A careful comparison between LHC and direct detection

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Dark Matter at the LHC 2016
Amsterdam – 31 March 2016
LHC vs Direct Detection

LHC

\[ pp \to \chi \chi j \]
\[ \sqrt{s} = 13 \text{ TeV} \]

Direct Detection

\[ \chi N \to \chi N \]
\[ \langle E_{\text{recoil}} \rangle \simeq 2 \frac{m_{\text{DM}}^2 M_N}{(m_{\text{DM}} + M_N)^2} v^2 \simeq 50 \text{ keV} \]

Xe and \( m_{\text{DM}} = 100 \text{ GeV} \)
LHC vs Direct Detection

LHC

\[ pp \rightarrow \chi \chi j \]
\[ \sqrt{s} = 13 \text{ TeV} \]

Energy scales:
LHC \gg Direct Detection

Direct Detection

\[ \chi N \rightarrow \chi N \]
\[ \langle E_{\text{recoil}} \rangle \simeq 2 \frac{m_{DM}^2 M_N}{(m_{DM} + M_N)^2} v^2 \simeq 50 \text{ keV} \]

Xe and \( m_{DM} = 100 \text{ GeV} \)

LUX experiment
LHC vs Direct Detection

In this talk

Deal with scale separation by using Effective Field Theory (EFT) techniques

Mandatory for a careful comparison between LHC and DD
A known SM example

B meson decay: $B \rightarrow D \pi$

$$\mathcal{M}_{B \rightarrow D \pi} = \langle D \pi | \mathcal{L}_{\text{SM}} | B \rangle$$
A known SM example

B meson decay: \( B \rightarrow D \pi \)

\[ \mathcal{M}_{B \rightarrow D\pi} = \langle D\pi | \mathcal{L}_{\text{SM}} | B \rangle \]

Direct calculation hard:
\( W \) boson mediates the decay in the \( B \) rest frame

\( m_W \gg m_B \)

EFT: systematically deal with one scale at the time

and

arbitrarily improve the calculation precision
A known SM example

B meson decay: \( B \rightarrow D \pi \)

\[ \mathcal{M}_{B \rightarrow D\pi} = \langle D\pi | \mathcal{L}_{SM} | B \rangle \]
A known SM example

B meson decay: $B \rightarrow D \pi$

$\mathcal{M}_{B \rightarrow D\pi} = \langle D\pi | \mathcal{L}_{SM} | B \rangle$

Integrate-out heavy SM states ($W$, $Z$, $h$, $t$)
A known SM example

**B meson decay: B \rightarrow D \pi**

\[ M_{B \rightarrow D\pi} = \langle D\pi | L_{SM} | B \rangle \]

Integrate-out heavy SM states (W, Z, h, t)

**ElectroWeak Hamiltonian**

\[ \mathcal{H}_W = V_G F \left[ C_1 \bar{c}_\alpha \gamma^\mu P_L b_\alpha \bar{d}_\beta \gamma^\mu P_L u_\beta + C_2 \bar{c}_\alpha \gamma^\mu P_L b_\beta \bar{d}_\beta \gamma^\mu P_L u_\alpha \right] \]

Buras, hep-ph/9806471
A known SM example

B meson decay: $B \to D \pi$

$\mathcal{M}_{B \to D \pi} = \langle D \pi | L_{SM} | B \rangle$

Integrate-out heavy SM states ($W$, $Z$, $h$, $t$)

ElectroWeak Hamiltonian

$\mathcal{H}_W = \mathcal{V} G_F \left[ C_1 \bar{c}_\alpha \gamma^\mu P_L b_\alpha \bar{d}_\beta \gamma^\mu P_L u_\beta + C_2 \bar{c}_\alpha \gamma^\mu P_L b_\beta \bar{d}_\beta \gamma^\mu P_L u_\alpha \right]$

$C_1(m_W) = 1 \quad C_2(m_W) = 0$

$m_W$

$\nu m_b$

Buras, hep-ph/9806471
A known SM example

**B meson decay: B → D π**

\[ \mathcal{M}_{B \to D\pi} = \langle D\pi | \mathcal{L}_{SM} | B \rangle \]

**Integrate-out heavy SM states (W, Z, h, t)**

**ElectroWeak Hamiltonian**

\[ \mathcal{H}_W = V G_F \left[ C_1 \overline{c}_\alpha \gamma^\mu P_L b_\alpha \overline{d}_\beta \gamma^\mu P_L u_\beta + C_2 \overline{c}_\alpha \gamma^\mu P_L b_\beta \overline{d}_\beta \gamma^\mu P_L u_\alpha \right] \]

Buras, hep-ph/9806471

**Renormalization Group Evolution (RGE)**

\[ C_1(m_W) = 1 \quad C_2(m_W) = 0 \]

\[ m_b \]

\[ C_1(m_b) \approx 1.12 \quad C_2(m_b) \approx -0.28 \]
A known SM example

B meson decay: \( B \rightarrow D \pi \)

\[
\mathcal{M}_{B \rightarrow D\pi} = \langle D\pi|\mathcal{L}_{SM}|B\rangle
\]

Integrate-out heavy SM states (W, Z, h, t)

ElectroWeak Hamiltonian

\[
\mathcal{H}_W = V G_F \left[ C_1 \bar{c}_\alpha \gamma^\mu P_L b_\alpha \bar{d}_\beta \gamma^\mu P_L u_\beta + C_2 \bar{c}_\alpha \gamma^\mu P_L b_\beta \bar{d}_\gamma \gamma^\mu P_L u_\alpha \right]
\]

Buras, hep-ph/9806471

\( C_1(m_W) = 1 \quad C_2(m_W) = 0 \)

Renormalization Group Evolution (RGE)

\[
C_1(m_b) \approx 1.12 \quad C_2(m_b) \approx -0.28
\]

Effective couplings at the scale \( m_b \)

\[
\langle D\pi|H_W(m_b)|B\rangle
\]
DM Direct Detection

B → D π

Dark Matter Direct Detection

Energy Scale

m_W

Energy Scale

M_{med}

Energy Scale

m_b \rightarrow \langle D \pi | H_W(m_b) | B \rangle

Energy Scale

\mu_N
DM Direct Detection

B -> D \pi

Dark Matter Direct Detection

Integrate-out mediator

\langle D\pi|H_W(m_b)|B\rangle

m_{\text{med}}

\mu_N

Energy Scale

Energy Scale
DM Direct Detection

Dark Matter Direct Detection

\[ \mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{SM}} + \overline{\chi} \left( i\tau - m_{\chi} \right) \chi + \sum_{d>4} \sum_{\alpha} \frac{c_{\alpha}^{(d)}}{M_{\text{med}}^{d-4}} \mathcal{O}_{\alpha}^{(d)} \]

EFT for DM interactions with SM particles

Integrate-out mediator

Energy Scale

Energy Scale

\[ m_W \]

\[ M_{\text{med}} \]

\[ (\text{RGE}) \]

\[ m_b \sim \langle D\pi | H_W(m_b) | B \rangle \]

\[ \mu_N \]
DM Direct Detection

**EFT for DM interactions with SM particles**

\[ \mathcal{L}_{SM\chi} = \mathcal{L}_{SM} + \bar{\chi} (i\dot{\phi} - m_\chi) \chi + \sum_{d>4} \sum_\alpha \frac{c^{(d)}_\alpha}{M^d_{\text{med}}} \mathcal{O}^{(d)}_\alpha \]

**Integrate-out mediator**

**Energy Scale**

\[ m_W \]

\[ M_{\text{med}} \]

**Energy Scale**

\[ m_b \sim \langle D\pi | H_W(m_b) | B \rangle \]

\[ \mu_N \]
DM Direct Detection

**EFT for DM interactions with SM particles**

\[
\mathcal{L}_{\text{SM}_\chi} = \mathcal{L}_{\text{SM}} + \bar{\chi} (i\phi - m_\chi) \chi + \sum_{d>4} \sum_\alpha \frac{c_\alpha^{(d)}}{M_{\text{med}}^{d-4}} \mathcal{O}_\alpha^{(d)}
\]

**Renormalization Group Evolution (RGE)**

\[
c_\alpha^{(d)} (M_{\text{med}})
\]

\[
c_\alpha^{(d)} (\mu_N)
\]
Dark Matter Direct Detection

EFT for DM interactions with SM particles

\[ \mathcal{L}_{\text{SM}_\chi} = \mathcal{L}_{\text{SM}} + \bar{\chi}(i\phi - m_\chi)\chi + \sum_{d>4} \sum_\alpha \frac{c_\alpha^{(d)}}{M_{\text{med}}^{d-4}} \mathcal{O}_\alpha^{(d)} \]

Renormalization Group Evolution (RGE)

Couplings at the nuclear scale \( \mu_N \sim 1 \text{ GeV} \)
Why is this relevant?

Should we worry about loop corrections in a pre-discovery era?
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RGE effects

- changing size of the effective couplings
- generating new interactions (operator mixing)
Why is this relevant?

Should we worry about loop corrections in a pre-discovery era?

RGE effects
- changing size of the effective couplings
- generating new interactions (operator mixing)

DM-Nucleus elastic scattering:
- only through couplings to light SM degrees of freedom
- and
- very sensitive to the details of the interactions

Goodman and Witten, PRD31 (1985)
Why is this relevant?

Should we worry about loop corrections in a pre-discovery era?

RGE effects

• changing size of the effective couplings

• generating new interactions (operator mixing)

How about...

Suppressed interactions between DM and SM

Renormalization Group Evolution (RGE)

Unsuppressed DM interactions with light SM d.o.f.
Direct detection rates can be orders of magnitude larger than the one computed without carefully accounting for the scale separation.
Plan for Today’s Talk

DD for Vector Mediators

Comparison with mono-jet searches
FD, Kavanagh, Panci, in preparation

A 750 GeV scalar mediator
FD, Kavanagh, Panci, in preparation
Plan for Today’s Talk

DD for Vector Mediators


FD, Kavanagh, Panci, in preparation

Comparison with mono-jet searches

A 750 GeV scalar mediator

FD, de Vries, Panci, arXiv:
Vector Mediators

Simplified Model

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_V + J_{\mu}^{DM} V_\mu + J_{\mu}^{SM} V_\mu \]

Compact and powerful tool to explore LHC phenomenology and complementarity among DM searches

Alves, Profumo, Queiroz, JHEP04 (2014), arXiv:1312.5281
Arcadi, Mambrini, Tytgat, Zaldivar, JHEP03 (2014), arXiv:1401.0221
Lebedev, Mambrini, PLB734 (2014), arXiv:1403.4837
Harris, Khoze, Spannowsky, Williams, PRD91 (2015), arXiv:1411.0535
Vector Mediators

Simplified Model

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_V + J_{\text{DM}}^\mu V_\mu + J_{\text{SM}}^\mu V_\mu \]

Both scalar DM (complex) and fermion DM (Dirac or Majorana)

\[ \mathcal{L}_{\text{DM}} = \begin{cases} 
|\partial_\mu \phi|^2 - m_\phi^2 |\phi|^2 & \text{scalar DM} \\
\kappa_\chi \bar{\chi} (i\phi - m_\chi) \chi & \text{fermion DM}
\end{cases} \]

\[ \kappa_\chi = \begin{cases} 
1 & \text{Dirac} \\
1/2 & \text{Majorana}
\end{cases} \]
Vector Mediators

Simplified Model

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_V + J_{DM}^\mu V_\mu + J_{SM}^\mu V_\mu \]

Spin-1 massive mediator

\[ \mathcal{L}_V = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + \frac{1}{2} m_V^2 V^\mu V_\mu \]
Vector Mediators

Simplified Model

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_V + J_{DM}^\mu V_\mu + J_{SM}^\mu V_\mu \]

Mediator coupled to spin-1 DM currents

\[ J_{DM}^\mu = \begin{cases} 
\mathcal{K}_\chi (c_{\chi V} \bar{\chi} \gamma^\mu \chi + c_{\chi A} \bar{\chi} \gamma^\mu \gamma^5 \chi) & \text{scalar DM} \\
\mathcal{K}_\chi (c_{\chi V} \bar{\chi} \gamma^\mu \chi + c_{\chi A} \bar{\chi} \gamma^\mu \gamma^5 \chi) & \text{fermion DM} 
\end{cases} \]

\[ \begin{array}{c}
\text{V} \\
\text{DM} \\
\text{DM}
\end{array} \]
Vector Mediators

Simplified Model

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_V + J_{DM}^\mu V_\mu + J_{SM}^\mu V_\mu \]

Mediator coupled to spin-1 currents of SM fermions

\[ J_{SM}^\mu = \sum_{i=1}^{3} \left[ c_q^{(i)} \bar{q}_L^i \gamma^\mu q_L^i + c_u^{(i)} \bar{u}_R^i \gamma^\mu u_R^i + c_d^{(i)} \bar{d}_R^i \gamma^\mu d_R^i + c_l^{(i)} \bar{l}_L^i \gamma^\mu l_L^i + c_e^{(i)} \bar{e}_R^i \gamma^\mu e_R^i \right] \]

15 independent SU(2)_L \times U(1)_Y gauge invariant couplings to SM fermions
Apply EFT techniques to evaluate direct detection rates for this broad class of models.
Direct Detection Rates

**STEP 1:** Integrate-out mediator

\[
\frac{1}{q^2 - m_V^2} \approx -\frac{1}{m_V^2}
\]

EFT: DM contact interactions
Direct Detection Rates

STEP I: Integrate-out mediator

\[ \frac{1}{q^2 - m_V^2} \sim -\frac{1}{m_V^2} \]

EFT: DM contact interactions

STEP II: Connecting Energy Scales

EFT couplings at the scale \( m_V \)

Nuclear scale
- size couplings changed
- new interactions are generated (mixing)
Direct Detection Rates

**STEP I:** Integrate-out mediator

\[
\frac{1}{q^2 - m_V^2} \sim - \frac{1}{m_V^2}
\]

**STEP II:** Connecting Energy Scales

EFT couplings at the scale \( m_V \)

Nuclear scale
- size couplings changed
- new interactions are generated (mixing)

**STEP III:** Matrix Elements

EFT for DM interactions with quarks and gluons

matching onto EFT with nucleons

Nuclear Matrix Elements
Direct Detection Rates

**STEP I:** Integrate-out mediator

- Straightforward for vector mediator

**STEP II:** Connecting Energy Scales

- Complete one-loop RGE analysis done for spin-1 currents
  

**STEP III:** Matrix Elements

- Matching to nucleons and nuclear matrix elements known for spin-1 currents

  Cirelli, Del Nobile, Panci, JCAP1310 (2013), arXiv:1307.5955
Interested in the RGE-induced currents with light quarks

On this slide: approximate solution
Interested in the RGE-induced currents with light quarks

\[ V \text{ coupled to vector currents of SM fermions} \]

Important if \( V \) not coupled to light quarks (e.g. leptons or heavy quarks)
Otherwise \( O(1\%) \) correction

\[ \Delta c_V \simeq \frac{e^2}{16\pi^2} \ln\left(\frac{m_V}{\mu_N}\right) \]
Interested in the RGE-induced currents with light quarks

Phenomenologically important
Dominated by heavy SM fermions (prop. to Yukawa)

\[ \Delta c_{V,A} \simeq \frac{\lambda_f^2}{16\pi^2} \ln\left(\frac{m_V}{\mu_N}\right) \]
Results I: quarks vector

Mediator with flavor universal couplings to quark vector currents

\[ \mathcal{L}_{\text{EFT}} = -\frac{1}{m_V^2} J_{\text{DM}} \mu \sum_{i=1}^{3} \left[ \bar{u}^i \gamma^\mu u^i + \bar{d}^i \gamma^\mu d^i \right] \]

Flavor universal: Quarks only

RGE effects are O(1%) correction to EFT couplings

LUX 2014, LZ projected

FD, Kavanagh, Panci, in preparation
Results II: quarks axial

Mediator with flavor universal couplings to quark axial currents

\[ \mathcal{L}_{EFT} = -\frac{1}{m_V^2} J_{DM} \mu \sum_{i=1}^{3} \left( \bar{u}^i \gamma^\mu \gamma^5 u^i + \bar{d}^i \gamma^\mu \gamma^5 d^i \right) \]

RGE effects drive by Yukawa couplings alter the rates

FD, Kavanagh, Panci, in preparation
Results II: quarks axial

Mediator with flavor universal couplings to quark axial currents

\[ \mathcal{L}_{\text{EFT}} = -\frac{1}{m_V^2} J_{\text{DM}} \mu \sum_{i=1}^{3} \left[ \overline{u}^i \gamma^\mu \gamma^5 u^i + \overline{d}^i \gamma^\mu \gamma^5 d^i \right] \]

RGE effects drive by Yukawa couplings alter the rates

FD, Kavanagh, Panci, in preparation
Results II: quarks axial

Mediator with flavor universal couplings to quark axial currents

\[ \mathcal{L}_{EFT} = -\frac{1}{m_V^2} J_{DM \mu} \sum_{i=1}^{3} \left[ \bar{u}^{i} \gamma^{\mu} \gamma^{5} u^{i} + \bar{d}^{i} \gamma^{\mu} \gamma^{5} d^{i} \right] \]

RGE effects drive by Yukawa couplings alter the rates

FD, Kavanagh, Panci, in preparation
Results II: quarks axial

Mediator with flavor universal couplings to quark axial currents

\[ \mathcal{L}_{\text{EFT}} = - \frac{1}{m_V^2} J_{\text{DM}} \mu \sum_{i=1}^{3} \left[ \bar{u}^i \gamma^\mu \gamma^5 u^i + \bar{d}^i \gamma^\mu \gamma^5 d^i \right] \]

RGE effects drive by Yukawa couplings alter the rates

FD, Kavanagh, Panci, in preparation
Results III: other cases

Our analysis valid also if $V$ not coupled to light quarks

Exhaustive study of different cases (including scalar DM) in upcoming paper

FD, Kavanagh, Panci, in preparation
Results III: other cases

Our analysis valid also if V not coupled to light quarks

Exhaustive study of different cases (including scalar DM) in upcoming paper

FD, Kavanagh, Panci, in preparation
Plan for Today’s Talk

DD for Vector Mediators

Comparison with mono-jet searches

A 750 GeV scalar mediator
Axial–axial operator

\[ \sigma \propto g_q \cdot g_\chi \]

\[ m_\chi \text{ [GeV]} \]

\[ \sigma_{SD} \text{ (DM-neutron)} \text{ [cm}^2\text{]} \]

\[ \sigma_{SD} \text{ (DM-proton)} \text{ [cm}^2\text{]} \]

LUX, \text{ arXiv:1602.03489}
PICO-2L, \text{ arXiv:1601.03729}

ATLAS monojet, talk by Andreas Korn at this workshop
Axial–axial operator

![Graph showing dark matter mass vs. cross-section for SD (DM-proton) and SD (DM-neutron) interactions with LUX 2016 and PICO-2L limits.]

LUX, arXiv:1602.03489
PICO-2L, arXiv:1601.03729
ATLAS monojet, talk by Andreas Korn at this workshop
Axial–axial operator

RGE effects: ~ factor of 2 in $\sigma_{SD}$

LUX, arXiv:1602.03489
PICO-2L, arXiv:1601.03729
ATLAS monojet, talk by Andreas Korn at this workshop
Plan for Today’s Talk

DD for Vector Mediators
FD, Procura, JHEP1504 (2015), arXiv:
FD, Kavanagh

Comparison with mono-jet searches
FD, Kavanagh

A 750 GeV scalar mediator
FD, de Vries, Panci, arXiv:1601.01571
A 750 GeV Portal?

Could this new hypothetical particle be the mediator between DM and SM?
Could this new hypothetical particle be the mediator between DM and SM?

Scalar Mediator
- LHC (invisible decays)
- Direct Detection

Pseudo-Scalar Mediator
- LHC (invisible decays)
- Indirect Detection

FD, de Vries, Panci, arXiv:1601.01571
A 750 Scalar Portal

Simple EFT for a 750 GeV scalar portal ($S$) and fermion DM ($\chi$)

$$\mathcal{L}_{\text{EFT}} = \frac{S}{\Lambda} \left[ c_{GG} G_{\mu\nu}^A G_{\mu\nu}^A + c_{WW} W_{\mu\nu}^I W_{\mu\nu}^I + c_{BB} B_{\mu\nu} B_{\mu\nu} \right] + c_{\chi S} S \bar{\chi} \chi$$
A 750 Scalar Portal

Simple EFT for a 750 GeV scalar portal ($S$) and fermion DM ($\chi$)

$$\mathcal{L}_{\text{EFT}} = \frac{S}{\Lambda} \left[ c_{GG} G^{A \mu \nu} G^{A \mu \nu} + c_{WW} W^{I \mu \nu} W^{I \mu \nu} + c_{BB} B^{\mu \nu} B_{\mu \nu} \right] + c_{\chi S} S \bar{\chi} \chi$$

Excess initiated by gluon fusion

$$\mathcal{L}_{\text{DD}} = c_{G} \bar{\chi} \chi G^{A \mu \nu} G^{A \mu \nu}$$

$$c_{GG}(\mu_N) \simeq 4.01 \frac{c_{\chi S}}{\Lambda m_s^2} c_{GG}(m_S)$$

RGE change DD rates by a factor of 16!

FD, de Vries, Panci, arXiv:1601.01571
Outlook

Comparing LHC with DD not always straightforward
Outlook

Comparing LHC with DD not always straightforward

Vector Mediator

FD, Kavanagh, Panci, in preparation
Outlook

Comparing LHC with DD not always straightforward

Vector Mediator

750 GeV Scalar Mediator

FD, Kavanagh, Panci, in preparation

FD, de Vries, Panci, arXiv:1601.01571
Comparing LHC with DD not always straightforward

Vector Mediator

750 GeV Scalar Mediator

Still need to quantify RGE effects for other simplified models!
Outlook

Comparing LHC with DD not always straightforward

Vector Mediator

750 GeV Scalar Mediator

FD, Kavanagh, Panci, in preparation

FD, de Vries, Panci, arXiv:1601.01571

Thank You!