Possible Extensions of the Standard Model and M∅ller Scattering Non SUSY

John N Ng

Triumf

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Our Missions

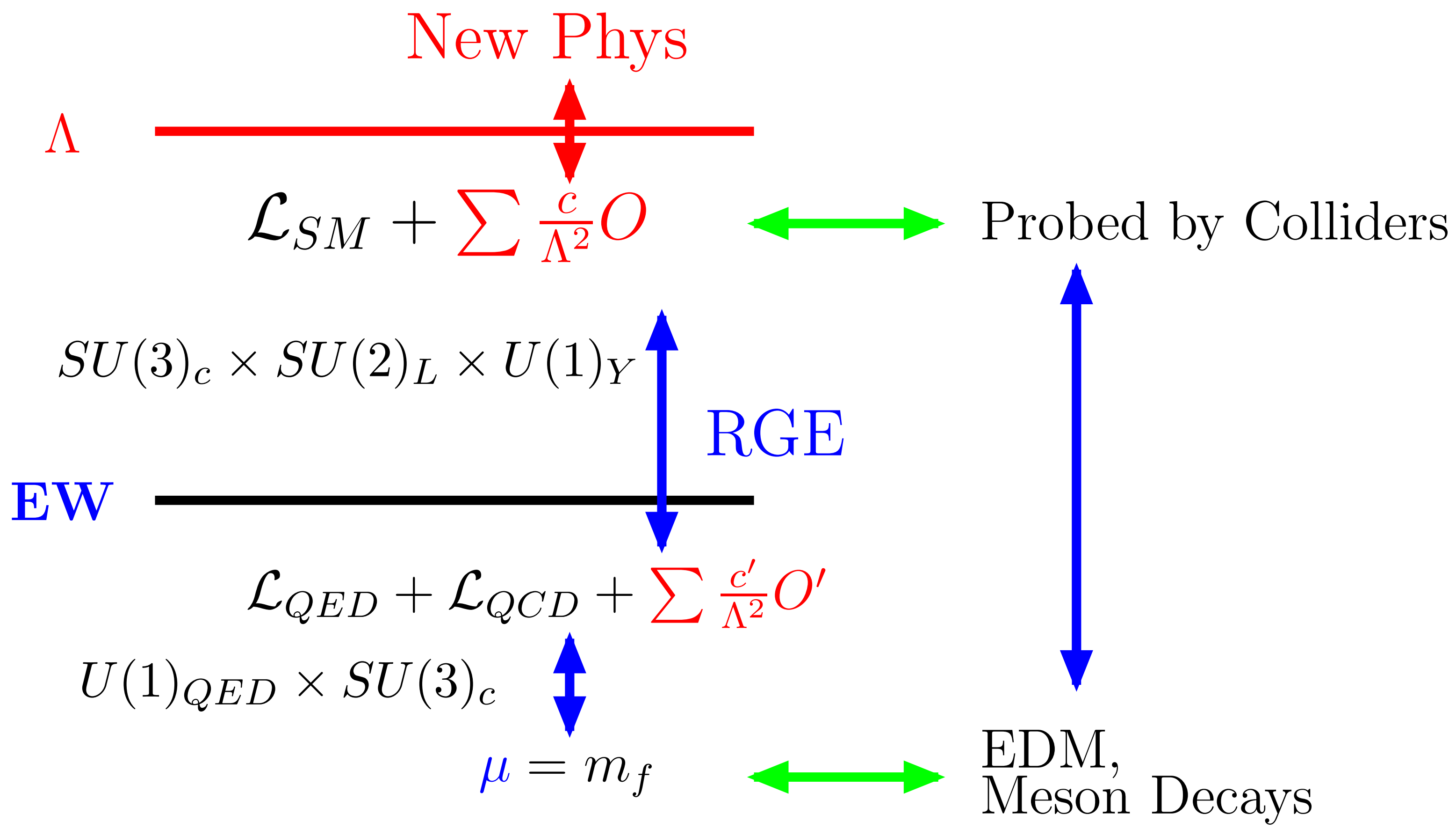
The aim of physics is to find new terms in the Hamiltonian of the universe. Everything else is chemistry.

M. Schwartz

SM Rules

- The SM is phenomenally successful.
- No one believes it is the final theory
  (a) Too many parameters (19 + ν parameters)
  (b) Higgs sector is unstable under quantum corrections
  (c) Neutrino masses and fermion masses in general are not understood
  (d) Gravity remains outside the framework
- **There must be new physics lurking behind it**
- How to find it?
  (a) Build ever more elaborate models that solve some of the problems
  (b) Take a Effective Theory Approach similar to Fermi's

Effective Operators approach—Cartoon



Effective Operators

View the SM as an effective theory at the weak scale $v \sim$ 250 GeV.
The Lagrangian is then

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_5}{\Lambda_5}\mathcal{L}_5 + \frac{c_6}{\Lambda_6^2}\mathcal{L}_6 + \cdots$$

- $\mathcal{L}_{SM}$ is the SM Lagrangian and contains only dimension 4 operators renormalizable

$$\mathcal{L}_{SM} = \bar{\Psi}\gamma^\mu D_\mu \Psi - \frac{1}{4}F^{\mu\nu}\cdot F_{\mu\nu} + |D_\mu \Phi|^2 + y\bar{\Psi}\Psi\Phi - V(\Phi) + h.c.$$

(a) $D_\mu = \partial_\mu - igT \cdot A_\mu$ is the covariant derivative. A_μ are all the gauge fields

(b) Ψ represents all the fermions of the SM 15 per family or 16 if N_R is very light or massless

(c) Φ is the Higgs field which give masses to all particles.

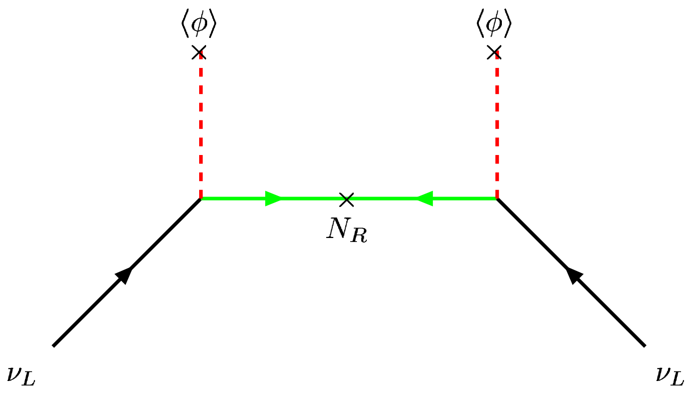
Rules for constructing EFT

- Decide on the gauge symmetry and global symmetries betwee new physics and the electroweak scale $v = 174$ GeV. Extended guage symmetries
- The spacetime symmetry
  (a) Extra fermionic corodinates $\rightarrow$ supersymmetry
  (b) Bosonic coordiantes
- The operators must be **invarant** under these symmetries
- Other degrees of freedom other than the SM
- These operators mix under renormalization (loops invovling SM particles)
- Use the renormalization group to run the coefficients from one scale to the another after accounting for mixings.
- In general $\Lambda_5 \neq \Lambda_6$

Dim 5 Neutrino Mass term

- $\mathcal{L}_\nu$ is the seasaw neutrino mass term if N_R is above several TeV

$$\mathcal{L}_\nu = \frac{1}{\Lambda_N} \nu^c \nu \Phi \Phi$$



- If neutrinos are Dirac particles then this term does not exist and we fine tune the Yukawa's

Our assumptions for higher dim operators

- The SM is good to some scale $\Lambda \sim O(TeV)$
- The gauge group is $SU(3)_c \times SU(2) \times U(1)$ and the acccidental global symmetry of $U(1)_{B-L}$
- Most theories with extended gauge symmetry has this feature.

  e.g. $SU(2)_R \times SU(2)_L \times U(1) \xrightarrow{\Lambda} SU(2)_L \times U(1)$
- **No** extra degrees of freedom. Not even N_R
  - (a) If there are new states such as superpartners or additional Higgs just construct terms including them
  - (b) The rules of construction are the same.
- The terms that are allowed has to be invariant under the symmetries of the SM
- The reason for this being any terms that do not obey the SM symmetry will grossly precision measurements.

  They must be very small.

Types of Dim 6 operators I

- Involving only gauge bosons, e.g. $G^{\mu\nu}$ denotes any of the SM gauge fields

$$\frac{1}{\Lambda^2} G_{\mu\rho} G^{\rho\omega} G^{\mu}_{\omega}$$

$G = W$ term modifies W-boson magnetic moment and dipole moment.

- Gauge bosons and Higgs; e.g.

$$\frac{1}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} \phi\phi$$

After SSB they modify the SM Higgs production and decay.

(a) $h \to gg$

(b) $h \to \gamma\gamma$

Important for LHC

Dim 6 operators II

- Involving Two fermions gauge bosons and Higgs, important examples are the magnetic and electric dipole moment operators

$$C_D(\mu^2)\frac{1}{\Lambda^2}\bar{\Psi}_L\sigma^{\mu\nu}\Psi_R G_{\mu\nu}\phi$$

c_D the Wilson coeff of the operator. μ is scale dependence.

- After SSB they contribute to $g-2$ and EDM d_f of the fermion involved.
- The precision which has been achieved for muon and electron limits

$$|C_D^{e,\mu}| < 10^{-10}(\Lambda/\mathrm{Te}V)$$

- We will set $c_D = 0$ at tree level

Dim 6 4-fermi operators most relevant for Low Energy Phyiscs

- The pure leptonic list of vector operators $L = (\nu e)_L \text{and} e = e_R$

$$\mathcal{L}_V^6 = \frac{c_{LL}}{\Lambda^2}(\bar{L}_{ia}\gamma^\mu L_{ja})(\bar{L}_{kb}\gamma_\mu L_{lb}) + \frac{c_{LR}}{\Lambda^2}(\bar{L}_{ia}\gamma^\mu L_{ja})(\bar{e}_k\gamma_\mu e_l) + \frac{c_{RR}}{\Lambda^2}(\bar{e}_i\gamma^\mu e_j)(\bar{e}_k\gamma_\mu e_l) + \frac{d_{LL}}{\Lambda^2}\left(\bar{L}_{ia}\gamma^\mu L_{jb}\right)\left(\bar{L}_{kb}\gamma_\mu L_{la}\right) + h.c.$$

- We have assumed that the coefficients are family independent.
- The scalar operators are not family independent in general

$$\mathcal{L}_s = \sum \frac{c_S^{ii,jj}}{\Lambda^2}\overline{L_i}e_{Ri}\overline{e_{Rj}}L_j + h.c.$$

- Tensor operaotrs $O_T = (\bar{L}\sigma^{\alpha\beta}e)(\bar{e}\sigma_{\alpha\beta}L)$ is identically zero.

If light Sterile Netrinos Exist

The list of additional 4-fermi operators with ν_R are

$$\begin{aligned} Q_1 &= \left(\overline{e^i_R}\gamma^\mu \nu^j_R\right)\left(\overline{\nu^k_R}\gamma_\mu e^l_R\right) \\ Q_2 &= \left(\overline{L^i}\nu^j_R\right)\left(\overline{\nu^k_R}L^l\right) \\ Q_3 &= \left(\overline{L^i_a}e^j_R\right)\left(\overline{L^k_b}\nu^l_R\right)\epsilon^{ab} \\ Q_4 &= \left(\overline{L^i_a}\sigma^{\mu\nu}e^j_R\right)\left(\overline{L^k_b}\sigma_{\mu\nu}\nu^l_R\right)\epsilon^{ab}. \end{aligned}$$

where a, b are $SU(2)$ indices. These have to be included when there is evidence for light sterile neutrinos.

Semileptonic 4-fermi operaotrs

- In the mass basis and with no flavor violation in vector coefficients ($i, j, k.l$ are family indices

$$-\Lambda^2 \mathcal{L}_6 = \sum_{A=1}^{7} C_{VA}^{ii,kk} O_{VA}^{ii,kk} + \sum_{A=1}^{2} C_{SA}^{ij,kl} O_{SA}^{ij,kl} + C_T^{ij,kl} O_T^{ij,kl} + h.c.$$

- The Wilson operators are

$$\begin{aligned}
O_{V1}^{ij,kl} &= (\bar{Q}^i \gamma^\mu Q^j)(\bar{L}^k \gamma_\mu L^l)\,, \\
O_{V2}^{ij,kl} &= (\bar{Q_a}^i \gamma^\mu {Q_b}^j)(\bar{L_b}^k \gamma_\mu {L_a}^k)\,, \\
O_{V3}^{ij,kl} &= (\bar{Q}^i \gamma^\mu Q^j)(\bar{e}^k \gamma_\mu e^l)\,, \\
O_{V4}^{ij,kl} &= (\bar{d}^i \gamma^\mu d^j)(\bar{L}^k \gamma_\mu L^l)\,, \\
O_{V5}^{ij,kl} &= (\bar{u}^i \gamma^\mu u^j)(\bar{L}^k \gamma_\mu L^l)\,, \\
O_{V6}^{ij,kl} &= (\bar{d}^i \gamma^\mu d^j)(\bar{e}^k \gamma_\mu e^l)\,, \\
O_{V7}^{ij,kl} &= (\bar{u}^i \gamma^\mu u^j)(\bar{e}^k \gamma_\mu e^l)\,,
\end{aligned}$$

- They affect neutral current measurements

SL operators II

- the scalar and tensor operators

$$
\begin{aligned}
O_{S1}^{ij,kl} &= (\bar{Q}^i d^j)(\bar{e}^k L^l)\,, \\
O_{S2}^{ij,kl} &= (\bar{Q_a}^i u^j)(\bar{L_b}^k e^l)\epsilon^{ab}\,, \\
O_{T}^{ij,kl} &= (\bar{Q_a}^i \sigma^{\mu\nu} u^j)(\bar{L_b}^k \sigma_{\mu\nu} e^l)\epsilon^{ab}\,,
\end{aligned}
$$

- The scalar ones affect meson decays $\pi(K) \to l\nu$ and $K \to \pi\mu\nu$
- Can be probed by beta -decay
- EDM
- If no new physics signature these are directly probed by LHC.

Operators for MØller scattering

For scattering with cm energy $\sqrt{s} \ll \Lambda$ the effective Lagrangian is

$$\begin{aligned}\Lambda^2 \mathcal{L} &= (c_{LL} + d_{LL})\bar{e}\gamma^\mu Le\ \bar{e}\gamma_\mu Le \\ &+ (c_{LR} - c_s)\bar{e}\gamma^\mu Le\ \bar{e}\gamma_\mu Re \\ &+ c_{RR}\bar{e}\gamma^\mu Re\ \bar{e}\gamma_\mu Re\end{aligned} \tag{I}$$

This is applicable to all polarizations of the 4 electrons.

Digression

As oppose to being conmpletely free the operators here are connected to other Low Eenrgy precision measurements becuse of the $SU(2) \times U(1)$ symmetry.

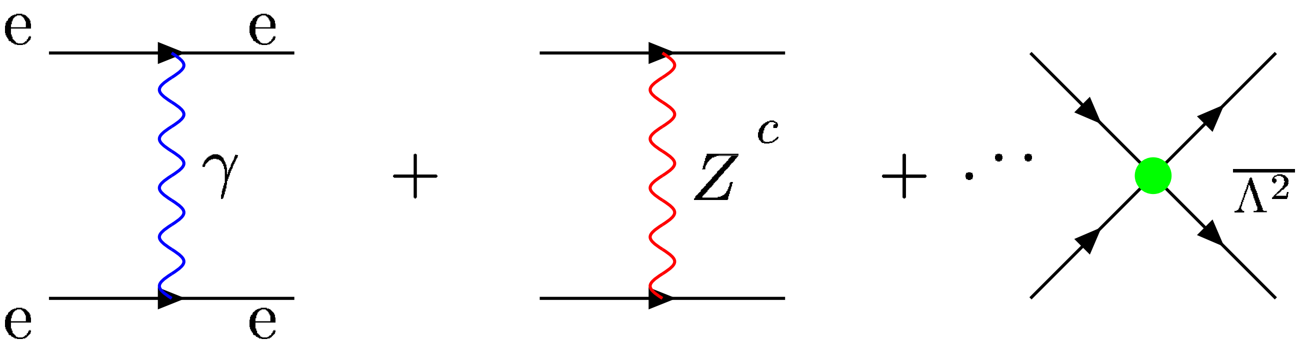
- $$\nu_i + e \to \nu_i + e$$

  The efffective Lagrangian is

  $$\Lambda^2 \mathcal{L} = (2c_{LL} + d_{LL})(\bar{\nu}_i \gamma^\mu L \nu_i)(\bar{e}\gamma_\mu L e)$$
  $$+ (c_{LR} - \frac{1}{2}c_s^i - \frac{1}{2}c_s^e)(\bar{\nu}_i \gamma^\mu L \nu_i)(\bar{e}\gamma_\mu R e)$$

  Due to the stringent limits now. Needs a intense ν facility.
- EDM of the electron is sensitive to $\Im\mathfrak{m} c_s$ at 2-loops.

Feynman Diagrams



+ cross terms

Polarized MØller Scattering :Tree Level Predictions

$$e^-(L,R)e^- \to e^- e^-$$

For $\Lambda^2 \gg s \gg m_e^2$ which is good for a 12 GeV exp

$$A_{LR} = \left(\frac{d\sigma_L}{dt} - \frac{d\sigma_R}{dt}\right)$$
$$= \frac{4G_\mu}{\sqrt{2}\pi\alpha}\,\frac{y(1-y)}{1+y^4+(1-y)^4}\left[\left(\frac{1}{4} - \sin^2\theta_W\right) + \frac{c'_{LL} - c_{RR}}{4\pi\alpha}\frac{M_W^2}{\Lambda^2}\right]$$

where $y = -\frac{t}{s}$ and $c'_{LL} = c_{LL} + d_{LL}$

Remarks

- Parameters $\sin^2\theta_W$ ect. are usually evaluted in the $\overline{\mathrm{MS}}$ scheme.
- Notice the scalar coefficients are not probed by this exp.
- Need one more spin measurements to do that
- $g_e - 2$ is not sensitive enough
- Semi-leptonic counter part is tested in $\pi \to e\nu$ and $K \to e\nu$

Limits from LEP

The direct limit comes from compositeness of the electron test from LEP

$$e^+e^- \to e^+e^-$$

at $\sqrt{s} = 103 - -207$ GeV. No Polarization.

- The parameterization by PDG is

$$\mathcal{L} = \frac{g^2}{2\Lambda^2}[\eta_{LL}(\bar{\psi}\gamma^\mu L\psi)(\bar{\psi}\gamma_\mu L\psi)$$
$$+ \eta_{RR}(\bar{\psi}\gamma^\mu R\psi)(\bar{\psi}\gamma_\mu R\psi)$$
$$+ 2\eta_{LR}(\bar{\psi}\gamma^\mu L\psi)(\bar{\psi}\gamma_\mu R\psi)]$$

  where the η's are ± 1.

- The limit is for $\Lambda^+_{LL} > 8.3$ and $\Lambda^-_{LL} > 10.3$ TeV
- No limit is given for RR or LR.
- Assumption $g^2(\Lambda)/4\pi = 1$.

E158

Using the same assumptions as PDG E158 alone gives

$$\Lambda \sim 6 - 14\text{TeV}$$

Very competitive with colliders.

: *Advantages and disadvantages of Effective Operators approach*

- Advantages
  (a) Independent of theoretical biases and based on data only.
  (b) Applicable to a wide range of models.
  (c) The limits on the parameters of new physics can be independently obtained without new data analysis.
- Disadvantages
  (a) Direct comparison with other experiments are limited
  e.g. Pol MØller scattering can be compared with LEP or ILC but not LHC or Fermi Lab data.
  (b) Only a combination of new physics parameters can be constrained .
  (c) Origin of the new physics is not obvious.
    (a) New Scale ?
    (b) Modification of SM effective neutral current couplings only? i.e. change in $\sin^2\theta_{eff}$
    (c) Both effects at play

Origin of the Dim 6 operators

In very general terms they can arise from

- At tree level of the new physics
  (a) Spin 1 exchange :$G \to G_{SM} \times U(1)' \to G_{SM}$ The new physics is the gauge boson of the extra $U(1)'$
  (b) Spin 0 exchange. Fierzing of a doubly charged Higgs. $\Psi^{\pm\pm}$
  (c) Loop effects such as SUSY
- In general the tree level gives large effect and the limits are stringent if there are direct couplings $\Lambda \gtrsim \mathrm{O(TeV)}$
- If due to loop then $\Lambda \gtrsim \mathrm{O(100)GeV}$ due to the suppressed couplings from the loop factors.

Extra Z

- Direct coupling to SM fermions
  (a) GUT inspired Z' usually from $SO(10)$ or E_6 resulting in an extra $U(1)$.
  (b) The lowest mass state of a tower of Kaluza-Klein excitations of the Z.
- No direct couplings to the SM fermions. String or brane world inspired extra $U(1)$
  (a) shadow $U(1)$. Only interacts through the Higgs sector.
  Chang, Wu, and JNN 06

  Kumar and Wells 06
  (b) Provide a Stuckelberg Mass to the Higgs.

  Feldman, Liu and Nath 06

An Old Z' Model

The best known is the E_6 Guts model. One possible gauge breaking route is

$$E_6 \longrightarrow SO(10) \times U(1)_\psi \longrightarrow SU(5) \times U(1)_\psi \times U(1)_\chi$$

The Z' is a linear combination

$$Z' = \psi \cos\beta + \chi \sin\beta$$

and the mixing angle is in general free.

- $\Lambda \to M'_Z$
- $c'_{LL} - c_{RR} \to \frac{\pi\alpha}{3\cos^2\theta_W} \cos\beta(2\cos\beta + \frac{5}{\sqrt{15}}\sin\beta)$
- Take the special case of $\beta \sim 0$
- The limit from MØller is $\Lambda > 840$ GeV

Extra Dimensions KK Z

- Consider the simplest 5D one extra spatial dim compactified in a circle of radius R
- $SU(2) \times U(1)$ in the bulk
- The spectrum of KK tower of Z boson is given by

$$M_{Z_n}^2 = M_Z^2 + \frac{n^2}{R^2} \quad (n = 1, 2, 3, \cdots)$$
$$\longrightarrow \frac{n^2}{R^2} \quad (nR^{-1} \gg M_Z^2)$$

- All the KK Z bosons have the same coupling to electrons as the SM Z
- The tower can be summed in the limit above

$$c_{LL} - c_{RR} \to \frac{4\pi\alpha}{4\cos^2\theta_W \sin^2\theta_W}(1 - 4\sin^2\theta_W)$$

- We get $R^{-1} > 6$ TeV from MØller alone
- LHC can at best see the lowest one or two KK modes.

Shadow Z_s

This is an example in which MØller is **not** sensitive to the mass scale of new physics. But very sensitive to how the new physics changes the effective NC couplings

The Model

- The gauge group is $SU(2)_L \times U(1)_Y \times U(1)_s$ in 4D
- The Lagrangian :

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{SM} - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} - \frac{\epsilon}{2} B^{\mu\nu} X_{\mu\nu} \\ &+ \left| \left(\partial_\mu - \frac{1}{2} g_s X_\mu \right) \phi_s \right|^2 - V(\phi_s, \Phi) , \end{aligned}$$

where $B_{\mu\nu}, X_{\mu\nu}$ are field strengths of $U(1)_Y, U(1)_s$. ϕ_s is the shadow Higgs.

- Notice the kinetic mixing term ϵ can arise from string theory of order $10^{-2} - 10^{-4}$.
- The potential is

$$\begin{aligned} V(\Phi, \phi_s) &= \mu_s^2 \phi_s^* \phi_s + \lambda_s (\phi_s^* \phi_s)^2 + 2\kappa \left(\Phi^\dagger \Phi \right) (\phi_s^* \phi_s) \\ &+ \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 . \end{aligned}$$

Φ is the SM Higgs. **NO** direct coupling to the SM fermions

Effects from the Shadow World

- Higgs mixing portal to new physics. Exotic Higgs decays such as invisible modes.
- $Z - Z_s$ mixing through ϵ and Higgs loop. Must necessarily be small.
- This arises becuse we have three neutral gauge bosons and they mix after SSB

$$\begin{bmatrix} B' \\ A_3 \\ X' \end{bmatrix} = \begin{bmatrix} c_W & -s_W & 0 \\ s_W & c_W & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\eta & -s_\eta \\ 0 & s_\eta & c_\eta \end{bmatrix} \begin{bmatrix} \gamma \\ Z \\ Z_s \end{bmatrix}$$

where $s_W = \sin\theta_W \, , c_W = \cos\theta_W$ and similarly for the rotation angle η. Also $s_\epsilon = \frac{\epsilon}{\sqrt{1-\epsilon^2}}$ The first rotation is the standard one that gives rise to the SM Z and the second one diagonalizes the mixing of the two Z bosons.

- The couplings of the Z-boson to fermions $(Z f F)$ is now modified due to the mixing

$$i\gamma^\mu \frac{e}{c_W s_W} \left[\left(c_\eta g_f^L - s_\eta s_W s_\epsilon Y_f^L \right) \left(\frac{1-\gamma_5}{2}\right) + \left(c_\eta g_f^R - s_\eta s_W s_\epsilon Y_f^R \right) \left(\frac{1+\gamma_5}{2}\right) \right]$$

and $g_f^{L,R} = T^3(f_{L,R}) - s_W^2 Q^f$ is the coupling of the SM Z to fermions.

Shadow World and MØller

- $\delta A_P{}^V$ can come from two sources
  - (a) $\gamma - Z_s$ interference. This is small because
    - (a) $Z_s ee$ coupling is suppressed
    - (b) Also a factor of $\frac{M_Z^2}{M_{Z_s}^2}$
  - (b) Modified Zee couplings effect is larger
- We have

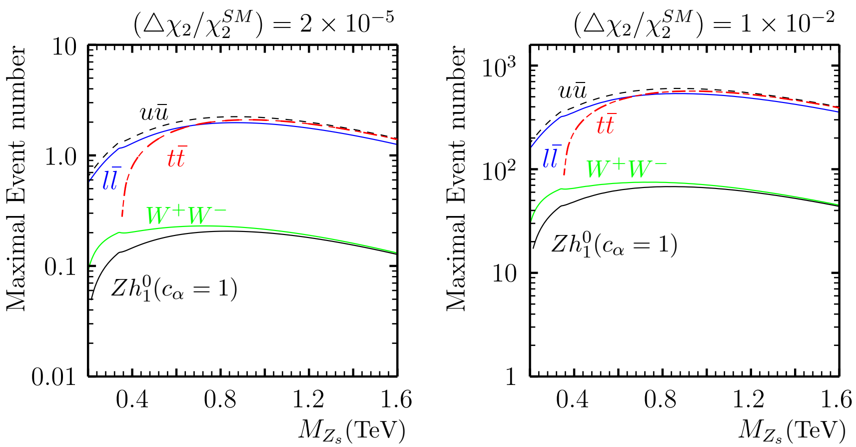
$$\frac{\delta A_P{}^V}{A_P{}^V} \simeq -[s_\eta^2 + 9.171 s_\eta^2 s_\epsilon^2 + 18.60 c_\eta s_\eta s_\epsilon]\,.$$

This translates into

$$\begin{aligned}\delta \sin^2\theta_{eff} &\simeq -\frac{1-4s_W^2}{4}\frac{\delta A_P{}^V}{A_P{}^V}\\ &\simeq 0.019\,[s_\eta^2 + 9.17 s_\eta^2 s_\epsilon^2 + 18.60 c_\eta s_\eta s_\epsilon]\end{aligned}$$

contd

- There are many constriants on the shadow world. Complete analysis see ref.
- At LHC Z_s can be produced by the Drell-Yan process.



The maximal expected number of Z_s events at the LHC for integrated luminosity of $100fb^{-1}$ For a given M_{Z_s}, we have used the largest allowed s_ϵ comes from the global fit studied in previous section. The left and right panes are for two deviations from SM fit respectively.
There is practically no event for $M_{Z_s} > 2$ TeV

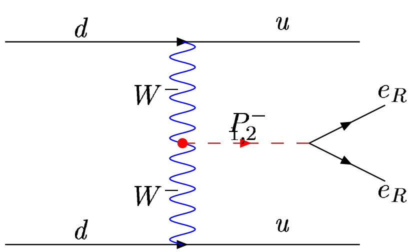
- MØller is independent of M_{Z_s} and still can be important even if NO were found at the LHC

Doubly Charged Scalars $P^{\pm\pm}$

- They are either $SU(2)$ singlet or triplet.
- They violate lepton number and used in generating Majorana masses for active neutrinos.
- Two varieties
  (a) Couple to SM lepton doublet $e_L e_L P^{++}$
  (b) Couple to the singlet $y_{ee} e_R e_R P^{++}$ [a]
- Effective coupling for the RR case is

$$\frac{y_{ee}^2}{M_P^2}(\overline{e_R^c} e_R)(\overline{e_R} e_R^c) = \frac{y_{ee}^2}{2M_P^2}(\bar{e}\gamma^\mu Re)(\bar{e}\gamma_\mu Re)$$

- The limit is $M_P > 6y_{ee}$ TeV
- This is ~ 3 times better than from $0\nu\beta\beta$ decays which goes by



if short distance physics dominates

[a] Chen, Geng and JNN 06

Conclusions

- Pol MØller scattering is probing new physics as via interference with the SM amplitude; hence it goes like c/Λ^2.
- It is theoretically very clean and physics interpretation is unambiguous
- It complements collider physics since the accuracy now is at the TeV scale
- For doubly charged scalars it is more sensitive to $0\nu\beta\beta$ if short distance dominates there. Otherwise it gives a more stringent constraint.
- In certain senarios it probes new physics via modified NC couplings when the scale beyond the reach of LHC or ILC.
- Here every factor of improvement helps.
- Good luck and happy hunting.