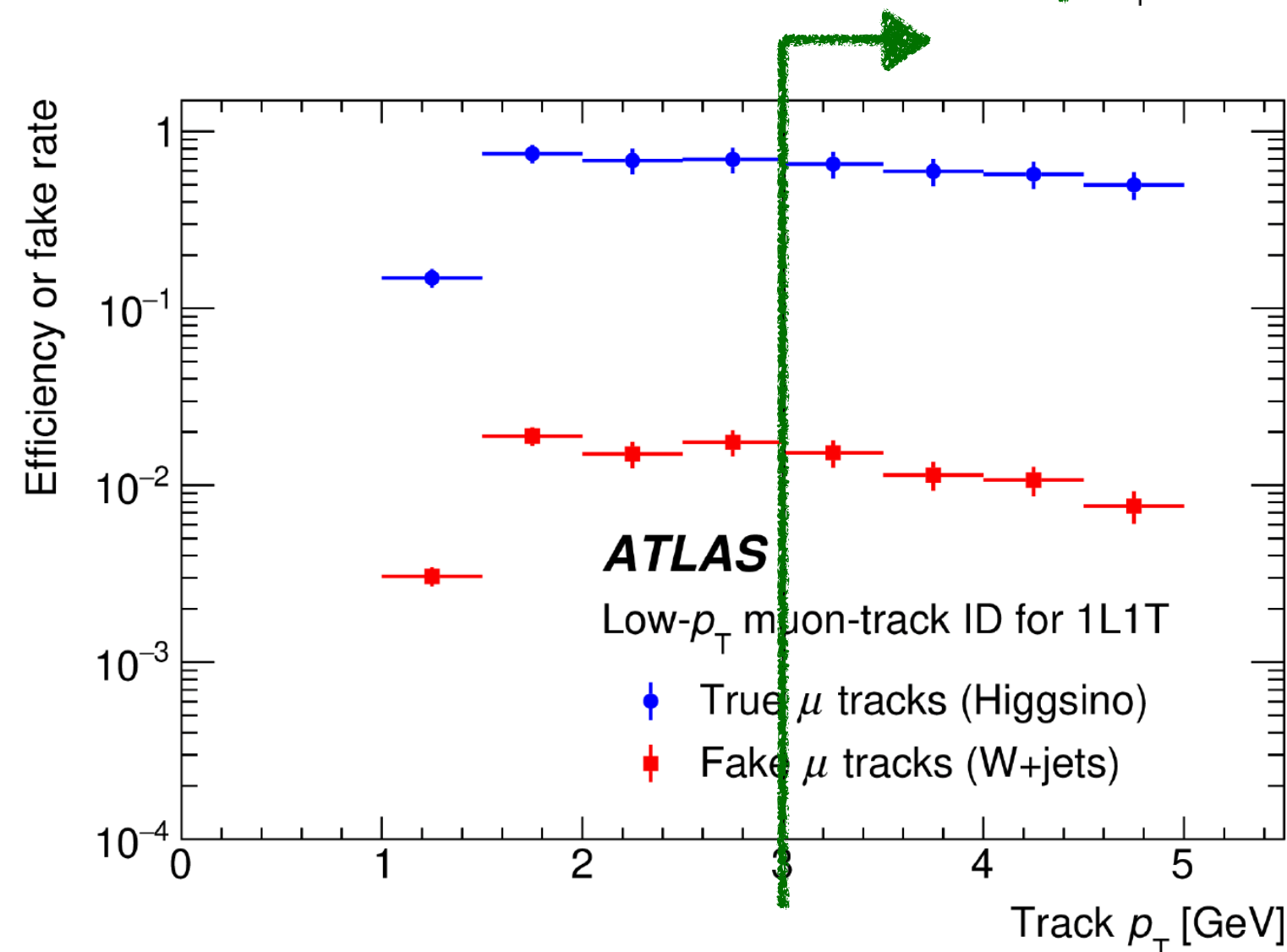
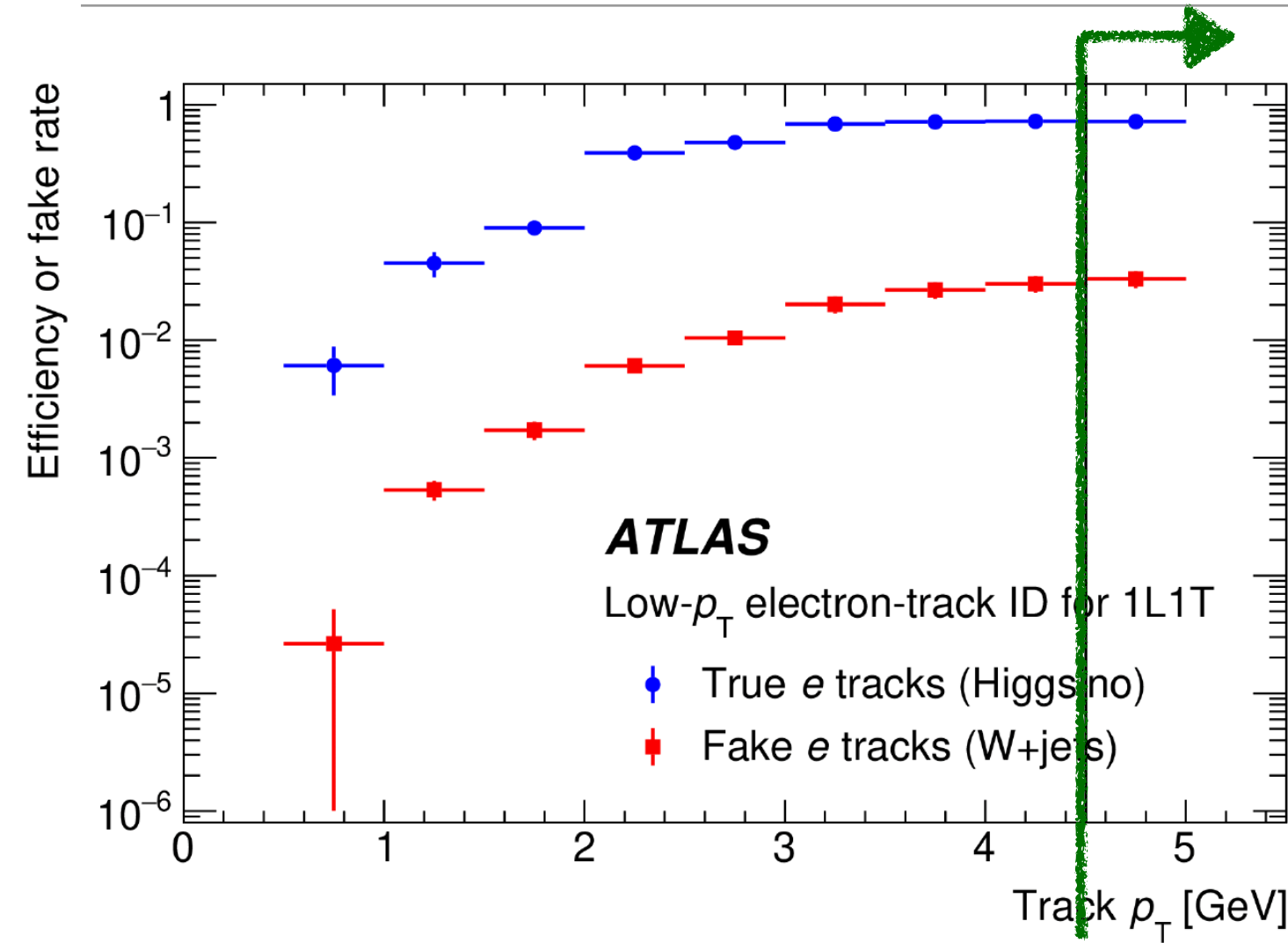


The soft lepton & track analysis



- Target $\Delta m \sim 1$ GeV
- Use di-electron and di-muon events
- Key aspect: develop low momentum lepton taggers using neural networks
- Extend pT threshold below 4.5/3 GeV for electrons/muons

The soft lepton & track analysis



- Immense effort developing dedicated neural networks to identify low-momentum tracks as electrons or muons
- Dedicated neural network parametrised by mass splitting
- Data-driven fake lepton estimation



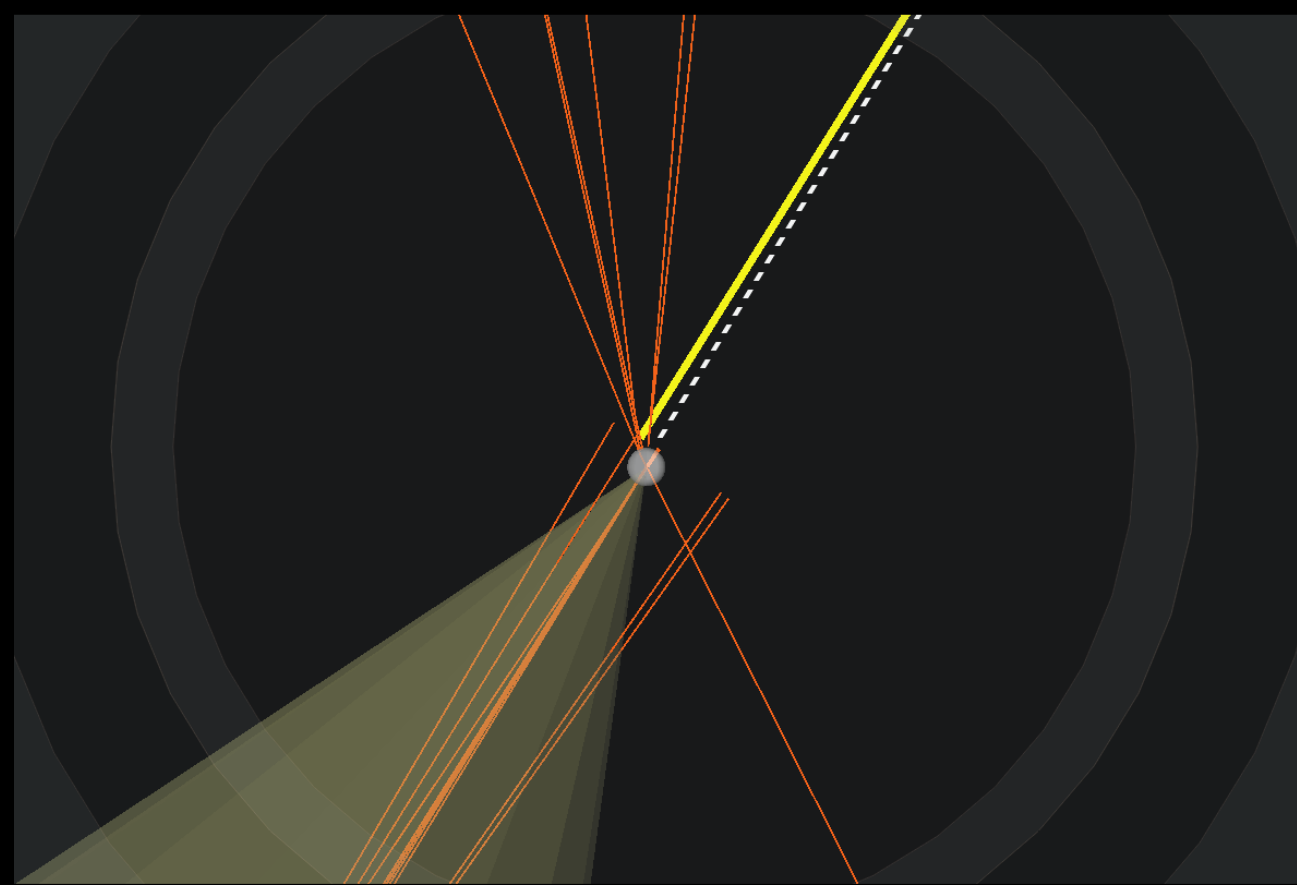
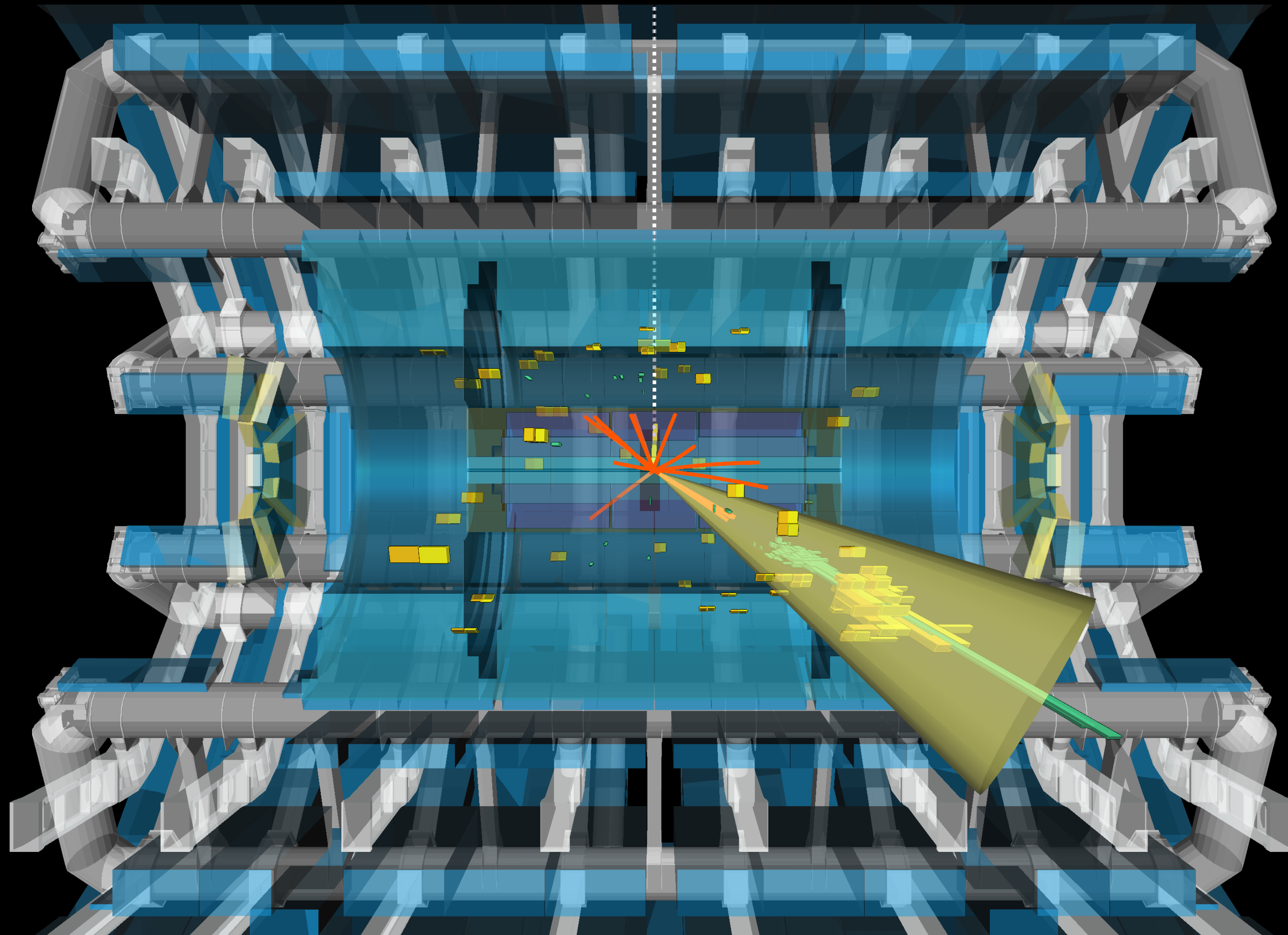
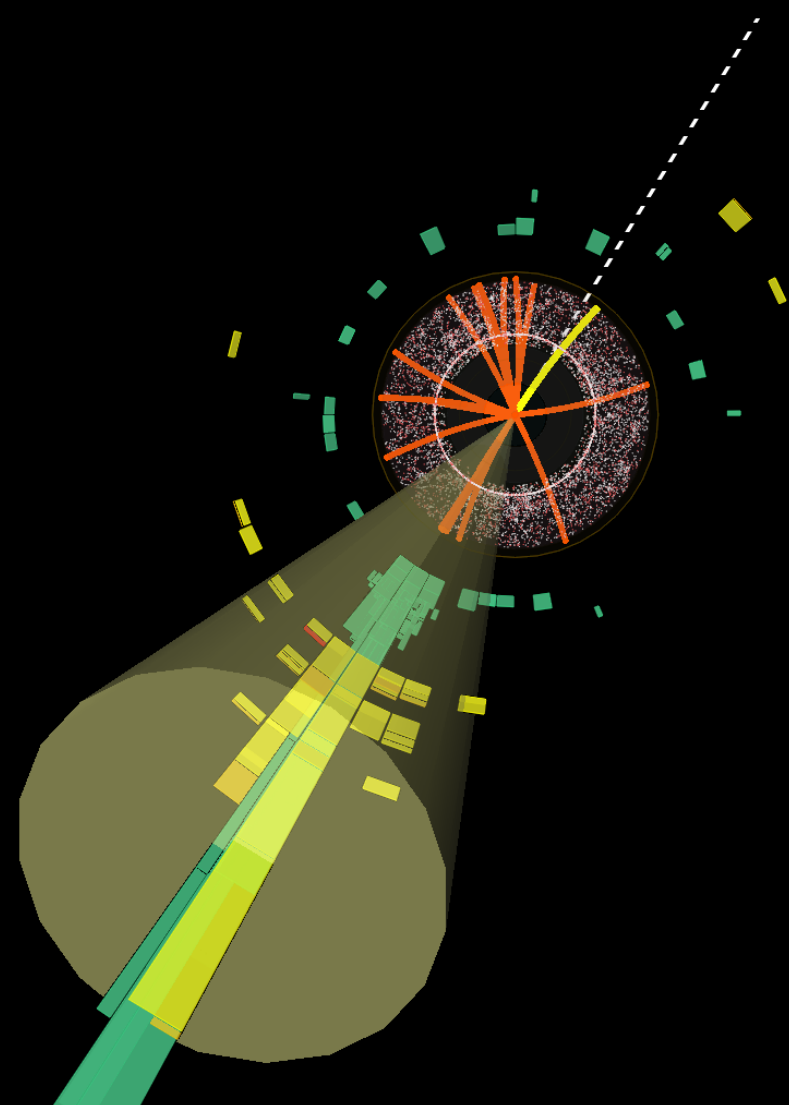
ATLAS

EXPERIMENT

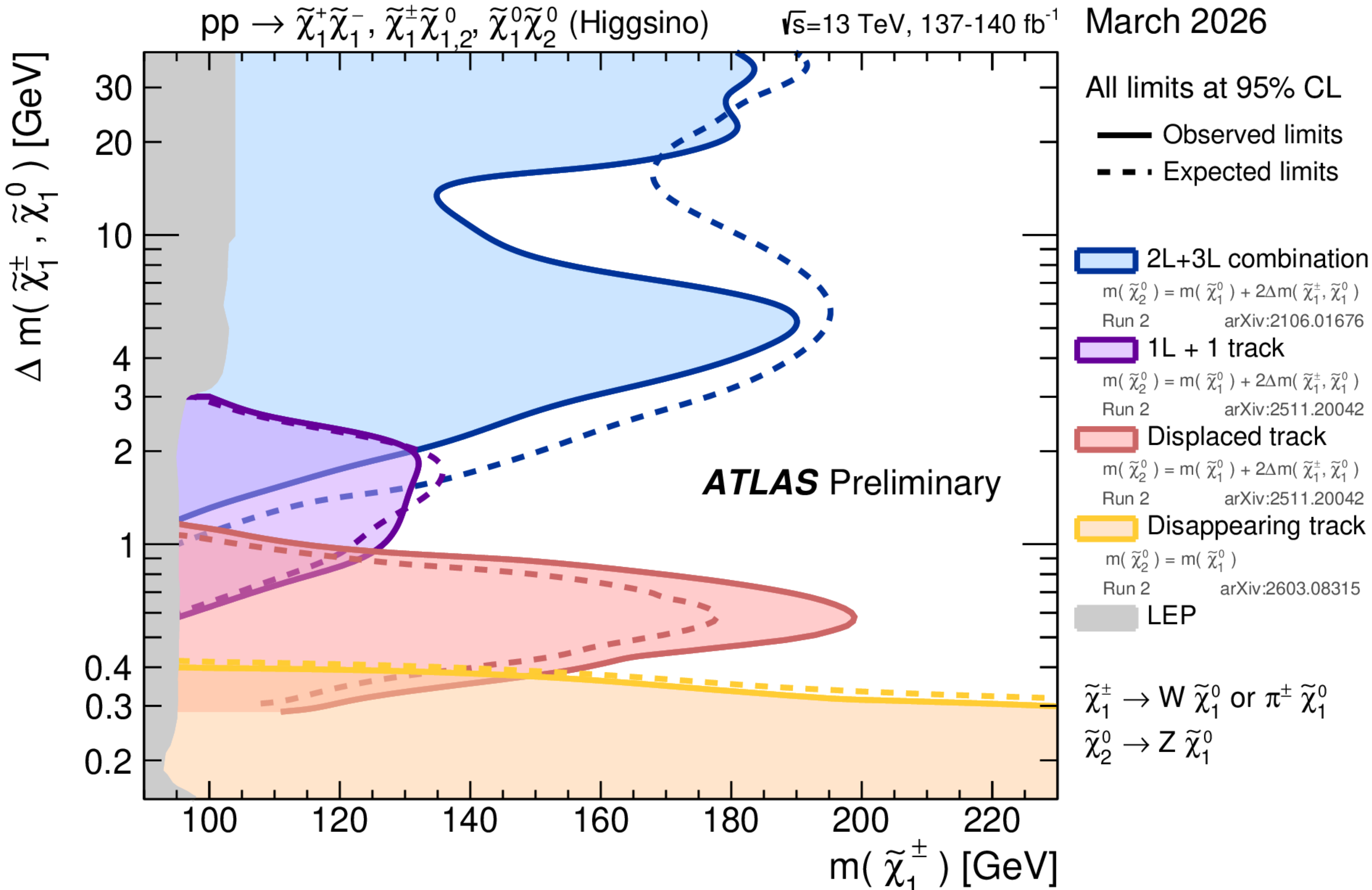
Run: 349309

Event: 1342904905

2018-05-01 16:21:51 CEST



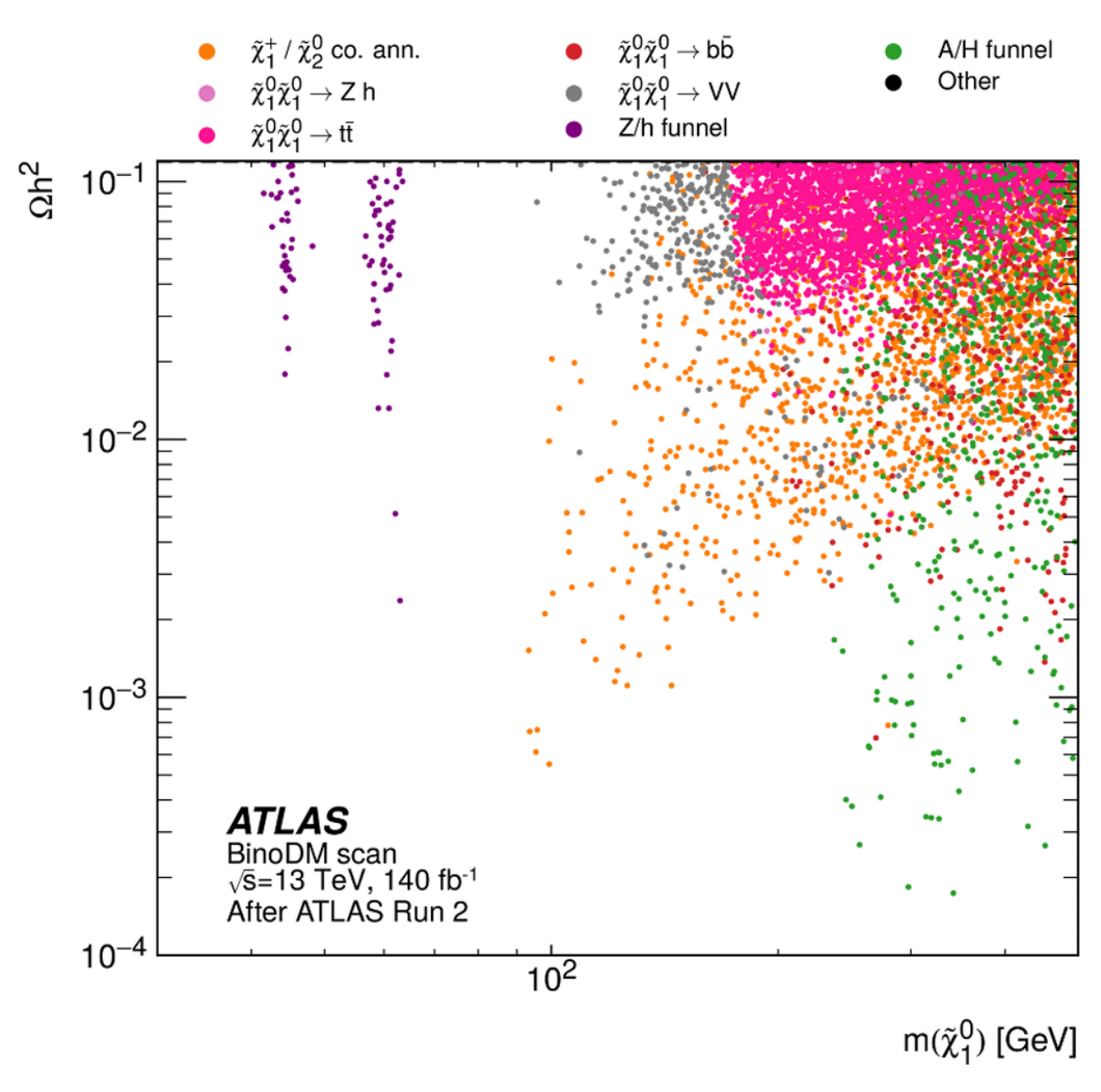
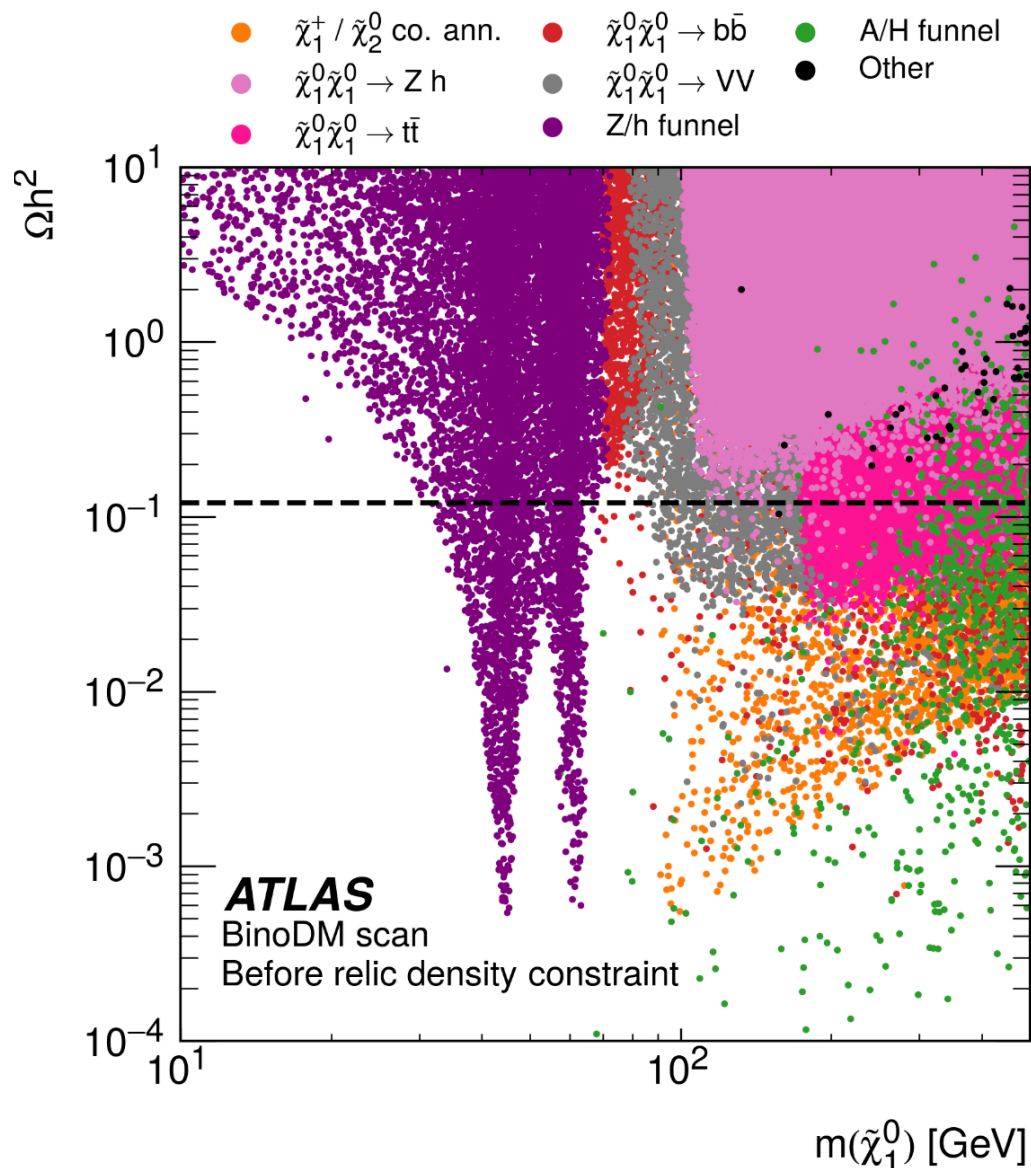
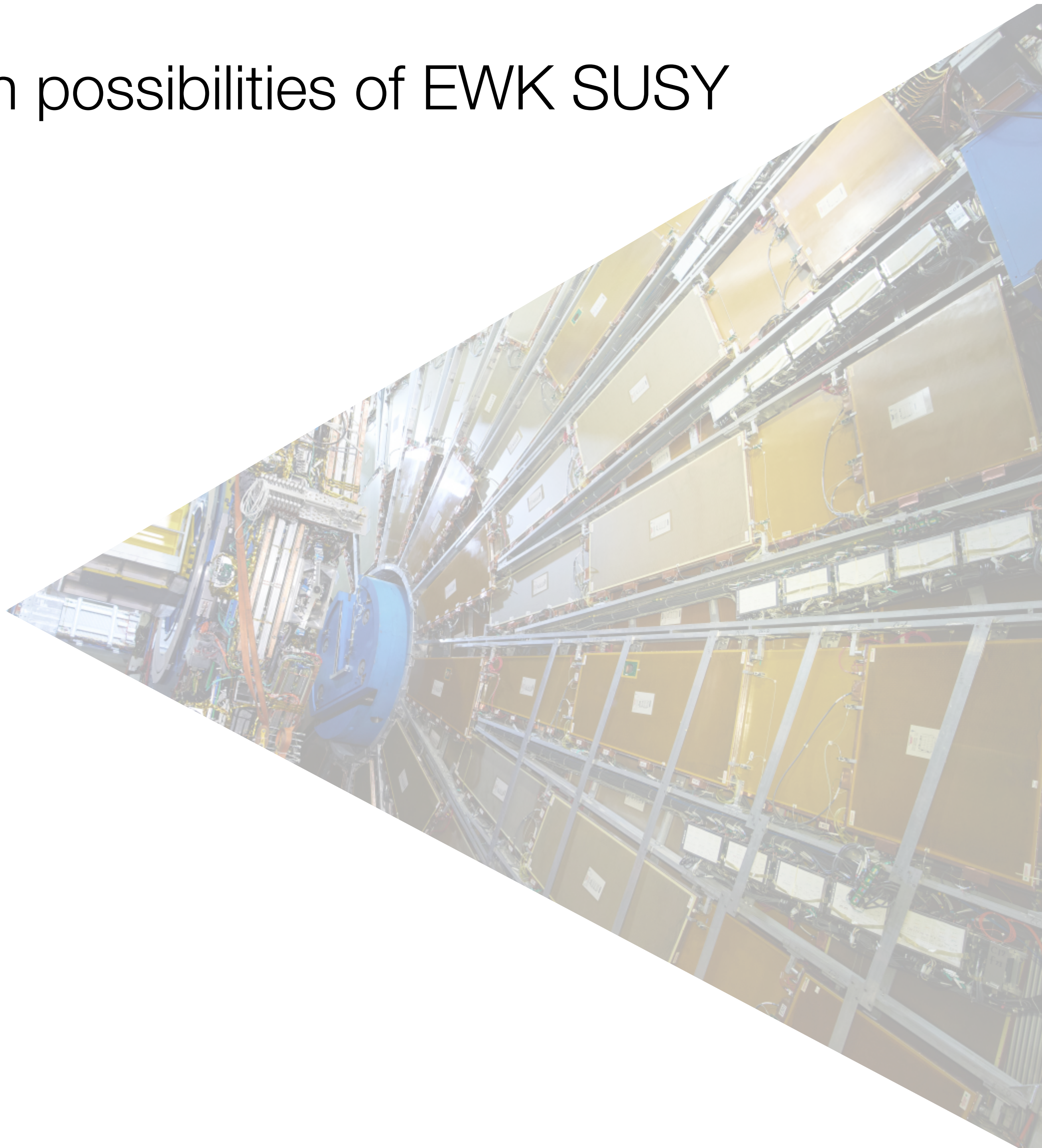
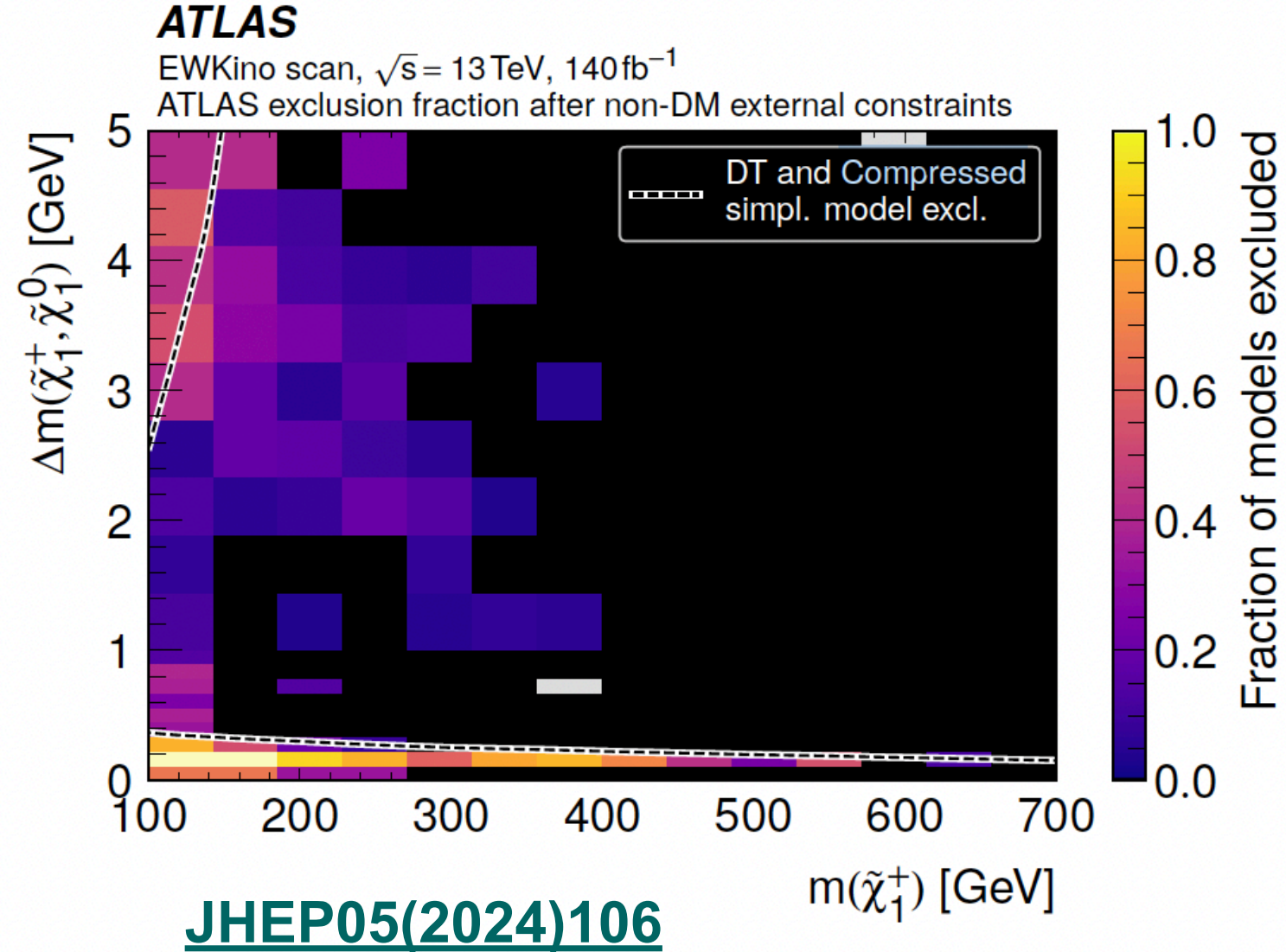
Zooming into compressed mass spectra

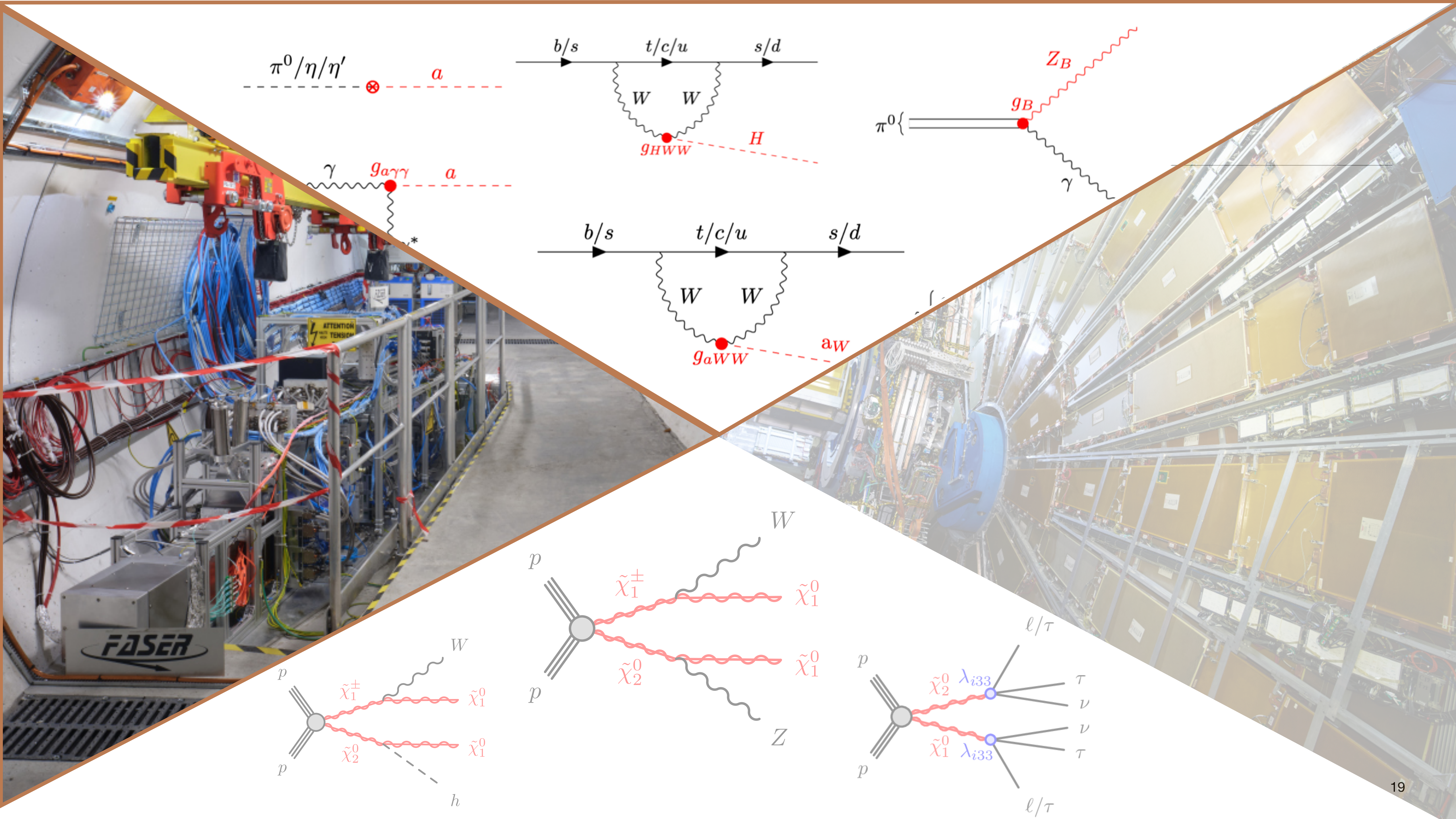


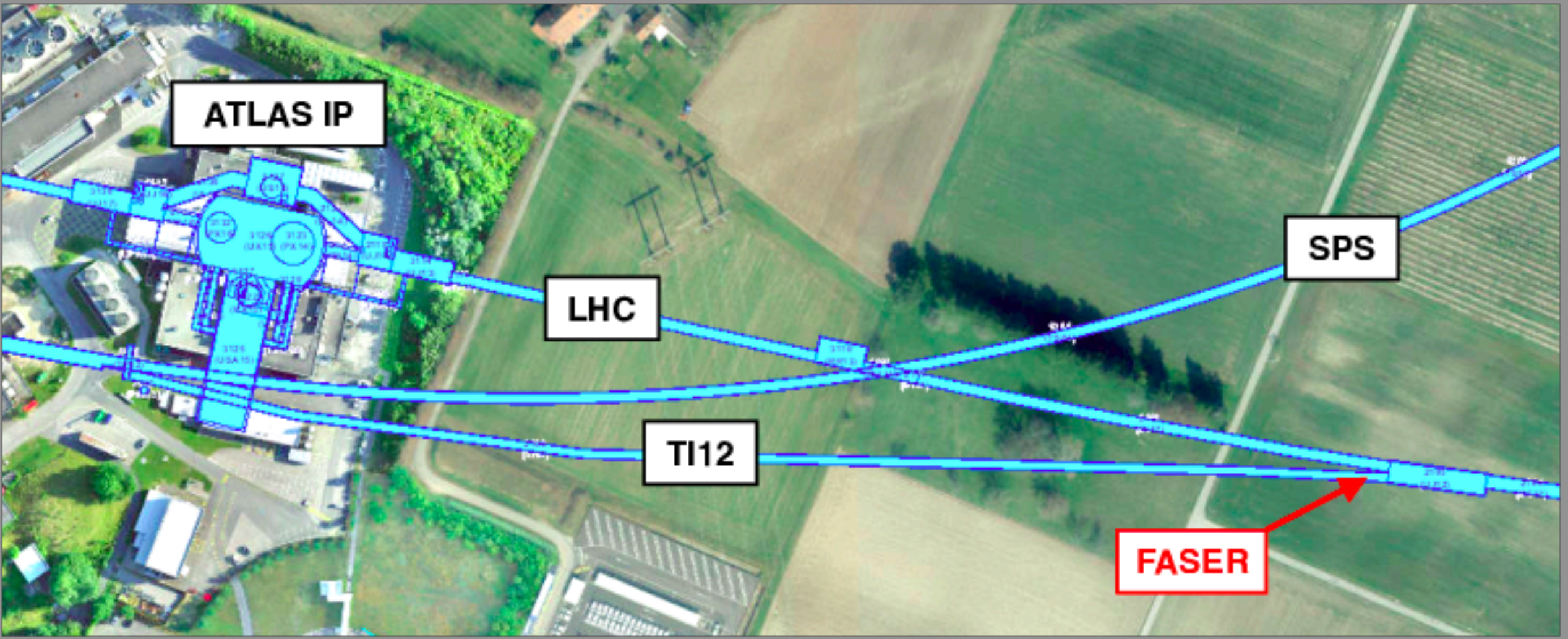
- Immense effort to use large Run-2 dataset and narrow into challenging phase space
- Pushes detector performance in many ways
- **First time probed since LEP**

Continuous challenge for Run-3 and beyond

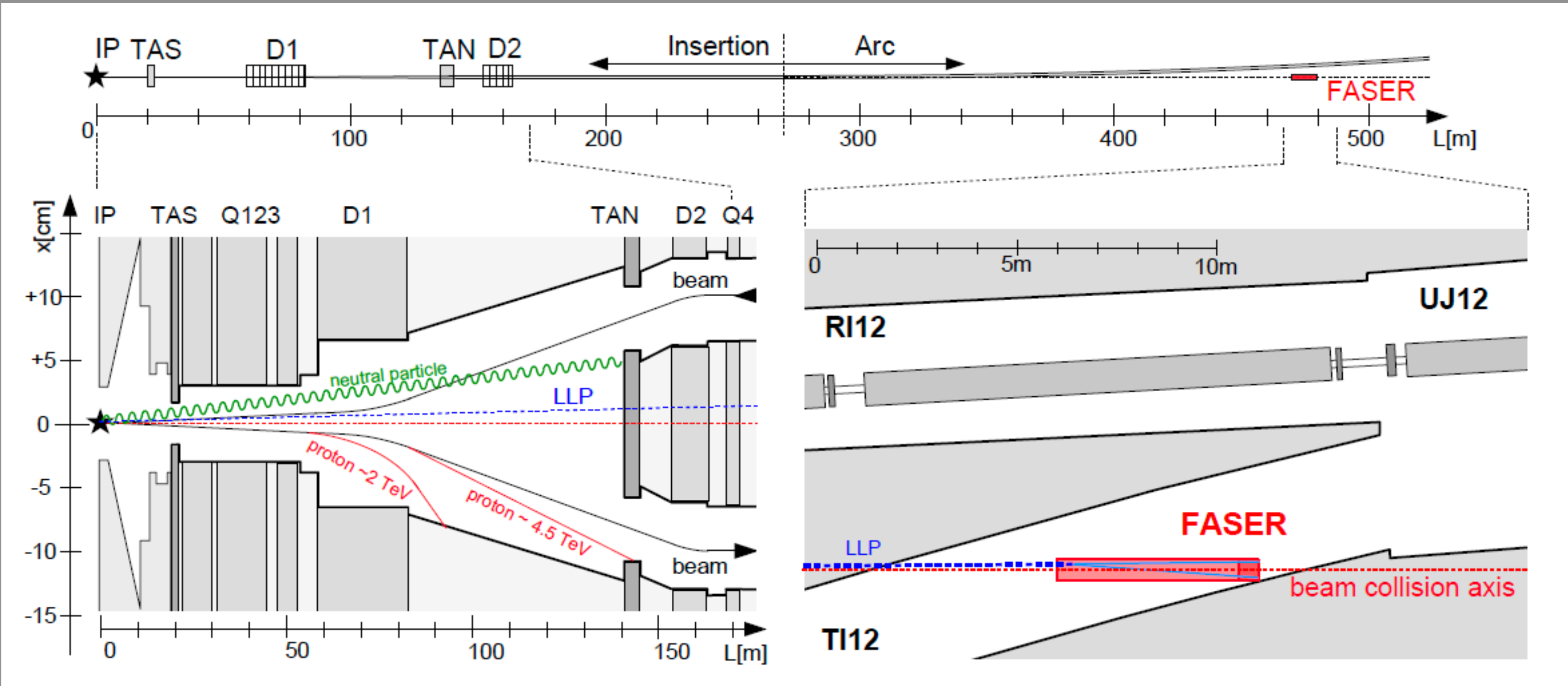
Only a tiny glimpse into the vast open possibilities of EWK SUSY







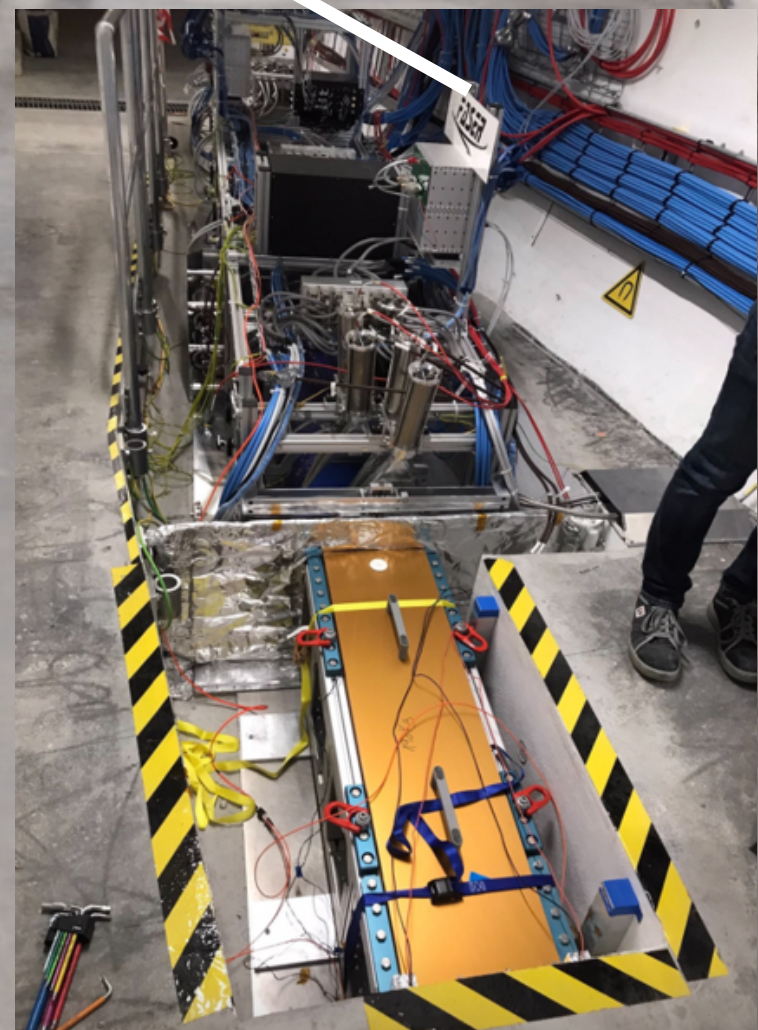
FASER

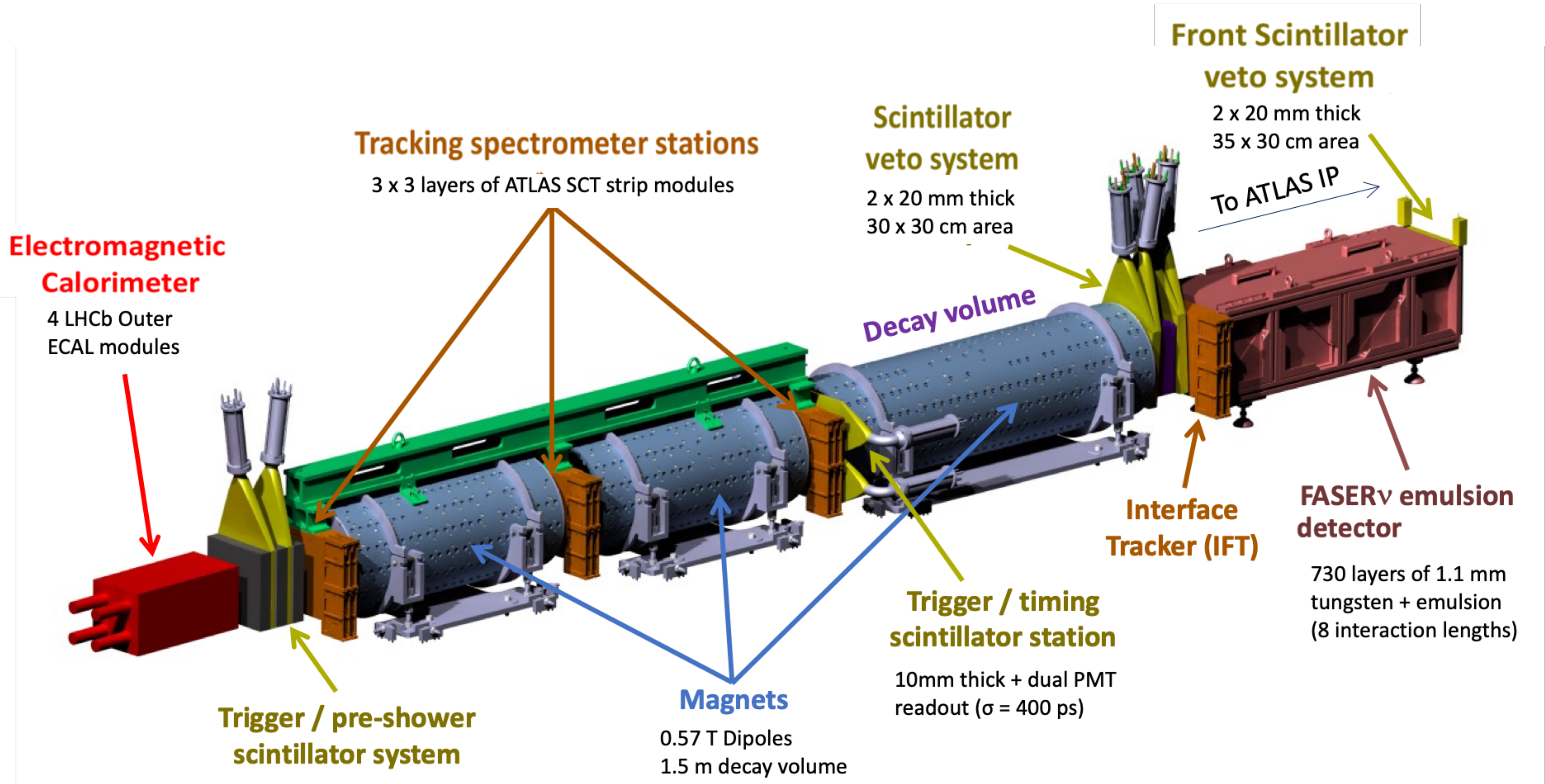


~ 480m from ATLAS



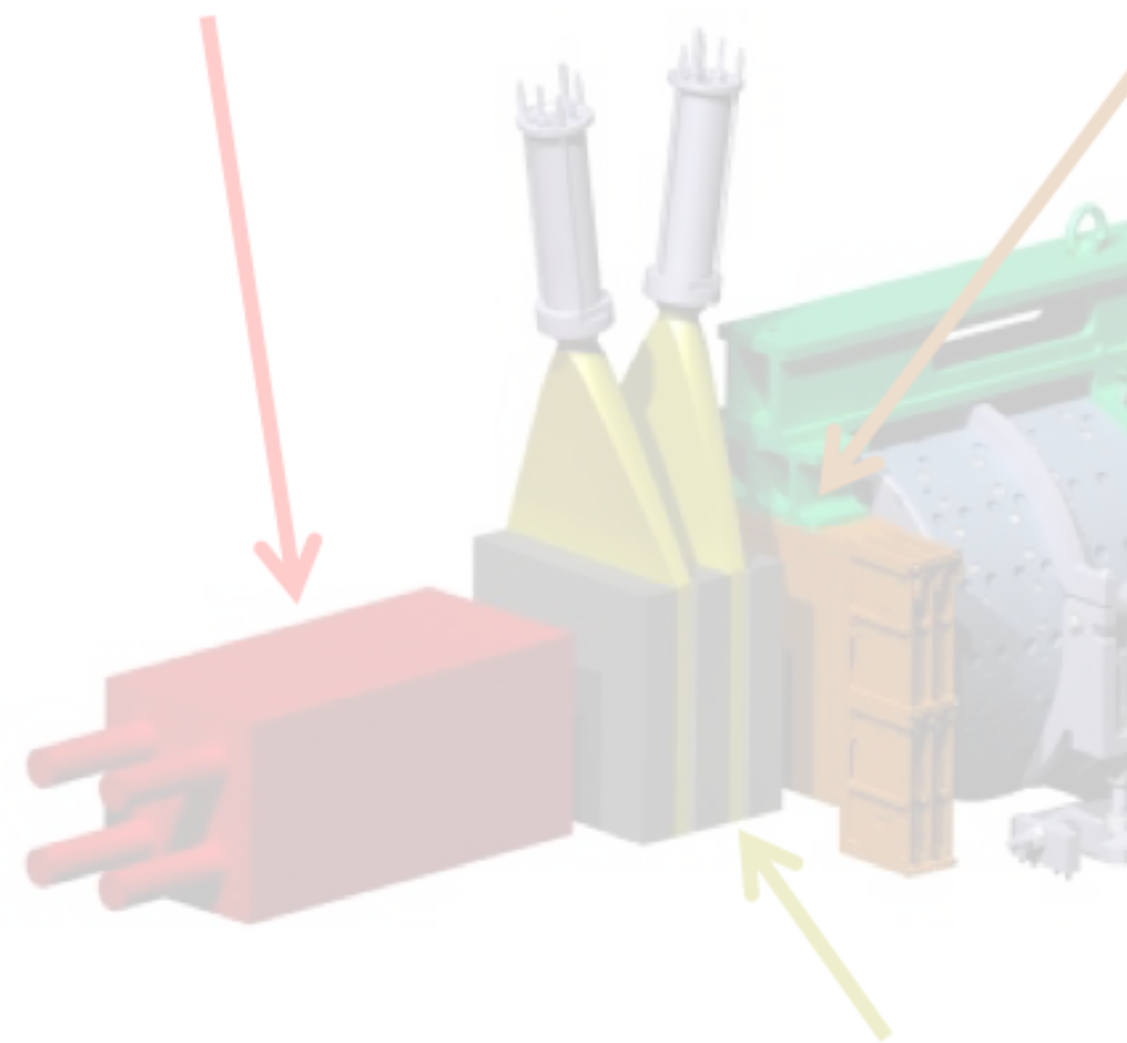






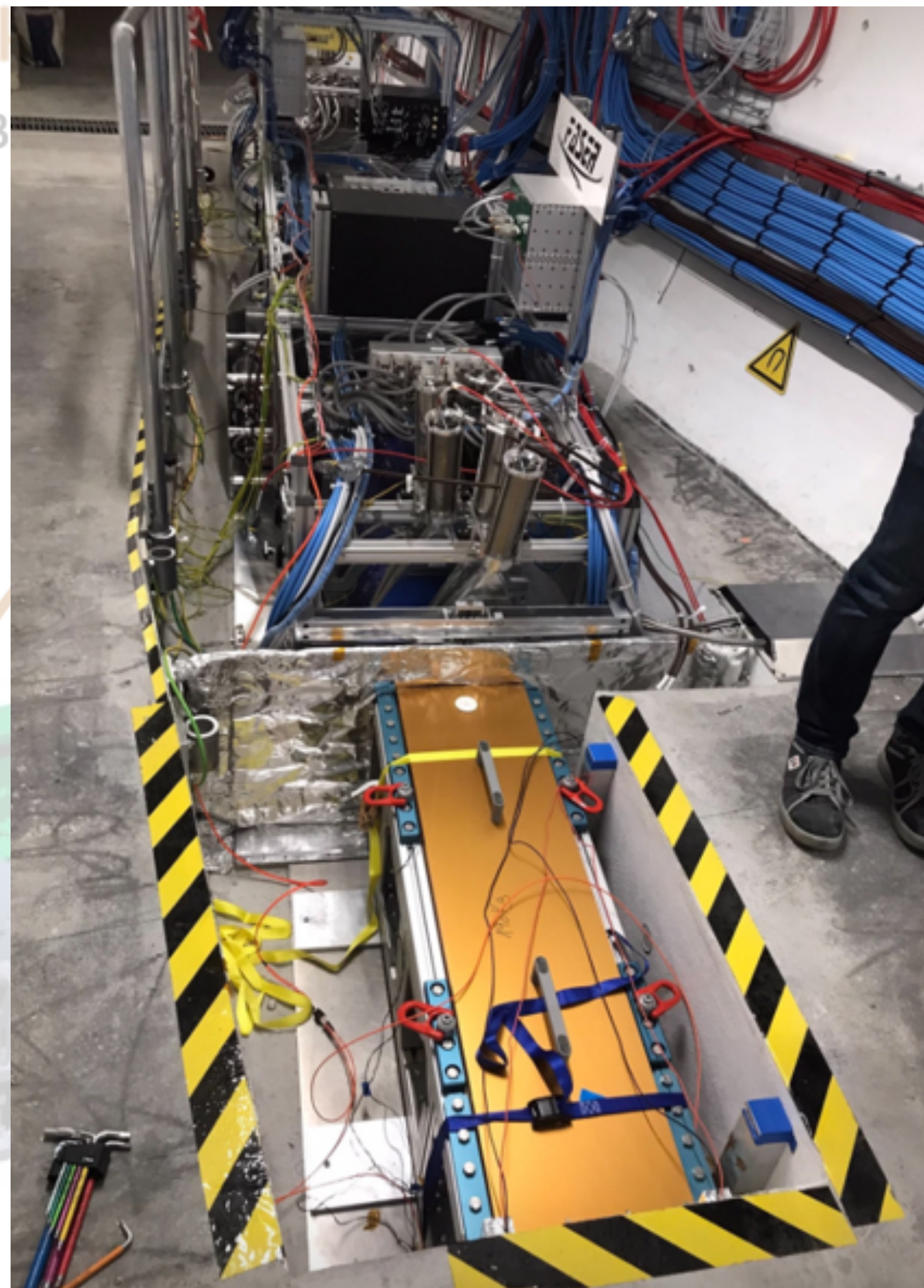
Electromagnetic Calorimeter

4 LHCb Outer ECAL modules



Trigger / pre-shower scintillator system

Track
3 x 3

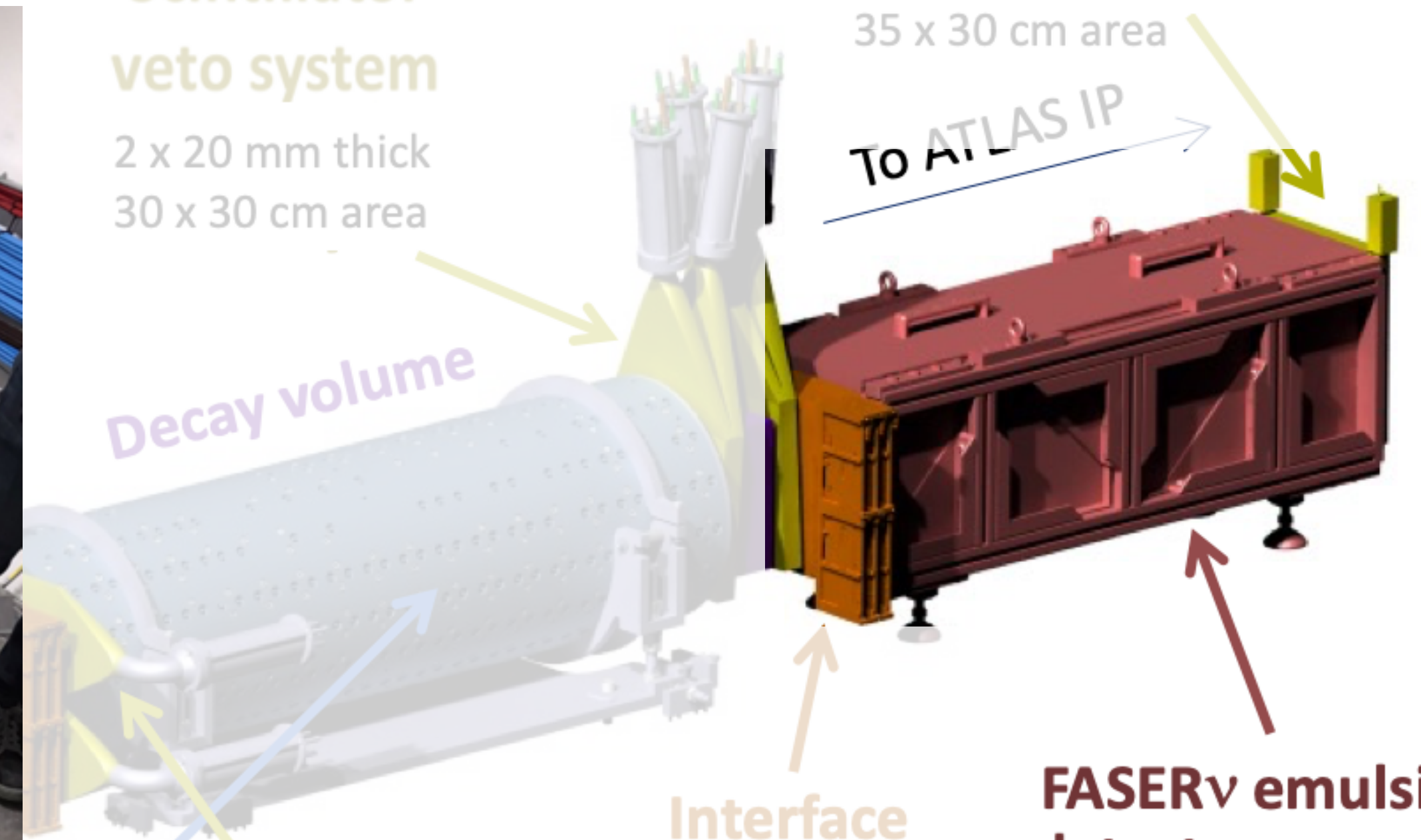


Magnets

0.57 T Dipoles
1.5 m decay volume

Scintillator veto system

2 x 20 mm thick
30 x 30 cm area



Trigger / timing scintillator station

10mm thick + dual PMT readout ($\sigma = 400$ ps)

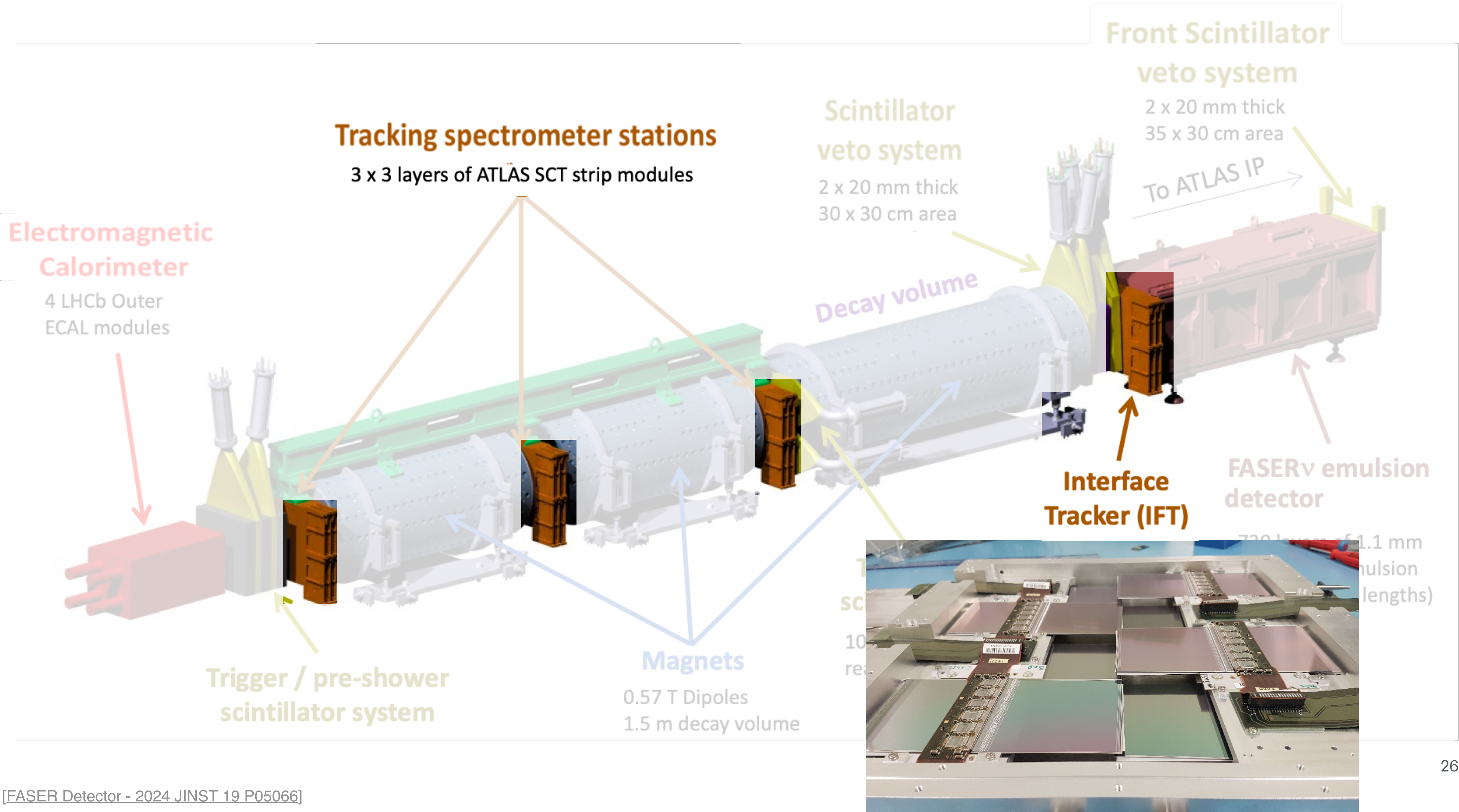
Front Scintillator veto system

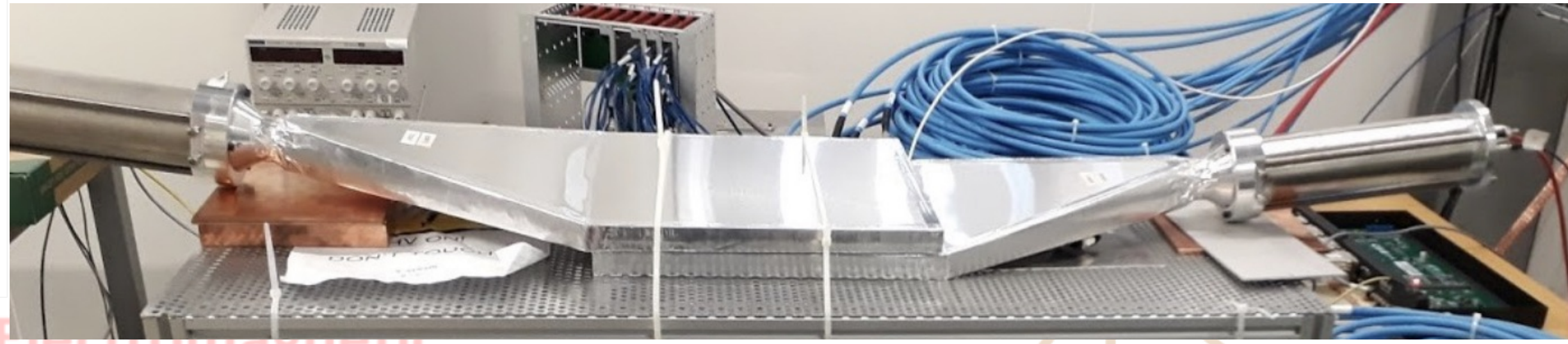
2 x 20 mm thick
35 x 30 cm area

FASERv emulsion detector

730 layers of 1.1 mm tungsten + emulsion (8 interaction lengths)

Interface Tracker (IFT)





Front Scintillator veto system

veto system

2 x 20 mm thick
35 x 30 cm area

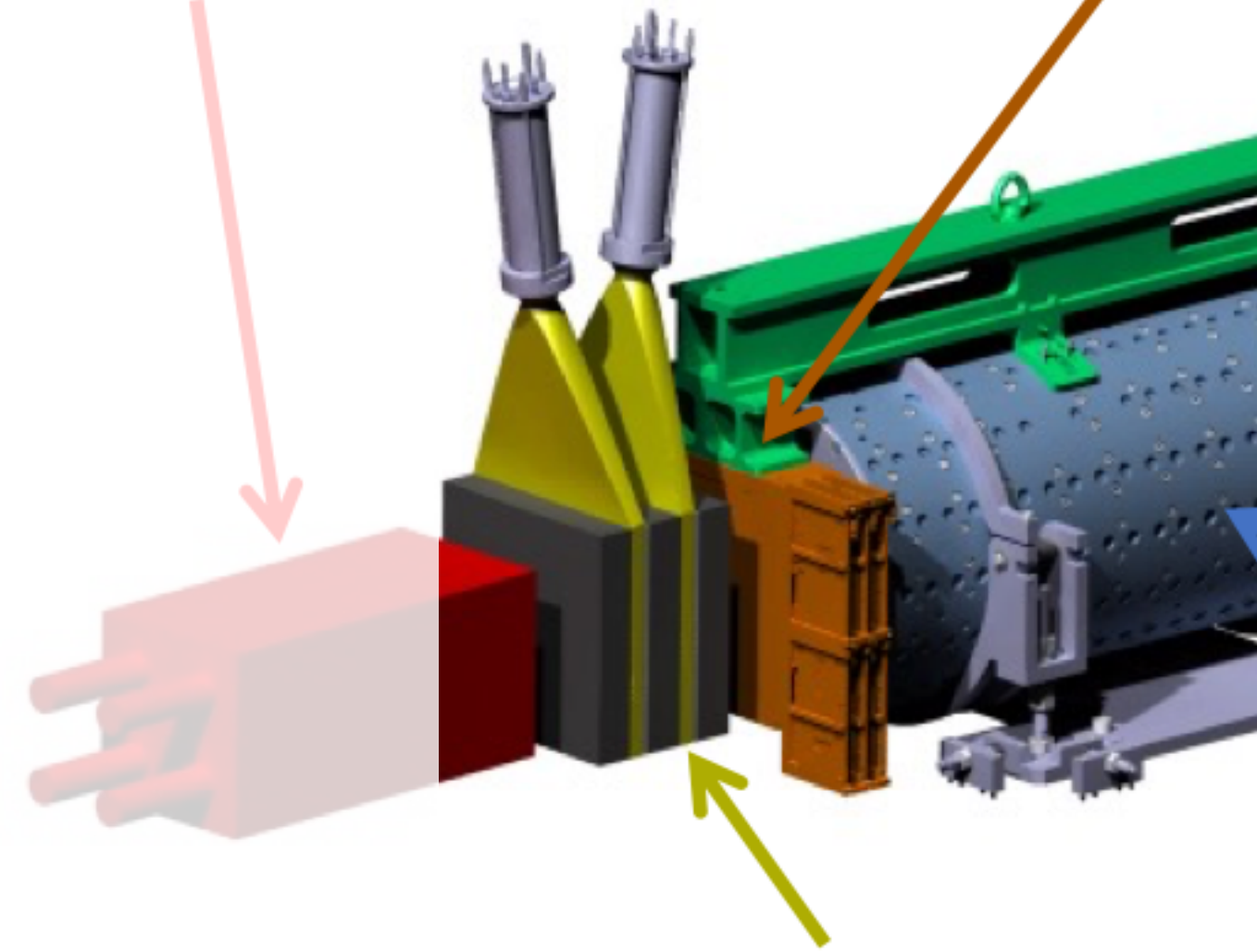
To ATLAS IP

Scintillator veto system

2 x 20 mm thick
30 x 30 cm area

Electromagnetic Calorimeter

4 LHCb Outer ECAL modules



Trigger / pre-shower scintillator system

Decay volume

Magnets

0.57 T Dipoles
1.5 m decay volume

Trigger / timing scintillator station

10mm thick + dual PMT readout ($\sigma = 400$ ps)

Interface Tracker (IFT)

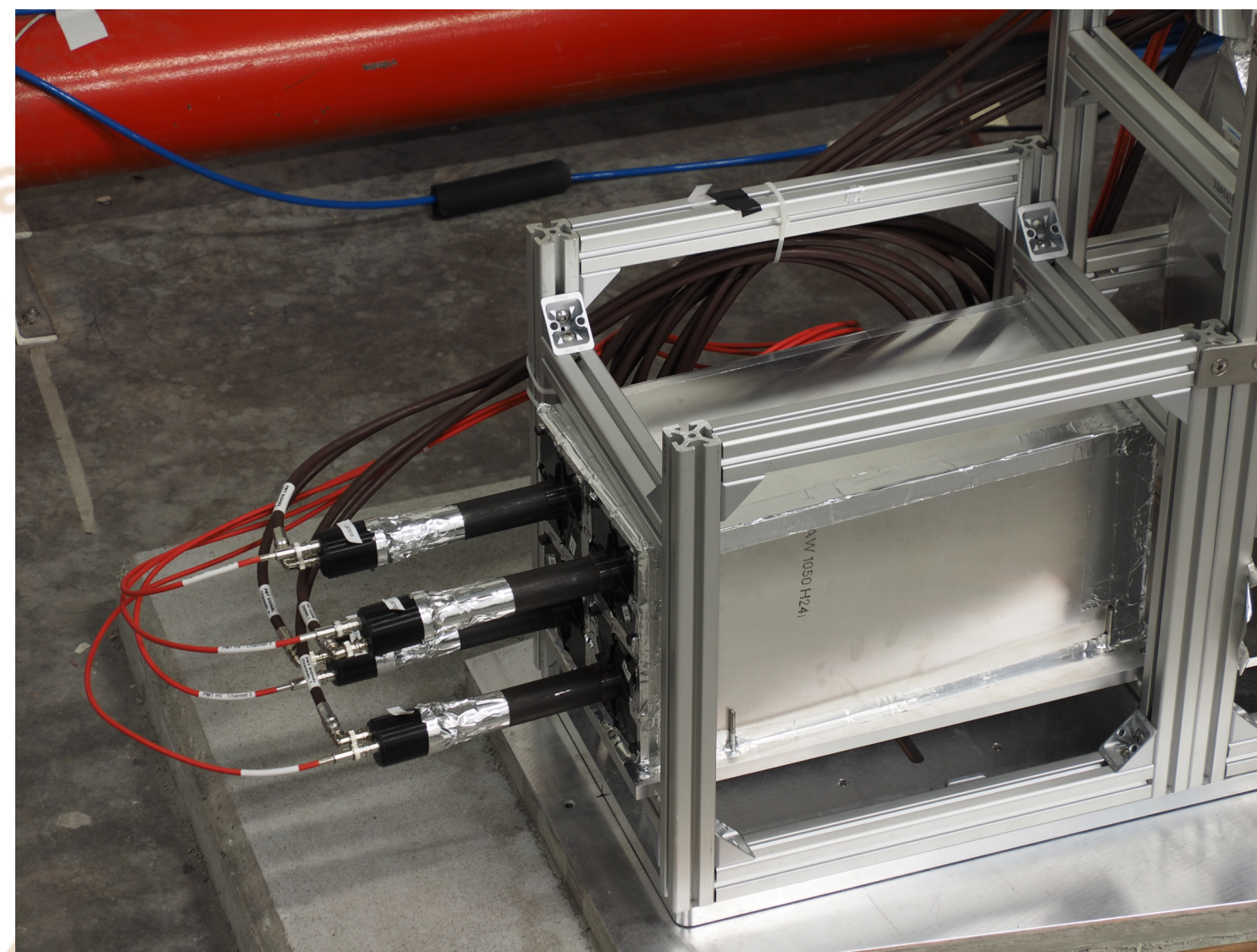
FASERv emulsion detector

730 layers of 1.1 mm tungsten + emulsion (8 interaction lengths)

Electromagnetic Calorimeter

4 LHCb Outer ECAL modules

Tra
3



Scintillator veto system

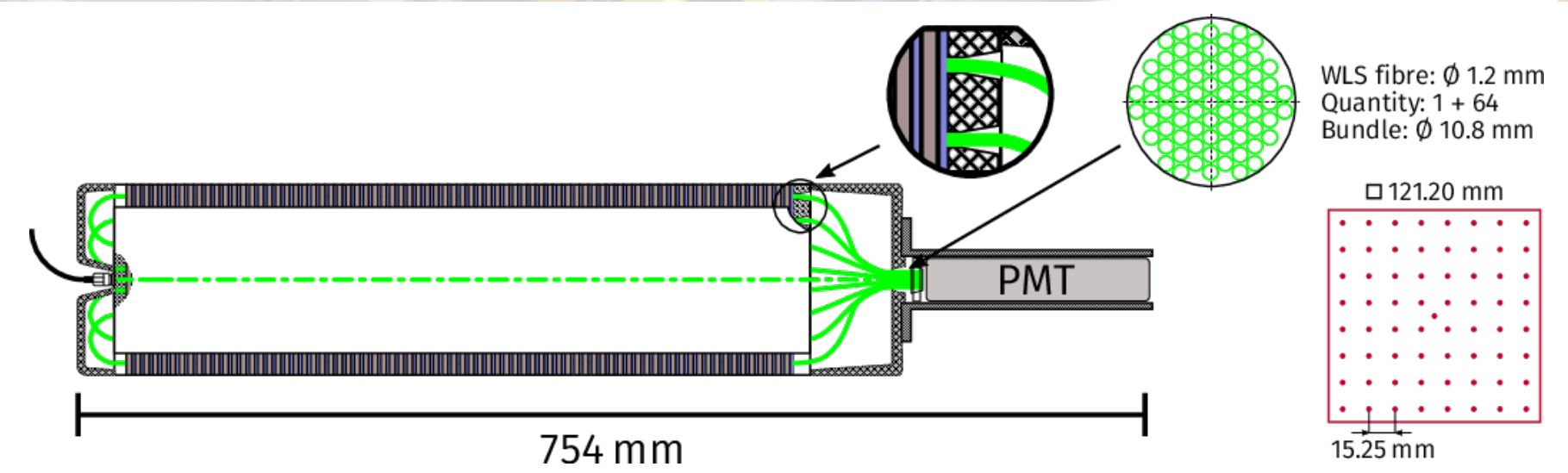
2 x 20 mm thick
30 x 30 cm area

Front Scintillator veto system

2 x 20 mm thick
35 x 30 cm area

To ATLAS IP

Decay volume



Magnets

0.57 T Dipoles
1.5 m decay volume

10mm thick + dual PMT readout ($\sigma = 400$ ps)

Trigger / pre-shower scintillator system

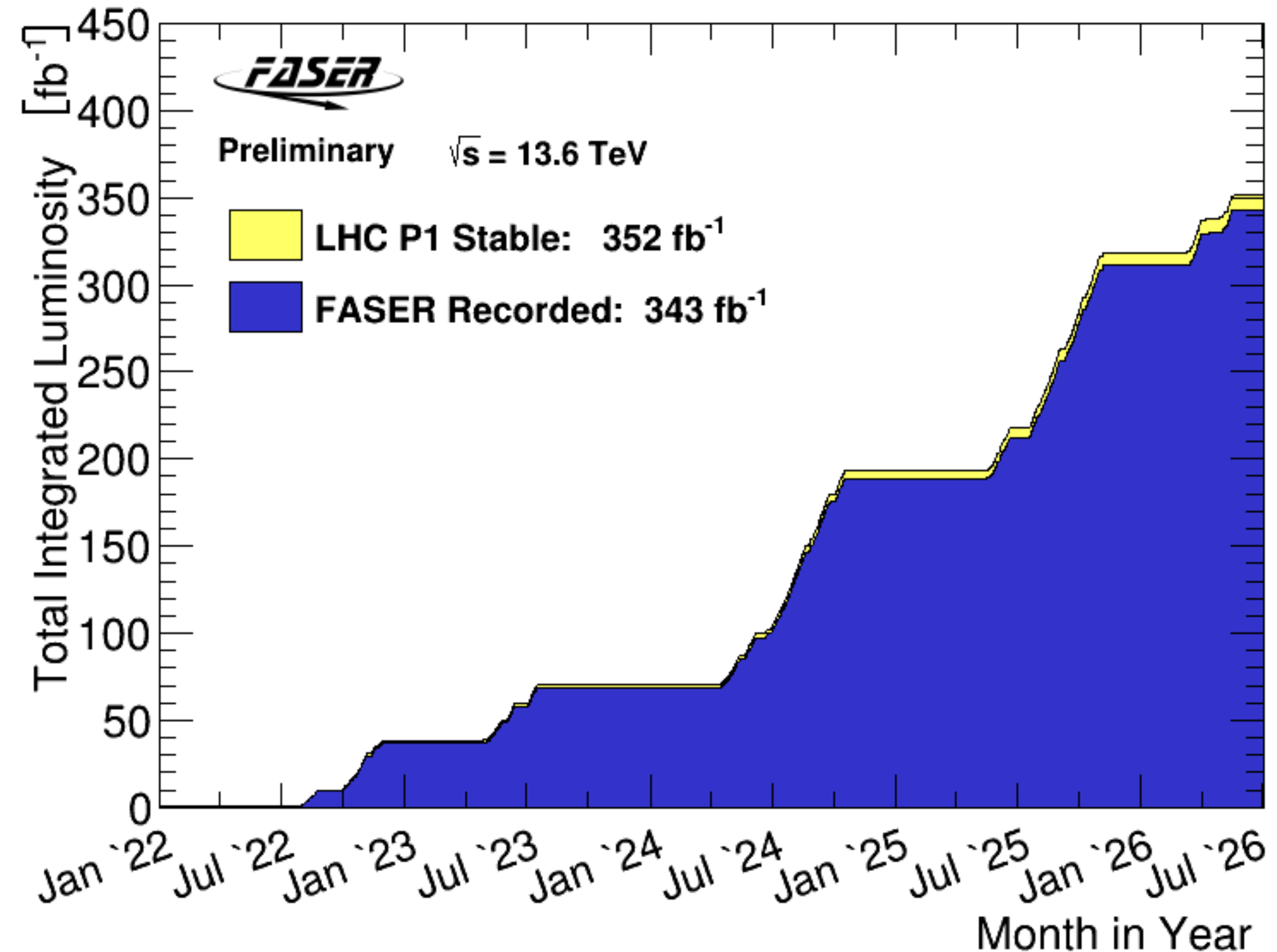
FASERv emulsion detector

730 layers of 1.1 mm tungsten + emulsion (8 interaction lengths)

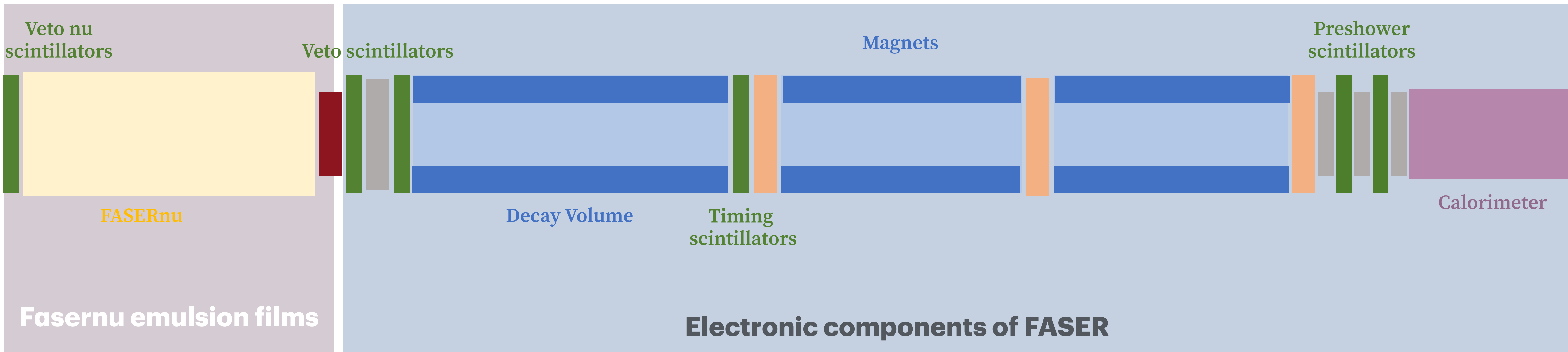
ce IFT)

FASER during LHC Run-3

- Proposed in 2017, installed and taking data in 2021!!
- Start of (physics) data taking in July 2022
- 343 fb⁻¹ of Luminosity between 2022-2025
- Very high (~98%) data-taking efficiency and excellent detector performance



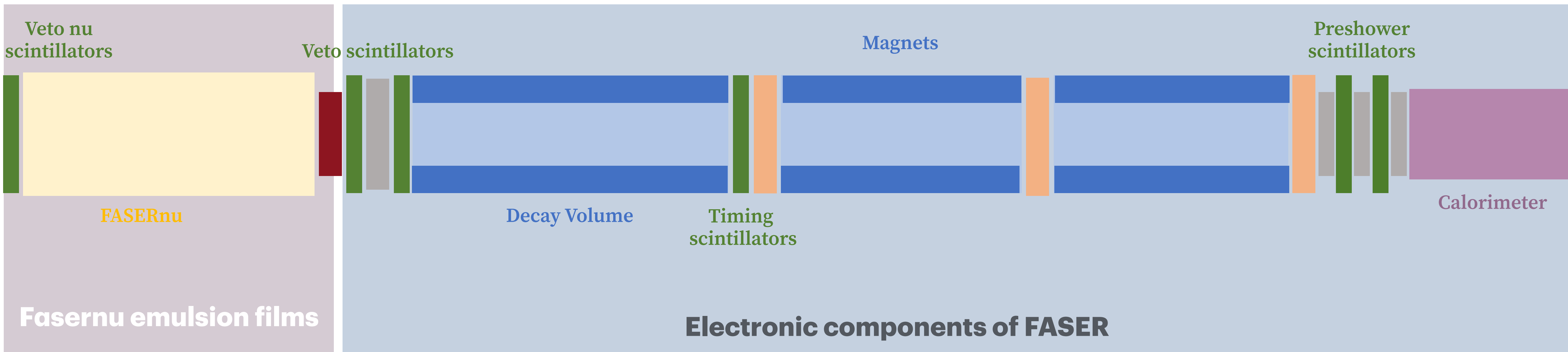
Neutrino measurements with FASER



- Analysing FASERnu emulsion films
- Sensitive to all neutrino flavours
- Very good spatial resolution
- Due to scanning and processing of films time intensive

- FASERnu as target (1.1 t) - using electronic components to detect muon from charged current interaction
- Can separate neutrino and anti-neutrino
- Fast analysis of data possible
- **Only sensitive to muon neutrinos**

Neutrino measurements with FASER



- Analysing FASERnu emulsion

Updated results of high-energy electron and muon neutrino interactions with FASER's emulsion detector at the LHC

CERN-FASER-CONF-2025-002

- Very good spatial resolution
- Due to scanning and processing of films time intensive

Rnu as target (1.1 t) - using electronic components to detect muon from charged current interaction

- Can separate neutrino and anti-neutrino

First Measurement of Muon Neutrinos as a Function of Energy and Rapidity with FASER

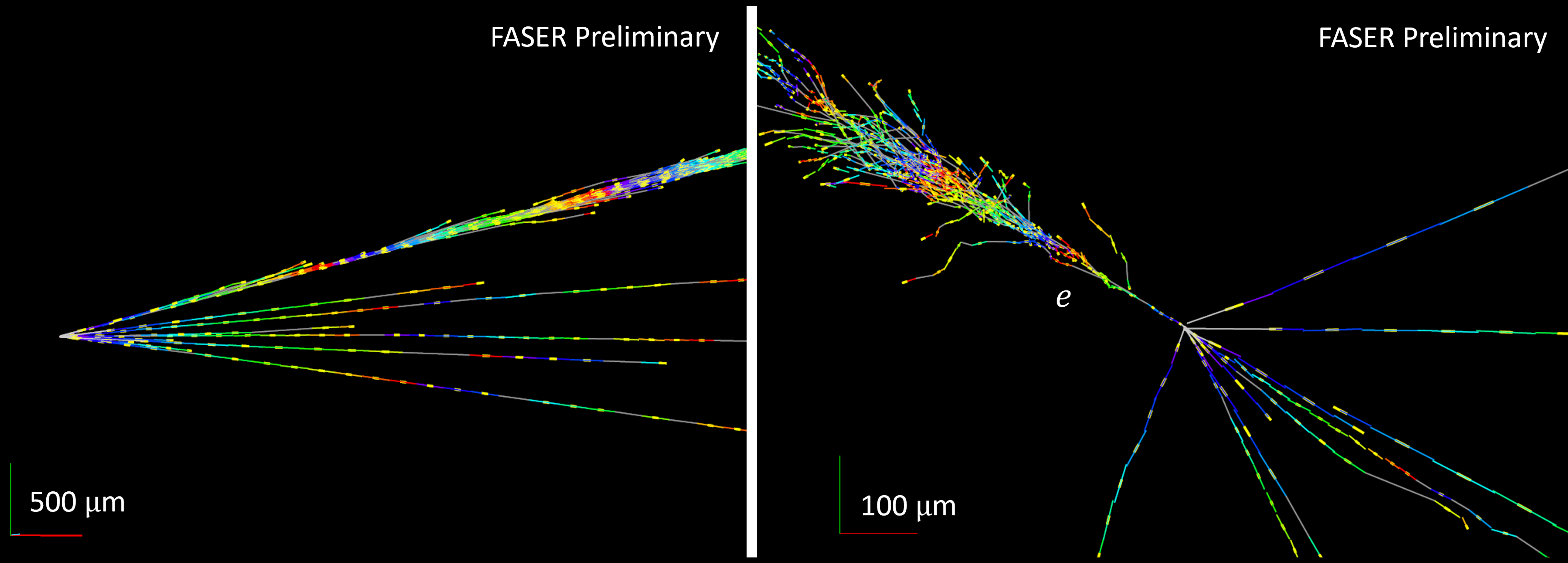
CERN-FASER-CONF-2026-005

20 March 2026

- **Only sensitive to muon neutrinos**

FASER Preliminary

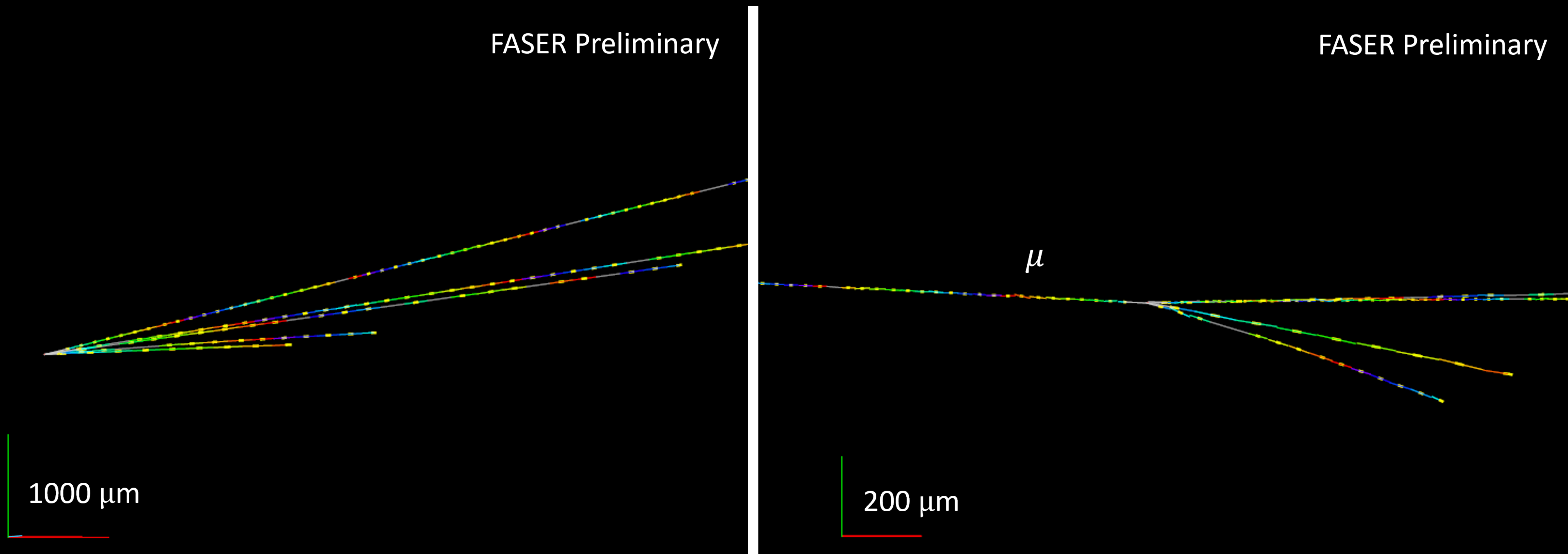
FASER Preliminary



Updated results of high-energy electron and muon neutrino interactions with FASER's emulsion detector at the LHC

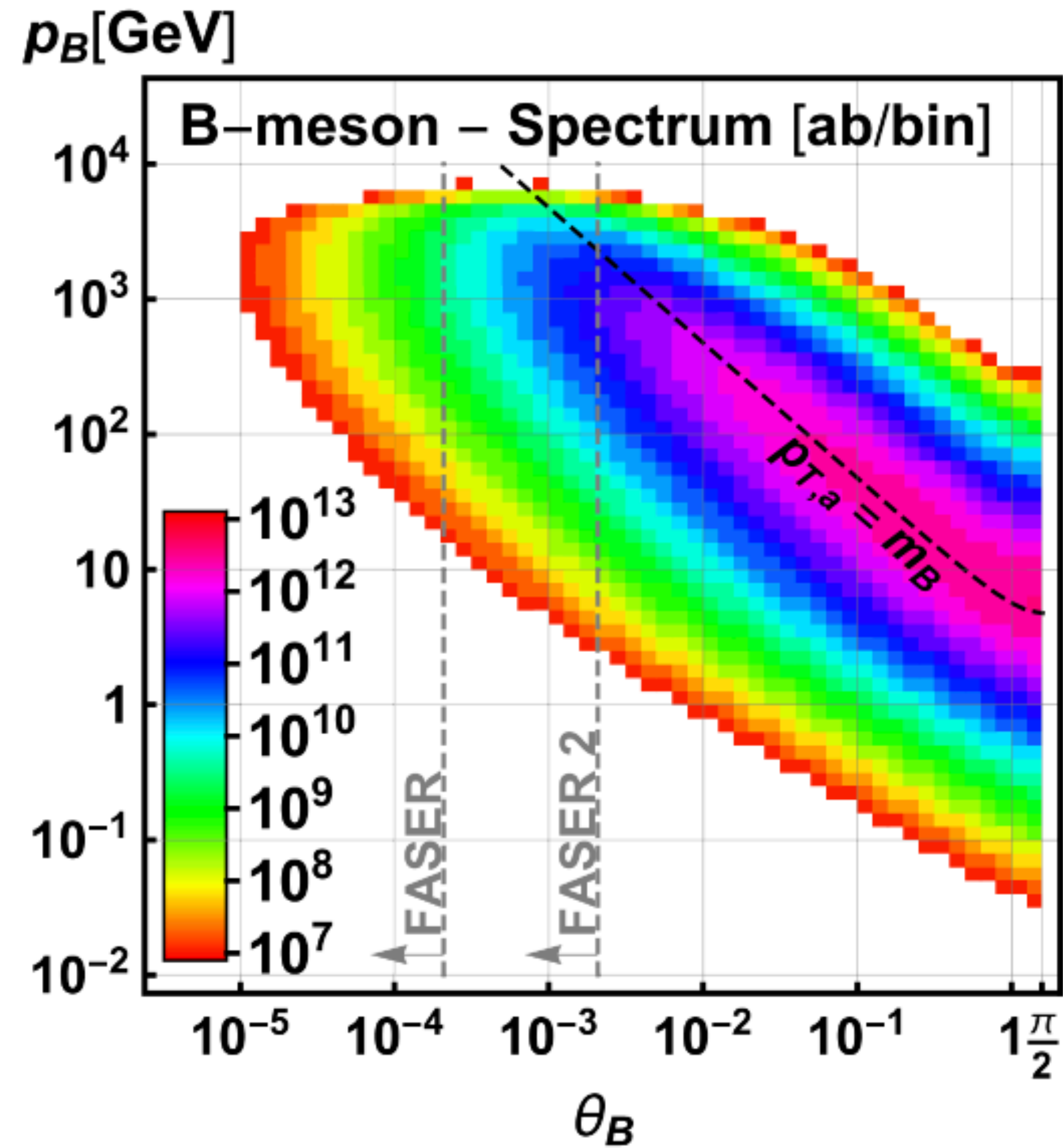
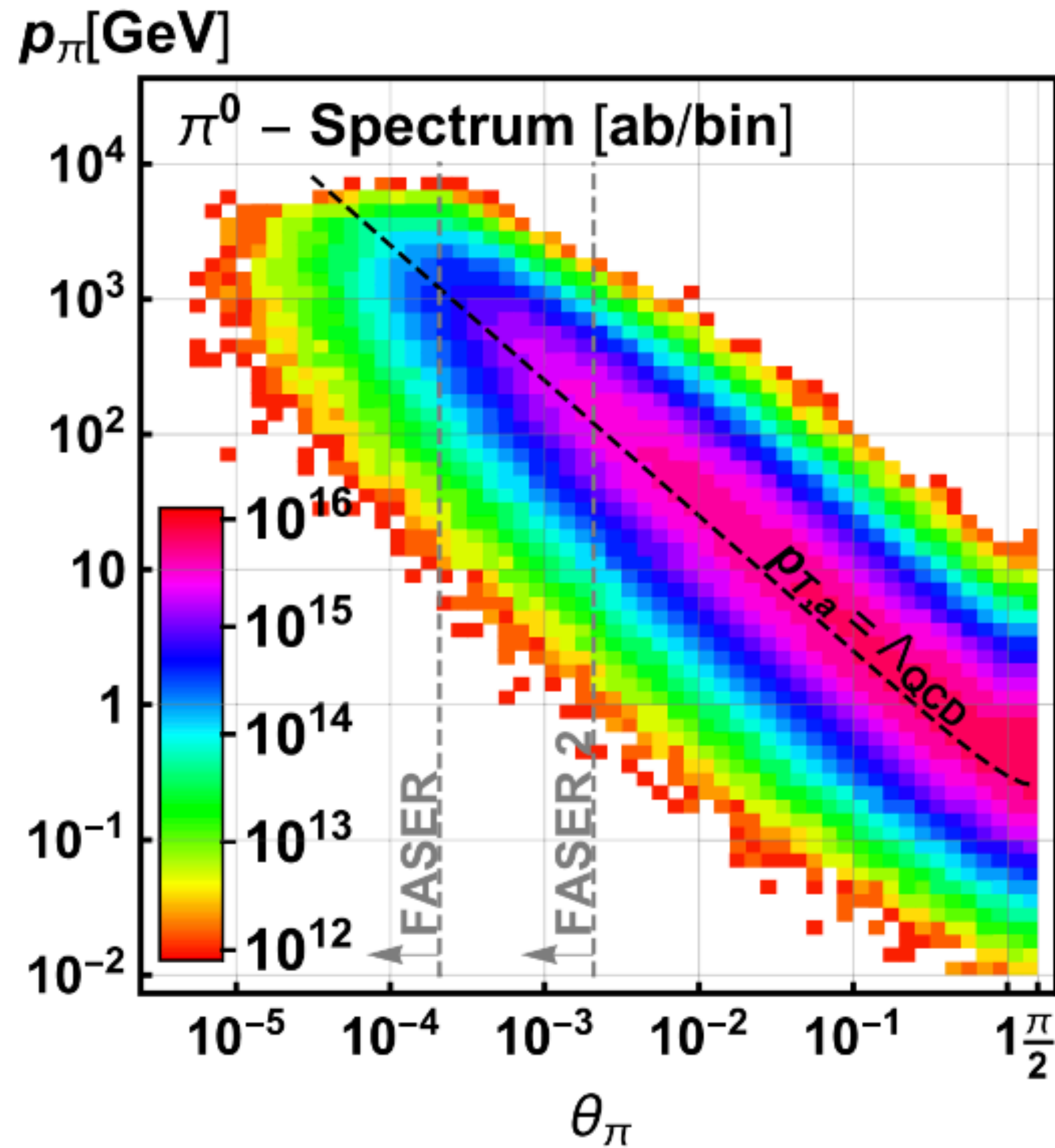
FASER Preliminary

FASER Preliminary



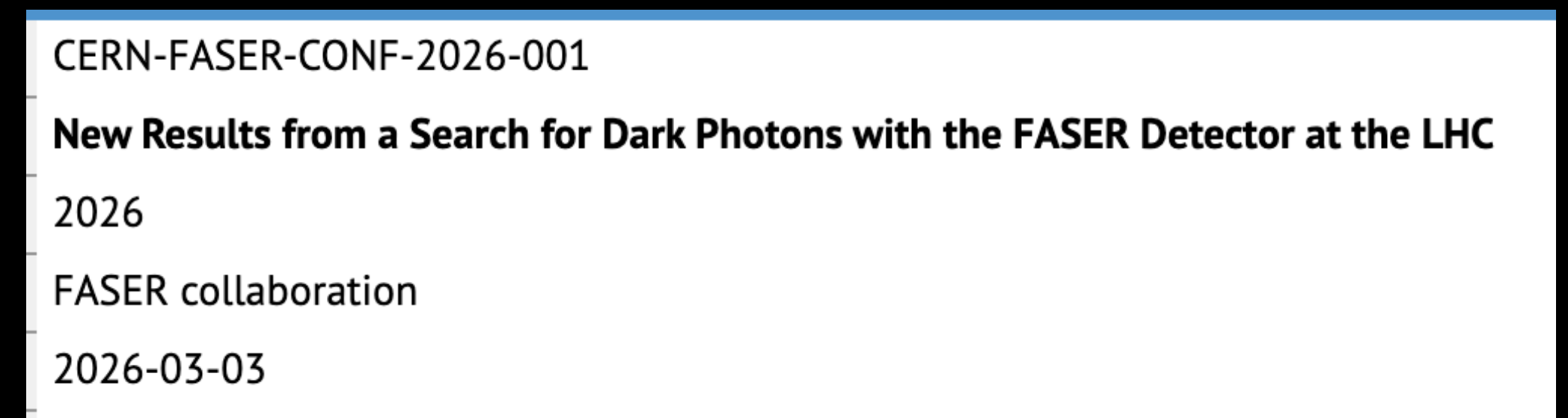
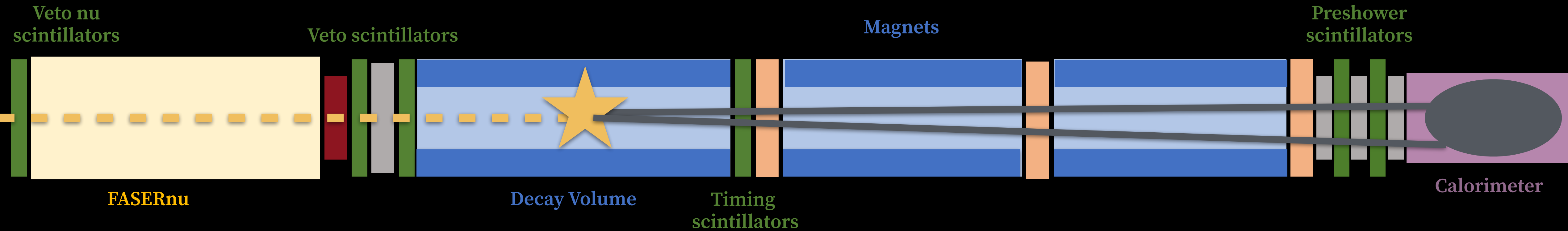
Updated results of high-energy electron and muon neutrino interactions with FASER's emulsion detector at the LHC

Forward produced particles at IP1



Long-lived particle searches with FASER

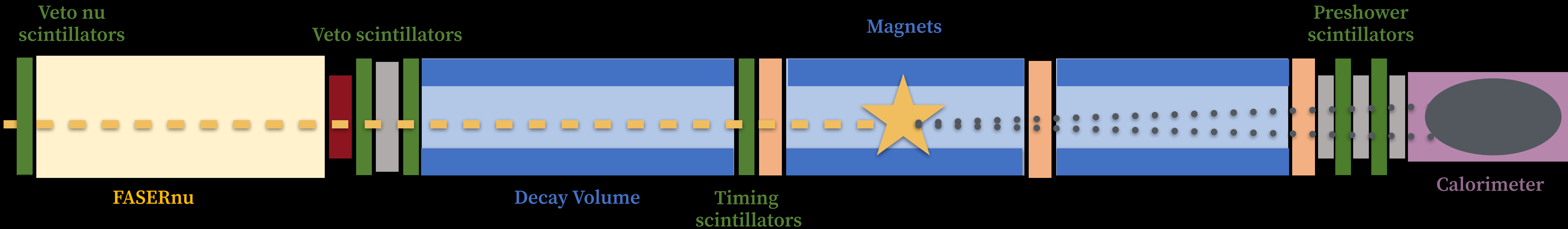
charged particle tracks



Very first FASER BSM search!

Latest Moriond result

Long-lived particle searches with FASER



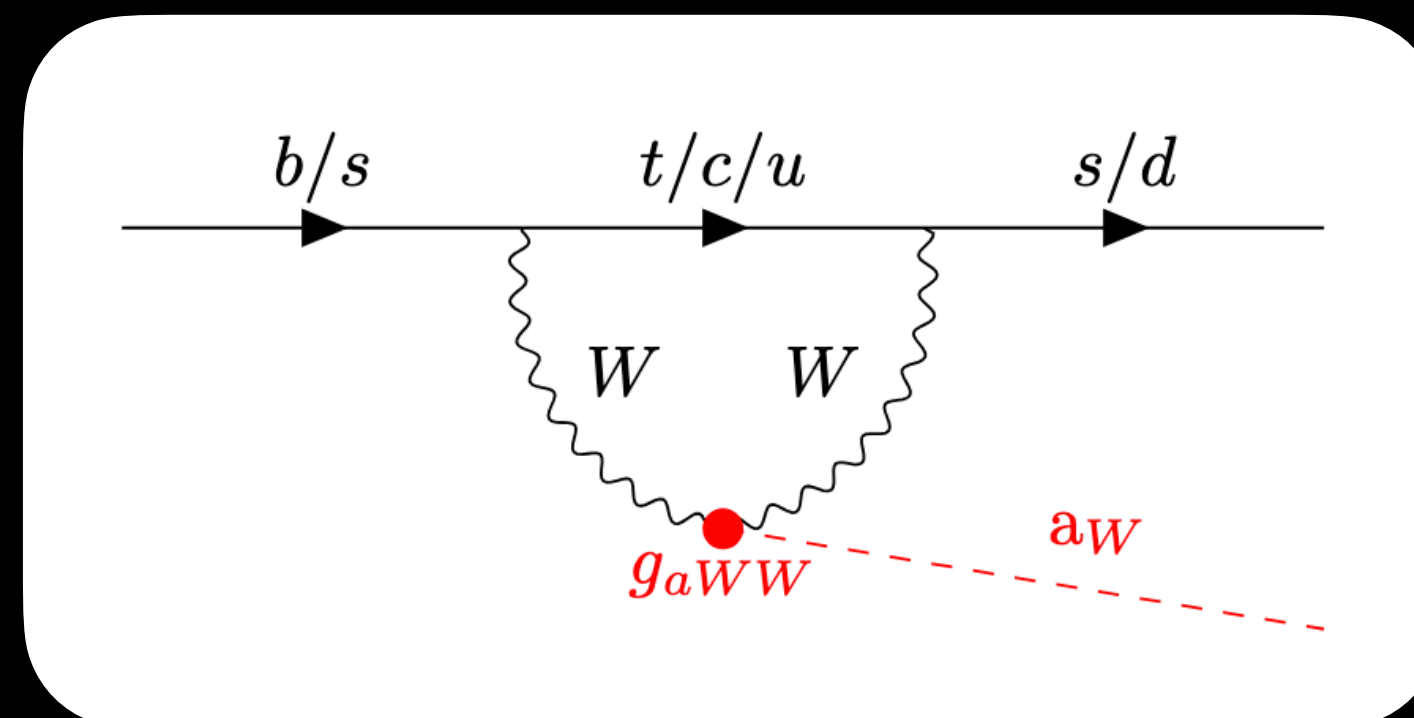
NO charged particle tracks

Calorimeter energy

Shining light on the dark sector: search for axion-like particles and other new physics in photonic final states with FASER

Regular Article - Experimental Physics | [Open access](#)
Published: 31 January 2025

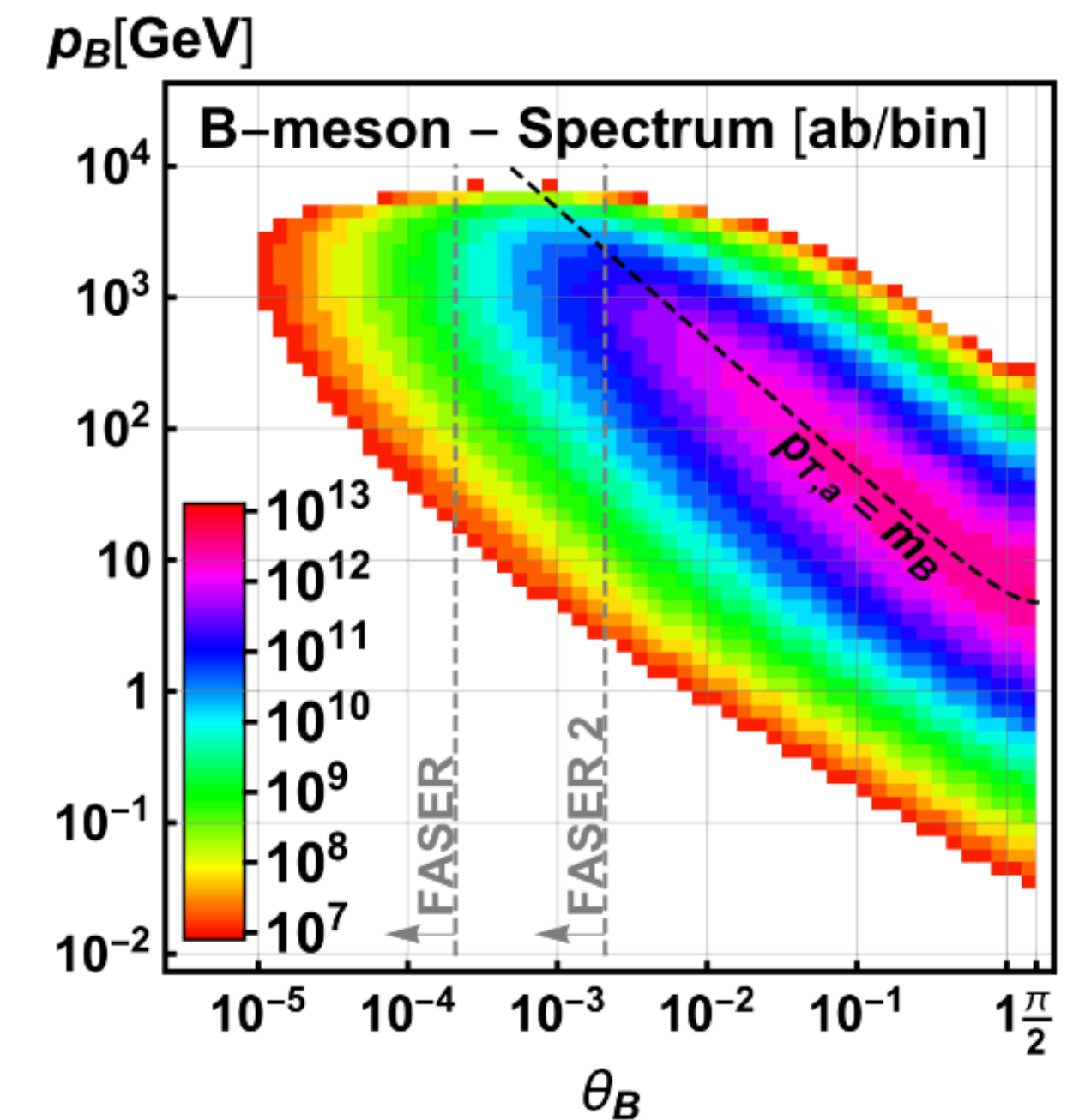
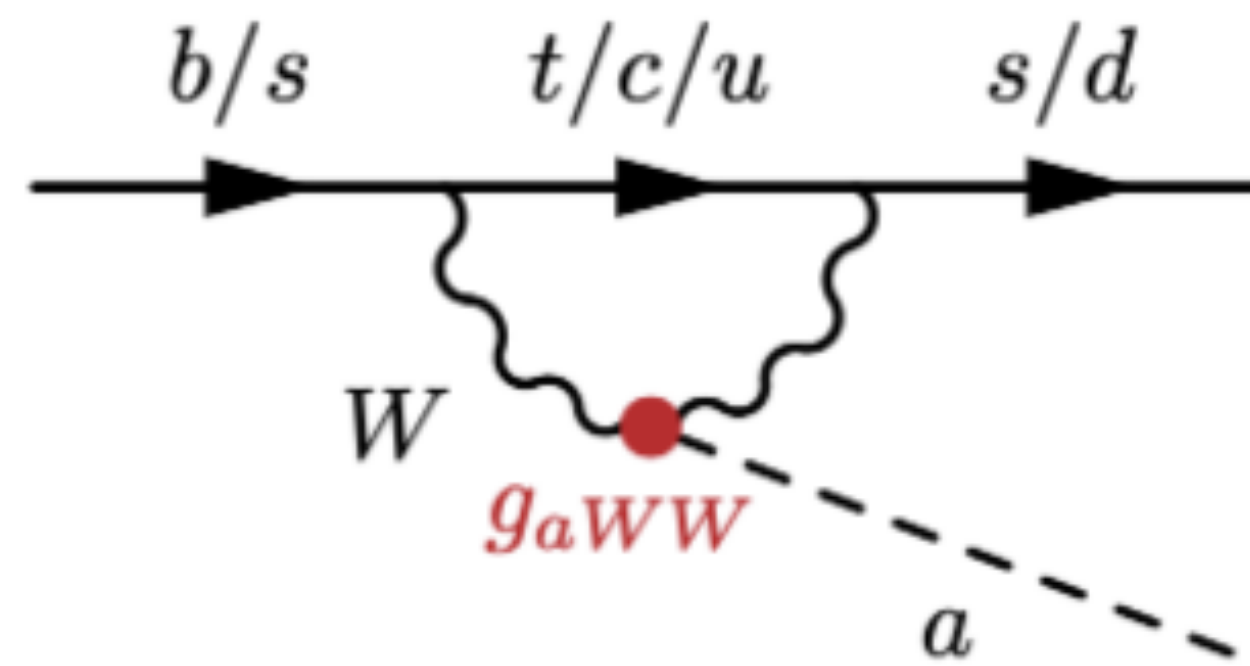
Volume 2025, article number 199 (2025) | [Cite this article](#)



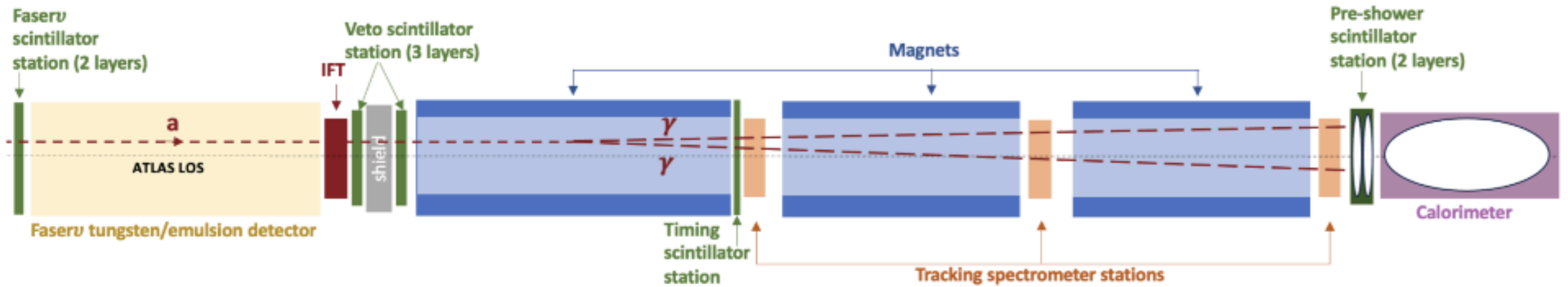
Axion like particles

- Axions & axion-like particles as pseudo scalar arising from broken symmetries
- Motivated through strong CP problem
- Extended Dark Sector possibilities
- Here considered: axion-like particles (ALPs) coupling to SU(2)_L

$$\mathcal{L} \supset -\frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{aWW} a W^{a,\mu\nu} \tilde{W}_{\mu\nu}^a$$

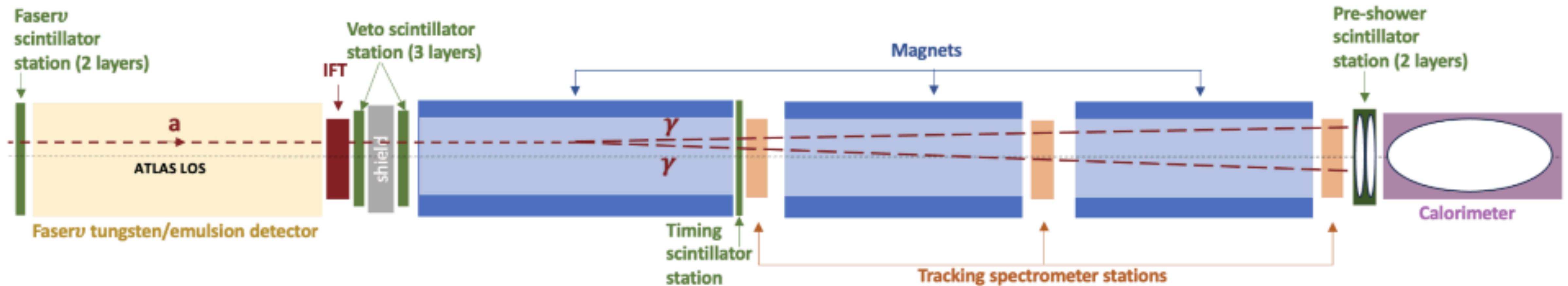


Axion like particles in FASER



- Considering ALP decay into two photons

Axion like particles



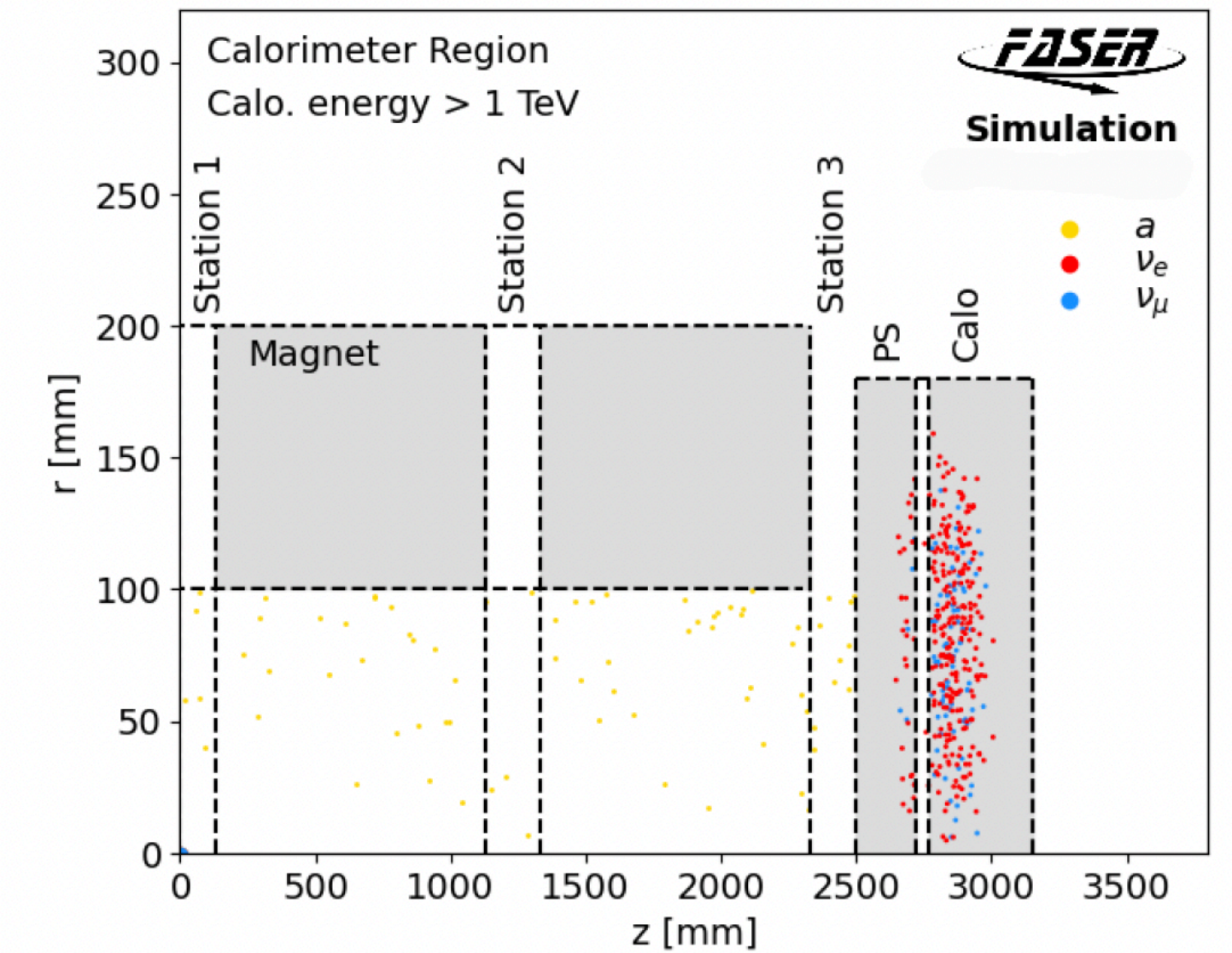
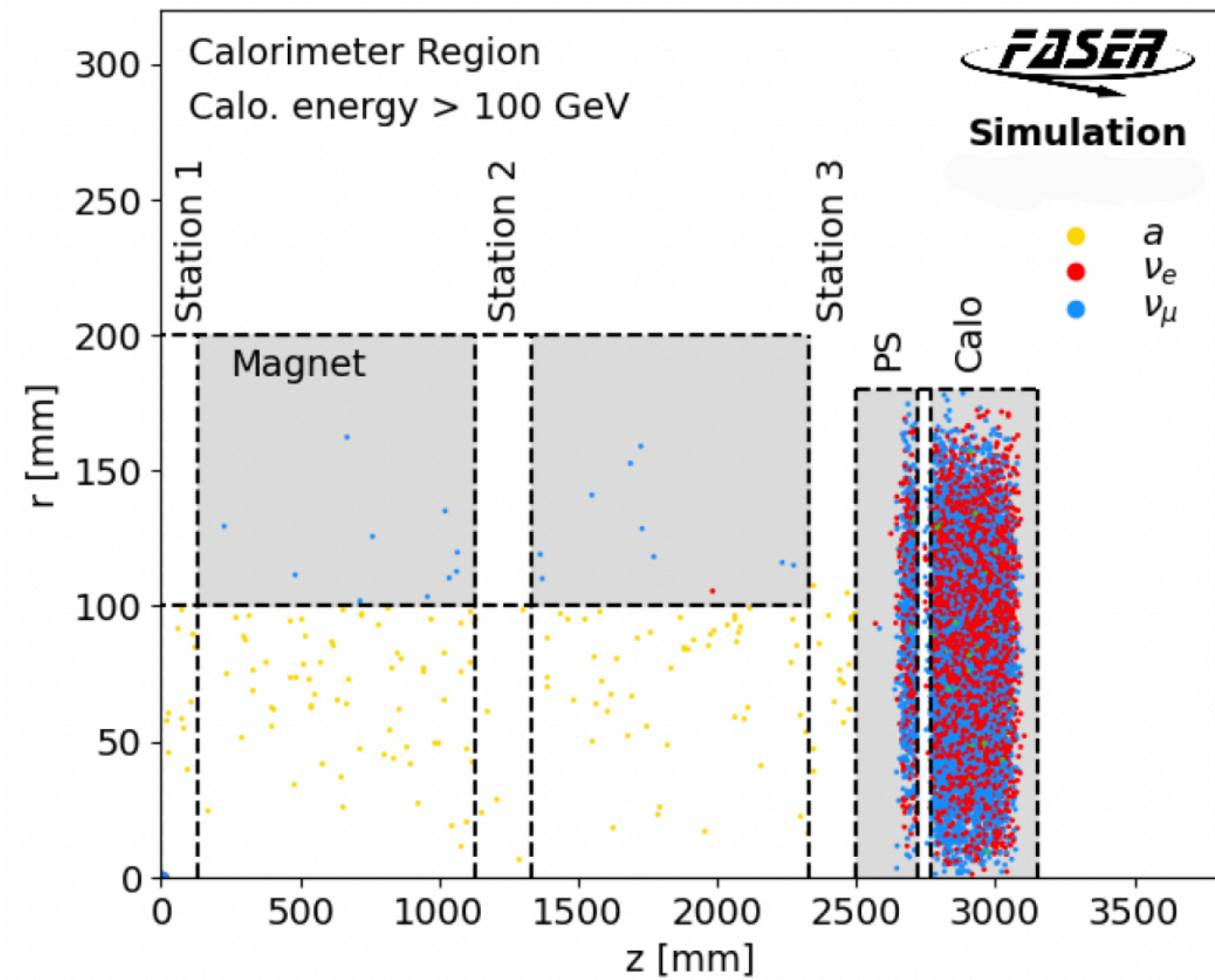
- **High energy photons appearing in FASER**

- No signal in front, Vetonu scintillator stations or Veto scintillator stations
- No signal in Timing Scintillator station

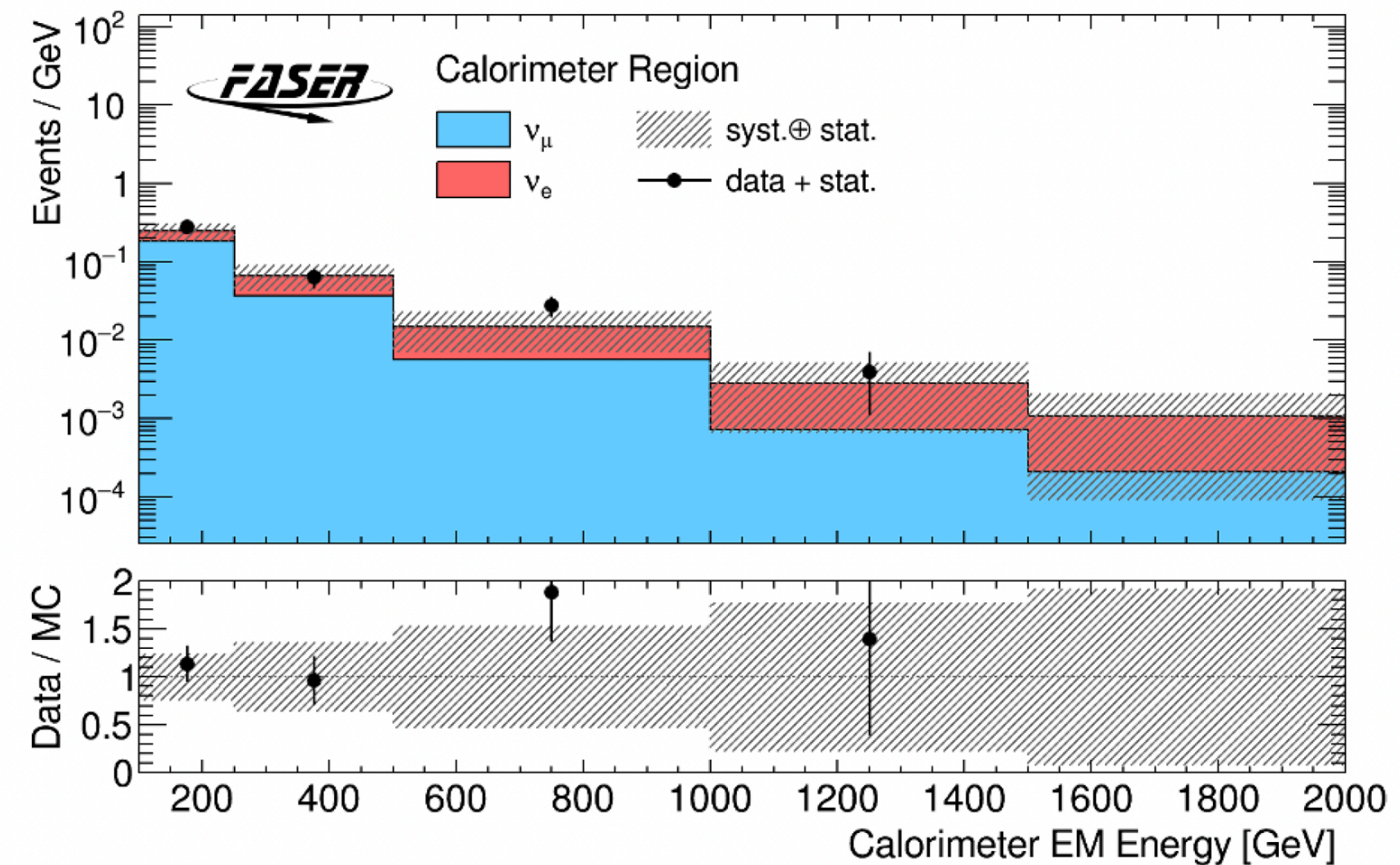
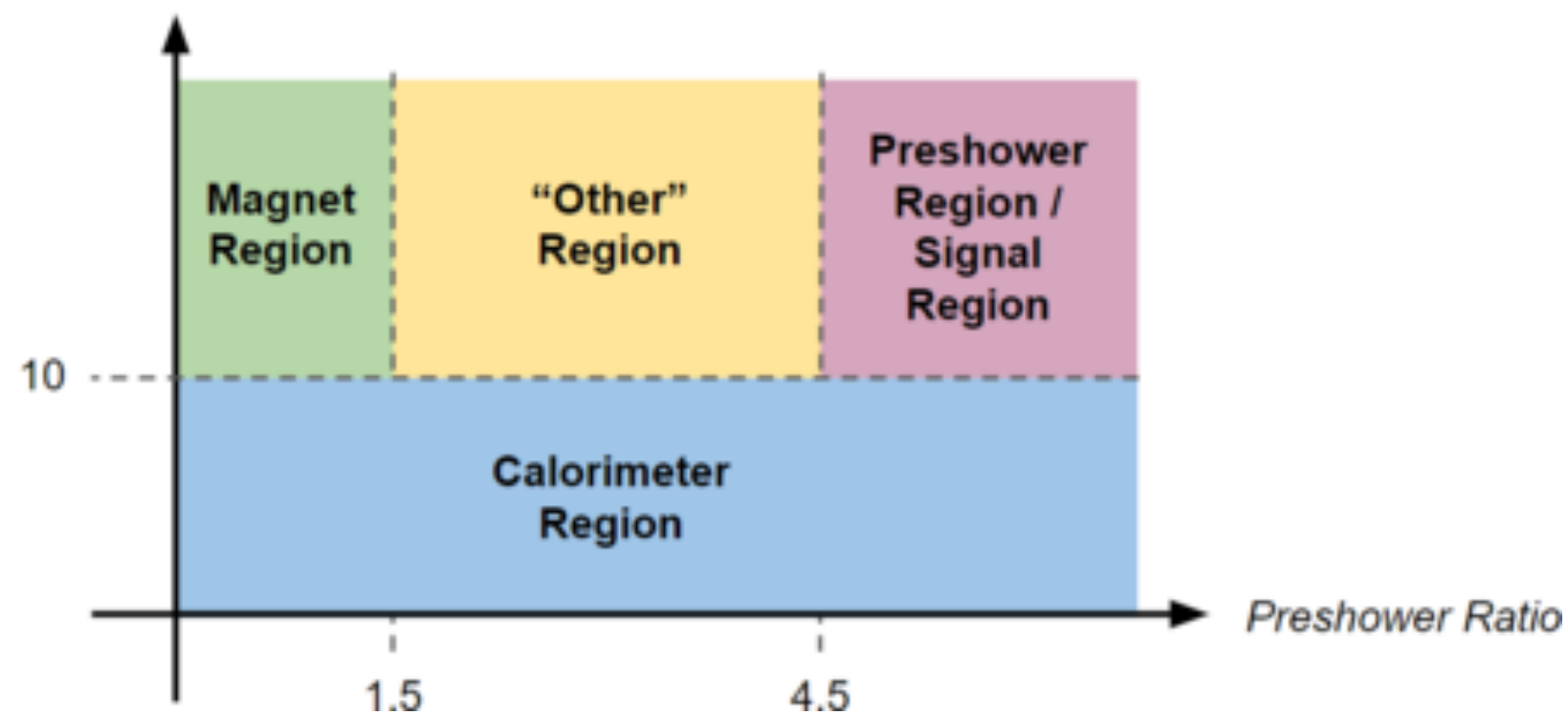
- Evidence of EM shower in preshower scintillator
- > 1.5 TeV in calorimeter
- Extended decay volume, no track reliance

Neutrinos as background

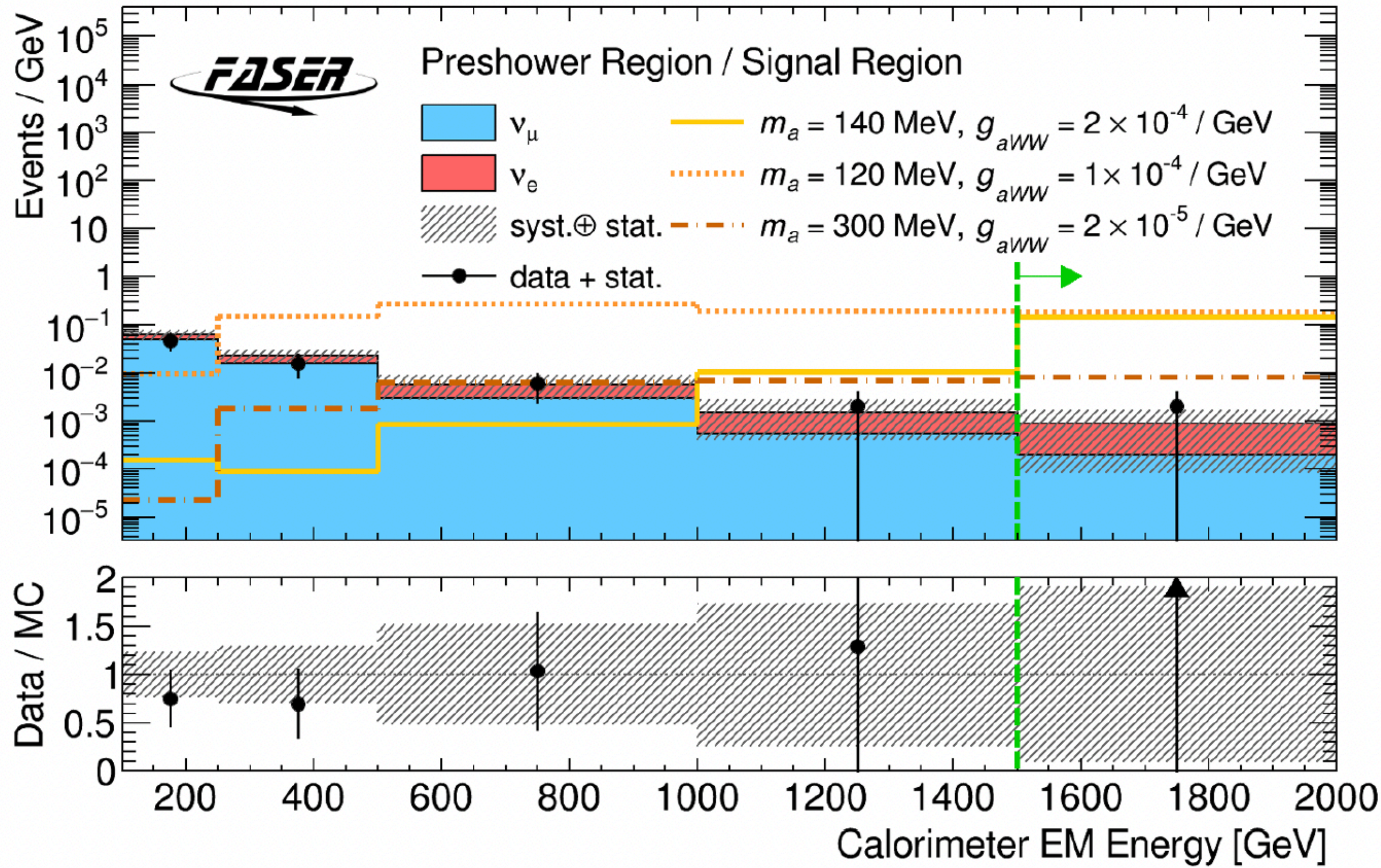
- Dominant contribution
- Estimated through MC (300 ab⁻¹)
- Dedicated validation regions



Second Preshower Layer nMIP



Results

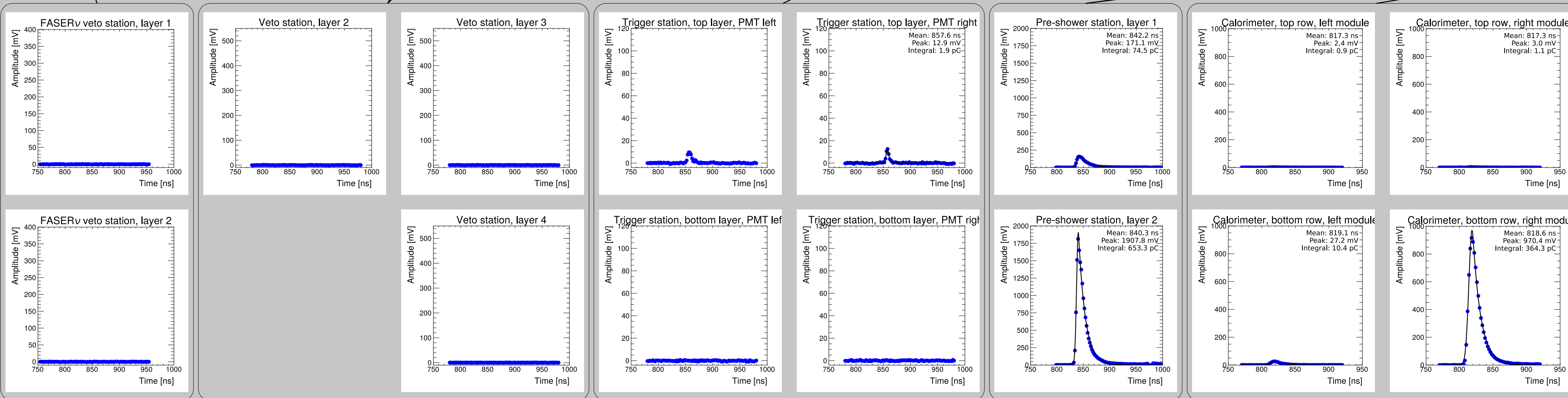
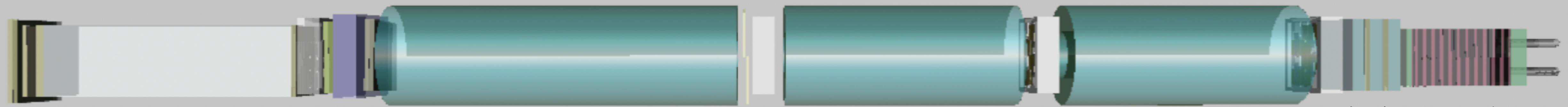


Source	Event Rate
Neutrino Background	0.44 ± 0.35 (flux) ± 0.01 (Luminosity) ± 0.15 (Calo E-scale) ± 0.06 (PS ratio) ± 0.02 (second PS) ± 0.02 (PS geometry) ± 0.05 (MC stat.) Total: 0.44 ± 0.39 (88.6%)
$a_W (m_a = 140 \text{ MeV}, g_{aWW} = 2 \times 10^{-4} \text{ GeV}^{-1})$	70.7 ± 42.0 (theo.) ± 6.4 (exp.) ± 1.3 (MC stat.)
$a_W (m_a = 120 \text{ MeV}, g_{aWW} = 1 \times 10^{-4} \text{ GeV}^{-1})$	91.1 ± 52.2 (theo.) ± 16.2 (exp.) ± 3.2 (MC stat.)
$a_W (m_a = 300 \text{ MeV}, g_{aWW} = 2 \times 10^{-5} \text{ GeV}^{-1})$	4.0 ± 2.3 (theo.) ± 0.6 (exp.) ± 0.1 (MC stat.)
Data	1

The "ALPtrino" event



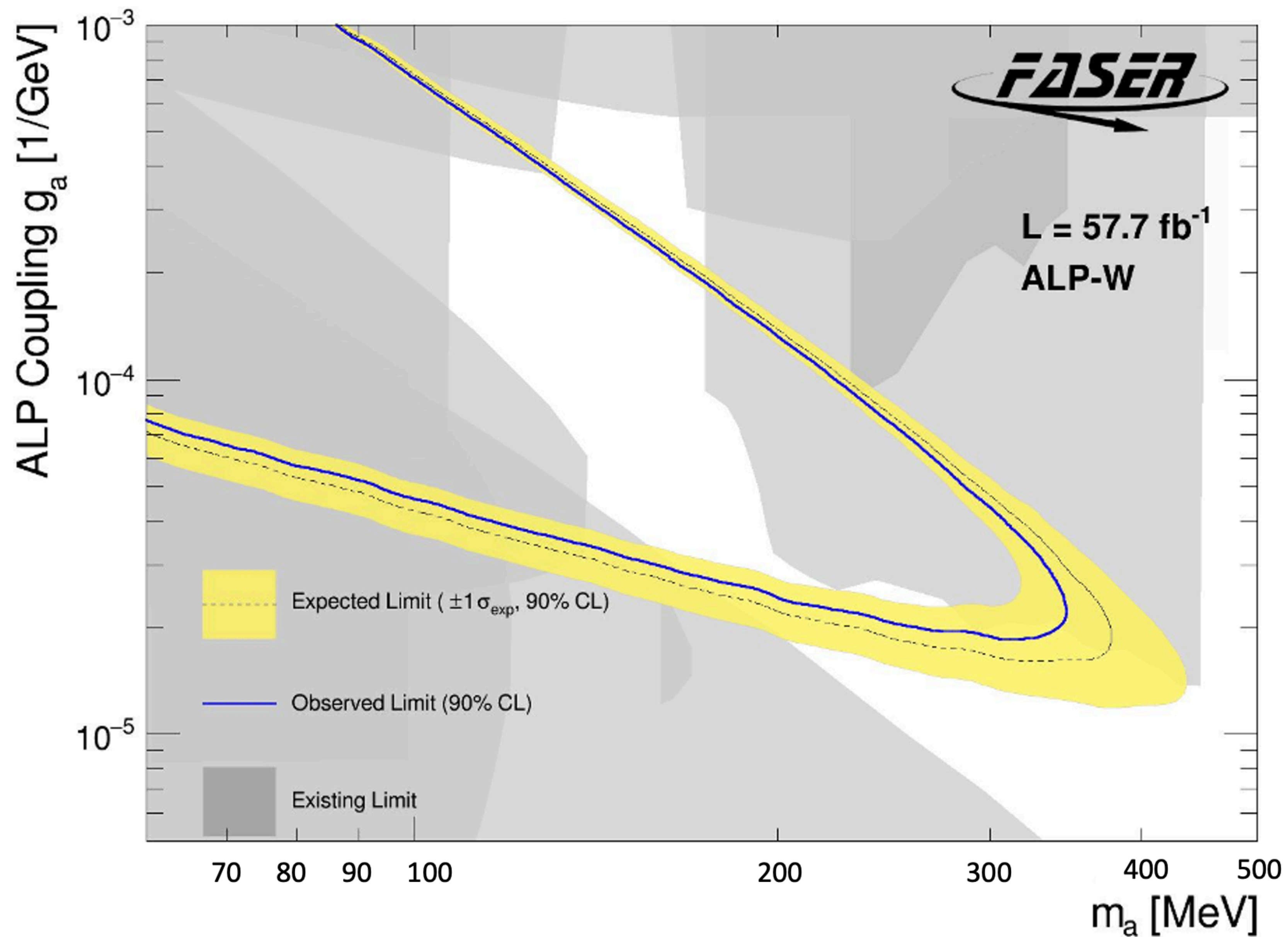
Run 8834
Event 44421456
2022-10-13 16:09:44



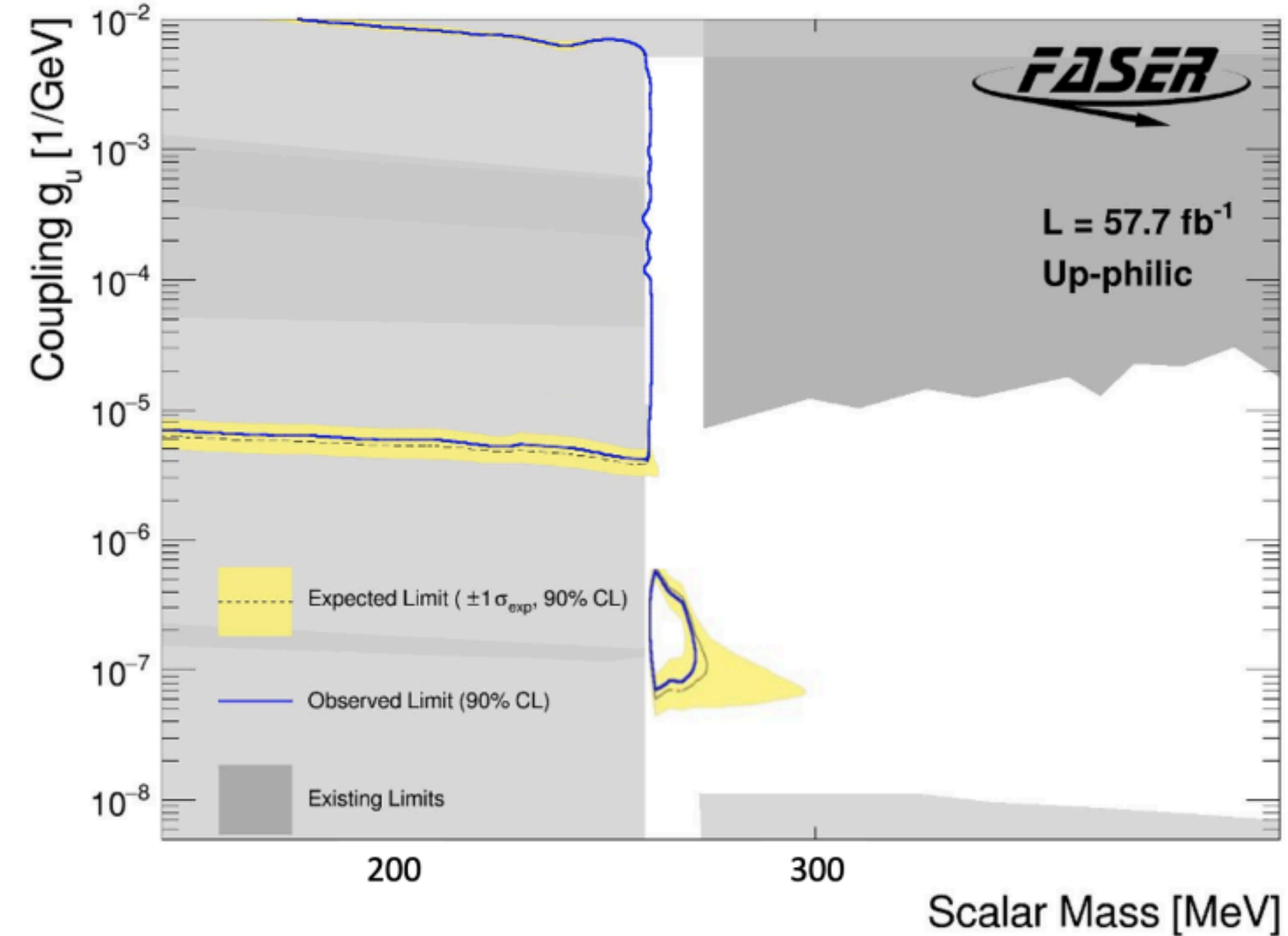
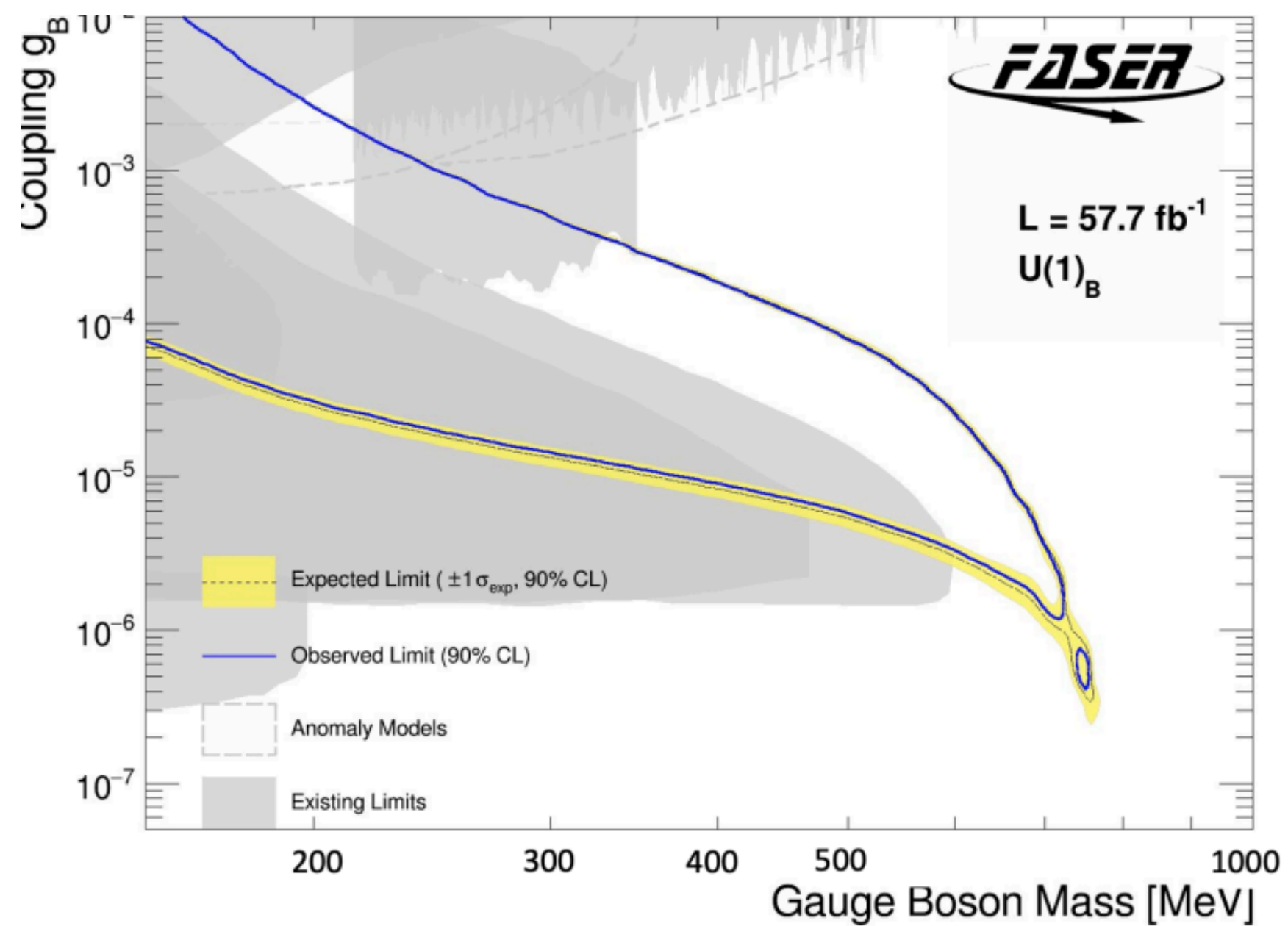
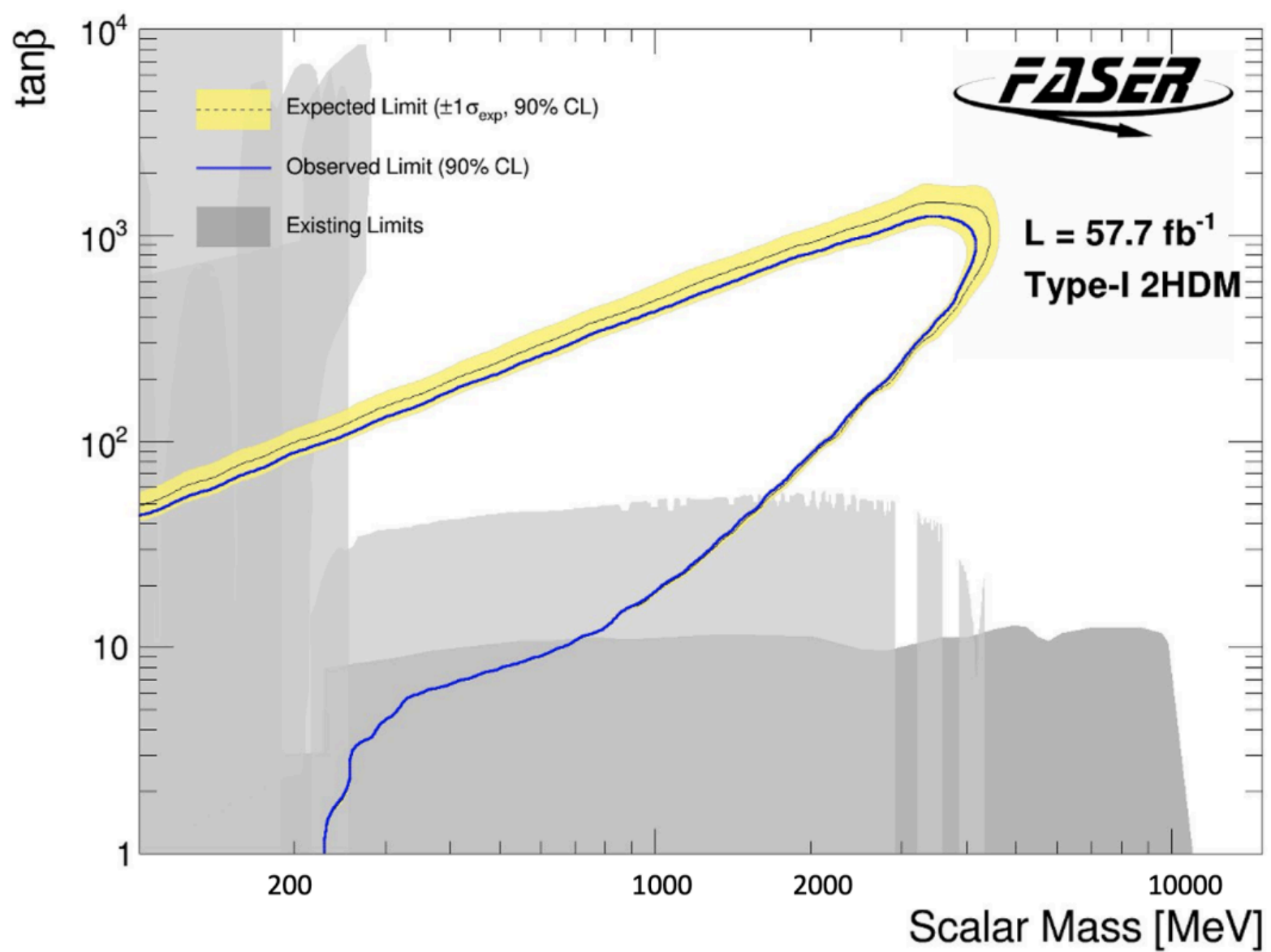
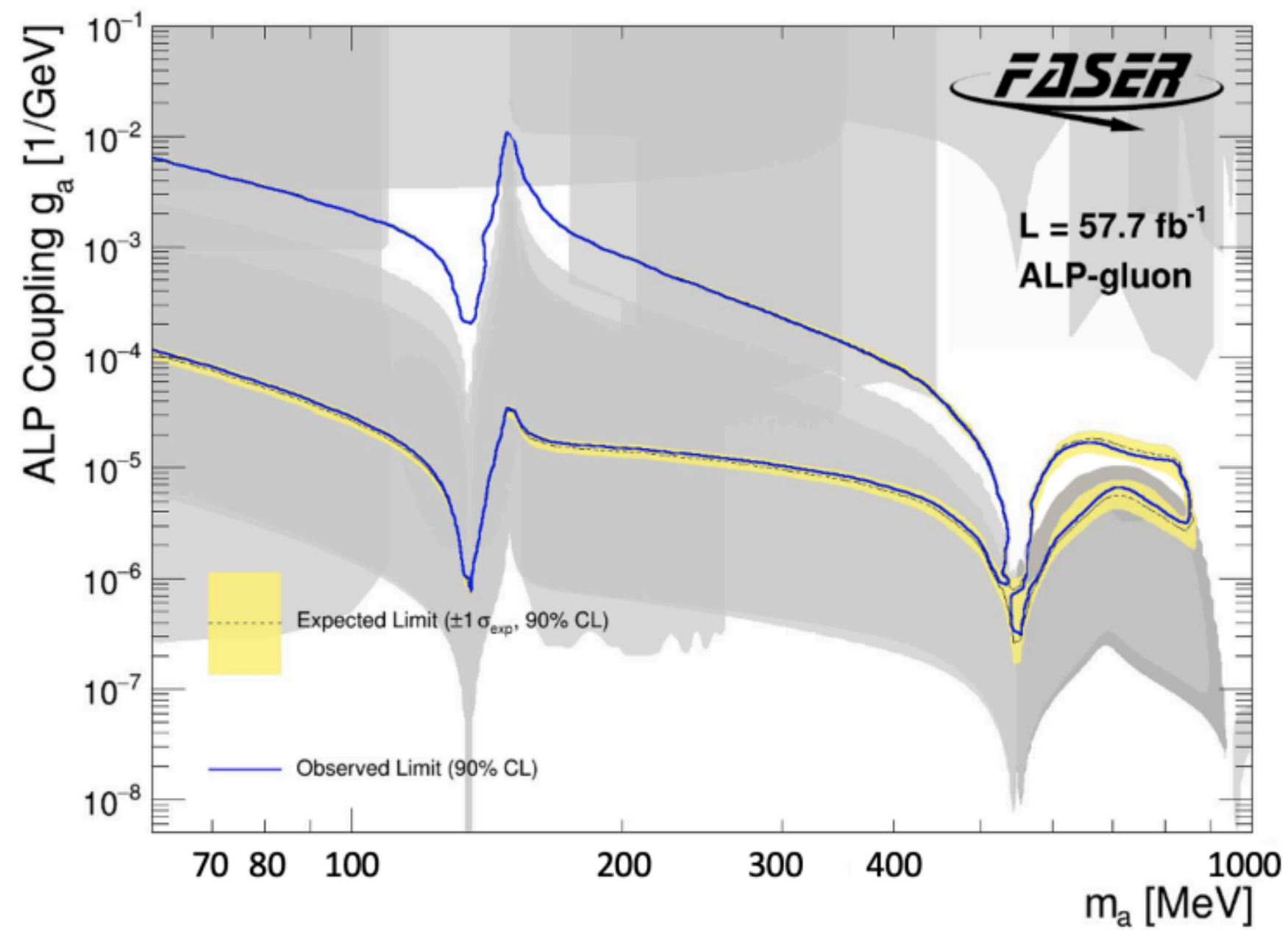
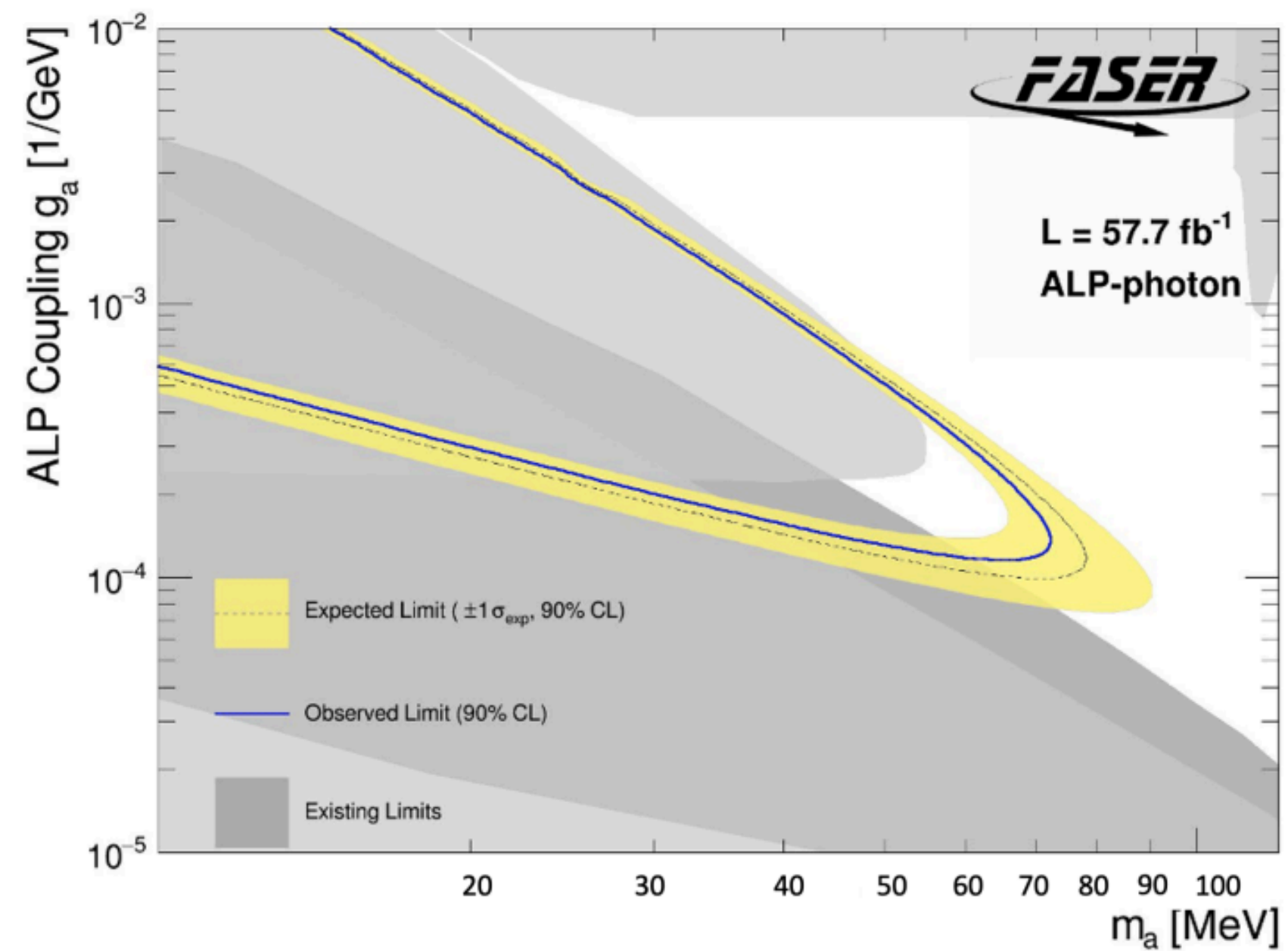
consistent with an ALP signal, or a neutrino background event

Results

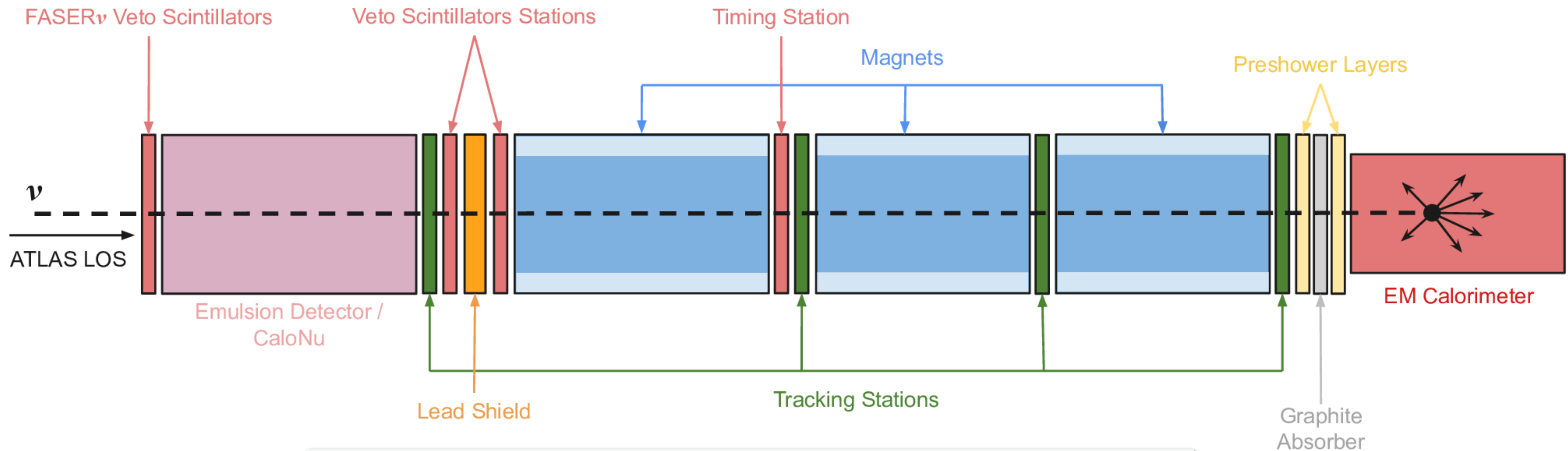
- Existing limits from varying experiments
- Probing inaccessible parameter space



Not
stopping
there..



The interplay with neutrino measurements



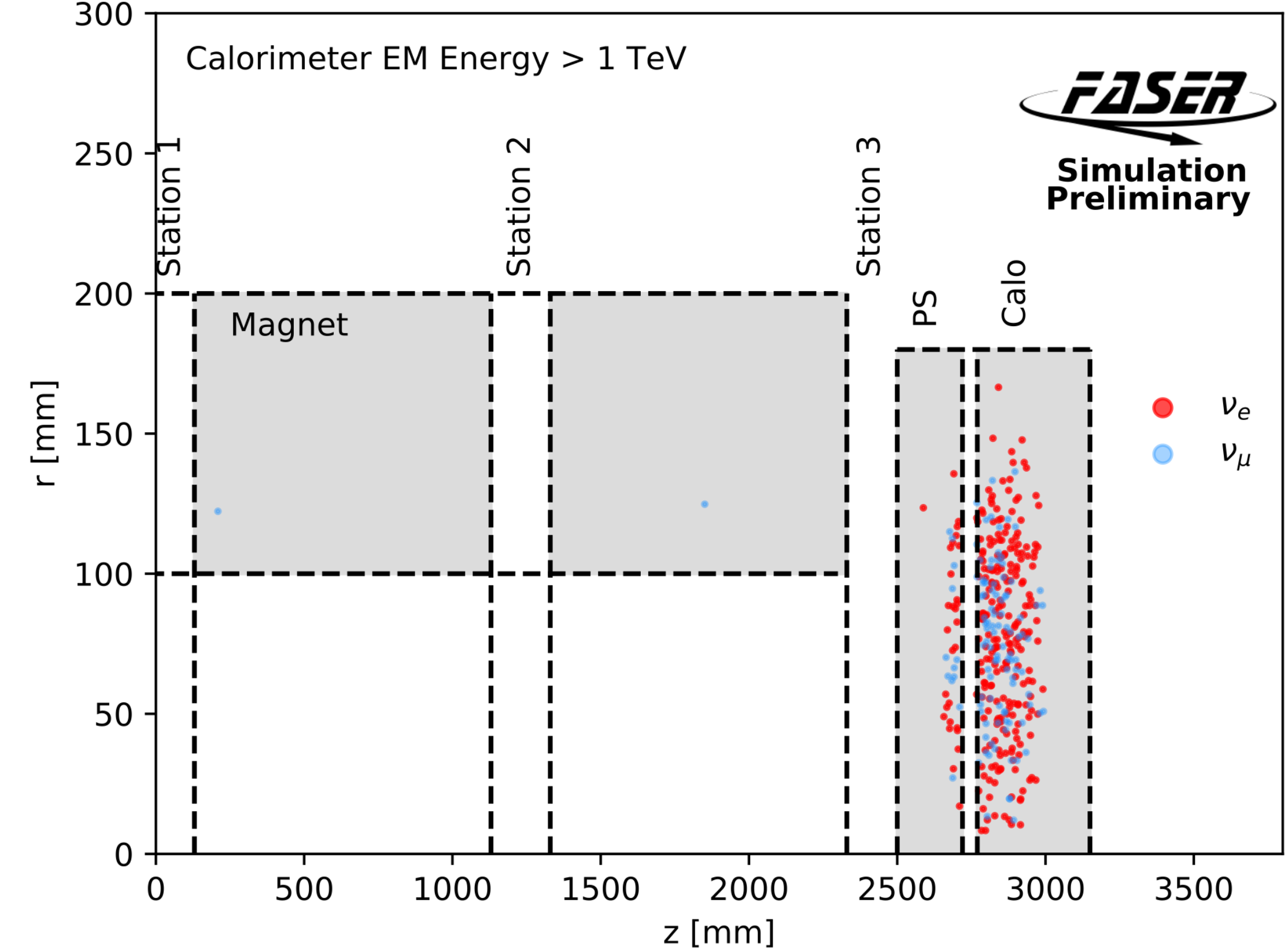
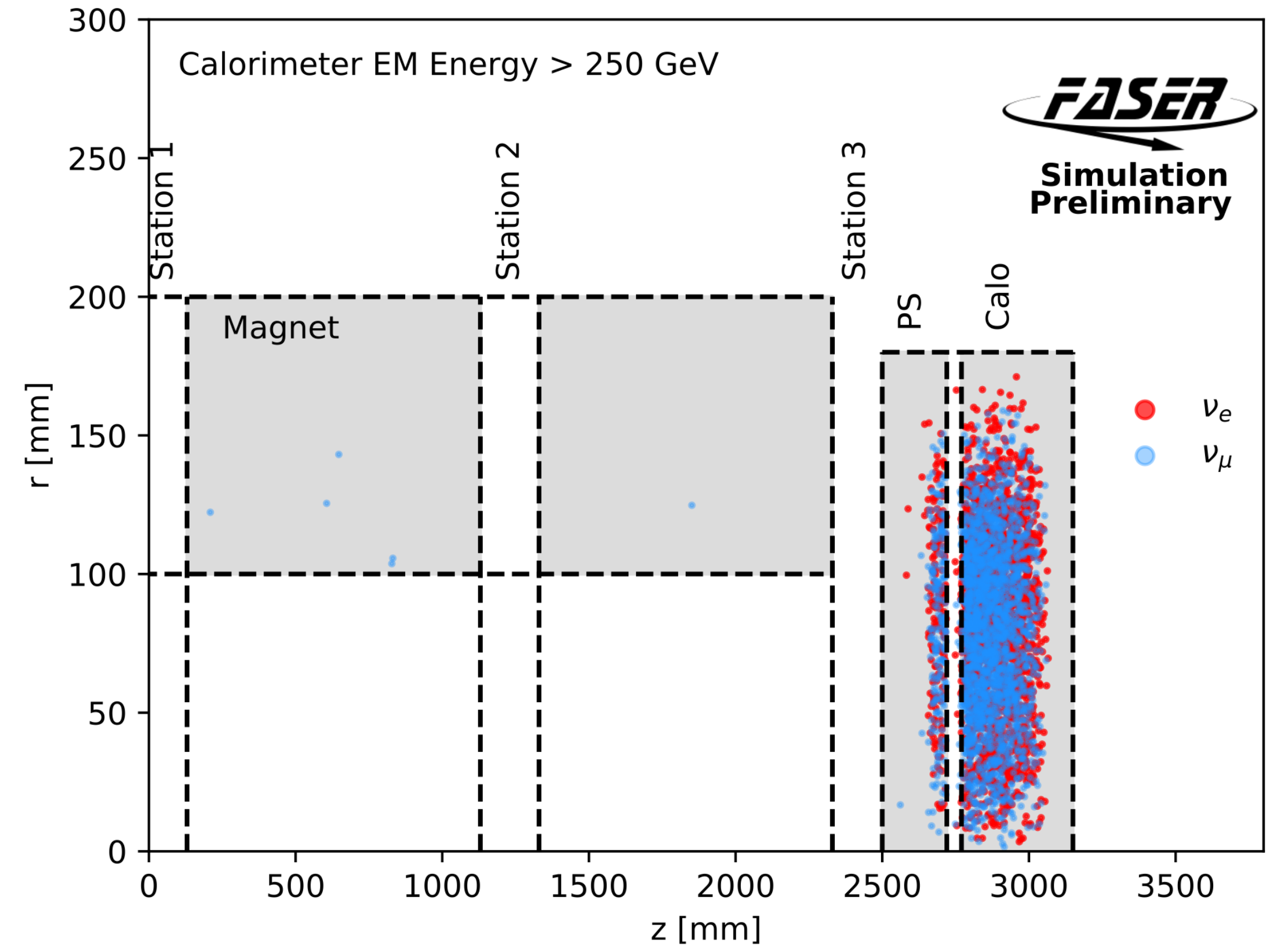
Measurement of High-Energy Electron Neutrino Interactions with the FASER Calorimeter at the LHC

CERN-FASER-CONF-2026-004

20 March 2026

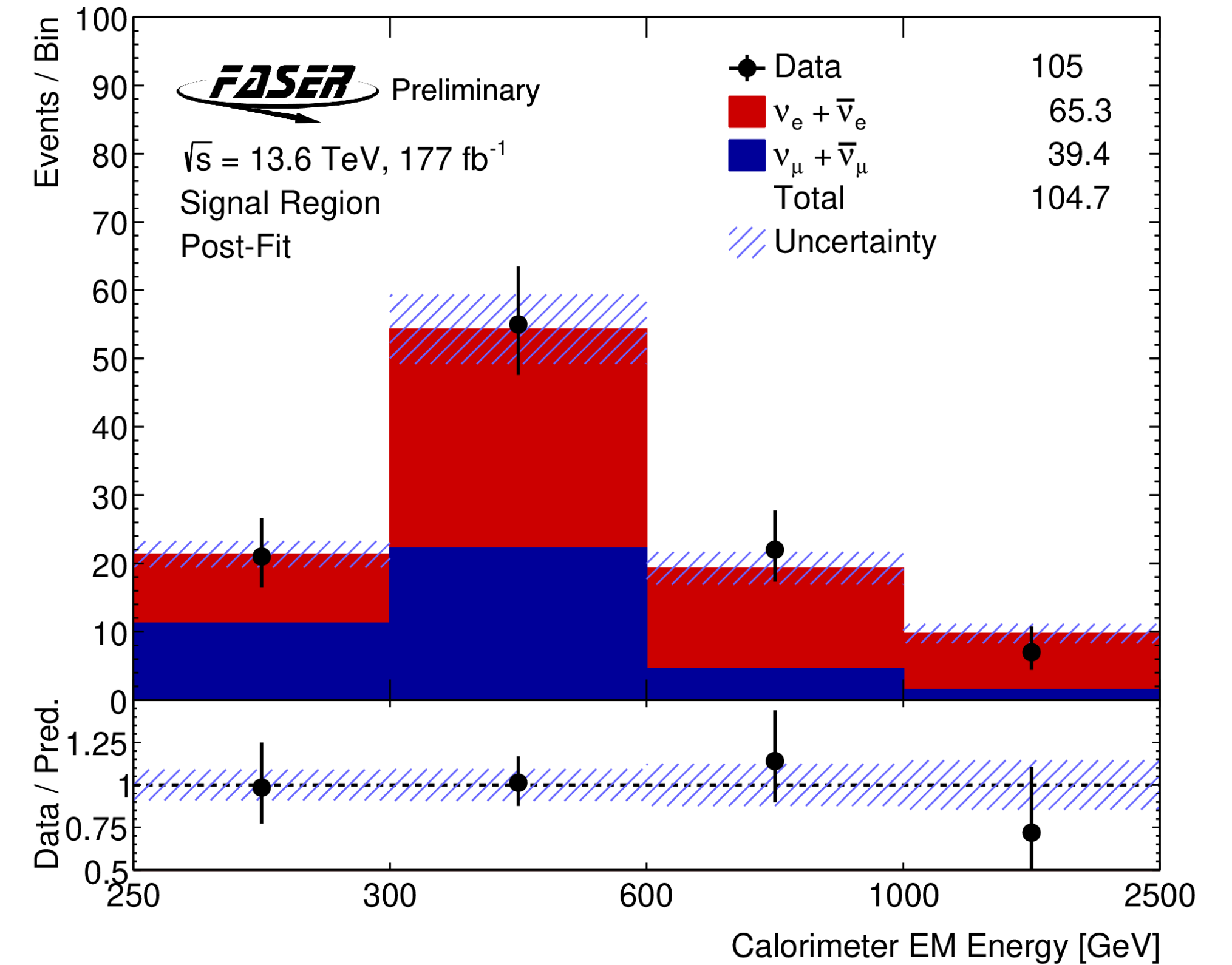
The interplay with neutrino measurements

Selection	Description
Raw VetoNu charge < 40 pC	No signal in all VetoNu scintillators
Raw Veto charge < 40 pC	No signal in all Veto scintillators
Timing scintillator charge < 20 pC	No signal in timing scintillator
PS1 nMIP < 10	Little shower development in the second preshower layer
Calorimeter EM Energy > 250 GeV	Large deposits in the calorimeter



ALP neutrino analysis

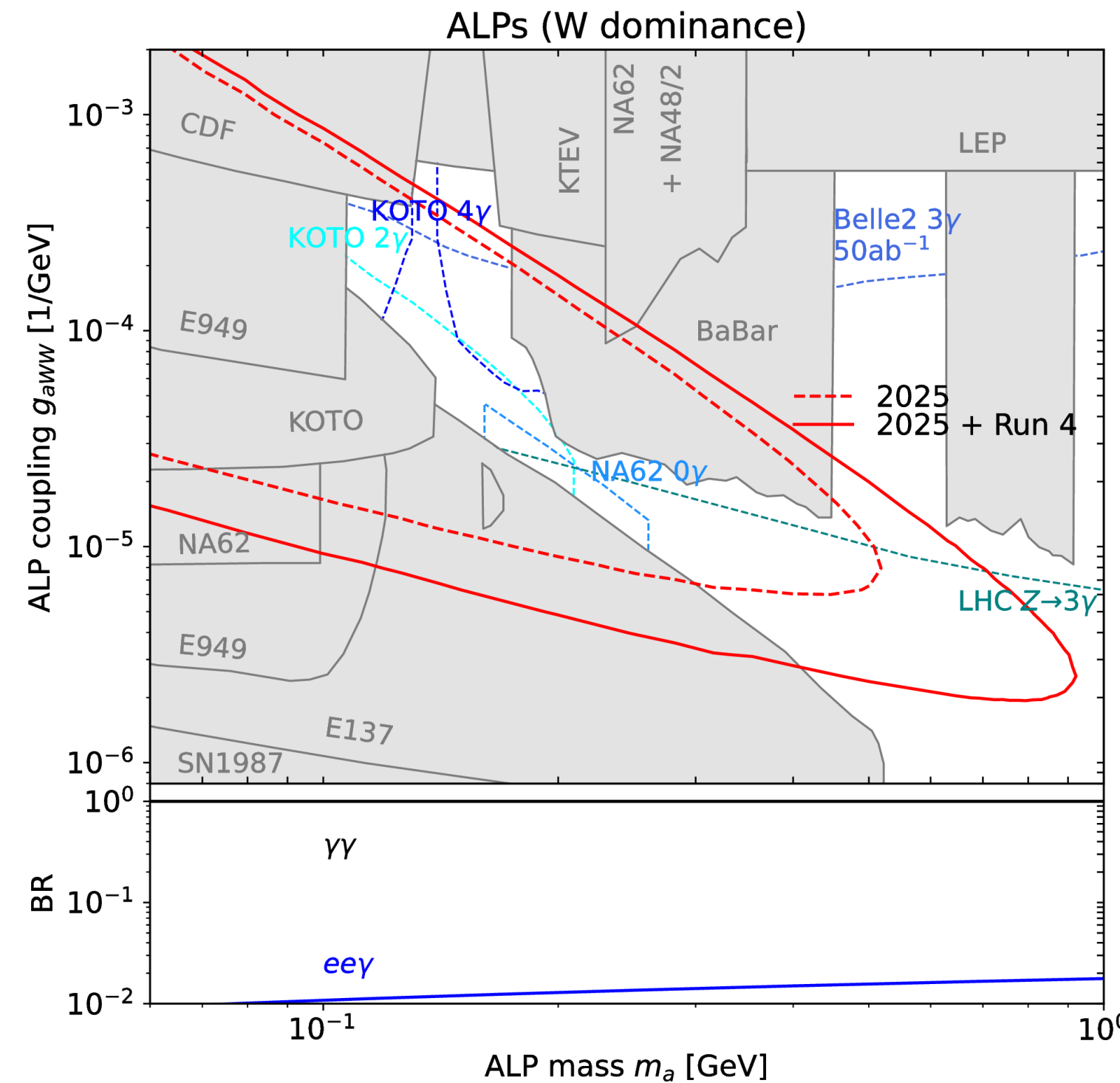
- Measure electron neutrinos using calorimeter selections inspired by ALP search
- Electron neutrino observation with 5.5σ



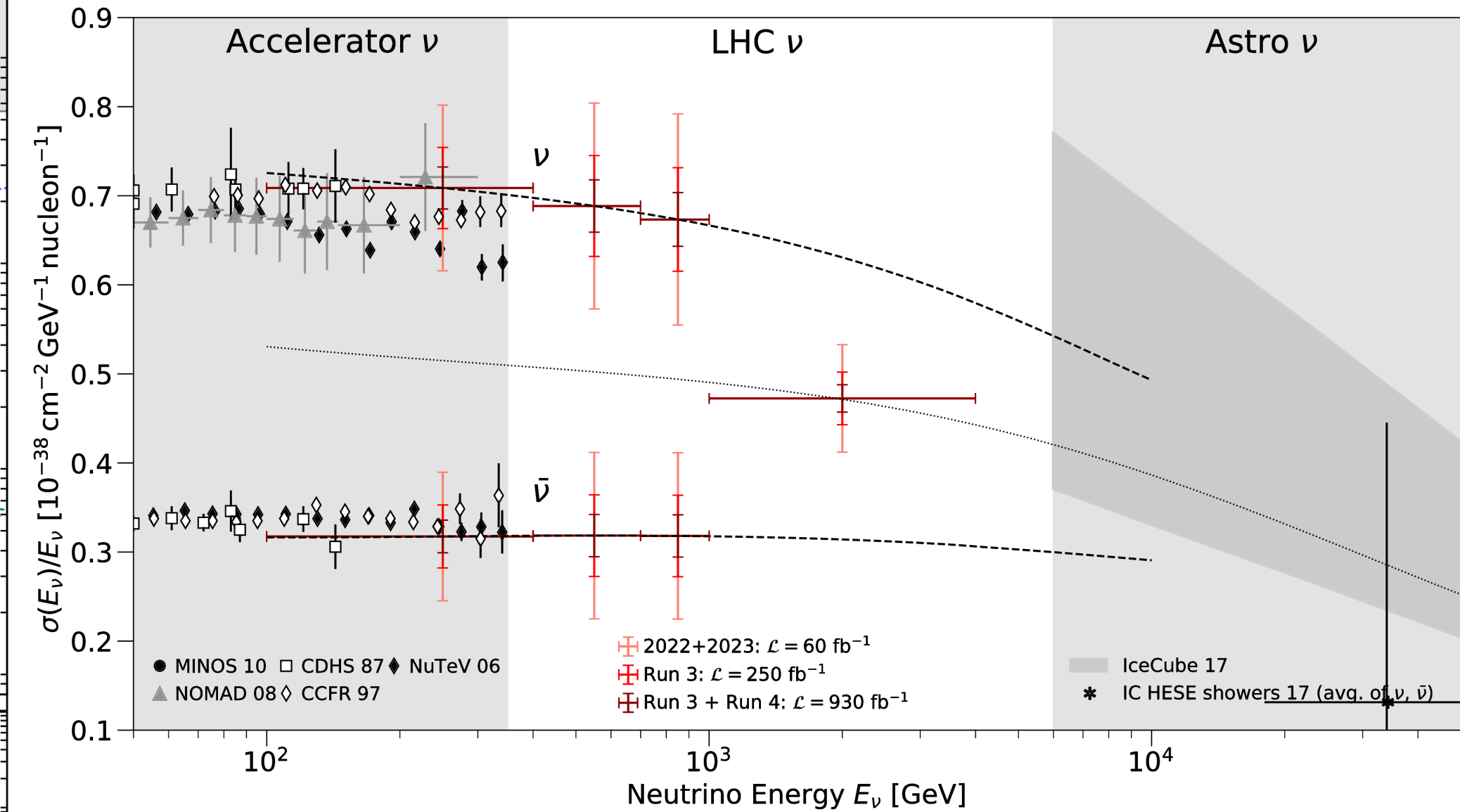
E_{Calo} [GeV]	[250-300]	[300-600]	[600-1000]	[+1000]	Total
$(\nu_\mu + \bar{\nu}_\mu)$ FV	9.85 ± 2.76	19.5 ± 4.97	3.94 ± 1.02	1.26 ± 0.32	34.6 ± 9.07
$(\nu_\mu + \bar{\nu}_\mu)$ Out-FV	1.11 ± 0.30	2.12 ± 0.54	0.52 ± 0.12	0.14 ± 0.03	3.89 ± 0.99
$\nu_\tau + \bar{\nu}_\tau$	0.10 ± 0.18	0.22 ± 0.37	0.04 ± 0.09	0.03 ± 0.04	0.40 ± 0.67
Background	11.1 ± 2.78	21.9 ± 5.01	4.50 ± 1.03	1.43 ± 0.32	38.9 ± 9.15
Signal $(\nu_e + \bar{\nu}_e)$	6.52 ± 3.32	20.6 ± 12.6	9.44 ± 7.01	5.32 ± 4.40	41.9 ± 27.3
Expected	17.6 ± 4.33	42.5 ± 13.6	13.9 ± 7.09	6.75 ± 4.41	80.8 ± 29.4
Observed	21	55	22	7	105

Further prospects of FASER

- FASER run approved for Run-4 (HL-LHC)
- Multiple configurations for FASERnu discussed
- Available data with preshower upgrade!
[FASER Preshower upgrade]
- Large statistics for neutrino measurements



[FASER in Run-4 LHCC]



Very active field - for many more years!



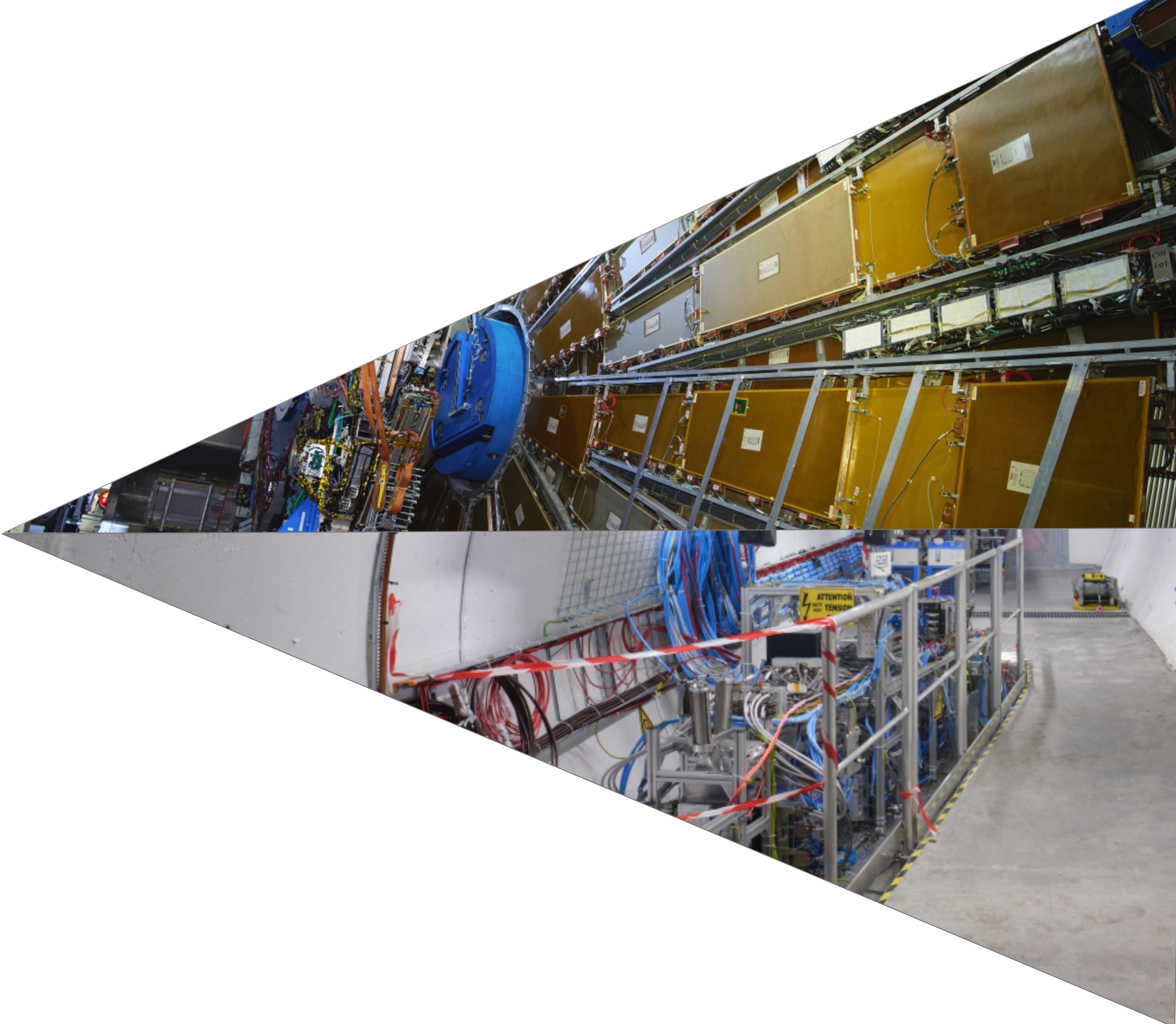
- Vast landscape to hunt for signs of dark matter at the LHC
- Electroweak SUSY in ATLAS narrowing down into challenging parameter space

Looking forward to HL-LHC

- FASER complementing ATLAS through long-lived particle searches
- Measuring Neutrinos from colliders



Backup

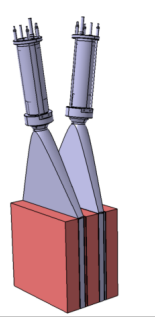
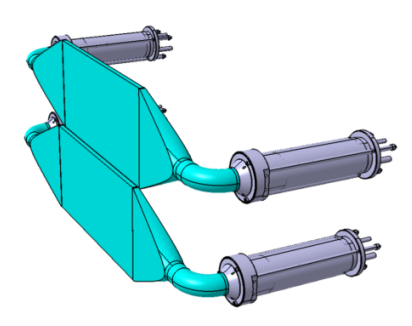
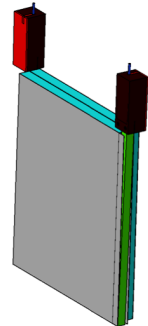
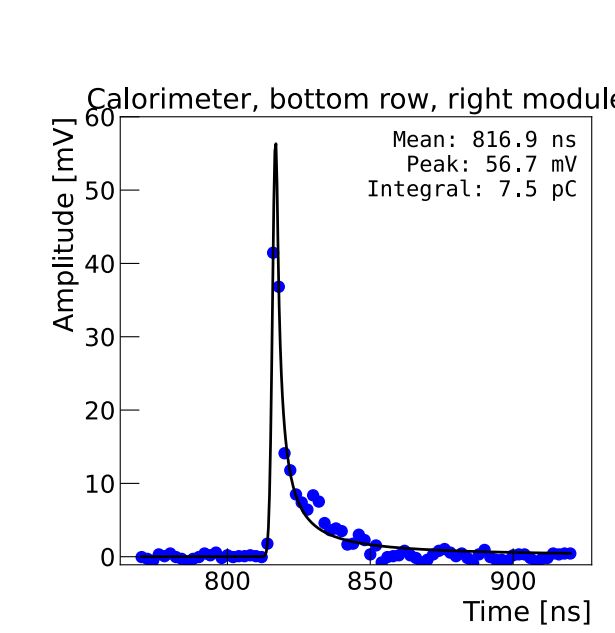
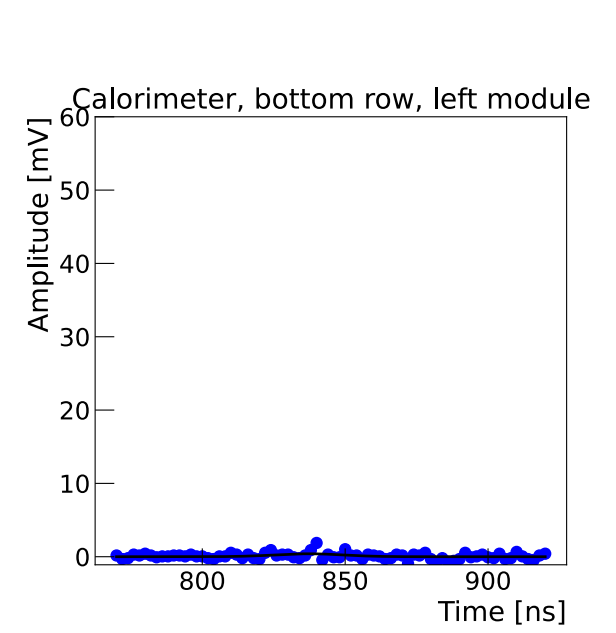
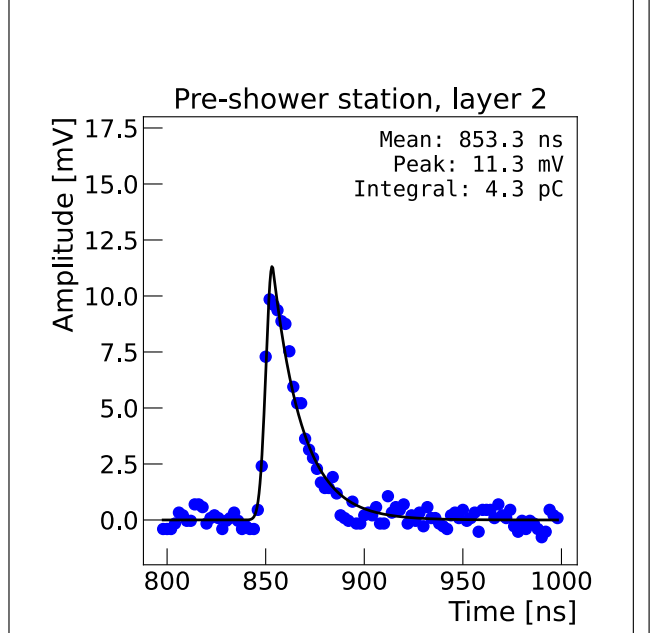
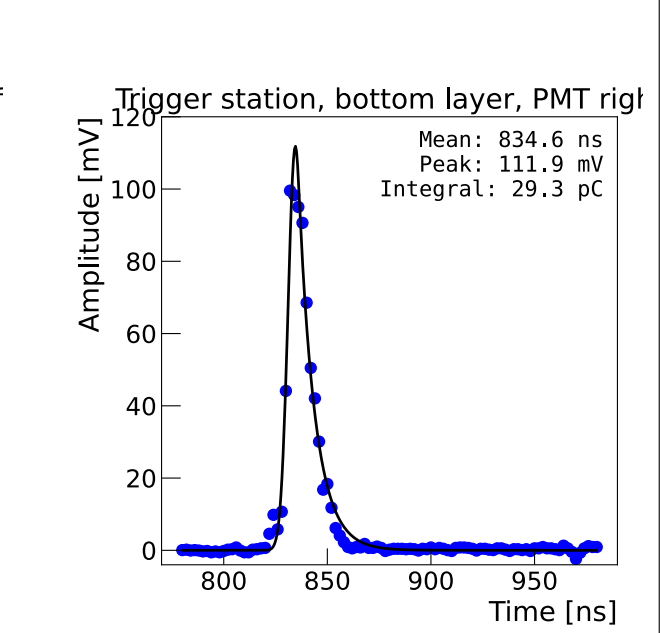
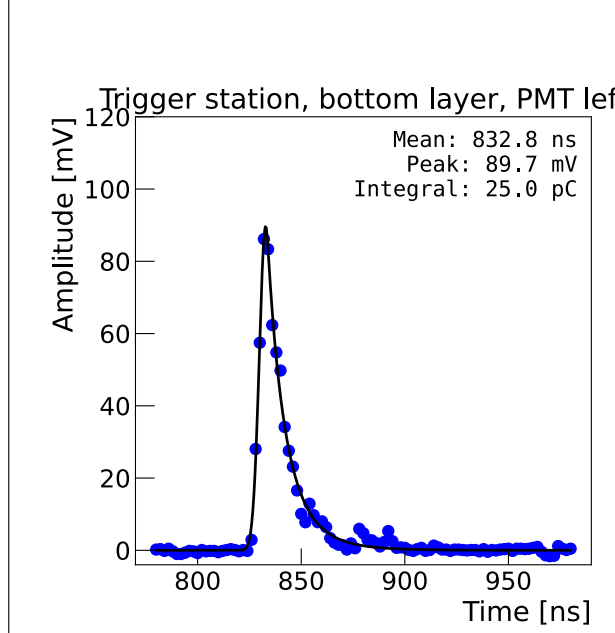
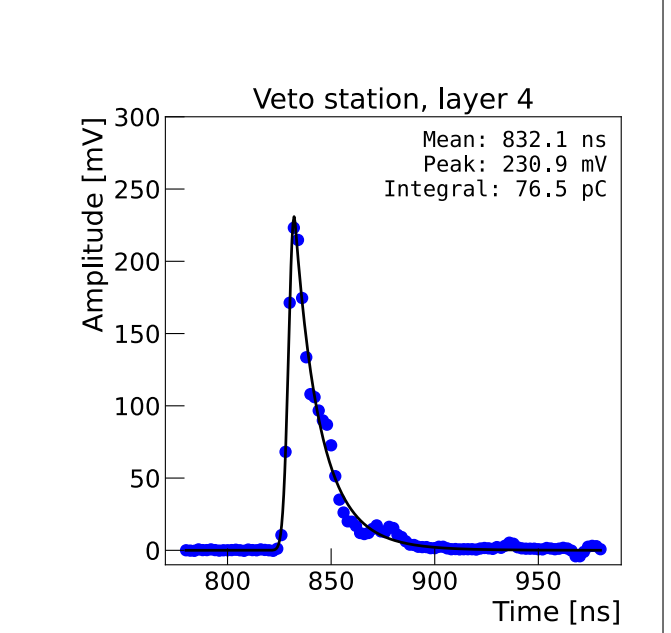
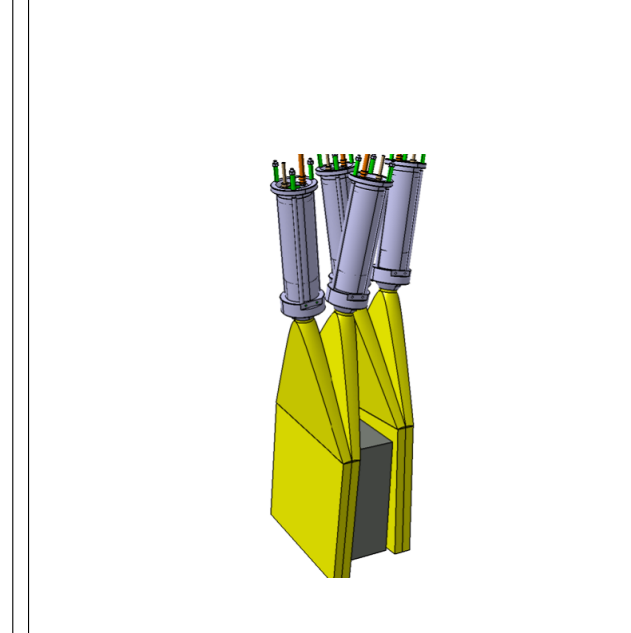
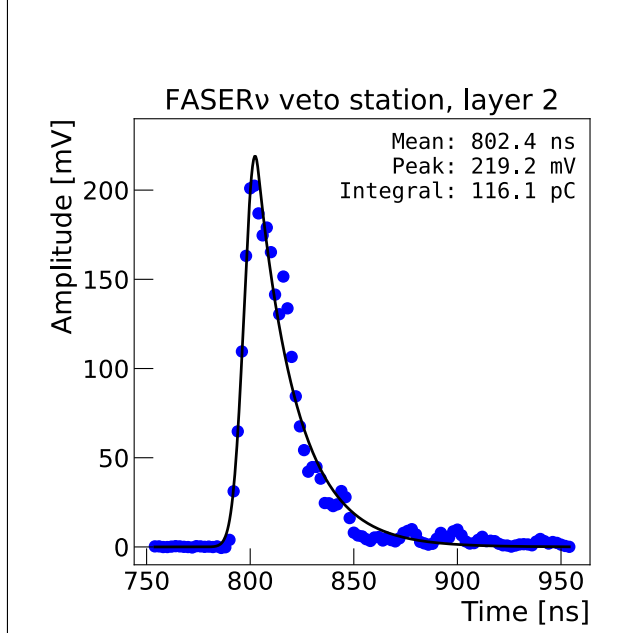
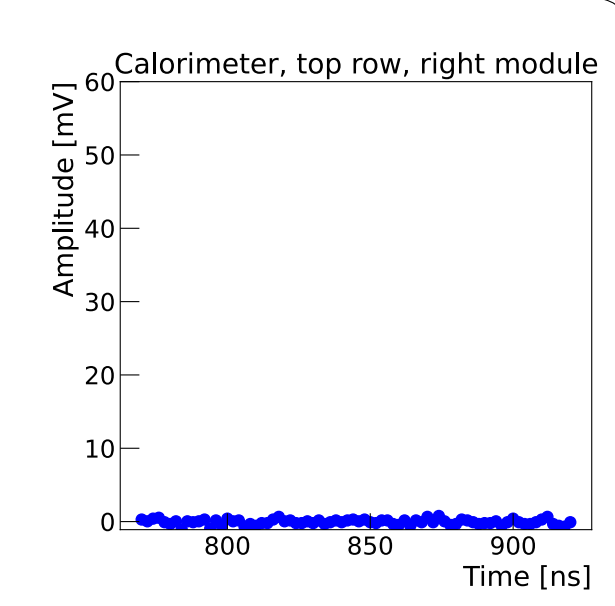
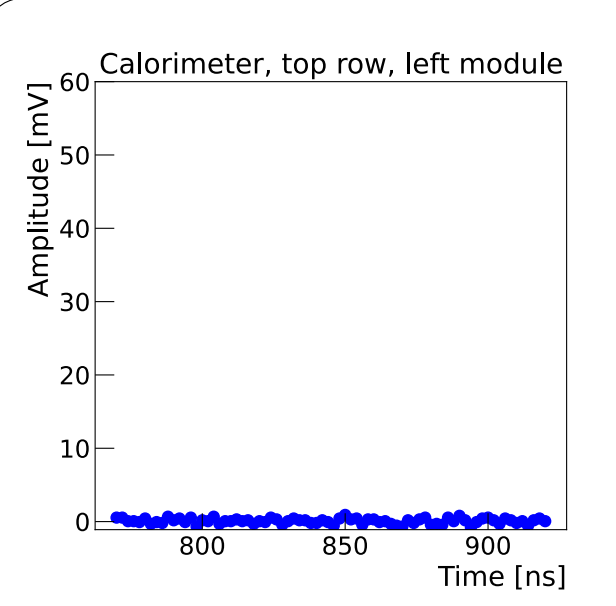
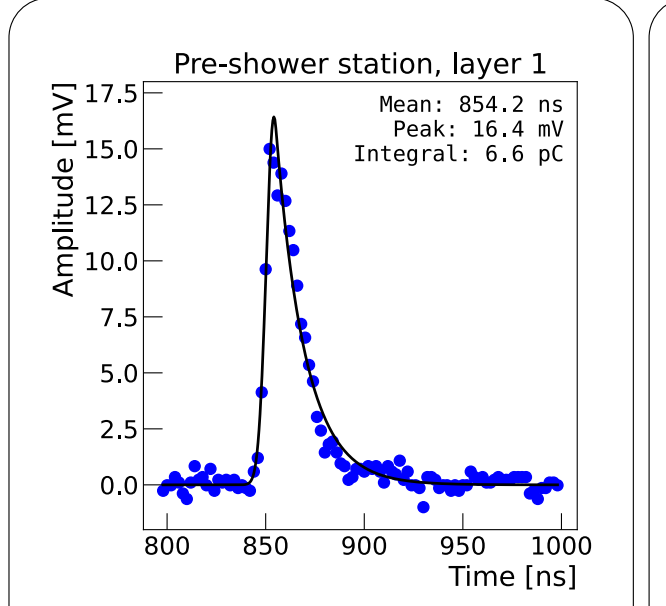
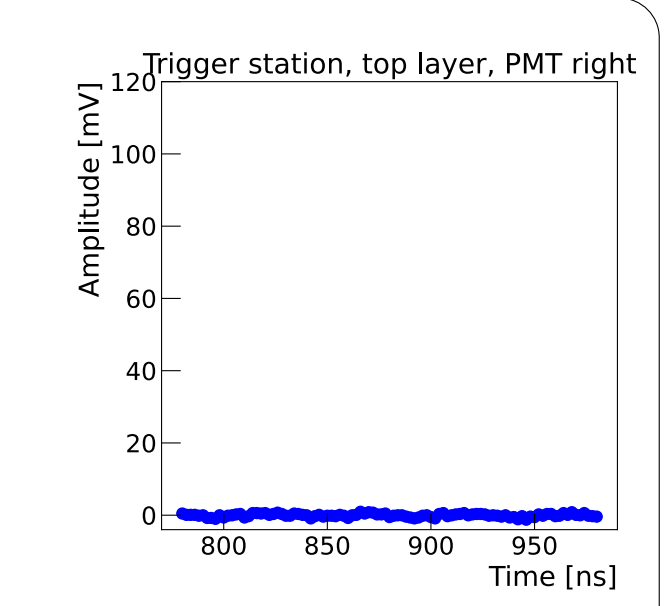
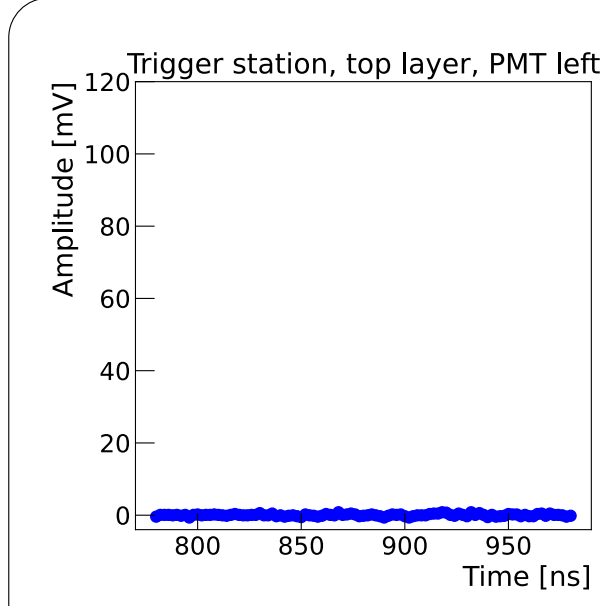
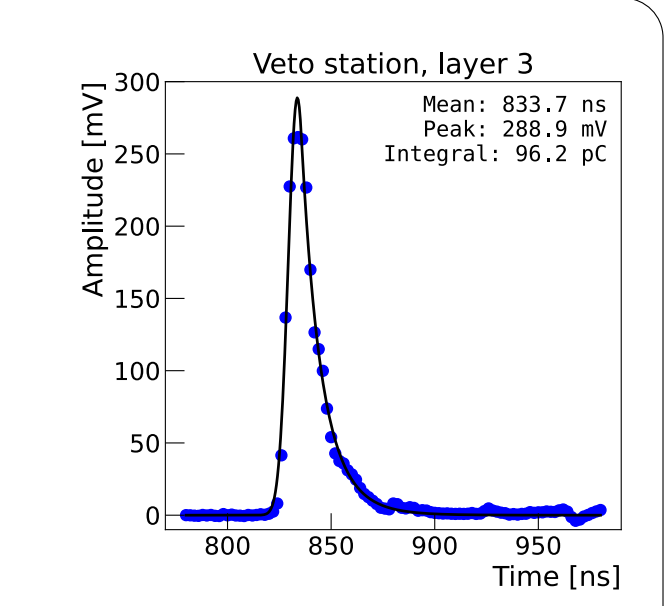
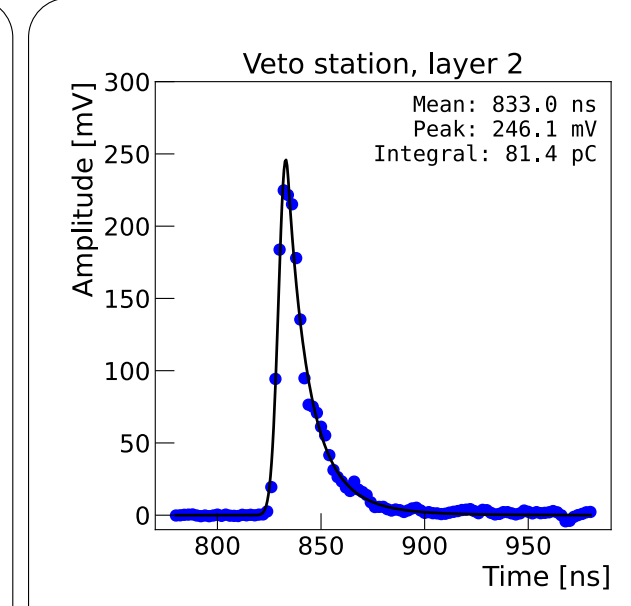
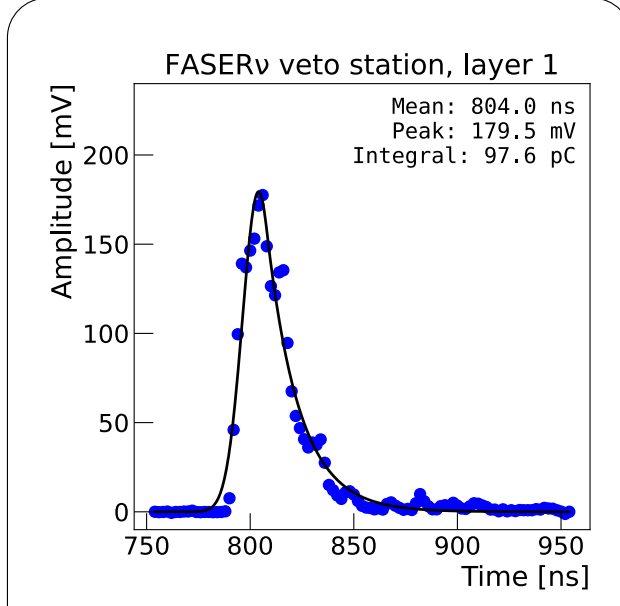
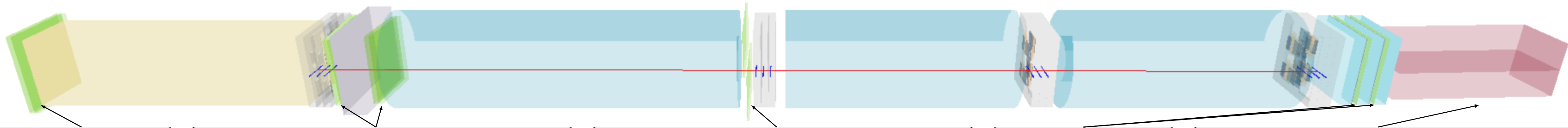


Scintillator performance **interlude**



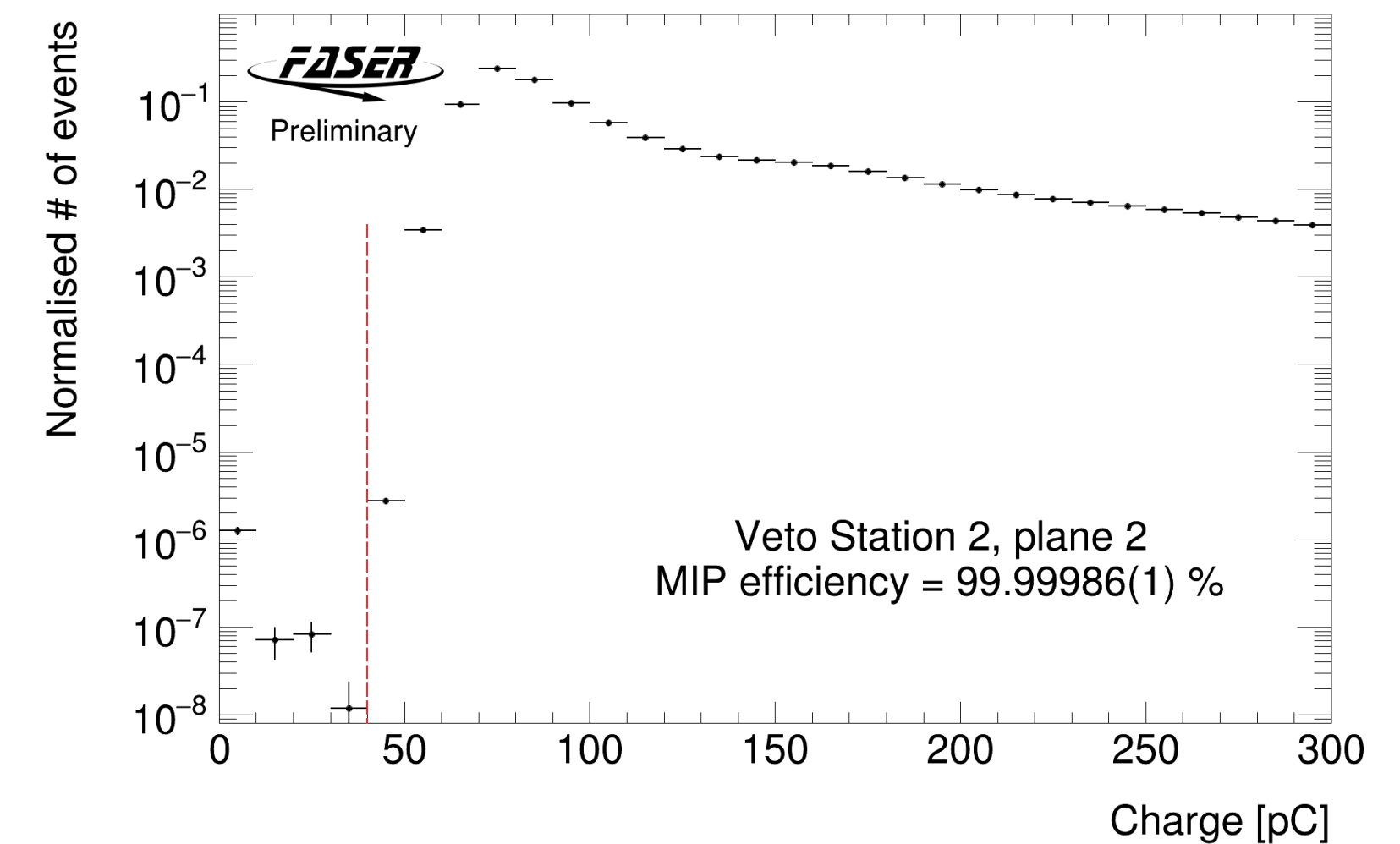
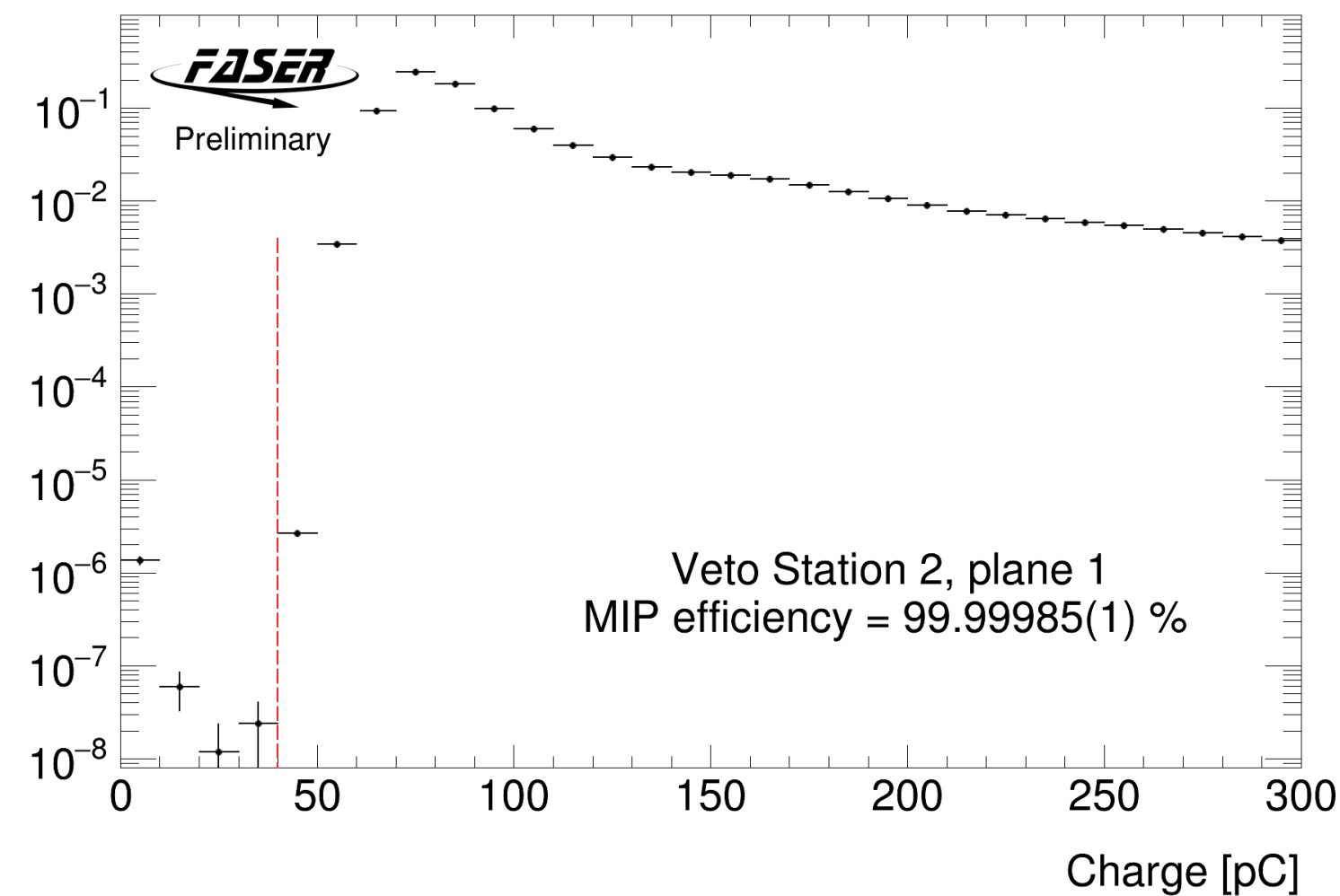
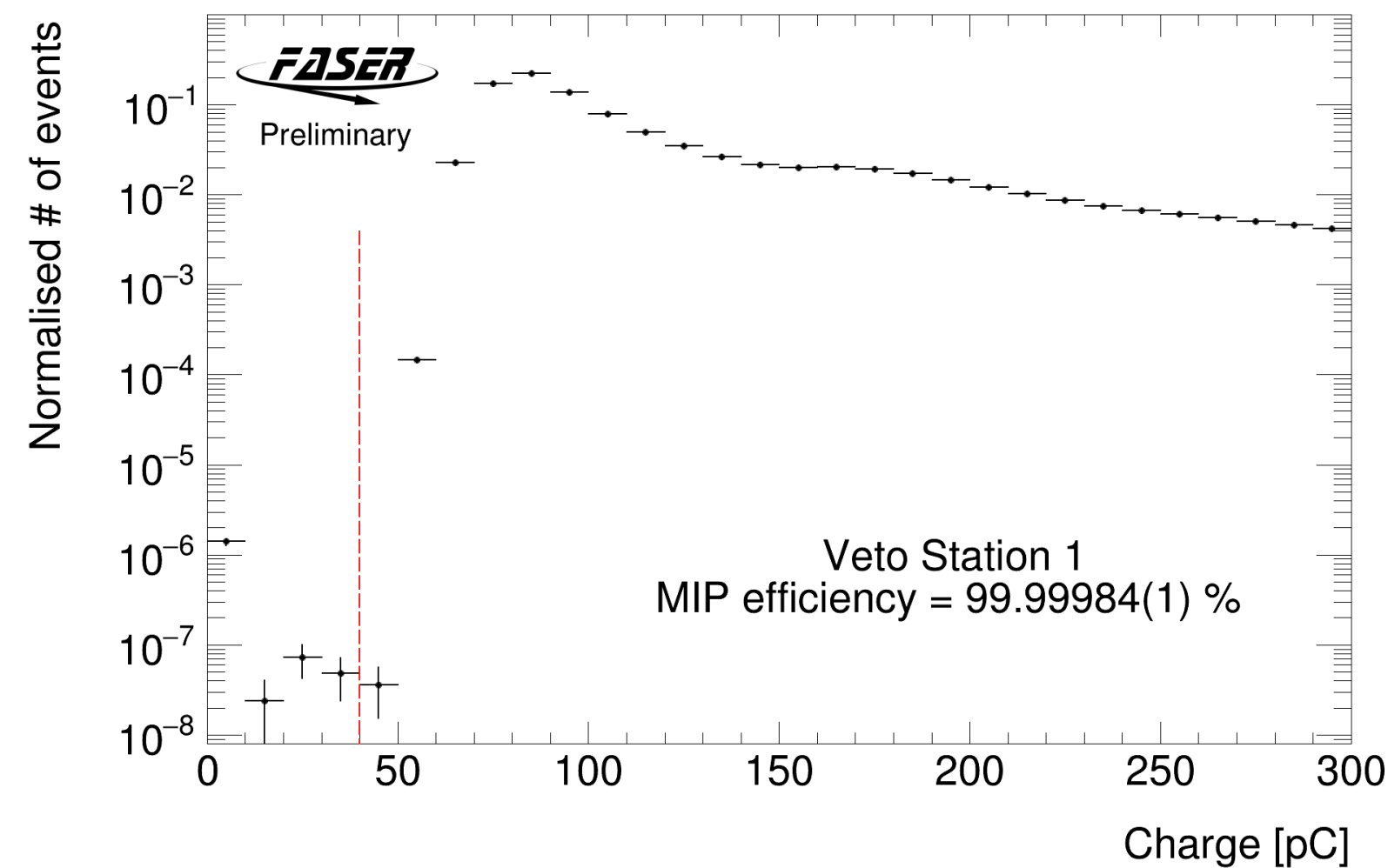
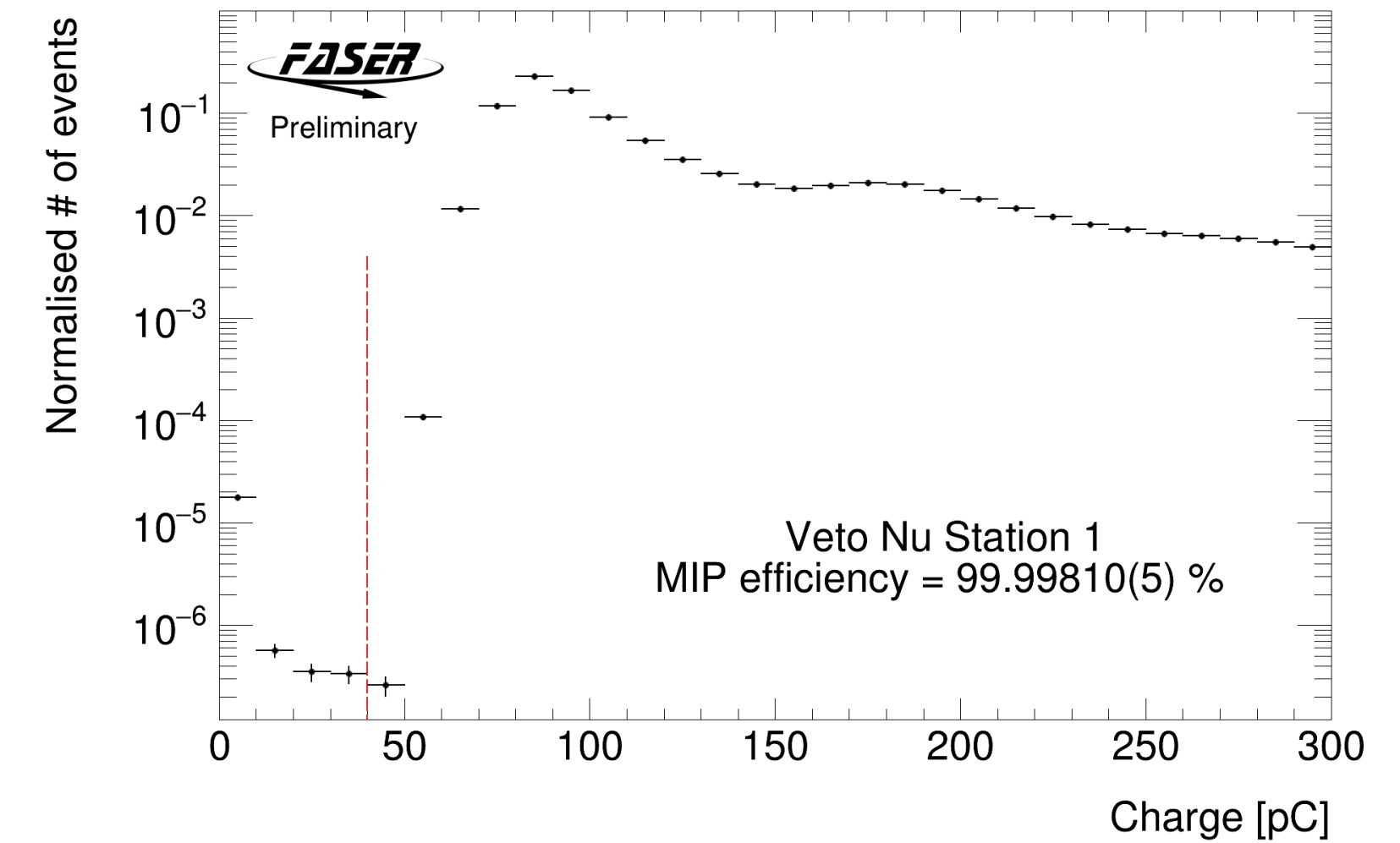
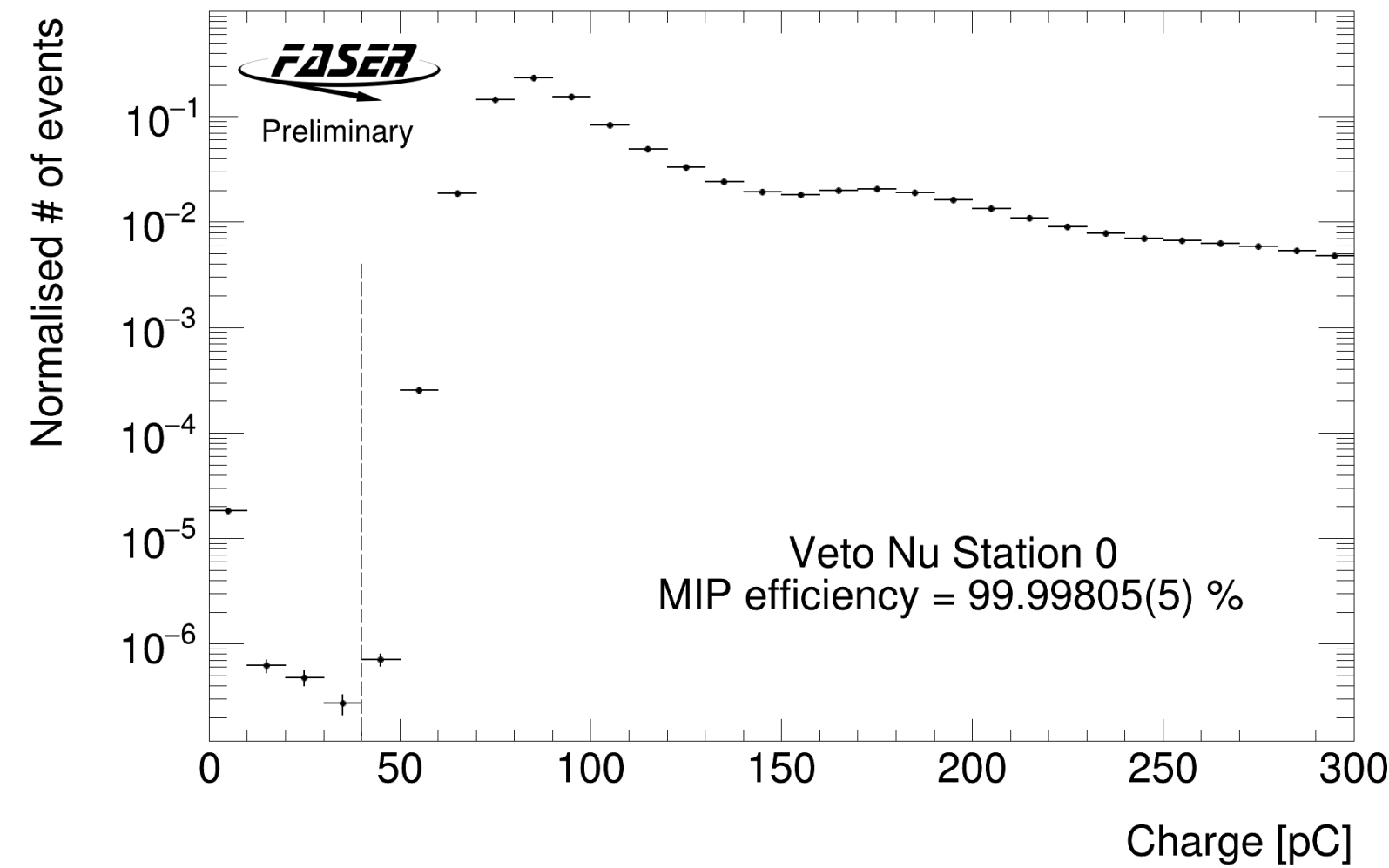
Run 10417
Event 12340
2023-04-21 19:44:55

One-track event: muon crossing FASER



Scintillator performance **interlude**

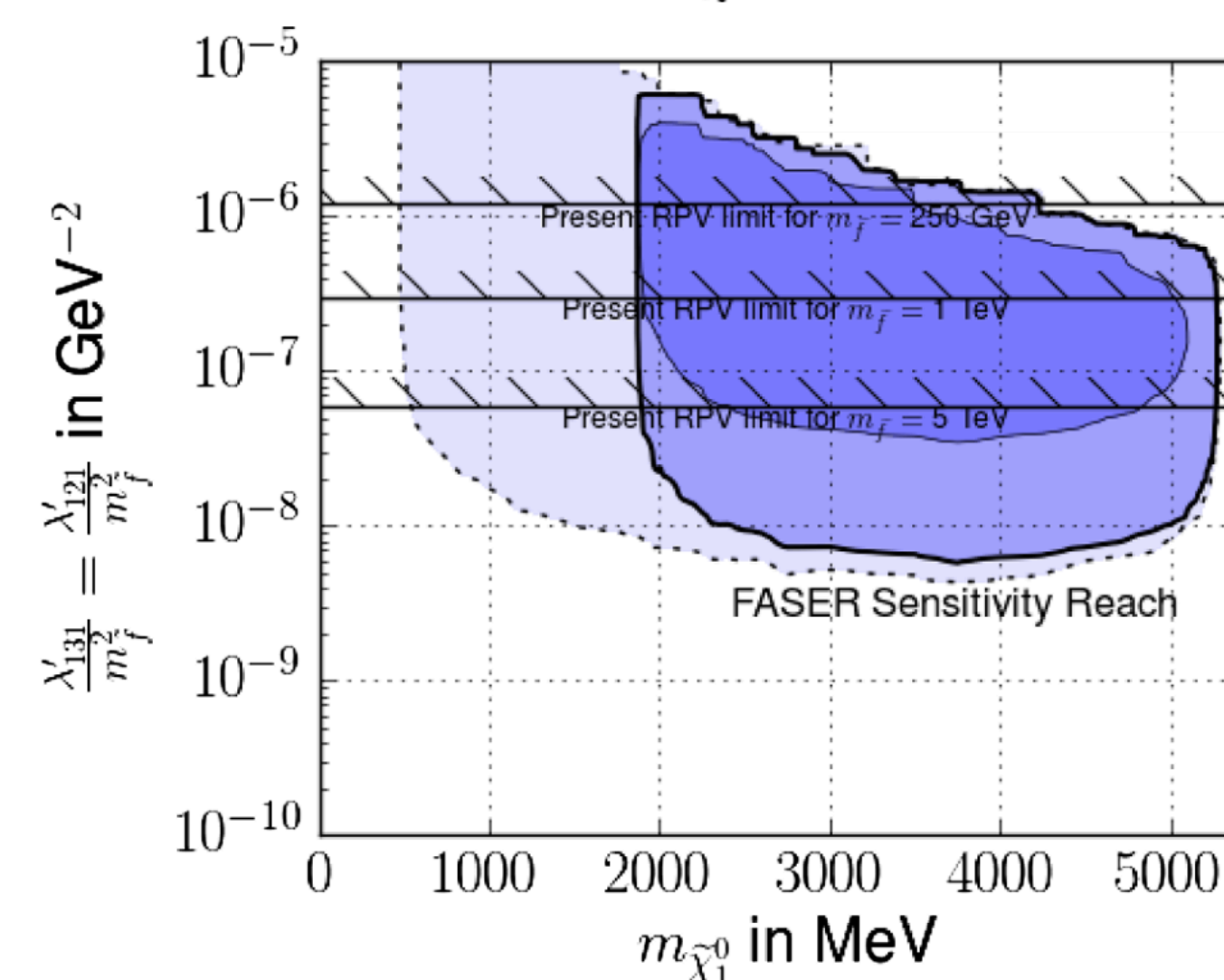
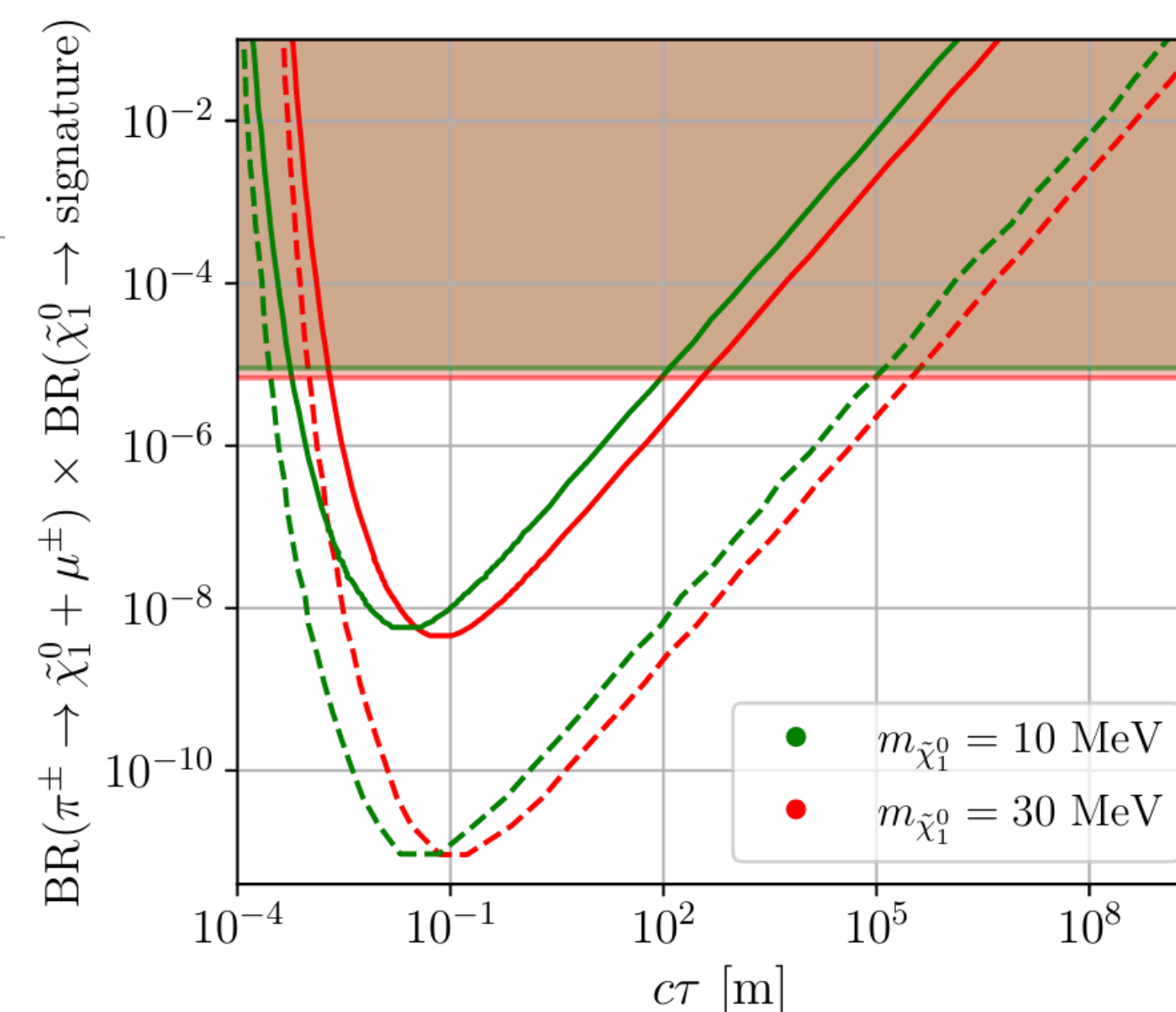
- 10^8 muons expected
- Measured in data layer-by-layer in one-track events
- Each layer efficiency $> 99.998\%$ (within $r < 95$ mm)
- 5 layers reduce veto-inefficiency background to a negligible level



Experiment overlaps: FASER

- R-Parity Violating couplings can lead to long lived particles leaving ATLAS along the beam axis!
- These would leave ATLAS, but might decay in FASER
 —> many open possibilities!

- Herbi paper: [/https://journals.aps.org/prd/pdf/10.1103/PhysRevD.99.055039](https://journals.aps.org/prd/pdf/10.1103/PhysRevD.99.055039)
- Upper plot for rpv light neutralino [/https://arxiv.org/pdf/2207.05100](https://arxiv.org/pdf/2207.05100)
- Possibility of compressed higgsino searches with FASER?

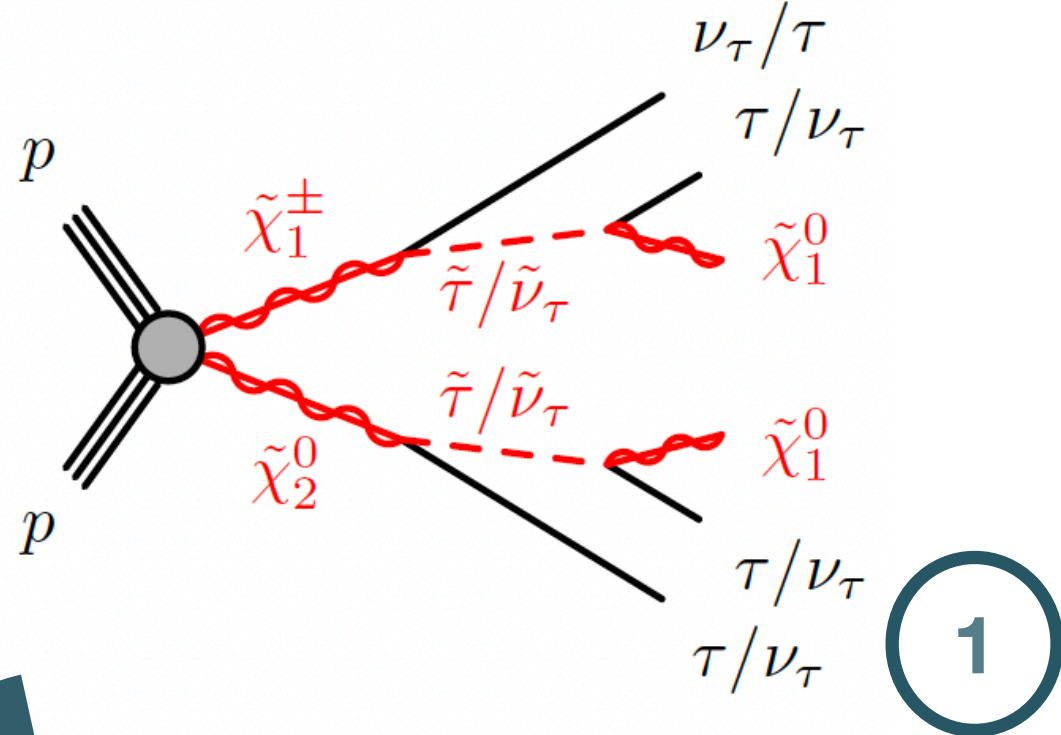


Soft lepton identification

- Electrons
- Neural network using hits, TRT information, calorimeter cluster matching
- Muons
- Neural network

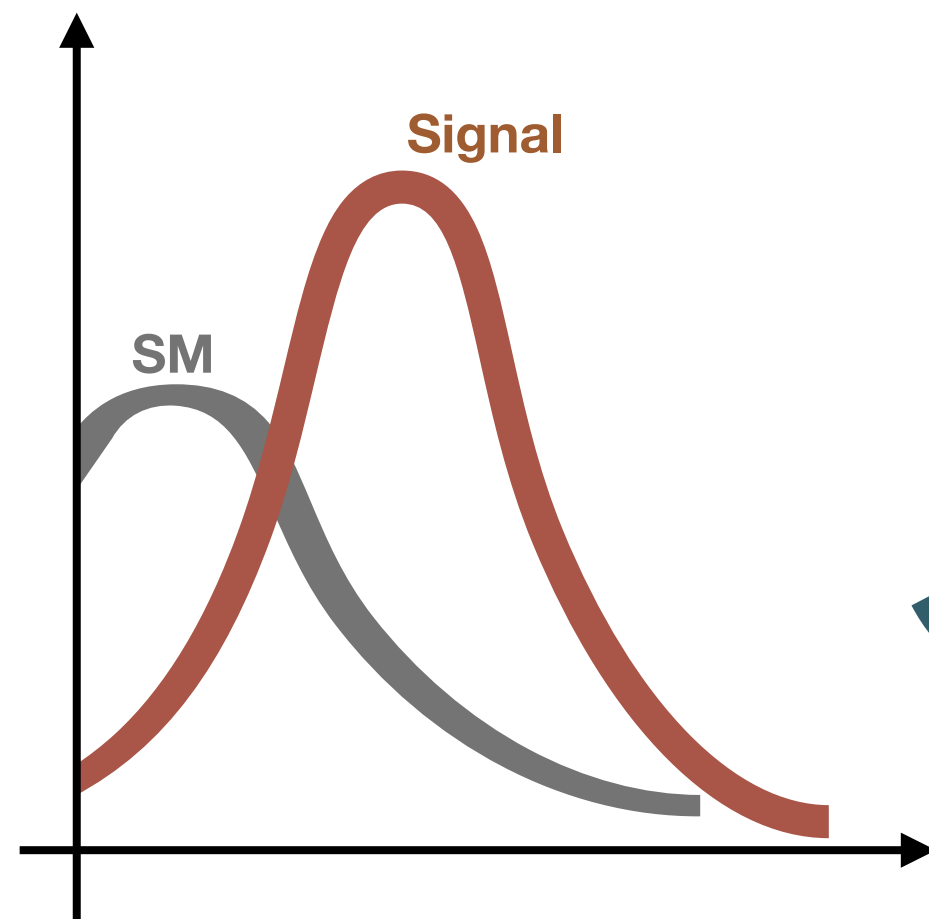
A search in a nutshell

0 Target scenario



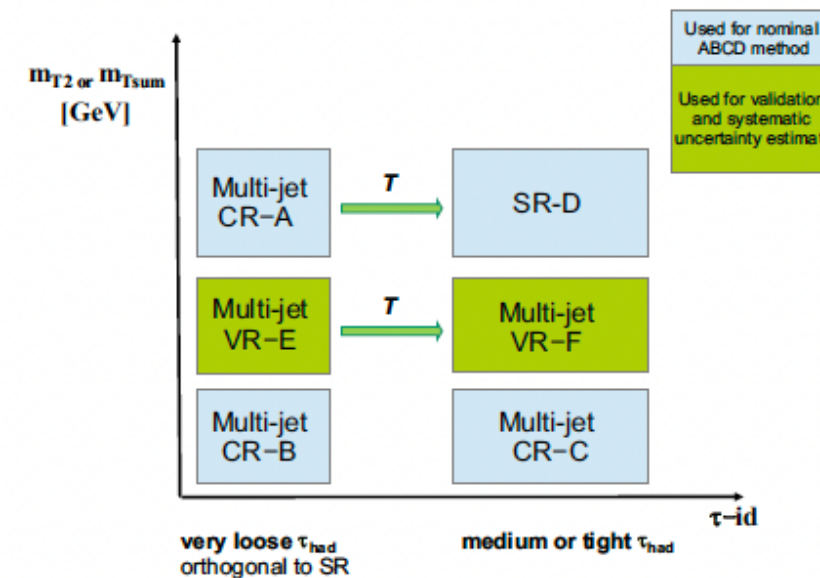
1 Final state

2 Kinematics

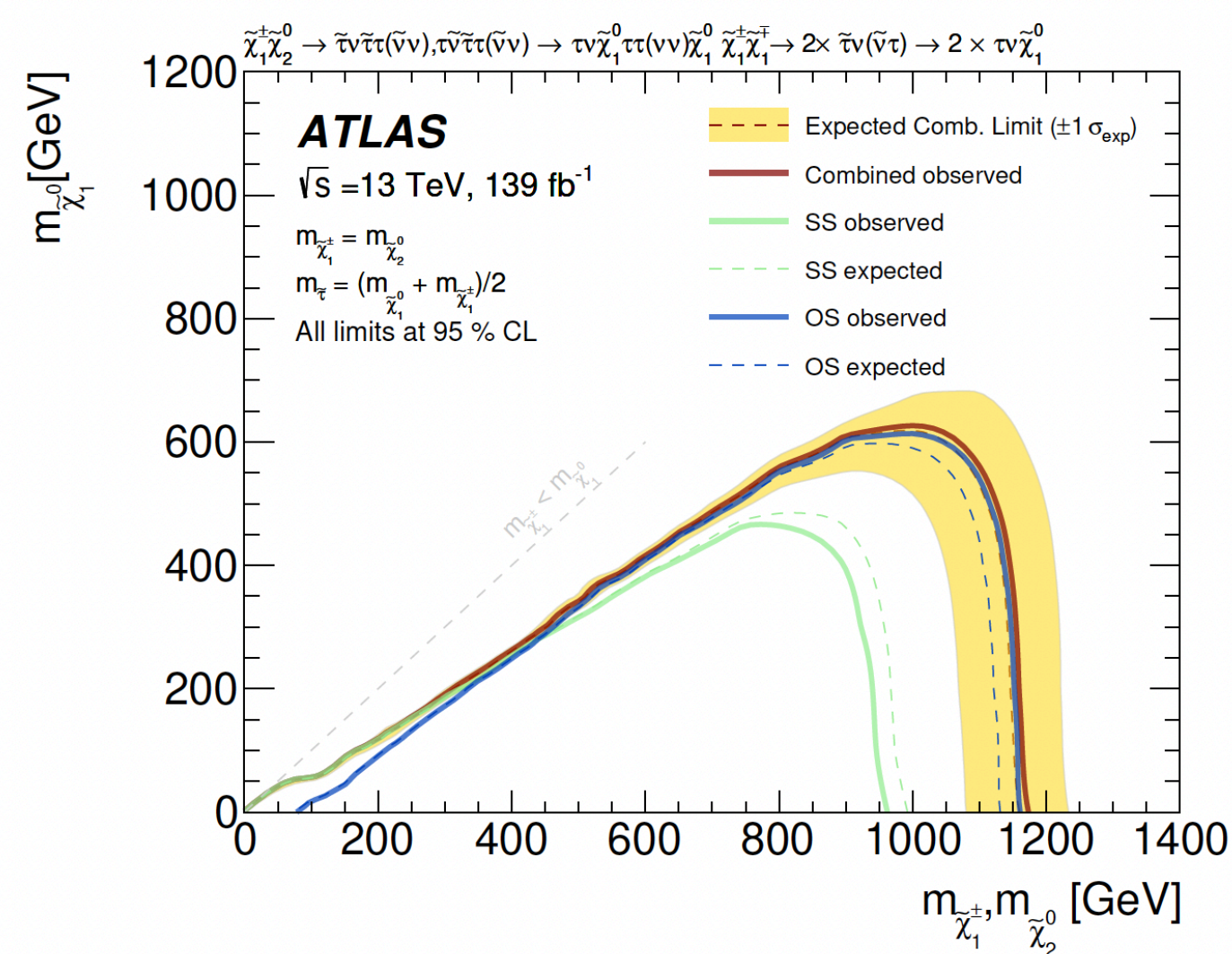


3

Estimate background

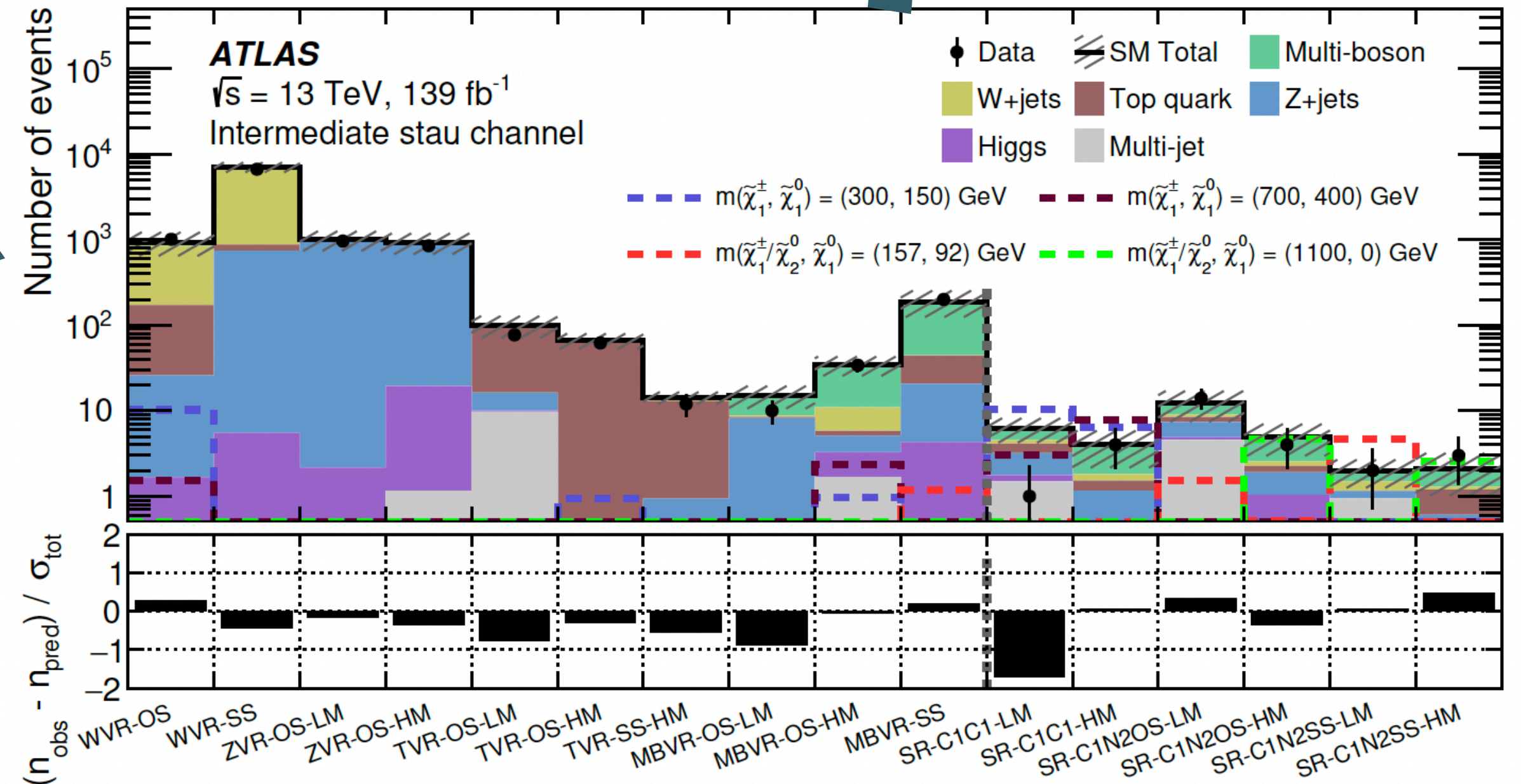


Examples from Phd work in: JHEP 05 (2024) 150



6

Statistical Interpretation



4

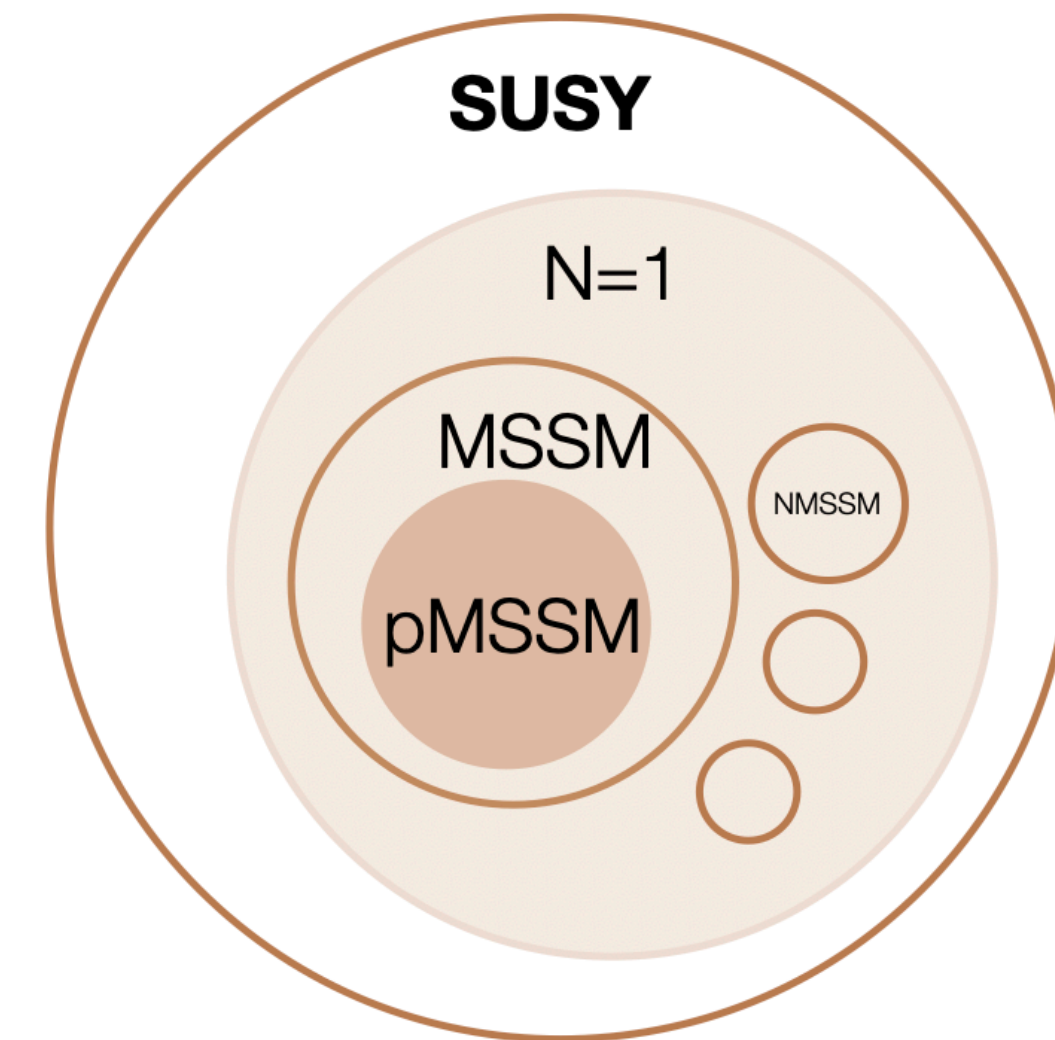
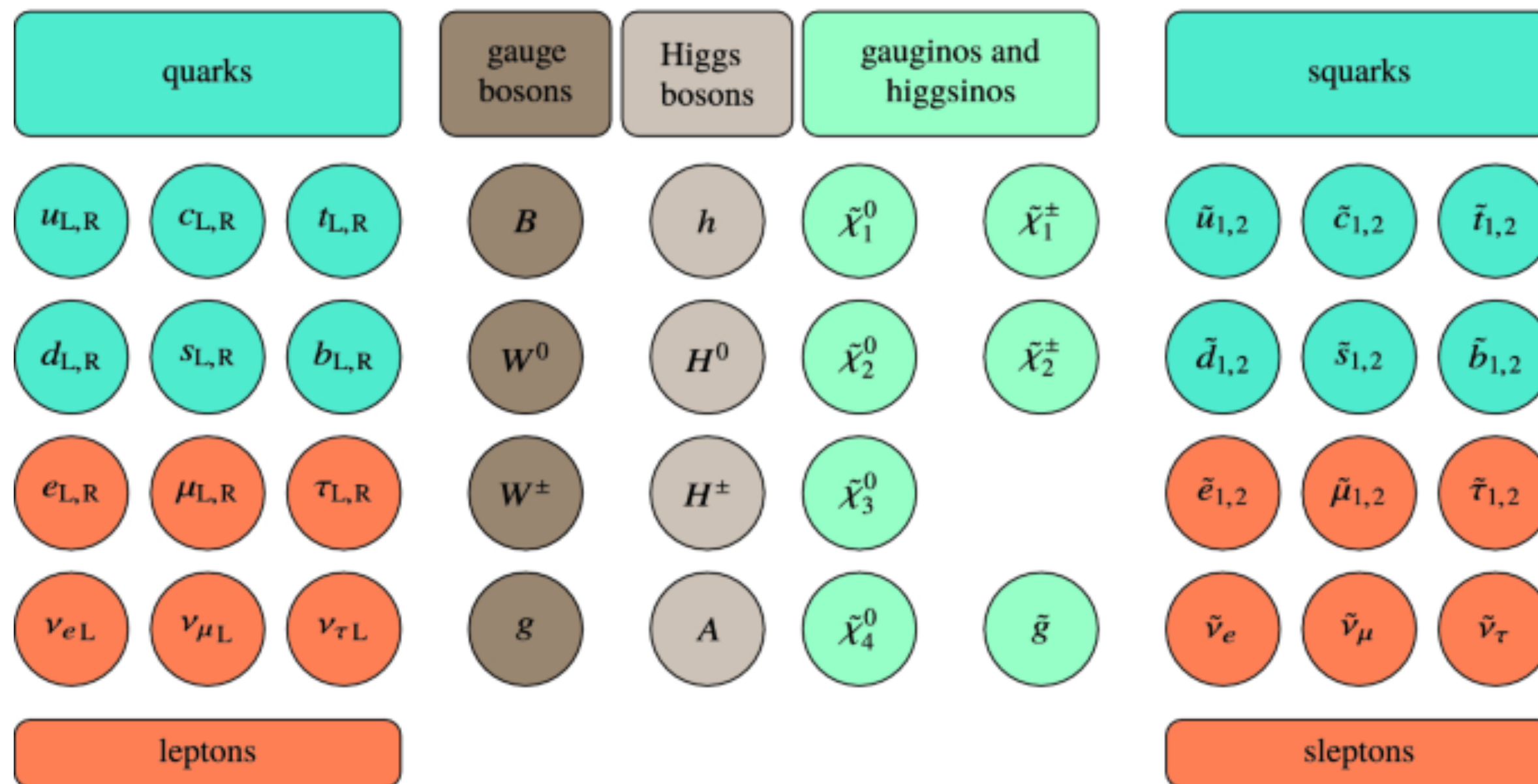
Validate

5

Unblind

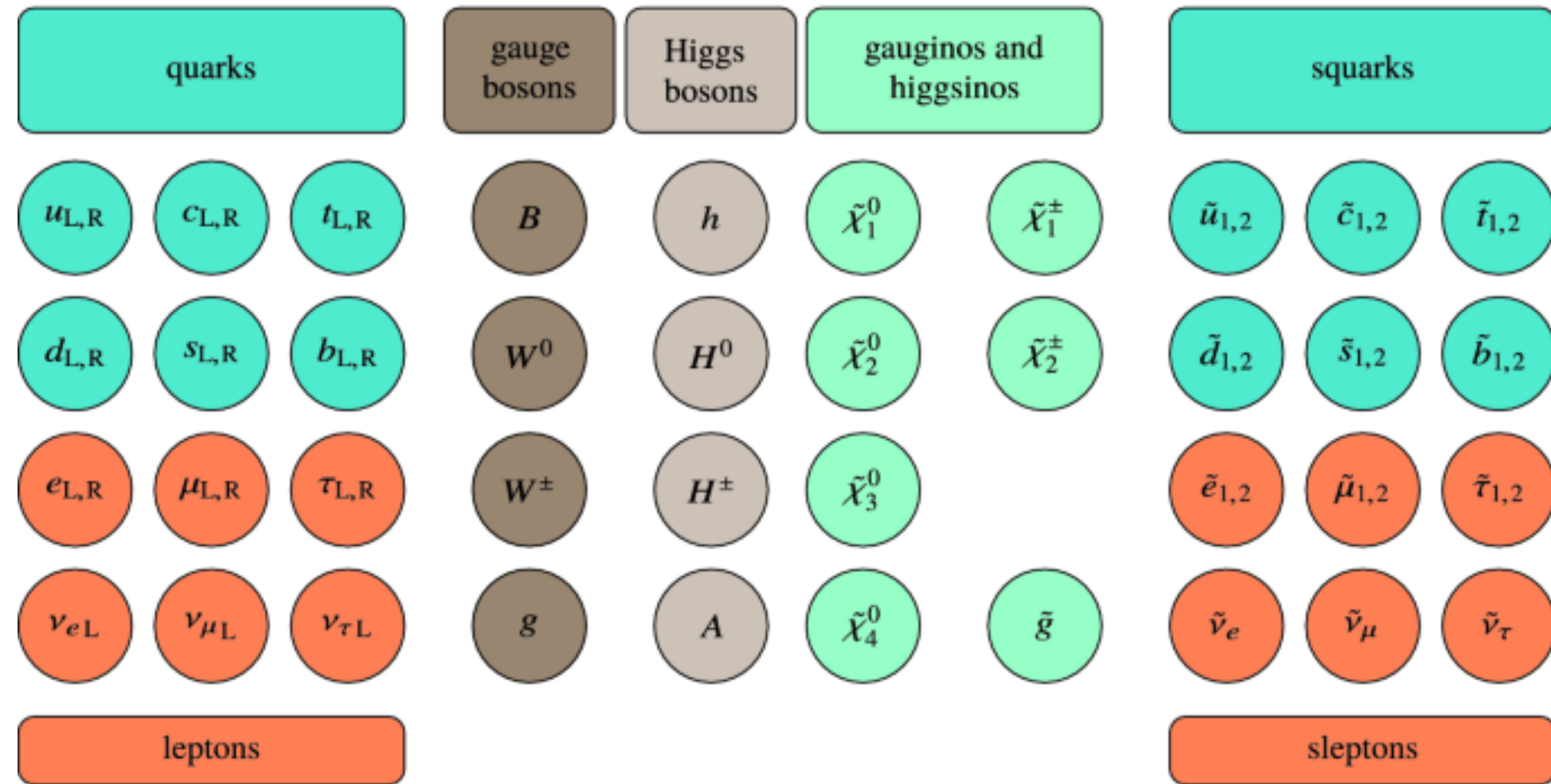
Supersymmetry (SUSY)

- Class of theories imposing additional symmetry between fermions and bosons to the SM, investigated since 70's
- Copy of SM particles with spin shifted by 1/2
- As unbroken symmetry would replicate SM particles



- Needs to be broken symmetry to be realized in nature

Particle spectrum in SUSY



$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^T \mathbf{M}_{\tilde{\chi}_j^0} \psi^0 + c.c,$$

with $\psi^0 = (\tilde{B}^0, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$

$$\mathcal{L}_{\text{chargino mass}} = -\frac{1}{2}(\psi^\pm)^T \mathbf{M}_{\tilde{\chi}_i^\pm} \psi^\pm + c.c,$$

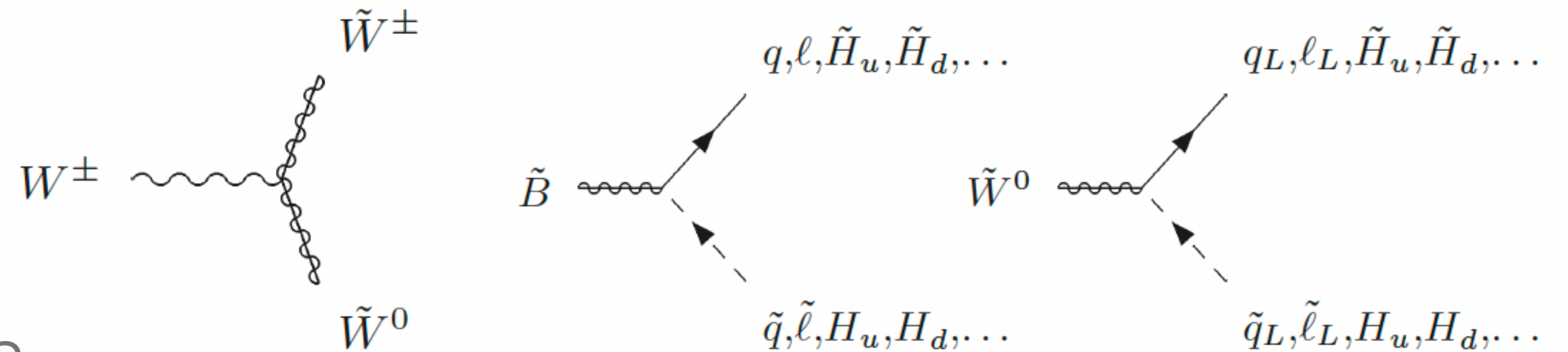
with $\psi^\pm = (\tilde{W}^\pm, \tilde{H}_u^\pm, \tilde{W}^\mp, \tilde{H}_d^\mp)$

$$\mathbf{M}_{\tilde{\chi}_i^0} = \begin{pmatrix} M_1 & 0 & -g'v_d/\sqrt{2} & g'v_u/\sqrt{2} \\ 0 & M_2 & gv_d/\sqrt{2} & -gv_u/\sqrt{2} \\ -g'v_d/\sqrt{2} & gv_d/\sqrt{2} & 0 & \mu \\ g'v_u/\sqrt{2} & -gv_u/\sqrt{2} & -\mu & 0 \end{pmatrix}$$

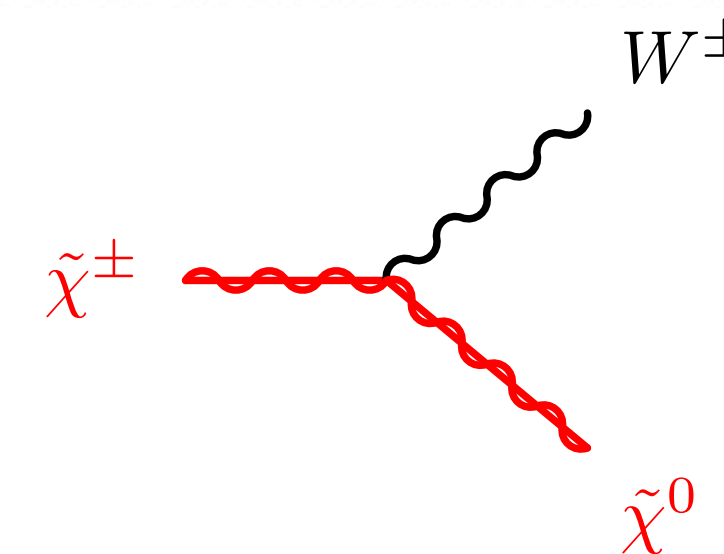
$$\mathbf{M}_{\tilde{\chi}_j^\pm} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix}, \text{ with } \mathbf{X} = \begin{pmatrix} M_2 & gv_u \\ gv_d & \mu \end{pmatrix}$$

- Interactions dominated by underlying fields

Field vertices



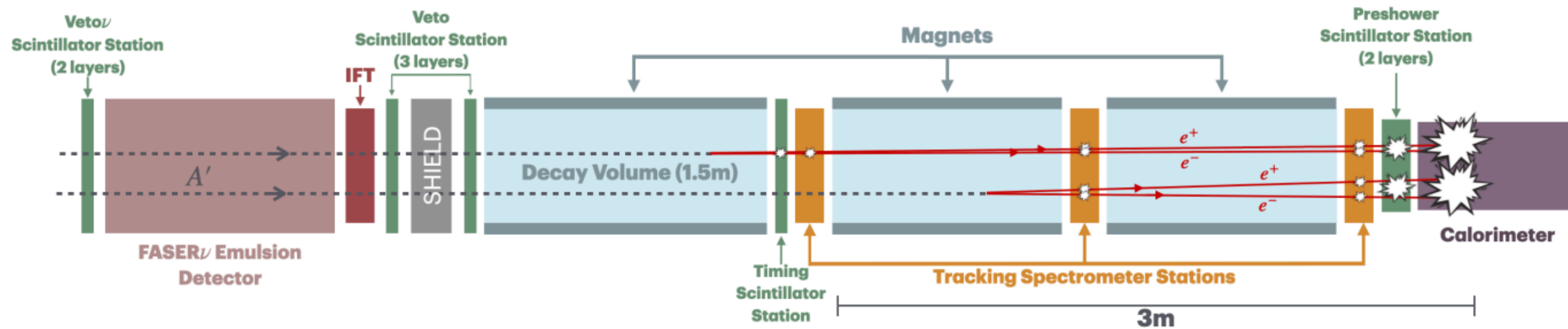
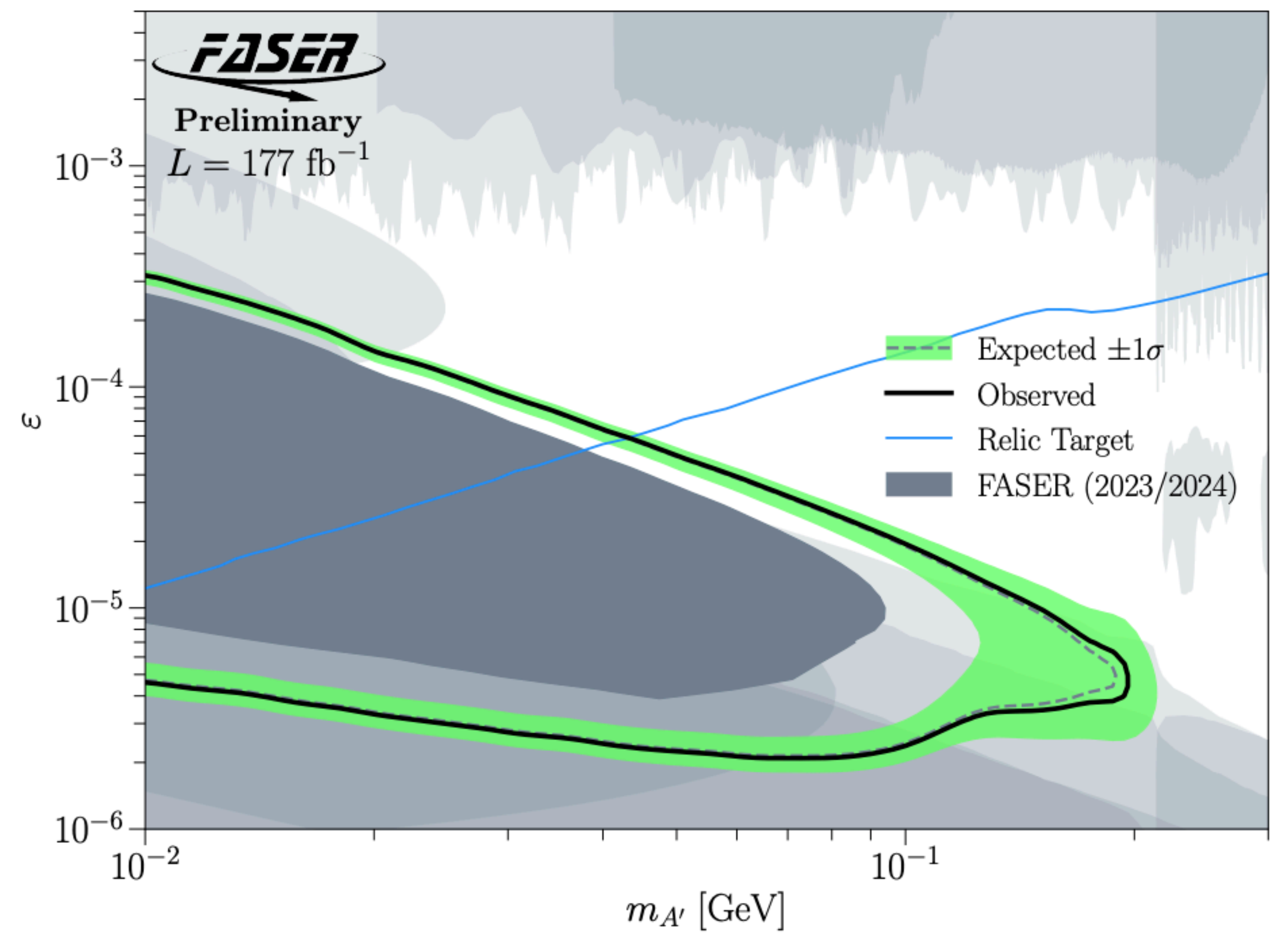
Particle interactions



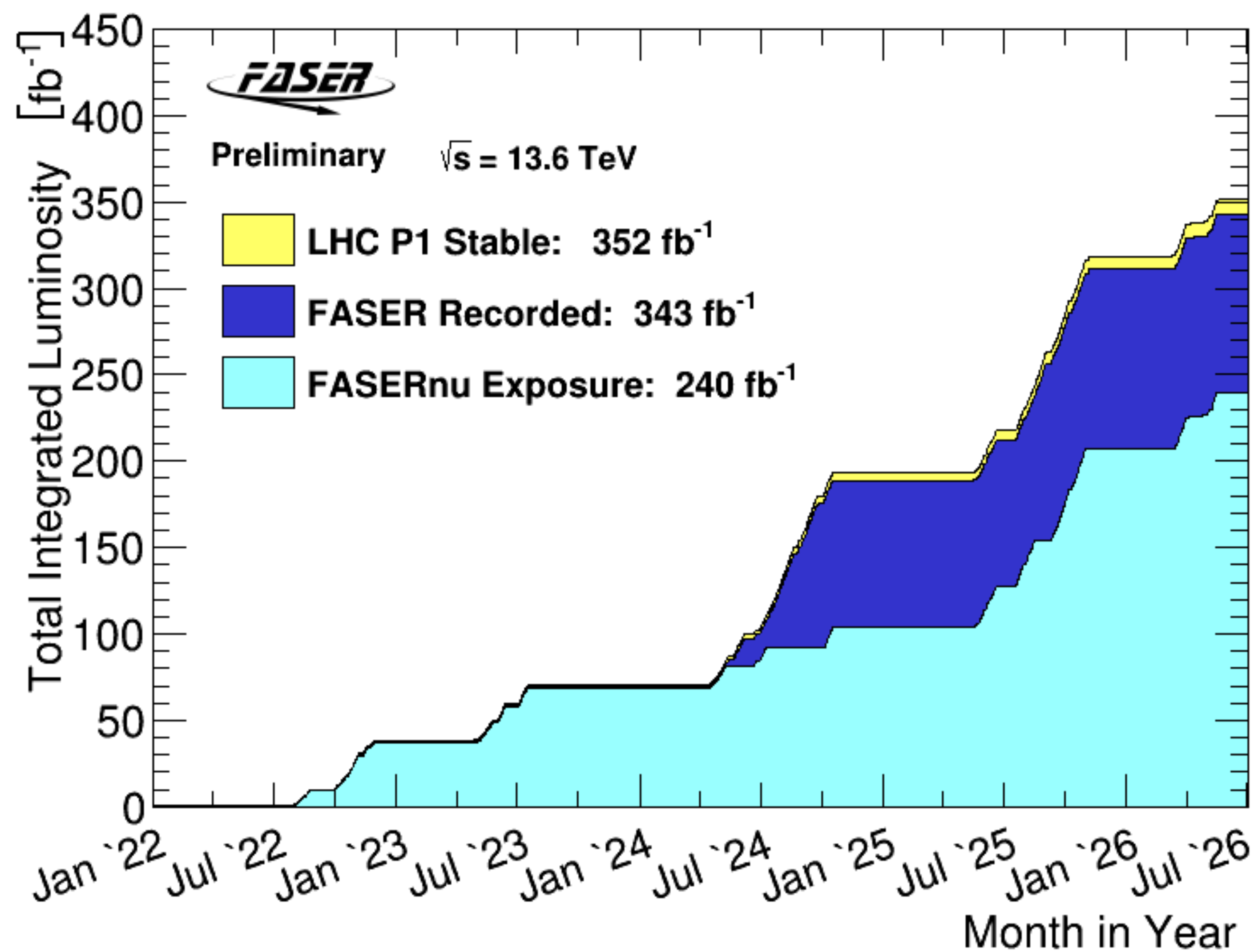
111t backup

Variable	Electron channel	Muon channel
Trigger		E_T^{miss}
E_T^{miss} [GeV]		> 200
Number of jets with $p_T > 20$ GeV		≥ 1
Leading jet p_T [GeV]		> 100
Number of b -tagged jets ($N_{b\text{-jet}}^{20}$)		$= 0$
Number of signal leptons ($N_{\text{sig-lep}}$)	$= 1$ (electron)	$= 1$ (muon)
Lepton p_T [GeV]	[4.5, 10]	[3, 10]
Lepton $ z_0 \sin \theta $ [mm]		< 0.5
Lepton $ d_0/\sigma(d_0) $	< 5	< 3
Number of tracks		≥ 1

Latest Dark
Photon search -
2022-2024 data



Emulsion data taking



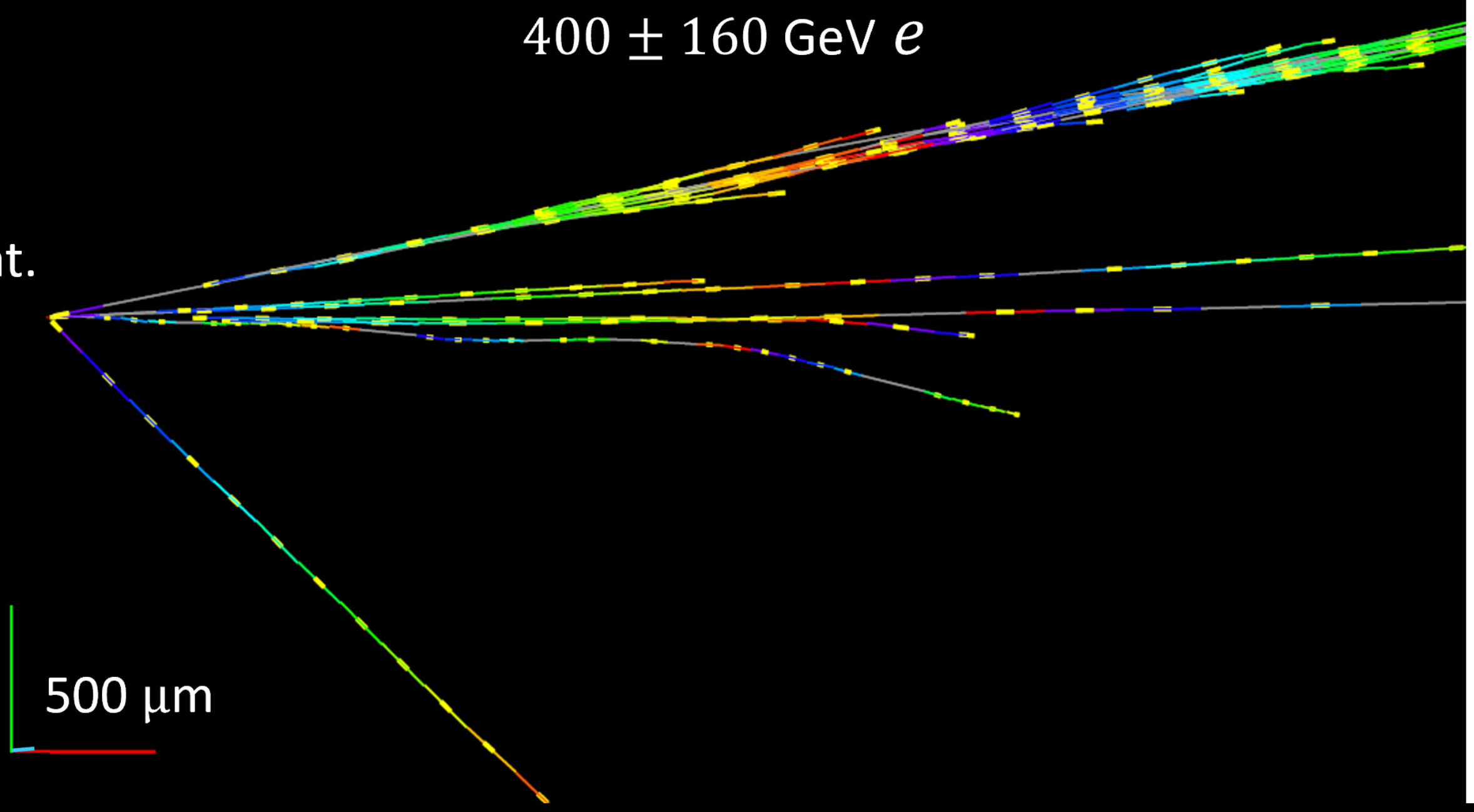


Preliminary

$400 \pm 160 \text{ GeV } e$

$\nu \text{ int.}$

500 μm

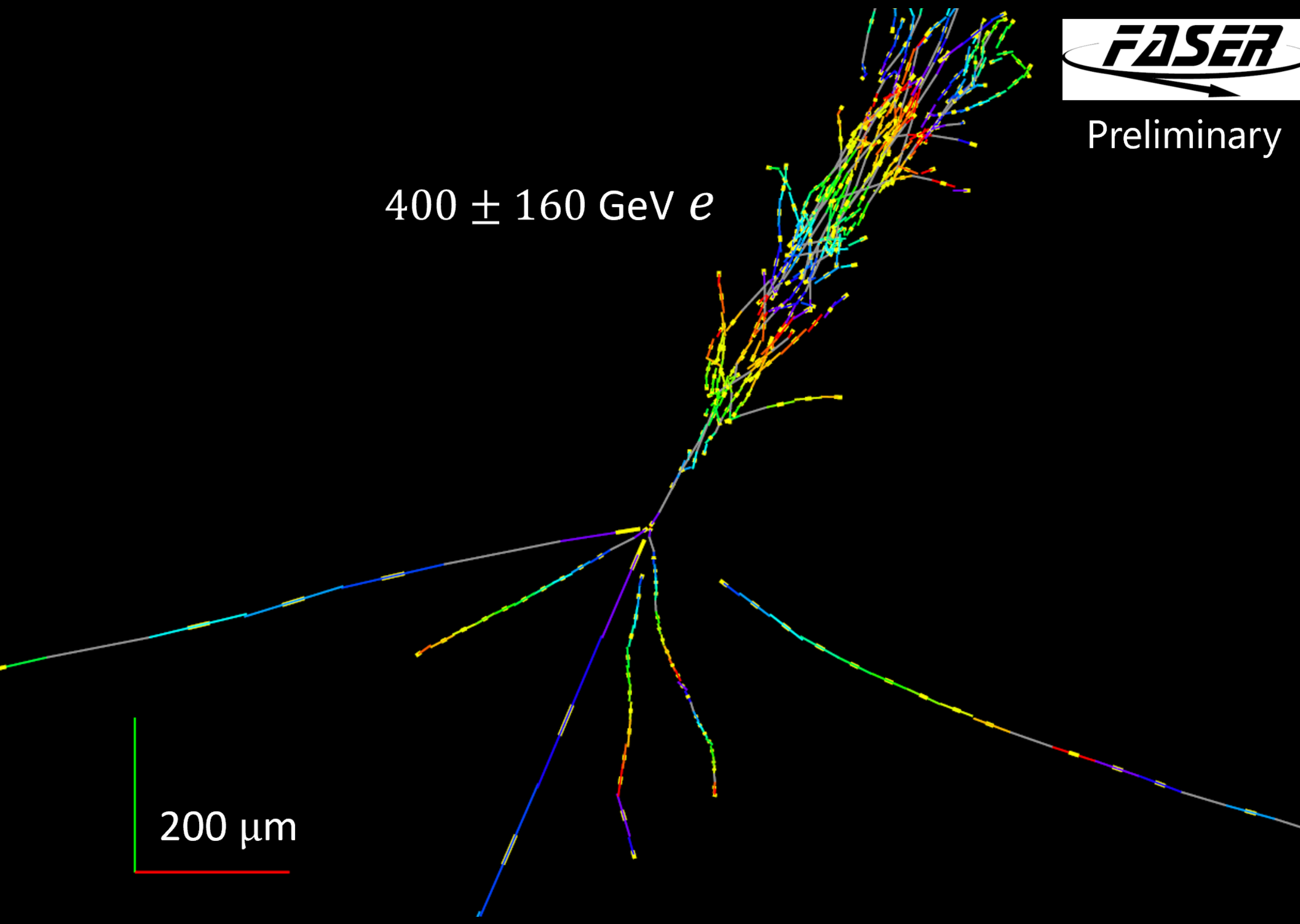


$400 \pm 160 \text{ GeV } e$

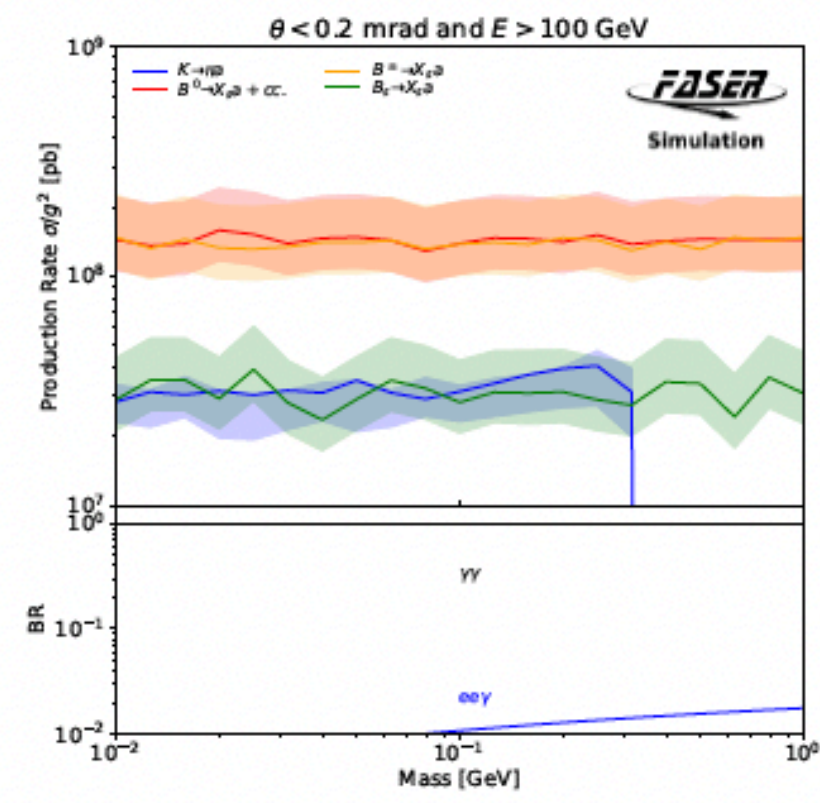


Preliminary

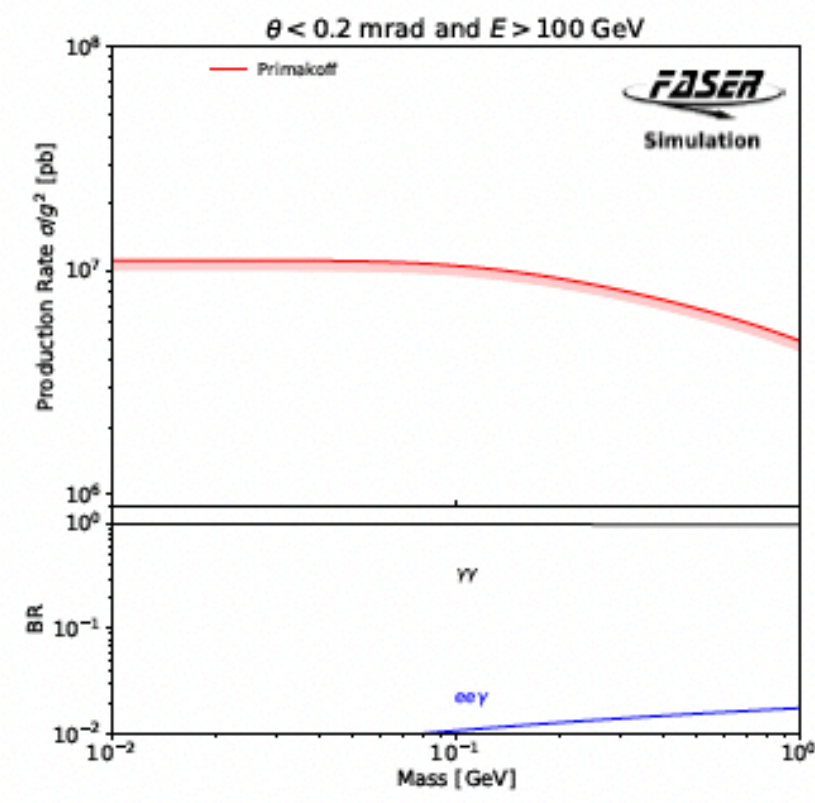
200 μm



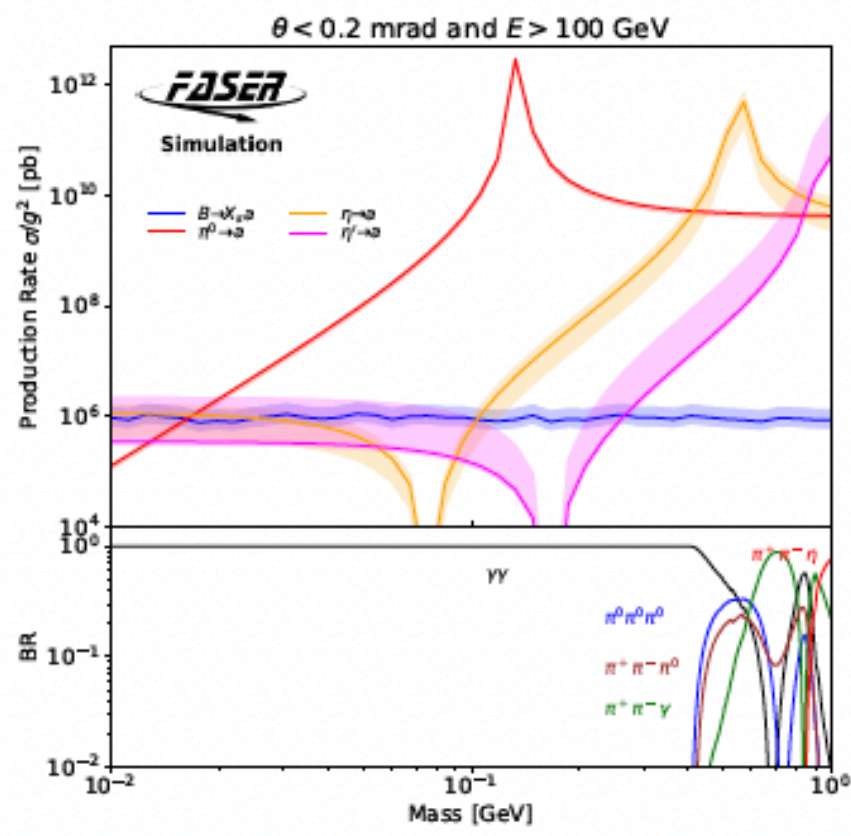
Updated results of high-energy electron and muon neutrino interactions with FASER's emulsion detector at the LHC



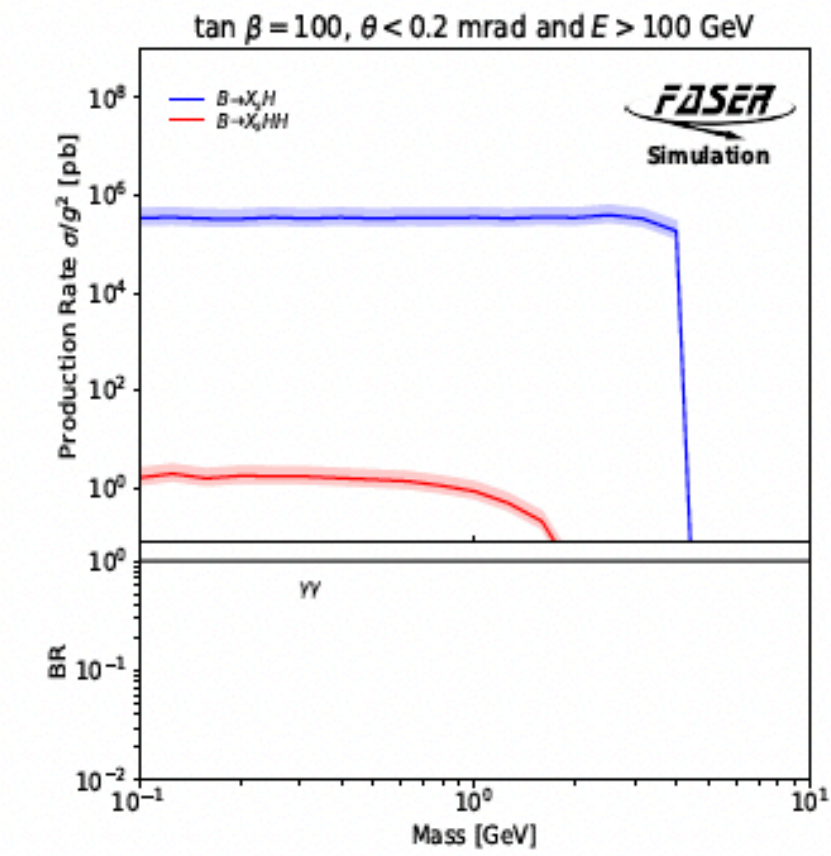
(a) ALP-W



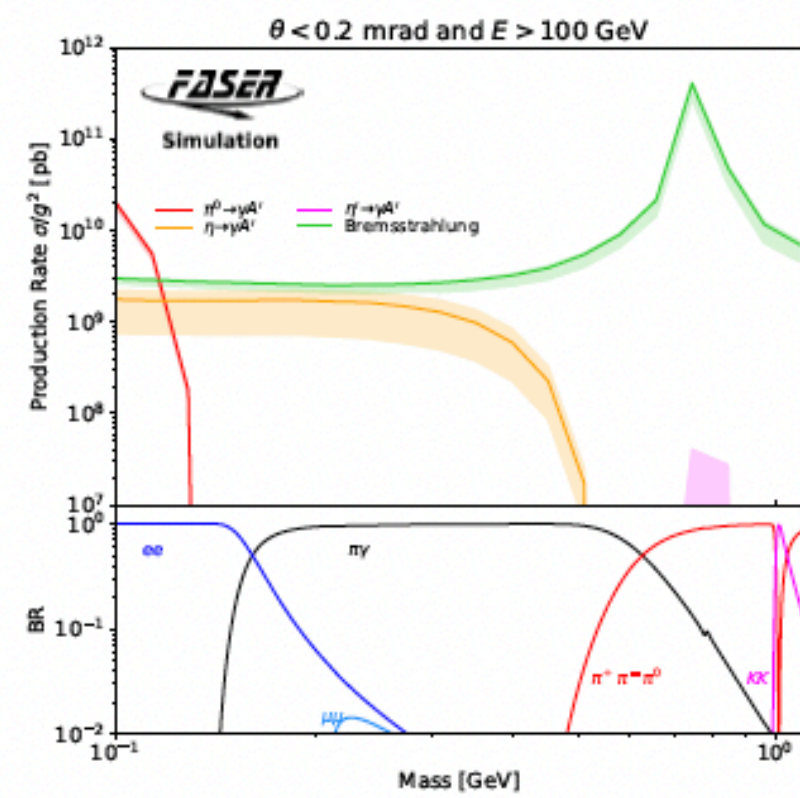
(b) ALP-photon



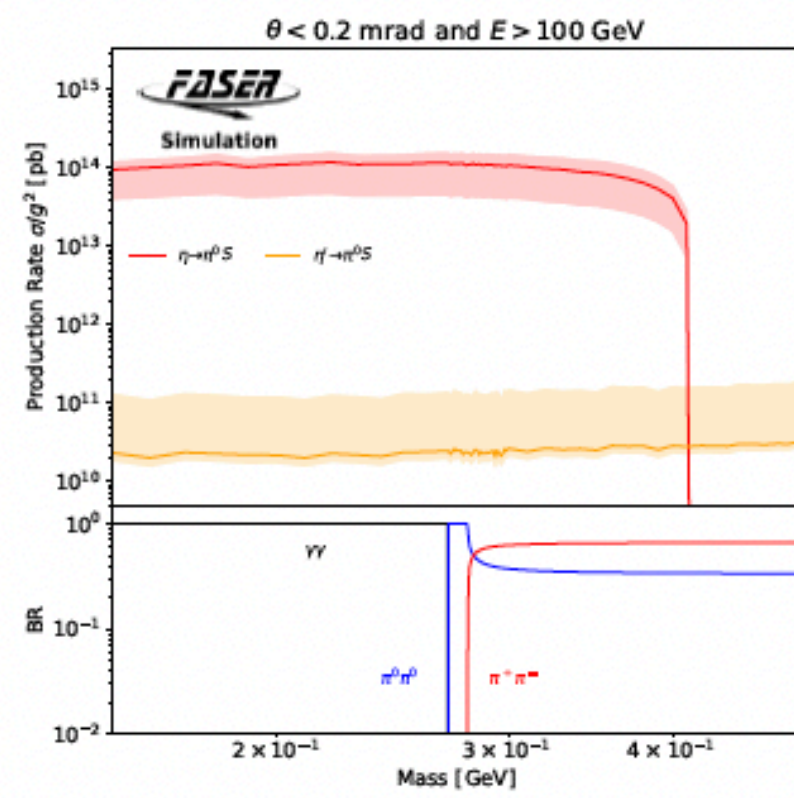
(c) ALP-gluon



(d) 2HDM (type-I)



(e) U(1)_R



(f) U_P-philic scalar