Non-Perturbative Collider Phenomenology of Stealth Dark Matter

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L S D

Lattice Strong Dynamics Collaboration

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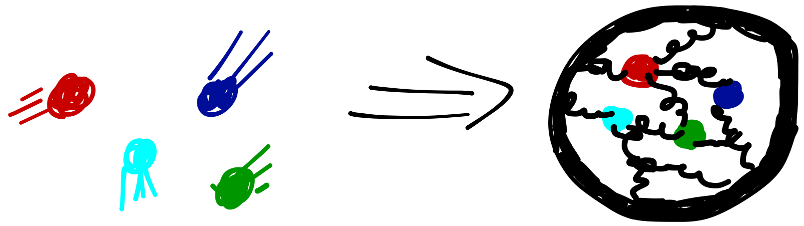
Strongly-coupled composite dark matter

- Our focus: composite DM as a strongly-bound state of some more fundamental objects (think of the neutron)



- Non-Abelian **SU(N_D)** gauge sector, with some fermions in the fundamental rep. Not the only possibility (e.g. “dark atoms”, other non-Abelian theories) but a well-motivated, somewhat familiar foundation.

- Constituents can carry SM charges, and charged excited states active in early universe. Composite DM relic interacts via SM particles (**photon**, **Higgs**) but with form factor suppression!

Symmetries of stealth DM

- Start with $SU(N_D)$ gauge theory and N_F Dirac fermions, in the fundamental rep, and impose some conditions.

- First requirement: *baryons are bosons* - even N_D. No magnetic moment. $N_D \geq 4$ gives automatic DM stability from Planck-scale violations.

- Second requirement: *couplings to electroweak and Higgs* - one EW doublet and one singlet, $N_F \geq 3$. Ensures meson decay as well.

- Third requirement: *custodial SU(2) for electroweak precision* - $N_F = 4$. As a bonus, charge radius is eliminated —> stealth DM!

Stealth dark matter: model details

Field	$SU(N_D)$	$(SU(2)_L, Y)$	Q
$F_1 = \begin{pmatrix} F_1^u \\ F_1^d \end{pmatrix}$	$\mathbf{N}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
$F_2 = \begin{pmatrix} F_2^u \\ F_2^d \end{pmatrix}$	$\overline{\mathbf{N}}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
F_3^u	$\mathbf{N}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_3^d	$\mathbf{N}$	$(\mathbf{1}, -1/2)$	$-1/2$
F_4^u	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_4^d	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

EW-preserving mass:

$$\mathcal{L} \supset M_{12}\epsilon_{ij}F_1^i F_2^j - M_{34}^u F_3^u F_4^d + M_{34}^d F_3^d F_4^u + h.c.,$$

EW-breaking mass:

$$\mathcal{L} \supset y_{14}^u \epsilon_{ij} F_1^i H^j F_4^d + y_{14}^d F_1 \cdot H^\dagger F_4^u - y_{23}^d \epsilon_{ij} F_2^i H^j F_3^d - y_{23}^u F_2 \cdot H^\dagger F_3^u + h.c.\,,$$

- SU(4) gauge group with 4 Dirac fermions ($SU(2)_L$ and $SU(2)_R$ doublets)
- Two sources of mass allowed: vector-like and Higgs-Yukawa
- Custodial symmetry is identified as u <—> d exchange symmetry

Mass eigenstates

- Two sources of mass, electroweak breaking and preserving.

$$M \equiv \frac{M_{12}+M_{34}}{2} \qquad \Delta \equiv \left|\frac{M_{12}-M_{34}}{2}\right|, \qquad y_{14} = y+\epsilon_y\,, \quad y_{23} = y-\epsilon_y\,, \quad |\epsilon_y| \ll |y|\,.$$

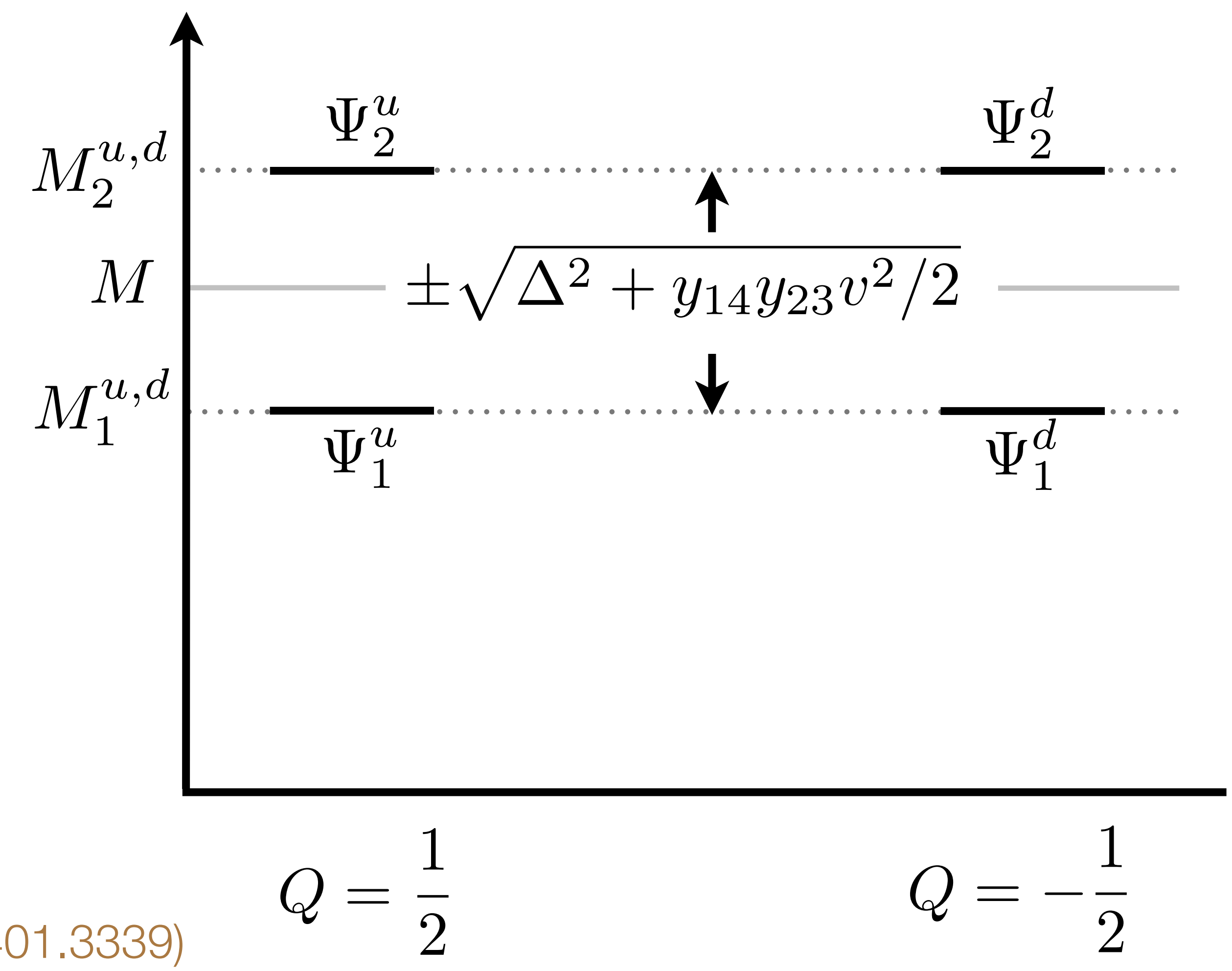
- Assume *yv*<<*M*, to avoid vacuum alignment issues w/EWSB. Then two regimes arise, depending on the origin of the mass splitting:

<u>Linear Case:</u> $yv \gg \Delta$

$$y_\Psi = \frac{y}{\sqrt{2}}$$

<u>Quadratic Case:</u> $yv \ll \Delta$

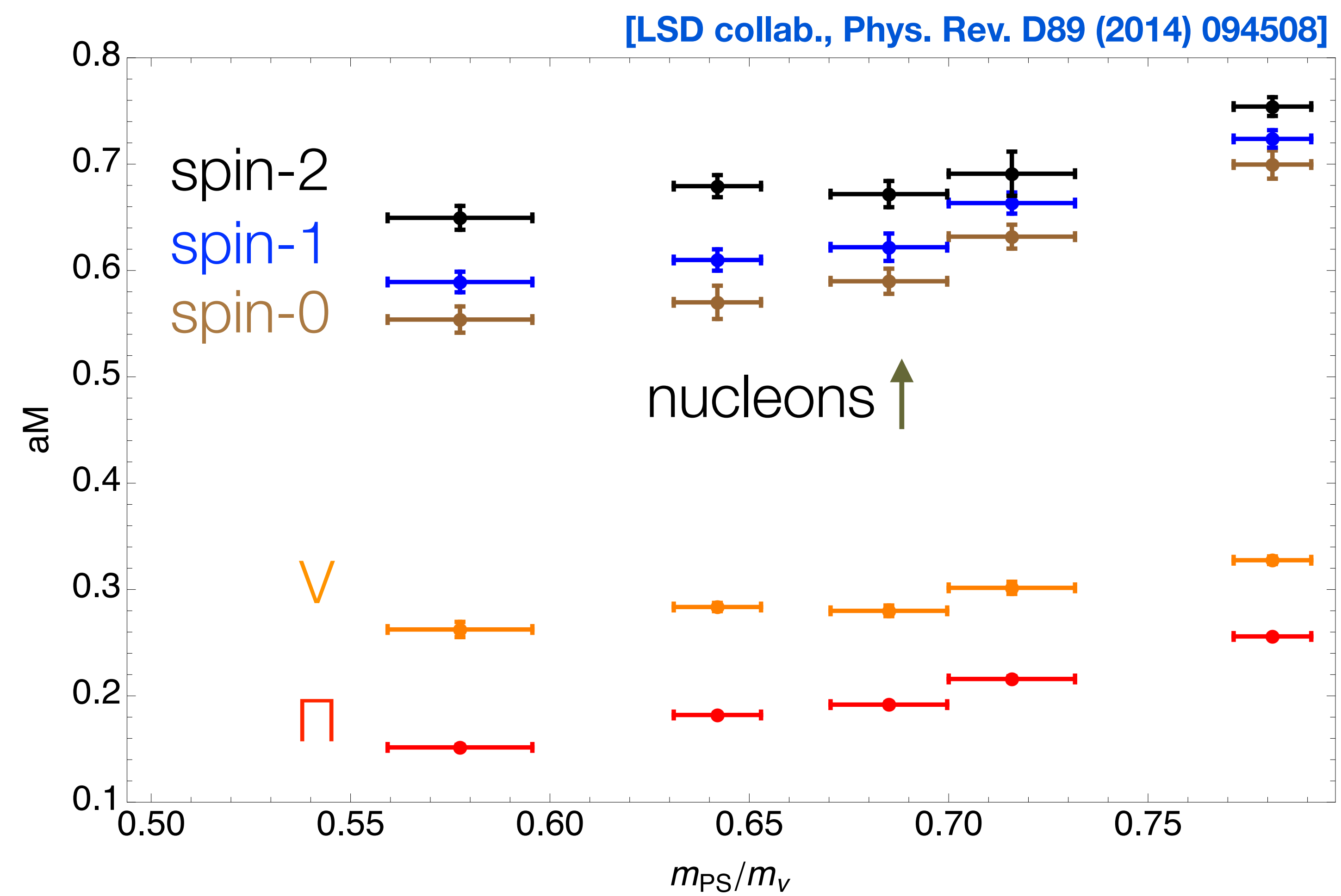
$$y_\Psi = \frac{y^2 v}{2\Delta}$$



(linear/quadratic effect observed before, see Hill and Solon 1401.3339)

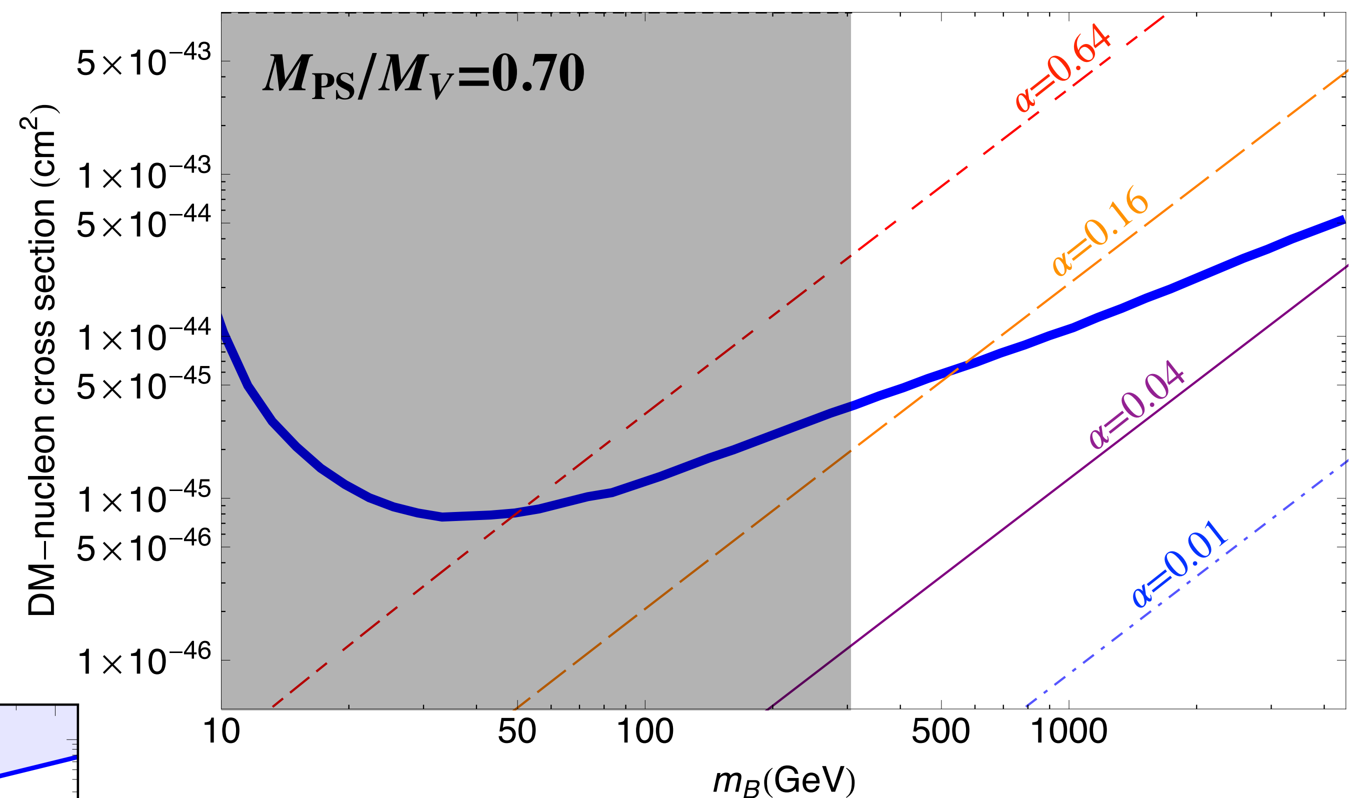
Stealth dark matter on the lattice

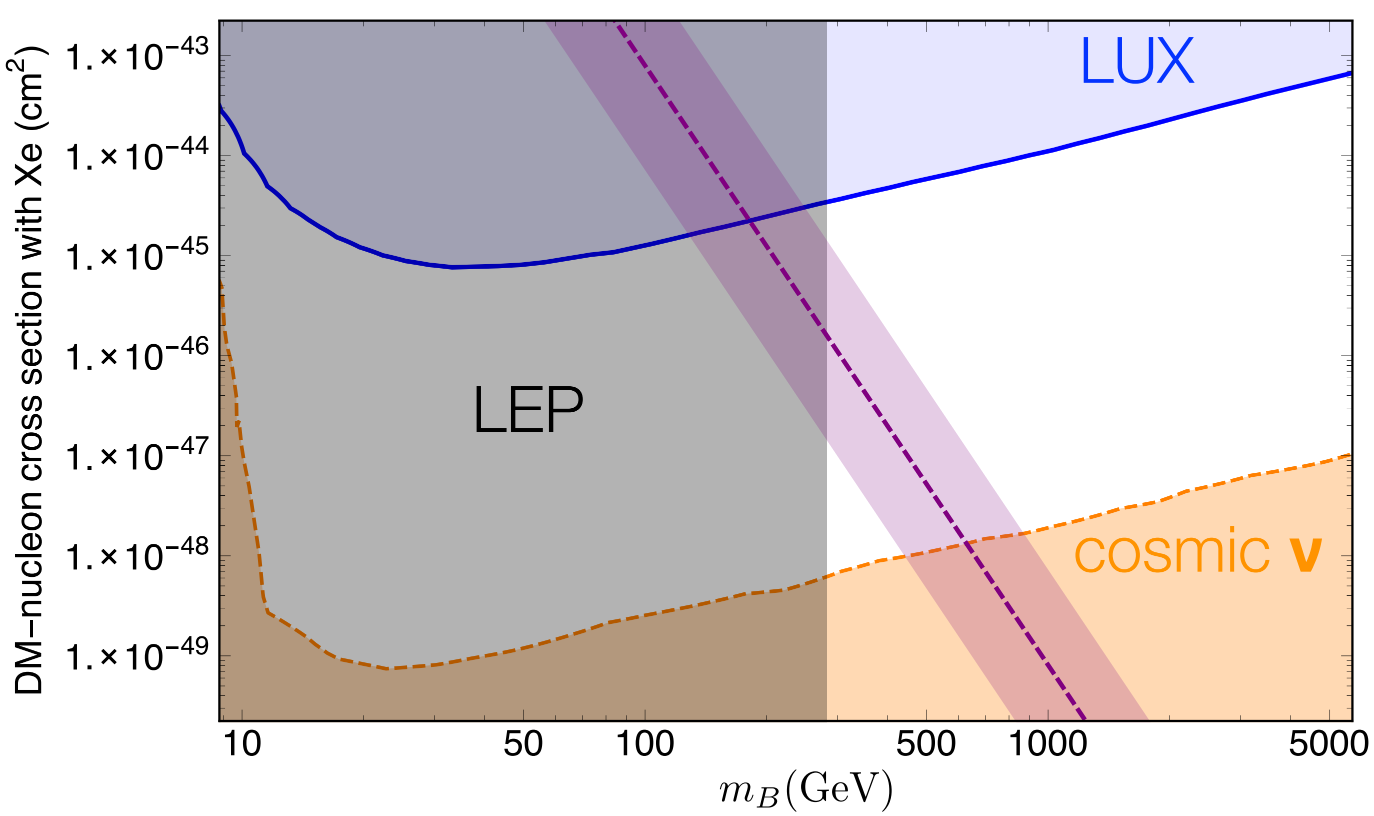
- The model: SU(4) gauge theory at moderately heavy fermion mass
- On the lattice: plaquette gauge action, Wilson fermions *(quenched)*
- Spectrum shown to the right



Stealth dark matter: lattice results so far

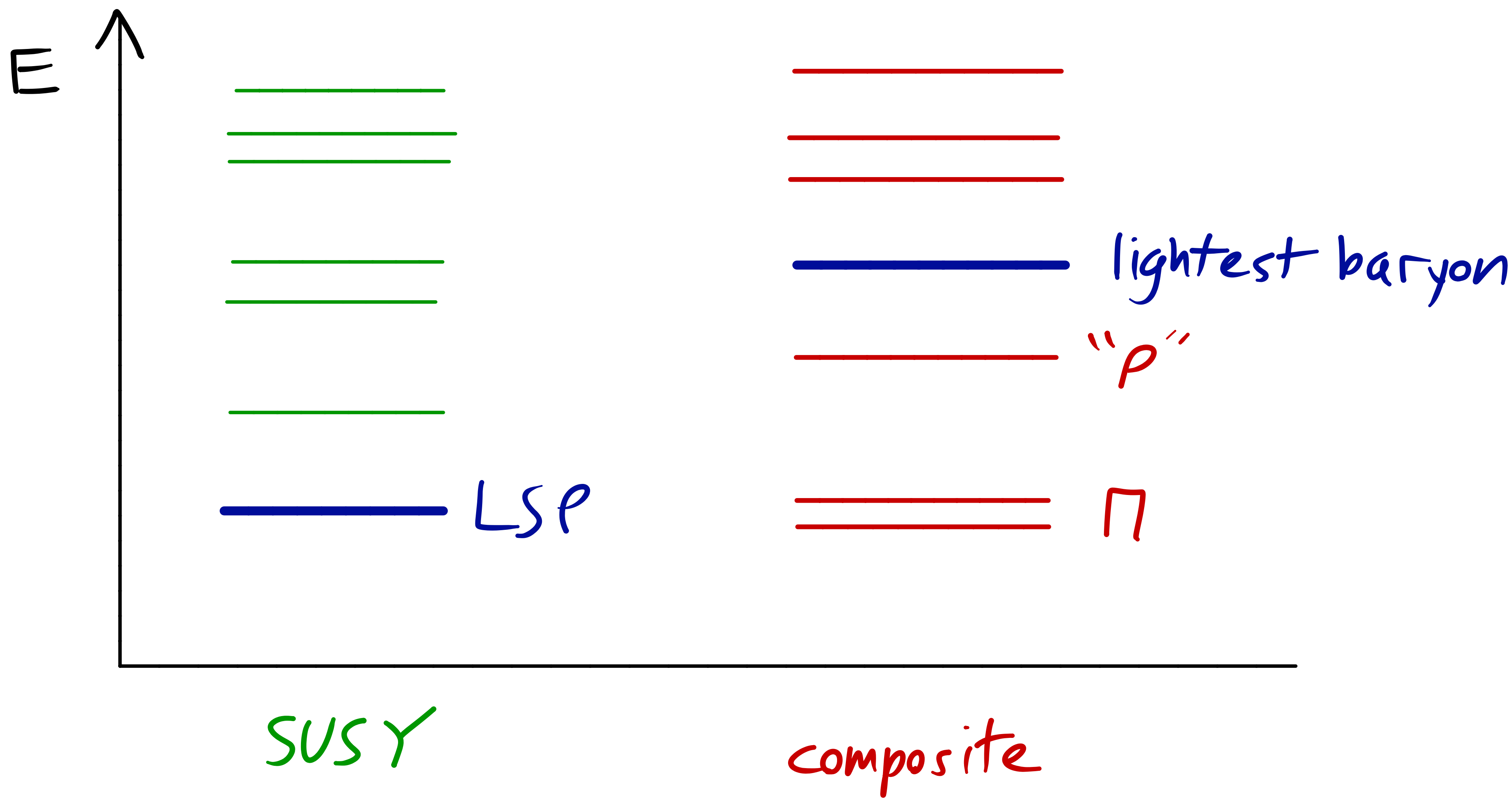
- Spectrum and scalar current calculation: mass generation from Higgs strongly constrained.





- EM polarizability: lower bound on direct detection for theories with charged constituents. Stealth DM visible below a TeV or so.

Comparison between typical SUSY DM and composite DM:

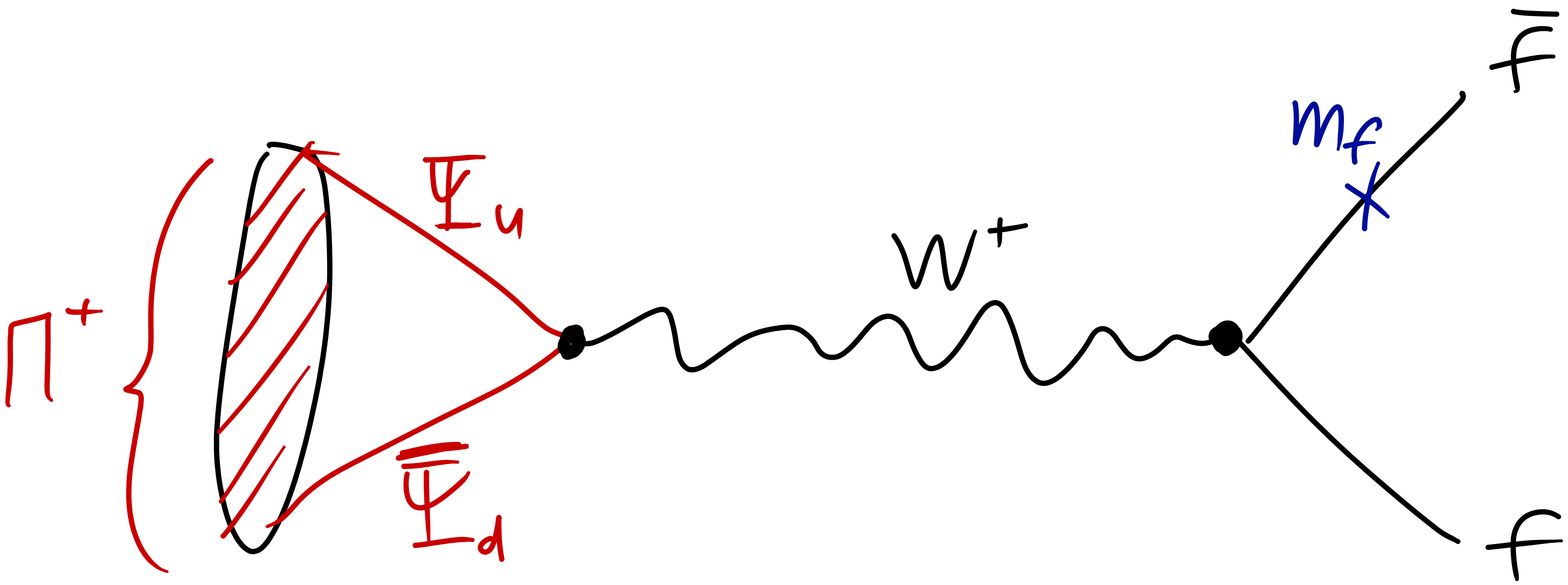


- DM is far from lightest particle in the new sector! Much harder to produce directly in colliders, so MET signals are greatly suppressed.

- On the other hand, presence of the much lighter and charged Π states gives strong bounds from complementary searches.

Meson decay

- Important consequence of electroweak coupling: allow mesons to decay, especially the charged ones!

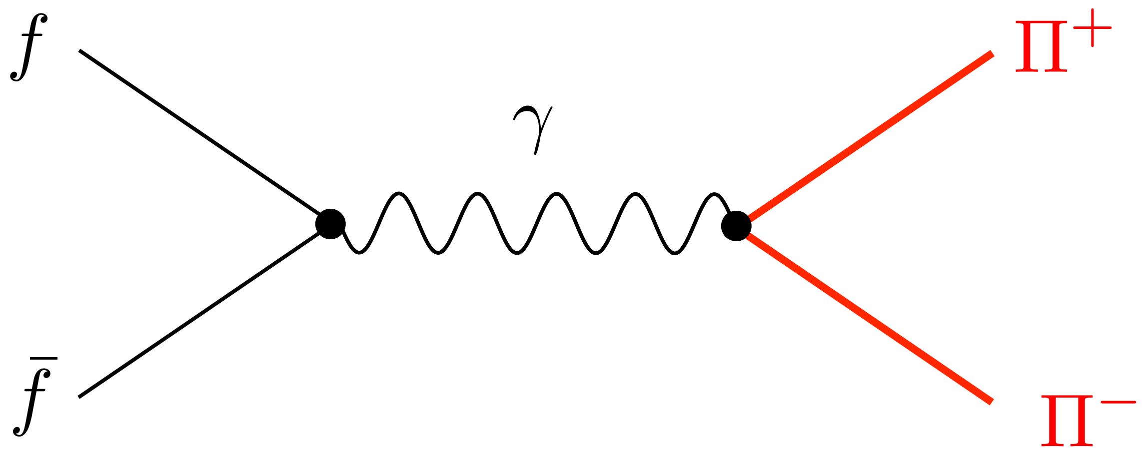


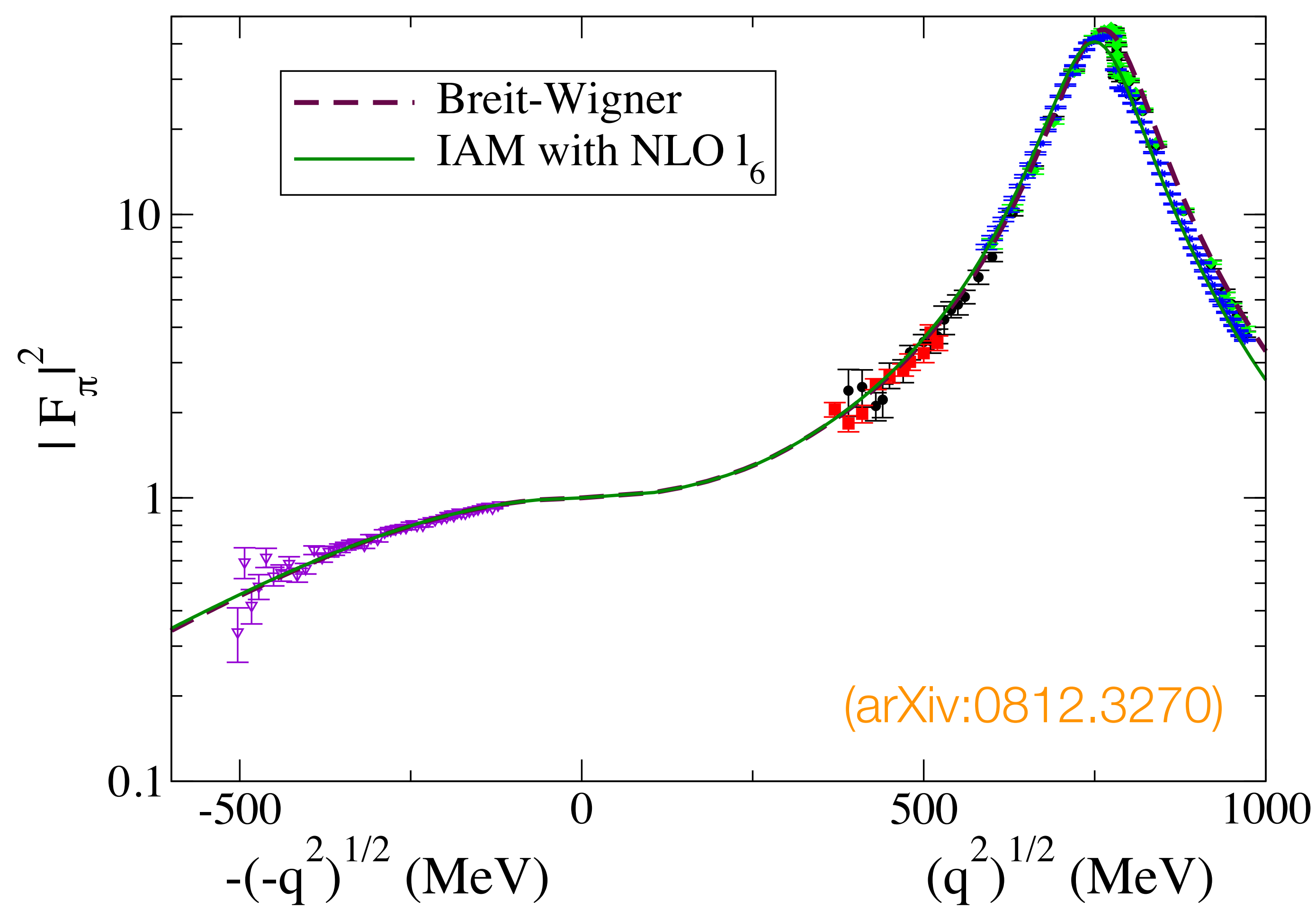
$$\langle 0 | j^\mu_{\text{axial}} | \Pi^\pm \rangle = i f_\Pi p^\mu$$

- Mass flip in final state, due to decay of pseudoscalar bound state (same for QCD pions.) Gives preferred decay to heaviest SM states:

$$\Gamma(\Pi^+ \to f\overline{f}') = \frac{G_F^2}{4\pi} f_\Pi^2 m_f^2 m_\Pi c_{\text{axial}}^2 \left(1 - \frac{m_f^2}{m_\Pi^2}\right)$$

Meson production



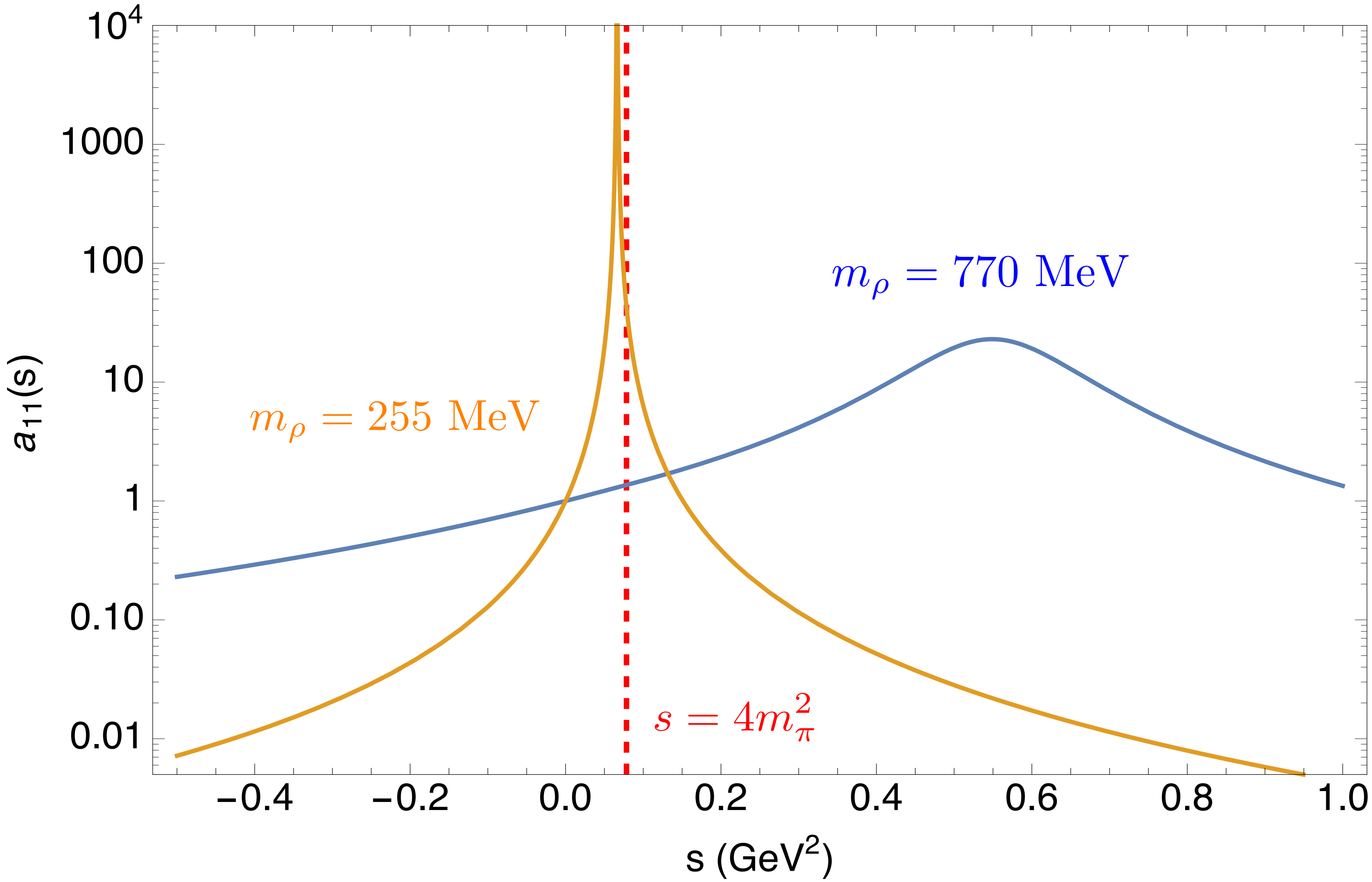


- First signature expected: Drell-Yan photon production of charged Π
- To calculate rate, pion form factor needed at threshold: $F_V(Q^2=4m_\Pi^2)$
- Hard to access at this momentum on lattice. In QCD, "vector meson dominance" does pretty well…

How the picture changes for m_ρ below threshold:

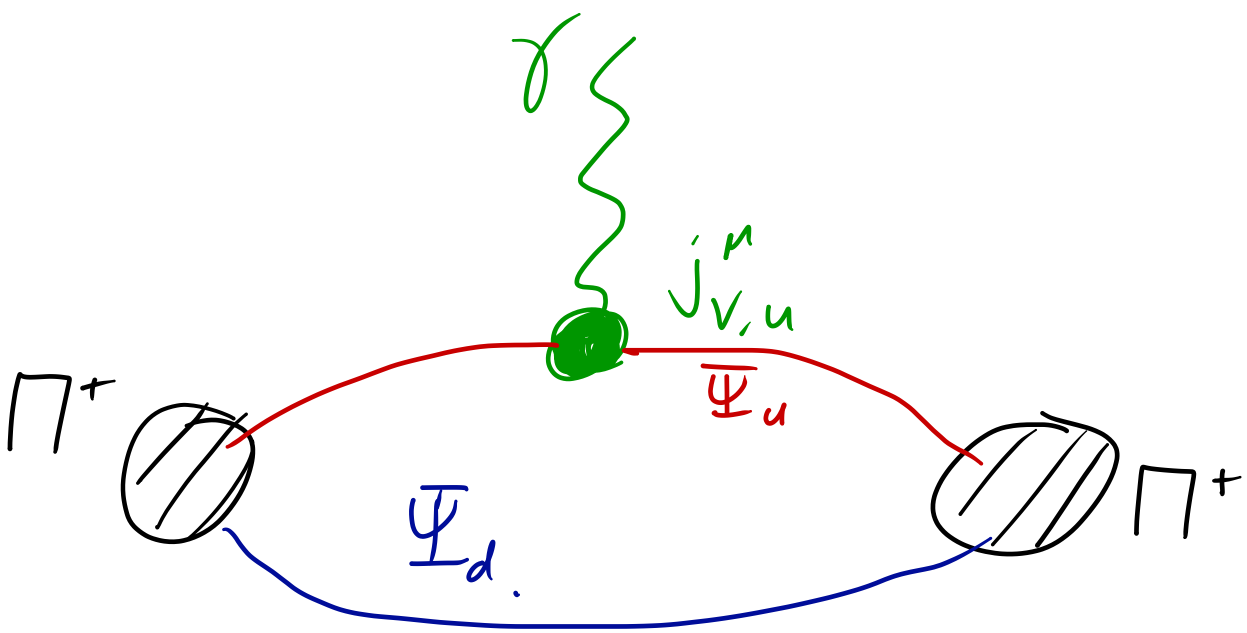
π-π scattering amplitude with m_π=140 MeV, for QCD (m_π/m_ρ~0.18) and for a stealth-DM-like theory (m_π/m_ρ~0.55)

(*note: this is not $F_V(Q^2)$, it's a Breit-Wigner model of I=1 π-π scattering.)



- Here, "rho" resonance is below 2π threshold - but it's also much closer to the threshold. Vector-meson dominance should be reliable, but further study is needed
- The "dark rho" is very narrow, since decay to ππ is closed. Another (TeV-scale) state to look for in colliders!

Our plan



- Determine "stealth ρ" decay constant and calculate decay width
- Measure "stealth π" $F_V(Q^2)$ at space-like momenta from three-point function (pion charge radius)
- Combine with vector-meson dominance model to predict $F_V(4m_\Pi^2)$ for collider production

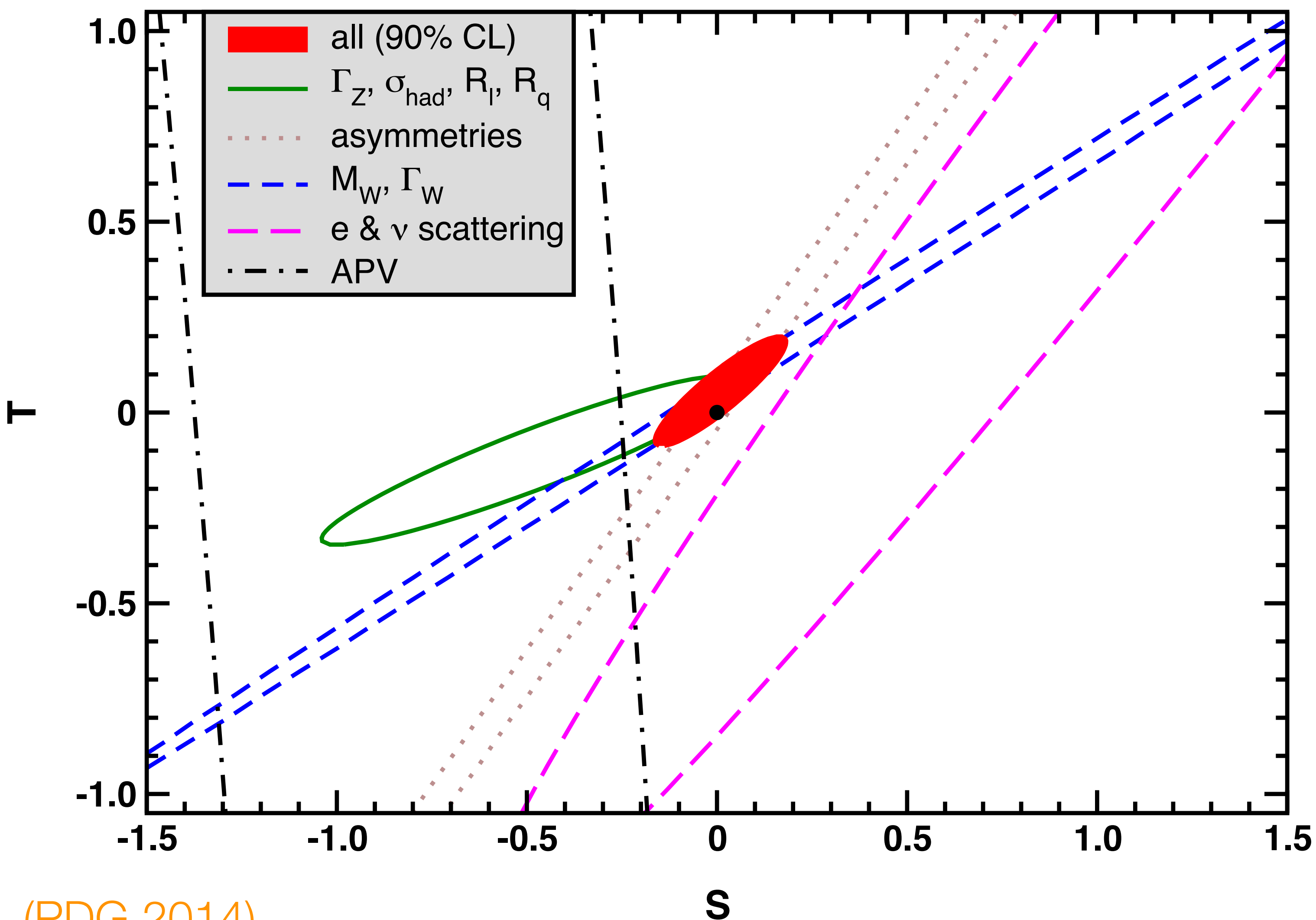
pion charge radius ρ width, mass

$$F_V(Q^2) = \exp\left(\frac{\langle r_\Pi^2 \rangle Q^2}{6} + \frac{Q^4}{\pi} \int_{4m_\Pi^2}^{\infty} ds \, \frac{\delta_{11}(s)}{s^2(s - Q^2 - i\epsilon)} \right)$$

(arXiv:0812.3270)

Electroweak precision

- No T parameter by construction (custodial symm), but S parameter is an important constraint! Two asymptotic forms of S contribution:



(PDG 2014)

$M_2 \gg M_1$

$$\Pi_{3Y}(q^2) = \frac{1}{8}\frac{y^2v^2}{y^2v^2 + 2\Delta^2}\Pi_{VV}(q^2)$$

$M_1 \approx M_2$

$$\Pi_{3Y}(q^2) \approx \frac{\epsilon_y^2 v^2}{4M^2}\Pi_{LR}(q^2)$$

- Calculation of strong-coupling part yields direct bounds on Yukawa couplings (important for asymmetric relic density)

Lattice calculation details

- Form factor: calculate $\langle\pi(t)V_\mu(t')\pi(0)\rangle$ and $\langle\pi(t)\pi(0)\rangle$. Construct appropriate ratio to extract vector-current matrix element.

- Three vector-current insertion locations, four sources per config —> 12 Wilson propagators; 500 (pure-gauge) configurations.

- S-parameter: calculate conserved-local correlators $\langle V_C(x)V_L(0)\rangle$ and $\langle A_C(x)A_L(0)\rangle$. Two source positions, $L_s=8$.

- By-products of DWF calculation: F_π, mass renormalization (m_f/M_B).

Resource request

β	vol	κ	$m_{PS}L$	m_{PS}/m_V	Cost (DWF)	Cost (Wilson)	Total cost
11.028	$32^3 \times 64$	0.1554	11.1	0.76	0.61	0.46	1.07
		0.15625	9.2	0.69	—	0.68	1.58
		0.1568	7.7	0.62	1.28	0.97	2.25
		0.1572	6.6	0.55	—	1.36	3.16
		0.1575	5.9	0.49	2.55	1.93	4.48
11.5	$32^3 \times 64$	0.1523	6.1	0.69	0.90	0.68	1.58
Total					5.34	6.08	11.42

- Three mass points for domain-wall S parameter calculation; we expect mild mass dependence, based on experience

- One point at β=11.5, to test discretization effects (spectroscopy here shows no significant deviations)

- We are working on a new fully threaded/vectorized code base, meant to replace QDP/C; Wilson solver in progress. Up to 2x speed-up in calculations expected, but no benchmarks available yet, and we don’t include this factor above

Backup slides

(nice discussion here: arXiv:1503.08749)

*M. Buckley and EN, arXiv:1209.6054
**Y. Bai and R. Hill, arXiv:1005.0008

Stability of composite dark matter candidates

$$\Pi \sim \bar{\Psi}\Psi \qquad\qquad B \sim \Psi\Psi\ldots\Psi$$

← N_D constituents

- Lightest mesons (Π) can be stabilized by flavor symmetries* or G-parity**, but then one has to argue against the presence of dimension-5 operators like

$$\frac{1}{\Lambda}\bar{\Psi}\Psi H^\dagger H$$

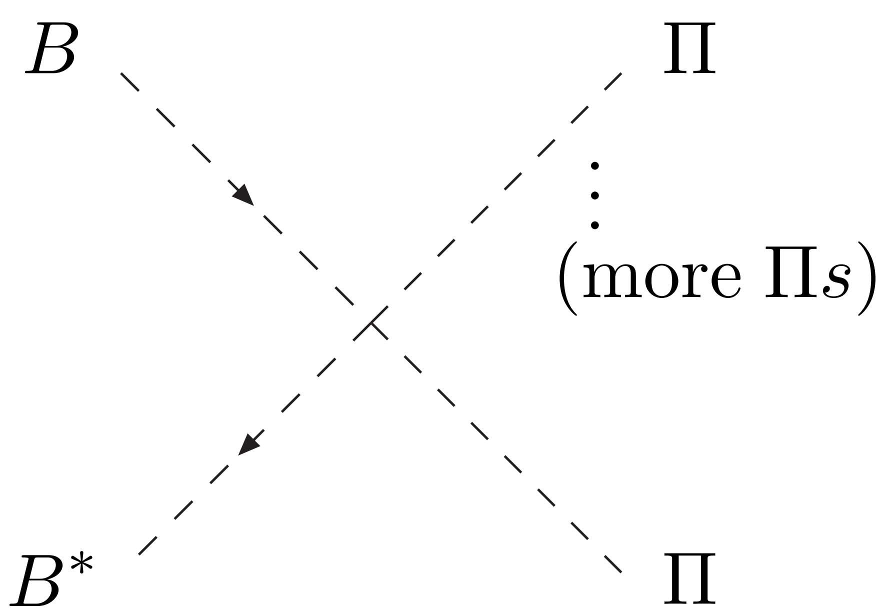
→ instability over lifetime of the universe.

- Accidental dark baryon number symmetry provides automatic stability for B on very long timescales (as long as $N_D > 2$!) E.g. for N_D=4, decay through dimension-8(!)

$$\frac{1}{\Lambda^4}\Psi\Psi\Psi\Psi H^\dagger H$$

Abundance

Symmetric



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

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

Griest, Kamionkowski; 1990

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

Asymmetric

e.g., through EW sphalerons

Chivukula, Farhi, Barr; 1990

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

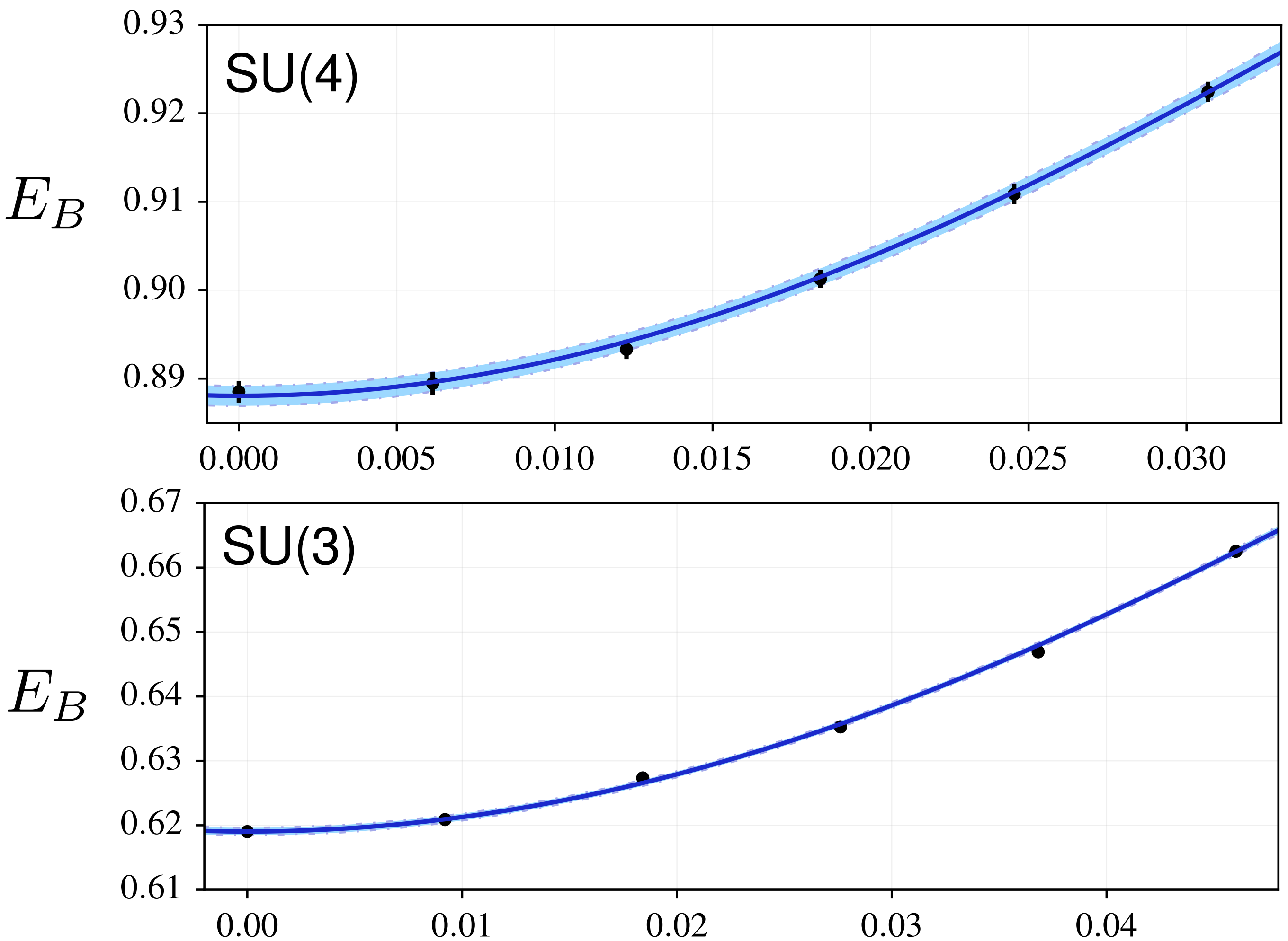
IF EW breaking comparable to EW preserving masses, expect roughly

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

How much less depends on several factors...

(slide from G. Kribs)

Polarizability on the lattice



N_D	m_{PS}/m_V	$\tilde{m}_B$	$\alpha \tilde{C}_F$	$\alpha^2 \tilde{C}'_F$	$\tilde{\mu}_B$	$\tilde{\mu}'_B$	χ^2/dof
4	0.77	0.98204(93)	0.1420(56)	-0.089(29)	—	—	0.7/3
	0.70	0.88805(113)	0.1514(106)	-0.142(68)	—	—	4.8/3
3	0.77	0.69812(51)	0.2829(127)	-0.177(45)	-6.87(26)	714(103)	3.0/7
	0.70	0.61904(59)	0.2829(81)	-0.165(24)	-5.55(18)	396(78)	13.4/7

- Technique pioneered by Detmold, Tiburzi, Walker-Loud (arXiv:1001.1131)
- Measure response to applied background field E (quadratic Stark shift)

$$E_{B,4c} = m_B + 2C_F|\mathcal{E}|^2 + \mathcal{O}\left(\mathcal{E}^4\right)$$

- SU(3) case simulated for comparison; complicated by magnetic moment μ_B

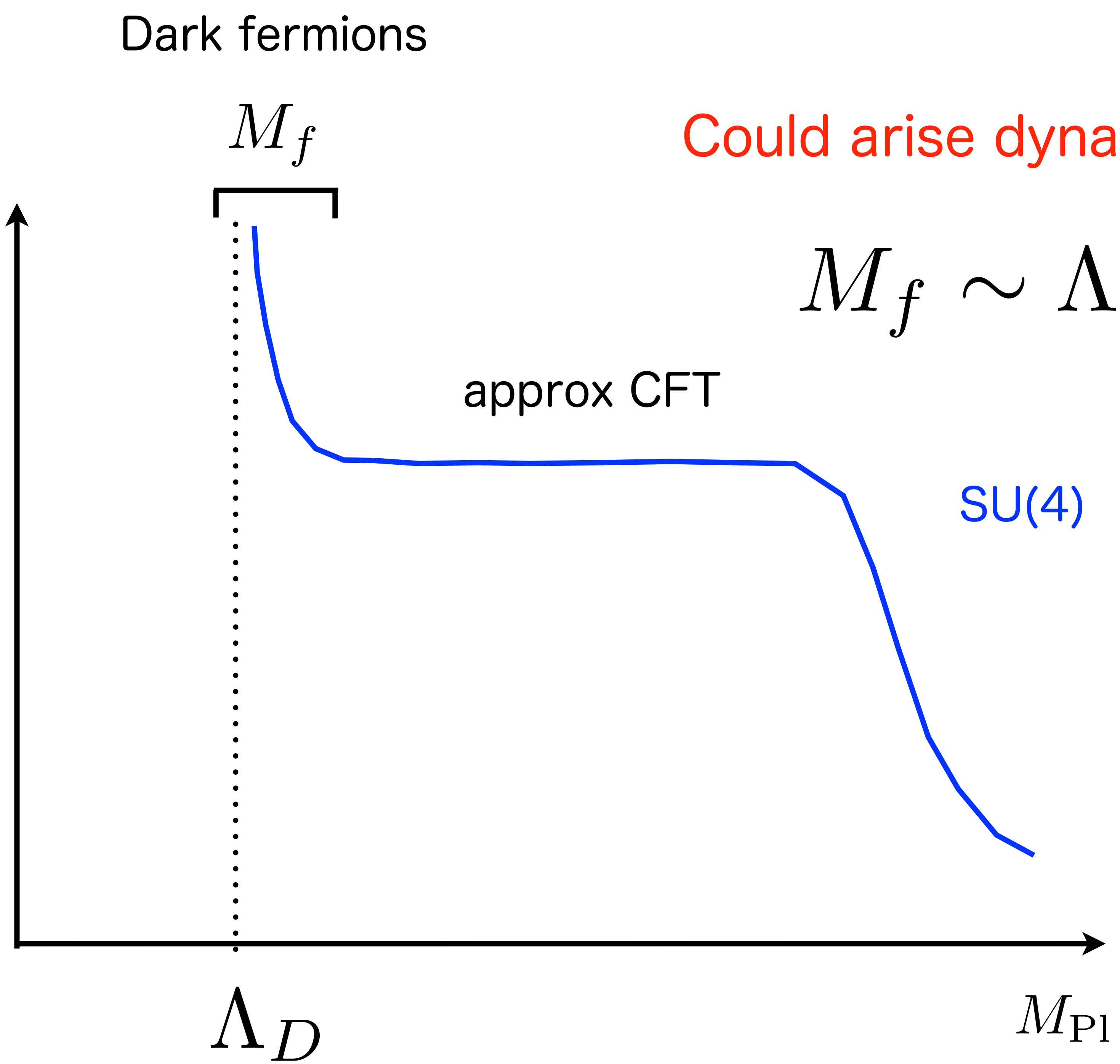
$$E_{B,3c} = m_B + \left(2C_F - \frac{{\mu_B}^2}{8m_B^3}\right)|\mathcal{E}|^2 + \mathcal{O}\left(\mathcal{E}^4\right)$$

- Comparable results for SU(3) and SU(4), in units of m_B.

Mass scales

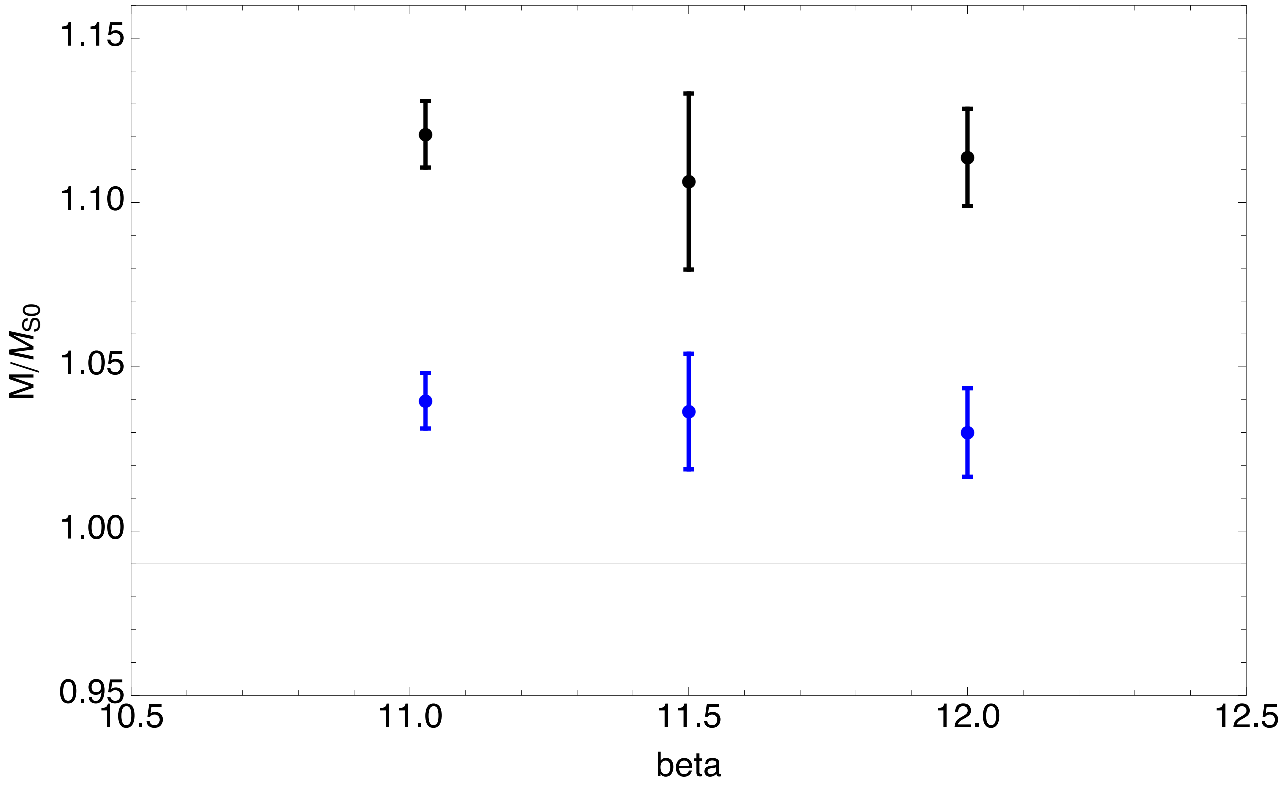
Could arise dynamically

$$M_f \sim \Lambda_D$$



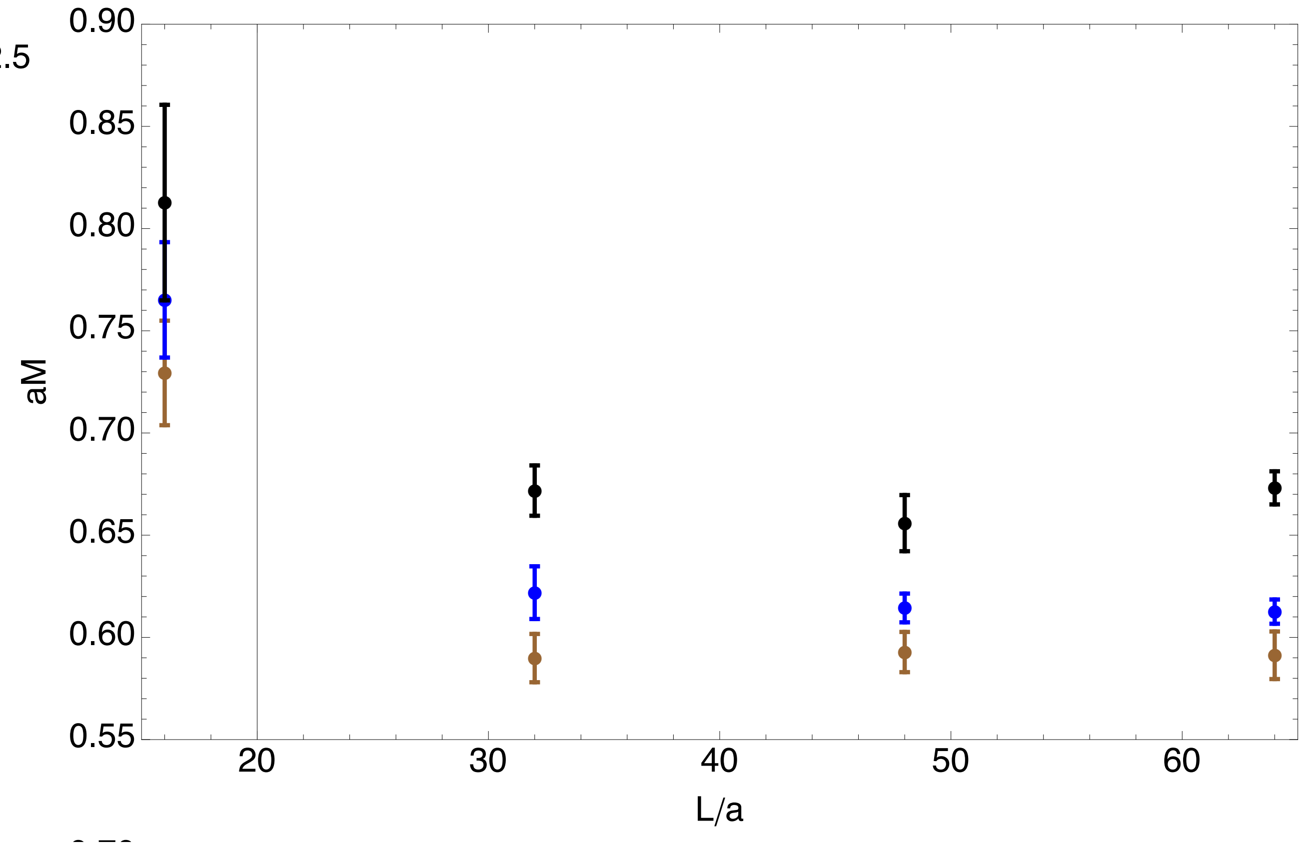
(plot from G. Kribs)

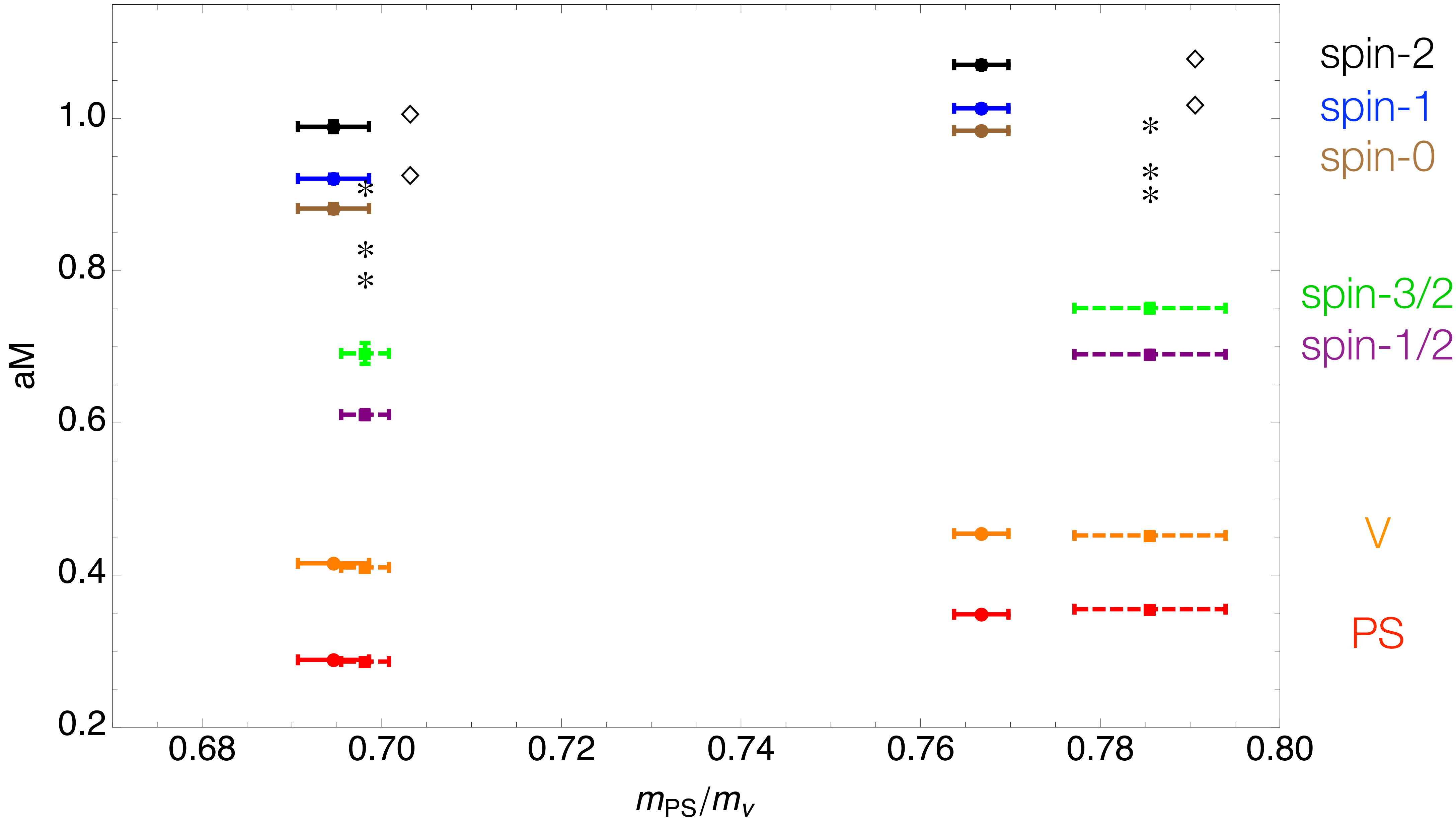
Study of systematic effects



Cutoff effects

Finite-volume effects





$$* : \quad M(N_c, J) = N_c m_0 + \frac{J(J+1)}{N_c} B + \mathcal{O}(1/N_c^2)$$

$$\diamond : \quad M(N_c, J) = N_c m_0^{(0)} + C + \frac{J(J+1)}{N_c} B + \mathcal{O}(1/N_c^2)$$

SU(3) polarizability vs. the PDG

- Our polarizability differs from the PDG convention:

$$\alpha_E = C_F/\pi$$

- Have to compare at very different masses! Expected scaling is

$$\alpha_E \sim \frac{A}{m_\pi} + B$$

$$m_B \sim C + D m_\pi^2$$

- Qualitative agreement with expected trend! (Can't fit well - mass range too large.)