Light hadrophilic scalars

Ahmed Ismail

University of Pittsburgh

Light Dark World 2018
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based on 1712.10022, 1812.15103 with B. Batell, A. Freitas and D. McKeen

Motivation: dark sector mediators

Evade lower bound on WIMP DM with light mediators

Fully renormalizable portals:

- vector

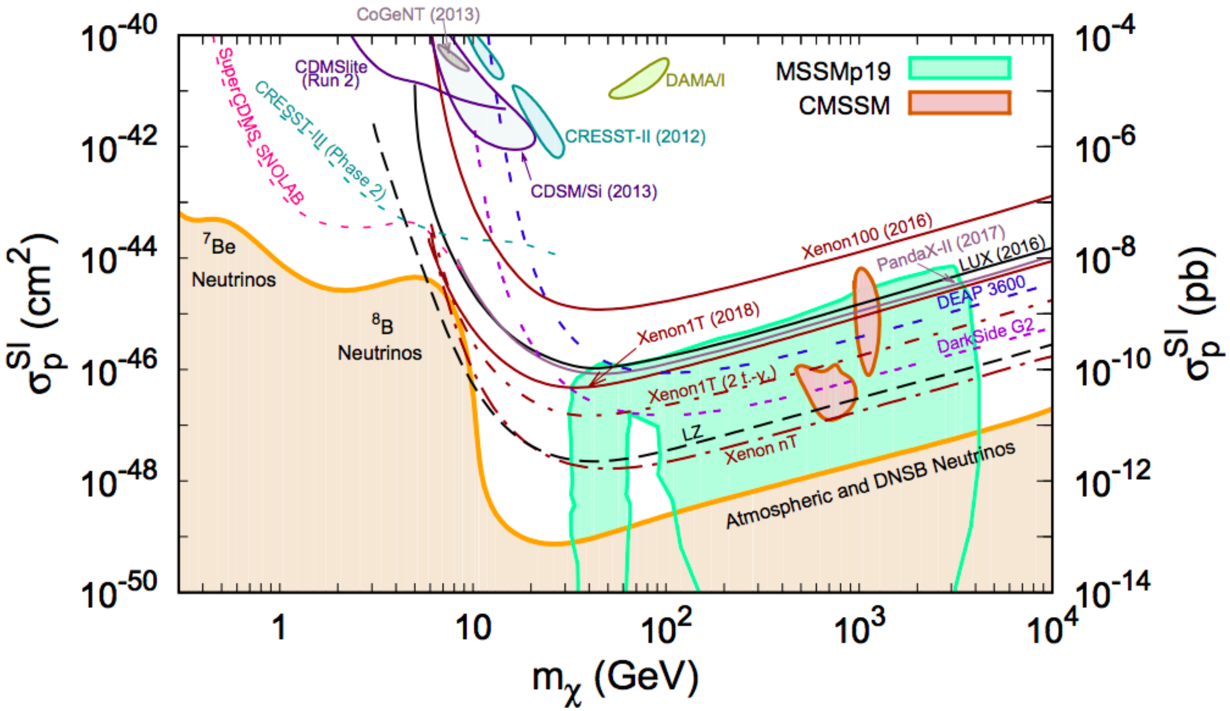
$$F_{\mu\nu}F'^{\mu\nu}$$

- scalar

$$|S|^2|H|^2$$

- fermion

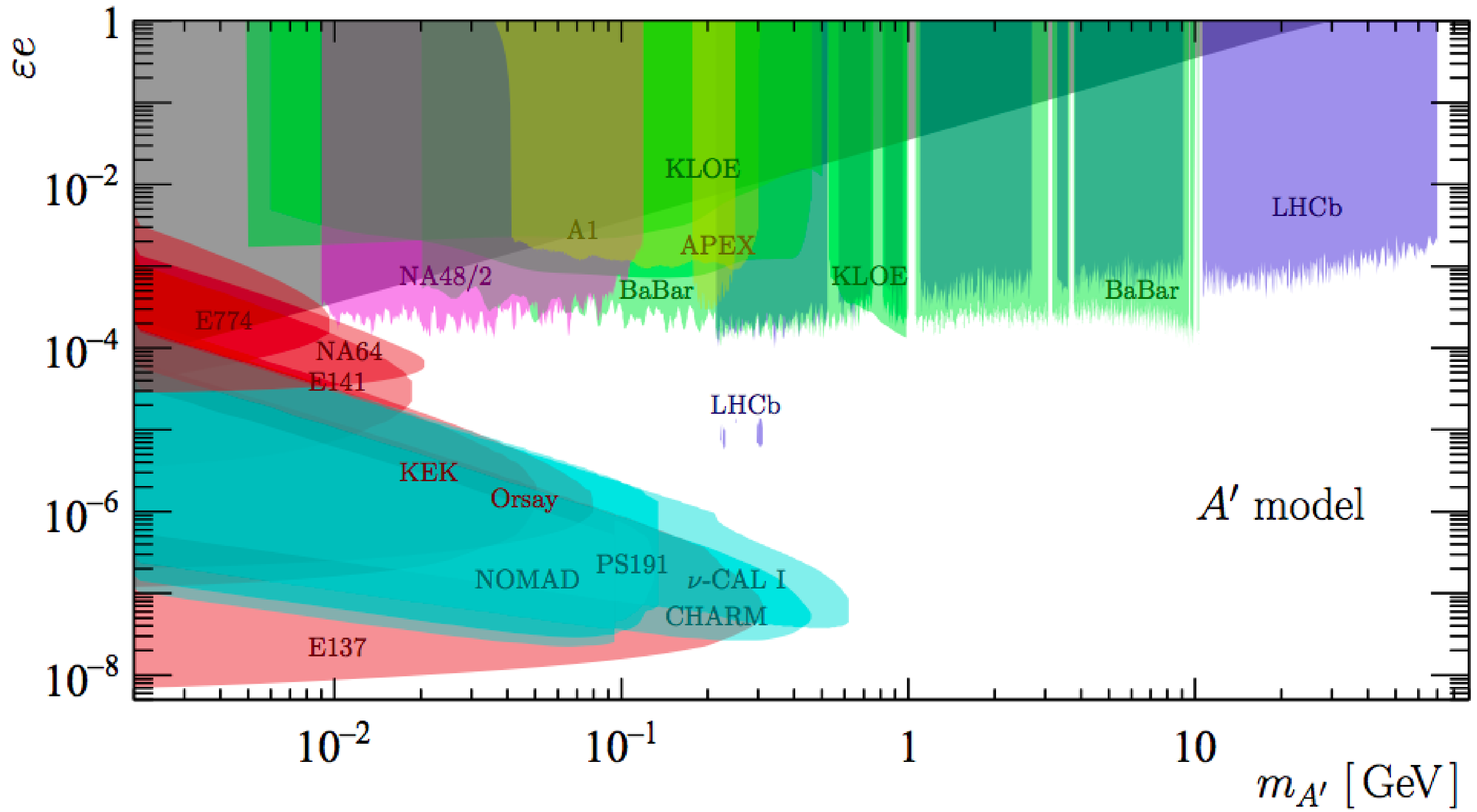
$$\bar{L}HN$$



Still lots of room for light DM

Example: dark photon

Assuming dark photon decays visibly $\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$



Quark and lepton couplings linked

Ilten et al., 1801.04847

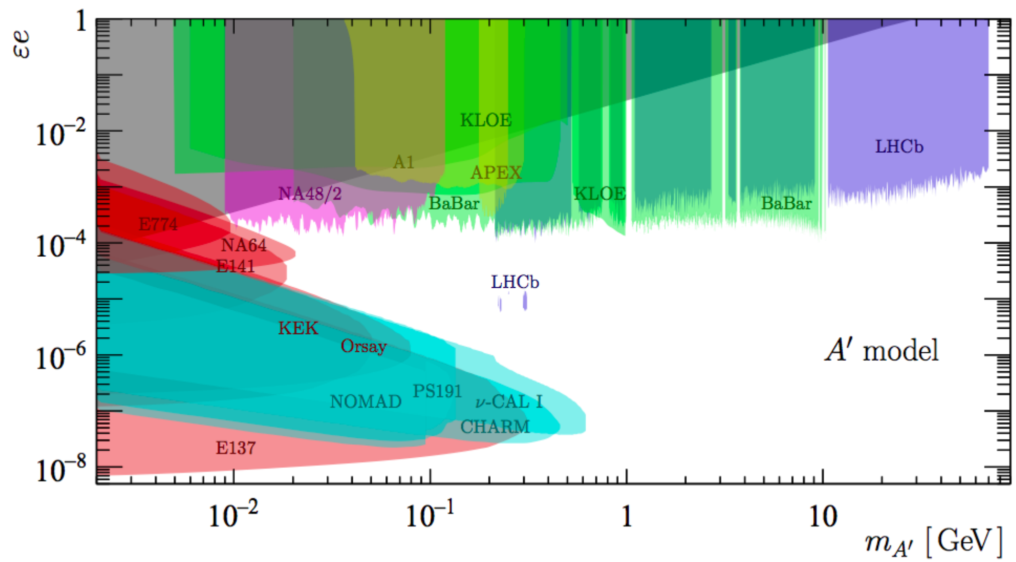
Going beyond fermion universality

Model dependence, e.g. for a kinetically mixed dark photon, all fermions couple proportionally to their charge

How to change?

Can gauge B – L or inter-generational symmetries instead of having simple kinetic mixing

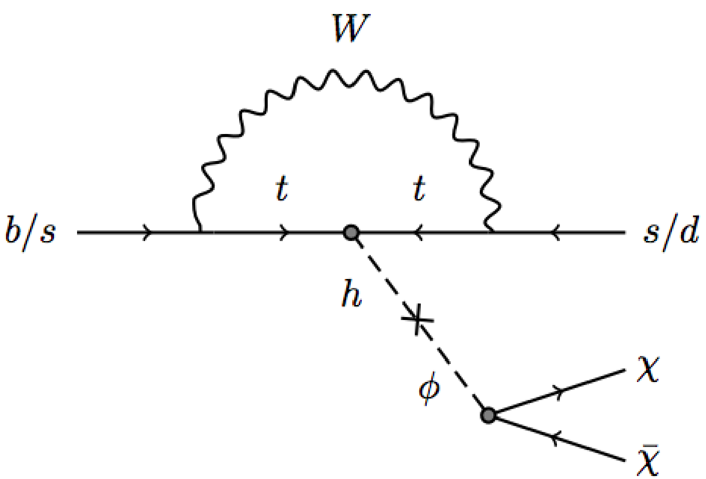
Other options possible but require more particles for anomalies

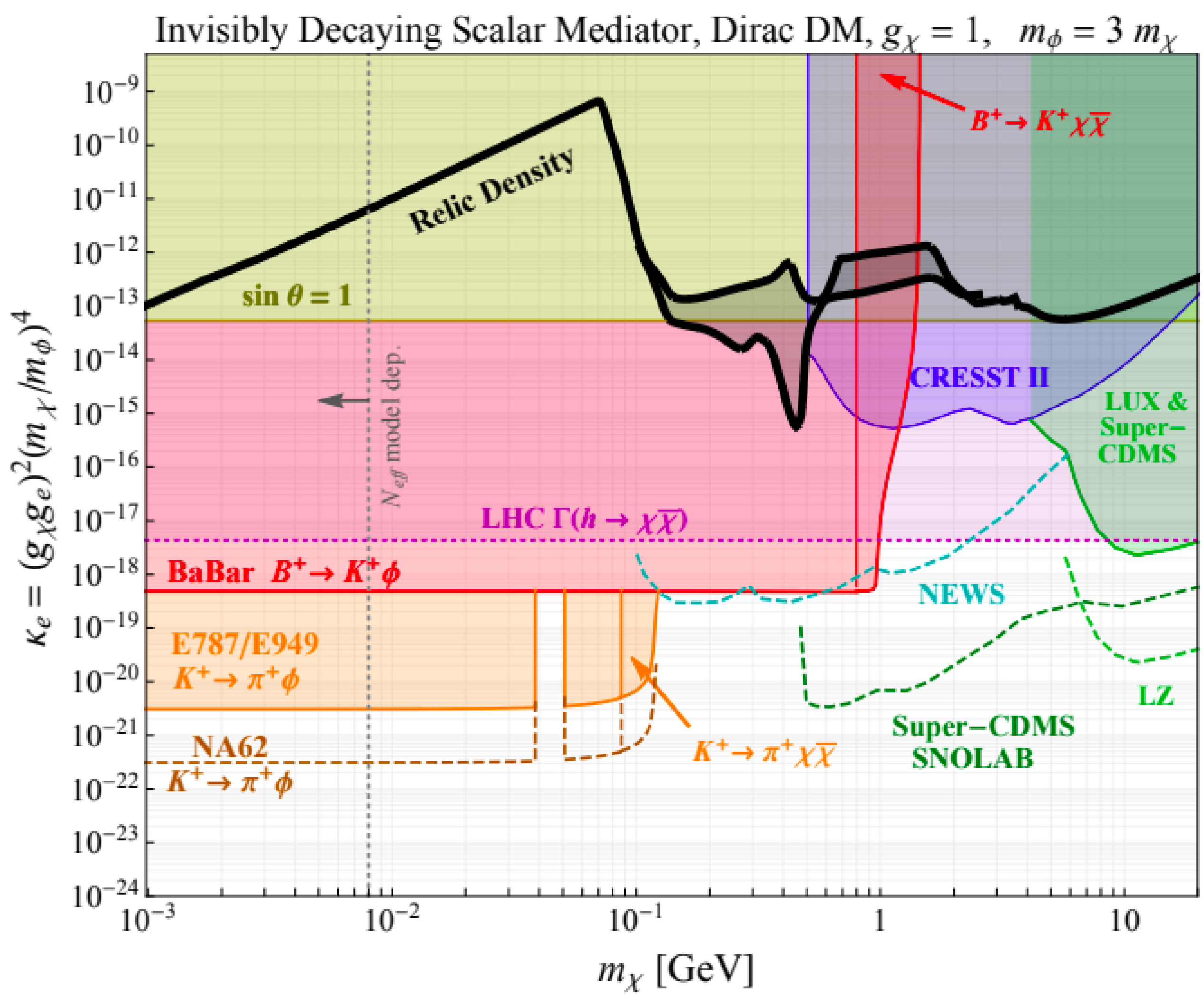


Going beyond fermion universality

Same question arises for other portals

Krnjaic, 1512.04119



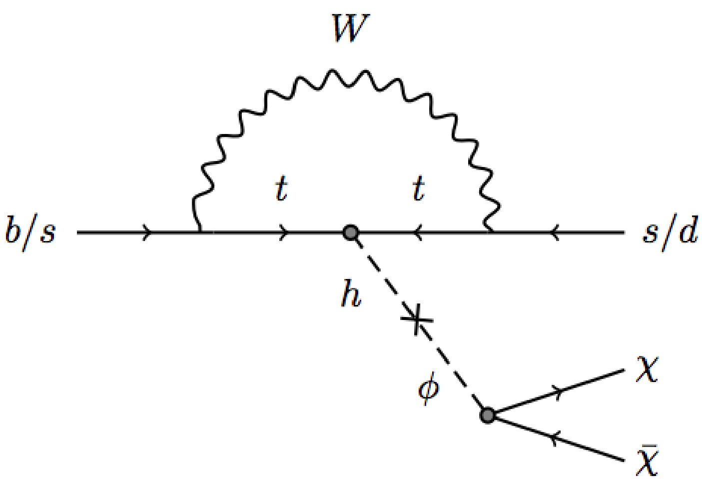


Rare meson decays very constraining

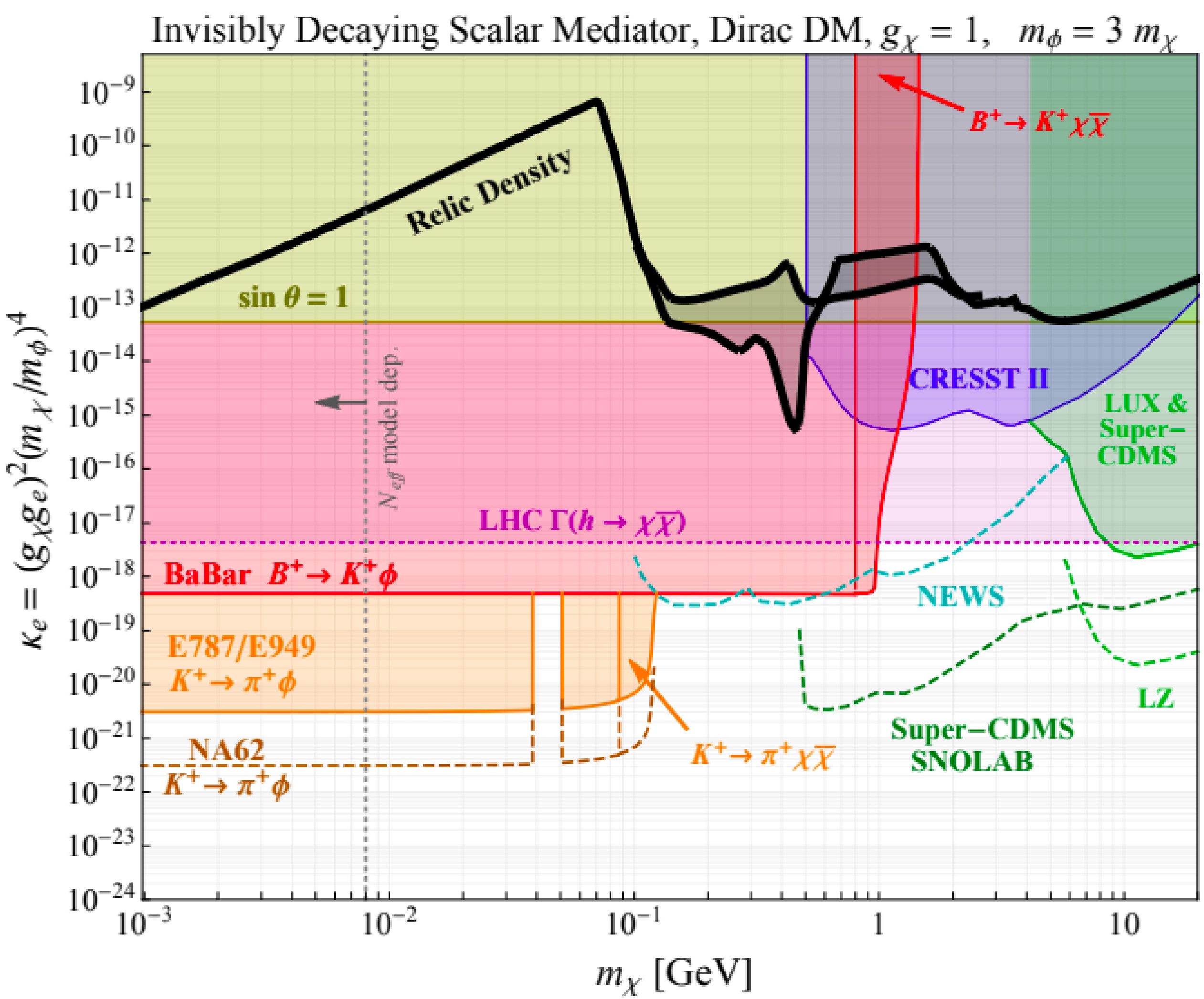
Going beyond fermion universality

Same question arises for other portals

Krnjaic, 1512.04119



What if scalar mediator had no effective coupling to top quarks?



Adding a new flavored scalar

Goal: dark scalar coupling to one fermion preferentially (today – up quark)

Renormalizable operator forbidden for SM singlet

$$\frac{c_S}{M} S\bar{Q}H_c U \qquad\qquad \frac{d_S}{M}\partial_\mu S\bar{U}\gamma^\mu U$$

Can change these into each other with field redefinitions

$$U \to U(1 - i d_S)/M$$

Induces non-derivative operator with strength proportional to Yukawa

Flavor symmetries

Consider non-derivative operator $\frac{c_S}{M} S\bar{Q}H_c U$

Coefficient is matrix in flavor space, generically leads to flavor-changing neutral currents

Recall: SM without Yukawas has flavor symmetry

$$U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$$

Minimal flavor violation hypothesis: Yukawas are only source of flavor symmetry breaking $\to c_S \sim Y_u$

Beyond Minimal Flavor Violation

MFV = new physics preserves $U(3)^3$ of quark sector

Next-to-minimal flavor violation = new physics couples only to third generation, respecting $U(2)^3$

Agashe, Papucci, Perez, Pirjol hep-ph/0509117

Meson mixing is proportional to misalignment between interaction basis of new physics and Yukawas

Generalize: a coupling to a single quark preserves $U(2)^2 \times U(3)$ see also General MFV, Kagan et al. 0903.1794

Spurion analysis

Take flavor and shift, parity symmetries associated with the scalar *S*

Estimate sizes of all operators in EFT in terms of leading couplings

$$\frac{c_S}{M} S\bar{Q}H_c U \qquad\qquad m_S^2 S^2$$

- Flavor changing operators
- Scalar potential

Flavor for up-philic scalar

Orientation of single up-type quark interacting with scalar in mass eigenbasis determines FCNCs

- e.g. *S* coupling to O(1) mixture of *u* and *c* mass eigenstates faces stringent *D* meson bounds

$$(c_S)_{12}/M \lesssim (10^8\ \mathrm{GeV})^{-1}$$

→ *Assume* that chiral symmetry broken by *S* interactions = symmetry broken by up quark mass

$$c_S \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

quark mass eigenbasis

$$U(3)^2 \to U(2)_Q \times U(2)_U \times U(1)_{u+q^1}$$

Flavor for up-philic scalar

All flavor violation now goes as Y_d with appropriate CKM elements; in basis with diagonal up Yukawas,

$$Y_d = V_{\rm CKM} Y_d^D$$

In up sector, have flavor-violating correction

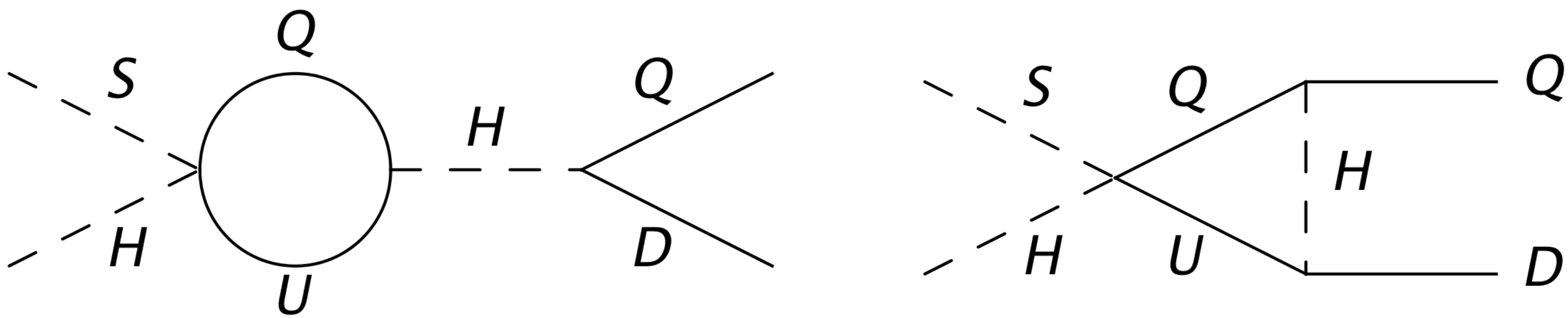
$$\frac{1}{M}\left(V_{\rm CKM} Y_d^D (Y_d^D)^\dagger V_{\rm CKM} c_S^\dagger\right) S\bar{Q} H_c U$$

Small down-type Yukawas, off-diagonal CKM elements yield negligible D mixing

$$c_S/M \lesssim (1\ \mathrm{GeV})^{-1}$$

Flavor for up-philic scalar

Down-type scalar couplings induced at loop level



Both flavor-conserving and flavor-violating couplings go as $Y_u\ Y_d\ c_S$ and are loop suppressed

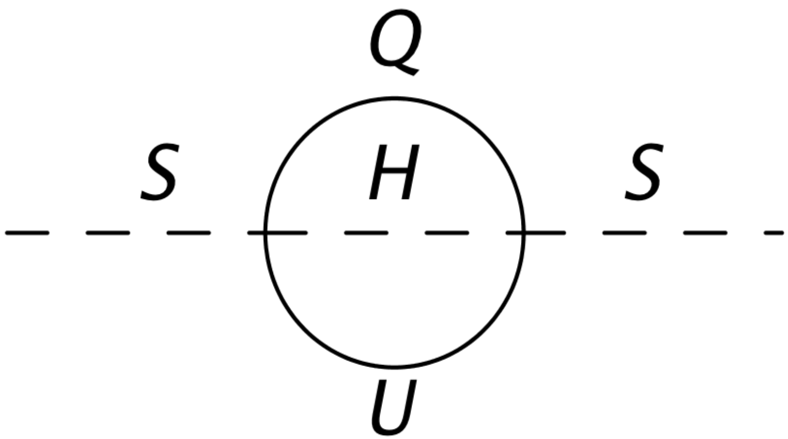
$$\frac{1}{M}\left(V_{\mathrm{CKM}}^{\dagger} c_S (Y_u^D)^{\dagger} V_{\mathrm{CKM}} Y_d^D\right) S\bar{Q}HD$$

Tend to be less important for up-philic case

Other induced couplings – scalar potential

New scalar suffers from usual hierarchy problem

Assume new physics regulates divergence at scale *M*



$$\delta m_S^2 \lesssim m_S^2$$

$$\begin{aligned} c_S &\lesssim (16\pi^2)\frac{m_S}{M} \\ &\approx (3 \times 10^{-3})\left(\frac{m_S}{0.1\ \mathrm{GeV}}\right)\left(\frac{5\ \mathrm{TeV}}{M}\right) \end{aligned}$$

Summary – building a scalar theory

Can build theories with new scalars that preferentially couple to a single fermion without huge FCNC

Initial alignment of couplings is required, but then well preserved up to small Yukawas due to MFV-inspired symmetry principle

Effective theory is eventually resolved, with different UV completions possible

Imposing naturalness implies small coupling size

Searching for an up-philic scalar

Take *S* to be the mediator between us and some DM χ

$$\frac{c_S}{M} S\bar{Q}H_c U \qquad\qquad g_\chi S\bar{\chi}\chi$$

Effective coupling of *S* to up quarks $\quad g_u = \frac{c_S v}{\sqrt{2}M}$

Assume sizable DM coupling → BR(*S* → $\chi\,\chi$) = 0 or 1

$m_\chi < m_S / 2$: *S* decays invisibly

$m_\chi > m_S / 2$: *S* can only decay to SM particles

Visible decays of the scalar

$m_S < 2\ m_\pi$: *S* decays to photons, can be long-lived

S above pion threshold but below QCD scale: use scalar form factors extracted from scattering data

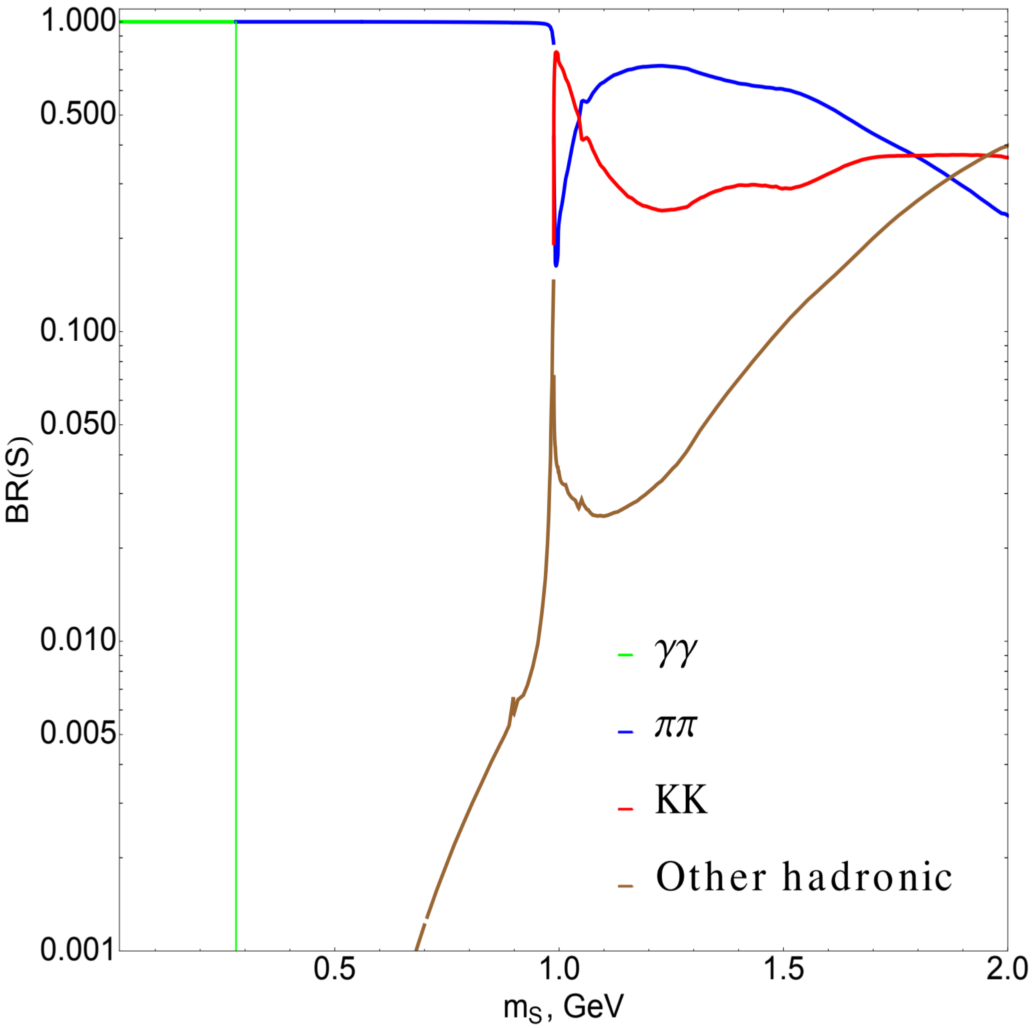
$$g_{S\pi\pi} = \frac{g_u}{m_u}\Gamma_\pi$$

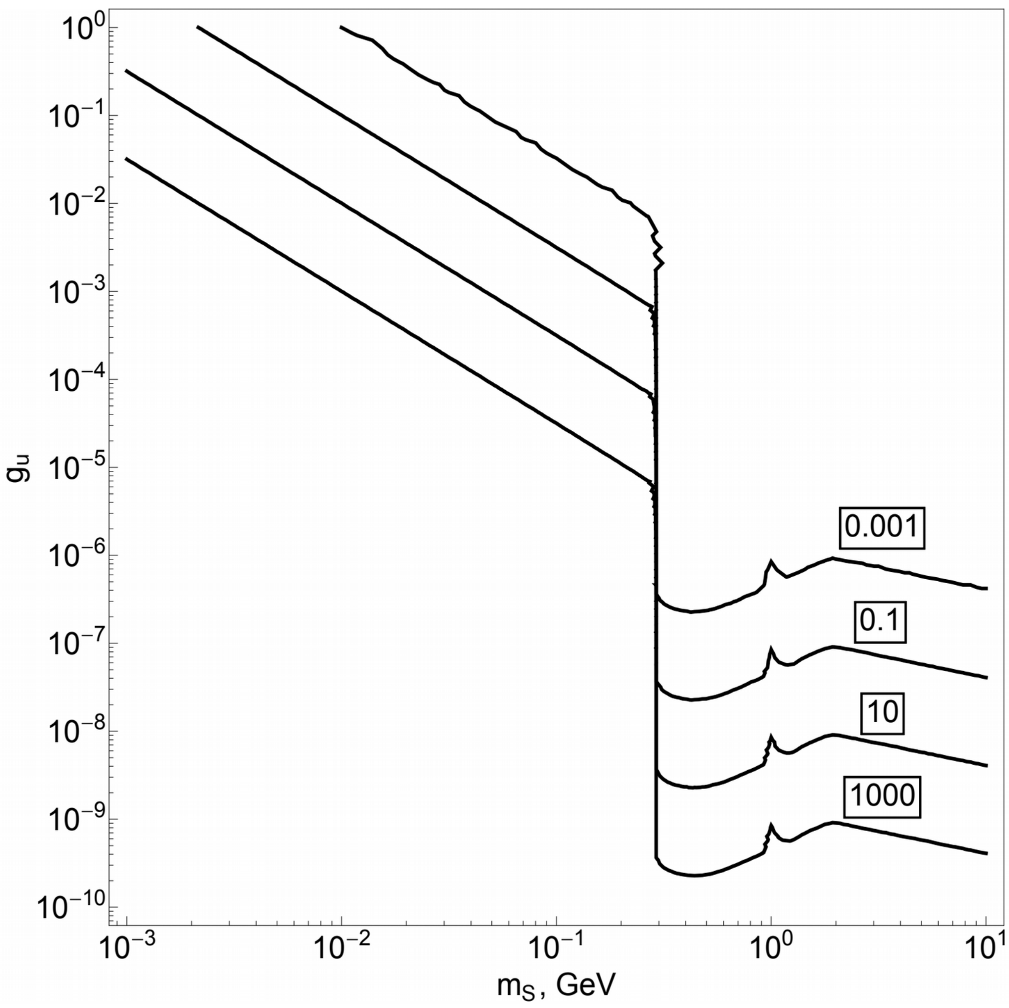
$$\Gamma_\pi((p+p')^2) = \langle \pi(p)\pi(p')|m_u\bar{u}u + m_d\bar{d}d|0\rangle$$

$$\Omega_\pi((p+p')^2) = \langle \pi(p)\pi(p')|m_u\bar{u}u - m_d\bar{d}d|0\rangle \approx 0$$

$m_S >$ few GeV: parton level calculation

Visible decays of the scalar





DM annihilation

Annihilation to SM particles

$$\sigma v(\bar{\chi}\chi \to \mathrm{SM\ SM}) = \frac{9 g_\chi^2 m_\chi^2 v^2 \Gamma_S \Big|_{m_S = 2m_\chi}}{8(m_S^2 - 4m_\chi^2)^2}$$

m_χ > ~GeV: annihilate to free quarks

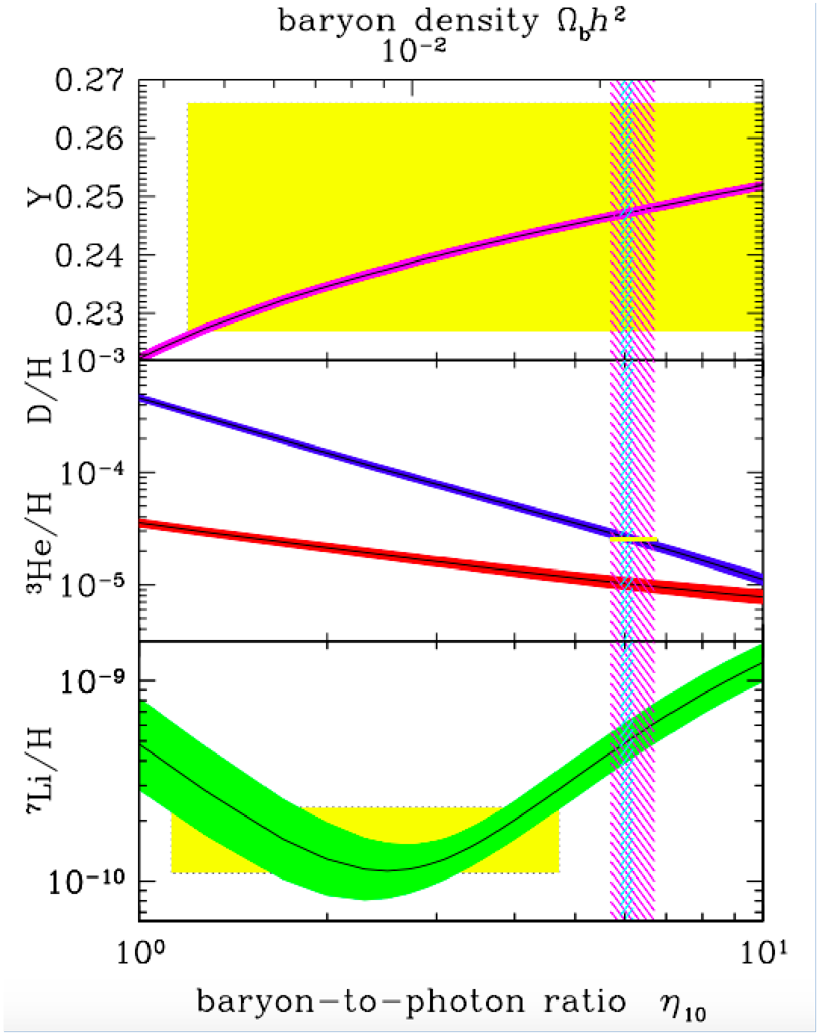
Form factor implicitly used for sub-GeV annihilation

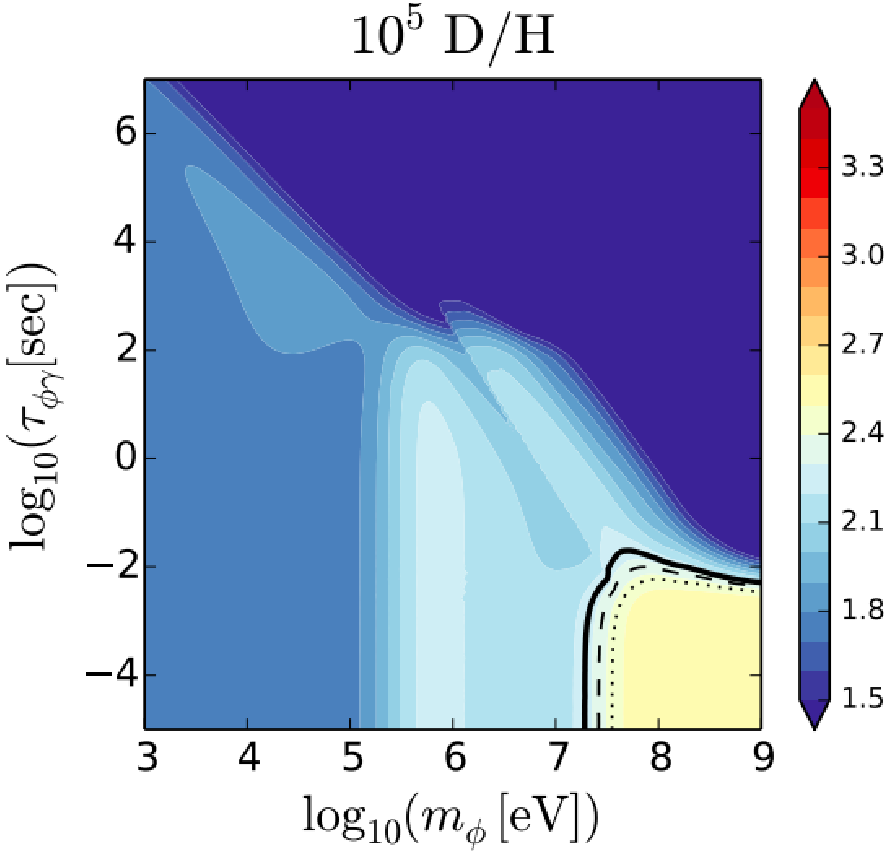
p-wave, avoiding CMB constraints

$m_\chi > m_S$: secluded annihilation, $\chi\chi \to S\,S$

Big Bang Nucleosynthesis

If light enough, *S* decays increase effective baryon/photon ratio at start of BBN





Millea, Knox, Fields 1501.04097

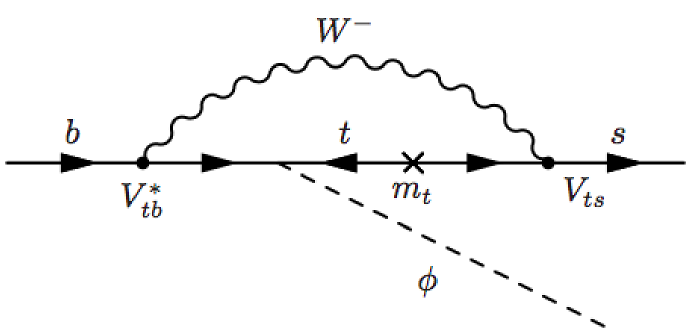
Meson decays to scalars

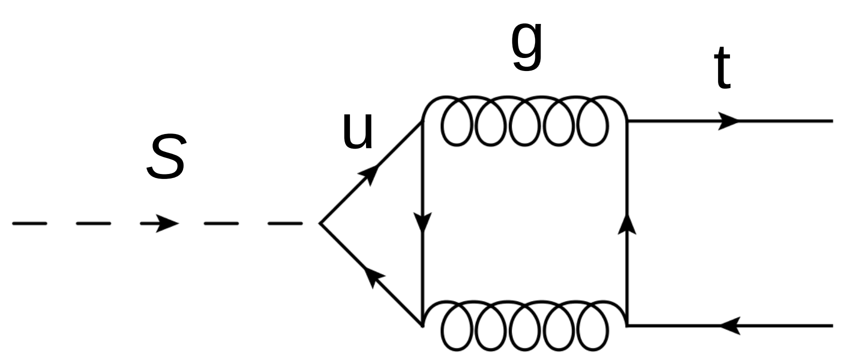
M $\rightarrow$ M' + photons, when *S* $\rightarrow \gamma\,\gamma$

M $\rightarrow$ M' + 2π, above pion threshold

Mesons M, M' are B, K, η, π

Unlike dark Higgs, top coupling only arises from loops





Much weaker limits from B $\rightarrow$ K + *S*

Scalar production from eta decays

Estimate $\eta \rightarrow \pi\, S$ from chiral QCD

$$\mathcal{L} \supset \frac{f^2}{4}\mathrm{tr}[(D_\mu\Sigma)^\dagger D^\mu\Sigma] + \frac{f^2}{4}\mathrm{tr}\left[\Sigma^\dagger\chi + \chi^\dagger\Sigma\right]$$

$$\Sigma = e^{2i\pi/f} \qquad\qquad \chi = 2B\begin{pmatrix} m_u + g_u\, S & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

$$B \approx 2.6\ \mathrm{GeV}$$

S-meson-meson couplings are all of order $g_u\, B$

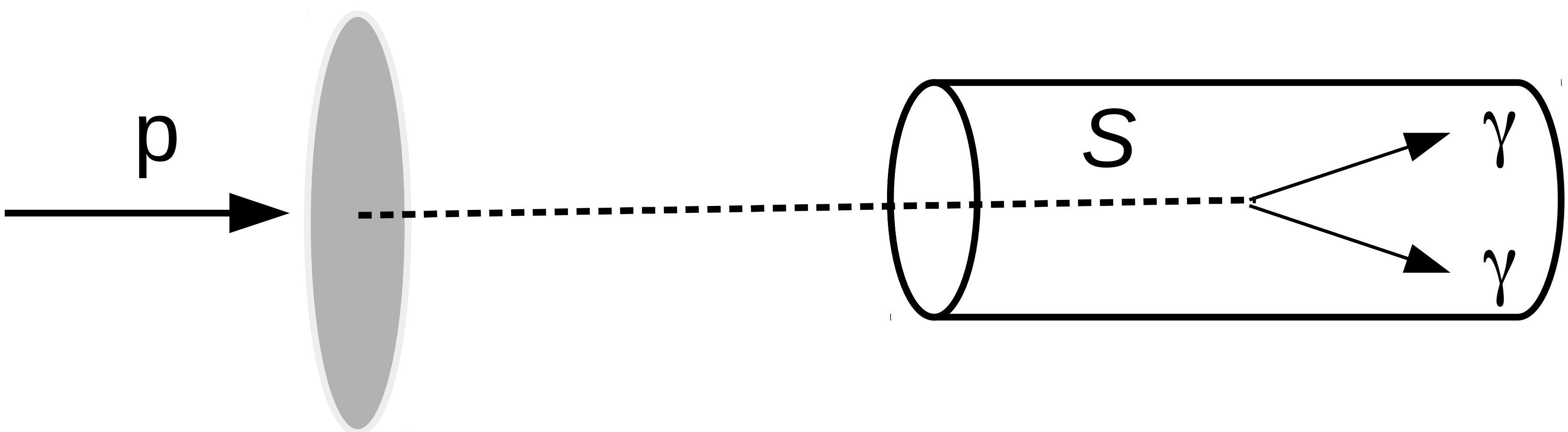
- can do same for kaon decays

Ignores higher derivative terms

Eta decays at beam dumps

$$\mathrm{BR}(\eta \to \pi S) \sim 10^{-3} \left(\frac{g_u}{10^{-4}}\right)^2$$ *S* light

Produce η at proton beam dump, then look for decay products of *S*: photons, or pions if low coupling



e.g. CHARM used a 400 GeV proton beam and looked ~500 m downstream; can recast ALP search

Meson precision measurements

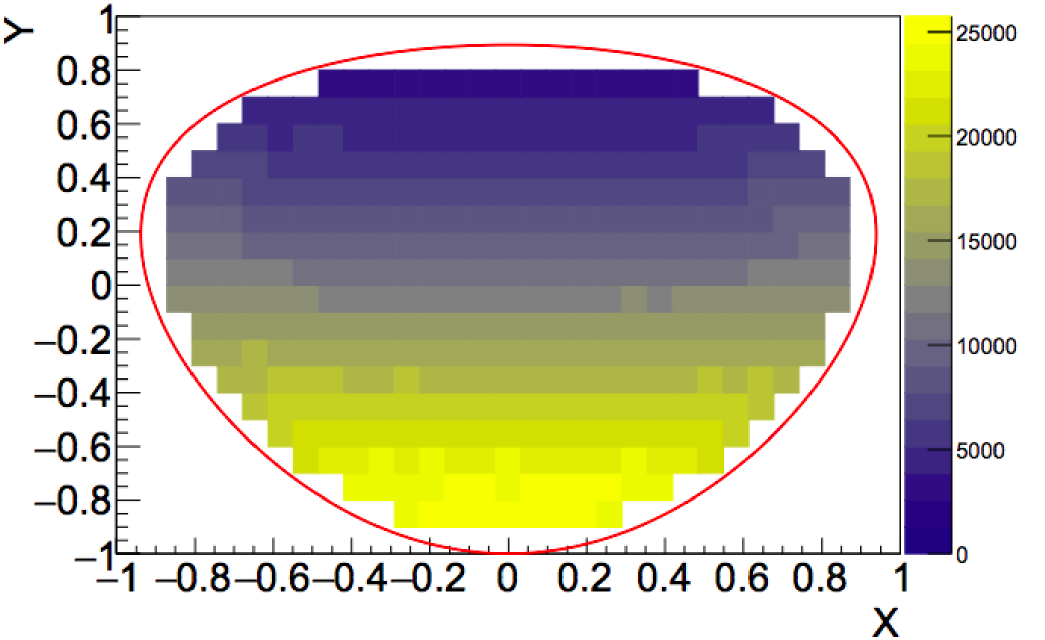
Studying η, K properties can constrain *S*

$\eta \rightarrow 3\pi$ Dalitz analysis useful in small window for *S* between 2 m_π and m_η - m_π

Also $\eta \rightarrow \pi \gamma \gamma$ (MAMI)

$\eta \rightarrow \pi$ + invisible not searched for currently

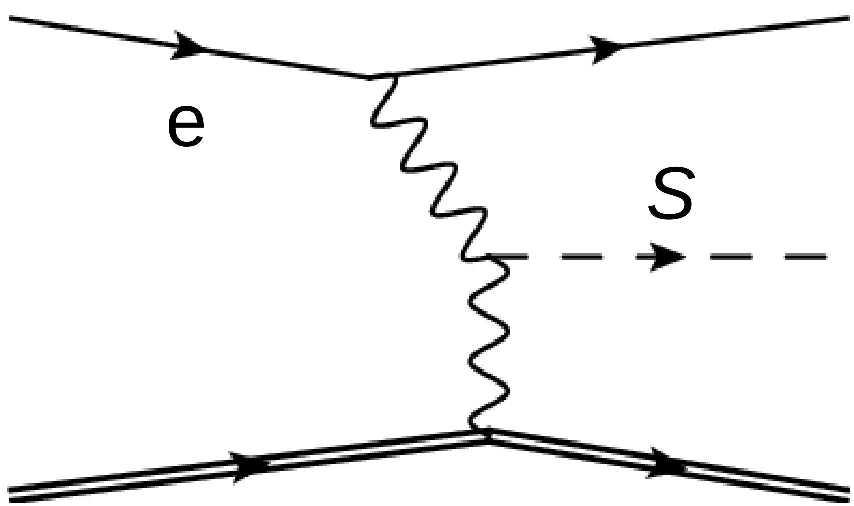
$K \rightarrow \pi\nu\nu$ at E787/E949, to be improved by NA62



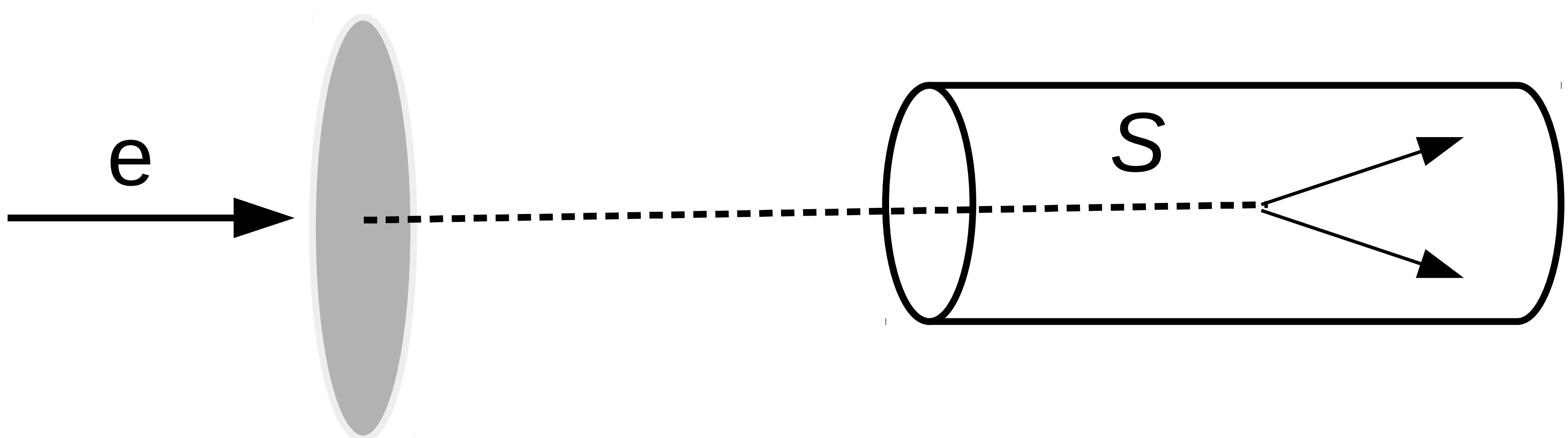
KLOE 3π
1601.06985

Electron beam dump searches

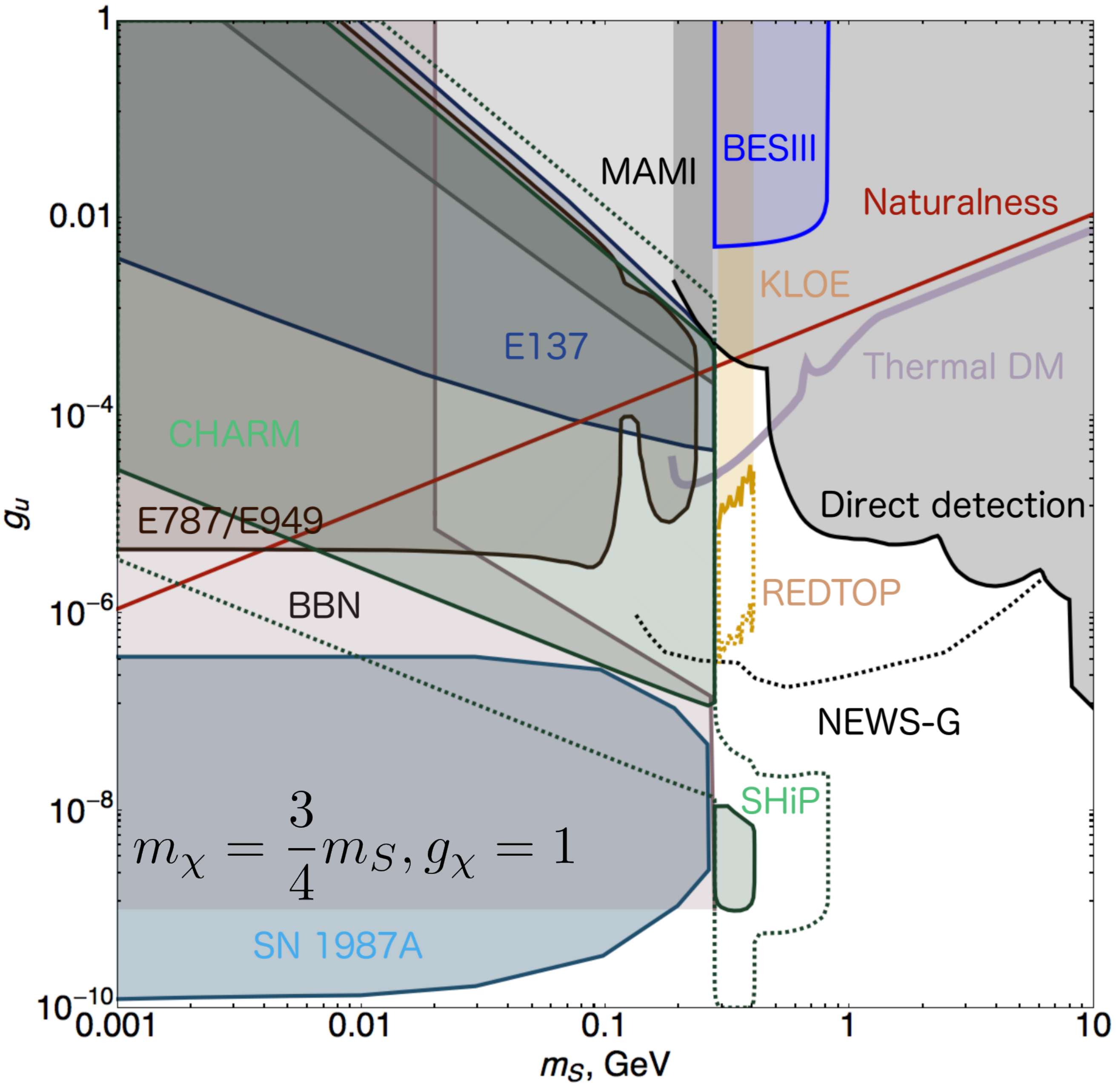
Use induced photon coupling to recast axion-like particle analyses when *S* has long-lived decay to $\gamma\gamma$



Relevant for electron beam dumps such as E137 at SLAC

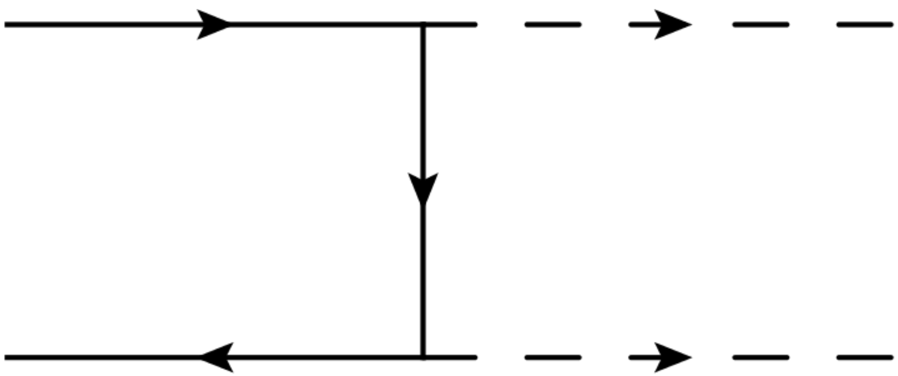


Up-philic S decaying visibly



Secluded annihilation

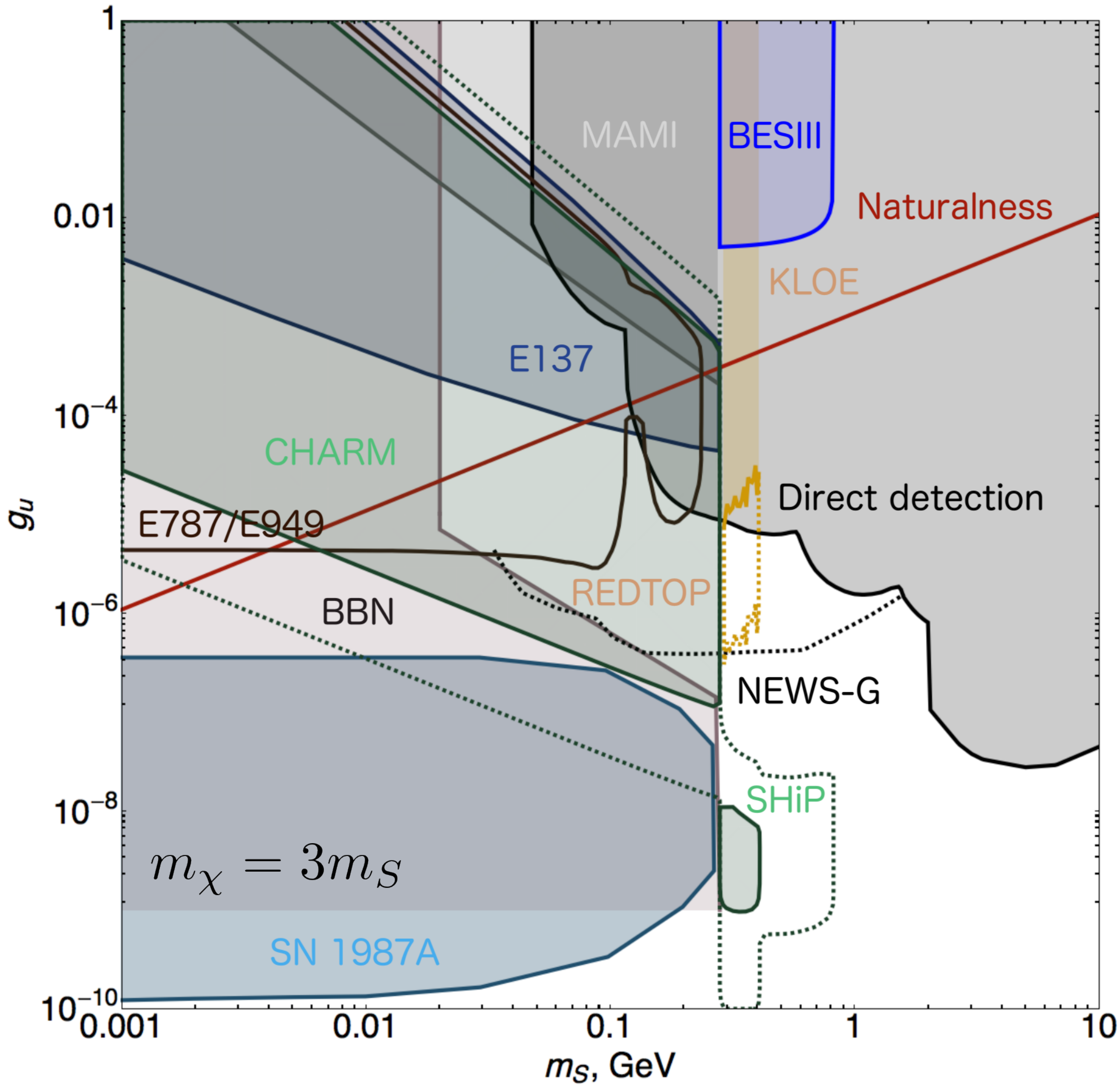
Annihilation independent of SM coupling of scalar when kinematically feasible



$$\sigma v \sim \frac{g_\chi^4 v^2}{m_\chi^2}$$

Thermal relic cross section can generally be reached for any g_u

Secluded annihilation

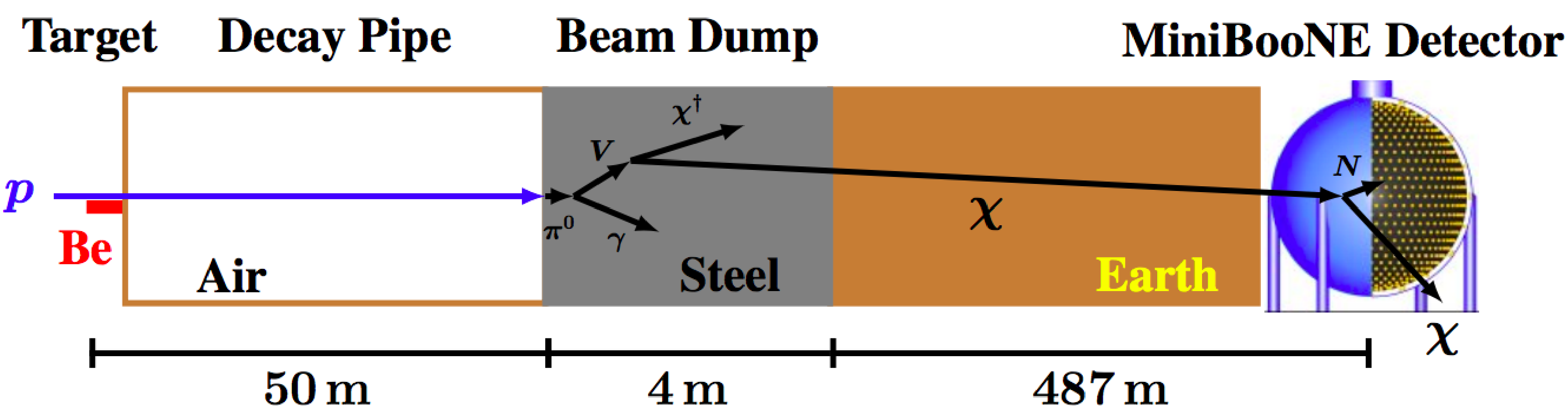


S decaying to dark matter

Rare meson decays: M → M' + invisible

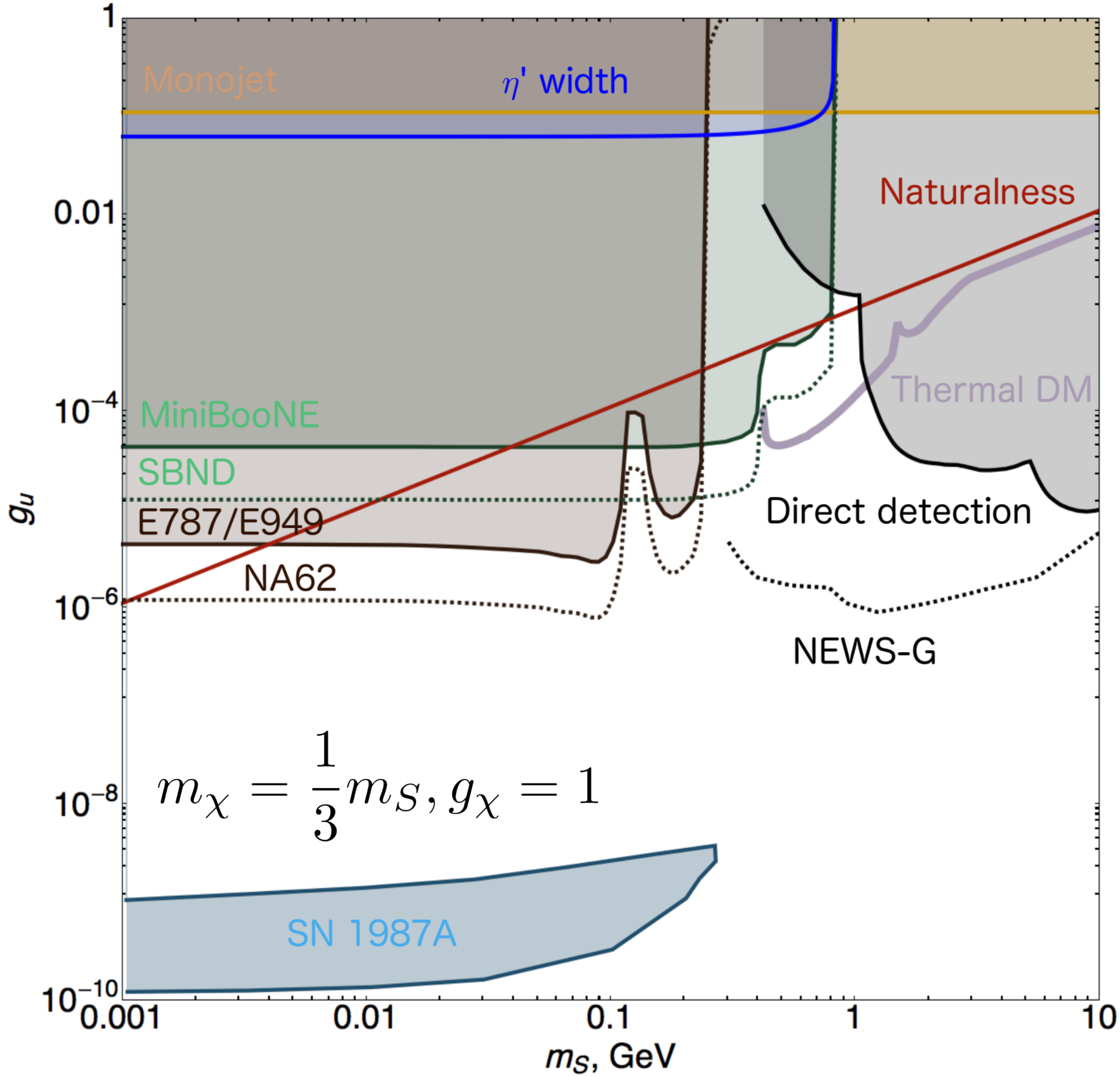
Use precision measurements, e.g. K → πνν

Or: produce DM beam, look for recoil downstream in large detector   Batell, Pospelov, Ritz 0906.5614



Monojet production at LHC from initial state radiation

Up-philic S decaying invisibly



Summary

Generalization of MFV allows fermion-specific new scalar, with suppressed flavor signatures

Useful for building new dark sector models

Technical naturalness suggests small couplings

Up-specific example

- weaker heavy meson constraints than dark Higgs

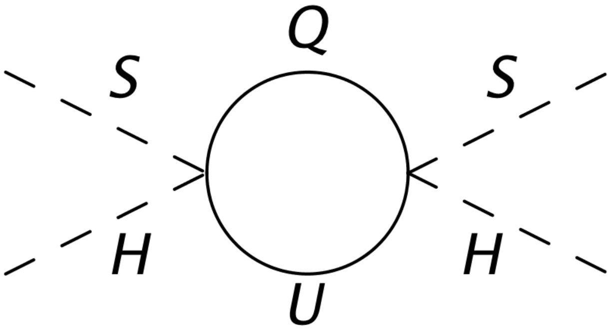
- constrained by beam dumps, colliders, BBN, SN

- will be tested by upcoming low mass direct detection, long-lived particle searches, precision light meson measurements

Backup slides

Other induced couplings – scalar/Higgs

For low *M*, diagrams with Higgs vevs dominate naturalness constraints

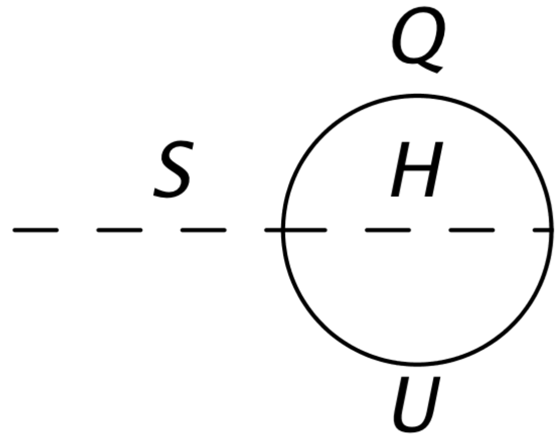


$$\delta m_S^2 \lesssim m_S^2 \to c_S \lesssim (4\pi\sqrt{2})\frac{m_S}{v}$$

→ small Higgs-*S* mixing

Other induced couplings – scalar vev

Protected by combination of *S* shift symmetry and chiral symmetry



$$v_S \approx -\frac{\delta_S}{2m_S^2} \sim \frac{c_S^\dagger Y_u}{2(16\pi^2)^2}\left(\frac{M}{m_S}\right)^2 M$$

S vev generally larger than scalar mass for $M >> m_s$

S^n operators for $n > 2$ don't significantly affect scalar potential when generated radiatively

Other induced couplings – scalar vev

Immediately gives correction to quark mass which is technically natural but still dangerous for $m_s \ll M$

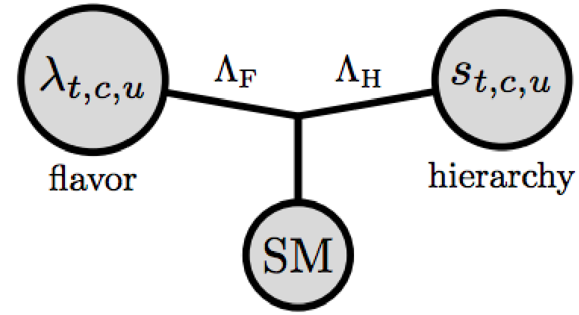
$$\delta m_u \sim \frac{c_S^2}{2(16\pi^2)^2}\left(\frac{M}{m_S}\right)^2 m_u$$

Leads to same bound on c_s as S mass correction

$$\mathrm{c}_S \lesssim (16\pi^2)\,\frac{m_S}{M}$$

Dynamical alignment

$$H^c \bar{Q}\left(\frac{s_c}{\Lambda_H}\frac{\lambda_c}{\Lambda_F}+\frac{s_t}{\Lambda_H}\frac{\lambda_t}{\Lambda_F}+\frac{s_u}{\Lambda_H}\frac{\lambda_u}{\Lambda_F}\right)U$$



Parity symmetry for flavons λ

Positive coefficients in most general potential → alignment

Knapen and Robinson, 1507.00009

$$\begin{aligned}
V_{2\mathrm{f}}^{\alpha\beta} &= \mu_3^{\alpha\beta}\Big[\mathrm{Tr}(\lambda_\alpha^\dagger\lambda_\alpha)+\mathrm{Tr}(\lambda_\beta^\dagger\lambda_\beta)-r_\alpha^2-r_\beta^2\Big]^2 \\
&+\sum_{\pm}\mu_{4,\pm}^{\alpha\beta}\Big|\mathrm{Tr}\Big[\lambda_\alpha^\dagger\lambda_\beta\pm\lambda_\beta^\dagger\lambda_\alpha\Big]\Big|^2 \\
&+\sum_{i=1,2}\mu_{5,i}^{\alpha\beta}\mathrm{Tr}\Big[[\lambda_\alpha,\lambda_\beta]_i^\dagger[\lambda_\alpha,\lambda_\beta]_i\Big] \\
&+\mu_6^{\alpha\beta}\Big\{\mathrm{Tr}\Big[(\lambda_\alpha\lambda_\beta^\dagger)^\dagger(\lambda_\alpha\lambda_\beta^\dagger)\Big]+\mathrm{Tr}\Big[(\lambda_\alpha^\dagger\lambda_\beta)^\dagger(\lambda_\alpha^\dagger\lambda_\beta)\Big]\Big\}
\end{aligned}$$

$$\begin{aligned}
V_{1\mathrm{f}}^{\alpha} &= \mu_1^\alpha\Big|\mathrm{Tr}(\lambda_\alpha^\dagger\lambda_\alpha)-r_\alpha^2\Big|^2 \\
&\quad+\mu_2^\alpha\Big[\mathrm{Tr}(\lambda_\alpha^\dagger\lambda_\alpha)^2-\mathrm{Tr}(\lambda_\alpha^\dagger\lambda_\alpha\lambda_\alpha^\dagger\lambda_\alpha)\Big] \\
&=\mu_1^\alpha\Big|\sum_i|d_{\alpha i}|^2-r_\alpha^2\Big|^2+2\mu_2^\alpha\sum_{i<j}|d_{\alpha i}|^2|d_{\alpha j}|^2
\end{aligned}$$

Dynamical alignment

Add new physics flavon λ_{np} with coefficients arranged

$$\mu_1^{\rm np} > |\mu_2^{\rm np}| \gg \mu_{4,+}, \mu_6$$

Leads to aligned vev for λ_{np}, either flavor-specific or universal

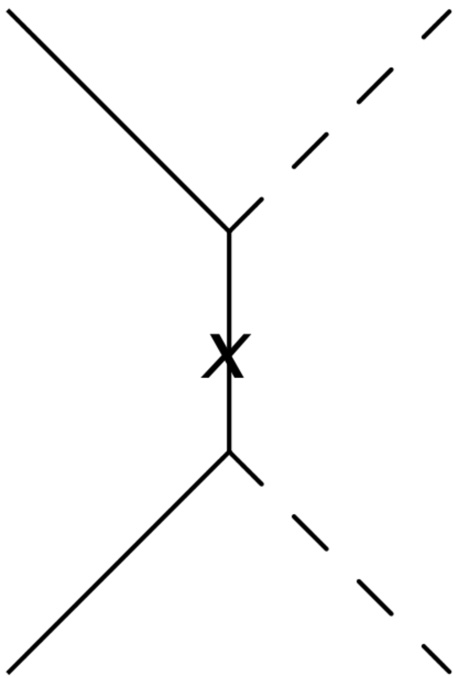
Knapen and Robinson, 1507.00009

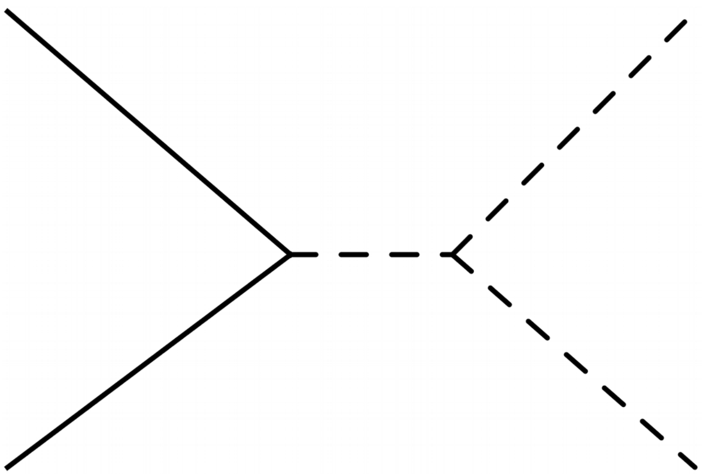
$$\begin{aligned} V_{2\rm f}^{\alpha\beta} &= \mu_3^{\alpha\beta}\Big[\mathrm{Tr}(\lambda_\alpha^\dagger\lambda_\alpha) + \mathrm{Tr}(\lambda_\beta^\dagger\lambda_\beta) - r_\alpha^2 - r_\beta^2\Big]^2 \\ &+ \sum_{\pm}\mu_{4,\pm}^{\alpha\beta}\Big|\mathrm{Tr}\Big[\lambda_\alpha^\dagger\lambda_\beta \pm \lambda_\beta^\dagger\lambda_\alpha\Big]\Big|^2 \\ &+ \sum_{i=1,2}\mu_{5,i}^{\alpha\beta}\mathrm{Tr}\Big[[\lambda_\alpha,\lambda_\beta]_i^\dagger[\lambda_\alpha,\lambda_\beta]_i\Big] \\ &+ \mu_6^{\alpha\beta}\Big\{\mathrm{Tr}\Big[(\lambda_\alpha\lambda_\beta^\dagger)^\dagger(\lambda_\alpha\lambda_\beta^\dagger)\Big] + \mathrm{Tr}\Big[(\lambda_\alpha^\dagger\lambda_\beta)^\dagger(\lambda_\alpha^\dagger\lambda_\beta)\Big]\Big\} \end{aligned}$$

$$\begin{aligned} V_{1\rm f}^{\alpha} &= \mu_1^{\alpha}\Big|\mathrm{Tr}(\lambda_\alpha^\dagger\lambda_\alpha) - r_\alpha^2\Big|^2 \\ &\quad + \mu_2^{\alpha}\Big[\mathrm{Tr}(\lambda_\alpha^\dagger\lambda_\alpha)^2 - \mathrm{Tr}(\lambda_\alpha^\dagger\lambda_\alpha\lambda_\alpha^\dagger\lambda_\alpha)\Big] \\ &= \mu_1^{\alpha}\Big|\sum_i|d_{\alpha i}|^2 - r_\alpha^2\Big|^2 + 2\mu_2^{\alpha}\sum_{i<j}|d_{\alpha i}|^2|d_{\alpha j}|^2 \end{aligned}$$

UV completions

Can get dimension 5 *S* coupling by integrating out heavy vector-like fermion or scalar





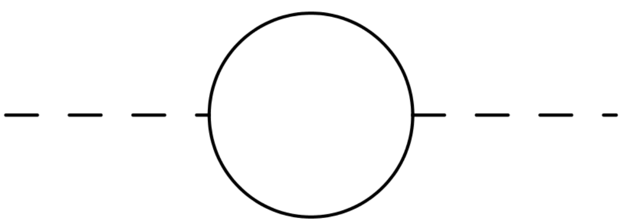
Full theory can have additional contributions to scalar potential, changing power counting for naturalness relative to effective theory

UV completions

New vector-like quark *Q′* with same SM charge as *Q*

$$y_S S\bar{Q}Q'_R + M\bar{Q}'_L Q'_R + y'\bar{Q}'_L H_c U \to \frac{y_S y'}{M} S\bar{Q}H_c U$$

Naturalness bounds slightly different



$$(y_S)^{ij} \lesssim (4\pi)\frac{m_S}{M}$$

$$(y')^{ij} \lesssim (4\pi)\frac{v}{M}$$

compare with effective theory

$$(c_S)^{ij} \lesssim (16\pi^2)\frac{m_S}{M}$$