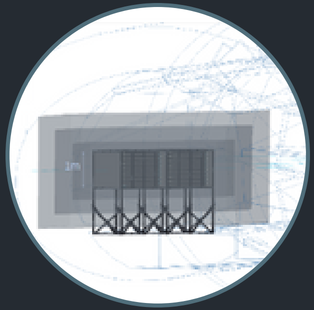
MoEDAL-MAPP Weekly Meets

July 31 2020

Michael Staelens
staelens@ualberta.ca

Overview



MAPP Detector Construction

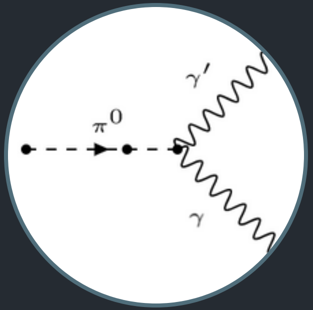
Polishing and wrapping scintillator bars for MAPP-mCP (inner core of MAPP)

Update this week from Alejandro

MAPP - Fiducial Efficiency Calculations

Large # of simulations needed suggests using an alternative approach. (for LLPs)

Can use a mixture of simulations and numerical integration.. but we are still working this out.



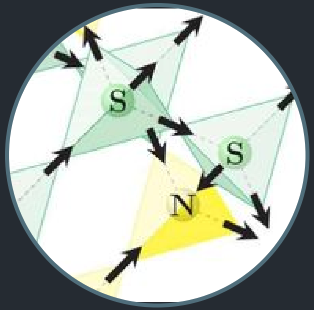
The Physics Case of the MAPP Detector

Updates on LLP Models:

Dark Photons

ALPs

mCP EPJ Paper Draft Shared



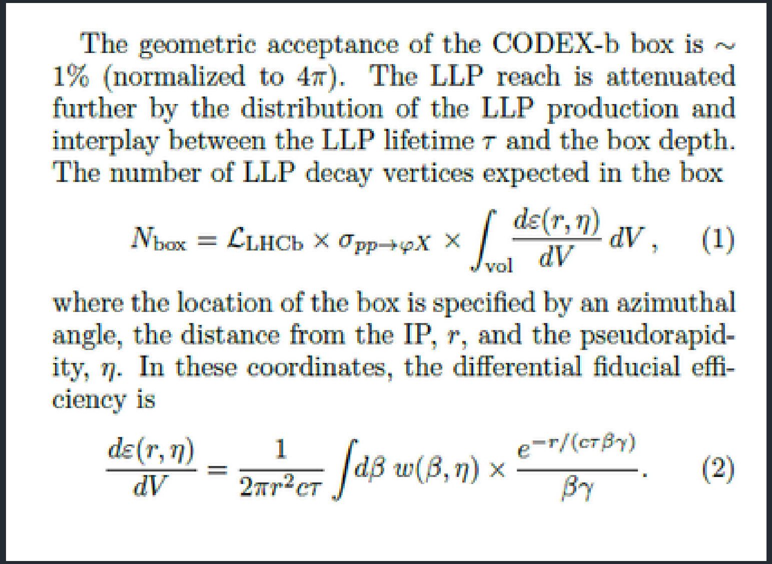
Emergent Monopoles

Modeling Emergent Monopole Excitations in spin ice.

Calculation Part 1: Second Quantized Hamiltonian

MAPP - Fiducial Efficiency Calculations

Fiducial Efficiency Calculations



The geometric acceptance of the CODEX-b box is $\sim$ 1% (normalized to 4π). The LLP reach is attenuated further by the distribution of the LLP production and interplay between the LLP lifetime τ and the box depth. The number of LLP decay vertices expected in the box

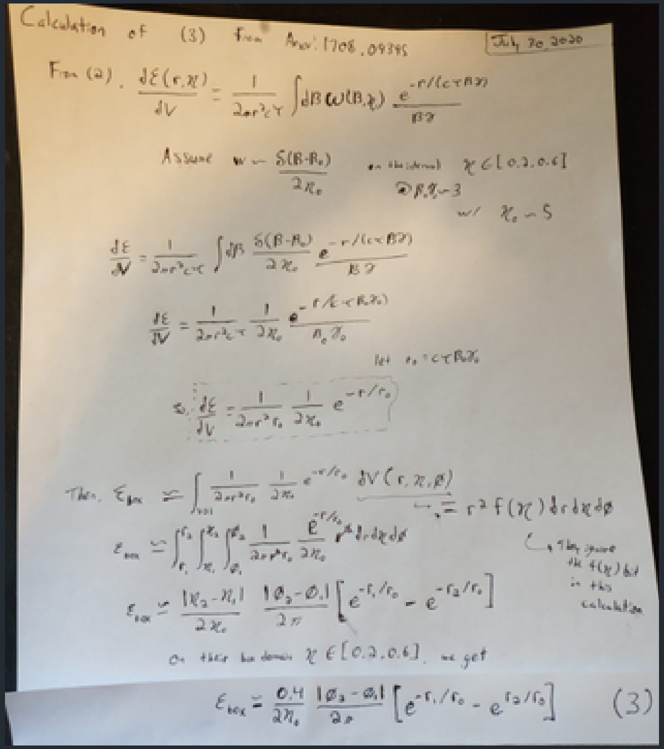
$$N_{\rm box} = \mathcal{L}_{\rm LHCb} \times \sigma_{pp\to\varphi X} \times \int_{\rm vol} \frac{d\varepsilon(r,\eta)}{dV}\, dV\,, \qquad (1)$$

where the location of the box is specified by an azimuthal angle, the distance from the IP, r, and the pseudorapidity, η. In these coordinates, the differential fiducial efficiency is

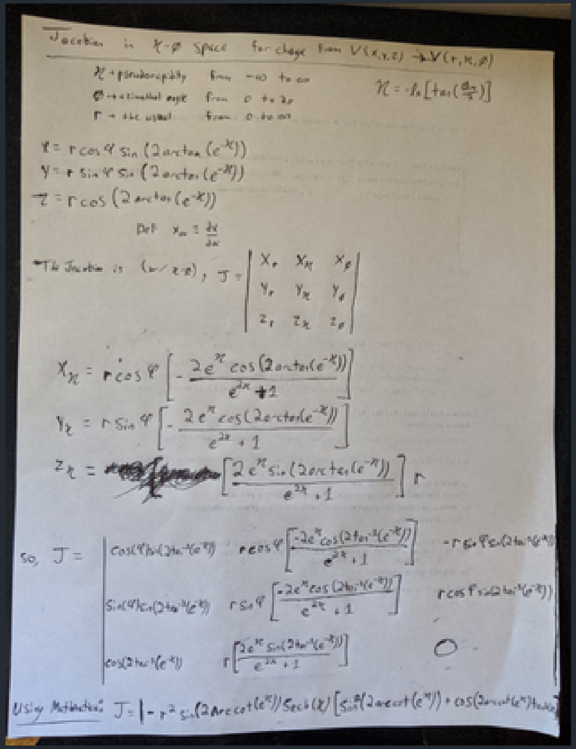
$$\frac{d\varepsilon(r,\eta)}{dV} = \frac{1}{2\pi r^2 c\tau} \int d\beta\, w(\beta,\eta) \times \frac{e^{-r/(c\tau\beta\gamma)}}{\beta\gamma}. \qquad (2)$$

Codex-b Method for Integrating over Box

c.f. Arxiv:1708.09395



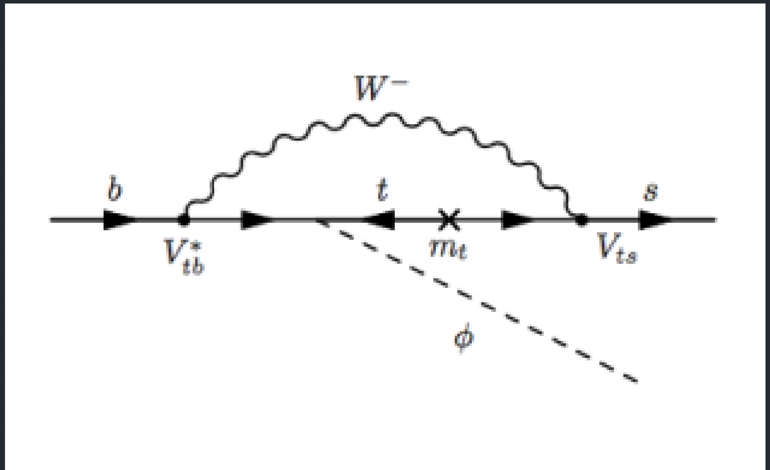
Calculation of (3)



Jacobian for change to eta-phi space

Physics Performance of the MoEDAL-MAPP Detector

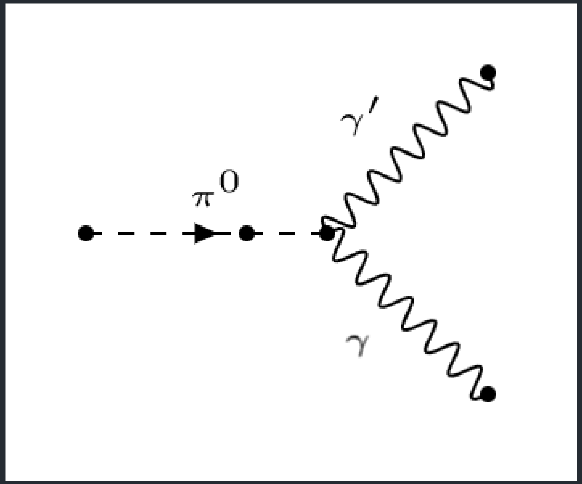
MAPP-LLP Physics Performance Cases



Light Scalar Portal (Dark Higgs)

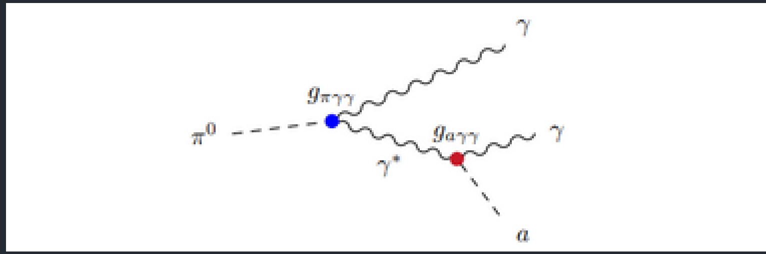
We are working on solutions to the large # of events required to generate MAPP-2, 3 ab-1, limit curves.

c.f. Arxiv:1708.09395



Vector Portal (Dark Photon)

Limit Plots are being updated (we can now show the full limits curves from 10-300 MeV or so)



Axion-Like Particle (ALPs)

Branching Ratio Formula Doesn't Match Plot

Calculated it w/ Mathematica to clarify.

c.f. Arxiv:1806.02348 (Published version still has same issue)

LLPs @ MAPP via Rare Meson Decays: A Summary

B, π and η decays are being studied.

Dark Higgs

$$N_{\phi,events} = \mathcal{L}_{LHCb} \times \sigma_{pp\to\phi X} \times BR(B \to X_s\phi) \quad (1)$$

$$N_{\phi,Codex-b} = \mathcal{L}_{LHCb} \times \sigma_{b\bar{b}} \times BR(B \to X_s\phi) \times \epsilon_{fid,Codex-b} \quad (2)$$

$$N_{\phi,MAPP} = \mathcal{L}_{LHCb} \times \sigma_{b\bar{b}} \times BR(B \to X_s\phi) \times \epsilon_{fid,MAPP} \quad (3)$$

where $\sigma_{b\bar{b}}$ ~500 μb for $\sqrt{s}$ =14 TeV, and $\mathcal{L}_{LHCb}$=300 fb^{-1}. Here ϵ_{fid} should take into account $BR(\phi \to \mu^+\mu^-)$. (Any cuts as well.. e.g. tracking requirements.) In any case, ϵ_{fid} is obtained by simulations (Pythia8).

Dark Photons

$$N_{\gamma',events} = \mathcal{L}_{LHCb} \times \sigma_{pp,inel} \times N_{M/pp} \times BR(M \to \gamma'\gamma) \quad (4)$$

$$N_{\gamma',MAPP} = N_{M,tot} \times BR(M \to \gamma'\gamma) \times \times\epsilon_{fid,MAPP} \quad (5)$$

where $N_{M,tot}$ is the total number of expected mesons M given $\mathcal{L}_{LHCb}$=300 fb^{-1} and $\sigma_{pp,inel} \sim 75mb$ at $\sqrt{s}$ =13 TeV. Here ϵ_{fid} should take into account $BR(\gamma' \to l^+l^-)$ for $(l = e, \mu)$.

More precisely $\sigma_{pp,inel} = 75.4 \pm 3.0 \pm 4.5$ mb.
(Taken from https://arxiv.org/pdf/1803.10974.pdf)

N.B. I calculated $N_{\pi^0,tot} \sim 4.7 * 10^{17}$ (which matches the multiplicity of pions found by both Pythia simulations and the paper from ACTA PHYSICA POLONICA Vol. B4 1973). Eta multiplicities are in alignment as well. $N_{\eta,tot} \sim 5.1 * 10^{16}$.

Axion-like Particles

$$N_{a,events} = \mathcal{L}_{LHCb} \times \sigma_{pp,inel} \times N_{M/pp} \times BR(M \to a\gamma\gamma) \quad (6)$$

$$N_{a,MAPP} = N_{M,tot} \times BR(M \to a\gamma\gamma) \times \times\epsilon_{fid,MAPP} \quad (7)$$

Light Scalar Portal (Dark Higgs)

Limit plots enforce 2 requirements:

1. 4 Decays phi--> μ+μ- inside MAPP-LLP-1
2. Both μ hit at least 2 planes of the detector (~80% eff.?)

Vector Portal (Dark Photon)

Limit plots here require only 3 decays of γ' --> l+l- (l=e,μ-) inside MAPP-LLP-1.

No cuts.

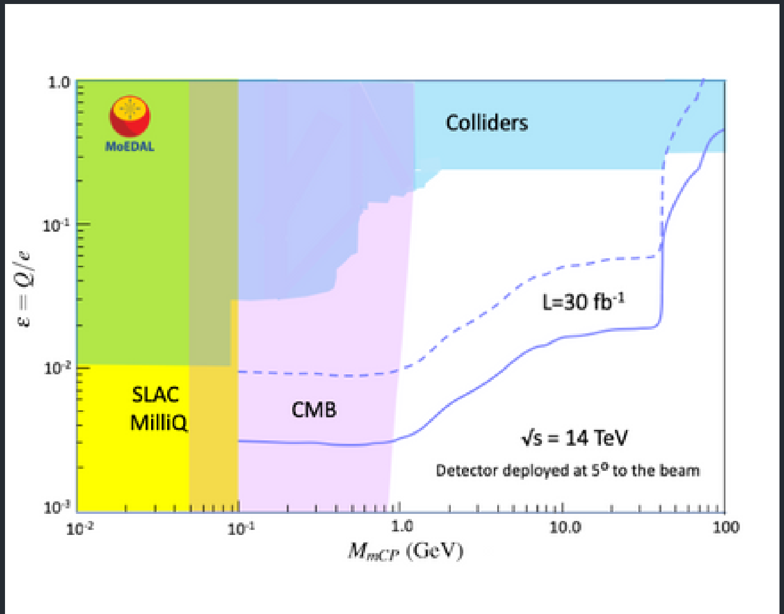
Axion-like Particle (ALPs)

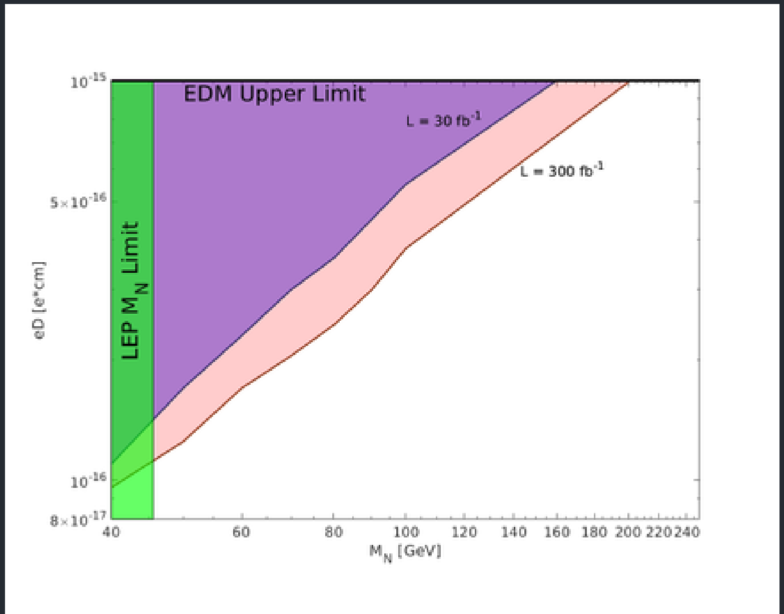
First limit plots here will be for MAPP-mCP-1 and MAPP-LLP-1 (Phase 1 section),

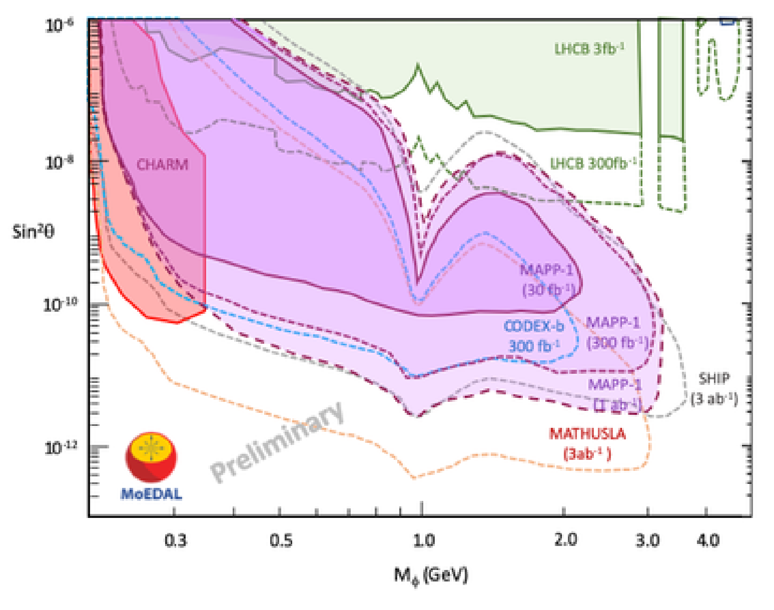
requiring 3 fiducial decays of a --> γγ.

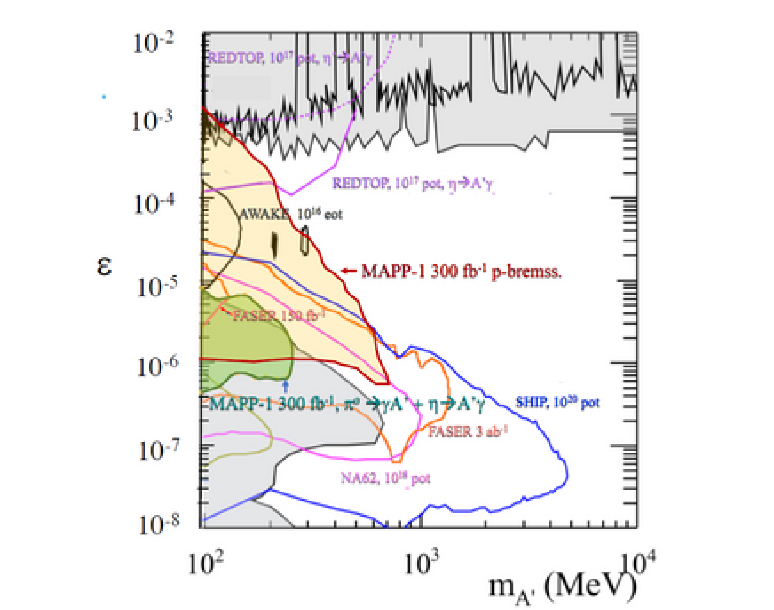
Slide will be updated to include LLP decay length/width formulae as well.

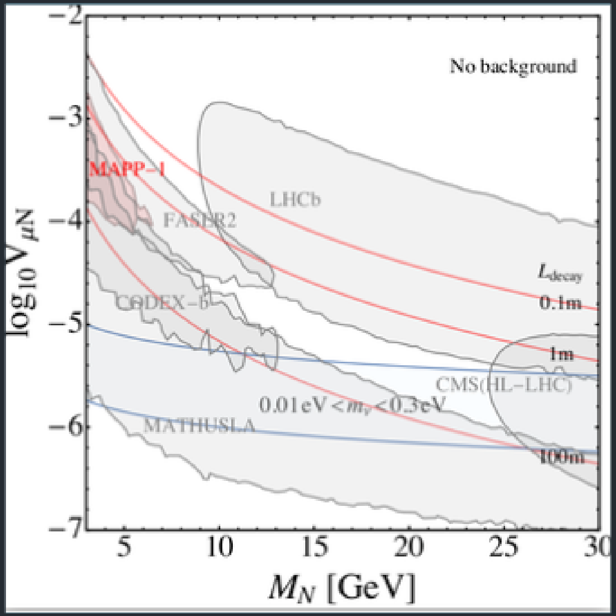
MAPP-1.. Results So Far











Progress with ALPs @ MAPP-1 (via rare meson decays)

The differential decay width is, then,

$$\frac{d\Gamma(\pi^0 \to a\gamma\gamma)}{dE_1 dE_2} = \frac{1}{2}\frac{1}{(4\pi)^3 M}\sum_{\text{pols}}|M|^2 = \frac{(g_{\pi^0\gamma\gamma}g_{a\gamma\gamma})^2}{2(4\pi)^3 M} f(E_1, E_2), \tag{B4}$$

where

$$\begin{aligned} f(E_1, E_2) = {} & \frac{E_1^2 E_2^2[M^2(1+\cos^2\theta_{12}) + 2E_1(E_1 - M)(1-\cos\theta_{12})^2]}{(M-2E_1)^2} \\ & + 2\frac{E_1^2 E_2^2[M^2(1+\cos^2\theta_{12}) + [2E_1E_2 - M(E_1+E_2)](1-\cos\theta_{12})^2]}{(M-2E_1)(M-2E_2)} \\ & + \frac{E_1^2 E_2^2[M^2(1+\cos^2\theta_{12}) + 2E_2(E_2 - M)(1-\cos\theta_{12})^2]}{(M-2E_2)^2}. \end{aligned} \tag{B5}$$

Integrating over phase space results in the total decay width

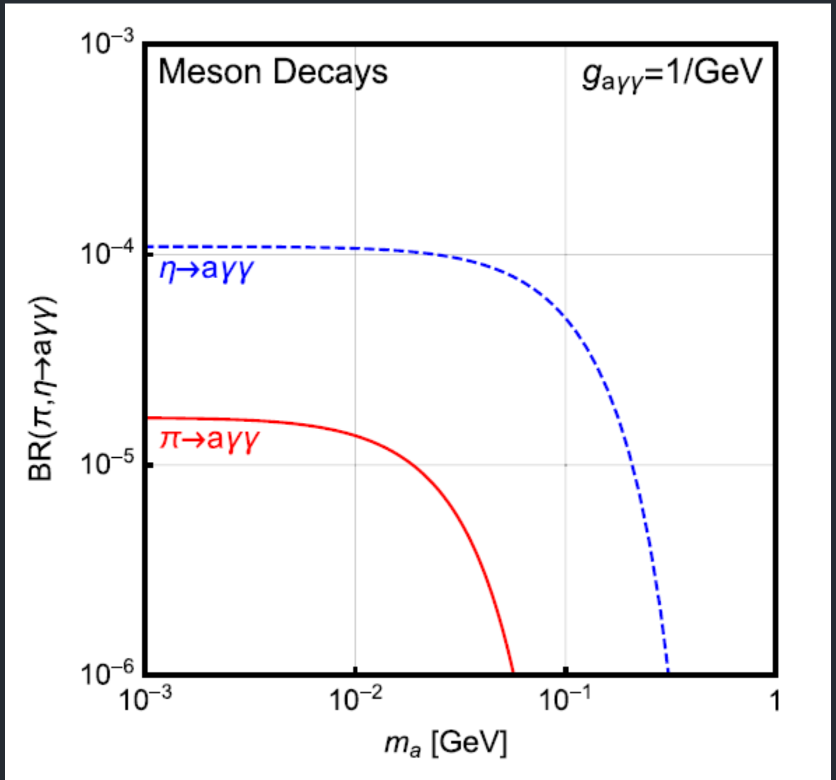
$$\Gamma(\pi^0 \to a\gamma\gamma) = \int_0^{\frac{M^2-m^2}{2M}} dE_1 \int_{\frac{M^2-m^2}{2M}-E_1}^{\frac{M}{2}+\frac{m^2}{4E_1-2M}} dE_2 \frac{d\Gamma(\pi^0 \to a\gamma\gamma)}{dE_1 dE_2} = \frac{(g_{\pi^0\gamma\gamma}g_{a\gamma\gamma})^2}{768(4\pi)^3 M^3} F(M, m), \tag{B6}$$

where

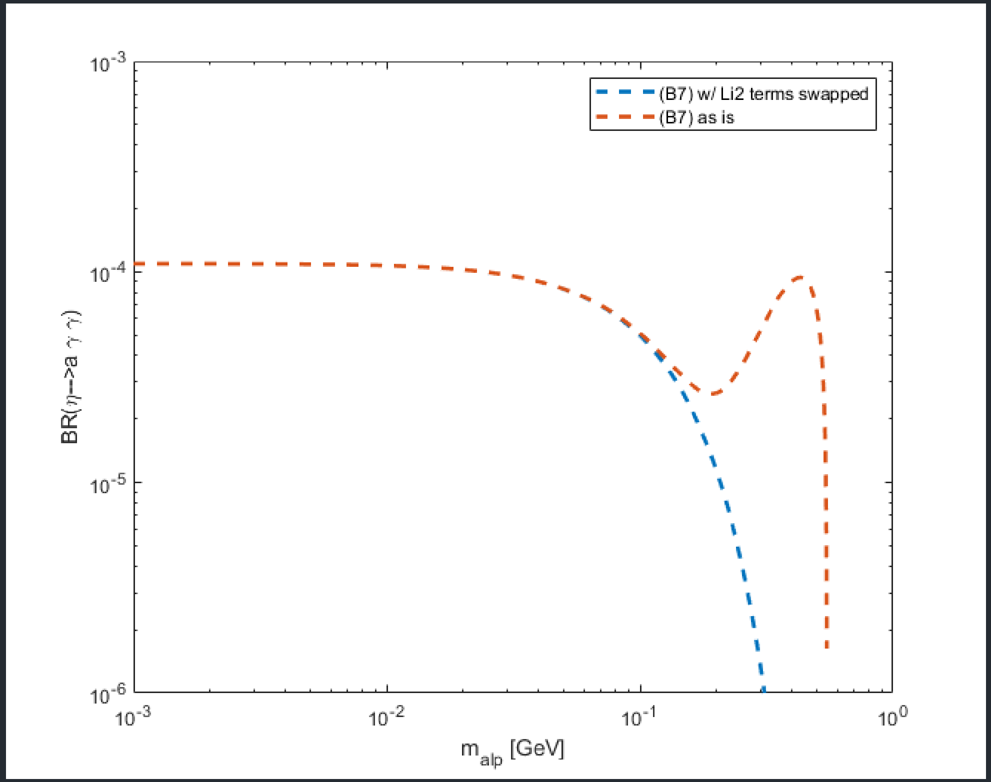
$$\begin{aligned} F(M, m) = {} & 24\log\left(\frac{m}{M}\right)\left[6m^2M^2(M^4+m^4) + 15m^4M^4 + 2m^4M^4\log\left(\frac{mM}{m^2+M^2}\right)\right] \\ & + 7(M^8 - m^8) + 148M^2m^2(M^4-m^4) + 24m^4M^4\left[\mathrm{Li}_2\left(\frac{m^2}{m^2+M^2}\right) - \mathrm{Li}_2\left(\frac{M^2}{m^2+M^2}\right)\right]. \end{aligned} \tag{B7}$$

- B6 is plotted & calculated in PhysRevD.98.055021
- In-house script to plot B6 as validation of the calculation does not work (unless one switches the order of the Li2 terms)
- Plots on the next slide show this..
- B6 & B7 will be calculated to check this.

FASER Decay width plot vs. mine



FASER



Me

(Eta process)

Calculation of B6 & B7 in Mathematica

The differential decay width is, then,

$$\frac{d\Gamma(\pi^0 \to a\gamma\gamma)}{dE_1 dE_2} = \frac{1}{2}\frac{1}{(4\pi)^3 M}\sum_{\text{pols}}|M|^2 = \frac{(g_{\pi^0\gamma\gamma} g_{a\gamma\gamma})^2}{2(4\pi)^3 M} f(E_1, E_2), \tag{B4}$$

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Integrating over phase space results in the total decay width

$$\Gamma(\pi^0 \to a\gamma\gamma) = \int_0^{\frac{M^2-m^2}{2M}} dE_1 \int_{\frac{M^2-m^2}{2M}-E_1}^{\frac{M}{2}+\frac{m^2}{4E_1-2M}} dE_2 \frac{d\Gamma(\pi^0 \to a\gamma\gamma)}{dE_1 dE_2} = \frac{(g_{\pi^0\gamma\gamma} g_{a\gamma\gamma})^2}{768(4\pi)^3 M^3} F(M, m), \tag{B6}$$

where

$$\begin{aligned} F(M, m) = &24\log\left(\frac{m}{M}\right)\left[6m^2M^2(M^4+m^4) + 15m^4M^4 + 2m^4M^4\log\left(\frac{mM}{m^2+M^2}\right)\right] \\ &+ 7(M^8 - m^8) + 148M^2m^2(M^4 - m^4) + 24m^4M^4\left[\mathrm{Li}_2\left(\frac{m^2}{m^2+M^2}\right) - \mathrm{Li}_2\left(\frac{M^2}{m^2+M^2}\right)\right]. \end{aligned} \tag{B7}$$

- Feeding the integral to Mathematica
- Need to go term by term..
- ~12 integrals to do.. will take a bit more time.
- Also, still need the Full Decay width for pi0..

Is Phys. Rev. Lett. 33, 1400 reliable? (8.02±0.42 eV???)

```
(* Try term by term... *)
(* Row 1 - Term 1 *)
Integrate[1/(M - 2*E1)^2 E1^2 E2^2*(M^2*(1 + (1/(2*E1*E2)*(M^2 - m^2 - 2*M*(E1 + E2) + 2*E1*E2))^2)), {E2, (M^2 - m^2)/(2*M) - E1, M/2 + m^2/(4*E1 -
```

$$\frac{E1^3\,(m^2 + (2\,E1 - M)\,M)^3\,(2\,E1^2 - 2\,E1\,M + M^2)}{3\,(2\,E1 - M)^5\,M}$$

```
(* Row 1 - Term 2 *)
Integrate[1/(M - 2*E1)^2 E1^2 E2^2*(2*E1*(E1 - M)*(1 - 1/(2*E1*E2)*(M^2 - m^2 - 2*M*(E1 + E2) + 2*E1*E2))^2), {E2, (M^2 - m^2)/(2*M) - E1,
```

$$-\frac{2\,E1^4\,(E1 - M)\,(m^2 + (2\,E1 - M)\,M)^3}{3\,M\,(-2\,E1 + M)^5}$$

$$\text{FullSimplify}\left[\frac{E1^3\,(m^2 + (2\,E1 - M)\,M)^3\,(2\,E1^2 - 2\,E1\,M + M^2)}{3\,(2\,E1 - M)^5\,M} - \frac{2\,E1^4\,(E1 - M)\,(m^2 + (2\,E1 - M)\,M)^3}{3\,M\,(-2\,E1 + M)^5}\right]$$

$$\frac{E1^3\,(m^2 + (2\,E1 - M)\,M)^3}{3\,(2\,E1 - M)^3\,M}$$

Then integrating over E1....

```
(* If you scale it by the constants out front... (first line of eq. B5 only) *)
```

$$\frac{g_{\pi 0\gamma\gamma}{}^2\, g_{a\gamma\gamma}{}^2}{384\,(4\,\pi)^3\,M^3} * \left(-m^8 - 28\,m^6\,M^2 + 28\,m^2\,M^6 + M^8 + 12\,m^2\,M^2\,(m^4 + 3\,m^2\,M^2 + M^4)\left(\text{Log}\left[-\frac{m^2}{M}\right] - \text{Log}[-M]\right)\right)$$

Plan Ahead

- 1. Continuing to investigate the integration formula for the fiducial efficiency with Ameir.
- 2. Run ALP simulations on office PC to get 95% CL for MAPP-mCP-1 & MAPP-LLP-1
- 3. Run Dark Photon simulations on laptop, to complete 95% C.L. for MAPP-LLP-1
- 4. Will also give an update next week on CM omonpoles.
- 5. Some words on the mIP paper for EPJ...

  GEANT4 Simulations to come soon, we chat w/ Matti this morning.

Questions?

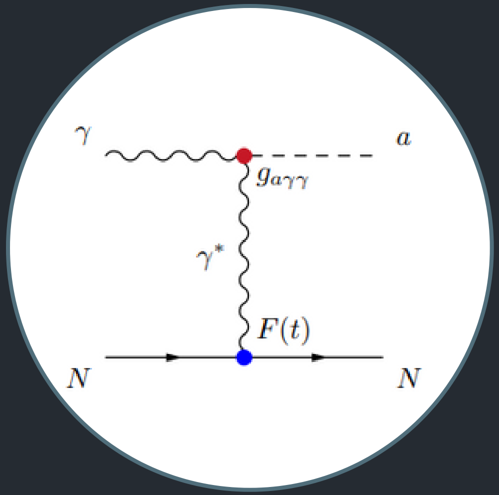
Modeling Emergent Monopoles

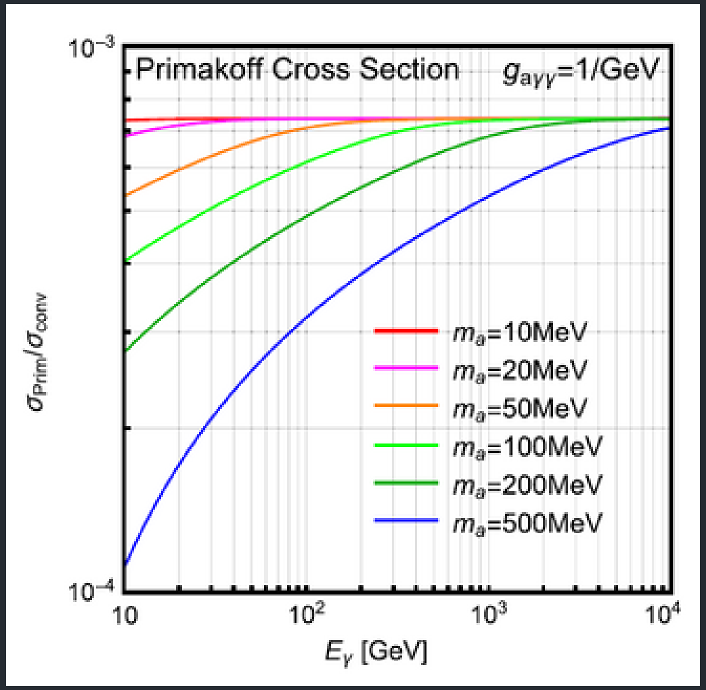
Using the Method of Coherent Structures (MCS)

Second Quantized Hamiltonian next week.

Future work.. ALPs - Production via Primakoff Process

For the Primakoff Process; resonant production of neutral pseudoscalar mesons by high-energy photons interacting with an atomic nucleus. (γ N --> a N)





Ratio between the Primakoff and pair-production cross section (in iron)

The relevant pair-production cross section in iron for the photon energies of interest is of the order of σconv = 5 barn [Faser ALP paper]

MAPP-mCP Physics Performance Cases

Case 1: Minicharged (mCP) Particles in Dark QED

Kinetic mixing leads to fractionally charged particles

Mass range of 0.1-100 GeV

Charges could be as low as ~e/500

Case 2: “Heavy Neutrinos” With a Large EDM

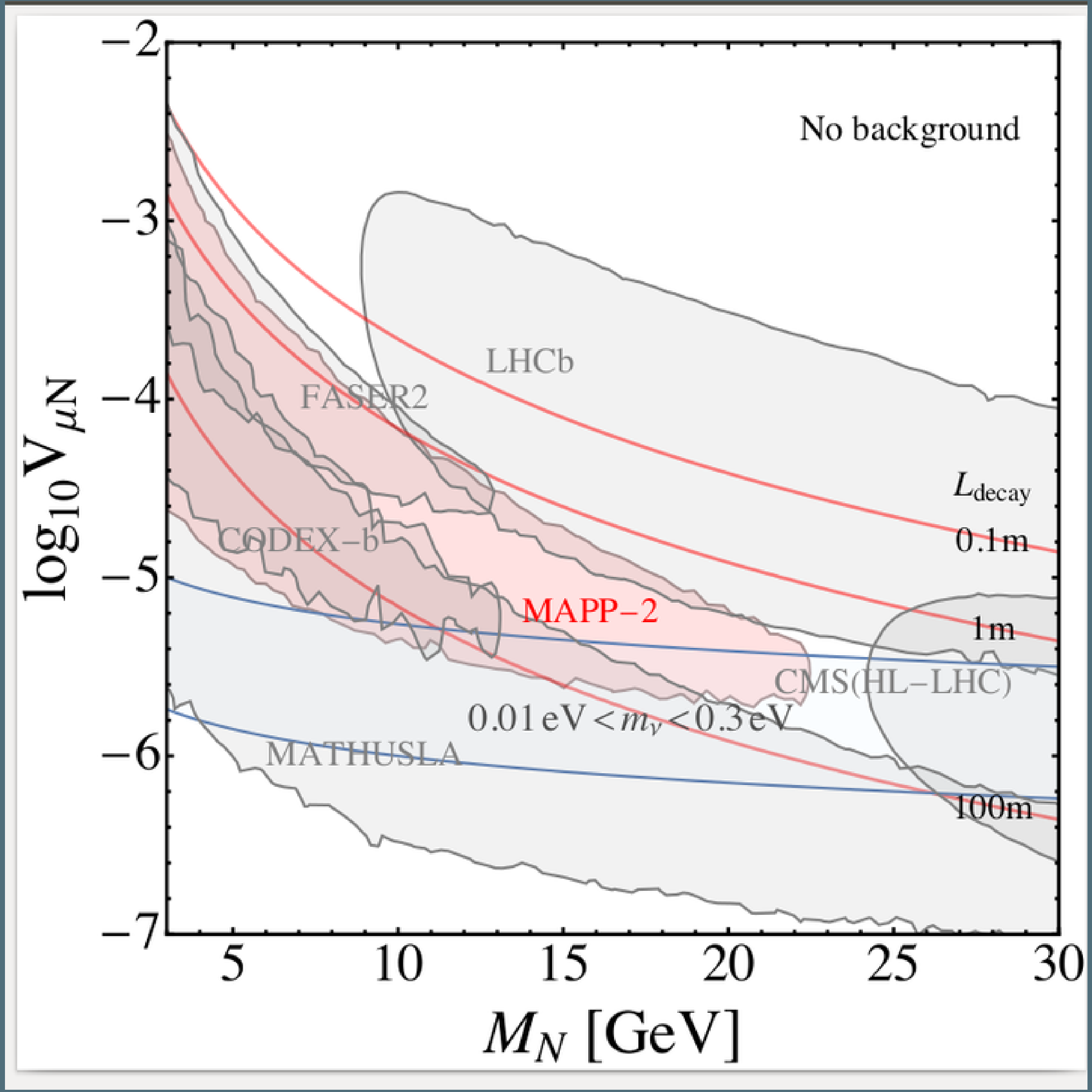
EDM of a new heavy neutral Dirac fermion could be as large as ~10^-15 e*cm (predicted by 5-D EFT).

Mass range of ~45.6-200 GeV

EDMs as low as 10^-16

Case 3: (Dark) Mini-Dyons via “Magnetic Mixing”

WIP.. Still in the model building & computational implementation phase.


No background
LHCb
FASER2
CODEX−b
MAPP−2
CMS(HL−LHC)
MATHUSLA
$0.01\,\mathrm{eV} < m_\nu < 0.3\,\mathrm{eV}$
L_{decay}
0.1m
1m
100m
$\log_{10} V_{\mu N}$
M_N [GeV]
−2
−3
−4
−5
−6
−7
5
10
15
20
25
30