CHIRAL EFT FOR DARK MATTER DIRECT DETECTION

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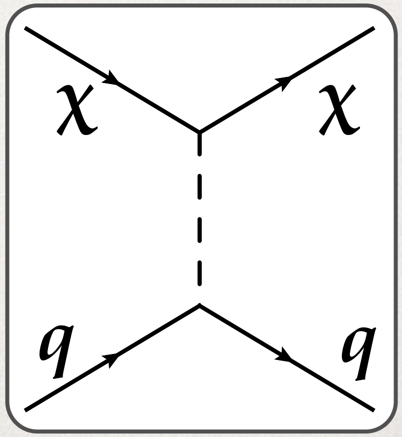
U. of Cincinnati & CERN

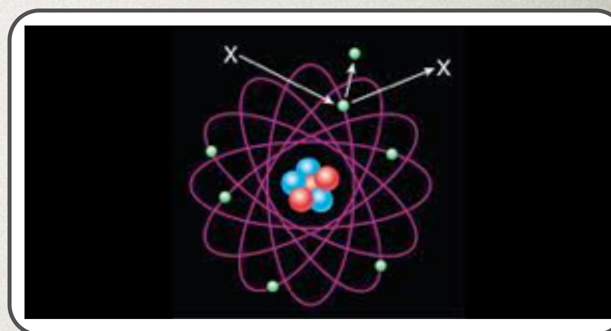
based on work with F. Bishara, J. Brod, B. Grinstein, JZ, 1610.nnnnn

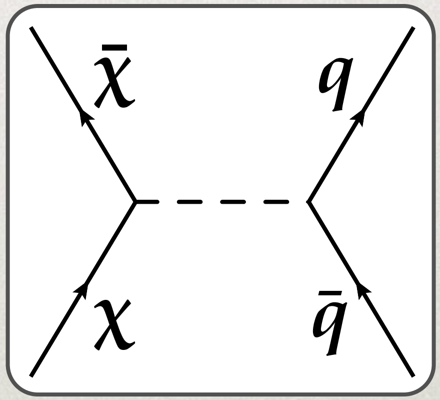
Belica, Oct 20 2016

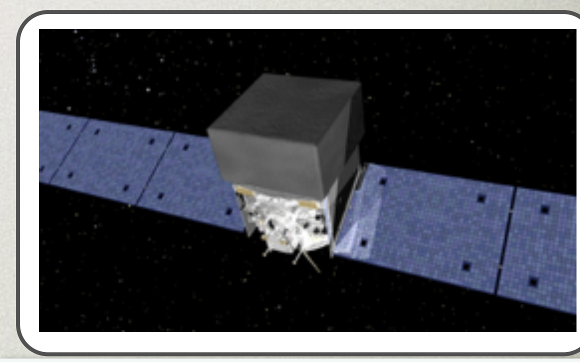
THE AIM/MOTIVATION

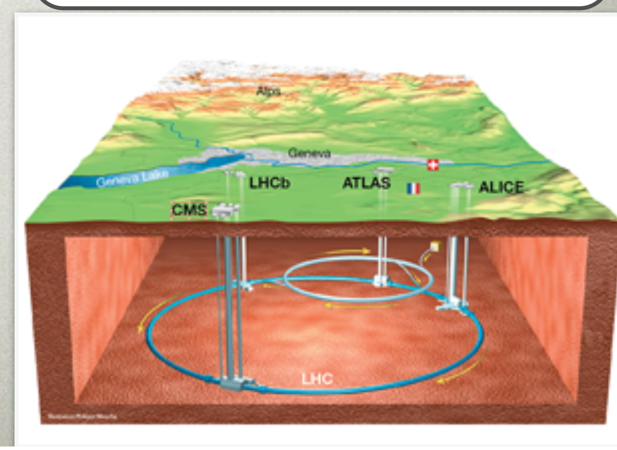
- several probes of DM
  - direct detection
  - indirect detection
  - production at colliders
- can one relate experimental results "model independently"?



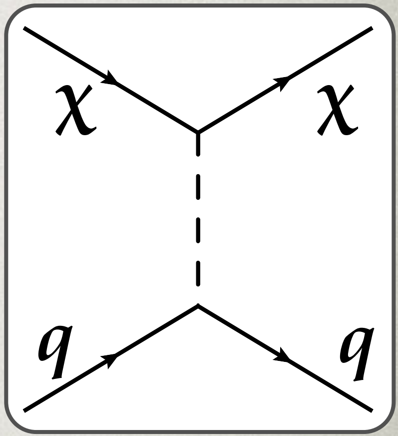






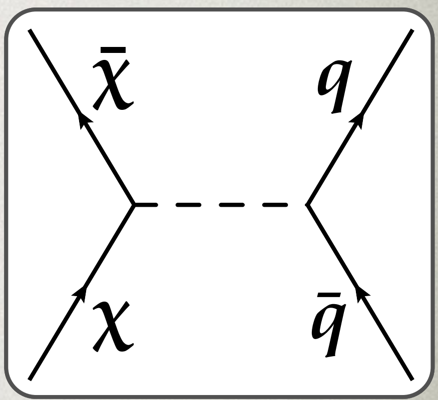


MOTIVATION



- at first the problem seems simple
  - "just invert the diagram"
- but many subtleties
- most importantly: physics governed by different energy scales
  - direct detection: ~200 MeV
  - indirect detection: DM mass (~ 100 GeV ?)
  - LHC production: DM mass + LHC kinematics

MOTIVATION



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  - direct detection: ~200 MeV
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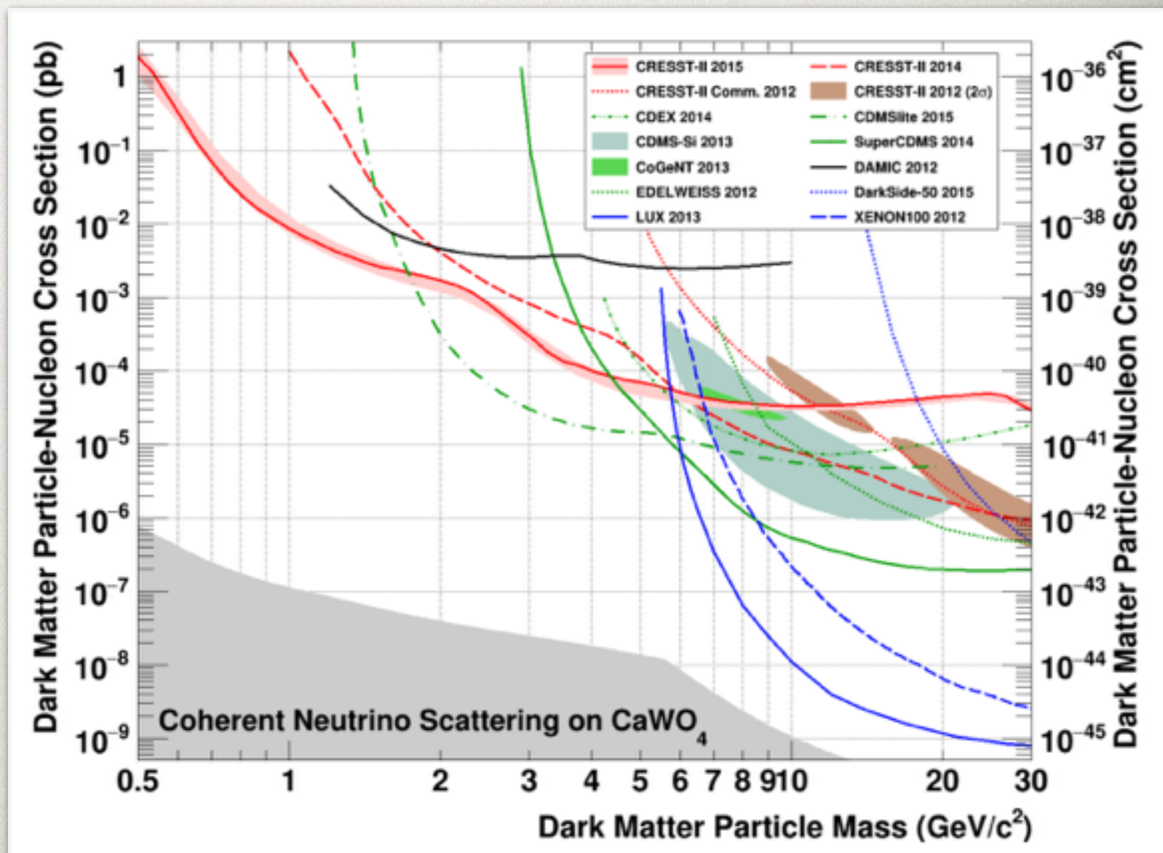
MOTIVATION

- in fact two problems
  - comparing different DM direct detection experiments
  - comparing direct detection with LHC and indirect detection



MOTIVATION

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  - comparing

  on

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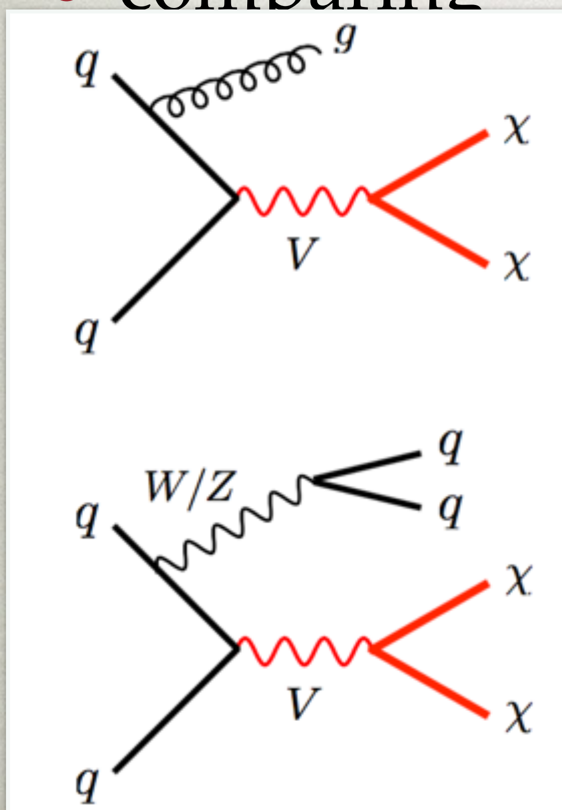
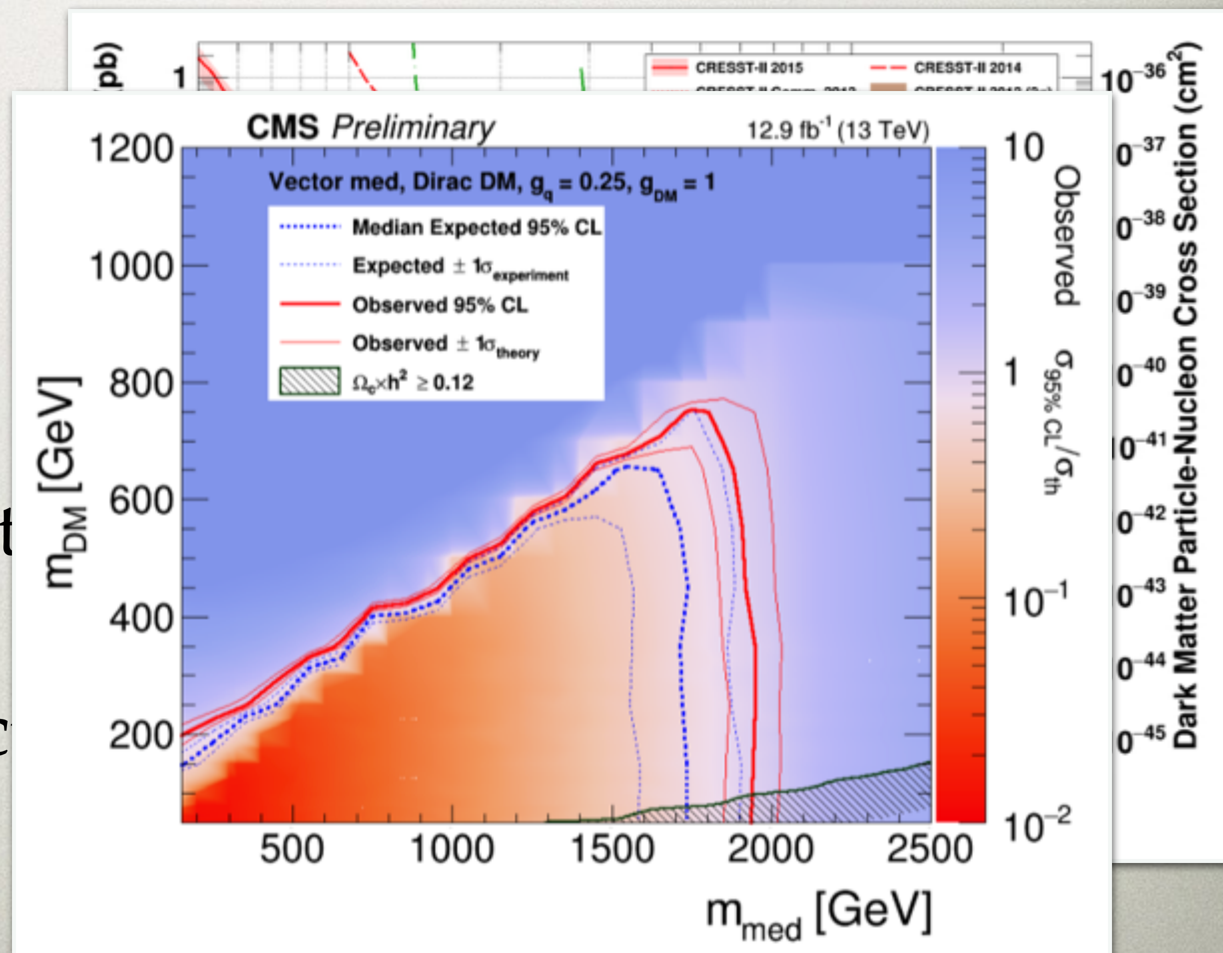
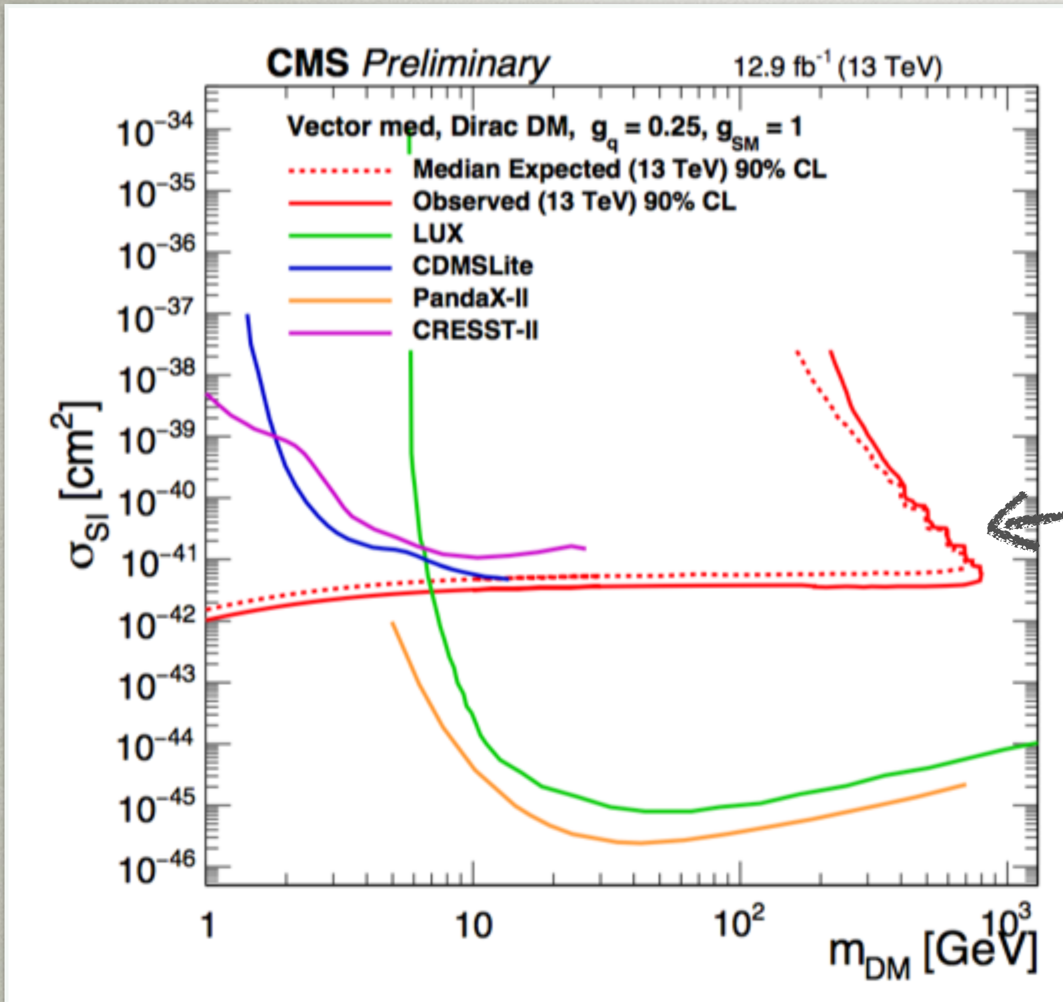
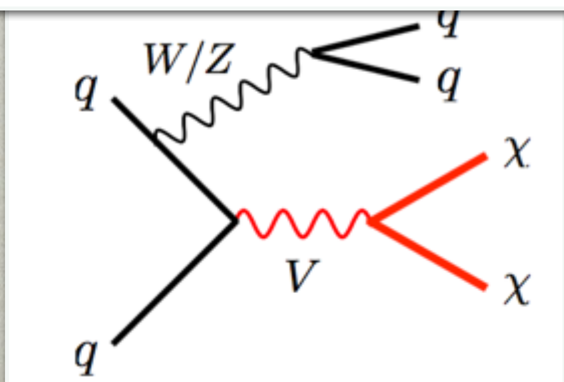




TION


CMS Preliminary
12.9 fb^{-1} (13 TeV)
Vector med, Dirac DM, g_q = 0.25, g_{SM} = 1
Median Expected (13 TeV) 90% CL
Observed (13 TeV) 90% CL
LUX
CDMSLite
PandaX-II
CRESST-II
σ_{SI} [cm^2]
m_{DM} [GeV]


W/Z
q
q
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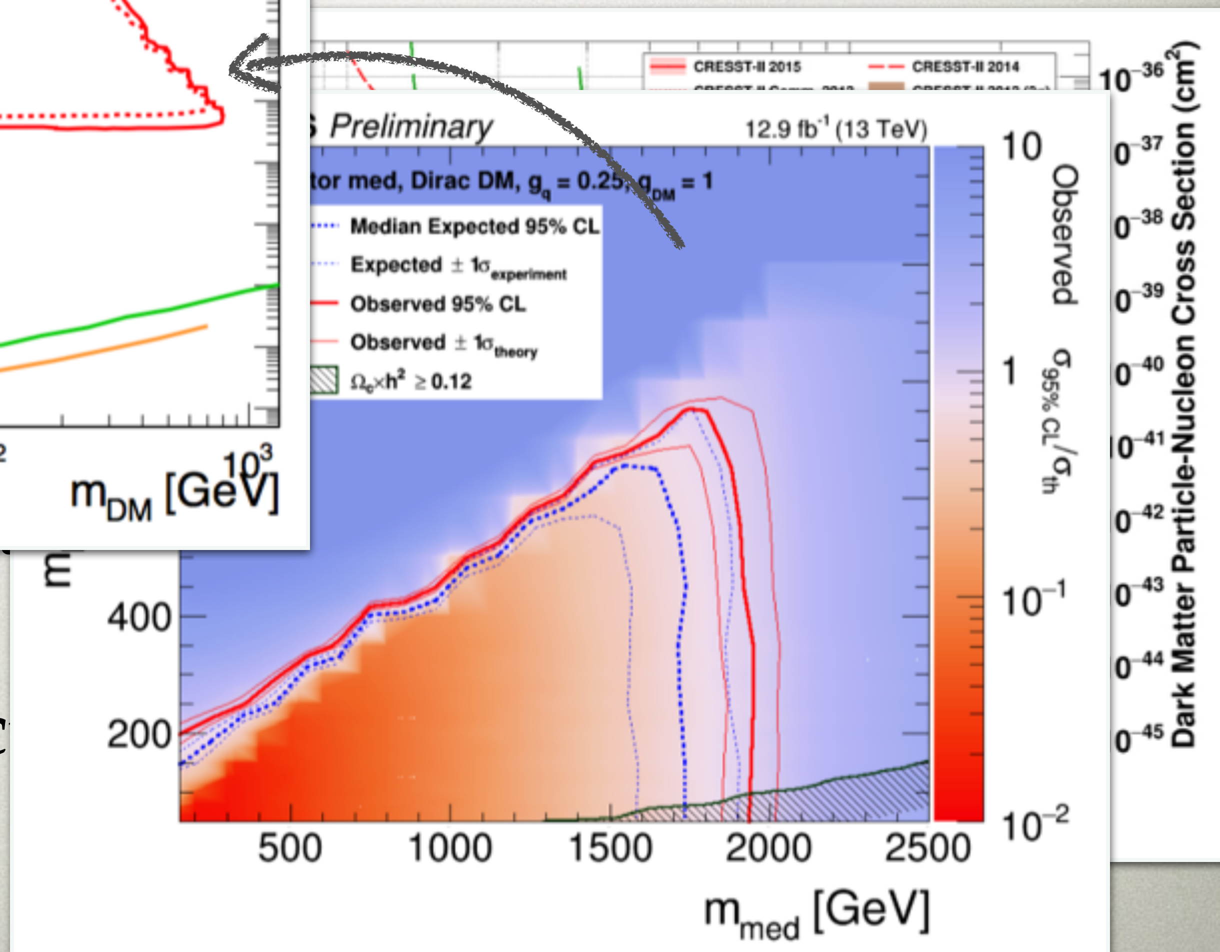
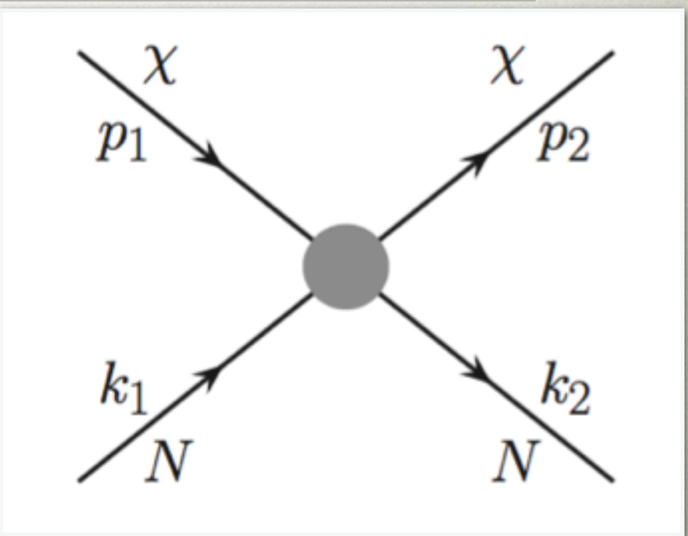

CRESST-II 2015
CRESST-II 2014
Preliminary
12.9 fb^{-1} (13 TeV)
tor med, Dirac DM, g_q = 0.25, g_{DM} = 1
Median Expected 95% CL
Expected $\pm$ 1$\sigma_{experiment}$
Observed 95% CL
Observed $\pm$ 1σ_{theory}
$\Omega_c \times h^2 \geq 0.12$
Observed $\sigma_{95\% CL}/\sigma_{th}$
m_{med} [GeV]
Dark Matter Particle-Nucleon Cross Section (cm^2)

HIERARCHY OF SCALES

- direct DM detection
  - energy deposited in keV range
  - for cold DM, $v \sim 10^{-3}$, typical momentum exchange

$$q_{\rm max} \sim 200 \text{ MeV}.$$

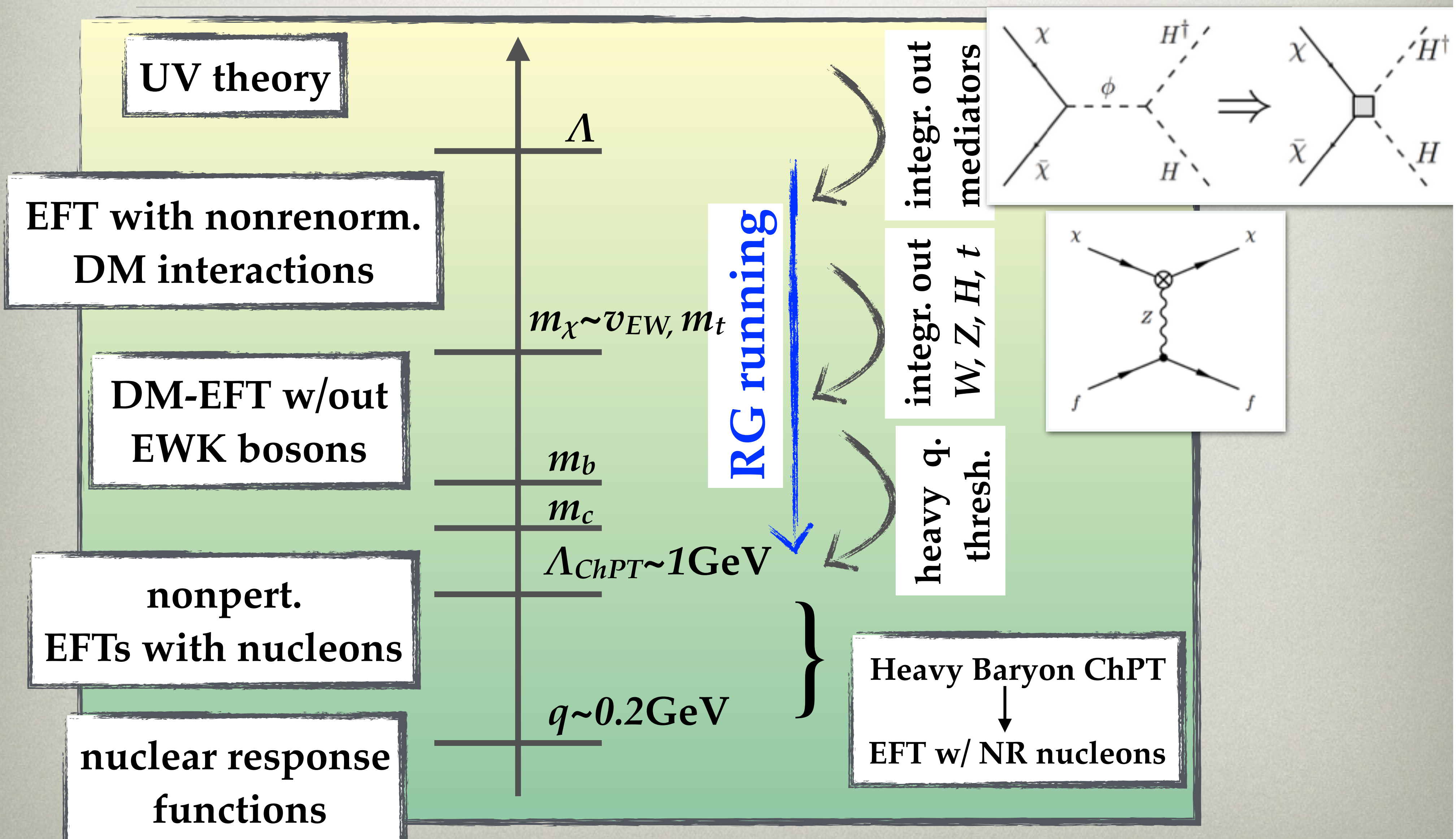


- a series of well separated scales

$$\Lambda \gg m_\chi \sim v_{\rm EW} \gg \Lambda_{\rm QCD} \gg q$$

  - need to relate operators at Λ to operators at scales $\sim$few x $\Lambda_{\rm QCD}$
  - need to treat the confinement, nuclear physics

Tower of EFTs



ABOVE EW SCALE

- for now limit the discussion to
  - dim-5 and dim-6 operators above EW scale
  - here only fermionic DM
- e.g., dim-5 operators:

CP even

$$Q_1^{(5)} = \frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)B_{\mu\nu}, \quad Q_2^{(5)} = \frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\chi)W^a_{\mu\nu},$$

$$Q_3^{(5)} = (\bar{\chi}\chi)(H^\dagger H), \qquad Q_4^{(5)} = (\bar{\chi}\tilde{\tau}^a\chi)(H^\dagger\tau^a H),$$

CP odd

$$Q_5^{(5)} = i\frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi)B_{\mu\nu}, \quad Q_6^{(5)} = i\frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\gamma_5\chi)W^a_{\mu\nu},$$

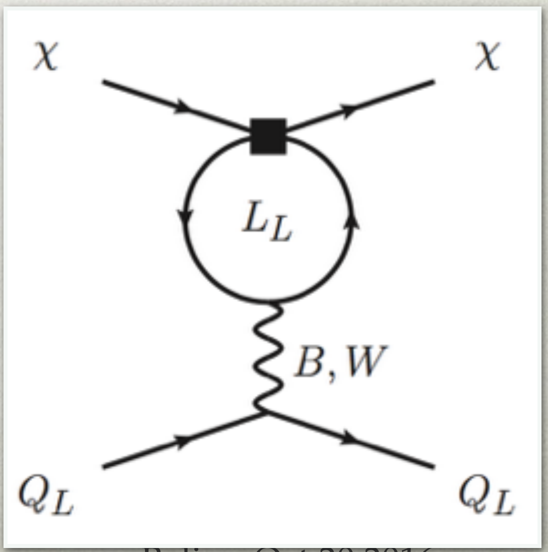
$$Q_7^{(5)} = i(\bar{\chi}\gamma_5\chi)(H^\dagger H), \qquad Q_8^{(5)} = i(\bar{\chi}\tilde{\tau}^a\gamma_5\chi)(H^\dagger\tau^a H).$$

RENORMALIZATION GROUP EFFECTS

- mixing of operators through RGE (Renormalization Group Equations):

$$\frac{d}{d\log\mu}\mathcal{C}(\mu) = \gamma^T \mathcal{C}(\mu)$$

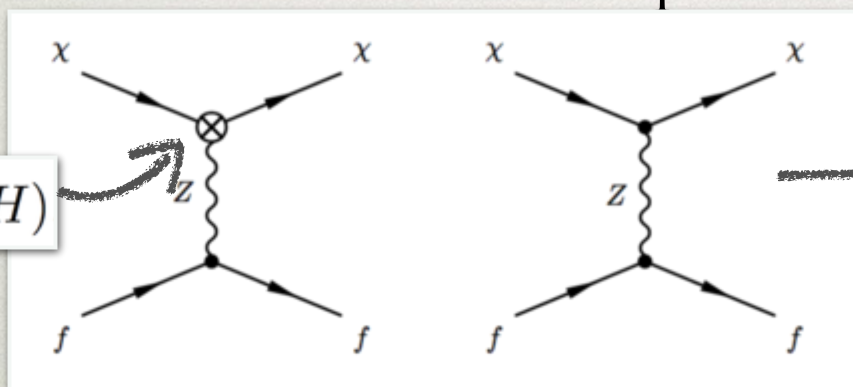
- Do we need to re-sum the logs?
  - $\alpha_1(\mu_{EW}) \approx 0.01$, $\alpha_2(\mu_{EW}) \approx 0.03$, $\alpha_\lambda(\mu_{EW}) \approx 0.04$, $\alpha_t(\mu_{EW}) \approx 0.08$
  - No – would need $\Lambda \sim 10^4$ TeV
- importance of RGE:
  - mixing of suppressed and unsuppressed operators
  - penguin insertions mix lepton and quark operators



MATCHING AT EW SCALE

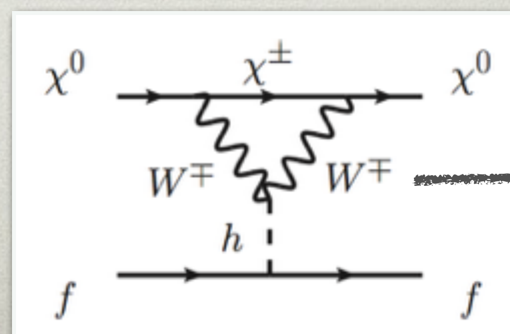
- at EW scale integrate out *W*, *Z*, *h*, *t*
  - $m_\chi \sim v_{EW}$: DM is "HQET" field in EFT
- example: *Z* exchange contribution
  - can come from either dim-6 ops or from dim-4 interaction

$$(\bar{\chi}\gamma^\mu\chi)(H^\dagger i \overleftrightarrow{D}_\mu H)$$



$$\mathcal{Q}_{1,f}^{(6)} = (\bar{\chi}_v\gamma_\mu\chi_v)(\bar{f}\gamma^\mu f),$$
$$\mathcal{Q}_{3,f}^{(6)} = (\bar{\chi}_v\gamma_\mu\chi_v)(\bar{f}\gamma^\mu\gamma_5 f),$$

- also do 1-loop matching
  - example "Higgs penguin" contrib.

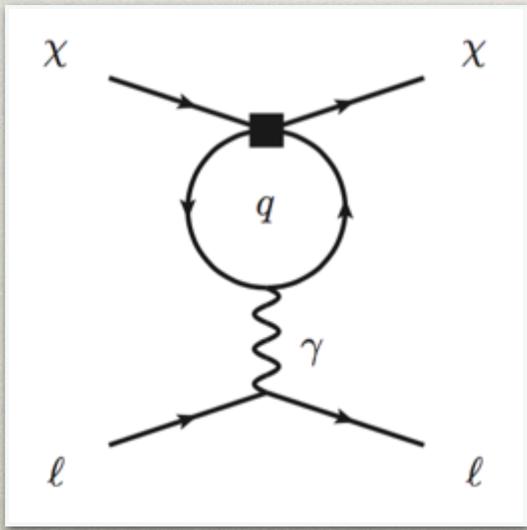


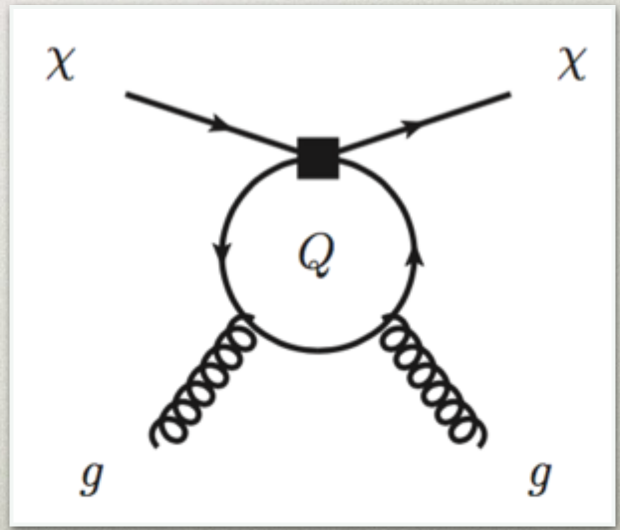
$$\mathcal{Q}_{5,f}^{(7)} = m_f(\bar{\chi}_v\chi_v)(\bar{f}f)$$

RUNNING AND MATCHING AT FLAVOR THRESHOLDS

e.g., Hill, Solon, 1409.8290

- QCD / QED running is well-known
- Penguin insertions will mix lepton and quark operators
- Matching at flavor thresholds





NUCLEAR RESPONSE

NUCLEAR RESPONSE

- for nuclear response we use the formalism of Anand, Fitzpatrick, Haxton
- match onto ops. with NR nucleons
- only this subset of NR operators is generated
- xsec prop. to

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N\,, \qquad \mathcal{O}_2^N = (v_\perp)^2\, \mathbb{1}_\chi \mathbb{1}_N\,,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi\, \vec{S}_N \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right), \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N\,,$$

$$\mathcal{O}_5^N = \vec{S}_\chi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right) \mathbb{1}_N\,, \qquad \mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right),$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi \left(\vec{S}_N \cdot \vec{v}_\perp\right), \qquad \mathcal{O}_8^N = \left(\vec{S}_\chi \cdot \vec{v}_\perp\right) \mathbb{1}_N\,,$$

$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N\right), \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\right),$$

$$\mathcal{O}_{11}^N = -\left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\right) \mathbb{1}_N\,, \qquad \mathcal{O}_{12}^N = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp\right),$$

Wilson coeffs. in R_i

***W_i* are nuclear response functions**

$$\frac{1}{2J_\chi+1}\frac{1}{2J_A+1}\sum_{\text{spins}} |\mathcal{M}|^2_{\text{nucleus,NR}} = \frac{\overline{|\mathcal{M}|^2}}{(4m_\chi m_A)^2} =$$

$$\frac{4\pi}{2J_A+1}\sum_{\tau=0,1}\sum_{\tau'=0,1}\Big\{\Big[R_M^{\tau\tau'}W_M^{\tau\tau'}(y) + R_{\Sigma''}^{\tau\tau'}W_{\Sigma''}^{\tau\tau'}(y) + R_{\Sigma'}^{\tau\tau'}W_{\Sigma'}^{\tau\tau'}(y)\Big]$$

$$+\frac{\vec{q}^{\,2}}{m_N^2}\Big[R_\Delta^{\tau\tau'}W_\Delta^{\tau\tau'}(y) + R_{\Delta\Sigma'}^{\tau\tau'}W_{\Delta\Sigma'}^{\tau\tau'}(y)\Big]\Big\},$$

$$\vec{v}_T^{\perp} = \vec{v} - \vec{q}/(2\mu_{\chi A}),$$

$$R_M^{\tau\tau'} = (4m_\chi m_N)^2\Big[c^\tau_{\text{NR},1}c^{\tau'}_{\text{NR},1} + \frac{1}{4}\Big(\frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2}c^\tau_{\text{NR},5}c^{\tau'}_{\text{NR},5}$$

$$+\vec{v}_T^{\perp 2}c^\tau_{\text{NR},8}c^{\tau'}_{\text{NR},8} + \frac{\vec{q}^{\,2}}{m_N^2}c^\tau_{\text{NR},11}c^{\tau'}_{\text{NR},11}\Big)\Big],$$

NUCLEAR RESPONSE FUNCTIONS

- $W_M(q)$: from vector operator
  - in $q \to 0$ limit counts nucleons ⇒ spin-indep. (coherent) scattering
- $W_{\Sigma''}$ and $W_{\Sigma'}$: longit. and transverse axial ops.
  - related to conventional spin form factors

$$S_{00,11} = \frac{1}{4\pi} \sum_{\text{spins}} |\langle \vec{S}_p \pm \vec{S}_n \rangle|^2,$$

$$S_{01} = \frac{1}{2\pi} \sum_{\text{spins}} |\langle \vec{S}_p \rangle|^2 - |\langle \vec{S}_n \rangle|^2,$$

$$W_{\Sigma'}^{\tau\tau'} + W_{\Sigma''}^{\tau\tau'} = S_{\tau\tau'}, \qquad \tau, \tau' = 0, 1.$$

  - measure the nucleon spin content of the nucleus
- W_Δ : vector transverse magnetic operators
  - nucleon angular momentum content of the nucleus
- (very) rough scaling:

$$W_M \sim \mathcal{O}(A^2), \qquad W_{\Sigma'}, W_{\Sigma''}, W_\Delta, W_{\Delta\Sigma'} \sim \mathcal{O}(1)$$

- in general three more response functions
  - these not generated to the order we work

ALL OPERATORS?

- do we need all the operators?
  - general dim 5 and 6 EFT only require for LO description:

$$\boxed{\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N\,,} \qquad \mathcal{O}_2^N = (v_\perp)^2\, \mathbb{1}_\chi \mathbb{1}_N\,,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi\, \vec{S}_N \cdot \Big(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\Big)\,, \qquad \boxed{\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N\,,}$$

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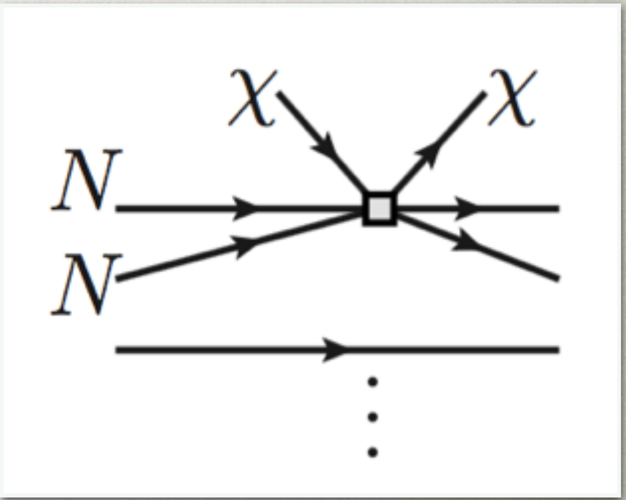
  - using the rough scalings $A \sim 100$, $q/m_N \sim 0.1$, $v_T \sim 10^{-3}$
  - allow for fine-tuning to get VxA, AxV structures
    - then 2 derivative ops. can be LO
  - due to pion poles 2 derivative ops. can be of LO size

Heavy Baryon ChPT



- assumption in the formalism for nuclear response functions
  - DM scatters on single nucleon
- how justified is this assumption?
  - how large are contributions from DM coupling to four-nucleon operators
- can be addressed using
  - Heavy Baryon Chiral Perturbation Theory (HBChPT)
  - ChEFT of nuclear forces
  - proton and neutron treated as heavy, $m_{p,n} \gg q \sim 200$MeV

HBChPT counting

Weinberg, NPB363, 3 (1991); Kaplan, Savage, Wise, nucl-th/9605002; Cirigliano, Graesser, Ovanesyan, 1205.2695

- HBChPT allows for consistent counting of "A-nucleon potentials"
  - expansion in $q/\Lambda_{\text{ChEFT}} \sim q/m_{p,n} \sim 0.3$
- *A*-nucleon irreducible amplitudes scale as ~ q^{ν}

$$\nu = 4 - A - 2C + 2L + \sum_i V_i \epsilon_i + \epsilon_\chi,$$

effective chiral dimensions

\# of connected diagrams

\# of loops

\# of vertices of type *i*

$$\epsilon_i = d_i + n_i/2 - 2,$$

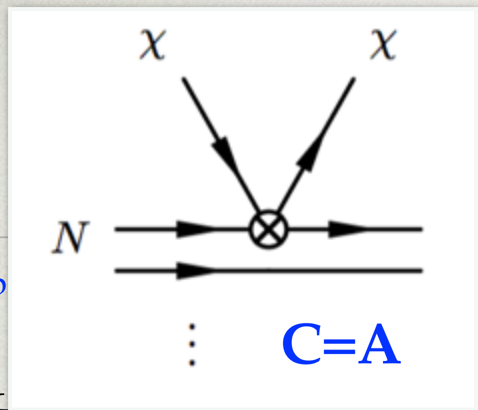
chiral dimension ~ # of derivatives

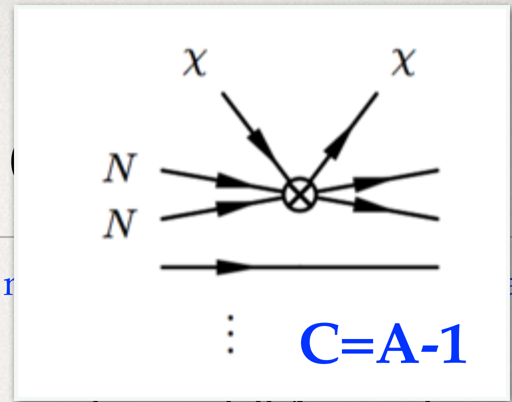
\# of nucleon legs

  - more nucleon legs in a vertex more suppressed
- gives scaling for LO and NLO potentials

hPT

Weinb… , Savage, Wise, … aesser, Ovanesyan, 1205.2695





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chiral dimension ~ # of derivatives

# of nucleon legs

- more nucleon legs in a vertex more suppressed
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LO diagrams

- quark and gluon currents hadronize as

nucleon currents

$$\tilde{J}^V_{q,\mu} \sim v^\mu_B \bar{N}N + \cdots\,, \qquad \tilde{J}^A_{q,\mu} \sim S_\mu \bar{N}N + \cdots\,,$$

$$\tilde{J}^S_q \sim m_q \bar{N}N + \cdots\,, \qquad \tilde{J}^P_q \sim m_q \bar{N}N\pi + \cdots\,,$$

$$\tilde{J}^G \sim \bar{N}N + \cdots\,, \qquad \tilde{J}^\theta \sim q^\mu S_\mu \bar{N}N + \cdots\,,$$

$$J^V_{q,\mu} \sim \pi\partial_\mu\pi + \cdots\,, \qquad J^A_{q,\mu} \sim \partial_\mu\pi + \cdots\,,$$

$$J^G \sim \pi^2, \qquad J^S_q \sim m_q\pi^2 + \cdots\,, \qquad J^P_q \sim m_q\pi + \cdots\,,$$

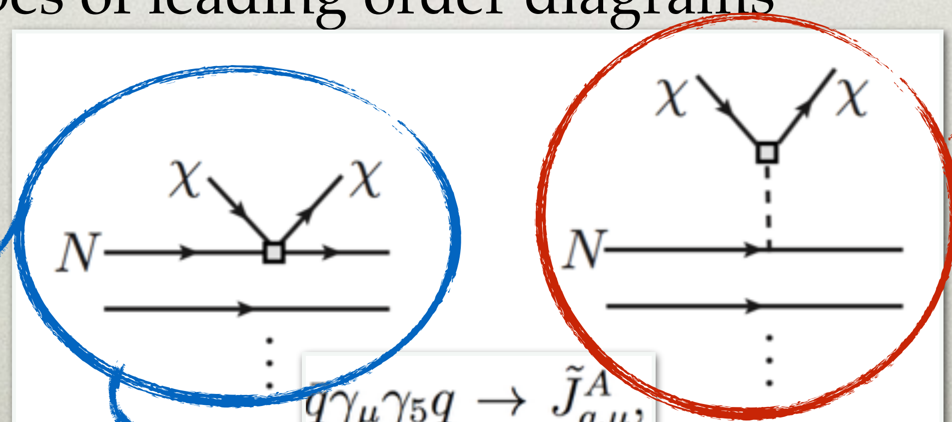
meson currents

- two types of leading order diagrams

$\bar{q}\gamma_\mu q \to \tilde{J}^V_{q,\mu}$,

$\bar{q}q \to \tilde{J}^S_q$,

$GG \to \tilde{J}^G$,



$i\bar{q}\gamma_5 q \to \tilde{J}^P_q$,

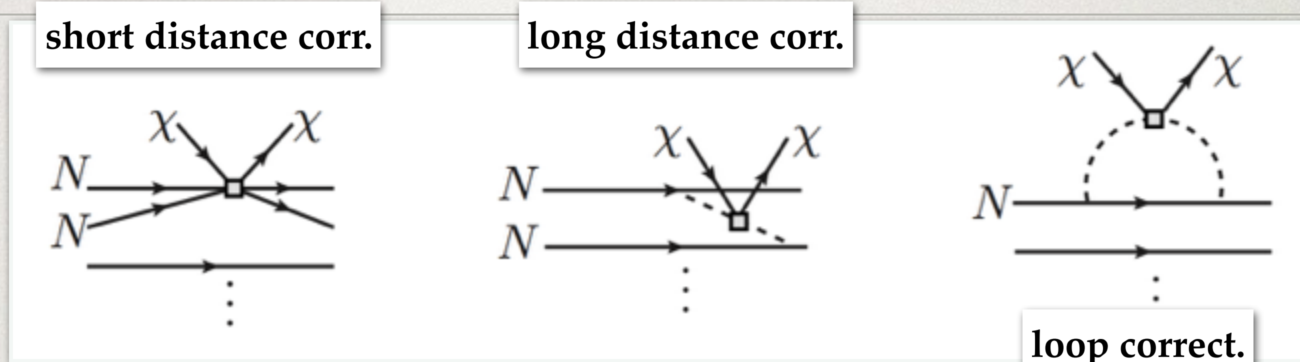
$\bar{q}\gamma_\mu\gamma_5 q \to \tilde{J}^A_{q,\mu}$,

$G\tilde{G} \to \tilde{J}^\theta$

*for vector DM only left diagr. important

NLO CORRECTIONS

sample higher order corrections



- SD always scales as $\sim q^{\nu_{\rm LO}+3}$
- only for $J_\chi^A \cdot \tilde{J}_q^V, J_\chi^S \tilde{J}_q^S, J_\chi^P \tilde{J}_q^S$ and $J_\chi^V \cdot \tilde{J}_q^A$ LD parametrically larger,
  $\sim q^{\nu_{\rm LO}+1}$ $\sim q^{\nu{\rm LO}+2}$

- we work to LO, results have relative $O(q/\Lambda_{ChEFT}) \sim 30\%$ accuracy
  - at this order: DM couples only to single nucleon currents
- at NLO, e.g., $\bar{q}q$ has LD DM interaction with two nucleons
  - calculable using HBChPT, error $\sim(q/\Lambda_{ChEFT})^2 \sim 10\%$
- genuine SD DM-2nucleon interaction at NNNLO (error~1%)
  - will require lattice QCD

conclusions

- presented work on general DM-EFT
- counting result for nuclear response and leading order coefficients
- renormalization group running important for suppressed operators

BACKUP SLIDES

OUR FRAMEWORK

- our working assumptions
  - field content is DM + SM particles
  - additional mediators (if any) to the dark sector are heavy
- $\Rightarrow$ DM interactions with SM described by Effective Field Theory
- allow for DM to
  - have EWK quantum numbers
  - be admixture of several multiplets
    - e.g., in MSSM: bino, wino, higgsino
    - Minimal Dark Matter Cirelli et al. hep-ph/0512090,…
    - "Technibaryons" Nussinov, Phys.Lett. B165 (1985) 55,…

see also D'Eramo, Procura, 1411.3342;
Berlin, Robertson, Solon, Zurek, 1511.05964;
Hill, Solon, 1401.3339, 1309.4092, 1409.8290;
Crivellin, Haisch, 1408.5046;

DIM-5 OPERATORS

- for now limit the discussion to
  - dim-5 and dim-6 operators above EW scale
  - only fermionic DM
- dim-5 operators:

CP even

$$Q_1^{(5)} = \frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)B_{\mu\nu}, Q_2^{(5)} = \frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\chi)W_{\mu\nu}^a,$$

$$Q_3^{(5)} = (\bar{\chi}\chi)(H^\dagger H), \qquad Q_4^{(5)} = (\bar{\chi}\tilde{\tau}^a\chi)(H^\dagger\tau^a H),$$

CP odd

$$Q_5^{(5)} = i\frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi)B_{\mu\nu}, Q_6^{(5)} = i\frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\gamma_5\chi)W_{\mu\nu}^a,$$

$$Q_7^{(5)} = i(\bar{\chi}\gamma_5\chi)(H^\dagger H), \qquad Q_8^{(5)} = i(\bar{\chi}\tilde{\tau}^a\gamma_5\chi)(H^\dagger\tau^a H).$$

DIM-6 OPERATORS

- DM coupling to quark currents

$$Q_{1,i}^{(6)} = (\bar\chi\gamma_\mu\tilde\tau^a\chi)(\bar Q_L^i\gamma^\mu\tau^a Q_L^i),\quad Q_{5,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\tilde\tau^a\chi)(\bar Q_L^i\gamma^\mu\tau^a Q_L^i).$$

$$Q_{2,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar Q_L^i\gamma^\mu Q_L^i),\quad Q_{6,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar Q_L^i\gamma^\mu Q_L^i),$$

$$Q_{3,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar u_R^i\gamma^\mu u_R^i),\quad Q_{7,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar u_R^i\gamma^\mu u_R^i),$$

$$Q_{4,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar d_R^i\gamma^\mu d_R^i),\quad Q_{8,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar d_R^i\gamma^\mu d_R^i).$$

- DM coupling to lepton currents

$$Q_{9,i}^{(6)} = (\bar\chi\gamma_\mu\tilde\tau^a\chi)(\bar L_L^i\gamma^\mu\tau^a L_L^i),\quad Q_{12,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\tilde\tau^a\chi)(\bar L_L^i\gamma^\mu\tau^a L_L^i),$$

$$Q_{10,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar L_L^i\gamma^\mu L_L^i),\quad Q_{13,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar L_L^i\gamma^\mu L_L^i),$$

$$Q_{11,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar\ell_R^i\gamma^\mu\ell_R^i),\quad Q_{14,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar\ell_R^i\gamma^\mu\ell_R^i).$$

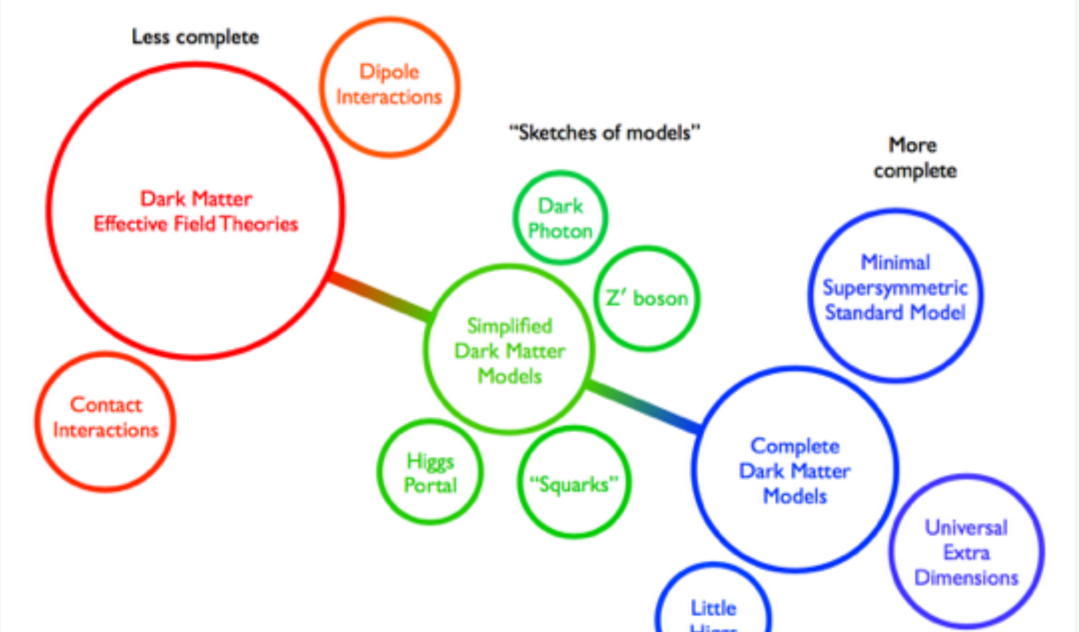
- DM coupling to Higgs currents

$$Q_{15}^{(6)} = (\bar\chi\gamma^\mu\tilde\tau^a\chi)(H^\dagger i\overleftrightarrow{D}^a{}_\mu H),\quad Q_{17}^{(6)} = (\bar\chi\gamma^\mu\gamma_5\tilde\tau^a\chi)(H^\dagger i\overleftrightarrow{D}^a{}_\mu H),$$

$$Q_{16}^{(6)} = (\bar\chi\gamma^\mu\chi)(H^\dagger i\overleftrightarrow{D}_\mu H),\quad Q_{18}^{(6)} = (\bar\chi\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D}_\mu H).$$

DIFFERENT APPROACHES

Bouvier et al 1603.04156; Abdallah et al., 1506.03116; 1409.2893; Haisch, Kahlhoefer, Tait, 1603.01267; Papucci, Vichi, Zurek,1402.2285; DiFranzo, Nagao, Rajaraman, Tait,1308.2679; An, Ji, Wang, 1202.2894; +more



from Abdallah et al., 1506.03116

- simplified models
  - introduce *t*- or *s*-channel mediators
- we limit ourselves to EFT region of parameter space

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783; Bai, Fox, Harnik, 1005.3797; + many refs.

  - get "universal" behavior from RG
  - anomalous dimension due to exchanges of the SM particles

GENERAL EFT LAGRANGIAN

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783; Bai, Fox, Harnik, 1005.3797; + many refs.

- the general EFT DM interaction Lagrangian thus

$$\mathcal{L}_\chi = \mathcal{L}_\chi^{(4)} + \mathcal{L}_\chi^{(5)} + \mathcal{L}_\chi^{(6)} + \cdots ,$$

  - we allow DM to have EWK charges

$$\mathcal{L}_\chi^{(4)} = \overline{\chi} i \gamma^\mu D_\mu \chi - m_\chi \bar{\chi} \chi$$

  - also allow for many DM multiplets
  - for now take DM to be a fermion (scalar, vector future)

- non-renormalizable interactions (mass of mediators ~Λ)

$$\mathcal{L}_\chi^{(5)} = \sum_a \frac{\mathcal{C}_a^{(5)}}{\Lambda} Q_a^{(5)}, \qquad \mathcal{L}_\chi^{(6)} = \sum_a \frac{\mathcal{C}_a^{(6)}}{\Lambda^2} Q_a^{(6)}, \qquad \ldots$$

CROSS SECTIONS

- DM is non-relativistic in the lab frame $v{\sim}10^{-3}$
- nucleons non-relativistic inside the nucleus, $v_N{\sim}\Lambda_{QCD}/m_N{\sim}0.1$
- DM-nucleon scattering non-relativistic
  - DM can only couple to nuclear mass or spin
  - spin dependent (SD) or spin indep. (SI) scattering
  - depending on details of interactions either can be velocity suppressed by v or v_N

RATE

- differential counting rate

$$\frac{dR}{dE_d} = \frac{\rho_0}{m_\chi}\frac{\eta}{\rho_{\rm det}}\int_{v>v_{\rm min}} d^3v\, \frac{d\sigma}{dE_d}\, v f_\odot(\vec{v})$$

$$\rho_0 = 0.3\ {\rm GeV/cm^3}$$

- minimal velocity $\chi N \to \chi' N$

$$v_{\rm min} = \frac{1}{\sqrt{2m_N E_d}}\left(\frac{m_N E_d}{\mu_{\chi N}} + \delta\right) \qquad v_{\rm min} > v_{\rm esc}$$

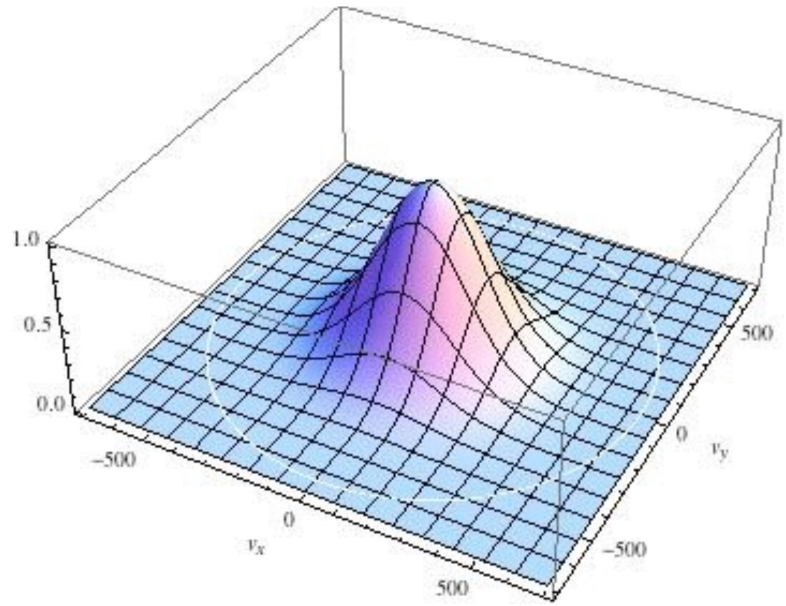
- for mass splitting large enough

- dif

$$\frac{dR}{dE_d}$$

ρ

$$f_{\rm gal}(\vec{v}) \propto \exp(-\vec{v}^2/\bar{v}^2) - \exp(v_{\rm esc}^2/\bar{v}^2)$$



$\bar{v} = 220\,\mathrm{km\,s^{-1}}$ $\quad v_{\rm esc} = 650\,\mathrm{km\,s^{-1}}$

- mi

$$v_{\rm min} = \frac{1}{\sqrt{2 m_N E_d}}\left(\frac{m_N E_d}{\mu_{\chi N}} + \delta\right) \qquad v_{\rm min} > v_{\rm esc}$$

- for mass splitting large enough

RATE

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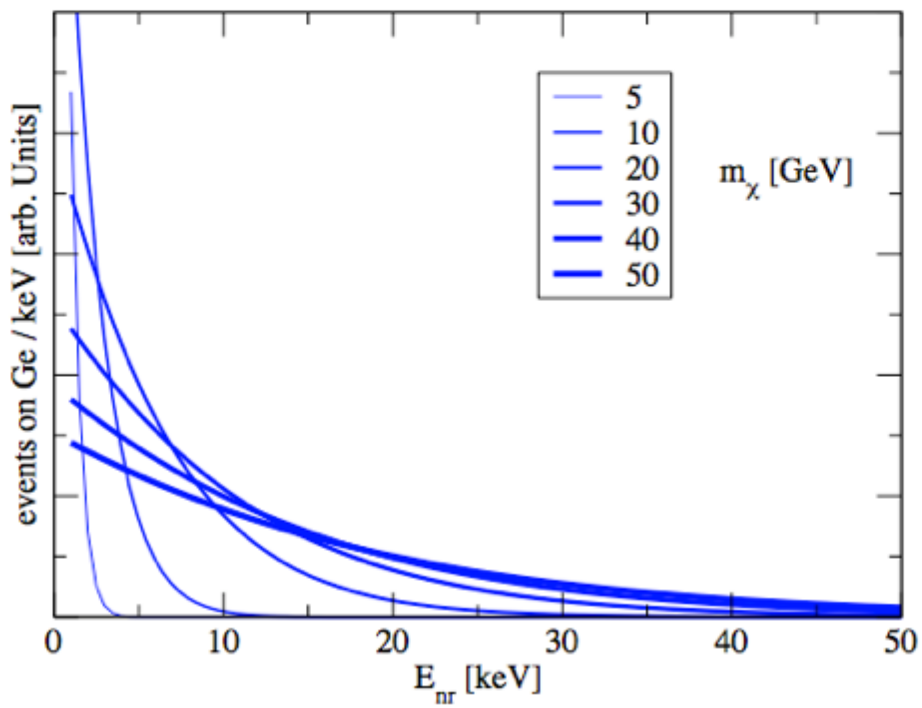
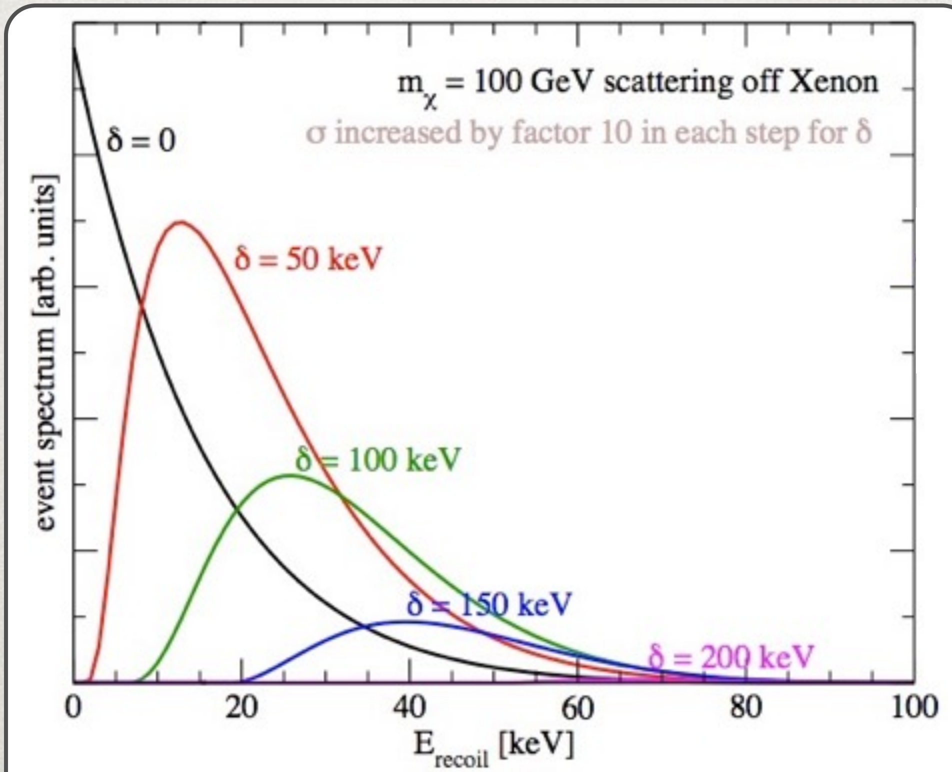
ELASTIC SCATTERING



Schwetz, GGI Conf., May 2010

- elastic scattering: featureless spectrum
- lower DM mass ⇒ smaller E_{nr}
- for low mass DM crucial low thresholds

INELASTIC SCATTERING



Schwetz, GGI Conf., May 2010

- for δ large enough only tails of v distr. contribute
- suppression of events at low E_{nr}

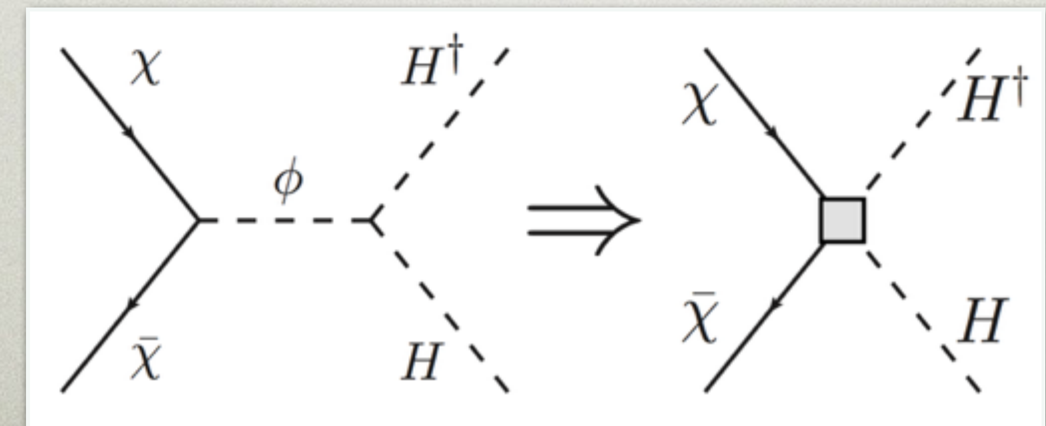
TOY EXAMPLE

- an example: scalar mediator ϕ, fermionic DM χ
- interacts with both the Higgs and DM

$$\mathcal{L}_\phi \supset \lambda_\chi \phi \bar{\chi}\chi + \mu_{H\phi}\phi H^\dagger H$$

- integrating out ϕ gives dim5 operator

$$Q_3^{(5)} = (\bar{\chi}\chi)(H^\dagger H),$$

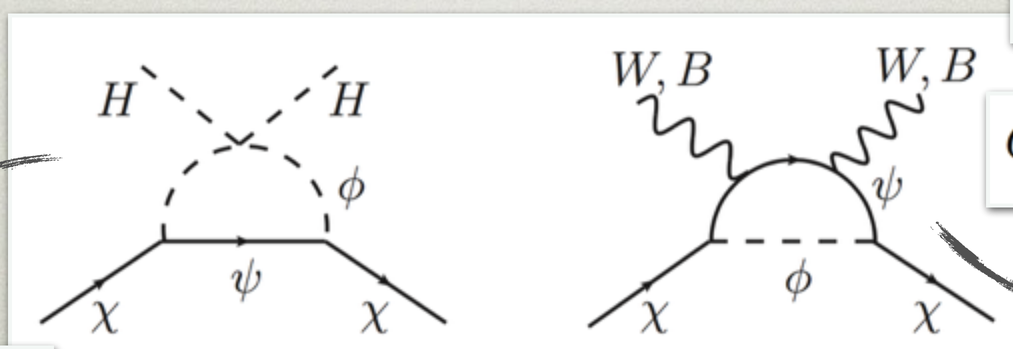


TOY EXAMPLE: LOOP ONLY

- mediators:
  - Z_2-odd electroweak singlet scalar ϕ
  - Z_2-even fermion ψ (the same EWK quantum numbers as DM)
- DM interacts with the SM only through loops
  - generate dim-5 operators

$$Q_1^{(5)} = \frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)B_{\mu\nu},$$

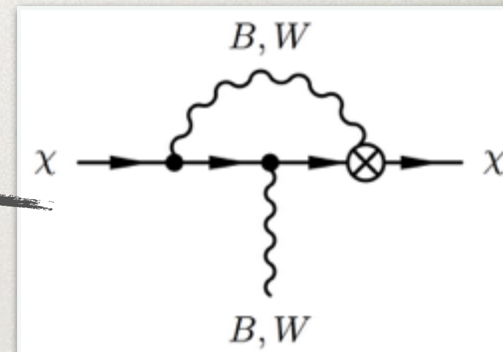
$$Q_2^{(5)} = \frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\chi)W^a_{\mu\nu},$$



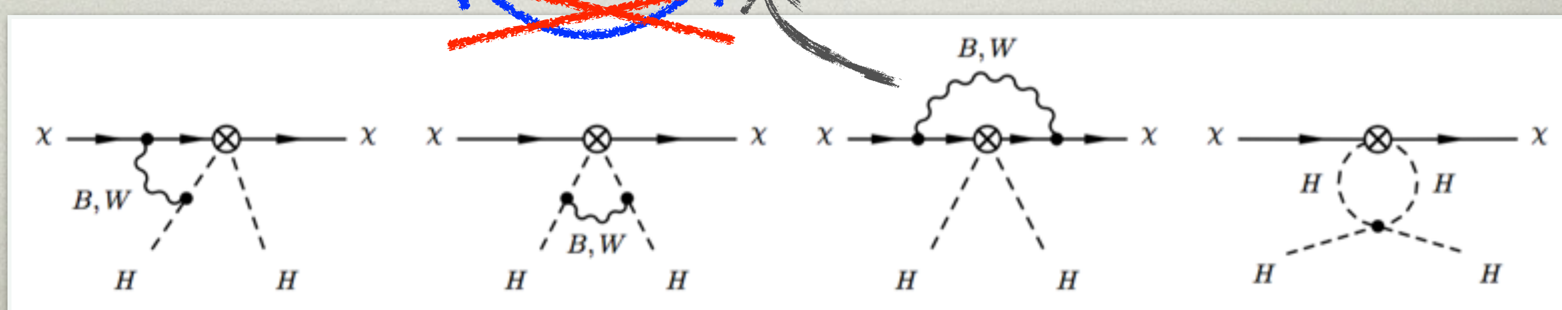
$$Q_3^{(5)} = (\bar{\chi}\chi)(H^\dagger H),$$

RUNNING ABOVE EW SCALE

- running above EW scale can mix velocity suppressed and unsuppressed ops.
- dim.-5 ops: only non-diag. mixing if $Y_\chi \neq 0$
    - for dipole operators
    - higgs current ops. diagonal anomal. dim.

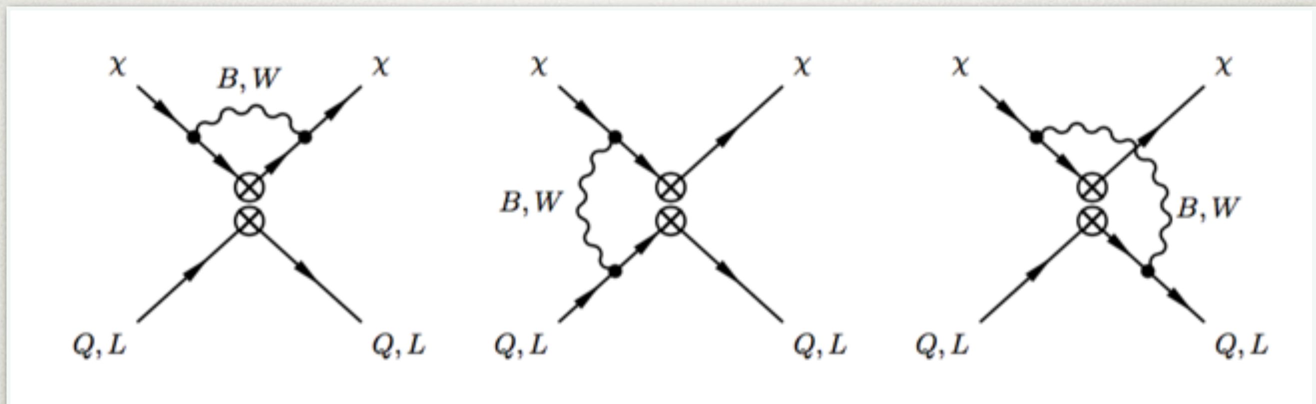


$$Q_1^{(5)} = \frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)B_{\mu\nu},\; Q_2^{(5)} = \frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\chi)W^a_{\mu\nu},$$
$$Q_3^{(5)} = (\bar{\chi}\chi)(H^\dagger H), \qquad Q_4^{(5)} = (\bar{\chi}\tilde{\tau}^a\chi)(H^\dagger\tau^a H),$$

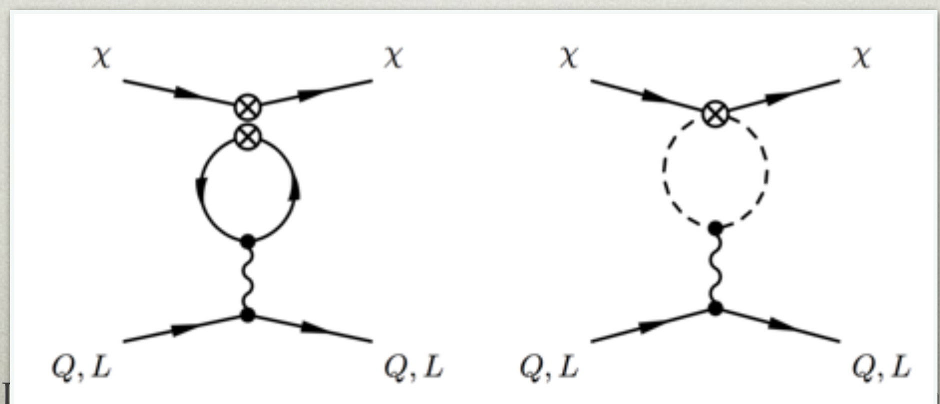


RUNNING ABOVE EW SCALE

- for dimension 6 operators
  - mixing that is present only for DM with EW charges



  - mixing that is there even for EWK neutral DM



WHY MIXING EFFECTS?

- momentum/velocity suppressed interact.s can be leading in UV models
- electroweak loops can mix suppressed and unsuppressed ops.
  - we calculate all relevant radiative corrections
- the aim is to build a complete EFT connecting UV scale to atomic scales
  - right now: partial results shown

Freytsis, Ligeti, 1012.5317;
Haisch et al. 1302.4454;
Crivellin et al. 1402.1173, 1408.5046;
D'Eramo et al. 1409.2893