Hidden valleys in CMS muon endcap detector

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Hidden Valley/Dark Shower

- **Hidden Valley**
  Connected the Dark sector and SM with a Z_D portal.

$$\mathcal{L} \supset g_{\rm SM} Q_{\rm SM} \gamma^{\mu} Z_D q\bar{q} + g_{\rm D} Q_{\rm D} \gamma^{\mu} Z_D q_D \bar{q_D}$$

  g_{SM} is the coupling of Z_D to SM quarks.
  g_D is the coupling of Z_D to dark quarks
  No other couplings
  Z_D and g_{SM} are constrained by the resonance searches of dijets

- **Dark Shower**
  dark chiral symmetry breaking scale is low, parton shower and hadronization
  dark quarks form bound states, **dark mesons**
  Three free characteristic parameter
  $\boldsymbol{\Lambda_D}$, the scale of the theory
  $\boldsymbol{M_{\pi_D}/\Lambda_D}$, the ratio of dark pion mass to scale
  $\boldsymbol{N_F}$, the number of flavours

$\boldsymbol{N_C}$ the number of colors, $\boldsymbol{c\tau_{LLP}}$ the proper decay lifetime of long-lived pions
Number of pions which decay are fixed by several benchmarks

Hidden Valley/Dark Shower

- **Hadrons**

$$\frac{m_{\pi_D}}{\Lambda_D} = 5.5\sqrt{\frac{m_{q_D}}{\Lambda_D}}, \qquad \frac{m_{\rho_D}}{\Lambda_D} = \sqrt{5.76 + 1.5\frac{m_{\pi_D}^2}{\Lambda_D^2}}.$$

$N_F(N_F\text{-}1)\ \pi_D^{\pm}$ and $\boldsymbol{N_F}$ π_D^0, same for ρ_D

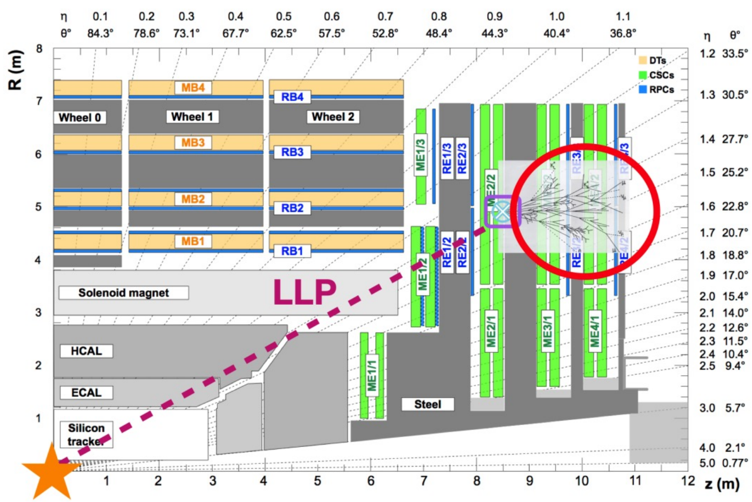
- **Benchmark**

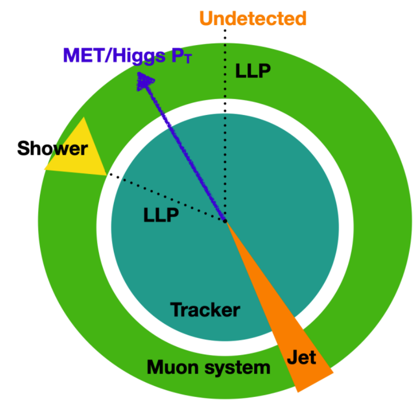
Benchmark name	N_C	N_F/N_C	m_{π_D}/Λ_D	Λ_D GeV	Stable mesons	Meson decay modes
One π_D^0 decay	5	0.5 - 2.5	0.2 - 1.5	0 - 60	All $\pi_D^{\pm}$ $N_F - 1\ \pi_D^0$	$\rho_D^0 \to \pi_D^{\pm}\pi_D^{\pm}$ $\rho_D^{\pm} \to \pi_D^{\pm}\pi_D^0$ $\pi_D^0 \to q\bar{q}$
All π_D^0 decay	5	0.5 - 2.5	0.2 - 1.5	0 - 60	All $\pi_D^{\pm}$ $0\ \pi_D^0$	$\rho_D^0 \to \pi_D^{\pm}\pi_D^{\pm}$ $\rho_D^{\pm} \to \pi_D^{\pm}\pi_D^0$ $\pi_D^0 \to q\bar{q}$

One π_D^0 decay, branching ratio $1/\ N_F$ to $q\bar{q}$, $1 - 1/\ N_F$ stable,
All π_D^0 decay, branching ratio 100% to $q\bar{q}$.
the decay π_D^0 has lifetime 100 or 1000 mm by hand,
as **long-lived particle (LLP)**
$\pi_D^0 \to s\bar{s}, c\bar{c}, b\bar{b},$ according to threshold

CMS Muon Endcap Detector

- **Displaced Shower search at the CMS muon endcap detector**





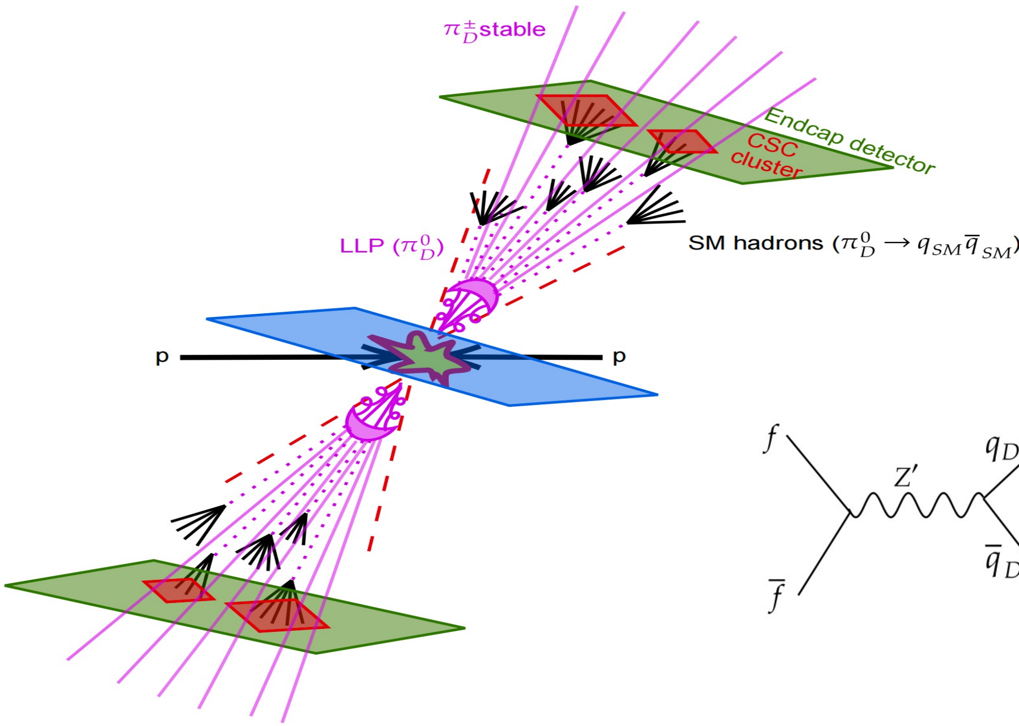
CMS collaboration, Phys.Rev.Lett. 127 (2021) 26, 261804

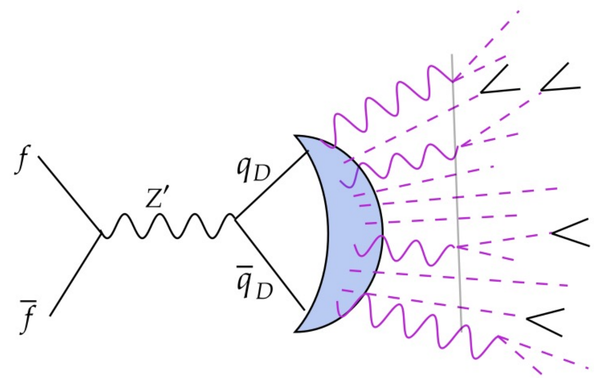
- **Signature**

  Displaced Shower at the muon endcap, shower yield larger number of hits
  Capture by **cathode strip chambers (CSC)**
  Number of hits over 130, forming CSC cluster
  MET > 200 GeV as trigger requirement

CMS Muon Endcap Detector

- **The Process**





pp→ $Z_D \rightarrow q_D\overline{q_D}$, quarks forming hadrons
$\pi_D^{\pm}$ are stable, some of the π_D^0 decays to SM quarks as LLP
Leaving displaced shower signature at endcap
Large MET measured by the initial state radiation jets

Efficiency Dependence

- **Master formula**

$$\begin{aligned}\epsilon_{\rm tot} &= N_{\rm LLP} \times \epsilon_{\rm geo}(\beta\gamma c\tau_{\rm LLP}) \times \epsilon_{\rm reco}\left(E_{\rm had}^{\rm CSC}\right) \times \epsilon_{\rm cut}(\rm MET),\\ &= N_{\rm LLP}^{\rm CSC} \times \epsilon_{\rm reco}\left(E_{\rm had}^{\rm CSC}\right) \times \epsilon_{\rm cut}(\rm MET),\end{aligned}$$

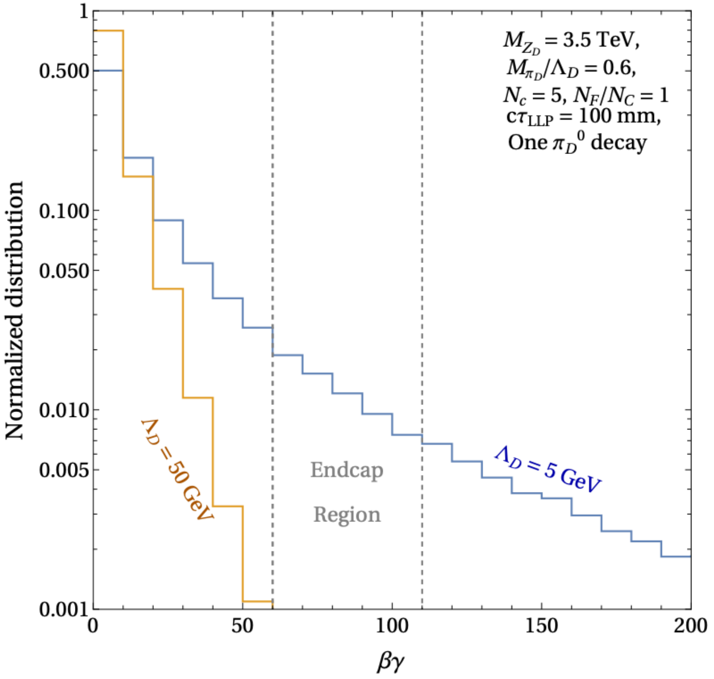
N_{LLP}, the total number of long-lived dark pions produced
N_{LLP}^{CSC}, the one inside the endcap detector
ϵ_{geo}, the geometrical efficiency
ϵ_{reco}, the reconstruction efficiency as a function of E_{had}^{CSC}
ϵ_{cut}, the cut efficiency mainly due to the trigger requirement of MET

$f_{cluster} \approx \epsilon_{total} / \epsilon_{cut}$

$f_{cluster}$, the fraction of events containing at least one cluster

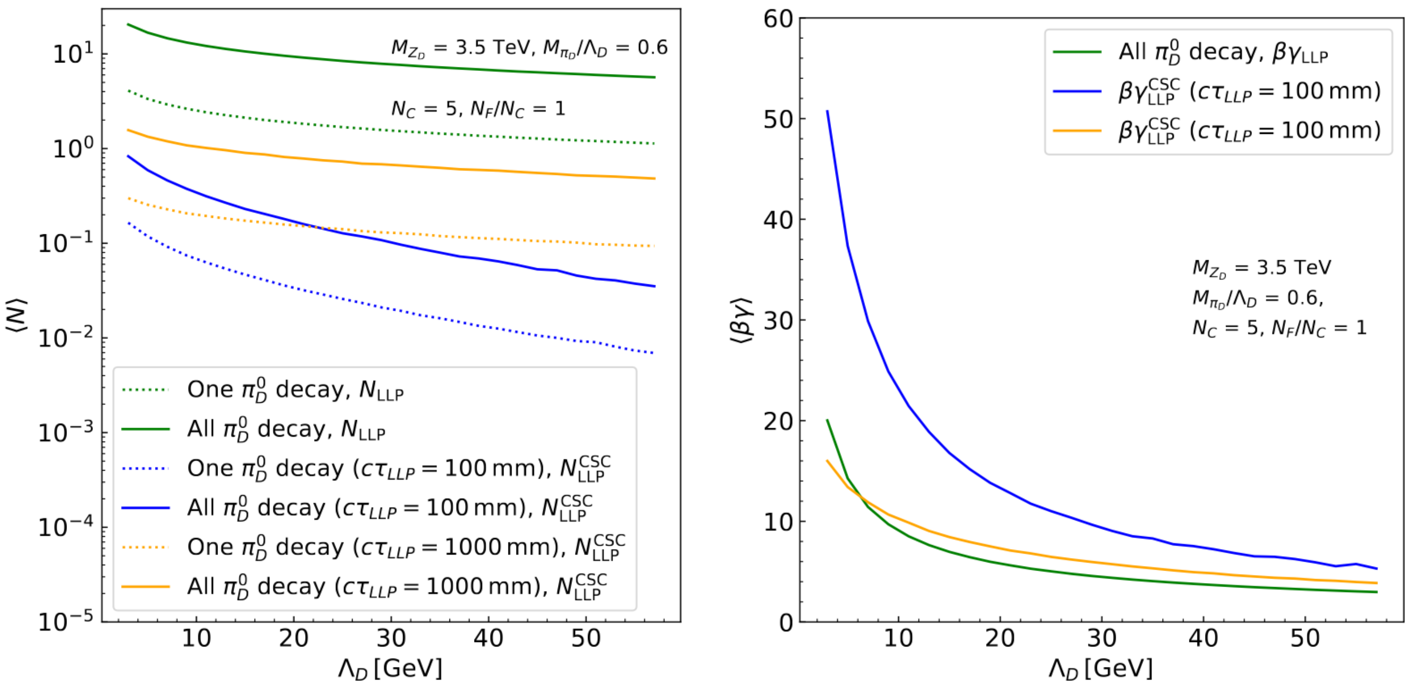
Efficiency Dependence

- $\boldsymbol{\epsilon_{geo}}$
  As we fixed $c\tau_{LLP}$, it is mainly a function of $\beta\gamma$, which is a distribution
  $\beta\gamma$=p_{π_D}/M_{π_D}, N_{π_D} is large, so p_{π_D} changed weakly, mainly by M_{π_D}
  When we fix M_{π_D}/Λ_D, M_{π_D} dependent on Λ_D
  Strong dependence



Λ_D, the scale of the theory

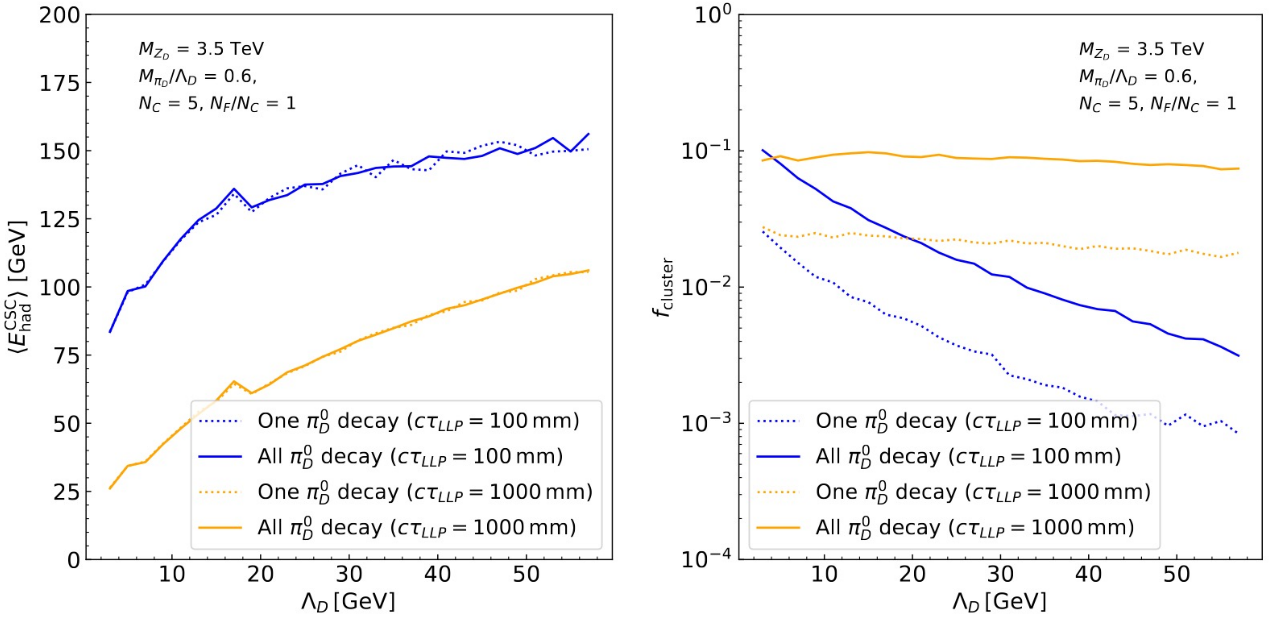
- **Kinematic Distribution**



Average N_{LLP} smaller as Λ_D increase, since M_{π_D} increase
$c\tau_{LLP} \approx$ 100 mm require large boost at tail, rapidly drops
$c\tau_{LLP} \approx$ 1000 mm is flat, since change boost still makes it inside volume
One pion decay has $1/N_F$ times smaller number

Λ_D, the scale of the theory

- **Kinematic Distribution**



$E_{had}^{CSC} \approx p_{\pi_D} \approx M_{\pi_D}\,\beta\gamma$, larger $c\tau_{LLP}$ require smaller $\beta\gamma$, so smaller E_{had}^{CSC}

E_{had}^{CSC} increase as Λ_D increase, since M_{π_D} increase

$f_{cluster} \approx \epsilon_{total}/\ \epsilon_{cut}$, mainly by N_{LLP}^{CSC}, or ϵ_{geo} from $\beta\gamma$ distribution

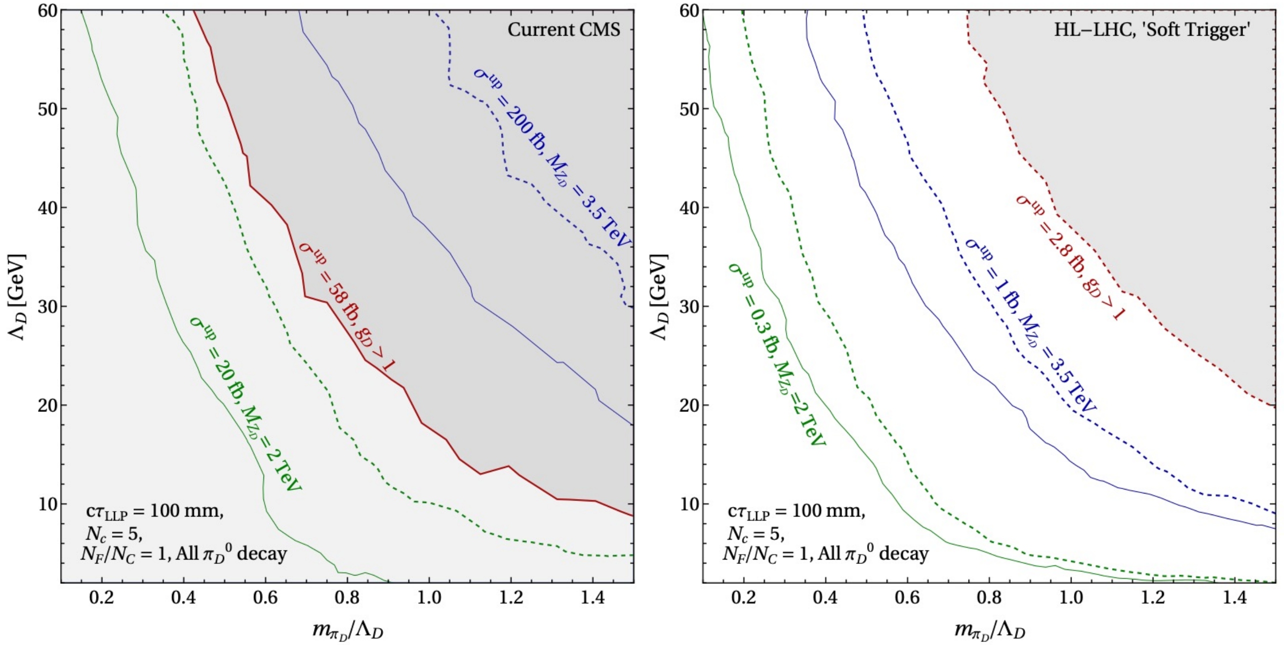
Λ_D, the scale of the theory

- **Model Independent Upper limits**

$$\sigma^{\rm up} \times \mathcal{L} \times \epsilon \approx N^{\rm up}.$$

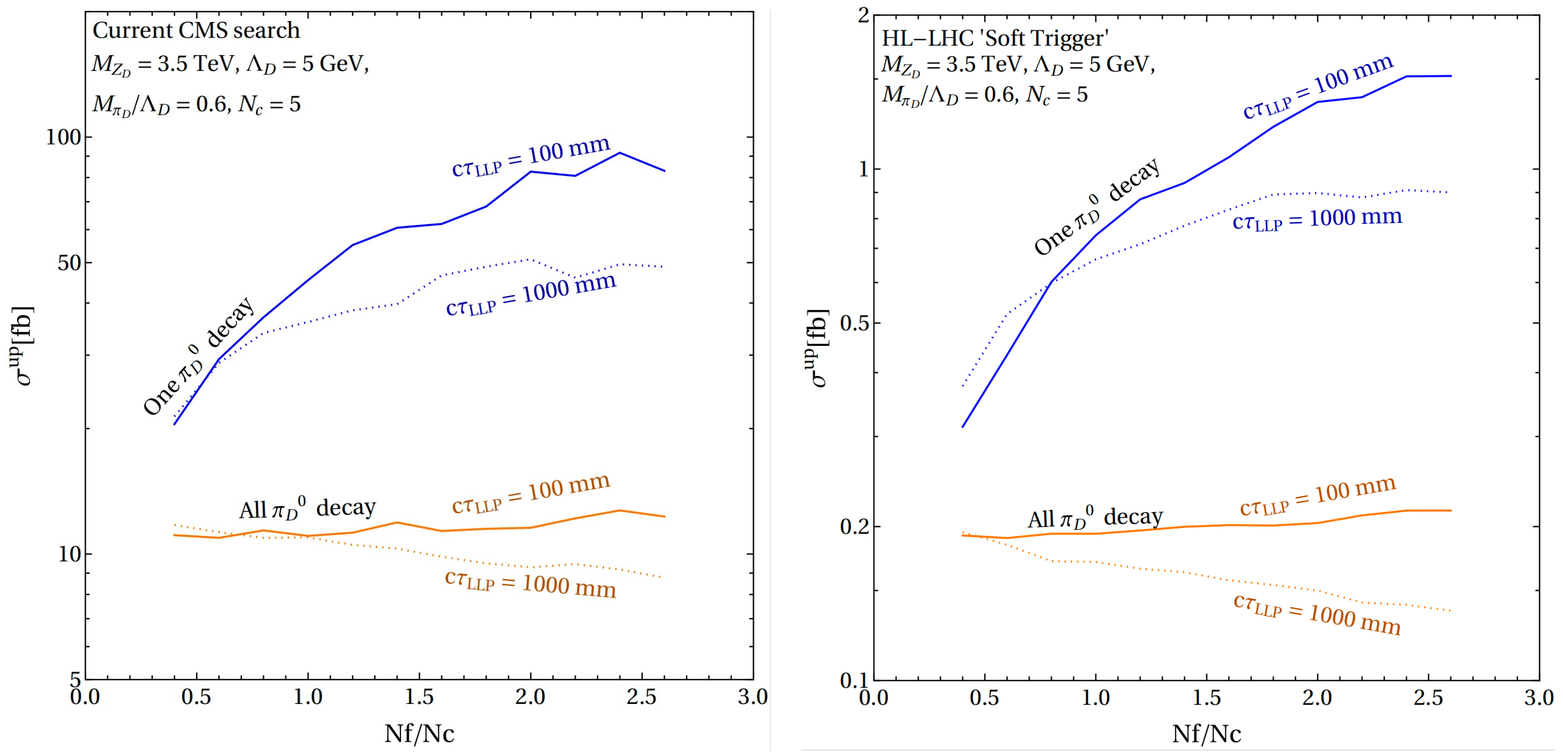
Current CMS: $\mathcal{L} = 137\ fb^{-1}$, MET > 200 GeV, $N^{up} \approx 6$
HL-LHC, 'Soft Trigger': $\mathcal{L} = 3000\ fb^{-1}$, MET > 50 GeV, $N^{up} \approx 3$
by requiring more hits, see JHEP 02 (2023) 011

M_{π_D}/Λ_D **< 1.5** has similar dependence, since also change M_{π_D},
Displaced shower search is sensitive to **low Λ_D and M_{π_D}/Λ_D**



$N_F/\ N_C$, the number of flavor and color

- **Sensitivity**
  Displaced shower search is sensitive to small N_F, **when only one pion decay**



Summary

- We recast the **existing displaced shower search at CMS endcap** to look for **dark shower models,** and derive **model independent upper limits cross section**

- We are interested in three free characteristic parameter $\boldsymbol{\Lambda_D}$, $\boldsymbol{M_{\pi_D}/\Lambda_D}$ and $\boldsymbol{N_F}$

- The efficiency of displaced shower search can be amplified since we can have 10s of LLPs, is mainly controlled by the geometrical acceptance, which dependent on the boost factor, and so M_{π_D} the mass of pions

- Certain $c\tau_{LLP}$= 100 mm, different $\boldsymbol{\Lambda_D}$, $\boldsymbol{M_{\pi_D}/\Lambda_D}$ lead to boost factor changes, so the efficiency varies. Displaced shower search is sensitive to these parameters and **$\boldsymbol{g_D}$ can still be small**.

- Displaced shower search **is sensitive to $\boldsymbol{N_F}$** when the portion of dark pions decay dependent on N_F.