Flavor and light scalars

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with B. Batell, A. Freitas and D. McKeen

Light SM singlet scalars

Motivated by hints of new physics / questions in SM

- muon g – 2
- proton radius
- strong CP
- dark matter

Compared to light vectors, no anomaly cancellation issues

this talk

axion-like, see talk by Sang Hui Im

Possible couplings: $S\bar{Q}H_cU\,, \partial_\mu S\bar{Q}\gamma^\mu Q$

Flavor structure

New couplings generally break flavor symmetry, leading to significant flavor changing neutral currents

$$\frac{(c_S)^u_q}{M} S\bar{Q}^q H_c U_u$$

Compare with SM, where Yukawas break $U(3)^5$ to $U(1)_B$ x $U(1)_L$ x $U(1)_Y$

$$(Y_u)^u_q \bar{Q}^q H_c U_u, (Y_d)^d_q \bar{Q}^q H D_d$$

Minimal flavor violation: assume Yukawas are only source of symmetry breaking → all FCNCs are proportional to CKM matrix, i.e. $c_S \sim Y_u$

D'Ambrosio, Giudice, Isidori, Strumia hep-ph/0207036

Beyond MFV

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 $U(2)^2 \times U(3)$

Flavor for up-specific 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

→ *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

Flavor for up-specific scalar

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

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

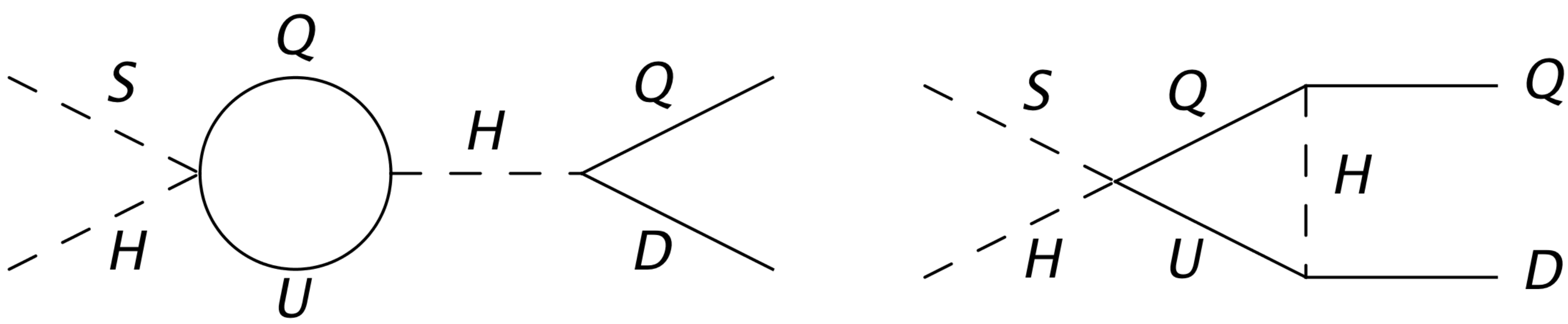
In up sector, have flavor-violating correction

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

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

Flavor for up-specific scalar

Down-type scalar couplings induced at loop level



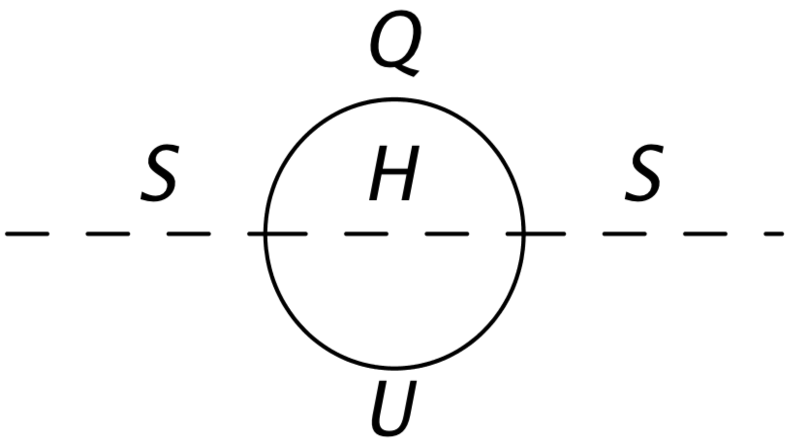
Both flavor-conserving and flavor-violating couplings go as $Y_u\, Y_d\, c_S$ and are loop suppressed

$$\frac{1}{M}\left(V_{\rm CKM}^{\dagger} c_S (Y_u^D)^{\dagger} V_{\rm CKM} Y_d^D\right)_q^d S\bar{Q}^q H D_d$$

Naturalness: scalar potential

New scalar suffers from usual hierarchy problem

Assume new physics regulates divergence at scale *M*

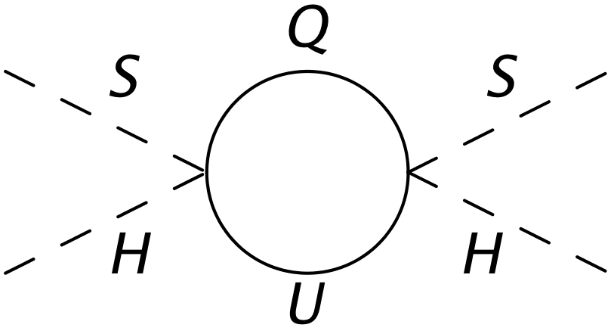


$$\delta m_S^2 \lesssim m_S^2$$

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

Naturalness: scalar potential

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

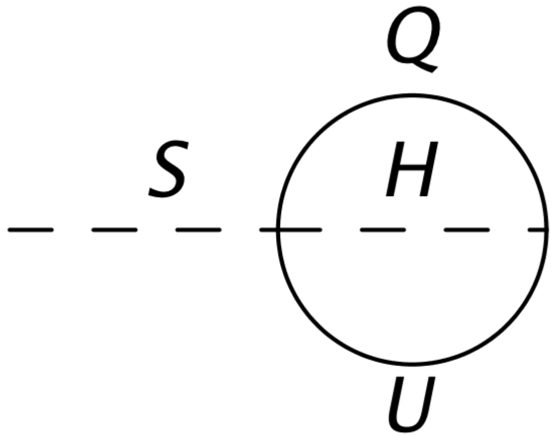


$$\delta m_S^2 \lesssim m_S^2 \to (c_S)^{ij} \lesssim (4\pi\sqrt{2})\frac{m_S}{v}$$

→ small Higgs-*S* mixing

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

Scalar vev

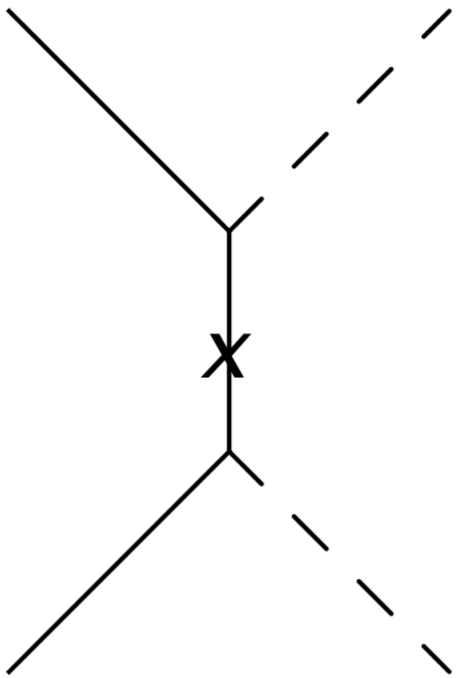
Immediately gives correction to quark mass which is technically natural but still dangerous for $m_s << M$

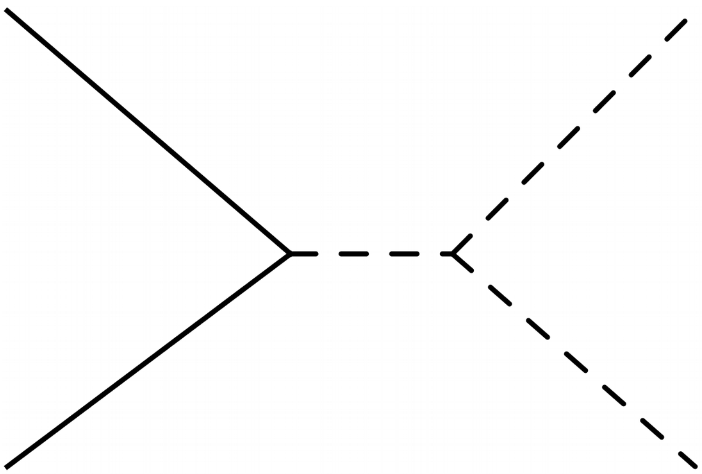
$$\delta m_{u_1} \sim \frac{(c_S^{11})^2}{2(16\pi^2)^2} \left(\frac{M}{m_S}\right)^2 m_{u_1}$$

Leads to similar bound on c_s as S mass correction

UV completions

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





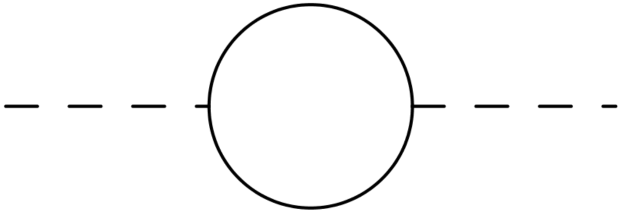
Full theory can have additional contributions to scalar potential, changing power counting for naturalness relative to effective theory

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

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

Summary so far

MFV-inspired symmetry principle for flavored scalar couplings

Spurion analysis gives small scalar potential terms

Different UV completions possible

Applies equally well to scalar coupling to a single up quark, down quark, or lepton

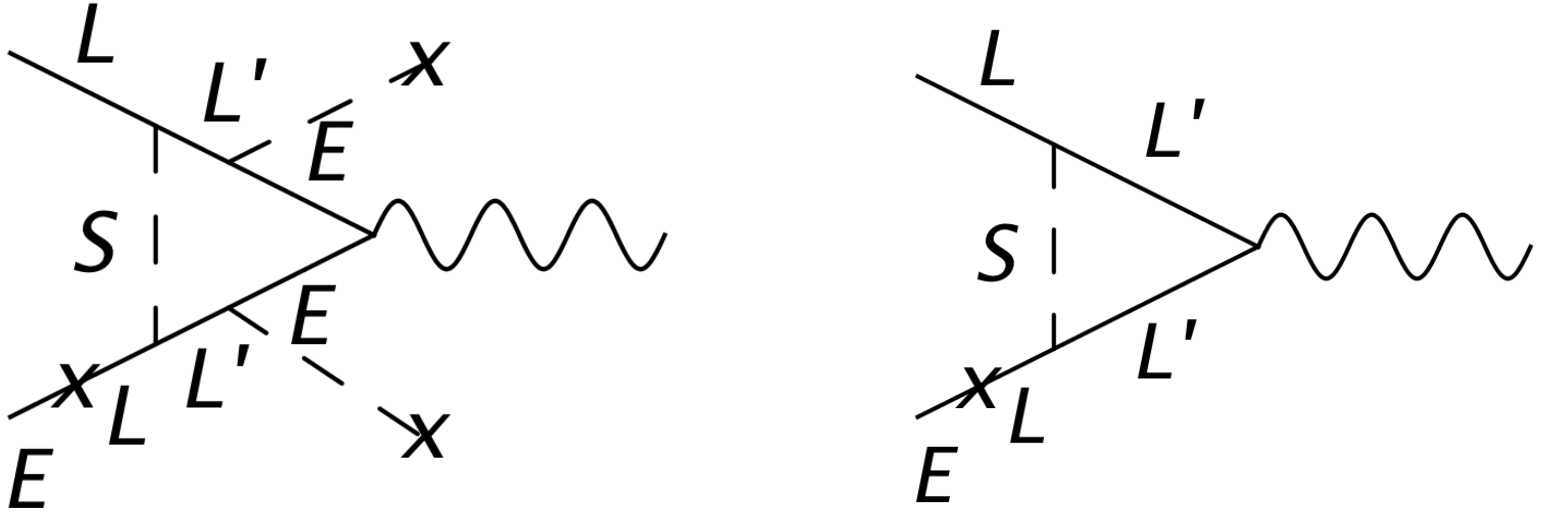
Muon-specific scalar

Can explain muon anomalous magnetic moment

Chen, Davoudiasl, Marciano, Zhang 1511.04715; Batell et al. 1606.04943

We use same UV completion as quark case, with vector-like lepton *L'*

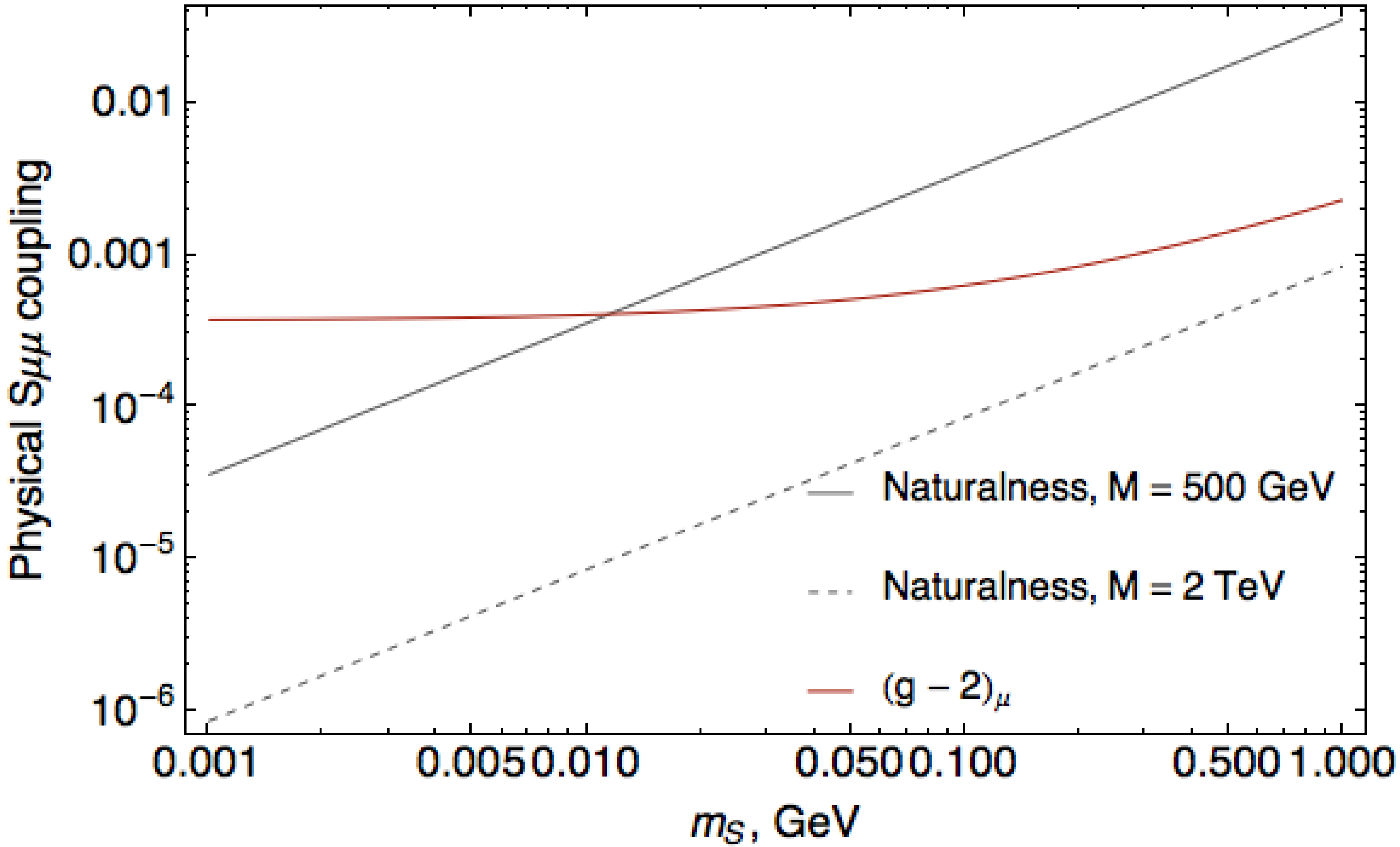
$$y_S S \bar{L} L'_R + M \bar{L}'_L L'_R + y' \bar{L}'_L H E$$



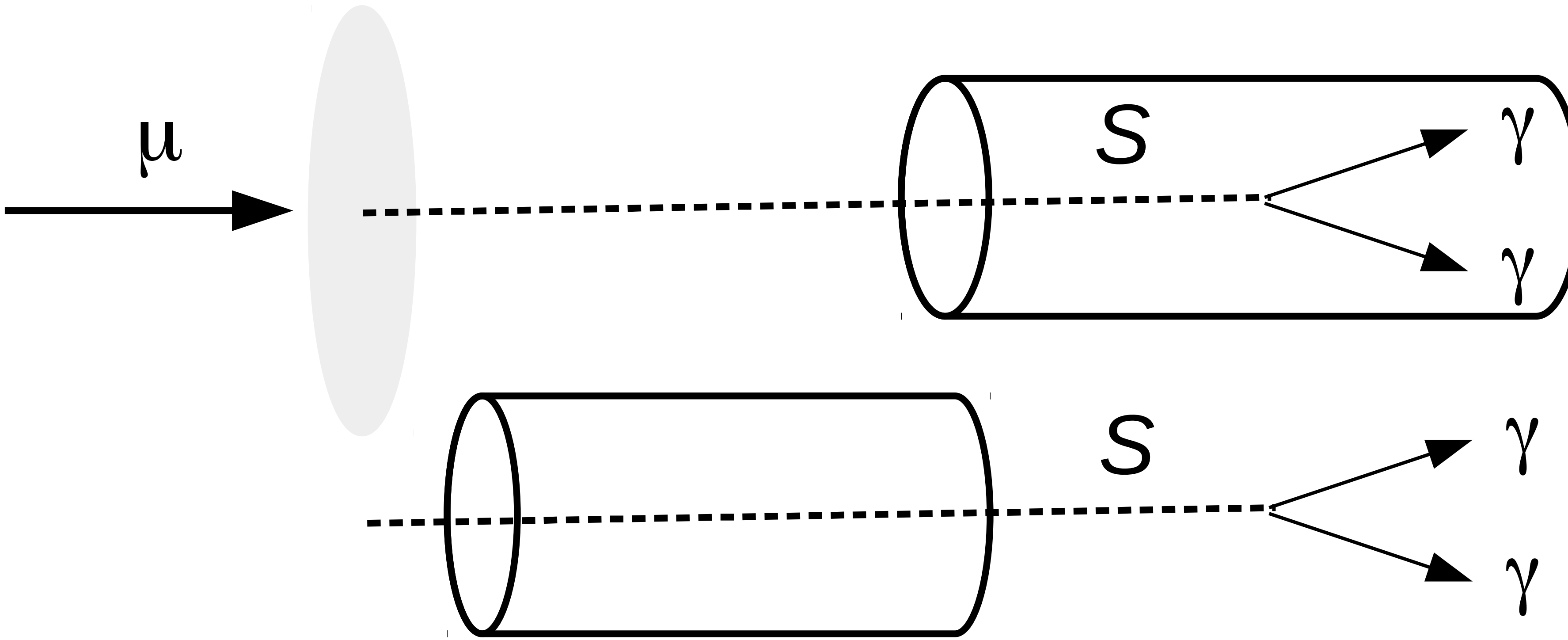
Muon-specific scalar

$$y_S S \bar{L} L'_R + M \bar{L}'_L L'_R + y' \bar{L}'_L H E$$

Tuned unless UV completion is nearby

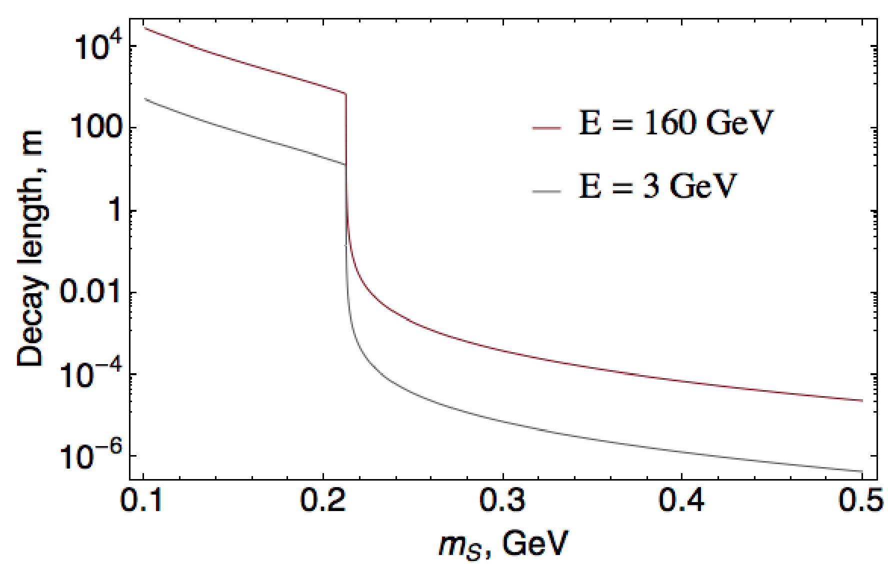


μ beam signatures

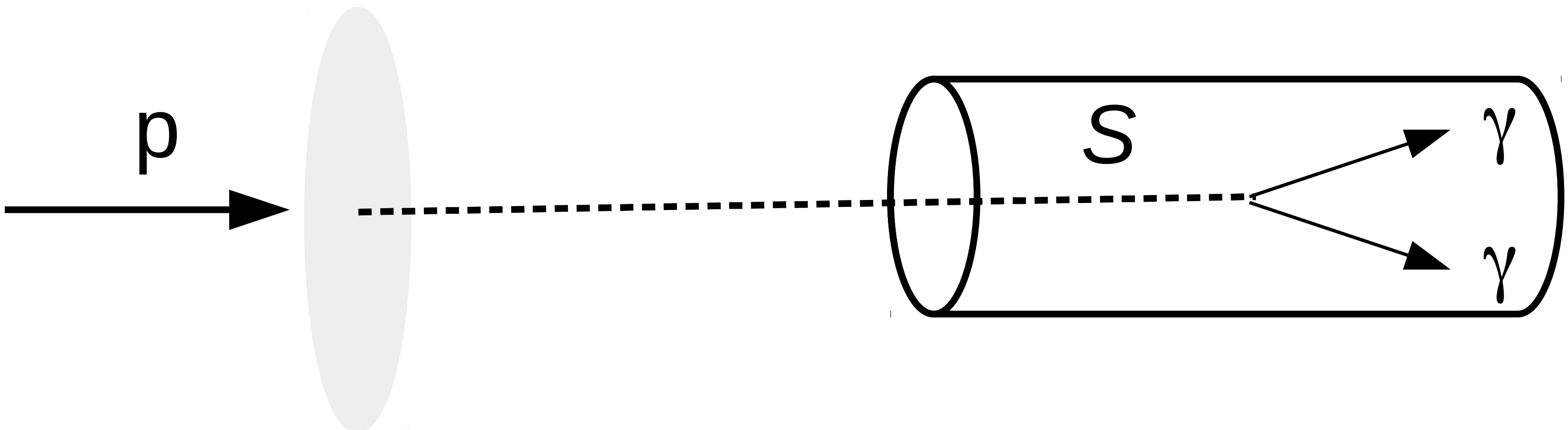


Look for visible decay or missing momentum from long-lived *S*

Chen, Pospelov, Zhong 1701.07437



p beam signatures



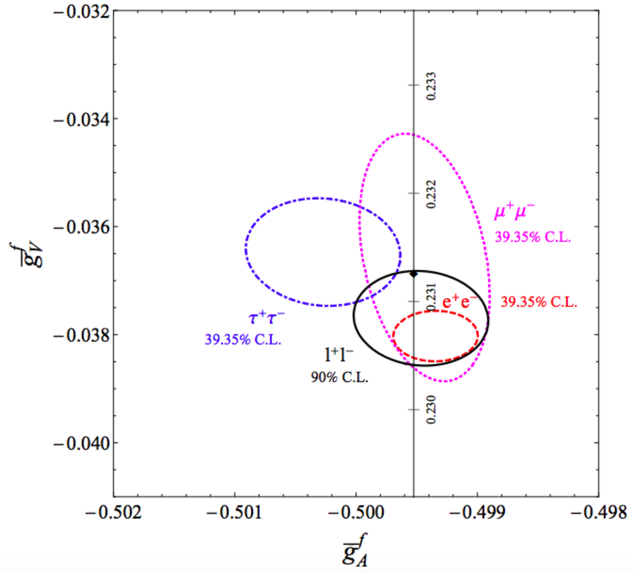
At SHiP, some K mesons from proton beam decay before being stopped

Look for K → μ ν S, S → γ γ

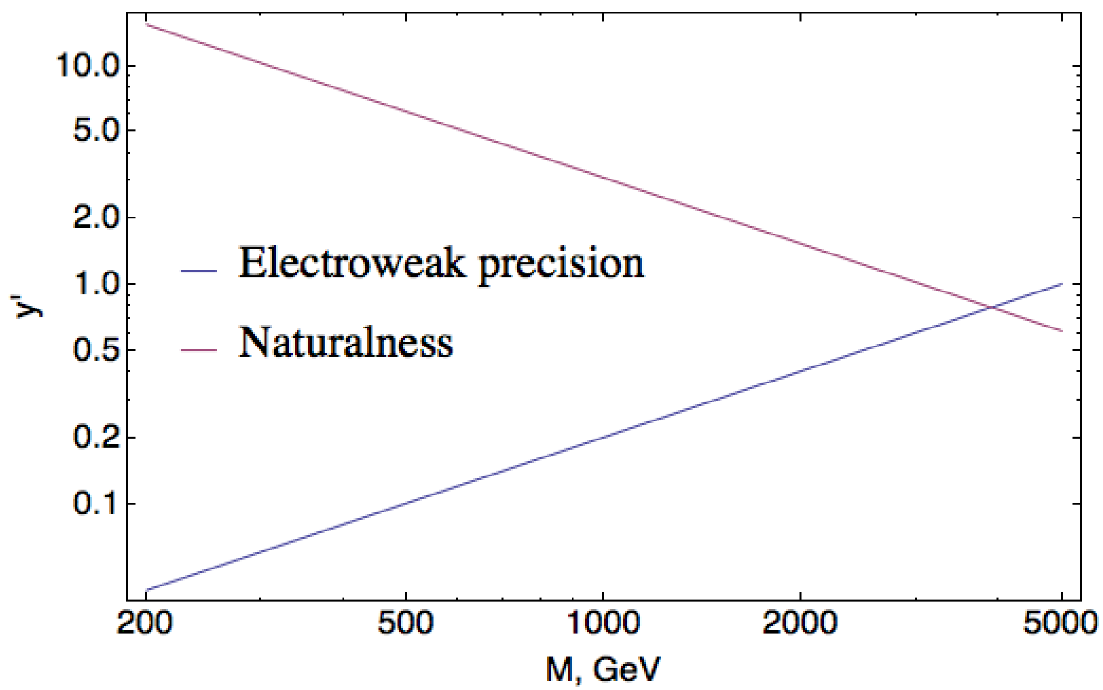
~10^{18} kaons produced, can decay between 55 and 125 m downstream

Electroweak precision

$$\begin{pmatrix}\bar{\mu}_L & \bar{\mu}'_L\end{pmatrix}\begin{pmatrix}y_\mu v & y_s v_s \\ y' v & M\end{pmatrix}\begin{pmatrix}\mu_R \\ \mu'_R\end{pmatrix} \qquad \theta_R \approx \frac{y' v}{M} \lesssim 0.05$$



LEP EWWG

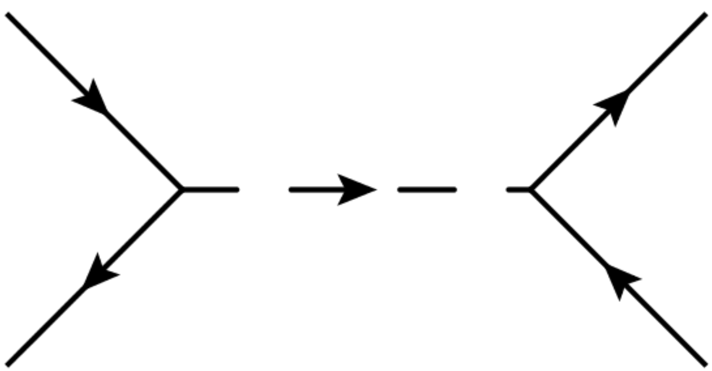


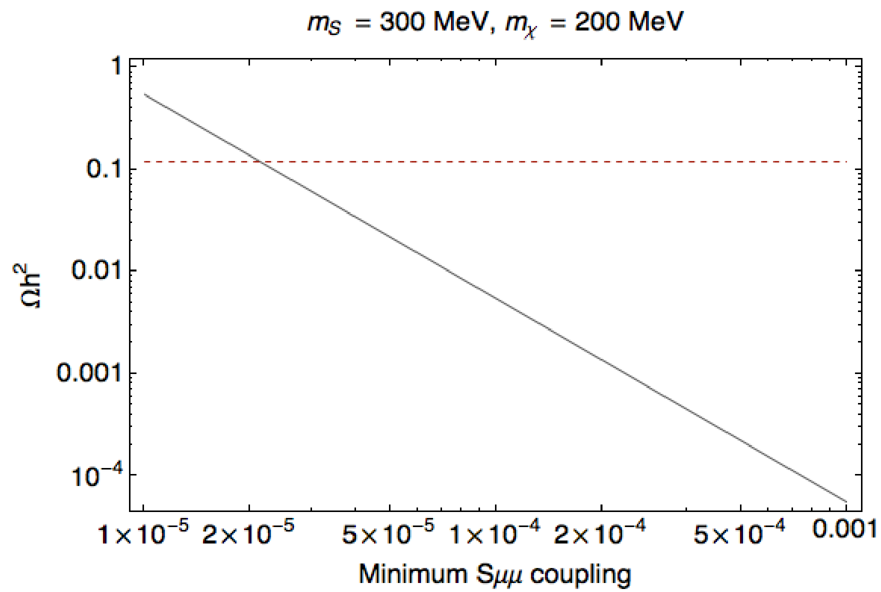
Mixing between fermions modifies electroweak RH muon coupling

Add dark matter

$\chi\chi \rightarrow \mu\mu$ annihilation through *S* can give relic density

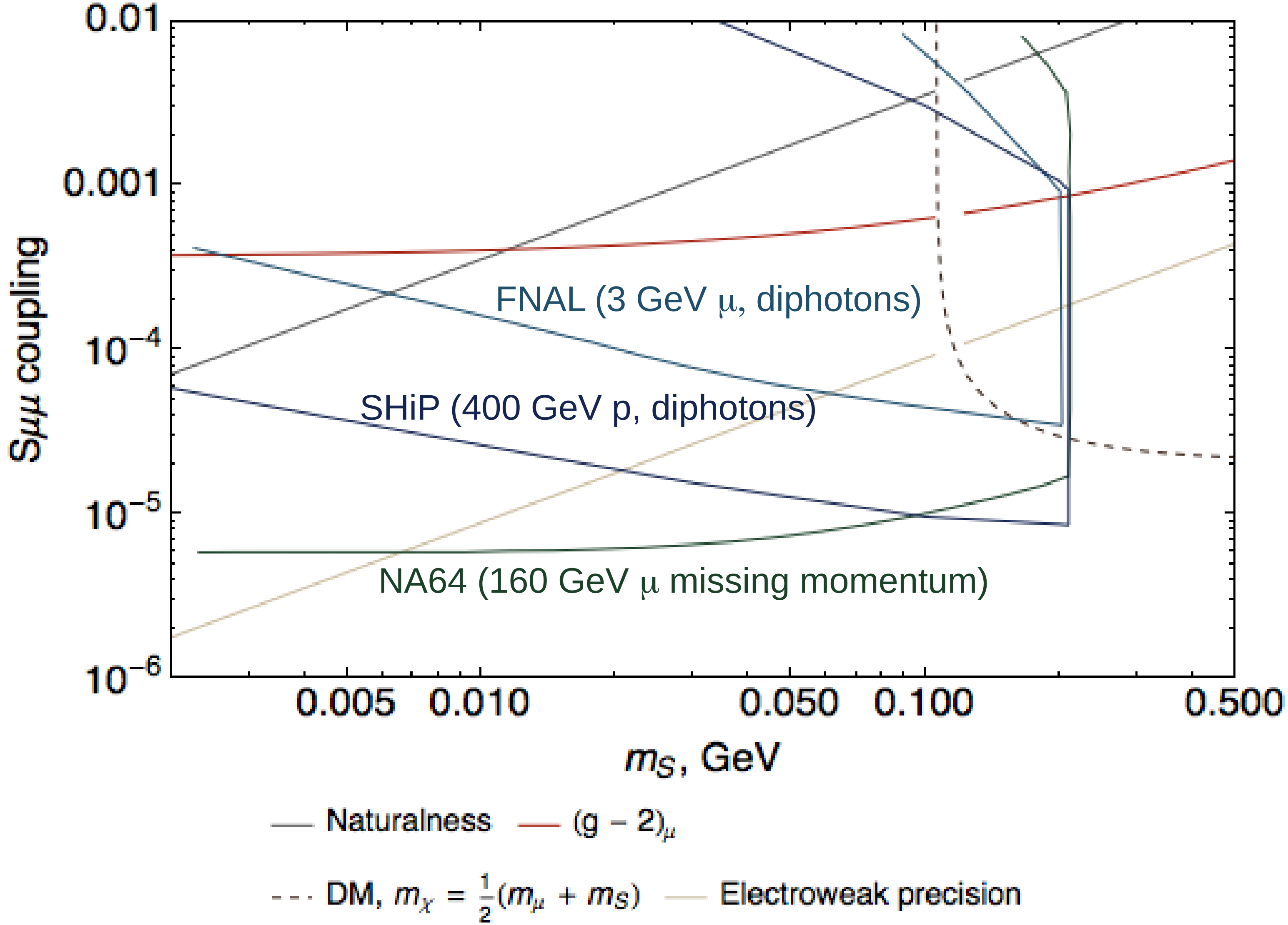
Minimal $S\mu\mu$ coupling implied for thermal relic χ and perturbative $S\chi\chi$ coupling





If $m_S < m_\chi$, $\chi\chi \rightarrow SS$ annihilation also possible, but unrelated to muon coupling

Testing a muon-philic scalar



Summary

Generalization of MFV allows generation-specific couplings of new light scalar, with possibly suppressed flavor signatures

Technical naturalness bounds require small couplings

Leptophilic case: resolution of muon g – 2 with naturalness implies nearby accessible states from UV completion

Upcoming experiments will probe natural couplings

Backup slides

S lifetime

$m_S > 2\, m_\mu$: prompt decay to muons

$$\Gamma(S \to \mu^+ \mu^-) = \frac{y_S^2 y'^2 v^2}{16\pi M^2} m_S \left(1 - \frac{4m_\mu^2}{m_S^2}\right)^{3/2}$$

$m_S < 2\, m_\mu$: slow decay to photons

$$\Gamma(S \to \gamma\gamma) = \frac{\alpha^2 m_\mu^2 y_S^2 y'^2 v^2}{8\pi^3 m_S M^2} \left| 1 + \left(1 - \frac{4m_\mu^2}{m_S^2}\right) f\left(\frac{4m_\mu^2}{m_S^2}\right) \right|^2$$