Bound-state effects on DM Phenomenology

~from Cosmology to the LHC~

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(based on...) **1604.07828 with K. Hamaguchi**
and work in progress with F. Luo

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Summary

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by an almost mass-degenerate colored particle.

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cosmology

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LHC

The 750 GeV excess *could* be a bound state of 375 GeV colored particles

As an example, consider R-parity conserving Minimal Supersymmetric Standard Model (MSSM)

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Wino-like neutralino: ~3 TeV

Higgsino-like neutralino: ~1 TeV

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Bino?

depends on the masses of squarks & sleptons

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Consider χ_1 produced thermally.

Specifically, 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 et al. '91]

conditions:

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

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

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χ_2 can convert to χ_1 efficiently.

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

Boltzmann equations

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

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

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

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

without coannihilation

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

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Two limits

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

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

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

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

$\tilde{g}\tilde{g} \leftrightarrow \tilde{R}g,\ \tilde{R} \leftrightarrow gg$ 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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for stop

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

note: bound state formation is important only when

$$\Gamma_{\rm ann} \gtrsim \Gamma_{\tilde{t}/\tilde{g}}$$

bound state annihilation rate

decay rate

Use Coulomb approximation

$$V(r) = -C\frac{\alpha_s}{r}$$

with $$C = \frac{1}{2}\left(C_1 + C_2 - C_{(12)}\right)$$

SU(3) quadratic casimir of constituent particle

SU(3) quadratic casimir of bound state

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MSSM	binding	non-binding
$\tilde{g}\tilde{g}$	$\mathbf{1}, \mathbf{8_S}, \mathbf{8_A}$	$\mathbf{10}, \overline{\mathbf{10}}, \mathbf{27}$
$\tilde{t}\tilde{t}^*$	$\mathbf{1}$	$\mathbf{8}$
$\tilde{t}\tilde{t}$	$\overline{\mathbf{3}}$	$\mathbf{6}$
$\tilde{t}\tilde{g}$	$\mathbf{3}, \overline{\mathbf{6}}$	$\mathbf{15}$

MSSM	SU(3)	C
$(\tilde{g}\tilde{g})$	$\mathbf{1}$	3
	$\mathbf{8}$	3/2
$(\tilde{t}\tilde{t}^*)$	$\mathbf{1}$	4/3
$(\tilde{t}\tilde{t}), (\tilde{t}^*\tilde{t}^*)$	$\overline{\mathbf{3}}, \mathbf{3}$	2/3
$(\tilde{t}\tilde{g}), (\tilde{t}^*\tilde{g})$	$\mathbf{3}, \overline{\mathbf{3}}$	3/2
	$\overline{\mathbf{6}}, \mathbf{6}$	1/2

Use methods in Landau's QM textbook

photoelectric effect: $H\gamma \to e^- p$

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Electromagnetic Hamiltonian $H = \dfrac{1}{2m}(\vec{p} + e\vec{A})^2$

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$$H \approx \frac{p^2}{2m} + \frac{e}{m}\vec{A}\cdot\vec{p}$$

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calculate the matrix $\langle \phi_f | \frac{e}{m}\vec{A}\cdot\vec{p} | \phi_i \rangle$

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rescale with appropriate color factors

Stoponium (preliminary)

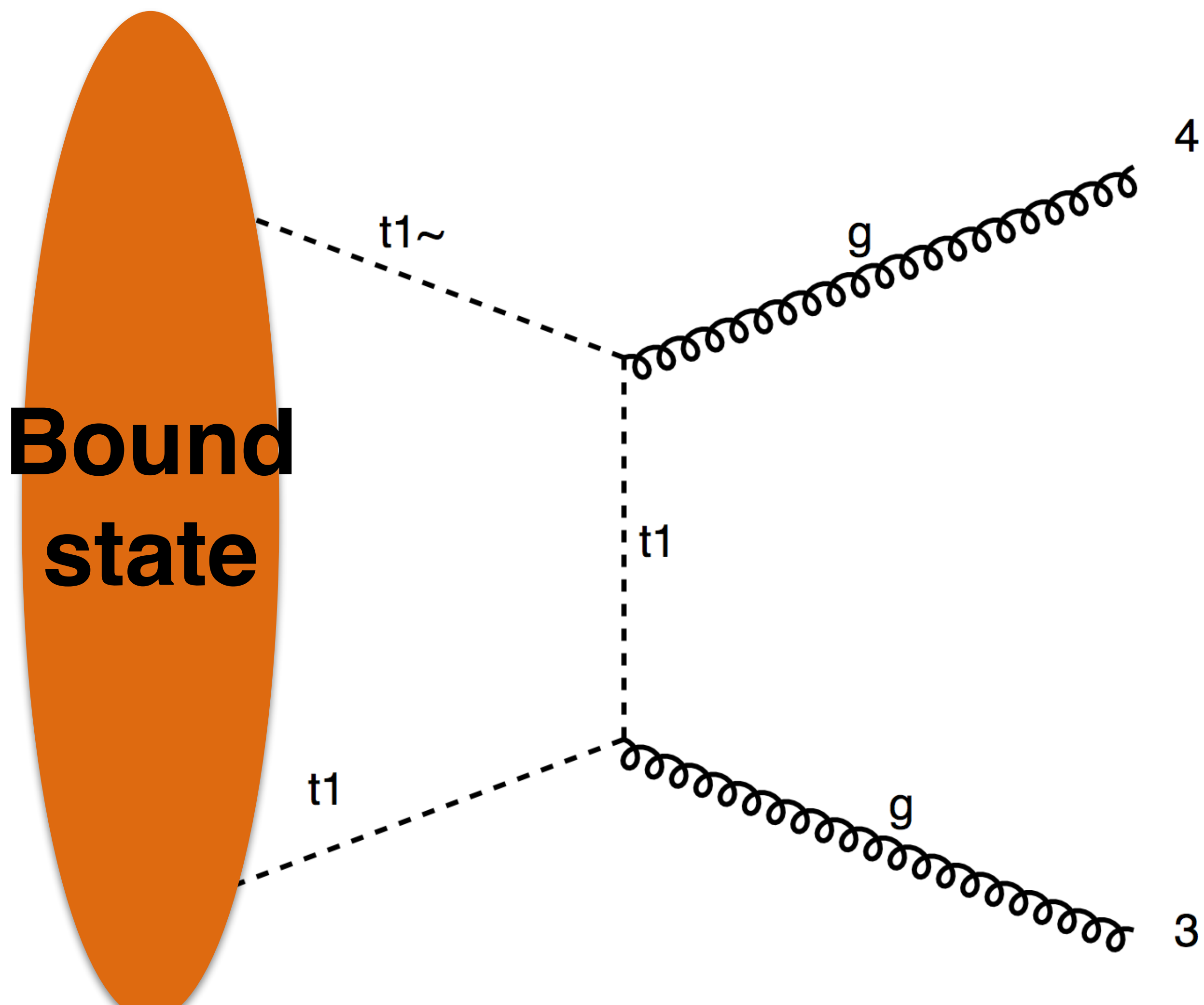
$$\begin{aligned} E_B &= \left(\frac{4}{3}\alpha_s\right)^2 \left(\frac{m_{\tilde{t}}}{2}\right)/2\,, \\ a^{-1} &= \left(\frac{4}{3}\alpha_s\right)\left(\frac{m_{\tilde{t}}}{2}\right)\,, \\ \nu &= \left(\frac{1}{6}\alpha_s\right)/v_{rel}\,, \end{aligned}$$

$$\begin{aligned} \sigma^0_{dis} &= \frac{2^6\pi^2}{3}\alpha_s a^2 \left(\frac{E_B}{\omega}\right)^4 \frac{1+\nu^2}{1+(8\nu)^2}\frac{e^{4\nu\cot^{-1}(8\nu)-2\pi\nu}}{1-e^{-2\pi\nu}}\,, \\ \sigma_{dis} &= \frac{4}{3}\times\frac{1}{8}\times\sigma^0_{dis} \end{aligned}$$

Bound state annihilation removes 2 R-odd particles, thus helps reducing DM density

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

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



The Boltzmann equation is modified by adding the following terms:

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

$$\boxed{-\langle \sigma v \rangle_{\tilde{g}\tilde{g} \to \tilde{R}g} \frac{\langle \Gamma \rangle_{\tilde{R} \to gg}}{\langle \Gamma \rangle_{\tilde{R} \to gg} + \langle \Gamma \rangle_{\tilde{R}g \to \tilde{g}\tilde{g}}} \left(n_{\tilde{g}}^2 - {n_{\tilde{g}}^{eq}}^2\right)}$$

see also [Ellis et al.'15]

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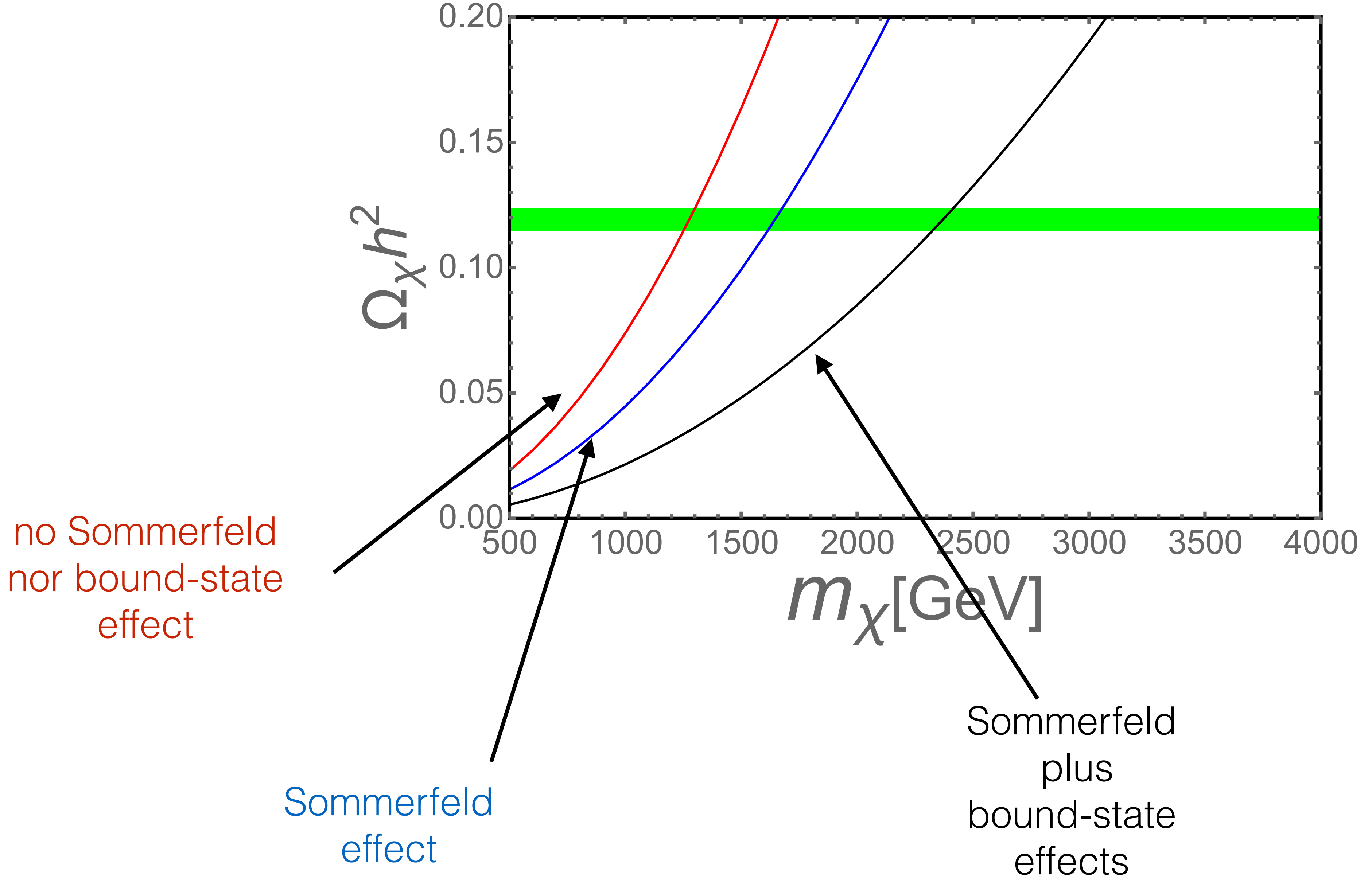
see also [Ellis et al.'15]

$\tilde{R}g \to \tilde{g}\tilde{g}$ becomes unimportant at low temperature compared to $\tilde{R} \to gg$

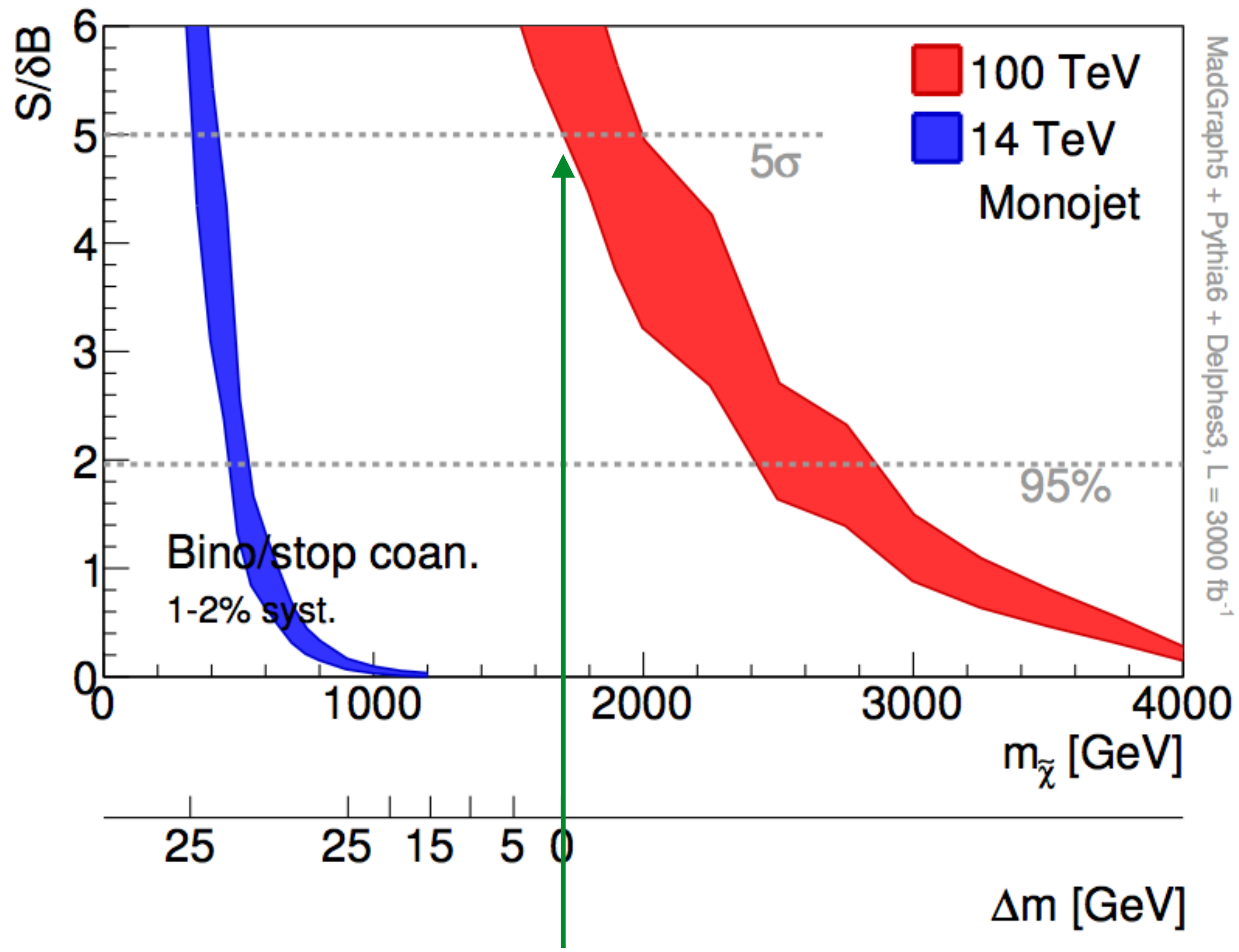
Assume zero mass splitting (stop)

The relic abundance vs mass plane is as follows:



preliminary

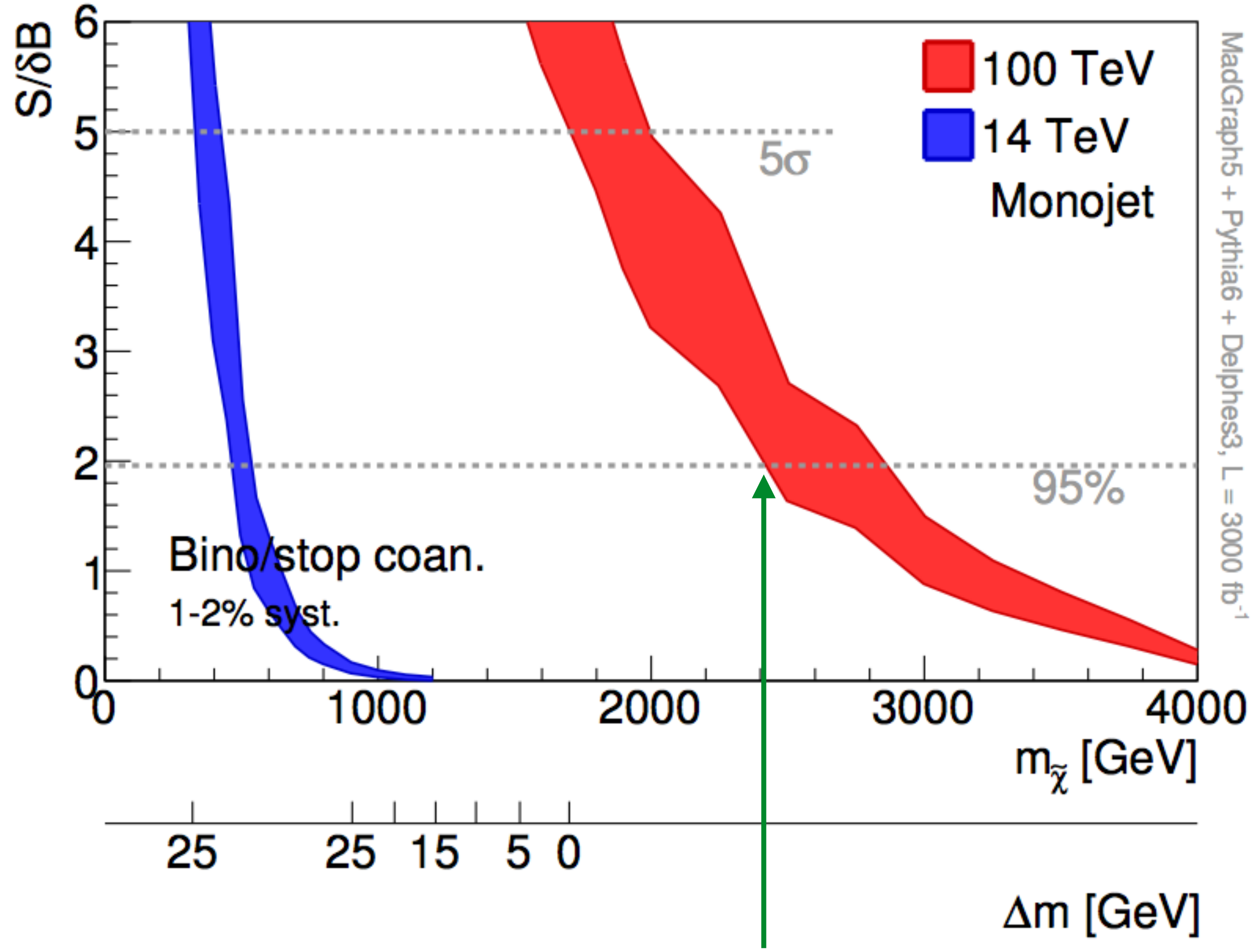
bino/stop coan. 5-sigma discovery becomes impossible at 100 TeV collider

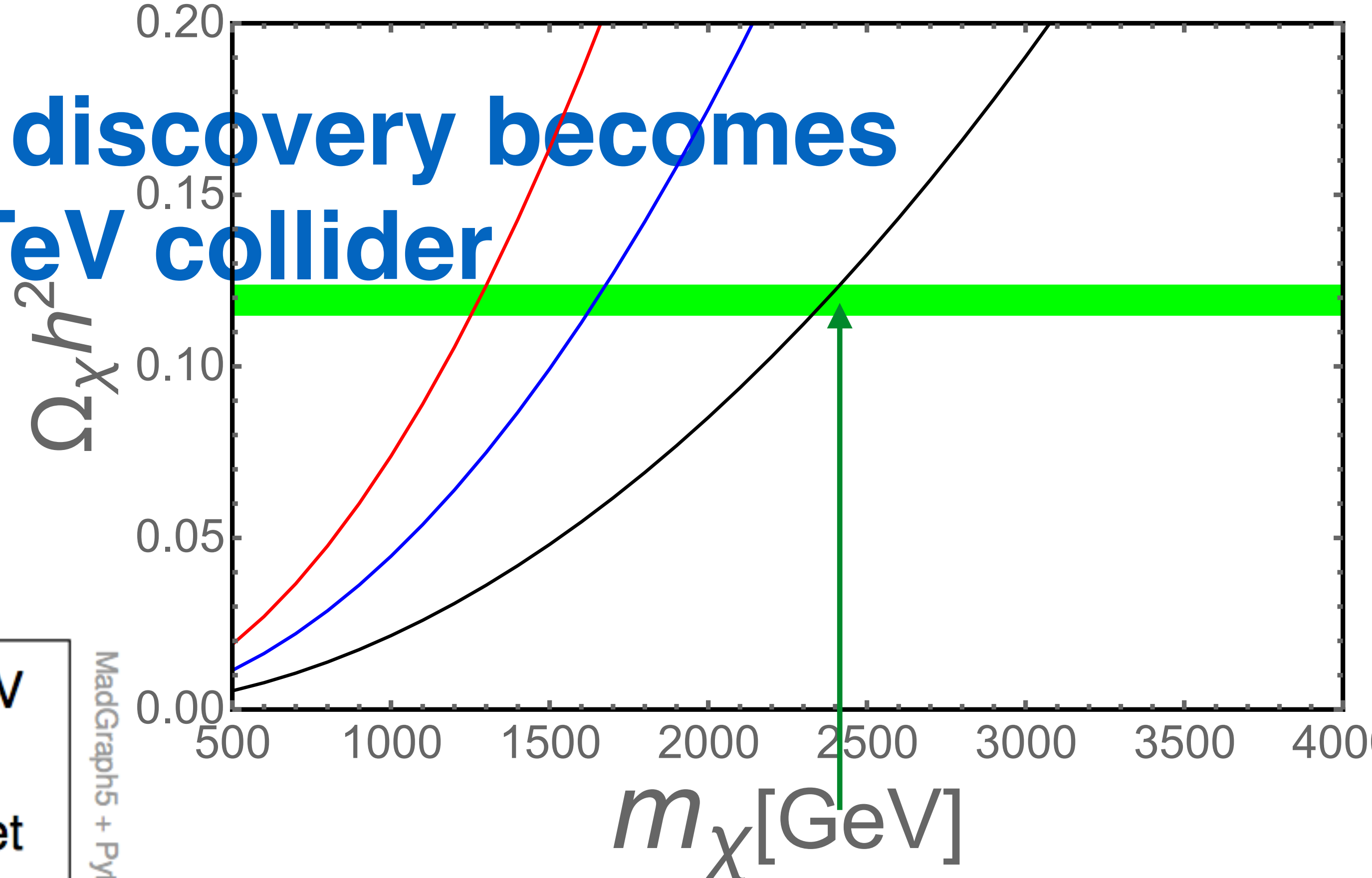


previous estimate

[Low, Wang '14]

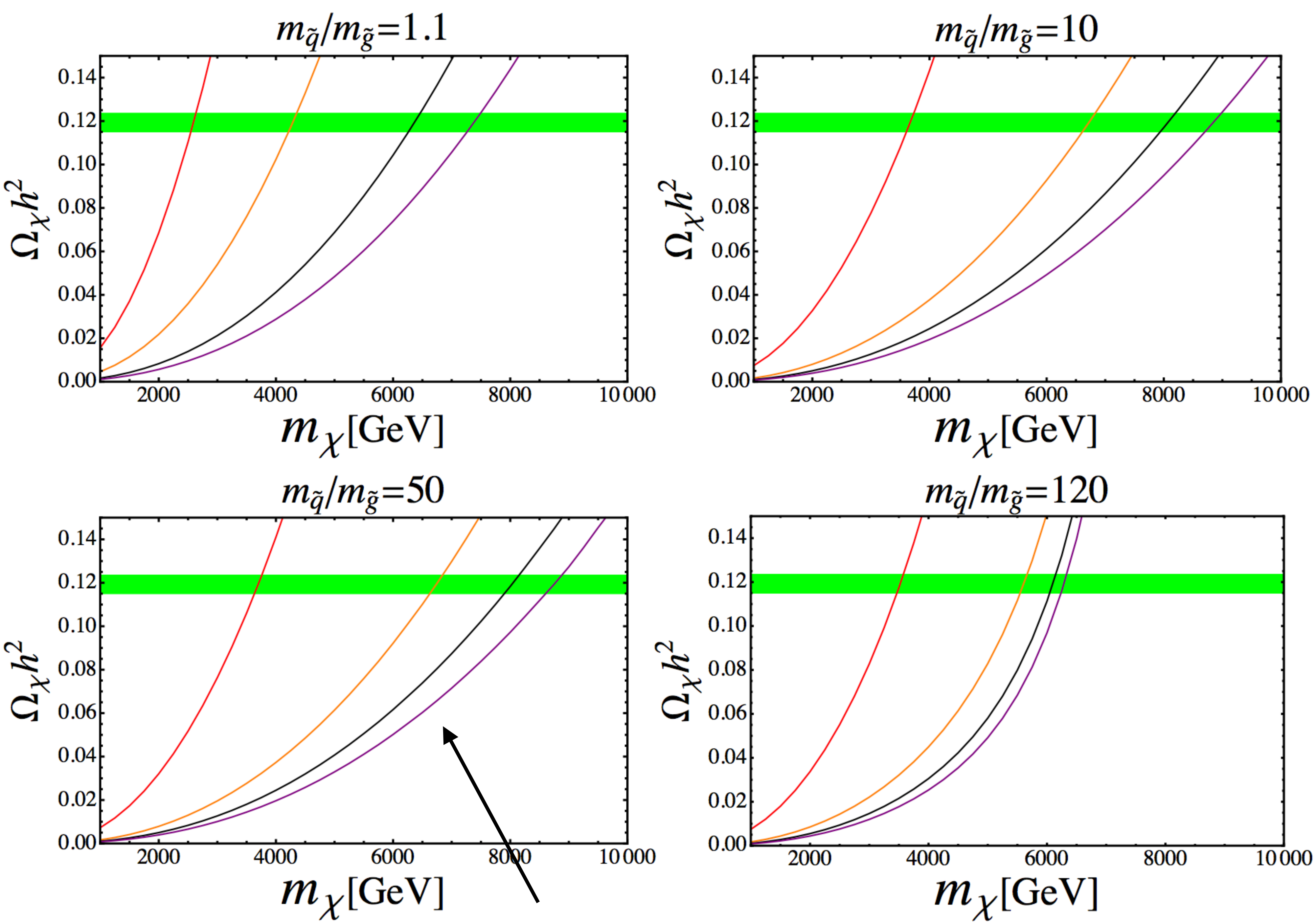
bino/stop coan. 5-sigma discovery becomes impossible even at 100 TeV collider





[Low, Wang '14]

Assume zero mass splitting (gluino)



bound state
formation rate times 2

[Ellis et al.'15]

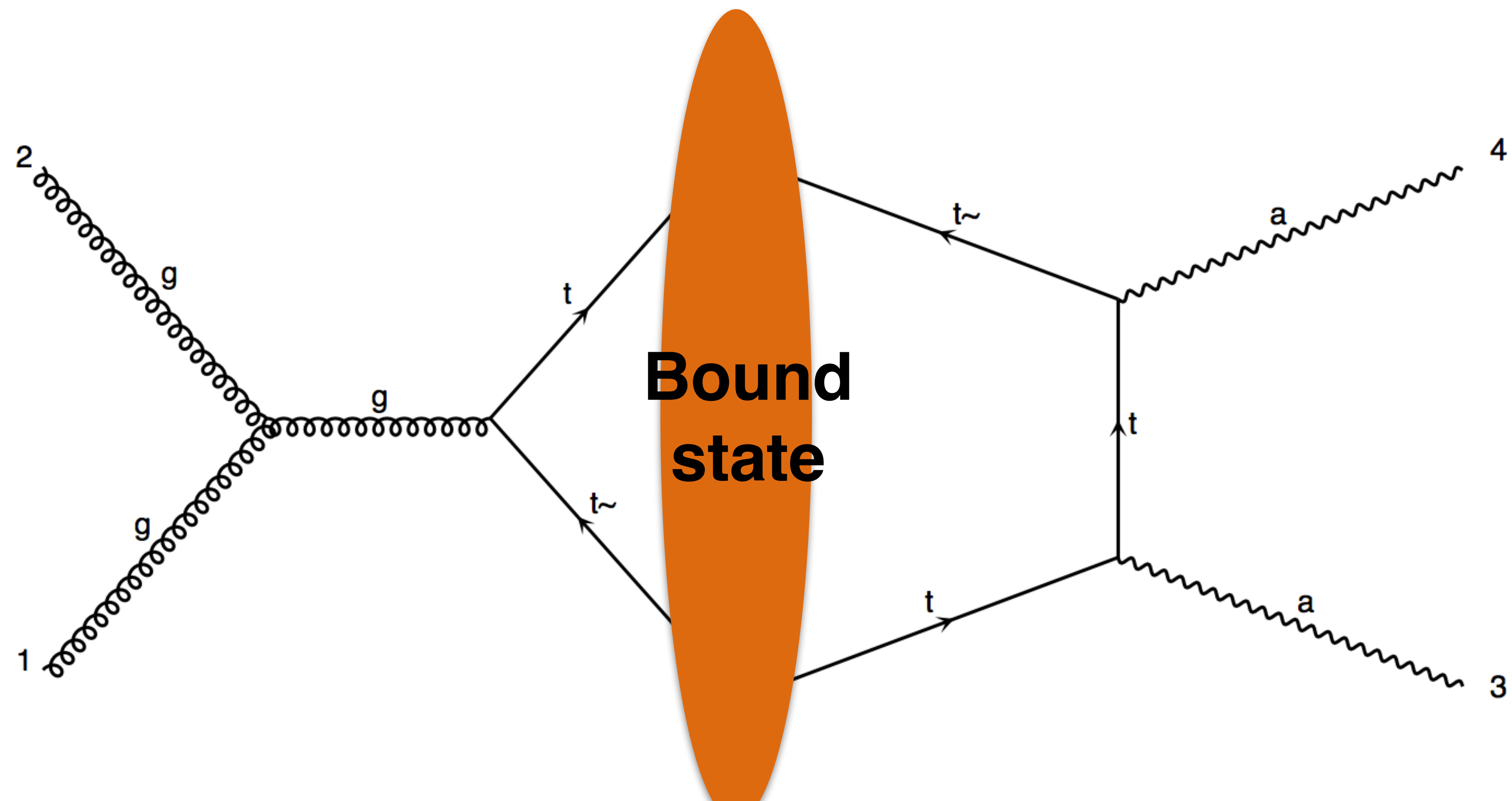
A slightly different topic…

The 750 GeV **LHC** excesses *could* be a bound state of 375 GeV colored particles

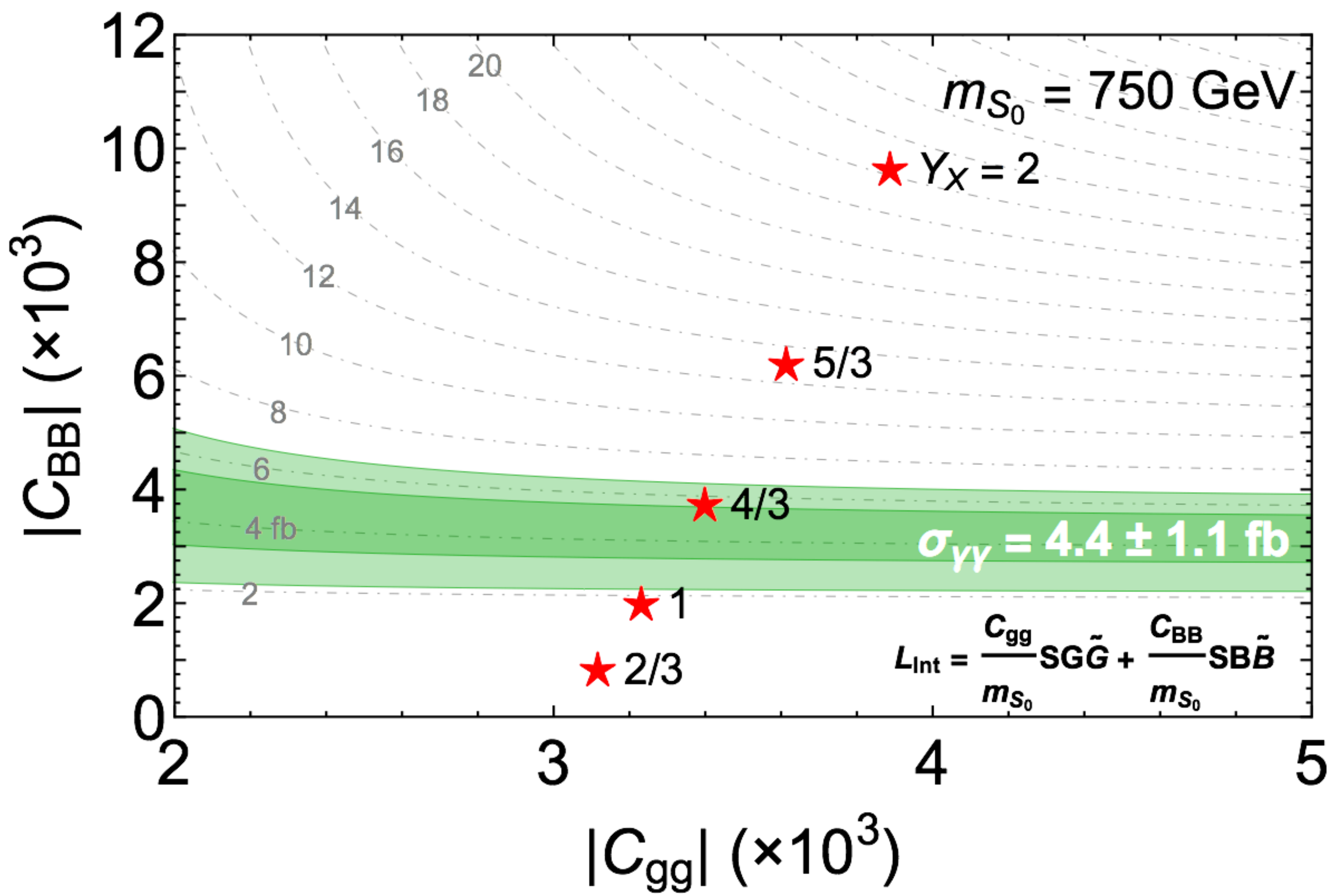
e.g. [Han et al. '16]

[Kats, Strassler '16]

[Hamaguchi, SPL '16]



Consider a 375 GeV colored vector-like fermion



requires hypercharge **4/3** to fit the data

[Han et al.'16]

The 375 GeV colored vector-like fermion cannot be long-lived due to cosmological and collider constraints.

The 375 GeV particle has to decay

Model building is not straightforward as the -4/3 hypercharged particle cannot have renormalizable couplings to SM particles

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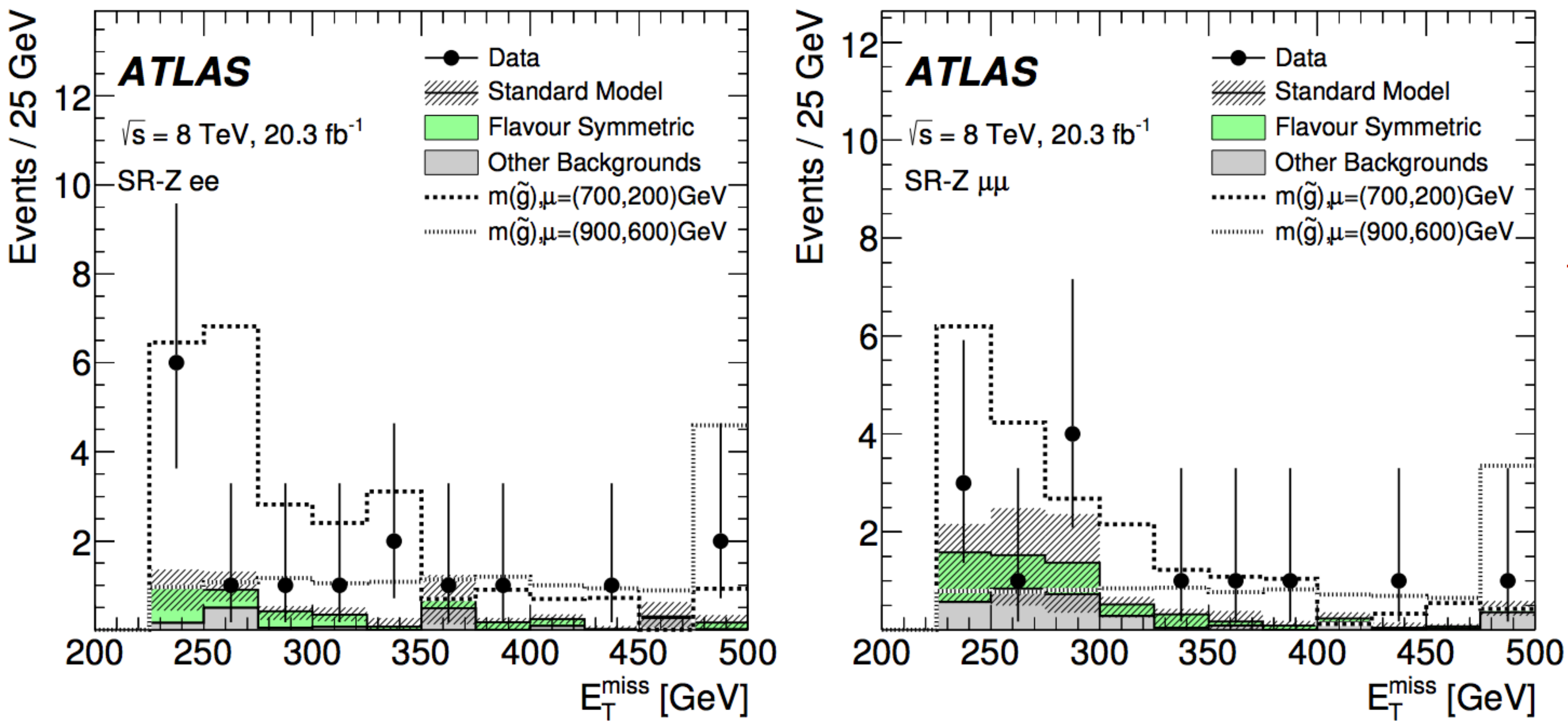
Extra colored mediator needs to be introduced to mediate its decay

There is another excess: ATLAS on-Z excess



8 TeV: 3 sigma

13 TeV: 2.2 sigma

interpreted with GMSB models in the paper

$$\tilde{g} \to jj\tilde{\chi} \to jj\tilde{G} + Z$$

gluino Higgsino gravitino

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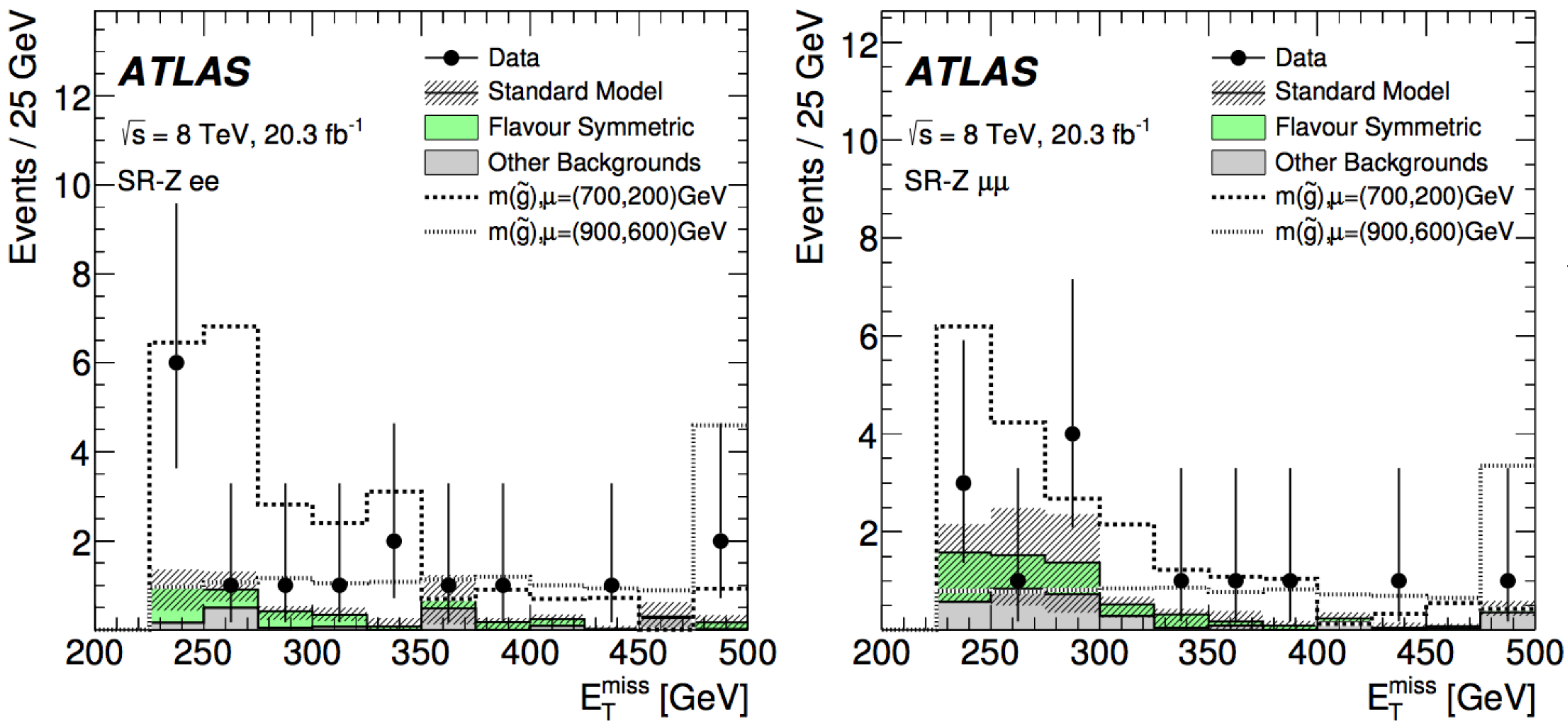

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We also attempt to accommodate it (w/ colored mediator) simultaneously with the 750 GeV excess

Model

	model $XY\eta$	$(SU_3, SU_2)_{U_{1Y}}$
~375 GeV particle	X	$(\mathbf{3}, \mathbf{1})_{-4/3}$
colored mediator	$Y = (B', X')^T$	$(\mathbf{3}, \mathbf{2})_{-5/6}$
scalar doublet	$\eta = (\eta^+, \eta^0)^T$	$(\mathbf{1}, \mathbf{2})_{1/2}$

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colored mediator

scalar doublet

Dark Matter

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Dark Matter

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{F=Y,X} \bar{F}(i\gamma^\mu D_\mu - m_F)F + |D_\mu \eta|^2 - m_\eta^2|\eta|^2 - V(H,\eta)$$
$$\boxed{-(\bar{Y}H)(\lambda_X + \lambda_{X5}\gamma_5)X} - \boxed{y_{\eta i}\overline{d_{Ri}}P_L(Y\cdot\eta)} + h.c.$$

X mixes with Y

Y decays to DM plus jet

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$$X_2 \to \begin{cases} X_1 Z \\ X_1 h \end{cases}, \quad B' \to X_1 W, \quad X_1 \to b\eta^-, \quad \eta^- \to \eta^0 + \pi^- .$$

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on-Z excess

750 GeV excess

DM (missing energy)

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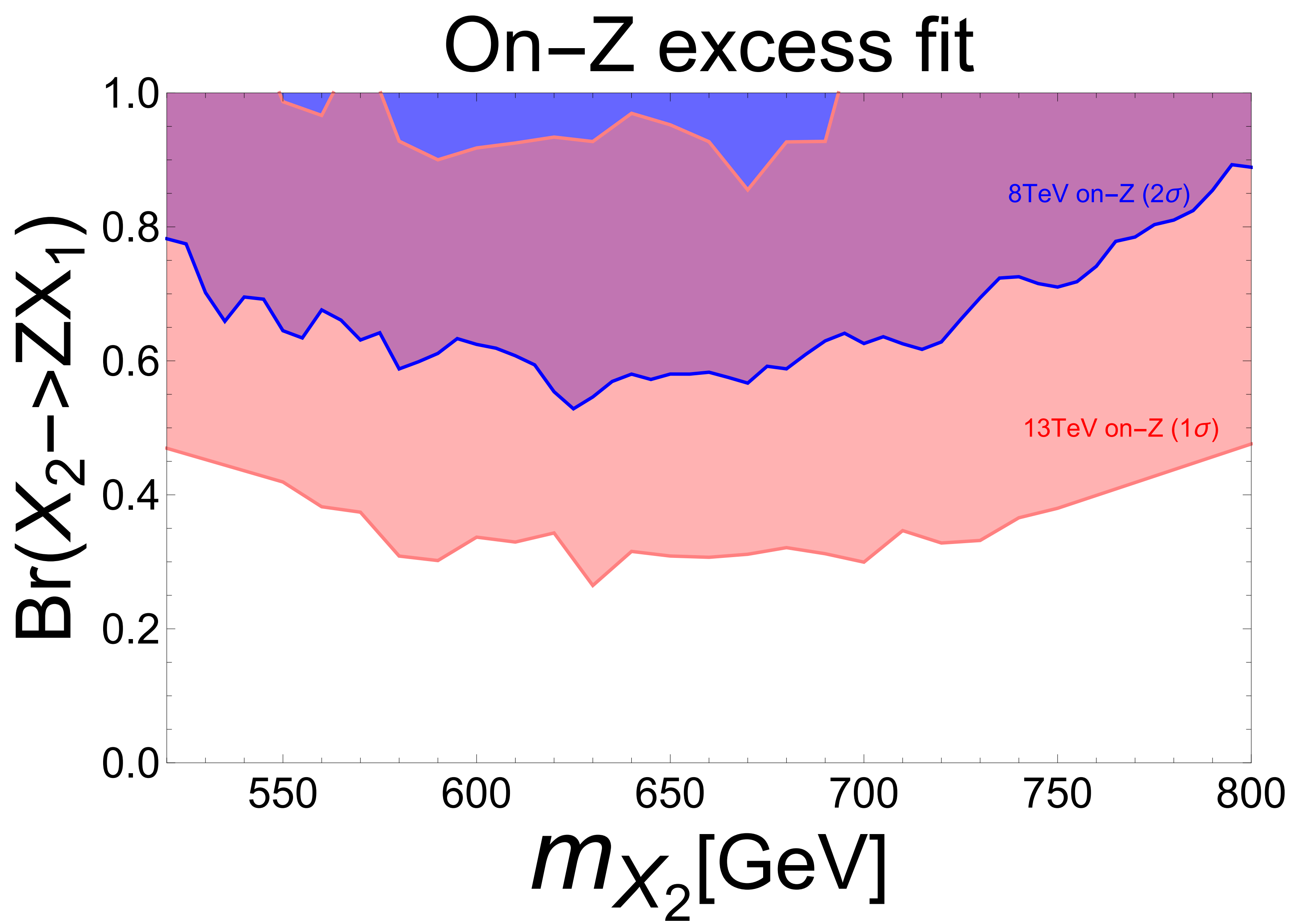
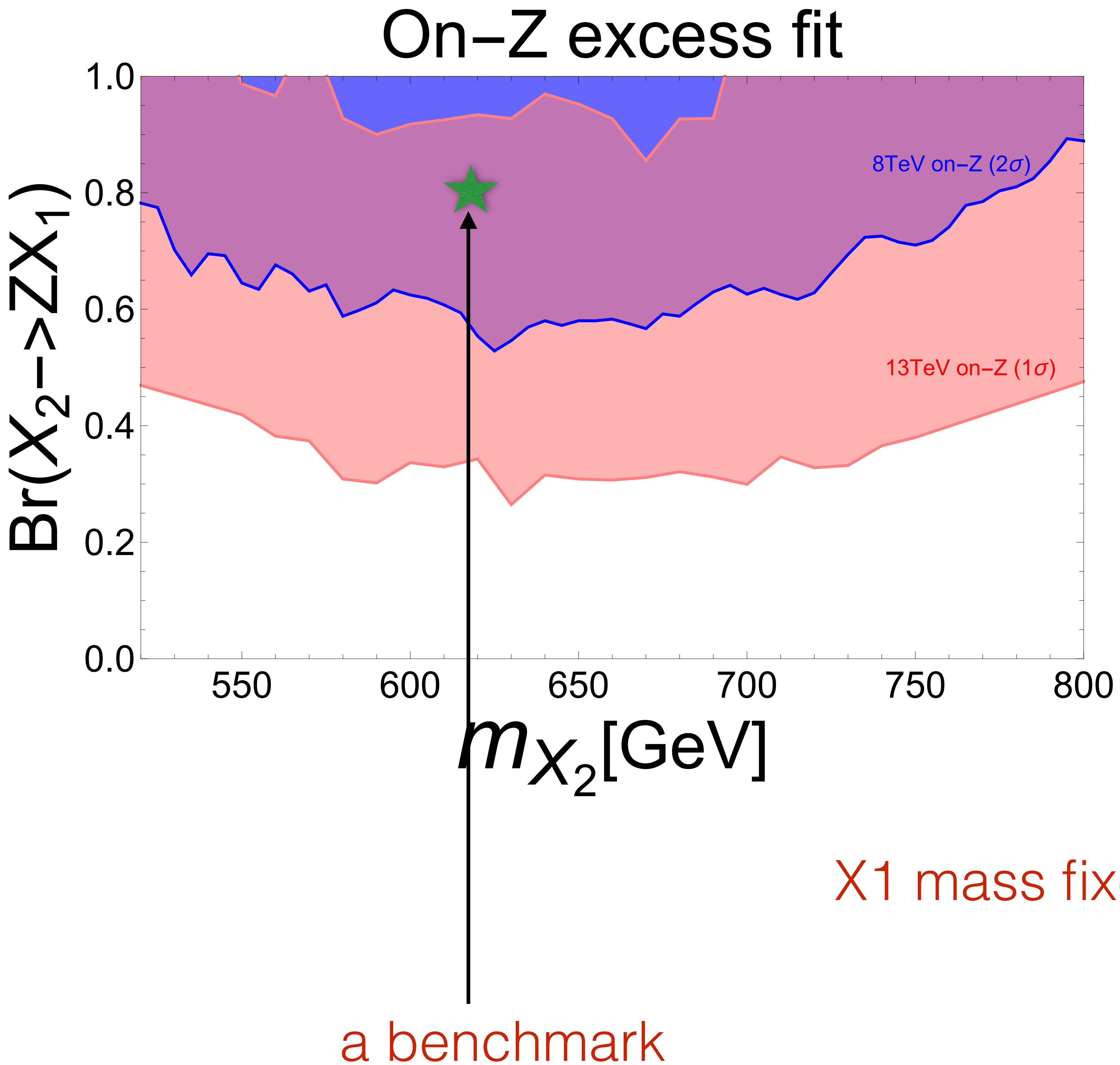


X1 mass fixed at **375 GeV**



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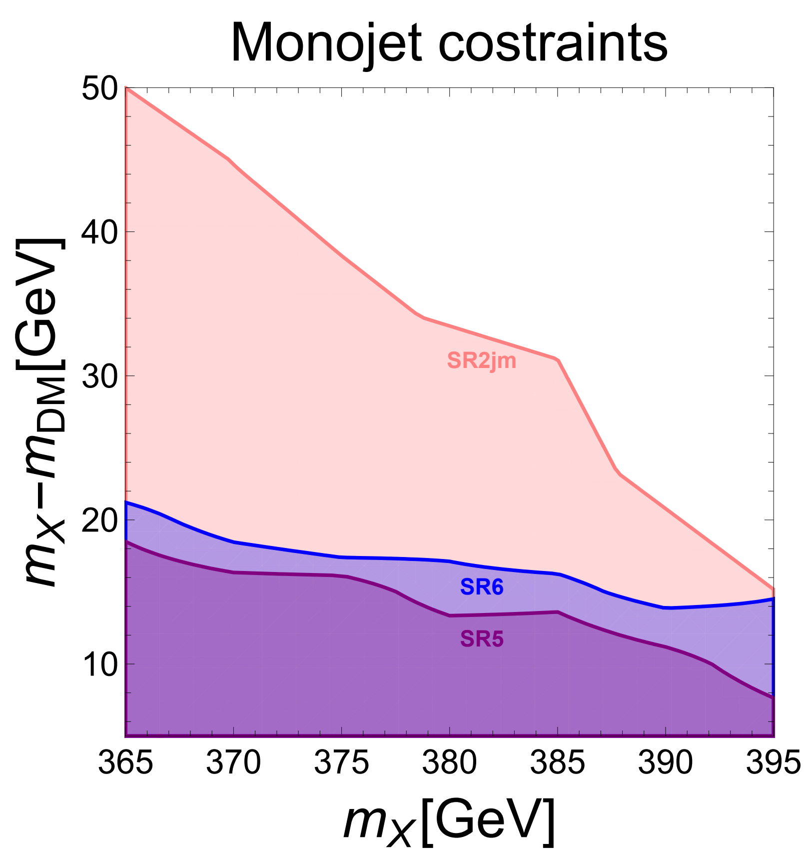
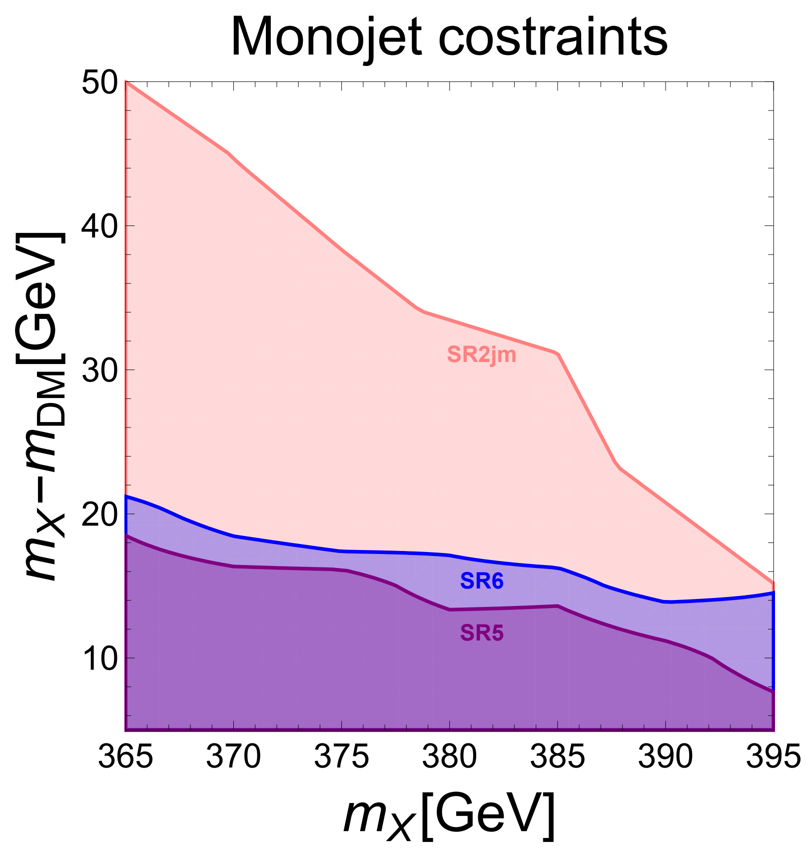


Monojet costraints
50
40
30
20
10
$m_X - m_{DM}$[GeV]
SR2jm
SR6
SR5
365
370
375
380
385
390
395
m_X[GeV]



A benchmark

$$m_{X_2} = 620\text{GeV}$$
$$m_{X_1} = 375\text{GeV}$$
$$m_\eta = 335\text{GeV}$$

explains **750 GeV** excess, **on-Z** excess, and gives a **DM** candidate!

DM phenomenology

$\eta = (\eta^+, \eta^0)^T$ is an inert scalar doublet with mass splitting $\Delta m \simeq 350\text{MeV}$

decay rate $\Gamma(\eta^- \to \eta^0 + \pi^-) \simeq 3 \times 10^{-14}\text{GeV}\left(\frac{\Delta m}{350\text{MeV}}\right)^3 \beta$

annihilation cross section

$$\sigma v \simeq 9 \times 10^{-26}\text{cm}^3\text{s}^{-1}\left(\frac{m_{\text{DM}}}{335\ \text{GeV}}\right)^{-2}$$

e.g. [Cirelli et al. '05]

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We have considered dark matter accompanied by an almost mass-degenerate colored particle.

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