Natural Scherk-Schwarz SUSY Breaking

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Fermilab Theory Seminar 4/16/15

based on…
Savas Dimopoulos, K.H, John March-Russell. *Maximally Natural Supersymmetry,* arXiv:1404.7554.
Savas Dimopoulos, K.H, John March-Russell, James Scoville. *Auto-concealment of Supersymmetry in Extra Dimensions*. arXiv:1412.0805.
Savas Dimopoulos, K.H, John March-Russell, Isabel Garcia-Garcia. *Natural Scherk-Schwarz SUSY Breaking*. (in preparation)
Isabel Garcia-Garcia, John March-Russell, *Rare Flavor Processes in Maximally Natural Supersymmetry.* arXiv:1409.5669

On the eve of 13 TeV collisions...

NO SUPERPARTNERS

$$m_{\tilde{g}}, m_{\tilde{q}_{1,2}} \gtrsim 2 \text{ TeV}$$

$$m_{\tilde{t},\tilde{b}} \gtrsim 700 \text{ GeV}$$

$$(m_{\tilde{H}} \gtrsim 300 \text{ GeV})$$

hiding superpartners

(RPV, compressed, ...)

OR

Little Hierarchy

$(m^2_{\text{soft}} \gg v^2)$

SM-LIKE HIGGS

$$\Delta(\sigma \times \text{BR}) \lesssim 10\%$$

$$\sim 125 \text{ GeV}$$

→ decoupling limit in Higgs sector $(V = -m^2 h^2 + \lambda h^4)$

→ beyond MSSM (D-terms, singlet, VL matter)

Is the Little Hierarchy a Little Hierarchy PROBLEM?

"Maximally Naive SUSY"

$$m_{\tilde{g}}, m_{\tilde{q}_{1,2}} \approx 2 \text{ TeV}$$

$$m_{\tilde{t},\tilde{b}} \approx 700 \text{ GeV}$$

$$m_{H_u}, m_{H_d} \approx 100 \text{ GeV}$$

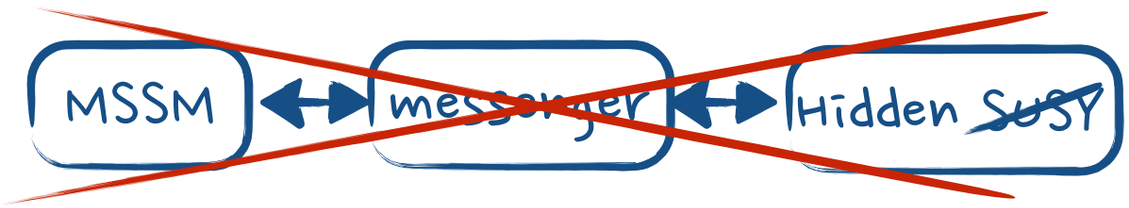
$$\Delta^{-1} \sim 50\% \times \ln\left(\frac{\Lambda}{\text{TeV}}\right)$$

(See e.g. Papucci et al. arXiv:1110.6926)

i) Scale of Mediation

$$\Lambda \gtrsim 100 \text{ TeV} \rightarrow \Delta^{-1} \gtrsim 10\%$$

$$\Lambda \sim 1 \text{ TeV}$$ - Not tuned?



ii) Origin of natural spectrum?

tuning ~ 1% for realistic models

(See e.g. Arvanitaki et al. arXiv:1309.3568)

Maximally NATURAL SUSY

[(1) Natural Spectrum + Higgs from Scherk-Schwarz ~~SUSY~~]

fundamental scale:

$M_* \sim 30\ \mathrm{TeV} - 100\ \mathrm{TeV}$

$(\pi M_* R \sim 20)$

(perturbativity)

4D SUSY

3rd Gen

(flat) 5D SUSY

Gauge, Higgs,

1st + 2nd Gen

[(3) bulk collider Pheno]

[(2) brane collider pheno]

$R \sim 1/(4\,\mathrm{TeV}) \sim 1/m_{soft}$

n-dimensional bulk

See: Delgado, Pomarol, Quiros '98; Antoniadis, Dimopoulos, Pomarol, Quiros '99; Delgado, Quiros, '01 Barbieri, Hall, Nomura '00, '01; Hall, Marandella, Nomura, et. al. '02; Barbieri, Marandella, Papucci, '02,'03;

[(1) Natural Spectrum from Scherk-Schwarz ~~SUSY~~]

"Maximal Scherk-Schwarz Twist"

" $S_1/(Z_2 \times Z_2')$ orbifold "

SM: Higgs, Gauge, 1st/2nd family → A_μ : + , + , 0

MSSM partners → $\tilde{\lambda}$: + , - , $\frac{1}{2R}$

N=2 partners → $\tilde{\lambda}^c$: - , + , $\frac{1}{2R}$

→ Σ : - , - , $\frac{1}{R}$

3rd Generation

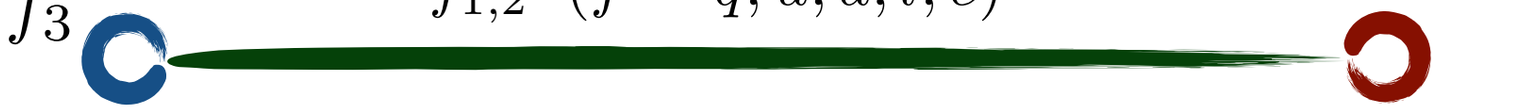
… + A FULL KK TOWER

KK Excitations of MSSM…

$y = 0$ $\qquad$ $y = \pi R$

Tree-level Scherk-Schwarz Spectrum

$$H_u, H_d$$
$$SU(3) \times SU(2) \times U(1)$$
$$f_{1,2} \quad (f = q, u, d, l, e)$$



$$m_{\tilde{f}}^2 = m_{\tilde{\lambda}}^2 = m_{\tilde{H}}^2 = \frac{1}{2R}$$

No tree-level tuning!!

Direct & universal bulk soft masses

Dirac Higgsino and Gaugino Masses

$$m_{\tilde{H}} \tilde{H} \tilde{H}^c \quad m_{\tilde{\lambda}} \tilde{\lambda} \tilde{\lambda}^c$$

NO SUSY flavor problems

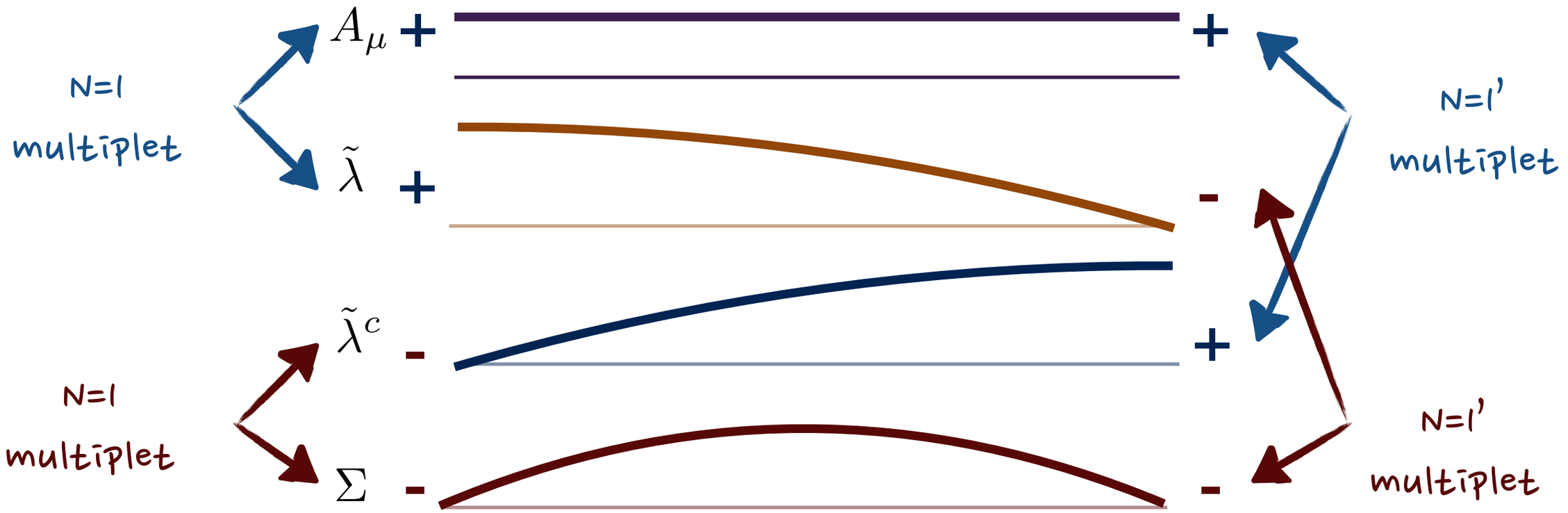
(leading flavor from SM KK, see J. March-Russell, I. Garcia-Garcia 1409.5669)

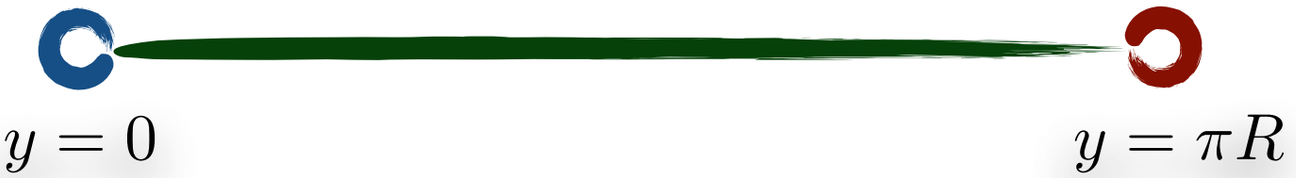
$$\lesssim$$

$$m_{\tilde{f}_3}^2 = m_{h_{u,d}}^2 = 0$$

locality bulk zero mode

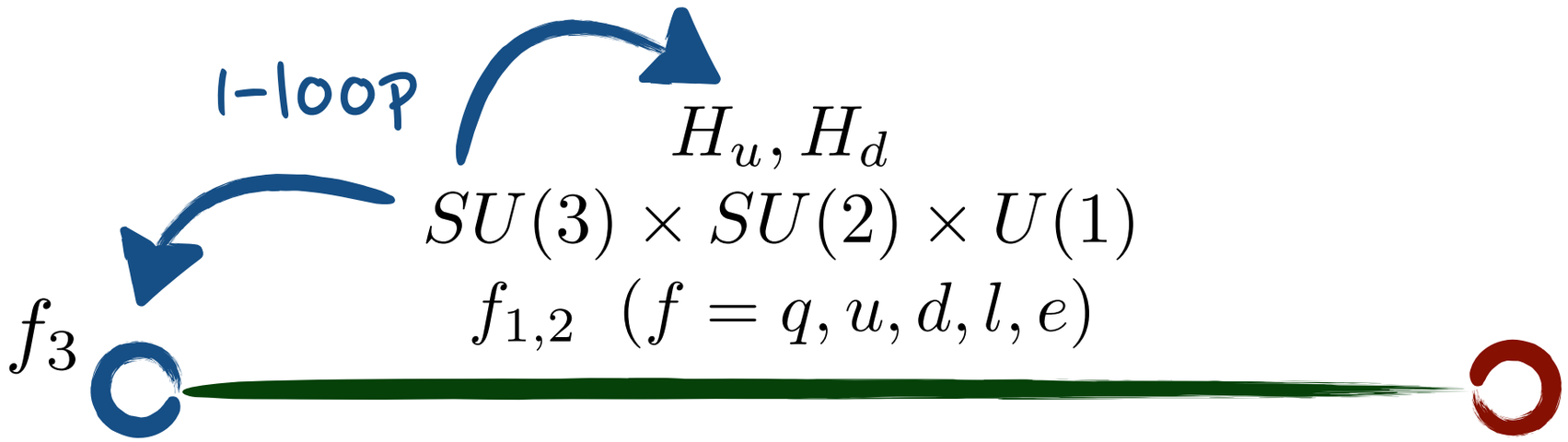
Softness of Scherk Schwarz





SUSY Breaking loops $\sim e^{-\pi R E}$ → "Messenger Scale" $\Lambda \sim \frac{1}{\pi R} \sim$ Tev!!!

Loop-level Scherk-Schwarz Spectrum



1-loop masses:

$$\tilde{m}^2 \sim \frac{g^2}{16\pi^2}(\mathrm{TeV})^2 \ln \frac{\Lambda^2}{\mathrm{TeV}^2}$$

100 TeV : ~10

M_{gut} : ~100

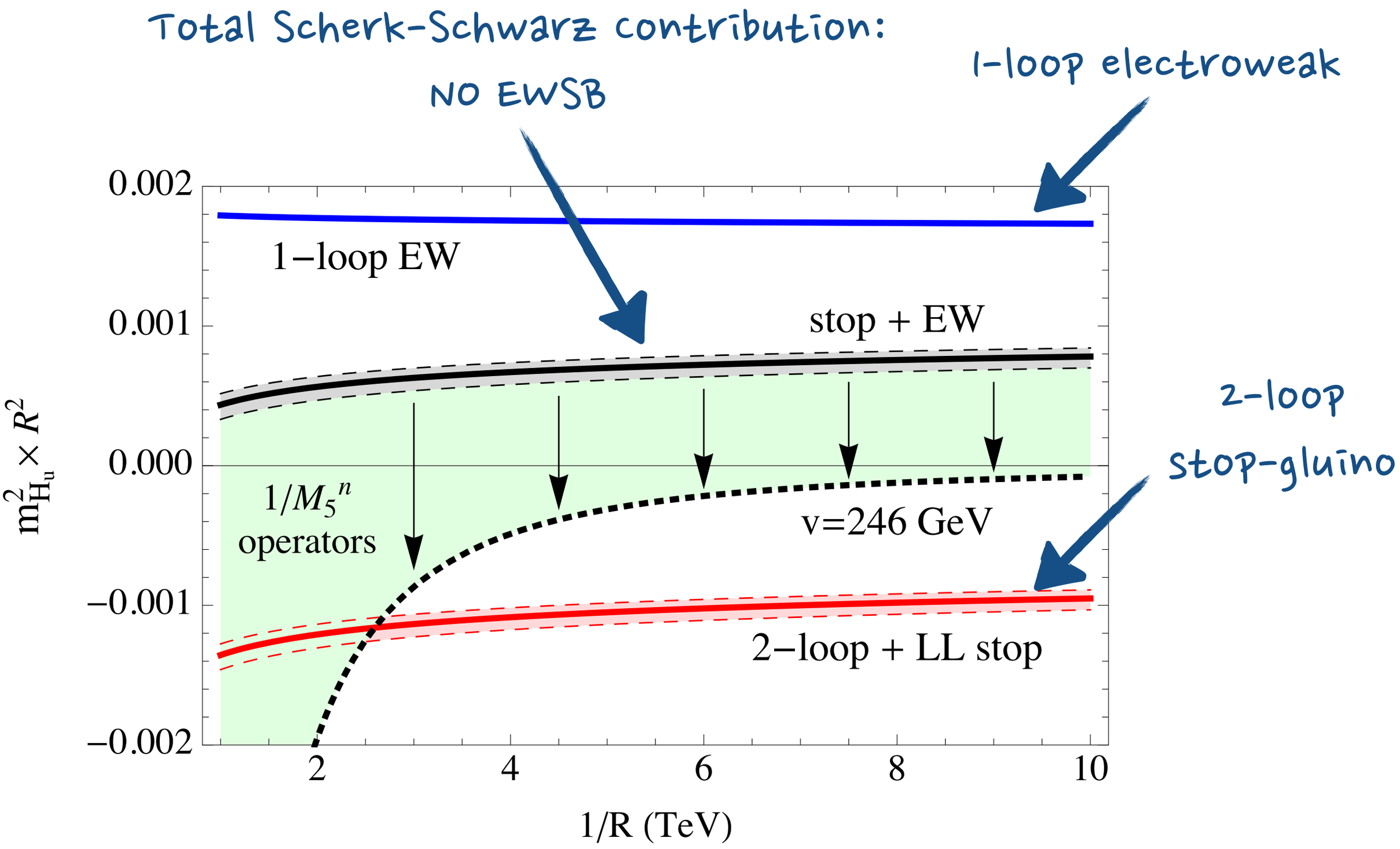
$$m_{H_u}^2 \approx \left(\frac{1}{30} \times \frac{1}{R}\right)^2$$

1/R ~ 4 TeV for natural weak scale!

$$m_{\tilde{t}}^2 \approx \left(\frac{1}{10} \times \frac{1}{R}\right)^2 \approx \left(\frac{1}{5} \times M_3\right)^2$$

Large stop-gluino hierarchy (gluino doesn't suck)

EWSB in single parameter model?



Extra Contributions to Soft Mass?

Radius stabilization?

e.g. bulk casimir energy stabilization:

$$U \sim -\left(\frac{1}{\pi R}\right)^4$$

+ ~vanishing 4D cc

(comparable to 1-loop)

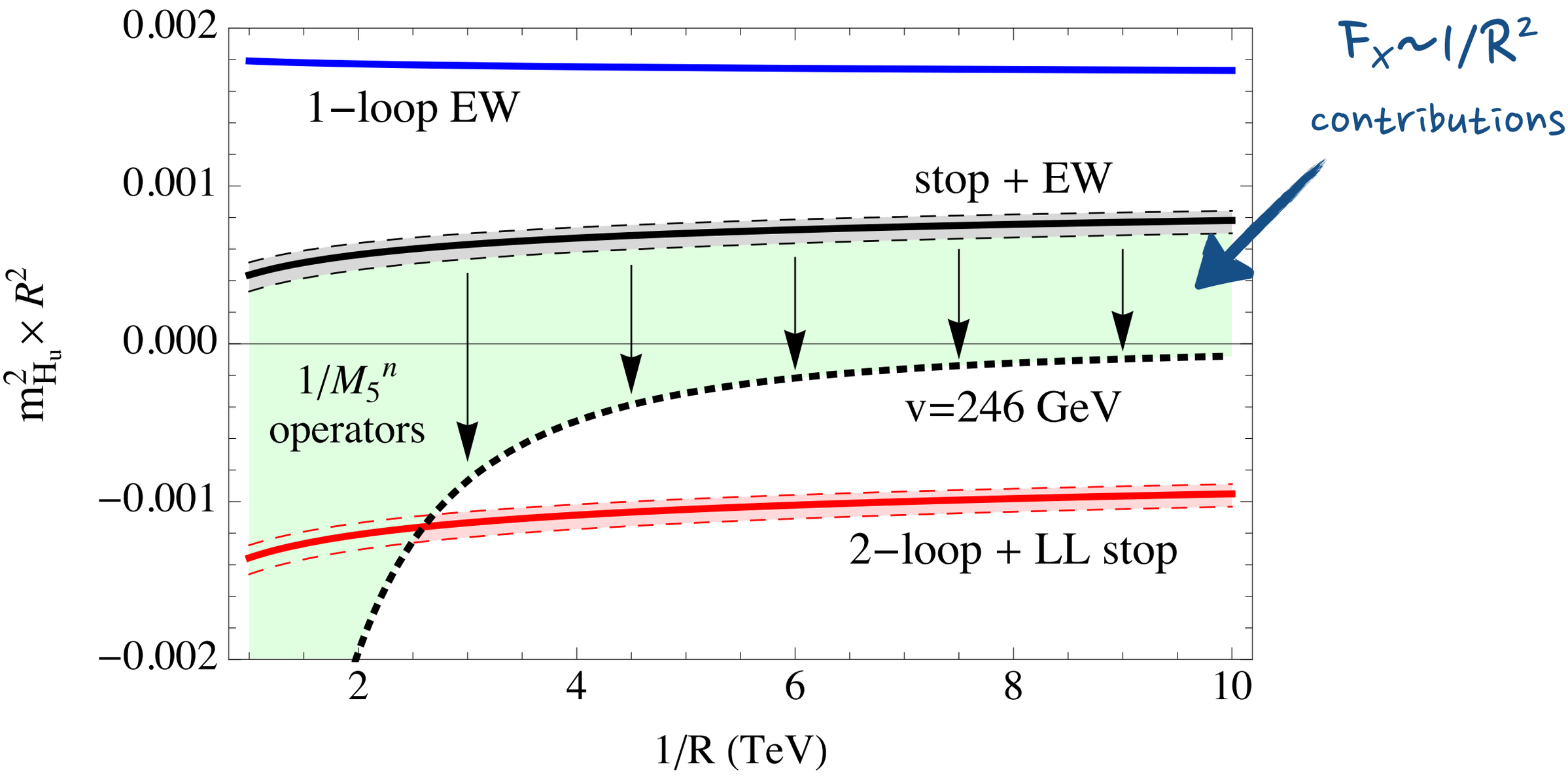
$$\Delta m^2_{\tilde{f}_3} \sim \frac{F_X^2}{M_*^2} \sim \left(\frac{1}{20} \times \frac{1}{R}\right)^2$$

Brane-localized X, $F_X \sim 1/R^2$

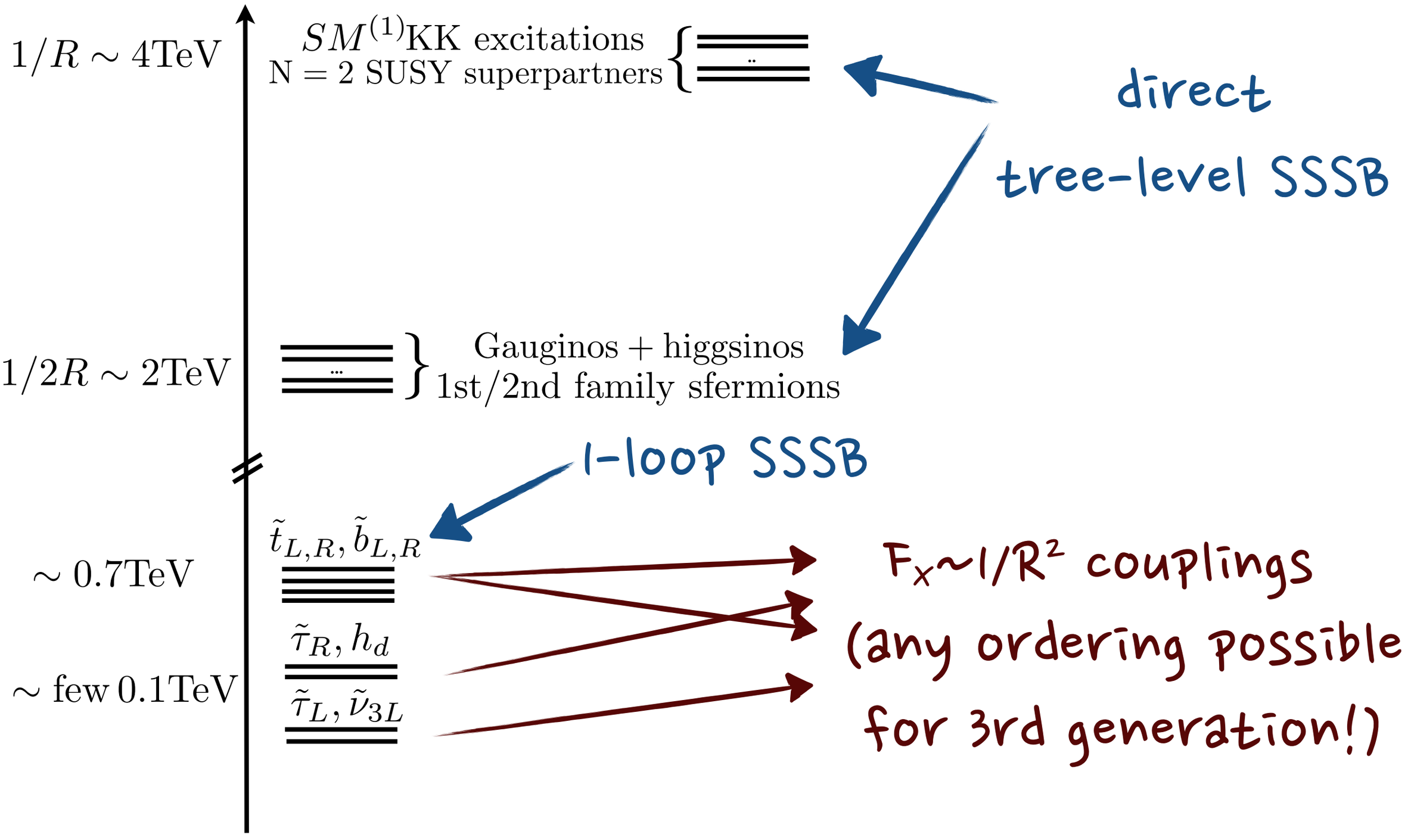
($\pi M_* R \sim 20$ fixed by perturbativity)

(also extra bulk states, quasi-localization, ...)

EWSB?

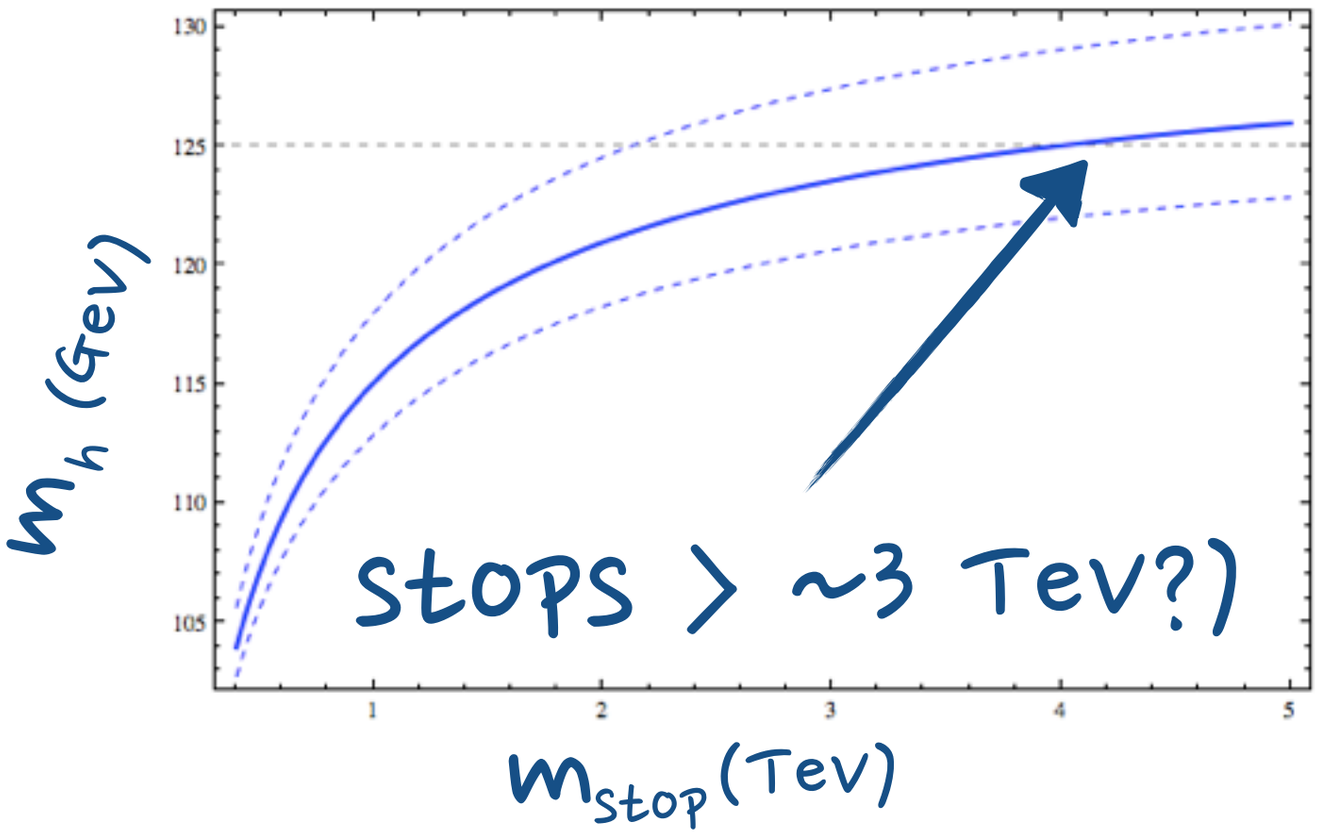

0.002
0.001
0.000
−0.001
−0.002
2
4
6
8
10
1/R (TeV)
$m_{H_u}^2 \times R^2$
1−loop EW
stop + EW
$1/M_5{}^n$
operators
v=246 GeV
2−loop + LL stop
$F_X \sim 1/R^2$
contributions

Overall Spectrum



125 GeV Higgs?

Radiatively



$\tan\beta \to \infty$

naturally w/non-holomorphic couplings

dirac gauginos w/ D-terms

low tuning comparatively

Extended Sectors

Singlets/ (N)MSSM

Vector-like Matter

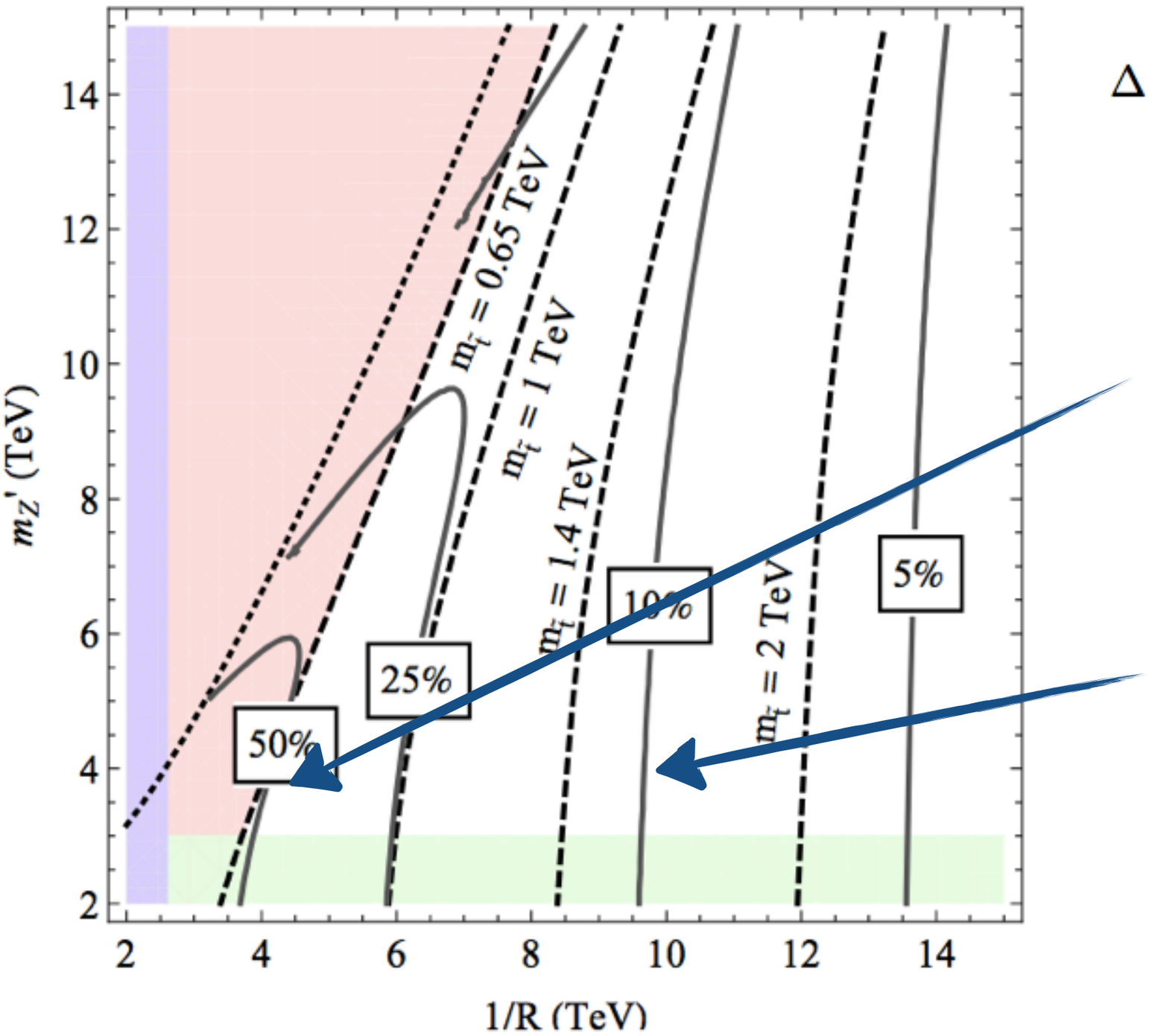
Gauge Extensions

$M_* \lesssim 100$ TeV → low cut-off for landau poles

$\Delta m^2_{H_u} \propto \Delta\lambda$ → soft masses suppressed

M_V, M_F, μ_S → new scales ~ 1/R inherited

Tuning [U(1)' variation]



$$\Delta = \sqrt{\left(\frac{\partial \ln v^2}{\partial \ln m_{\tilde{t}}^2}\right)^2 + \left(\frac{\partial \ln v^2}{\partial \ln m_{\tilde{Z}'}^2}\right)^2}$$

NO TUNING(!)

For ~700 Gev Stop &

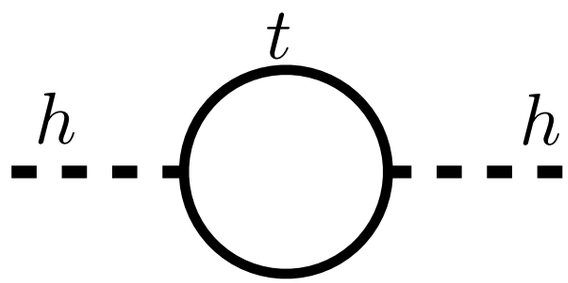
2 Tev Gluinos/Squarks

~10% Tuned

within LHC13 Reach

"Maximal" ~saturates one-loop tuning

$$\Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2} M^2$$

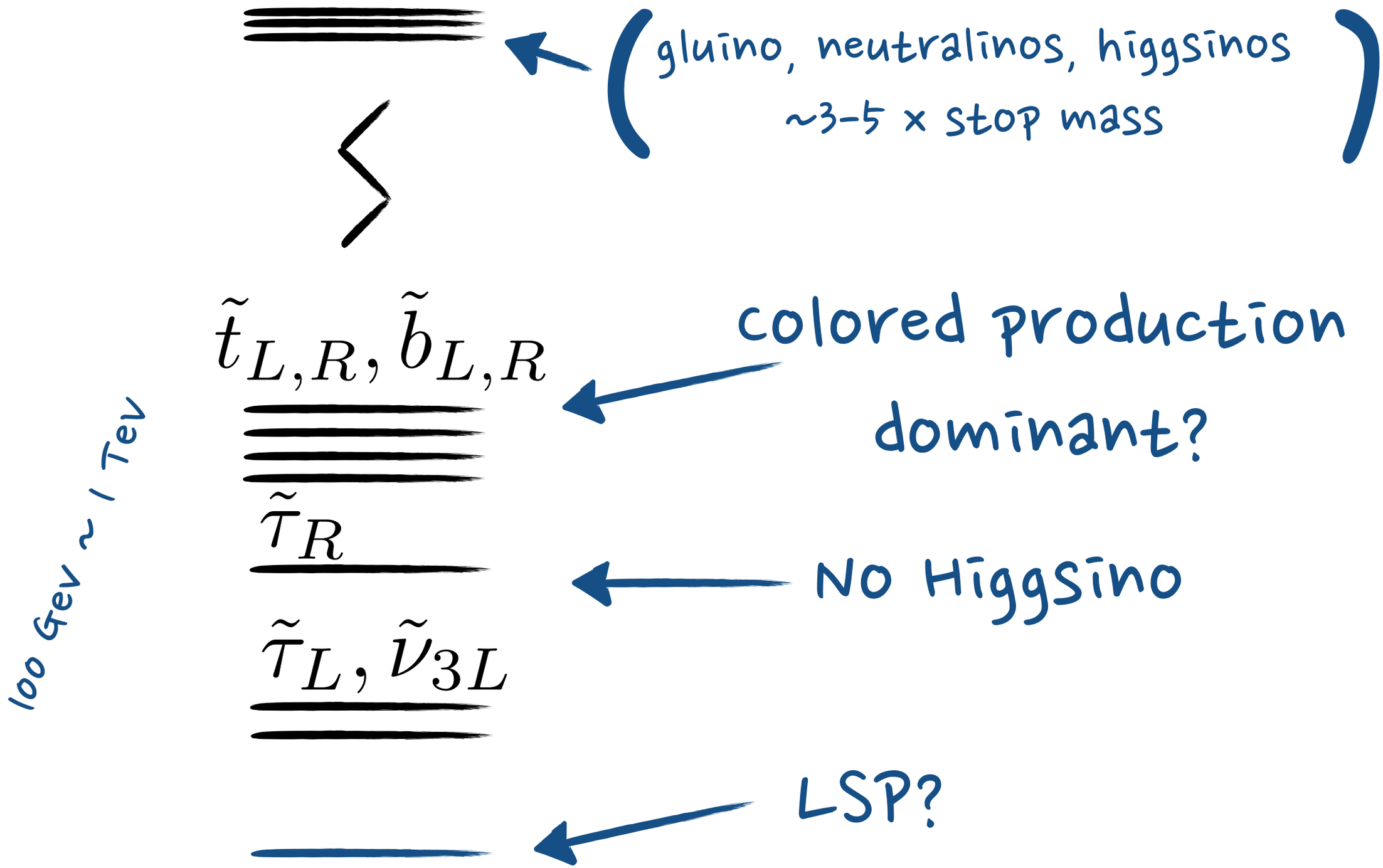


[(2) Brane LHC Pheno]

i) UV complete Nat. SUSY
Simplified Model

ii) Non-standard Nat.
SUSY Phenomenology

3rd Generation Sfermion Signatures

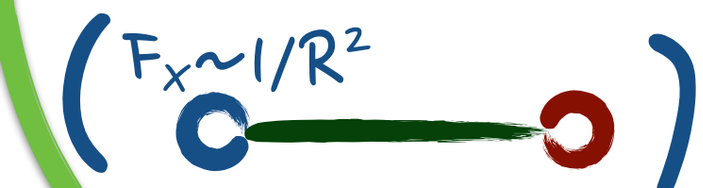


LSP Candidates

Natural candidates for LSP:

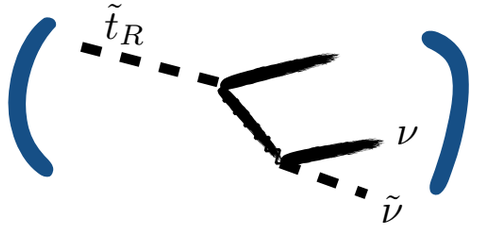
1) ψ_X

Brane-localized goldstino, R-symmetry, ...



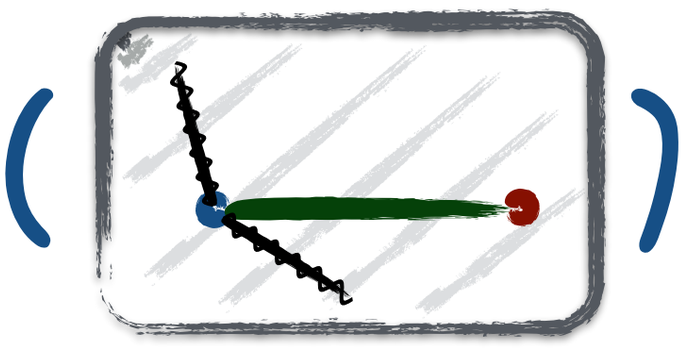
2) $\tilde{\nu}_3$

Brane-localized left handed sneutrino

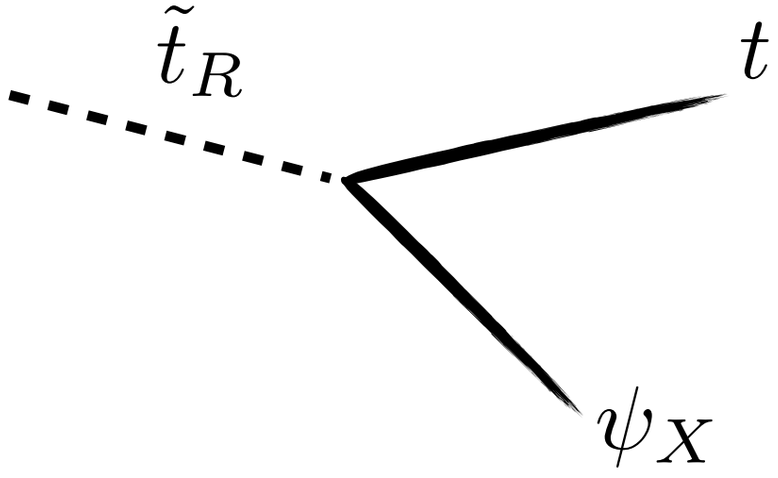


3) $\tilde{G}_{\rm bulk}$

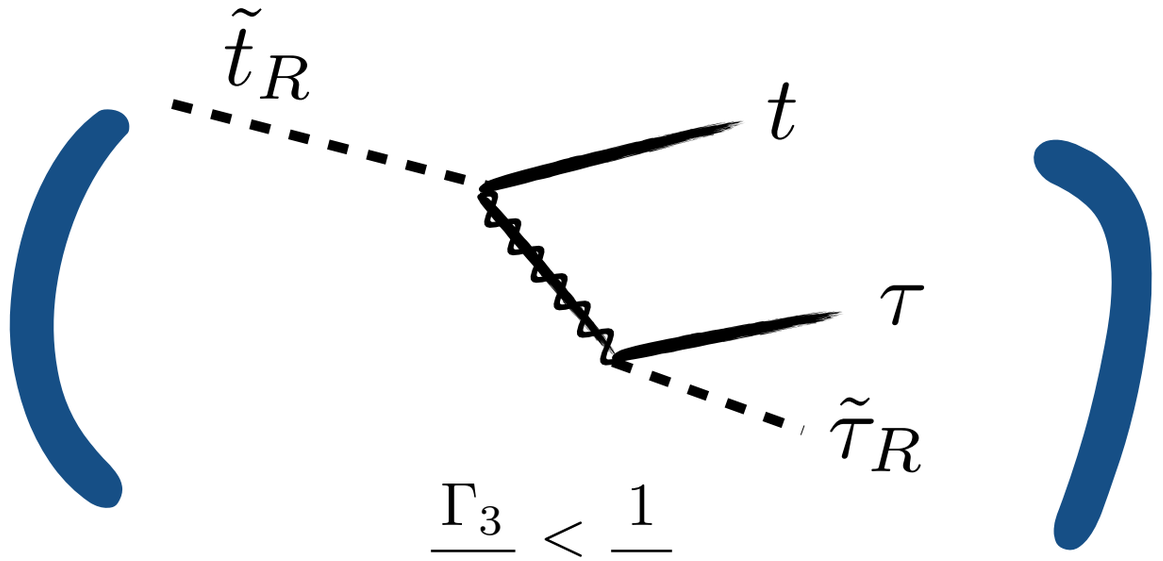
n-dimensional BULK states



ψ_X LSP: UV Complete Natural SUSY Simplified Model

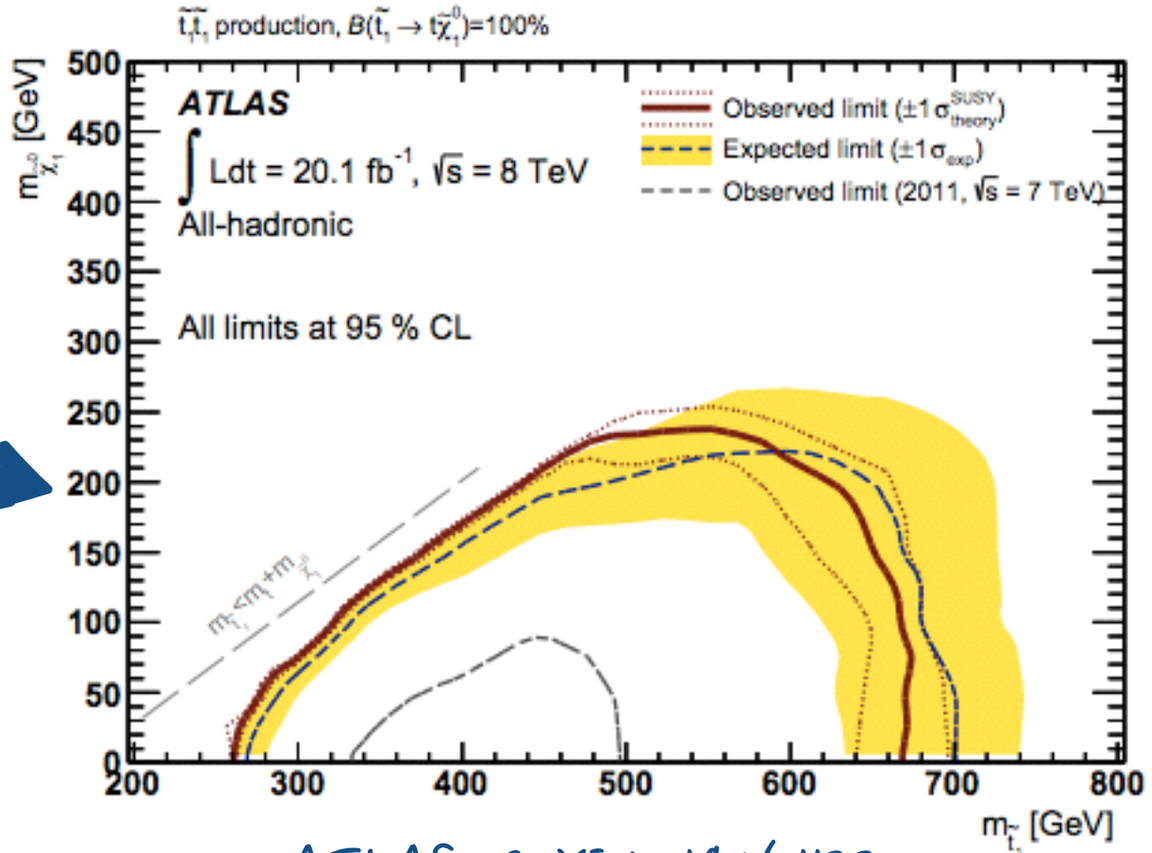


$M_X \sim 1 \sim 100$ GeV

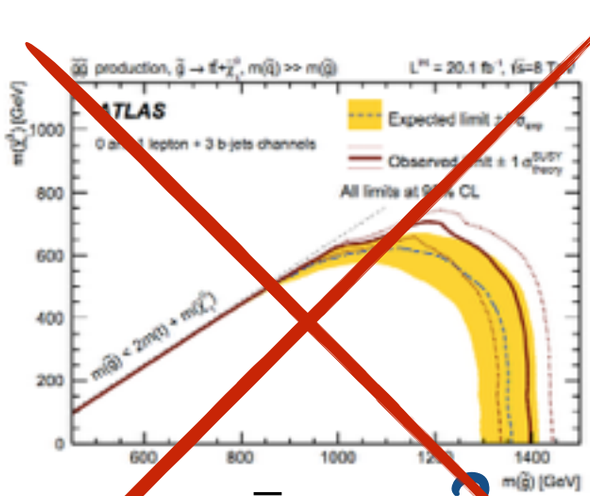


$$\frac{\Gamma_3}{\Gamma_X} \lesssim \frac{1}{10}$$

Higgsino?
Gravitino?



ATLAS, arXiv: 1406.1122



$$\tilde{g} \to t\bar{t} + X ?$$

"vanilla" simplified model
captures full UV complete model!

(collider-stable) LSP Candidates

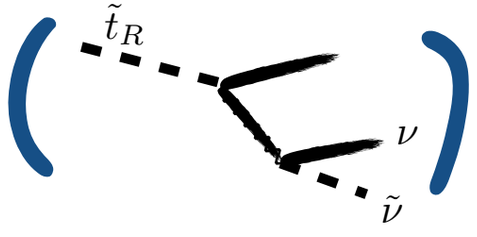
Natural candidates for LSP:

1) ψ_X

Brane-localized goldstino of x SUSY breaking

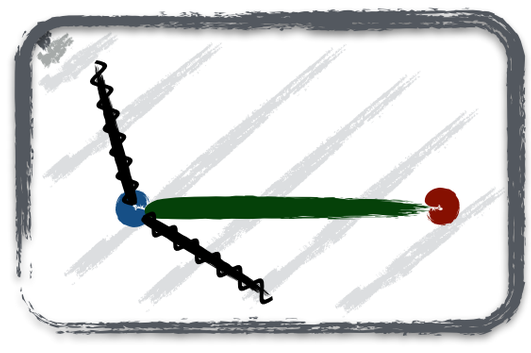
2) $\tilde{\nu}_3$

Brane-localized left handed sneutrino

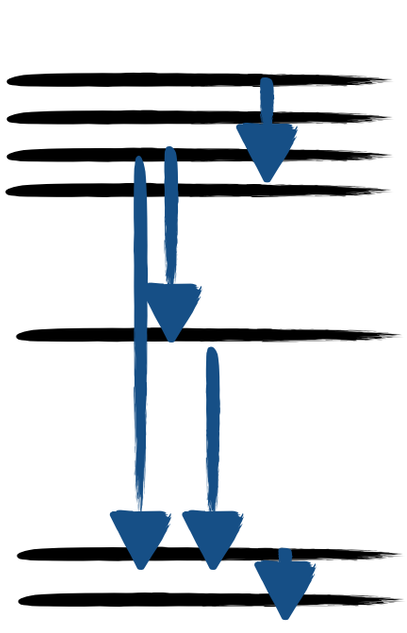


3) $\tilde{G}_{\rm bulk}$

n-dimensional BULK states



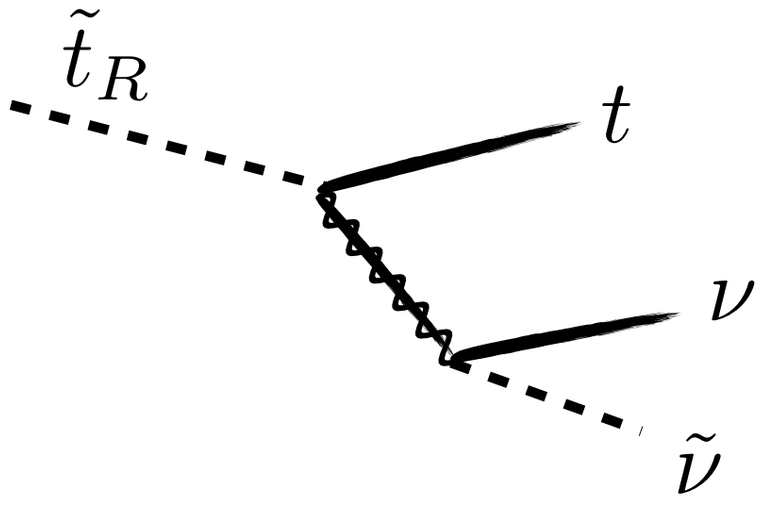
$\tilde{\nu}_3$ LSP: New Signatures of Naturalness?

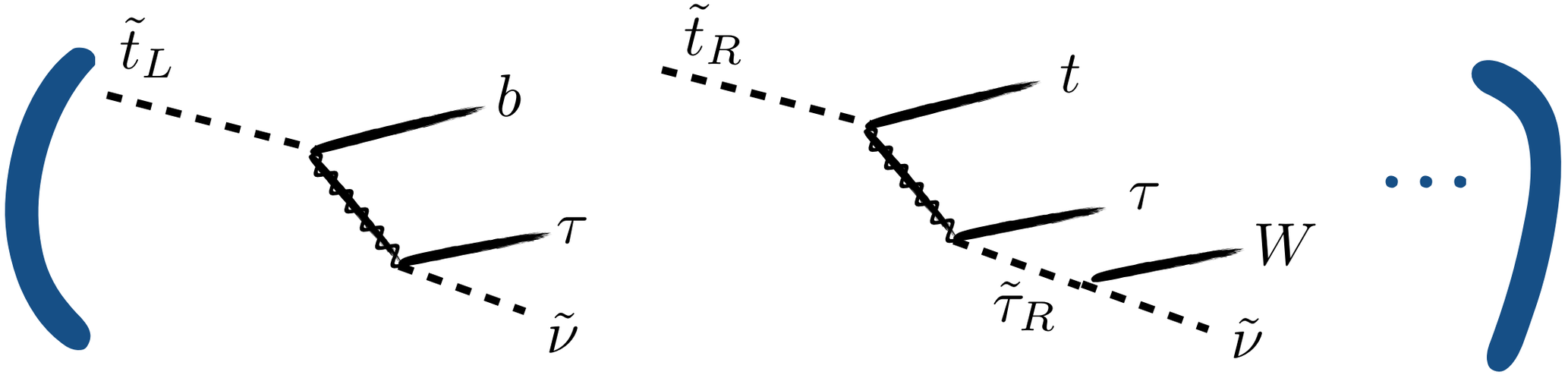


$\tilde{t}_{L,R}, \tilde{b}_{L,R}$

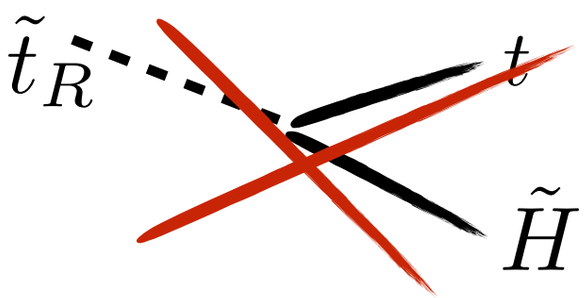
$\tilde{\tau}_R$

$\tilde{\tau}_L, \tilde{\nu}_{3L}$





3-body kinematics, taus + b's final states, ...



Reduced MET?

Alves et. al. arXiv:1312.4965

ATLAS-CONF-2014-014

ATLAS-CONF-2013-026

[(3) Bulk LHC Pheno]

[Savas Dimopoulos, K.H, John March-Russell, James Scoville. arXiv:1412.0805.]

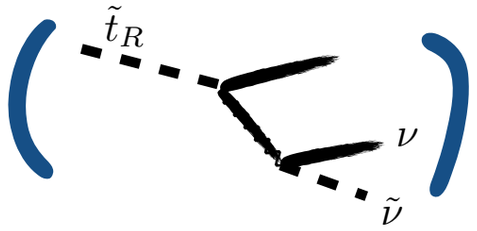
Natural candidates for LSP:

1) ψ_X

Brane-localized
goldstino
of x SUSY breaking

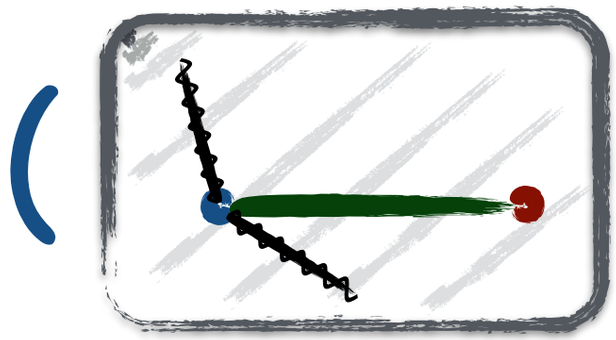
2) $\tilde{\nu}_3$

Brane-localized
left handed
sneutrino

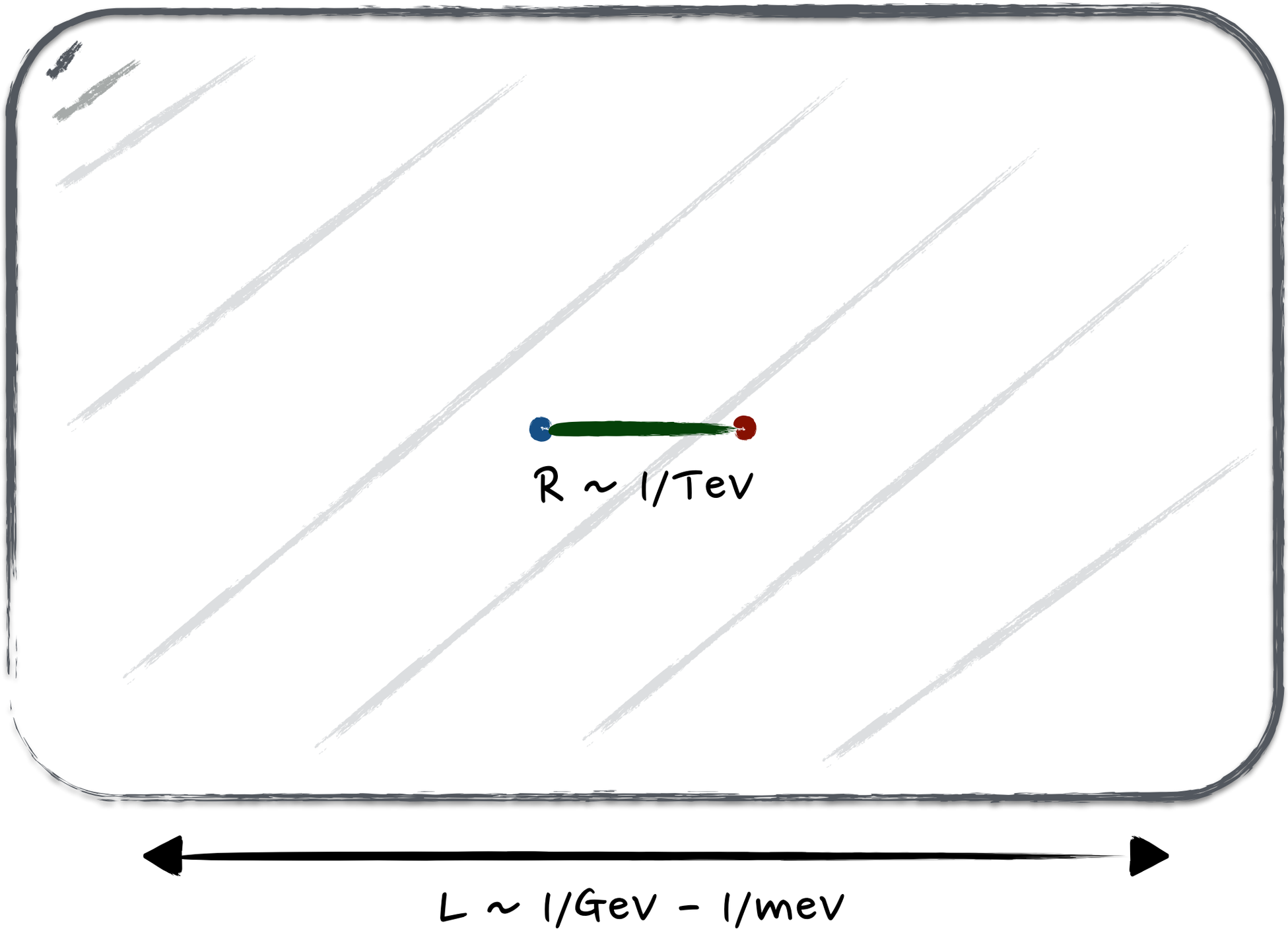


3) $\tilde{G}_{\text{bulk}}$

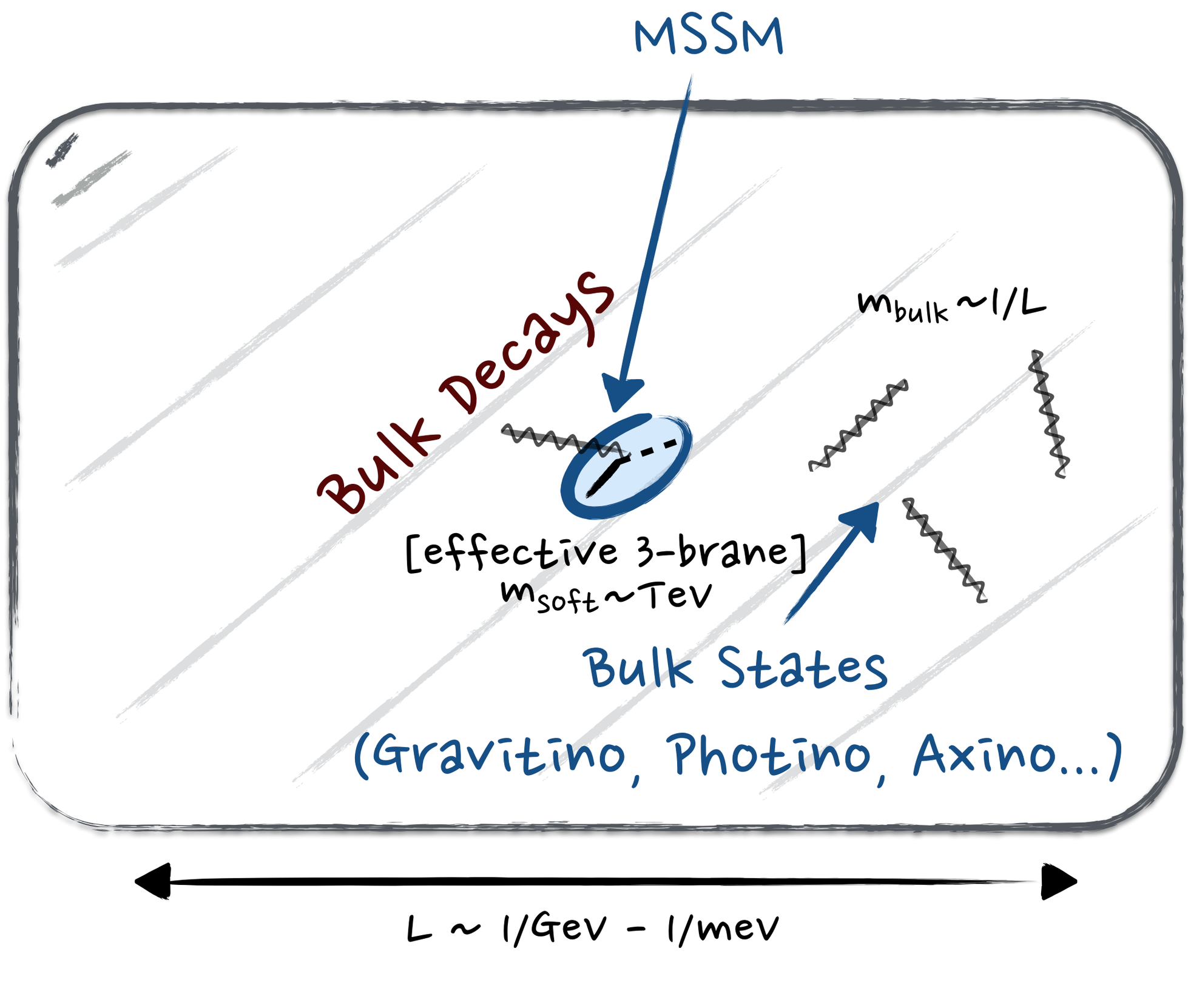
n-dimensional
BULK states



Decaying to the Bulk



Decaying to the Bulk



Auto-concealment?

visible sparticles

Bulk sparticles

(Extends to M_*)

$\Gamma_n \sim \dfrac{M^3}{M_{\rm pl}^2}$

LOSP

M

$dN \sim m^{d-1}$

$d\Gamma \sim dN \sim m^{d-1}$

$\left(\Gamma = \int d\Gamma \sim \dfrac{M^{d+3}}{M_*^{d+2}} \right)$

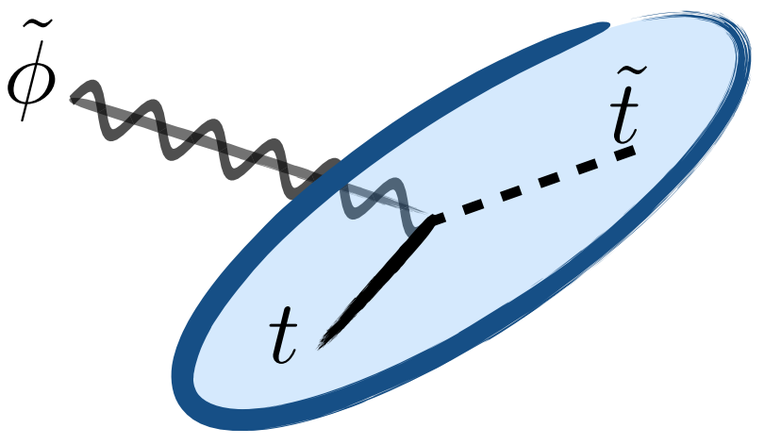
LSP(3)

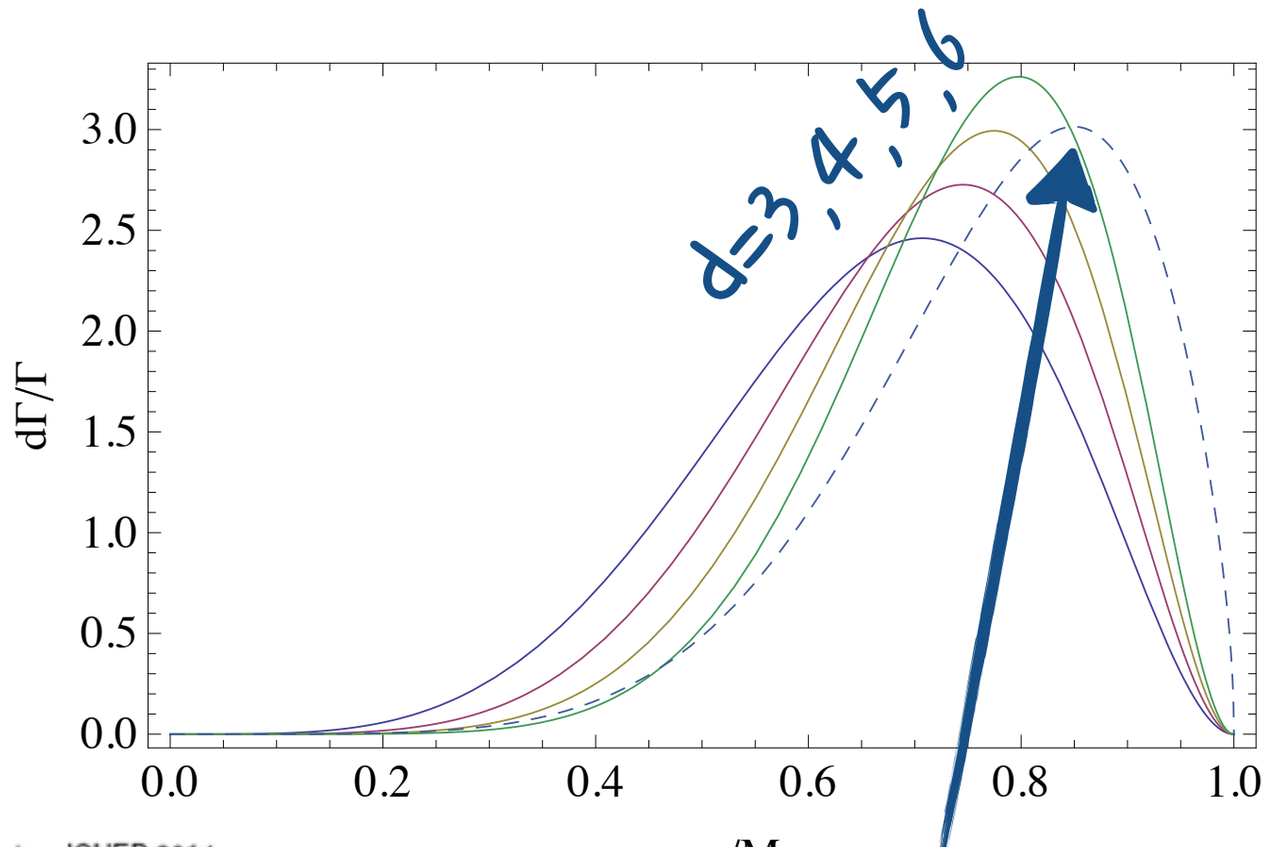
LSP(2)

LSP(1)

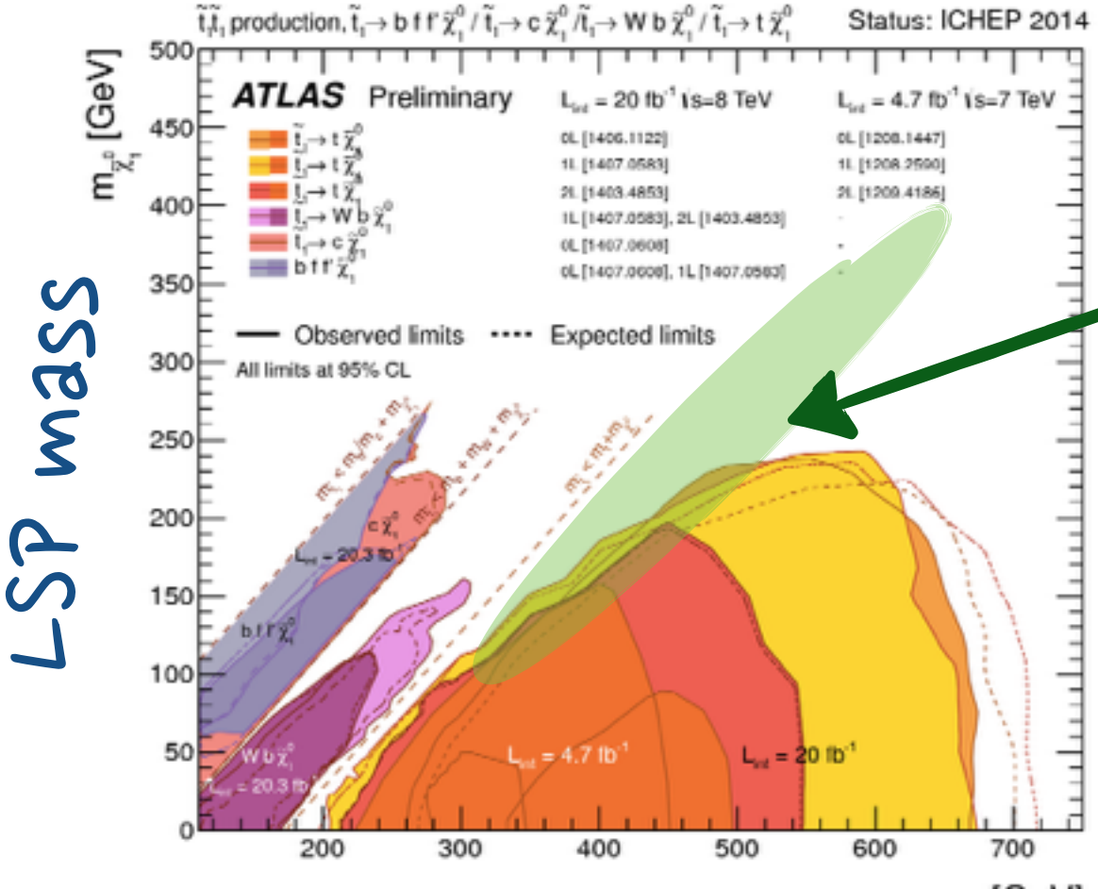
LSP(0)

Prompt Auto-concealment?



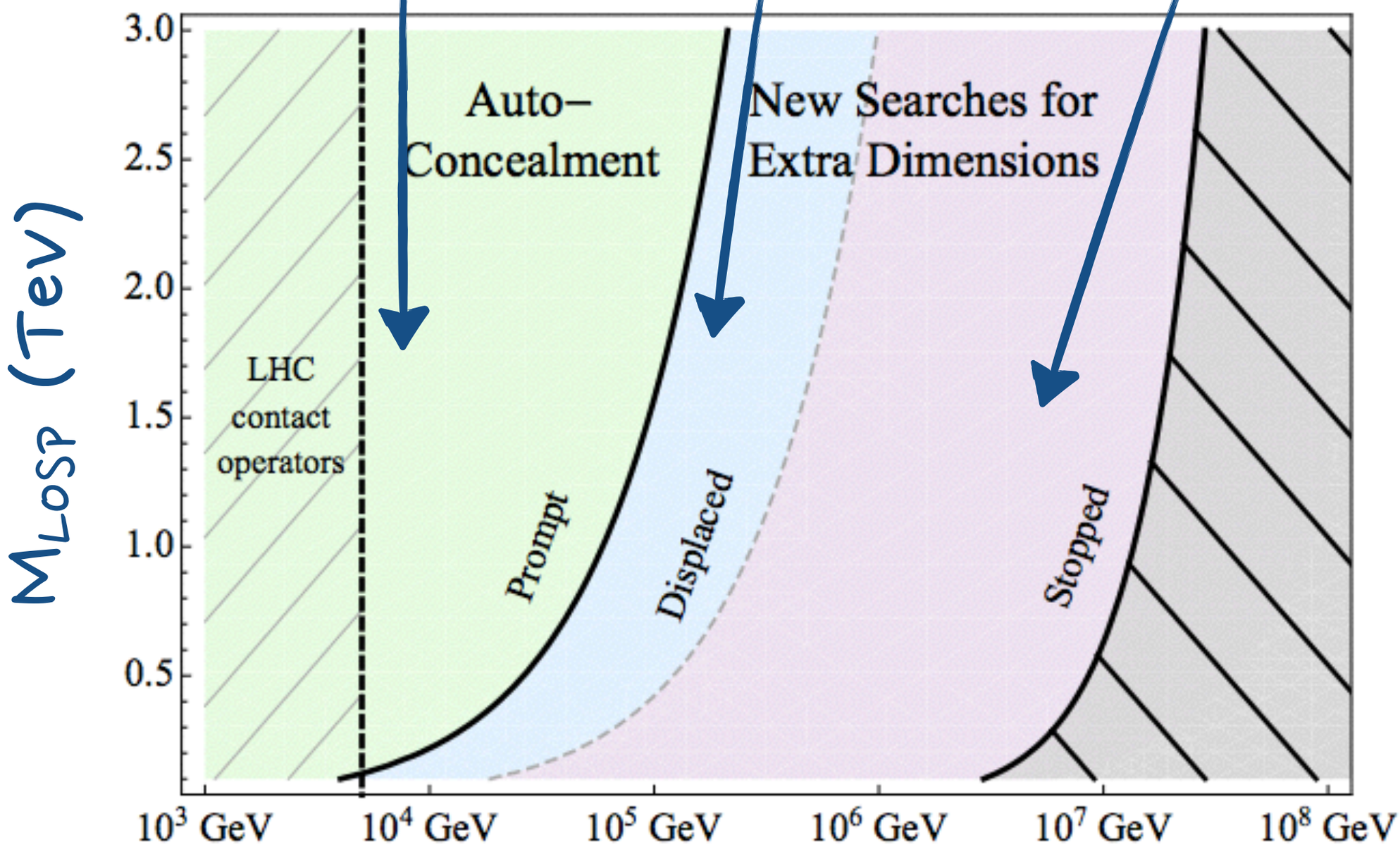


$\langle m \rangle \sim 0.8\ (m_{stop} - m_t)$



Decay length

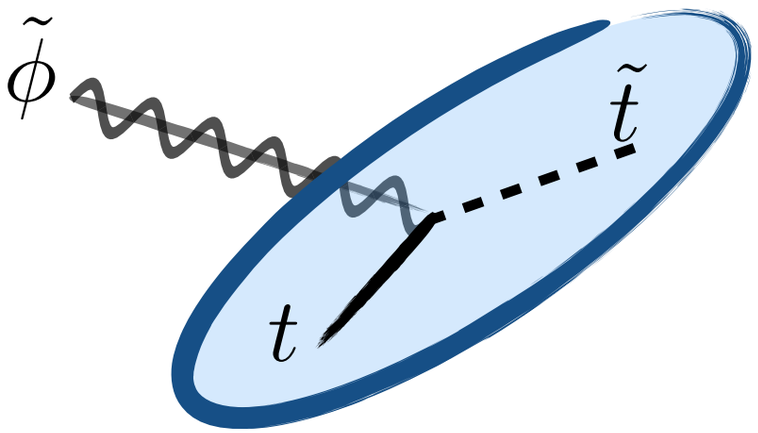
(1) Prompt (2) Displaced (3) Stopped

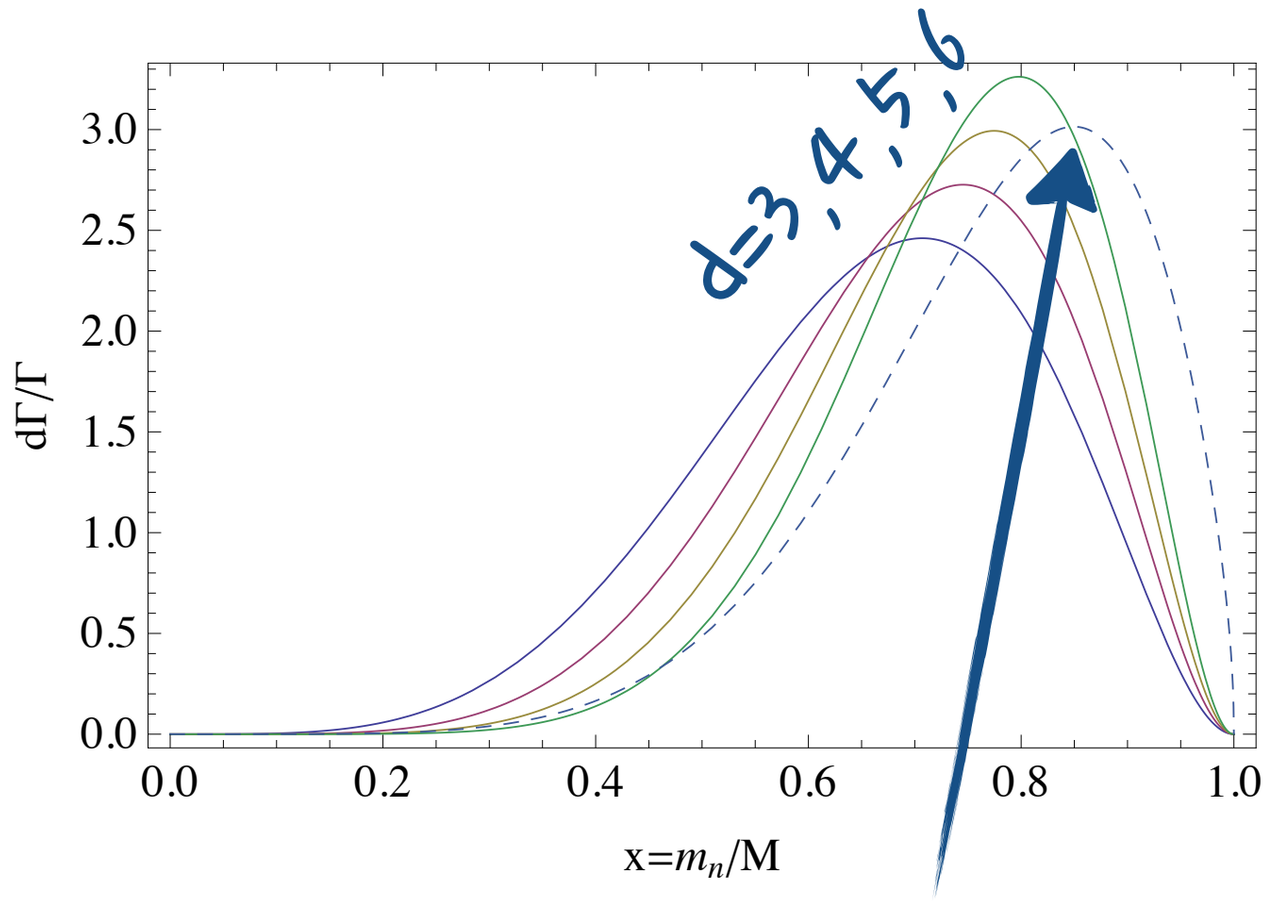


M_{LoSP} (TeV)

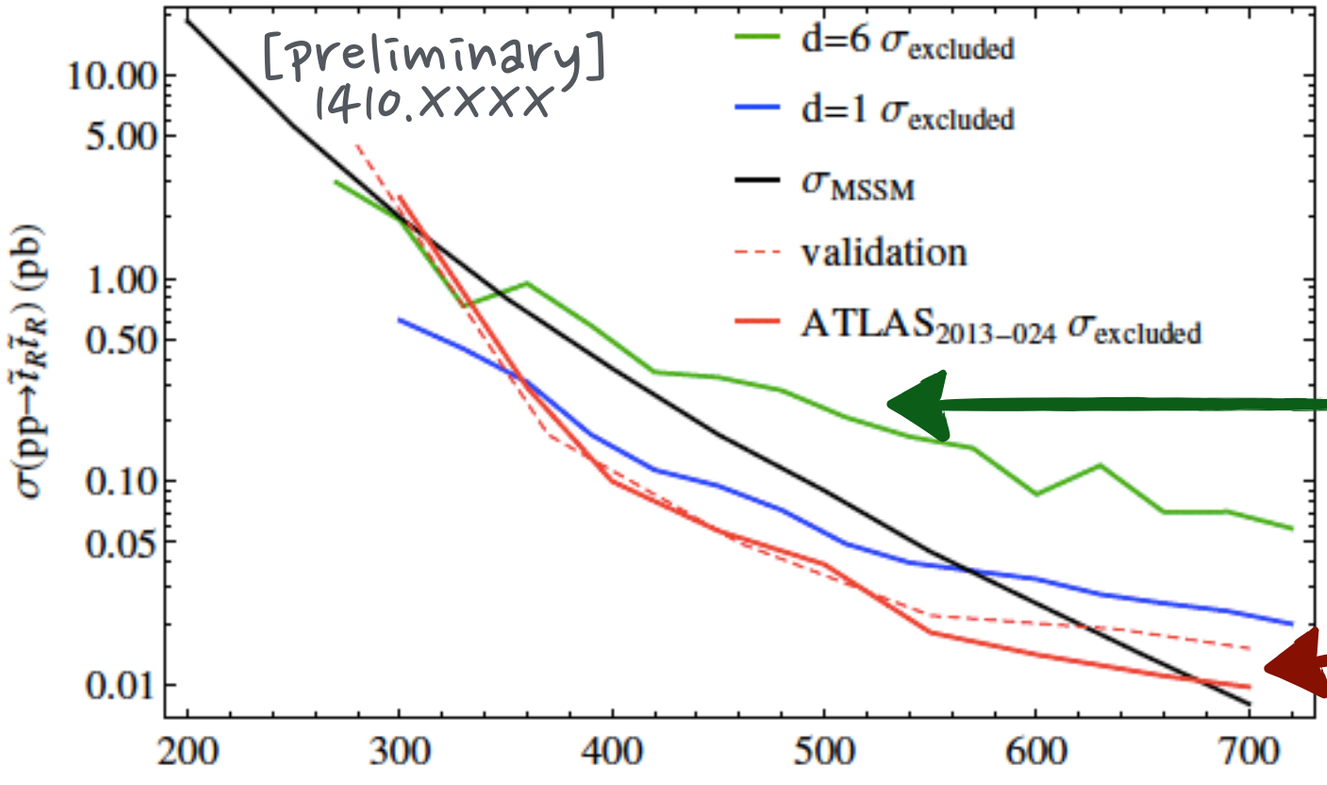
M_* (bulk codimension d=4)

Prompt Auto-concealment?





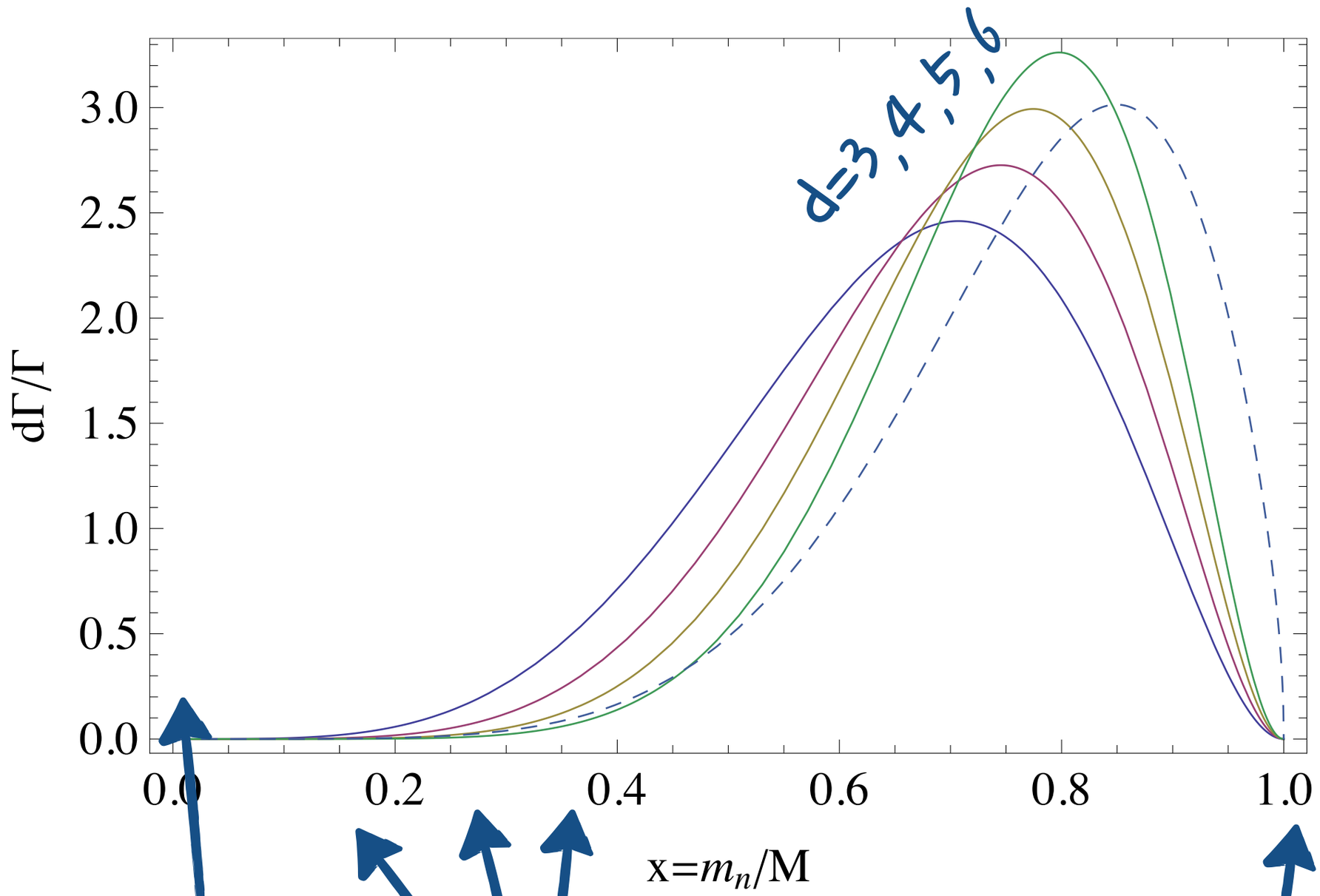
$\langle m \rangle \sim 0.8\ (m_{stop} - m_t)$



d=6, m_{stop} > ~400 Gev

validation

Displaced Signatures?



Low-scale GMSB

~Split SUSY Gluino

Wino LSP

Conclusions

1) Locality + Low-scale of SSSB

(i) Sets and protects natural Spectrum

(ii) accommodates 125 GeV Higgs

n-dimensional bulk

3) decays to bulk

(i) auto-concealment

(ii) new displaced and stopped signatures

4D SUSY

3rd Gen

5D SUSY

Gauge, Higgs,

1st + 2nd Gen

2) 3rd Gen Sfermions

(i) untuned Simplified Model

(ii) heavy higgsinos: 3-body decays

$R \sim 1/TeV \sim m_{soft}$

Spectra variations

Bulk States

Higgs Mass =>Pheno

Gauge unification

...

work in progress w/

I. Garcia-Garcia, J. Huang, J. Scoville, S.Dimopoulos, J. March-Russell

Questions?

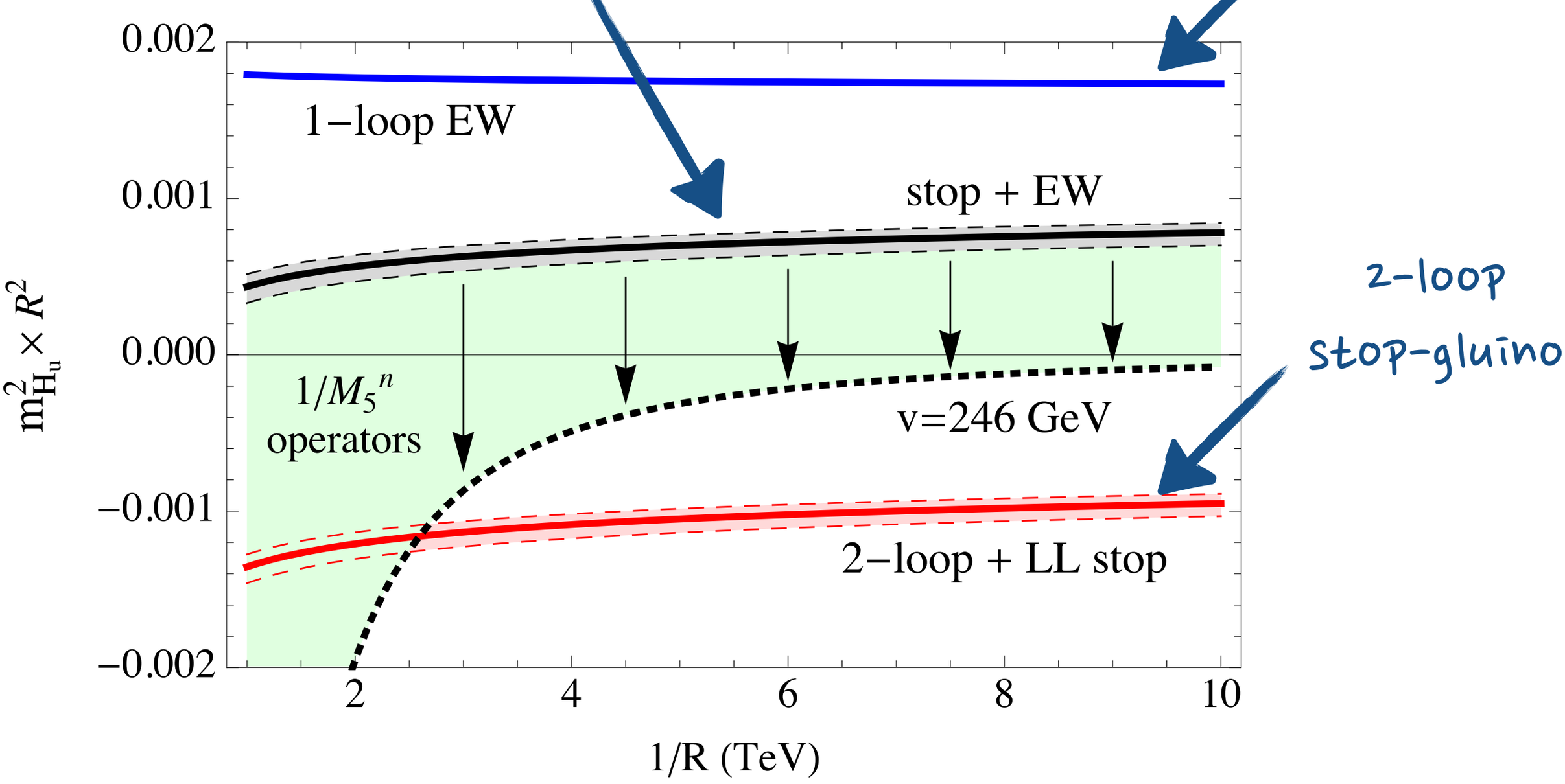
[Back-ups]

EWSB?

Total Scherk-Schwarz contribution:

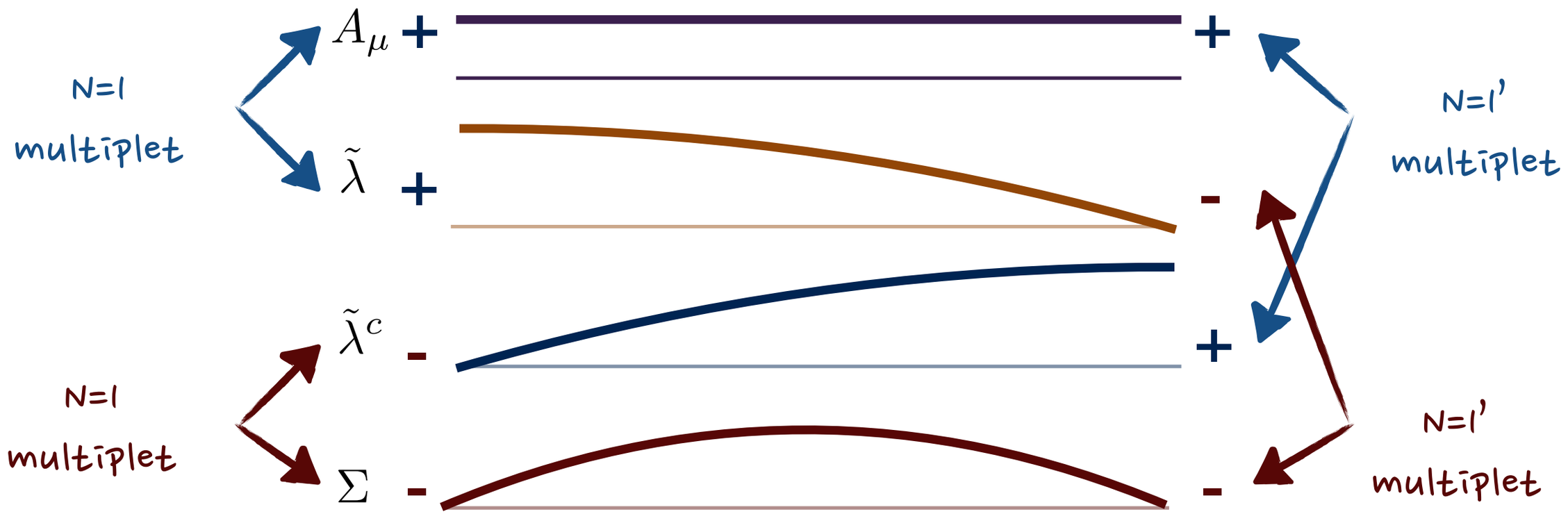
NO EWSB

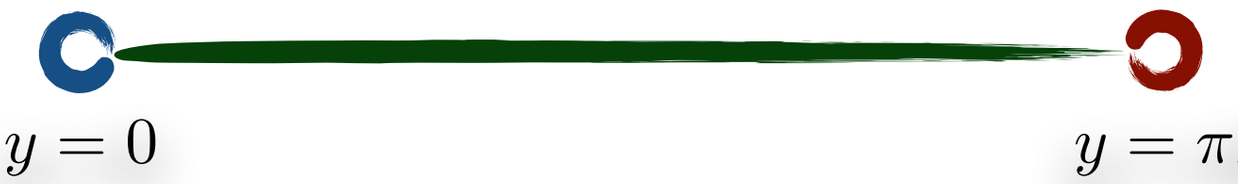
1-loop electroweak



2-loop stop-gluino

Softness of Scherk Schwarz





SUSY Breaking loops $\sim e^{-\pi R E}$ → "Messenger Scale" $\Lambda \sim \frac{1}{\pi R} \sim$ Tev!!!

1-loop masses:

$$\tilde{m}^2 \sim \frac{g^2}{16\pi^2}(\mathrm{TeV})^2 \ln \frac{\Lambda^2}{\mathrm{TeV}^2}$$

100 Tev : ~10

M_{gut} : ~100

EWSB & Max Natural SUSY

How EWSB works:

$$\delta\tilde{m}_i^2 \simeq \frac{7\zeta(3)}{16\pi^4 R^2}\left(\sum_{I=1,2,3} C_I(i) g_I^2 + C_t(i) y_t^2\right)$$

For light scalar modes & EWSB higher-dimension operators also make important contribution

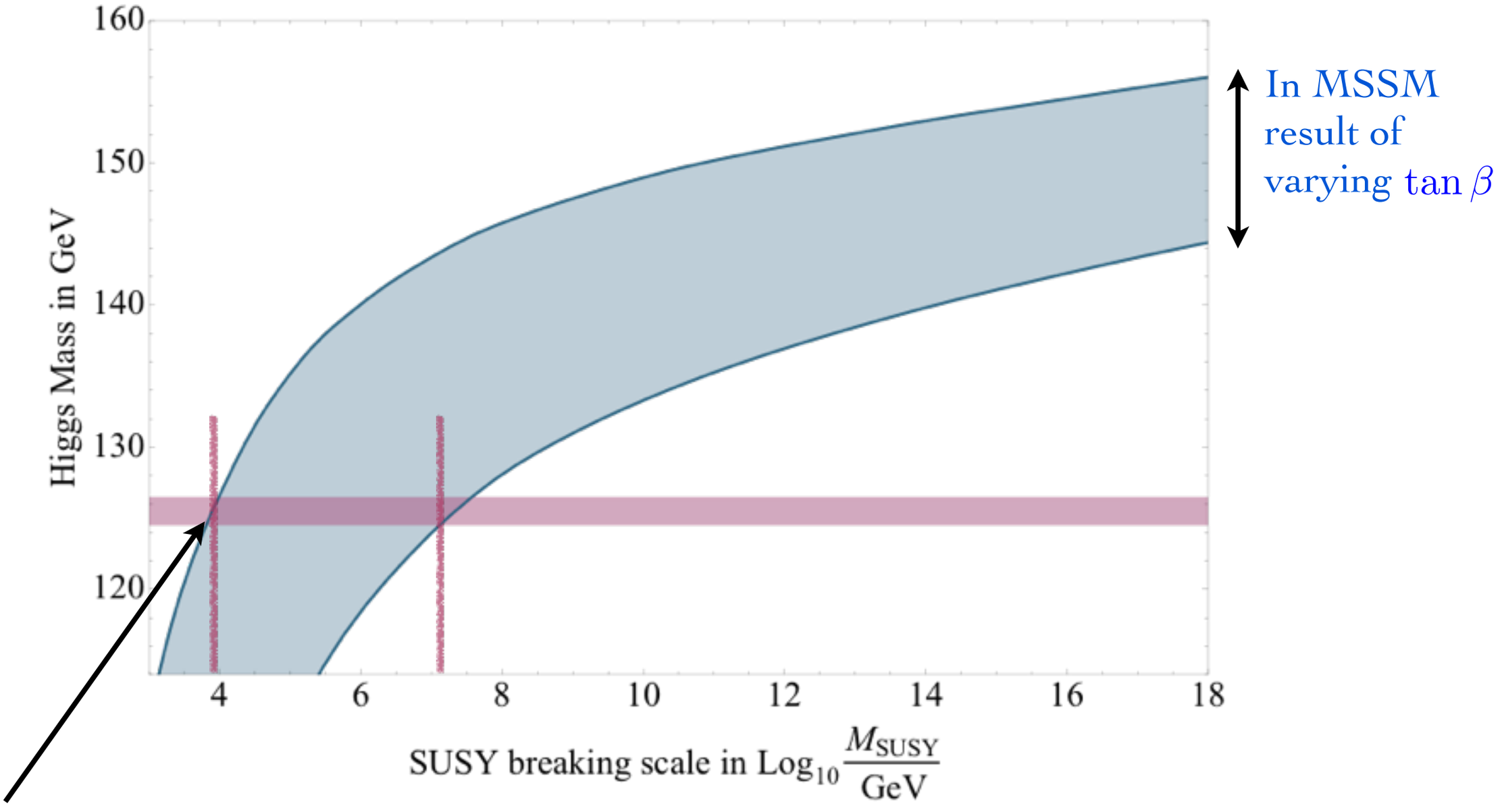
$$\Delta\mathcal{K}_{m_H^2} = \delta(y)\frac{c_H}{M_5^3} X^\dagger X H_u^\dagger H_u$$

$$\Delta\mathcal{K}_{m_{\tilde{t}}^2} = \delta(y) X^\dagger X \left(\frac{c_Q}{M_5^2} Q_3^\dagger Q_3 + \frac{c_U}{M_5^2} U_3^{c\dagger} U_3^c\right)$$

leading HDOs in our range of parameters

down-like Yukawas: $\delta(y)(H_u(y)^\dagger X^\dagger)\left(\frac{\tilde{y_b}}{M_5^{5/2}} Q_3 D_3^c + \ldots\right).$

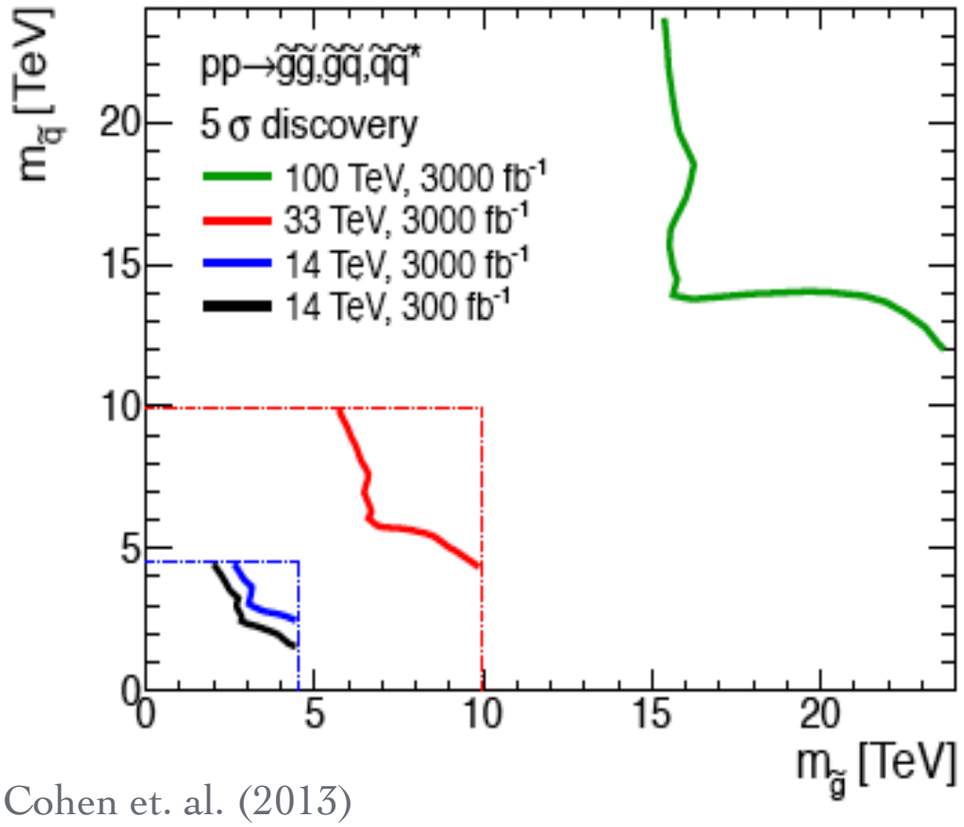
Amusing Possibility for 126 GeV Higgs



For stop mass ~3TeV & 10TeV gluino (~ 3% tuning) successful Higgs mass without need of U(1)' sector as model automatically realises $\tan\beta \to \infty$ limit without flavour problems

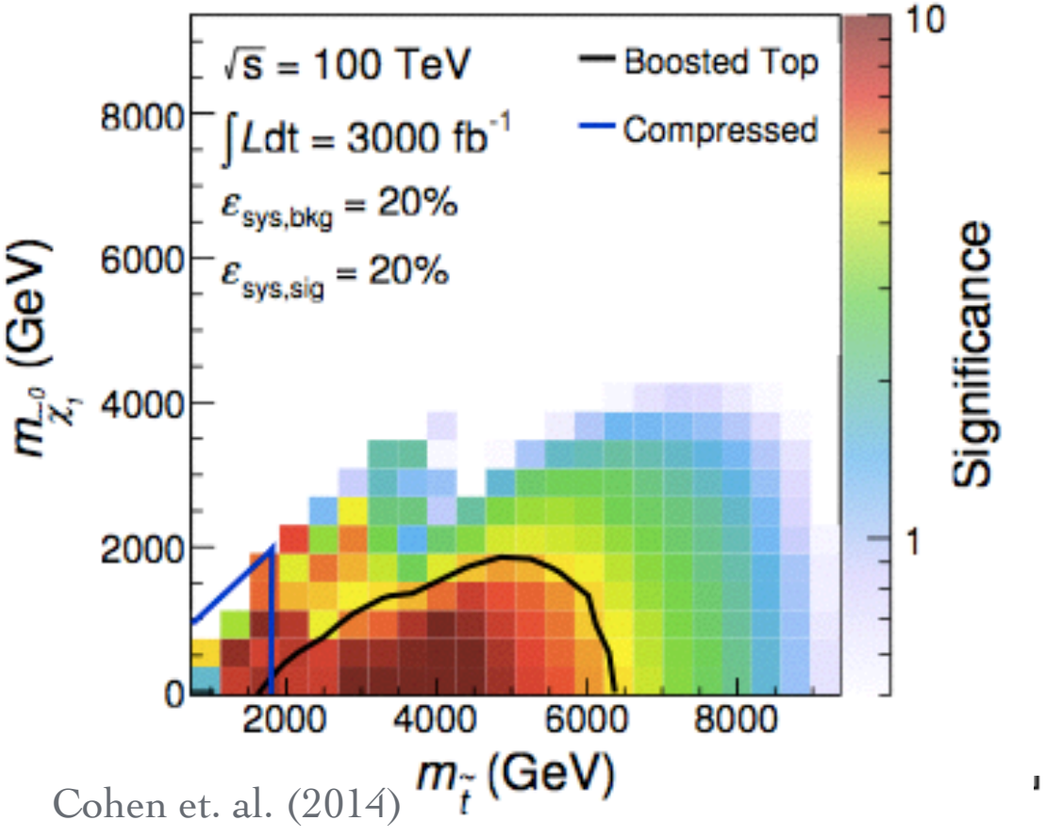
Discovery Reach of 100 TeV

squark-gluino



Cohen et. al. (2013)

stop-neutralino



Cohen et. al. (2014)

LHC 14: Probing MSSM-like theories much worse than 1% tuned, and Max Natural SUSY in dominant region of parameter space

100 TeV Collider: Probes MSSM-like theories at 0.01% level, and can discover simplest Max Natural SUSY in regime giving 126GeV higgs at ~3% tune