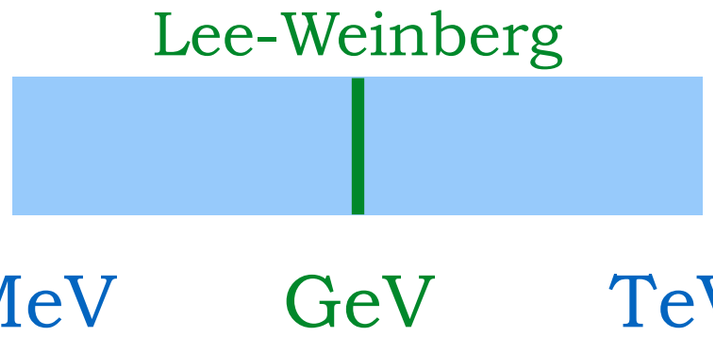
Dark Sector Searches with SeaQuest

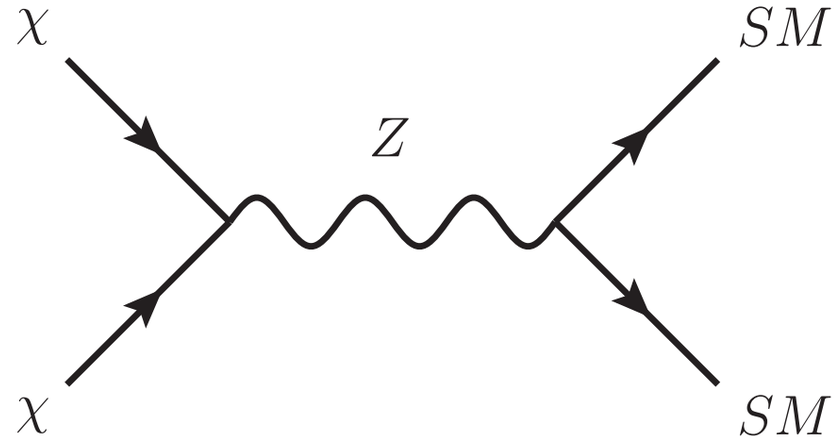
ASHER BERLIN

Dark Matter Detection and Detectability: Paradigm Confirmation or Shift?
KITP
May 3, 2018

collaboration with Stefania Gori, Philip Schuster, & Natalia Toro
based on arXiv:1804.00661

Light Mediators





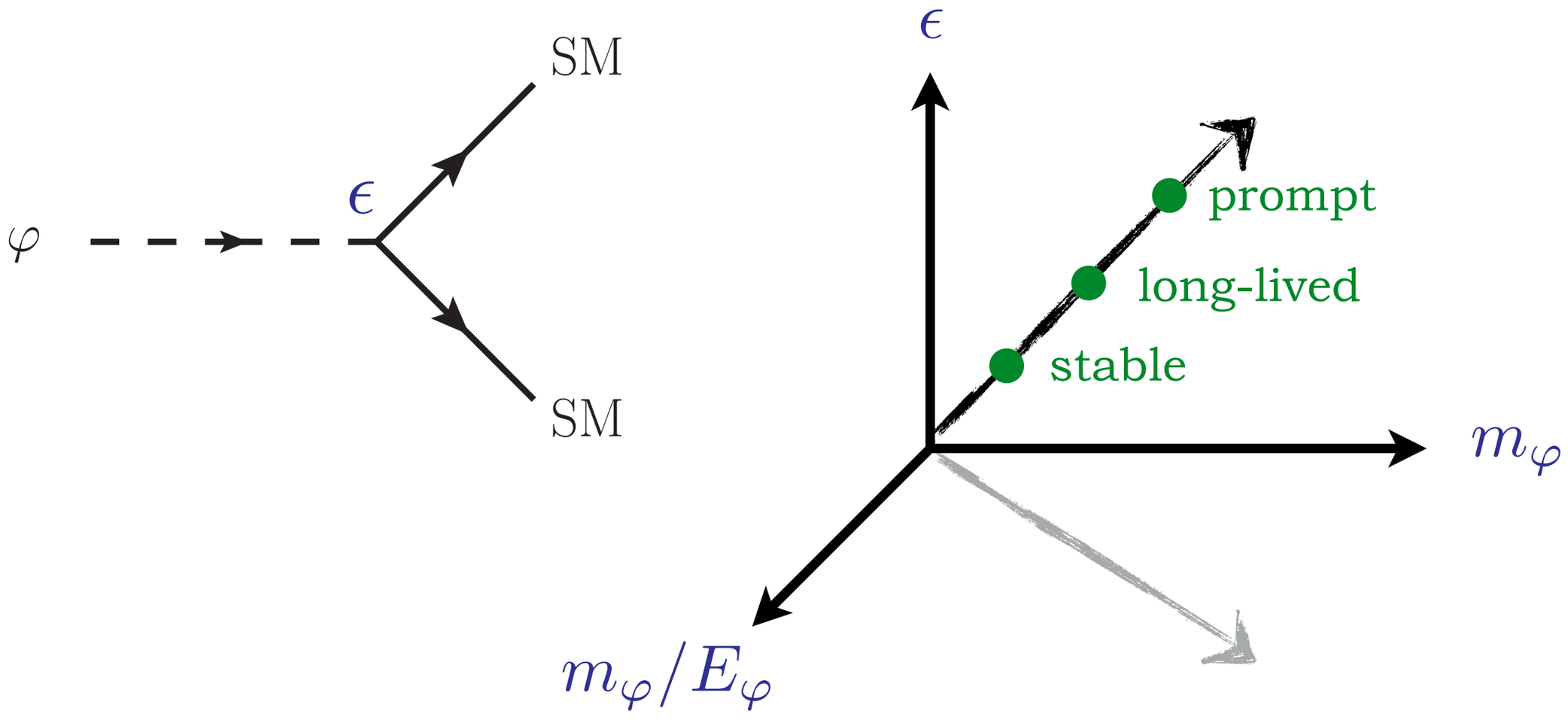
$$\sigma v \lesssim \frac{m_\chi^2}{m_Z^4} \implies m_\chi \gtrsim \frac{m_Z^2}{(T_{\rm eq}\, m_{\rm pl})^{1/2}} \sim \text{GeV}$$

Sub-GeV thermal DM requires light mediators: $m_\varphi \sim m_\chi$

B. Lee and S. Weinberg,
Phys.Rev.Lett. 39 (1977) 165-168

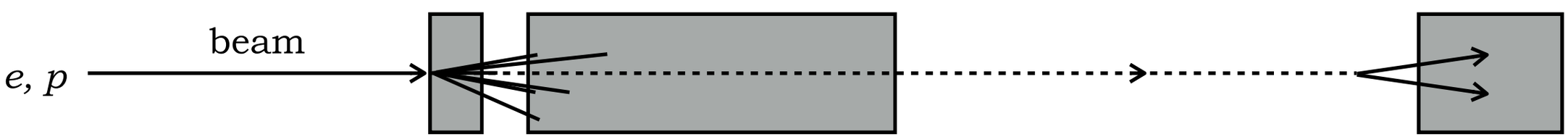
C. Boehm and P. Fayet
arXiv: hep-ph/0305261

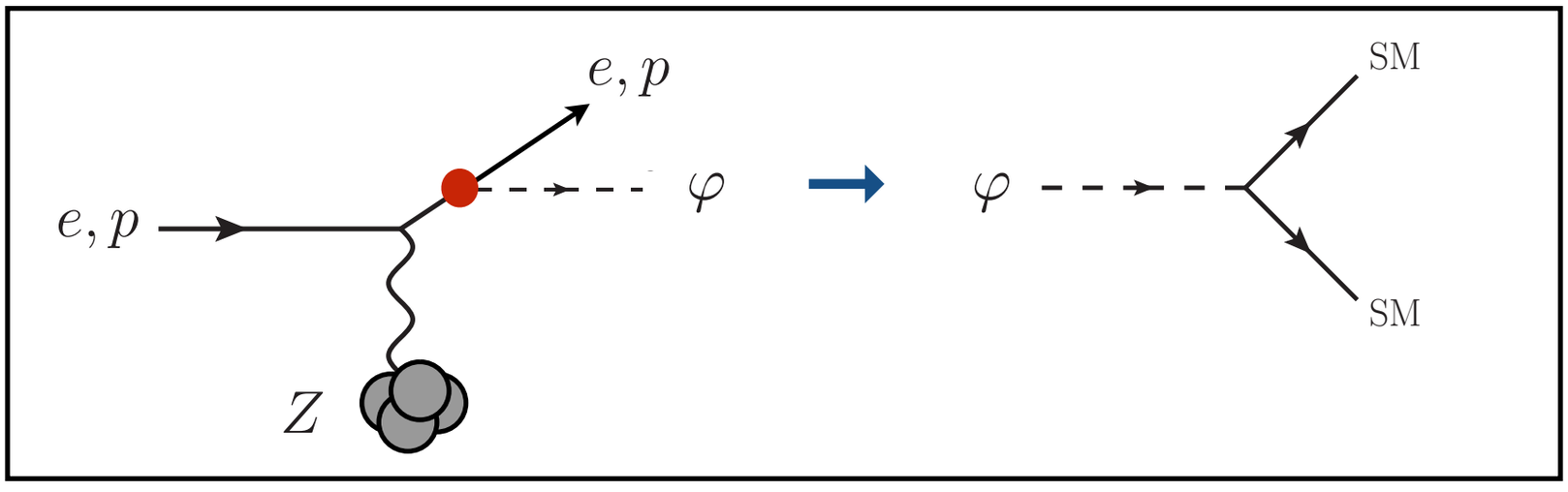
Lifetime



$$\gamma\,\tau_\varphi \sim 100\ \text{cm} \times \left(\frac{E_\varphi}{100\ \text{GeV}}\right) \times \left(\frac{10\ \text{MeV}}{m_\varphi}\right)^2 \times \left(\frac{10^{-4}}{\epsilon}\right)^2$$

Fixed-Target Search

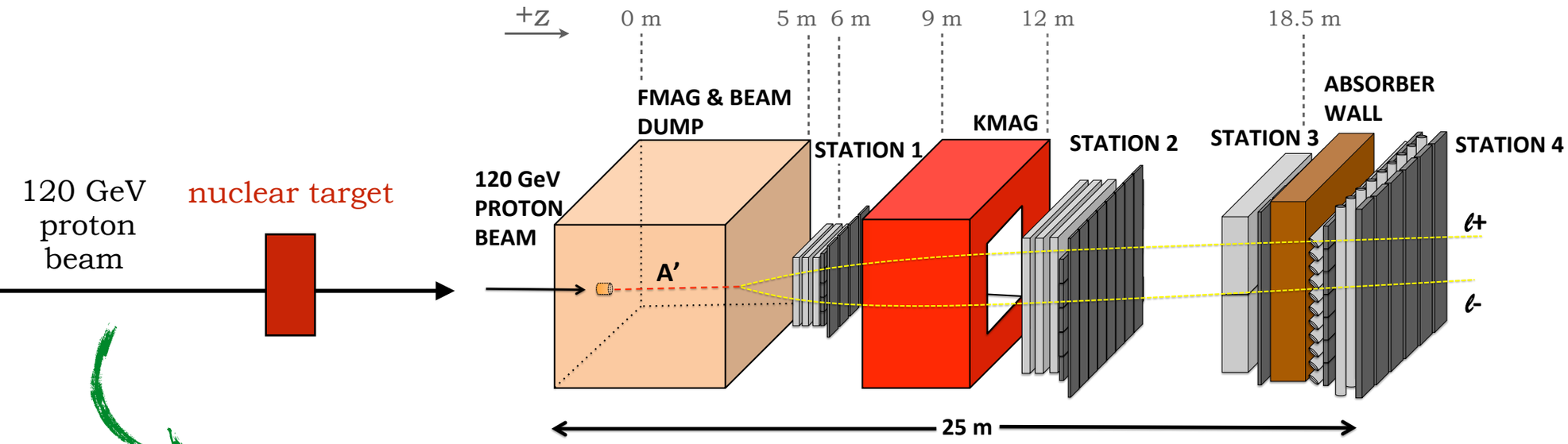




The Fermilab SeaQuest Experiment

arXiv:1509.00050

The Fermilab SeaQuest Experiment



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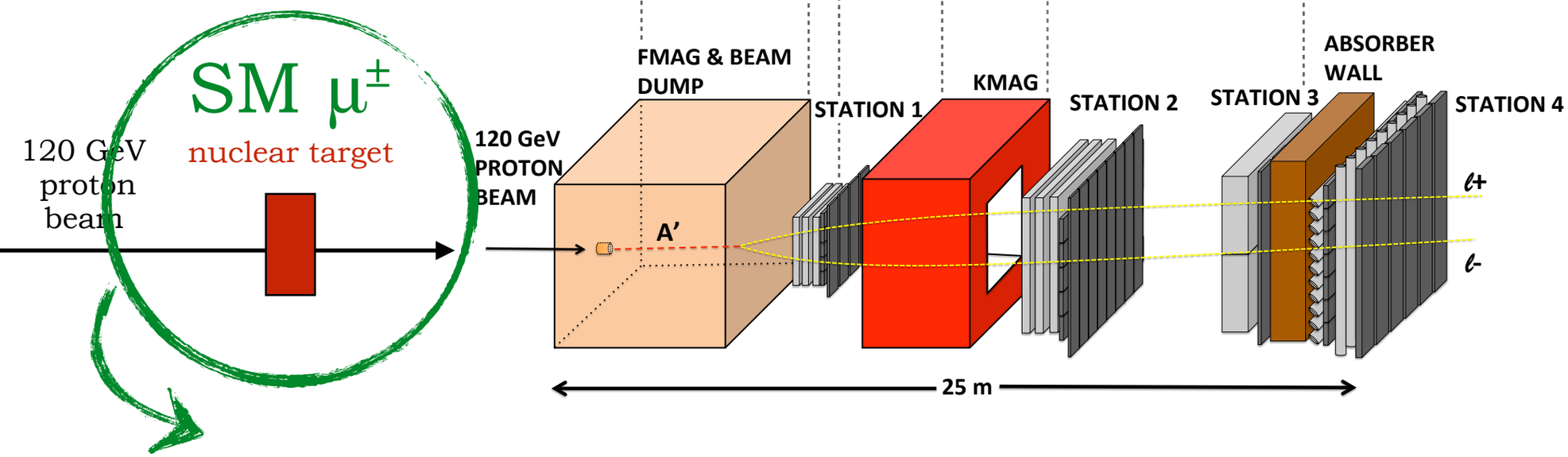

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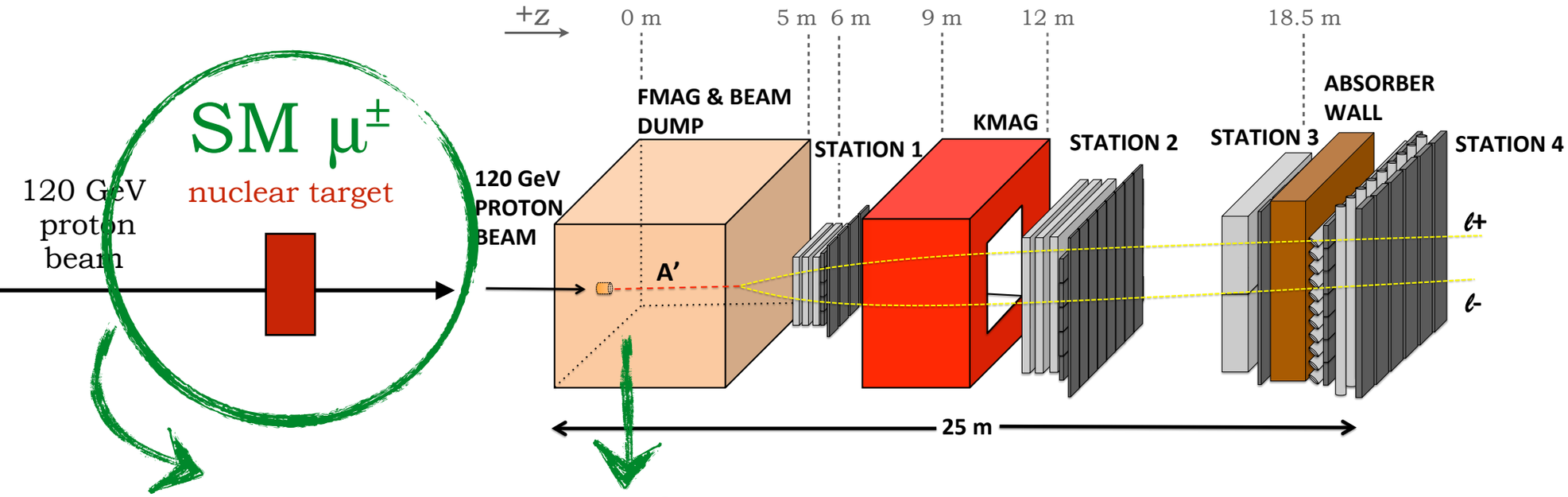

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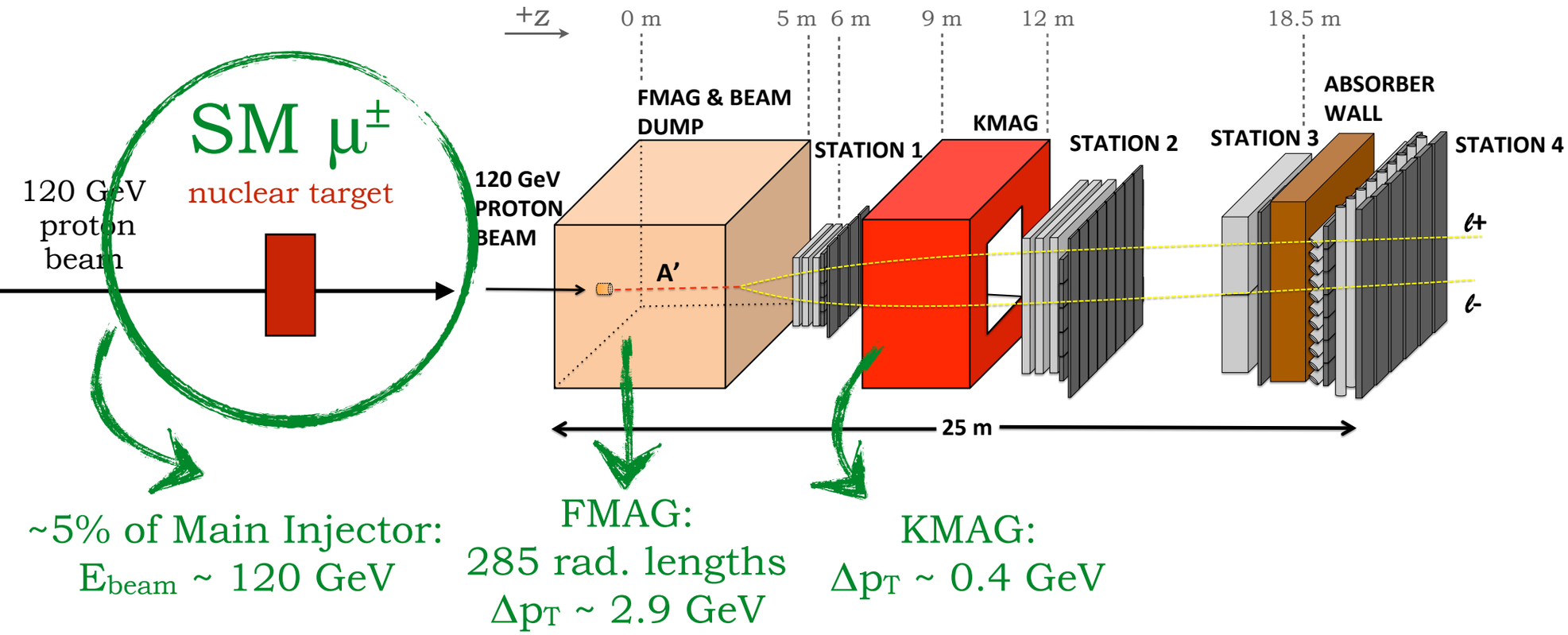

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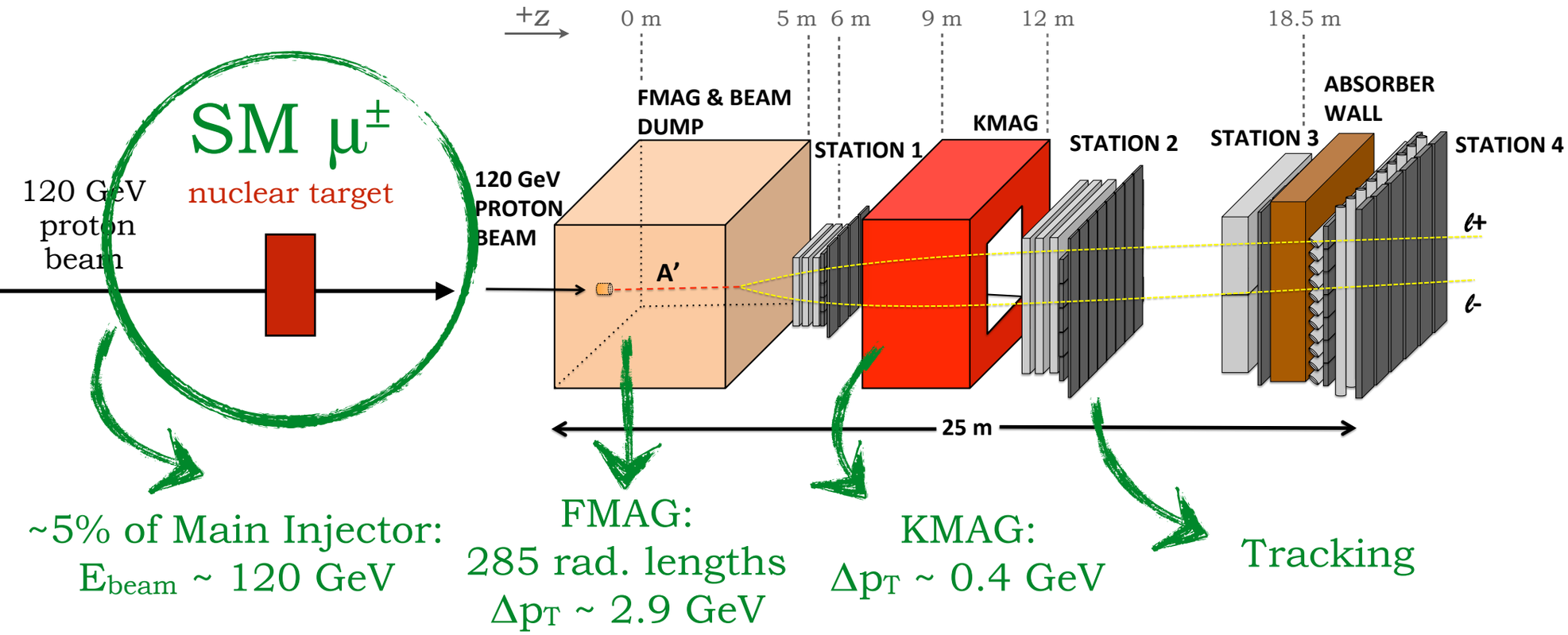

arXiv:1509.00050

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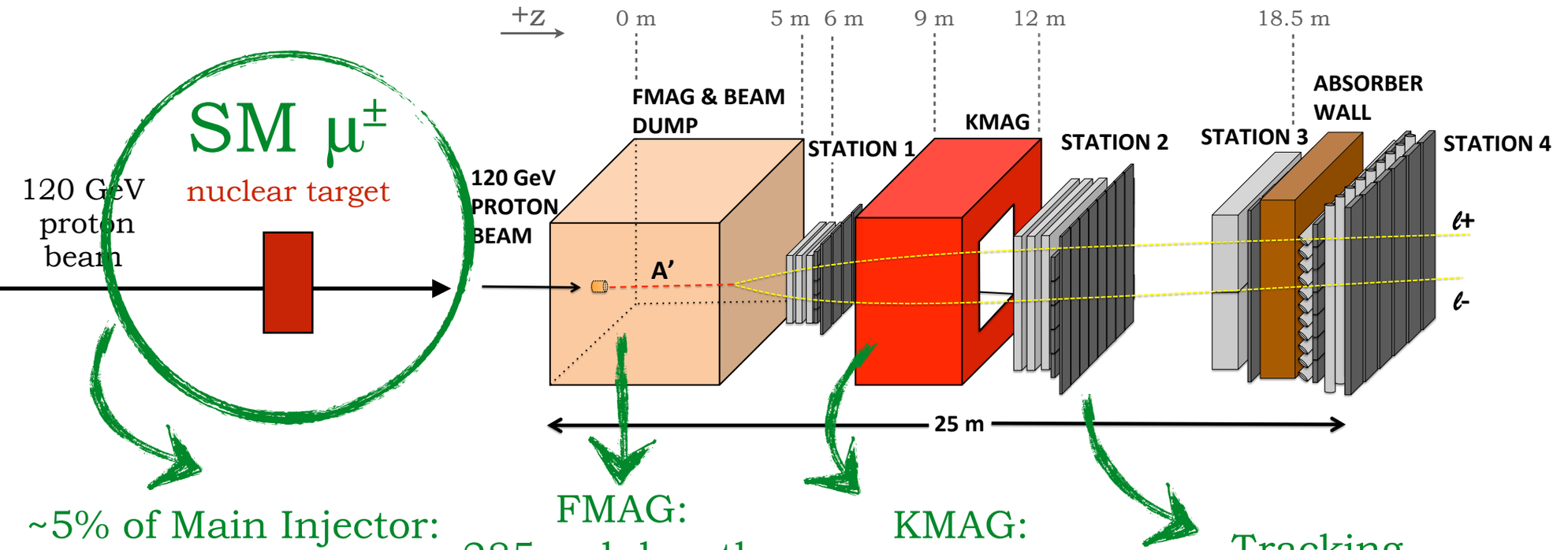
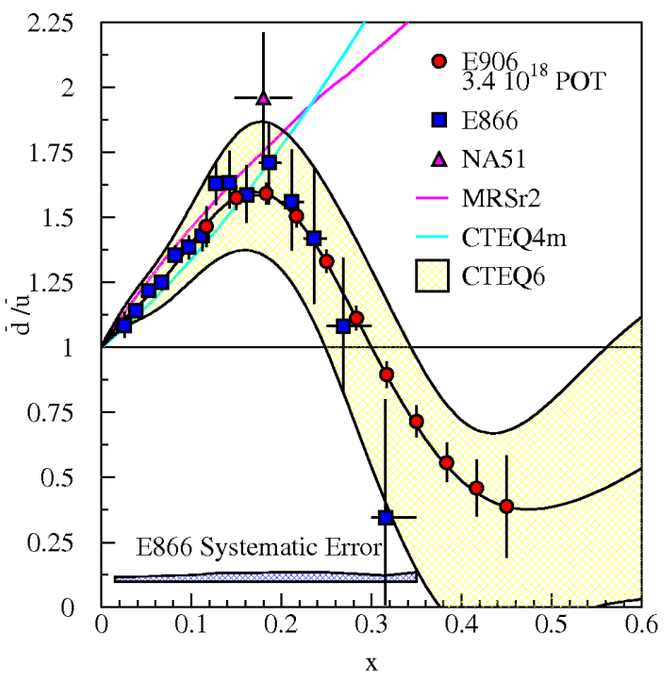


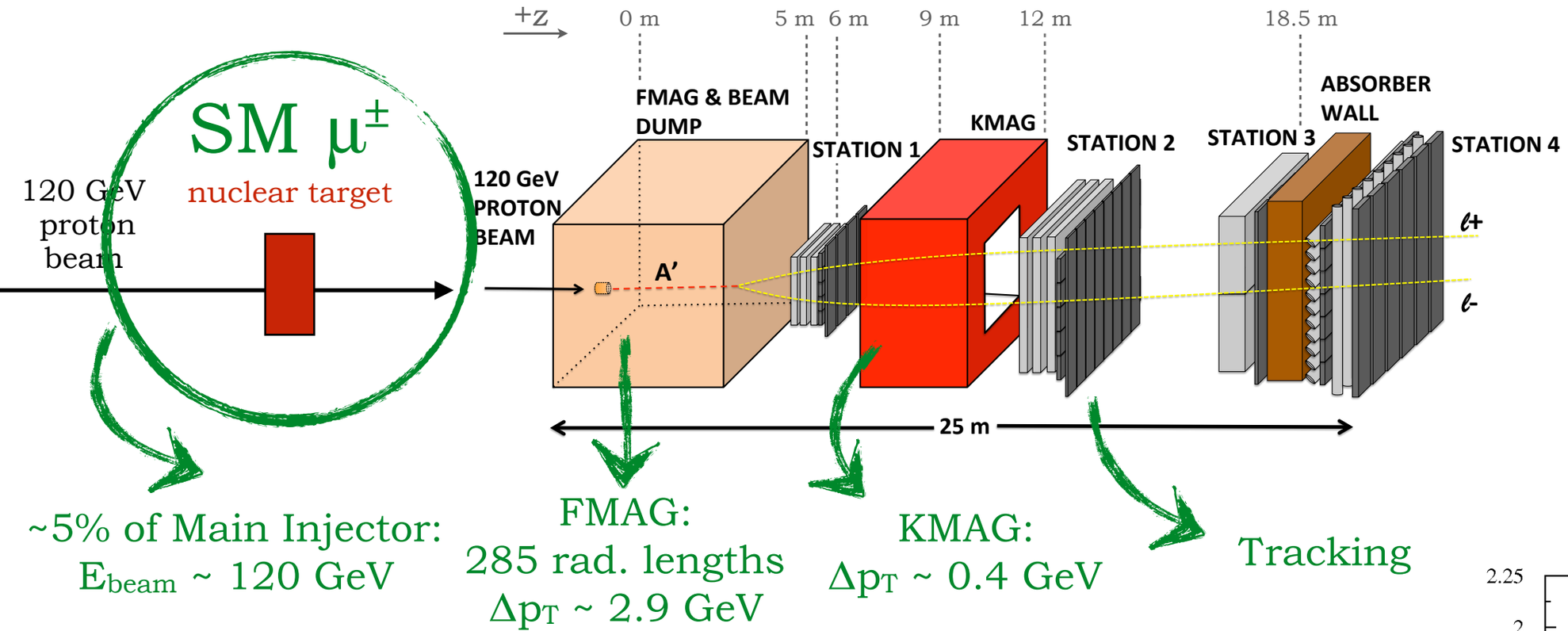
arXiv:1509.00050

- Designed to study SM Drell-Yan dimuons
- Parasitic trigger: displaced dimuons @ > 5 meters
- 5 days of running in April 2017: 3×10^{16} POT
- Approved for 2019 run: ~10^{18} POT
- Plans for installation of ECAL from Phenix experiment



Ming X. Liu

The Fermilab SeaQuest Experiment



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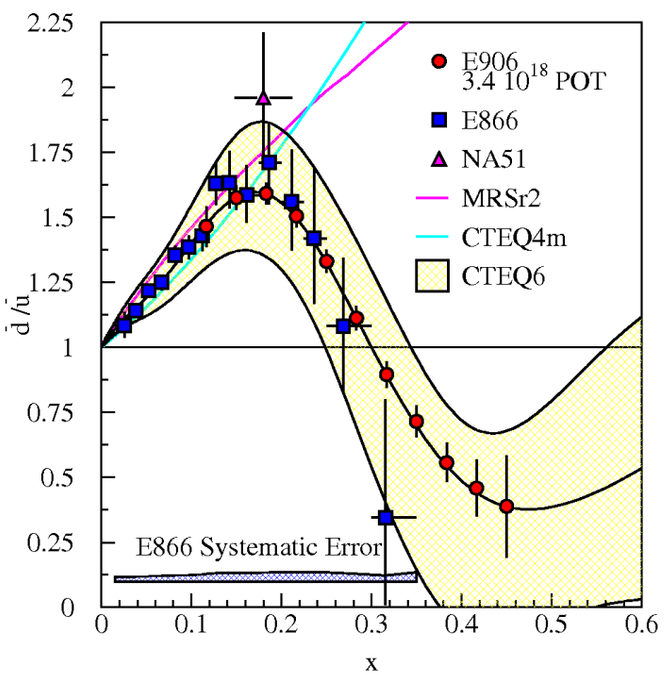
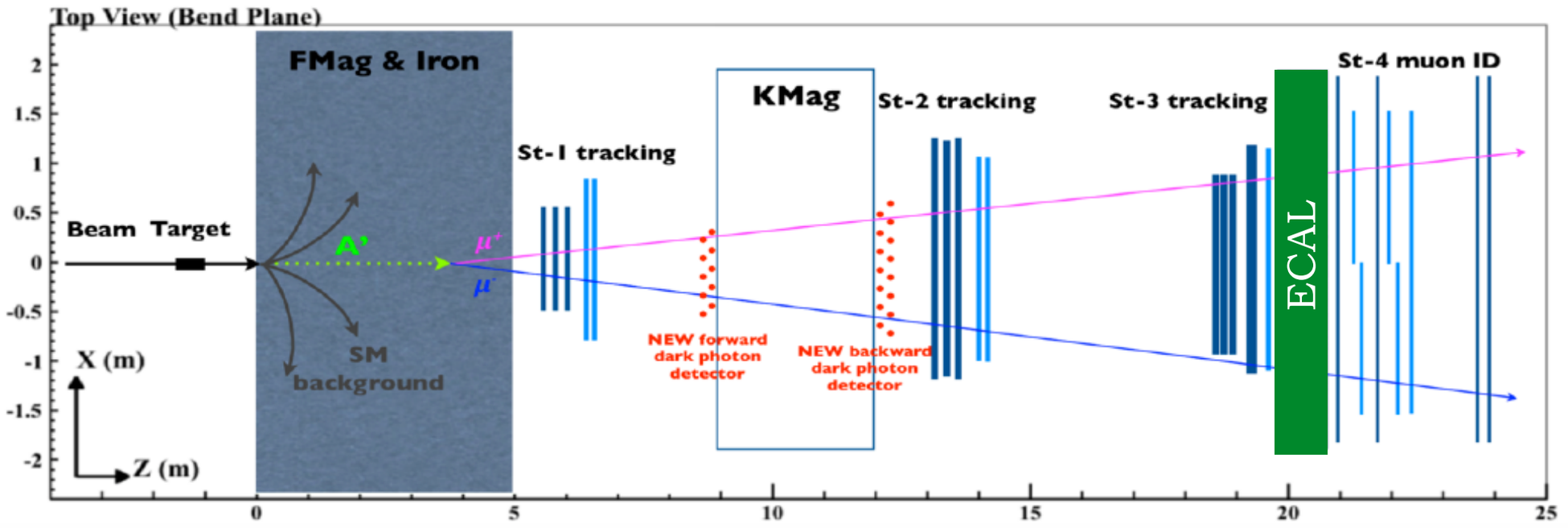
Regions of Interest

- Physics reach for ECAL with 10^{18} POT and higher.
- Models: dark photons, dark Higgs, axion-like particles, leptophilic scalars, light dark matter



Displaced Electrons



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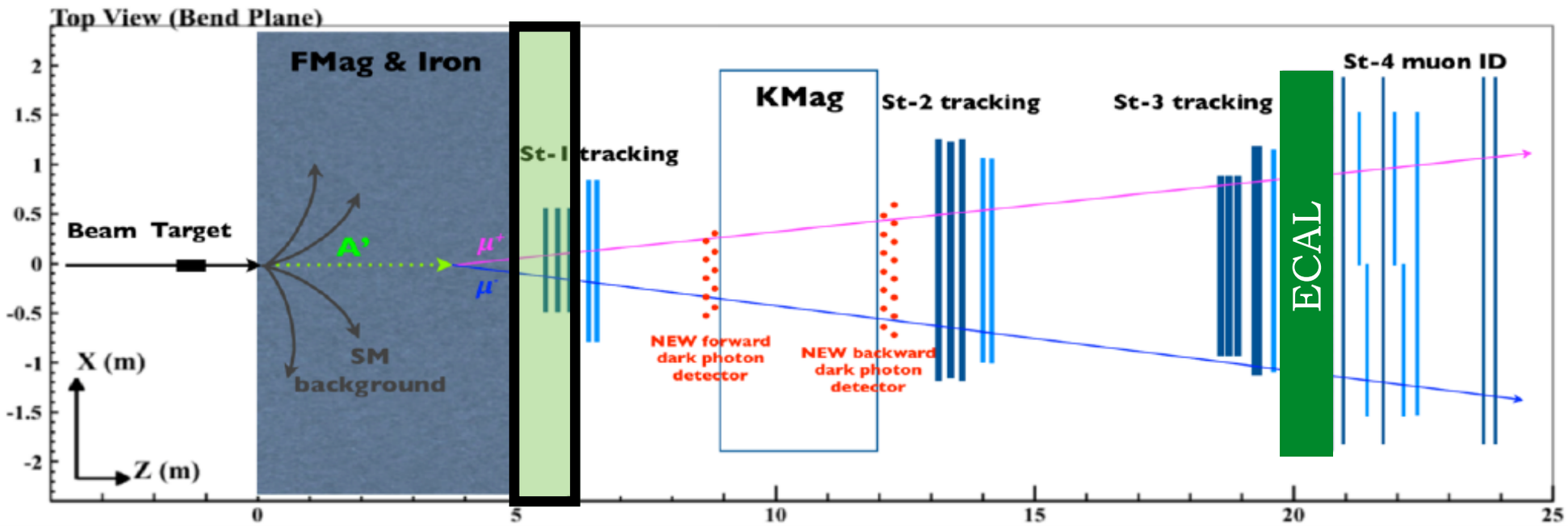
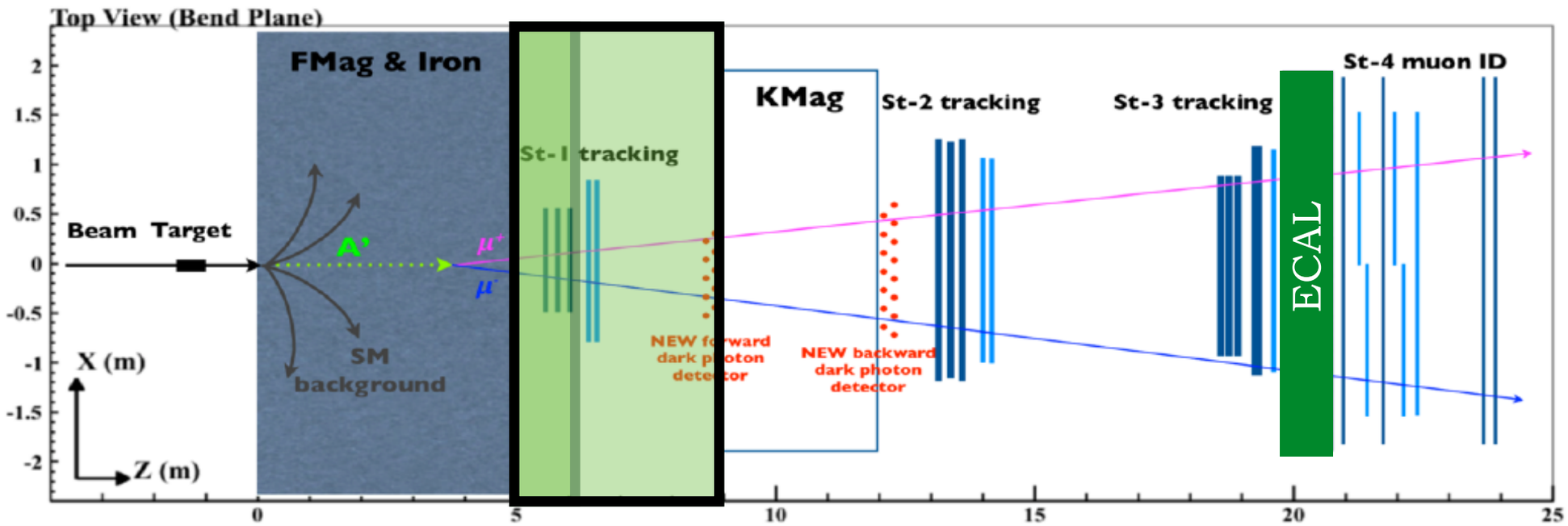


(5-6) m ⟷ tracking in St. 1-3 + bending in KMAG
⟹ accurate momentum and pointing

Displaced Electrons



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(5-9) m ⟷ ECAL ⟹ degraded momentum and pointing

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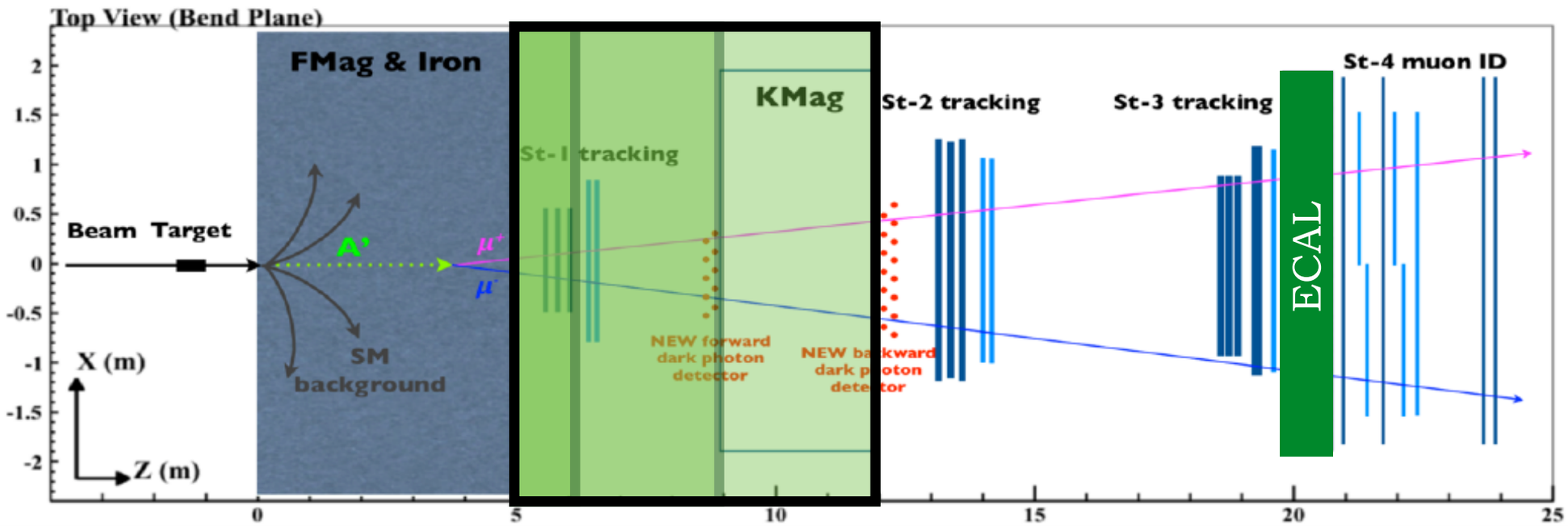

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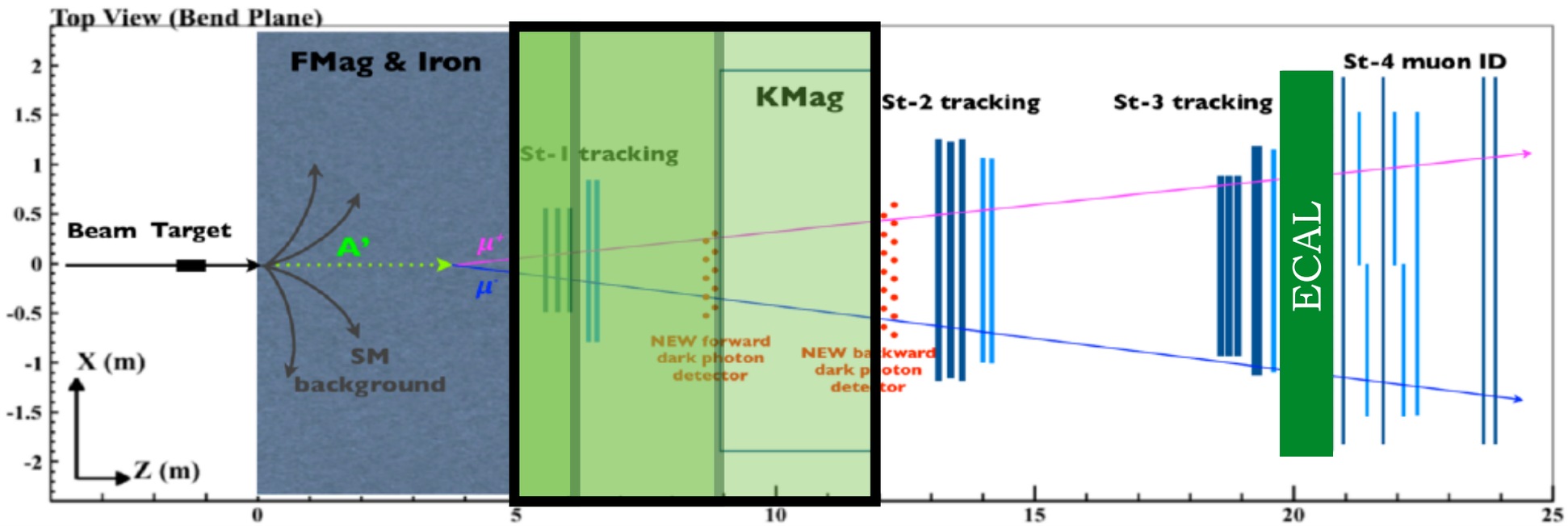
(5-9) m ⟷ ECAL ⟹ degraded momentum and pointing

(5-12) m ⟷ + smaller KMAG kick
⟹ low-energy signals and background

Displaced Electrons



larger backgrounds

(5-6) m $\longleftrightarrow$ tracking in St. 1-3 + bending in KMAG
$\Longrightarrow$ accurate momentum and pointing

(5-9) m $\longleftrightarrow$ ECAL $\Longrightarrow$ degraded momentum and pointing

(5-12) m $\longleftrightarrow$ + smaller KMAG kick
$\Longrightarrow$ low-energy signals and background

$$K_L \to \pi^{\pm}\, e^{\mp}\, \nu \qquad (\tau \sim 10 \text{ meters})$$

Might be relevant for larger decay regions.
A few extra meters of iron reduces this by several orders of magnitude

Proton vs. Electron Beams

Proton		Electron

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• nuclear collision length ~ 10 cm	$L \sim n_{\mathrm{atom}}\ \ell$	• radiation length ~ 1 cm

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• $\gamma + \pi + \mu + \cdots$	dark Higgs, axion, leptophilic scalar	• $\gamma + \cdots$

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• $\gamma + \pi + \mu + \cdots$	dark Higgs, axion, leptophilic scalar	• $\gamma + \cdots$
• Main Injector (FNAL), SPS and LHC (CERN)	100 GeV $\gg$ 1 GeV	• LCLS (SLAC), CEBAF (JLab)

SeaQuest vs. Others

	E_{beam}	p_{min}	POT	z_{min}	z_{max}	$z_{\text{min}}/E_{\text{beam}}$
SeaQuest	120 GeV	10 GeV	$10^{18} - 10^{20}$	5 m	10 m	4 cm / GeV
NA62	400 GeV	-	10^{18}	100 m	250 m	25 cm / GeV
SHiP	400 GeV	100 GeV	10^{20}	65 m	125 m	16 cm / GeV
FASER	6500 GeV	1 TeV	$10^{16} - 10^{17}$	390 m	400 m	6 cm / GeV

Dark Photons

$$\mathcal{L} \supset \frac{\epsilon}{2\,\cos\theta_w}\,A'_{\mu\nu}\,B^{\mu\nu} \implies A_\mu\,J^\mu_{\rm em} \to A_\mu\,J^\mu_{\rm em} + \epsilon\,A'_\mu\,J^\mu_{\rm em}$$

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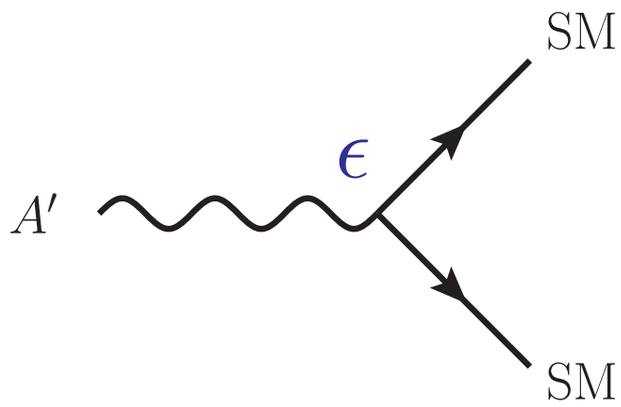
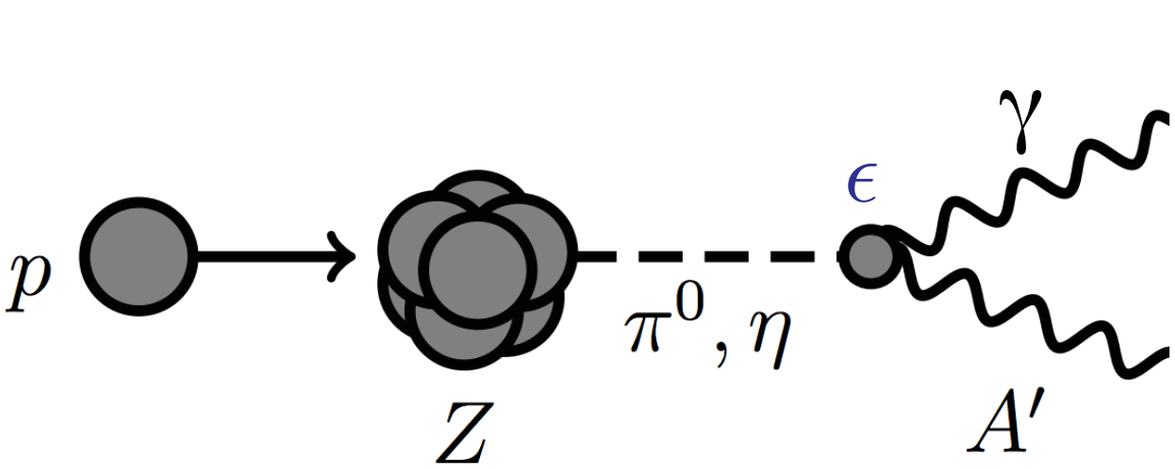
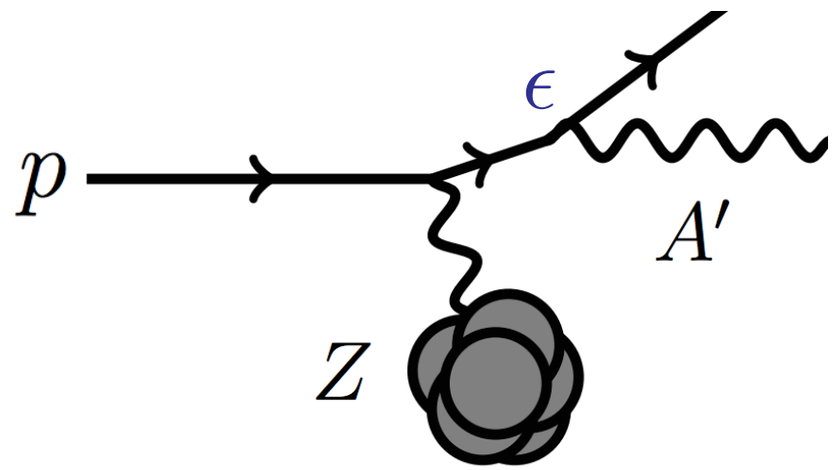


$$\tau_{A'} \sim 10\ \text{cm} \times \left(\frac{\text{GeV}}{m_{A'}}\right) \times \left(\frac{10^{-6}}{\epsilon}\right)^2$$

Dark Photons at SeaQuest



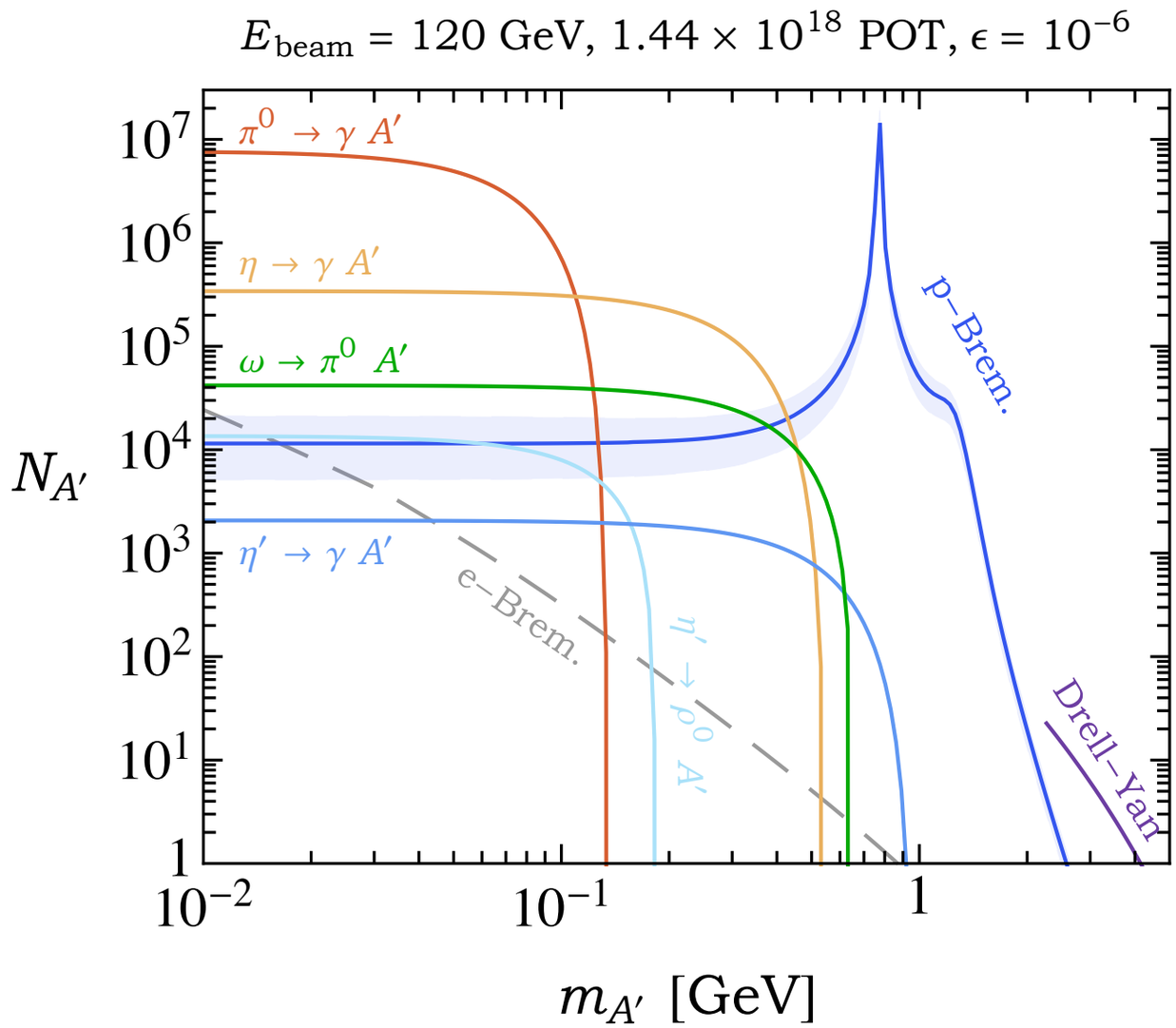
$m_{A'} \lesssim 100$ MeV



$m_{A'} \lesssim 1$ GeV

+ Drell-Yan at higher masses

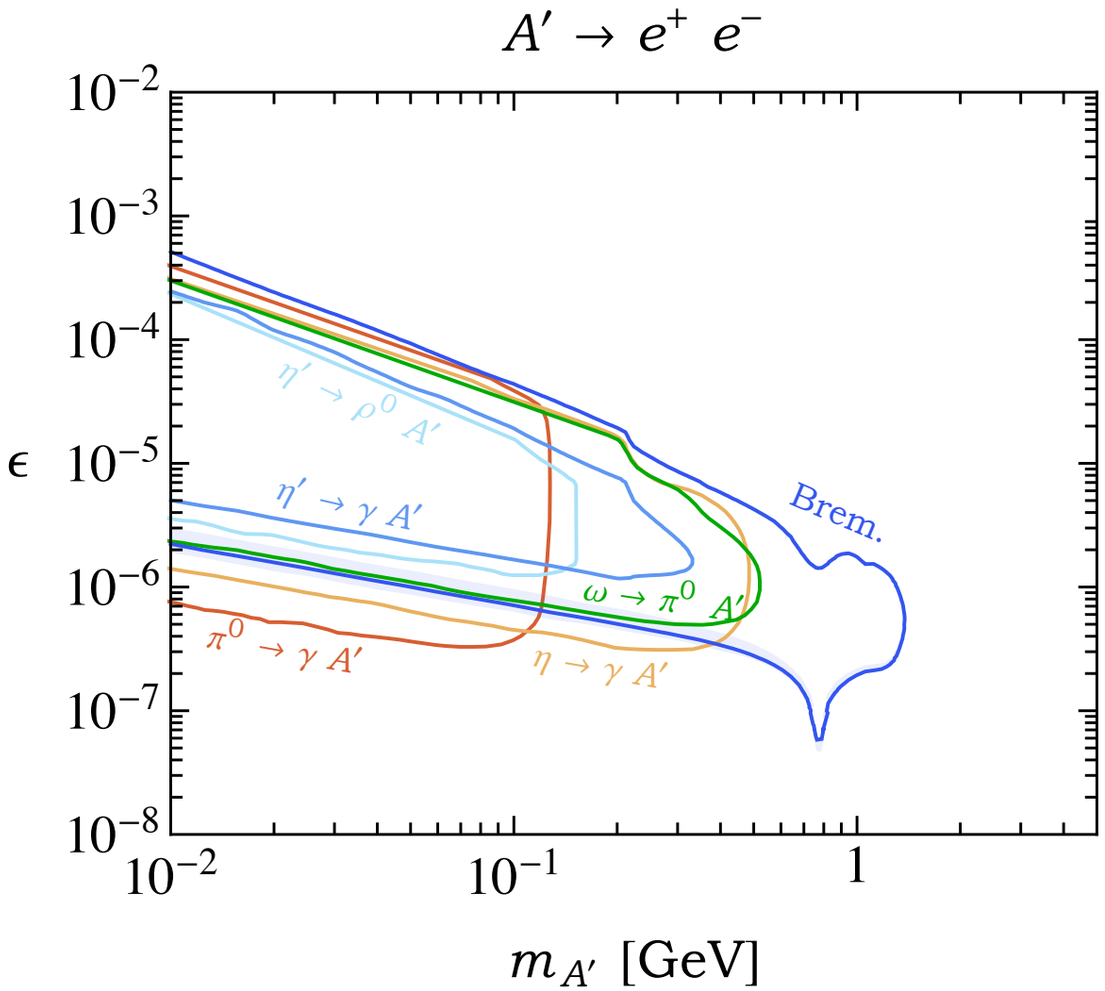
Dark Photons at SeaQuest

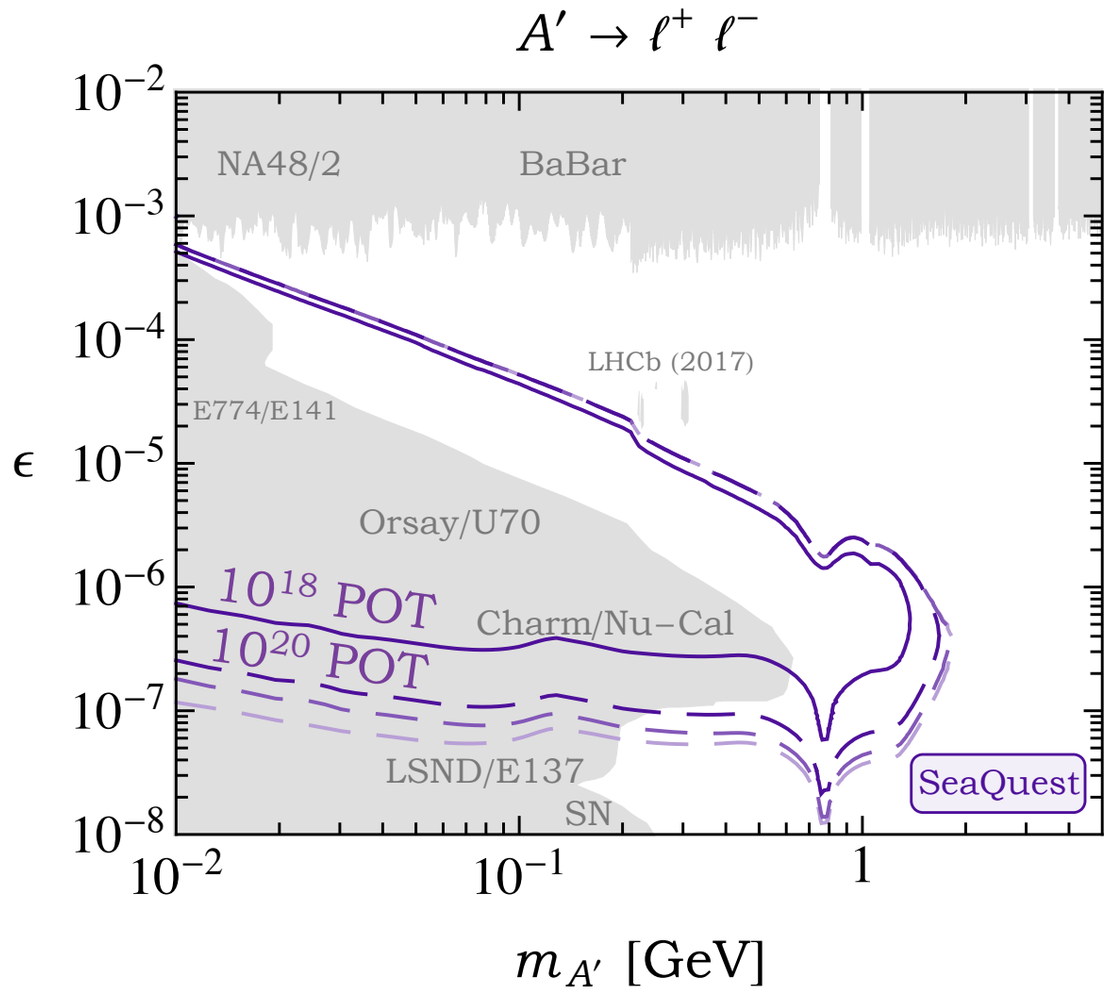


$$L \simeq 35\ \text{ab}^{-1} \times \left(\frac{\text{POT}}{1.44 \times 10^{18}} \right)$$

arXiv:1804.00661

Dark Photons at SeaQuest





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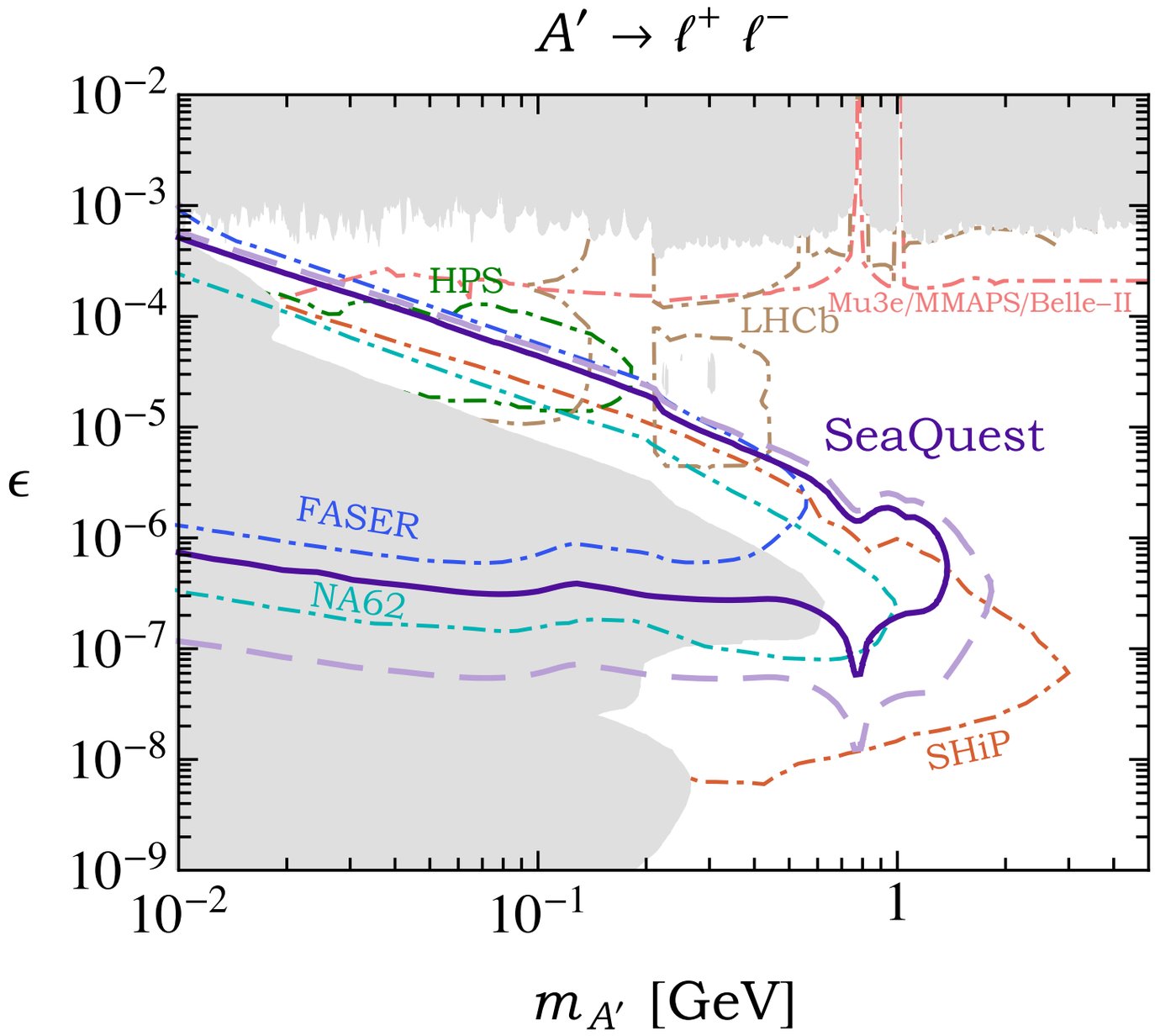
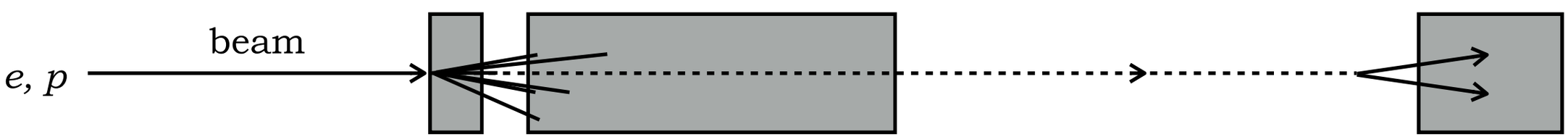


see also arXiv:1509.00050
arXiv:1804.00661

Secondary Production



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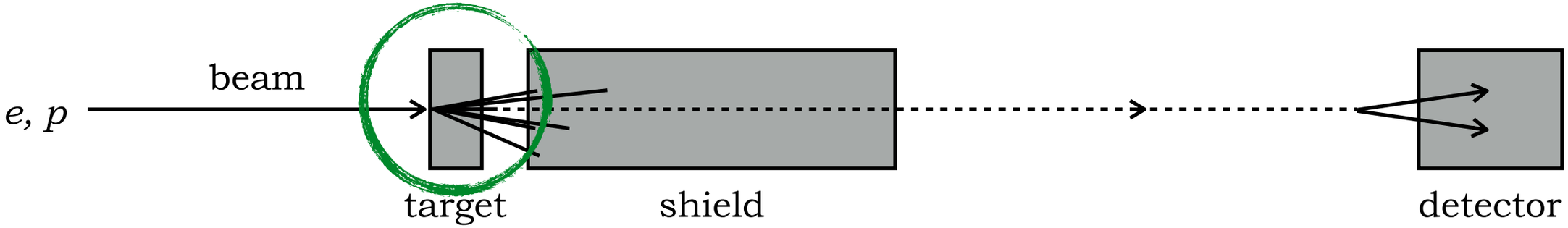
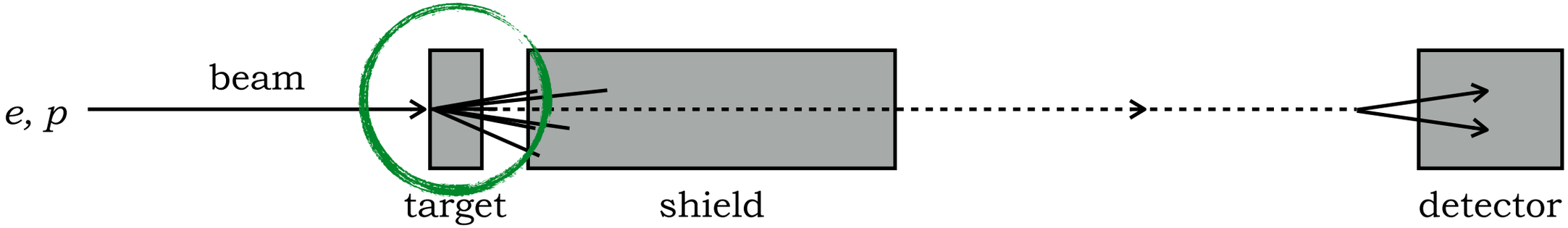


$$p\,p \to \pi^0 + \pi^\pm + \cdots \to \gamma + \mu^\pm + \cdots$$

Secondary Production



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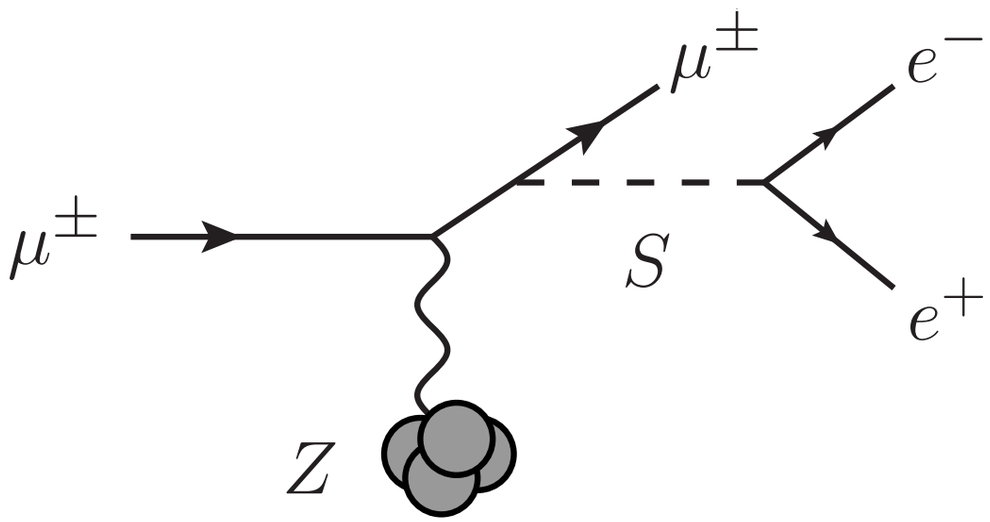
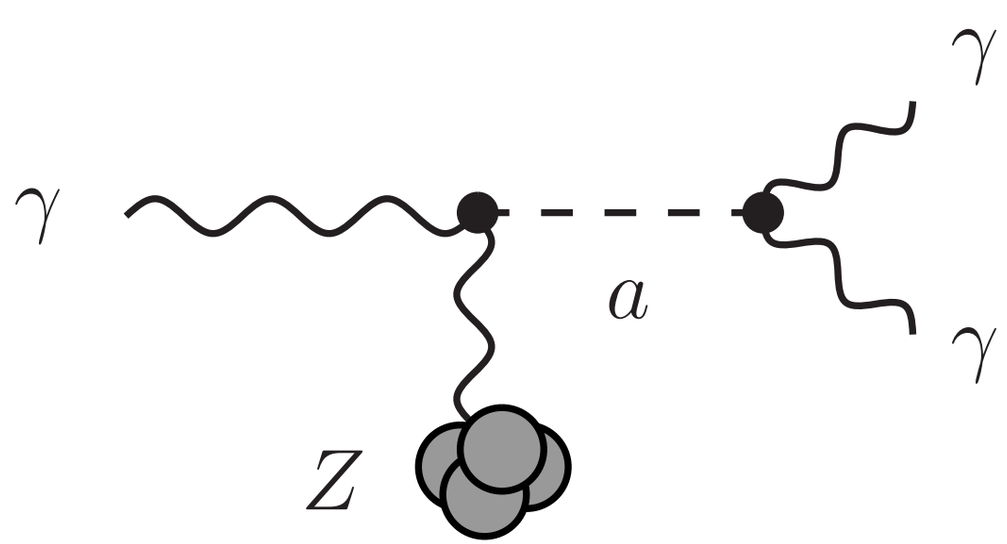
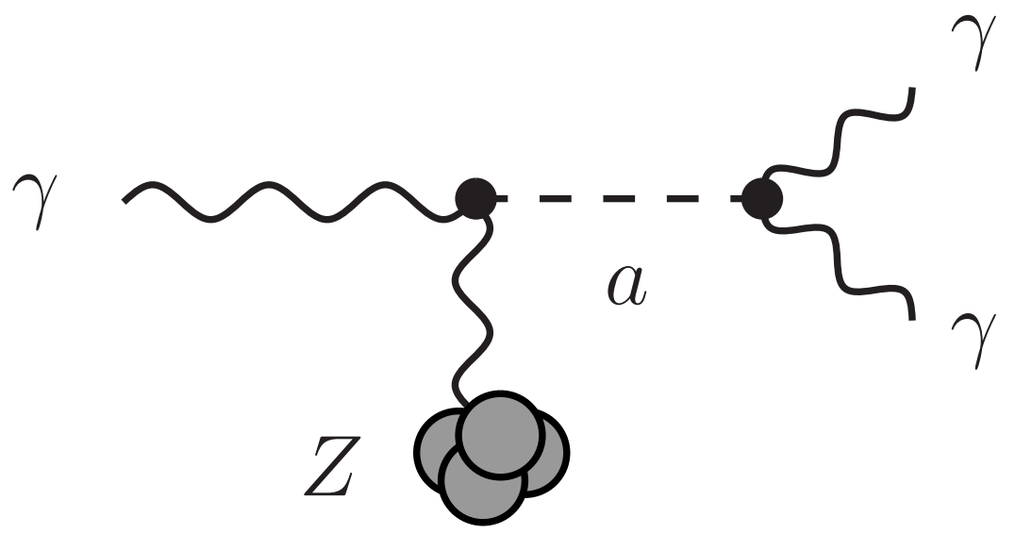




arXiv:1606.04943

Axion-like Particles

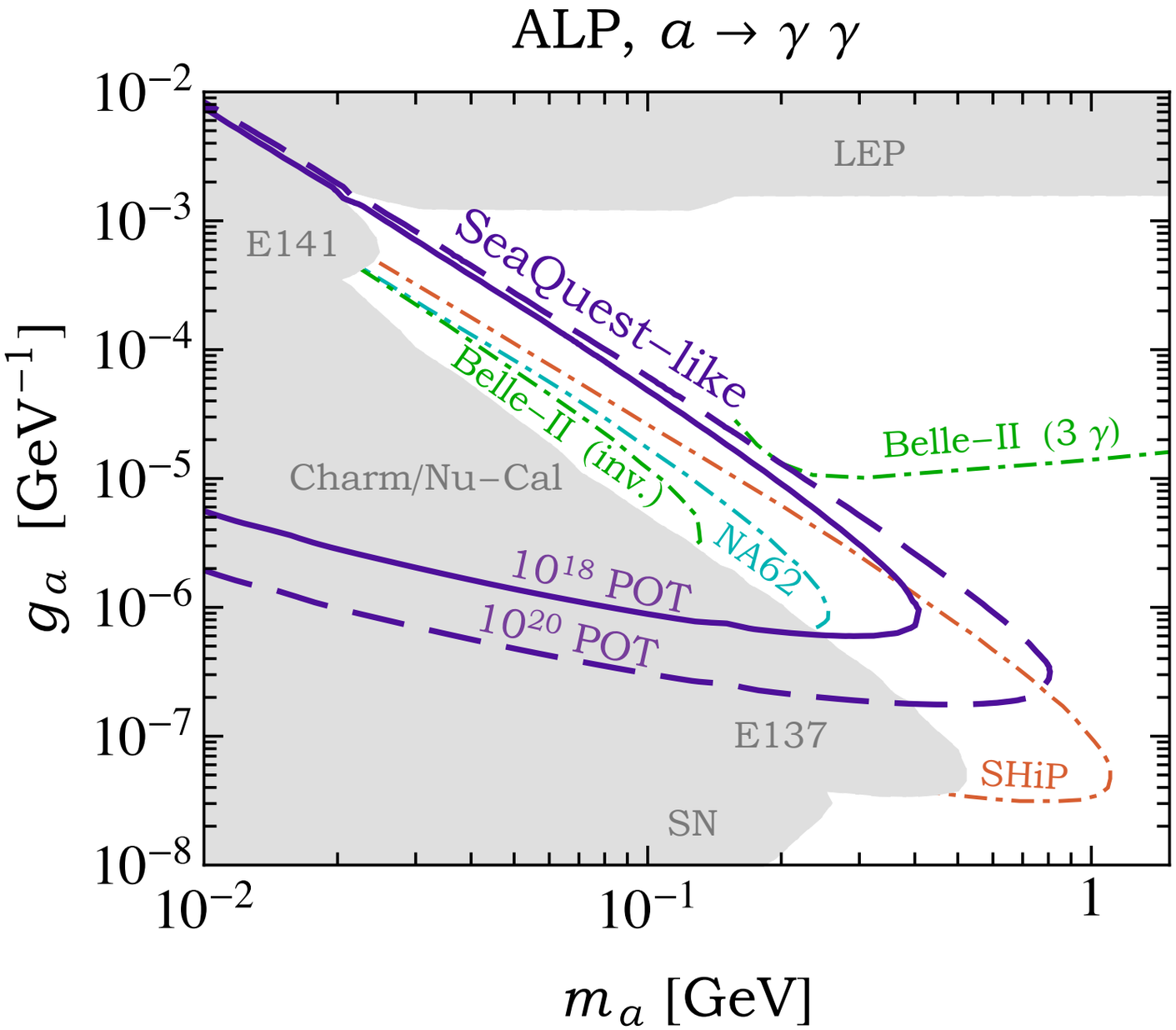


$$\mathcal{L} \supset g_a \, a \, F_{\mu\nu} \, \tilde{F}^{\mu\nu}$$

Consider a few extra meters of iron to counter degradation
in pointing and momentum measurements

arXiv:1804.00661

Axion-like Particles



$$g_a \sim \frac{\alpha_{\rm em}}{f_a} \implies f_a \lesssim 10\ \text{TeV} - 100\ \text{TeV}$$

arXiv:1512.03069
arXiv:1709.00009
arXiv:1804.00661

Timeline Summary

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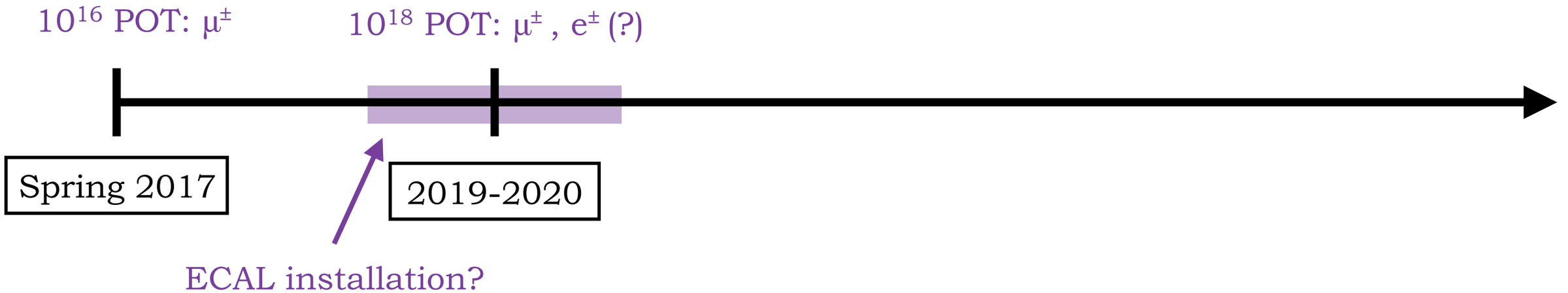
SeaQuest

10^{16} POT: $\mu^{\pm}$

Spring 2017

Timeline Summary

SeaQuest



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SeaQuest

10^{16} POT: $\mu^{\pm}$

Spring 2017

10^{18} POT: $\mu^{\pm}$, $e^{\pm}$ (?)

2019-2020

ECAL installation?

LHC Run 3

LHCb, NA62 (dump),
SHiP (5 yrs = 10^{20} POT)?,
FASER?, …

2021-2023

Belle-II (50 ab^{-1})

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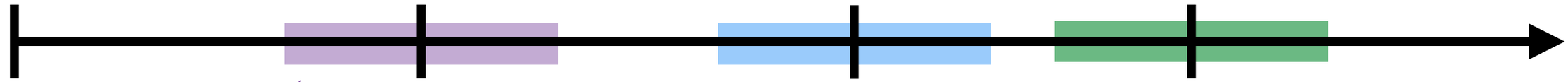

Spring 2017

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2024

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<u>SeaQuest</u>

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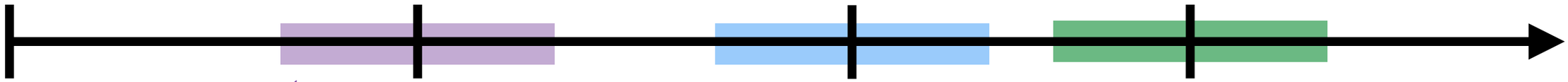

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ECAL installation?

<u>Belle-II (50 ab^{-1})</u>

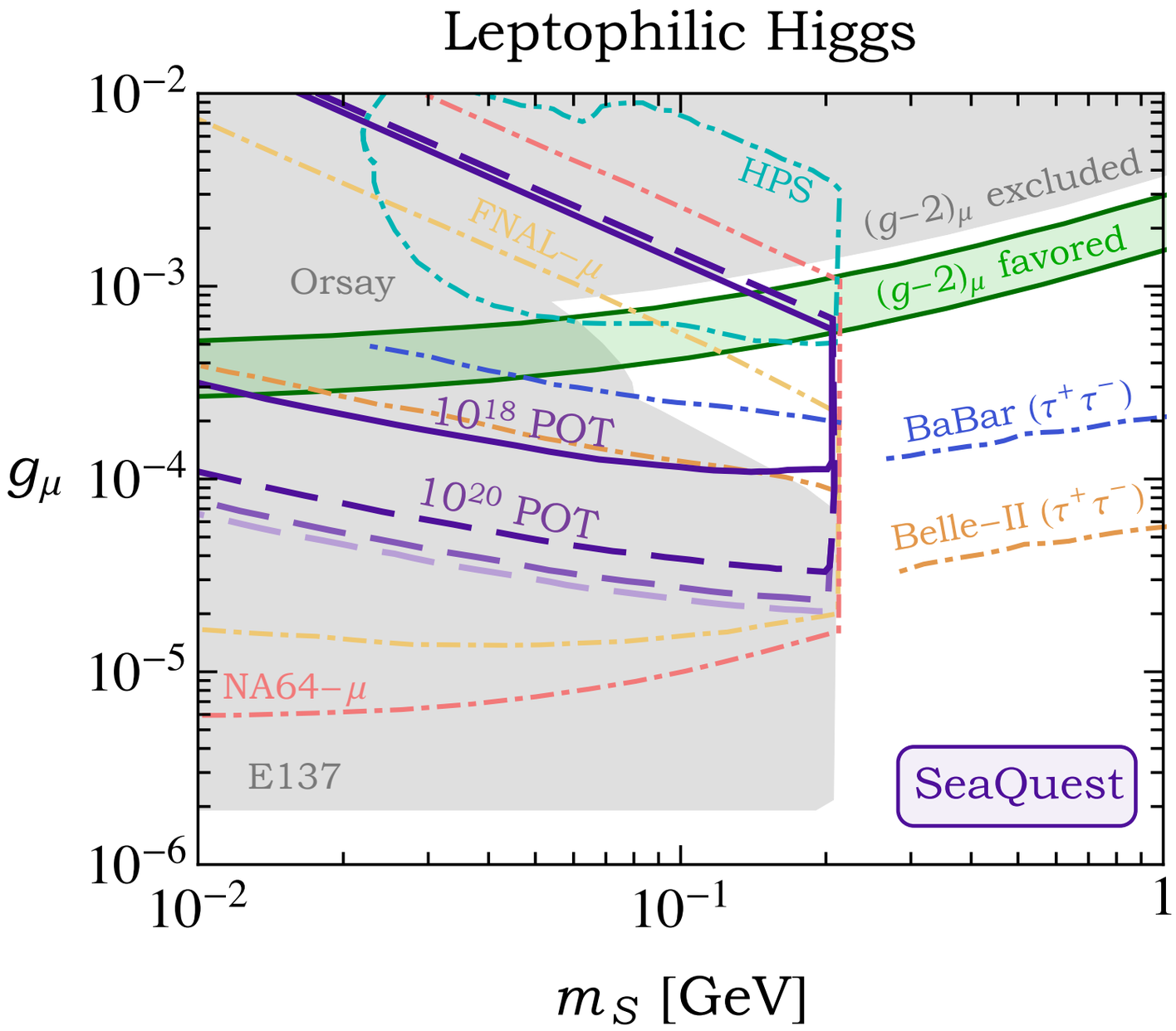
<u>Reminder to register for:</u>

KITP 2026, Dark Matter Detection and Detectability: Shift Again?

KITP 2026, QCD Axion Dark Matter: KSVZ or DFSZ?

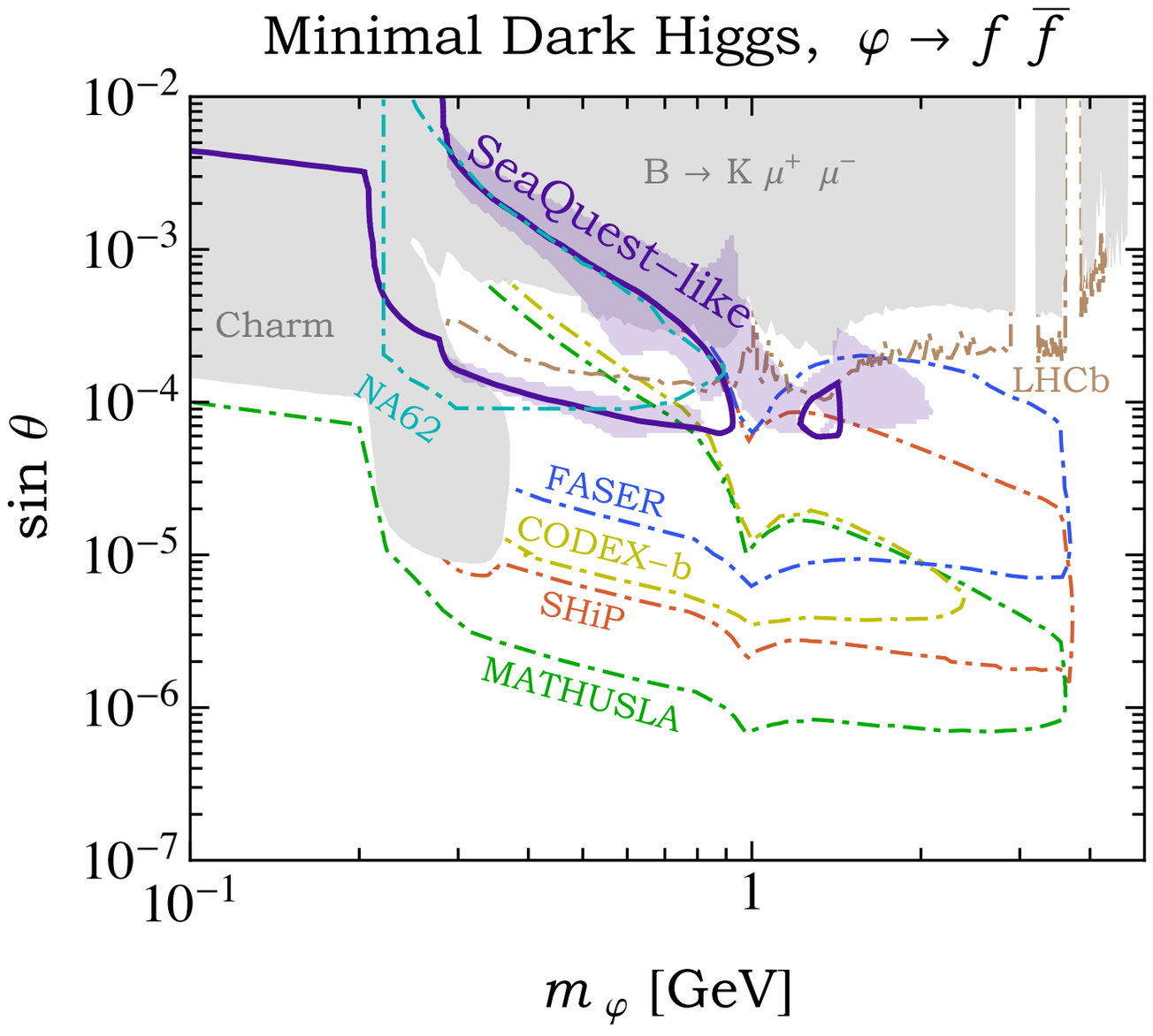
Back Up Slides

Secondary Production



arXiv:1606.04943
arXiv:1701.07437
arXiv:1804.00661

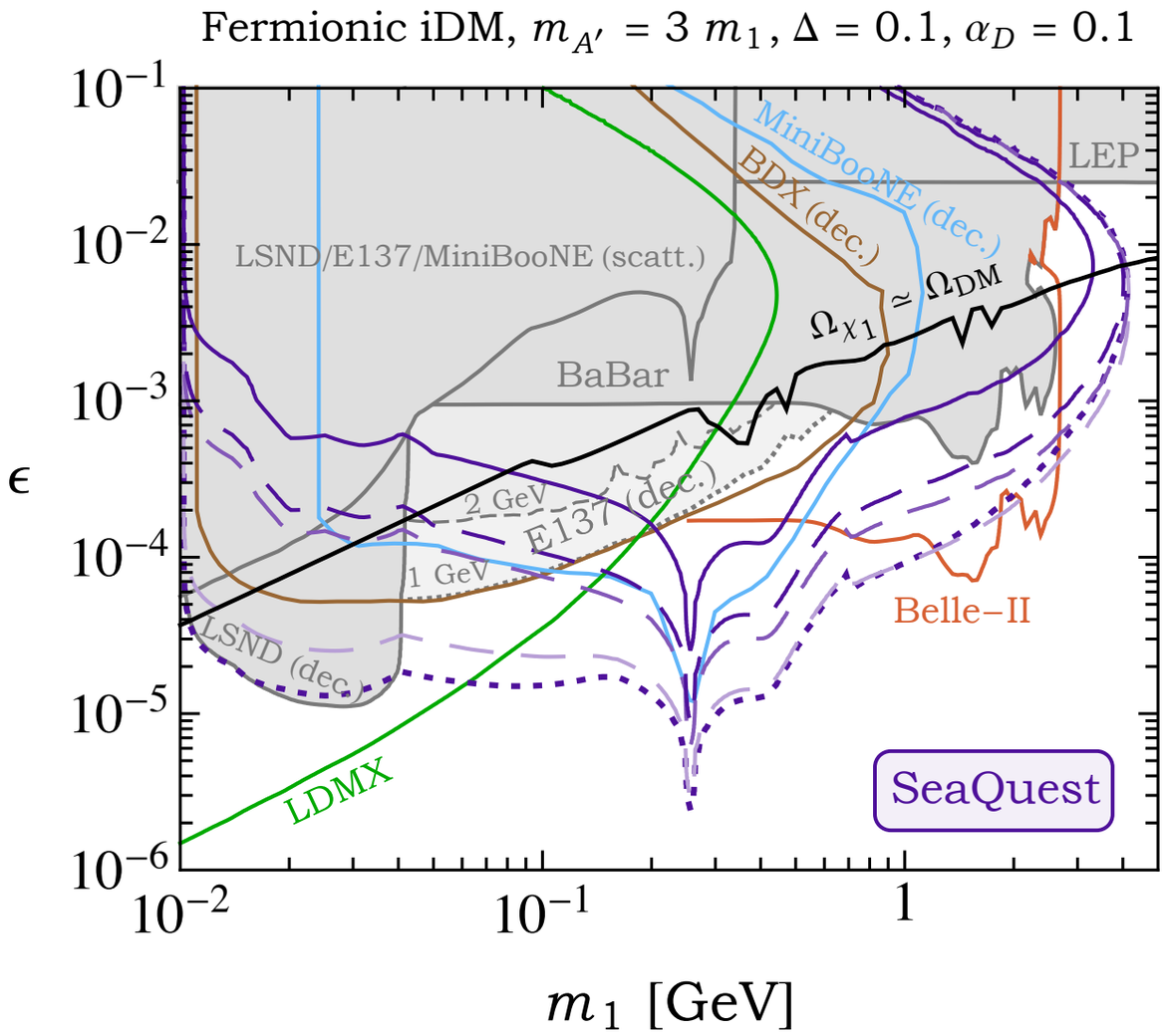
Minimal Dark Higgs

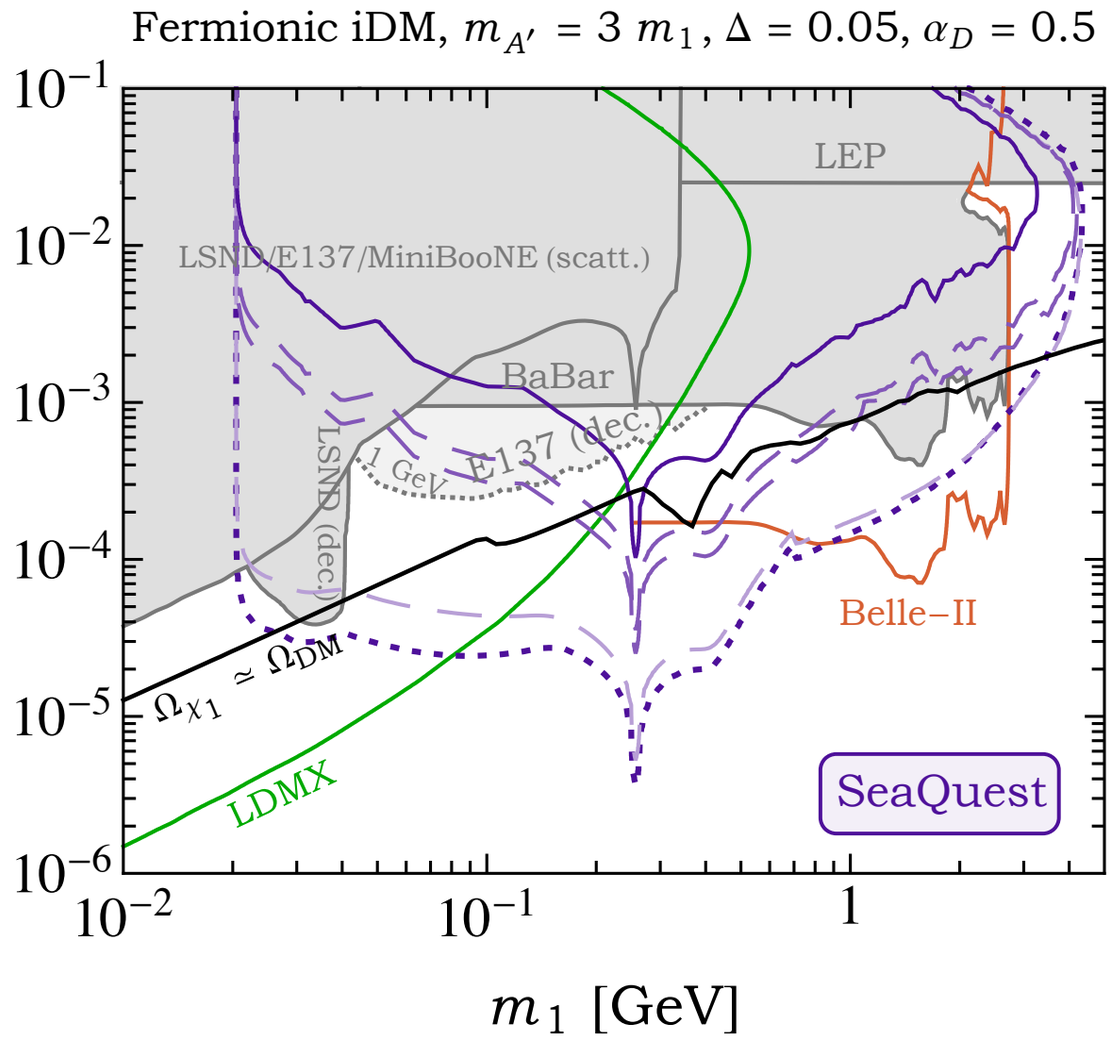


$$-\mathcal{L} \supset \sin\theta\ \frac{m_f}{v}\ \varphi\, \bar{f} f$$

arXiv:1804.00661

Inelastic Dark Matter at SeaQuest



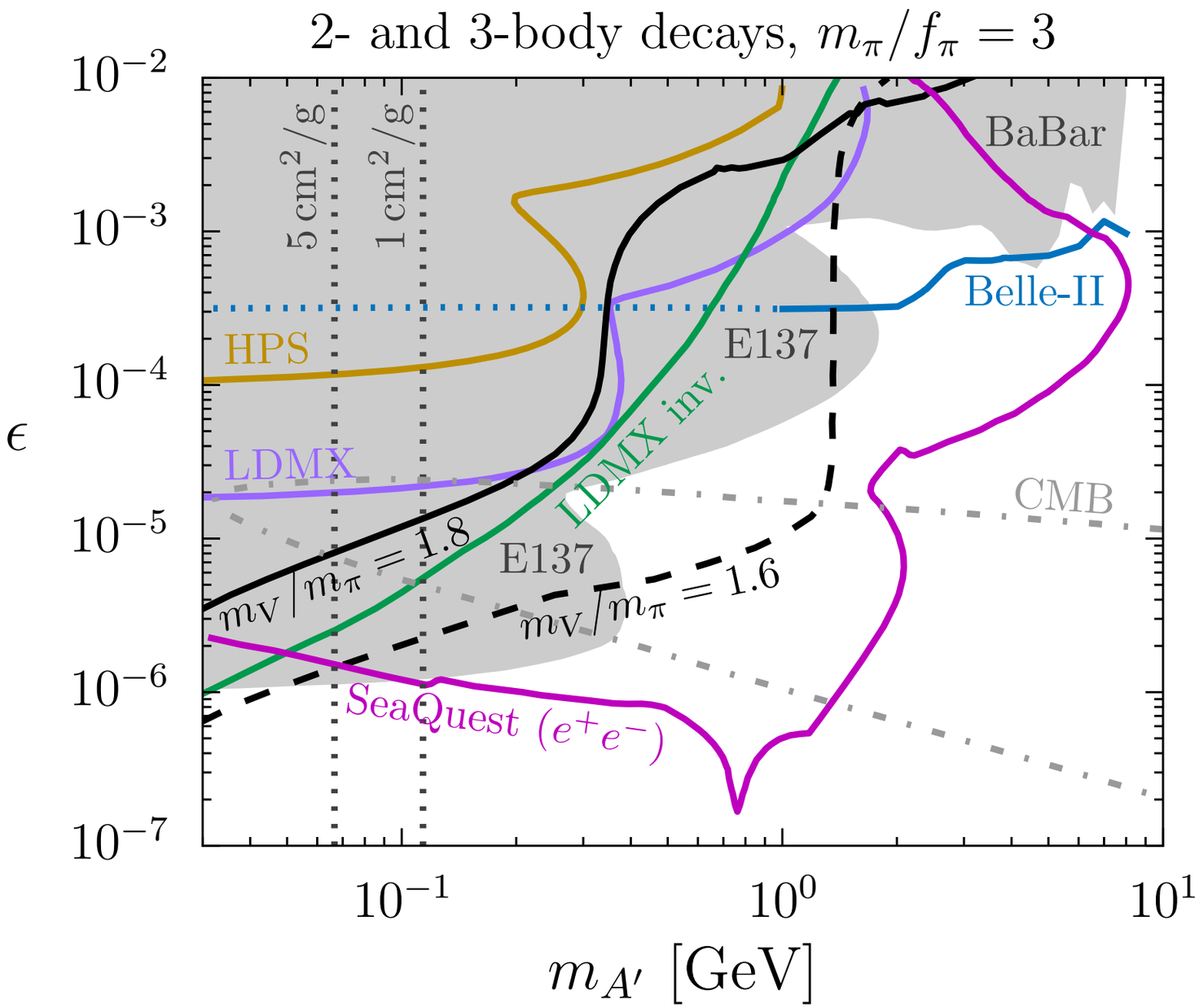


10^{18} POT — (5-6) m

10^{20} POT — (5-6) m, (5-9) m, (5-12) m, (5-6) m No KMAG

arXiv:1508.03050
arXiv:1703.06881
arXiv:1804.00661

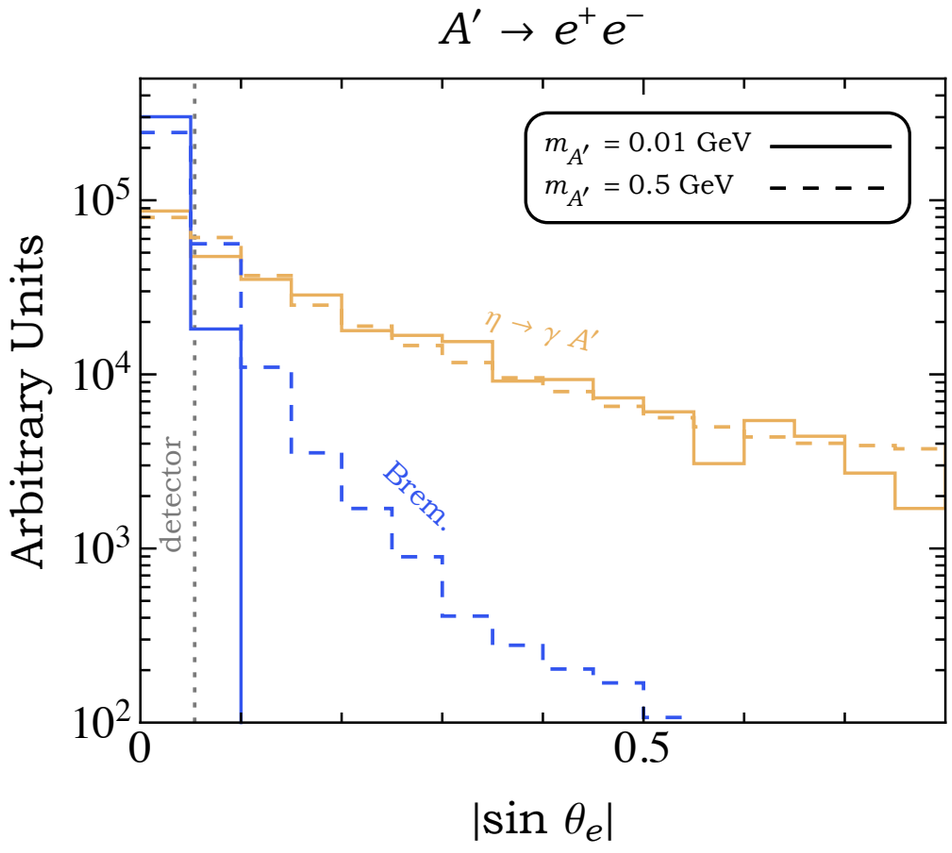
SIMPs

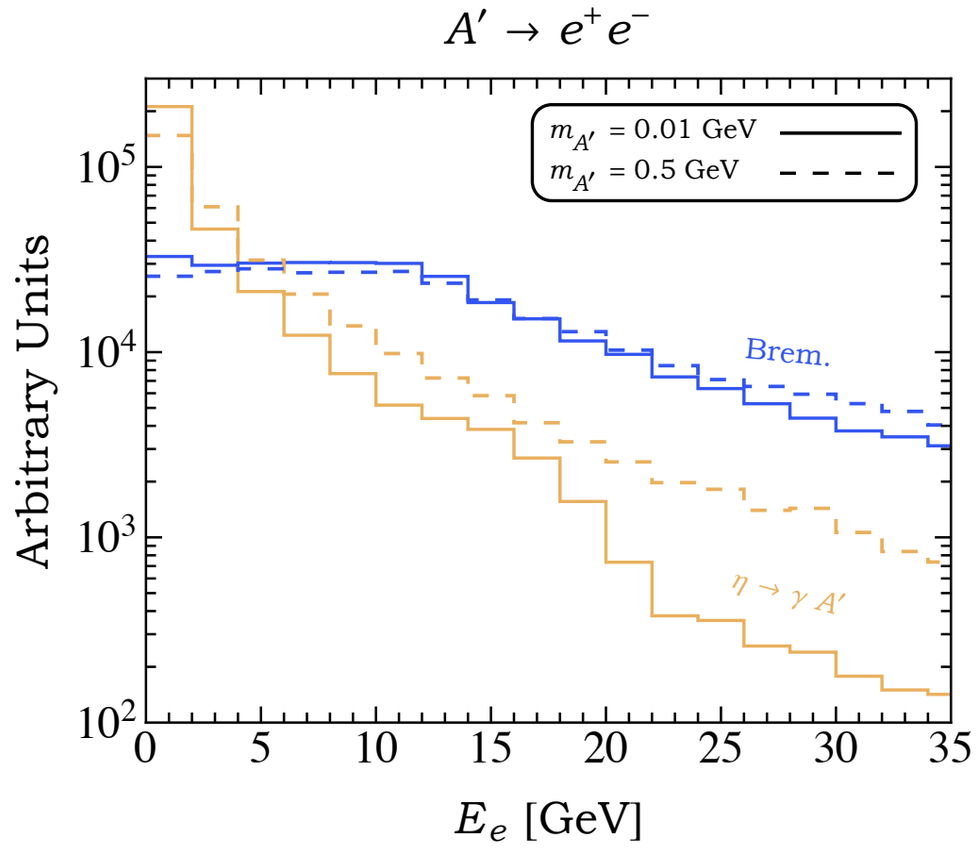


($m_{A'}$ / m_π = 3)

Berlin, Blinov, Gori, Schuster, Toro
arXiv:1801.05805

Dark Photons at SeaQuest

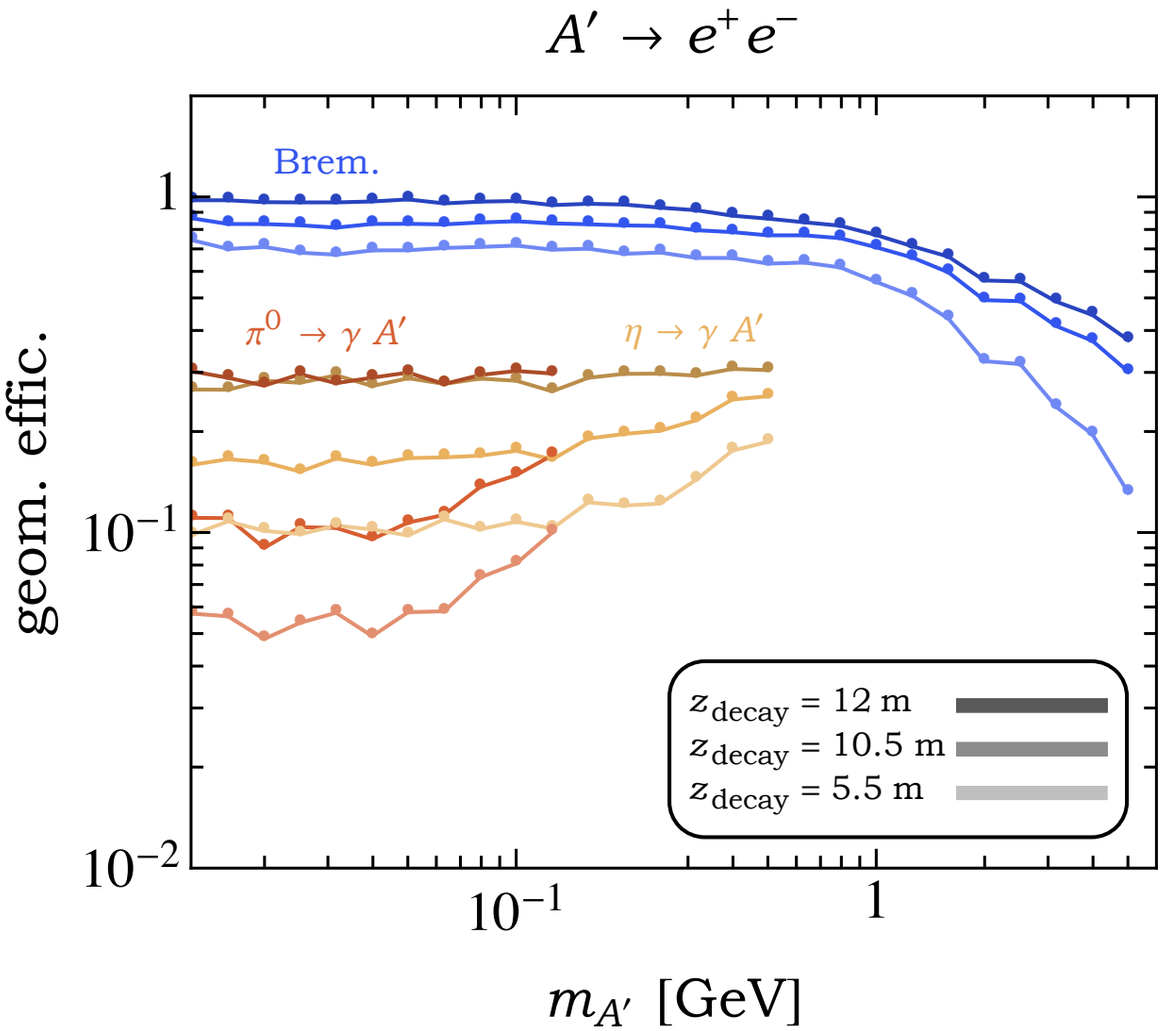




proton Bremsstrahlung is more energetic and forward

arXiv:1804.00661

Dark Photons at SeaQuest



proton Bremsstrahlung is more energetic and forward

arXiv:1804.00661

Inelastic Dark Matter

$\mathcal{L} \supset i e_D \; A'_\mu \; \bar{\chi}_1 \gamma^\mu \chi_2$ $\Longrightarrow$ off-diagonal (inelastic) coupling

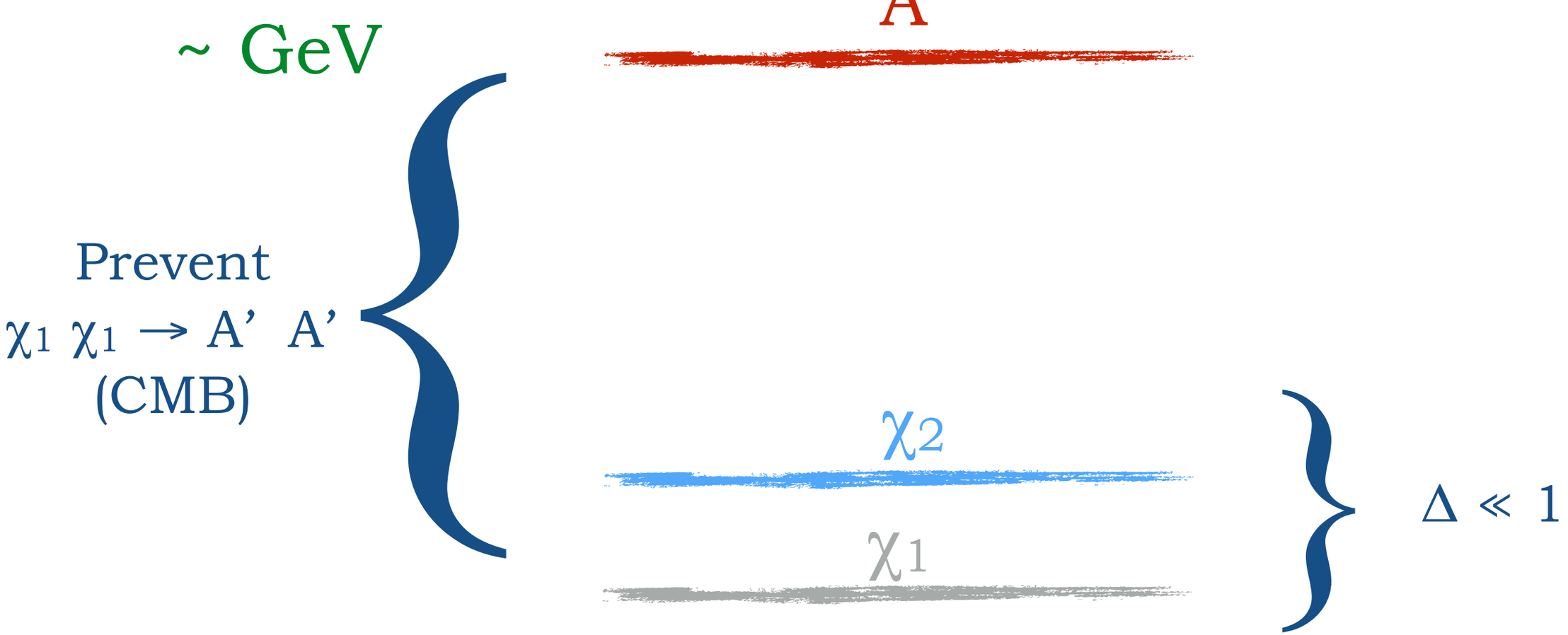
$\Delta \equiv \dfrac{m_2 - m_1}{m_1} \ll 1$ $\Longrightarrow$ small mass-splitting

$\Delta \gtrsim v_{\rm DM}^2 \sim 10^{-6}$ $\Longrightarrow$ suppressed rates at direct detection experiments

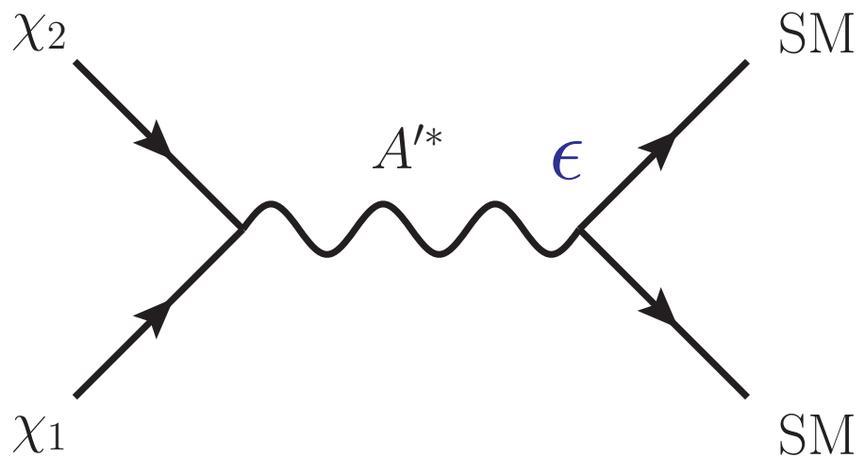
arXiv:hep-ph/0101138

Inelastic Dark Matter

Mass Spectrum



Inelastic Dark Matter



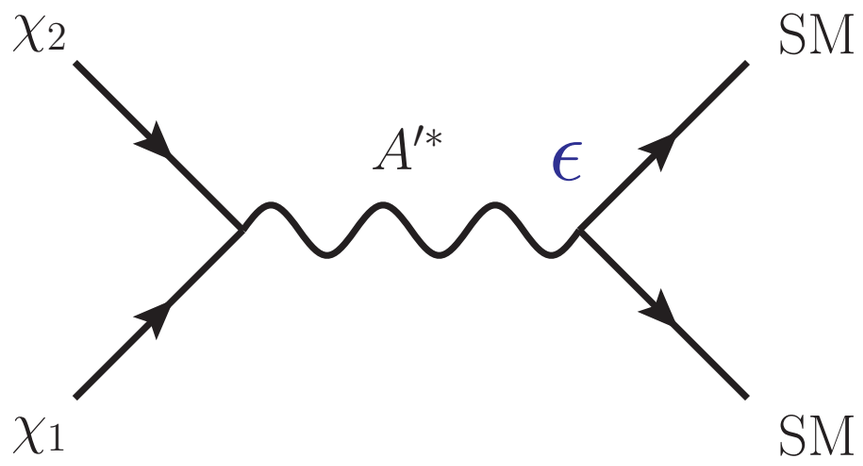
$$\langle \sigma v \rangle \sim \alpha_D \, \alpha_{\rm em} \, \epsilon^2 \, \frac{m_1^2}{m_{A'}^4} \, e^{-(m_1/T)\,\Delta}$$

$$m_1 \sim \text{few} \times \frac{\epsilon \, (\alpha_D \, \alpha_{\rm em} \, T_{\rm eq} \, m_{\rm pl})^{1/2}}{(m_{A'}/m_1)^2} \, e^{-x_f \Delta/2}$$

$$\sim \mathcal{O}(100) \text{ MeV} \times \left(\frac{\epsilon}{10^{-3}}\right) \times \left(\frac{\alpha_D}{0.1}\right)^{1/2} \times \left(\frac{3\,m_1}{m_{A'}}\right)^2 \, e^{-x_f \Delta/2}$$

arXiv:hep-ph/0101138
arXiv:1803.02901

Inelastic Dark Matter



CMB Safe

$$\langle \sigma v \rangle \sim \alpha_D \, \alpha_{\rm em} \, \epsilon^2 \, \frac{m_1^2}{m_{A'}^4} \, e^{-(m_1/T)\,\Delta}$$

$$m_1 \sim \text{few} \times \frac{\epsilon \, (\alpha_D \, \alpha_{\rm em} \, T_{\rm eq} \, m_{\rm pl})^{1/2}}{(m_{A'}/m_1)^2} \, e^{-x_f \Delta/2}$$

$$\sim \mathcal{O}(100) \text{ MeV} \times \left(\frac{\epsilon}{10^{-3}}\right) \times \left(\frac{\alpha_D}{0.1}\right)^{1/2} \times \left(\frac{3\, m_1}{m_{A'}}\right)^2 \, e^{-x_f \Delta/2}$$

arXiv:hep-ph/0101138

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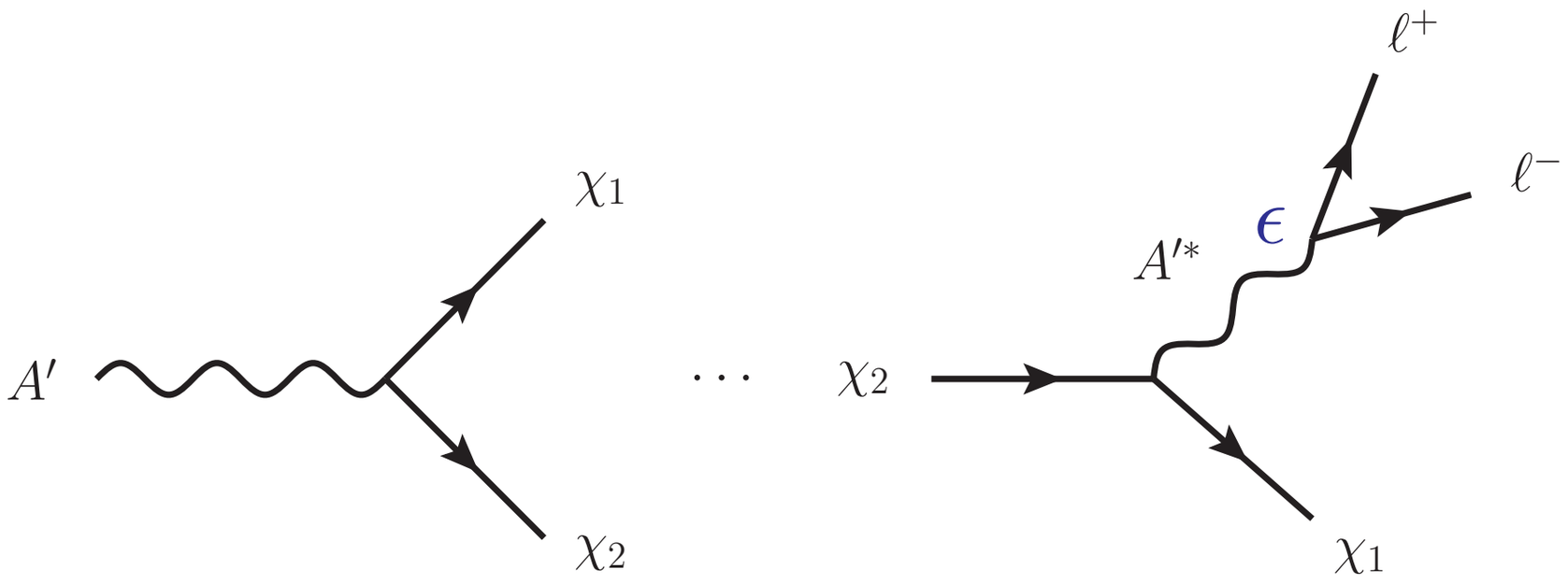
Inelastic Dark Matter

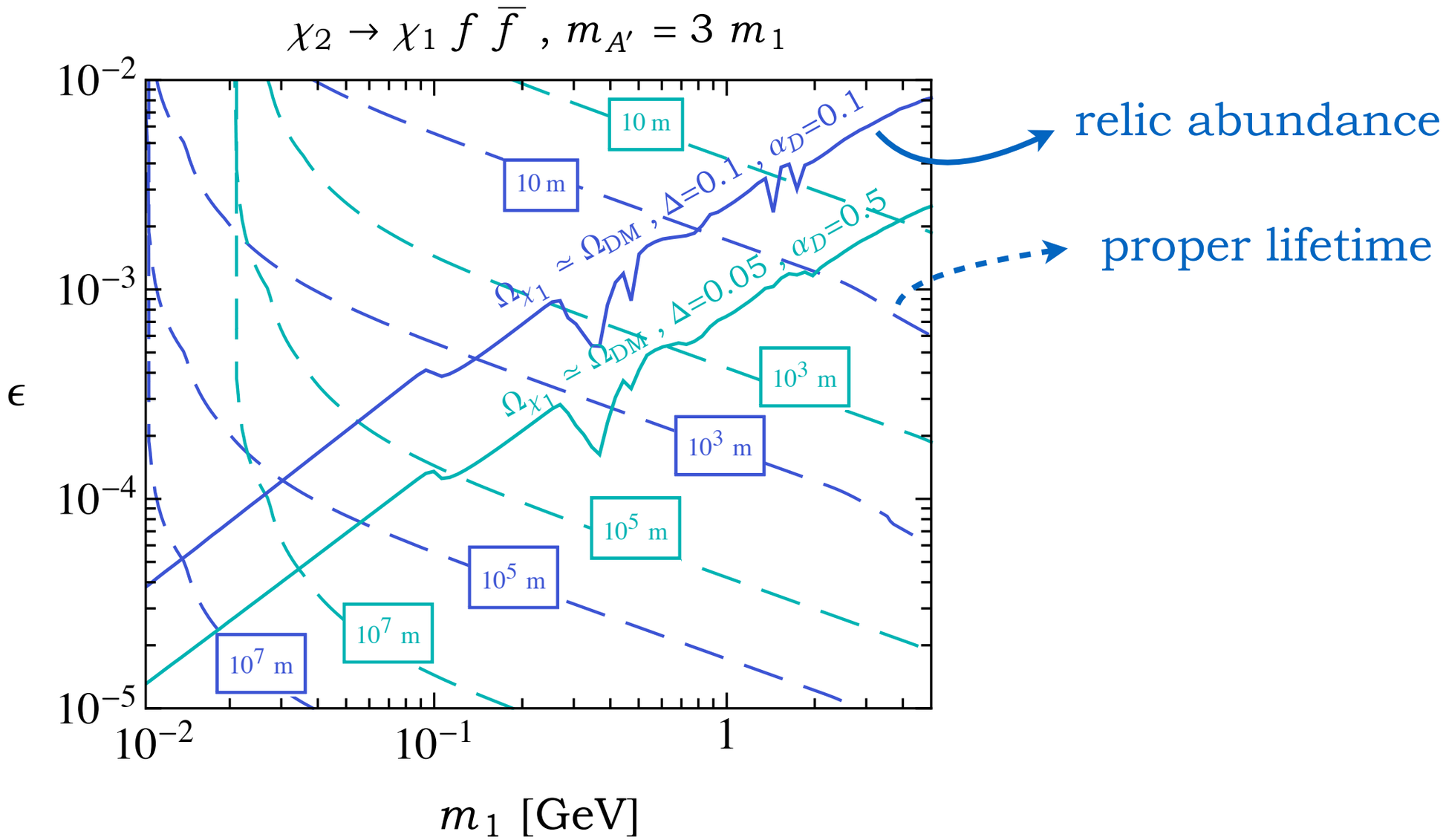


(prompt) (displaced)

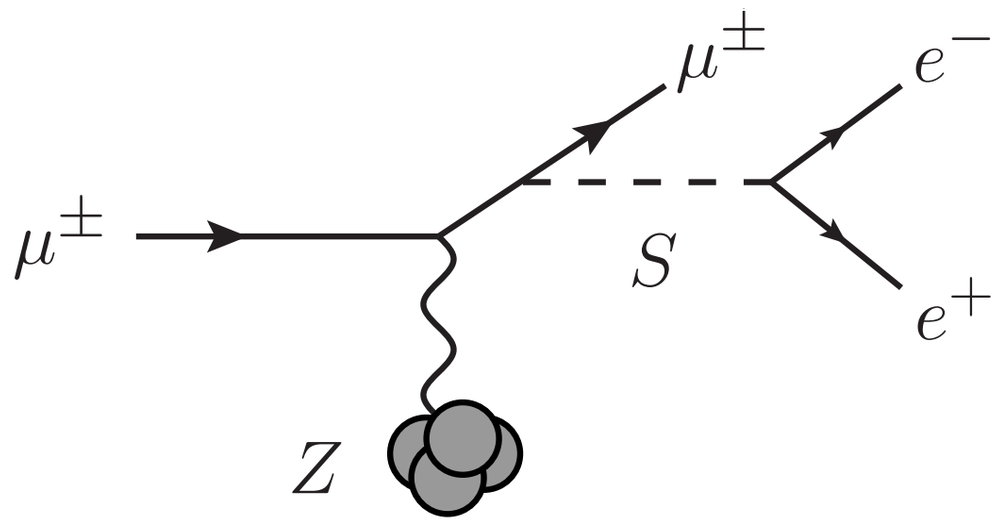
$$\Gamma(\chi_2 \to \chi_1\, \ell^+\ell^-) \simeq \frac{4\,\epsilon^2\,\alpha_{\rm em}\,\alpha_D\,\Delta^5 m_1^5}{15\pi\, m_{A'}^4}$$

arXiv:hep-ph/0101138

Inelastic Dark Matter



Leptophilic Higgs



$$-\mathcal{L} \supset \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{\Lambda}\, S\, \bar{\ell}\ell \;\equiv\; g_\mu \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{m_\mu}\, S\, \bar{\ell}\ell$$

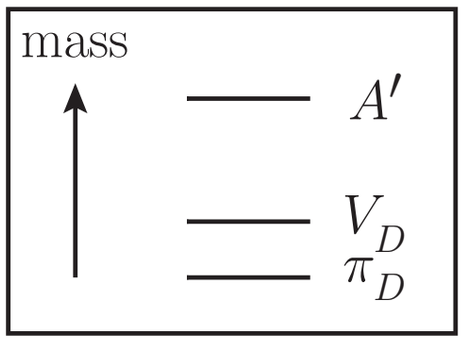
$$\mathcal{O}_S \sim \frac{S}{\Lambda}\, \bar{E}_L\, H\, e_R \;\leftrightarrow\; \text{2HDM} + \text{singlet scalar}$$

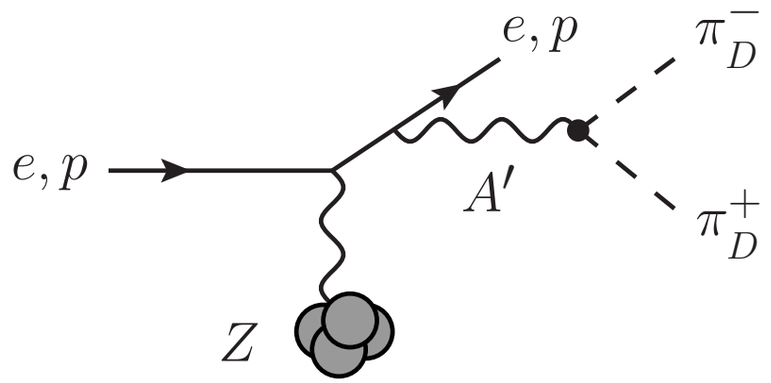
$$m_S \lesssim 2\, m_\mu \implies \text{lifetime is enhanced for fixed production rate}$$

arXiv:1606.04943
arXiv:1804.00661

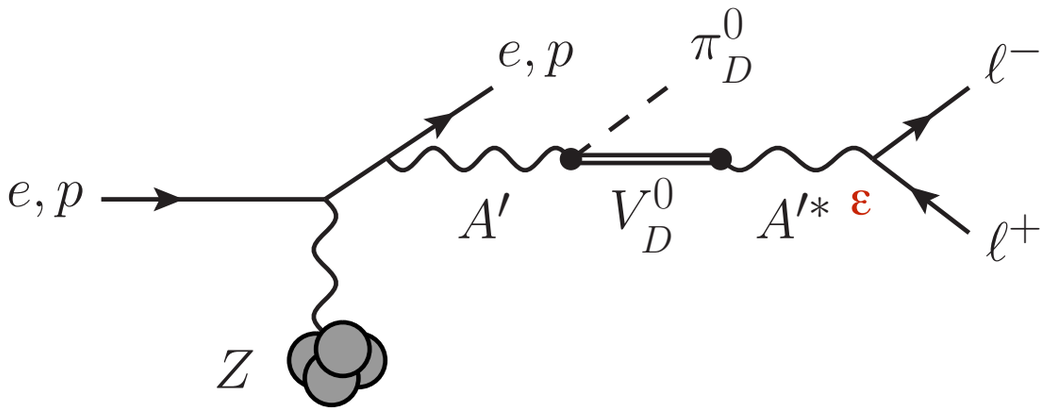
SIMPs

(vector mesons are long-lived)

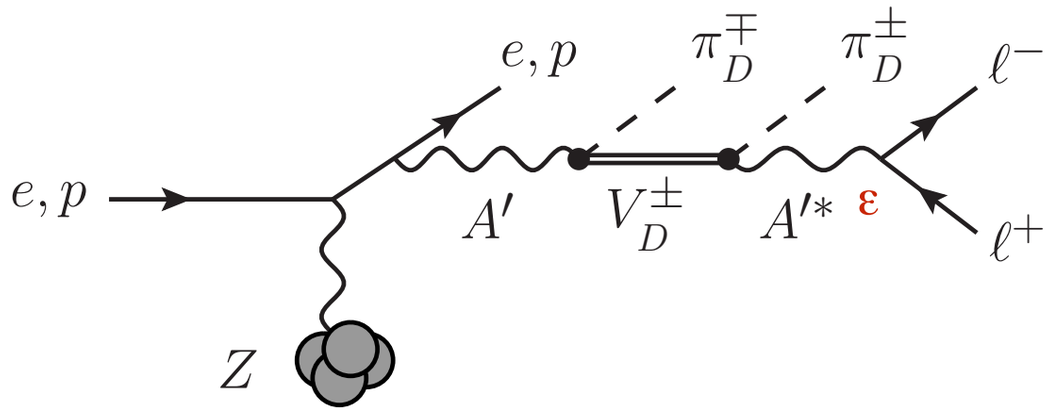




invisible decay



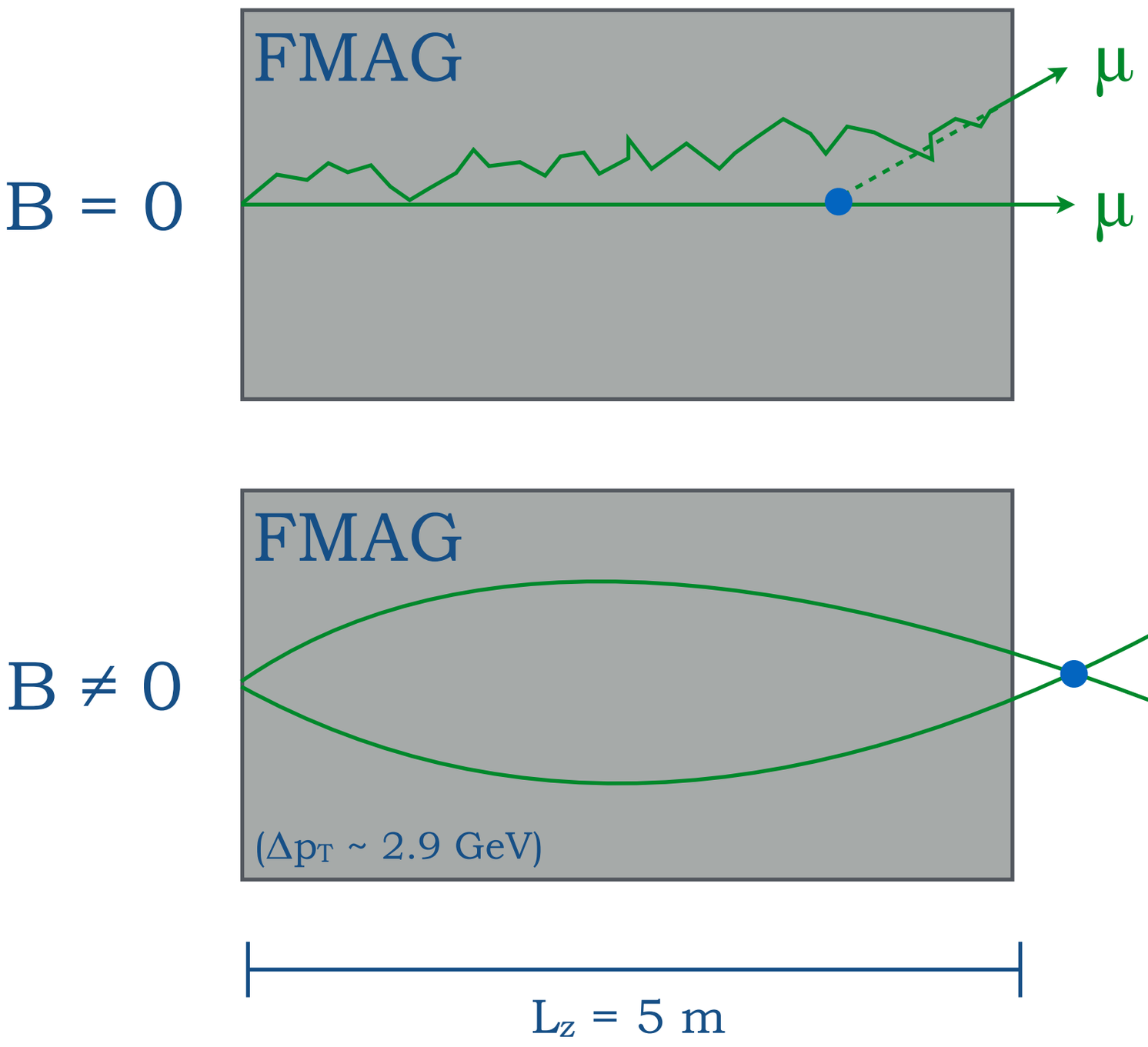
2-body V^0 decay



3-body $V^\pm$ decay

Berlin, Blinov, Gori, Schuster, Toro
arXiv:1801.05805

Magnetic Focusing of Muons



$\delta z / L_z \sim 100 \text{ MeV}/m_{\mu\mu}$

$\delta z / L_z \sim \Delta p_T / m_{\mu\mu}$