# Beyond the Realm of the MSSM

John March-Russell
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- Savas Dimopoulos, Kiel Howe, JMR; *Maximally Natural Supersymmetry,* arXiv:1404.7554
- Isabel Garcia Garcia, JMR; *Rare Flavor Processes in Maximally Natural Supersymmetry,* arXiv:1409.5669
- Savas Dimopoulos, Kiel Howe, JMR, James Scoville; *Auto-Concealment of SUSY in Extra Dimensions,* arXiv:1411.0805
- Isabel Garcia Garcia, Kiel Howe, JMR; *Natural Scherk-Schwarz Theories of the Weak Scale,* arXiv:1510.07045
- Junwu Huang, JMR; *Unified Maximally Natural Supersymmetry,* arXiv:1607.08622

# All MSSM-variants are unnatural?

eg

- Natural SUSY (1st/2nd generation sfermions heavy)
- R-Parity breaking: B violation (hide via hadrons)

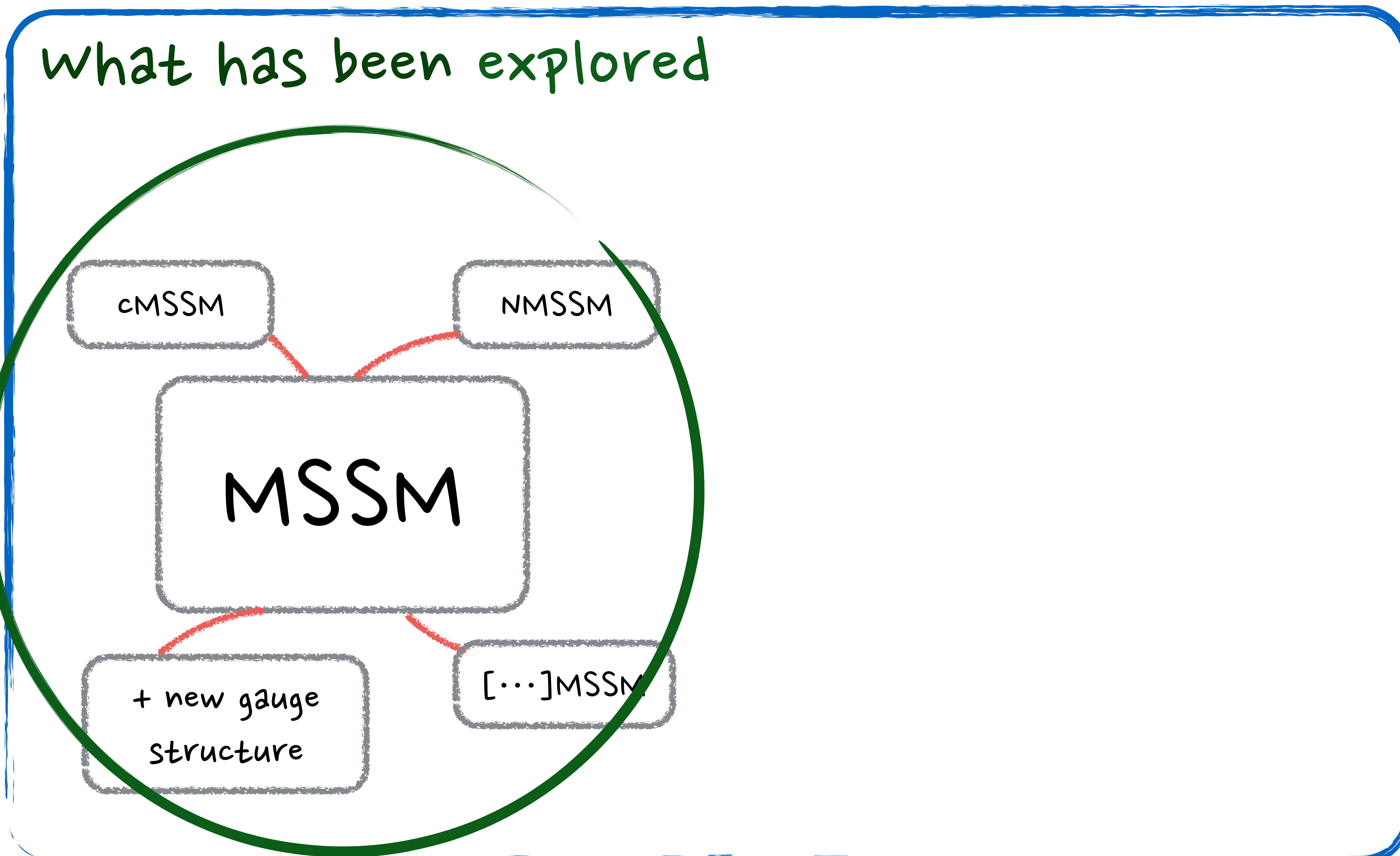
} Gluino bounds already imply ~1% tuning

- Hide and Seek (compressed "just-so" spectra and decays)

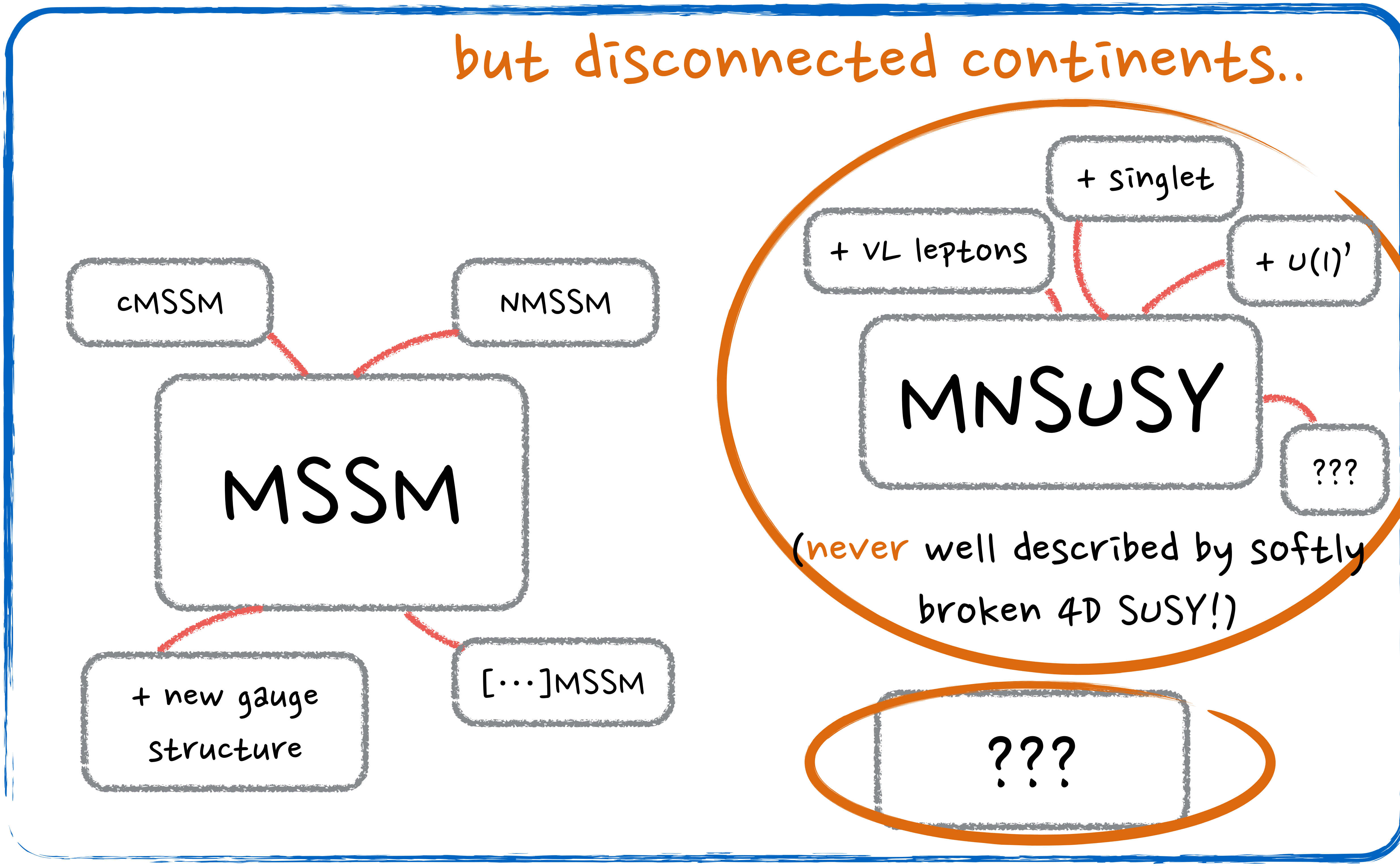
Many `coincidences' needed so still tuned

So must we give up search for fully natural theory??

# Supersymmetric Theory Space



# Supersymmetric Theory Space



# Topic of talk...

(1) Scherk-Schwarz ~~SUSY~~ (non-local in 5D breaking using R-symmetry twist)

(2) Natural Spectrum + EWSB

(3) LHC pheno (*very* brief)

(4) Auto-concealment of SUSY

Important previous work:

Antoniadis, Dimopoulos, Pomarol, Quiros - 1998

Delgado, Pomarol, Quiros - 1998

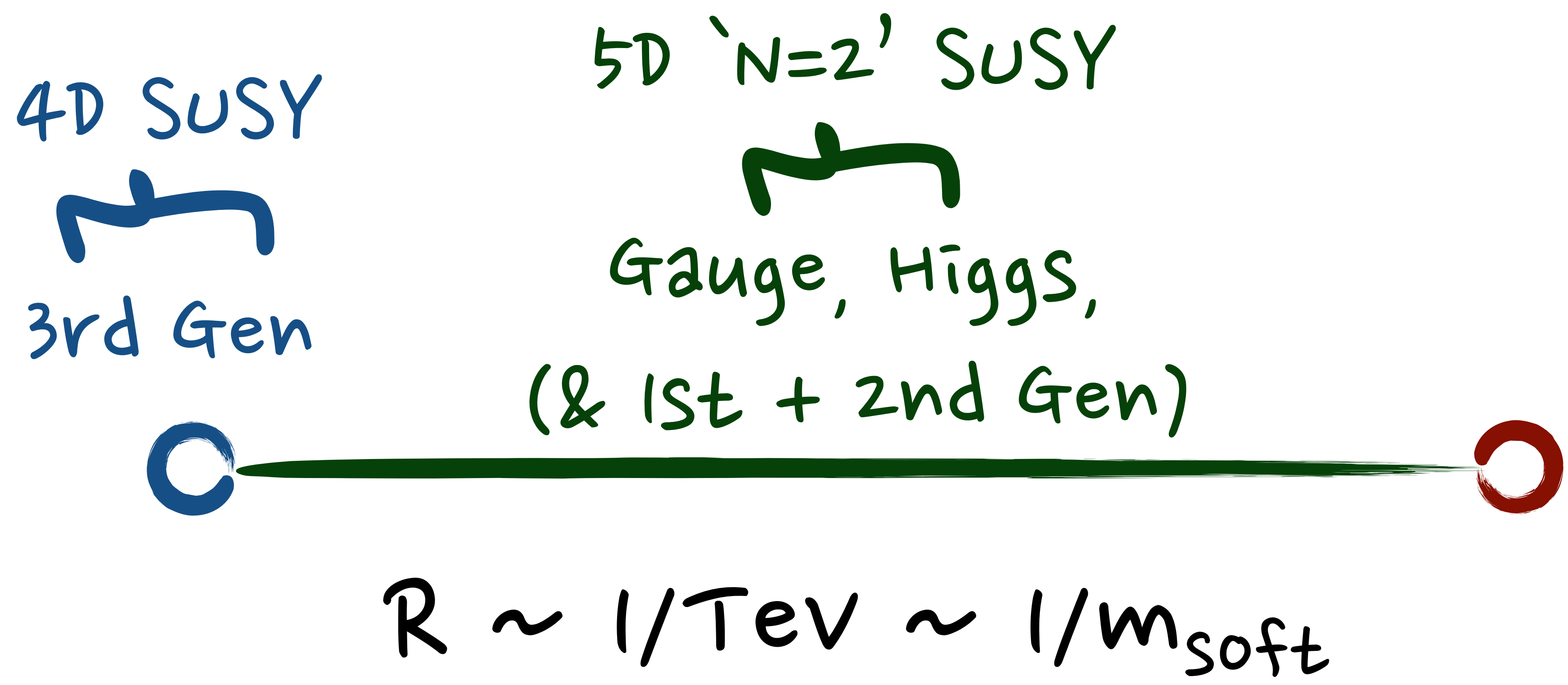
Delgado, Quiros - 2001

Barbieri, Hall, Nomura - 2000, 2001

Hall, Marandella, Nomura et al. - 2002

Barbieri, Marandella, Papucci - 2002, 2003

# The Basic Setup




fundamental scale:

$M_5 \equiv M_* \sim 30 - 100$ TeV

($\pi M_* R \sim 30$ by perturbativity)

# (1) Scherk-Schwarz SUSY (SSSB)

Impose a non-trivial periodicity condition along the extra dimension for 5D fields (a *twist* along the extra dimension):

Scherk-Schwarz parameter

generator of global symmetry of 5D theory

$$\Phi(x^\mu, y + 2\pi R) = e^{i2\pi\alpha T}\Phi(x^\mu, y)$$

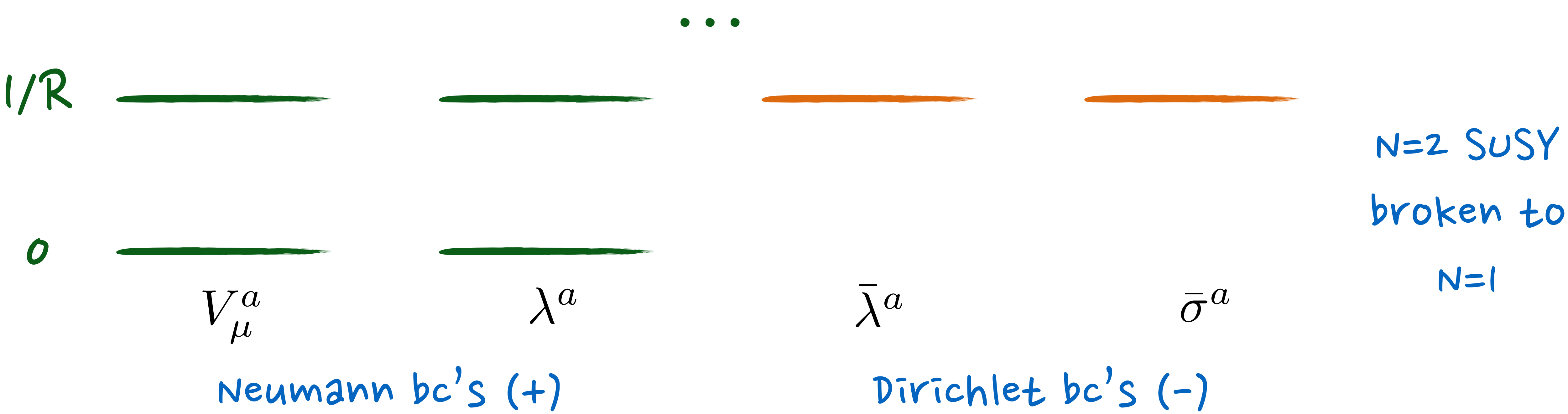
$T$ : generator of $SU(2)_R$ symmetry

$\Rightarrow$ the twist shifts the masses of the different components of a 5D supermultiplet

# (1) Scherk-Schwarz ~~SUSY~~ (SSSB)

For example, for a vector supermultiplet:

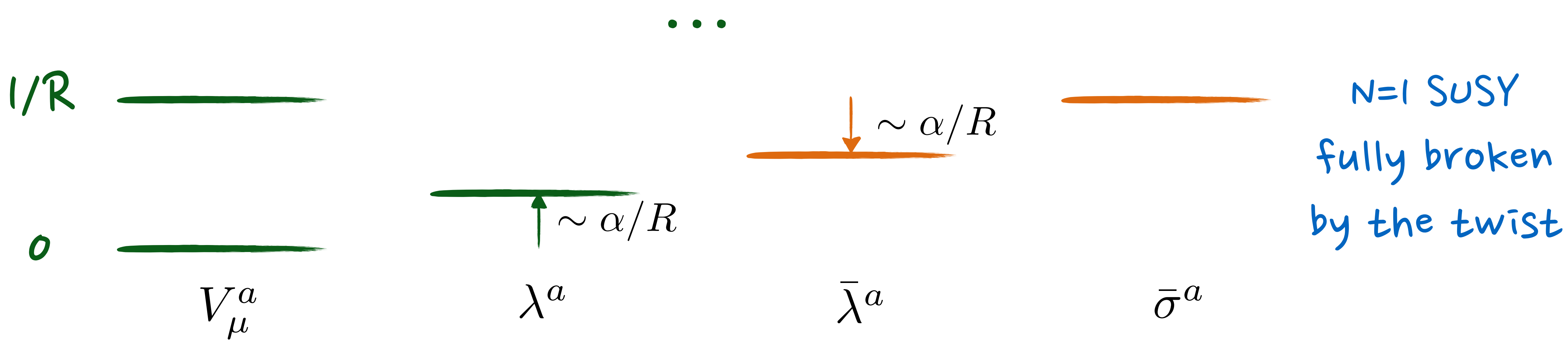
- compactification on $S^1/\mathbb{Z}_2$ :



# (1) Scherk-Schwarz ~~SUSY~~ (SSSB)

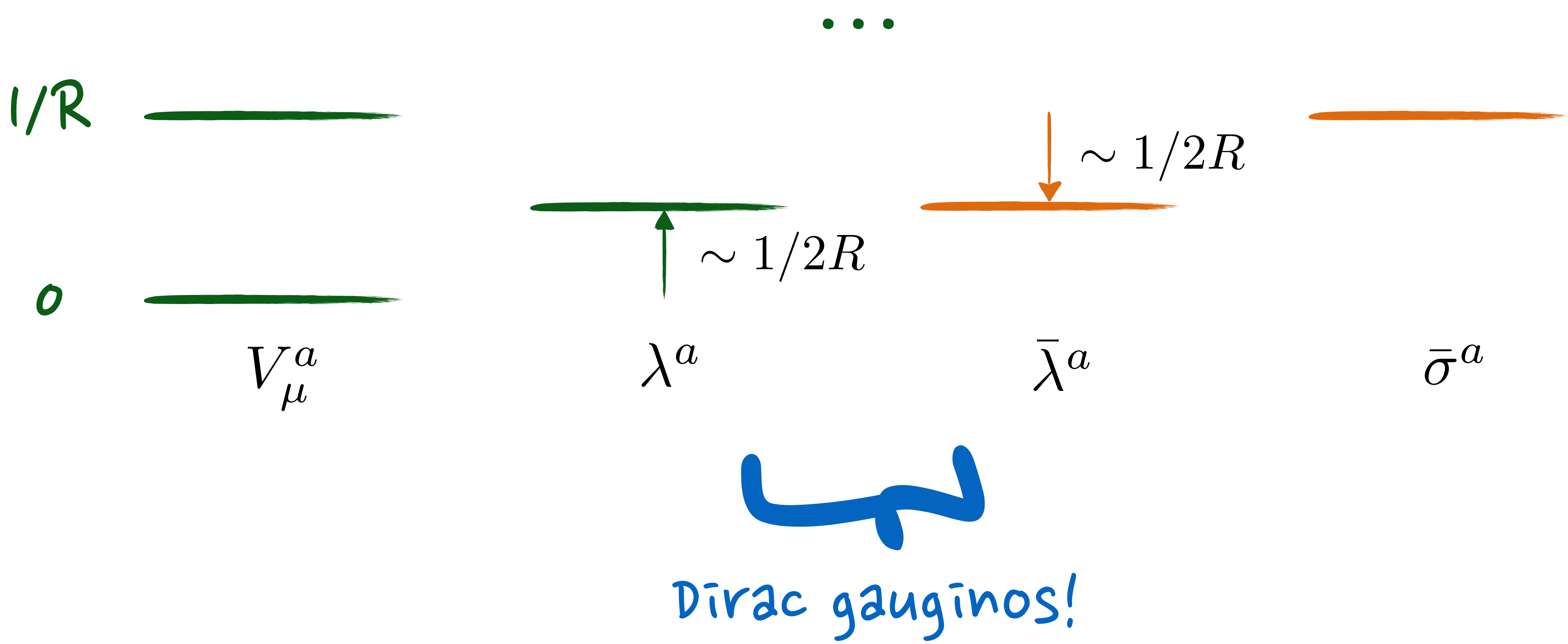
For example, for a vector supermultiplet:

- Scherk-Schwarz SUSY breaking:



# (1) Scherk-Schwarz SUSY (SSSB)

and for maximal twist $(\alpha = 1/2)$




$$m_\lambda^2 = m_{\bar{\lambda}}^2 = \left(\frac{2n+1}{2R}\right)^2$$

An accidental $U(1)_R$ symmetry is recovered in the limit of maximal twist

# Maximal SSSB Twist

$\Rightarrow$ Scherk-Schwarz with maximal twist is a special point in terms of symmetries

Forbidden by the $R$-symmetry:

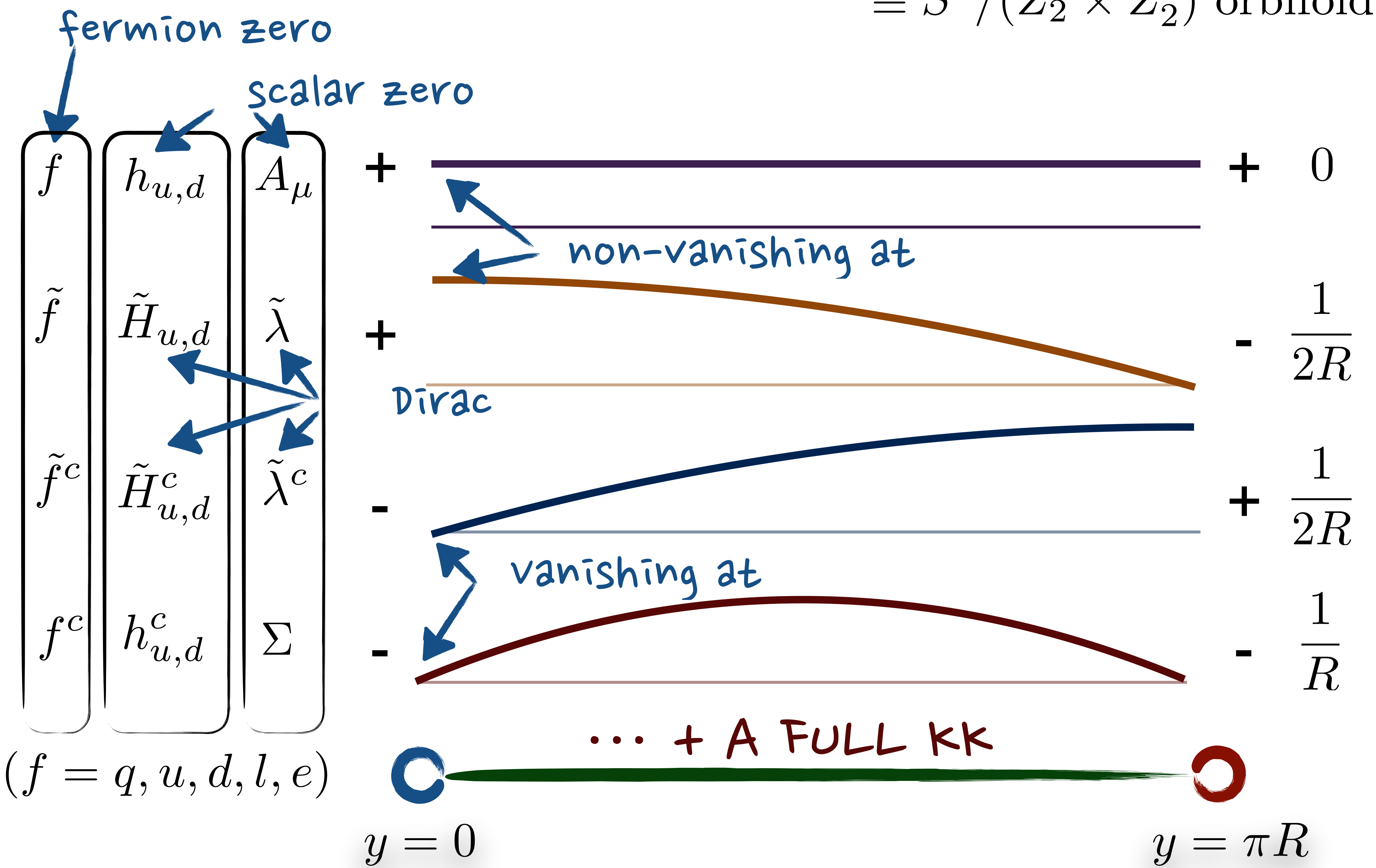
- Higgsino and Majorana gaugino masses
- $A$-terms

} helps solve the SUSY flavour problem

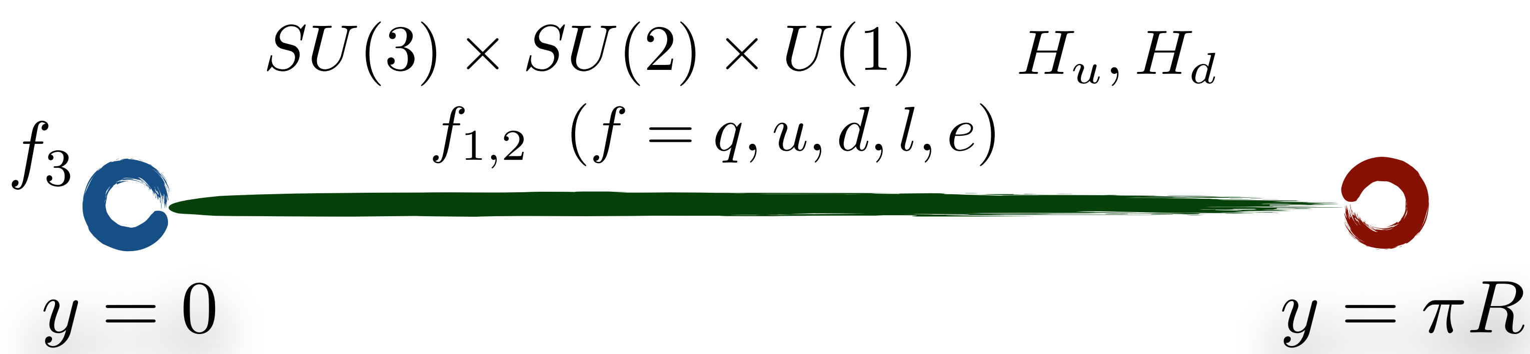
etc…

# Maximal SSSB Twist

$\equiv S^1/(Z_2 \times Z_2')$ orbifold



# Tree-level Scherk-Schwarz Spectrum




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

Direct & universal
bulk soft masses

No tree-level
tuning!!

Almost exact $U(1)_R$
Dirac Masses

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

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

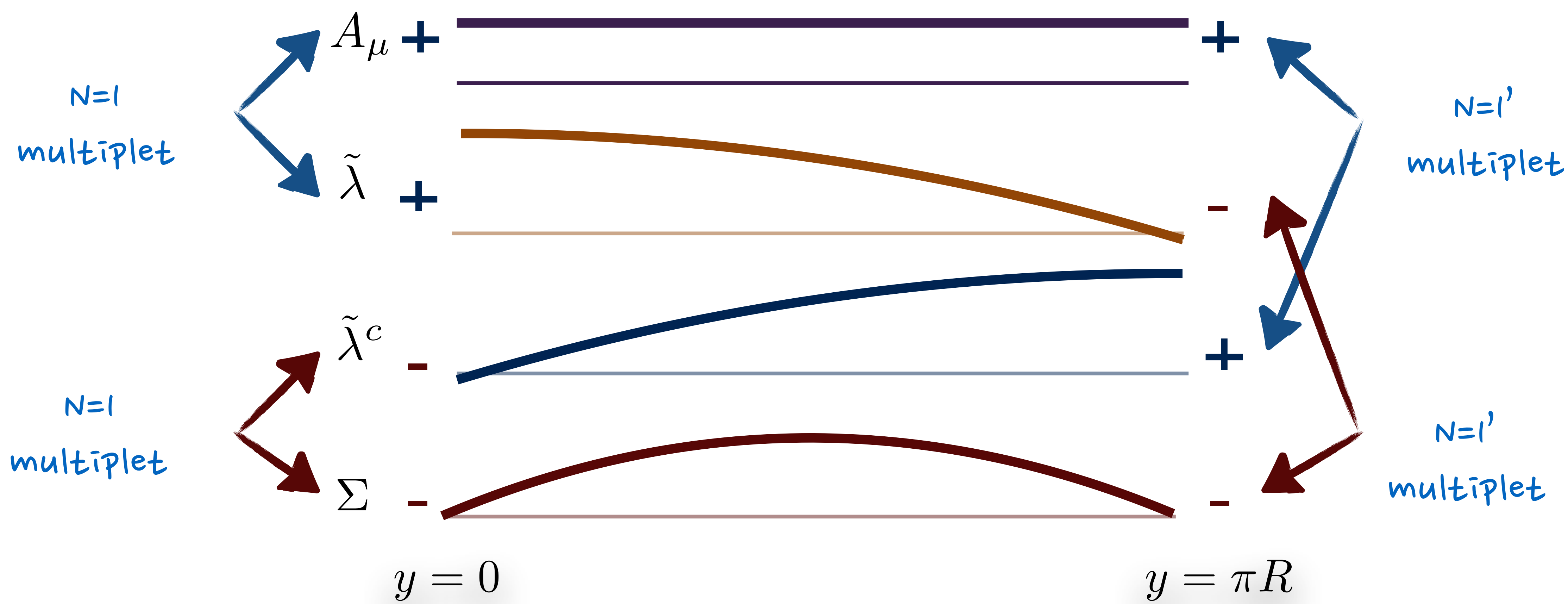
locality

zero mode

No SUSY
flavor problem!

leading rare flavor from SM KK, see
I. Garcia Garcia, JMR: 1409.5669

# Exceptional Softness of Scherk-Schwarz




~~SUSY~~ loops finite (as must go from brane to brane) → "Messenger Scale" $\Lambda \sim \frac{1}{\pi R} \sim$ Tev !!

cf. usually 1-loop masses:

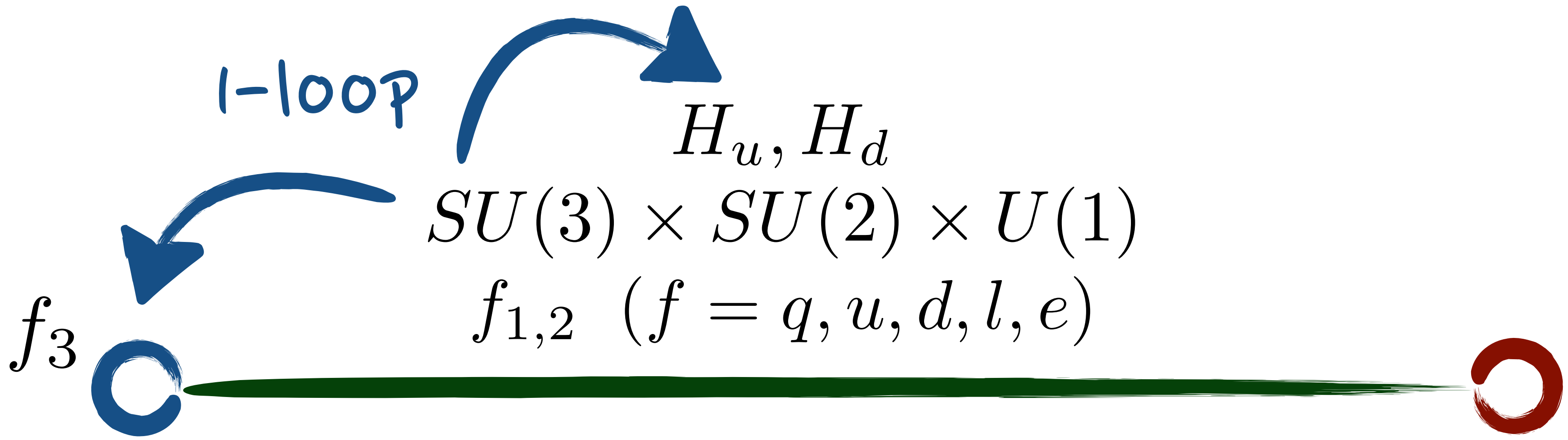
$$\tilde{m}^2 \sim \frac{g^2}{16\pi^2}(\text{TeV})^2 \ln \frac{\Lambda^2}{\text{TeV}^2}$$

←

100 Tev : ~12

$M_{gut}$ : ~70

# Loop-level Scherk-Schwarz Spectrum




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

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

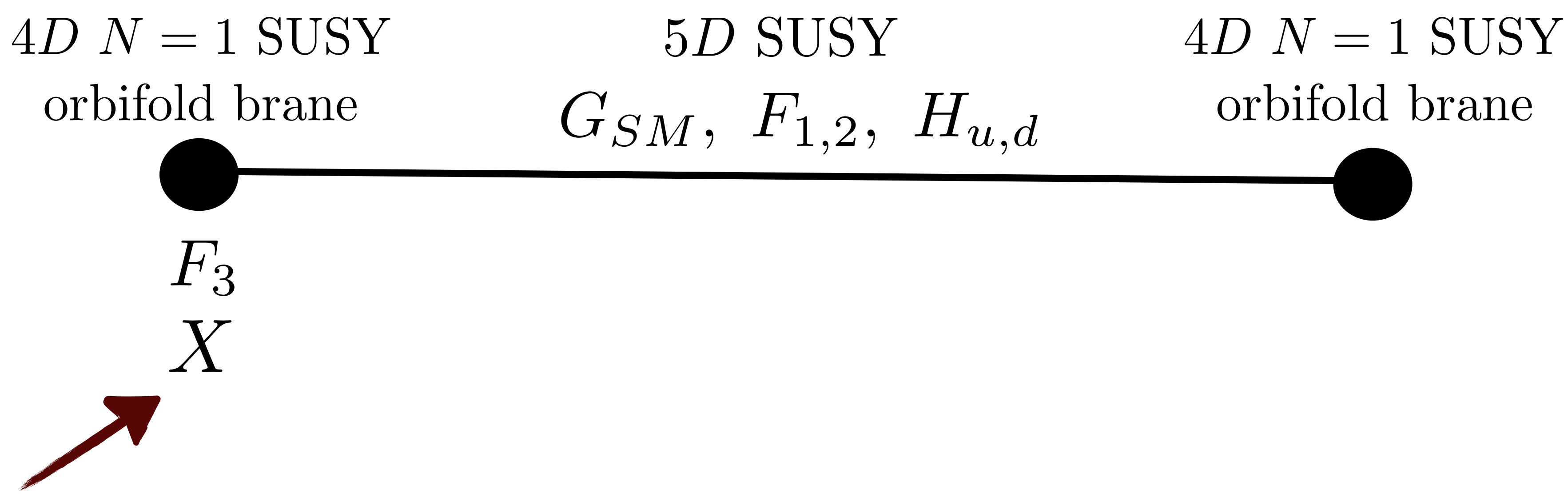
→ 1/R ~ 4 Tev for natural weak scale!

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

→ Large stop-gluino hierarchy

(gluino doesn't suck)

# Radius Stabilization & CC




Crucial extra ingredient - $\langle F_X \rangle \neq 0$ - necessary to give zero CC after radius stabilisation

$$V_{vac} \simeq -\left(\frac{1}{\pi R}\right)^4 + |F_X|^2$$

Leads to new sources of soft masses via higher-dim ops (this F-term triggered by SSSB so still no log enhancements)

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

(comparable to 1-loop)

# EWSB?

- At tree level, the Higgs mass squared vanishes

- At loop level

1-loop contribution from EW sector

$$\delta m^2_{H_u}\big|_{\rm EW} \approx \frac{7\zeta(3)}{16\pi^4 R^2}\frac{3}{4}g_2^2 \sim \left(\frac{1}{20R}\right)^2$$

$$\delta m^2_{H_u}\big|_{y_t} \approx -\frac{3y_t^2(\mu)}{16\pi^2}(\tilde{m}^2_{Q_3}(\mu) + \tilde{m}^2_{\bar{U}_3}(\mu))\log\left(\frac{\mu^2}{\tilde{m}_{Q_3}(\mu)\tilde{m}_{\bar{U}_3}(\mu)}\right)\Bigg|_{\mu=\frac{1}{\pi R}}$$

2-loop piece from top sector (+ finite + 3-loop leading log included in numerics)

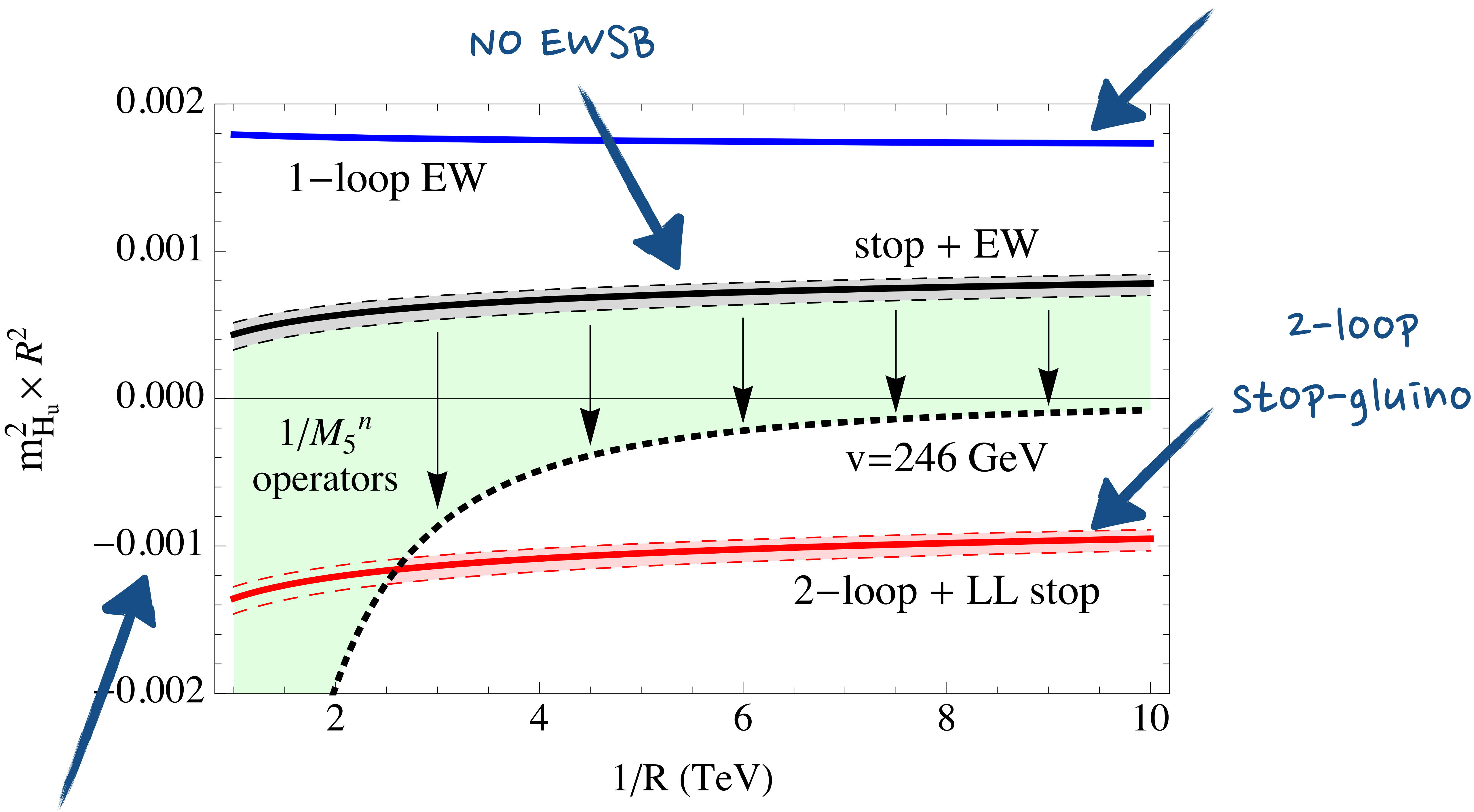
Barbieri, Marandella, Papucci, '02,'03;

Dimopoulos, Howe, JMR; '14

Garcia Garcia, Howe, JMR; '15

# EWSB?

Total Scherk-Schwarz contribution:




Note scale: very close to EWSB -> small perturbations important

# EWSB & Max Natural SUSY

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

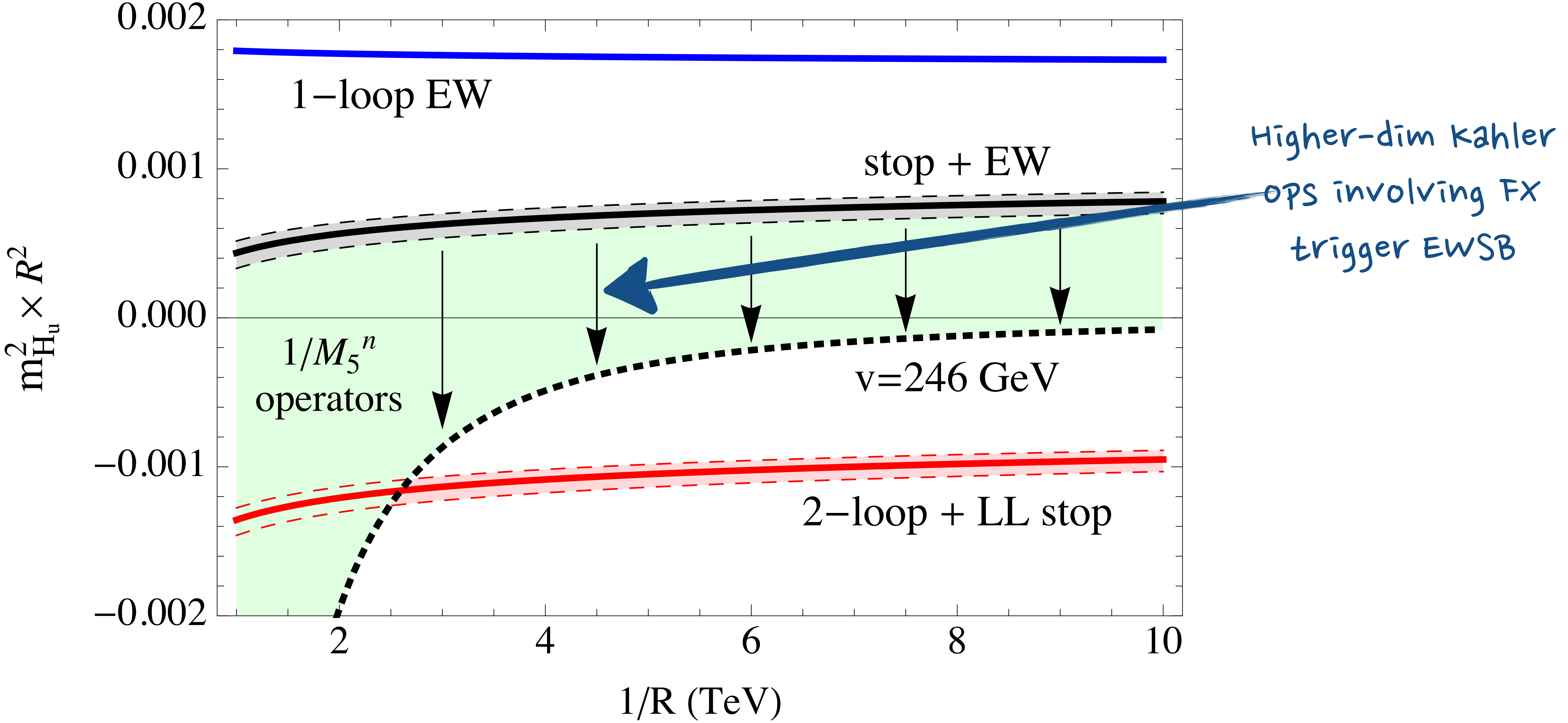
$$\Delta\mathcal{K}_{m_H^2} = \delta(y)\frac{c_H}{M_5^3}X^\dagger X H_u^\dagger H_u$$

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

leading HDOs in our range of parameters

cf down-like Yukawas (more later): $\delta(y)(H_u(y)^\dagger X^\dagger)\left(\frac{\tilde{y_b}}{M_5^{5/2}}Q_3D_3^c + ...\right).$

# EWSB?



0.002
0.001
0.000
−0.001
−0.002
$m^2_{H_u} \times R^2$
2
4
6
8
10
1/R (TeV)
1−loop EW
stop + EW
$1/M_5{}^n$ operators
v=246 GeV
2−loop + LL stop
Higher-dim Kahler ops involving FX trigger EWSB

# Who is Higgs?

ONLY $\langle H_u \rangle \neq 0$. Down-like quark and lepton masses from Kahler couplings to $H_u^\dagger$

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

NO $\tan\beta, \; B_\mu, \; \mu$

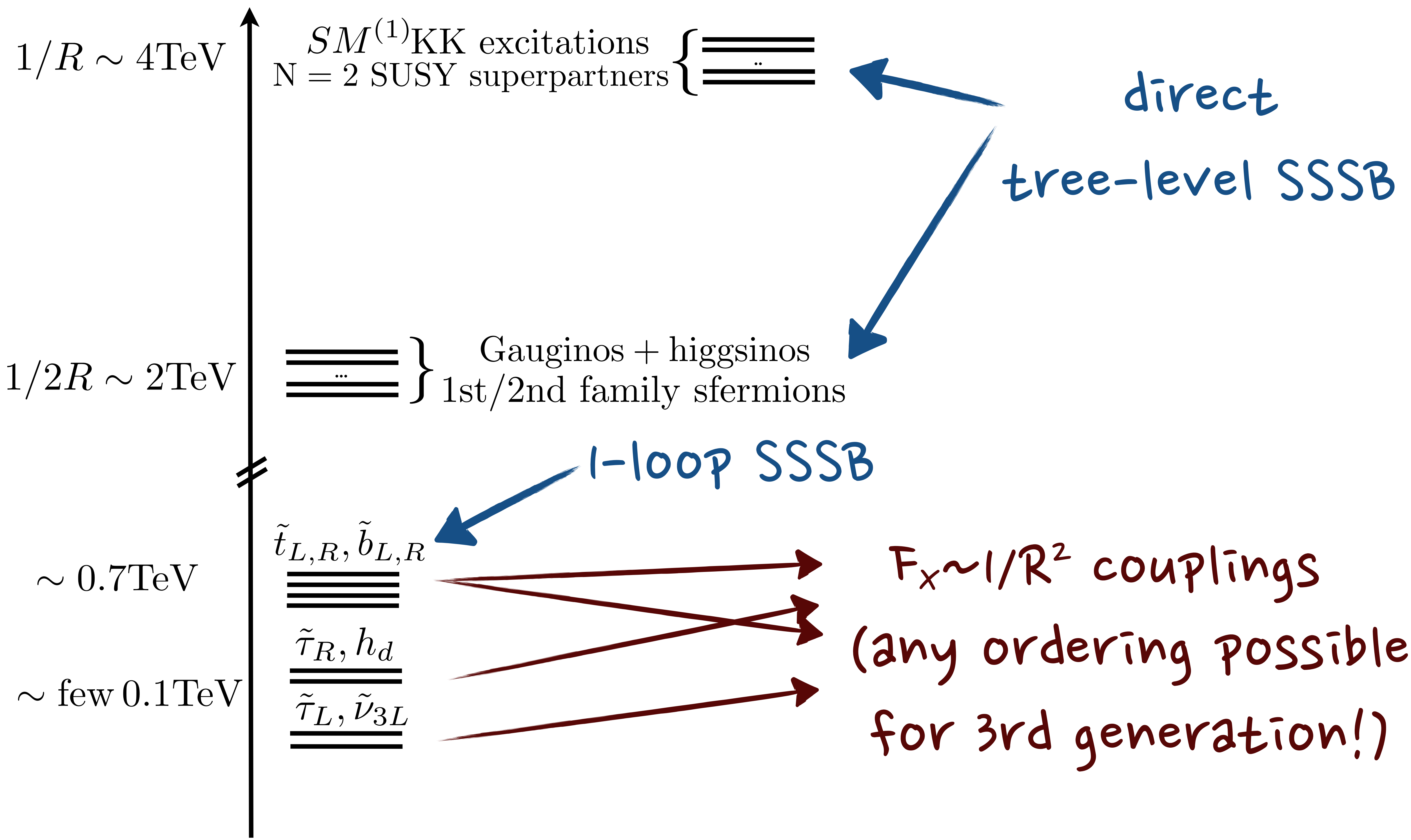
(Hd is an inert spectator)

Single-Higgs-doublet SUSY is realised in these models

R. Davies. JMR. M. McCullough. arXiv1103.1647

Physical Higgs is automatically SM-like up to loop-level effects!

# Overall Spectrum

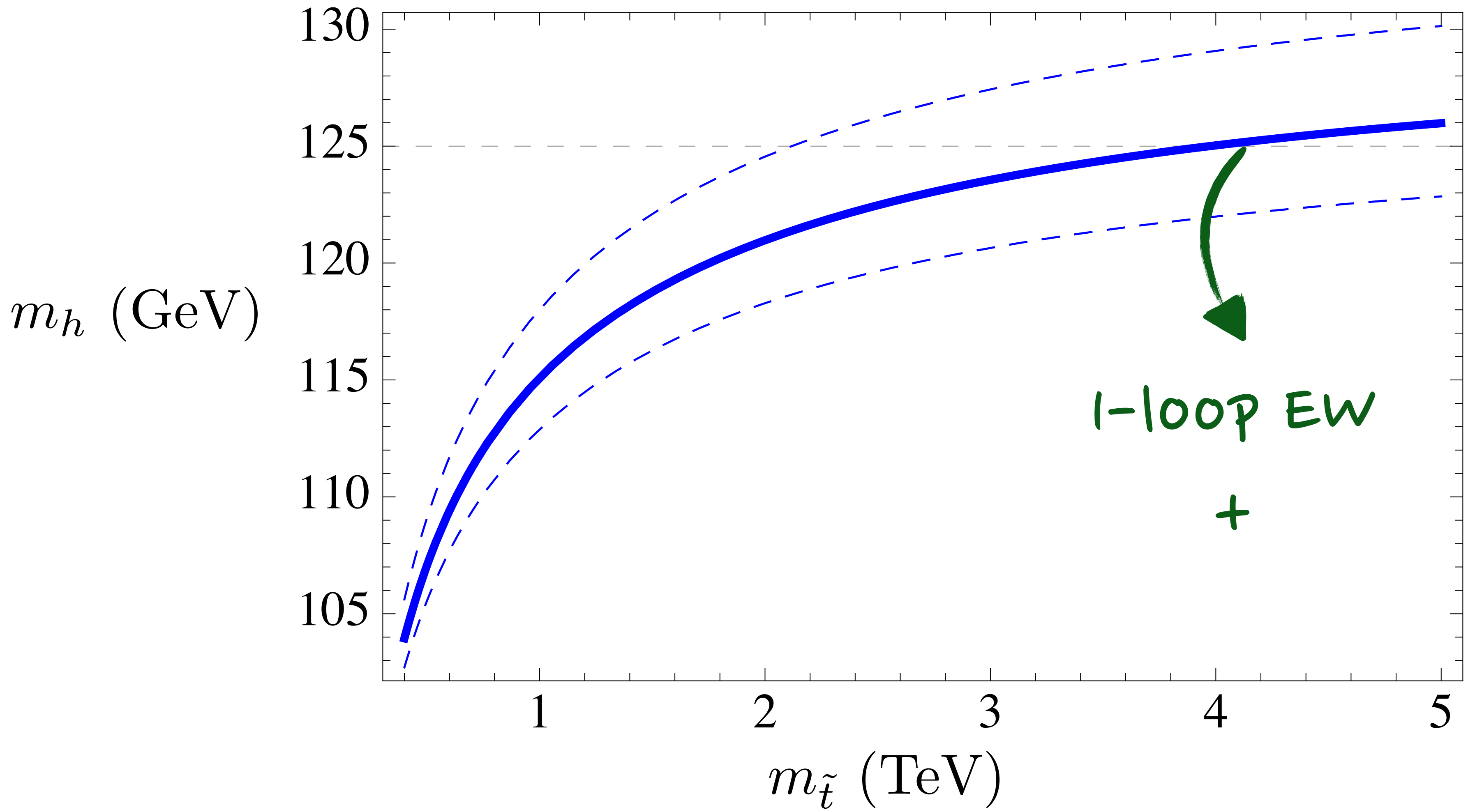


But...

# 125 GeV Higgs?

In the minimal version of the model, to get the correct Higgs mass one needs $\gtrsim 4$ TeV stops ($1/R \sim 40$TeV)

$\Rightarrow$ 1 % tuning!




(model automatically realises $\tan\beta \to \infty$ limit of MSSM higgs mass without flavour problems)

# Summary so far…

- EWSB happens with *low tuning* for $1/R \sim 4 - 10$ TeV and it is OK with all constraints

- Achieving a 125 GeV Higgs with heavy stops implies ~ 1% tuning

but this is still much better than in the MSSM !

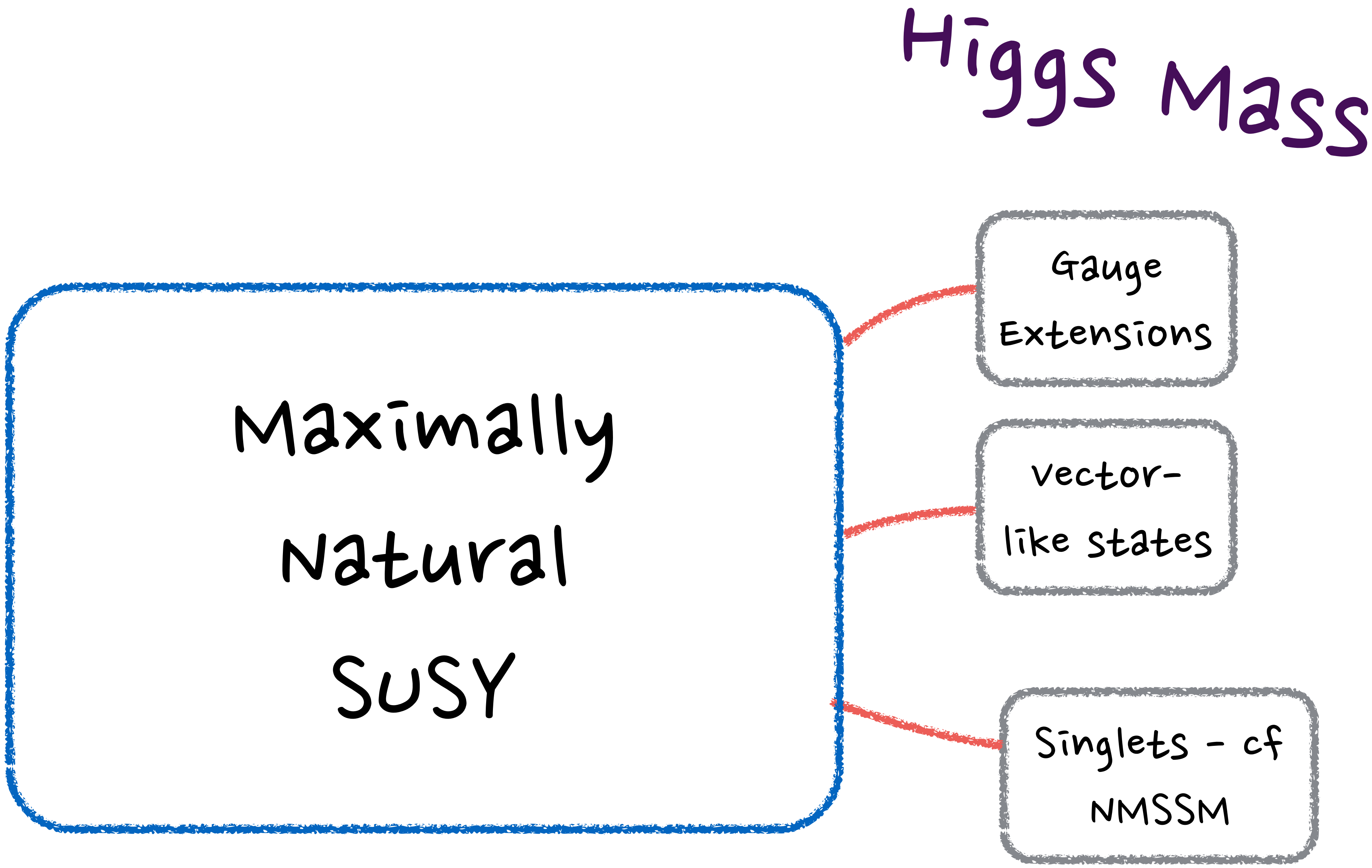
$$\delta m^2_{H_u} \sim -\frac{3|y_t|^2}{4\pi^2}\left(m^2_{\tilde{t}} + \frac{1}{2}|A_t|^2\right) \log\left(\frac{\Lambda}{\tilde{m}}\right)$$

0

# 125 GeV Higgs?

Is it possible to extend MNSUSY
to achieve the correct Higgs
mass at a low value of 1/R
so maintaining low tuning...?

# 125 GeV Higgs?

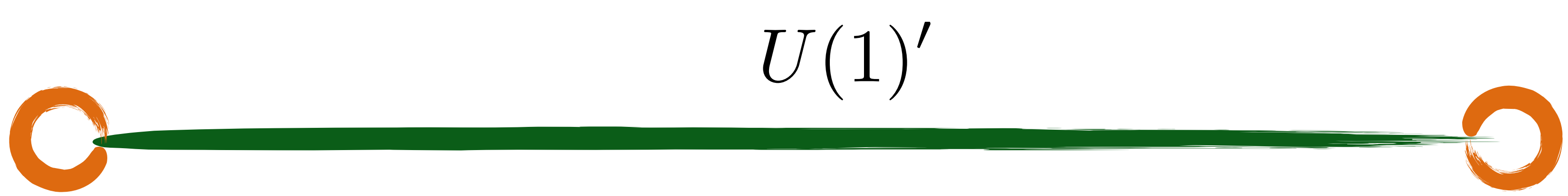


# MNSUSY+U(1)’

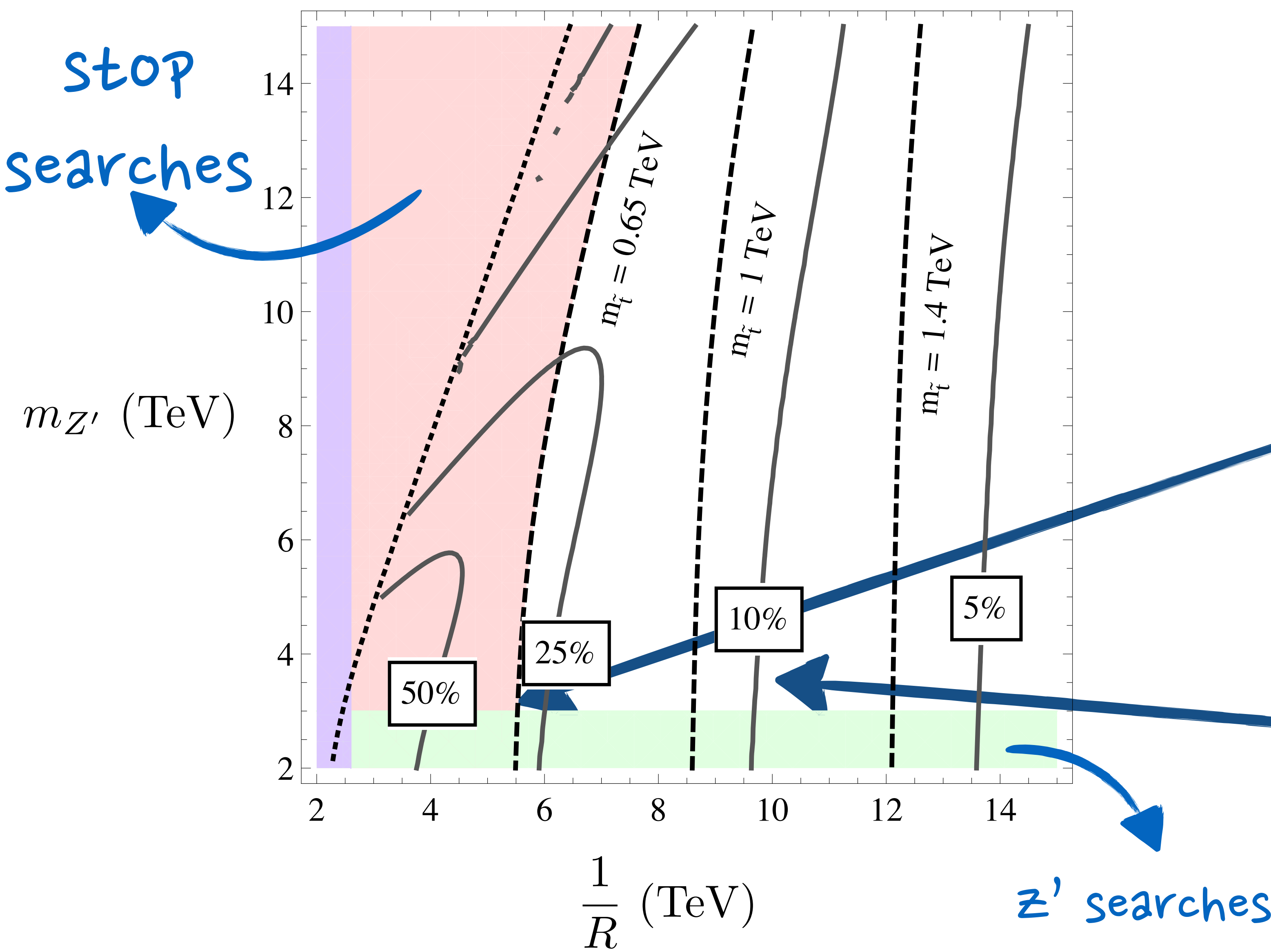
Dimopoulos, Howe, JMR; arXiv:1404.7554

Garcia Garcia, Howe, JMR; arXiv:1510.07045

- Extra gauge group that generates a non-decoupling $D$-term for the Higgs quartic
- Simplest choice: $U(1)'$ in the bulk with breaking scale comparable to the scale of SUSY breaking
- Experimental constraints require the new $U(1)'$ to be broken at scale $m_{Z'} \gtrsim 3$ TeV



# Tuning: U(1)' Variation




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

TUNING ~30%(!)

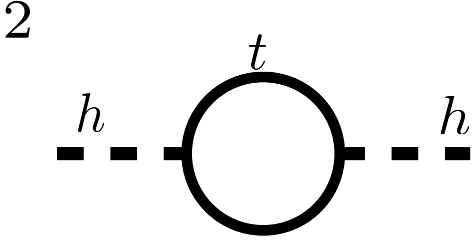
For ~700 GeV Stop &

2.5 TeV Gluinos/Squarks

~10% Tuned

within LHC13 Reach

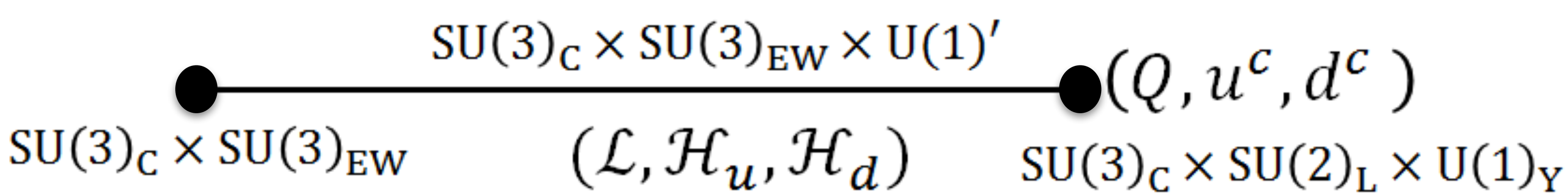
"Maximal" ~ saturates one-loop tuning $\Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2}M^2$



# Unification?

Junwu Huang, JMR; *Unified Maximally Natural Supersymmetry,* arXiv:1607.08622

Can get an extended version of 5d $SU(3)_{EW}$ unification (with tree-level $s^2$=1/4)




Scale preferred by $SU(3)_{EW}$ unification (1/R=4.4TeV) agrees with 1/R of MNSUSY at low tuning!

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Junwu Huang, JMR; *Unified Maximally Natural Supersymmetry*, arXiv:1607.08622

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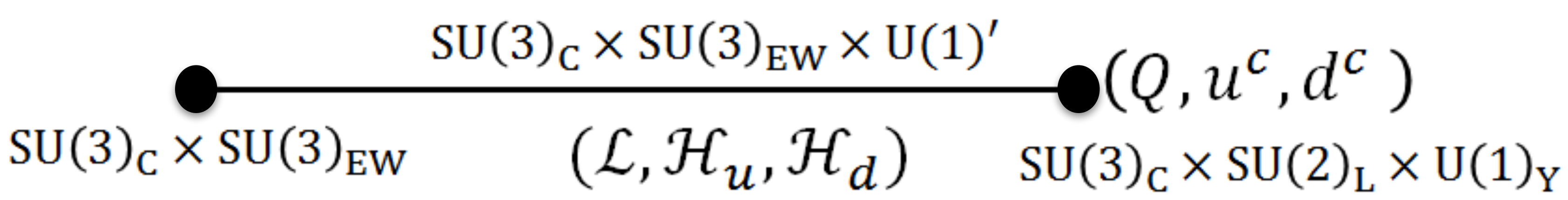


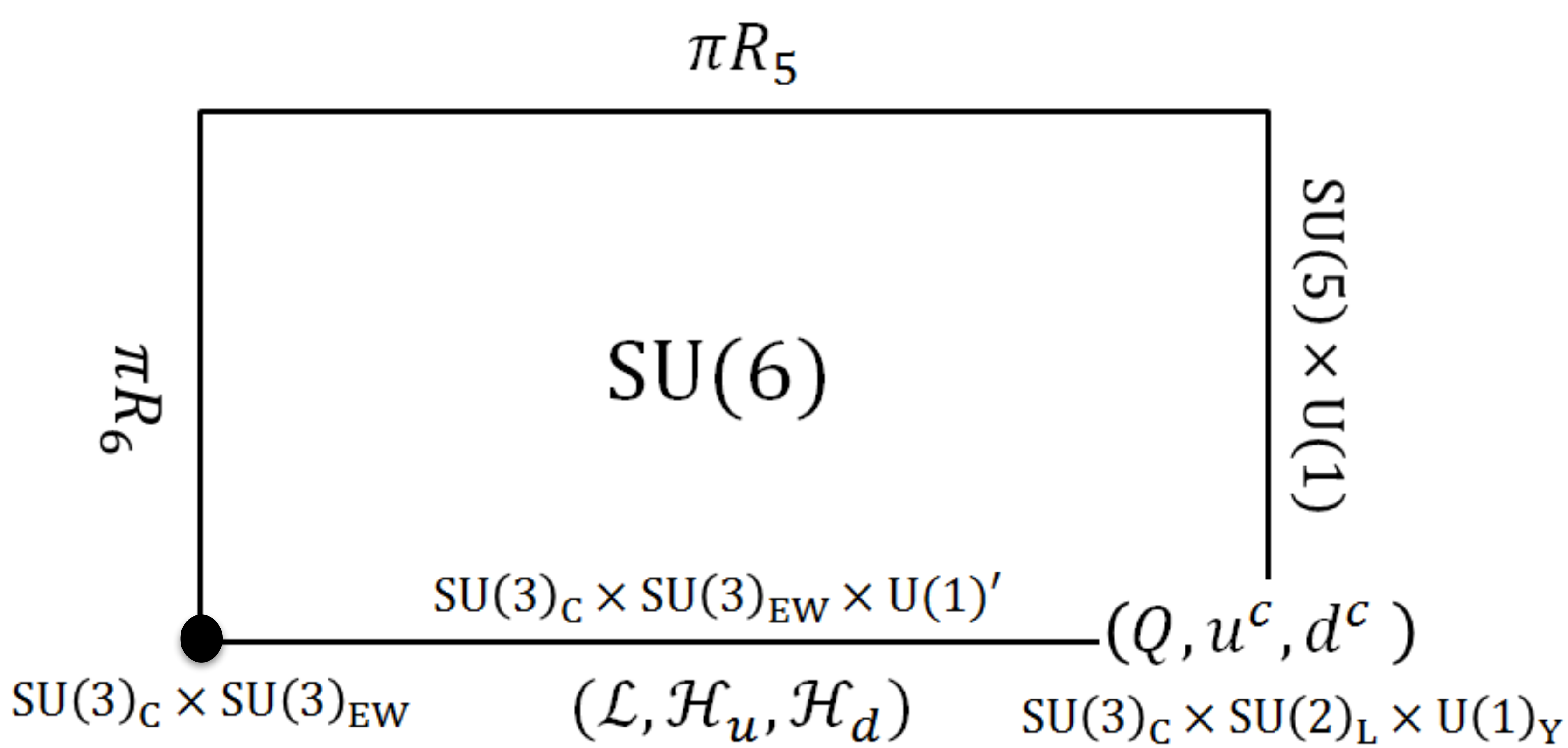

$$
\begin{aligned}
\frac{4\pi}{g^2(\mu)} = \frac{1}{\alpha_{M_Z}} - \frac{b_{\rm SM}}{2\pi}\log[\frac{\mu}{M_Z}] - \frac{b_{\rm Squark}}{2\pi}\log[\frac{\mu}{M_{\rm Squark}}] \\
- \frac{b_{\rm HeavyHiggs}}{2\pi}\log[\frac{\mu}{M_{\rm HeavyHiggs}}] - \frac{b_{\lambda x}}{2\pi}\log[\frac{\mu}{M_{\lambda x}}] - \frac{b_{\rm S}}{2\pi}\log[\frac{\mu}{M_S}] \\
- \frac{b_{\rm even}}{2\pi}(\log[\mu/M_R] + 1 + \log[\pi] - 0.02) - \frac{b_{\rm odd}}{2\pi}\log[2] + \cdots
\end{aligned}
$$

| Group | $b_{\rm SM}$ | $b_{\rm Squark}$ | $b_{\rm HeavyHiggs}$ | $b_{\lambda x}$ | $b_S$ | $b_{\rm even}$ | $b_{\rm odd}$ |
|---|---|---|---|---|---|---|---|
| $SU(3)_C$ | -7 | 2 | 0 | 0 | 0 | 5 | -2 |
| $SU(2)_L$ | -19/6 | 3/2 | 1/6 | 2/3 | 0 | 4/3 | -5/6 |
| $U(1)_Y$ | 41/18 | 11/18 | 1/18 | 2 | 2/9 | -10/3 | 23/6 |

After log differential running get $s^2$ = 0.2315 to 1% uncertainty!

# Unification?

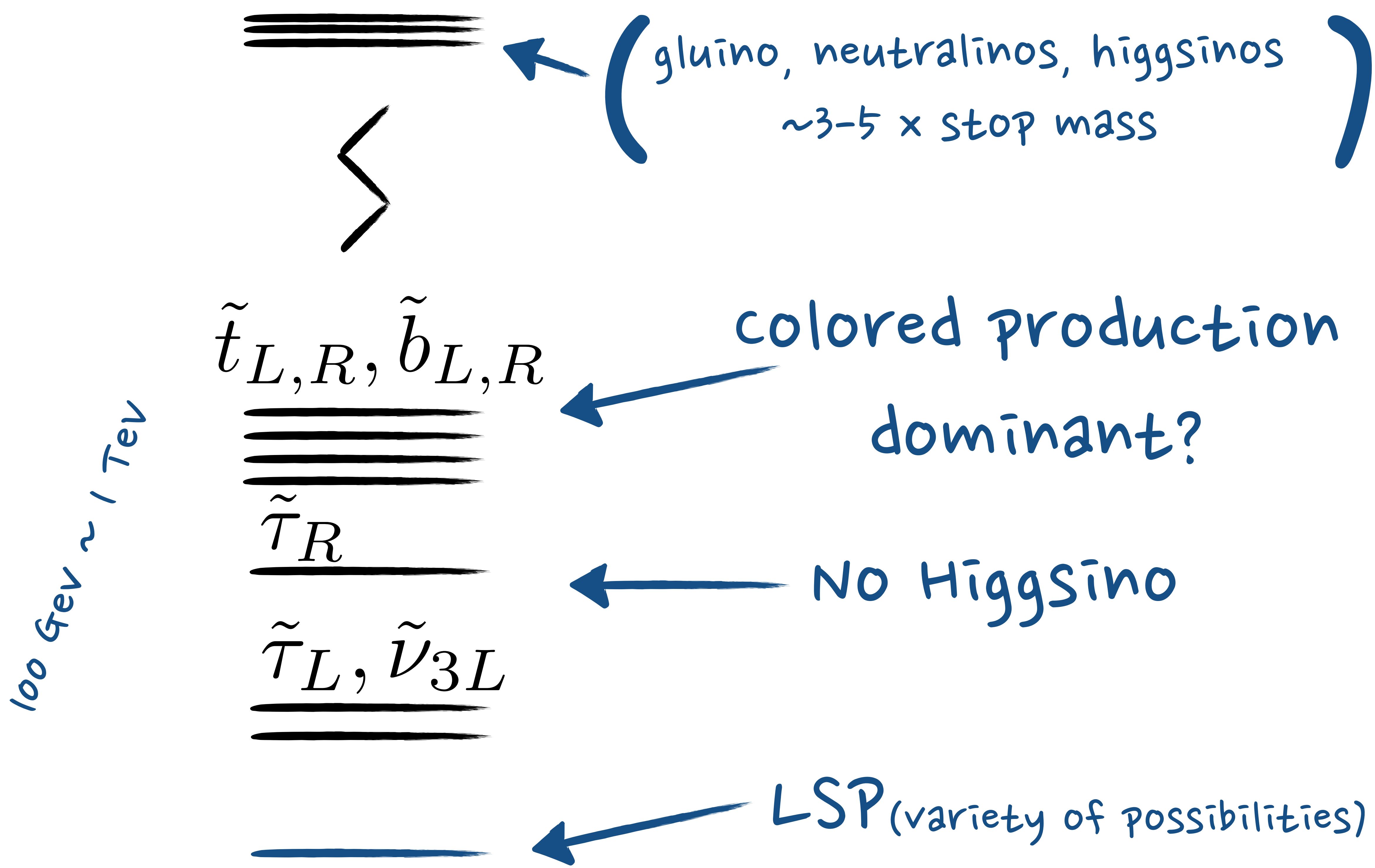
If you want can further unify $SU(3)_{EW}$ with $SU(3)_c$ and $U(1)'$ into $SU(6)$ theory in 6d




for complicated details see

Junwu Huang, JMR; *Unified Maximally Natural Supersymmetry,* arXiv:1607.08622

# (3) LHC Pheno: 3rd Generation Sfermion Signatures



# LSP Candidates

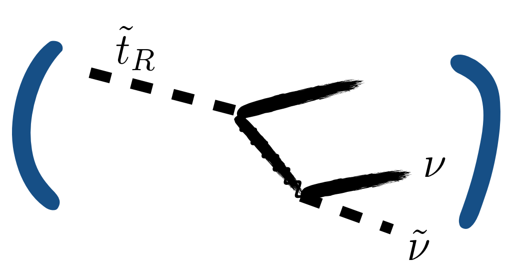
Natural candidates for (collider-stable) LSP:

1) $\psi_X$

Brane-localized goldstino of X SUSY breaking


2) $\tilde{\nu}_3$

Brane-localized left handed sneutrino

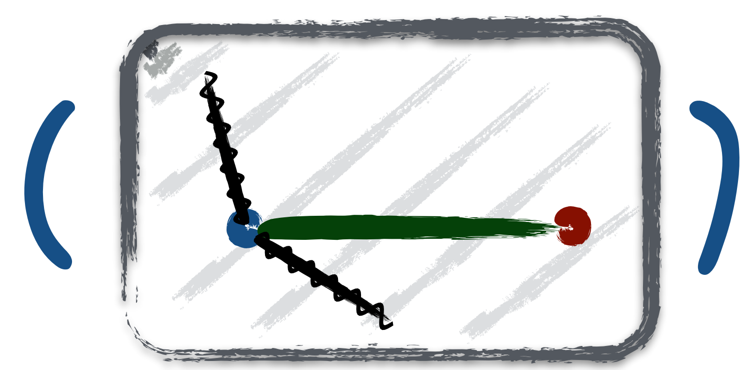



3) $\tilde{f}_3$

Brane-localized meta-stable charged sfermion (CHAMP: out-of-time decays, dE/dx, ...)

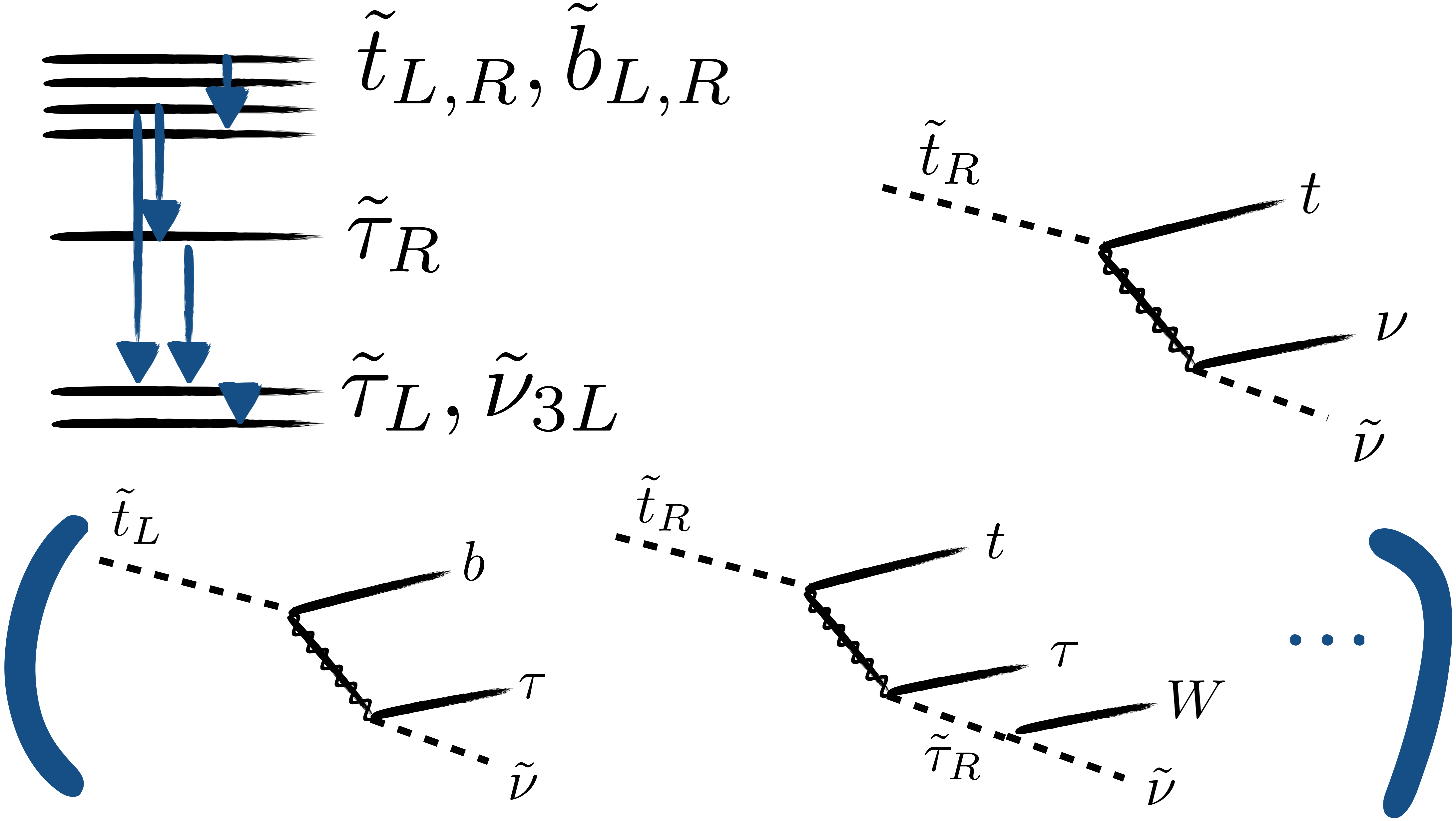
4) $\tilde{G}_{\text{bulk}}$

n-dimensional Gravitational BULK states

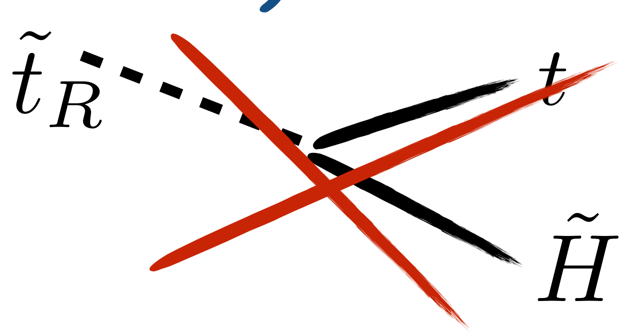


(bulk decay kinematics, displaced vertices, ...)

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




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




Reduced MET?

Alves et. al. arXiv:1312.4965

ATLAS-CONF-2014-014

ATLAS-CONF-2013-026

# LSP Candidates

Natural candidates for (collider-stable) LSP:

Qualitatively new behaviour!

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()


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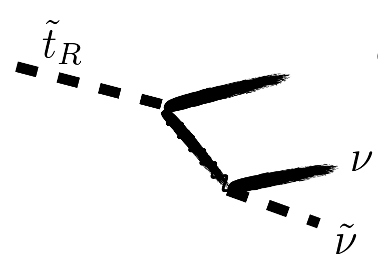
()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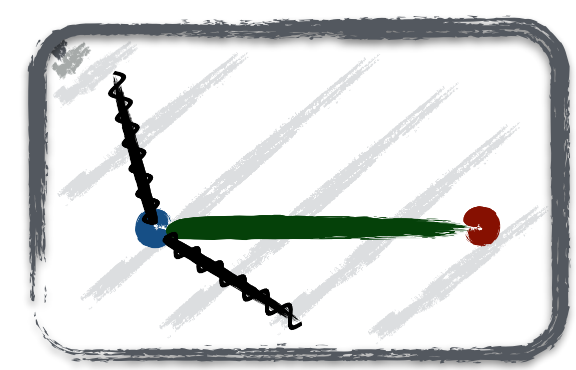
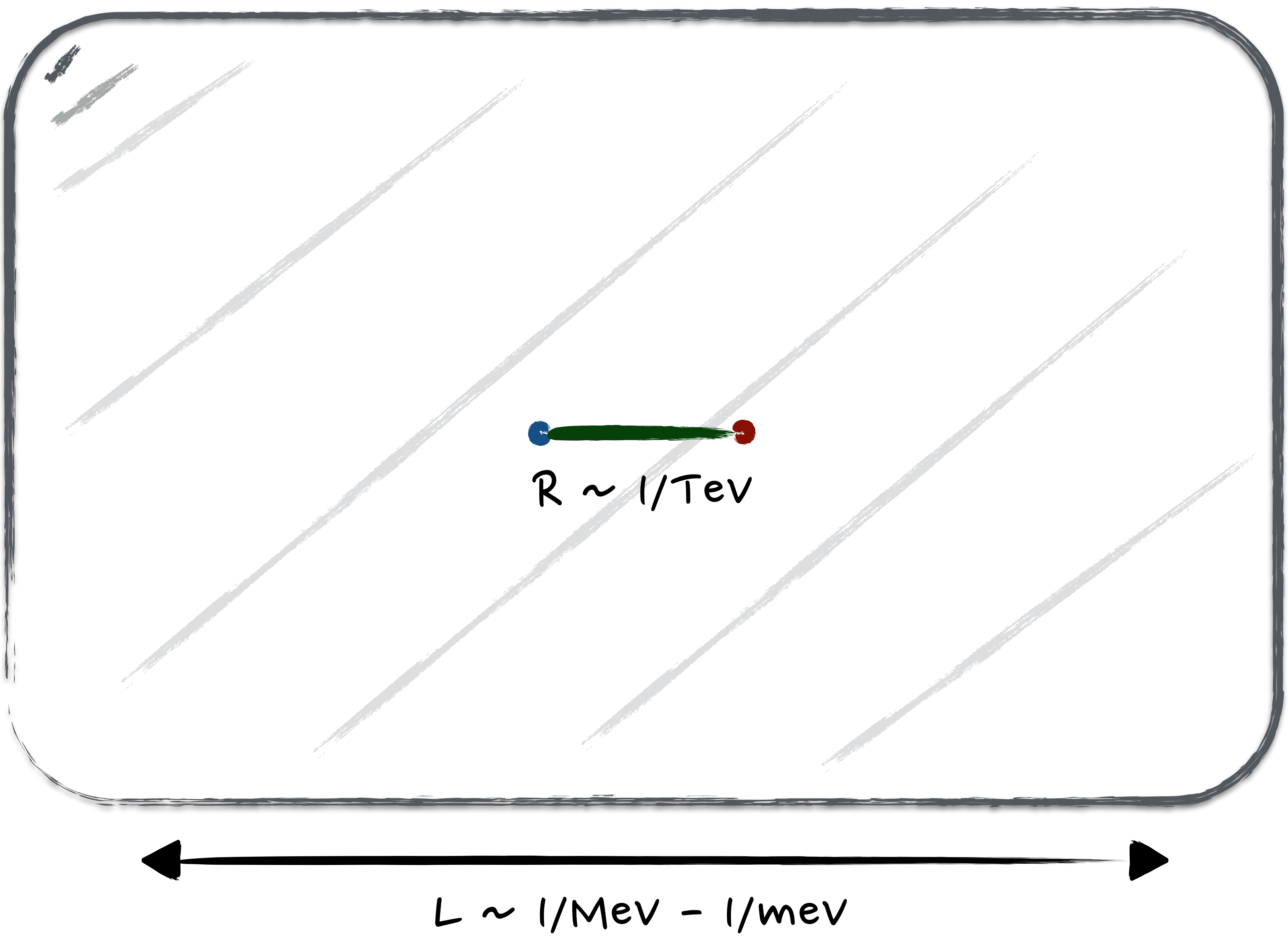
()

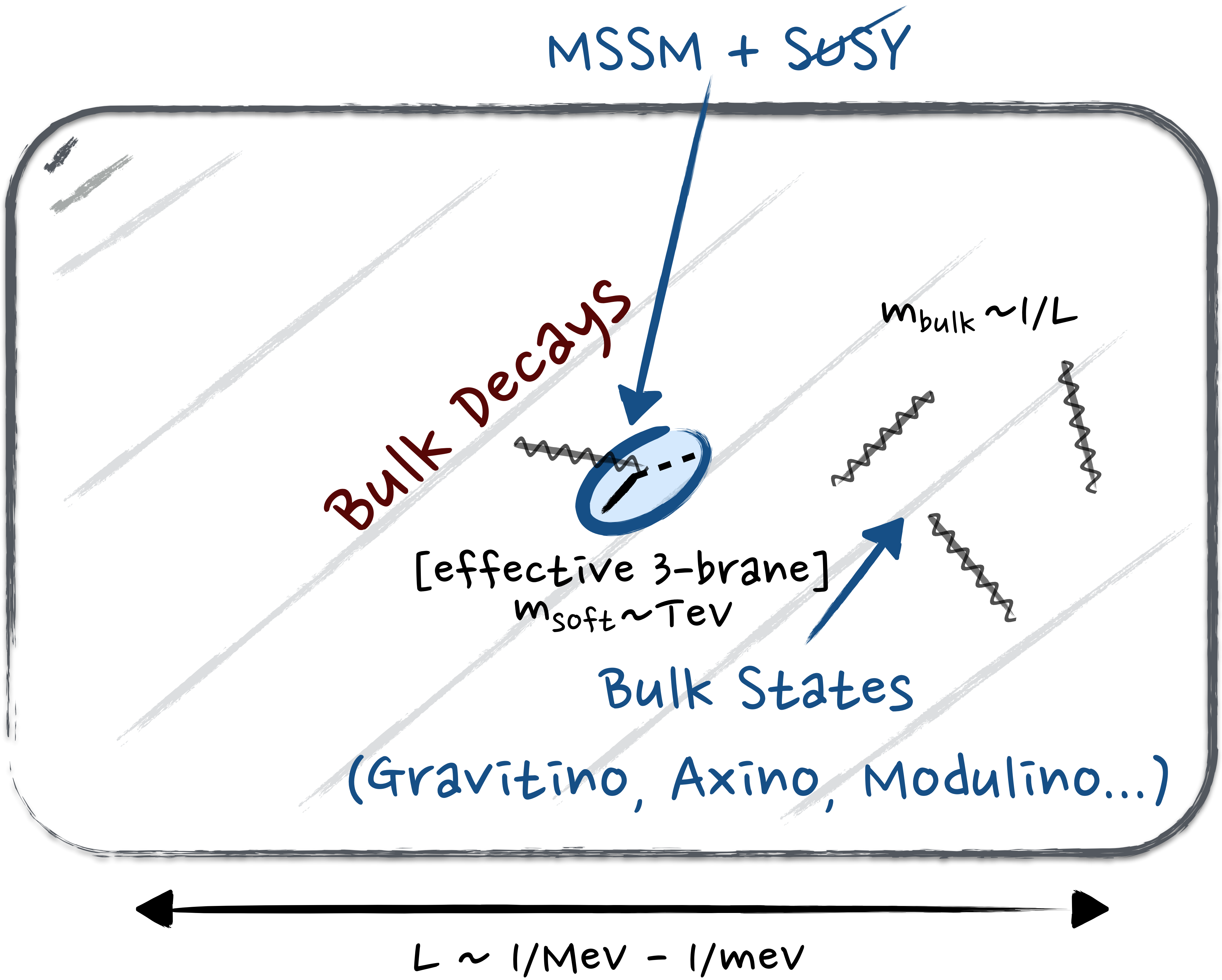
(bulk decay kinematics, displaced vertices, ···)

# (4) Auto-Concealment of SUSY

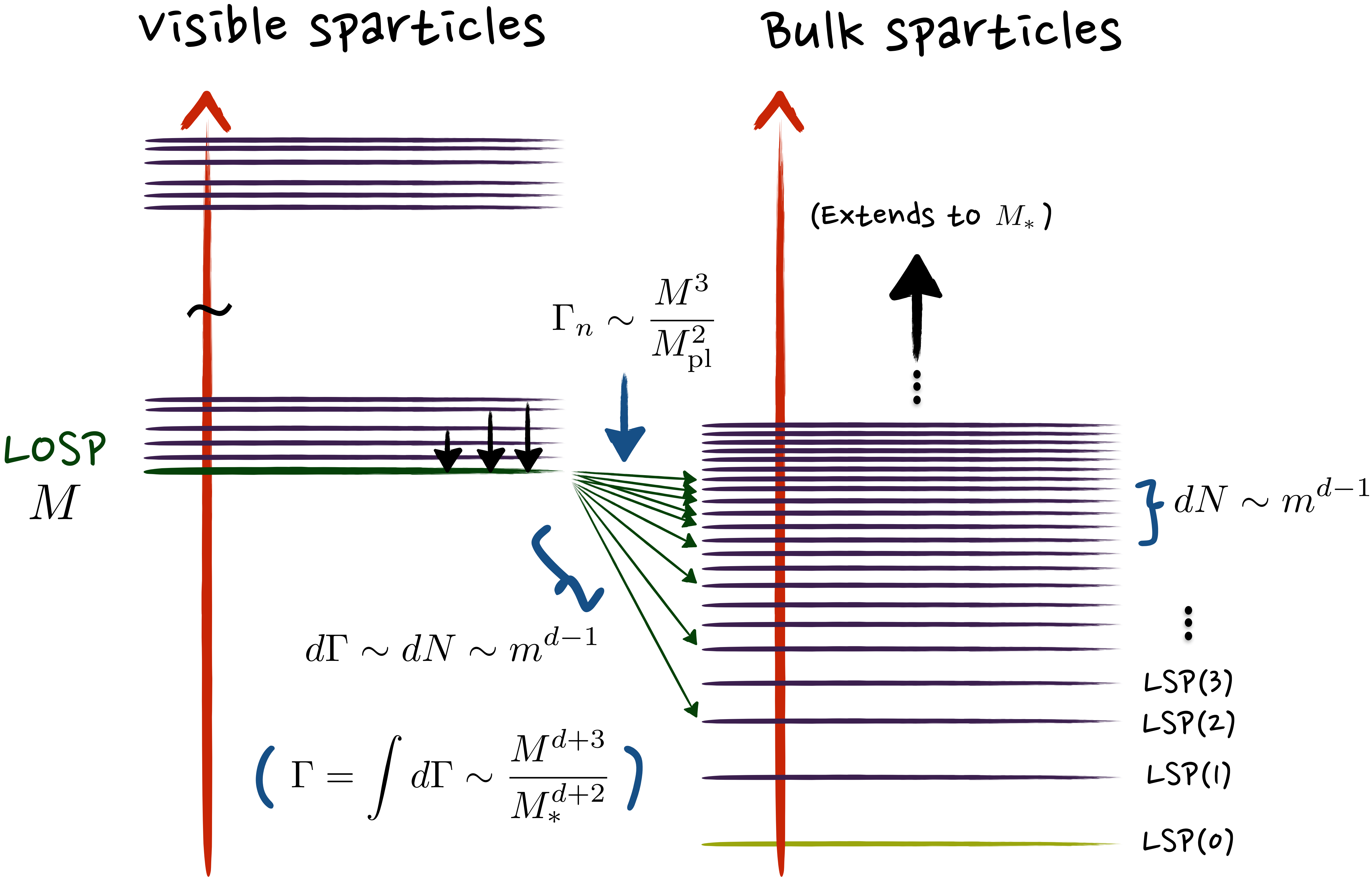
"Decaying to the Bulk"



# Auto-Concealment of SUSY

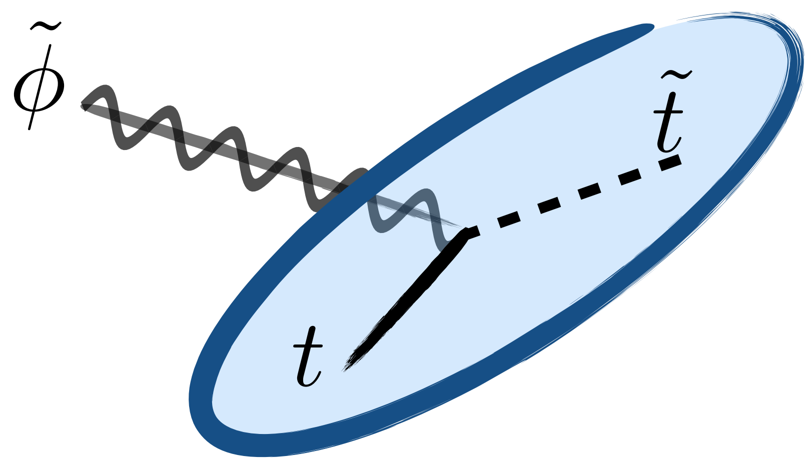


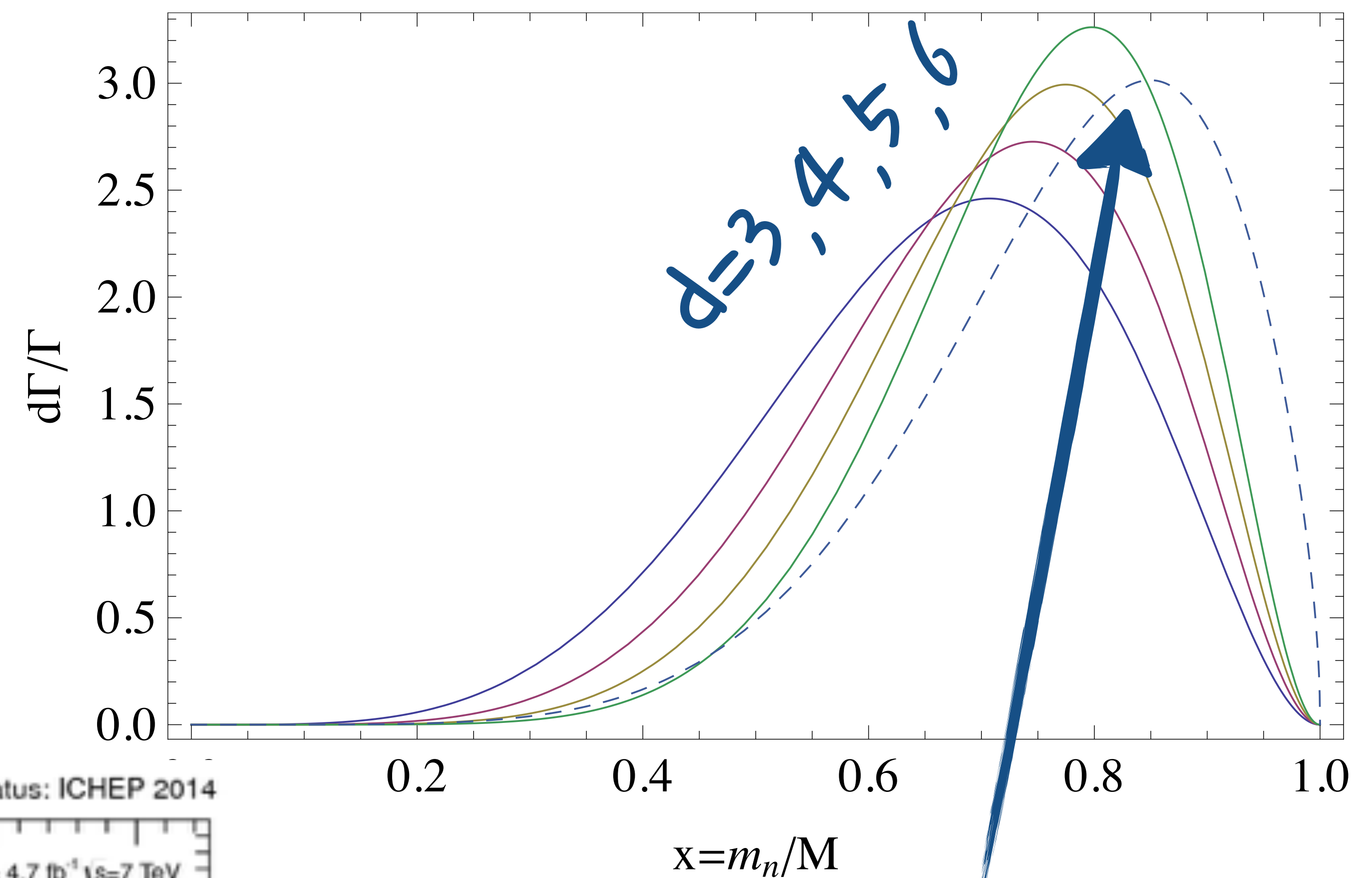
# Auto-Concealment of SUSY



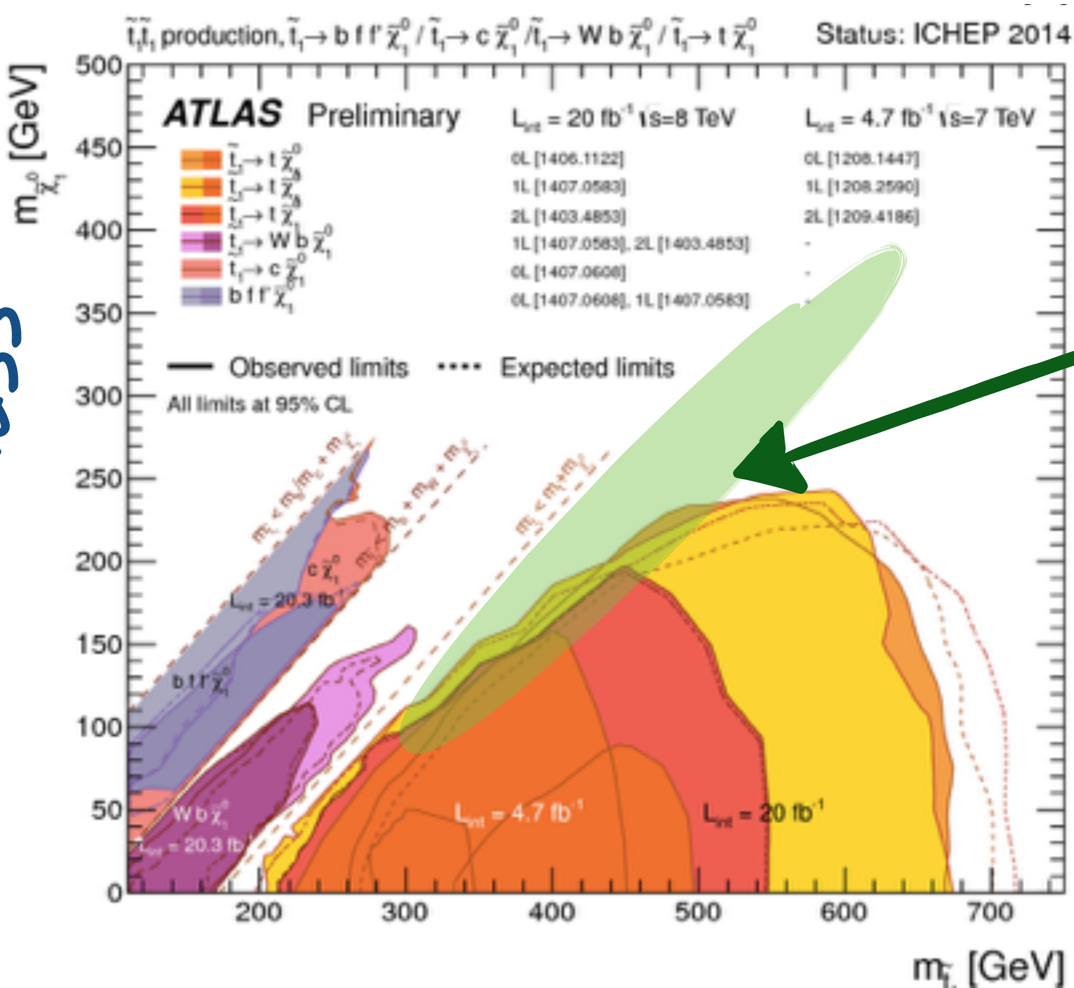
# Auto-Concealment of SUSY

eg, stop case



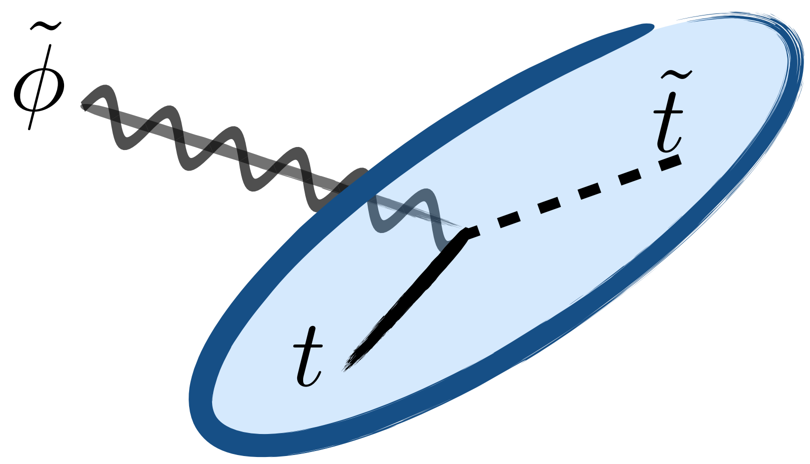



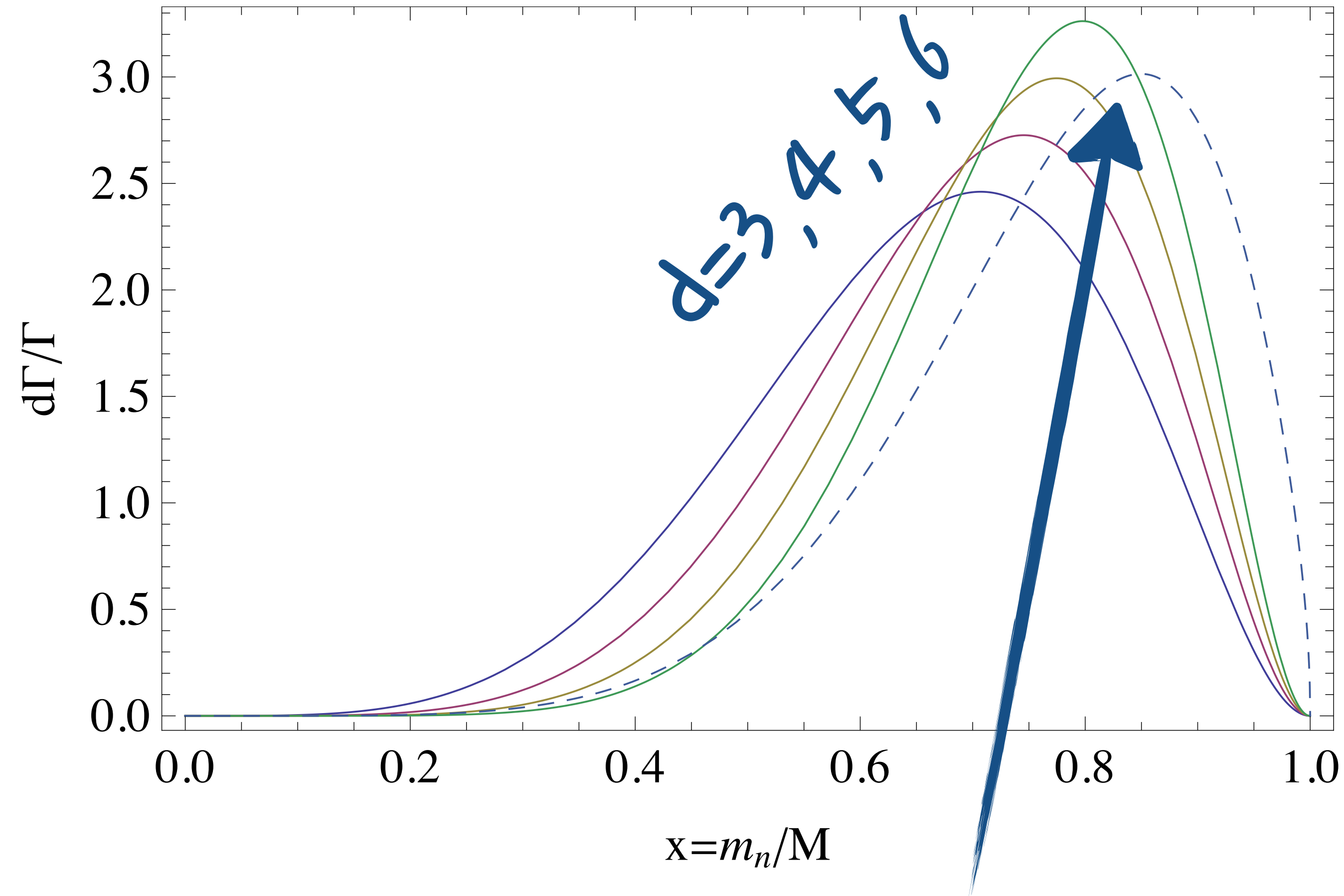

$\langle m \rangle \sim 0.8\ (m_{stop} - m_t)$




Decays to bulk KK modes dynamically realise compressed spectrum

# Auto-Concealment of SUSY



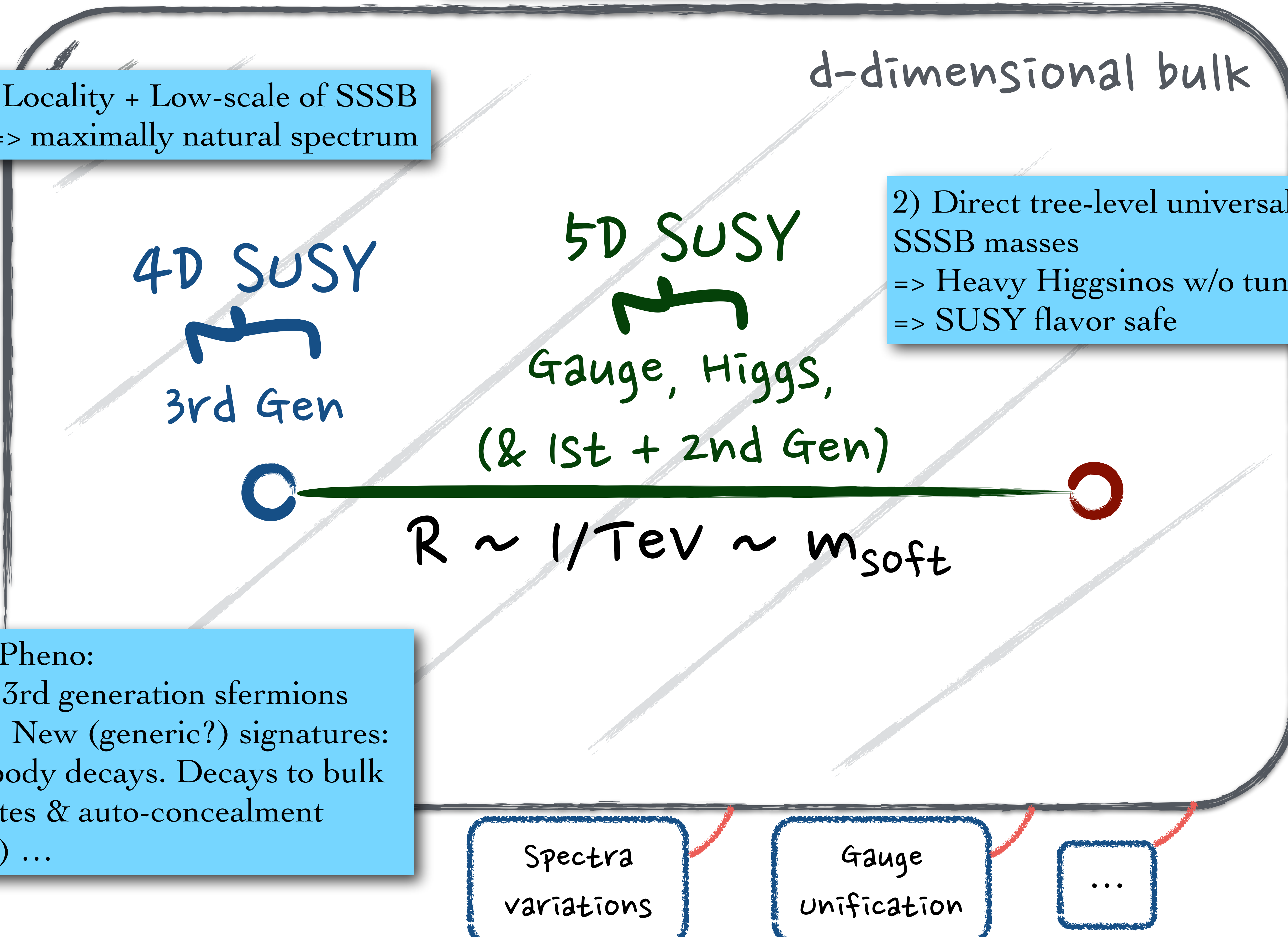

$\langle m \rangle \sim 0.8\ (m_{stop} - m_t)$

typically reduces stop limits by 200-300 Gev

# Conclusions

1) Locality + Low-scale of SSSB
=> maximally natural spectrum

2) Direct tree-level universal SSSB masses
=> Heavy Higgsinos w/o tuning
=> SUSY flavor safe




3) Pheno:
(i) 3rd generation sfermions
(ii) New (generic?) signatures: 3-body decays. Decays to bulk states & auto-concealment
(iii) …

# MNSUSY Summary: Reasons for Naturalness

- No tree-level tuning (no mu-term!)
- SSSB is super-soft as it is a non-local (in 5d) breaking of SUSY: No logs; higgs soft mass not enhanced; gluino sucks problem solved
- Natural SUSY spectrum easy to obtain via localization of the 3rd family on 4D brane (also vital for successful EWSB)