FROM EW SCALE TO DM DIRECT DETECTION

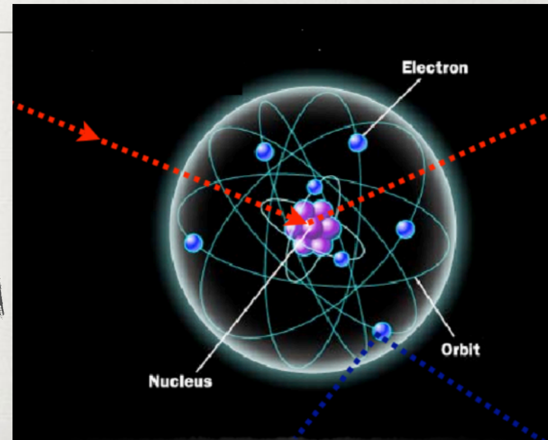
Jure Zupan
U. of Cincinnati

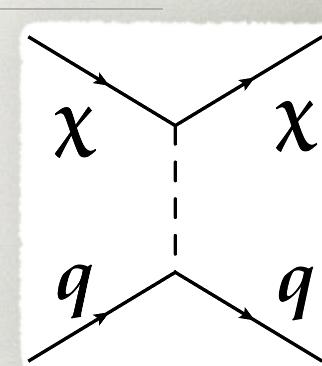
based on work with F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368, 1707.06998;1707.06998;+
J. Brod, A. Gootjes-Dreesbach, M. Tammaro, JZ, 1710.10218
J. Brod, E. Stamou, JZ, 1801.04240

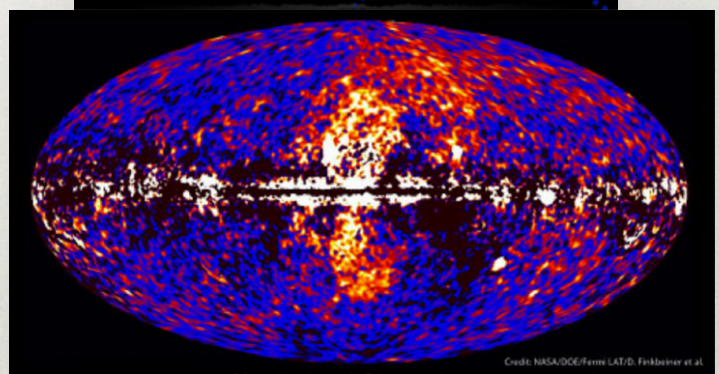
Preparing for Dark Matter Particle Discovery, Gothenburg, Jun 11 2018

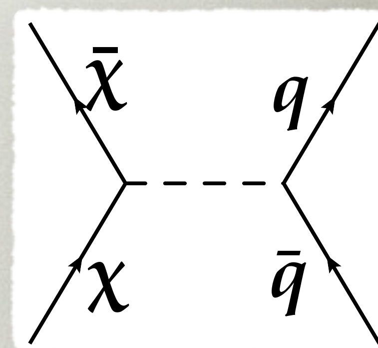
CHALLENGE #1

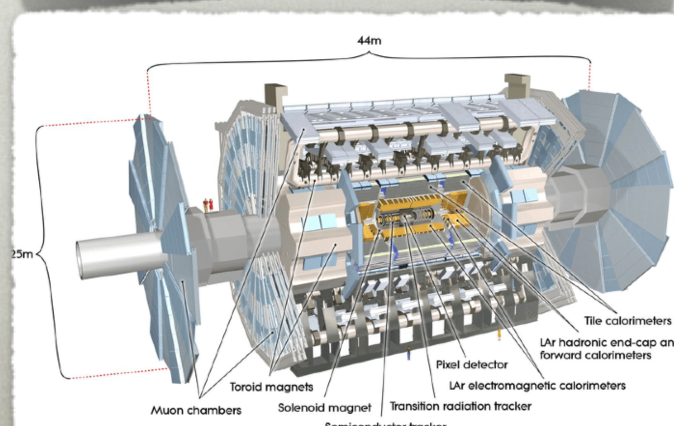
- experimental DM probes at very different energies
  - direct detection: ~200 MeV
  - indirect detection: DM mass (~ 100 GeV ?)
  - LHC production: DM mass + LHC kinem.

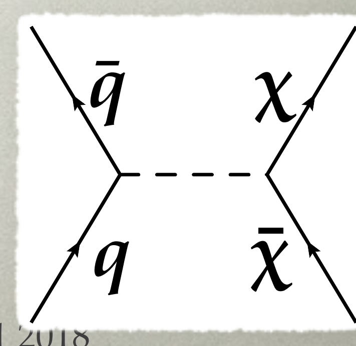












CHALLENGE #2

- we do not know how DM interacts with visible matter
- could we be missing something?
- EFTs ideal to ask "model independent" questions*

***in their domain of validity**

AIM

- the aim is to be able to

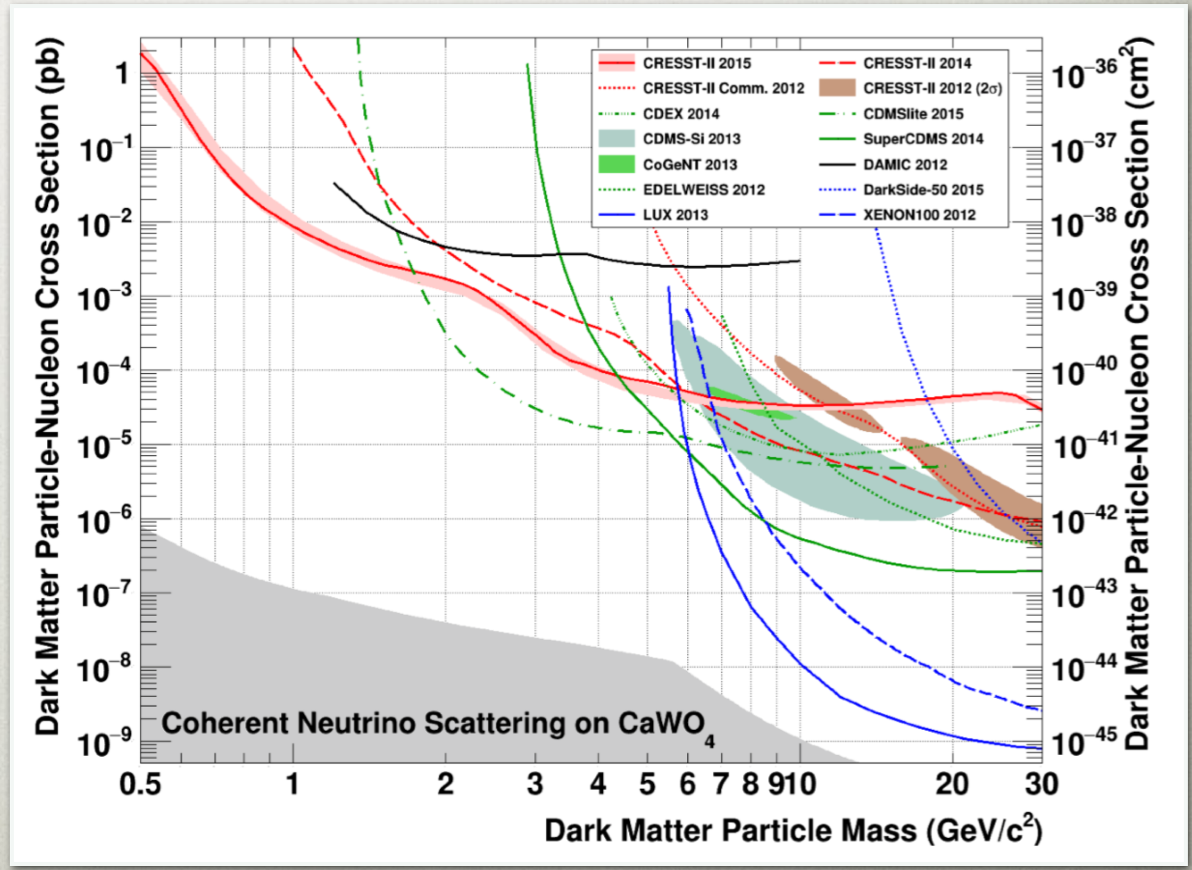
  J. Brod, A. Gootjes-Dreesbach, M. Tammaro, JZ, 1710.10218
  - take any DM EFT up to dim 7 above EW scale
  - consistently give the leading expression for cross section

  F. Bishara, J. Brod, B. Grinstein, JZ, 1806.nnnn
  - including renormalization group running

  F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368, 1707.06998
  - consistent counting, including ChPT
- part of this already available in a **Mathematica** & **Python** package **DirectDM** F. Bishara, J. Brod, B. Grinstein, JZ, 1708.02678

AIM

- in fact the aim is to help with two different problems
- DM-EFT ideal for:
    - comparing different DM direct detection experiments
- DM-EFT interm. step:
    - comparing direct detection with LHC and indirect detection



OUTLINE

- renormalization group running
- chiral EFT for DM direct detection
  - from quarks and gluons to nucleons
- neutrino nonstandard interactions

TOWER OF EFTs

UV theory

EFT with nonrenorm. DM interactions

$m_\chi \sim v_{EW}, m_t$

DM-EFT w/out EWK bosons

m_b

m_c

$\Lambda_{ChPT} \sim 1\mathrm{GeV}$

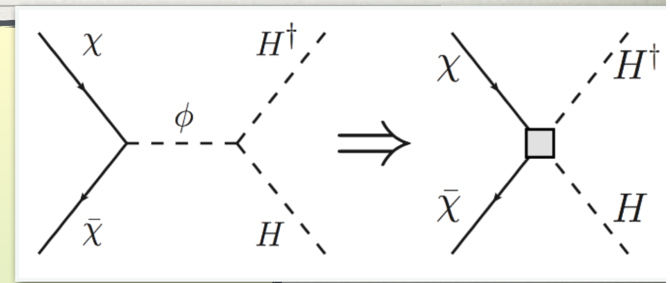
nonpert. EFTs with nucleons

$q \sim 0.2\mathrm{GeV}$

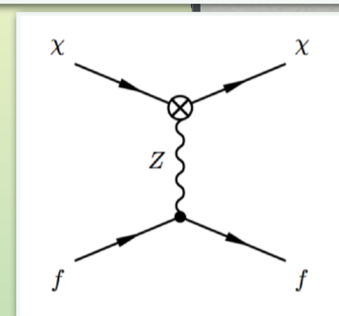
nuclear response functions

RG running

integr. out mediators



integr. out W, Z, H, t



heavy q. thresh.

Heavy Baryon ChPT $\downarrow$ EFT w/ NR nucleons

EFT expansion

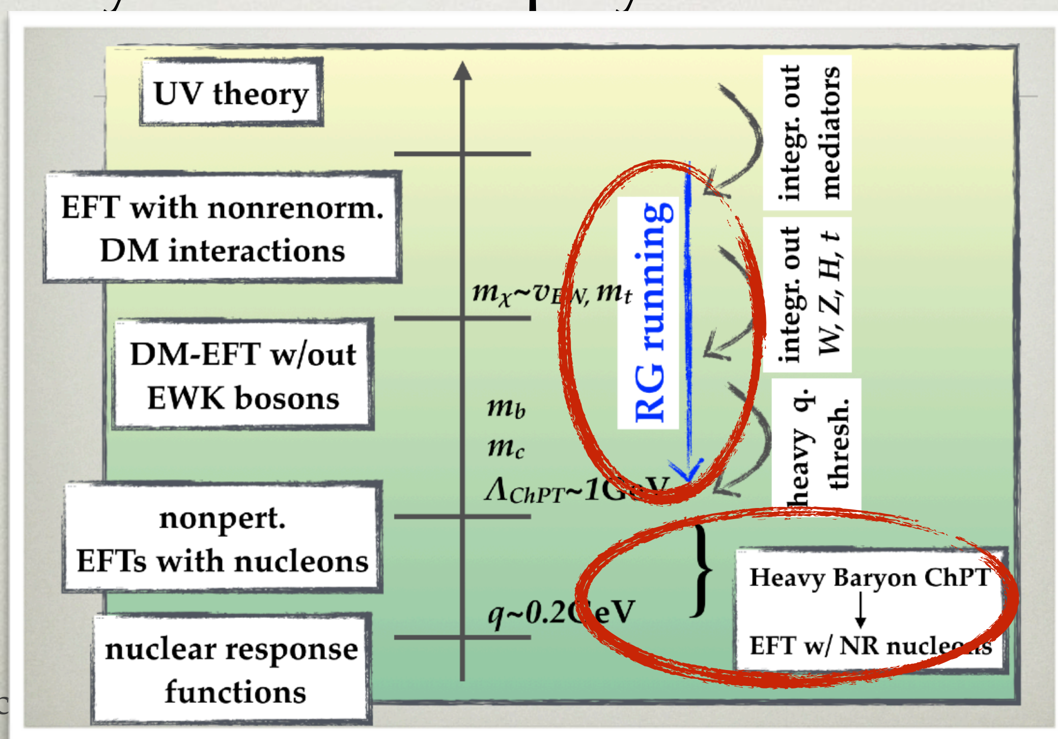
- at which mass dimension to stop?

$$\mathcal{L}_{\rm EW} = \sum_{a,d} \frac{C_a^{(d)}}{\Lambda^{d-4}} Q_a^{(d)}$$

- at dimension 7 all chiral/Lorentz structures without derivatives
  - probably captures leading behaviour in most theories of DM
- already a large set of operators
  - above EW, if Dirac fermion DM in general EW multiplet
    - 8 dim-5 ops., 18 dim-6 ops., 100 dim-7 ops.
    - this not counting flavor multiplicities
  - at μ_{str}~2 GeV smaller set
    - 2 dim-5 ops., 4 dim-6 ops., 22 dim-7 ops.

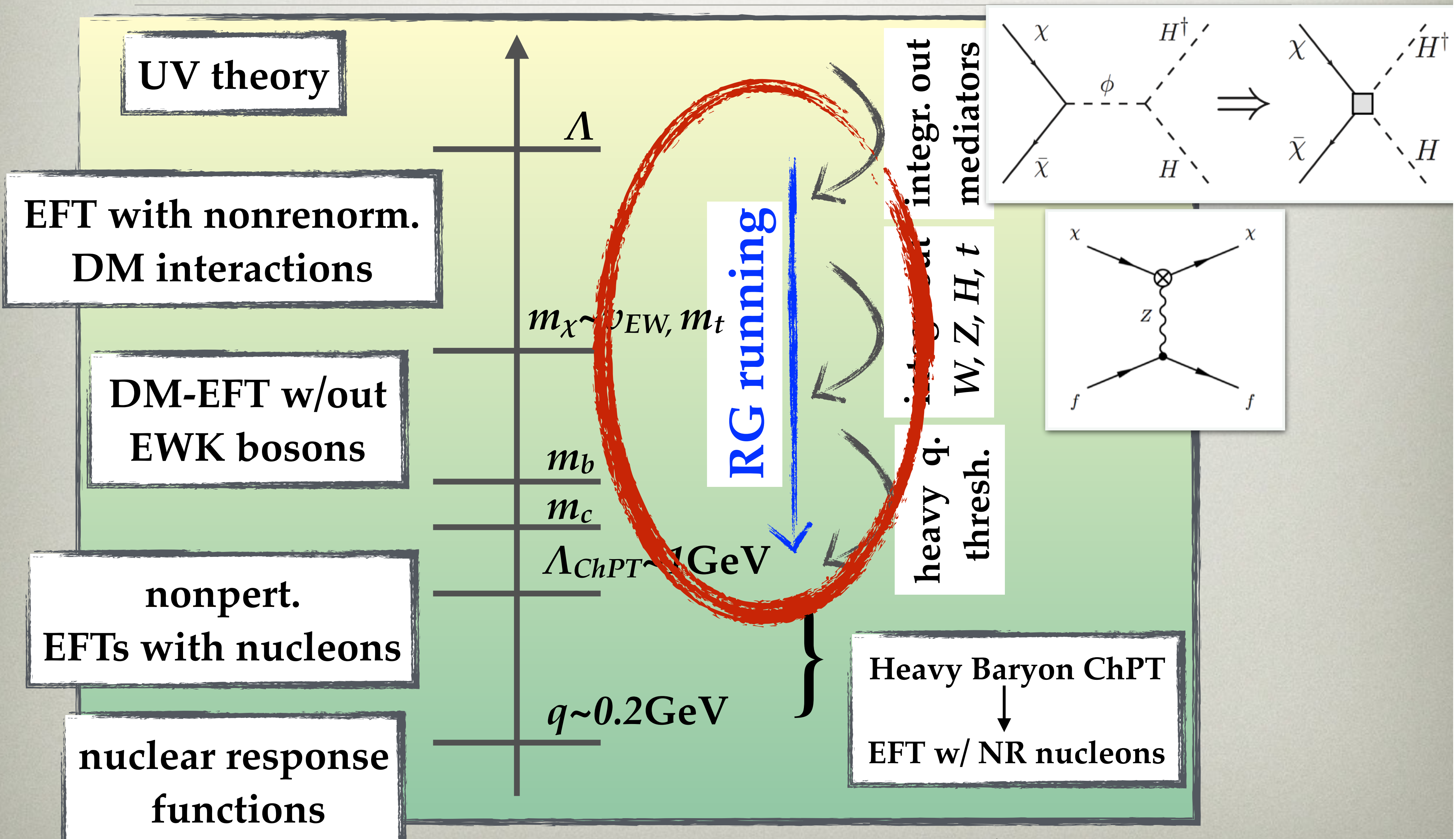
GOALS FOR TODAY

- 2 parts of the talk
  - RG running from UV to μ_{str}~2 GeV
  - matching at μ_{str}~2 GeV from relativistic theory to nuclear physics



RG RUNNING

Tower of EFTs



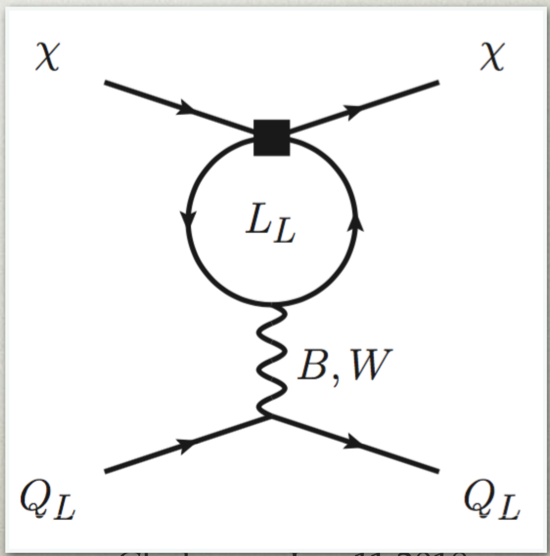
LOOP CORRECTIONS

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; + many more

- 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 velocity suppressed and unsuppressed operators
  - penguin insertions mix lepton and quark operators



RG running above EW

- allow DM to carry electroweak charges

F. Bishara, J. Brod, B. Grinstein, JZ, 1806.nnnnn

- for now: only fermion DM
- only dim5 and dim6 ops
    - dim7 to be included in the future

J. Brod, A. Gootjes-Dreesbach, M. Tammaro, JZ, yymm.nnnnn

DIM-5 OPERATORS

- 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

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

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

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

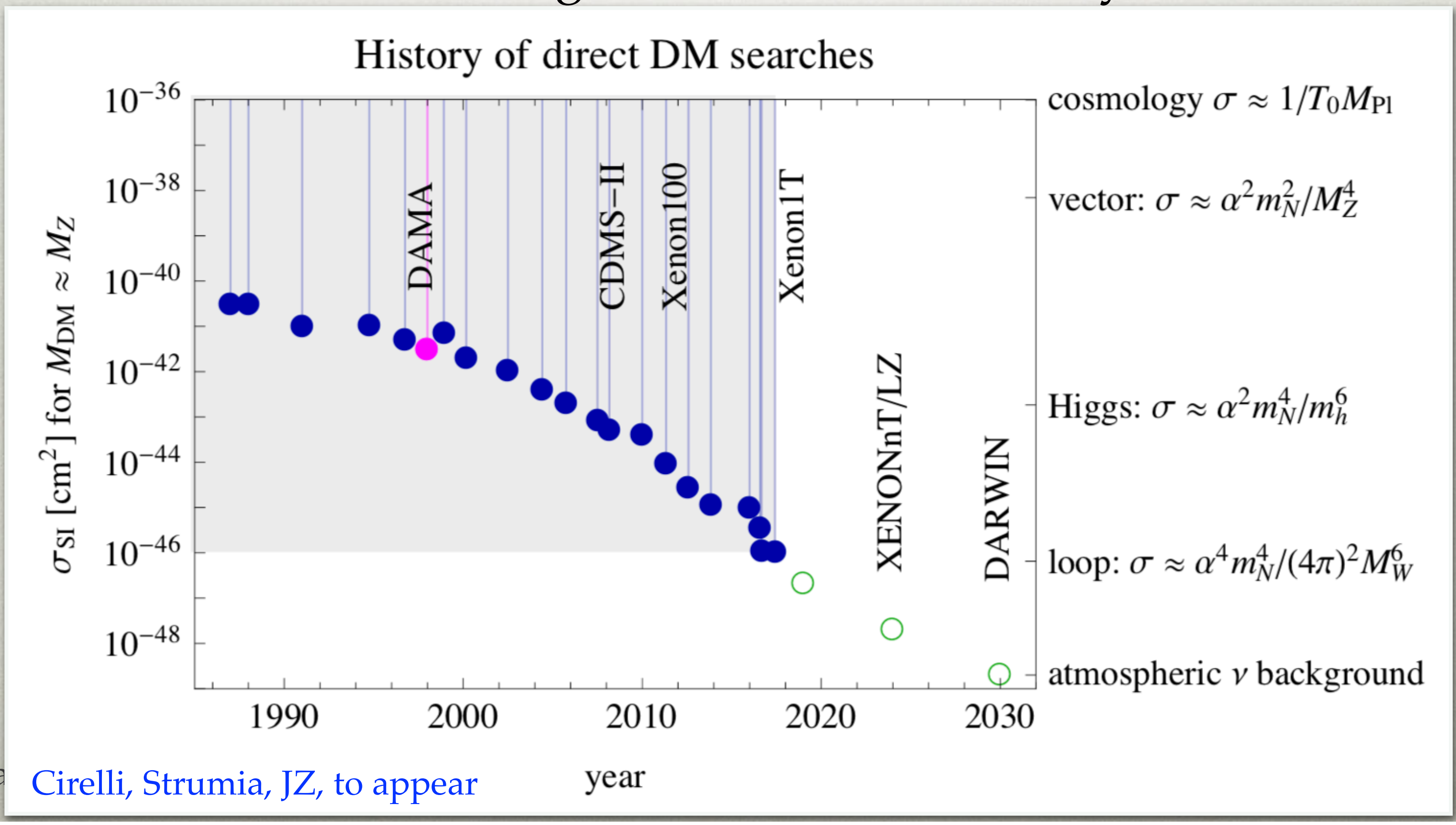
$$Q_{9,i}^{(6)} = (\bar\chi\gamma_\mu\tilde\tau^a\chi)(\bar L_L^i\gamma^\mu\tau^a L_L^i),\quad Q_{12,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\tilde\tau^a\chi)(\bar L_L^i\gamma^\mu\tau^a L_L^i),$$
$$Q_{10,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar L_L^i\gamma^\mu L_L^i),\quad Q_{13,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar L_L^i\gamma^\mu L_L^i),$$
$$Q_{11,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar\ell_R^i\gamma^\mu \ell_R^i),\quad Q_{14,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar\ell_R^i\gamma^\mu \ell_R^i).$$

- DM coupling to Higgs currents

$$Q_{15}^{(6)} = (\bar\chi\gamma^\mu\tilde\tau^a\chi)(H^\dagger i \overleftrightarrow{D}^a{}_\mu H),\quad Q_{17}^{(6)} = (\bar\chi\gamma^\mu\gamma_5\tilde\tau^a\chi)(H^\dagger i \overleftrightarrow{D}^a{}_\mu H),$$
$$Q_{16}^{(6)} = (\bar\chi\gamma^\mu\chi)(H^\dagger i \overleftrightarrow{D}_\mu H),\quad Q_{18}^{(6)} = (\bar\chi\gamma^\mu\gamma_5\chi)(H^\dagger i \overleftrightarrow{D}_\mu H).$$

HIGHER DIM OPS?

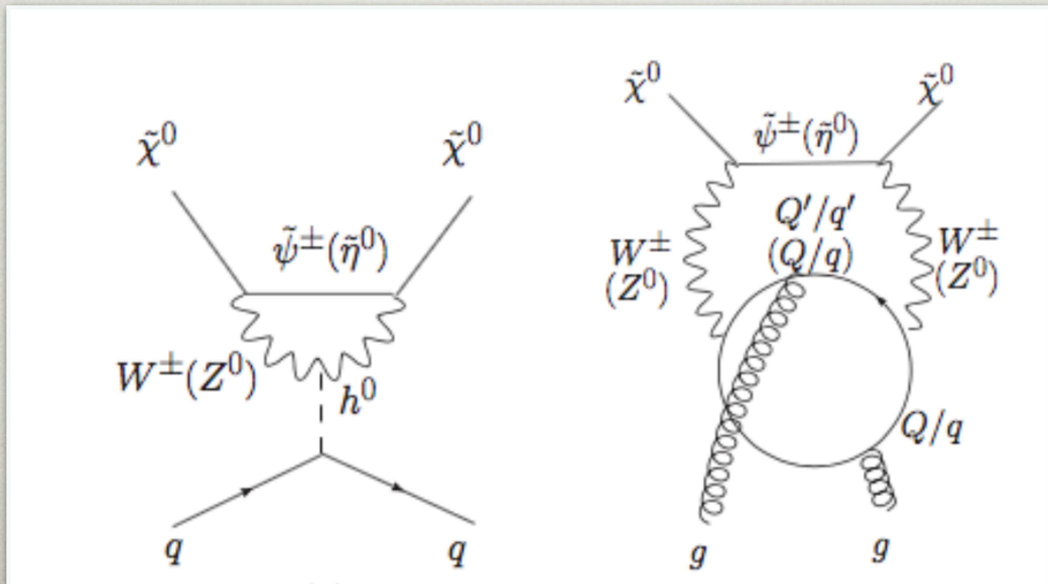
- 0-th order question:
  - since renormalizable EW interactions, do we care about higher dim ops?
- if tree level Z exchange allowed, ruled out by direct detection



HIGHER DIM OPS?

F. Bishara, J. Brod, B. Grinstein, JZ, 1806.nnnn

- 0-th order question:
  - since renormalizable EW interactions, do we care about higher dim ops?
- if tree level Z exchange allowed, ruled out by direct detection
- this leaves 1-loop and 2-loop as leading
- higher dim ops can dominate



Hisano et al, 1104.0228, 1007.2601

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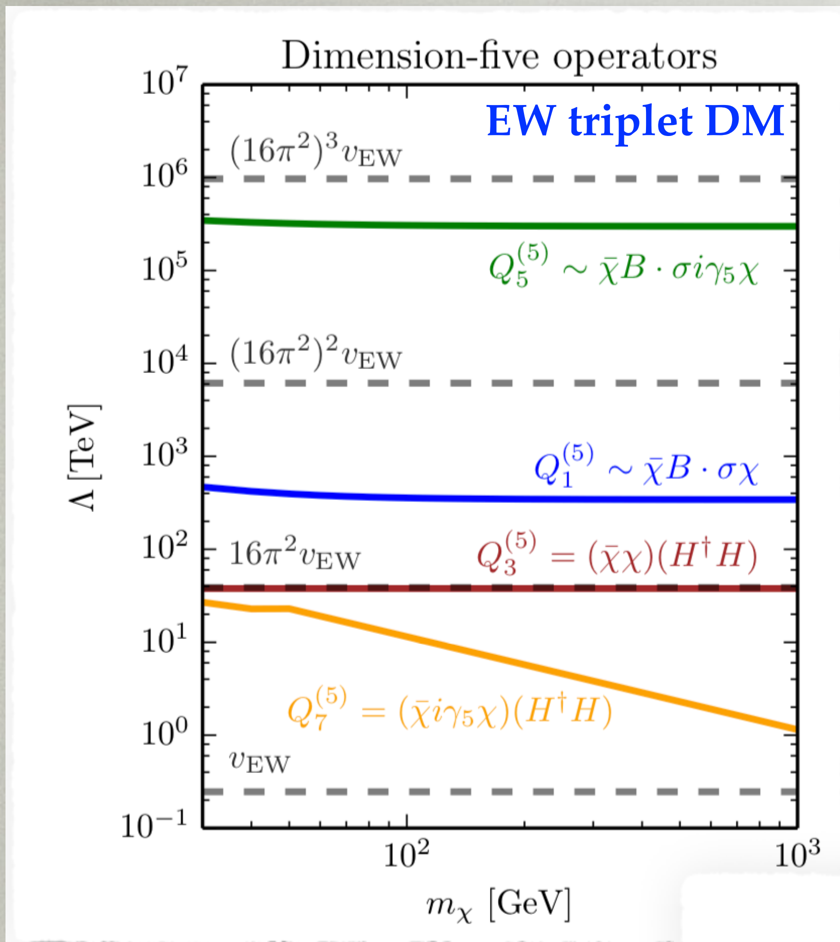
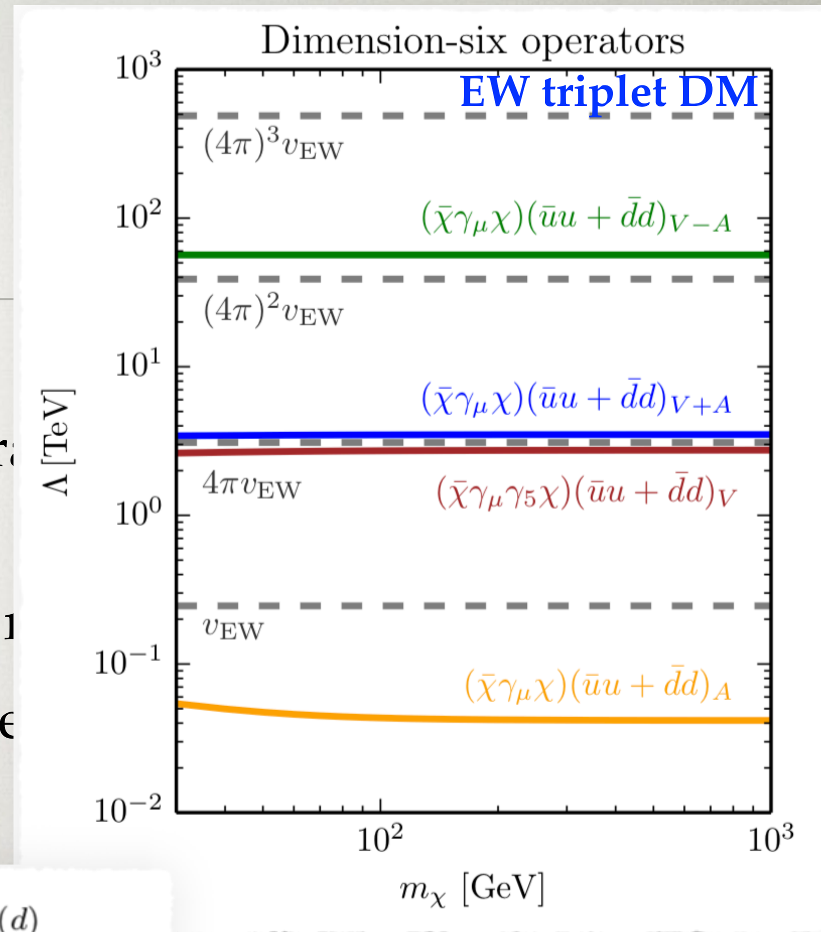
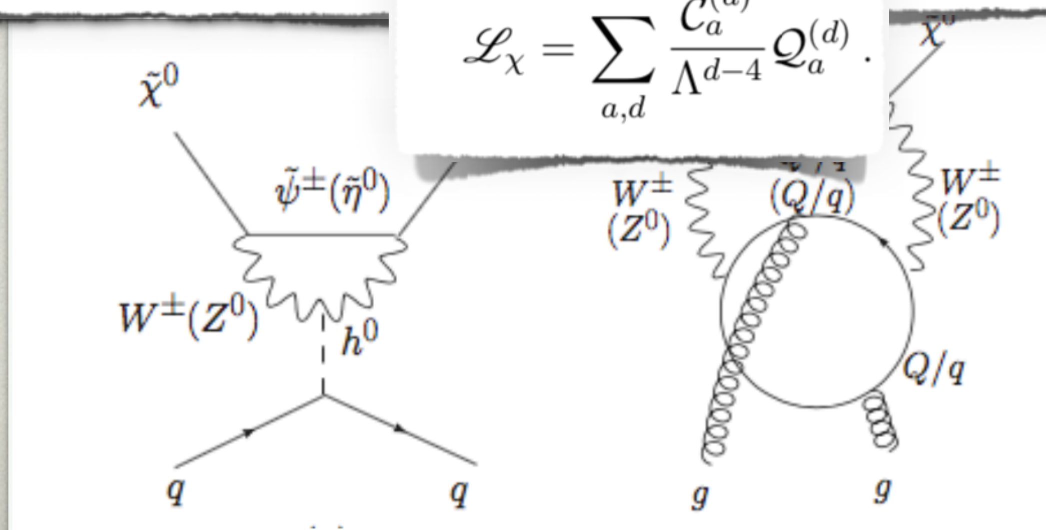




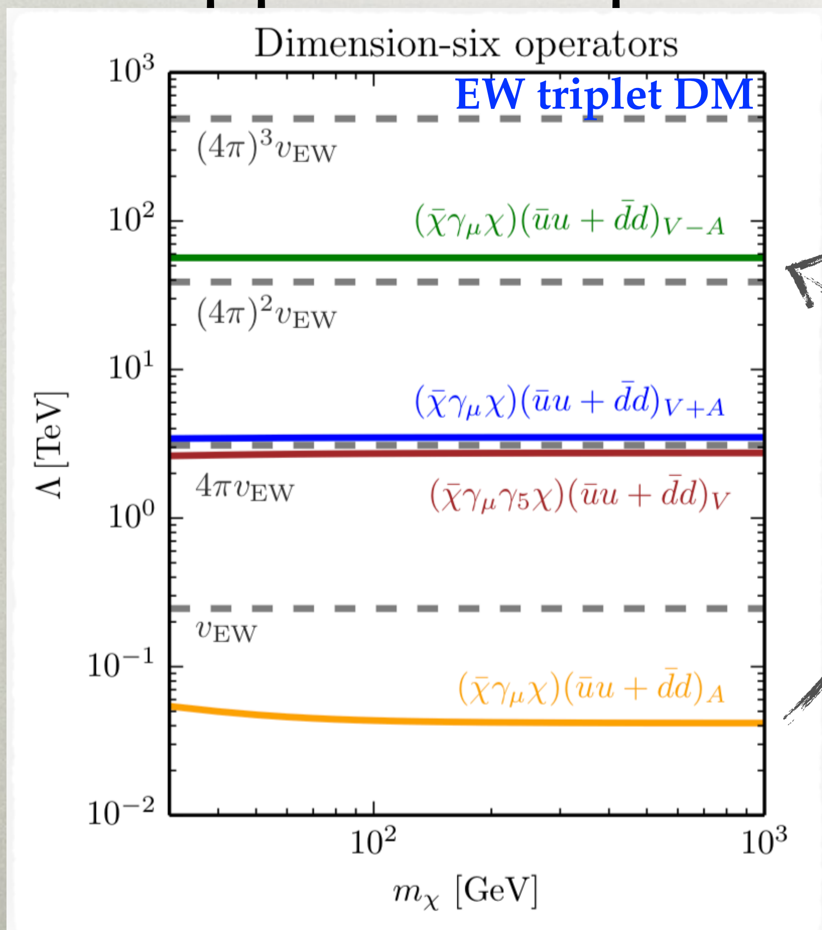
$$\mathscr{L}_\chi = \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)} .$$

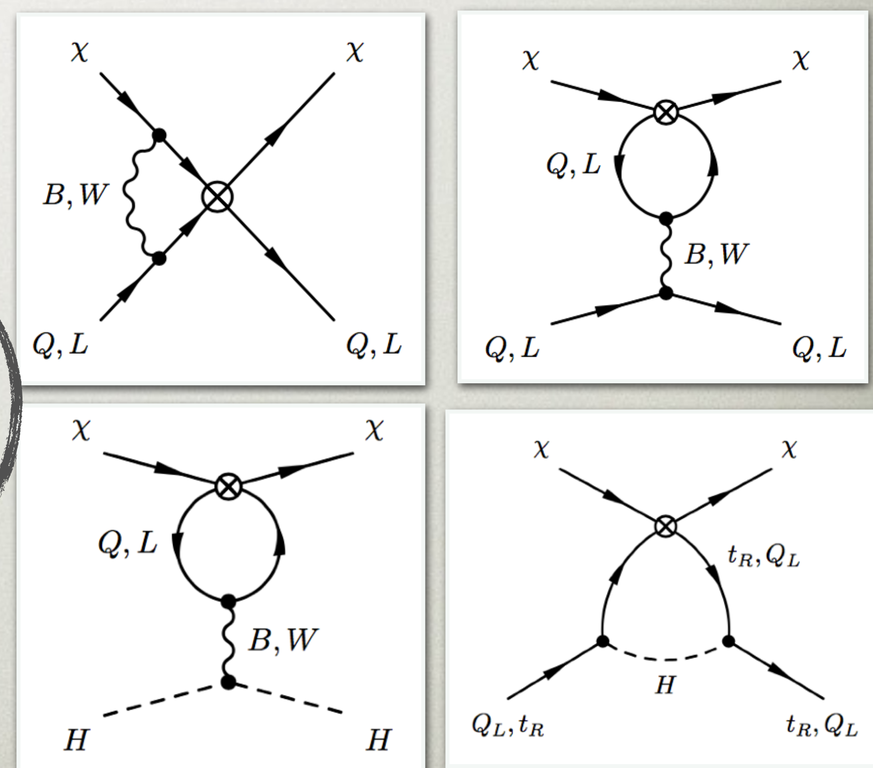


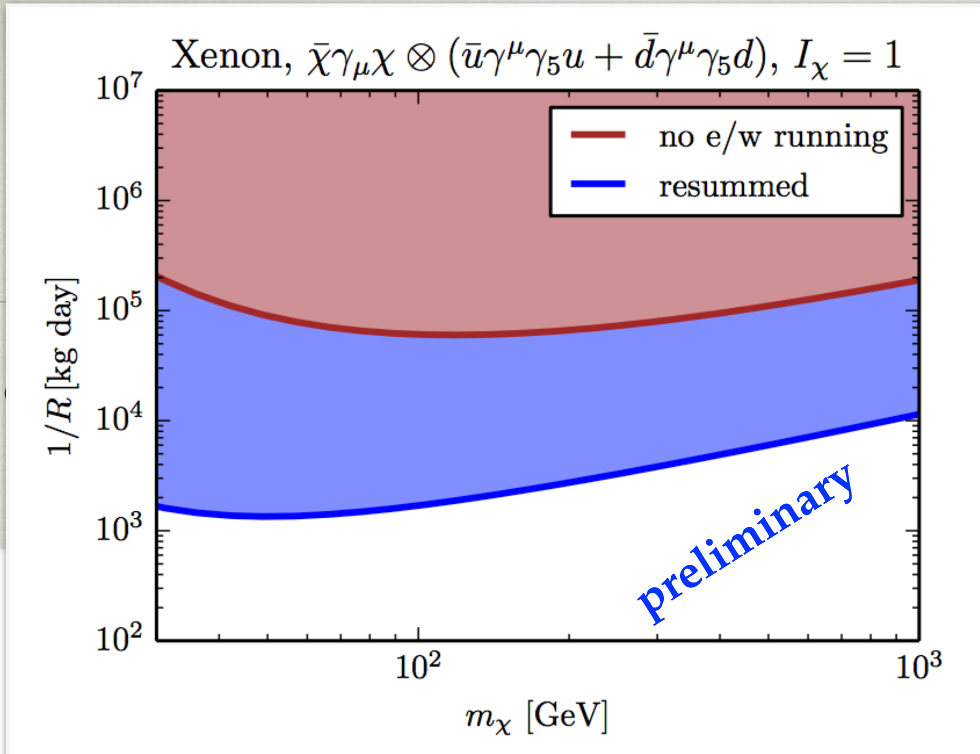
EFFECTS OF MIXING

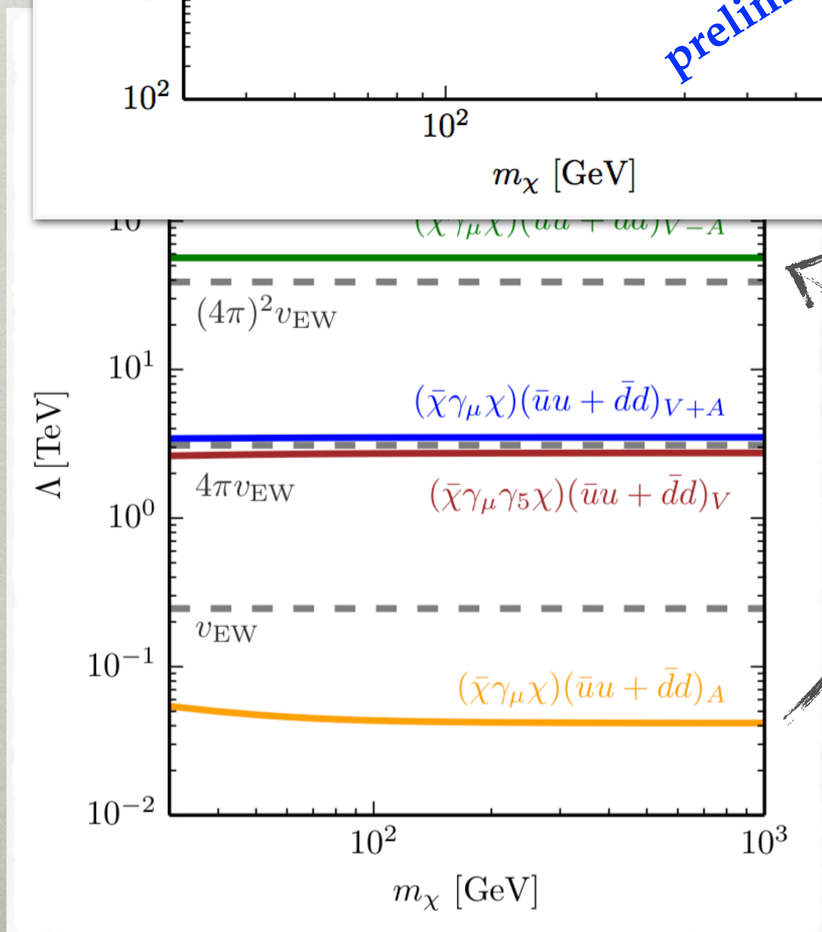
F. Bishara, J. Brod, B. Grinstein, JZ, 1806.nnnn

- the mixing important if from velocity suppressed ops. to unsuppressed







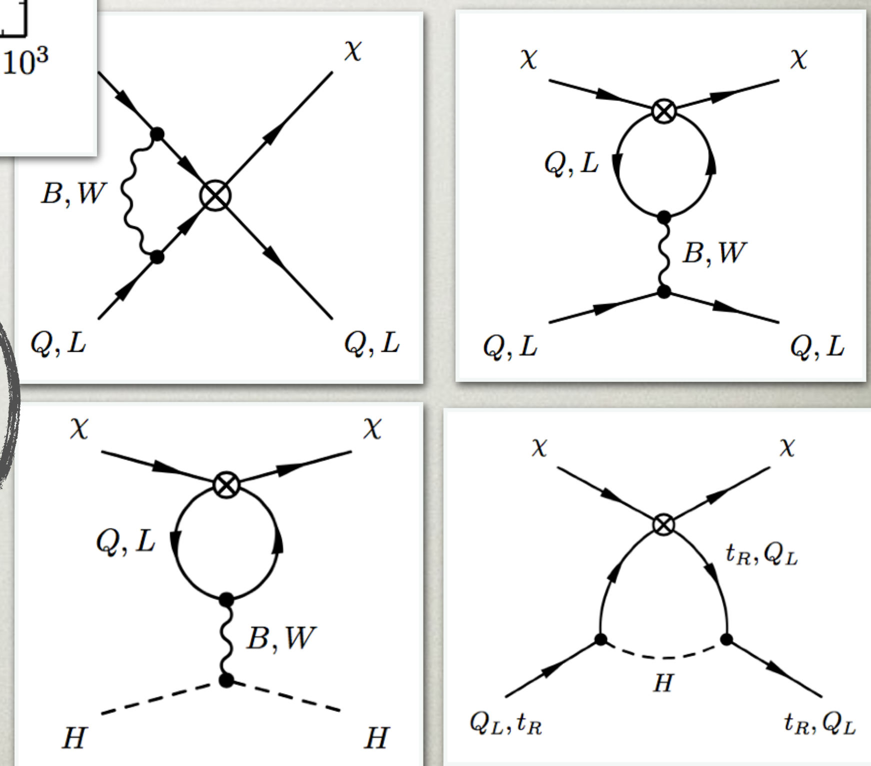


...IXING

F. Bishara, J. Brod, B. Grinstein, JZ, 1806.nnnn

...from velocity

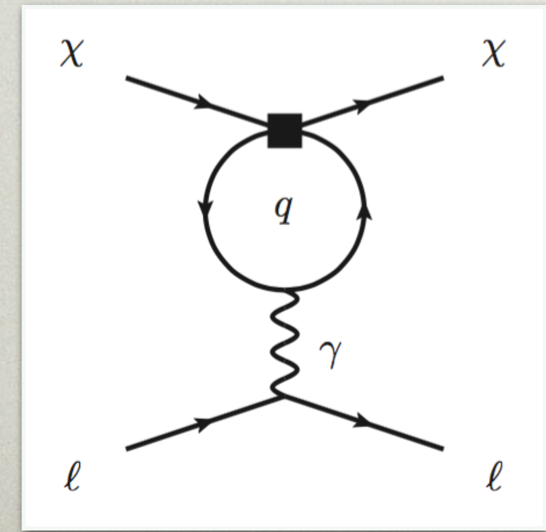
...ppressed

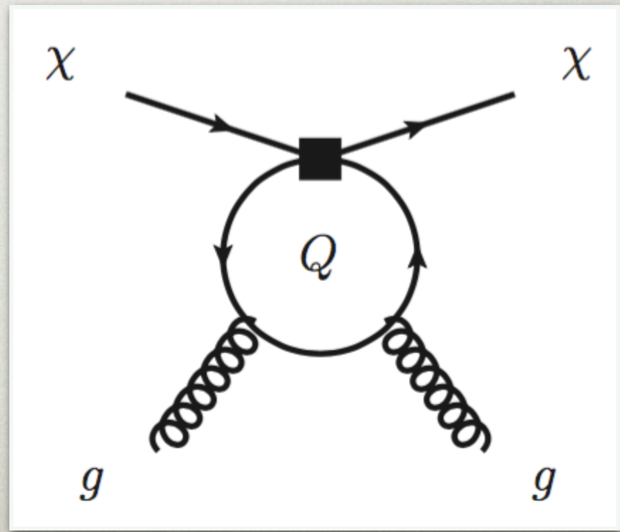


RUNNING BELOW EW

e.g., Hill, Solon, 1409.8290

- below EW: QCD / QED running is well-known
- penguin insertions mix lepton and quark ops
- matching at flavor thresholds

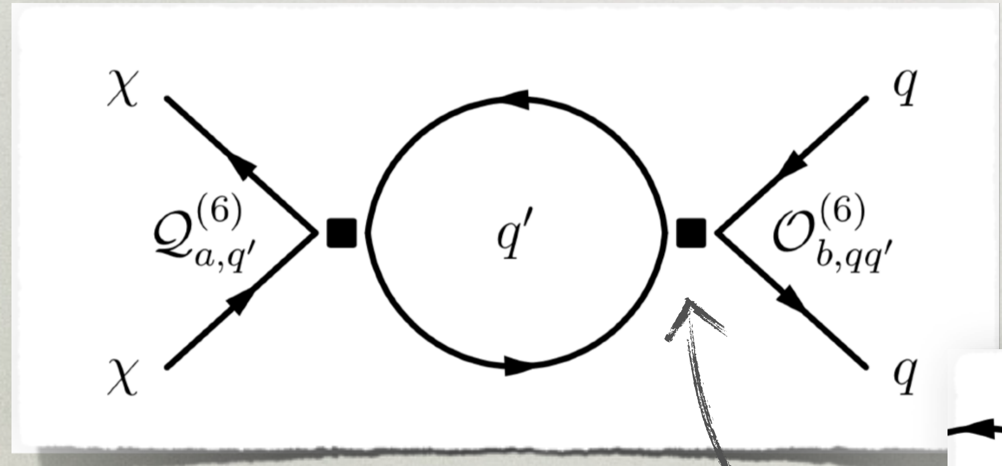


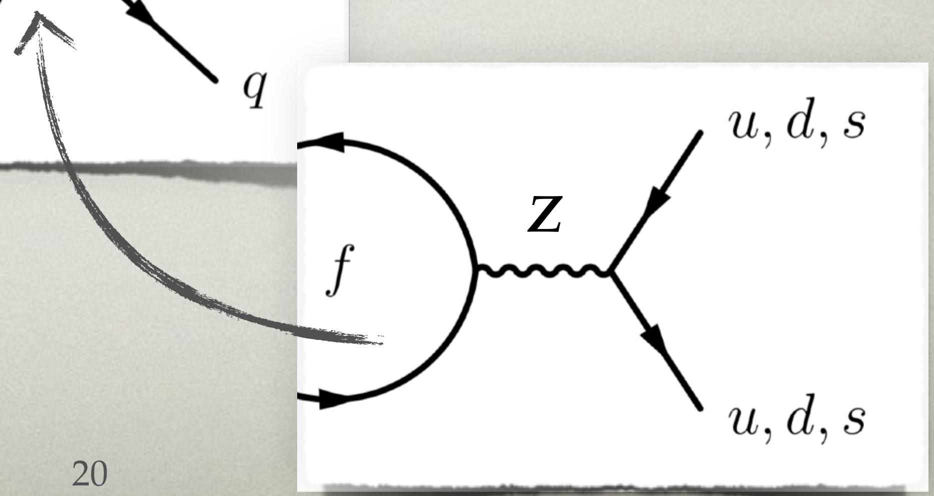


DOUBLE WEAK INSERTIONS

D'Eramo, Procura, 1411.3342; Brod, Stamou, JZ, 1801.04240

- in order to have xsecs to *O(1)* need to include double weak insertions
  - and resum QCD logs





DOUBLE WEAK INSERTIONS

Brod, Stamou, JZ, 1801.04240

- QED and double weak insertions important only for dim 6 operators

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

$$\mathcal{Q}_{2,f}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{f}\gamma^\mu f)\,,$$
$$\mathcal{Q}_{4,f}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{f}\gamma^\mu\gamma_5 f)\,,$$

- cross sections

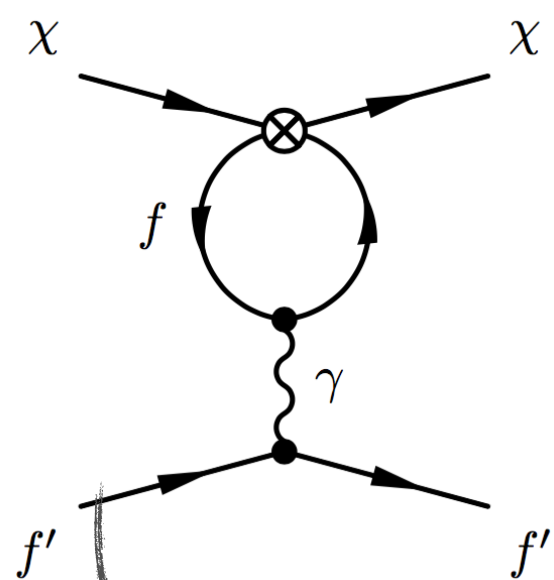
$$\sigma \propto \left(\frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}}\mathcal{A}[\mathcal{Q}_a^{(d)}]\right)^2$$

$$\begin{aligned}
&\mathcal{A}[\mathcal{Q}_{1,u(d)}^{(6)}] \sim A\,, && \mathcal{A}[\mathcal{Q}_{1,s}^{(6)}] = 0\,, && \mathcal{A}[\mathcal{Q}_{1,c(b)}^{(6)}] = 0\,,\\
&\mathcal{A}[\mathcal{Q}_{2,u(d)}^{(6)}] \sim \max\left\{v_T A, \frac{q}{m_N}\right\}, && \mathcal{A}[\mathcal{Q}_{2,s}^{(6)}] = 0\,, && \mathcal{A}[\mathcal{Q}_{2,c(b)}^{(6)}] = 0\,,\\
&\mathcal{A}[\mathcal{Q}_{3,u(d)}^{(6)}] \sim \max\left\{v_T, \frac{q}{m_\chi}\right\}, && \mathcal{A}[\mathcal{Q}_{3,s}^{(6)}] \sim \Delta s \mathcal{A}[\mathcal{Q}_{3,q}^{(6)}]\,, && \mathcal{A}[\mathcal{Q}_{3,c(b)}^{(6)}] \sim \Delta c(b) \mathcal{A}[\mathcal{Q}_{3,q}^{(6)}]\,,\\
&\mathcal{A}[\mathcal{Q}_{4,u(d)}^{(6)}] \sim 1\,, && \mathcal{A}[\mathcal{Q}_{4,s}^{(6)}] \sim \Delta s \mathcal{A}[\mathcal{Q}_{4,q}^{(6)}]\,, && \mathcal{A}[\mathcal{Q}_{4,c(b)}^{(6)}] \sim \Delta c(b) \mathcal{A}[\mathcal{Q}_{4,q}^{(6)}]\,,
\end{aligned}$$

$$\Delta c \approx -5 \cdot 10^{-4},\ \Delta b \approx -5 \cdot 10^{-5}$$

DOU… INSERTIONS

including QED corrections



Brod, Stamou, JZ, 1801.04240

- QED a… nsertions important only fo… s

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

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$$\mathcal{A}[\mathcal{Q}_{1,u(d)}^{(6)}] \sim A\,,$$

$$\mathcal{A}[\mathcal{Q}_{2,u(d)}^{(6)}] \sim \max\left\{v_T A, \frac{q}{m_N}\right\}\,,$$

$$\mathcal{A}[\mathcal{Q}_{3,u(d)}^{(6)}] \sim \max\left\{v_T, \frac{q}{m_\chi}\right\}\,,$$

$$\mathcal{A}[\mathcal{Q}_{4,u(d)}^{(6)}] \sim 1\,,$$

$$\mathcal{A}[Q_{1,s}^{(6)}] \sim \frac{\alpha}{4\pi}\mathcal{A}[Q_{1,q}^{(6)}], \qquad \mathcal{A}[Q_{1,c(b)}^{(6)}] \sim \frac{\alpha}{4\pi}\mathcal{A}[Q_{1,q}^{(6)}],$$

$$\mathcal{A}[Q_{2,s}^{(6)}] \sim \frac{\alpha}{4\pi}\mathcal{A}[Q_{2,q}^{(6)}], \qquad \mathcal{A}[Q_{2,c(b)}^{(6)}] \sim \frac{\alpha}{4\pi}\mathcal{A}[Q_{2,q}^{(6)}],$$

$$\mathcal{A}[\mathcal{Q}_{3,s}^{(6)}] \sim \Delta s\mathcal{A}[\mathcal{Q}_{3,q}^{(6)}]\,, \quad \mathcal{A}[\mathcal{Q}_{3,c(b)}^{(6)}] \sim \Delta c(b)\mathcal{A}[\mathcal{Q}_{3,q}^{(6)}]\,,$$

$$\mathcal{A}[\mathcal{Q}_{4,s}^{(6)}] \sim \Delta s\mathcal{A}[\mathcal{Q}_{4,q}^{(6)}]\,, \quad \mathcal{A}[\mathcal{Q}_{4,c(b)}^{(6)}] \sim \Delta c(b)\mathcal{A}[\mathcal{Q}_{4,q}^{(6)}]\,,$$

$$\Delta c \approx -5\cdot 10^{-4},\ \Delta b \approx -5\cdot 10^{-5}$$

DOU… INSERTIONS

- QED a… …nser… only fo… …s

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

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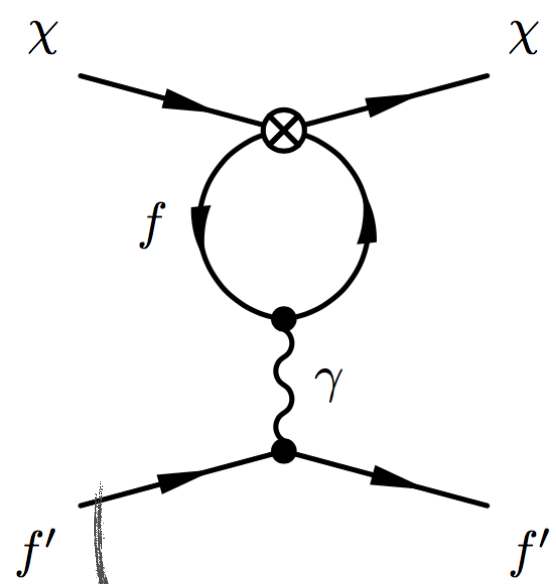
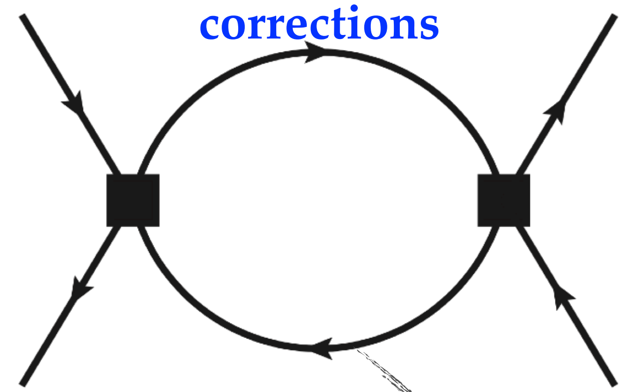
- cross sections

$$\sigma \propto \left(\frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}}\mathcal{A}[\mathcal{Q}_a^{(d)}]\right)^2$$

including QED corrections



including electroweak corrections



$$\mathcal{A}[\mathcal{Q}_{1,u(d)}^{(6)}] \sim A\,,$$
$$\mathcal{A}[\mathcal{Q}_{2,u(d)}^{(6)}] \sim \max\left\{v_T A, \frac{q}{m_N}\right\},$$
$$\mathcal{A}[\mathcal{Q}_{3,u(d)}^{(6)}] \sim \max\left\{v_T, \frac{q}{m_\chi}\right\}, \qquad \mathcal{A}[\mathcal{Q}_{3,s}^{(6)}] \sim \Delta s\,\mathcal{A}[\mathcal{Q}_{3,q}^{(6)}]\,,$$
$$\mathcal{A}[\mathcal{Q}_{4,u(d)}^{(6)}] \sim 1\,, \qquad \mathcal{A}[\mathcal{Q}_{4,s}^{(6)}] \sim \Delta s\,\mathcal{A}[\mathcal{Q}_{4,q}^{(6)}]\,,$$

$$\mathcal{A}[Q_{1,s}^{(6)}] \sim \frac{\alpha}{4\pi}\mathcal{A}[Q_{1,q}^{(6)}], \qquad \mathcal{A}[Q_{1,c(b)}^{(6)}] \sim \frac{\alpha}{4\pi}\mathcal{A}[Q_{1,q}^{(6)}],$$
$$\mathcal{A}[Q_{2,s}^{(6)}] \sim \frac{\alpha}{4\pi}\mathcal{A}[Q_{2,q}^{(6)}], \qquad \mathcal{A}[Q_{2,c(b)}^{(6)}] \sim \frac{\alpha}{4\pi}\mathcal{A}[Q_{2,q}^{(6)}],$$

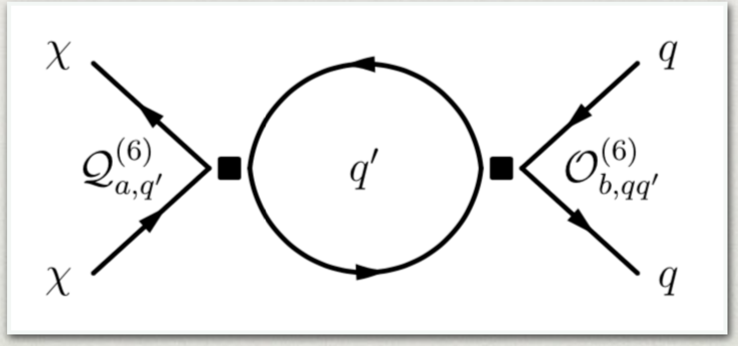
$$\mathcal{A}[Q_{3,c(b)}^{(6)}] \sim \frac{g_2^2}{16\pi^2}\frac{m_{c(b)}^2}{m_Z^2}A$$
$$\mathcal{A}[Q_{4,c(b)}^{(6)}] \sim \frac{g_2^2}{16\pi^2}\frac{m_{c(b)}^2}{m_Z^2}\max\left\{v_T A, \frac{q}{m_N}\right\}$$

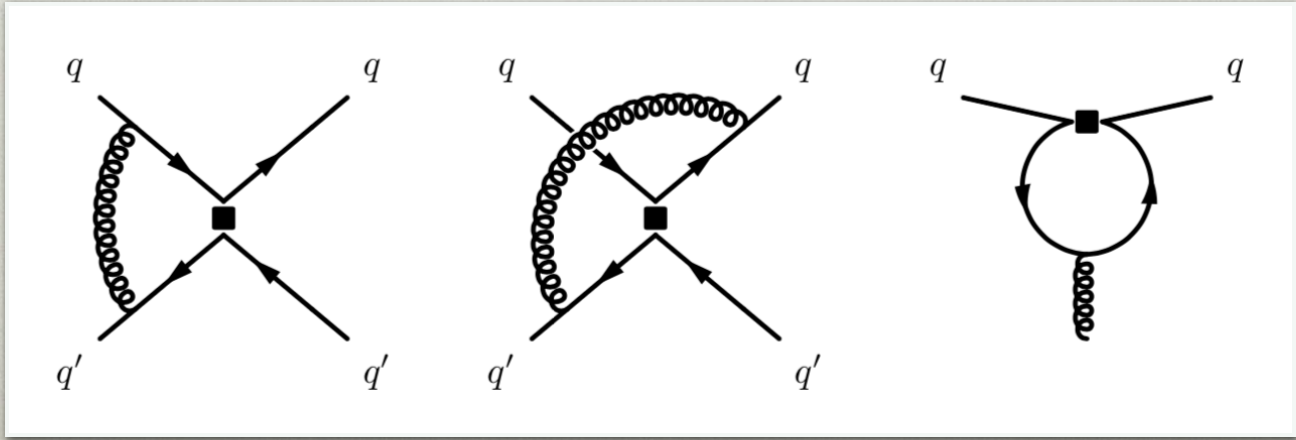
$$\Delta c \approx -5\cdot 10^{-4},\ \Delta b \approx -5\cdot 10^{-5}$$

QCD resummation

Brod, Stamou, JZ, 1801.04240

- QCD resummation for double insertions
- required since $(\alpha_s/\pi)\log(m_W/\Lambda_{had}) \sim O(1)$

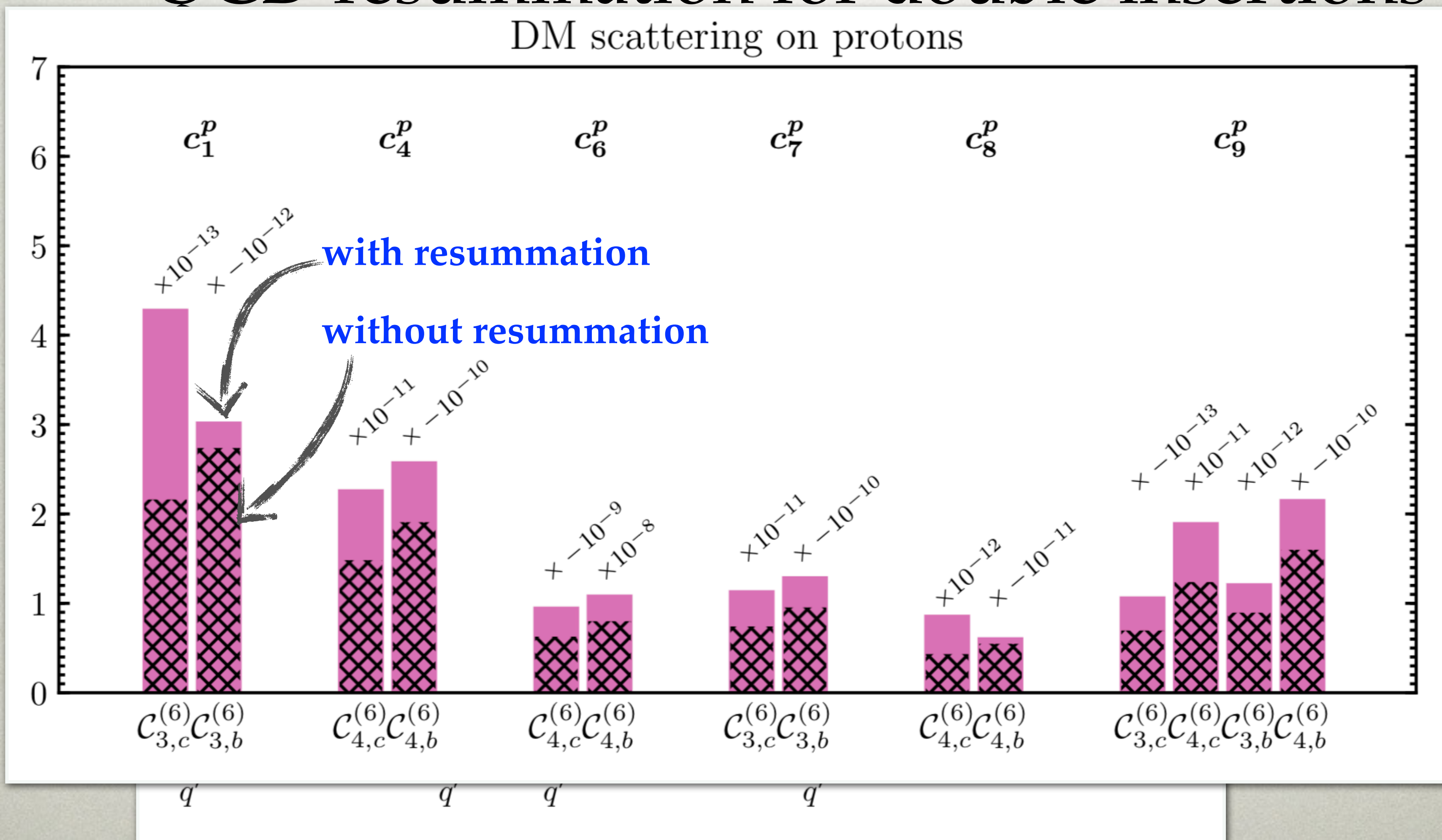




QCD resummation

Brod, Stamou, JZ, 1801.04240

- QCD resummation for double insertions



WHAT KIND OF MODELS?

- not completely trivial to write models where these the leading effect
- e.g. at EW scale AxA op. with only *b*-quarks requires

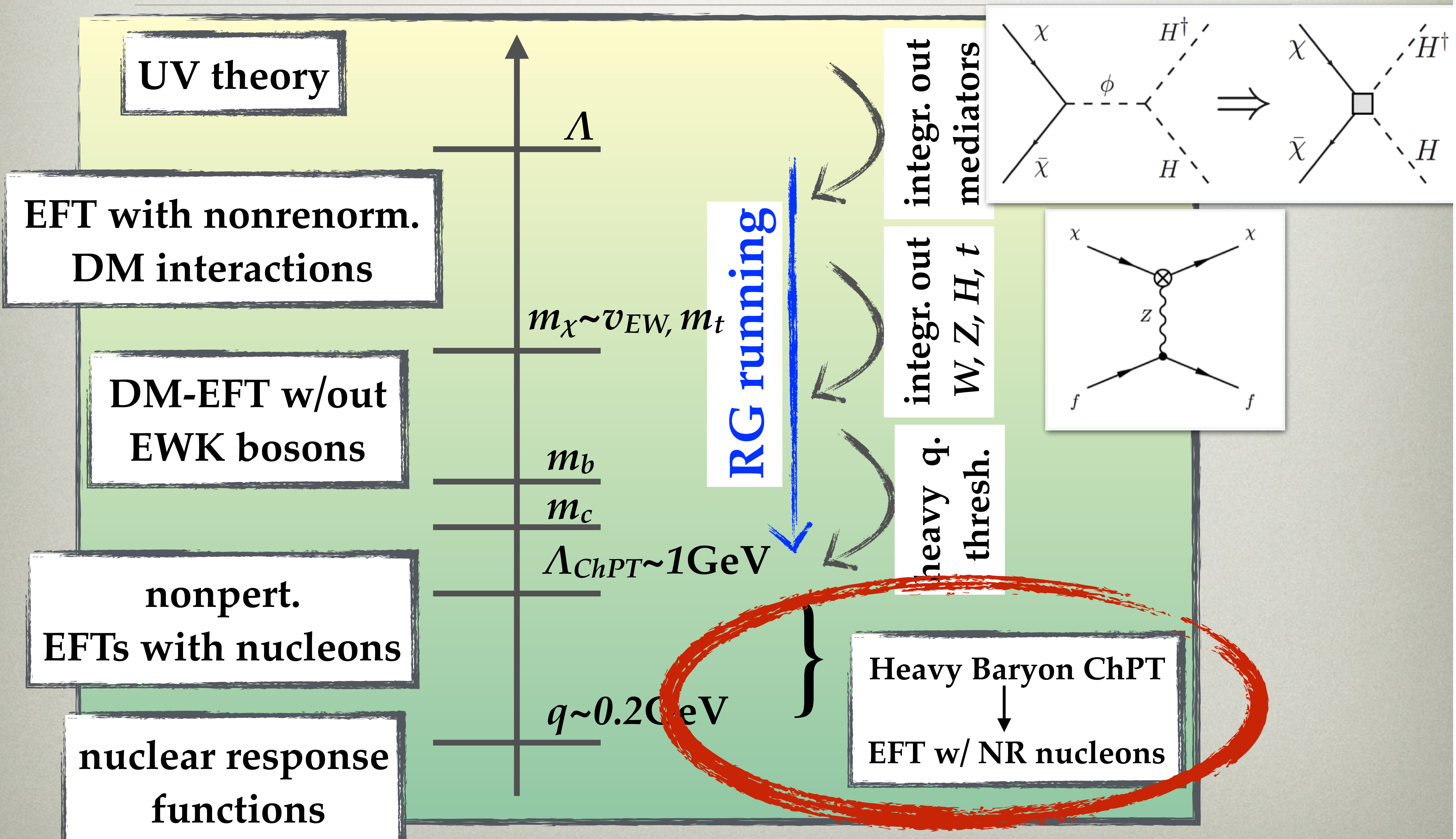
$$Y_\chi C_{5,3}^{(6)} = 4C_{6,3}^{(6)} = -2C_{8,3}^{(6)} \,.$$

$$\begin{aligned}
Q_{5,i}^{(6)} &= (\bar{\chi}\gamma_\mu\gamma_5\tilde{\tau}^a\chi)(\bar{Q}_L^i\gamma^\mu\tau^a Q_L^i)\,,\\
Q_{6,i}^{(6)} &= (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L^i\gamma^\mu Q_L^i)\,,\\
Q_{7,i}^{(6)} &= (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{u}_R^i\gamma^\mu u_R^i)\,,\\
Q_{8,i}^{(6)} &= (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{d}_R^i\gamma^\mu d_R^i)\,,
\end{aligned}$$

- DM needs to be part of EW multiplet
- DM mass eigenstate a Majorana to suppress Z exchange
- if DM a singlet then necessarily also couplings to tops

MATCHING TO NUCLEAR PHYSICS

Tower of EFTs



DIRECT DM DETECTION KINEMATICS

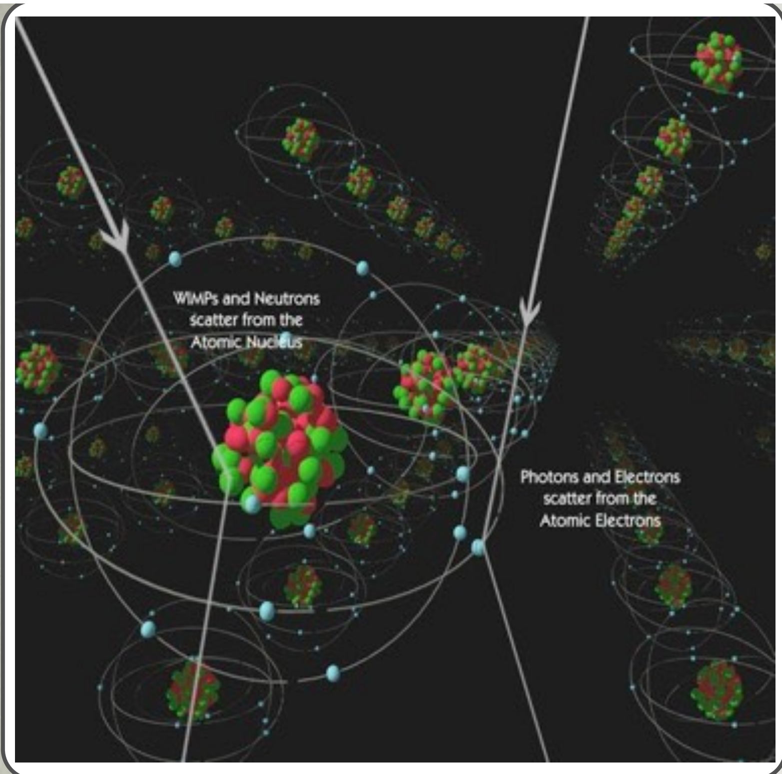
- WIMPS form DM halo
  - typical velocity $v \sim 10^{-3}$
- scatters on target nuclei $\chi N \to \chi N$
  - typical energy deposit

$$E_d = 2\frac{\mu_\chi^2}{M_A}v^2 \sim 2\text{keV}\left(\frac{120GeV}{M_A}\right)\left(\frac{\mu_\chi}{10\text{GeV}}\right)^2\left(\frac{v}{10^{-3}}\right)^2$$

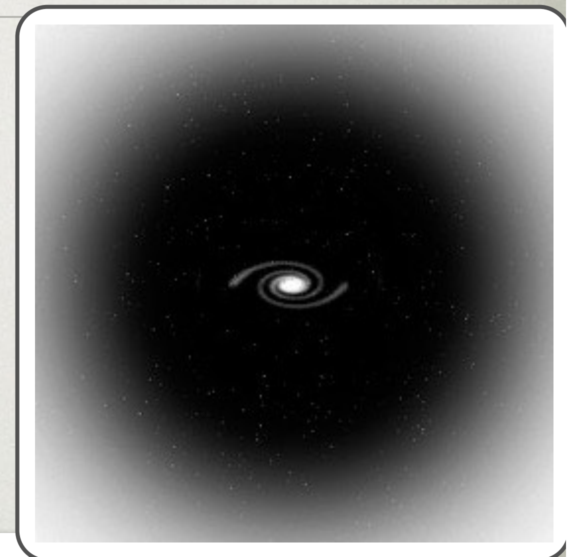
  - typical momentum exchange

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

  - this allows for treatment with ChPT
    - use Heavy Baryon ChPT to NLO



DM DETECTION
NEMATICS



- [halo
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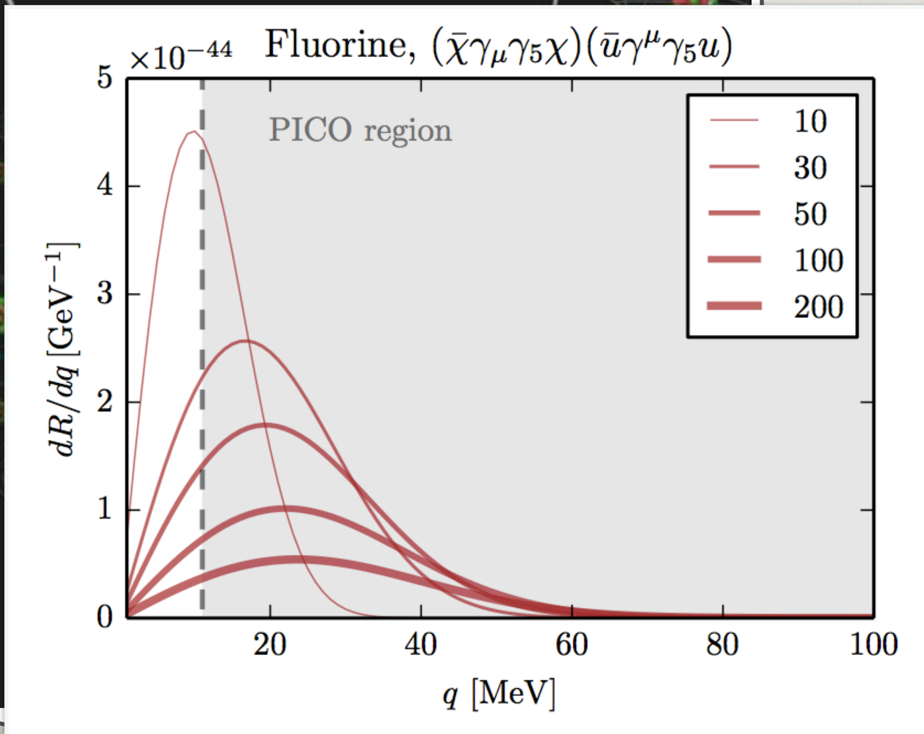

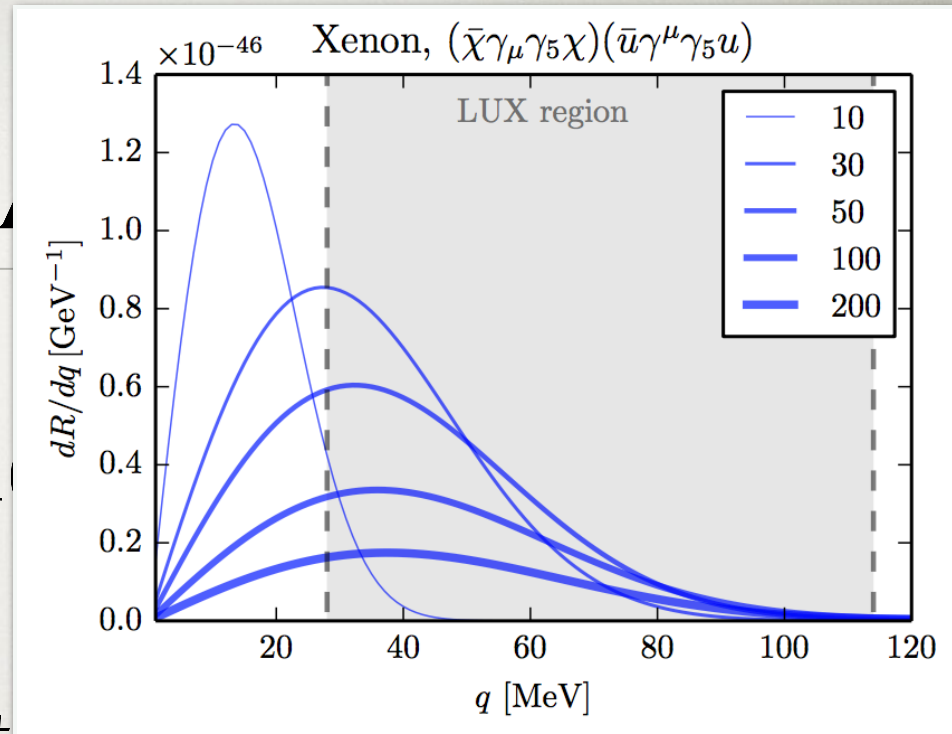

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- typical momentum exchange

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

- this allows for treatment with ChPT
  - use Heavy Baryon ChPT to NLO

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\chi)F_{\mu\nu}\,, \qquad \mathcal{Q}_2^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}i\gamma_5\chi)F_{\mu\nu}$$

$$\mathcal{Q}_{1,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu q), \qquad \mathcal{Q}_{2,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu q),$$

$$\mathcal{Q}_{3,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu\gamma_5 q)\,, \qquad \mathcal{Q}_{4,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu\gamma_5 q)\,,$$

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\bar\chi\chi)G^{a\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$

$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,, \qquad \mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$

$$\mathcal{Q}_{5,q}^{(7)} = m_q(\bar\chi\chi)(\bar q q)\,, \qquad \mathcal{Q}_{6,q}^{(7)} = m_q(\bar\chi i\gamma_5\chi)(\bar q q)\,,$$

$$\mathcal{Q}_{7,q}^{(7)} = m_q(\bar\chi\chi)(\bar q i\gamma_5 q)\,, \qquad \mathcal{Q}_{8,q}^{(7)} = m_q(\bar\chi\gamma_5\chi)(\bar q\gamma_5 q)\,.$$

relativistic theory with quarks and gluons

?

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

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

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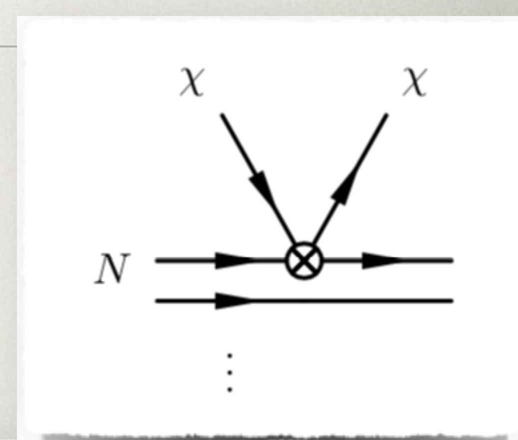
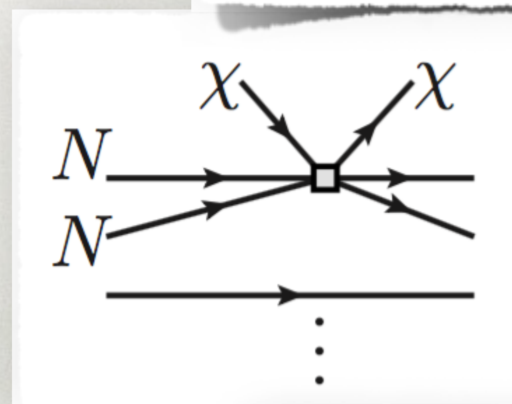
non-relativistic theory with nucleons

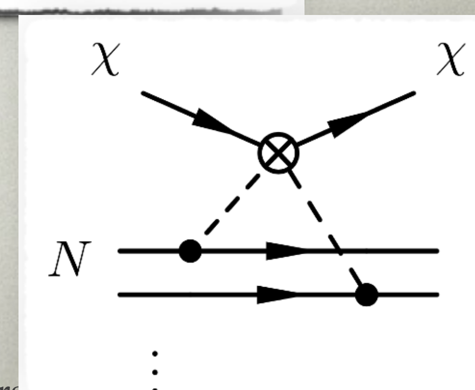
GENERAL LESSONS

F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368

- chirally leading contributions due to DM scattering on a single nucleon current
  - DM coupling to four-nucleon ops. always $O(q^3)$ suppressed
  - long distance contribs. only $O(q)$ suppr. for scalar couplings
- not all NR ops. generated
- switching on just one NR oper. at a time not justified







IMPLICATIONS FOR COMBINED EXCLUSIONS

- what is often done in global analyses of DM direct detection results
  - take only one NR operator
  - keep coefficient *q* independent

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

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

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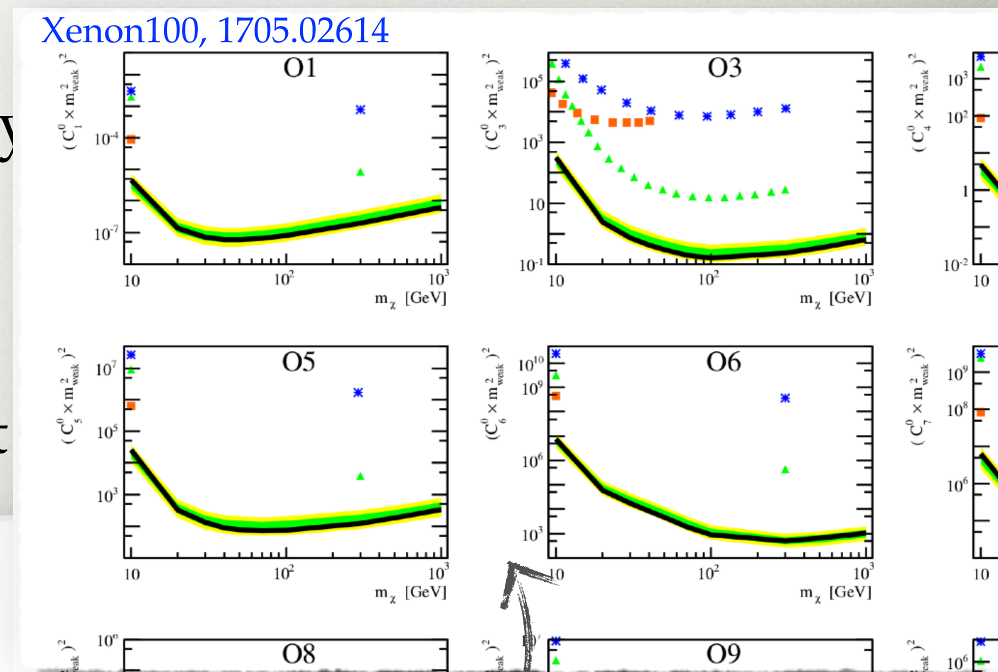

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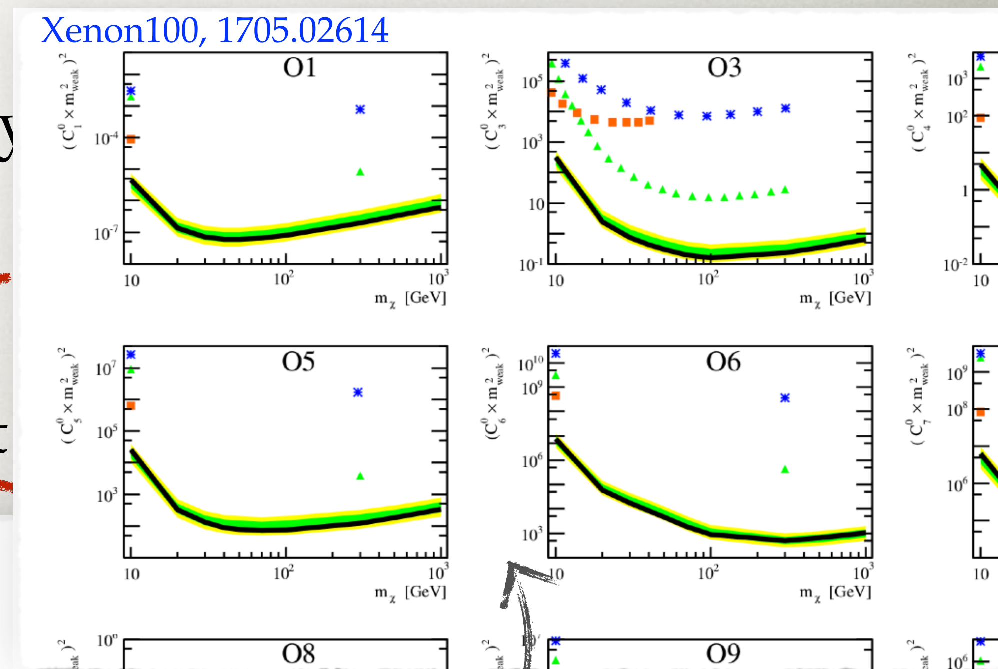

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ALL OPERATORS?

- do we need all the operators? F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368; 1707.06998
  - 15 operators with up to 2 derivatives
  - general dim 5 and 6 EFT above EW scale requires at LO

$$\mathcal{O}_{2b}^N = \big(\vec{S}_N\cdot\vec{v}_\perp\big)\big(\vec{S}_\chi\cdot\vec{v}_\perp\big)$$

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

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$$\mathcal{O}_{13}^N = -\Big(\vec{S}_\chi\cdot\vec{v}_\perp\Big)\Big(\vec{S}_N\cdot\frac{i\vec{q}}{m_N}\Big)\,, \qquad \mathcal{O}_{14}^N = -\Big(\vec{S}_\chi\cdot\frac{i\vec{q}}{m_N}\Big)\Big(\vec{S}_N\cdot\vec{v}_\perp\Big)\,,$$

- do we need the *O(q²)* terms? Can we stop at *O(q²)*?

AT LO IN HEAVY BARYON CHPT

F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368

- 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

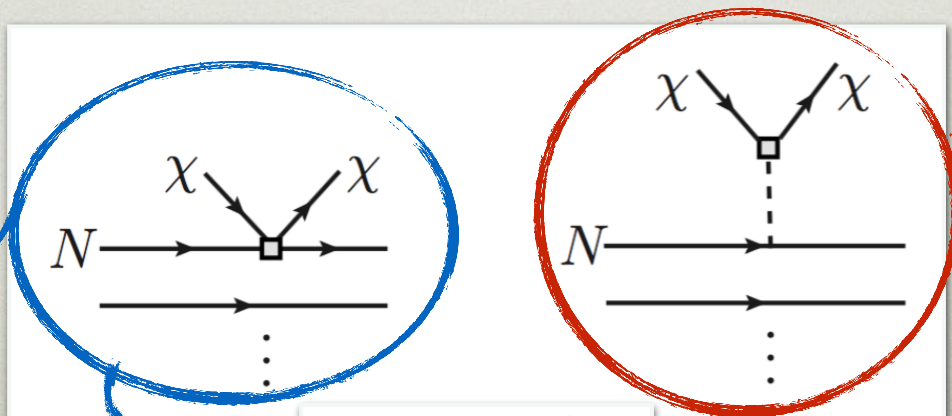
- two types of leading order diagrams

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

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

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

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



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

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

*for vector DM only left diagr. important

COMPARISON

F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368; 1707.06998

see also, e.g., Cirelli, Del Nobile, Panci, 1307.5955;
Hill, Solon, 1409.8290;

- what is new?
  - for most NR operators the results agree with previous literature

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

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

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COMPARISON

see also Hoferichter, Klos, and Schwenk, 1503.04811

- what is new?
  - re-amphasising the importance of (pion) pole enhanced contribs.

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

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PION POLES

- the pion poles important for

$$\mathcal{Q}_{4,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu\gamma_5 q)$$

$$\mathcal{Q}_{4}^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}\widetilde G^a_{\mu\nu}$$

$$\mathcal{Q}_{8,q}^{(7)} = m_q(\bar\chi\gamma_5\chi)(\bar q\gamma_5 q)$$

$$\sim \frac{\Delta q}{m_\chi}\frac{\vec q^{\,2}}{m_\pi^2+\vec q^{\,2}}\mathcal{C}_4^{(7)}$$

$$\sim \frac{\Delta q}{m_\chi}\frac{m_\pi^2}{m_\pi^2+\vec q^{\,2}}\mathcal{C}_{8,q}^{(7)}$$

$$\sim \frac{\Delta q}{m_\pi^2+\vec q^{\,2}}\mathcal{C}_{4,q}^{(6)}$$

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

$$\cdot\left(\vec v_\perp\times\frac{i\vec q}{m_N}\right),$$

$$\mathcal{O}_4^N = \vec S_\chi\cdot\vec S_N\,,$$

$$\mathcal{O}_5^N = \vec S_\chi\cdot\left(\vec v_\perp\times\frac{i\vec q}{m_N}\right)\mathbb{1}_N\,,$$

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$$\mathcal{O}_7^N = \mathbb{1}_\chi\left(\vec S_N\cdot\vec v_\perp\right),$$

$$\mathcal{O}_8^N = \left(\vec S_\chi\cdot\vec v_\perp\right)\mathbb{1}_N\,,$$

$$\mathcal{O}_9^N$$

$$\sim \Delta q\frac{m_\pi^2}{m_\pi^2+\vec q^{\,2}}\mathcal{C}_{7,q}^{(7)}$$

$$\boxed{\mathcal{O}_{10}^N = -\mathbb{1}_\chi\left(\vec S_N\cdot\frac{i\vec q}{m_N}\right),}$$

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$$\mathcal{O}_{12}^N = \vec S_\chi\cdot\left(\vec S_N\times\vec v_\perp\right)$$

$$\sim \Delta q\frac{\vec q^{\,2}}{m_\pi^2+\vec q^{\,2}}\mathcal{C}_3^{(7)}$$

$$\mathcal{Q}_{7,q}^{(7)} = m_q(\bar\chi\chi)(\bar q i\gamma_5 q)$$

$$\mathcal{Q}_{3}^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi\chi)G^{a\mu\nu}\widetilde G^a_{\mu\nu}$$

COMPARISON

- what is new?
  - consistent chiral counting
  - for instance: *A*x*A* operator

$$\mathcal{Q}_{4,q}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$$

$$\sim \Delta q\, \mathcal{C}_{4,q}^{(6)}$$

$$\sim \frac{\Delta q}{m_\pi^2 + \vec{q}^{\,2}} \mathcal{C}_{4,q}^{(6)}$$

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

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

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

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

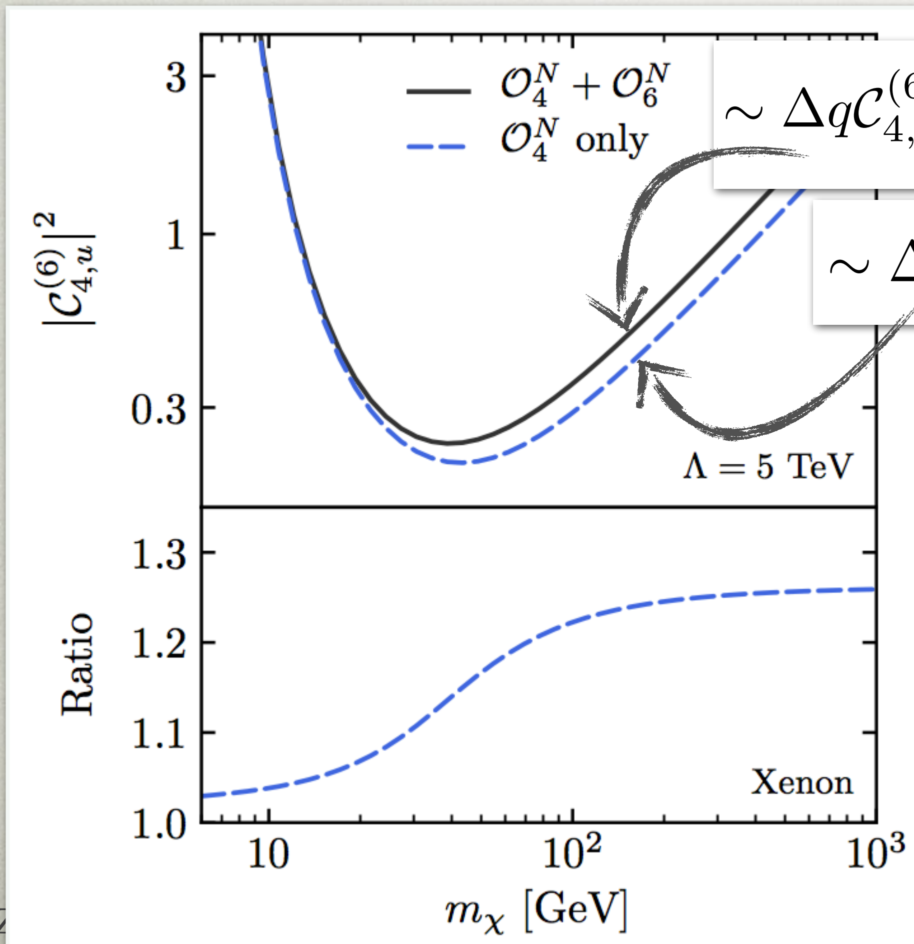
$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N\right), \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\right),$$

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

AXIAL-AXIAL

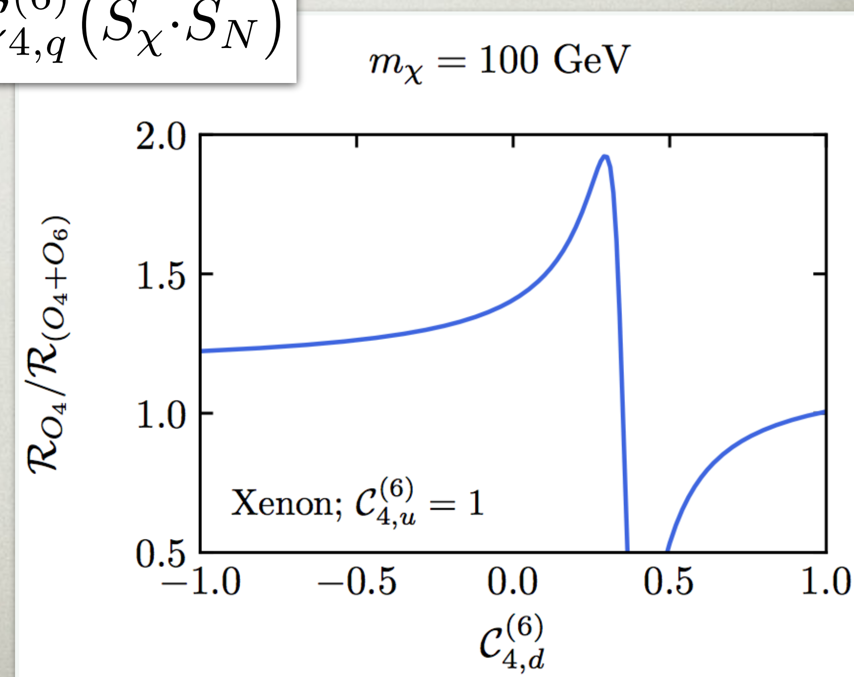
- the classis spin-dep. oper.
  - axial-axial interaction: C_{4u}=-C_{4d}

$$\mathcal{Q}_{4,q}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$$



$$\sim \Delta q \mathcal{C}_{4,q}^{(6)} (\vec{S}_\chi \cdot \vec{S}_N) + \frac{\Delta q}{m_\pi^2 + \vec{q}^2} \mathcal{C}_{4,6}^{(6)} (\vec{S}_\chi \cdot \vec{q}) (\vec{S}_N \cdot \vec{q})$$

$$\sim \Delta q \mathcal{C}_{4,q}^{(6)} (\vec{S}_\chi \cdot \vec{S}_N)$$



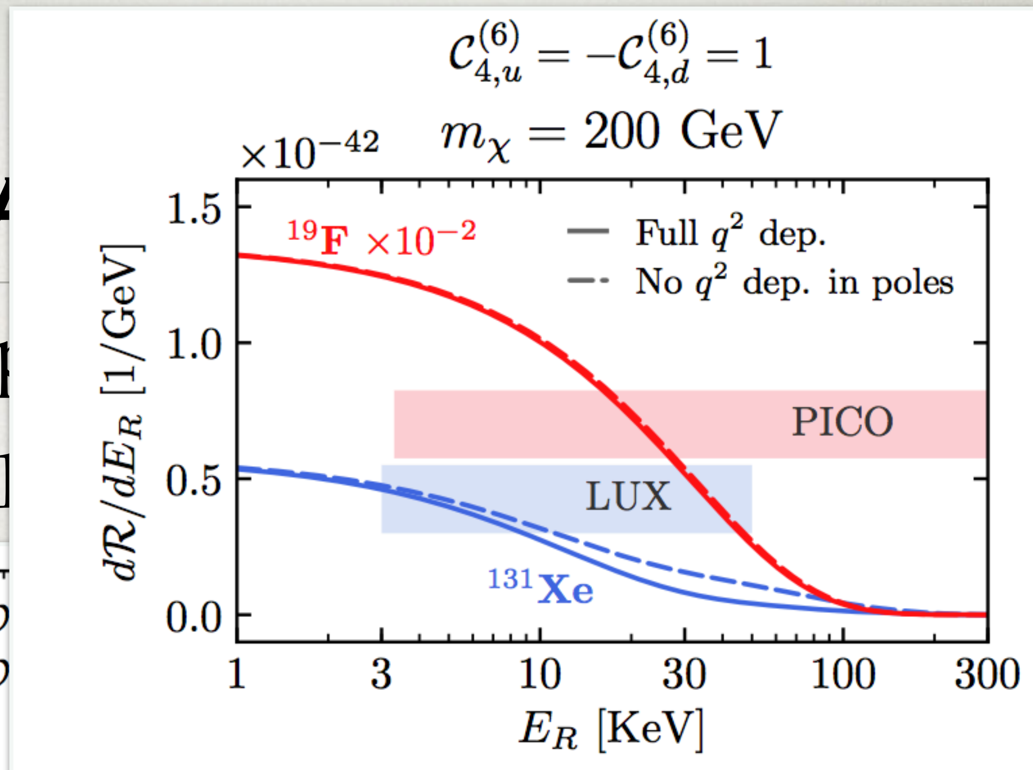
- the classis sp

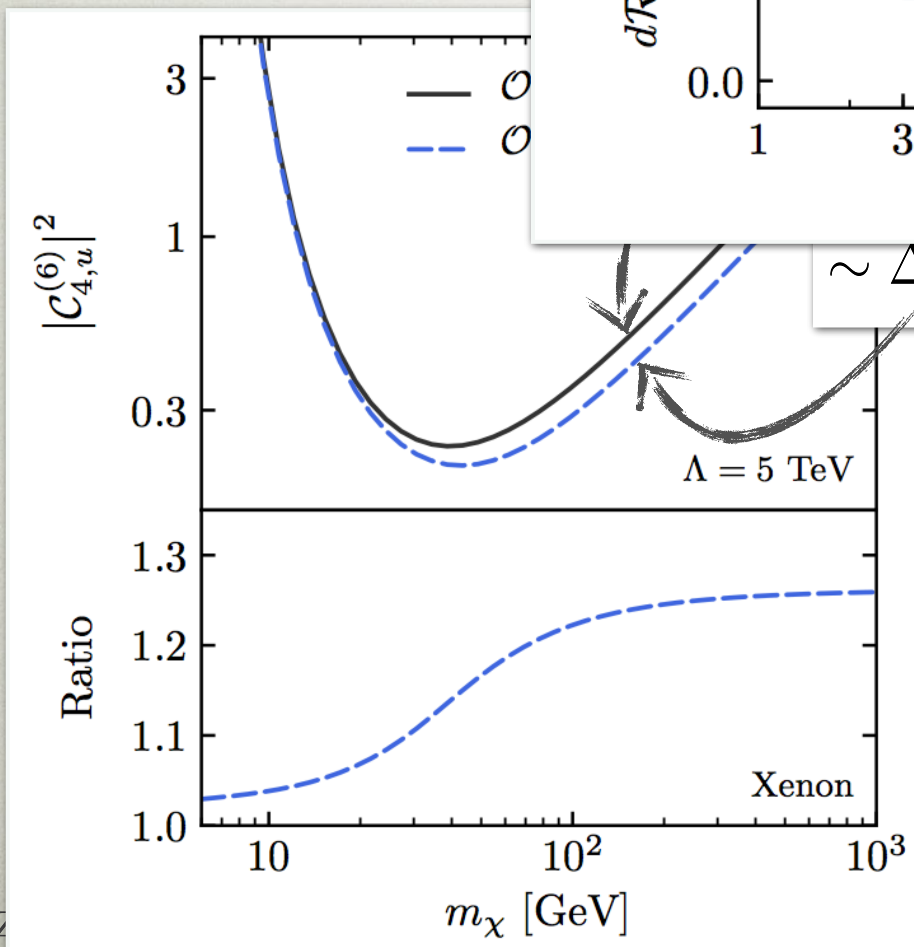
    - axial-axial

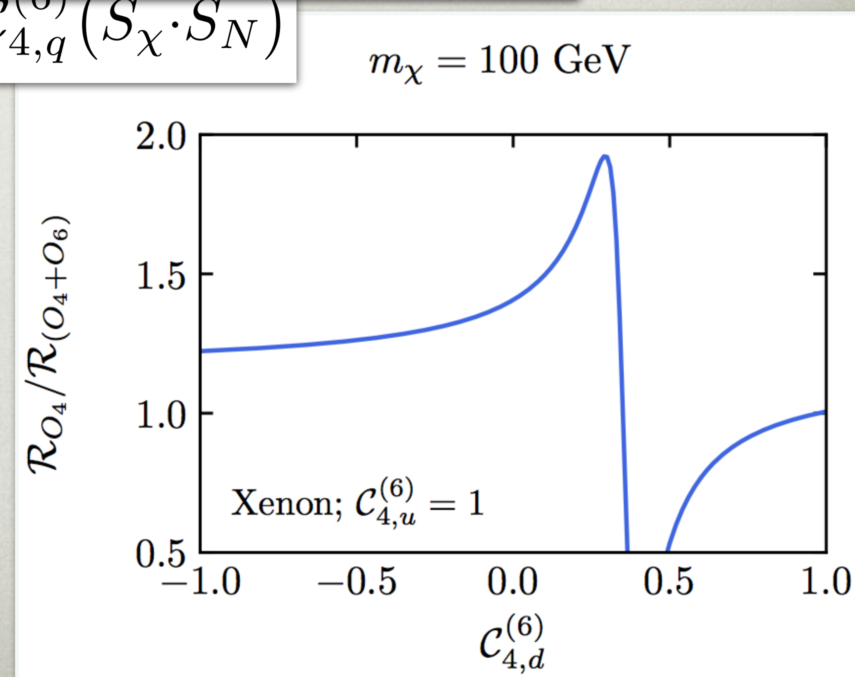
$\chi)(\bar{q}\gamma^\mu\gamma_5 q)$

$\vec{S}_\chi\cdot\vec{q})\,(\vec{S}_N\cdot\vec{q})$

$\sim \Delta q\,\mathcal{C}^{(6)}_{4,q}\,(S_\chi\cdot S_N)$



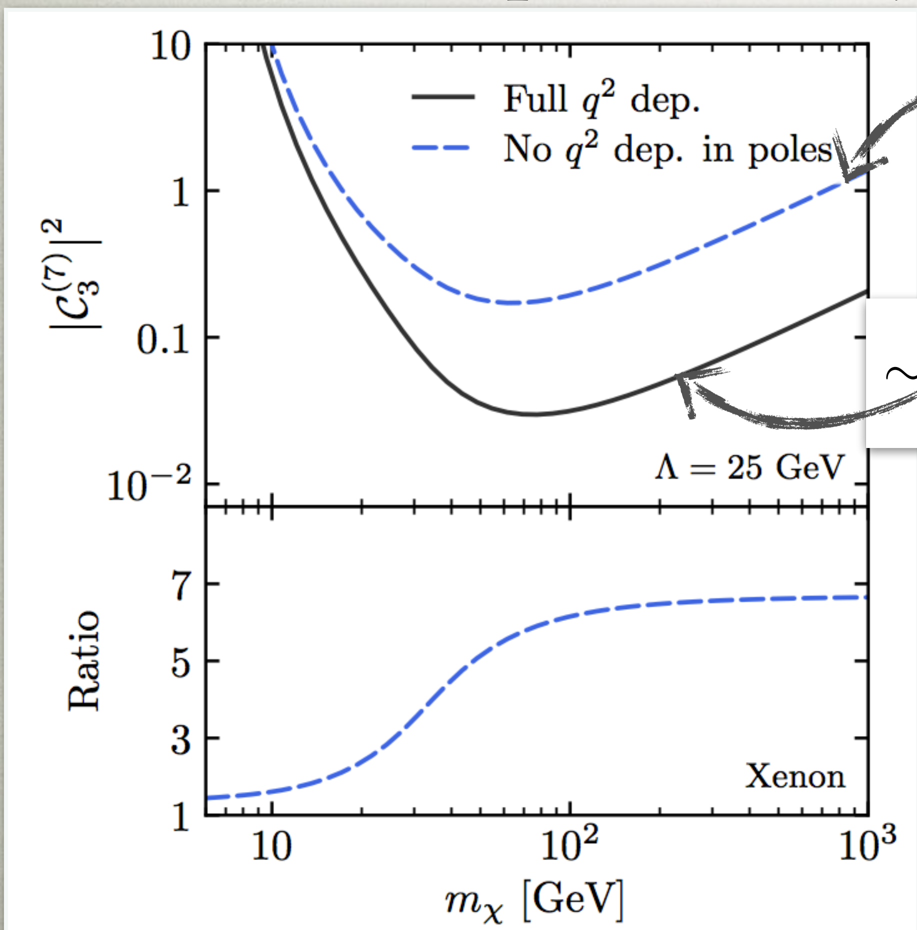




CP-odd gluonic operator

- SxCP-odd gluonic operator
  - compare with $q \to 0$ limit

$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$



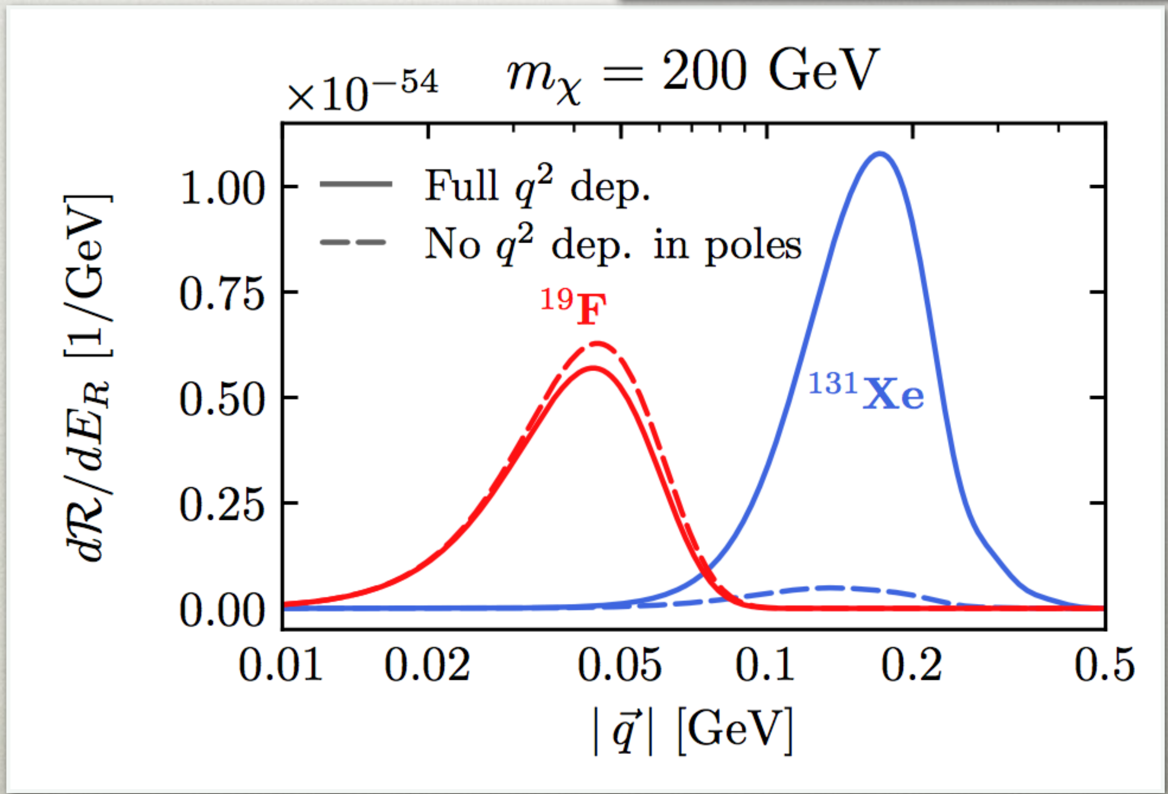
$$\sim \frac{\Delta q}{m_q}(\vec{S}_N \cdot \vec{q})$$

$$\sim \left(\frac{\Delta q}{m_q} + \left(\frac{1}{m_u} - \frac{1}{m_d}\right)\frac{(\Delta u - \Delta d)\vec{q}^2}{m_\pi^2 + \vec{q}^2}\right)(\vec{S}_N \cdot \vec{q})$$

ENERGY DEPENDENCE

- The differential event rate as a function of the momentum transfer as an example: $Q_4^{(7)}$

$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$



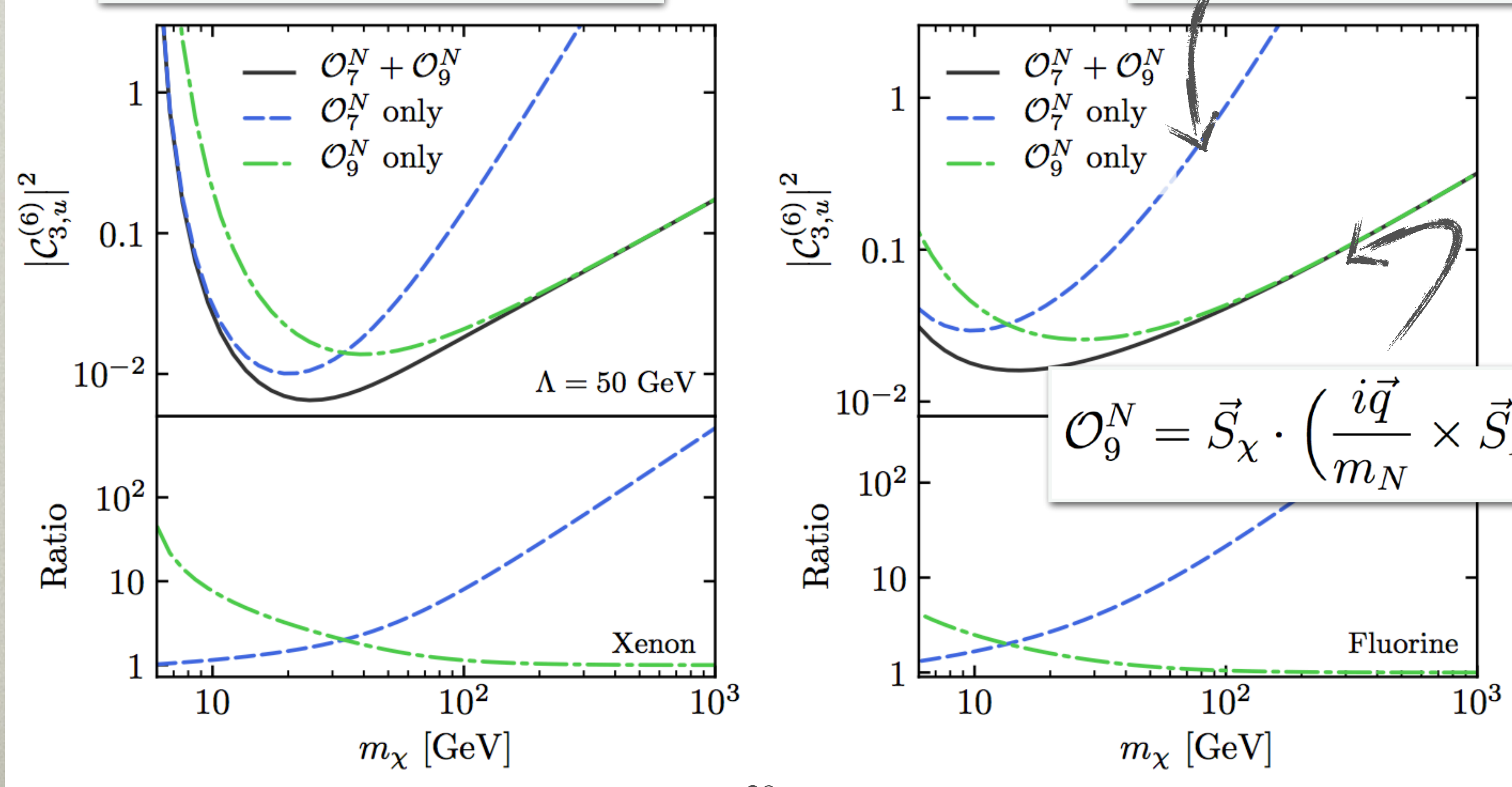
VECTOR-AXIAL

- vector-axial interaction: C_{3u}=C_{3d}=C_{3s}=*1*

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

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

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



PHOTON POLES

- due to photon poles also need $O(q^2)$ ops

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\chi)F_{\mu\nu}$$

$$\sim m_N \frac{\alpha\mu_p}{\vec q^{\,2}}\mathcal{C}_1^{(5)}$$

$$\sim \frac{\alpha\mu_p}{m_N}\mathcal{C}_1^{(5)}$$

$$\sim \frac{\alpha Q_p}{m_\chi}\mathcal{C}_1^{(5)}$$

$$\sim m_N \frac{\alpha Q_p}{\vec q^{\,2}}\mathcal{C}_1^{(5)}$$

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

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

$$\boxed{\mathcal{O}_5^N = \vec S_\chi\cdot\Big(\vec v_\perp\times\frac{i\vec q}{m_N}\Big)\,\mathbb{1}_N\,,} \qquad \boxed{\mathcal{O}_6^N = \Big(\vec S_\chi\cdot\frac{\vec q}{m_N}\Big)\Big(\vec S_N\cdot\frac{\vec q}{m_N}\Big)}$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi\,(\vec S_N\cdot\vec v_\perp)\,, \qquad \mathcal{O}_8^N = (\vec S_\chi\cdot\vec v_\perp)\,\mathbb{1}_N\,,$$

$$\mathcal{O}_9^N = \vec S_\chi\cdot\Big(\frac{i\vec q}{m_N}\times\vec S_N\Big)\,, \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi\Big(\vec S_N\cdot\frac{i\vec q}{m_N}\Big)\,,$$

$$\boxed{\mathcal{O}_{11}^N = -\Big(\vec S_\chi\cdot\frac{i\vec q}{m_N}\Big)\,\mathbb{1}_N\,,} \qquad \mathcal{O}_{12}^N = \vec S_\chi\cdot\Big(\vec S_N\times\vec v_\perp\Big)\,,$$

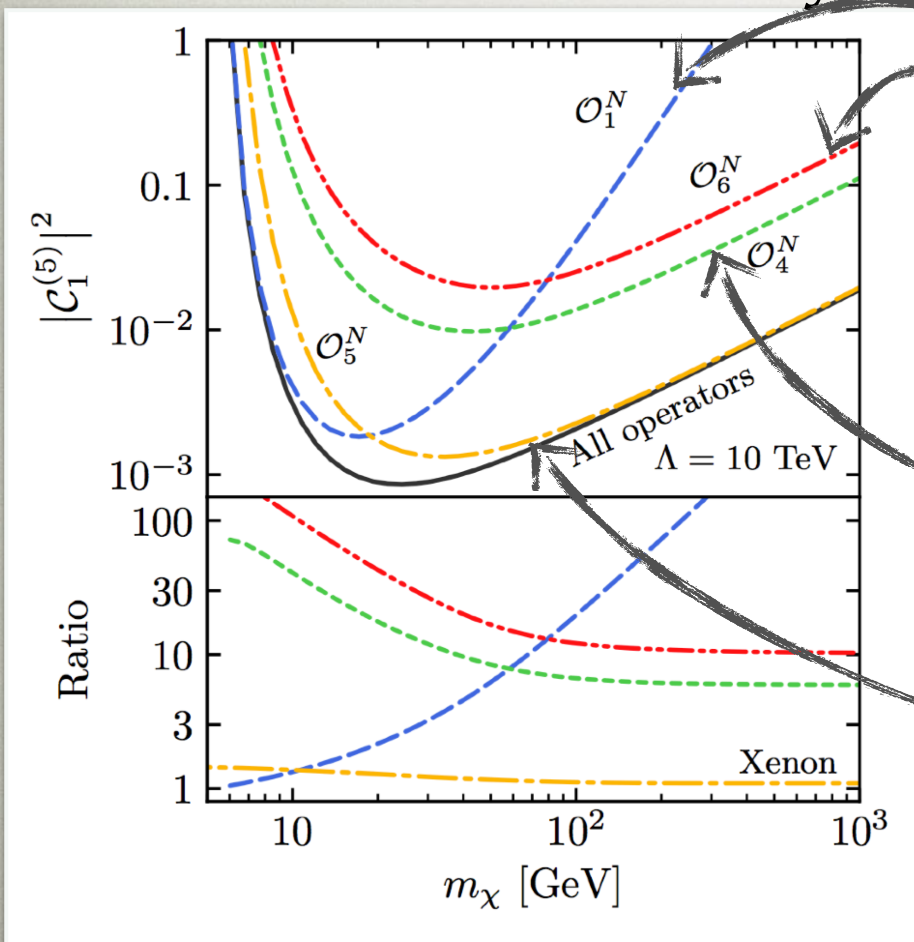
$$\mathcal{Q}_2^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}i\gamma_5\chi)F_{\mu\nu}$$

$$\sim m_N \frac{\alpha Q_p}{\vec q^{\,2}}\mathcal{C}_2^{(5)}$$

PHOTON POLES - XENON

- for magnetic dipole interaction
  - two coherently enhanced operators

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}$$



$$-\frac{\alpha Q_p}{2\pi m_\chi}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N$$

$$\frac{2\alpha}{\pi}\frac{\mu_N m_N}{\vec{q}^2}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

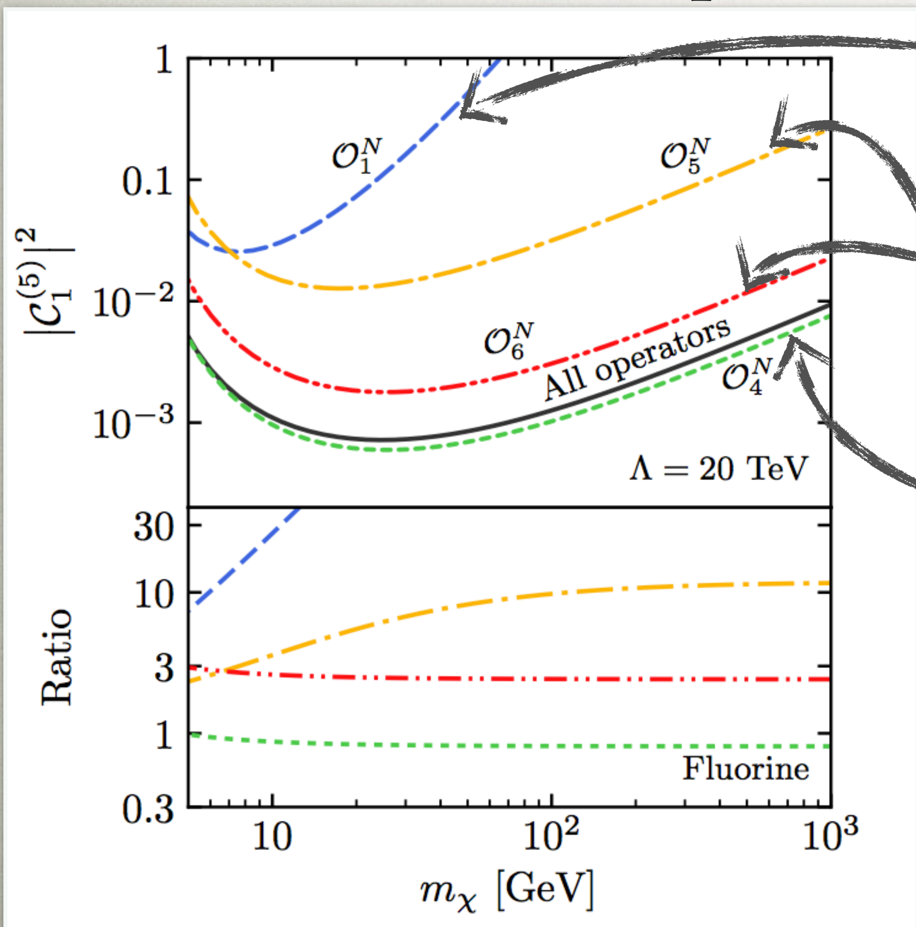
$$-\frac{2\alpha}{\pi}\frac{\mu_N}{m_N}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N$$

$$\frac{2\alpha Q_p m_N}{\pi \vec{q}^2}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_5^N = \vec{S}_\chi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right)\mathbb{1}_N$$

PHOTON POLES - FLUORINE

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}$$

- magnetic dipole interaction
  - both SD operators important



$$-\frac{\alpha Q_p}{2\pi m_\chi}\hat{\mathcal{C}}_1^{(5)}$$

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N$$

$$\frac{2\alpha}{\pi}\frac{\mu_N m_N}{\vec{q}^2}\hat{\mathcal{C}}_1^{(5)}$$

$$\mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

$$-\frac{2\alpha}{\pi}\frac{\mu_N}{m_N}\hat{\mathcal{C}}_1^{(5)}$$

$$\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N$$

$$\frac{2\alpha Q_p m_N}{\pi \vec{q}^2}\hat{\mathcal{C}}_1^{(5)}$$

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

THE INVERSE PROBLEM

- which of the NR operators can consistently switch on one by one?
- $\exists \mathcal{Q}_a^{(d)}$: only one $\mathcal{O}_i^N$ generated

assume d≤6 above EW

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

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

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

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

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

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

THE INVERSE PROBLEM

- which of the NR operators can consistently switch on one by one?
- $\exists \mathcal{Q}_a^{(d)}$: only one $\mathcal{O}_i^N$ generated

assume d≤7 above EW

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

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

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

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

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

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

NLO - SINGLE CURRENTS

F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368; 1707.06998

- for many operators two-nucleon currents highly suppressed
- are q^2 corrections to single currents ever important?
  - part of it captured by form factors for LO operators
  - but also new operators generated
- example: tensor-tensor operator

$$\mathcal{Q}_{9,q}^{(7)} = m_q(\bar\chi\sigma^{\mu\nu}\chi)(\bar q\sigma_{\mu\nu}q) \quad \sim \frac{\Delta q}{m_q}(\vec{S}_\chi\cdot\vec{S}_N) + \frac{\vec{q}^2}{m_N m_\chi}\mathbb{1}_\chi\mathbb{1}_N$$

LO spin-dep.

NLO spin-indep.
coherently enhanced ~A²

  - numerical factors make it small, though

SCALAR DARK MATTER

- analysis for scalar DM easier
- no DM spin ⇒ no cancellations in products of J_χx(leading chiral J_q)
- for P_q and A_q currents the contribs. are enhanced by pion poles

$$\mathcal{Q}_{1,q}^{(6)} = \big(\varphi^* i\overleftrightarrow{\partial}_\mu \varphi\big)\big(\bar q \gamma^\mu q\big), \qquad \mathcal{Q}_{2,q}^{(6)} = \big(\varphi^* i\overleftrightarrow{\partial}_\mu \varphi\big)\big(\bar q \gamma^\mu \gamma_5 q\big),$$

$$\mathcal{Q}_{3,q}^{(6)} = m_q(\varphi^*\varphi)(\bar q q)\,, \qquad \mathcal{Q}_{4,q}^{(6)} = m_q(\varphi^*\varphi)(\bar q i\gamma_5 q)\,,$$

$$\mathcal{Q}_{5}^{(6)} = \frac{\alpha_s}{12\pi}(\varphi^*\varphi)G^{a\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{Q}_{6}^{(6)} = \frac{\alpha_s}{8\pi}(\varphi^*\varphi)G^{a\mu\nu}\widetilde G^a_{\mu\nu}\,.$$

$$\mathcal{Q}_{7}^{(6)} = i\frac{e}{8\pi^2}\big(\partial_\mu\varphi^*\partial_\nu\varphi\big)F^{\mu\nu}\,,$$

relativistic theory with quarks and gluons

non-relativistic theory with nucleons

$$Q_{1,p}^{(0)} = \big(\varphi_v^*\varphi_v\big)\big(\bar p_v p_v\big),$$

$$Q_{1,p}^{(1)} = \big(\varphi_v^*\varphi_v\big)\big(\bar p_v i q\cdot S_N p_v\big),$$

$$Q_{2,p}^{(1)} = m_N\big(\varphi_v^*\varphi_v\big)\big(\bar p_v\, v_\perp\cdot S_N\, p_v\big),$$

NONSTANDARD NEUTRINO INTERACTIONS

COHERENT

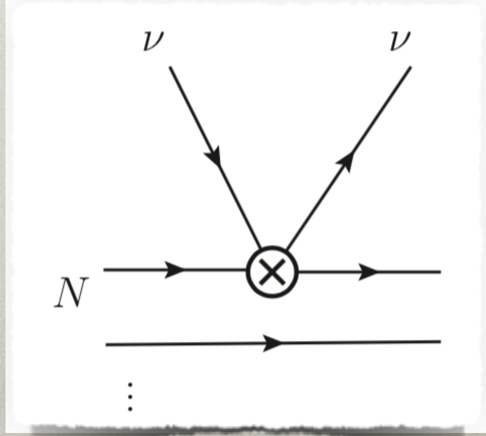
Altmannshofer, Tammaro, JZ, 1806.nnnn

- nonstandard neutrino interactions for decades only from neutrino oscillations

$$\mathcal{L}_{\rm NSI} \supset \frac{G_F}{\sqrt{2}} \sum_{f,\alpha,\beta} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta) \left(\varepsilon^{fV}_{\alpha\beta} \bar{f}\gamma^\mu f + \varepsilon^{fA}_{\alpha\beta} \bar{f}\gamma^\mu\gamma_5 f \right)$$

- qualitative change with measurement of coherent neutrino scattering

COHERENT, 1708.01294



- can now probe many more NSI
  - one dim-5 and 11 dim-7 ops.

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2} (\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha) F_{\mu\nu}$$

NSI AND COHERENT

- one important change: neutrinos are relativistic
- simplifies things, since $p_\nu.S_N \sim O(E_\nu)$, while for DM $p_\chi.S_N \neq O(m_\chi)$
- three types of operators
    - interfere with the SM contrib.
    - coherently enchanced but no interf. with SM
    - no coherent enhancement
- bounds on NP scale from few GeV to TeV

$$\mathcal{Q}_{1,f}^{(6)} = (\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha)(\bar{f}\gamma^\mu f)$$

$$\mathcal{Q}_{1}^{(5)} = \frac{e}{8\pi^2}(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha) F_{\mu\nu}$$

$$\mathcal{Q}_{4}^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\nu}_\beta P_L \nu_\alpha) G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$

WHAT KIND OF MODELS?

- need to include LEP/EW precision bounds
  - some operators not constrained at all

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha) F_{\mu\nu}$$

  - others only possible with fine-tuning

$$\mathcal{Q}_{1,f}^{(6)} = (\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha)(\bar{f}\gamma^\mu f)$$

- future directions
  - include EW+QCD+QED running in the above analysis
  - types of UV complete models
  - can also write EFTs for light mediator NP

CONCLUSIONS

- presented LO + (partial) NLO matching from DM interacting with gluons and quarks to nuclear physics
- not consistent to take single NR operators, should use EFT with gluons and quarks

BACKUP SLIDES