BSM problems w/ the r_p Problem

↳ PROTON RADIUS

Work "in progress" (on hold) w/ Gordan Krnjaic
→ LOOKING FOR "COLLABORATORS"
↳ grad students to do calculations

REFERENCES

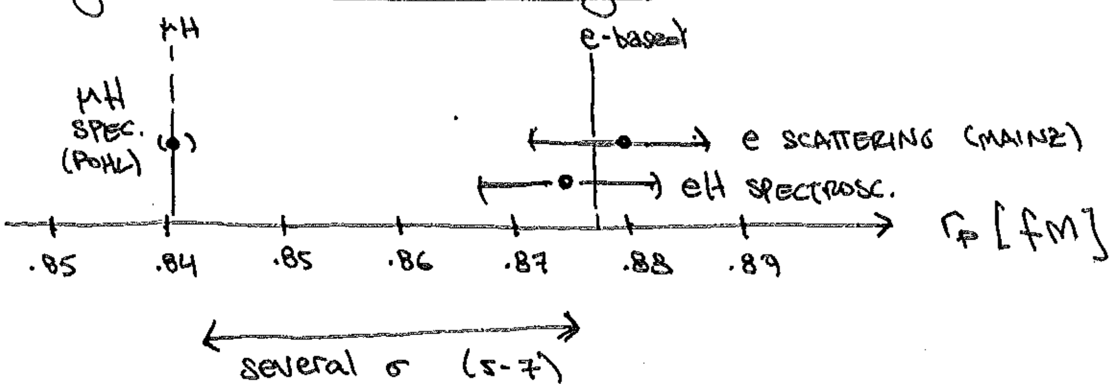
r_p PROBLEM REVIEW: Pohl et al. 1301.0905

New physics attempts: DTS & Yavin 1011.4922
Barger et al. 1011.3519

Carlson & Rislow 1206.3587
PI guys 1405.4864

THIS TALK: ASSUME solution is new physics, see what we can do.
↳ (HUGE ASSUMPTION)

Summary of the anomaly



$$r_p^{e} = 0.8770(45)\ \mathrm{fm}$$

$$r_p^{\mu} = 0.8409(04)\ \mathrm{fm}$$

ASIDE: WHAT is r_p? ⟵ CHARGE RADIUS; DEVIATION FROM POINT-LIKE CHARGE

technically: $r_p^2 \equiv -6 \frac{dG_E}{dQ^2}\Big|_{Q^2=0}$ ⟵ TRANSFER MOMENTUM

G_E: SACH'S ELECTRIC FORM FACTOR modifying POINT PROTON APPROX.

this is heuristically $\langle r^2 \rangle = \int d^3r \, r^2 \psi(r)$

but not quite → cf. Miller 1002.0355, 0908.1535
IT'S REALLY A "TRANSVERSE CHARGE DENSITY" (ACCOUNTS FOR RECOIL EFFECTS)

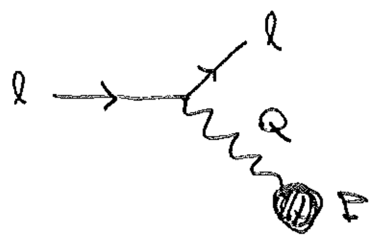
↳ [non-relativistically, $\psi(\vec{r}_1, \vec{r}_2) = e^{i\vec{P}\cdot\vec{R}} \phi(\vec{r})$

& form factor is $F = \int d^3r \, |\phi|^2 e^{i\vec{q}\cdot\vec{r}/2}$

BUT RELATIVISTICALLY MUST SOLVE BS EQ & P DOESN'T FACTORIZE]

EFFECTIVELY: $G_E(Q^2)$ IS PROB. AMP FOR P TO ABSORB THE EXCHANGED PHOTON (w/o EXCITING TO A NEW STATE)

& anyway, this is the actual thing that shows up in expts.



so: $\delta V(\vec{r}) = -4\pi\alpha \int d^3q \, \frac{1}{q^2} \left[G_E(q^2) - 1 \right] e^{-i\vec{q}\cdot\vec{r}}$

POINT PROTON

$G_E(q^2) \approx 1 - \frac{1}{6} q^2 r_p^2 + \mathcal{O}\left(\frac{r_p}{a_{BOHR}}\right)$

$= \frac{2}{3}\pi\alpha\, \delta^{(3)}(\vec{r})$

$a_{BOHR} = \frac{1}{\alpha m_r}$

$\Rightarrow \Delta E = \langle \psi_s | \delta V | \psi_s \rangle = \frac{2\pi}{3}\alpha\, |\psi_s(0)|^2 \, r_p^2$

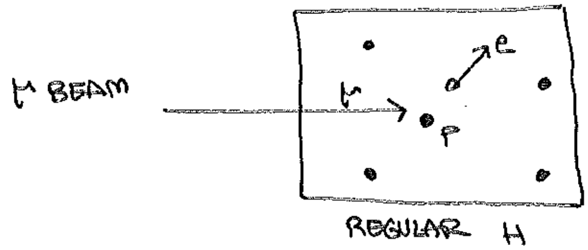
need: $\boxed{\sim 0.3 \text{ meV}}$

shifts S-wave states $\approx (1/a_{BOHR})^3$

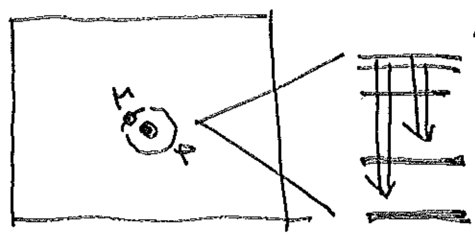
What are we measuring

I. SPECTROSCOPY → atomic transitions

PREPARE MUONIC HYDROGEN



} some μ replace e in atoms

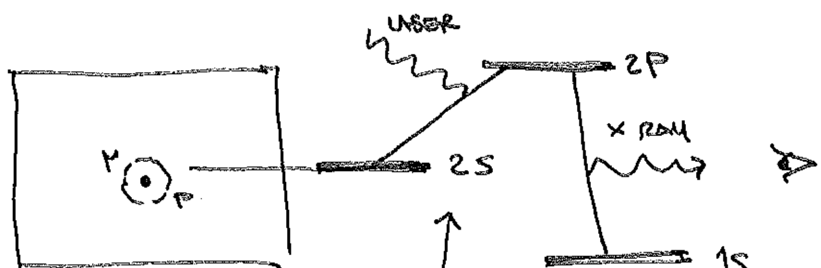


} EXCITED STATES quickly fall into lower E states

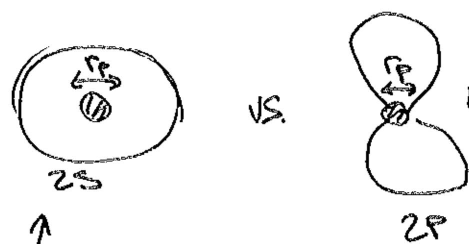
2S ← about 1%

EXCITE 2S STATES INTO 2P STATES W/ LASER TUNED TO RIGHT FREQ.

Pohl had to find this!



note: 2S state probes proton size while 2P does not.

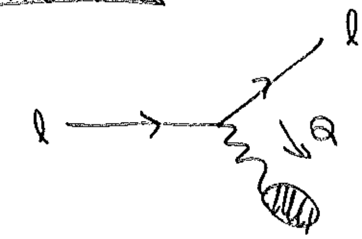


← insensitive to PROTON RADIUS, $|\psi_p(0)|^2 = 0$

So this ENERGY LEVEL SHIFTS DUE TO THE PROTON RADIUS

Similar meas. for e^-:

II. SCATTERING

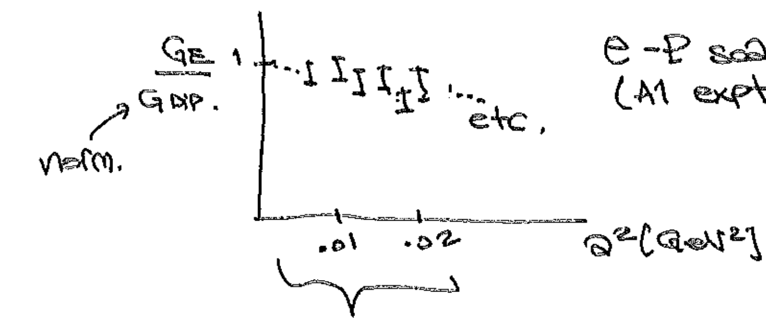


LOOKS LIKE DEEP INELASTIC SCATTERING ... BUT WE TAKE <u>OPPOSITE</u> LIMIT.

INSTEAD OF HIGH Q^2 → SHORT WAVELENGTH PROBE P SUBSTRUCTURE

WANT <u>LOW</u> Q^2 → <u>LONG</u> WAVELENGTH PROBE P ~~SIZE~~ "MACROSCOPIC" PROPERTIES.

OF COURSE, CANNOT MEASURE $Q^2=0$
HAVE TO TAKE "AS LOW AS YOU CAN GO" Q^2 &
EXTRAPOLATE.



e-P scattering (A1 expt in Mainz)

<u>remark</u>: in this ~linear region, linear extrapolation gives $r_p \approx 0.84$ fm !!

↳ <u>BUT</u>: in this regime, $\mathcal{O}(r_p^4)$ effects contribute & they are positive def. So 0.84 fm is UNDERSHOOTING.

[claim by Carl Carlson & Griffioen in r_p PROBLEM REVIEW]

Now <u>ASSUME</u> the resolution is BSM particle physics.

What ingredients do we need?

1. new particle to correct V_{Coulomb} → new <u>mediator</u>
   spin s
   mass m

$$\Delta V = (-)^{s+1}\left(\frac{g_e g_p}{e^2}\right)\alpha\,\frac{e^{-mr}}{r}$$

2. COUPLES TO <u>PROTONS</u>

   ↳ couples to quarks/gluons ---→ also NEUTRONS?

3. COUPLES TO <u>LEPTONS</u>: μ and/or e

   either pull μ closer or push e further

   IMMEDIATE CONCERN: <u>LEPTON UNIVERSALITY</u>

   ↳ flavor constraints in lepton sector (so IGNORE SPIN-1)

   <u>but</u>: this only applies to SPIN-1 Mediators

   basically: kinetic terms must be flavor diagonal s.t. rotation to fermion mass basis does not introduce tree-level FCNCs.

WE KNOW (but understated in r_p literature) that SCALARS <u>want</u> to couple according to Mass.

↳ by assump. that scalar is SM singlet, it must couple to gauge singlet product of SM fields, eg $\langle H\rangle L e$

in other words, couples ~ Yukawas.
SO EXPECT MASS-WEIGHTED COUPLINGS.

⇒ this is <u>exactly</u> what we want!

$$\boxed{\Delta E_{NP} = (-)^{S+1} \frac{\alpha}{2a^3} \frac{g_\ell g_p}{e^2} \frac{f(am)}{m^2}} \leftarrow \quad f(x) = \frac{x^4}{(1+x)^4}$$

2S−2P

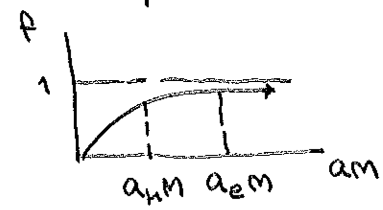
BOHR RADIUS, $a = \frac{1}{\alpha m_{red.}} \approx \frac{1}{\alpha m_\ell}$

see Jaeckel + Roy 1008.3536

compare to proton radius correction to Lamb shift

$$\Delta E_{r_p} = \frac{2\alpha}{3n^3a^3} \langle r_p^2 \rangle$$

$$\Rightarrow \Delta E_{TOTAL} = \frac{2\alpha}{3n^3a^3}\Big[\underbrace{r_p^2 + \left(\frac{3n^2}{2}\right)(-)^{S+1}\left(\frac{g_\ell g_p}{e^2}\right)\frac{f(am)}{m^2}}_{(r_p^2)_{EFFECTIVE}}\Big]$$



SO! if $(-)^{S+1}\left(\frac{g_\ell g_p}{e^2}\right)$ is universal & negative, (ATTRACTIVE)
eg for a spin-1 mediator,

then the effective r_p is <u>SMALLER</u> for electrons, vs. muons.

this is the <u>wrong</u> direction!

WANT $r_p^{(e)} > r_p^{(\mu)}$

$\Rightarrow$ $\boxed{\text{disfavor spin-1 MEDIATOR}}$

can do "weird" things like $U(1)_{\tau-\mu}$
BUT WE'LL NOT.

<u>Alternative</u> : $|g_e| = |g_\mu|$ but opposite sign

eg $(\mu - e)$ GAUGED

→ repulsive force for e-p system

<u>BUT</u> : THIS EFFECT IS SUPPRESSED @ HIGH MOMENTUM TRANSFER, eg FROM SCATTERING DATA.

→ would not explain Mainz proton radius measurements

SO: WE'RE LEFT w/ $\boxed{\text{SPIN-0}}$ COUPLING ~ YUKAWAS

↳ immediately think Higgs portal!

OPTIONS: SCALAR ✓ vs. PSEUDOSCALAR

↓

does not contribute in NR limit (derivative interaction) [cf 1011.3519]

SO EITHER REAL SPIN 0^+ OR $\mathbb{C}$ FIELD WORKS.

LET $\varepsilon^2 = \frac{g_\mu g_p}{e^2}$ $\Rightarrow$ $\Delta r_p^{2\,(\mu)} = -6\varepsilon^2 \frac{f(a_\mu m)}{m^2}$

α'/α

$\Delta r_p^{2(e)} = -6\varepsilon^2 \frac{m_e}{m_\mu} \frac{1}{m^2}$

USING $f(a_e m) \to 1$

& fit to $\Delta r_p^{2\,(\mu)} - \Delta r_p^{2\,(e)} = -0.063\ \mathrm{fm}^2$

SEE PI GUYS' PAPER & notebook

note: our ε^2 differs from theirs

BALLPARK ESTIMATE: $\boxed{\boxed{\varepsilon^2 \sim 10^{-6}}}$ ← CHECK THIS.

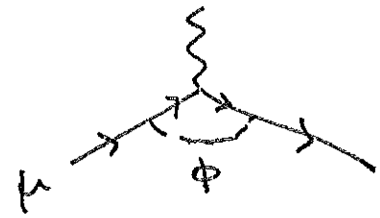
↳ nb PI guys: e-coupling $\frac{g_e g_p}{e^2} \sim 1.3 \times 10^{-8}$

so now we have a target

$$\boxed{\frac{g_\mu g_p}{e^2} \sim 10^{-6}}$$

IN FACT, IN "KICKSTARTER" FASHION, THERE'S ALSO AN IMMEDIATE "REACH" GOAL!

WE KNOW μ-SPECIFIC (i.e. LEPTON NON-UNIVERSAL) FORCES CAN BE APPLIED TO THE $(g-2)_\mu$ ANOMALY



- only depends on g_μ
- sensitive to both SPIN-0^+ AND $\boxed{0^-}$

see Carlson & Rislow

Pseudoscalar: DIDN'T DO ANYTHING FOR r_p B/C DOESN'T AFFECT NON-RELATIVISTIC MEASUREMENT OF r_p.

BUT CONTRIBUTES @ SAME ORDER AS SCALAR IN $(g-2)_\mu$

in fact, CONTRIBUTES w/ OPPOSITE SIGN → DESTRUCTIVE INTERF.

We can actually use this.

IN FRACTIONAL TERMS, r_p DISCREPANCY IS $\mathcal{O}(10^4)$ LARGER THAN $(g-2)_\mu$ & ANY PARTICLE CONTRIBUTING TO THE LAMB SHIFT WILL ~~[illegible]~~ ALSO CONTRIBUTE TO $(g-2)_\mu$.

↳ SO YOU MIGHT NEED TO ENGINEER/TUNE A CANCELLATION.

~~anyway — we're getting ahead of ourselves. WE HAVEN'T ESTABLISHED THAT LNB CAN SOLVE r_p PROBLEM!~~

More:

Carlson & Rislow : $m \sim \mathcal{O}(100)$ MeV

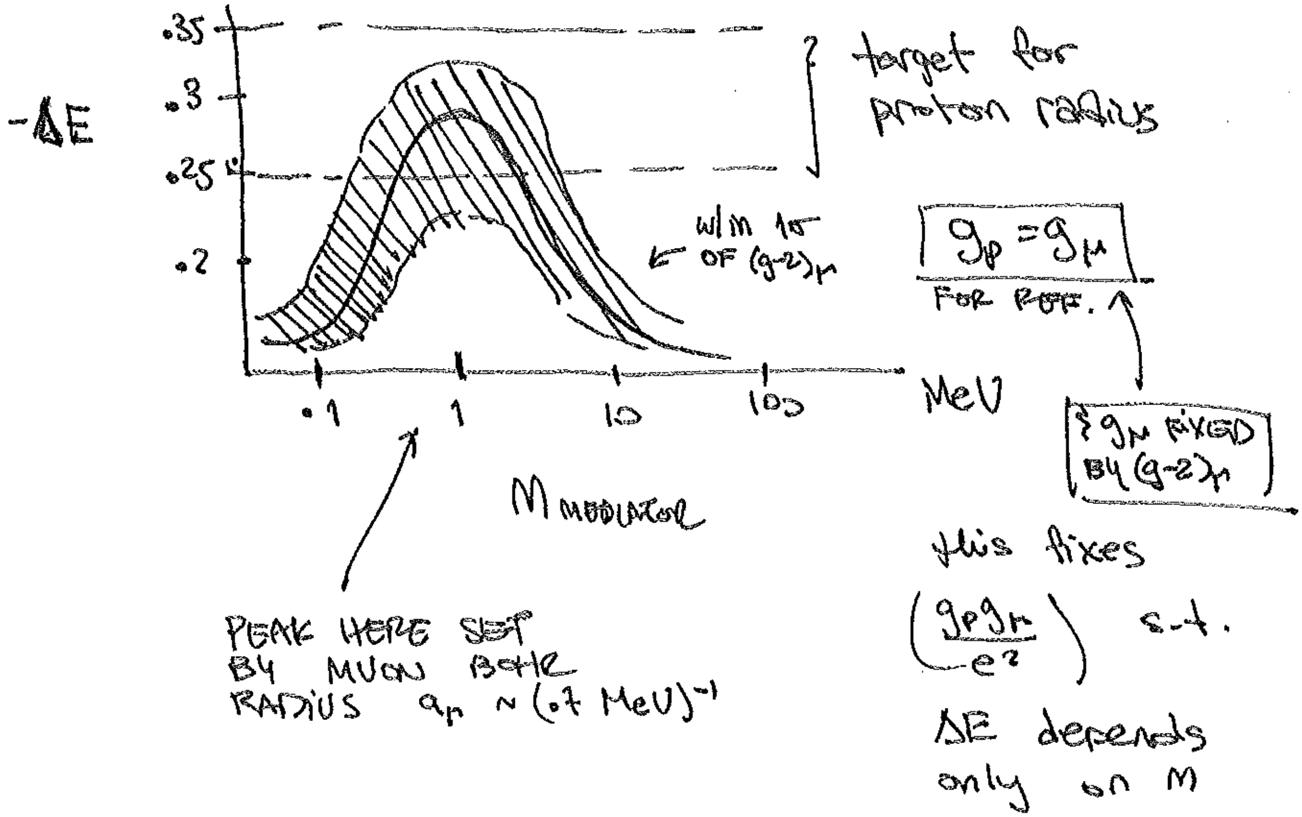
↳ require a tuning
IN FACT, MAYBE IT'S EVEN A FINE-TUNING.

<u>DTS & Tray</u> : $m \sim \underbrace{\mathcal{O}(.1) - \mathcal{O}(100)}$ MeV

in this mass range
$m < m_\mu$ & target
for muon coupling g_μ
is insensitive to m.

for $m \ll m_\mu \Rightarrow \boxed{\frac{g_\mu}{e} \sim 10^{-3}}$
SAT. at

A NICE PLOT FOR ESTIMATES (DTS & TRAY)



this fixes
$\left(\frac{g_p g_\mu}{e^2}\right)$ s.t.
ΔE depends
only on m

but we're getting ahead of ourselves

WE'VE ESTABLISHED WHERE WE WANT TO GO, $\left(\frac{g_\mu g_p}{e^2}\right) \sim 10^{-6}$, BUT NOW WE HAVE TO SEE WHAT STANDS IN OUR WAY.

1. BIGGEST CONSTRAINT: <u>neutron-Pb scattering</u>

↳ Barbieri & Ericson (1975) (Phys Lett 57B)

in fact, almost exact same story
ANOMALY IN ATOMIC TRANSITIONS OF π'ic ATOMS
MAYBE NEW BOSON → YUKAWA POTENTIAL?

<u>BUT</u>: n SCATTERING ON HEAVY NUCLEI (in keV region for STUDYING n ELECTRIC POLARIZABILITY) GIVES A VERY SPECIFIC <u>ANGULAR DISTRIBUTION</u> COMING FROM THE STRONG FORCE

INTERFERENCE w/ A WEAKLY COUPLED SCALAR EXCHANGE DIAGRAM WILL MODIFY THE ANGULAR DISTRIBUTION.

Result: $\boxed{\frac{g_n^2}{4\pi}\left(\frac{\text{MeV}}{M}\right)^4 < 3\times 10^{-11}}$

≈1 for us.

cf. $\boxed{\frac{g_\mu g_p}{e^2} \sim 10^{-6}}$

<u>IN FACT</u>: LIGHT HIGGS SEARCH FOR $\phi \to e^+e^-$ PUSHES US TO $\boxed{M < 2M_e}$

SO CAN'T USE THIS FACTOR TO HELP.

so: $\frac{e^2}{4\pi} \sim \frac{1}{100}$, $4\pi \sim 10$, $e^2 \sim \frac{1}{10}$

TYPICALLY EXPECT $g_p = g_n$

$10^{-7} \sim g_\mu g_p \sim g_n^2 < 10^{-9}$

if $g_\mu = g_p$... but this is preferred by $(g-2)_\mu$

$\left(\frac{g_\mu}{e}\right)\left(\frac{g_p}{e}\right) \sim 10^{-6}$ & $\left(\frac{g_\mu}{e}\right) \sim 10^{-3}$

So this kinda sucks, by about $\mathcal{O}(100)$.

WHAT TO DO: make $g_p = g_n$ SMALL
$\Downarrow$
make g_μ LARGE
BUT THEN $(g-2)_\mu$ BECOMES A BOUND, NOT AN OPPORTUNITY
(ie YOU OVERSHOOT)

BUT I'M FROM UCI, SO MAYBE I CONSIDER ~~ISOSPIN~~,
$g_p \neq g_n$ in such a way that $g_p \gg g_n$.
↑ we'll explore this.

OTHER BOUNDS

2. $(g-2)_{\mu,e}$ ← already mentioned $(g-2)_\mu$

$(g-2)_e$ is ACTUALLY USED TO DEFINE α
↳ SHIFT IN $(g-2)_e$ → SHIFT IN α

$$\Delta\alpha = 2\pi \Delta a_e$$

↑ this is $(g-2)_e/2$ NOT BOHR RADIUS

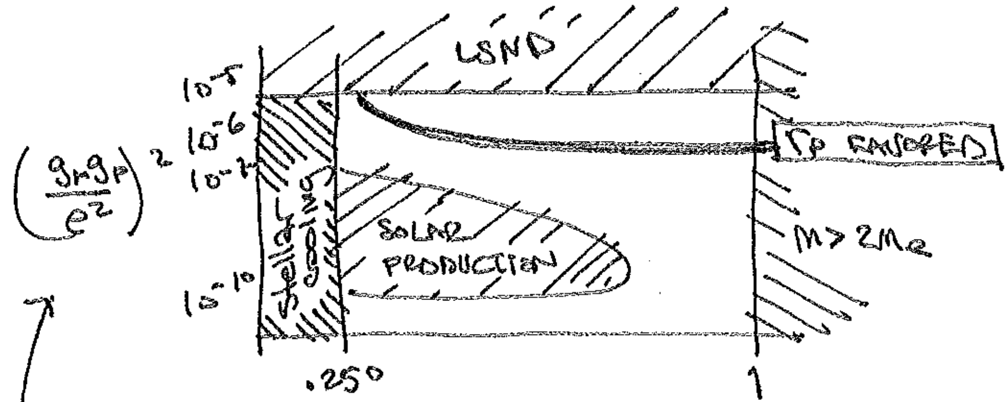
& CHECK VS. Rb & Cs ATOM CHECKS.
SEE REFS IN DTS & IRAY.

RESULT: $\frac{\alpha}{2\pi}\left(\frac{g_e}{e}\right)^2 \underbrace{\int_0^1 \frac{(1-z)^2(1+z)}{(1-z)^2+(m/m_e)z}\,dz}_{\to 3/2} < \frac{\alpha}{2\pi}\, 15\times 10^{-9}$

$$\Rightarrow \boxed{\frac{g_e}{e} \lesssim 10^{-4}} \quad \text{for } m \sim \text{MeV}$$

→ also $g_\mu^2 \lesssim 10^{-6}$ from $\left(\frac{m_\mu}{m_e}\right)$ factors

3. ASTROPHYSICS & LIGHT PARTICLE BOUNDS
from PI GUYS



← we're OK down to $\frac{1}{4}$ MeV

nb I RESCALED THEIR BOUNDS, WHICH WERE CAST IN TERMS OF $(g_e g_p)$.

4. others : FLAVOR (kaon decays to μ)
OTHER ATOMIC SYSTEMS w/ μ.

anyway, 1-3 are the big ones.

Now get back to model building

So I WANT: ① HIGGS PORTAL → nonuniversal couplings
→ also automatically gives couplings to quarks & leptons

SOMETHING LIKE $\phi^2|H|^2$ & RELATED TERMS

$$\boxed{\begin{array}{l} \text{w/ } m \in [\tfrac{1}{4}, 1]\,\text{MeV} \\ \dfrac{g_p g_\mu}{e^2} \sim 10^{-6} \\ \dfrac{g_n}{4\pi} < 10^{-11} \end{array}}$$

② ISOSPIN VIOLATION → $g_n \ll g_p$
TO AVOID n-Pb scattering BOUND.

Simplest Higgs portal doesn't work
→ can only really play w/ mixing w/ Higgs
→ cannot further discriminate between $\underbrace{g_p, g_n \text{ \& } g_\mu}_{\text{IDEALLY INDEP.}}$

RECALL COUPLING OF SCALAR (HIGGS) TO NUCLEONS
(SHIFMAN et al, triumph of HIGGS low-E thm — see DIRECT DETECTION REVIEWS)

$$\sum_{q} c_q m_q \phi \bar{q} q \longrightarrow c_N m_N \phi \bar{N} N \quad (\text{assume } c_g = 0)$$

$$c_N \equiv \sum_{q=uds} c_q \underline{f_q^{(N)}} + \frac{2}{27} f_G^{(N)} \left(\sum_{q'=cbt} c_{q'} \right)$$

NUCLEAR FORM FACTORS

only this has some discrimination between proton & neutron.

DARKSUSY: eg $f_u^{(p)} = 0.023$ $\quad f_u^{(n)} = 0.019$
$f_d^{(p)} = 0.034$ $\quad f_d^{(n)} = 0.041$

CAN SEE THAT YOU'LL NEED TO TUNE c_q's A BIT.

<u>other options</u>

PROBLEM IS THAT IN $c_q m_q \phi \bar{q} q + c_\ell m_\ell \phi \bar{\ell} \ell$

$c_q = c_\ell$ = UNIVERSAL

so to discriminate P from n, need to be able to tune c_u vs c_d.

I. More hidden sector ~~(...)~~

~~(Higgs portal) Portal~~ HIDDEN HIGGSES

INTRODUCE INERT (NO VEV) HIGGS $\tilde{H}$ (DOUBLET) WHICH ONLY COUPLES TO, SAY, UP-TYPE.

~~THEN YOU STILL GET THE~~
THEN MIX ϕ WITH $\tilde{H}$ TO GET A DIFFERENT ϕ COUPLING TO UP QUARKS

<u>But</u>: flavor constraints
YOU HAVE TO ENGINEER (OR ASSUME) THAT $\tilde{H}$ HAPPENS TO ALSO COUPLE PORORTIONALLY TO THE SM YUKAWAS.

II MORE VISIBLE SECTOR

↳ MORE HIGGSES. eg 2HDM IS WELL MOTIVATED.

→ SPENT LOTS OF TIME PLAYING W/ THIS IN ASPEN, ENDS UP NOT WORKING, WE <u>THINK</u>.

↑

because we weren't clever enough to diagonalize the 3x3 subject to our constraints.

[DEF. DOESN'T WORK IN THE SMALL MIXING LIMIT WHICH IS THE OBVIOUS FIRST ATTEMPT]

Some issues w/ 2HDM

→ Pheno: HEAVY HIGGS SEARCHES CONSTRAIN PARAMETER SPACE

→ ~~[illegible]~~ CONSTRAINTS
IN THE SMALL MIXING LIMIT, END UP w/

$$C_p = d_u\,(0.14) + d_d\,(0.23)$$
$$C_n = d_u\,(0.14) + d_d\,(0.24)$$

PARAMS.
(func of mixings)

sums of form factors

HAVE TO TUNE AT LEAST TO 1% TO CANCEL C_n

then you also know that $C_\ell = d_d \frac{m_\ell}{m_n}$
for type II

these have bounds from
$(g-2)_{e,\mu}$

SO YOU CAN'T JUST TUNE THE MIXINGS IN THE QUARKS TO CANCEL C_n, THEN PUMP UP C_p TO HIT f_p TARGET,

B/C THIS "PUMPING UP" ALSO PUSHES C_ℓ TOO LARGE!

I CAN TRY OTHER 2HDM, BUT IF u & d TALK TO ONE HIGGS, no room to tune away C_n.

IF ℓ & u, same prob. as above.

So what now?

PROJECT SHELVED B/C OTHER IDEAS CAME UP.
BUT WE HAVE A LOT OF WORK ALREADY DONE
(Mathematica notebooks, DRAFT)

& WE'RE LOOKING FOR COLLABORATORS (GRAD STUDENTS?)
INTERESTED IN PLAYING WITH THIS.

Ways forward

1. LARGE MIXING IN 2HDM
   ↳ MIXING COULD GIVE CANCELLATIONS
   (this is what happens in 1HDM
   & in SEE-SAW)

2. 3HDM? still 3 nontrivial benchmarks ...

3. Bigger hidden sector?

4. connection to Dark Matter?
   ↳ WE'VE BASICALLY BEEN RIFFING ON
   THE HIGGS PORTAL.
   CAN WE USE ϕ AS A MEDIATOR?

⋮ others?

OnGoing EXPTS

- MUSE: (2016 start??) μ-P SCATTERING
- other μ'ic ATOMS (deuterons?)