Dark Mesons at the LHC

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GK, Adam Martin, Ethan Neil, Bryan Ostdiek, Tom Tong [in preparation]
GK, Ethan Neil 1604.04627
GK with “Lattice Strong Dynamics” (LSD) Collaboration: 1402.6656; 1503.04203; 1503.04205

CERN-CKC Workshop “What is going on at LHC” @ Jeju | 3 June 2017

Motivation:
Strongly-coupled "Dark" Sectors near the Weak Scale

"Dark" sectors that contain a new, strongly-coupled, confining force near the weak scale are exceedingly interesting and well motivated from a wide variety of perspectives:

- Theories with strongly-coupled composite dark matter, e.g.,
  Dark baryons ("Stealth Dark Matter")
  Dark mesons (Ectocolor DM; heavy chiral DM; etc.)
  SIMP mechanism (3->2 thermal freezeout via WZW)

- Theories that explain electroweak symmetry breaking, e.g.,
  Bosonic technicolor / induced EWSB
  Composite Higgs theories
  Relaxion with new (non-QCD) dark sector

- Theories that provide interesting / novel LHC phenomena, e.g.,
  Hidden valleys
  Quirky theories and signals
  Vectorlike confinement

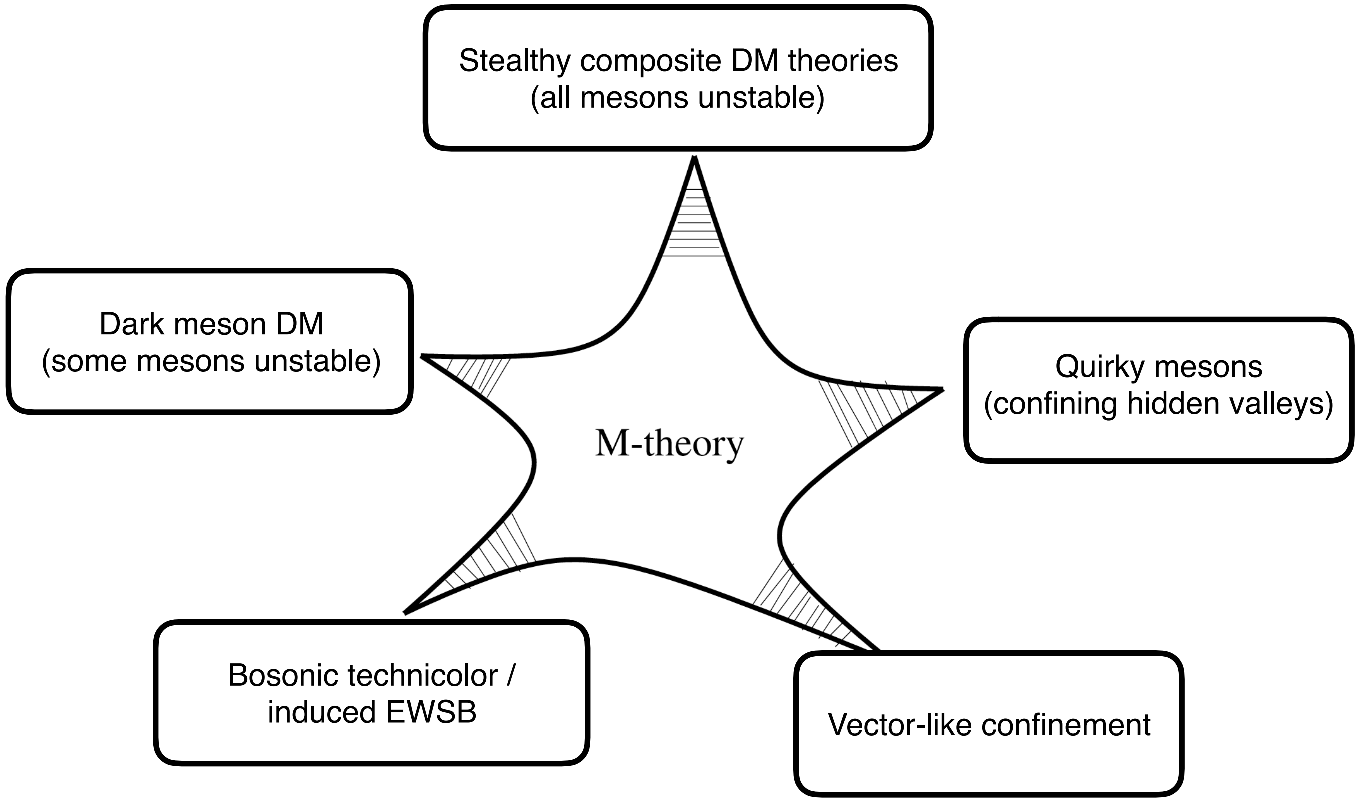
Motivation: Dark Mesons @ LHC

A wide class of these strongly-coupled theories have interesting dark meson phenomenology at LHC.

My focus is mainly on the meson sector that arises from “stealth dark matter” theories (while briefly discussing the close cousins in model space).

The “dark matter” part will only play a role in choosing fermion representations and motivating the scales relevant to LHC energies.

As we’ll see, there are continuous connections between “stealthy” theories and other strongly-coupled models (some that have nothing to do with dark matter)



Dictionary

“dark sector”	⟷	strongly-coupled SU(N_{dark}) sector with N_f “dark fermions”
“dark fermions”	⟷	fermions transforming under SU(N_{dark}) and part of SM
“dark mesons”	⟷	low energy description — not “dark” to LHC searches!

Outline

- Stealth dark matter as strongly-coupled weak scale dark matter
  - suppressed direct detection cross section
  - best bounds from collider constraints on dark pions

- “Dark” Mesons of stealth dark matter theories
  - features when fermions contain vector-like and EW breaking masses
  - compare/contrast to vectorlike confinement and bosonic technicolor

- Dark meson phenomenology
  - dark pion decay
  - dark ρ production/constraints
  - resonant production/decay of pairs of dark pions
    (LHC signals, constraints, and opportunities at higher luminosity)

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What's Special about Strongly-Coupled Composite Dark Matter?

GK, Neil; 1604.04627

Purely from a model perspective…

1) Automatic dark matter stability without imposing additional (discrete) symmetries (dark baryon number conservation)

2) At high temperatures, thermalization with SM proceeds through ordinary electroweak interactions (no new mediators required when fermions transform under EW)

3) Direct detection rates elegantly suppressed through higher dimensional operators suppressed by compositeness scale

4) New scales are (technically) natural

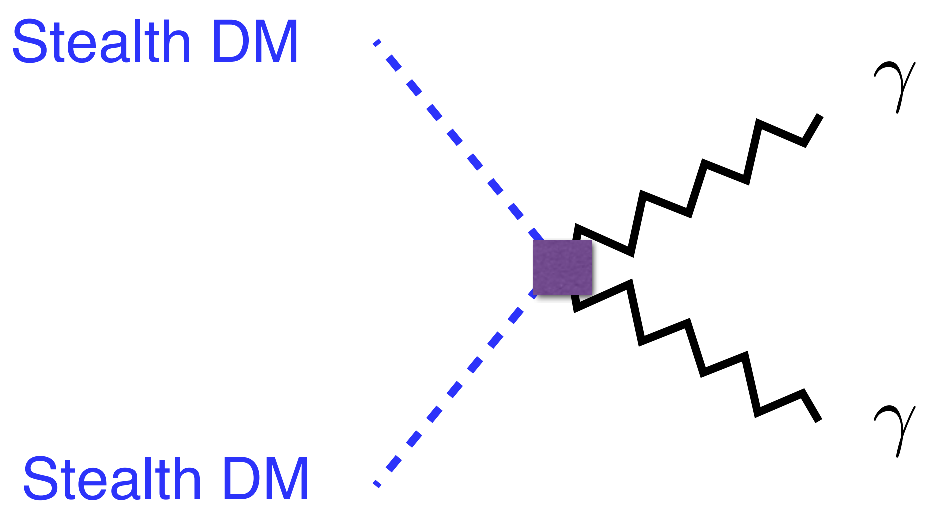
5) Abundance can arise from asymmetric or symmetric mechanism (wide range of scales possible*)

*GK, Adam Martin, Ethan Neil [in progress]

What's Special about "Stealth Dark Matter"?

GK with LSD Collaboration; 1503.04203

Strongly-coupled confining SU(N) theory in which dark matter is a scalar baryon (N = even) has its leading direct detection interaction through its electromagnetic polarizability:



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

(dimension-7 in non-relativistic EFT)

This happens because the UV theory contains massive dark fermions that transform under the electroweak group (with a custodial symmetry that also causes the charge radius to vanish). More on this in a bit.

In scenarios where $M_f \sim \Lambda_{\rm dark}$ the polarizability (and hadron spectrum) can be calculated with lattice gauge theory — which is exactly what my lattice collaborators and I did two years ago — for SU(4).

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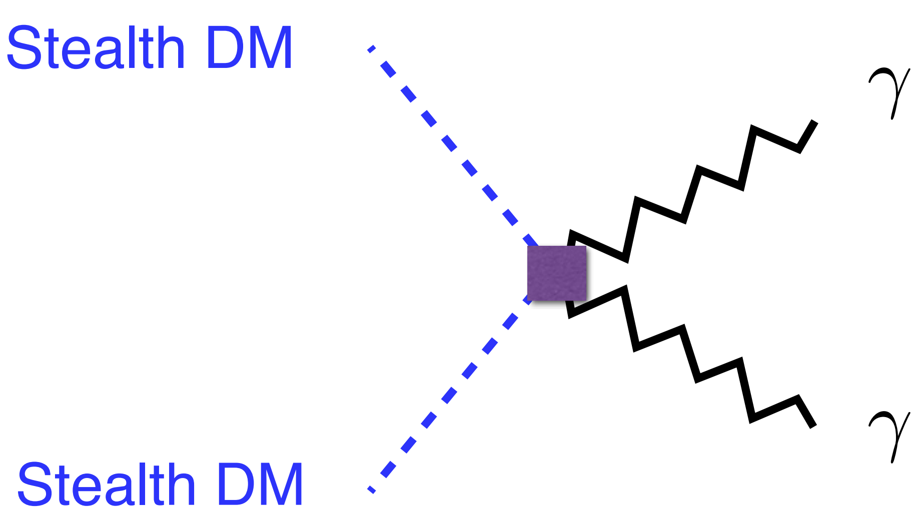

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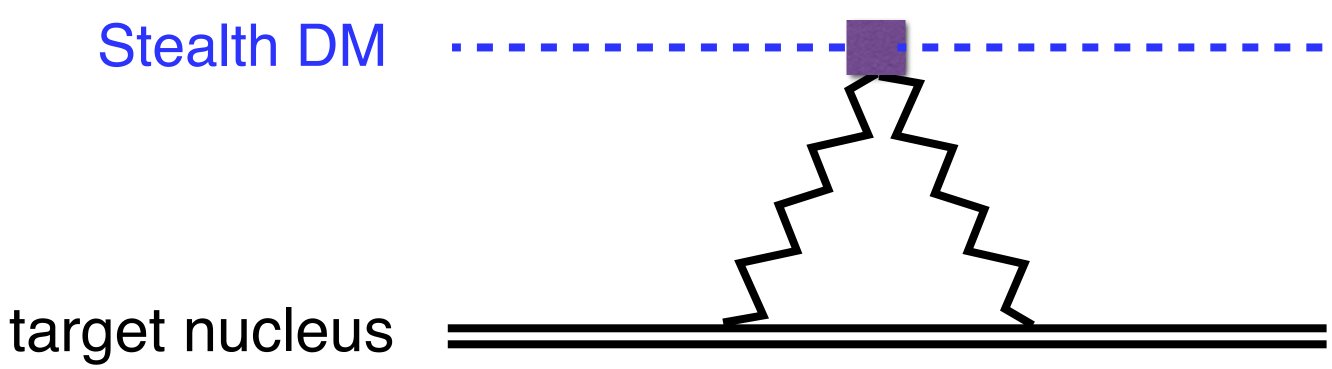
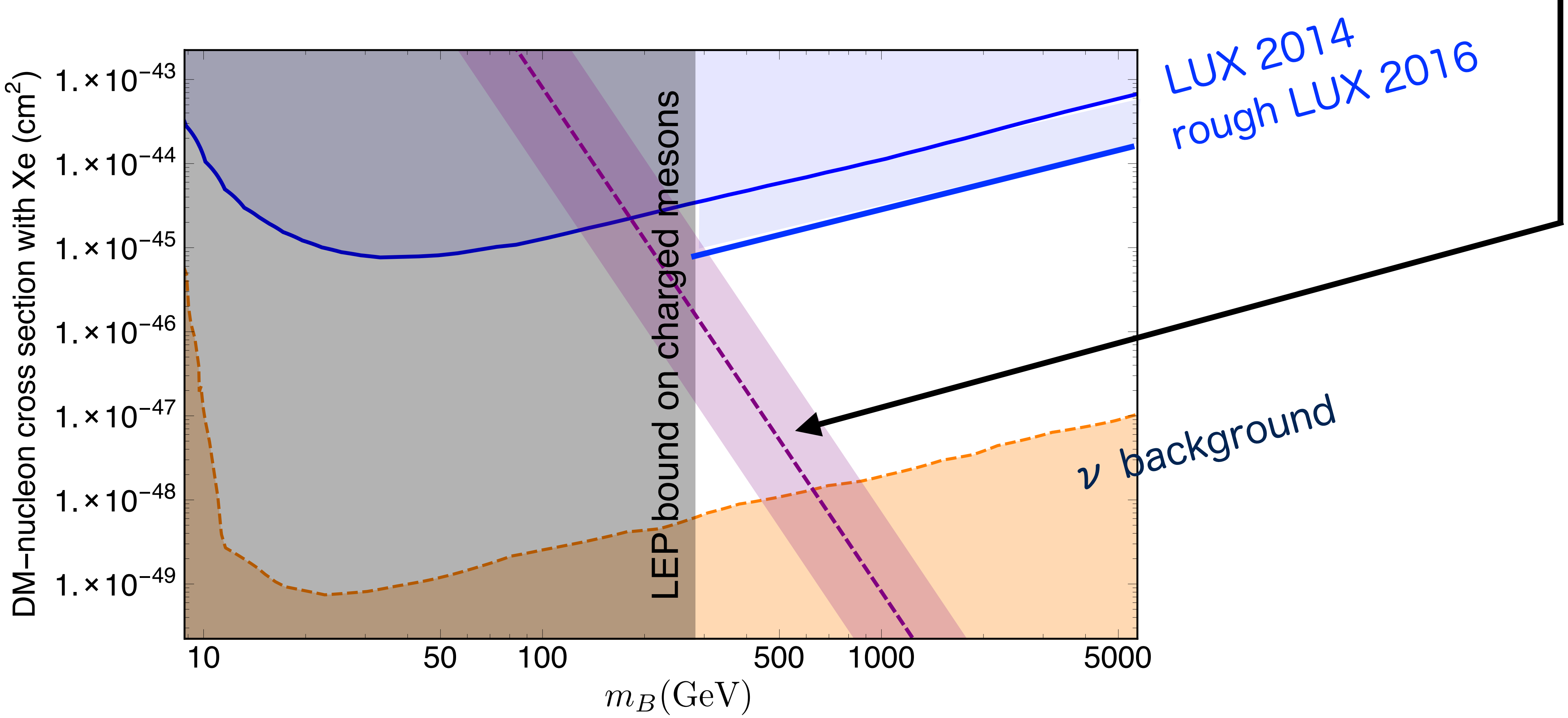
T. Appelquist, G. Fleming (Yale)
E. Berkowitz, M. Buchoff, E. Rinaldi, C. Schroeder, P. Vranas (Livermore)
R. Brower, C. Rebbi, E. Weinberg (Boston U)
X. Jin, J. Osborn (Argonne)
J. Kiskis (UC Davis)
GK (Oregon)
E. Neil (Colorado & Brookhaven)
S. Sryitsyn (Brookhaven)
D. Schaich (Syracuse)
O. Witzel (Boston U & Edinburgh)

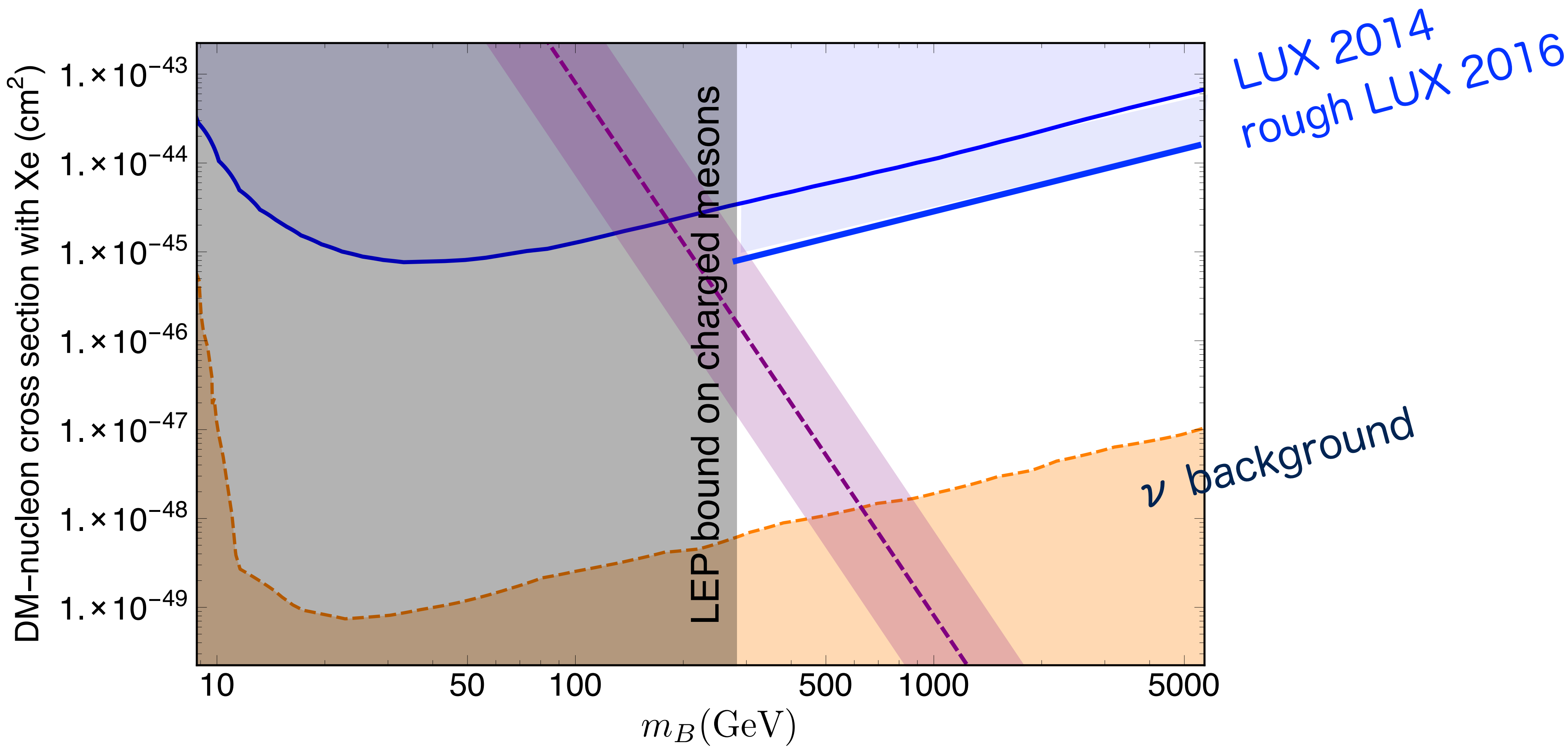
Why should you care?

Stealth dark matter spin-independent cross section from its polarizability





GK with LSD Collaboration; 1503.04205



- Scalar baryon is rather "stealthy", and yet, suppressed direct detection cross section provides a great target for "conventional" direct detection experiments.

- Best experimental bounds come from collider bounds on dark mesons (LEP bound on non-observation of electrically charged dark mesons)

Can the LHC do better?

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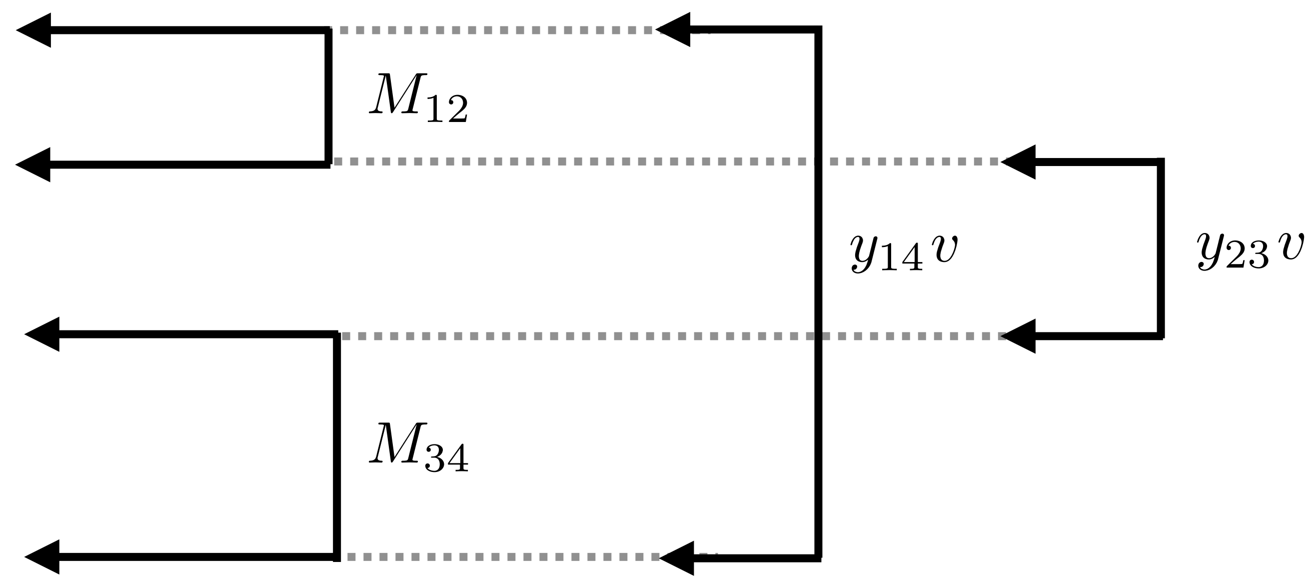
Dark Fermion Masses in Stealth DM Theories

Stealth DM

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

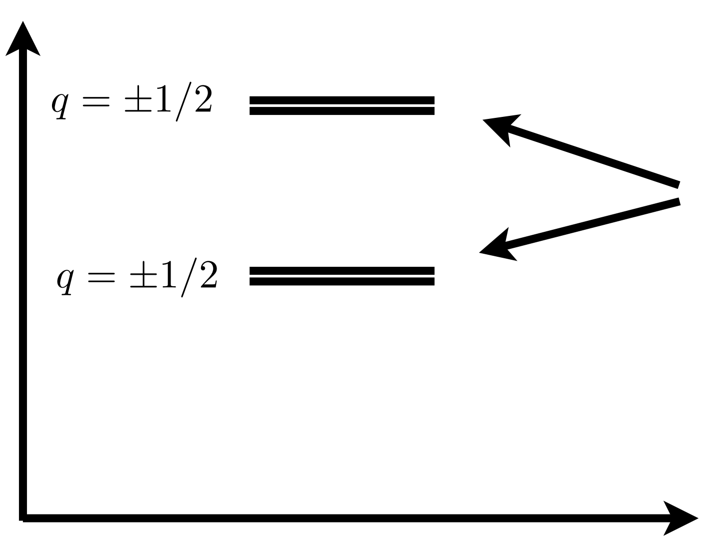
vector-like masses

Yukawa couplings
(chiral masses)



[And u <—> d exact custodial SU(2).]

Leads to
dark fermion
mass spectrum:



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

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

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

Observations

1) Vector-like masses plus Higgs interactions with dark fermions

$$yF_1HF_{4d} + yF_1H^\dagger F_{4u} + yF_2HF_{3d} + yF_2H^\dagger F_{3u} + h.c.$$

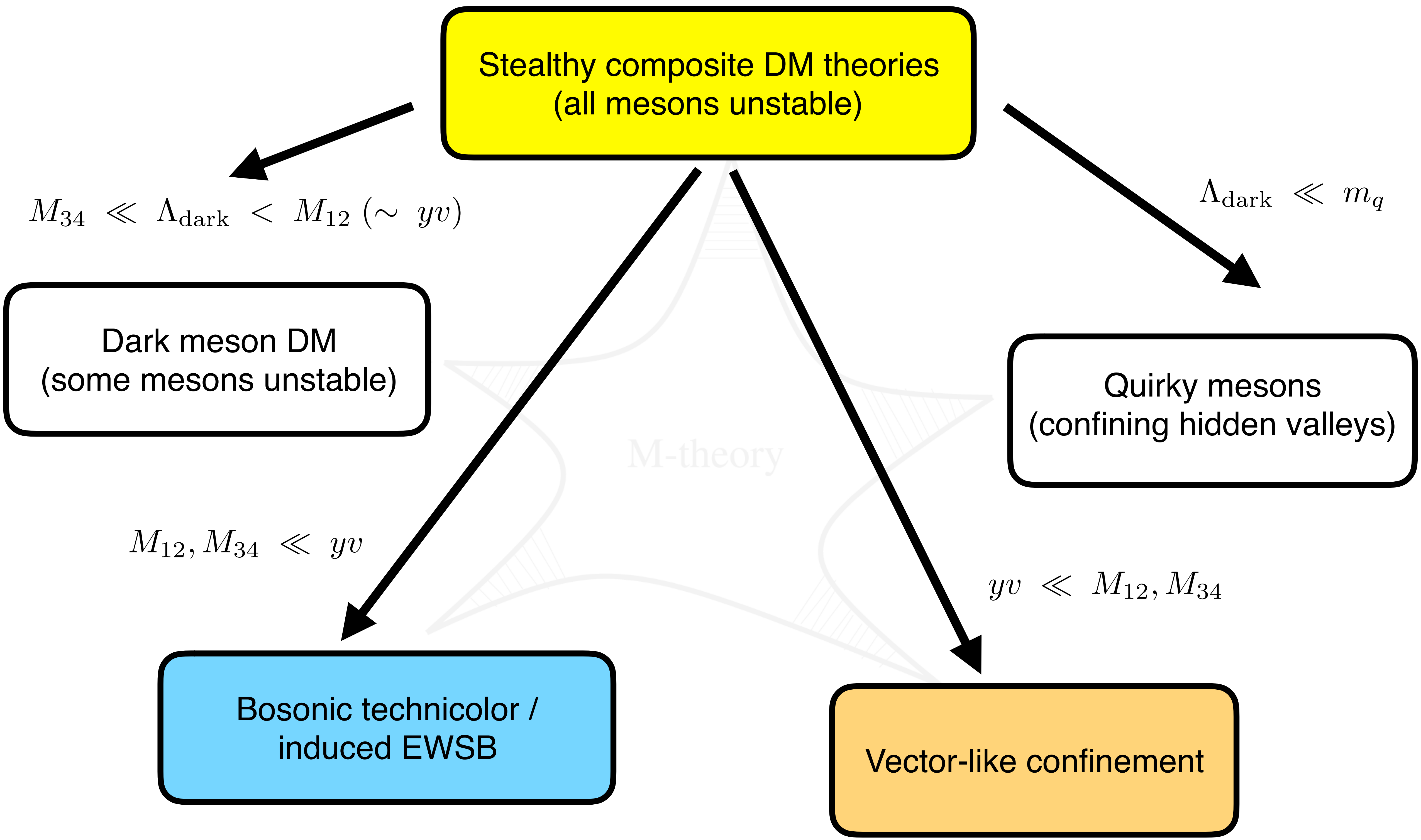
completely break global flavor symmetries to just $U(1)_{dark\ baryon}$

2) In the limit $y \to 0$ condensate $\langle F_L F_R \rangle \sim \Lambda^3_{\rm dark}$ does not break EW symmetry, but some mesons are stable (enhanced global "species" symmetries)

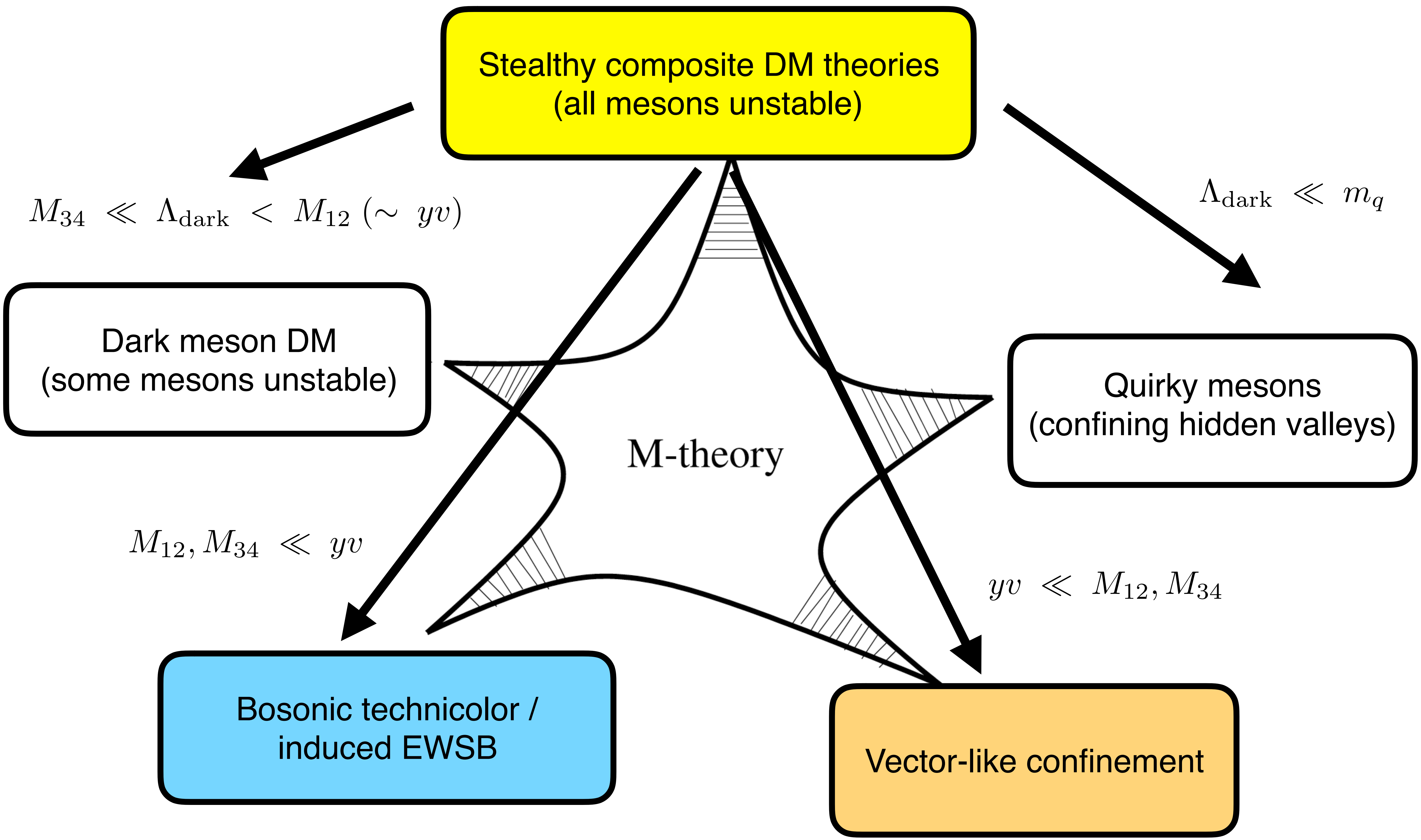
3) In the limit $M_{12}, M_{34} \to 0$ and in the presence of an (elementary) Higgs boson, the condensate can "induce" electroweak symmetry breaking (bosonic technicolor)

4) Sweet spot is $y \ll 1$ where there is a negligible contribution to EWSB and yet all global flavor symmetries are broken (all mesons decay)

Connections within Meson Theory Space



Connections within Meson Theory Space



Comments on Vector-like Confinement

Kilic, Okui, Sundrum; 0906.0577
Kilic, Okui; 1001.4526

Kilic, Okui, Sundrum argued that we ought to be "generically" looking for new, strongly-coupled physics in which the "dark fermions" transform under some part of the Standard Model gauge group.

In theories like QCD — confining SU(N) theories with N >= 3 and $M_f \lesssim \Lambda_{\rm dark}$, the low energy physics is dominated by meson phenomenology.

But, they wanted to avoid even the "whiff" of technicolor, so they focused on theories with fermions in pure vector-like representations of the Standard Model.

The similarity to stealth dark matter is:

- Meson production is dominated by kinetic mixing of the vector meson (ρ) with SM gauge bosons
- Pseudoscalar mesons (π's) are pair-produced, since there is no Higgs-π mixing

The differences with stealth dark matter are:

- Many mesons stable in absence of higher dimensional operators (no predictivity of so-called "long-lived" meson decays)
- Neutral pions do not decay to γγ through anomaly

Comments on Bosonic Technicolor / Induced EWSB

Carone, Simmons; hep-ph/9207273
Brod, Drobnak, Kagan, Stamou, Zupan; 1407.8188
Chang, Luty, Salvioni, Tsai; 1411.6023

In the waning years of the technicolor, “bosonic technicolor” proposed strong dynamics caused EWSB by “inducing” a VEV for an (elementary) Higgs. This also easily allowed fermion masses.

Here, the “dark” fermions transformed under pure chiral representations of the SM, with Yukawa couplings with the Higgs boson.

The low energy effective theory is described by a NLσM as well as interactions with H

$$\mathcal{L} \supset \frac{f^2}{4} \mathrm{Tr}\, \mathrm{D}_\mu \Sigma^\dagger \mathrm{D}^\mu \Sigma + \mathrm{D}_\mu \mathrm{H}^\dagger \mathrm{D}^\mu \mathrm{H} + \left(4\pi \mathrm{f}^3\, \mathrm{Tr}\, \mathrm{y} \mathrm{H} \Sigma^\dagger + \mathrm{h.c.}\right)$$

The linear term causes $m_H^2 < 0$.

<u>The similarities with stealth dark matter are:</u>

- We also have a linear term, but it is parametrically suppressed as $\frac{yv}{M}$

<u>The differences with stealth dark matter when $y \ll 1$ are:</u>

- We don’t have (severe) constraints from EW parameters
- Higgs-pion mixing is parametrically small
  - — negligible constraints from Higgs coupling measurements (modified by Higgs-pi mixing)
  - — negligible rates for single pion production

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Explore Stealthy Mesons

Work in the limit

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

The low energy effective theory described by mesons that can be represented in non-linear representation

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

$$\pi^a_{\rm d} \sim \left(\begin{array}{cc|cc} \pi^0_{d1} & \sqrt{2}\pi^+_{d1} & \bar{K}^0_{d,a} & \sqrt{2}K^+_{d,a} \\ \sqrt{2}\pi^-_{d1} & -\pi^0_{d1} & -\sqrt{2}K^-_{d,a} & K^0_{d,a} \\ \hline \bar{K}^0_{d,b} & -\sqrt{2}K^+_{d,b} & \pi^0_{d2} & \sqrt{2}\pi^+_{d2} \\ \sqrt{2}K^-_{d,b} & K^0_{d,b} & \sqrt{2}\pi^-_{d2} & -\pi^0_{d2} \end{array}\right)$$

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

Small EW Breaking from Dark Sector

The Yukawa couplings in the UV theory cause a mixing between EW gauge bosons and pions:

$$\frac{\epsilon v}{\sqrt{2}M} f_d \, W_\mu^a \, \partial^\mu \pi^a_{\text{absorbed}}$$

where

$$y \;\equiv\; (y_{14} + y_{23})/2 \qquad \epsilon \;\equiv\; (y_{14} - y_{23})/2$$

which implies a small amount of π_d^a gets absorbed into the longitudinal component of W:

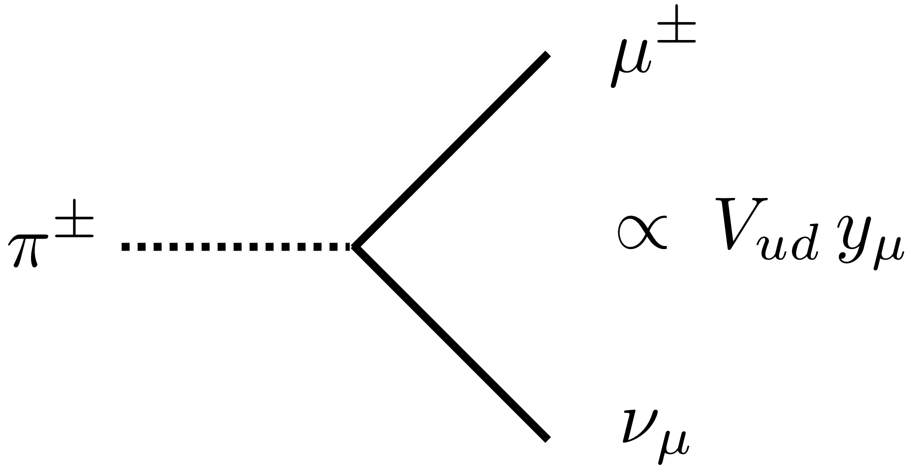
$$\pi^a_{\text{absorbed}} \;\sim\; \frac{yv}{\sqrt{2M^2 + (yv)^2}} \, (\pi^a_{d1} - \pi^a_{d2}) + \frac{\sqrt{2}M}{\sqrt{2M^2 + (yv)^2}} \left(K^a_{d,a} - K^a_{d,b}\right)$$

The smallness of the breaking characterized by S parameter (rough estimate)

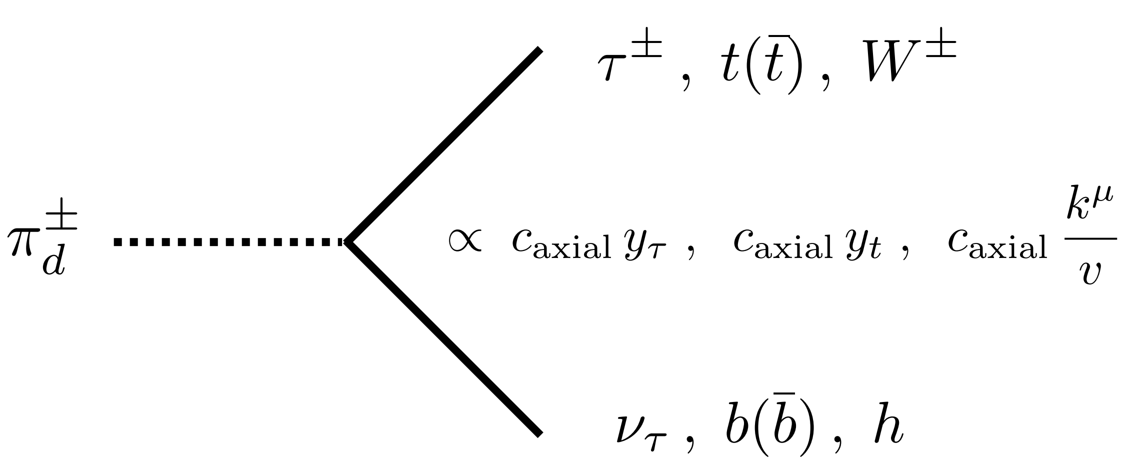
$$S \;\sim\; 0.03 \times \left(\frac{\epsilon v/(\sqrt{2}M)}{0.2}\right)^2 \times \frac{N_f}{4} \frac{N_{\text{dark}}}{4}$$

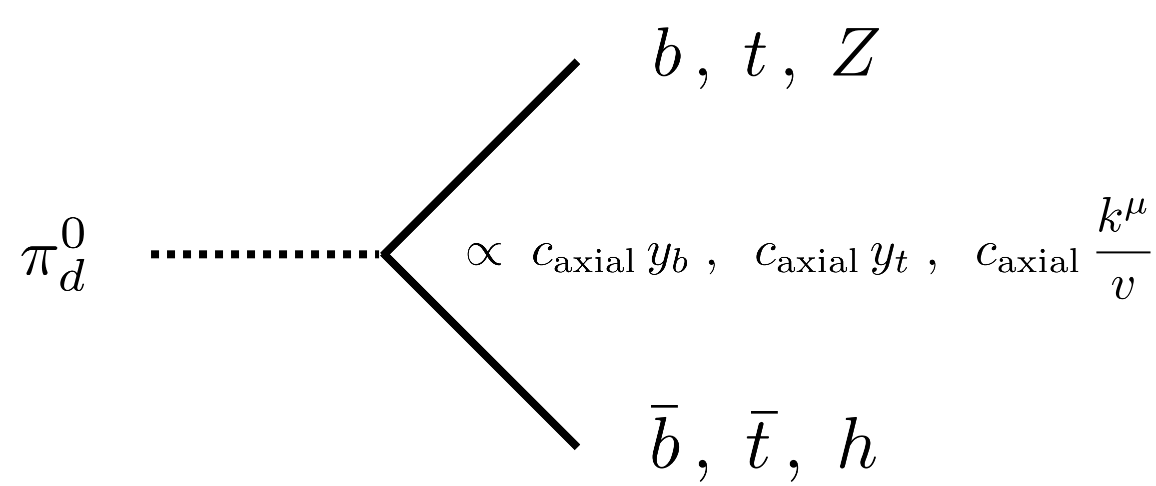
Dark Pion Decay

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 $\langle 0 | j^{\mu a}_{\mathrm{axial}} | \pi^a_d \rangle = i f_d p^\mu$





Where

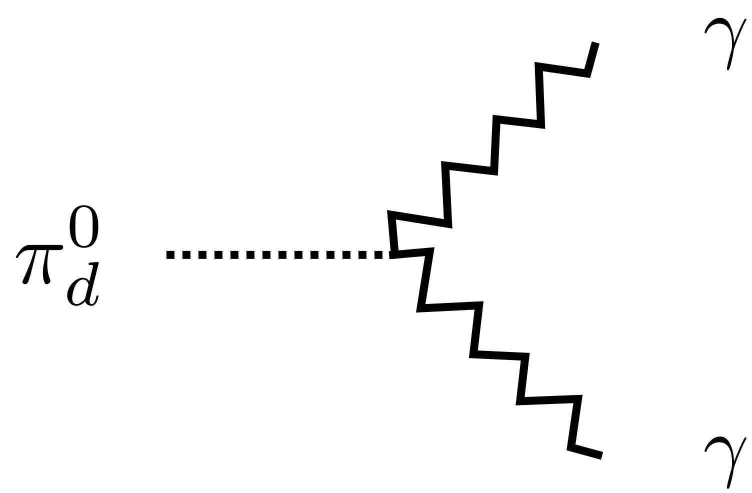
$$f_\pi \ll f_d \gtrsim \text{weak scale}$$

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

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

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

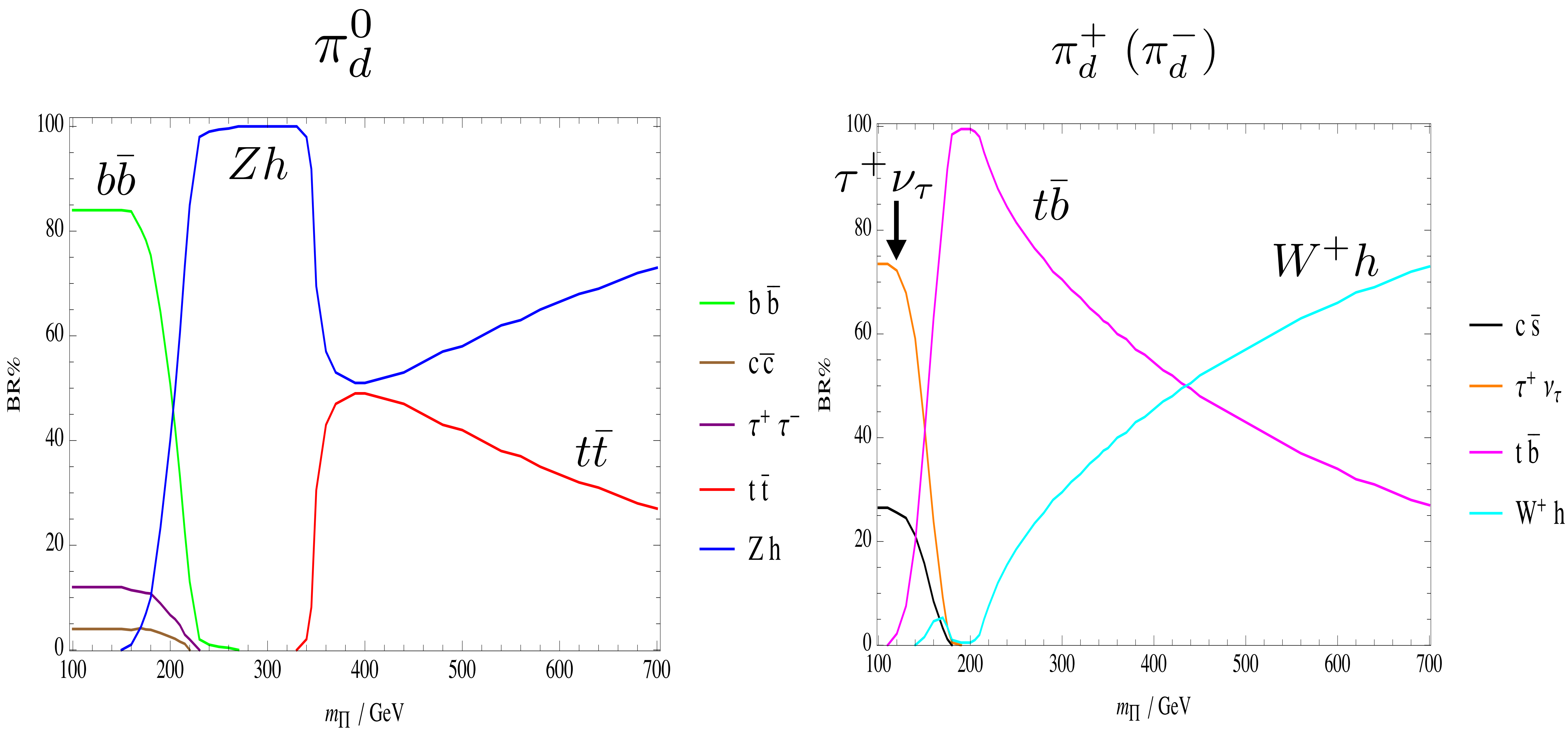
For stealthy dark matter theories, the “u”-like and “d”-like fermions have equal and opposite charge [and the same mass due to custodial SU(2)]

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

And so $\pi_d^0 \to \gamma\gamma$ does not occur.

(Small breaking of custodial SU(2) would re-open this mode, but I won’t consider it further today.)

Dark Pion Branching Fractions



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

Completely determined once the pion mass is specified!

Dark ρ's

There are also a set of vector resonances

$$\rho_{\rm d}^{a} \sim \begin{pmatrix} \begin{matrix} \rho^0_{d1} & \sqrt{2}\rho^+_{d1} \\ \sqrt{2}\rho^-_{d1} & -\rho^0_{d1} \end{matrix} & K^*_d\text{'s} \\ K^*_d\text{'s} & \begin{matrix} \rho^0_{d2} & \sqrt{2}\rho^+_{d2} \\ \sqrt{2}\rho^-_{d2} & -\rho^0_{d2} \end{matrix} \end{pmatrix}$$

Meson-meson interactions include

$$g_{\rho_d\pi_d\pi_d} f^{abc} (\rho^a_d)_\mu \pi^b_d D^\mu \pi^c_d$$

$$g_{\rho_d\pi_d\pi_d} \sim \frac{4\pi}{\sqrt{N_{\rm dark}}}$$

As well as kinetic mixing with the EW gauge bosons

$$\epsilon_B B_{\mu\nu} F^{\mu\nu}_{\rho_d} + \epsilon_W W_{\mu\nu} F^{\mu\nu}_{\rho'_d}$$

$$\epsilon \sim g\frac{\sqrt{N_{\rm dark}}}{4\pi}$$

Two types!

U(1)-like (ρ^0 only) → $\epsilon_B B_{\mu\nu} F^{\mu\nu}_{\rho_d}$

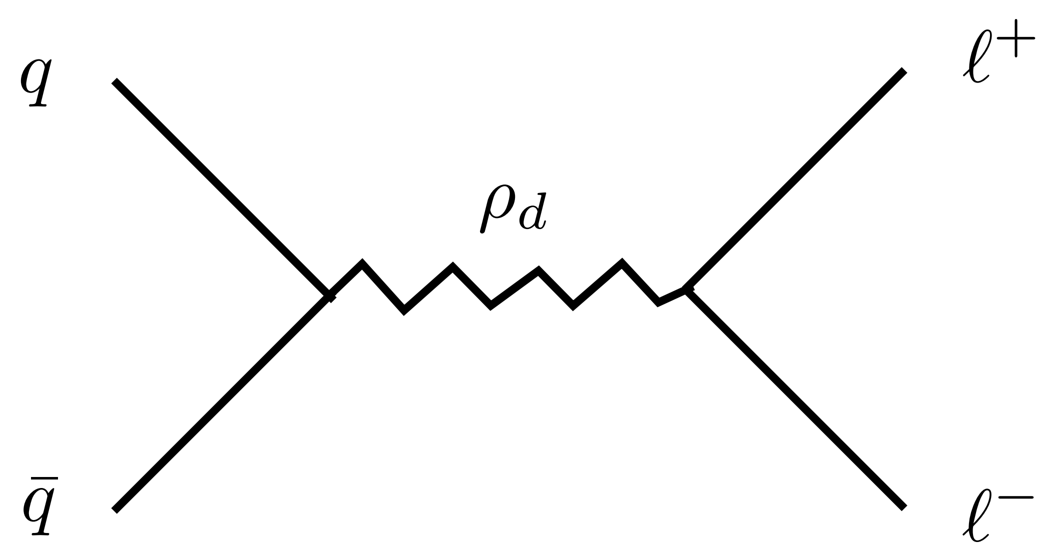
SU(2)-like $\rho^{\pm,0}$ → $\epsilon_W W_{\mu\nu} F^{\mu\nu}_{\rho'_d}$

Resonance searches for dark ρ's

Upon diagonalizing the kinetic terms, leads to ρ 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:

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

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

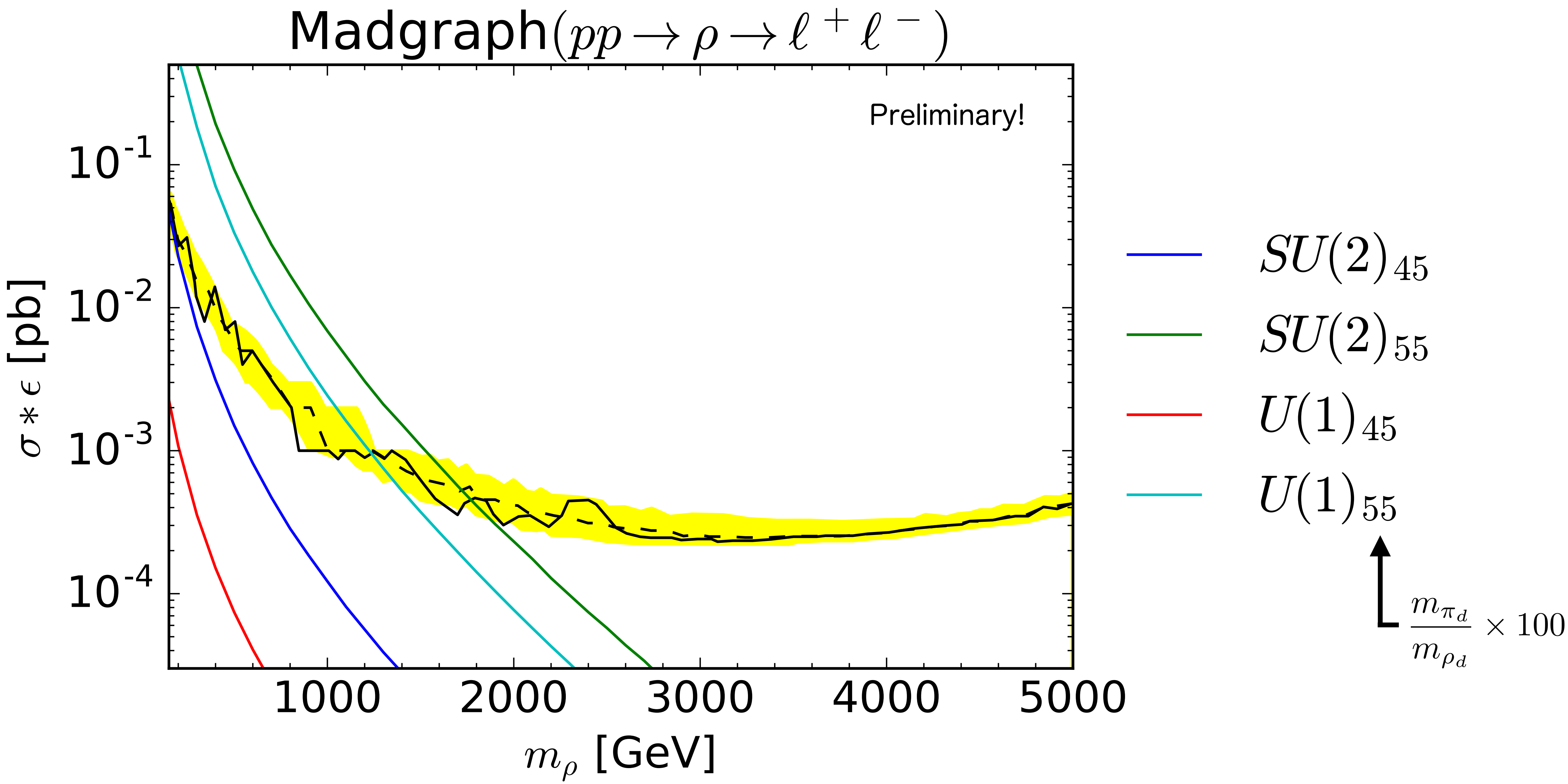
$$\frac{m_{\pi_d}}{m_{\rho_d}} > 0.5$$

The strong 2-body decay

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

is closed. ρ decay is narrow and decays to SM modes dominate.

Resonance searches for dark ρ's



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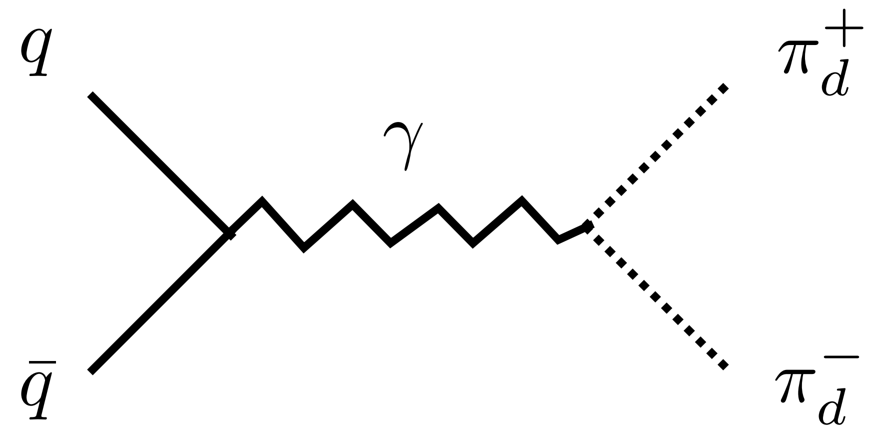
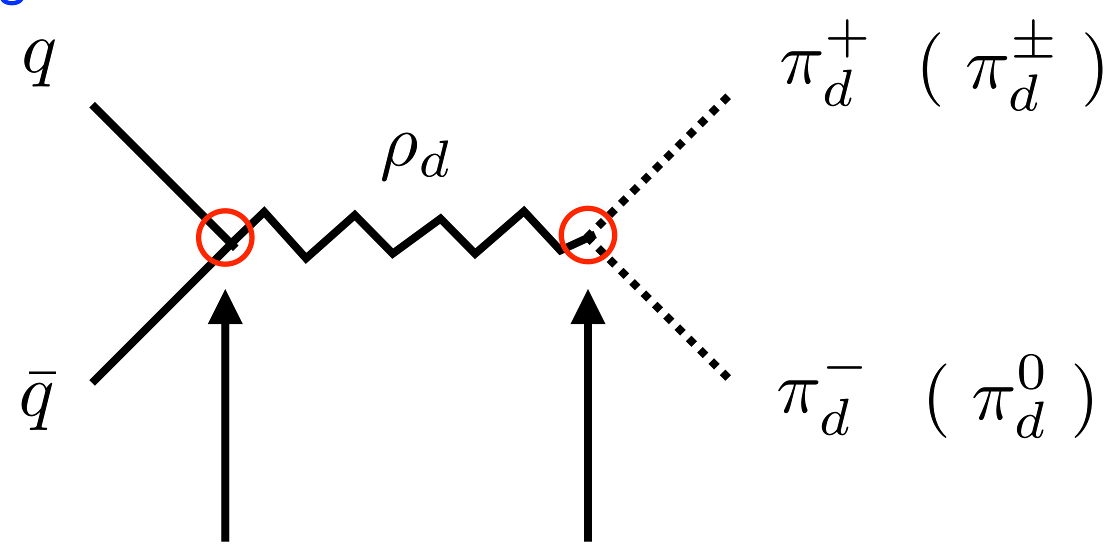
Dark pion production

Production of charged pions proceeds through Drell-Yan



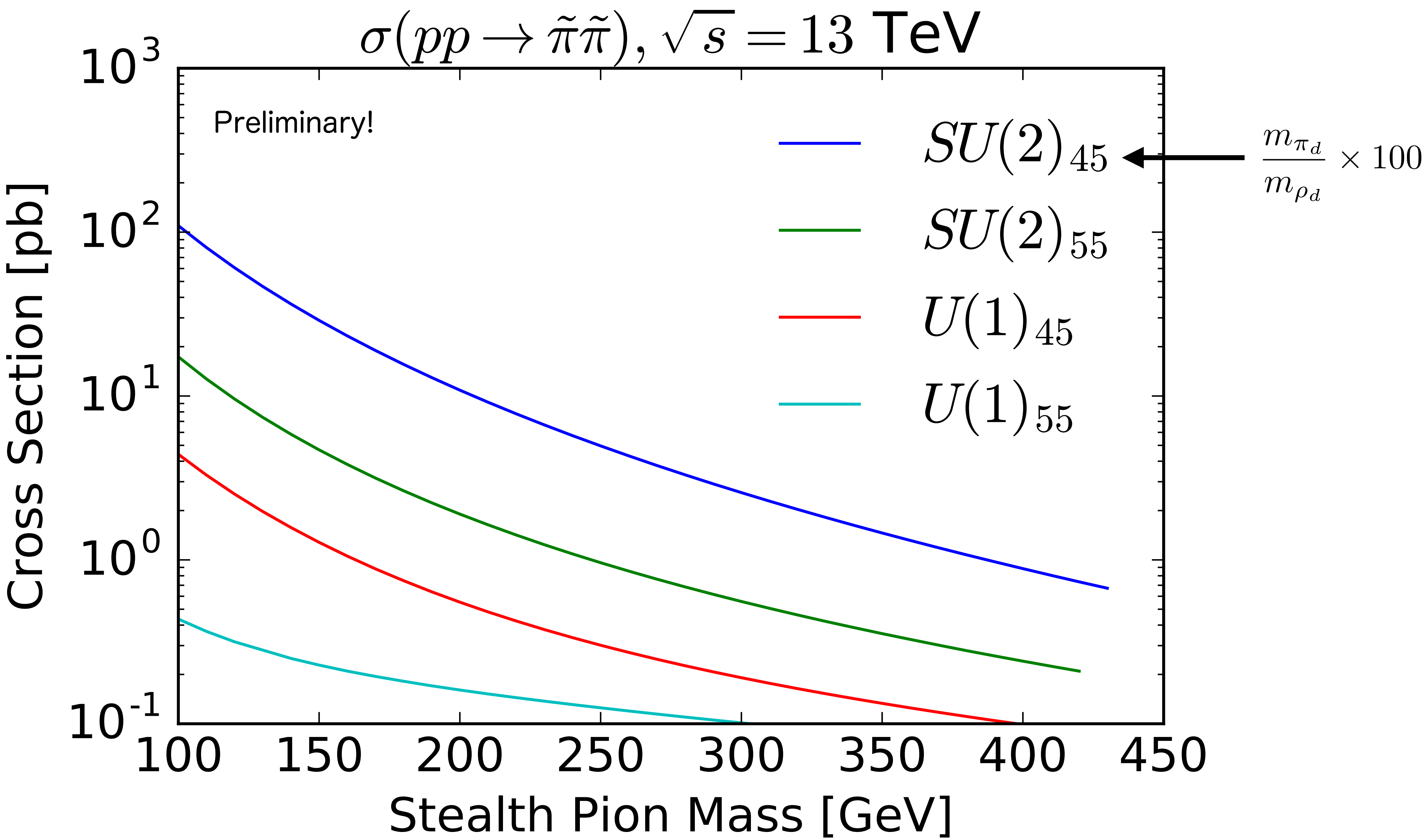
as well as ρ_d exchange



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

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

Dark pion production



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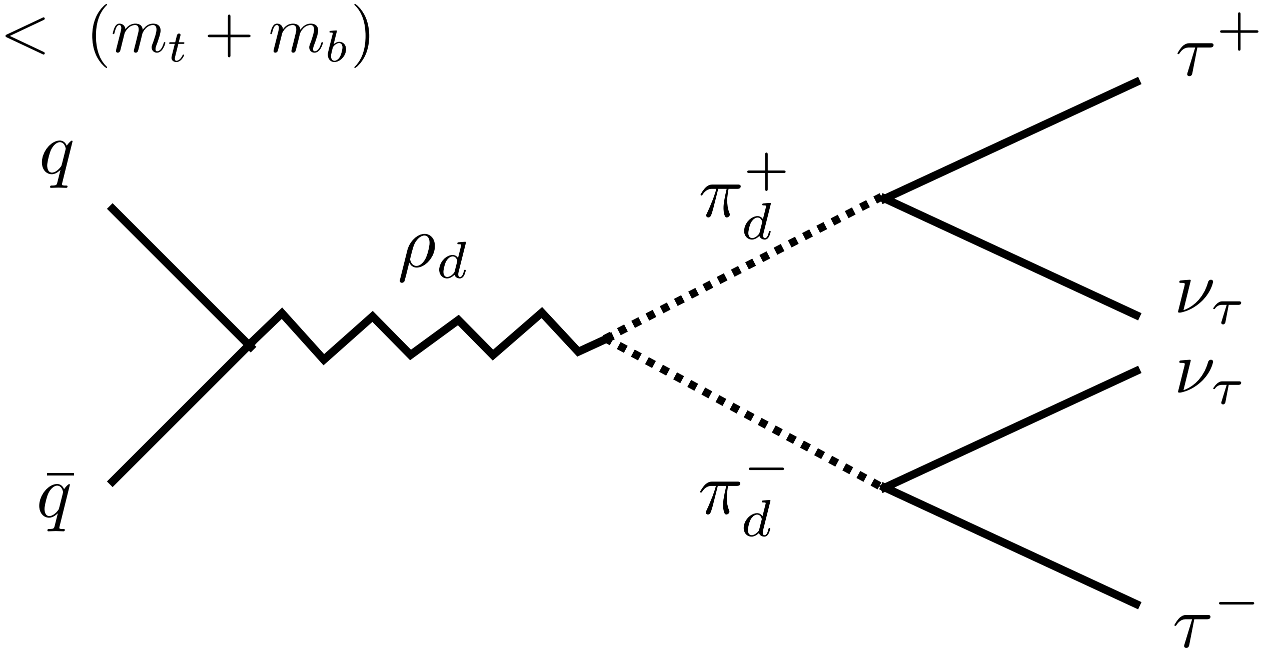
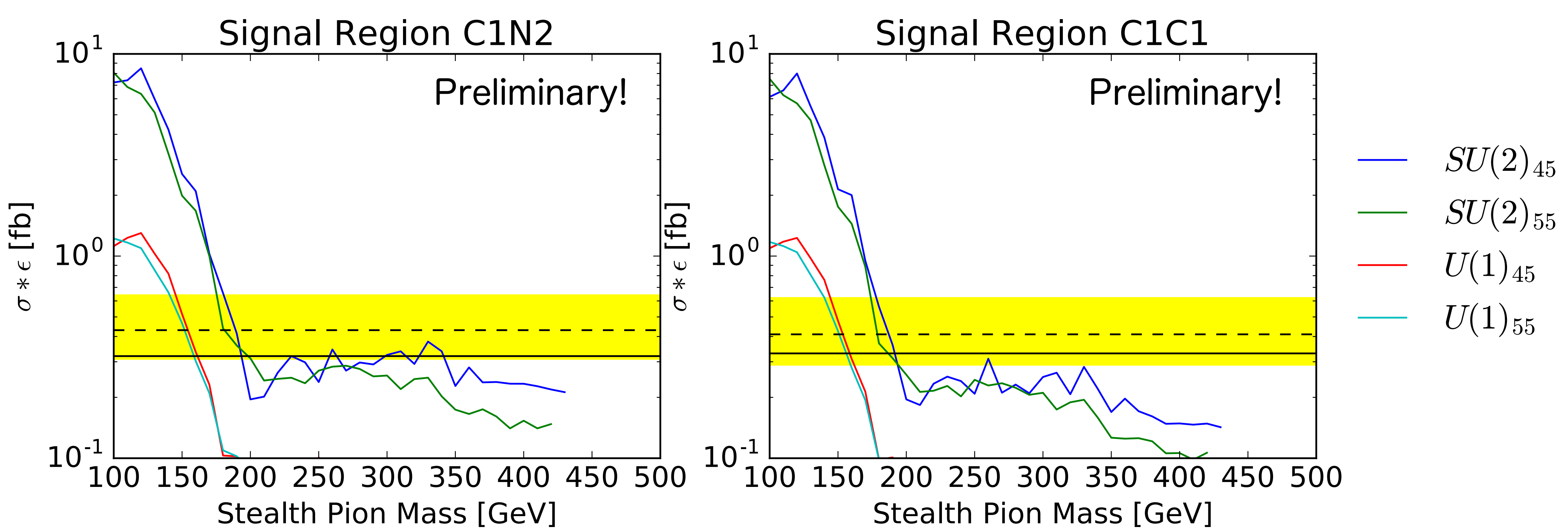
Signals of dark pion production

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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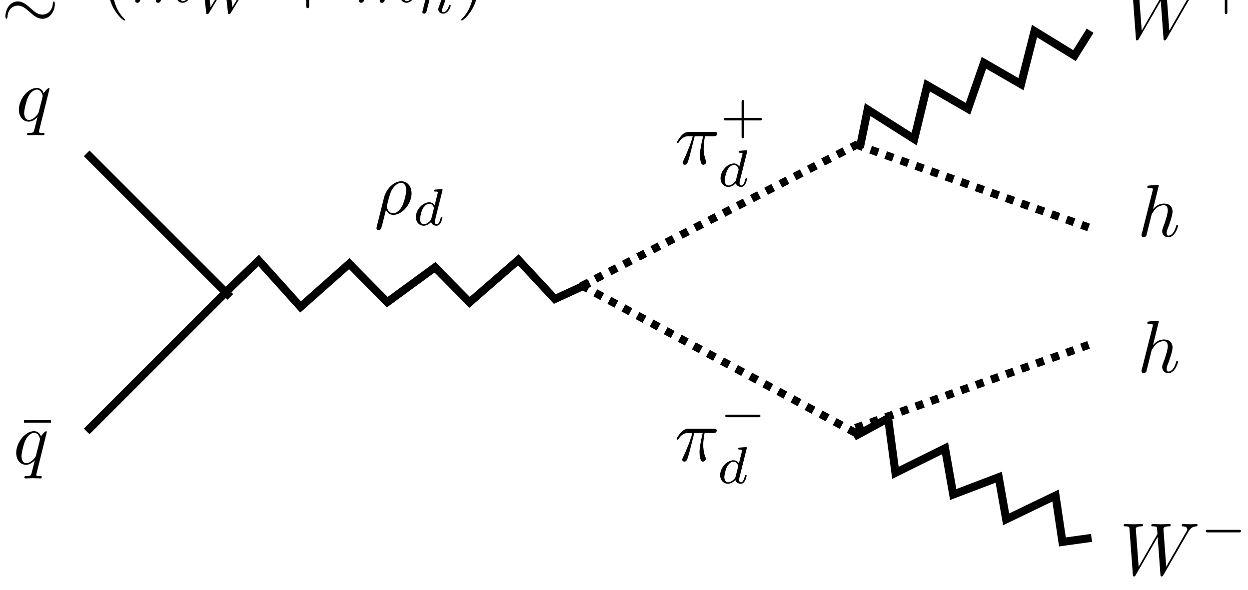
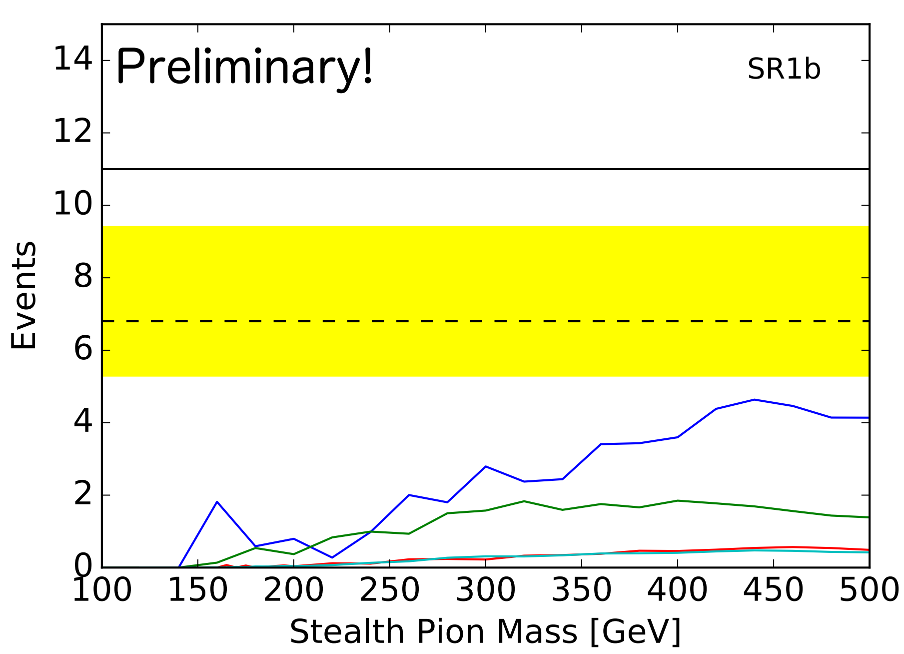
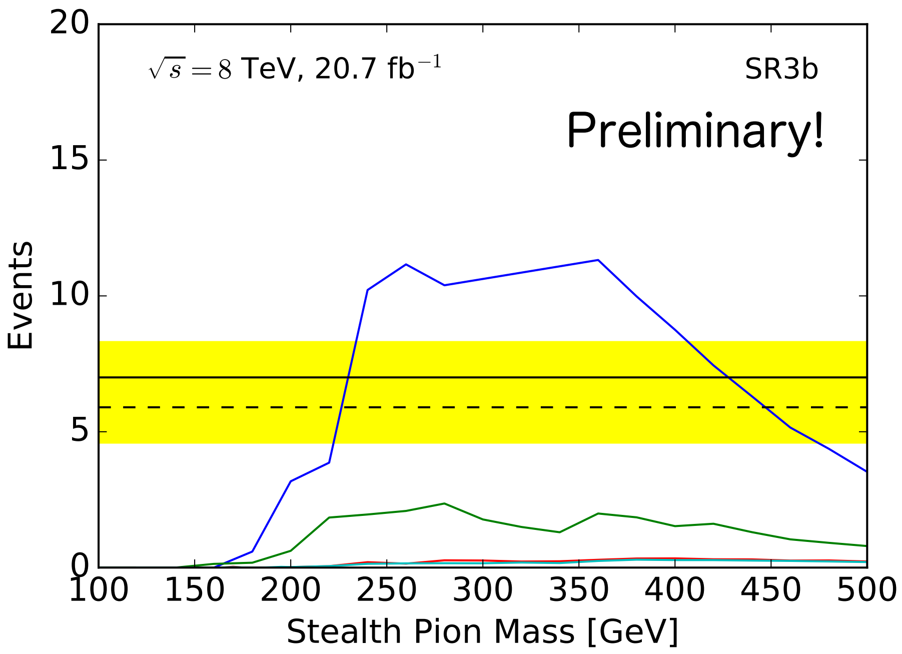
Signals of dark pion production

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) have sensitivity:





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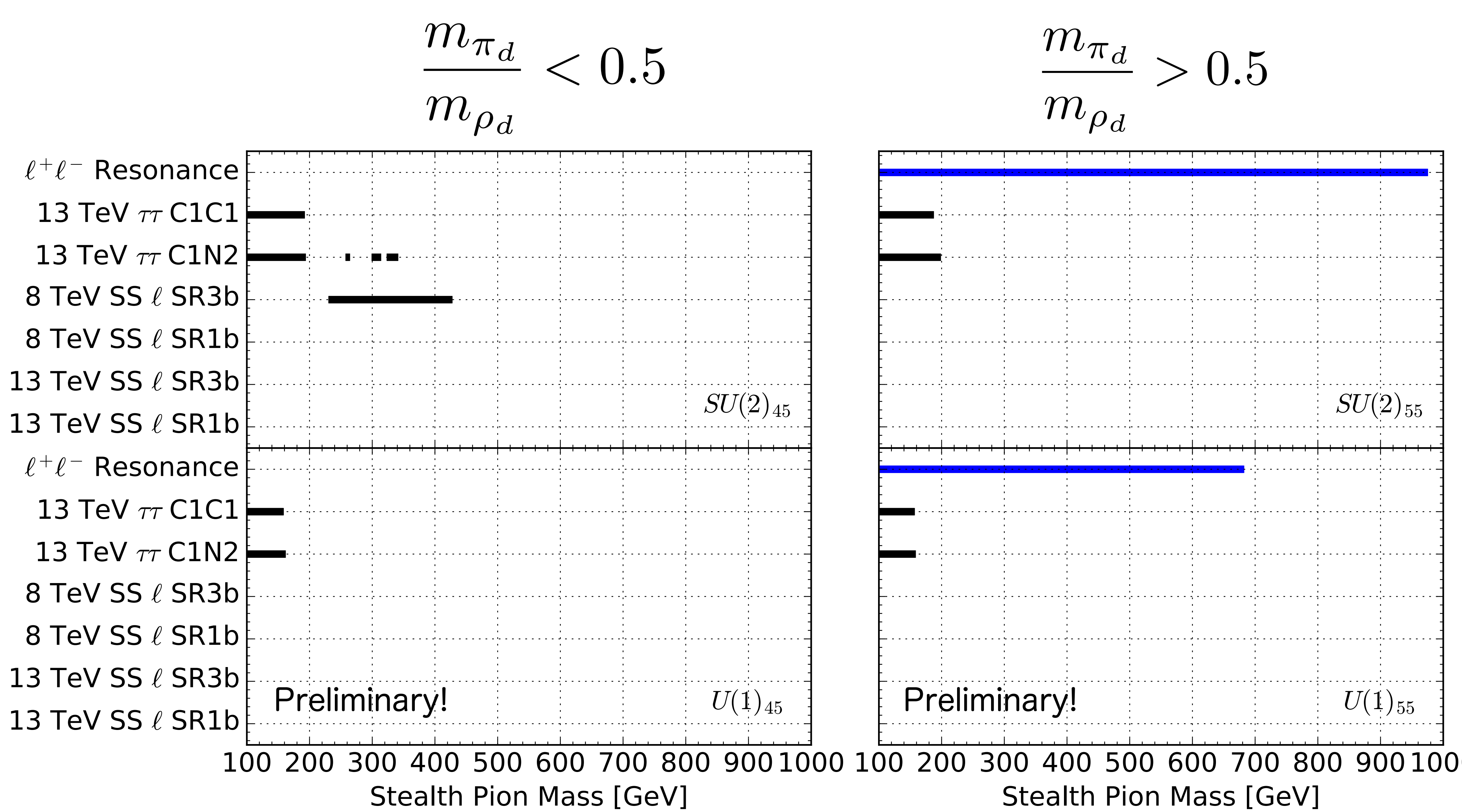
Constraints on dark pion production

Thus far, we have found:

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

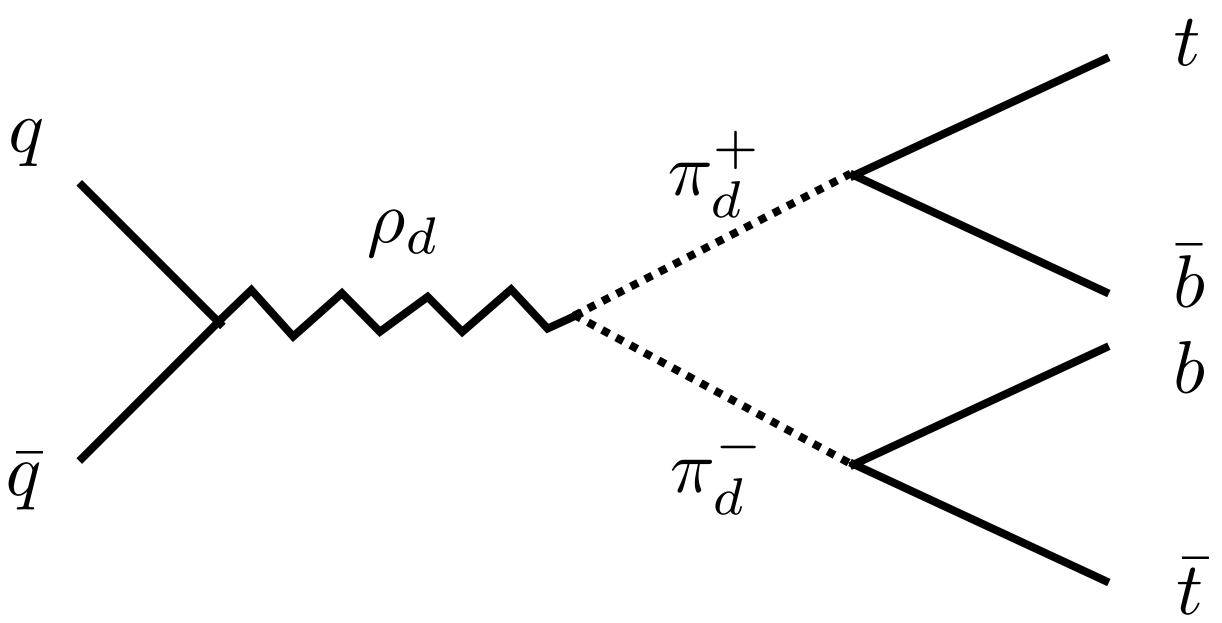


GK, Martin, Neil, Ostdiek, Tong (to appear)

Gaps in Searches?

Optimal searches do not exist. In some cases, sensitivity (from other searches) not even clear (use of BDTs, etc). 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. (No searches easily recast … yes we thought about t-t-h!)

Conclusions

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

- 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 made up of EW charged constituents to be as light as several hundred GeV.

- Dark Meson phenomenology
  — dark rho singly produced through kinetic mixing with EW gauge bosons
  — dark pions resonantly pair-produced (single production suppressed by c_{axial})
  — dark pion decay through small mixing with Higgs completely determined by dark pion mass —> highly predictive

- I'm excited about the 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!