# Supersymmetry Beyond the MSSM

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M.B., Conlon, Marsh, Witkowski ’12
M.B., Buchberger, Ghilencea, Petersson ’12
...

Nordita “Beyond the LHC” workshop, July 2013

# Plan

1. Higgs physics: Effective supersymmetry

2. Nonminimal Z’ bosons

3. Supersymmetry, flavor physics and naturalness

# Obvious possible reasons why no superpartners yet

• They're not there

• Not enough energy (cf. SSC at 40 TeV)

• Enough energy in principle but somewhat "hidden":
somewhat difficult to produce at hadron collider,
or somewhat difficult to discover with present search strategies

# “Unnatural MSSM”: one example

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski ’12

“Simply unnatural supersymmetry” (100+ TeV scalars)
Presented as “anthropic tuning”, but 10-100 TeV is large but not obviously unreasonable finetuning.

*“generic models of supersymmetry breaking produce much larger scalar masses than gaugino masses, that is, this is what the models want to do”*

*“the Higgs mass $m_H \sim 125$ GeV already requires some tuning in the MSSM, or some significant departure from it”*

# Hierarchy problem

Of course, finetuning increases as
superpartner masses increase

cf. SM fermion mass hierarchy, already spans five (or more) orders of magnitude

More important to have some motivation for model
(e.g. high-energy theory is supersymmetric)
than to satisfy any given finetuning bound, like
NMSSM “finetuning 200”, GNMSSM “finetuning 30”

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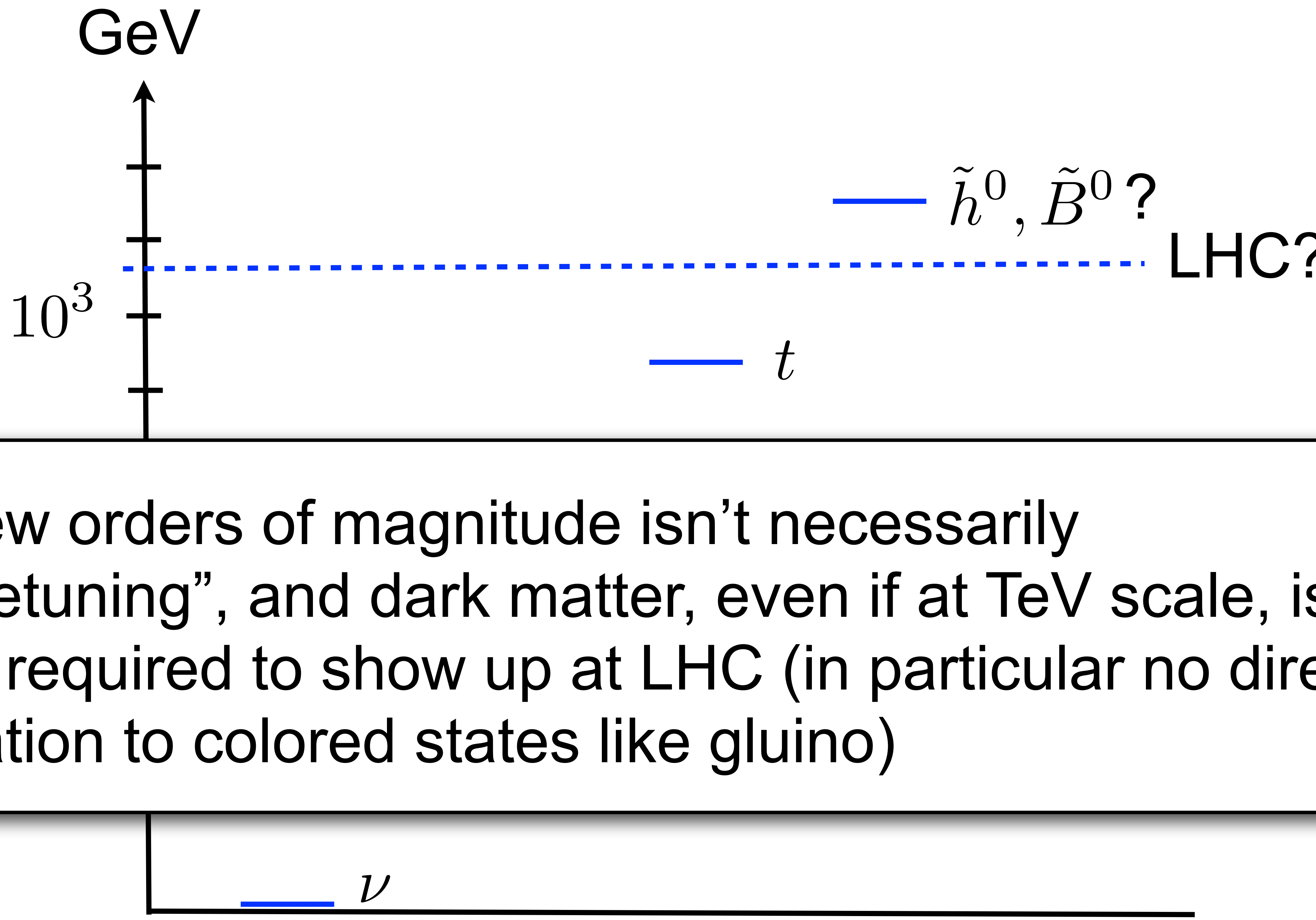
(e.g. high-energy theory is supersymmetric)
than to satisfy any given finetuning bound, like
NMSSM “finetuning 200”, GNMSSM “finetuning 30”

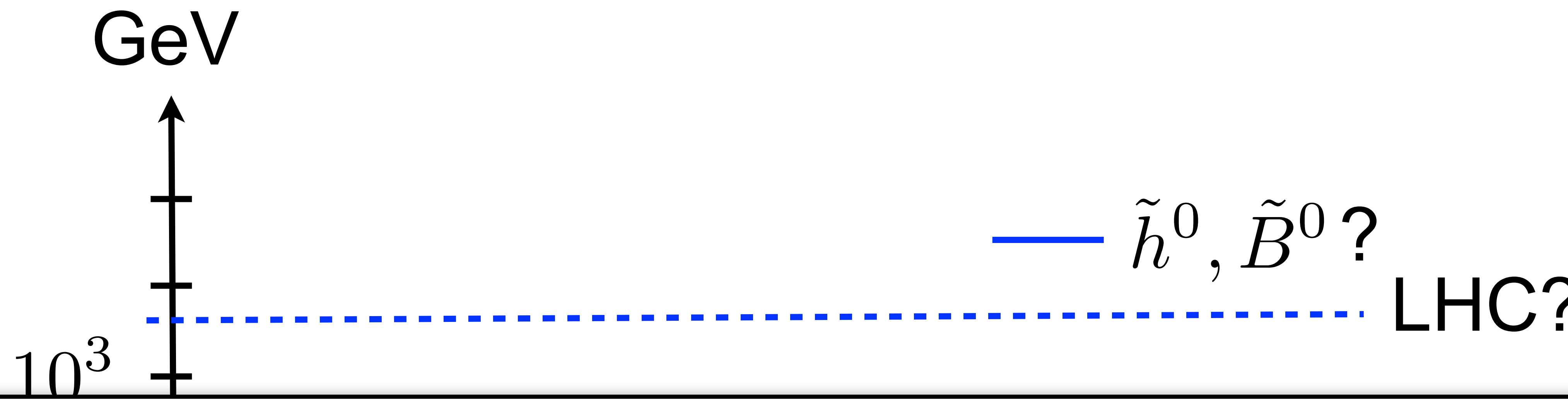
Having said that, at some point (“finetuning 10000”?)
it ceases to be a reasonable solution!

# Fermion mass hierarchy




a few orders of magnitude isn't necessarily "finetuning", and dark matter, even if at TeV scale, is not required to show up at LHC (in particular no direct relation to colored states like gluino)

# Fermion mass hierarchy




Compare to before electroweak theory was confirmed: hints from Fermi theory (dimension-6 operators).

Maybe we should hope for hints through effective theory? If so, would effects appear e.g. in ATLAS analysis?

# 1. Beyond the MSSM (BMSSM)

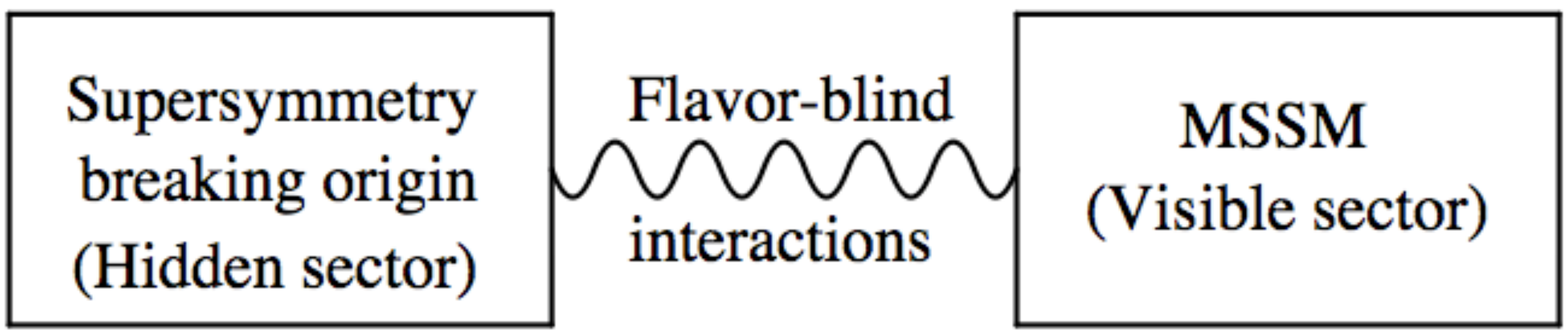
Piriz, Wudka ’97
Strumia ’99
Brignole, Casas, Espinosa, Navarro ’03
Casas, Espinosa, Hidalgo ’04
Dine, Seiberg, Thomas ’07
Antoniadis, Dudas, Ghilencea, Tziveloglou ’09

- No new particles
- Operators of dimension 5 and 6 mostly classified
- Generically on the order of >100 parameters
  (but fewer than in a nonsupersymmetric effective theory)
- Not all created equal, focus on some for some purposes

# What is so minimal about the MSSM?

e.g. Martin, hep-ph/9709356

supersymmetry breaking by F-terms:




$\Phi_i$ $C^\alpha$

$$
\begin{aligned}
W &= \hat{W}(\Phi) + \mu(\Phi) H_1 H_2 + \frac{1}{6} Y_{\alpha\beta\gamma}(\Phi) C^\alpha C^\beta C^\gamma + \ldots, \\
K &= \hat{K}(\Phi, \bar{\Phi}) + \tilde{K}_{\alpha\bar{\beta}}(\Phi, \bar{\Phi}) C^\alpha C^{\bar{\beta}} + \left[ Z(\Phi, \bar{\Phi}) H_1 H_2 + h.c. \right] + \ldots, \\
f_a &= f_a(\Phi).
\end{aligned}
$$

$$
F^m = e^{\hat{K}/2} \hat{K}^{m\bar{n}} D_{\bar{n}} \hat{\bar{W}}
$$

# Soft supersymmetry breaking

e.g. Martin, hep-ph/9709356

supersymmetry breaking:

$$\mathcal{L}_{\mathrm{MSSM}} = \mathcal{L}_{\mathrm{susy}} + \underbrace{\mathcal{L}_{\mathrm{soft}}}_{\text{dimension}\leq 3}$$

$$W = \hat{W}(\Phi) + \mu(\Phi)H_1H_2 + \frac{1}{6}Y_{\alpha\beta\gamma}(\Phi)C^\alpha C^\beta C^\gamma + \ldots,$$
$$K = \hat{K}(\Phi,\bar{\Phi}) + \tilde{K}_{\alpha\bar{\beta}}(\Phi,\bar{\Phi})C^\alpha C^{\bar{\beta}} + [Z(\Phi,\bar{\Phi})H_1H_2 + h.c.] + \ldots,$$
$$f_a = f_a(\Phi).$$

$$F^m = e^{\hat{K}/2}\hat{K}^{m\bar{n}}D_{\bar{n}}\bar{\hat{W}} \longrightarrow$$

$$M_a = \frac{1}{2}\frac{F^m\partial_m f_a}{\mathrm{Re}f_a}$$

$$A_{ijk}, B_{ij}, m_\alpha, \ldots$$

# Soft supersymmetry breaking

e.g. Martin, hep-ph/9709356

supersymmetry breaking:

$$\mathcal{L}_{\rm MSSM} = \mathcal{L}_{\rm susy} + \underbrace{\mathcal{L}_{\rm soft}}_{\rm dimension \leq 3}$$

forget about origin:
effective renormalizable
field theory

$$\Phi_i \longrightarrow \langle \Phi_i \rangle \longrightarrow c_i$$

gaugino masses $M_a = \frac{1}{2} \frac{F^m \partial_m f_a}{{\rm Re} f_a}$

$$A_{ijk}, B_{ij}, m_\alpha, \ldots$$

$$F^m = e^{\hat{K}/2} \hat{K}^{m\bar{n}} D_{\bar{n}} \bar{\hat{W}}$$

# What is so minimal about the MSSM?

e.g. Martin, hep-ph/9709356

supersymmetry breaking:

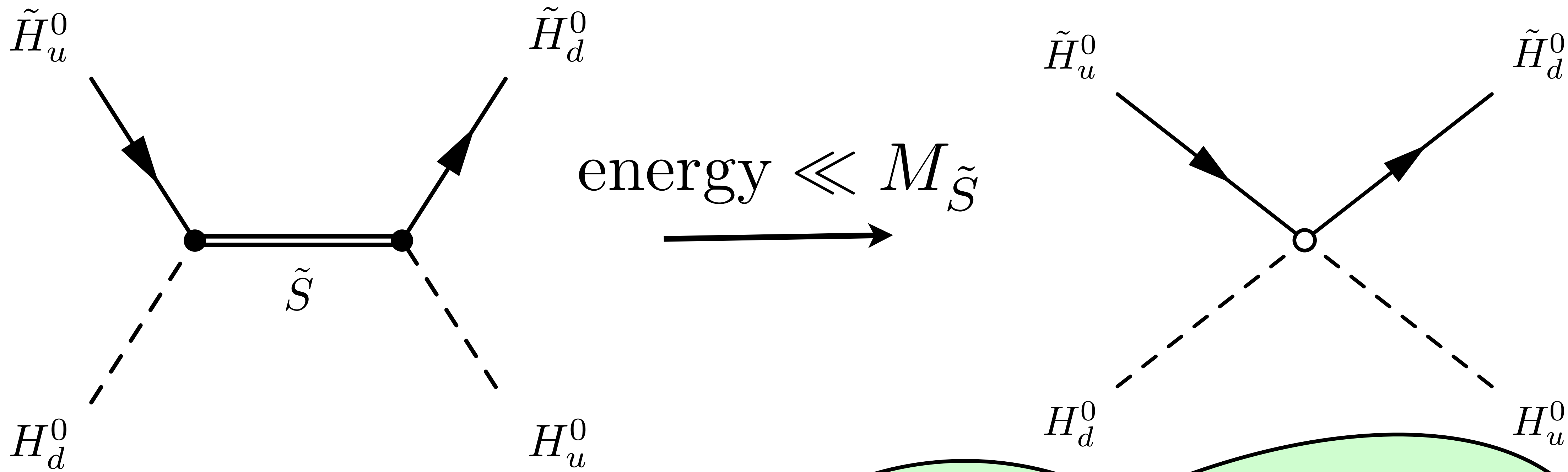
$$\mathcal{L}_{\mathrm{MSSM}} = \mathcal{L}_{\mathrm{susy}} + \underbrace{\mathcal{L}_{\mathrm{soft}}}_{\mathrm{dimension} \leq 3}$$

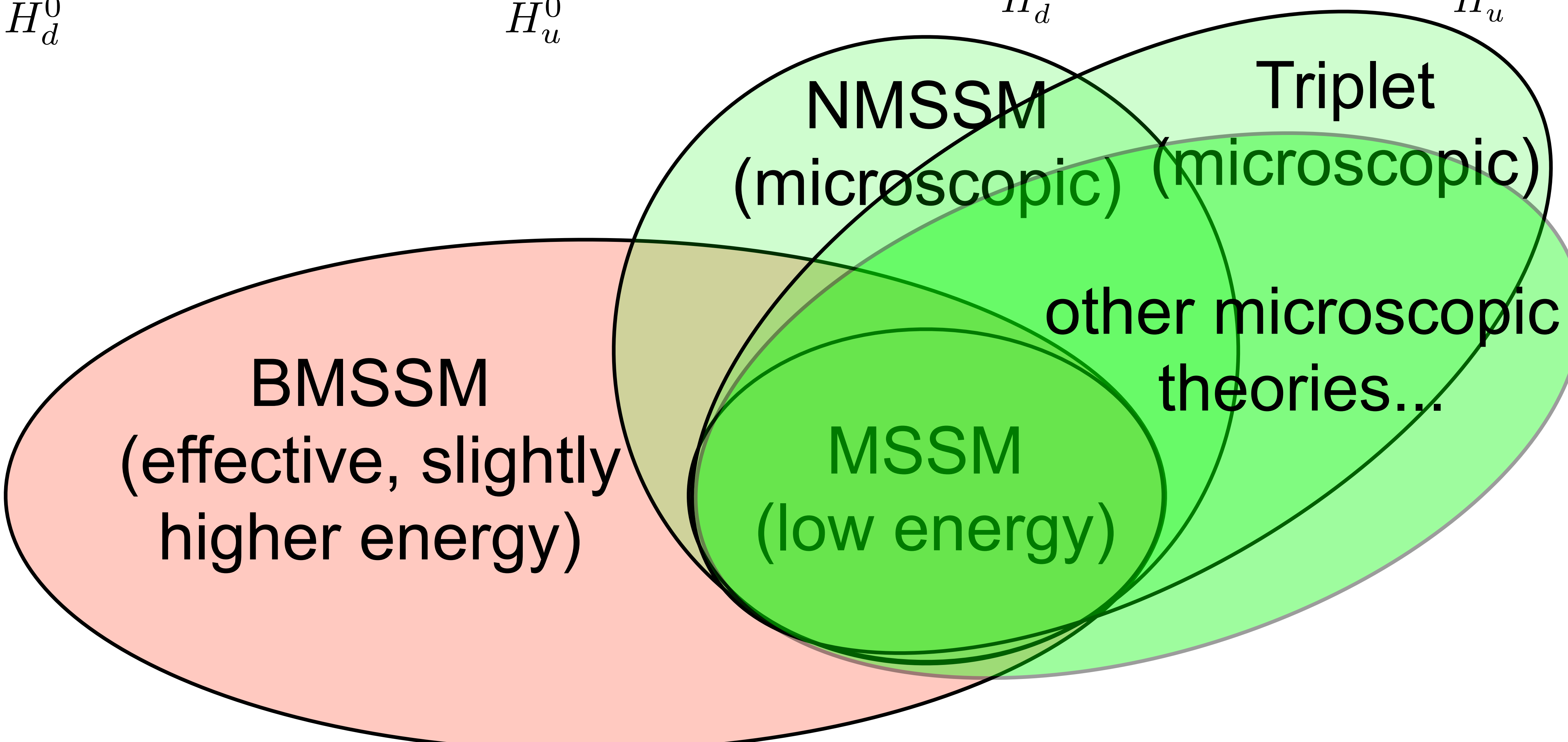
operators of dimension 4 are *minimal*
(e.g Higgs self-coupling completely fixed ~ 0.07,
no free parameter there at all, unlike in SM)

coefficients of higher-dimension operators
set to exactly zero

# Microscopic vs. effective

NMSSM = MSSM + gauge singlet chiral superfield S

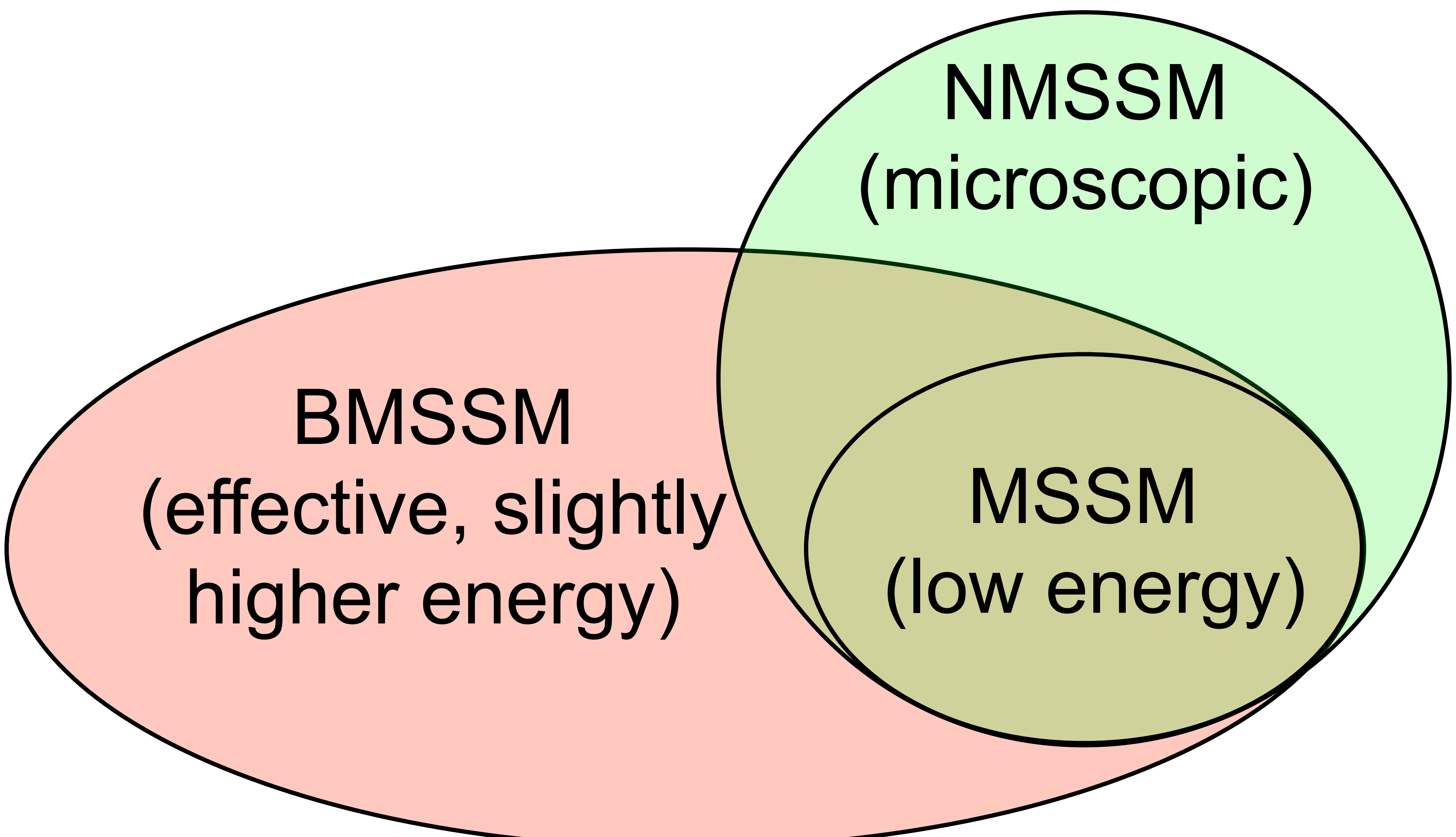


# Microscopic vs. effective

Let's be clear:
microscopic is *better* than effective
if you believe in it (say if it's natural...)

but if you don't know what to believe in,
an effective theory is a good place to start!



# Beyond the MSSM (BMSSM)

$$W = W_{\text{MSSM}} + W_5$$

$$W_5 = \frac{c_0}{M}(H_u H_d)^2 \qquad \epsilon_1 = -\frac{\bar{\mu}\, c_0}{M}$$

first BMSSM subset = MSSM Lagrangian +

$$\left(2\epsilon_1 (H_u H_d)(H_u^\dagger H_u + H_d^\dagger H_d) + \text{ h.c.}\right) \text{ -}$$

$$+\left[\frac{\epsilon_1}{\mu^*}\left(2(\widetilde{H}_u \widetilde{H}_d)(H_u H_d) + 2(H_u \widetilde{H}_d)(\widetilde{H}_u H_d) + (\widetilde{H}_u H_d)^2 + (H_u \widetilde{H}_d)^2\right) + \text{ h.c.}\right]$$

- six operators, one coefficient
- modifies Higgs sector, but also charginos and neutralinos (hence dark matter)
- effective dimension 5, but scaling dimensions 4 and 5
- $H^4$ terms now have one dimensionless free parameter, before were completely fixed.

# Beyond the MSSM (BMSSM)

$$\epsilon_1 = -\frac{\bar{\mu}\, c_0}{M}$$

first BMSSM subset = MSSM Lagrangian +

$$\Big(2\epsilon_1 (H_u H_d)(H_u^\dagger H_u + H_d^\dagger H_d) + \text{ h.c.}\Big)$$
$$+\left[\frac{\epsilon_1}{\mu^*}\Big(2(\widetilde{H}_u\widetilde{H}_d)(H_u H_d) + 2(H_u\widetilde{H}_d)(\widetilde{H}_u H_d) + (\widetilde{H}_u H_d)^2 + (H_u\widetilde{H}_d)^2\Big) + \text{ h.c.}\right]$$

- neglects baryon, lepton number violating operators
- neglects dim-5 operators in squark/slepton sector
- neglects extra CP violation: make coefficients real
- neglects dim-6 operators in Kähler potential ($1/M^2$)

# Beyond the MSSM (BMSSM)

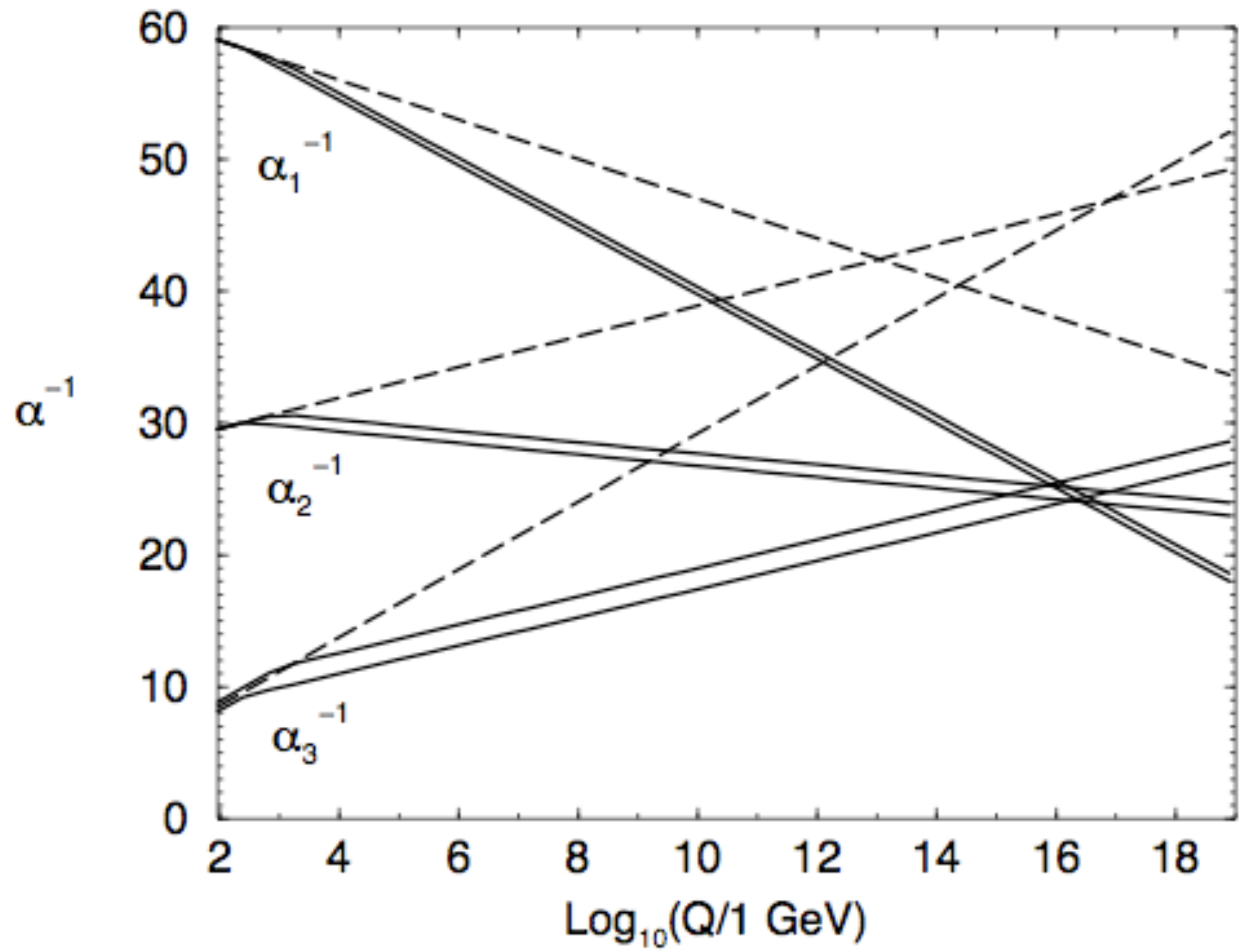
$$\epsilon_1 = -\frac{\bar{\mu}\, c_0}{M}$$

what should M be?

what is a “natural” scale of
new physics beyond the MSSM?

# Scale of new supersymmetric physics?

Contrast the MSSM: no interesting mass scales between the TeV and GUT scale!



# String theory as a source for ideas beyond the Standard Model

Supersymmetry constructed in string theory in 1971

Strings of 1980s: no new physics below GUT/Planck scale

Since around 2000: various scales of new physics:
TeV string scale models (“String Hunter’s Guide”) to intermediate string scales, to Planck scale.

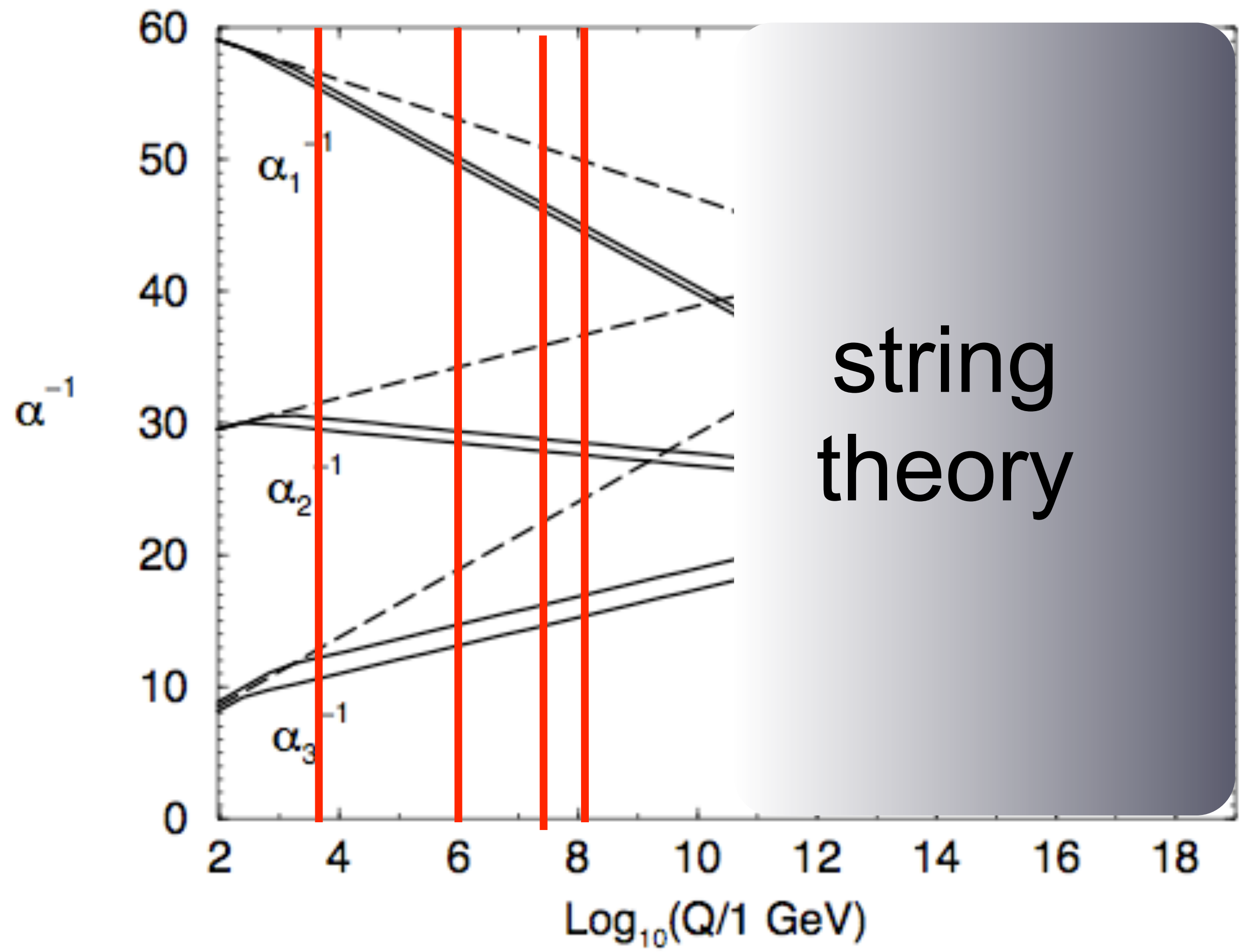
In general, no universal theory argument to exclude nonminimal physics at low scales.

# Scale of new supersymmetric physics?

Balasubramanian, Berglund, Conlon, Quevedo ’05

Sample string model: Large Volume Scenario, string scale around $10^{11}$ GeV.

lower thresholds



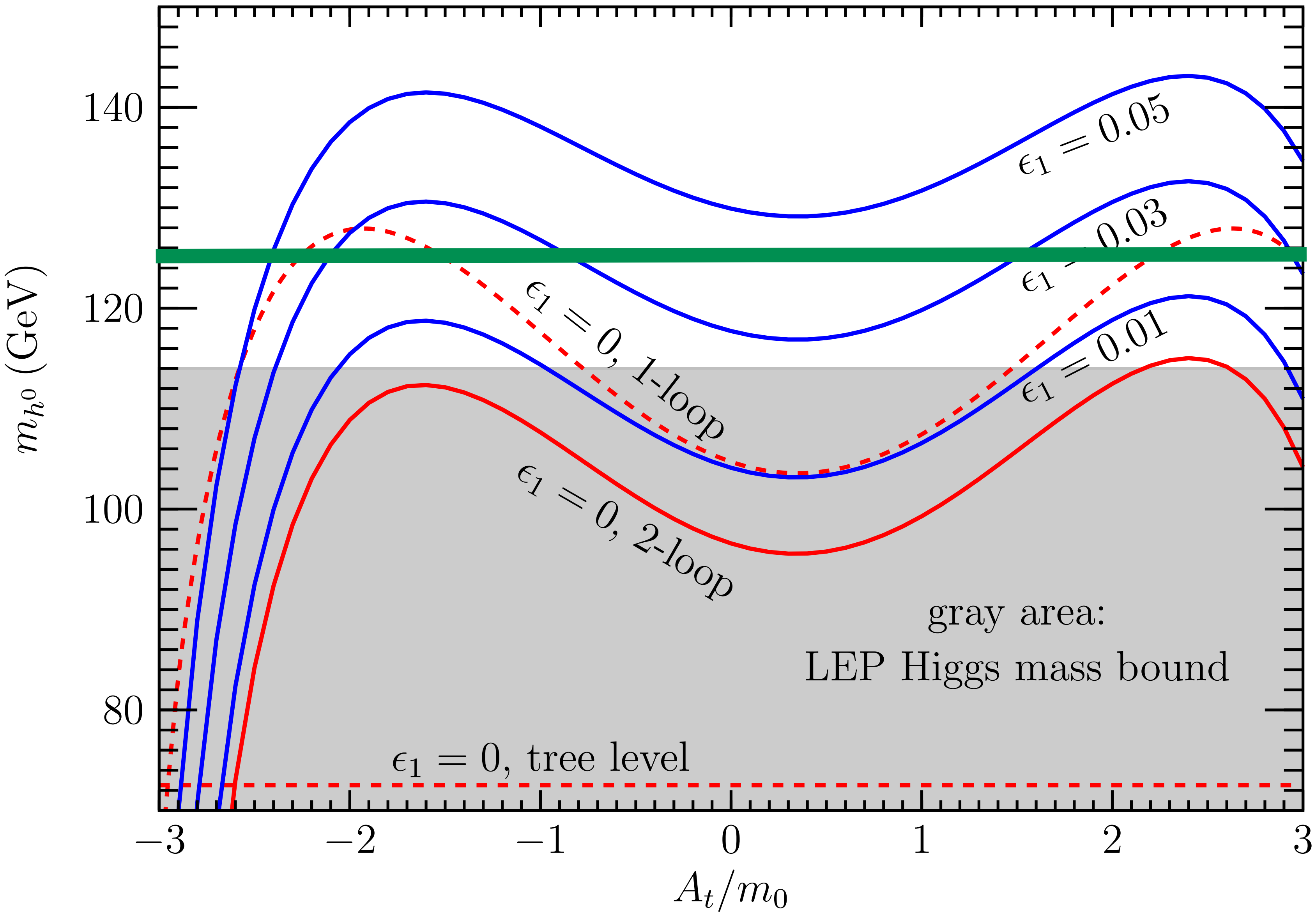
Will allow the scale of new supersymmetric physics to be as low as phenomenologically allowed,
typically $M \sim 5 - 10$ TeV.

# Higgs mass: MSSM vs. BMSSM

$$\epsilon_1 = -\frac{\bar{\mu}\, c_0}{M}$$

M.B., Edsjö, Gondolo, Lundström, Sjörs ’08

(added green band)

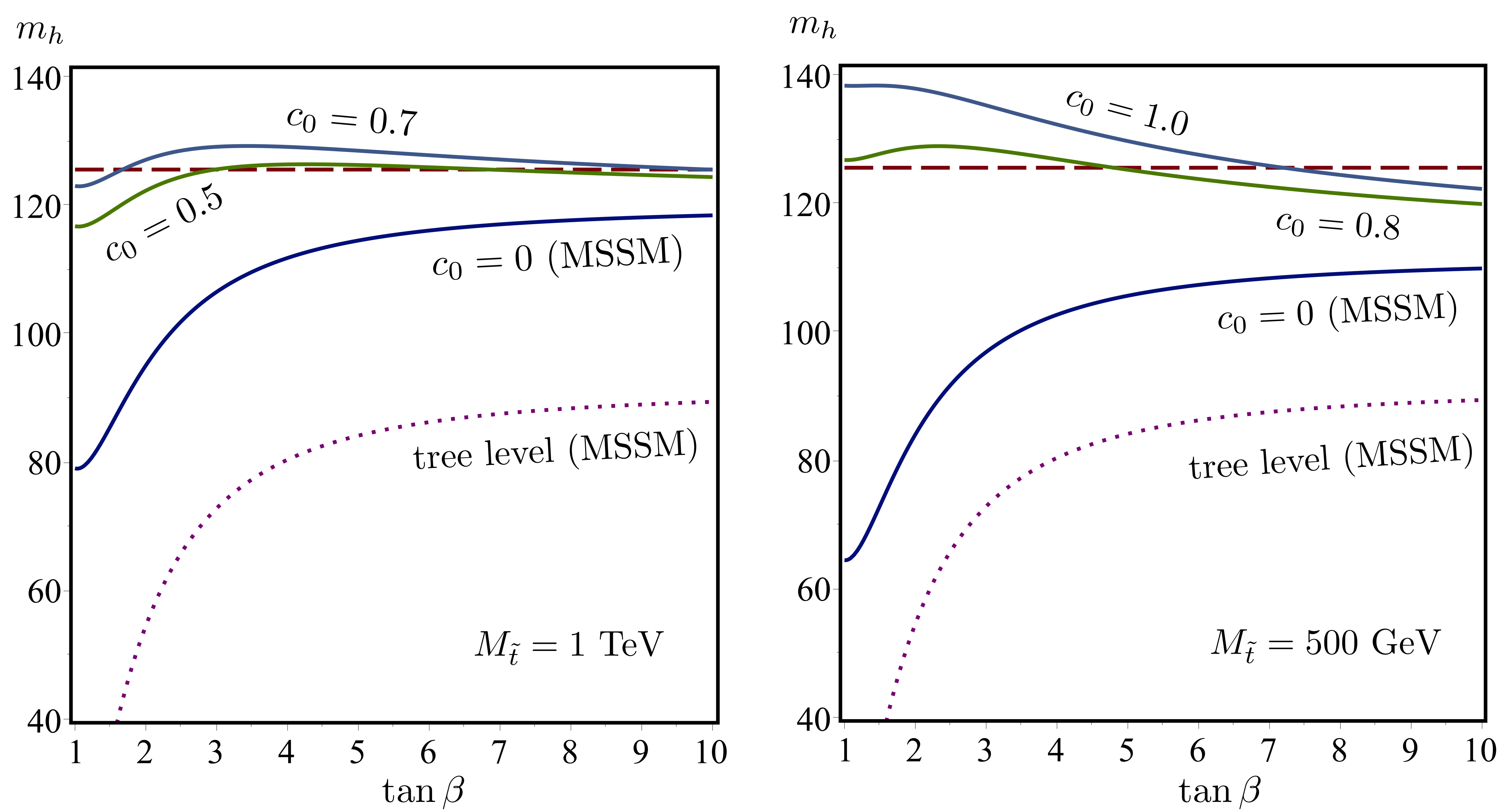



used FeynHiggs for loop corrections

# Higgs mass: MSSM vs. BMSSM

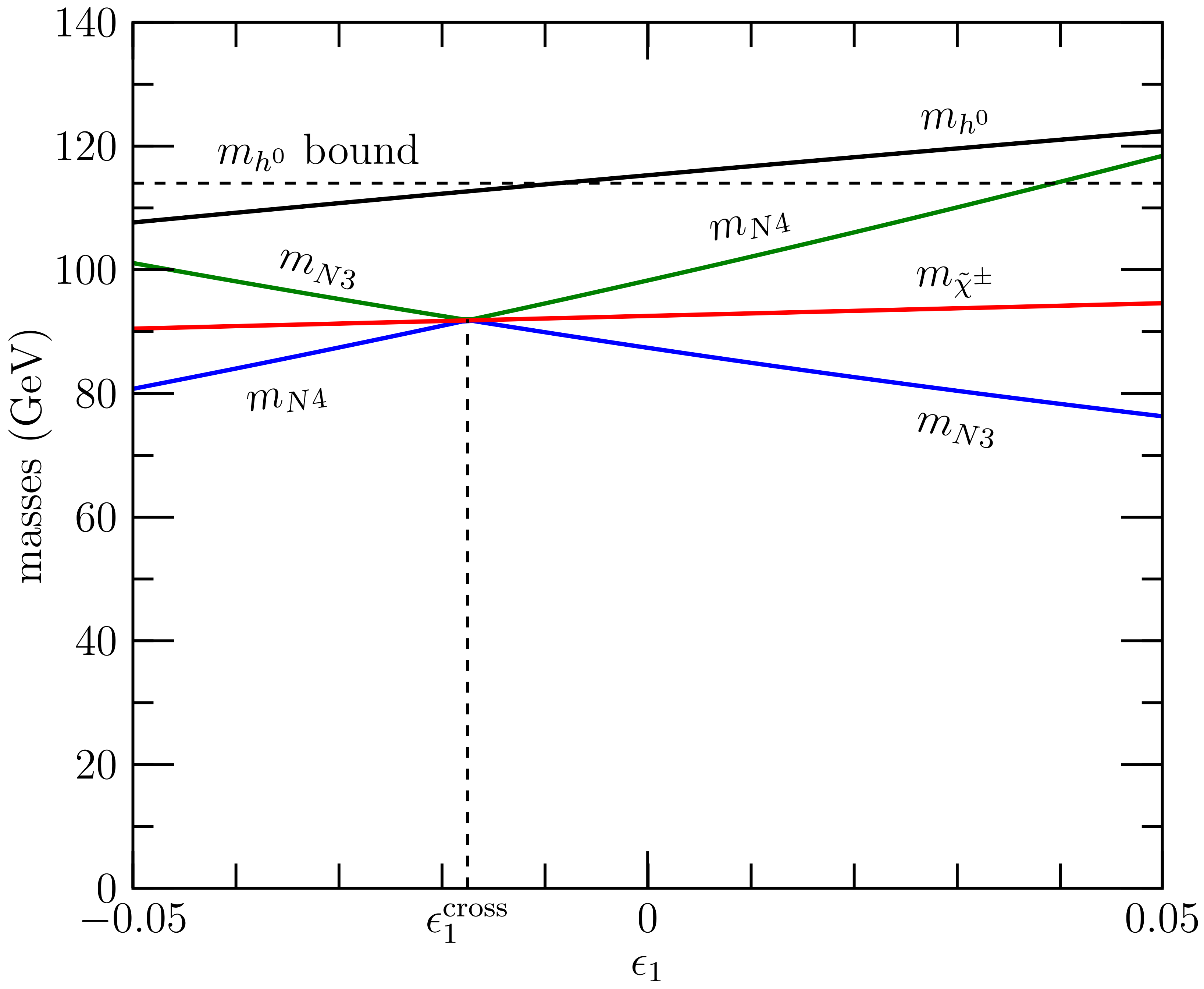
M.B., Buchberger, Ghilencea, Petersson '12

$M = 5\,\mathrm{TeV}$



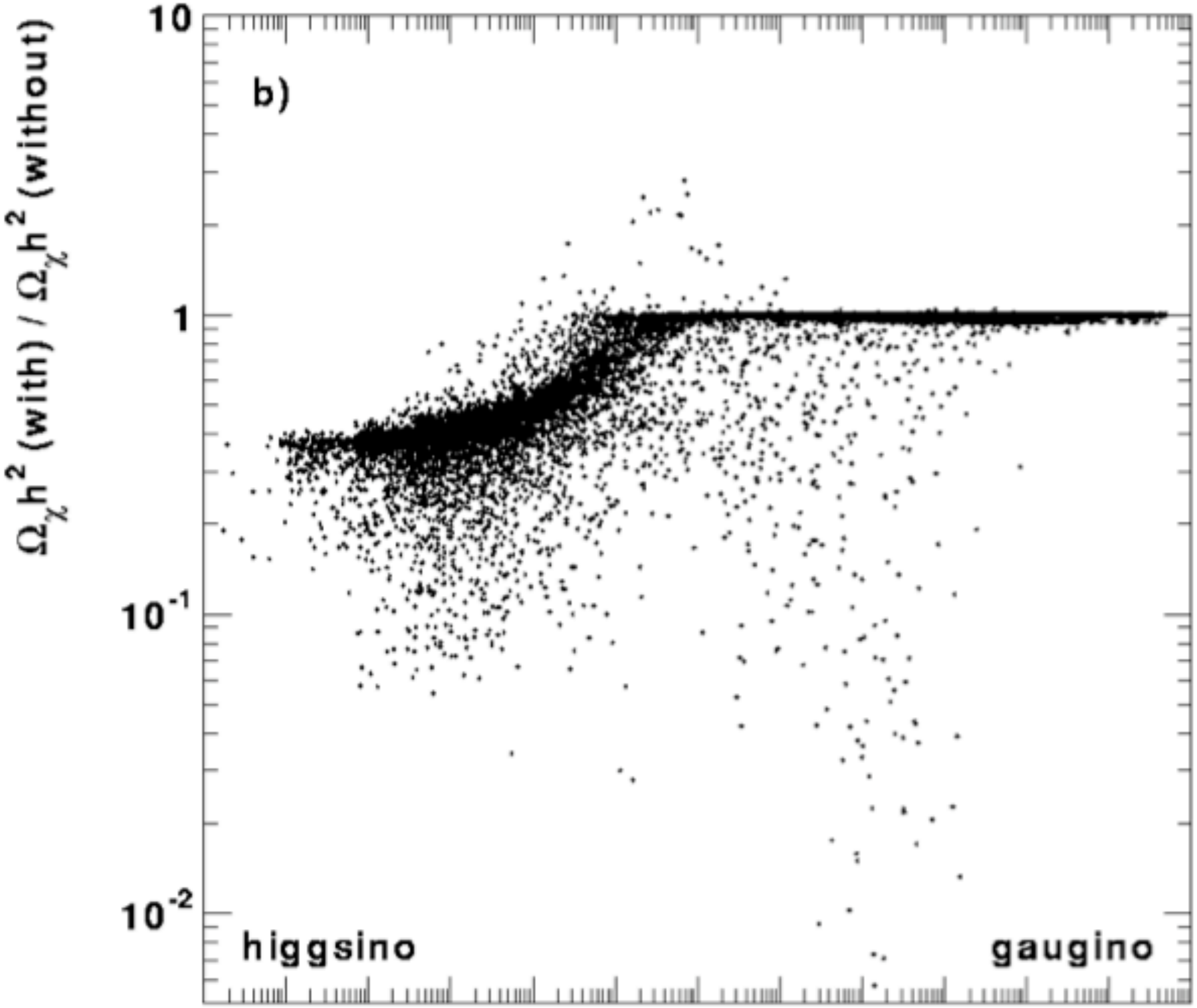

used simple but decent approximations
for one-loop and leading two-loop corrections.

# BMSSM neutralino-chargino splitting




LEP bound on chargino mass $m_{\chi^{\pm}}$
more stringent that that on neutralino:
helps to be able to increase chargino mass

# Coannihilation for near mass degeneracy

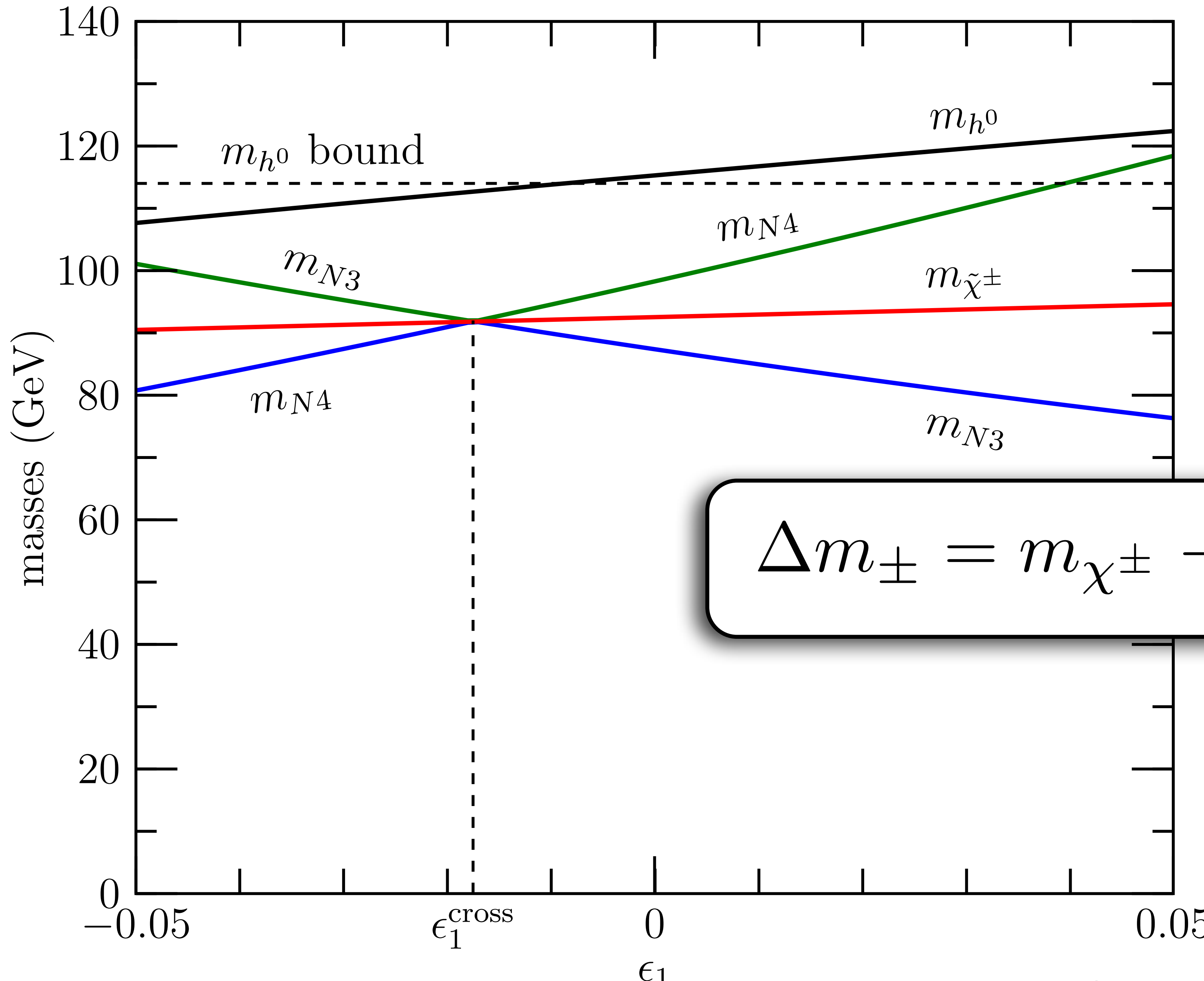



Griest, Seckel '91
...
Edsjö, Gondolo '97
...

"co-annihilations": with a velocity distribution,
a small mass difference gives increased annihilation
prevents most light Higgsinos from giving decent dark matter

# BMSSM neutralino-chargino splitting

M.B., Edsjö, Gondolo, Lundström, Sjörs '08

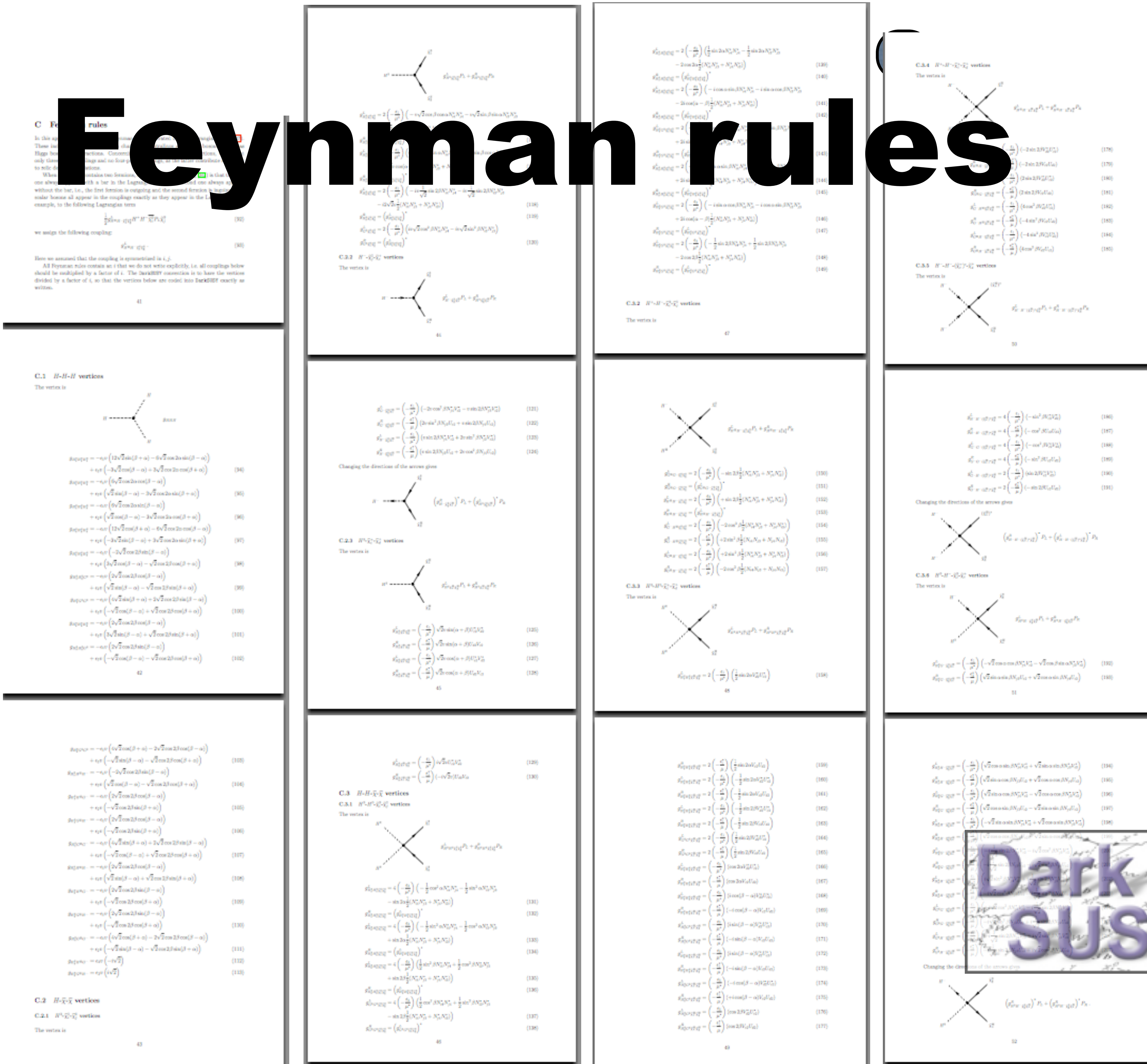



$$\Delta m_\pm = m_{\chi^\pm} - m_{\rm LSP}$$

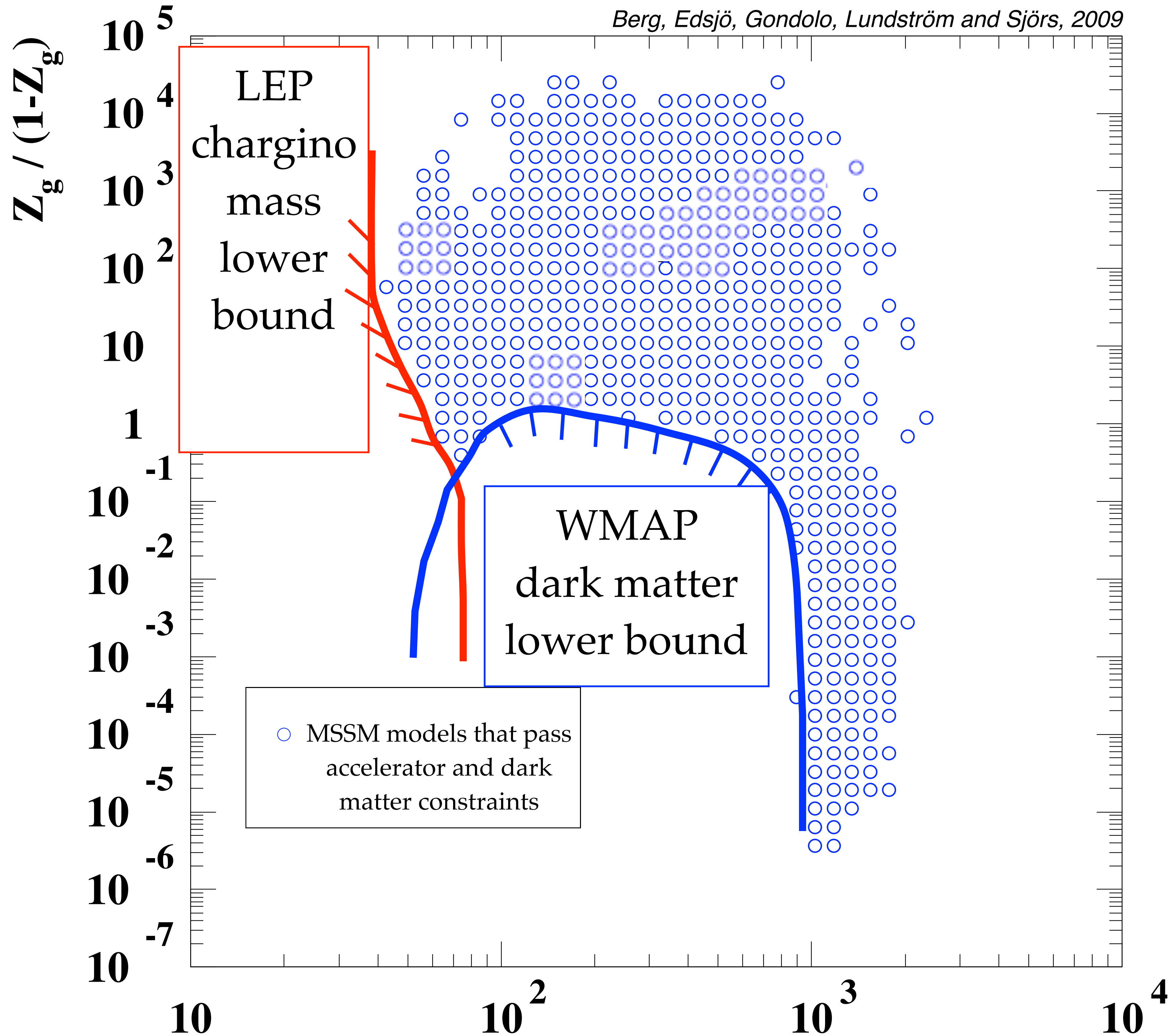
for regions of parameter space where $\Omega_\chi h^2$ is too low:

need $\Delta m_\pm > 3$ GeV to prevent coannihiltions

# Feynman rules

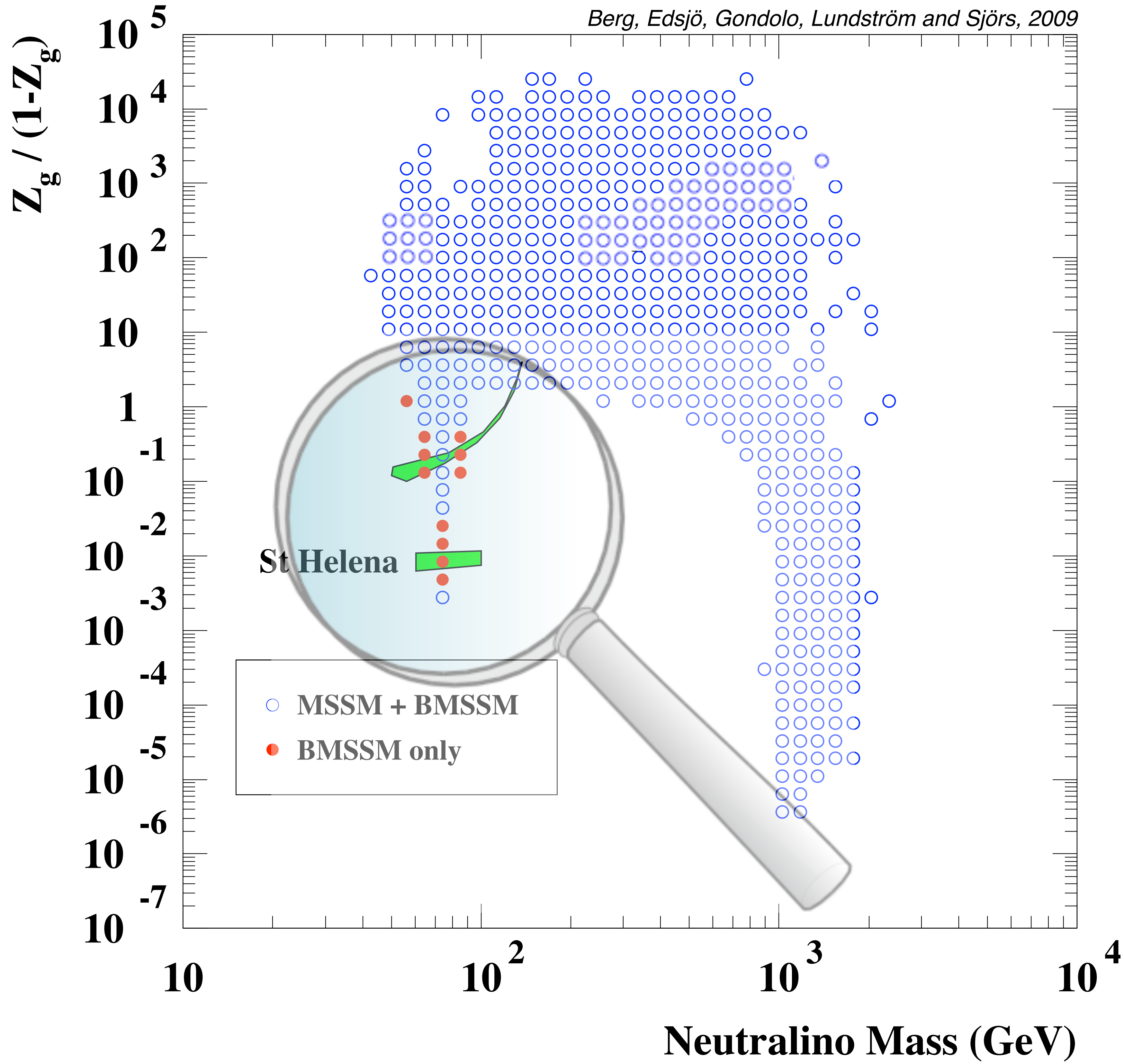


# Parameter scan

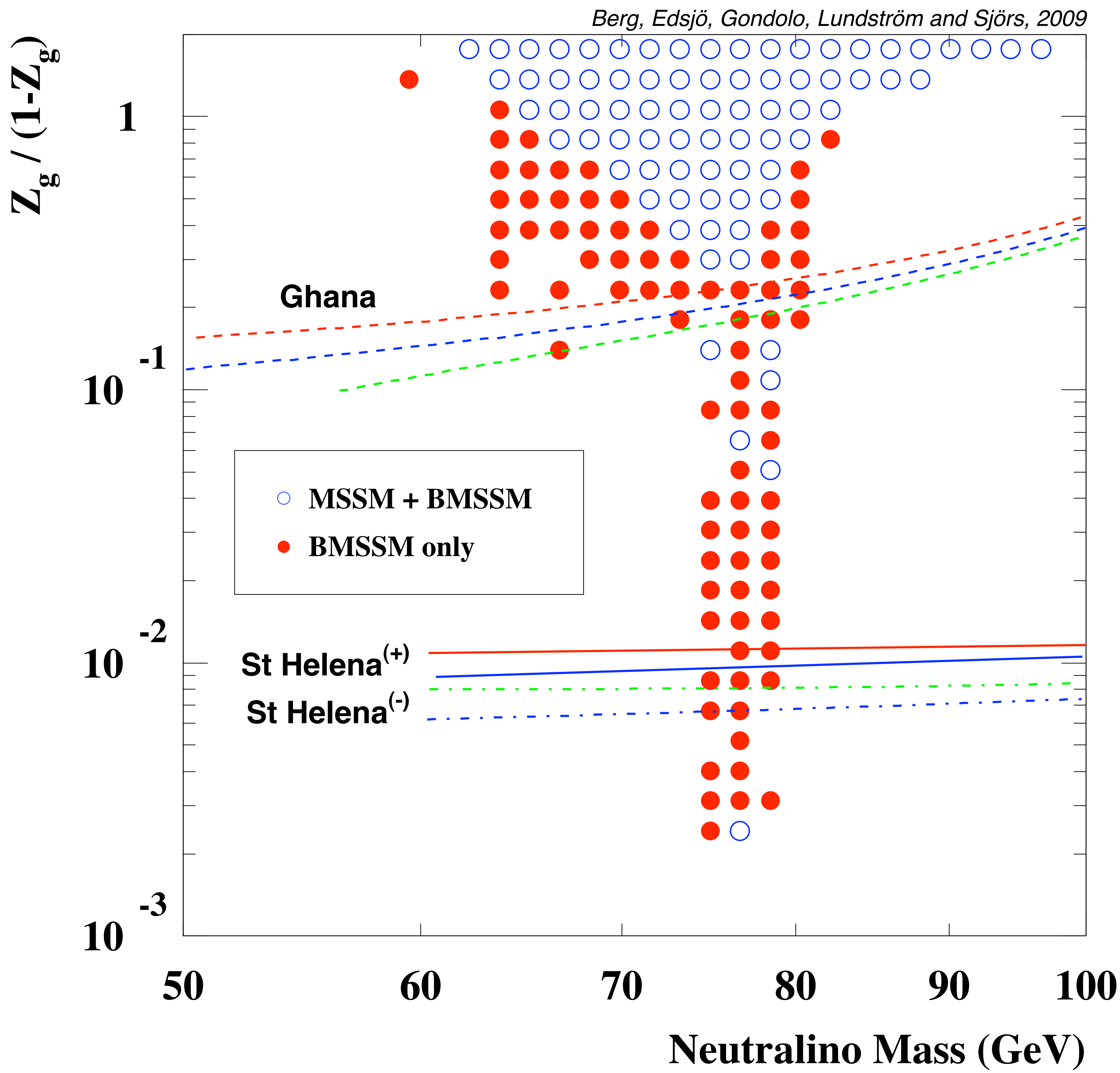



co-annihilations prevent most light Higgsinos from being decent dark matter

# The Quest for New BMSSM Models



# BMSSM vs MSSM: Light Higgsinos

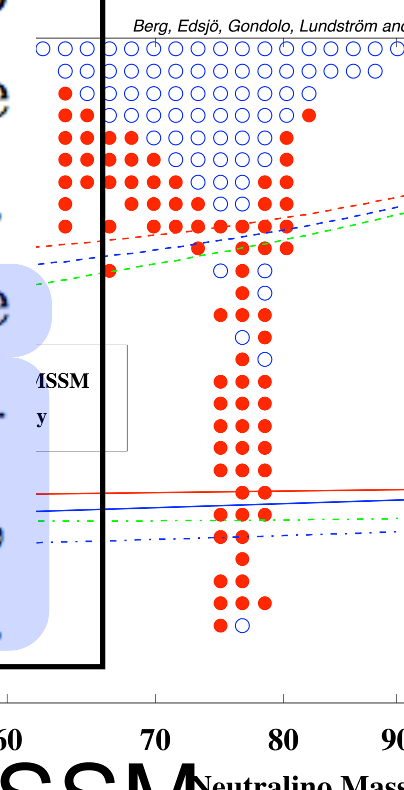


# PDG supersymmetry searches, summary

...

from $W$ pair production, was observed. A scan over $M_2$, $\mu$, and $\tan\beta$ provided a robust chargino mass lower limit of 103 GeV for sneutrino masses larger than 200 GeV [7], except for unnaturally large values of $M_2$ ($>\sim$ 1 TeV), in the so-called "deep higgsino" region, where the $\tilde{\chi}^{\pm}$–$\tilde{\chi}^0_1$ mass splitting is very small.

This limit is degraded for lower sneutrino masses for two reasons. First, the production cross section is reduced by the negative interference between the $s$- and $t$-channel exchanges. Second, two-body decays open up, which may reduce the selection efficiency. This is the case in particular in the so-called "corridor" where $m_{\tilde{\chi}^{\pm}} - m_{\tilde{\nu}}$ is smaller than a few GeV, so that the lepton from the $\tilde{\chi}^{\pm} \to \ell\tilde{\nu}$ decay is hardly visible.



if we can finetune MSSM parameters to mimic BMSSM physics, how could we ever decide?

# 1976 Oxford-Seattle “bismuth crisis”

“There were still two experiments that contradicted the [Glashow-Weinberg-Salam] theory’s predictions for the neutral-current weak force between electrons and nuclei and only one that supported them [...]

Why then [...] did physicists generally agree that the theory must indeed be correct? One of the reasons surely was that we were all relieved that we were not going to have to deal with any of the unnatural variants of the original electroweak theory. ...”

S. Weinberg, Dreams of a Final Theory (1992)

# 1976 Oxford-Seattle "bismuth crisis"

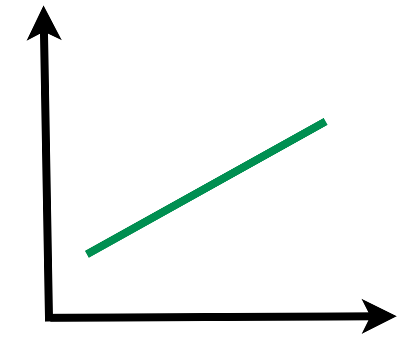
"The aesthetic criterion of naturalness was being used to help physicists weigh conflicting experimental data."

S. Weinberg, Dreams of a Final Theory (1992)

# Moral for MSSM vs. BMSSM?

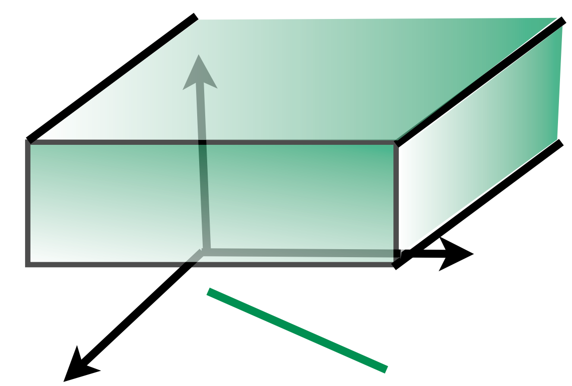
Let's say you have two models to fit a single signature:

**Model A**



2 parameters, only fits signature for specific relation between them, without explanation (e.g. symmetry)

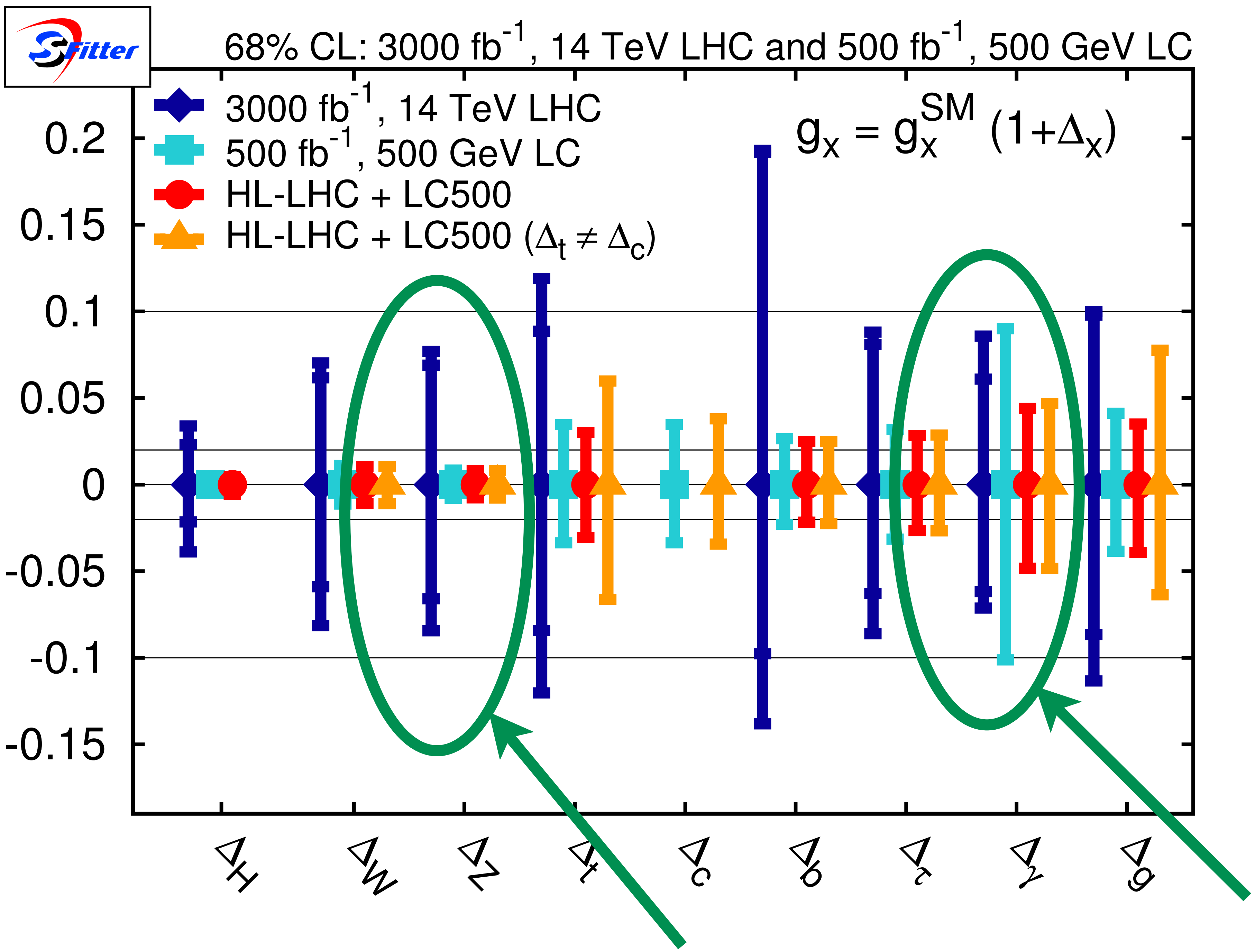
**Model B**



2+1 parameters, fits signature for any value 0.1 to 1

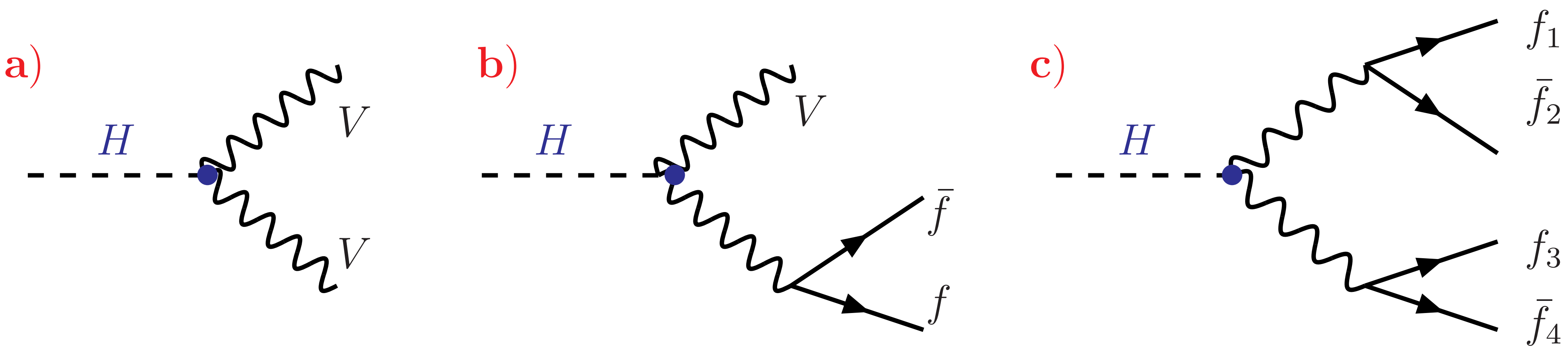
Which one is more beautiful?

# Higgs couplings: expected accuracy



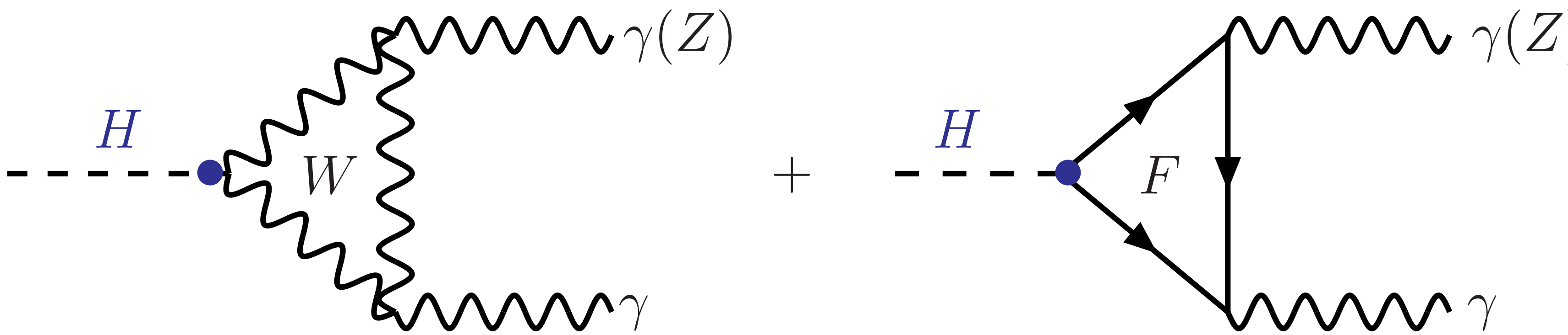

Klute, Lafaye, Plehn, Rauch, Zerwas '13

# Higgs to Z (or W), to leptons




big tree-level coupling
not optimal probe of new physics

# Higgs to Diphoton in the SM

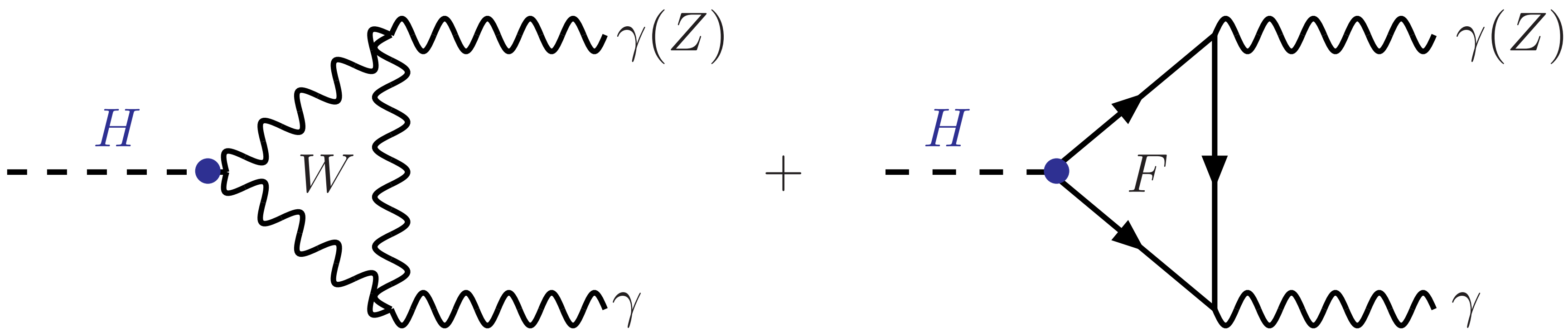



loop-level coupling – small

good probe of new physics

e.g. Djouadi ’05

# Higgs to Diphoton in the SM

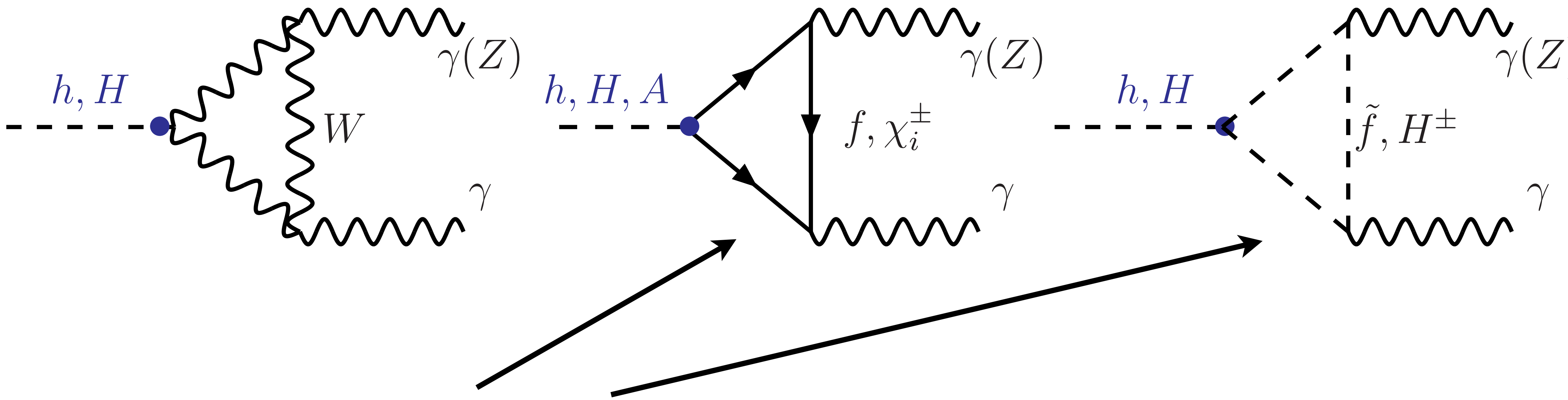



W loop and top loop:

$$-1 \qquad + \qquad \frac{1}{5}$$

e.g. Djouadi ’05

# Higgs to Diphoton in the MSSM




Most of these give *positive* contributions, hence *decrease* the partial width

100-150 GeV sleptons would be an exception, but eventually will have LHC bounds. Can be avoided by "hiding sleptons". Still: for large enough excess, MSSM is disfavored for almost all parameter values!

Also: vacuum stability? (In BMSSM, automatic!)

# Higgs to Diphoton in the BMSSM

Antoniadis, Dudas, Ghilencea, Tziveloglou '09
Heckman, Kumar, Wecht '12
M.B., Buchberger, Ghilencea, Petersson '12

$$\frac{c_i}{M^2}\int d^2\theta\,(H_u H_d)\,\mathrm{Tr}\,W^\alpha W_\alpha$$

One for SU(2), one for U(1): two parameters $c_1$, $c_2$

Also keep dimension 5 operator with coefficient $c_0$

# Higgs to Diphoton in the BMSSM

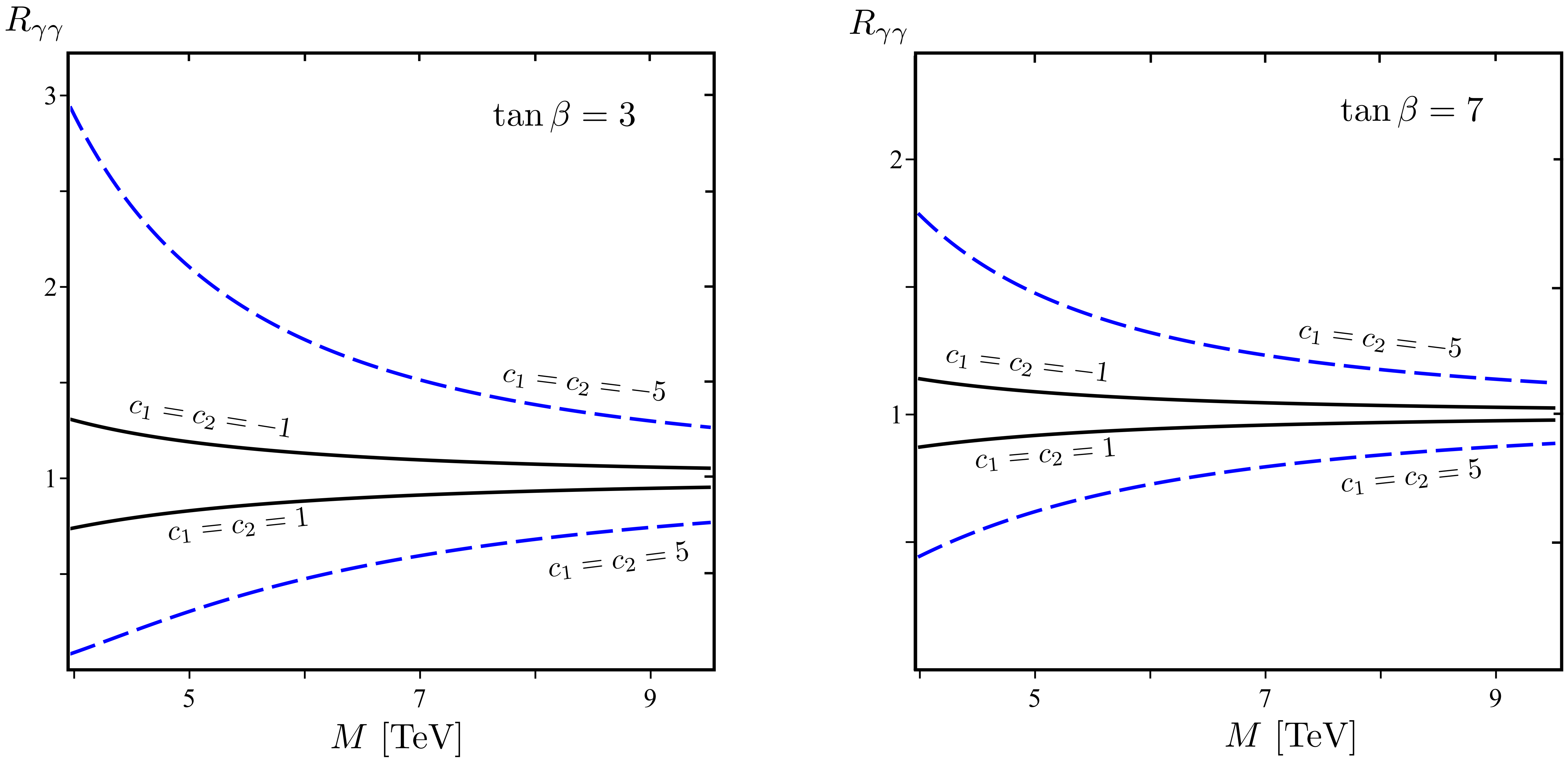
$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{2}\;\Big[D_2^a D_2^a\;\Big(1+\frac{c_2}{2M^2}\,(h_u\cdot h_d+\mathrm{h.c.})\Big)+(2\to 1)\Big] \\
- & \;\Big|\mu+2\,\frac{c_0}{M}\,h_d\cdot h_u\Big|^2\;\left(|h_d|^2+|h_u|^2\right)+\Big[\frac{\mu}{4}\;\Big(\frac{c_2}{M^2}\,\lambda_2^a\,\lambda_2^a+\frac{c_1}{M^2}\lambda_1^2\Big)\left(|h_d|^2+|h_u|^2\right)+\mathrm{h.c.}\Big] \\
+ & \;\Big\{\frac{c_2}{4M^2}\,(h_u\cdot h_d)\Big[i\,(\lambda_2^a\sigma^\mu\mathcal{D}_\mu\overline{\lambda}_2^a-\mathcal{D}_\mu\overline{\lambda}_2^a\overline{\sigma}^\mu\lambda_2^a)\Big]+\mathrm{h.c.}+(2\to 1)\Big\} \\
+ & \;\frac{c_0}{M}\Big[2\,(h_u\cdot h_d)(\psi_d\cdot\psi_u)-(h_u\cdot\psi_d+\psi_u\cdot h_d)^2\Big]+\mathrm{h.c.} \\
+ & \;\Big\{\frac{c_2}{4M^2}\;\Big[-\frac{1}{2}\,(h_u\cdot h_d)\,(F_2^{a\,\mu\nu}F^a_{2\,\mu\nu}+\frac{i}{2}\,\epsilon^{\mu\nu\rho\sigma}F^a_{2\,\mu\nu}F^a_{2\,\rho\sigma}) \\
- & \;\sqrt{2}\,(h_u\cdot\psi_d+\psi_u\cdot h_d)\,\sigma^{\mu\nu}\lambda_2^a F^a_{2\,\mu\nu}-\psi_u\cdot\psi_d\,\lambda_2^a\lambda_2^a\;\Big]+(2\to 1)+\mathrm{h.c.}\Big\} \\
+ & \;\Big[\mu\,B\,(h_d\cdot h_u)+\mathrm{h.c.}\Big]-\tilde{m}_d^2\,|h_d|^2-\tilde{m}_u^2|h_u|^2
\end{aligned}
$$

One for SU(2), one for U(1): two parameters $c_1$, $c_2$

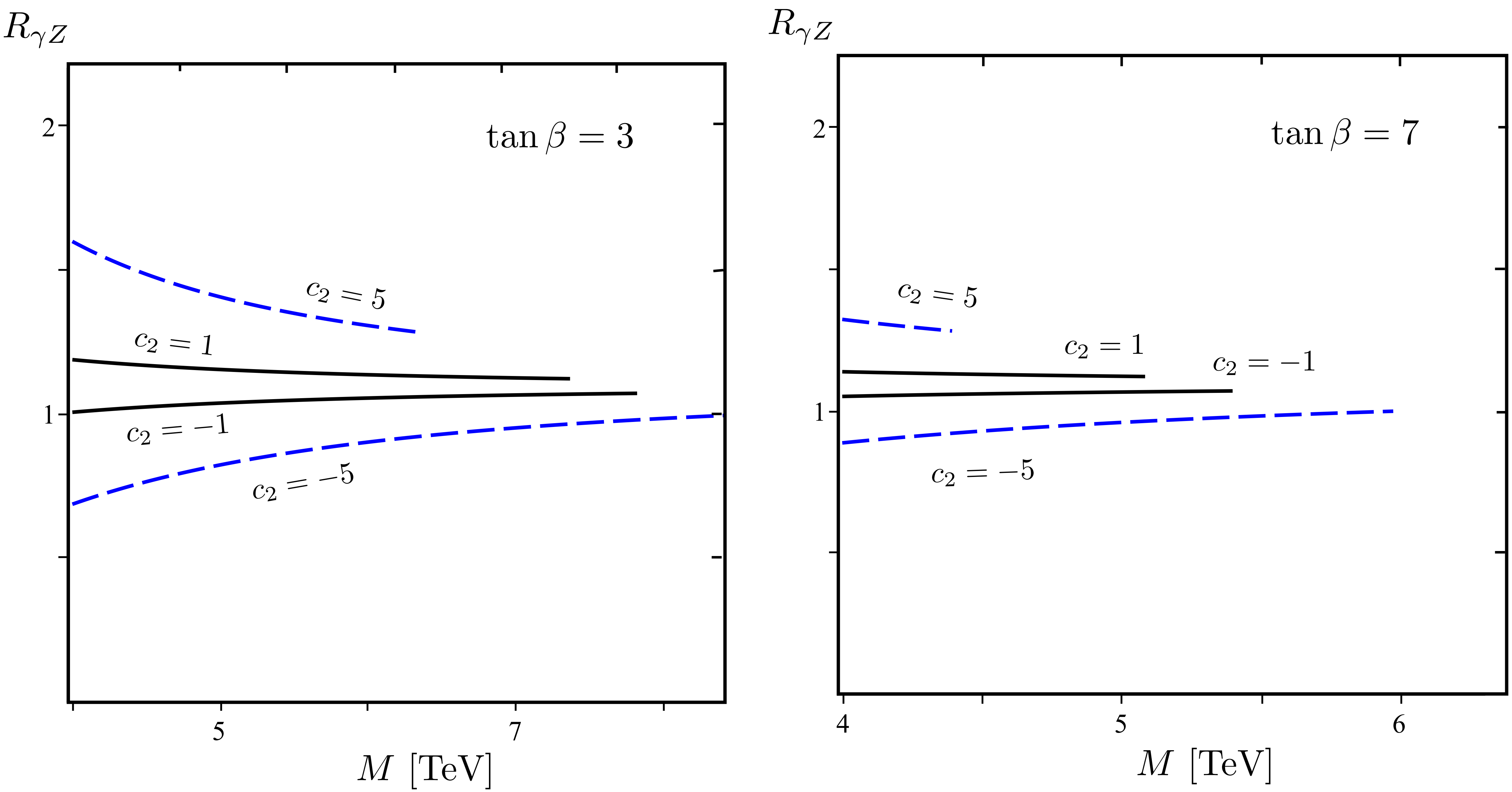
Also keep dimension 5 operator with coefficient $c_0$

# Higgs to Diphoton in the BMSSM

$$R_{\gamma\gamma} = \frac{\Gamma_{h\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{h\gamma\gamma}} = \left| 1 + \frac{c^{\mathrm{BMSSM}}_{\gamma,\mathrm{dec}}}{c^{\mathrm{SM}}_{\gamma}} \right|^2$$



# Higgs to Z gamma in the BMSSM



# Beyond the MSSM (BMSSM)

Point: there can be phenomenology that is not easy to describe in the MSSM

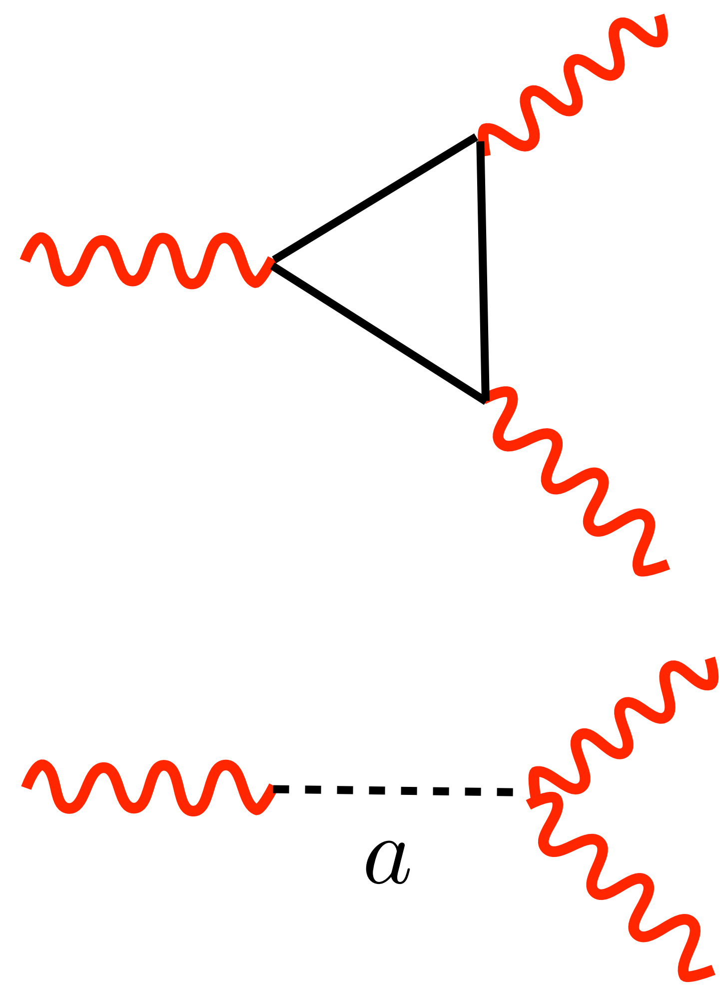
if so, may be better to add a BMSSM parameter rather than the 23rd MSSM parameter.

# 2. Z' and (4D version of) Green-Schwarz anomaly cancellation

Nonminimal gauge bosons:
anomalies cancel between triangle and additional axion couplings

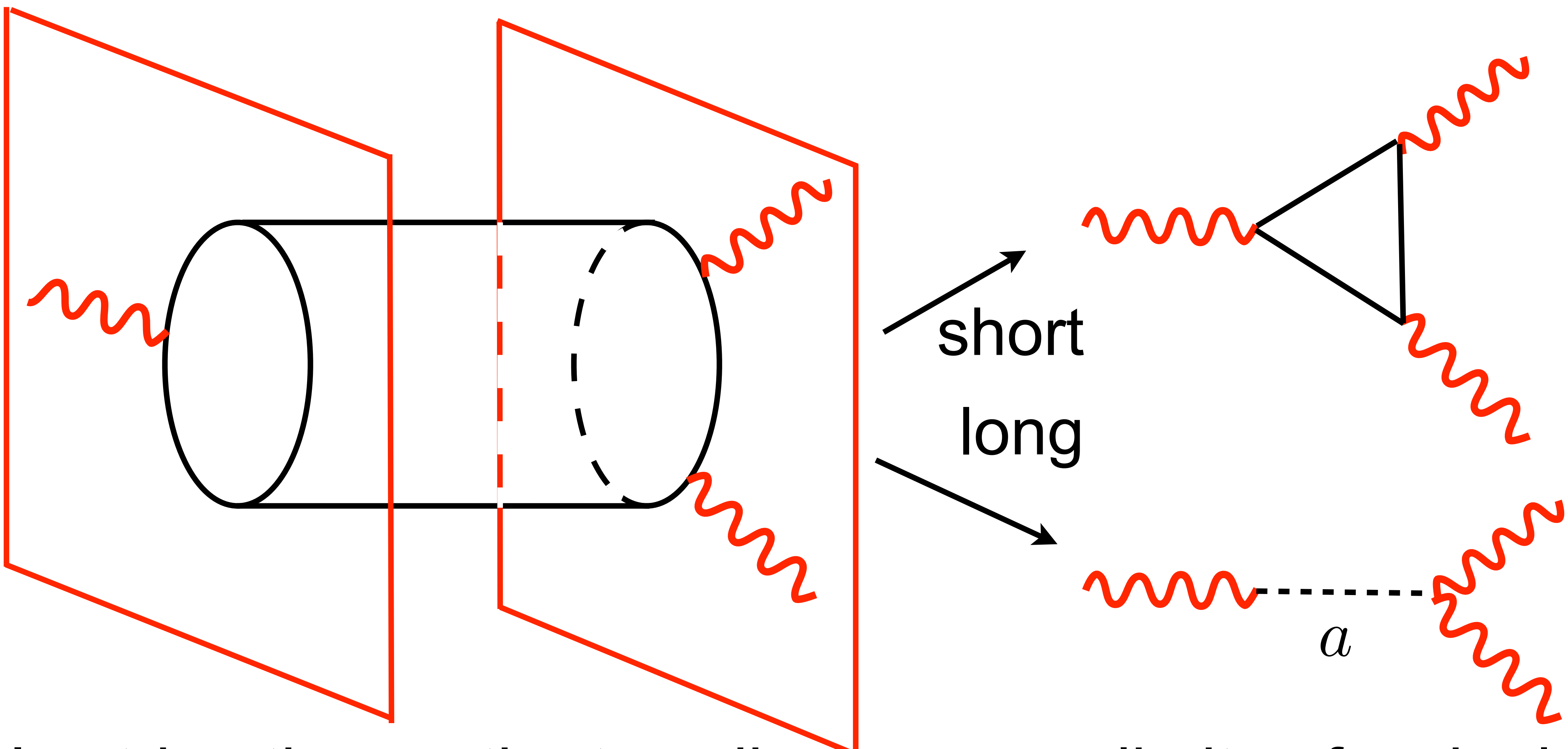
Couplings are not only "finetuned", but axion coupling must contain loop factor.

Sometimes called "anomalous U(1)" – but there is no anomaly.




e.g. Anastasopoulos et al '08

# Z' and (4D version of) Green-Schwarz anomaly cancellation



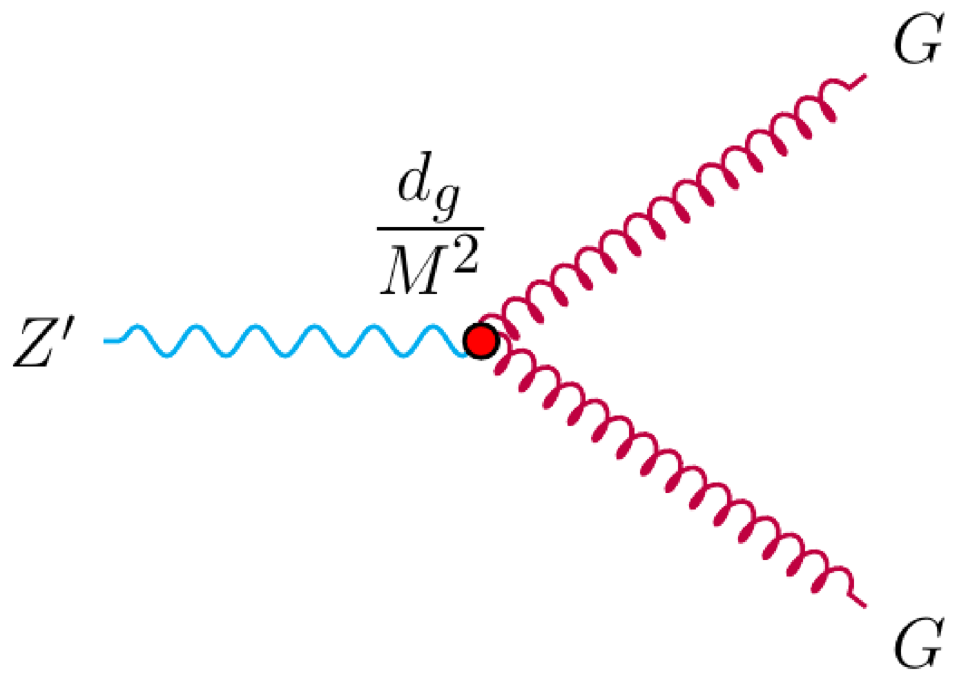

In string theory, the two diagrams are limits of a single diagram, so relation between couplings is built in.

If this was found, would you believe in string theory?

e.g. Anastasopoulos et al '08

# Some nonminimal Z' phenomenology

Standard Model neutral under Z'

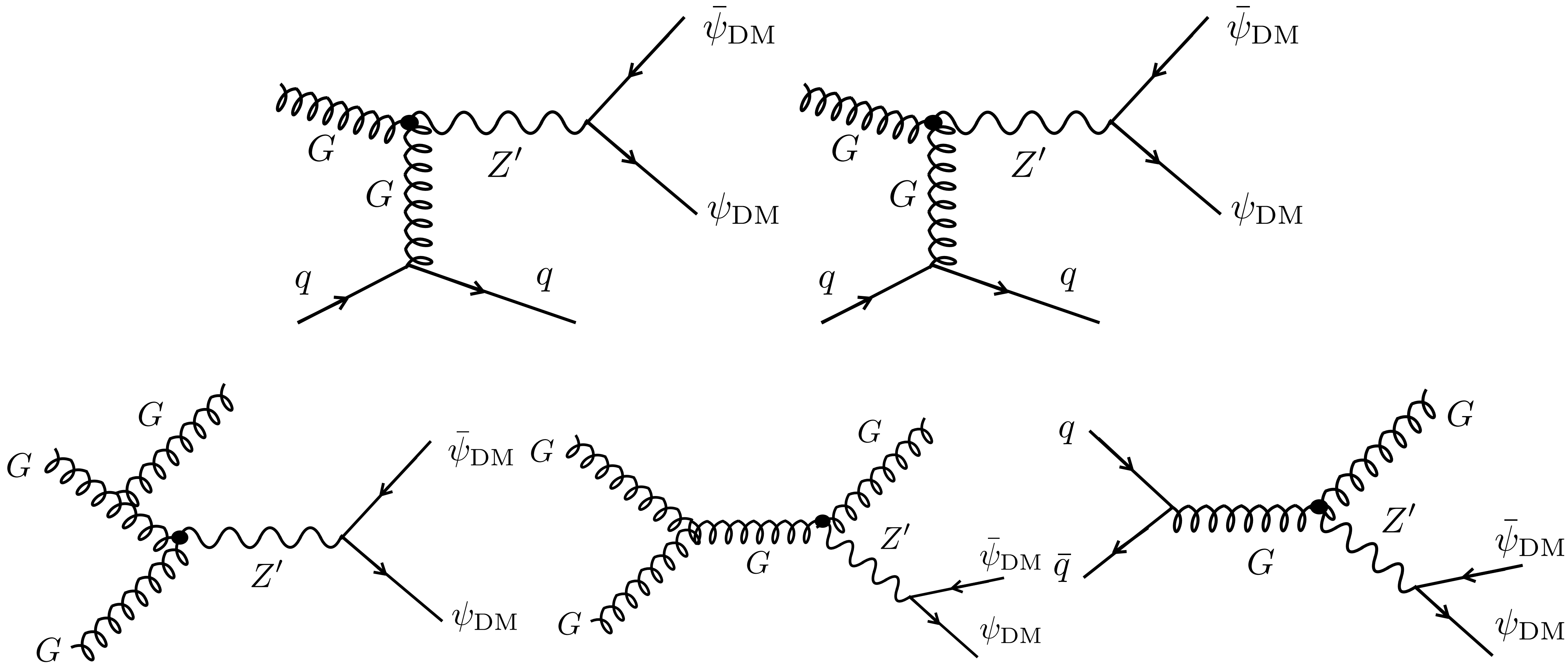



lightest stable fermion charged under Z'
is dark matter $\psi_{\mathrm{DM}}$

Dudas, Heurtier, Mambrini, Zaldivar '13

# Some nonminimal Z' phenomenology

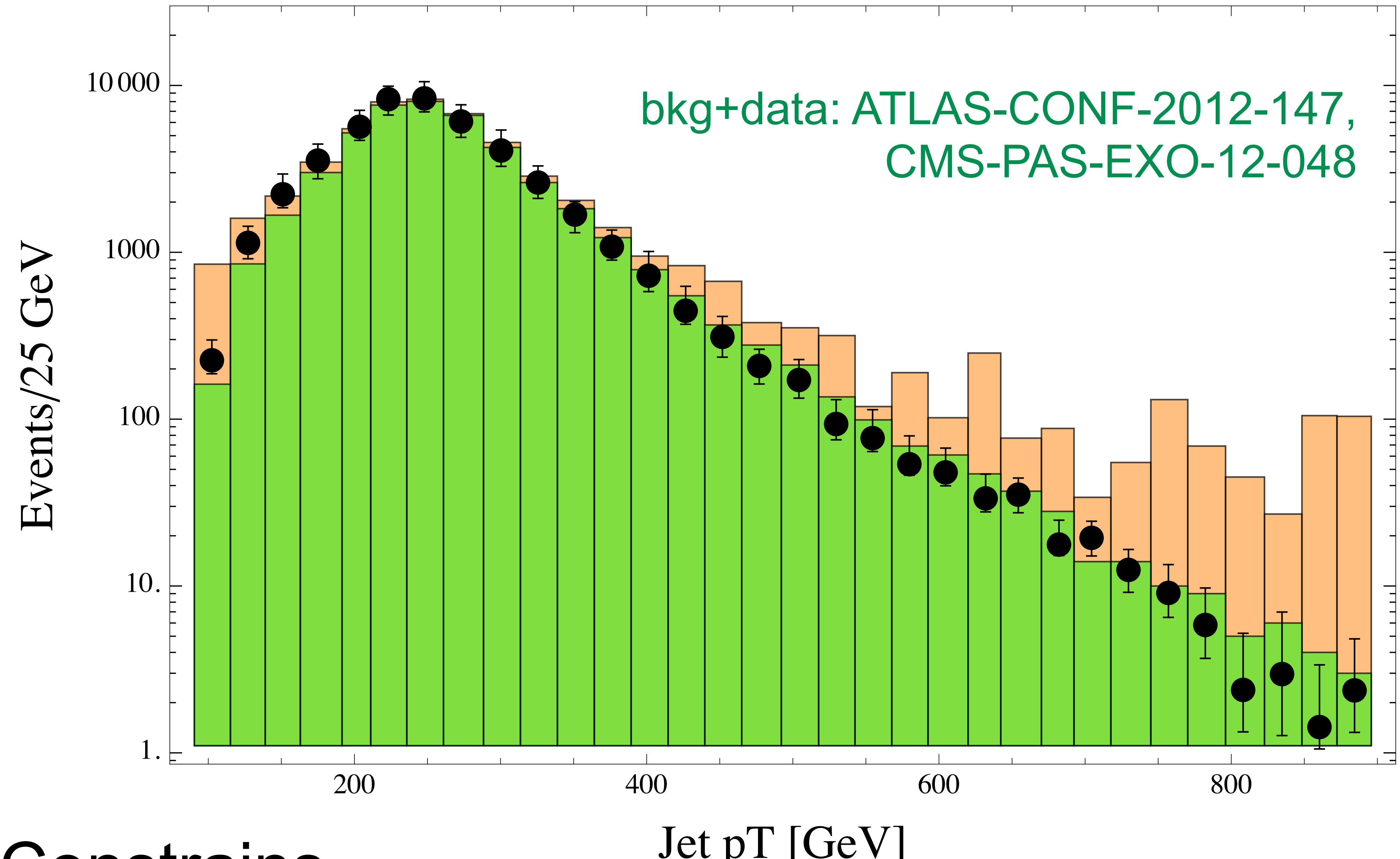
Monojet phenomenology: $p\,p \to j\,\bar{\psi}_{\rm DM}\,\psi_{\rm DM}$




Dudas, Heurtier, Mambrini, Zaldivar ’13

# Some nonminimal Z' phenomenology

Some monojet phenomenology: $p\,p \to j\,\bar{\psi}_{\mathrm{DM}}\,\psi_{\mathrm{DM}}$




Constrains coefficient to ~ $10^{-5}$

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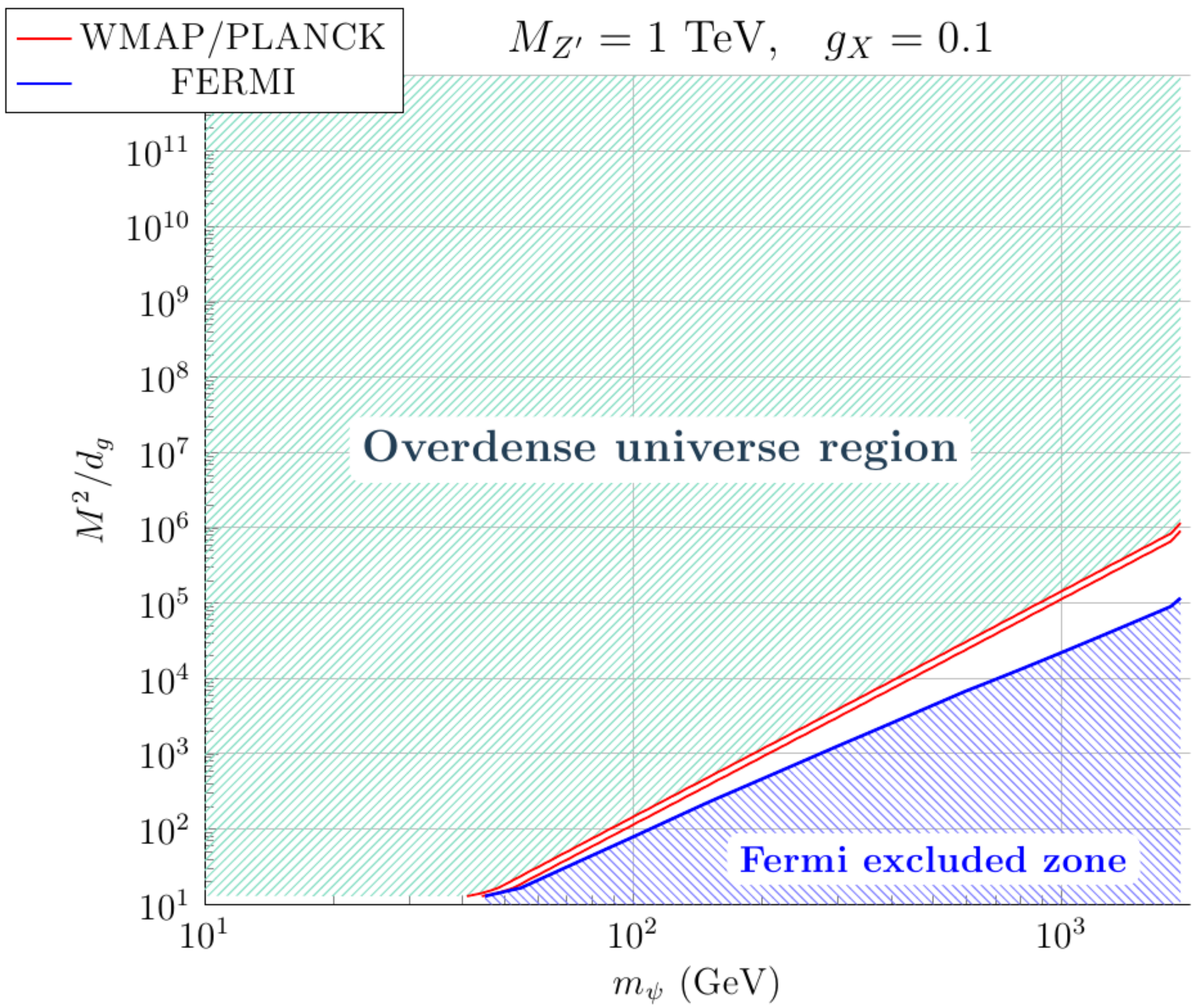
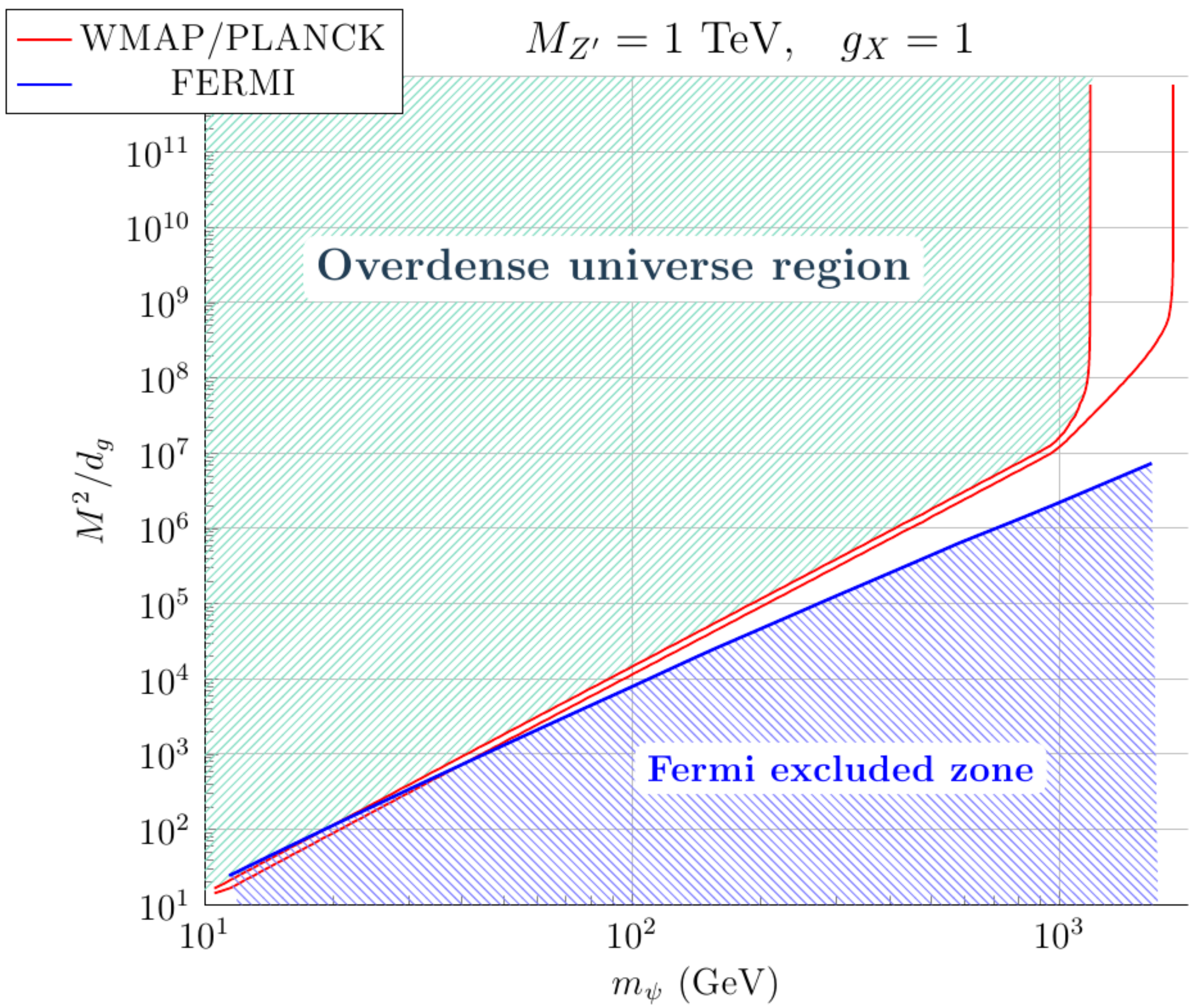
# Some nonminimal Z' phenomenology

$$\langle \sigma v \rangle \sim \left( \frac{d_g}{M^2} \right)^2 \cdot \frac{m_\psi^6}{M_{Z'}^4}$$

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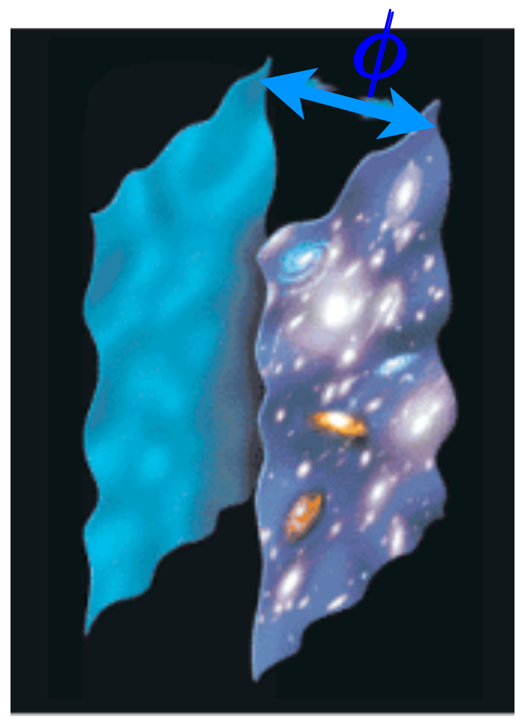
# 3.Supersymmetry and flavor physics

Randall, Sundrum '98

brane models strongly constrain soft terms: "sequestering" supposed to solve supersymmetry flavor problem

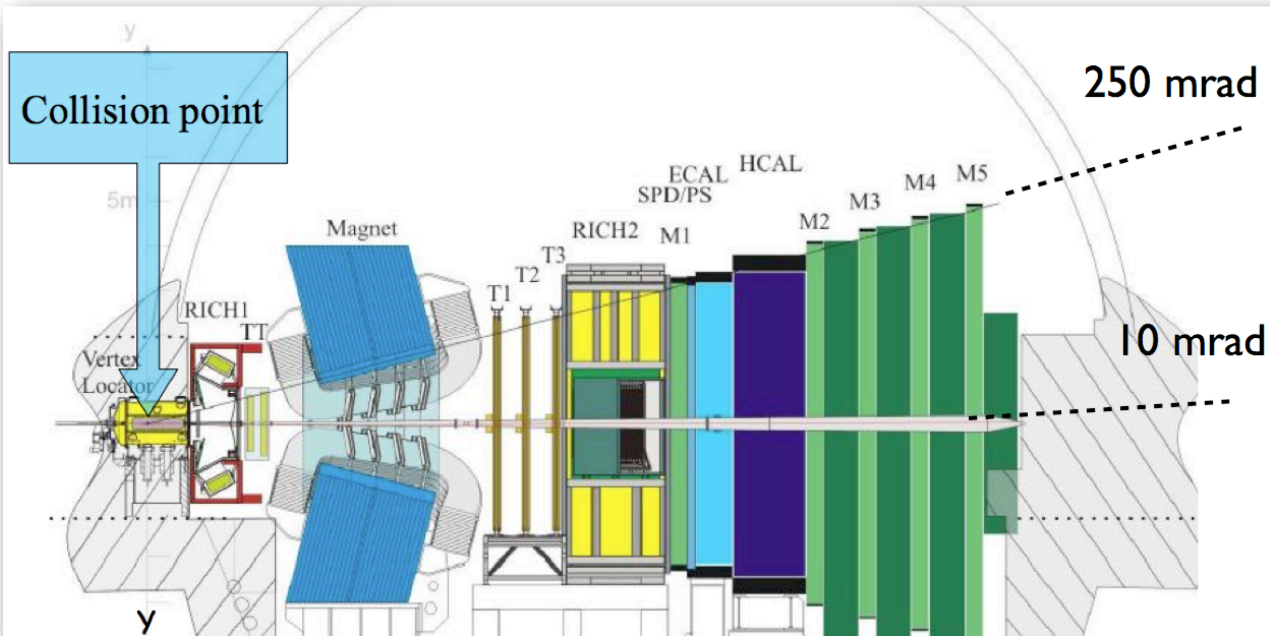



$$\left(f = -3M_P^2 e^{-\frac{K}{3M_P^2}}\right)$$

$$\begin{aligned} f &= f_{\text{hid}} + f_{\text{vis}} \\ W &= W_{\text{hid}} + W_{\text{vis}} \end{aligned} \quad \Rightarrow \; A_{ijk} = 0\,, \quad m^2_{i\bar{\jmath}} = 0$$

this simple ansatz "clears the way" for anomaly mediation

# Supersymmetry and flavor physics




LHCb experiment

LHCb collaboration, 1211.2674

studies rare decays, e.g. $B_s \to \mu\mu$ (observed Nov 2012, now also at CMS)

Blumenhagen, Conlon et al '09
M.B., Marsh, McAllister, Pajer '10
M.B. Conlon, Marsh Witkowski '12

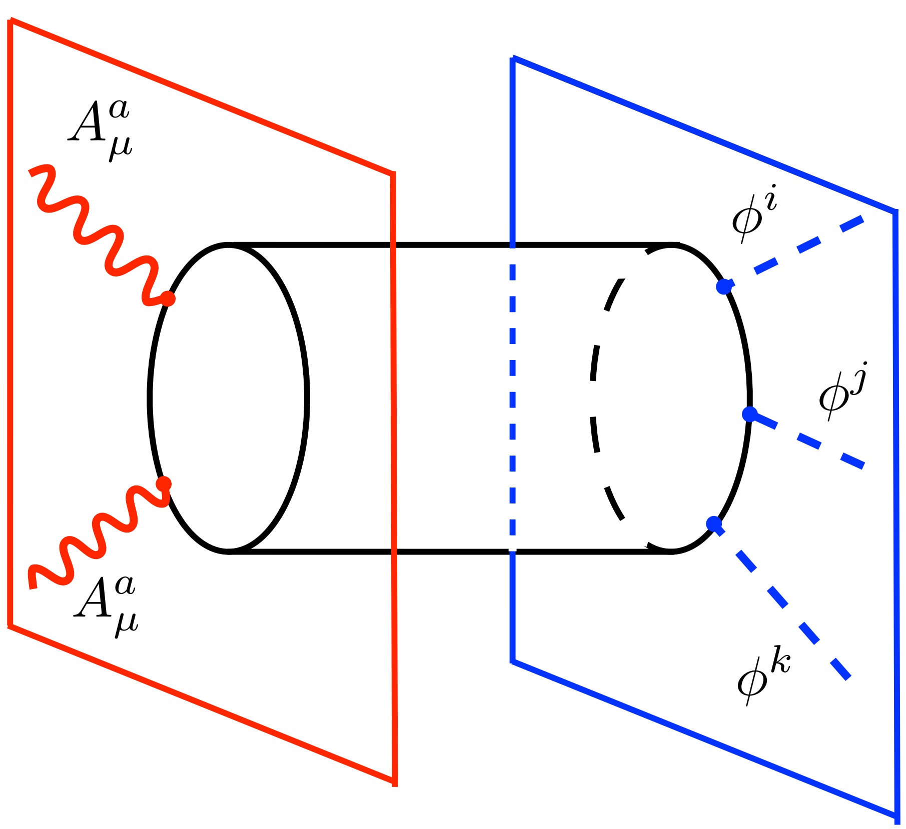
sequestering in Large Volume Scenario is sensitive to certain operators:
limits on rare decays produce strong constraints on volume of extra dimensions

# Flavor physics in string models

*Sequestering* is one strategy to deal with the flavor problem of gravity-mediated supersymmetry breaking.

Blumenhagen, Conlon et al '09
M.B., Marsh, McAllister, Pajer '10
de Alwis '12
M.B. Conlon, Marsh, Witkowski '12

Contributions to the effective action like from this string diagram can potentially affect sequestering.

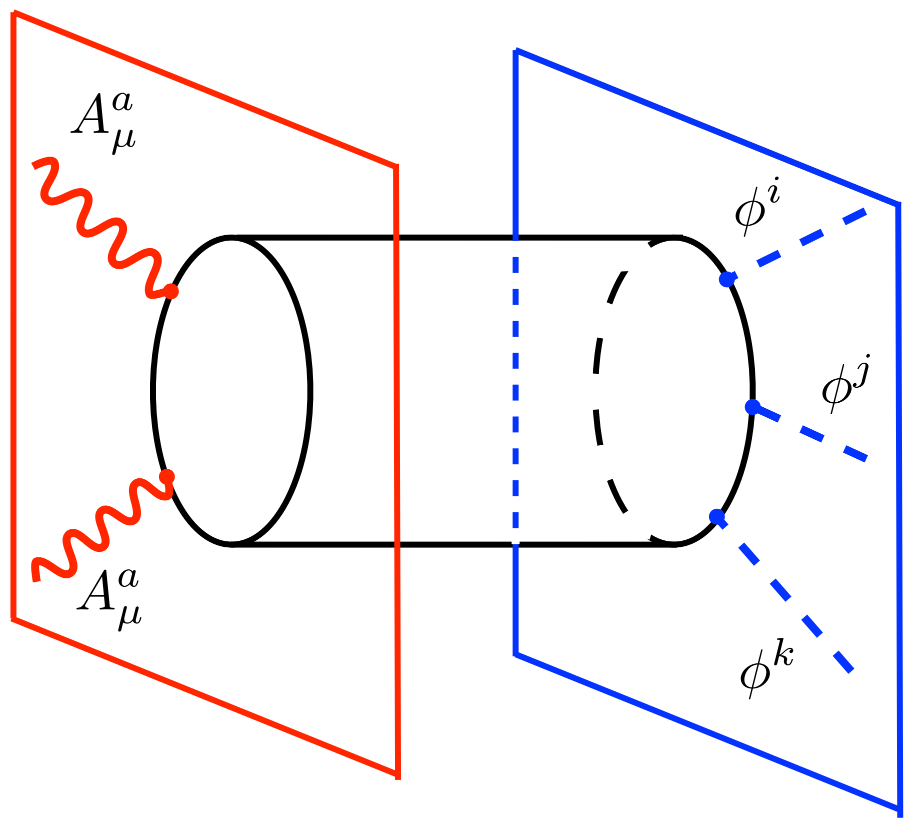



superpotential de-sequestering

$$\int d^4x \int d^2\theta \, \lambda_{ij}^{\rm new} \, e^{-aT} H Q^i q^j$$

(important: $e^{-aT}$ is not allowed to be too small, by stability)

# Flavor physics in supersymmetry




superpotential de-sequestering

$$\int d^4x \int d^2\theta \, \lambda^{\text{new}}_{ij} \, e^{-aT} H Q^i q^j$$

In field theory, can think of interactions in addition to gravity, mediated by semi-heavy scalar field (modulus) ... that can have many other implications.

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski '12

*"We will make the assumption that sequestering is not generic."*

# “Other implications” … e.g. axion dark radiation

in aforementioned string model (Large Volume Scenario)
axion scales related to scale of superpartners

“Dark radiation” cosmic axion background,
detectable through axion-photon conversion in
astrophysical magnetic fields,
maybe explain excess soft X-rays from galaxy clusters?

e.g. Conlon, Marsh ’13

# Summary

- Higgs physics: Effective supersymmetry
- Nonminimal Z' bosons
- Supersymmetry, flavor physics and naturalness

Exist phenomena that seem to not be easily captured by MSSM. Let's keep an eye open!

For the future: if no direct production at LHC energies, do we learn enough fundamental physics at ILC?

GAMBIT project (talk to Pat Scott): Global fits. Include BMSSM parameters?

# Thank you!