Long-lived Coannihilation Particle search at LHC

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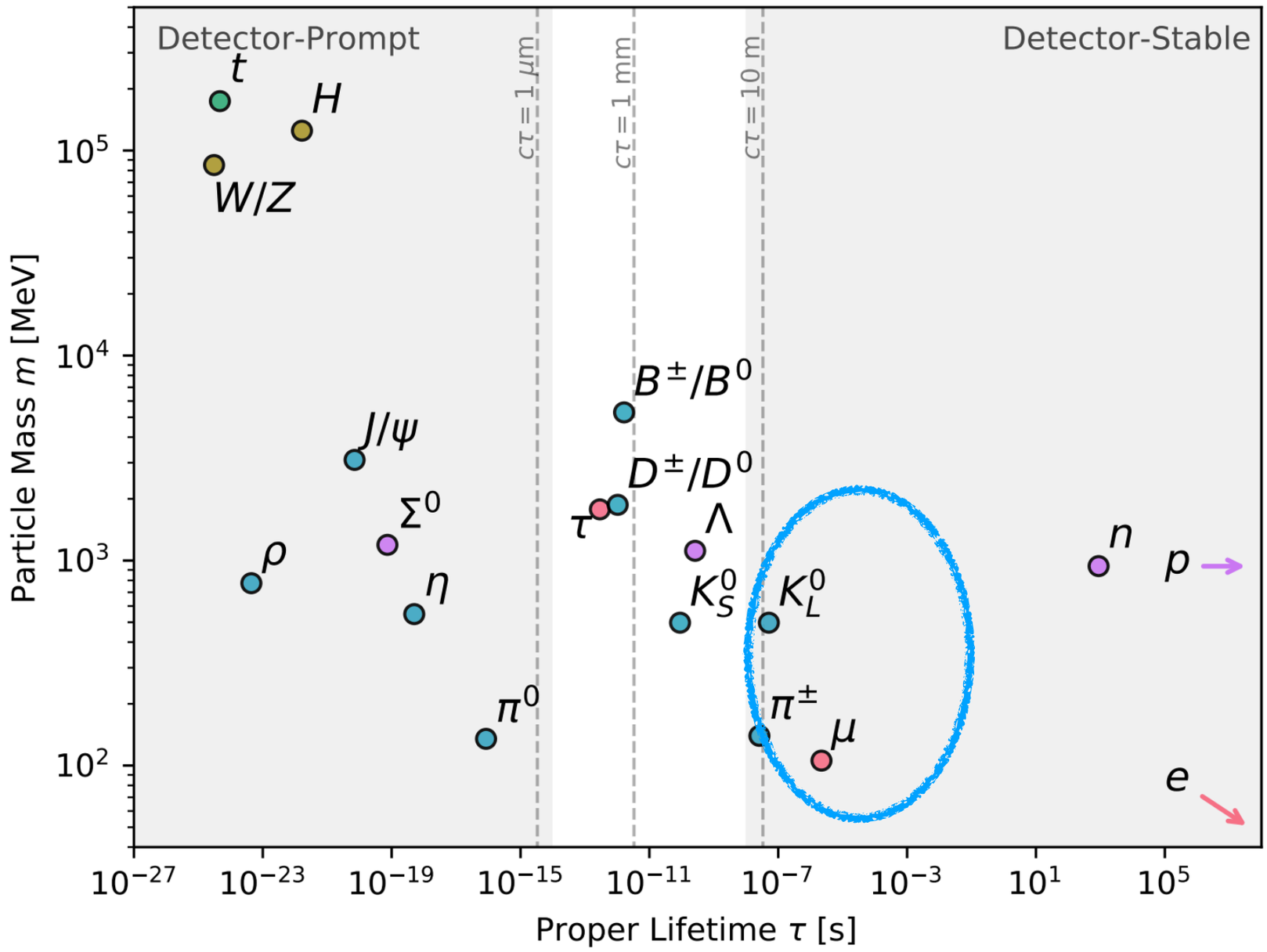
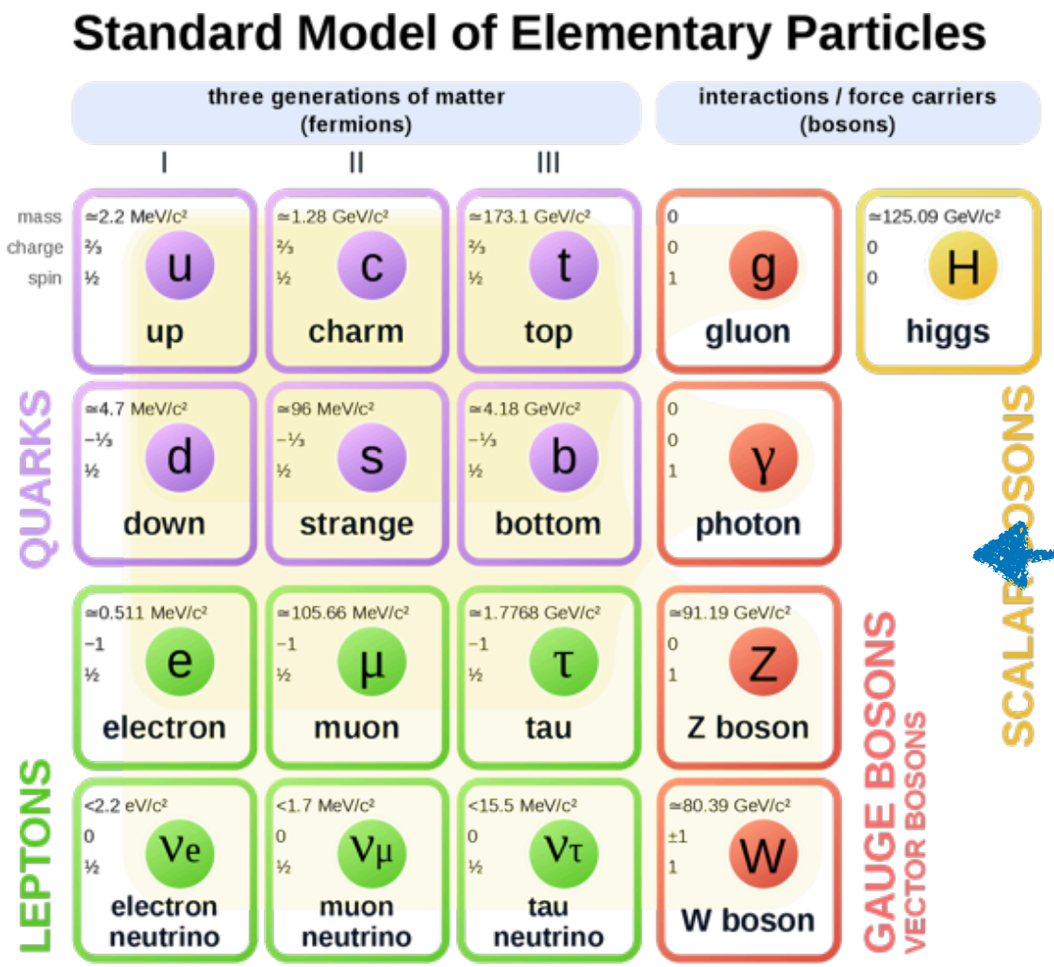
Collaborated with Jia Liu(刘佳), Jinhui Guo and Yuxuan He

Why Long-lived Particles?

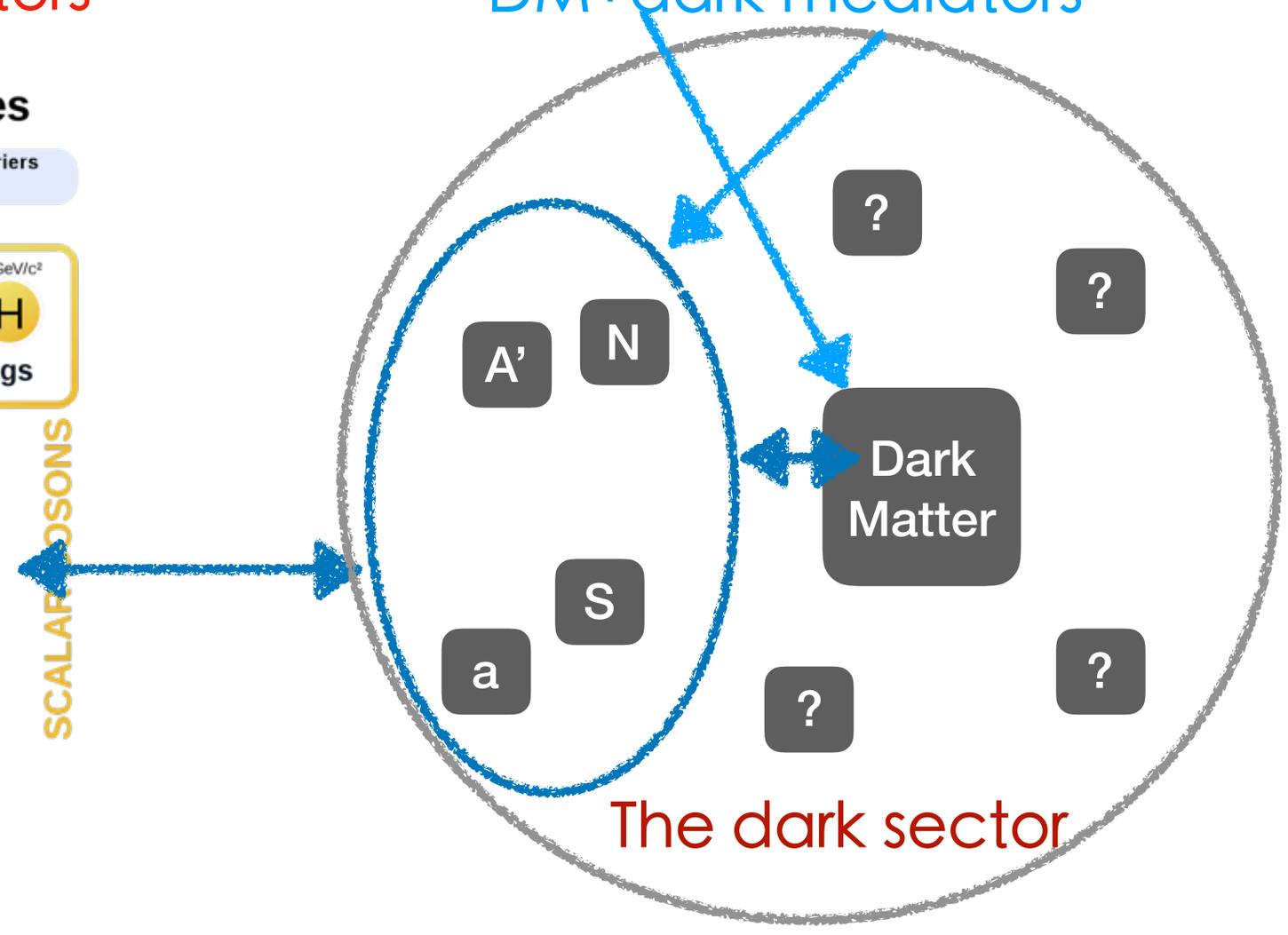


Why Long-lived Particles?

- Standard Model
  =fermions+force mediators

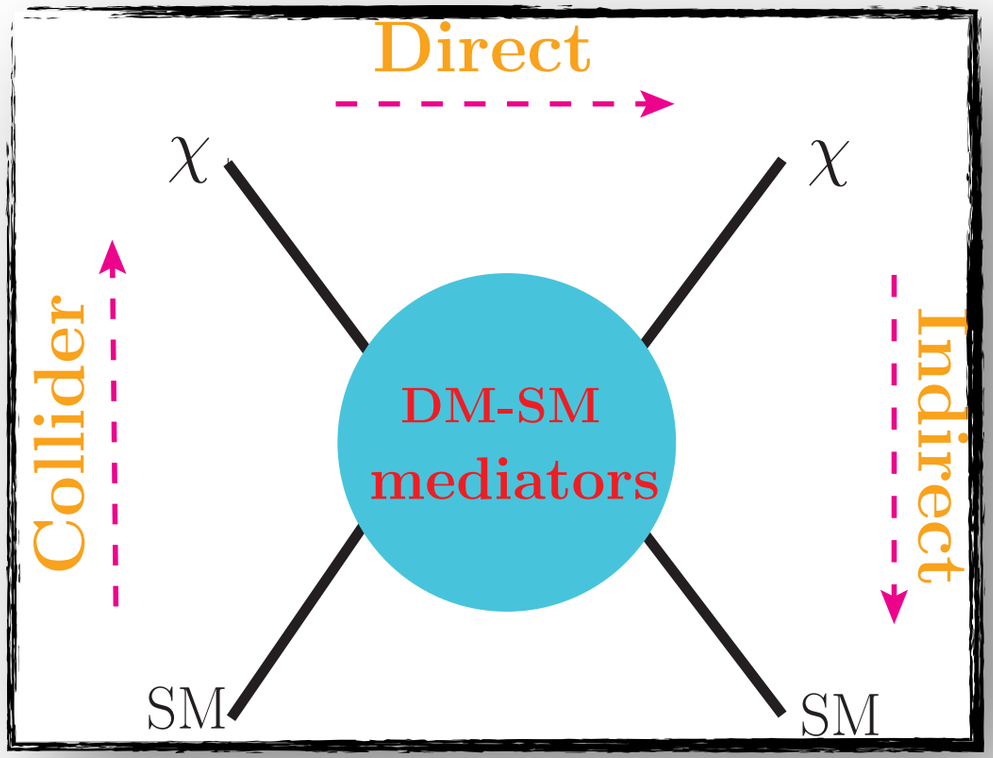


- Dark sector
  =DM+dark mediators



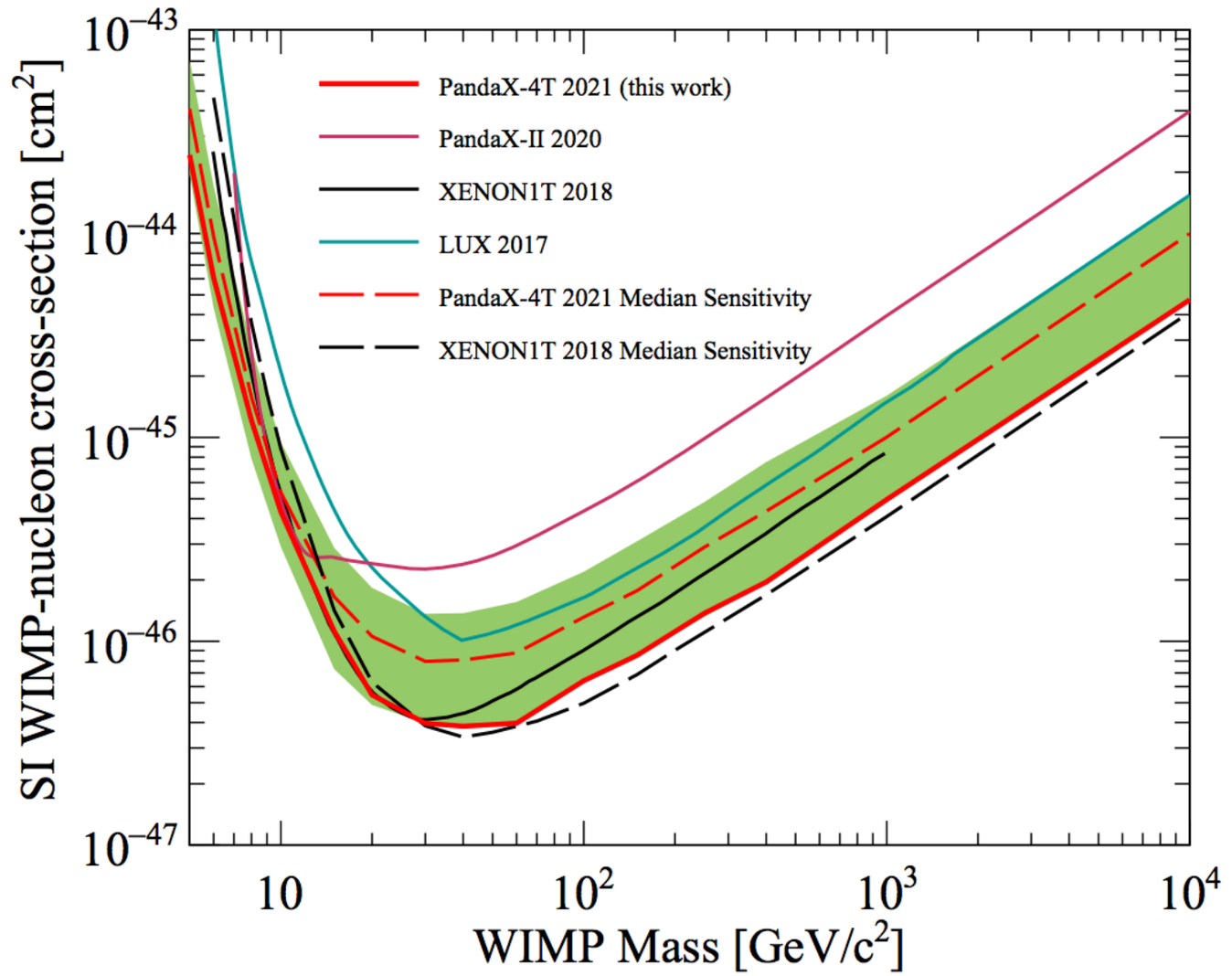
- **Not a surprise: dark sector particles have a wide spread in lifetime**

Dark Matter Search



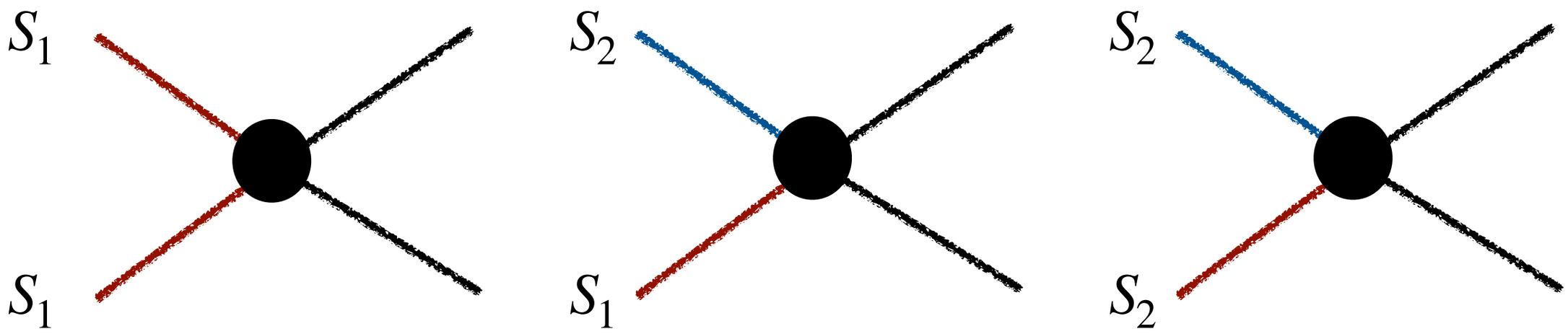
$$\Omega h^2 = 0.12 \pm 0.001$$

$$\sim \frac{10^{-38}\mathrm{cm}^2}{\langle \sigma v \rangle}$$



Coannihilation Dark Matter

Relic density set by the processes:



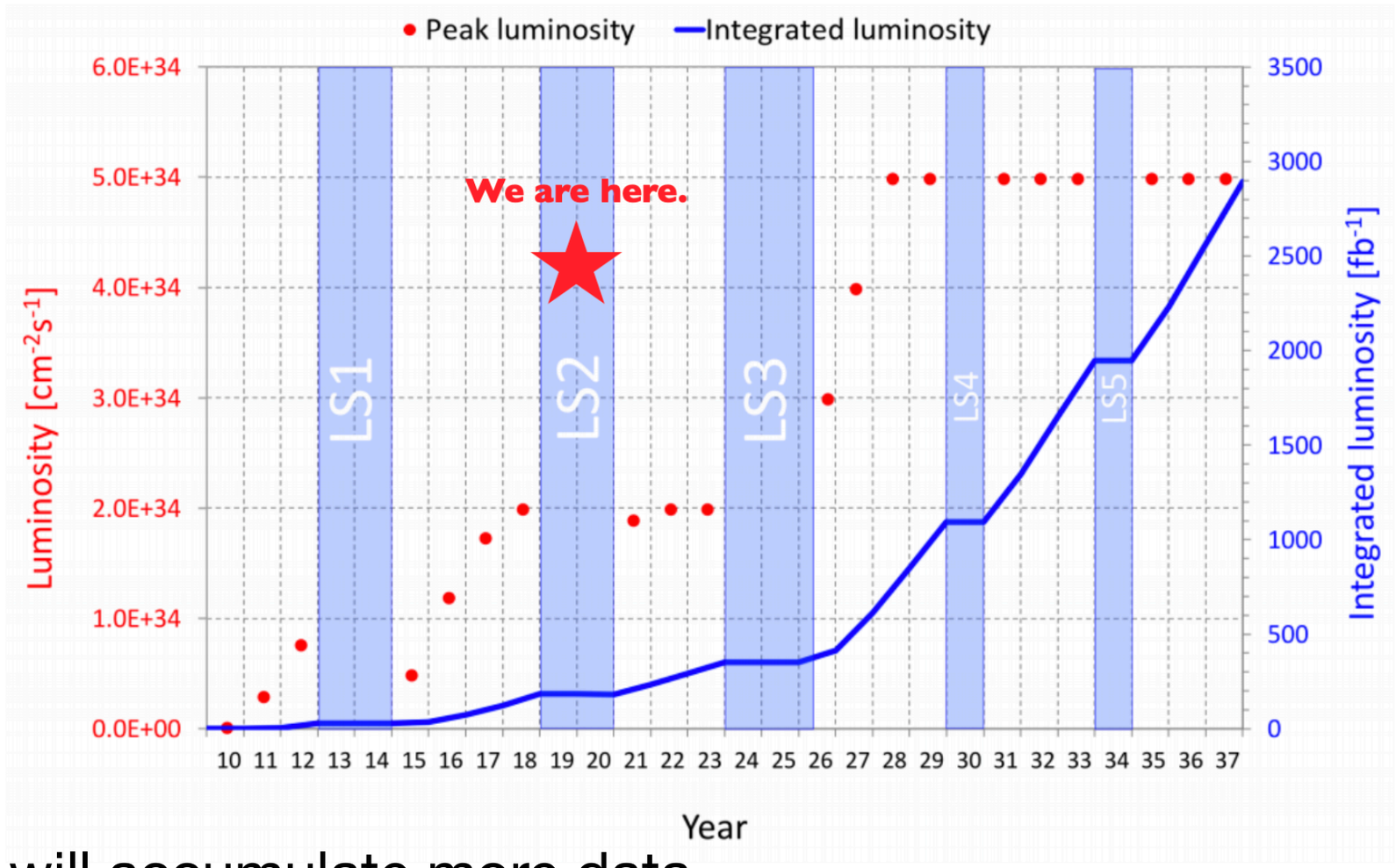
The effective cross section is

$$\sigma_{\text{eff}} = \frac{g_{s_1}^2}{g_{\text{eff}}^2}\left(\sigma_{11} + 2\sigma_{12}\frac{g_{s_2}}{g_{s_1}}(1+\Delta)^{3/2}e^{-x_f\Delta} + \sigma_{22}\frac{g_{s_2}^2}{g_{s_1}^2}(1+\Delta)^3 e^{-2x_f\Delta}\right)$$

$$\Delta \equiv \frac{m_2 - m_1}{m_1} \sim 0.1$$
$$\sigma_{11} \approx 0, \quad \sigma_{12} \ll \sigma_{22}$$

→ **~100GeV Long-lived s_2**

Why Looking for LLP at LHC?



- LHC will accumulate more data
- Exp collaborations have broad physics programs: SUSY, composite H, extra Dim, etc.
- New directions?

Inelastic Scalar DM Model

Lagrangian with global $U(1)$ symmetry, with $\hat{S} = \left(\hat{s}_1 + i\hat{s}_2\right)/\sqrt{2}$

$$\mathscr{L}_{U(1)} = \left(\partial_\mu \hat{S}\right)^* \left(\partial^\mu \hat{S}\right) - m_S^2 \hat{S}^* \hat{S}$$

After U(1) symmetry breaking:

$$\mathscr{L} = -\delta \hat{m}_{ij}^2 \hat{s}_i \hat{s}_j - \hat{\lambda}_{ij} \hat{s}_i \hat{s}_j \left(H^\dagger H - \frac{v^2}{2}\right)$$

The effective Lagrangian is our baseline model and in the mass eigenstates,

$$\mathscr{L}_{\text{eff}} = \left(\partial_\mu S\right)^\dagger (\partial^\mu S) - m_1^2 s_1^2 - m_2^2 s_2^2 - \lambda_{22} s_2^2 \left(H^\dagger H - \frac{v^2}{2}\right)$$

Inelastic Scalar DM Model

There is a massive dark photon A', from the U(1) gauge field in the hidden sector

$$\mathscr{L}_{A'} = -\frac{1}{4}\hat{F}'^{\mu\nu}\hat{F}'_{\mu\nu} - \frac{\epsilon}{2c_w}\hat{F}'^{\mu\nu}B_{\mu\nu} + \frac{m_{A'}^2}{2}\hat{A}'^{\mu}\hat{A}'_{\mu}$$

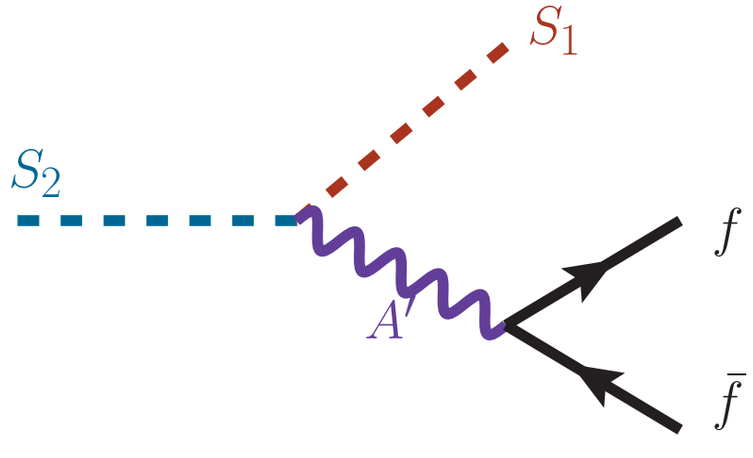
After mixing

$$\mathscr{L}_{\mathbf{int}} = A_\mu e J^\mu_{\rm em} + Z_\mu\left(gJ^\mu_Z - \epsilon g_D\frac{m_Z^2 t_w}{m_Z^2 - m_{A'}^2}J^\mu_D\right) + A'_\mu\left(g_D J^\mu_D + e\epsilon J^\mu_{\rm em} + \epsilon g\frac{m_{A'}^2 t_w}{m_Z^2 - m_{A'}^2}J^\mu_Z\right)$$

With

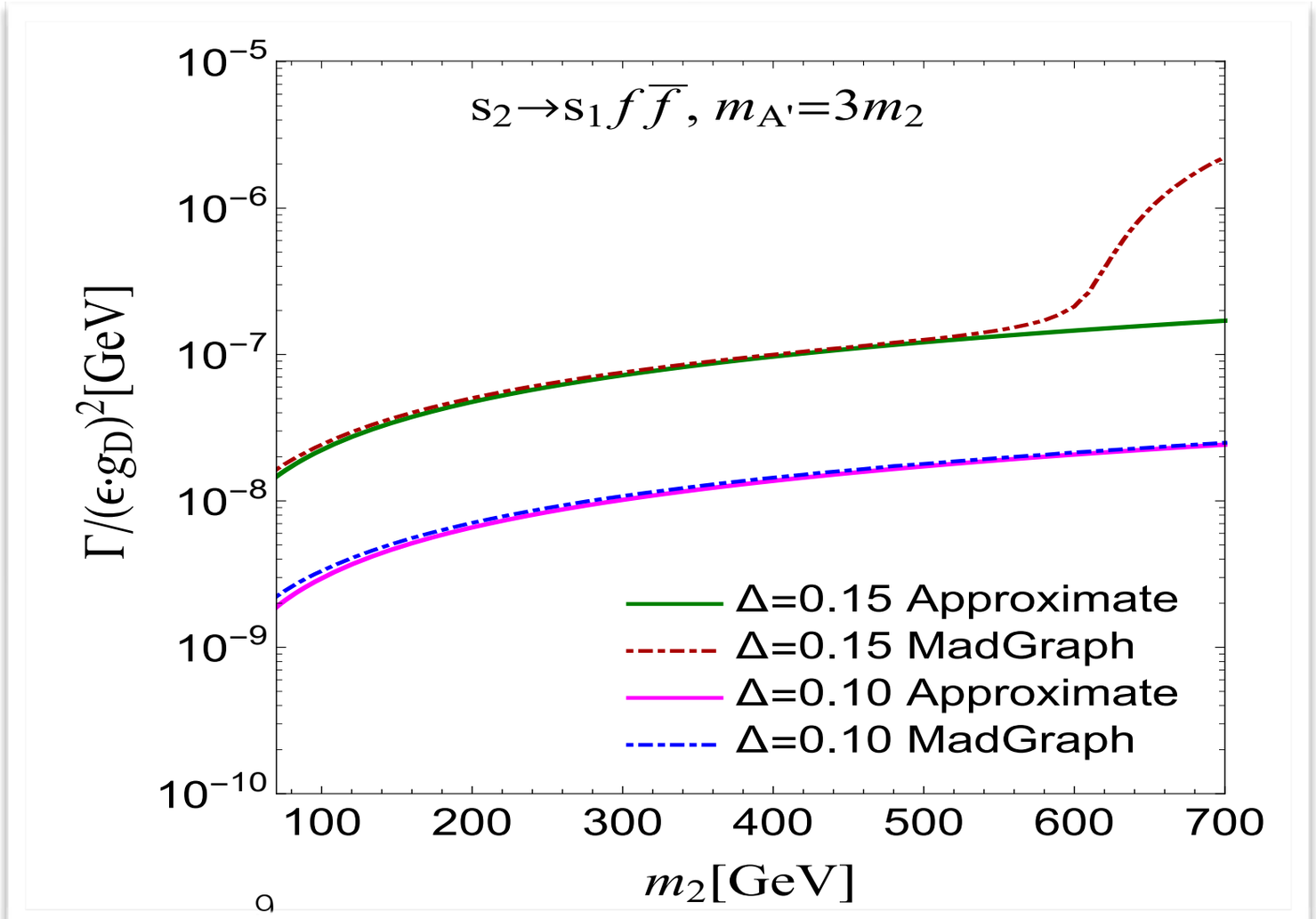
$$J^\mu_D = i\left(S^\dagger\partial^\mu S - S\partial^\mu S^\dagger\right) = s_2\partial^\mu s_1 - s_1\partial^\mu s_2$$

Long-lived S_2

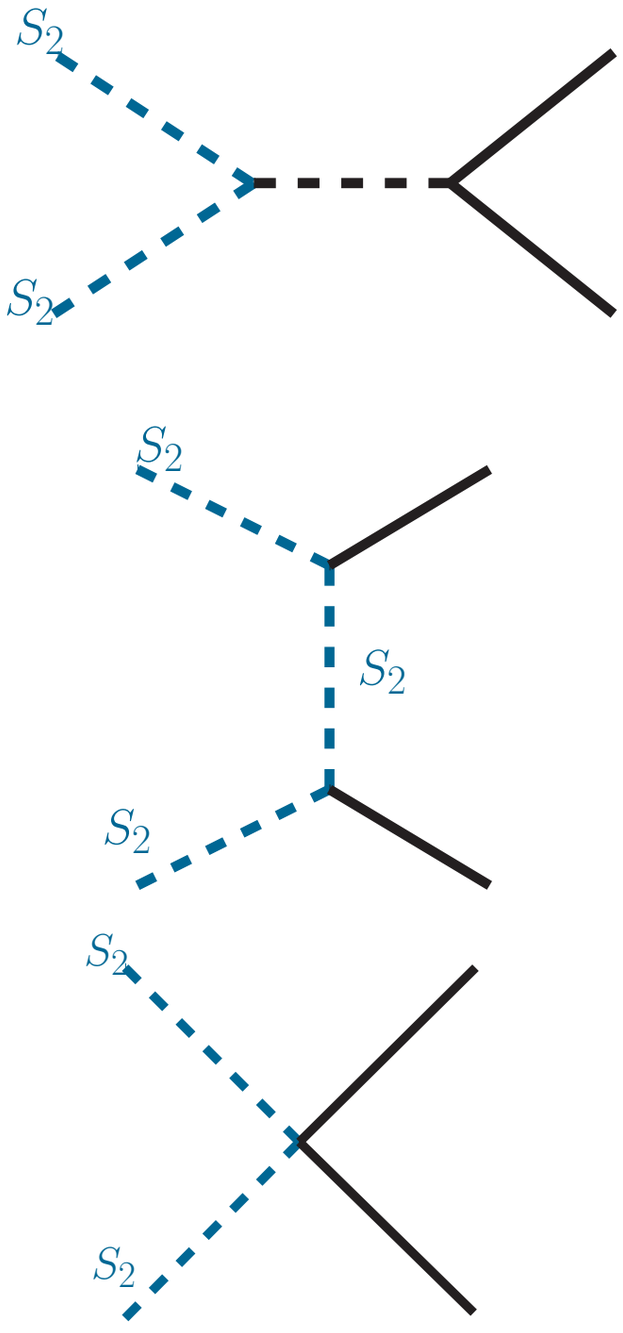


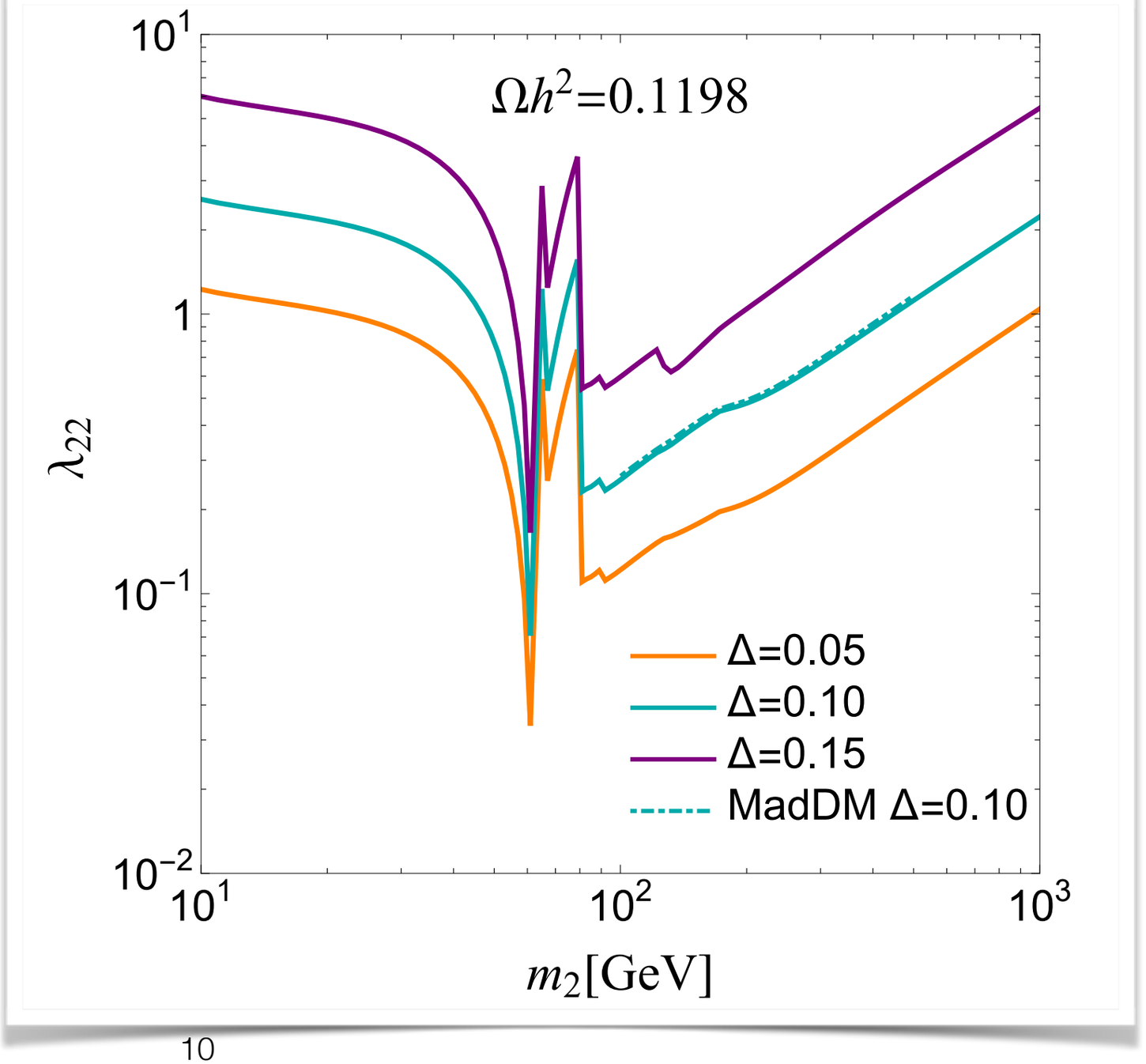
$$\Gamma\left(s_2 \to s_1 f\bar{f}\right) \simeq Q_f^2 \frac{\left(\epsilon g_D\right)^2 e^2 m_2^5 \Delta^5}{60\pi^3 m_{A'}^4}$$

$$\simeq Q_f^2 \left(\frac{\epsilon g_D}{10^{-3}}\right)^2 \left(\frac{\Delta}{0.1}\right)^5 \left(\frac{3m_2}{m_{A'}}\right)^4 \frac{m_2}{100\text{GeV}} \cdot 0.92\ \text{ns}^{-1}$$



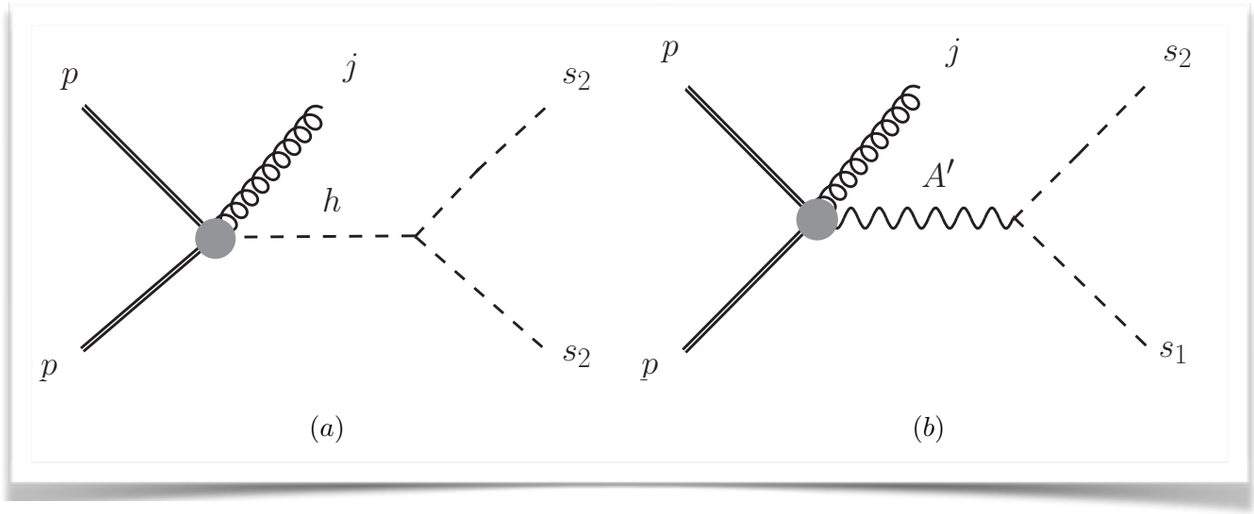
DM annihilation cross section

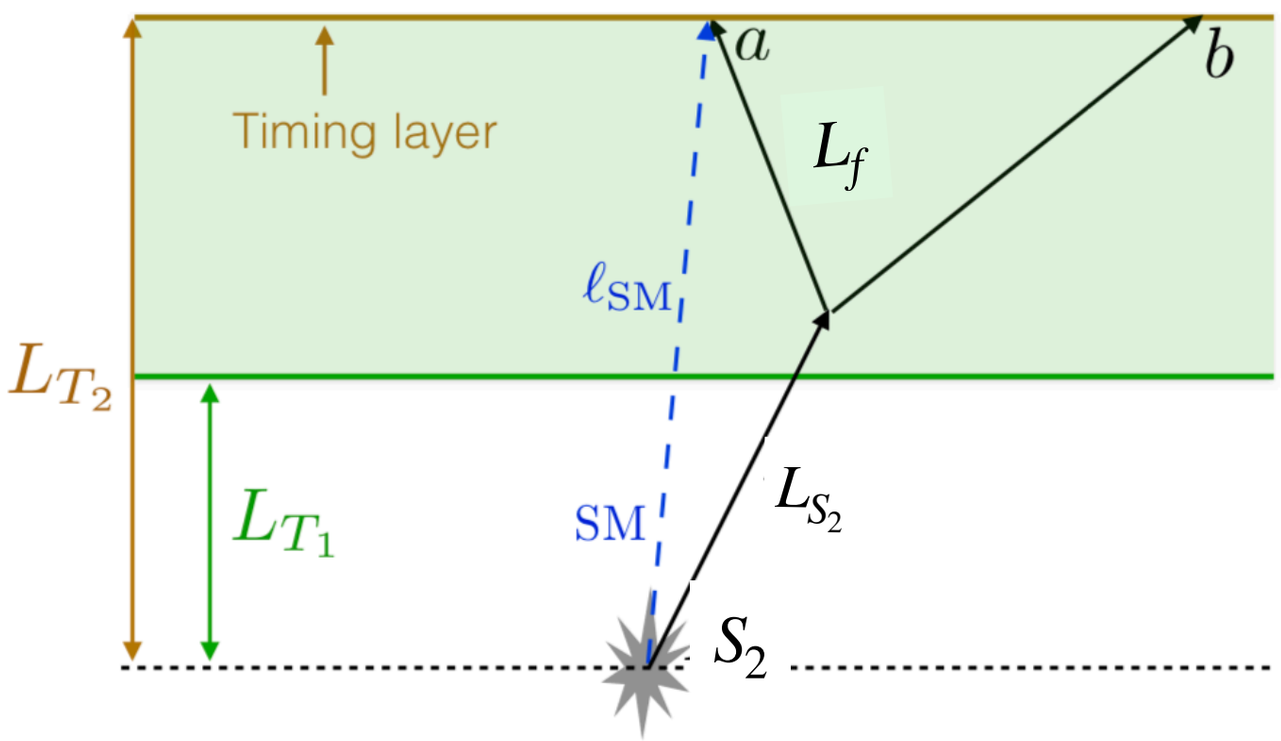




S_2 Production at LHC

S_2 Production Feynman diagrams





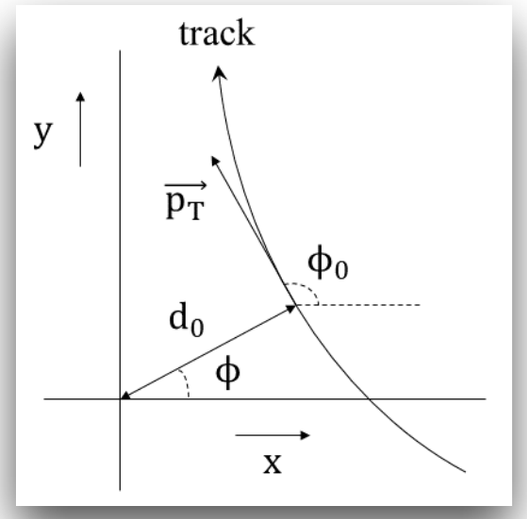
$$\Delta t_f = \frac{L_{s_2}}{\beta_{s_2}} + \frac{L_f}{\beta_f} - \frac{L_{\rm SM}}{\beta_{\rm SM}}$$

Long-lived S_2 search

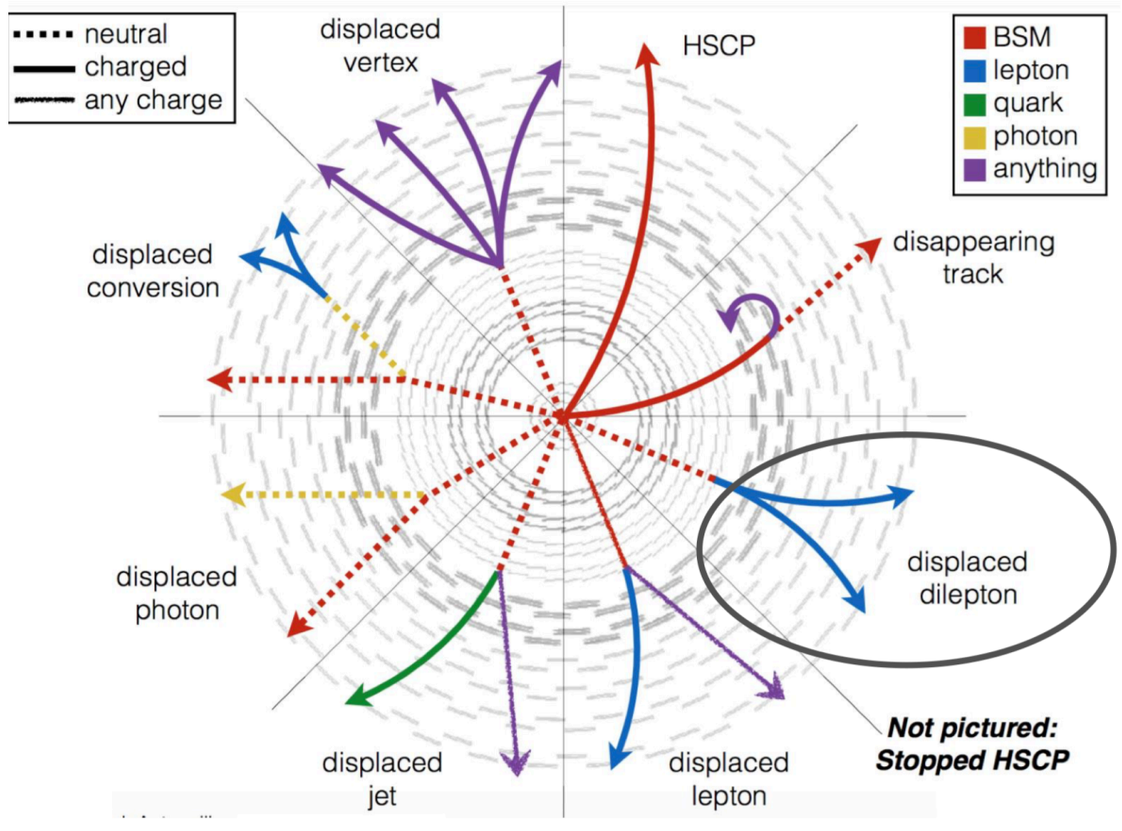
Free parameters:

$$\{g_D = 0.1,\ \ m_{A'} = 3m_2,\ \ \lambda_{22}(\Omega h^2),\ \ \Delta,\ \ \epsilon\}$$

- **Displaced muon jet:**



$$d_0 = \sqrt{x^2 + y^2 - \frac{(xp_x + yp_y)^2}{p_x^2 + p_y^2}}$$



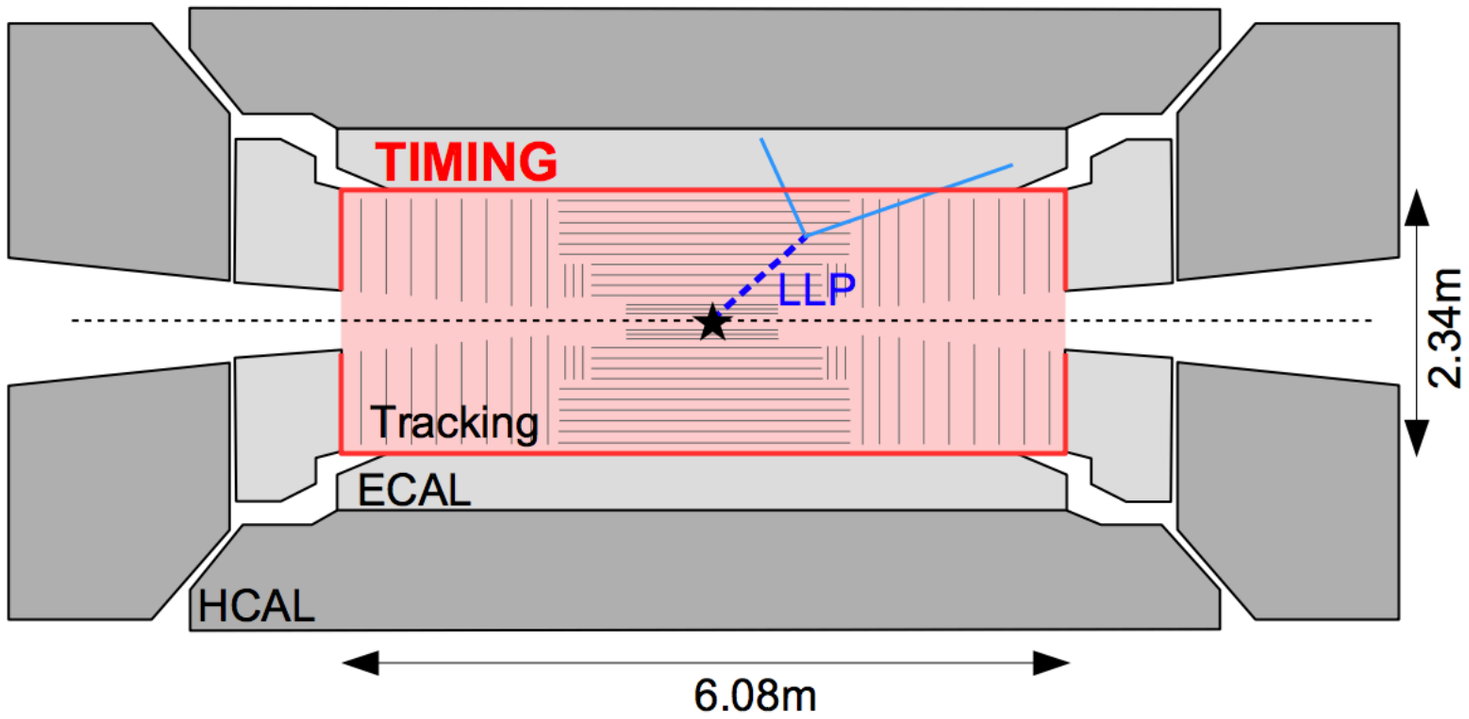
$$p_T^j > 120\text{GeV}, \quad p_T^\mu > 5\text{GeV}, \quad r_{s_2} < 30\ \text{cm}, \quad d_0^\mu > 1\ \text{mm}$$

Long-lived S_2 search

Free parameters:

$$\{g_D = 0.1,\ \ m_{A'} = 3m_2,\ \ \lambda_{22}(\Omega h^2),\ \ \Delta,\ \ \epsilon\}$$

- **Timing:**



$$p_T^j > 120\text{GeV}(30\text{GeV}),\quad p_T^\ell > 3\text{GeV},\quad |\eta| < 2.4$$

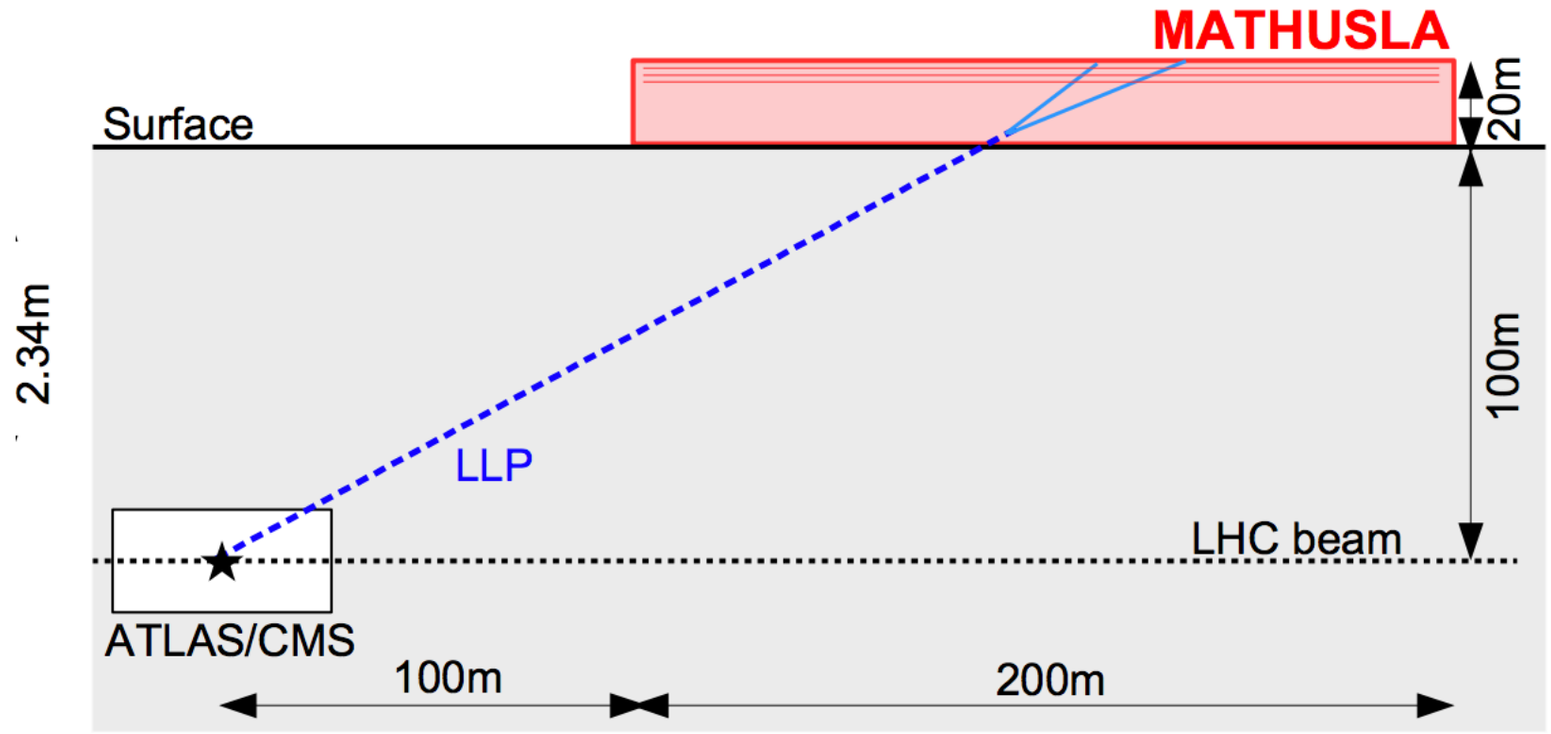
$$\Delta t_\ell > 0.3\ \text{ns},\quad 5\ \text{cm} < r_{s_2} < 1.17\ \text{m},\quad z_{s_2} < 3.04\ \text{m}$$

Long-lived S_2 search

Free parameters:

$$\{g_D = 0.1,\ \ m_{A'} = 3m_2,\ \ \lambda_{22}(\Omega h^2),\ \ \Delta,\ \ \epsilon\}$$

- **MATHUSLA:**

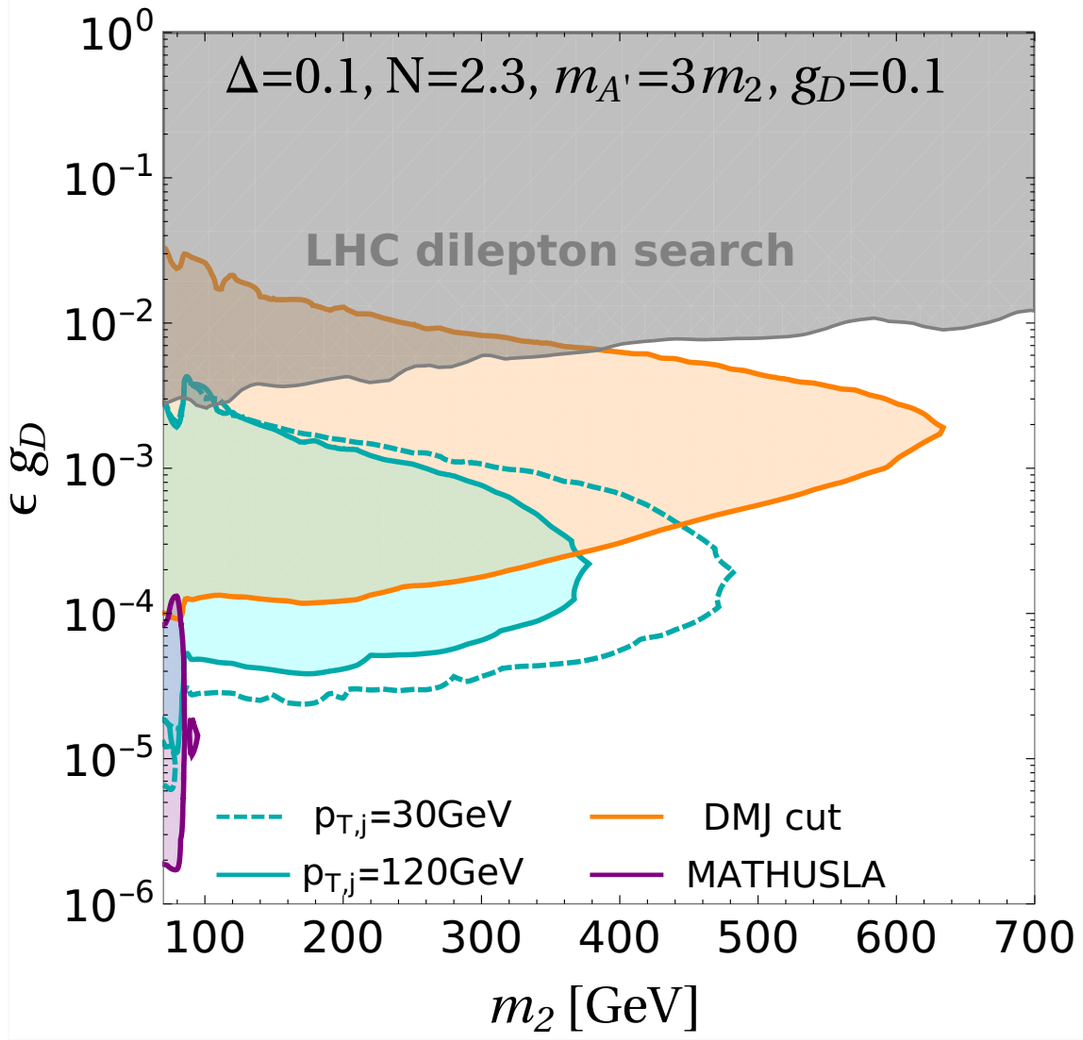


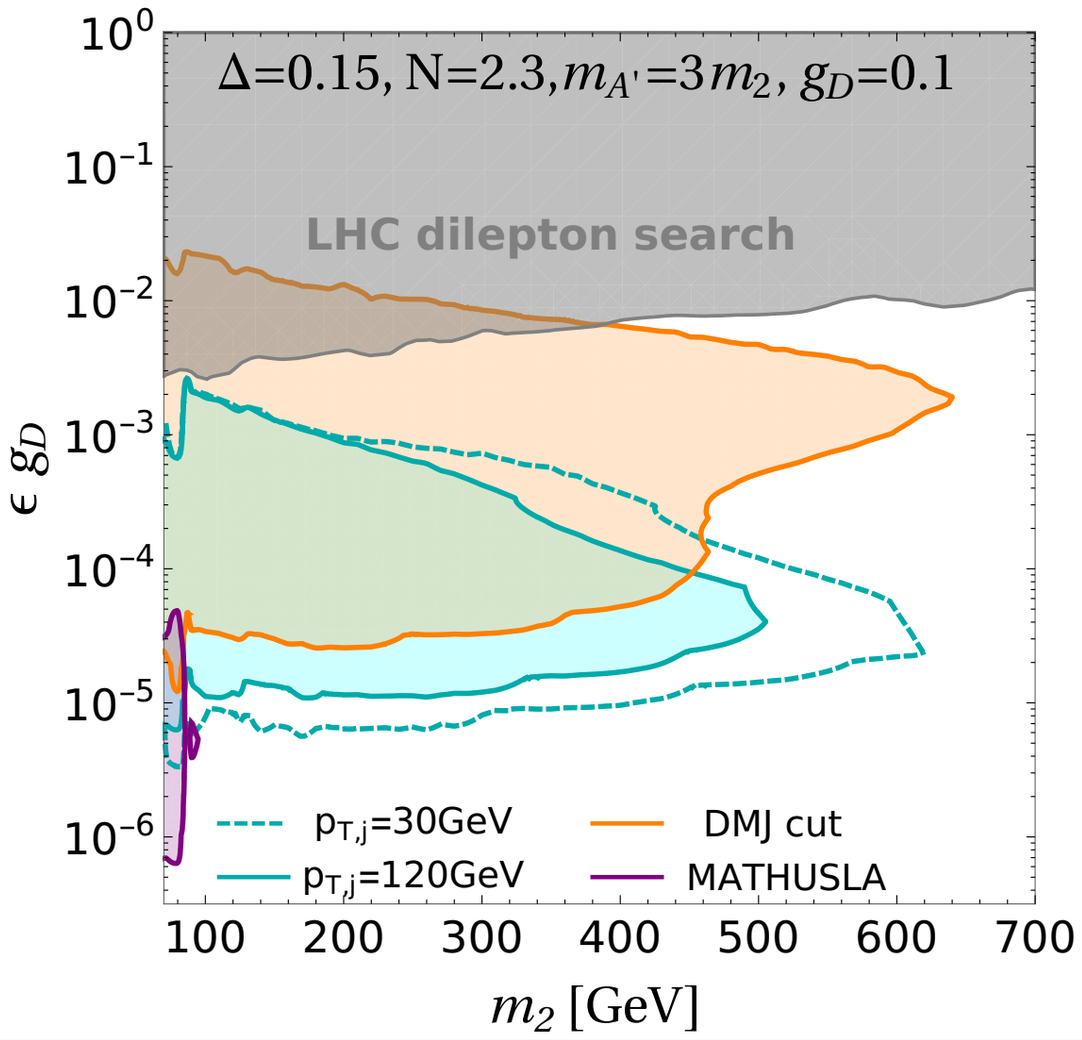
$$100\ \text{m} < x_{s_2} < 120\ \text{m}, -100\ \text{m} < y_{s_2} < 100\ \text{m}, 100\ \text{m} < z_{s_2} < 300\ \text{m}$$

Long-lived S_2 search results

Free parameters:

$$\{g_D = 0.1,\ \ m_{A'} = 3m_2,\ \ \lambda_{22}(\Omega h^2),\ \ \Delta,\ \ \epsilon\}$$





Summary

- Long-lived particle is well-motivated and is new direction of future LHC

- The coannihilation DM can evade the Direct detection constraint

- Long-lived coannihilation particle can be search at LHC

Thank you!