



Effective Theory of Freeze-in Dark Matter

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Cosmology from Home, 2020



Plan of talk

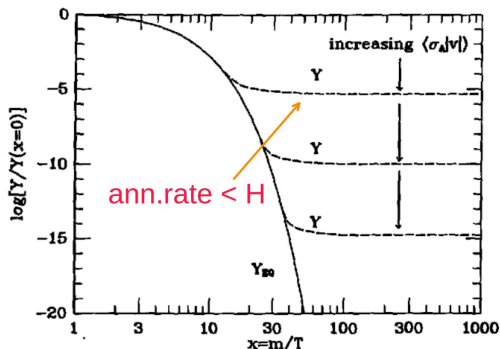
- ▶ The WIMP paradigm & its drawback
- ▶ Freeze-in: a possible alternative
- ▶ DM in EFT framework.
- ▶ Effective theory DM freeze-in (based on **arxiv: 2007.08768**)
 - Relevant operators
 - DM yield: annihilation & decay channels
 - Comparison with scale of neutrino mass generation
 - DM from radiative inflaton decay
- ▶ Concluding remarks



The Canonical story of Dark Matter

The standard lore:

- ▶ DM in thermal equilibrium with SM at $T \gg m_{\text{DM}}$.
- ▶ As T falls below $m_{\text{DM}} \Rightarrow n_{\text{DM}} \sim \exp(-m_{\text{DM}}/T)$.
- ▶ Before $n_{\text{DM}} \rightarrow 0$, DM is rescued by 'freeze-out' $\Gamma < H$.
- ▶ $\rho_{\text{DM}} \sim a^{-3}$, eventually dominating over radiation.



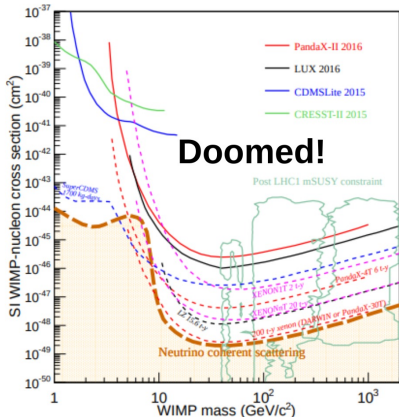
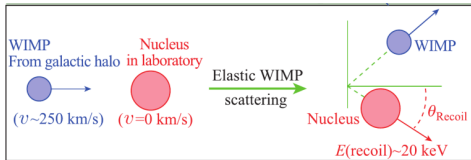
$$Y_{\text{DM}} = n_{\text{DM}}/s, \quad x = m_{\text{DM}}/T$$

WIMP miracle

a new particle with weak-scale interaction can account for DM density in the universe!



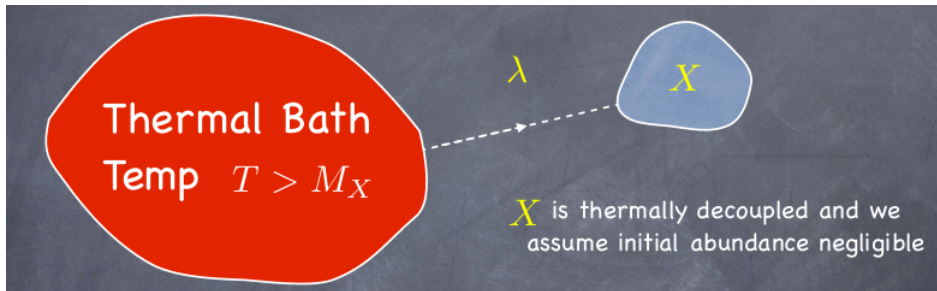
Direct Search: The Grim Reaper (Image:1709.00688,1611.06553,Zhao Yu talk)



- ▶ Canonical WIMP scenario is getting cornered by DD.
- ▶ No significant excess @ colliders \sim TeV scale.
- ▶ A possible alternative:
 - ▶ avoid thermal eq. with SM by extremely tiny DM-SM coupling \rightarrow **Freeze-in.**
- ▶ Also: WIMPZillas ([hep-ph/9810361](https://arxiv.org/abs/hep-ph/9810361)), SIMP ([1402.5143](https://arxiv.org/abs/1402.5143)), ELDER ([1706.05381](https://arxiv.org/abs/1706.05381))...

FIMPs

Image: Talk by Stephen West



- ▶ DM-SM coupling $\mathcal{O}(10^{-10}) \implies$ DM can not freeze-‘out’.
- ▶ Initial DM abundance $\rightarrow 0$ (by inflation or other mechanism).
- ▶ Produced via bath-particle annihilation/decay.
- ▶ Two classes: IR (Hall et.al.1402.5143) & UV (Elahi et.al.1410.6157).

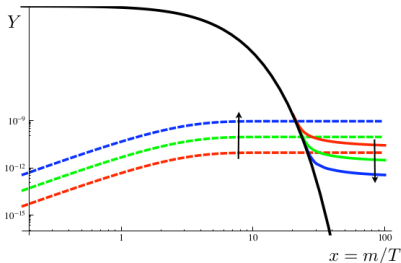


IR freeze-in (Image: 1706.07442)

- DM couples to SM via renormalizable coupling:

$$\underbrace{\lambda X B_1 B_2}_{B_1 \rightarrow B_2, X}, \quad \underbrace{\lambda X B_1 B_2 B_3}_{B_1, B_2 \rightarrow B_3, X}$$

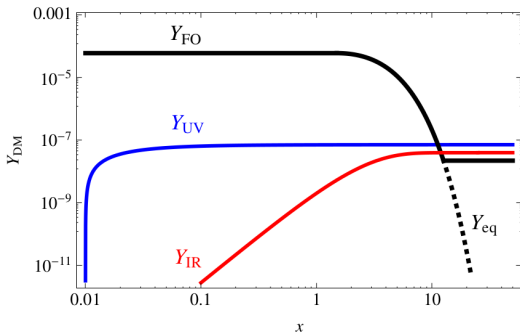
- $\lambda \sim \mathcal{O}(10^{-10})$ gives right abundance avoiding thermal eq.
- $Y_{\text{DM}} \sim \lambda^2 \frac{M_{\text{pl}}}{T} \implies$ IR dominated process favoring low T .
- Dominant production at $T \sim m$, lower temp. $\sim \exp(-m/T)$.
- Caveat: Unnaturally small coupling.





UV freeze-in (Image:1410.6157)

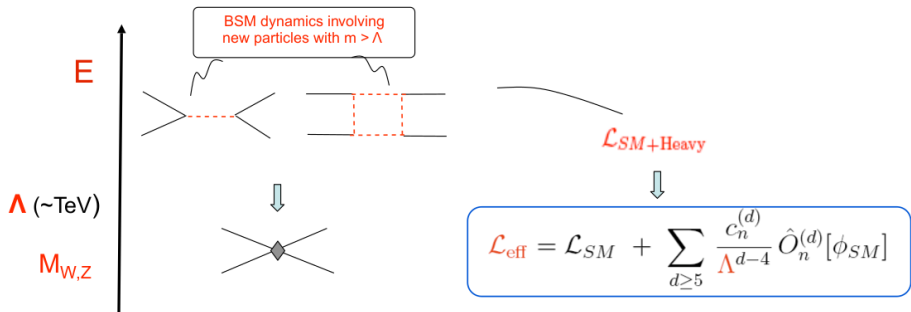
- Dark sector $\xrightarrow{\propto \frac{1}{\Lambda^n}}$ visible sector.
- Small coupling is natural when Λ is very large.
- $Y_{DM} \propto \frac{M_{pl} T^{2n-1}}{\Lambda^{2n}}$ if $T_{RH} \gg m_i$.
- DM production dominated at highest T i.e., $T = T_{RH}$.
- DM freezes in immediately.





General BSM EFT (Image: Talk by Vincenzo Cirigliano)

- Assume existence of new particles with $M \gg E_{\text{weak}}$.
- “Integrate out” these particles: describe dynamics below $\Lambda \sim$ mass of new particle via \mathcal{L}_{eff} .
- Simplest approach to combine different expts.





DM in EFT framework

Effective DM-SM int.

top-down:

- The high energy theory containing a DM and a prescription how the DM couples to SM is known.
- 'Systematically' eliminate DOF with energies $\gtrsim E_{\text{ref}}$.
- Obtain the low energy theory with fewer parameters.

Bottom-up:

- The fundamental high-energy theory is not known.
- $\mathcal{L} \supset \Lambda^{-n} \mathcal{O}_{\text{DM}} \mathcal{O}_{\text{SM}}$.
- $\mathcal{O}_{\text{SM(DM)}}$ need not to be Lorentz singlet.
- $\mathcal{G}_{\text{DM}} \times \mathcal{G}_{\text{SM}}$ invariant.
- Simplest case: $\mathcal{G}_{\text{DM}} \in Z_2$.
- Exhaustively applied in WIMP paradigm:

0808.3384,1003.1912,1008.1783,

1308.6799,1404.2283,1707.00725...



DM in EFT framework

- The DM χ is a singlet Majorana fermion (no tree-level coupling with SM):

$$\mathcal{L}_{\text{DM}} = i\bar{\chi}^c \not{\partial} \chi - M_\chi \bar{\chi}^c \chi$$

- Z_2 : SM \rightarrow SM, $\chi \rightarrow -\chi$.
- Vector current $\bar{\chi}\gamma^\mu\chi$ and dipole moments $\bar{\chi}\sigma^{\mu\nu}\chi$, $\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi$ identically vanish.
- Only scalar, pseudoscalar and axial vector DM bilinears survive.
- Operators are in the basis of unbroken electroweak phase.
- All our ignorances dumped into Λ .
- For simplicity we *only* consider scalar ops. for DM analysis.
- $\Lambda \gtrsim \frac{M_\chi}{2\pi}, T_{\text{RH}}$.



Relevant operators (with DB & RR arxiv: 2007.08768)

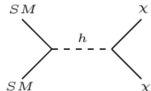
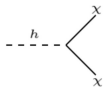
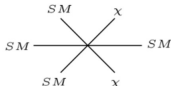
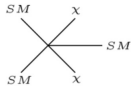
- $\bar{\chi}\Gamma^\mu (1, \gamma^5, \gamma^\mu\gamma^5) \chi$ itself makes up dim.3.
- 13 dim.4, 1 dim.5, 63 dim.6 & 20 dim.7 ops. invariant under SM (1008.4884, 1410.4193).
- We consider DM-SM scalar gauge invariant ops. up to and including dim.8. $\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_{d>4}$.

DM bilinear (dim.3)	Λ^{-1}	Λ^{-2}	Λ^{-3}	Λ^{-4}
$\bar{\chi}^c \chi,$ $\bar{\chi}^c i\gamma^5 \chi$	$H^\dagger H$		$X_{\mu\nu} X^{\mu\nu}, X_{\mu\nu} \widetilde{X}^{\mu\nu}$ $ H^\dagger H ^2$ $ \mathcal{D}_\mu H ^2$ $i\bar{L}\not{\partial}L, i\bar{R}\not{\partial}R$ $\bar{L}HR, \bar{L}\tilde{H}R$	$(\bar{\ell}_L \tilde{H}) (\bar{\ell}_L \tilde{H})$
$\bar{\chi}^c \gamma^\mu \gamma^5 \chi$		$\bar{L}(R)\gamma_\mu L(R)$ $iH^\dagger \mathcal{D}_\mu H$		$\bar{L}(R)\gamma_\mu L(R) (H^\dagger H)$ $iH^\dagger \mathcal{D}_\mu H (H^\dagger H)$



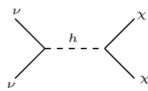
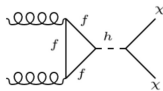
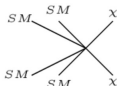
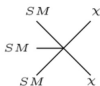
Annihilation & decay channels

- $T > T_{EW}$: $2 \rightarrow 2, 3 \rightarrow 2(2 \rightarrow 3), 4 \rightarrow 2(2 \rightarrow 4)$ channels (massless SM) \implies UV.
- Boltzmann Eqs. with many-body initial/final states.
- $T < T_{EW}$: $1 \rightarrow 2, 2 \rightarrow 2$ channels (massive SM) \implies UV+IR.



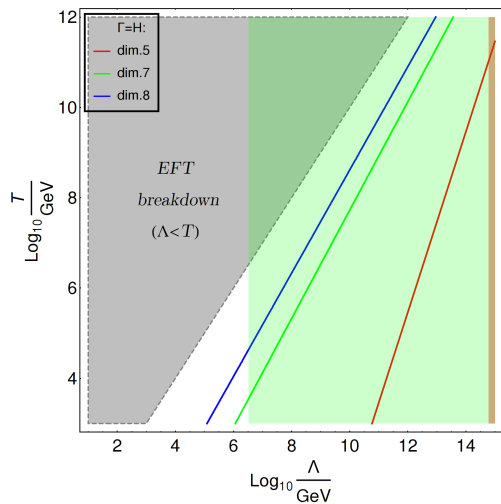
Before EWSB

After EWSB





Out of equilibrium Cond.



$$\mathcal{R} = \frac{\Gamma_{n \rightarrow m}}{H} \leq 1$$

Reaction rate:

$$\Gamma_{n \rightarrow m} = \begin{cases} n_{\text{SM}}^{n-1} \langle \sigma v \rangle_{n \rightarrow m} \\ \Gamma_{\text{decay}} \end{cases}$$

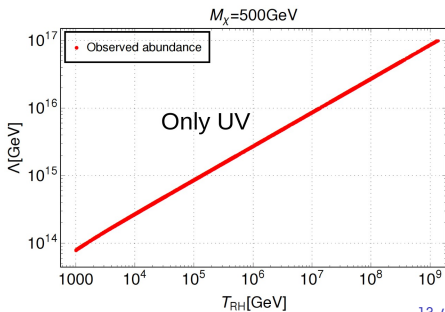
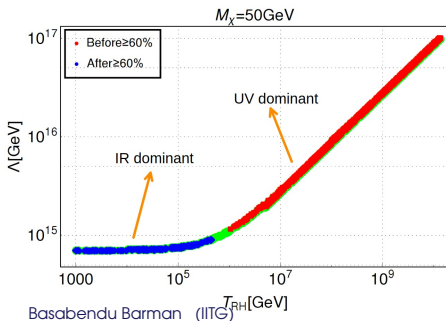
density of SM particles:

$$n_{\text{SM}} = \begin{cases} g_{\text{SM}}(T) \frac{3}{4} \frac{\zeta(3)}{\pi^2} T^3 \\ g_{\text{SM}}(T) \left(\frac{m_{\text{SM}} T}{2\pi} \right)^{3/2} e^{-m_{\text{SM}}/T} \end{cases}$$



Parameter space: $\{M_{\text{DM}}, \Lambda, T_{\text{RH}}\}$

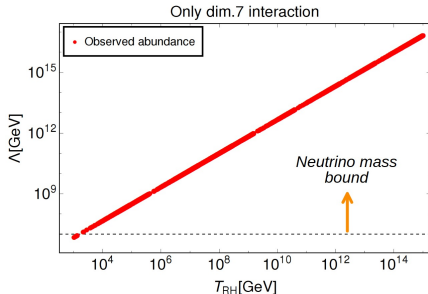
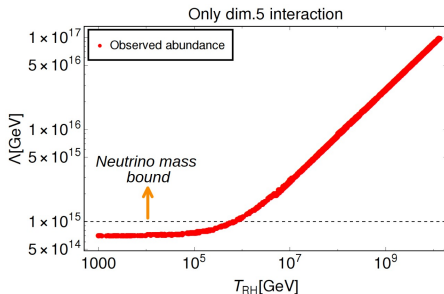
- $\underbrace{4.7 \text{ MeV}}_{\text{BBN (1511.00672)}} \lesssim T_{\text{RH}} \lesssim \underbrace{10^{10} \text{ GeV}}_{\text{gravitino production (PLB,303 (1993)289-294)}}$
- $$Y_\chi \sim \underbrace{\int_{T_{\text{EW}}}^{T_{\text{RH}}} |\mathcal{M}_{n \rightarrow m}|^2}_{\text{before EWSB}} + \underbrace{\int_{T_0}^{T_{\text{EW}}} |\mathcal{M}_{1 \rightarrow 2, 2 \rightarrow 2}|^2}_{\text{after EWSB}} \implies \Omega_X^{\text{PLANCK}} \sim M_\chi Y_\chi(T_0)$$
- $T_{\text{RH}} > T_{\text{EW}} \implies$ yield after EWSB is small.
- dim.5 interactions always dominate.





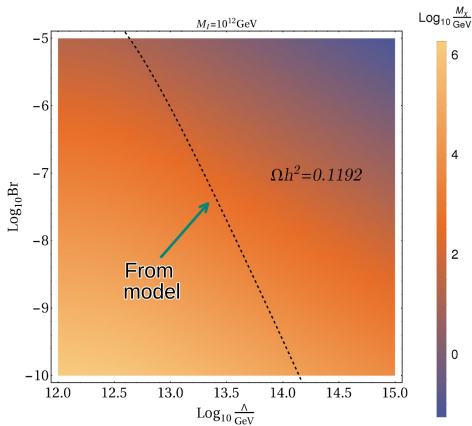
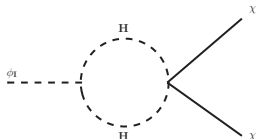
Connection with neutrino mass scale

- $\frac{(LH)(LH)}{\Lambda_\nu} (\Delta L = 2) \rightarrow m_\nu \sim \frac{v_h^2}{\Lambda_\nu} \implies \Lambda_\nu \gtrsim 10^{14} \text{ GeV}.$
- $\frac{(LH)(LH)(H^\dagger H)}{\Lambda_\nu^3} (\Delta L = 2) \rightarrow m_\nu \sim \frac{v_h^4}{\Lambda_\nu^3} \implies \Lambda_\nu \gtrsim 10^6 \text{ GeV}.$
- DM-SM ops. of same dim. can produce right relic.





DM from inflaton decay



- No direct inflaton-DM coupling.

- Inflaton decay via 1-loop can produce DM

(1709.01549, 1901.04449, 2004.08404).

- $\Omega_\chi h^2 = M_\chi \times \text{Br} \times (T_{\text{RH}}/M_I)$ with

$$\text{Br} = \frac{\Gamma_{\phi_I}^{\text{loop}}}{\Gamma_{\phi_I \rightarrow hh} + \Gamma_{\phi_I \rightarrow ff} + \Gamma_{\phi_I}^{\text{loop}}}$$

- Small branching to avoid over abundance.
- Can account for total DM abundance for lower Λ .



Conclusion

- ▶ We provide the simplest possible operators connecting DM and SM relevant for freeze-in scenario up to and including dim.8.
- ▶ $\{\Lambda, T_{RH}\}$ can be simultaneously constrained from DM relic and neutrino mass generation from operators of the same dim.
- ▶ Connection to neutrino mass can be made more profound in a UV-complete set-up.
- ▶ It is also possible to obtain right DM relic from inflaton decay even in the absence of DM-inflaton coupling.
- ▶ Detectability of (UV) freeze-in models & connection to certain inflationary scenarios could be interesting to explore.



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Thank you!

Questions/comments/critique?



Backup Slides



Scalar kinetic term

Before EWSB:

$$|\mathcal{D}_\mu H|^2 \supset \left(\partial_\mu \phi^+ \partial^\mu \phi^- + \partial_\mu \phi^0 \partial^\mu \overline{\phi^0} \right) + \frac{g_1^2}{4} B_\mu B^\mu \left(\phi^+ \phi^- + \phi^0 \overline{\phi^0} \right) \\ + \frac{g_2^2}{4} \sum_{i=1,2,3} W_{i\mu} W^{i\mu} \left(\phi^+ \phi^- + \phi^0 \overline{\phi^0} \right).$$

After EWSB:

$$|\mathcal{D}_\mu H|^2 \supset \frac{1}{2} \partial_\mu h \partial^\mu h + (h + v_h)^2 \left\{ \frac{g_2^2}{4} W_\mu^+ W^{-\mu} + \frac{g_2^2}{8c_w^2} Z_\mu Z^\mu \right\}.$$



BEQ for $3 \rightarrow 2$ process

$$\begin{aligned}
 n_{\chi} + 3Hn_{\chi} &= \int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 d\Pi_5 |\overline{\mathcal{M}}|_{123 \rightarrow 45}^2 (2\pi)^4 \delta^4(p_f - p_i) \prod_{i=1}^3 f_i \\
 &= \int d\text{LIPS}_3 d\Pi_4 d\Pi_5 |\overline{\mathcal{M}}|_{123 \rightarrow 45}^2 f_1 f_2 f_3,
 \end{aligned}$$

$$d\text{LIPS}_2 = d^3 p_4 d^3 p_5 = (4\pi |\vec{p}_4|) (4\pi |\vec{p}_5|) \frac{1}{2} d \cos \theta.$$

Change variables [Nucl.Phys.B 360 \(1991\) 145-179](#):

$$E_+ = E_4 + E_5, E_- = E_4 - E_5, s = 2M_{\chi}^2 + 2E_4 E_5 - 2|\vec{p}_4| |\vec{p}_5| \cos \theta:$$

$$\int d\Pi_4 d\Pi_5 = \int \frac{1}{(2\pi)^4} \frac{\sqrt{E_+^2 - s}}{4} \sqrt{1 - \frac{4M_{\chi}^2}{s}} dE_+ ds,$$



Continued...

$$\dot{n}_\chi + 3Hn_\chi = \frac{T}{(2\pi)^4} \int_{4M_\chi^2}^{\infty} ds \frac{\sqrt{s}}{4} \sqrt{1 - \frac{4M_\chi^2}{s}} |\mathcal{M}|_{123 \rightarrow 45}^2 K_1 \left(\frac{\sqrt{s}}{T} \right) d\text{LIPS}_3$$

as $E_1 + E_2 + E_3 = E_4 + E_5$.

Performing all the integrals for overall rotations:

$$\int d\text{LIPS}_3 = \int \frac{ds_{23}}{2\pi} \frac{1}{8\pi} \left(1 - \frac{s_{23}}{s} \right) \frac{d \cos \theta_{23}}{2} \frac{1}{8\pi},$$

where

$$x_1 = 1 - \frac{s_{23}}{s}$$

$$x_2 = \frac{1}{2} (2 - x_1 + x_1 \cos \theta_{23}),$$

$$E_1 = x_1 \frac{\sqrt{s}}{2}, \quad E_2 = x_2 \frac{\sqrt{s}}{2},$$

$$E_3 = \frac{\sqrt{s}}{2} (2 - x_1 - x_2).$$



BEQ for $4 \rightarrow 2$ process

$$\begin{aligned} \dot{n}_\chi + 3Hn_\chi &= \int \prod_{i=1}^6 d\Pi_i |\overline{\mathcal{M}}|_{1234 \rightarrow 56}^2 (2\pi)^4 \delta^4(p_f - p_i) \prod_{i=1}^4 f_i \\ &= \int d\text{LIPS}_4 d\Pi_5 d\Pi_6 |\overline{\mathcal{M}}|_{1234 \rightarrow 56}^2 f_1 f_2 f_3 f_4, \end{aligned}$$

Use energy conservation:

$$\dot{n}_\chi + 3Hn_\chi = \frac{T}{(2\pi)^4} \int_{4M_\chi^2}^{\infty} ds \frac{\sqrt{s}}{4} \sqrt{1 - \frac{4M_\chi^2}{s}} |\overline{\mathcal{M}}|_{1234 \rightarrow 56}^2 K_1 \left(\frac{\sqrt{s}}{T} \right) d\text{LIPS}_4,$$

Continued...

For massless initial states:

$$\int d\text{LIPS}_4 = \frac{1}{4\pi^2(8\pi)^3} \int_0^{\sqrt{s}} ds_{12} \int_0^{(\sqrt{s}-\sqrt{s_{12}})^2} ds_{34} \sqrt{1 + \frac{s_{12}^2}{s^2} - \frac{2s_{12}s_{34}}{s^2} + \frac{s_{34}^2}{s^2} - \frac{2s_{12}}{s} - \frac{2s_{34}}{s}} \int \frac{d\cos\theta_{12}}{2} \int \frac{d\cos\theta_{34}}{2}.$$

BEQ in terms of yield:

$$\frac{dY_{\chi}^{4 \rightarrow 2}}{dT} \simeq -\frac{1}{s(T) \cdot H(T)} \frac{1}{64(2\pi)^9} \int_{4M_{\chi}^2}^{\infty} ds \sqrt{s} \sqrt{1 - \frac{4M_{\chi}^2}{s}} |\overline{\mathcal{M}}|_{1234 \rightarrow 56}^2 K_1\left(\frac{\sqrt{s}}{T}\right) \int_0^{\sqrt{s}} ds_{12} \int_0^{(\sqrt{s}-\sqrt{s_{12}})^2} ds_{34} \sqrt{1 + \frac{s_{12}^2}{s^2} - \frac{2s_{12}s_{34}}{s^2} + \frac{s_{34}^2}{s^2} - \frac{2s_{12}}{s} - \frac{2s_{34}}{s}} \int \frac{d\cos\theta_{12}}{2} \int \frac{d\cos\theta_{34}}{2},$$