2020 Energy Frontier in Particle Physics: LHC and Future Colliders

Comprehensive Study of the Inert Doublet Model with U(1) Symmetry

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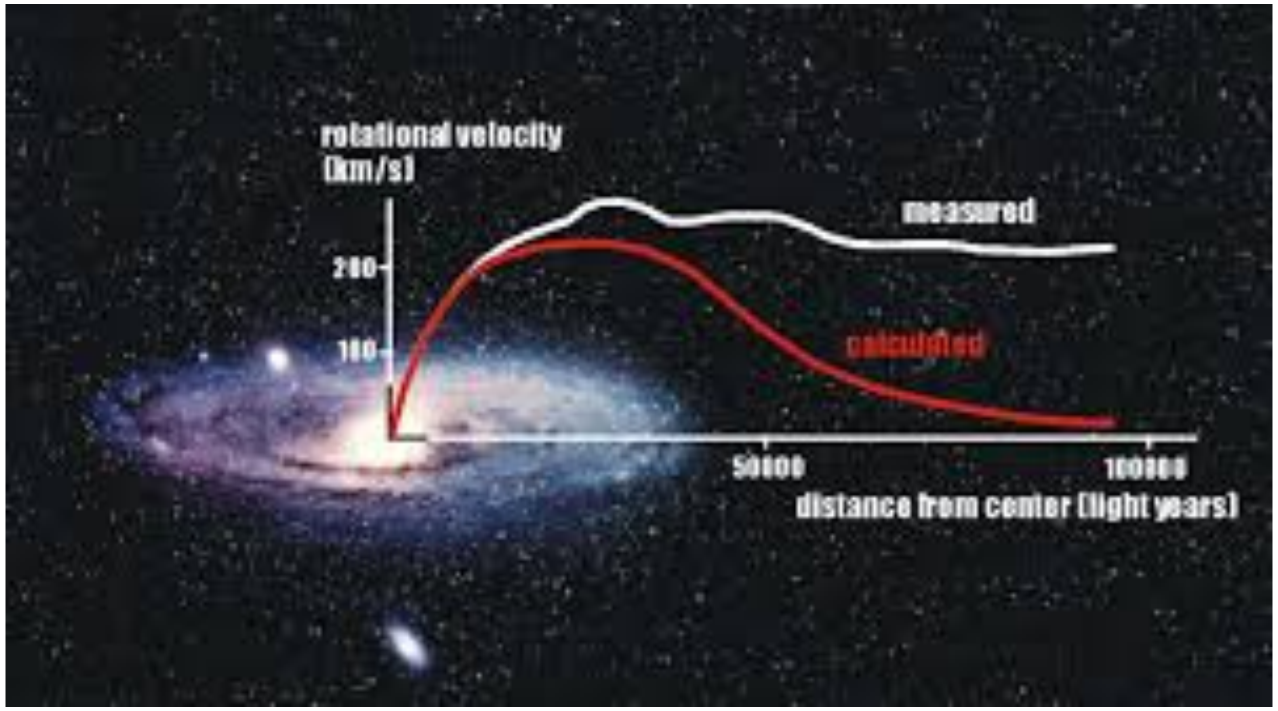
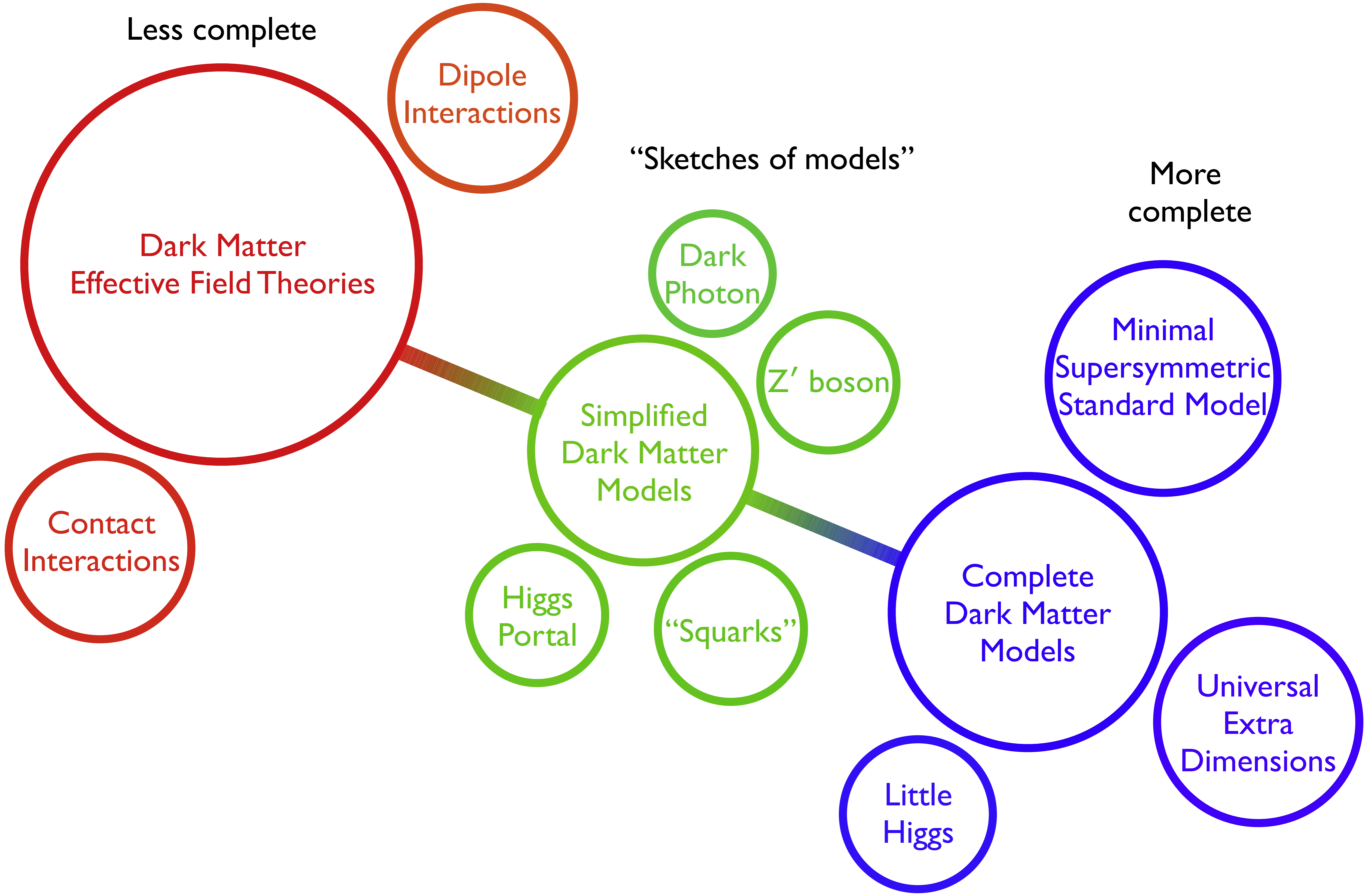
1. Motivation: DM
2. Inert Doublet Model with Z_2 parity
3. Inert Doublet Model with U(1) symmetry
4. Constraints on the IDM with U(1)
5. LHC phenomenology of the IDM with U(1)
6. Conclusions

1. Motivation: DM

Dark Matter:
Compelling evidence for NP



3 approaches to DM



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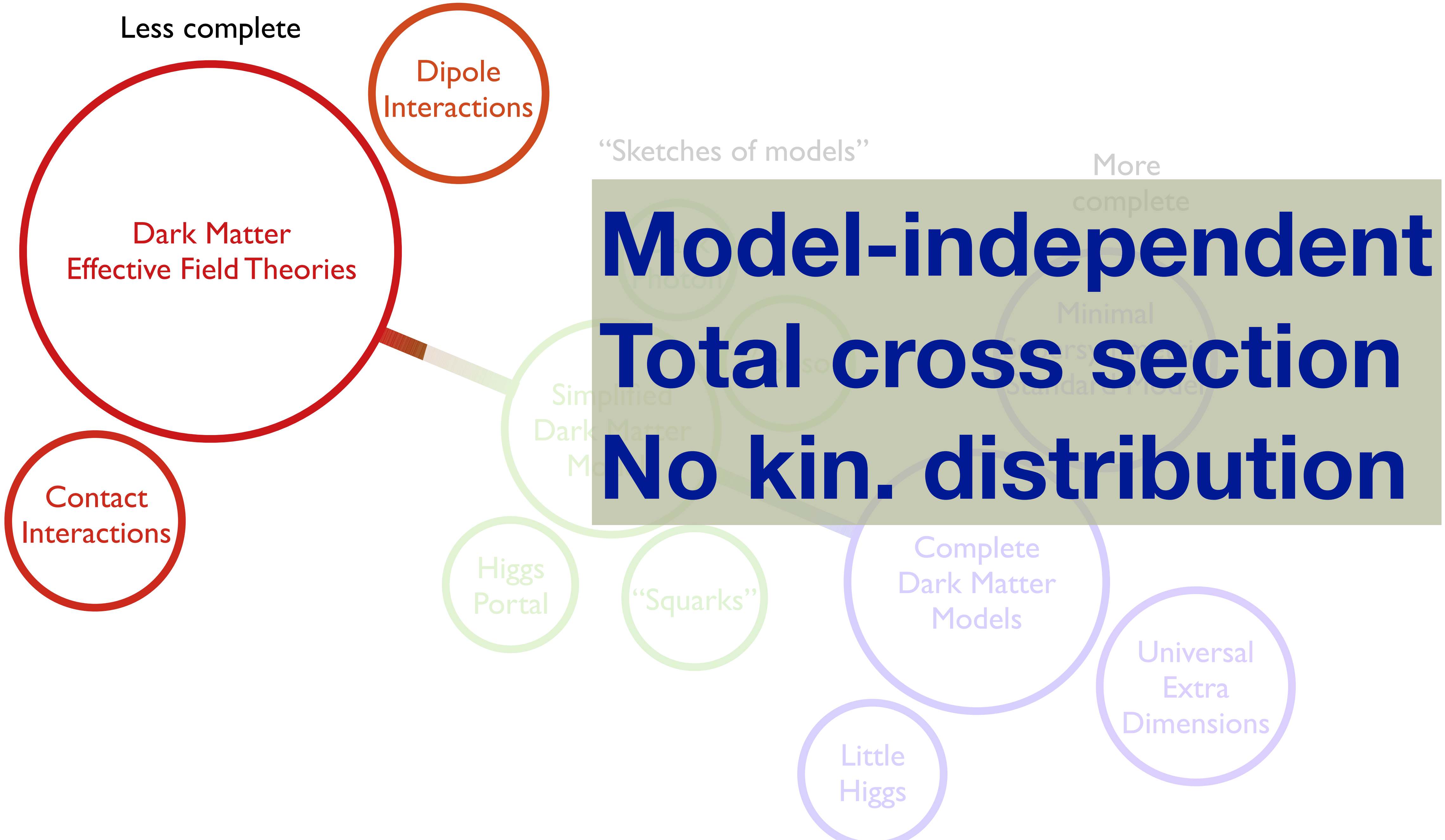

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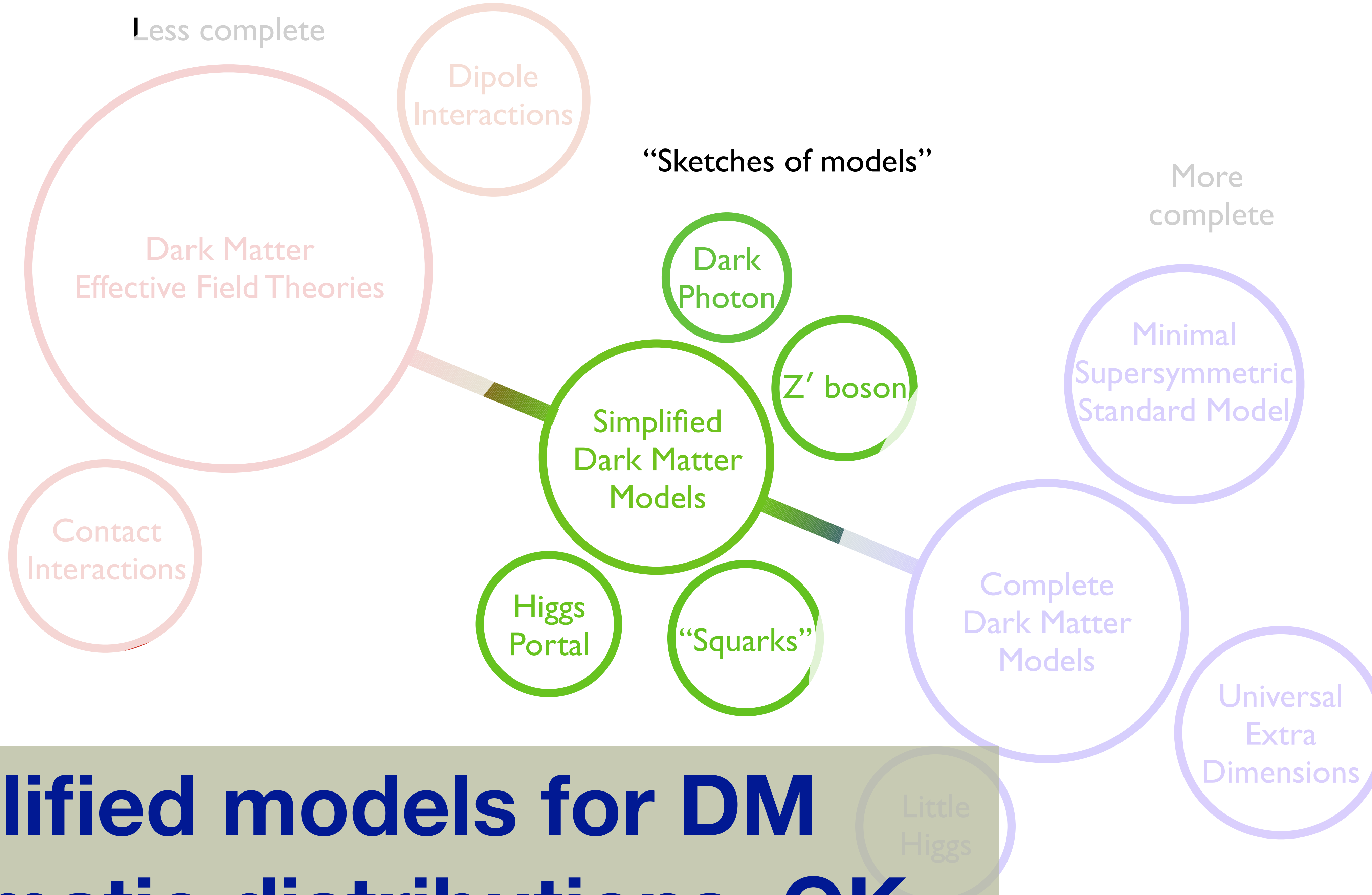

Simplified models for DM
Kinematic distributions: OK
No correlation b/w processes

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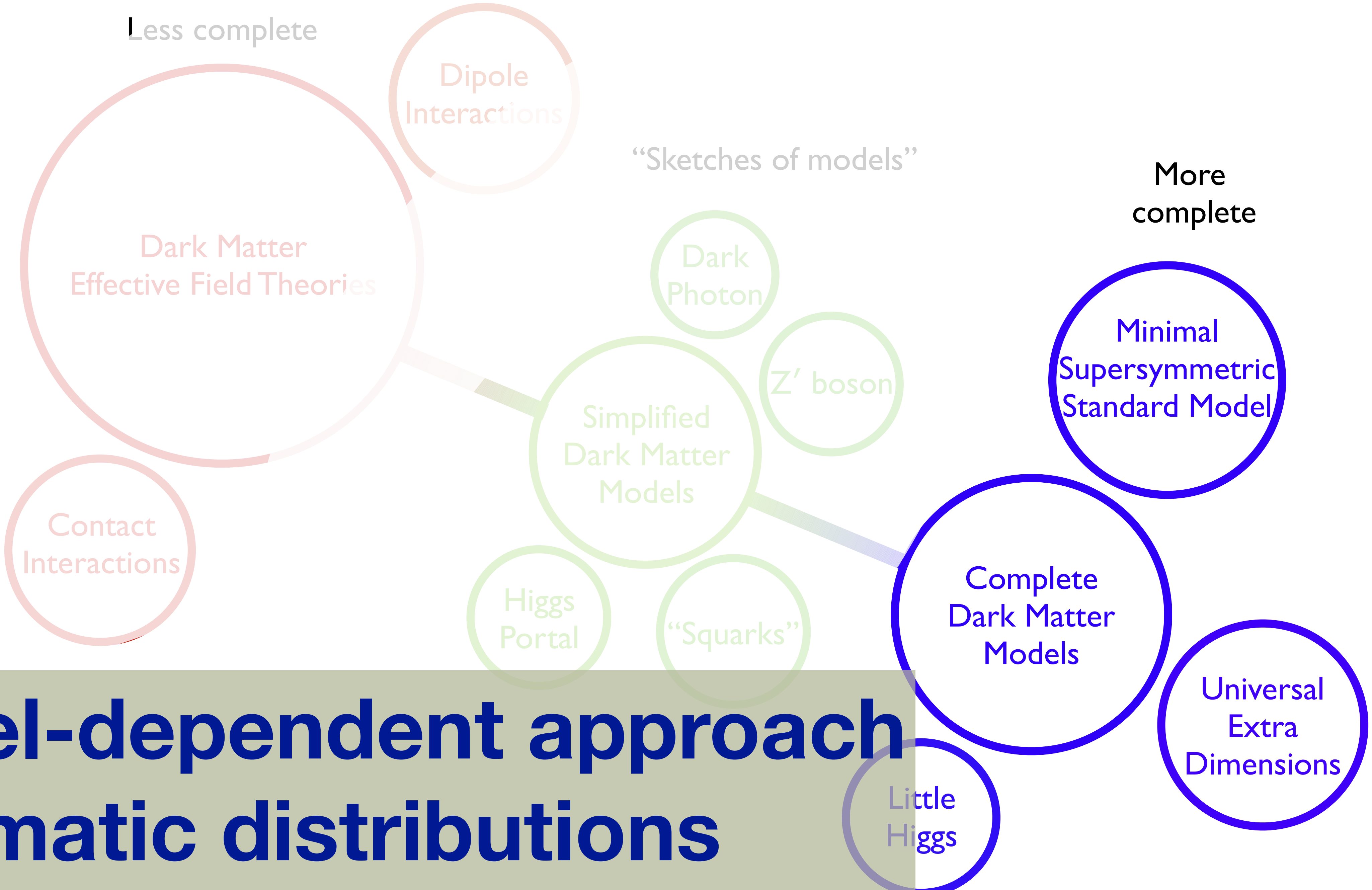

Model-dependent approach
Kinematic distributions
Correlation b/w processes
Golden mode!

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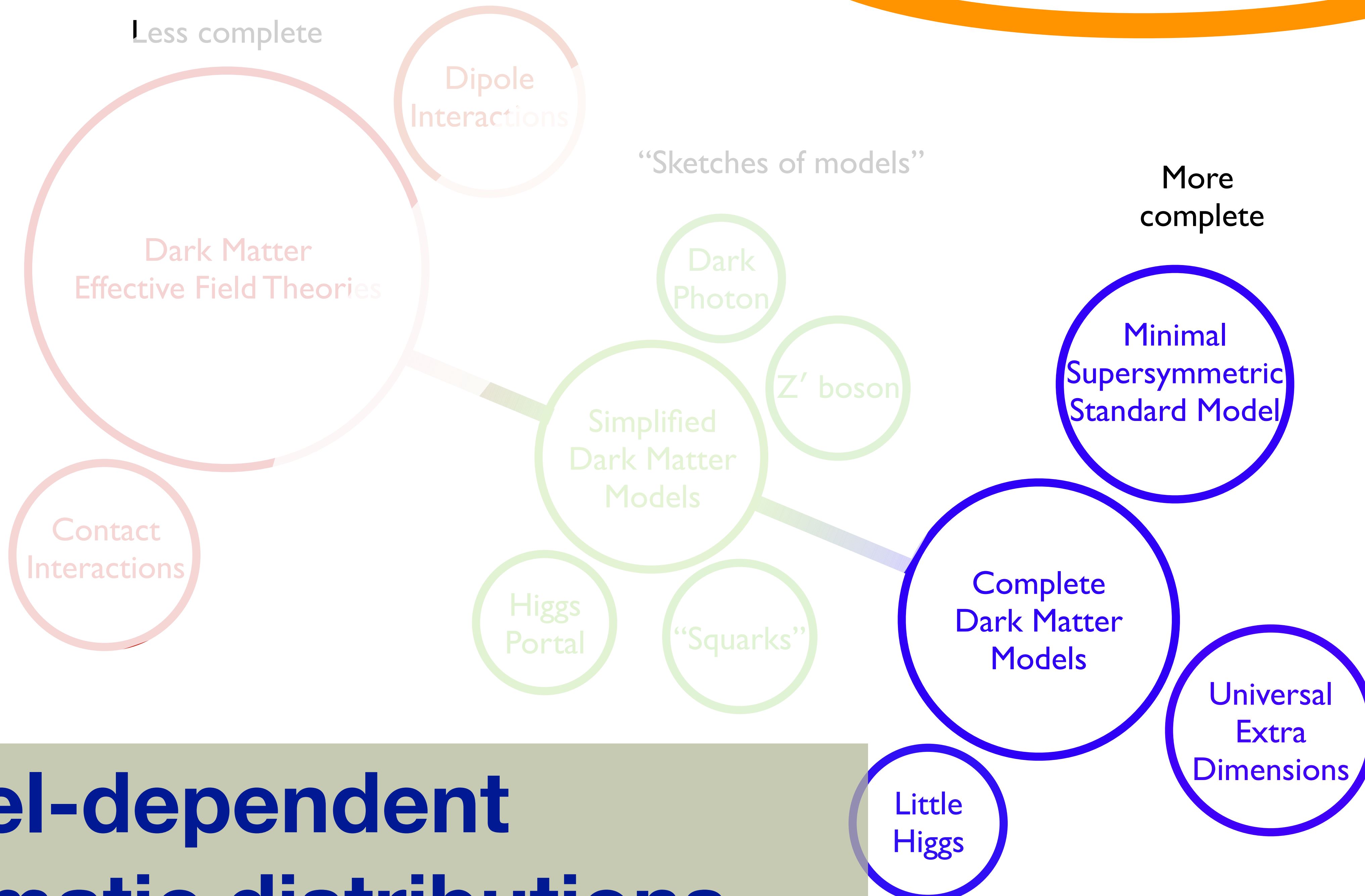
Inert Doublet Model



Model-dependent
Kinematic distributions
Correlation b/w processes

of the Dark Universe 9–10 (2015) 8–23

2. The Inert Doublet Model with discrete Z_2 parity

SM Higgs boson ϕ_1 & another Higgs doublet ϕ_2

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \boxed{Z_2\text{-even}}$$

All the SM particles

$$\phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}h^+ \\ h_1 + ih_2 \end{pmatrix} \quad \boxed{Z_2\text{-odd}}$$

The scalar potential allowed by Z_2 symmetry

$$
\begin{aligned}
V = & -m_1^2(\phi_1^\dagger\phi_1) - m_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 \\
& + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2) \\
& + \frac{\lambda_5}{2}[(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2].
\end{aligned}
$$

- No mixing b/w H and $h_{1,2}$
- No Yukawa coupling b/w new scalars & SM fermions

Inert

New scalar bosons

$\boxed{\begin{array}{l}\text{Two neutral scalar: } h_1 \ \& \ h_2 \\ \\ \text{charged scalars: } H^{\pm}\end{array}}$

Masses of the new scalars

$$M_H^2 = 2\lambda_1 v^2 = 2m_1^2, \qquad M_{h^+}^2 = \frac{1}{2}\lambda_3 v^2 - m_2^2,$$

$$M_{h_1}^2 = \frac{1}{2}(\lambda_3 + \lambda_4 - |\lambda_5|)v^2 - m_2^2,$$

$$M_{h_2}^2 = \frac{1}{2}(\lambda_3 + \lambda_4 + |\lambda_5|)v^2 - m_2^2 > M_{h_1}^2.$$

3. Inert Doublet Model with U(1)

continuous $U(1)$ symmetry,
not spontaneously broken by the vacuum.

$$\phi_1 \to \phi_1, \quad \phi_2 \to e^{i\theta}\phi_2$$

ArXiv ePrint: 1808.08629

The scalar potential allowed by U(1) symmetry

$$\boxed{\phi_1 \to \phi_1, \quad \phi_2 \to e^{i\theta}\phi_2}$$

$$\begin{aligned}
V = & -m_1^2(\phi_1^\dagger\phi_1) - m_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 \\
& + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2) \\
& + \frac{\lambda_5}{2}\left[(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2\right].
\end{aligned}$$

The scalar potential allowed by U(1) symmetry

$$\boxed{\phi_1 \to \phi_1, \quad \phi_2 \to e^{i\theta}\phi_2}$$

$$V = -m_1^2(\phi_1^\dagger\phi_1) - m_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2$$
$$+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2)$$
$$\xcancel{+ \frac{\lambda_5}{2}[(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2].}$$

$$\boxed{\lambda_5 = 0}$$

The scalar potential allowed by U(1) symmetry

$$\boxed{\phi_1 \to \phi_1, \qquad \phi_2 \to e^{i\theta}\phi_2}$$

$$\begin{aligned} V = & -m_1^2(\phi_1^\dagger\phi_1) - m_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 \\ & + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2) \\ & \cancel{+ \frac{\lambda_5}{2}[(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2]}. \end{aligned}$$

$$\boxed{\lambda_5 = 0}$$

- h_1 & h_2: opposite CP parities
- Impossible to tell which is CP-even.

- Assume the CP transformation

$$h_1 \to h_1, \quad h_2 \to -h_2$$

$$\boxed{\color{red}{\text{Under the rephasing } \phi_2 \to i\phi_2}}$$

$$\begin{aligned} V = & -m_1^2(\phi_1^\dagger\phi_1) - m_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 \\ & + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2) \\ & \cancel{+ \frac{\lambda_5}{2}[(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2].} \qquad (2 \end{aligned}$$

$$h_1 \to -h_1, \quad h_2 \to h_2$$

The scalar potential allowed by U(1) symmetry

$$\boxed{\phi_1 \to \phi_1, \quad \phi_2 \to e^{i\theta}\phi_2}$$

$$V = -m_1^2(\phi_1^\dagger\phi_1) - m_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2$$
$$+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2)$$
$$\xcancel{+ \frac{\lambda_5}{2}[(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2].}$$

$$\boxed{\lambda_5 = 0}$$

$$M_{h_1}^2 = \frac{1}{2}(\lambda_3 + \lambda_4 - \xcancel{|\lambda_5|})v^2 - m_2^2,$$
$$M_{h_2}^2 = \frac{1}{2}(\lambda_3 + \lambda_4 + \xcancel{|\lambda_5|})v^2 - m_2^2$$

$$\boxed{M_{h_1} = M_{h_2} \text{ by } U(1) \text{ symmetry}}$$

The mass degeneracy is protected even at loop level.

Q. Phenomenological characteristics of $\mathrm{IDM}_{U(1)}$?

Inert Higgs couplings w/ V

$$\mathscr{L}_{VHH} = \frac{1}{2} g_Z Z^\mu \boxed{h_2 \overset{\leftrightarrow}{\partial}_\mu h_1} - \frac{g}{2}\left[i W^+ \boxed{H^- \overset{\leftrightarrow}{\partial}_\mu (h_1 + i h_2)} + \text{H.c.}\right]$$
$$\left[ie A^\mu + i g_Z \left(\frac{1}{2} - s_W^2\right) Z^\mu \right] \boxed{H^+ \overset{\leftrightarrow}{\partial}_\mu H^-},$$

$$\begin{aligned}\mathscr{L}_{VVHH} = &\left(\frac{1}{4} g^2 W_\mu^+ W^{-\mu} + \frac{1}{8} g_Z^2 Z_\mu Z^\mu\right)(h_1^2 + h_2^2) \\ &+ \left[\frac{1}{2} g^2 W_\mu^+ W^{-\mu} + e^2 A_\mu A^\mu + g_Z^2 \left(\frac{1}{2} - s_W^2\right)^2 Z_\mu Z^\mu \right. \\ &\left. + 2 g_Z e \left(\frac{1}{2} - s_W^2\right) A_\mu Z^\mu \right] H^+ H^- \\ &+ \left[\left(\frac{1}{2} e g A^\mu W_\mu^+ - \frac{1}{2} g_Z^2 s_W^2 Z^\mu W_\mu^+\right) H^- (h_1 + i h_2) + h.c.\right],\end{aligned}$$

The SM gauge boson interacts w/ two inert scalars

Inert Higgs couplings w/ Higgs

$$\mathscr{L}_{3h} = -\frac{1}{2}\lambda_{34} v \boxed{H(h_1^2 + h_2^2)} - \lambda_3 v \boxed{H H^+ H^-},$$

$$\mathscr{L}_{4h} = -\frac{\lambda_{34}}{4} H^2 (h_1^2 + h_2^2) - \frac{\lambda_3}{2} H^2 H^+ H^-$$

$$-\frac{\lambda_2}{4}(h_1^2 + h_2^2)^2 - \lambda_2 H^+ H^- (h_1^2 + h_2^2 + H^+ H^-).$$

$$\boxed{\lambda_{34} = \lambda_3 + \lambda_4}$$

Inert Higgs couplings

$$\mathscr{L}_{3h} = -\frac{1}{2}\boxed{\lambda_{34}}vH(h_1^2 + h_2^2) - \boxed{\lambda_3}vHH^+H^-,$$

$$\mathscr{L}_{4h} = -\frac{\boxed{\lambda_{34}}}{4}H^2(h_1^2 + h_2^2) - \frac{\boxed{\lambda_3}}{2}H^2H^+H^-$$

$$-\frac{\lambda_2}{4}(h_1^2 + h_2^2)^2 - \lambda_2 H^+H^-(h_1^2 + h_2^2 + H^+H^-).$$

- λ_{34}, λ_3: couplings with the Higgs boson.
- λ_2: couplings among inert scalars.

Setting

$$\boxed{\lambda_2 = 0}$$

Three model parameters

$$\{M_S, M_{H^\pm}, \lambda_{34}\}$$

$$
\begin{aligned}
\lambda_1 &= \frac{m_H^2}{2v^2}, \\
\lambda_3 &= \lambda_{34} + \frac{2}{v^2}\left(M_{H^\pm}^2 - M_S^2\right), \\
\lambda_4 &= -\frac{2}{v^2}\left(M_{H^\pm}^2 - M_S^2\right) < 0, \\
M_{h_1} &= M_{h_2} = M_S.
\end{aligned}
$$

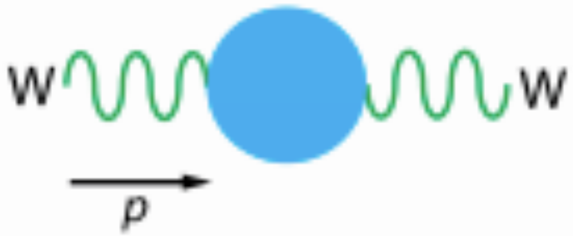
Decays of inert scalars

- $h_1, \ h_2$: stable
- $H^\pm \to W^\pm h_1, W^\pm h_2$

4. Constraints on the IDM with U(1)

1. **EWPD oblique parameters:** S, T
2. **Theoretical constraints including vacuum stability**
3. **LEP data**
4. **LHC Higgs data**
5. **Relic density & Direct dark matter detection**

EWPD constraints



$$\Pi_{WW}(p^2) = \Pi_{WW}(0) + p^2\Pi'_{WW}(0) + \cdots$$

$$\Pi_{ZZ}(p^2) = \Pi_{ZZ}(0) + p^2\Pi'_{ZZ}(0) + \cdots$$

$$\boxed{\begin{aligned} \alpha S &= 4s^2c^2\left[\Pi'_{ZZ}(0) - \frac{c^2 - s^2}{sc}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right] \\ \alpha T &= \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} \end{aligned}}$$

$$S = 0.02 \pm 0.07, \quad T = 0.07 \pm 0.06, \quad \boxed{\rho_{ST} = 0.92,}$$

Strong correlation!

$$S = 0.02 \pm 0.07, \quad T = 0.07 \pm 0.06, \quad \boxed{\rho_{ST} = 0.92,}$$

Strong correlation!

$$\chi^2 = \sum_{\mathcal{O}=S,T} \frac{(\mathcal{O} - \mathcal{O}_{\text{exp}})^2}{\sigma_{\mathcal{O}}^2 (1 - \rho_{ST})} - 2\rho_{ST} \frac{(S - S_{\text{exp}})(T - T_{\text{exp}})}{\sigma_S \sigma_T (1 - \rho_{ST})},$$

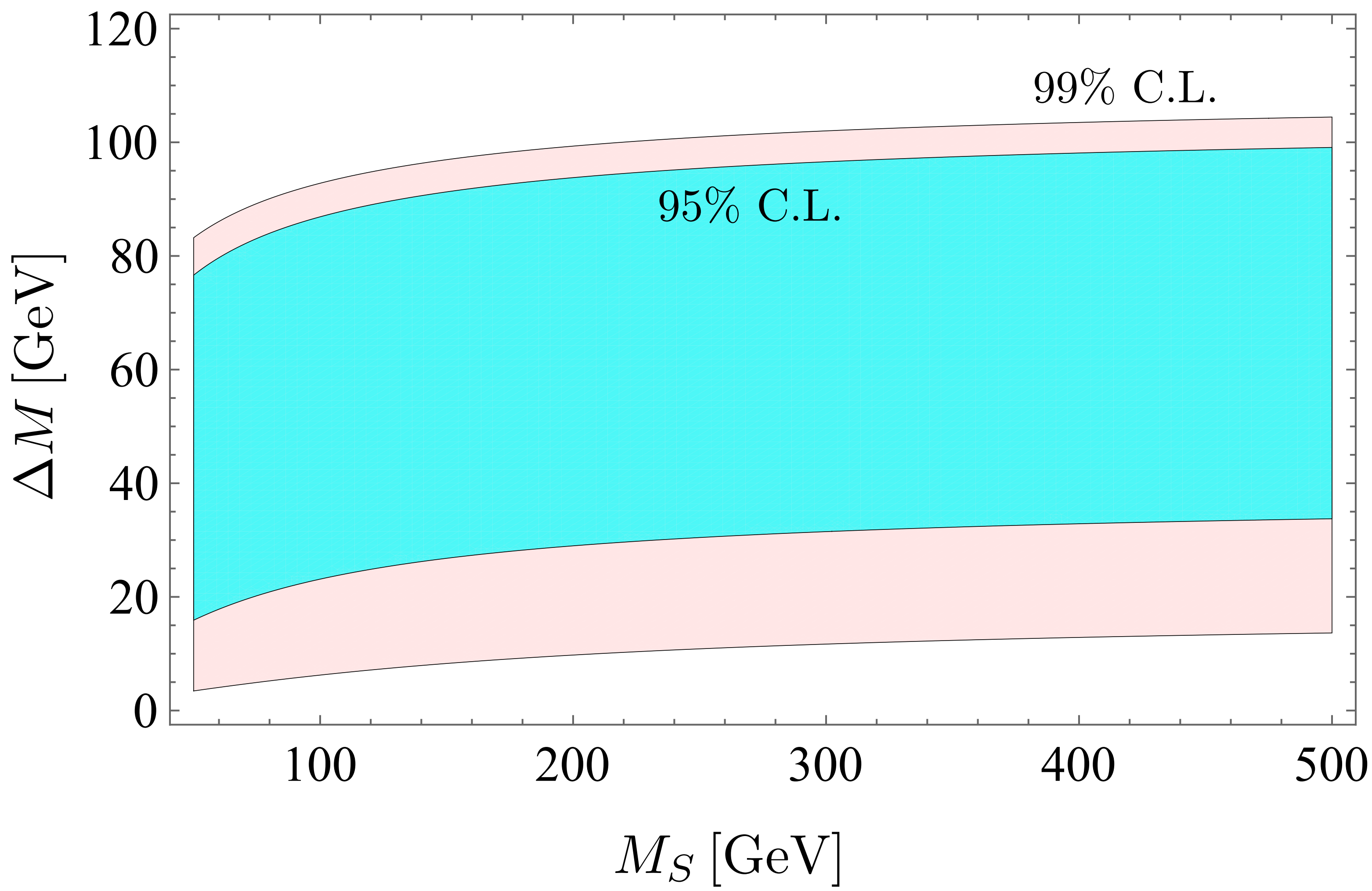
$$S = 0.02 \pm 0.07, \quad T = 0.07 \pm 0.06, \quad \boxed{\rho_{ST} = 0.92,}$$

Strong correlation!

$$\chi^2 = \sum_{\mathcal{O}=S,T} \frac{(\mathcal{O} - \mathcal{O}_{\rm exp})^2}{\sigma^2_{\mathcal{O}}(1-\rho_{ST})} - 2\rho_{ST}\frac{(S - S_{\rm exp})(T - T_{\rm exp})}{\sigma_S \sigma_T (1-\rho_{ST})},$$

Allowed masses

$$\boxed{\Delta M \equiv M_{H^\pm} - M_S.}$$



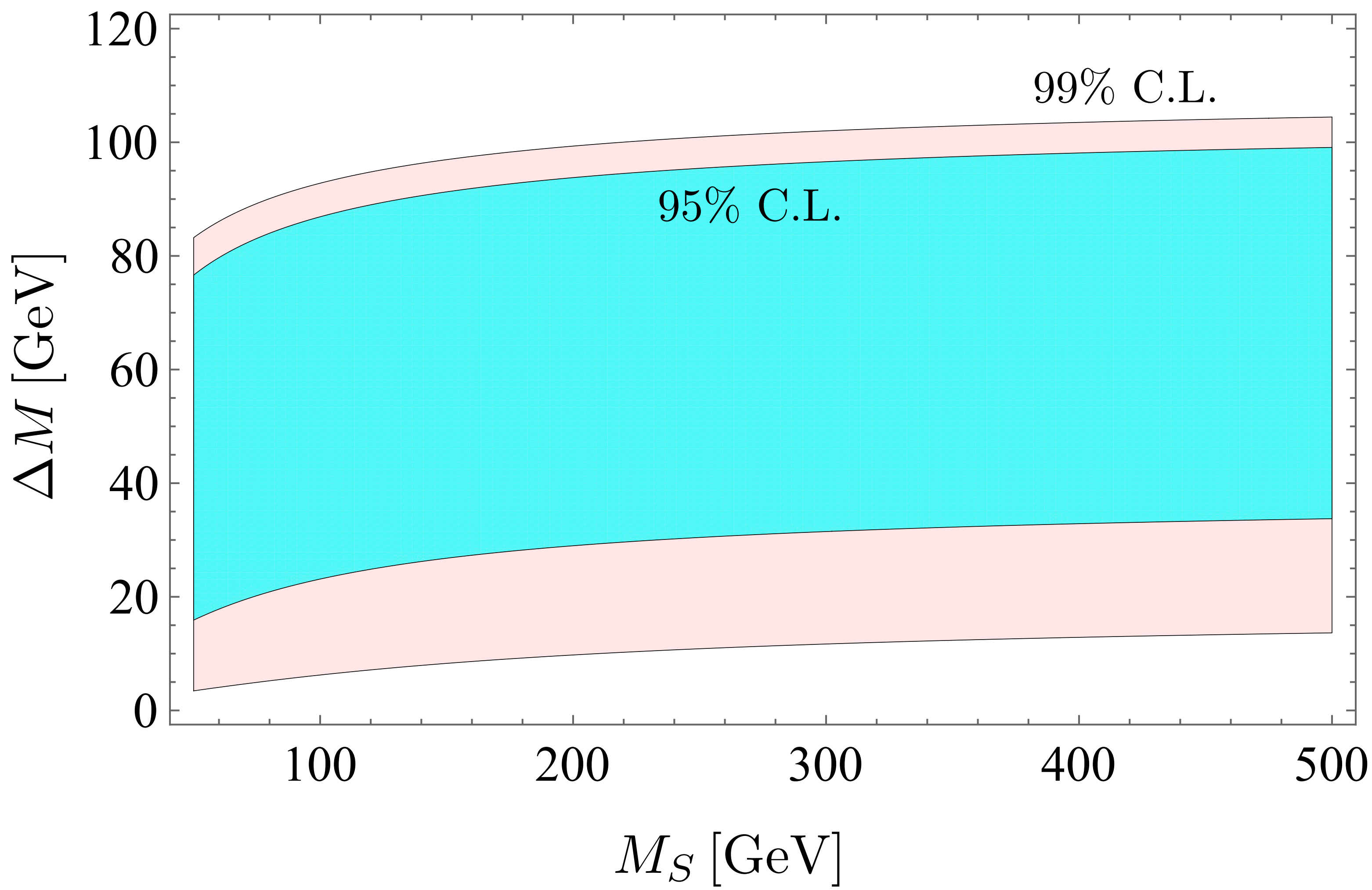
$$S = 0.02 \pm 0.07, \quad T = 0.07 \pm 0.06, \quad \boxed{\rho_{ST} = 0.92,}$$

Charge Higgs boson cannot be much heavier than the DM scalar!

$\mathcal{O}=S,T$

Allowed masses

$$\boxed{\Delta M \equiv M_{H^\pm} - M_S.}$$



Theoretical constraints

1. Perturbativity:

$$|\lambda_i| \leq 8\pi.$$

2. Vaccum stability:

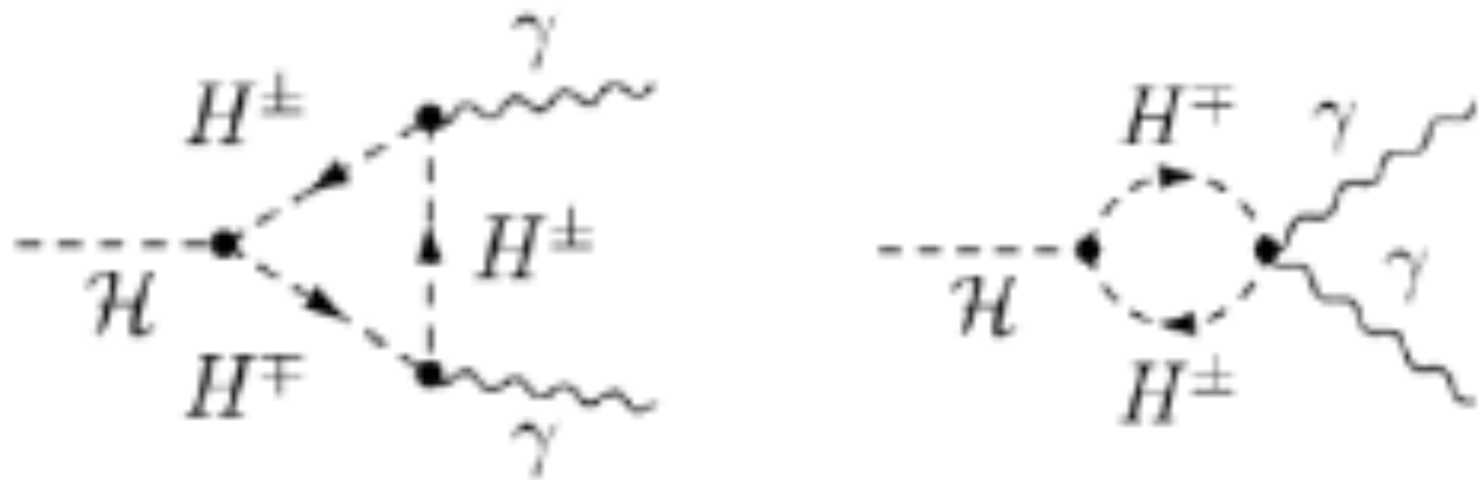
$$\lambda_{34} > 0.$$

3. Tree level unitarity:

$$|a_i| \leq 8\pi$$

$$\begin{aligned}
a_{1,2} &= \lambda_3 \pm \lambda_4, \quad a_3 = \lambda_3, \quad a_4 = \lambda_3 + 2\lambda_4, \\
a_{5,6} &= -\lambda_1 - \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_4^2}, \\
a_{7,8} &= -3\lambda_1 - 3\lambda_2 \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2}, \\
a_9 &= -2\lambda_1, \quad a_{10} = -2\lambda_2.
\end{aligned}$$

LHC Higgs precision data
(1) diphoton rate



$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 G_F m_h^2}{128\sqrt{2}\pi^3} \left| \sum_i N_{ci} Q_i^2 F_i + g_{hH^\pm H^\mp} \frac{m_W^2}{m_{H^\pm}^2} F_0(\tau_{H^\pm}) \right|^2,$$

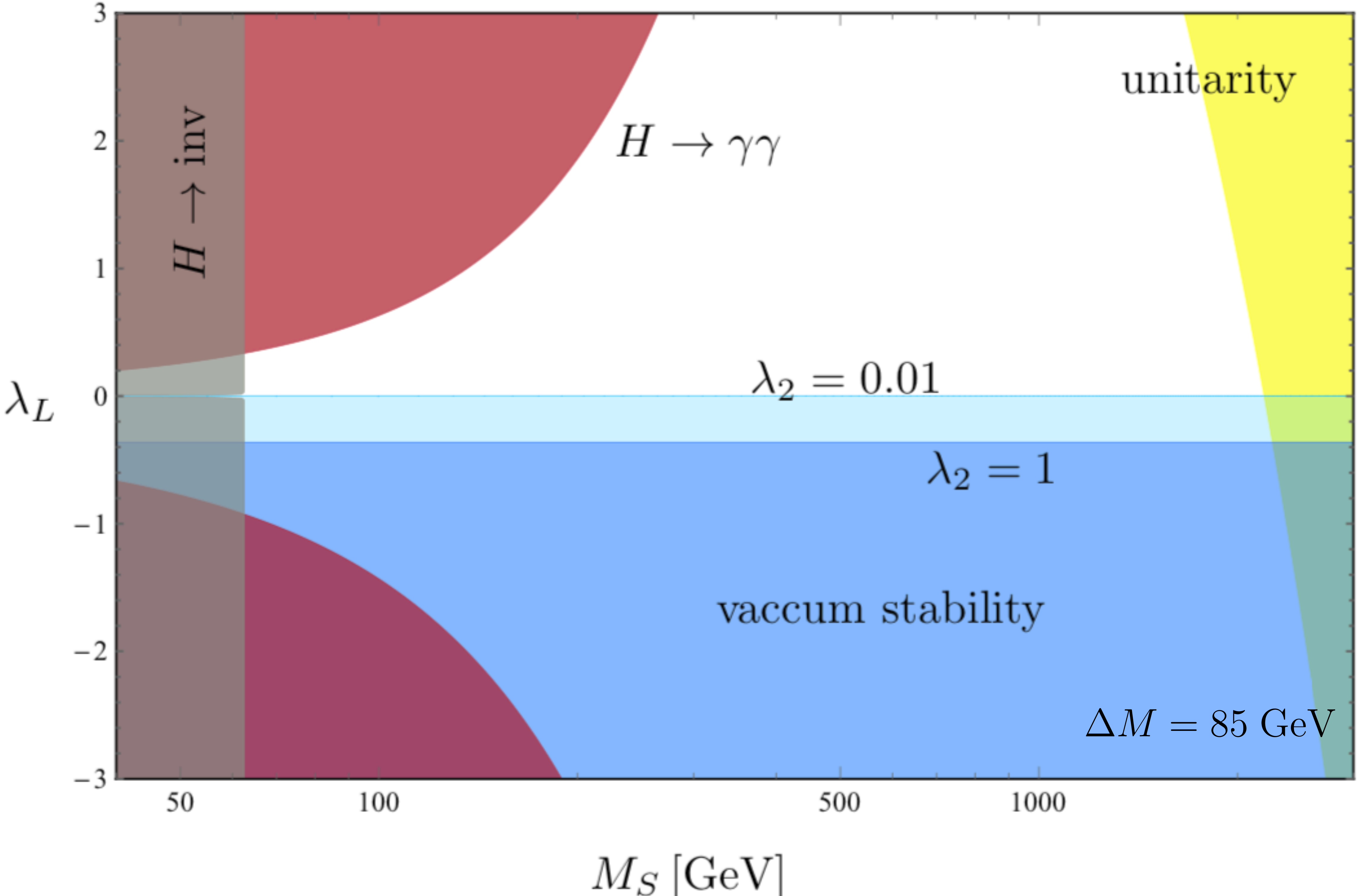
LHC Higgs precision data (2) Higgs invisible decay

When $M_S < m_h/2$,

$$\mathcal{B}_{\rm inv} < 0.28 \; [\textbf{ATLAS JHEP 08 (2016) 045}]$$

- **For** $M_S \ll m_H$, $|\lambda_{34}| < 0.019$.
- **For** $M_S \simeq 60$ GeV, $|\lambda_{34}| < 0.036$.

Theoretical & Higgs constraints



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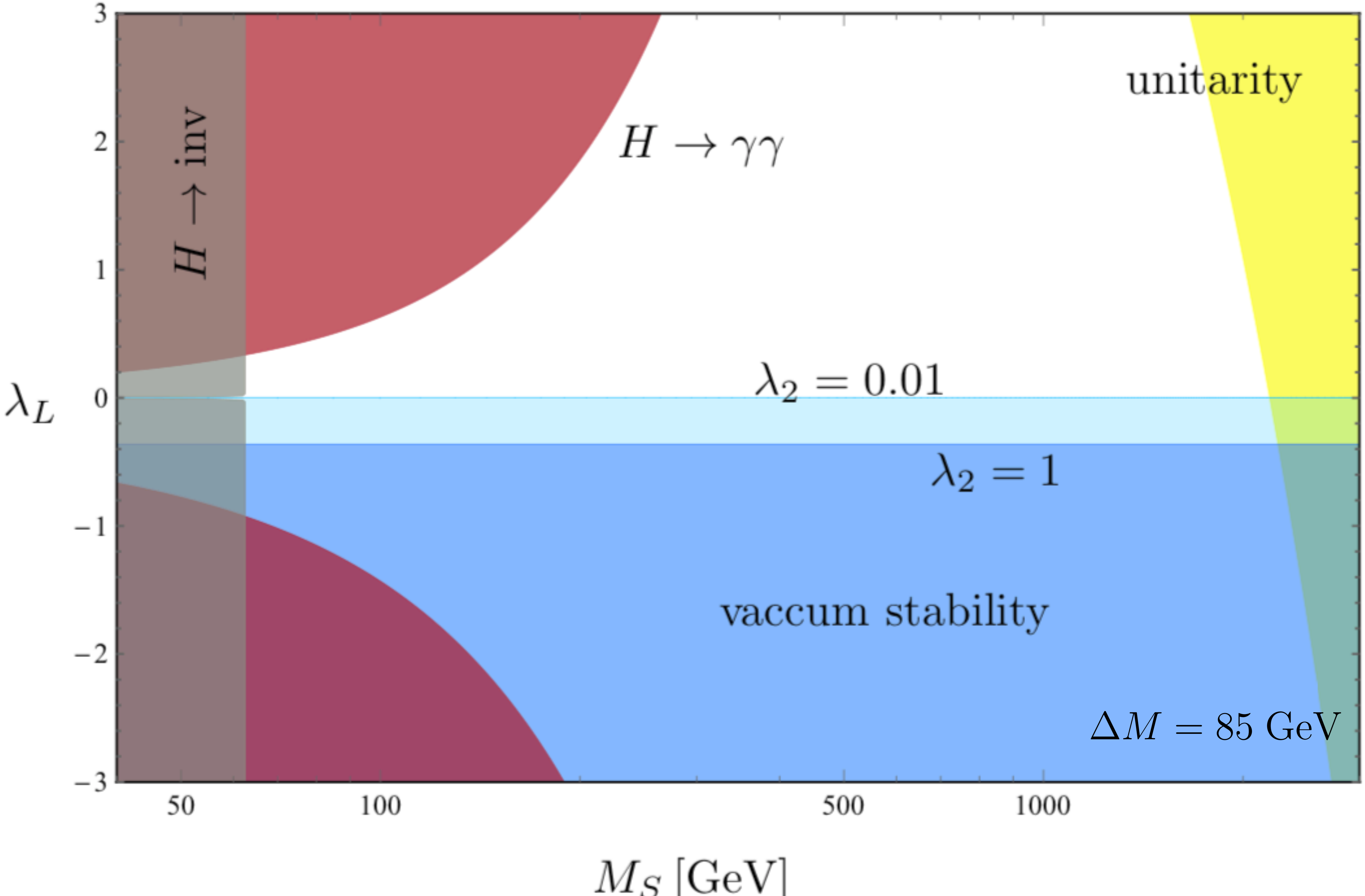
Light DM → small λ_L



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Relic density

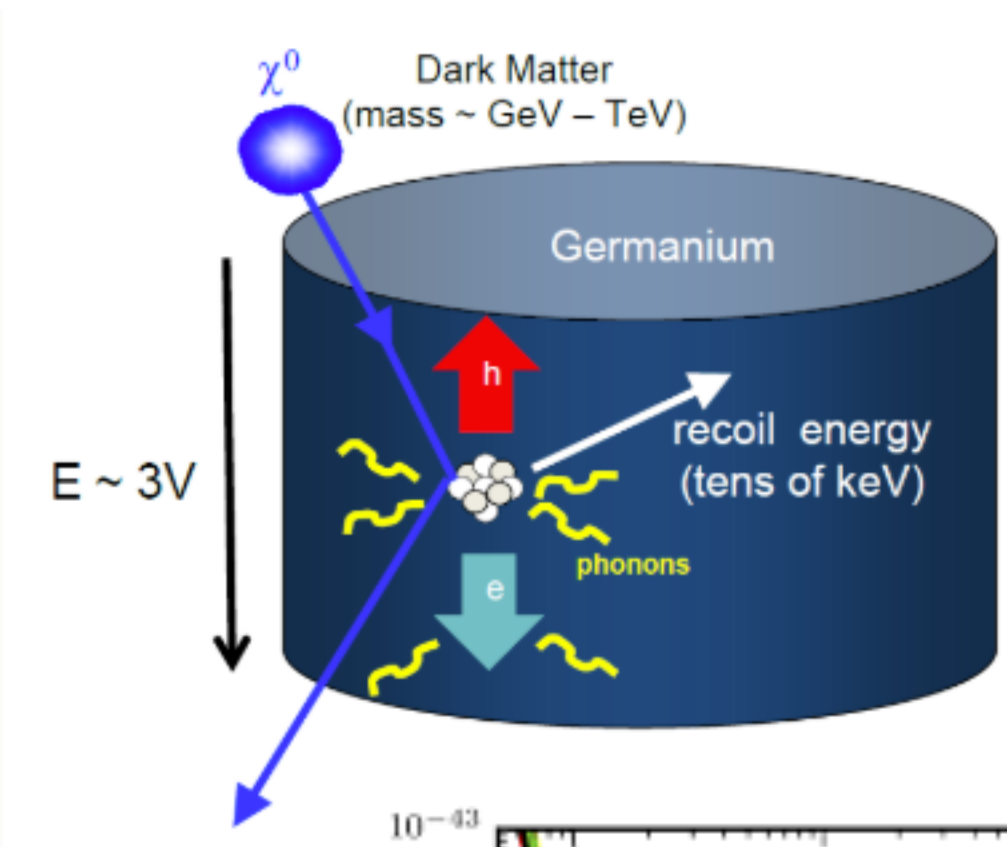
Planck, Astron. Astrophys. 594 (2016) A13,

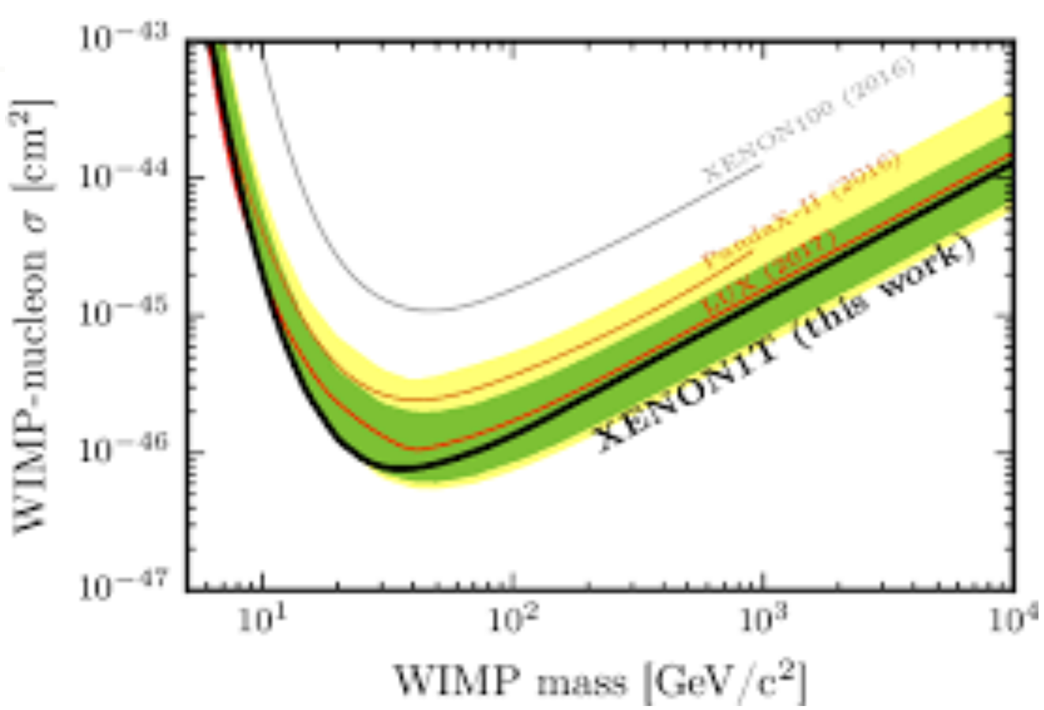
$$\Omega_{\rm DM}^{\rm Planck} h^2 = 0.1184 \pm 0.0012$$

Avoid the over-closure of the Universe,

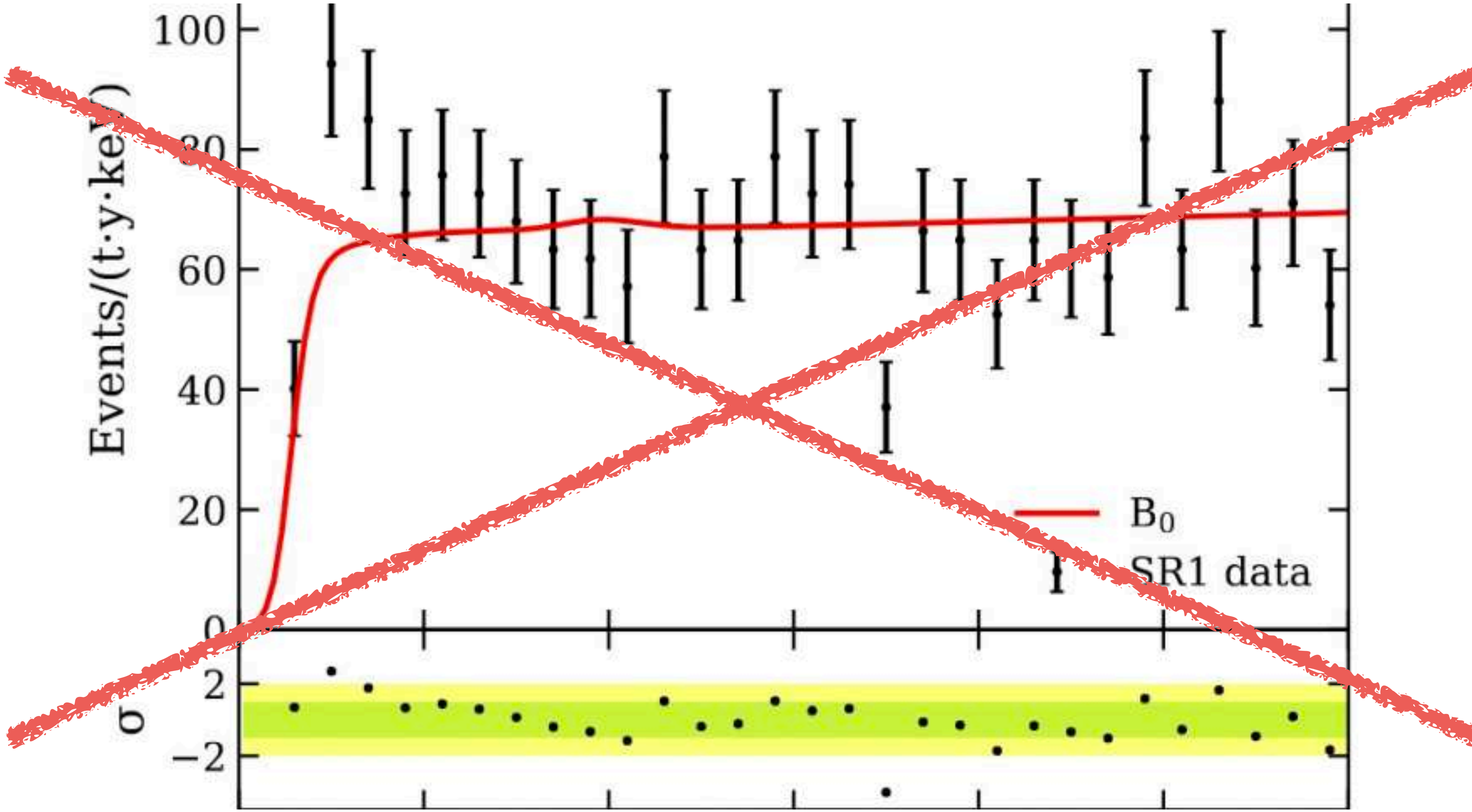
$$\boxed{\Omega_{H,A} h^2 < \Omega_{\rm DM}^{\rm Planck} h^2}$$

Direct detection of DM



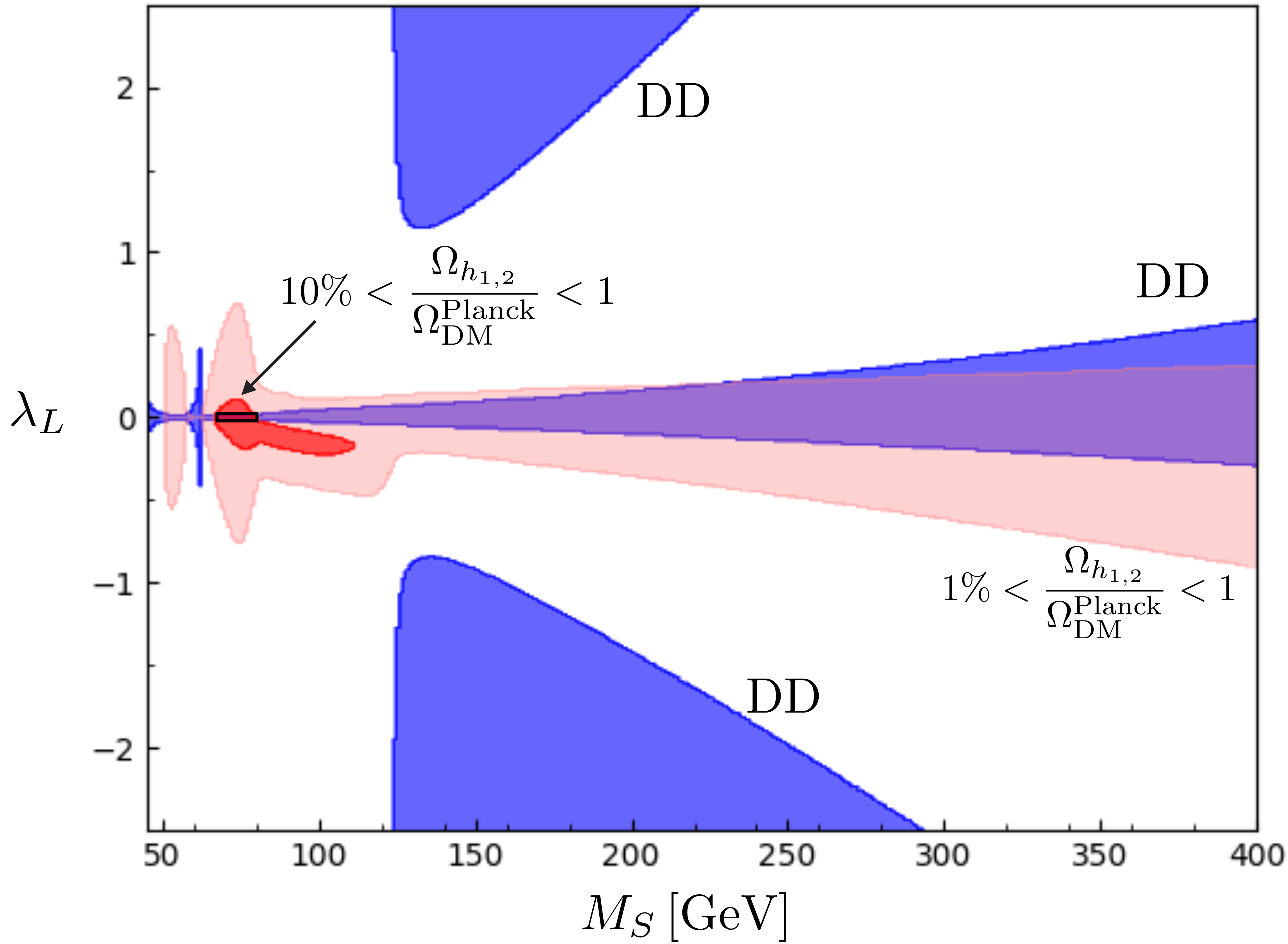


Ignore the electronic recoil event excess



If the relic density in our model is smaller than the Planck measurement,

$$\hat{\sigma}_{\rm SI} = \frac{\Omega_{h_{1,2}} h^2}{\Omega_{\rm DM}^{\rm Planck} h^2}\, \sigma_{\rm SI}.$$



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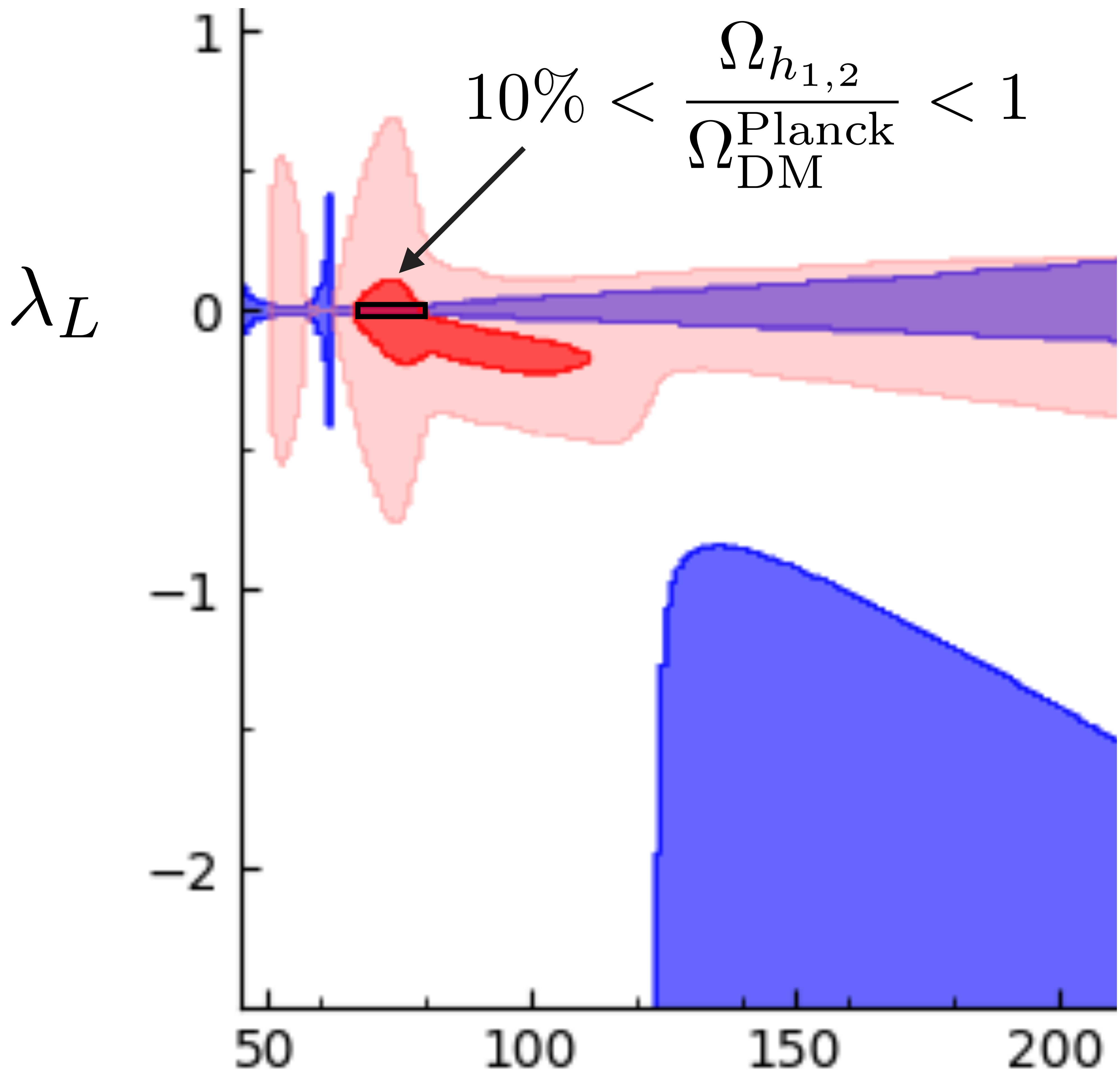

$10\% < \frac{\Omega_{h_{1,2}}}{\Omega_{\rm DM}^{\rm Planck}} < 1$
λ_L
1
0
−1
−2
50
100
150
200

5. LHC phenomenology of the IDM with U(1)

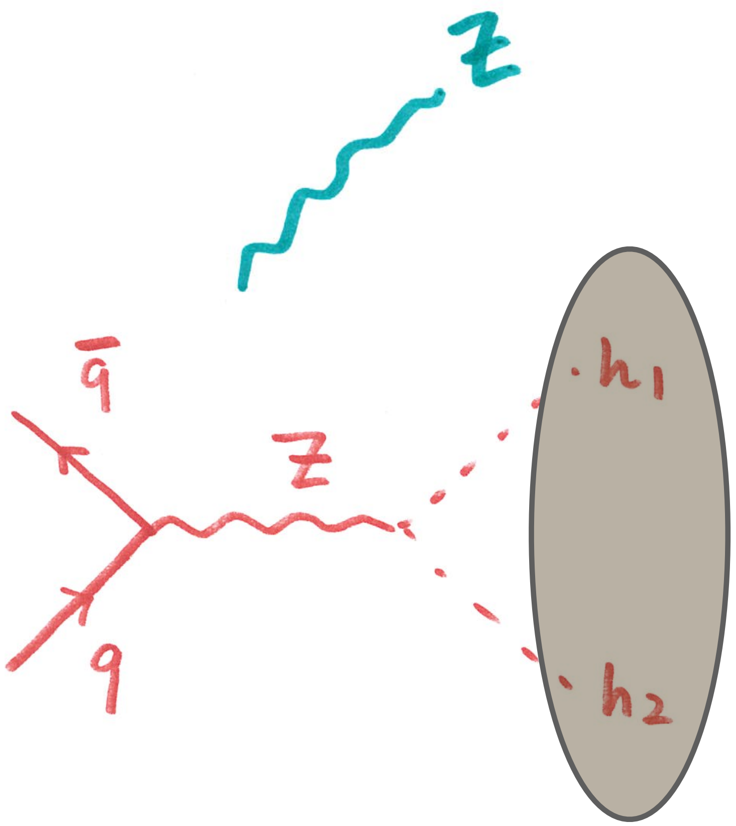
IDM$_{Z2}$

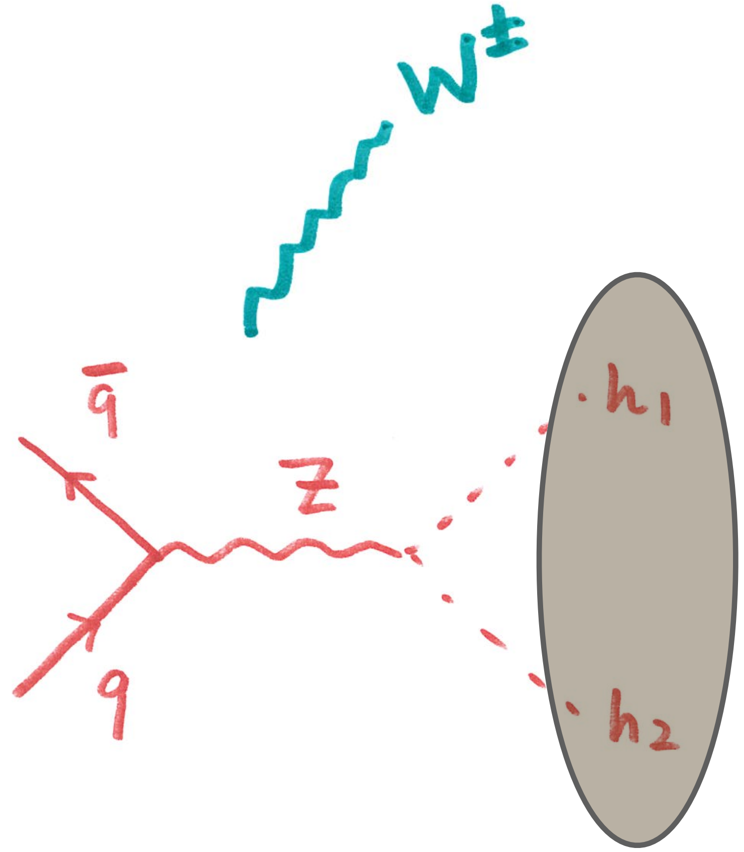
- **One DM particle,** h_1**.**
- $M_{h_1} = M_{h_2}$**: broken at loop level.**
- $M_{H^\pm}$**: much heavier than the DM mass.**

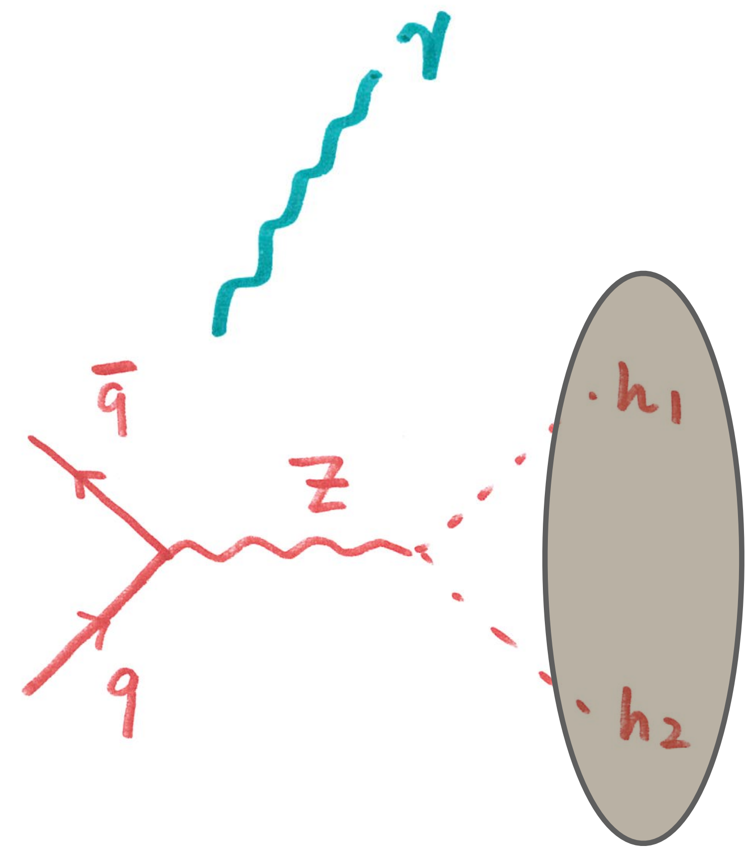
IDM$_{U(1)}$

- **Two DM particles,** h_1 **or** h_2**.**
- $M_{h_1} = M_{h_2}$**: protected by** $U(1)$ **symmetry**
- $M_{H^\pm}$**: within** ~ 90 GeV **from the DM mass.**

IDM$_{U(1)}$



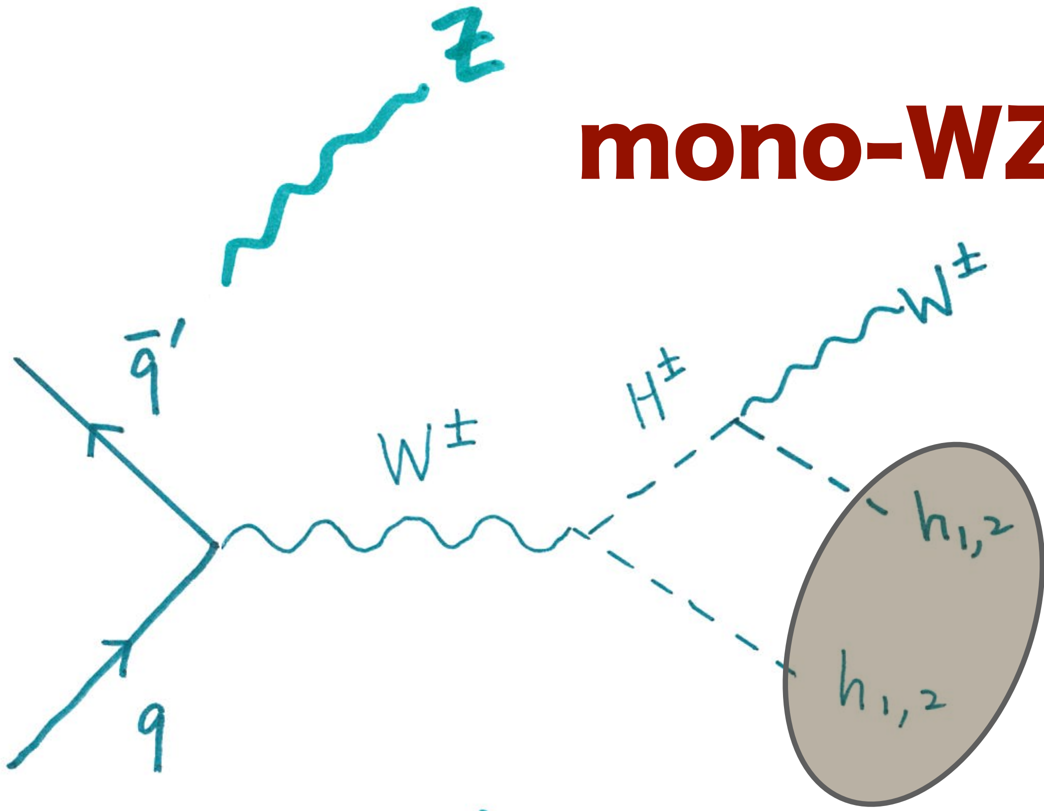




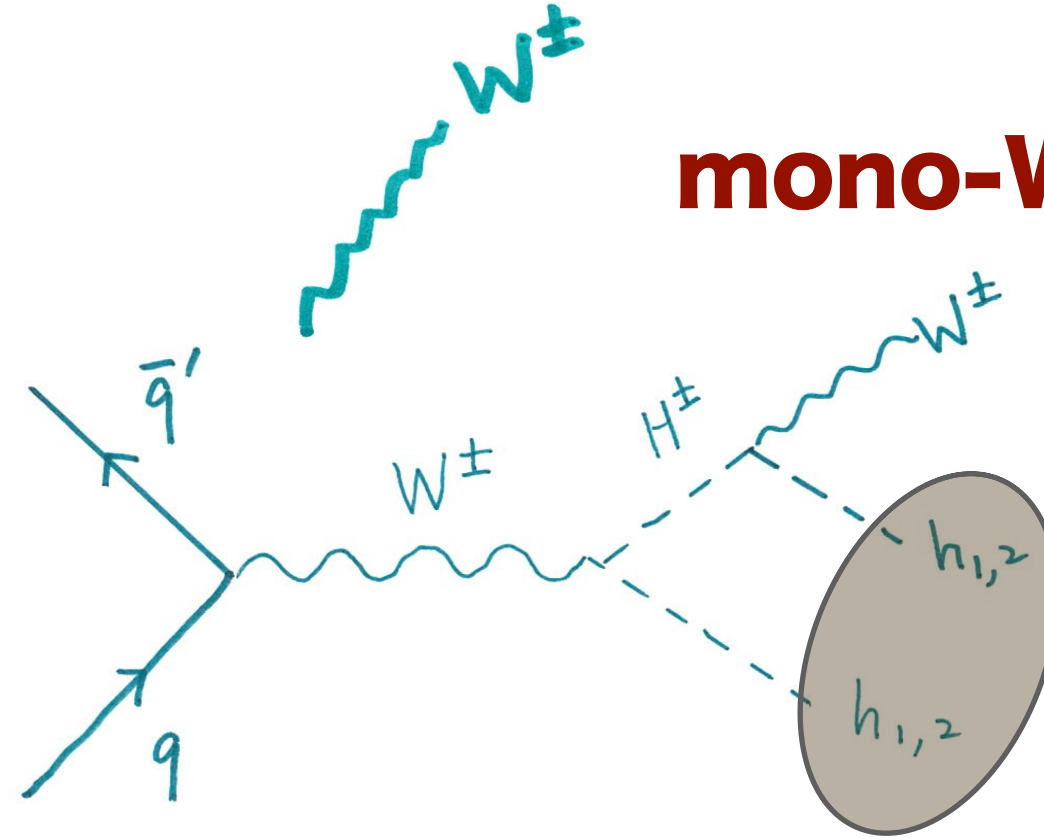
mono-Z **mono-W** **mono-γ**

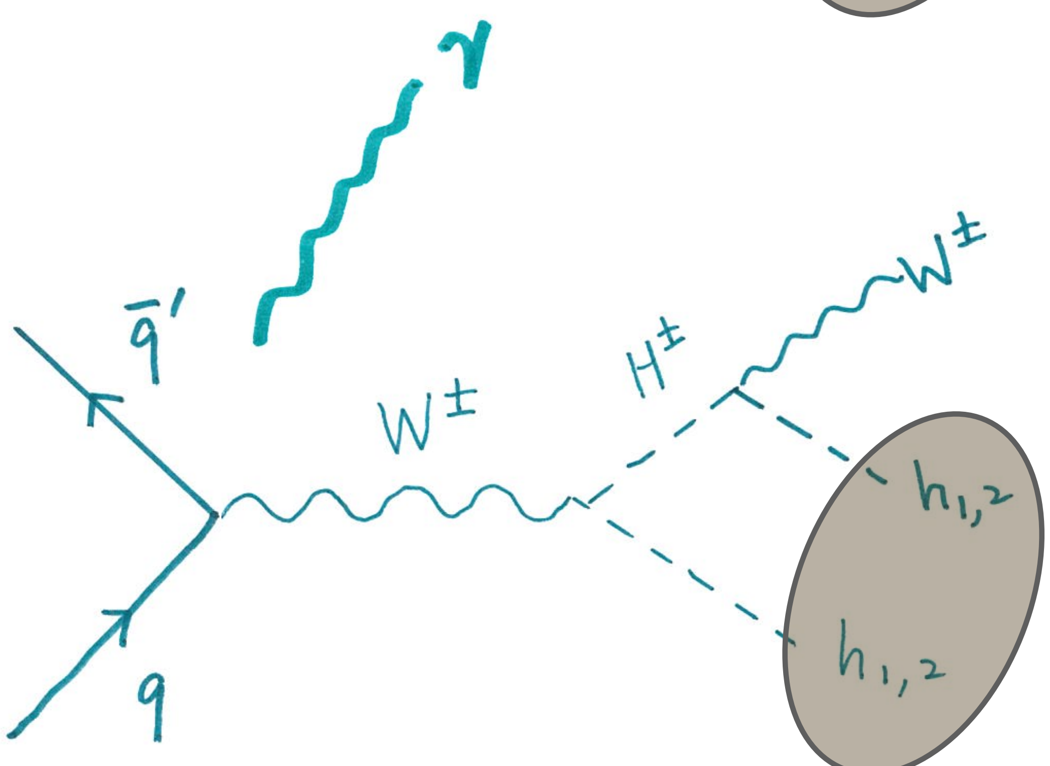
$IDM_{U(1)}$

mono-WZ

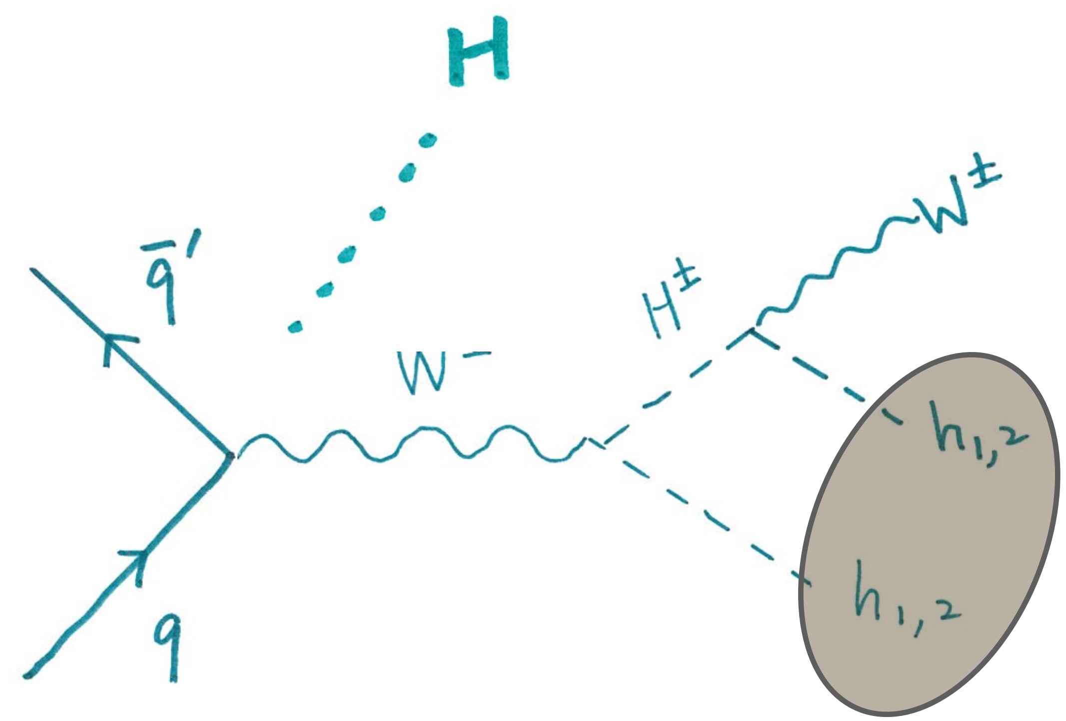


mono-WW

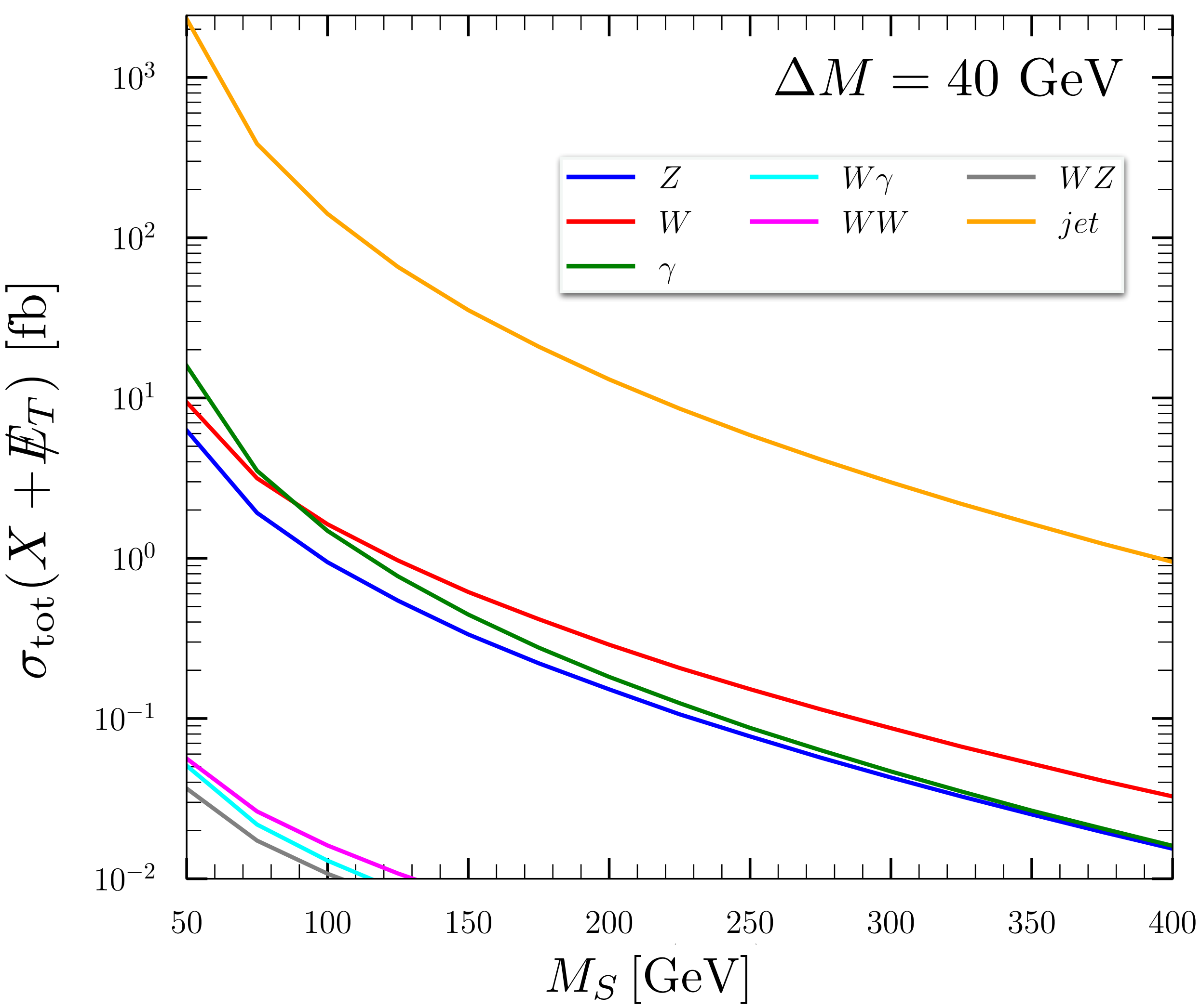


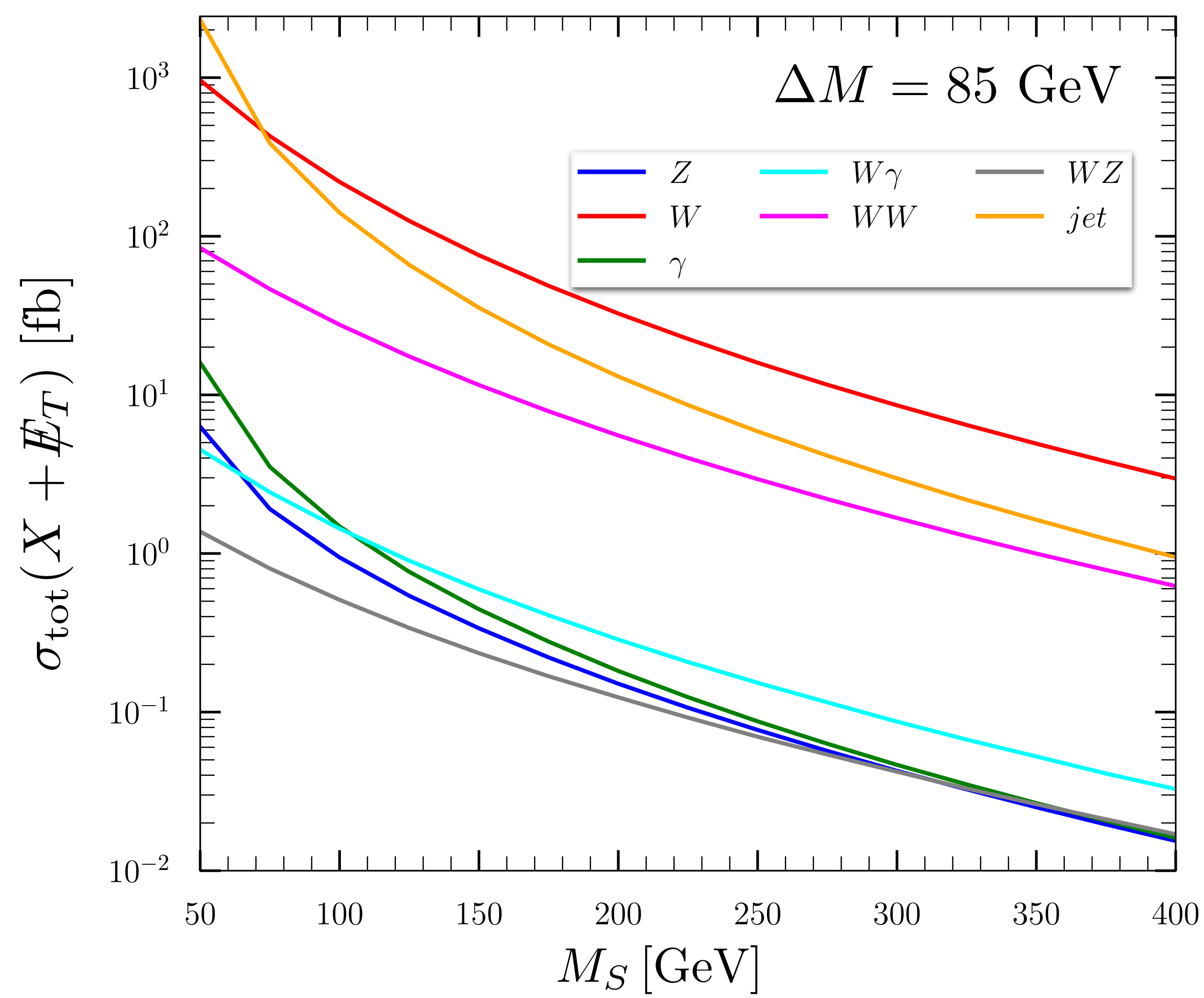


mono-Wγ

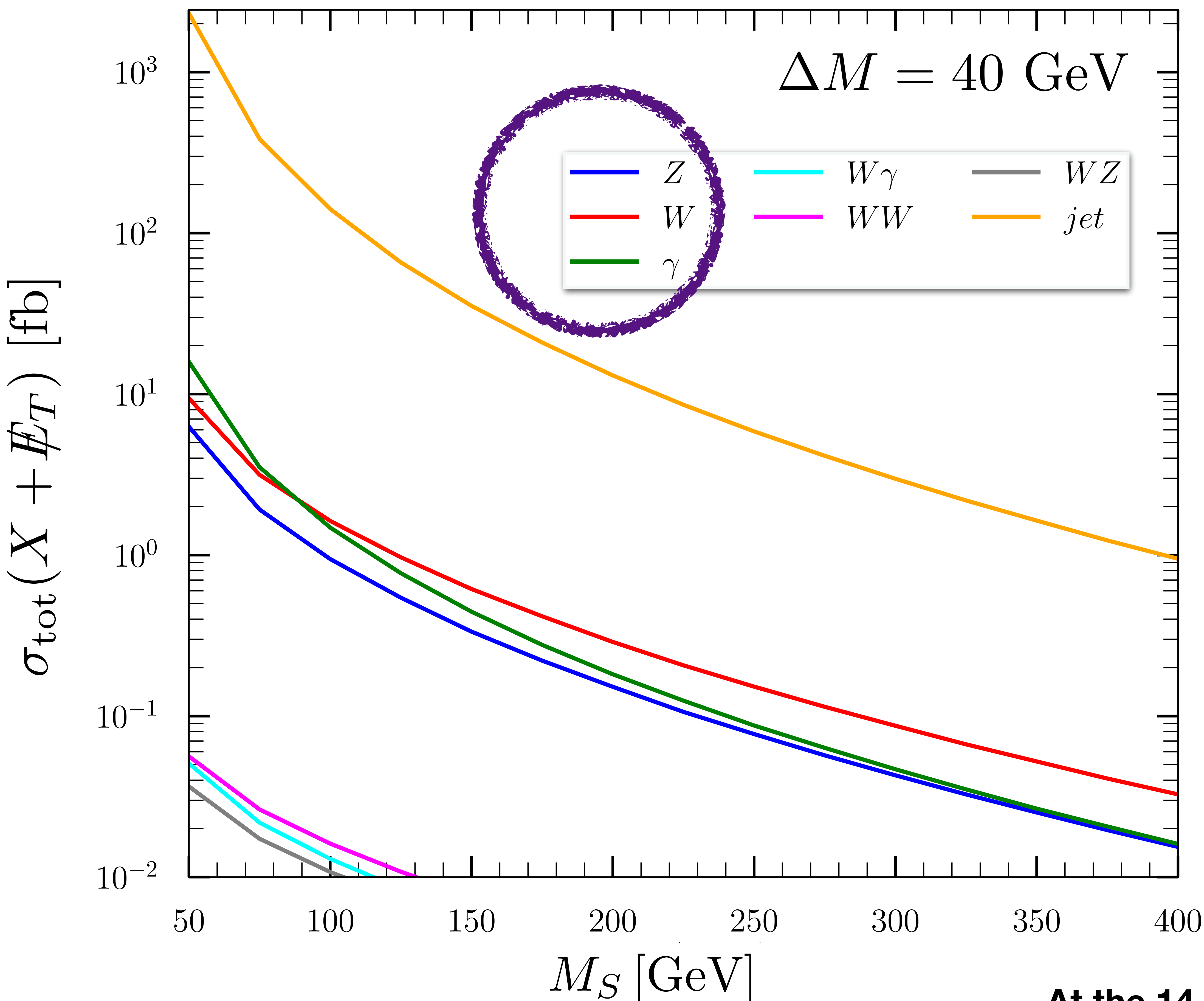


mono-WH

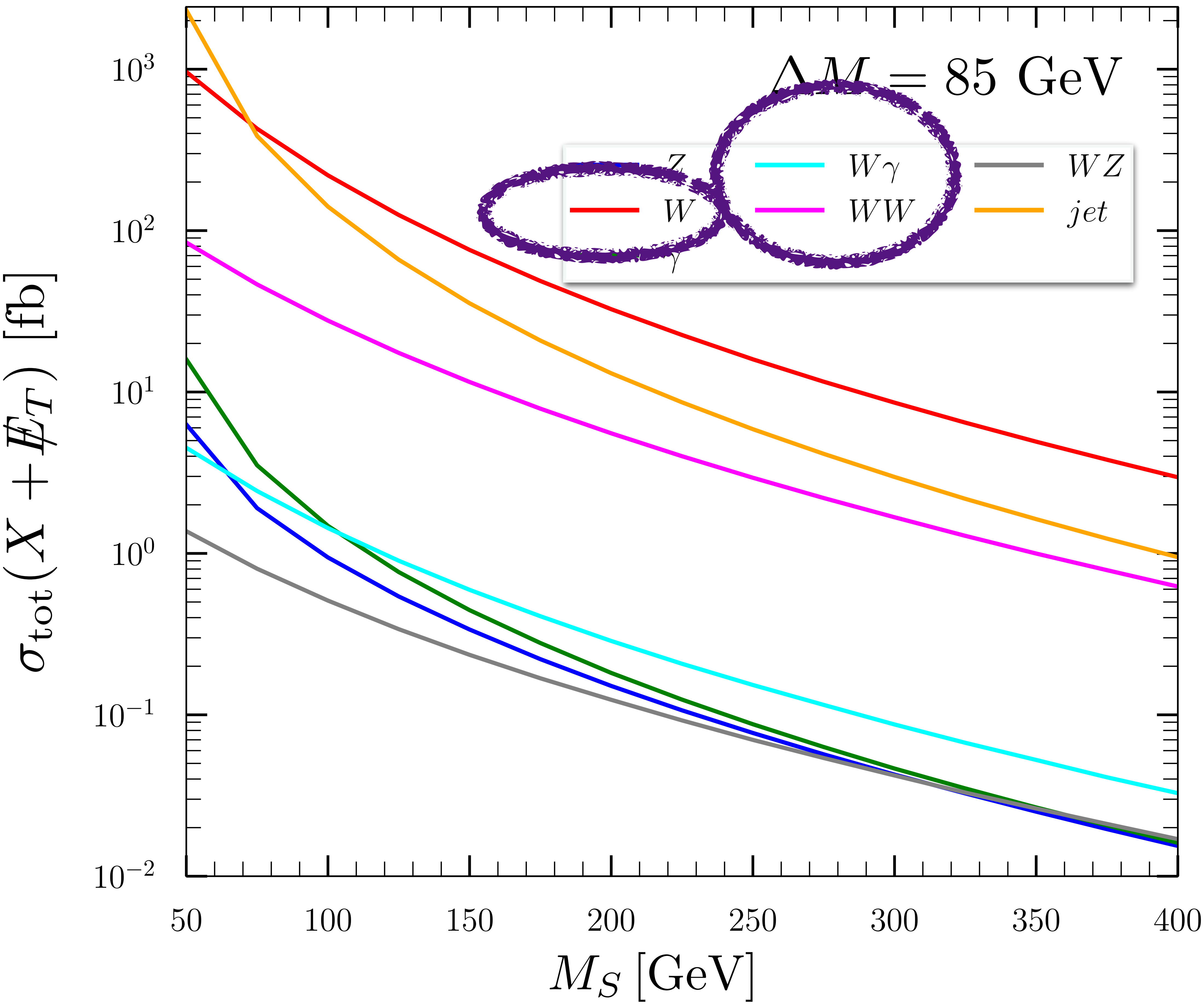




At the 14 TeV LHC



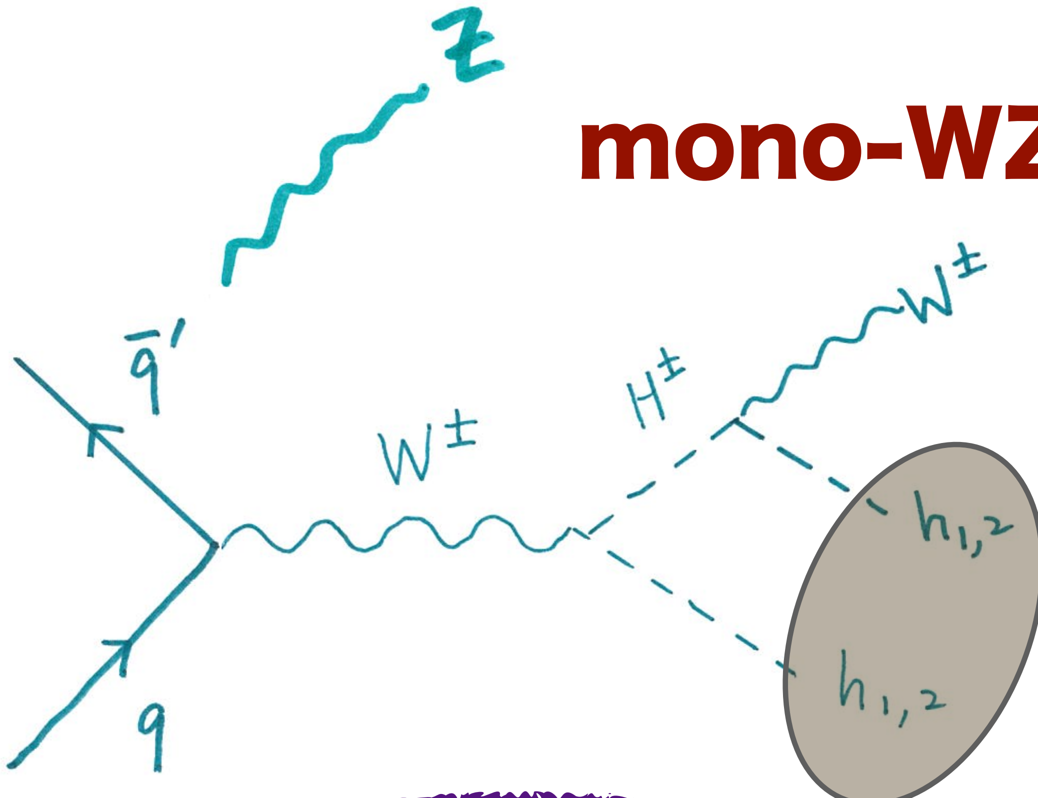
At the 14 TeV LHC



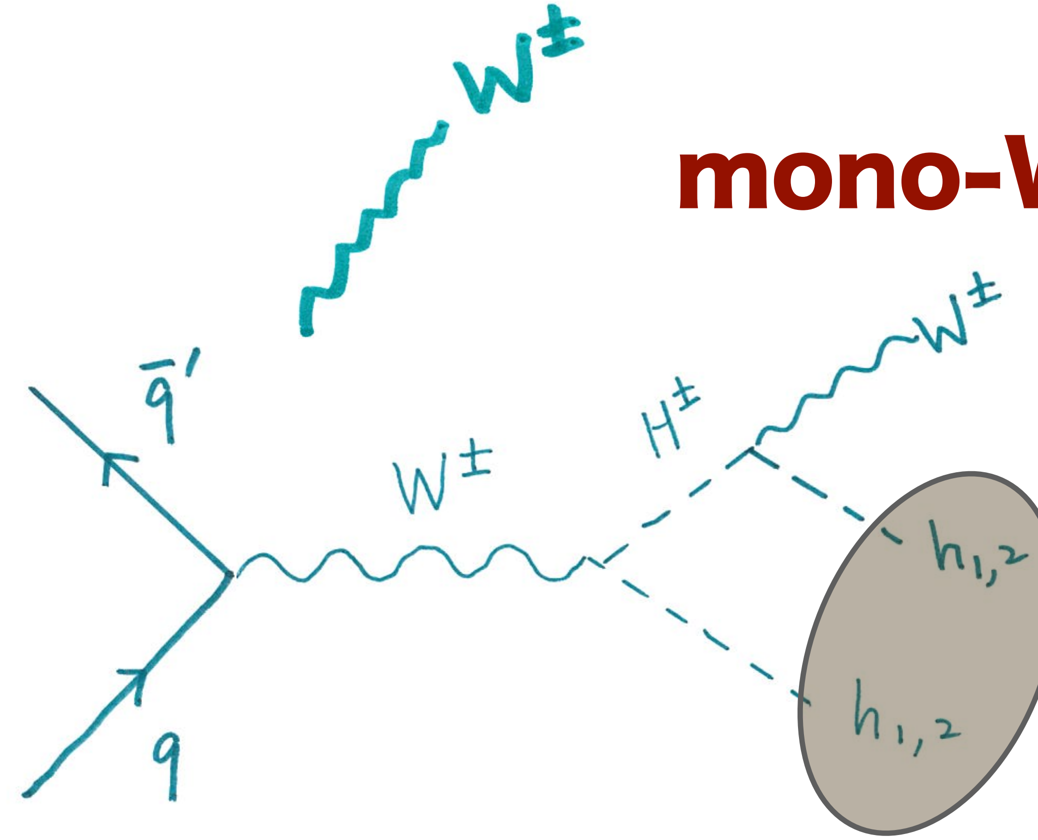
$\Delta M = 85$ GeV
Z
W
γ
$W\gamma$
WW
WZ
jet
$\sigma_{\rm tot}(X + \not{E}_T)$ [fb]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
50
100
150
200
250
300
350
400
M_S [GeV]

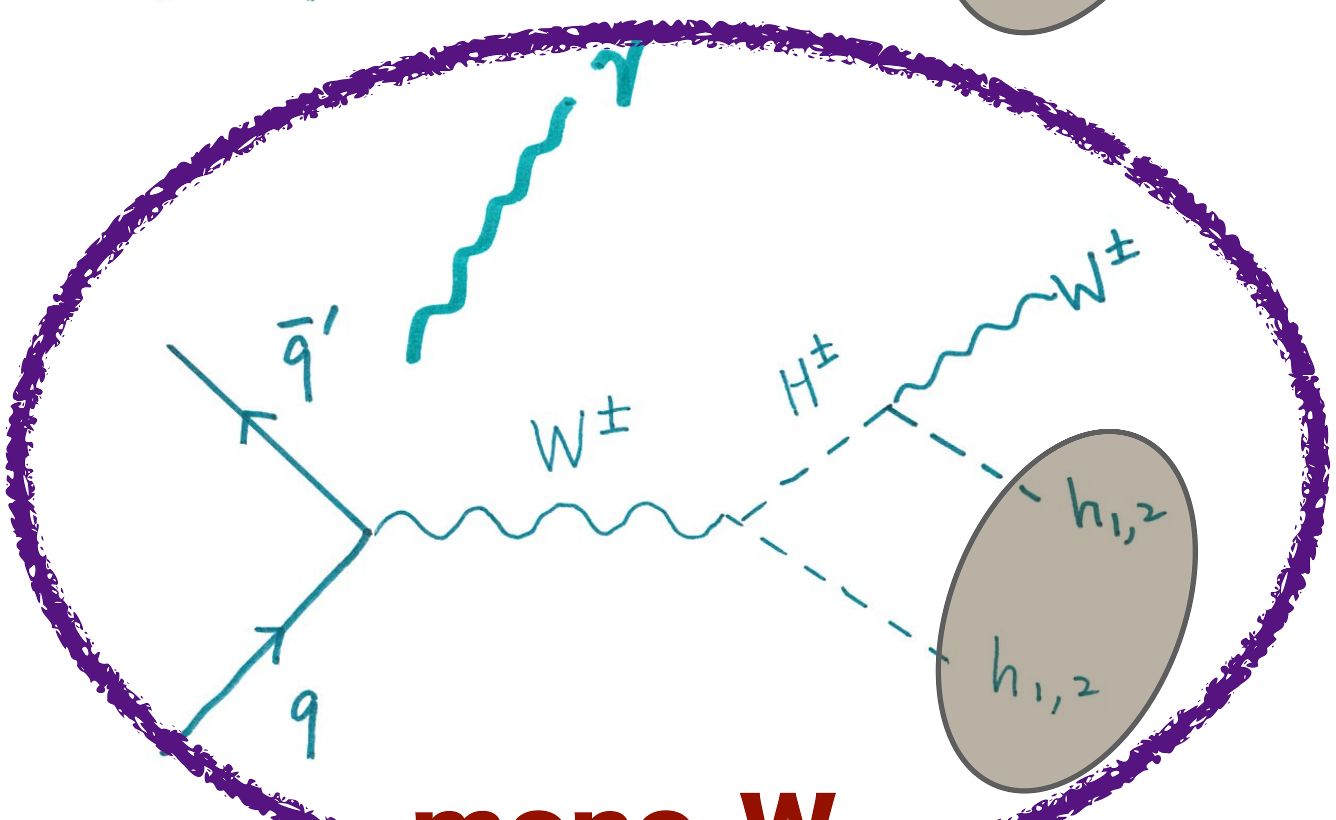
$IDM_{U(1)}$

mono-WZ

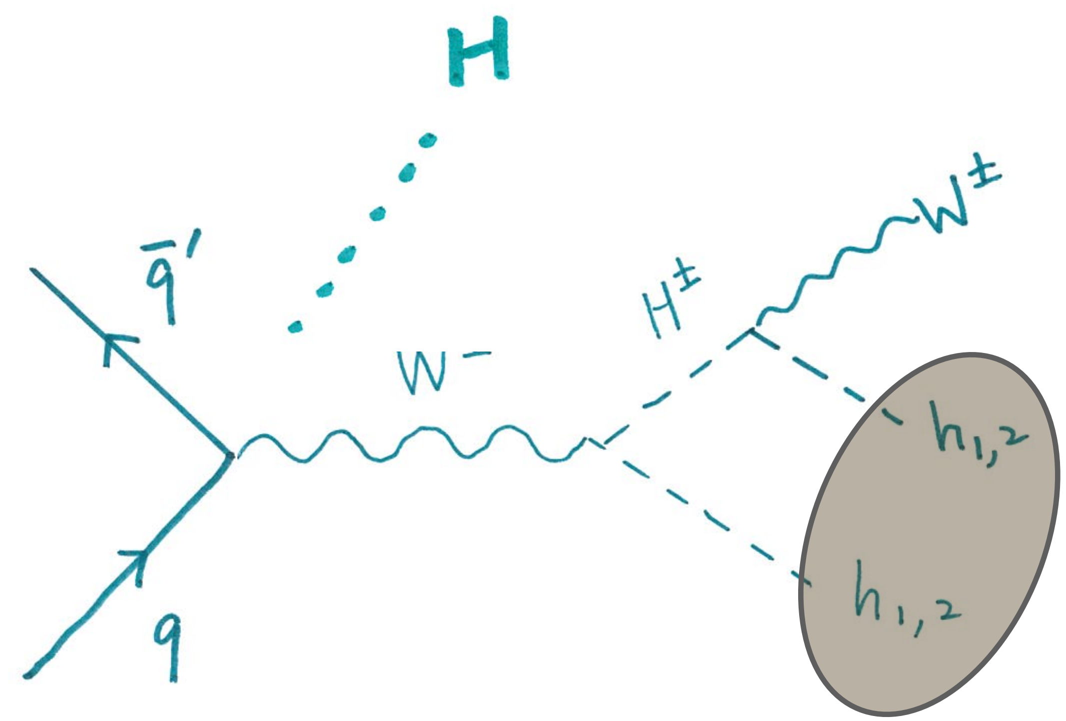


mono-WW





mono-Wγ



mono-WH

$$\boxed{pp \to W^{\pm}(\to q\bar{q}')\gamma + E_T^{\text{miss}}.}$$

- Irreducible backgrounds:
  - $Z(\to \bar{\nu}\nu)\gamma + \text{jets}$;
  - $Z(\to \bar{\nu}\nu)Z(\to \bar{q}q)\gamma$;
  - $W^{\pm}(\to \bar{q}q')Z(\to \bar{\nu}\nu)\gamma$.
- Reducible backgrounds
  - $W^{\pm}(\to \ell^{\pm}_{\text{esc}}\nu)\gamma + \text{jets}$;
  - $W^{\pm}(\to \ell^{\pm}_{\text{esc}}\nu)W^{\mp}(\to \bar{q}q')\gamma$ and $W^{\pm}(\to \ell^{\pm}_{\text{esc}}\nu)Z(\to q\bar{q})\gamma$;
  - $t\bar{t}\gamma$, followed by the semi-leptonic decay of the $t\bar{t}$ pair.

14 TeV LHC with the luminosity 3/ab

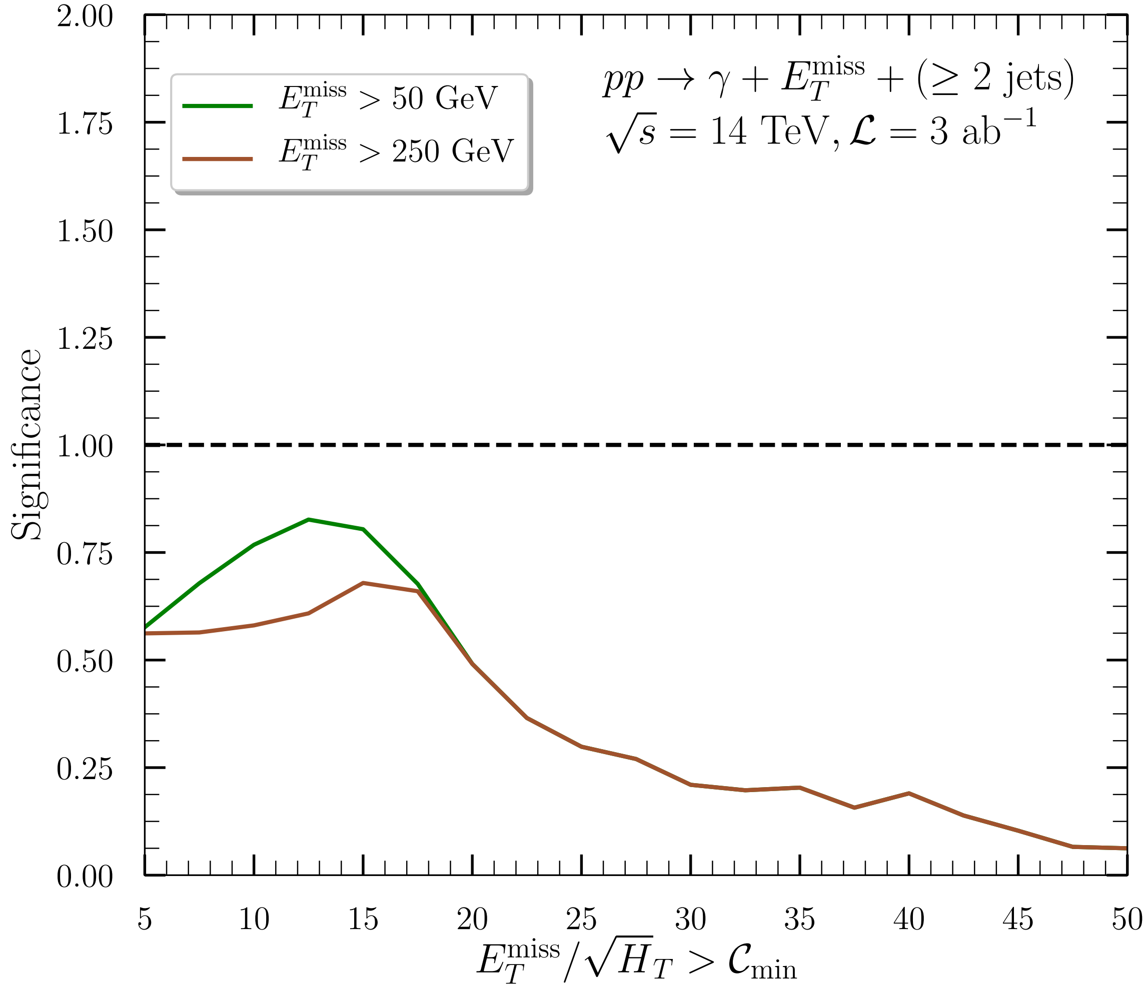
Selection	Signal	$V\gamma$ + jets	$t\bar{t}\gamma$	$VV\gamma$	$n_s/\sqrt{n_b}$
Initial events	9.69×10^3	2.04×10^8	2.14×10^6	2.56×10^6	2.54×10^{-3}
$n_\gamma \geq 1, n_j \geq 2$	1.90×10^3	1.40×10^7	7.60×10^5	4.48×10^5	6.83×10^{-3}
Lepton veto	1.89×10^3	9.38×10^6	4.02×10^5	3.72×10^5	1.02×10^{-2}
b-tag veto	1.77×10^3	8.94×10^6	1.40×10^5	3.30×10^5	1.03×10^{-2}
$\Delta R_{j_1 j_2} < 1$	5.85×10^2	1.99×10^6	8.16×10^5	1.01×10^5	1.48×10^{-2}
$\|M_{j_1 j_2} - m_W\| < 10$ GeV	1.49×10^2	1.08×10^5	1.30×10^4	2.21×10^4	5.71×10^{-2}

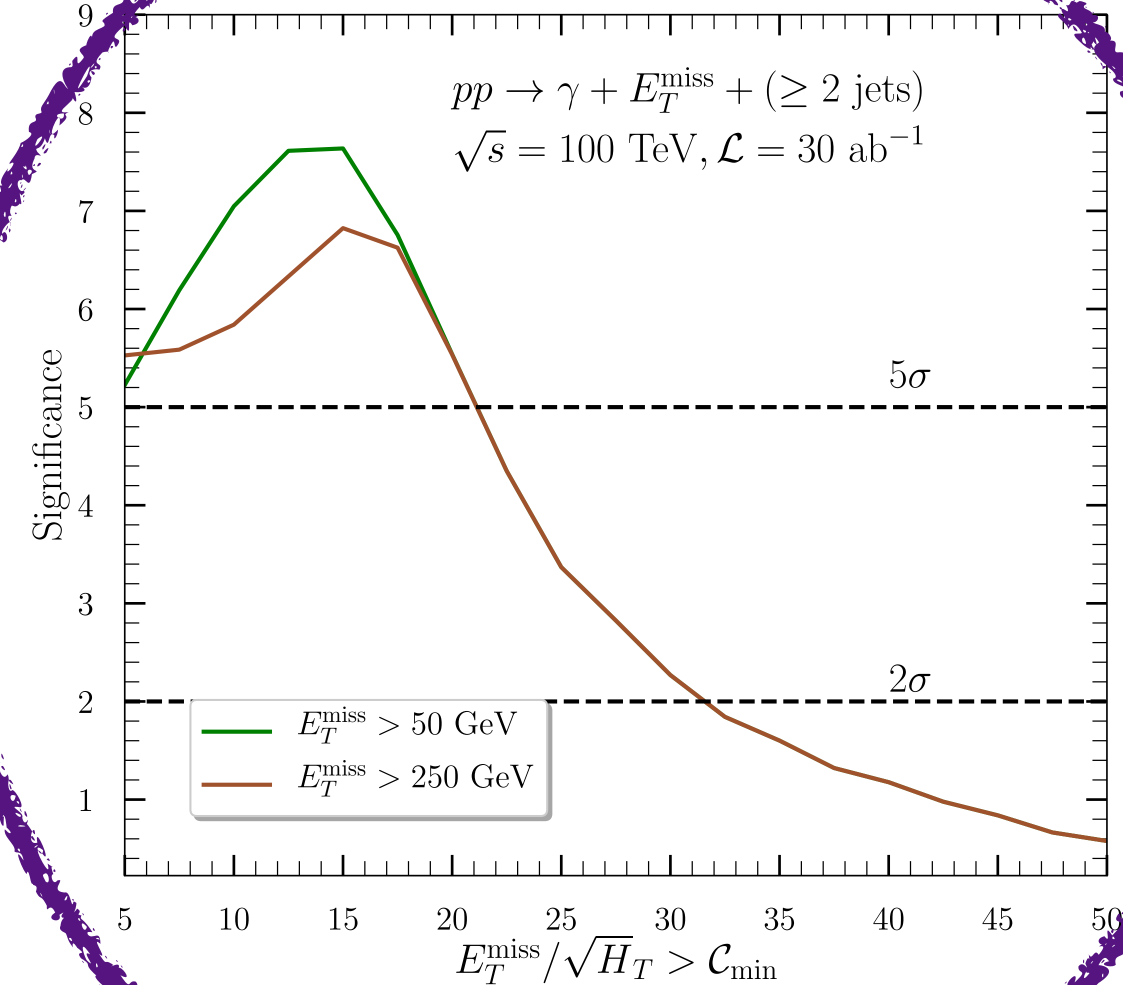
$\boxed{\text{for the FCC-hh at } \sqrt{s} = 100 \text{ TeV and } \mathcal{L} = 30 \text{ ab}^{-1}}$

Selection	Signal	$V\gamma + \text{jets}$	$t\bar{t}\gamma$	$VV\gamma$	$n_s/\sqrt{n_b}$
Initial events	8.82×10^5	1.23×10^{10}	8.70×10^8	1.76×10^8	1.15×10^{-2}
$n_\gamma \geq 1, n_j \geq 2$	1.71×10^5	1.46×10^9	3.36×10^8	3.13×10^7	1.62×10^{-2}
Lepton veto	1.71×10^5	8.73×10^8	1.67×10^8	2.55×10^7	2.78×10^{-2}
b-tag veto	1.64×10^5	8.33×10^8	5.65×10^7	2.30×10^7	3.11×10^{-2}
$\Delta R_{j_1 j_2} < 1$	6.23×10^4	2.09×10^8	3.38×10^7	7.97×10^6	4.31×10^{-2}
$\lvert M_{j_1 j_2} - m_W \rvert < 10$ GeV	1.86×10^4	1.66×10^7	6.64×10^6	2.02×10^6	1.28×10^{-1}

Efficient kinematic variable!
Purified MET

$$\mathcal{P}_{E_T^{\rm miss}} = \frac{E_T^{\rm miss}}{\sqrt{H_T}}.$$


$pp \to \gamma + E_T^{\rm miss} + (\geq 2 \text{ jets})$
$\sqrt{s} = 14$ TeV, $\mathcal{L} = 3$ ab^{-1}
$E_T^{\rm miss} > 50$ GeV
$E_T^{\rm miss} > 250$ GeV
Significance
$E_T^{\rm miss}/\sqrt{H_T} > \mathcal{C}_{\rm min}$


$pp \to \gamma + E_T^{\rm miss} + (\geq 2 \text{ jets})$
$\sqrt{s} = 100$ TeV, $\mathcal{L} = 30$ ab^{-1}
5σ
2σ
$E_T^{\rm miss} > 50$ GeV
$E_T^{\rm miss} > 250$ GeV
Significance
$E_T^{\rm miss}/\sqrt{H_T} > \mathcal{C}_{\rm min}$

7. Conclusions

- IDM with U(1) is well-motivated simple model for DM.
- There are two DM particles, neutral scalar and pseudo-scalar bosons, because the mass degeneracy between them is protected by U(1).
- mono-W+photon shall lead to smoking-gun signatures at the FCC-hh.