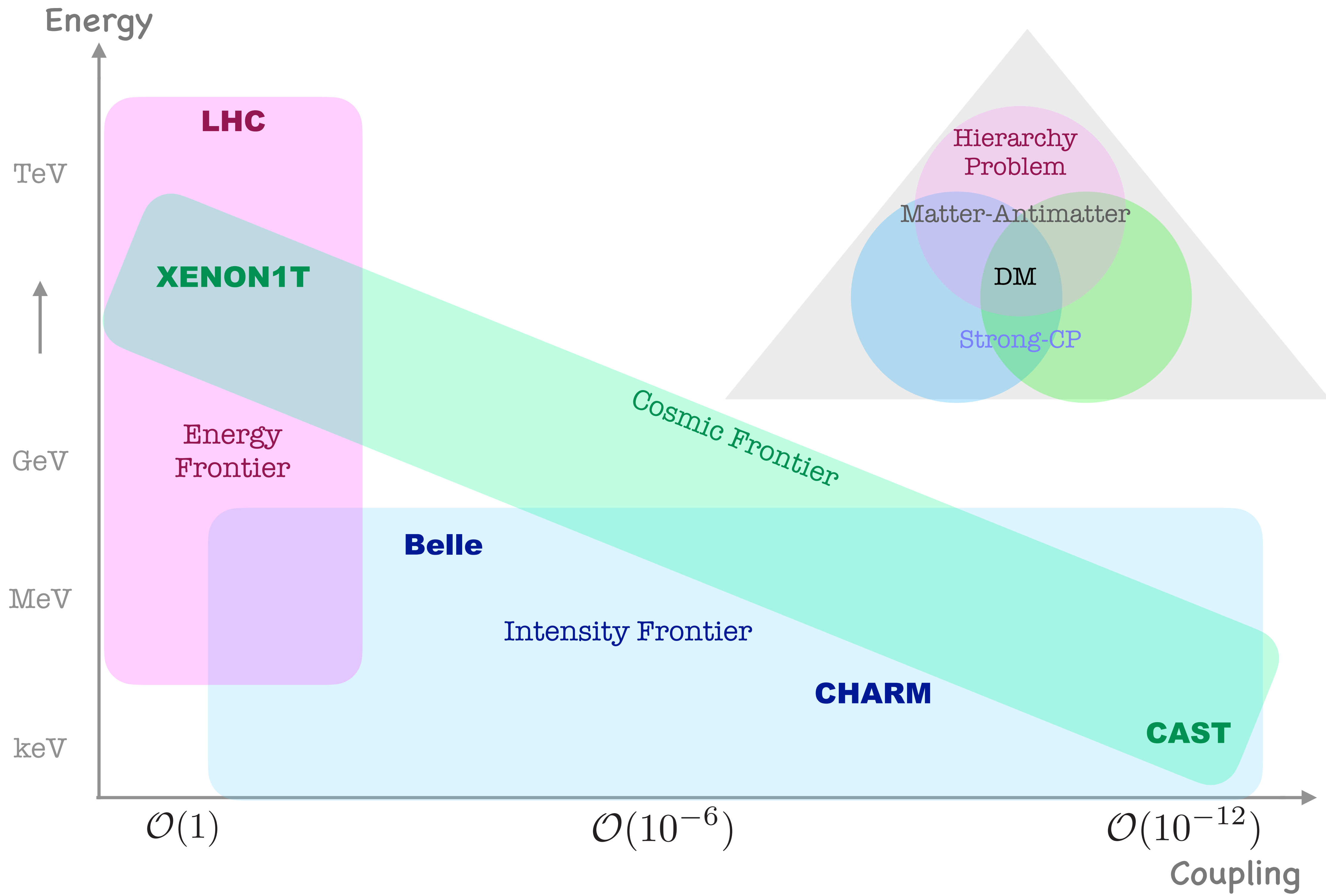
Theory & Phenomenology: Axion & ALPs

Sabyasachi Chakraborty (IIT-Kanpur)

(ICHEPAP2023)

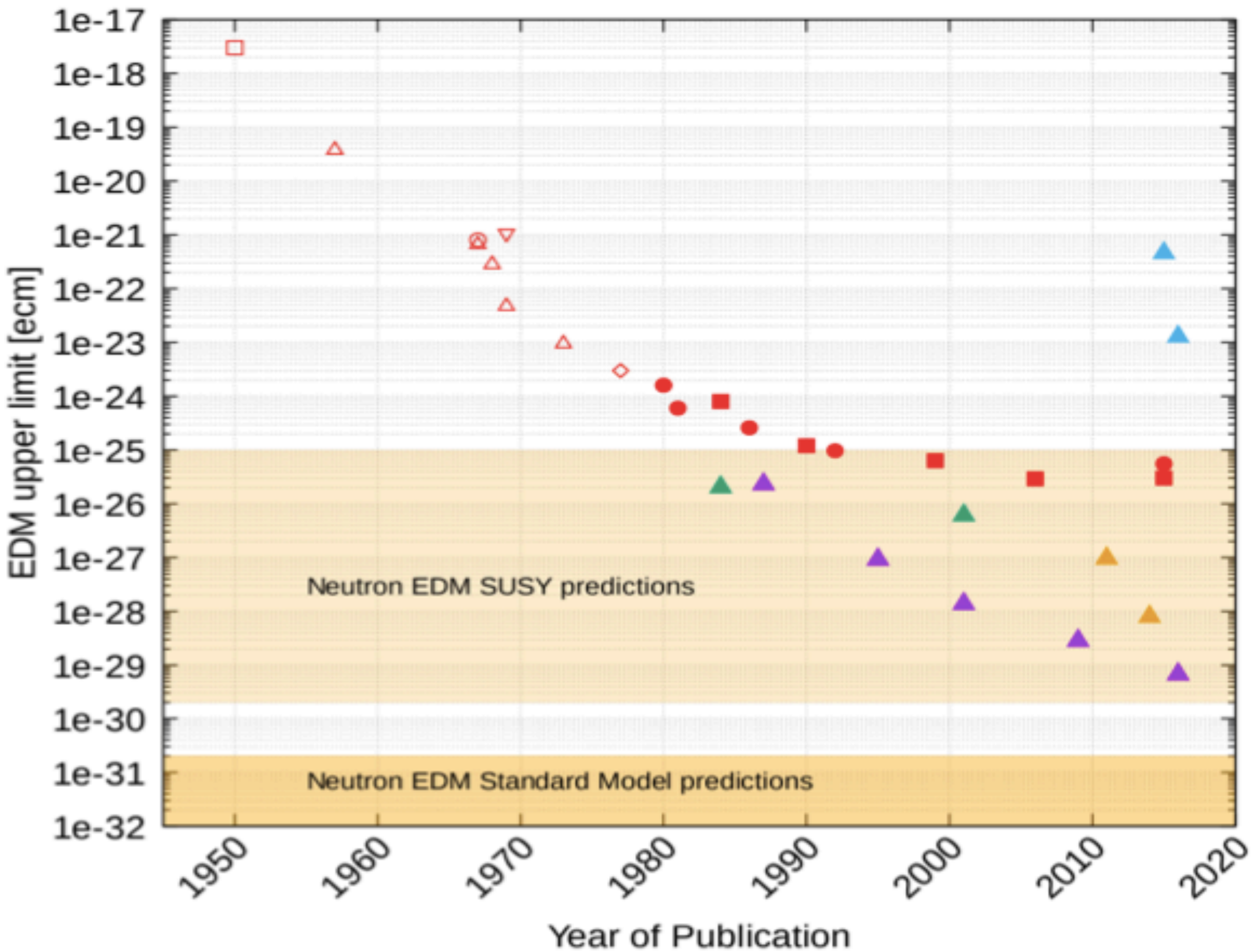
Axions at the Fundamental Frontiers

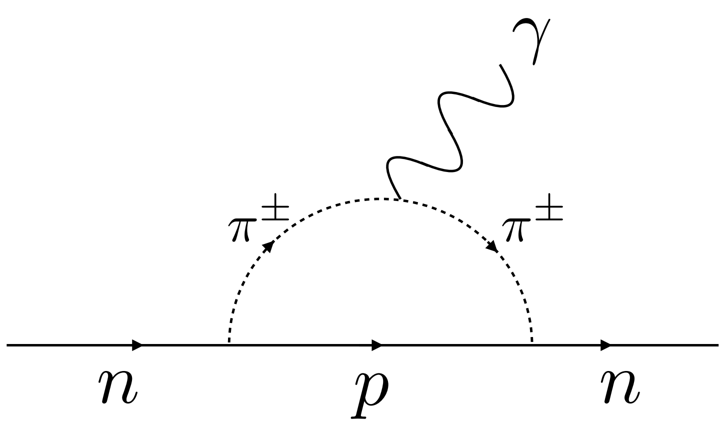


Introduction: Standard Model & CP

- 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

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

: Strong CP problem

Introduction: Axion as a solution

- Dynamical Solution, Axion a(x):

$$\mathcal{L}_{\text{eff}} \supset \bar{q}\,(i\not{D} - \mathcal{M}_q)\,q + \frac{a}{f_a}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{\mu\nu a} + \dots \star \qquad q \to \text{Exp}\left(i\kappa_q \frac{a}{2f_a}\gamma_5\right) q$$

However generates

$$\mathcal{L}_{\text{eff}} \supset \bar{q}\left(i\not{D} - \hat{\mathcal{M}}_q\right) q - \frac{\partial^\mu a}{2f_a}\bar{q}\gamma_\mu\gamma_5 q + \dots \quad \text{where} \quad \hat{\mathcal{M}}_q = e^{i\kappa\frac{a}{f_a}\gamma_5}\mathcal{M}_q e^{i\kappa\frac{a}{f_a}\gamma_5}$$

Matching with ChPT

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

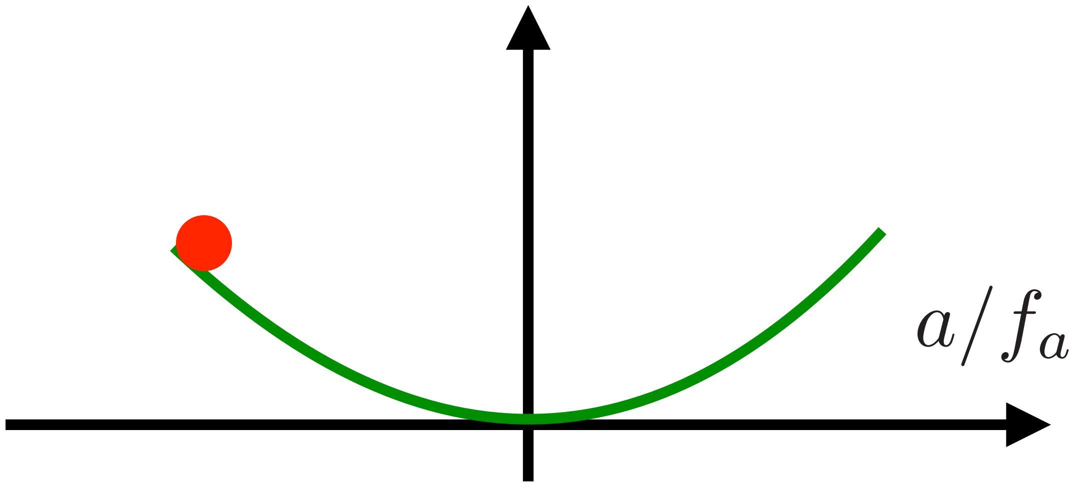
Introduction: Axion as a solution

- ChPT + Axions

$$\mathcal{L}_{\chi\mathrm{PT}} \supset \frac{f_\pi^2}{8}\,\mathrm{Tr}\left[D^\mu\Sigma\, D_\mu\Sigma^\dagger\right] + \frac{f_\pi^2}{4} 2B_0\mathrm{Tr}\,\left[\Sigma\hat{\mathcal{M}}_q{}^\dagger + \mathrm{h.c.}\right] + \dots$$

$$\Sigma = \mathrm{Exp}\left[i\frac{\sqrt{2}\pi^a\tau^a}{f_\pi}\right]$$

$$\theta\; G\widetilde{G} \to \frac{a}{f_a} G\widetilde{G} \Rightarrow$$



Dynamical solution to strong CP

- Mass and mixing $V_{\pi,a} \to m_a \sim \frac{m_\pi f_\pi}{f_a}\;,\quad g_{aff} \sim g_{\pi^0 ff} \times \frac{f_\pi}{f_a} \Rightarrow \sin\theta$

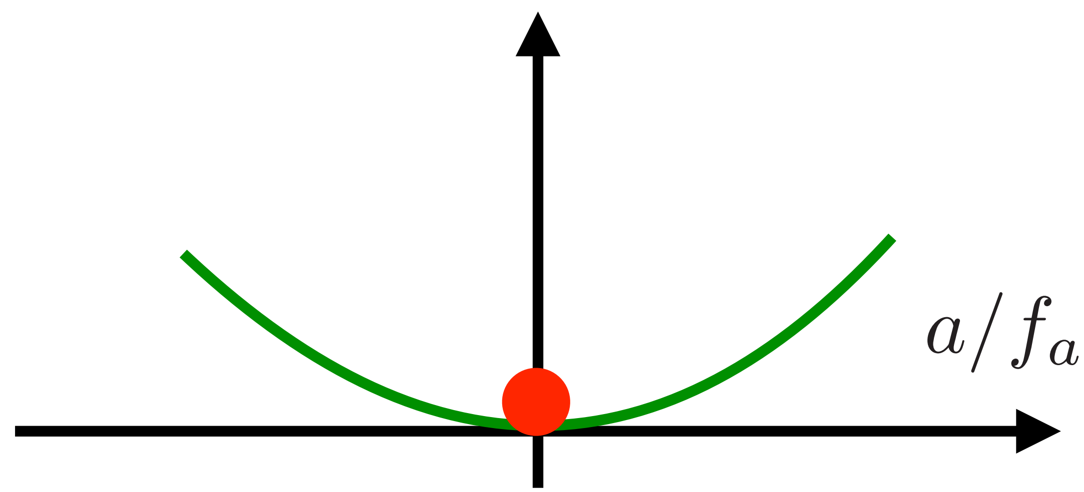
Introduction: Axion as a solution

- ChPT + Axions

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

$$\Sigma = \mathrm{Exp}\left[i\frac{\sqrt{2}\pi^a\tau^a}{f_\pi}\right]$$

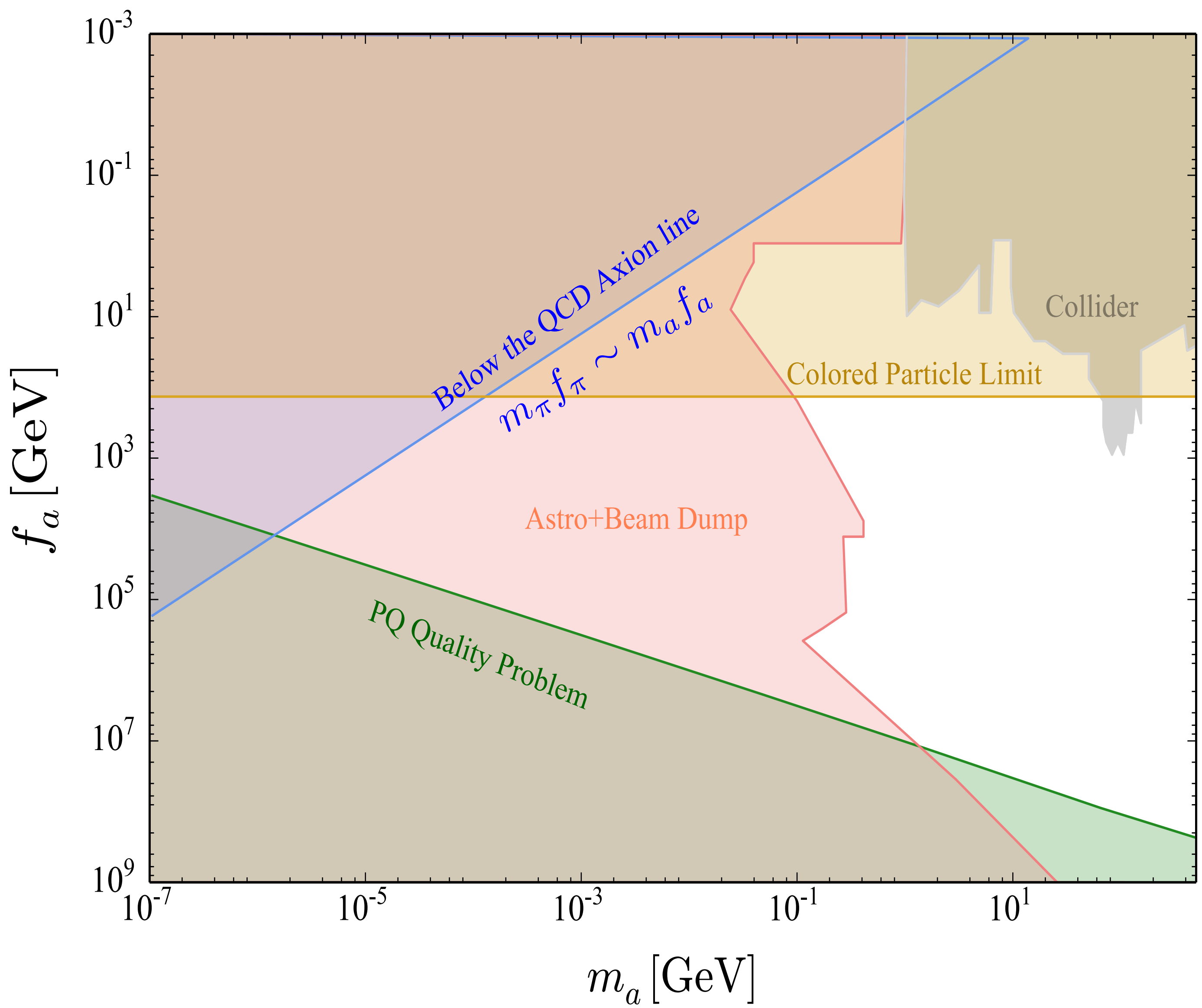
$$\theta\, G\widetilde{G} \to \frac{a}{f_a} G\widetilde{G} \Rightarrow$$



Dynamical solution to strong CP

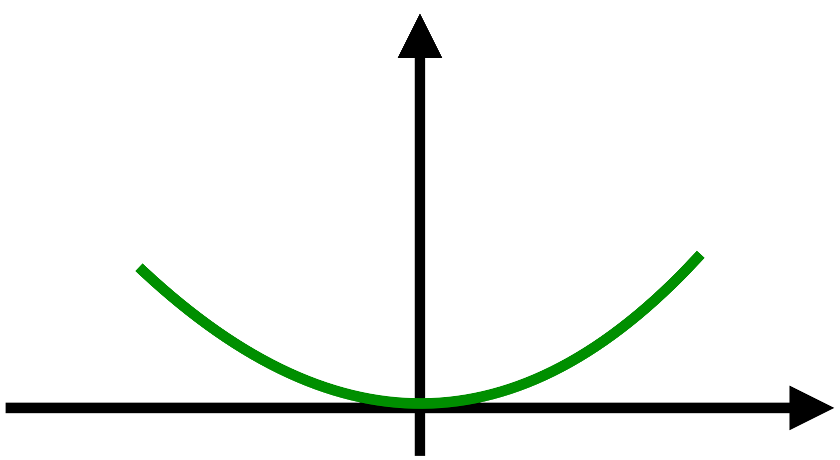
- Mass and mixing $V_{\pi,a} \to m_a \sim \frac{m_\pi f_\pi}{f_a}\,,\quad g_{aff} \sim g_{\pi^0 ff} \times \frac{f_\pi}{f_a} \Rightarrow \sin\theta$

Quality Problem and Heavy Axion



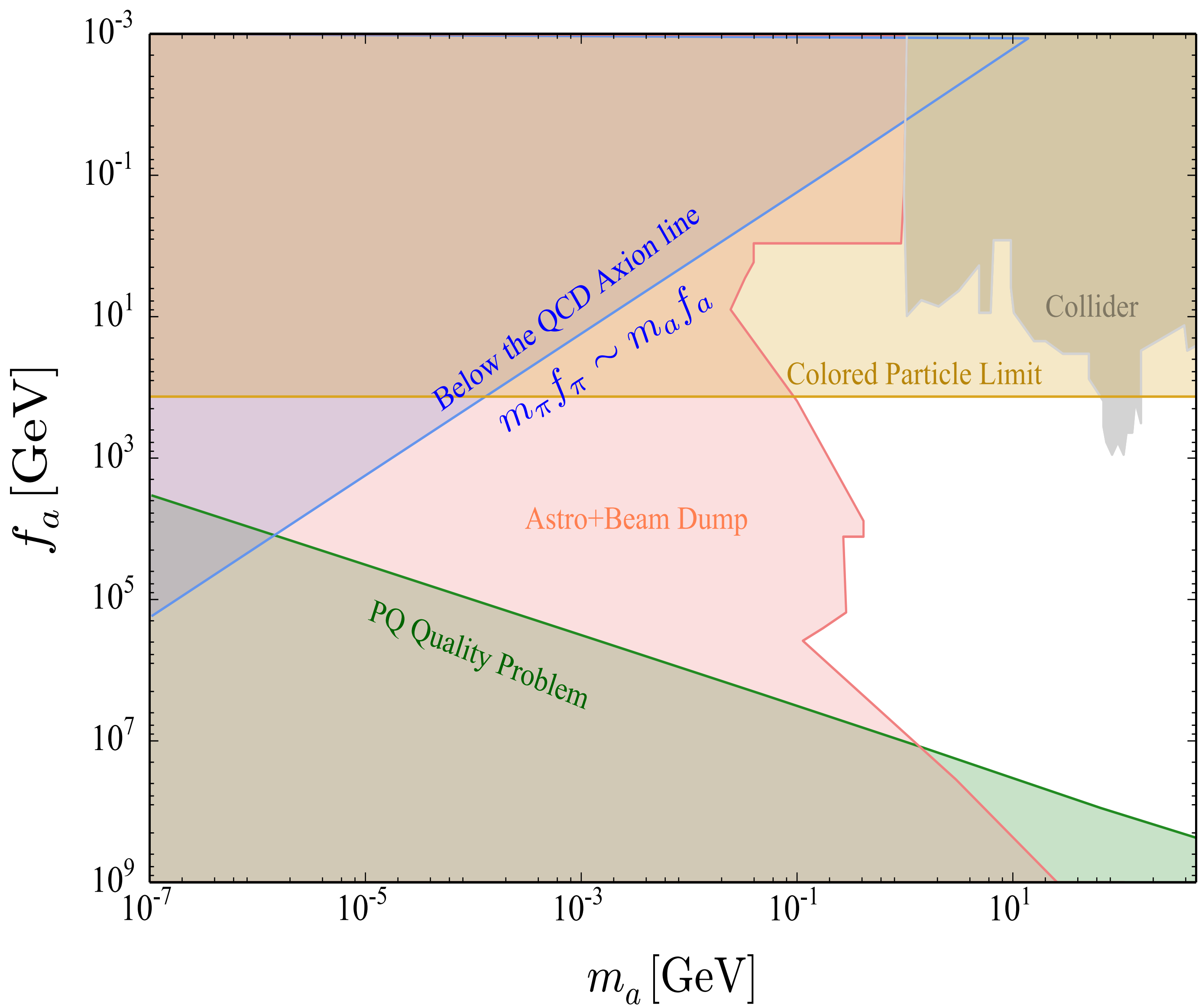
See: Rubakov 9703409
Fukuda, Harigaya, Ibe, Yanagida 1504.06084
Hook, Kumar, Liu, Sundrum 1911.12364 etc.

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

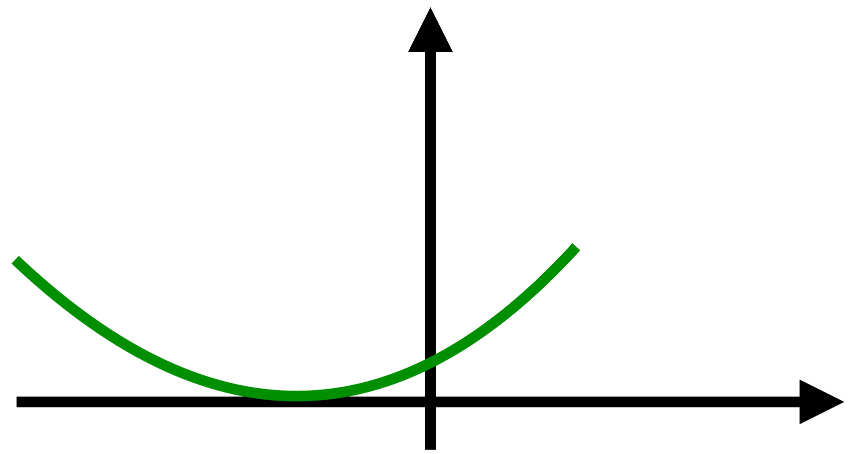


$$\frac{\lambda f_a^5}{M_{\rm pl}} < \Lambda_{\rm QCD}^4 \implies \lambda < 10^{-10}\left(\frac{10^5}{f_a}\right)^5$$

Quality Problem and Heavy Axion



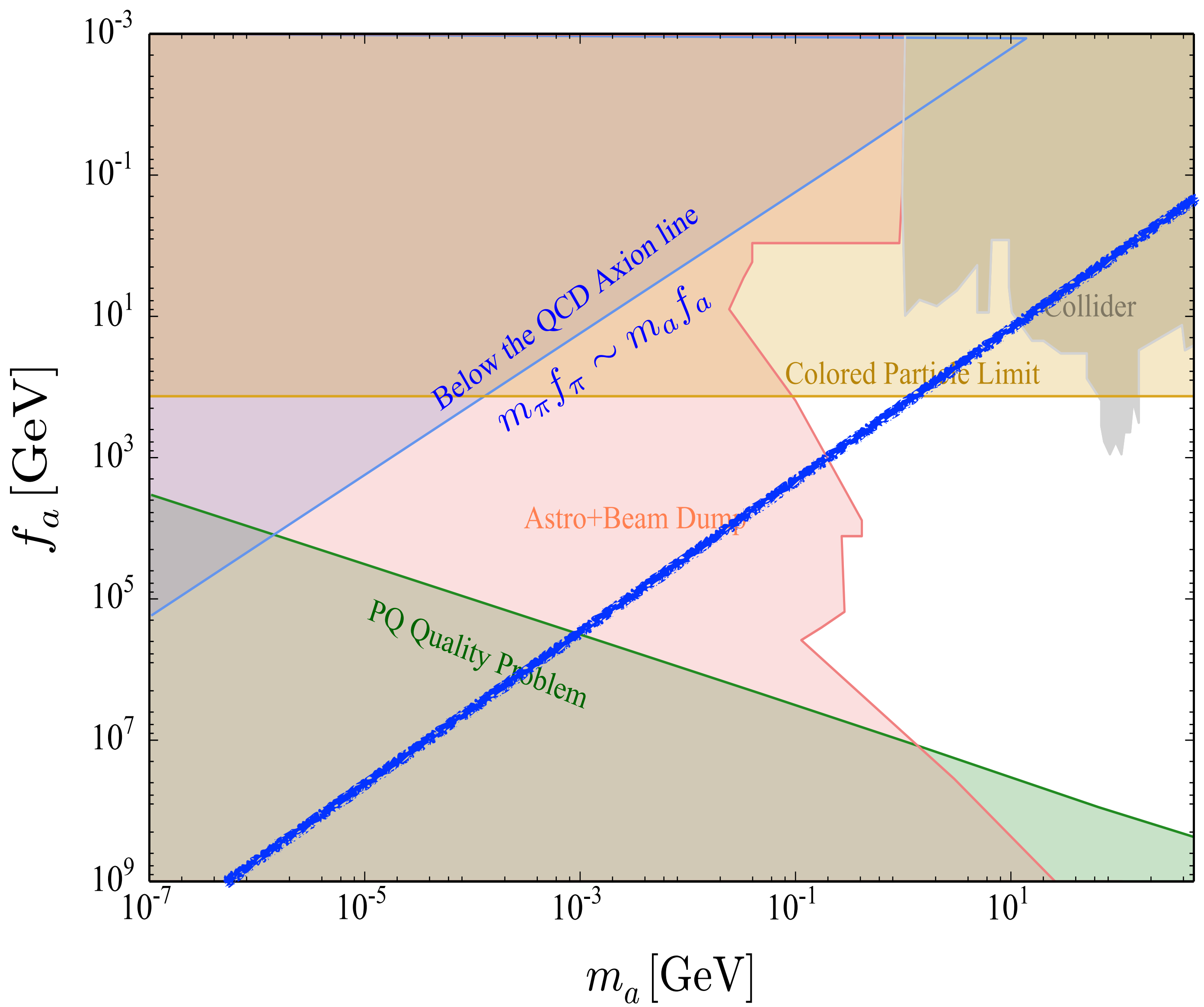
- QCD Axion with large fa is problematic => Quality Problem



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

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

Quality Problem and Heavy Axion

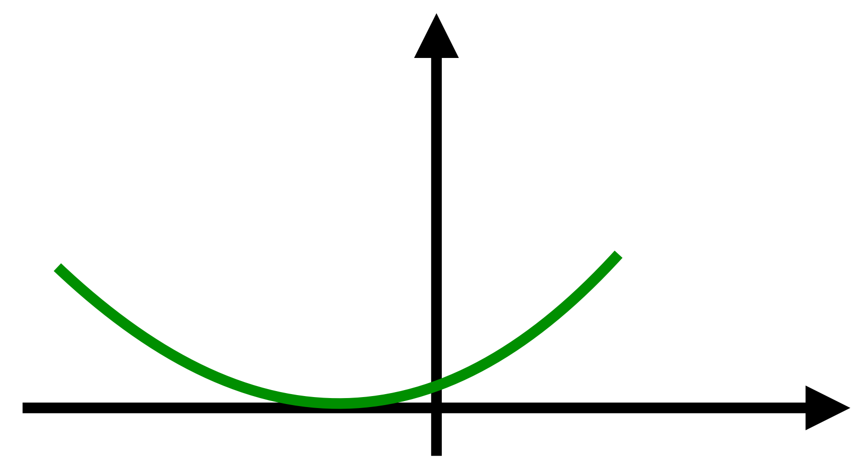


See: Rubakov 9703409

Fukuda, Harigaya, Ibe, Yanagida 1504.06084

Hook, Kumar, Liu, Sundrum 1911.12364 etc.

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



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

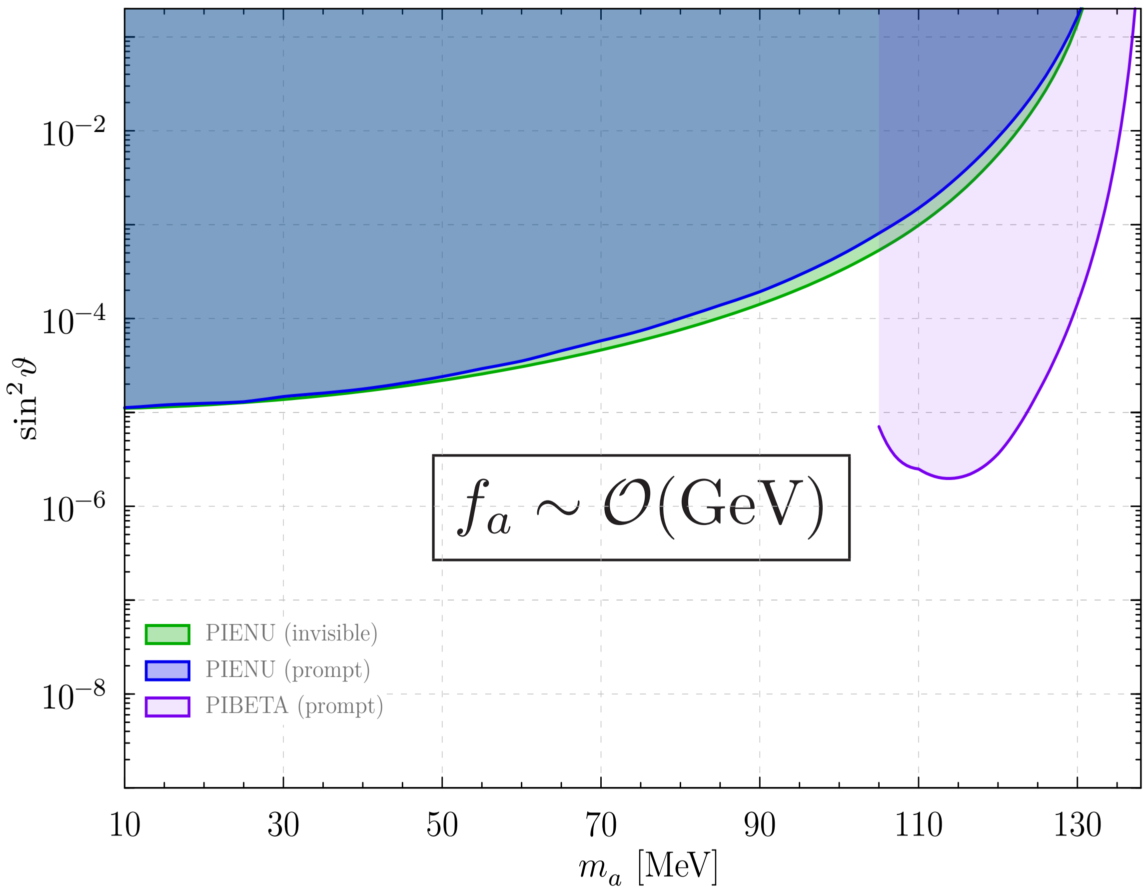
Intensity Frontier: Bounds from Meson decay

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

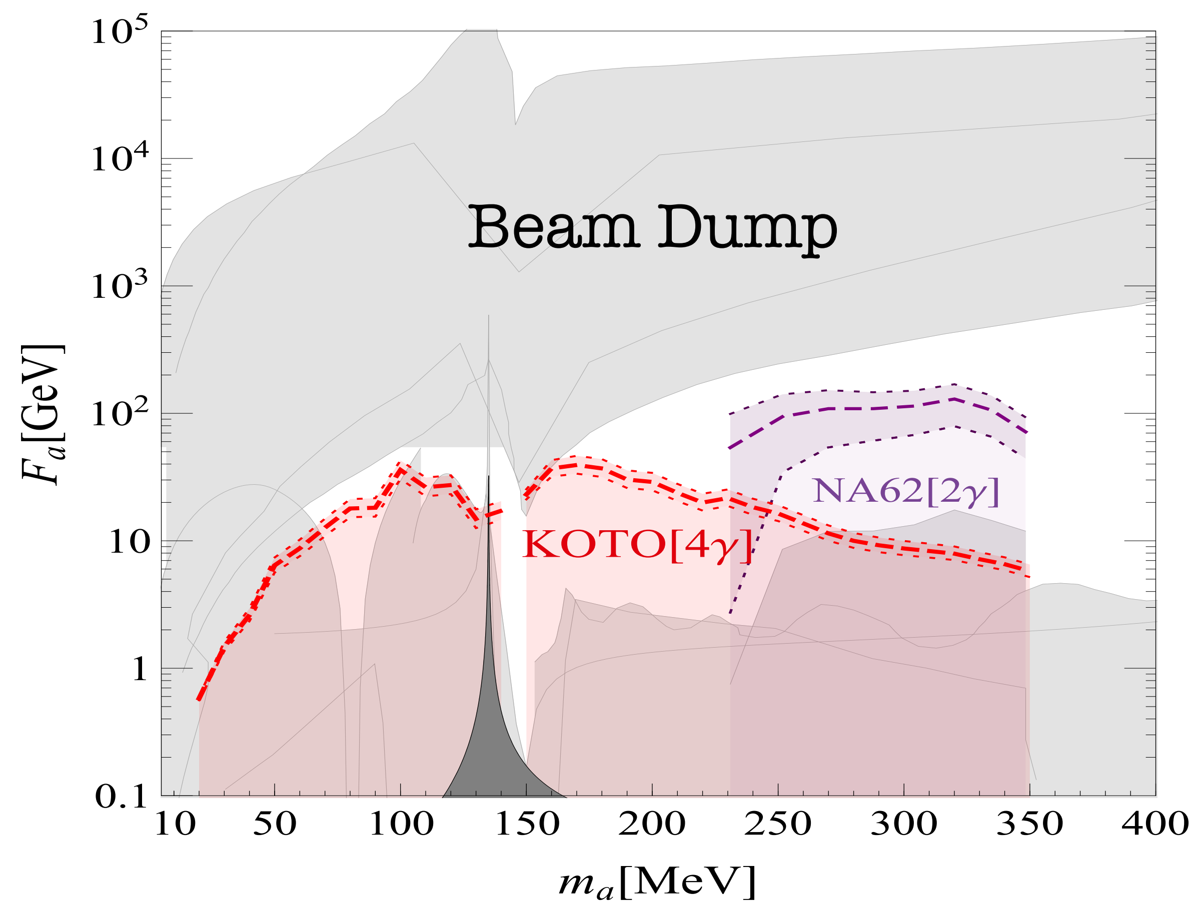
$\pi^+ \to \pi^0\,(a)\,e^+\nu$

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

Altmannshofer, Gori, Robinson 1909.00005



Gori, Perez, Tobioka 2005.05170



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

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

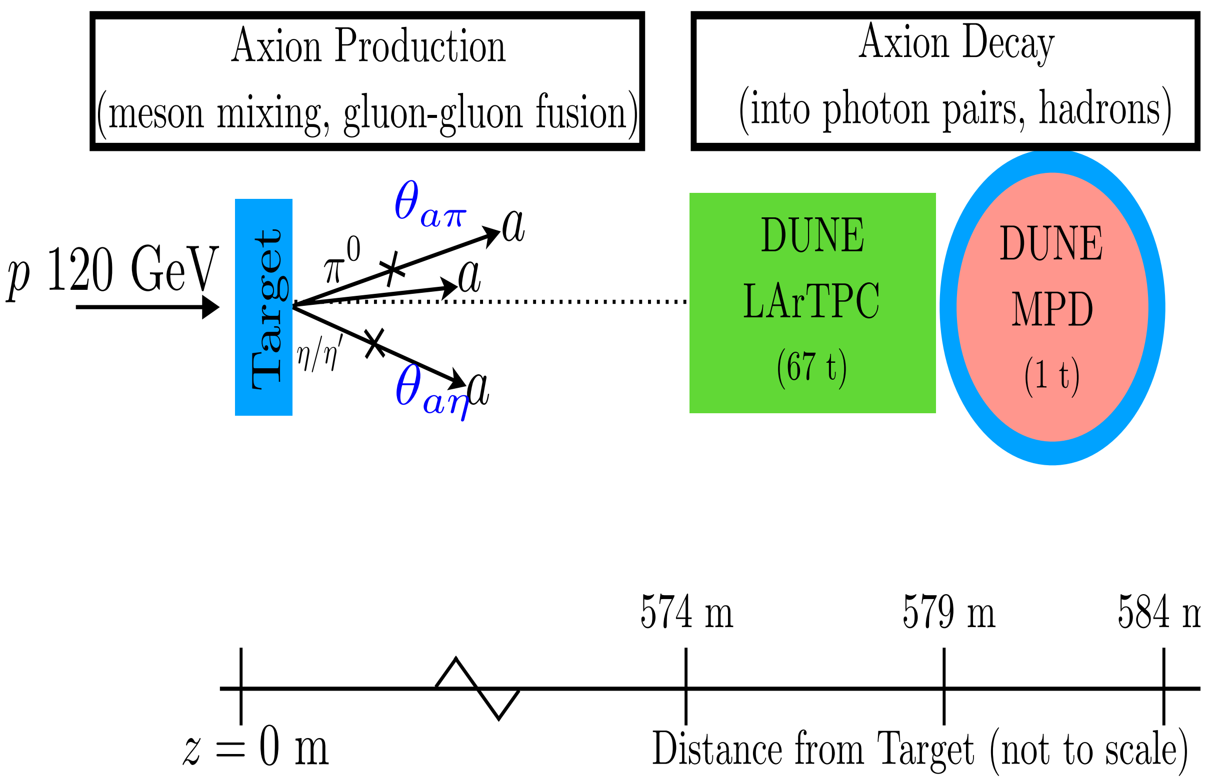
NA62 Exp: $\mathrm{Br}\left[K^+ \to \pi^+\nu\bar{\nu}\right] \sim 10^{-10}$

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

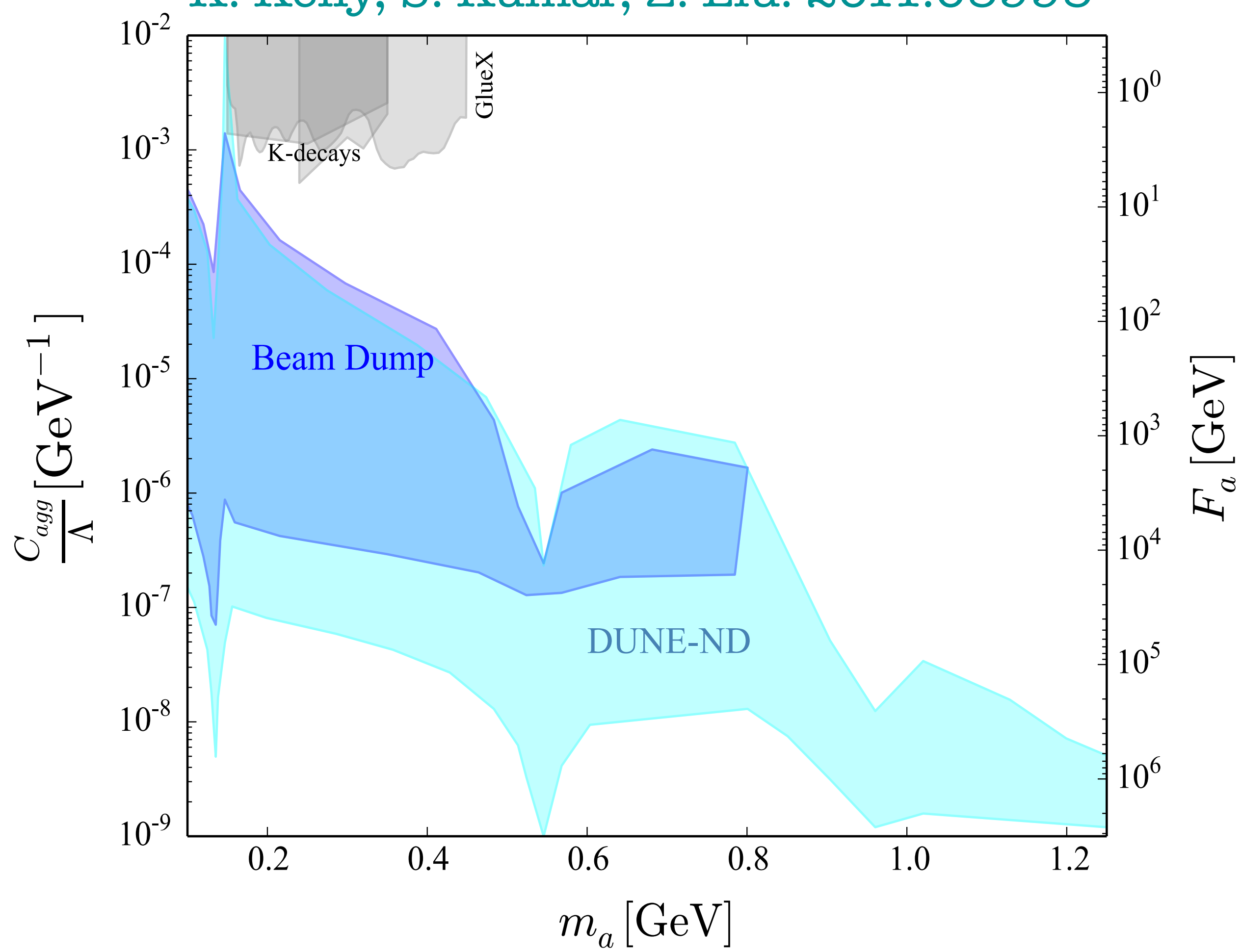
Indirect Probes: Triparno, Subhajit, Tuhin 2022

Intensity Frontier: Bounds from Beam-dump

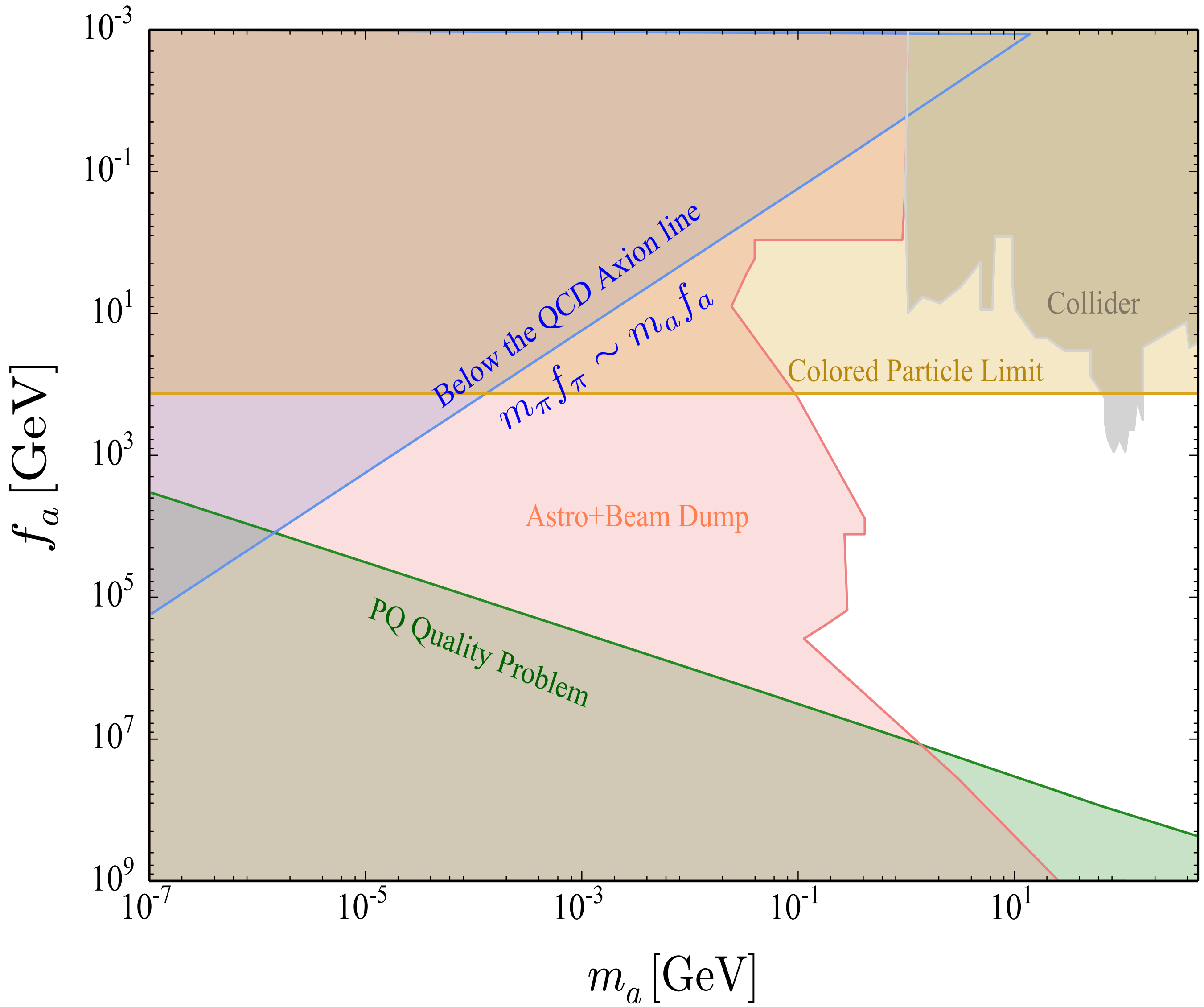
Example: DUNE (Also could be MiniBooNE, microBooNE etc.)



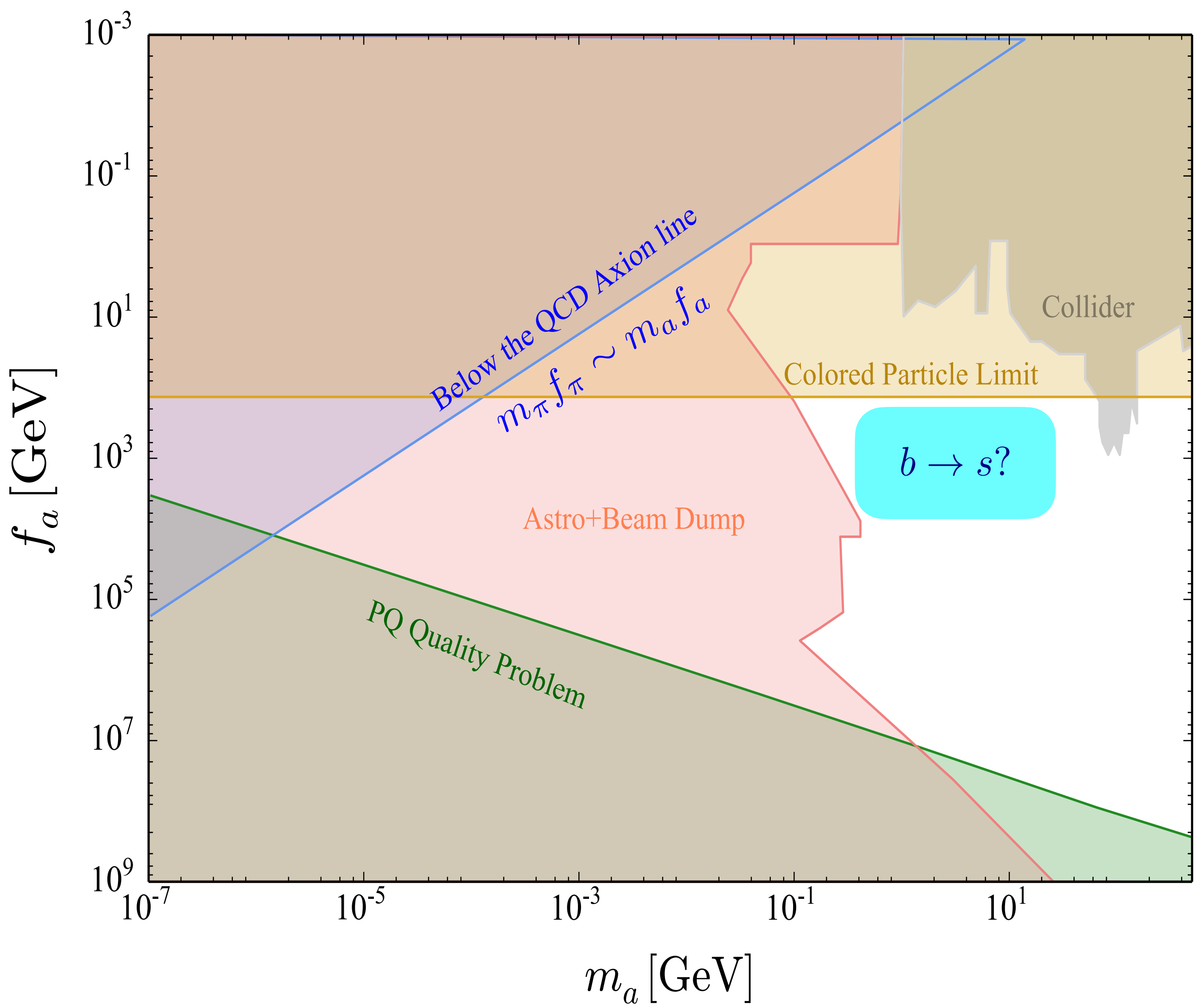
K. Kelly, S. Kumar, Z. Liu: 2011.05995



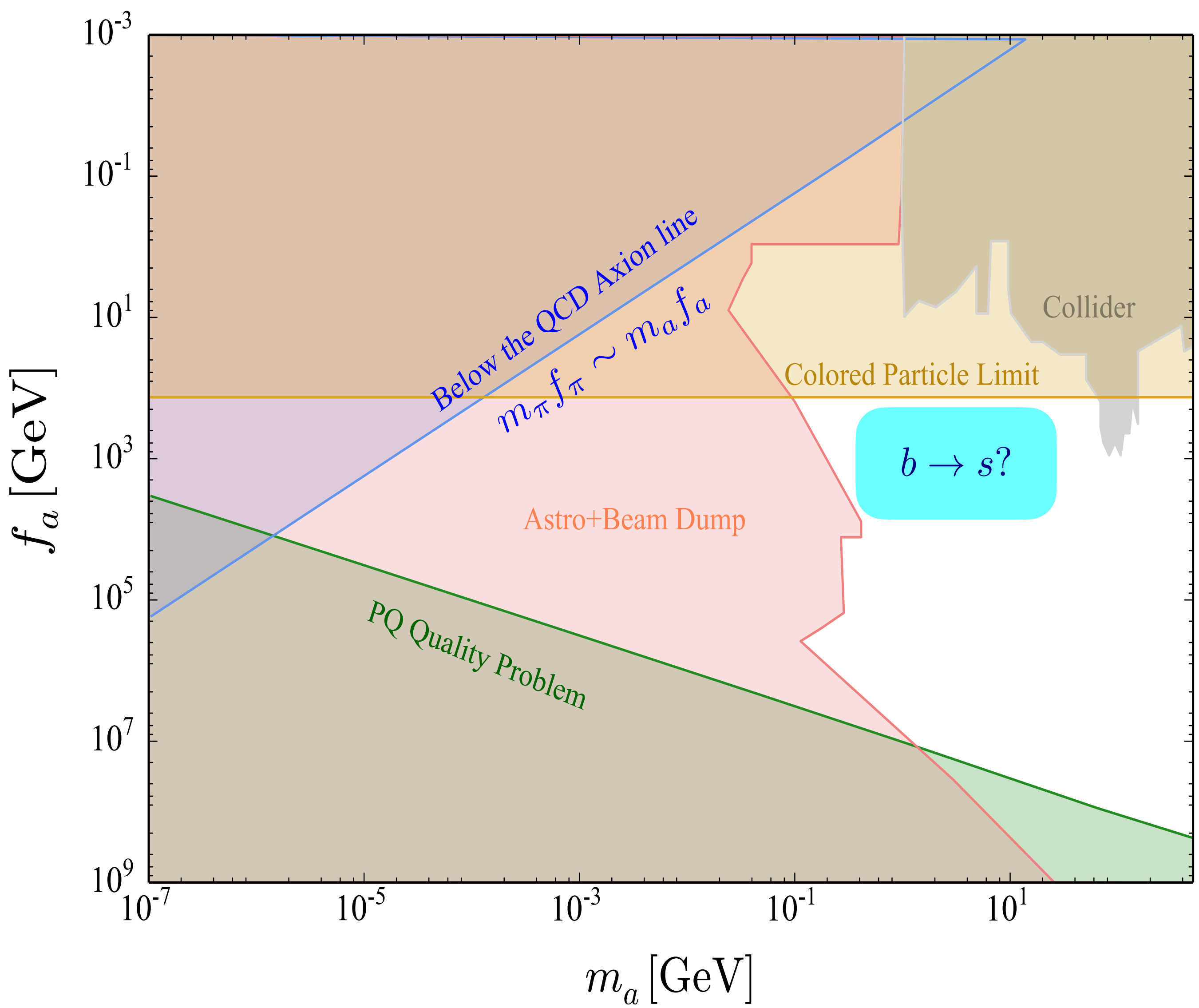
MeV-GeV region open! Technically Challenging



MeV-GeV region open! Technically Challenging



MeV-GeV region open! Technically Challenging



- Recall, the chiral Lagrangian for matching

$$\mathcal{L}_{\chi PT} \supset \frac{f_\pi^2}{8} \mathrm{Tr}\left[D^\mu \Sigma\, D_\mu \Sigma^\dagger\right] + \frac{f_\pi^2}{4} 2B_0\ \mathrm{Tr}\left[\Sigma \hat{\mathcal{M}}_q^\dagger + \hat{\mathcal{M}}_q \Sigma^\dagger\right] + ...$$

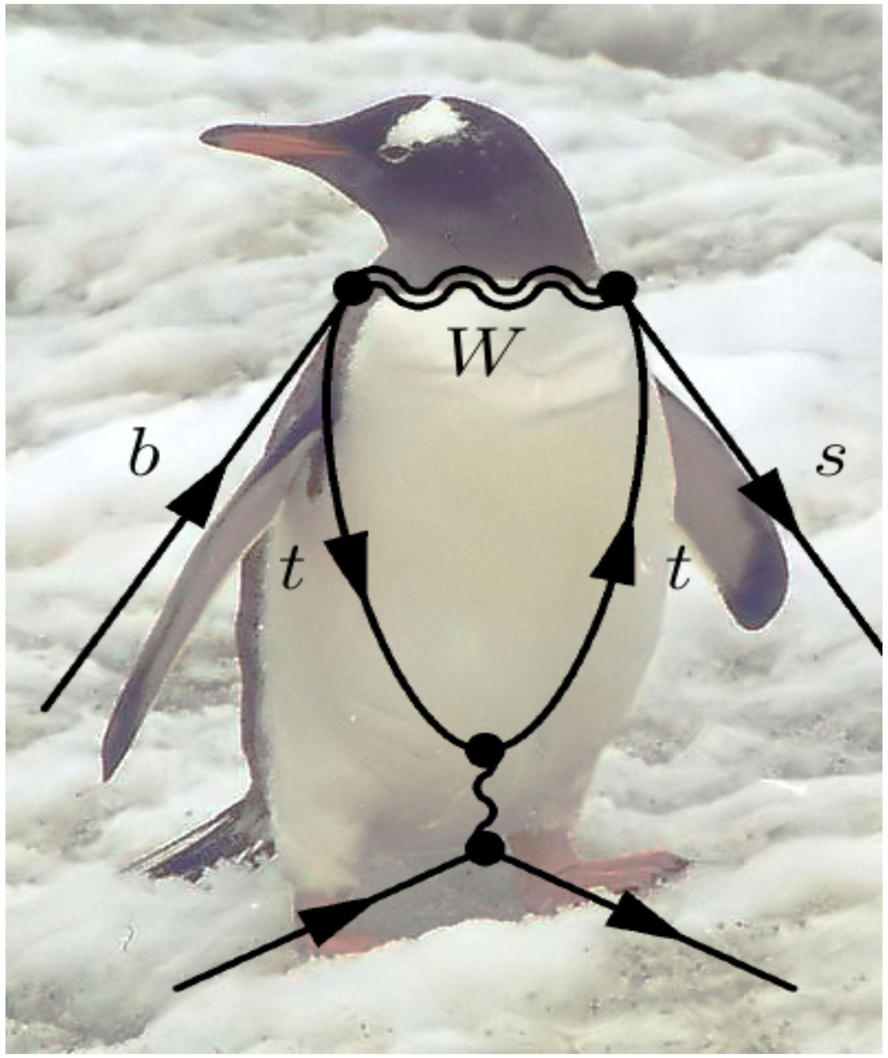
- Infinite number of operators beyond LO

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

- Breaks down for momentum for p>1 GeV

MeV-GeV region - Minimal ALP

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



Wikipedia

- Our Starting Point:

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

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

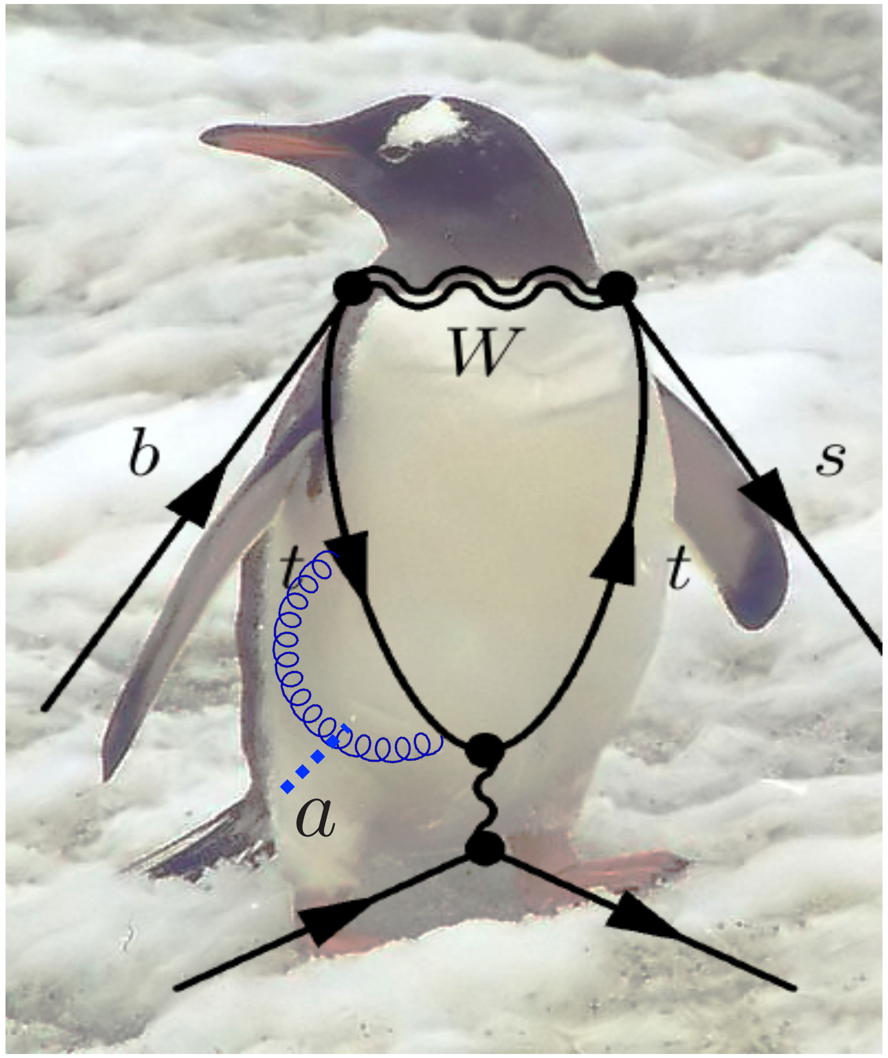
Matching Operator

- Need to know what else gets generated

SC et. Al. 2102.04474

MeV-GeV region - Minimal ALP

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



Wikipedia

- Our Starting Point:

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

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

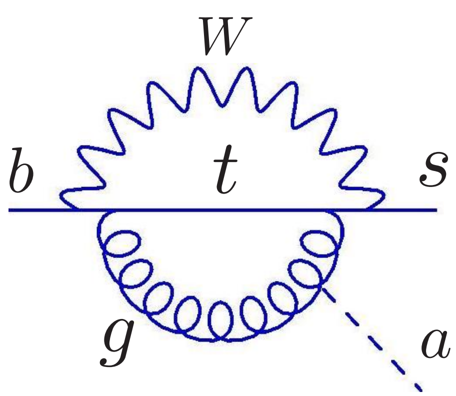
Matching Operator

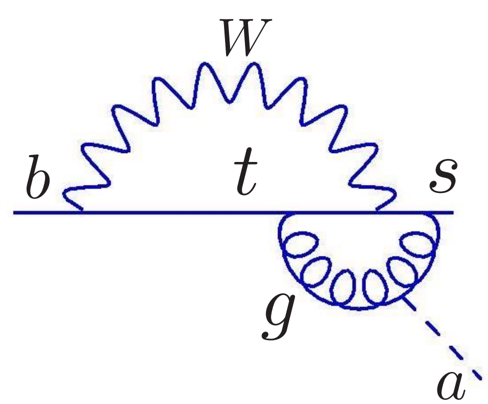
- Need to know what else gets generated

SC et. Al. 2102.04474

Counterterms => Operators

- Two Loop Diagrams:

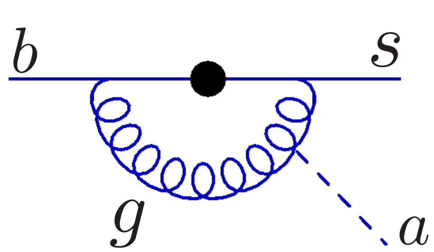


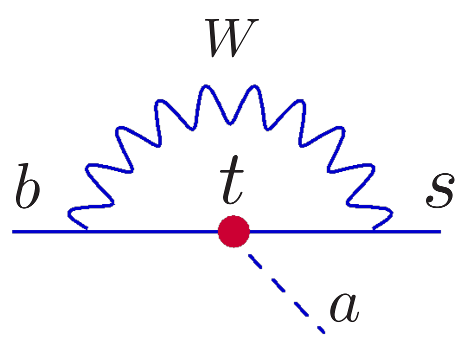


....

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

- Counterterms:



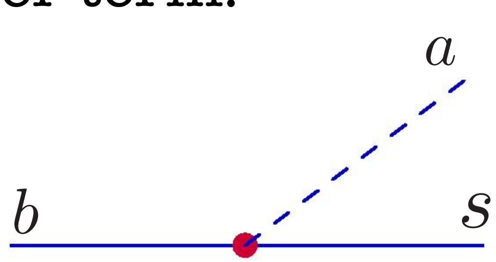


....

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

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

SC et. Al. 2102.04474

Running and Matching

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

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

Using RGEs ↓

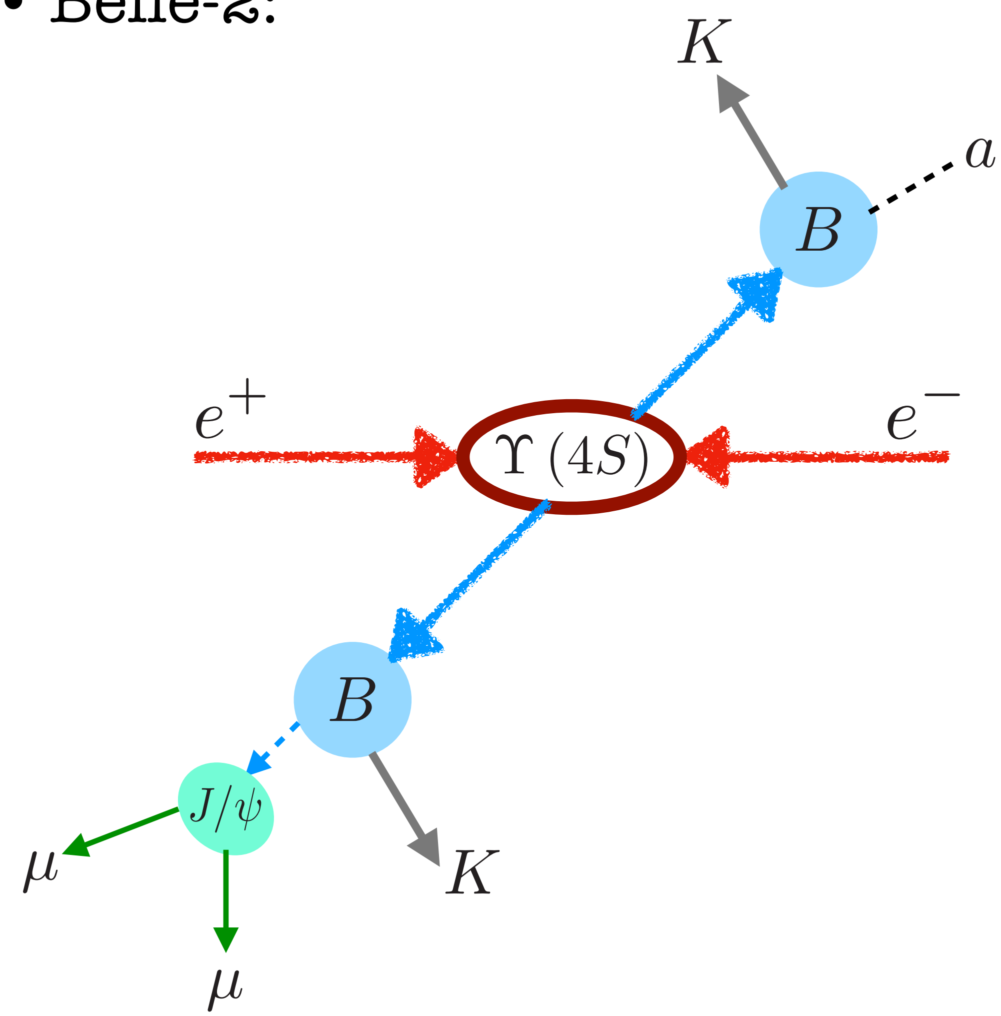
m_b — **Experimental Data**

$B\to Ka$

SC et. Al. 2102.04474

Axions: Experimental Searches

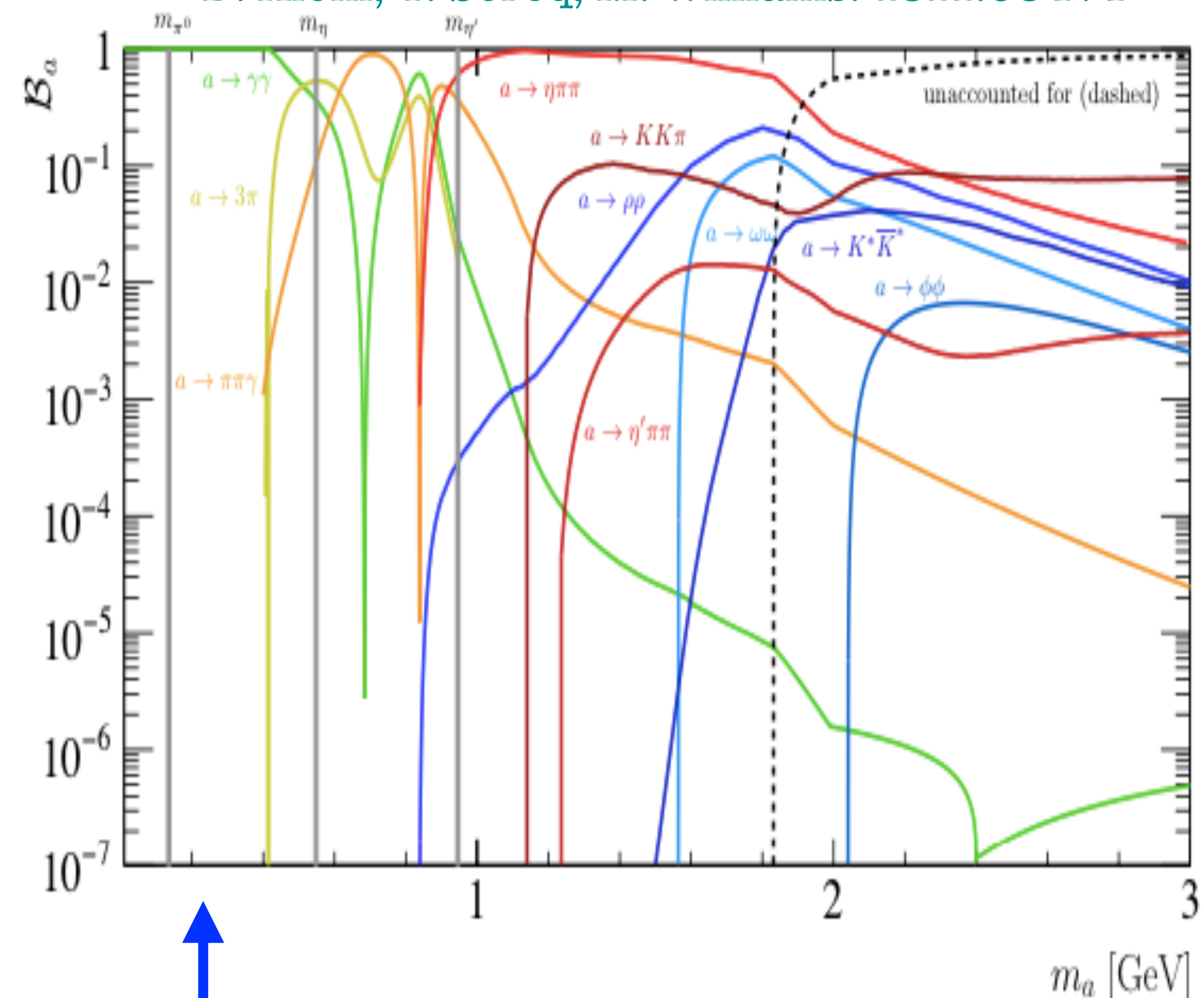
- Belle-2:



Belle Experiment

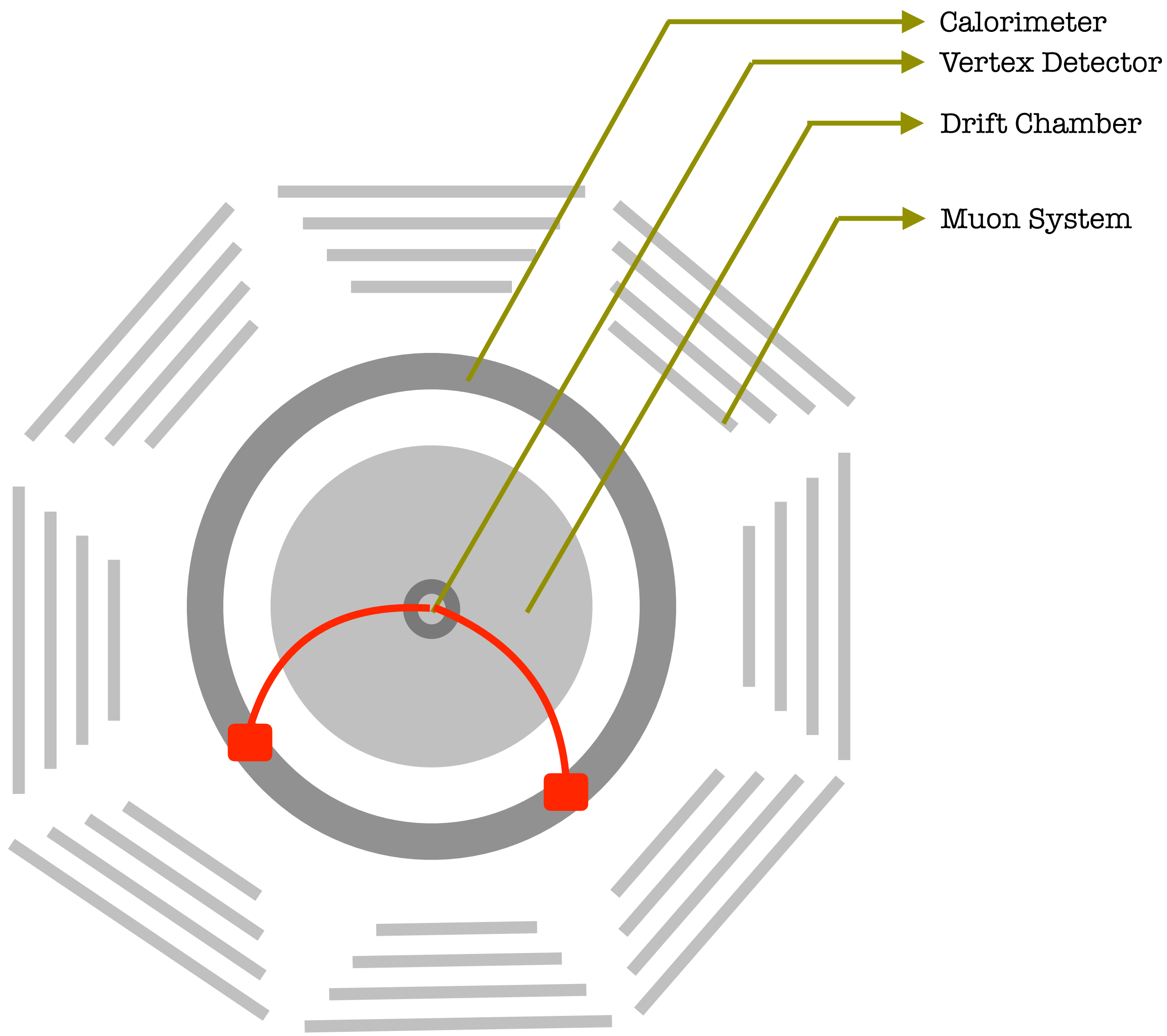
$a \to (\eta\pi\pi\ , KK\pi\ , 3\pi\ , \phi\phi)$

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



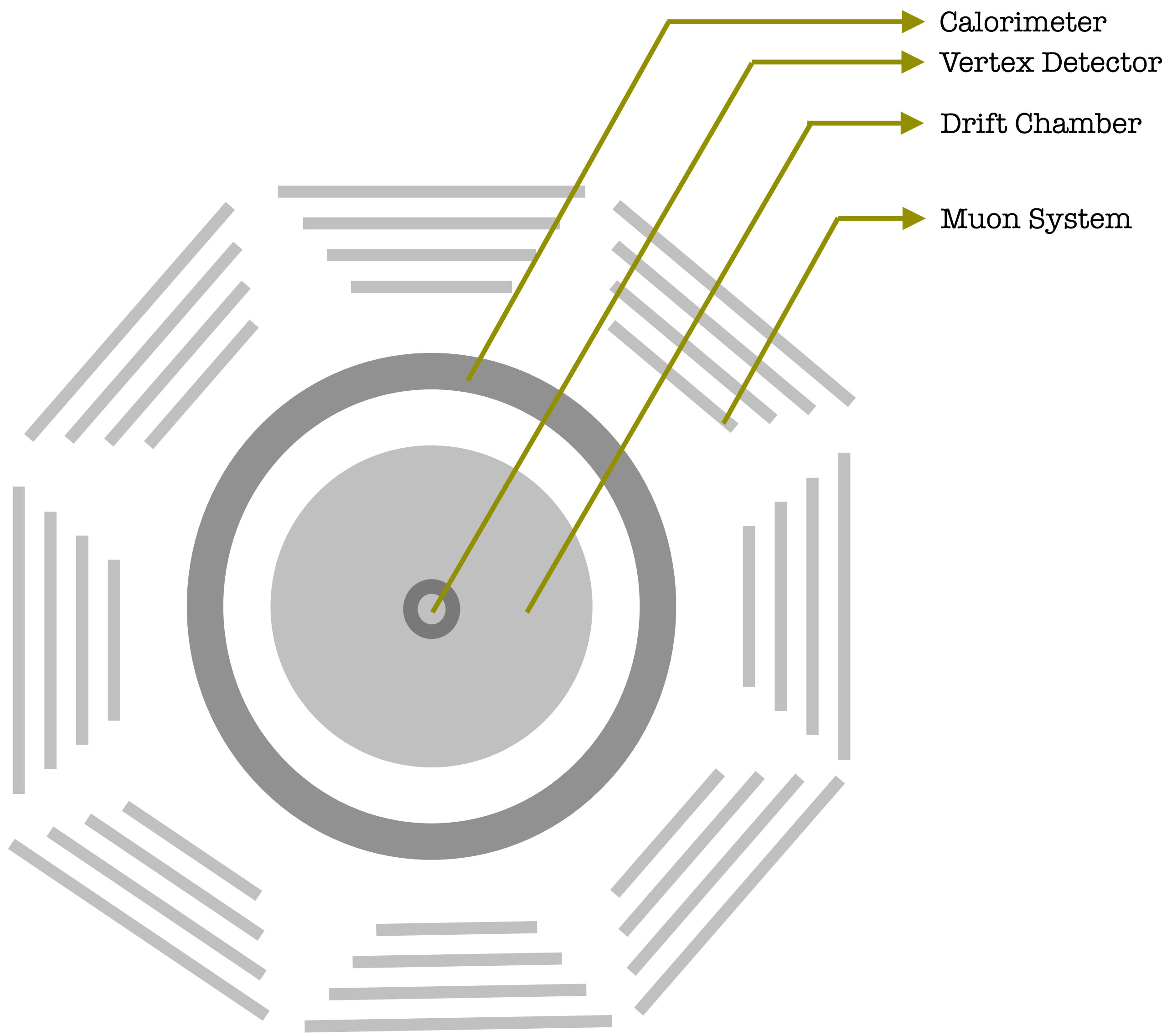
$$N_{\rm sig} = \underbrace{N_{BB}}_{10^8} \times \underbrace{\mathrm{BR}\,(B \to Ka)}_{\text{Our Calculation}} \times \boxed{\mathrm{BR}\,(a \to X)} \times \underbrace{\epsilon_{\rm eff}}_{\text{Required}} \times \underbrace{\mathcal{O}(1)}_{\text{Isospin Factors}}$$

Belle Detector



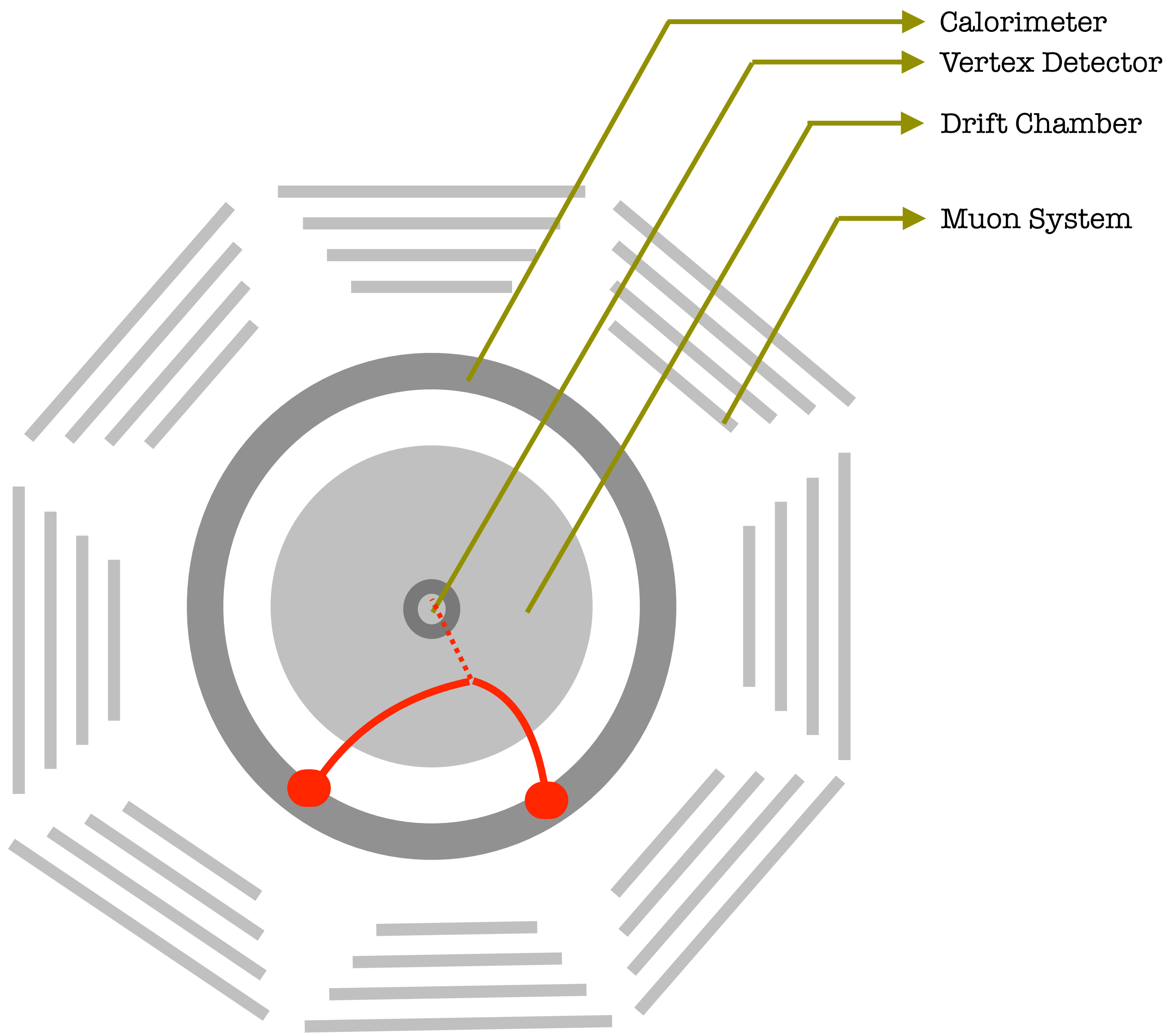
Recent Works at Belle: 1908.09719, 1911.03176, 2108.10331 etc.

Belle Detector



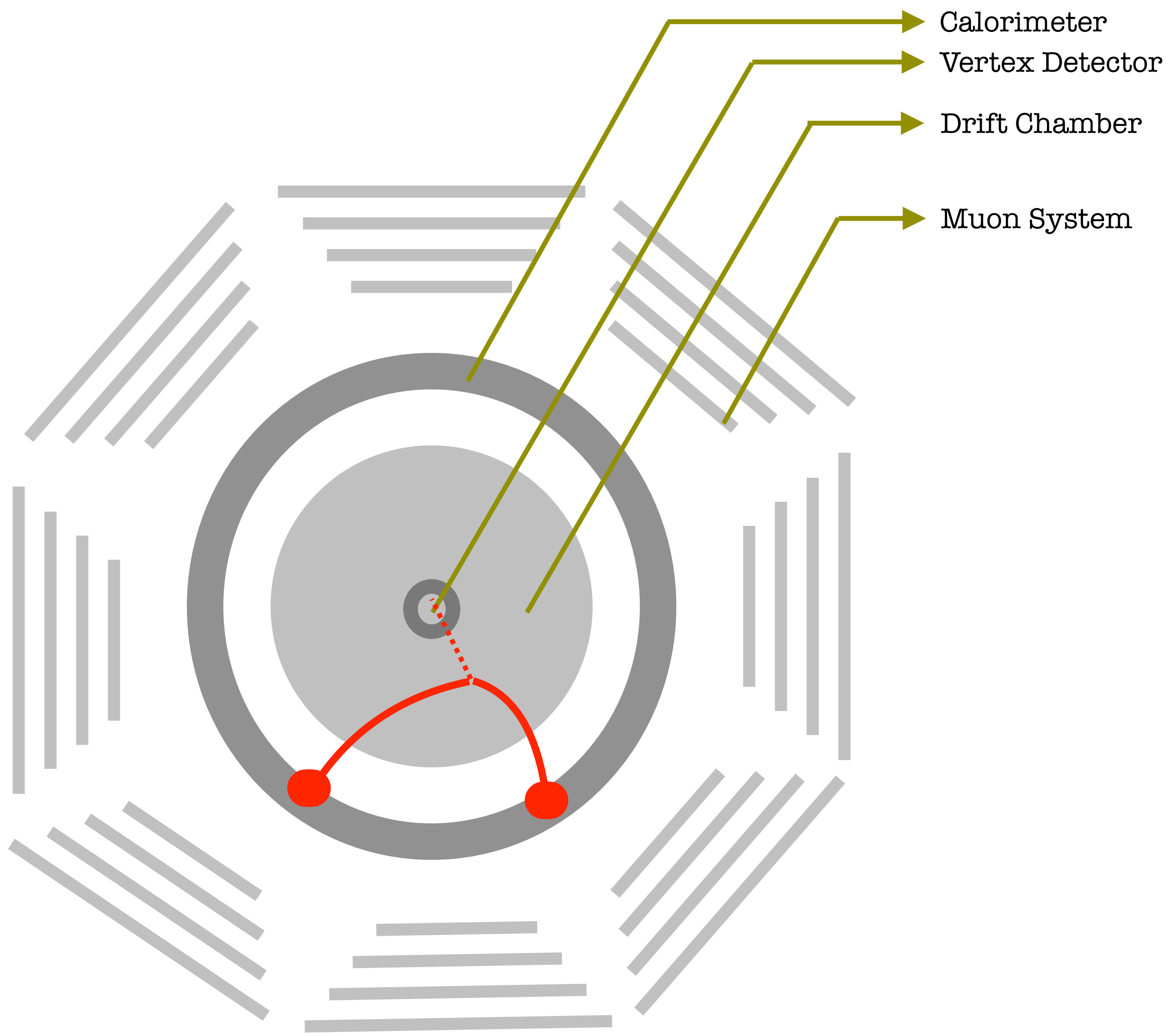
Recent Works at Belle: 1908.09719, 1911.03176, 2108.10331 etc.

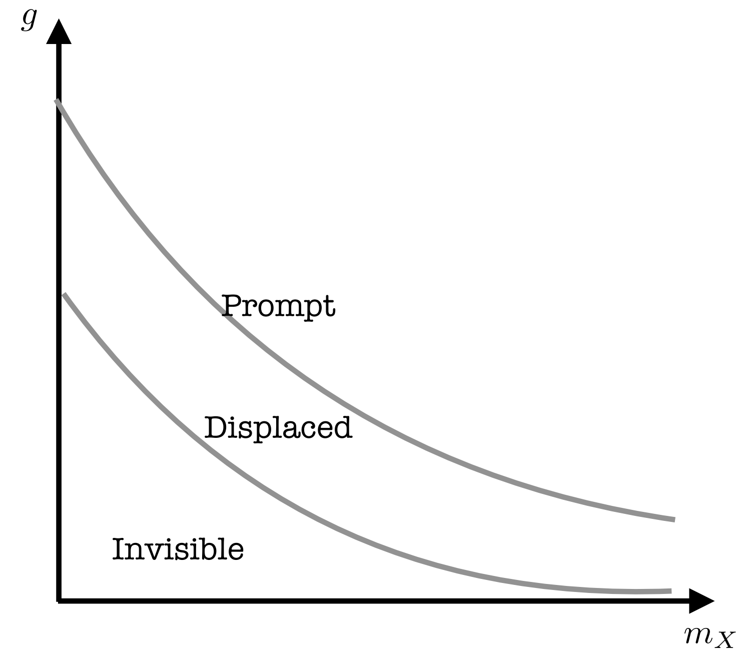
Belle Detector



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

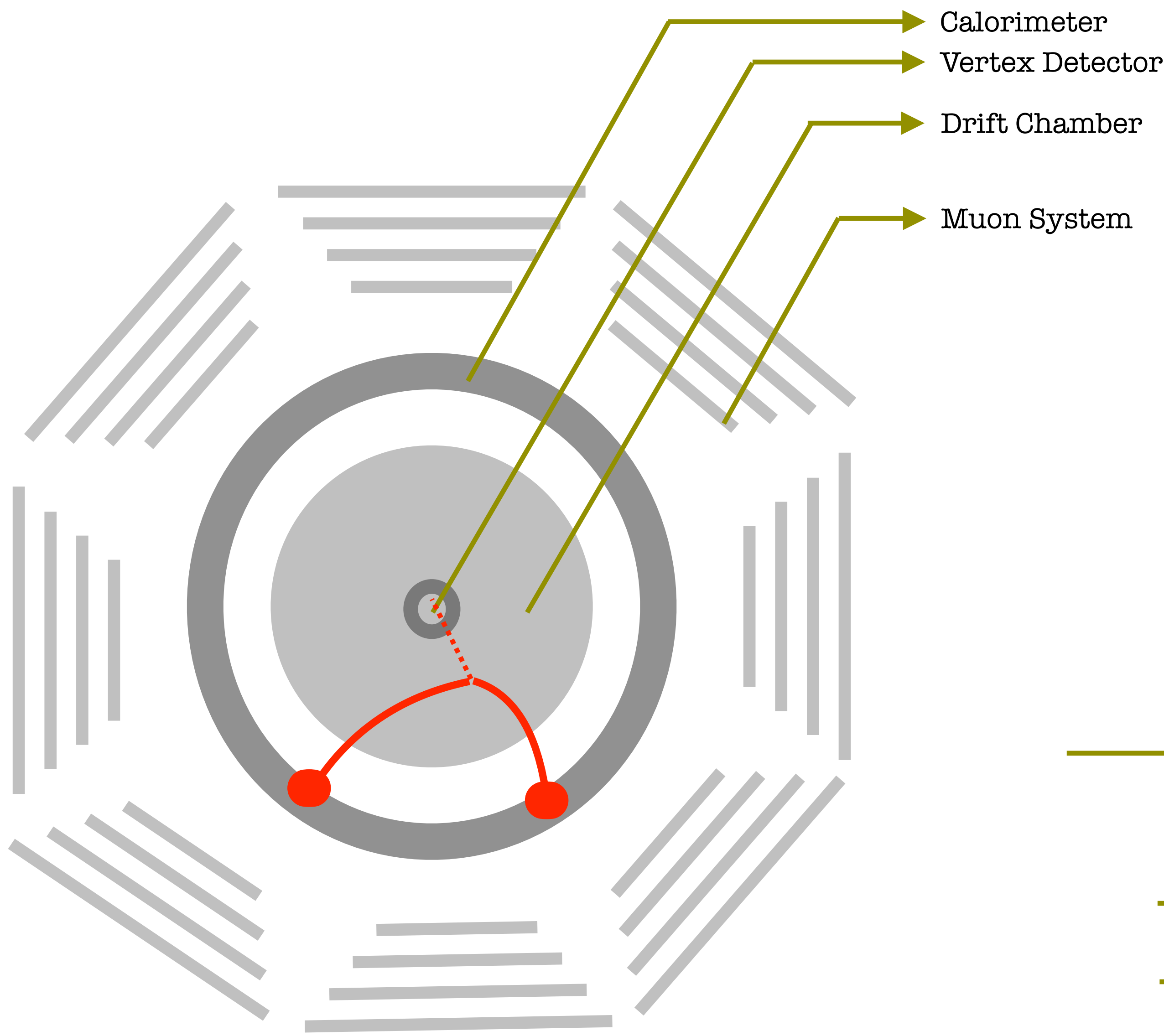
Belle Detector

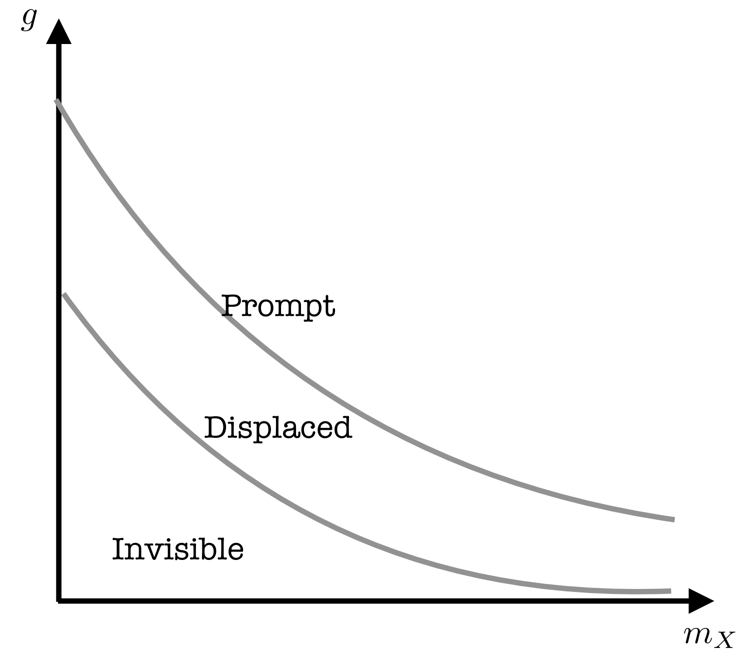


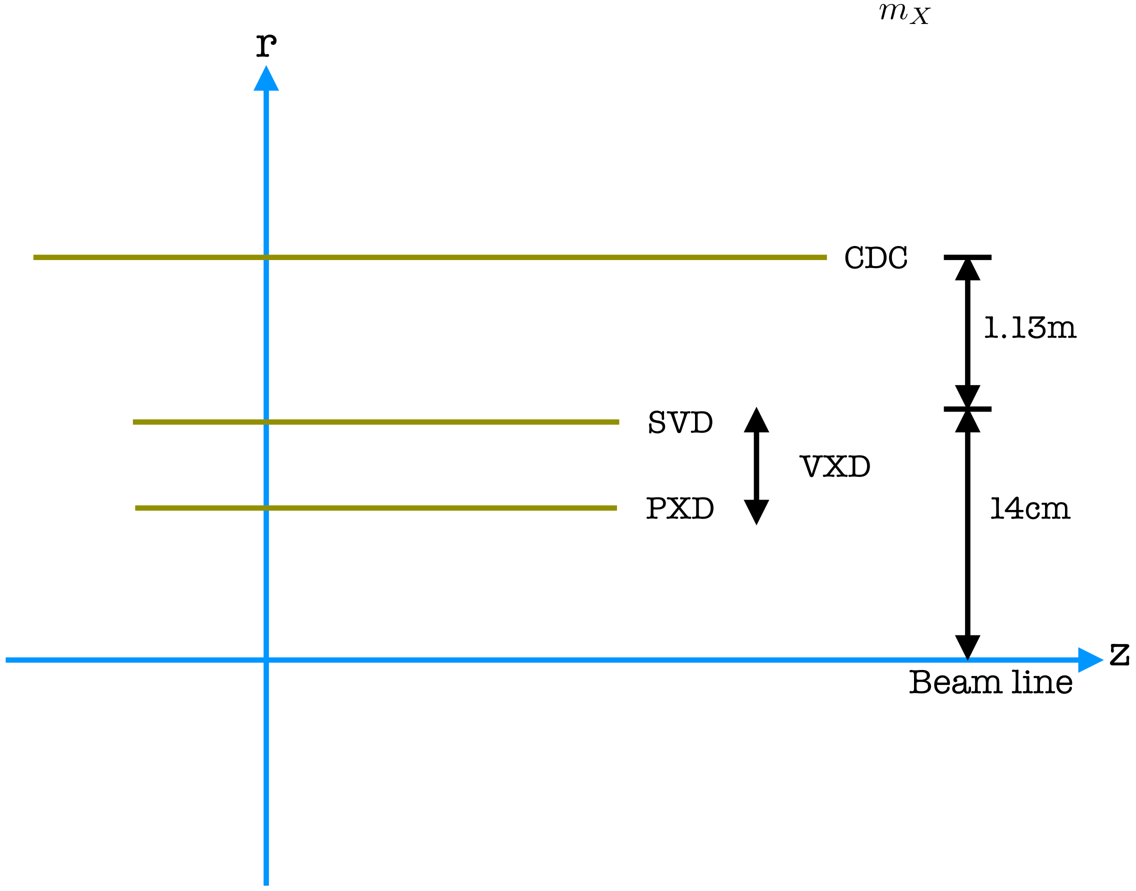


Recent Works at Belle: 1908.09719, 1911.03176, 2108.10331 etc.

Belle Detector

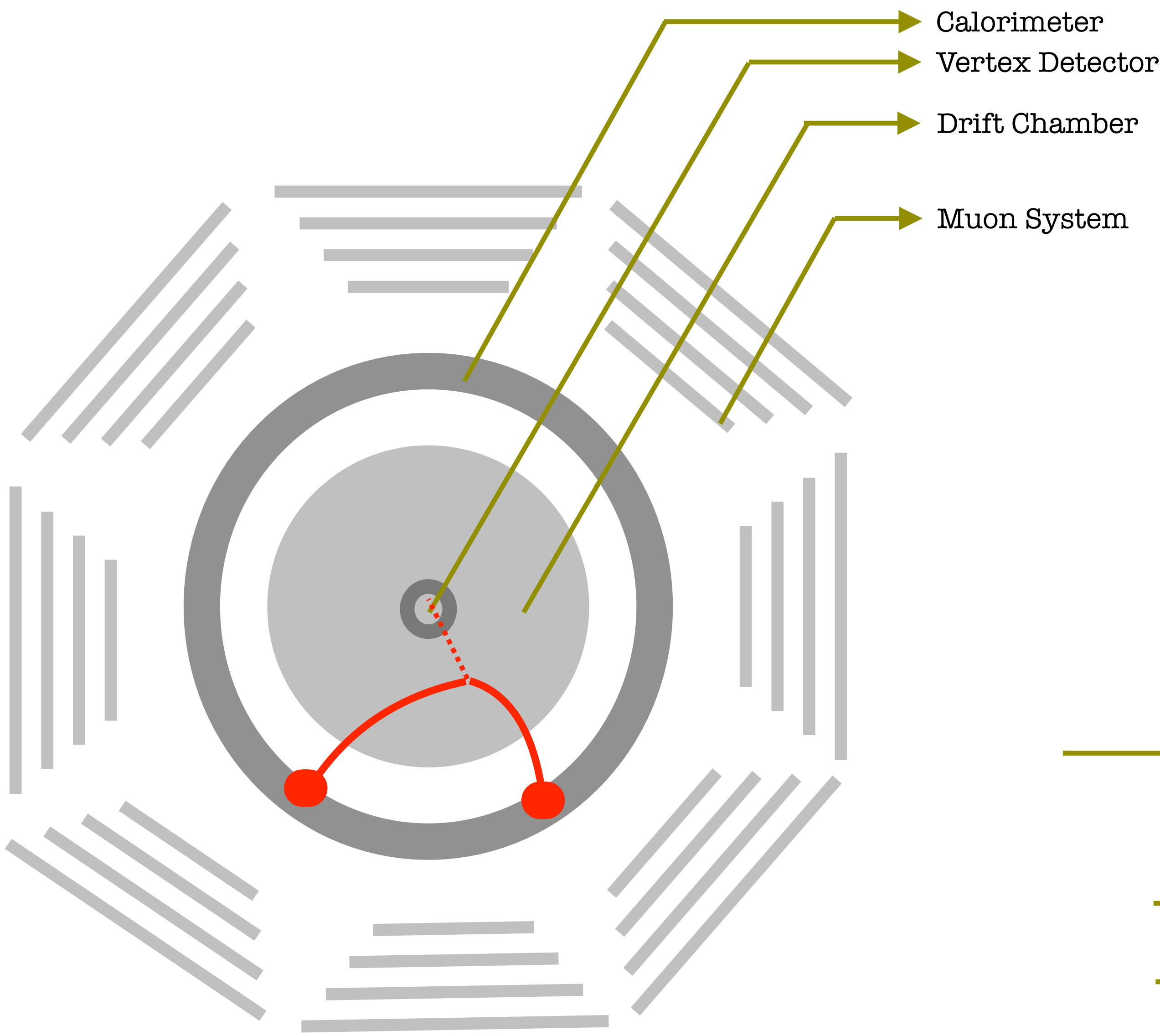


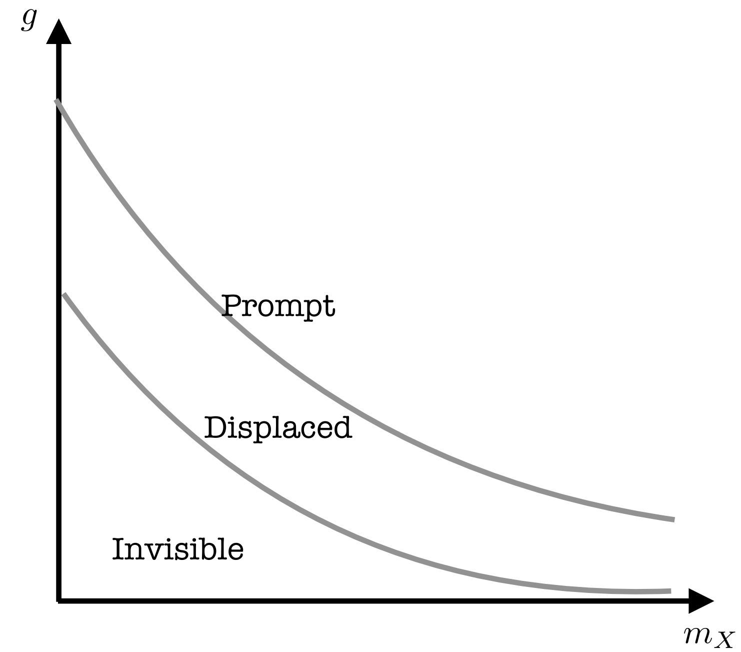


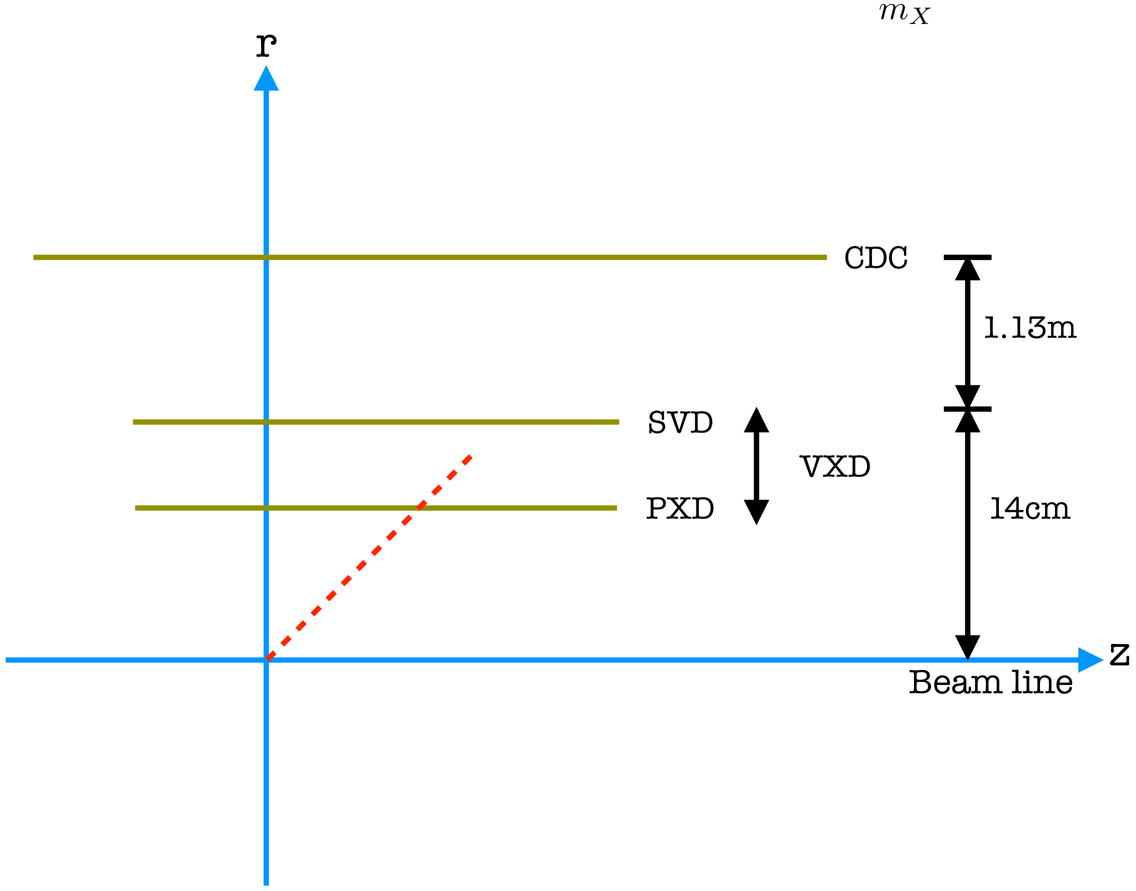


Recent Works at Belle: 1908.09719, 1911.03176, 2108.10331 etc.

Belle Detector

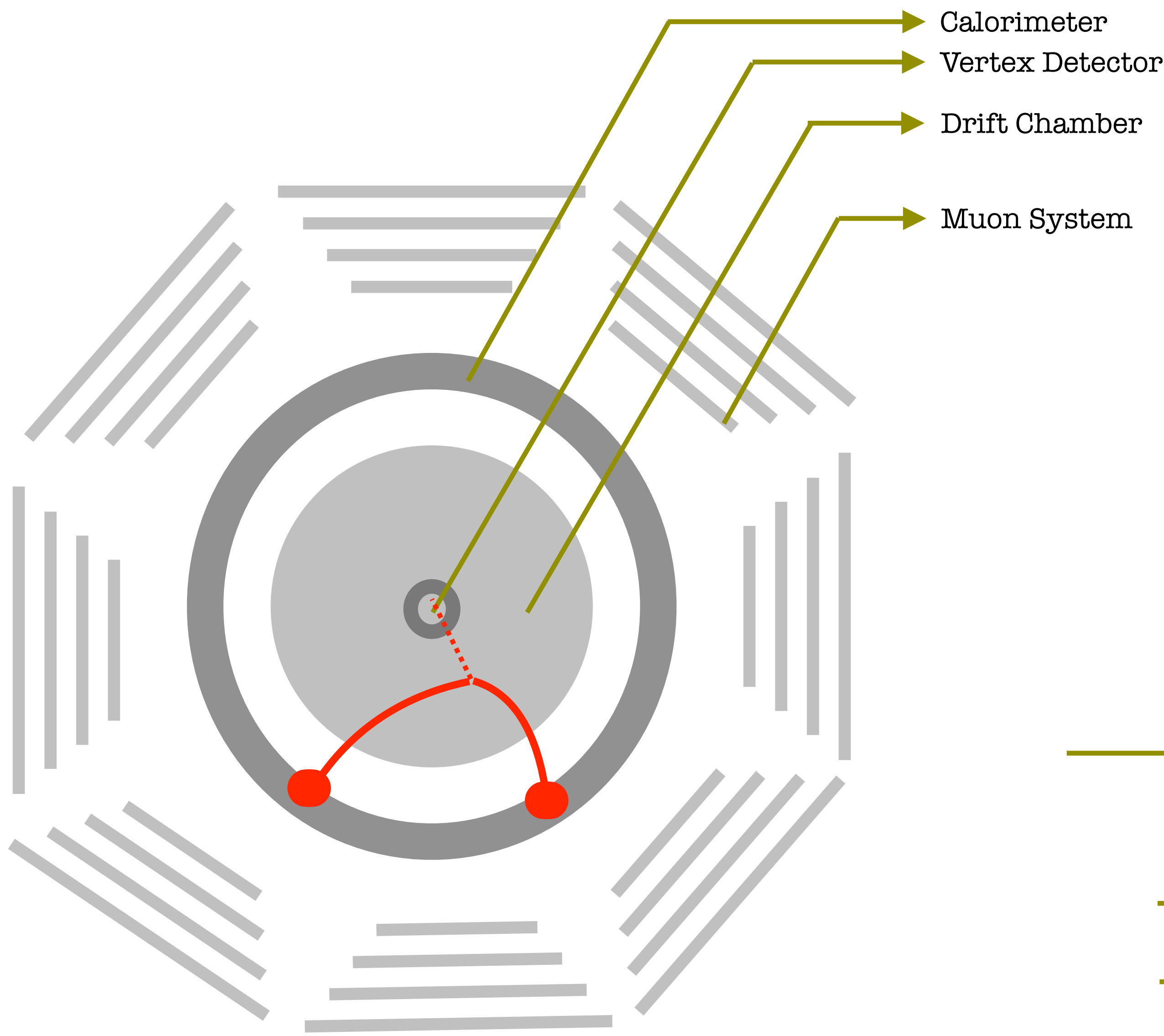


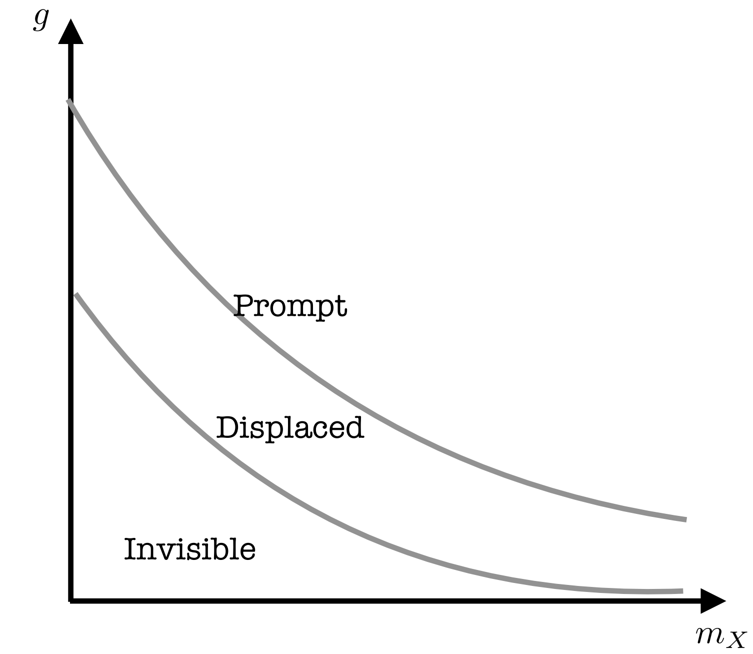


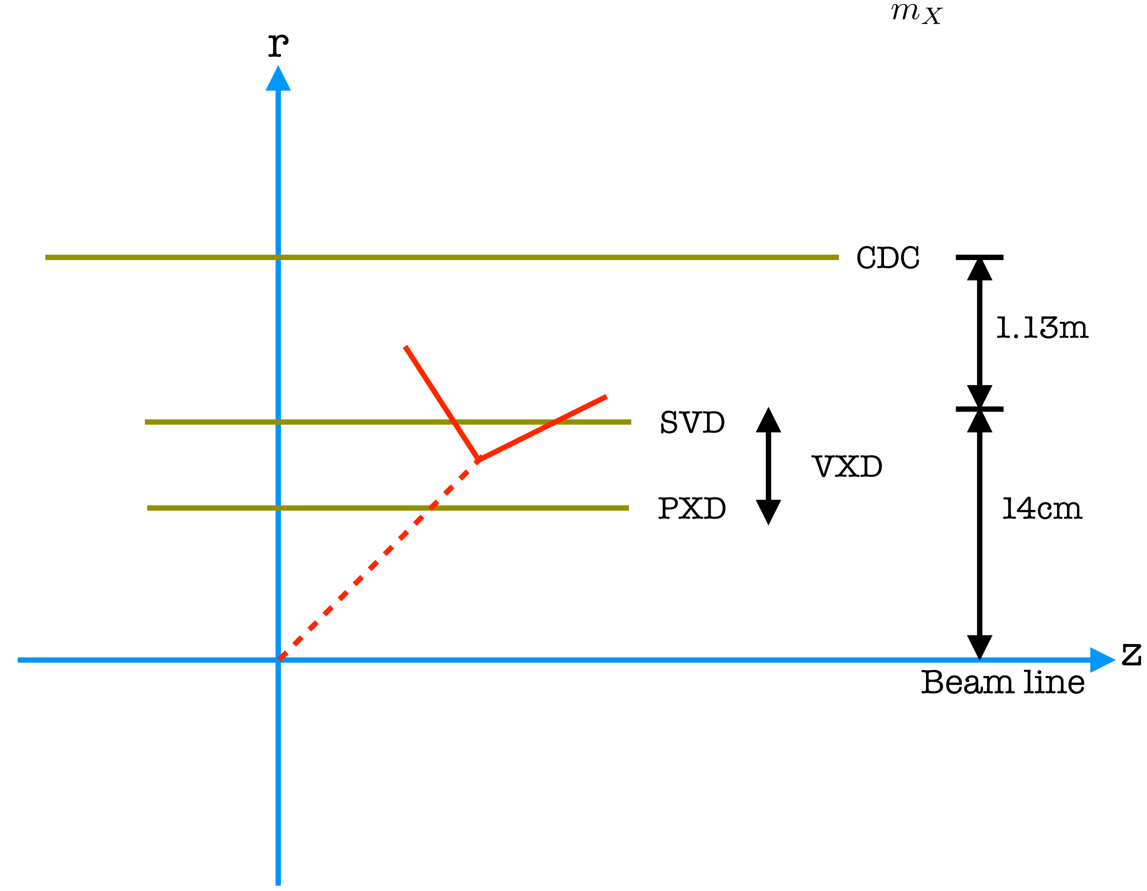


Recent Works at Belle: 1908.09719, 1911.03176, 2108.10331 etc.

Belle Detector

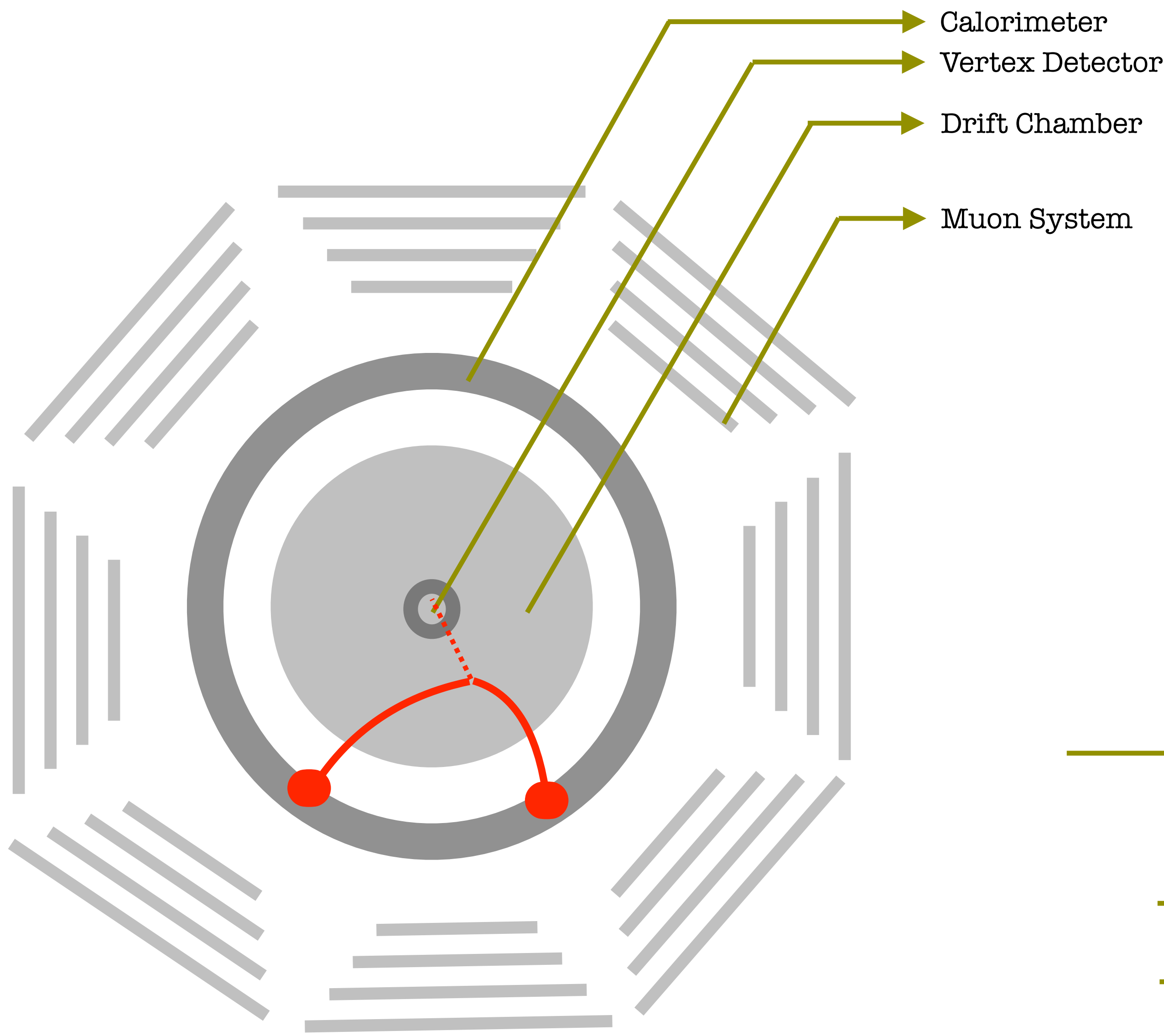


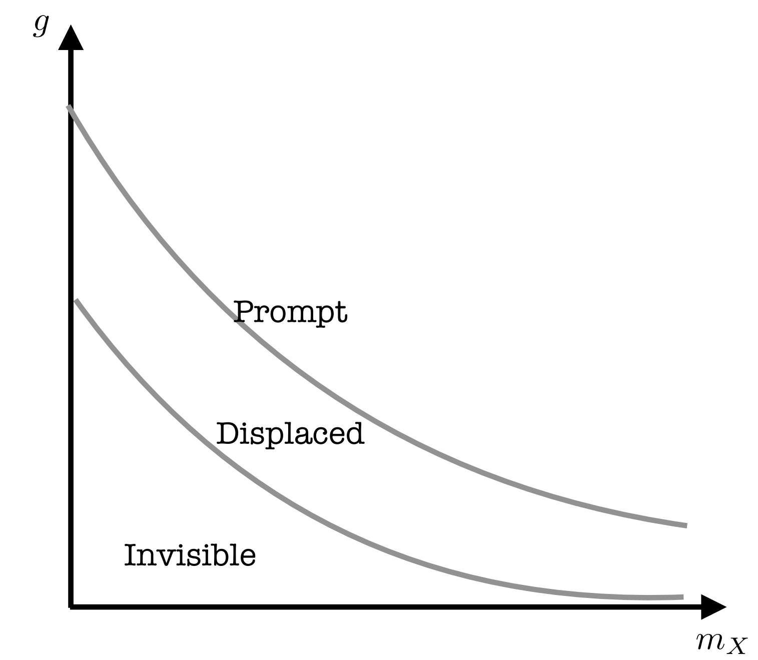


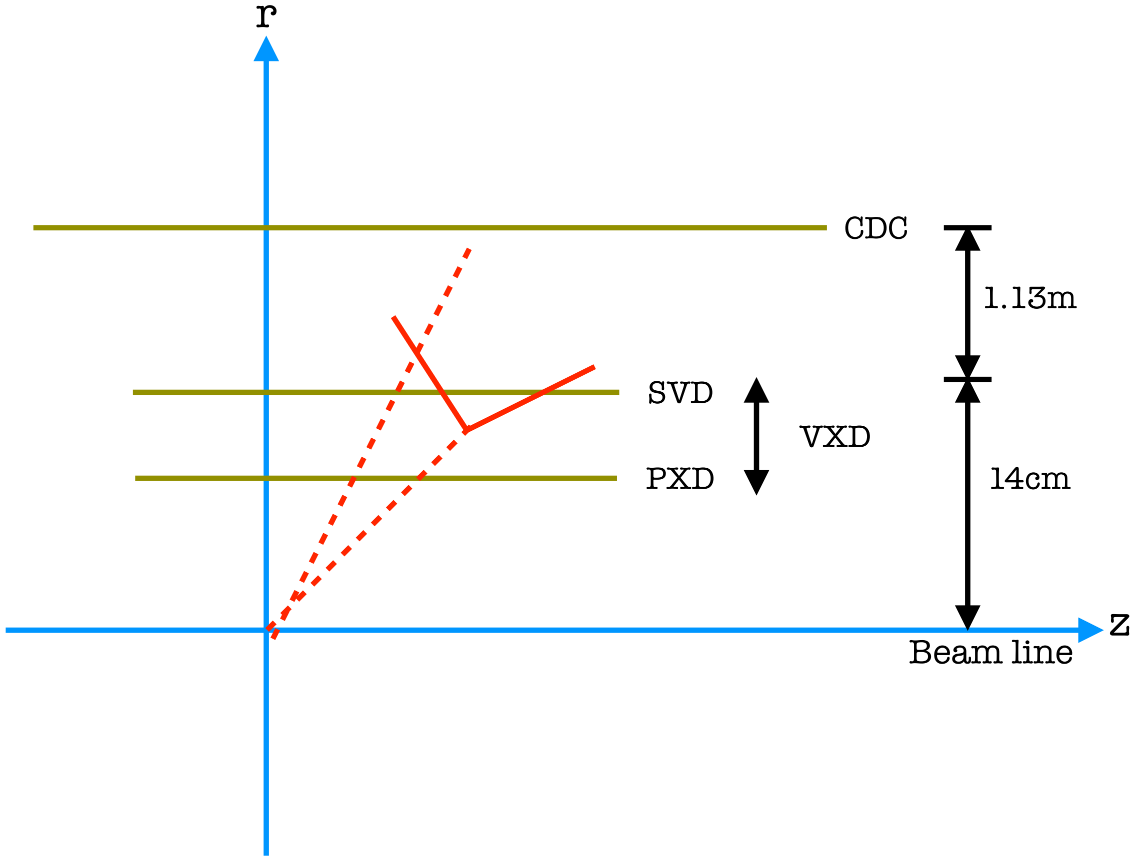


Recent Works at Belle: 1908.09719, 1911.03176, 2108.10331 etc.

Belle Detector

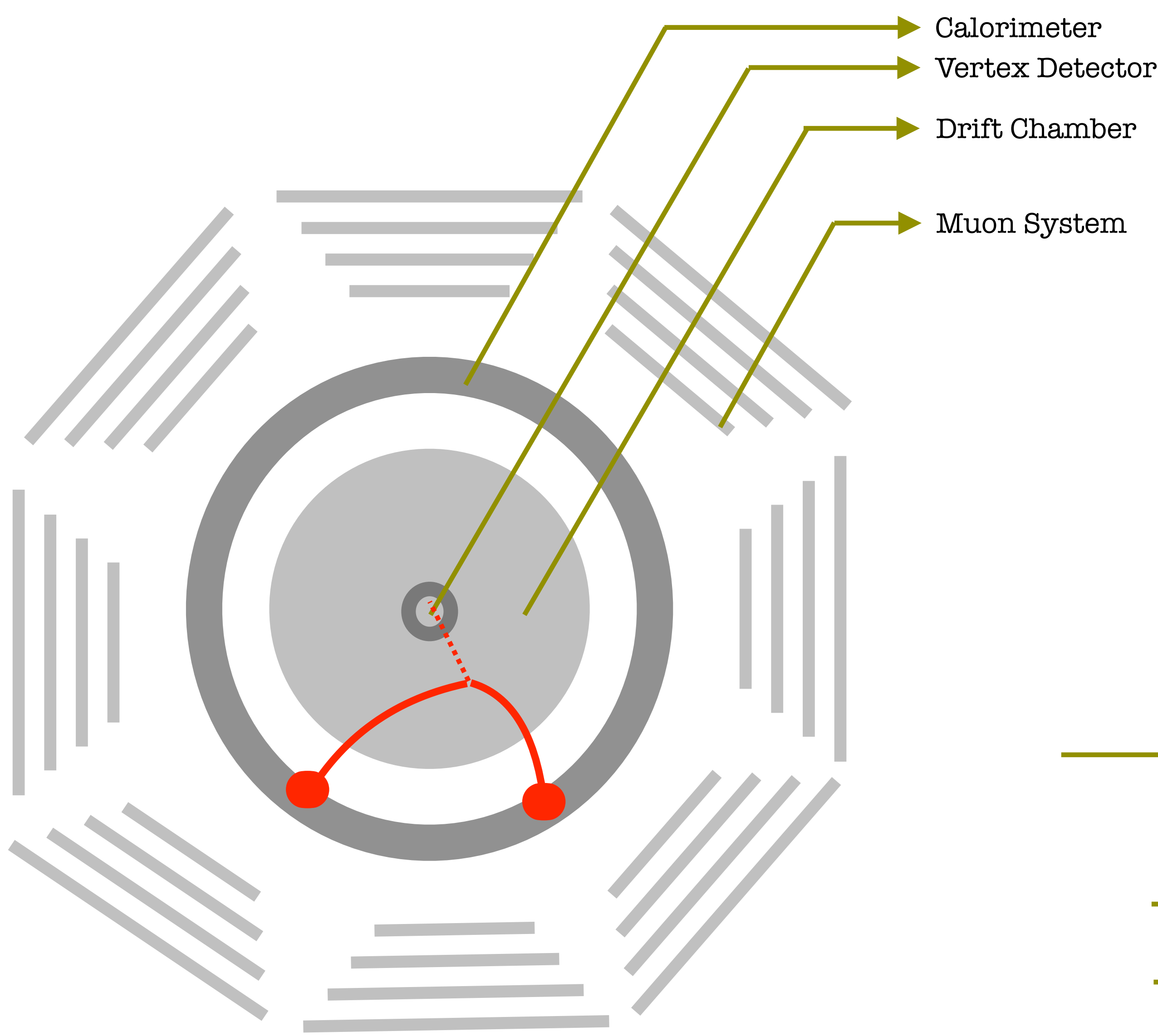


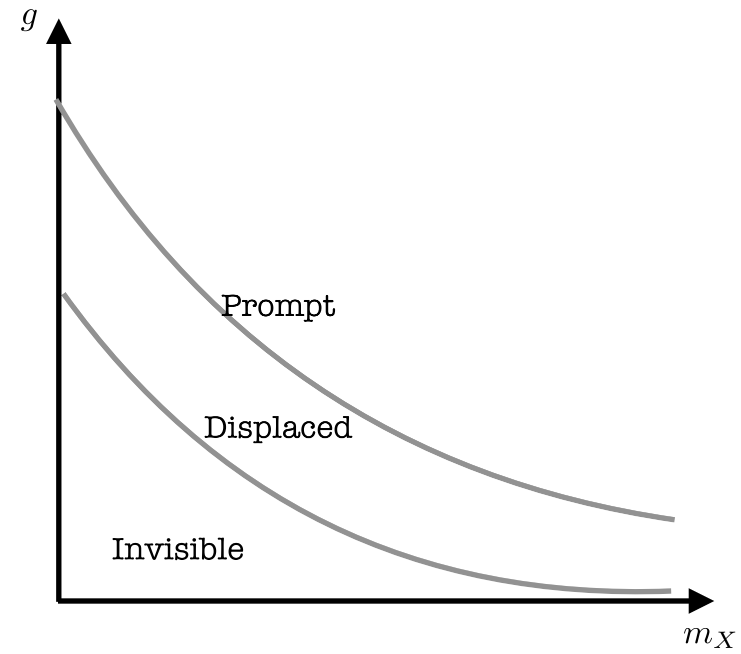


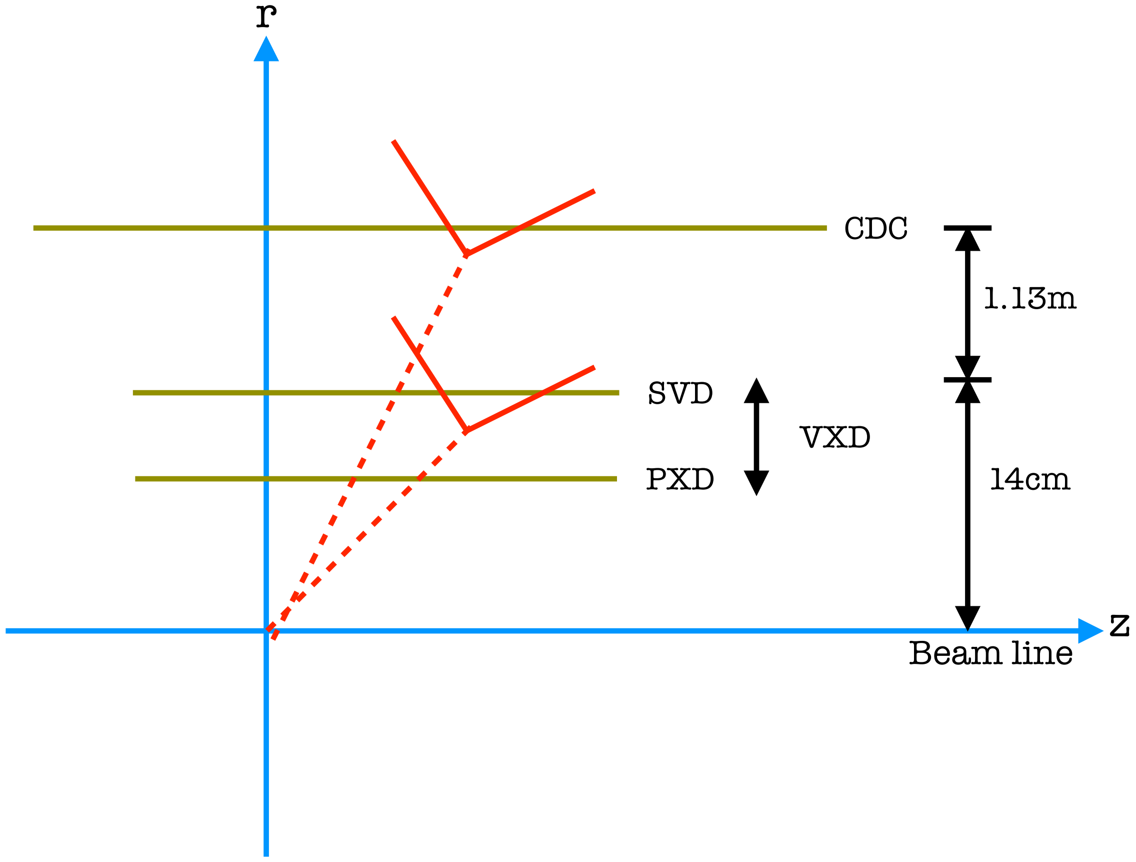


Recent Works at Belle: 1908.09719, 1911.03176, 2108.10331 etc.

Belle Detector



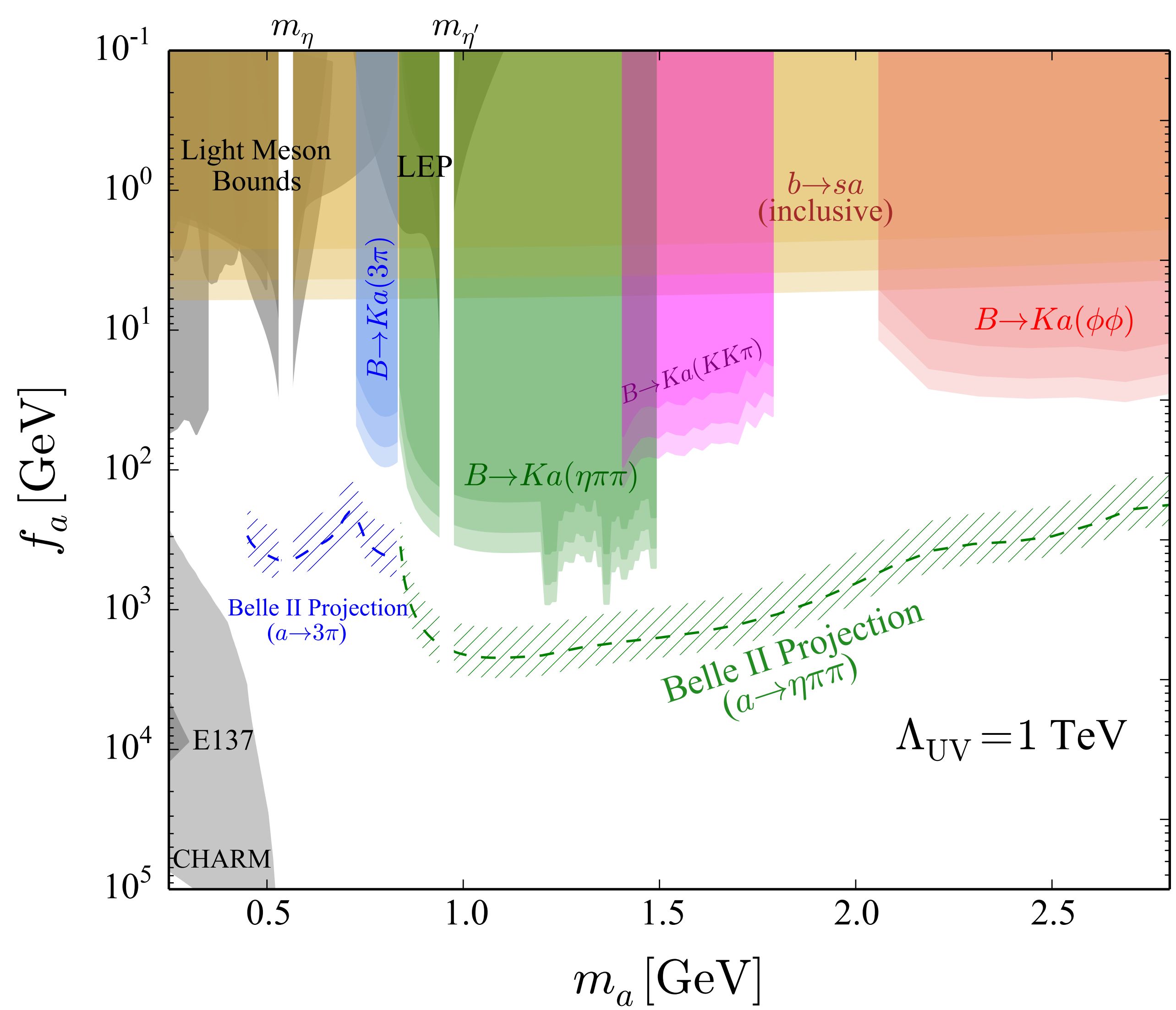


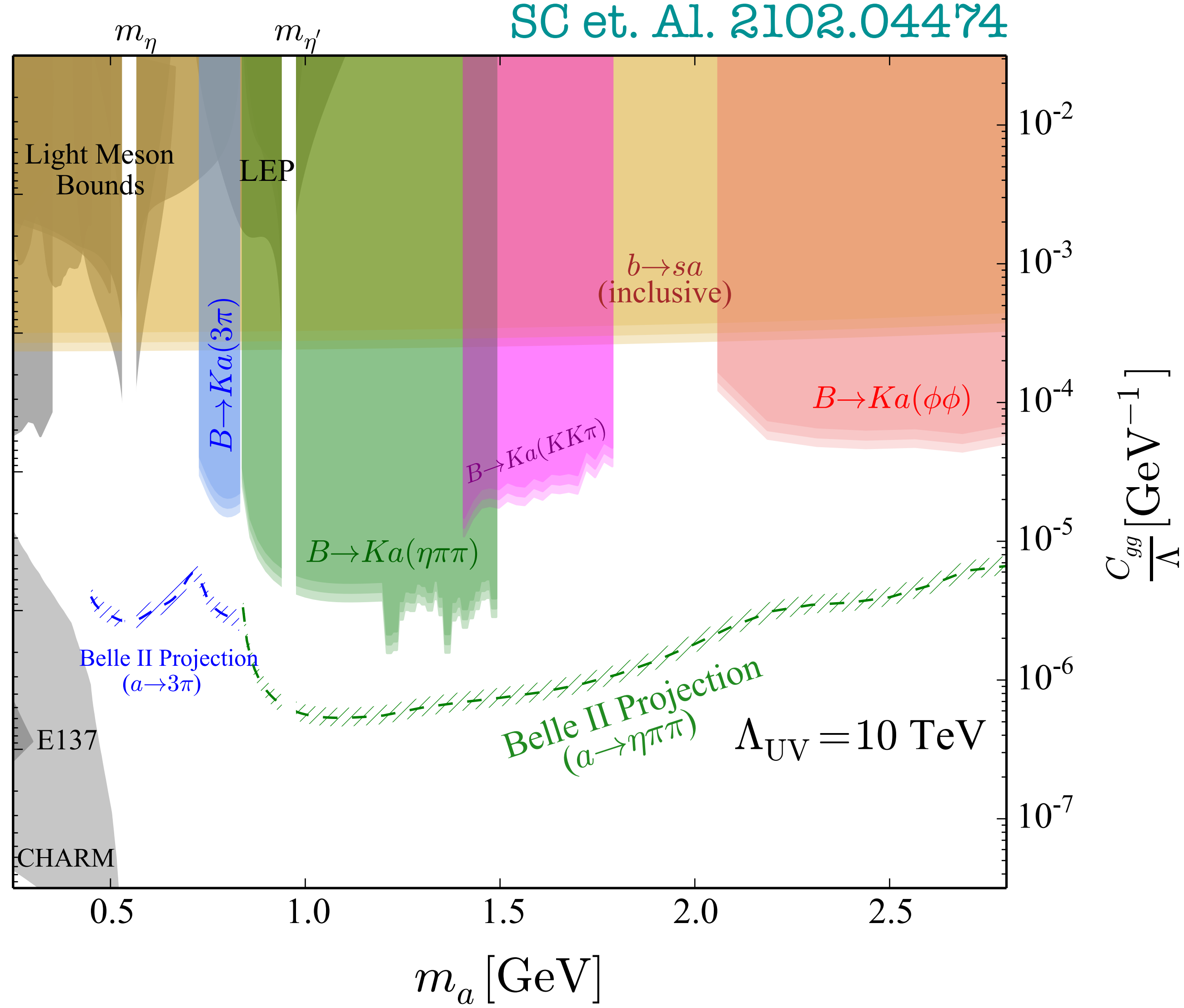


Recent Works at Belle: 1908.09719, 1911.03176, 2108.10331 etc.

Prompt Searches: Minimal Coupling

SC et. Al. 2102.04474



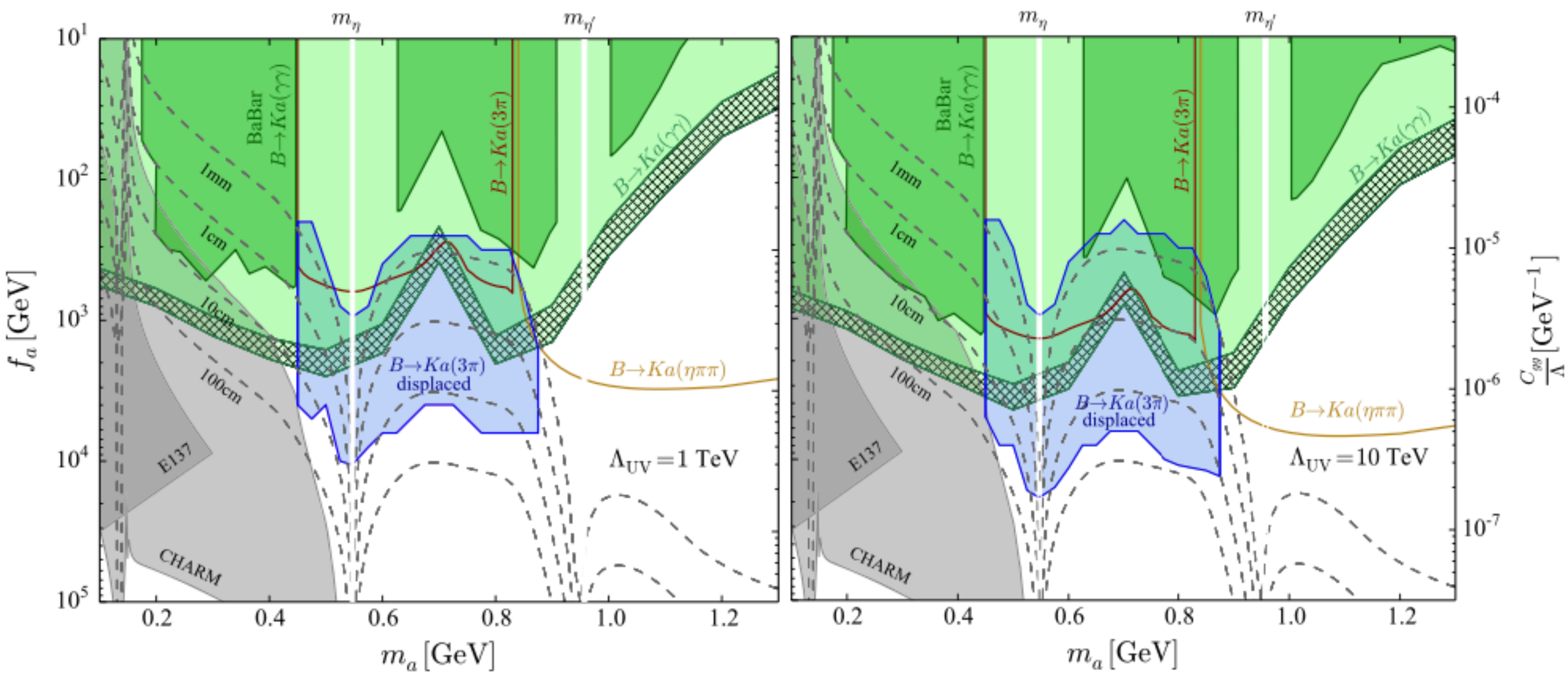


$\Lambda_{UV} = 1$ TeV

$\Lambda_{UV} = 10$ TeV

Displaced Searches: Minimal Coupling

SC et. Al. 2108.10331



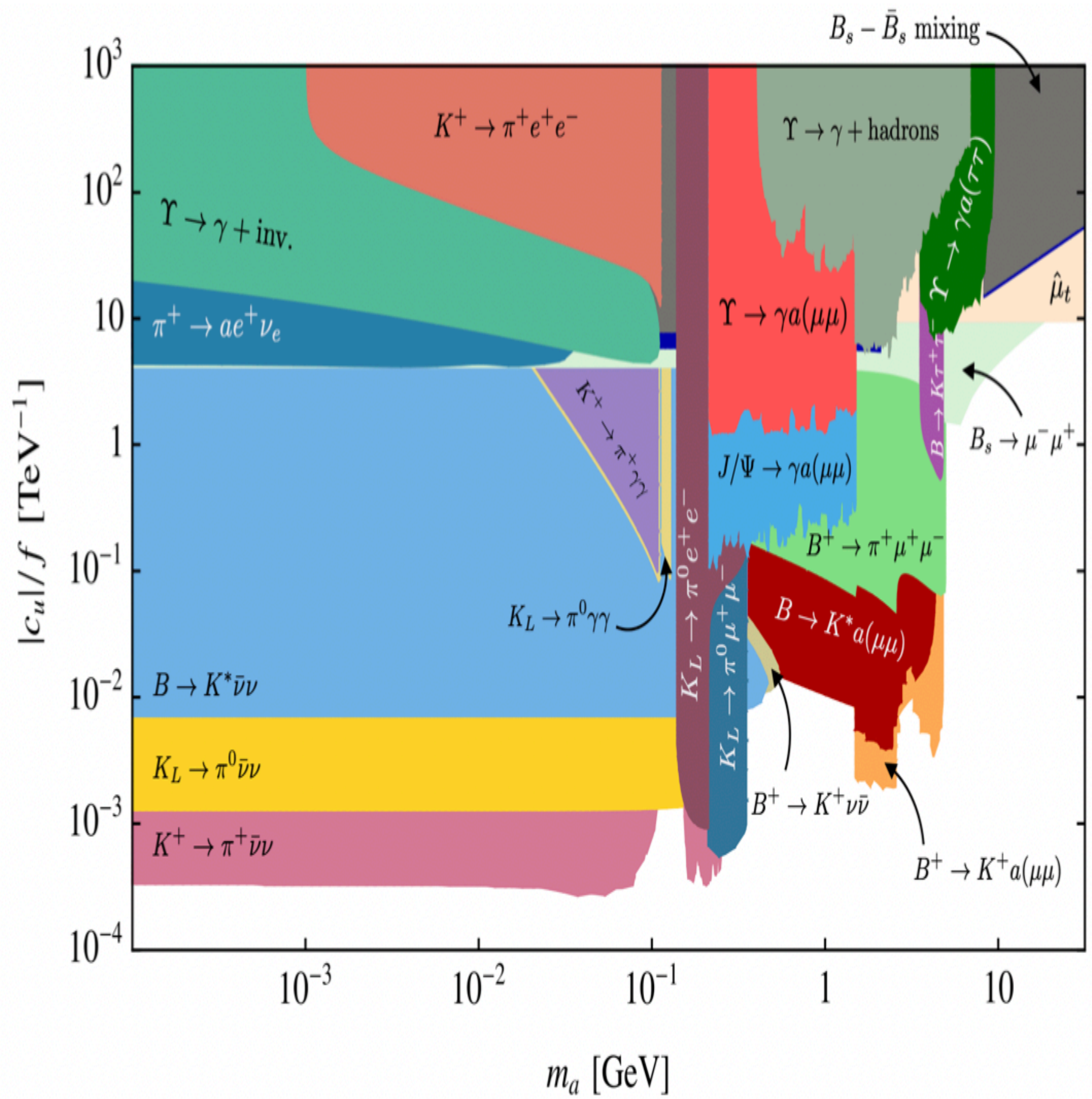
$\Lambda_{\rm UV} = 1$ TeV

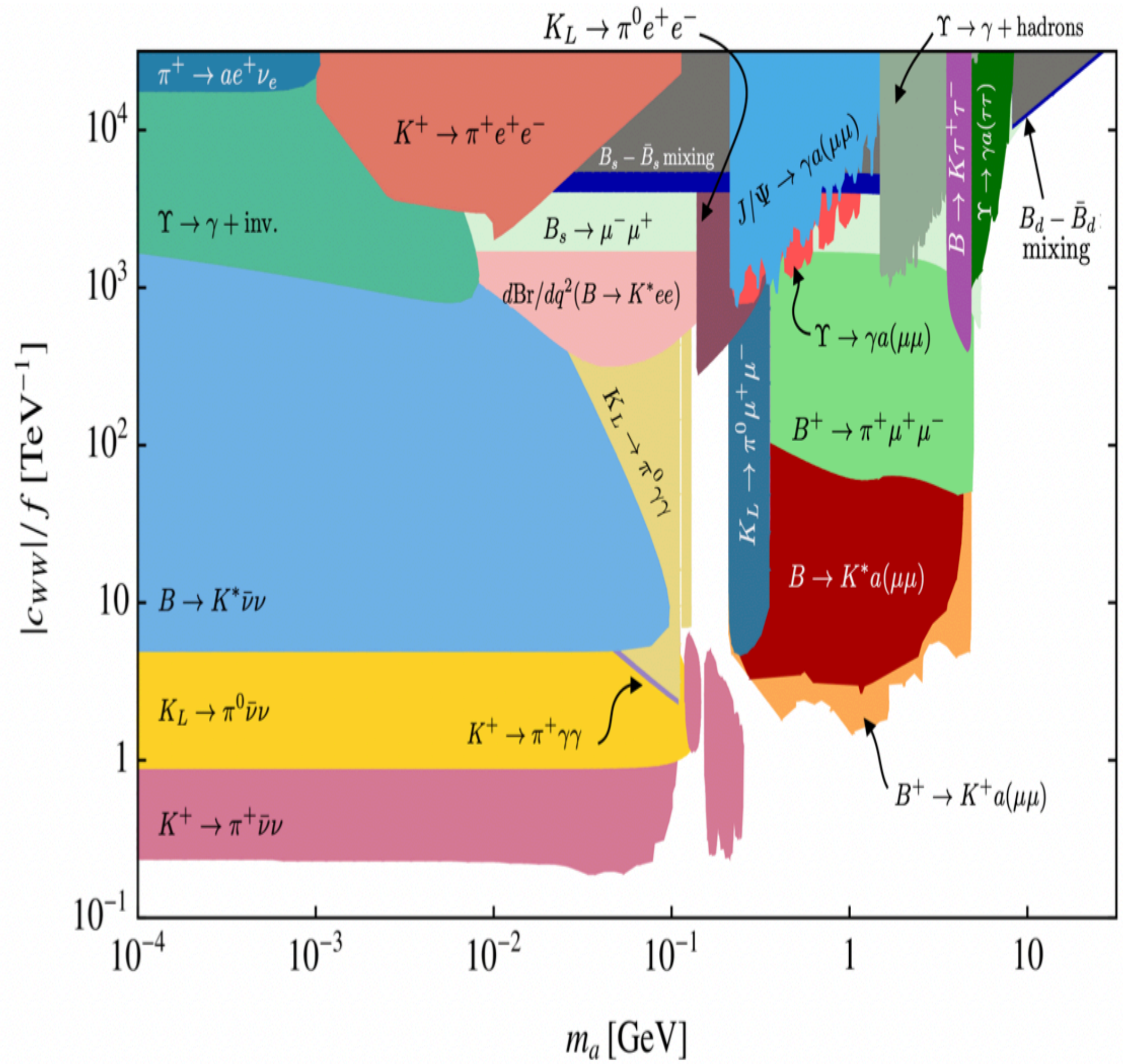
$\Lambda_{\rm UV} = 10$ TeV

Backgrounds: $B \to K\omega\,(3\pi)$, $B^- \to K^- K_L\left(\pi^+\pi^-\pi^0\right)$, $B^- \to K^- K_0^*\left(K_s\pi^0\right)$

Other Couplings of ALP

$$\mathcal{L} \supset C_{agg}\,\frac{a}{f_a}G\widetilde{G} + C_{aWW}\,\frac{a}{f_a}W\widetilde{W} + C_{aBB}\,\frac{a}{f_a}B\widetilde{B} + C_{aq_iq_j}\sum_{i,j}\frac{\partial_\mu a}{f_a}\,\bar{q}_i\gamma^\mu\gamma_5 q_j$$

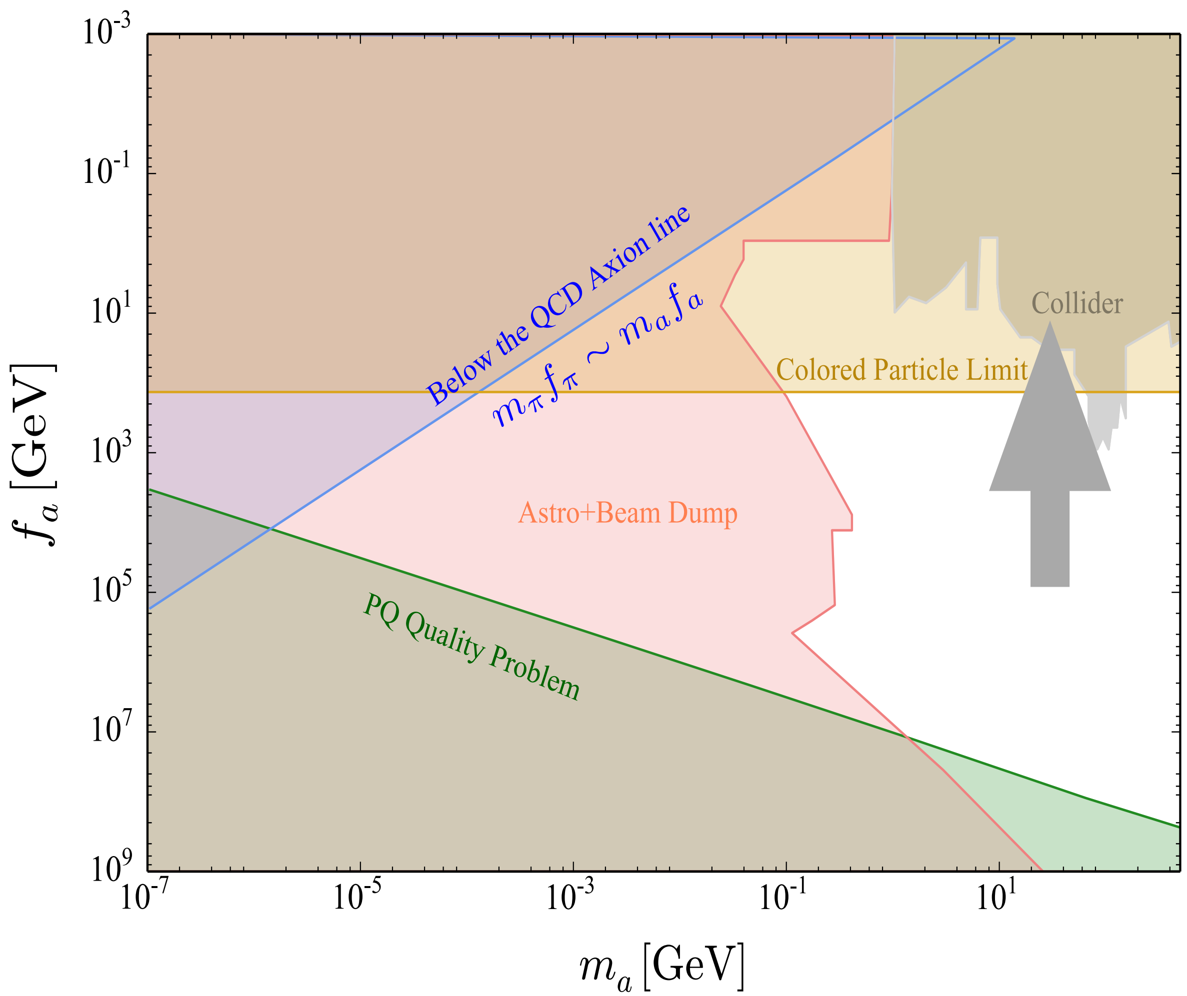




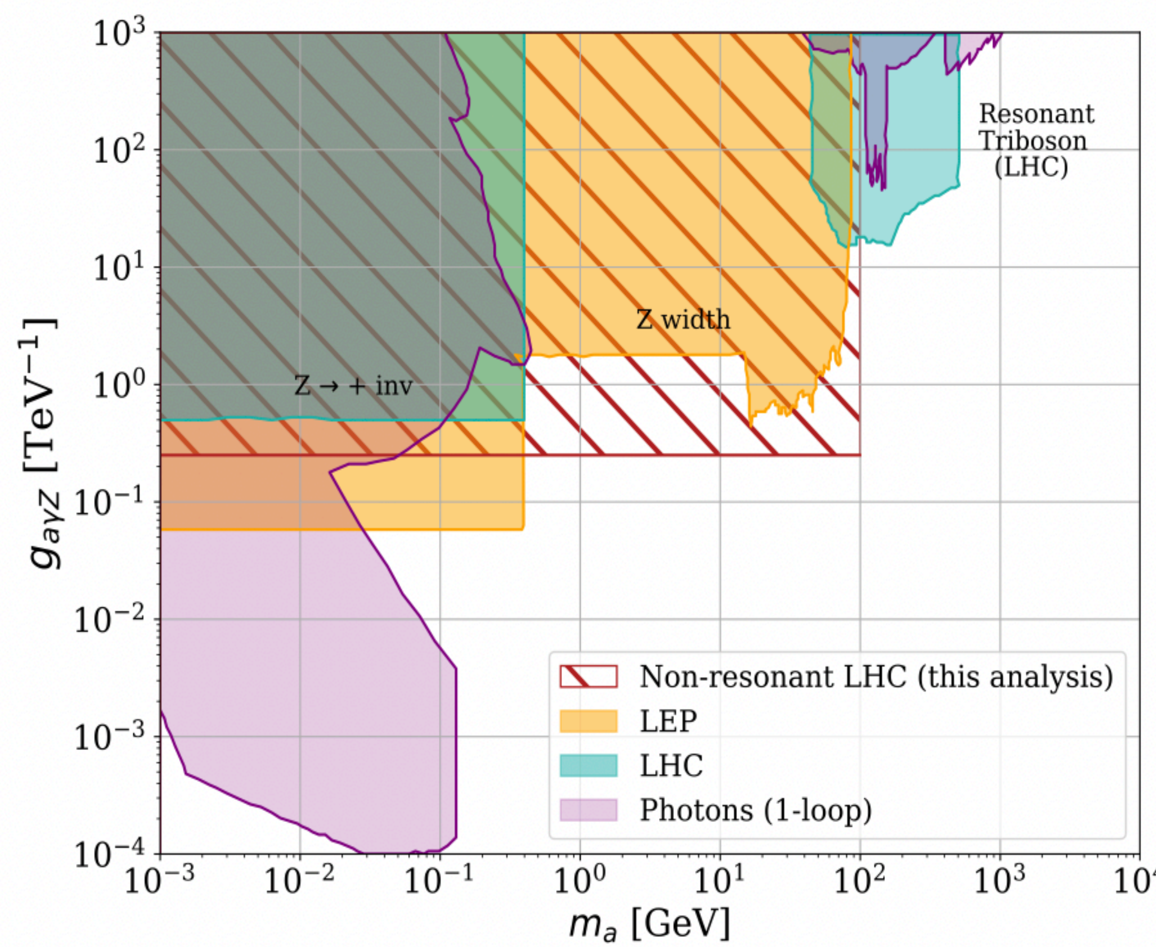
Bauer et. Al. 2110.10698

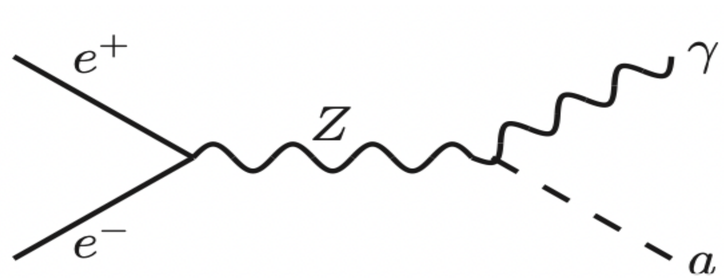
ALPs: Energy Frontier

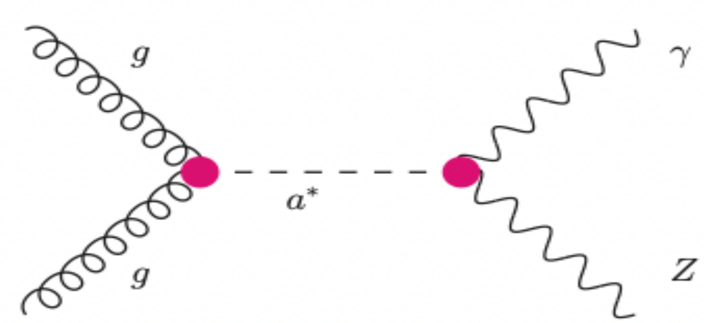
Bauer et. Al. 1808.10323



Tisa Biswas. 2312.05992







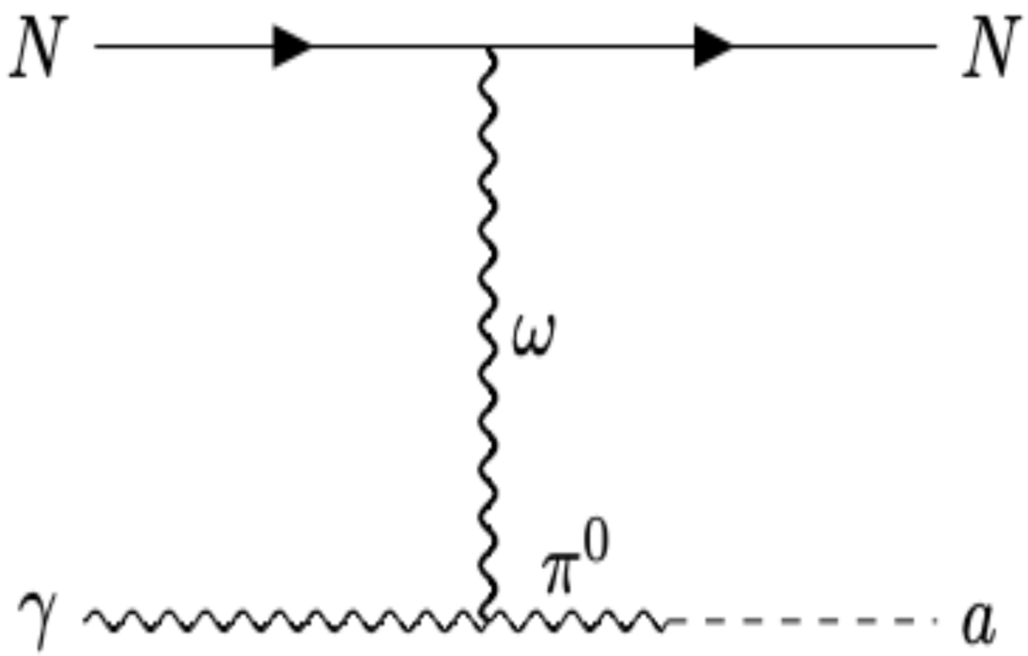
WZW-Terms?

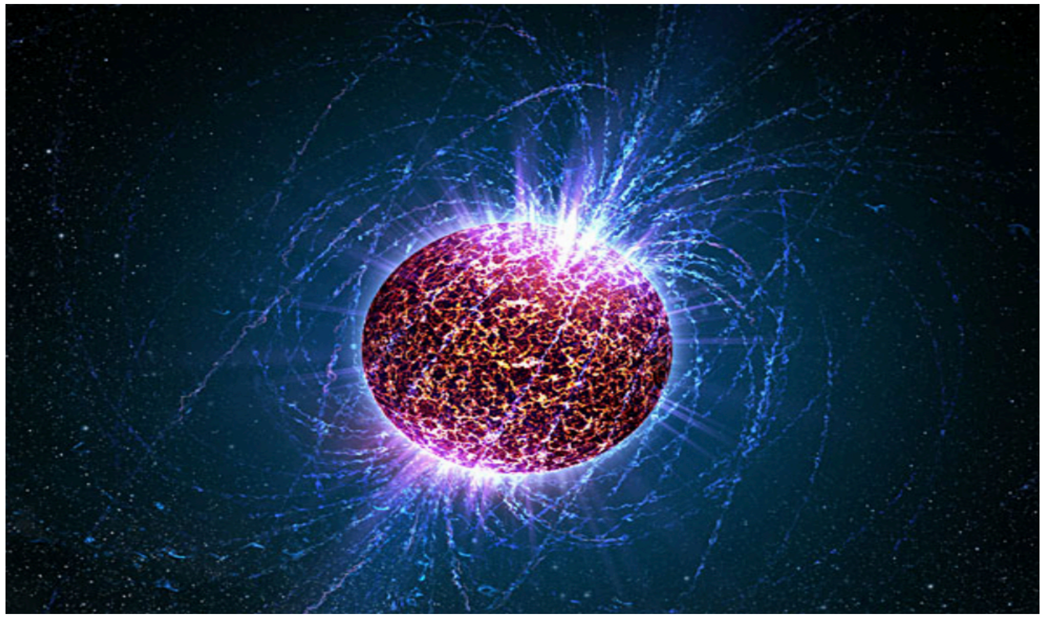
UV (QCD)		IR (ChPT)
$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + i\bar{\psi}\not{D}\psi_i$	$\longrightarrow$	$\mathcal{L}_{\chi\mathrm{PT}} \supset \frac{f_\pi^2}{8} \mathrm{Tr}\left[D^\mu\Sigma\, D_\mu\Sigma^\dagger\right] + ..$
$G = SU(N_f)_L \times SU(N_f)_R$		$H = SU(N_f)_V$
’t Hooft Anomaly?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

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

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
- Probing such interactions at the intensity frontiers, GlueX etc.

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

Fantastic Axions & where to find them

Intensity Frontier

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

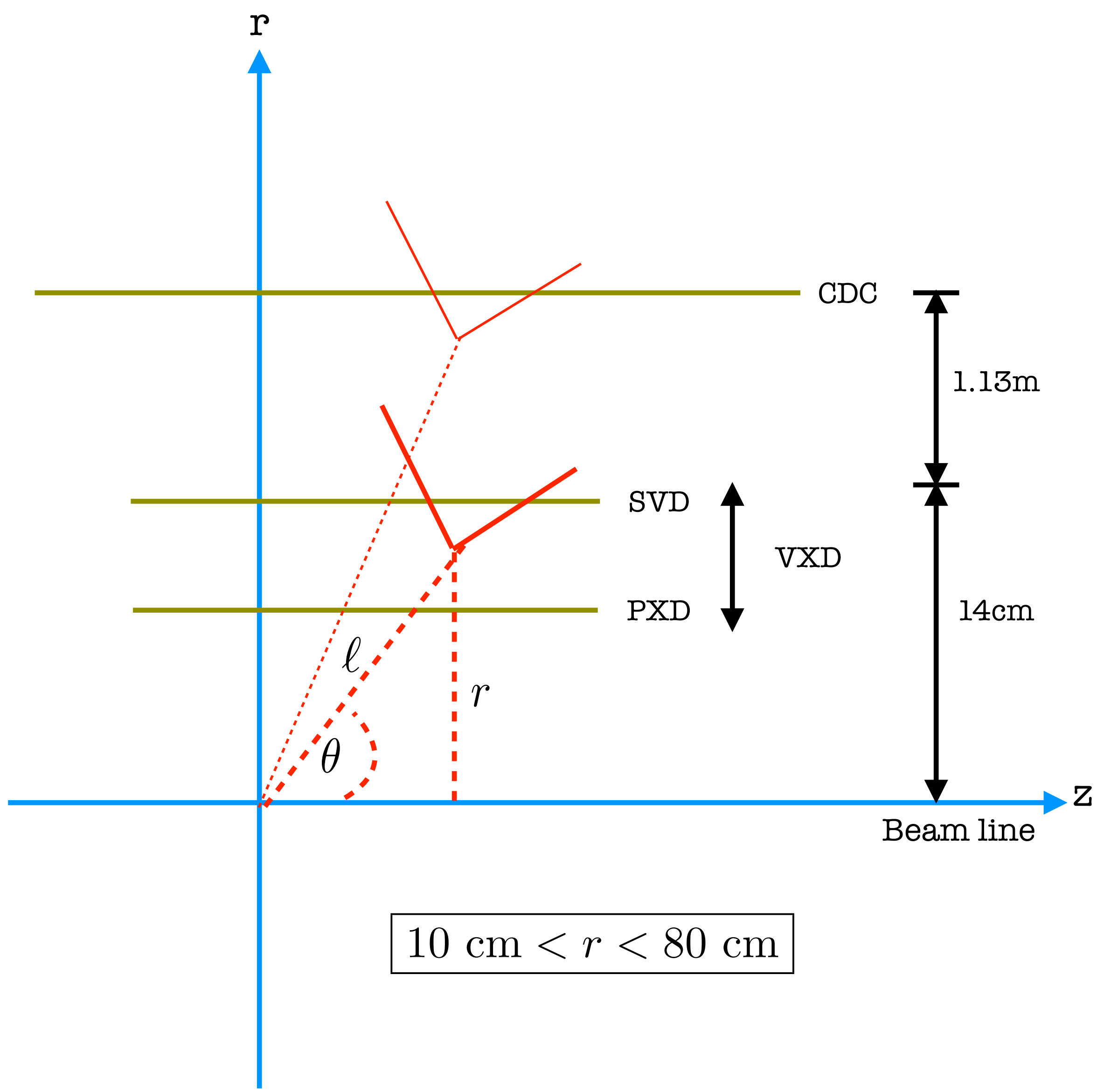
Energy Frontier

- 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)

Displaced Searches at Belle



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

- Linear Falling Efficiency:

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

- Probability for decay

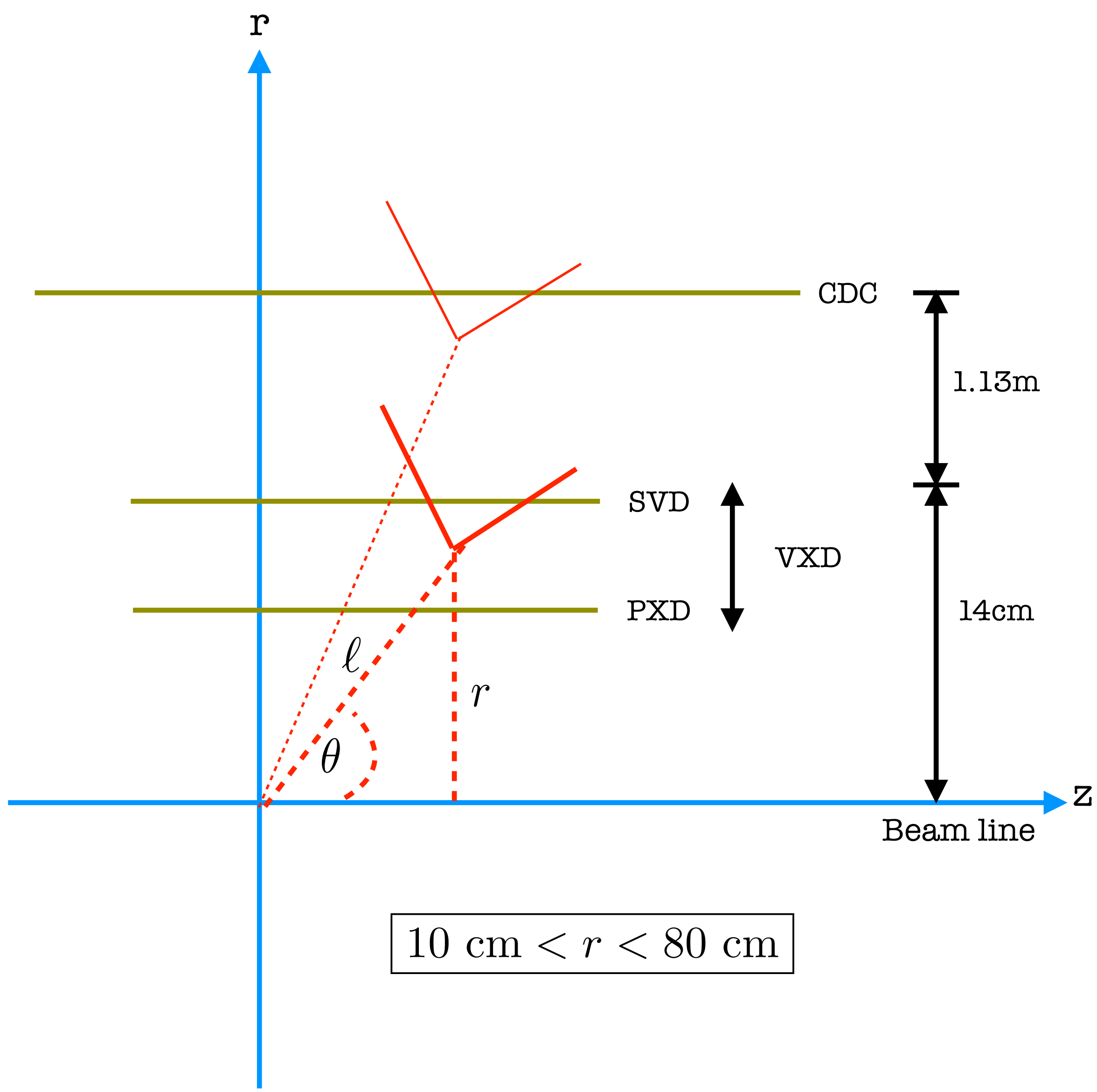
$$P(\ell) = \frac{e^{-\ell/\lambda}}{\lambda}$$

- Probability for identifying displaced vertex

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

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

Displaced Searches at Belle



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

- Linear Falling Efficiency:

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

- Probability for decay

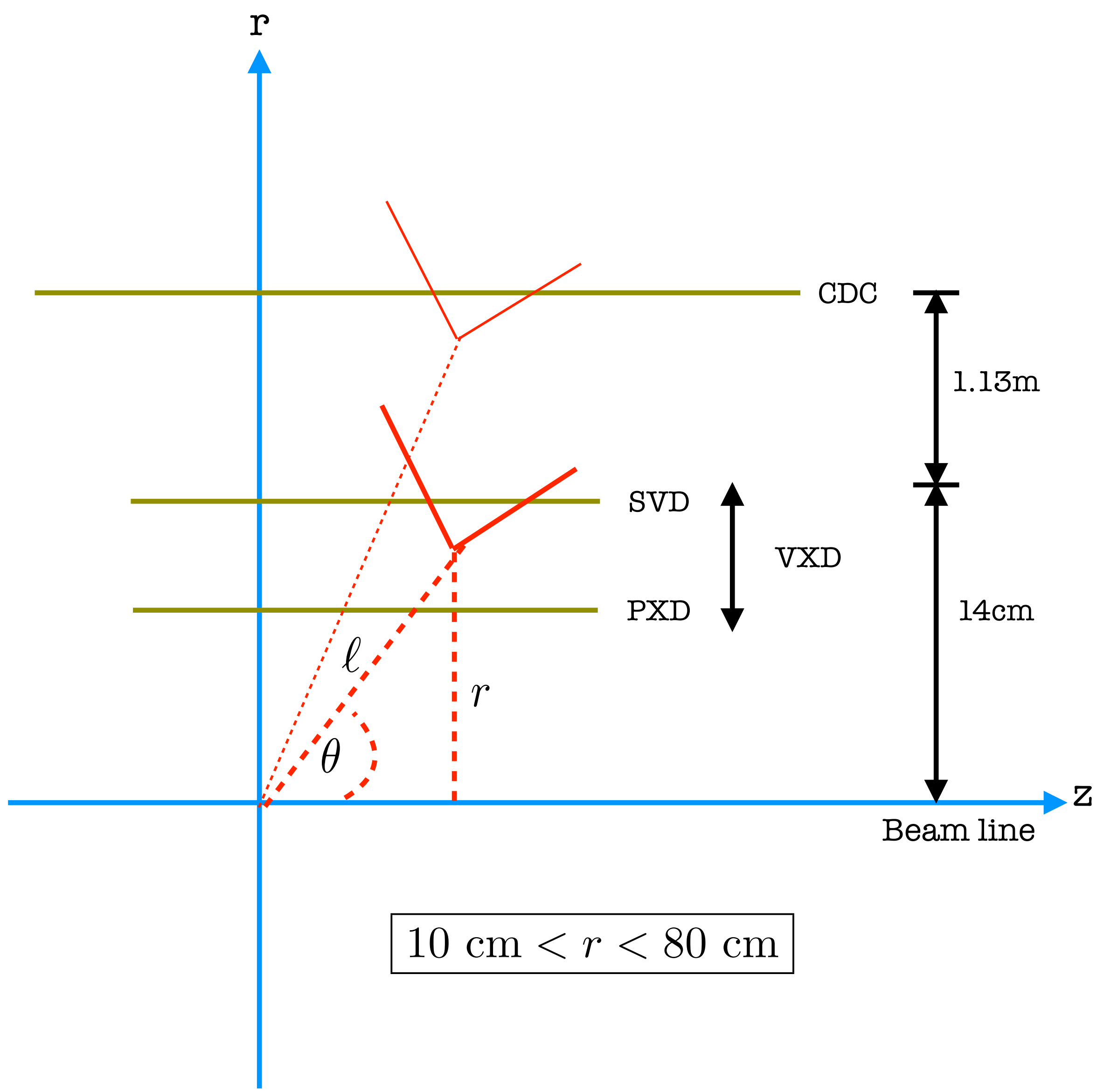
$$P(\ell) = \frac{e^{-\ell/\lambda}}{\lambda}$$

- Probability for identifying displaced vertex

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

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

Displaced Searches at Belle



- Linear Falling Efficiency:

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

- Probability for decay

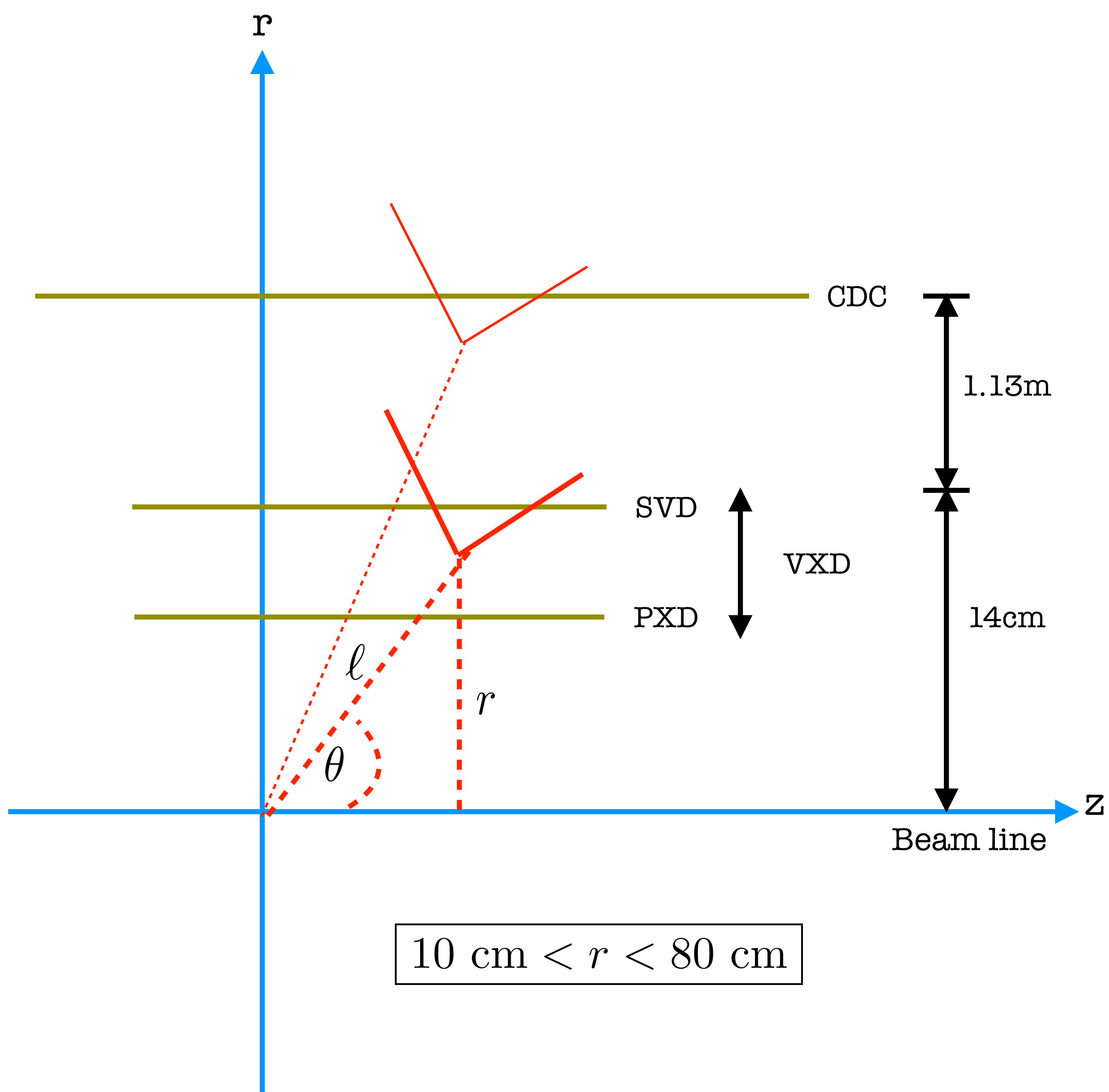
$$P(\ell) = \frac{e^{-\ell/\lambda}}{\lambda}$$

- Probability for identifying displaced vertex

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

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

Displaced Searches at Belle



- 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

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

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

Backup4: Axions

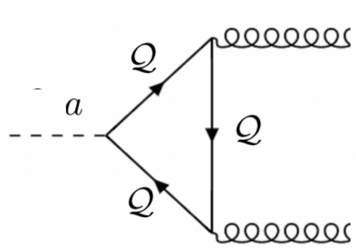
$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$ ★

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

Example of a UV model

- 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: $\frac{\alpha_s}{8\pi} \frac{a}{f_a} G\tilde{G}$