Model Independent Constraints on WIMPs Interactions from Standard Model RGEs

A.Crivellin, FD, M. Procura, PRL 112(2014) (arXiv:1402.1173)
FD and M. Procura (arXiv:141x.xxxx)

Francesco D'Eramo

15 October 2014, UC Irvine

BERKELEY LAB
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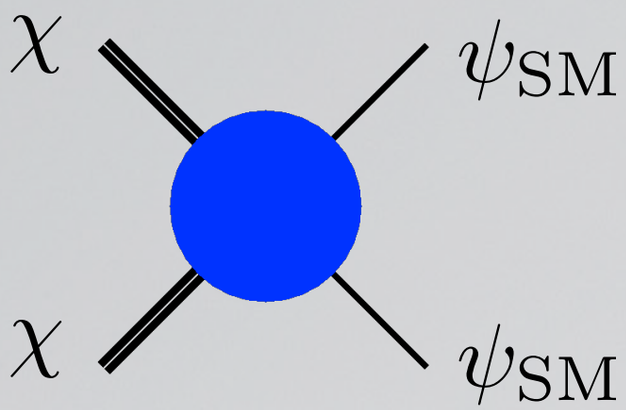
The Adolph C. and Mary Sprague Miller Institute for Basic Research in Science

Searching for WIMPs

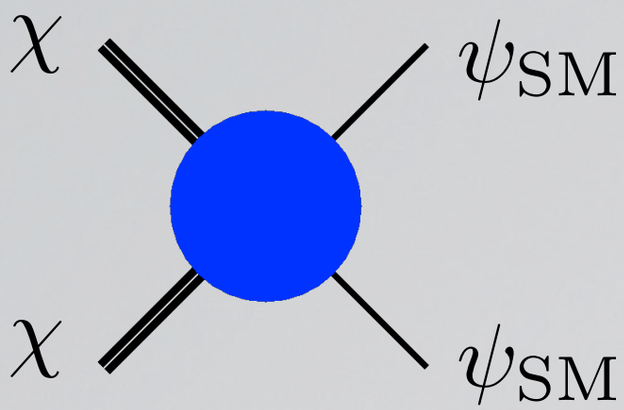


$m_\chi \simeq m_{\rm weak}$

$\langle \sigma v_{\rm rel} \rangle_{\chi\chi \to \psi_{\rm SM}\psi_{\rm SM}} \simeq 1 \text{ pb}$

- WIMPs theoretically motivated by the gauge hierarchy problem
- WIMP paradigm testable in multiple ways

Searching for WIMPs



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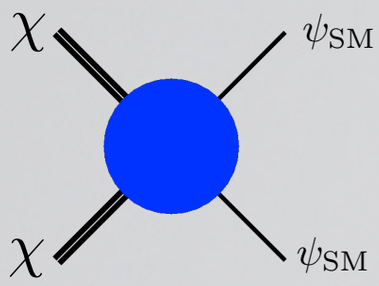
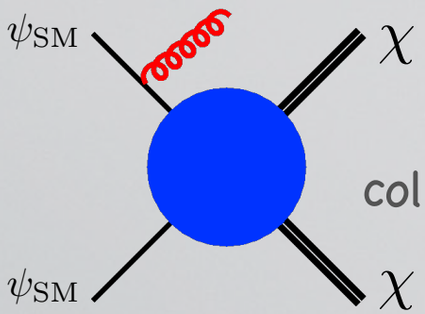


Indirect Searches

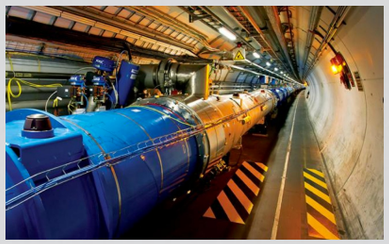
Milky Way WIMPs annihilations source of cosmic rays

FERMI GRT, Source: http://fermi.gsfc.nasa.gov



Collider Searches

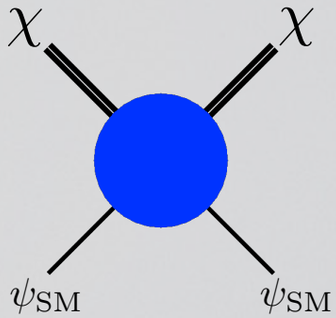
WIMPs may be pair-produced at colliders, accompanied by SM particles



LHC @ CERN, Source: http://home.web.cern.ch

Direct Searches

Milky Way WIMPs may scatter off target nuclei on the Earth



LUX detector, Source: http://lux.brown.edu

Energy Scales and EFT

Energy probed by collider and indirect searches

$$E_{\rm ind} \simeq E_{\rm col} \simeq m_\chi \simeq m_{\rm weak}$$

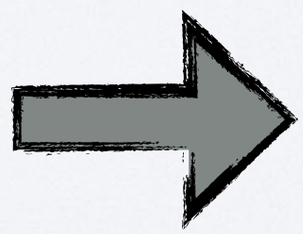
Direct Searches are sensitive to energies much smaller than the weak scale

$$\chi N \to \chi N$$

$$E_R^{\rm max} = \frac{4\mu_{\chi N}^2 v_\chi^2}{2M_N} \simeq 200\,{\rm keV}$$

(for Xe detector and $m_\chi \approx$ 1 TeV)

Large scale $\Lambda \gtrsim 1$ TeV and we are interested in physics at energies $E \approx E_R \ll \Lambda$



Treatable within EFT framework

EFT for Direct Detection

$$\overline{\chi}\gamma^\mu\chi\,\overline{q}\gamma_\mu q \qquad \overline{\chi}\sigma^{\mu\nu}\chi\,F_{\mu\nu} \qquad \overline{\chi}\chi\,\overline{q}q \qquad \overline{\chi}\chi\,G_{\mu\nu}G^{\mu\nu}$$

Wilsonian Operator Product Expansion

$$\mathcal{L}^{\text{eff}} = \sum C_i(\mu)\,\frac{\mathcal{O}_i(\mu)}{\Lambda^{d_i-4}}$$

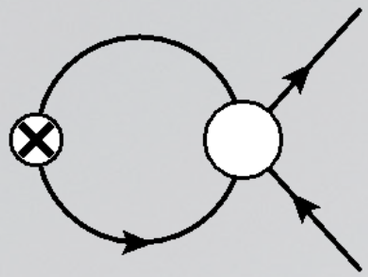
Factorization of short-distance (coefficients) and long-distance (operators)

$$d\Gamma \propto |C_i(\mu_N)|^2\,|\langle\mathcal{N}|\mathcal{O}_i(\mu_N)|\mathcal{N}\rangle|^2$$

Encodes unresolved dynamics at scales between Λ and μ_N

Low-energy contribution

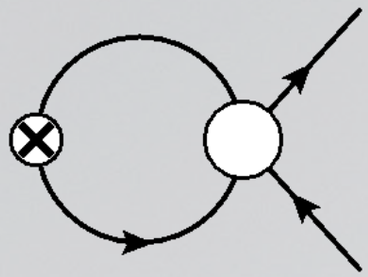
Is This Relevant?



$$\frac{\lambda_t^2}{4\pi^2} N^c \log\left(\frac{10\,\mathrm{TeV}}{1\,\mathrm{GeV}}\right) \simeq 1$$

Should we worry about order of a few corrections in a pre-discovery era?

Is This Relevant?



$$\frac{\lambda_t^2}{4\pi^2} N^c \log\left(\frac{10\,\mathrm{TeV}}{1\,\mathrm{GeV}}\right) \simeq 1$$

Should we worry about order of a few corrections in a pre-discovery era?

Yes! And This is Why

- Only light quarks and gluons as targets
- Different sensitivity for different operators

Goodman and Witten, PRD31 (1985)

D5	$\overline{\chi}\gamma^\mu\chi\,\overline{q}\gamma_\mu q$	SI
D6	$\overline{\chi}\gamma^\mu\gamma^5\chi\,\overline{q}\gamma_\mu q$	SI v^2 and SD q^2
D7	$\overline{\chi}\gamma^\mu\chi\,\overline{q}\gamma_\mu\gamma^5 q$	SD v^2 or q^2
D8	$\overline{\chi}\gamma^\mu\gamma^5\chi\,\overline{q}\gamma_\mu\gamma^5 q$	SD

Goodman et al., PRD82 (2010) (arXiv:1008.1783)

Effective Operators Mix Under RGE

Plan for Today's Talk

Energy Scales Connection in 3 Steps

RGE from Mediators to EWSB Scale

Integrating-out EW States

RGE from EWSB to Nuclear Scale

Applications to Direct Searches

Outlook

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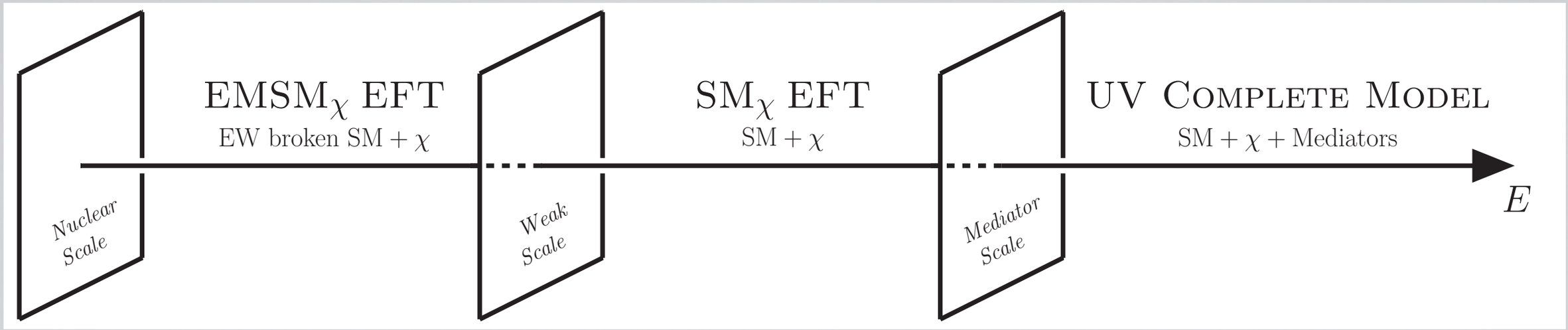
Outlook

Scales Connection via EFT

Conceptual starting point:
UV complete model for SM gauge singlet fermion WIMP



Mediators are integrated-out, model matched onto the SMχ EFT

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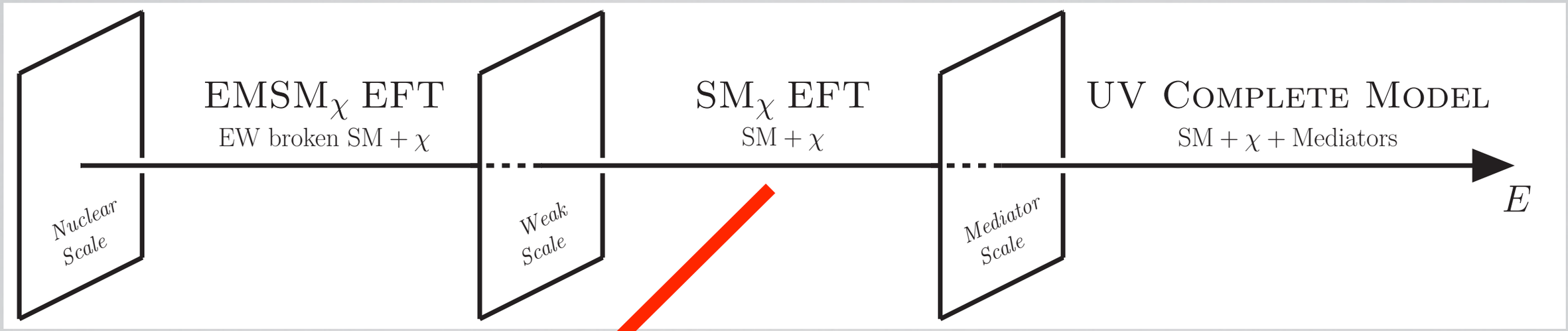

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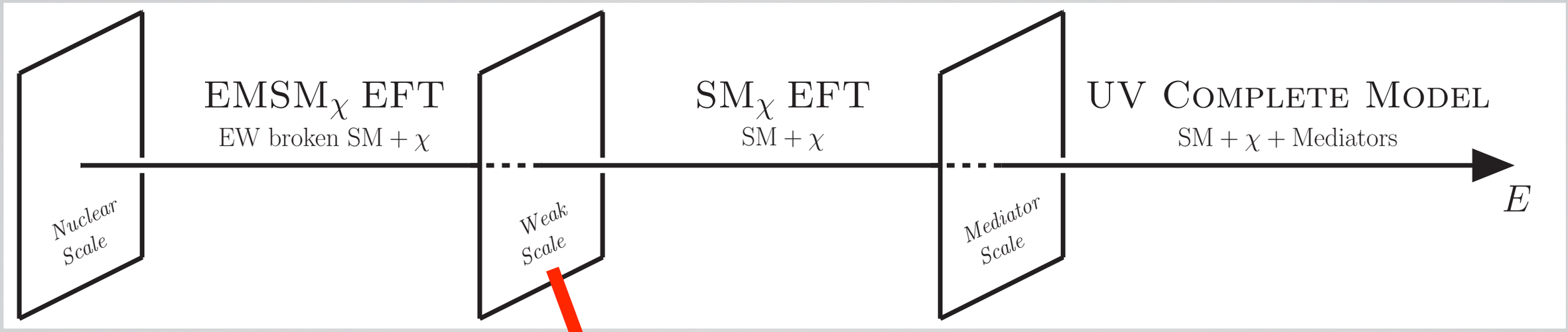

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- RG Evolution between Λ and m_{weak}
- Integrate-out ElectroWeak d.o.f. (t, W, Z, h), match onto the EMSM$_\chi$ EFT

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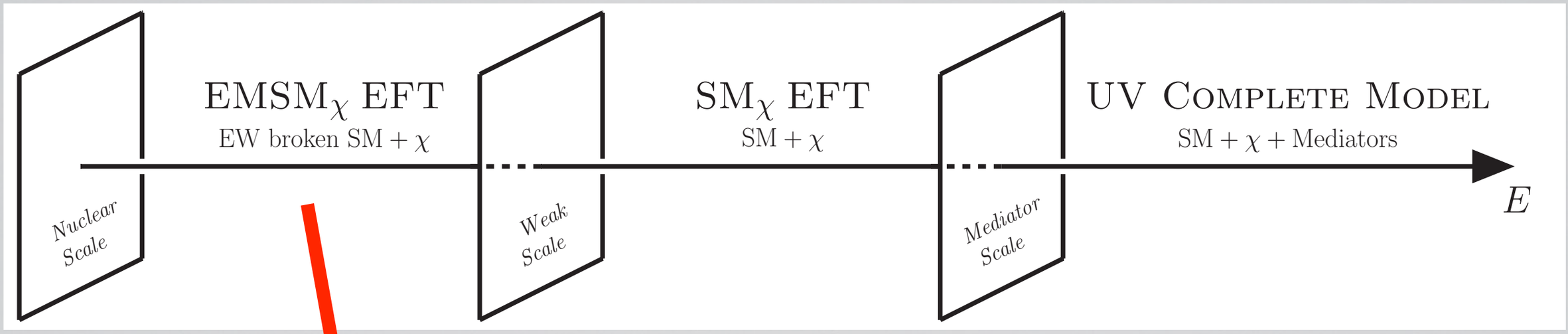

Mediators are integrated-out, model matched onto the SMχ EFT

- RG Evolution between Λ and m_{weak}
- Integrate-out ElectroWeak d.o.f. (t, W, Z, h), match onto the EMSM$_\chi$ EFT
- RG Evolution between m_{weak} and the Nuclear Scale

Scales Connection via EFT

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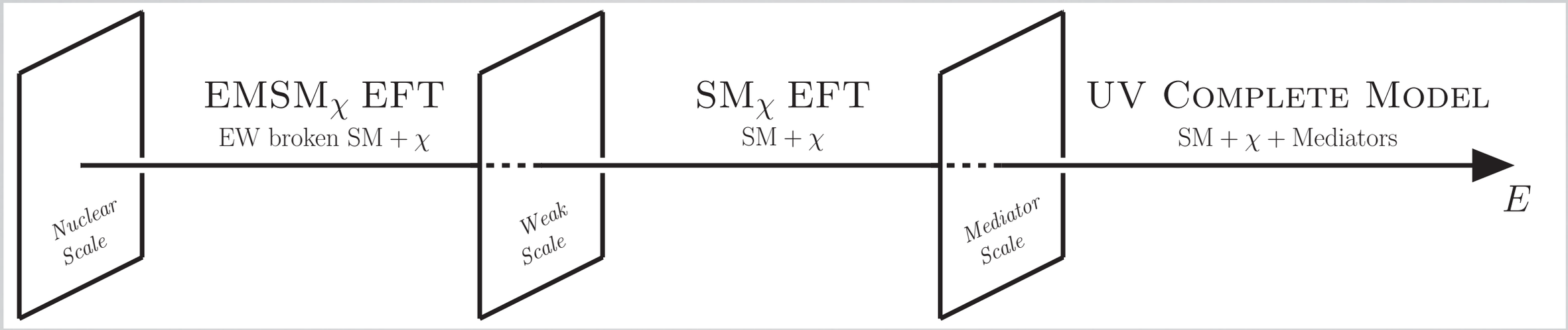


Mediators are integrated-out, model matched onto the SMχ EFT

All we are assuming is the existence of the
Standard Model between Λ and the Nuclear Scale

Plan for Today's Talk

Energy Scales Connection in 3 Steps

RGE from Mediators to EWSB Scale

Integrating-out EW States

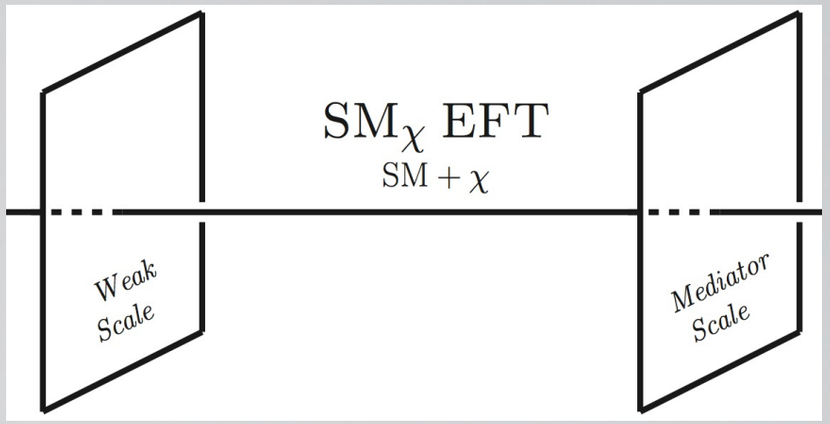
RGE from EWSB to Nuclear Scale

Applications to Direct Searches

Outlook

The SMχ EFT

$$\mathcal{L}_{\mathrm{SM}_\chi} = \mathcal{L}_{\mathrm{SM}} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \sum_{\alpha, d>4} \frac{c_\alpha^{(d)}}{\Lambda^{d-4}} \mathcal{O}_\alpha^{(d)}$$



Direct Detection:
SM interactions with WIMP bilinears

$$\mathcal{O}_\alpha^{(d)} = \overline{\chi}\,\Gamma^\alpha \chi \times \mathcal{O}_{\alpha\mathrm{SM}}^{(d-3)}$$

Dimension 5

$\mathcal{O}_S$	$\overline{\chi}\chi\, H^\dagger H$
$\mathcal{O}_P$	$\overline{\chi}\gamma^5\chi\, H^\dagger H$
$\mathcal{O}_M$	$\overline{\chi}\sigma^{\mu\nu}\chi\, B_{\mu\nu}$
$\mathcal{O}_E$	$\overline{\chi}\sigma^{\mu\nu}\chi\, \epsilon_{\mu\nu\rho\sigma} B^{\rho\sigma}$

Dimension 6

$\mathcal{O}_{Vf}^{(i)}$	$\overline{\chi}\,\gamma^\mu\chi\, \overline{f^i}\gamma_\mu f^i$
$\mathcal{O}_{Af}^{(i)}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\, \overline{f^i}\gamma_\mu f^i$
$\mathcal{O}_{VH}$	$\overline{\chi}\,\gamma^\mu\chi\, H^\dagger \overleftrightarrow{D_\mu} H$
$\mathcal{O}_{AH}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\, H^\dagger \overleftrightarrow{D_\mu} H$

$$f^i = q_L^i, u_R^i, d_R^i, l_L^i, e_R^i$$

The SMx EFT

SM threshold corrections to Higgs operators known

Shifman, Vainshtein and Zakharov, PLB78 (1978)

Dipole Dark Matter constrained by direct searches

Barger, Keung and Marfatia, PLB696 (2011)
Banks, Fortin and Thomas arXiv:1007.5515
Fortin and Tait, PRD85 (2012)

Dimension 5

$\mathcal{O}_S$	$\overline{\chi}\chi\, H^\dagger H$
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The SMχ EFT

Interesting mixing can happen among dim. 6 operators

A.Crivellin, FD, M. Procura, PRL 112(2014)

Our goal:

complete one-loop analysis of dim. 6 operators in SMχ EFT

FD and M. Procura, arXiv:141x.xxxx

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- (5 x 3 + 1) x 2 = 32 operators
- DM bilinear invariant under RGE
- Two independent 16 x 16 blocks

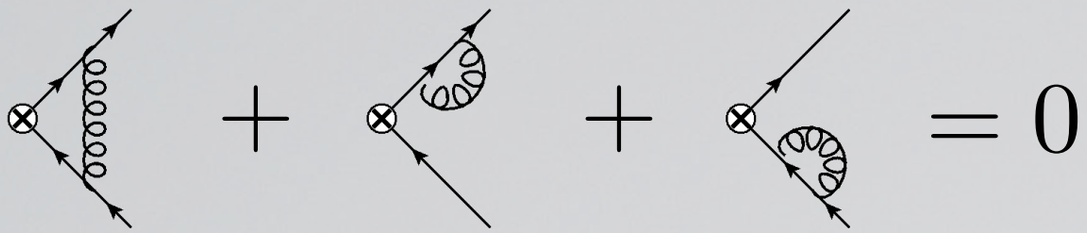
Dimension 6

$\mathcal{O}^{(i)}_{Vf}$	$\overline{\chi}\gamma^\mu\chi\ \overline{f^i}\gamma_\mu f^i$
$\mathcal{O}^{(i)}_{Af}$	$\overline{\chi}\gamma^\mu\gamma_5\chi\ \overline{f^i}\gamma_\mu f^i$
$\mathcal{O}_{VH}$	$\overline{\chi}\gamma^\mu\chi\ H^\dagger \overleftrightarrow{D_\mu} H$
$\mathcal{O}_{AH}$	$\overline{\chi}\gamma^\mu\gamma_5\chi\ H^\dagger \overleftrightarrow{D_\mu} H$

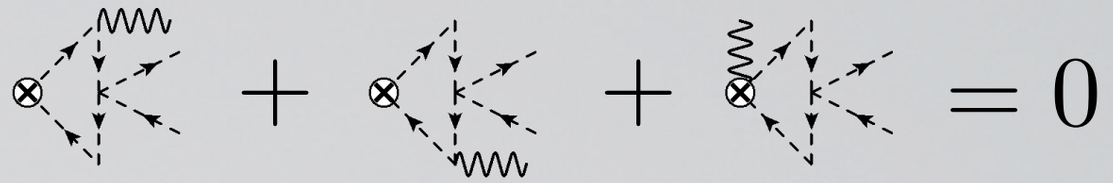
$$f^i = q^i_L, u^i_R, d^i_R, l^i_L, e^i_R$$

Loops in the SMx EFT

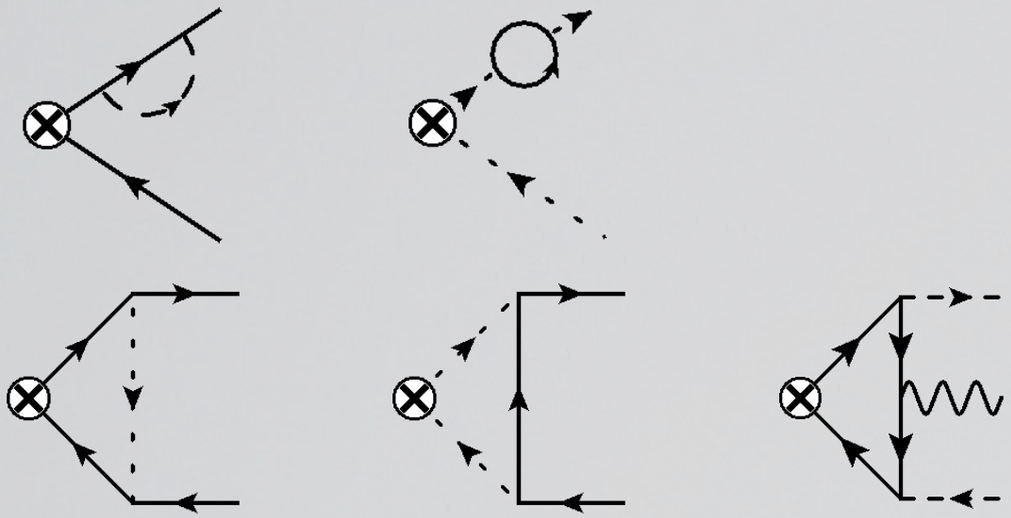
Gauge Vertex Correction



Higgs Self-Interactions

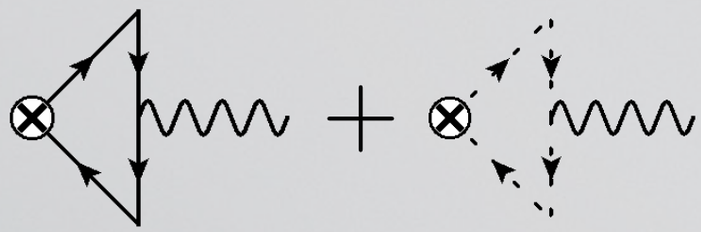


Yukawa Interactions



- external leg corrections induce diagonal renormalization
- vertex corrections induce off-diagonal renormalization

Hypercharge Interactions

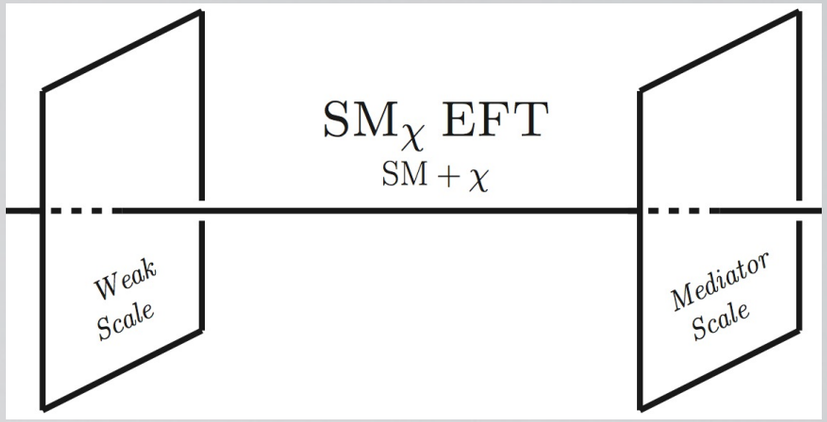


$$\propto \frac{g'}{\Lambda^2}\,\overline{\chi}\,\Gamma^\mu\chi\,\partial^\nu B_{\nu\mu} \;\rightarrow\; -\frac{g'^{\,2}}{\Lambda^2}\,\overline{\chi}\,\Gamma^\mu\chi\,J^{(Y)}_\mu$$

RG Equations - SMχ EFT

$$\mathcal{C}^T_{\mathrm{SM}_\chi} = \Big(\; c^{(1)}_{\Gamma q} \quad c^{(1)}_{\Gamma u} \quad c^{(1)}_{\Gamma d} \;\vdots\; c^{(1)}_{\Gamma l} \quad c^{(1)}_{\Gamma e} \;\Big|\; c^{(2)}_{\Gamma q} \quad c^{(2)}_{\Gamma u} \quad c^{(2)}_{\Gamma d} \;\vdots\; c^{(2)}_{\Gamma l} \quad c^{(2)}_{\Gamma e} \;\Big|\; c^{(3)}_{\Gamma q} \quad c^{(3)}_{\Gamma u} \quad c^{(3)}_{\Gamma d} \;\vdots\; c^{(3)}_{\Gamma l} \quad c^{(3)}_{\Gamma e} \;\Big\|\; c_{\Gamma H} \; \Big)$$

$$\frac{d\,\mathcal{C}_{\mathrm{SM}_\chi}}{d\ln\mu} = \left(\gamma_{\mathrm{SM}_\chi}\big|_\lambda + \gamma_{\mathrm{SM}_\chi}\big|_Y \right) \mathcal{C}_{\mathrm{SM}_\chi}$$



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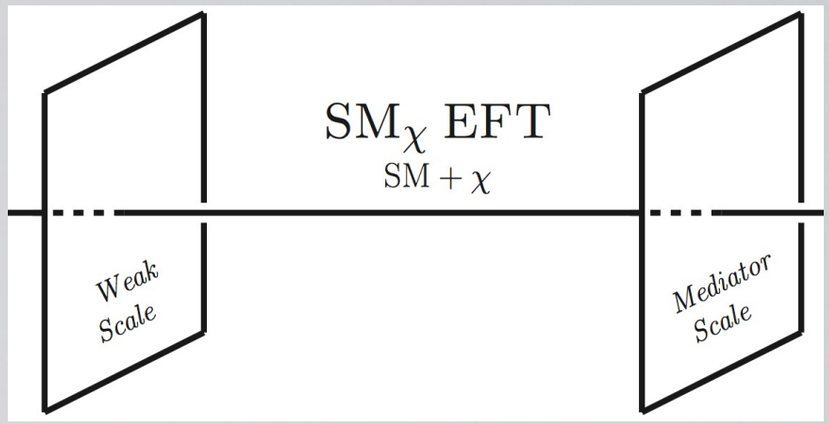
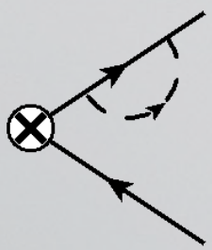
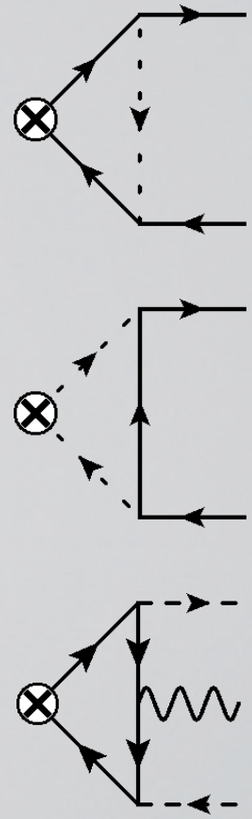


Running Driven by Yukawa Interactions

$$\gamma_\lambda\big|_{1-\mathrm{fam}} = \frac{1}{8\pi^2}\left(\begin{array}{ccc:cc||c} \left(\lambda_u^2+\lambda_d^2\right)/2 & -\lambda_u^2/2 & -\lambda_d^2/2 & 0 & 0 & \left(\lambda_u^2+\lambda_d^2\right)/2 \\ -\lambda_u^2 & \lambda_u^2 & 0 & 0 & 0 & \lambda_u^2 \\ -\lambda_d^2 & 0 & \lambda_d^2 & 0 & 0 & \lambda_d^2 \\ \hdashline 0 & 0 & 0 & \lambda_e^2/2 & -\lambda_e^2/2 & \lambda_e^2/2 \\ 0 & 0 & 0 & -\lambda_e^2 & \lambda_e^2 & \lambda_e^2 \\ \hline\hline 3\left(\lambda_u^2-\lambda_d^2\right) & -3\lambda_u^2 & 3\lambda_d^2 & -\lambda_e^2 & \lambda_e^2 & 3\left(\lambda_u^2+\lambda_d^2\right)+\lambda_e^2 \end{array}\right)$$





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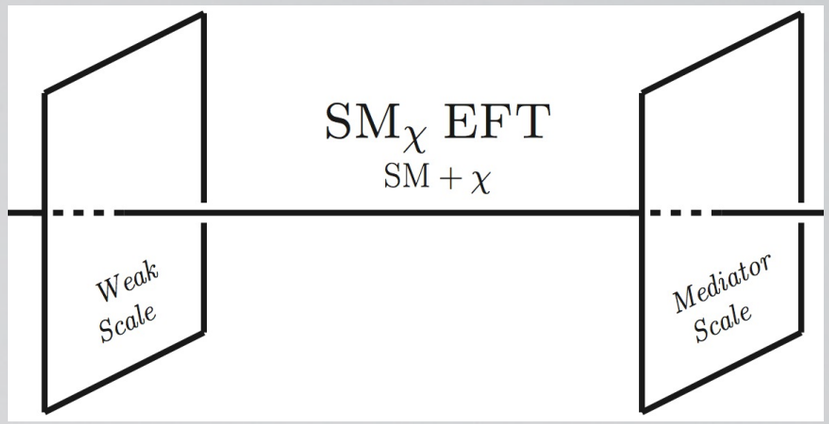
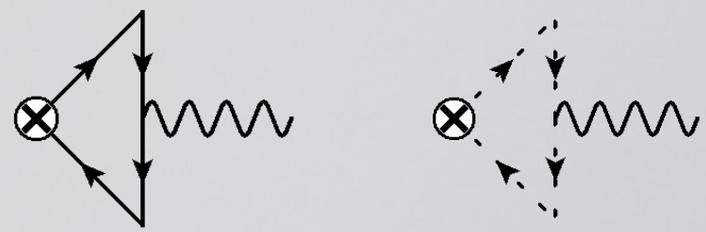


Running Driven by Hypercharge Interactions

$$\left(\gamma_{\mathrm{SM}_\chi}\big|_Y\right)_{\alpha\beta} = \frac{4}{3}\frac{g'^2}{16\pi^2}\, N^c_\beta N^w_\beta\, y_\alpha y_\beta$$

$N^c = 3$ for quarks

$N^w = 2$ for fermion EW doublets



Plan for Today's Talk

Energy Scales Connection in 3 Steps

RGE from Mediators to EWSB Scale ☑

Integrating-out EW States

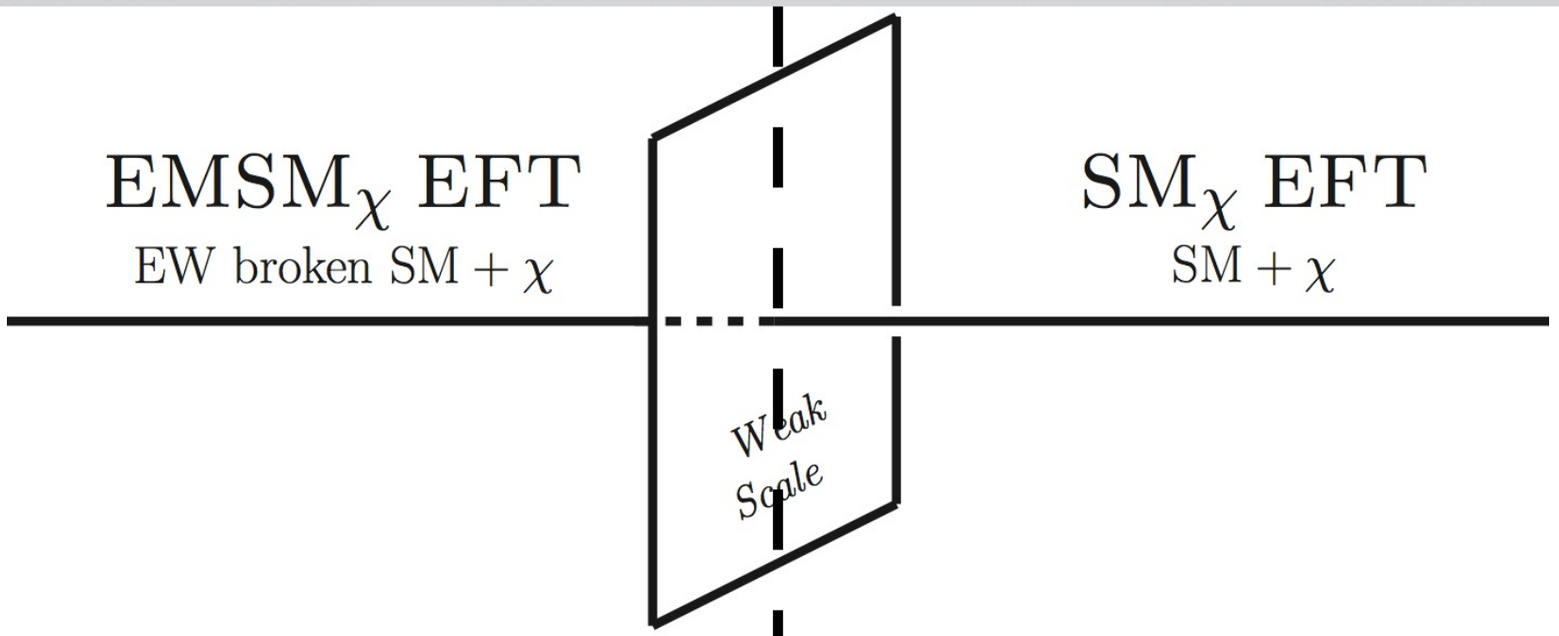
RGE from EWSB to Nuclear Scale

Applications to Direct Searches

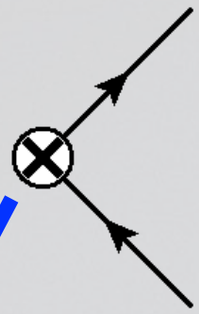
Outlook

Matching at EWSB Scale

Integrate-out EW d.o.f. and match SM_χ EFT onto $EMSM_\chi$ EFT



Main correction for our analysis:



$$\overline{\chi}\,\Gamma^{\mu}_{A}\chi\;\overline{f}\Gamma_{B\mu}f\big|_{\mathrm{EMSM}_\chi}$$

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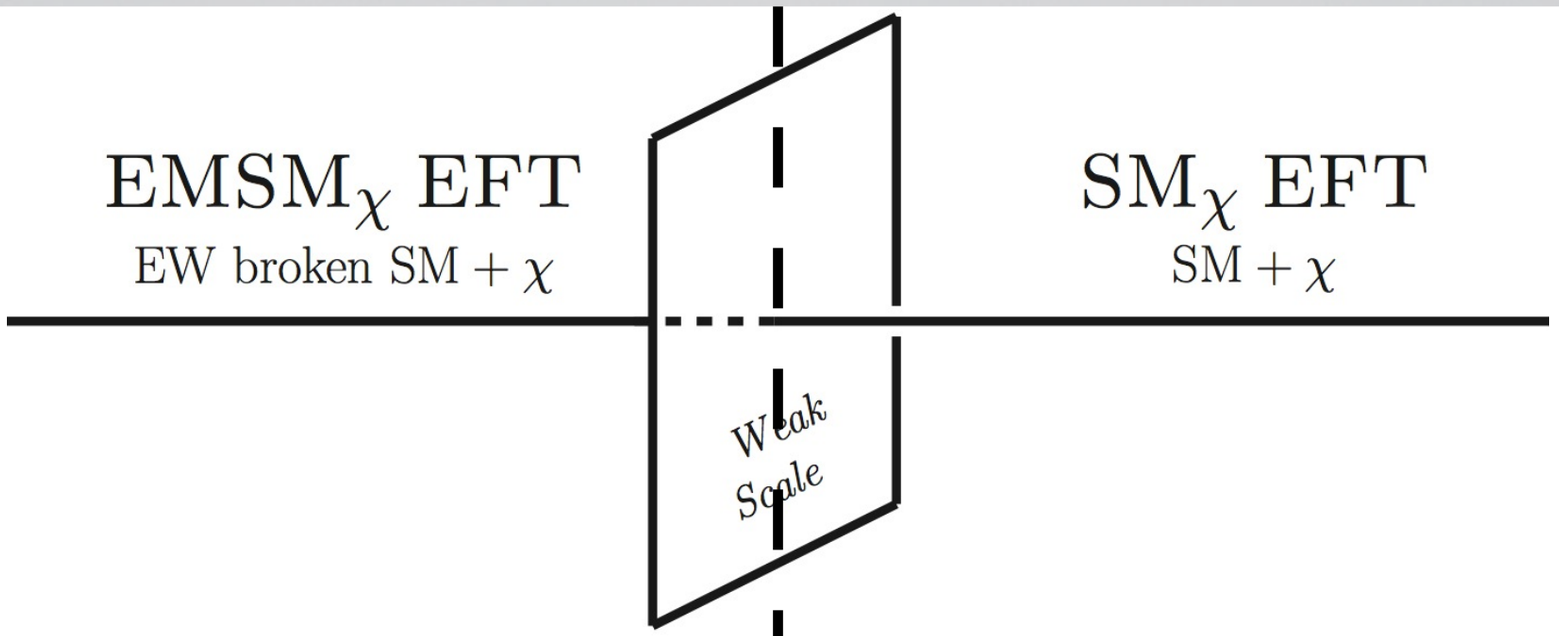
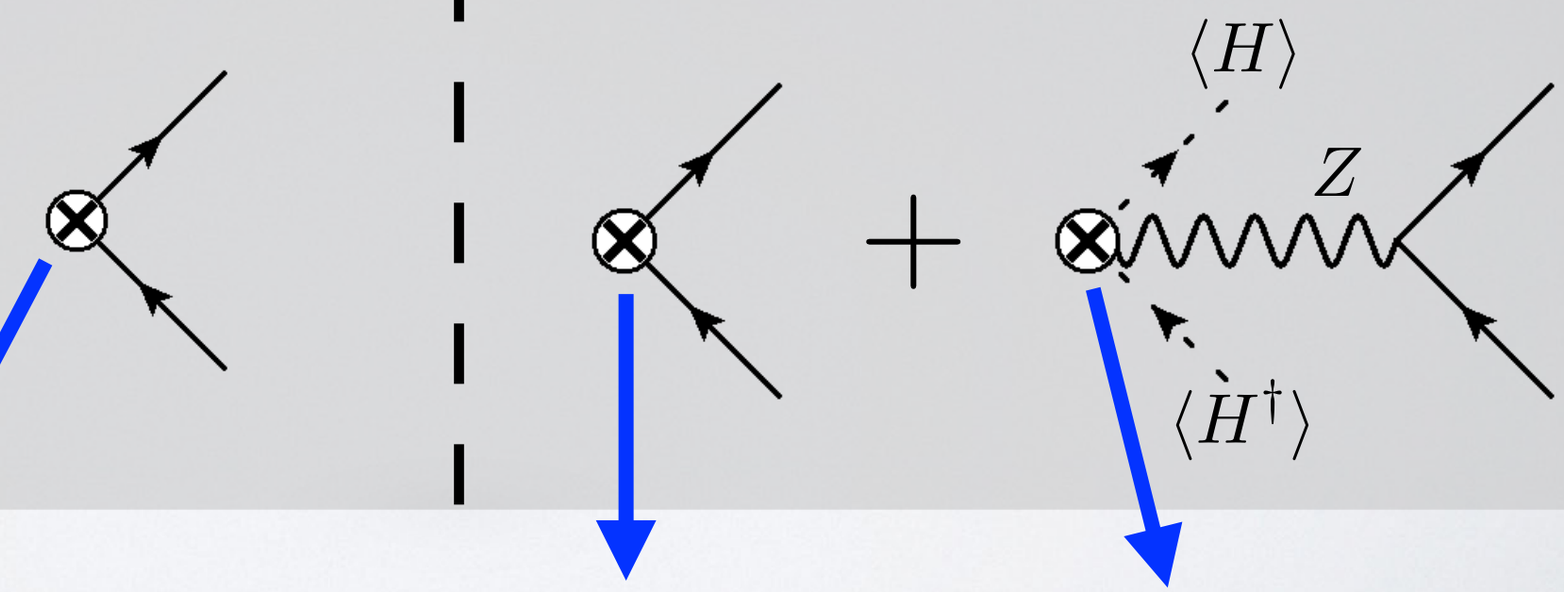


Main correction for our analysis:



$$\overline{\chi}\,\Gamma^\mu_A \chi\;\overline{f}\Gamma_{B\mu} f\big|_{\mathrm{EMSM}_\chi}$$

$$\overline{\chi}\,\Gamma^\mu_A \chi\;\overline{f}\Gamma_{B\mu} f\big|_{\mathrm{SM}_\chi}$$

$$\overline{\chi}\,\Gamma^\mu \chi\, H^\dagger \overleftrightarrow{D_\mu} H\Big|_{\mathrm{SM}_\chi}$$

Plan for Today's Talk

Energy Scales Connection in 3 Steps

RGE from Mediators to EWSB Scale ☑

Integrating-out EW States ☑

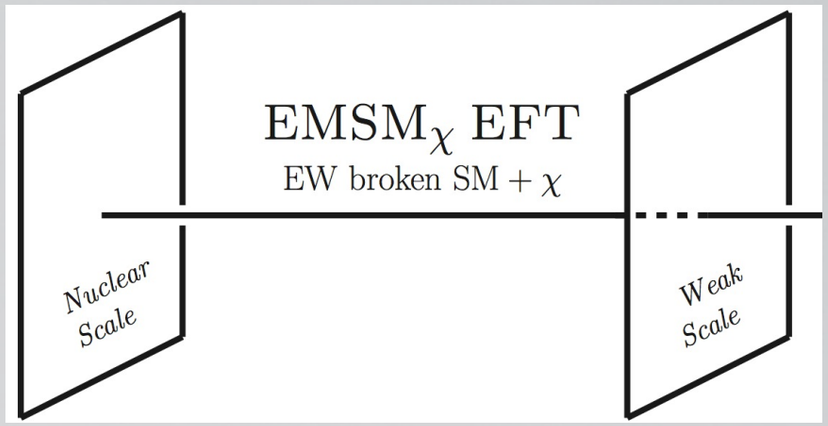
RGE from EWSB to Nuclear Scale

Applications to Direct Searches

Outlook

The EMSMχ EFT

$$\mathcal{L}_{\mathrm{EMSM}_\chi} = \mathcal{L}_{\mathrm{EMSM}} + \overline{\chi}\left(i\not{\partial} - m_\chi\right)\chi + \sum_{d>4}\sum_{\alpha}\frac{c_\alpha^{(d)}}{\Lambda^{d-4}}\mathcal{O}_\alpha^{(d)}$$



Dimension 5

$\mathcal{O}_{M,F}$	$\overline{\chi}\sigma^{\mu\nu}\chi\, F_{\mu\nu}$
$\mathcal{O}_{E,F}$	$\overline{\chi}\sigma^{\mu\nu}\chi\, \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$

Dimension 6

$\mathcal{O}^{(i)}_{VVu}$	$\overline{\chi}\,\gamma^\mu\chi\,\overline{u^i}\gamma_\mu u^i$	$\mathcal{O}^{(i)}_{VVd}$	$\overline{\chi}\,\gamma^\mu\chi\,\overline{d^i}\gamma_\mu d^i$	$\mathcal{O}^{(i)}_{VVe}$	$\overline{\chi}\,\gamma^\mu\chi\,\overline{e^i}\gamma_\mu e^i$
$\mathcal{O}^{(i)}_{VAu}$	$\overline{\chi}\,\gamma^\mu\chi\,\overline{u^i}\gamma_\mu\gamma_5 u^i$	$\mathcal{O}^{(i)}_{VAd}$	$\overline{\chi}\,\gamma^\mu\chi\,\overline{d^i}\gamma_\mu\gamma_5 d^i$	$\mathcal{O}^{(i)}_{VAe}$	$\overline{\chi}\,\gamma^\mu\chi\,\overline{e^i}\gamma_\mu\gamma_5 e^i$
$\mathcal{O}^{(i)}_{AVu}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{u^i}\gamma_\mu u^i$	$\mathcal{O}^{(i)}_{AVd}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{d^i}\gamma_\mu d^i$	$\mathcal{O}^{(i)}_{AVe}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{e^i}\gamma_\mu e^i$
$\mathcal{O}^{(i)}_{AAu}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{u^i}\gamma_\mu\gamma_5 u^i$	$\mathcal{O}^{(i)}_{AAd}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{d^i}\gamma_\mu\gamma_5 d^i$	$\mathcal{O}^{(i)}_{AAe}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{e^i}\gamma_\mu\gamma_5 e^i$

$$u^i = u, c\,; \qquad d^i = d, s, b\,; \qquad e^i = e, \mu, \tau$$

The EMSMχ EFT

- (2 + 3 + 3) x 2 x 2 = 32 operators
- DM bilinear invariant under RGE
- Two independent 16 x 16 blocks

Dimension 6

$\mathcal{O}^{(i)}_{VVu}$	$\overline{\chi}\,\gamma^\mu\chi\,\overline{u^i}\gamma_\mu u^i$	$\mathcal{O}^{(i)}_{VVd}$	$\overline{\chi}\,\gamma^\mu\chi\,\overline{d^i}\gamma_\mu d^i$	$\mathcal{O}^{(i)}_{VVe}$	$\overline{\chi}\,\gamma^\mu\chi\,\overline{e^i}\gamma_\mu e^i$
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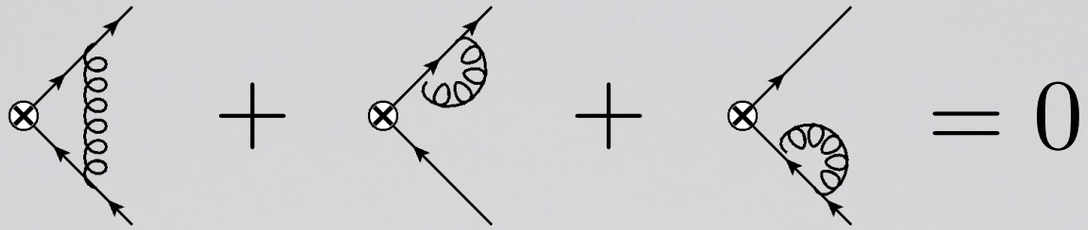
$\mathcal{O}^{(i)}_{AVu}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{u^i}\gamma_\mu u^i$	$\mathcal{O}^{(i)}_{AVd}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{d^i}\gamma_\mu d^i$	$\mathcal{O}^{(i)}_{AVe}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{e^i}\gamma_\mu e^i$
$\mathcal{O}^{(i)}_{AAu}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{u^i}\gamma_\mu\gamma_5 u^i$	$\mathcal{O}^{(i)}_{AAd}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{d^i}\gamma_\mu\gamma_5 d^i$	$\mathcal{O}^{(i)}_{AAe}$	$\overline{\chi}\,\gamma^\mu\gamma_5\chi\,\overline{e^i}\gamma_\mu\gamma_5 e^i$

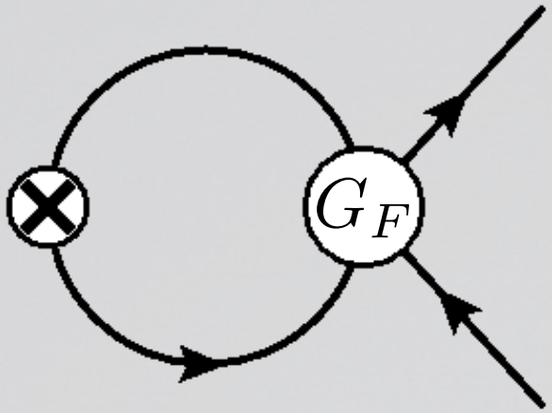
$$u^i = u, c\,; \qquad d^i = d, s, b\,; \qquad e^i = e, \mu, \tau$$

Loops in the EMSMx EFT

Gauge Vertex Correction

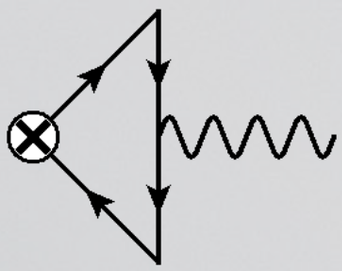


SM Four-Fermion Interactions



$$\propto G_F\, m_f^2 \propto \lambda_f^2$$

Electromagnetic Interactions

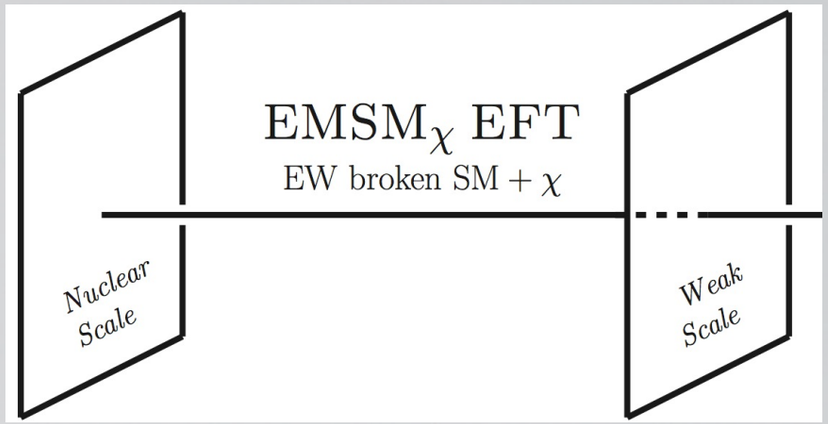


$$\propto \frac{e}{\Lambda^2}\overline{\chi}\Gamma^\mu\chi\,\partial^\nu F_{\nu\mu} \;\rightarrow\; -\frac{e^2}{\Lambda^2}\overline{\chi}\Gamma^\mu\chi\,J_\mu^{(\mathrm{e.m.})}$$

RG Equations - EMSMχ EFT

$$\mathcal{C}^{T}_{\mathrm{EMSM}_\chi} = \left(\begin{array}{ccccc|ccc||ccccc|ccc} c^{(1)}_{\Gamma V u} & c^{(1)}_{\Gamma V d} & c^{(2)}_{\Gamma V u} & c^{(2)}_{\Gamma V d} & c^{(3)}_{\Gamma V d} & c^{(1)}_{\Gamma V e} & c^{(2)}_{\Gamma V e} & c^{(3)}_{\Gamma V e} & c^{(1)}_{\Gamma A u} & c^{(1)}_{\Gamma A d} & c^{(2)}_{\Gamma A u} & c^{(2)}_{\Gamma A d} & c^{(3)}_{\Gamma A d} & c^{(1)}_{\Gamma A e} & c^{(2)}_{\Gamma A e} & c^{(3)}_{\Gamma A e} \end{array} \right)$$

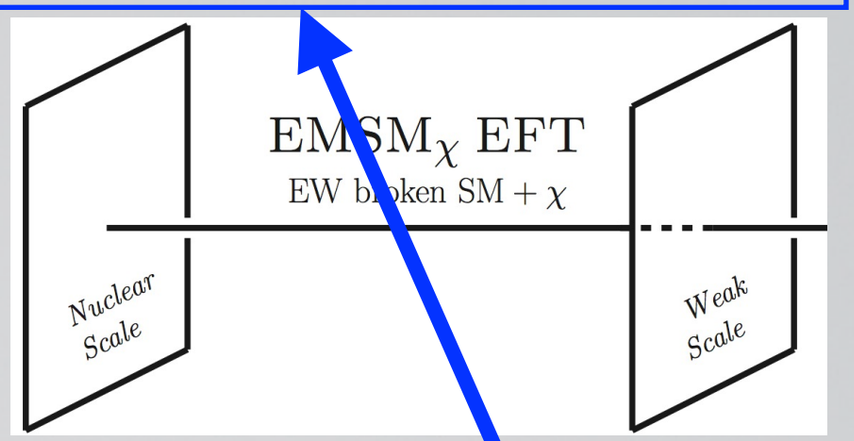
$$\frac{d\,\mathcal{C}_{\mathrm{EMSM}_\chi}}{d\ln\mu} = \left(\gamma_{\mathrm{EMSM}_\chi}\big|_{\lambda} + \gamma_{\mathrm{EMSM}_\chi}\big|_{\mathrm{e.m.}}\right)\mathcal{C}_{\mathrm{EMSM}_\chi}$$



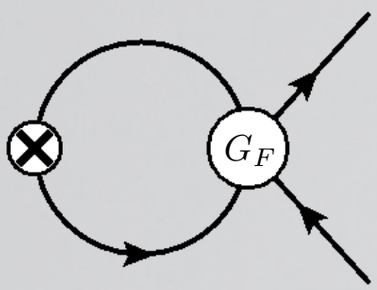
RG Equations - EMSMx EFT

$$\mathcal{C}^T_{\mathrm{EMSM}_\chi} = \left(\begin{array}{ccccc|ccc||ccccc|ccc} c^{(1)}_{\Gamma V u} & c^{(1)}_{\Gamma V d} & c^{(2)}_{\Gamma V u} & c^{(2)}_{\Gamma V d} & c^{(3)}_{\Gamma V d} & c^{(1)}_{\Gamma V e} & c^{(2)}_{\Gamma V e} & c^{(3)}_{\Gamma V e} & c^{(1)}_{\Gamma A u} & c^{(1)}_{\Gamma A d} & c^{(2)}_{\Gamma A u} & c^{(2)}_{\Gamma A d} & c^{(3)}_{\Gamma A d} & c^{(1)}_{\Gamma A e} & c^{(2)}_{\Gamma A e} & c^{(3)}_{\Gamma A e} \end{array} \right)$$

$$\frac{d\,\mathcal{C}_{\mathrm{EMSM}_\chi}}{d\ln\mu} = \left(\gamma_{\mathrm{EMSM}_\chi}\big|_\lambda + \gamma_{\mathrm{EMSM}_\chi}\big|_{\mathrm{e.m.}}\right)\mathcal{C}_{\mathrm{EMSM}_\chi}$$



Running Driven by ``Yukawa" Interactions



$$\left(\gamma_{\mathrm{EMSM}_\chi}\big|_\lambda\right)_{\alpha\beta} = \frac{1}{2\pi^2}\, g_\alpha\, N^c_\beta\, \lambda^2_\beta\, g_\beta \qquad \beta \in$$

Only mixing from axial-couplings to SM fermions

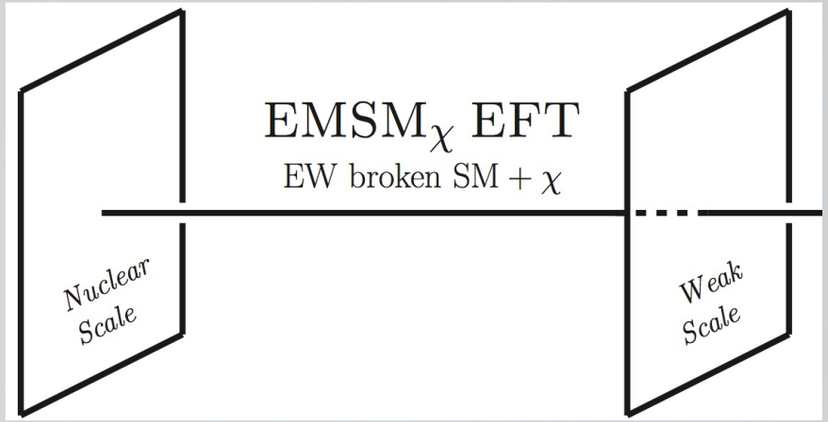
Proportional to Yukawas and SM couplings to Z boson:

$$g_{Vu} = \frac{1}{2} - 2s^2_w Q_u\ , \quad g_{Au} = -\frac{1}{2}\ , \qquad g_{Vd} = -\frac{1}{2} - 2s^2_w Q_d\ , \quad g_{Ad} = \frac{1}{2}\ , \qquad g_{Ve} = -\frac{1}{2} - 2s^2_w Q_e\ , \quad g_{Ae} = \frac{1}{2}$$

RG Equations - EMSMχ EFT

$$\mathcal{C}^T_{\mathrm{EMSM}_\chi} = \left(\begin{array}{ccccc|ccc||ccccc|ccc} c^{(1)}_{\Gamma V u} & c^{(1)}_{\Gamma V d} & c^{(2)}_{\Gamma V u} & c^{(2)}_{\Gamma V d} & c^{(3)}_{\Gamma V d} & c^{(1)}_{\Gamma V e} & c^{(2)}_{\Gamma V e} & c^{(3)}_{\Gamma V e} & c^{(1)}_{\Gamma A u} & c^{(1)}_{\Gamma A d} & c^{(2)}_{\Gamma A u} & c^{(2)}_{\Gamma A d} & c^{(3)}_{\Gamma A d} & c^{(1)}_{\Gamma A e} & c^{(2)}_{\Gamma A e} & c^{(3)}_{\Gamma A e} \end{array} \right)$$

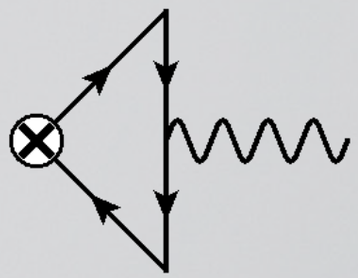
$$\frac{d\,\mathcal{C}_{\mathrm{EMSM}_\chi}}{d\ln\mu} = \left(\gamma_{\mathrm{EMSM}_\chi}\big|_{\lambda} + \gamma_{\mathrm{EMSM}_\chi}\big|_{\mathrm{e.m.}} \right) \mathcal{C}_{\mathrm{EMSM}_\chi}$$



Running Driven by ElectroMagnetic Interactions

$$\left(\gamma_{\mathrm{EMSM}_\chi}\big|_{\mathrm{e.m.}} \right)_{\alpha\beta} = \frac{8}{3}\frac{e^2}{16\pi^2}\, N^c_\beta\, Q_\alpha Q_\beta$$

Mixing only in the vector/vector sub-block



Plan for Today's Talk

Energy Scales Connection in 3 Steps ☑

RGE from Mediators to EWSB Scale ☑

Integrating-out EW States ☑

RGE from EWSB to Nuclear Scale ☑

Applications to Direct Searches

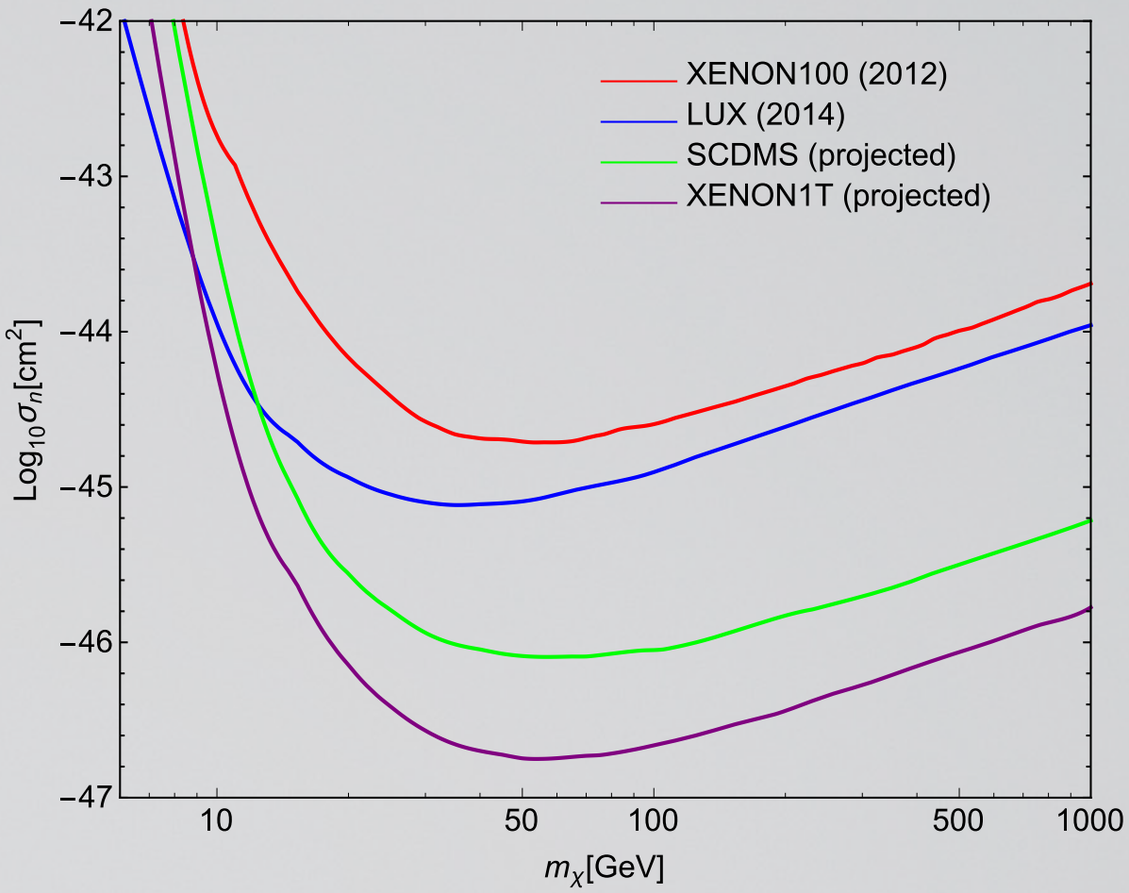
Outlook

Spin-Independent Scattering

Only vector-vector coupling to valence quarks relevant

$$\mathcal{L}^{\text{eff}} = \overline{\chi}\gamma^{\mu}\chi \left[\frac{c_{VVu}}{\Lambda^2}\overline{u}\gamma_{\mu}u + \frac{c_{VVd}}{\Lambda^2}\overline{d}\gamma_{\mu}d\right]_{\mu_N}$$

Best Experimental Limits due to Coherent WIMP-Nucleus Scattering



E. Aprile et al. PRL109 (2012), D. Akerib et al., PRL 112 (2014), T. Saab (SuperCDMS), Talk at SSI 2012, E. Aprile (XENON1T) Proceedings DM2012 at UCLA

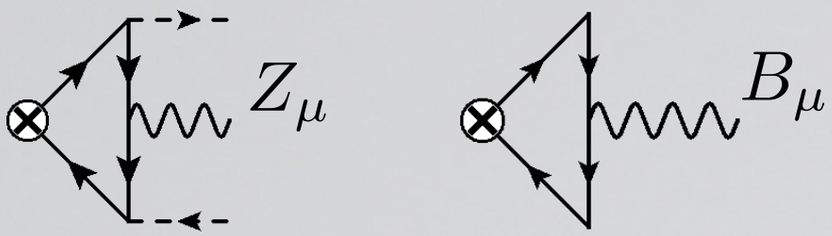
$$\sigma_{\text{SI}} = \frac{m_{\chi}^2 m_N^2}{(m_{\chi}+m_N)^2\pi\Lambda^4}\left[(A+Z)\mathcal{C}_{VVu} + (2A-Z)\mathcal{C}_{VVd}\right]^2$$

Suppressed Couplings

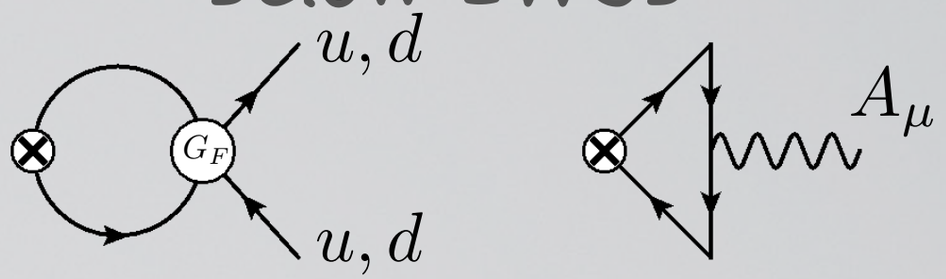
Dark Matter couples mostly to SM quark axial currents

A.Crivellin, FD, M. Procura, PRL 112(2014)

Above EWSB



Below EWSB



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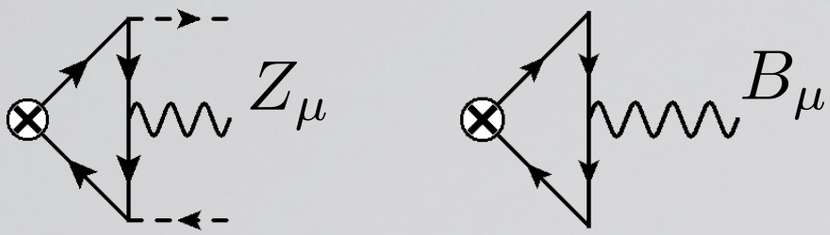

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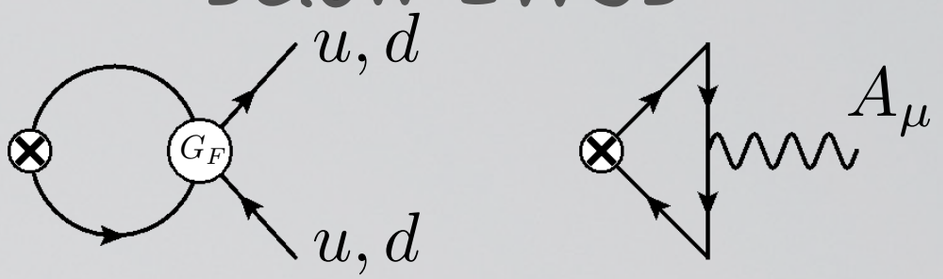
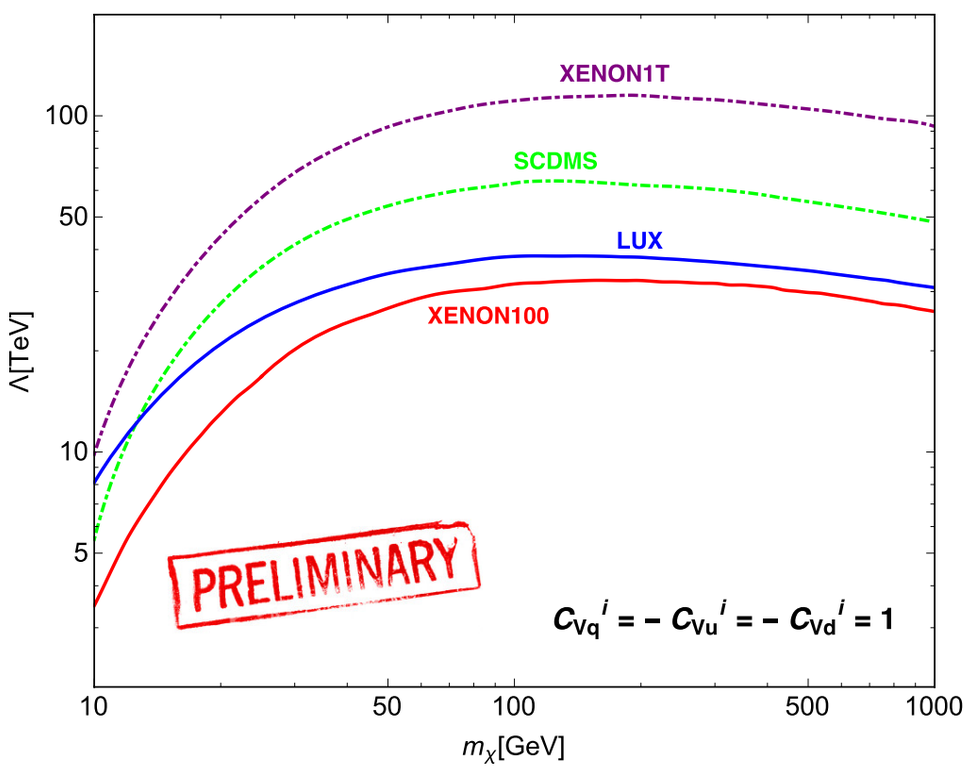
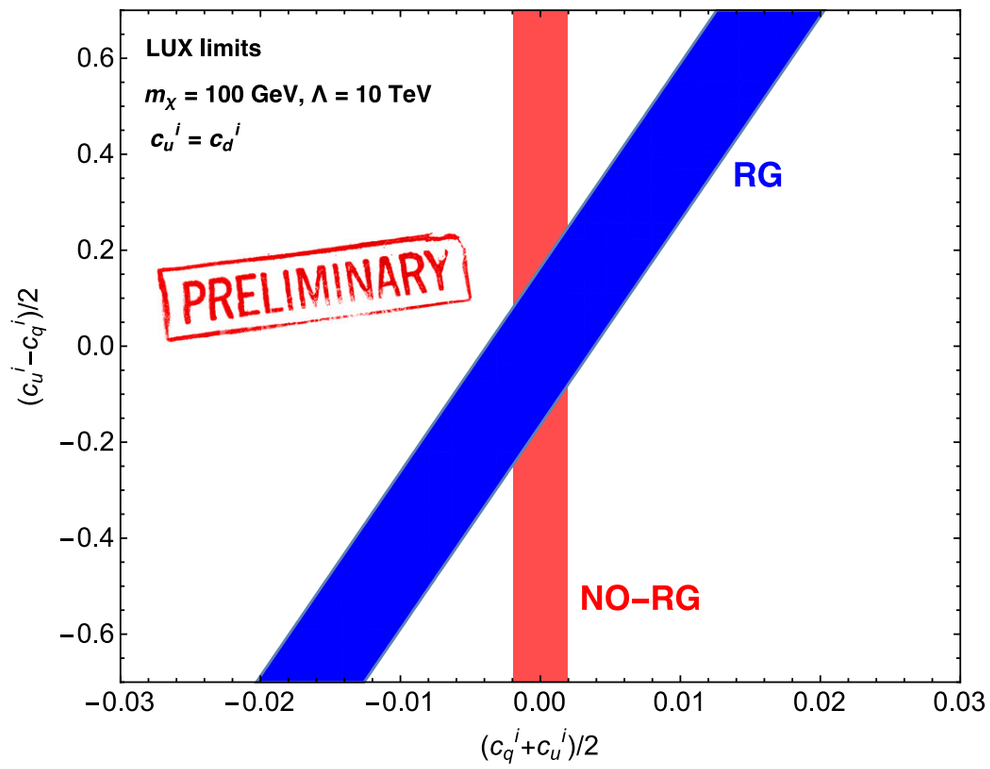


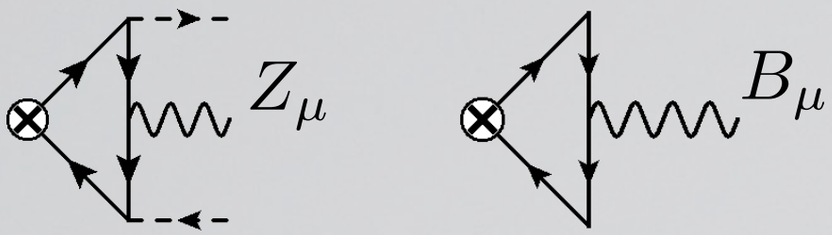




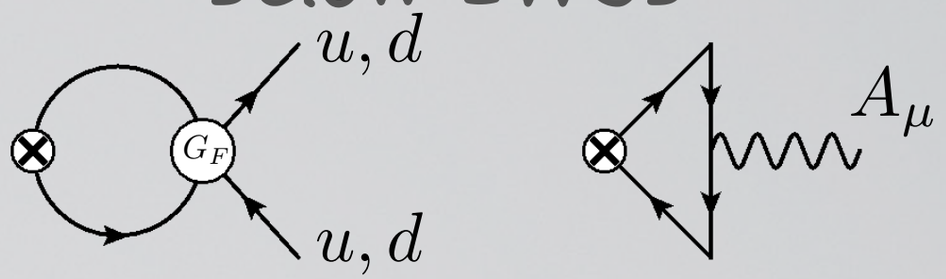
Third Generation, Leptophilic

Dark Matter couples to third generation SM fermions

Above EWSB



Below EWSB



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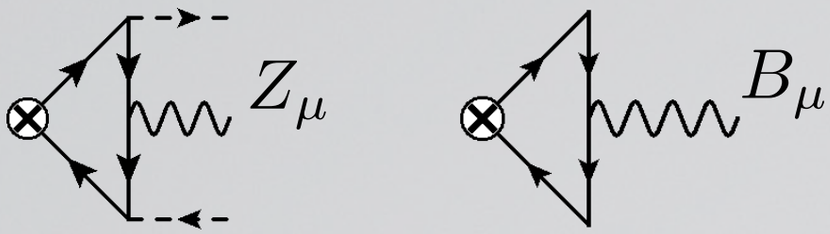
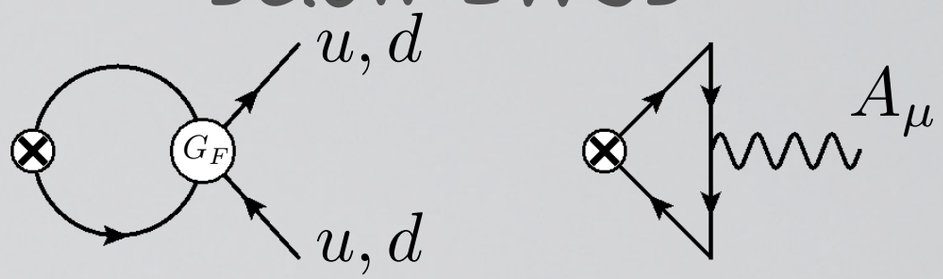
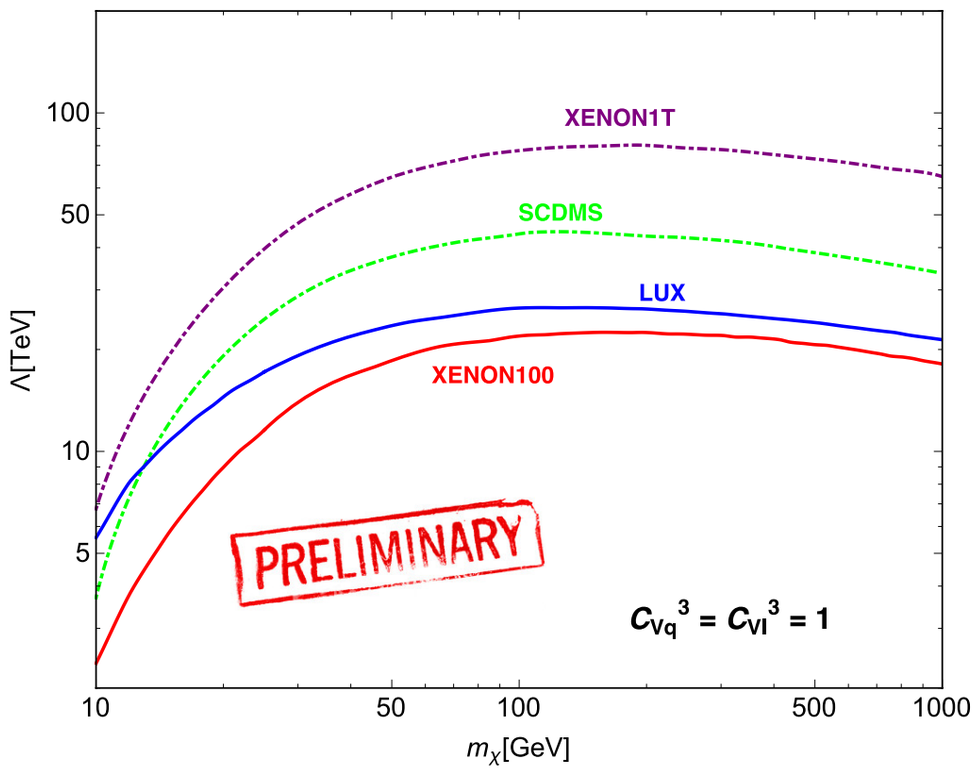
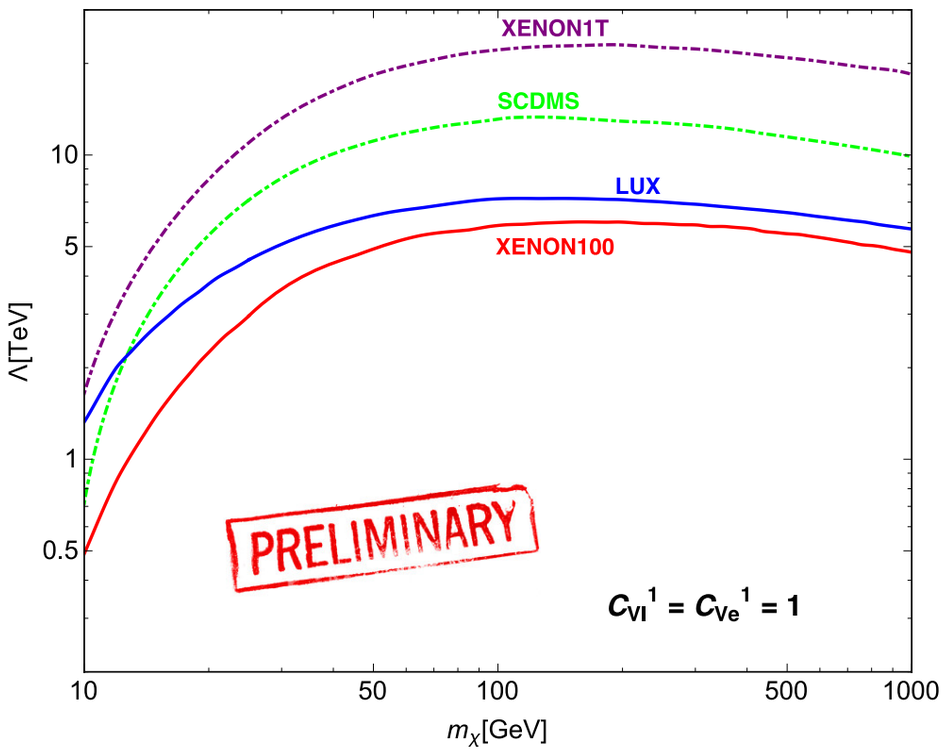


Below EWSB







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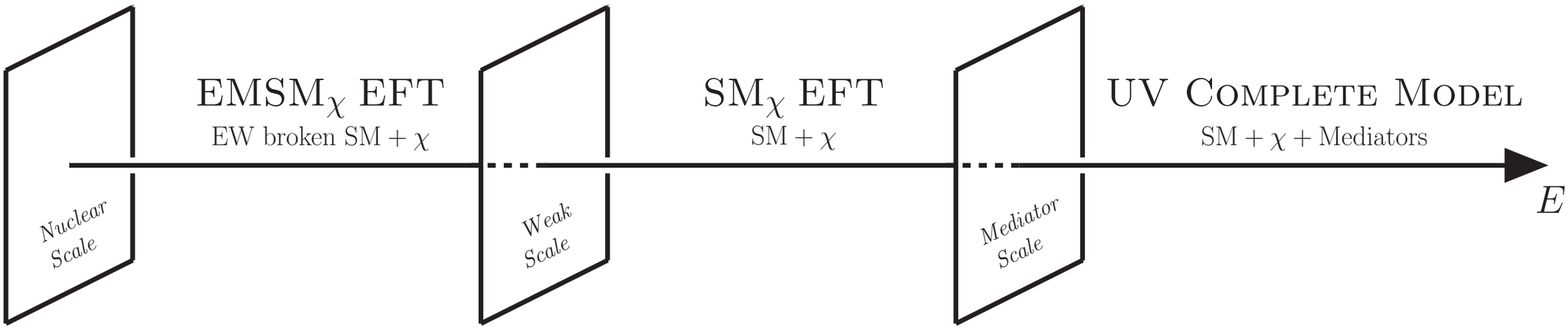
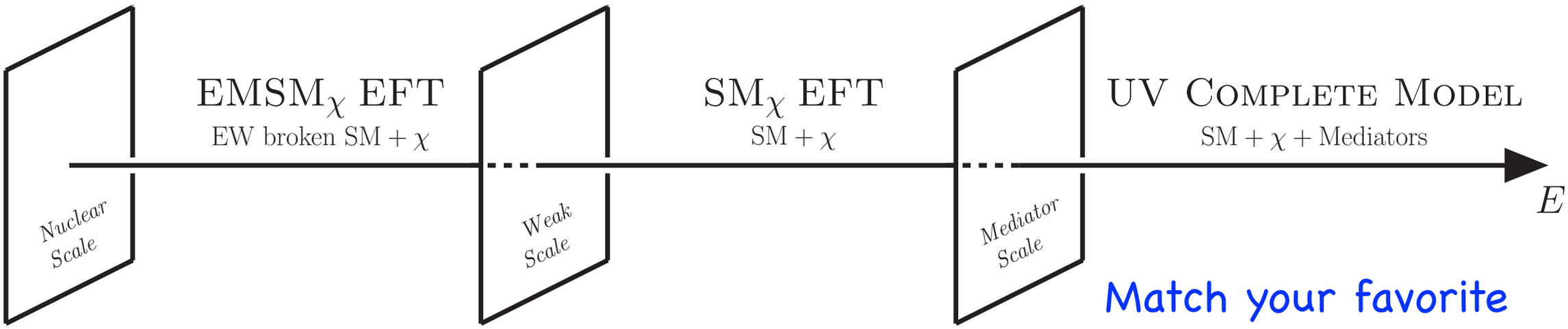
Outlook

Outlook



FD and M. Procura, arXiv:141x.xxxx

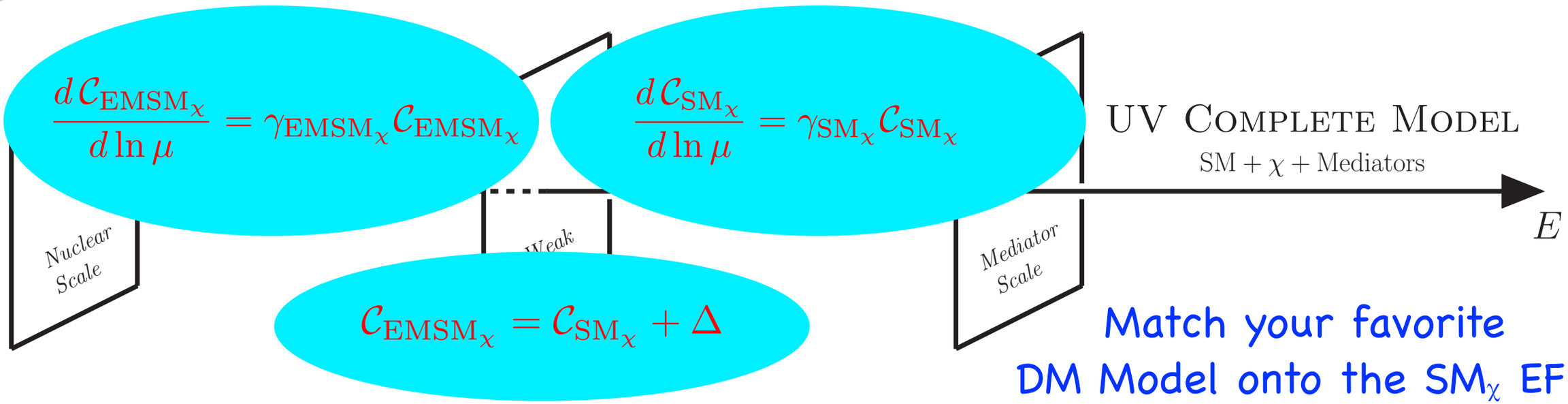
Outlook



Match your favorite
DM Model onto the SM$_\chi$ EFT

FD and M. Procura, arXiv:141x.xxxx

Outlook



FD and M. Procura, arXiv:141x.xxxx

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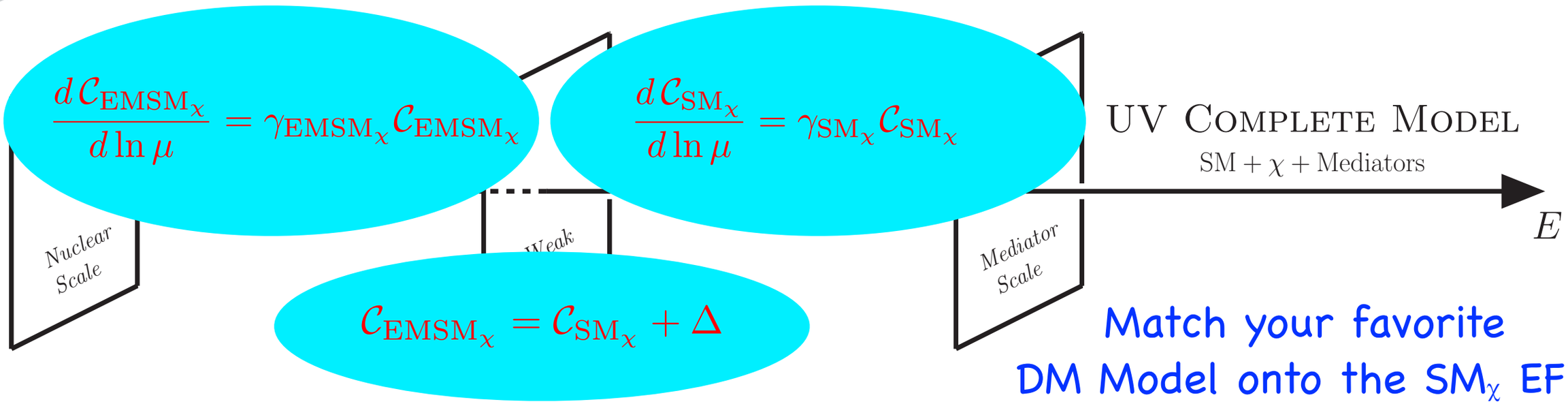

FD and M. Procura, arXiv:141x.xxxx

THANK YOU!!!