Probing dark matter above TeV and below meV

Giovanni Grilli di Cortona

based on:
- JHEP 1505(2015)035 (arXiv: 1412.5952)
- work in progress with E. Hardy, J. Pardo Vega and G. Villadoro

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ma per seguir virtute e canoscenza
SISSA

Introduction

DM properties:

- stable
- electrical and color neutral
- not relativistic today -> Cold DM
- collisionless

several candidates:

WIMPs, axion, ...

Introduction

Two of the best CDM candidates:

WIMP

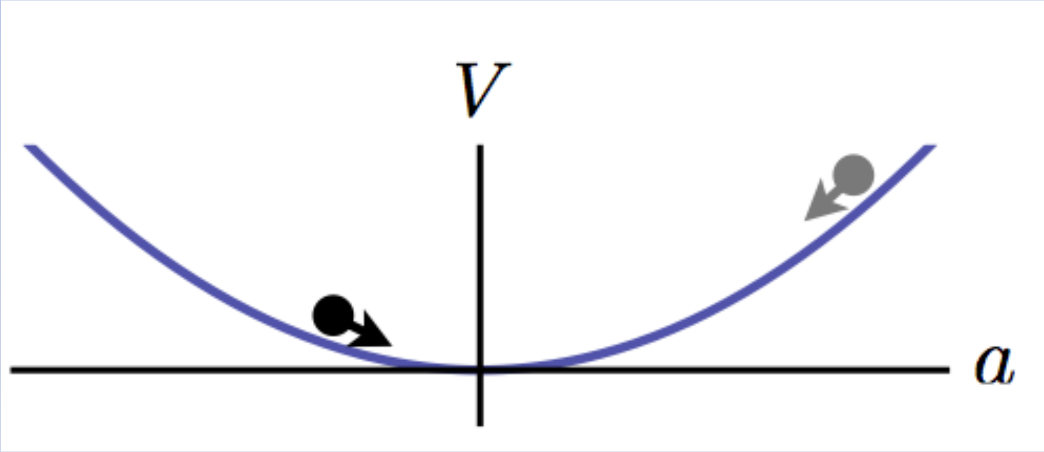
$\Omega h^2 \sim 0.1 \, (\sigma_{EW} / \sigma_{DM})$

+ unitarity constraint

DM mass GeV-TeV

axion

misalignment mechanism



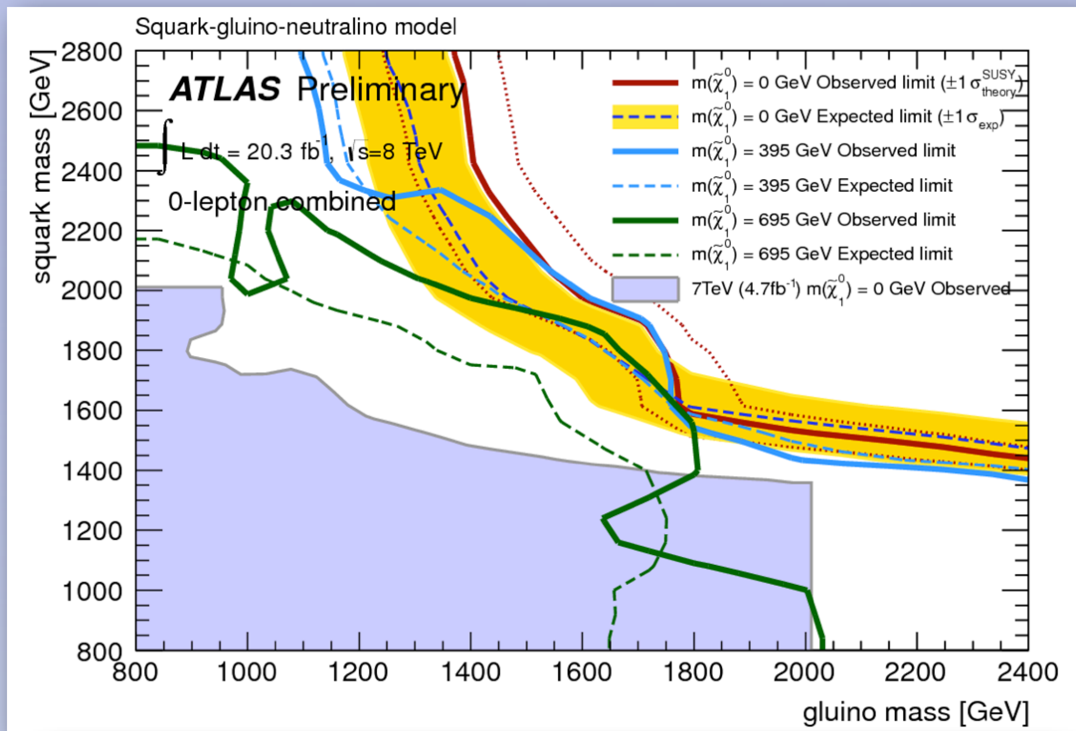
correct relic abundance

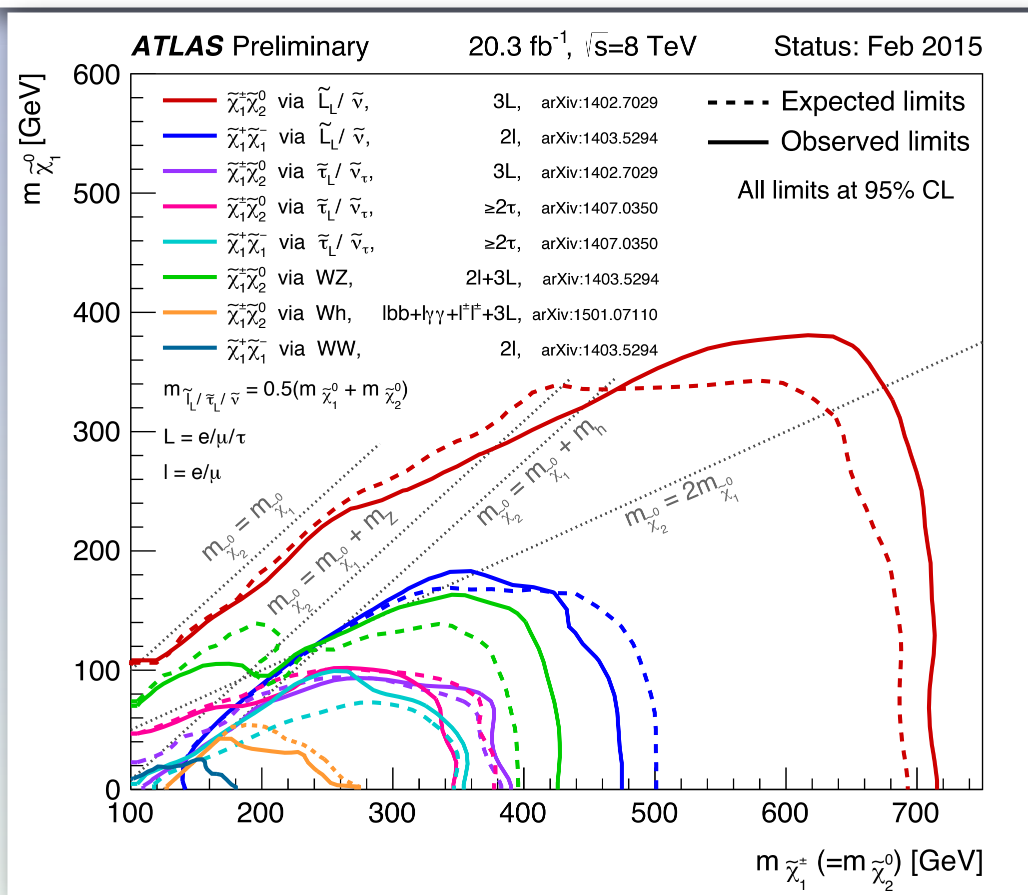
Outline

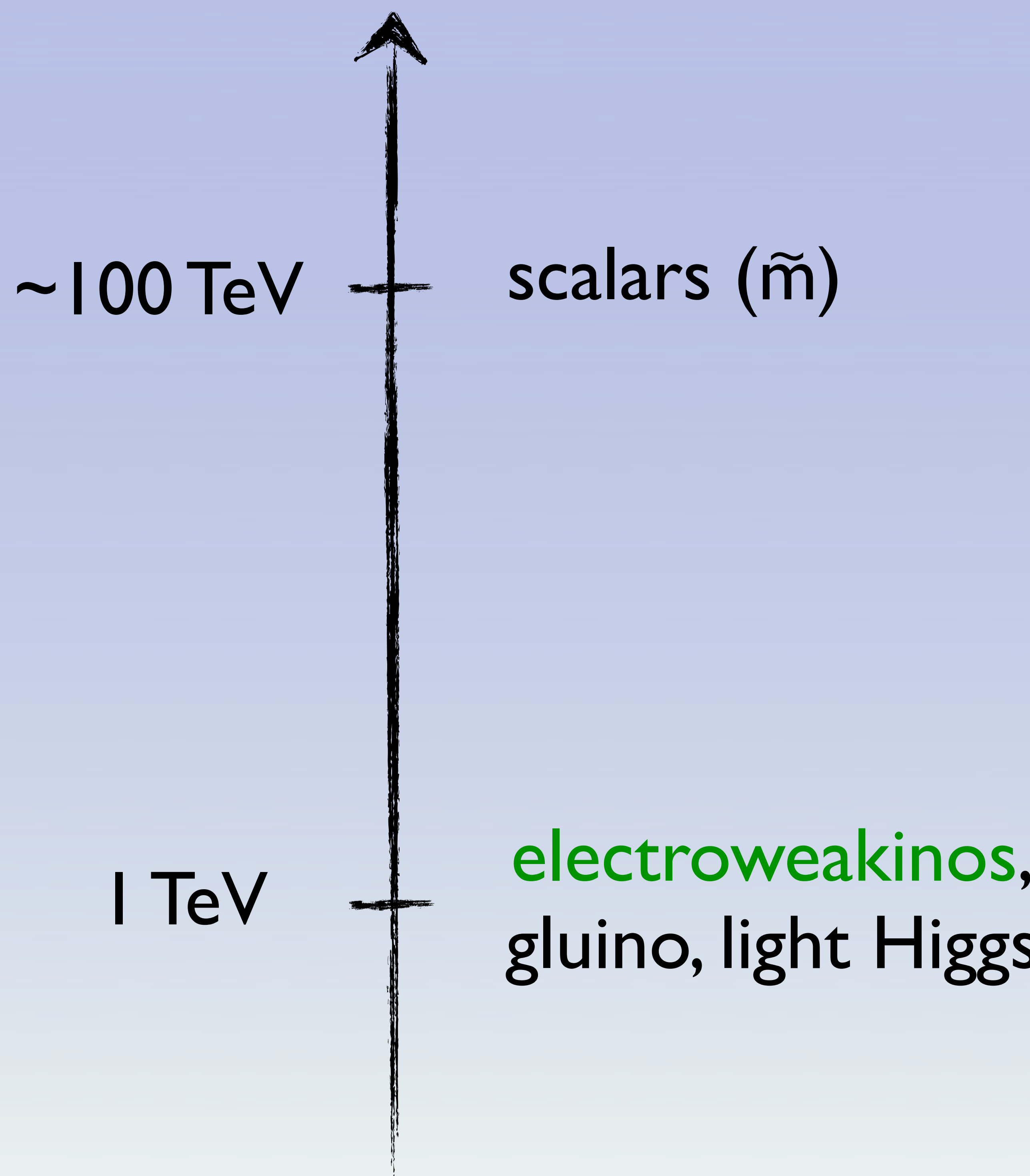
- TeV dark matter: split SUSY
  - Motivations
  - Anomaly mediation
  - Universal gaugino masses
- meV dark matter: QCD axion
  - Motivations
  - Axion properties
- Conclusions

Above the TeV...

Split SUSY: motivations





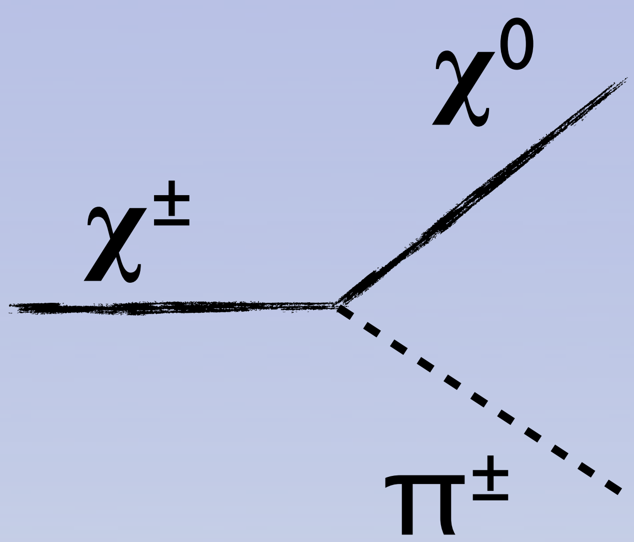


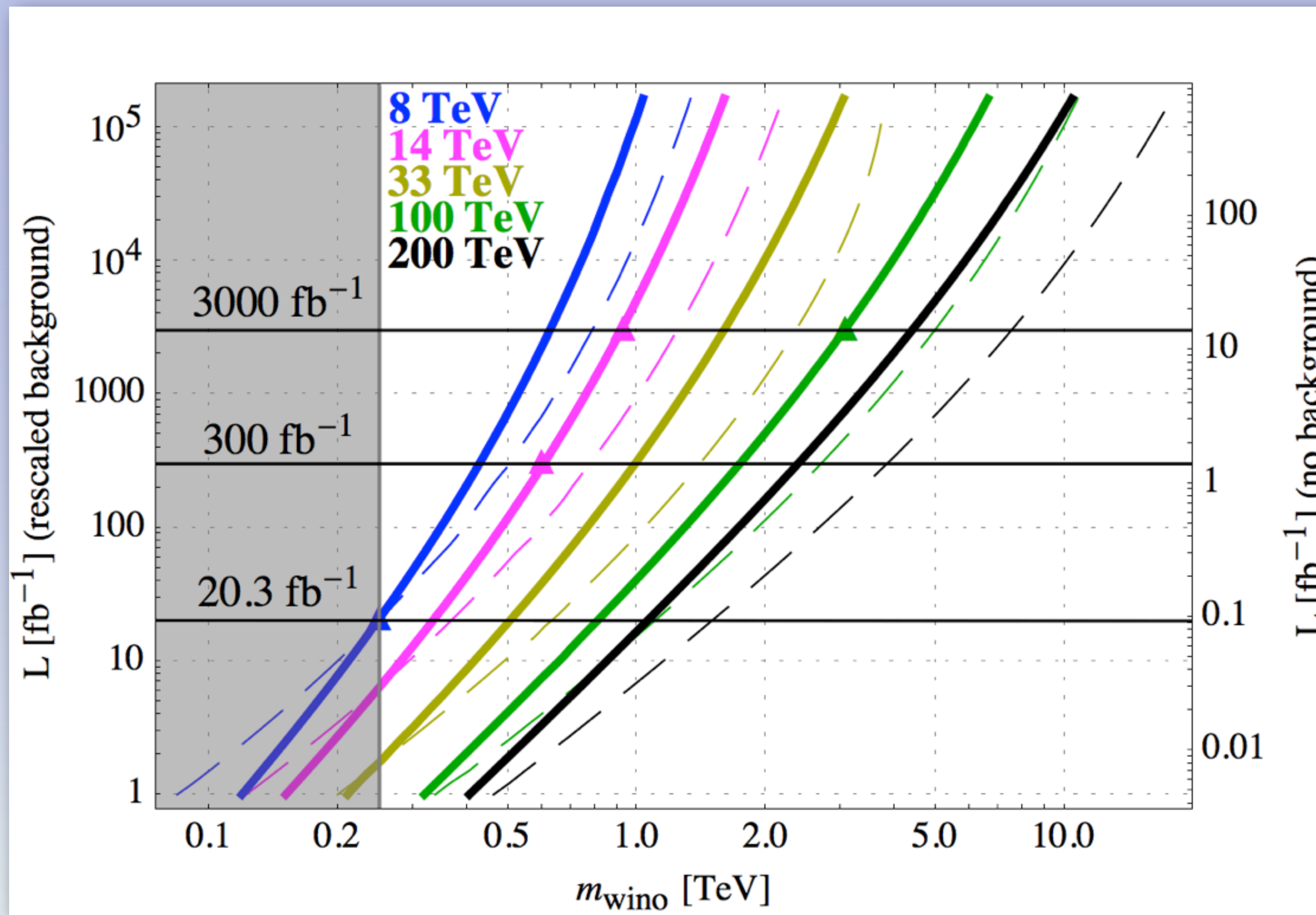
Anomaly mediation

$$\begin{cases} M_{1,2} = \dfrac{\beta_{1,2}}{g_{1,2}} m_{3/2} + \dfrac{\alpha_{1,2}}{2\pi} \dfrac{(\tilde{m}^2 + \mu^2)\mu \tan\beta}{(\tan^2\beta + 1)\tilde{m}^2 + \mu^2} \ln\left[(1 + \tan^{-1}\beta)\left(1 + \dfrac{\tilde{m}^2}{\mu^2}\right)\right] \\ M_3 = \dfrac{\beta_3}{g_3} m_{3/2} \end{cases}$$

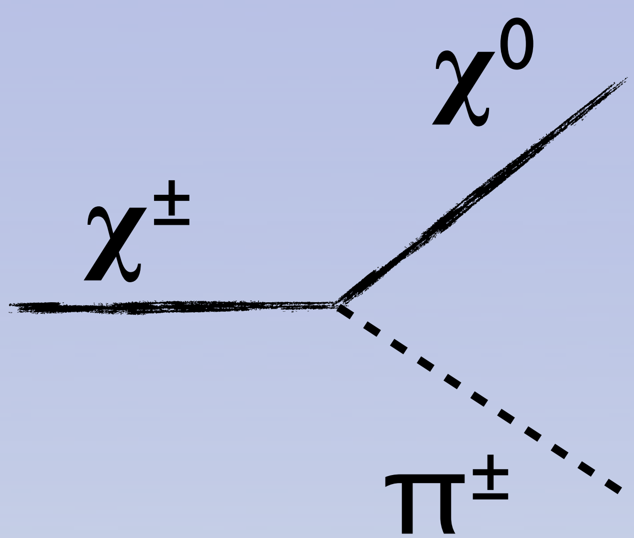
The **Bino** has to mix with the **Wino** in order not to overclose

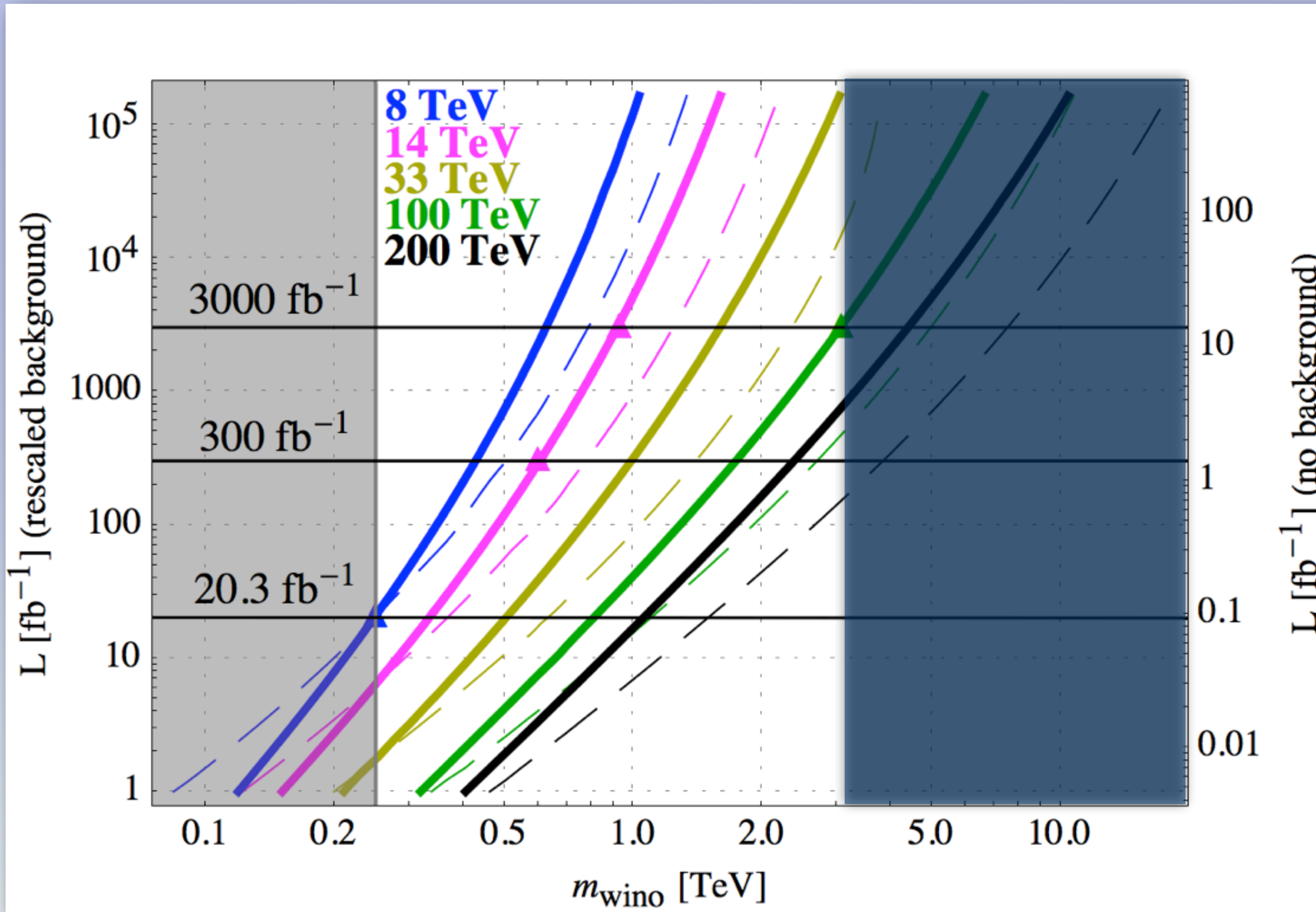
Long-lived Winos





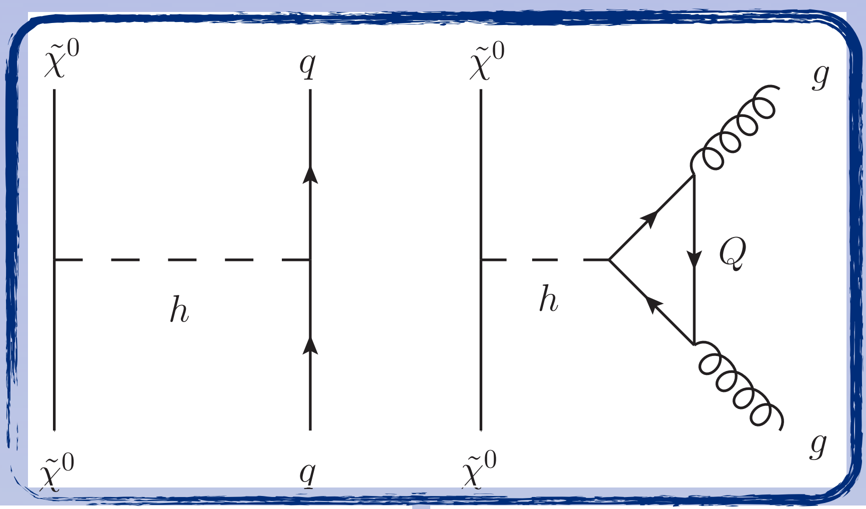
Long-lived Winos

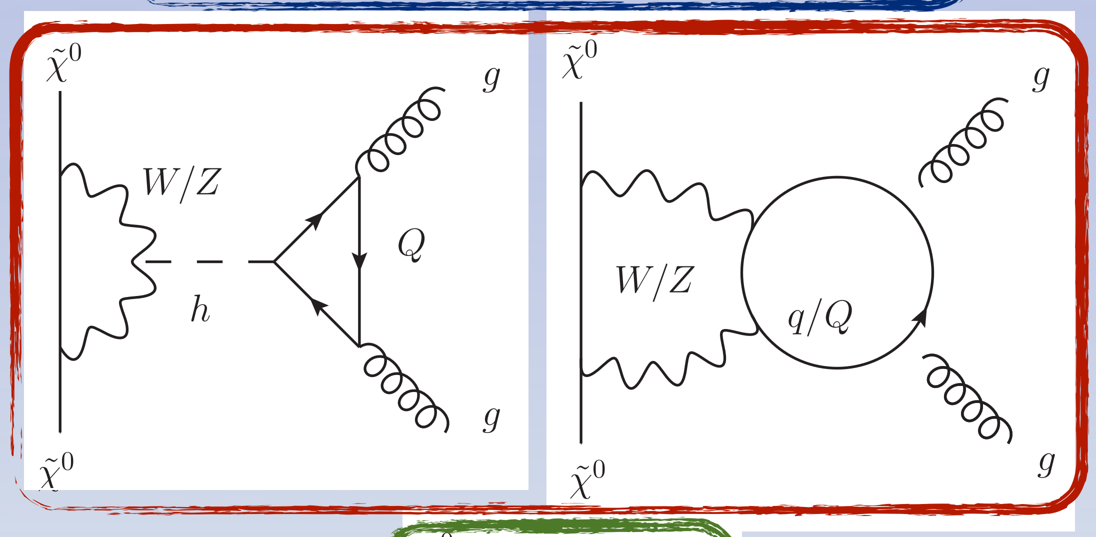


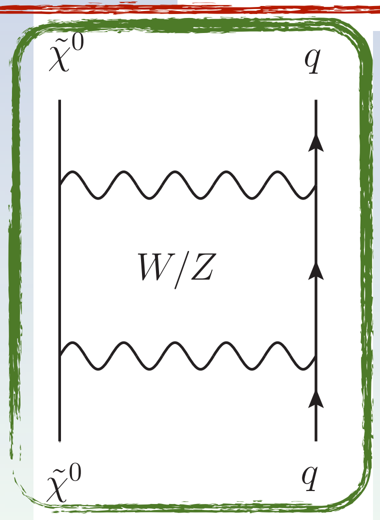


Direct detection

σ_{SI}=|Higgs+gluon+twist-2|^2







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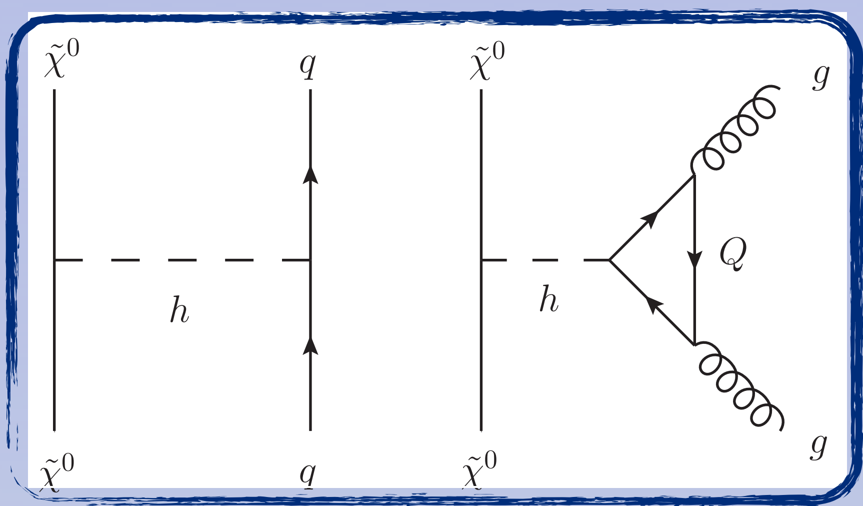
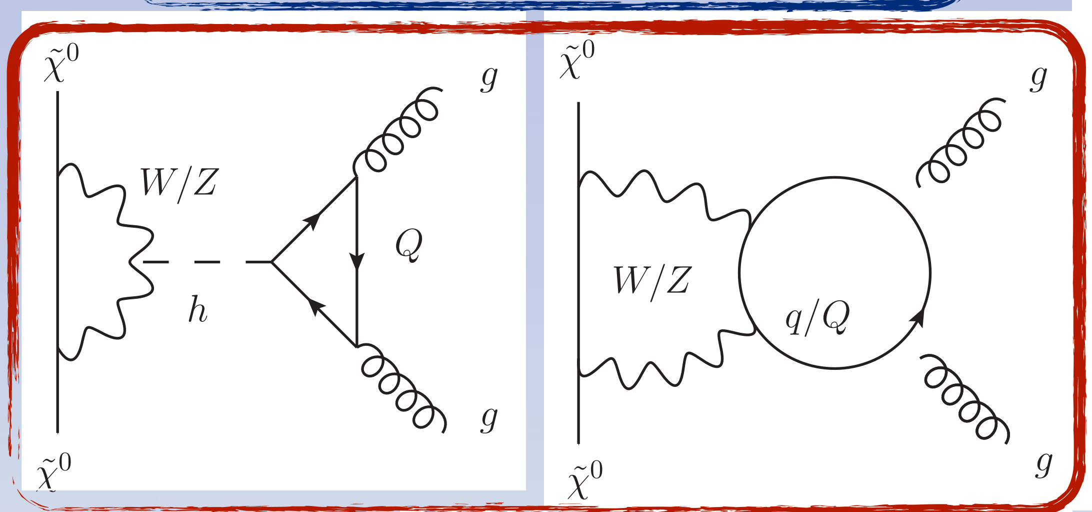
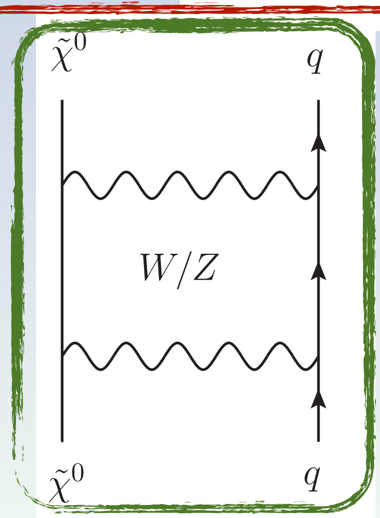
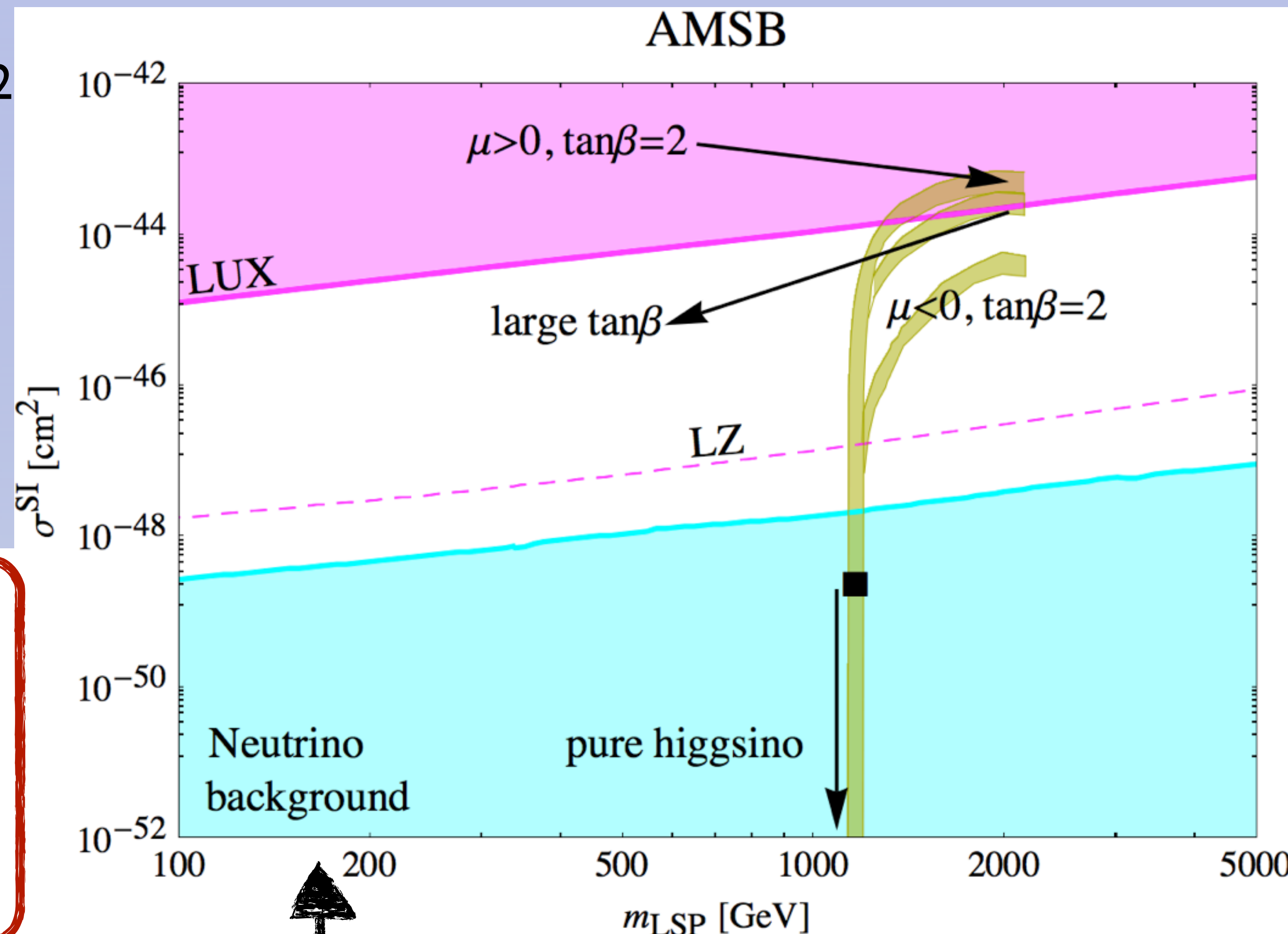








gluino

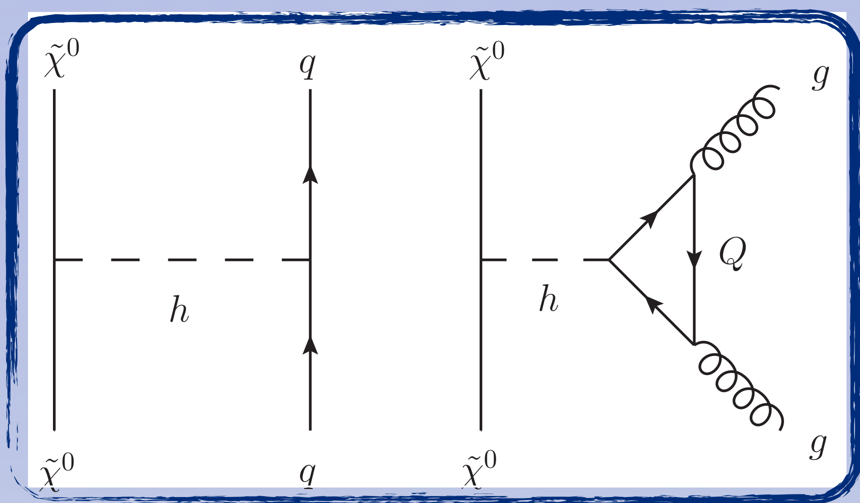
Bino

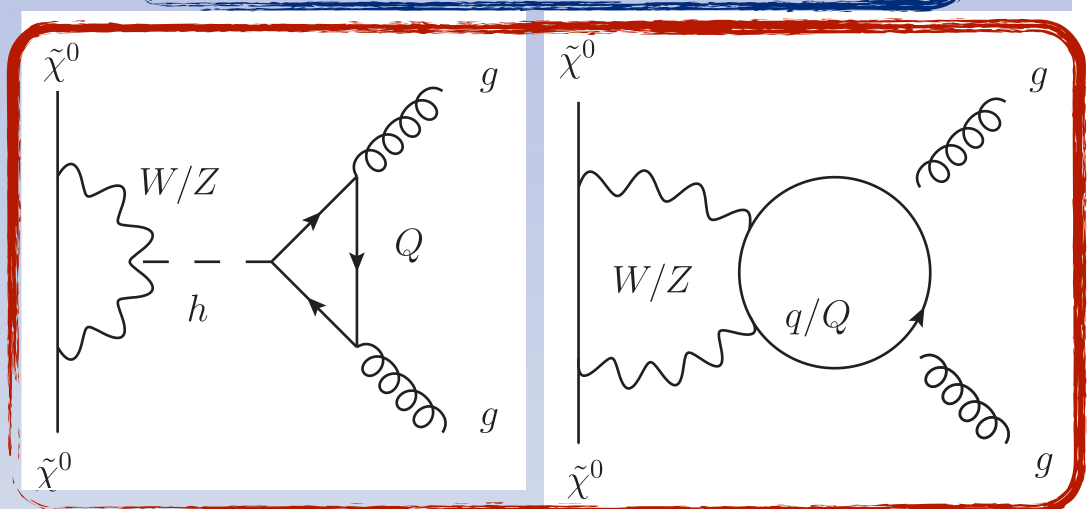
Wino

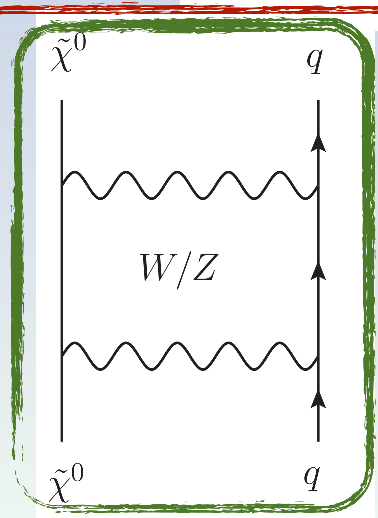
higgsino

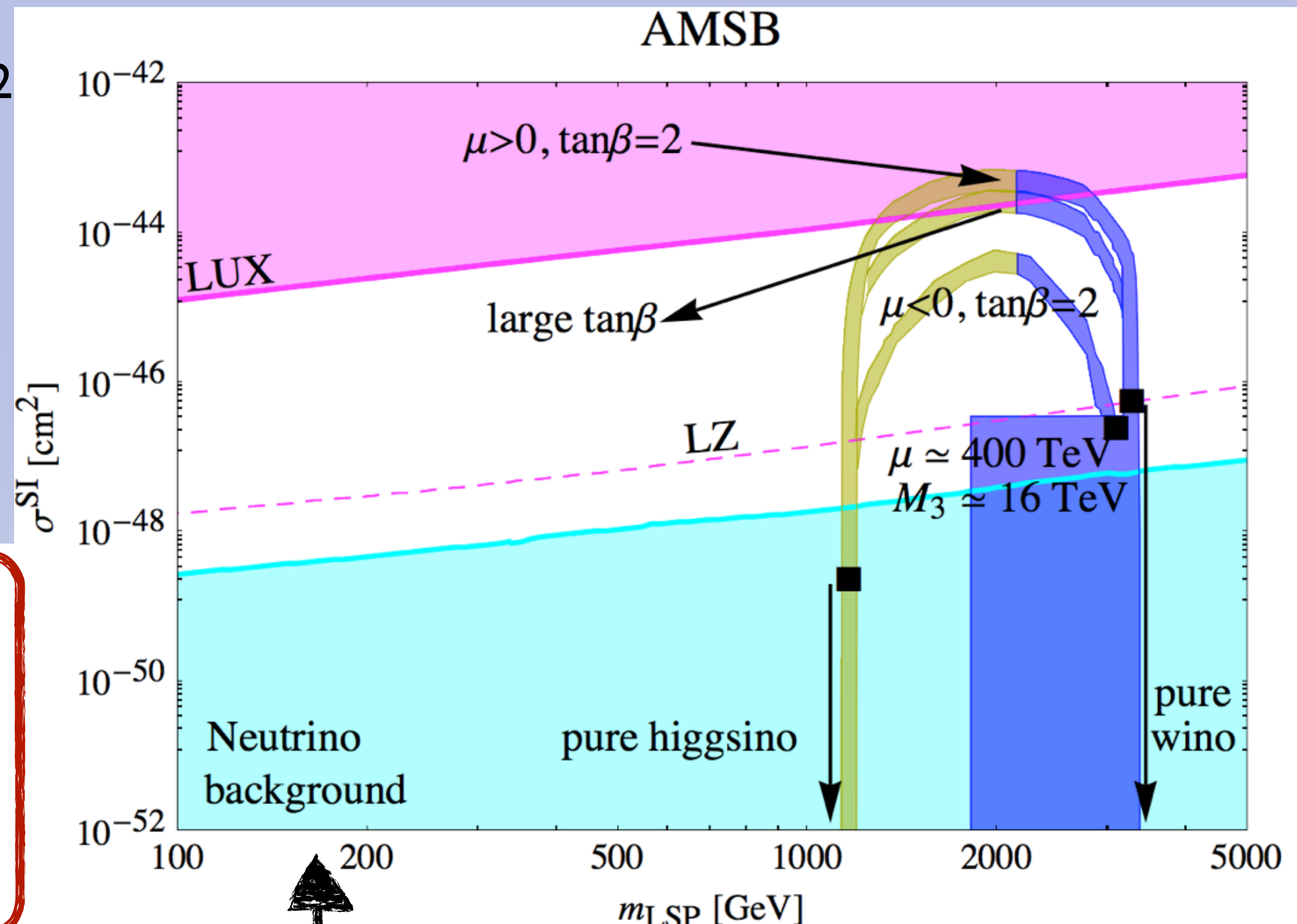
Direct detection

$\sigma_{SI}=|\text{Higgs}+\text{gluon}+\text{twist-2}|^2$









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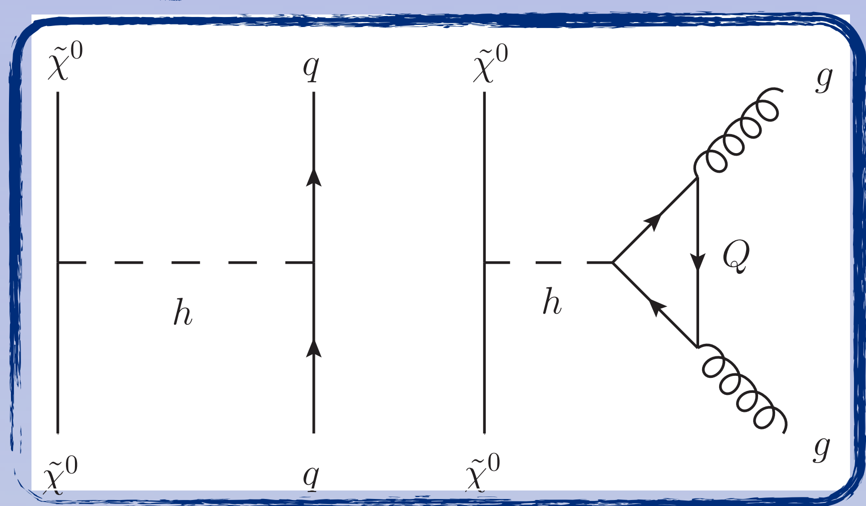
Bino

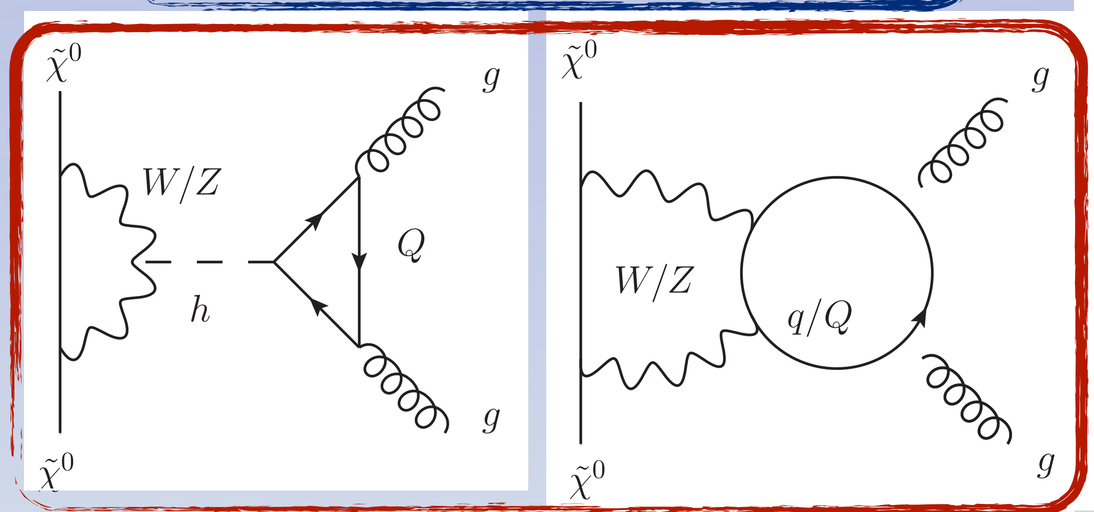
higgsino

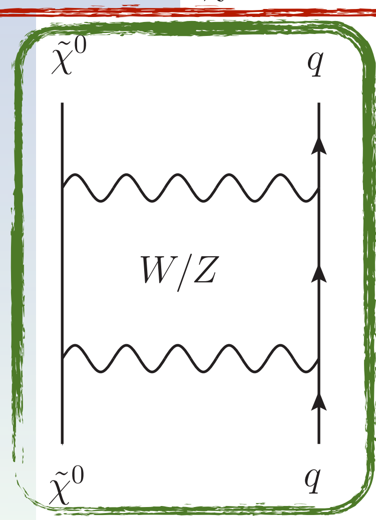
Wino

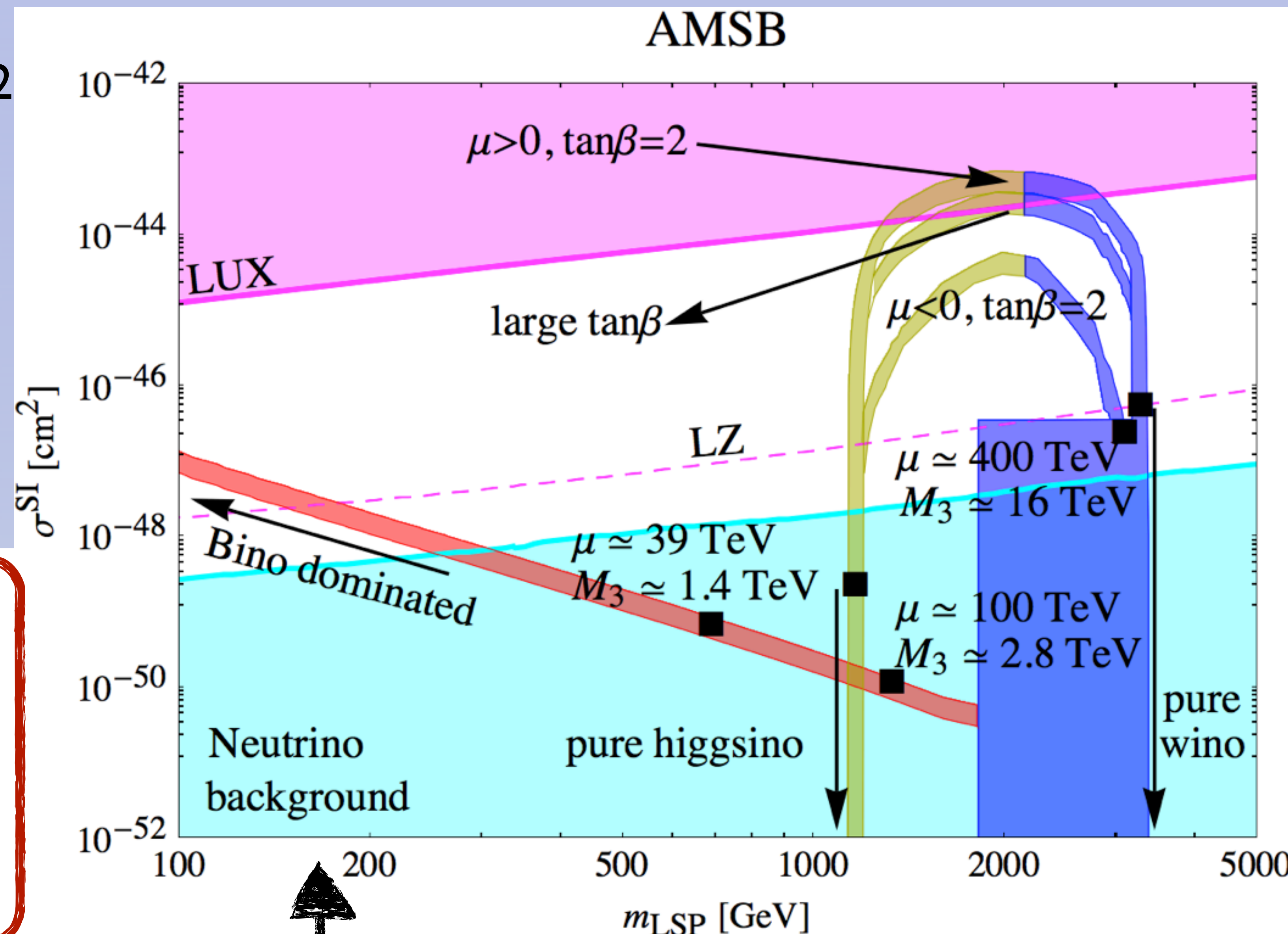
Direct detection

$\sigma_{SI} = |\text{Higgs} + \text{gluon} + \text{twist-2}|^2$









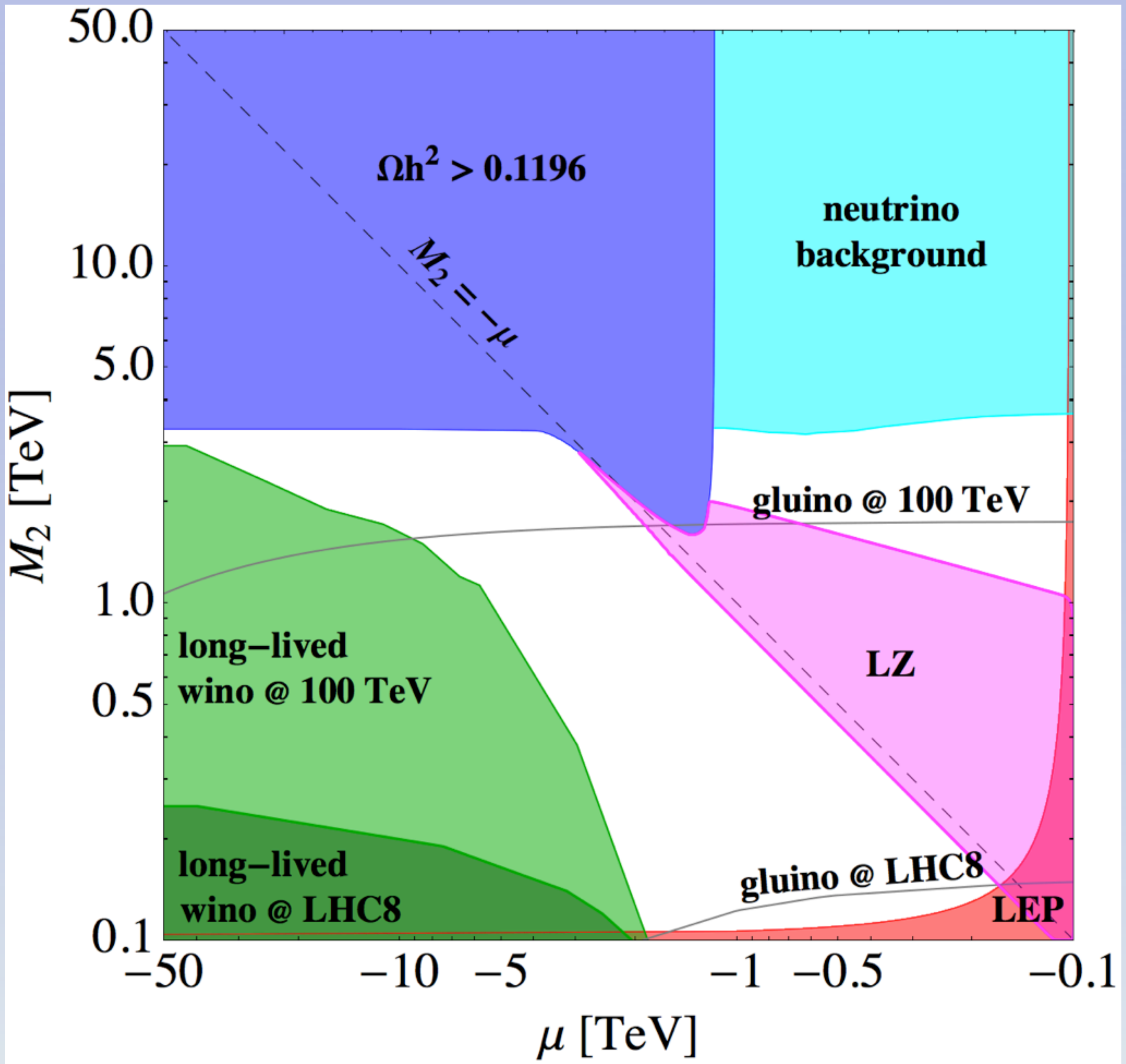
higgsino

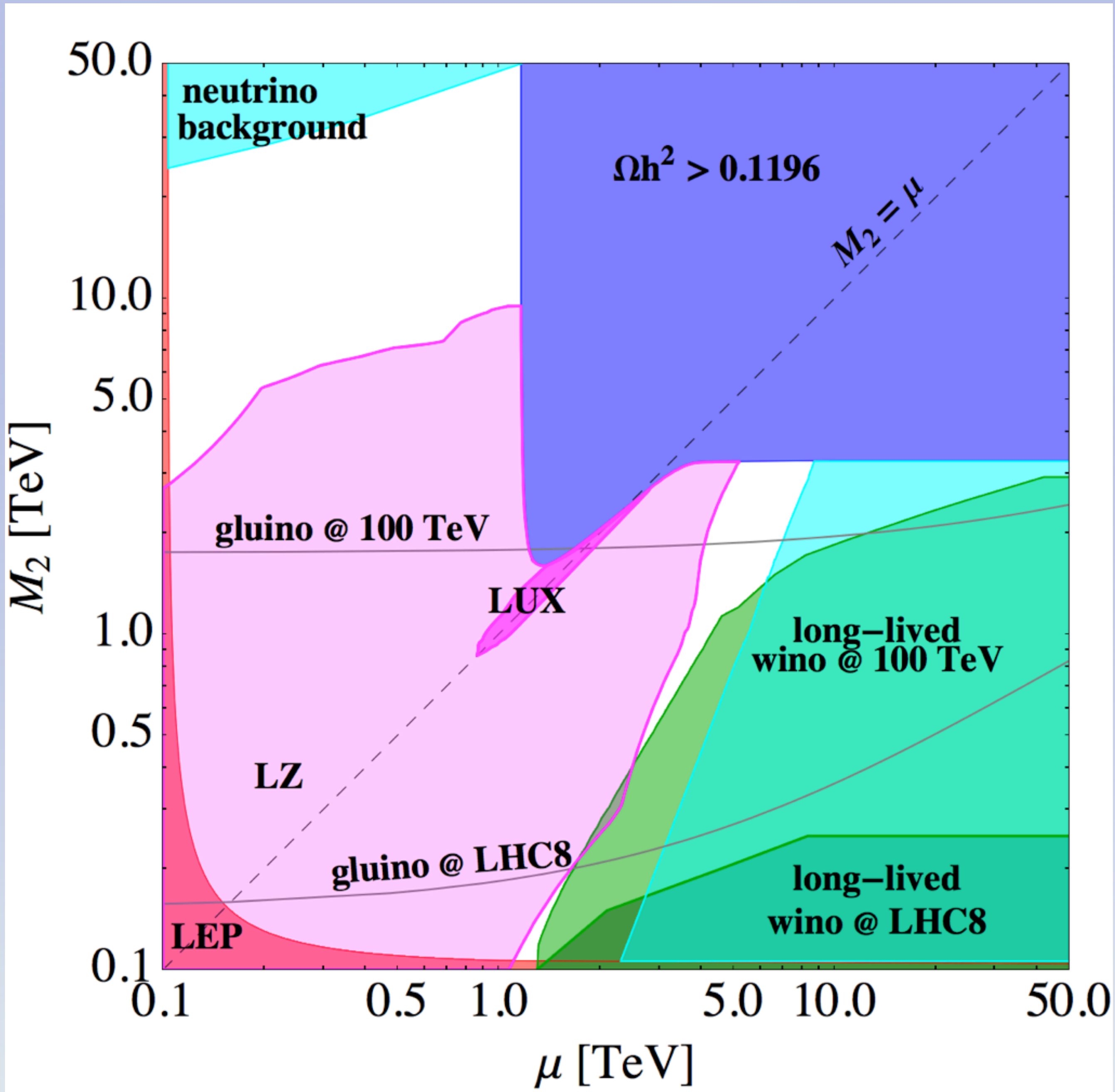
gluino

Wino

Bino

Collider vs direct detection





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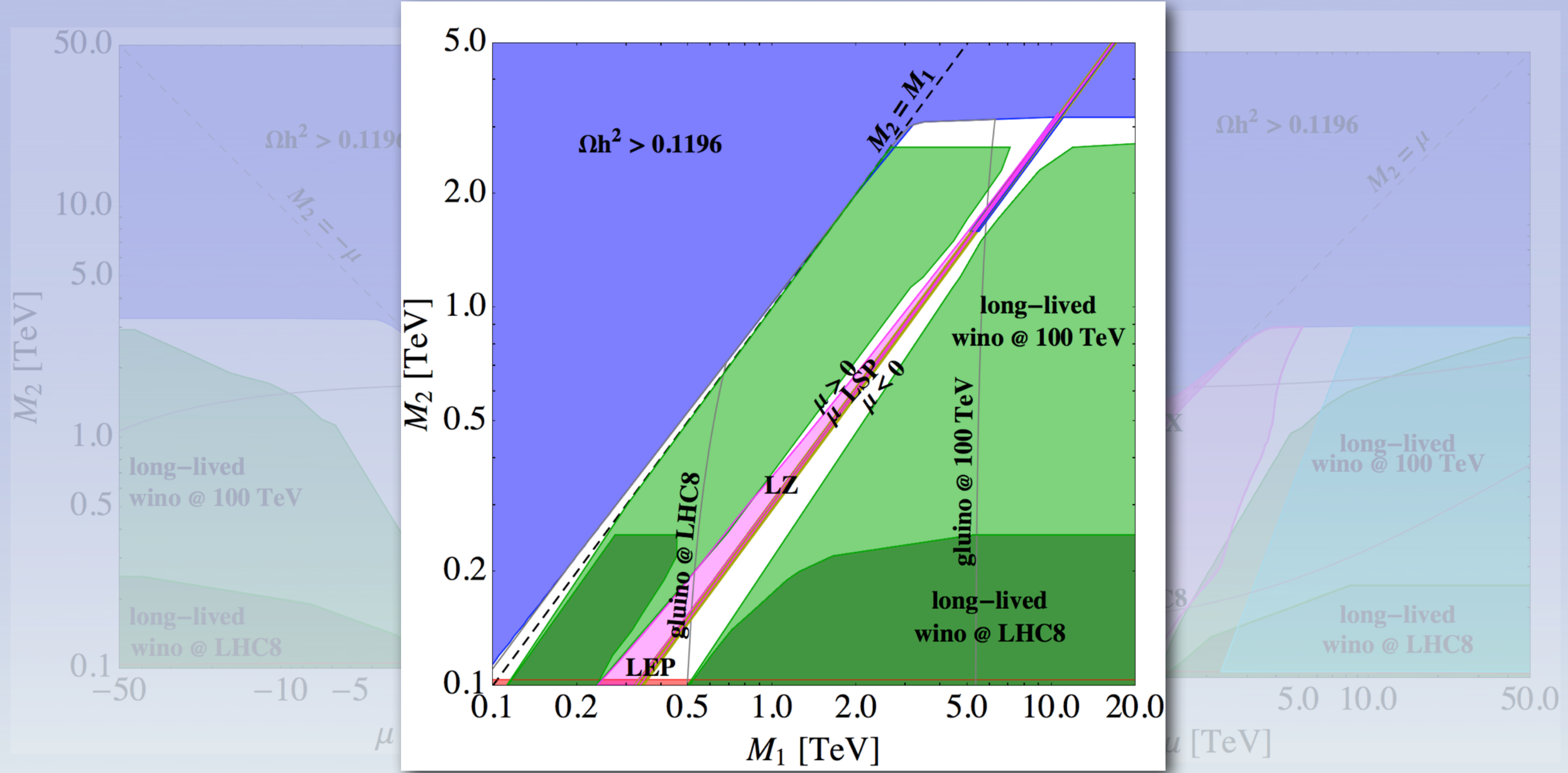
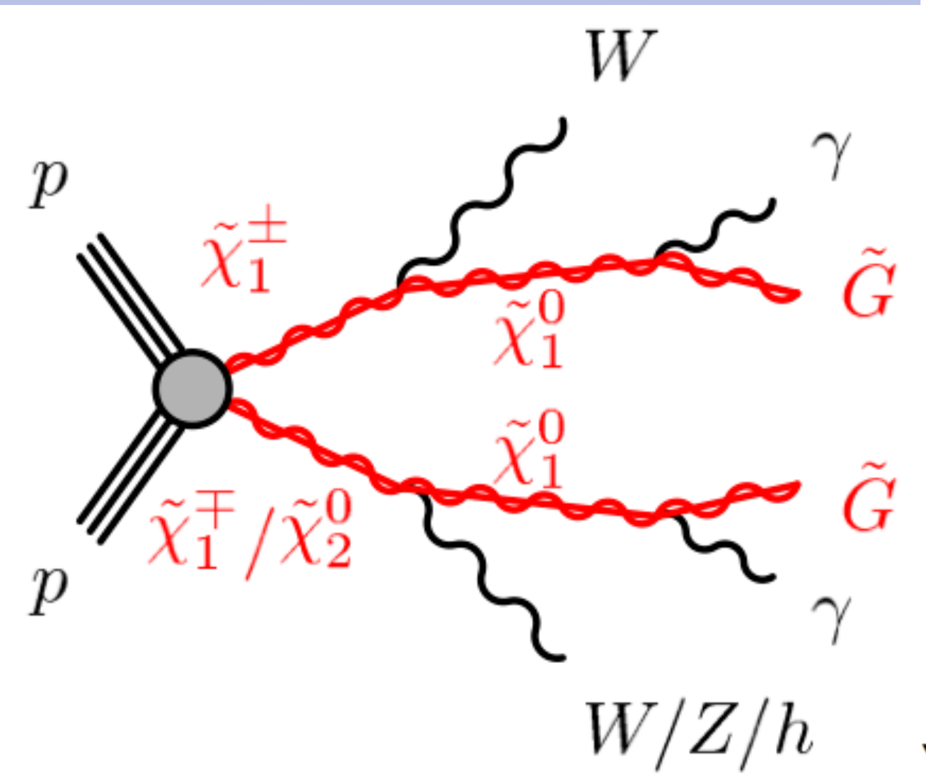
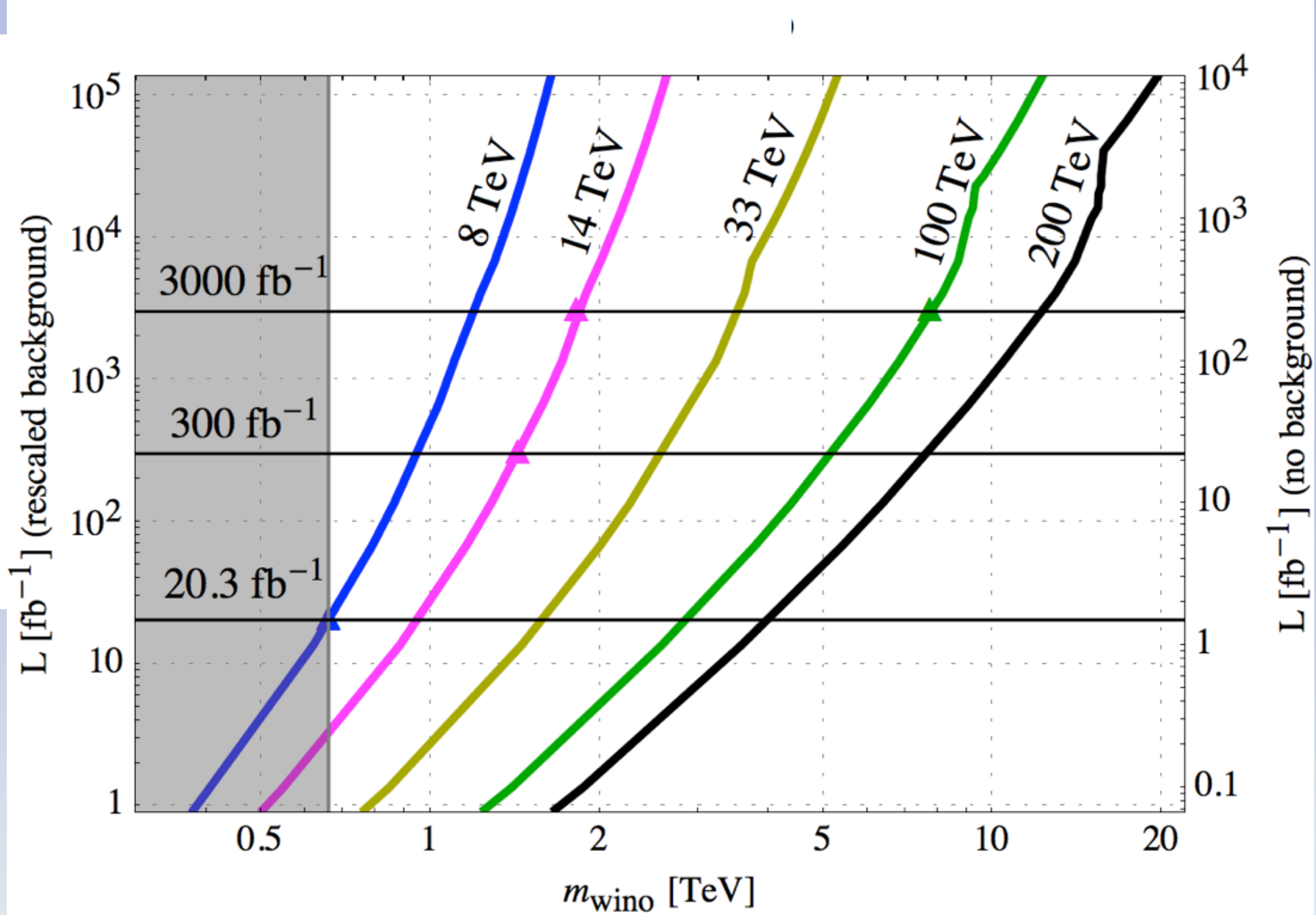


GMSB Wino-Bino





Wino

Bino

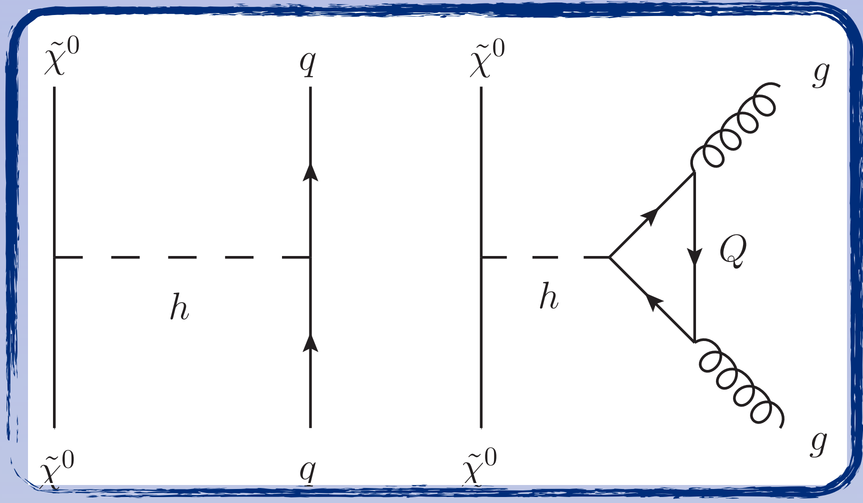
gravitino

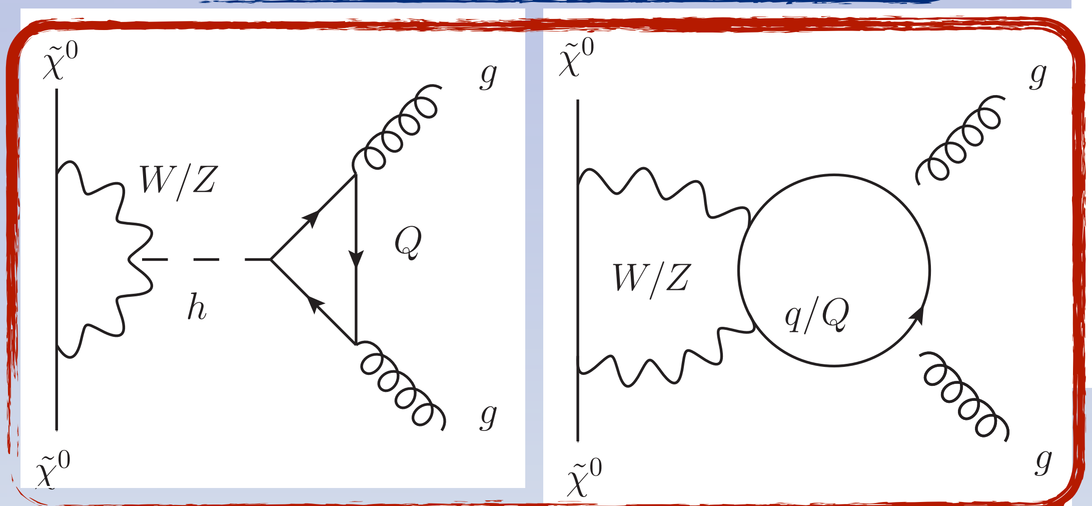
Universal gaugino masses

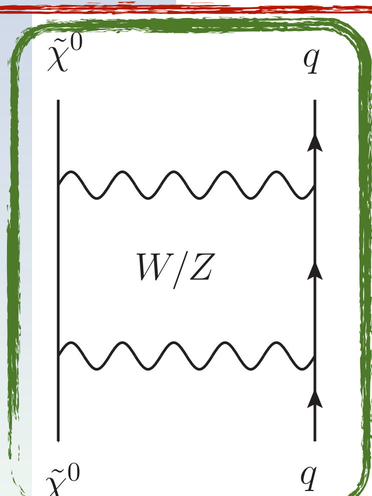
$$M_i \propto \alpha_i M_0$$

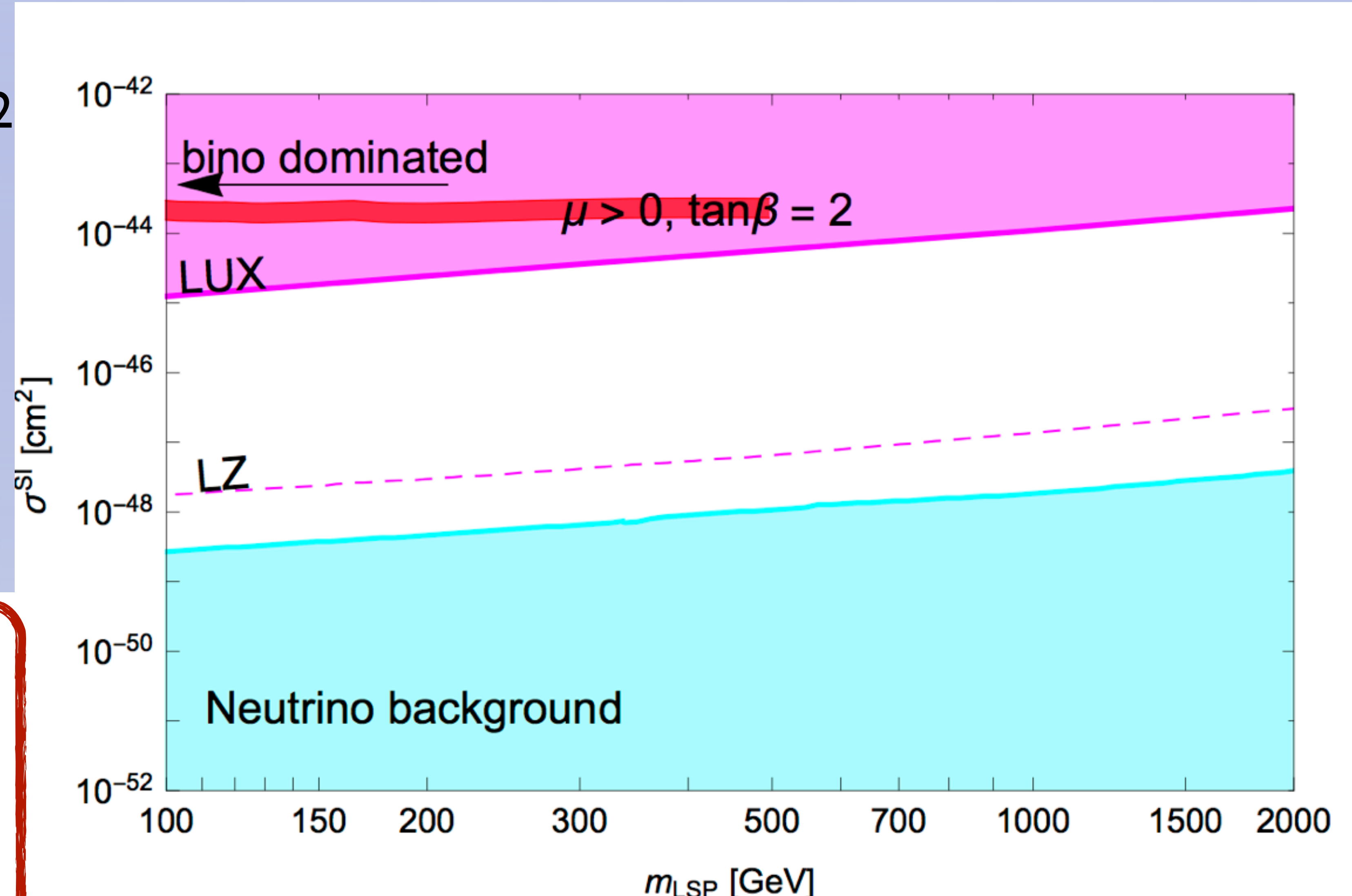
Direct detection

$\sigma_{SI}=|\text{Higgs}+\text{gluon}+\text{twist-2}|^2$









gluino

Wino

higgsino

Bino

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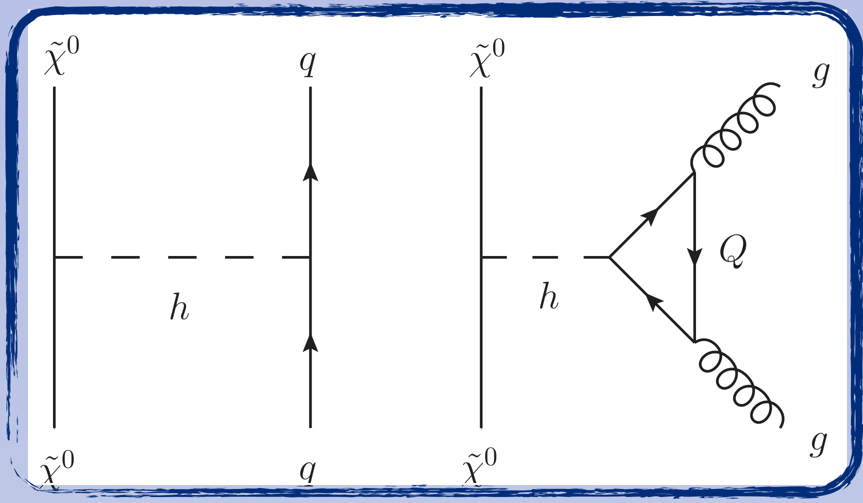
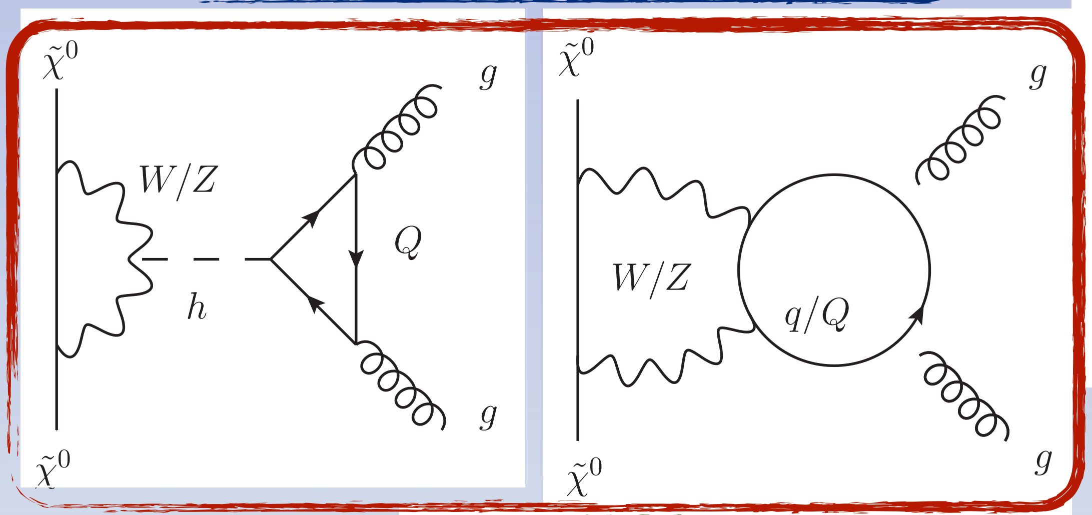
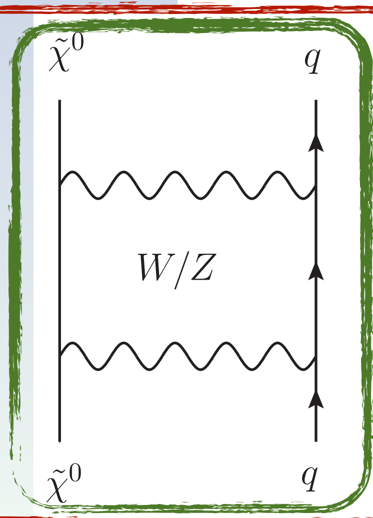
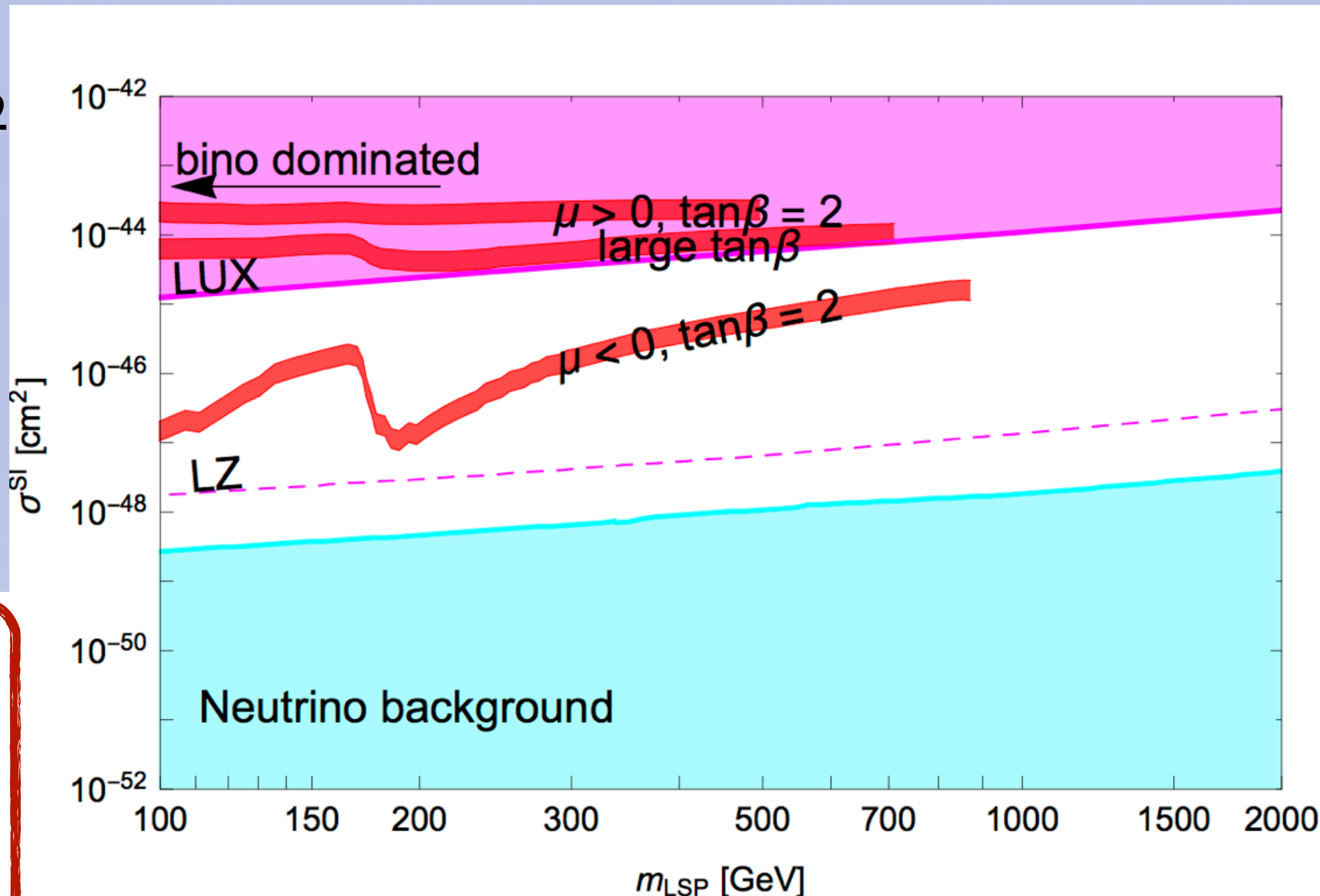
$\sigma_{SI}=|\text{Higgs}+\text{gluon}+\text{twist-2}|^2$









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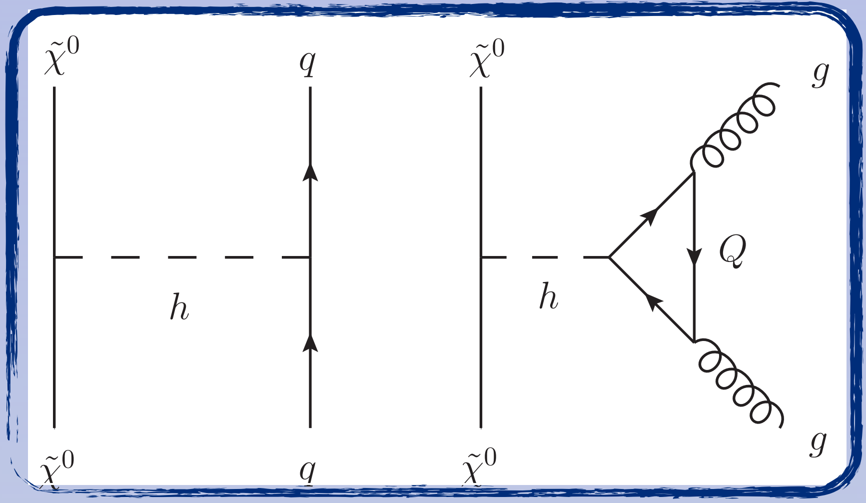

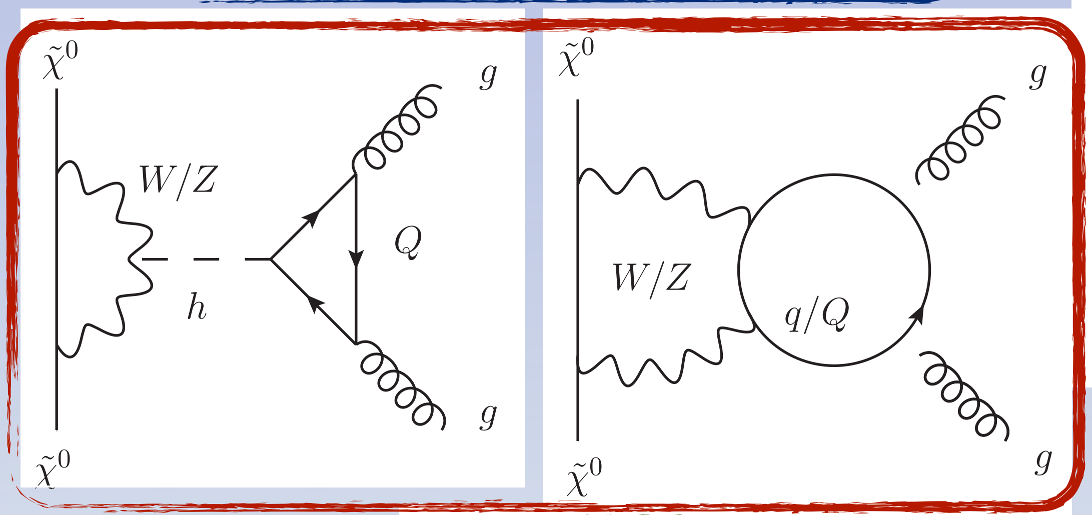

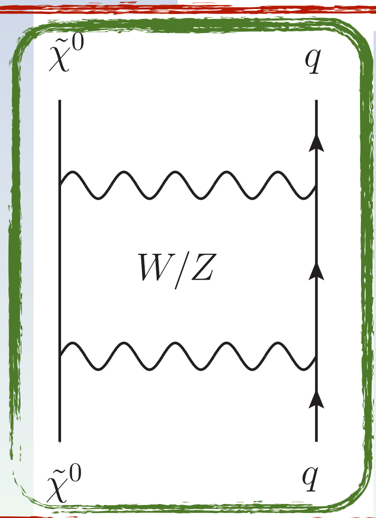

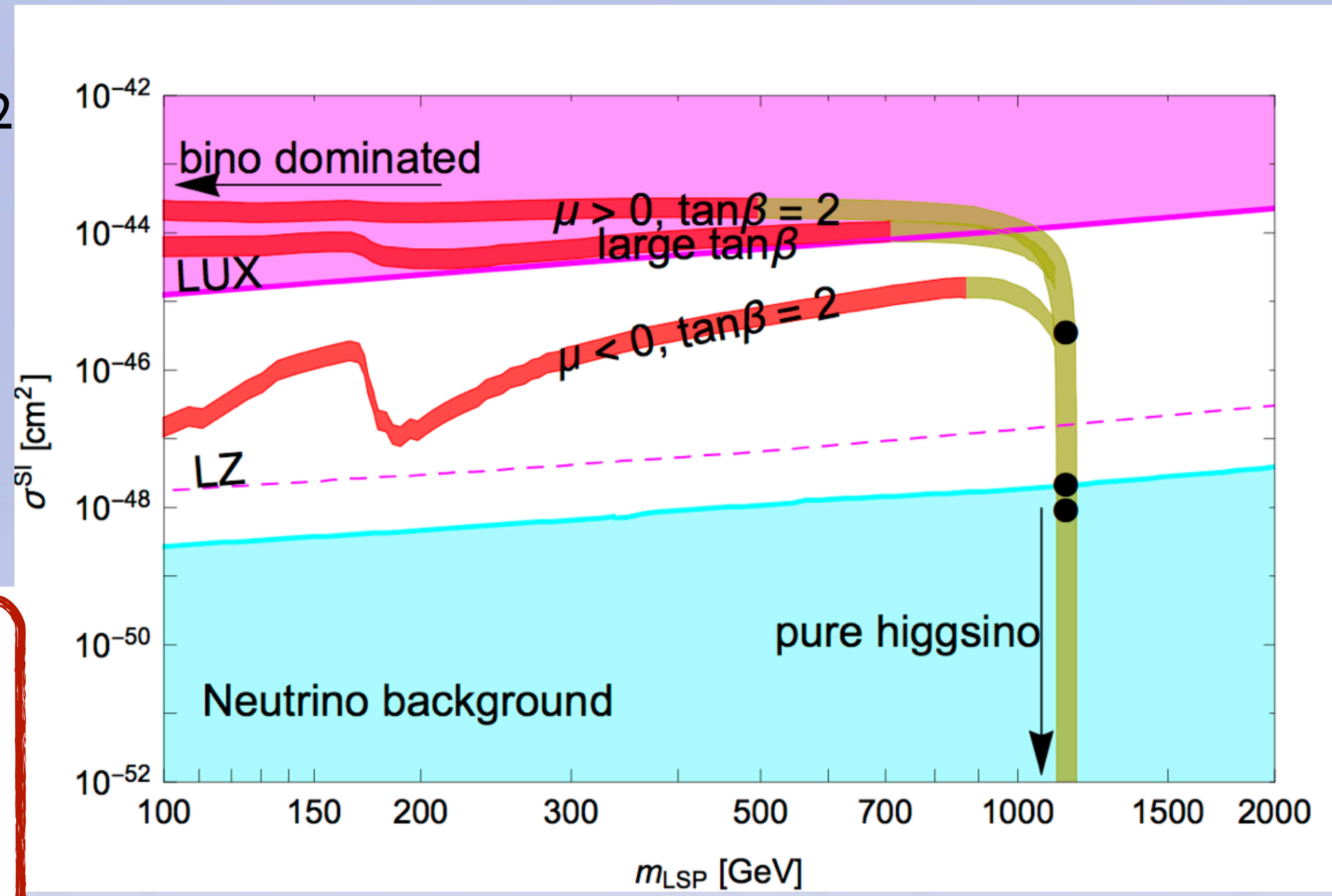

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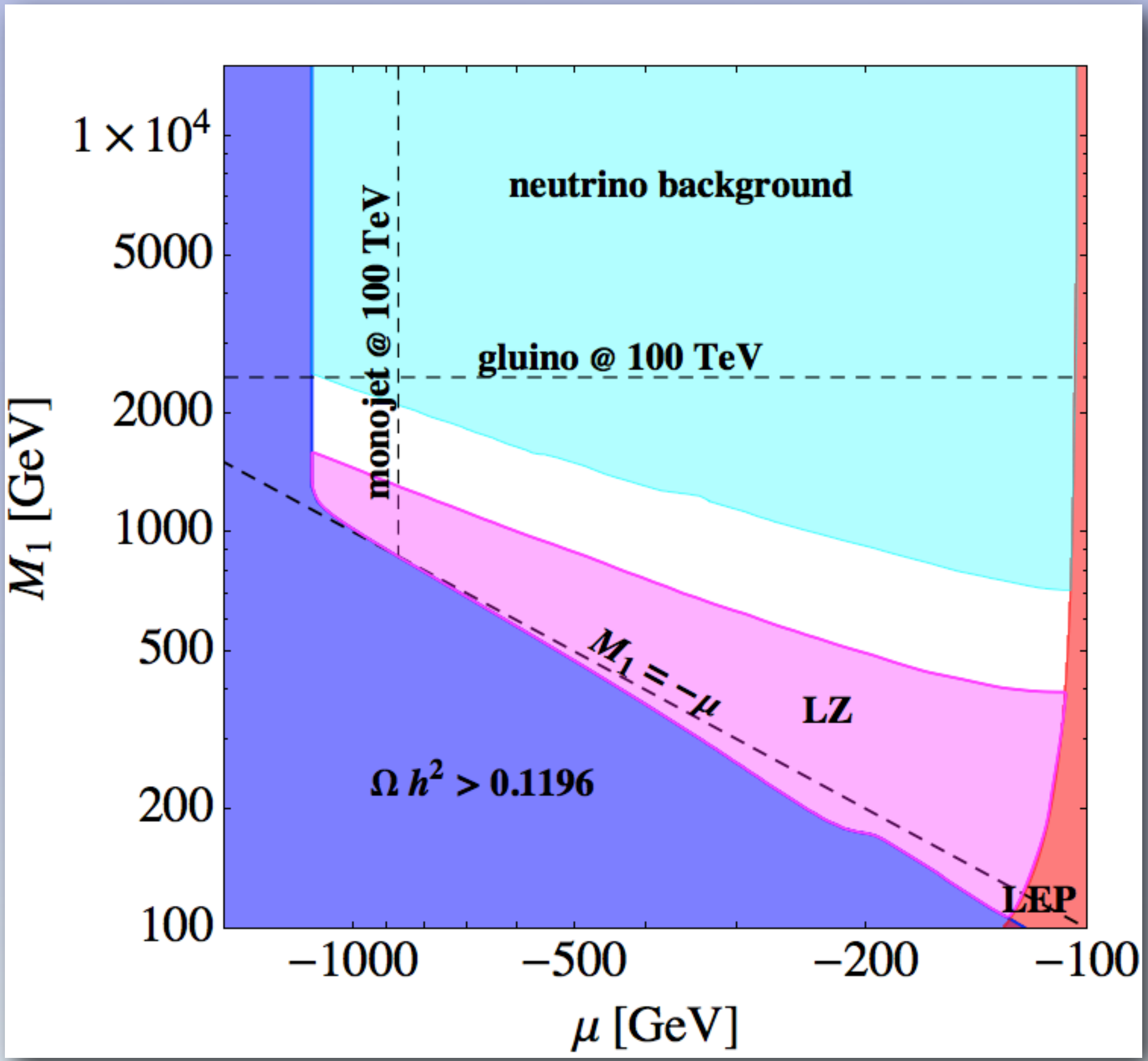
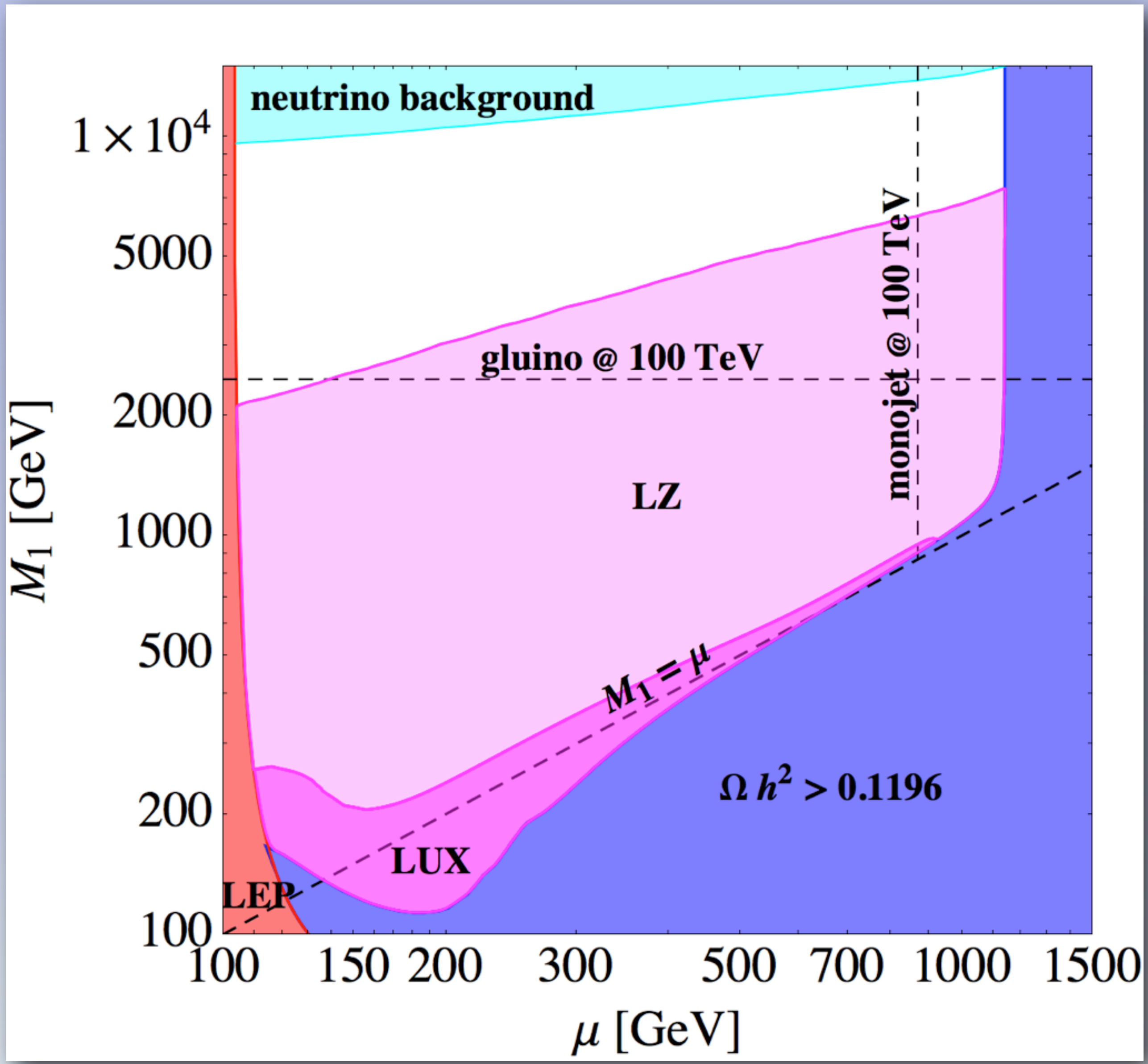
Collider vs direct detection





… and below meV

QCD axion: motivations

Strong CP problem:

$$\mathcal{L} \supset -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \frac{\theta g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} + \sum_{j=1}^{n}\left[i\bar{q}_j\gamma^\mu D_\mu q_j - (m_j q_{Lj}^\dagger q_{Rj} + \text{h.c.})\right]$$

$$\overline{\theta} = \theta + \arg(\det(m_j))$$

CP violation

$$d_n \simeq \overline{\theta} \times 10^{-16}\text{e cm}$$

$$d_n^{\text{exp}} < 3 \cdot 10^{-26}\text{cm e}$$

$$\overline{\theta} \leq 10^{-10}$$

Why the quark masses and the theta term should cancel so exactly even if they come from completely different sources?

QCD axion: motivations

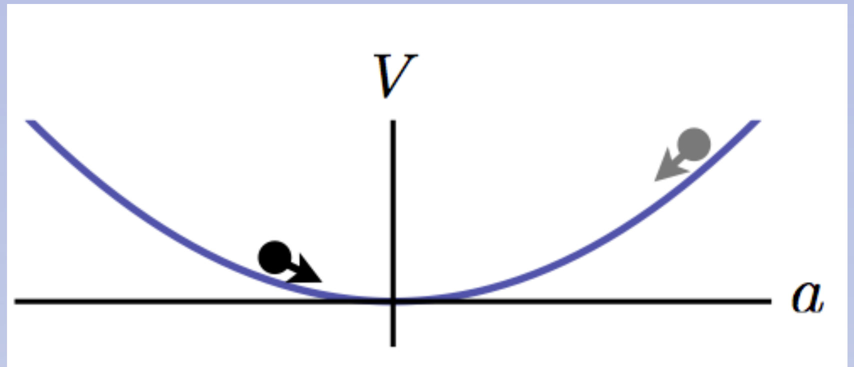
The solution:

$$\mathcal{L} \supset -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \left(\bar{\theta} + \frac{a}{f_a}\right)\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$$
$$+ \sum_{j=1}^{n}\left[i\bar{q}_j\gamma^\mu D_\mu q_j - (m_j q_{Lj}^\dagger q_{Rj} + \text{h.c.})\right]$$

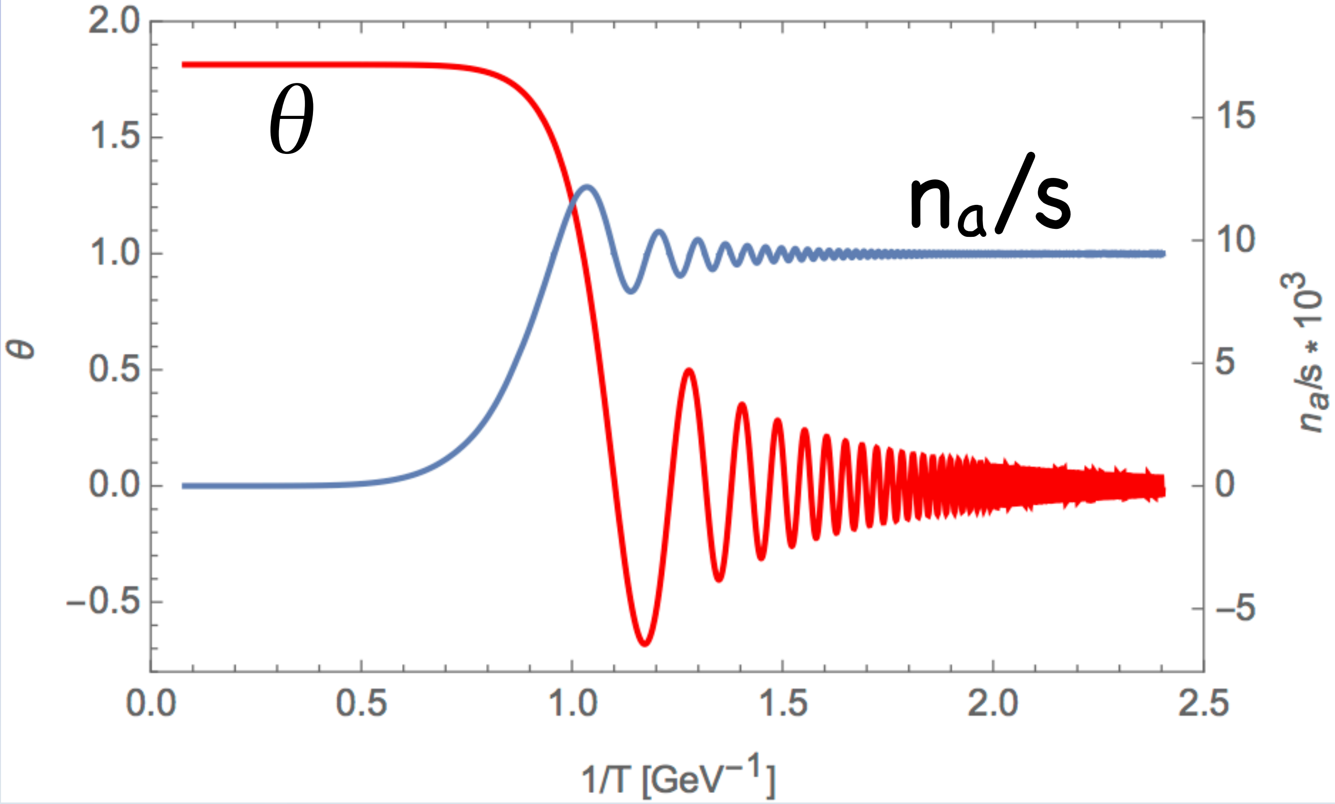
$$\bar{\theta} + \frac{a}{f_a} = 0$$

Axion dark matter

Misalignment mechanism:



$f_a \simeq 10^{11}$, $\theta_0 \simeq \pi/\sqrt{3}$



$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

$a(t) \simeq a_0 \cos(m_a t)$

Axion experiments

$$\mathcal{L} \supset \frac{g}{4} a G_{\mu\nu} \tilde{G}^{\mu\nu} = g a \vec{E} \cdot \vec{B}$$

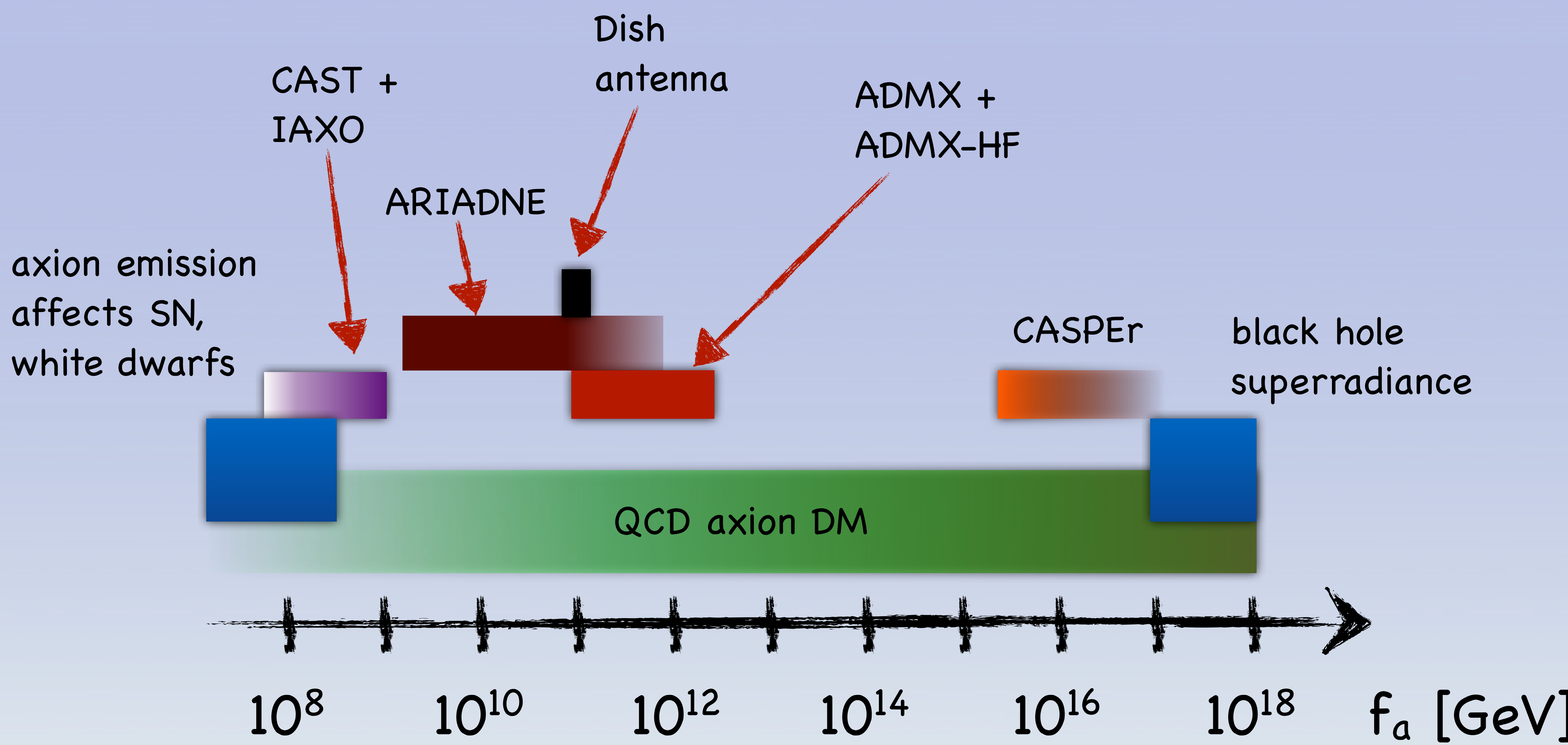
In a static magnetic field, the oscillating axion field generates EM-fields, oscillating at a frequency given by m_a: **ADMX**, **CAST**, **IAXO**, **dish antenna**…

$$\mathcal{L} \supset -\frac{i}{2} g_d a \overline{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

NMR searches:

- Axion gives all nucleons an oscillating EDM independent of f_a: **CASPEr**.
- Axion mediates short ranges spin-dependent forces between objects: **ARIADNE**.

Constraints on axions



Chiral perturbation theory

$$Z(j) = \int \delta q \delta \bar{q} \delta G \, e^{iS_{QCD}(\phi,j)} = \int \delta\pi \, e^{iS(\pi,j)}$$

$SU(N_f)_L \times SU(N_f)_R \longrightarrow SU(N_f)_V$

$$\mathcal{L} = \frac{f_a^2}{4}\left[\mathrm{Tr}(\partial_\mu U \partial^\mu U) + 2B_0 \mathrm{Tr}(M^\dagger U + M U^\dagger)\right]$$

$$U = e^{i\Pi/f_\pi}$$

$$\Pi = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$$

$$M_0 = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}$$

Chiral perturbation theory

$$\mathcal{L} = \frac{f_\pi^2}{4}\left[\mathrm{Tr}(D_\mu U D^\mu U) + 2B_0 \mathrm{Tr}(MU^\dagger + M^\dagger U)\right]$$

$$M = e^{i\frac{a}{2f_a}Q_a} M_0 e^{i\frac{a}{2f_a}Q_a}$$

and in order to avoid axion-pion mixing:

$$Q_a = \frac{M_0^{-1}}{\mathrm{Tr}(M_0^{-1})}$$

$$\mathcal{L}_4 = \sum_{i=1}^{12} l_i \mathcal{O}_i^l + \sum_{i=1}^{7} h_i \mathcal{O}_i^h \qquad \mathcal{L}_6^W = \sum_{i=1}^{13} c_i \mathcal{O}_i^c$$

Axion mass

$$m_a^2 = \frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2}\left[1+2\frac{m_\pi^2}{f_\pi^2}\left(h_1^r - h_3^r - l_4^r + \frac{m_u^2 - 6m_u m_d + m_d^2}{(m_u+m_d)^2} l_7^r\right)\right]$$

Axion mass

$$m_a^2 = \frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2}\left[1+2\frac{m_\pi^2}{f_\pi^2}\left(h_1^r - h_3^r - l_4^r + \frac{m_u^2 - 6m_u m_d + m_d^2}{(m_u+m_d)^2} l_7^r\right)\right]$$

$$l_7^r = 7(4)\cdot 10^{-3} \qquad h_1^r - h_3^r - l_4^r = 4.8 \pm 1.4 \cdot 10^{-3}$$

$$z \equiv \frac{m_u^{\overline{MS}}(2\text{GeV})}{m_d^{\overline{MS}}(2\text{GeV})} = 0.47(2)$$

Axion mass

$$m_a^2 = \frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2}\left[1+2\frac{m_\pi^2}{f_\pi^2}\left(h_1^r - h_3^r - l_4^r + \frac{m_u^2 - 6 m_u m_d + m_d^2}{(m_u+m_d)^2} l_7^r\right)\right]$$

$$l_7^r = 7(4)\cdot 10^{-3} \qquad h_1^r - h_3^r - l_4^r = (4.8 \pm 1.4)\cdot 10^{-3}$$

$$z \equiv \frac{m_u^{\overline{MS}}(2\mathrm{GeV})}{m_d^{\overline{MS}}(2\mathrm{GeV})} = 0.47(2)$$

$$m_a = 5.68(4)(4)\ \mu\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right) = 5.68(6)\ \mu\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$

Coupling to photon

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

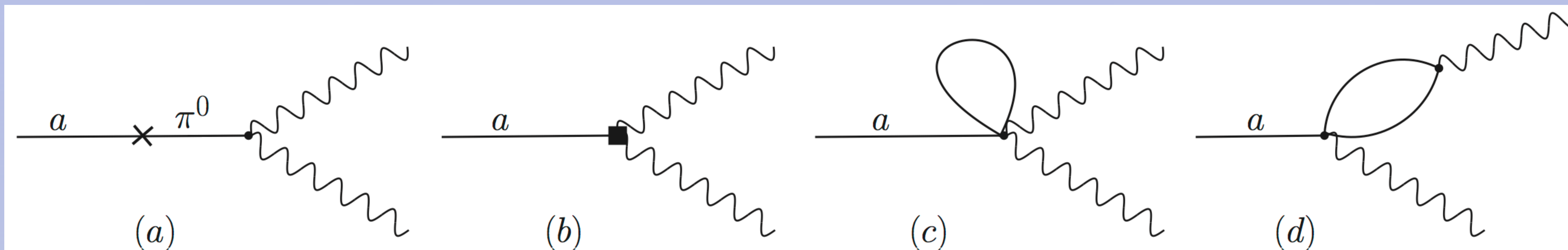
$$Q_e = \mathrm{diag}(2/3, -1/3)$$

$$g_{a\gamma\gamma} \to g_{a\gamma\gamma} - \frac{\alpha}{2\pi}\frac{1}{f_a}\mathrm{Tr}(Q_a Q_e Q_e)$$

$$Q_a = \frac{1}{2}\frac{M^{-1}}{\mathrm{Tr}(M^{-1})}$$

$$g_{a\gamma\gamma} = \frac{a}{2\pi}\frac{1}{f_a}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right) \qquad z = \frac{m_u}{m_d}$$

Coupling to photons



$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\frac{1}{f_a}\left[\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z} - \frac{8m_\pi^2}{f_\pi^2}\frac{z(1-z)}{(1+z)^3}l_7^r + \frac{1024}{9}\frac{z\,\pi^2 m_\pi^2}{(1+z)^2}(5c_3^W + c_7^W + 2c_8^W)\right]$$

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\frac{1}{f_a}\left(\frac{E}{N} - 1.91 \pm 0.04\right) = \left[(0.2044 \pm 0.0023)\left(\frac{E}{N}\right) - 0.390 \pm 0.013\right]\frac{m_a}{\text{GeV}^2}$$

Coupling to nucleons

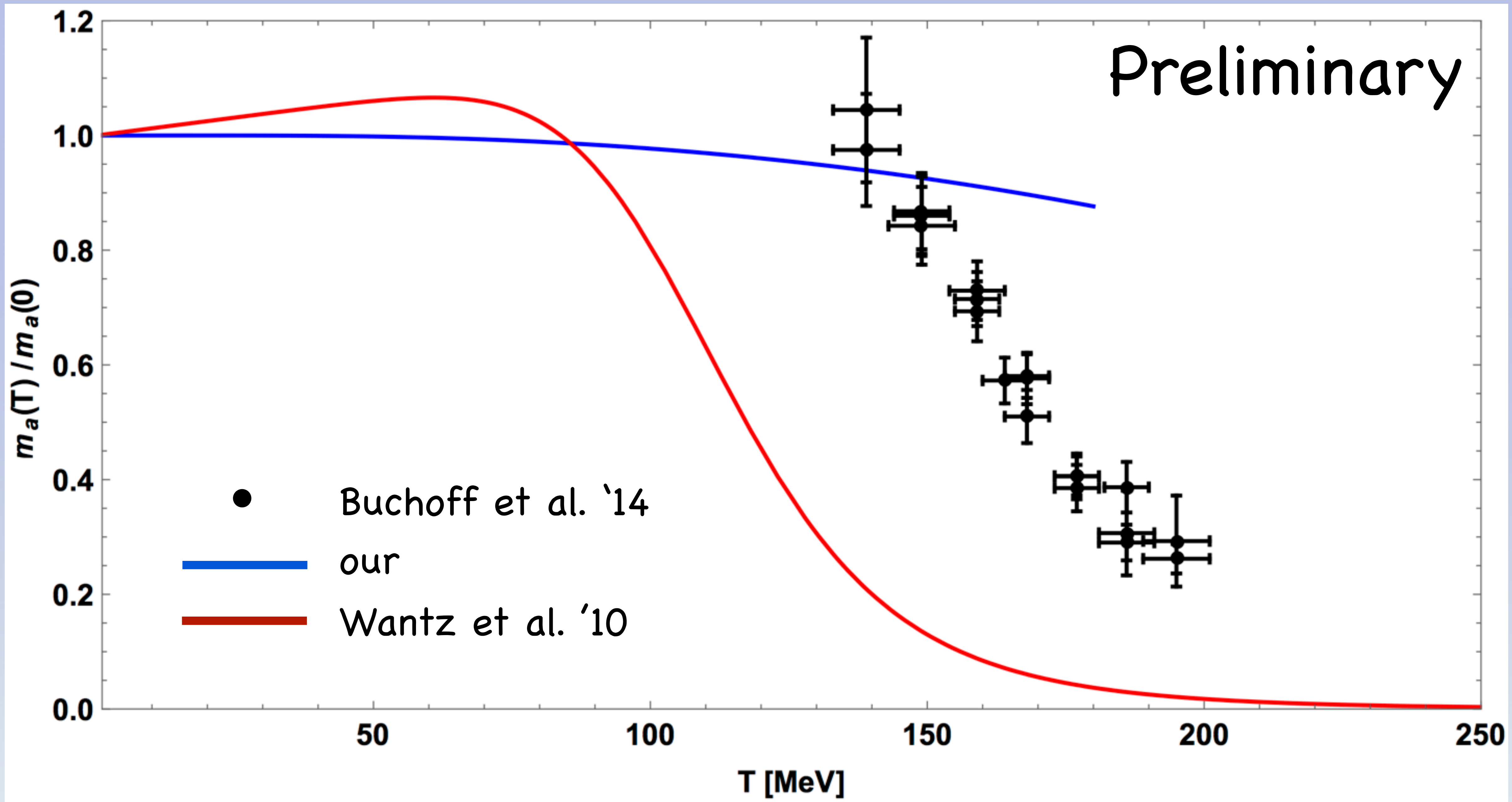
$$\frac{\partial_\mu a}{2 f_a} c_N \overline{N} \gamma^\mu \gamma_5 N$$

$$\begin{aligned} c_p &= -0.487(27) + 0.894(24) c_u^0 - 0.378(24) c_d^0 - 0.036(4) c_s^0 \\ &\quad -0.013(4) c_c^0 - 0.0091(9) c_b^0 - 0.0036(4) c_t^0 \\ c_n &= -0.028(27) + 0.894(24) c_d^0 - 0.378(24) c_u^0 - 0.036(4) c_s^0 \\ &\quad -0.013(4) c_c^0 - 0.0091(9) c_b^0 - 0.0036(4) c_t^0 \end{aligned}$$

$$c_p^{KSVZ} = -0.487(27)$$
$$c_n^{KSVZ} = -0.028(27)$$

$$c_p^{DFSZ} = -0.628 + 0.434 \sin^2 \beta \pm 0.020$$
$$c_n^{DFSZ} = 0.255 - 0.415 \sin^2 \beta \pm 0.020$$

Axion mass at finite T



Conclusions

- LHC14 might probe Winos up to ~1 TeV with 3000 fb^{-1}, while a 100 TeV collider may reach 3 TeV Winos.
- Direct detection experiments can probe complementary area of the parameter space for higgsino DM.
- In order to explore all the parameter space for Wino and higgsino DM, a 100 TeV collider seems to be a necessary tool.

- We showed that it is possible to achieve high precision in the axion physics. Improvement in lattice calculation will increase more the precision on the mass and the couplings of the axion.
- The ChPT computation of the axion mass at high temperature match nicely with the lattice data. In order to improve the computation of the relic density we need a better understanding of the uncertainty of the mass at high T.