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# Dark matter indirect detection limits including complete annihilation patterns

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Based on 2210.01220 [hep-ph]

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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

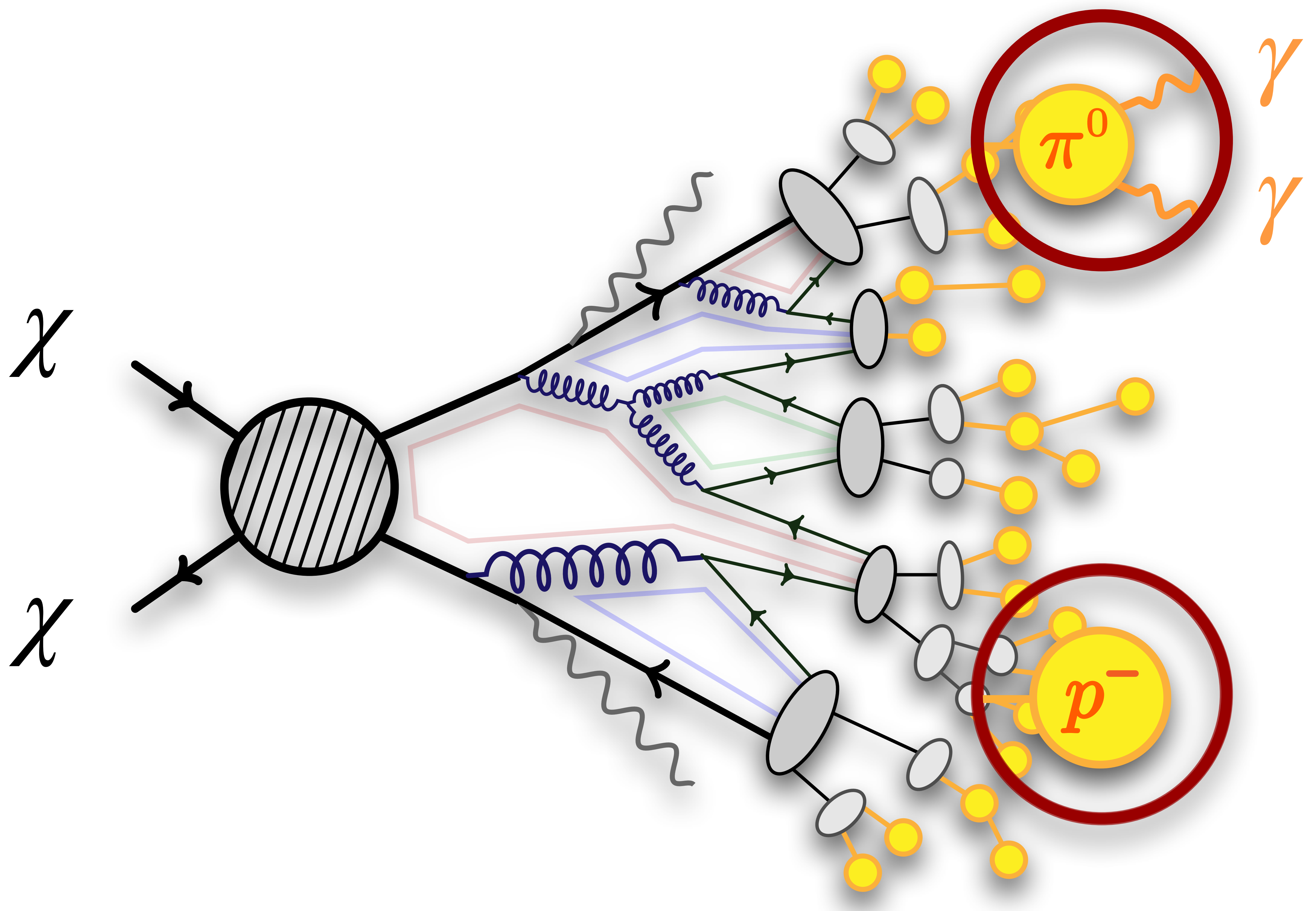
# GOALS

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:** Combination of expertise (astro and particle physics) 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

**Astrophysical**
J factor

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

**Particle Physics**
factor

**where**

- **<σv>** = annihilation cross-section
- **$m_\chi$** = DM particle mass
- **$BR_f$** = branching ratio
- **$dN_f/dE$** = differential spectrum
- **$\rho_{DM}$** = DM density

# STATISTICAL ANALYSIS

## LOG-LIKELIHOOD RATIO TEST STATISTICS

**Constrained** minimization

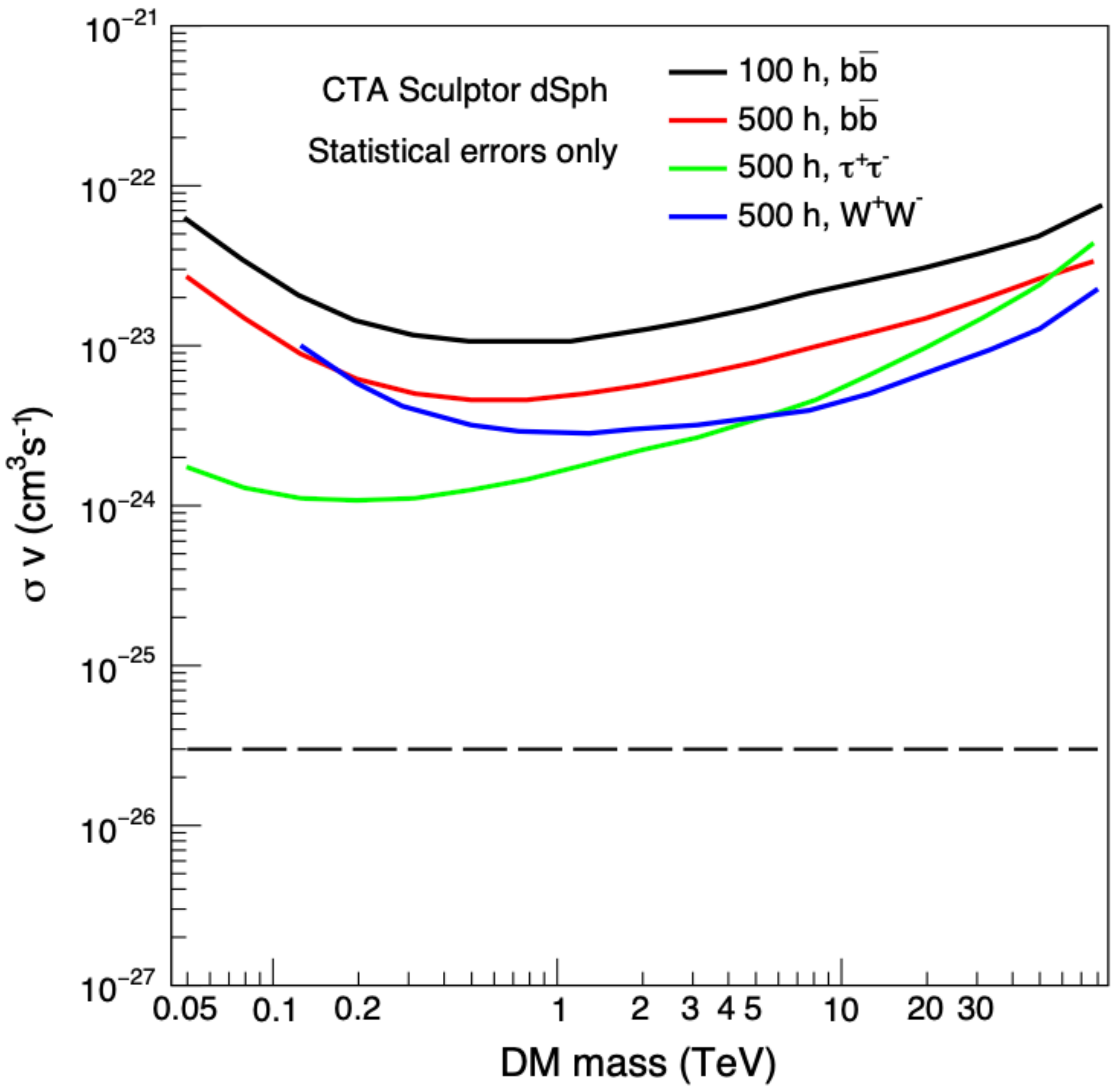
$$\Lambda = -2\ln\frac{\mathscr{L}_{H_0}}{\mathscr{L}_{H_1}} = -2\ln\frac{\mathscr{L}(\langle\sigma v\rangle_0 \,|\, \hat{\hat{N}}_B, \hat{\hat{J}})}{\mathscr{L}(\langle\hat{\sigma v}\rangle, \hat{N}_B, \hat{J})}$$

**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

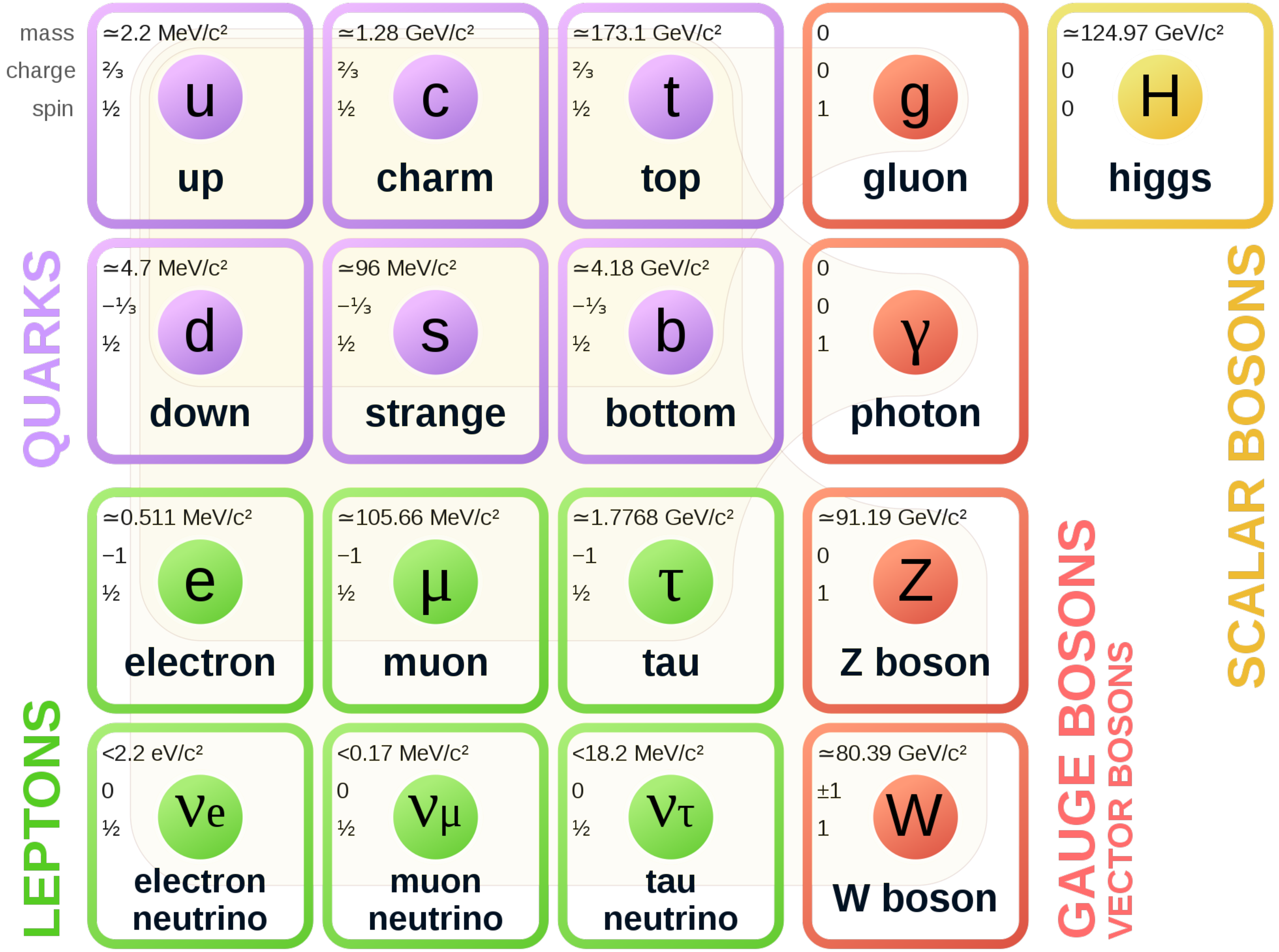



- Each annihilation channel **treated independently**
- Corresponding to a **branching ratio of 100%**
- **Simplest** model possible where all DM particles annihilate through the same channel

# WHAT IF

## We change the particle physics model?

# STANDARD MODEL…




en.wikipedia.org/wiki/Standard_Model

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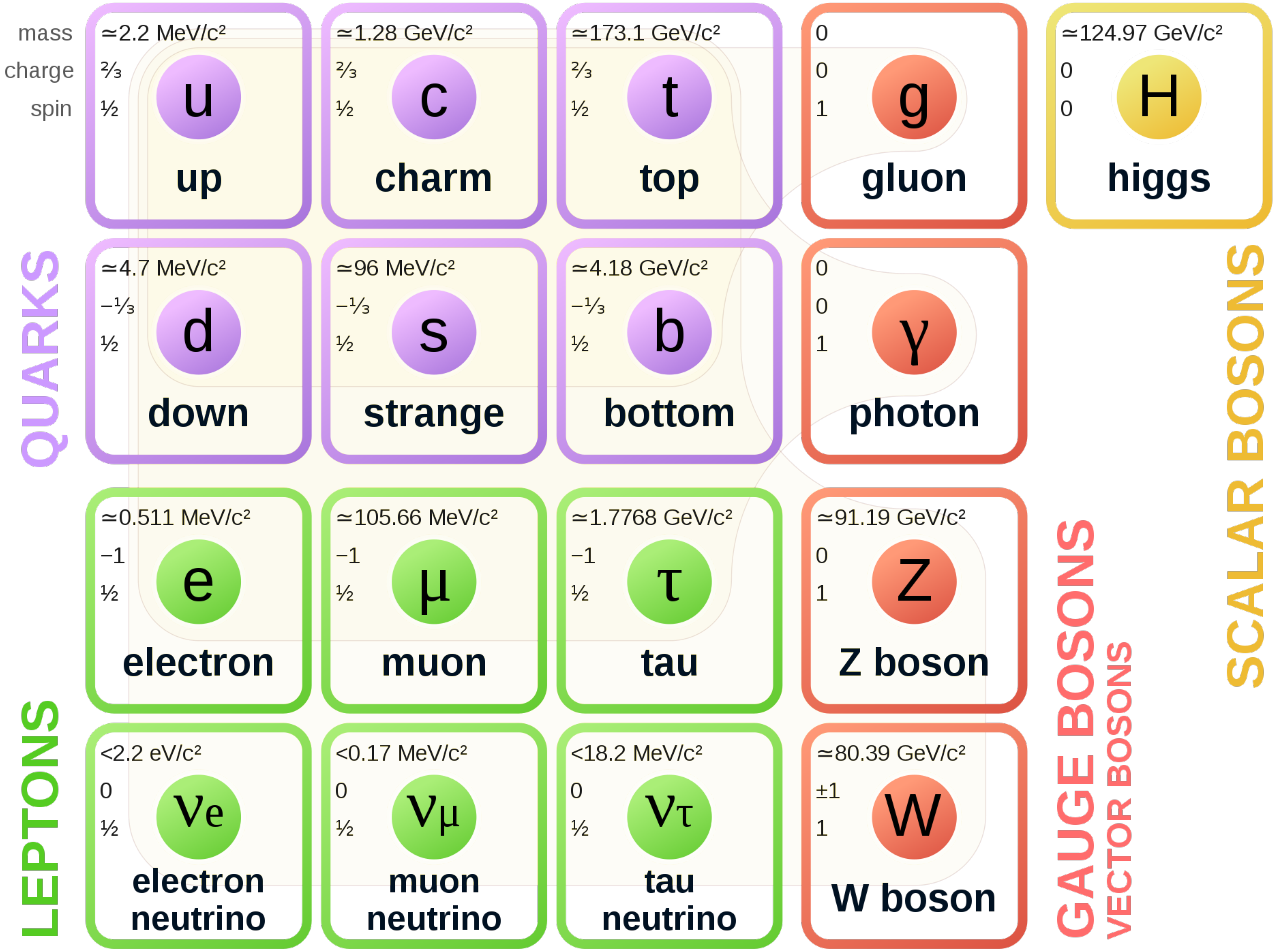



en.wikipedia.org/wiki/Standard_Model

Dark matter in the Universe...?

Neutrino masses...?

Hierarchy problem...?

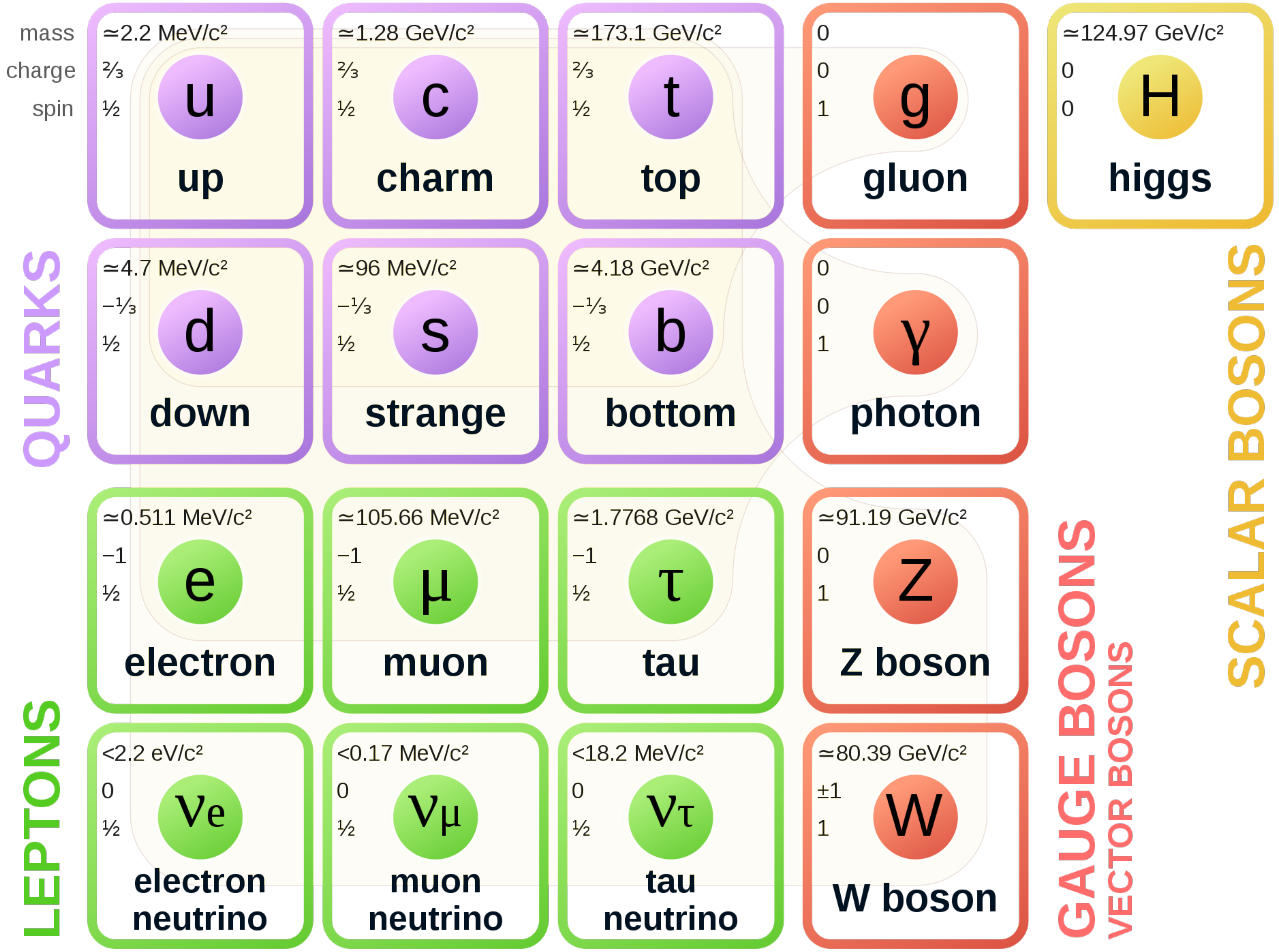
Gauge coupling unification...?

Gravity...?

Lepton-flavour non-universality...?

Flavour problem...?

# STANDARD MODEL... AND BEYOND

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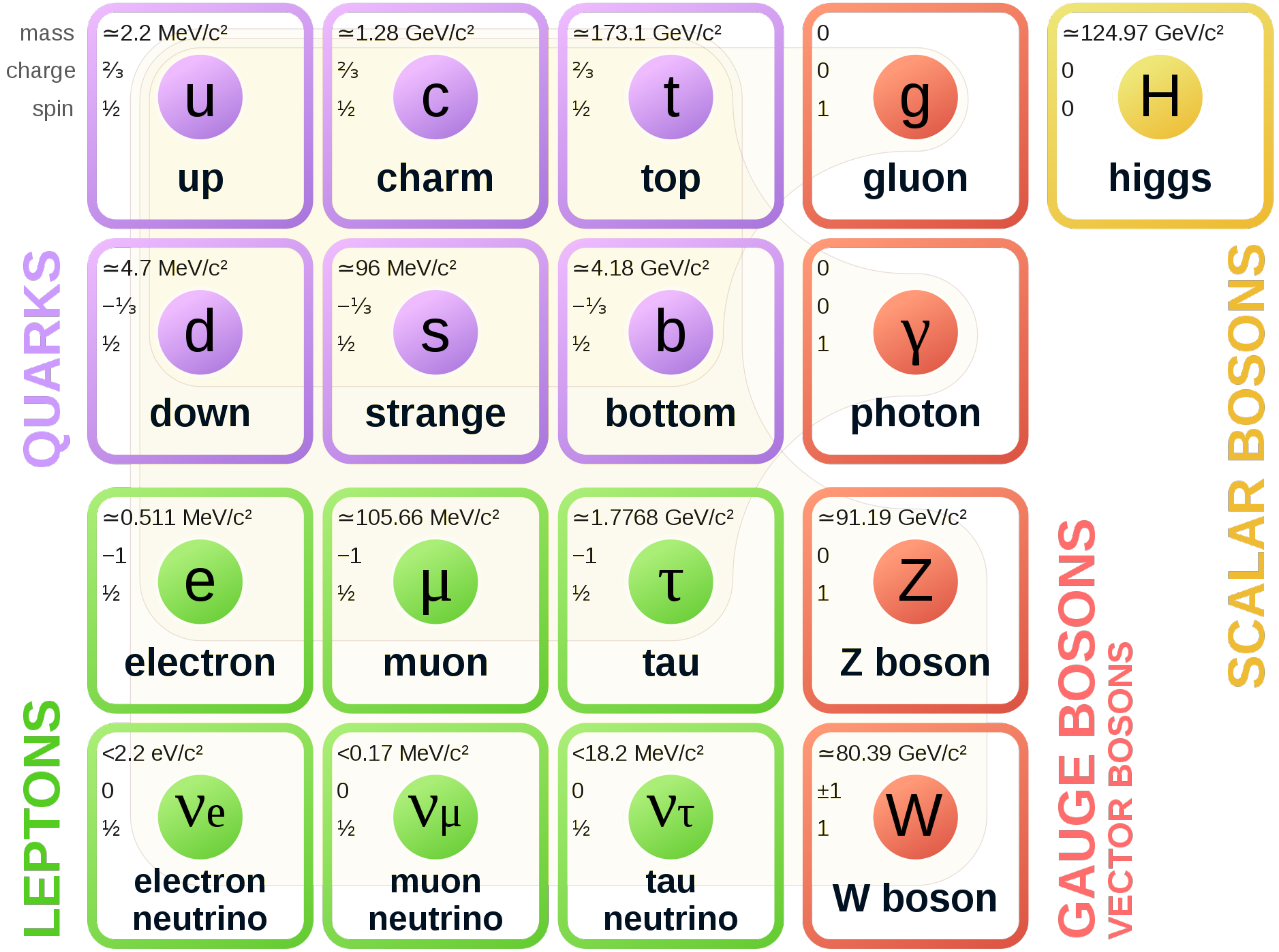



en.wikipedia.org/wiki/Standard_Model

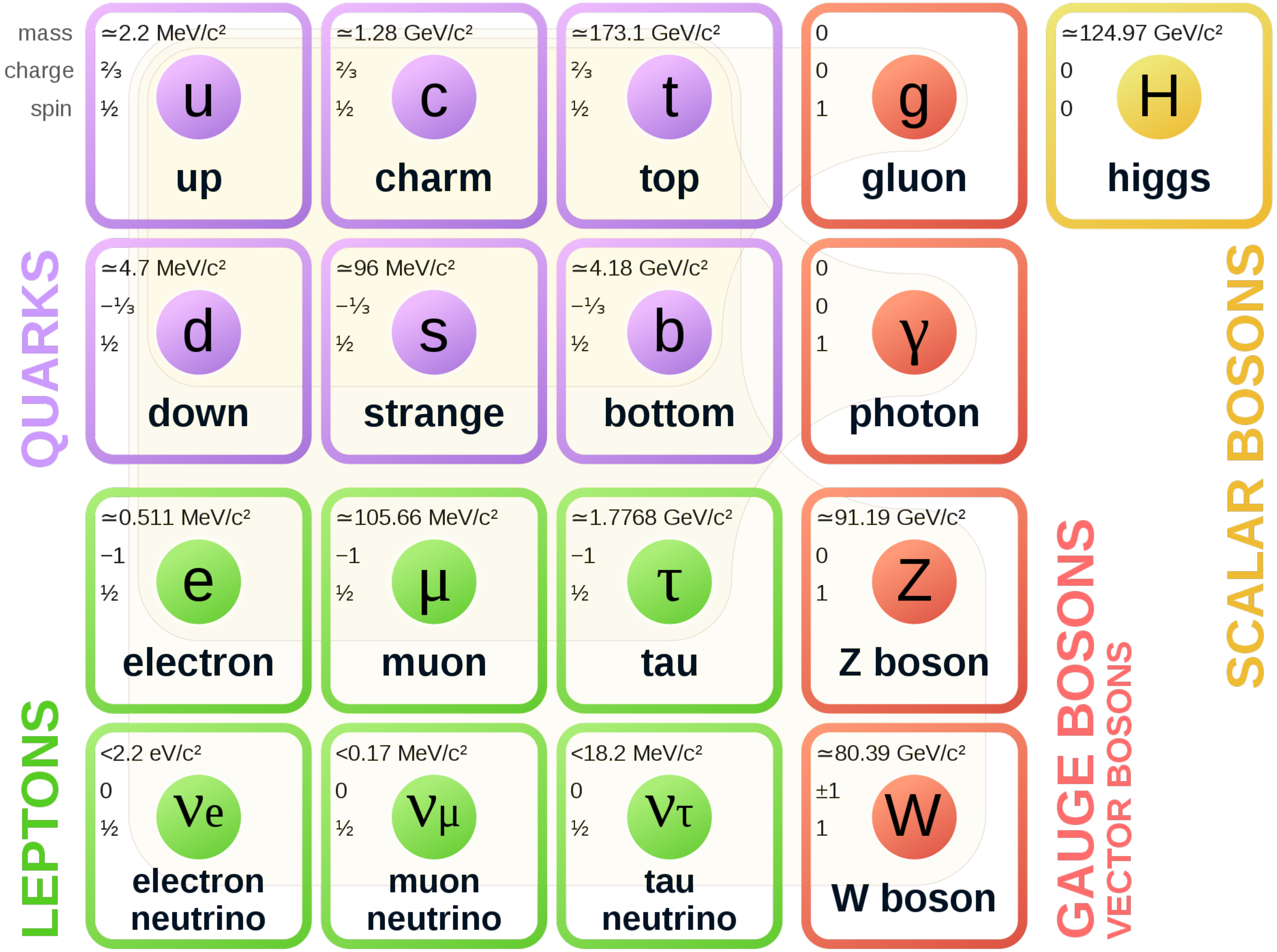
+

DM

Other stuff ?

Fermion…?
Scalar…?

# **SINGLET SCALAR** DARK MATTER




en.wikipedia.org/wiki/Standard_Model

\+ S

**Scalar singlet**

(stable due to $\mathbb{Z}_2$ symmetry)

# **SINGLET SCALAR** DARK MATTER

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")

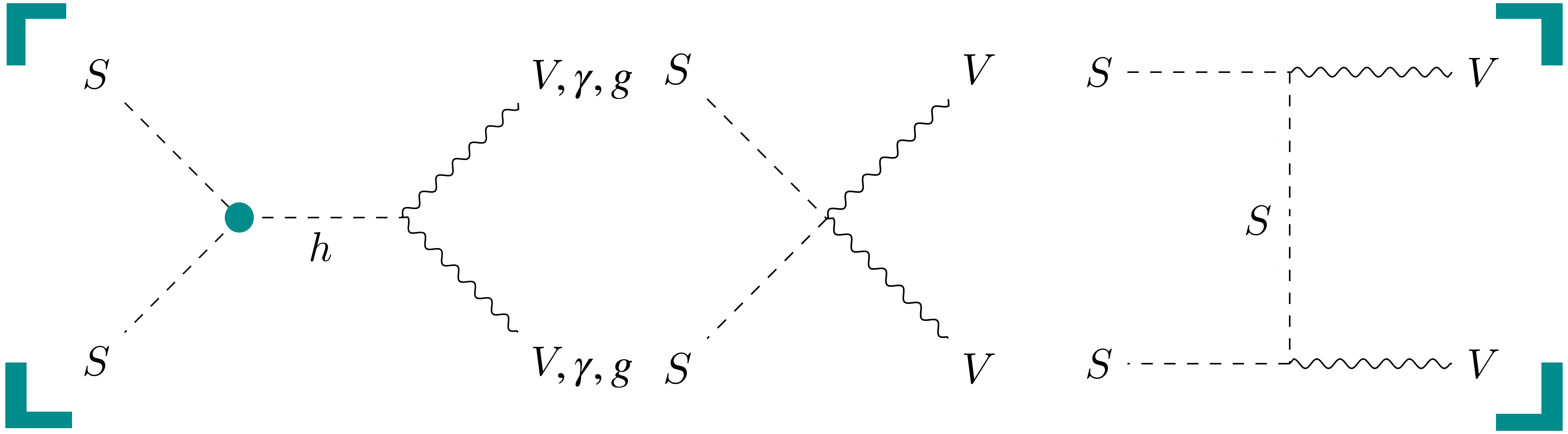
**Phenomenology governed by**

$m_S$ (DM mass)

$\lambda_{SH}$ (DM coupling)

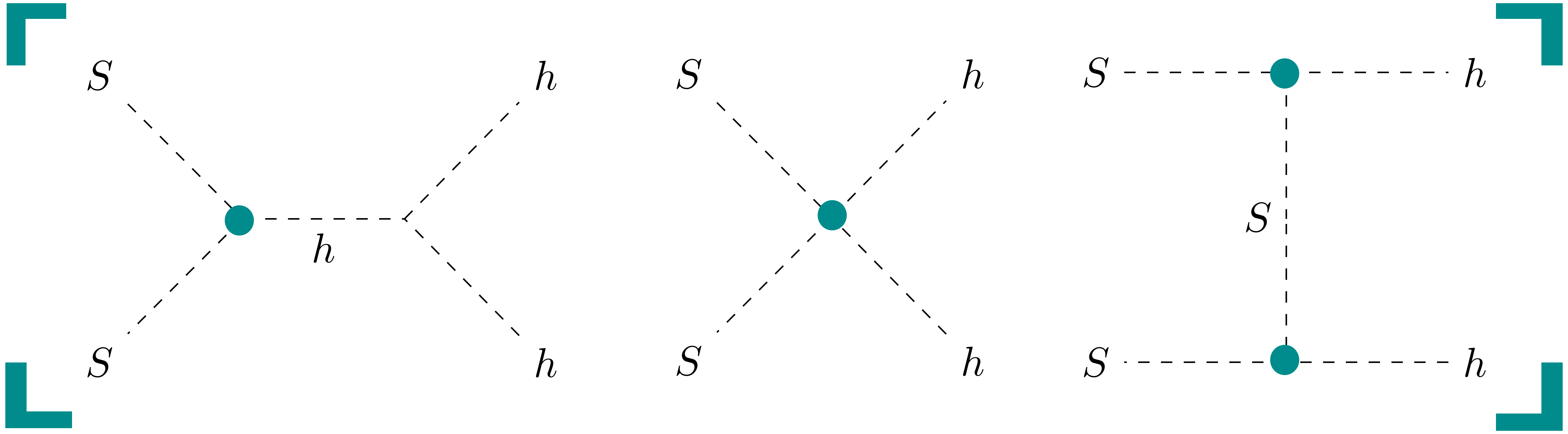
# **SINGLET SCALAR** DARK MATTER

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

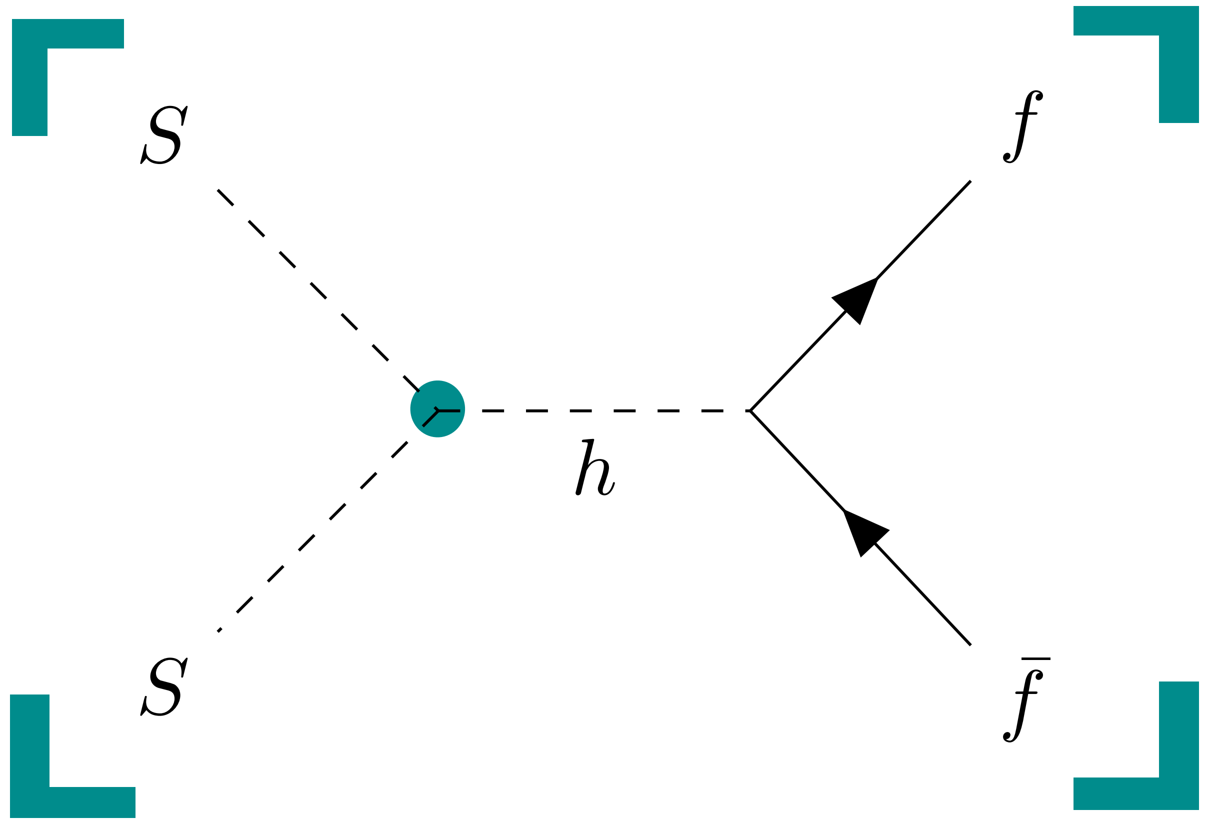



**Gauge boson** final states

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




**Higgs boson** final states




**Quark or lepton** final states

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

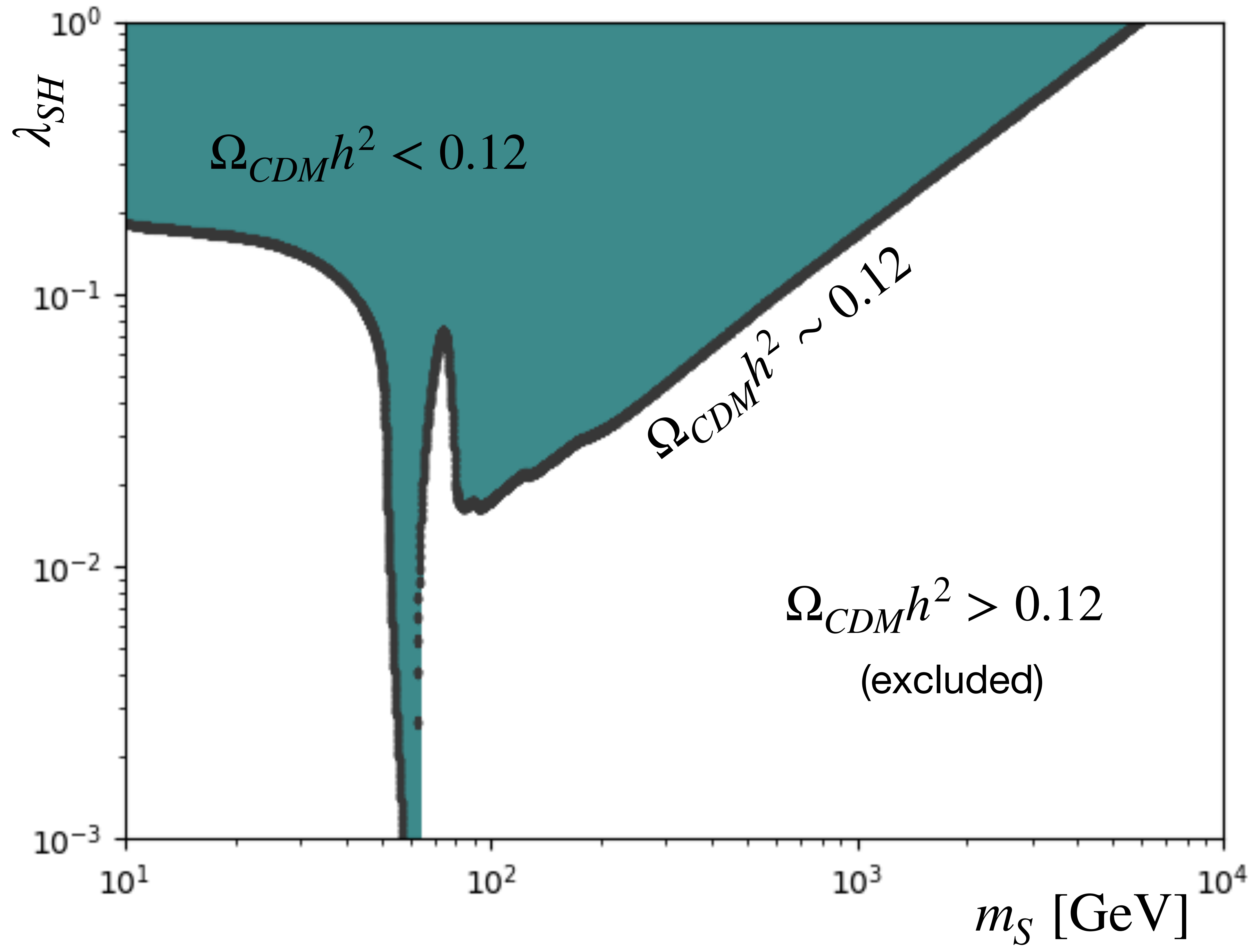
# **SINGLET SCALAR** DARK MATTER

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



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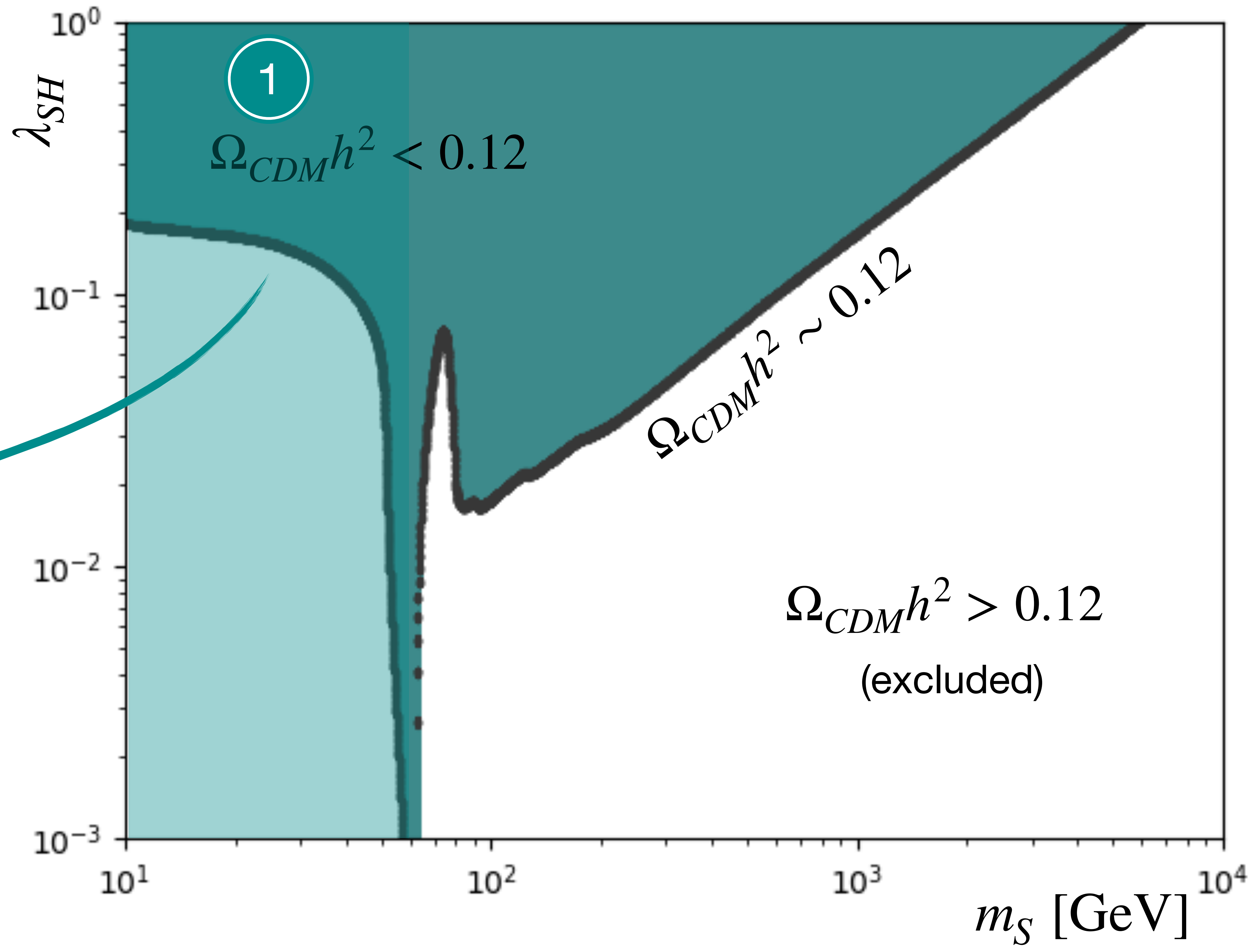
$SS \to b\bar{b}$ $\sim 75 - 85\,\%$
$SS \to \tau^+\tau^-$ $\sim 7 - 10\,\%$
$SS \to c\bar{c}$ $\sim 3 - 4\,\%$
$SS \to gg$ $\sim 3 - 15\,\%$



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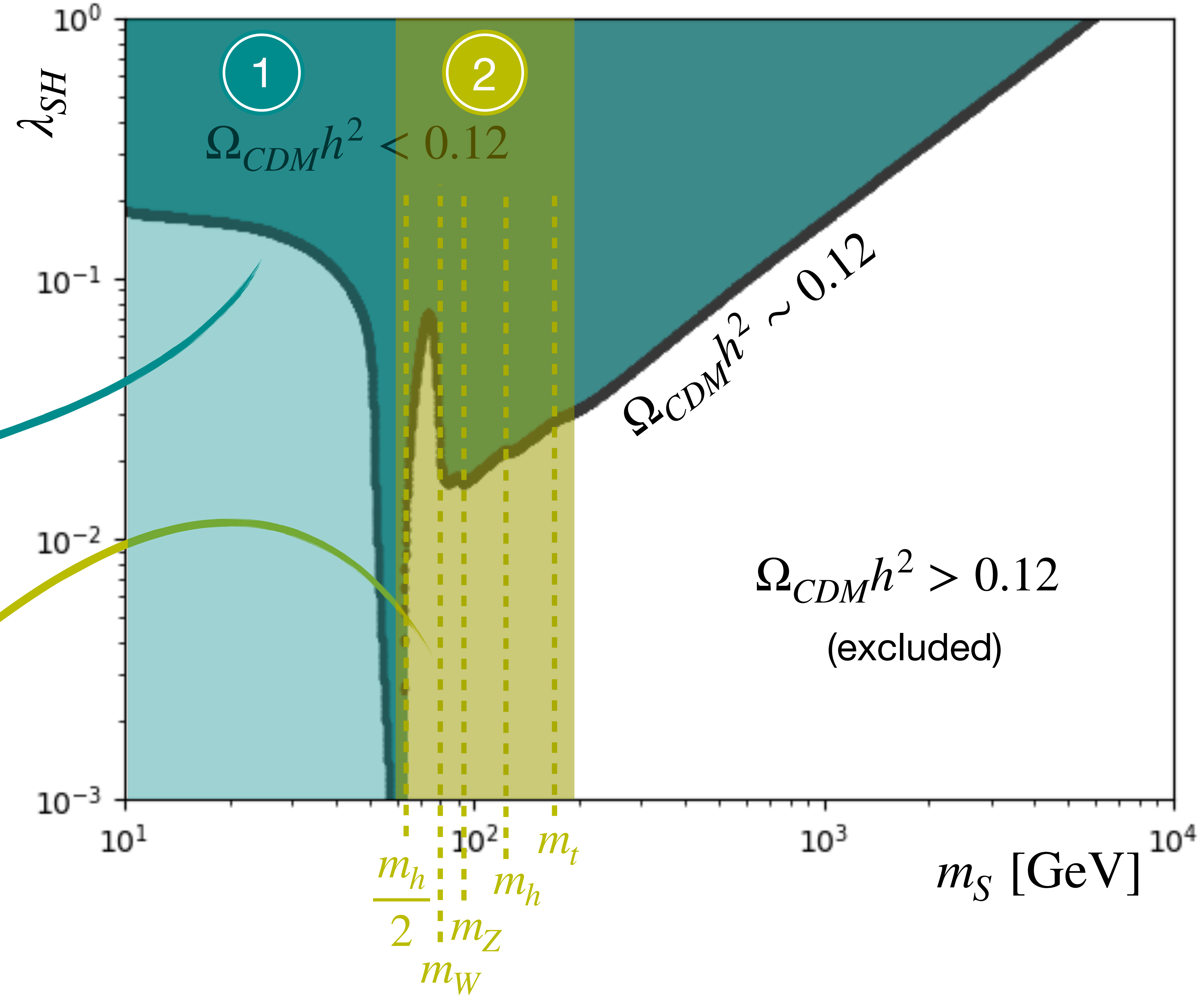
Region of frequent change of the dominant annihilation channel

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



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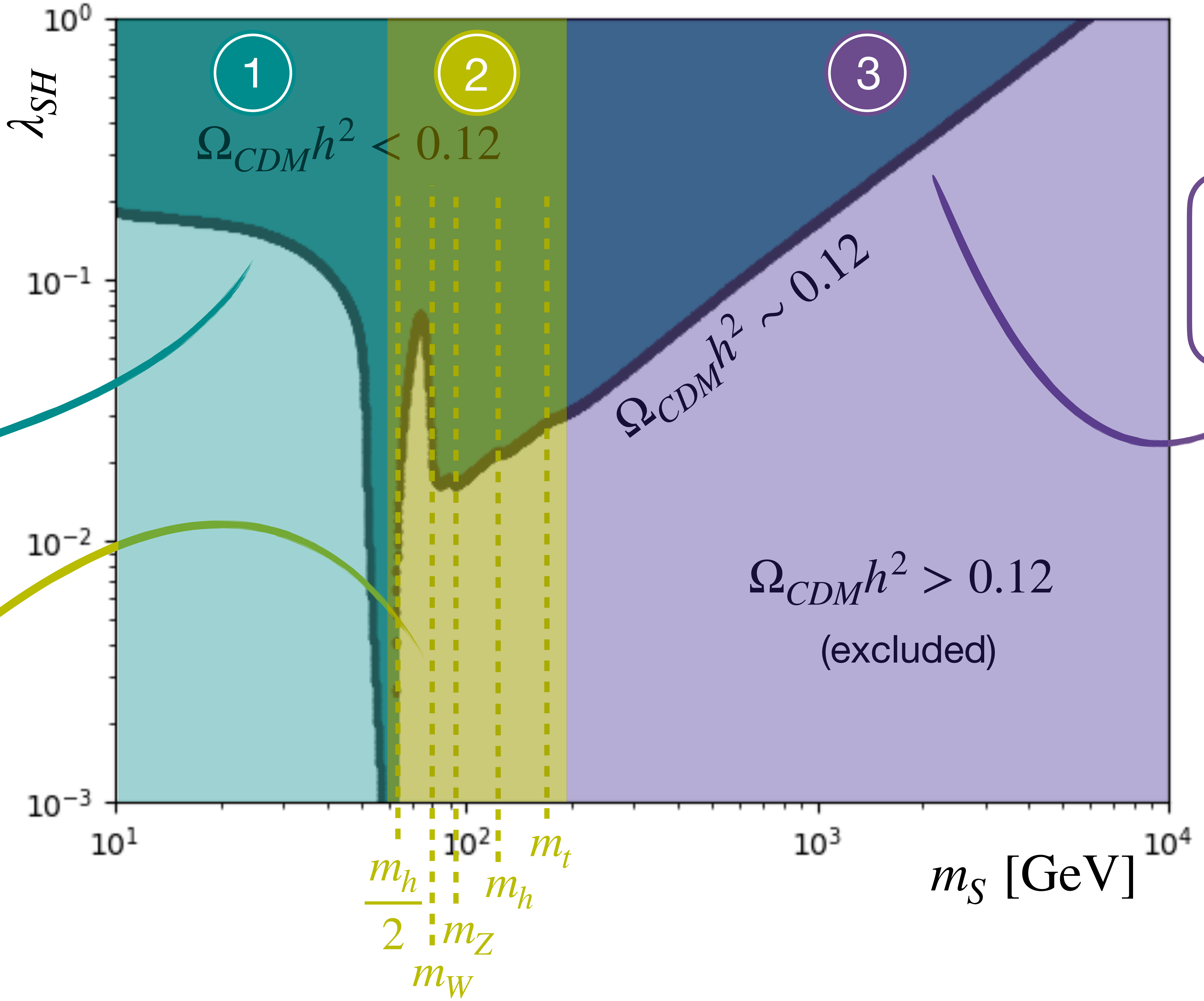
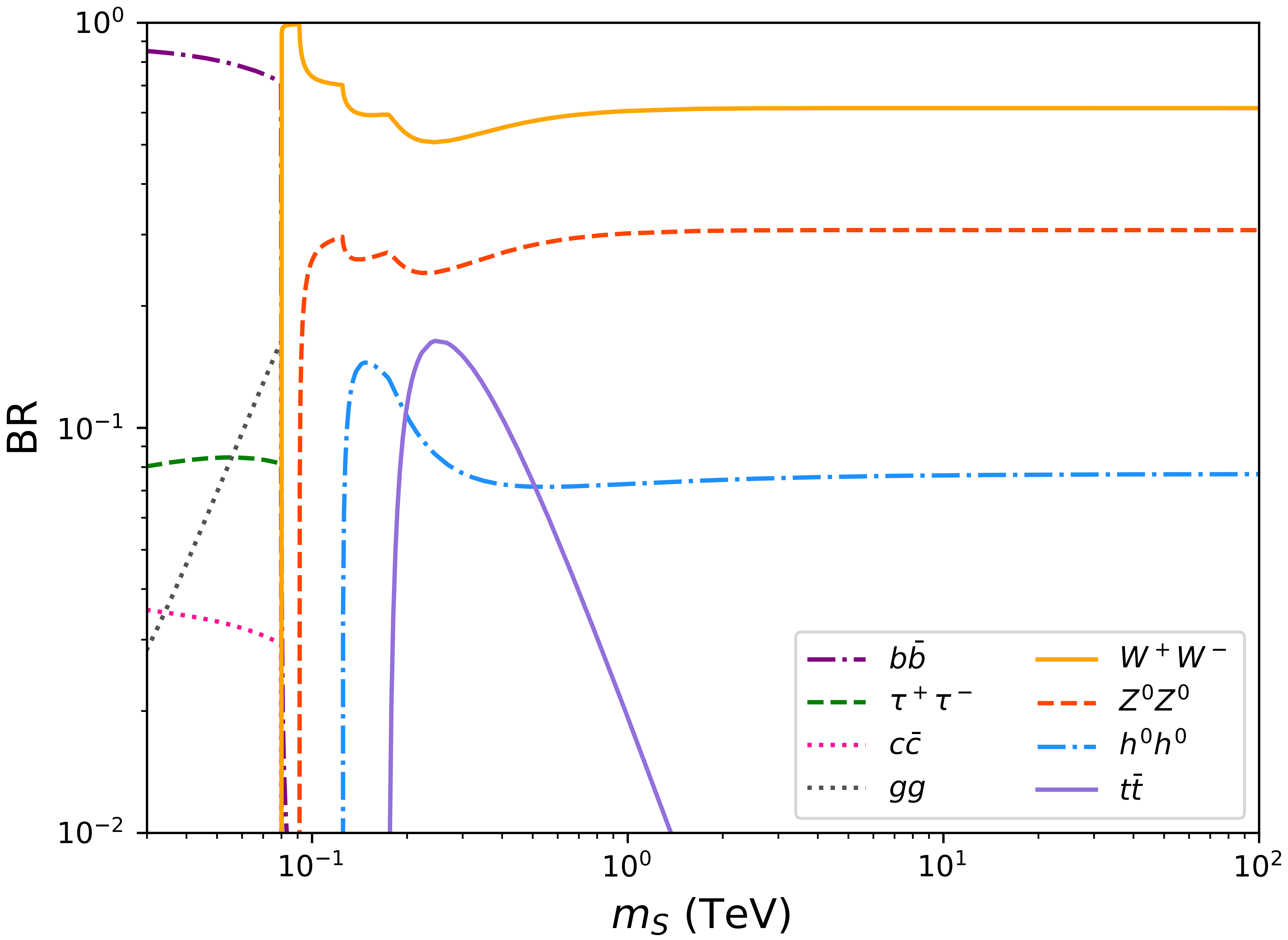



$SS \to W^+W^- \quad \sim 62\,\%$
$SS \to Z^0Z^0 \quad \sim 30\,\%$
$SS \to h^0h^0 \quad \sim 8\,\%$

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

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

## Sculptor

Mock data prepared with Gammapy 0.18.2

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

Background only

# NEW UPPER LIMITS

NEW UPPER LIMITS

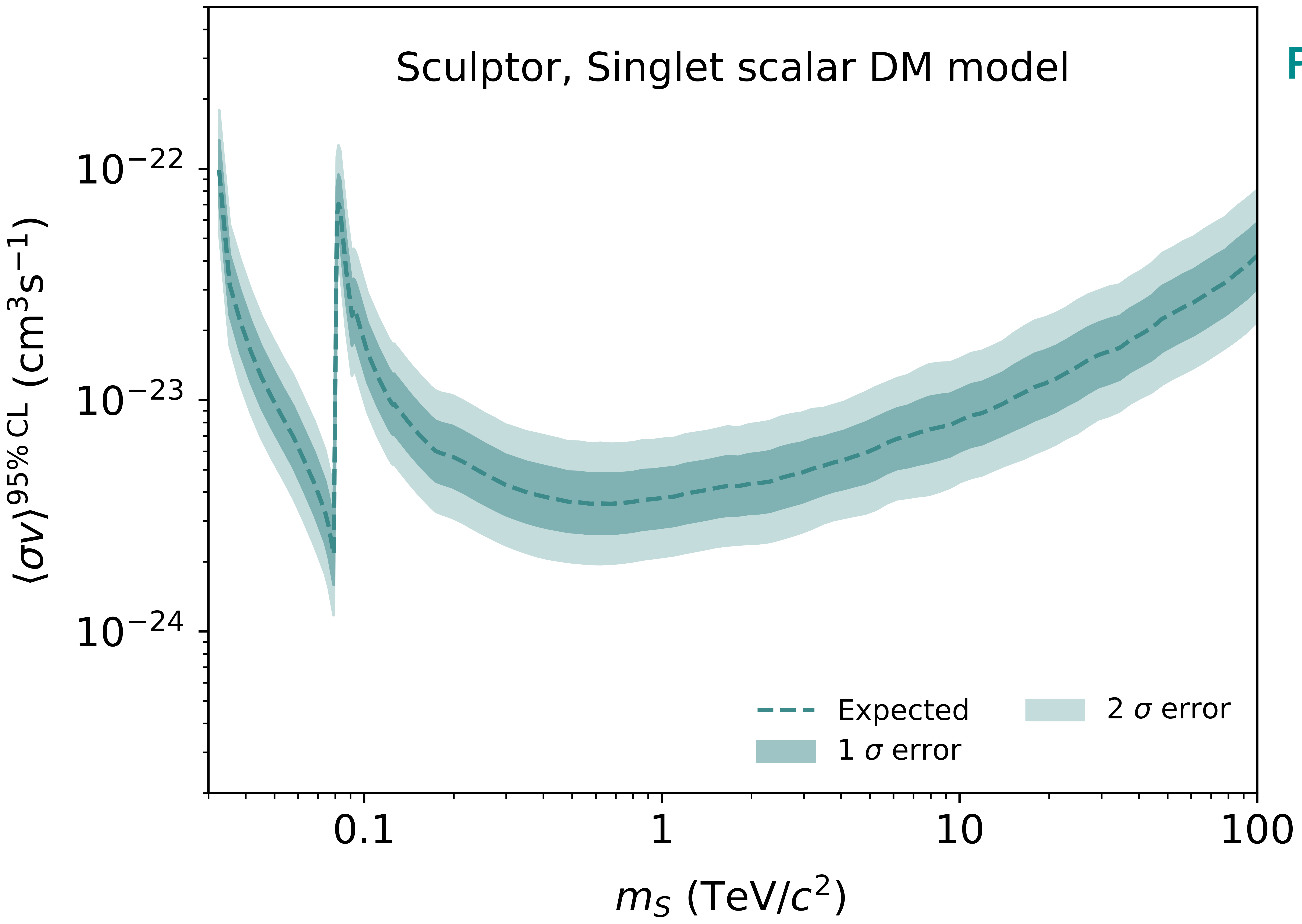
## Computation of the predicted DM cross section
## VS
## DM particle mass

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

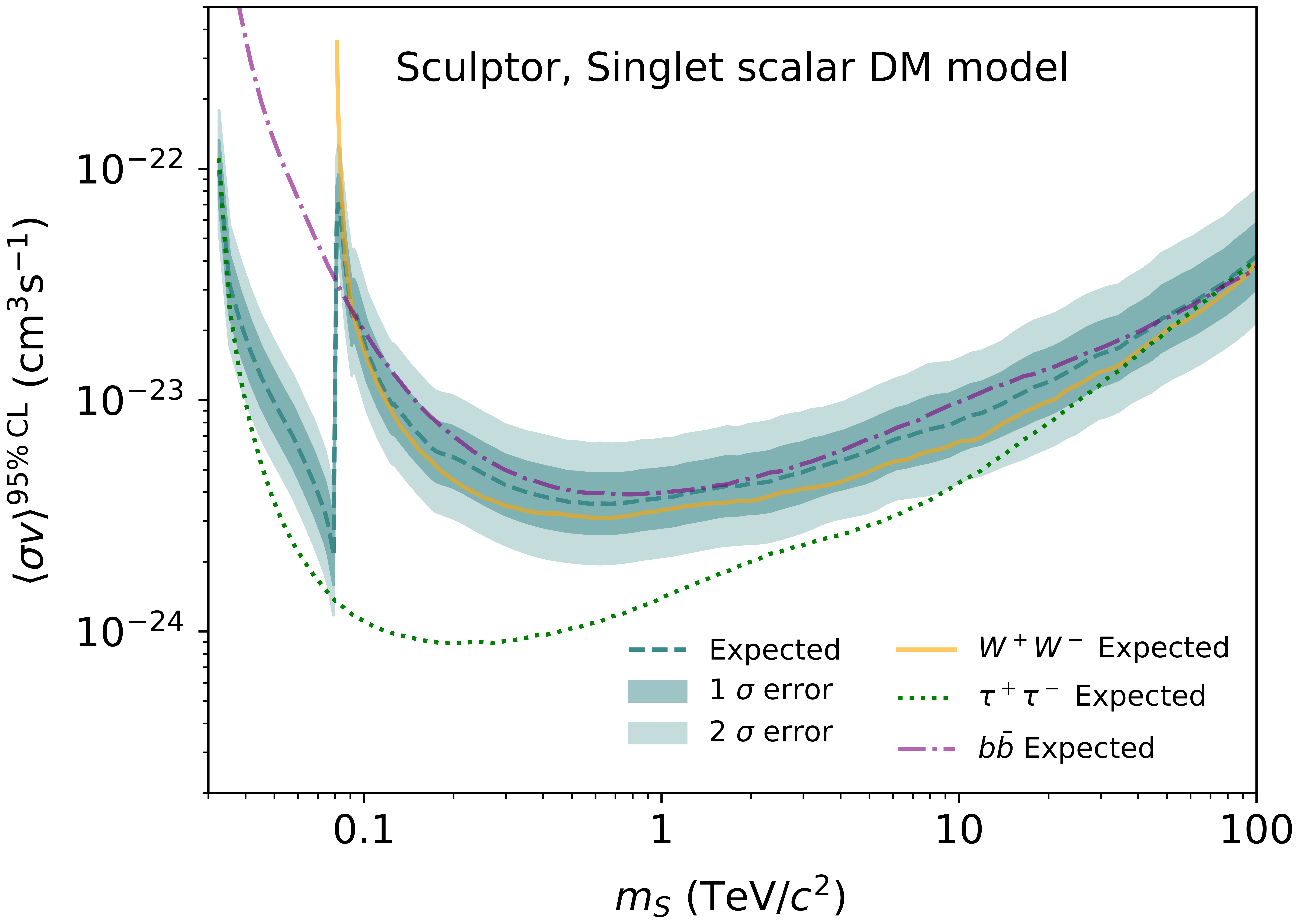
### Inflection point

Due to the Higgs resonance

### Sudden increase

Due to the opening of the WW channel

# COMPARISONS




**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

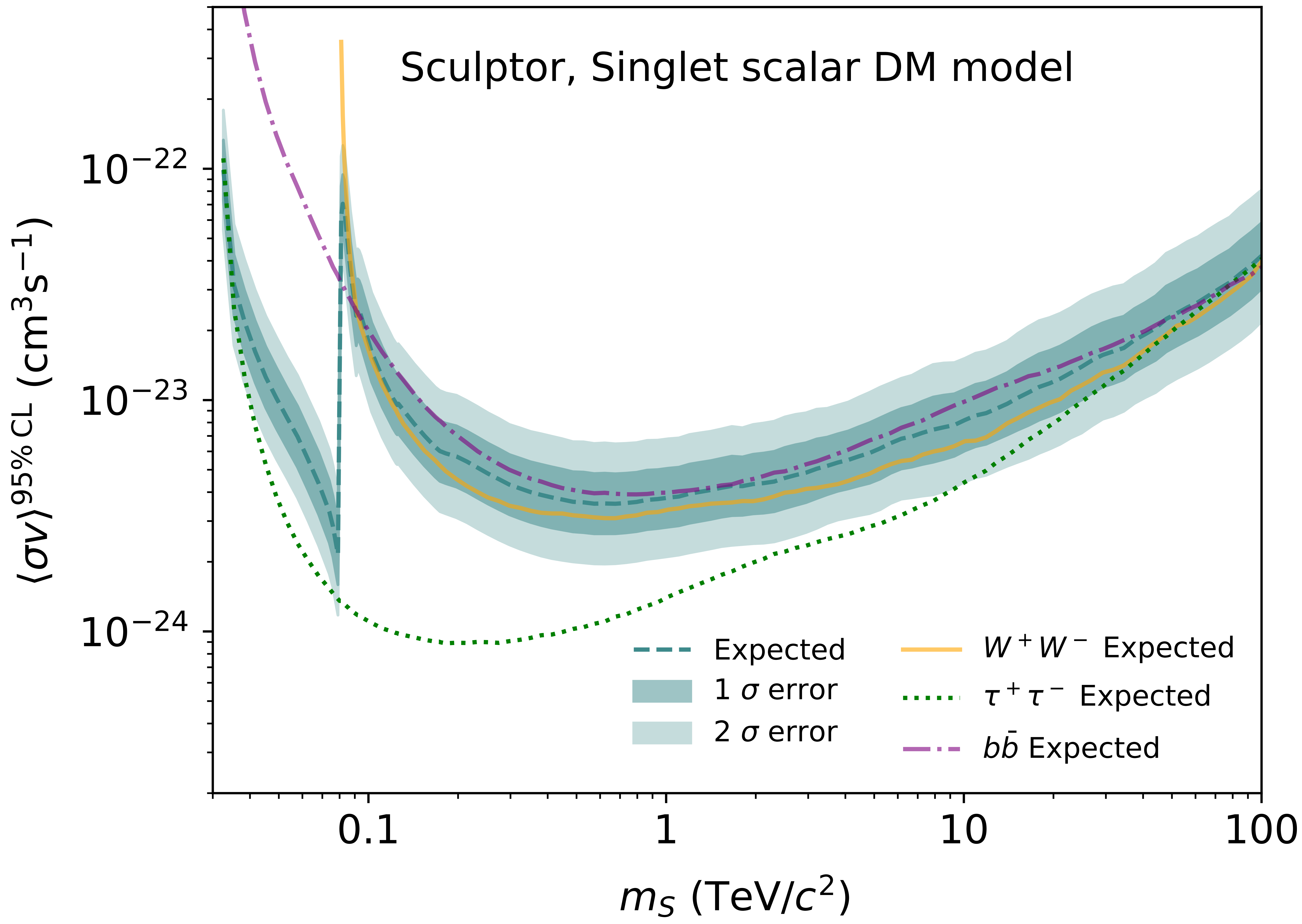
**Additional contributions:** ZZ, hh, tt which produce less γ than the WW channel

### Above 1 TeV

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

**More conservative limit** with the singlet scalar DM model

# COMPARISONS



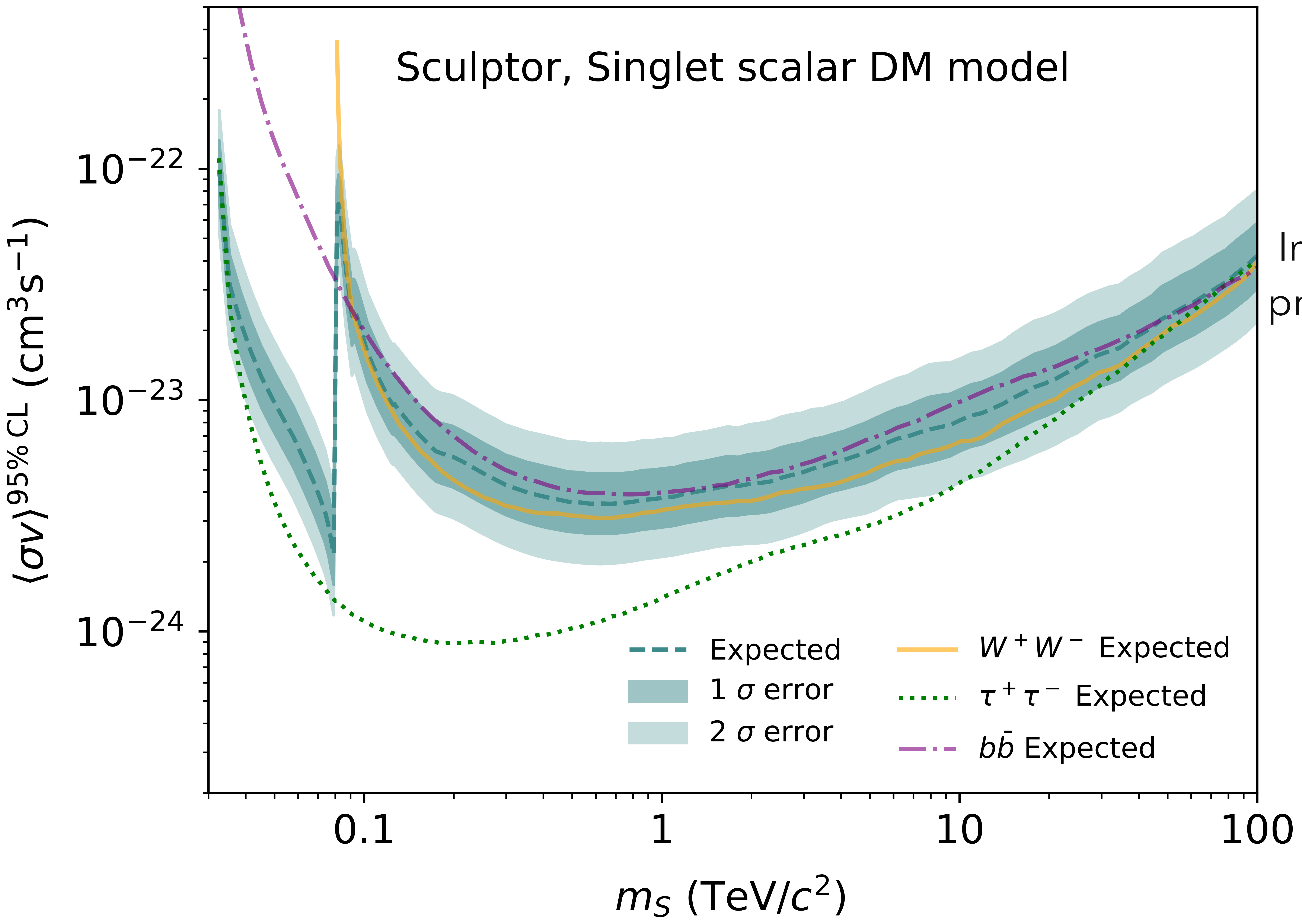

**SINGLET SCALAR MODEL**
**VS**
**100% $\tau^+\tau^-$**

**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

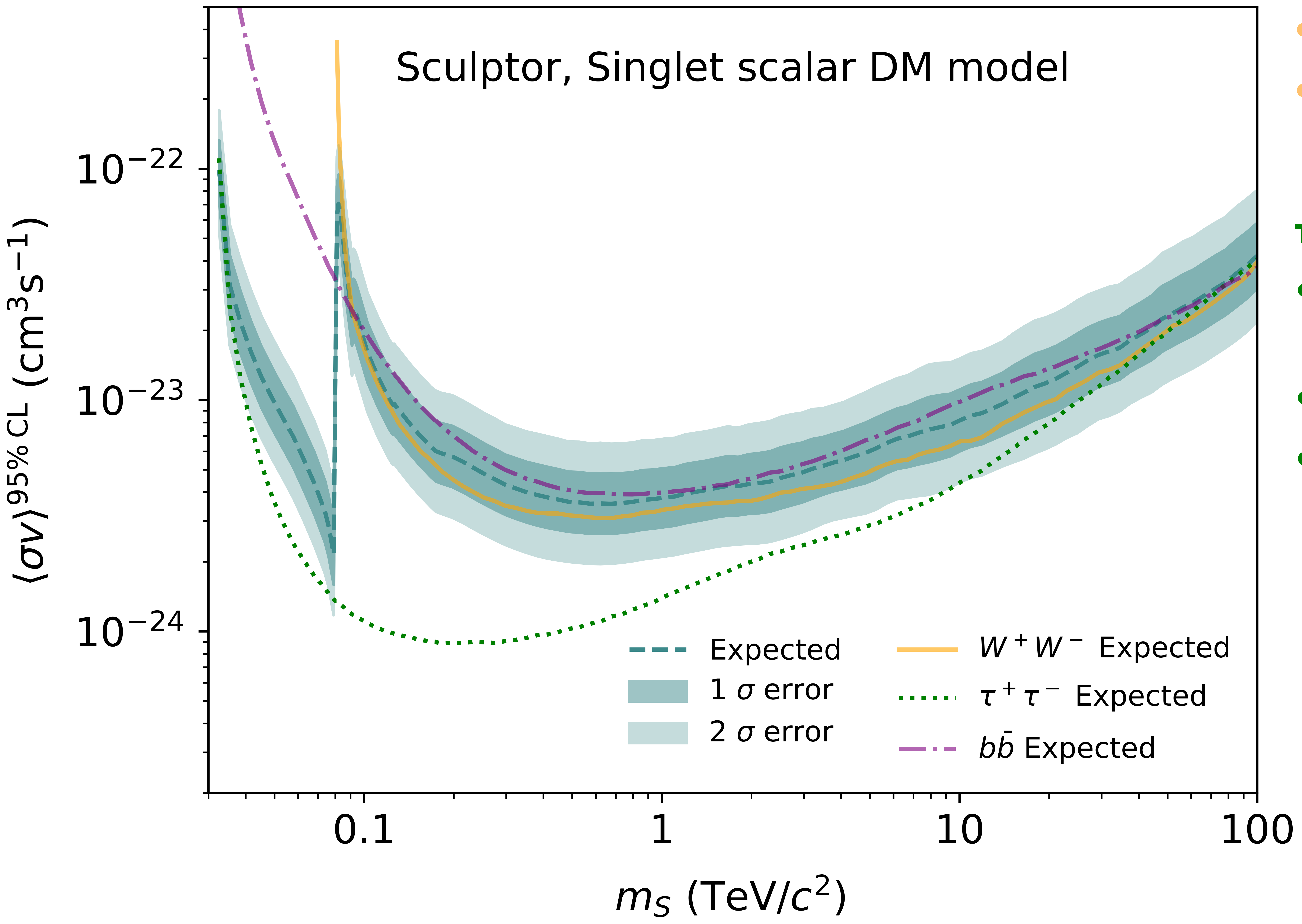
**Above the W mass**

**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

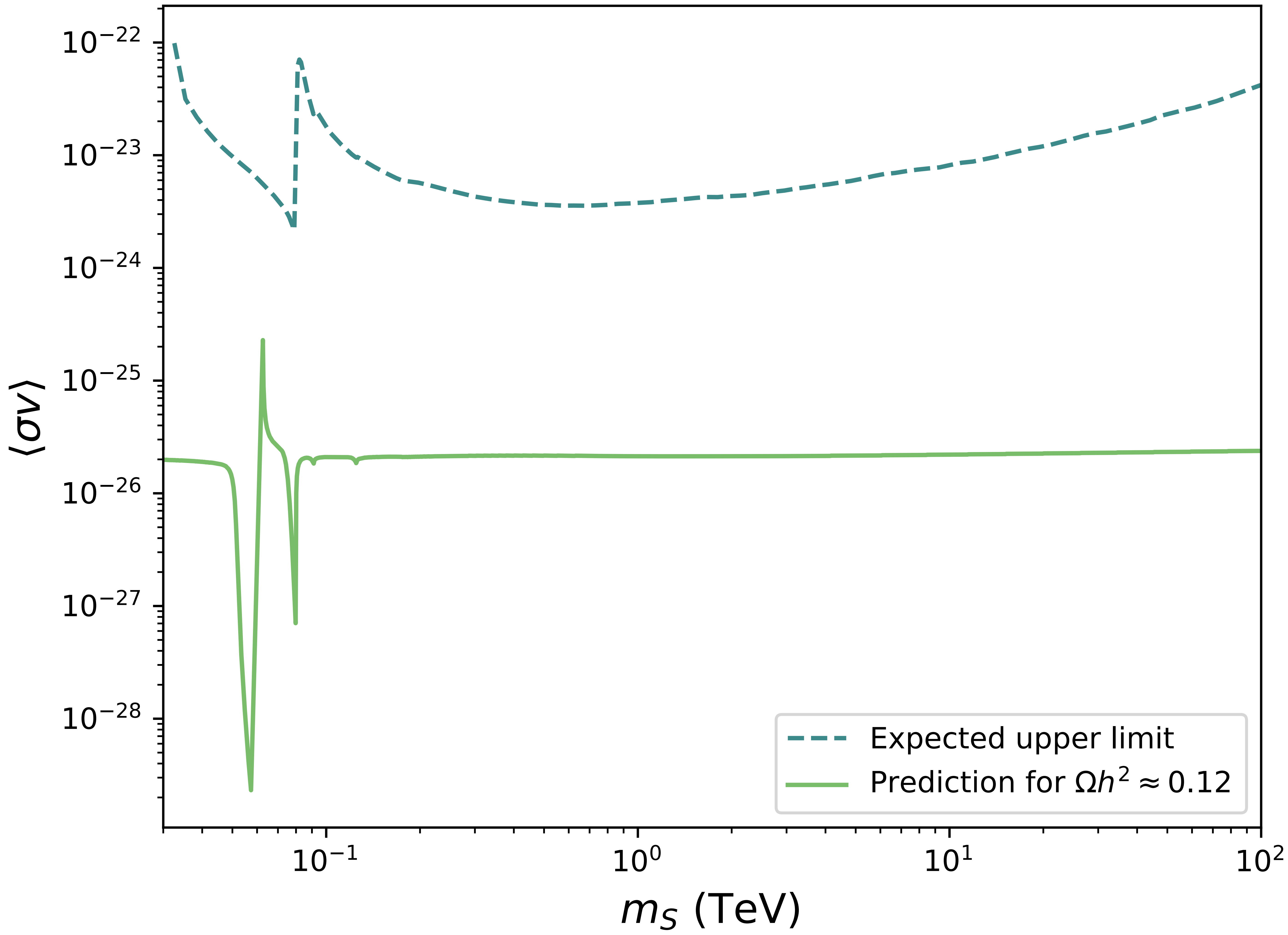
### $\tau^+\tau^-$

- 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

- 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

$$\mathcal{L}(\langle\sigma v\rangle, N_B, J) = \prod_{i=1} \underbrace{\mathcal{L}_{P_i}(\langle\sigma v\rangle, N_{B_i}, J \,|\, N_{\mathrm{ON}_i}, N_{\mathrm{OFF}_i}, \alpha)}_{\text{Poisson likelihood}} \underbrace{\mathcal{L}^J(J \,|\, \bar{J}, \sigma_J)}_{\text{Log-normal likelihood}}$$

Poisson likelihood

Log-normal likelihood

## Poisson likelihood for each energy bin

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

ON REGION

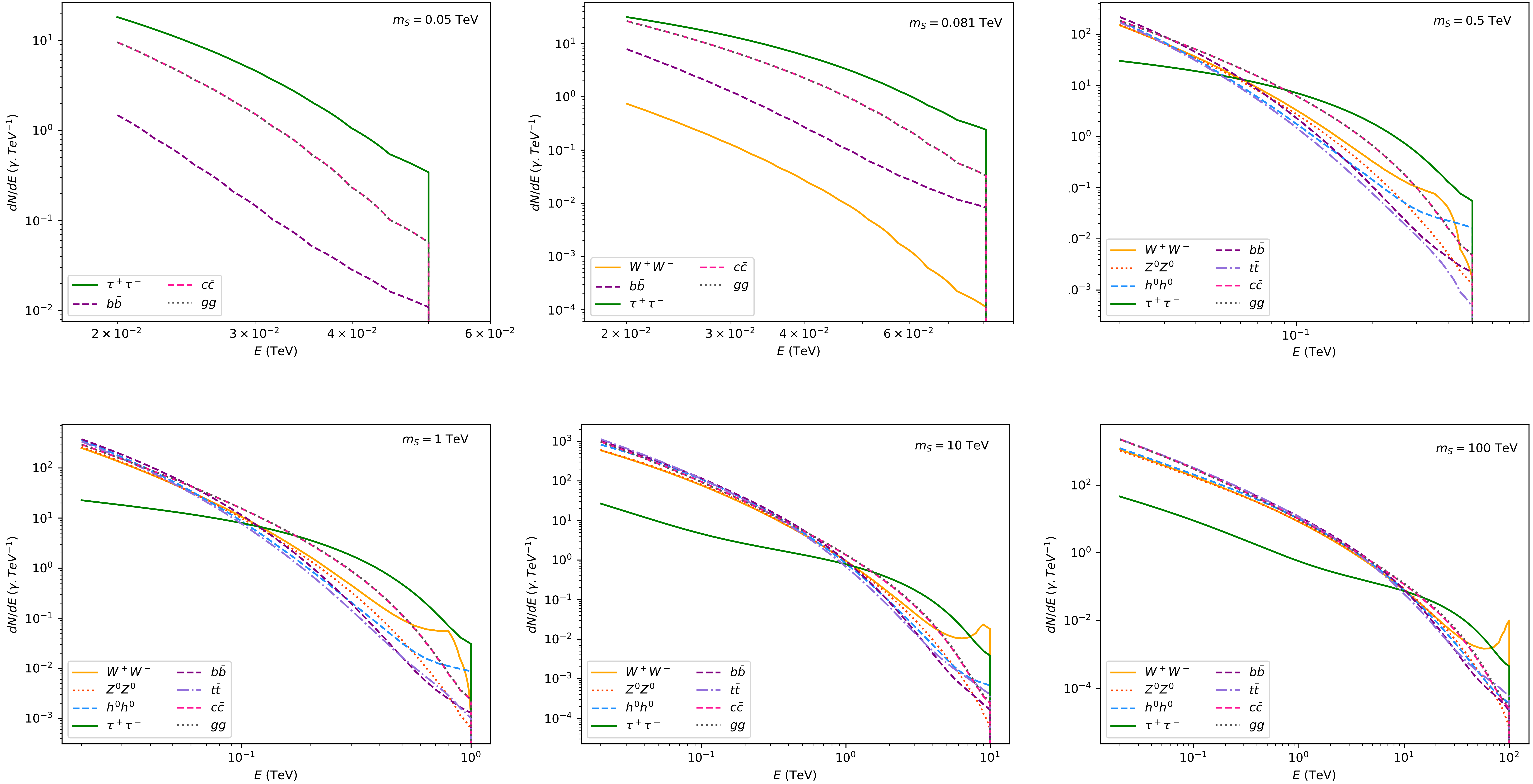
OFF REGION

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

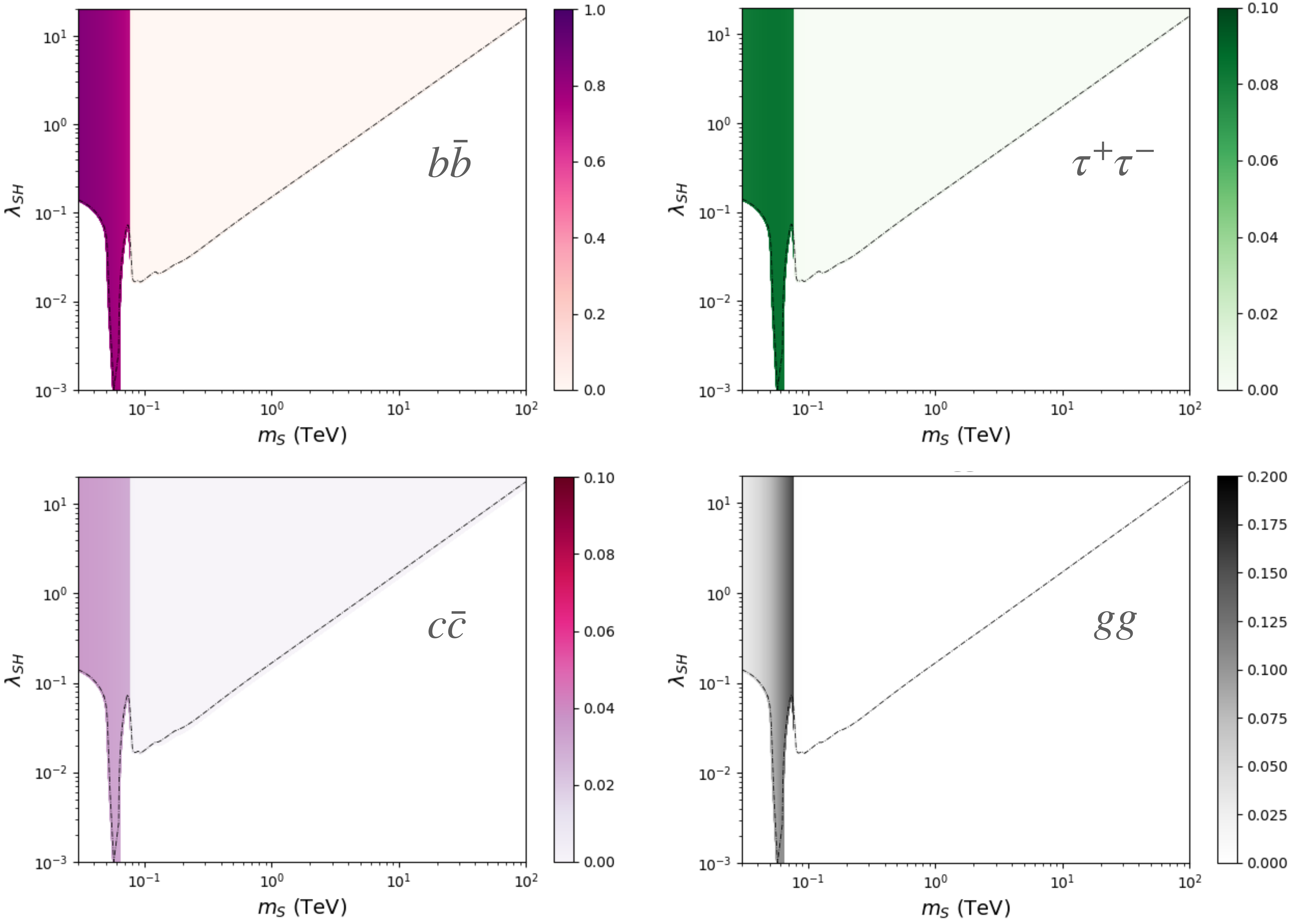
$$\mathcal{L}^J = \frac{1}{\ln(10)\sqrt{2\pi}\sigma_J J} \exp - \frac{(\log_{10} J - \log_{10} \bar{J})^2}{2\sigma_J^2}$$

# SPECTRA

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



# BRANCHING RATIOS




$$m_S \lesssim m_W$$

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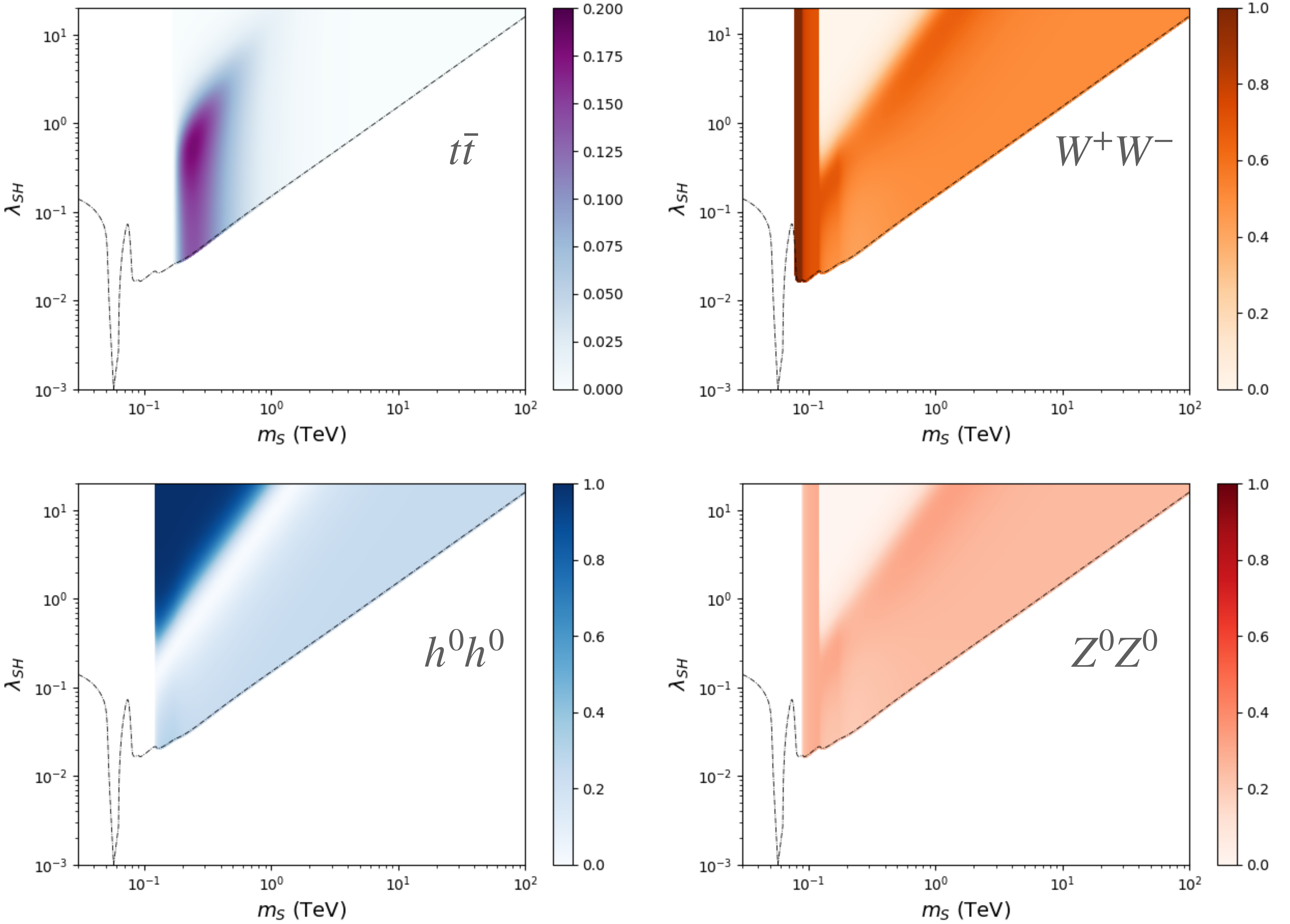


$m_S \gtrsim m_W$