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Bridging the Higgs Portal to the Dark Sector: From FCCee to LHC

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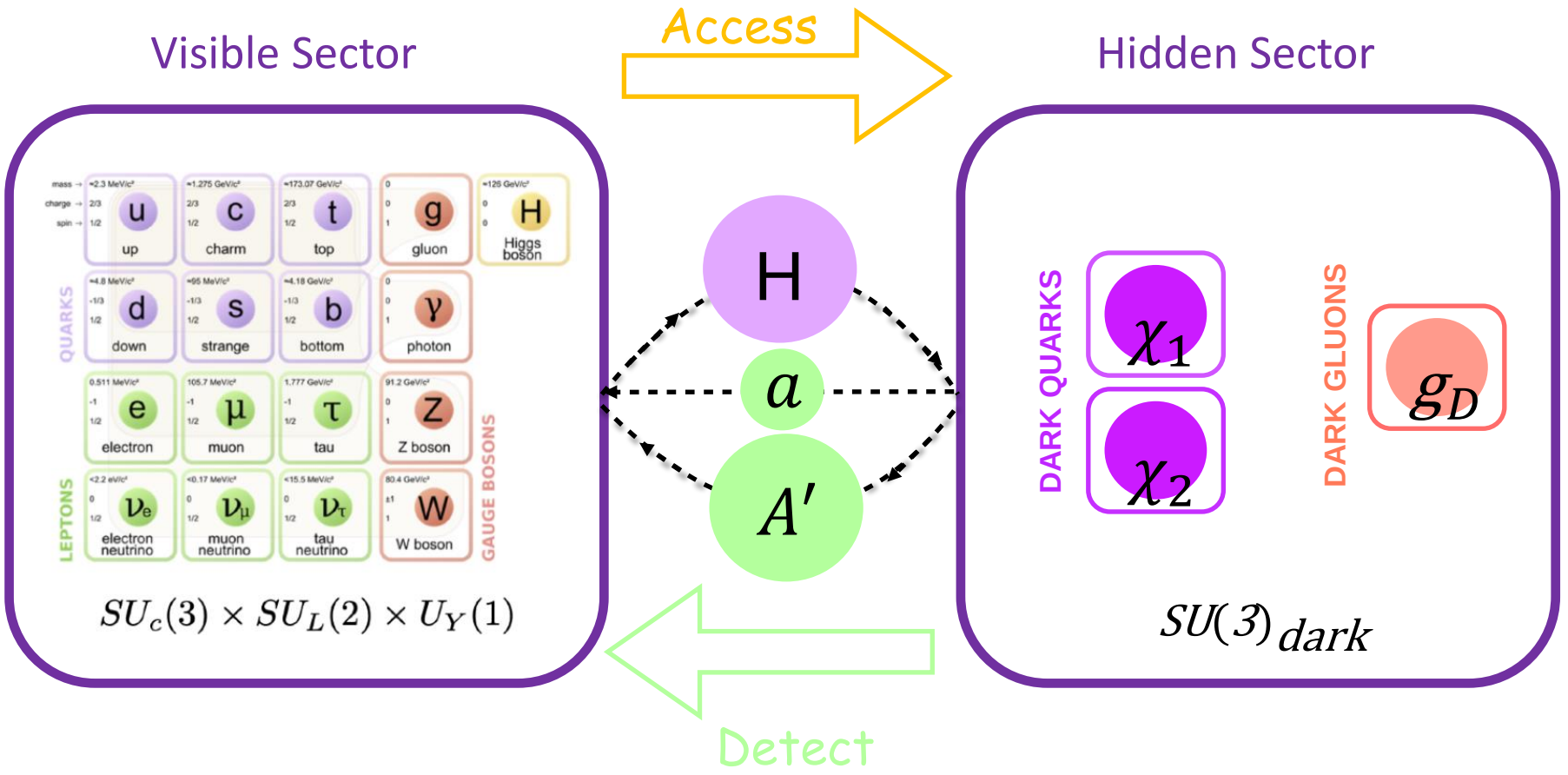
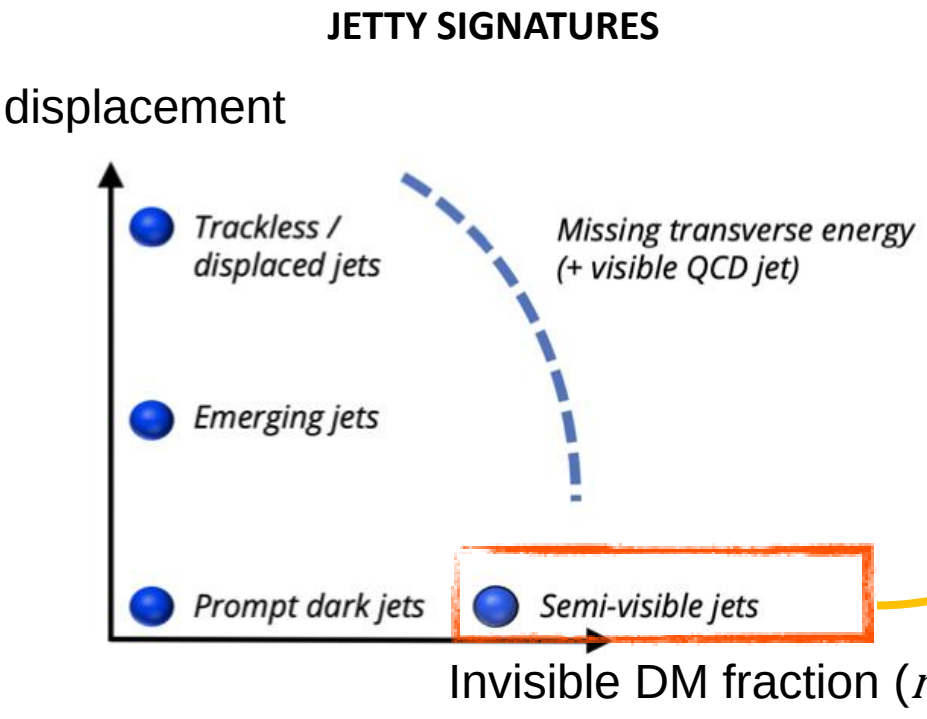
22.1.25, CERN

Higgs Portal to DS



Semi-Visible Jets Signatures

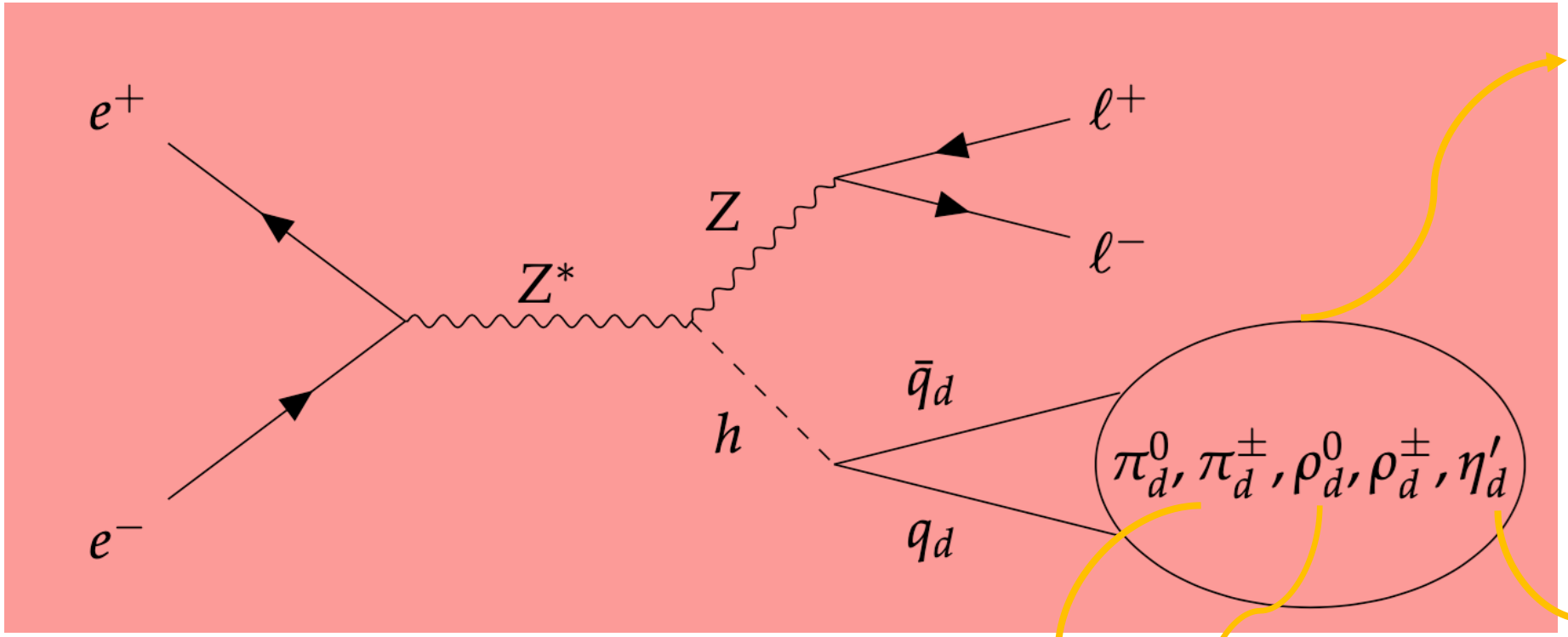


more general signature including leptons, hadrons and photons

SVJ-h, SVJ-l and SVJ-tau, and SVJ-photons

possibility for displacement

Model Building for FCCee



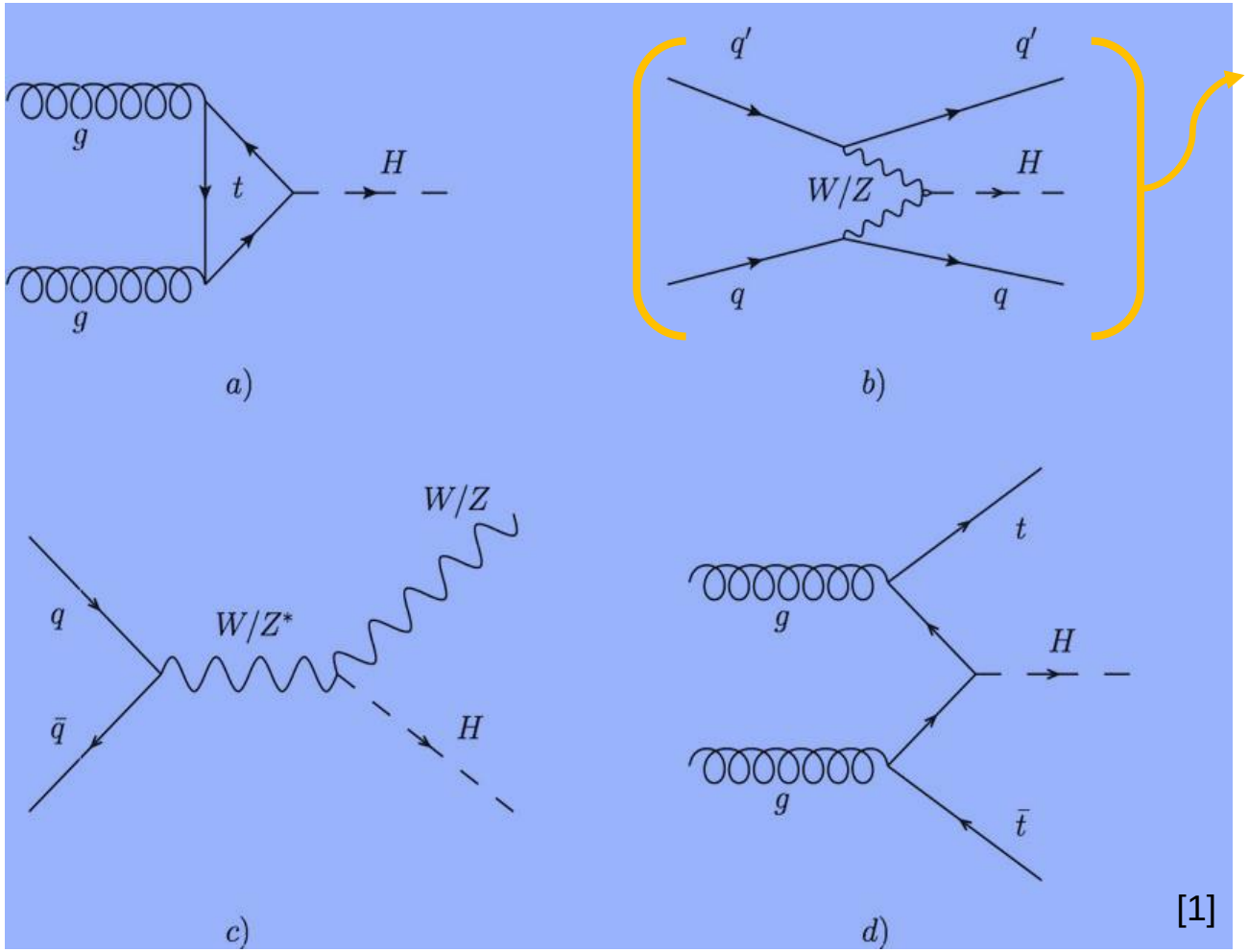
pseudo-scalar mesons $\eta_d', \pi^{\pm,0}$ and vector mesons ρ_d^0, $\rho_d^\pm$

$\rho_d^\pm$,$\pi^{\pm,0}$ are detector stable (DM candidates)

Decay to SM leptons and quarks

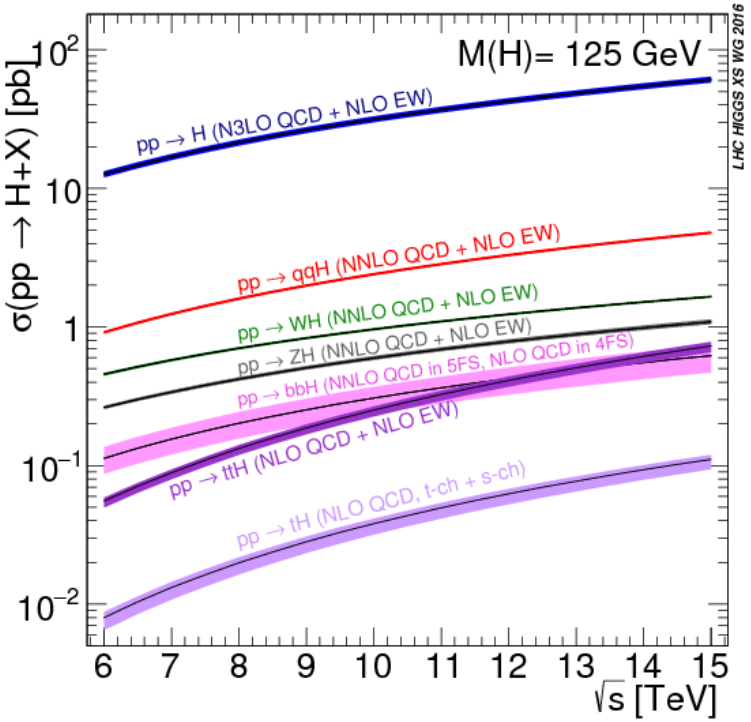
Decay to SM photons

Main Higgs boson production processes at the LHC



[1]

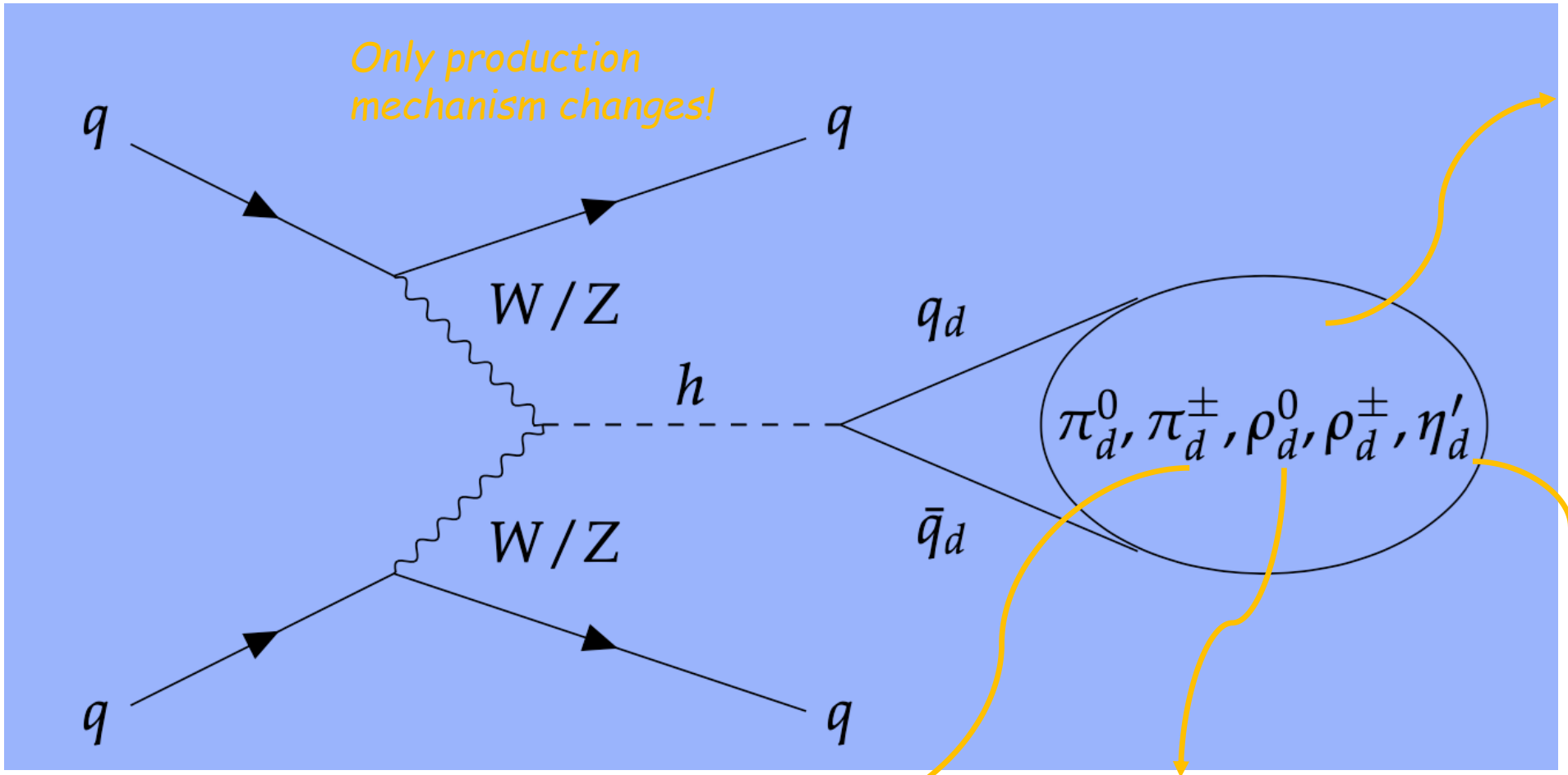
Most interesting



[2]

Gluon fusion can also be explored!

Model Building for LHC



pseudo-scalar mesons $\eta_d', \pi^{\pm,0}$ and vector mesons ρ_d^0, $\rho_d^\pm$

Decay to SM photons

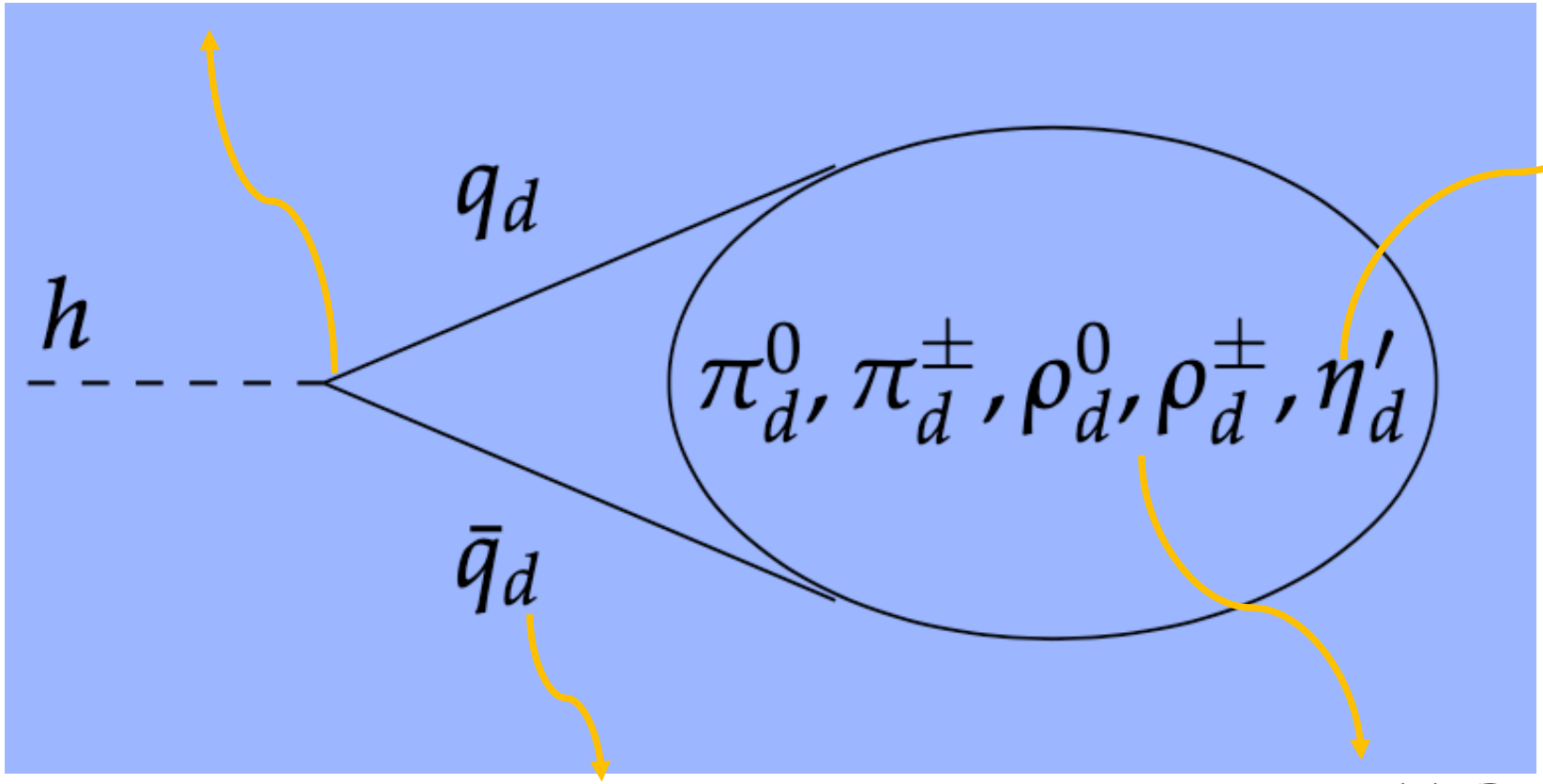
$\rho_d^\pm$,$\pi^{\pm,0}$ are detector stable (DM candidates)

Decay to SM leptons and quarks

Higgs coupling to DS

Higgs coupling to dark quarks

$P(\eta)$: Probability factor of η'_d meson production over dark pions $\pi^{\pm,0}$



Spin-0 dark quarks

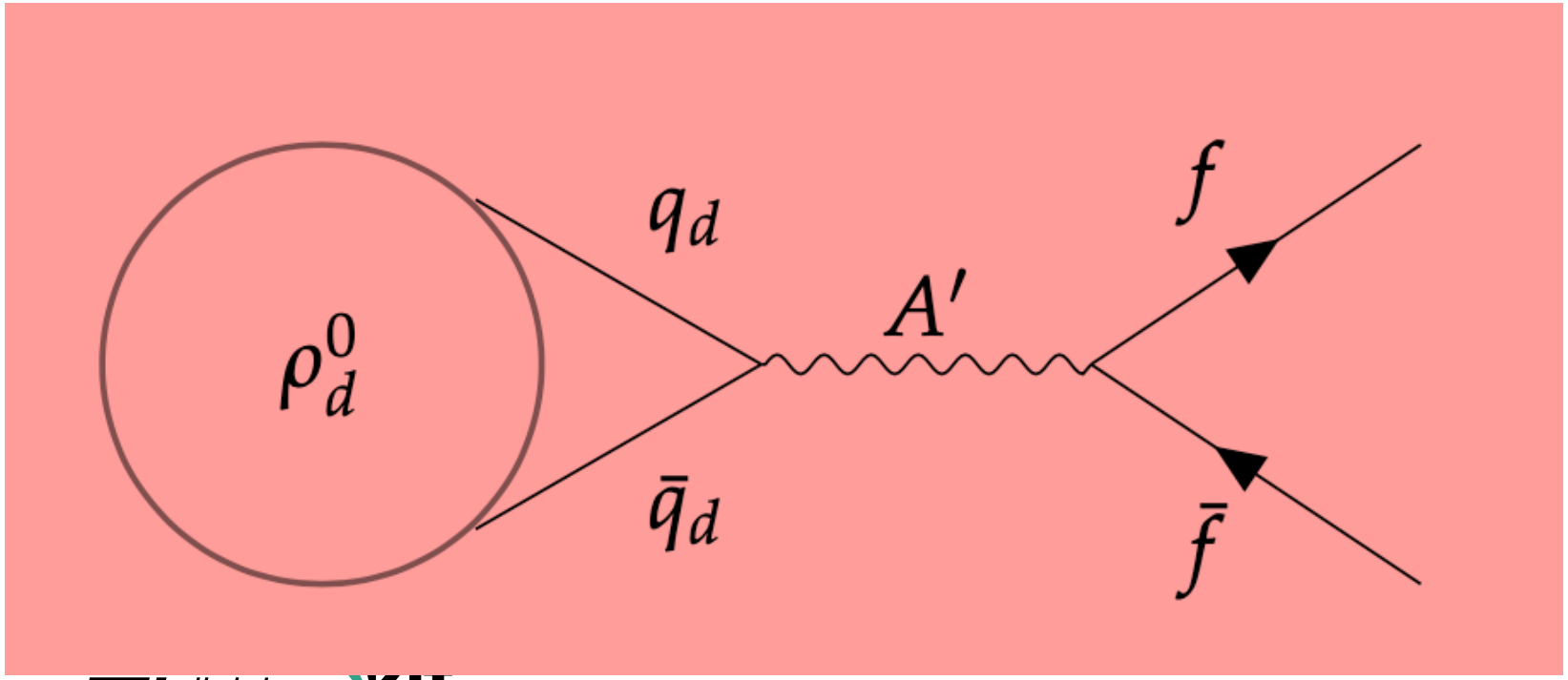
$P(\rho)$: Fraction of dark vector mesons to dark pseudo-scalar mesons

ρ-Decay

$$\Gamma(\rho_d^0 \to q\bar{q}) = N_c \times \frac{\kappa^2 e^2 m_{\rho_d^0}}{12\pi}\left(1+2\frac{m_q^2}{m_{\rho_d^0}^2}\right)\sqrt{1-4\frac{m_q^2}{m_{\rho_d^0}^2}}.$$

$$\Gamma(\rho_d^0 \to \ell^+\ell^-) = \frac{\kappa^2 e^2 m_{\rho_d^0}}{12\pi}\left(1+2\frac{m_\ell^2}{m_{\rho_d^0}^2}\right)\sqrt{1-4\frac{m_\ell^2}{m_{\rho_d^0}^2}}.$$

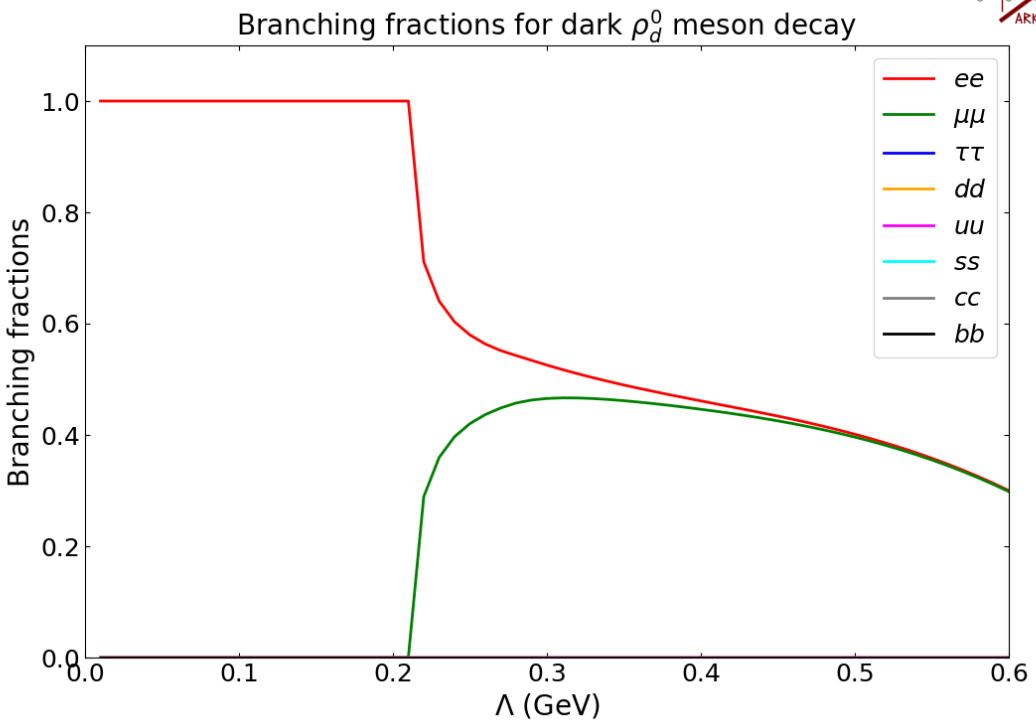
- N_C: Number of QCD colors
- κ: The mixing parameter
- q_f: The fermion charge

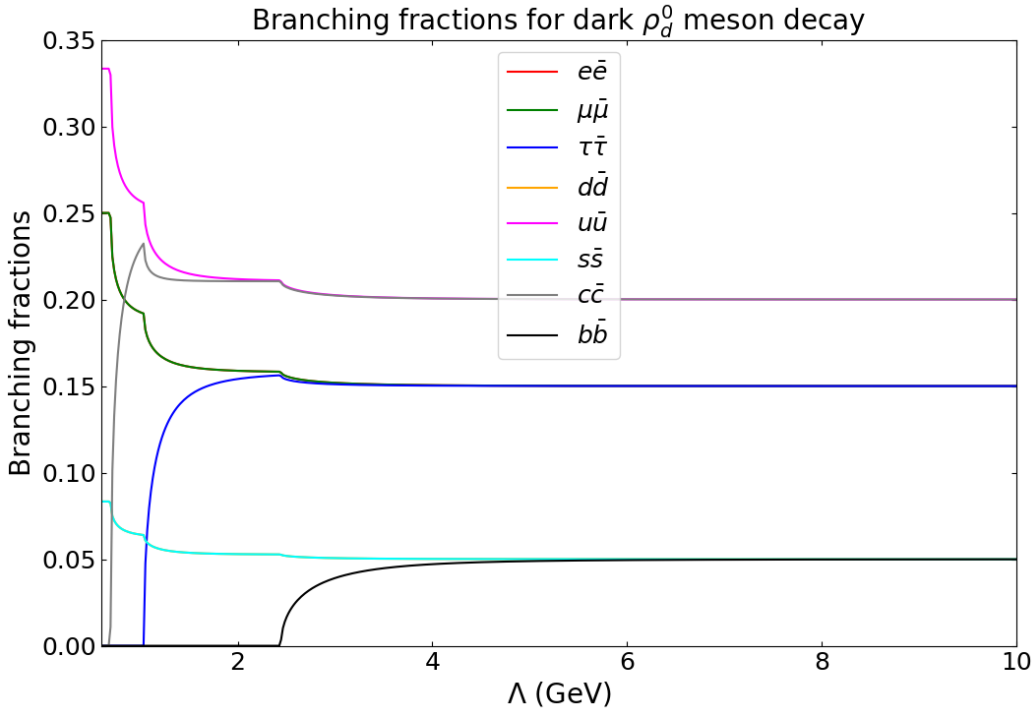


- m_q: SM Quark mass
- m_l: SM Lepton mass
- $m_{\rho_d^0}$: ρ_d^0 mass
- e: Electric charge

Model Predictions on SM signatures

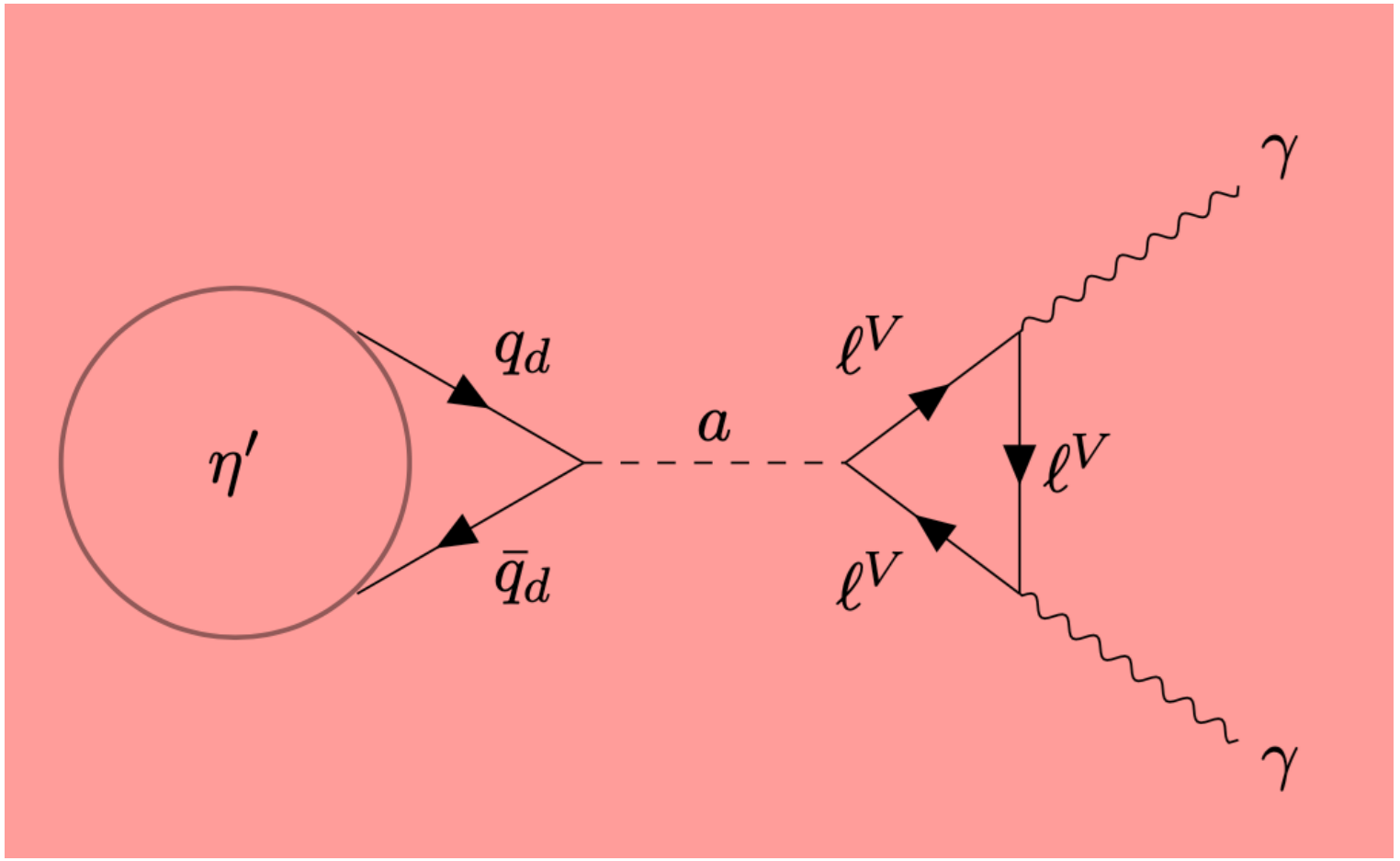
[3]





Plots for some specific choice of couplings!

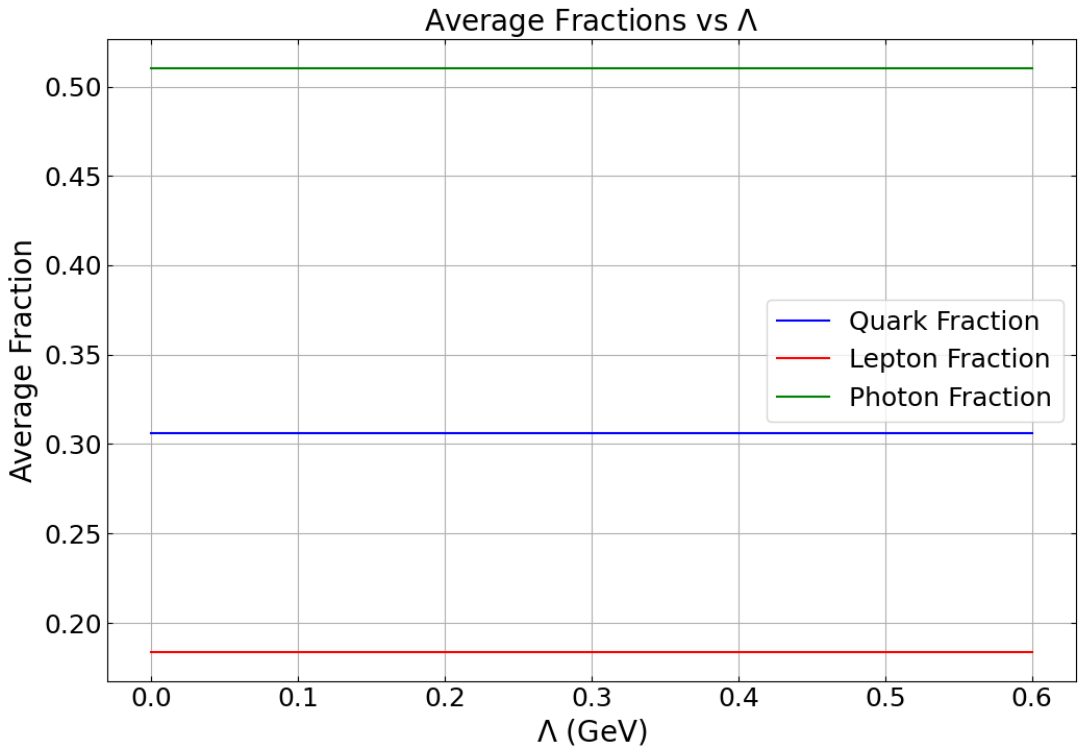
η' -Decay

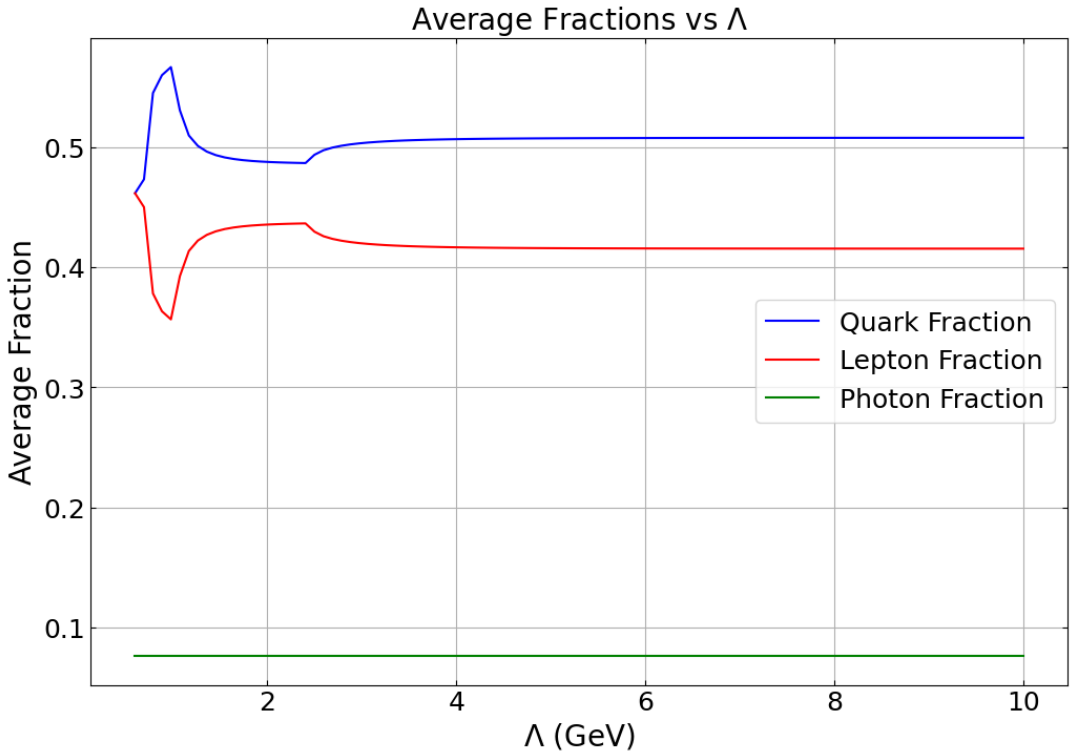


$$\Gamma(\eta'_d \to \gamma\gamma) = \frac{\alpha^2}{256\pi^2} \frac{m^3_{\eta'_d}}{f^2_{\eta'_d}}.$$

- α : Fine structure constant
- $m_{\eta'_d}$: Mass of η'_d
- $f_{\eta'_d}$: η'_d decay constant

Model Predictions on SM final states

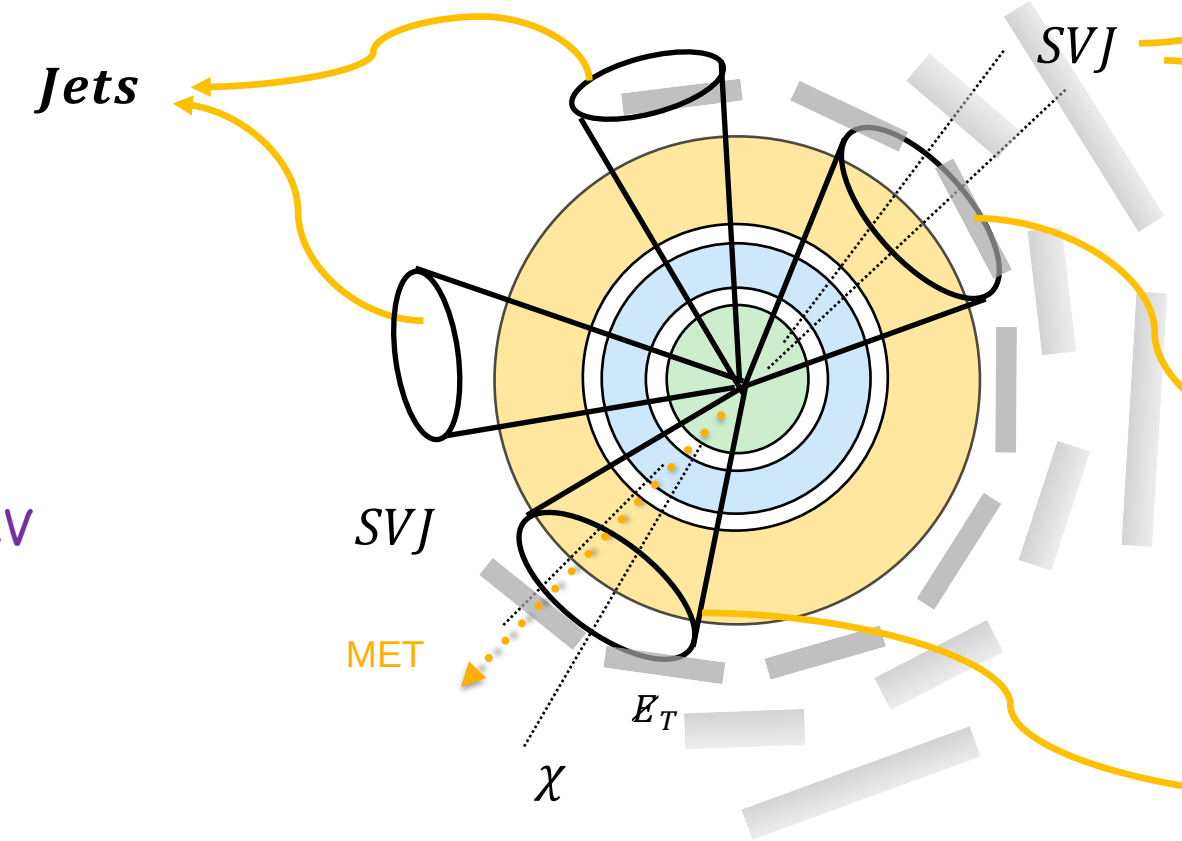




$P(\eta)$: HiddenValley: probkeepeta1 = 0.25
$P(\rho)$: HiddenValley: probvec = 0.75

Signatures for Higgs associated production

Higgs to Dark Showers



uncovered: (SVJ) enriched in photons and leptons, with displaced decay

Challenging! Ad Hoc search for strategies!

$H \rightarrow q_d q_d$

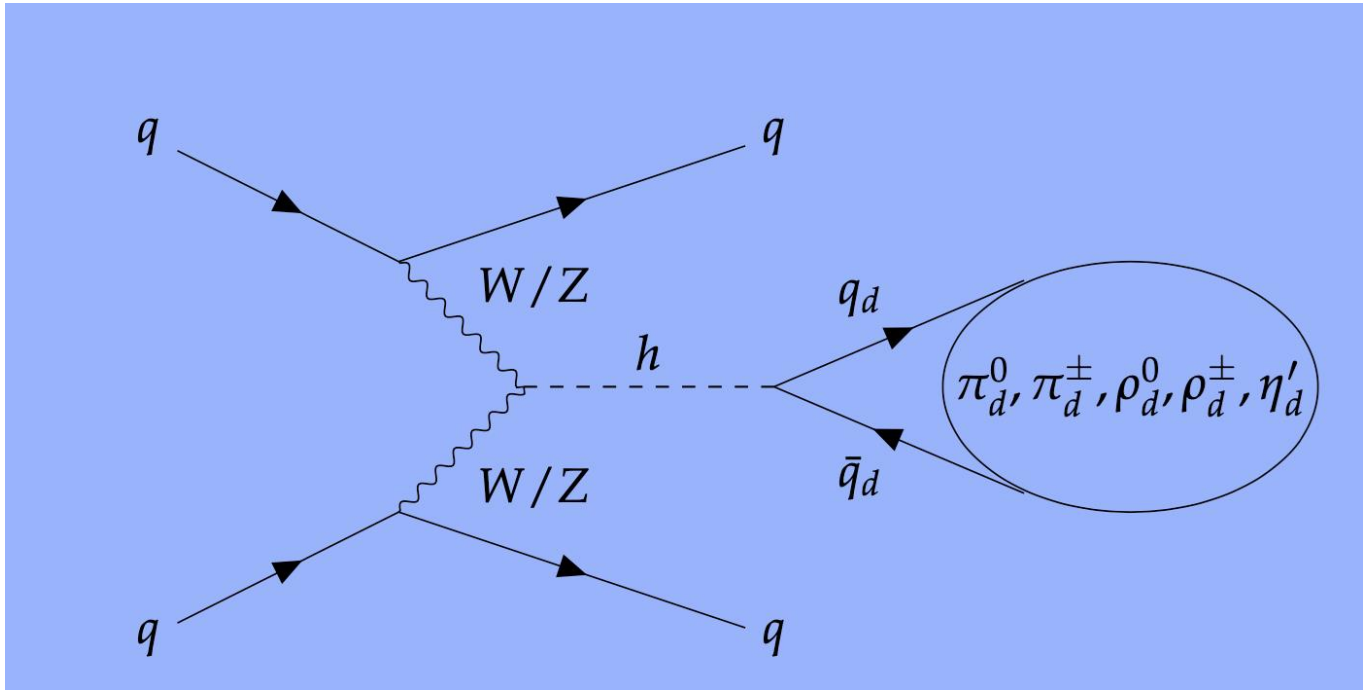
jets might fail the standard identification criteria for LHC

Higgs to b-jets background!

High-mass Z' searches at TeV scale: Ongoing work

Summary

- Easy implementation to LHC
- Challenges can be targeted by using specific analysis methods (e.g., DNN tagger)
- Currently producing samples for LHC!

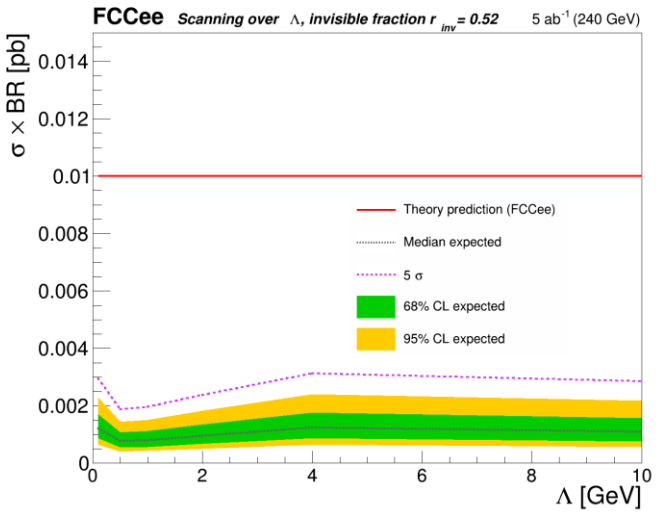


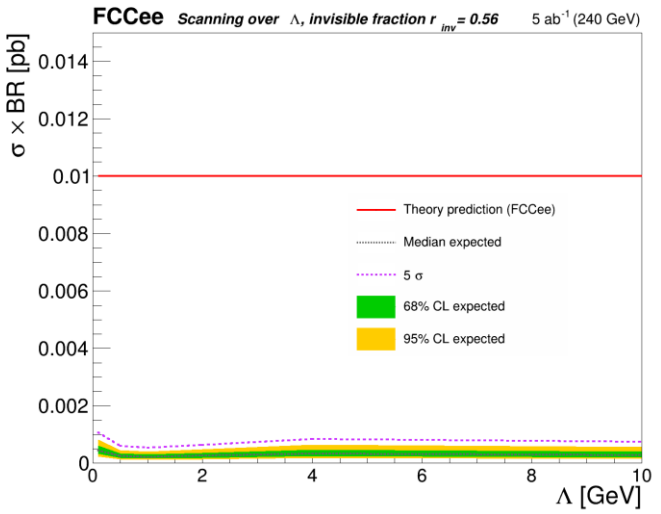
References

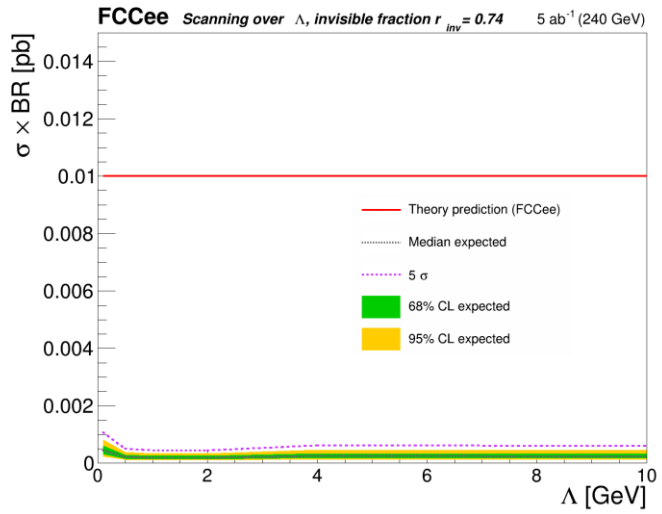
- [1] Mausolf, Florian & Bianco, Gianluca & Nackenhorst, Olaf & Albrecht, Johannes & Franchini, Matteo. (2020). Tandem Project Report: Classification in particle physics using machine learning. 10.13140/RG.2.2.24097.02408.
- [2] CERN. (n.d.). Figures for production analysis [Image]. CERN Document Server. Retrieved January 20, 2025, from https://cds.cern.ch/record/2243593/files/Figures_Prod.png
- [3] T. D. Collaboration, “Darkcast: A dark sector tool,” GitLab Repository, 2023. [Online]. Available: https://gitlab.com/darkcast/releases.

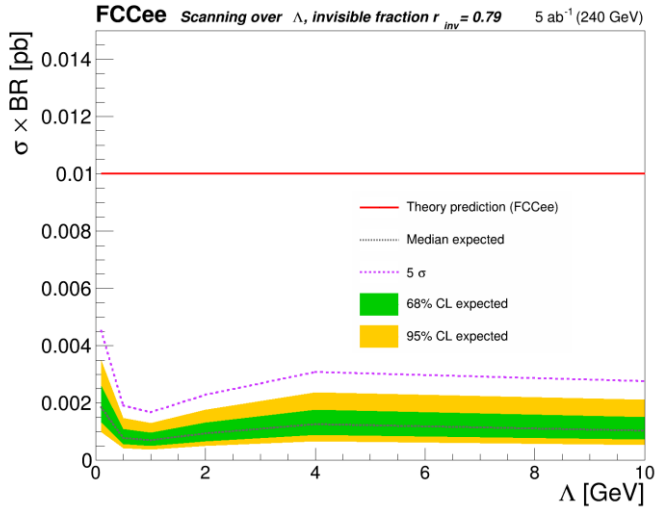
Backup Slides

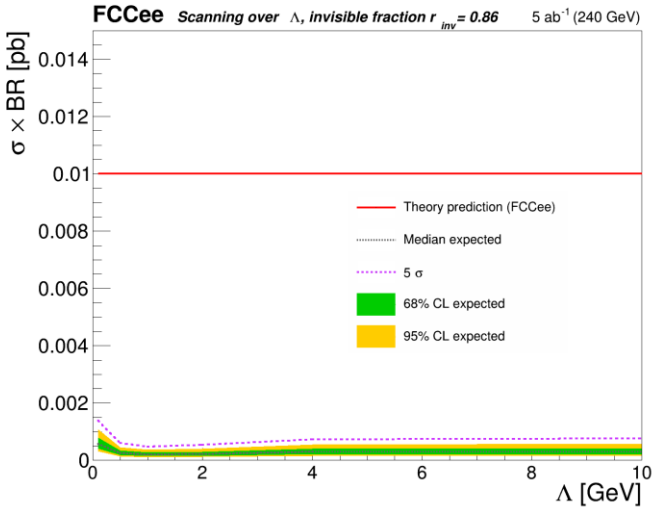
FCCee Sensitivity Studies

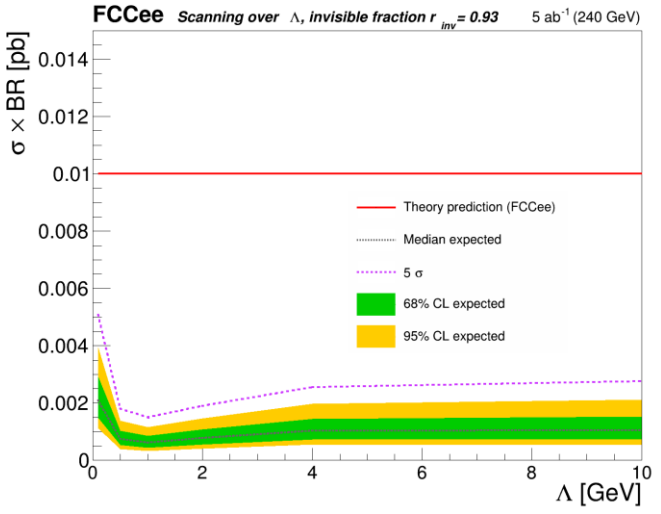












Effective Lagrangian for ALP

In the IR limit, the ALP couples to SM photons via

$$\mathcal{L}_{\text{IR}} \supset -\frac{1}{2}m_a^2 a^2 - \frac{\alpha}{4\pi}\frac{g_L N_L}{M_L} aF\tilde{F} - ig_d a\bar{q}_d\gamma_5 q_d.$$

Effectively this leads to

$$\mathcal{L}_{\text{IR}} \supset \frac{\alpha}{8\pi}\frac{1}{f_{\eta_d'}}\eta_d' F\tilde{F},$$

where

$$\frac{1}{f_{\eta_d'}} = \frac{2g_L g_d N_L \Lambda F_{\eta_d'}}{m_a^2 M_L}$$

Effective Lagrangian for Dark Photon

$$\mathcal{L}_{\text{med}} \supset -\kappa e A_\mu{}' q_f \bar{f}\gamma^\mu f - g_\chi A_\mu{}' \bar{\chi}\gamma^\mu \chi$$

- $\kappa = 1.0 \times 10^{-4}$: the mixing parameter.
- $m_a = 40$: the ALP mass.
- $m_L = 700$: the VLL (Vector-Like Lepton) mass.
- $g_L = 1$: the coupling of the VLL and the ALP.
- $g_d = 1$: the coupling of the dark quarks and the ALP.
- $f_{\eta_d} = \frac{m_a^2 \cdot m_L}{g_L \cdot g_d}$: the decay constant.

Model Prediction on FCCee SVJ signatures

To understand what particles are expected in which fractions in the FCCee signatures simulations, we compute the average fractions. For this we set the fraction of vector mesons $\rho_d^0, \rho_d^\pm$ to the pseudo-scalar mesons $\pi_d^0, \pi_d^\pm, \eta_d'$ `HiddenValley:probVector = 0.75` . Also we set the production ratio of η_d' to all of the pseudo-scalar mesons `HiddenValley:probKeepEta1 = 0.25` . First, we calculate the total photon, quark and lepton branching fractions:

$$\mathbf{Br}(\eta_d' \to \gamma\gamma) = 1$$

$$\mathbf{Br}(\rho_d^0 \to l\bar{l}) = \frac{\Gamma(\rho_d^0 \to l\bar{l})}{\Gamma(\rho_d^0 \to q\bar{q}) + \Gamma(\rho_d^0 \to l\bar{l})}$$

$$\mathbf{Br}(\rho_d^0 \to q\bar{q}) = \frac{\Gamma(\rho_d^0 \to q\bar{q})}{\Gamma(\rho_d^0 \to q\bar{q}) + \Gamma(\rho_d^0 \to l\bar{l})}$$

Model Prediction on FCCee SVJ signatures

Weighted fractions are obtained by considering `HiddenValley:probVector = 0.75` and `HiddenValley:probKeepEta1 = 0.25` :

$$\mathbf{Br}_w(\eta'_d \to \gamma\gamma) = 1 \times 0.25 \times 0.25$$
$$\mathbf{Br}_w(\rho^0_d \to l\bar{l}) = \mathbf{Br}(\rho^0_d \to l\bar{l}) \times 0.75$$
$$\mathbf{Br}_w(\rho^0_d \to q\bar{q}) = \mathbf{Br}(\rho^0_d \to q\bar{q}) \times 0.75$$

Model Prediction on FCCee SVJ signatures

To normalize we introduce the sum of weighted fractions:

$$\Sigma = \mathbf{Br}_w(\eta'_d \to \gamma\gamma) + \mathbf{Br}_w(\rho^0_d \to l\bar{l}) + \mathbf{Br}_w(\rho^0_d \to q\bar{q})$$

We obtain for the average fractions:

$$\mathbf{Br}_{av}(\eta'_d \to \gamma\gamma) = \frac{\mathbf{Br}_w(\eta'_d \to \gamma\gamma)}{\Sigma}$$

$$\mathbf{Br}_{av}(\rho^0_d \to l\bar{l}) = \frac{\mathbf{Br}_w(\rho^0_d \to l\bar{l})}{\Sigma}$$

$$\mathbf{Br}_{av}(\rho^0_d \to q\bar{q}) = \frac{\mathbf{Br}_w(\rho^0_d \to q\bar{q})}{\Sigma}$$

$$r_{\text{inv}} = \frac{1 + \frac{2}{3} \cdot \text{probvec} \cdot (1 + \text{probkeepeta1})}{1 + \text{probvec} \cdot (1 + \text{probkeepeta1}) + \text{probkeepeta1}}.$$