Displaced Searches for New Physics at Belle

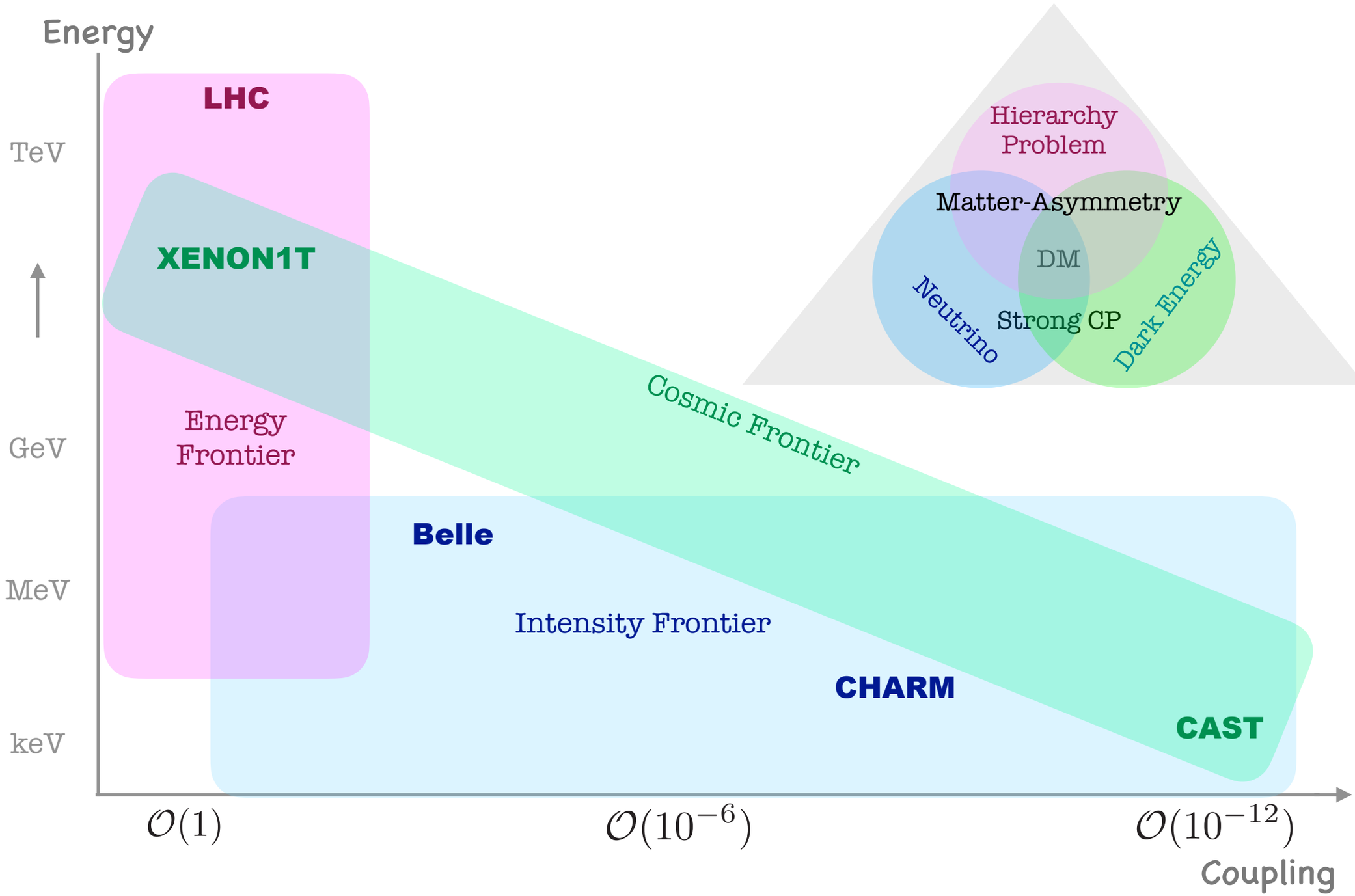
Sabyasachi Chakraborty (IIT-Kanpur)

(QNP2022)

2108.10331, Heavy QCD Axion at Belle-II: Displaced and Prompt Signals

2203.03280, Displaced Searches for Light Vector Bosons at Belle-II

Frontier Business



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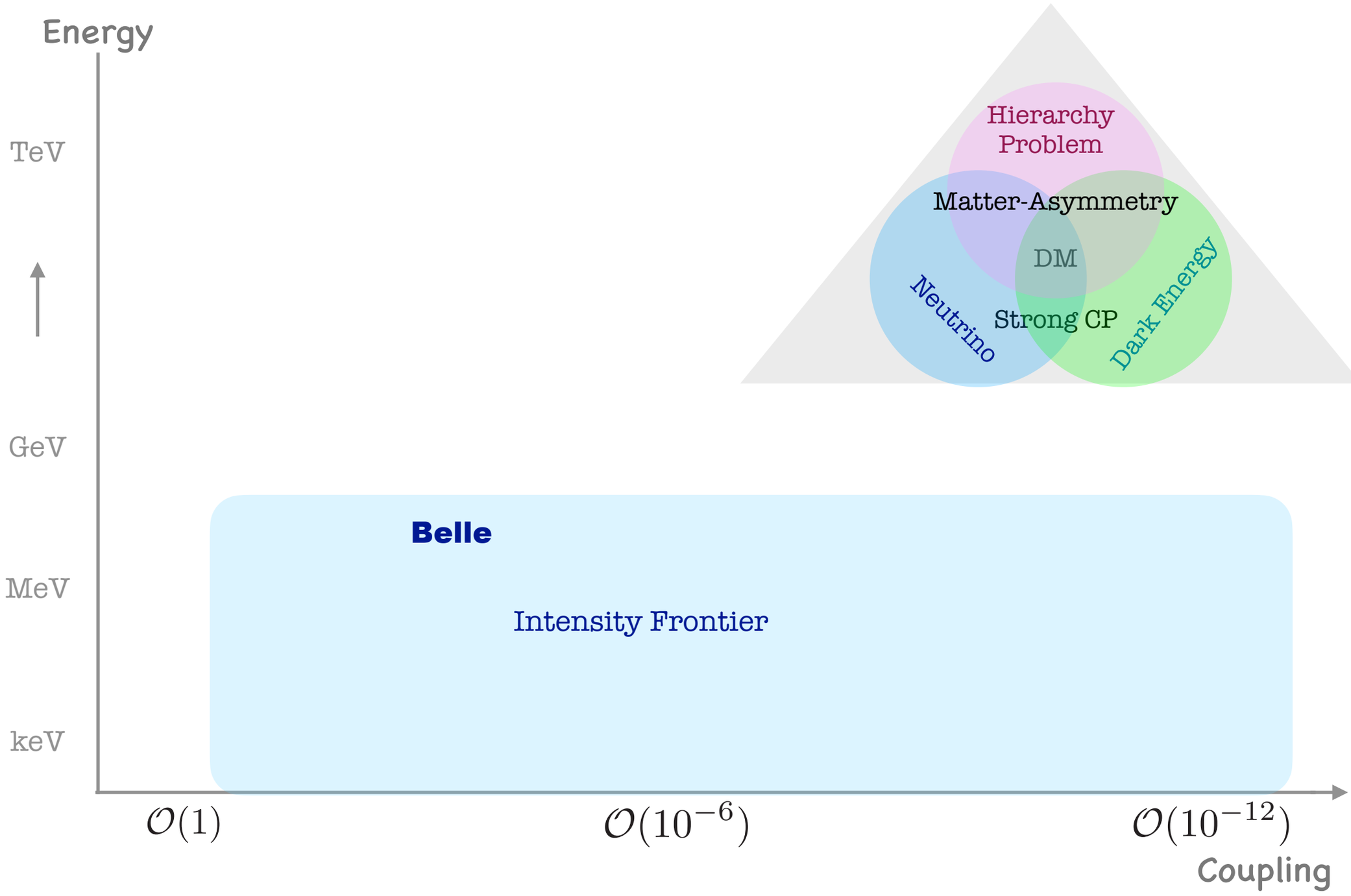

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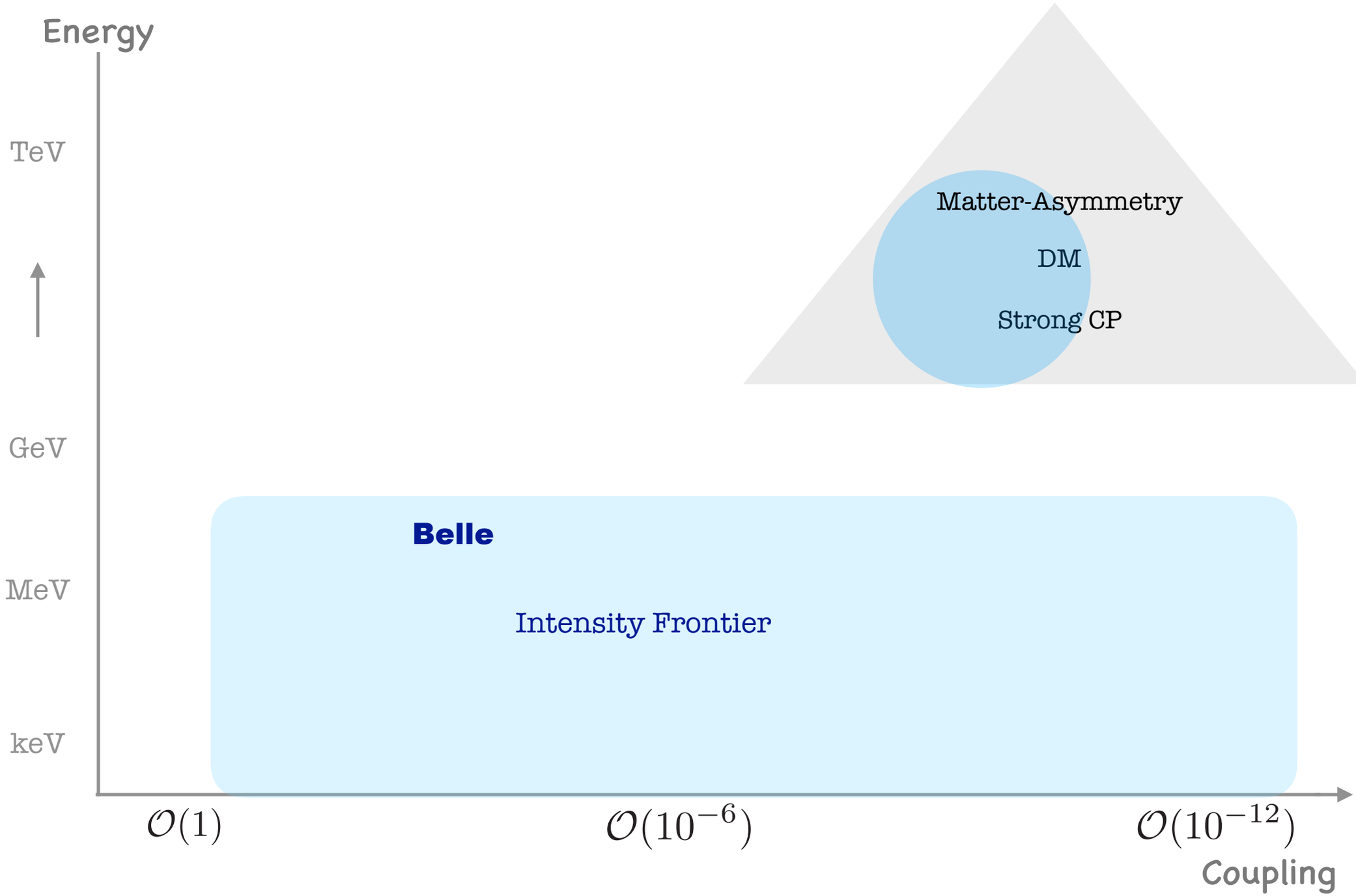
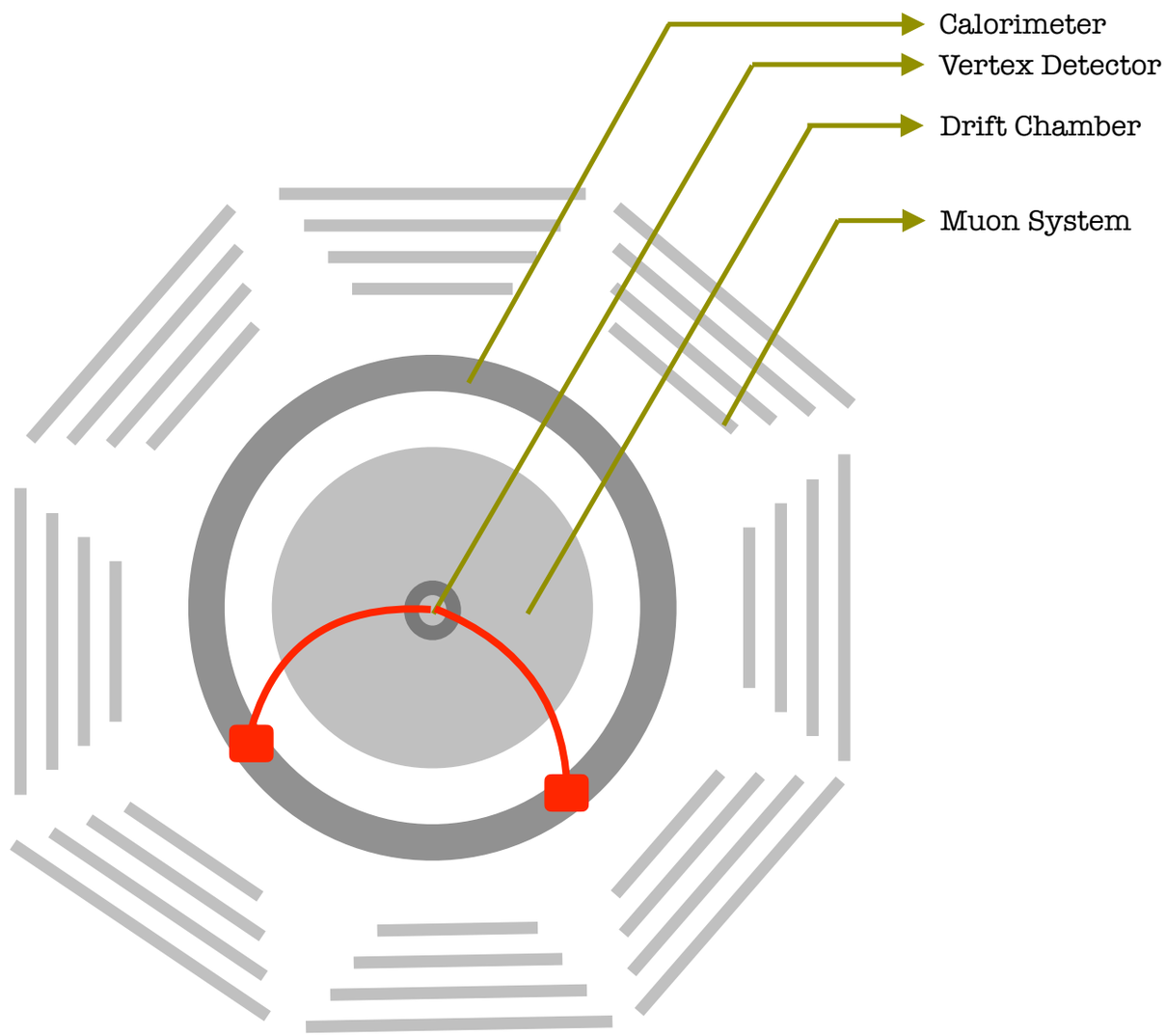


Belle Detector



Recent Works at Belle: 1908.09719, 1911.03176, 2108.10331 etc.

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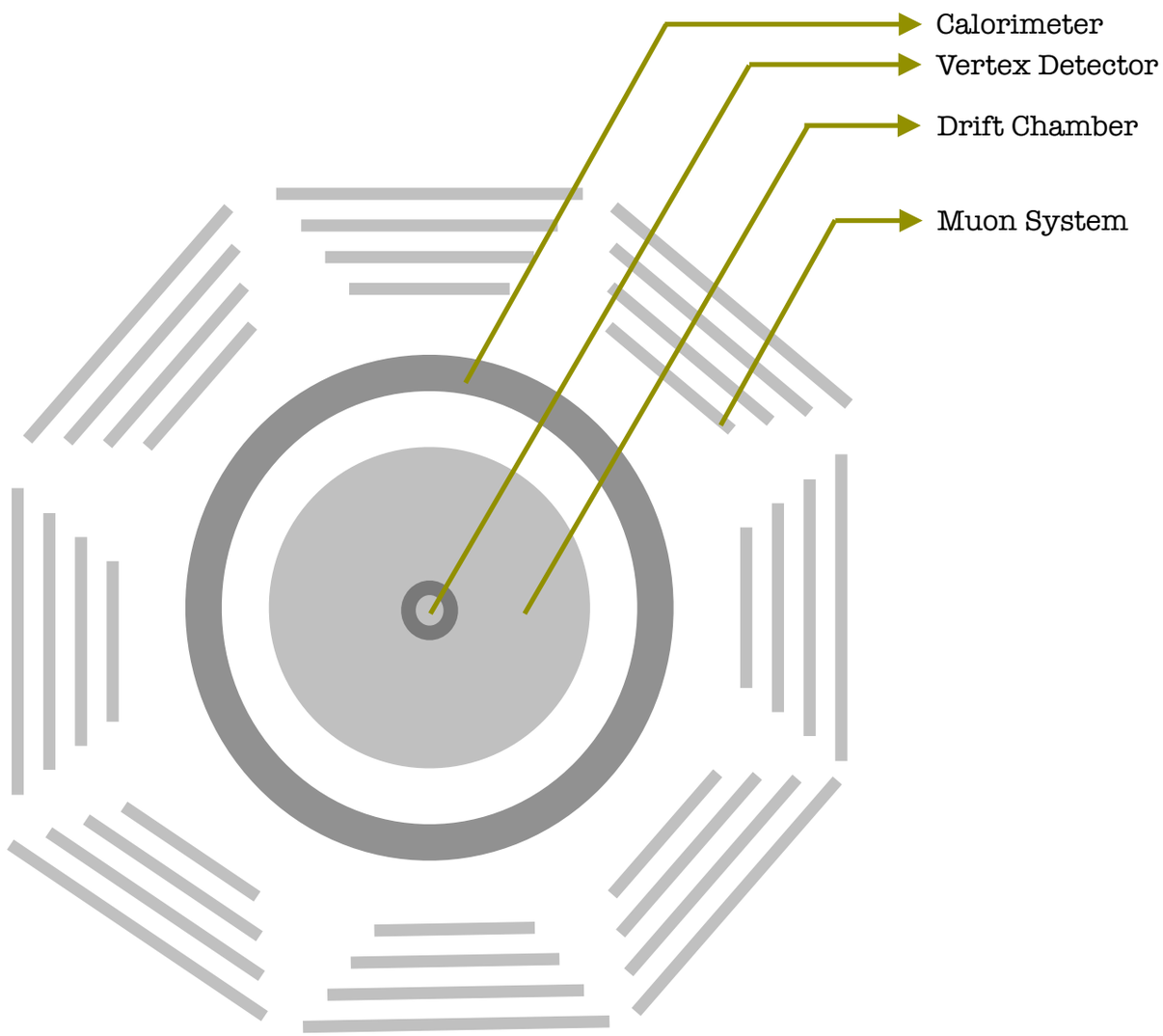

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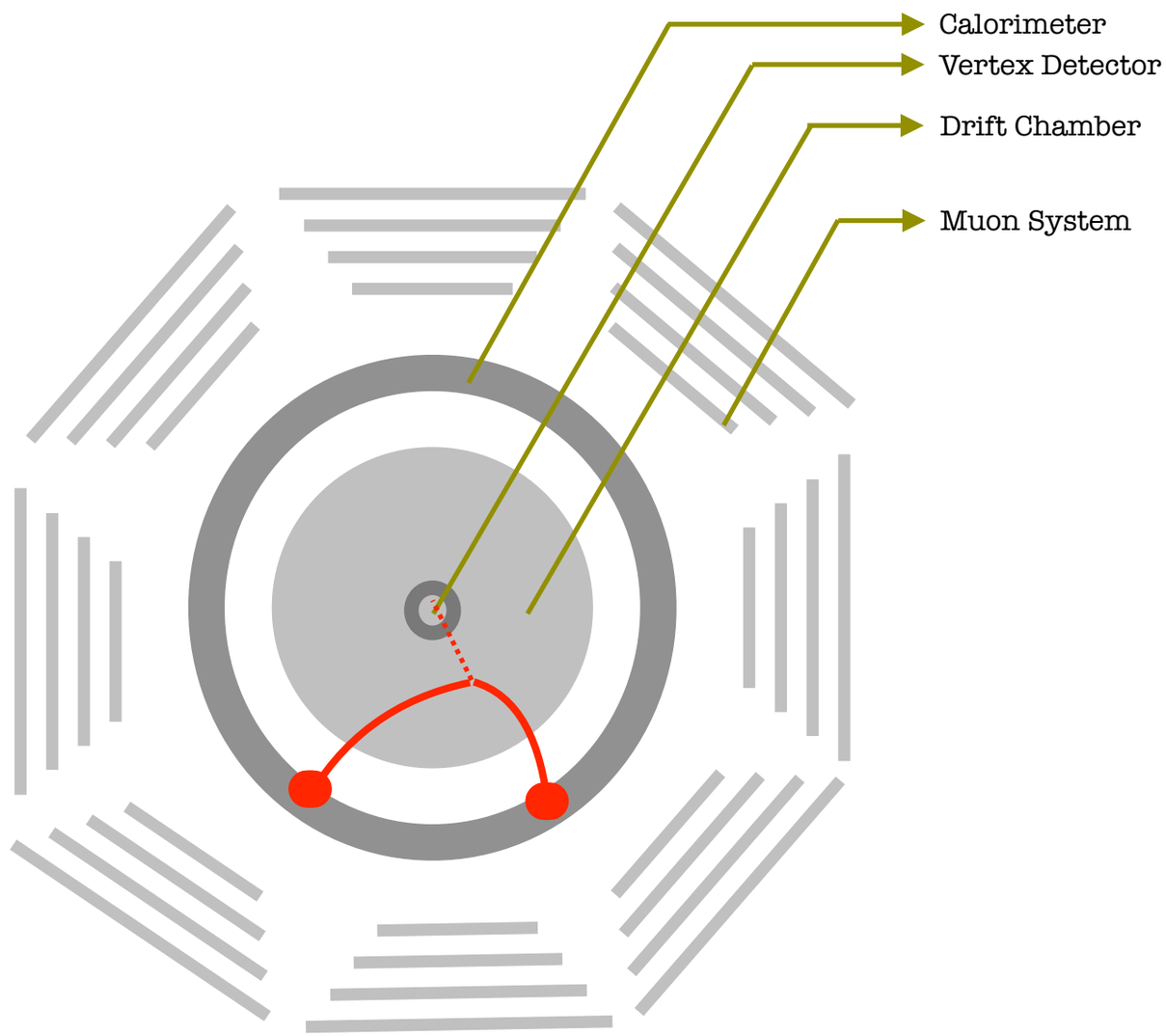

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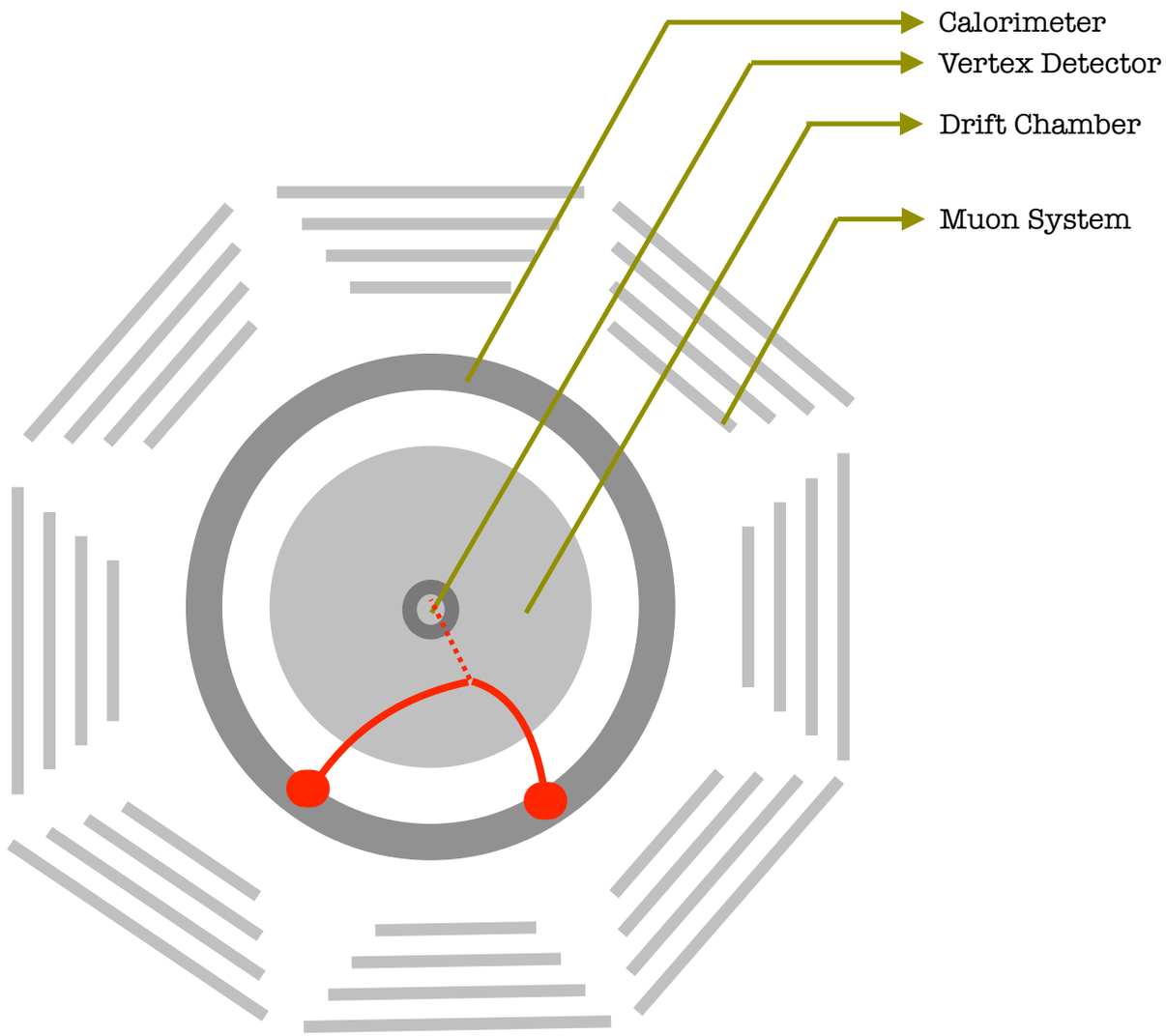

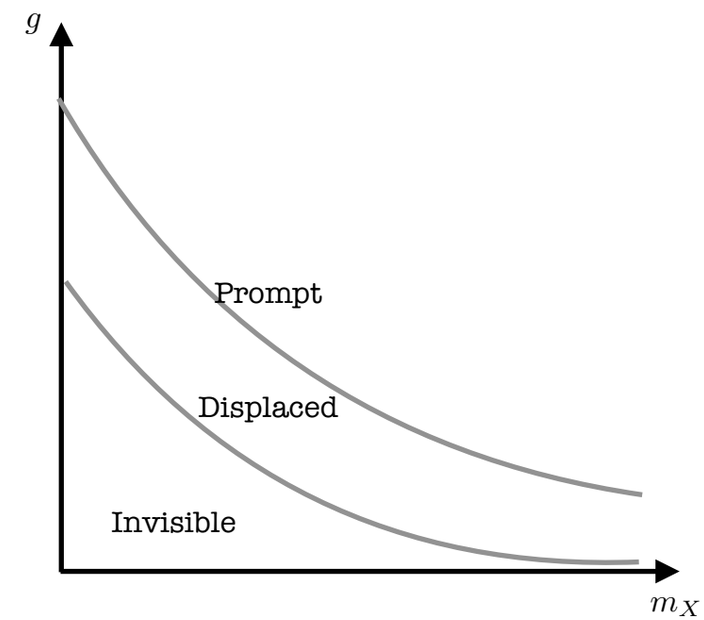

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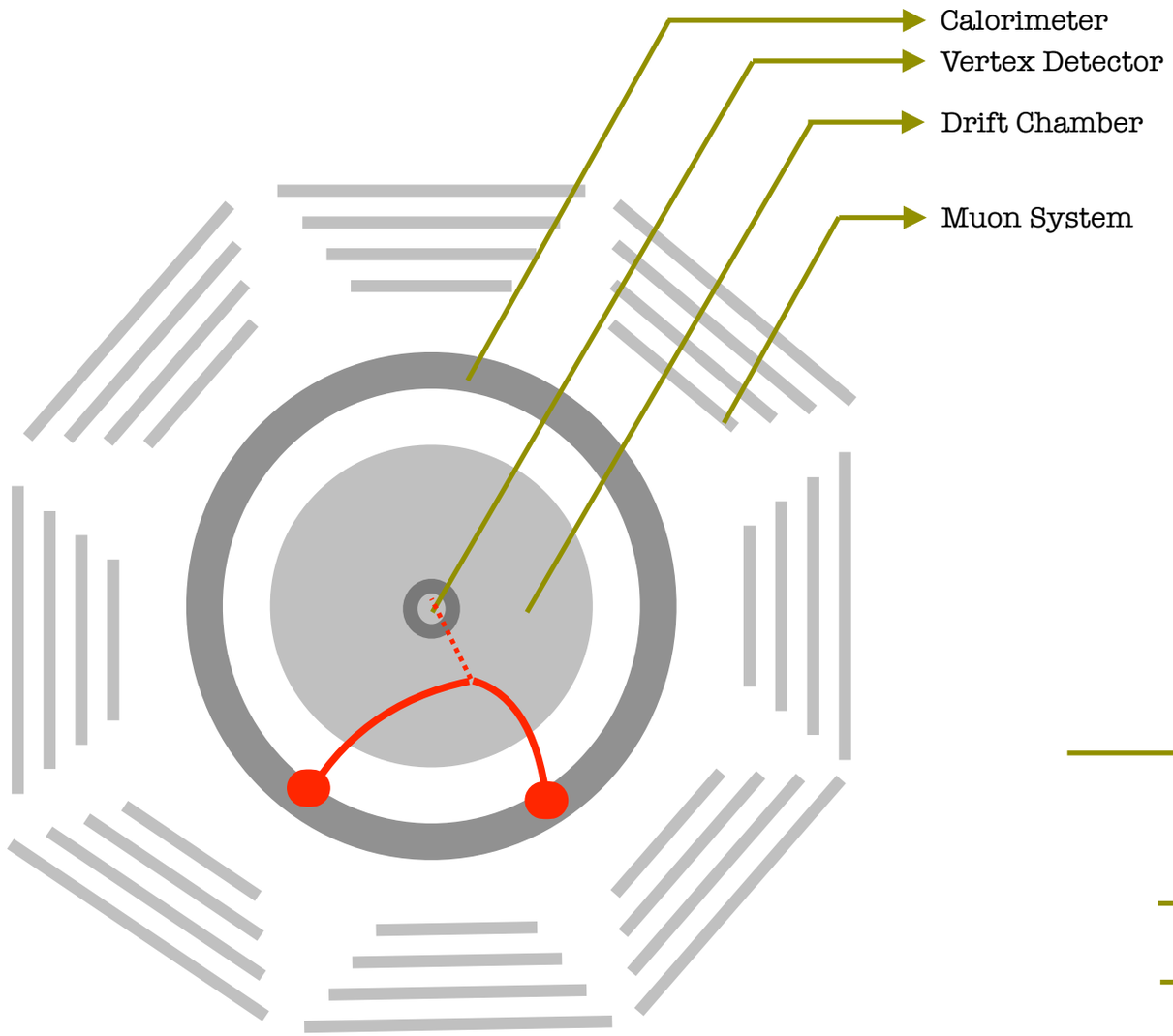

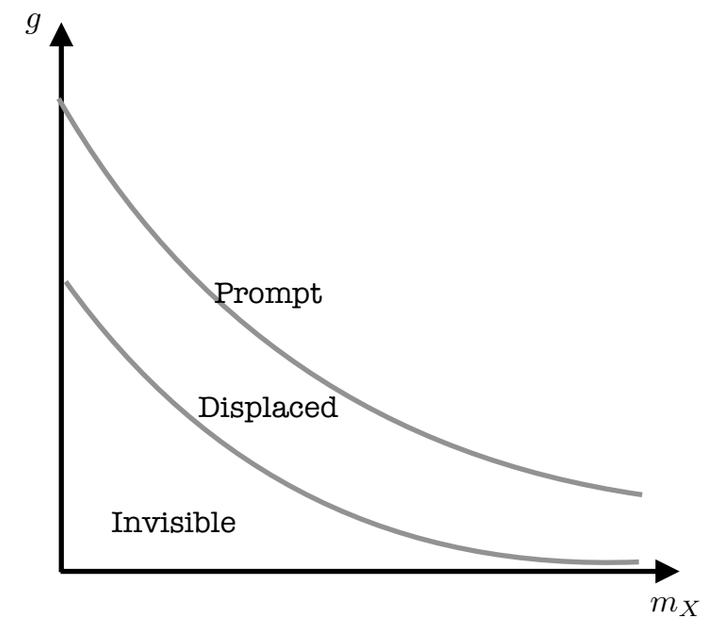

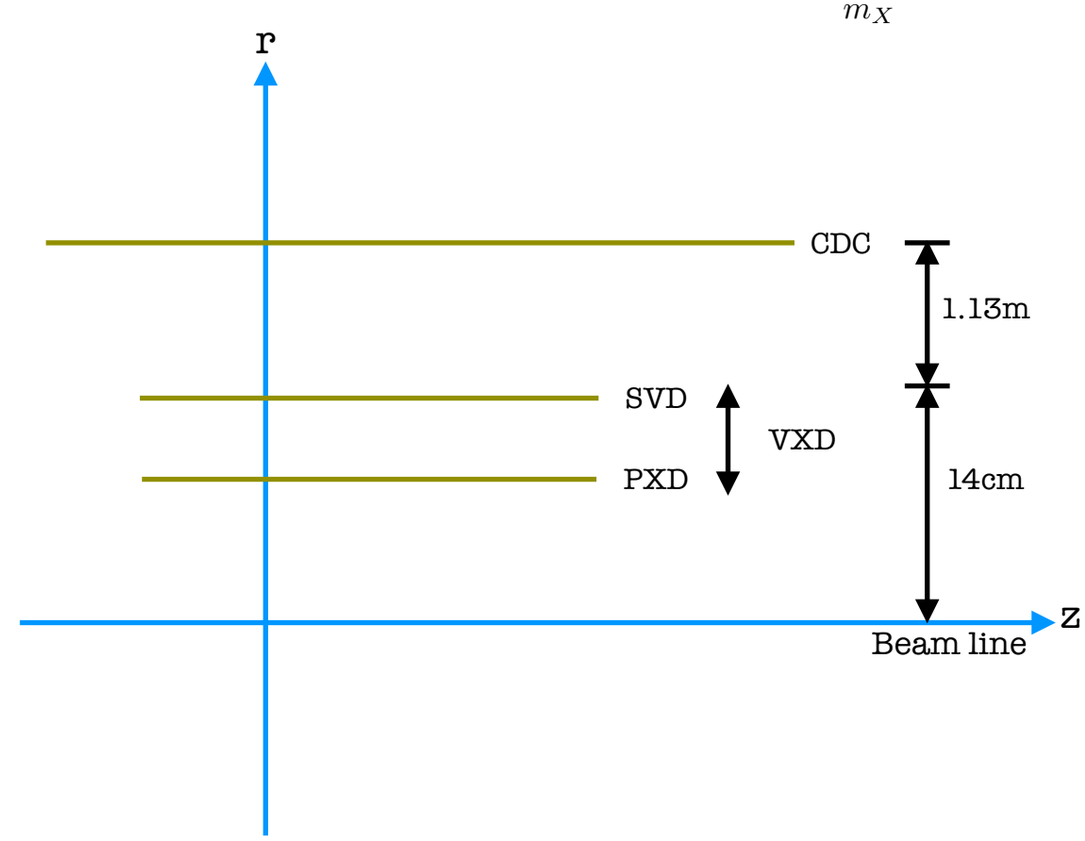

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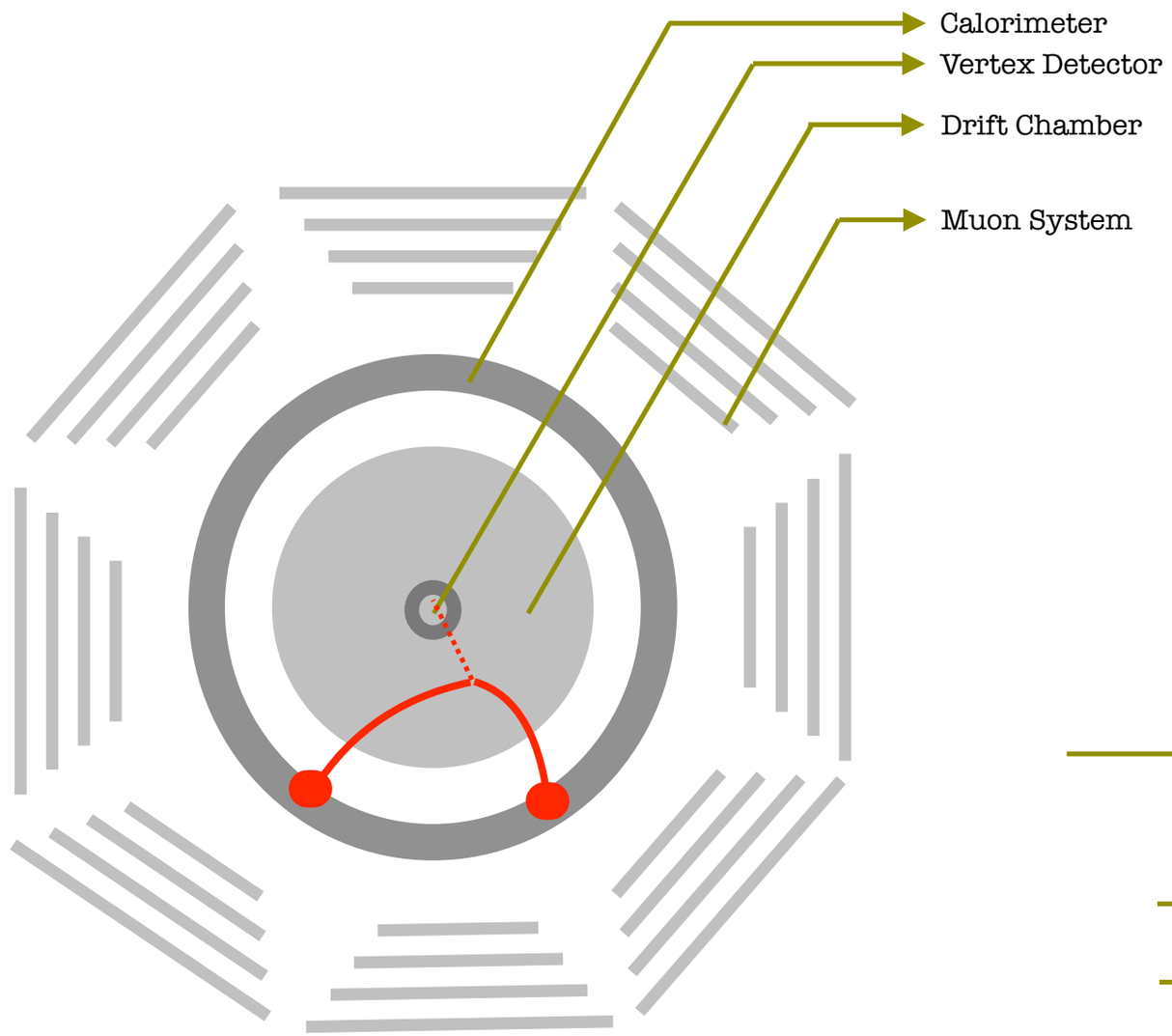

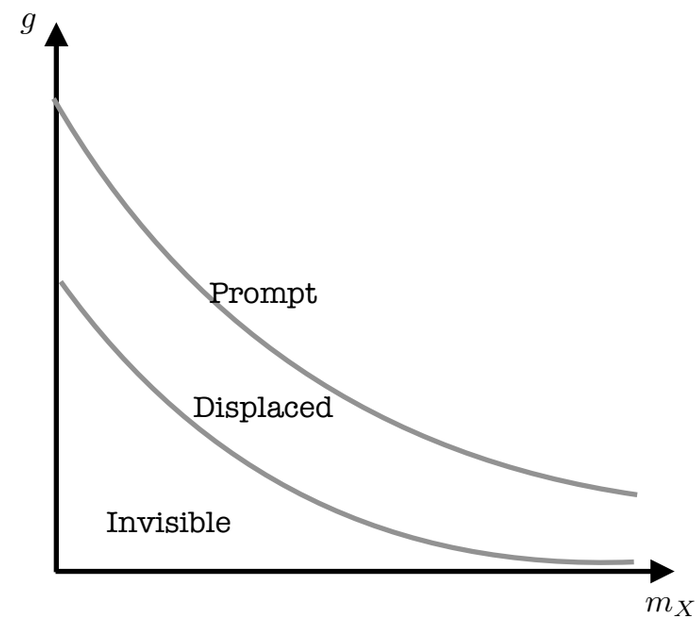

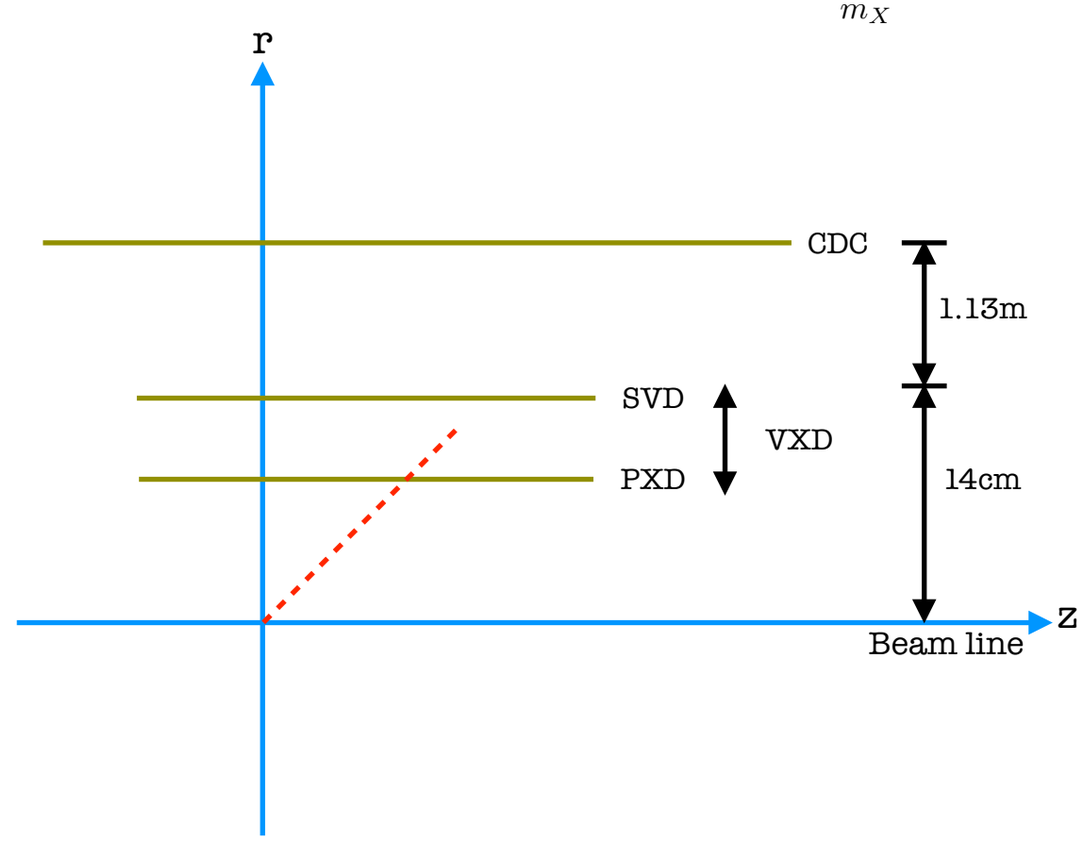

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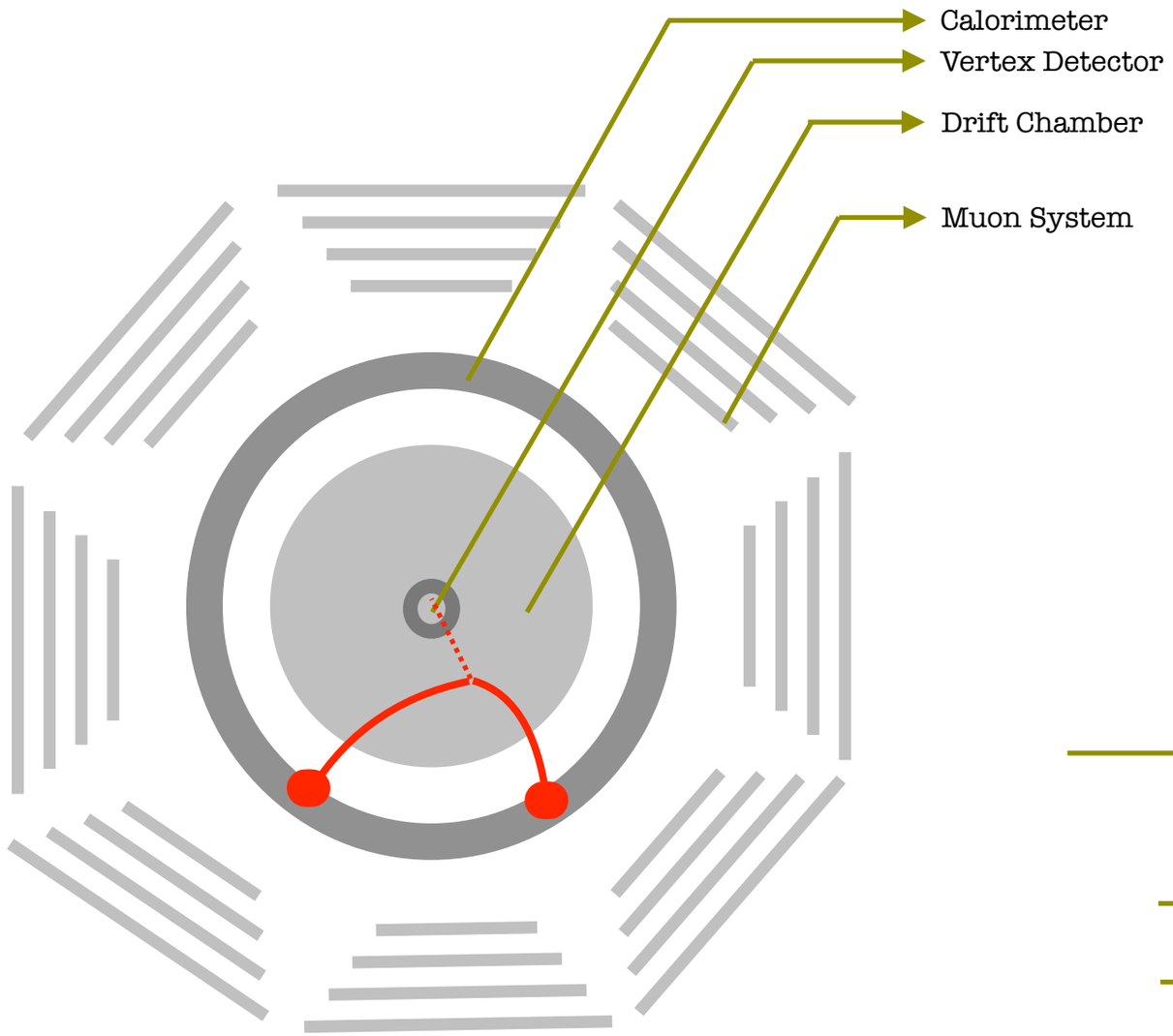

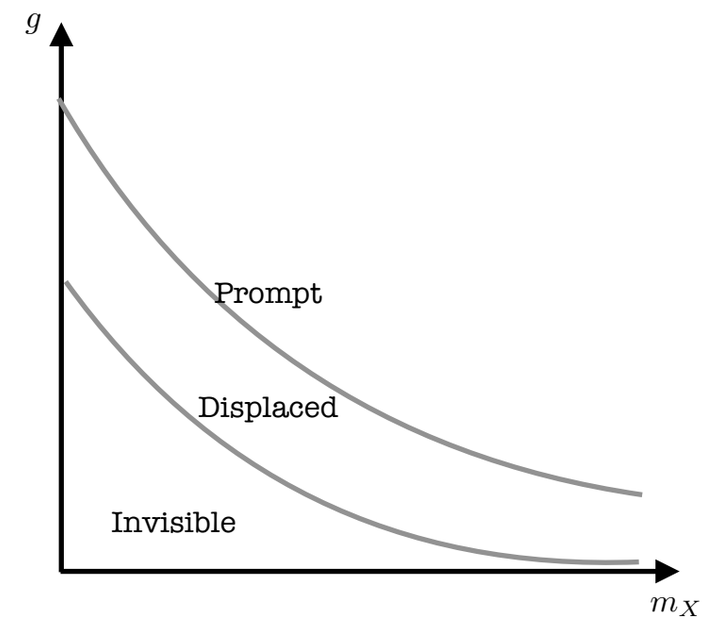

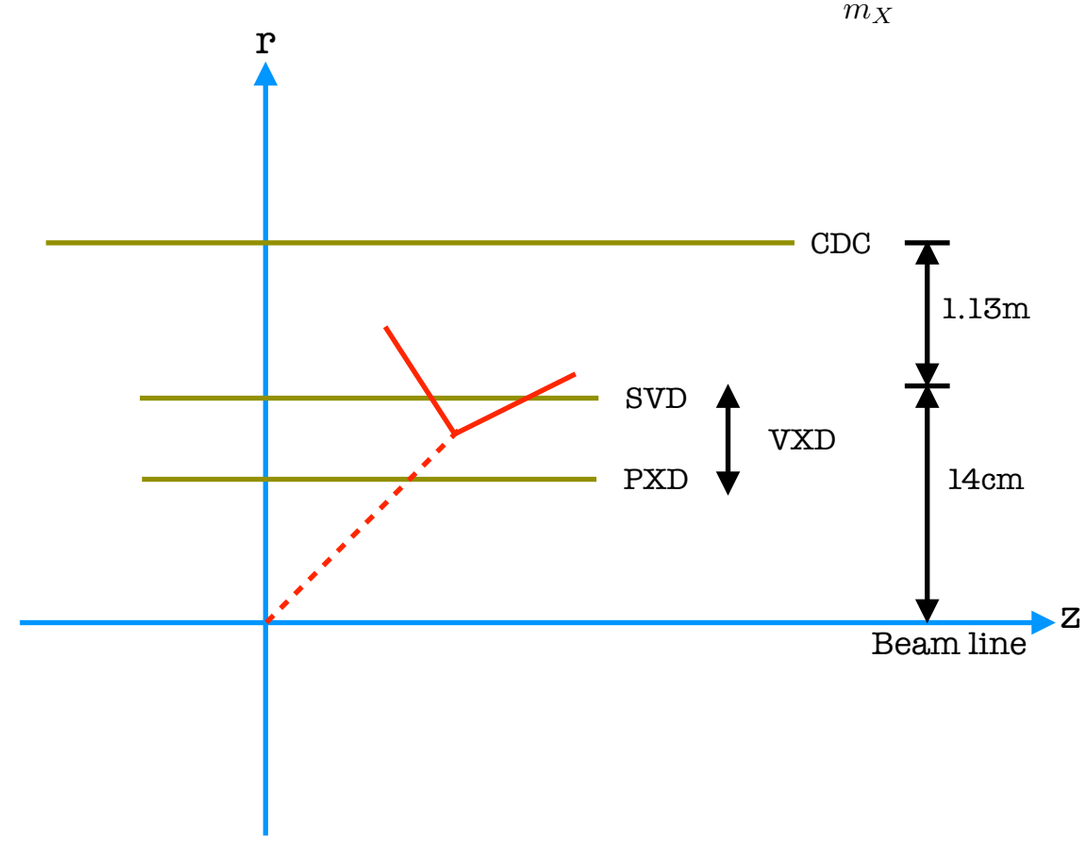

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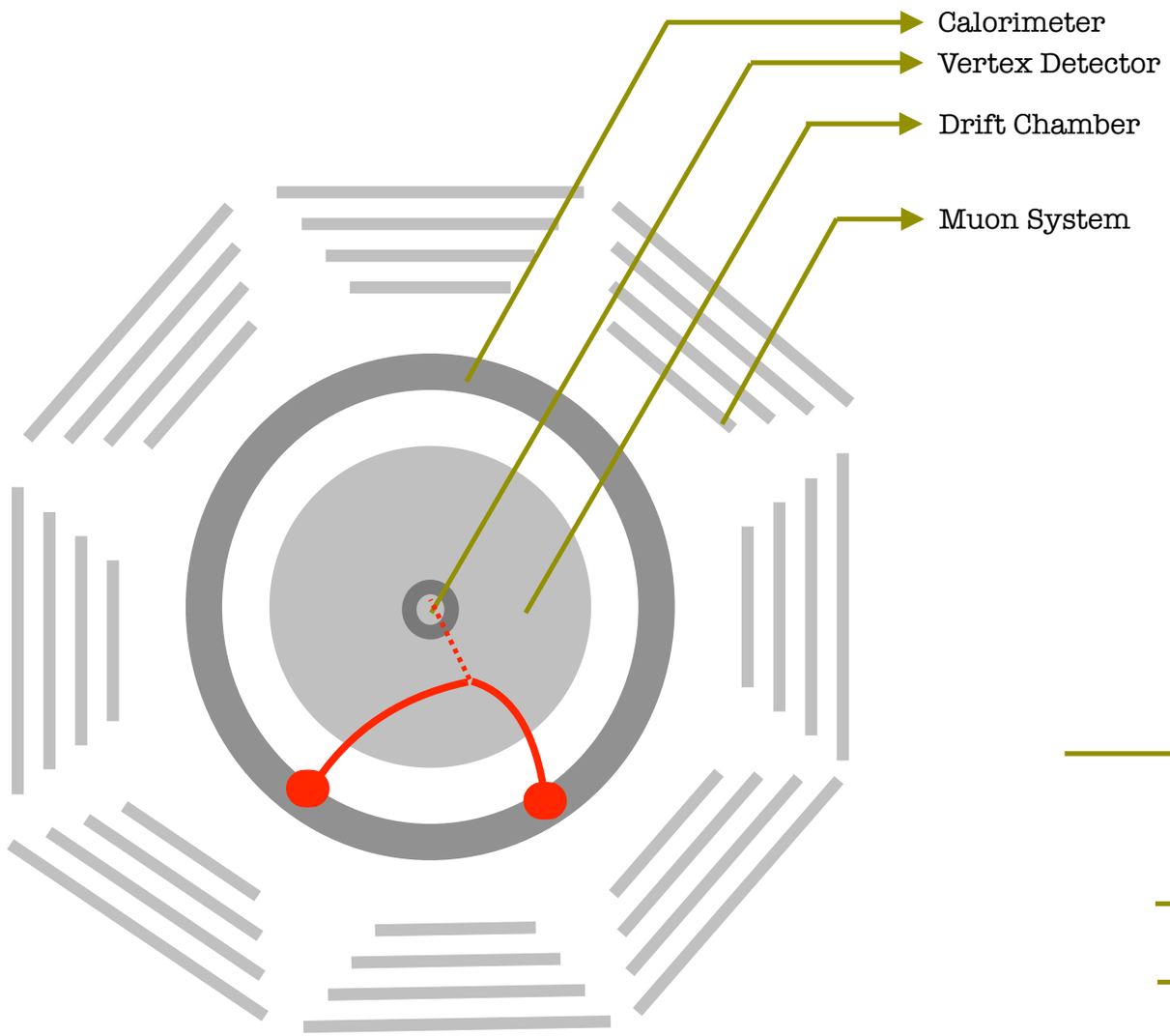

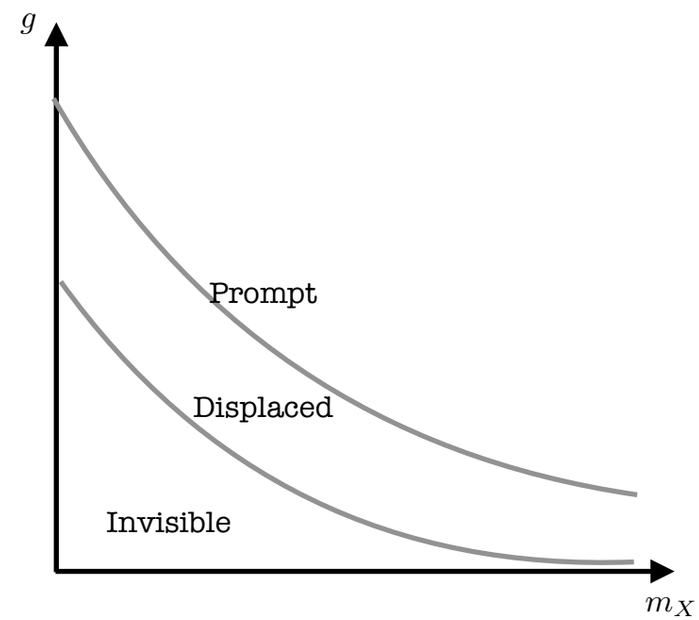

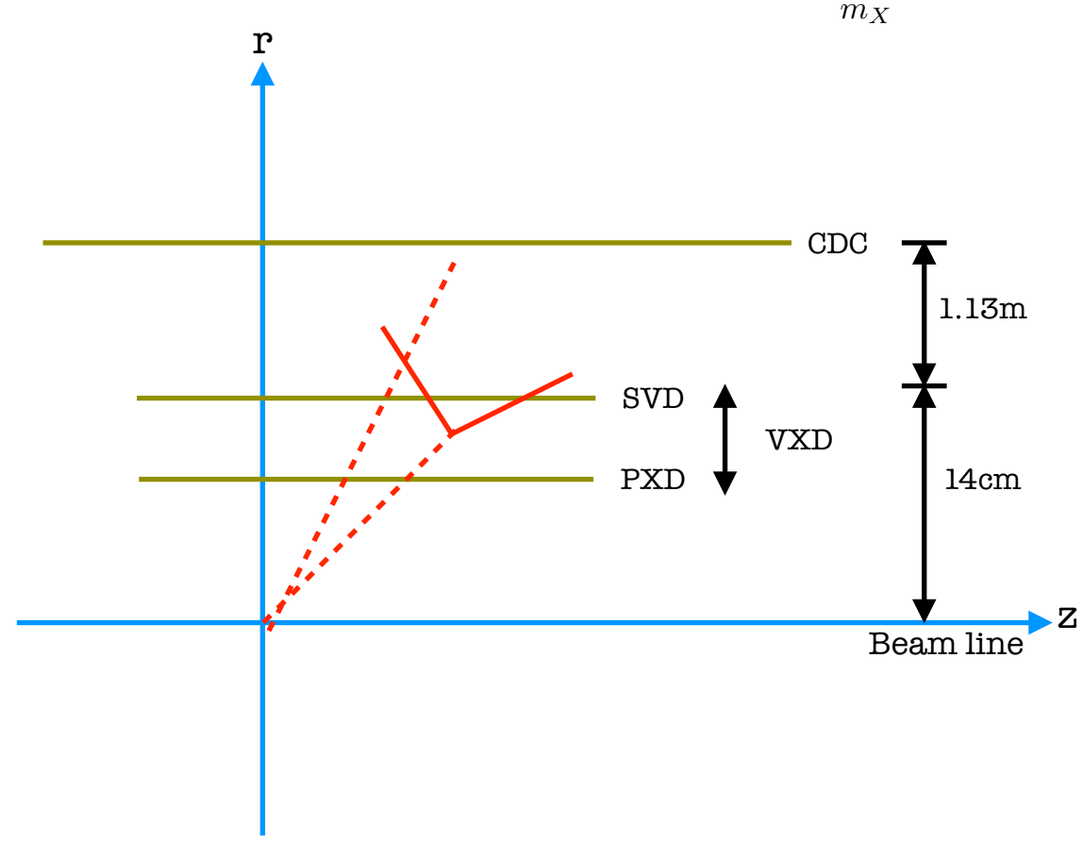

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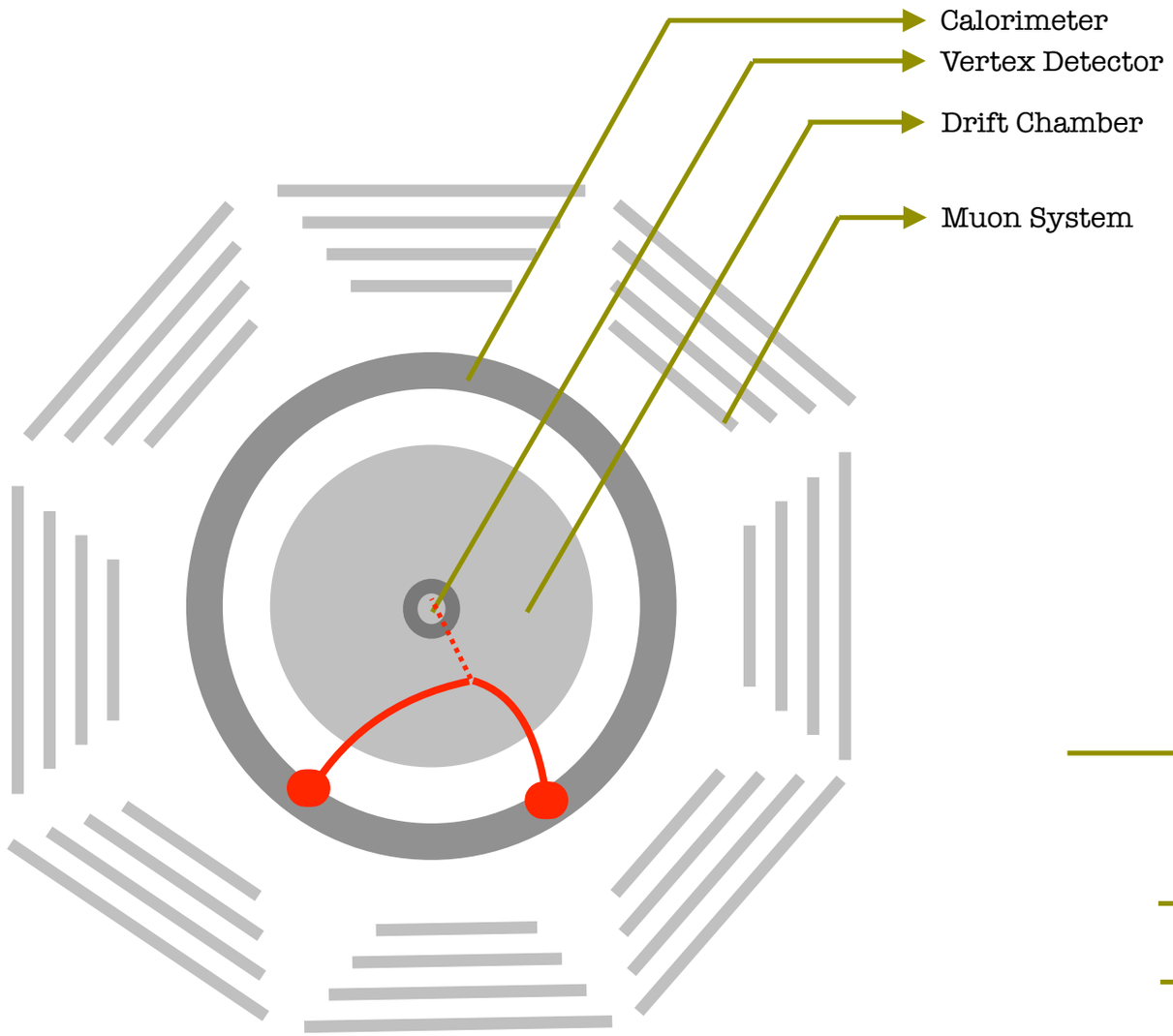

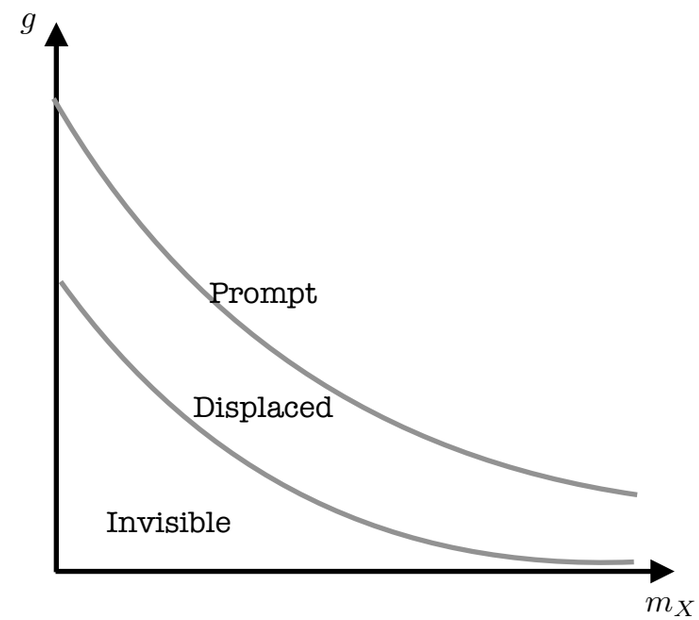

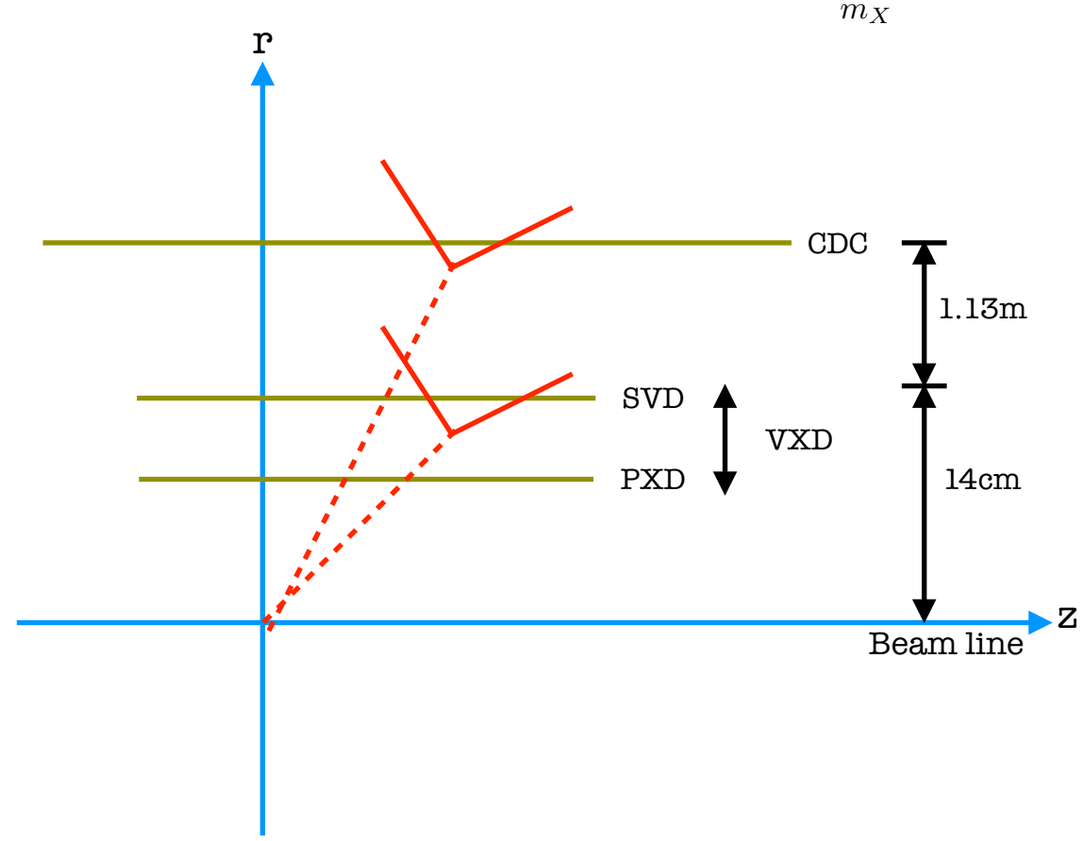

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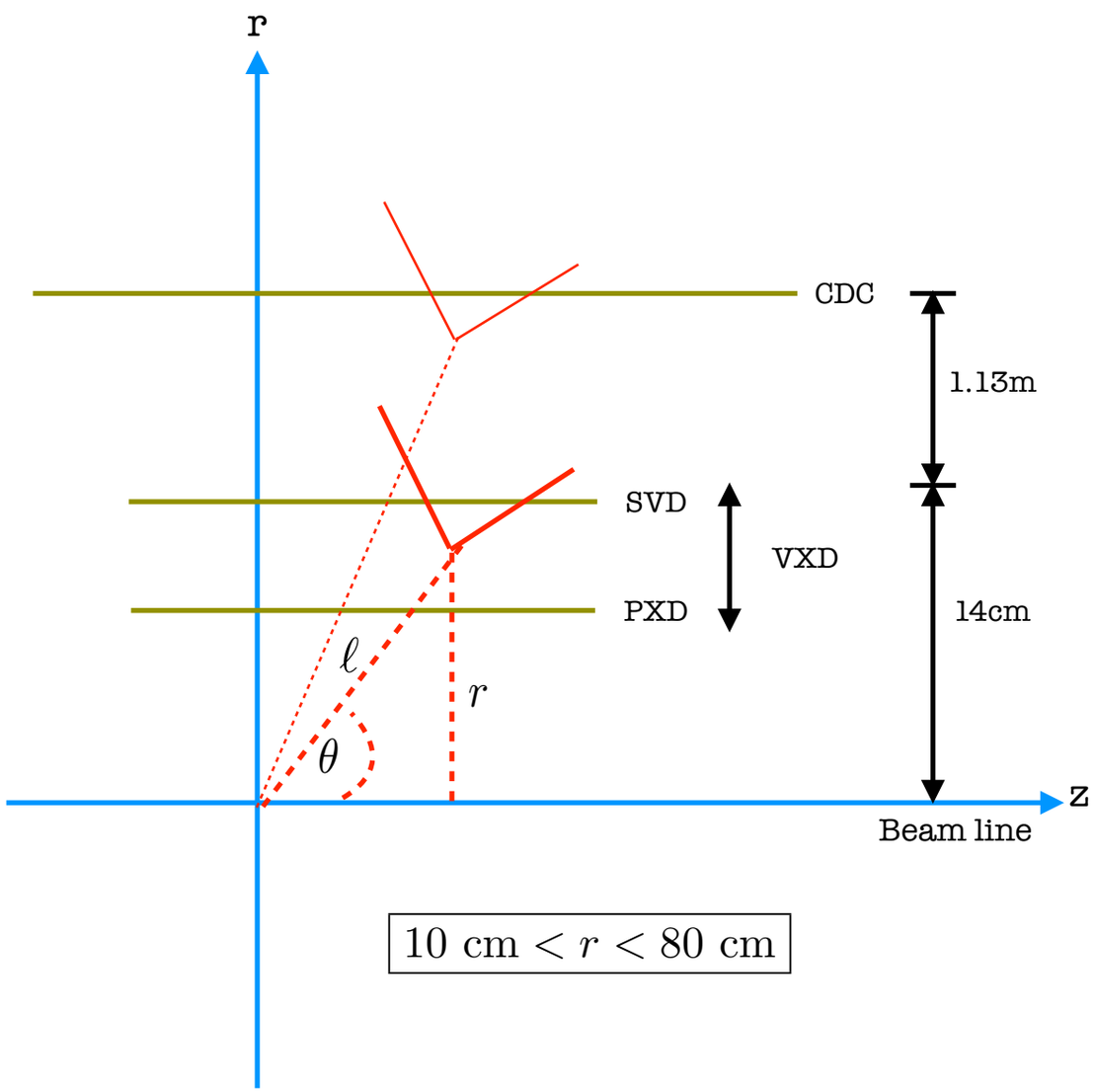

- Linear Falling Efficiency:

$$\epsilon(r) = \frac{r_{\max} - r}{r_{\max} - r_{\min}}$$

- Probability for decay

$$P(\ell) = \frac{e^{\ell/\lambda}}{\lambda}$$

- Probability for identifying displaced vertex

$$\epsilon(\theta) = \frac{\int_{\ell_{\min}}^{\ell_{\max}} d\ell \, \frac{e^{-\ell/\lambda}}{\lambda} \left(r_{\max - \ell \sin\theta}\right) \bar{\theta}(\ell)}{\int_{\ell_{\min}}^{\ell_{\max}} d\ell \, \frac{e^{-\ell/\lambda}}{\lambda} \left(r_{\max} - r_{\min}\right) \bar{\theta}(\ell)}$$

$$N_{\mathrm{signal}} = \mathrm{Production} \times \mathrm{Decay\ Branching} \times \mathrm{Efficiency}$$

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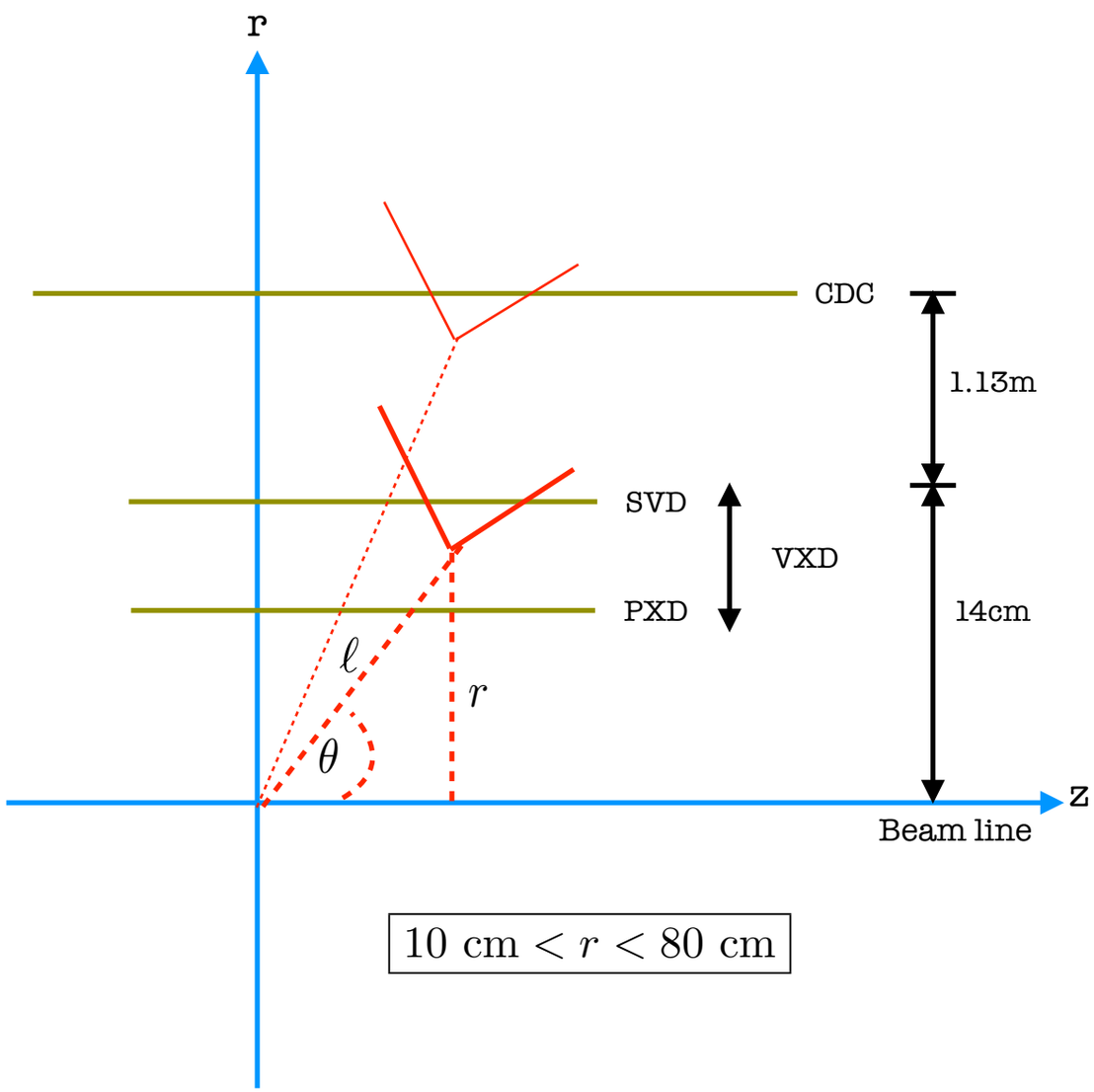

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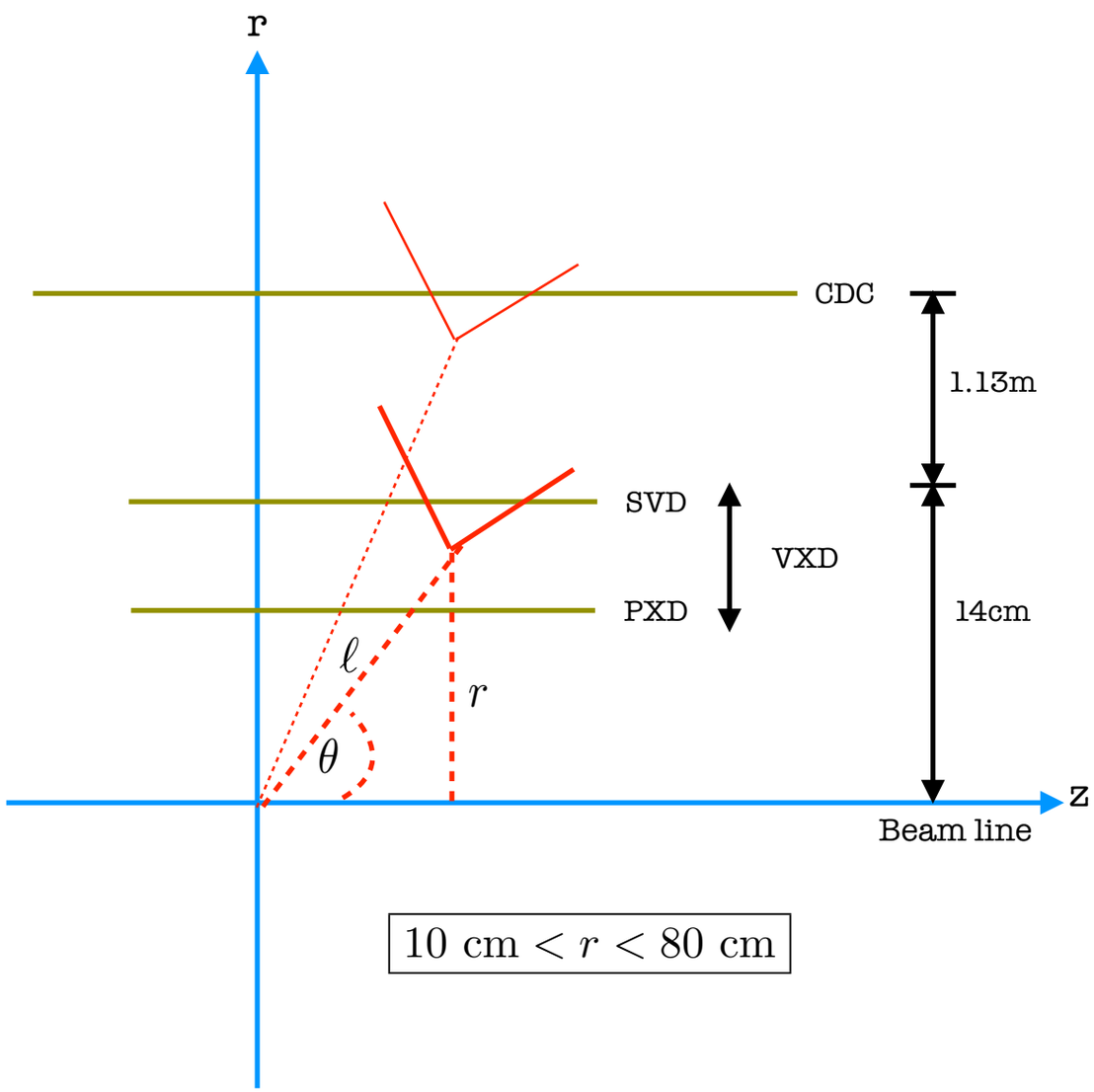

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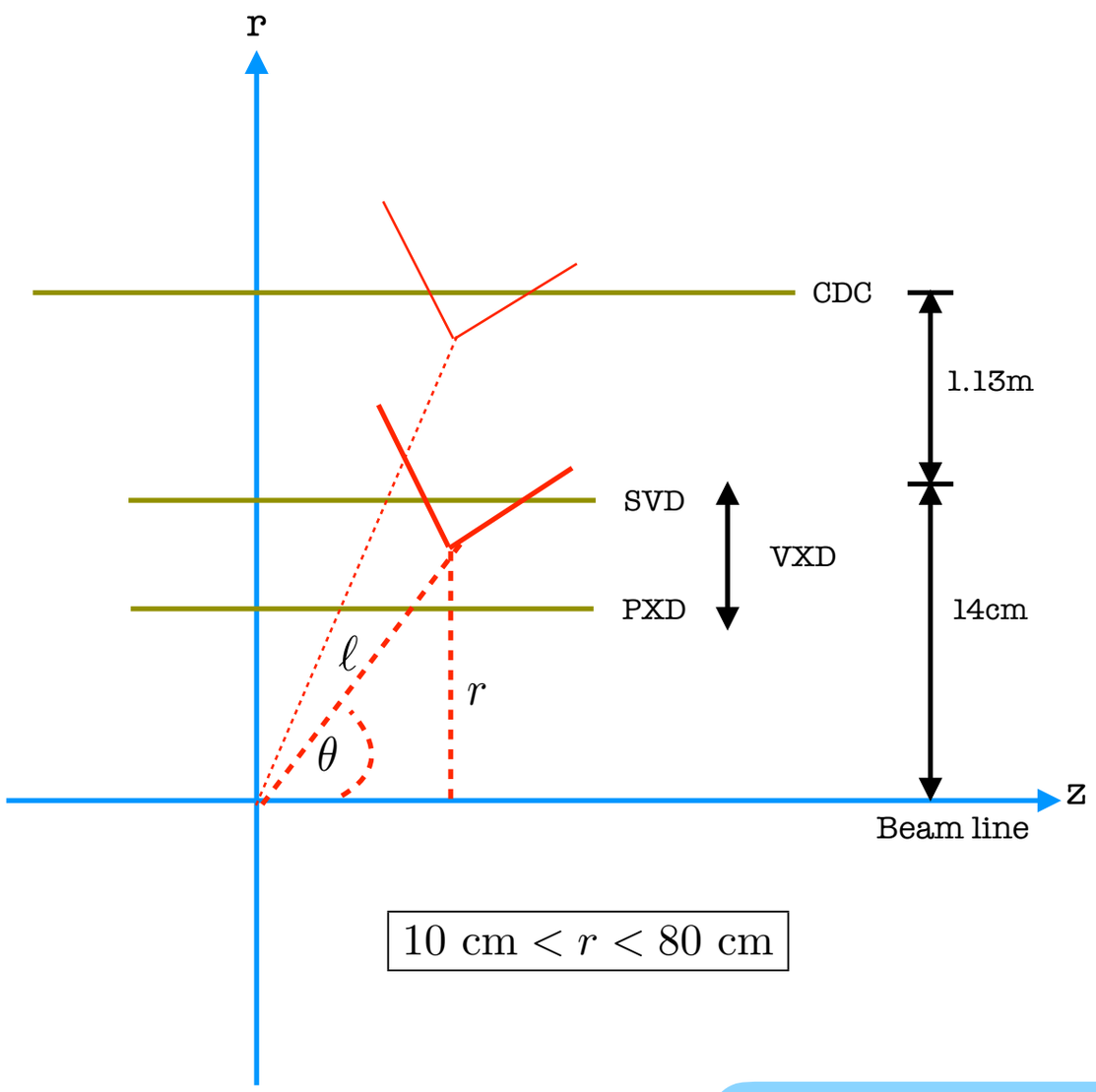

$$10\ \text{cm} < r < 80\ \text{cm}$$

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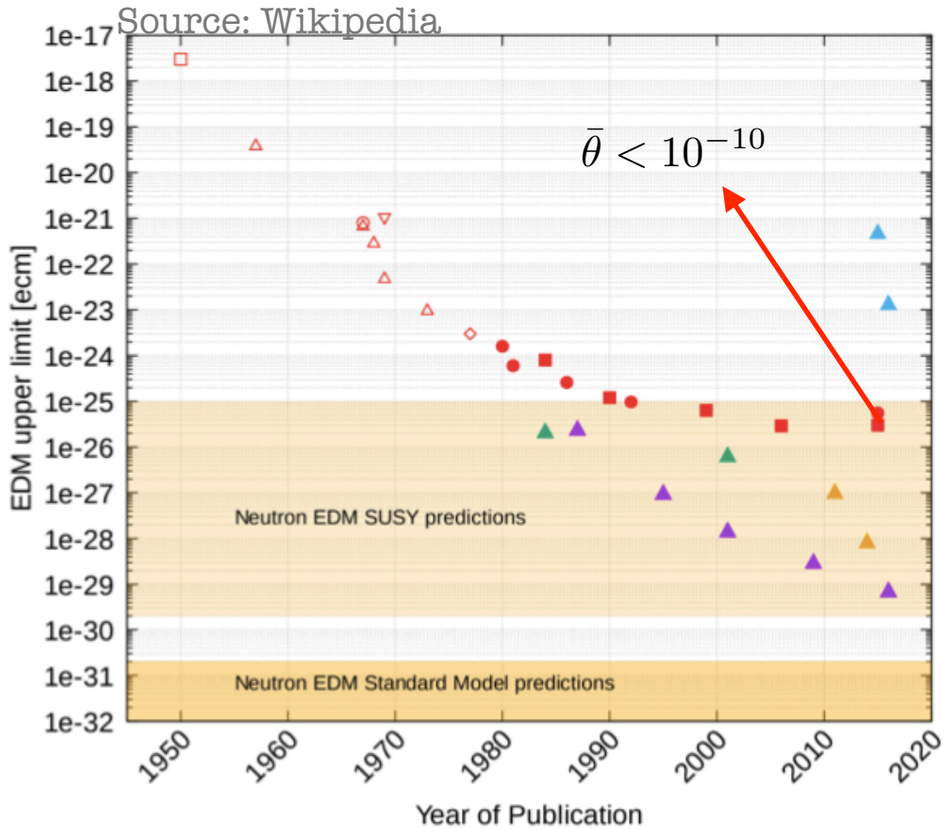
Case Studies for displaced searches: Axions

- Strong CP Problem and Axions:

$$\mathcal{L}_{\rm QCD} = \mathcal{L}^{\rm SM}_{\rm QCD} + \bar{\theta}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{\mu\nu a}$$

Source: Wikipedia



- Dynamical Solution: Axions

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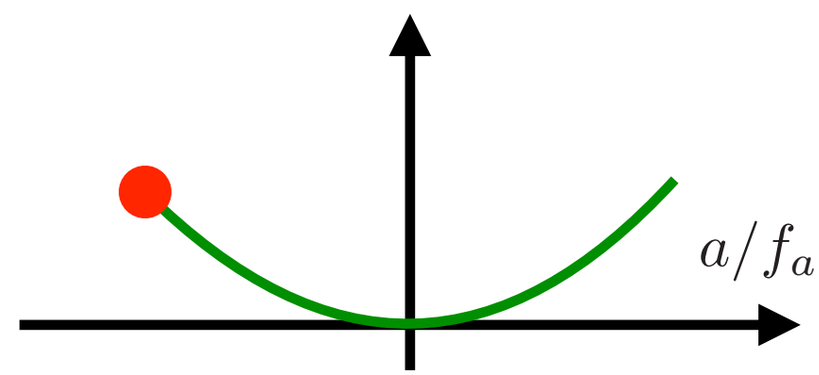

- Fine-Tuning issue in the SM

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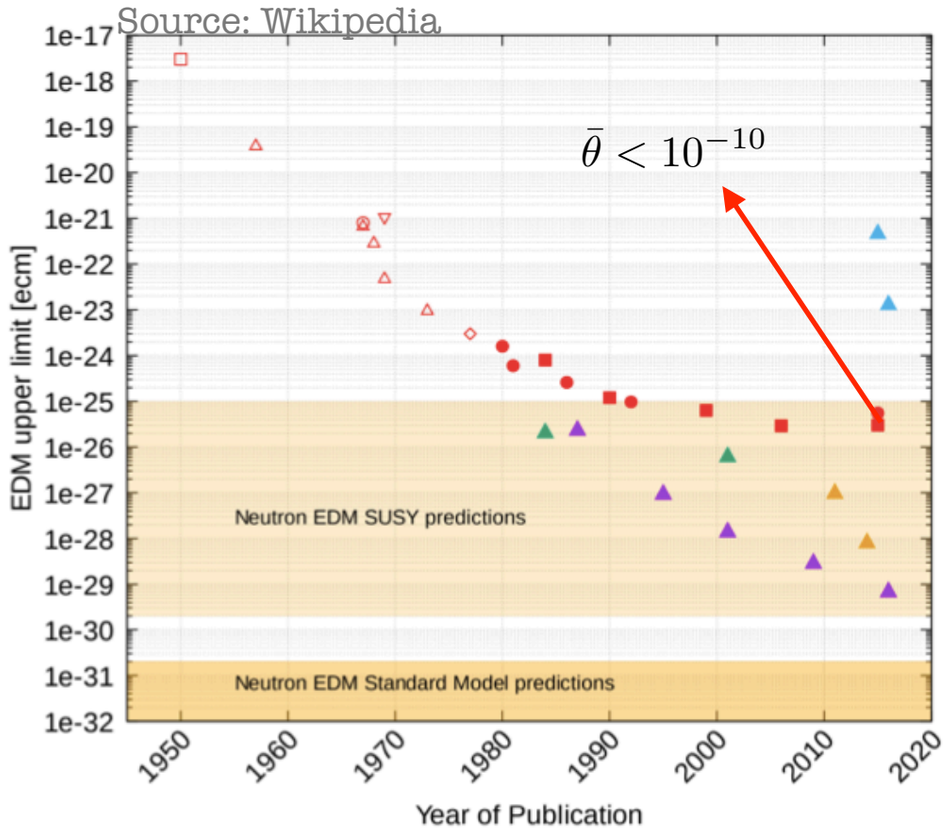

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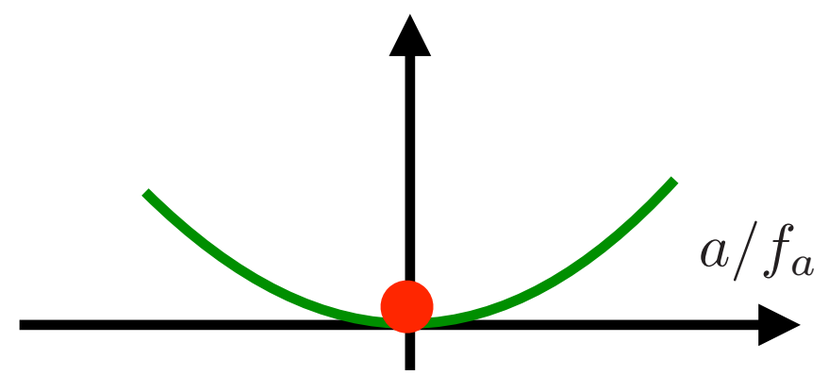

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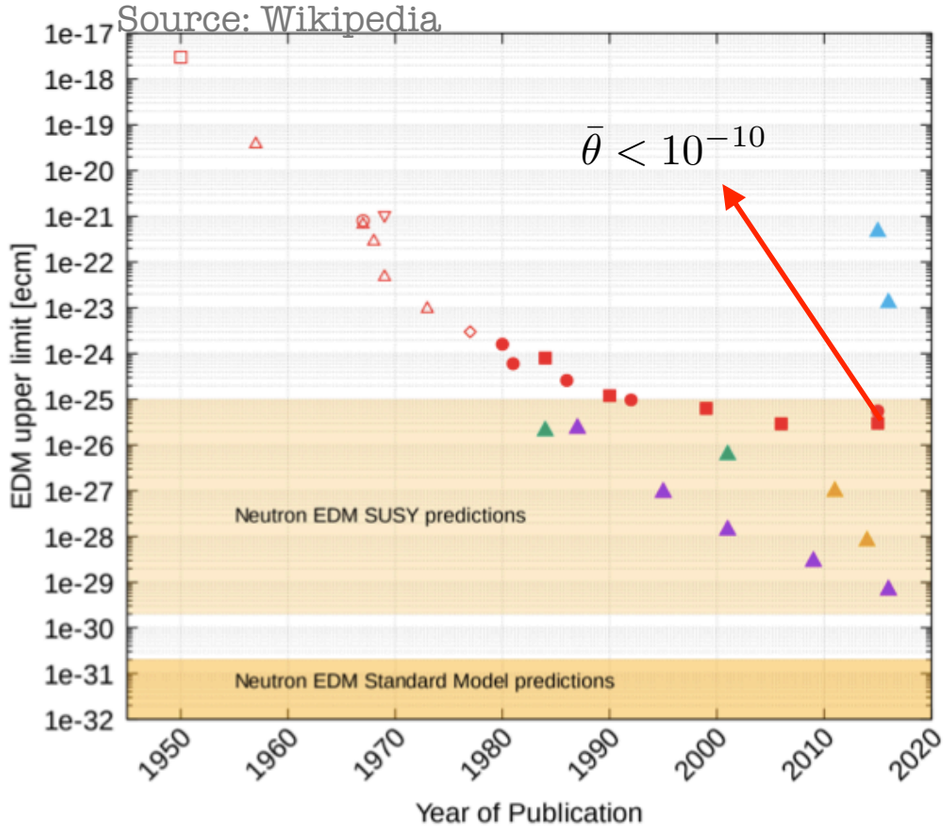

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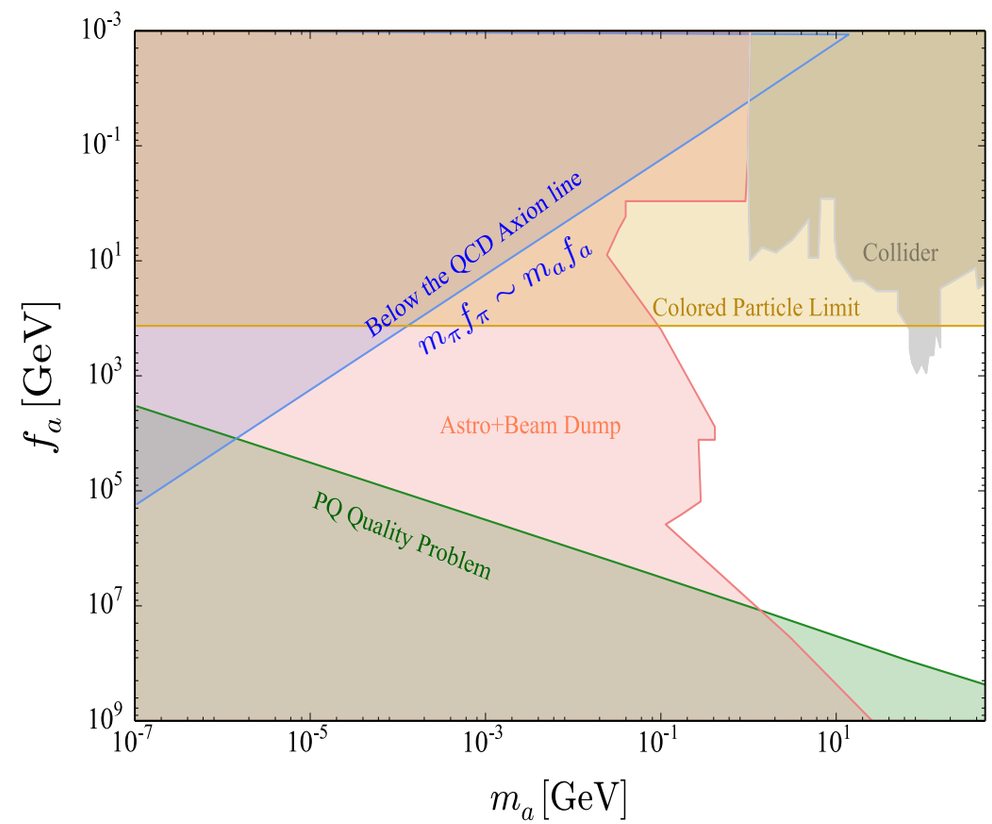

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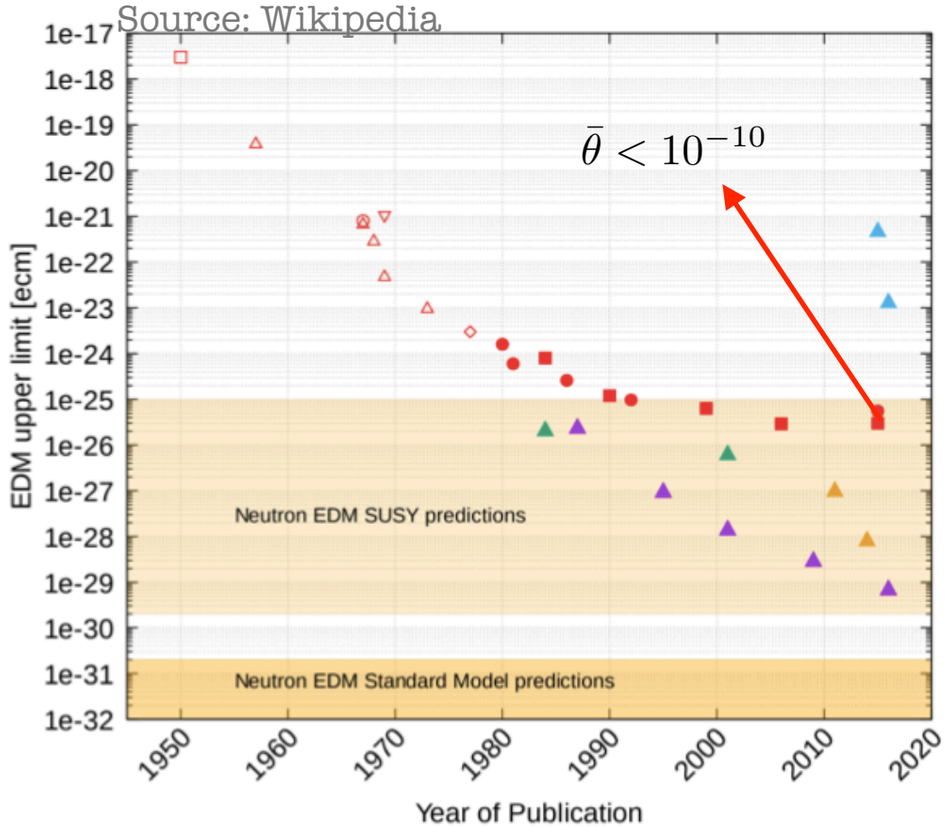

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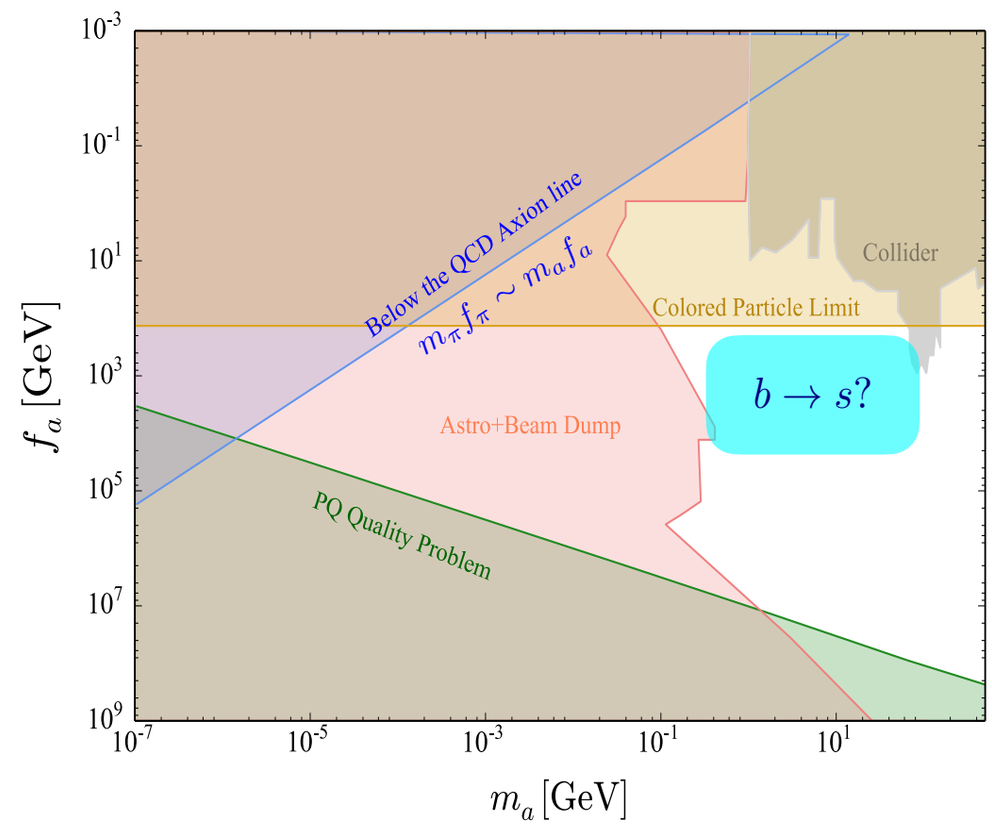

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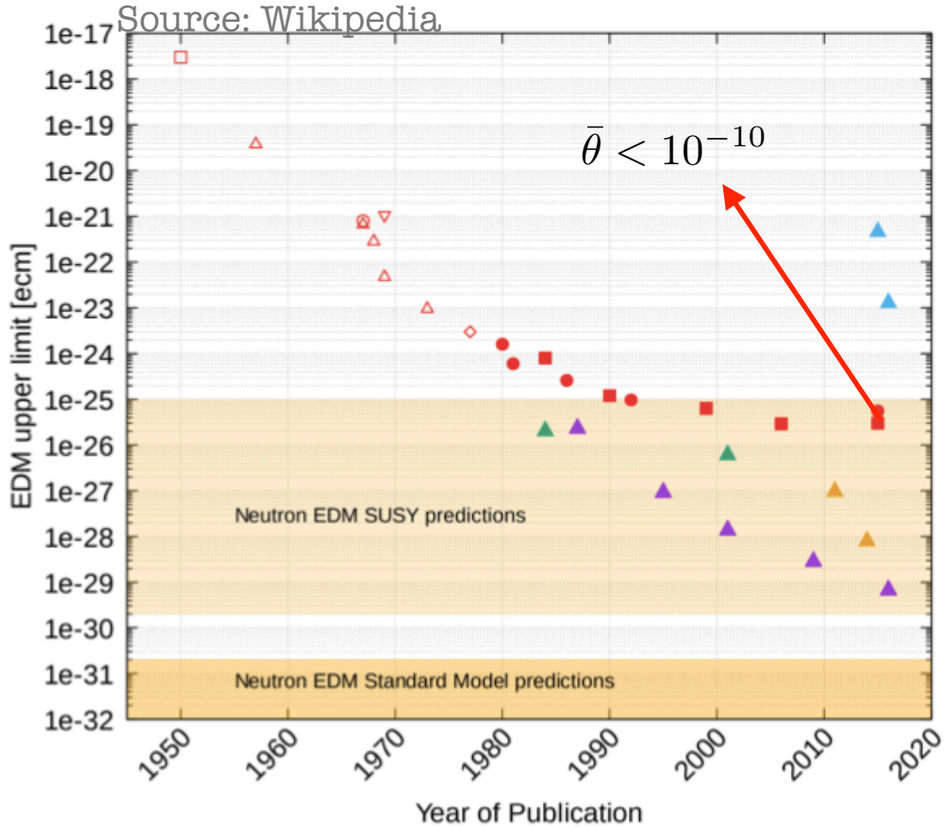

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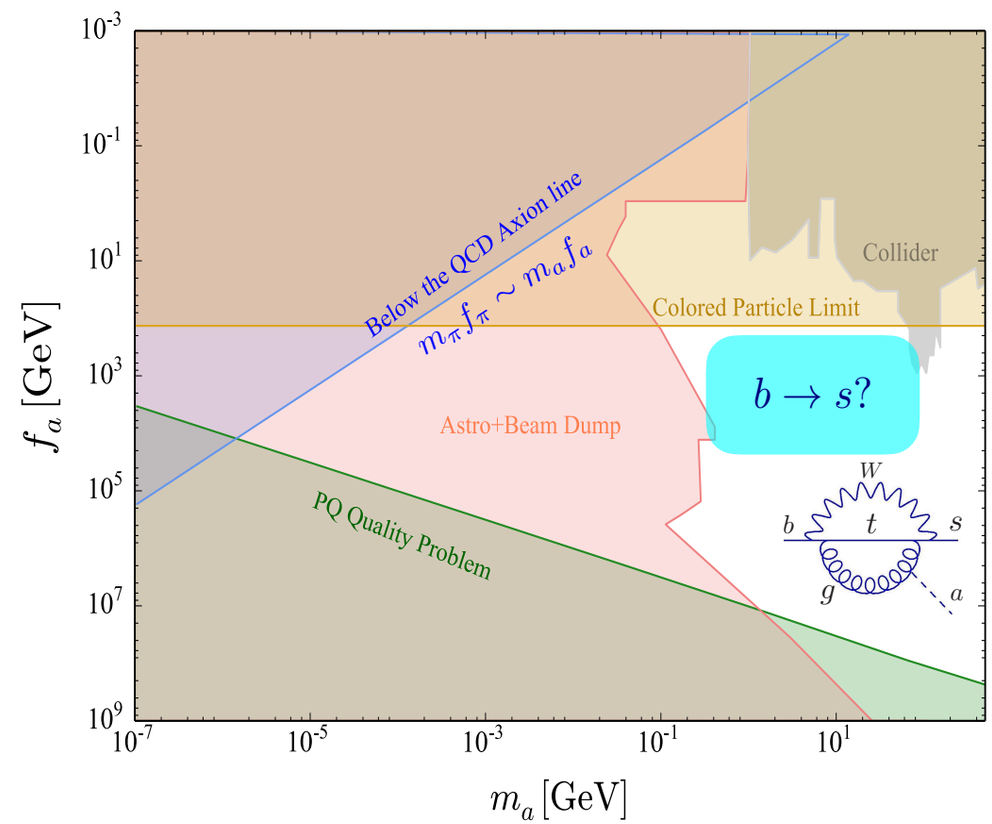
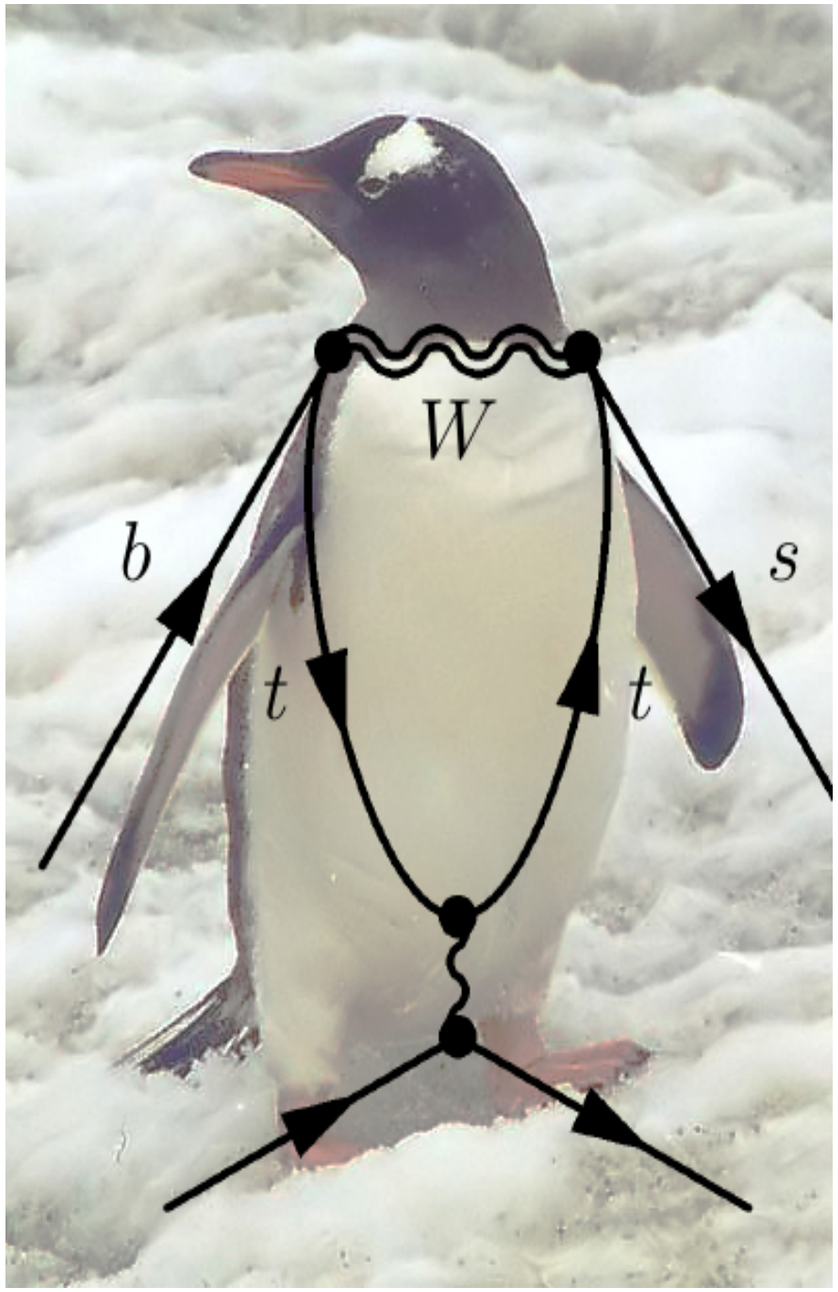


- Fine-Tuning issue in the SM

Calculation of the Production B-> Ka



Ref: 2102.04474, 2108.10331

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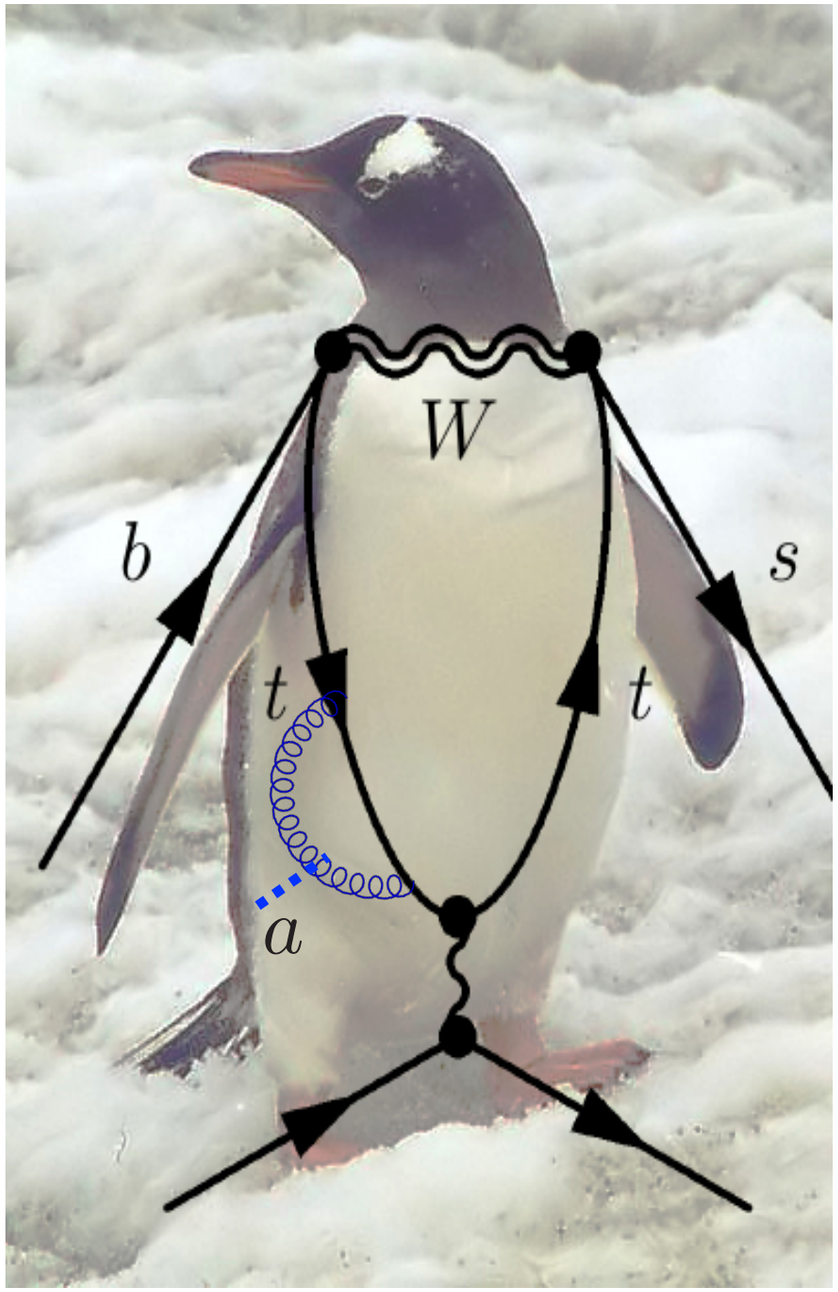

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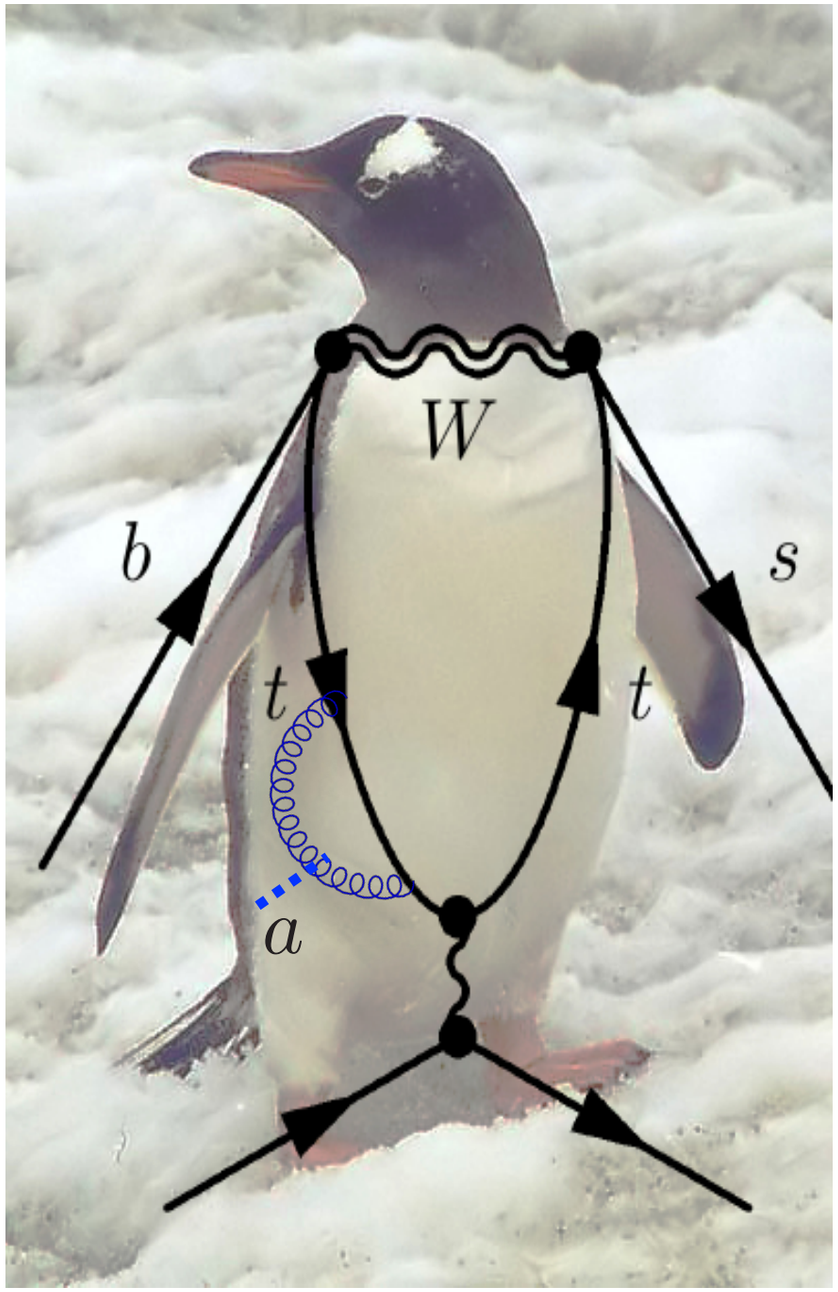

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$\Lambda_{\rm UV}$ — Start with $\frac{\alpha_s}{8\pi}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{\mu\nu a}, \quad \frac{\partial_\mu a}{f_a}\bar{q}\gamma^\mu\gamma_5 q, \quad \frac{\partial_\mu a}{f_a}\bar{s}_L\gamma^\mu\gamma_5 b_L$

Using RGEs ↓ $\mu\frac{d}{d\mu}\left(\mathcal{C}_i\mathcal{Z}_{ij}\right)=0$

M_W — $\mathcal{C}_W\left(M_W\right)\bar{s}\gamma^\mu\gamma_5 P_L b\frac{\partial_\mu a}{F_a}$

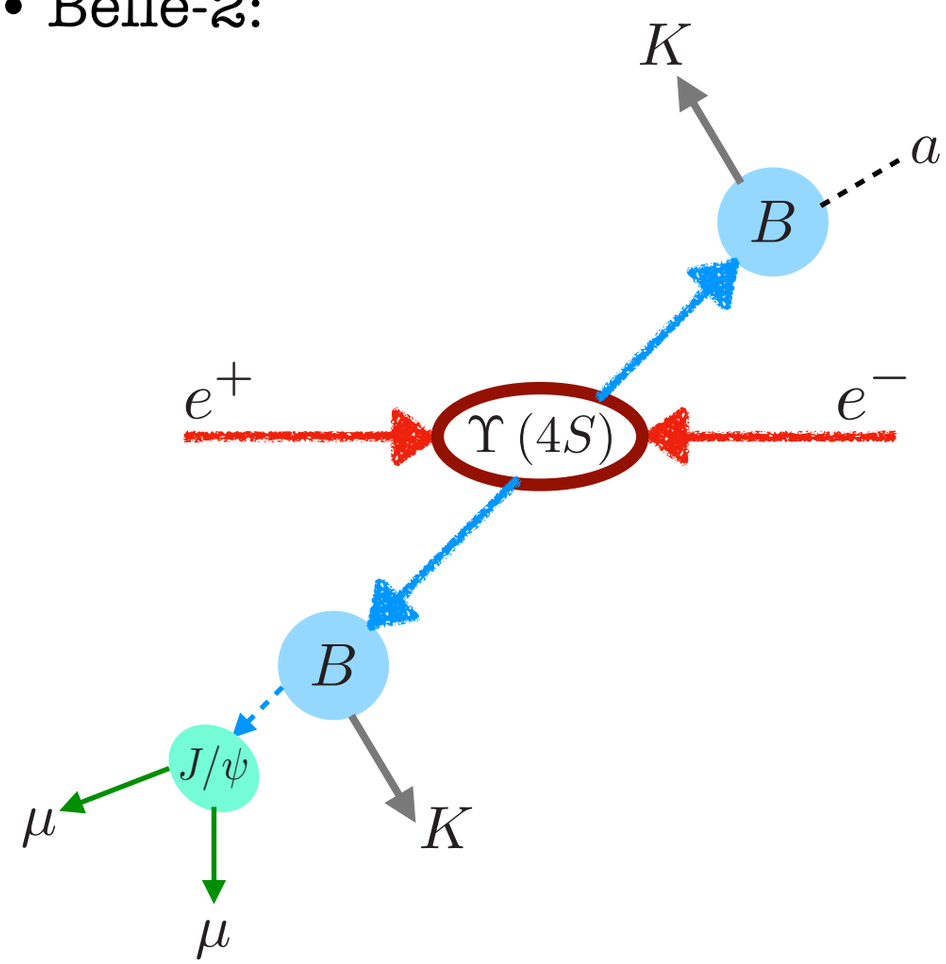
Using RGEs ↓

m_b — Experimental Data

$B \to Ka$

Axions: Experimental Searches

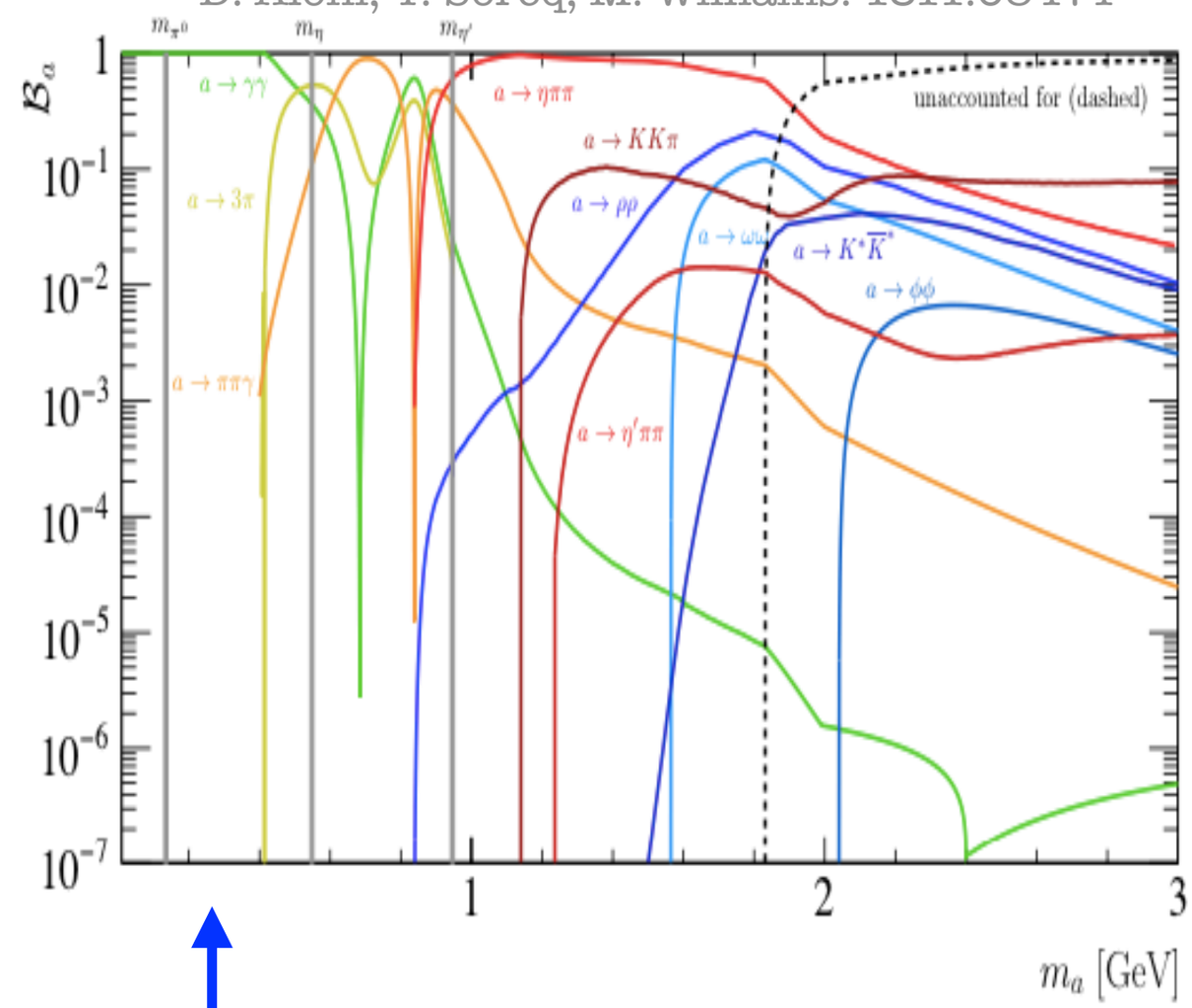
- Belle-2:



Belle Experiment

$a \to (\eta\pi\pi\ , KK\pi\ , 3\pi\ , \phi\phi)$

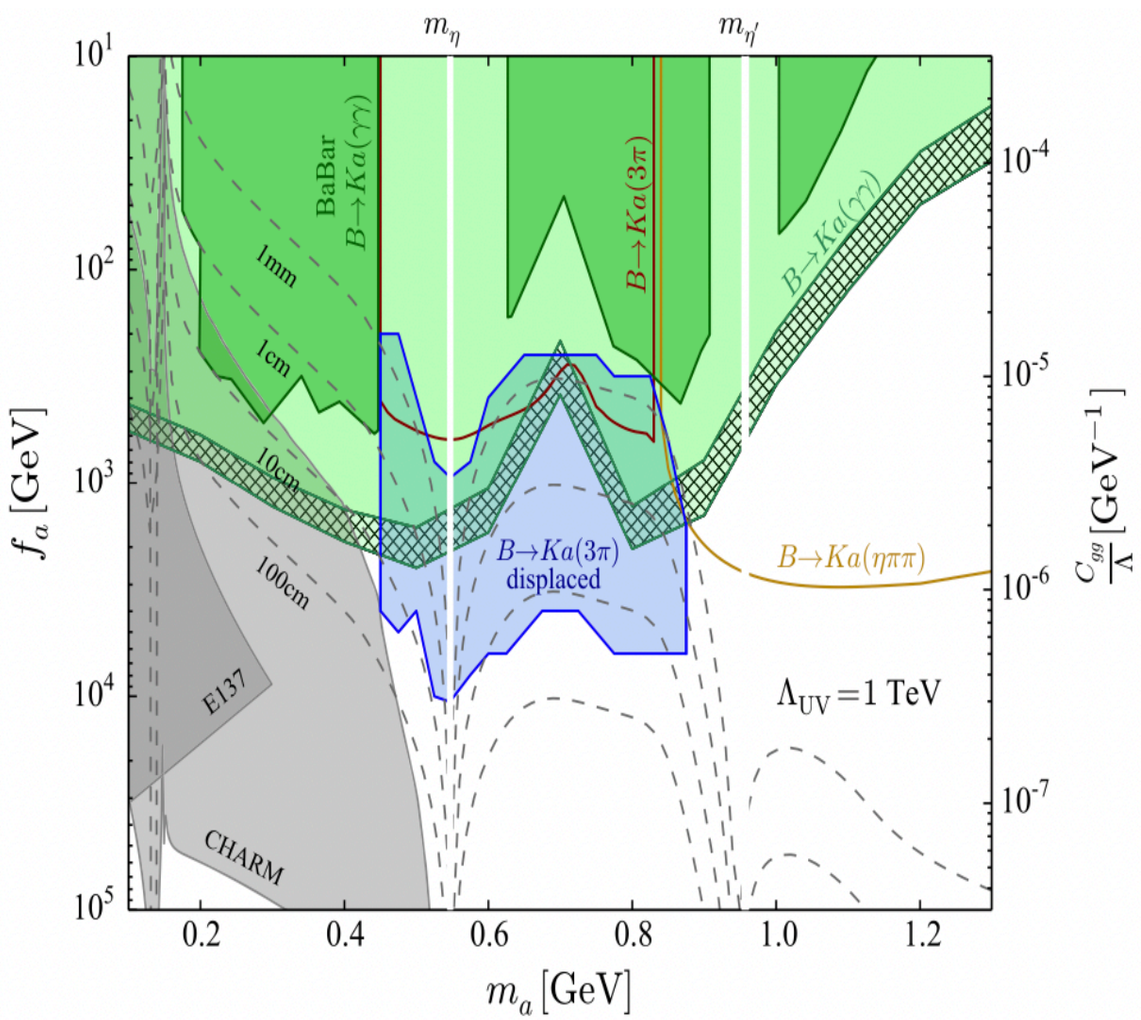
D. Aloni, Y. Soreq, M. Williams: 1811.03474



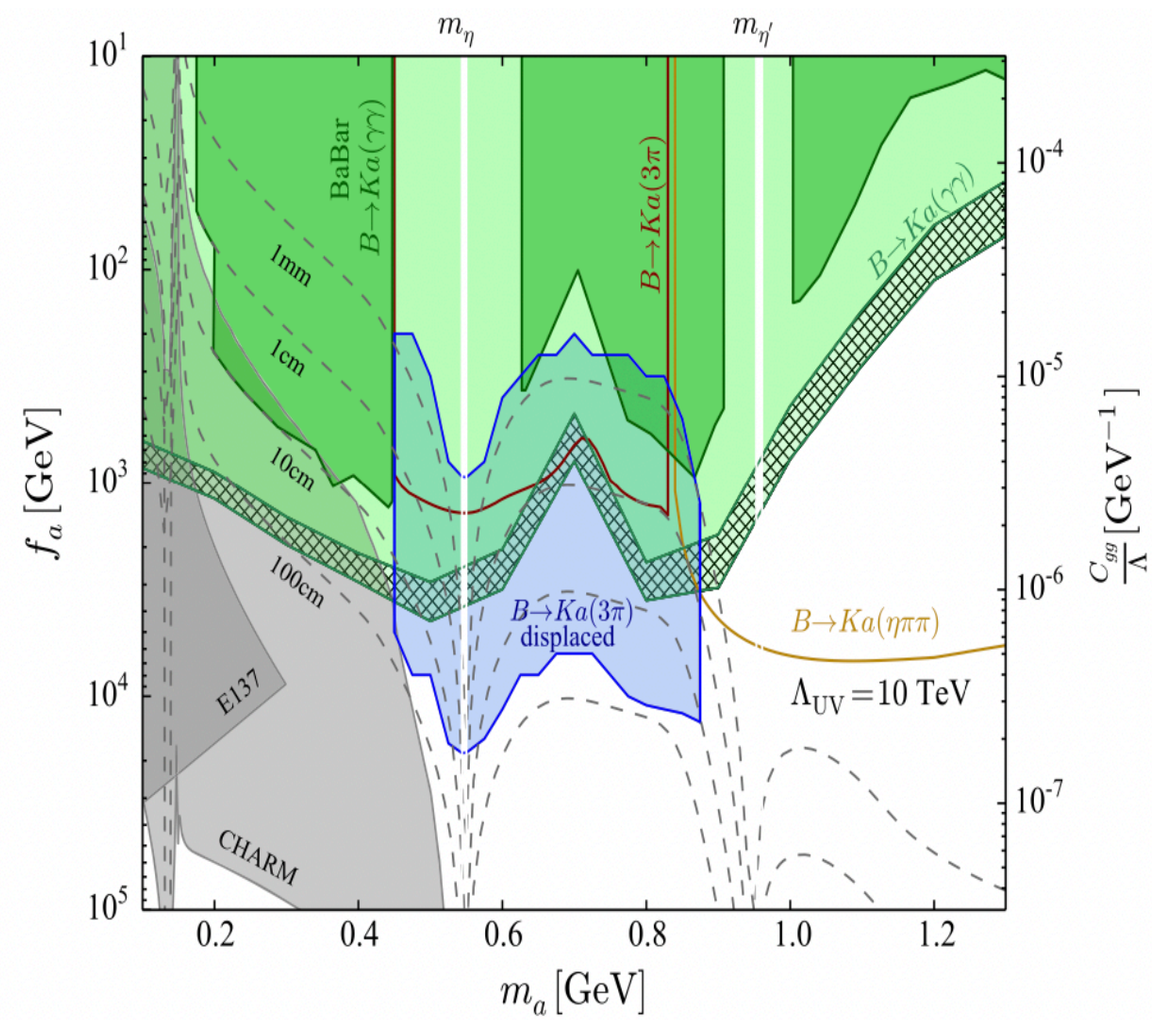
$$N_{\rm sig} = \underbrace{N_{BB}}_{10^8} \times \underbrace{\mathrm{BR}\,(B \to Ka)}_{\text{Our Calculation}} \times \boxed{\mathrm{BR}\,(a \to X)} \times \underbrace{\epsilon_{\rm eff}}_{\text{Required}} \times \underbrace{\mathcal{O}(1)}_{\text{Isospin Factors}}$$

Axions: Limits from Displaced Searches

Bertholet, Chakraborty, Loladze, Okui, Soffer, Tobioka 2021



$\Lambda_{\rm UV} = 1$ TeV

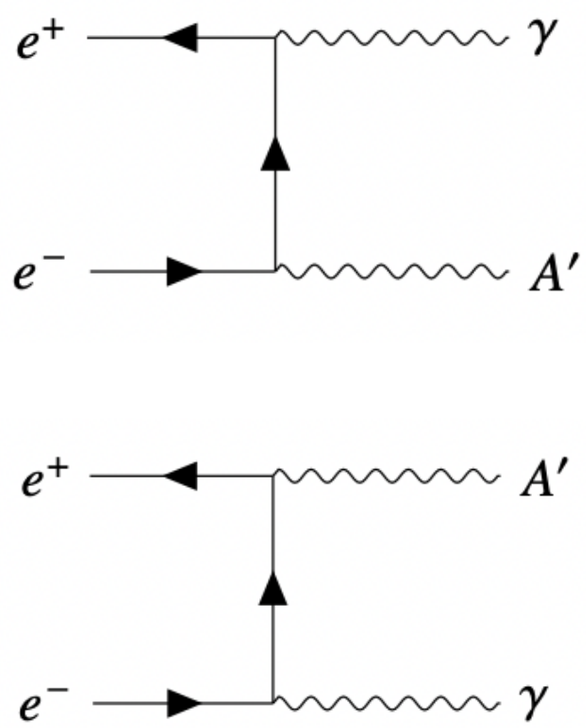


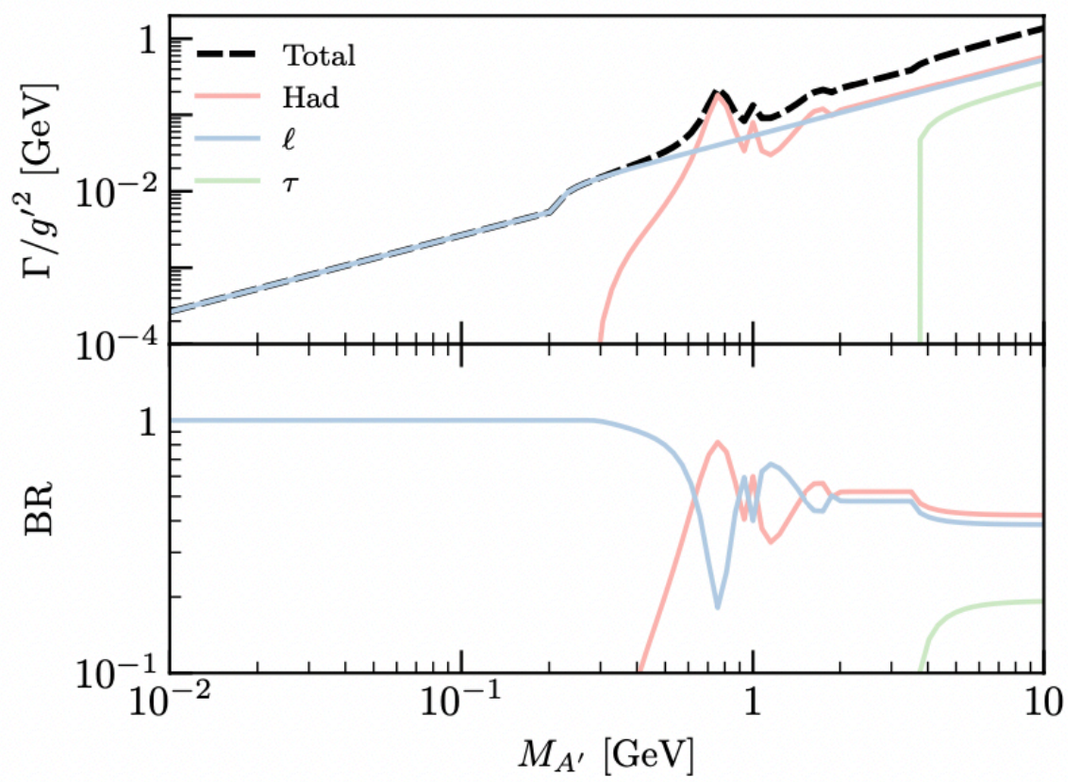
$\Lambda_{\rm UV} = 10$ TeV

Dark Photon: Limits from Displaced Searches

Bandyopadhyay, Chakraborty, Trifinopoulos 2022

$$\mathcal{L} = -\frac{1}{4}\hat{F}'_{\mu\nu}\hat{F}'_{\mu\nu} - \frac{\epsilon}{2}\hat{F}'_{\mu\nu}\hat{F}^{\mu\nu}$$





$$N_{\rm sig} = L_1 \times \int_{\eta_{\rm min}}^{\eta_{\rm max}} d\eta \, \frac{d\sigma}{d\eta} \times {\rm BR}_F \, \epsilon_F \, \mathcal{E}\left(\eta\right) \, \Theta\left(p_T^{\rm min} - \sin\theta\left(\eta\right)|\vec{p}|\right)$$

Dark Photon: Limits from Displaced Searches

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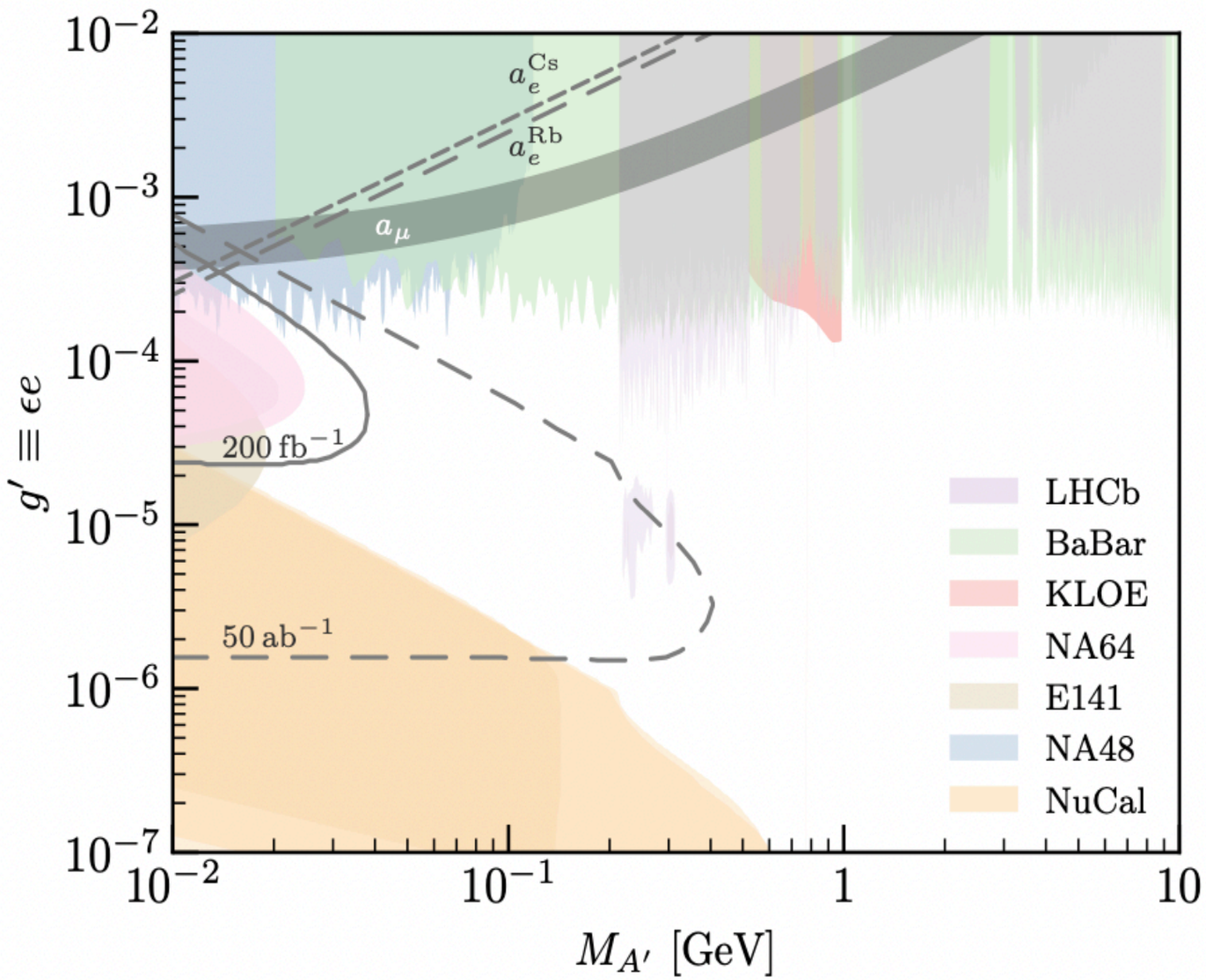
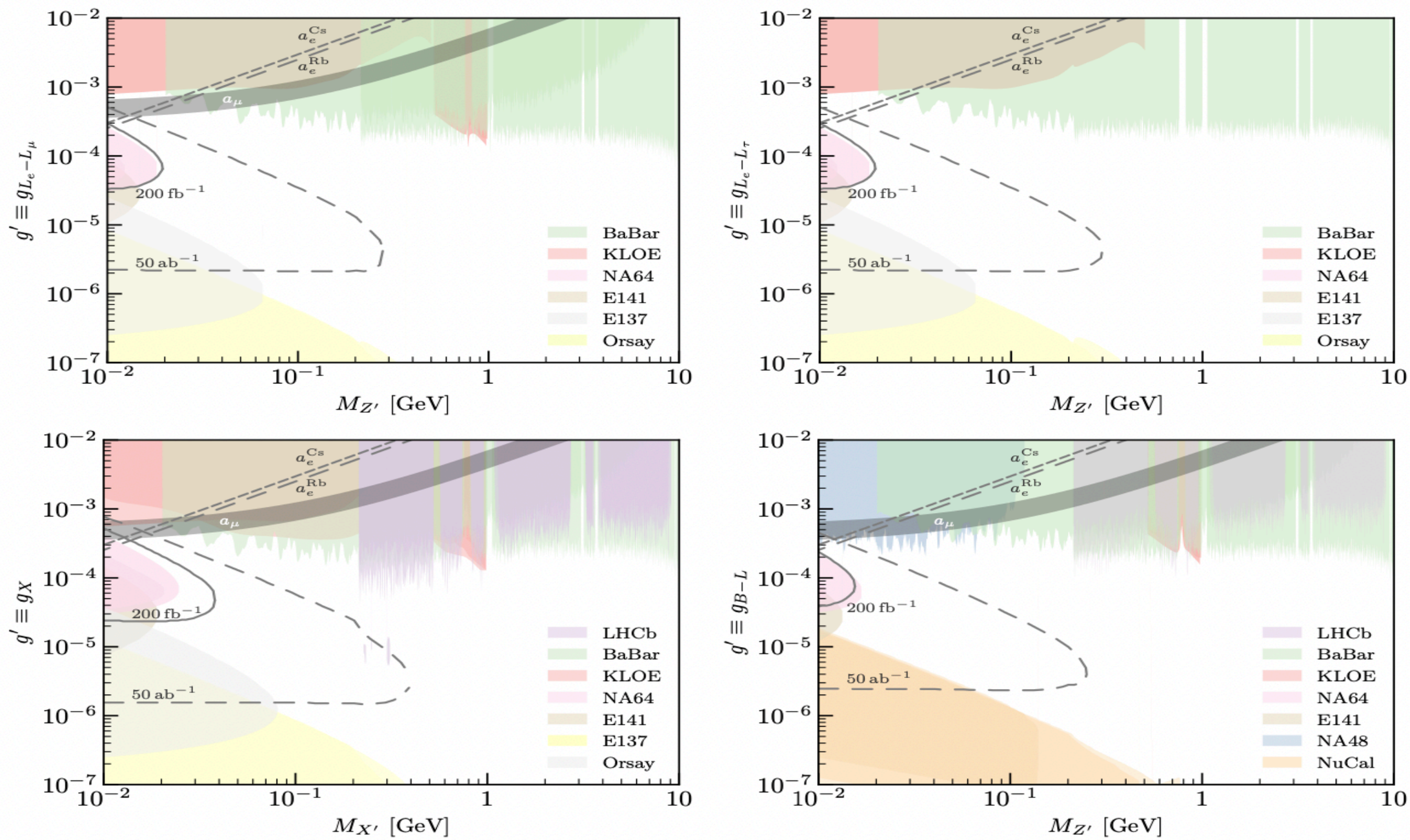


Vector Bosons: Limits from Displaced Searches

Bandyopadhyay, Chakraborty, Trifinopoulos 2022



Conclusion

- Displaced vertices give rise to unique signatures with almost no bkg.
- Proposed new search strategies for $a \to \pi^+\pi^-\pi^0$, $a \to \gamma\gamma$
- Similar searches are proposed for $A' \to \gamma + \text{displaced tracks}$
- Complementary test for the ATOMKI anomaly

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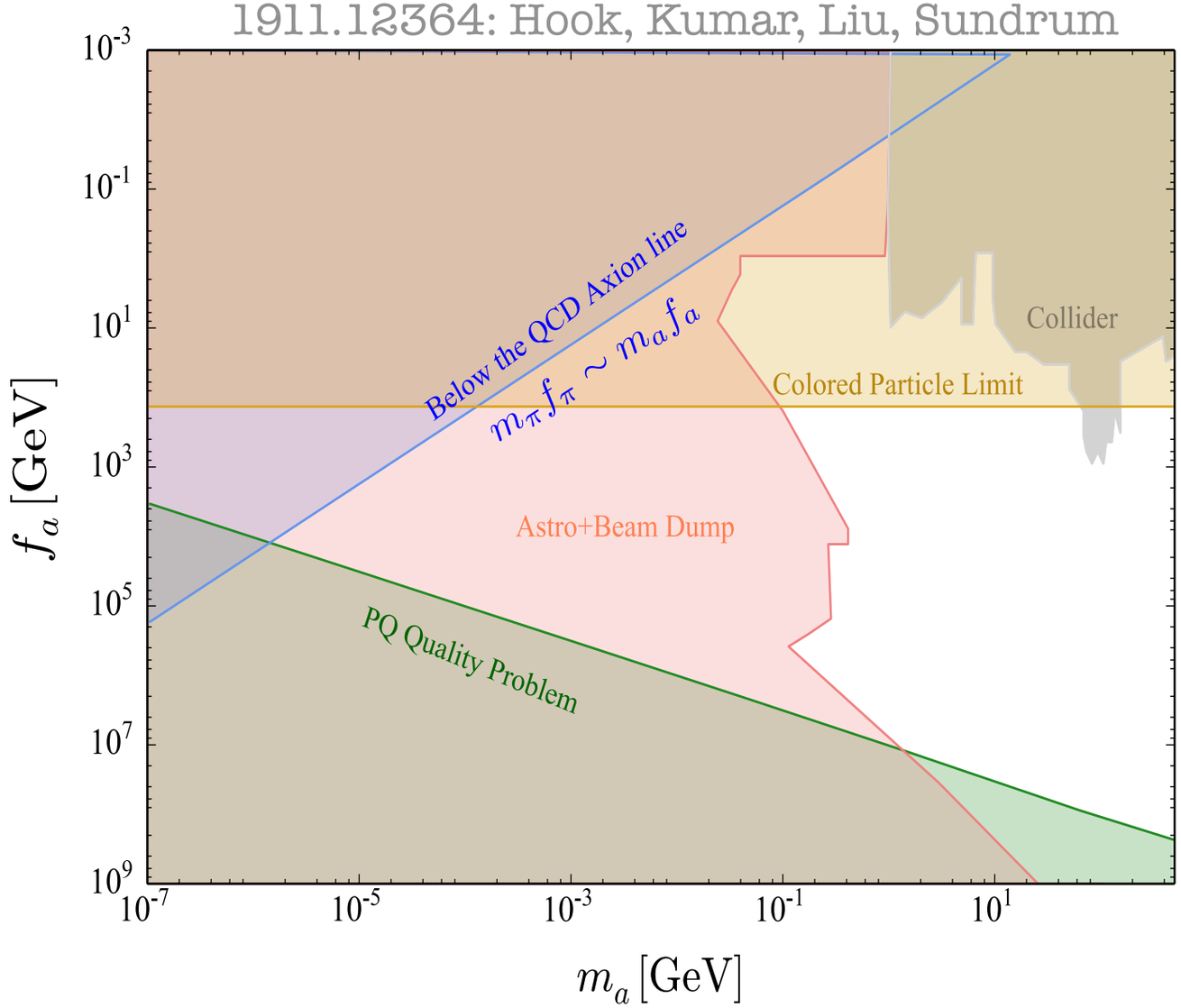
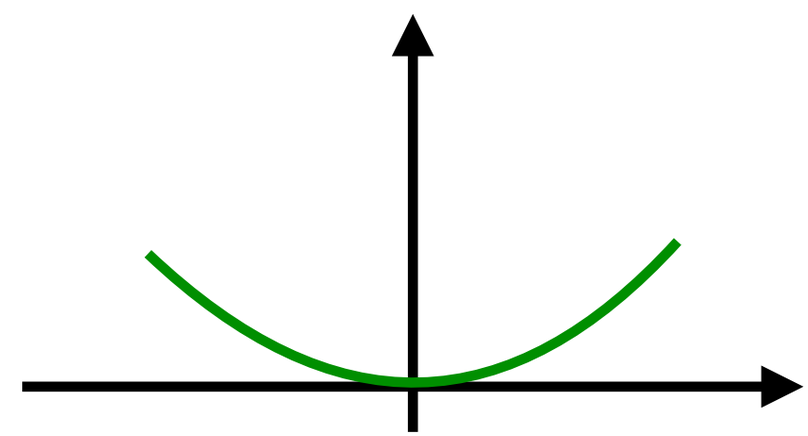
Thank you!

Backup: Quality Problem and Heavy Axion

1911.12364: Hook, Kumar, Liu, Sundrum



- QCD Axion with large fa is problematic => Quality Problem



See: Rubakov 9703409
Fukuda, Harigaya, Ibe, Yanagida 1504.06084
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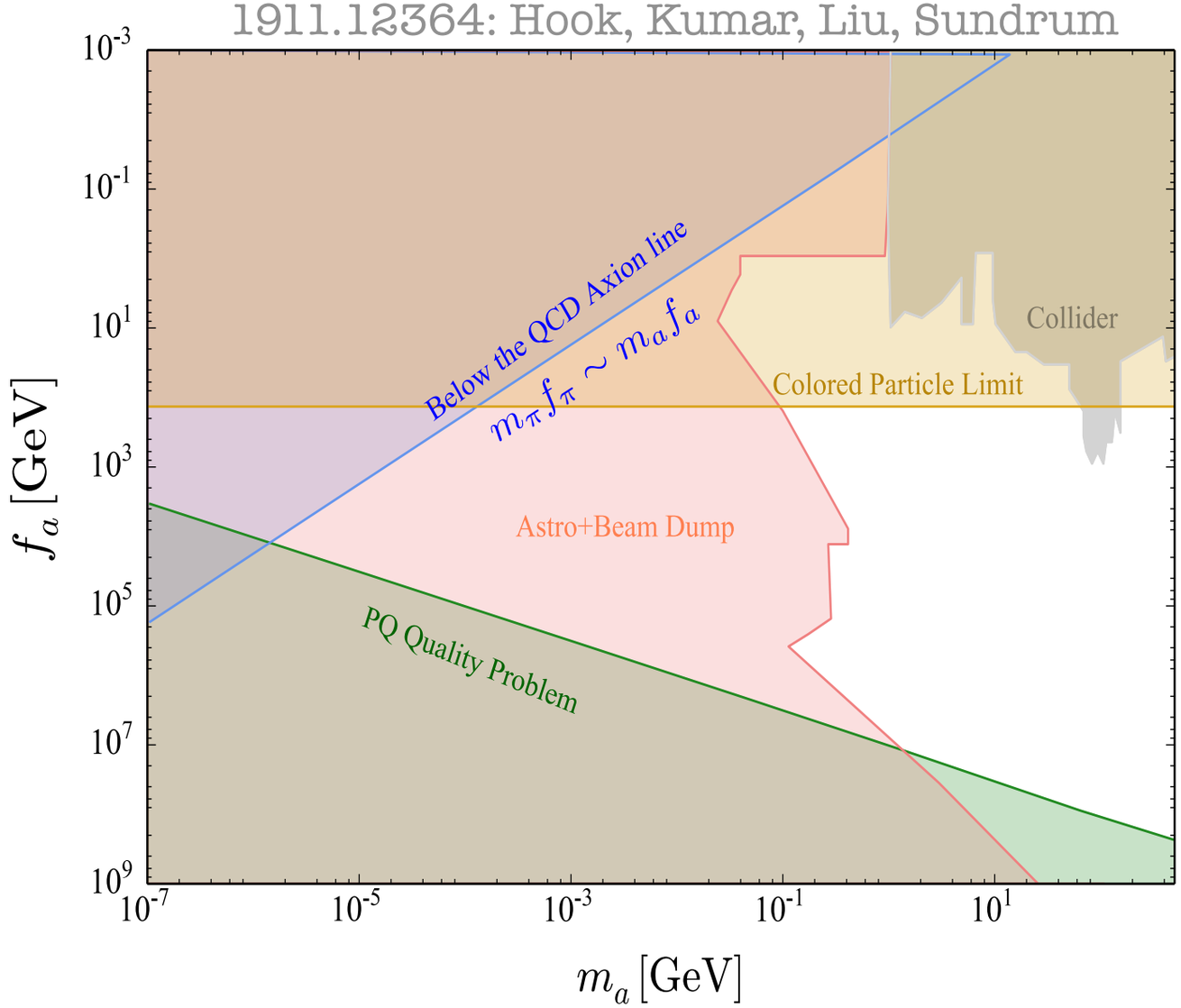

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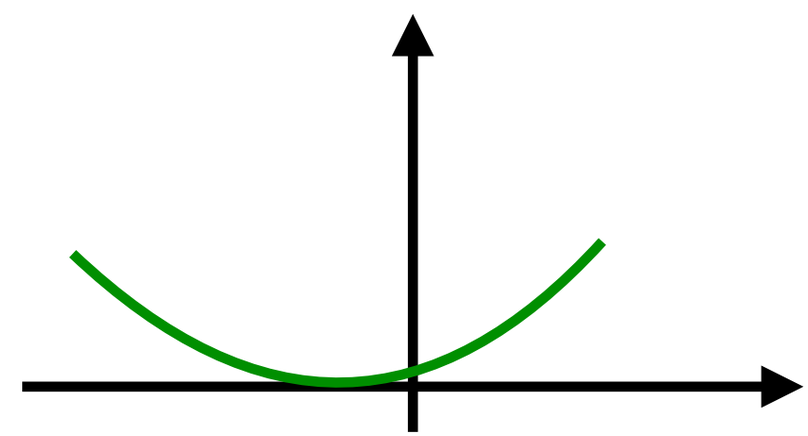

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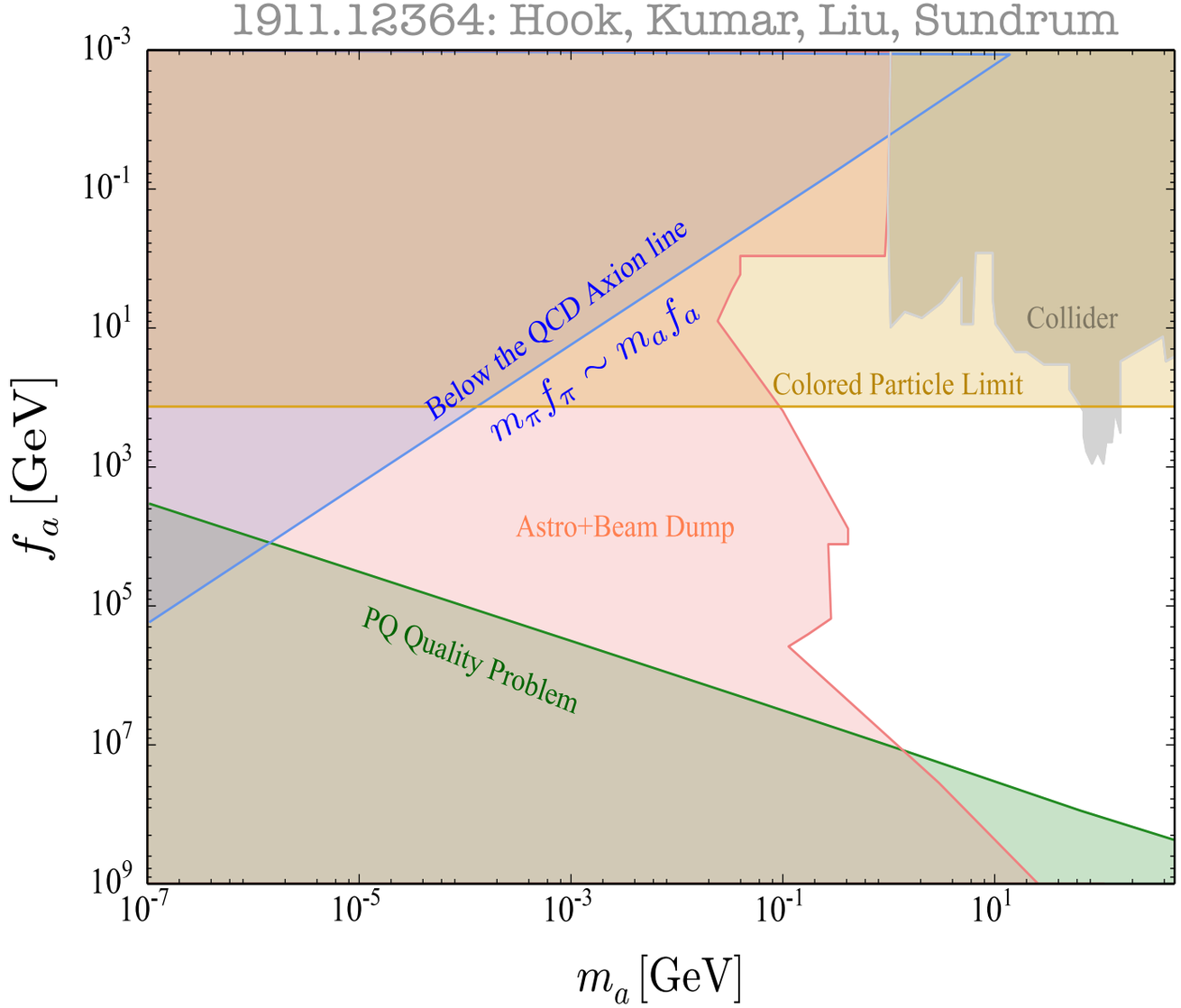

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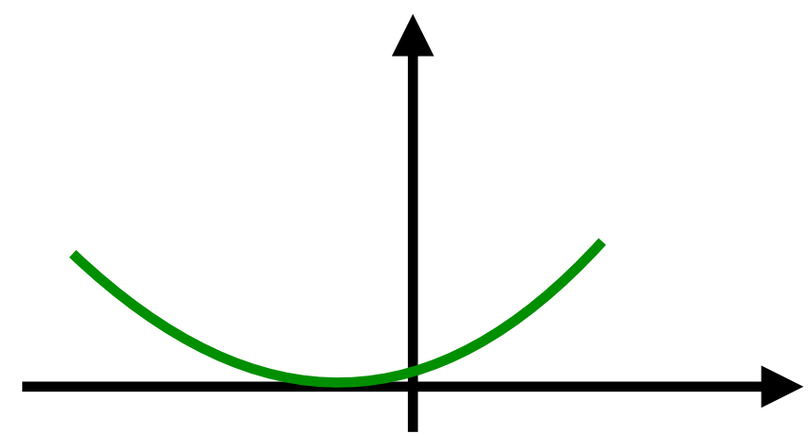


$$\frac{\lambda f_a^5}{M_{\rm pl}} < \Lambda_{\rm QCD}^4 \implies \lambda < 10^{-10}\left(\frac{10^5}{f_a}\right)^5$$

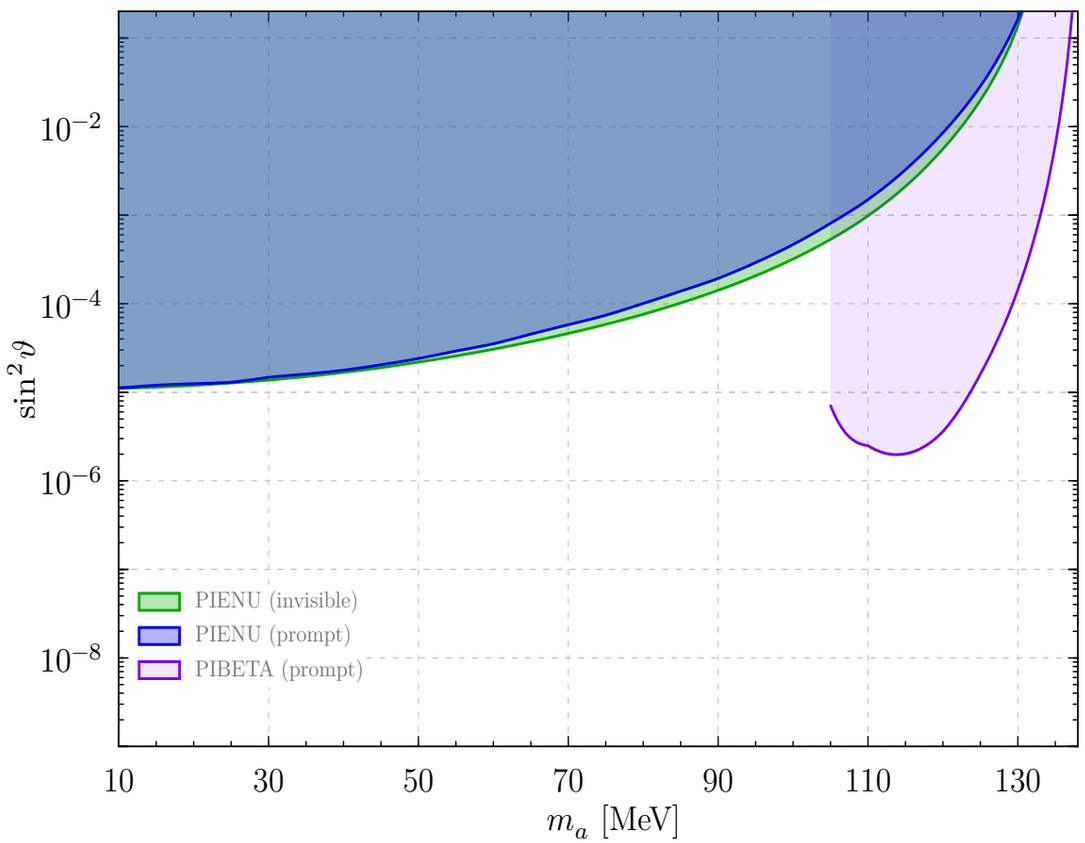
See: Rubakov 9703409
Fukuda, Harigaya, Ibe, Yanagida 1504.06084
Hook, Kumar, Liu, Sundrum 1911.12364 etc.

Backup: Bounds from Meson decay

$$g_{aff} \sim g_{\pi^0 ff} \times f_\pi / f_a \Rightarrow \sin\theta$$

$\pi^+ \to \pi^0 (a) e^+ \nu$

Altmannshofer, Gori, Robinson 1909.00005



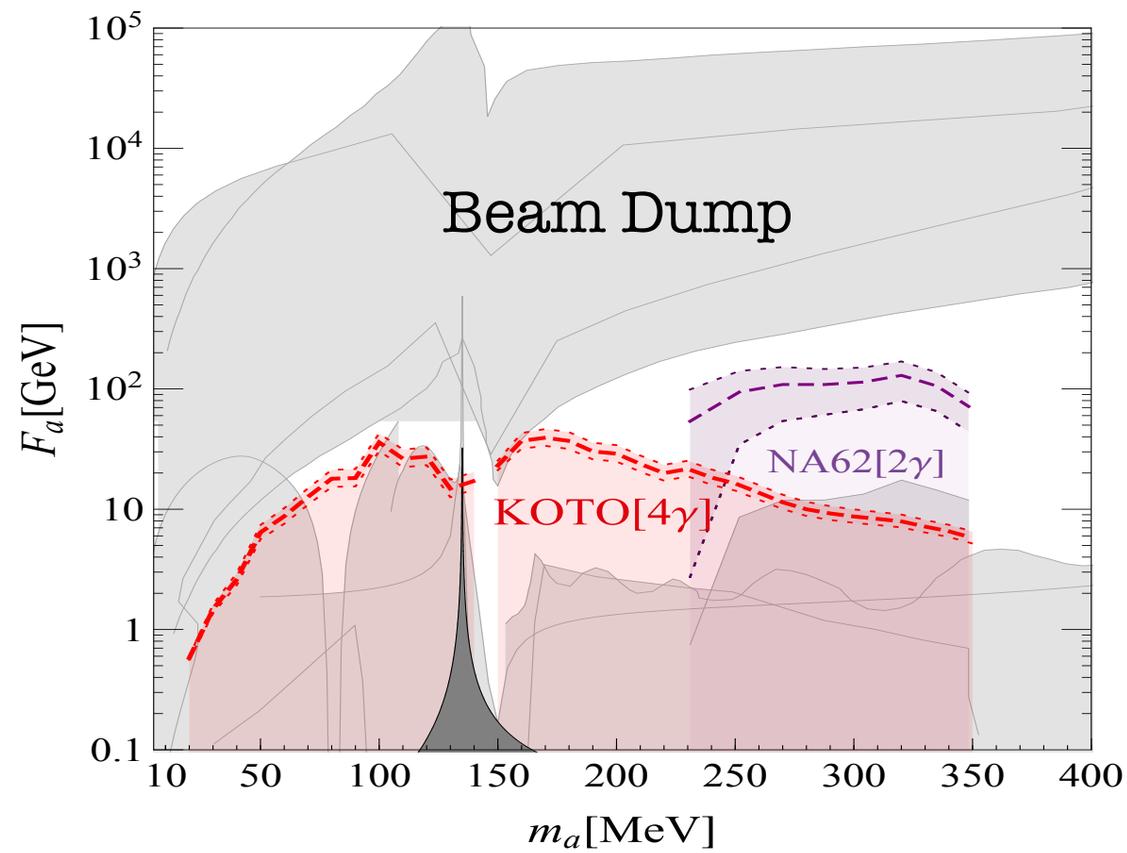
PIBETA Exp. $\mathrm{Br}\left[\pi^+ \to \pi^0 e\nu\right] \sim 10^{-8}$

PIENU Exp. $\mathrm{Br}\left[\pi^+ \to e\nu\right] \sim 10^{-4}$

$$f_a \sim \mathcal{O}(\mathrm{GeV})$$

$K^+ \to \pi^+ a \, , K_L \to \pi^0 a$

Gori, Perez, Tobioka 2005.05170

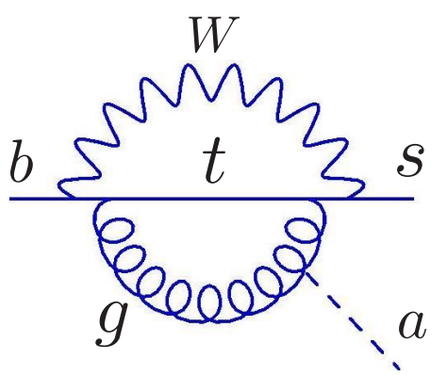


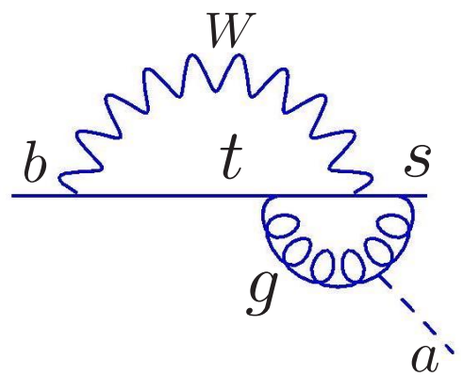
NA62 Exp: $\mathrm{Br}\left[K^+ \to \pi^+ \nu\bar{\nu}\right] \sim 10^{-10}$

KOTO Exp: $\mathrm{Br}\left[K_L \to \pi^0 \nu\bar{\nu}\right] \sim 10^{-9}$

Backup: Counterterms & Operators

- Two Loop Diagrams:

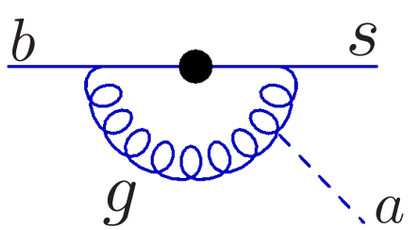


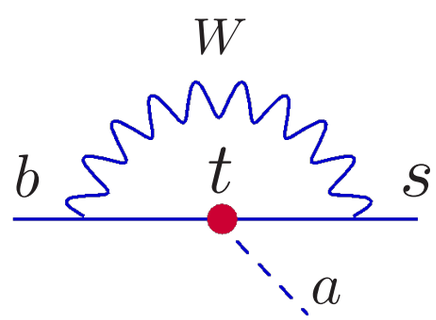


....

$$\mathcal{M} = \frac{\mathcal{A}}{\epsilon^2} + \frac{\mathcal{B}}{\epsilon} + \mathcal{C}$$

- Counterterms:



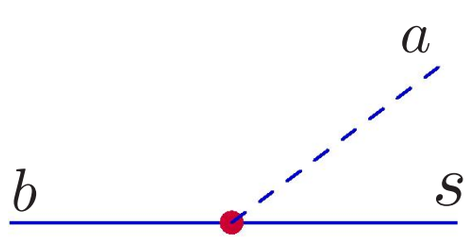


....

$$\mathcal{M} + \mathcal{M}_{ct} = \cancelto{0}{\frac{\mathcal{A}}{\epsilon^2}} + \frac{\mathcal{B}'}{\epsilon} + \mathcal{C}'$$

$\Rightarrow$ Need aqq operator, $\mathcal{C}_{aqq}$

- Overall counter term:

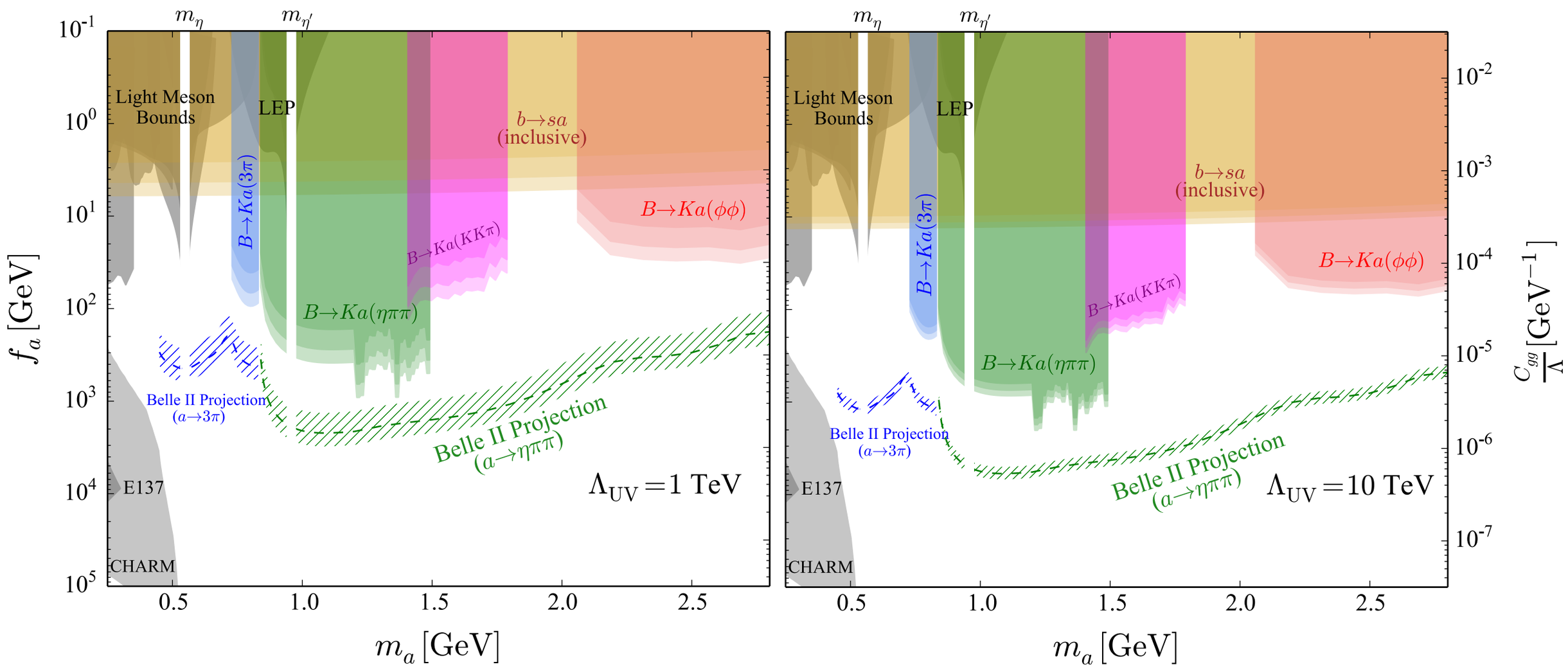


$$\mathcal{M} + \mathcal{M}_{ct} + \mathcal{M}_{oct} = \cancelto{0}{\frac{\mathcal{B}'}{\epsilon}} + \mathcal{C}_W$$

$\Rightarrow$ Need abs operator, $\mathcal{C}_{abs}$

Backup: Limits from Prompt Decays

Chakraborty, Kraus, Loladze, Okui, Tobioka 2021

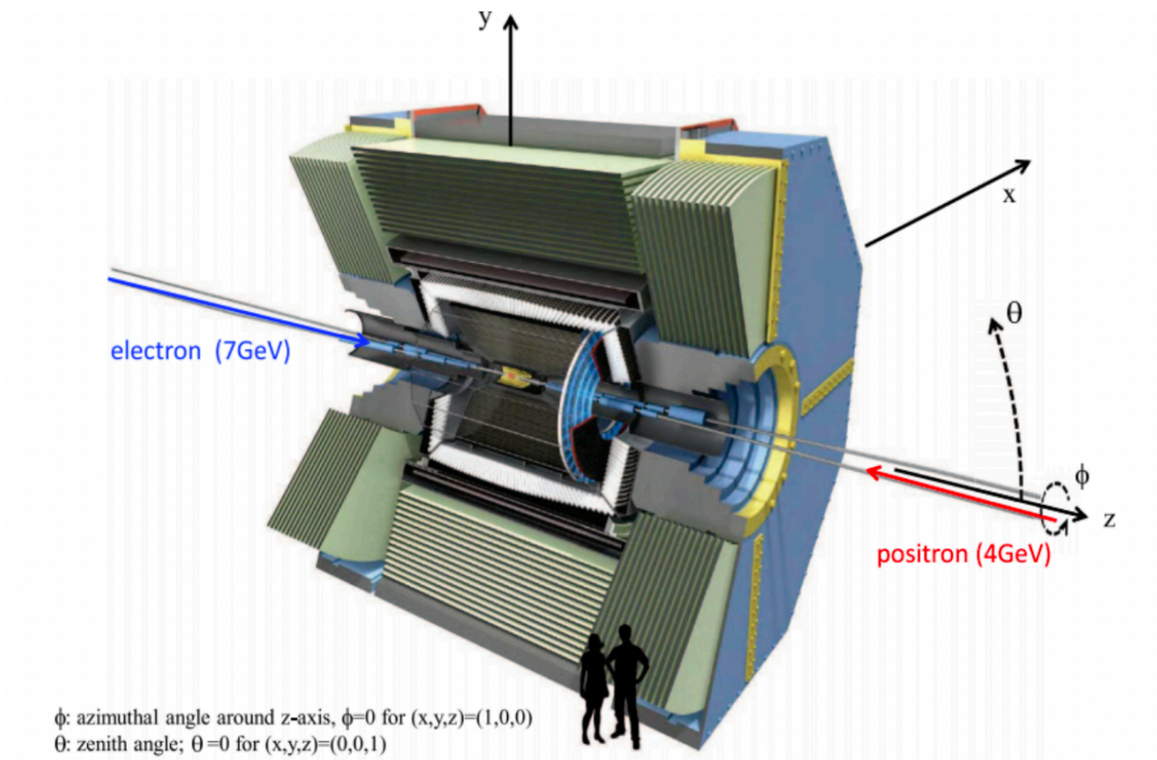


$\Lambda_{\rm UV} = 1$ TeV

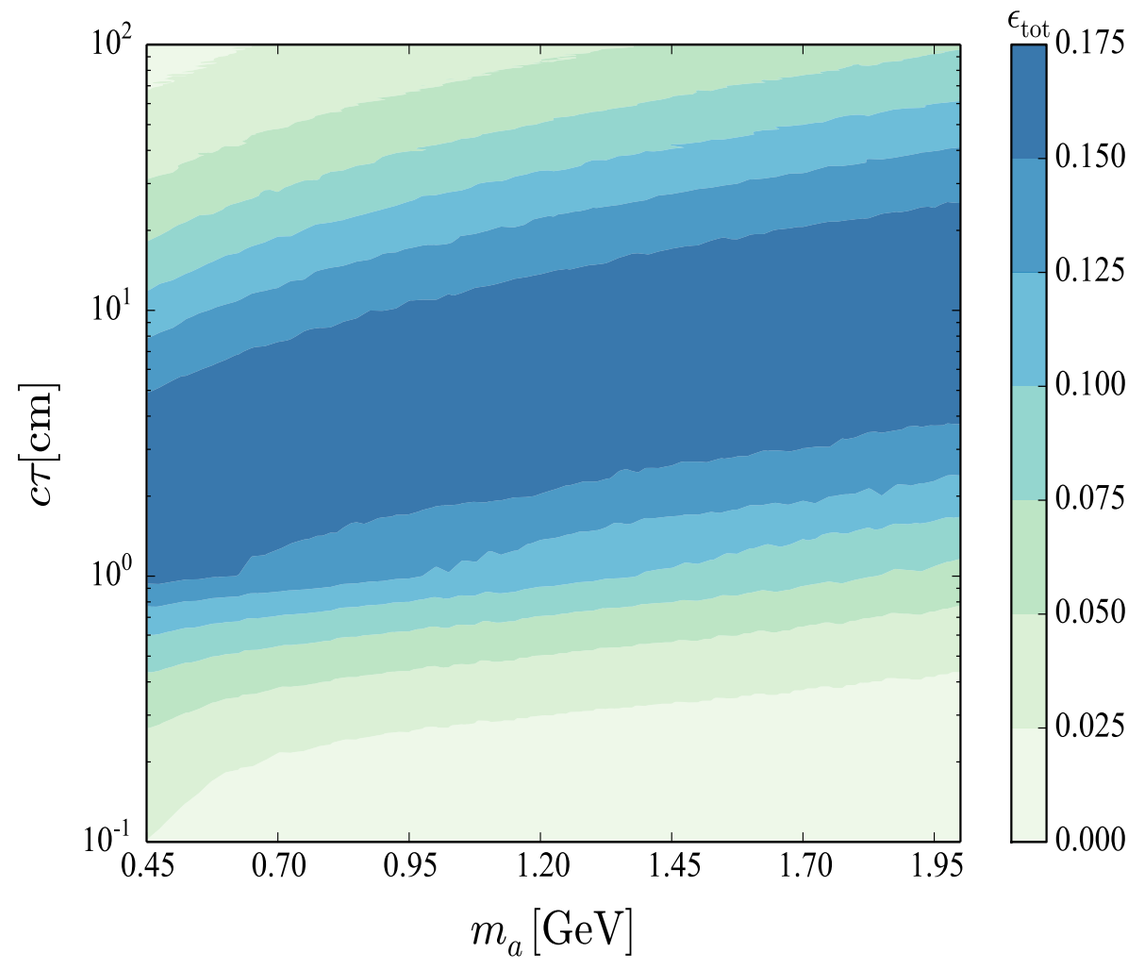
$\Lambda_{\rm UV} = 10$ TeV

Backup: Efficiency for Displaced Analysis

$$N_{\text{sig}} = \underbrace{N_{BB}}_{10^8} \times \underbrace{\text{BR}\left(B \to Ka\right)}_{\text{Our Calculation}} \times \text{BR}\left(a \to X\right) \times \underbrace{\epsilon_{\text{eff}}}_{\text{Required}} \times \underbrace{\mathcal{O}(1)}_{\text{Isospin Factors}}$$



$$\epsilon\left(r\right) = -\frac{r}{r_b - r_a} + \frac{r_b}{r_b - r_a}$$



Backup: Mu-Tau