Hunting muonic forces at emulsion detectors

Reuven Balkin

TECHNION
Israel Institute
of Technology

Based on 2305.03102, with A. Ariga, I. Galon, E. Kajomovitz and Y. Soreq

11/07/2023

FLArE Far Forward Physics working group meeting

Talk layout

- Theory: motivation and status
- Basic search idea
- Signal
- Background
- Results and summary

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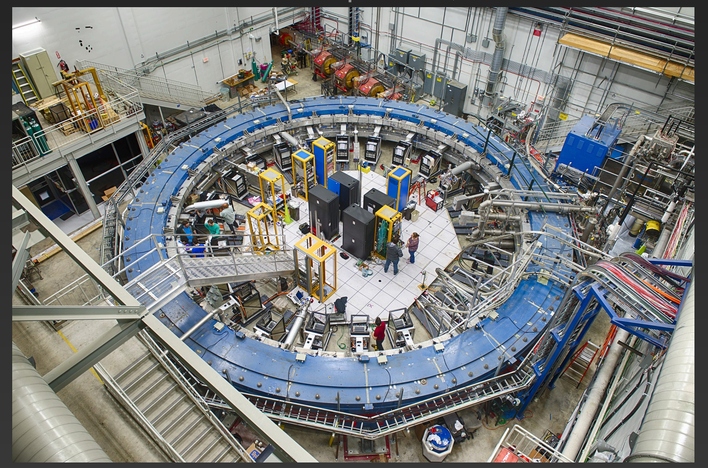
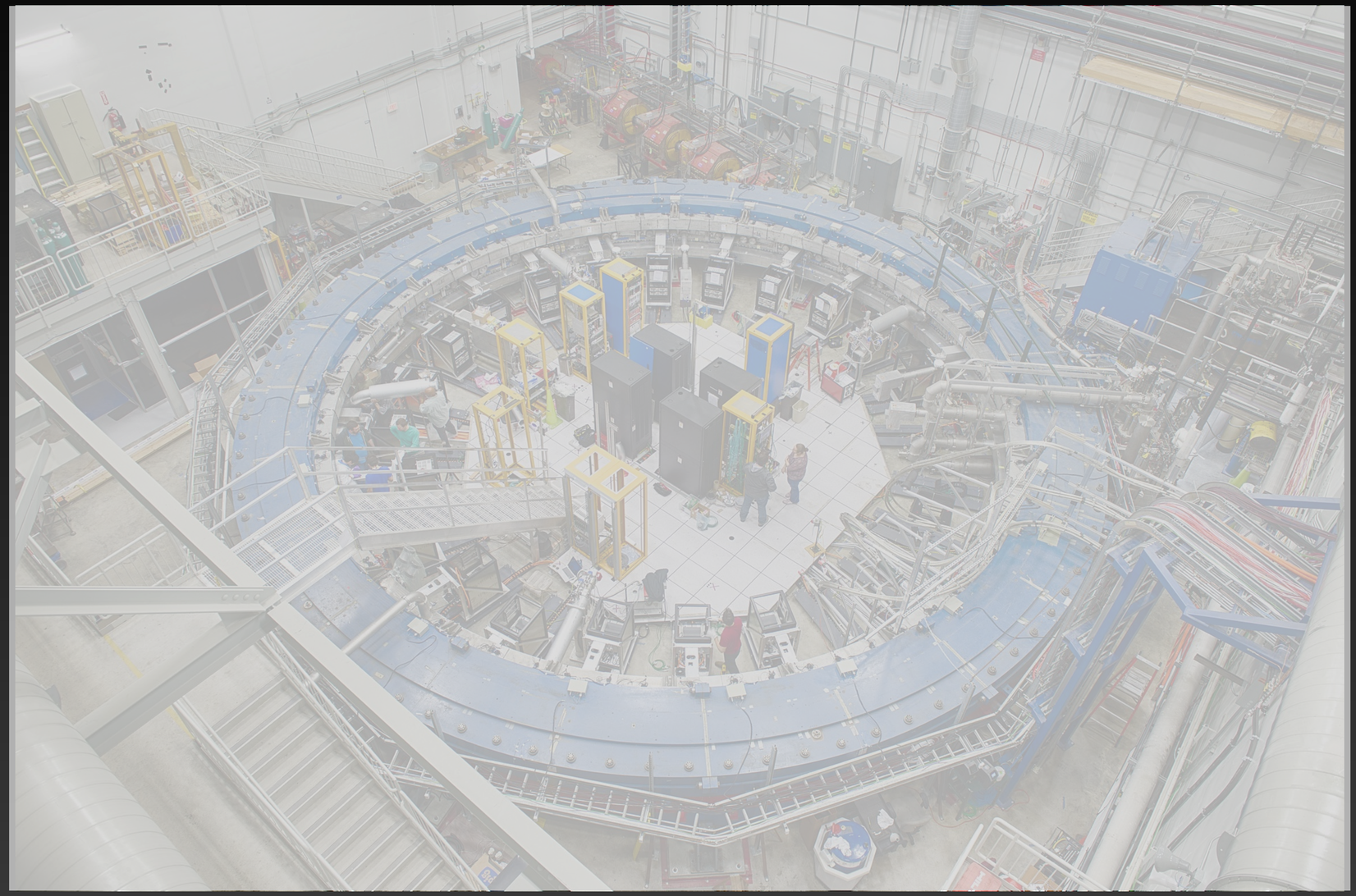
FermiLab April 7th, 2021



Did we already observe it??

According to the news: yes.



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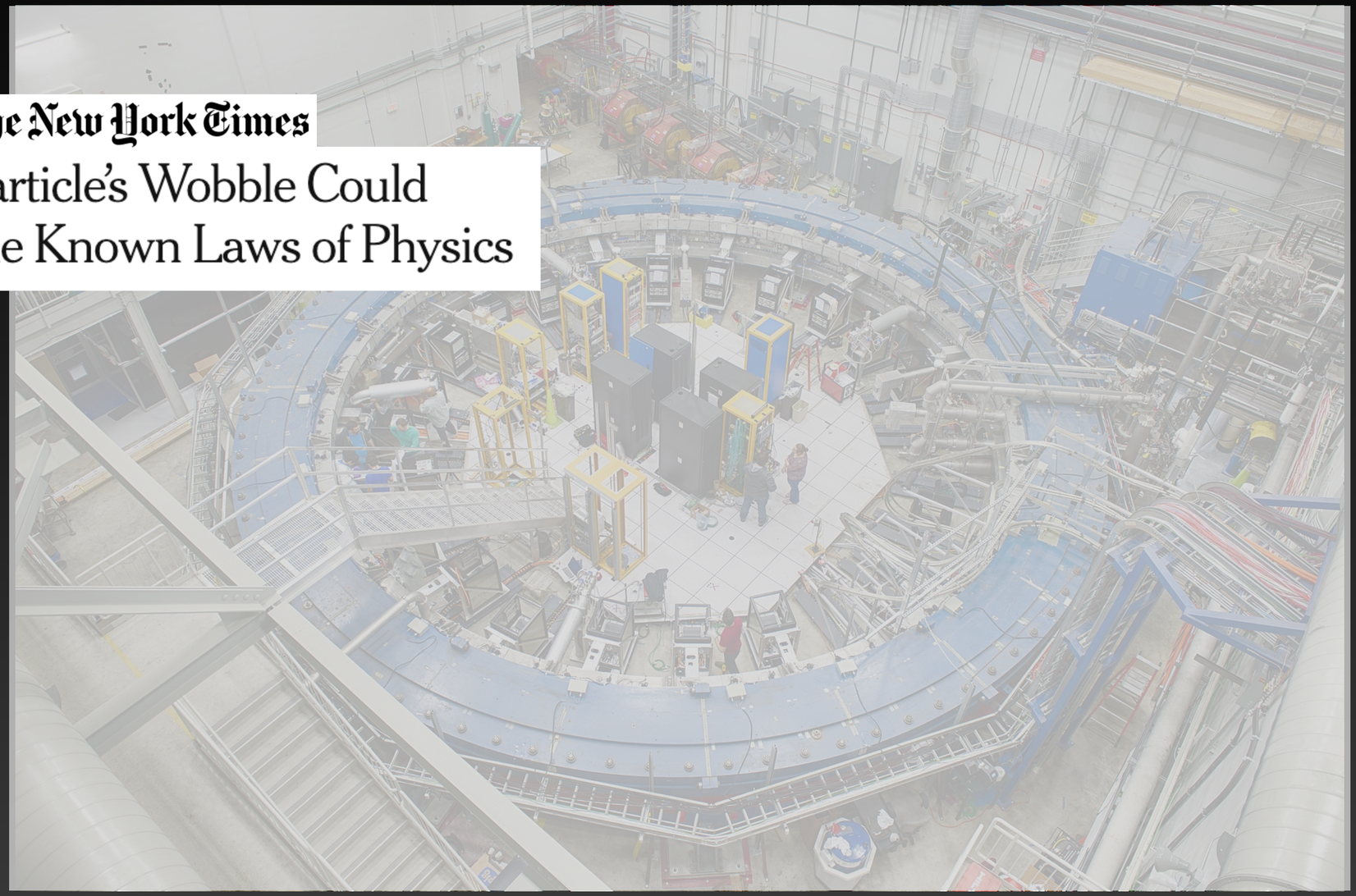

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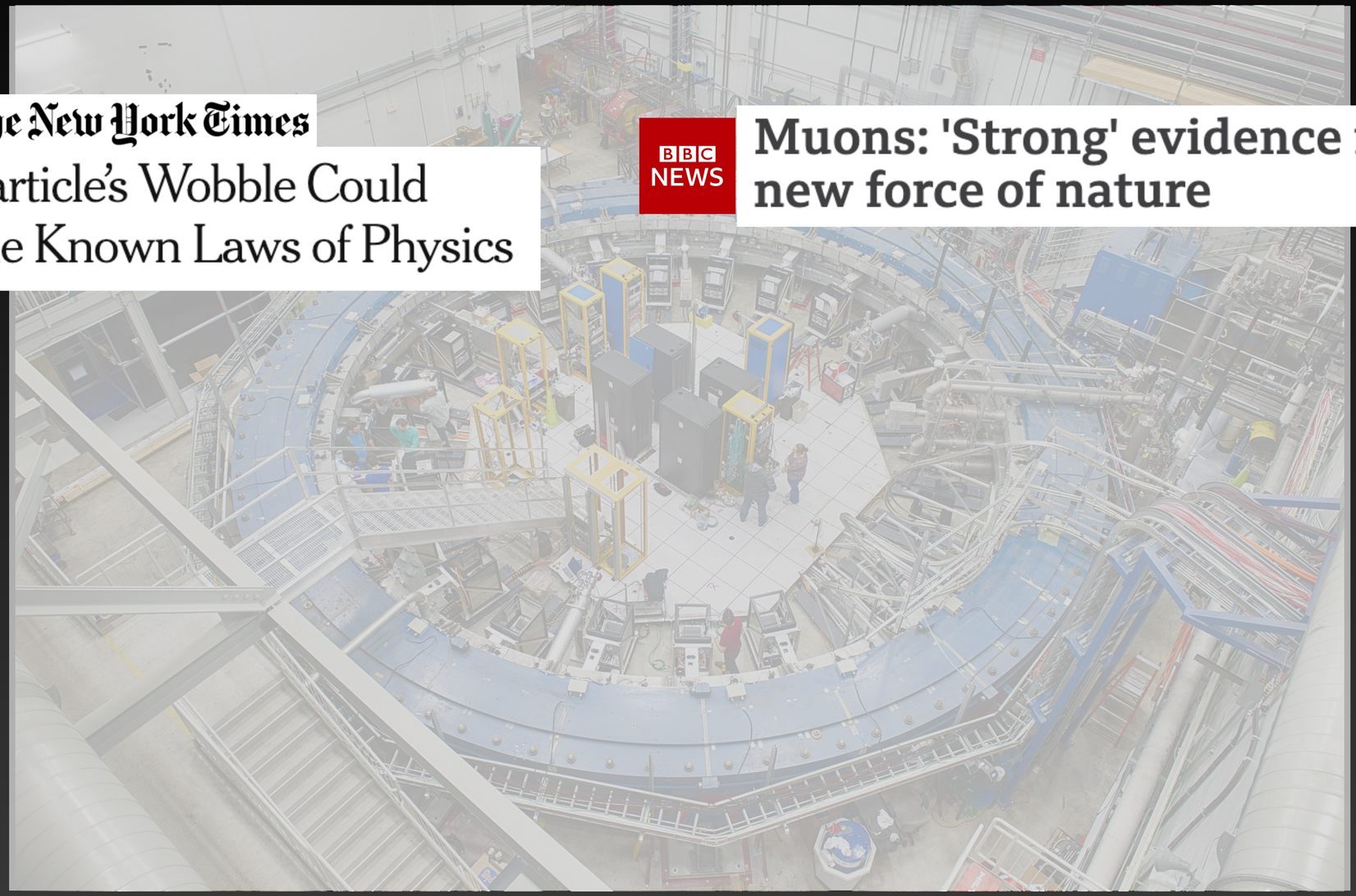

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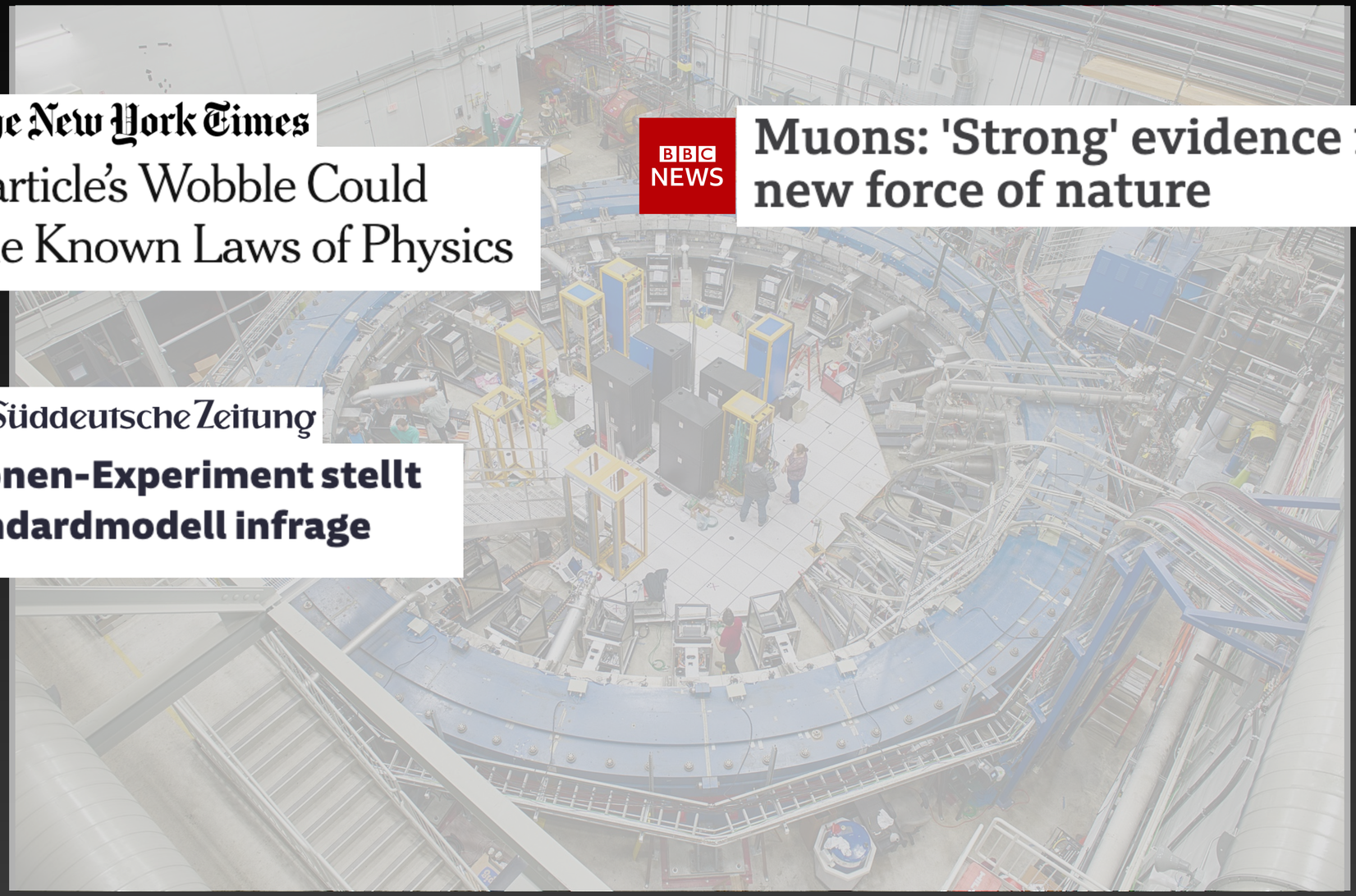

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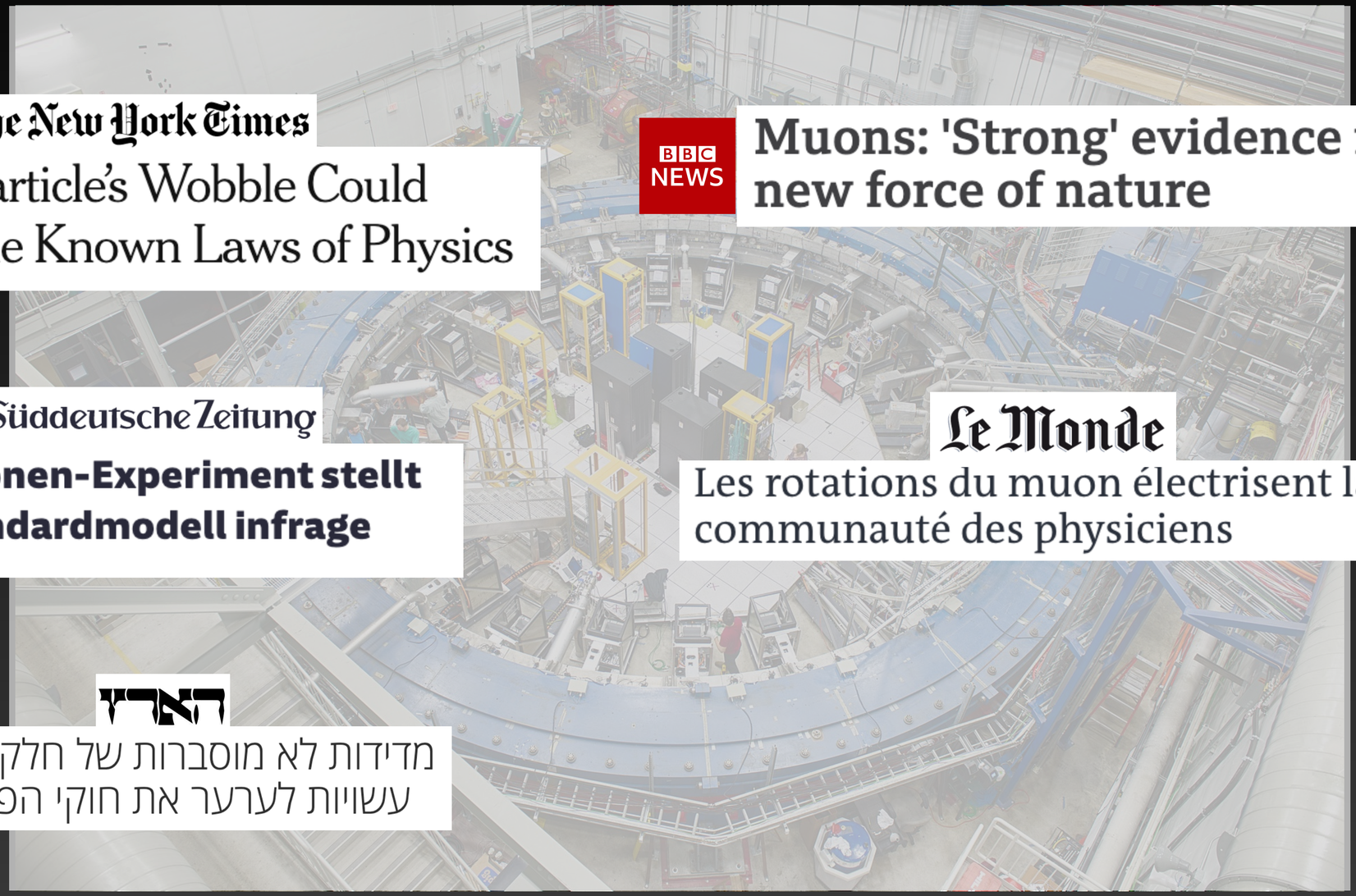

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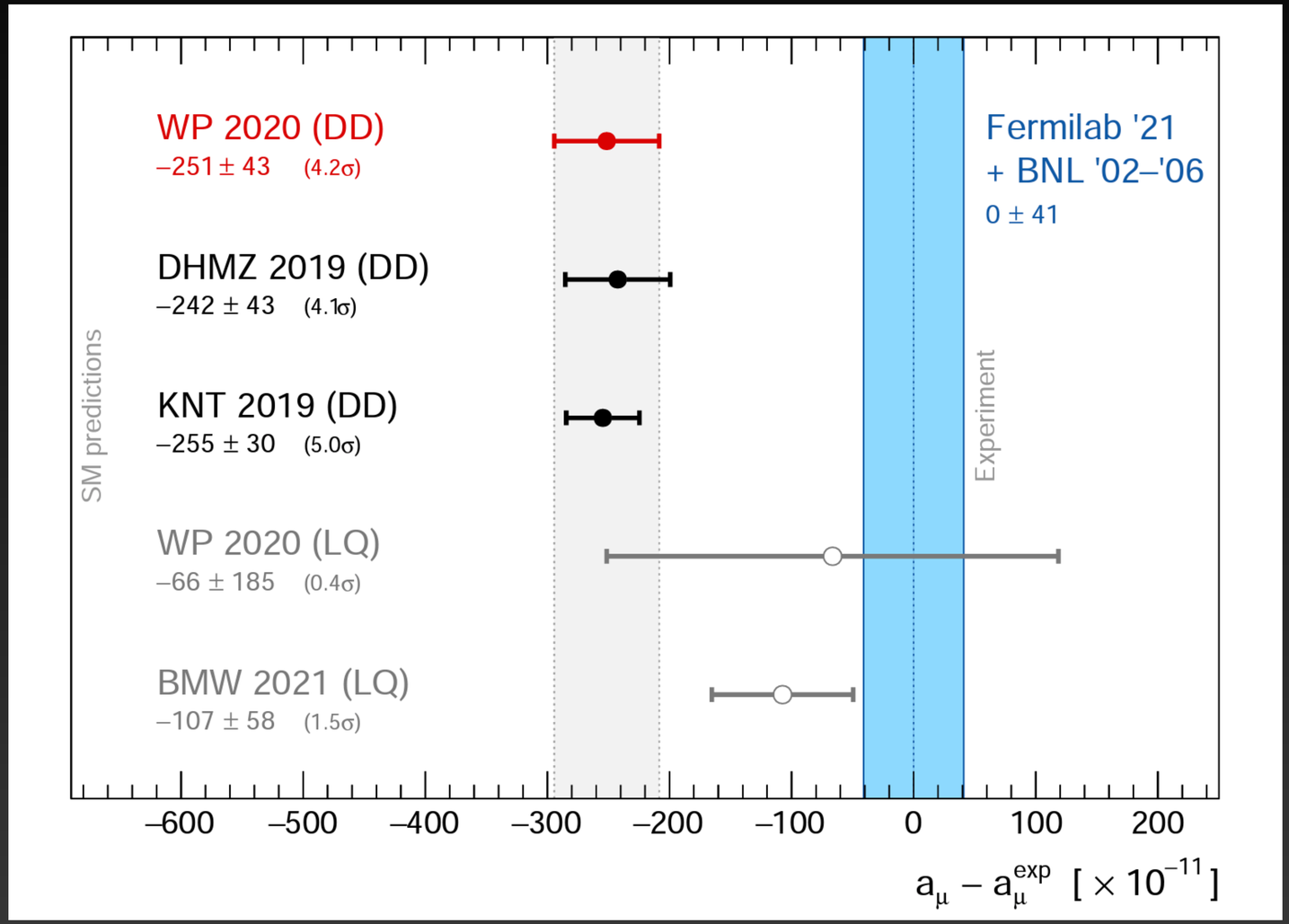
ynet ידיעות אחרונות

הניסויים שעשויים לשנות את חוקי הפיזיקה

"הממצא הכי חשוב מאז החלקיק האלוהי": תוצאות ניסויים בארה"ב ואירופה הדהימו את המדענים. האם יתגלה כוח יסוד חמישי - ומה הסיכוי שזו טעות?

Muon anomalous magnetic moment

PDG



$$\mathcal{H} = -(1 + a_\mu)\left(\frac{q}{m}\right)\vec{s}\cdot\vec{B} \qquad a_\mu^{\mathrm{SM}} = \mathcal{O}(g_{\mathrm{SM}}^2)$$

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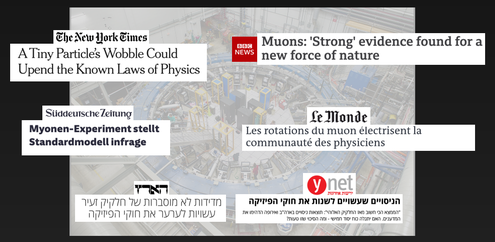

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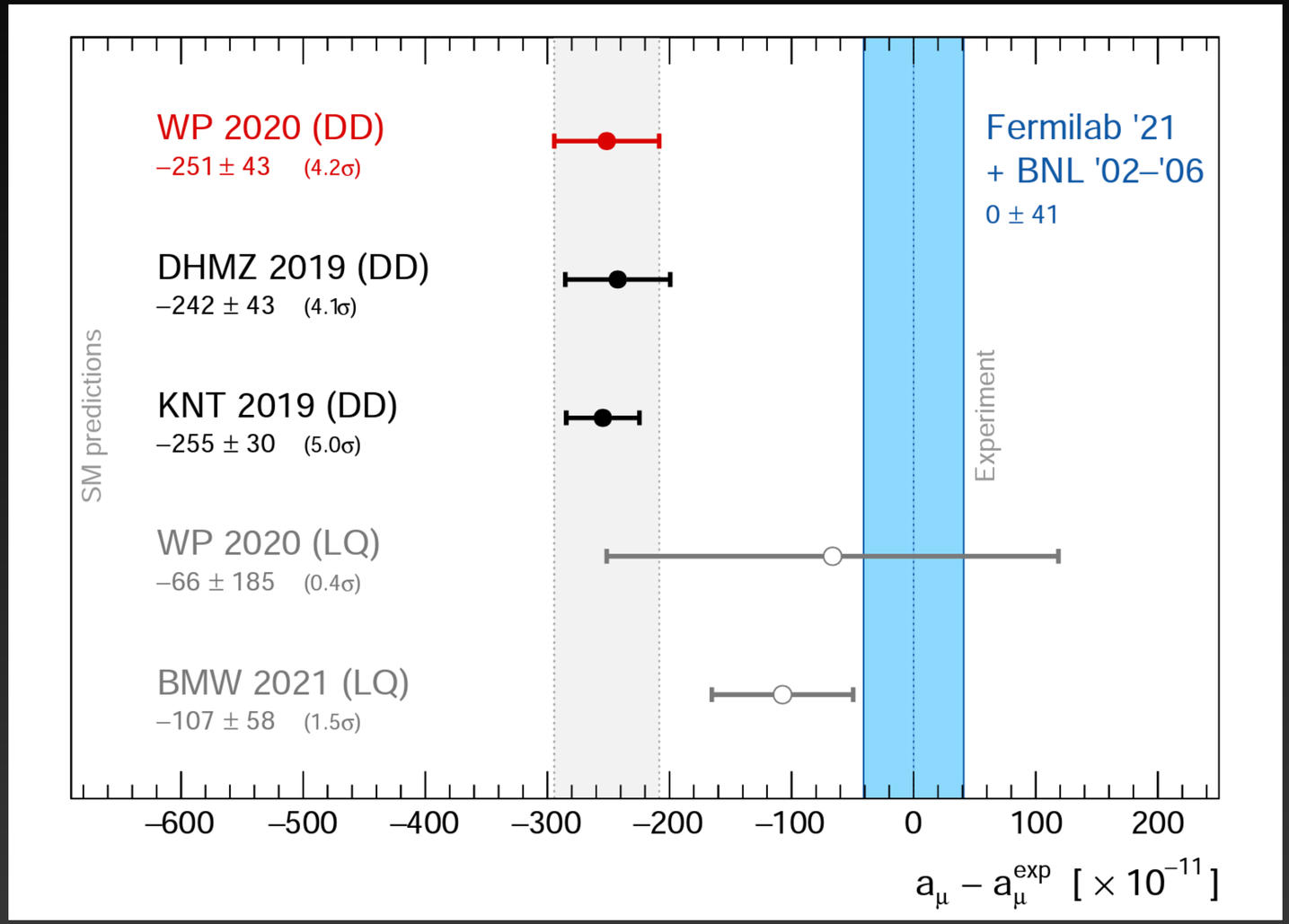

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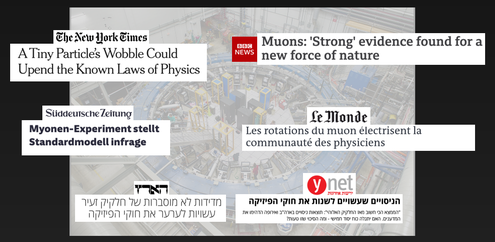

SM ftw :)

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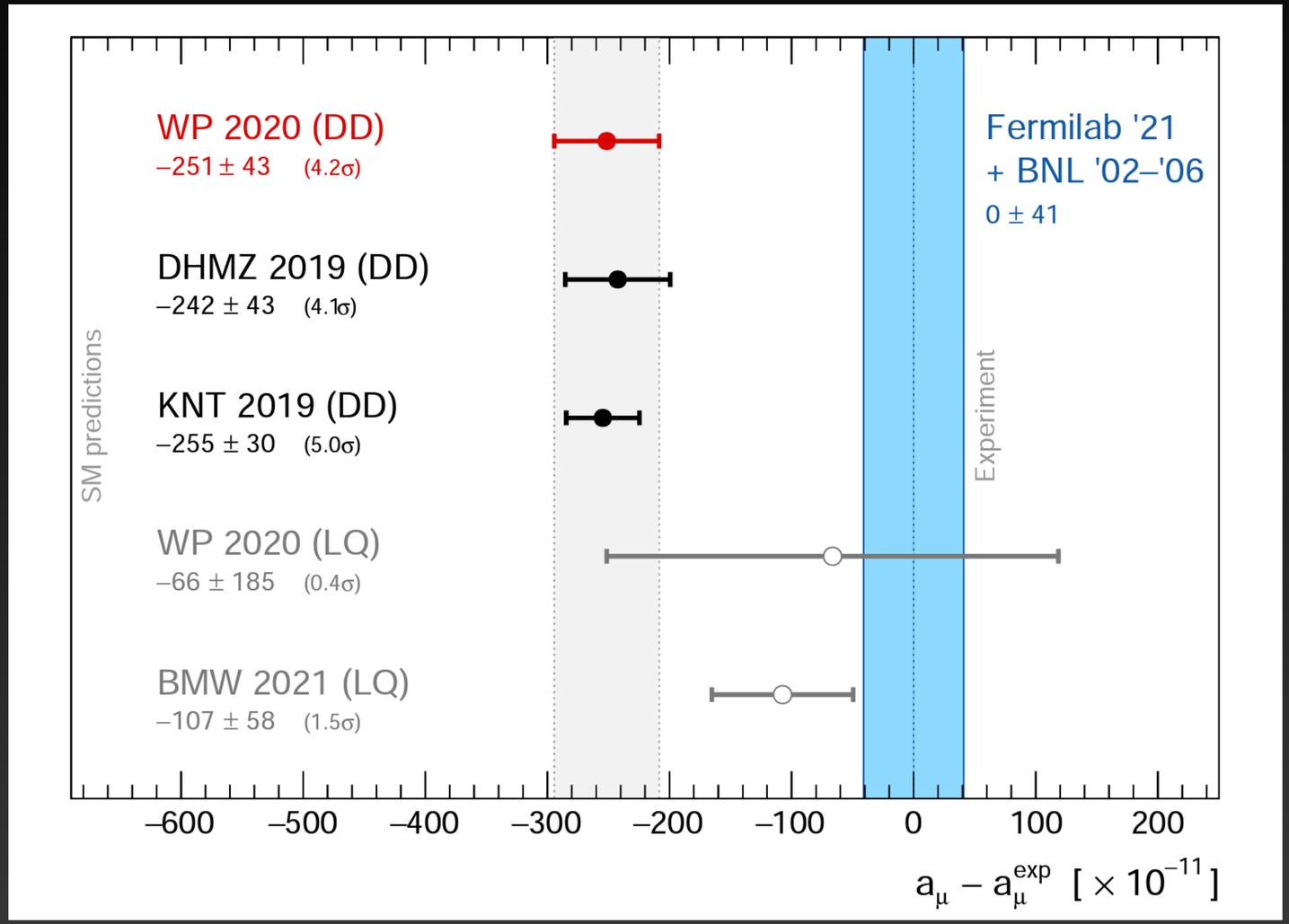

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PRD 104 (2021) 5, 053009, arXiv:2104.08289

RB, Delaunay, Geller, Kajomovitz, Perez, Shpilman, Soreq

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Tree-level searches (e.g this talk) **are important !**

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- S effectively stable? **Look for missing energy**

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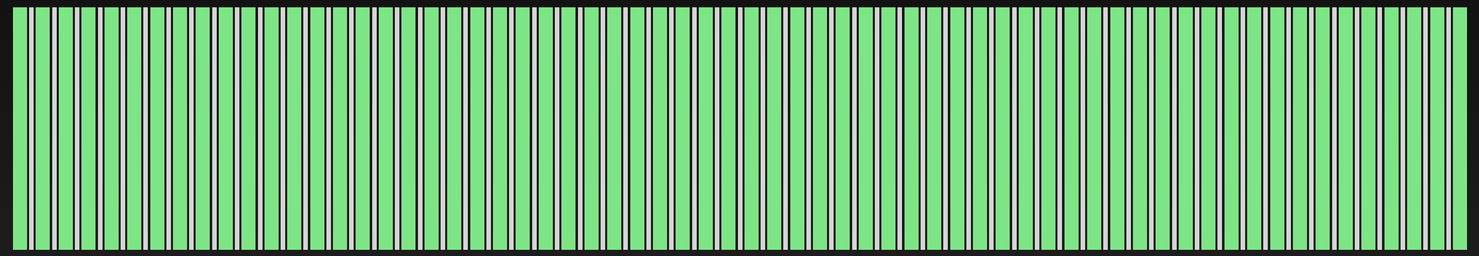
Basic idea

FASERν as a muon fixed target



Large number of energetic muons

$$N_\mu \sim 10^9$$

With $E_\mu \gtrsim 100$ GeV

For $\mathscr{L}_{\mathrm{LHC}} = 150\ \mathrm{fb}^{-1}$

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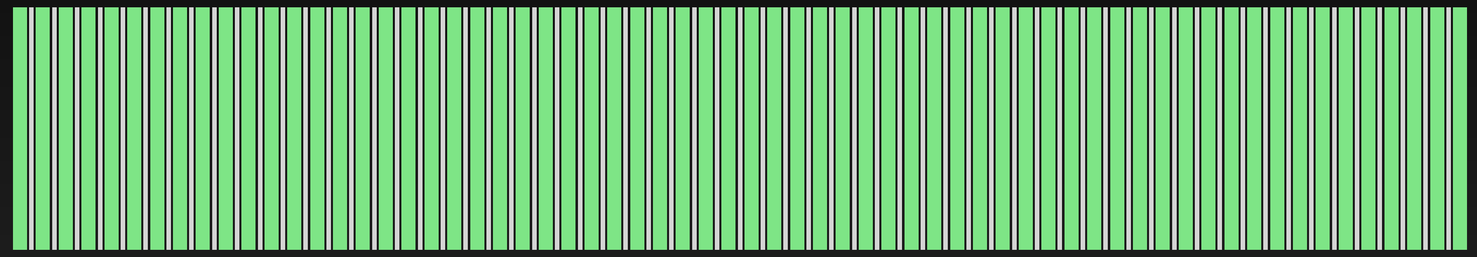

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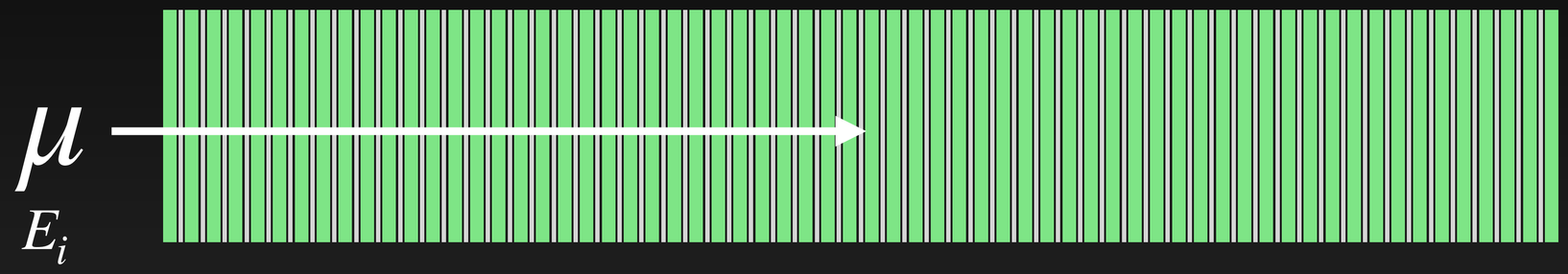

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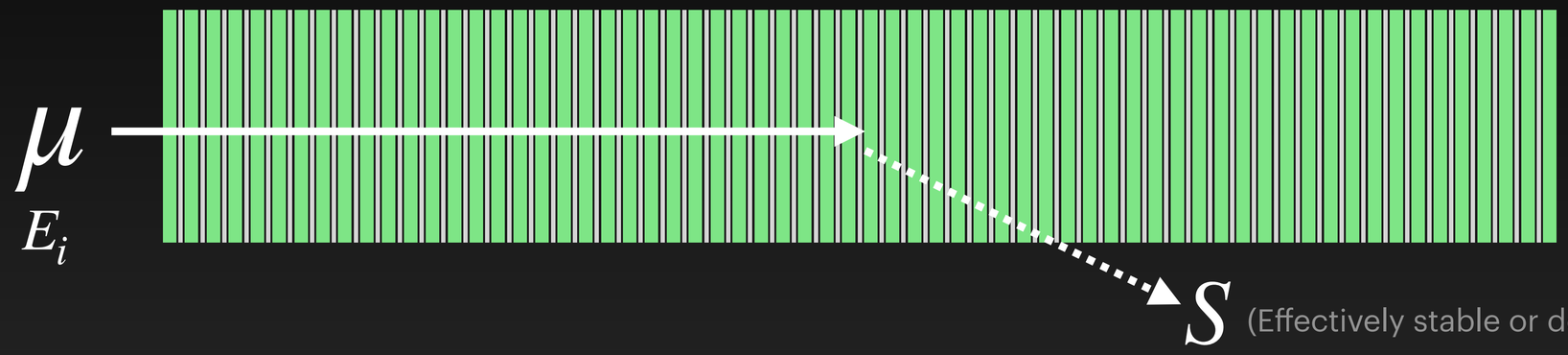

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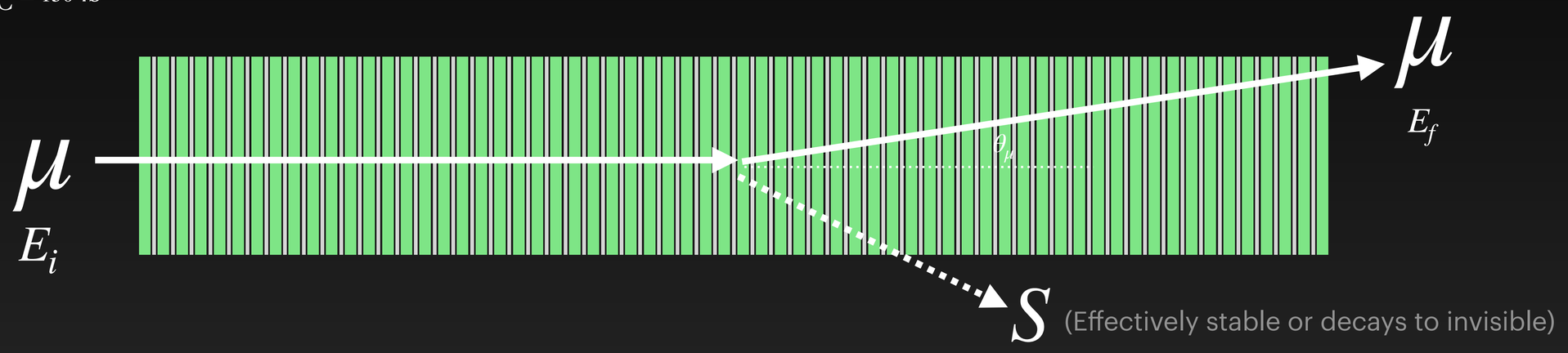

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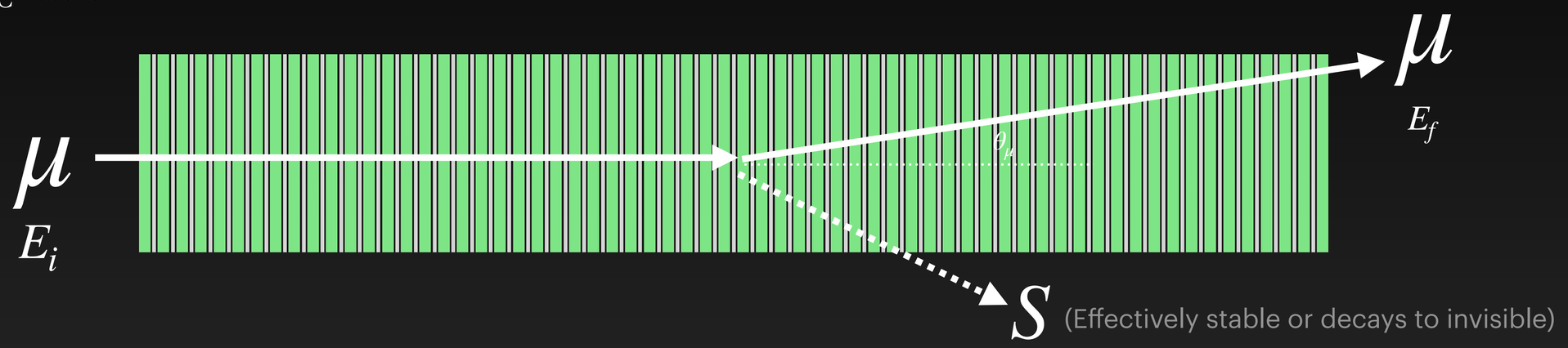

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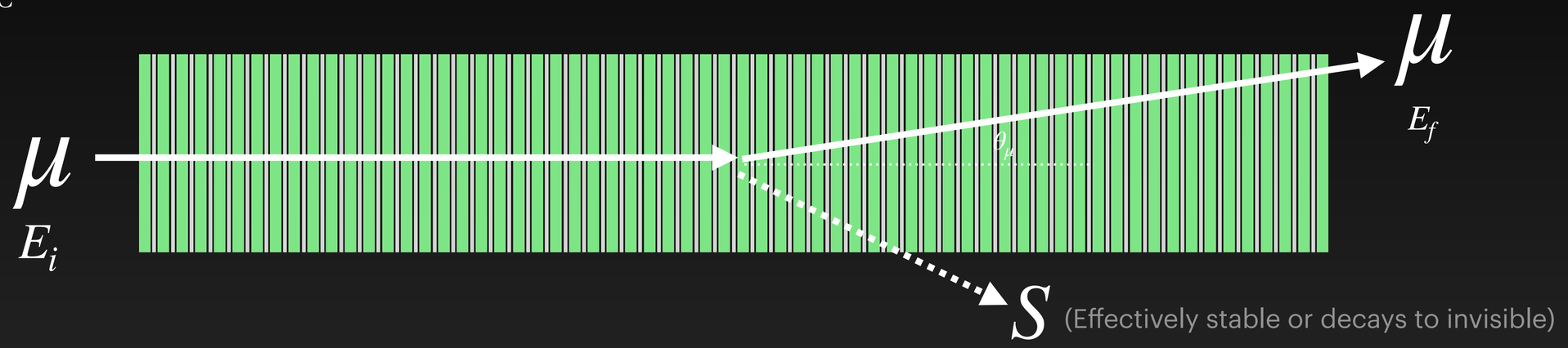

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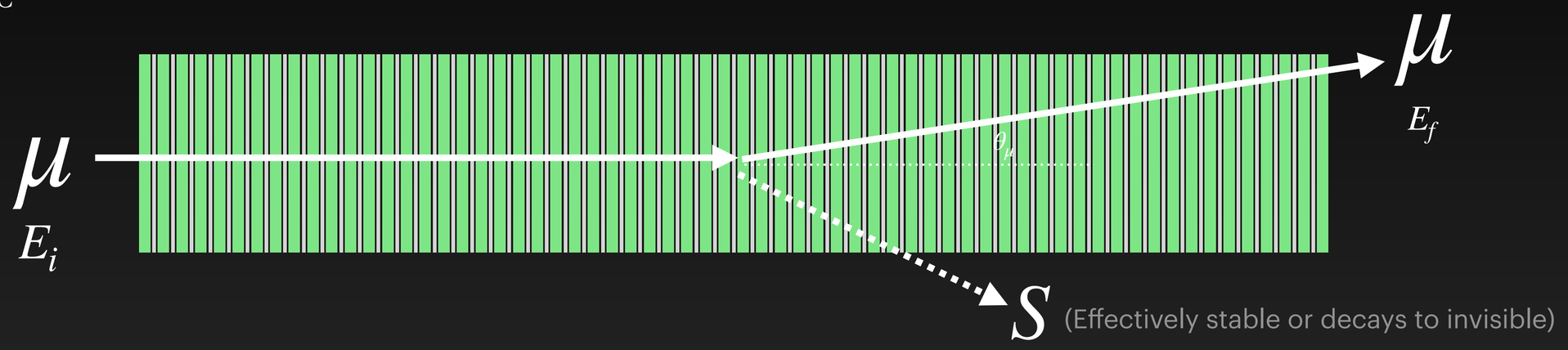

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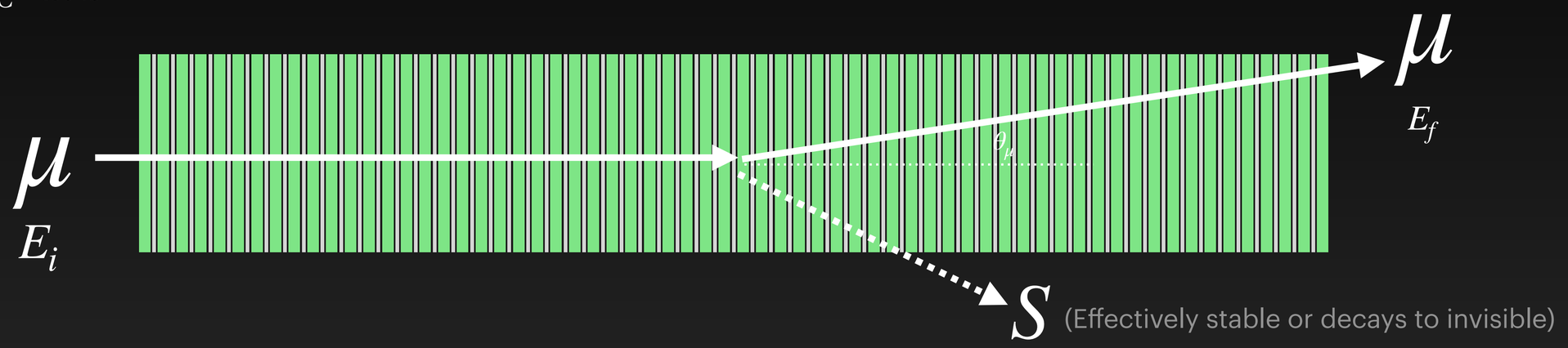

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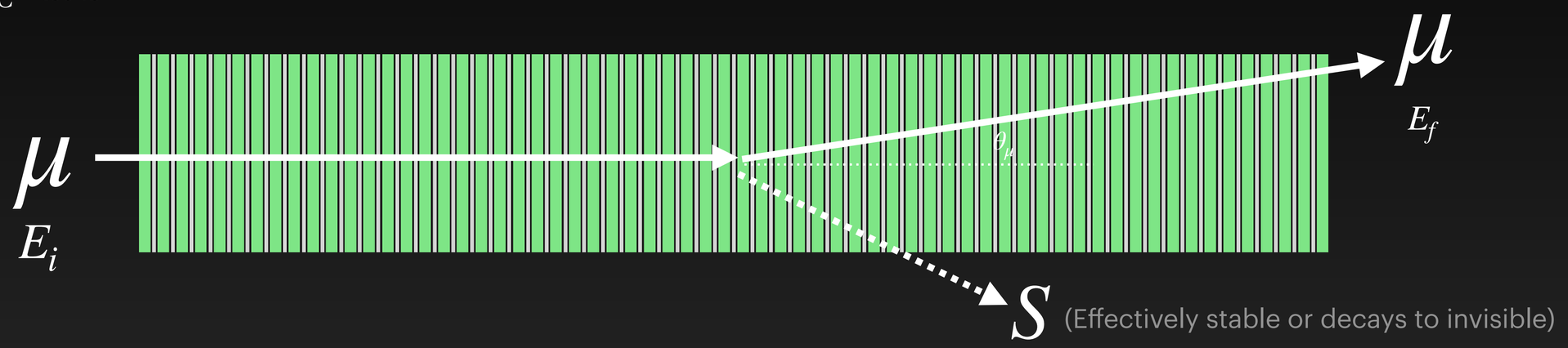

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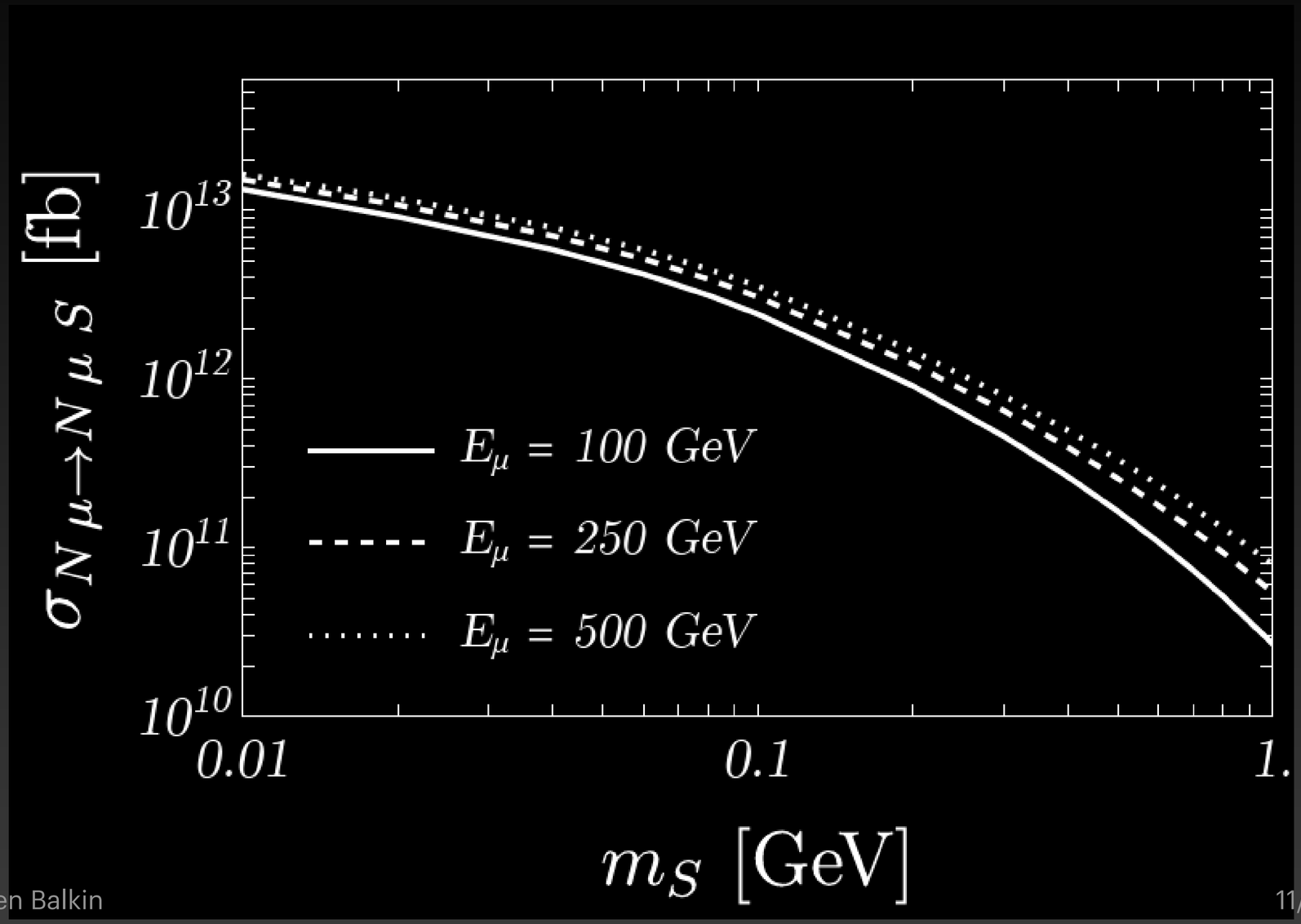

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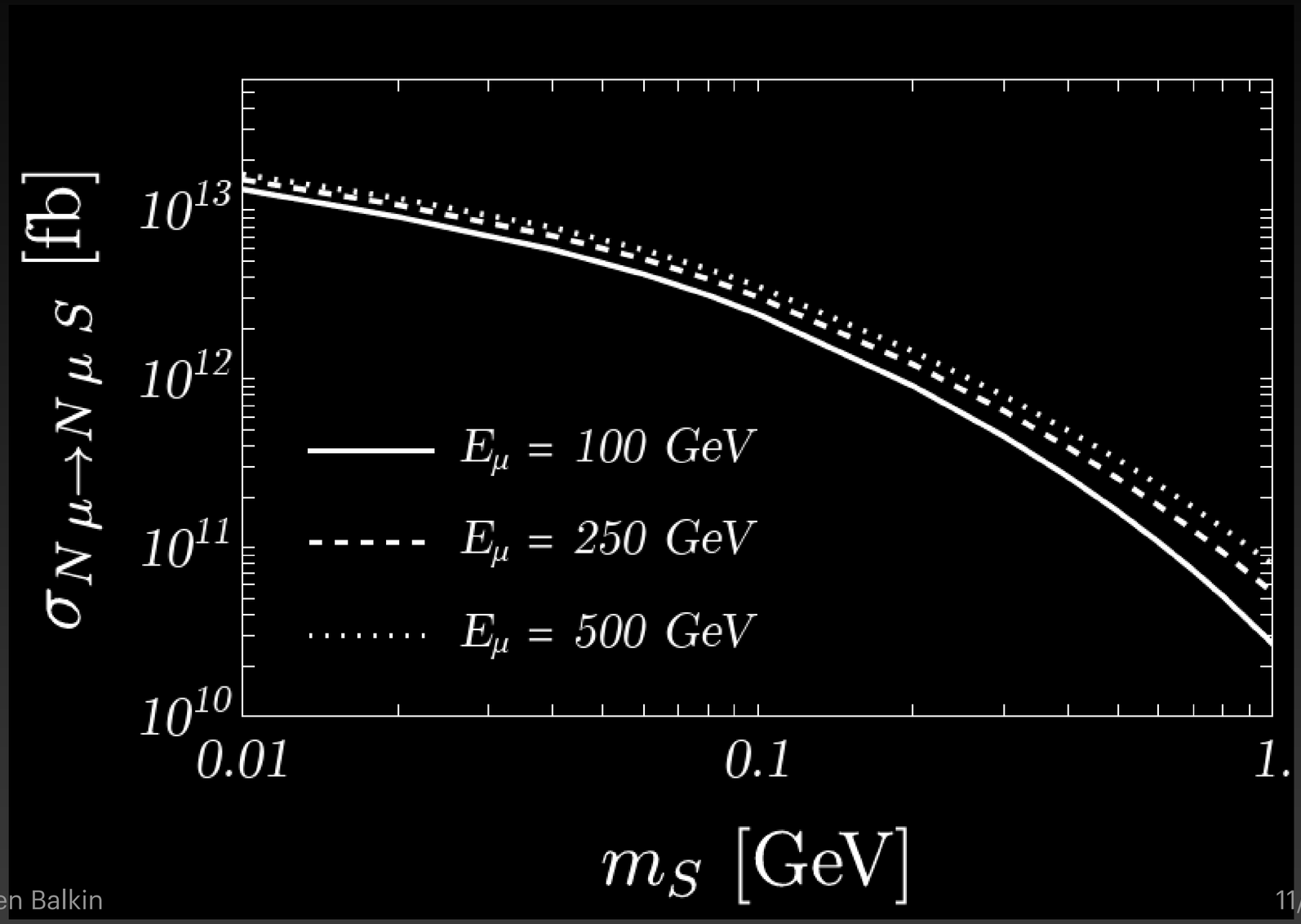

Strong mass dependence

Weak energy dependence

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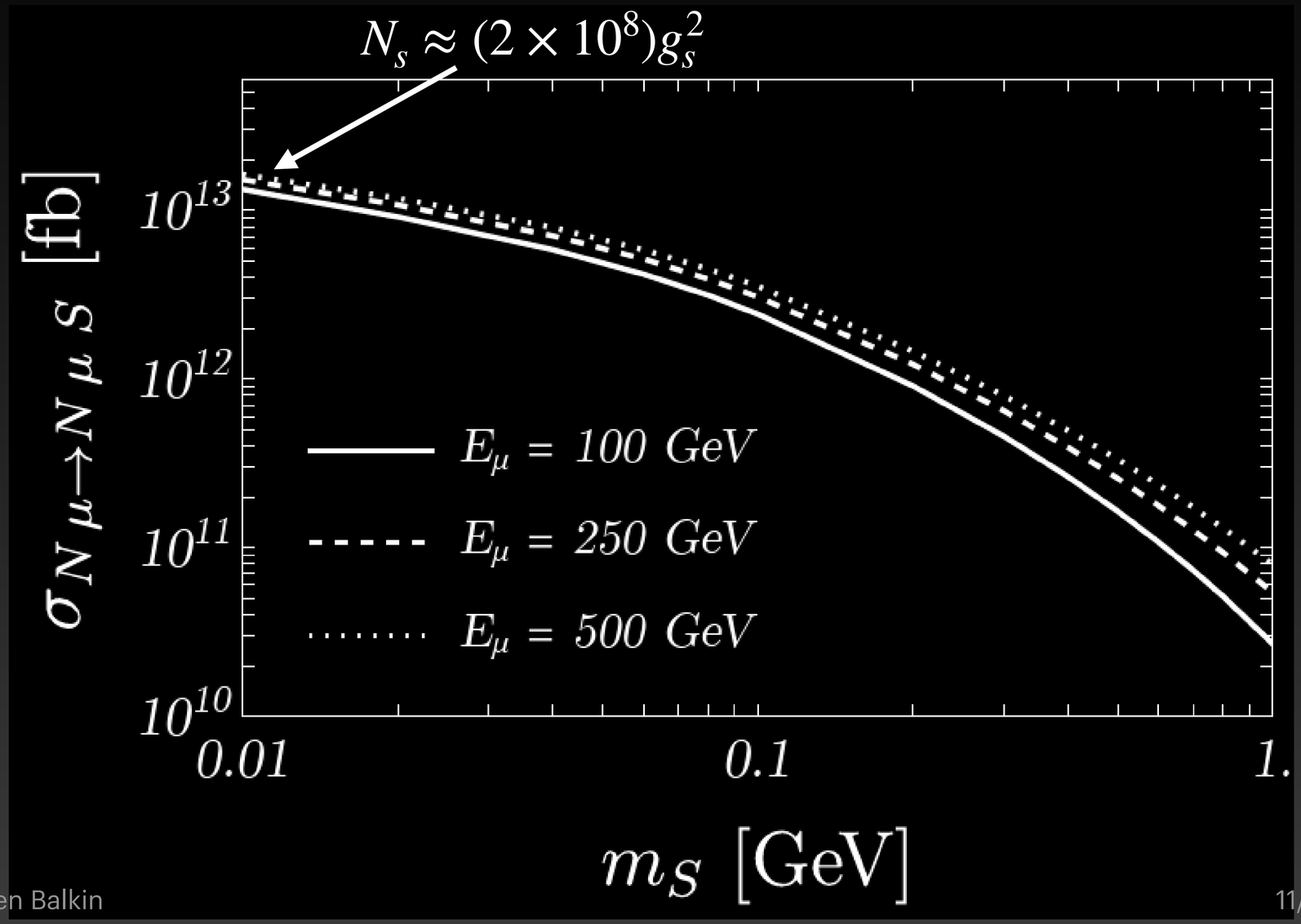

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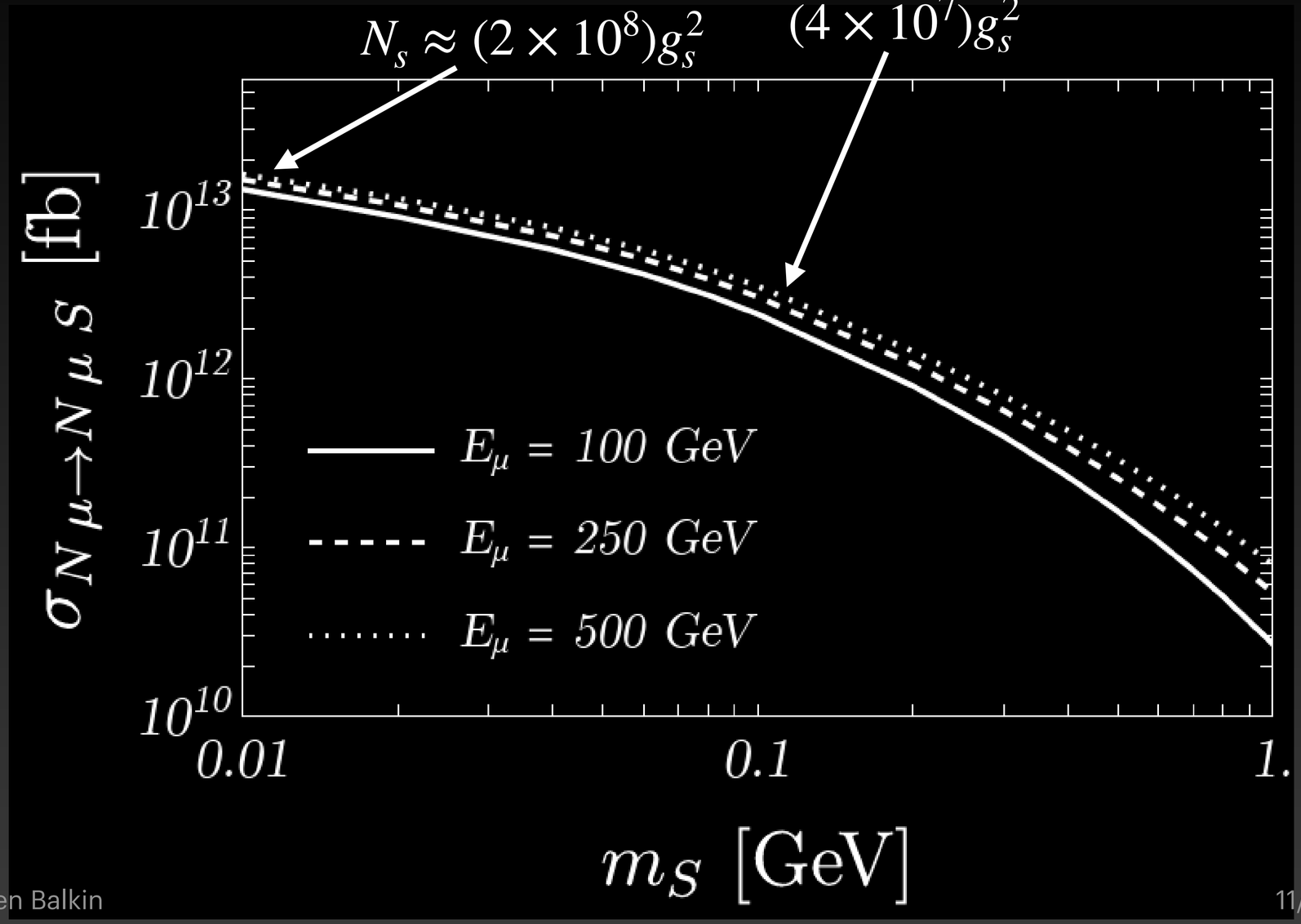

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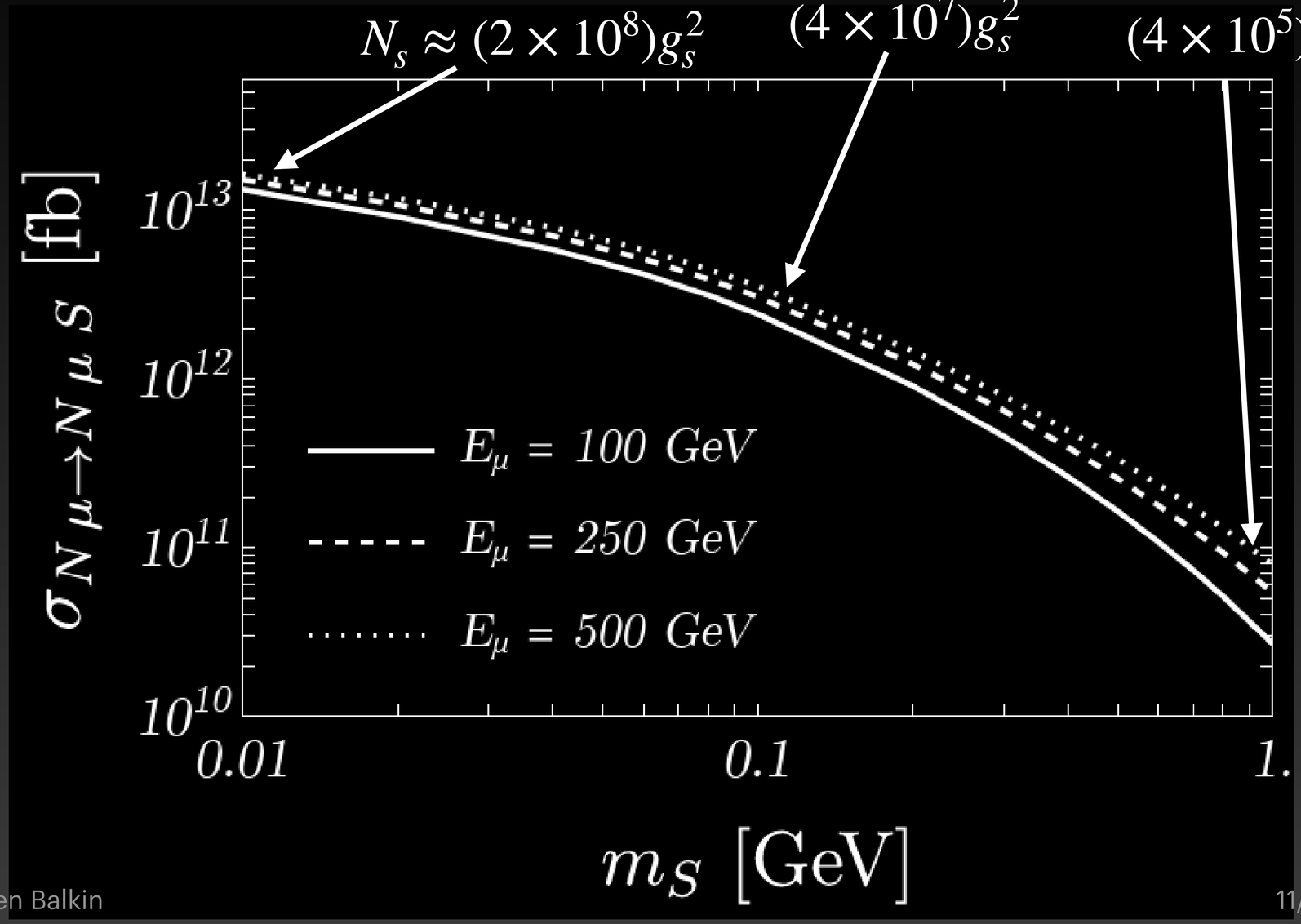

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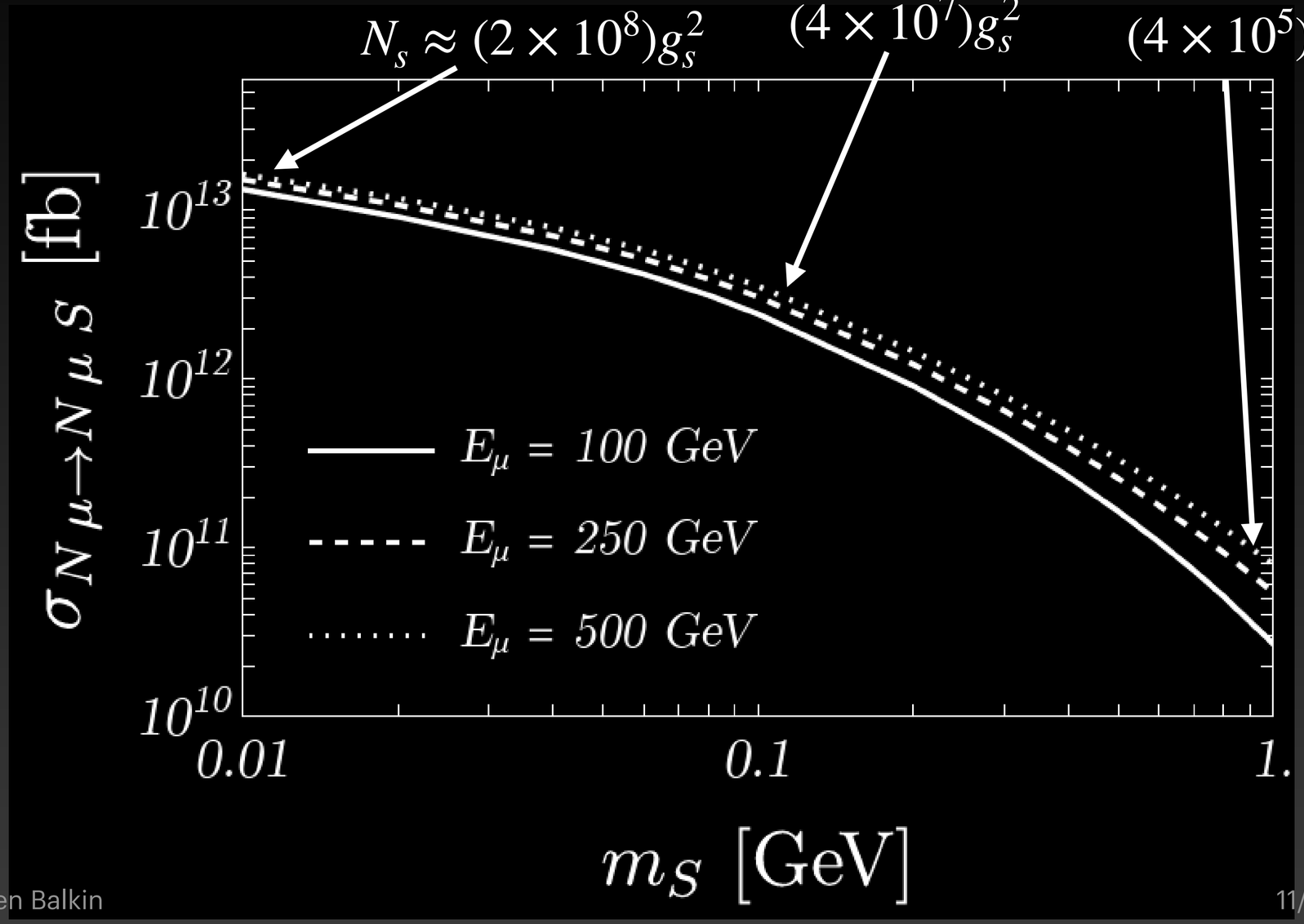

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$$\mathscr{L}_{\text{eff}} = \frac{N_\mu}{10^9}\frac{\rho_W}{m_W}\Delta_{\text{FASER}\nu}$$

$$\sim 5\times10^{-6}\ \text{fb}^{-1}$$

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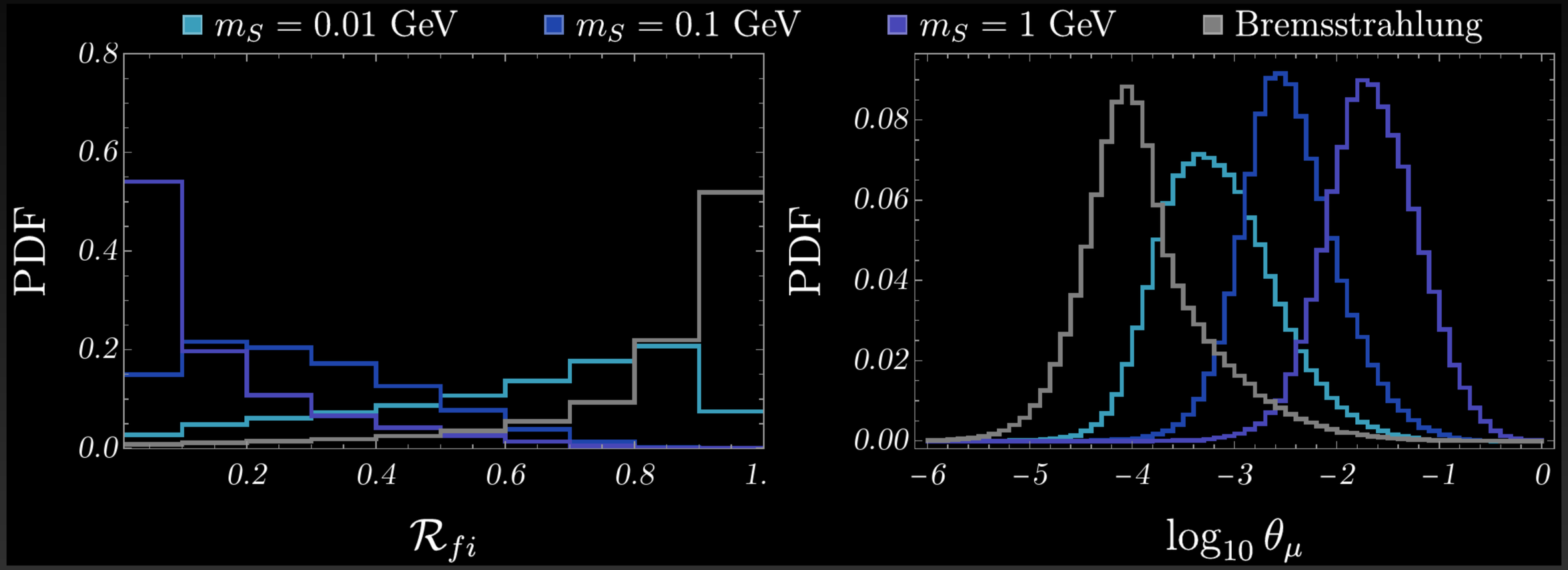
Signal distributions - scalar MFC



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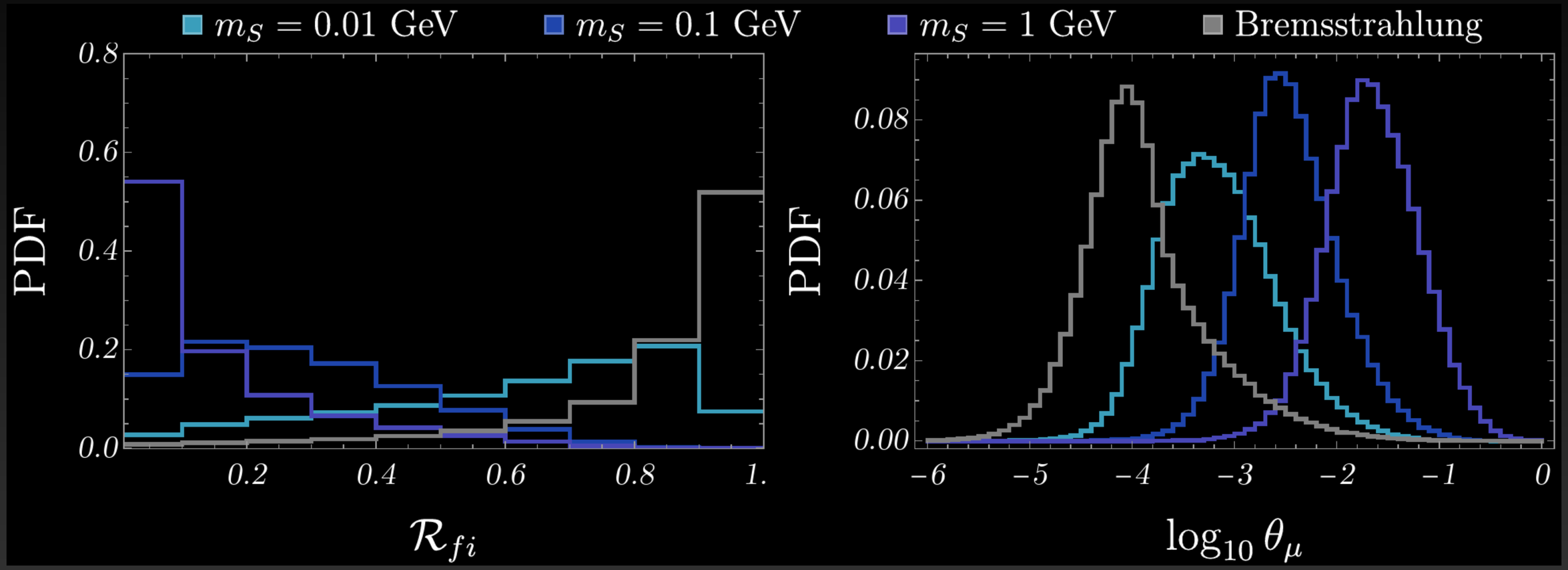

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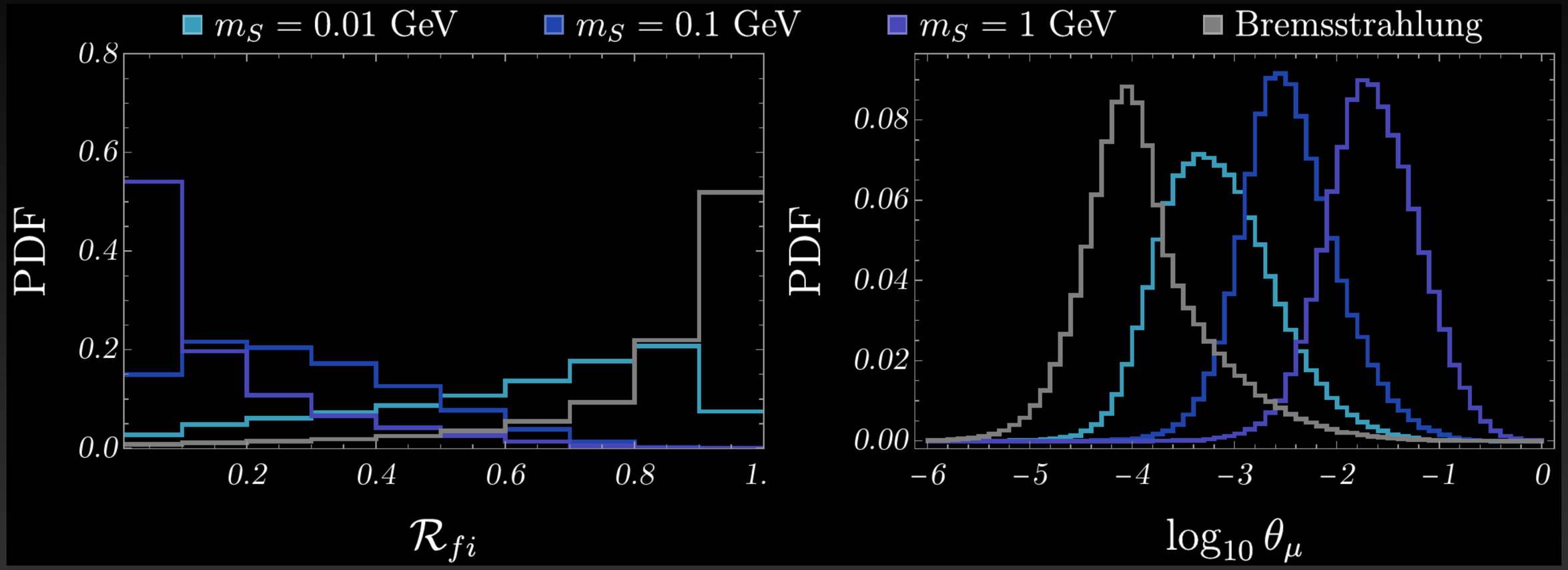

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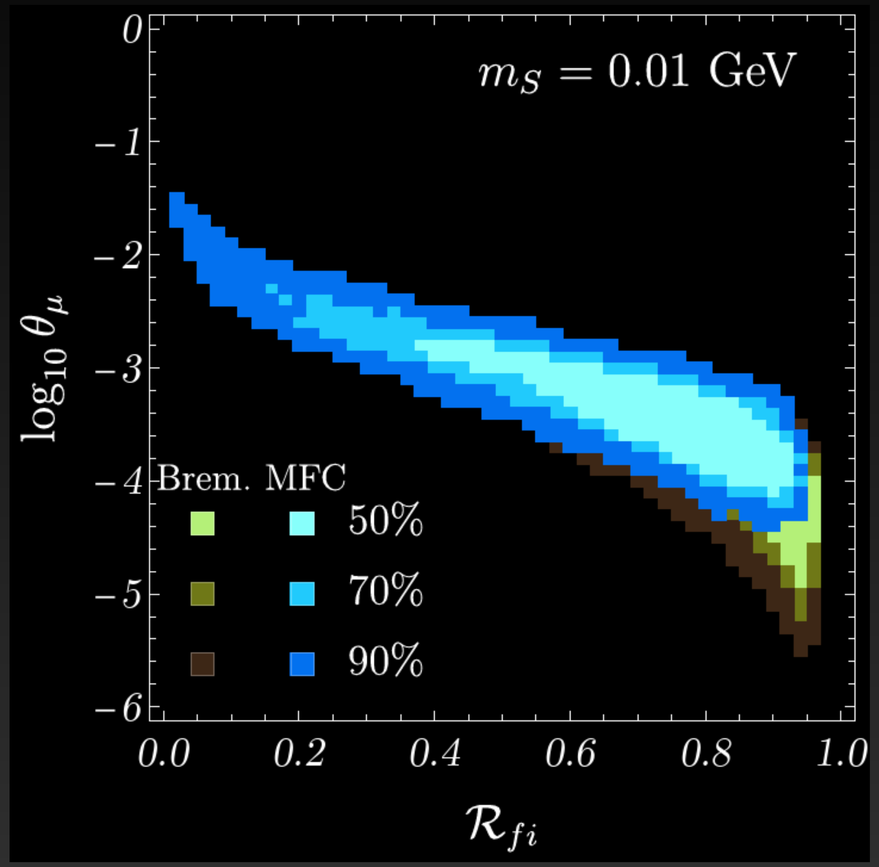

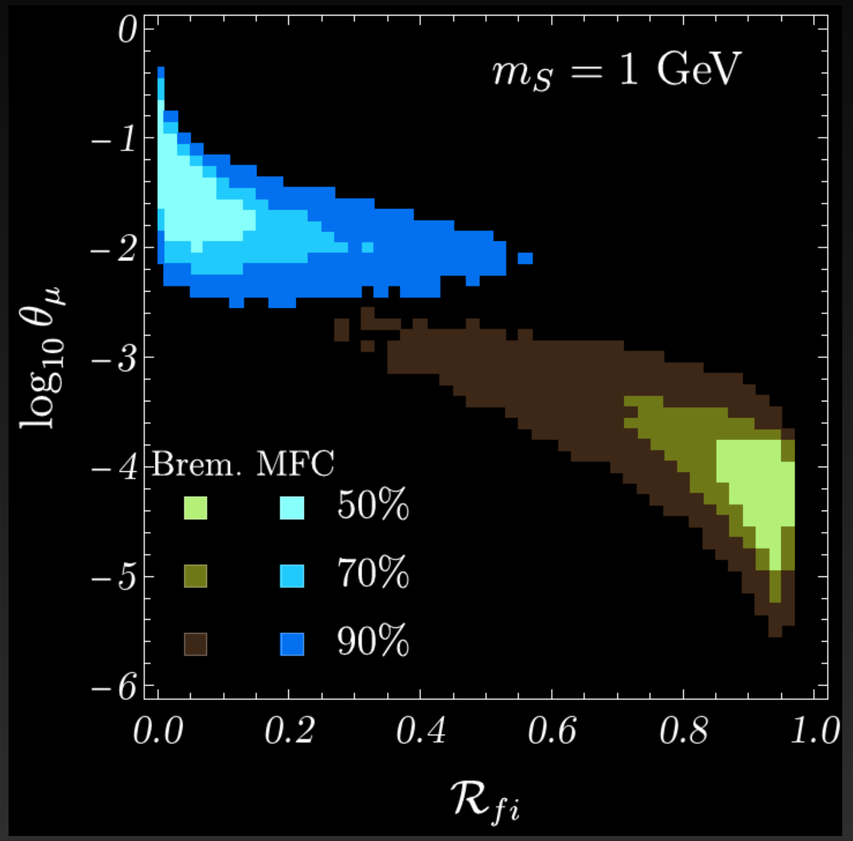

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Ionization $N\,\mu \to N^+\,\mu\,e^-$

Background - rare SM energy loss events

Pair production $N\,\mu \to N\,\mu\,e^+\,e^-$

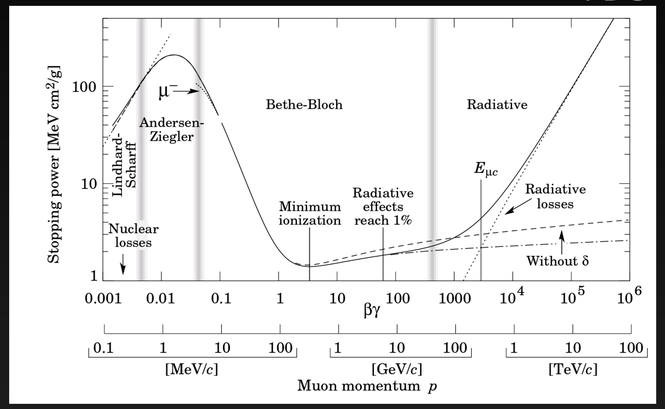
Nuclear (incoherent) $N\,\mu \to N^*\,\mu + \ldots$

Ionization $N\,\mu \to N^+\,\mu\,e^-$

Bremsstrahlung $N\,\mu \to N\,\mu\,\gamma$

Background - rare SM energy loss events

PDG



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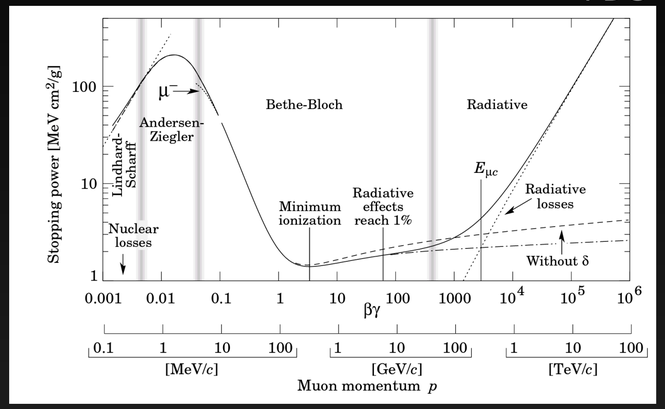

100 GeV muon in Tungsten:

$$\langle \mathrm{d}E/\mathrm{d}X \rangle = 0.311 \left(\frac{\text{GeV m}^2}{\text{gr}}\right) \times 19.3 \left(\frac{\text{gr}}{\text{m}^3}\right) \sim 6 \left(\frac{\text{GeV}}{\text{m}}\right)$$

with

ion:pair:brem:nuc $\sim 1 : 0.4 : 0.25 : 0.01$

(**not** rare)

Background - rare SM energy loss events

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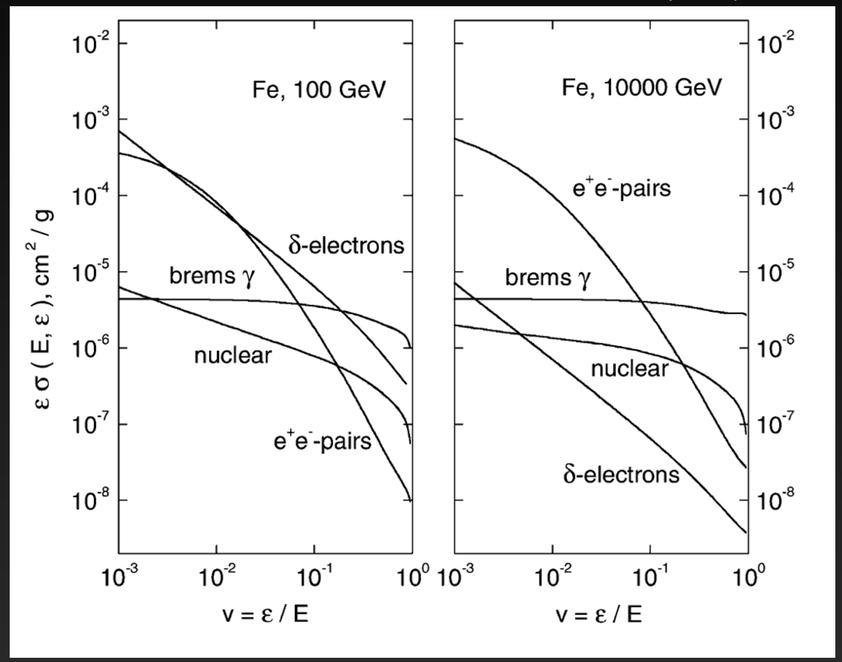
IEEE Trans.Nucl.Sci. 53 (2006) 513-519



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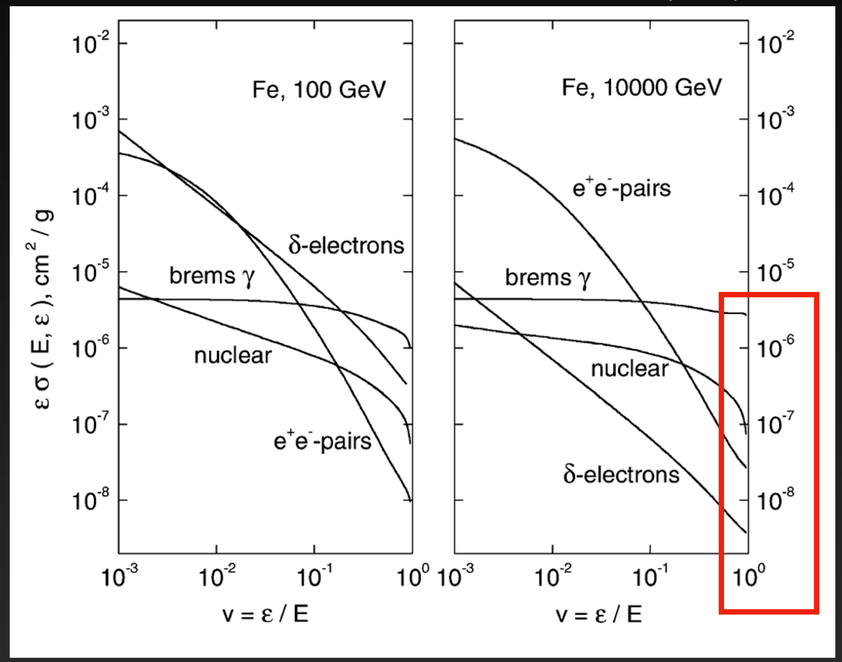

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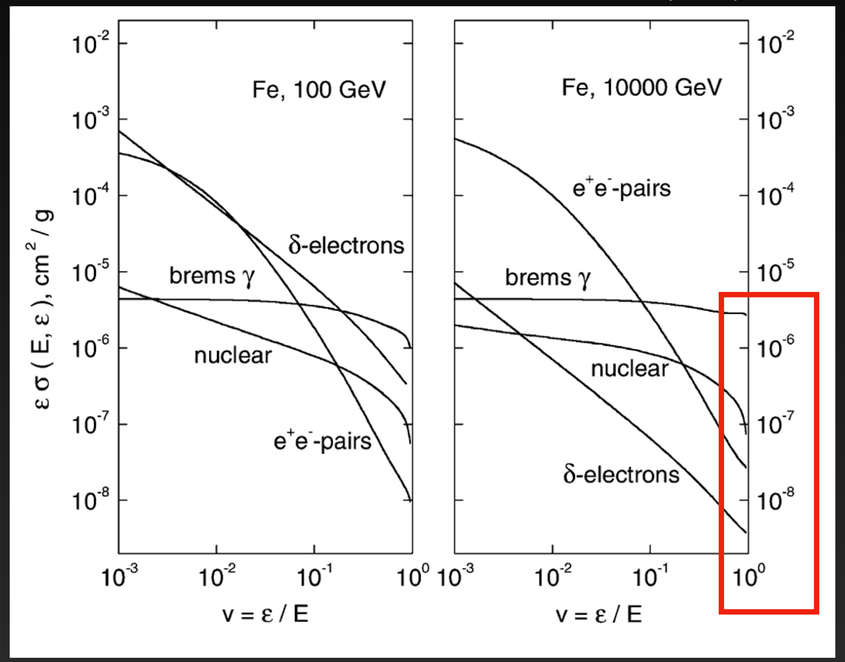
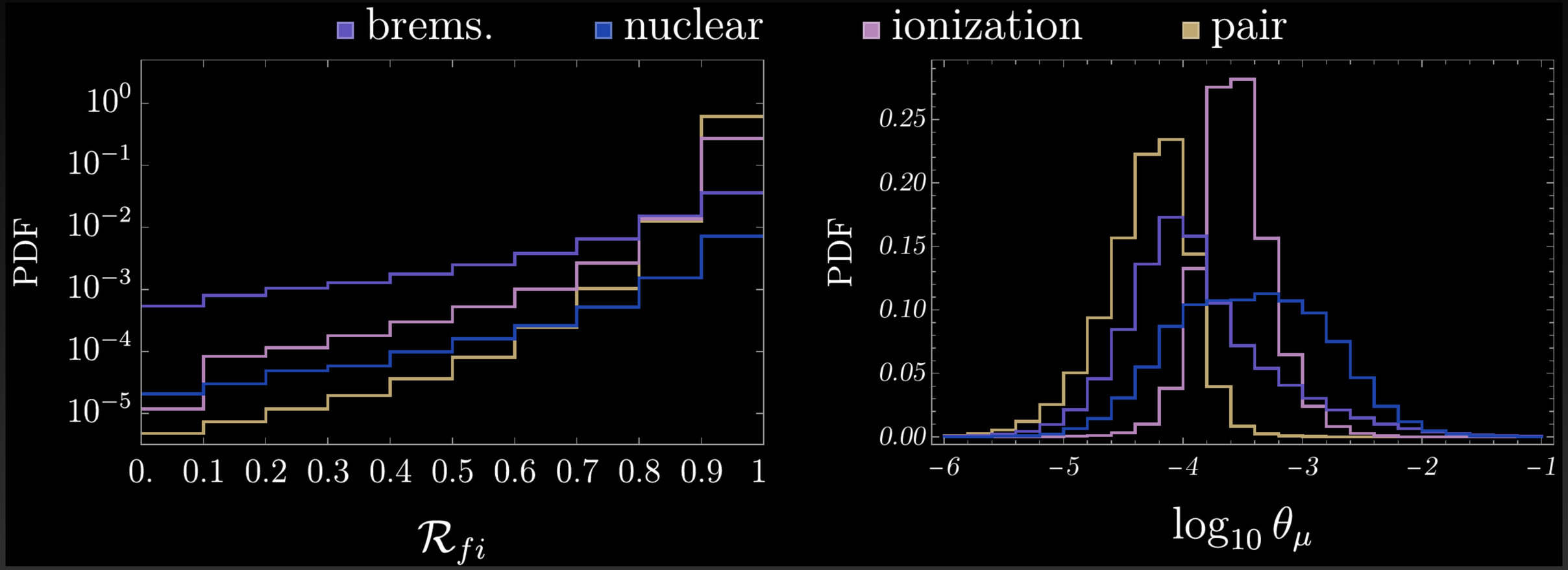


	Pair	Ionization	Brems.	Nuclear	Total
# of tracks	3.15×10^6	1.42×10^6	3.45×10^5	4.7×10^4	4.96×10^6
Fraction	0.63	0.29	0.07	0.009	1.0

(Labeled by single largest energy-loss event)

Background - rare SM energy loss events



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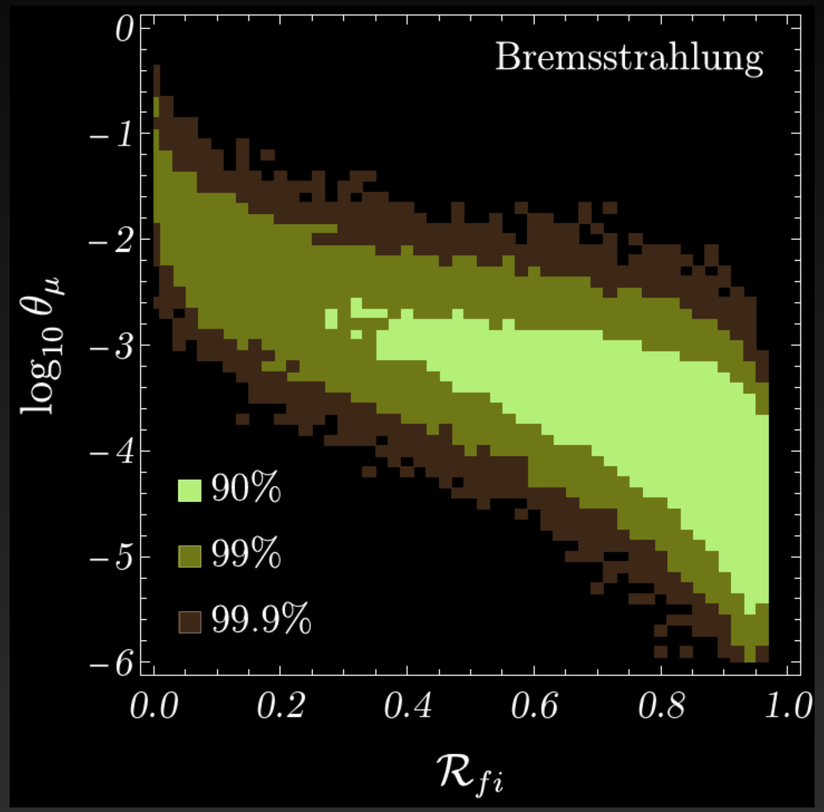

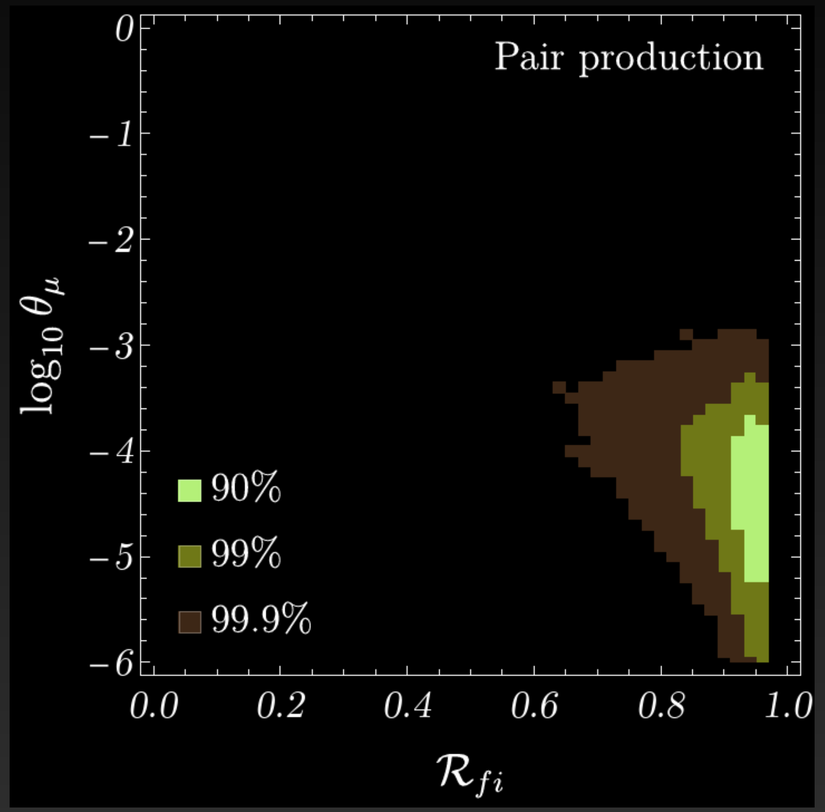

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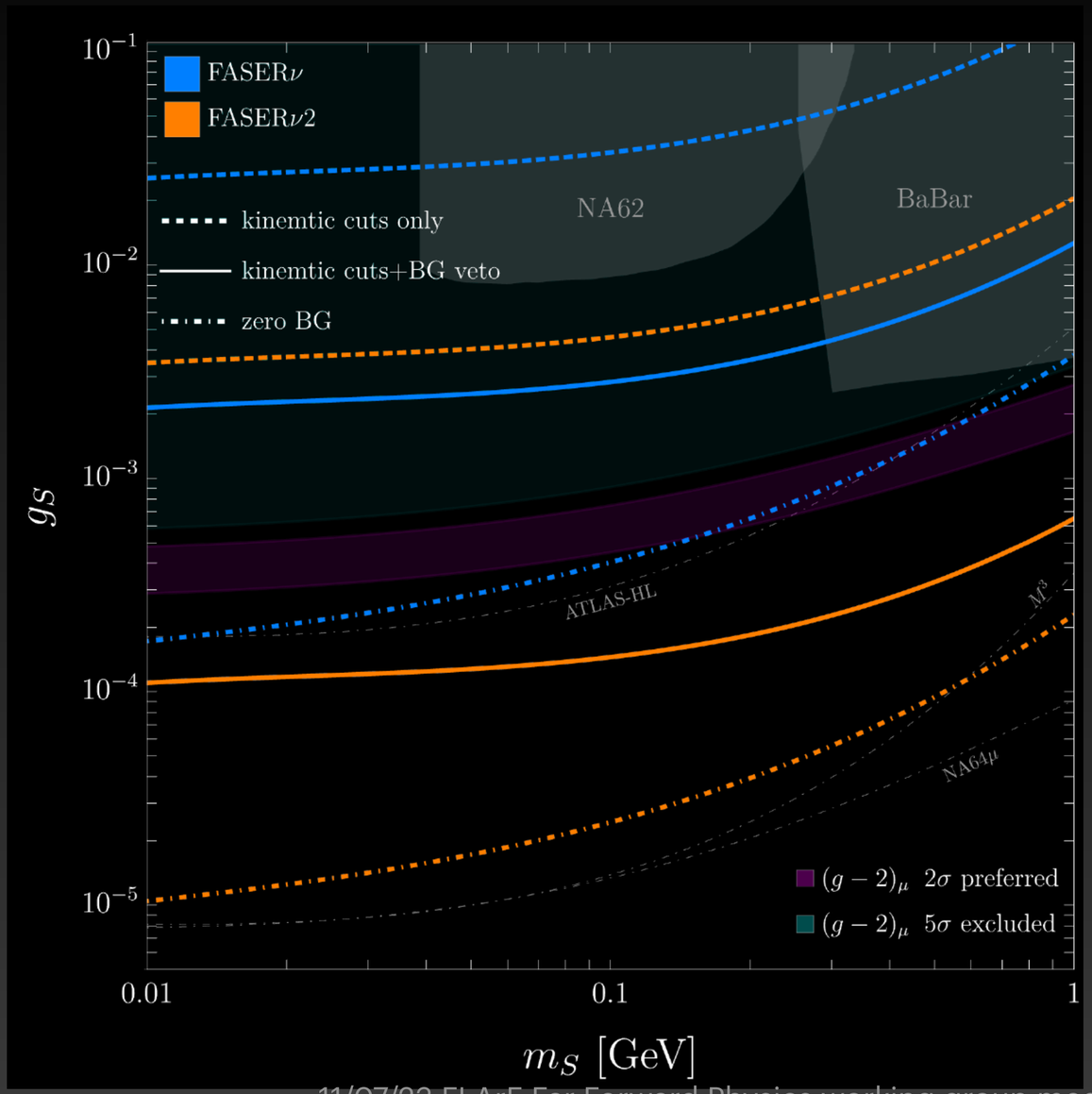
Talk layout

- Theory: motivation and status
- Basic search idea
- Signal
- Background
- **Results and summary**

Results

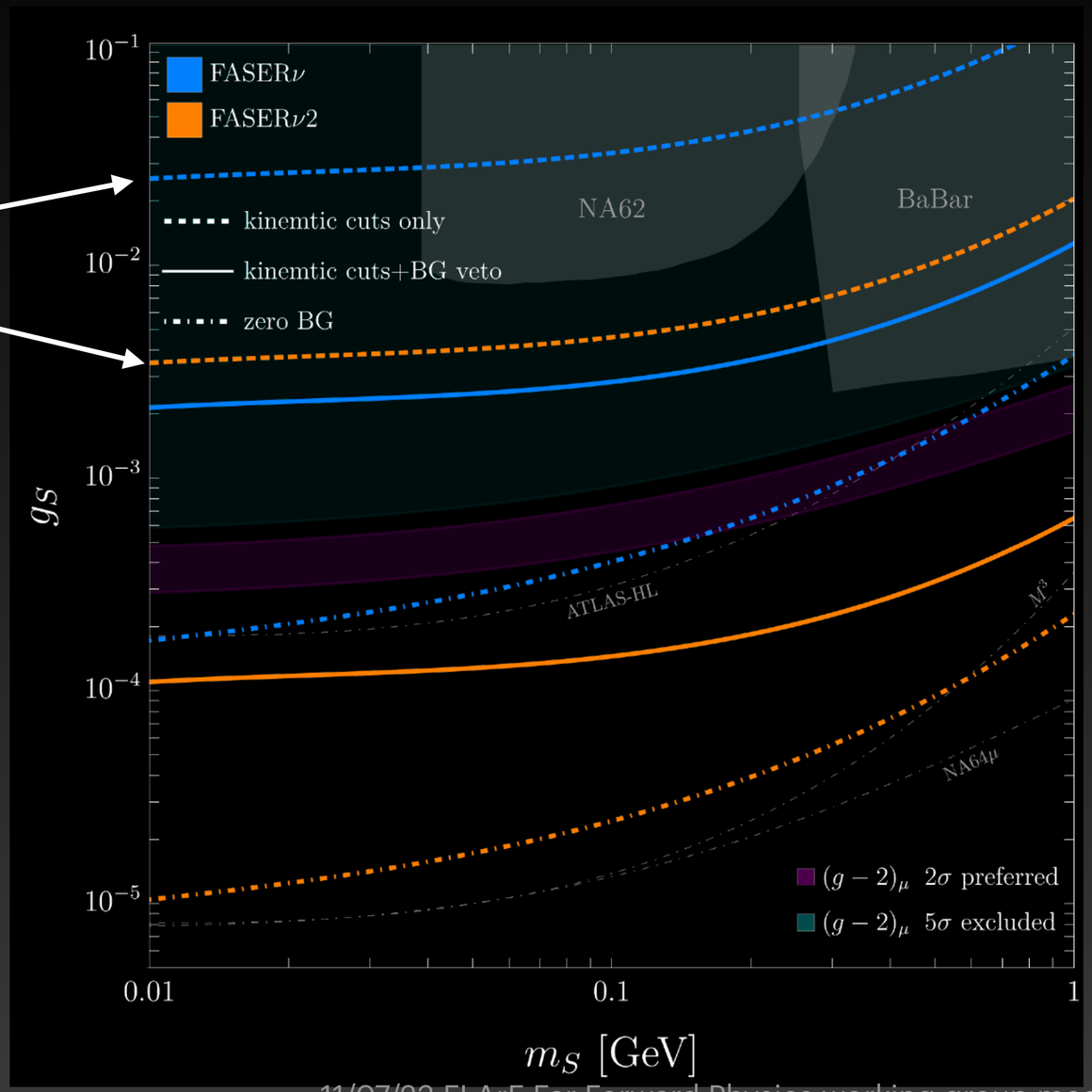

FASERν
FASERν2
kinemtic cuts only
kinemtic cuts+BG veto
zero BG
NA62
BaBar
ATLAS-HL
M³
NA64μ
(g − 2)μ 2σ preferred
(g − 2)μ 5σ excluded
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
gS
0.01
0.1
1
mS [GeV]

Results

$\text{Faser}\nu : \mathcal{L} = 250\,\text{fb}^{-1}, \text{S} = 25 \times 30\,\text{cm}^2, \Delta = 730 \times 1.1\,\text{mm}$

$\text{Faser}\nu 2 : \mathcal{L} = 3\,\text{ab}^{-1}, \text{S} = 40 \times 40\,\text{cm}^2, \Delta = 3300 \times 2\,\text{mm}$

Worst case
(kinematic cuts only)



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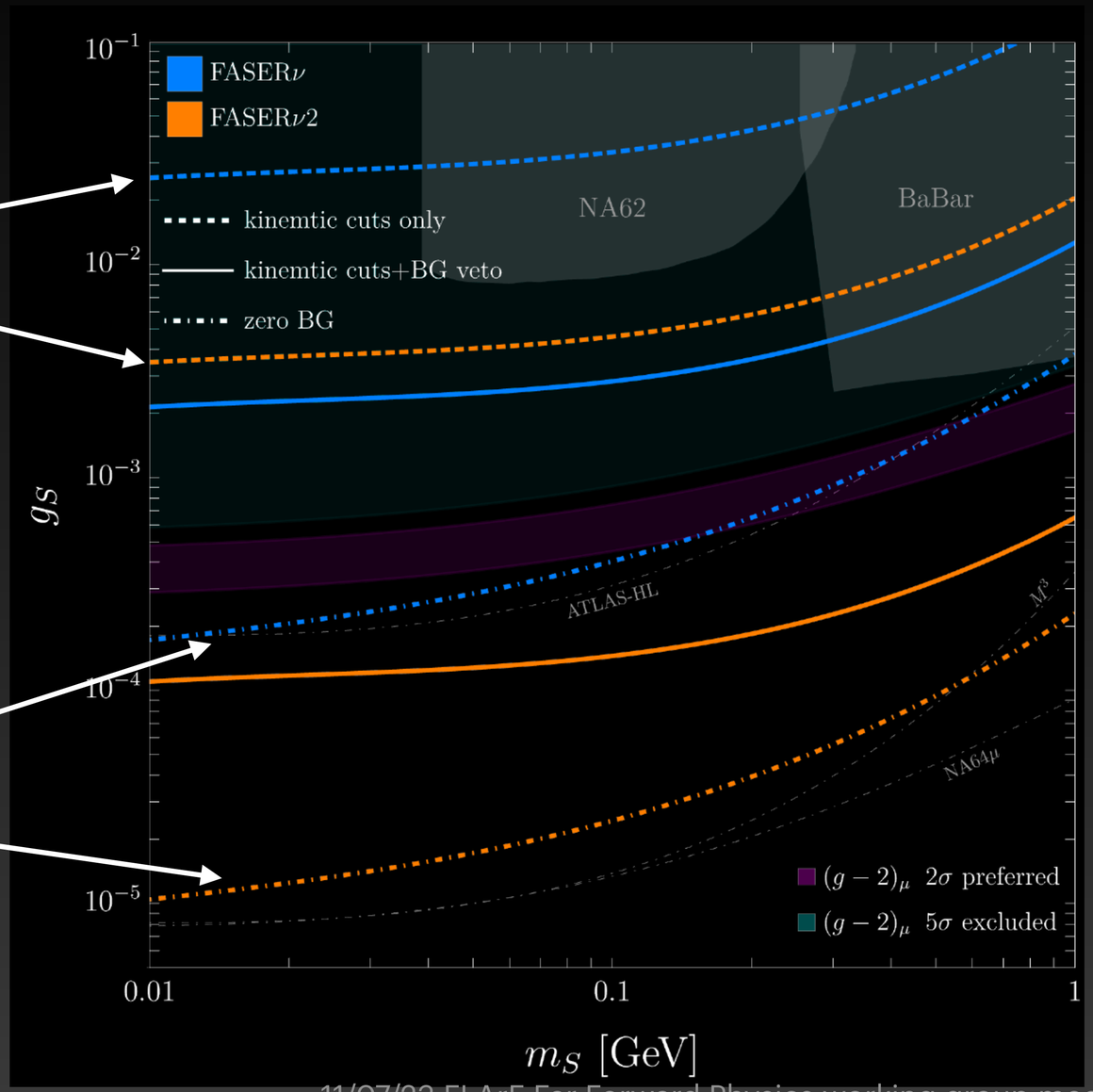
(kinematic cuts only)

Best case
(Background free)



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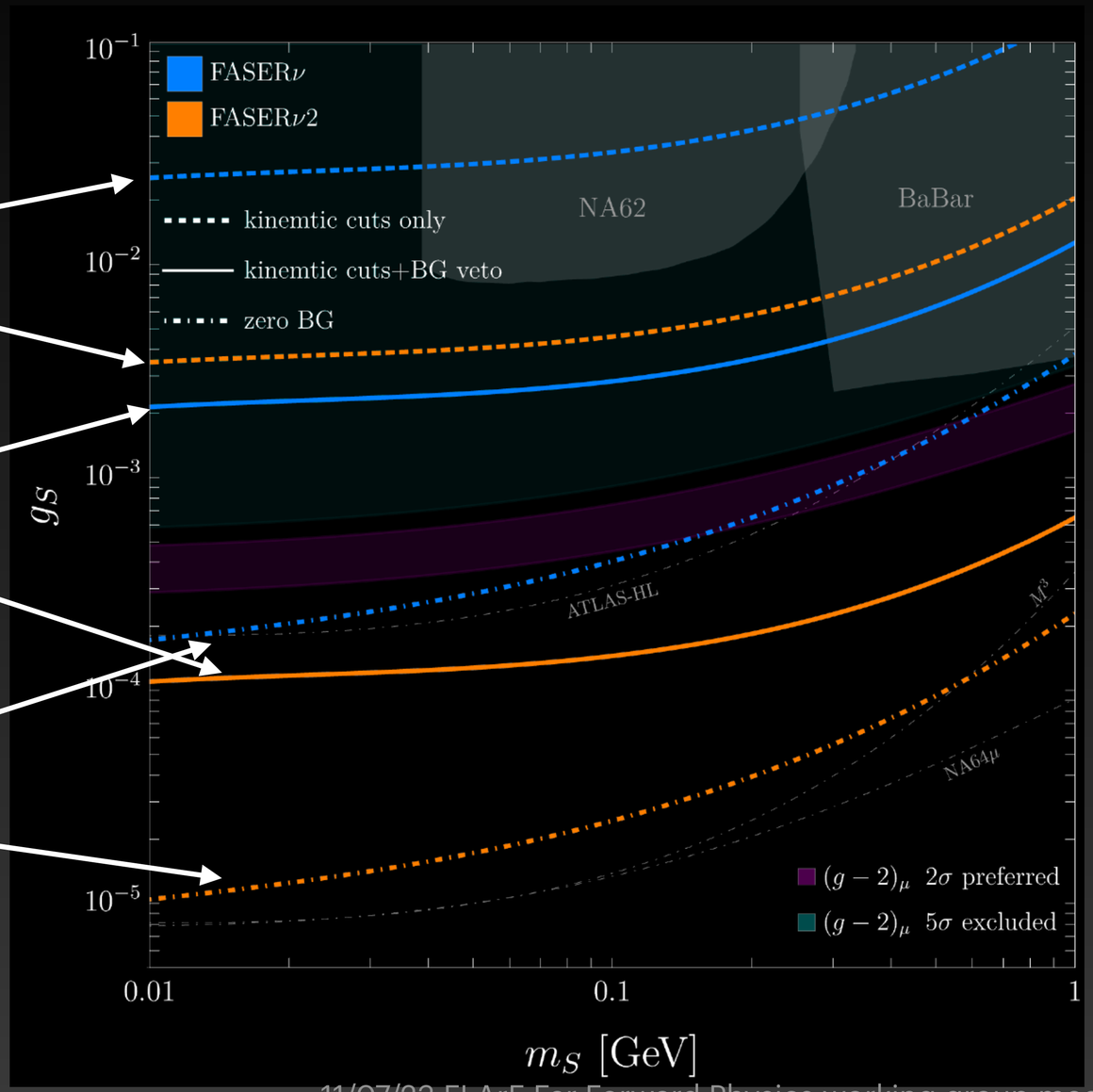

Results

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$$N_{\mathrm{BG}}\,(\mathrm{total}) \sim \mathrm{N}_{\mu} \sim 10^{9}$$

	$\mathcal{R}_{fi}$	θ_μ	$\epsilon_{\mathrm{S}}^{\mathrm{kin.}}$	$N_{\mathrm{BG,brem}}$	$N_{\mathrm{BG,ion}}$	$N_{\mathrm{BG,pair}}$	$N_{\mathrm{BG,nuc}}$
$m_S = 0.01$ GeV	$\lesssim 0.7$	$\gtrsim 1$ mrad	~ 0.2	9.9×10^6	8.9×10^6	2.5×10^5	2.0×10^6
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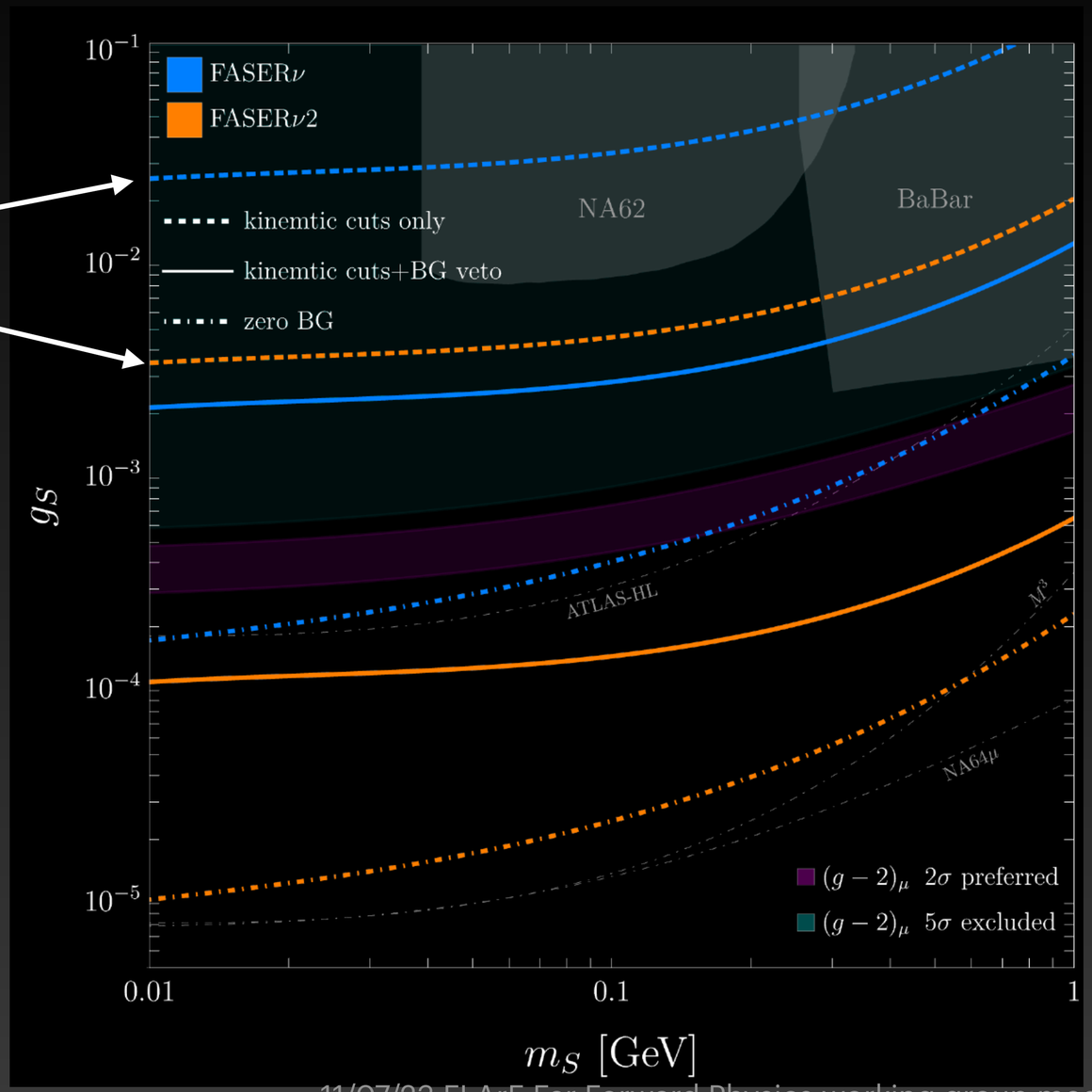

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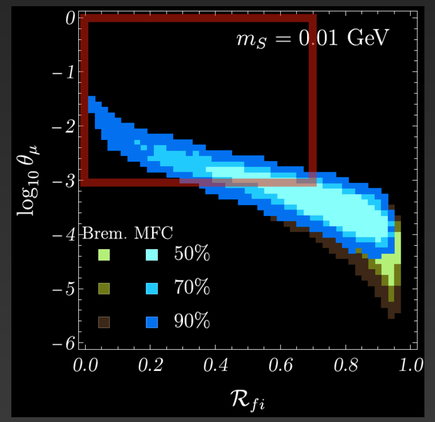

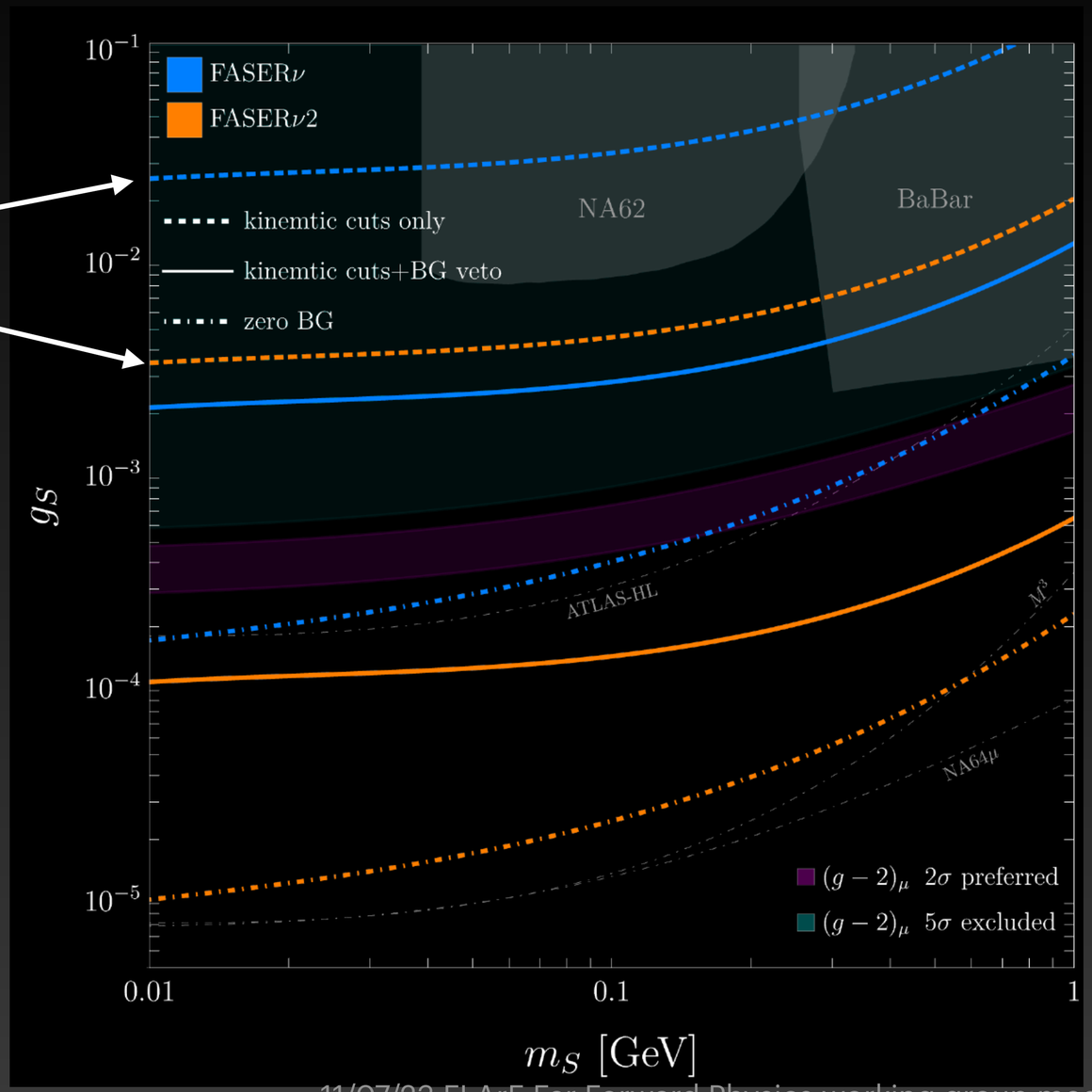

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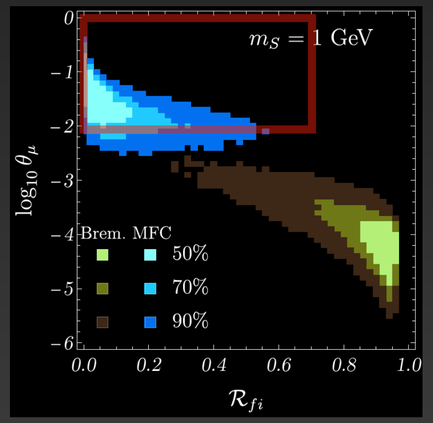

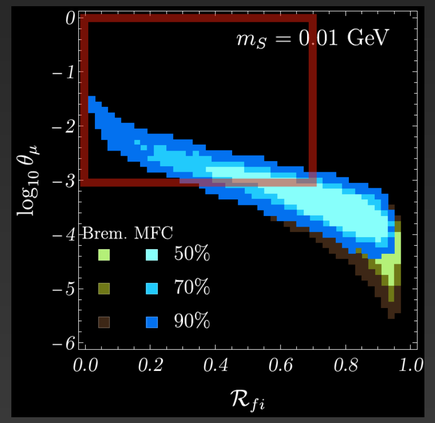

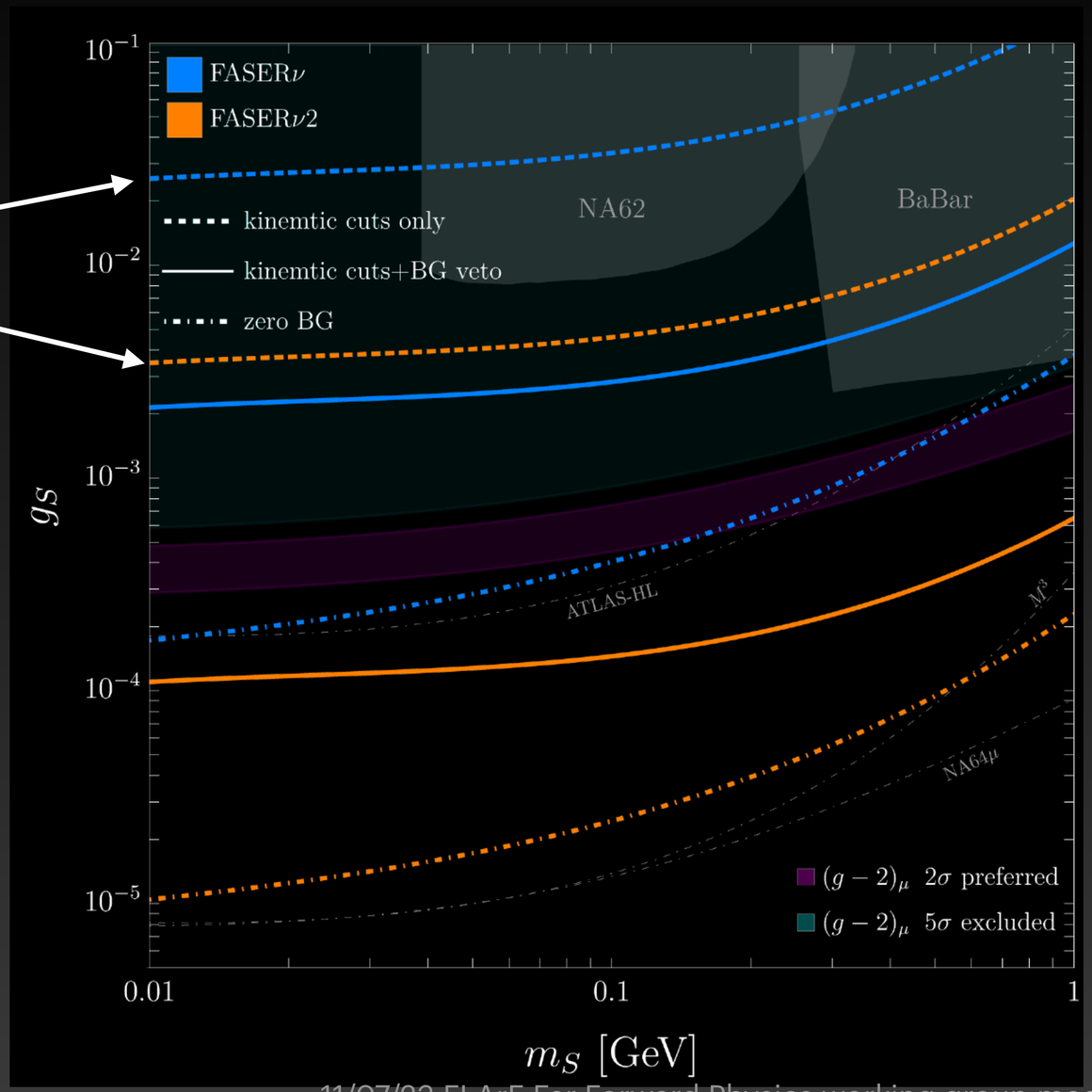

- 40% energy resolution from MCS method

Results

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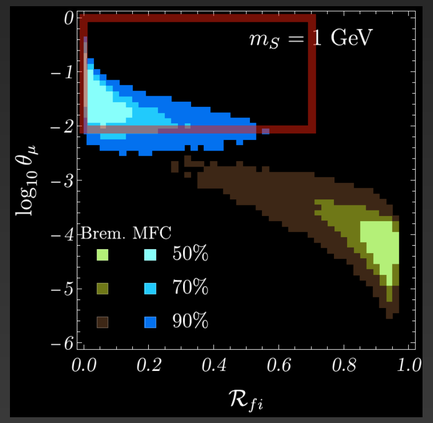

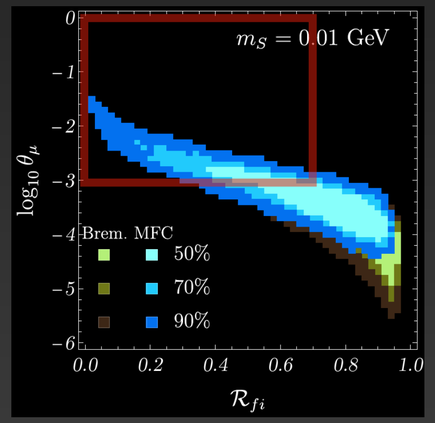

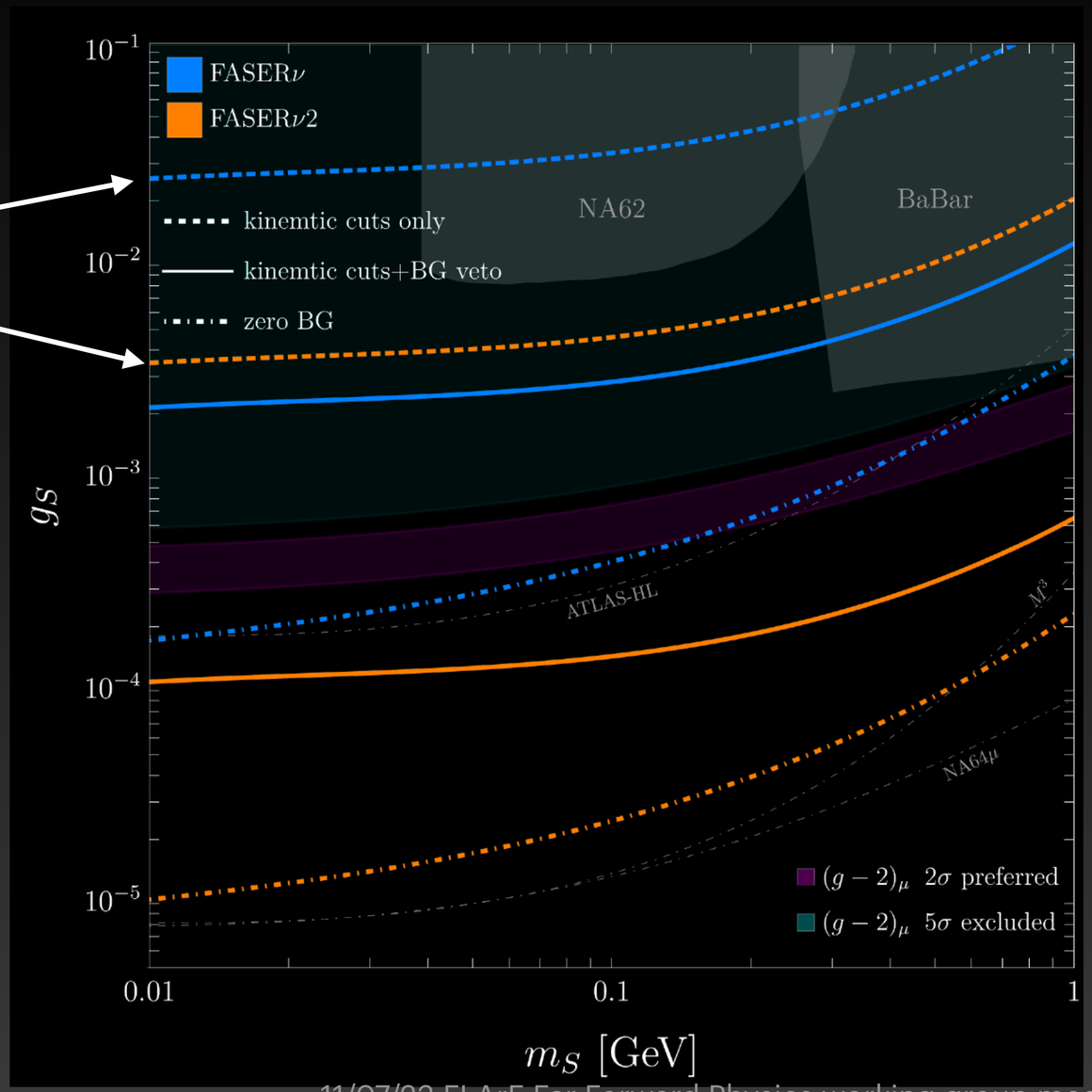

Results

- 40% energy resolution from MCS method
- Reduced signal efficiency from removing edges

Worst case
(kinematic cuts only)

$$N_{\mathrm{BG}}\,(\mathrm{total}) \sim \mathrm{N}_{\mu} \sim 10^{9}$$

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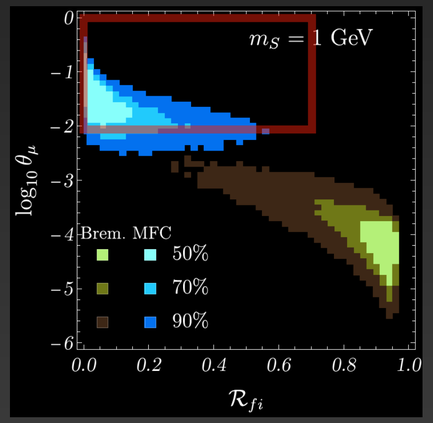

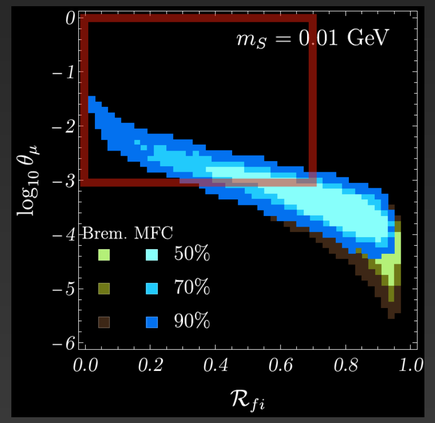

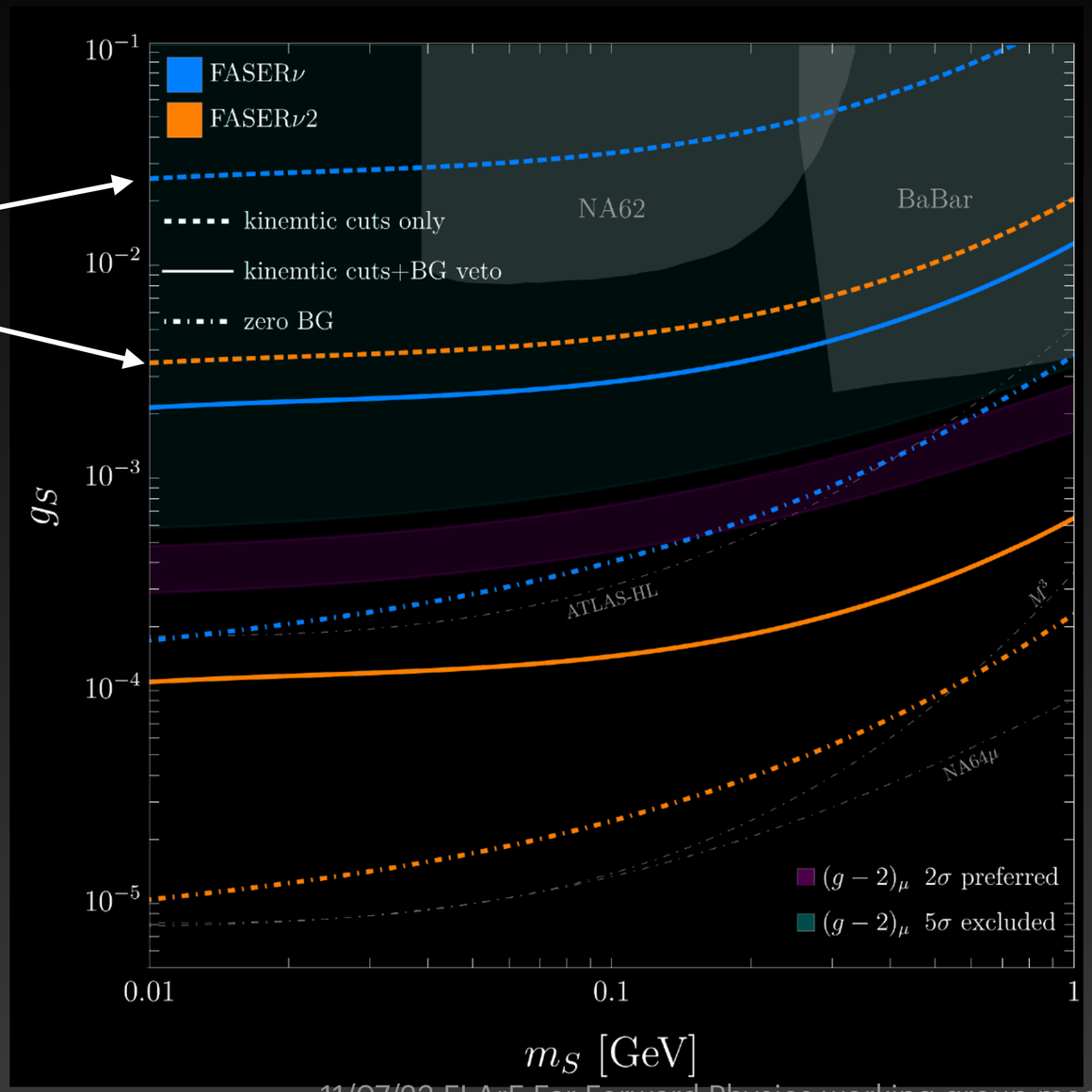

Results

- 40% energy resolution from MCS method
- Reduced signal efficiency from removing edges
- Assumed kink location is known (sliding window)

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(kinematic cuts only)

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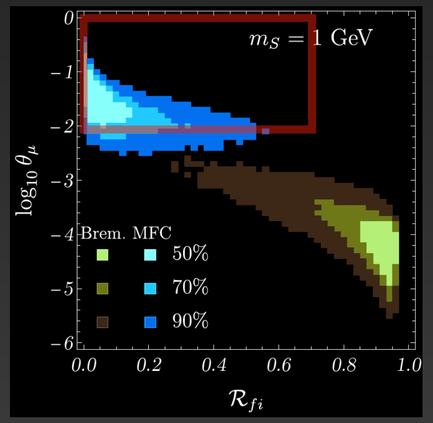

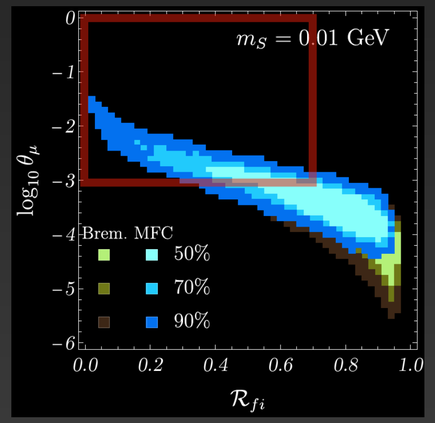

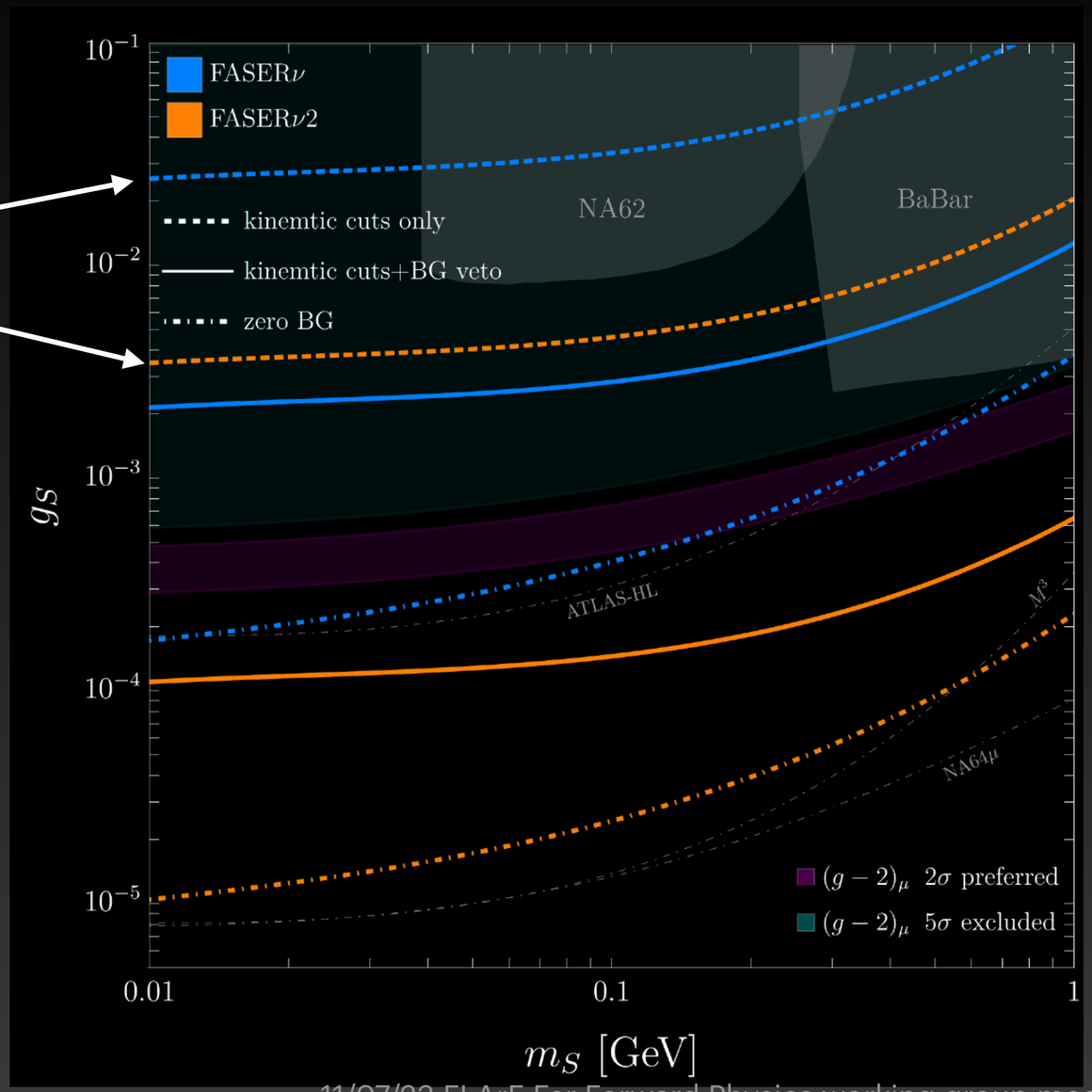

Results

- 40% energy resolution from MCS method
- Reduced signal efficiency from removing edges
- Assumed kink location is known (sliding window)
- Angular resolution (single layer) $\sigma_\theta = \sqrt{2}\sigma_{xy}/L \sim 2 \times 10^{-4}$

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(kinematic cuts only)

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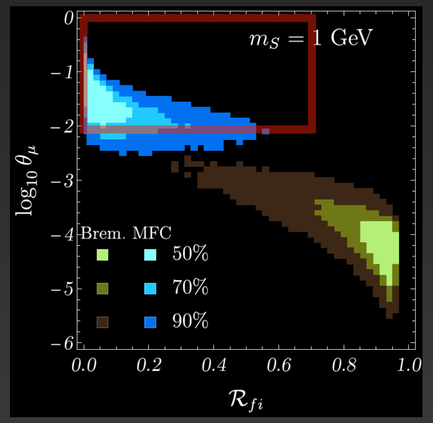
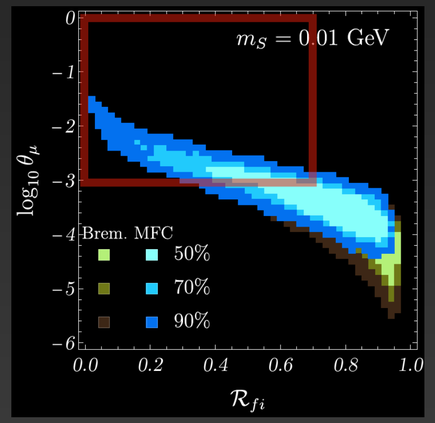
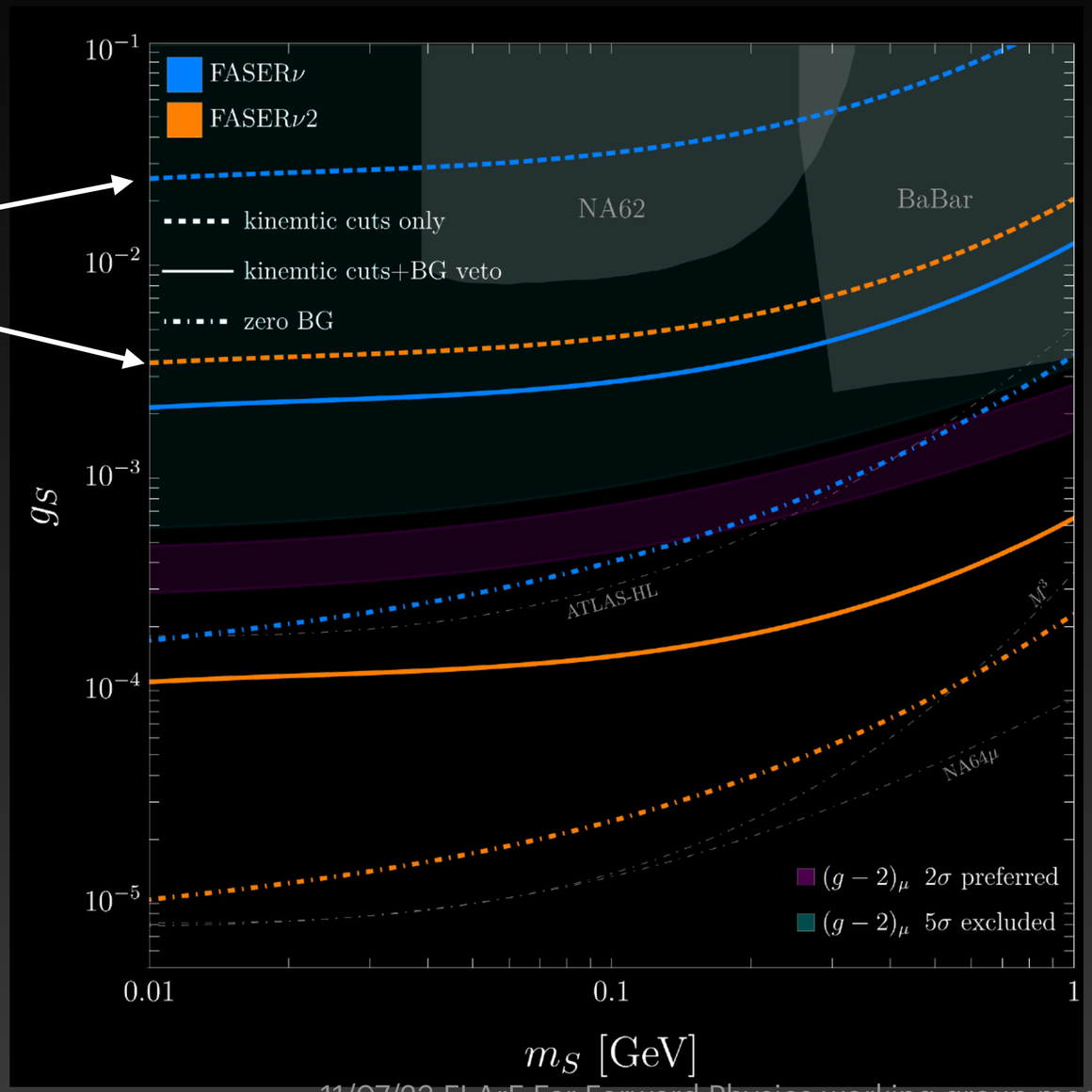


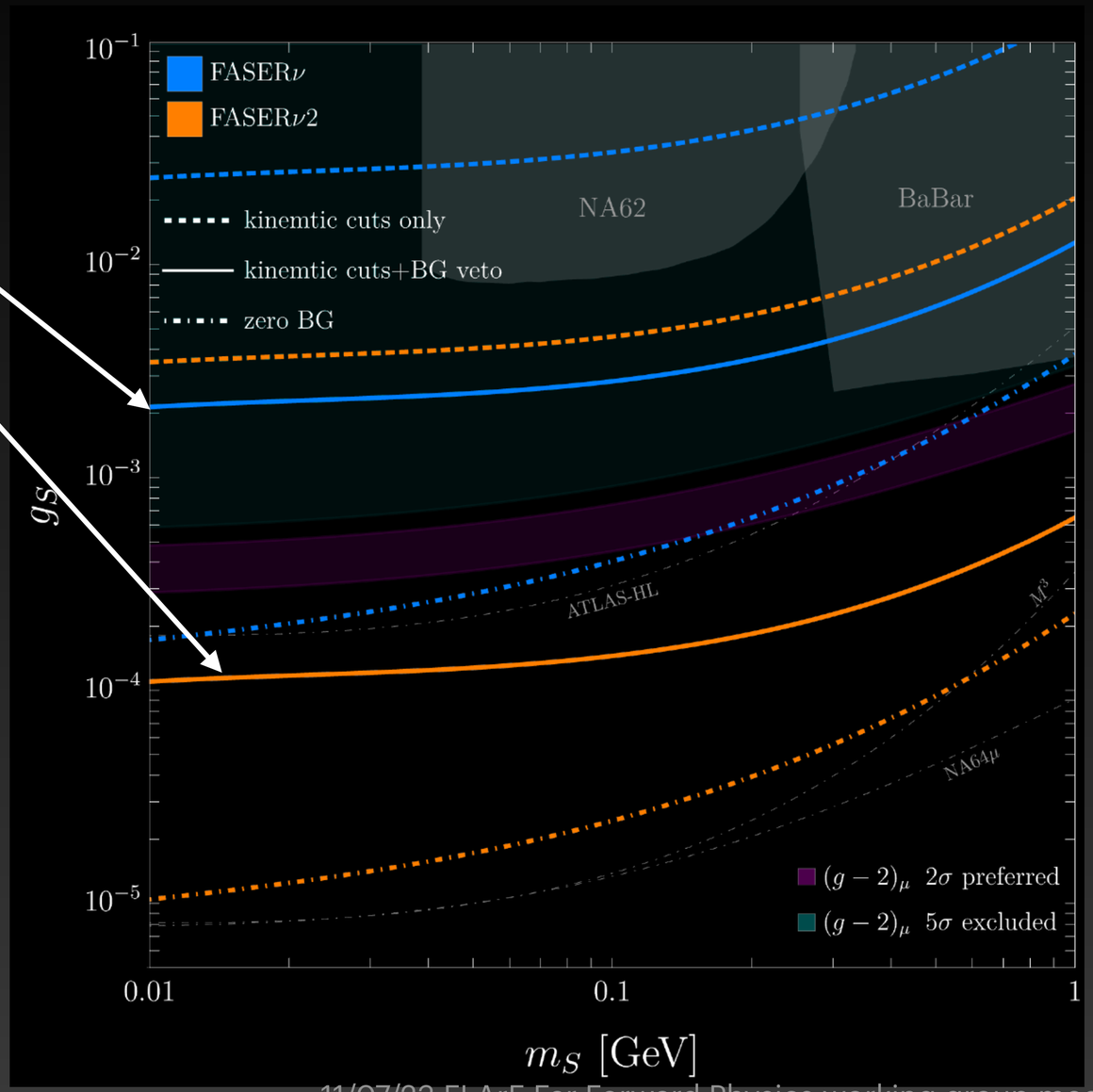




Results

Realistic case
(Cuts+veto)

$$\varepsilon_{\text{brem}} = 5 \times 10^{-5}\,(10^{-6})$$



Results

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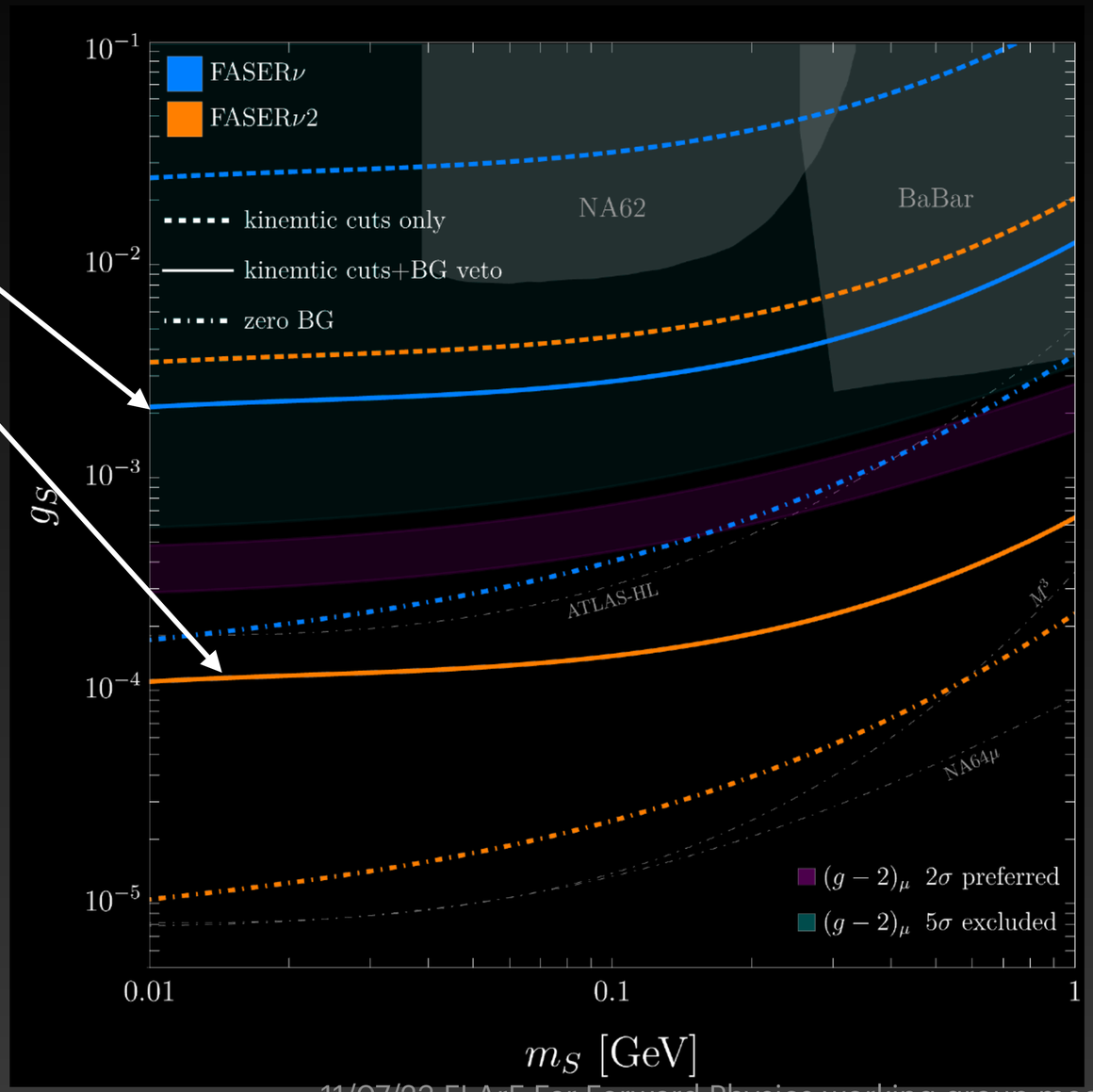
(Cuts+veto)

$$\varepsilon_{\text{brem}} = 5 \times 10^{-5}\,(10^{-6})$$

-All BGs except brems are prompt - easier to find

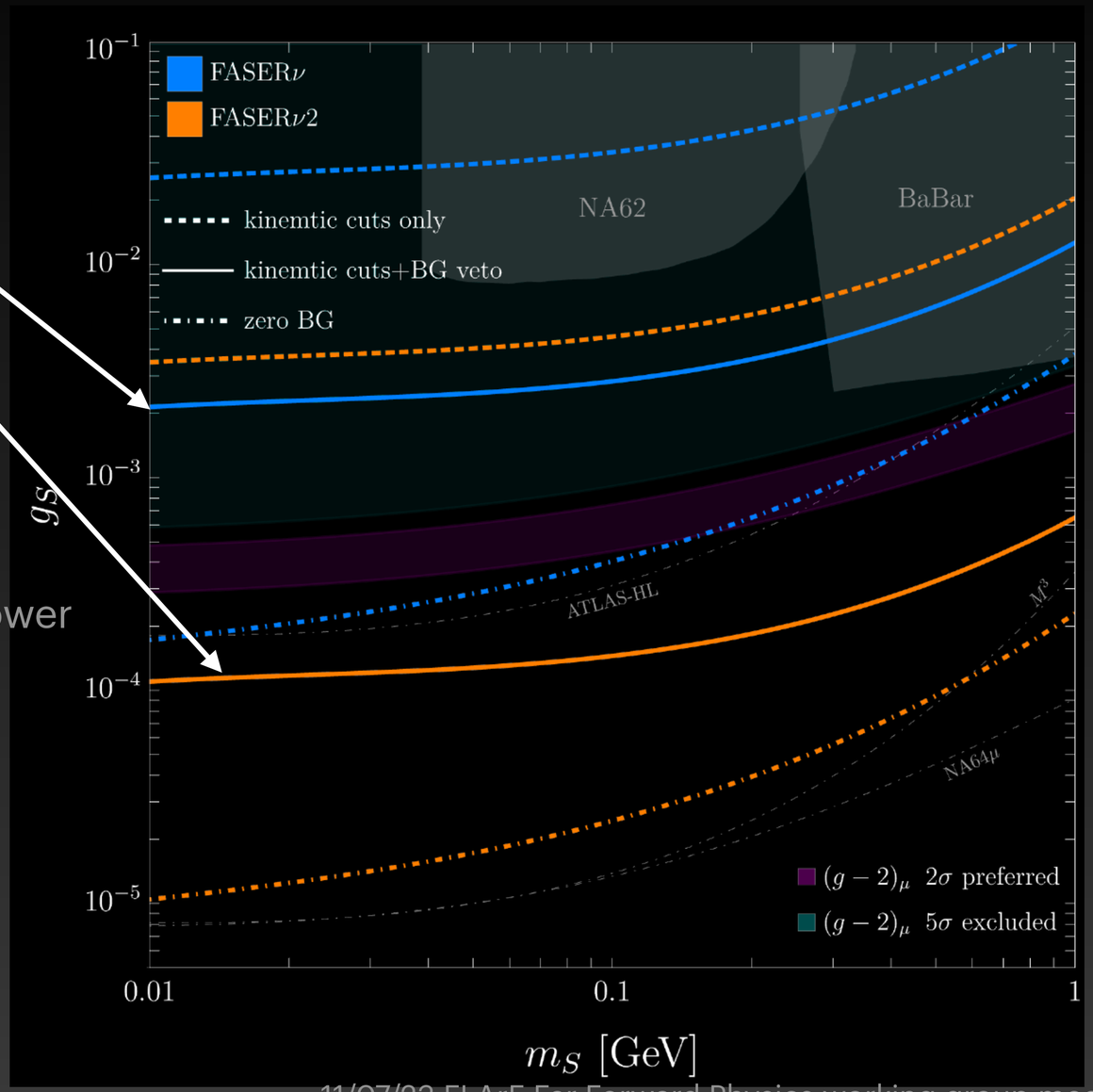


Results

Realistic case
(Cuts+veto)

$$\varepsilon_{\text{brem}} = 5 \times 10^{-5}\,(10^{-6})$$

-All BGs except brems are prompt - easier to find
-Emitted photon first propagates and than “decays” via EM shower



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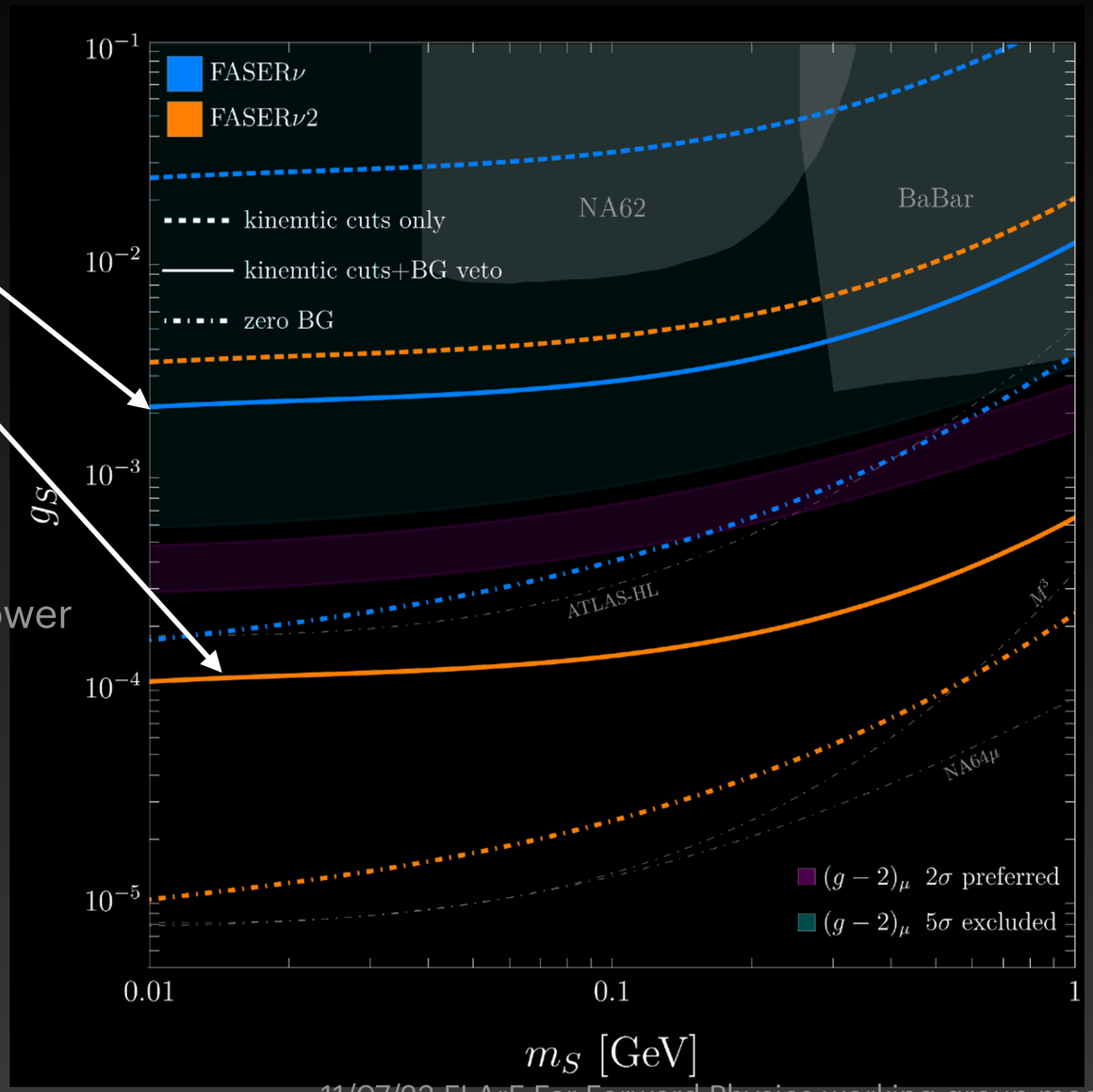
$$\langle \Delta_\gamma \rangle \sim X_0 \langle \sin\theta_\gamma \rangle \sim (4\ \text{mm}) \times 10^{-3}$$



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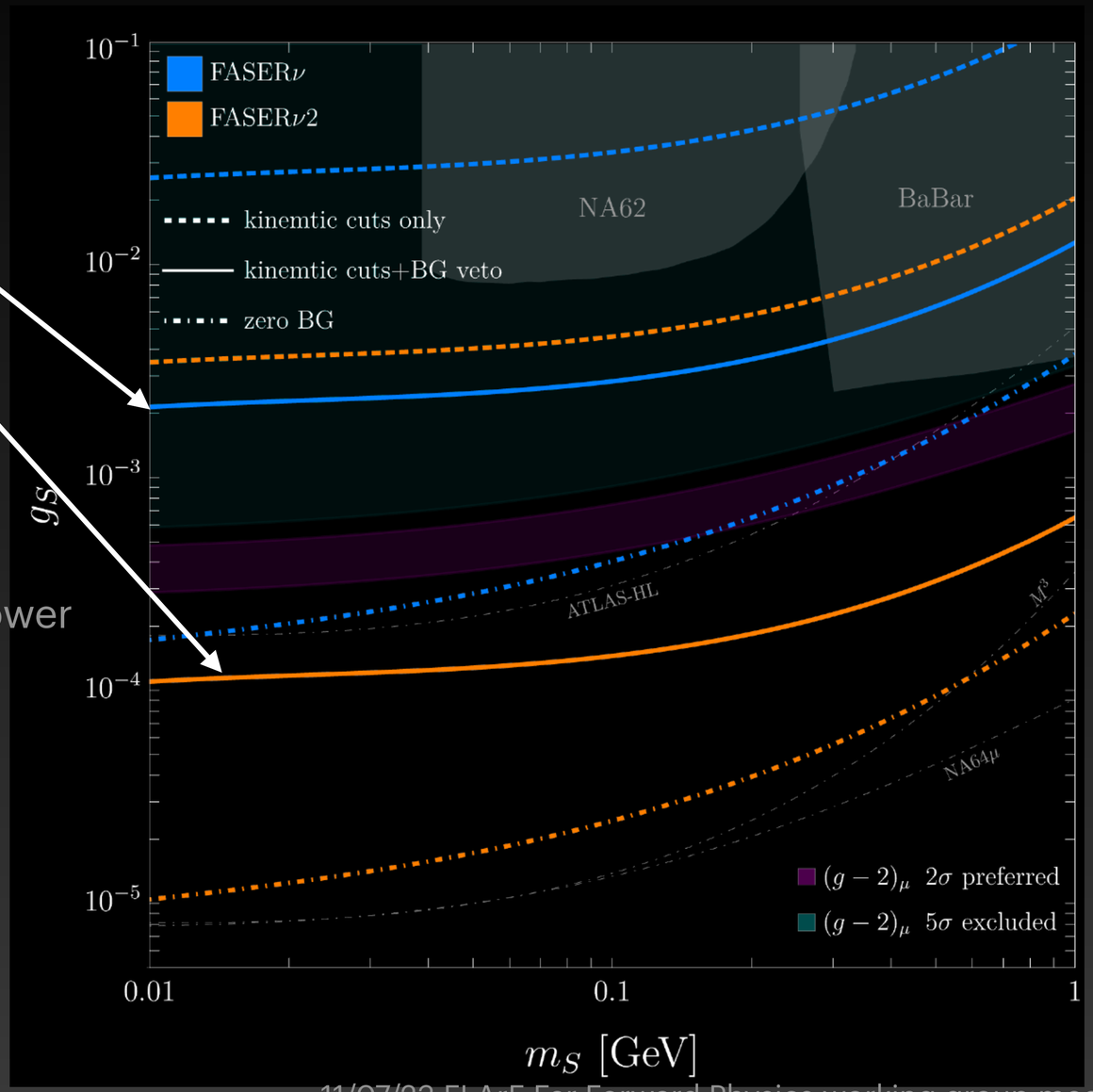

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Realistic case
(Cuts+veto)

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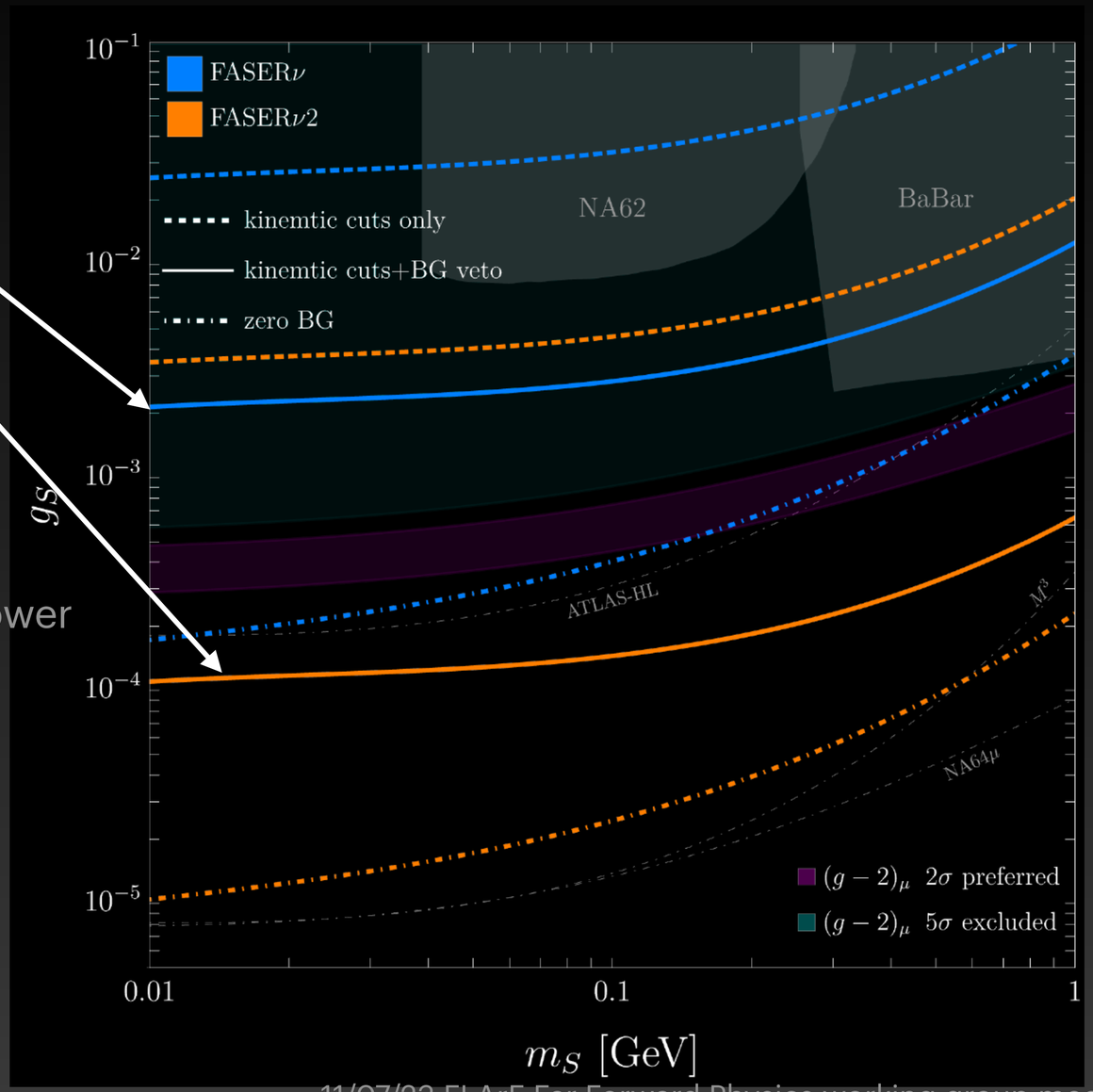

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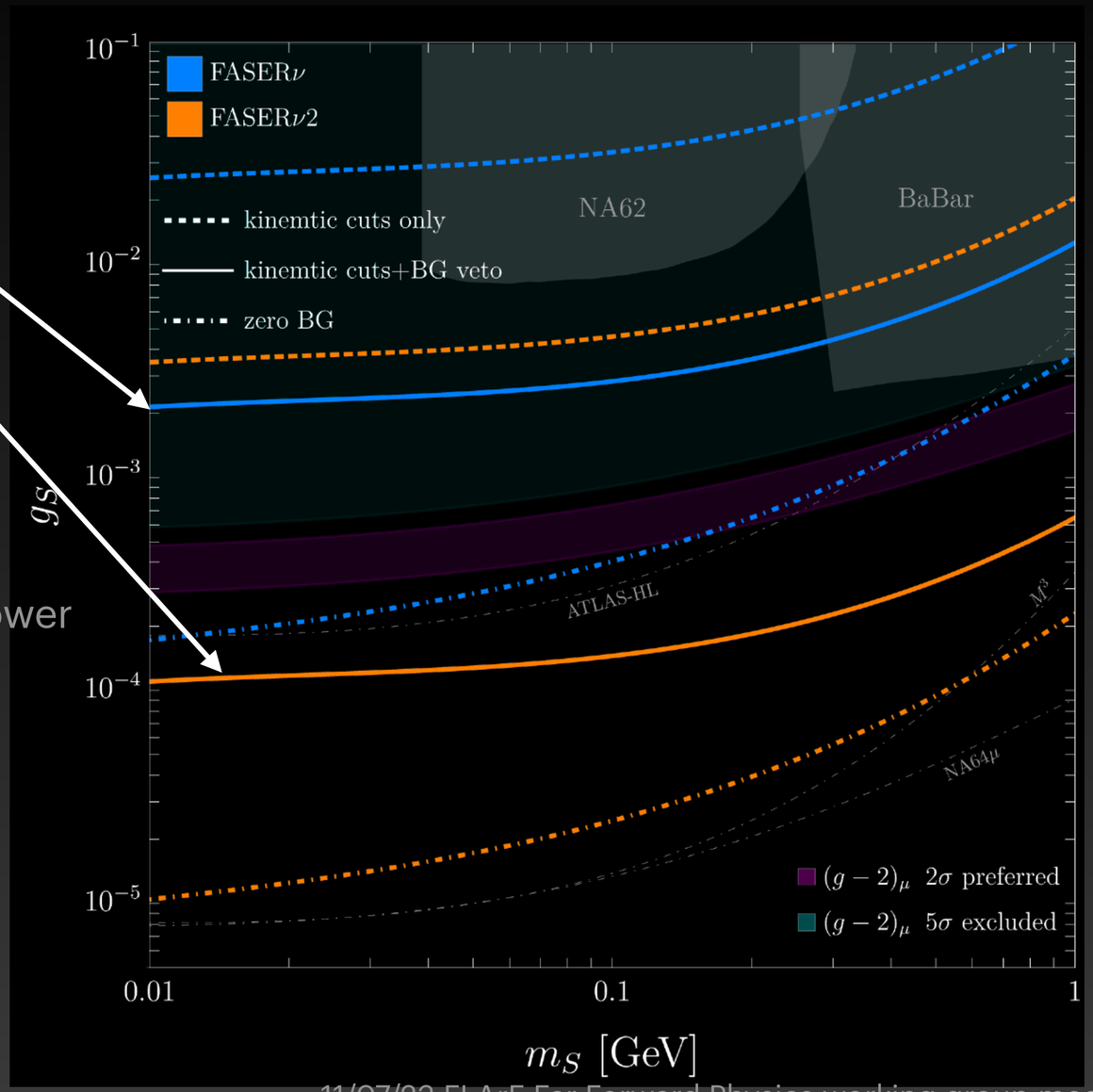

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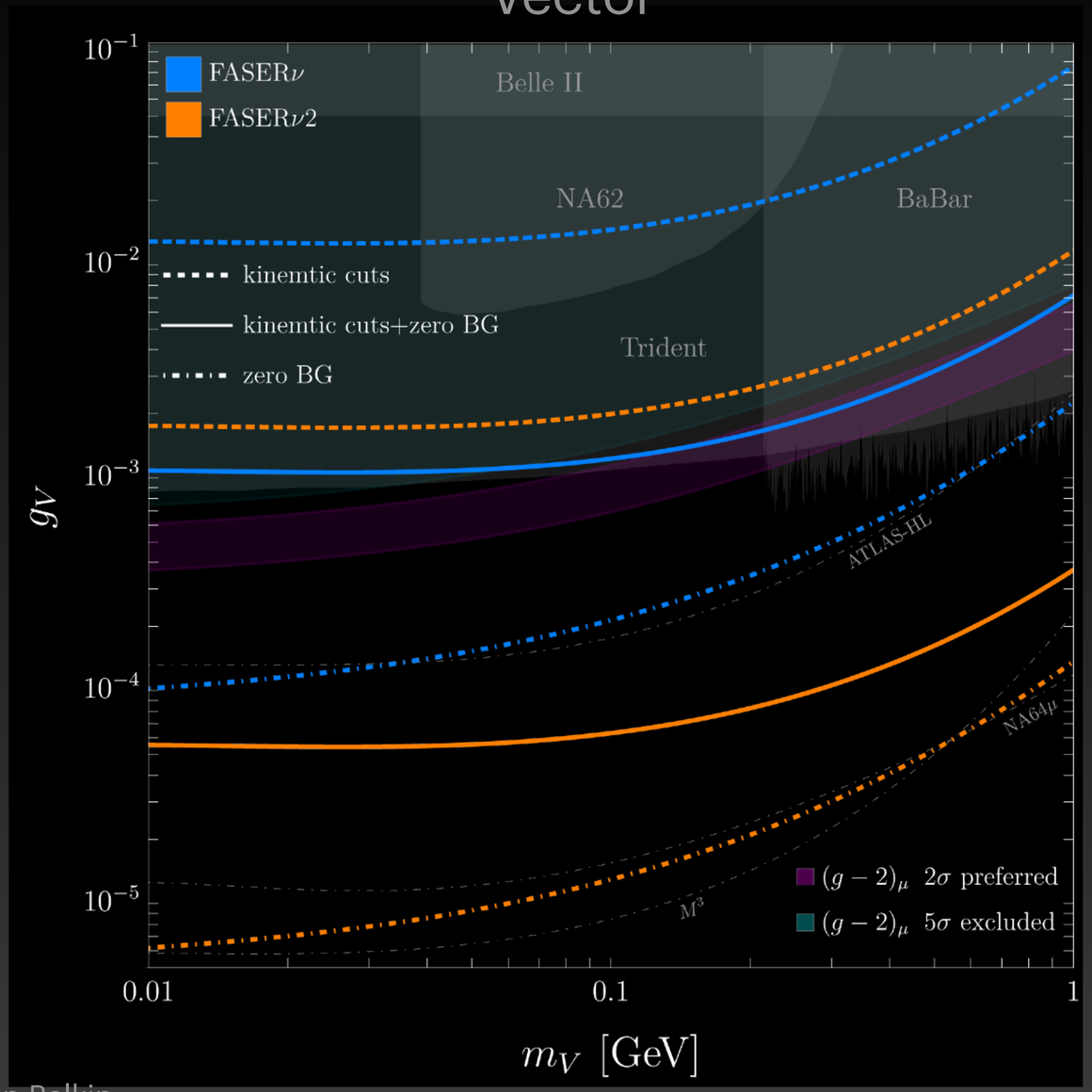
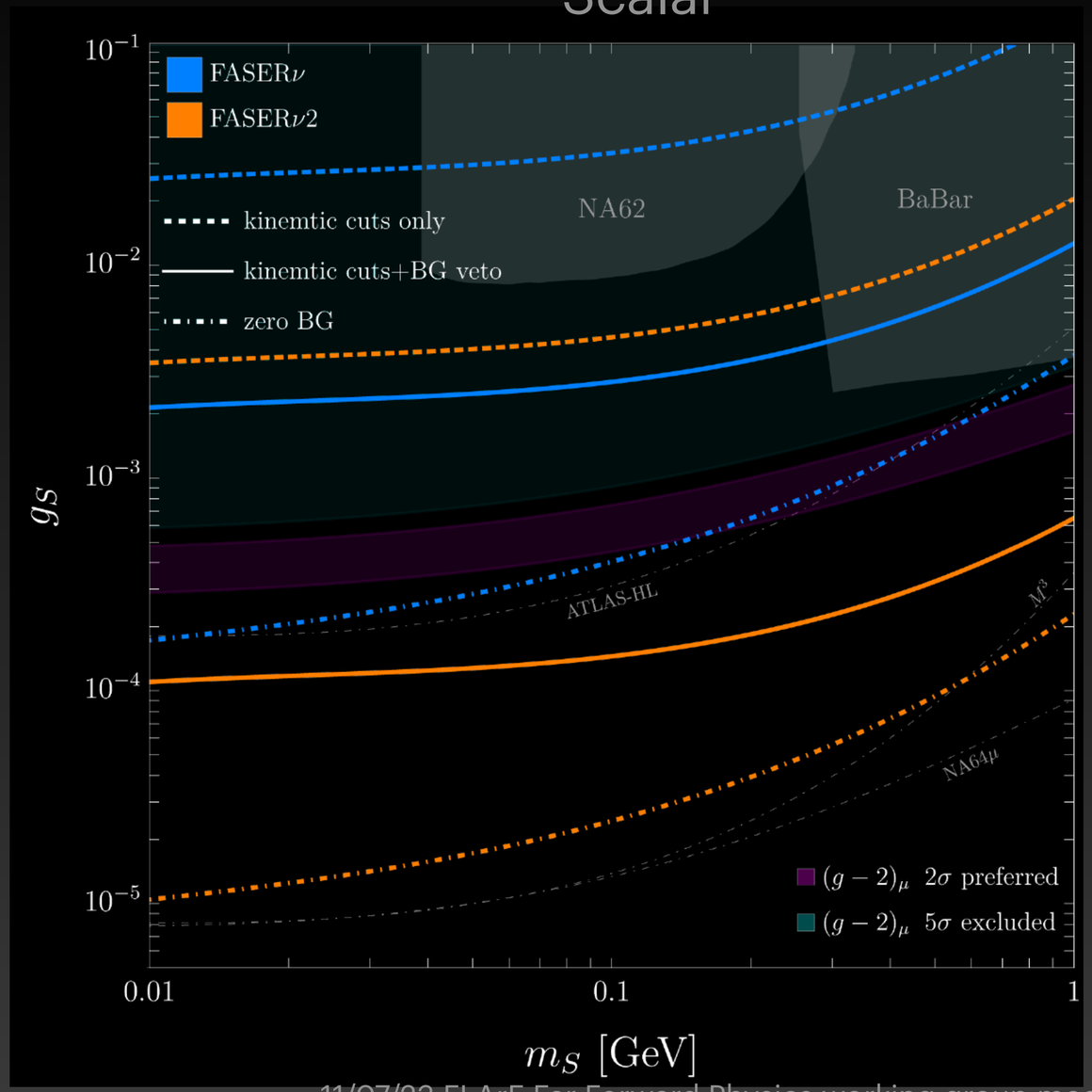
Vector



Scalar



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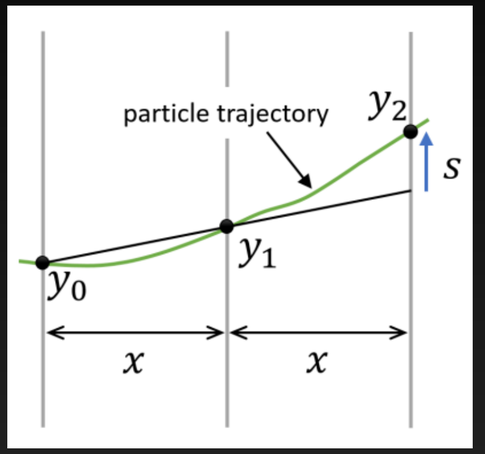
- Minimal BG rejection with kinematic cuts - sensitivity not very promising.
- With improved BG rejection could reach preferred and unexplored parameter space $g_S \lesssim 10^{-4}$.
- Plenty of room for optimization: MCS method, sliding window (kink finder), BG veto strategies i.e. for brem

Extra

Energy measurement
Multiple Coulomb scattering

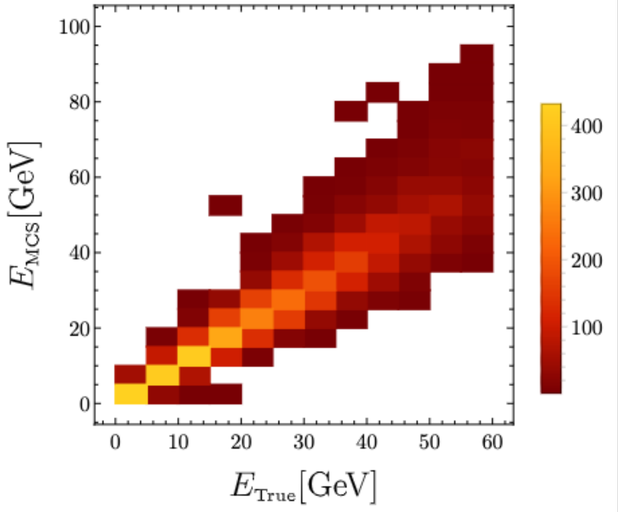
"Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC" (1908.02310)

$$s^{\mathrm{RMS}}(x)^2 = \left(\sqrt{\frac{2}{3}}\frac{13.6\ \mathrm{MeV}}{\beta P} x \sqrt{\frac{x}{X_0}}\right)^2 + \left(\sqrt{6}\ \sigma_{\mathrm{pos}}\right)^2$$



Toy model analysis - 200 Layers using both x and y shifts

$[E_{\mathrm{min}}, E_{\mathrm{max}}]$ [GeV]	# of tracks	$\langle E \rangle$ [GeV]	σ_E [GeV]	$\sigma_E / \langle E \rangle$
[0,10]	1028	5.63	3.13	55.6 %
[10,20]	1264	15.87	4.24	26.7 %
[20,30]	1214	25.8	5.36	20.8 %
[30,40]	1060	35.76	6.84	19.1%
[40,50]	726	45.28	8.4	18.5%
[50,60]	400	56.65	10.54	18.6 %
[99.9,100.1]	3557	102.75	18.78	18.3 %

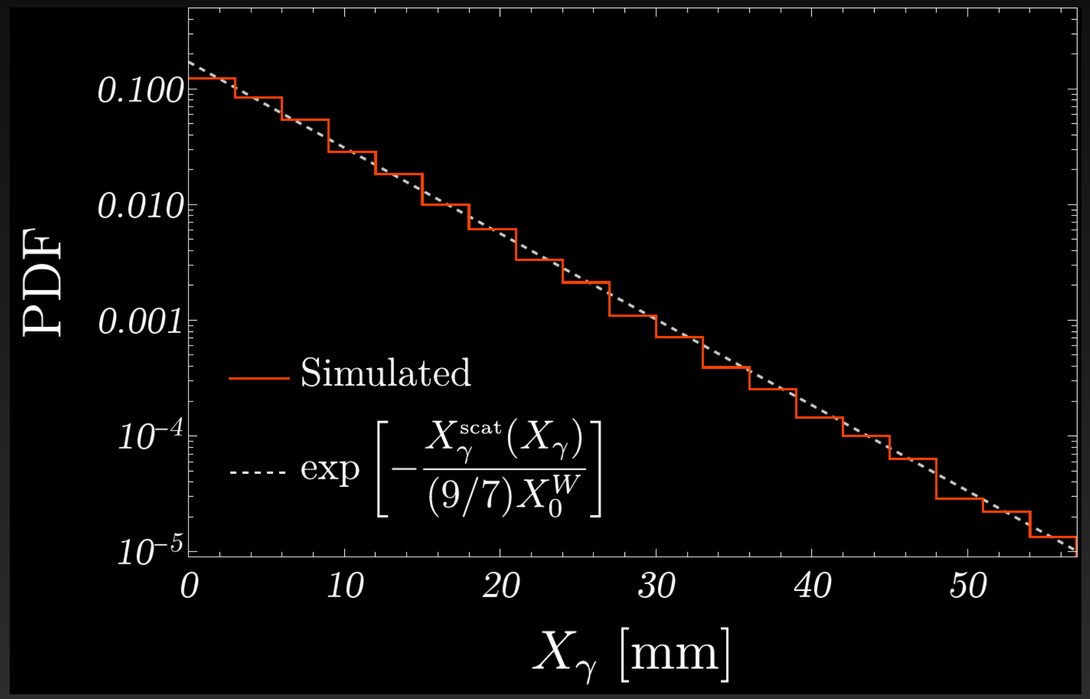


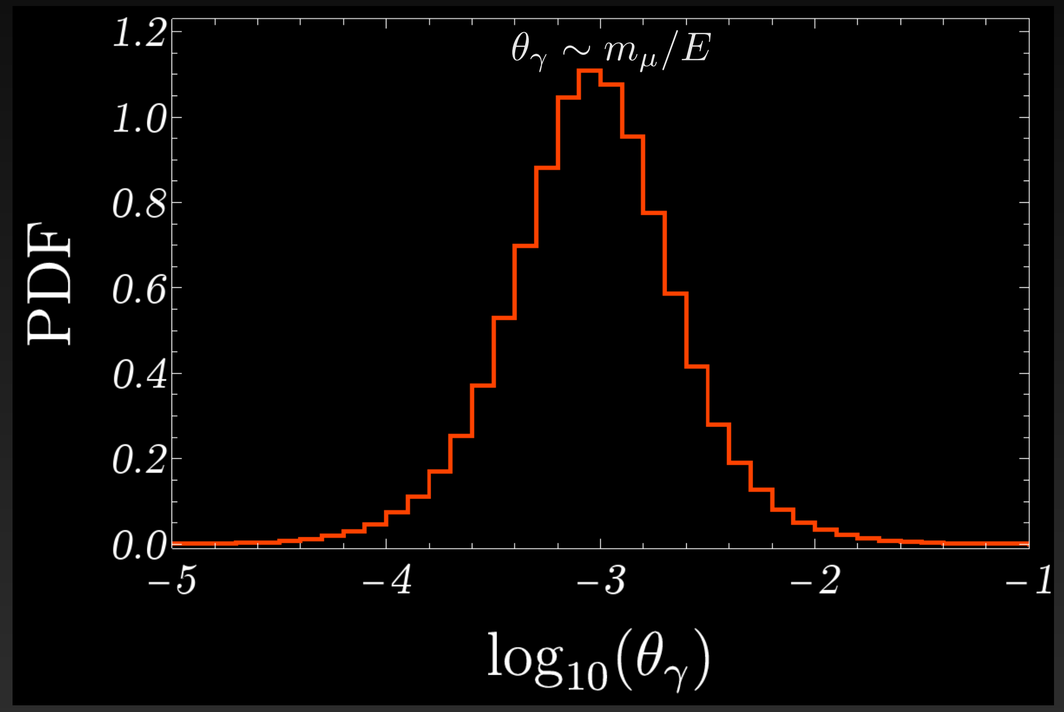
Energy resolution (from 1908.02310):

46 % at 200 GeV

57 % at 1 TeV

Bremsstrahlung efficiency





$$X^{\rm scat} = \frac{\Delta_W}{\Delta_W + \Delta_{\rm emu}} X^{\rm phys} \sim 0.76 X^{\rm phys}$$

Bremsstrahlung efficiency

$$P_{\mathrm{miss}} = \int_0^{\pi/2} \mathrm{d}\theta\, f(\theta) \exp\left[-\underbrace{\left(\frac{\Delta_{\mathrm{W}}}{\Delta_{\mathrm{W}} + \Delta_{\mathrm{emu.}}} \right)}_{= \frac{1.1}{1.1+0.34} \sim 0.76} \frac{\langle r_{\mathrm{track}} \rangle}{\sin\theta} \frac{1}{(9/7) X_0} \right]$$

= chance for the photon to reach the next "suspicious" track

$$\langle r_{\mathrm{track}} \rangle = \sqrt{\frac{N_{\mathrm{dev}} S_{\mathrm{FASER}}}{N_\mu^*}}$$

=search radius

$$N_\mu^*(\mathcal{R}_{fi}^{\mathrm{max}}) \approx \frac{N_\mu^{\mathrm{brem}}(\mathcal{R}_{fi} < \mathcal{R}_{fi}^{\mathrm{max}})}{L_{\mathrm{FASER}}/\Delta_{\mathrm{kink}}} \ll N_\mu$$

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Strong dependence on modeling of $f(\theta)$ at large angles