Dark Matter Co-annihilating with a Top/Bottom Partner with effects of bound states

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with Ian Low, and Yue Zhang

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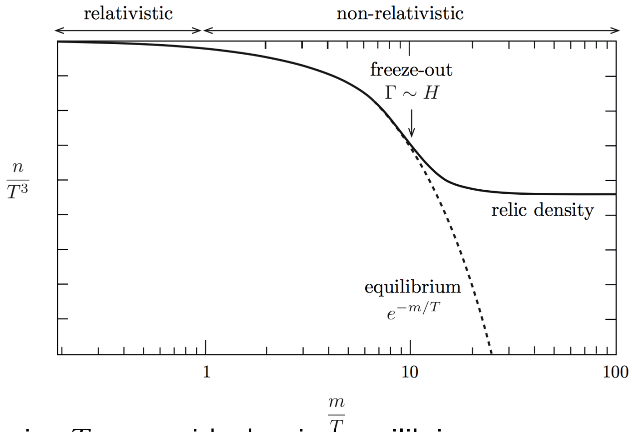
Background on DM annihilation and decoupling



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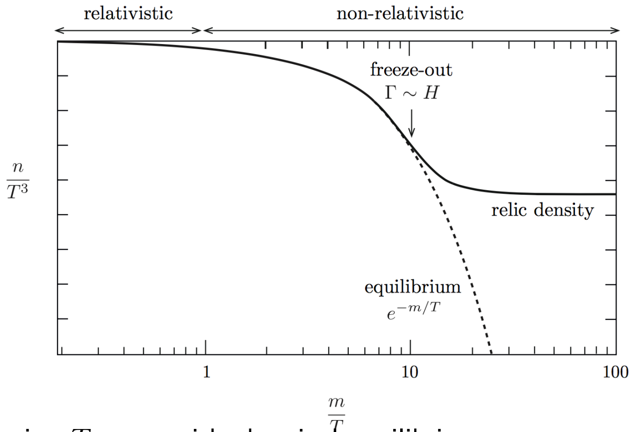

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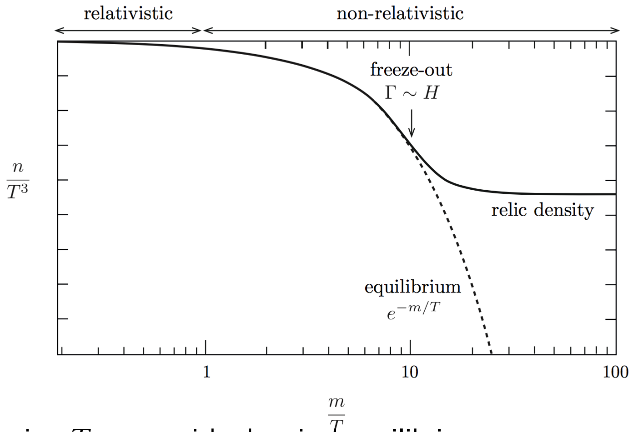

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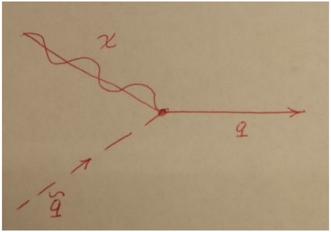

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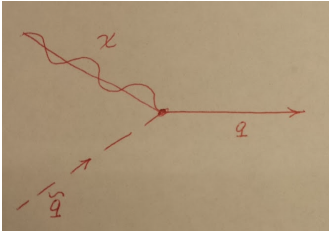

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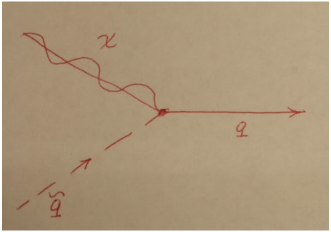

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- Parameter space: $m_\chi = 100$ GeV$\sim$1 TeV,
  $m_{\tilde{q}} - m_\chi < 100$ GeV.

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- In the cases we study, there is a tree level coupling between X, Y and a third generation SM quark, denoted by q.
- Furthermore, the bound states (onia) formed by co-annihilation partners Y and $\bar{Y}$ is denoted by B.

Physics added

- Sommerfeld effect [Hisano *et al.*, Cirelli *et al.*] ($\sqrt{s} > 2m_Y$) in the annihilation of the colored co-annihilating partner pair $Y\bar{Y}$, whose wavefunction at the origin is strongly distorted due to the gluon exchange between the two initial particles. $e.g.\ \tilde{q}\tilde{q}^*$.

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- $XX \to$ SM and YY to SM included

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- Bound state B radiative capture and dissociation (labelled by $B \leftrightarrow Y$): $Y\bar{Y} \leftrightarrow Bg$

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  s is the entropy density in the universe.
- $z \equiv m_X/T$ with Boltzmann distribution for calculating the thermal number densities. T is the temperature of the universe.

$$\gamma = \int d\Phi_i d\Phi_f (2\pi)^4 \delta^4(\Sigma p) |\mathcal{M}(i \leftrightarrow f)|^2 e^{-(E_i)/T}$$

Coupled Boltzmann equations involving X, Y, B

$$
\begin{aligned}
sHz\frac{d\mathcal{Y}_X}{dz} &= -\gamma_{XX}\left[\left(\frac{\mathcal{Y}_X}{\mathcal{Y}_X^{eq}}\right)^2 - 1\right] - 2\gamma_{XY}\left[\frac{\mathcal{Y}_X}{\mathcal{Y}_X^{eq}}\frac{\mathcal{Y}_Y}{\mathcal{Y}_Y^{eq}} - 1\right] \\
&\quad -2\gamma_{X\leftrightarrow Y}\left[\frac{\mathcal{Y}_X}{\mathcal{Y}_X^{eq}} - \frac{\mathcal{Y}_Y}{\mathcal{Y}_Y^{eq}}\right] - 2\gamma_{B\leftrightarrow X}\left[\left(\frac{\mathcal{Y}_X}{\mathcal{Y}_X^{eq}}\right)^2 - \frac{\mathcal{Y}_B}{\mathcal{Y}_B^{eq}}\right],
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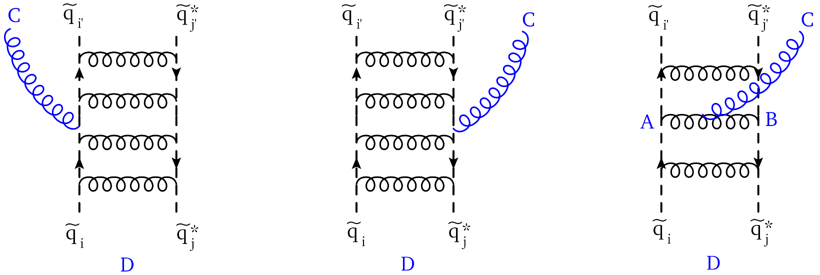
$$\sigma_{\tilde{t}\tilde{t}^* \leftrightarrow gg} v_{rel} \to \left(\frac{2}{7}\mathcal{S}_1 + \frac{5}{7}\mathcal{S}_8\right) \times \left(\sigma_{\tilde{t}\tilde{t}^* \leftrightarrow gg} v_{rel}\right)\Big|_{v_{rel}\to 0}$$

$$\sigma_{\tilde{t}\tilde{t}^* \leftrightarrow \bar{q}q} v_{rel} \to \mathcal{S}_1 \left(\sigma_{\tilde{t}\tilde{t}^* \leftrightarrow (h^*) \leftrightarrow \bar{q}q} v_{rel}\right)\Big|_{v_{rel}\to 0} + \mathcal{S}_8 \left(\sigma_{\tilde{t}\tilde{t}^* \leftrightarrow (g^*) \leftrightarrow \bar{q}q} v_{rel}\right)\Big|_{v_{rel}\to 0}$$

QM, Krammer extended



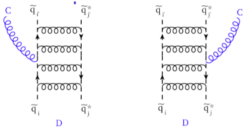
$$(\sigma v_{\rm rel})^{n,\ell}_{Y\bar{Y}\to Bg} = \frac{4\alpha_D}{81\pi}\omega_n \left[\ell \left|\int drr^3\left(\omega_n - \Delta V\right) R_{n\ell}R_{k\ell-1}\right|^2 \right.$$

$$\left. +(\ell+1)\left|\int drr^3\left(\omega_n - \Delta V\right) R_{n\ell}R_{k\ell+1}\right|^2\right]$$

$$\omega_n = E_n + k^2/(2\mu),\ \Delta V(r) = \Delta V_1(r) + \Delta V_2(r),$$

$$\Delta V_1(r) = \frac{4\alpha_S^{(f)}}{3r} + \frac{\alpha_S^{(i)}}{6r}\ ,\ \Delta V_2(r) = \frac{3\alpha_S^{(f)}}{2r}\ .$$

More on Dipole Transition



$$H_{int}^{(1)} = \frac{g_S T_{i'i}^C \delta_{j'j}}{m_Y} \vec{k} \cdot \vec{G}^C(\vec{r}/2) + \frac{g_S \delta_{i'i} T_{j'j}^C}{m_Y} \vec{k} \cdot \vec{G}^C(-\vec{r}/2)$$

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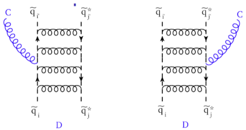

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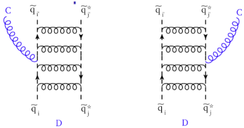

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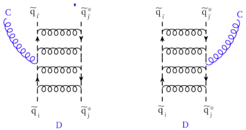
$$\vec{k} = -i\mu[\vec{r}, \mathsf{KE}] = -i\mu\left(\vec{r} H_8 - H_1 \vec{r} - \Delta V_1(r) \vec{r}\right)$$

More on Dipole Transition



$$H_{int}^{(1)} = \frac{g_S T^C_{i'i}\delta_{j'j}}{m_Y}\vec{k}\cdot\vec{G}^C(\vec{r}/2) + \frac{g_S \delta_{i'i}T^C_{j'j}}{m_Y}\vec{k}\cdot\vec{G}^C(-\vec{r}/2)$$

$$\mathcal{V}_{fi}^{(1)} = \frac{\delta^{CD}}{\sqrt{6}}\frac{g_S}{\mu}\langle\Psi_f|\vec{k}|\Psi_i\rangle\cdot\vec{\varepsilon}^{\,C}_\lambda$$

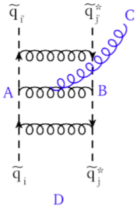
$$\vec{k} = -i\mu[\vec{r},\mathsf{KE}] = -i\mu\left(\vec{r}H_8 - H_1\vec{r} - \Delta V_1(r)\vec{r}\right)$$

$\hat{H}_1 = \vec{k}^2/(2\mu) - 4\alpha_s^{(f)}/(3r)$, and $\hat{H}_8 = \vec{k}^2/(2\mu) + \alpha_s^{(i)}/(6r)$.

$$\mathcal{V}_{fi}^{(1)} = \frac{\delta^{CD}}{\sqrt{6}}(-ig_S)\langle\Psi_f|\left(E_i - E_f - \Delta V_1(r)\right)\vec{r}|\Psi_i\rangle\cdot\vec{\varepsilon}^{\,C}_\lambda$$

Tri-gluon vertex

$$\mathcal{L}_{3G} = g_S f^{ABC} (\vec{\nabla} G_0^A) G_0^B \cdot \vec{G}^C$$



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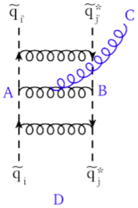

$$\mathcal{M} = 2(ig_S T^A_{i'i}) \left(\frac{-i}{q^2} \right) (ig_S f^{ABC})(i\vec{q} \cdot \vec{\varepsilon}^{\,C}) \left(\frac{-i}{q^2} \right) (-ig_S T^B_{j'j})$$

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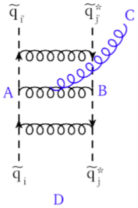
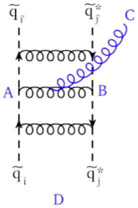


$$\mathcal{M} = 2(i g_S T^A_{i'i}) \left(\frac{-i}{q^2} \right) (i g_S f^{ABC})(i \vec{q} \cdot \vec{\varepsilon}^C) \left(\frac{-i}{q^2} \right) (-i g_S T^B_{j'j})$$

$$\mathcal{M} = 2 g_S^3 T^A_{i'i} T^B_{j'j} f^{ABC} \frac{\vec{q} \cdot \vec{\varepsilon}^C}{\vec{q}^4} \,, \quad H^{(2)}_{int} = -g_S \alpha_S T^A_{i'i} T^B_{j'j} f^{ABC} \vec{r} \cdot \vec{G}^C$$

Tri-gluon vertex



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$$\mathcal{V}^{(2)}_{fi} = i g_S \delta^{CD} \sqrt{\frac{1}{6}} \left\langle \Psi_f \left| \underbrace{\frac{3\alpha_S}{2r}}_{\Delta V_2(r)} \vec{r} \right| \Psi_i \right\rangle \cdot \vec{\varepsilon}^{\,C}_{\lambda}$$

Bino-Stop

$$\mathcal{L}_{\mathrm{bino-stop}} = \sqrt{2} g_1 \tfrac{2}{3} (\bar{\chi} \tfrac{1}{2} (1 + \gamma_5) t) \tilde{t}^* \; + \mathsf{h.c.}$$

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$$\tilde{t}^* \tilde{t} \to gg, hh, ZZ, WW, \gamma\gamma, gh, gZ, g\gamma, hZ, g\gamma, Z\gamma, \cdots$$

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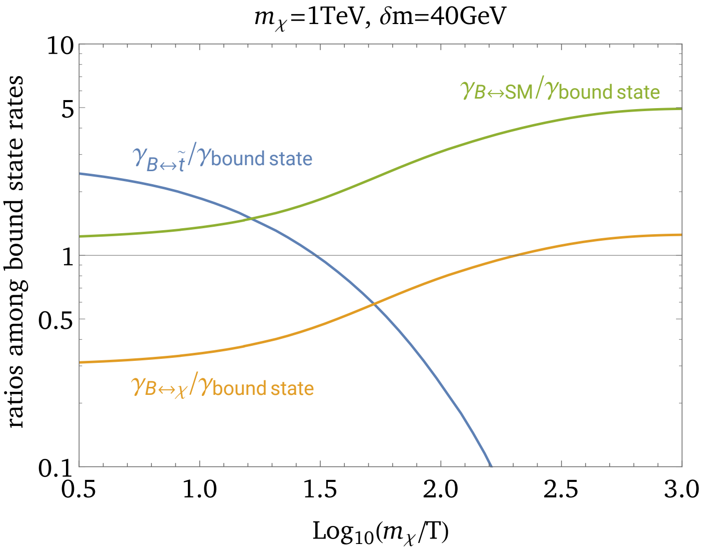
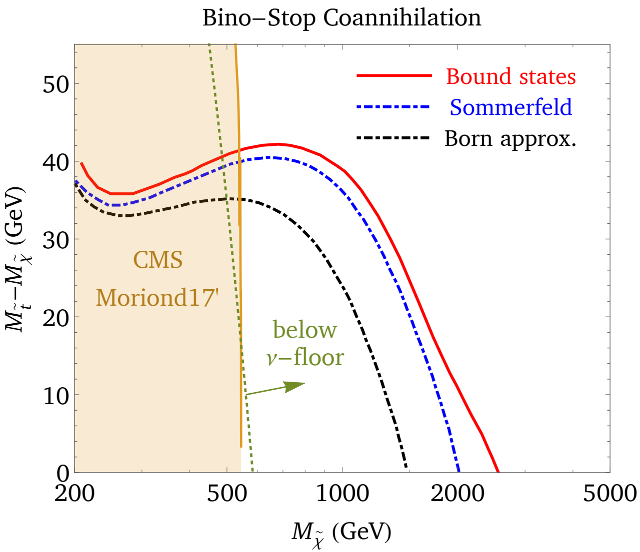
$$\tilde{t}^* \tilde{t} \to gg, hh, ZZ, WW, \gamma\gamma, gh, gZ, g\gamma, hZ, g\gamma, Z\gamma, \cdots$$

$$\Gamma_{B_{\tilde{t}} \to \chi\chi} = \frac{128 \pi \alpha_1^2 m_\chi^2 \left(m_{\tilde{t}}^2 - m_\chi^2 \right)^{3/2}}{27 m_{\tilde{t}}^3 \left(m_{\tilde{t}}^2 - m_\chi^2 + m_t^2 \right)^2} |\Psi(0)|^2$$

$$\Gamma_{B_{\tilde{t}} \to t\bar{t}} = \frac{64 \pi \alpha_1^2 m_t^2 \left(m_{\tilde{t}}^2 - m_t^2 \right)^{3/2}}{81 m_{\tilde{t}}^3 \left(m_{\tilde{t}}^2 - m_t^2 + m_\chi^2 \right)^2} |\Psi(0)|^2$$



m_χ=1TeV, δm=40GeV
10
5
1
0.5
0.1
0.5
1.0
1.5
2.0
2.5
3.0
ratios among bound state rates
$\text{Log}_{10}(m_\chi/\text{T})$
$\gamma_{B\leftrightarrow \text{SM}}/\gamma_{\text{bound state}}$
$\gamma_{B\leftrightarrow \tilde{t}}/\gamma_{\text{bound state}}$
$\gamma_{B\leftrightarrow \chi}/\gamma_{\text{bound state}}$



LHC constraint on the decay $\tilde{t} \to t^* + \chi \to W * + b + \chi$.

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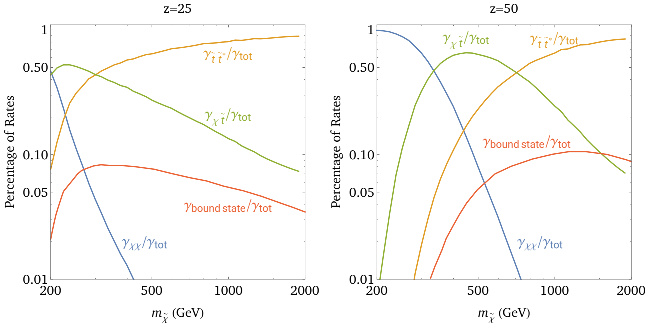
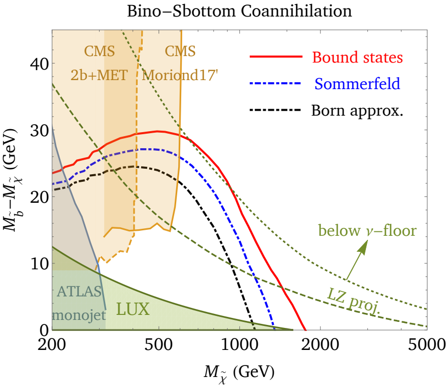
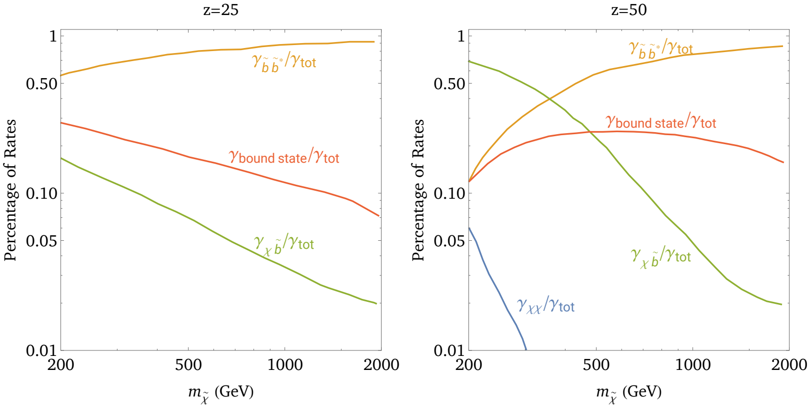
- Sommerfeld factors $\mathcal{S}_1 > 1$ ($\mathcal{S}_8 < 1$) for the color singlet (octet) are relevant.
- Attention of the color in the Krammer process for the bound state formation.

Backup material


z=25
z=50
Percentage of Rates
1
0.50
0.10
0.05
0.01
200
500
1000
2000
$m_{\tilde{\chi}}$ (GeV)
$\gamma_{\tilde{t}\tilde{t}^*}/\gamma_{\rm tot}$
$\gamma_{\chi\tilde{t}}/\gamma_{\rm tot}$
$\gamma_{\rm bound\ state}/\gamma_{\rm tot}$
$\gamma_{\chi\chi}/\gamma_{\rm tot}$



Bino–Sbottom Coannihilation
CMS
2b+MET
CMS
Moriond17'
Bound states
Sommerfeld
Born approx.
below ν–floor
LZ proj.
ATLAS
monojet
LUX
0
10
20
30
40
200
500
1000
2000
5000
$M_{\tilde{b}} - M_{\tilde{\chi}}$ (GeV)
$M_{\tilde{\chi}}$ (GeV)



z=25
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Percentage of Rates
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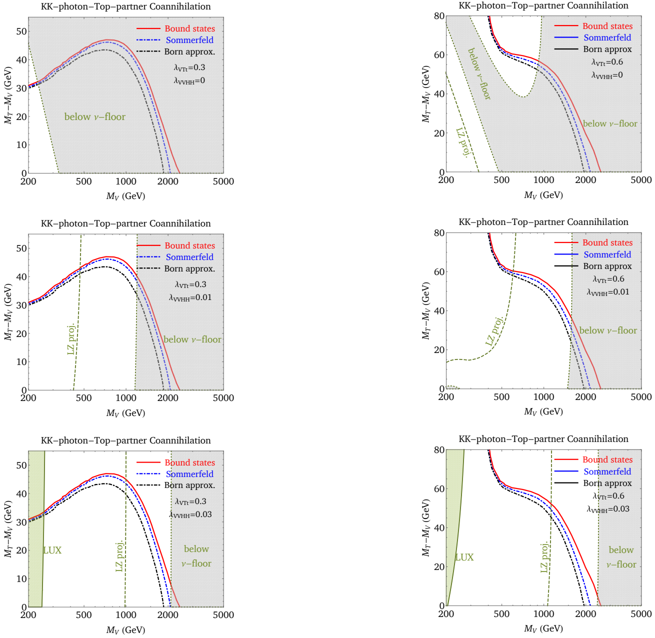
$m_{\tilde{\chi}}$ (GeV)
$\gamma_{\tilde{b}\,\tilde{b}^*}/\gamma_{\text{tot}}$
$\gamma_{\text{bound state}}/\gamma_{\text{tot}}$
$\gamma_{\chi\,\tilde{b}}/\gamma_{\text{tot}}$
$\gamma_{\chi\chi}/\gamma_{\text{tot}}$


KK–photon–Top–partner Coannihilation
Bound states
Sommerfeld
Born approx.
λVTt=0.3
λVVHH=0
below ν–floor
MT–MV (GeV)
MV (GeV)
KK–photon–Top–partner Coannihilation
Bound states
Sommerfeld
Born approx
λVTt=0.6
λVVHH=0
below ν–floor
LZ proj.
below ν–floor
MT–MV (GeV)
MV (GeV)
KK–photon–Top–partner Coannihilation
Bound states
Sommerfeld
Born approx.
λVTt=0.3
λVVHH=0.01
LZ proj.
below ν–floor
MT–MV (GeV)
MV (GeV)
KK–photon–Top–partner Coannihilation
Bound states
Sommerfeld
Born approx
λVTt=0.6
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below ν–floor
MT–MV (GeV)
MV (GeV)
KK–photon–Top–partner Coannihilation
Bound states
Sommerfeld
Born approx.
λVTt=0.3
λVVHH=0.03
LUX
LZ proj.
below
ν–floor
MT–MV (GeV)
MV (GeV)
KK–photon–Top–partner Coannihilation
Bound states
Sommerfeld
Born approx
λVTt=0.6
λVVHH=0.03
LUX
LZ proj.
below
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MT–MV (GeV)
MV (GeV)