Stealth Dark Matter

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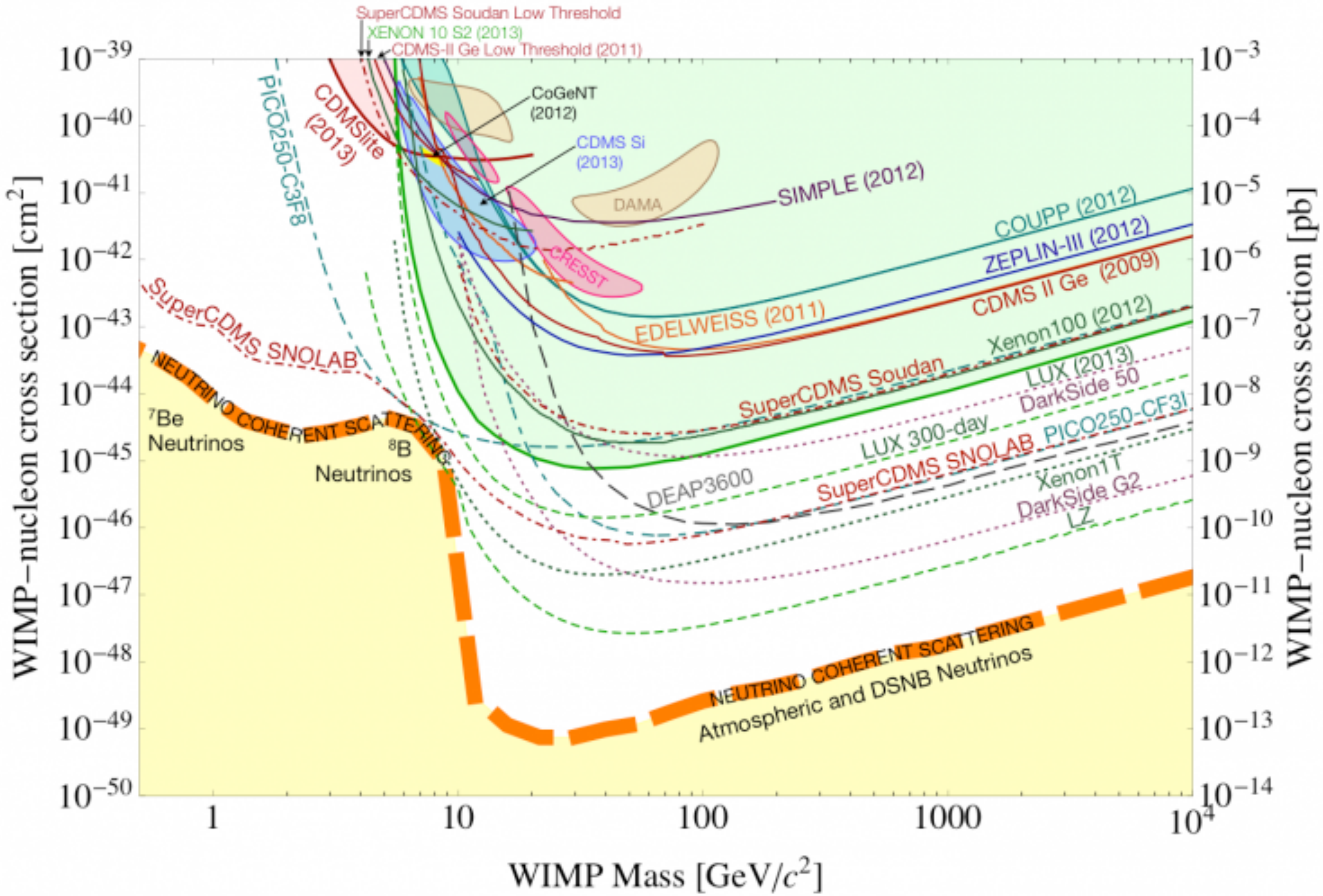
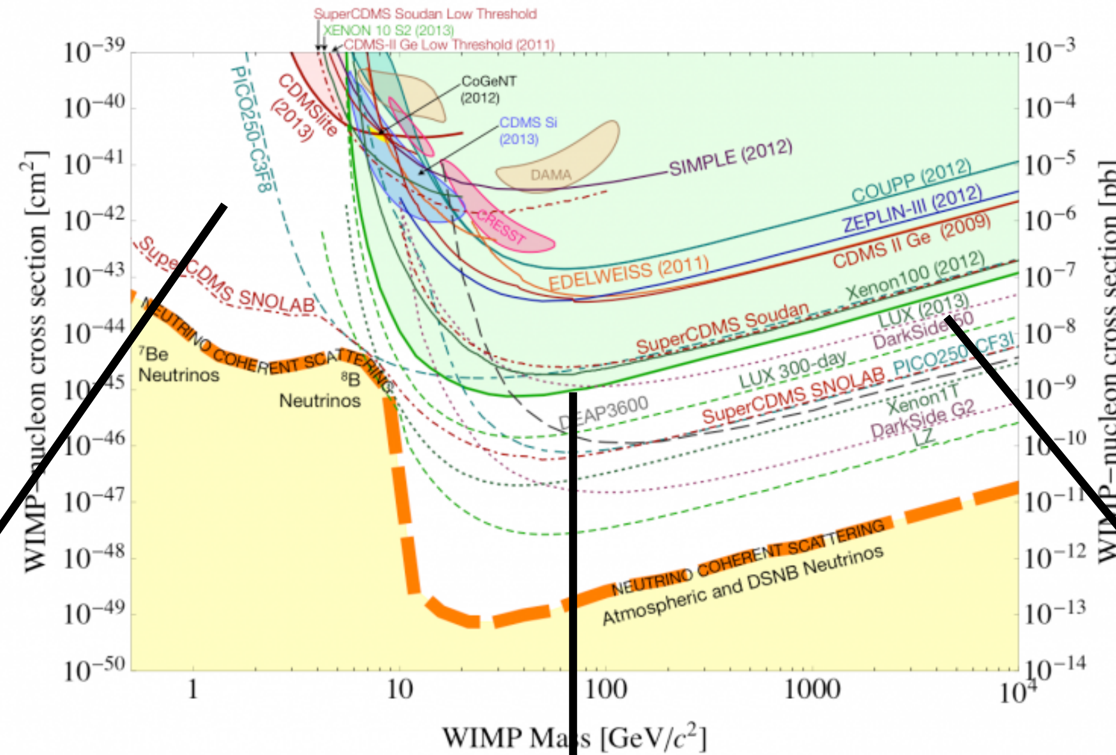
Based on 1402.6656 (PRD), 1503.04203 (PRD in press), 1503.04205 (PRL in press)
with Lattice Strong Dynamics (LSD) Collaboration
(and work in progress)

Brookhaven Forum | October 2015

Direct Detection



Interpretation with a Broad Brush



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

(no nuclear recoil above detection threshold)

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

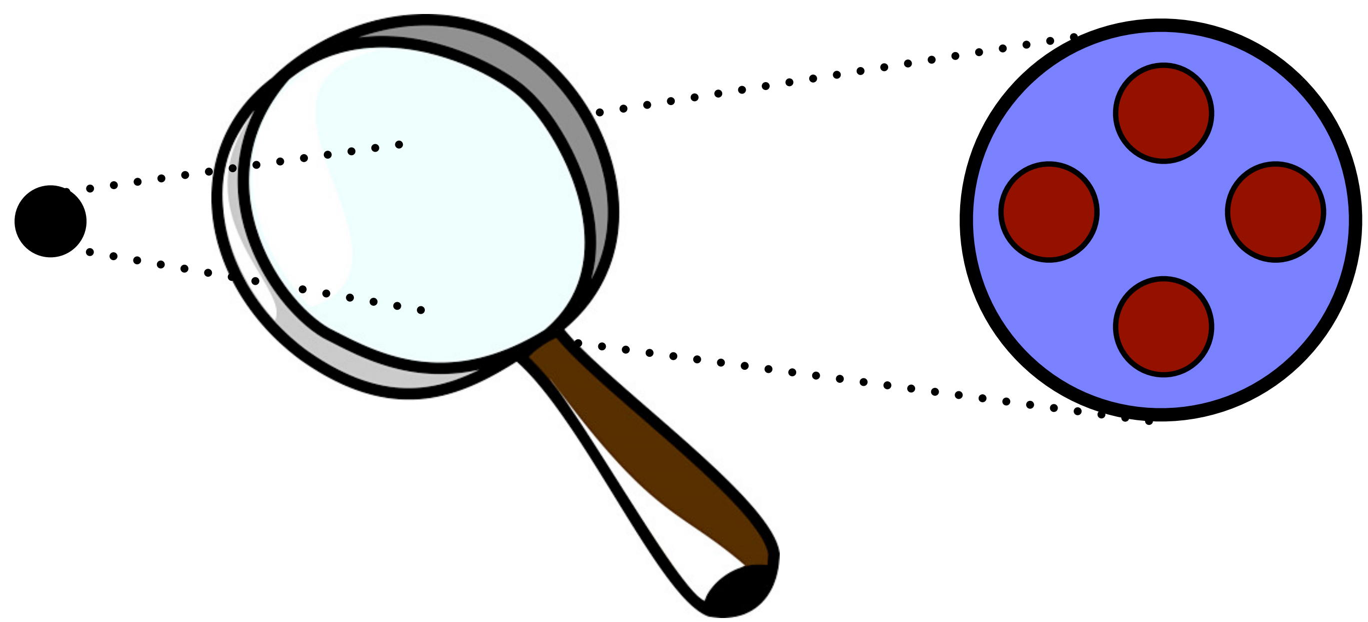
effective coupling of DM to Higgs must be suppressed

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

(suppression of Higgs coupling by at least

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

Composite Dark Matter?



—> new mass scales can be technically natural (Λ_{dark}, M_f)
—> DM stability automatic (e.g., baryon number)
—> interactions with SM matter can be suppressed by powers of the compositeness scale
—> self-interactions can be naturally strongly-coupled
—> has a rich spectrum of states (e.g., baryons and mesons), leading to qualitative changes to experimental signals

How can strong coupling mitigate direct detection constraints?

Effective interactions with the Standard Model arise in the expansion

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

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

How does SU(N) even N mitigate direct detection constraints?

Effective interactions with the Standard Model arise in the expansion

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

such as

magnetic moment: $\cancel{\dfrac{\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}}{\Lambda_{\rm dark}}}$ (DM is scalar baryon)

charge radius: $\cancel{\dfrac{(\bar{\psi}\psi)v_\mu\partial_\nu F^{\mu\nu}}{(\Lambda_{\rm dark})^2}}$ (dark custodial SU(2))

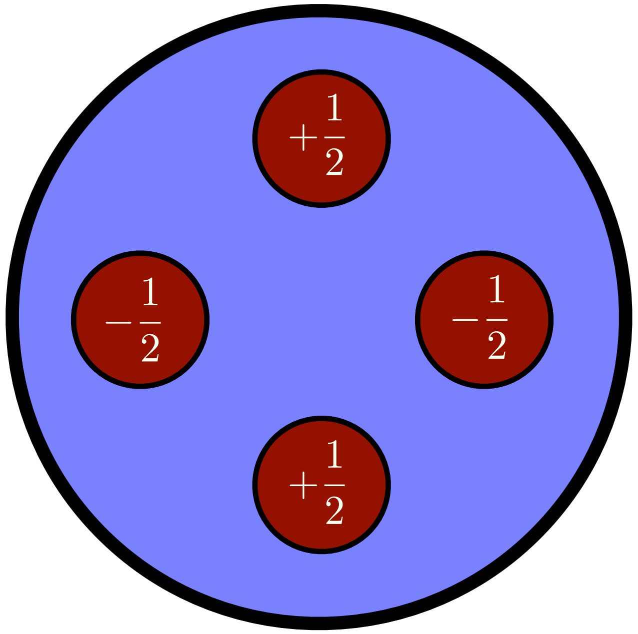
polarizability: $\dfrac{\phi\phi^* F_{\mu\nu}F^{\mu\nu}}{(\Lambda_{\rm dark})^3}$ (dimension-7 in non-relativistic EFT)

Naturally "stealthy" with respect to direct detection!

Stealth Dark Matter

"Stealth Dark Matter": a neutral composite scalar baryon of a strongly-coupled SU(N) (even N) confining theory made of electroweak-charged "dark fermions" in vector-like reps

Generally consider SU(4) with a range of scales that, as we will see, broadly extends from



$$100 \text{ GeV} \lesssim \Lambda_{\text{dark}} \sim M_f \lesssim 100 \text{ TeV}$$

Stealth Dark Matter Scales

$M_f \ll \Lambda_{\rm dark}$

$\Lambda_{\rm dark} \sim M_f$

$M_f \gg \Lambda_{\rm dark}$

chiral limit

bounds from LEP II
on light electrically
charged mesons
imply hierarchy

$m(B) \gtrsim \Lambda_{\rm dark}$

$m(\Pi^{\pm})$

quarkonia limit

bounds from light
glueballs becoming
too-long-lived

$m(B) \simeq N_c M_f$

$m(\Pi) \simeq 2 M_f$

$m(\text{glueball})$

Stealth Dark Matter Scales

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

chiral limit

bounds from LEP II
on light electrically
charged mesons
imply hierarchy

$m(B) \gtrsim \Lambda_{\text{dark}}$

$m(\Pi^{\pm})$

$\Lambda_{\text{dark}} \sim M_f$

all scales coincident

maximize discovery potential!

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

quarkonia limit

bounds from light
glueballs becoming
too-long-lived

$m(B) \simeq N_c M_f$

$m(\Pi) \simeq 2M_f$

$m(\text{glueball})$

Lattice Gauge Theory Simulations

Ideal tool to calculate properties of theories with

$$M_f \sim \Lambda_D$$

in the fully non-perturbative regime. Joy of these calculations is that what we simulate is interesting "out of the box" without chiral extrapolations.

What we have done: Accurate estimates of the spectrum, "sigma term", and polarizability. Ongoing work will nail down f_π, f_ρ...

Simulated with modified Chroma mainly on LLNL computers. Quenched, unmodified Wilson fermions. Several volumes and lattice spacings.

Lattice Strong Dynamics Collaboration

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E. Neil (Colorado & Brookhaven)
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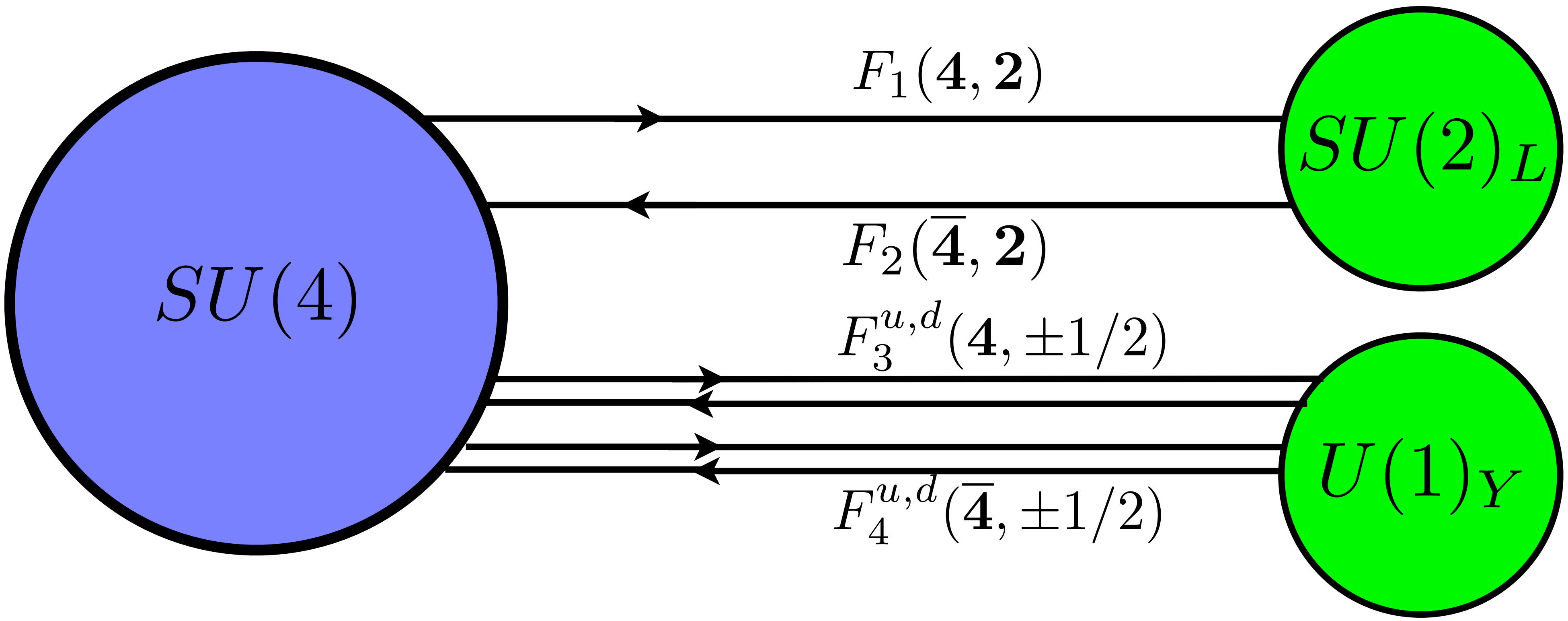
D. Schaich (Syracuse)
O. Witzel (Boston U & Edinburgh)

Dark Fermions

Dark fermions transform in vector-like representations:



Vector-like masses are permitted for dark fermions

$$\begin{pmatrix} M_{12} & \\ & M_{34}^u \end{pmatrix}_{+\frac{1}{2}}$$

$$\begin{pmatrix} M_{12} & \\ & M_{34}^d \end{pmatrix}_{-\frac{1}{2}}$$

as well as contributions from EWSB

$$\begin{pmatrix} M_{12} & y_{14}^u v/\sqrt{2} \\ y_{23}^u v/\sqrt{2} & M_{34}^u \end{pmatrix}_{+\frac{1}{2}}$$

$$\begin{pmatrix} M_{12} & y_{14}^d v/\sqrt{2} \\ y_{23}^d v/\sqrt{2} & M_{34}^d \end{pmatrix}_{-\frac{1}{2}}$$

Dark Flavor Symmetries

Under SU(4):	U(4) x U(4)
Weak gauging:	$[SU(2) \times U(1)]^4$ (that contains $SU(2)_L \times U(1)_Y$)
Vector-like masses:	$SU(2)_L \times U(1)_Y \times U(1) \times U(1)$
Yukawas with Higgs:	$U(1)_B$

Dark baryon number automatic.

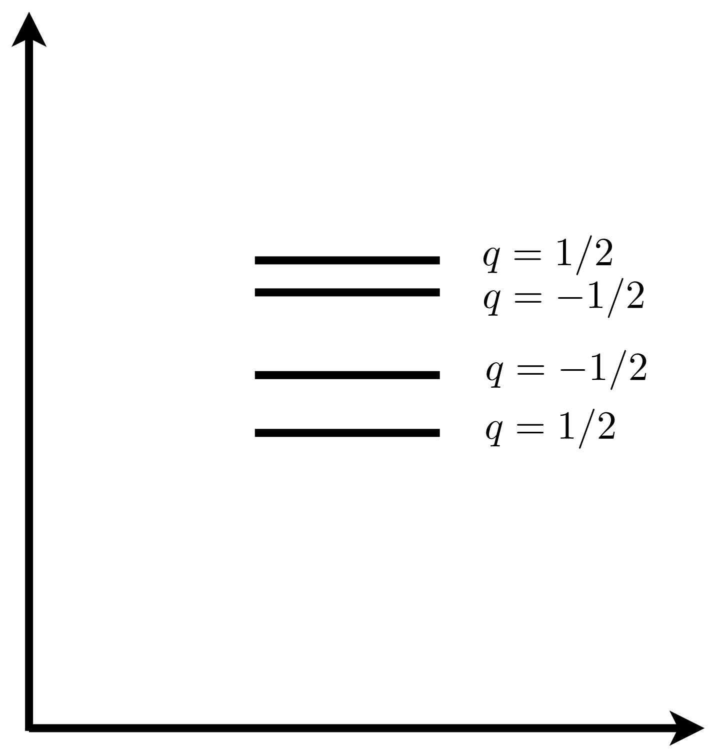
and very safe against cutoff scale violations of global symmetries
e.g.

$$\frac{qqqq\, H^\dagger H}{\Lambda^4_{\mathrm{cutoff}}}$$

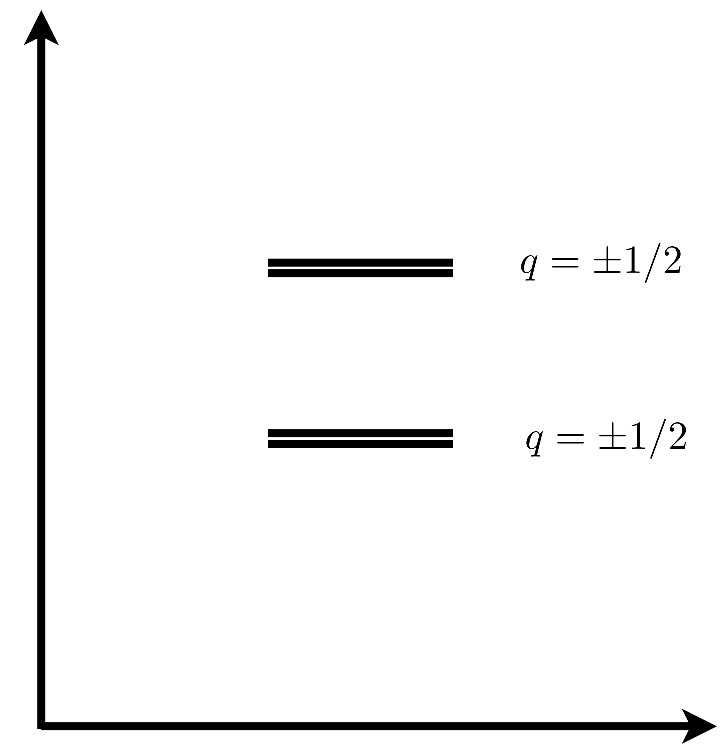
[This is one reason to prefer SU(4) over SU(2).]

Dark Fermion Mass Spectrum

General



Custodial SU(2)

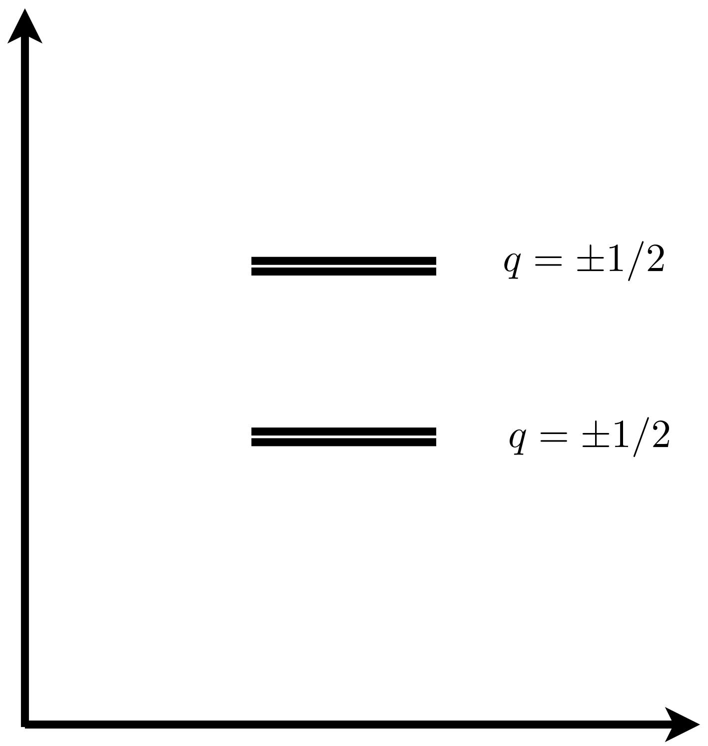


$$\begin{pmatrix} M_{12} & y^u_{14} v/\sqrt{2} \\ y^u_{23} v/\sqrt{2} & M^u_{34} \end{pmatrix}_{+\frac{1}{2}}$$

$$\begin{pmatrix} M_{12} & y^d_{14} v/\sqrt{2} \\ y^d_{23} v/\sqrt{2} & M^d_{34} \end{pmatrix}_{-\frac{1}{2}}$$

$$\begin{pmatrix} M_{12} & y_{14} v/\sqrt{2} \\ y_{23} v/\sqrt{2} & M_{34} \end{pmatrix}_{\pm\frac{1}{2}}$$

Custodial SU(2)



- Lightest baryon is a neutral complex scalar

  (eliminates operators dependent on spin,
  e.g., dim-5 magnetic moment)

- Contributions to T parameter vanish

  (no need to make life more complicated)

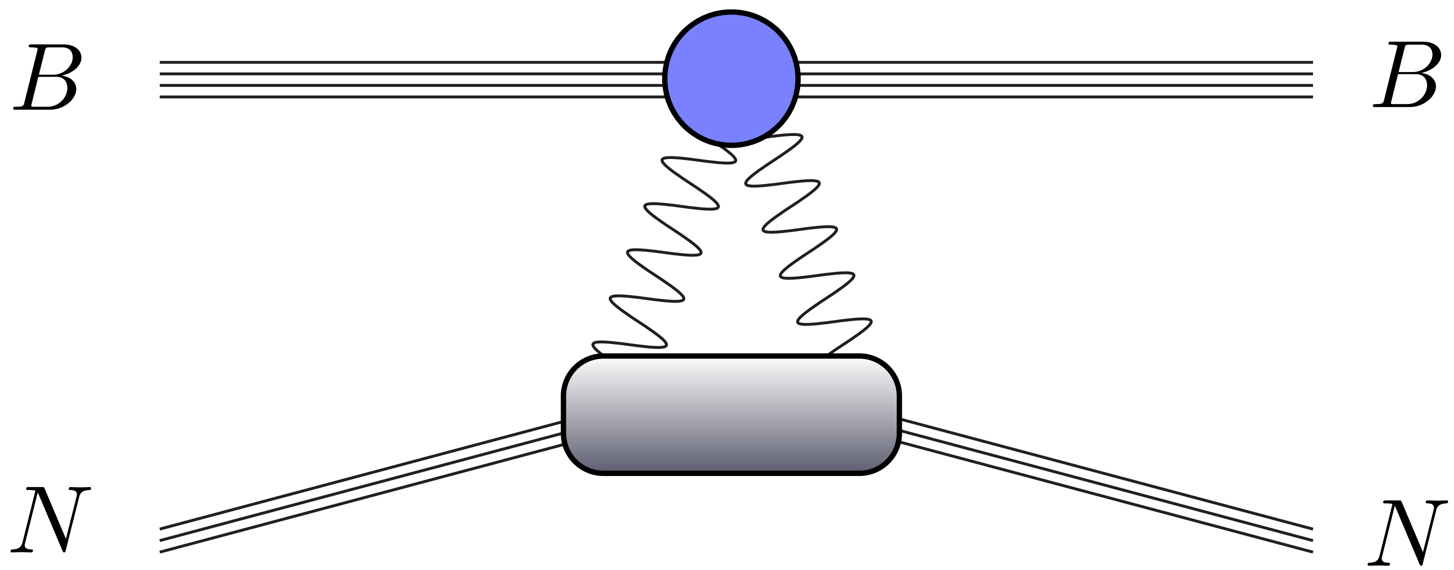
- Weak isospin exactly zero

  (no Z coupling to dark matter; otherwise significant constraints)

- Dim-6 charge radius vanishes

  (more stealthy w.r.t. direct detection;
  one less thing to calculate on lattice)

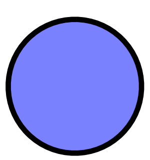
Direct Detection through Polarizability



Wonderful formalism for extracting the electric polarizability from lattice using background field methodology.

Detmold, Tiburzi, Walker-Loud

In the NR limit, the scalar baryon operator is dimension-7



$$\frac{c_F e^2}{m_B^3} B^* B F^{\mu\alpha} F^{\nu}_{\alpha} v_\mu v_\nu$$

$v_\mu = (1,0,0,0)$

extracted from our lattice simulations

Polarizability

The per nucleon cross section

$$\sigma_{\rm nucleon} = \frac{\mu_{nB}^2}{\pi A^2}\left|\frac{c_F e^2}{m_B^3} f_F^A\right|^2$$

has large uncertainties on the nuclear side (momenta-dependent structure factors, operator mixing, nuclear resonances)

Weiner, Yavin; 1206.2910
Frandsen et al; 1207.3971
Ovanesyan, Vecchi; 1410.0601

We parametrize simply as

$$f_F^A = 3Z^2\alpha\frac{M_F^A}{R}$$

$1/3 < M_F^A < 3$

$R = 1.2\ A^{1/3}\ \text{fm}$

To obtain

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

Where the nuclear structure factor remains the largest uncertainty.

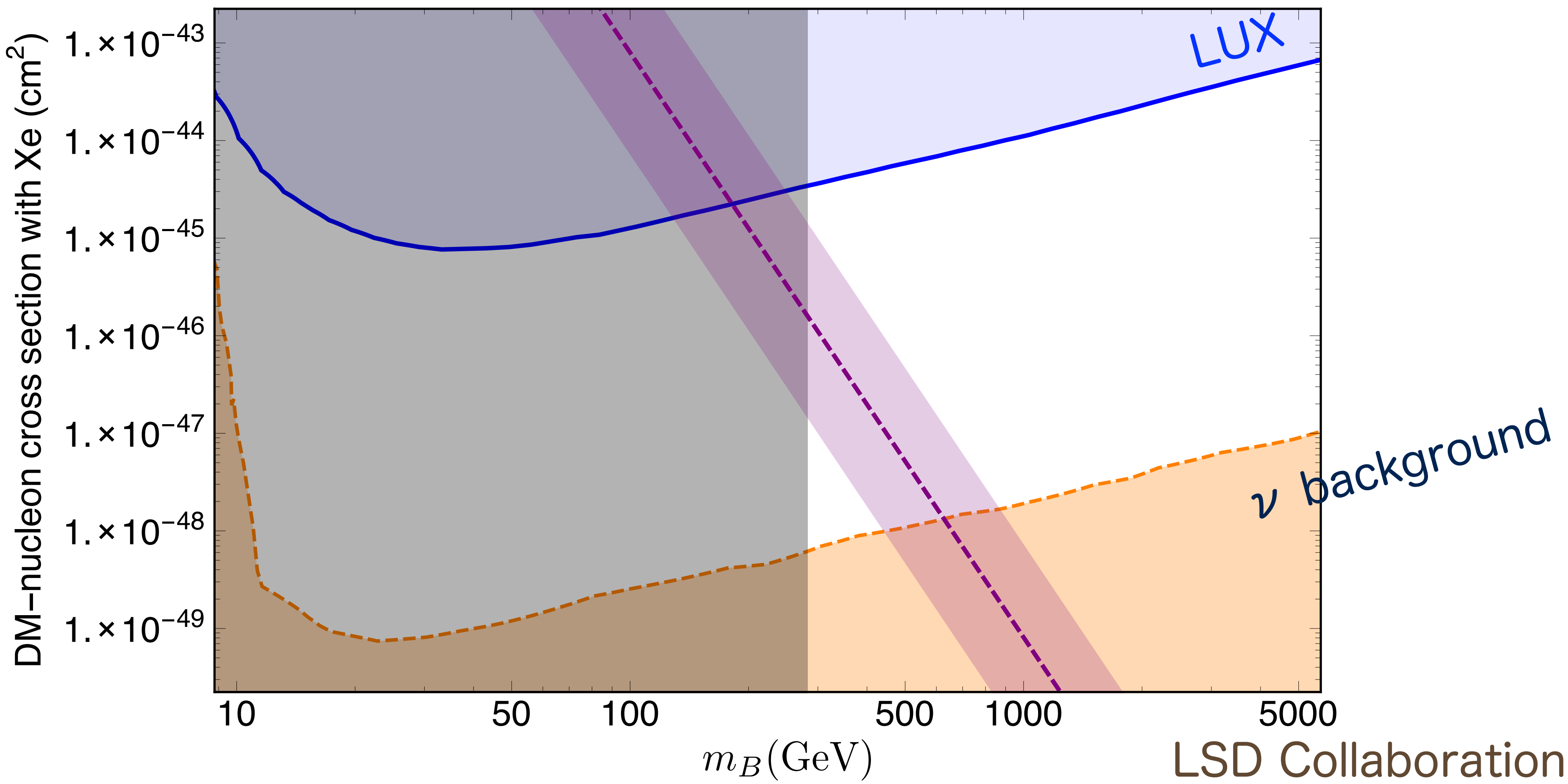
Polarizability

Note!

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

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.

Polarizabilities in SU(3) and SU(4)

	m_Π/m_V	c_F	
$SU(4)_{dark}$	0.77	13.3	
$SU(4)_{dark}$	0.70	10.5	LSD Collaboration; 1503.04205
$SU(3)_{dark}$	0.77	9.5	
$SU(3)_{dark}$	0.70	6.7	
neutron - $SU(3)_c$	0.18	2.8	(expt from PDG)

Much more to discuss ...

- Higgs exchange can also lead to spin-independent direct detection scattering

- Dark meson production and decay is an extremely interesting LHC signal
  --> meson form factors important to determine rates (lattice input)

- Indirect astrophysical signals (γ-rays) possible between
  —> excited states as well as annihilation of a symmetric component

- EW interaction allows thermal and/or asymmetric mechanisms

- Higgs couplings ensure charged mesons decay without new physics;
  —> contributions to S parameter controlable (lattice input)

Thank you!

Extra

Approximately Symmetric / Vector-Like

Convenient to expand around the symmetric matrix limit

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

$$|\epsilon_y| \ll |y|$$

Then the axial current

$$j^{\mu}_{+,\mathrm{axial}} \supset c_{\mathrm{axial}} \overline{\Psi^u_1} \gamma^\mu \gamma_5 \Psi^d_1$$

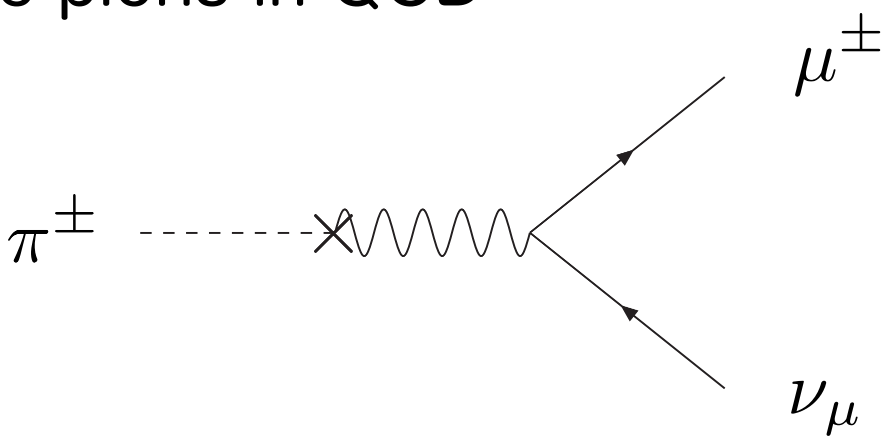
becomes

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

$$\simeq \frac{\epsilon_y v}{2M} \times \begin{cases} 1 & \text{Linear Case} \\ yv/(\sqrt{2}\Delta) & \text{Quadratic Case.} \end{cases}$$

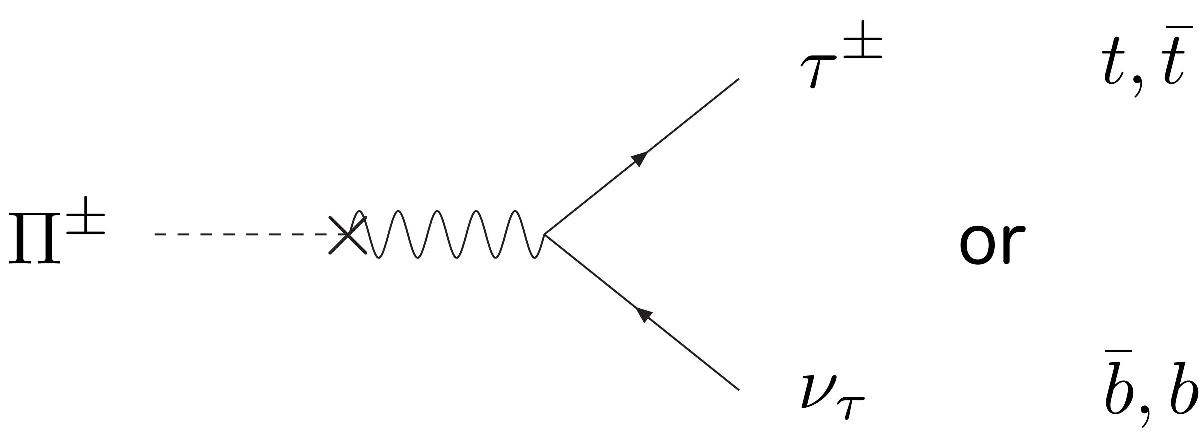
Charged Meson Decay

Like pions in QCD



$$\langle 0 | j^\mu_{\pm,\mathrm{axial}} | \pi^\pm \rangle = i f_\pi p^\mu$$

Lightest dark mesons decay through



$$\langle 0 | j^\mu_{\pm,\mathrm{axial}} | \Pi^\pm \rangle = i f_\Pi \, p^\mu$$

The non-zero Yukawa couplings with $\epsilon_y \neq 0$ cause $j^\mu_{\pm,\mathrm{axial}} \neq 0$

$$\frac{\Gamma(\Pi^+ \to f\overline{f}')}{\Gamma(\pi \to \mu^+ \nu_\mu)} \simeq \frac{c^2_{\mathrm{axial}}}{|V_{ud}|^2} \left(\frac{f_\Pi}{f_\pi}\right)^2 \left(\frac{m_f}{m_\mu}\right)^2 \left(\frac{m_\Pi}{m_\pi}\right)$$

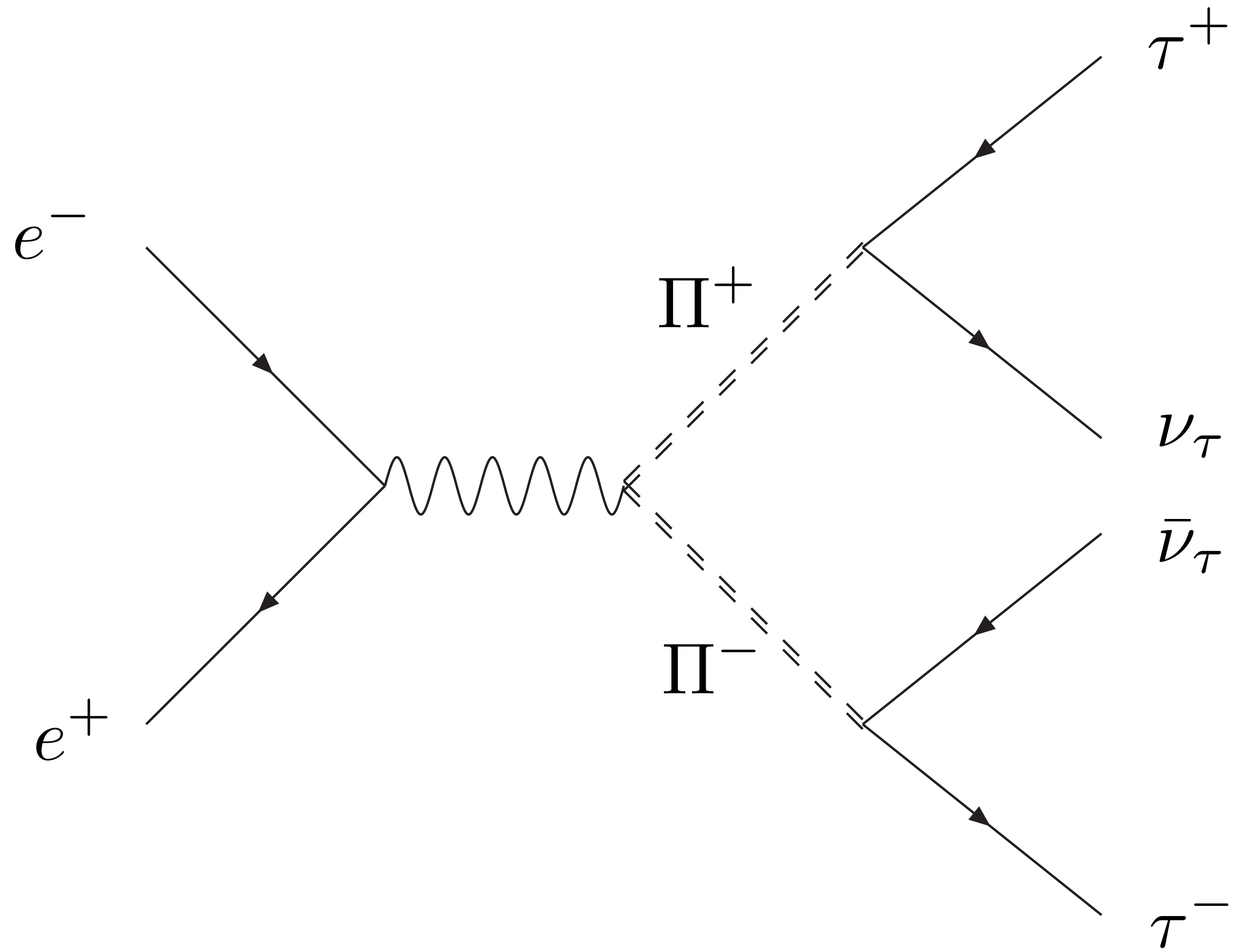
(unlike "Vector-like Confinement")

Kilic, Okui, Sundrum; 0906.0577

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

Lower bound on meson mass ...

Charged pion production at LEP II

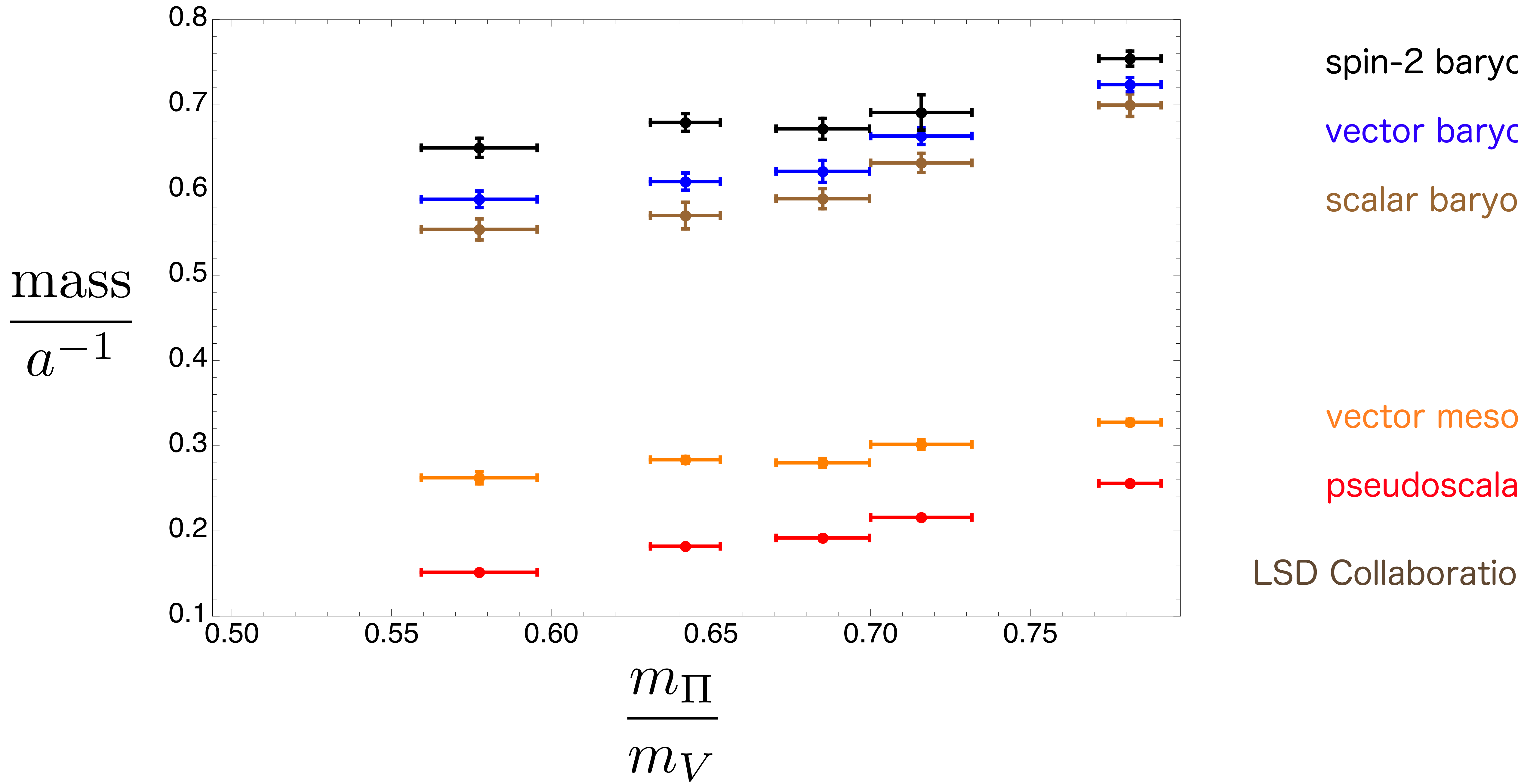


Assuming just Drell-Yan production, a crude recasting of bounds on staus gives

$$m_{\Pi^\pm} > 86 \text{ GeV}$$

This is fairly robust to promptness/non-promptness of dark meson decay.

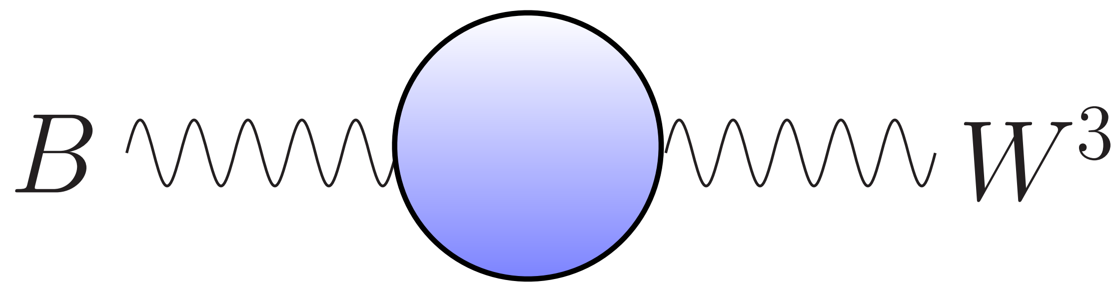
... becomes lower bound on the baryon mass



Within the range simulated on our lattices, we obtain

$$2.5 \lesssim \frac{m_B}{m_\Pi} \lesssim 3.8$$

S parameter



Peskin, Takeuchi (1990, 92)

Obviously ΔS -> 0 as (yv) -> 0.

With custodial SU(2), approximate symmetric, and M_1 close to M_2

$$S \;\propto\; \int d^4x\, e^{-i\mathbf{q}\cdot\mathbf{x}} \langle j_3^\mu(x) j_Y^\nu(0)\rangle \;\simeq\; \frac{\epsilon_y^2 v^2}{4M^2} G_{LR}^{\mu\nu},$$

$$G_{LR}^{\mu\nu} \equiv \langle \bar{\psi}^u \gamma^\mu P_L \psi^u \bar{\psi}^u \gamma^\nu P_R \psi^u \rangle\big|_{\rm connected}$$

and thus can be easily suppressed below experimental limits.

[Vector-like masses for dark fermions crucial.]

Effective Higgs Coupling

The Higgs coupling to the lightest dark fermions

$$\mathcal{L} \supset y_\Psi h \overline{\Psi}_1 \Psi_1$$

$$y_\Psi = \frac{y^2 v}{M_2 - M_1} + O(\epsilon_y) \simeq \begin{cases} \frac{y}{\sqrt{2}} & \text{Linear Case} \\ \frac{y^2 v}{2\Delta} & \text{Quadratic Case.} \end{cases}$$

This leads to an effective Higgs coupling to the dark scalar baryon

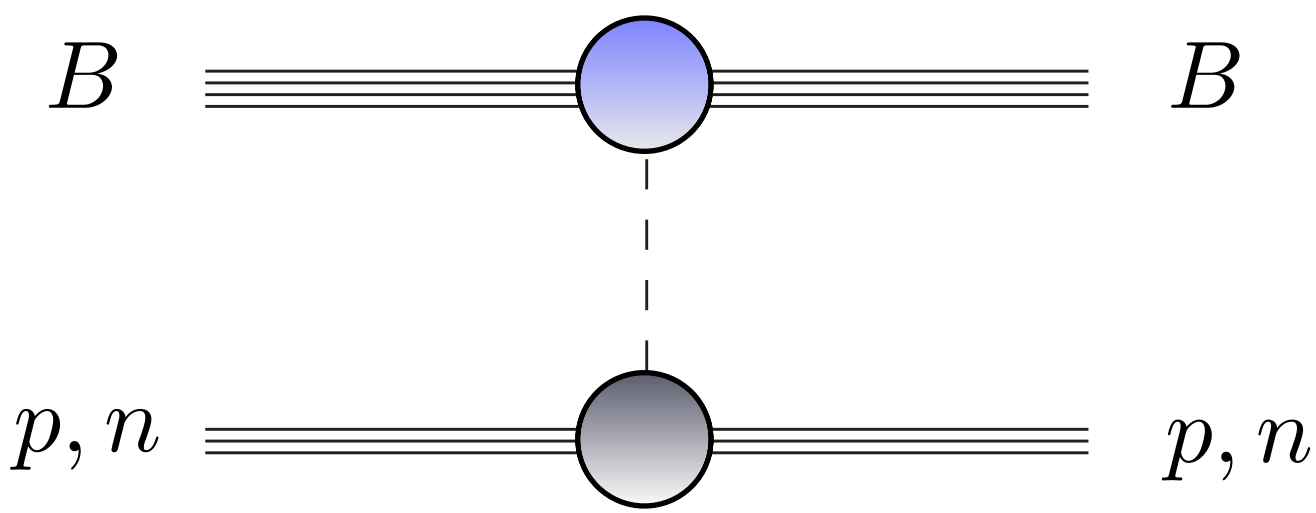
$$g_B \simeq f_f^B \times \begin{cases} y_{\text{eff}} & \text{Linear Case} \\ y_{\text{eff}}^2 \frac{v}{m_B} & \text{Quadratic Case} \end{cases}$$

$$y_{\text{eff}} \equiv \begin{cases} y \frac{m_B}{\sqrt{2} M_1} & \text{Linear Case} \\ y \frac{m_B}{\sqrt{2 \Delta M_1}} & \text{Quadratic Case.} \end{cases}$$

$$\langle B | \, m_f \bar{f} f \, | B \rangle = m_B f_f^B$$

Extracted from lattice!

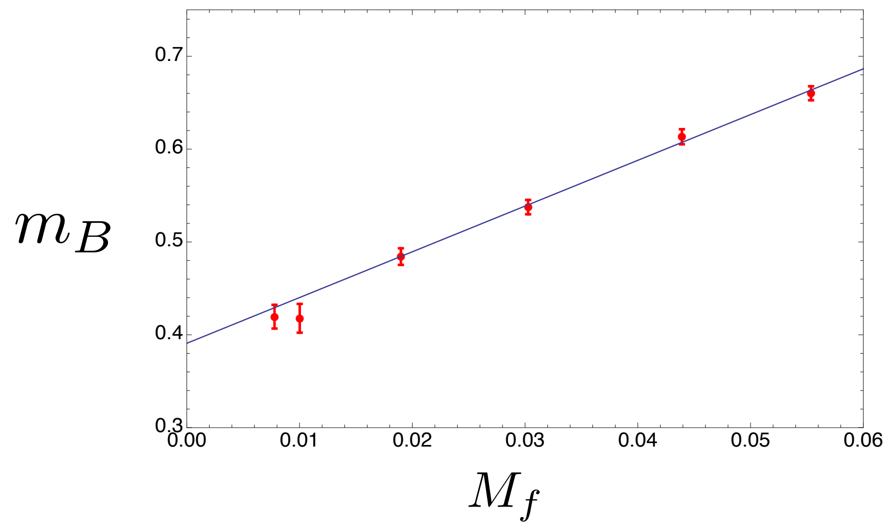
Direct Detection 1: Higgs exchange



Just as $\langle p, n|\; m_q \bar{q} q \;|p, n\rangle \;=\; m_{p,n} f_q^{p,n}$

We have $\langle B|\; m_f \bar{f} f \;|B\rangle \;=\; m_B f_f^B$

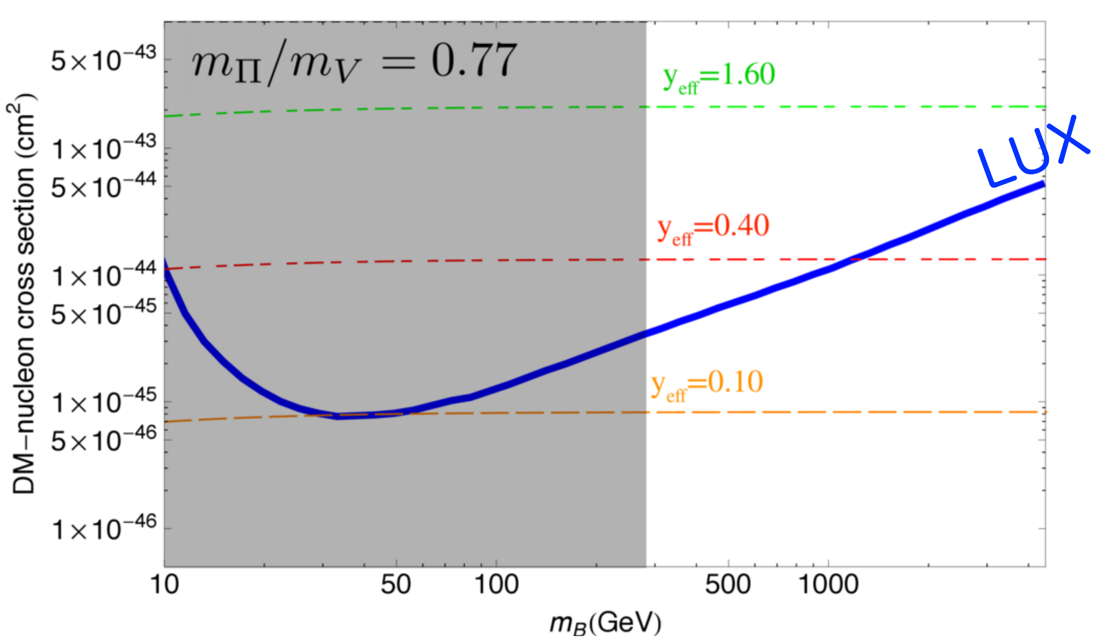
We can extract from lattice using Feynman-Hellman $\quad f_f^B = \dfrac{M_f}{m_B} \dfrac{\partial m_B}{\partial M_f}$



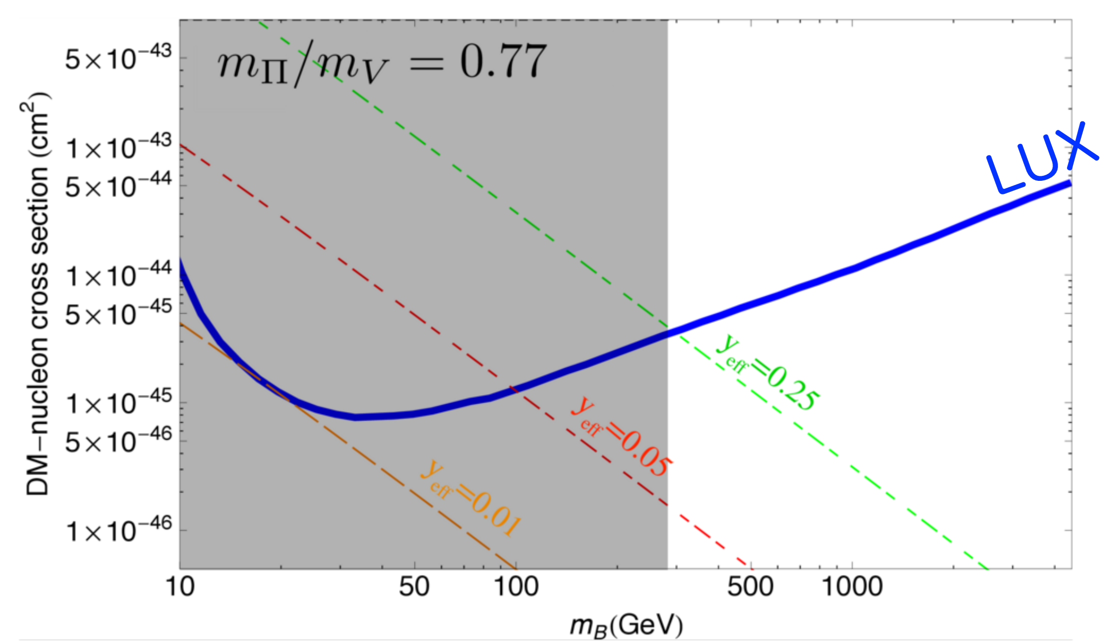
LSD Collaboration;

Higgs exchange results

Linear case



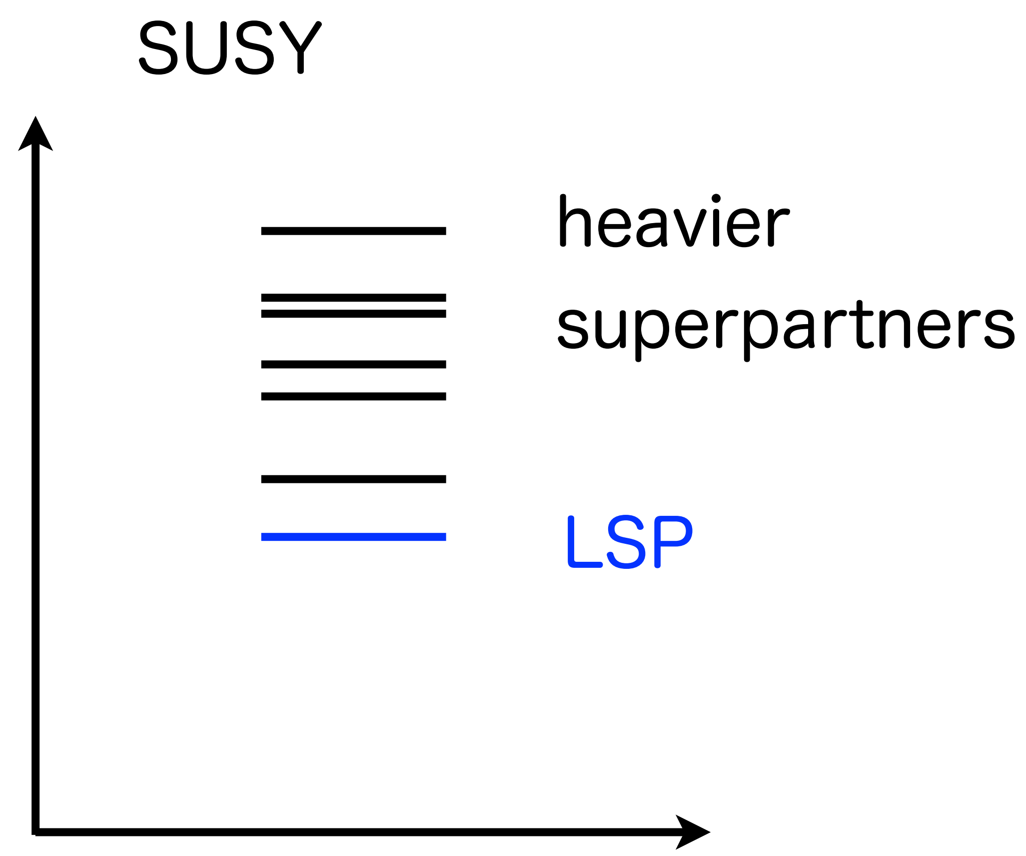
Quadratic case

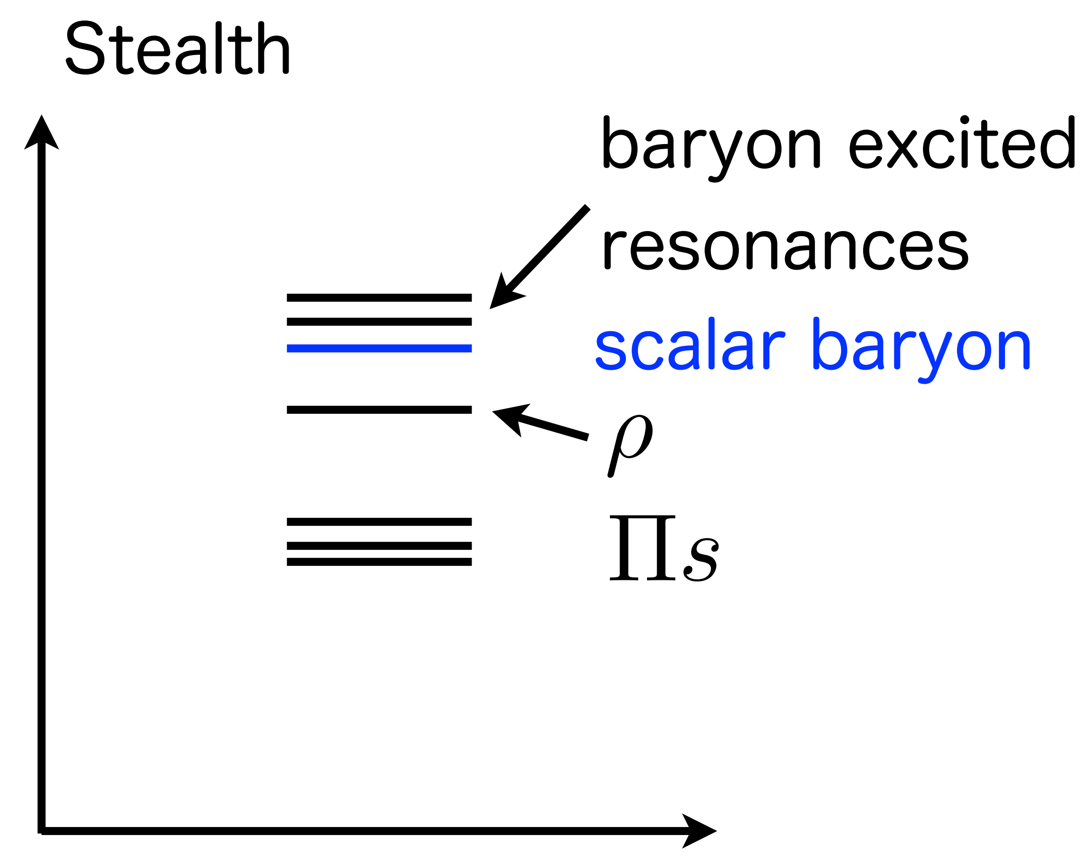


LSD Collaboration;

Roughly, yeff < 0.25 for lightest baryon mass, with constraints that become looser proportional to m_B for linear or $(m_B)^2$ for quadratic case.

Colliders

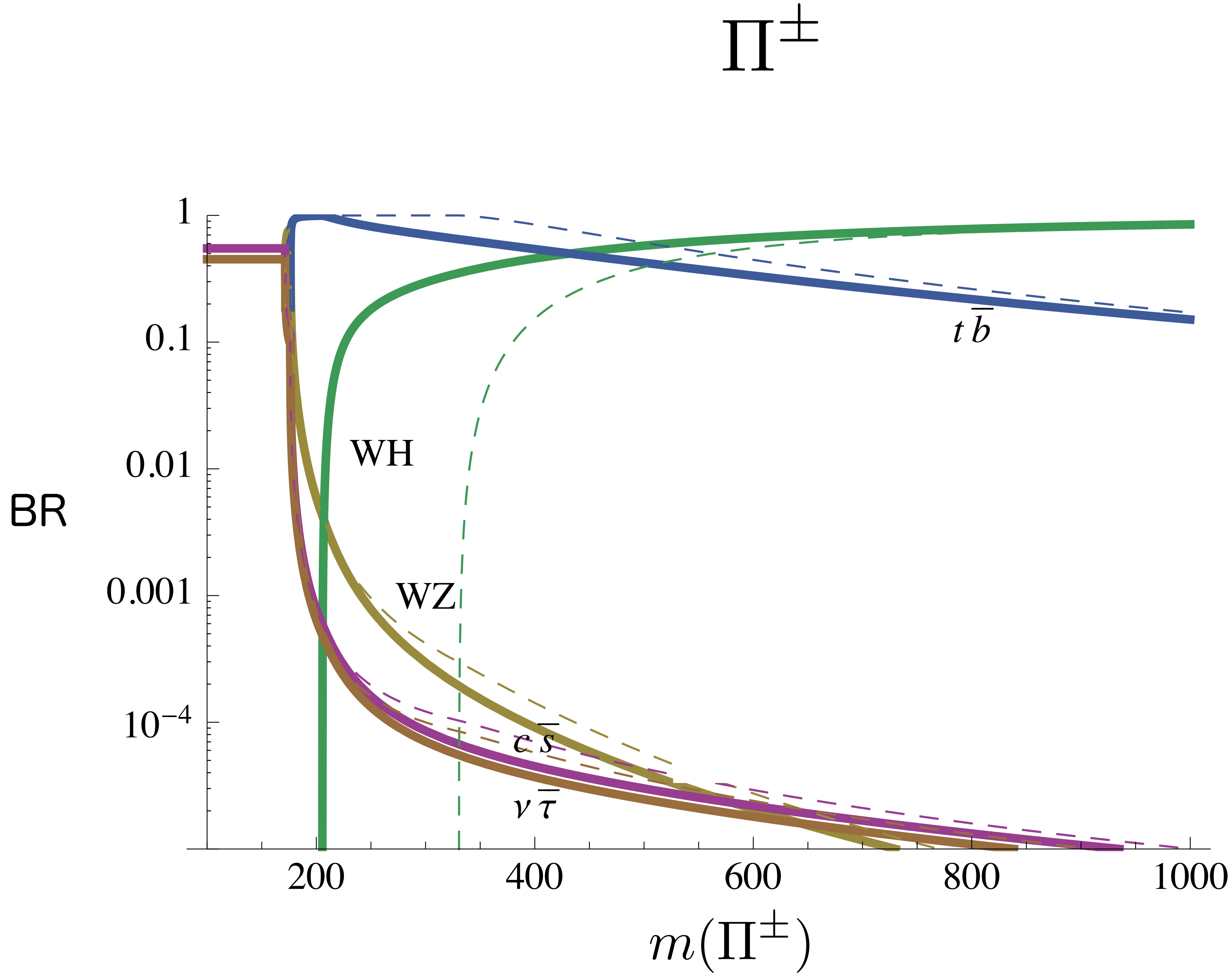




Collider searches dominated by light meson production and decay.

Missing energy signals largely absent!

Lightest Meson Decay Rates - A First Look



Fok, Kribs; 110

Also, vector meson (ρ) phenomenology interesting (and constrained); depends sensitively on f_ρ/m_ρ

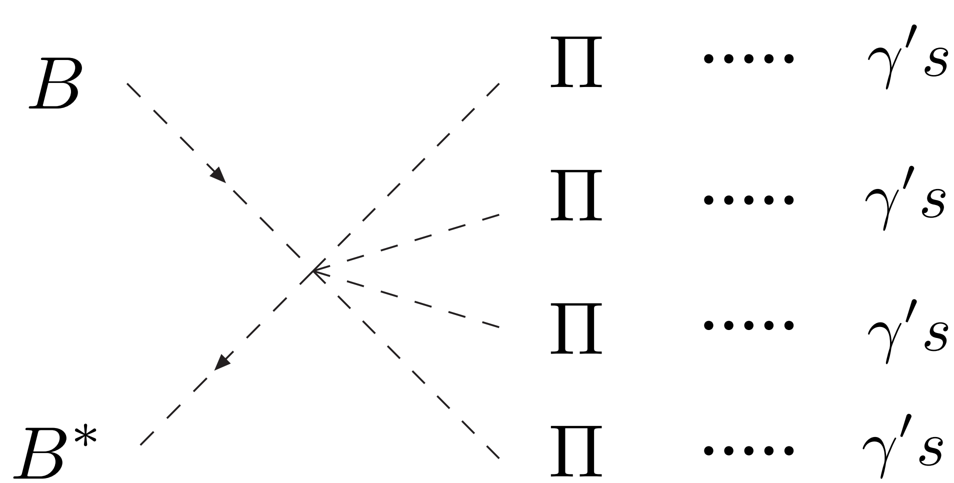
Astrophysical Signals - A First Look

Excited states of dark baryon that are nearby in mass

- fine structure
- hyperfine structure

could be visible through γ-ray emission/absorption lines.

If some symmetric component, annihilation signals (into γs) are extremely interesting. It could be that multibody final states are generic, e.g.



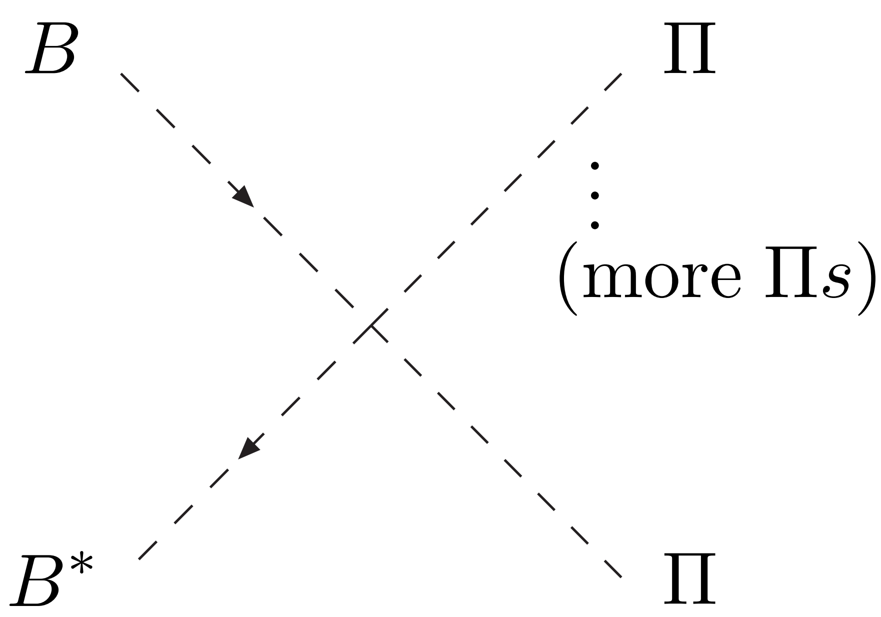
2->4->8-> etc cascade annihilation explored in

Elor, Rodd, Slatyer; 150

BUT! Expect 2->n gives qualitatively different distribution

Abundance

Symmetric



If 2 -> 2 dominates the thermal annihilation rate and saturates unitarity, expect

Griest, Kamionkowski; 1990

$$m_B \sim 100 \text{ TeV}$$

Unfortunately, this is a hard calculation to do using lattice...

Asymmetric

e.g., through EW sphalerons

Barr, Chivukula, F

$$n_D \sim n_B \left(\frac{yv}{m_B}\right)^2 \exp\left[-\frac{m_B}{T_{\rm sph}}\right]$$

IF EW breaking comparable to EW preserving masses, expect roughly

$$m_B \lesssim m_{\rm techni-B} \sim 1 \text{ TeV}$$

How much less depends on several factors...