Effects of QCD bound states on DM relic abundance

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Consider
R-parity conserving Minimal Supersymmetric Standard Model (MSSM)

Consider the R-odd lightest SUSY particle (LSP) as the lightest neutralino χ_1 and is the dark matter.

* note that our results presented here are not limited to scenarios in SUSY.

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$$\frac{dn_1}{dt} + 3Hn_1 = -\langle \sigma v \rangle_{11} (n_1^2 - {n_1^{eq}}^2)$$

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Consider bino.

bino is gauge singlet coupled only to sfermions and higgsinos

usually pure bino is overproduced

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Consider the R-odd lightest SUSY particle (LSP) as the lightest neutralino χ_1 and is the dark matter.

Consider χ_1 produced thermally.

Consider LSP coannihilating with an almost mass-degenerate R-odd SUSY particle χ_2 (not necessarily the second lightest neutralino). **Coannihilation** becomes vital.

How coannihilation works?

[Griest, Seckel '91]

conditions:

χ_2 has large annihilation cross section with *itself* or χ_1

$$\chi_2\chi_2 \leftrightarrow SMSM \qquad \chi_2\chi_1 \leftrightarrow SMSM$$

χ_2 can convert to χ_1 efficiently.

$$\chi_2 SM \leftrightarrow \chi_1 SM$$

Then, χ_1 freezes out together with χ_2 with a much smaller relic abundance

Boltzmann equations

assuming fast conversion $\chi_2 SM \leftrightarrow \chi_1 SM$

defining $n \equiv n_1 + n_2$

$$\frac{dn}{dt} + 3Hn = -\boxed{\sum_{i,j=1}^{2} \langle \sigma v \rangle_{ij \to SM} \frac{n_i^{eq} n_j^{eq}}{n_{eq}^2}} \left(n^2 - n_{eq}^2\right)$$

call this $\langle \sigma v \rangle_{\text{eff}}$

(note that χ_2 eventually decays to χ_1 .

So n is equivalent to the DM number density)

compare with $$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle_{\chi\chi \to SM} \left(n_\chi^2 - n_\chi^{eq\,2} \right)$$

without coannihilation

$$\frac{dn}{dt} + 3Hn = -\sum_{i,j=1}^{2} \langle \sigma v \rangle_{ij \to SM} \frac{n_i^{eq} n_j^{eq}}{n_{eq}^2} \left(n^2 - n_{eq}^2\right)$$

call this $\langle \sigma v \rangle_{\rm eff}$

Two limits

$m_2 \gg m_1$: $\langle \sigma v \rangle_{\rm eff} \simeq \langle \sigma v \rangle_{11 \to SM}$

$m_2 = m_1$: $\langle \sigma v \rangle_{\rm eff} = \dfrac{g_1^2 \langle \sigma v \rangle_{11 \to SM} + g_2^2 \langle \sigma v \rangle_{22 \to SM} + 2 g_1 g_2 \langle \sigma v \rangle_{12 \to SM}}{(g_1 + g_2)^2}$

note that $n_i^{eq} = g_i \left(m_i T / 2\pi\right)^{3/2} e^{-m_i/T}$

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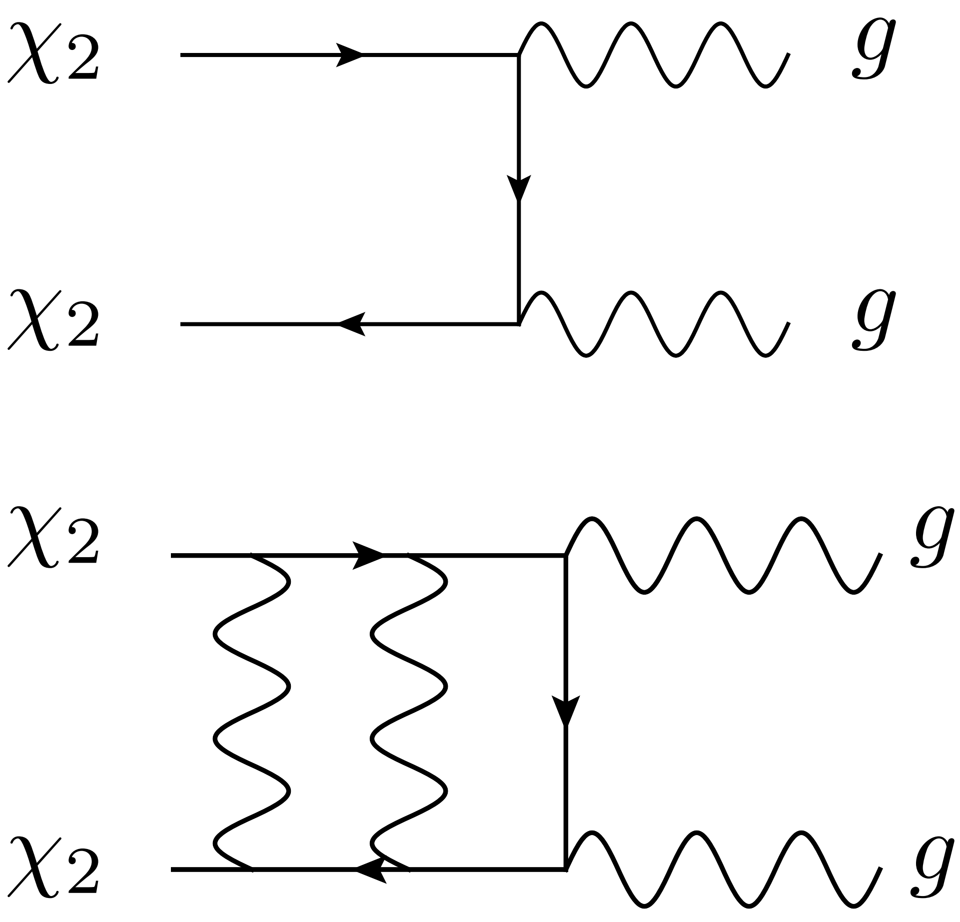
note that even DM has zero self annihilation cross section, its relic abundance can be reduced due to the (co-)annihilation of the partner particle as long as the mass difference is small!

If χ_2 is colored (squark or gluino in MSSM)
QCD Sommerfeld effect is important



tree-level annihilation

non-perturbative (Sommerfeld) effect that modifies the initial-state wave function

see e.g. [De Simone et al.'14]

If χ_2 is colored (squark or gluino in MSSM) formation of QCD bound state of χ_2 could be important as well

$\tilde{g}\tilde{g} \leftrightarrow \tilde{R}g,\ \tilde{R} \leftrightarrow gg$ for gluino [Ellis et al.'15]

$\tilde{t}\tilde{t}^* \leftrightarrow \tilde{\eta}g, \tilde{\eta} \leftrightarrow gg$ for stop

Compare recombination process $e^- p \leftrightarrow H\gamma$

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Compare recombination process $e^- p \leftrightarrow H\gamma$

for a pair of stops,

$$\tilde{t}\tilde{t}^* \leftrightarrow \tilde{\eta}g$$

$$8 = 1 \otimes 8$$

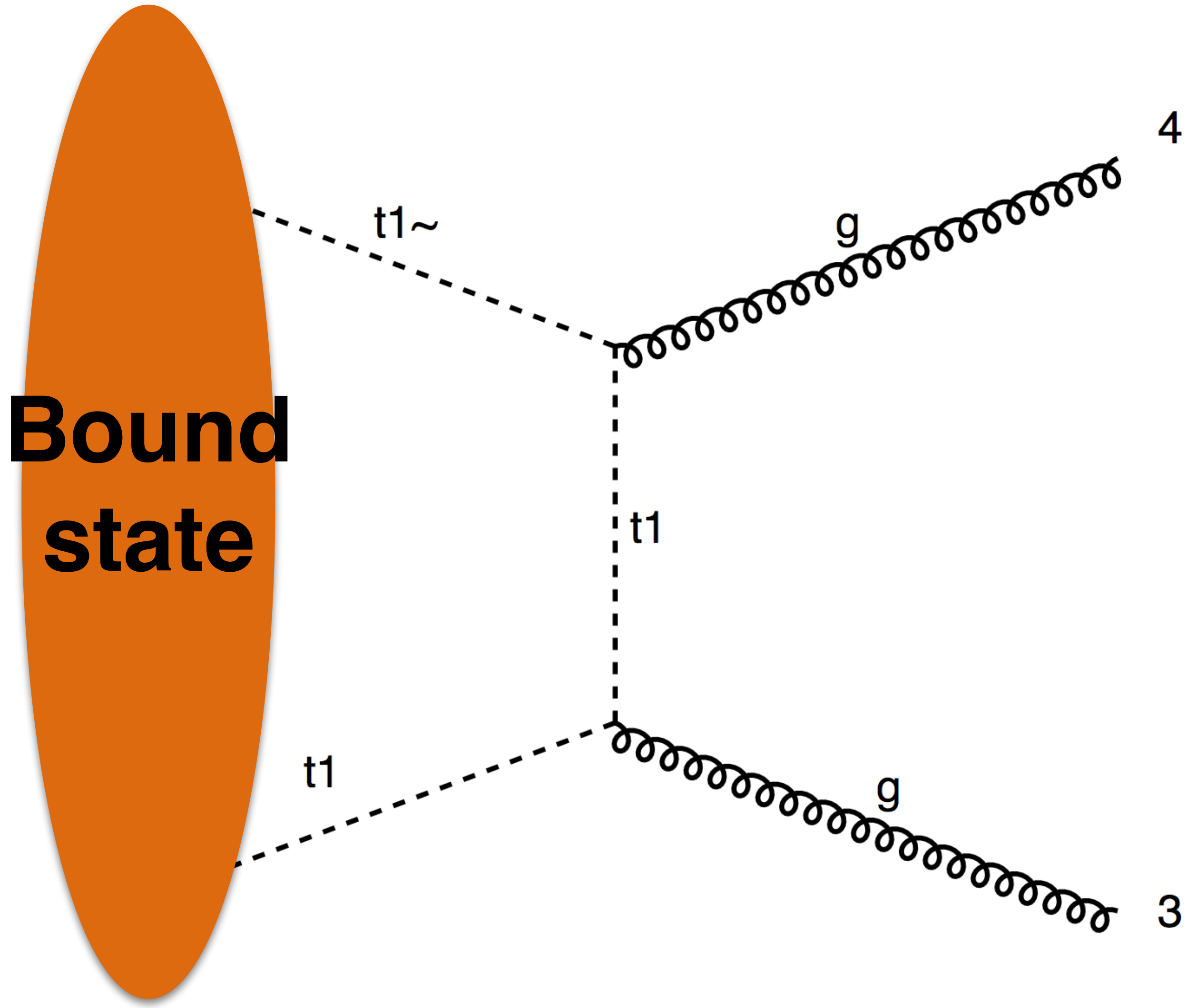
the potential of the stop pair is repulsive prior to forming a bound state

note that bound state annihilation removes 2 R-odd particles, thus helps reducing DM density

(because DM is R-odd)

gluino bound state $\tilde{R} \leftrightarrow gg$

stop bound state $\tilde{\eta} \leftrightarrow gg$



Effectively, the Boltzmann equation is modified by adding the following terms:

$$\frac{dn}{dt} + 3Hn \simeq -\sum_{i,j=1}^{2} \langle \sigma v \rangle_{ij \to SM} \frac{n_i^{eq} n_j^{eq}}{n_{eq}^2} \left(n^2 - n_{eq}^2\right)$$

$$-\langle \sigma v \rangle_{XX \to \eta g} \frac{\langle \Gamma \rangle_{\eta \to gg}}{\langle \Gamma \rangle_{\eta \to gg} + \langle \Gamma \rangle_{\eta g \to XX}} \left(n_X^2 - n_X^{eq2}\right)$$

bound state formation rate

bound state annihilation rate

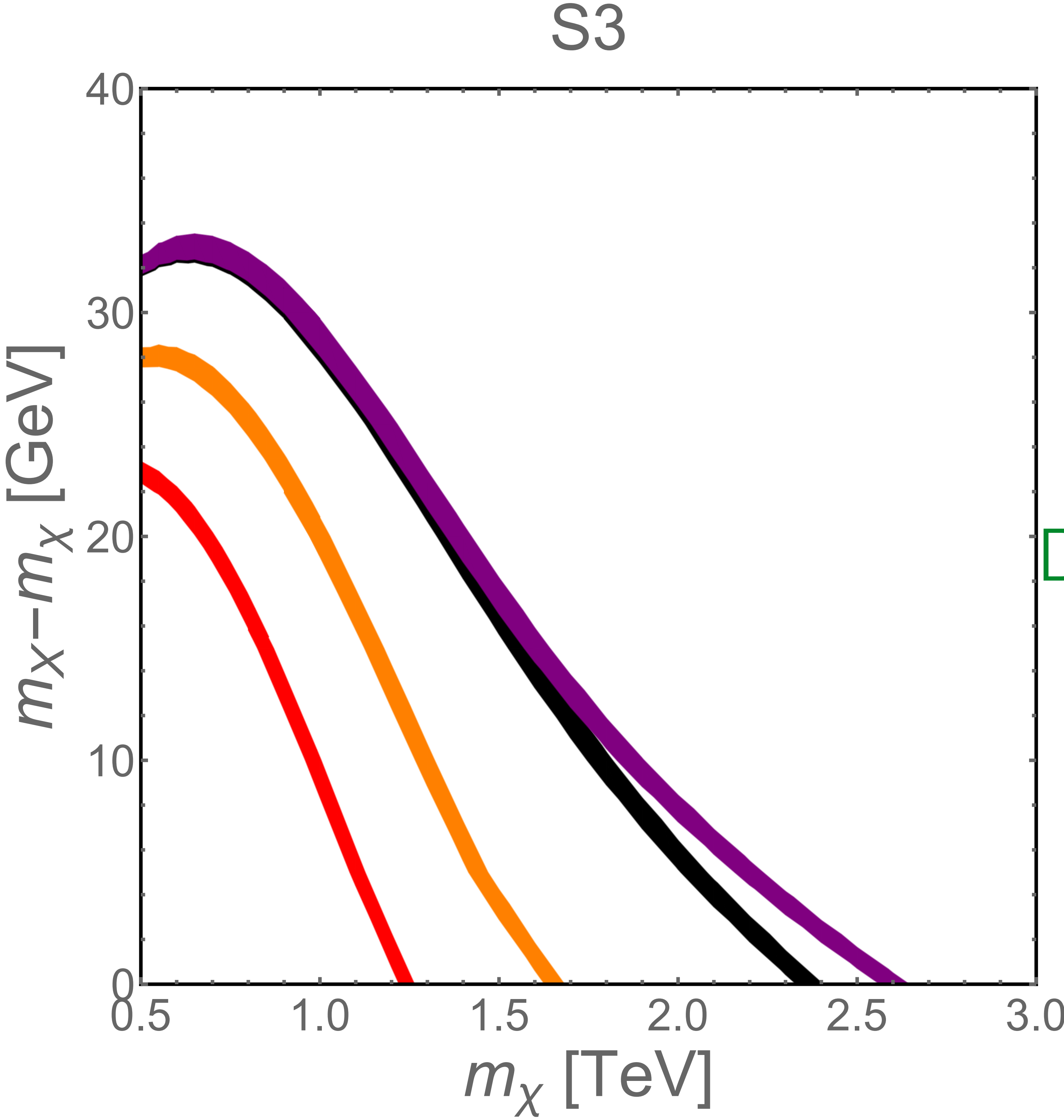
bound state dissociation rate

$\eta g \to XX$ becomes unimportant at low temperature compared to $\eta \to gg$

because gluon is not energetic enough to dissociate the bound state

Scalar triplet (stop) coannihilation

DM-stop mass splitting

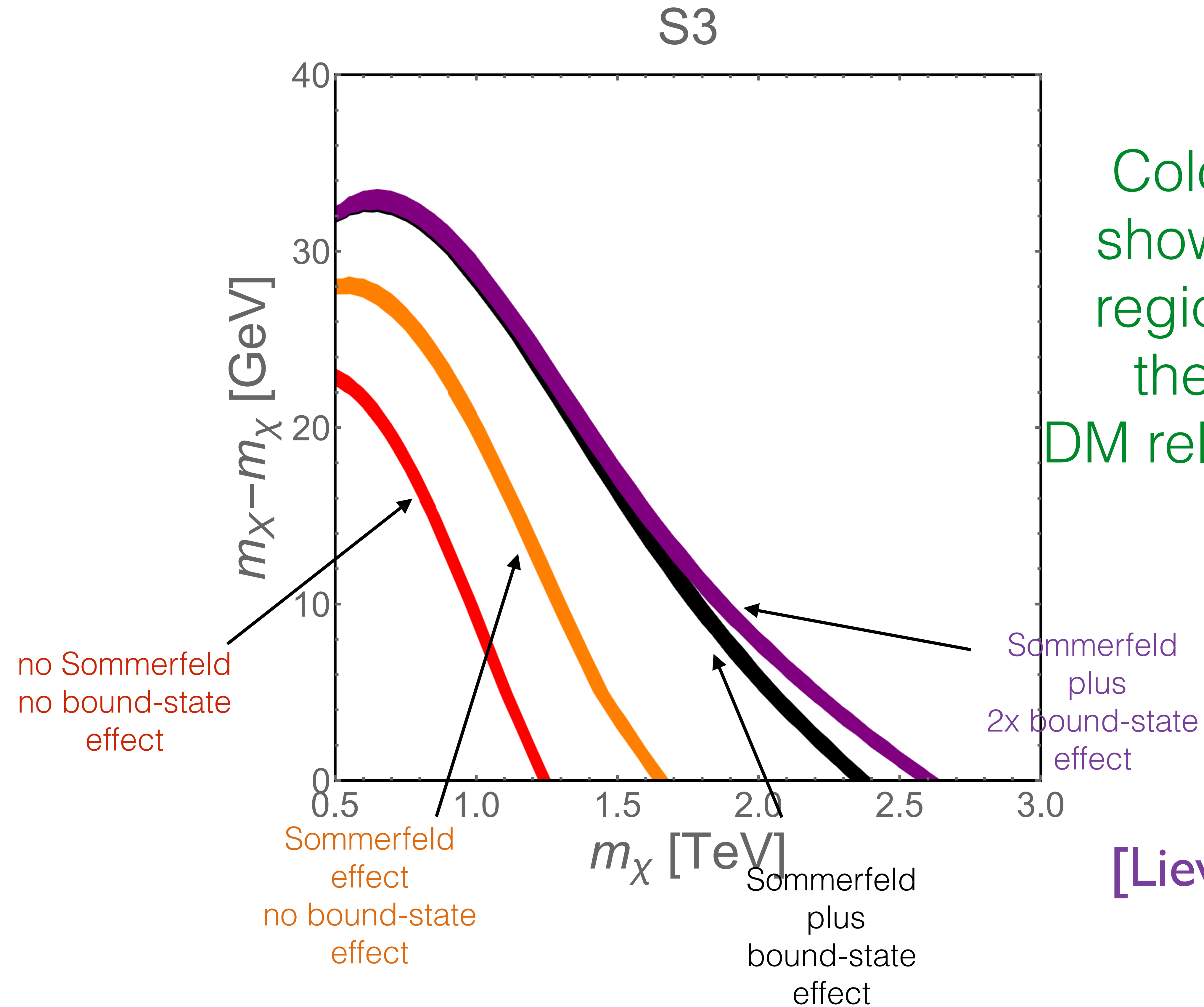


Colored bands show parameter region matching the observed DM relic abundance

DM mass

[Liew, Luo '16]

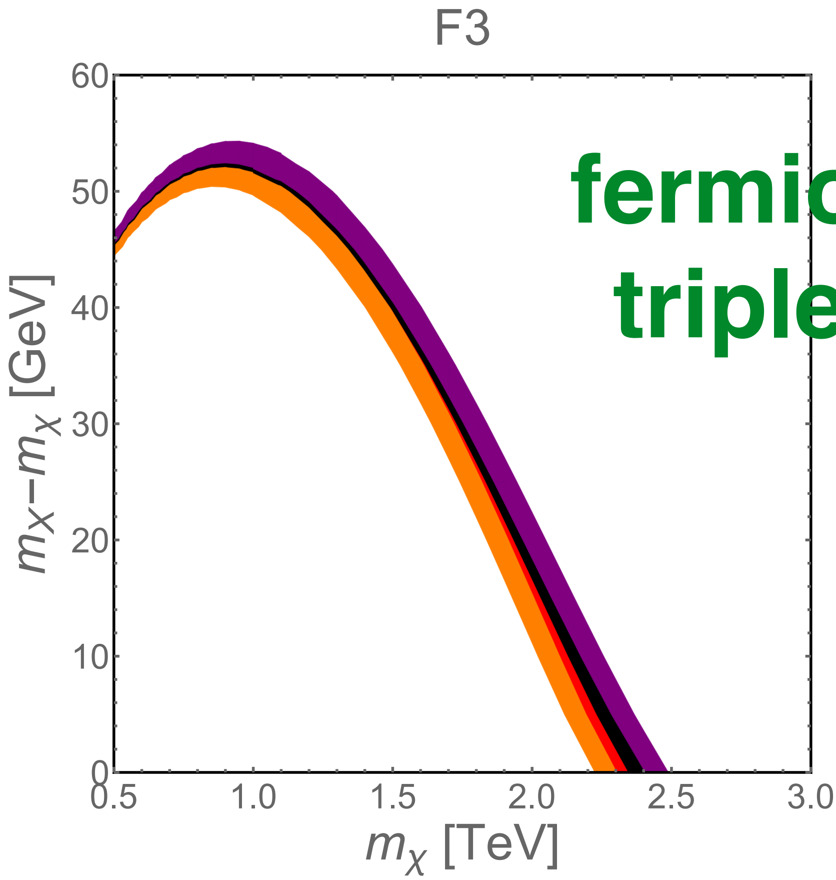
Scalar triplet (stop) coannihilation



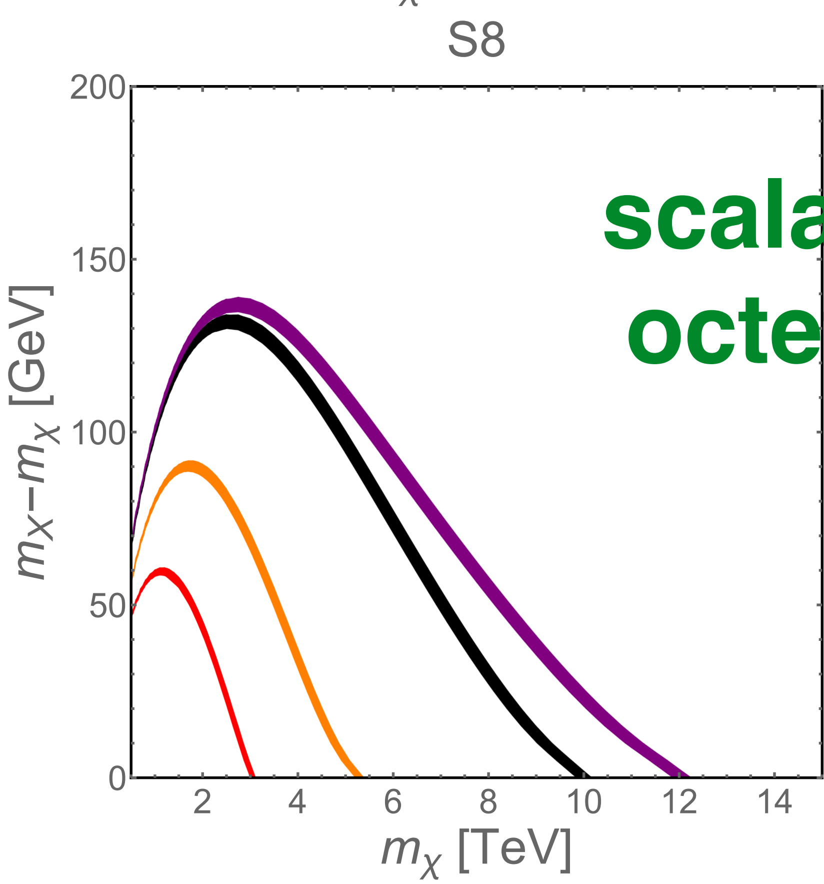
Colored bands show parameter region matching the observed DM relic abundance

[Liew, Luo '16]

Coannihilation with other types of colored particle

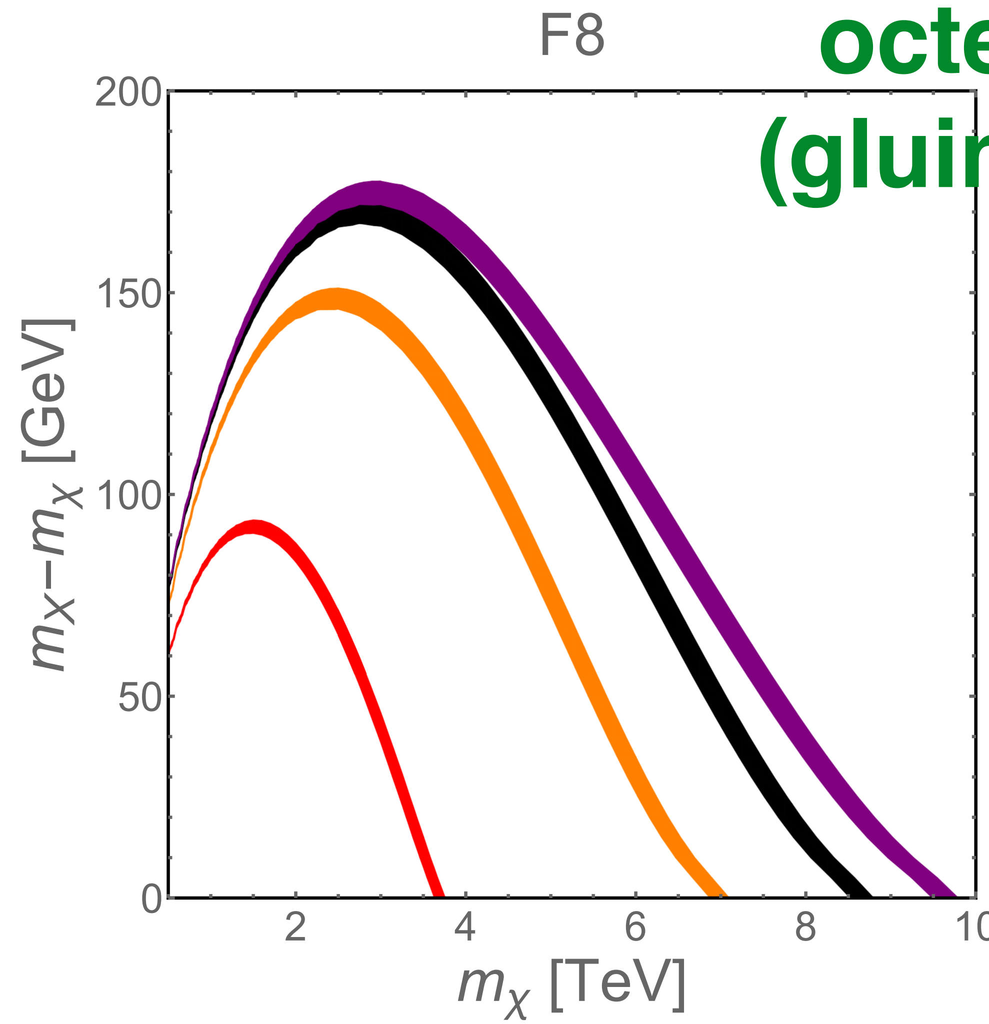


fermion triplet



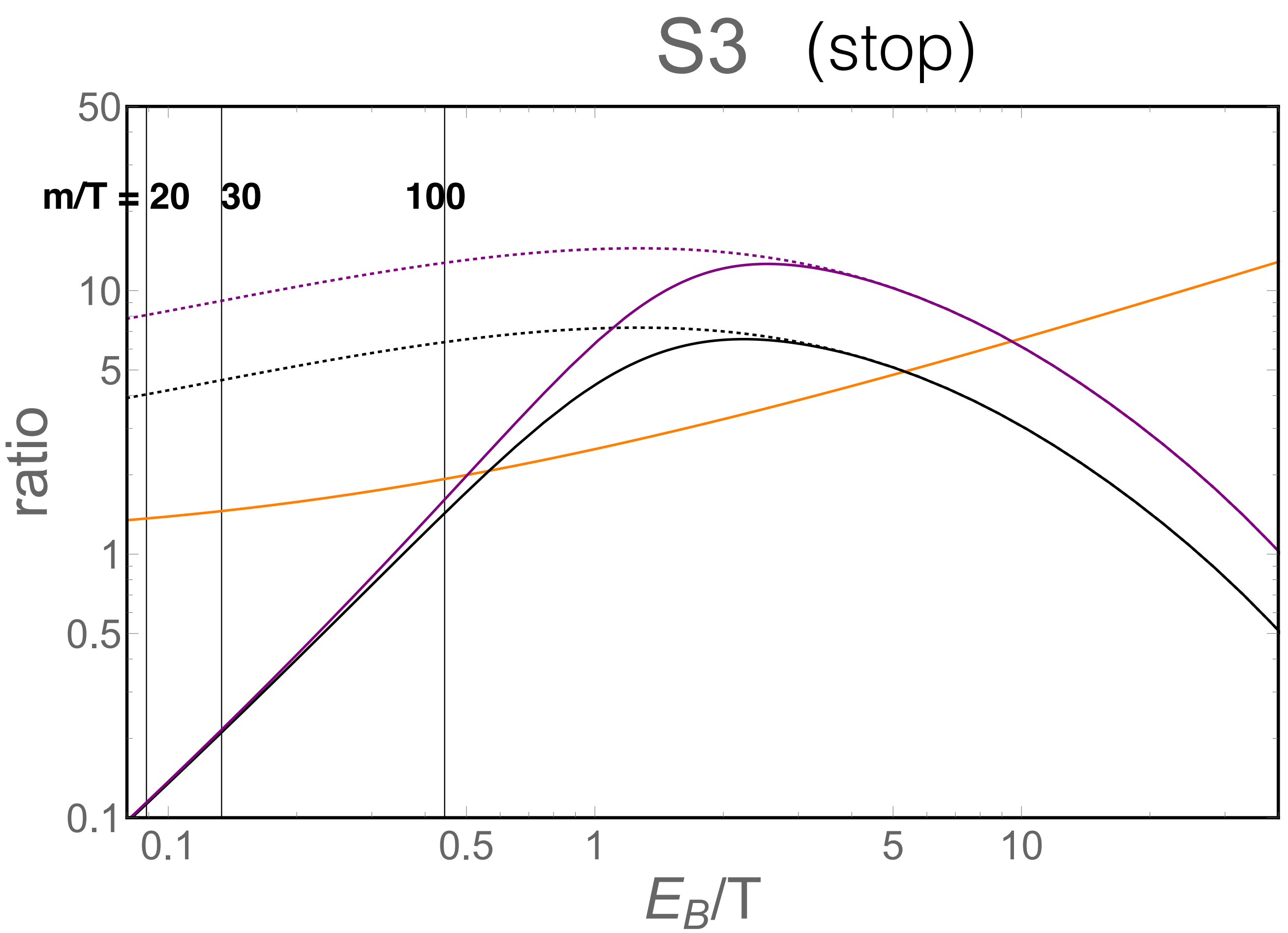
scalar octet

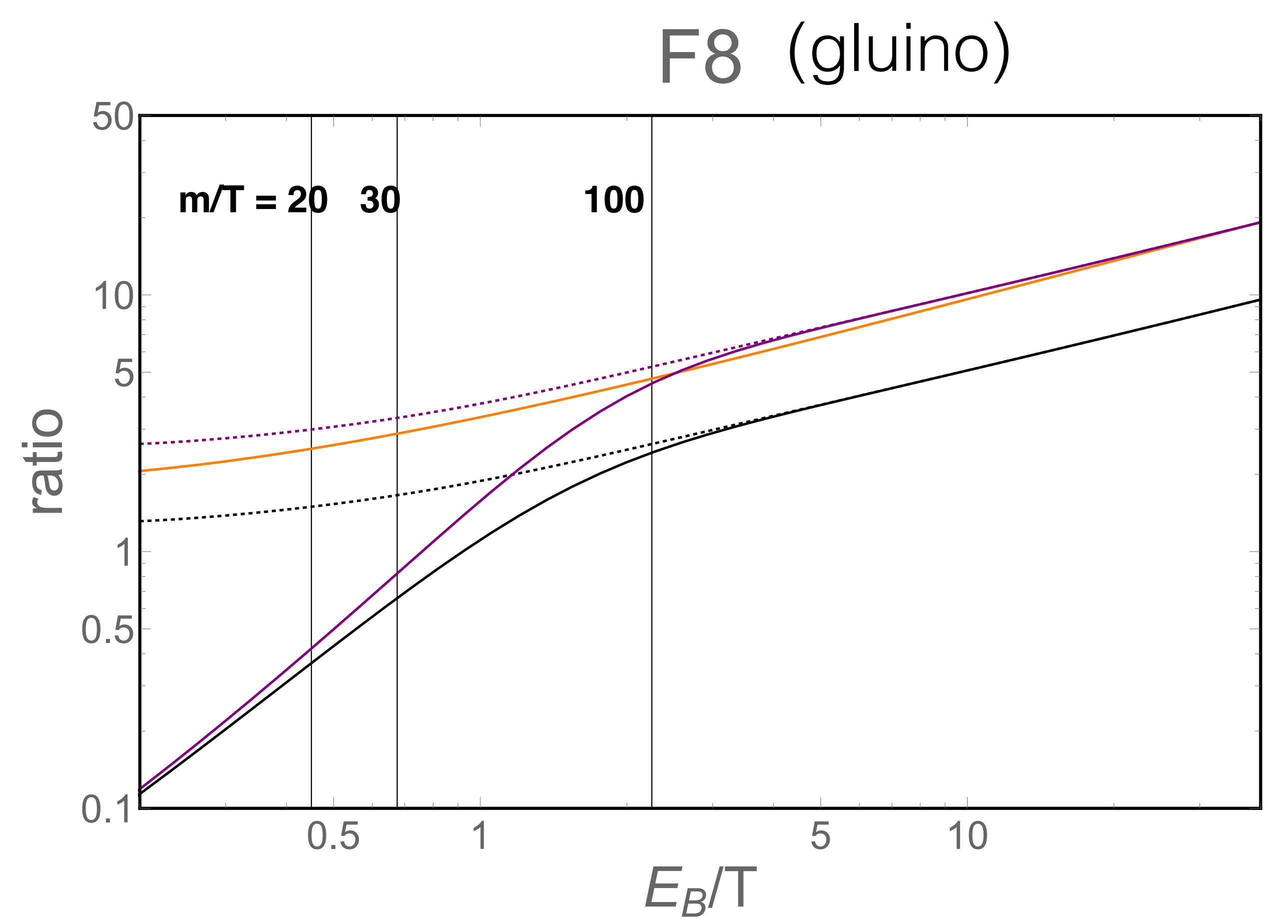
fermion octet (gluino)



[Liew, Luo '16]

Behavior of "effective" annihilation cross section with respect to temperature

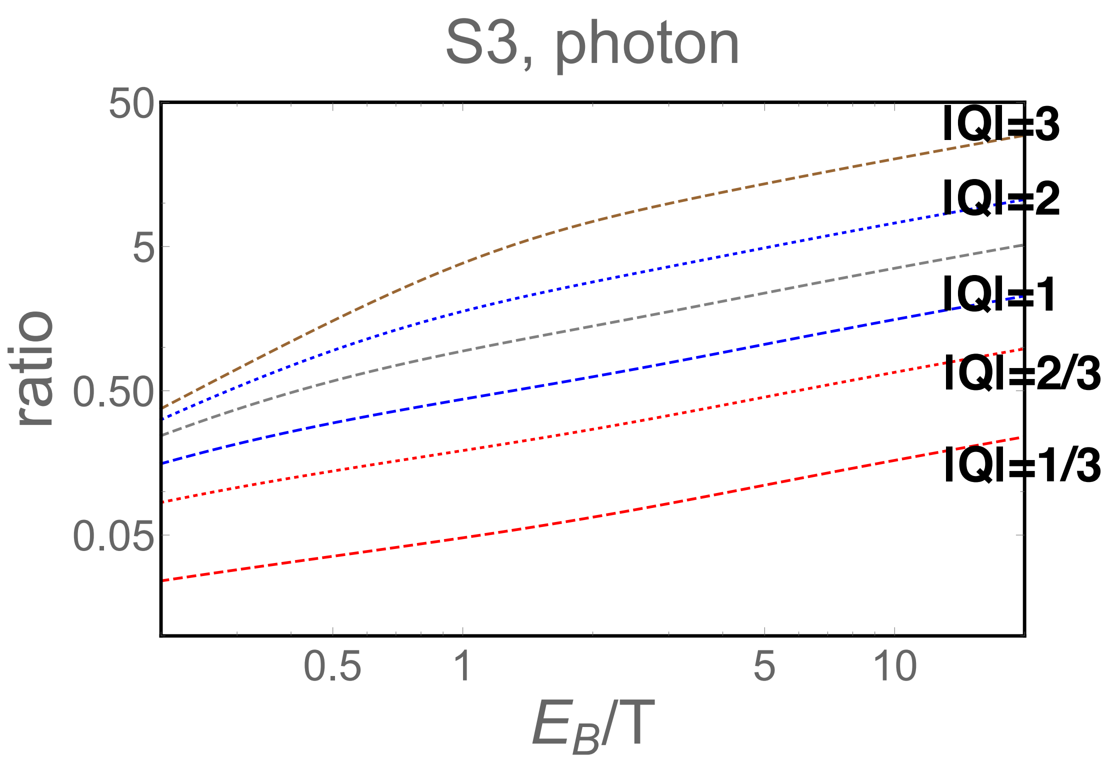


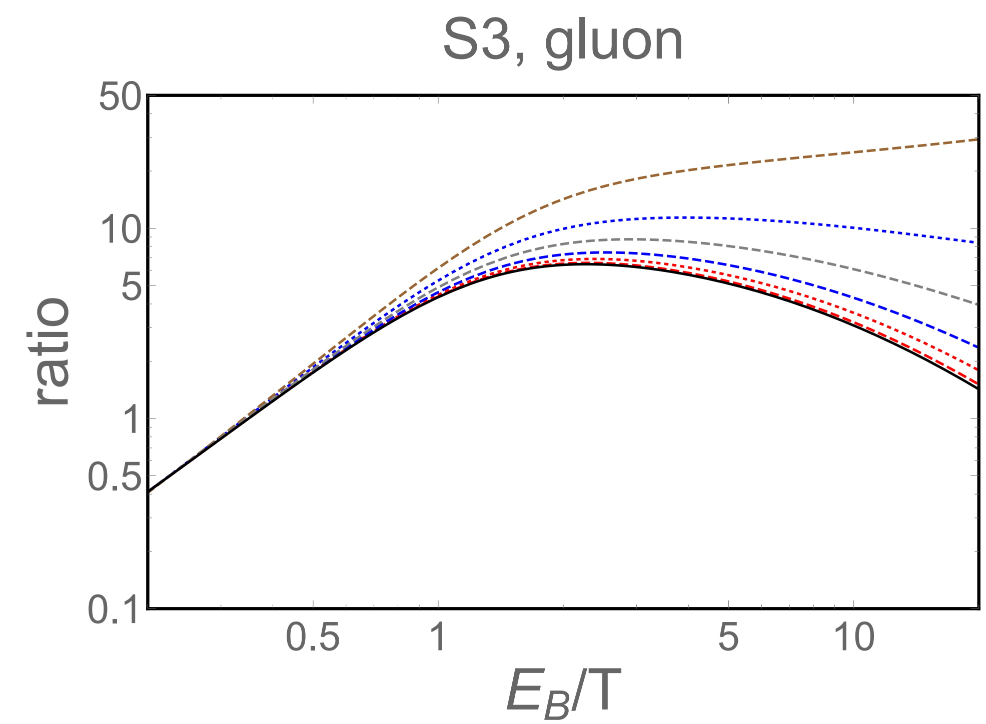


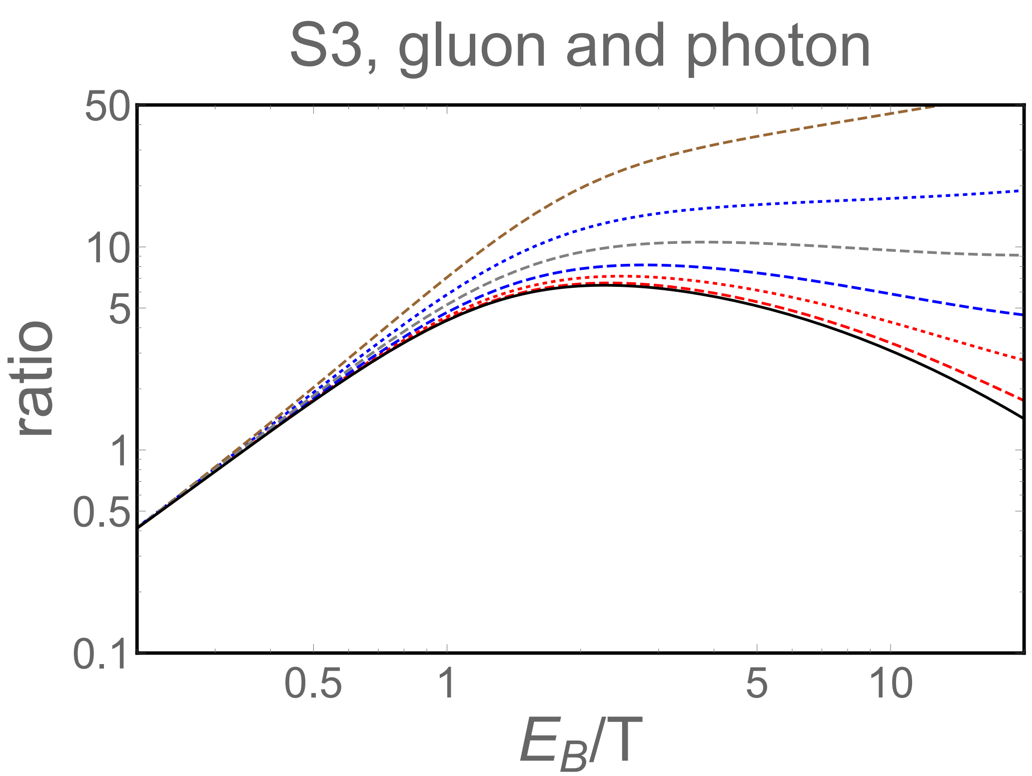
y-axis shows the ratio of the "effective" annihilation cross section due to the bound state normalized by the tree-level annihilation cross section.

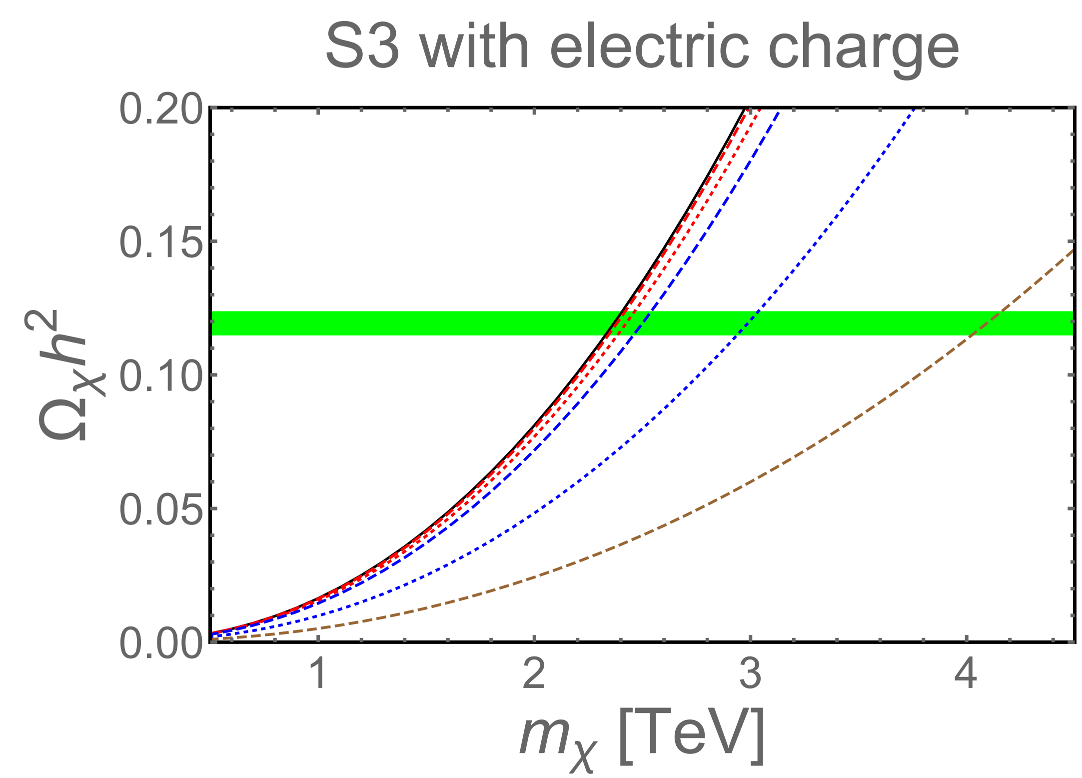
electric charge corrections

$$\tilde{t}\tilde{t}^* \leftrightarrow \tilde{\eta}\gamma$$
$$\tilde{t}\tilde{t}^* \leftrightarrow \tilde{\eta}g$$



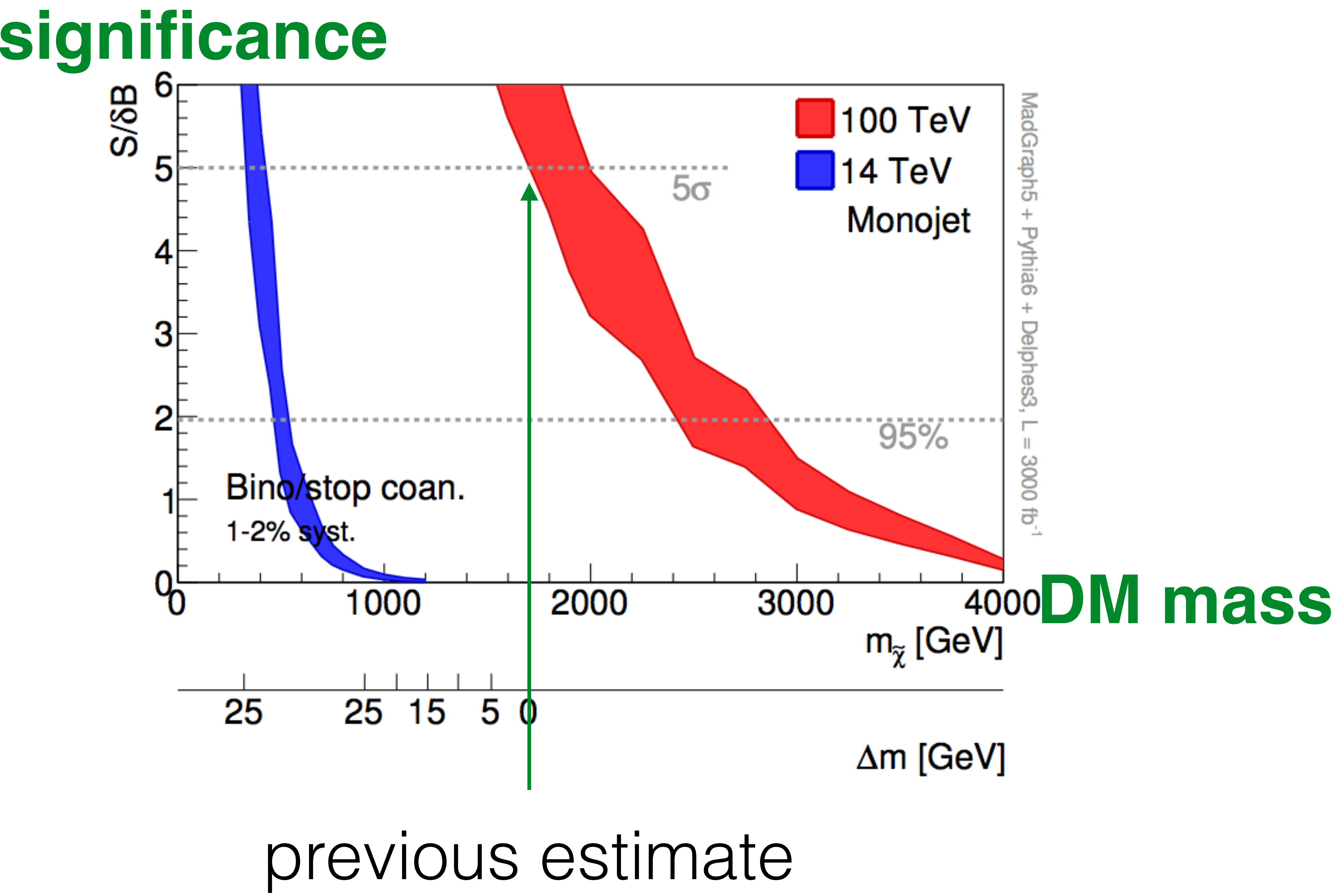






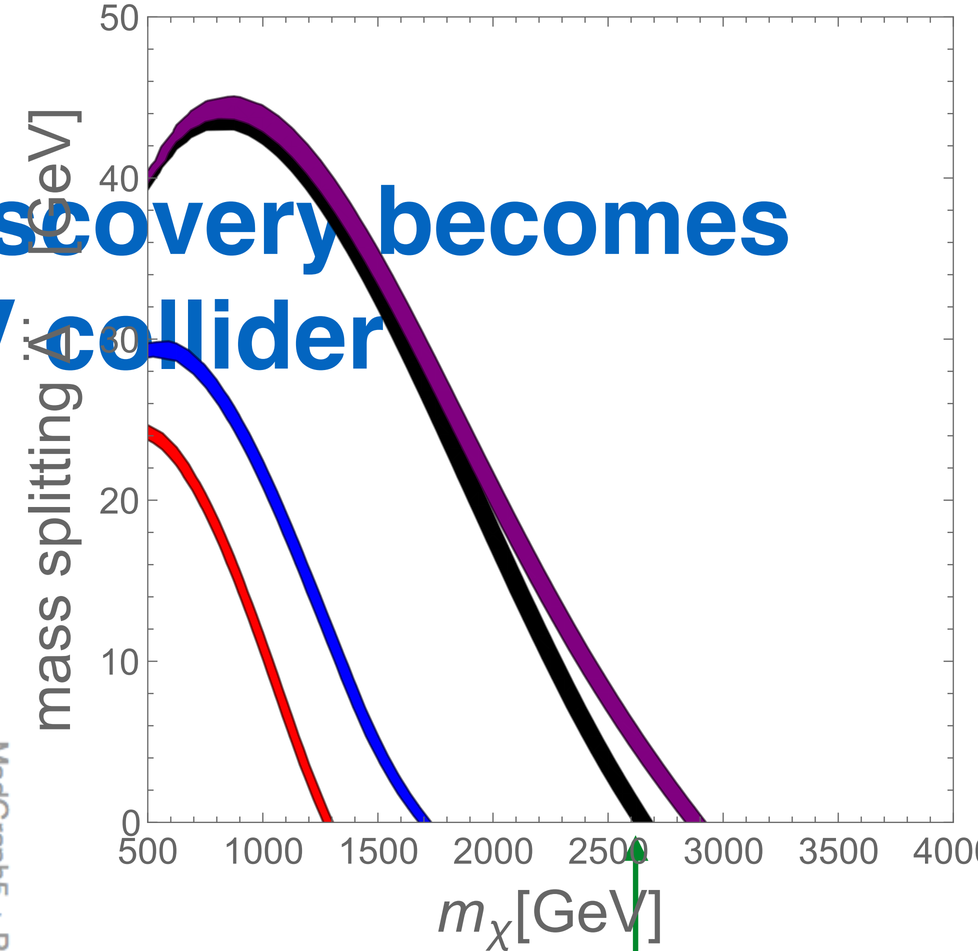
a short comment on 100 TeV collider prospects

bino/stop coan. 5-sigma discovery becomes impossible at 100 TeV collider

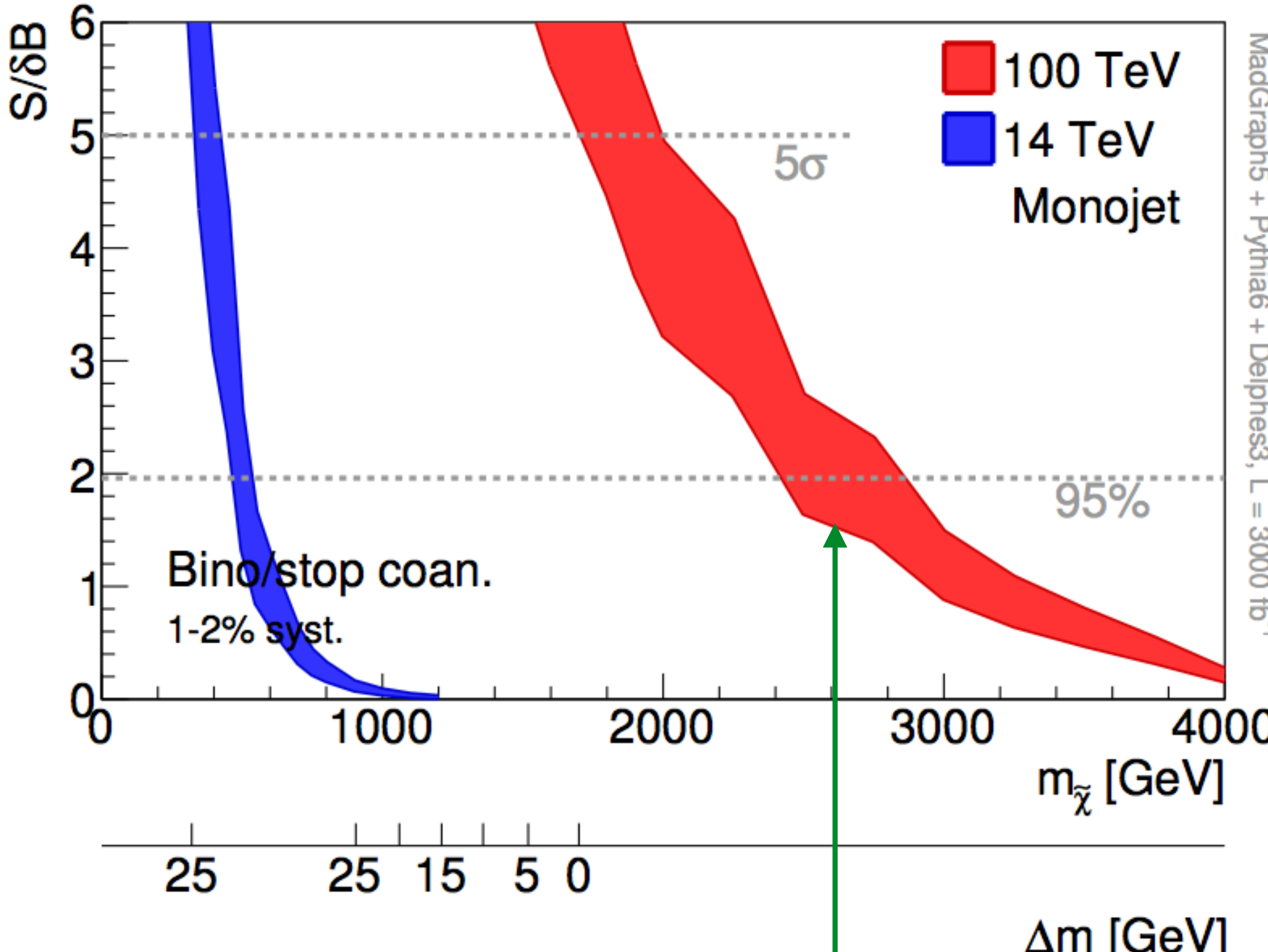


[Low, Wang '14]

bino/stop coan. 5-sigma discovery becomes impossible even at 100 TeV collider



significance



DM mass

[Low, Wang '14]

Subtleties

- Thermal mass of gluon?

Can be ignored as the typical momentum transfer is larger than the thermal mass

[1611.01394]

- Higher energy levels of bound state?

The excited states are easier to be dissociated by gluons in the thermal bath of the early universe

[1604.01776]

Thank you

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