# Fantastic Axions & Where To Find Them

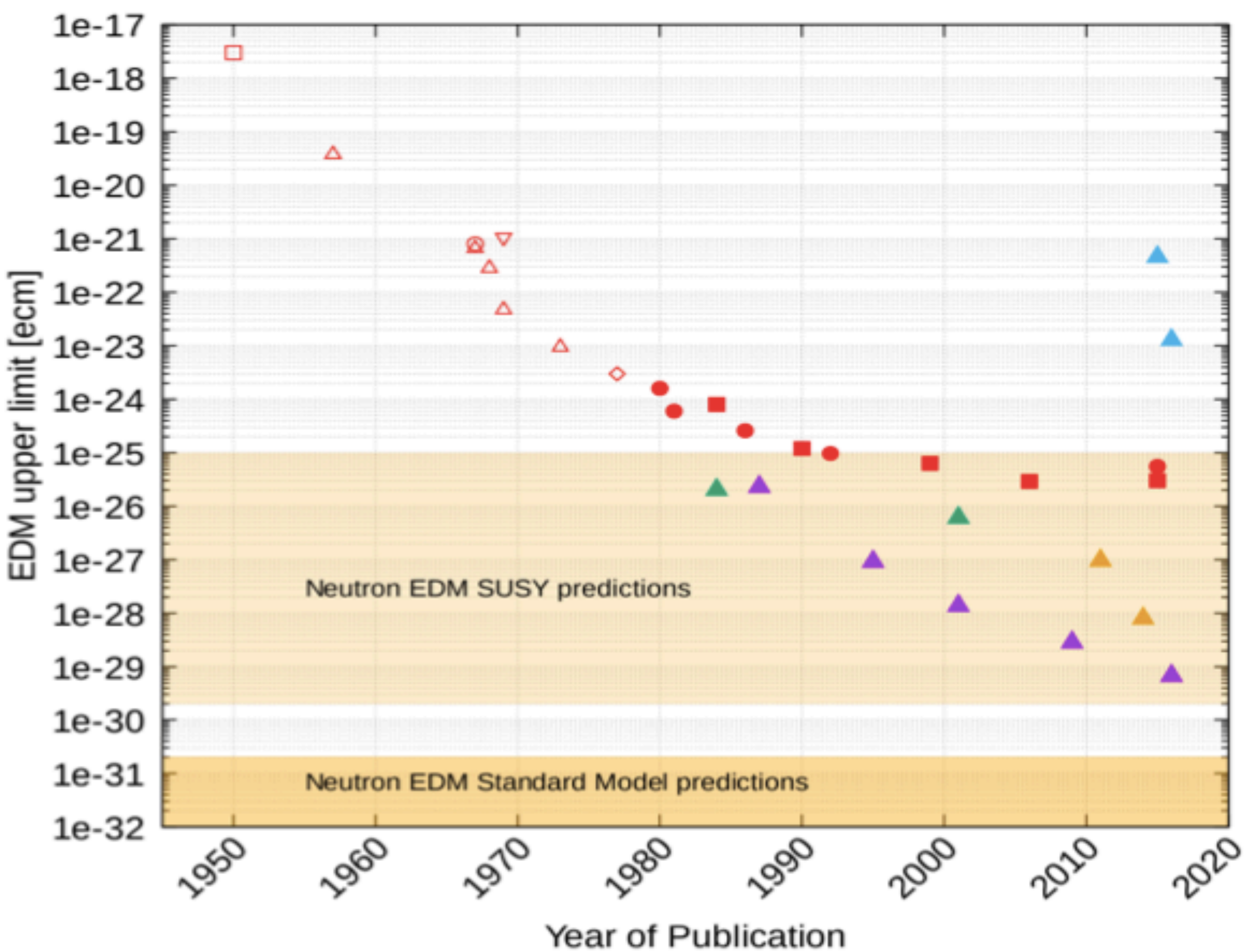
Sabyasachi Chakraborty (IIT-Kanpur)

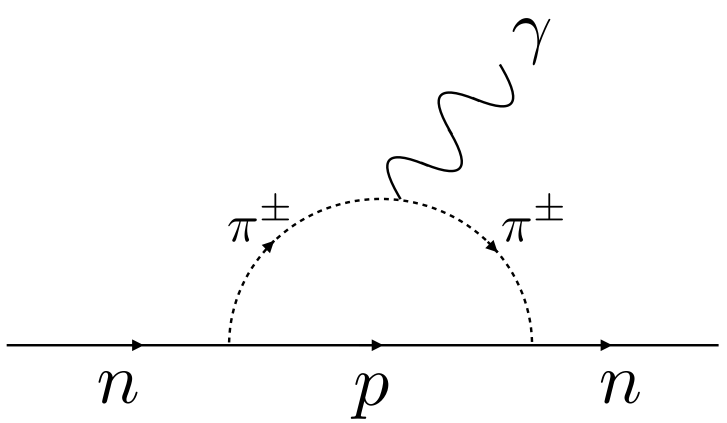
(In-House Symposium, 2024)

# Introduction: Standard Model & CP

- Strong CP Phase:

$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm QCD}^{\rm SM} + \overline{\theta}\,\frac{\alpha_s}{8\pi}\underbrace{G^a_{\mu\nu}\tilde{G}^{\mu\nu a}}_{\partial^\mu K_\mu \neq 0}$$




$$|d_n| < 1.8 \times 10^{-26}\ ecm$$

arXiv:2001.11966

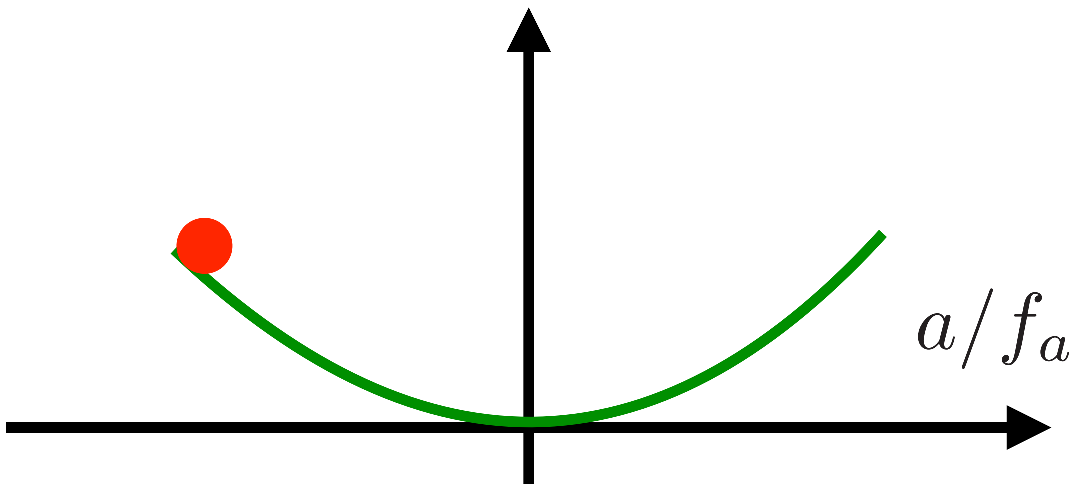
$$\bar{\theta} = \theta + {\rm Arg}\left({\rm Det} M\right) < 10^{-10}$$

: Strong CP problem

# Introduction: Axion as a solution

- Dynamical Solution, Axion a(x):

$$\mathcal{L}_{\rm eff} \supset \bar{q}\,(i\not{D} - \mathcal{M}_q)\,q + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{\mu\nu a} + \ldots.$$




Dynamical solution to strong CP

- How do we calculate this?

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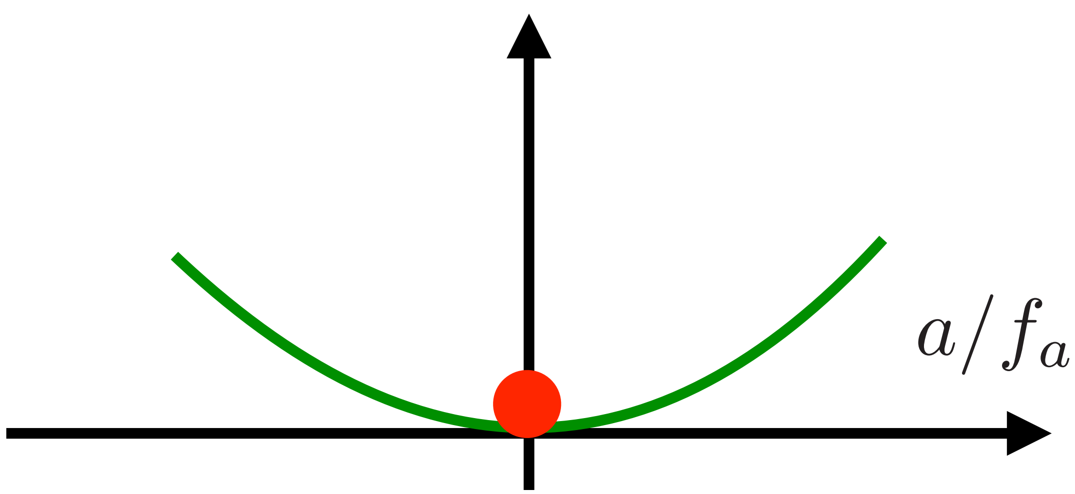


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However generates

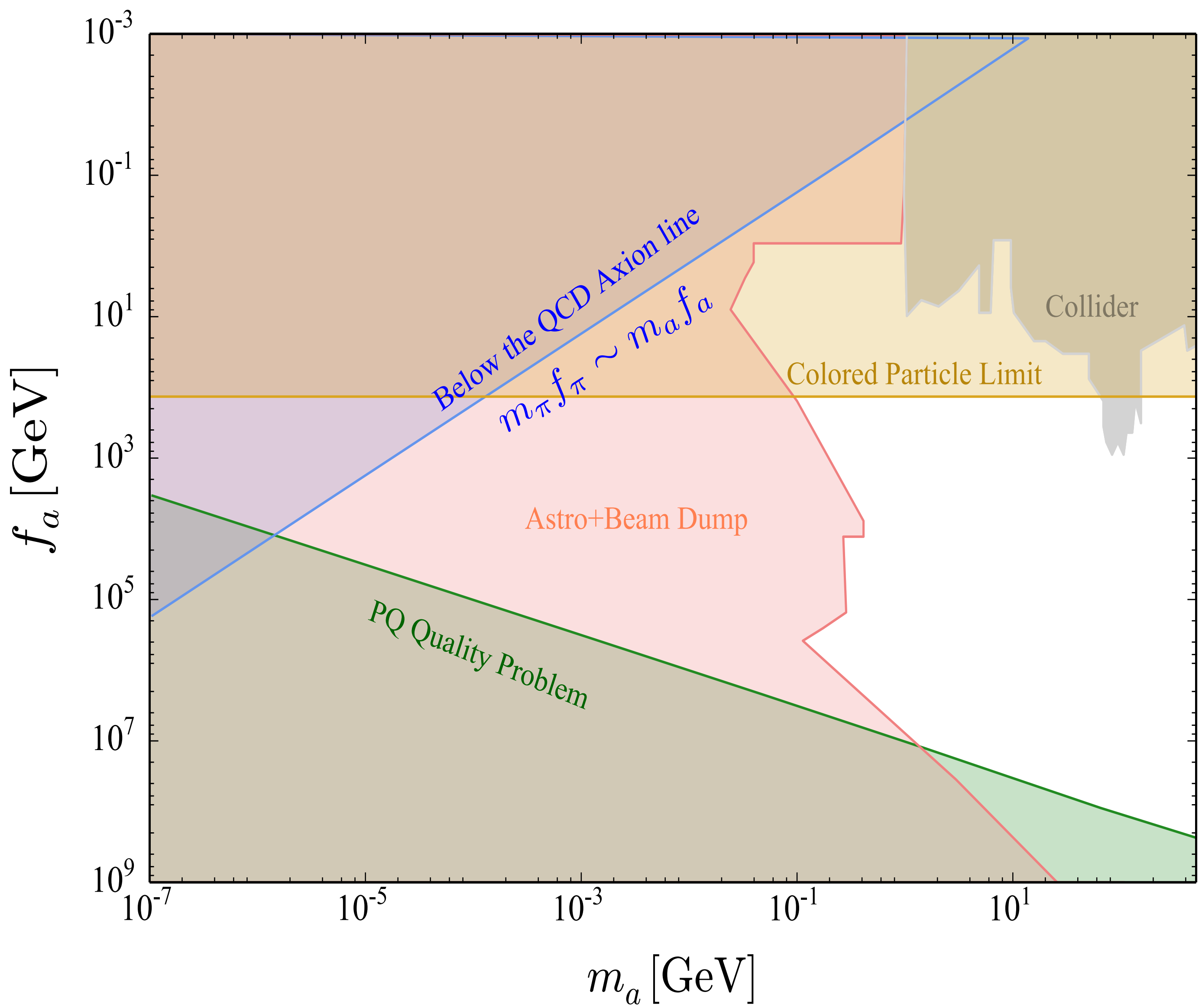
$$\mathcal{L}_{\rm eff} \supset \bar{q}\left(i\not{D} - \hat{\mathcal{M}}_q\right) q - \frac{\partial^\mu a}{2f_a}\bar{q}\gamma_\mu\gamma_5 q + \ldots$$

Matching with ChPT

$$\mathcal{L}_{\chi{\rm PT}} \supset \frac{f_\pi^2}{8}\,{\rm Tr}\left[D^\mu\Sigma\, D_\mu\Sigma^\dagger\right] + \frac{f_\pi^2}{4} 2B_0 {\rm Tr}\,\left[\Sigma\hat{\mathcal{M}}_q{}^\dagger + {\rm h.c.}\right] + \ldots \qquad \Sigma = {\rm Exp}\left[i\frac{\sqrt{2}\pi^a\tau^a}{f_\pi}\right]$$

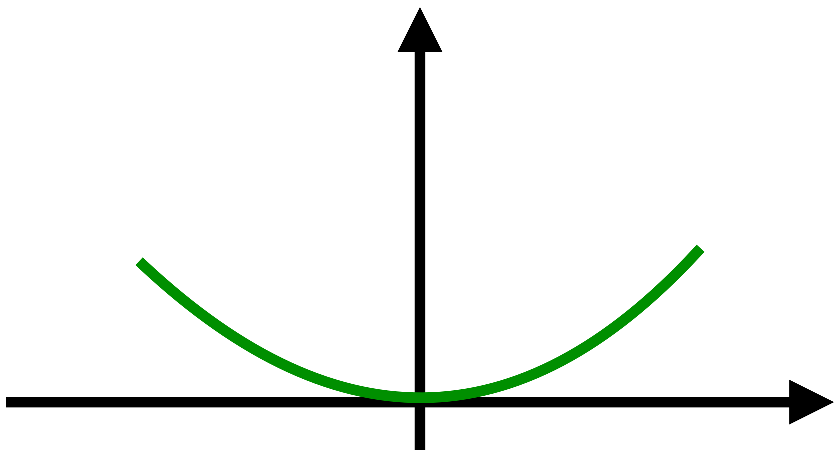
$$V_{\chi{\rm PT}} \sim m_\pi^2 f_\pi^2 \sim \Lambda_{QCD}^4\ , \quad m_a \sim \frac{m_\pi f_\pi}{f_a}\ , \quad g_{aff} \sim g_{\pi^0 ff} \times \frac{f_\pi}{f_a}$$

# Quality Problem and Heavy Axion




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

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



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

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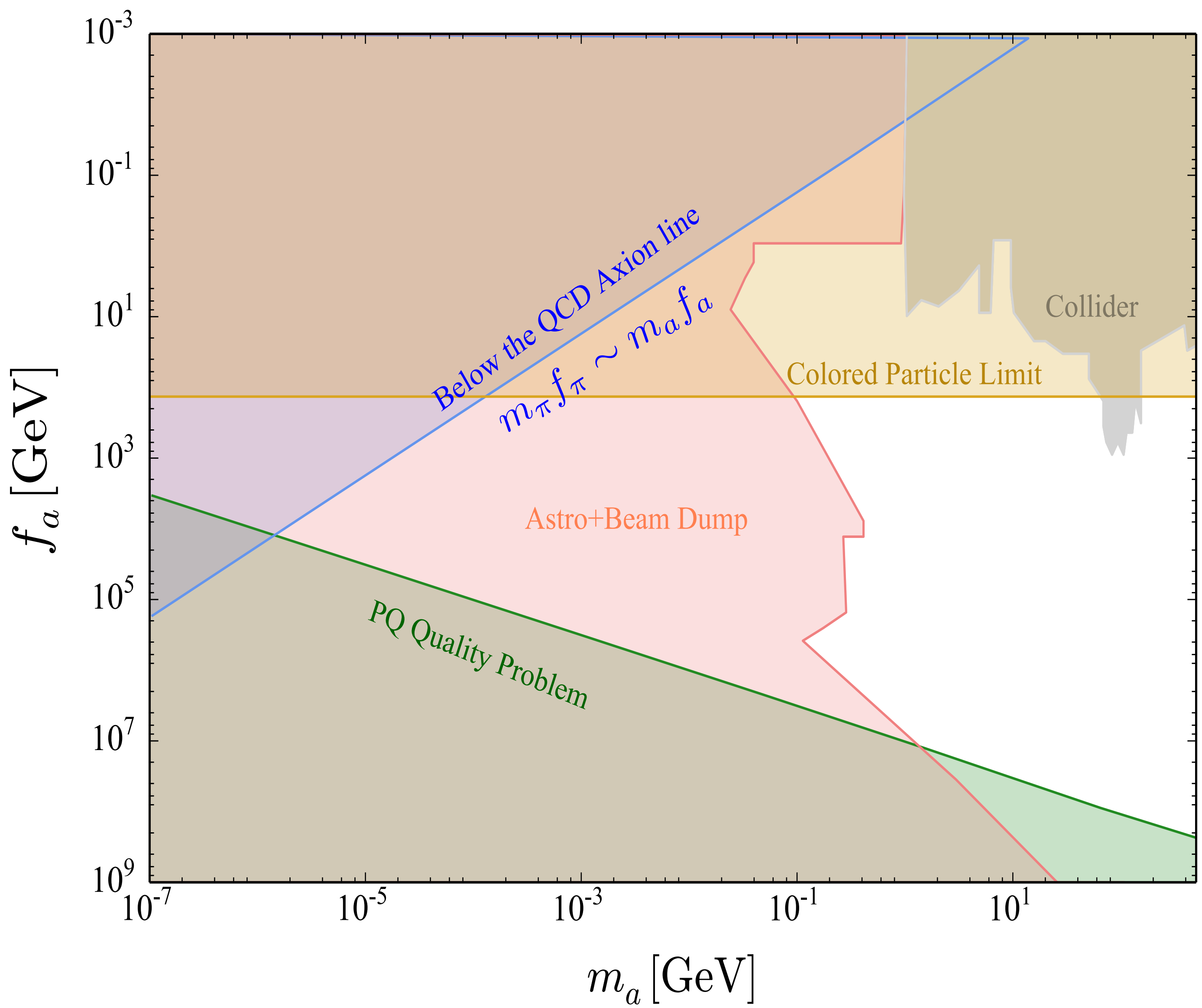


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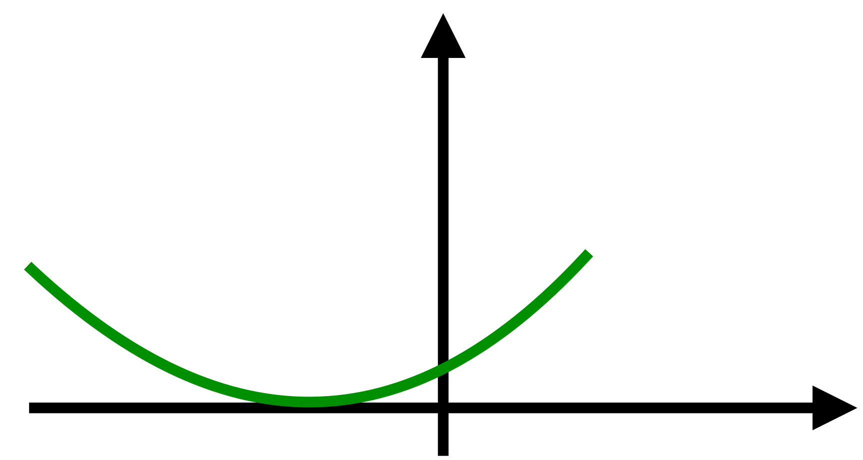

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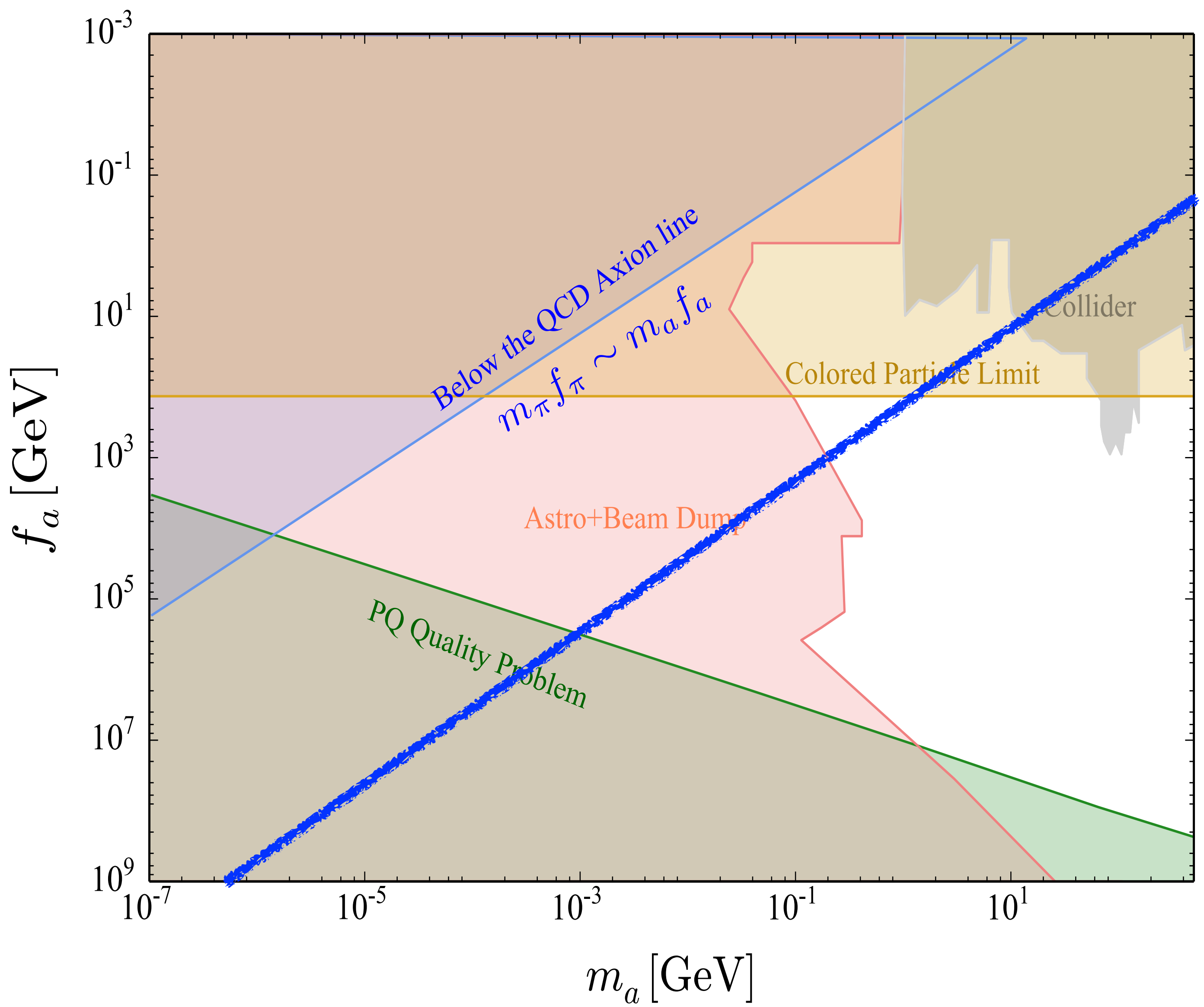


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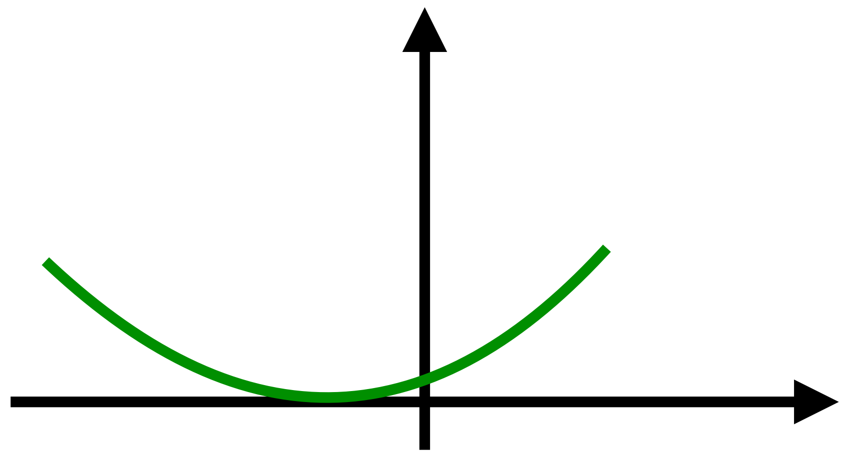

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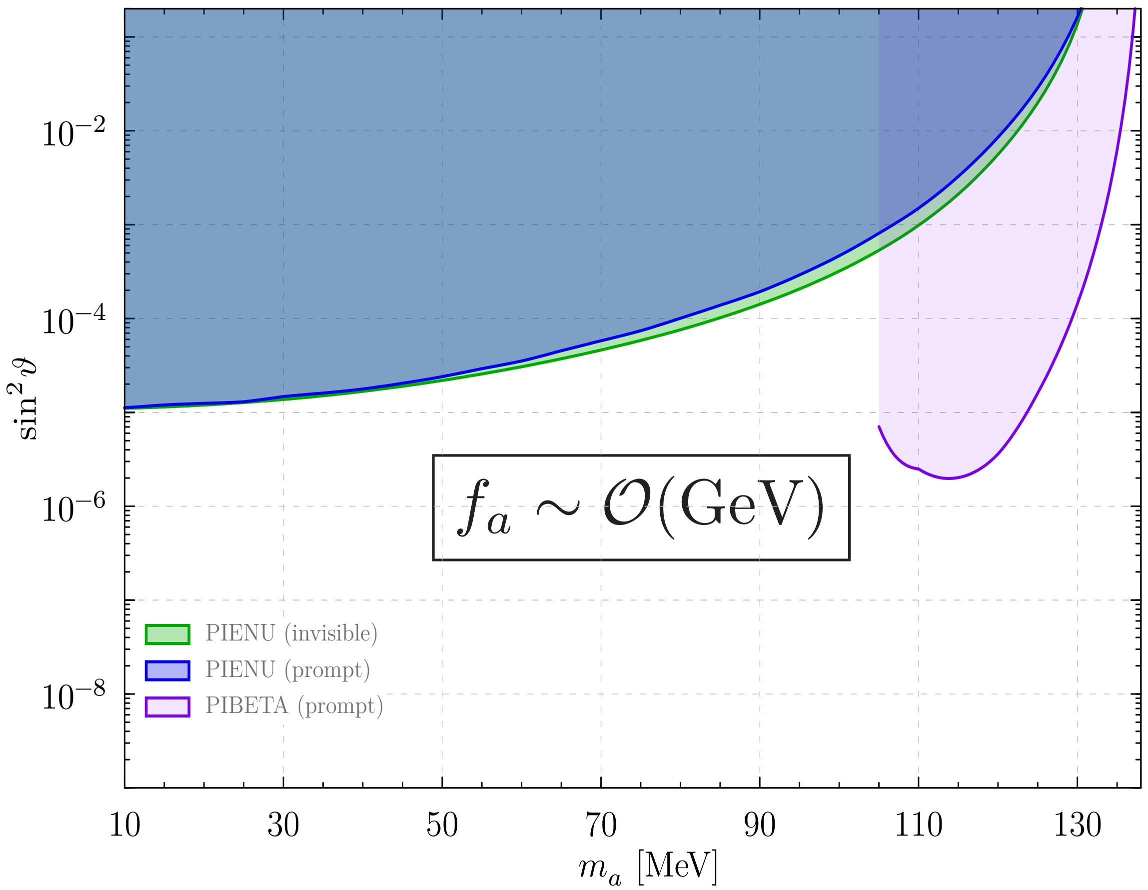
# Intensity Frontier: Bounds from Meson decay

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

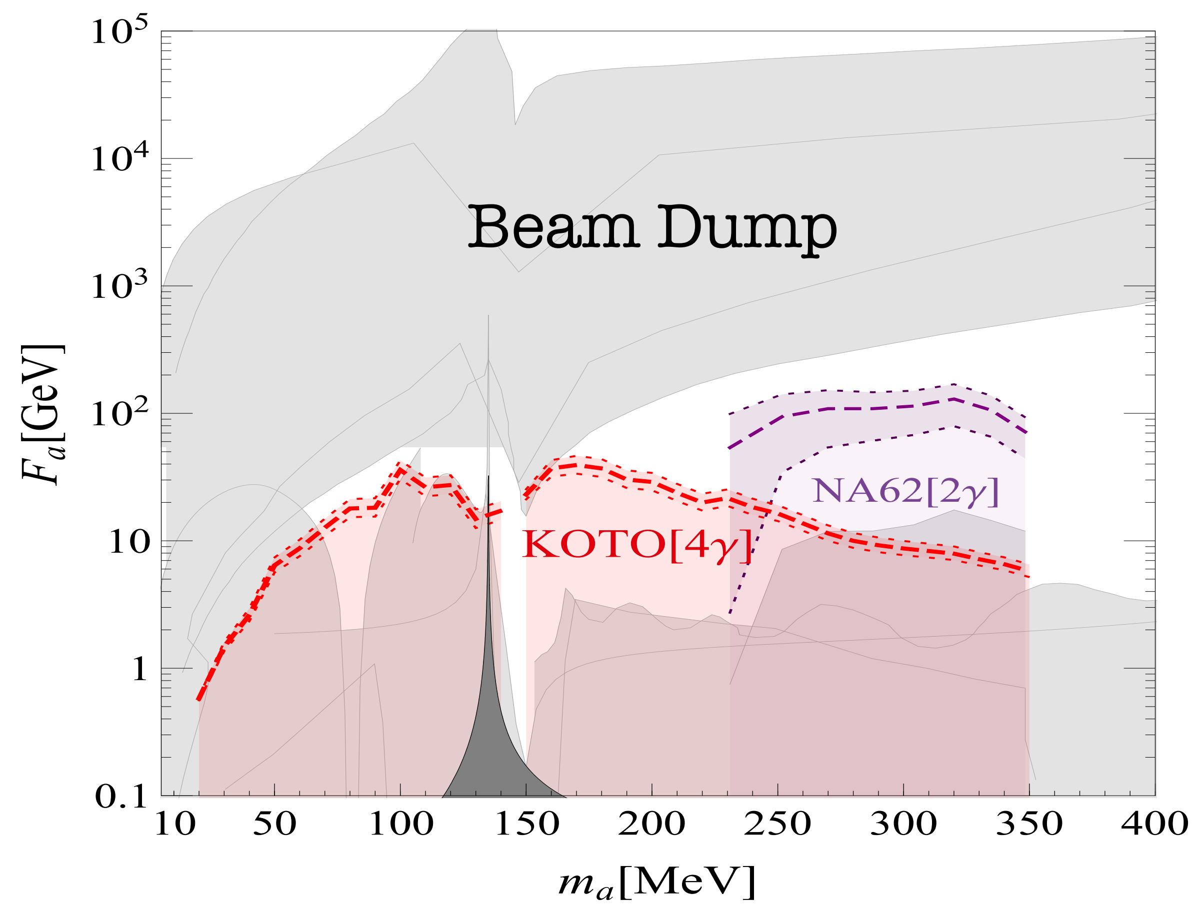
$\pi^+ \to \pi^0\,(a)\,e^+\nu$

Altmannshofer, Gori, Robinson 1909.00005




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

Gori, Perez, Tobioka 2005.05170




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

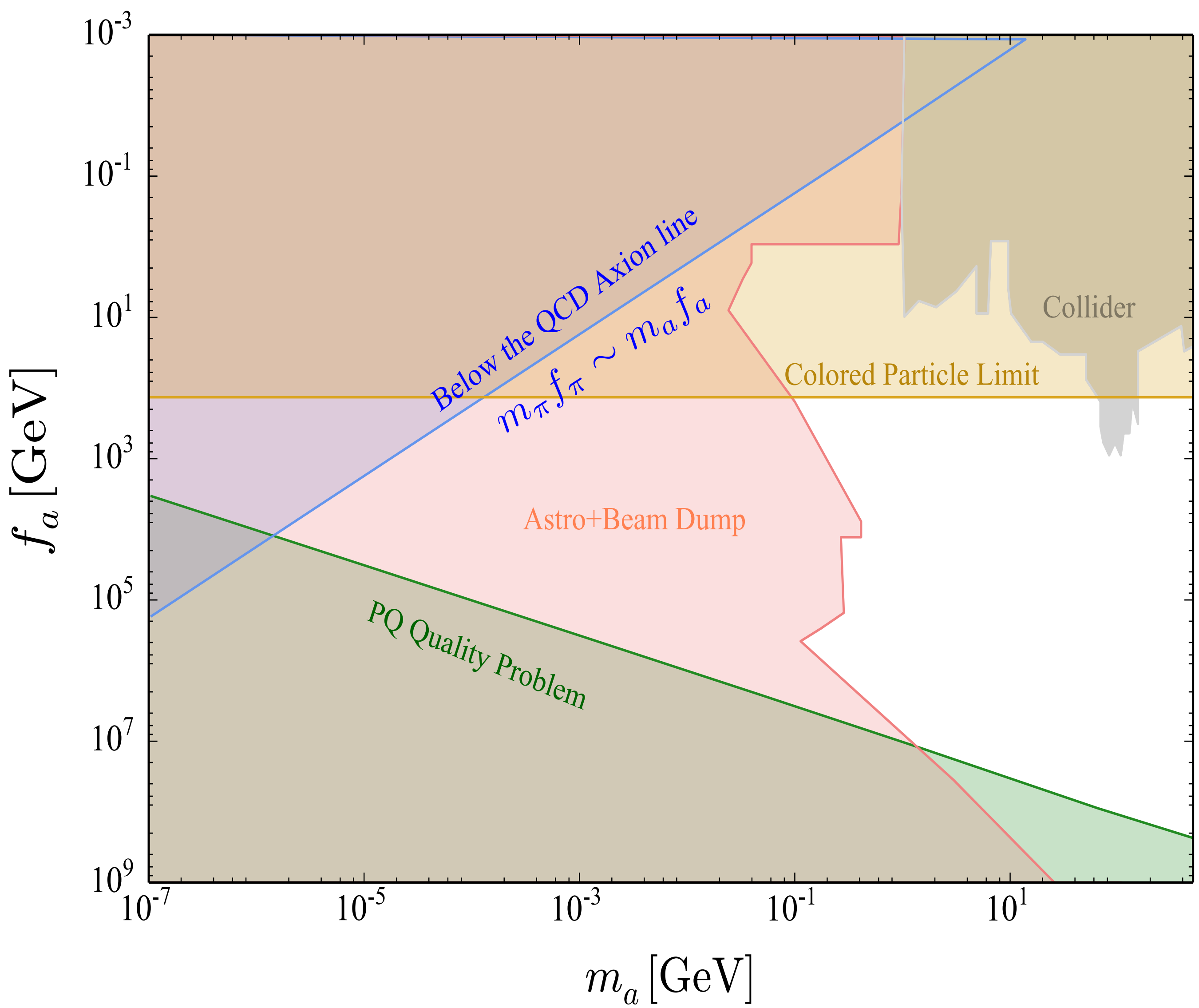
**PIENU Exp.** $\mathrm{Br}\left[\pi^+ \to e\nu\right] \sim 10^{-4}$

Indirect Probes: Triparno, Subhajit, Tuhin 2022

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

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

# MeV-GeV region open! Technically Challenging




- Infinite number of operators beyond LO

$$\left(\frac{\partial}{\Lambda}\right)^n \; : \Lambda \sim 4\pi f_\pi \sim 1 \text{ GeV}$$

- Breaks down for momentum for p>1 GeV

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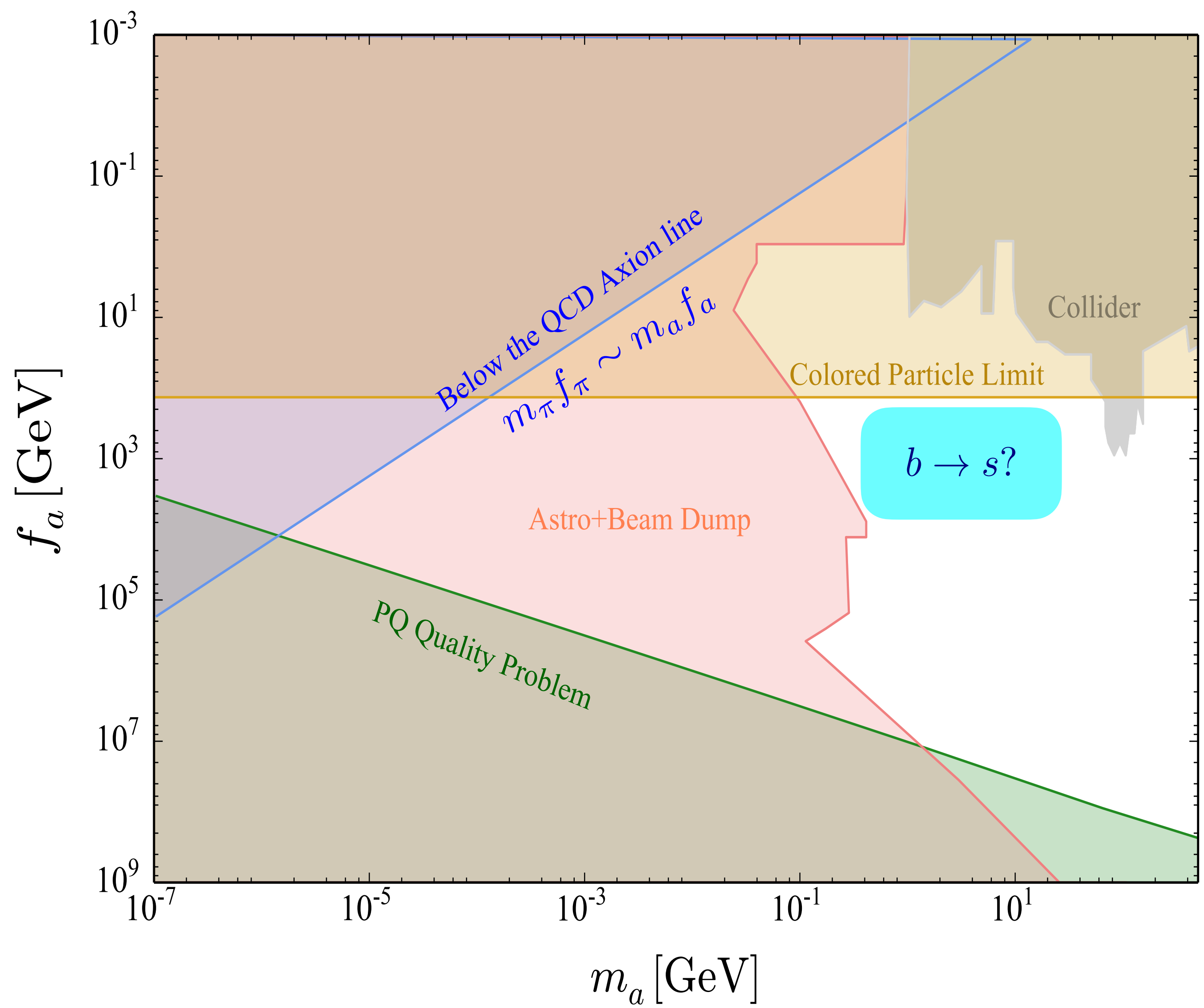


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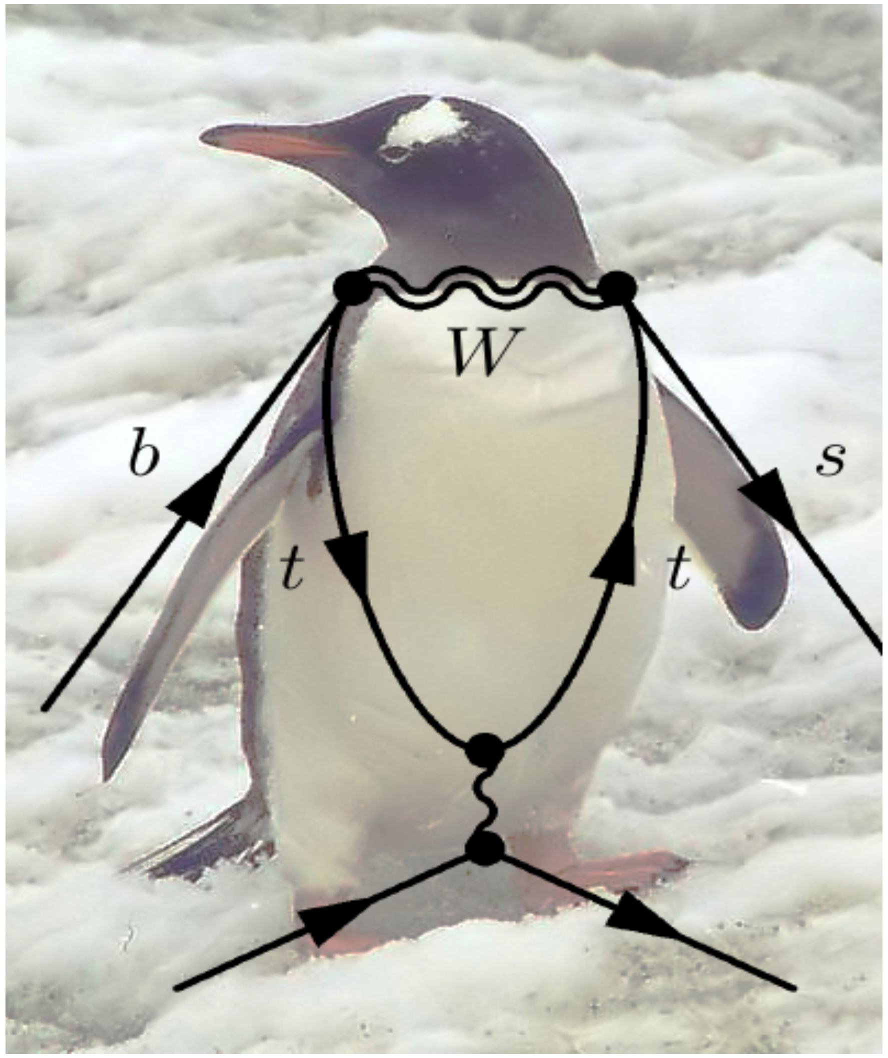
# MeV-GeV region

SC et. Al. 2021

- MeV-GeV range, b->s transition is the relevant process!




Wikipedia

- Our Starting Point:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{m_a^2}{2} a^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{\mu\nu a}$$

$$\mathcal{C}_W\left(M_W\right)\frac{\partial_\mu a}{f_a}\bar{s}_L\gamma^\mu\gamma_5 b_L + \text{h.c.}$$

Matching Operator

- Need to know what else gets generated

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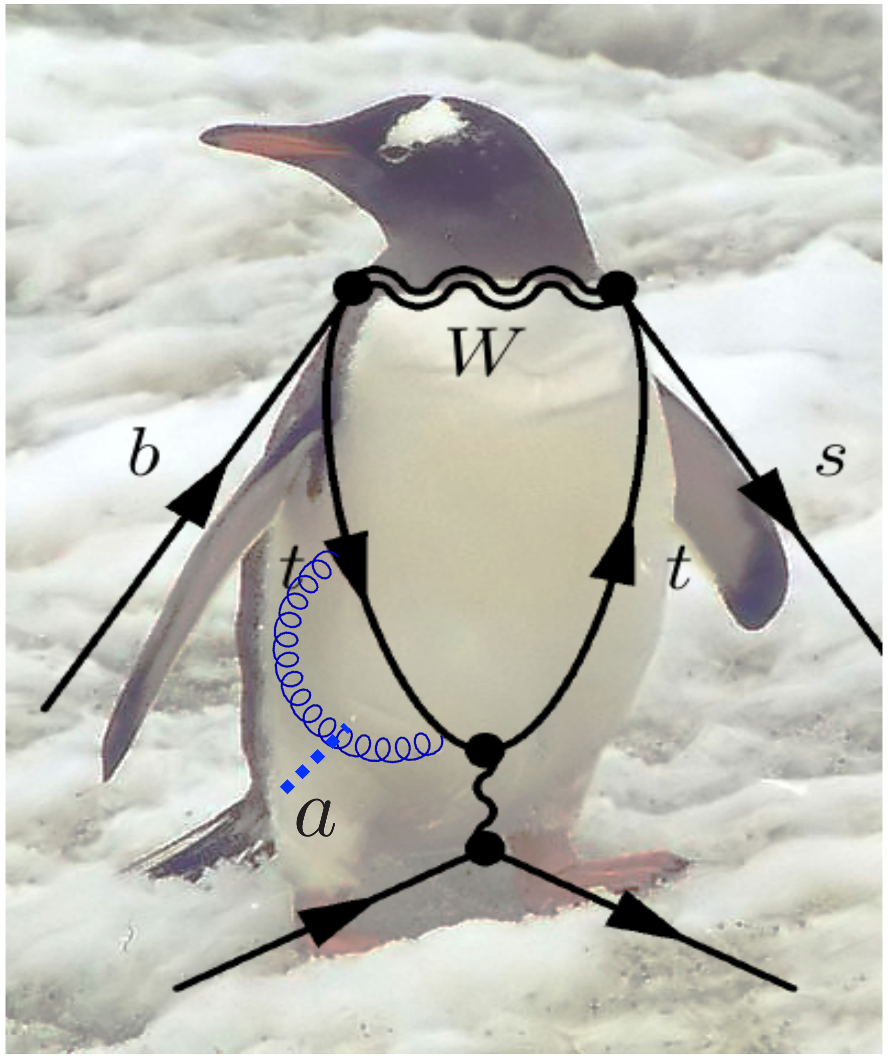


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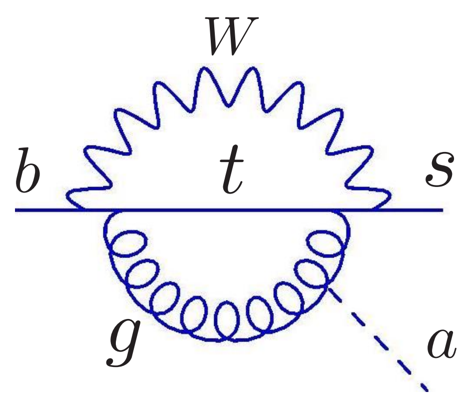
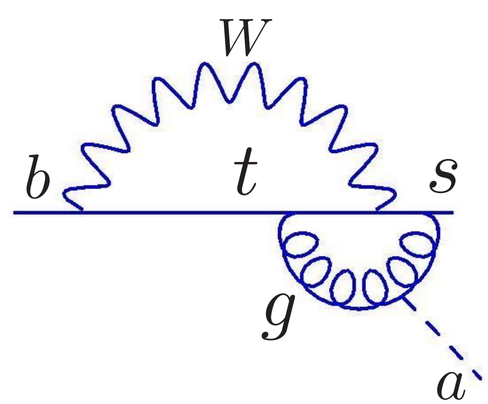
# Counterterms => Operators

SC et. Al. 2021

- Two Loop Diagrams:

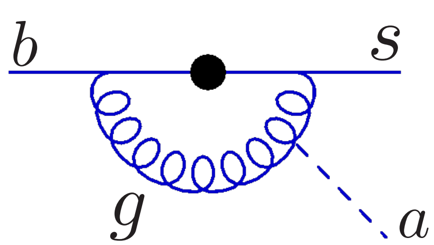


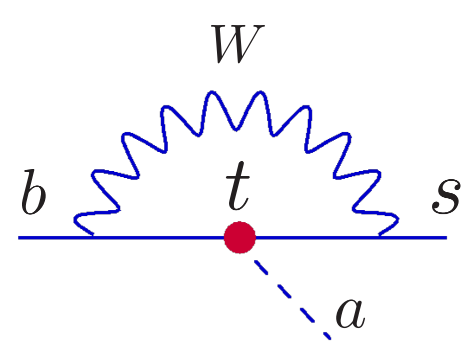




....

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

- Counterterms:



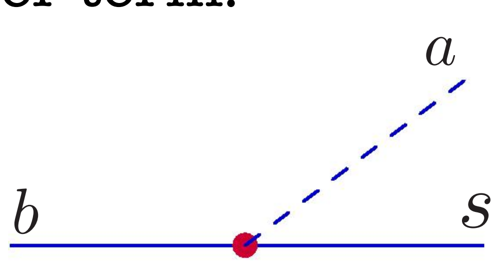




....

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

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

# Running and Matching

SC et. Al. 2021

$\Lambda_{\mathrm{UV}}$ — **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** ↓

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

$M_W$ —

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

$$C_W=\underbrace{C_{bs}}_{C_1}+\underbrace{\frac{\alpha_w}{4\pi}g\left(\mu_w\right)C_{qq}}_{C_2}+\underbrace{\frac{1}{2}\frac{\alpha_w}{4\pi}\left(\frac{\alpha_s}{4\pi}\right)^2 f\left(\mu_w\right)}_{C_3}$$

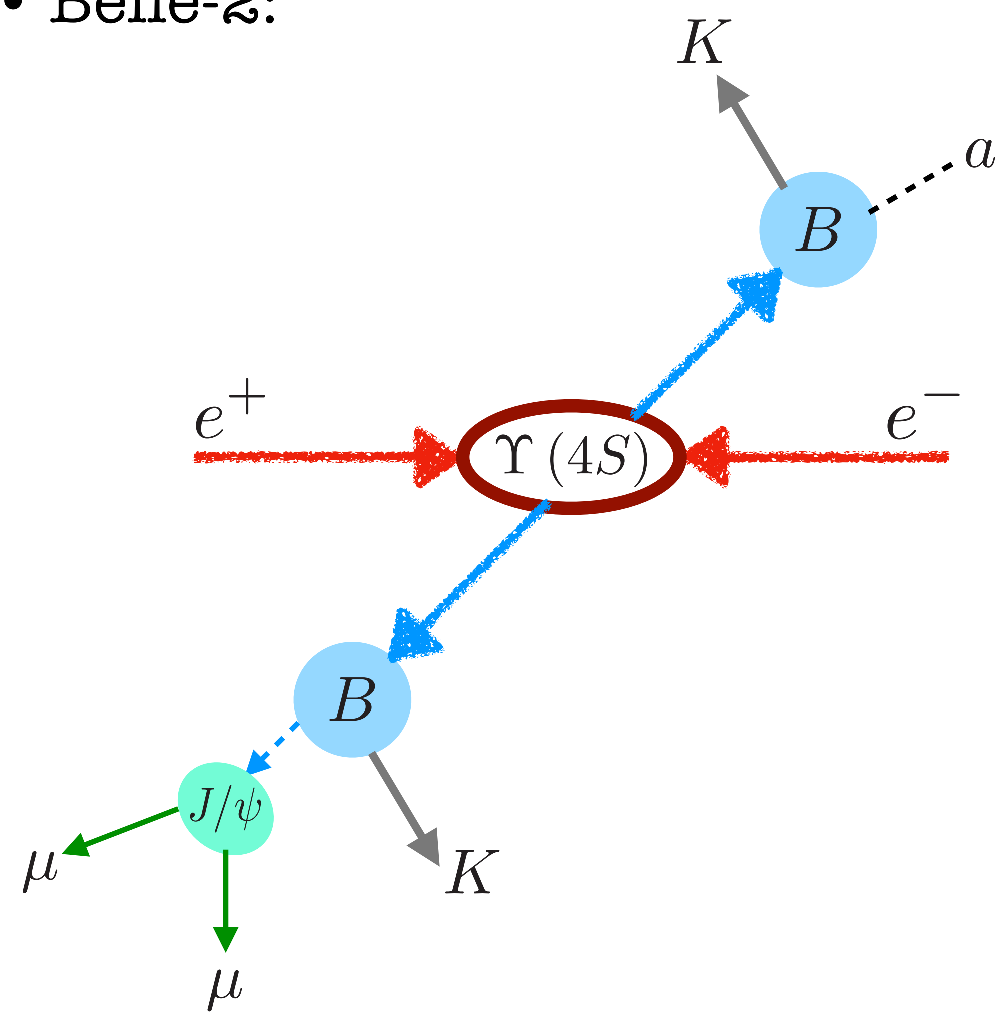
**Using RGEs** ↓

$m_b$ — **Experimental Data**

$B\to Ka$

# Axions: Experimental Searches

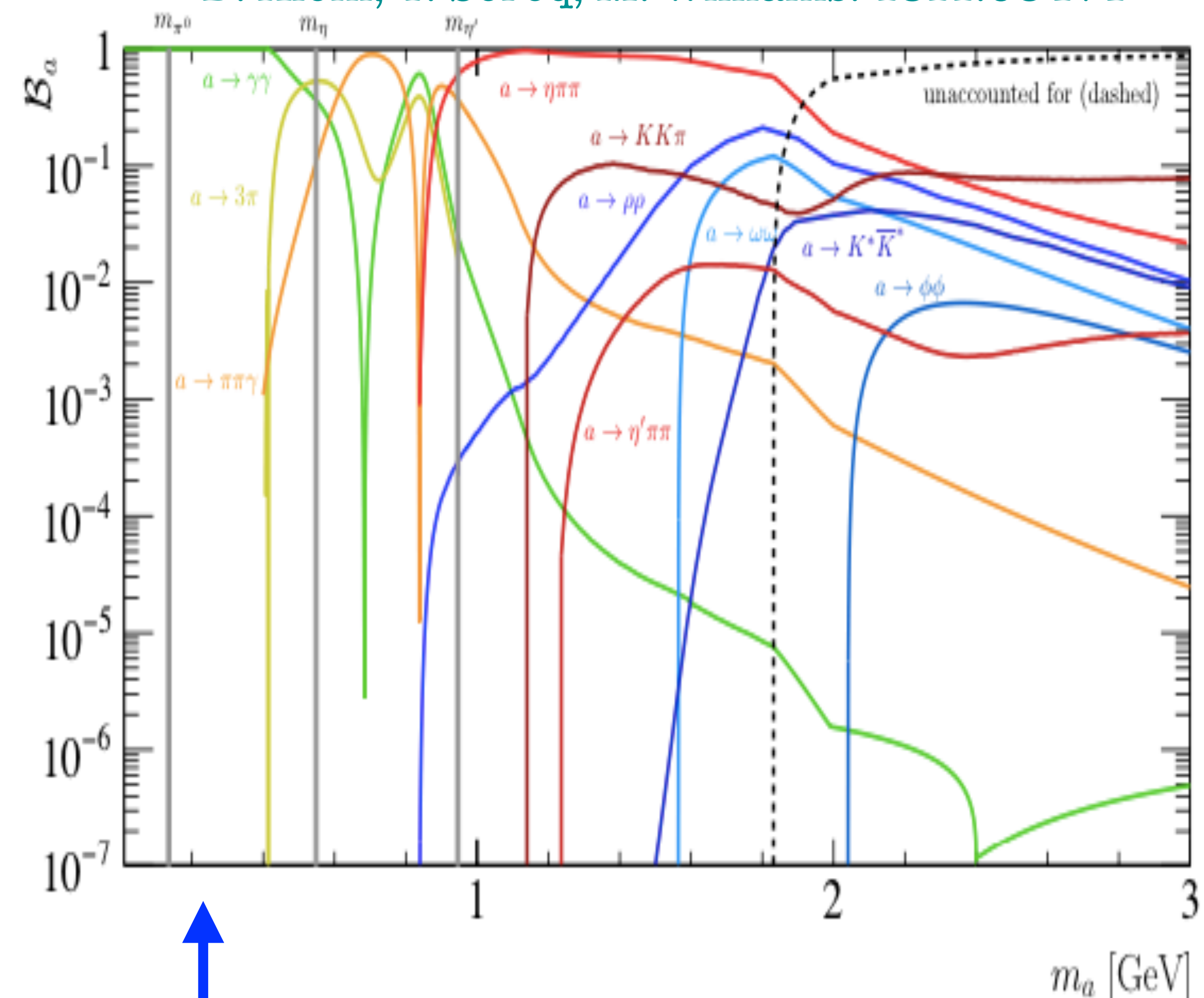
- Belle-2:




Belle Experiment

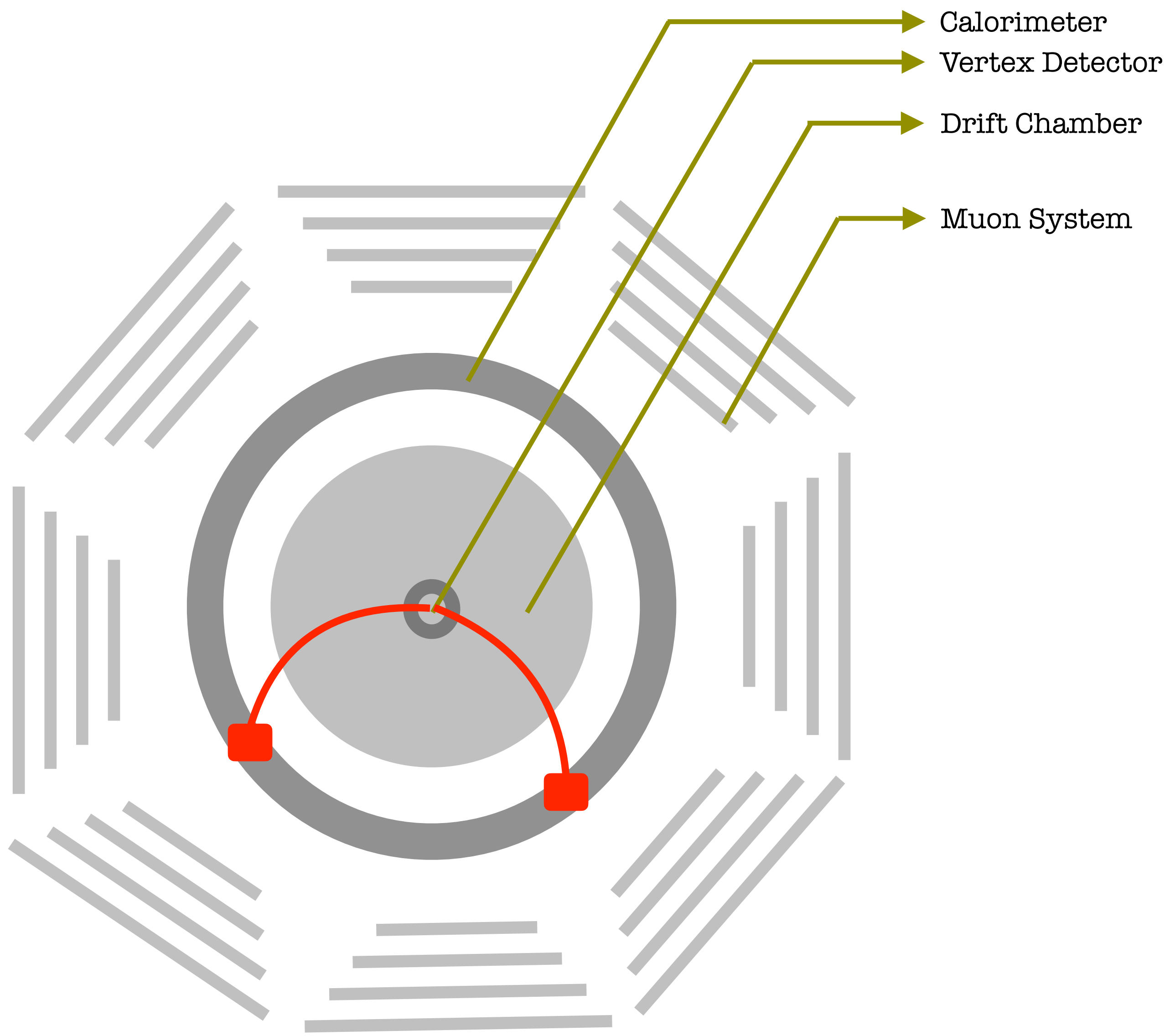
$a \to (\eta\pi\pi\ , KK\pi\ , 3\pi\ , \phi\phi)$

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




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

# Belle Detector




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

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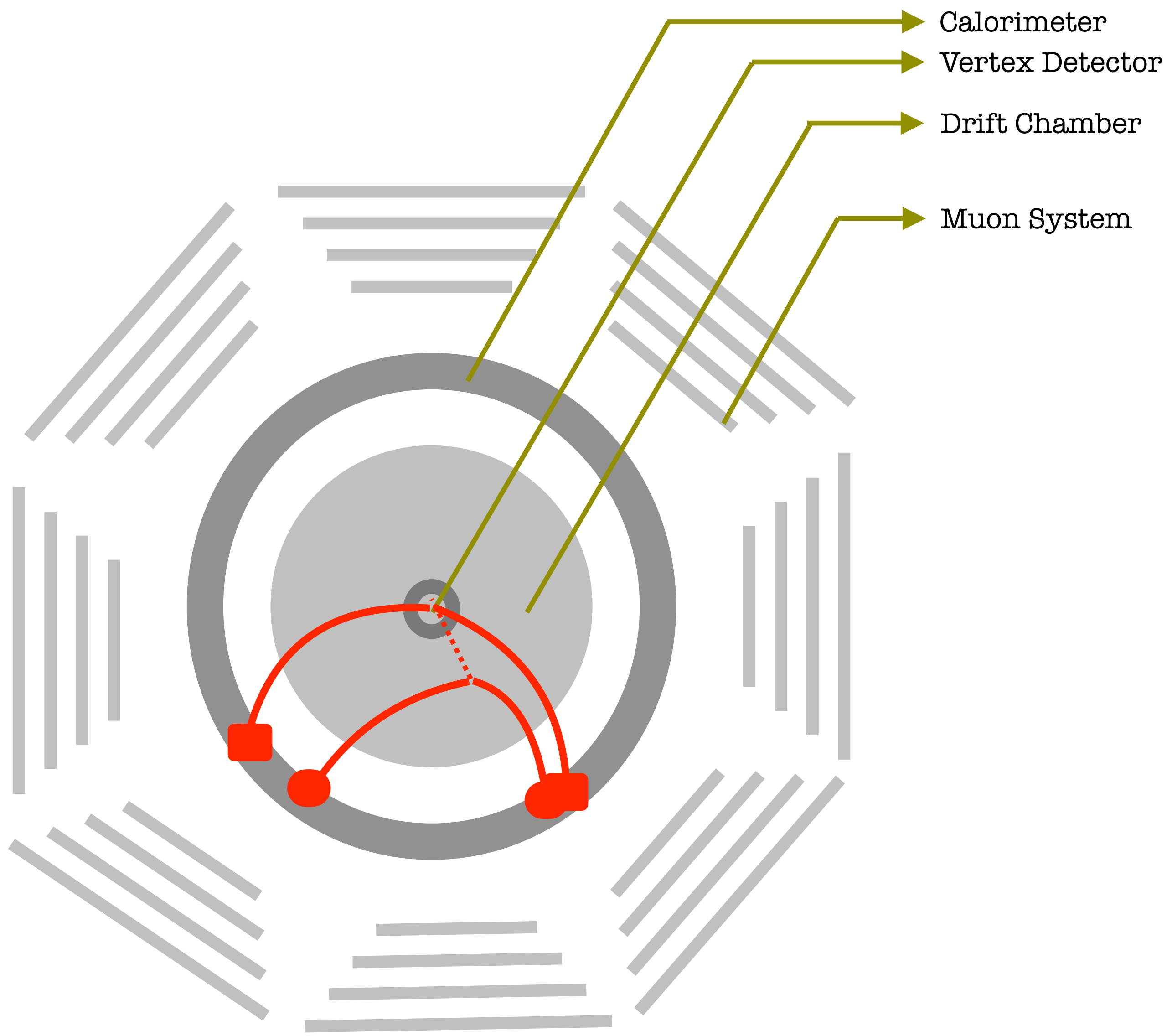


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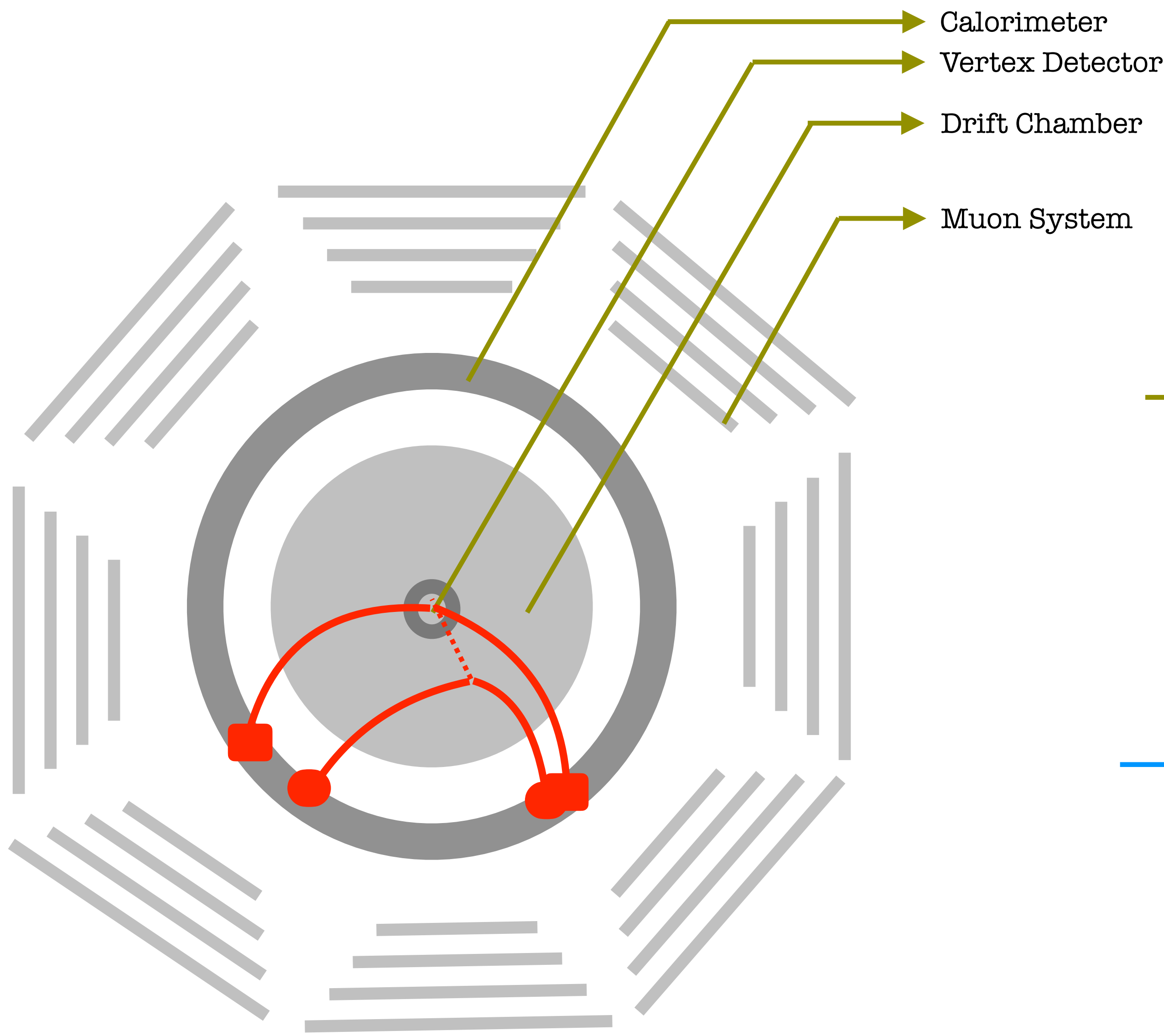


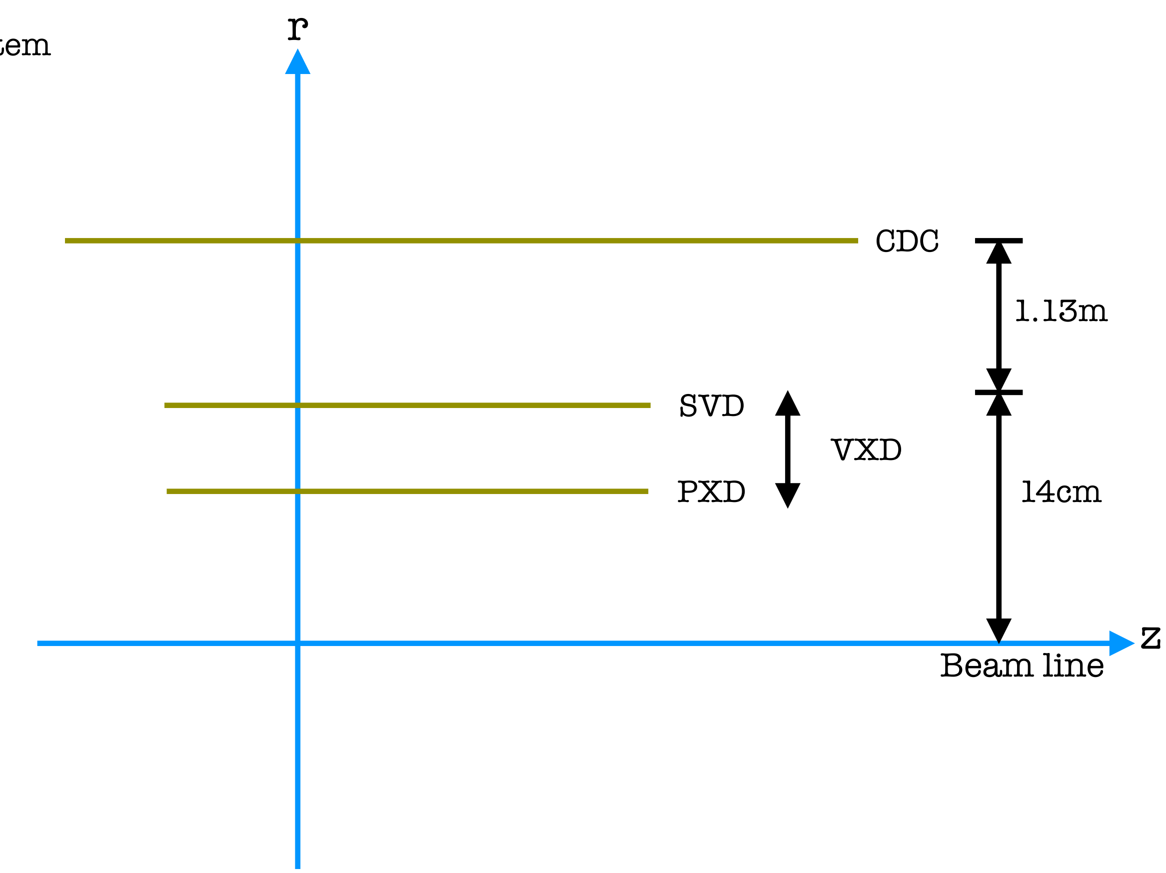


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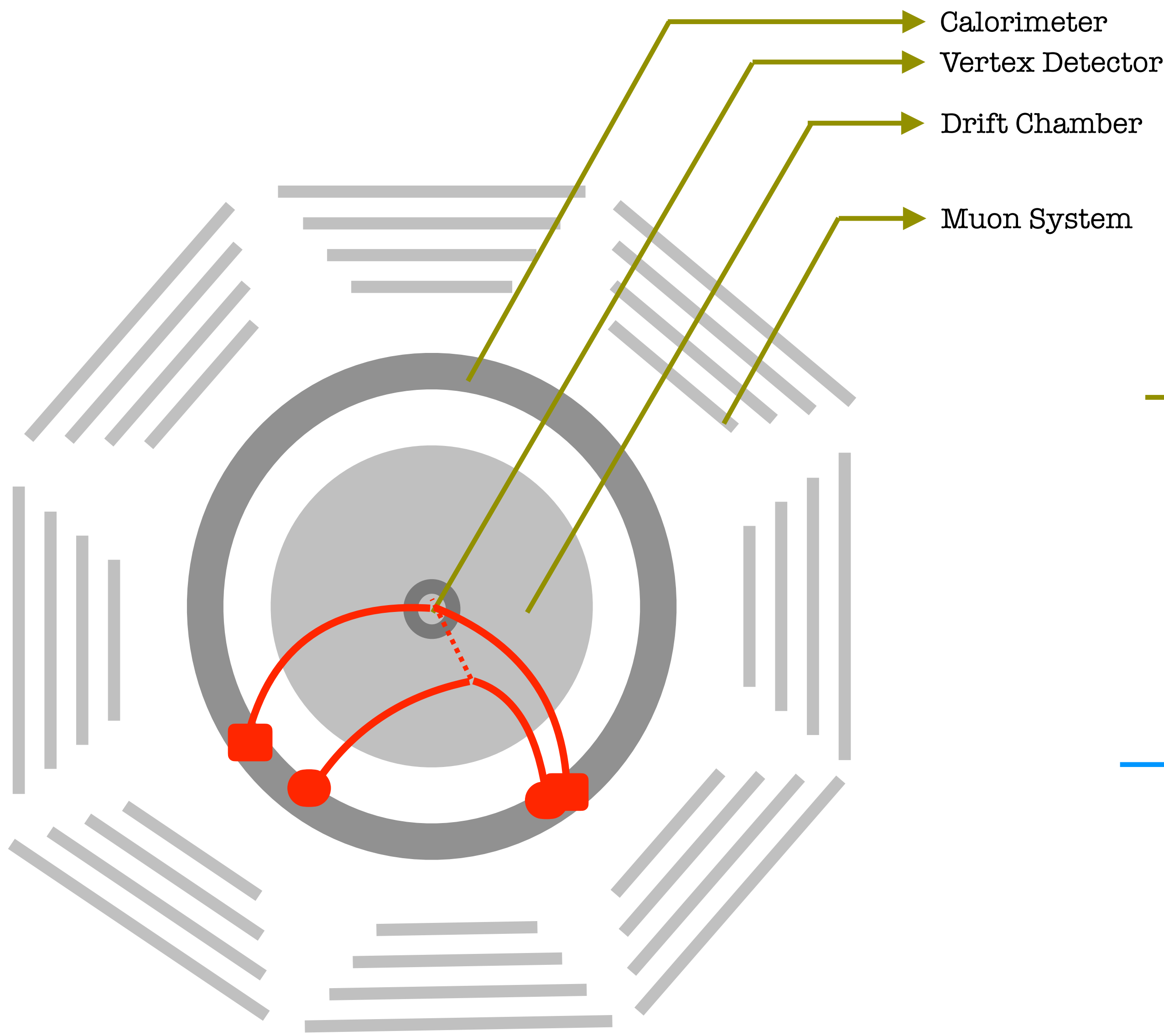


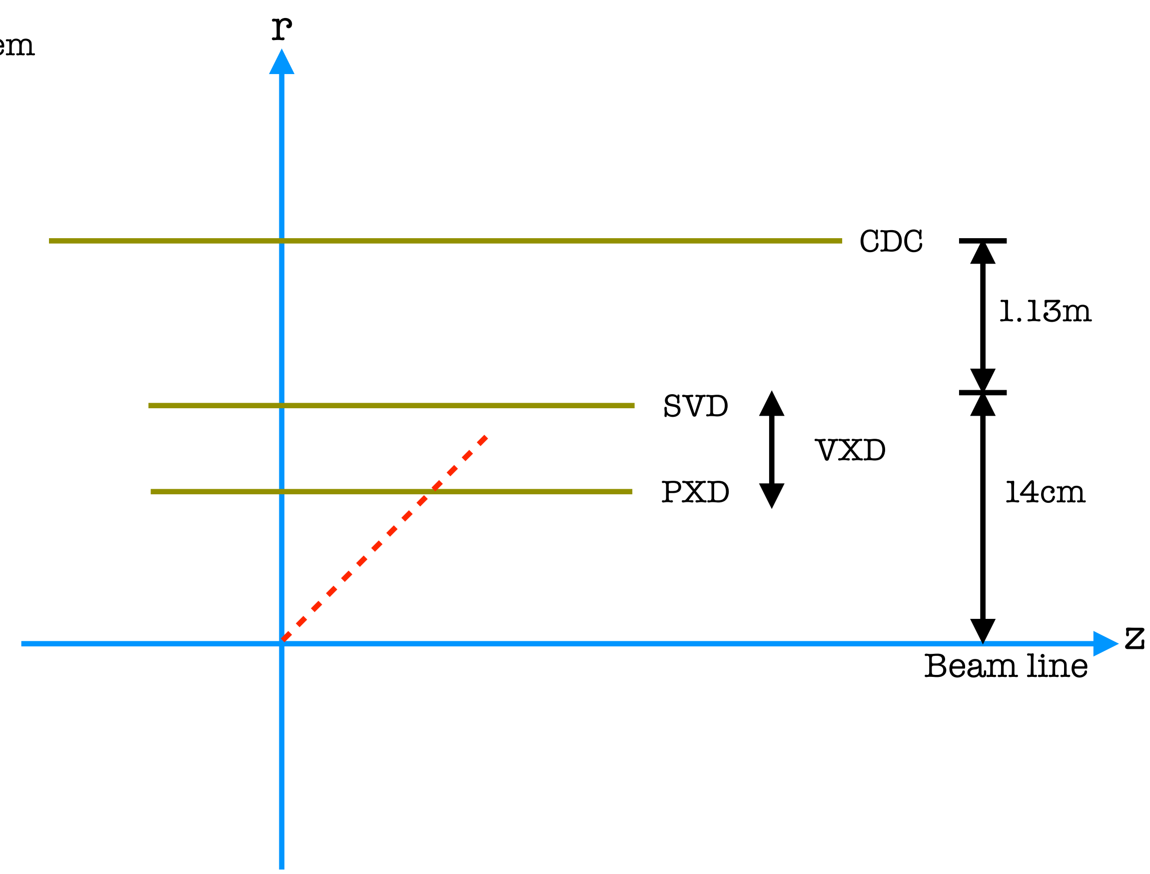


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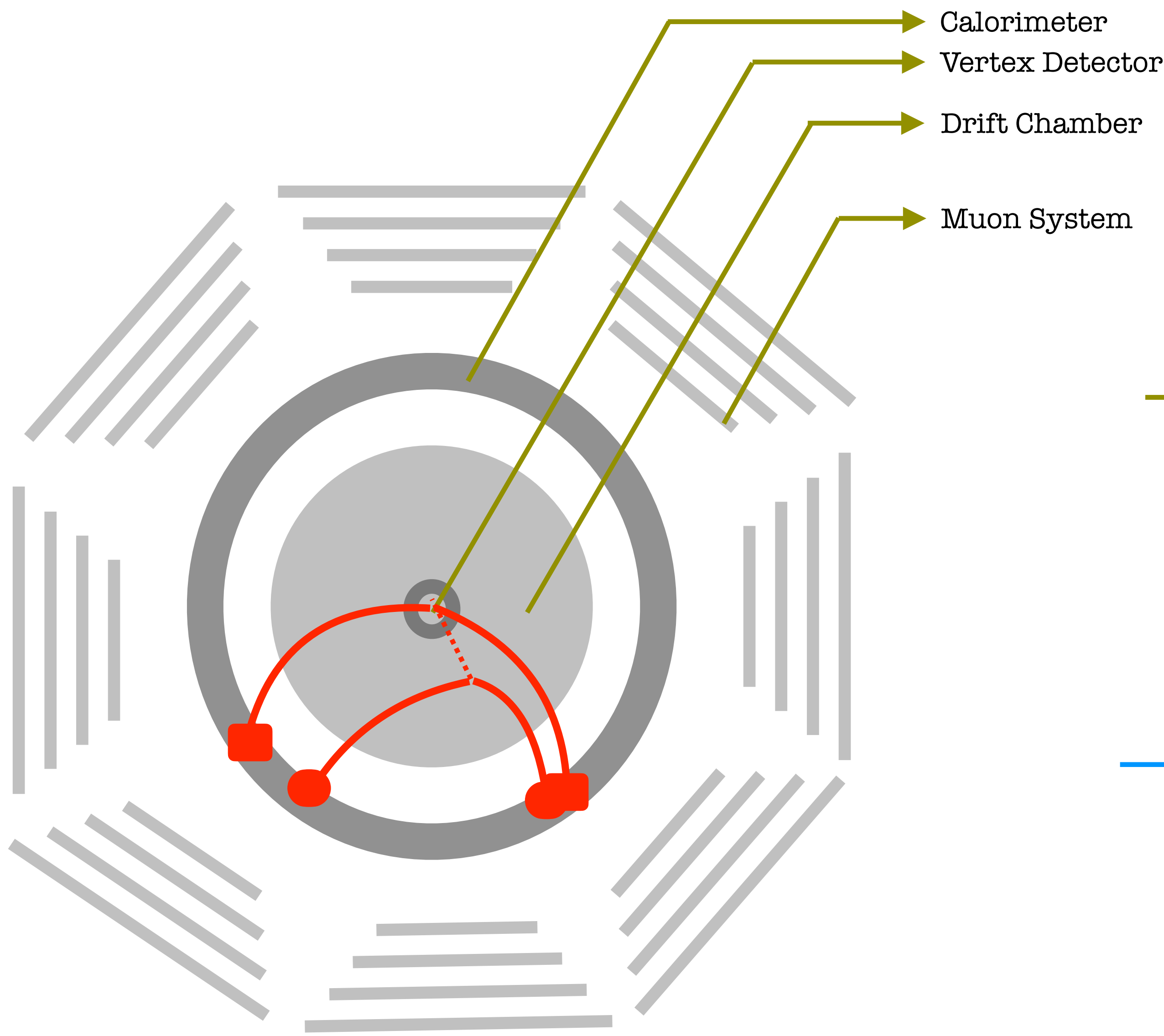


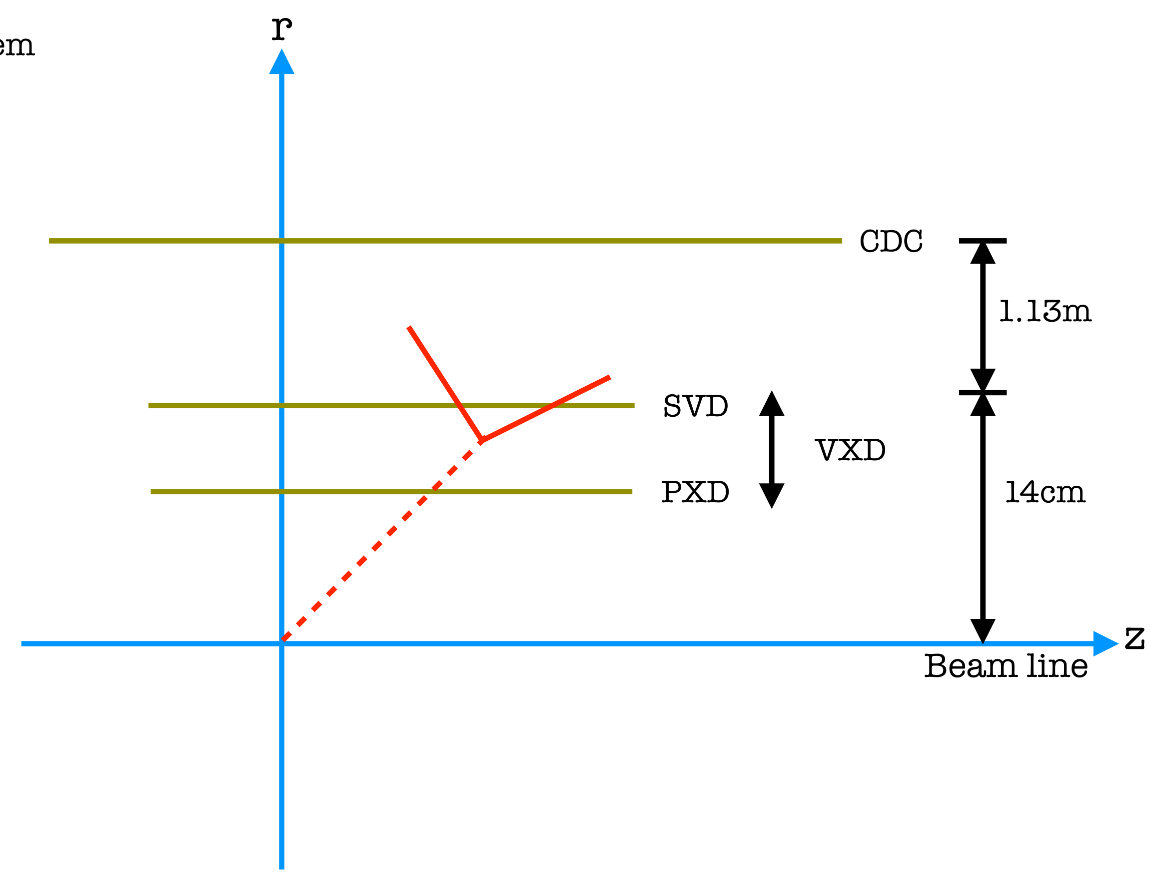


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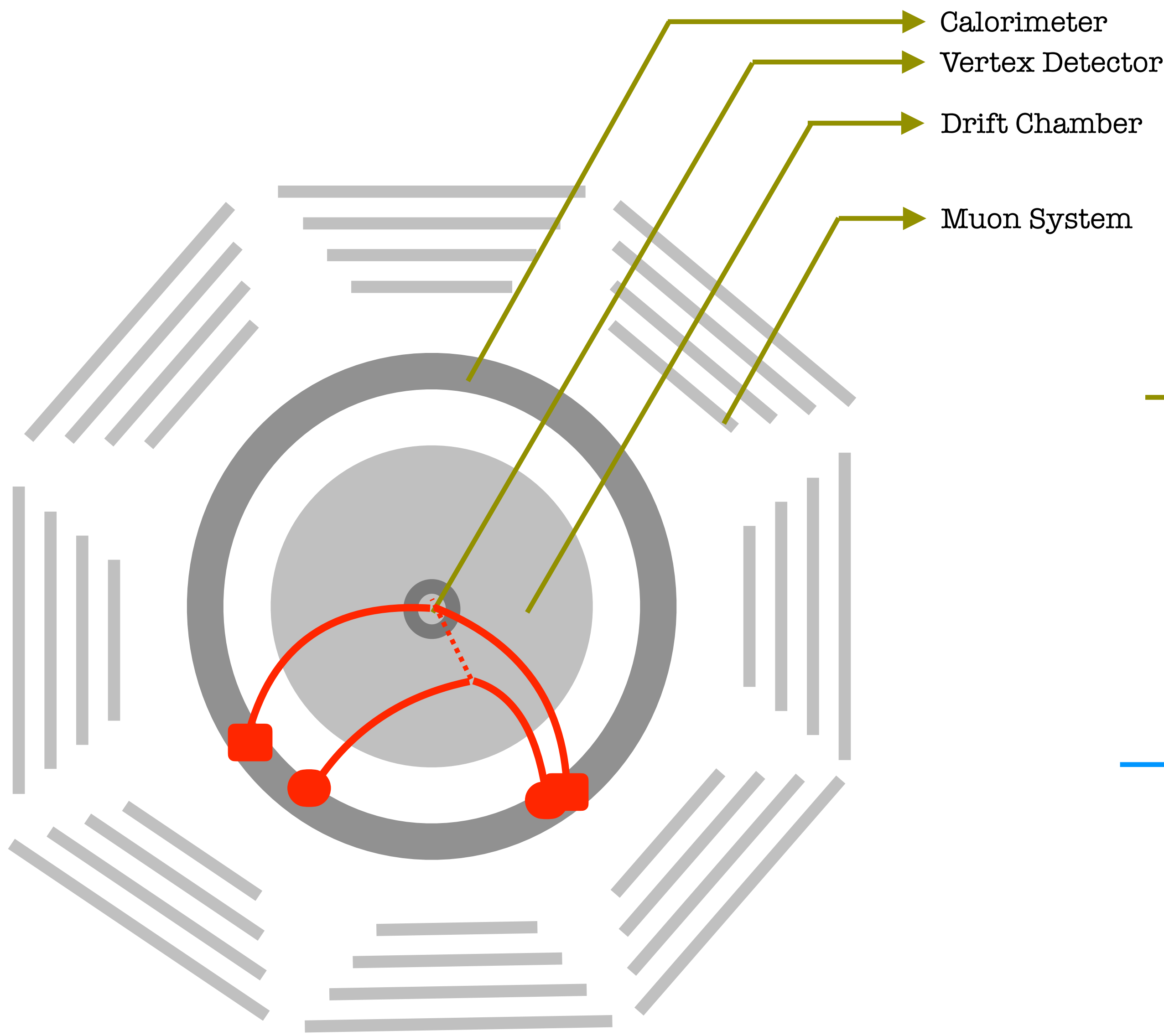


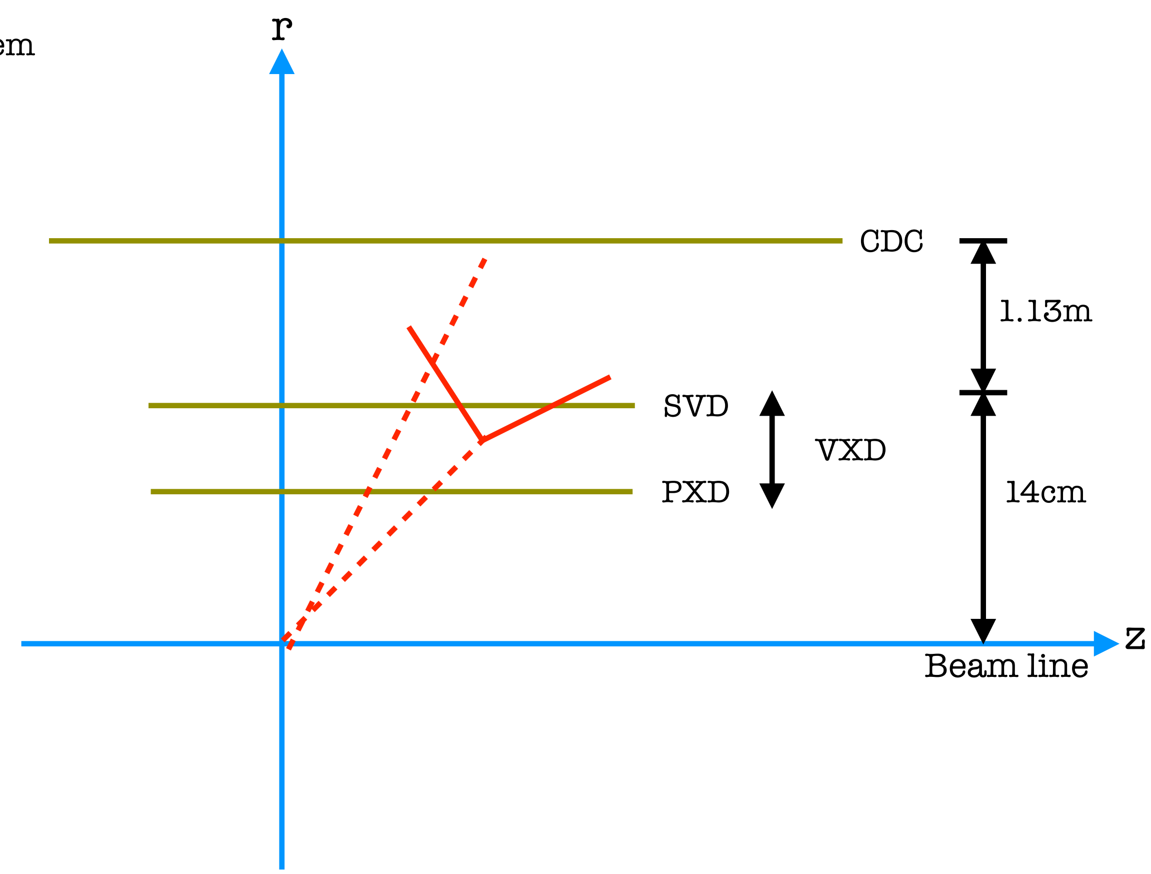


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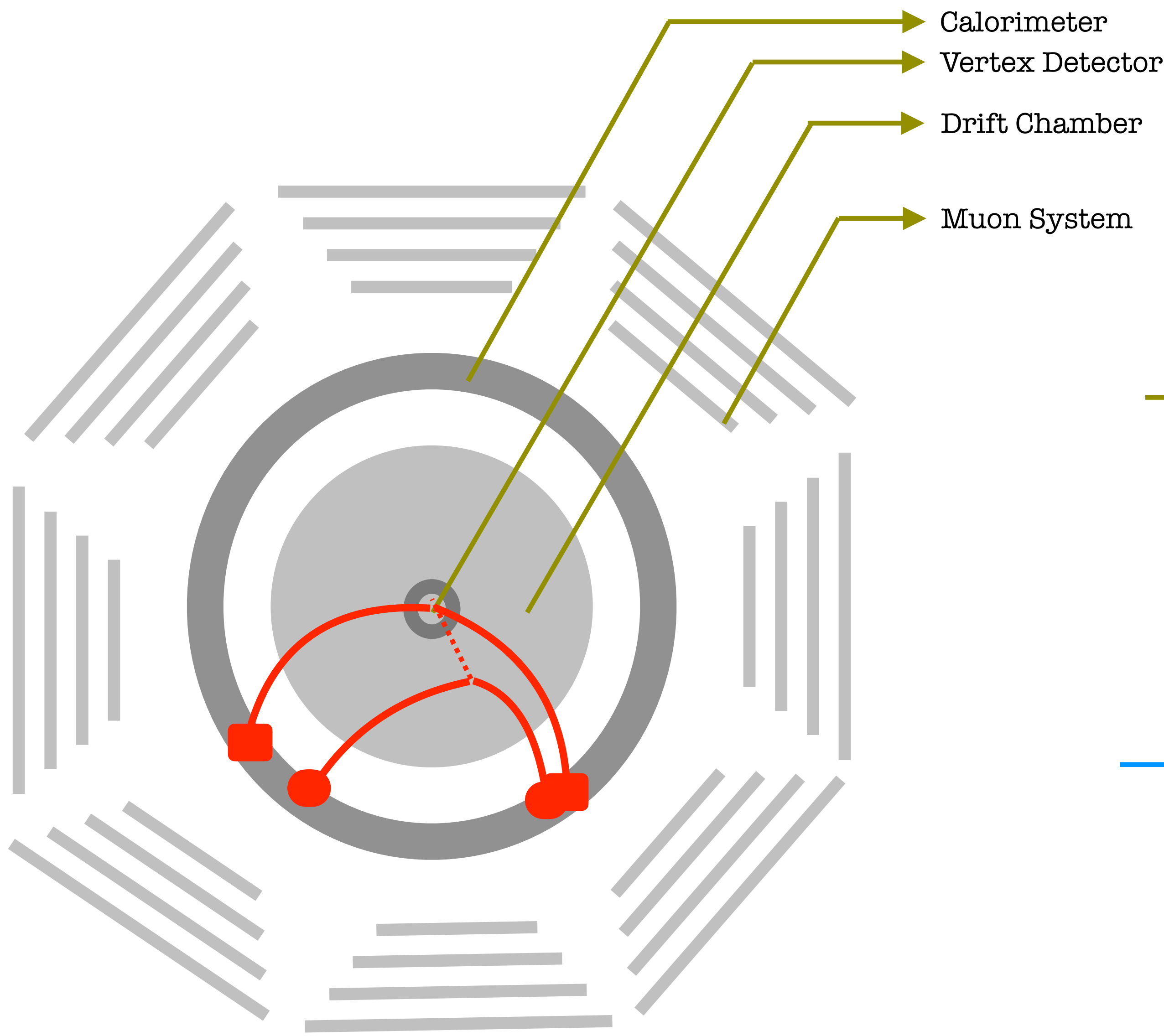


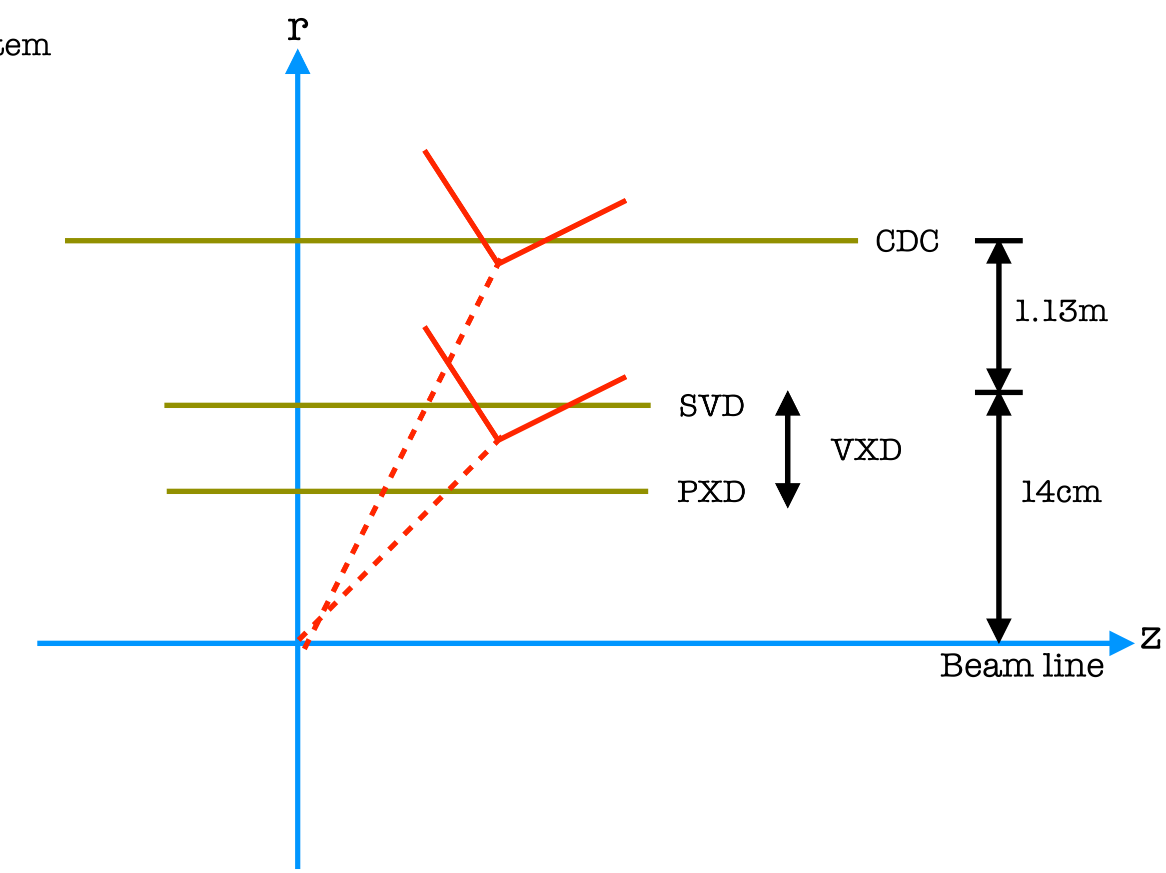


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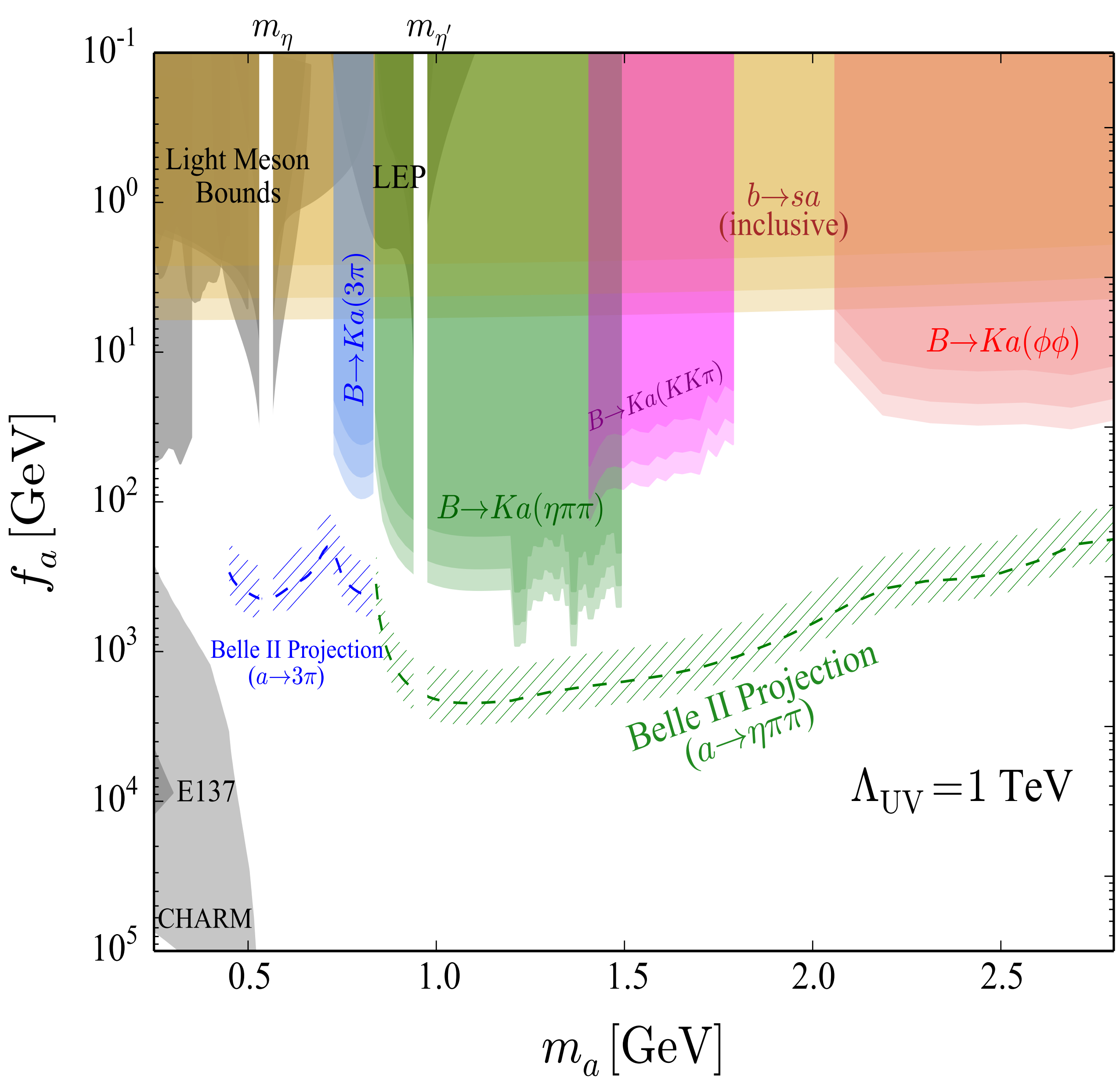
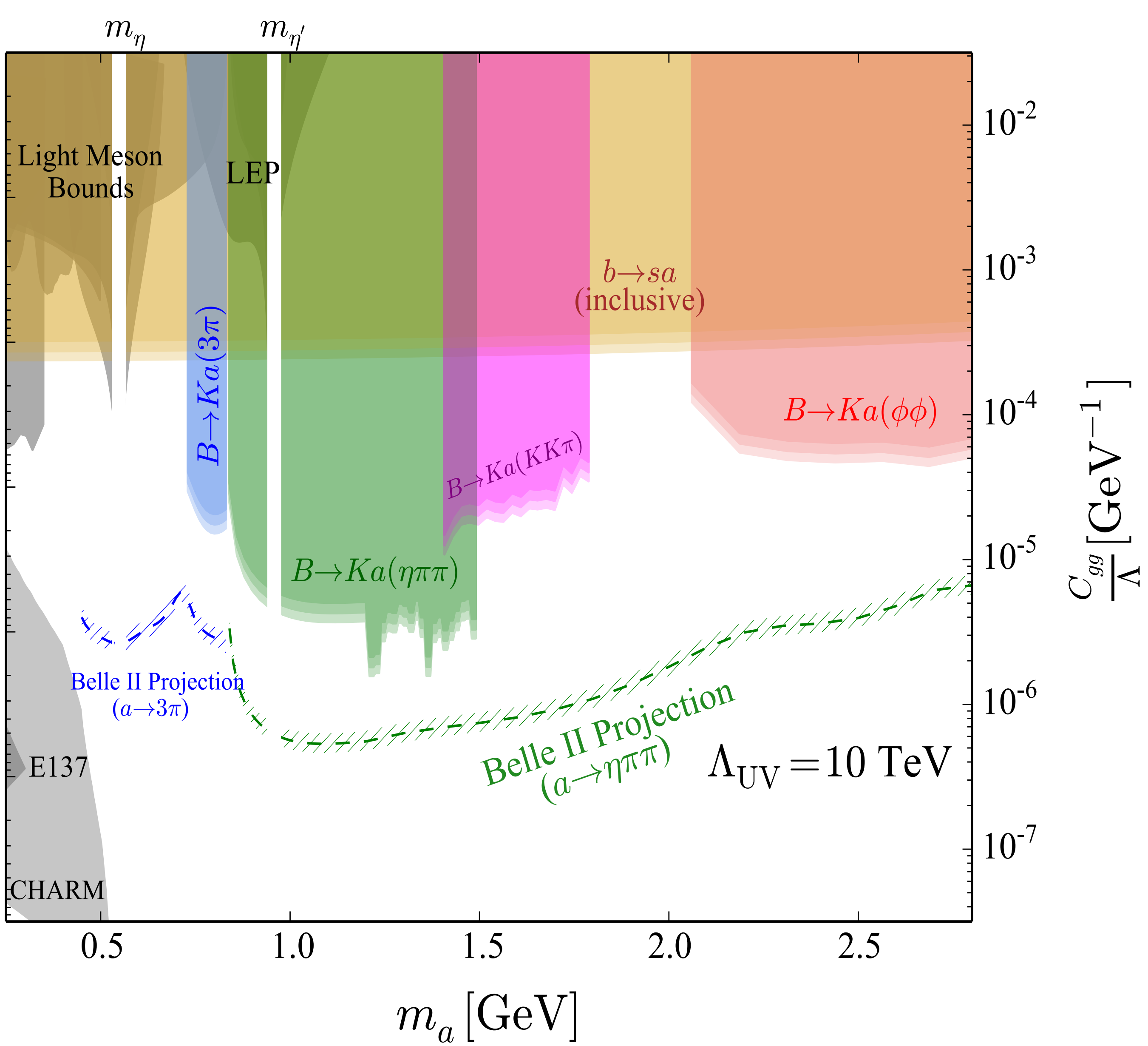
# Prompt Searches

SC et. Al. 2021



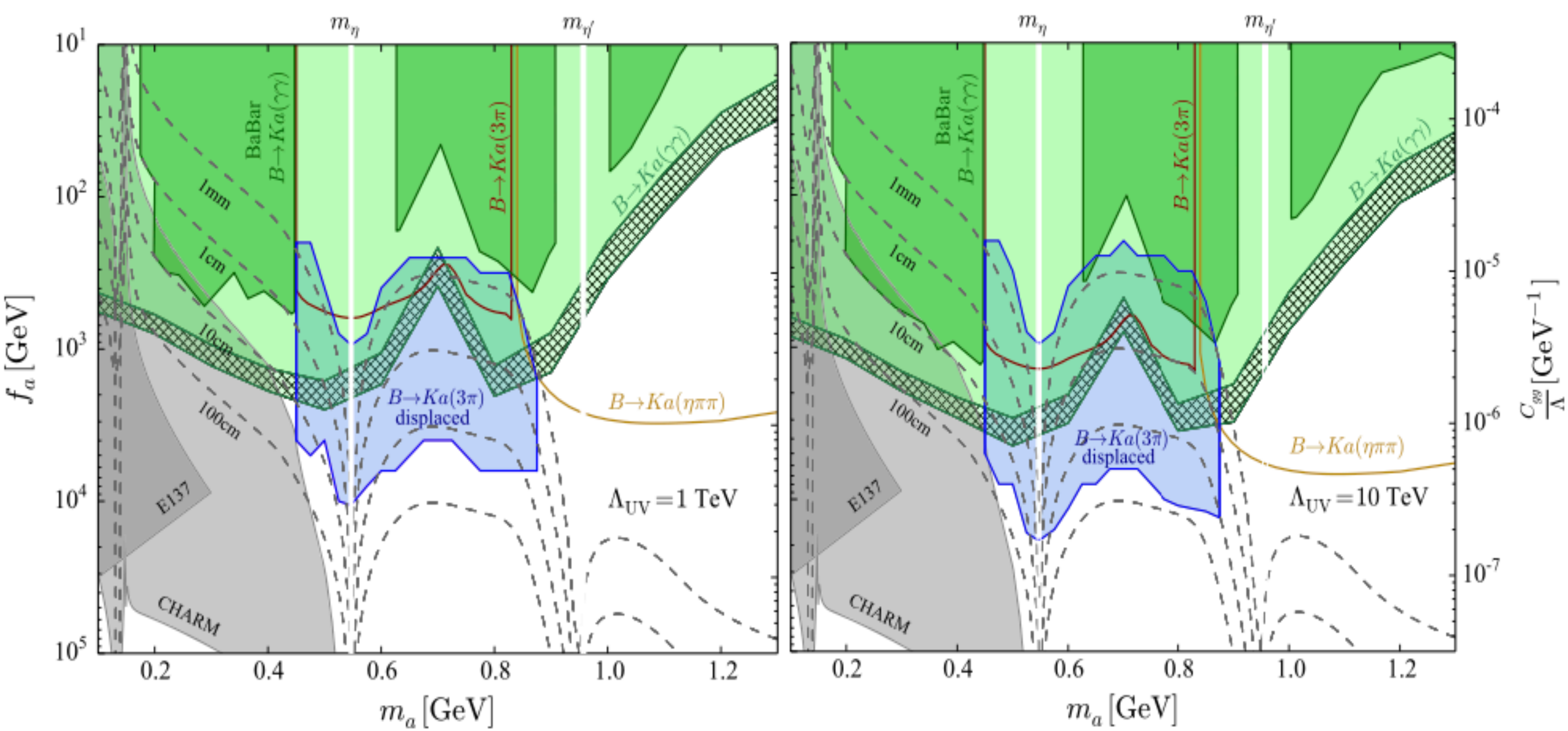

$\Lambda_{UV} = 1$ TeV




$\Lambda_{UV} = 10$ TeV

# Displaced Searches

SC et. Al. 2022




$\Lambda_{UV} = 1$ TeV

$\Lambda_{UV} = 10$ TeV

# EFTs with Axions

SC, Tuhin, Namit ongoing

- MeV-GeV range, EFTs are hard, Heavy Light Mixing
- Before axions, can we explain SM processes $B \to K\eta_c$

$$\boxed{\mathcal{L} \supset C_W \partial_\mu \eta_c \, \partial^\mu K \; B}$$

- Can successfully explain $B \to K\,\eta_c$ , $B \to \eta_c X$ , $B \to \eta' \, X$
- Looks promising, Axions?
- Ongoing similar study in the perturbative picture    SC, Atanu, Deepanshu

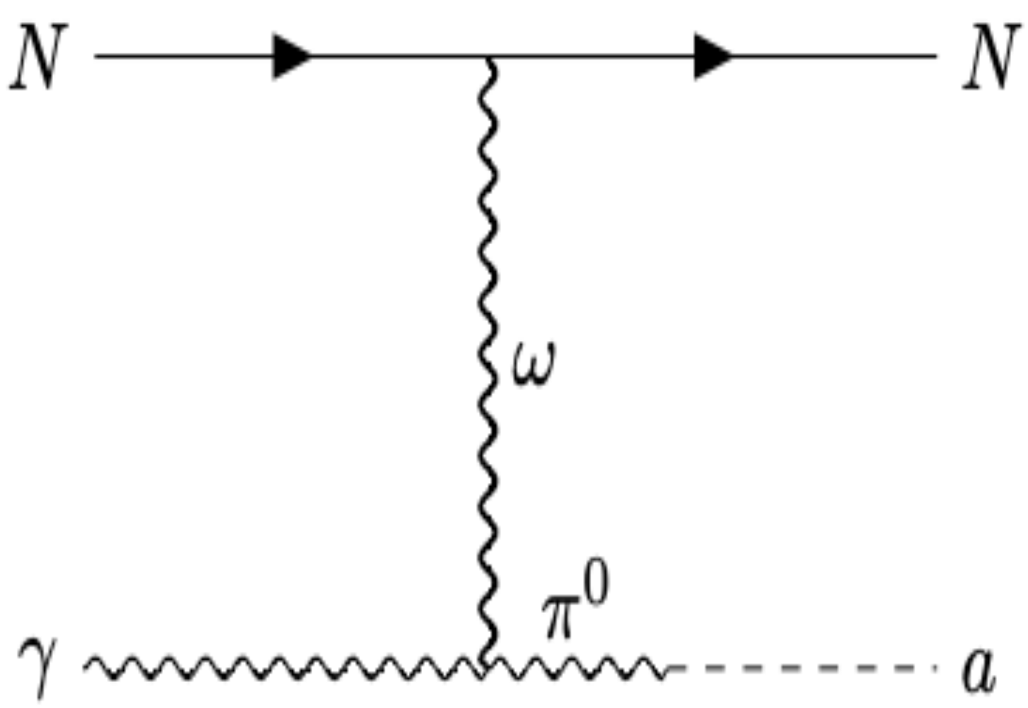
# WZW-Terms?

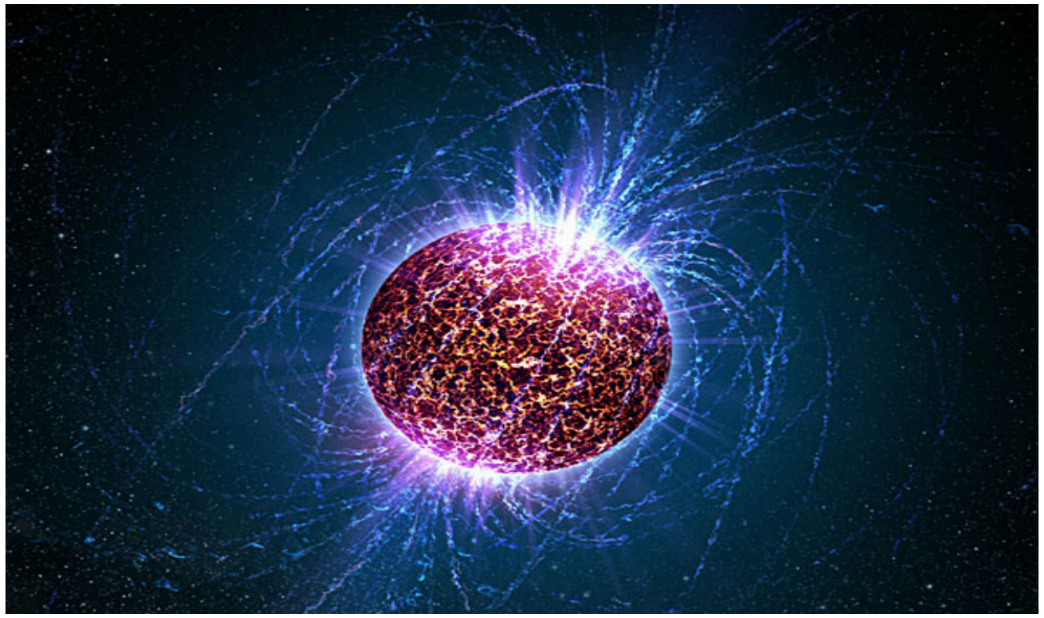
| UV (QCD) | | IR (ChPT) |
|---|---|---|
| $\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + i\bar{\psi} \not{D} \psi_i$ <br> $G = SU(N_f)_L \times SU(N_f)_R$ | $\longrightarrow$ | $\mathcal{L}_{\chi\mathrm{PT}} \supset \frac{f_\pi^2}{8} \mathrm{Tr}\left[D^\mu \Sigma \, D_\mu \Sigma^\dagger\right] + ..$ <br> $H = SU(N_f)_V$ |
| ’t Hooft Anomaly? | $\longrightarrow$ | $S_{WZW} = 2\pi i N_c \int_{W_5} \Gamma_5(\sigma)$ <br> Wess-Zumino(1971), Witten(1983) |

Harvey, Hill, Hill (0712.1230), SM WZW for MiniBooNE
SC, Gupta, Vanvlassaelaer (JCAP 2023), SM WZW Neutron Star Cooling

# Implications of WZW term

$$\Rightarrow \mathcal{L}^{a}_{WZW} \supset \epsilon^{\mu\nu\rho\sigma}\ \partial_\mu a\ F_{\nu\rho}\omega_\sigma$$

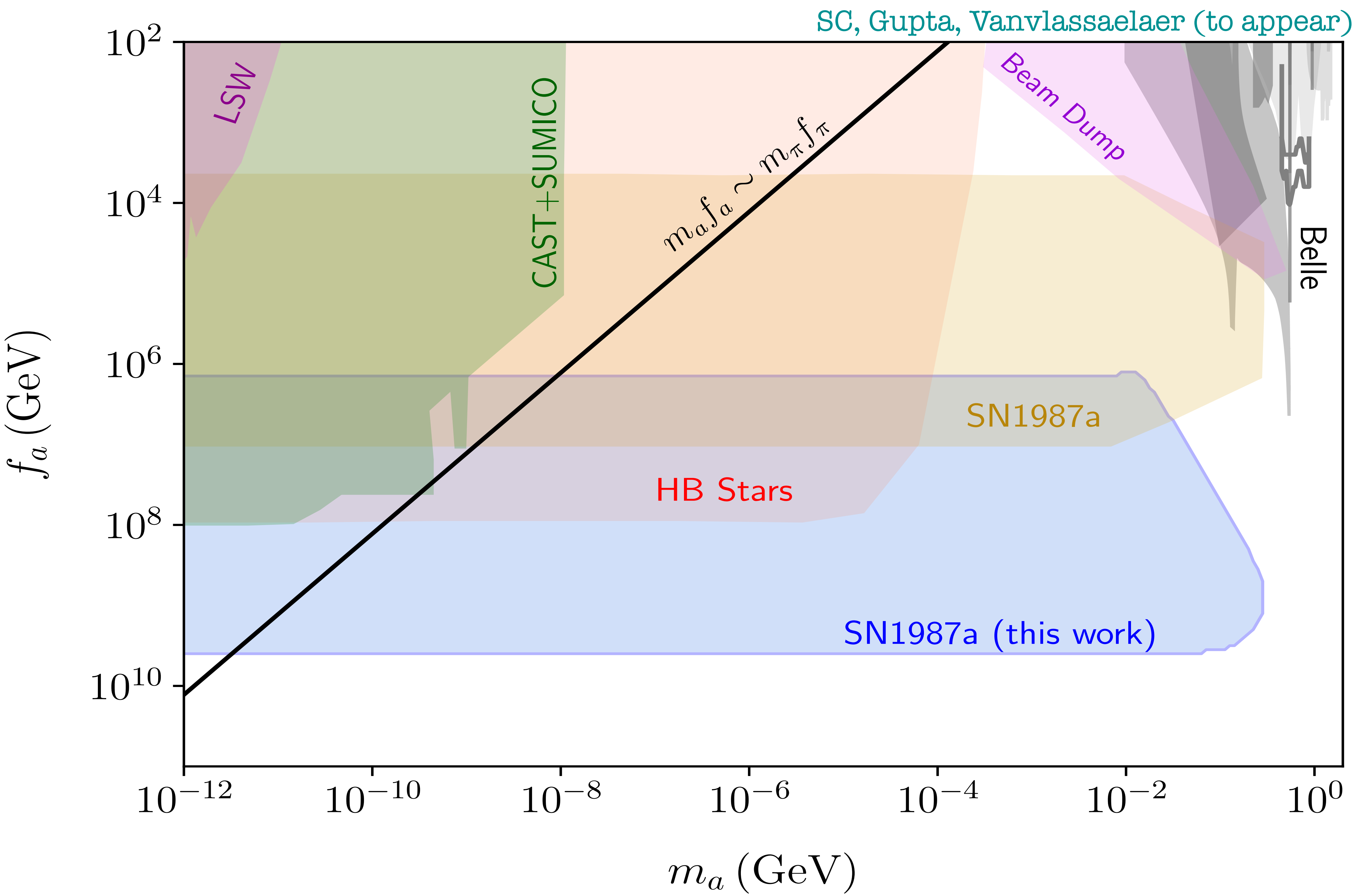


SC, Gupta, Vanvlassaelaer (to appear)

- Cooling of Neutron Stars/Supernova
- Probing such interactions at the intensity frontiers, GlueX etc.

# Implications of WZW term



# Fantastic Axions & where to find them

## Intensity Frontier

- Rare processes, Intensity Frontier Experiments, Developing EFTs (ongoing)
- Probing WZW interactions

## Energy Frontier

- Lepton Colliders, MATHUSLA (Long Lived Axions)

## Cosmic Frontier

- Cooling of neutron stars
- Axion-Meson Oscillations: $\partial_\mu a \ F_{\nu\rho}\omega_\sigma$
- Kinetic Misalignment, Axion Co-genesis (Harigaya, Hall, Co 2019, SC, Okui, Jung 2021)

# Backup-1

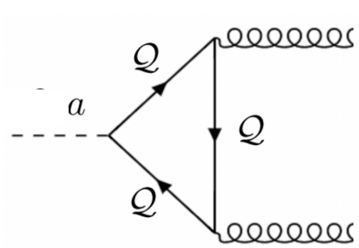
$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$ ★

Example of a UV model

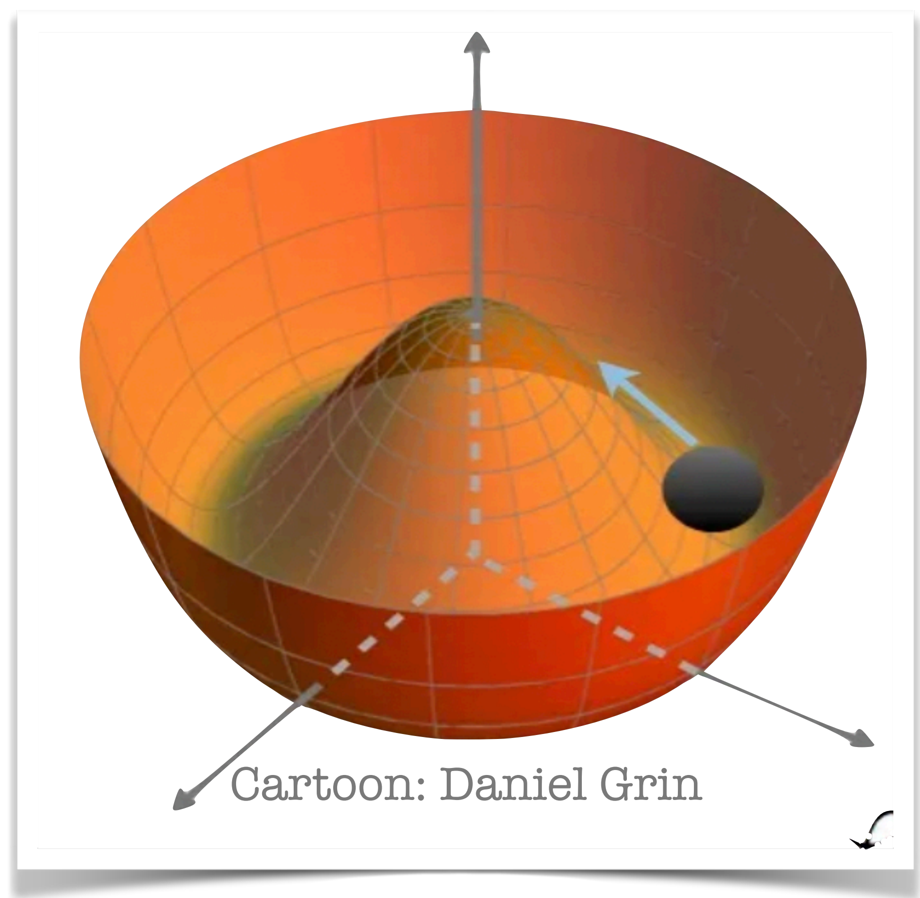
$$\mathcal{L}_{\rm KSVZ} = (\partial_\mu P)^\dagger (\partial^\mu P) + \bar{Q} i D Q - \left(y_Q P \bar{Q}_L Q_R + \text{h.c.}\right) - V(|P|^2)$$

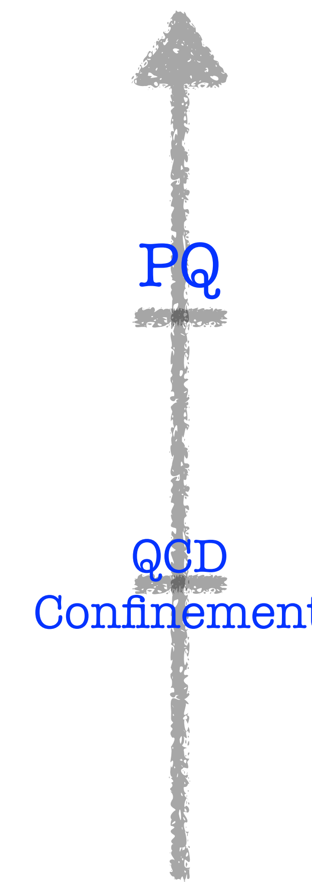
- After SB, P becomes a GB
- Heavy quarks generate a coupling

$$-\frac{\lambda f_a}{\sqrt{2}} \exp\left(i\frac{a}{f_a}\right) \bar{Q}_L Q_R + \text{h.c.}$$

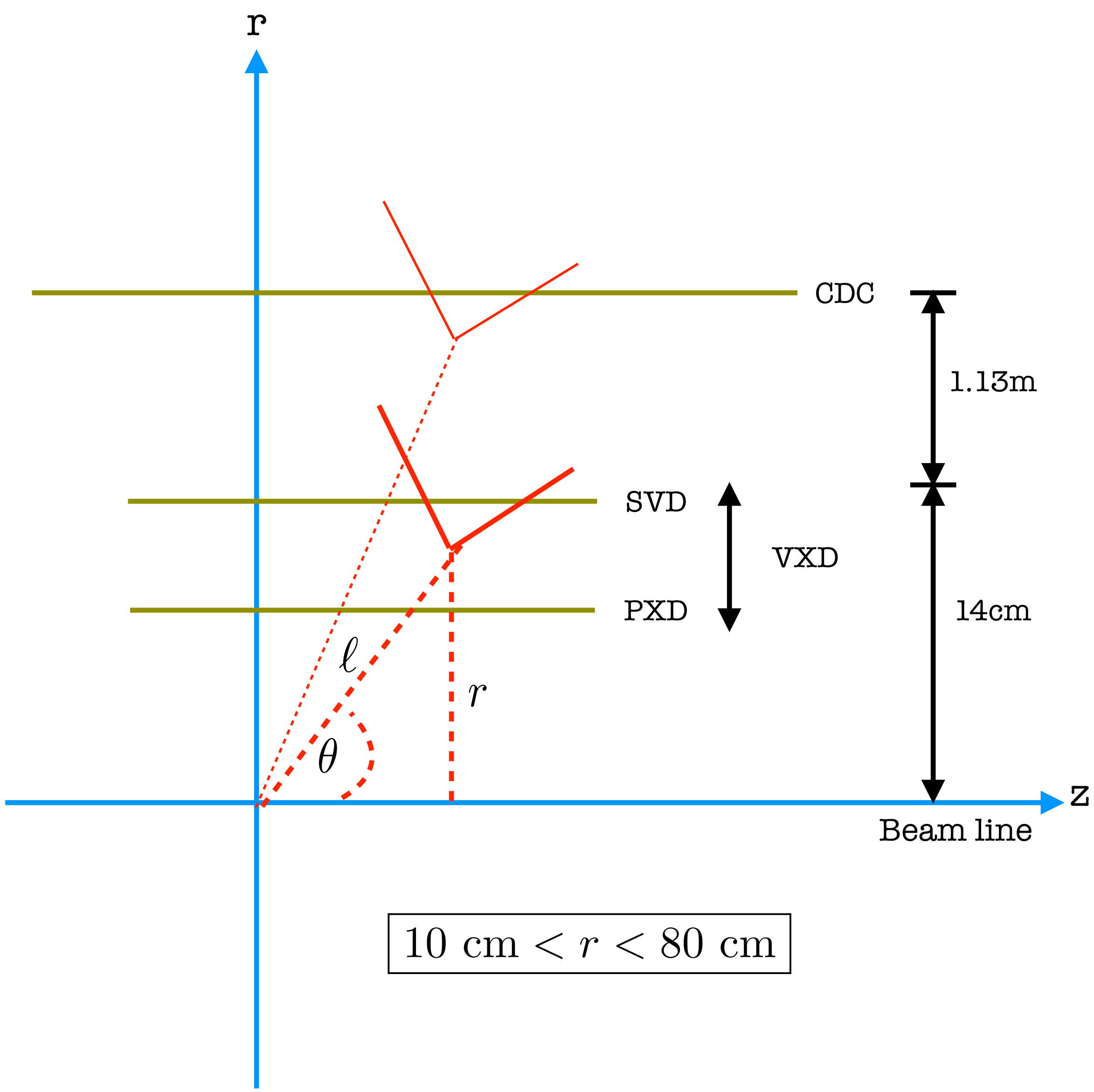



- Chiral rotation removes this
- However, generates: $\frac{\alpha_s}{8\pi}\frac{a}{f_a} G\tilde{G}$



# Backup-2




- Linear Falling Efficiency:

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

- Probability for decay

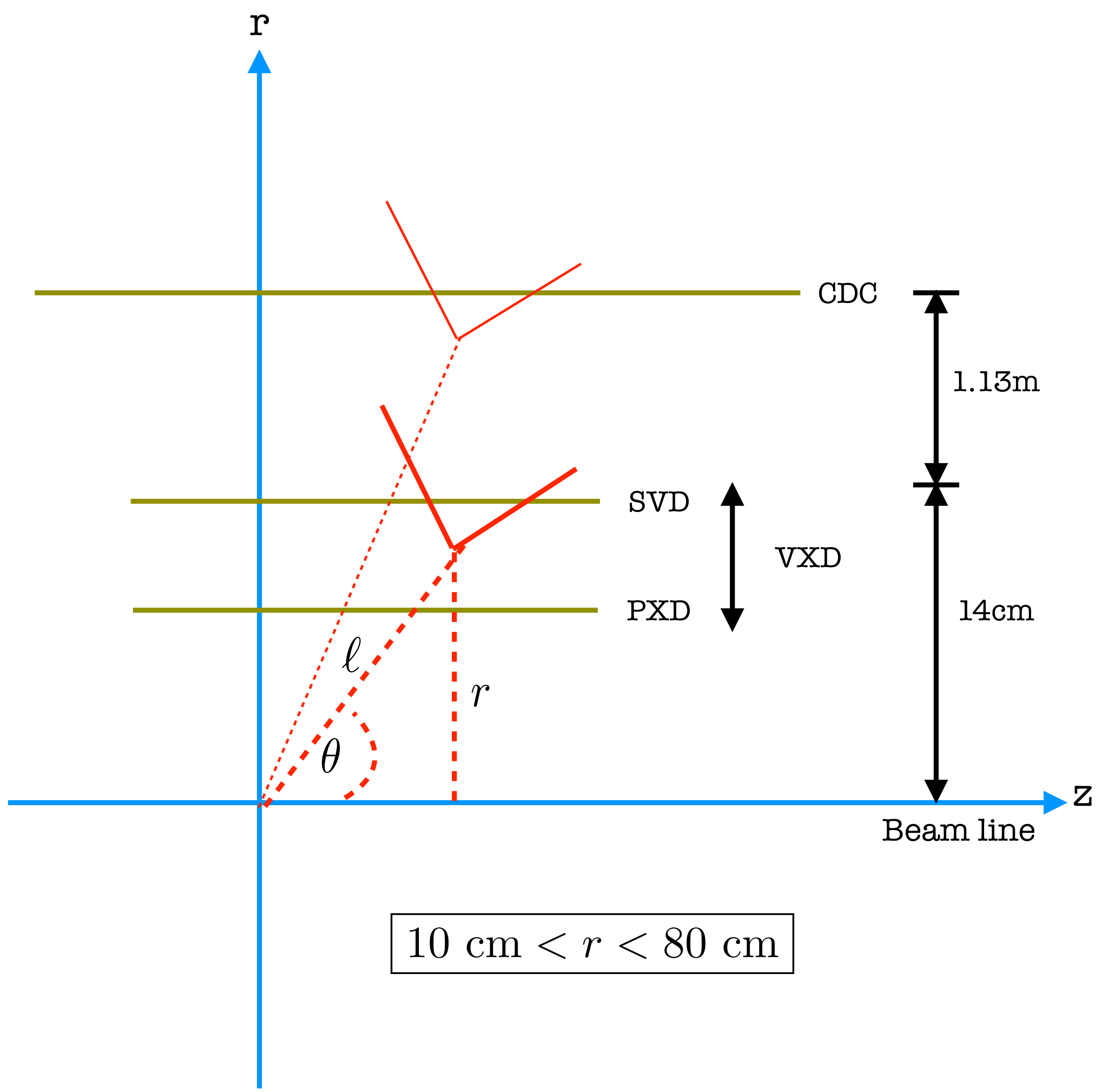
$$P(\ell) = \frac{e^{-\ell/\lambda}}{\lambda}$$

- Probability for identifying displaced vertex

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

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

# Backup-2




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

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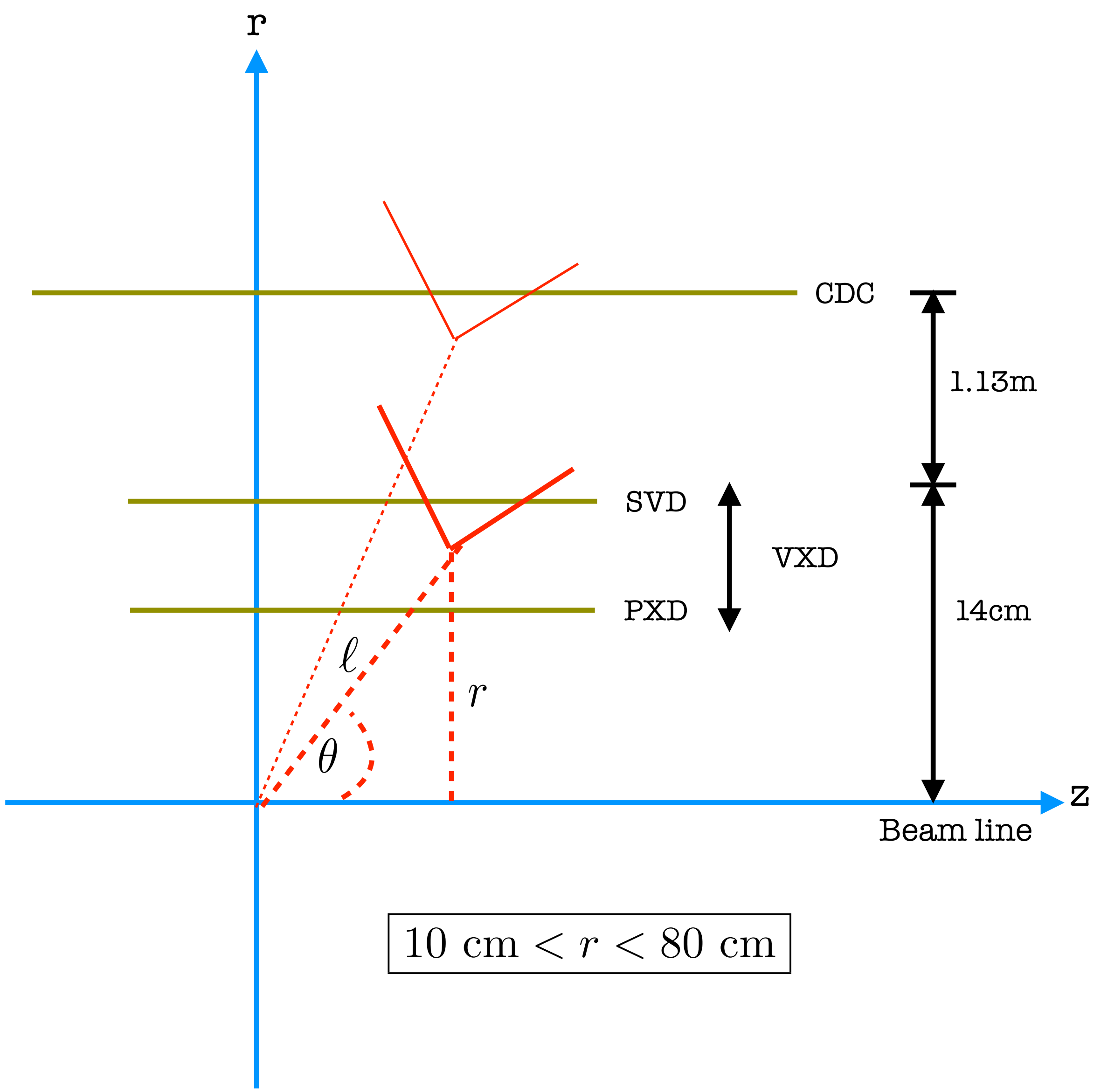
# Backup-2




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

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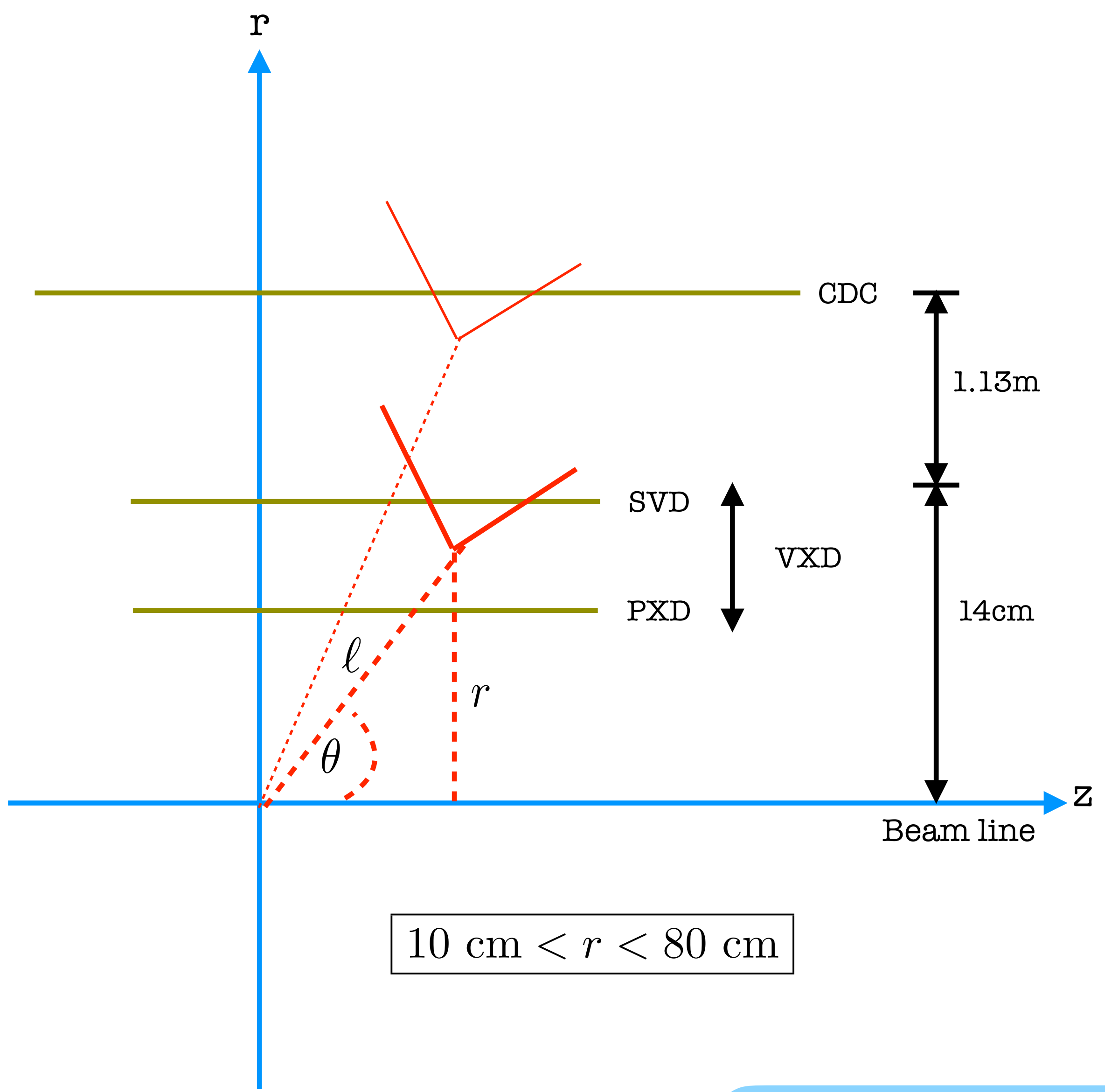


$\boxed{10 \text{ cm} < r < 80 \text{ cm}}$

- **Linear Falling Efficiency:**

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