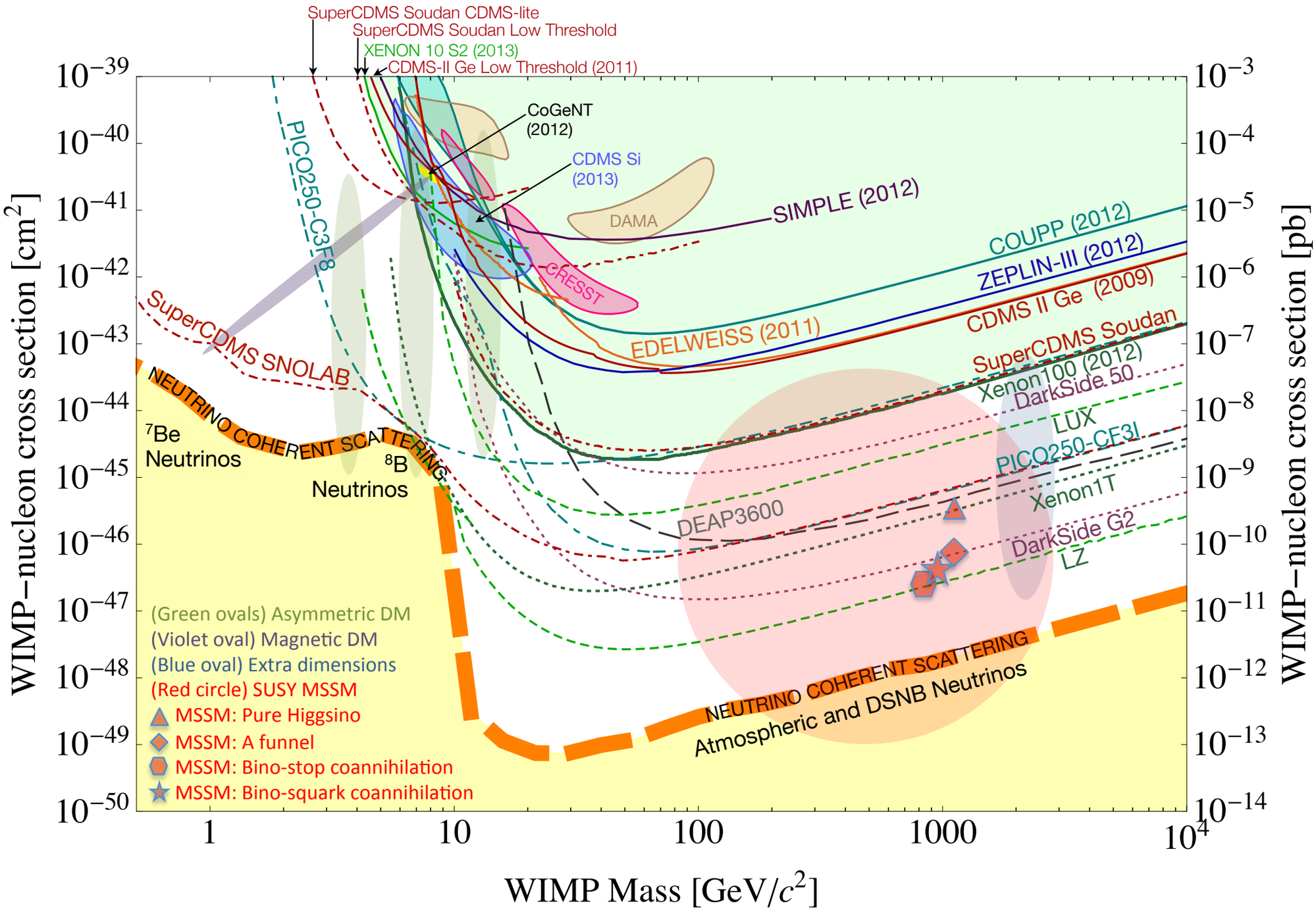
New Directions in Dark Matter Direct Detection

Asher Berlin

THE UNIVERSITY OF CHICAGO

UC Davis - November 1, 2015

“Moore’s Law”



Snowmass arXiv:1310.8327

“Moore’s Law”

σ_{SI} (cm^2)

σ_{SD} (cm^2)

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σ_{SI} (cm^2)		σ_{SD} (cm^2)
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Kinematic Suppression

Pseudoscalars

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- Generalize Bino-Higgsino to Singlet-Doublet dark matter coupled to a 2-Higgs-Doublet Model
- Slightly lighter pseudoscalar
- Near s-wave resonance, smaller couplings needed for freeze-out
- Dangerous couplings to CP-even Higgses come along for the ride.

"Coy Dark Matter"

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$$-\mathcal{L} \sim \frac{1}{2} M_S S^2 + M_D D_1 D_2 + y_1 S D_1 H_d + y_2 S H_u^\dagger D_2 + \ \mathrm{h.c.}$$

"Coy Dark Matter"

DM Phenomenology

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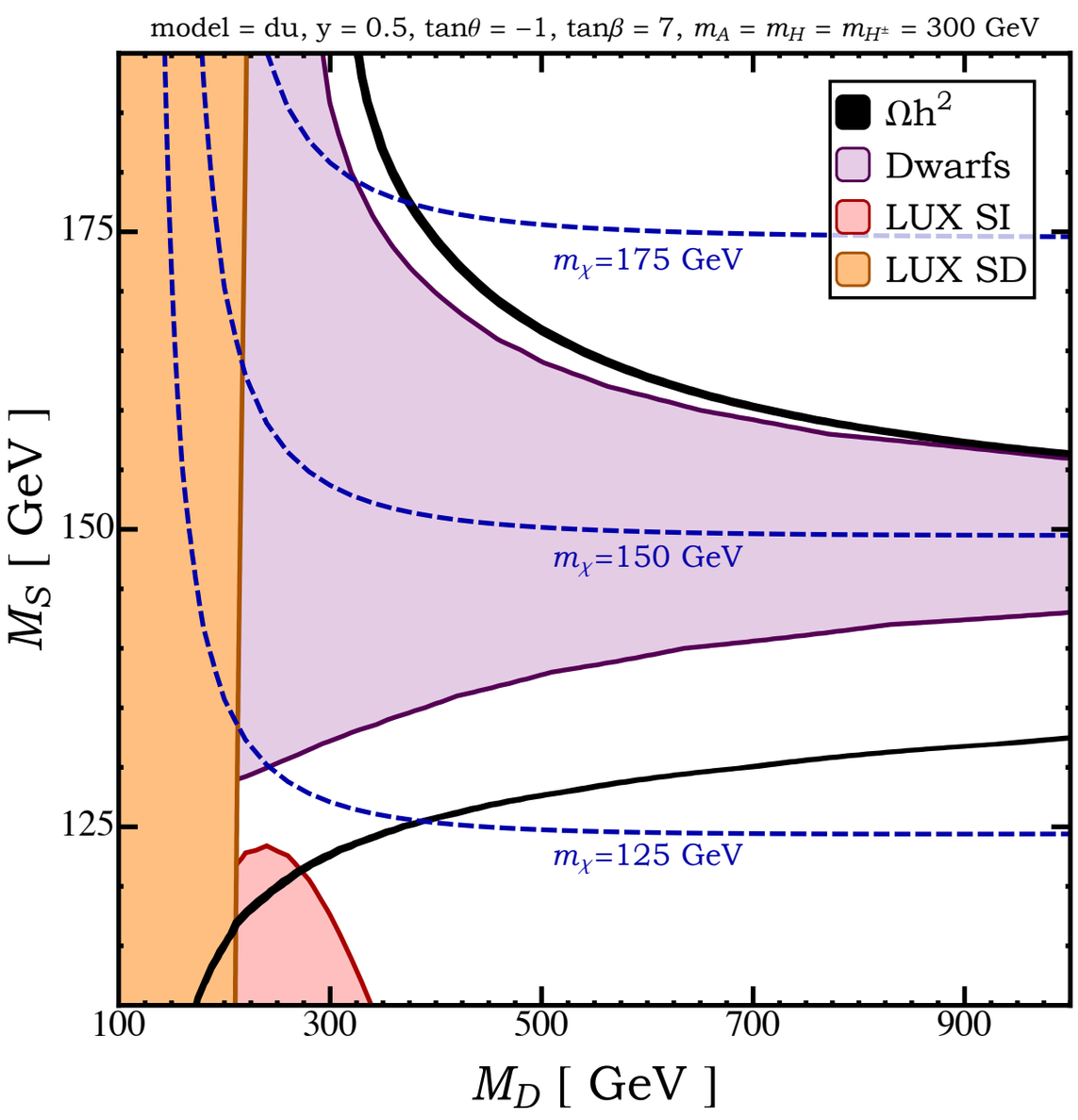
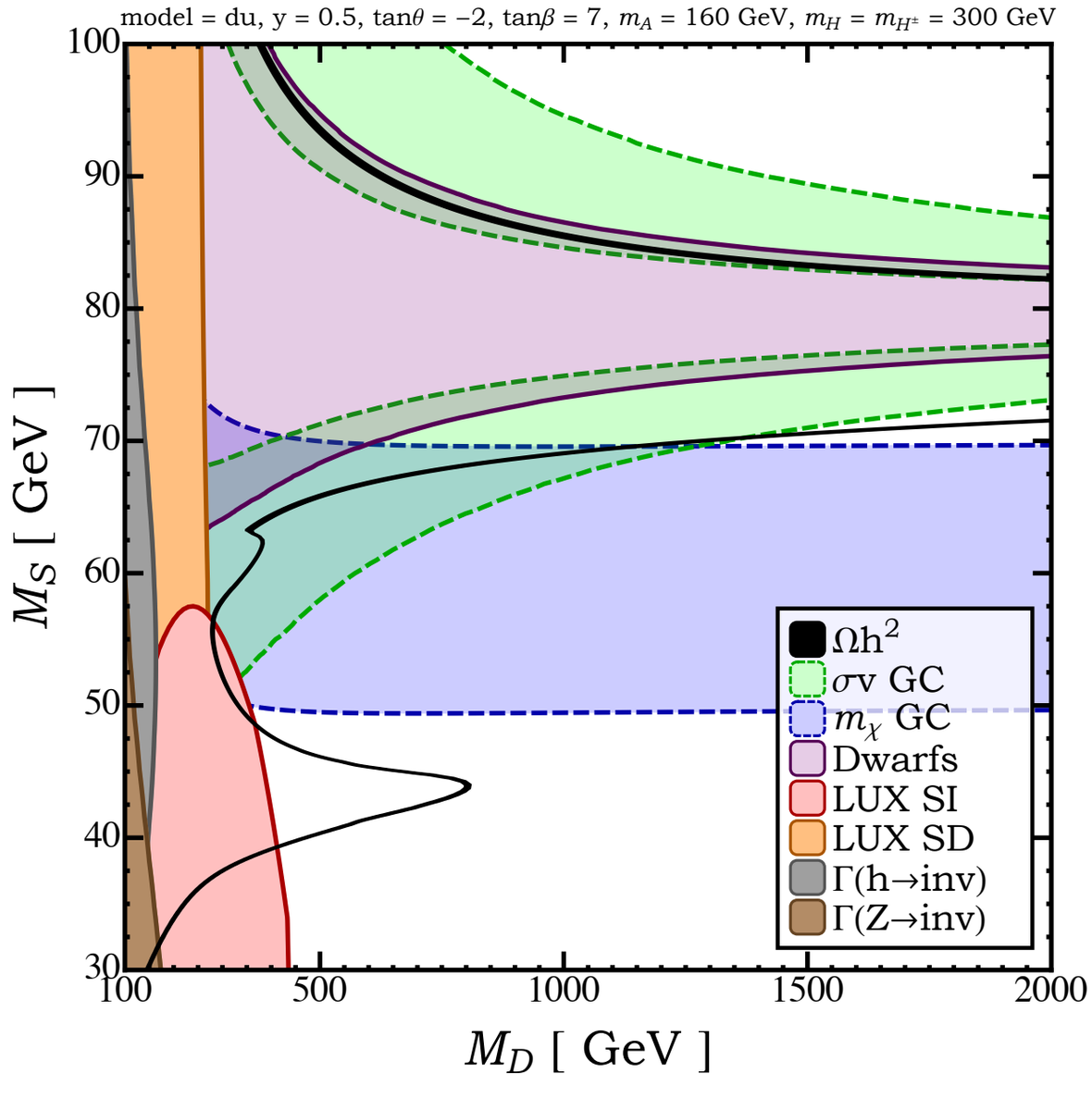
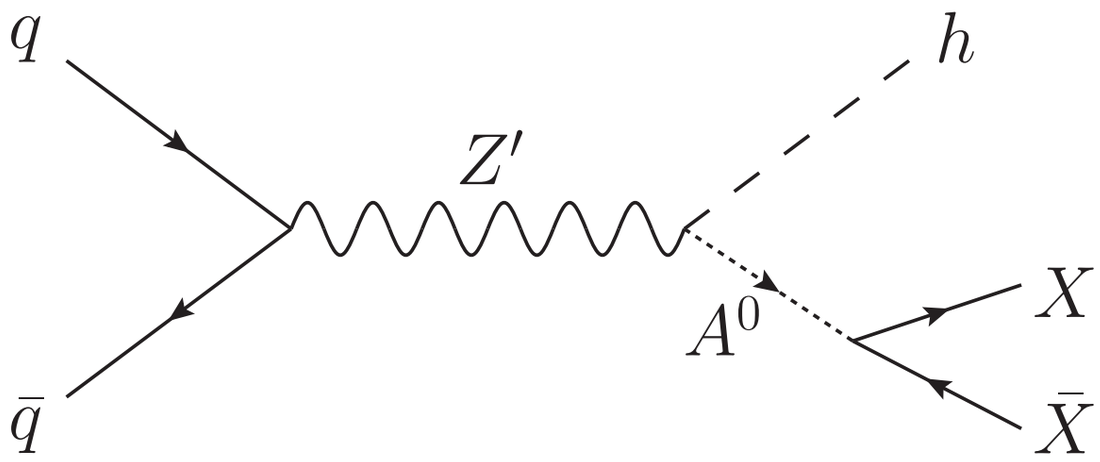




AB, Stefania Gori, Tongyan Lin, Liantao Wang,
arXiv:1502.06000

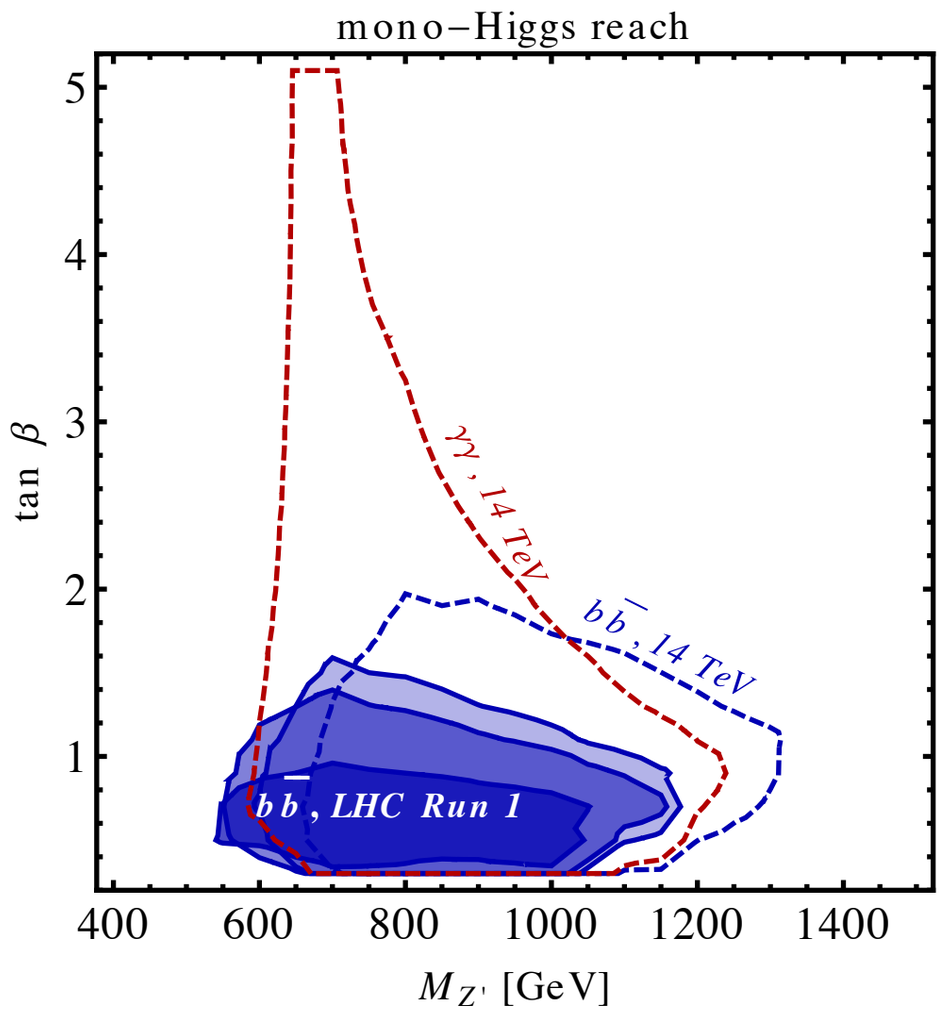
Mono-Higgs Phenomenology



$$\Gamma(Z' \to hA^0) \propto \sin^2 2\beta$$

$$\Gamma(Z' \to hZ) \propto \sin^4 \beta$$

$$\mathrm{BF}(A \to \chi\chi) \approx 1$$

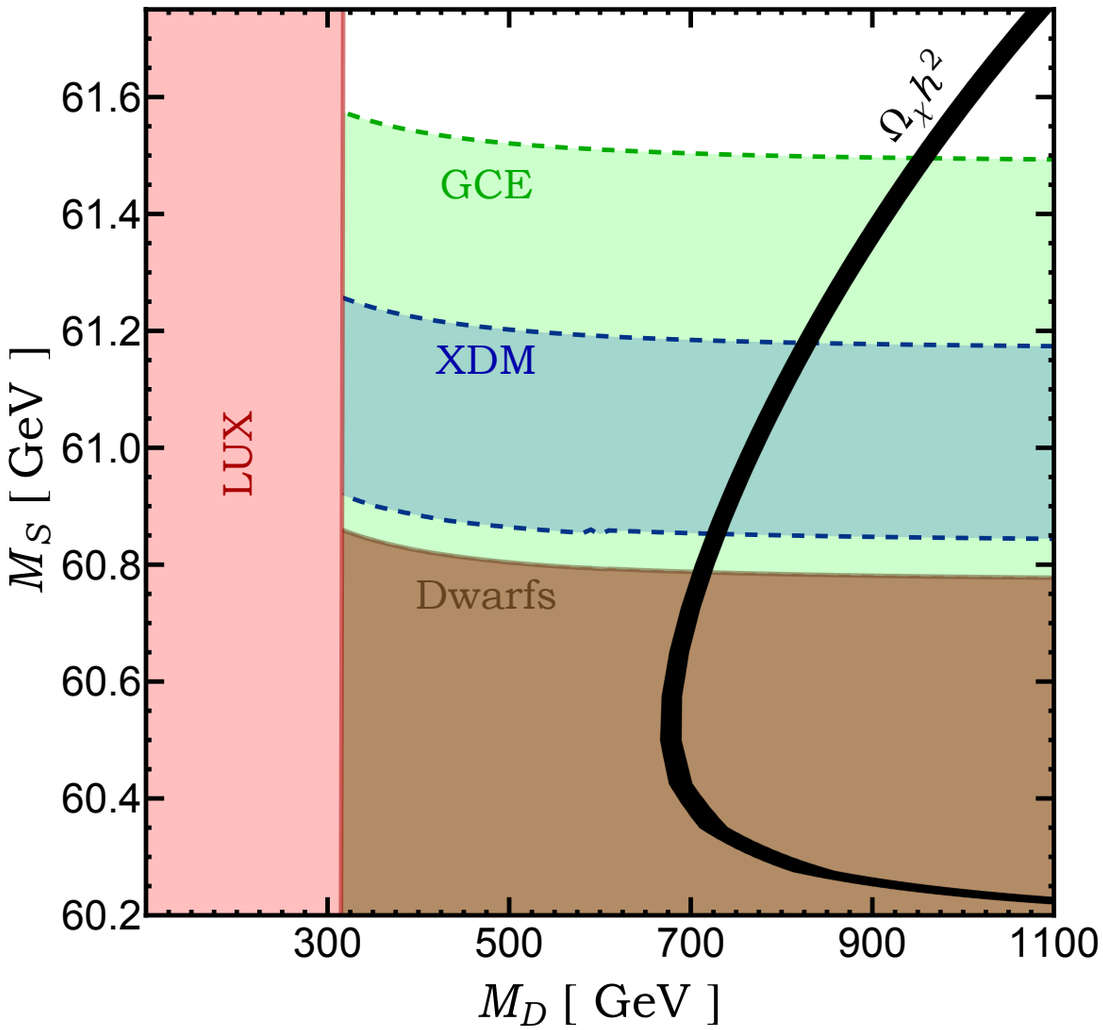


	Φ_d	Φ_u	Q_L	d_R	u_R
$U(1)_{Z'}$	0	1/2	0	0	1/2

AB, Tongyan Lin, Liantao Wang, arXiv:1402.7074

X-Ray Phenomenology

- 3.55 keV line in galaxy clusters, but not in dwarfs.
- Decays are in strong tension.
- "Exciting Dark Matter" suppresses low-velocity systems.



$$V_{\rm scalar} \supset V_{\rm 2HDM} + \frac{1}{2} m_{a_0}^2 a_0^2 + \left(i B_a a_0 H_d^\dagger H_u + \text{h.c.} \right)$$

$$-\mathcal{L} \supset M_S S_1 S_2 + M_D D_1 D_2 + i y_S a_0 S_1 S_2 + i y_D a_0 D_1 D_2 + y_{11} S_1 D_1 H_d + y_{21} S_2 D_1 H_d + y_{22} S_2 H_d^\dagger \cdot D_2 + y_{12} S_1 H_d^\dagger \cdot D_2 + \text{h.c.}$$

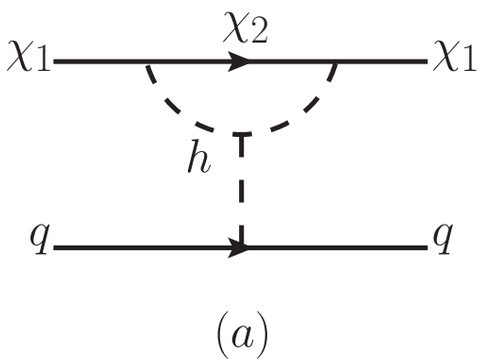
AB, Anthony Difranzo, Dan Hooper, arXiv:1501.03496

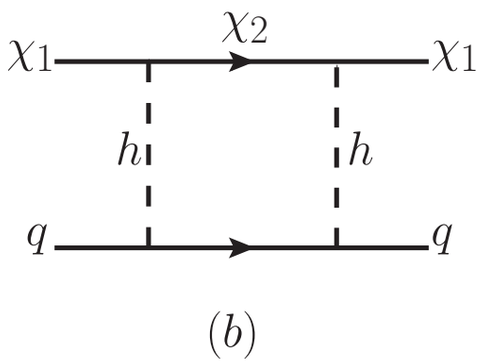
Loops at Leading Order

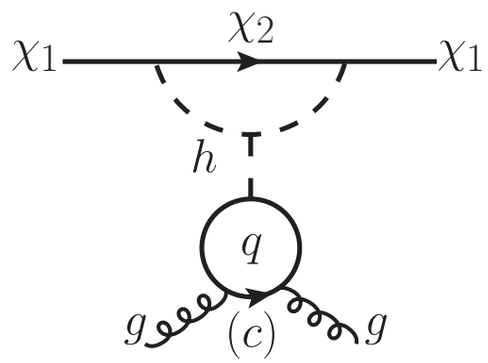
Simplified Models

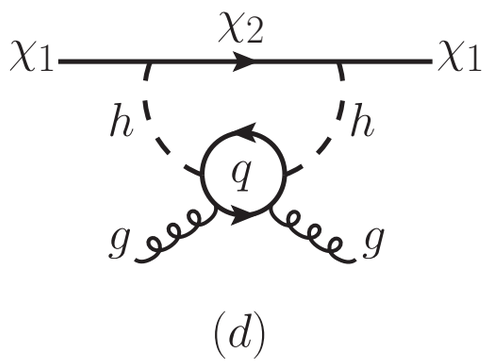
Annihilations to HH, HZ, ZZ

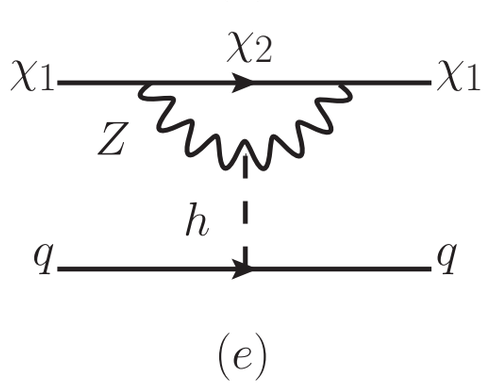
Simplified Models

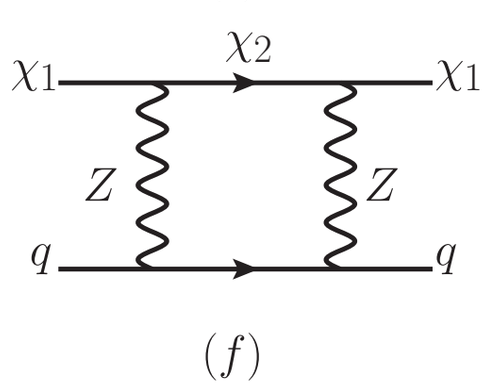


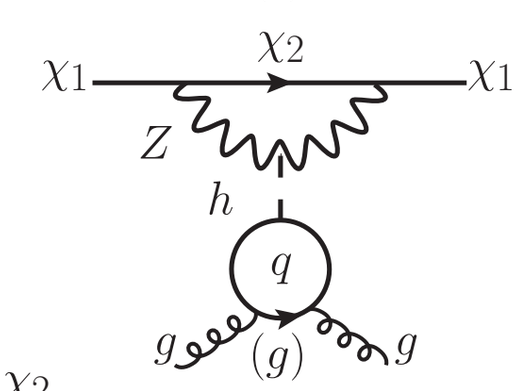


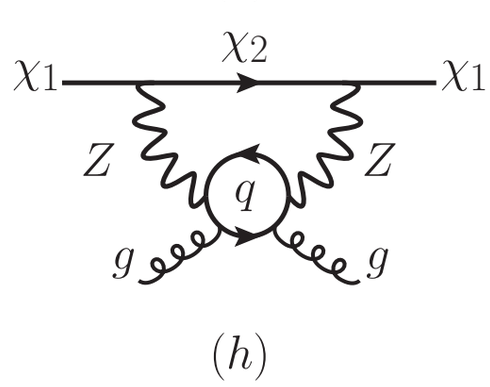


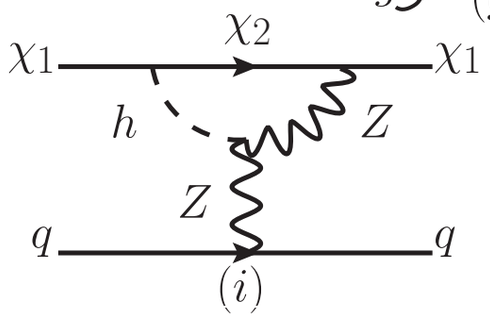






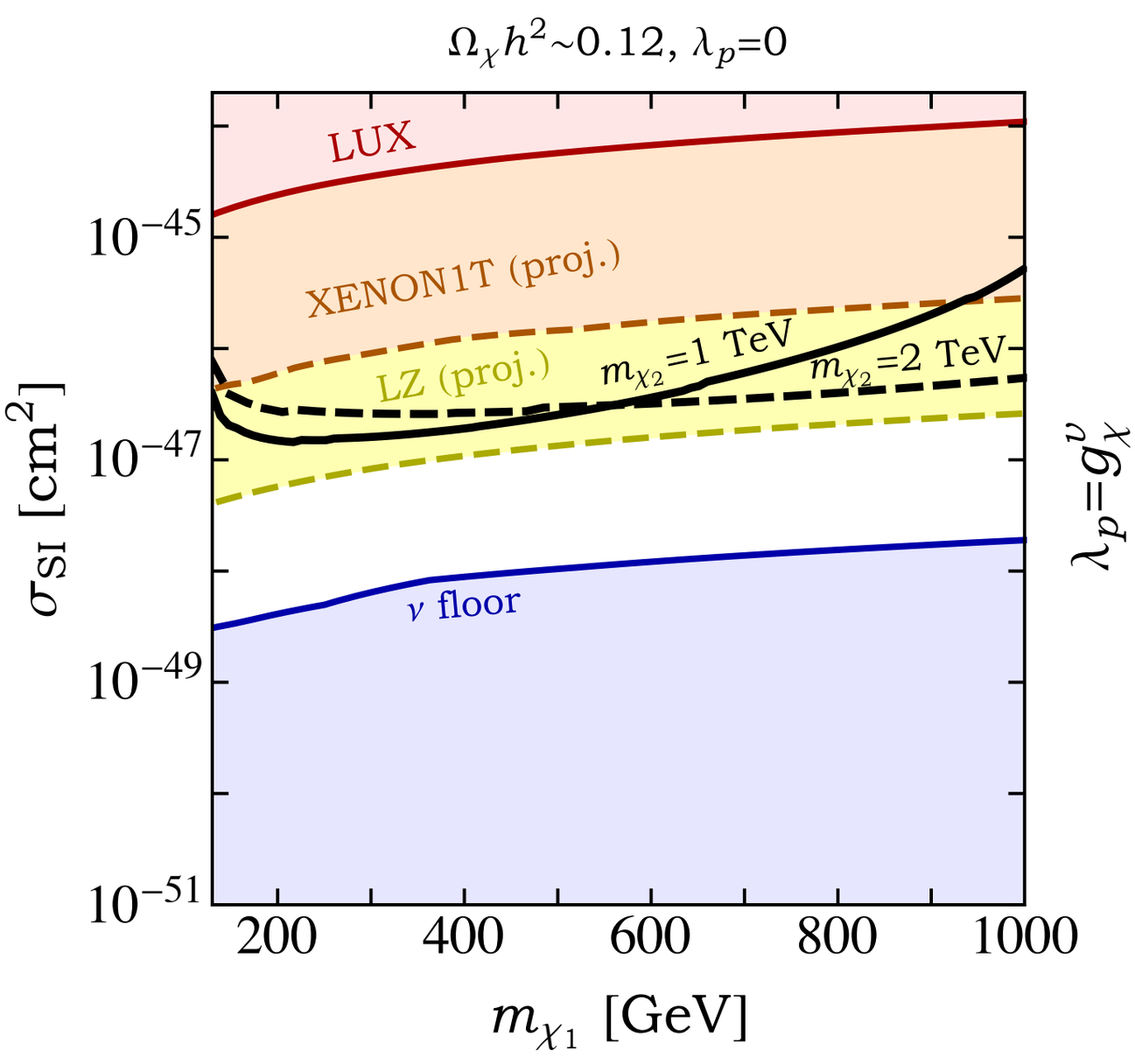


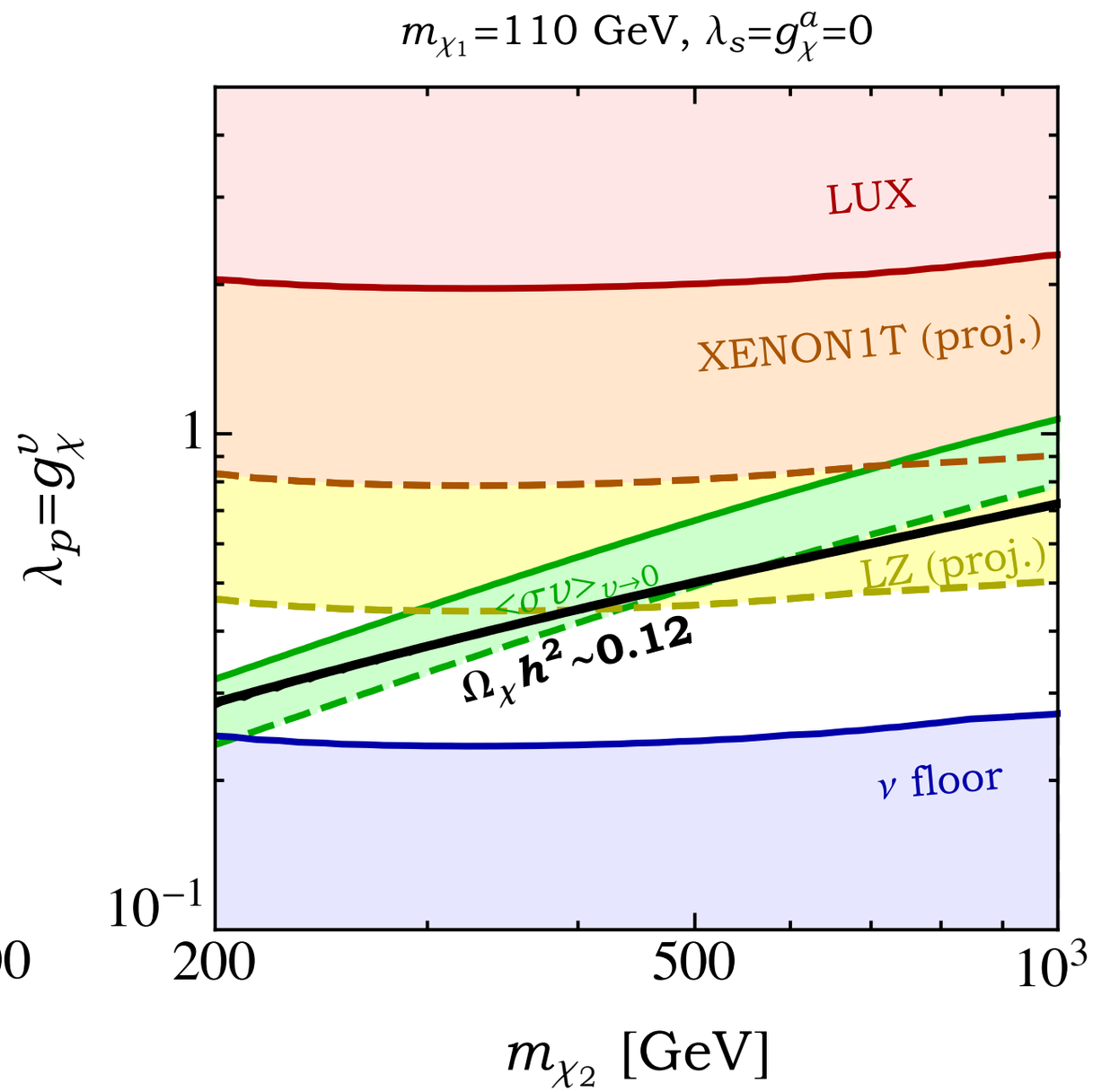




AB, Sam McDermott, Dan Hooper arXiv:1508.05390

Simplified Models





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Higgsino and Wino

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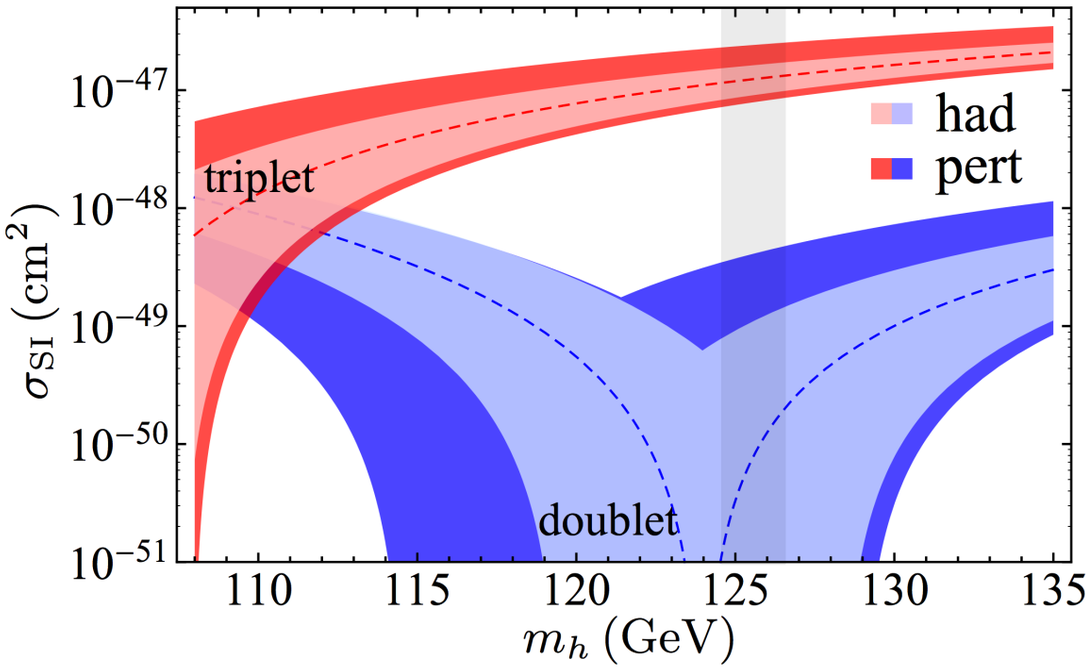

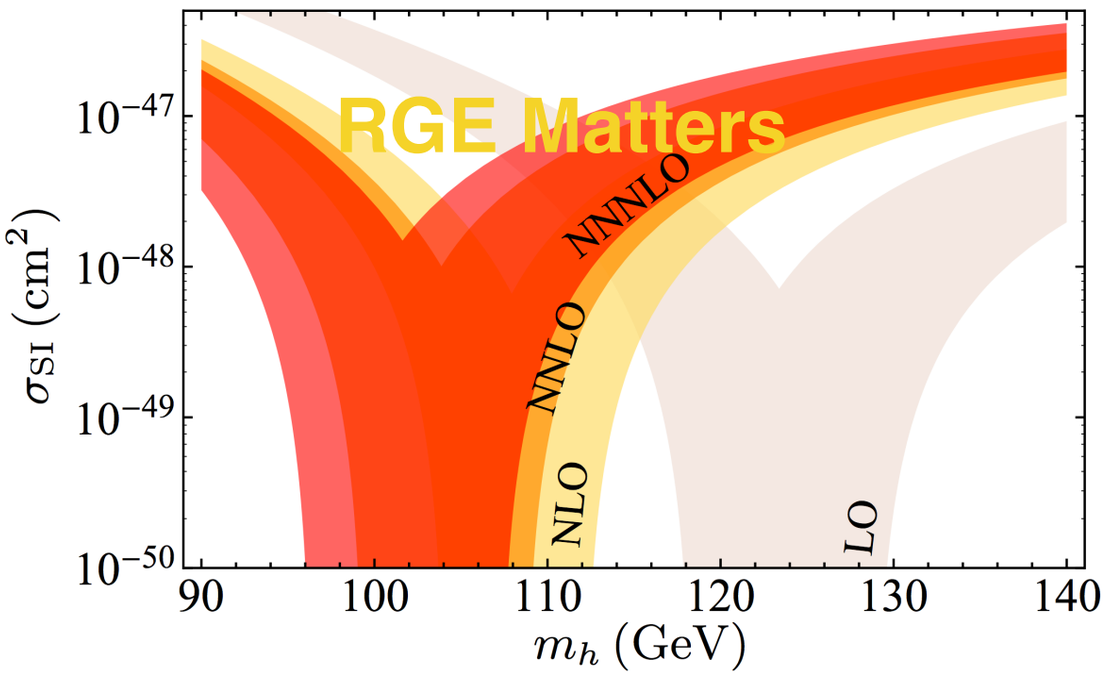

Solon, Hill, arXiv:1309.4092

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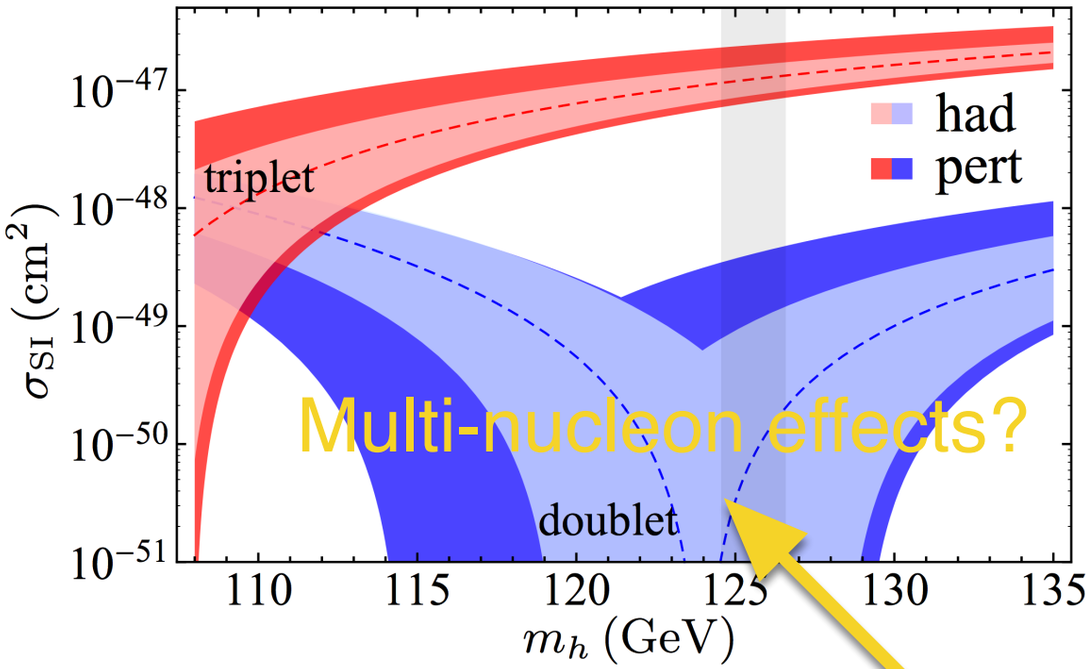
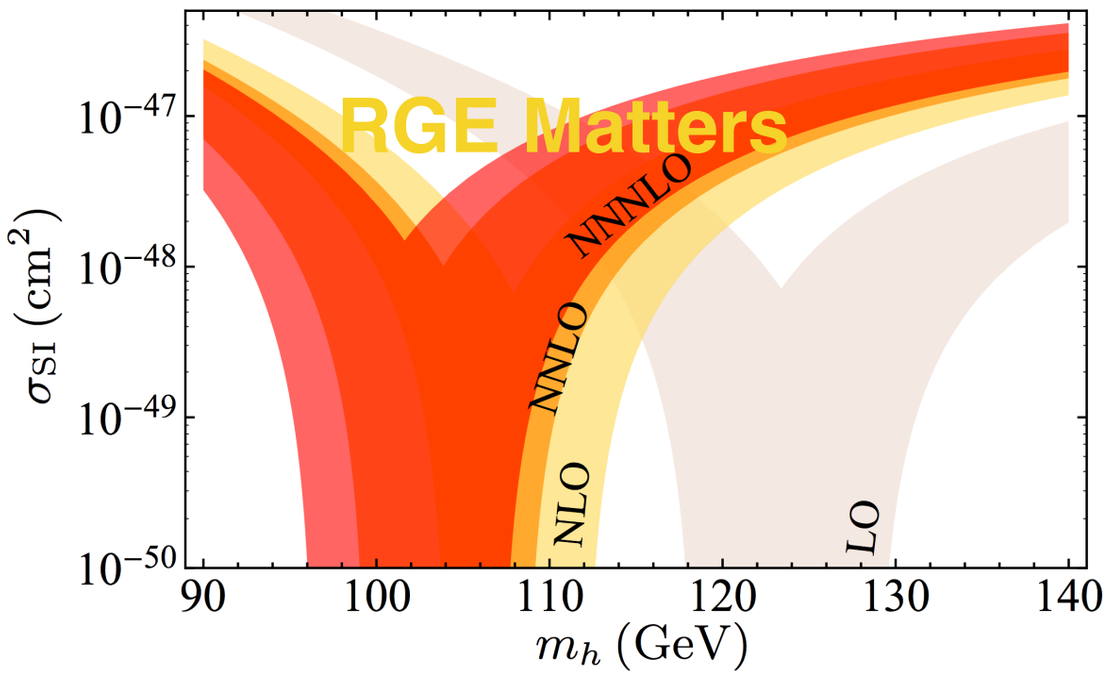
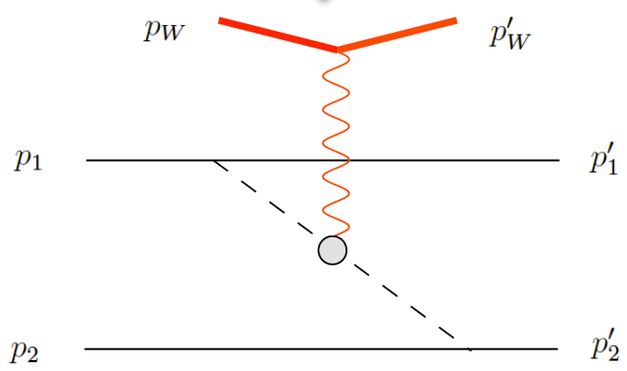
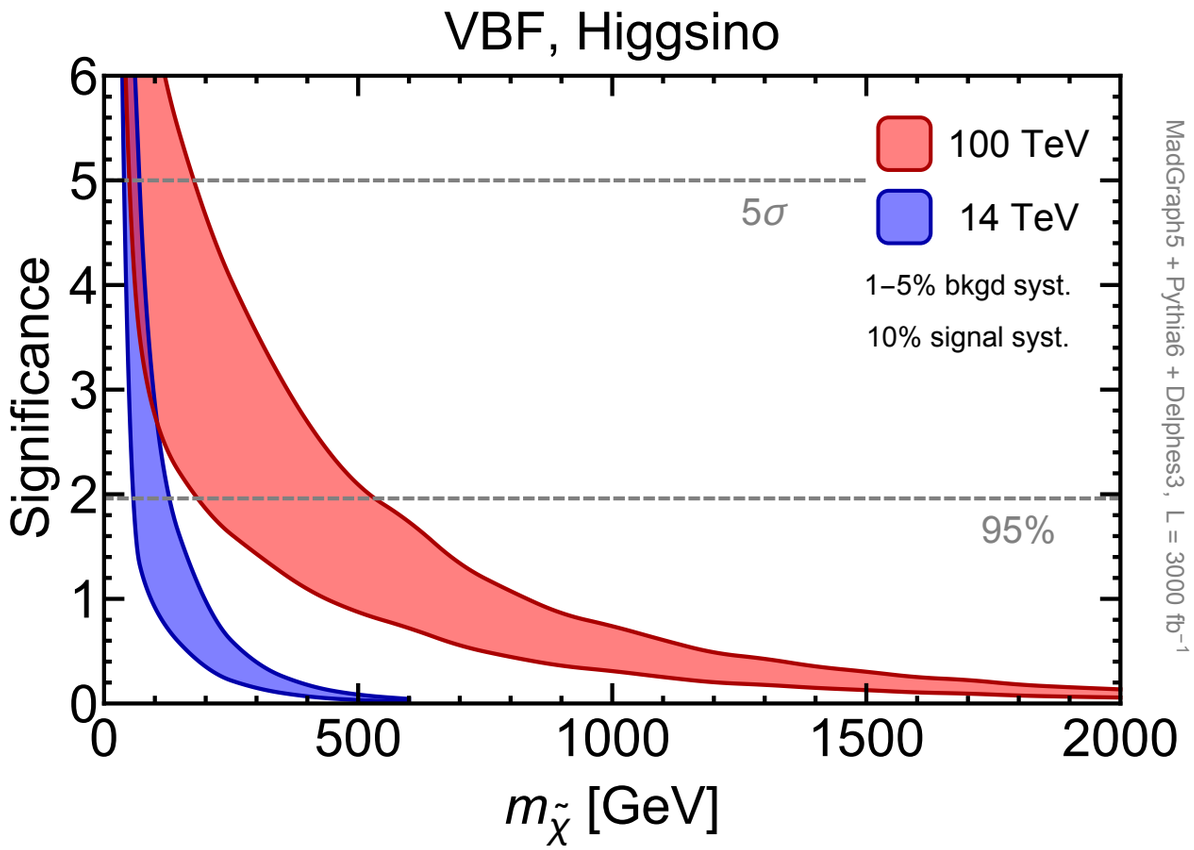


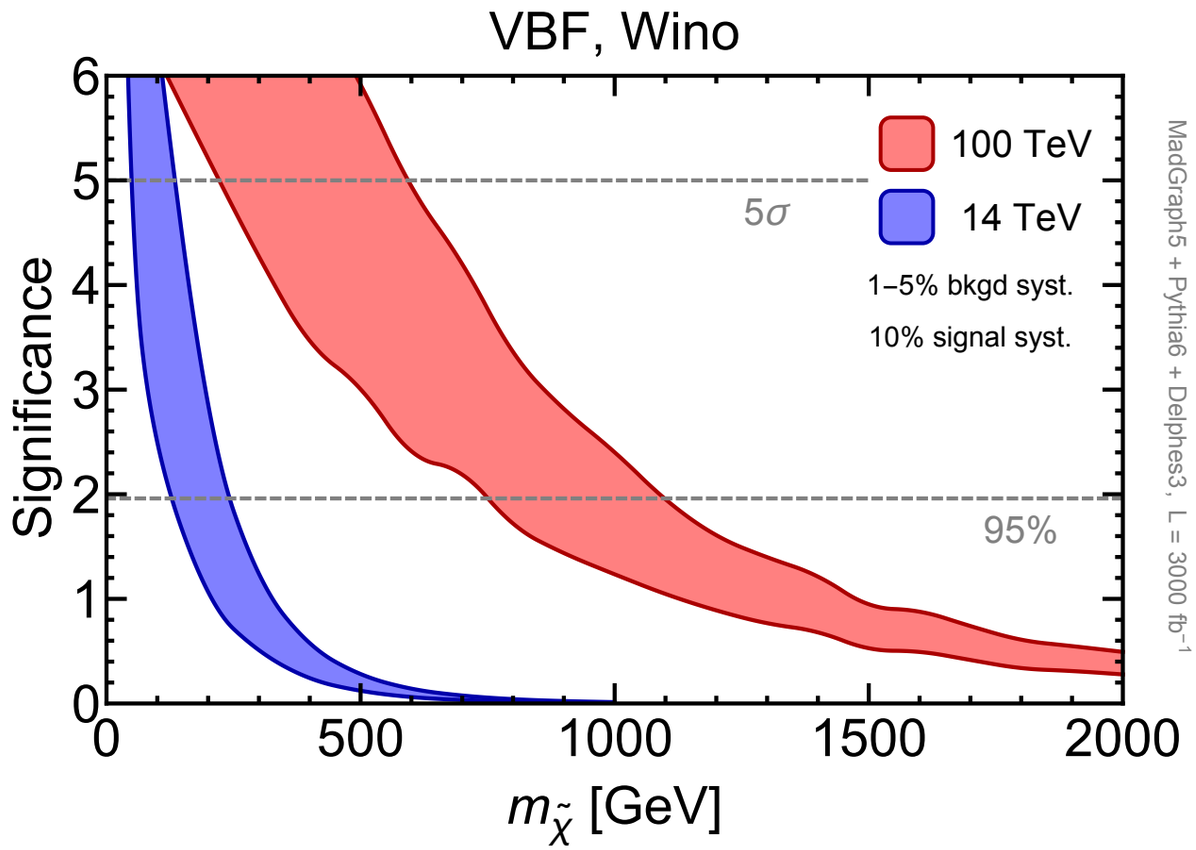




Solon, Hill, arXiv:1309.4092

Vector Boson Fusion





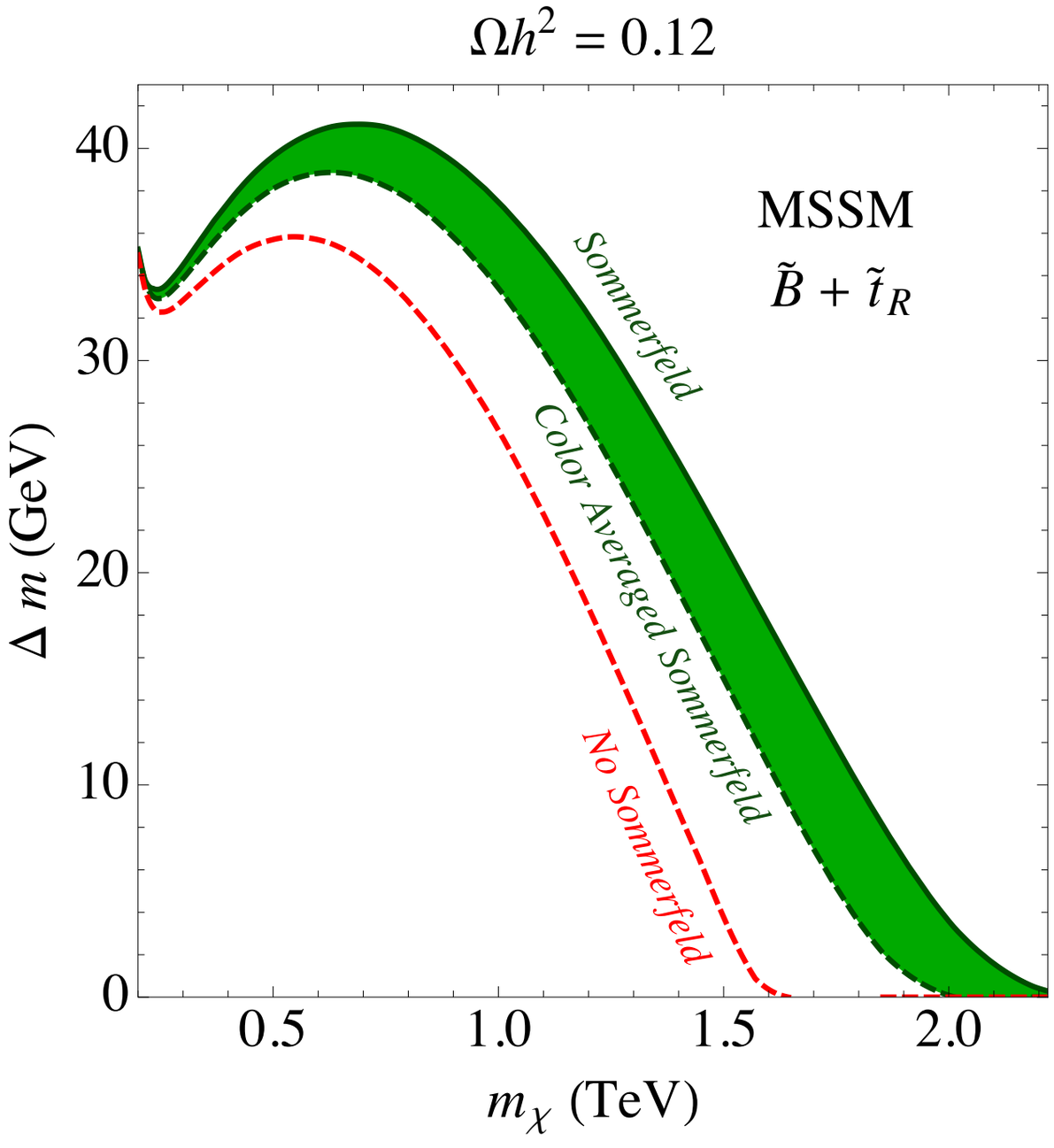
AB, Lin, Low, Wang arXiv:1502.05044

Bino Dark Matter

Bino Dark Matter

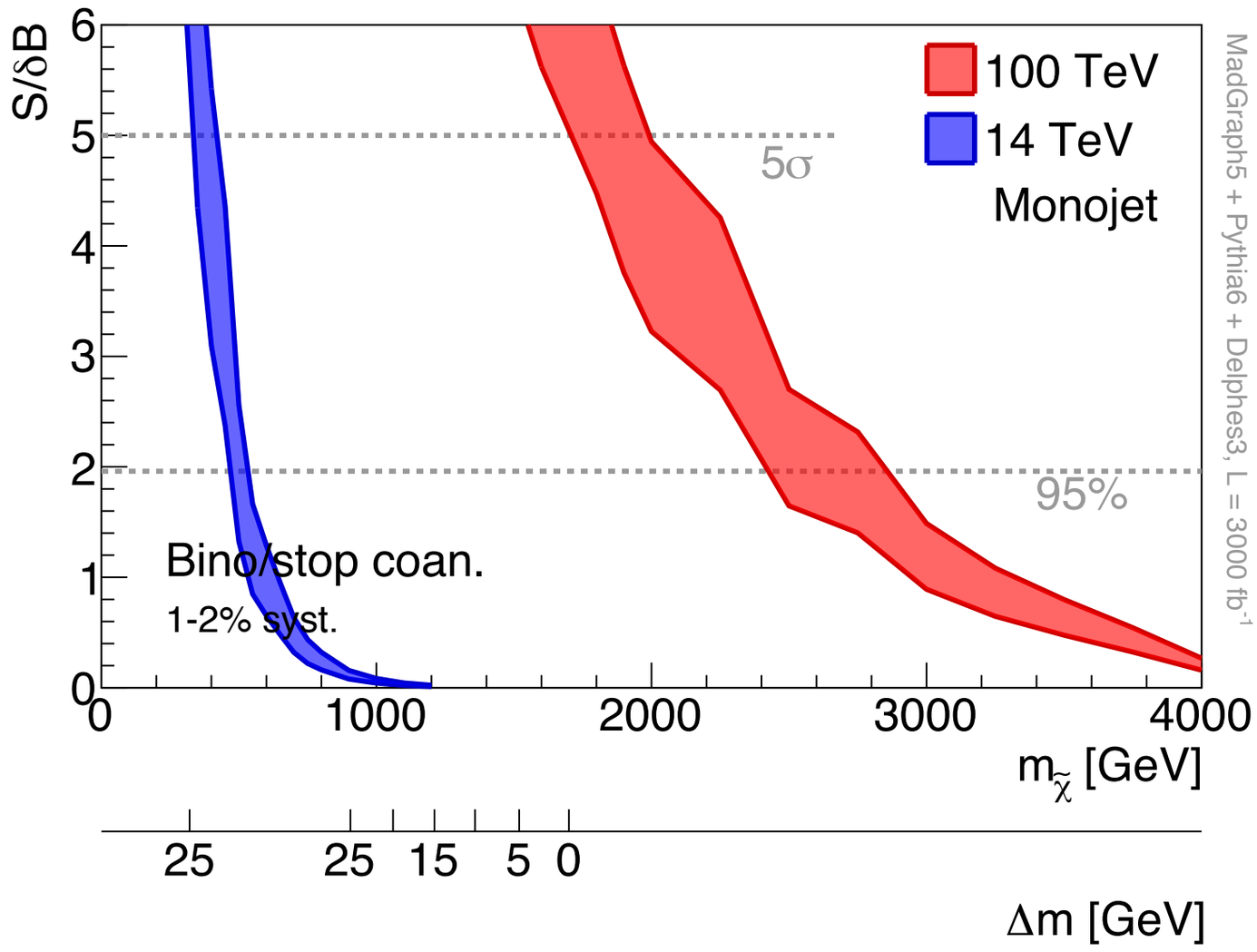
In progress

Cosmology



Ibarra, Pierce, Shah, Vogl, arXiv:1501.03164

Monojet



Low, Wang, arXiv:1404.0682

How much Bino is enough?

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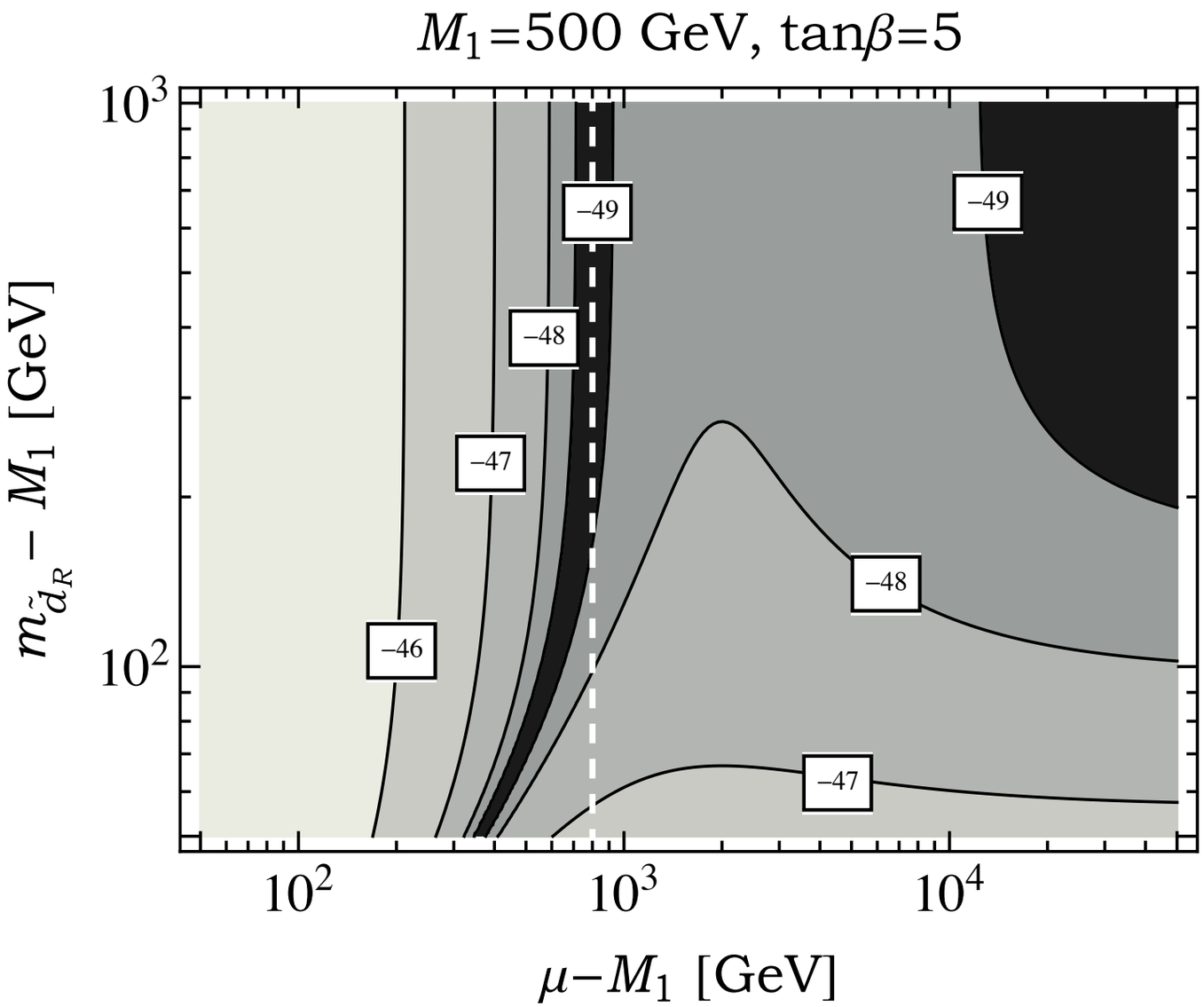

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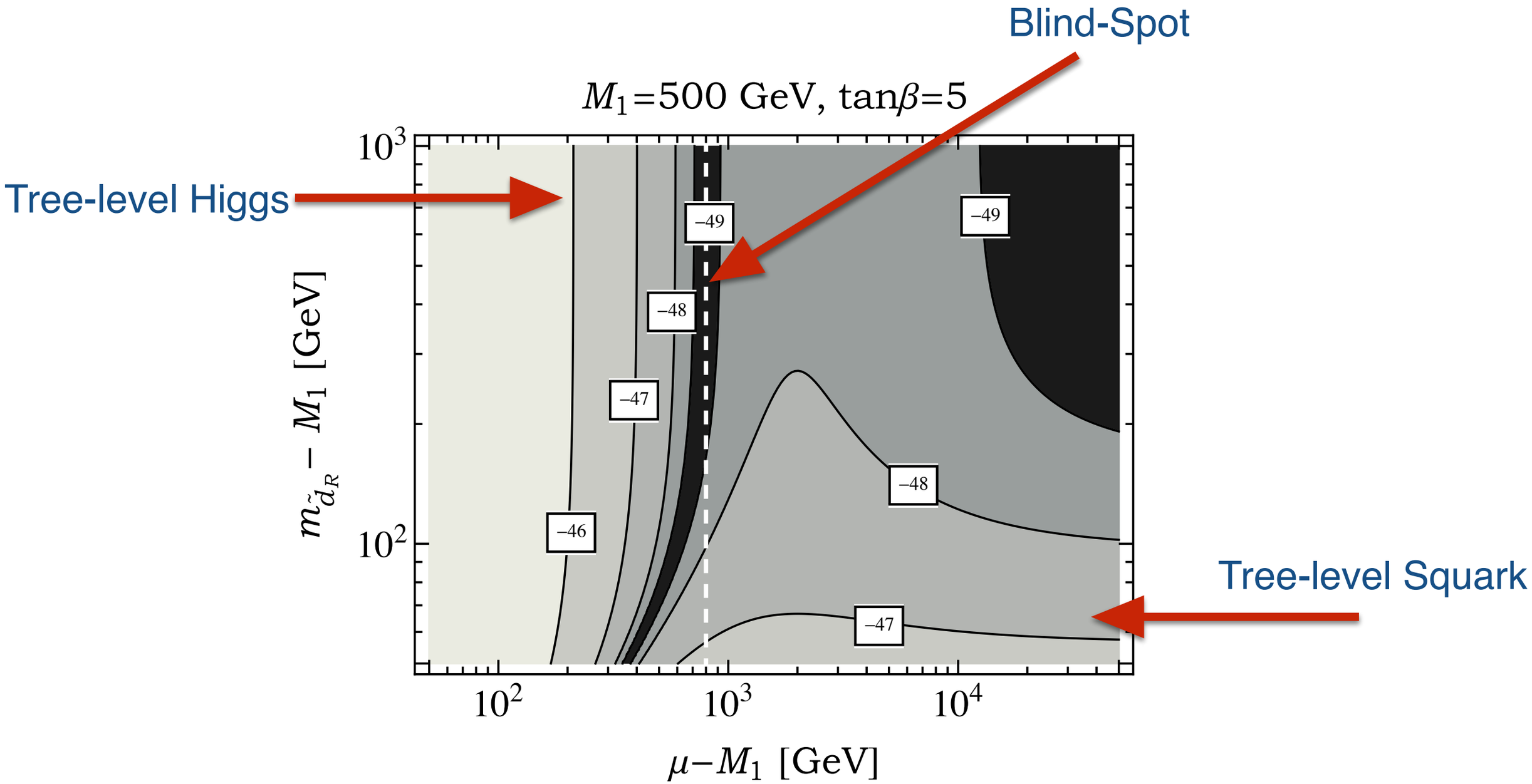


Fixed Order vs. EFT

Weak Scale Mediators

Hadronic Matrix Elements

Fixed Order vs. EFT

Fixed order

Weak Scale

$$\frac{\chi\,,\tilde{f}_i\,,\mathrm{SM}}{\chi_v\,,\mathrm{QCD}^{(3)}}$$

Hadronic Scale

Effective theory

Weak Scale

$$\mu_t \quad \frac{\chi\,,\tilde{f}_i\,,\mathrm{SM}}{\chi_v\,,\mathrm{QCD}^{(5)}\,,[\tilde{b}_{R,v}]}$$

RGE

5-Flavor QCD

$$\mu_b \quad \frac{\chi_v\,,\mathrm{QCD}^{(1+4)}\,,[\tilde{b}_{R,v}]}{\chi_v\,,\mathrm{QCD}^{(4)}}$$

RGE

4-Flavor QCD

$$\mu_c \quad \frac{\chi_v\,,\mathrm{QCD}^{(1+3)}}{\chi_v\,,\mathrm{QCD}^{(3)}}$$

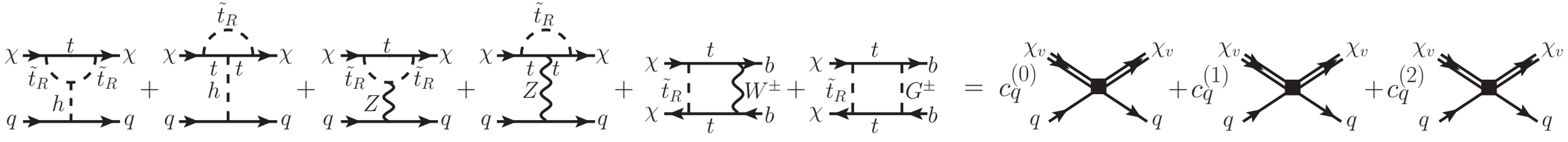
RGE

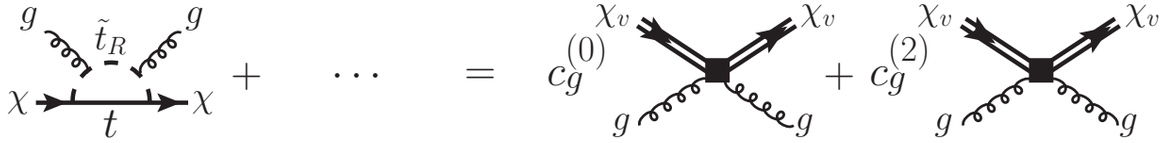
Hadronic Scale

$$\mu_0 \quad \chi_v\,,\mathrm{QCD}^{(3)}$$

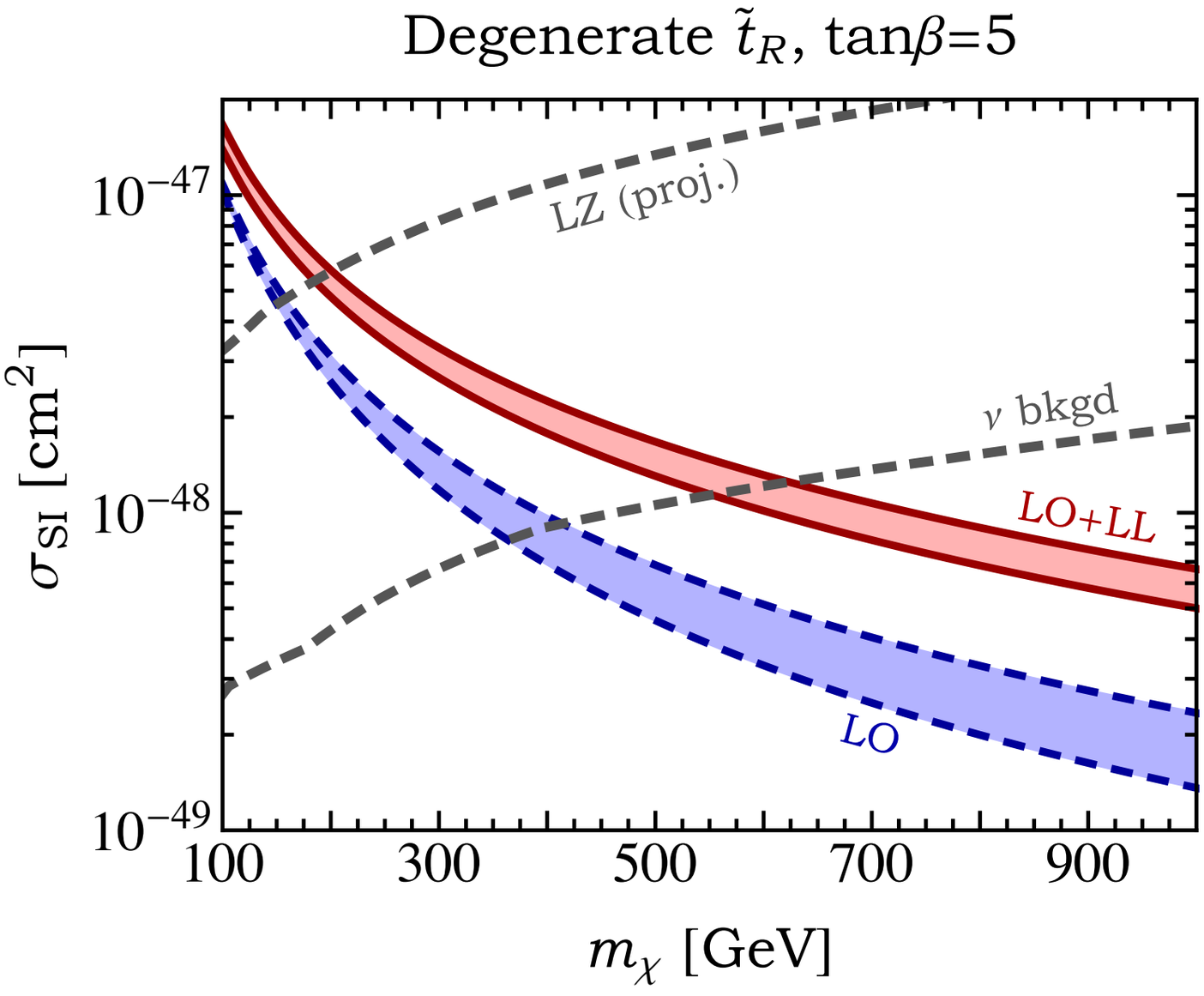
Bino + RH Stop

Bino + RH Stop


χ t χ $\tilde{t}_R$ $\tilde{t}_R$ h q q + $\tilde{t}_R$ χ χ t t h q q + χ t χ $\tilde{t}_R$ $\tilde{t}_R$ Z q q + $\tilde{t}_R$ χ χ t t Z q q + χ t b $\tilde{t}_R$ $W^\pm$ χ b t + χ t b $\tilde{t}_R$ $G^\pm$ χ b t = $c_q^{(0)}$ χ_v χ_v q q + $c_q^{(1)}$ χ_v χ_v q q + $c_q^{(2)}$ χ_v χ_v q q

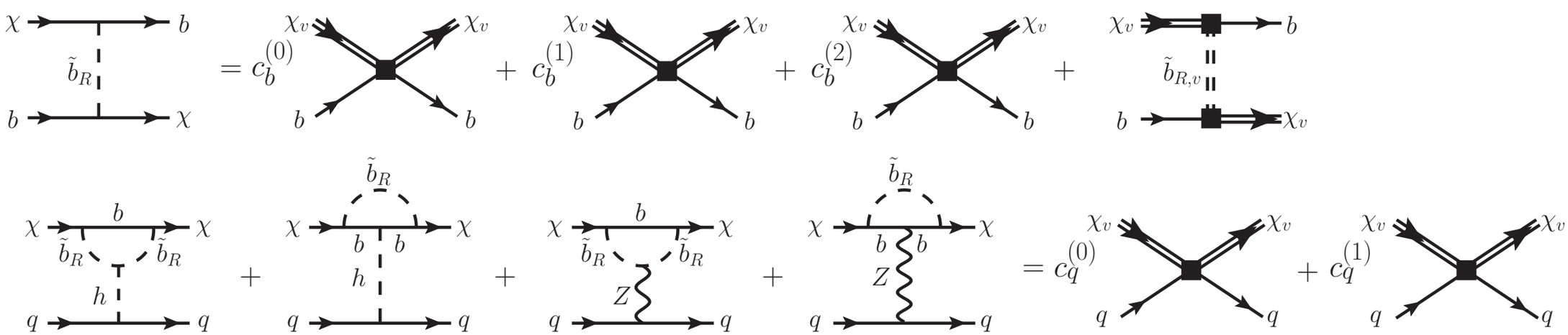

g g $\tilde{t}_R$ χ χ t + $\cdots$ = $c_g^{(0)}$ χ_v χ_v g g + $c_g^{(2)}$ χ_v χ_v g g

Bino + RH Stop

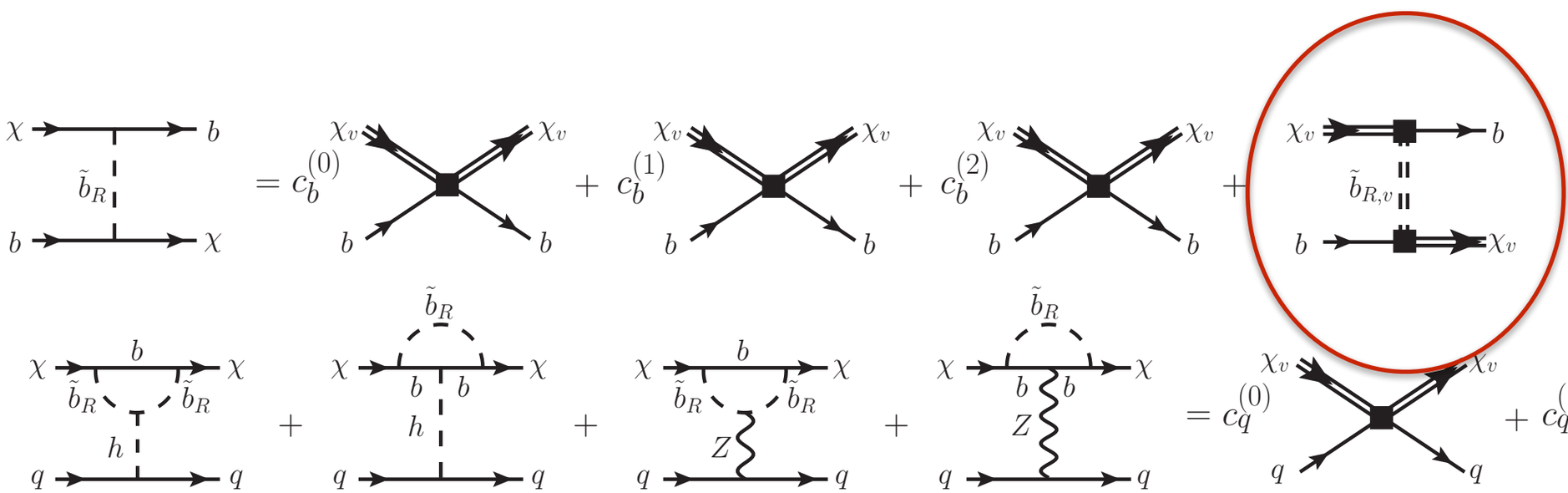

Degenerate $\tilde{t}_R$, tanβ=5
10^{-47}
10^{-48}
10^{-49}
σ_{SI} [cm^2]
100
300
500
700
900
m_χ [GeV]
LZ (proj.)
ν bkgd
LO+LL
LO

Bino + RH Sbottom

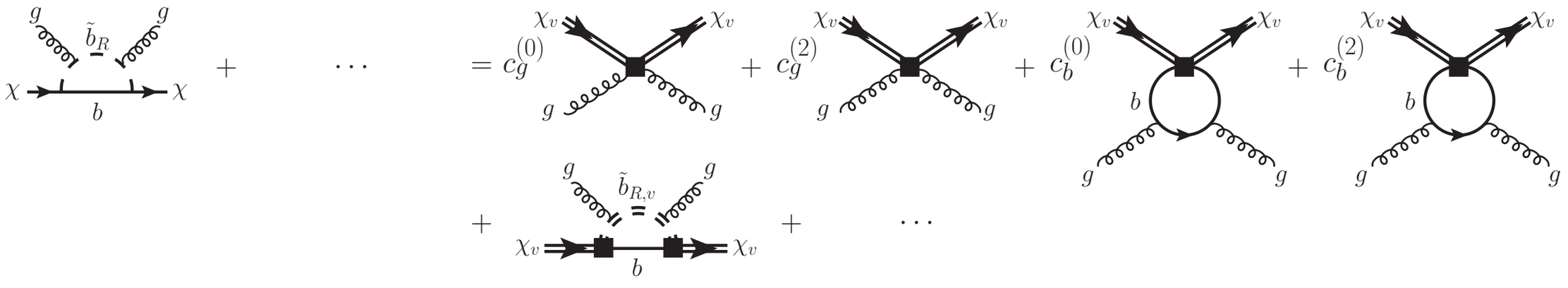
Bino + RH Sbottom



Bino + RH Sbottom



Kept until bottom quark threshold



Heavy-Light Current

$$\Gamma(B, D \to l\ \nu) \propto f_{B,D}^2\ m_{B,D}$$

- Decays of heavy-light metastable hadrons (B and D mesons)

- In $m_Q \to \infty$ limit, heavy-quark flavor symmetry gives:

$$\frac{f_B}{f_D} = \sqrt{\frac{m_D}{m_B}} + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_D}\right)$$

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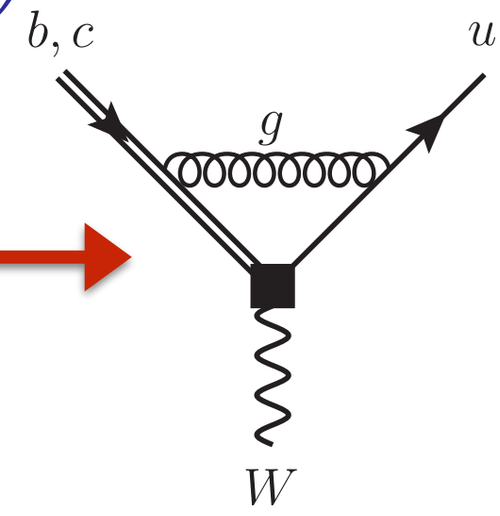
- RGE of heavy-light current eases tension →



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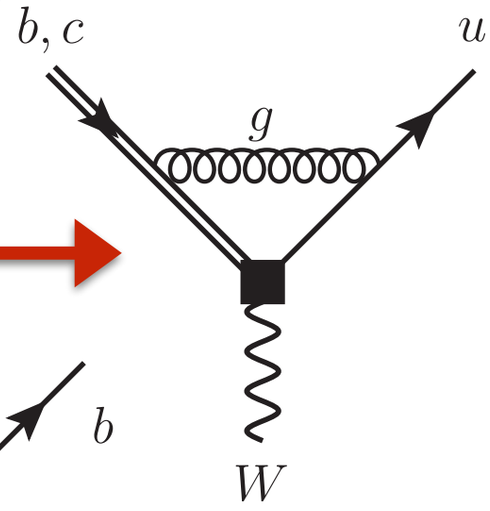
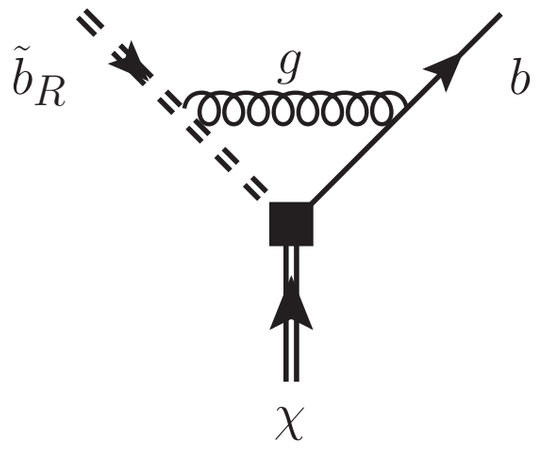
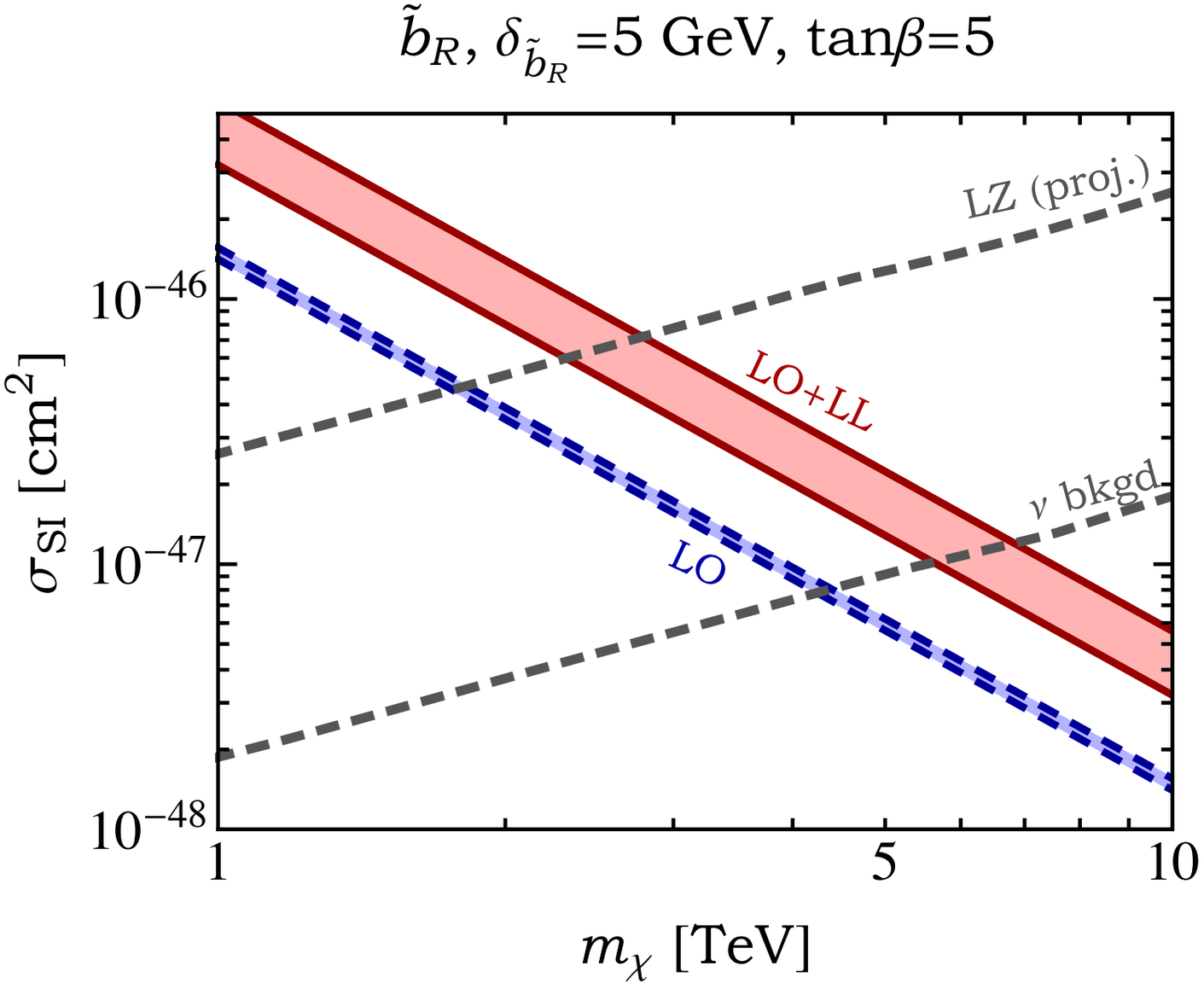


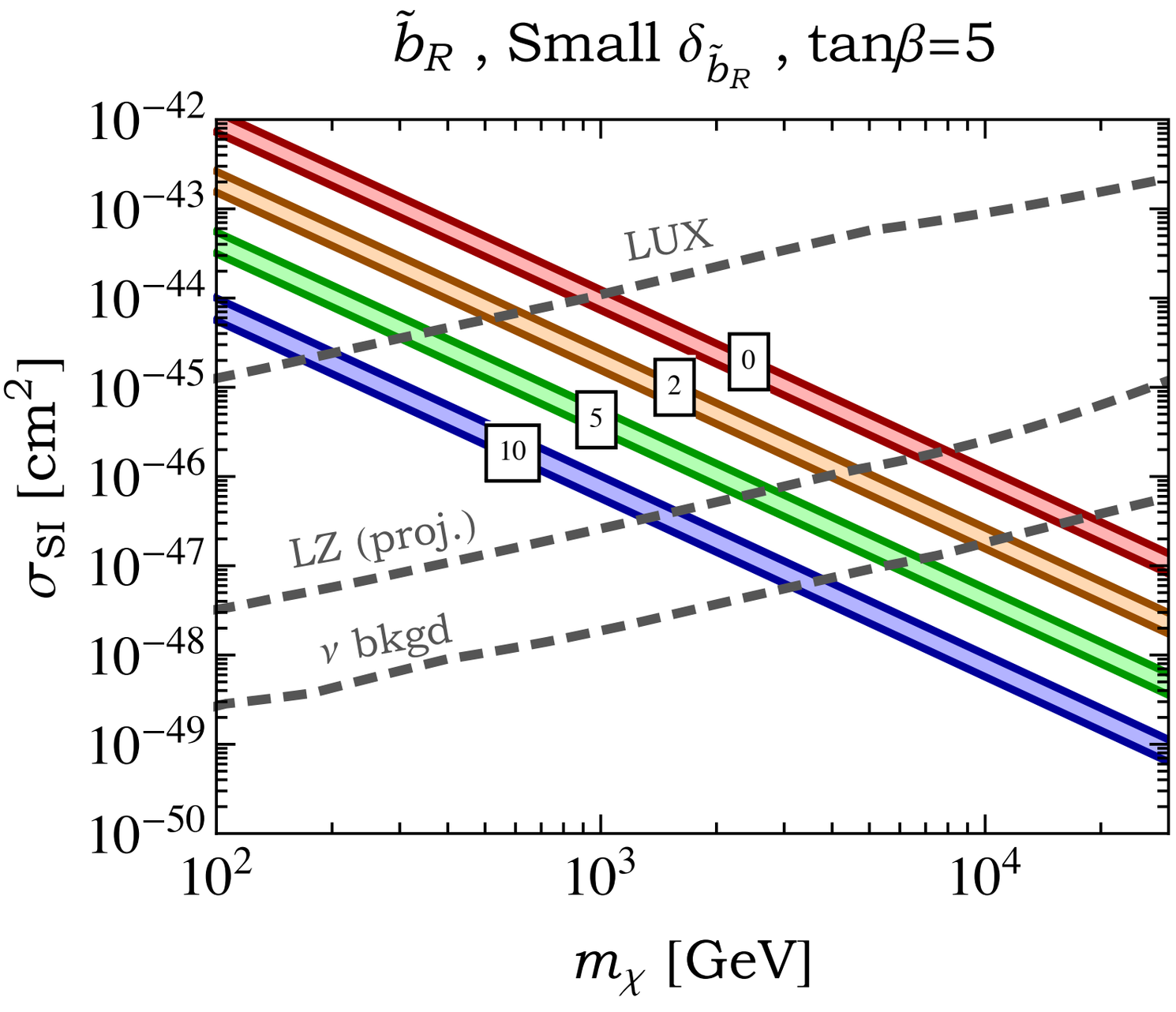
- RGE of heavy-light sbottom current enhances rate →



Fixed-Order vs EFT

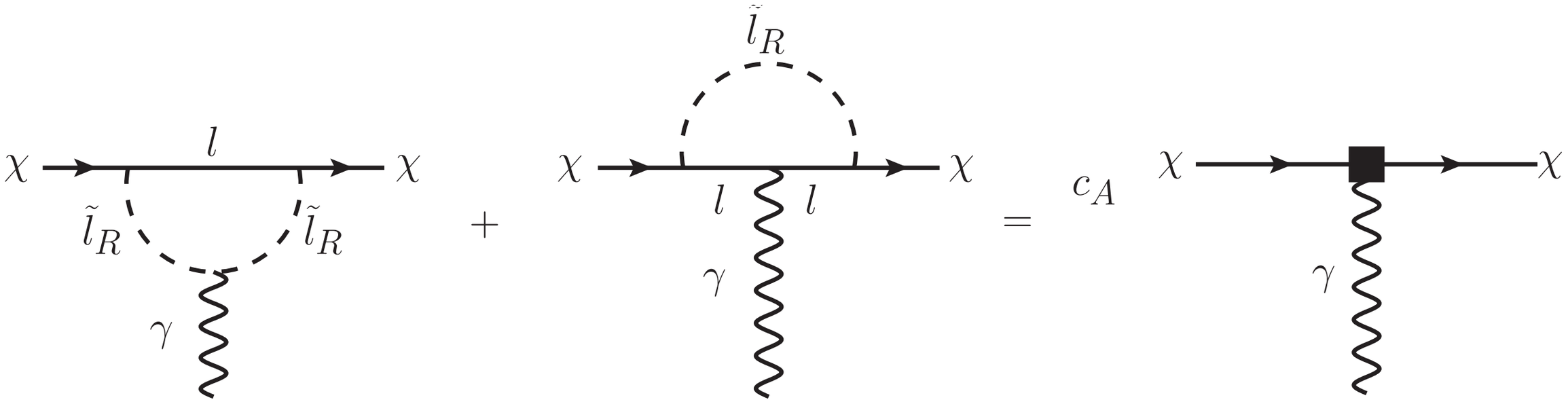


Bino + RH Sbottom

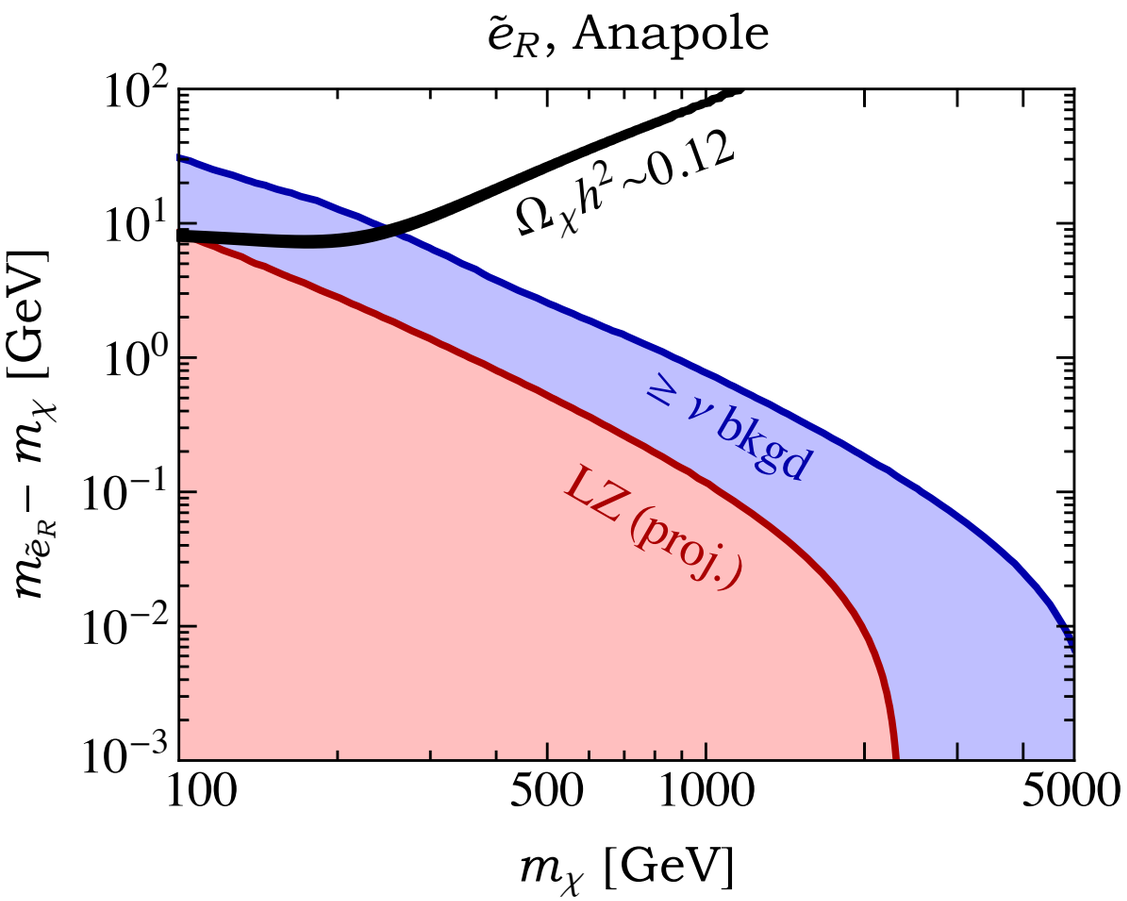


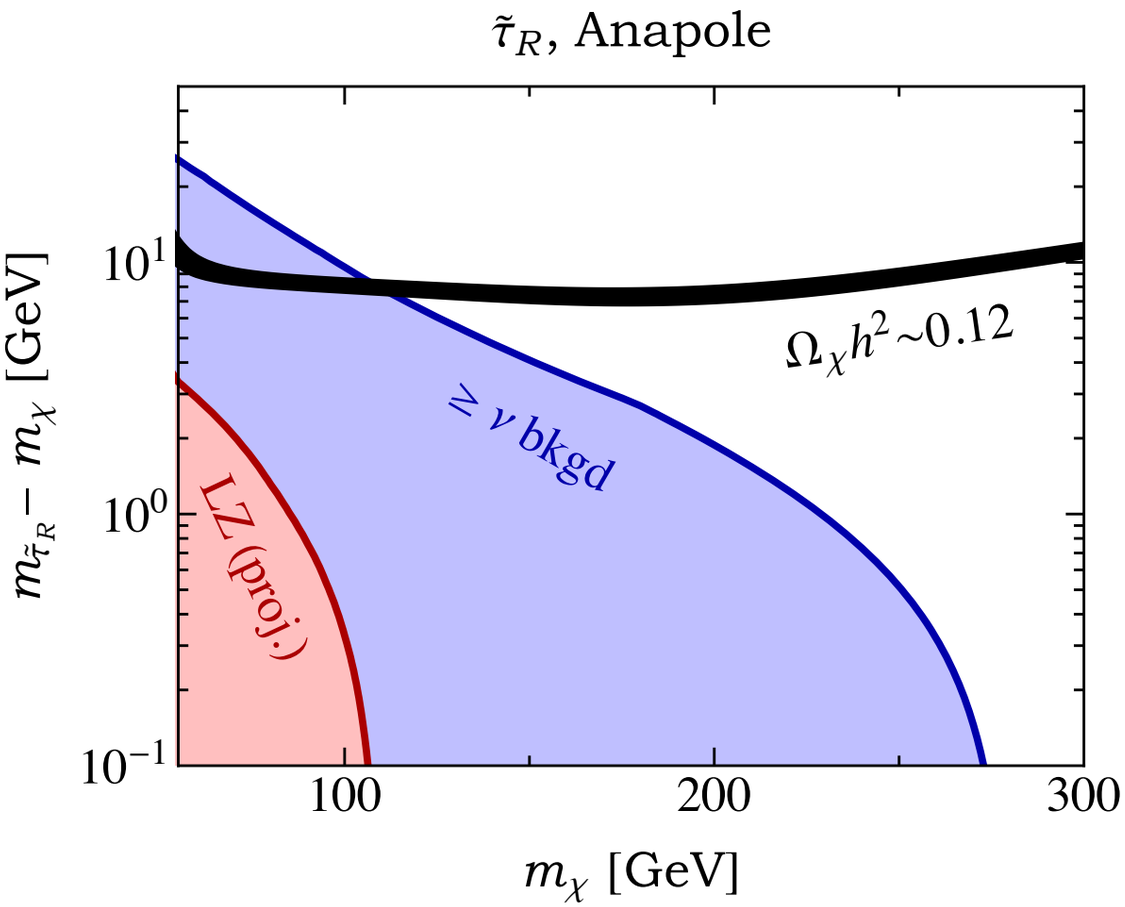
Bino + RH Slepton

Bino + RH Slepton



Bino + RH Slepton





Bino + Mixed Squarks

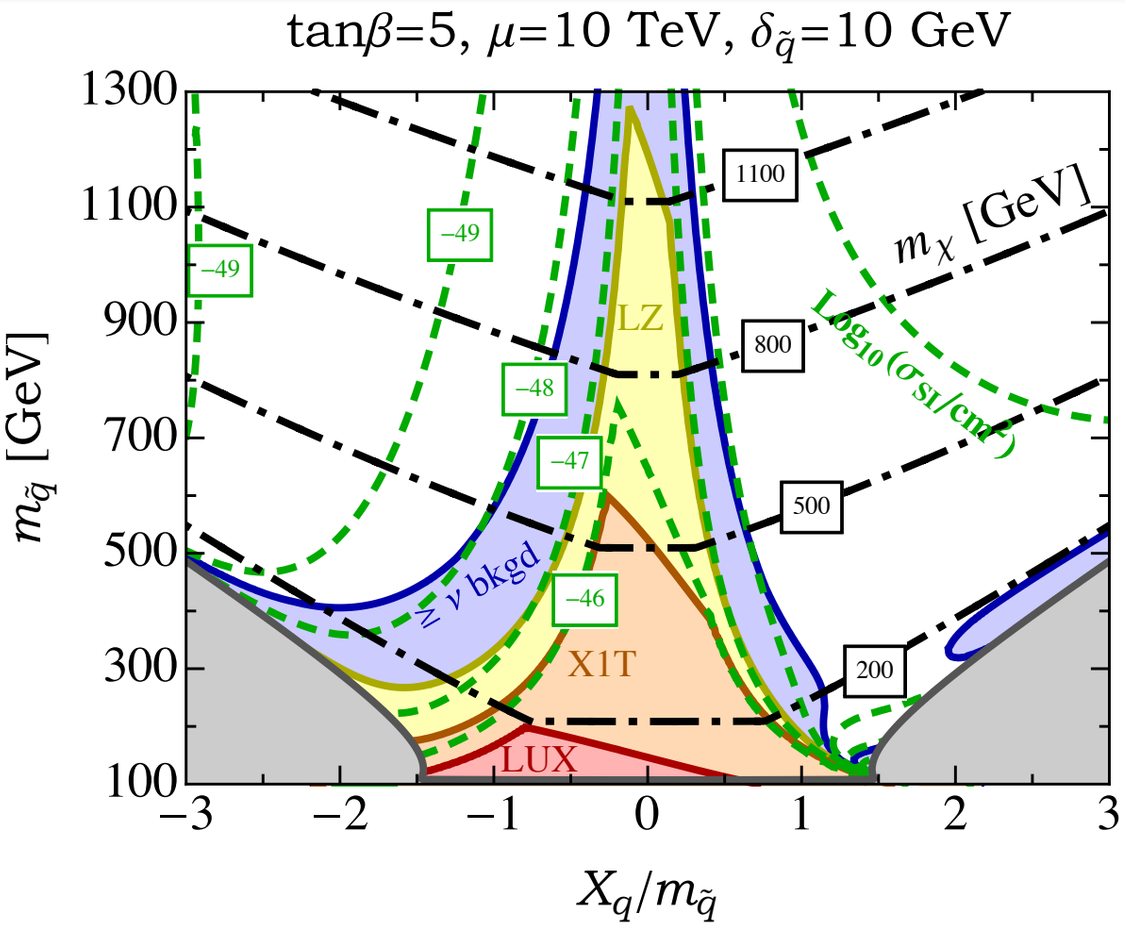
Bino + Mixed Squarks

$$m_{\tilde{q}} \equiv m_{\tilde{Q}_3} = m_{\tilde{t}_R} = m_{\tilde{b}_R} \ , \ X_q \equiv X_t = X_b$$

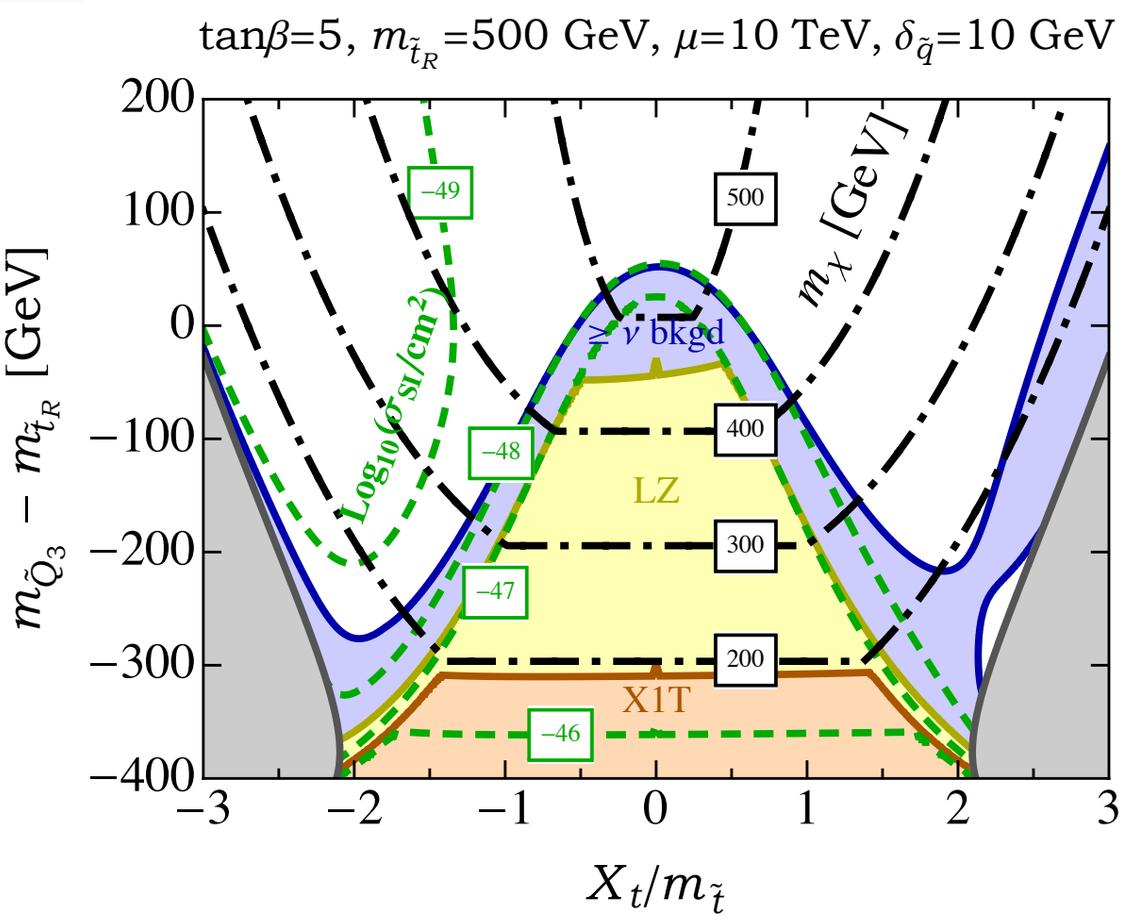
$$m_{\tilde{b}_R} \gg m_{\tilde{Q}_3}, m_{\tilde{t}_R} \ , \ m_{\tilde{Q}_3} \neq m_{\tilde{t}_R}$$

Bino + Mixed Squarks

$$m_{\tilde{q}} \equiv m_{\tilde{Q}_3} = m_{\tilde{t}_R} = m_{\tilde{b}_R} \ , \ X_q \equiv X_t = X_b$$

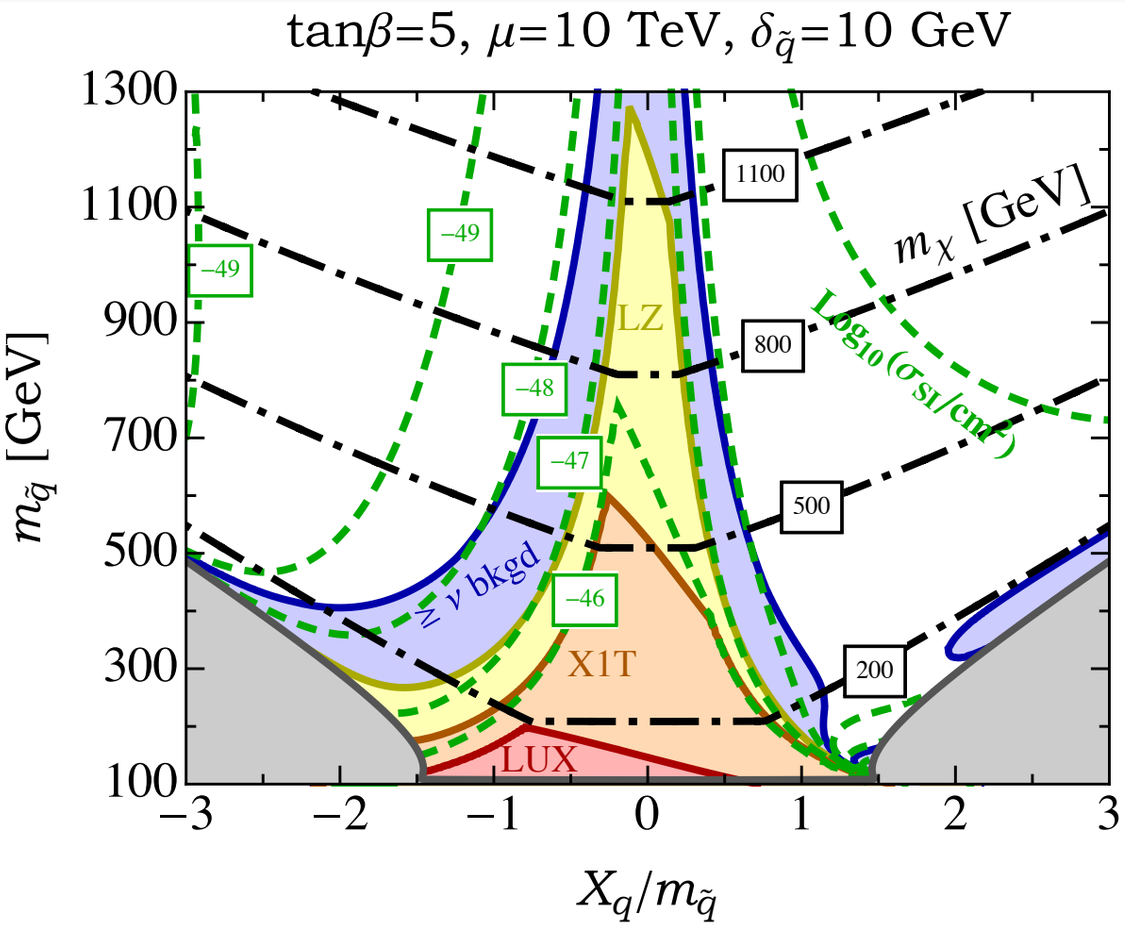


$$m_{\tilde{b}_R} \gg m_{\tilde{Q}_3}, m_{\tilde{t}_R} \ , \ m_{\tilde{Q}_3} \neq m_{\tilde{t}_R}$$

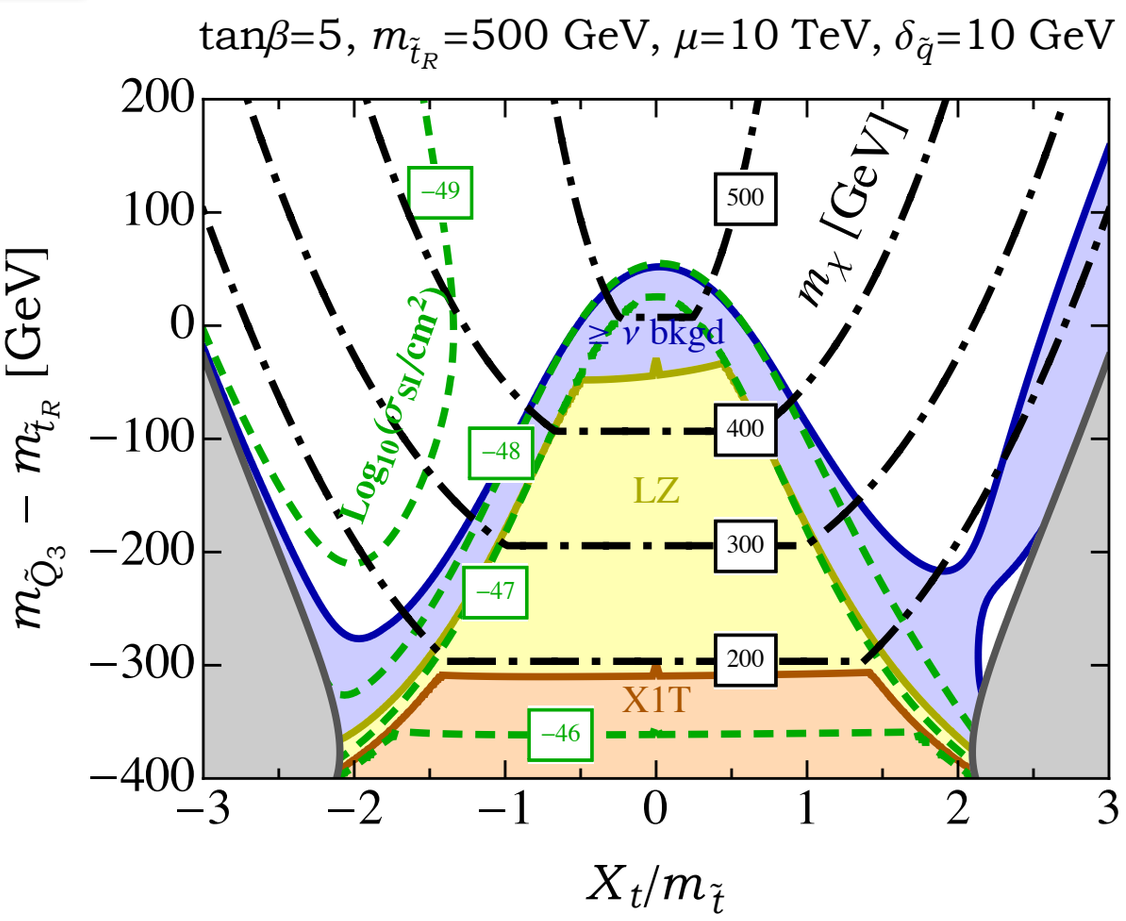


Bino + Mixed Squarks

$$m_{\tilde{q}} \equiv m_{\tilde{Q}_3} = m_{\tilde{t}_R} = m_{\tilde{b}_R} \ , \ X_q \equiv X_t = X_b$$

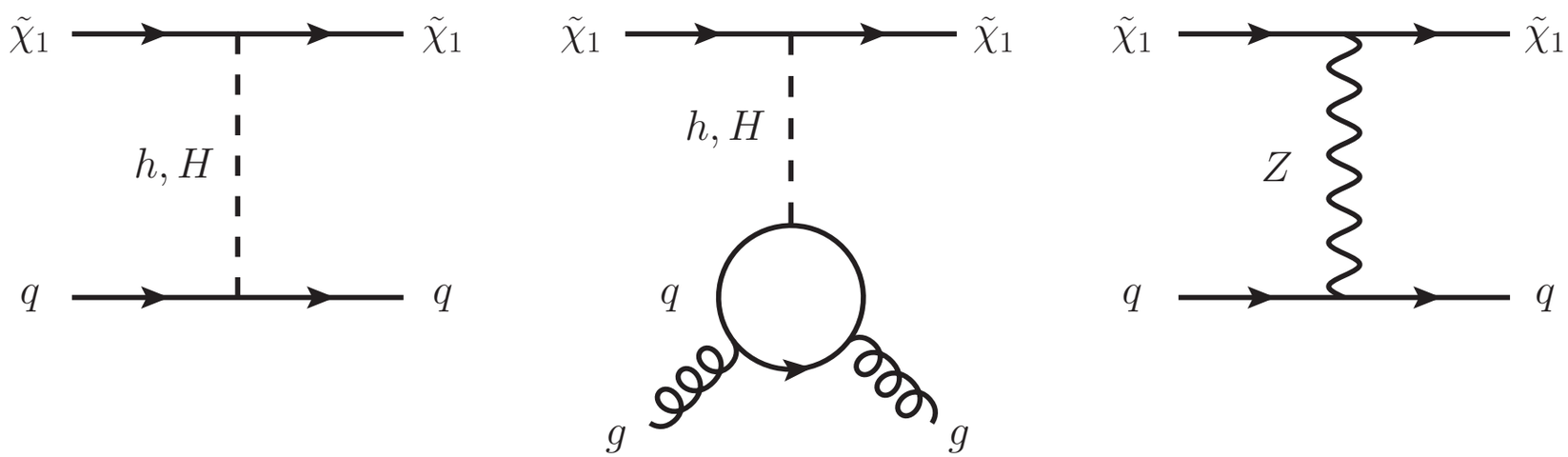


$$m_{\tilde{b}_R} \gg m_{\tilde{Q}_3}, m_{\tilde{t}_R} \ , \ m_{\tilde{Q}_3} \neq m_{\tilde{t}_R}$$

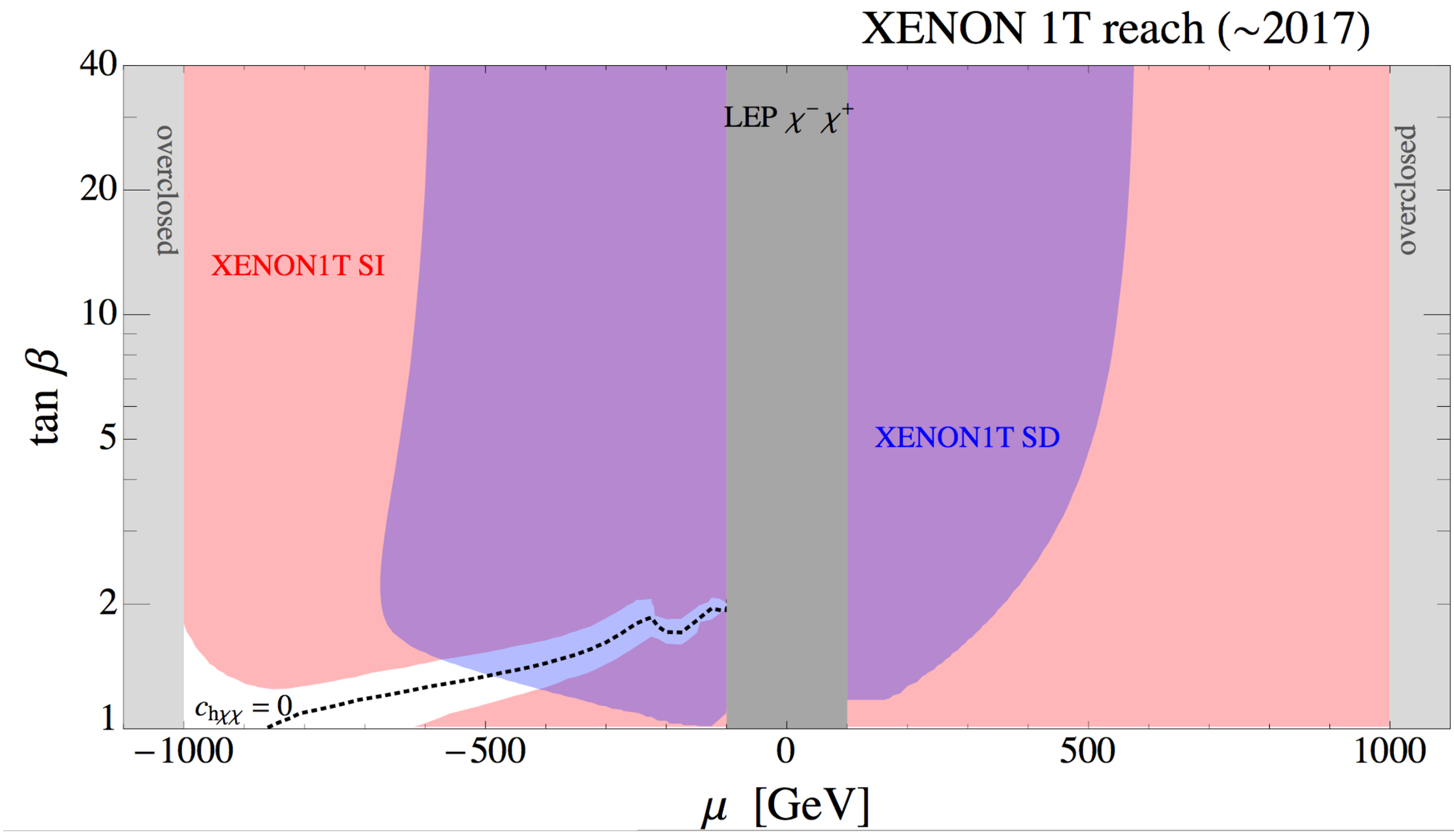


Mixing generally doesn't help

Blind-Spots at LO

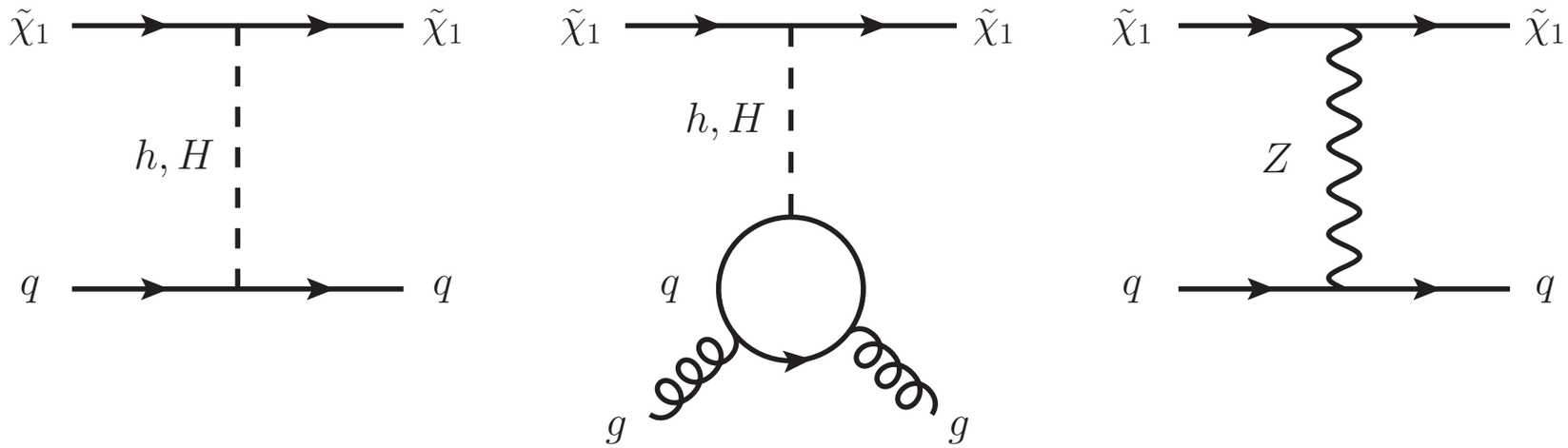


Standard Model Blind-Spot

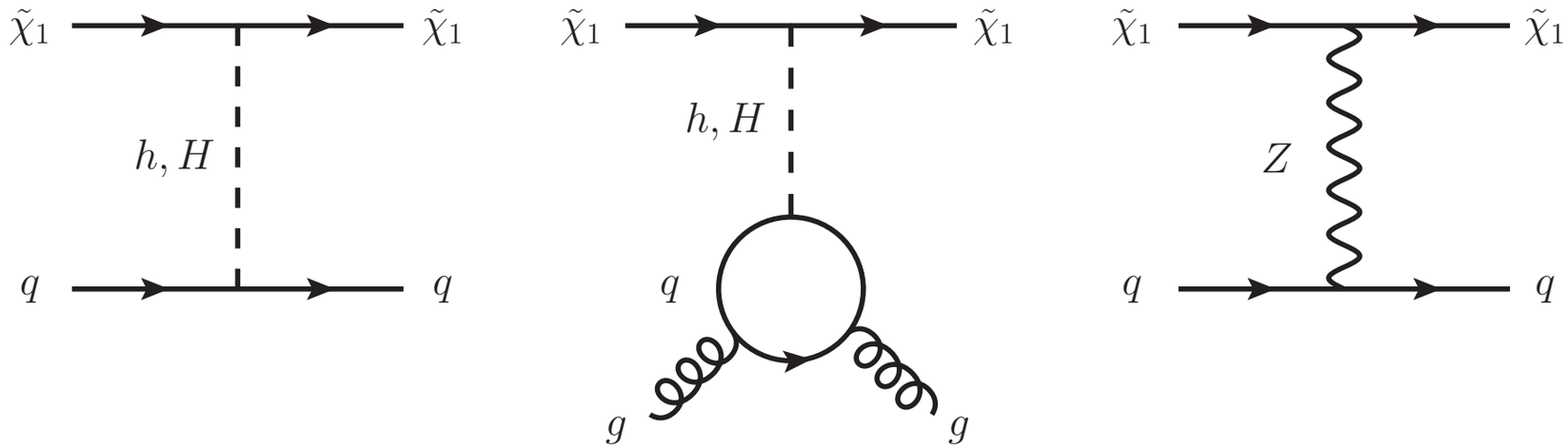


Cheung, Hall, Pinner, Ruderman, arXiv:1211.4873

Generalized Blind-Spot

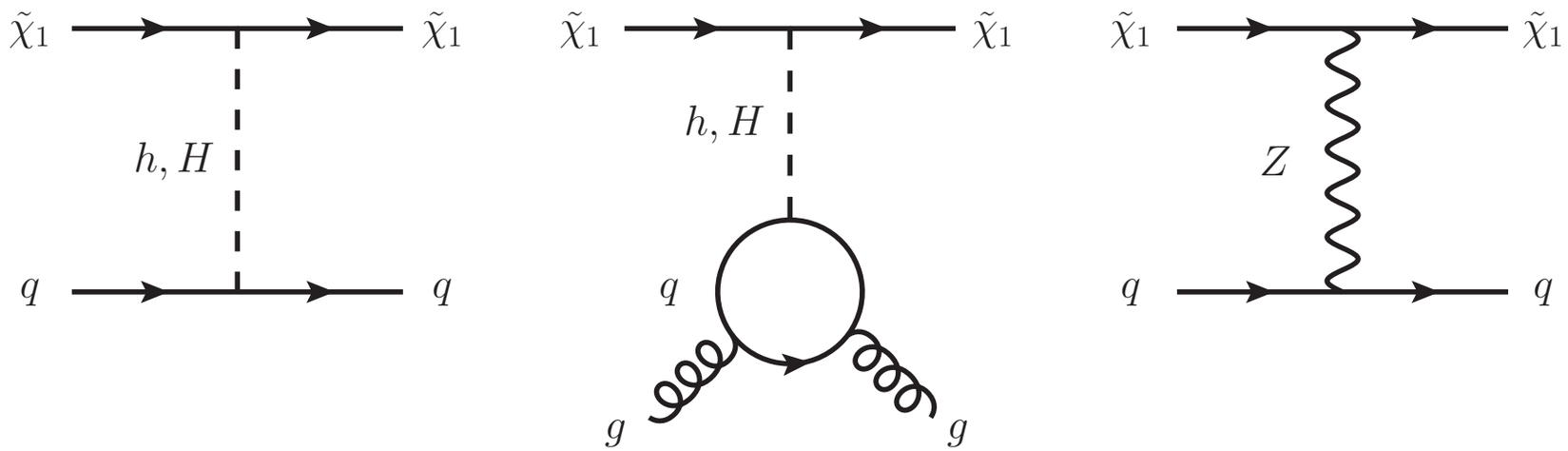


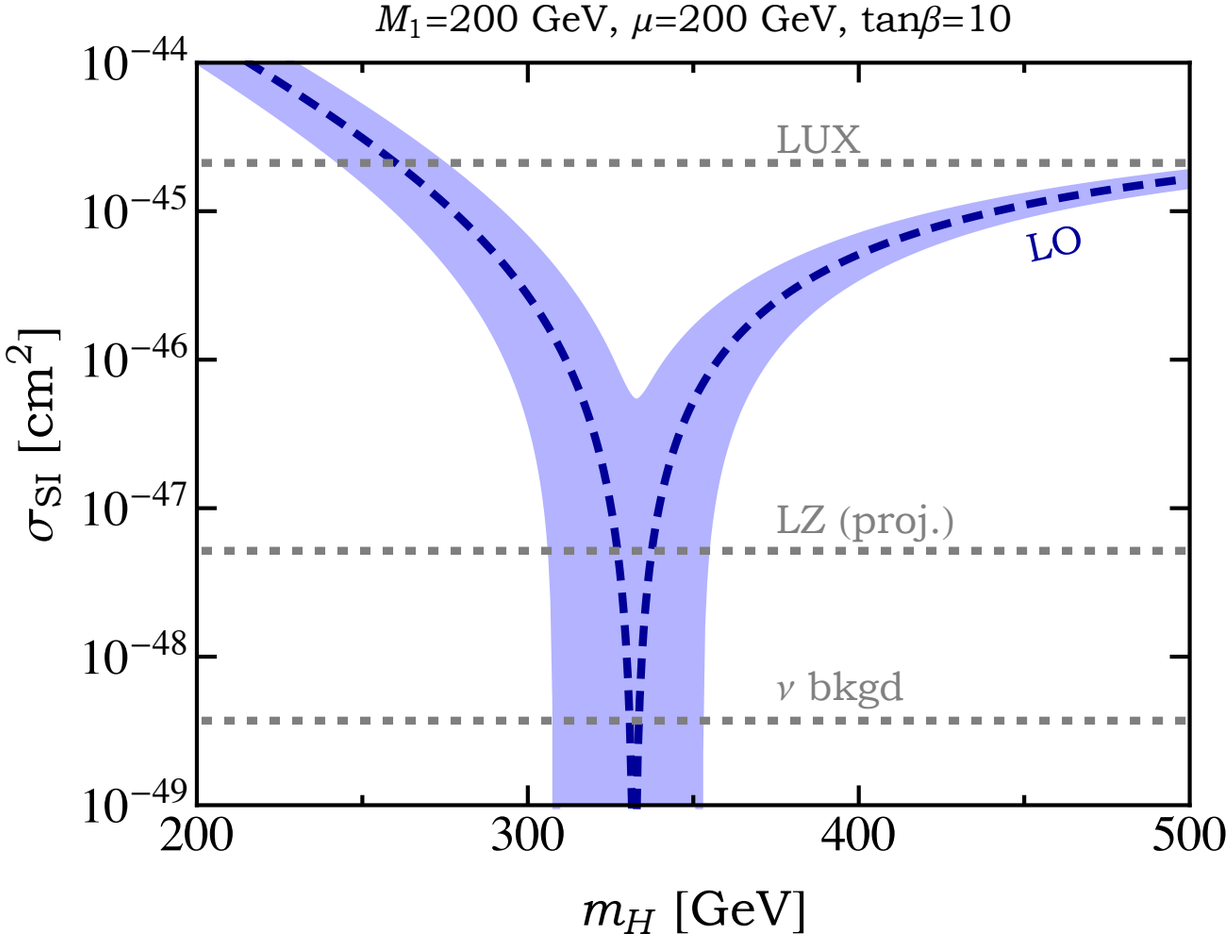
Generalized Blind-Spot



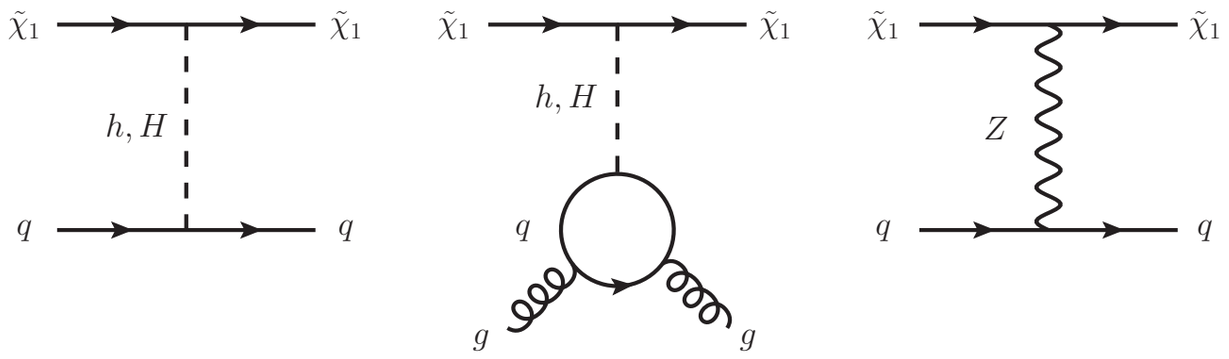
In progress with Carlos Wagner

Generalized Blind-Spot

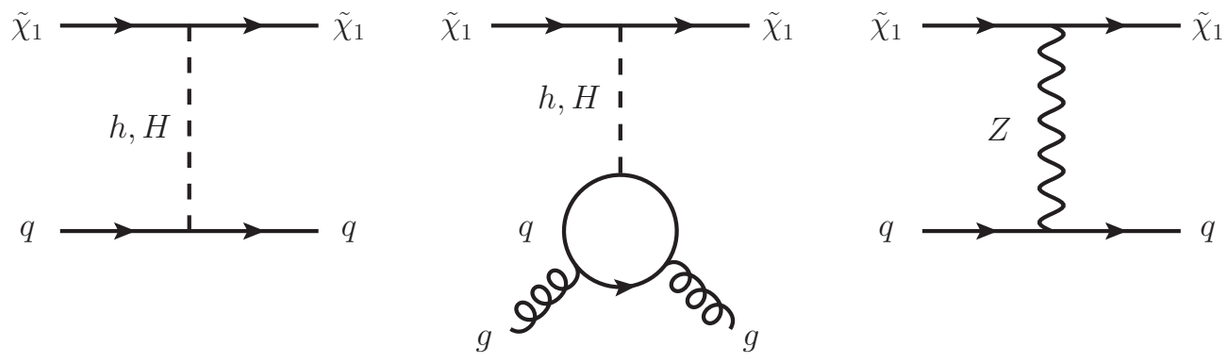


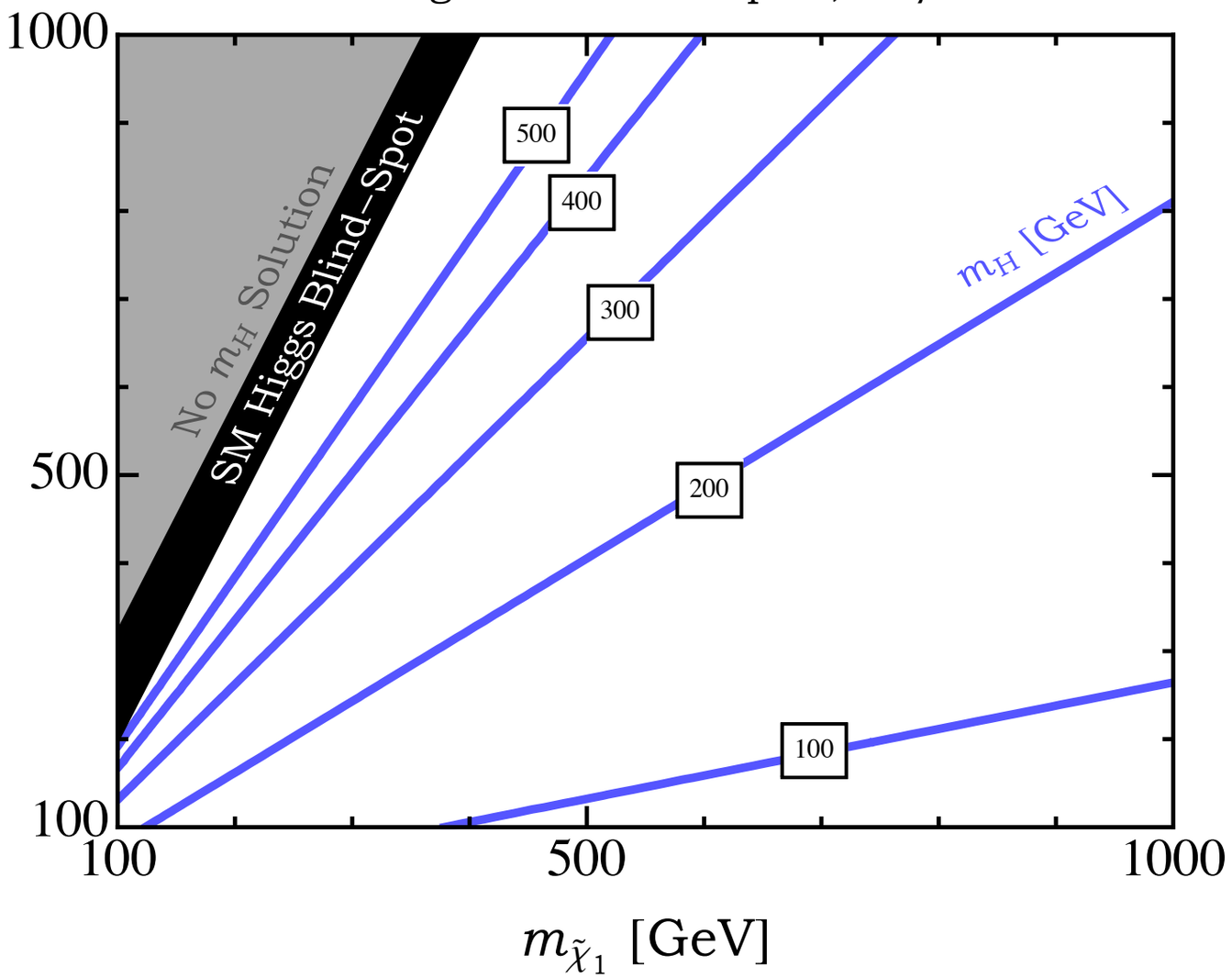


Blind-Spots

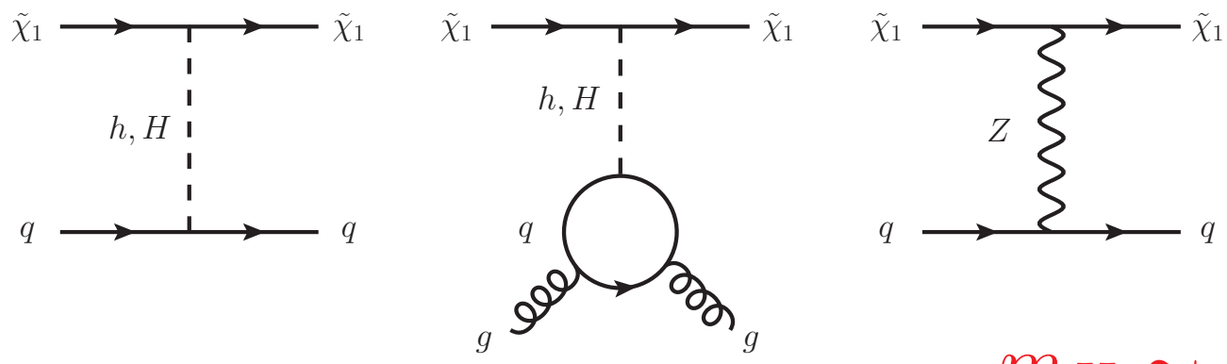

$\tilde{\chi}_1$
$\tilde{\chi}_1$
h, H
q
q
$\tilde{\chi}_1$
$\tilde{\chi}_1$
h, H
q
g
g
$\tilde{\chi}_1$
$\tilde{\chi}_1$
Z
q
q

Blind-Spots

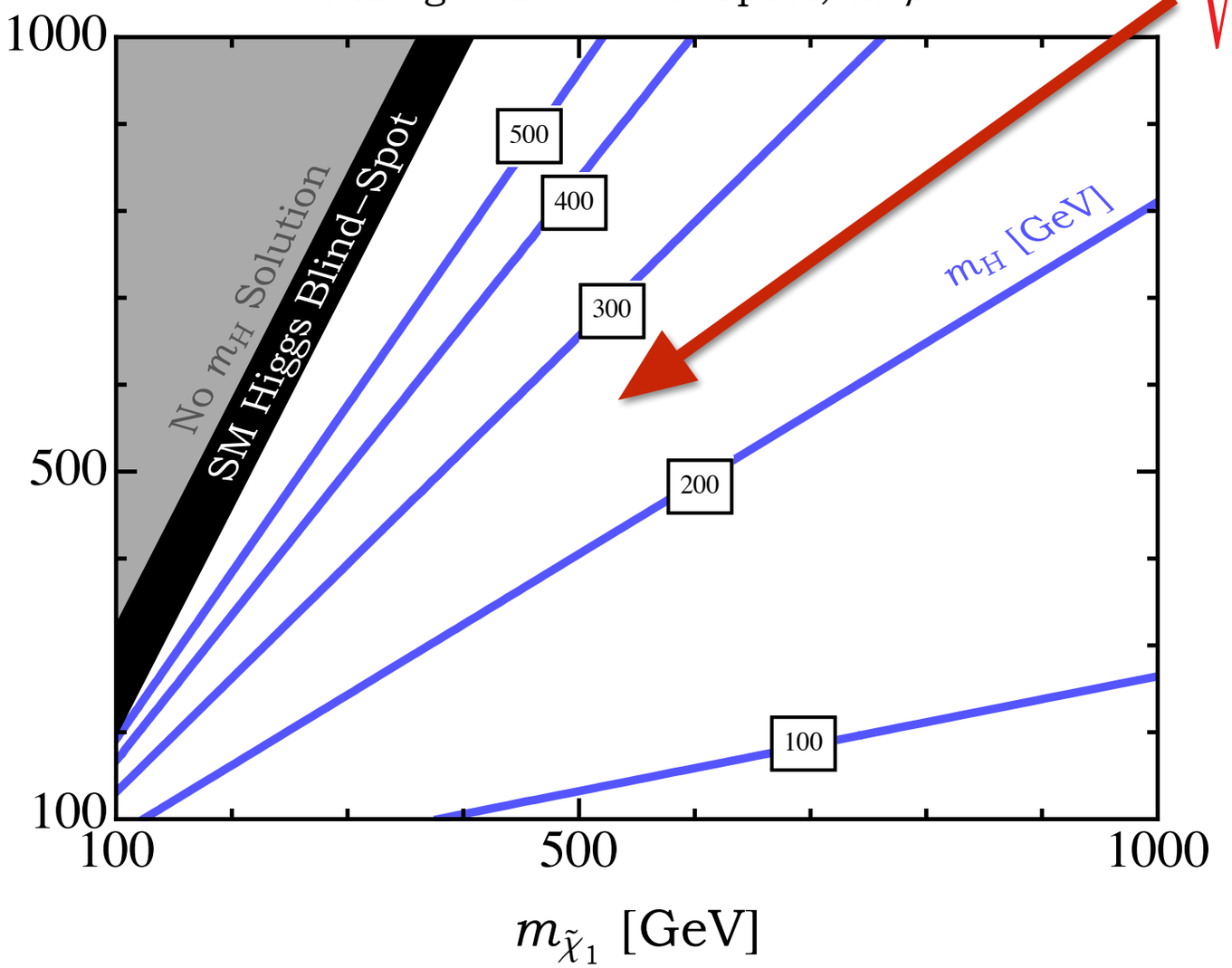

$\tilde{\chi}_1$
$\tilde{\chi}_1$
h, H
q
q
$\tilde{\chi}_1$
$\tilde{\chi}_1$
h, H
q
g
g
$\tilde{\chi}_1$
$\tilde{\chi}_1$
Z
q
q


Leading Order Blind–Spots, tanβ=5
1000
500
100
100
500
1000
μ [GeV]
$m_{\tilde{\chi}_1}$ [GeV]
No m_H Solution
SM Higgs Blind–Spot
500
400
300
200
100
m_H [GeV]

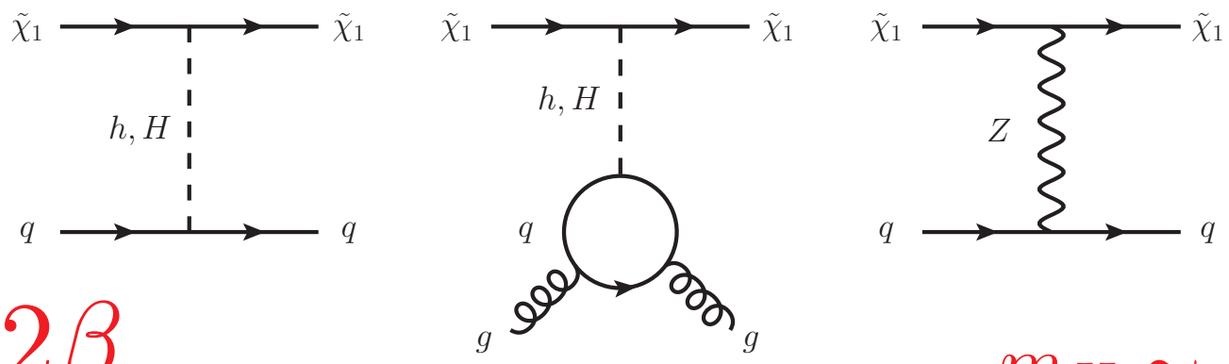
Blind-Spots



$$m_H \sim \sqrt{\frac{\mu \tan\beta}{m_{\tilde{\chi}_1}}} \times 100 \text{ GeV}$$

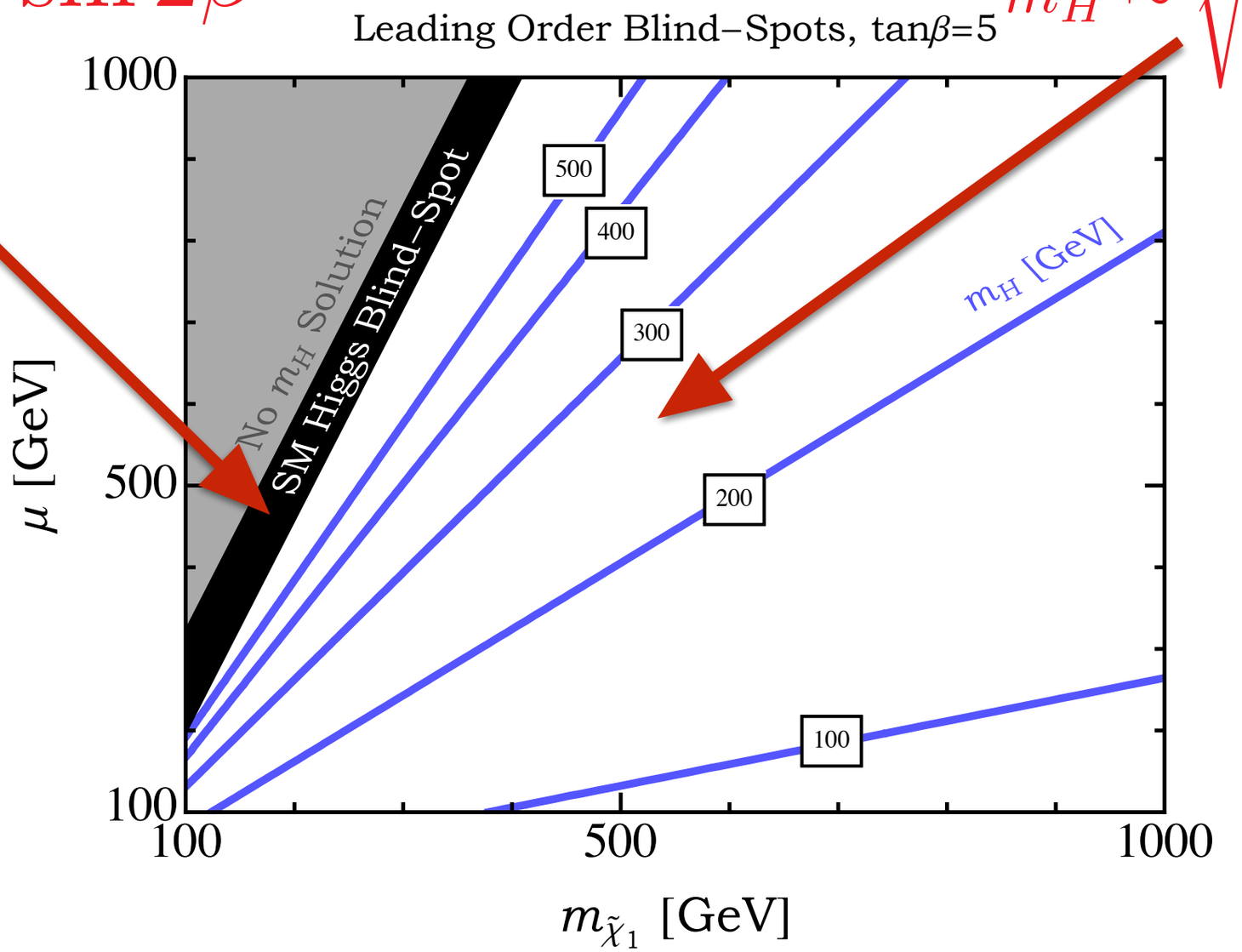


Blind-Spots

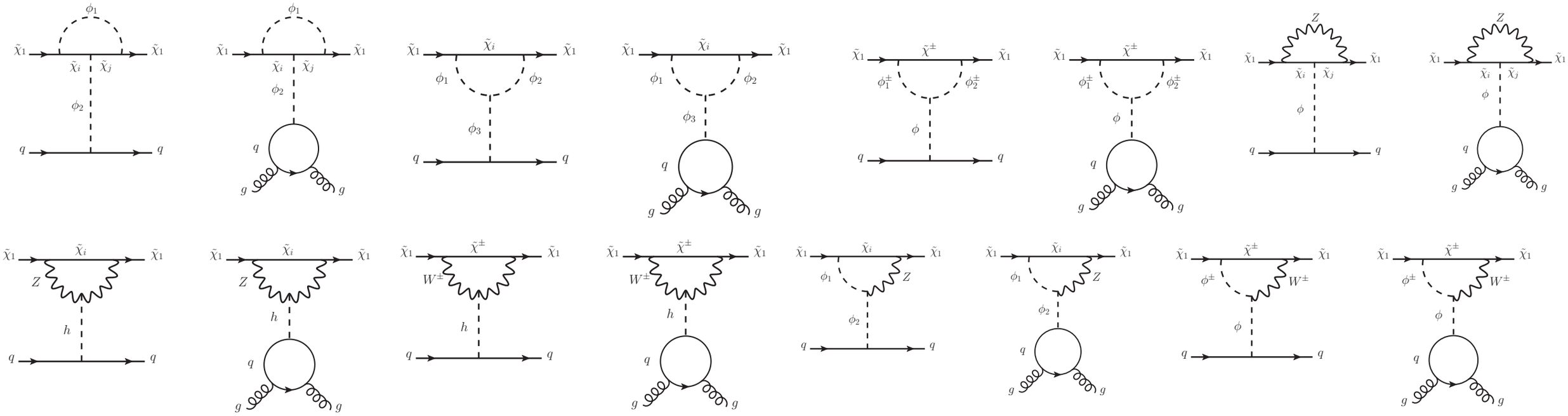


$$m_{\tilde{\chi}_1} = \mu \sin 2\beta$$

$$m_H \sim \sqrt{\frac{\mu \tan\beta}{m_{\tilde{\chi}_1}}} \times 100 \text{ GeV}$$



Blind-Spots at NLO



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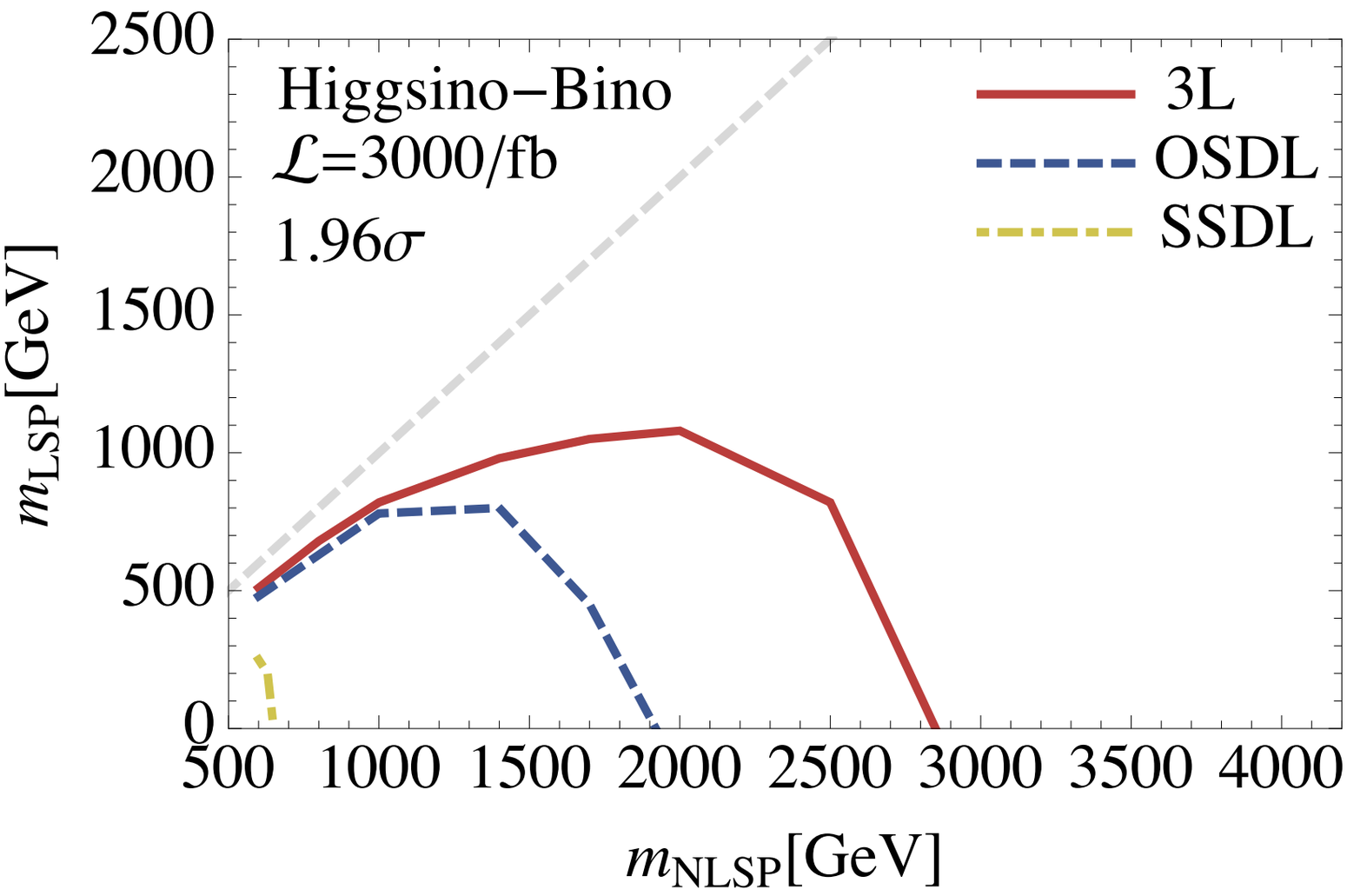
Tri-Lepton @ 100 TeV



Gori, Jung, Wang, Wells arXiv:1410.6287

Ways Out

- Spin-Dependent
- Pseudoscalars
- Resonance Freeze-Out
- Purity
- Co-Annihilation Freeze-Out
- Blind-Spots
- Inelasticity
- Sub-GeV
- Isospin Violation
- Hidden Sector
- Luminous Dark Matter

Thank You

Backup Slides

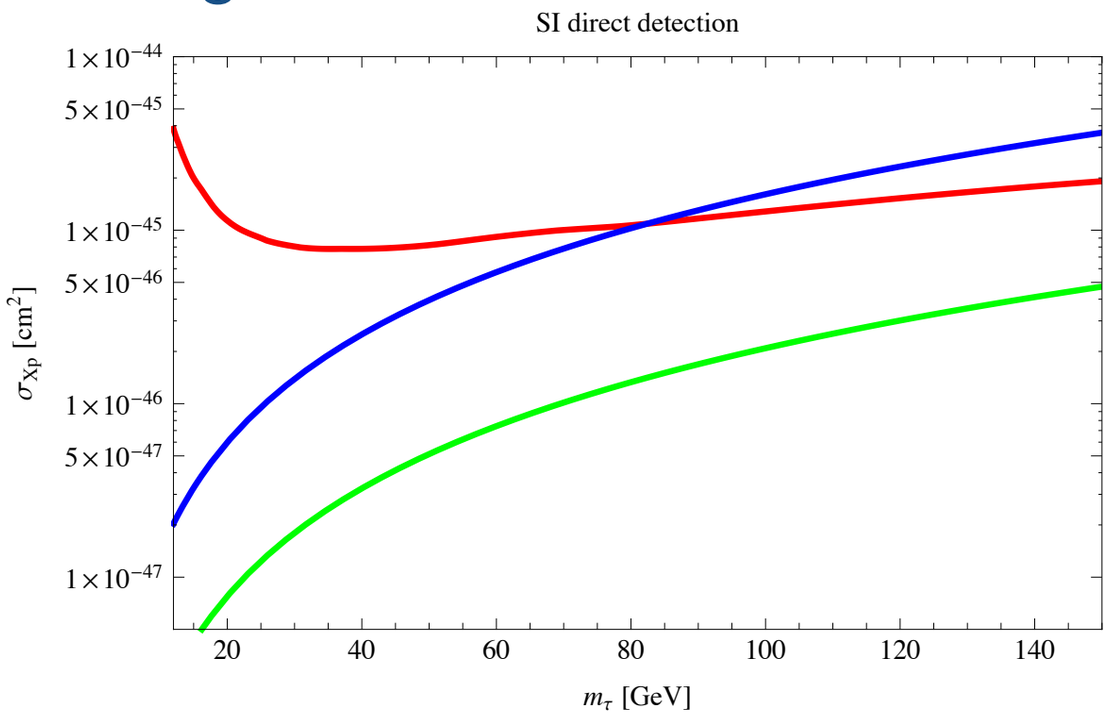
(Not-so-Hidden) Hidden Sector

Fraternal Twin Higgs

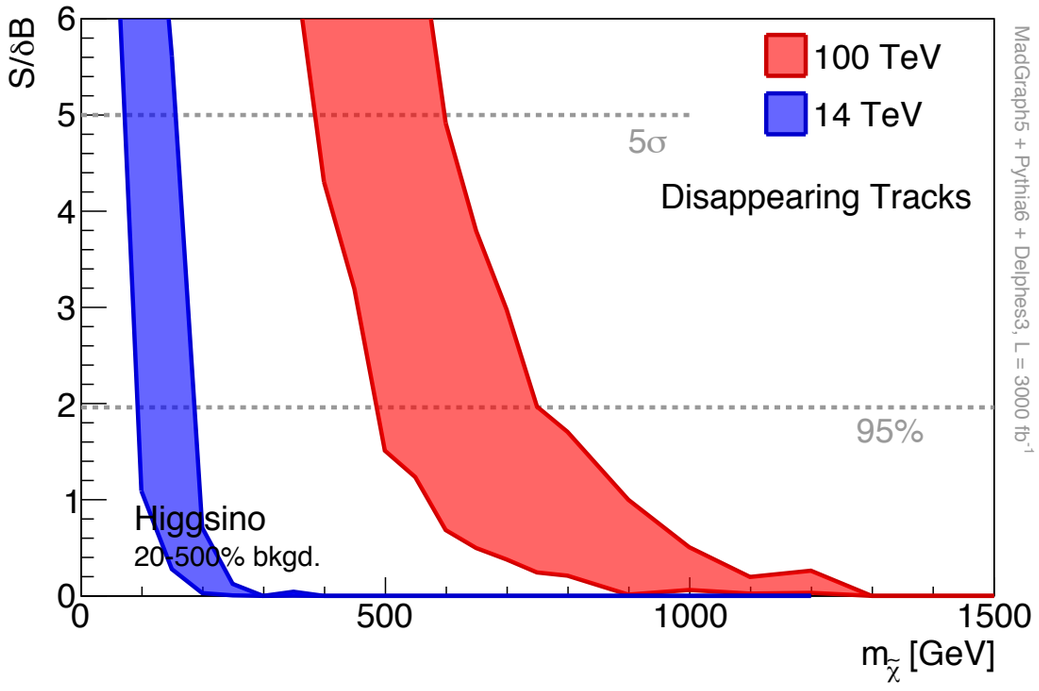
- Although unimportant for naturalness, internal consistency gives rise to twin taus.
- Stabilized by accidental global U(1) (Z_2 of hypercharge).
- Naturalness demands twin weak scale is comparable to SM weak scale. (“Twin WIMP Miracle”)
- Freeze-out via twin weak scale gauge bosons.
- Nucleon scattering via SM-twin Higgs mixing.

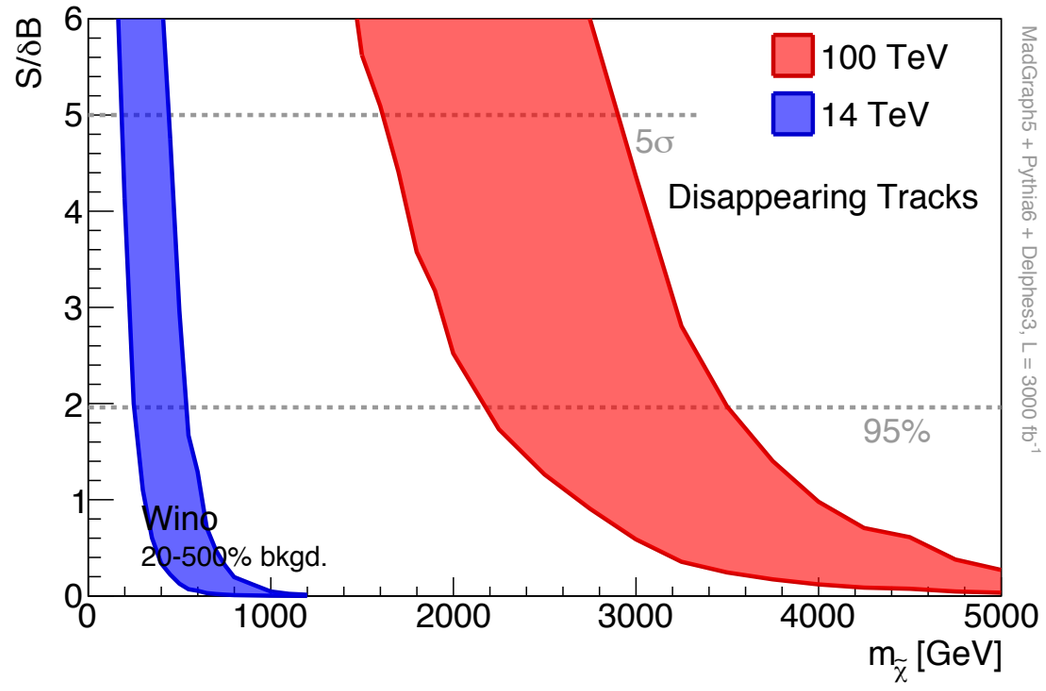
$$\mathcal{L} \supset \frac{m_{\hat{\tau}}}{f} \frac{v}{f} h \, \hat{\tau}\hat{\bar{\tau}} + \text{h.c.}$$

Craig, Katz, arXiv:1505.07113



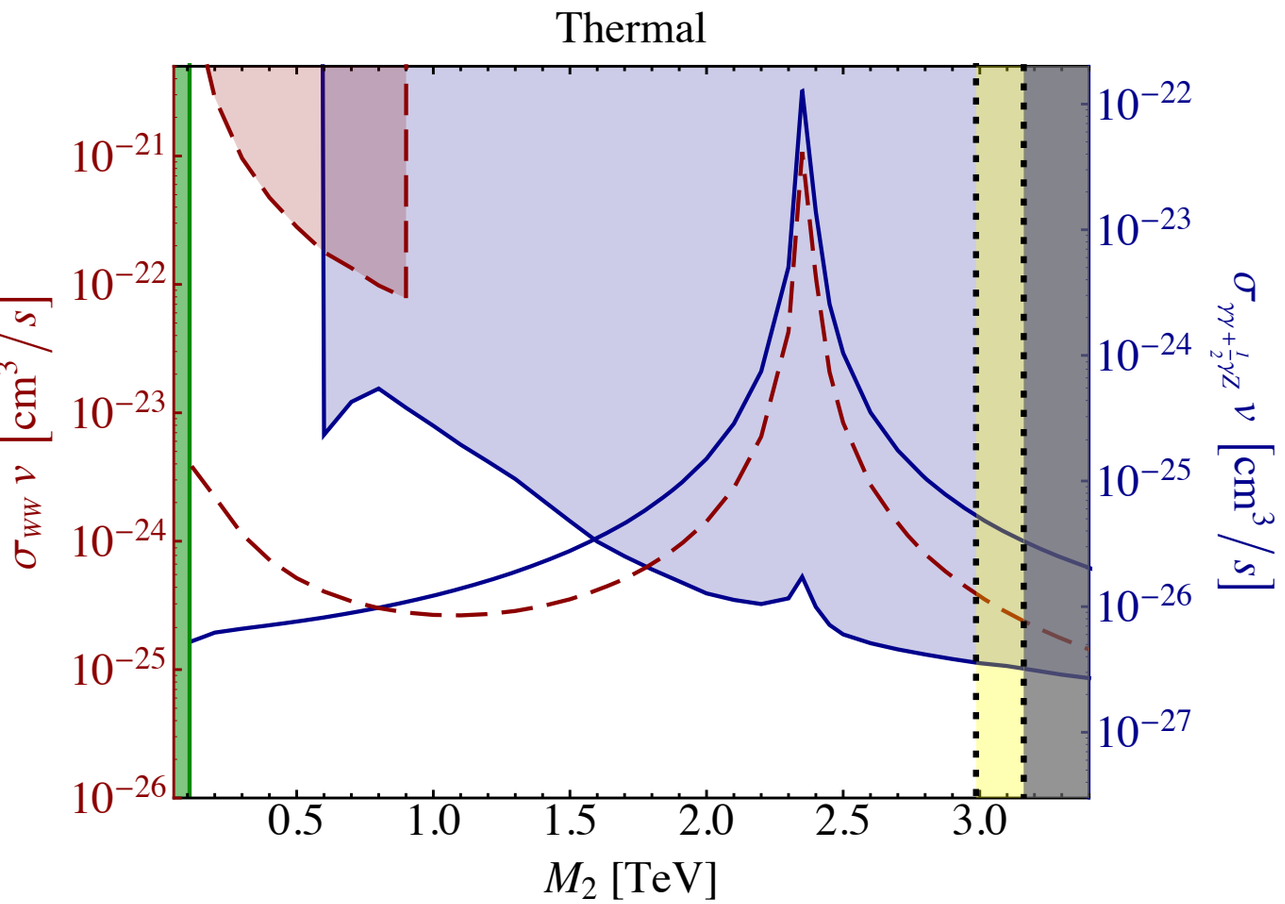
Disappearing Tracks

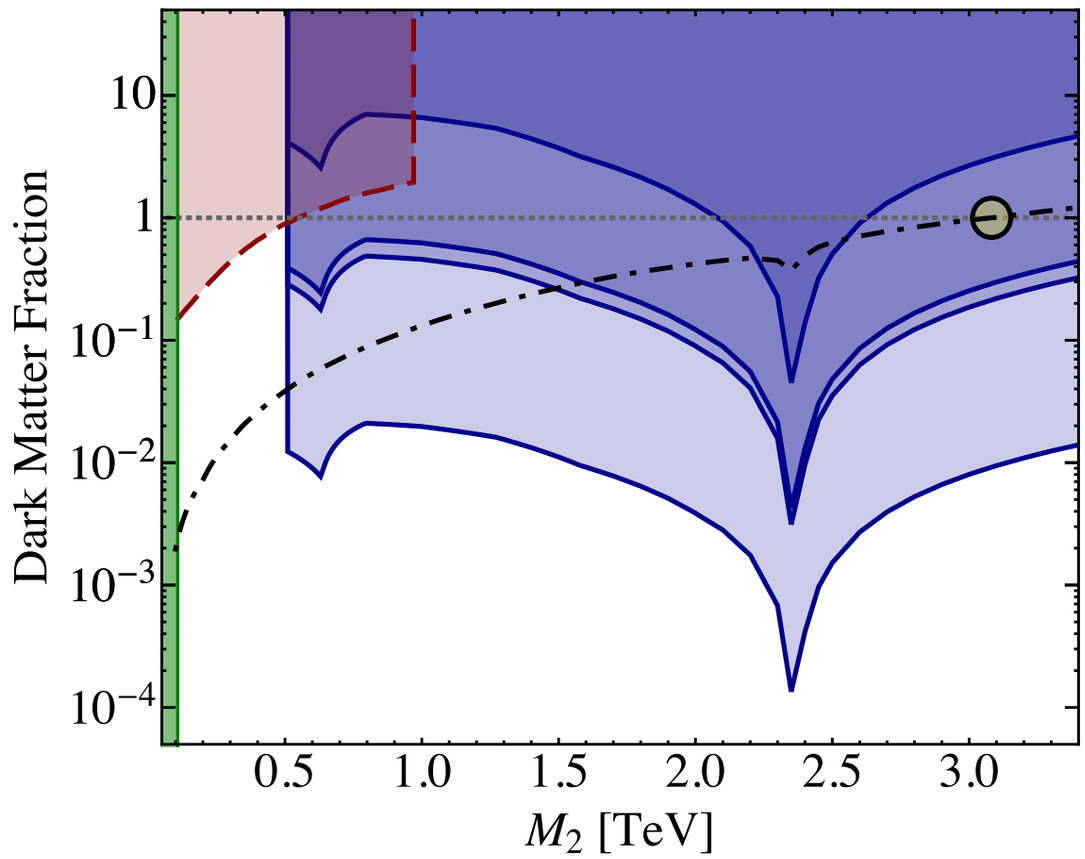




Low, Wang, arXiv:1404.0682

Wino Annihilation





Cohen, Lisanti, Pierce, Slatyer arXiv:1307.4082