Probing Muon g-2 at forward detectors at LHC

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DPF-Pheno 2024
May 16th, 2024

(With Max Fieg)

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One page summary

- Huge flux of muons in the forward direction at LHC.
- So far they were treated as a backgrounds at FASER.
- But we can also use it to study new physics.
- With FASER's capabilities and just 1 year of data (2025), FASER can probe the muon (g-2) band.

Muon (g-2) puzzle

- The Fermilab Muon (g-2) collaboration reported a value for $(g-2)_\mu$ that agrees with the old Brookhaven result (2308.06230).
- (Fermilab + Brookhaven) result differ from SM prediction by 4.2 σ!!!

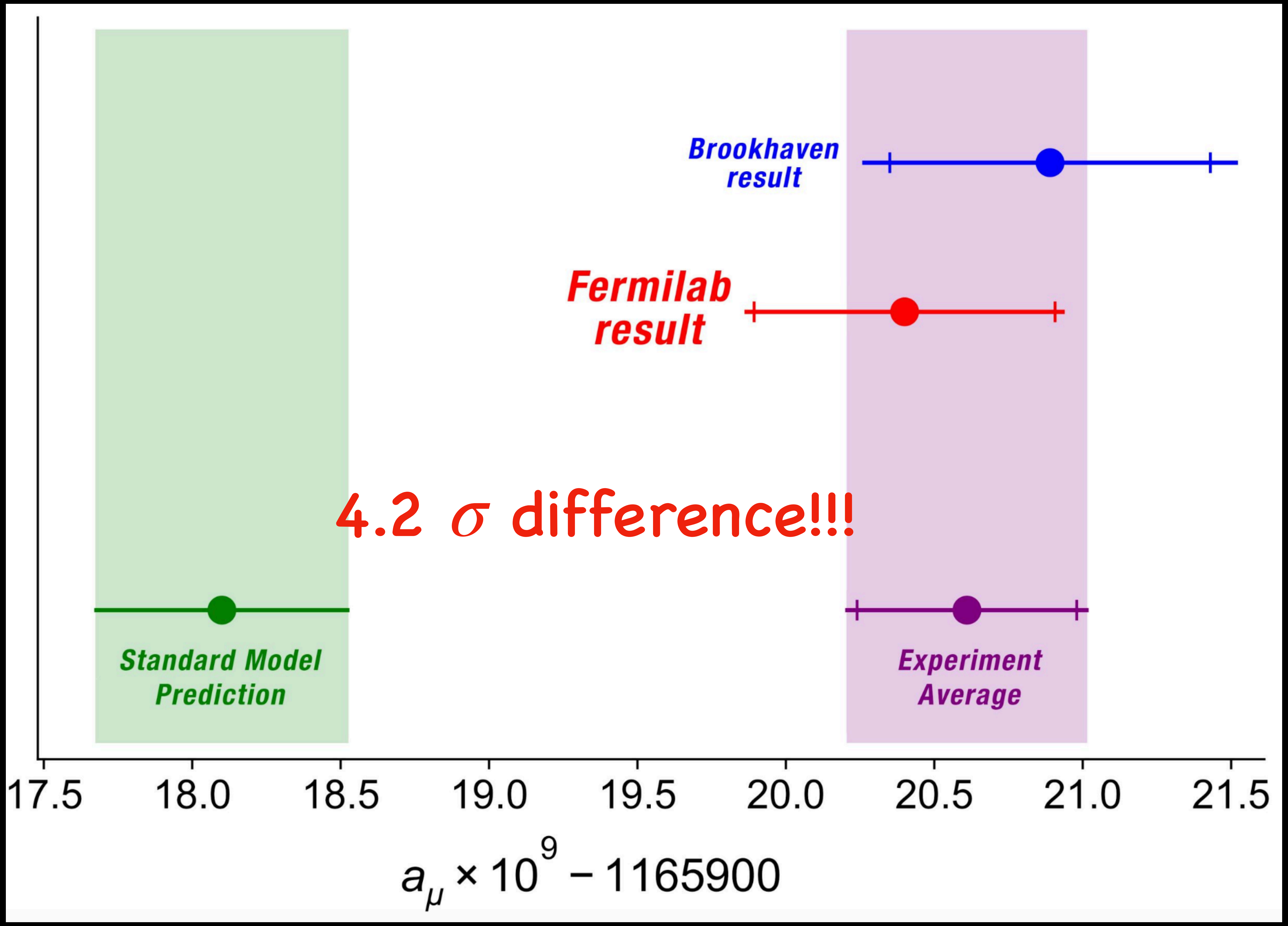


Image from here
Ryan Postel, Fermilab/Muon g-2 collaboration

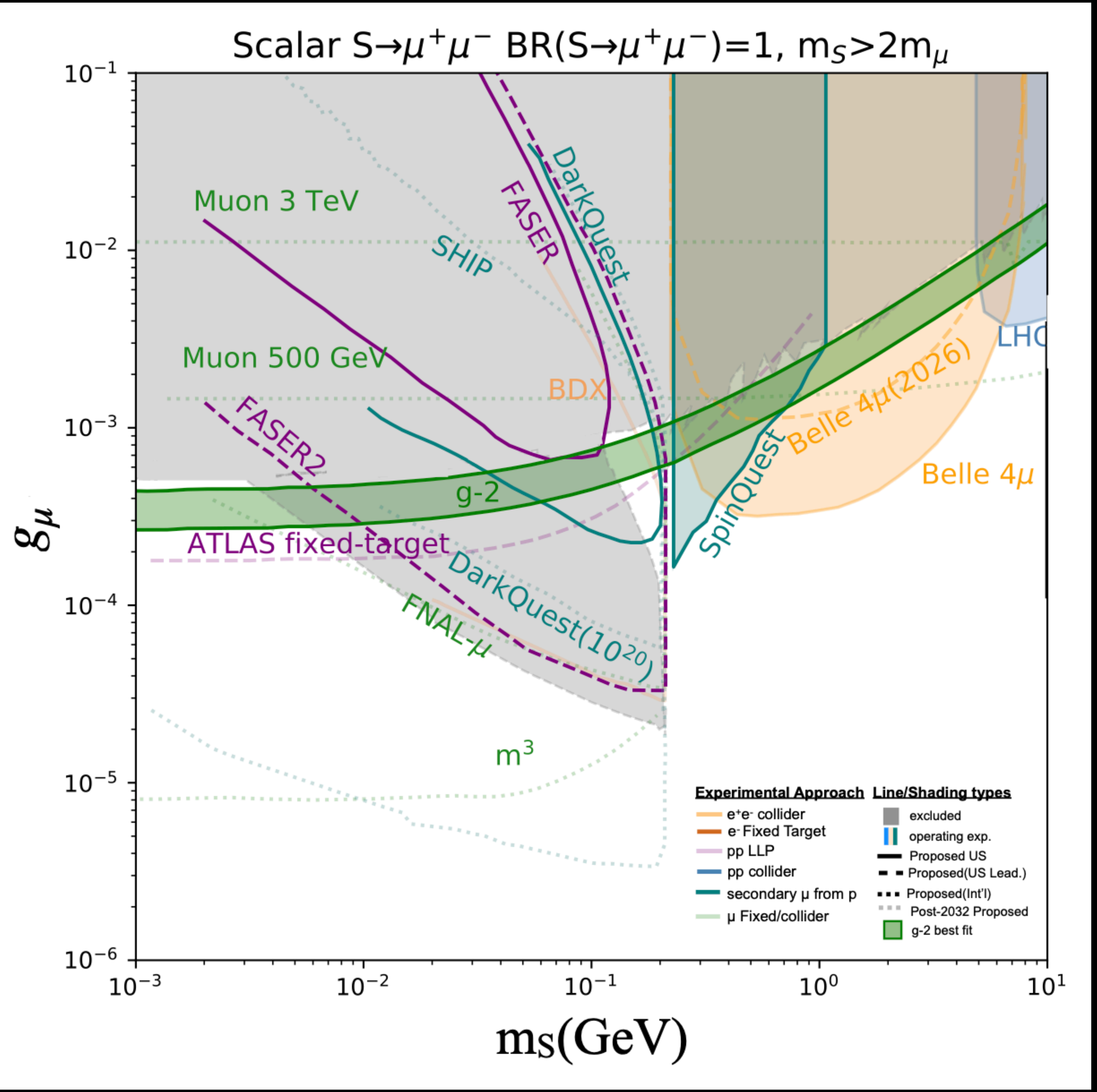
Simple model with a muonphilic scalar

- A SM singlet scalar, S, that couples only to the muons.
- $\mathscr{L} \supset \frac{1}{2}\left(\partial_\nu S\right)^2 - \frac{1}{2}m_S^2 S^2 - g_S S\bar{\mu}\mu$
- Contribution to $\Delta a_\mu = \left(g-2\right)_\mu/2$ is given by

$$\Delta a_\mu = \frac{g_\mu^2}{8\pi^2}\int_0^1 \mathrm{d}z \frac{(1-z)^2(1+z)}{(1-z)^2 + z(m_S/m_\mu)^2}$$

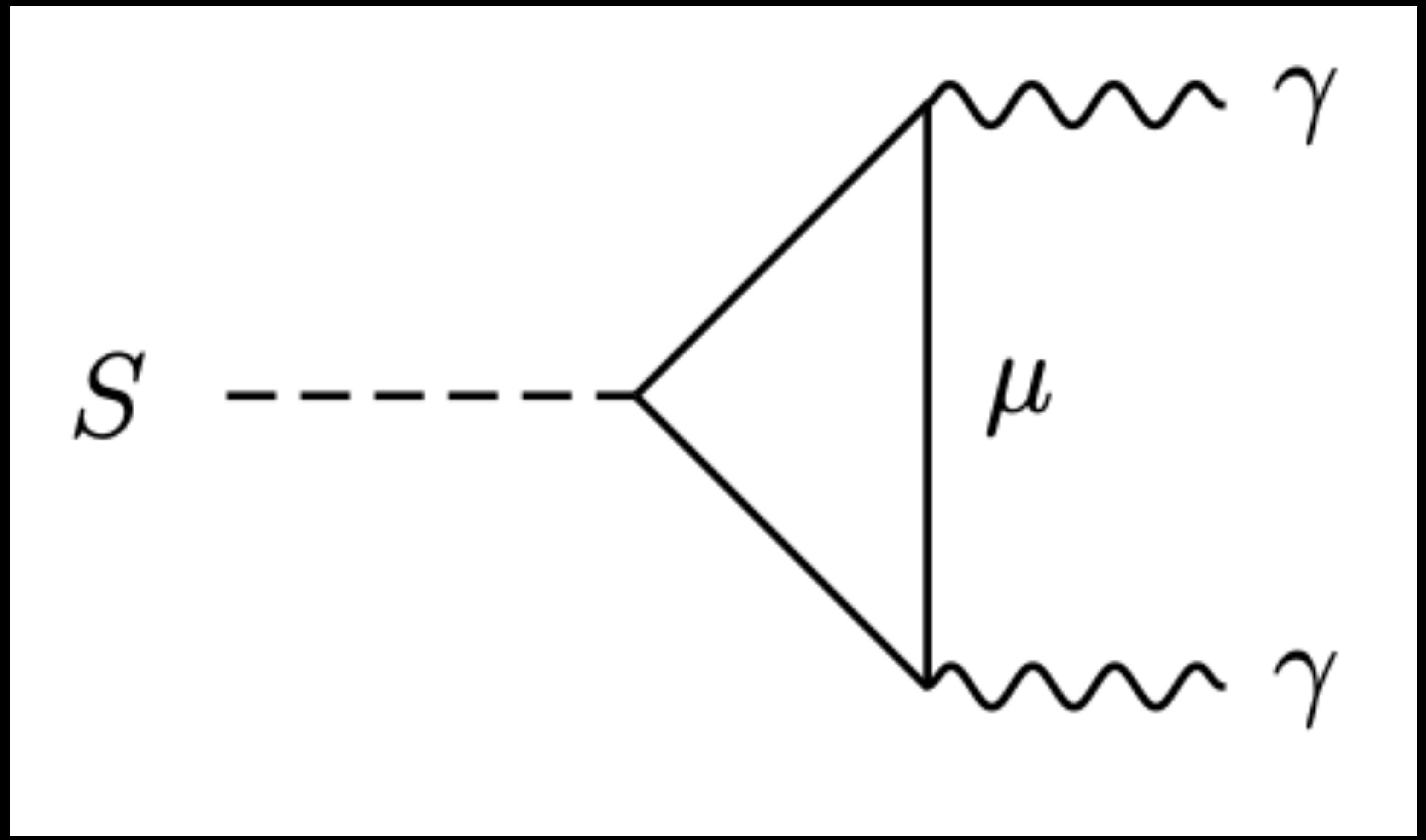
(1701.07437)

Simple model with a muonphilic scalar (Cont.)



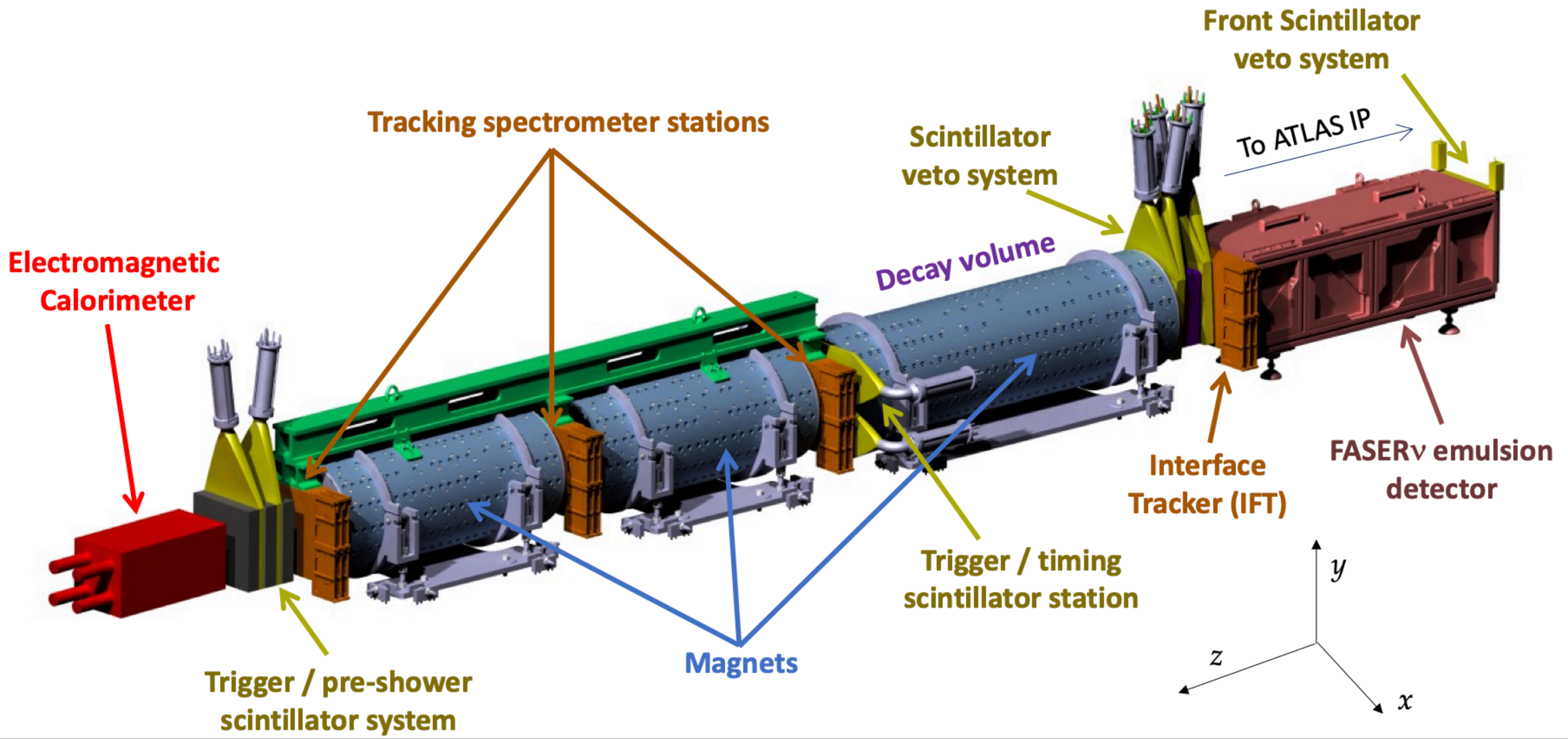
Snowmass White Paper: New flavors and rich structures in dark sectors
arXiv:2207.08990

- Current constraints miss a small region near $m_S \lesssim 2 * m_\mu$.
- For $m_S \lesssim 2 * m_\mu$, S decays to 2 photons.



ForwArd Search ExpeRiment(ν) - FASER(ν)

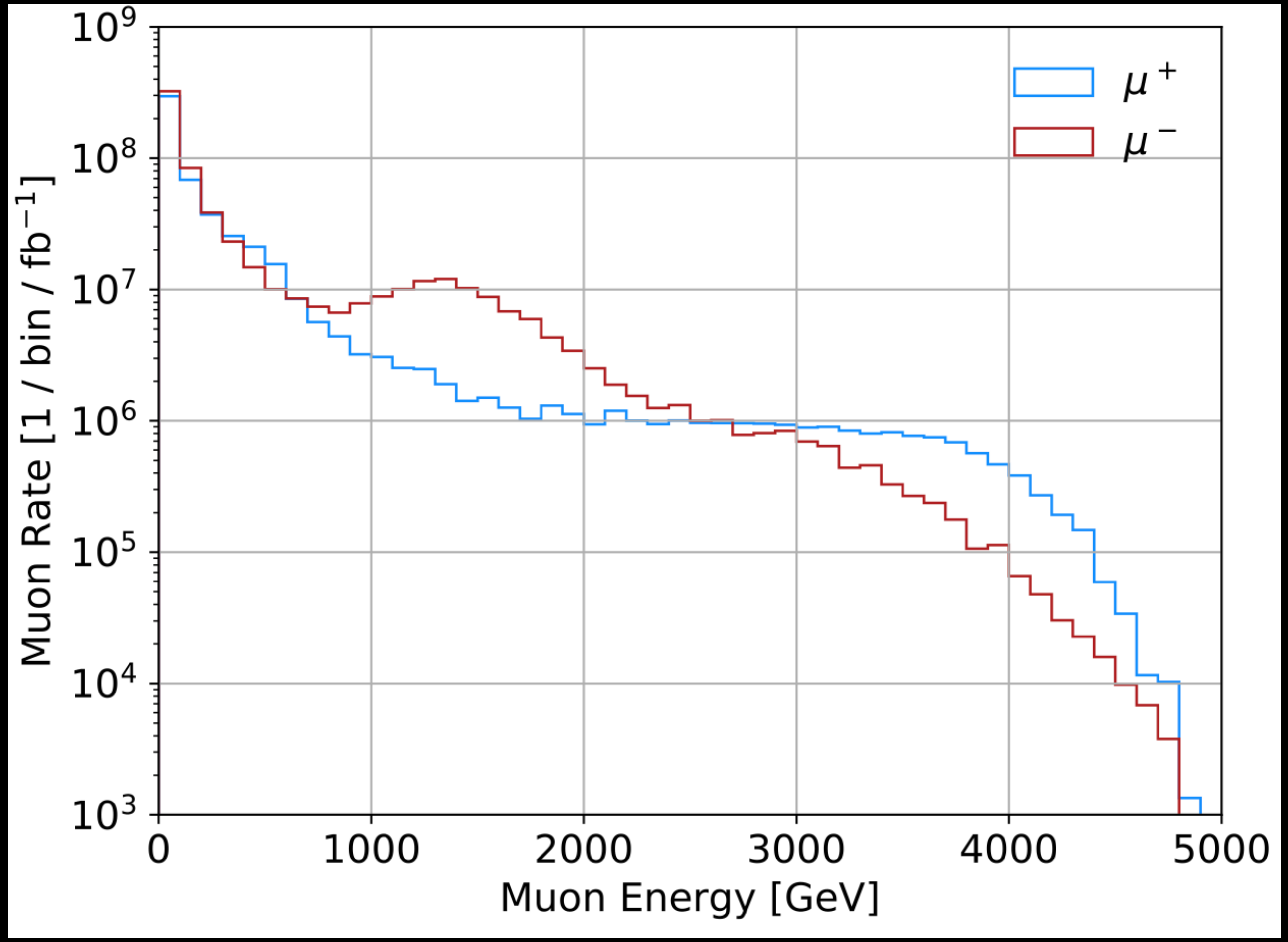
- FASER: 25cm x 25cm x 1m decay volume
  - 1708.09389 (first paper), 1811.10243 (LOI), 1812.09139
- FASERν: 25cm x 25cm x 1m tungsten emulsion detector
  - 1908.02310, 2001.03073



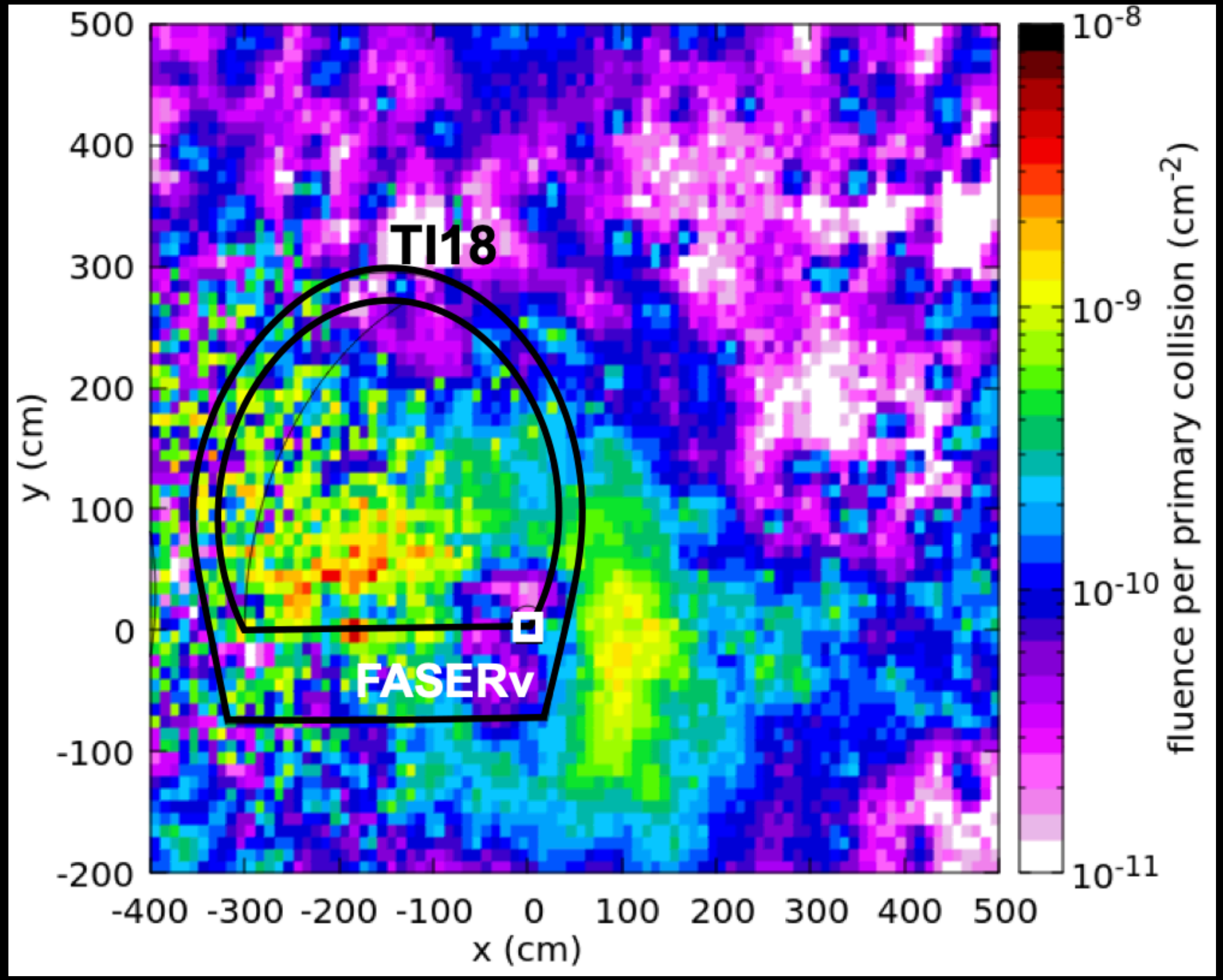
(For more on the forward detectors see the Minisymposium on forward physics.)

Muon flux in the Forward Direction at LHC

- Muons originate from the decays of mesons produced at the ATLAS IP.
- A very large of flux of muons pass through the FASER detector (~480 m from ATLAS IP).
- $N_\mu \sim 2 * 10^9$, through FASER during Run3!!!

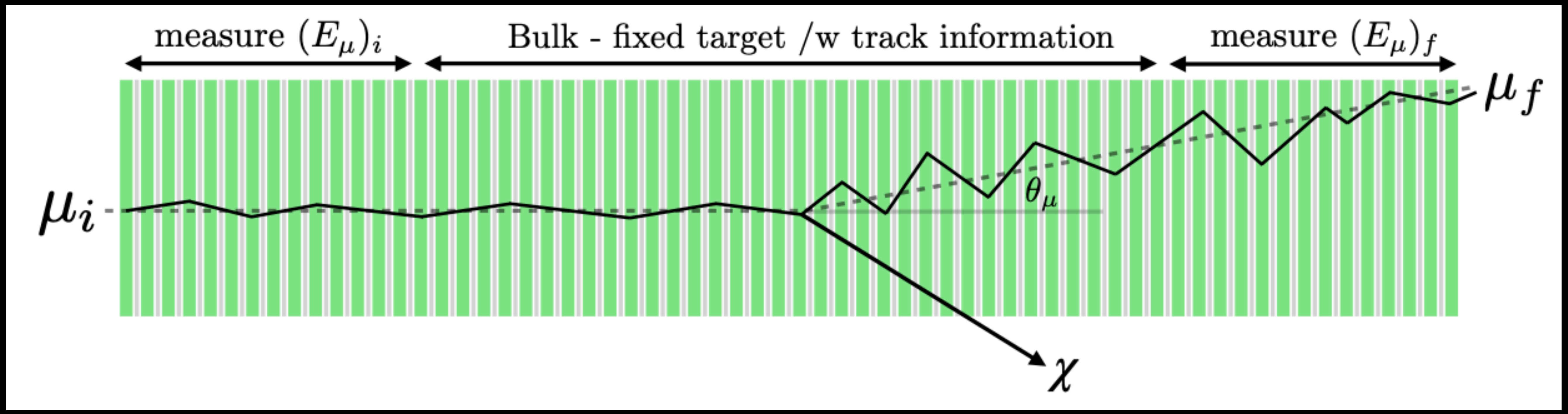


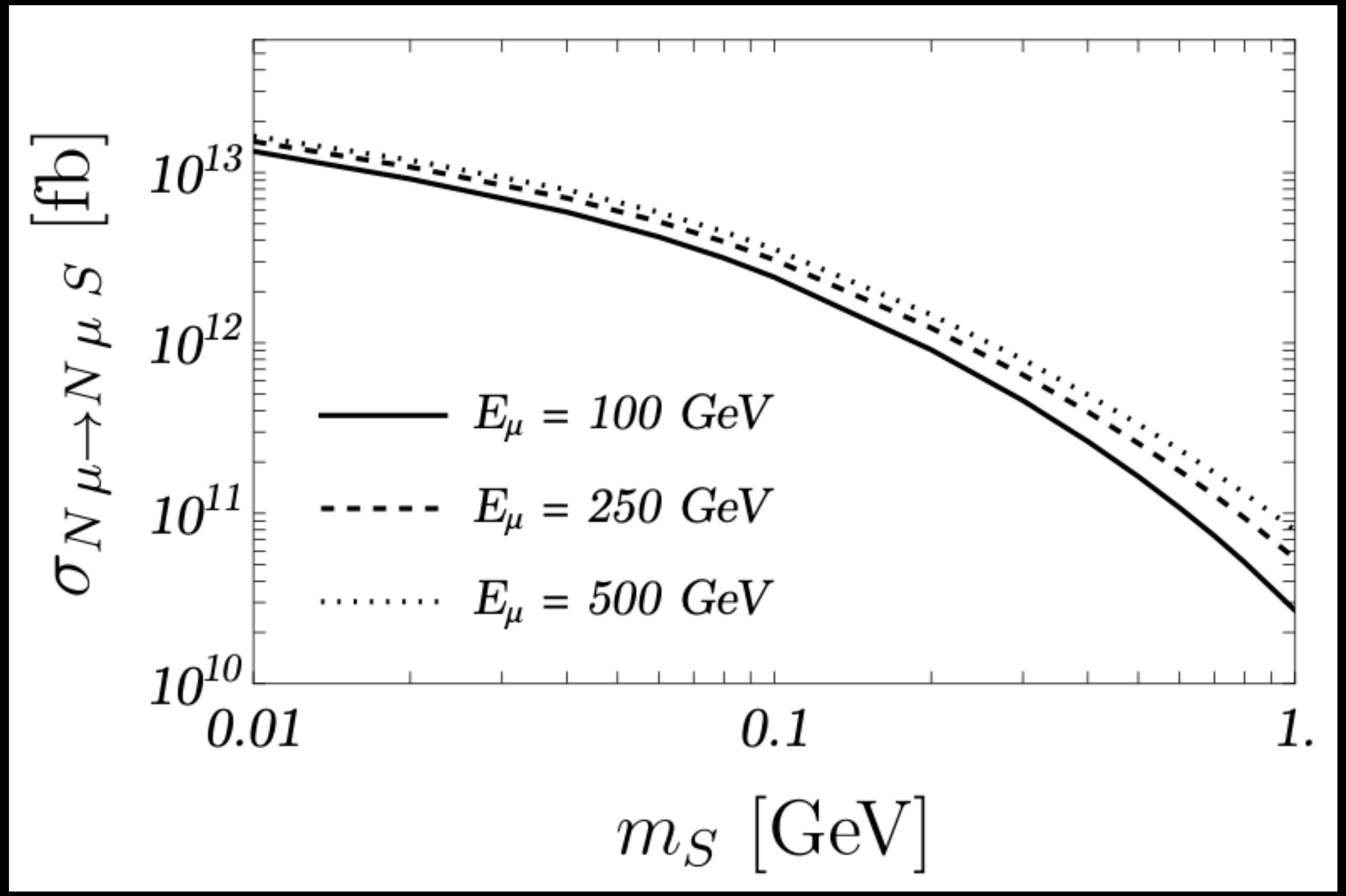
2105.06197



FASERν TP: 2001.03073

Using $FASER\nu$ emulsion detector





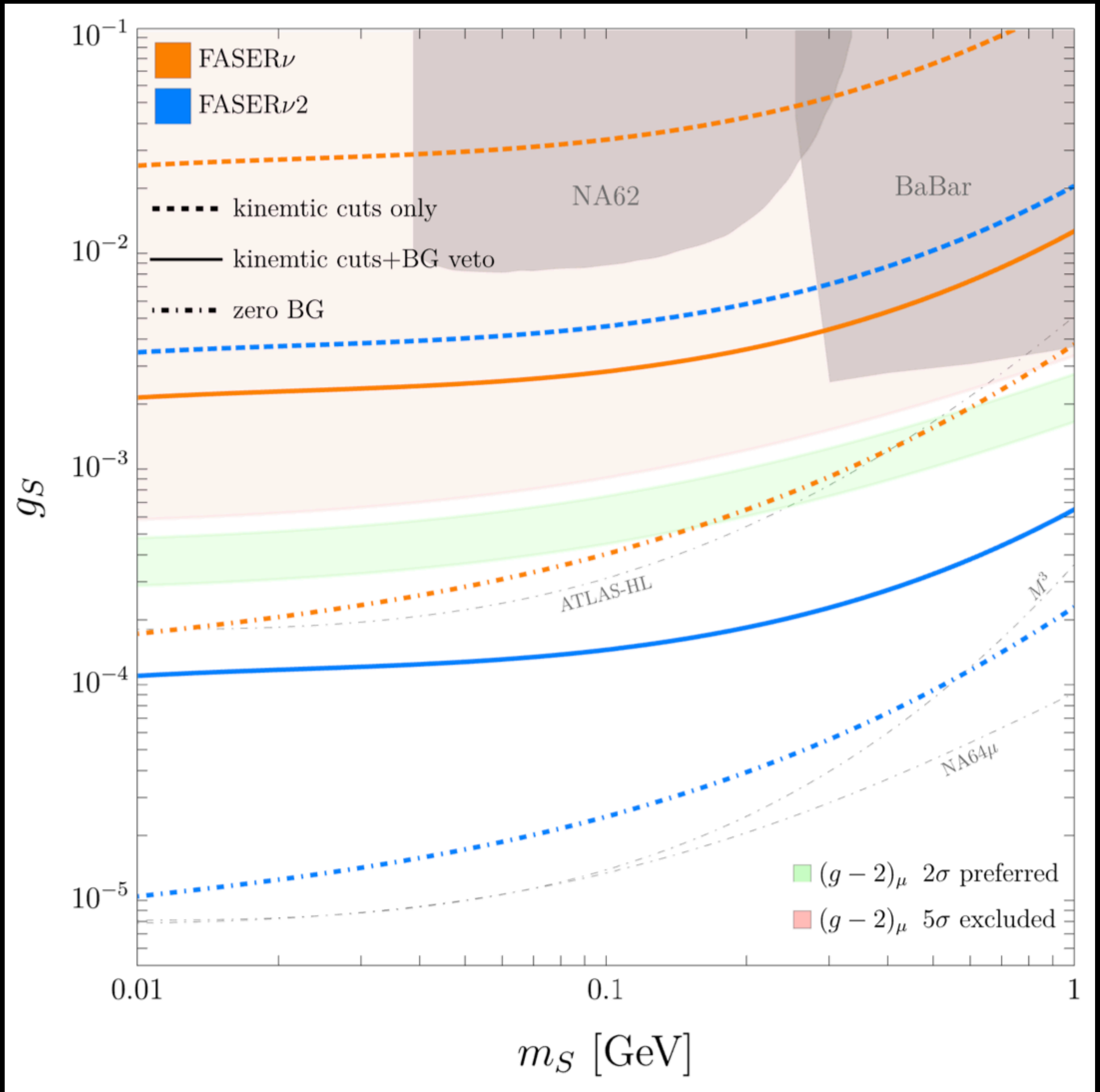
Backgrounds:

$$N + \mu \to \begin{cases} N + \mu + e^- + e^+ & \text{(Pair production)} \\ N^+ + \mu + e^- & \text{(Ionization)} \\ N + \mu + \gamma & \text{(Bremsstrahlung)} \\ N^* + \mu + \ldots & \text{(Nuclear)} \end{cases}$$

Akitaka Ariga, Reuven Balkin, Iftah Galon, Enrique Kajomovitz, Yotam Soreq
2305.03102

Using $FASER\nu$ emulsion detector (cont.)

- Muon (g-2) band only probed in the 0 background scenario at $FASER\nu$.
- Replacing and scanning emulsion is a resource intense exercise.
- Can we take advantage of visible decays of S in FASER detector?



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Method 1: 3 body decays

- Scalar decays via W 1206.3587

$$\frac{d\mathrm{BR}(K \to \mu\nu S)}{dE_S dQ^2} = \frac{m_K y^2 \times \mathrm{BR}(K \to \mu\nu)}{8\pi^2 m_\mu^2 (m_K^2 - m_\mu^2)^2 (Q^2 - m_\mu^2)^2} \times \Big((m_K^2 - 2m_K E_S + Q^2) Q^2 (Q^2 - m_\mu^2) - (Q^4 - m_\mu^2 m_K^2)(Q^2 + m_\mu^2 - m_S^2) + 2m_\mu^2 Q^2 (m_K^2 - Q^2) \Big)$$

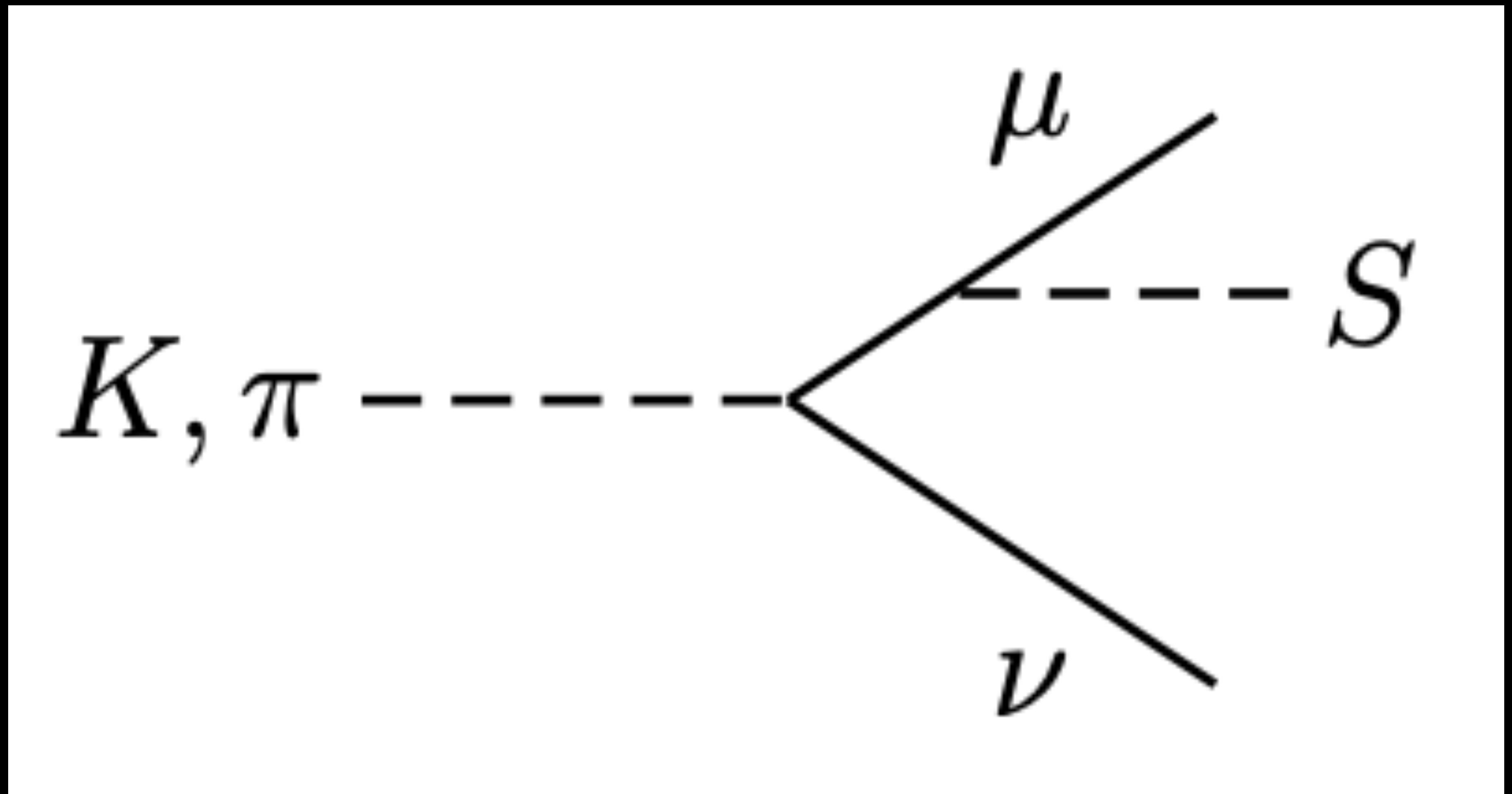
- Vector decays via γ 2103.08284

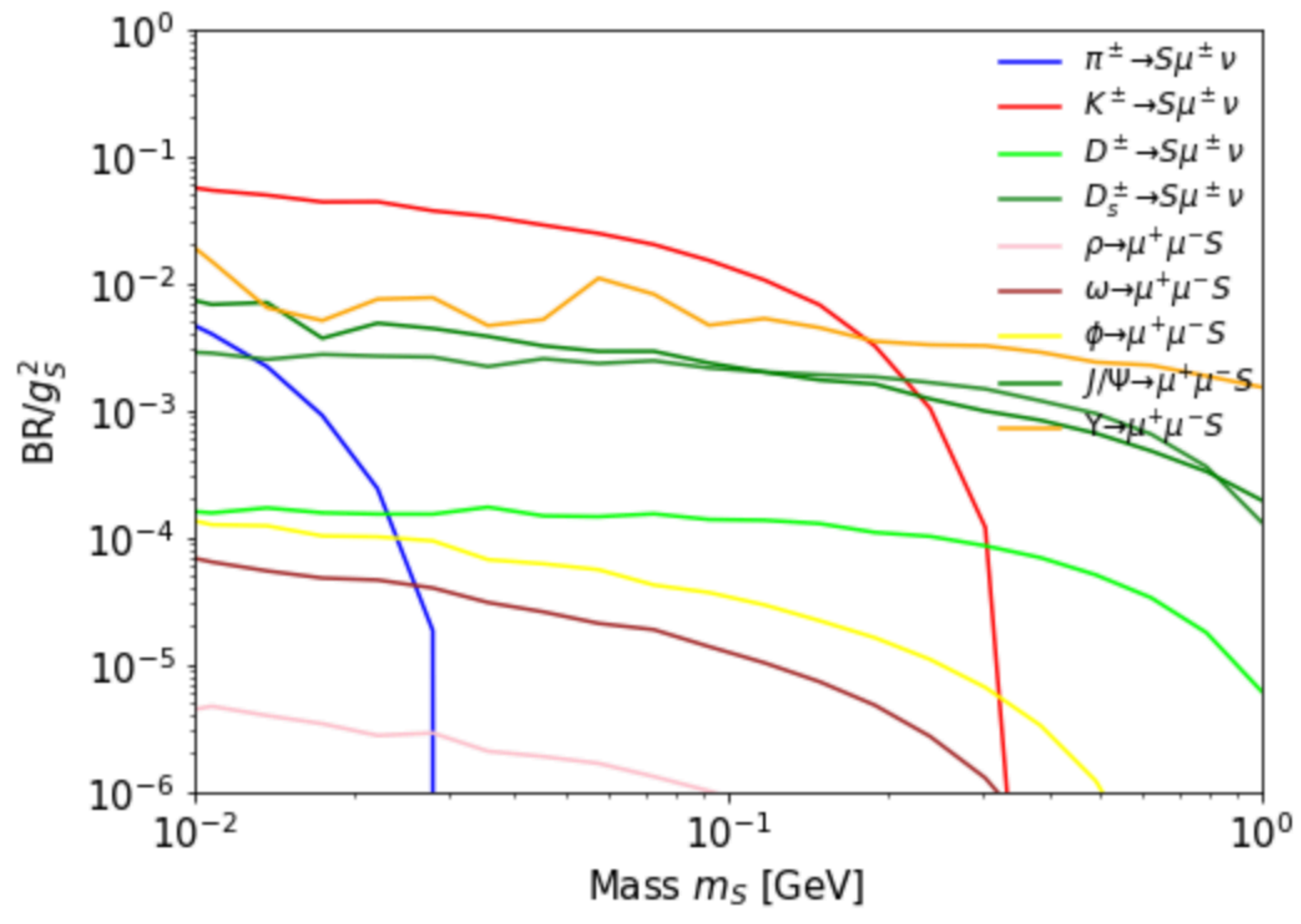
$$\frac{d^2\Gamma_{s^\pm}}{dt\,du} \equiv \frac{d^2\Gamma\,(J/\psi \to \mu^-\mu^+ X_{s^\pm})}{dt\,du} = \frac{\alpha^2\, g_{s\pm}^2\, f_J^2}{27\,\pi\, m_J^5\, Y} |A_{s^\pm}|^2$$

$$Y = (t - m_\mu^2)^2 (u - m_\mu^2)^2$$

Decay constant

Squared amplitude



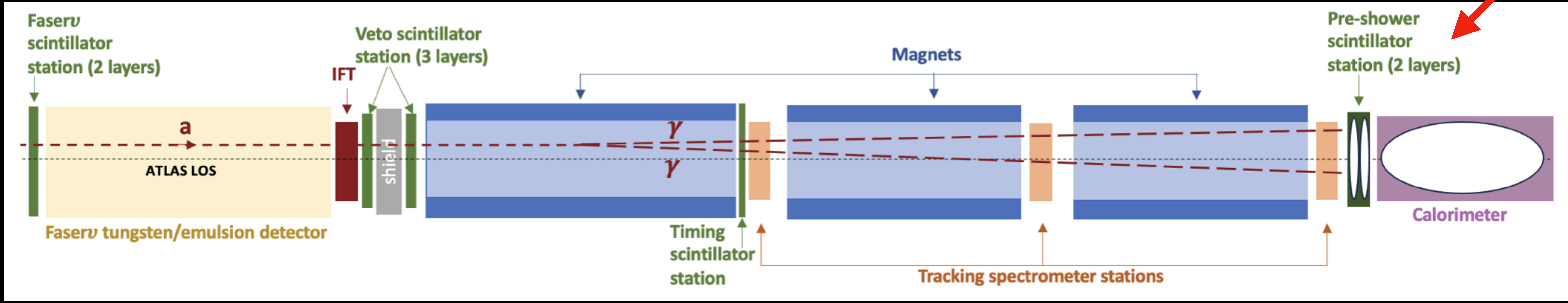


Implemented via FORESEE 2105.07077

Method 1: 3 body decays (cont.)

- The signal we expect is "no activity" with some energy deposition in the calorimeter.
- Very similar to FASER's ALPs analysis. (Conf note)
  - Their dominant background is from neutrino interactions.

ALP search at FASER

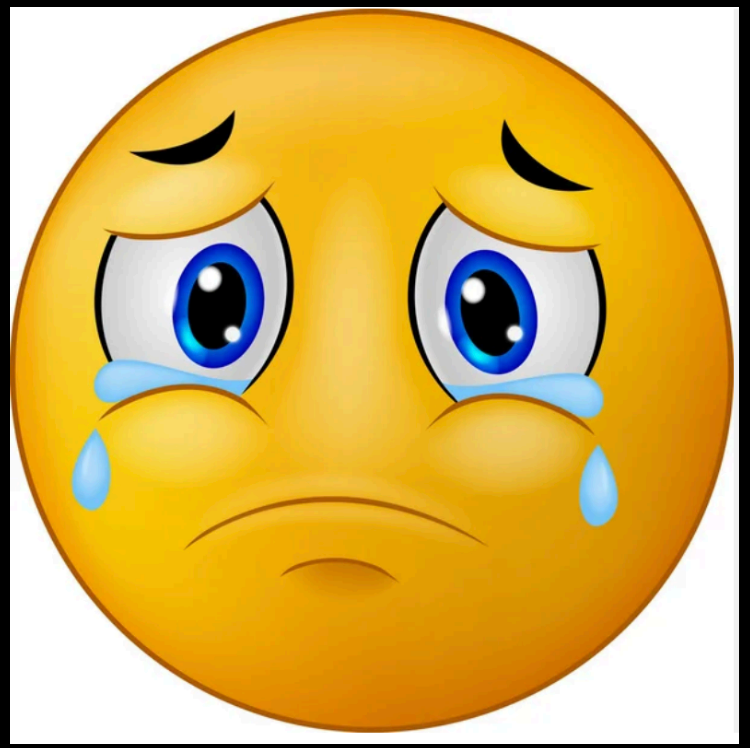


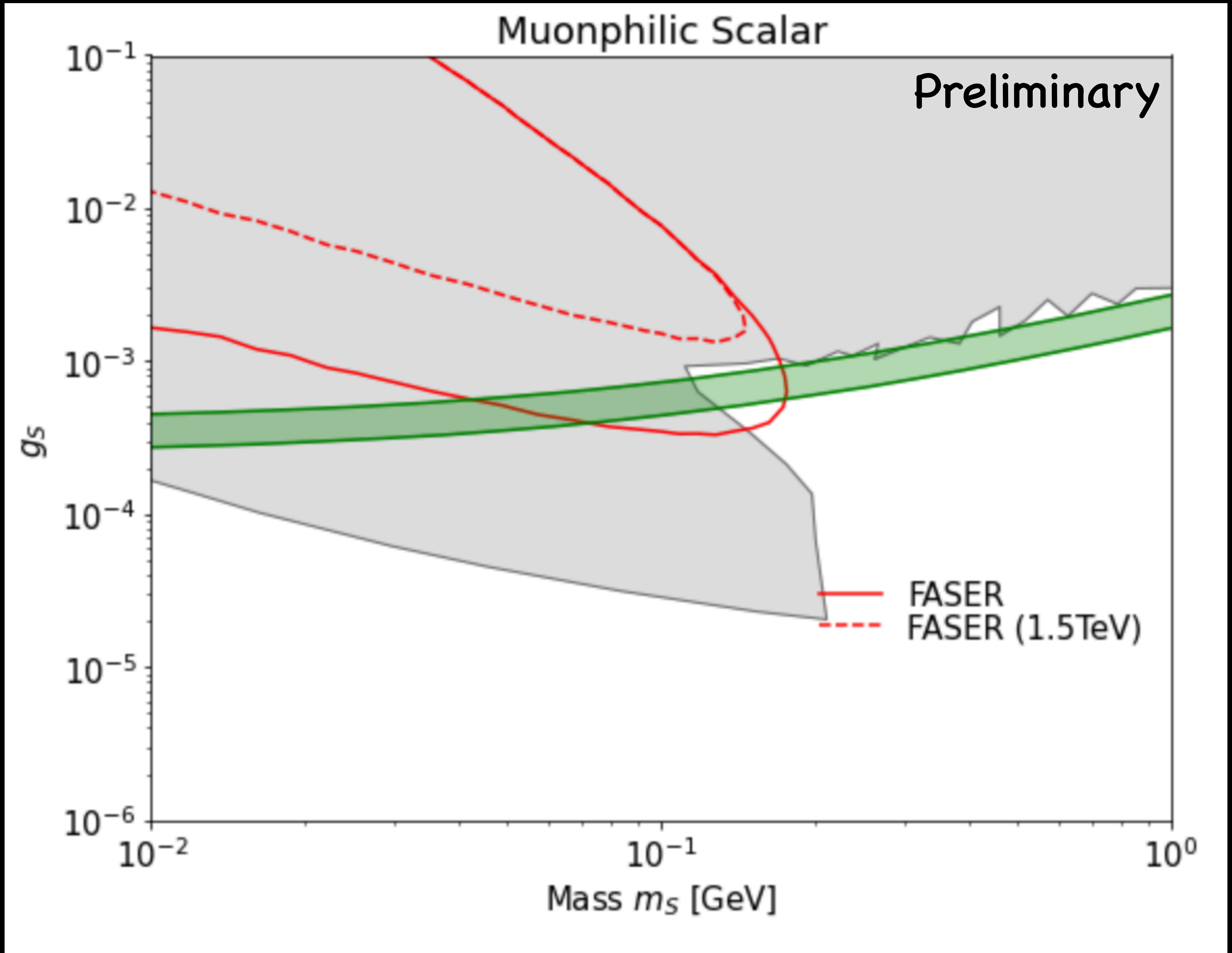
(See also talk by Ansh Desai)

- $E_{calo} > 1.5$ TeV reduced the neutrino backgrounds to ~ 0.42/50 fb^{-1}.

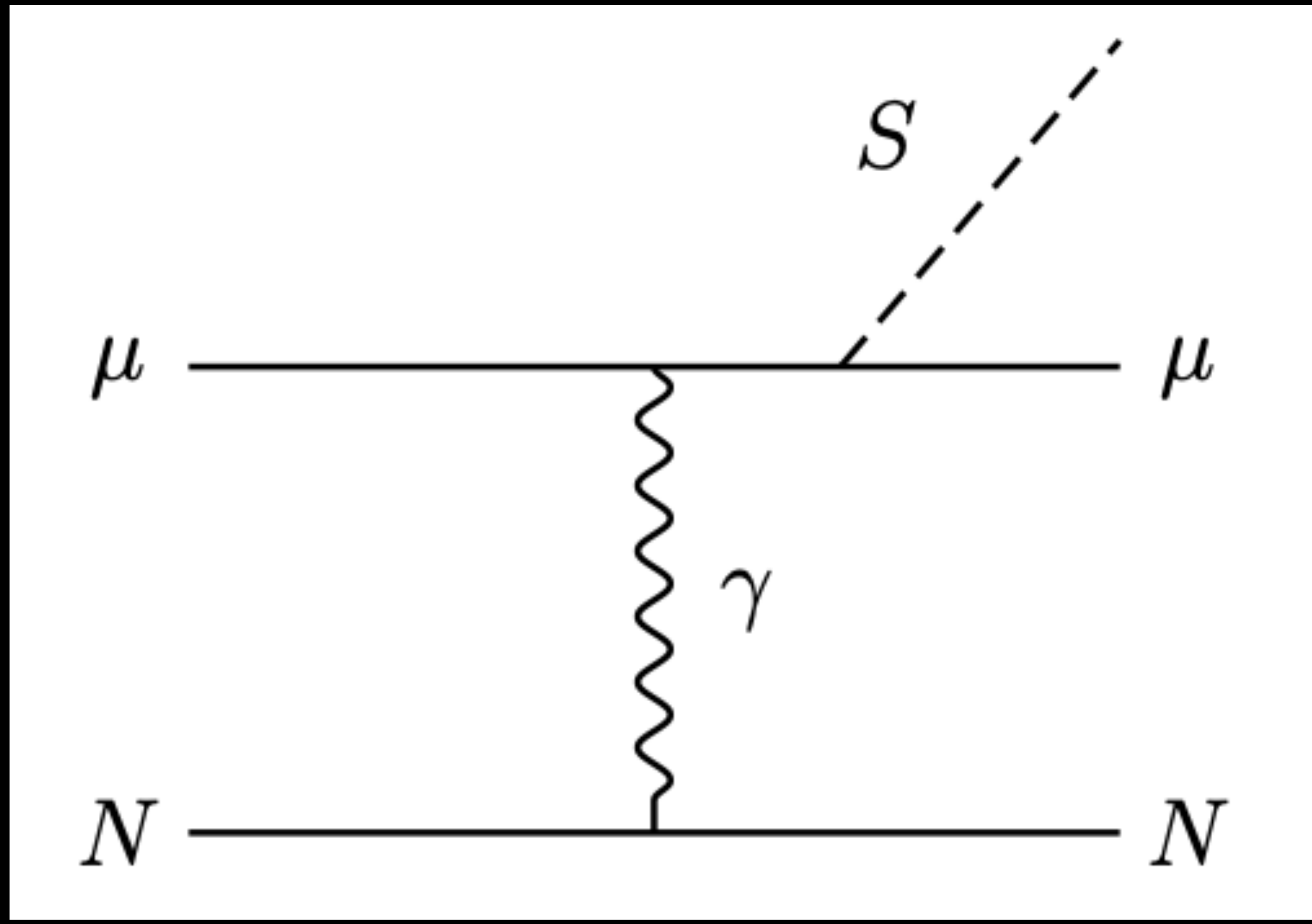
Method 1: 3 body decays (cont.)

- Applying the same energy cut, we do not probe the (g-2) band at FASER.



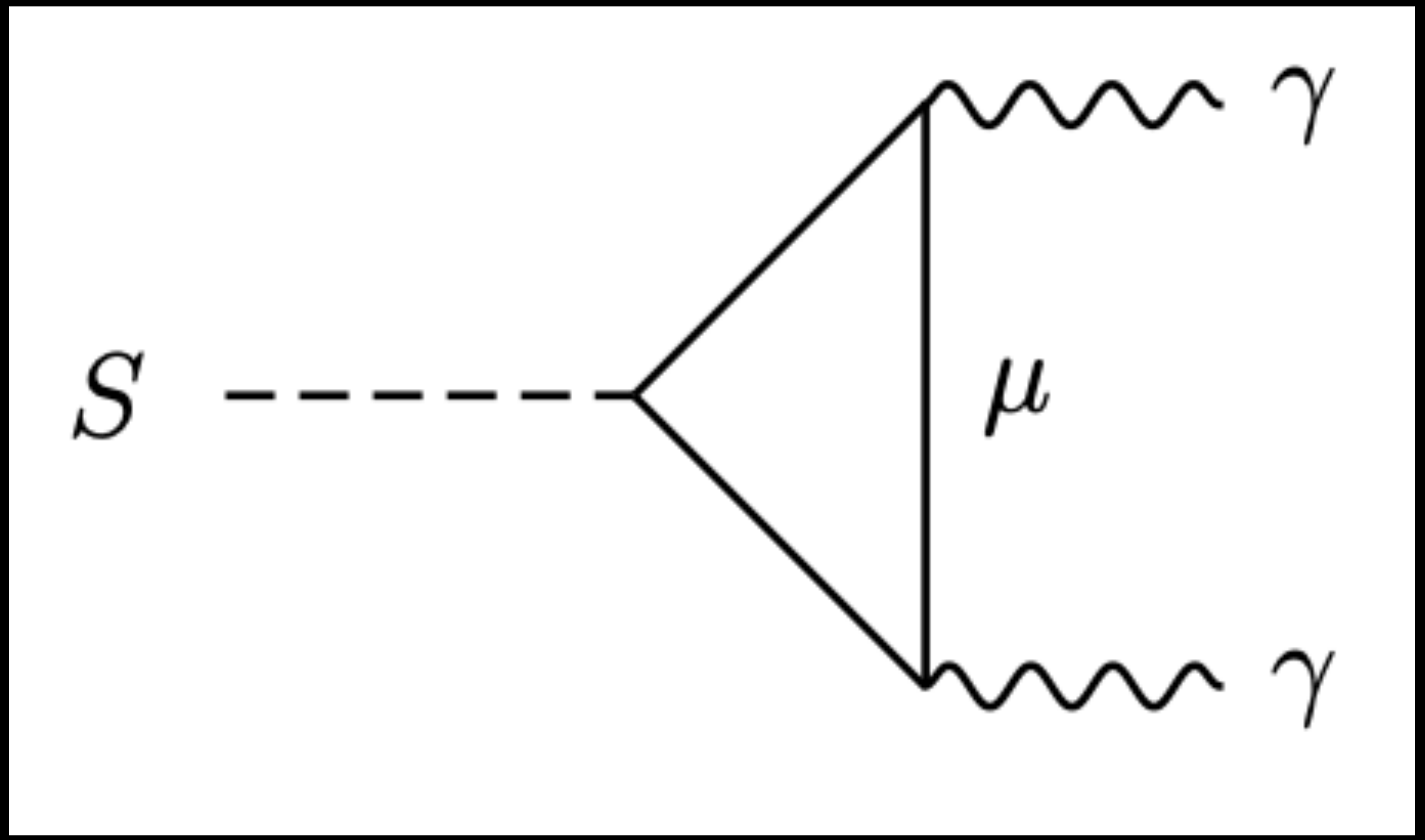


Method 2: Bremsstrahlung



- Incoming muon bremss off S within the $FASER\nu$ detector.
- If $m_S < 2 * m_\mu$, S can decay to 2 photons.
- Decay length is given by

$$L_S = 20\ m \times \left(\frac{E_s}{3\ GeV}\right) \times \left(\frac{5\times 10^{-4}}{g_S}\right)^2 \times \left(\frac{100\ MeV}{m_S}\right)^4$$

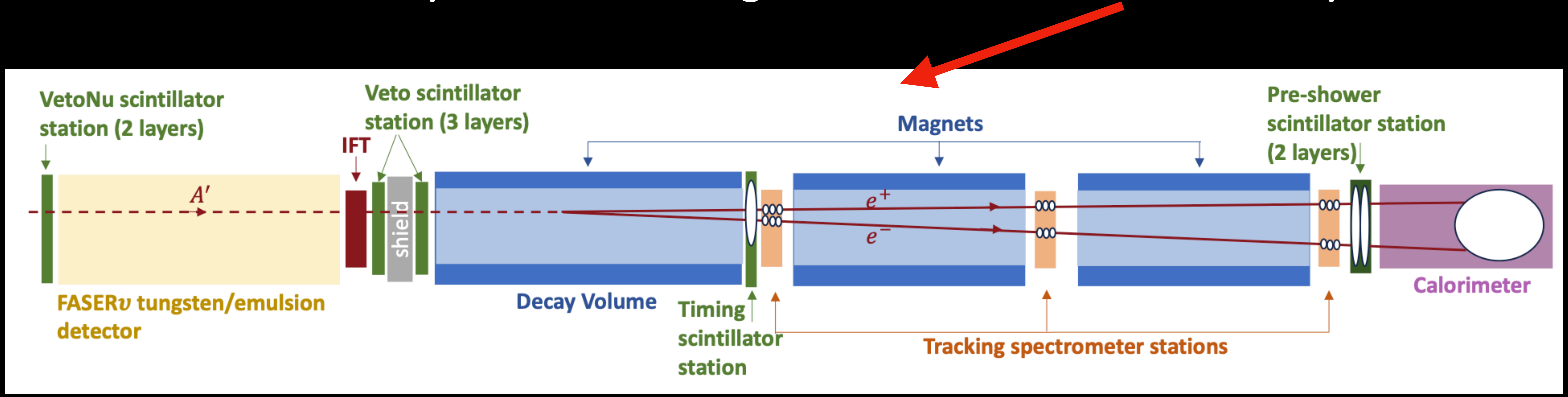


(1701.07437)

Method 2: Bremsstrahlung (cont.)

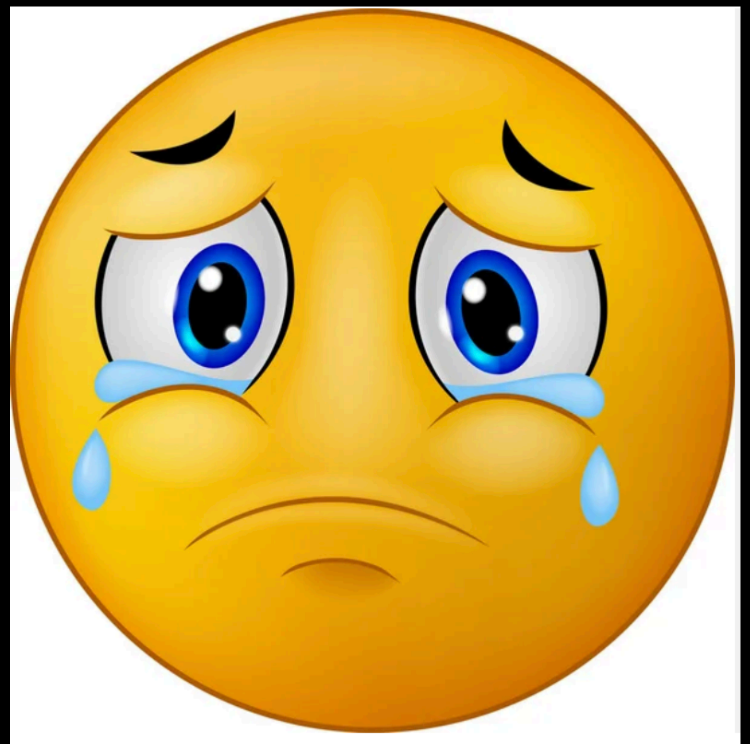
- The signal we expect is 1 muon track with some energy deposition in the calorimeter.
- But this was an important background to FASER's dark photon search.

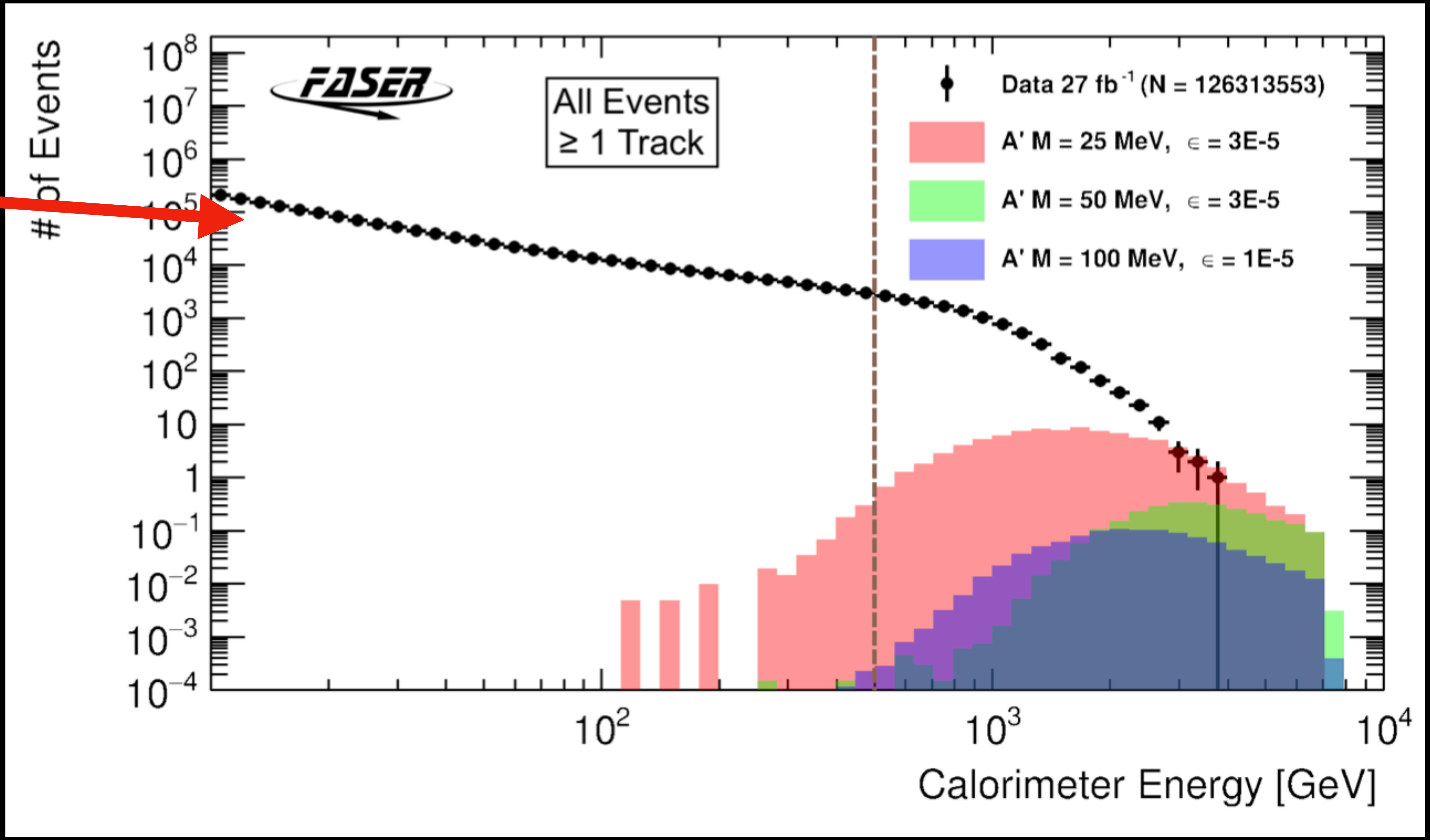
(2308.05587)



Method 2: Bremsstrahlung (cont.)

There is an overwhelming number of background events.





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Method 2.b: High Precision Preshower

- The FASER collaboration is working on a High Precision Preshower.

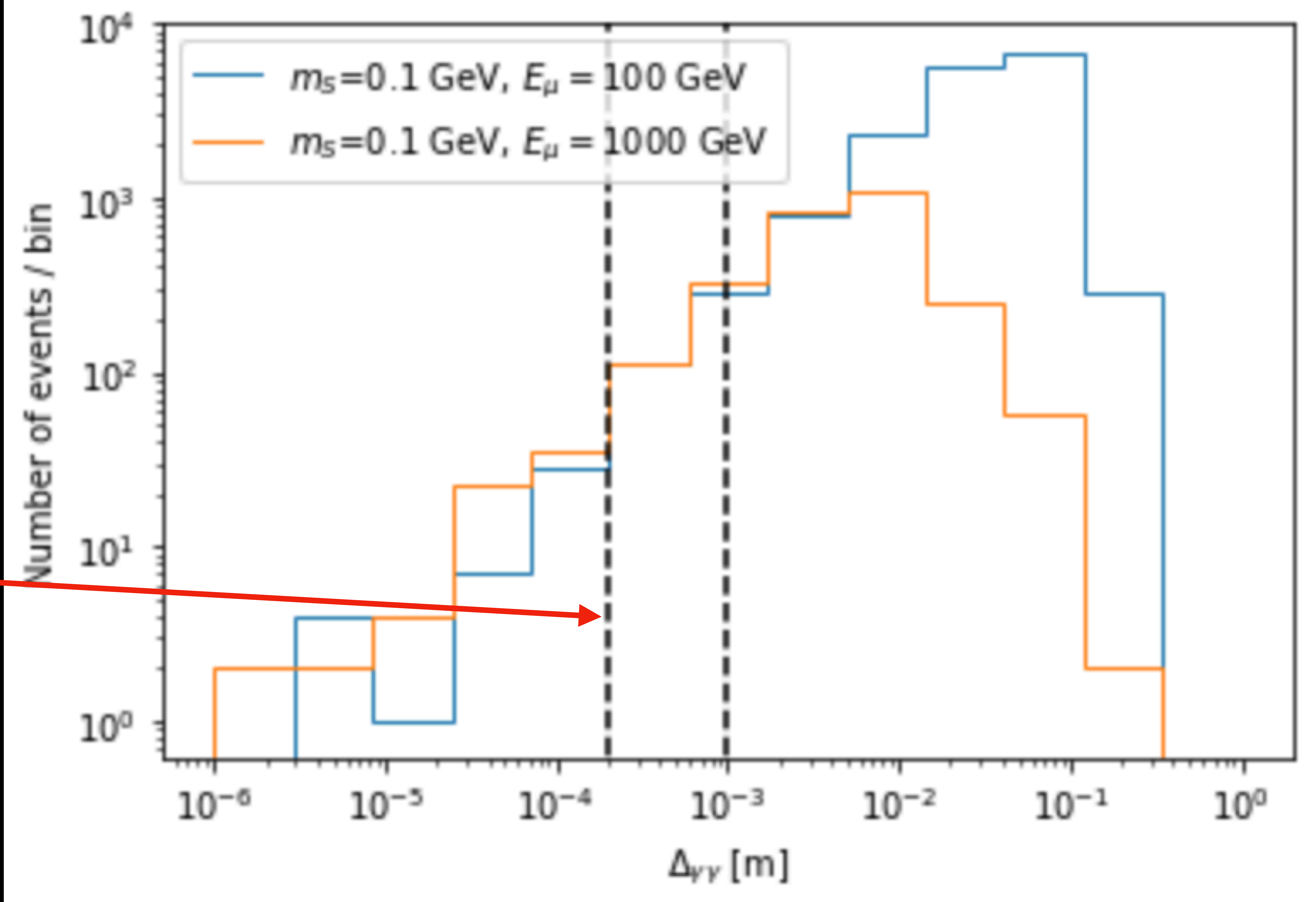
(Preshower TP)

ABSTRACT: The FASER detector is designed to search for light weakly interacting new particles decaying into charged final states at the LHC. While the first physics data will be taken at the start of Run 3 of the LHC program, an upgrade is already foreseen to enhance the sensitivity to long-lived particles decaying into photons. A high-precision preshower detector will be constructed within the next two years allowing to distinguish the predicted axion-like particles signature of two very closely spaced highly energetic photons. Profiting from recent developments in monolithic pixel silicon detectors, the FASER Collaboration plans to build instrumented silicon pixel detector planes with a granularity of 100 μm interleaved with tungsten absorber planes. The addition of the new pre-shower detector will expand the physics search capability of FASER.

- Can we make use of this to reduce backgrounds?

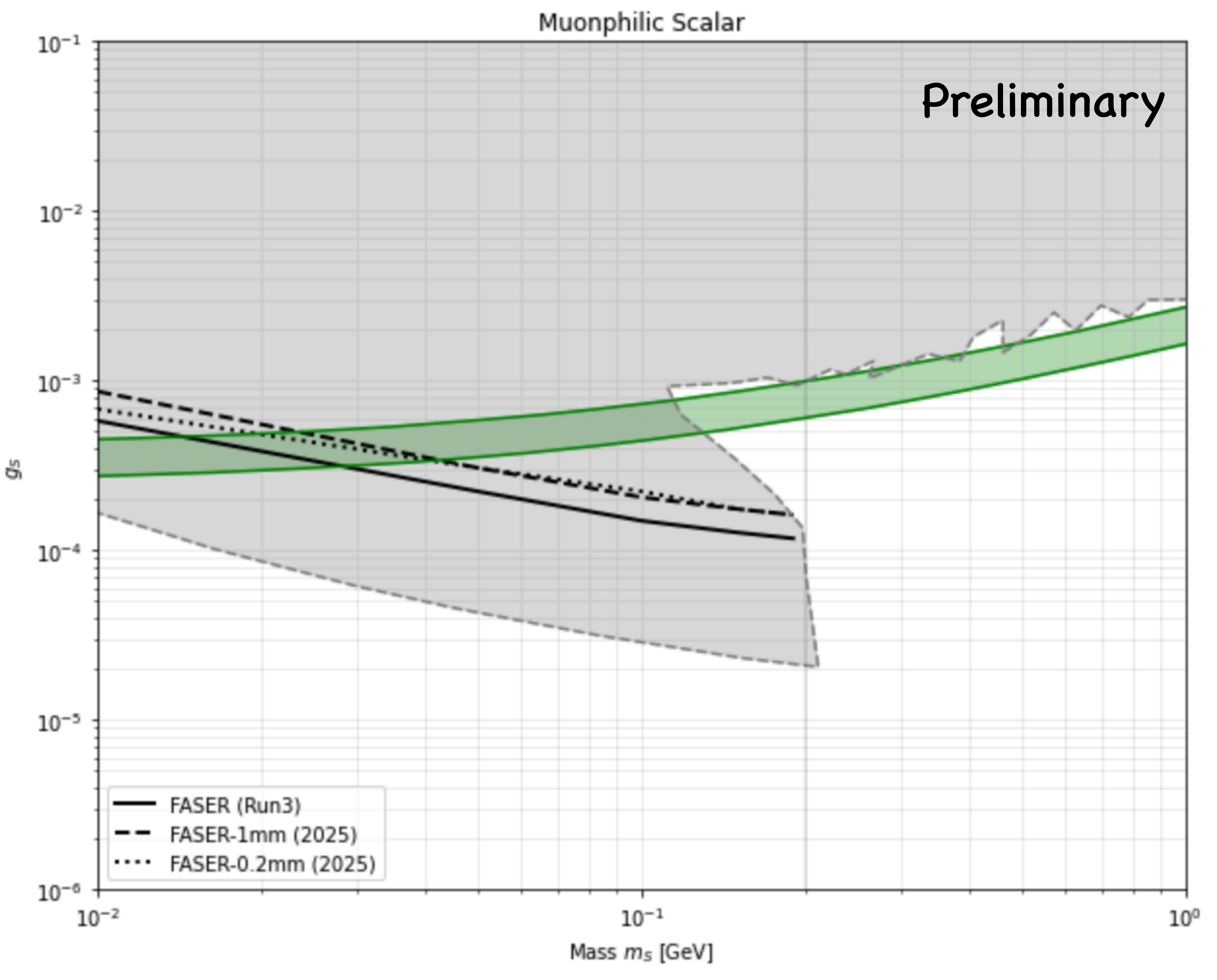
Method 2.b: High Precision Preshower (cont.)

- Low energy S tend to decay into 2 photons with greater separation.
- $\Delta_{\gamma\gamma} \sim \frac{m_S}{E_S}$
- The high precision preshower expects to be sensitive to photon spatial separation down to 0.2mm.



Method 2.b: High Precision Preshower (cont.)

- Pershower upgrade is expected to be installed before 2025 data taking.
  Run 4 proposal for FASER
- In 2025, FASER expects ~ 90 fb^{-1}.
- This is a reduction in luminosity (300 fb^{-1} -> 90 fb^{-1}).
- Even with only 2025 data, FASER can probe the unconstrained (g-2) band below $2 * m_{\mu}$!!!!



Conclusion

- This is the era of multi messenger collider physics. (See talk by Jonathan Feng)
- Many new physics opportunities in the forward direction.
- Muons were an annoying background to most of FASER's analysis.
- But we can take advantage of the huge muon flux to do muon physics.
- With just 1 year of data (2025), FASER can probe unexplored regions of the g-2 parameter space for a muonphilic scalar model.