Composite Dark Matter

Graham Kribs
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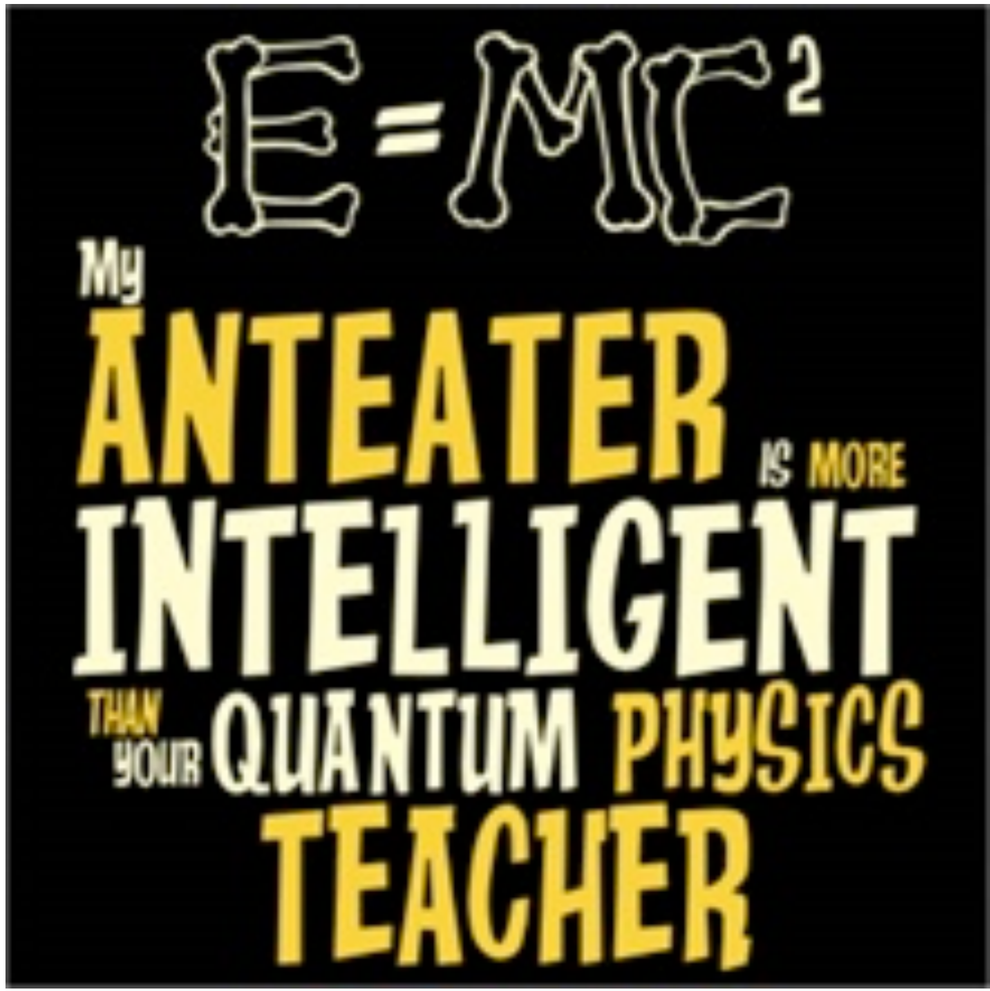
DM @ LHC @ UC Irvine | 4 April 2017



Dark Mesons in Composite Dark Matter Theories

Graham Kribs
University of Oregon

GK, Martin, Neil, Ostdiek, Tong [in preparation]

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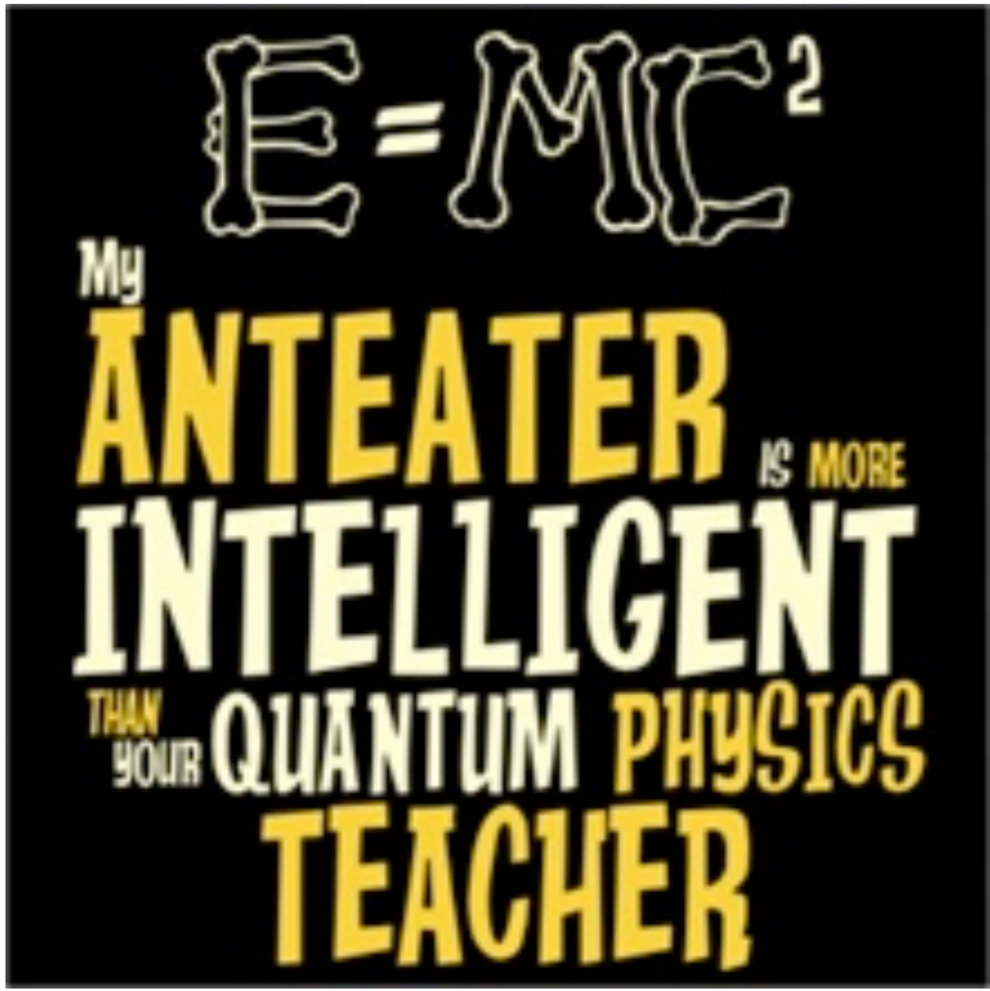
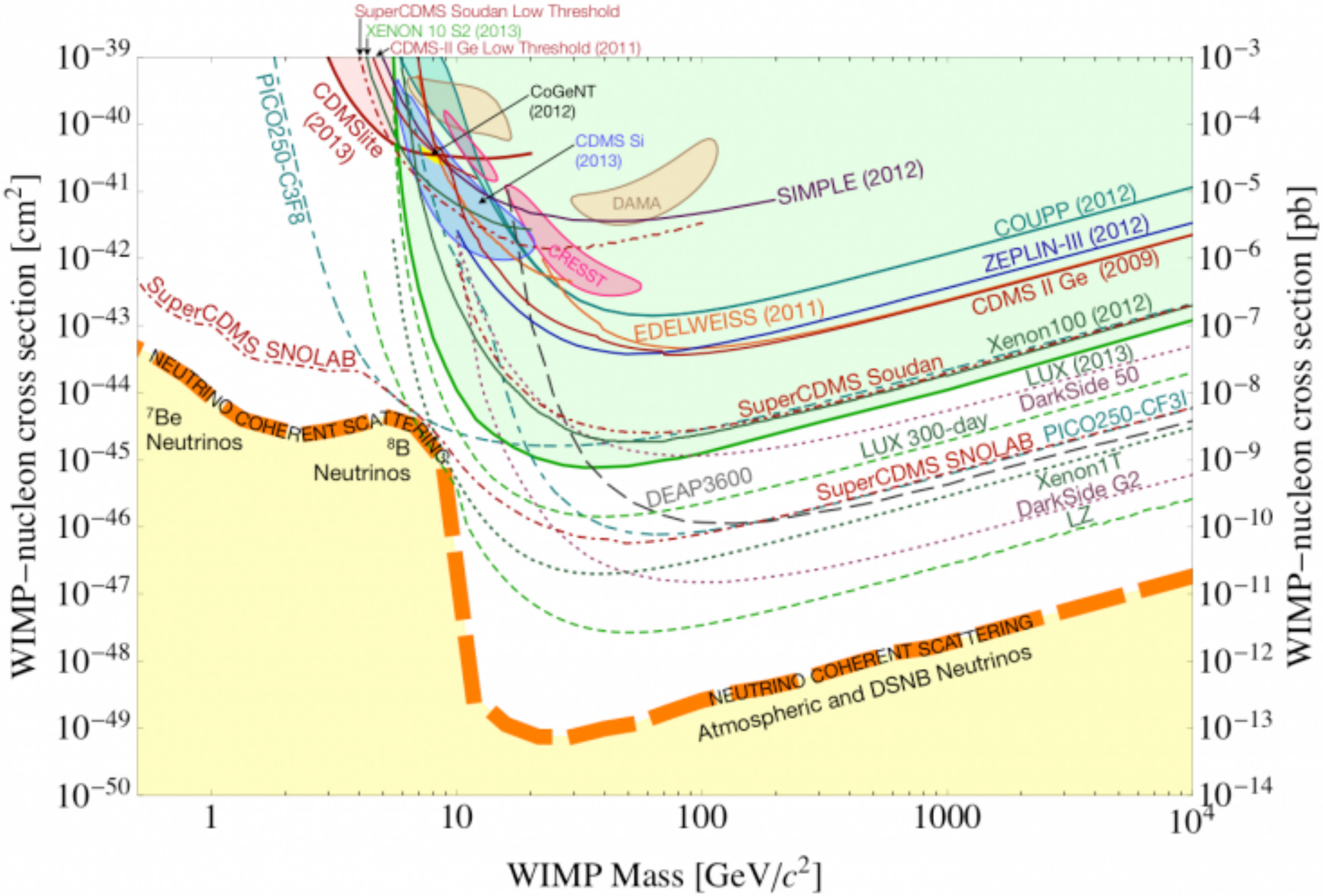
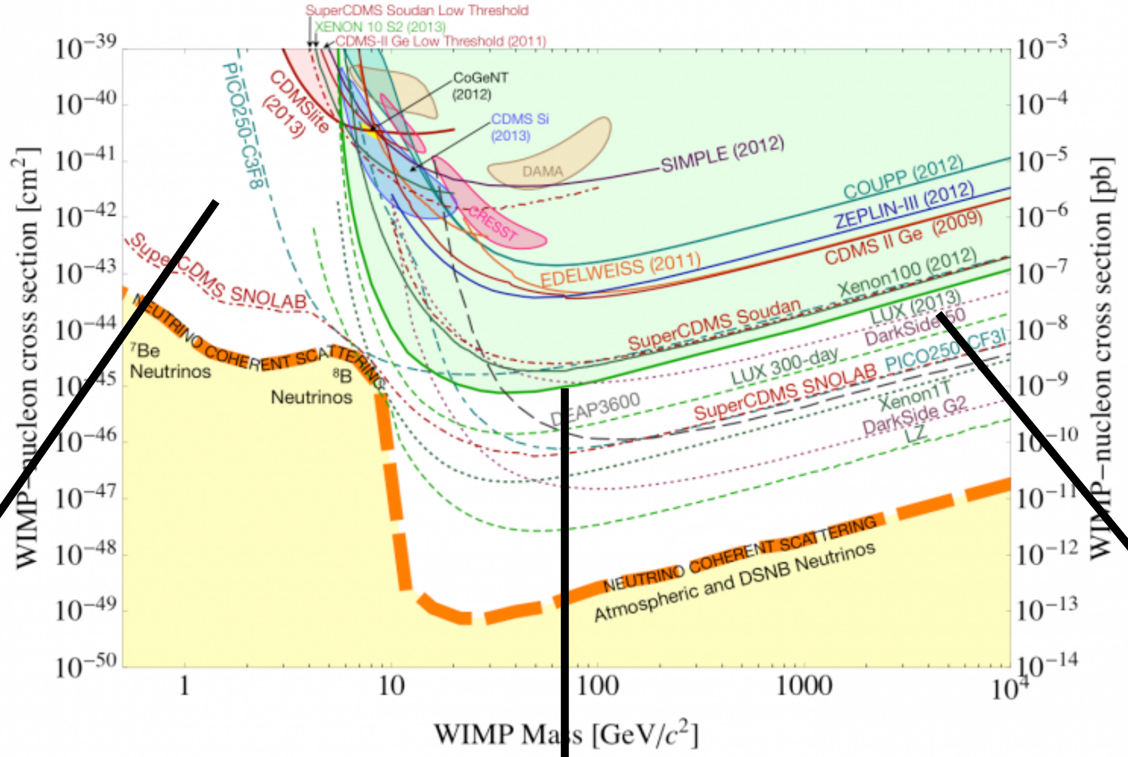


Direct Detection



Billard, Strigari, Figueroa-Feliciano; 1307.5458

Interpretation with a Broad Brush



Billard, Strigari, Figueroa-Feliciano; 1307.5458

$$m_{\rm DM} \lesssim \text{few GeV}$$

(no nuclear recoil above detection threshold)

$$\frac{y_{\rm eff}\, v}{m_{\rm DM}} \lesssim 0.1$$

effective coupling of DM to Higgs must be suppressed

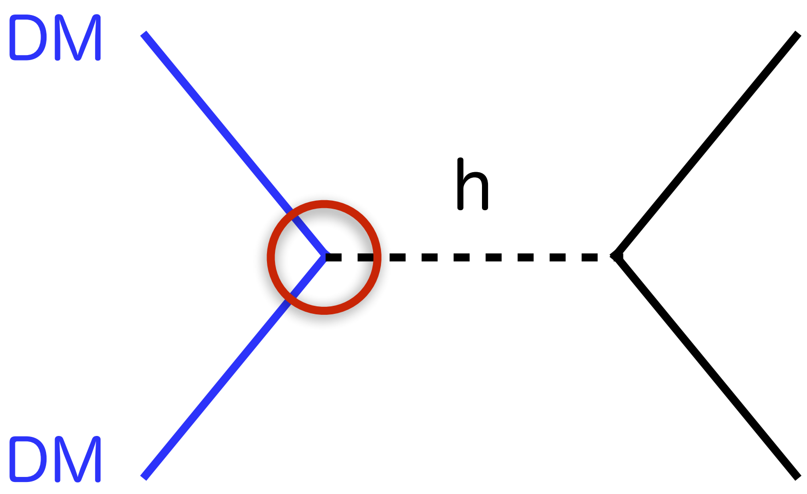
$$m_{\rm DM} \gtrsim \text{TeV}$$

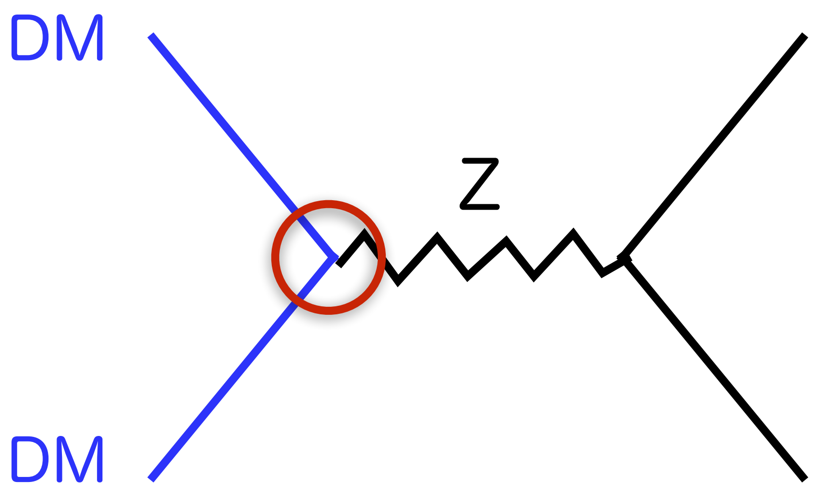
(suppression of Higgs coupling by at least

$$\left(\frac{v}{m_{\rm DM}}\right)^2$$

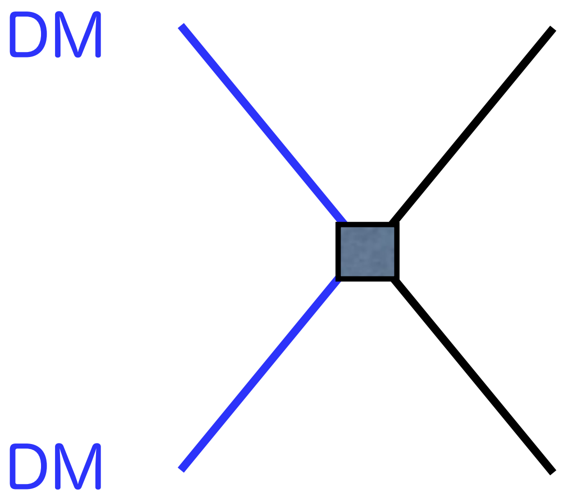
Scales in Direct Detection of WIMPs

Usual story is that DM has renormalizable interactions with SM mediators, e.g.,





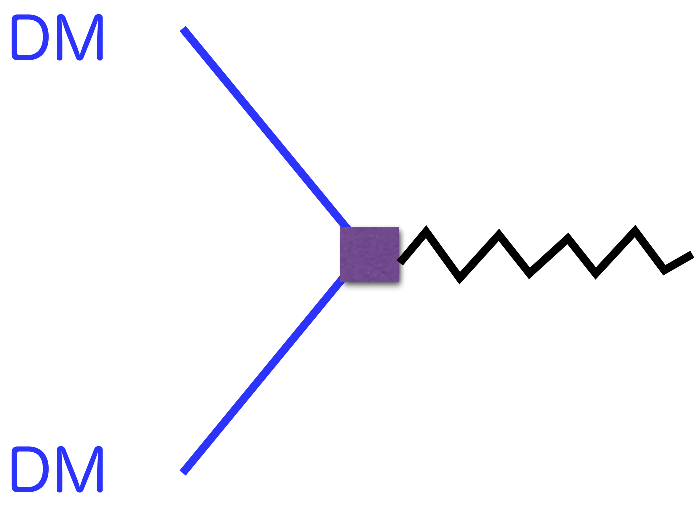
that are integrated out in the NR effective theory to give, e.g. dimension-6 spin-independent operator



But the only scales in town are $\frac{1}{M_Z^2}, \quad \frac{1}{m_h^2}$

New scale appears in composite DM theories

Effective interactions of strongly-coupled dark matter with SM mediators/matter is higher dimensional:

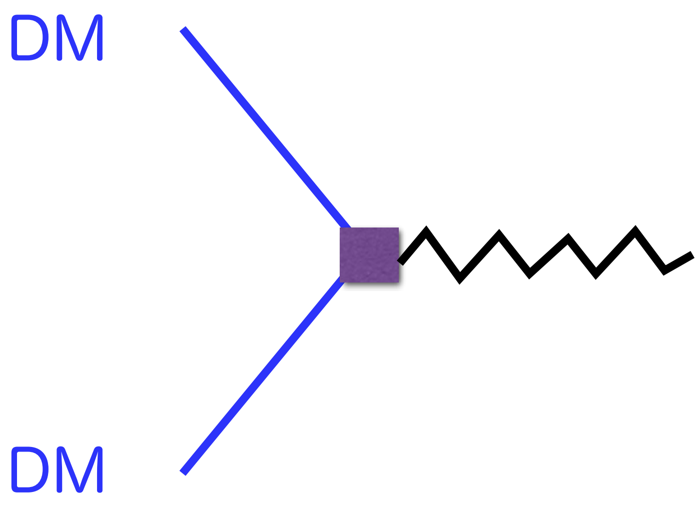


$$\frac{1}{(\Lambda_{\rm dark})^n}$$

New scale!
(natural)

New scale appears in composite DM theories

Effective interactions of strongly-coupled dark matter with SM mediators/matter is higher dimensional:



$$\frac{1}{(\Lambda_{\mathrm{dark}})^n}$$

New scale!
(natural)

e.g.:
magnetic moment:

$$\frac{\overline{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}}{\Lambda_{\mathrm{dark}}}$$

charge radius:

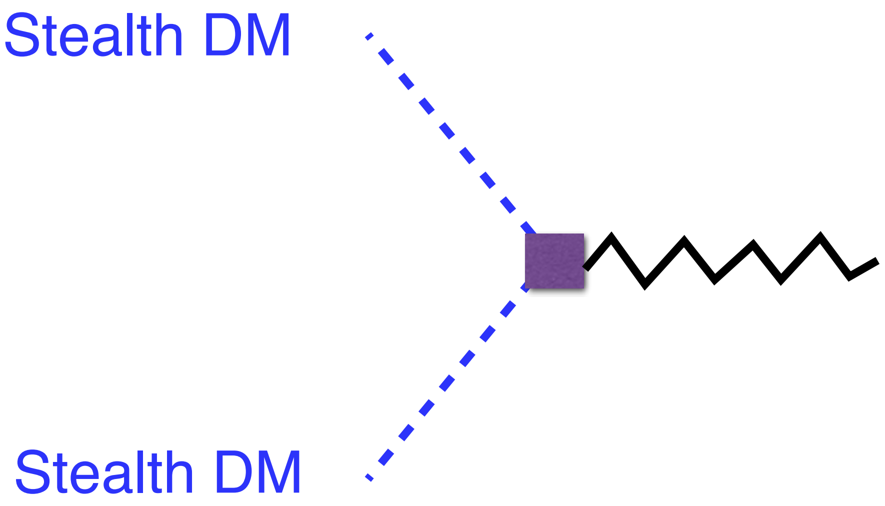
$$\frac{(\overline{\psi}\psi)v_\mu\partial_\nu F^{\mu\nu}}{(\Lambda_{\mathrm{dark}})^2}$$

polarizability:

$$\frac{(\overline{\psi}\psi)F_{\mu\nu}F^{\mu\nu}}{(\Lambda_{\mathrm{dark}})^3}$$

Stealth Dark Matter

Dark matter is a scalar baryon of a strongly-coupled $SU(N_{\mathrm{dark}})$ confining theory with dark fermions transforming under the electroweak group.



$$\frac{1}{(\Lambda_{\mathrm{dark}})^n}$$

New scale!
(natural)

e.g.:
magnetic moment:

$$\xcancel{\frac{\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}}{\Lambda_{\mathrm{dark}}}}$$

(DM is scalar baryon)

charge radius:

$$\xcancel{\frac{(\bar{\psi}\psi)v_\mu\partial_\nu F^{\mu\nu}}{(\Lambda_{\mathrm{dark}})^2}}$$

(dark custodial SU(2))

polarizability:

$$\frac{\phi\phi^* F_{\mu\nu}F^{\mu\nu}}{(\Lambda_{\mathrm{dark}})^3}$$

(dimension-7 in non-relativistic EFT)

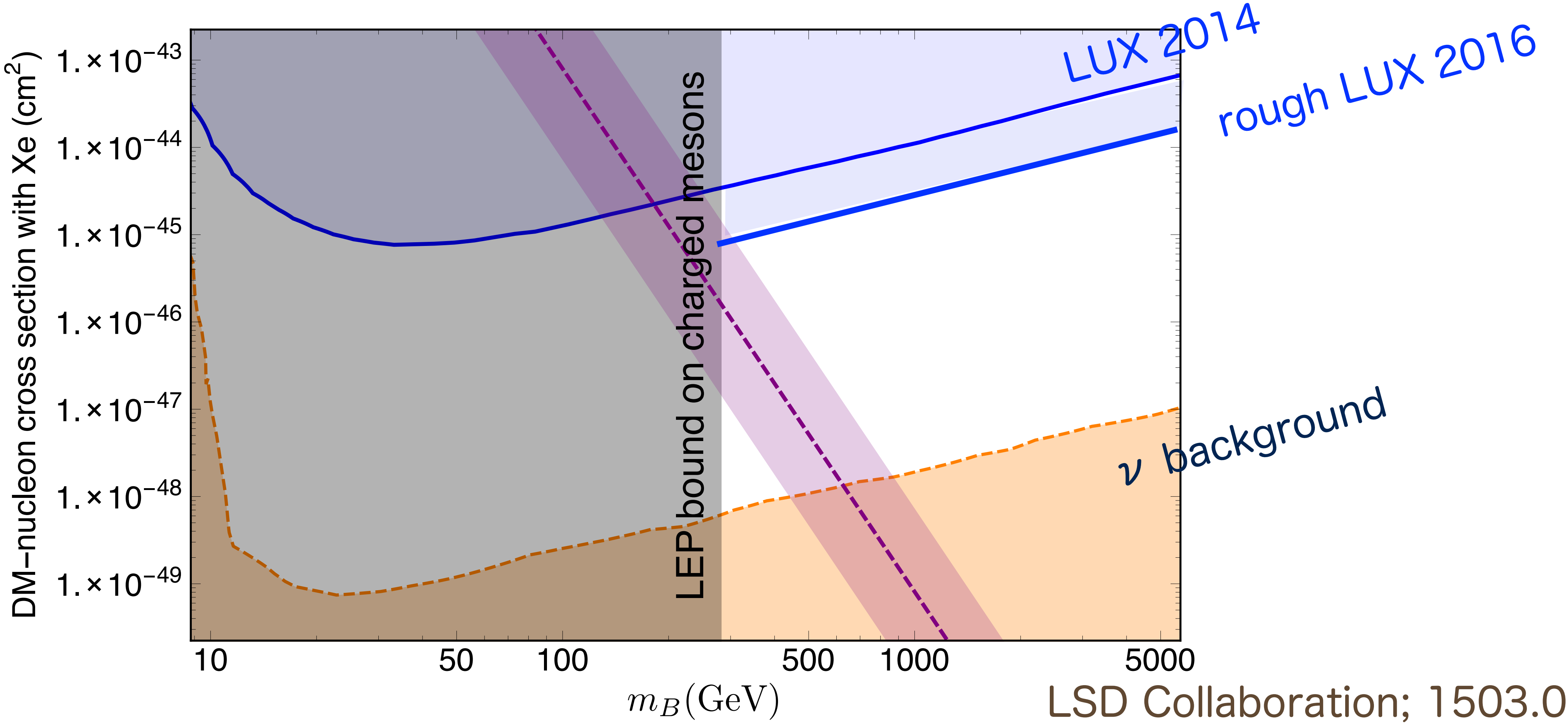
Naturally “stealthy” with respect to direct detection!

Direct Detection Bounds on Stealth Dark Matter

Elastic scattering through polarizability

$$\sigma_{\text{nucleon}} = \boxed{\frac{Z^4}{A^2}} \frac{144\pi\alpha^4\mu_{nB}^2(M_F^A)^2}{m_B^6 R^2}[c_F^2]$$

Depends on (Z,A), since it doesn't have A²-like (Higgs-like) scaling.
For Zenon, we obtain:



LSD Collaboration; 1503.04205

Confluence of collider and direct detection bounds, but for reasons completely different than ordinary (elementary) WIMPs.

Focus on “dark” mesons

Dark mesons
accompanying
dark baryonic DM

Focus on “dark” mesons

Dark mesons
accompanying
dark baryonic DM

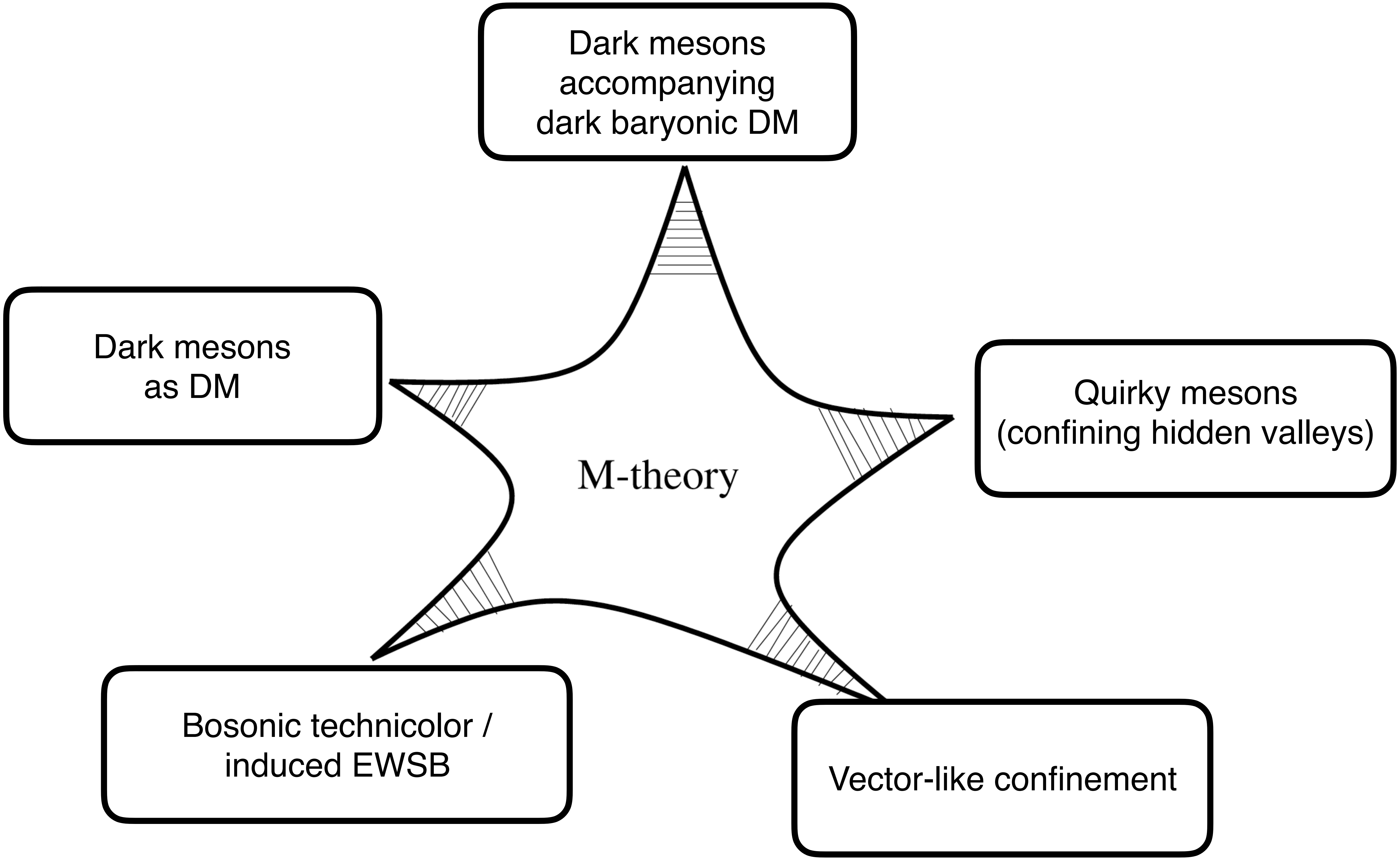
Dark mesons
as DM

Quirky mesons
(confining hidden valleys)

Bosonic technicolor /
induced EWSB

Vector-like confinement

Focus on “dark” mesons



Dark mesons accompanying dark baryonic DM

Dark mesons as DM

Quirky mesons (confining hidden valleys)

Bosonic technicolor / induced EWSB

Vector-like confinement

Model Space

	References include (not exhaustive!):
Bosonic TC / induced EWSB	Carone, Simmons; hep-ph/9207273 Brod, Drobnak, Kagan, Stamou, Zupan; 1407.8188 Chang, Luty, Salvioni, Tsai; 1411.6023
Quirks	Kang, Luty; 0805.4642
Vector-like confinement	Kilic, Okui, Sundrum; 0906.0577 Kilic, Okui; 1001.4526
Quirky DM	Kribs, Roy, Terning, Zurek; 0909.2034
Stealth DM	Appelquist et al (LSD Collaboration); 1402.6656; 1503.04203; 1503.04205
Bai-Hill Dark Mesons	Bai, Hill; 1005.0008
Buckley-Neil Dark Mesons	Buckley, Neil; 1209.6054
SIMP (WZW 3->2)	Hochberg, Kuflik, Murayama, Volansky, Wacker; 1411.3727 Hochberg, Kuflik, Murayama; 1512.07917
Light/heavy chiral DM	Harigaya, Nomura; 1603.03430 Co, Harigaya, Nomura; 1610.03848

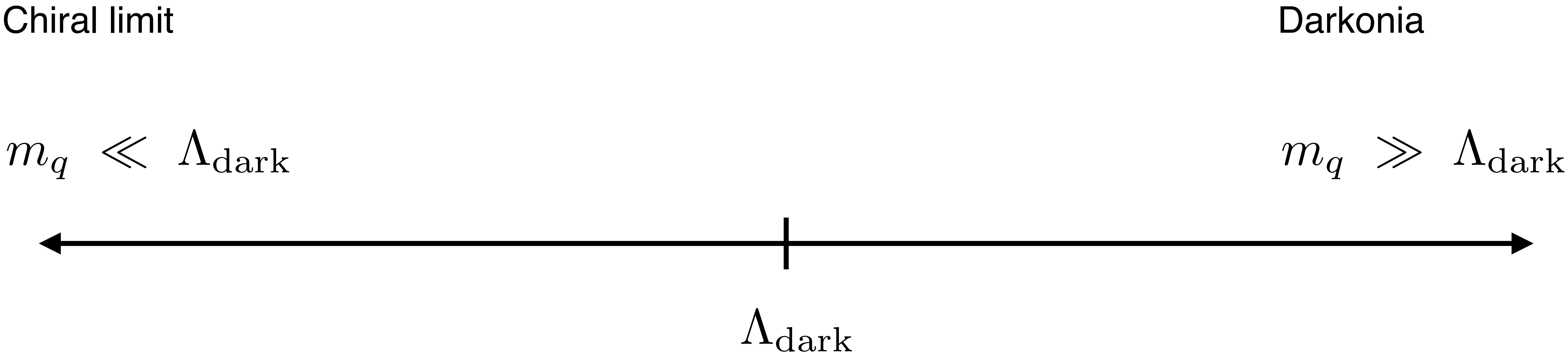
Model Space I

1) Determined by how the dark fermions transform under SM gauge symmetries:

	$SU(2)_L \times U(1)_Y$	$U(1)_Y$ only	$SU(3)_c \times \cdots$	$U(1)_{\text{dark}}$ only
Bosonic TC / induced EWSB	chiral			
Quirks	vector-like	vector-like	vector-like	
Vector-like confinement	vector-like		vector-like	
Quirky DM	chiral			
Stealth DM	vector-like			
Bai-Hill Dark Mesons	vector-like SU(2) only			
Buckley-Neil Dark Mesons		vector-like		
SIMP (WZW 3->2)				vector-like
Light/heavy chiral DM				chiral

Model Space II

2) Determined by dark fermion masses relative to confinement scale



Chiral limit

$m_q \ll \Lambda_{\text{dark}}$

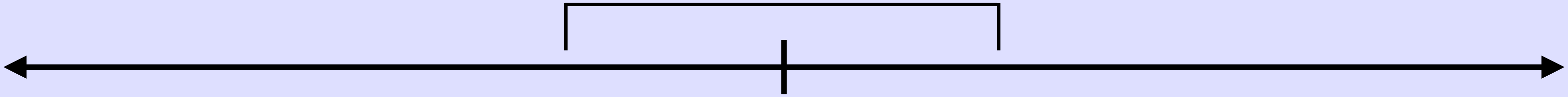
Darkonia

$m_q \gg \Lambda_{\text{dark}}$

Λ_{dark}

Model Space II

2) Determined by dark fermion masses relative to confinement scale



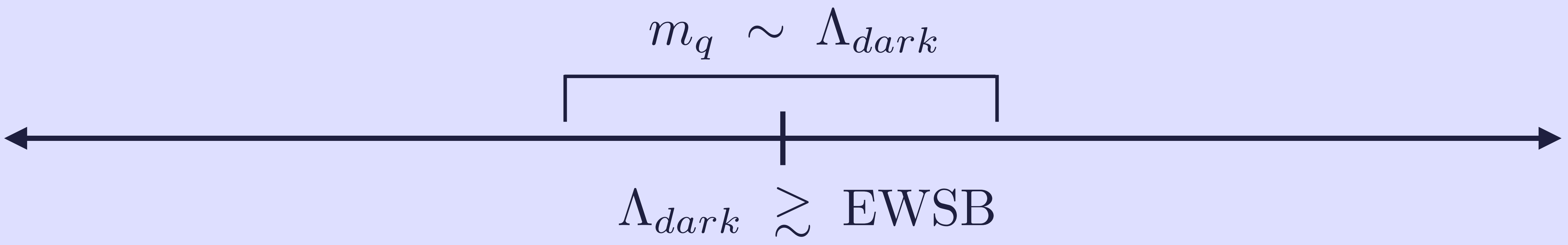
$m_q \sim \Lambda_{dark}$

$\Lambda_{dark} \gtrsim \text{EWSB}$

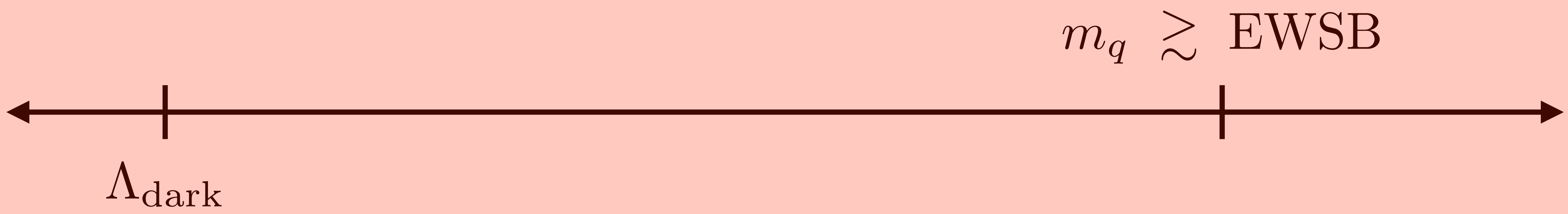
Stealth DM; Bai-Hill & Buckley-Neil DM; Vector-like Confinement; Bosonic TC / induced EWSB

Model Space II

2) Determined by dark fermion masses relative to confinement scale



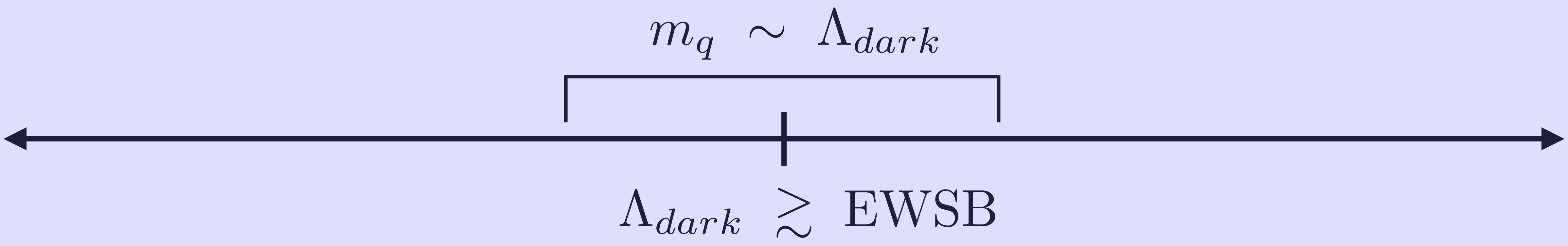
Stealth DM; Bai-Hill & Buckley-Neil DM; Vector-like Confinement; Bosonic TC / induced EWSB



(Truly) quirky theories; glueball DM

Model Space II

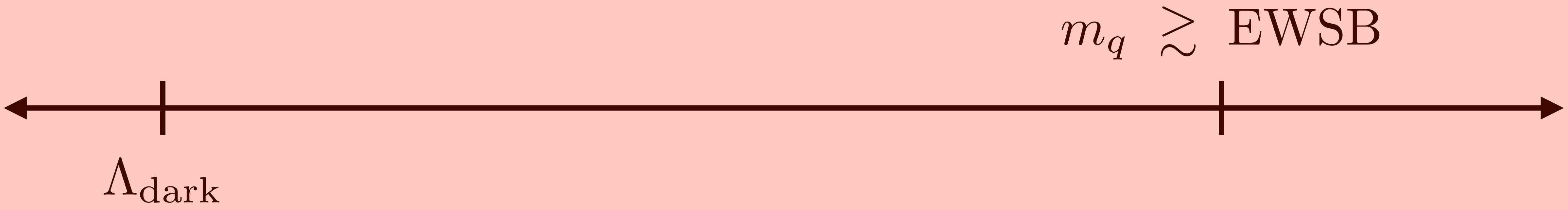
2) Determined by dark fermion masses relative to confinement scale



$m_q \sim \Lambda_{dark}$

$\Lambda_{dark} \gtrsim \text{EWSB}$

Stealth DM; Bai-Hill & Buckley-Neil DM; Vector-like Confinement; Bosonic TC / induced EWSB



$m_q \gtrsim \text{EWSB}$

$\Lambda_{\rm dark}$

(Truly) quirky theories; glueball DM

m_q

$\Lambda_{\rm dark} \sim \mathcal{O}(100\ \text{MeV})$

Dark U(1) theories; SIMP DM; Light Chiral DM;

Model Space III: Fermion content

Stealth DM

	$SU(N_{\text{dark}})$	$SU(2)_L \times U(1)_Y$
F_1	$\mathbf{N}$	$(\,\mathbf{2}\,,0\,)$
F_2	$\overline{\mathbf{N}}$	$(\,\mathbf{2}\,,0\,)$
$\begin{pmatrix} F_{3u} \\ F_{3d} \end{pmatrix}$	$\mathbf{N}$	$\left(\mathbf{1}\,,\begin{matrix} +1/2 \\ -1/2 \end{matrix}\right)$
$\begin{pmatrix} F_{4u} \\ F_{4d} \end{pmatrix}$	$\overline{\mathbf{N}}$	$\left(\mathbf{1}\,,\begin{matrix} +1/2 \\ -1/2 \end{matrix}\right)$

Hybrid

Vector-like confinement

(with SU(2) fermion doublets)

	$SU(N_{\text{dark}})$	$SU(2)_L \times U(1)_Y$
F_1	$\mathbf{N}$	$(\,\mathbf{2}\,,0\,)$
F_2	$\overline{\mathbf{N}}$	$(\,\mathbf{2}\,,0\,)$

Pure vector-like

Bosonic technicolor / induced EWSB

	$SU(N_{\text{dark}})$	$SU(2)_L \times U(1)_Y$
F_1	$\mathbf{N}$	$(\,\mathbf{2}\,,0\,)$
$\begin{pmatrix} F_{4u} \\ F_{4d} \end{pmatrix}$	$\overline{\mathbf{N}}$	$\left(\mathbf{1}\,,\begin{matrix} +1/2 \\ -1/2 \end{matrix}\right)$

Pure chiral

Mesons of Stealth Dark Matter

1) Unlike bosonic technicolor / induced EWSB (and QCD!);

—> condensate $\langle F_L F_R \rangle \sim \Lambda^3_{\rm dark}$ does not (hugely) break EW symmetry

2) Like bosonic technicolor, there are Higgs interactions with dark fermions

$$yF_1 H F_{4d} + yF_1 H^\dagger F_{4u} + yF_2 H F_{3d} + yF_2 H^\dagger F_{3u} + h.c.$$

that lead to (small) EW breaking contributions to dark fermion masses
(and break global symmetries down to $U(1)_{dark\ baryon}$

3) Unlike bosonic technicolor / induced EWSB & vector-like confinement (and QCD!);
(but like some composite Higgs models)

“Tunable” amount of $SU(2)_L \times U(1)_Y$ in $U(4)_V$ (preserved vector part of global symmetry)

$\cancel{SU(2)_L \times U(1)}_Y$ in $U(4)_A$ (broken axial part of global symmetry)

Connecting dark theories together

The “dials” are:

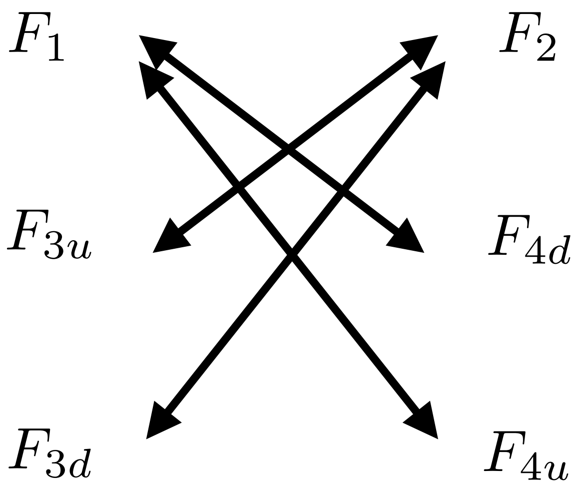
vector-like masses

$$F_1 \xleftrightarrow{M_{12}} F_2$$

$$F_{3u} \xleftrightarrow{M_{34}} F_{4d}$$

$$F_{3d} \xleftrightarrow{M_{34}} F_{4u}$$

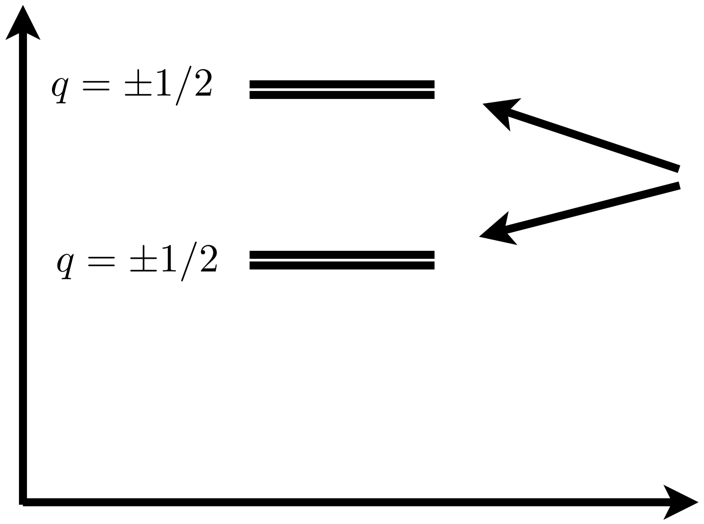
Yukawa couplings



With mass matrices

$$M^u \equiv \begin{pmatrix} M_{12} & y^u_{14} v/\sqrt{2} \\ y^u_{23} v/\sqrt{2} & M^u_{34} \end{pmatrix} \qquad M^d \equiv - \begin{pmatrix} M_{12} & y^d_{14} v/\sqrt{2} \\ y^d_{23} v/\sqrt{2} & M^d_{34} \end{pmatrix}$$

Lead to masses:



$$M_{1,2} = M \mp \sqrt{\Delta^2 + \frac{y_{14} y_{23} v^2}{2}}$$

$$\Delta \equiv \left| \frac{M_{12} - M_{34}}{2} \right|$$

$$M \equiv \frac{M_{12} + M_{34}}{2}$$

Contribution to Axial Current

Convenient to expand around the symmetric matrix limit

$$\begin{pmatrix} M_{12} & y_{14}v/\sqrt{2} \\ y_{23}v/\sqrt{2} & M_{34} \end{pmatrix} = \begin{pmatrix} M_{12} & yv/\sqrt{2} \\ yv/\sqrt{2} & M_{34} \end{pmatrix} + \frac{\epsilon_y v}{\sqrt{2}} \begin{pmatrix} & 1 \\ -1 & \end{pmatrix} \qquad |\epsilon_y| \ll |y|$$

Obtain

$$j^{\mu a}_{\rm axial} \sim c_{axial} \overline{\Psi}_1 \gamma^\mu \gamma_5 \Psi_1^{(\prime)}$$

Critical for light meson decay!

$$c_{\rm axial} = \frac{\epsilon_y y v^2}{2M\sqrt{2\Delta^2 + y^2 v^2}}$$

Correct limits:

$$c_{\rm axial} \xrightarrow{M\to\infty} 0 \qquad c_{\rm axial} \xrightarrow{yv\to 0} 0$$

Dark fermions —> Dark mesons

Consider the limit

$$yv \;\ll\; M_{12}, M_{34} \;<\; \Lambda_{\rm dark}$$

Light mesons can be represented in non-linear representation

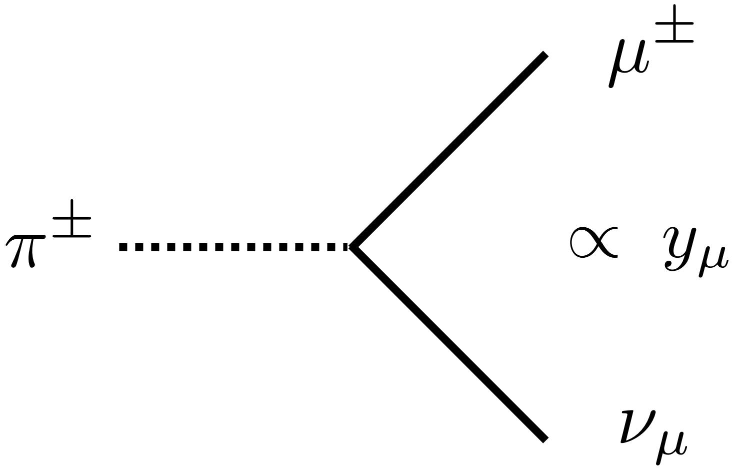
$$\Sigma \;=\; \exp\left[i \frac{\pi^a_{\rm d} t^a}{f_d} \right]$$

$$\pi^a_{\rm d} \;\sim\; \left(\begin{array}{cccc} \pi^0_{d1} & \sqrt{2}\pi^+_{d1} & & \\ \sqrt{2}\pi^-_{d1} & -\pi^0_{d1} & \multicolumn{2}{c}{K_d\text{'s}} \\ \multicolumn{2}{c}{K_d\text{'s}} & \pi^0_{d2} & \sqrt{2}\pi^+_{d2} \\ & & \sqrt{2}\pi^-_{d2} & -\pi^0_{d2} \end{array} \right)$$

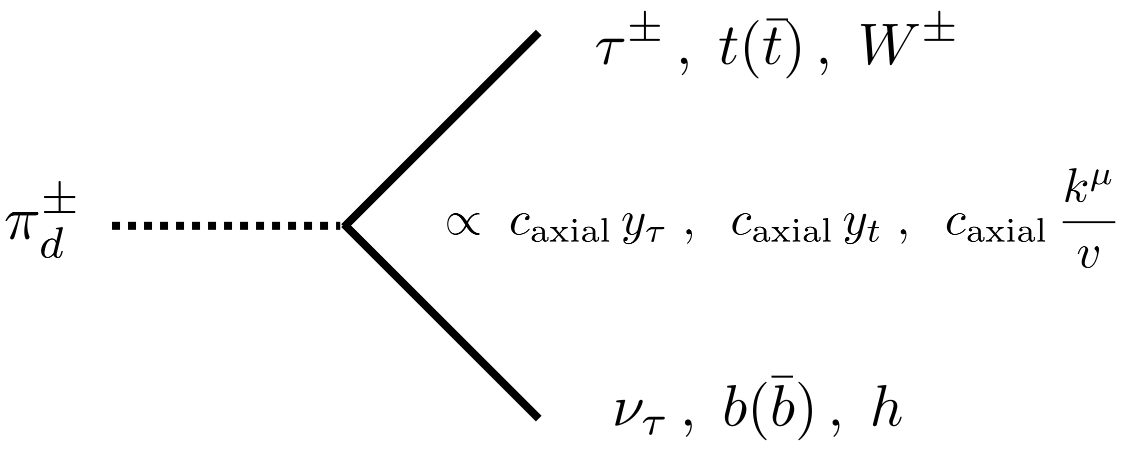
That includes one set of light “dark pions” (d1), eight “dark kaons”, another set of heavier “dark mesons” (d2), and an η (not shown).

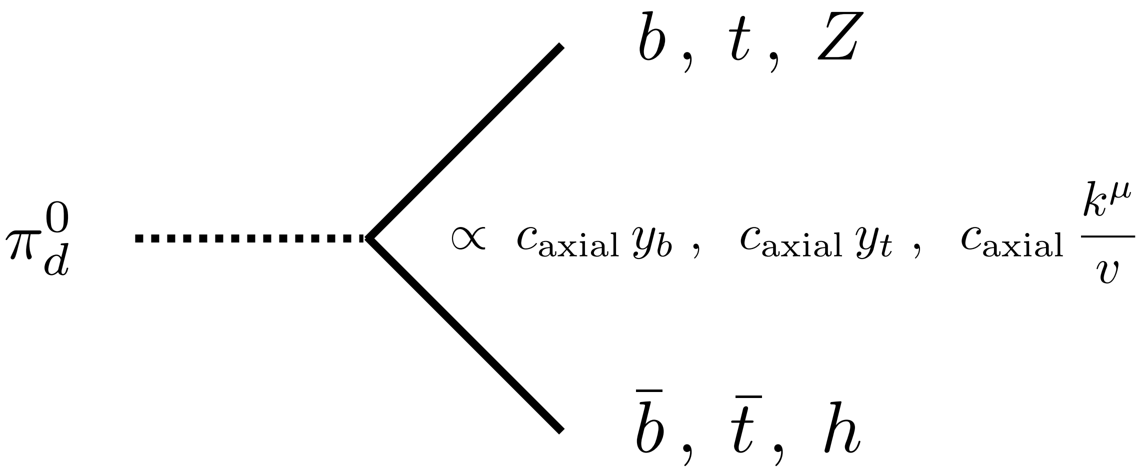
Dark pion decay

Like pion decay in QCD where $\langle 0|j^{\mu}_{\pm,\mathrm{axial}}|\pi^{\pm}\rangle = i f_{\pi} p^{\mu}$



Lightest dark mesons decay through $\langle 0|j^{\mu a}_{\mathrm{axial}}|\pi^{a}_{d}\rangle = i f_{d} p^{\mu}$





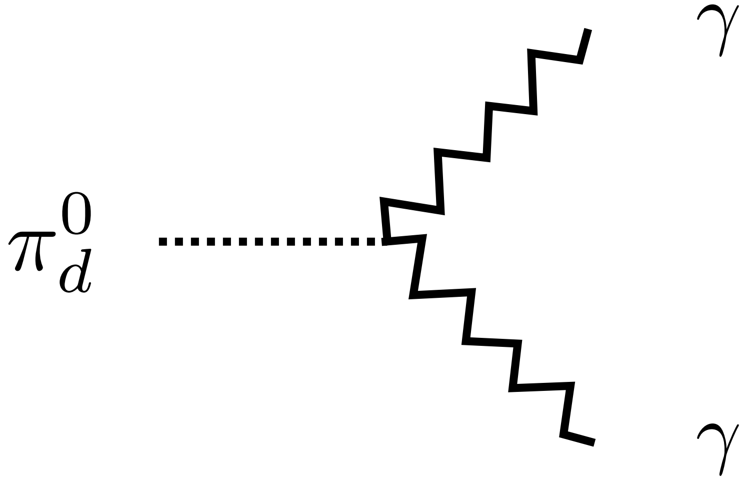
But the much larger f_d

$$f_{\pi} \ll f_{d} \gtrsim \text{weak scale}$$

so dark mesons decay much faster than QCD pions even with $c_{\mathrm{axial}} \ll 1$

π_d^0 decay through anomaly?

Unlike QCD,



The decay through the anomaly may or may not occur.
The QCD anomaly is proportional to

$$\mathrm{tr}[\tau_3 Q_f^2] \;\propto\; N_c[(2/3)^2 - (-1/3)^2]$$

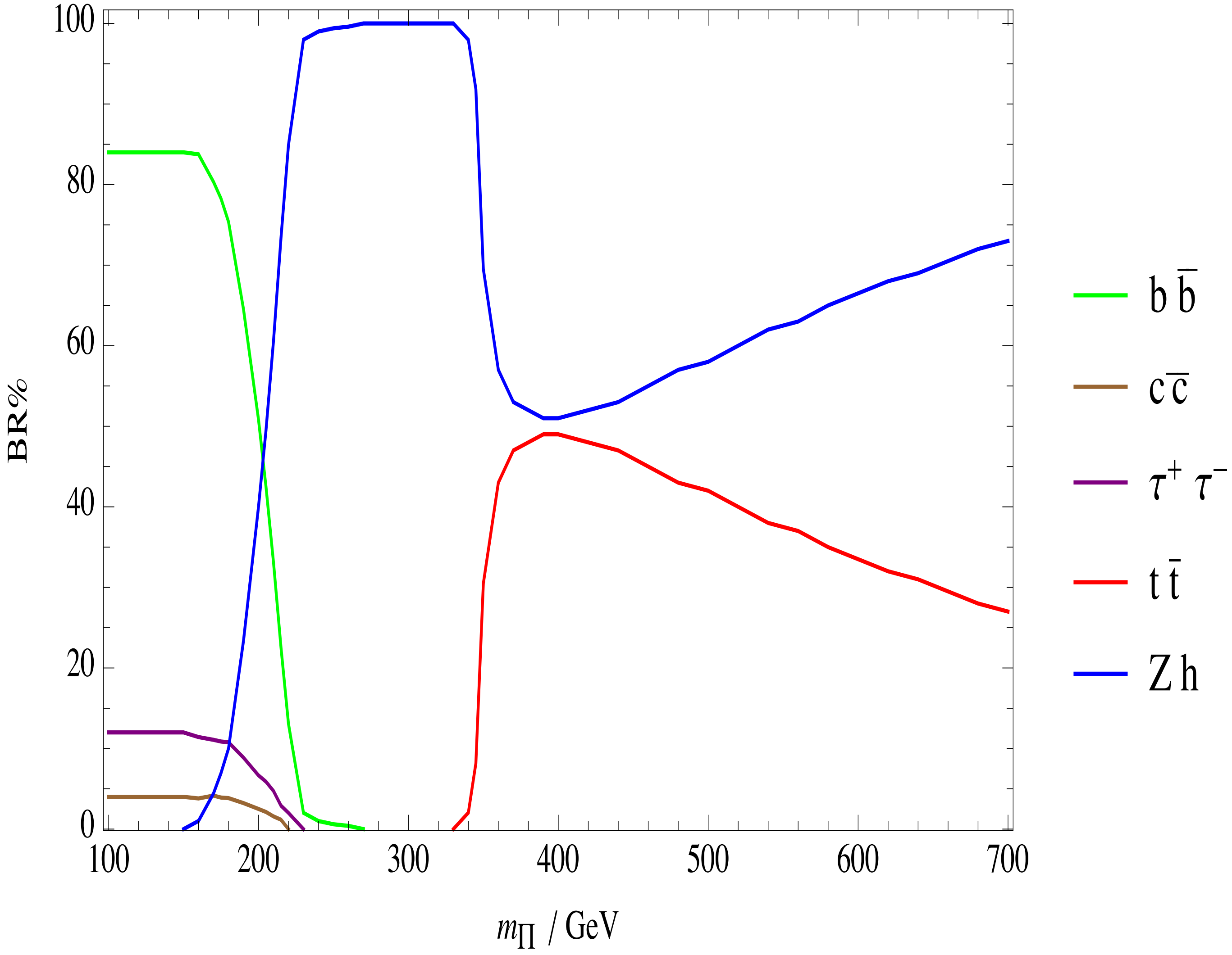
For stealth dark matter theories, the “u”-like and “d”-like fermions have equal and opposite charge

$$\mathrm{tr}[\tau_3 Q_f^2] \;\propto\; N_{\mathrm{dark}}[(1/2)^2 - (-1/2)^2] \;= 0$$

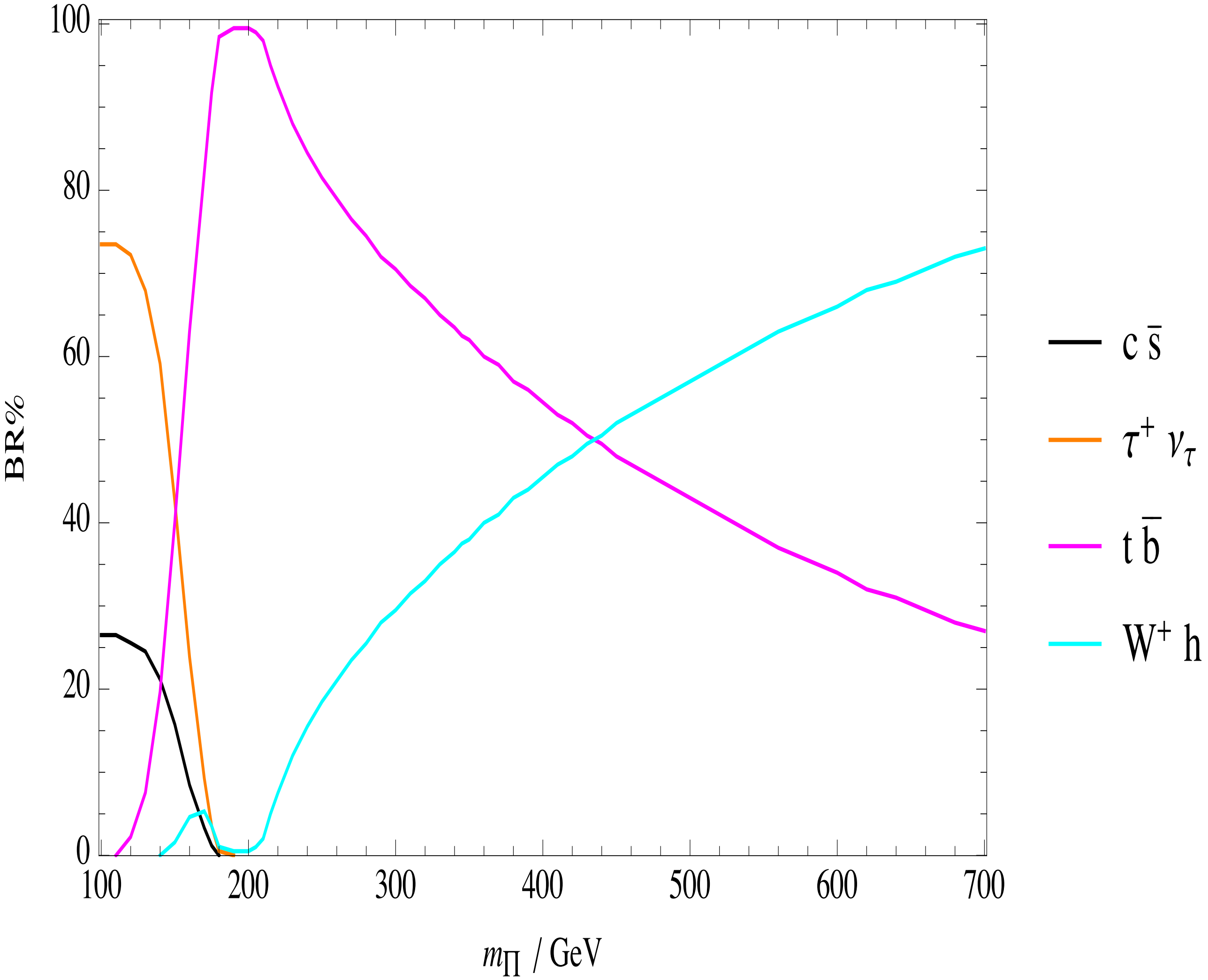
and so $\pi_d^0 \to \gamma\gamma$ is model dependent.

Dark pion branching fractions

π_d^0



$\pi_d^\pm$



Kribs, Martin, Neil, Ostdiek, Tong (to appear)

Dark ρ's

There are also a set of vector resonances

$$\rho_{\mathrm{d}}^{a} \sim \begin{pmatrix} \begin{array}{cc} \rho_{d1}^{0} & \sqrt{2}\rho_{d1}^{+} \\ \sqrt{2}\rho_{d1}^{-} & -\rho_{d1}^{0} \end{array} & K_d^{*}\text{'s} \\ K_d^{*}\text{'s} & \begin{array}{cc} \rho_{d2}^{0} & \sqrt{2}\rho_{d2}^{+} \\ \sqrt{2}\rho_{d2}^{-} & -\rho_{d2}^{0} \end{array} \end{pmatrix}$$

Meson-meson interactions include

$$g_{\rho_d \pi_d \pi_d} f^{abc} (\rho_d^a)_\mu \pi_d^b D^\mu \pi_d^c \qquad\qquad g_{\rho_d \pi_d \pi_d} \sim \frac{4\pi}{\sqrt{N_{\mathrm{dark}}}}$$

As well as kinetic mixing with the EW gauge bosons

$$\epsilon_B B_{\mu\nu} F_{\rho_d}^{\mu\nu} + \epsilon_W W_{\mu\nu} F_{\rho'_d}^{\mu\nu} \qquad\qquad \epsilon \sim g\frac{\sqrt{N_{\mathrm{dark}}}}{4\pi}$$

Two types!

U(1)-like (ρ^0 only)

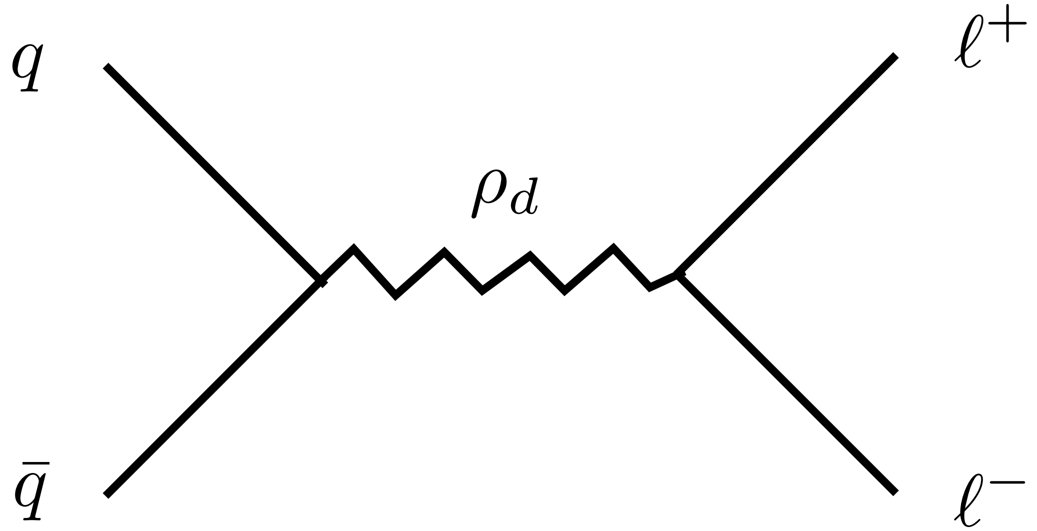
SU(2)-like $\rho^{\pm,0}$

Resonance searches for dark ρ’s

Upon diagonalizing the kinetic terms, leads to interactions with SM fermions

$$\epsilon\, g\, f^\dagger \bar{\sigma}^\mu (\rho_d)_\mu f$$

which leads to new resonances, e.g.,



The going rate for on-resonant ρ production and decay

$$\sigma(q\bar{q} \to \rho_d \to \ell^+\ell^-) \;\sim\; \frac{1}{m_{\rho_d}\Gamma^{\rm tot}_{\rho_d} s}\Gamma(\rho_d \to q\bar{q})\Gamma(\rho_d \to \ell^+\ell^-)$$

critically depends on the total width $\Gamma^{\rm tot}_{\rho_d}$

Resonance searches for dark ρ's

Two cases:

$$\frac{m_{\pi_d}}{m_{\rho_d}} < 0.5$$

The strong 2-body decay

$$\rho_d \;\rightarrow\; \pi_d \pi_d$$

is open, dominates, and leads to a wide resonance:

$$\frac{\Gamma(\rho_d \rightarrow \pi_d\pi_d)}{m_{\rho_d}} \;=\; \frac{g^2_{\rho_d\pi_d\pi_d} N_{\pi_d}}{96\pi}\left(1 - \frac{4m^2_{\pi_d}}{m^2_{\rho_d}}\right)^{3/2}$$

$$\sim\; 0.25\left(1 - \frac{4m^2_{\pi_d}}{m^2_{\rho_d}}\right)^{3/2}$$

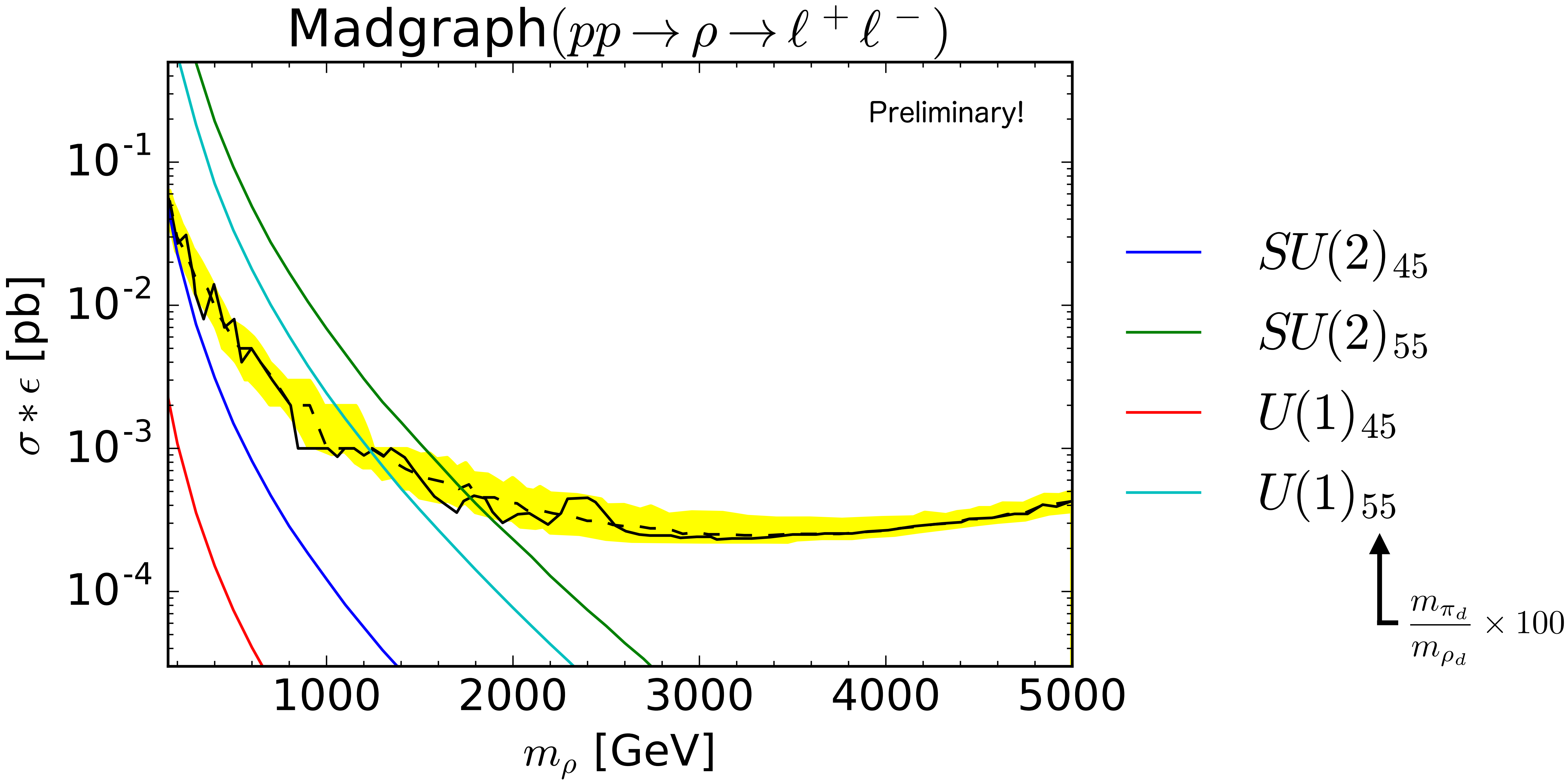
$$\frac{m_{\pi_d}}{m_{\rho_d}} > 0.5$$

The strong 2-body decay

$$\rho_d \;\rightarrow\; \pi_d \pi_d$$

is closed. Decays to SM modes dominate.

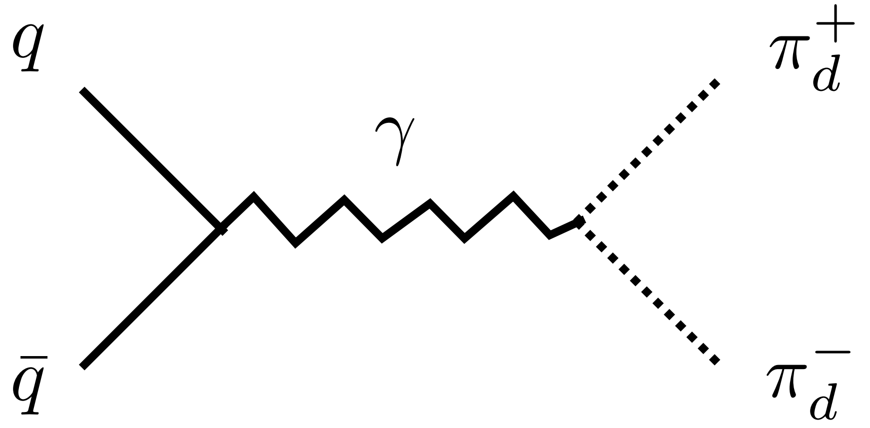
Resonance searches for dark ρ’s



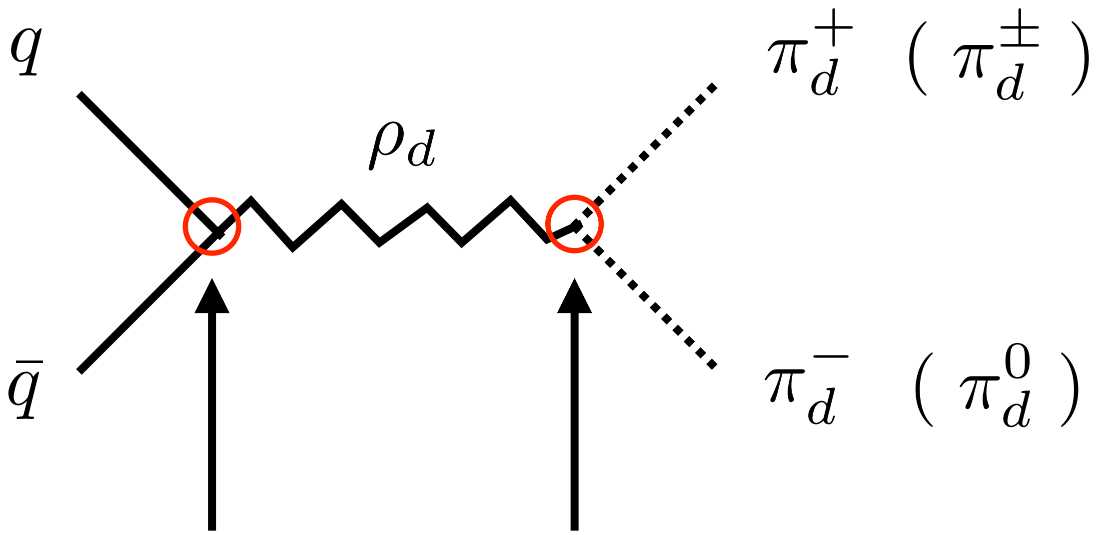
Kribs, Martin, Neil, Ostdiek, Tong (to appear)

Dark pion production

Production of charged pions proceeds through Drell-Yan



as well as ρ_d exchange

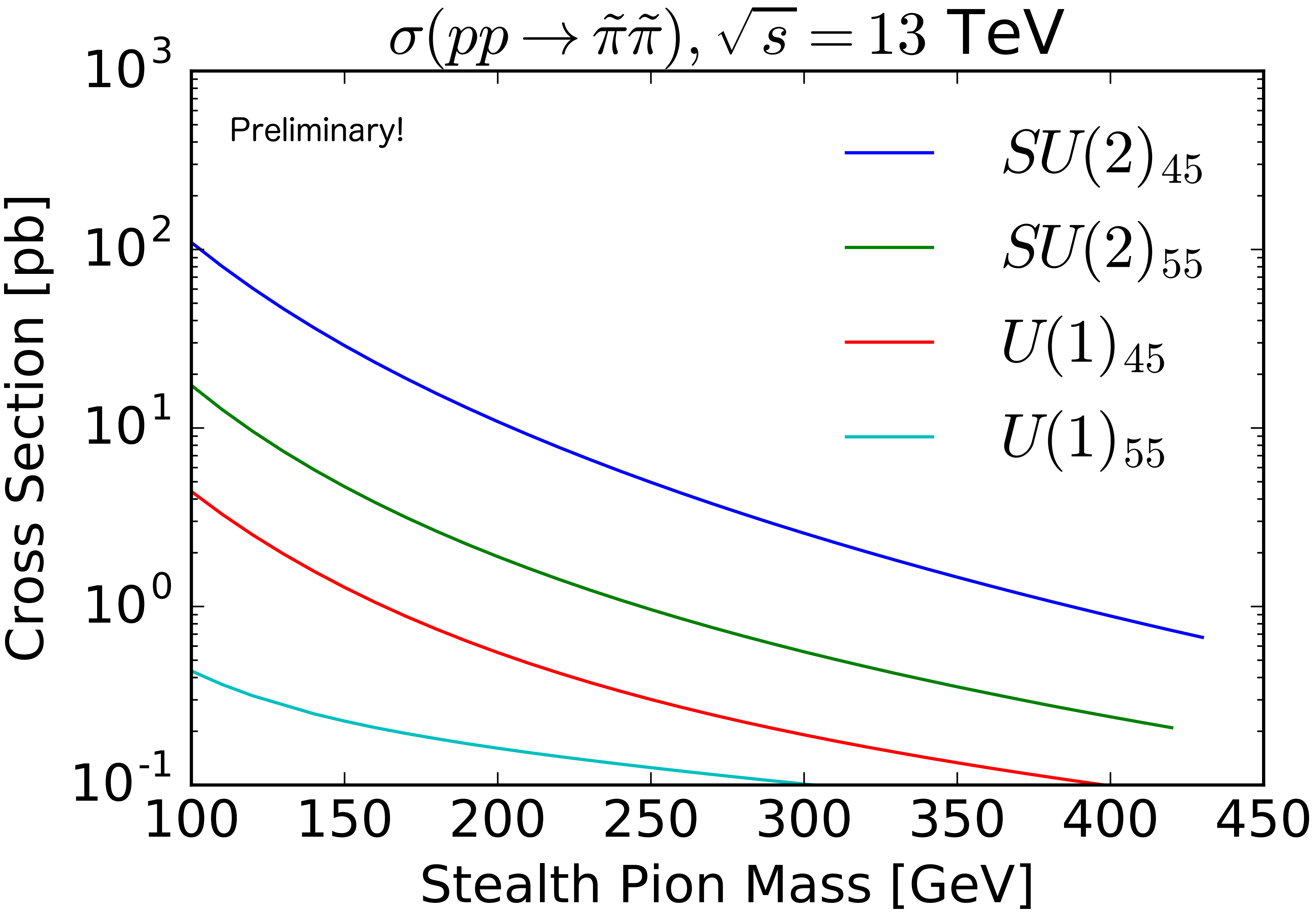


The couplings are: $\epsilon \sim g\frac{\sqrt{N_{\text{dark}}}}{4\pi}$ $g_{\rho_d\pi_d\pi_d} \sim \frac{4\pi}{\sqrt{N_{\text{dark}}}}$

If $\frac{m_{\pi_d}}{m_{\rho_d}} < 0.5,$ dark pions produced resonantly, providing a clear target of opportunity!

Dark pion production

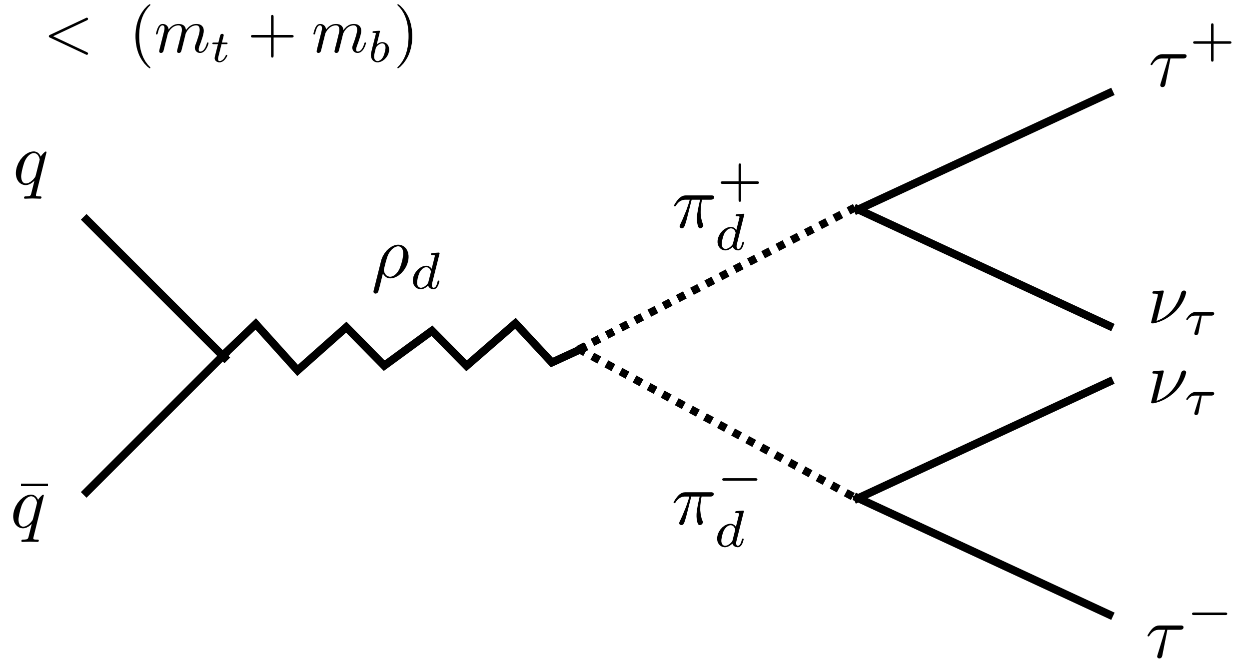
Cross sections



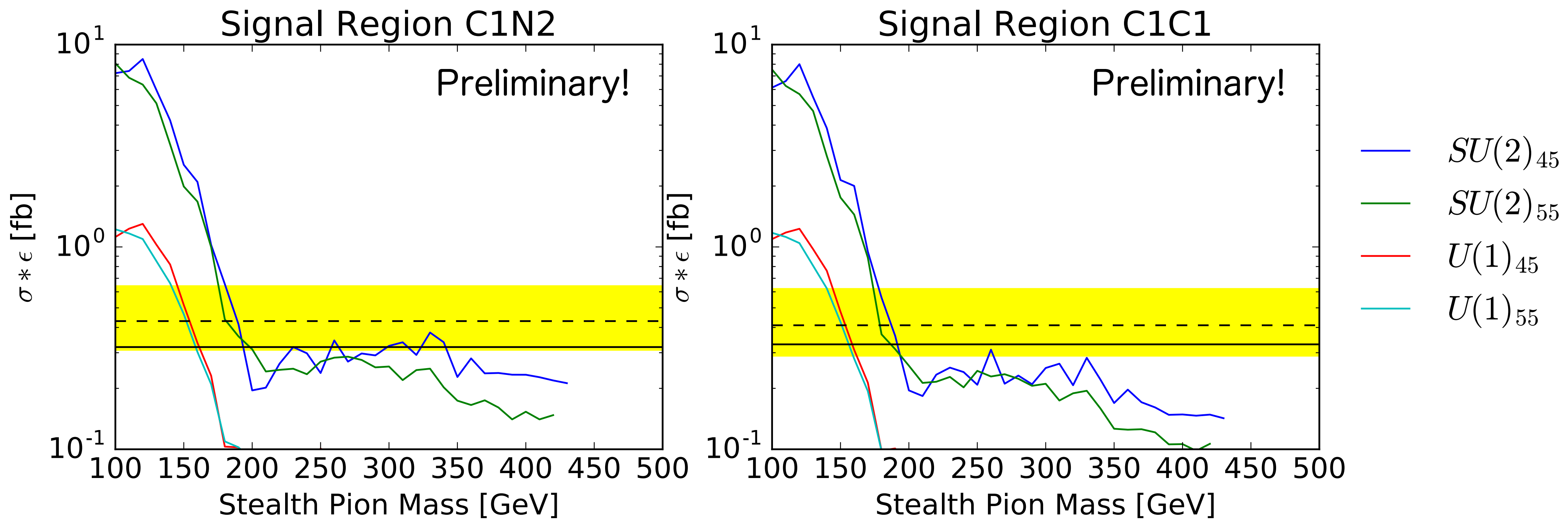
Kribs, Martin, Neil, Ostdiek, Tong (to appear)

Signals of dark pion production

When $m_{\pi_d} < (m_t + m_b)$



One can recast new physics searches involving final state tau's, e.g. EW gauginos @ ATLAS:



Suggests charged dark pions less than about 150-180 GeV are ruled out.

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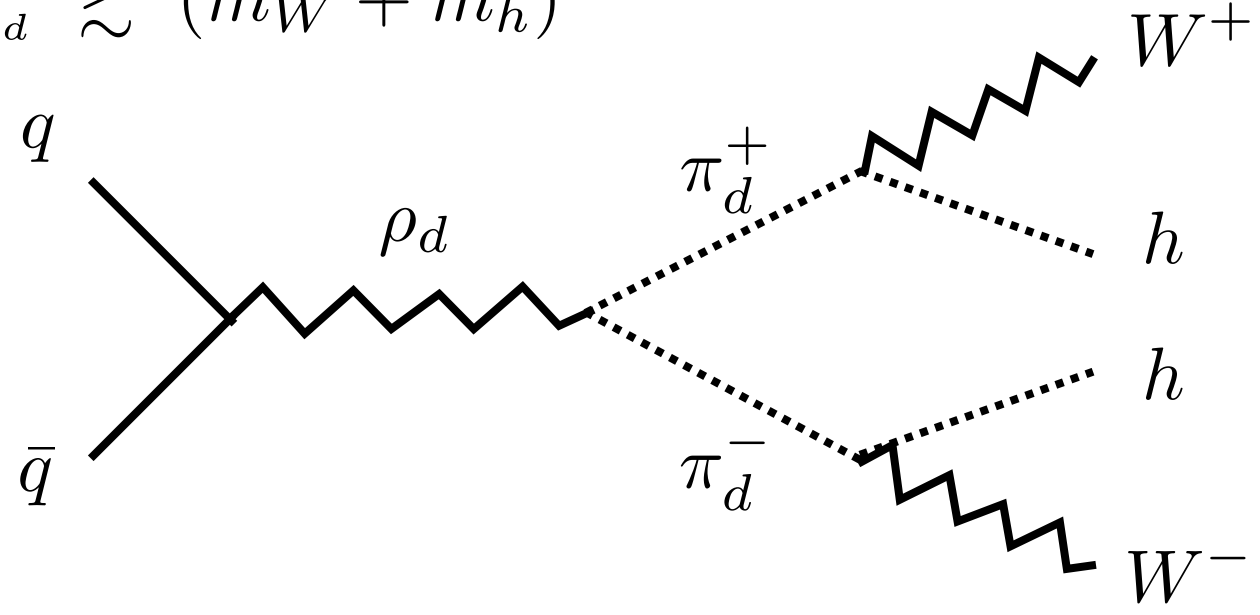
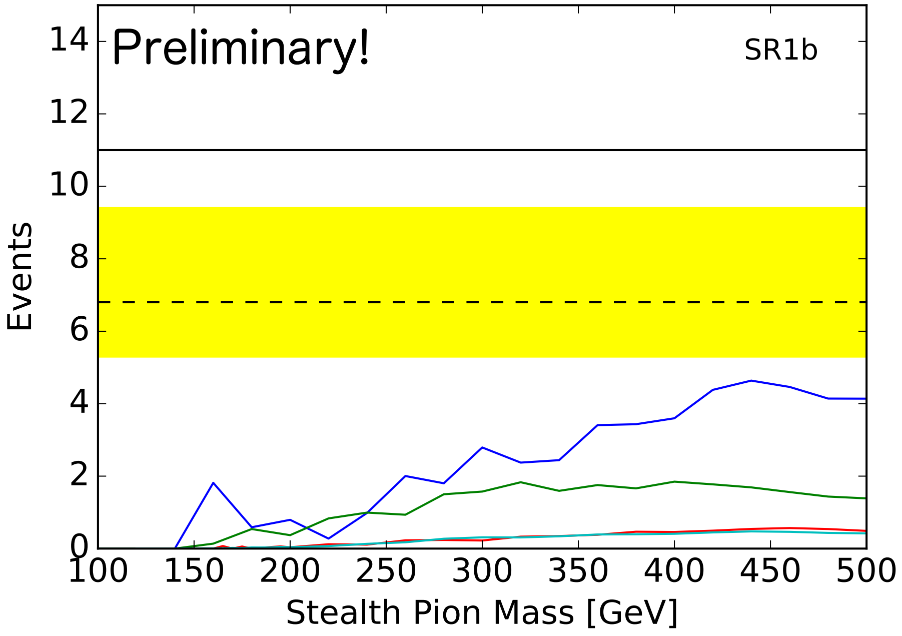
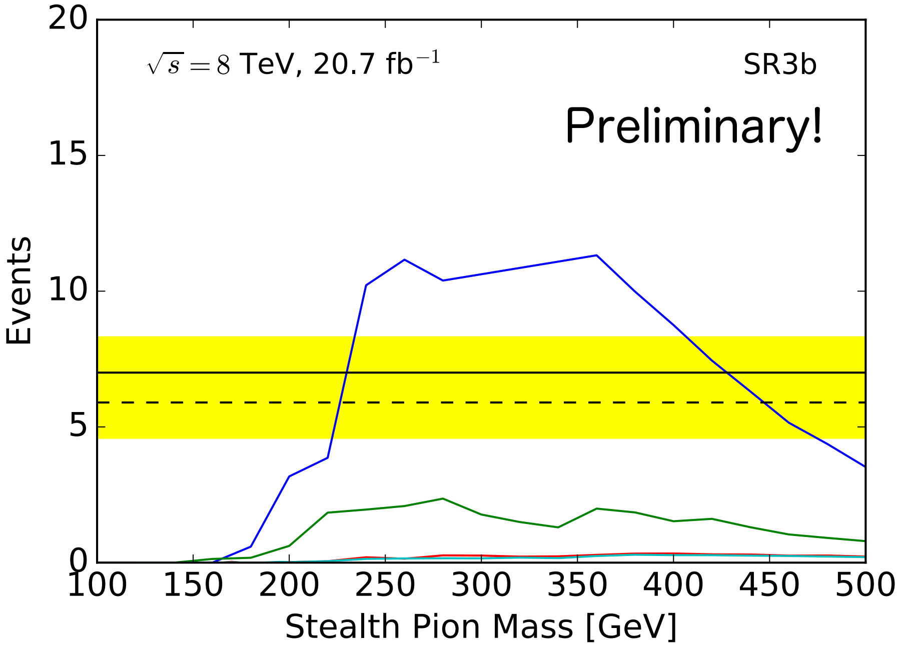
Signals of dark pion production

When $m_{\pi_d} \gtrsim (m_W + m_h)$



There are no optimal searches for this type of final state.
However, same-sign lepton searches (again, SUSY inspired) may have sensitivity:



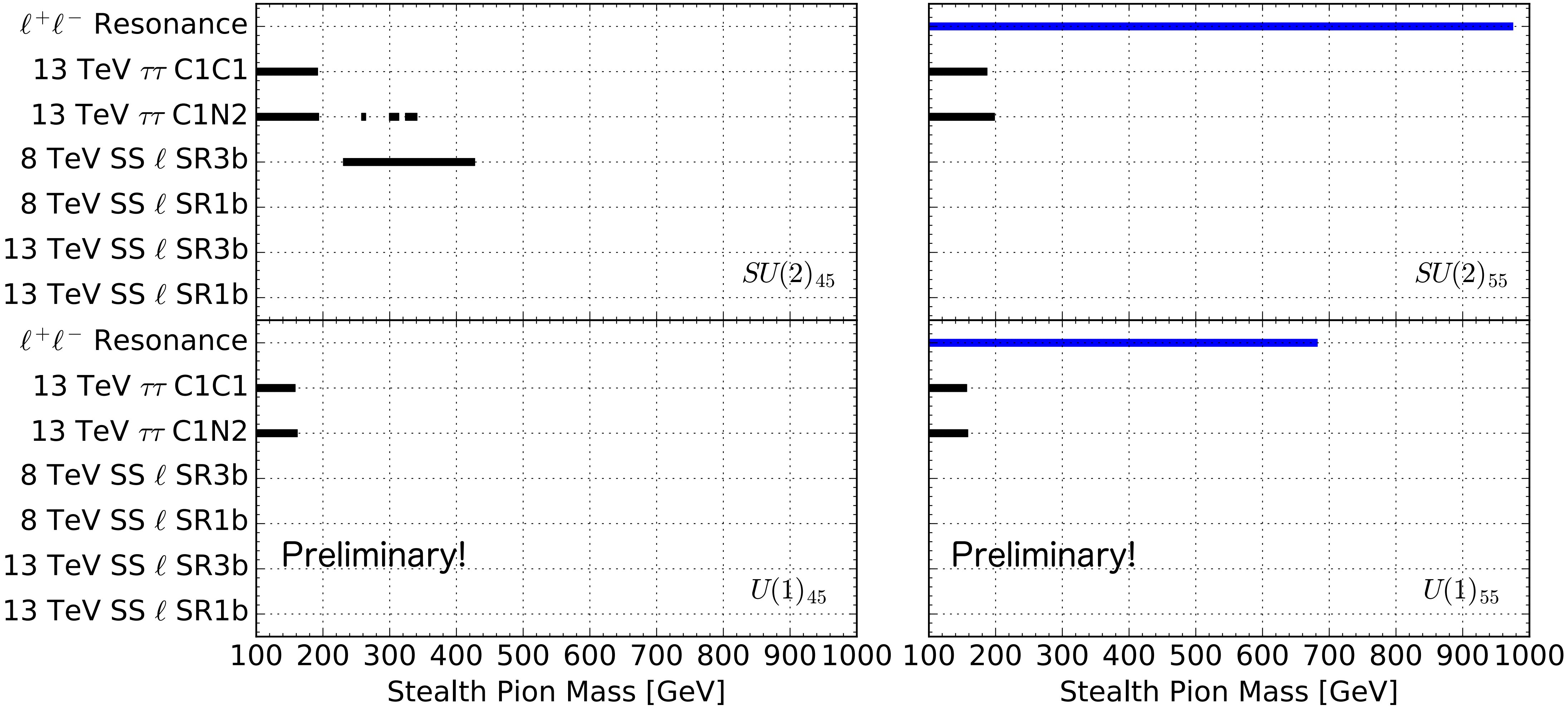


Kribs, Martin, Neil, Ostdiek, Tong (to appear)

Constraints on dark pion production

Thus far, we have found:

- Strong constraints on $pp \to \rho_d \to \ell^+\ell^-$ when $\dfrac{m_{\pi_d}}{m_{\rho_d}} > 0.5$
- Weak constraints on $pp \to \rho_d \to \pi_d\pi_d$

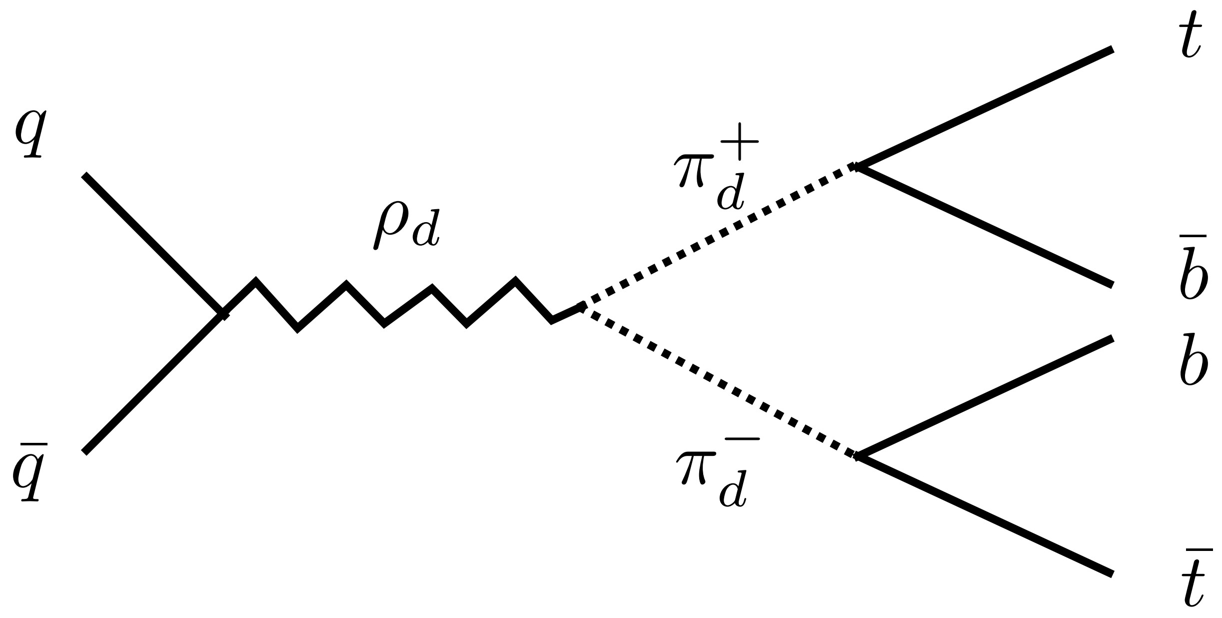


Kribs, Martin, Neil, Ostdiek, Tong (to appear)

Gaps in Searches?

Optimal searches do not exist. In some cases, sensitivity (from other searches) not even clear. For example, when

$$(m_t + m_b) \; < \; m_{\pi_d} \; < \; (m_W + m_h)$$



Smells like charged Higgs pair production, but with a much larger cross section than Drell-Yan. (We're still considering some recast-able searches…)

Conclusions

- Highly motivated theories beyond the Standard Model involving new strongly-coupled "dark" sectors are ripe for exploration.

- These "dark" sectors can have particles near EWSB scale and are relevant to a a wide class of theories:
  - dark baryonic dark matter theories (i.e., Stealth Dark Matter)
  - dark meson dark matter theories (i.e., Buckley-Neil dark SU(2) mesons)
  - models of EWSB (bosonic technicolor / strongly-coupled induced EWSB)

- Specifics in this talk were motivated by Stealth Dark Matter. This theory provides an existence proof of the power of compositeness to suppress leading interactions with matter, allowing dark matter to be as light as several hundred GeV.

- Outstanding opportunities for high(er) luminosity searches at LHC — digging into the "several hundred GeV" region with searches involving electroweak particles that may well yield amazing discoveries!