October 19th, 2022

IRN Terascale & GDR DUPhy, Nantes

Dark matter indirect detection limits including complete annihilation patterns

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Based on 2210.01220 [hep-ph]

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cnrs

Enigmass
The enigma of mass

DARK MATTER

85% of the total matter of our Universe

Relic density observed experimentally by Planck:

$$\Omega_\chi h^2 \simeq 0.1200 \pm 0.0012$$

Ref: Ade et al. 2016, Astrophys. 594, A13

Its identification would **reveal new Physics**

Proving its existence and nature would **improve our understanding** of the Universe

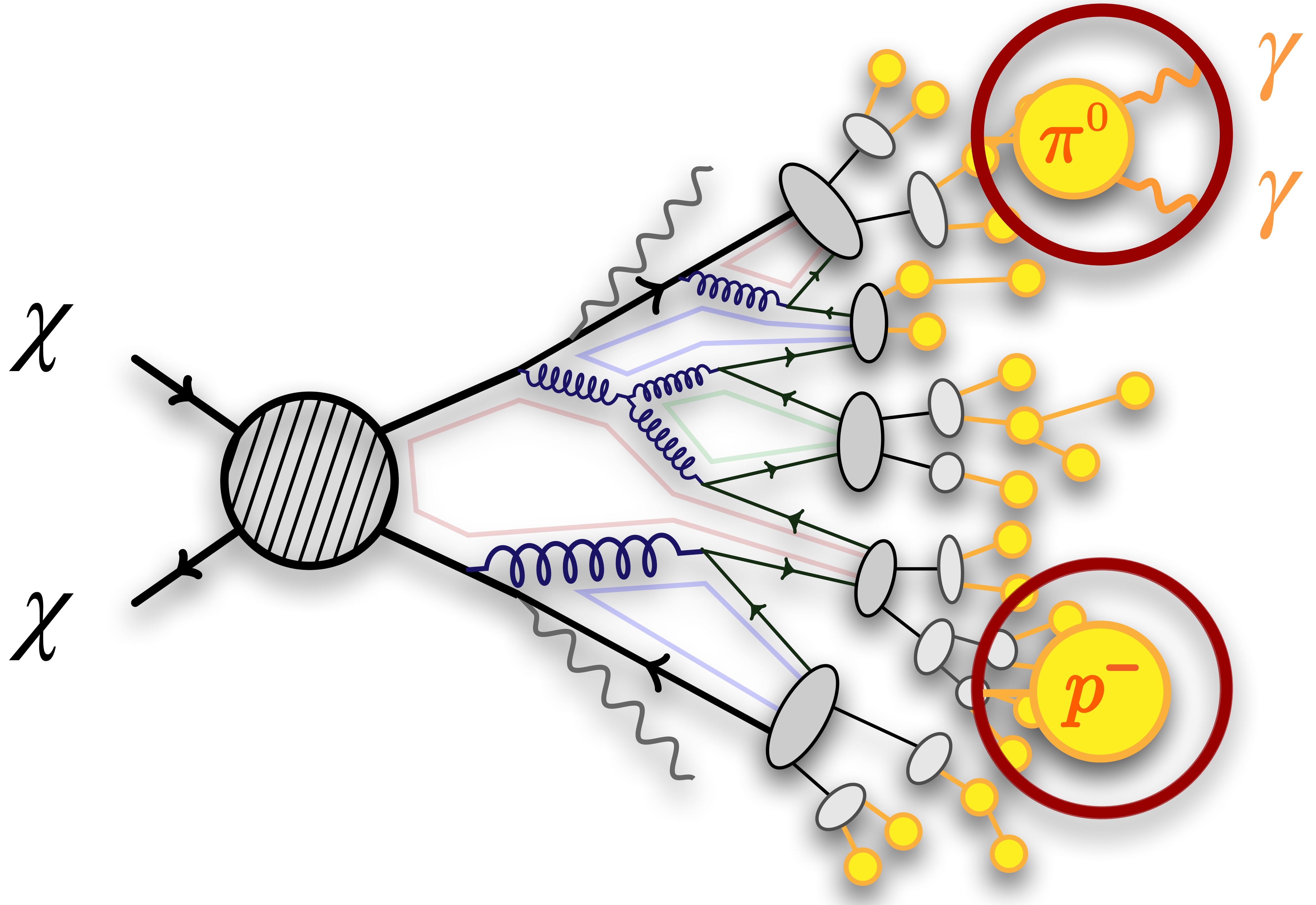
GOALS

Study of the impact of a more complete particle model

New prediction of DM upper limits with CTA mockdata of Sculptor

- **Previously:** use of individual annihilation channels
- **This work:** Collaboration with a theoretician to include a more complex and more complete model

INDIRECT **SEARCHES**



Dark Matter (DM) annihilation → Standard Model particles (bosons, quarks, leptons) → Final state products such as γ rays

INDIRECT **SEARCHES**

INDIRECT SEARCHES

Expected γ-ray flux from DM annihilation

$$\frac{d\Phi\left(\langle\sigma v\rangle, J\right)}{dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_f \mathrm{BR}_f \frac{\mathrm{d}N_f}{\mathrm{d}E} \times \int_{\Delta\Omega}\int_{\mathrm{los}} \rho_{\mathrm{DM}}^2 ds d\Omega$$

Particle Physics
factor

Astrophysical
J factor

where

- **<σv>** = annihilation cross-section
- **m_χ** = DM particle mass
- **BR_f** = branching ratio
- **dN_f/dE** = differential spectrum
- **ρ_{DM}** = DM density

STATISTICAL ANALYSIS

STATISTICAL ANALYSIS

LOG-LIKELIHOOD RATIO TEST STATISTICS

Constrained minimization

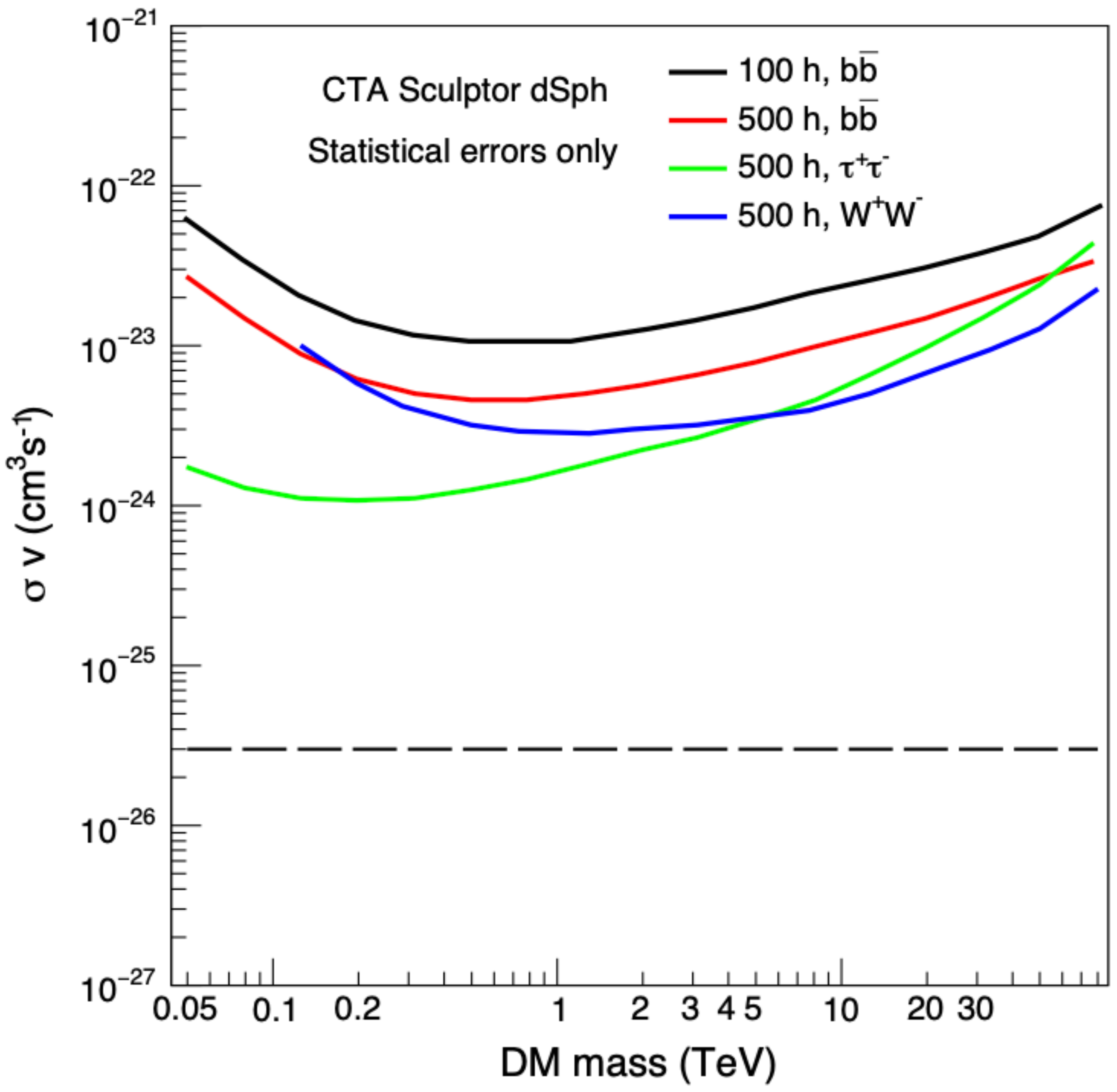
$$\Lambda = -2\ln\frac{\mathscr{L}_{H_0}}{\mathscr{L}_{H_1}} = -2\ln\frac{\mathscr{L}(\langle\sigma v\rangle_0\,|\,\hat{\hat{N}}_B,\hat{\hat{J}})}{\mathscr{L}(\langle\hat{\sigma v}\rangle,\hat{N}_B,\hat{J})}$$

Global minimization

Ref: Cowan et al, 2010
Eur.Phys.J.C71:1554,2011

<σv>	Parameter of interest
N_B, J	Nuisance parameters
Λ	2.71 at 95% Confidence Level

UPPER LIMITS



- Each annihilation channel **treated independently**
- Corresponding to a **branching ratio of 100%**
- **Simplest** model possible where all DM particles annihilate through the same channel

WHAT IF

We change the particle physics model?

SINGLET SCALAR DARK MATTER

Standard model extended by an additional scalar field (DM)

$$V_{\text{scalar}} \supset 2\lambda_H v^2 h^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_{SH} v^2 S^2 + \frac{1}{4}\lambda_{SH} v S^2 h + \lambda_{SH} S^2 h^2$$

DM mass

$$m_S^2 = \mu_S^2 + \frac{1}{2}\lambda_{SH} v^2$$

DM – Higgs interaction

("Higgs portal")

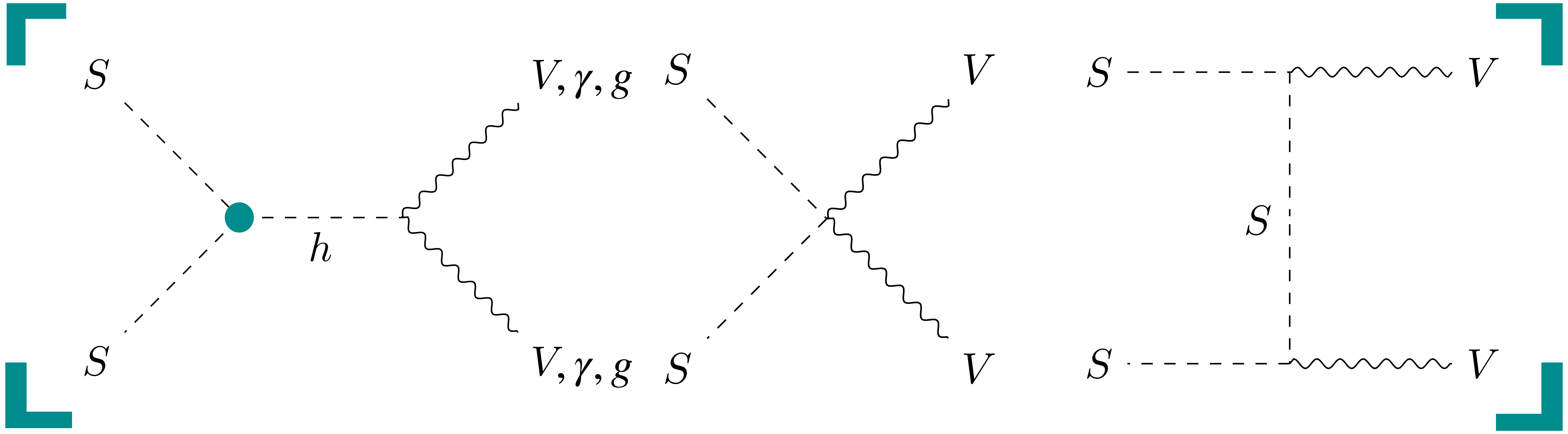
Phenomenology governed by

m_S (DM mass)

λ_{SH} (DM coupling)

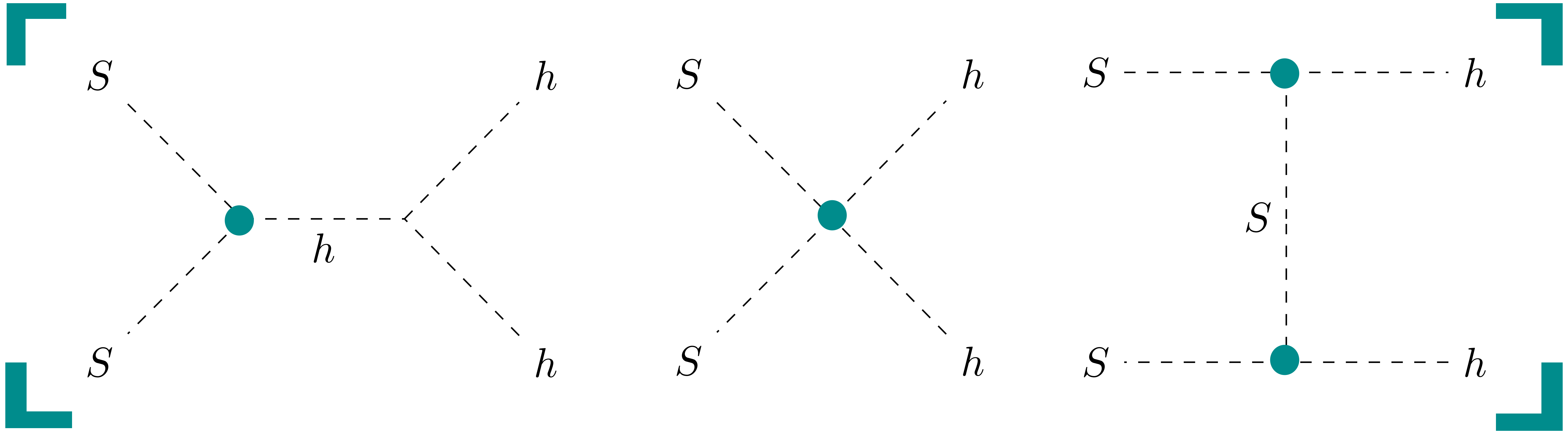
SINGLET SCALAR DARK MATTER

Possible dark matter annihilation channels (DM relic density + indirect detection)

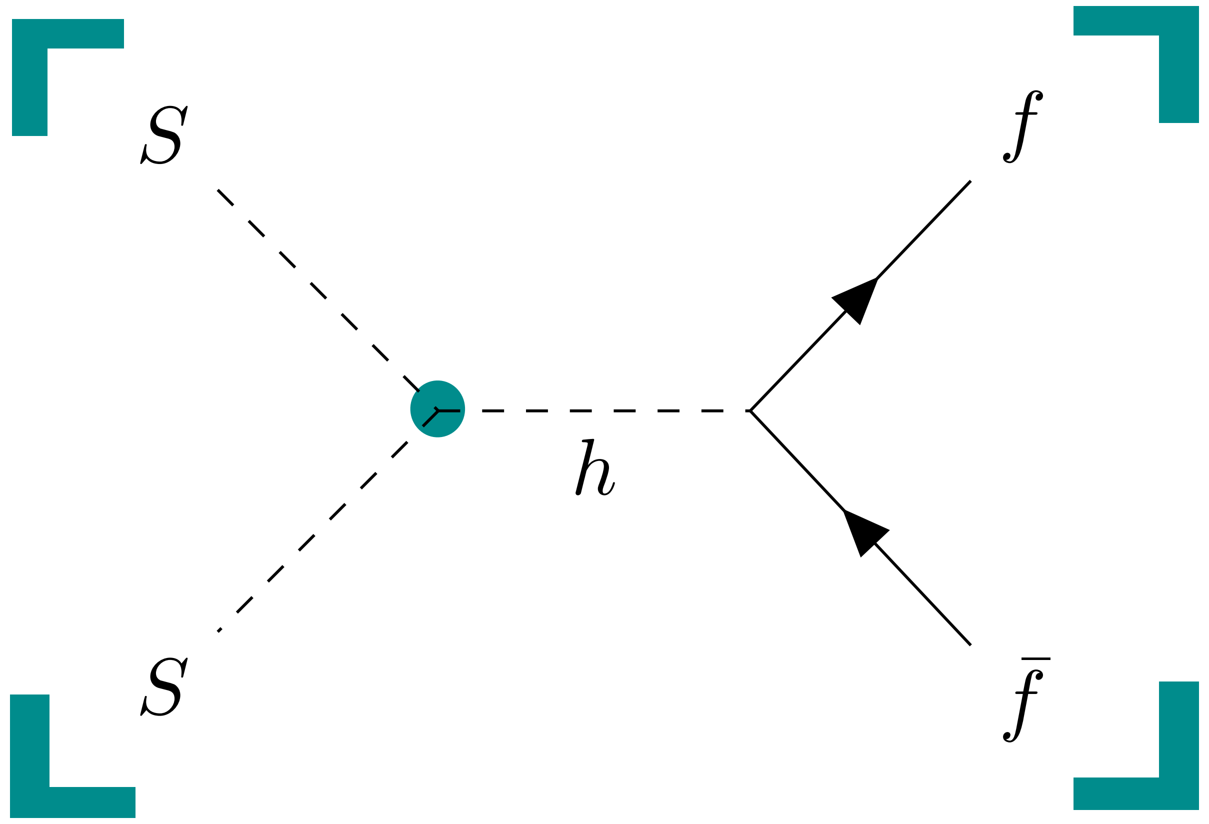


Gauge boson final states

$V = Z^0, W^\pm$



Higgs boson final states



Quark or lepton final states

$f = u, d, c, s, b, t, e, \mu, \tau$

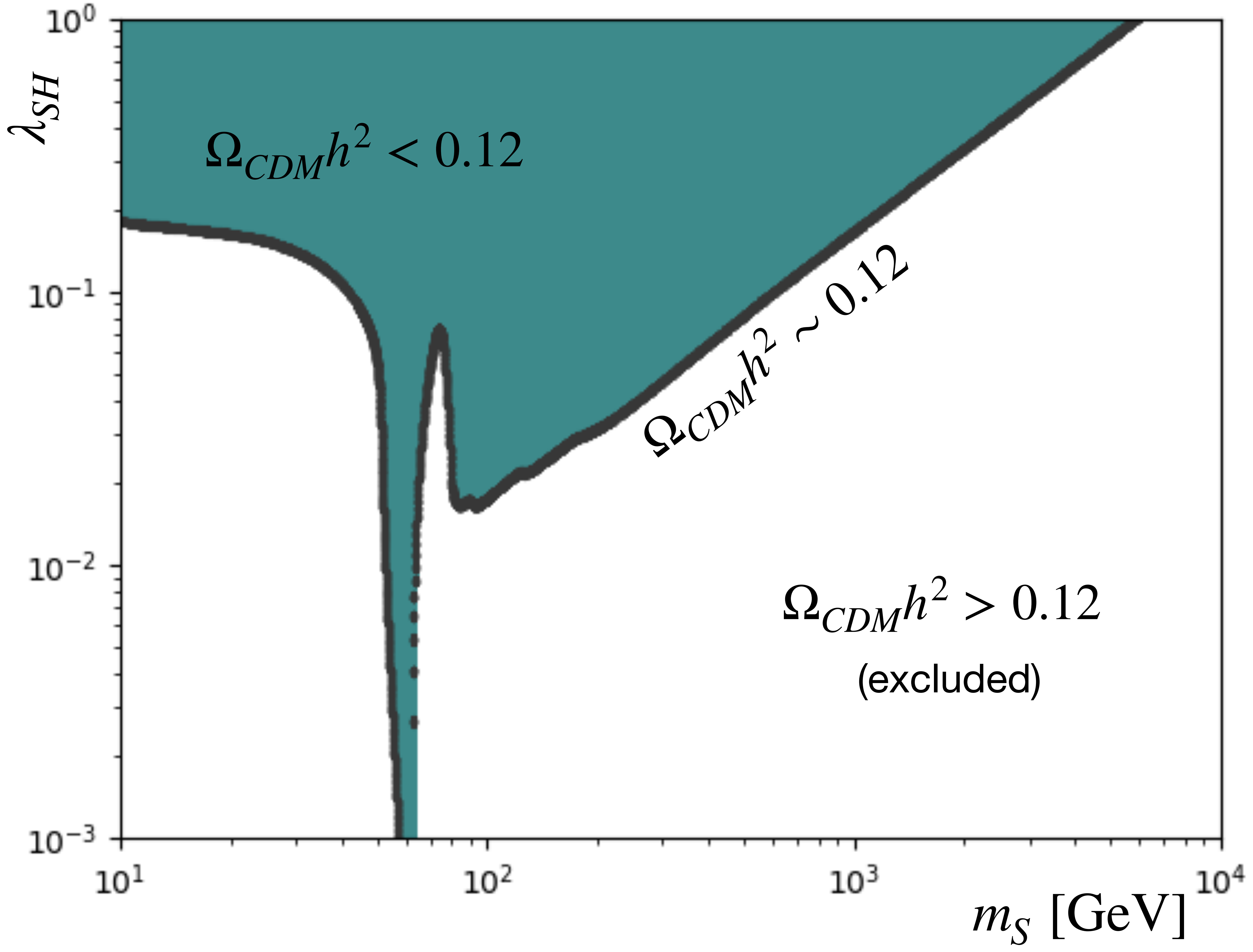
SINGLET SCALAR DARK MATTER

SINGLET SCALAR DARK MATTER

DM coupling vs DM mass

Relic density and branching ratio grid computed using **micrOMEGAs**

Ref: Bélanger, Pukhov et al. 2003 - 2022



SINGLET SCALAR DARK MATTER

DM coupling vs DM mass

Relic density and branching ratio grid computed using **micrOMEGAs**

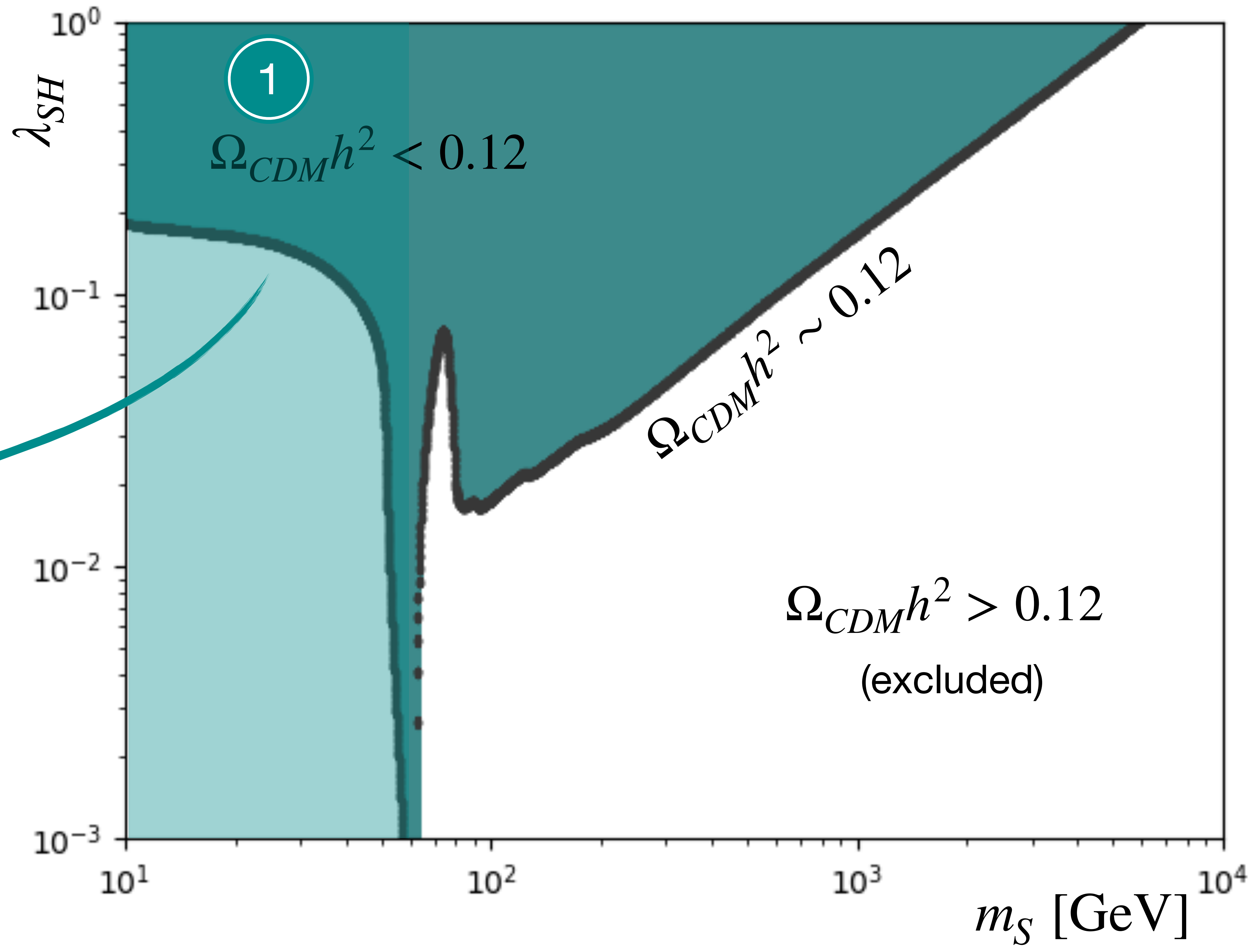
Ref: Bélanger, Pukhov et al. 2002 - 2022

$SS \to b\bar{b}$ $\sim 75 - 85\,\%$

$SS \to \tau^+\tau^-$ $\sim 7 - 10\,\%$

$SS \to c\bar{c}$ $\sim 3 - 4\,\%$

$SS \to gg$ $\sim 3 - 15\,\%$



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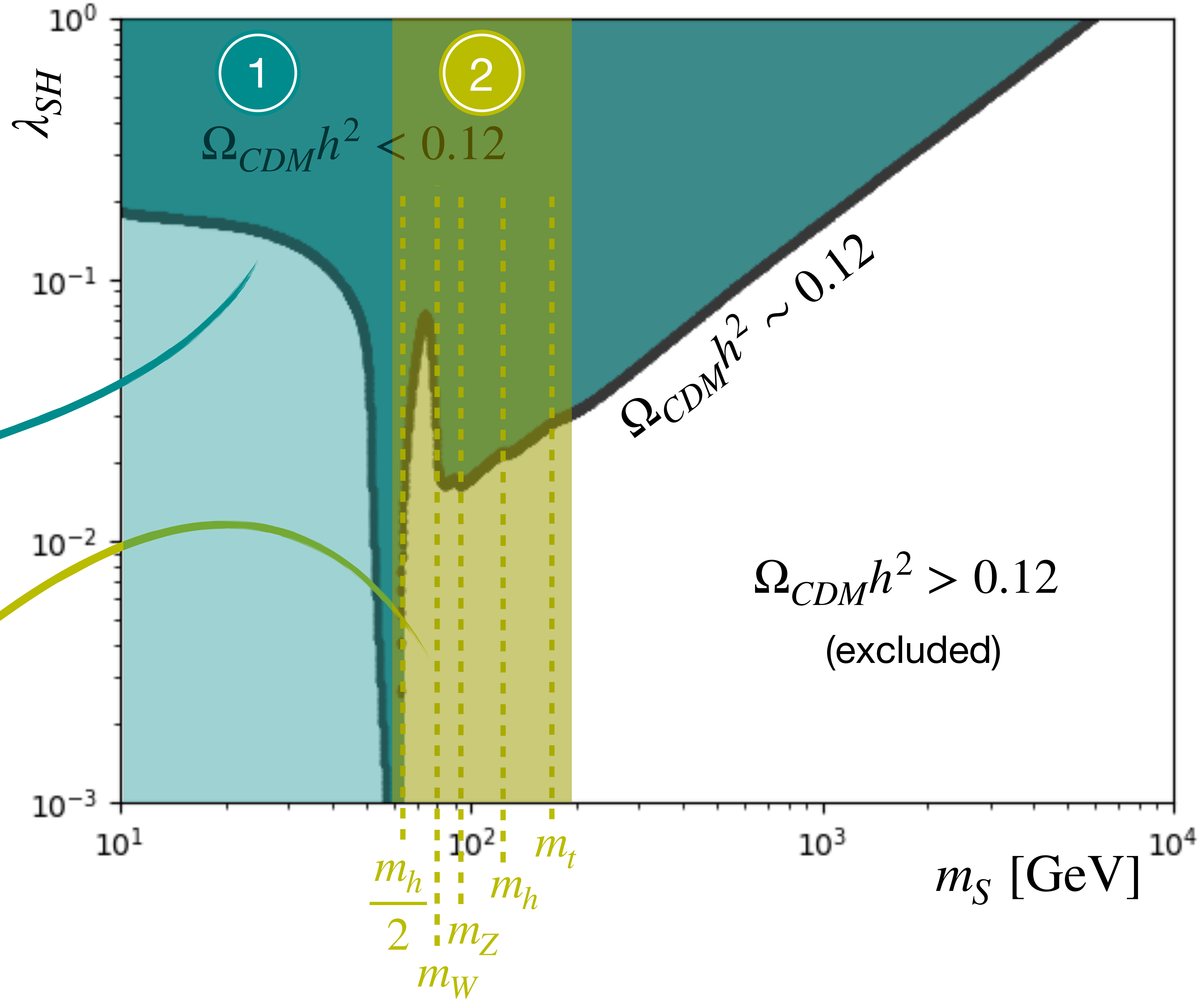
Region of frequent change of the dominant annihilation channel

New annihilation channels open, Higgs resonance at $m_h/2$



SINGLET SCALAR DARK MATTER

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Ref: Bélanger, Pukhov et al. 2002 - 2022

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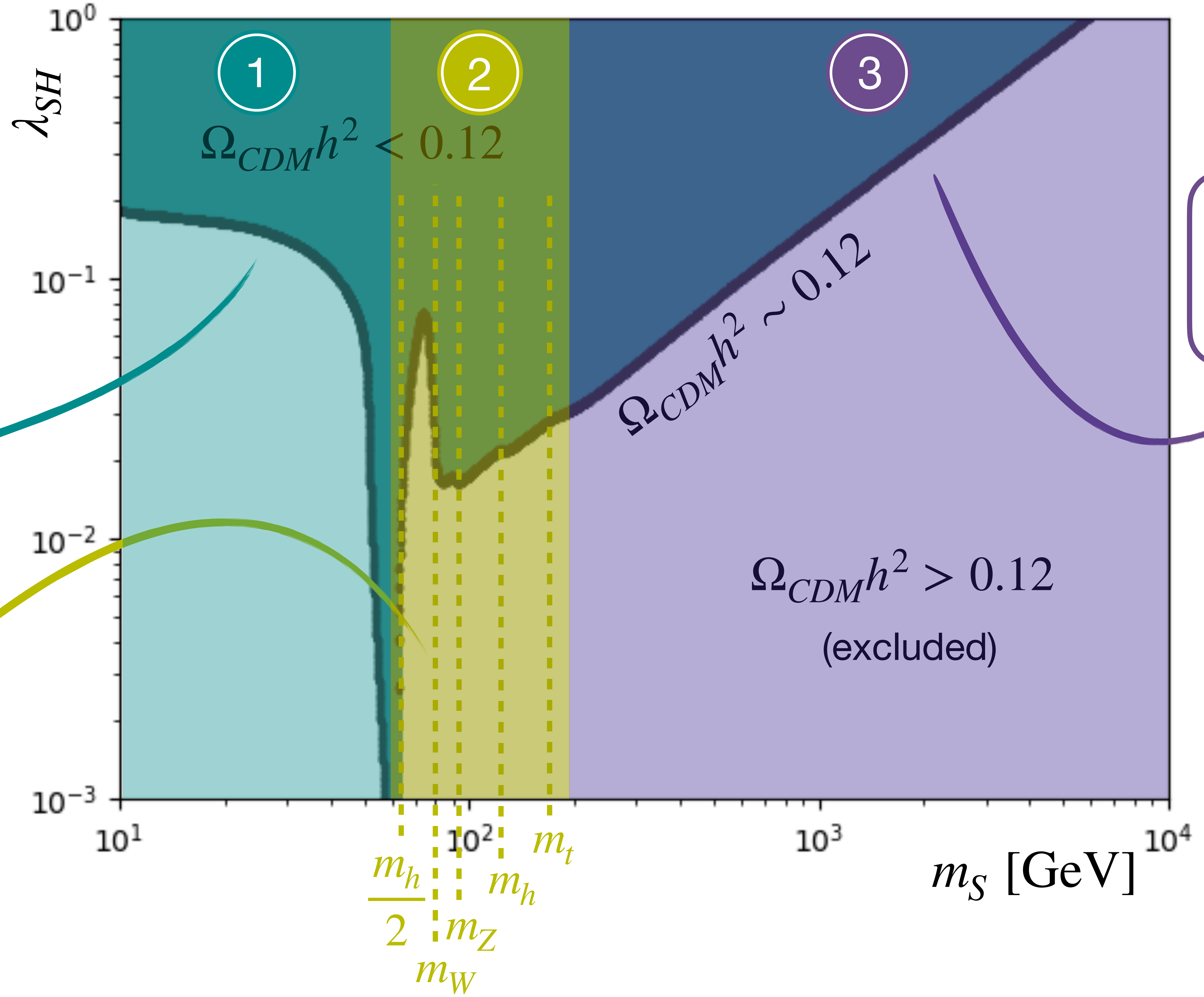
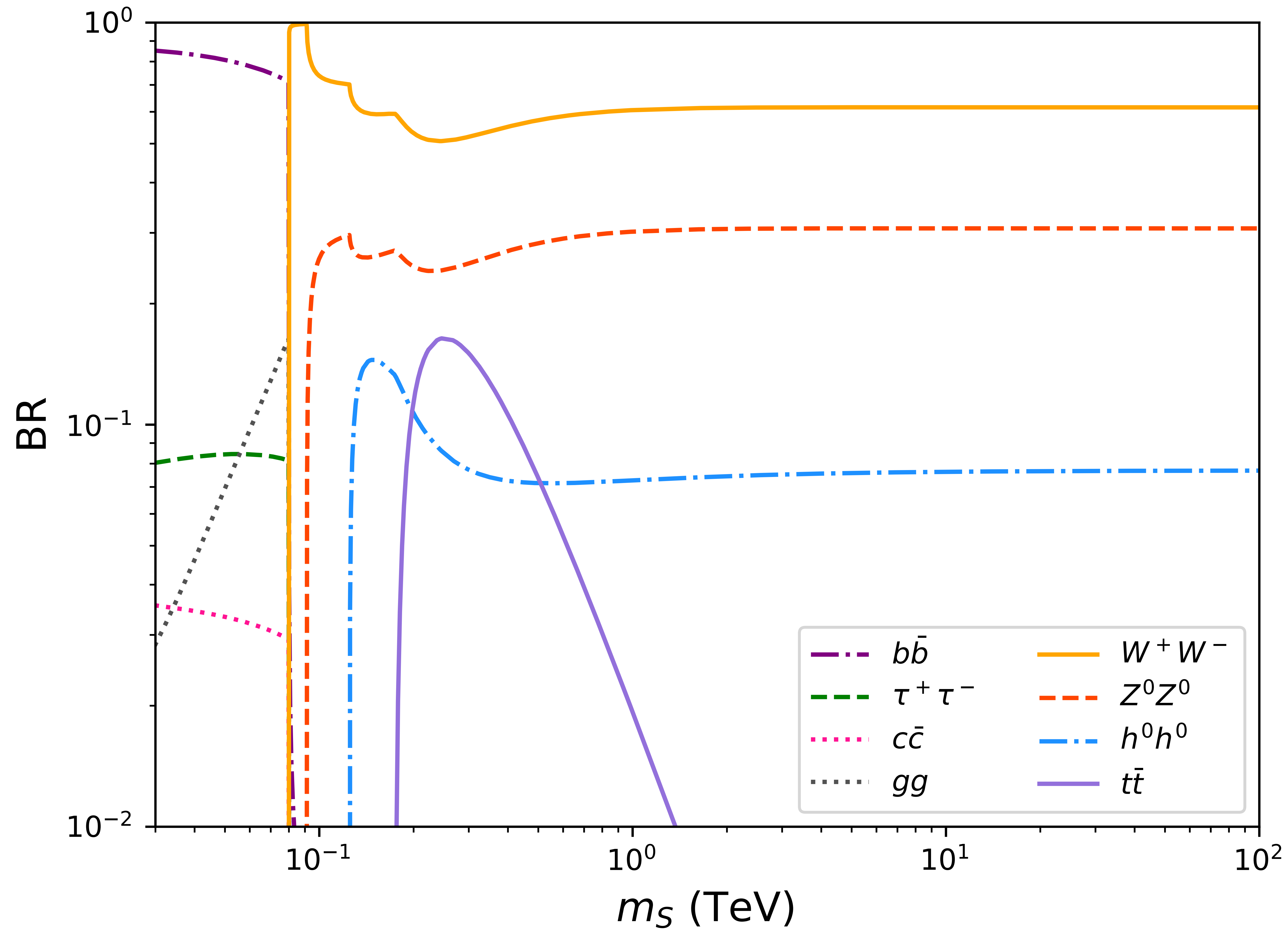


$SS \to W^+W^- \quad \sim 62\,\%$
$SS \to Z^0Z^0 \quad \sim 30\,\%$
$SS \to h^0h^0 \quad \sim 8\,\%$

All annihilation channels treated all together whose branching ratio varies with respect to the DM mass

SINGLET SCALAR DARK MATTER

Branching Ratio according to the relic density constraint



None of the annihilation channels are at 100% branching ratio over the full mass range

For the remaining part, we focus on the case where the relic density constraint is satisfied (black line in previous figure):

$$\Omega_\chi h^2 \simeq 0.1200 \pm 0.0012$$

Even in such a simple setup, the "100% hypothesis" is not justified…

More complex models invoke an even richer phenomenology…

TARGET SOURCE

Sculptor

Dwarf galaxy selected for the CTA dark matter program

South Hemisphere
l = 287.62°, b = -83.16°

J factor
Log10 $J_{0.1} = 18.3 \pm 0.3$

Ref: Bonnivard et al, 2015 ApJ 808 L3

Mock data prepared with Gammapy 0.18.2

Simulated events for 500h of observation at 20° zenith angle

Background only

NEW UPPER LIMITS

Computation of the predicted DM cross section

VS

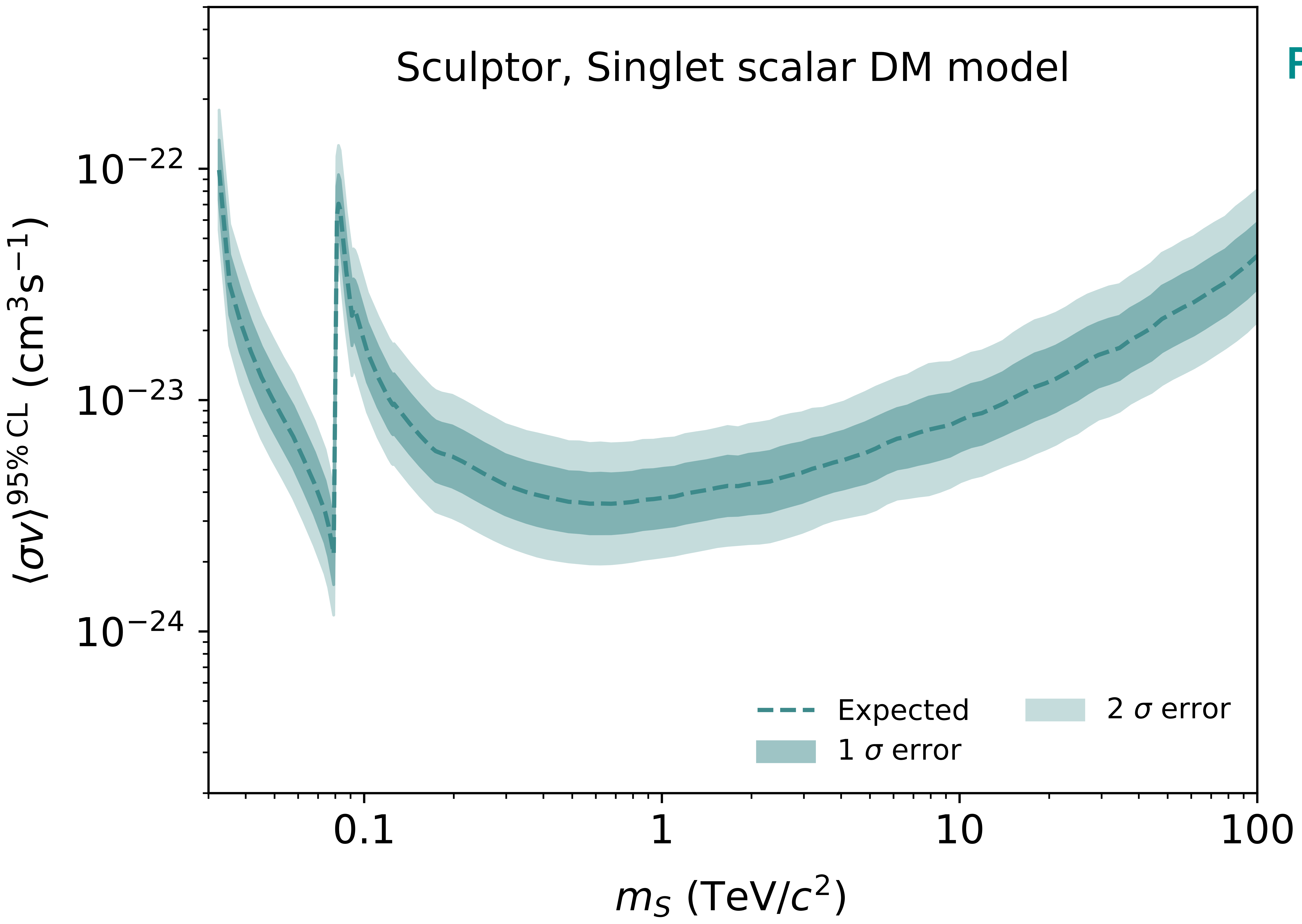
DM particle mass

1. **Expected** limits - Sample of **500 Poisson realizations** of the simulated background events

2. **Mean expected limits**
   Mean of the derived <σv> distribution

   Statistical uncertainty bands
   Standard deviation at 1 and 2σ

RESULTS



Predicted upper limit and uncertainties

Assuming a singlet scalar DM model

γ-ray spectra taken from Cirelli et al. *JCAP* 03 (2011) 051

Inflection point

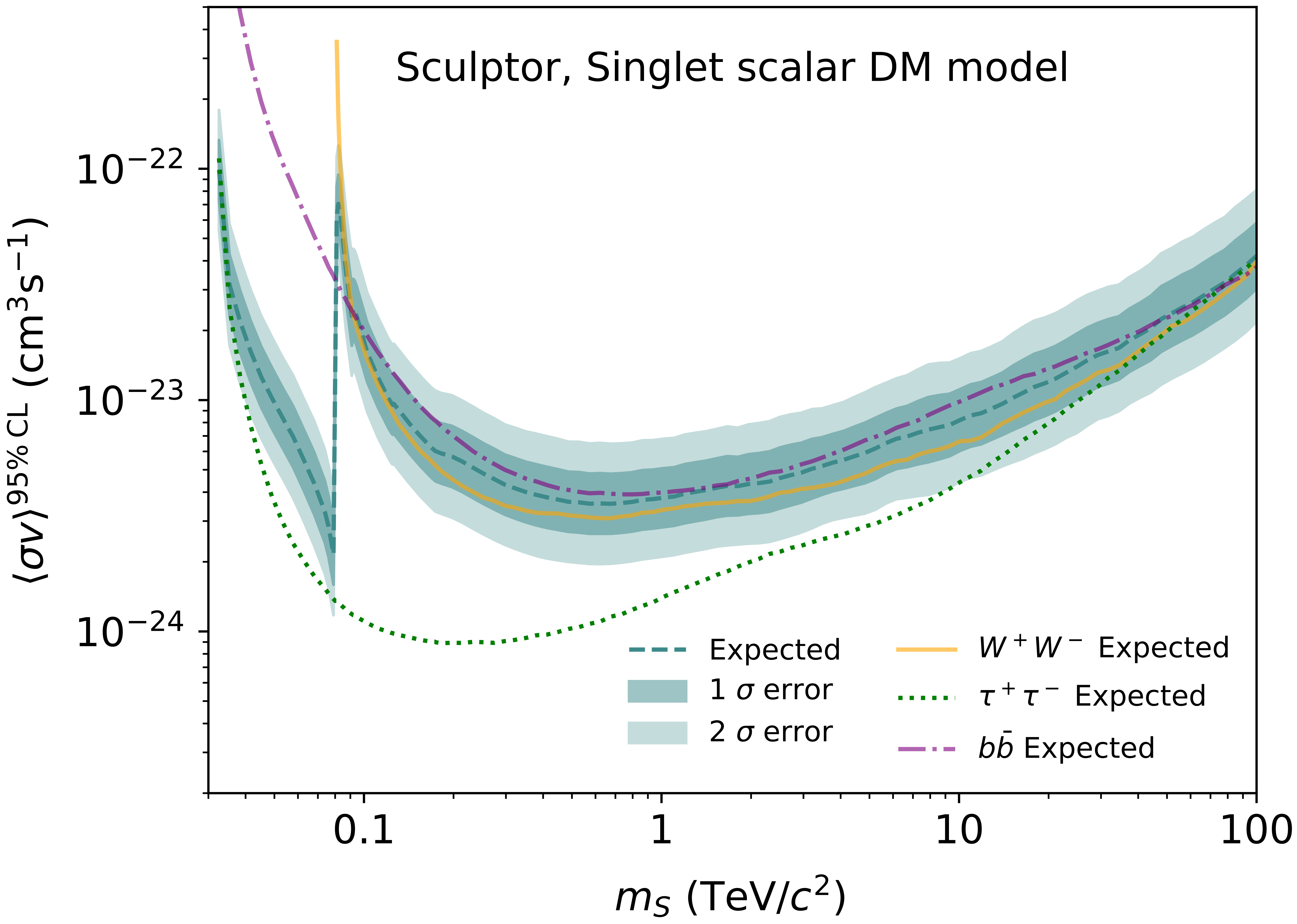
Due to the Higgs resonance

Sudden increase

Due to the opening of the WW channel

COMPARISONS

COMPARISONS



SINGLET SCALAR MODEL
VS
100% W^+W^-

Below the W mass

No upper limit for 100% WW since the WW channel **does not exist**

Above the W mass

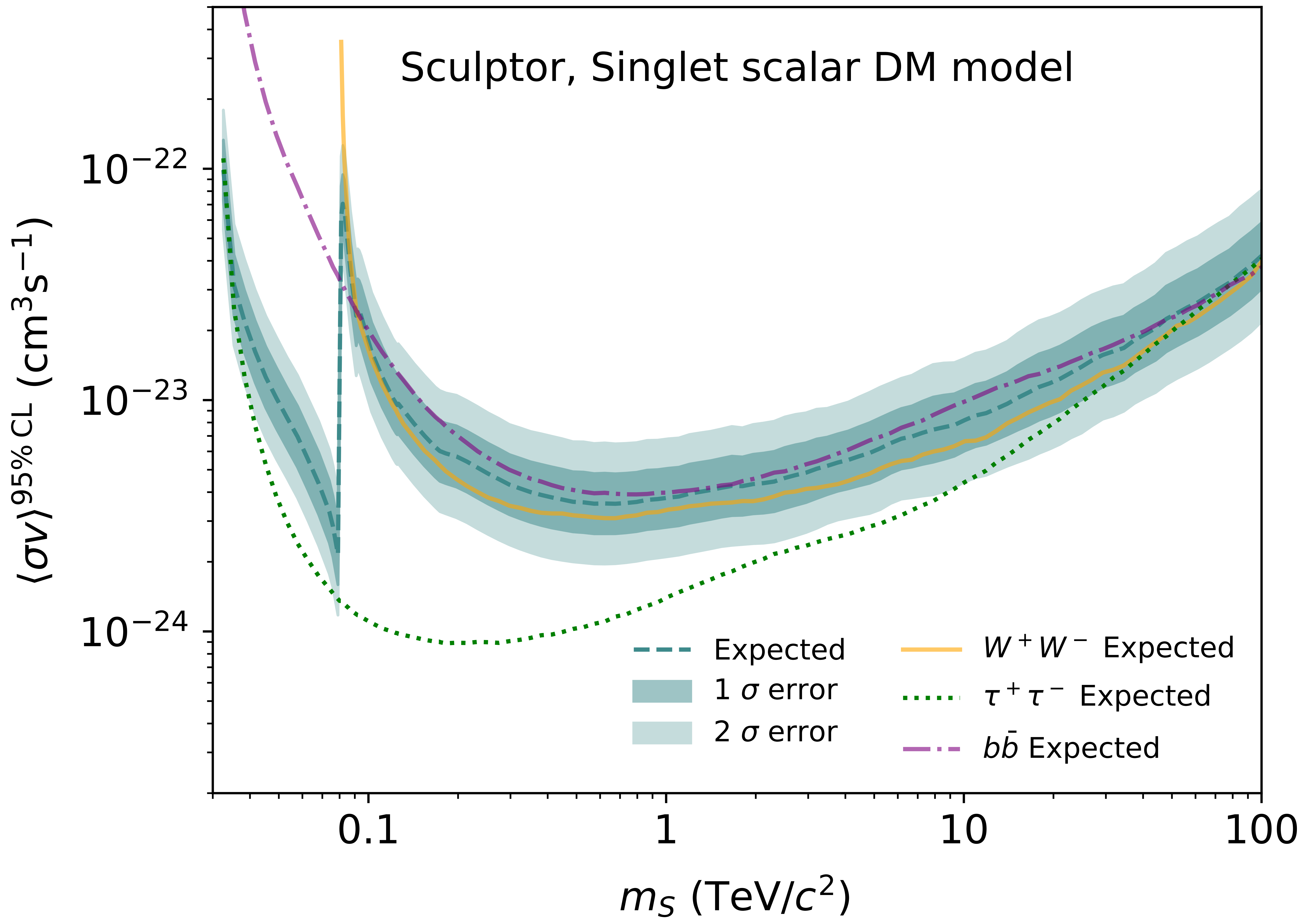
Additional contributions: ZZ, hh, tt which produce less γ than the WW channel

Above 1 TeV

Stability with ~62% WW - 30% ZZ - 8% hh

More conservative limit with the singlet scalar DM model

COMPARISONS



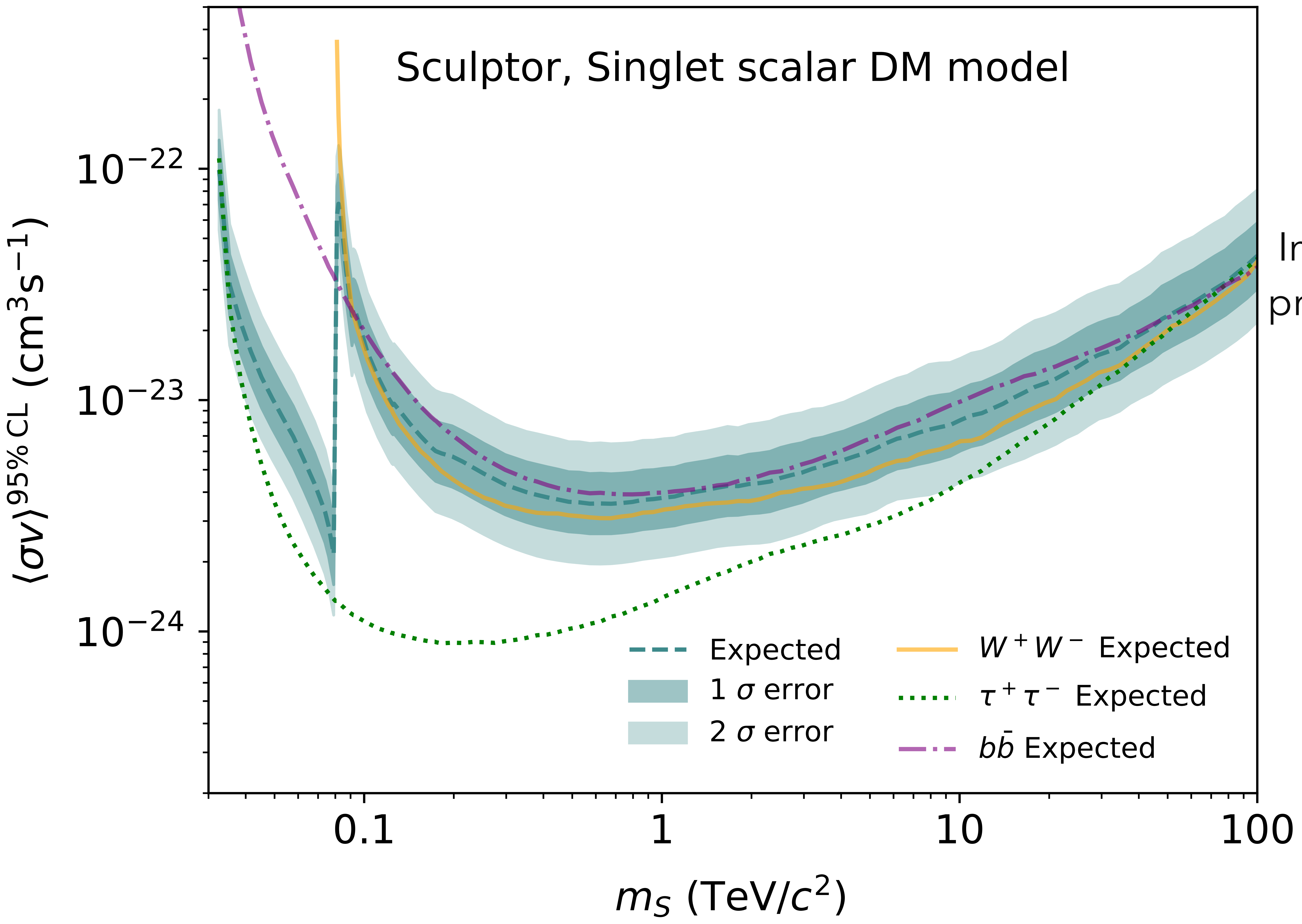
SINGLET SCALAR MODEL
VS
100% $\tau^+\tau^-$

100% $\tau^+\tau^-$ produces more γ rays
Leads to **more constraining** upper limits

However, in the singlet scalar model, **this $\tau^+\tau^-$ channel is never dominant**

100% $\tau^+\tau^-$ = over estimation of the contribution

COMPARISONS



SINGLET SCALAR MODEL
VS
100% bb

Below the W mass

Singlet scalar **much more constraining**

Important difference with 100% bb due to the presence of the subdominant channels $\tau^+\tau^-$, cc, and gg

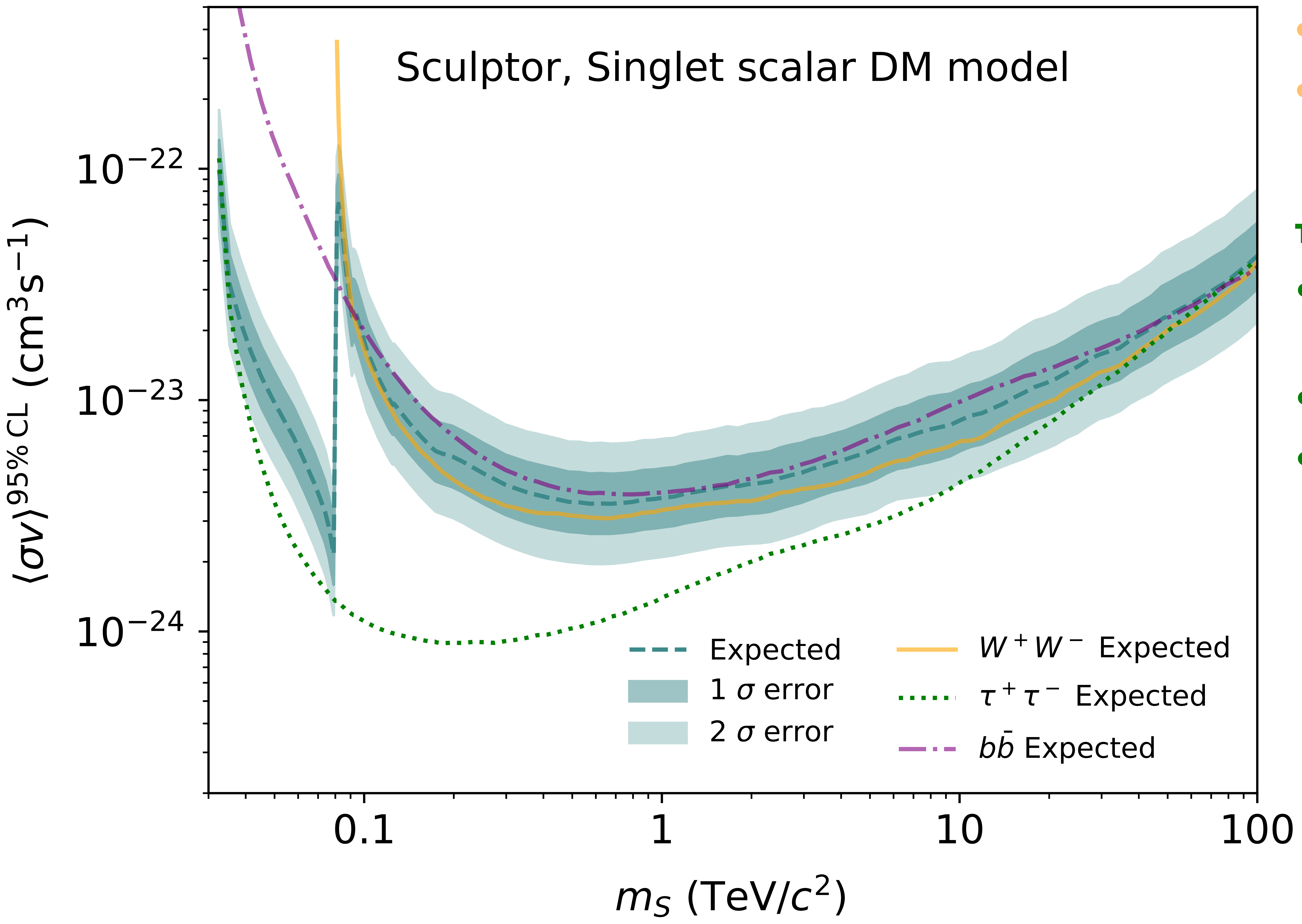
Above the W mass

bb suppressed in the singlet scalar

bb produces less γ than the 4 contributing channels WW, ZZ, hh, and tt (between the t mass and 1 TeV)

More constraining limit with the singlet scalar DM model

RELATIVE ERRORS



WW

- Ranges between **-22% and -6%**
- Reaches values **beyond 100%** for masses at the W mass threshold

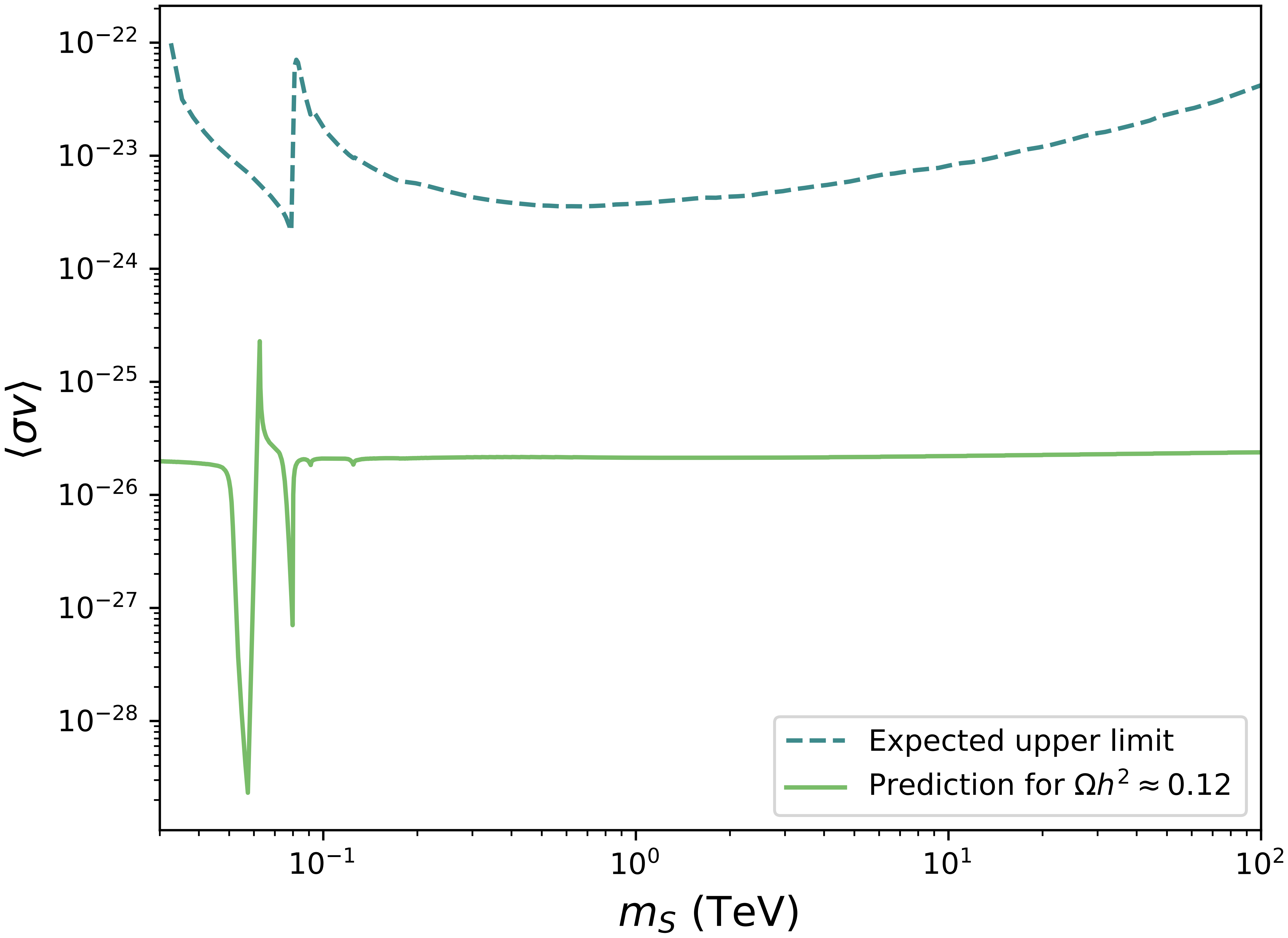
$\tau^+\tau^-$

- Ranges between **-65% and +12%** below the W mass threshold
- Around the W mass threshold **reaches -98%**
- Then decreases **to -3% at 100 TeV**

bb

- **In the order of 1000%** below the W mass threshold
- Then **drops to -56%** at the W mass threshold
- Then remains in the range of **-10% to +38%** after the threshold

EXCLUSION



Singlet scalar model **not excluded** by DM indirect detection

However, **resonance and kinematical thresholds** influence the exclusion curve together with the predicted annihilation cross-section

Generally, such fluctuations might lead to exclusion…

CONCLUSION & PERSPECTIVES

CONCLUSION & PERSPECTIVES

- Use of a more complex and more complete particle physics model
- Takes into account the full phenomenology with all annihilation channels at once
- Change of dominant annihilation channel(s) along with the DM particle mass
- Affects the predicted upper limits
- Feature can be expected in any particle physics model
- Derivation of a predicted upper limit and its 1σ and 2σ uncertainty bands
- Particle physics model could be used as well on the future data of CTA
- Paper submitted to JCAP & available on 2210.01220 [hep-ph]

Thanks for your attention

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Enigmass
The enigma of mass

BACKUP

STATISTICAL ANALYSIS

STATISTICAL ANALYSIS

Total likelihood

$$\mathcal{L}(\langle\sigma v\rangle, N_B, J) = \prod_{i=1} \mathcal{L}_{P_i}(\langle\sigma v\rangle, N_{B_i}, J \,|\, N_{\mathrm{ON_i}}, N_{\mathrm{OFF_i}}, \alpha)\,\mathcal{L}^J(J \,|\, \bar{J}, \sigma_J)$$

Poisson likelihood

Log-normal likelihood

Poisson likelihood for each energy bin

$$\mathcal{L}_i^P = \frac{(N_{S_i} + N_{B_i})^{N_{\mathrm{ON}_i}}}{N_{\mathrm{ON}_i}!} e^{-(N_{S_i}+N_{B_i})} \cdot \frac{(\alpha N_{B_i})^{N_{\mathrm{OFF}_i}}}{N_{\mathrm{OFF}_i}!} e^{-\alpha N_{B_i}}$$

ON REGION

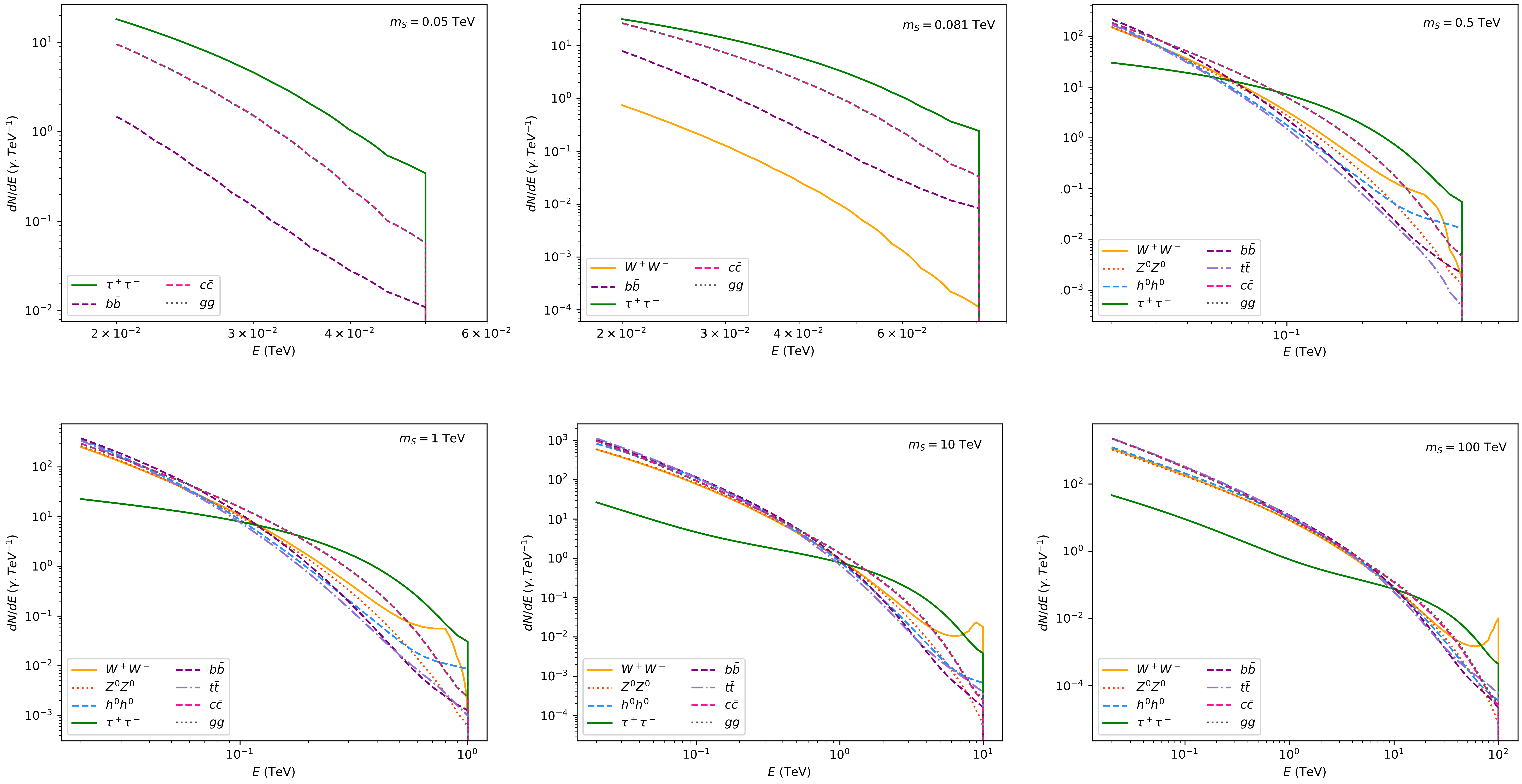
OFF REGION

Log-normal likelihood to model the uncertainties of the J factor

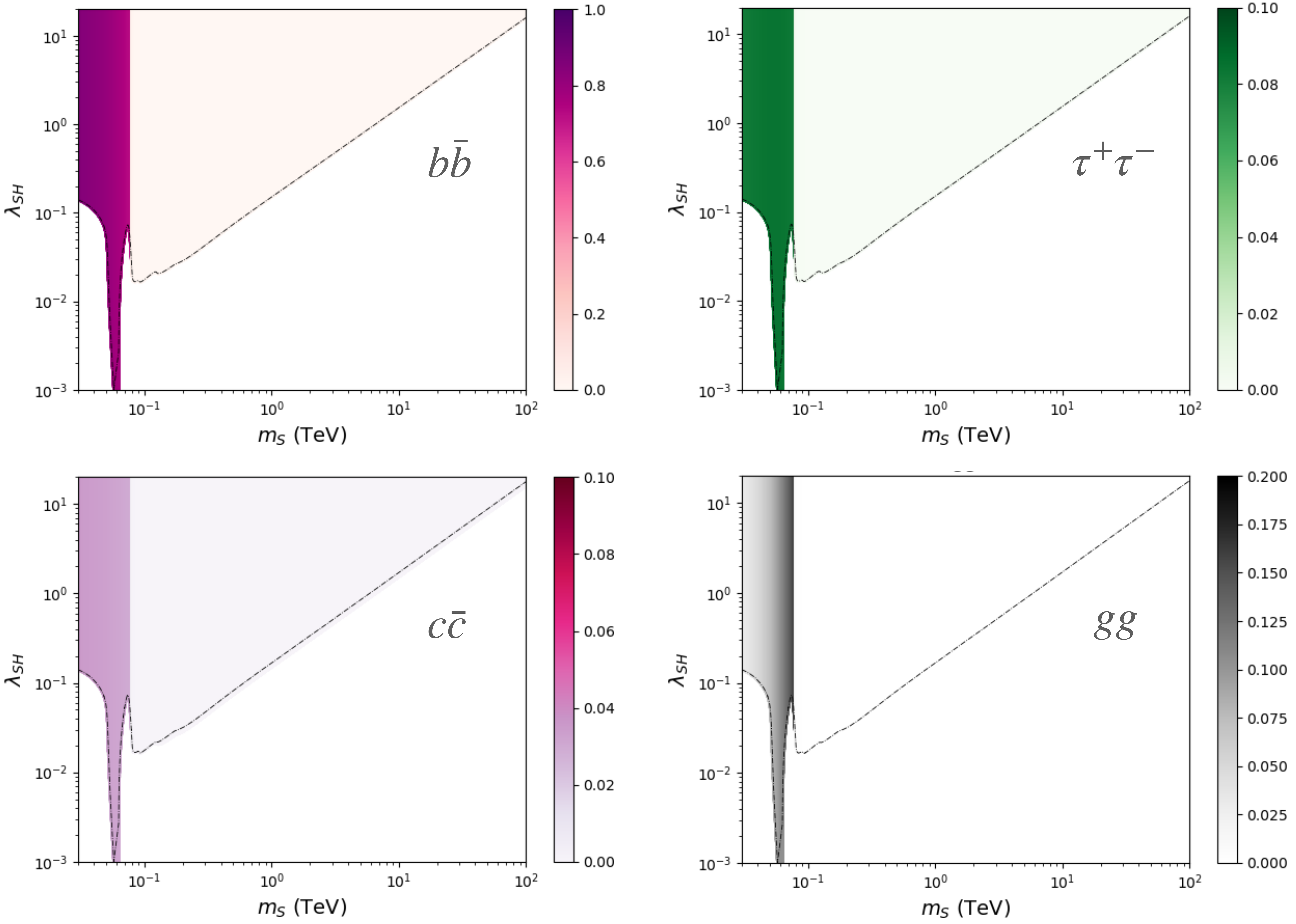
$$\mathcal{L}^J = \frac{1}{\ln(10)\sqrt{2\pi}\sigma_J J} \exp - \frac{(\log_{10} J - \log_{10} \bar{J})^2}{2\sigma_J^2}$$

SPECTRA

Ref: Cirelli et al. *JCAP* 03 (2011) 051

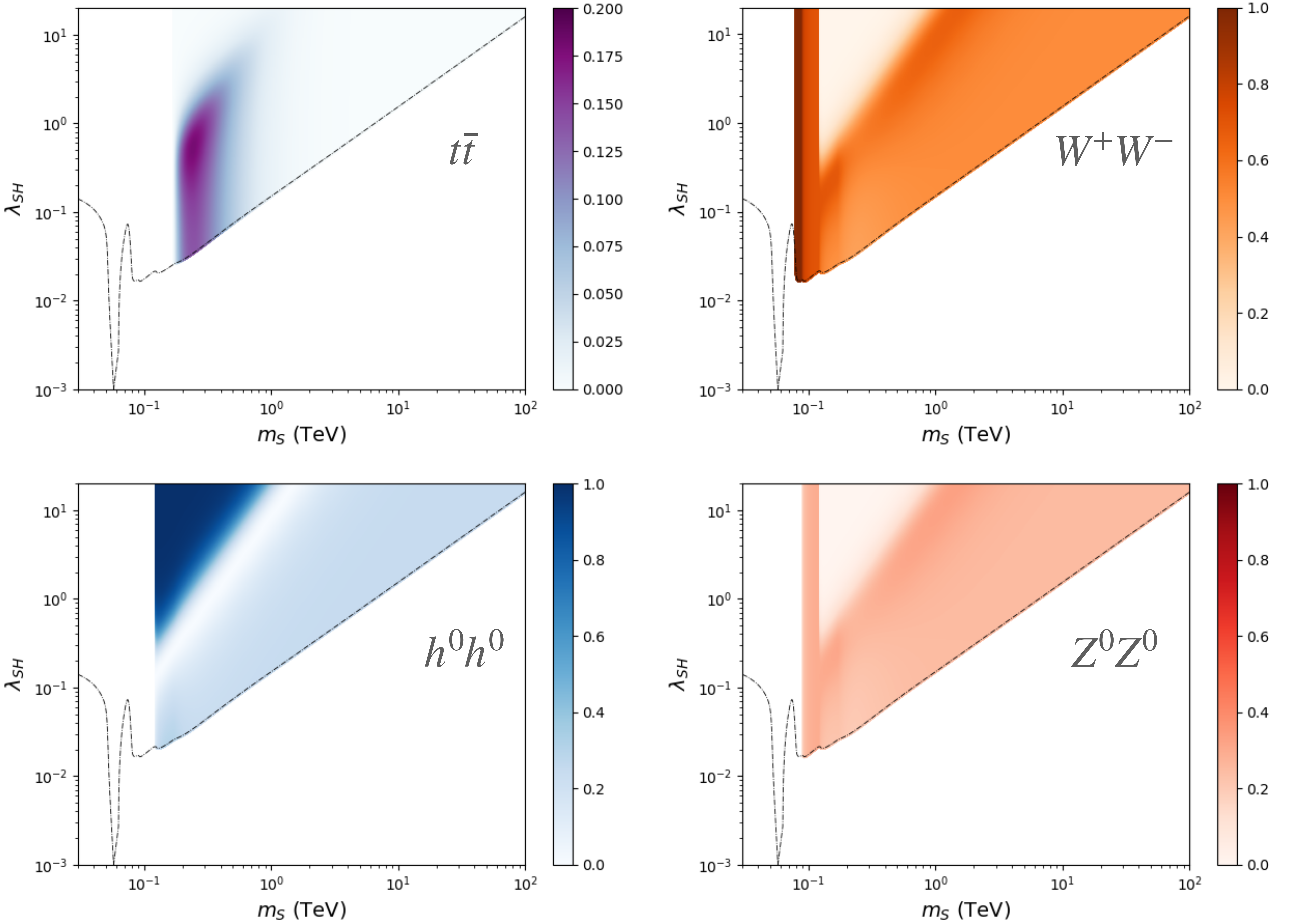


BRANCHING RATIOS



$$m_S \lesssim m_W$$

BRANCHING RATIOS



$m_S \gtrsim m_W$