Lecture 18, February 4, 2021

Wednesday, February 3, 2021 8:05 PM

Last time: EFTs in practice.
Constructing EFT for dark matter interactions.

Today: Collider phenomenology of DM EFT
EFT validity
Simplified models
$\nu$-physics

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Difficulty w/ DM phenomenology: get out exactly what you put

Attitude: Focus on direct interactions
↳ New gauge force, new renormalizable coupling to SM

Last time ← ☆ Focus on effective interaction
↳ Direct interaction at energy scale out of reach
↳ Parametrize effective operators to interact w/ SM.
No need to assume or know what underlying interaction exists.

$$\mathcal{L}_{\substack{DM-SM\\EFT}} = \frac{1}{\Lambda^2}\bar{q}q\bar{\chi}\chi + \frac{1}{\Lambda^2}\bar{q}\gamma^5 q\bar{\chi}\gamma^5\chi$$

$$+\frac{1}{\Lambda^2}\bar{q}\gamma^\mu q\bar{\chi}\gamma_\mu\chi + \frac{1}{\Lambda^2}\bar{q}\gamma^\mu\gamma^5 q\bar{\chi}\gamma_\mu\gamma_5\chi$$

$$+\frac{1}{\Lambda^2}\bar{q}\sigma^{\mu\nu}q\bar{\chi}\sigma_{\mu\nu}\chi$$ + mixed scalar-pseudo + vector-axial-vec.

UV completions are important, especially when EFT description fails

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Note: Scalar operators $\bar{q}q$ are actually dim-7 in unbroken EW phase:

$$\underbrace{\frac{C_6}{\Lambda^2}\bar{q}q\,\bar{\chi}\chi}_{\text{dim-6}} \to \underbrace{\frac{[C_{7d}^{ij}]}{\Lambda^3}\bar{Q}_i H d_{R_j}\,\bar{\chi}\chi}_{\text{dim-7}} \text{ or } \frac{[C_{7u}^{ij}]}{\Lambda^3}\bar{Q}_i\tilde{H}u_{R_j}\bar{\chi}\chi$$

$$\to \underbrace{\frac{m_d}{\Lambda^3}\bar{d}d\,\bar{\chi}\chi}_{''} \text{ or } \frac{m_u}{\Lambda^3}\bar{u}u\,\bar{\chi}\chi$$

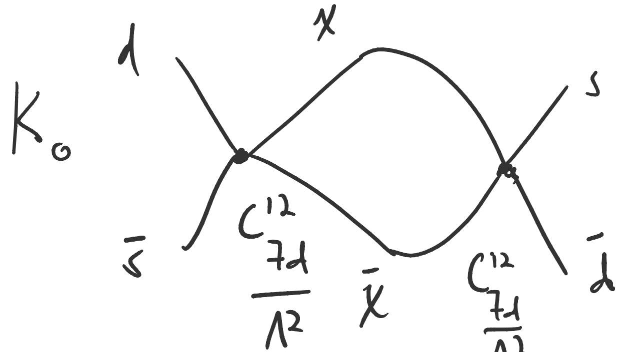
So, "natural" expectation is coeff. of

$\frac{C_6}{\Lambda^2}\bar{q}q\bar{\chi}\chi$ is prop. to $m_q \sim C_6$

Flavor physics bounds would essentially exclude other matrix structures in $C_{7d}^{ij}$, $C_{7u}^{ij}$.

$C_{7d}^{ij}$ does not have to be related $y_d^{ij}$.

Take $C_{7d}^{ij}$ as $\mathcal{O}(1)$ matrix.




$$\bar{K}_0 \sim \frac{(C_{7d}^{12})^2}{\Lambda^4}\int_0^\Lambda d^4k \left(\frac{k + m_\chi}{k^2 - m_\chi^2}\right)^2$$

$$(K_0\bar{K}_0) \sim \frac{(C_{7d}^{12})^2}{\Lambda^2}$$

For $\underbrace{C_{7d}^{12}}\sim 1 \Rightarrow \Lambda > 100$ TeV or larger.

For $C^{12} \sim 10^{-3} \Rightarrow \Lambda > \ldots$

For $C_{7d}^{12} \sim 10^{-3} \Rightarrow \Lambda > 100$ GeV

This problem of assigning flavor structure for NP operator is the <u>new physics flavor problem</u>.

Simplest ansatz that is safe is

<u>minimal flavor violation</u> $\Rightarrow$ all flavor structures are built from $Y_u, Y_d$ matrices.

Would set $C_{7d} \propto Y_d$ + $C_{7u} \propto Y_u$.

( This MFV ansatz ensures that SM global symm. of $U(3)^5$ can diagonalize all flavor matrices + the only flavor violation left is prop. to CKM.)

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$$\mathcal{L}^{\text{unrot}} = \underbrace{Y_d \bar{Q} H d_R} + \frac{\widehat{C_{7d}}}{\Lambda^3} \bar{Q} H d_R \bar{\chi} \chi + h.c.$$

$Y_d \not\propto C_{7d} \Rightarrow C_{7d}$ remains arbitrary.

$Y_d \propto C_{7d} \Rightarrow C_{7d}$ is diag. when you diagonalize $Y_d$.

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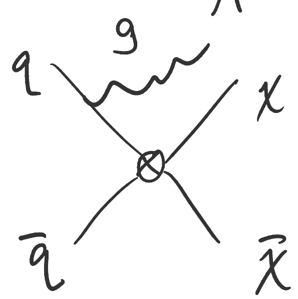
$\mathcal{L}_{DM\text{-}SM}$ used in collider study for DM production.

Simplify: Take AV - AV operator.

$$\mathcal{L} = C_{AV} \quad \bar{q} \gamma^\mu \gamma^5 q \quad \bar{\chi} \gamma_\mu \gamma^5 \chi$$

$$\mathcal{L} = \frac{C_{AV}}{\Lambda^2} \cdot \bar{q}\gamma^\mu\gamma^5 q \; \bar{\chi}\gamma_\mu\gamma^5\chi$$

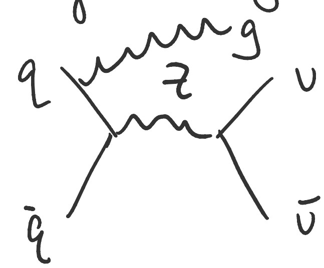



Signal

Collider signature: $\boxed{\text{jet} + \not{E}_T}$

To distinguish final states, always use multiplicity cuts first to remove reducible bkgds, then kinematic cuts to reduce irred. bkgds.

Leading background: SM production of $\not{E}_T$ is $\nu$'s



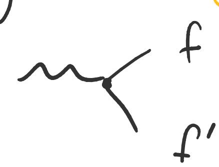

Drell-Yan

Irreducible bkgd

Background: $\boxed{pp \to Z + j,\ Z \to \nu\bar{\nu}}$

Trivia: $Br\,(Z \to \nu\bar{\nu}) \sim 20\%$

Trivia: W




$\frac{g}{\sqrt{2}}\gamma^\mu P_L$

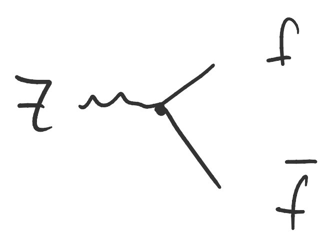
Dofs: $Br\begin{pmatrix} c\ s & \times 3 \\ u\ d & \times 3\end{pmatrix} \sim 66\%$

$(\tau\nu) \sim 11\%$

$Br\,(\mu\nu) \sim 11\%$

$Br\,(e\nu) \sim 11\%$

9 equally weighted final states




$(g_V^2 + g_A^2)$

$(g_V^2 - g_A^2)$

$\Rightarrow Br\,(\text{hadrons}) \sim 70\%$

$Br\,(\nu\bar{\nu}) \sim 20\%$

$Br\,(ee, \mu\mu, \text{and } \tau\tau) \sim 10\%$

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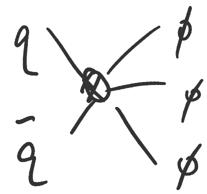
10 min. break.

Scalar DM $\phi$

$\phi \sim 1$ under $\mathbb{Z}_3$: $\quad \frac{1}{\Lambda^3} \bar{q} q \phi^3$




Fermionic DM $\chi$, $\quad \chi \sim 1$ under $\mathbb{Z}_3$

$$\mathcal{L} = y_\nu \bar{L} H N \quad + \cancel{\frac{c_i \bar{N}}{\Lambda^2} \underset{+1}{\chi} \, \underset{-1}{\bar{\chi}} \, \underset{+1}{\chi}} \quad +$$

$\bar{n}$

$$\mathcal{L} = \frac{(\bar{u} \bar{d} \bar{d})}{\Lambda^5} (\chi)^3$$

SM gauge singlet & spin 3/2

Violates global baryon # of SM.

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In practice, EFTs always have regime of validity.

Bounds on EFTs have to satisfy a closure test.

Using EFT, extract bound on NP s.t. the kinematics I study are within validity range of EFT.

Complication: Extract combination of EFT params $M_*$

$$\frac{1}{M_*} = \frac{c}{\Lambda} \Rightarrow M_* = \frac{\Lambda}{c}$$

If I get bound on $M_*$ that is small, still save a large $\Lambda$ bound by take $c$ to be huge.

large $\Lambda$ bound by take $C$ to be huge.

Ex. $30\text{ GeV} = \dfrac{\Lambda}{c} = \dfrac{1\text{ TeV}}{c}$

Set $\Lambda = 1\text{ TeV}$

$$c = \frac{1\text{ TeV}}{30\text{ GeV}} \sim 33$$

In Fermi theory $G_F = \dfrac{1}{M_*^2}$, $v = M_*$

In EFT, $C$ & $\Lambda$ play different roles.

$C$ is usually comb. of couplings & possible loop factors + factors of $\pi$, etc.

$\Lambda$ is the mass scale of new particles.

There is no hard & fast rule about to relate $M_*$ into individual $C$ & $\Lambda$.

i.e. Can restrict large $C$ by perturbativity, but what about strongly coupled UV theories?

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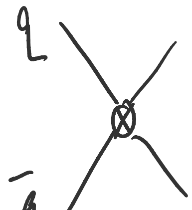
Validity question is main issue to drive DM EFT to using simplified models.

Simplified model:

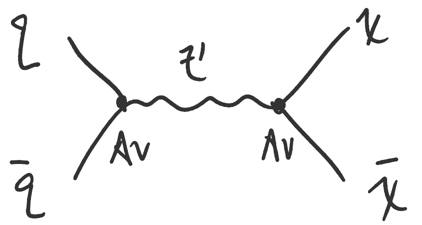
Next step from EFT operator to UV completion, where you "integrate in" minimal field content & interactions to realize particular EFT operator.

AV operator



$$\frac{1}{\Lambda^2}\left(\bar{q}\gamma^\mu\gamma^5 q\right)\left(\bar{\chi}\gamma_\mu\gamma^5\chi\right)$$

Simplified model s-channel, $Z'$ boson integrated in




$$\mathcal{L} \supset -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - g_{AV,q}\, Z'_\mu \bar{q} \gamma^\mu \gamma^5 q$$

$$- g_{AV,\chi}\, Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi + m_{Z'}^2 Z'_\mu Z'^\mu$$

$$+ \mathcal{L}_{DM} + \mathcal{L}_{SM}$$

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Vector mass $m_{Z'}^2$ should come from some Higgs mechanism.

Also, $g_{AV,q}$ & $g_{AV,\chi}$ : more UV-complete would specify charges / reps. for quarks & $\chi$ that give $g_{AV,q}$ & $g_{AV,\chi}$ params. Also, anomalies.

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Simplified models motivated to address deficiency of EFTs regarding kinematics but unsatisfactory regarding UV completeness.

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Set $Z'$ mass & $g_{AV,q}$, $g_{AV,\chi}$ to match the previous $M_*$.

$g_{AV,q} = g_{AV,\chi} = 1$, $m_{Z'} = 30$ GeV.

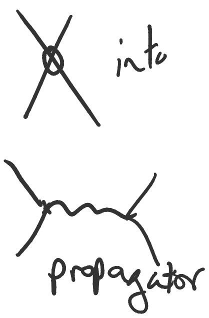
Dynamical $Z'$ interactions are readily included in simplified model.

On-shell $Z'$ production (since $M_*$ is light) & signatures.

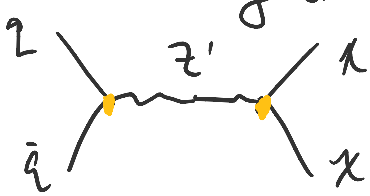
New set of params. in simplified model.

$g_{AV,q}$ = "visible" coupling

$g_{AV,\chi}$ = "invisible" coupling.



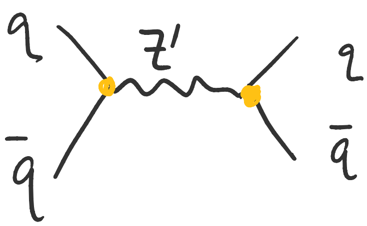

DM signal




dominates when $g_{AV,\chi} \gg g_{AV,q}$.

but scales $g_{AV,\chi} \cdot g_{AV,q}$

Visible resonance




Reuse production vertex as decay vtx. $Z'$ on-shell, get dijet resonance. In fact, necessary prediction given DM signal, since DM signal requires $g_{AV,q} \neq 0$.

Typically analyzed in mass-mass plane $(m_\chi, m_{Z'})$ for fixed couplings. (Analogous to Higgs + $h \to gg$.)

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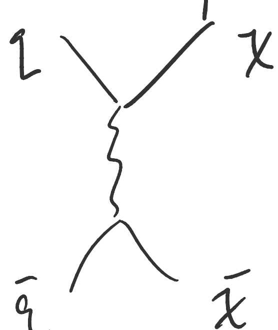
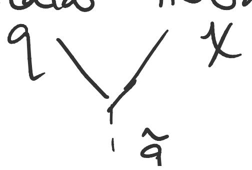
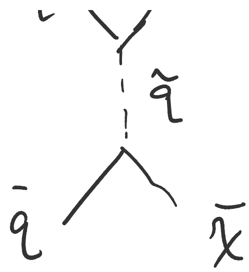
Another option: t-channel simplified model



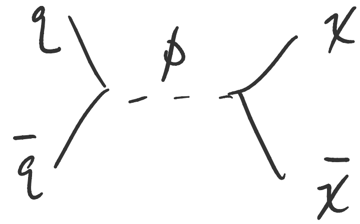

(hard from UV standpoint for AV model)

For scalar interaction:




$\tilde{q}$ is squark
Must be colored!




$\phi$ is a Higgs boson.