IV HIDDEN VALLEYS & DARK SECTORS

§1. Motivation

• stability: $M_{elw} \sim 100\,\text{GeV} \leftrightarrow M_{Planck} \sim 10^{19}\,\text{GeV}$
$\Rightarrow$ hierarchy problem

solutions:

(i) SUSY [$\Lambda \sim M_{GUT}$ possible]

(ii) extra dimensions @ few-TeV scale:
gravity tested for $d \gtrsim 0.1$ mm
[mechanical torsion experiments $\rightarrow$ F]
$\longrightarrow$ modifications for $d \lesssim 0.1$ mm possible
[ADD, Randall-Sundrum]

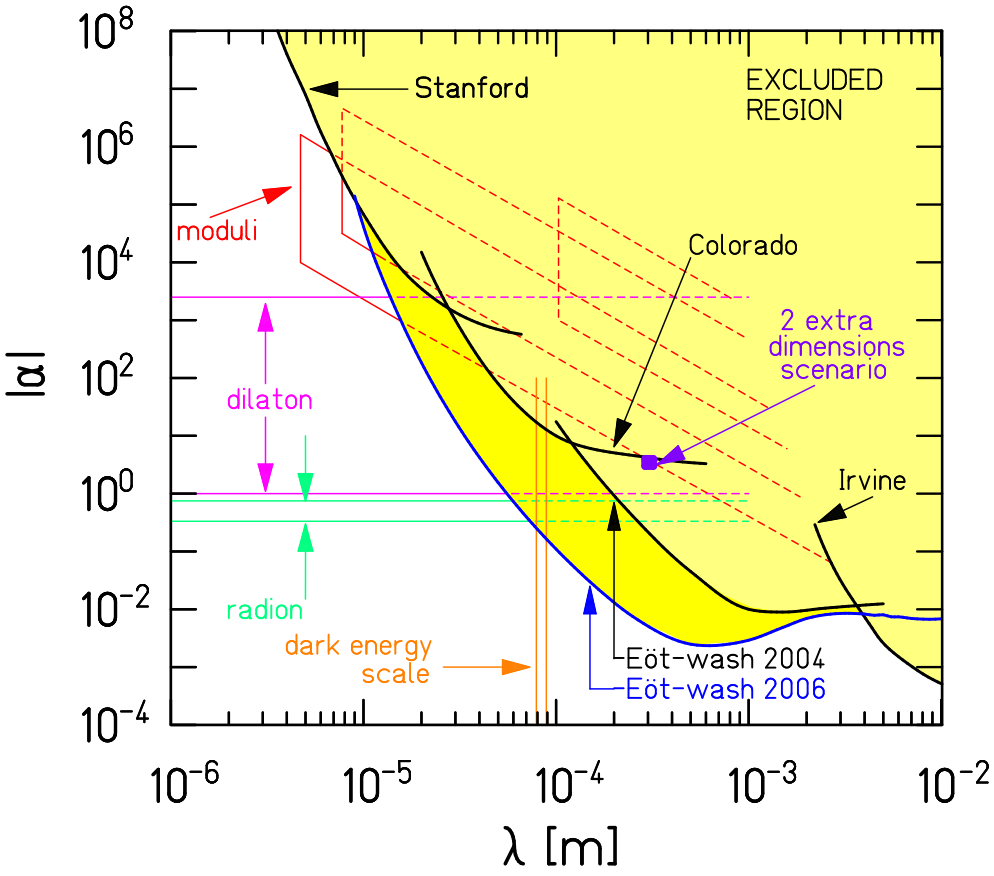
(iii) heavy mediator(s) [$\Lambda \sim M_{med} \gtrsim \mathcal{O}(\text{TeV})$]
$\rightarrow$ light dark sector possible

(iv) effective Lagrangians (dim 6) [$\Lambda \gtrsim \mathcal{O}(\text{TeV})$]

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots \quad \rightarrow 2499 \text{ dim6-operators}$$

modification of gravitational potential:

$$V(r) = -\frac{GM}{r}\left(1 + \alpha e^{-\frac{r}{\lambda}}\right)$$



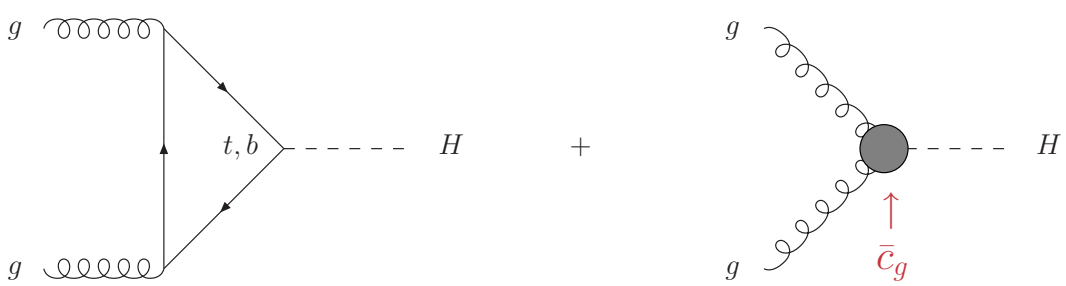
$$
\begin{aligned}
\Delta\mathcal{L}_{SILH} = \;& \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
+ \;& \left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\right) \\
+ \;& \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
+ \;& \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
+ \;& \frac{\bar{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu} \\
\Delta\mathcal{L}_{F_1} = \;& \frac{i\bar{c}_{Hq}}{v^2}\,(\bar{q}_L\gamma^\mu q_L)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\
+ \;& \frac{i\bar{c}_{Hu}}{v^2}\,(\bar{u}_R\gamma^\mu u_R)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
+ \;& \left(\frac{i\bar{c}_{Hud}}{v^2}\,(\bar{u}_R\gamma^\mu d_R)\left(H^{c\,\dagger} \overleftrightarrow{D}_\mu H\right) + h.c.\right) \\
+ \;& \frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu\sigma^i L_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\
+ \;& \frac{i\bar{c}_{Hl}}{v^2}\left(\bar{l}_R\gamma^\mu l_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
\Delta\mathcal{L}_{F_2} = \;& \frac{\bar{c}_{uB}\,g'}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}u_R\,B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\,y_u\,\bar{q}_L\sigma^i H^c\sigma^{\mu\nu}u_R\,W^i_{\mu\nu} \\
+ \;& \frac{\bar{c}_{uG}\,g_S}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}\lambda^a u_R\,G^a_{\mu\nu} + \frac{\bar{c}_{dB}\,g'}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}d_R\,B_{\mu\nu} \\
+ \;& \frac{\bar{c}_{dW}\,g}{m_W^2}\,y_d\,\bar{q}_L\sigma^i H\sigma^{\mu\nu}d_R\,W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}\lambda^a d_R\,G^a_{\mu\nu} \\
+ \;& \frac{\bar{c}_{lB}\,g'}{m_W^2}\,y_l\,\bar{L}_L H\sigma^{\mu\nu}l_R\,B_{\mu\nu} + \frac{\bar{c}_{lW}\,g}{m_W^2}\,y_l\,\bar{L}_L\sigma^i H\sigma^{\mu\nu}l_R\,W^i_{\mu\nu} + h.c.
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_{bos} &= \frac{\bar{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk} W_\mu^{i\,\nu} W_\nu^{j\,\rho} W_\rho^{k\,\mu} + \frac{\bar{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc} G_\mu^{a\,\nu} G_\nu^{b\,\rho} G_\rho^{c\,\mu} \\
&+ \frac{\bar{c}_{2W}}{m_W^2}\,(D^\mu W_{\mu\nu})^i\,(D_\rho W^{\rho\nu})^i + \frac{\bar{c}_{2B}}{m_W^2}\,(\partial^\mu B_{\mu\nu})\,(\partial_\rho B^{\rho\nu}) \\
&+ \frac{\bar{c}_{2G}}{m_W^2}\,(D^\mu G_{\mu\nu})^a\,(D_\rho G^{\rho\nu})^a \\
\Delta\mathcal{L}_{4f} &= \sum_{\psi,L/R,T^a} \bar{\psi}_i \gamma^\mu T^a \psi_j \bar{\psi}_k \gamma_\mu T^a \psi_l + \bar{\psi}_i T^a \psi_j \bar{\psi}_k T^a \psi_l \\
\Delta\mathcal{L}_{\mathcal{CP}} &= \frac{i\tilde{c}_{HW}\, g}{m_W^2}\,(D^\mu H)^\dagger \sigma^i (D^\nu H) \tilde{W}_{\mu\nu}^i + \frac{i\tilde{c}_{HB}\, g'}{m_W^2}\,(D^\mu H)^\dagger (D^\nu H) \tilde{B}_{\mu\nu} \\
&+ \frac{\tilde{c}_\gamma\, g'^2}{m_W^2}\, H^\dagger H B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\, g_S^2}{m_W^2}\, H^\dagger H G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \\
&+ \frac{\tilde{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk} W_\mu^{i\,\nu} W_\nu^{j\,\rho} \tilde{W}_\rho^{k\,\mu} + \frac{\tilde{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc} G_\mu^{a\,\nu} G_\nu^{b\,\rho} \tilde{G}_\rho^{c\,\mu}
\end{aligned}
$$

$$
\tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta} V^{\alpha\beta}
$$

- after using EOM: 59 independent dim6 operators for single generation
  $\Rightarrow$ 2499 operators for 3 generations

$gg \to H$:



§2. Hidden Valleys — Strassler, Zurek

gauge group $G_{SM} \times U(1) \times SU(N_v) \quad [N_v > 2]$

$\qquad\qquad\qquad\qquad\qquad\quad g' \qquad\quad g_v$

$[G_{SM} = SU(3) \times SU(2) \times U(1)]$

- confinement: 1 GeV $\lesssim \Lambda_v \lesssim$ 1 TeV

- new Higgs field ϕ: $\langle\phi\rangle$ breaks U(1)
  $\Rightarrow Z'$ with $M_{Z'} \sim 1 - 6$ TeV

- hidden U, C ferm., 3 right-handed neutrinos N_i:
  $m_{U,C} \leftarrow \langle\phi\rangle$
  Z_2 symm. $\rightarrow N_i$ no Dirac mass $\rightarrow$ stable $\rightarrow$ DM

- kinetic mixing of Z, Z': $\mathcal{L} = \frac{\kappa}{2} B^{\mu\nu} F'_{\mu\nu}$
  can be absorbed in field redef. $\rightarrow$ mod. charges
  $\Rightarrow$ SM ferm. coupl. to Z': $Q_{Z'} = Q^0_{Z'} - \kappa \frac{g_1}{g'} Y$

	q_i	$\bar{u}_i$	$\bar{d}_i$	ℓ_i	e_i^+	N_i	U	$\bar{U}$	C	$\bar{C}$	H	ϕ
$SU(3)$	**3**	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)$	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	0	0	0	0	$\frac{1}{2}$	0
$U(1)_\chi$	$-\frac{1}{5}$	$-\frac{1}{5}$	$\frac{3}{5}$	$\frac{3}{5}$	$-\frac{1}{5}$	-1	q_+	q_-	$-q_+$	$-q_-$	$\frac{2}{5}$	2
$SU(n_v)$	**1**	**1**	**1**	**1**	**1**	**1**	$\mathbf{n_v}$	$\overline{\mathbf{n_v}}$	$\mathbf{n_v}$	$\overline{\mathbf{n_v}}$	**1**	**1**

$q_+ + q_- = -Q_\phi = -2$ [anomaly freedom]

(i) 2LF: (two light flavours) [$\sim$ 2F-QCD]

$m_U \sim m_C \ll \Lambda_v \Rightarrow \pi_v^{0,\pm}$ pseudo Goldstones (light)

wfct. $\pi_v^0 \sim \bar{U}U - \bar{C}C \Rightarrow \pi_v^0 \to Z' \to f\bar{f}$

$$\Gamma_{\pi_v^0} = \frac{1}{8\pi} \frac{g'^2}{m_{Z'}^2} \frac{Q_\phi^2 Q_H^2 f_{\pi_v}^2 m_{\pi_v}^5}{(m_{\pi_v}^2 - m_Z^2)^2} \sum_f N_{cf} m_f^2 v_f$$

$\Rightarrow$ heavy flavour preferred [helicity flip $\propto m_f$]

$$\mathcal{L} = \overline{\psi}(i\partial\!\!\!/ - m_f)\psi = \overline{\psi_L} i\partial\!\!\!/ \psi_L + \overline{\psi_R} i\partial\!\!\!/ \psi_R + m_f(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$

$\Rightarrow \mathcal{L}_{eff} \propto i m_f \pi_v (\overline{\psi_L}\psi_R - \overline{\psi_R}\psi_L)$

$[\overline{\psi_L}\psi_L = \overline{\psi_R}\psi_R = 0]$

$m_{\pi_v} \gg m_Z$:

$$\Gamma(\pi_v^0 \to b\bar{b}) \sim 3 \times 10^{15} s^{-1} \frac{f_{\pi_v}^2 m_{\pi_v}}{(200 \text{ GeV})^3} \left(\frac{10 \text{ TeV}}{m_{Z'}/g'} \right)^4$$

$m_{\pi_v} \ll m_Z$:

$$\Gamma(\pi_v^0 \to b\bar{b}) \sim 6 \times 10^9 s^{-1} \frac{f_{\pi_v}^2 m_{\pi_v}^5}{(20 \text{ GeV})^7} \left(\frac{10 \text{ TeV}}{m_{Z'}/g'} \right)^4$$

(ii) 1LF: (one light flavour) [≠ QCD]

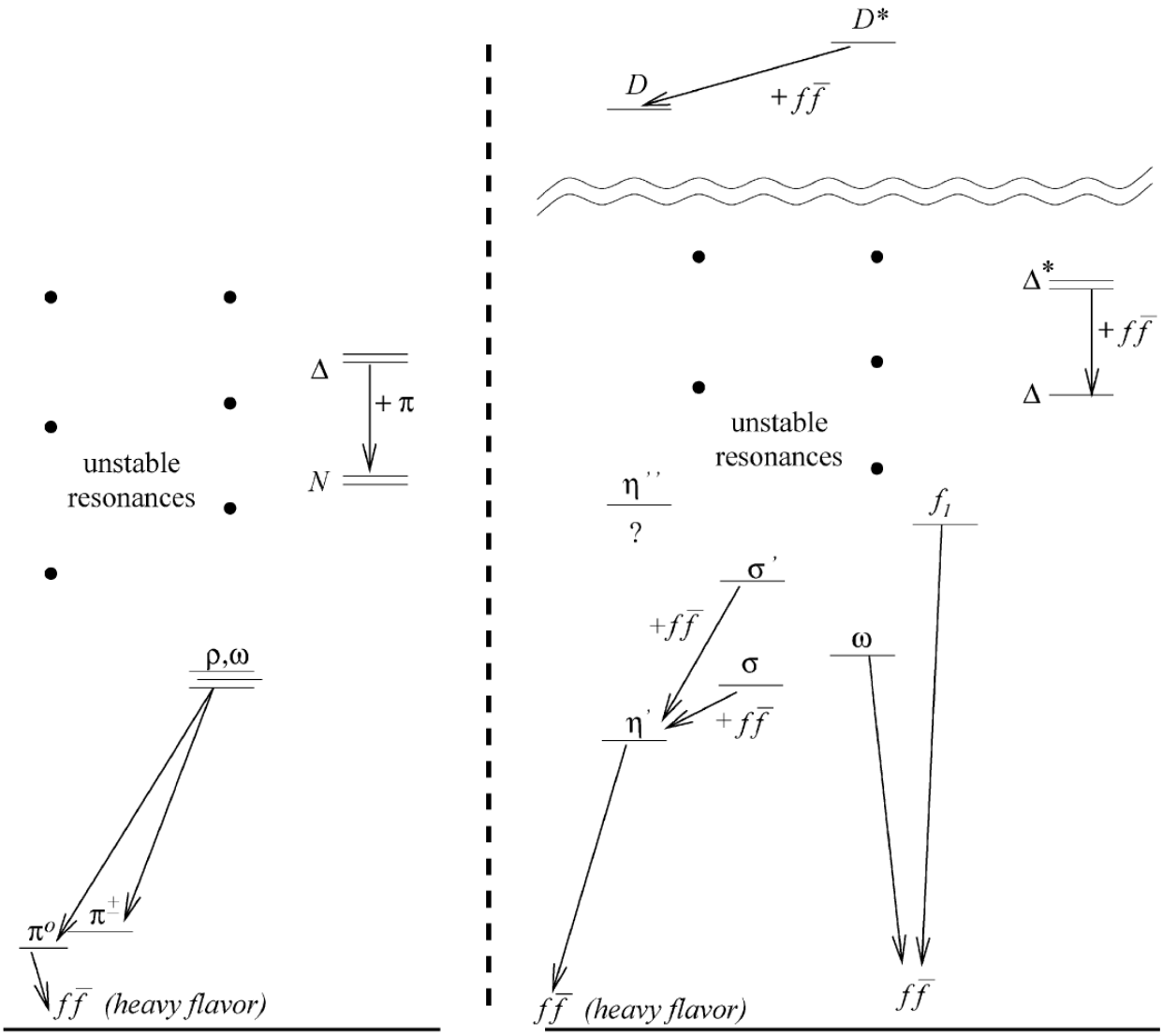
$m_U \ll \Lambda_v \ll m_C$

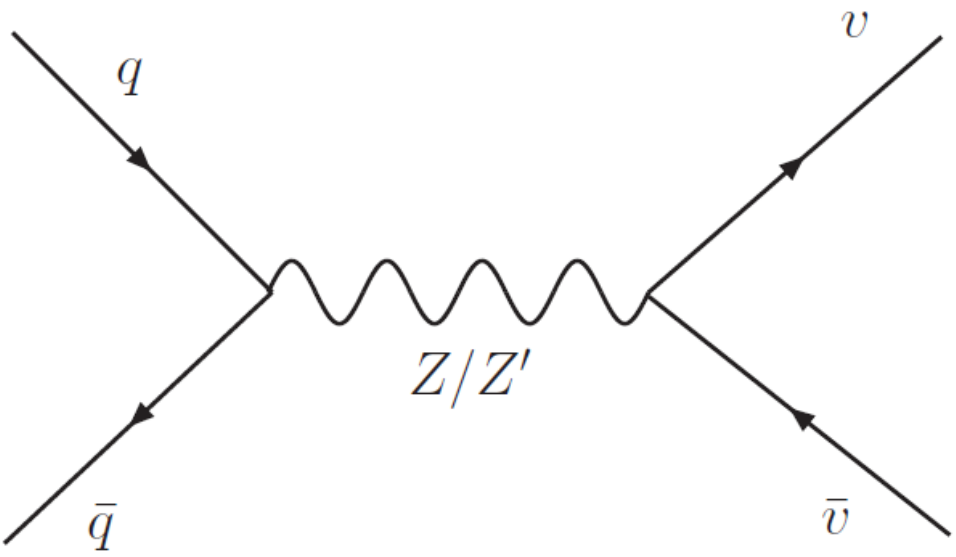
$\Rightarrow \eta'_v$ (pseudoscalar), ω_v (vector) lightest dark states

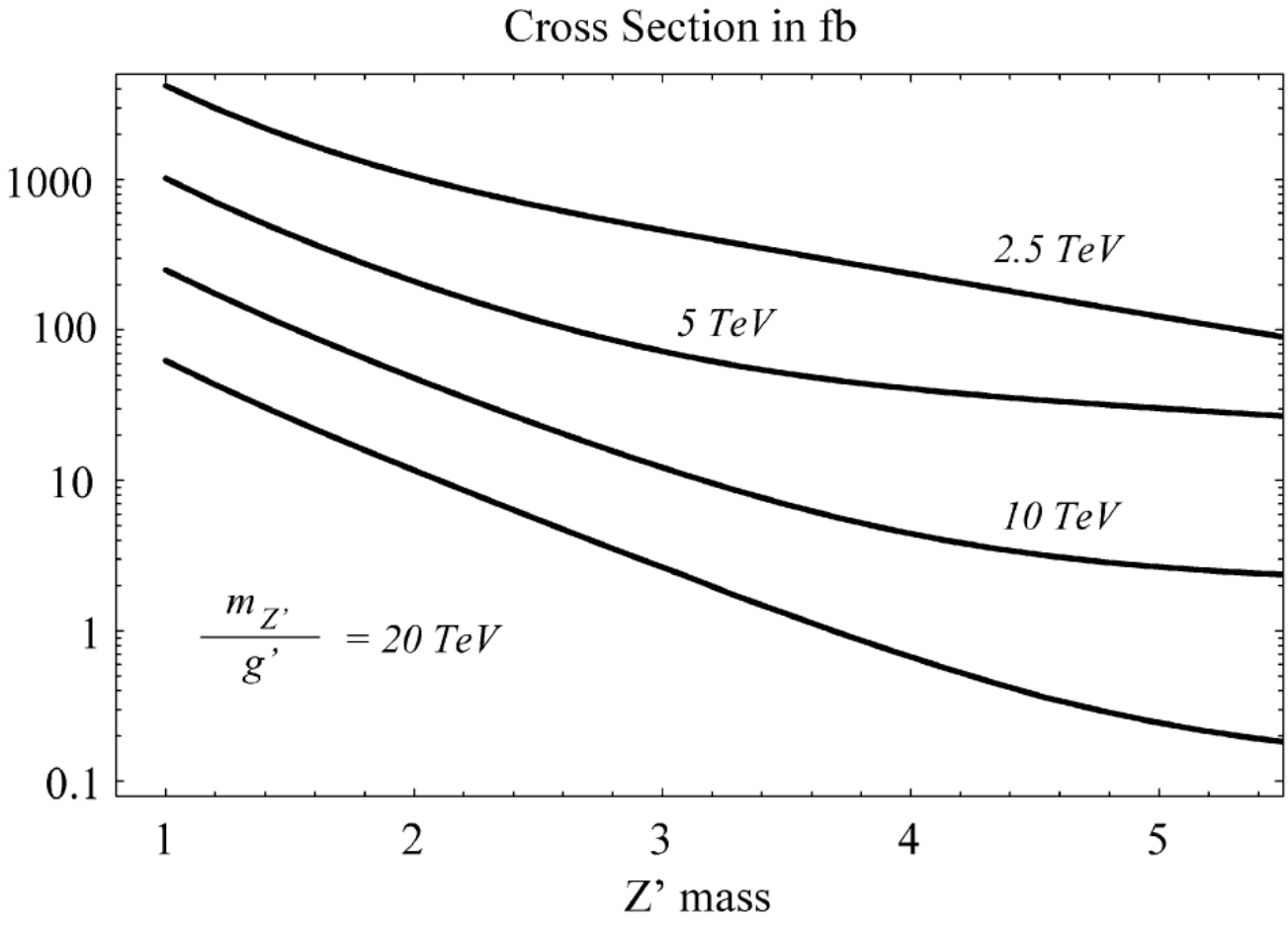
$\sigma_v \to f\bar{f} + \eta'_v$

$$\Gamma_{\omega_v} \sim 4 \times 10^{18} s^{-1} \left(\frac{m_{\omega_v}}{200\ \text{GeV}}\right)^5 \left(\frac{10\ \text{TeV}}{m_{Z'}/g'}\right)^4$$

($\Gamma_{\eta'_v}$: see above for π_v)




q
v
Z/Z'
q̄
v̄


Cross Section in fb
1000
100
10
1
0.1
2.5 TeV
5 TeV
10 TeV
m Z'
g'
= 20 TeV
1
2
3
4
5
Z' mass

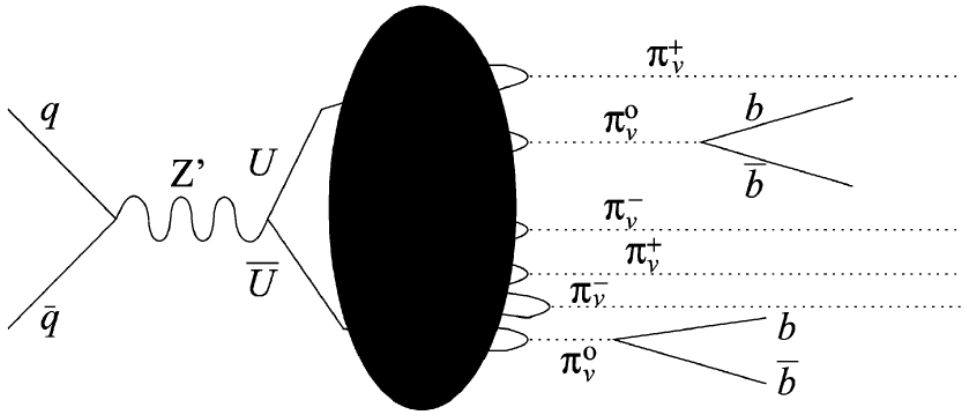


Fig. 3. A possible event in the two-light-flavor regime; note $\pi_v^{\pm}$ is electrically neutral and invisible.

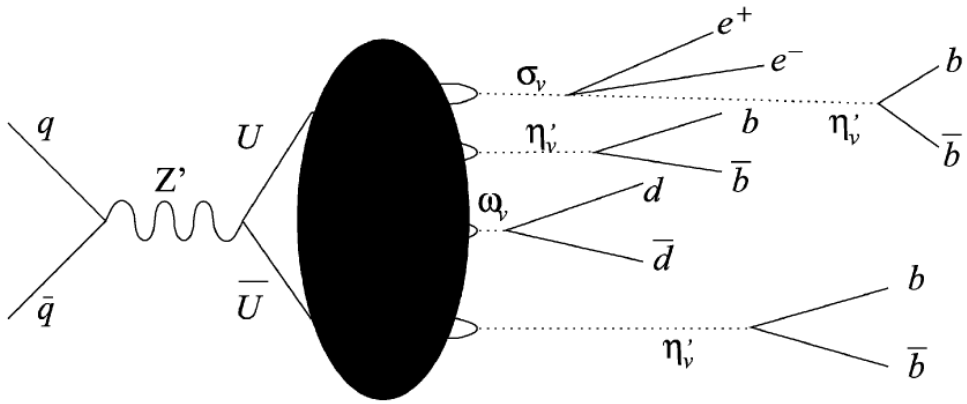


Fig. 4. A possible event in the one-light-flavor regime.

$\Rightarrow$ many displaced vertices $\rightarrow$ b-jets

§3. Dark QCD

gauge group $G_{SM} \times SU(N_d)$ $(N_d \geq 2)$

- n_f Dirac fermions: N_d colors, G_{SM} singlet
  $\Rightarrow$ dark quarks Q_d

- confinement scale Λ_d
  $m_{\pi_d} < \Lambda_d$ pseudo Goldstones ($\leftarrow$ QCD)

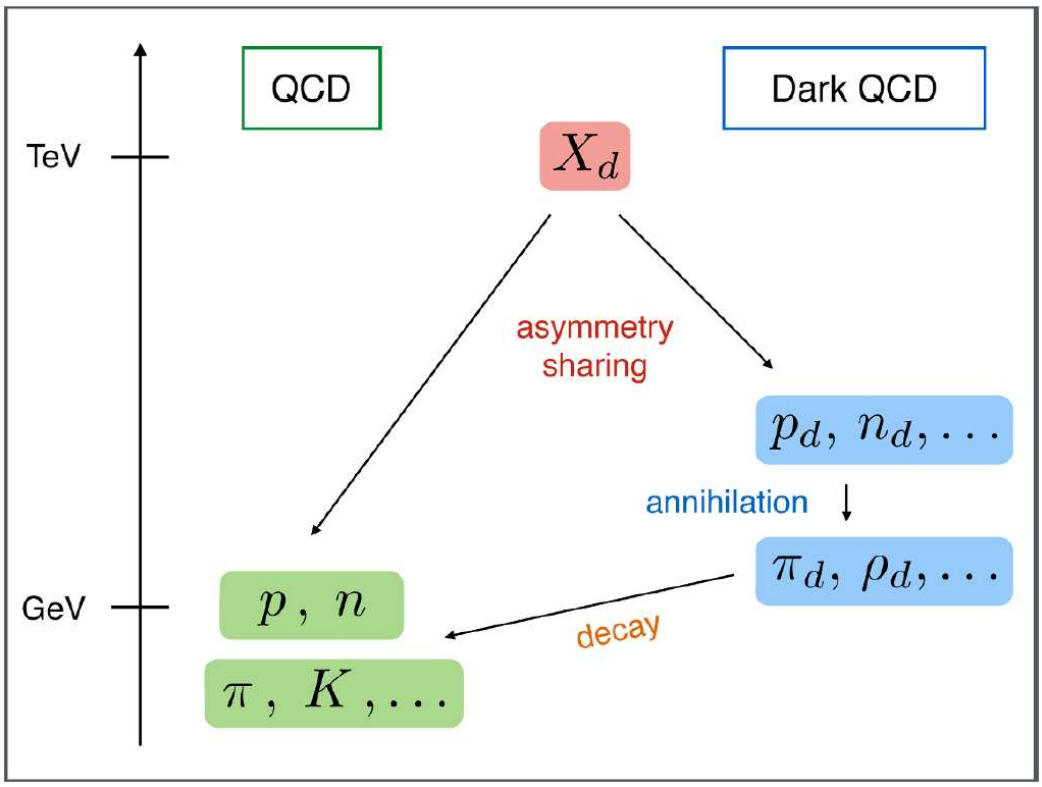
- $m_{\pi_d}, \Lambda_d \sim 1 - 10$ GeV

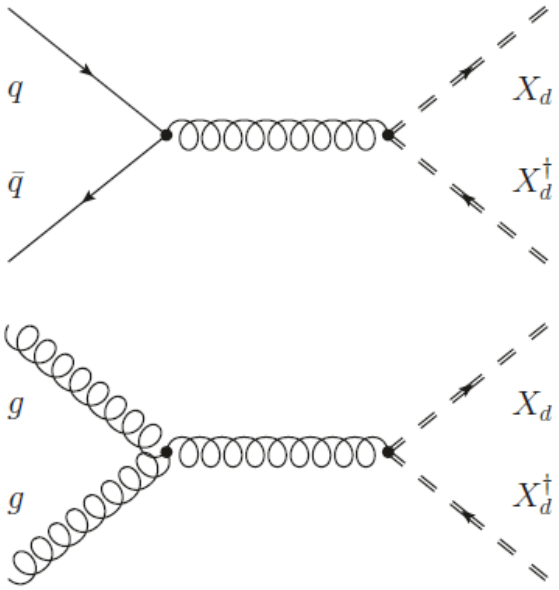
- dark baryon number conserved
  $\Rightarrow$ lightest dark baryon stable $\Rightarrow$ DM

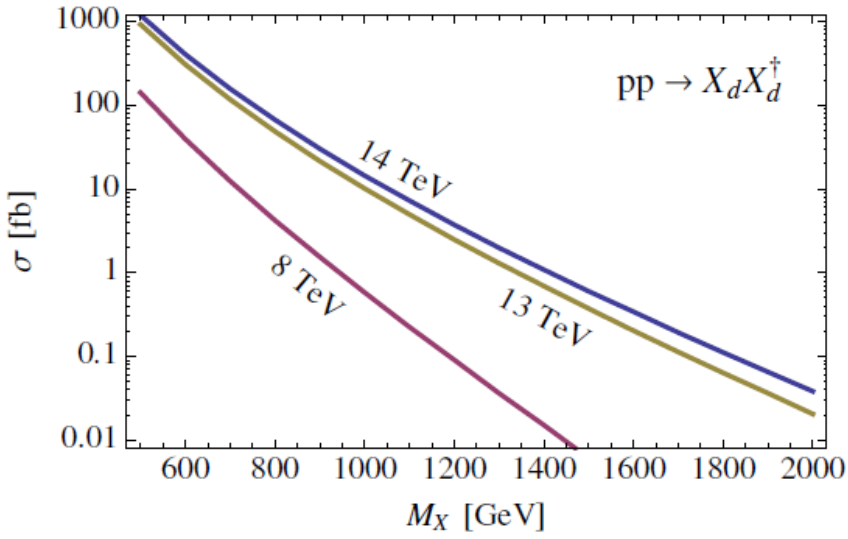
- scalar mediator: $\mathcal{L}_\kappa = \kappa \bar{Q}_d q X_d$

Field	SU(3) × SU(2) × U(1)	$SU(3)_{\text{dark}}$	Mass	Spin
Q_d	$(1, 1, 0)$	(3)	m_d $\mathcal{O}$(GeV)	Dirac Fermion
X_d	$(3, 1, \frac{1}{3})$	(3)	M_{X_d} $\mathcal{O}$(TeV)	Complex Scalar
Z_d	$(1, 1, 0)$	(1)	M_{Z_d} $\mathcal{O}$(TeV)	Vector Boson

Bai, Schwaller







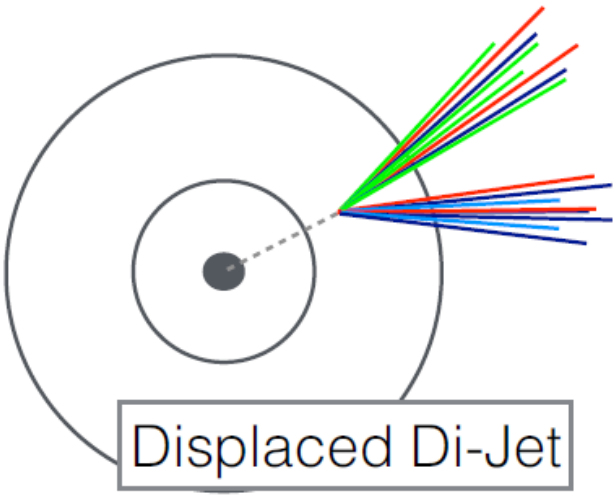
Schwaller, Stolarski, Weiler

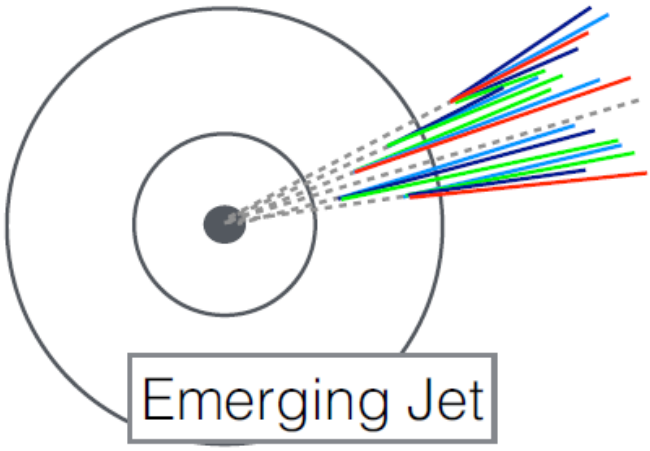
$$\Gamma(\pi_d \to d\bar{d}) \;=\; \frac{\kappa^4 N_c f_{\pi_d}^2 m_d^2}{32\pi M_{X_d}^4}\, m_{\pi_d}$$

$$\Rightarrow c\tau = 80mm \times \frac{1}{\kappa^4} \times \left(\frac{2\text{GeV}}{f_{\pi_d}}\right)^2 \left(\frac{100\text{MeV}}{m_d}\right)^2 \left(\frac{2\text{GeV}}{m_{\pi_d}}\right) \left(\frac{M_{X_d}}{1\text{TeV}}\right)^4$$

$\Rightarrow$ flight distances $\sim$ cm...m possible

Emerging Jets:





Schwaller, Stolarski, Weiler