Simplified t-channel dark matter models and LLPs Dipan Sengupta University of New South Wales, Sydney

With C.P-Yuan, B. Yan, K. Mohan, Tim Tait, Matthias Becker, Emanuele Copello and Julia Harz + LHC-t-channel Dark Matter Working Group

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Properties and the Particle Physics of Dark Matter

- Cold and Neutral: Non relativistic today.
- Preserves the success of Big Bang Nucleosynthesis (Formation of Atoms and Nuclei in the early Universe)
- "Almost" Dark with respect to other forces of nature.
- Collisionless within the DM sector at large scales.
- Stable, on Cosmological time scales.
- Forms halos in the galaxy

Dark Matter belongs in Astronomy/Cosmology . Why should we care about colliders ?

Dark Matter at Colliders

Comment : Even in the event of a

missing energy signature, we can't be sure it is dark matter

Supersymmetry as an Example

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A few mediators with specific DM couplings generates the relic density and direct detection rates. For heavy mediators, can integrate the mediator out And classify the DM by spin

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A few mediators with specific DM couplings generates the relic density and direct detection rates. • And it will fail to describe high energies, For heavy mediators, can integrate the mediator out And classify the DM by spin $\mathbf{b} \cdot \mathbf{b}$ TIN SPECITIC DN \blacksquare

 g^2 $M_{\tilde{q}}^2$ \tilde{q} $\leftrightarrow G_{eff}$

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Supersymmetry as an Example

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Majorana Dark Matter: 10 operators with an EFT strength M

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 $G_\chi \left[\bar\chi \Gamma^\chi \chi \right] G^2$ \blacktriangledown $G_{\chi}[\bar{q}\Gamma^{q}q][\bar{\chi}\Gamma^{\chi}\chi]$

Full Models vs EFTs

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Full Models vs EFTs

$$
f_N/m_N = \sum_{q=u,d,s} f_{Tq}(f_q) + \sum_{q=u,d,s,c,b} \frac{3}{4} [q(2) + \bar{q}(2)] \left(g_q^{(1)} + g_q^{(2)} \right)
$$

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$$
\frac{8\pi}{9\alpha_s} f_{TG}(f_G) + \frac{3}{4} G(2) \left(g_G^{(1)} + g_G^{(2)} \right).
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Full Models vs EFTs

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U(1)EM gauge invariance coupling the

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Full Models vs EFTs

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M9 GG

M10 NGG

 $\frac{1}{20}$ 120 140 160 180 200 220 240 260 280 300 G_{χ} \blacktriangledown $G_{\chi}[\bar{q}\Gamma^{q}q][\bar{\chi}\Gamma^{\chi}\chi]$

 $i\alpha_s/8M_*^3$

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Full Models vs EFTs

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• In principal control of the control of t $p_{T,jet}^{\,}$ (GeV)

Tevatron

M6

 $m_X = 5$ GeV

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where $\frac{H + F + T}{T}$ $\lim_{\log \theta}$

them, with related coefficients.

<u>nations.</u>

EFTs vs Simplified Models cally, one has in the case of spin-0 interactions and Dirac fermion In fact, in the limit of infinite mediator mass *ma* ! 1, the DMsimple and the DM-EFT Lagrangian (3) matches on the DM-EFT Lagrangian (1). The DM-EFT L The corresponding tree-level matching conditions are *C^f* α and α denotes the fifth Dirac matrix. The fifth Dirac matrix α inhimen tandiens

 $\mathcal{L}_{\sf DM-EFT} = \sum$ $f = u,d,s,c,b,t,e,\mu,\tau$ $\overline{1}$ C_1^f Λ^2 $f f \bar{\chi} \chi +$ C_2^f Λ^2 $\bar{f} \gamma_5 f \bar{\chi} \gamma_5 \chi + \cdots$

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where the ellipsis represents additional operators not relevant for relevant fo the further discussion, the sum over *^f* = *^u, ^d, ^s, ^c, ^b, ^t, ^e, µ,* ⌧ includes all SM quarks and charged leptons, the DM candidate is on PDFs, therefore hard to be absolutely quantitative

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\left\{ m_{\chi} , C_n^f / \Lambda^2 \right\} \quad \text{Justified for} \quad q^2 \ll \Lambda^2
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EFTs vs Simplified Models cally, one has in the case of spin-0 interactions and Dirac fermion In fact, in the limit of infinite mediator mass *ma* ! 1, the DMsimple and the DM-EFT Lagrangian (3) matches on the DM-EFT Lagrangian (1). The DM-EFT L The corresponding tree-level matching conditions are *C^f* α and α denotes the fifth Dirac matrix. The fifth Dirac matrix α inhimen tandiens

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' trates the relevant energy scales explored by DD, ID and collider else the WIMP would just decay

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Larger or smaller than the DM trateov show e.g. that the amplitudes *^A*(*qb* ! *q*⁰ *ta*) / ^p*^s* and *^A*(*gg* ! z and z and z diverge in the limit of large z The Feynman diagrams that lead to this behaviour are depicted to this behaviour are depicted to this behaviour
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g X g g The Coron Annihilation *X q* $\mathcal{A}(\mathbf{f})$ annihilation *X* χ_{bilotion} q *g* $y - \lambda$ *g* **Minestern Annihilation** \widetilde{Z}^X q q rilation (for the Annihilation *X g* $\left\{ \tilde{u},d,\tilde{s},\tilde{c},b,\tilde{t}\right\}$ *g* (c) Colored Annihilation *X q* (f) Colored Amnihilation *X* q $\left(SU(3), SU(2)\right)$ $\left(3, 1\right)$ $\left(3, 1\right)$ $\left(3, 2\right)$ $\left(3, 2\right)$ we restrict to the parameter of the parameter space in the mediator masses are the mediator masses are mediator masses are the Generation-dependent masses and couplings that are higher order in the Yukawa consider the generation $\sum_{i=1}^{\infty}$ (6) Coldified Annihilation $\sum_{i=1}^{\infty}$ ($\sum_{i=1}^{\infty}$ of $\sum_{i=1}^{\infty}$ and $\sum_{i=1}^{\infty}$ (6) Coldified Annihilation $\frac{1}{2}$ \widetilde{M} *is the SM* \widetilde{M} *is the SM* \widetilde{M} \widetilde{M} is the SM \widetilde{M} is the \widetilde{M} \widetilde{M} is the \widetilde{M} \widetilde{M} is \widetilde{M} is \widetilde{M} and \widetilde{M} is \widetilde{M} is \widetilde{M} \widetilde{M} \widetilde{M} constraints from the numerical results of \bar{q} Colored Annihilation, we take the second search to \bar{q} q^2 and $\frac{\chi\chi}{\chi}$ (i) colored Annihilation q
 α and $\chi\chi$ (i) colored Annihilation q $\chi\chi\approx\omega$ and $\chi\chi\approx\omega$ and $\chi\approx\omega$ \int $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}$ $\tilde{a} = \int \tilde{a} \tilde{d} \tilde{e} \tilde{e} \tilde{h} \tilde{f}$ $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$ $\left(3,1\right)_{\mathbb{R}}\left(3,1\right)_{\mathbb{R}}$ T the correspond to T the correspond to T mediators when T as T mediators and T mediators T mediators T mediators T and T as a T mediators of T mediators T mediators T mediators T mediators $\frac{1}{\sqrt{2\pi}}$, and a $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$ $\mathbf{r} = \mathbf{r}$ article. The assumption \mathbb{Z}_d , \mathbb{Z}_d , \mathbb{Z}_d , \mathbb{Z}_d of \mathbb{Z}_d and \mathbb{Z}_d are \mathbb{Z}_d . $\frac{1}{4}$ we assign the mediators the mediators of $\frac{1}{4}$ (d) $\$ $\tilde{u}^* = \frac{1}{2} \sum_{\ell=1}^N \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}^{\ell} + \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}^{\ell} + \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}^{\ell} + \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}^{\ell} \tilde{u}_{\ell}$ $\frac{1}{2} \left(\frac{1}{2} \frac{1}{2}$ *d*⇤ ˜ *d* $\frac{1}{2}$ $\frac{1}{2}$ \overline{a} *,* (2.4) T the corresponding to T , T and T is a T model (with T model α as a T model (with T mediators) T and T d $\liminf_{\lambda \to 0}$ and a $\limsup_{\lambda \to 0}$ and $\limsup_{\lambda \to 0}$ and $\limsup_{\lambda \to 0}$, $\limsup_{\lambda \to 0$ Matter particile. $\liminf_{q \to \infty} \frac{q}{x}$ $\liminf_{q \to \infty} \frac{q}{x}$ (6) $\liminf_{q \to \infty} \frac{q}{x}$ (2211, 2) $\lim_{q \to \infty} \frac{q}{x}$ (2211) $\lim_{q \to \infty} \frac{q}{x}$ (2211) $\lim_{q \to \infty} \frac{q}{x}$ $\mathbb{Z}_{\mathcal{A}}^{\mathcal{A}}$ assign the mediators triplets with $\frac{1}{\pi}$ $\mathbb{Z}_{\mathcal{A}}^{\mathcal{A}}$ or $\frac{1}{\pi}$ $\frac{1}{\pi}$ $\frac{1}{\pi}$ $\frac{1}{\pi}$ $\frac{1}{\pi}$ $\oint_{\mathbf{X}} \mathbf{x} \cdot \mathbf{x} = \oint_{\mathcal{X}} \mathbf{x} \cdot \mathbf{x} = \oint_{\mathcal{X}} \mathbf{x} \cdot \mathbf{x} \cdot \mathbf{x} = \int_{\mathcal{X}} \mathbf{x} \cdot \mathbf{x} \cdot \mathbf{x} = \int_{\mathcal{X}} \mathbf{x} \cdot \mathbf{x} \cdot \mathbf{x} = \int_{\mathcal{X}} \mathbf{x} \cdot \mathbf{x} \cdot \mathbf{x} + \int_{\mathcal{X}} \mathbf{x} \cdot \mathbf{x} \cdot \mathbf{x} + \int_{\mathcal{X}} \mathbf{x} \cdot \mathbf{x} \cdot \mathbf{x} + \int$ $\lim_{M \to \infty} \left[\frac{\sqrt{f}}{M} \right]^M$ $\left[\frac{\sqrt{f}}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ These three corresponds to the correspond to the with mediators and the with mediators and with mediators an *d*), and a *q^L* model (with mediators *Q*˜), $\min_{\{a\}}\max_{\{a\}}\min_{\$ we assign the mediators to $\frac{9}{4}$ $\frac{1}{4}$ $\frac{9}{4}$ $\frac{$ t is defined by \bar{t} and \bar{t} of \bar{t} of \bar{t} of \bar{t} of \bar{t} of \bar{t} of \bar{t} $\lim_{M\to\infty} \frac{M}{M} \frac{d}{dx} \frac{d}{dx} = M^2 \, \widehat{\mathbb{P}}^* \, \widetilde{d} + a_{DM} \, \widetilde{d}^* \, \nabla^* P_{DM} + a_{DM}^* \, \widetilde{d} \, \widetilde{d} P_I \, \nu$ $\int d^4x \frac{d^4y}{dx^4} \tilde{q}^* \tilde{q} + g_{DM} \tilde{q}^* \tilde{\chi} P_L q + g_D^*$ $\tilde{q} \bar{q} P_R \chi$) $q^2 \frac{1}{2} \frac{1}{2} \frac{1}{2}$ \ddot{a} $\tilde{\mathbf{y}}_k = \begin{bmatrix} \mathbf{x}_k^T \math$ $\widetilde{A}^* \widetilde{B}^*_{\$ $\sqrt{2^2 \tilde{a}^* \tilde{a}}$ $\big\{X$ $\tilde{a} = \int \tilde{u} \, d\tilde{\theta} \times \tilde{e} \times \tilde{h} \times \tilde{f}$ $\frac{1}{\sqrt{2\pi\hbar^2(a^2 - \alpha^2\hbar^2(a^2))}}$ (and $\frac{1}{\sqrt{2\hbar^2(a^2 - \alpha^2)}}$ models). $\frac{1}{\sqrt{N}}$ such that $\frac{1}{N}$ stable $\frac{1}{N}$ such that $\frac{1}{N}$ symmetry such that $\frac{1}{N}$ such that $\frac{1}{N}$ symmetry such that $\frac{1}{N}$ such that $\frac{1}{N}$ symmetry such that $\frac{1}{N}$ such that $\frac{1}{N}$ such \mathbf{X}^{t} *i,j* $g_{\rm DM}^{\rm in}$, i j X_i^{\dagger} $\bar{\chi}$ P_R q j $+$ $g_{\rm DM,}^{\ast}$ i j X_i \bar{q} j P_L χ $\phi_{\mathcal{X}}$ $\frac{q}{d}$, $q(d)$ Colored, appibilation, it is $\frac{q}{d}$, $\frac{1}{N}$, $1/\sqrt[3]{\bigoplus_{i=1}^{32} \bigoplus_{e \in Q_i}}$ and the same coupling for $\bigoplus_{e=1}^{4} X$ \sim $\left(\begin{array}{ccc} \sim & \sim & \sim & \sim & \sim\\ \sim & \sim & \sim & \sim & \sim & \sim \end{array}\right)$ T T T $(9 \ 1)$ $($ $\frac{1}{6}$ r and r the assumption of r of r assumption of r as r as r as r as r violation (MFV) r is r as r is r is r is we assign the mediators to flavor the mediators of t t and its description μ . χ is description of χ and χ and χ and η and χ of χ of χ of η of χ of η of χ of η $\left\langle \mathcal{D}^{\mu}\tilde{u}\right\rangle +\sqrt{\mathcal{M}^{2}_{\tilde{u}}\tilde{u}^{*}\tilde{u}+g_{DM}}\tilde{u}^{*}\right\rangle \tilde{u}^{*}}\sqrt{P_{R}u}+g_{DM}^{*}\tilde{u}\tilde{u}P_{L}\chi$ ⇤ *,* (2.3) $\frac{d}{d\mathbf{z}}\left(\frac{\partial}{\partial q}\mathbf{z}\right) - M\frac{\partial}{\partial q}\left(\frac{\partial}{\partial q}\mathbf{z}\right) + g_{DM}\left(\frac{\partial}{\partial q}\mathbf{z}\right) + g_{DM}\left(\frac{\partial}{\partial q}\mathbf{z}\right) + g_{DM}\left(\frac{\partial}{\partial q}\mathbf{z}\right)$ $\overline{1}$ $\left(\frac{d\Omega}{d\theta}\frac{dq}{d\theta}\right)$ $\left(\frac{d\Omega}{d\theta}\right)^{2}$ $\left(\frac{d\Omega}{d\theta}\right)^{2}$ $\left(\frac{d\Omega}{d\theta}\right)^{2}$ $\left(\frac{d\Omega}{d\theta}\right)^{2}$ $\left(\frac{d\Omega}{d\theta}\right)^{2}$ $\left(\frac{d\Omega}{d\theta}\right)^{2}$ $\left(\frac{d\Omega}{d\theta}\right)^{2}$ $\left(\frac{d\Omega}{d\theta}\right)^{2}$ $\left(\frac{d\Omega}{d\theta}\right)^{2}$ $\left(\frac{$

which can be constrained by flavor observables as for instance top quark flavor changing neutral currents \mathcal{A}

 \boldsymbol{M}

large corrections are expected to the cross section for scattering with nuclei. There

d

t- channel Simplified Models correspond to di↵erent values of h*v*i normalized to 10²⁶cm³*/*s*.*

$$
\langle \sigma v \rangle \simeq N_c^f g_{DM}^4 \left[\frac{m_f^2 \sqrt{1 - \frac{m_{\chi}^2}{m_{\chi}^2}}}{64\pi (m_{\tilde{q}}^2 + m_{\chi}^2 - m_f^2)^2} + \beta^2 \left\{ \frac{m_{\chi}^2 \sqrt{m_{\chi}^4 + m_{\tilde{q}}^4}}{32\pi (m_{\chi}^2 + m_{\tilde{q}}^2)^4} + \mathcal{O}(m_f^2) \right\} \right]
$$

Velocity independent part (s wave) Velocity dependent part (p wave)

velocity of the colliding DM particles (Mandelstam *s* = 4*m*²

/(1 ²)), which is

polic Density/velocity-averaged cross-section Relic Density/velocity averaged cross-section

SD(*E*))*.* (8)

 $+$ tzochannel-Simplifiedo \mathbf{Mod} els m_{χ} $(m^2 - M^2 - 3m_{\chi}^2)$ correspond to dividend the dividend to dividend to dividend the dividend to 1026cm3*/s*. T

The WIMP-nucleus reduced mass is described by *µA*. For spin independent interactions,

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f_N/m_N = \sum_{q=u,d,s} f_{Tq}(f_q) + \sum_{q=u,d,s,c,b} \frac{3}{4} [q(2) + \bar{q}(2)] (g_q^{(1)} + g_q^{(2)})
$$

$$
- \frac{8\pi}{9\alpha_s} f_{TG}(f_G) + \frac{3}{4} G(2) (g_G^{(1)} + g_G^{(2)}) .
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- \frac{8\pi}{9\alpha_s} f_{TG}(f_G) + \frac{3}{4} G(2) (g_G^{(1)} + g_G^{(2)}) .
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SD(*E*))*.* (8)

^u˜ − *m*²

$$
+ 2(m + M - m_{\chi})(m - M + m_{\chi})(m + M + m_{\chi})\{m_{\chi}^{2}(m - M - m_{\chi})(m^{2} - M^{2} - 3m_{\chi}^{2})
$$

Relic Density/velocity average

$$
- (m + M - m_{\chi})(m - M + m_{\chi})(-m + M + m_{\chi})^{2}(m + M + m_{\chi})\log(\frac{m}{M})\}
$$
 (32)

Direct Detection

$$
1 - \frac{\times}{192\pi m_{\chi}^4 (m+M-m_{\chi})^2 (m+M-m_{\chi})^2}
$$

SD(*E*))*.* (8)

The WIMP-nucleus reduced mass is described by *µA*. For spin independent interactions,

$$
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The WIMP-nucleus reduced mass is described by *µA*. For spin independent interactions,

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6 Outlook

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 $\frac{4}{\chi}(m + M - m_{\chi})^2(m - 3M \ \overline{PRN}$ KCIPLES+OR⁾²WIMP+DIRECT $\stackrel{(32)}{DETECTION}$

See K. Mohan, **DS**, T. Tait, B.Yan, C.P Yuan. JHEP 05 (2019) 115 for details \mathbf{F} and \mathbf{C} . Functioned in the section in contract in the section in the sec

t-channel Simplified Models

Precision Calculations can significantly improve constraints on the coupling (DM interaction)

Coannihilations, Radiative and Non-Perturbative Effects in Relic Density Calculation and the colored scalars *X*, *m*Pl the Planck mass, *g*⇤ (*g*⇤*S*) the number of e↵ective relativistic rurbative Effects in Relic Density Calculation **Assumptions:** \sim Committee below they are chosen into DMA in

Let's go deeper into the same model, $i=1$ think of small mass gap between DM and mediator think of small mass gap between DM and mediator

$$
\delta \equiv \frac{m_X - m_\chi}{m_\chi} \equiv \frac{\Delta m}{m_\chi}, \quad \Delta m \equiv m_X - m_\chi
$$

$$
(\beta g_s^2)^2 e^{-2x\delta} \qquad g_s^4 e^{-2x\delta} \qquad \delta = \frac{\Delta}{m_{\rm DM}}
$$

Large mass gap,

Coannihilations, Radiative and Non-Perturbative Effects in Relic Density Calculation Let's go deeper into the same model, and the colored scalars *X*, *m*Pl the Planck mass, *g*⇤ (*g*⇤*S*) the number of e↵ective relativistic rurbative Effects in Relic Density Calculation $m_X - m_\chi$ Δm **Assumptions:** $\frac{1}{2}$ **Assumptions:** \blacksquare **Coannih** I ot's go deeper into the same model **Contribution** $n = \sum_{i=1}^{n_i} \frac{n_i \sum_{i=1}^{n_i} e^{i\omega_i}}{n_i}$ $\delta = \frac{m_X - m_X}{m_X} = \frac{\Delta m}{m_X}$, $\Delta m \equiv m_X - m_X$

think of small mass gap between DM and mediator think of small mass gap between DM and mediator

g of small mass gap between DM and median to the same model,

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\frac{1}{q_i} \times \frac{1}{x_i} = \frac{1}{m_{\chi}}, \quad \Delta m = m_X - m_X
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Large mass gap,

AMPORTAPS OF COMPART OF THE PROPERTY OF THE COMPANY exclusion or discovery of dark matter models Julia Harz Importance of non-perturbative e*ects for the **3** exclusion or discovery of data matter models and discovery of days and discovery of days and discovery of days
Julia Harzogery Santa Harzogery of days and discovery of days and discovery of the same of the same of the sam only relevant processorta Small massugapye additional ecoannihilation channels become relevant

and the colored scalars *X*, *m*Pl the Planck mass, *g*⇤ (*g*⇤*S*) the number of e↵ective relativistic **Assumptions: Assumptions: Coannih** Coannihilations, Radiative and Non-Perturbative Effects in Relic Density Calculation $\frac{1}{2}$ \blacksquare I ot's go deeper into the same model **Contribution** $n = \sum_{i=1}^{n_i} \frac{n_i \sum_{i=1}^{n_i} e^{i\omega_i}}{n_i}$ $\delta = \frac{m_X - m_X}{m_X} = \frac{\Delta m}{m_X}$, $\Delta m \equiv m_X - m_X$ Let's go deeper into the same model, $m_X - m_\chi$ Δm $\delta \equiv$ $\Delta m \equiv m_X - m_\chi$ think of small mass gap between DM and mediator \equiv think of small mass gap between DM and mediator m_χ m_χ q_i V^{\dagger} and \overline{d} \overline{d} \overline{d} **Contributing processes to the relic abundance**

- q_i $g_{\rm DM}^2g_{\rm s}^2e^{-x\delta}_{2\,e^{-x\delta}g}$ $g_{\rm DM}$ **Assumptions: Large mass gap,** only relevant processorta Small massugapye additional ecoannihilation channels become relevant exclusion or disponder with models and discovery or discovery of data that is a set of data matter models and d
exclusion of data matter models and disponsible and disponsible and disponsible and disponsible and disponsibl Importances of representatives effects for the express of the dark of the dark matter models of the dark to the section of the section exclusion or discovery or discov
LIMDLIONS **Assumptions:**
- Coannihilating particle will later decay into I
- Coannihilating particle in thermal equilibrium

$$
\sum_{i=1}^{n_i} \frac{a_i}{i} \times \frac{X_i^{\dagger}}{x}
$$
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$$
\sum_{j=1}^{q_i} \frac{X_j^{\dagger}}{x}
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\sum_{j=1}^{n_i} \frac{g}{x}
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\sum_{j=1}^{n_i} \frac{g}{x}
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\sum_{j=1}^{n_i} \frac{g}{x^i e^{-2x\delta}}
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\sum_{j=1}^{n_i} \frac{g}{x^i e^{-2x\delta}}
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\sum_{j=1}^{n_i} \frac{1}{x}
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\

Two further novel effects can affect the velocity averaged cross section

Importance of non-perturbative effects for the exclusion or discovery of dark matter models Julia Harz

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$$
\frac{\alpha}{\rm rel} \bigg)^n \sim 1 \text{, which requires } \overline{\rm reg}
$$

Importance of non-perturbative effects for the exclusion or discovery of dark matter models Julia Harz

$$
\sigma_{\rm SE} = S_0 \left(\frac{\alpha_s^S C_{[\hat{\mathbf{R}}]}}{v_{\rm rel}} \right) \, \sigma_0
$$

Importance of non-perturbative effects for the exclusion or discovery of dark matter models Julia Harz

4 bound state ionisation

Importance of non-perturbative executive executive executive executive executive executive executive executive

bound state decay

4 bound state ionisation

bound state decay

Importance of non-perturbative executive executive executive executive executive executive executive executive

Impact of Sommerfeld Enhancement and bound states

perturbative only $+$ Sommerfeld effect $+$ bound states

Becker, Copello, JH, Mohan, Sengupta (2022)

- DD and LHC searches set upper bound on g_{DM}
- Requirement of non-overproduction sets lower bound on g_{DM}
	- \rightarrow Correction on g_{DM} due to SE and BSF lead to altered exclusion limits
	- **→ opens up parameter space that was previously thought to be excluded**

The package is now implemented in MicrOmegas Dark Matter Tool **M. Becker, E. Copello, J. Harz K. Mohan, DS**. JHEP08(2022) 145

1.The model tightly constrained by Direct Detection, 2. Model parameters then relaxed by SE + BSF.

t- channel Simplified Models : Bound State Production/decay at LHC at 95% C.L., which we correct by an almost flat economic flat economic flat economic flat economic flat experiments for a set of a c channel simplified widdels : bound state ridduction

 \sim 300 \sim \sqrt{r} and the binding energy as $\left|100\right.$ GeV $\approx m_{X} \approx 290$ GeV $100 \text{ GeV} \leq m \leq 290 \text{ GeV}$

Stable: Lives long enough so it can reach tracker and/or muon detectors or even get past them.

t- channel Simplified Models : HSCP searches t-channel Simplified Models : HSCP searche

• **Heavy**: Implies slow particles, β < 1.0

• **Charged**: Can be detected by the muon detectors.

★ The massive colored mediator X travels the detector producing an ionishizing track freeze-in models TUTT ,

 \bigstar Tf it decave outside the detector time of flight measu \star If it decays outside the detector, time of flight measured using hits in muon chamber is large.

Fraction of charged hadrons depend on hadronization model: typically use a cloud hadronization model. (Mackperang, Rizza: hep-ph/0612161, Kraan, hep-ex/0404001

t- channel Simplified Models : HSCP searches Searches of HSCP and ϵ the channel simplified Models \cdot HSCP searches

Searches for Heavy Stable Charged Particles at the LHC Past, Present and Future, Loïc Quertenmont. 12 February 2015 $\overline{}$ ϵ an internation for the characteristic provider ϵ and ϵ and ϵ in ϵ in ϵ Use two CMS analysis for reinterpretation using cross-section upper limits

- noted there, here, high-luminosity $\frac{1}{2}$ is the fact complete co 1. CMS : Search for LLP in pp collisions : JHEP 07 (2013) 122
- 2. CMS : Search for heavy stable charged particles CMS-PAS-EXO-16-036

Typicaly Tracker+TOF analysis is more constraining, requires HSCP decays outside the detector $\sigma_{\text{eff}} = \sigma \times f_{\text{LLP}}(L, \tau)$ The detector (tracker +TOF) : Computed using trigger and selection efficiencies (CMS: EPJC 75 (325))

t- channel Simplified Models: Combined limits

t- channel Simplified Models: Combined limits

 c_1 and c_2 non-thermal mechanisms, such as conversion-driven freeze-in. Such as conversion-driven freeze-in. The such as conversion-driven freeze-in. The such as conversion-driven freeze-in. The such as conversion-dr $T_{\rm t}$ regions are matches in orange. F Conello J Harz K Mohan DS JHFPO8(2022) 145 limits from spin-independent DD (spin-dependent DD, colliders, unitarity, stoponium searches) are M. Becker, E. Copello, J. Harz K. Mohan, **DS**. JHEP08(2022) 145

t- channel Simplified Models : Future projection

t- channel Simplified Models : Future projection

inder D. Harz K. Mohan, **D. J.** J. H. E. 2020, 145.
Illo. J. Harz K. Mohan, **D.S.** J. H. E. P. 2020, 145. searches, LLP searches), it is colored in green (magenta, blue, black, cyan, orange). We show the M. Becker, E. Copello, J. Harz K. Mohan, **DS**. JHEP08(2022) 145

t- channel Simplified Models : Current and future projections

t- channel Simplified Models : Current and future projections

M. Becker, E. Copello, J. Harz K. Mohan, **DS**. JHEP08(2022) 145

-in: deneral idea araman \overline{a} and \overline{a} are \overline{a} Freeze-in: general idea

Tweaked from arXiv:0911.1120

Alternative Mechanisms of Dark Ma Alternative Mechanisms of Dark Matter Production

arXiv:0911.1120 arXiv:hep-ph/0106249 arX iv:17.6.07 \pm . $\begin{array}{c} \n\text{arrayiv:} \n0.111120 \\
\text{arrayiv:} 176071.7\n\end{array}$

Cosmological Probes of SuperWIMP Dark Matter

- In Supergravity inspired Supersymmetry scenarios, the gravitino can be the lightest particle, and very very weakly coupled to the neutralino, leading to a long lived neutralino (decaying to a gravitino + a Photon).
- The neutralino (a WIMP) can Freeze-out, and long afterwards decay to gravitino (**SuperWIMP**).
- Being extremely long lived it will escape the detector without a trace (No prompt searches).
- However it will leave definite signatures in Cosmology due to energy dump as photon.

The gravitino mass is a free parameter related to the SUSY breaking scale F Feng, Rajaraman, Takayama hep-ph/0306204

What if Neutralinos are not the Lightest SUSY particle, but next to lightest?

Cosmological Probes of SuperWIMP Dark Matter $\sum_{n=1}^{\infty}$ of $\sum_{n=1}^{\infty}$ WIIMD $\sum_{n=1}^{\infty}$ Motton a topes of Super W LIVER Daik Iviaties

What if Neutralinos are not the Lightest SUSY particle, but next to lightest?

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The gravitino mass is a free parameter related to the SUSY breaking scale F $\overline{}$

$$
m_{\tilde{G}} \simeq \langle F \rangle / m_{\rm pl} \qquad \text{Extremely long lived} \qquad L = c\tau \simeq 2.8 \times 10^{22} \Bigg(
$$

 $\frac{1}{2}$ ompt searches).

Cosmological Probes of SuperWIMP Dark Matter $\sum_{n=1}^{\infty}$ of $\sum_{n=1}^{\infty}$ WIIMD $\sum_{n=1}^{\infty}$ Motton a topes of Super W LIVER Daik Iviaties

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The Lyl data from the Lyl data from th

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• Being extremely long lived it will escape the detector without a trace (No prompt searches). $\frac{1}{2}$ ompt searches*)*.
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\boxed{m_{\tilde{G}} \ \simeq \ \langle F \rangle / m_{\rm pl} \quad \text{Extremely long lived} \quad L = c \tau \simeq 2.8 \times 10^{22} \left(\frac{\text{GeV}}{m_{\chi_1^0}}\right)^3 \frac{(1-2\epsilon_{SM})}{\epsilon_{SM}^3 (1+3(1-2\epsilon_{SM}))} m} \quad \boxed{\epsilon_{\rm SM} \equiv \frac{E_\gamma}{m_{\chi_1^0}} = \frac{m_{\chi_1^0}^2 - m_{\tilde{G}}^2}{2 m_{\chi_1^0}^2}}
$$

 k_{max} $\sum_{i=1}^{n}$ nuclei and change primordial element abundances delgy can photodissociate 1. Big Bang Nucleosynthesis: Injected photons/energy can photodissociate

The gravitino mass is a free parameter related to the SUSY breaking scale F $\overline{}$ rajai Feng, Rajaraman, Takayama hep-ph/0306204

suppressed, we do not expect them to be eciently pro-2. **CMB Spectral Distortion**: If the lifetime is about 10⁶⁻10¹³ s can distort the CMB blackbody energy spectrum

3. CMB Anisotropies: Temperature and polarization anistotropies due to changes in accoustic peaks of CMB angular spectra 3. CMB Anisotropies: Temperature and polarization anistotropies due to changes in

straints from I 4. **CONSTANTS POINT**
leads to a non-zero velod small scale fluctuations 4. Constraints from Lyman-alpha forest: A relativistic component of the SuperWIMP leads to a non-zero velocity dispersion, hence a large free streaming scale and suppression of

\mathbf{C} experiments are sensitive to length scales of length scales

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t- channel Simplified Models : Constraints on gravitino Superwimps

the free mechanism given collider collider constraints on the neutralino constraints we do not how the neutralino constraints we do not how the neutralino constraints we do not how the neutralino constraints M . Deshibit constraint, since any one of non-thermal production mechanism, late entropy injection, or modified cosmological histories could $\mathcal{L}(\mathbf{r}, \mathbf{r})$. The hatched region indicates where a neutralino abundance the Universe intervals in the context of the context of \mathbf{r} M. Deshpande, J. Hamman, DS, M. White, A.G Williams, YY Wong [2309.05709](https://arxiv.org/abs/2309.05709) , EPJC XXX

t- channel Simplified Models : Constraints on axino Superwimps

DARK MATTER VIA *t*-CHANNEL PRODUCTION COSMOLOGY SECTION

A PREPRINT

LHC Dark Matter Working Group

This work is a submission to SciPost Physics Lecture Notes.

t- channel Simplified Models: Recommendations and benchmarks Convention Consequential

S SY

- CalRatio Displaced Jets
	- ^o 13 TeV ATLAS Displaced Jets in the calorimeter
- <u>Emerging Jets</u>
- Heavy Stable Charged Particles
- o 13 TeV ATLAS HSCP 139/fb
- o 13 TeV ATLAS HSCP 31.6/fb
- o 8 TeV CMS HSCP
- Disappearing Tracks

Andre Lessa's Github repo ⁸⁶ Note that the results in the left panel of Fig. 1 were obtained for the case of a right-handed \int

We need more recast codes implemented, for which **SPOSSO REPORTS REPORTS COMMUNITY REPORTS AND AN INTERNATIONAL COMMUNITY REPORTS OF A SUBMISSION COMMUNITY REPORTS**

We need help and resources from our experimental collleagues

Readme Activity

Running the Recasting Code

A README file can be found inside each folder with the required dependencies and basic instructions on how to run the recasting codes. top-philic scalar mediator and Majorana DM (S3M_tR). However, as long as *m mt* ⁸⁷ , the ⁸⁶ Note that the results in the left panel of Fig. 1 were obtained for the case of a right-handed

⁸⁸ results of other S3M_uR is exactly the same. Furthermore, we expect results for any other

t- channel Simplified Models : Recommendations and benchmarks **SciPost Physics Community Reports Submission**

Figure 1: Valid parameter space in the non-thermalized DM (considering a top-philic

Conclusions

※ Simplified models provide a robust pathway to analyze theoretical and experimental Constraints that map to constraints on full-models.

- $\%$ t-channel DM models provide a rich phenomenology, with complementary constraints from a variety of signatures
- **3. LLP searches form a crucial component in closing the gap between freeze-out and non**thermal mechanisms of dark matter in t-channel.
- **※ Needed: Experiment-theory collaborations, more recast/reinterpretation codes**

International Joint Workshop on the Standard Model and Beyond 2024 & 3rd Gordon Godfrey Workshop on Astroparticle Physics