

(some)

Natural Theories of the Electroweak Scale

Kiel Howe, Stanford, howek@stanford.edu,
SLAC ATLAS Physics Jamboree, 11/12/14

based on...

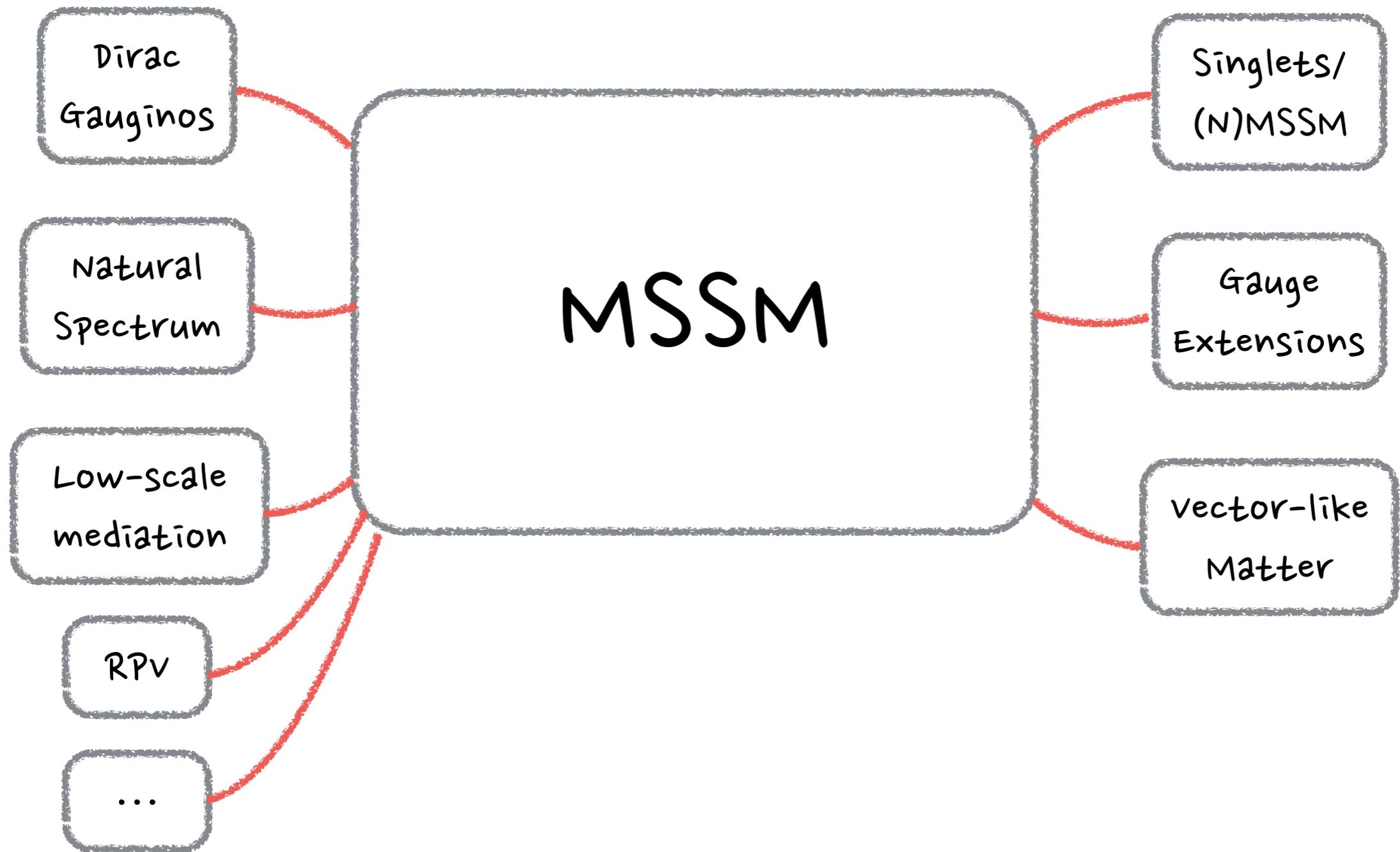
Savas Dimopoulos, K.H, John March-Russell. *Maximally Natural Supersymmetry*, arXiv:1404.7554.

Savas Dimopoulos, K.H, John March-Russell, James Scoville. arXiv:1411.XXXX

and works in progress....

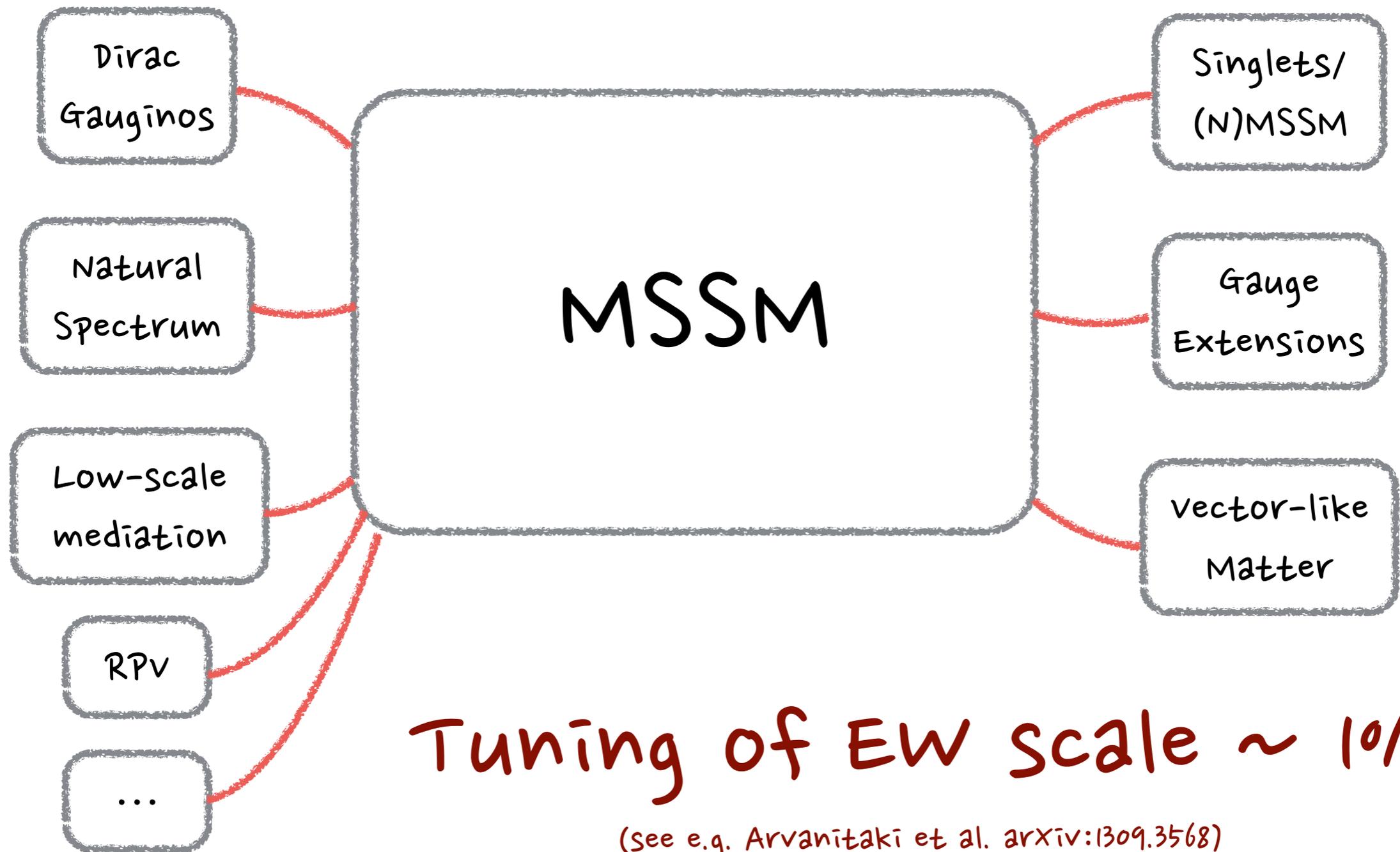
Naturalness

Higgs Mass



Naturalness

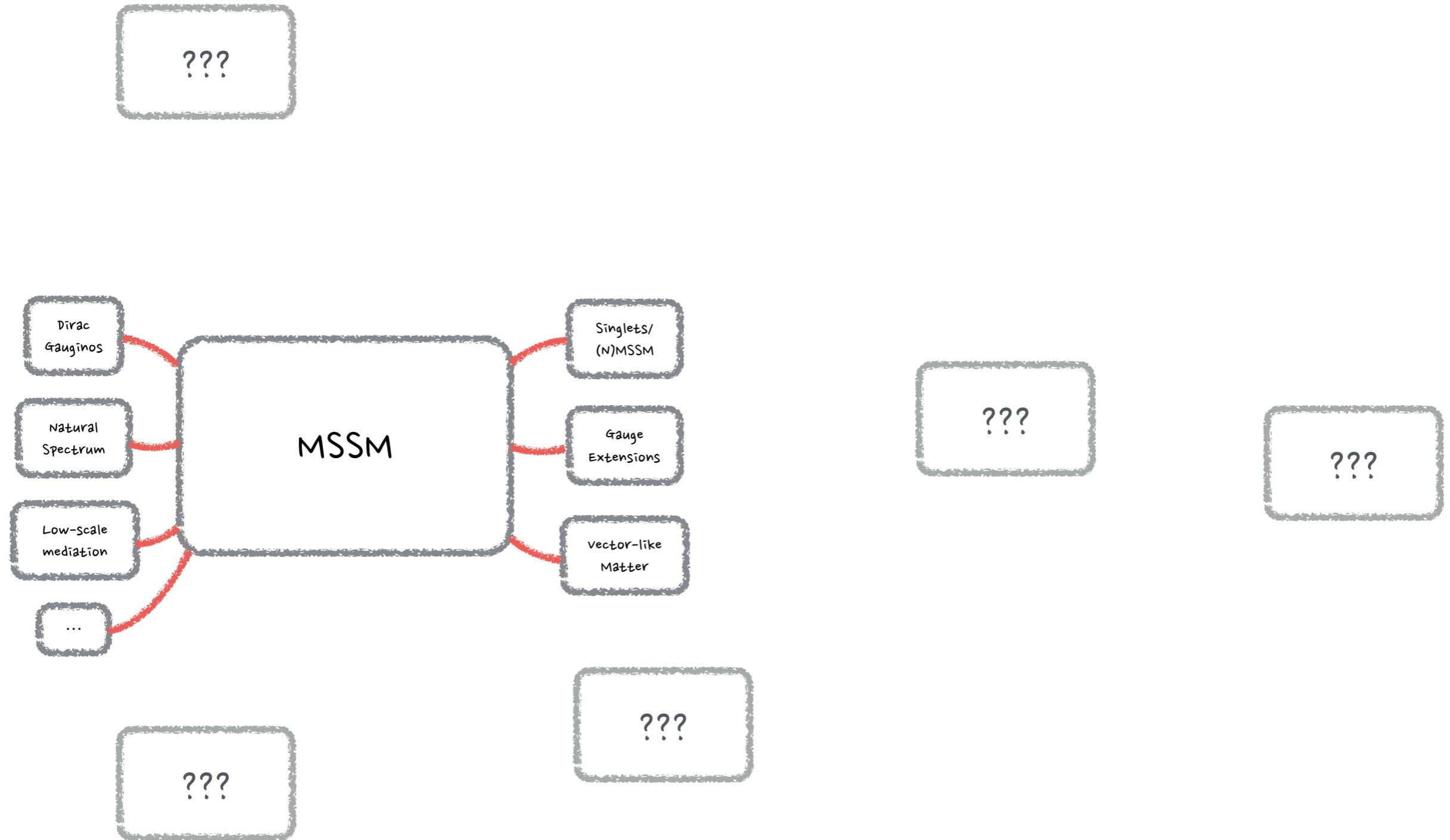
Higgs Mass



Tuning of EW scale $\sim 10\%$

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

Supersymmetric Theory Space



Outline

4D SUSY
↵
3rd Gen

5D SUSY
↵
Gauge, Higgs,
1st + 2nd Gen



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

Outline

n-dimensional bulk
fundamental scale:

$$M_* \sim 10 \text{ TeV} - 50 \text{ TeV}$$

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

(perturbativity)

4D SUSY



3rd Gen

5D SUSY



Gauge, Higgs,

1st + 2nd Gen



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

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[(2) brane
collider pheno]

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[(3) bulk collider
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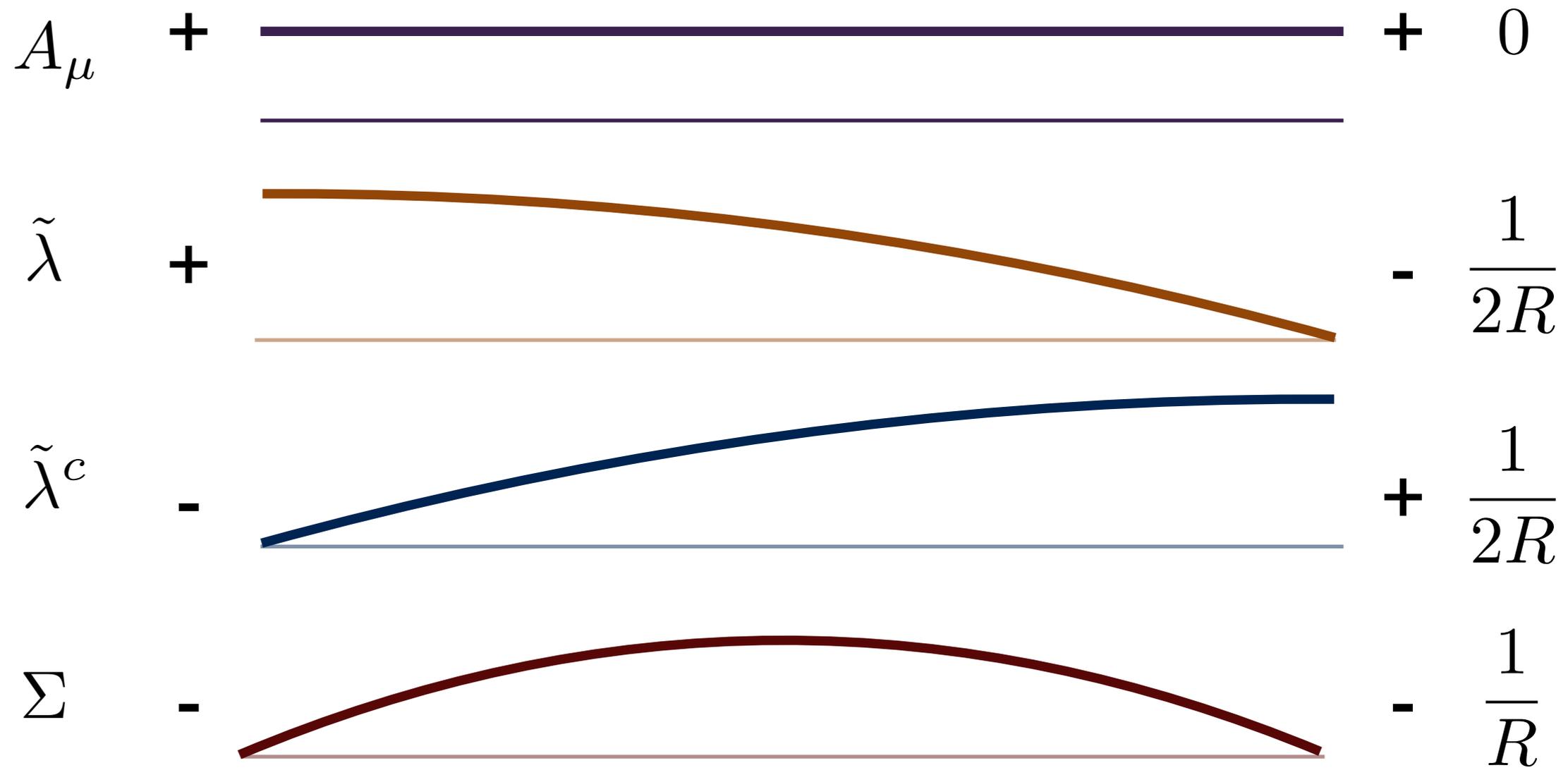
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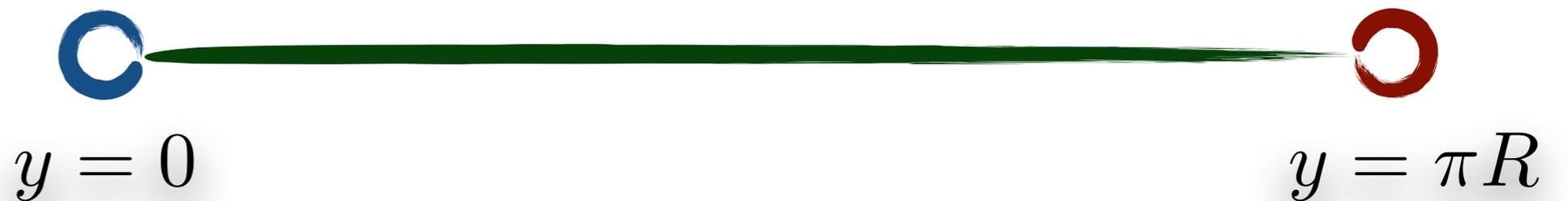
[(1) Natural Spectrum from
Scherk-Schwarz SUSY]

“Maximal Scherk-Schwarz Twist”

“ $S_1 / (Z_2 \times Z'_2)$ orbifold ”



... + A FULL KK TOWER



“Maximal Scherk-Schwarz Twist”

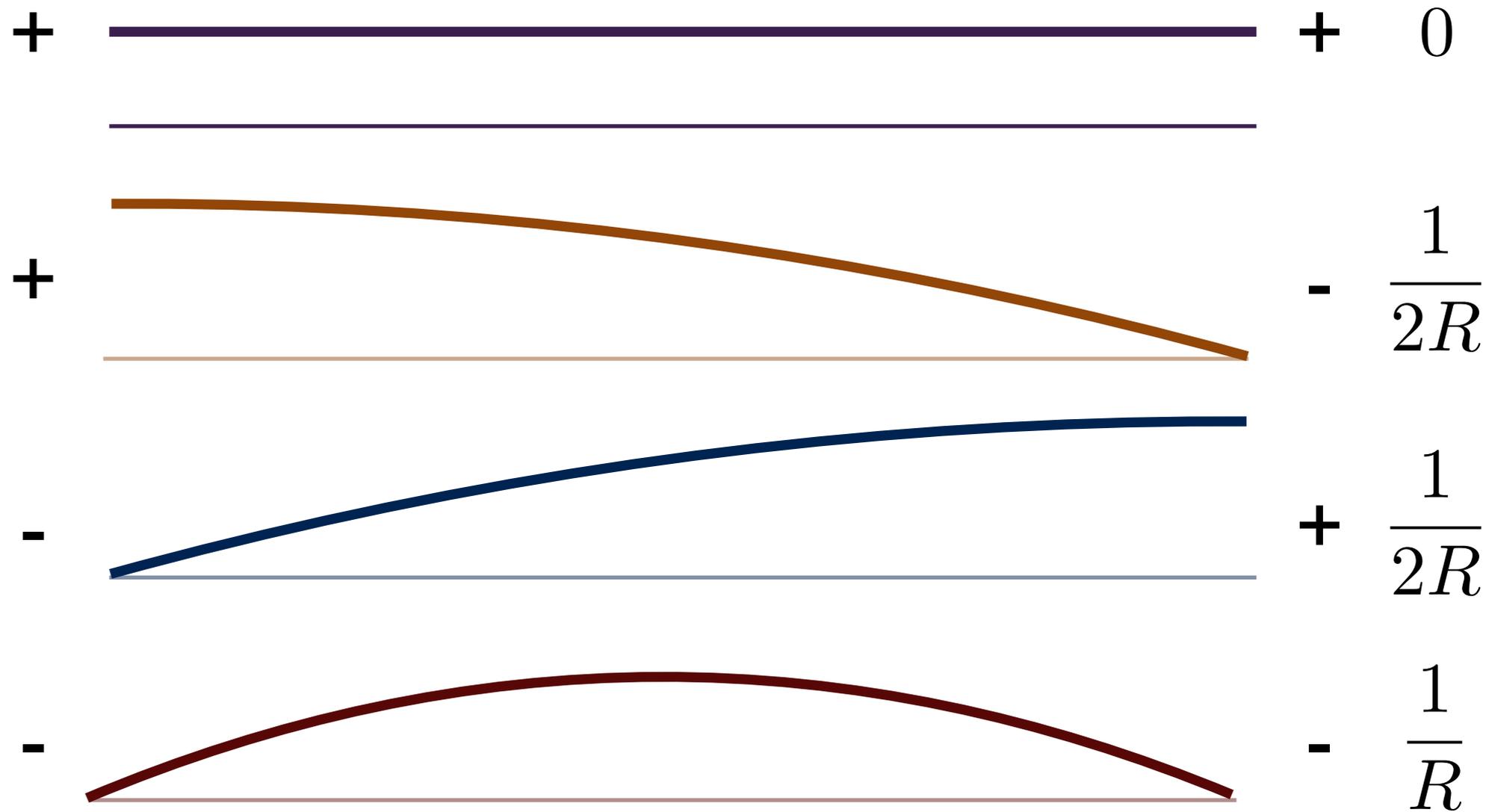
“ $S_1 / (Z_2 \times Z'_2)$ orbifold ”

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

MSSM partners
→ $\tilde{\lambda}$

$N=2$ partners
→ $\tilde{\lambda}^c$
→ Σ

3rd Generation
→

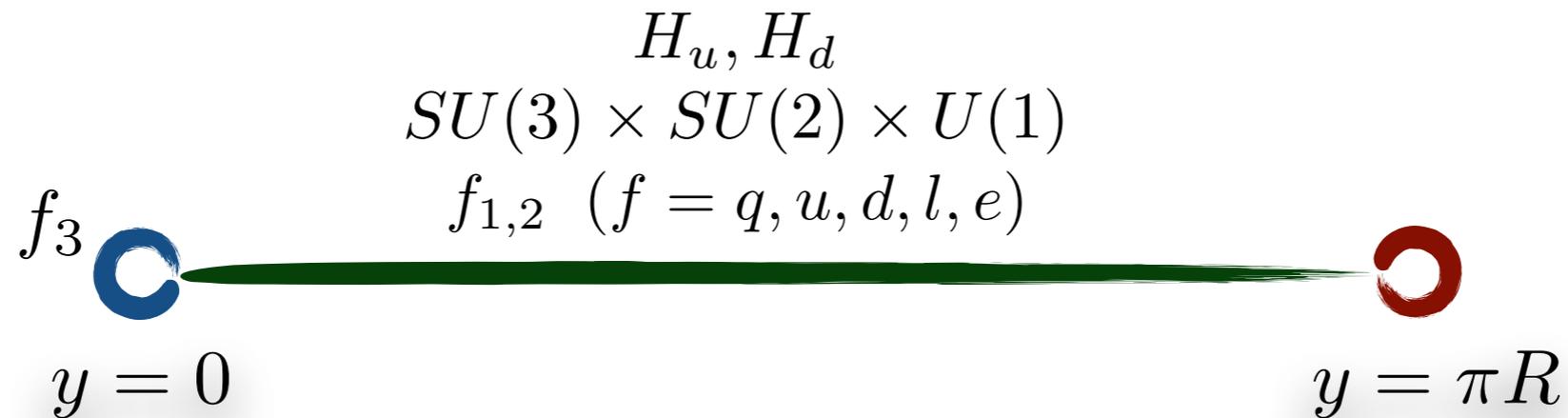


... + A FULL KK TOWER
KK Excitations of MSSM...

$y = 0$

$y = \pi R$

Tree-level Scherk-Schwarz Spectrum



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

Direct & universal
bulk soft masses



Dirac Higgsino and
Gaugino Masses

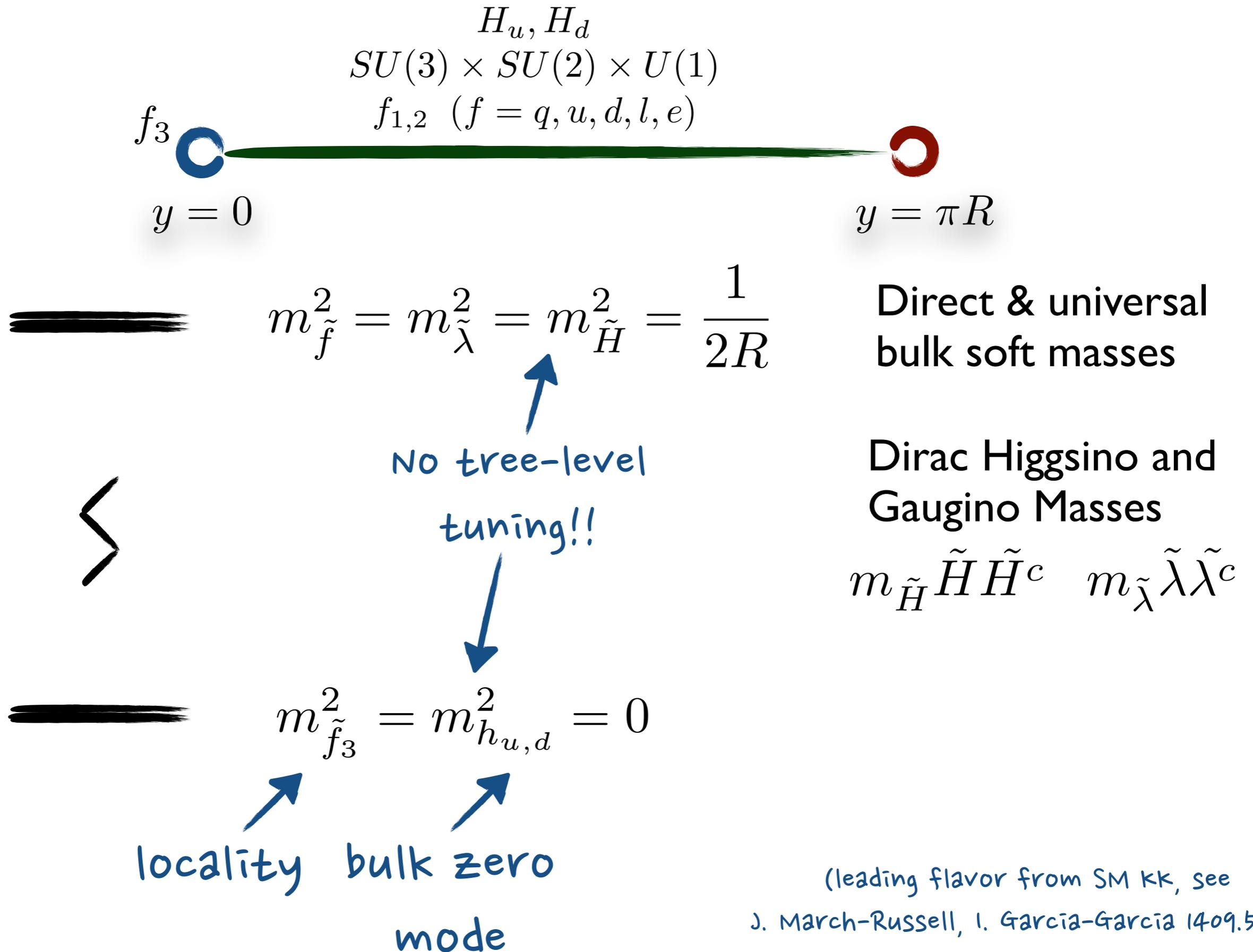
$m_{\tilde{H}} \tilde{H} \tilde{H}^c \quad m_{\tilde{\lambda}} \tilde{\lambda} \tilde{\lambda}^c$

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

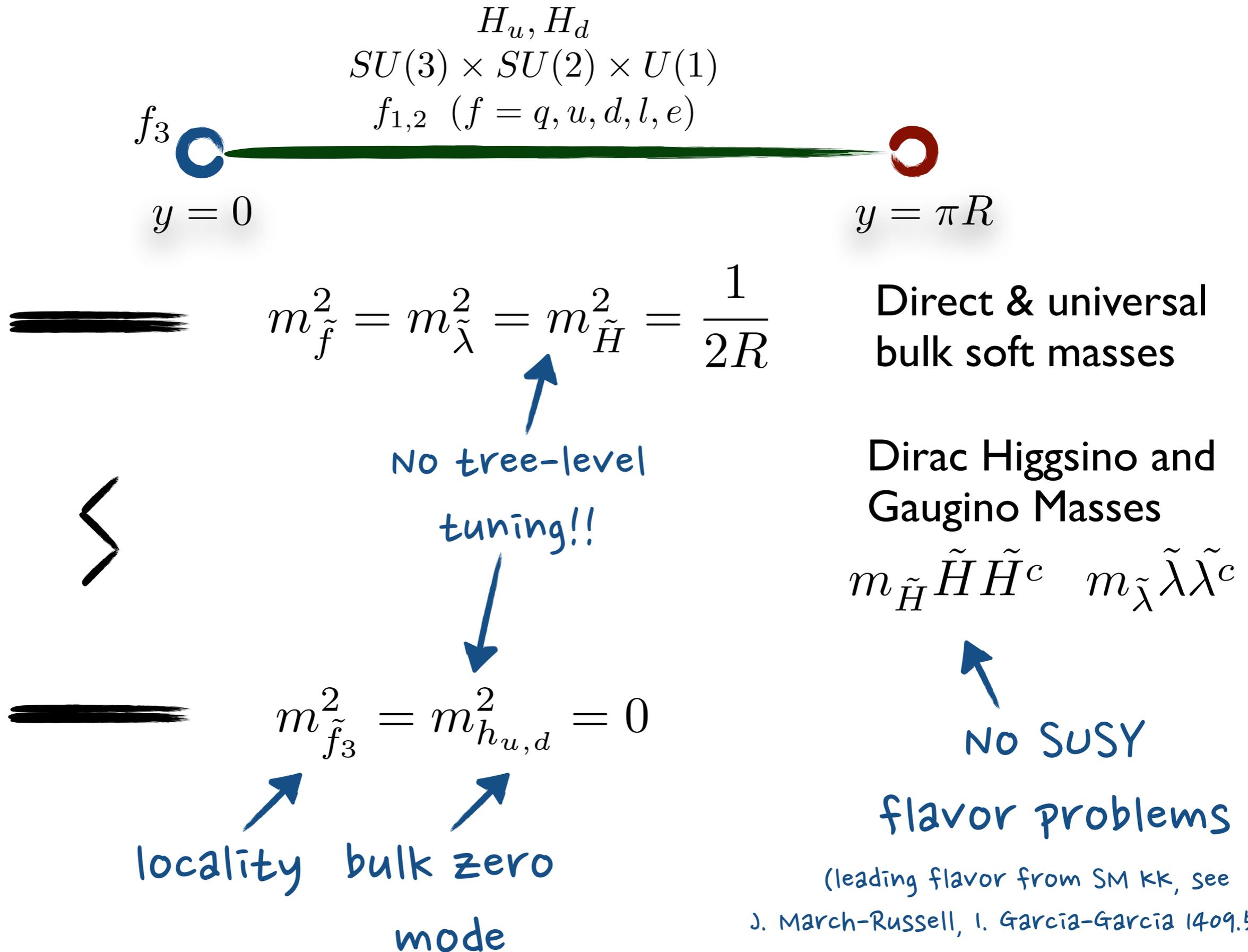
locality bulk zero mode

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

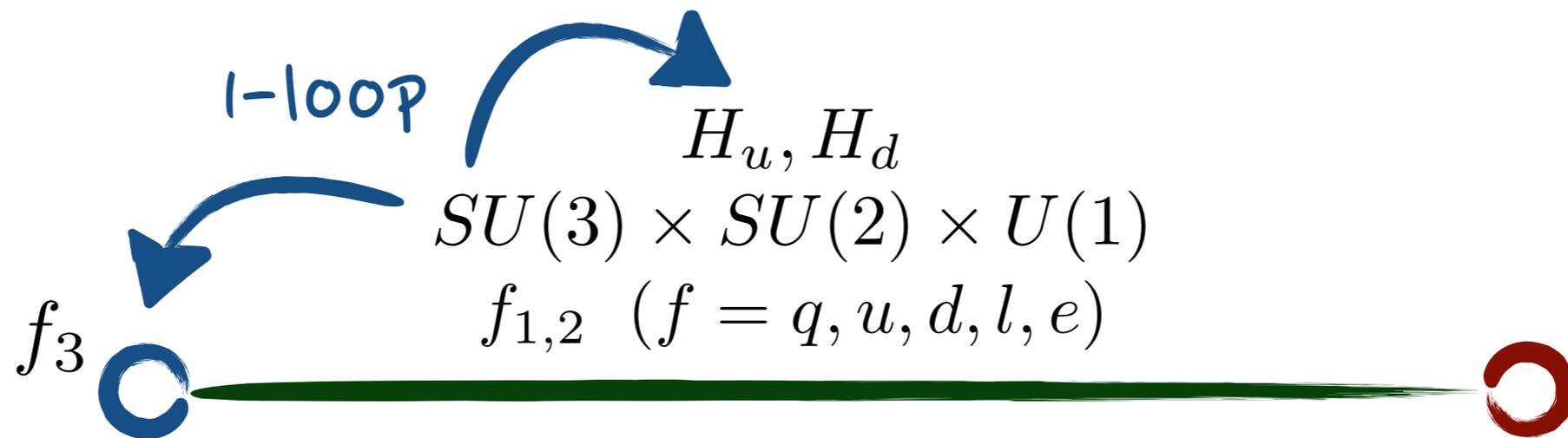
Tree-level Scherk-Schwarz Spectrum



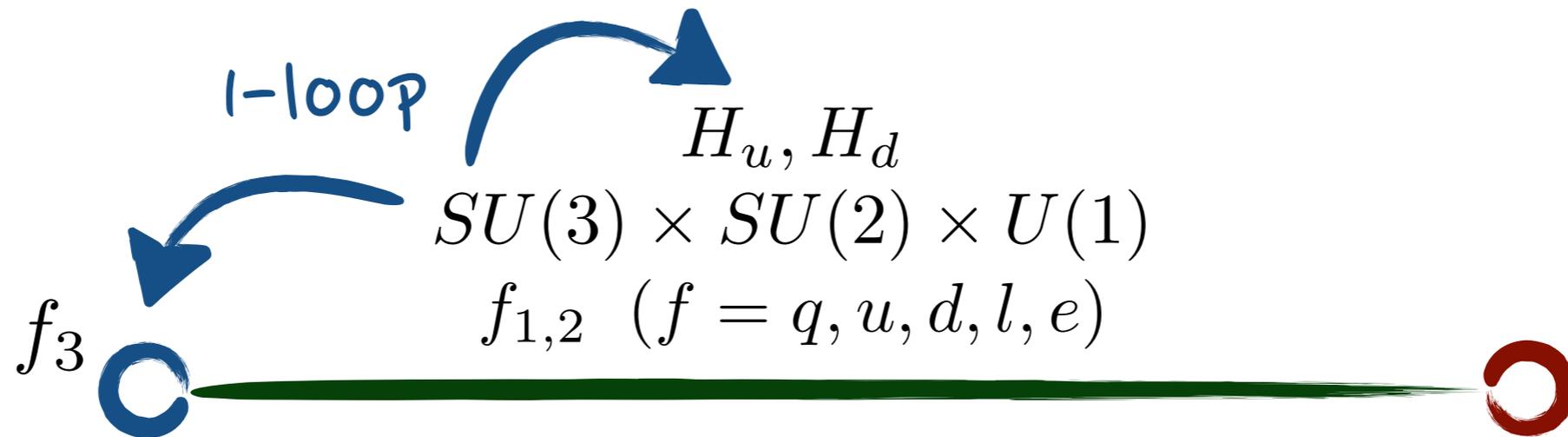
Tree-level Scherk-Schwarz Spectrum



Loop-level Scherk-Schwarz Spectrum



Loop-level Scherk-Schwarz Spectrum



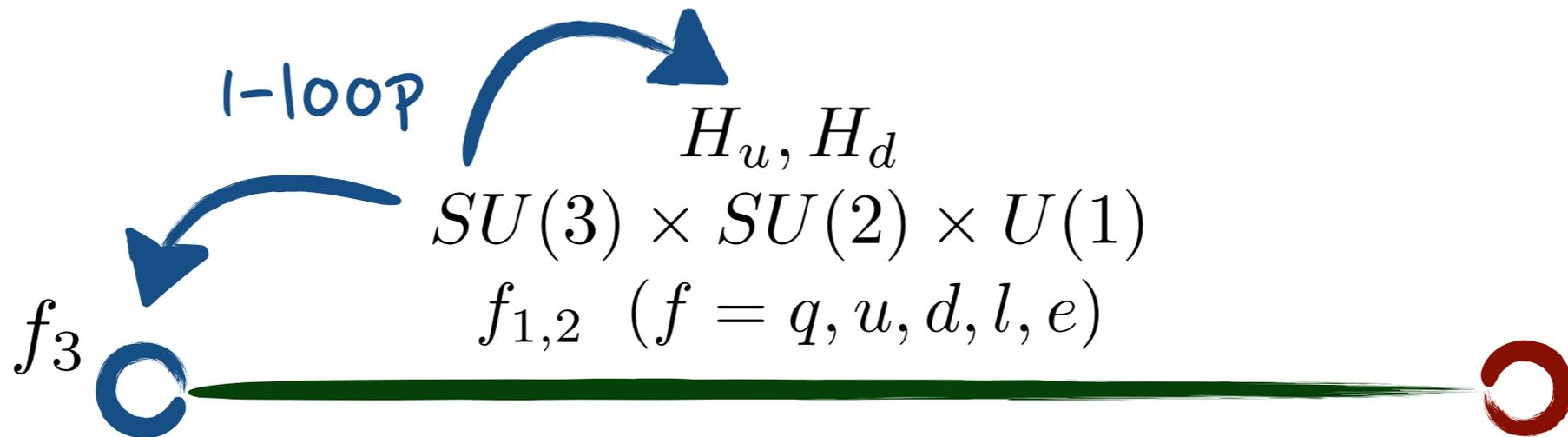
1-loop masses:

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

100 TeV : ~ 10

M_{gut} : ~ 100

Loop-level Scherk-Schwarz Spectrum



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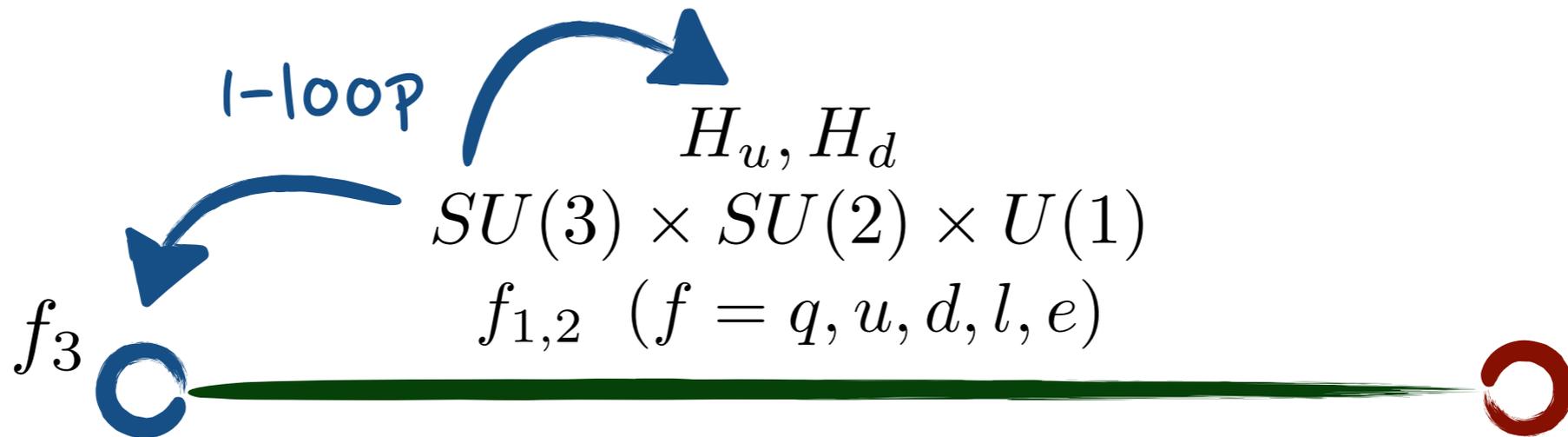
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$$m_{H_u}^2 \approx \left(\frac{1}{30} \times \frac{1}{R} \right)^2 \rightarrow \underline{1/R \sim 4 \text{ TeV for natural weak scale!}}$$

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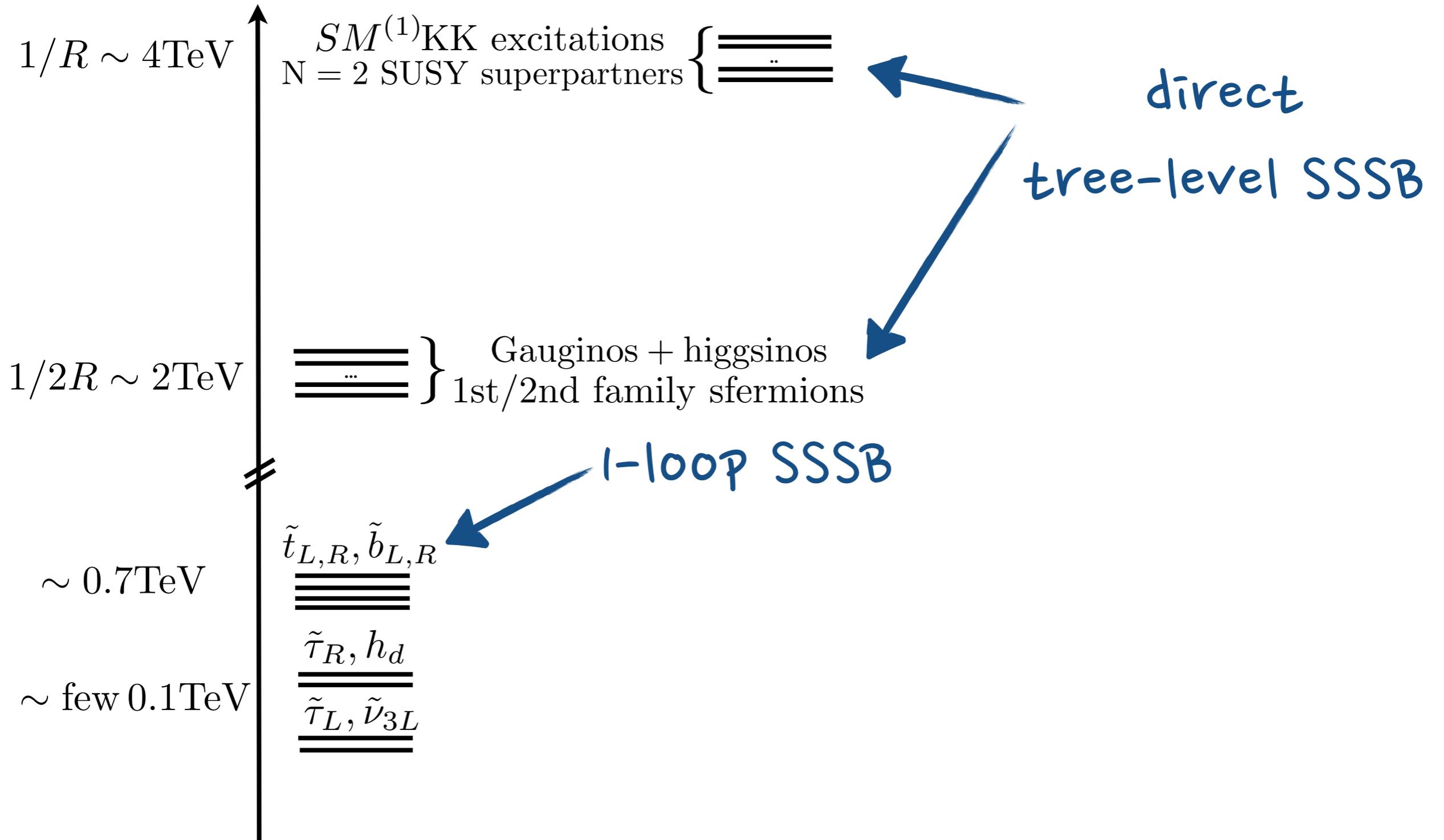
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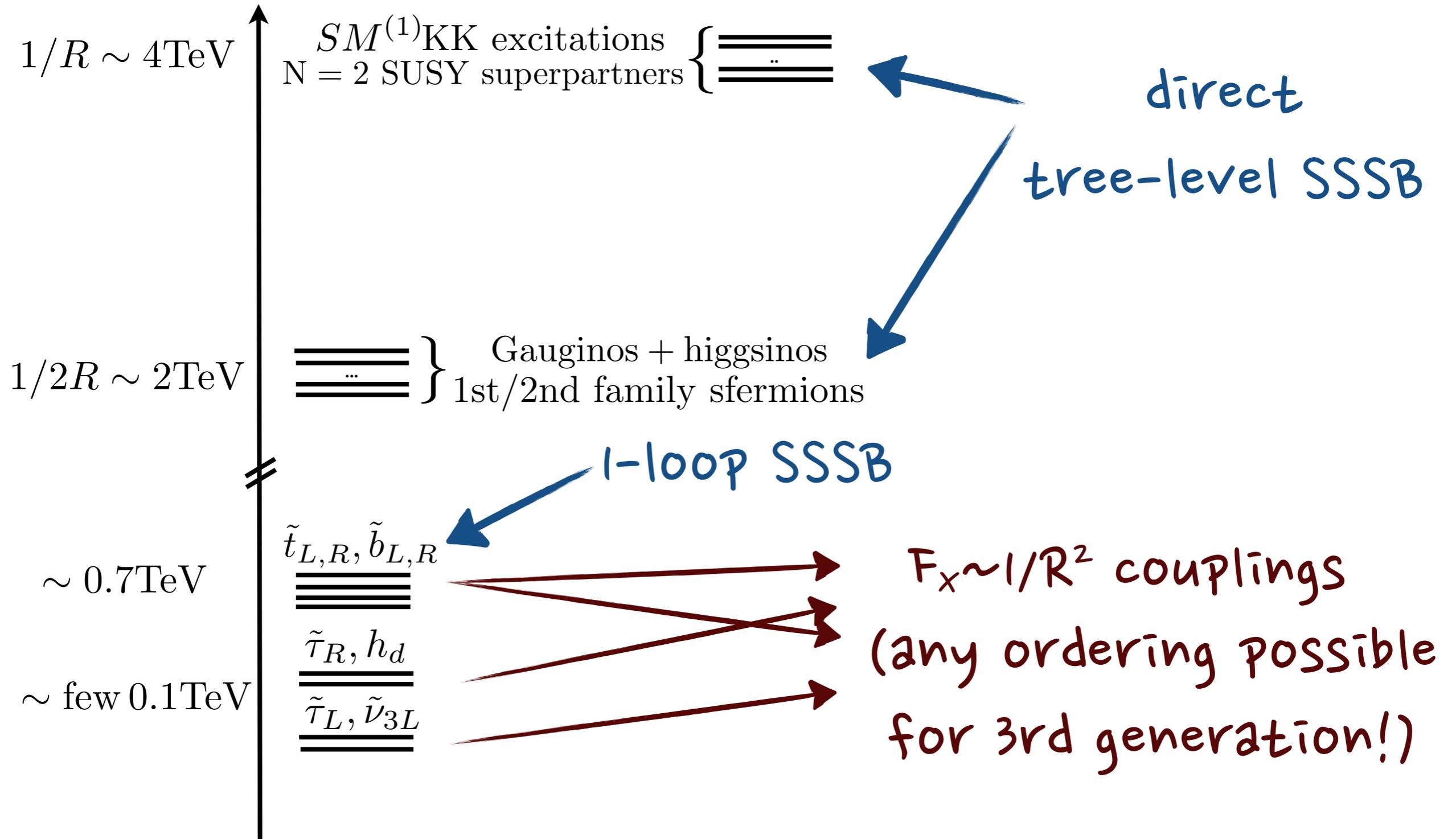
$$m_{H_u}^2 \approx \left(\frac{1}{30} \times \frac{1}{R} \right)^2 \rightarrow \underline{1/R \sim 4 \text{ TeV for natural weak scale!}}$$

$$m_{\tilde{t}}^2 \approx \left(\frac{1}{10} \times \frac{1}{R} \right)^2 \approx \left(\frac{1}{5} \times M_3 \right)^2 \rightarrow \text{Large stop-gluino hierarchy (gluino doesn't suck)}$$

Overall Spectrum



Overall Spectrum



[(2) Brane LHC Pheno]

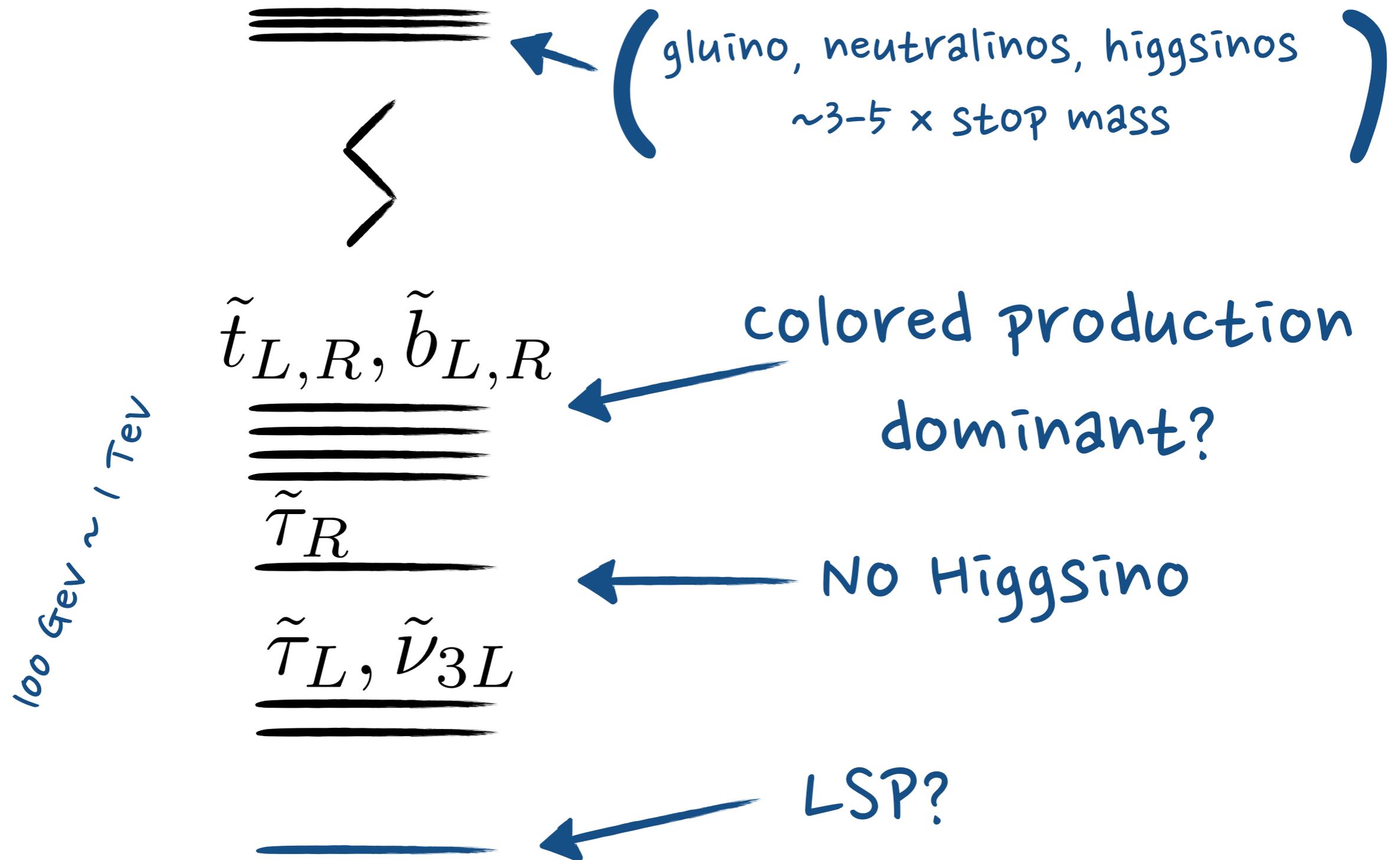
i) UV complete Nat. SUSY

Simplified Model

ii) Non-standard Nat.

SUSY Phenomenology

3rd Generation Sfermion Signatures



LSP Candidates

Natural candidates for LSP:

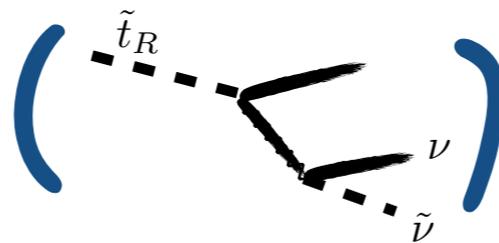
1) ψ_X

Brane-localized
goldstino
of X SUSY breaking



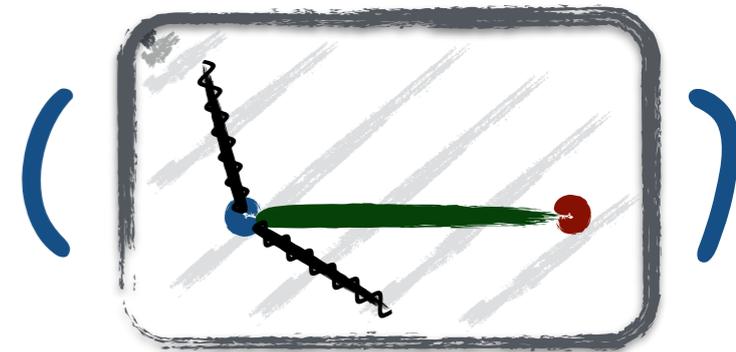
2) $\tilde{\nu}_3$

Brane-localized
left handed
sneutrino



3) \tilde{G}_{bulk}

n-dimensional
BULK states



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

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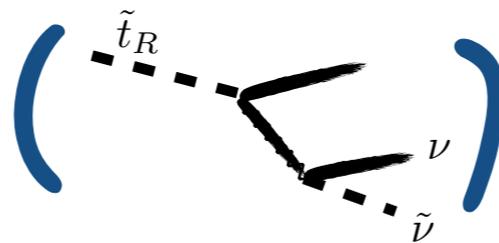
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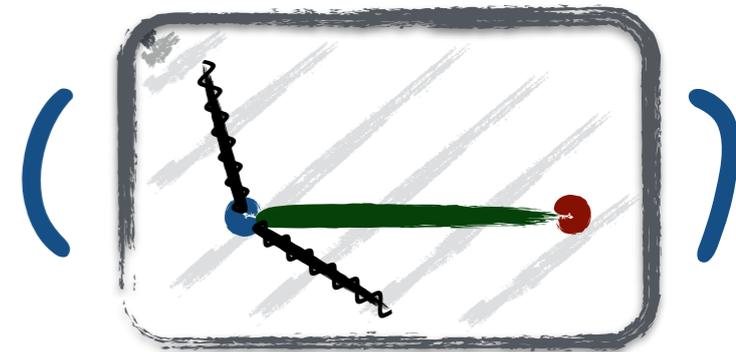
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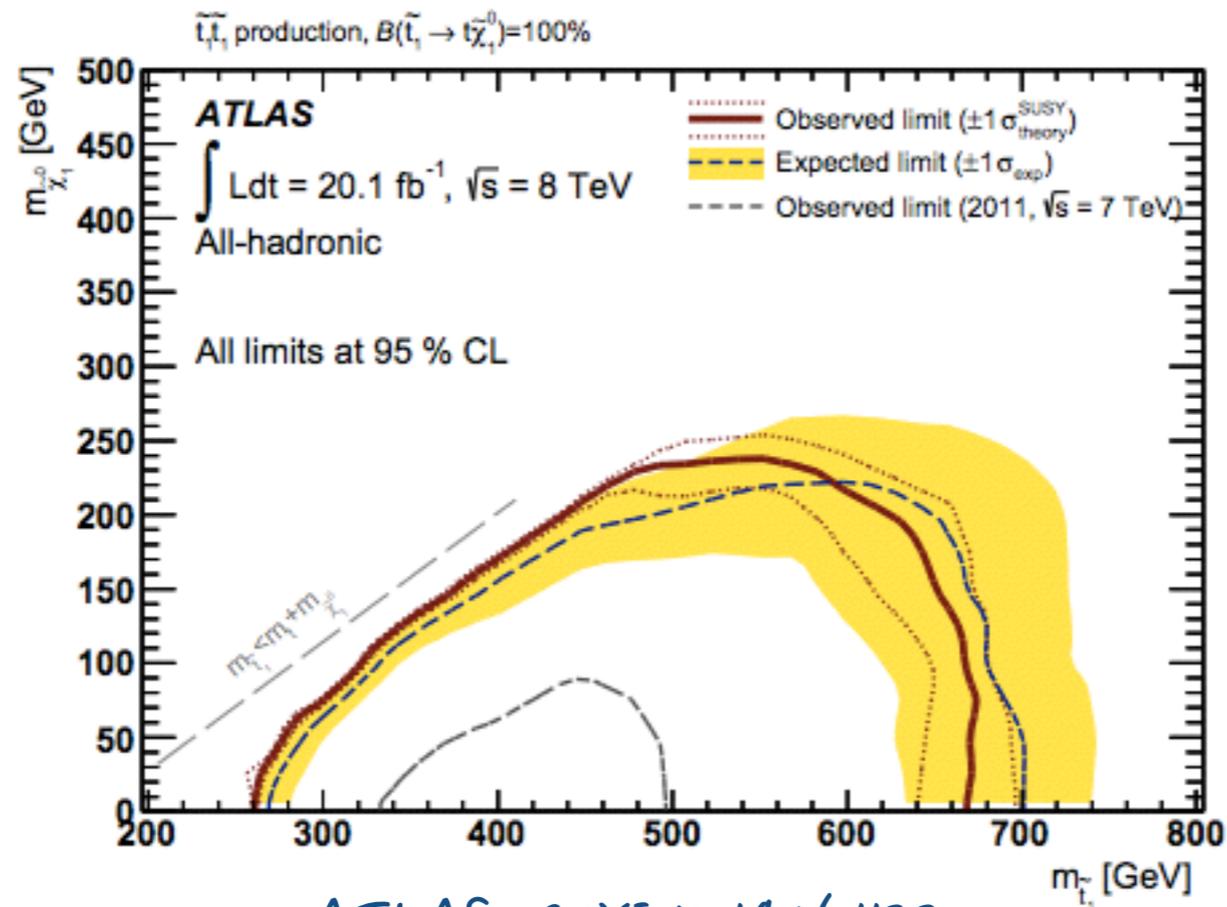
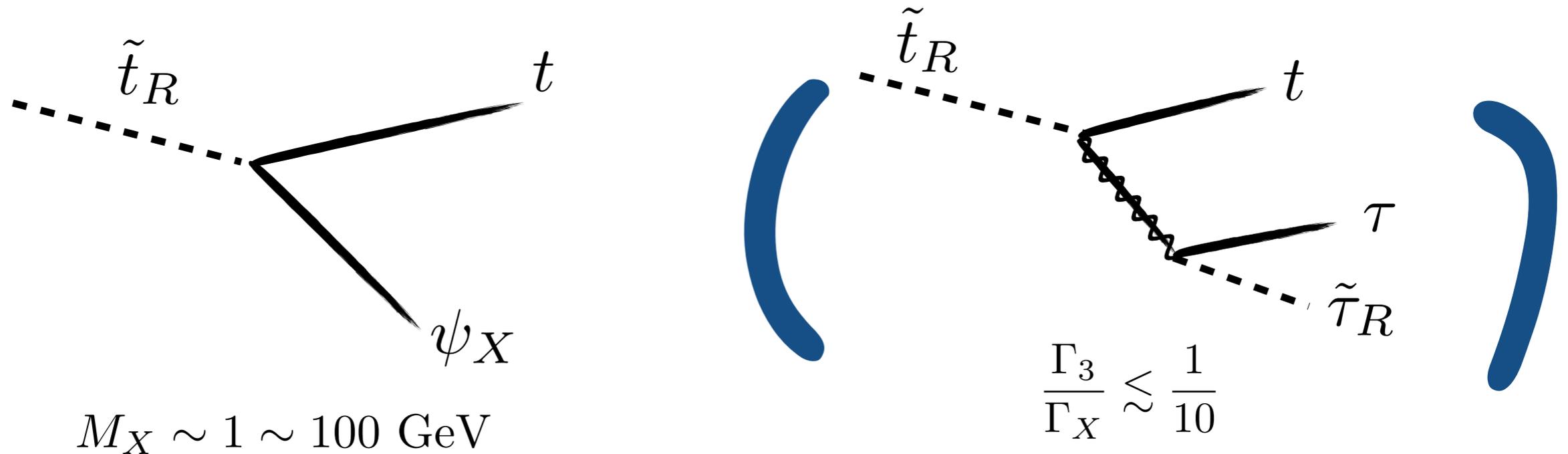
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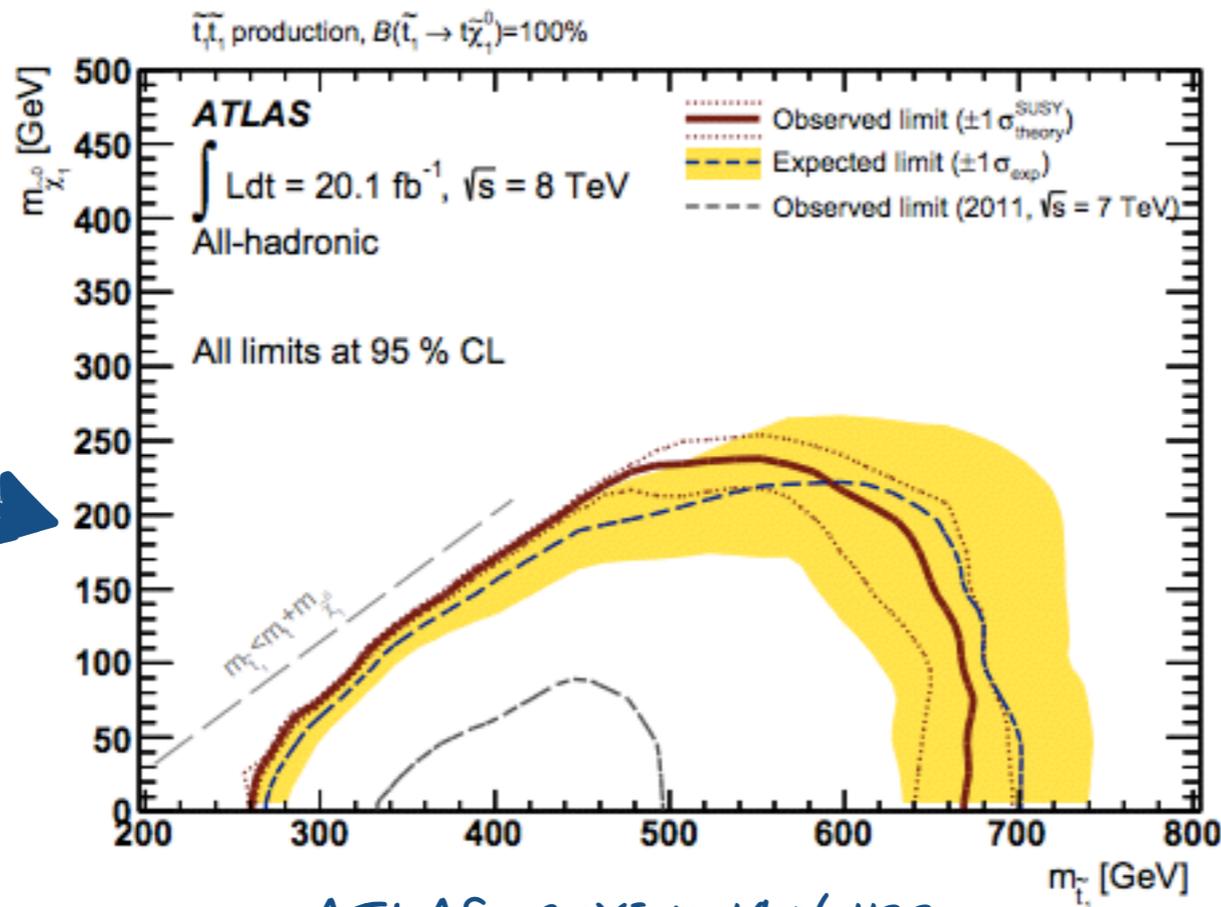
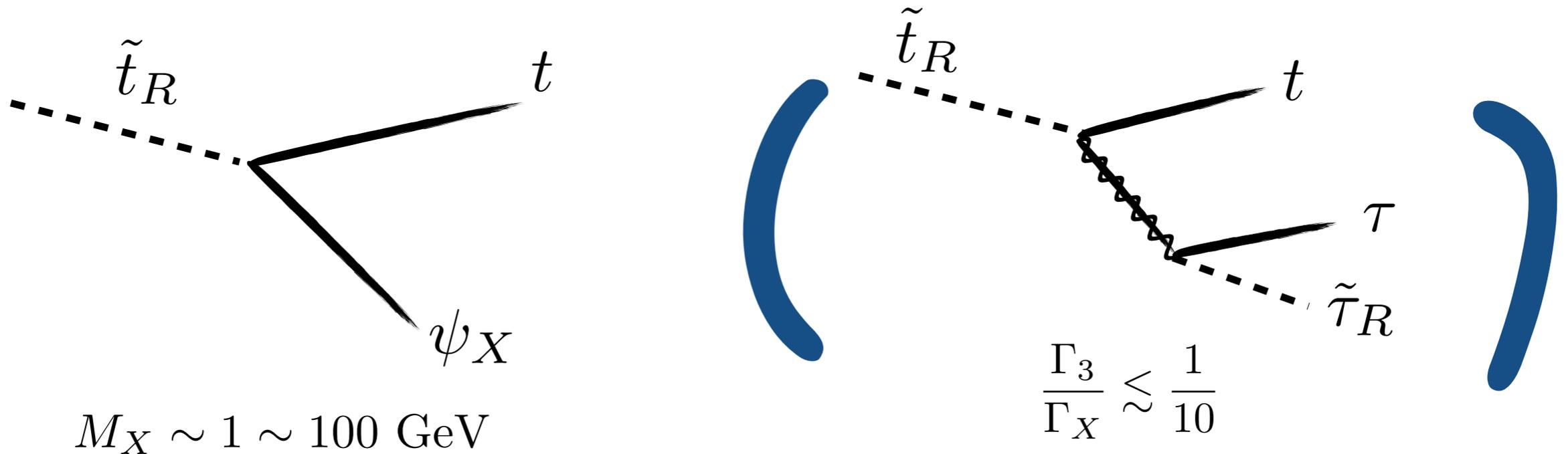
(bulk decay kinematics,
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ψ_X LSP: UV Complete Natural SUSY Simplified Model



ATLAS, arXiv: 1406.1122

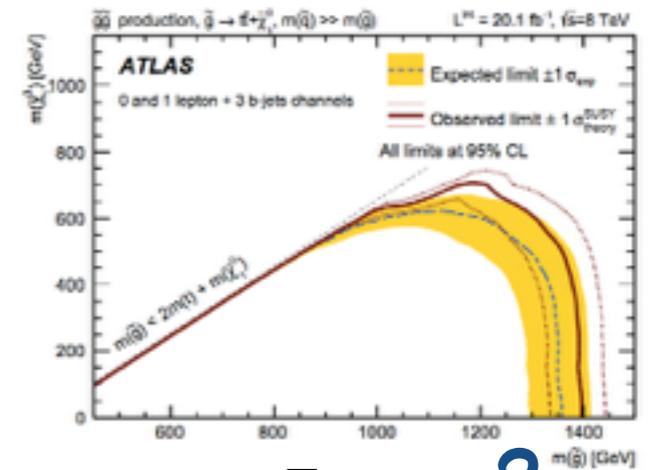
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Higgsino?
Gravitino?

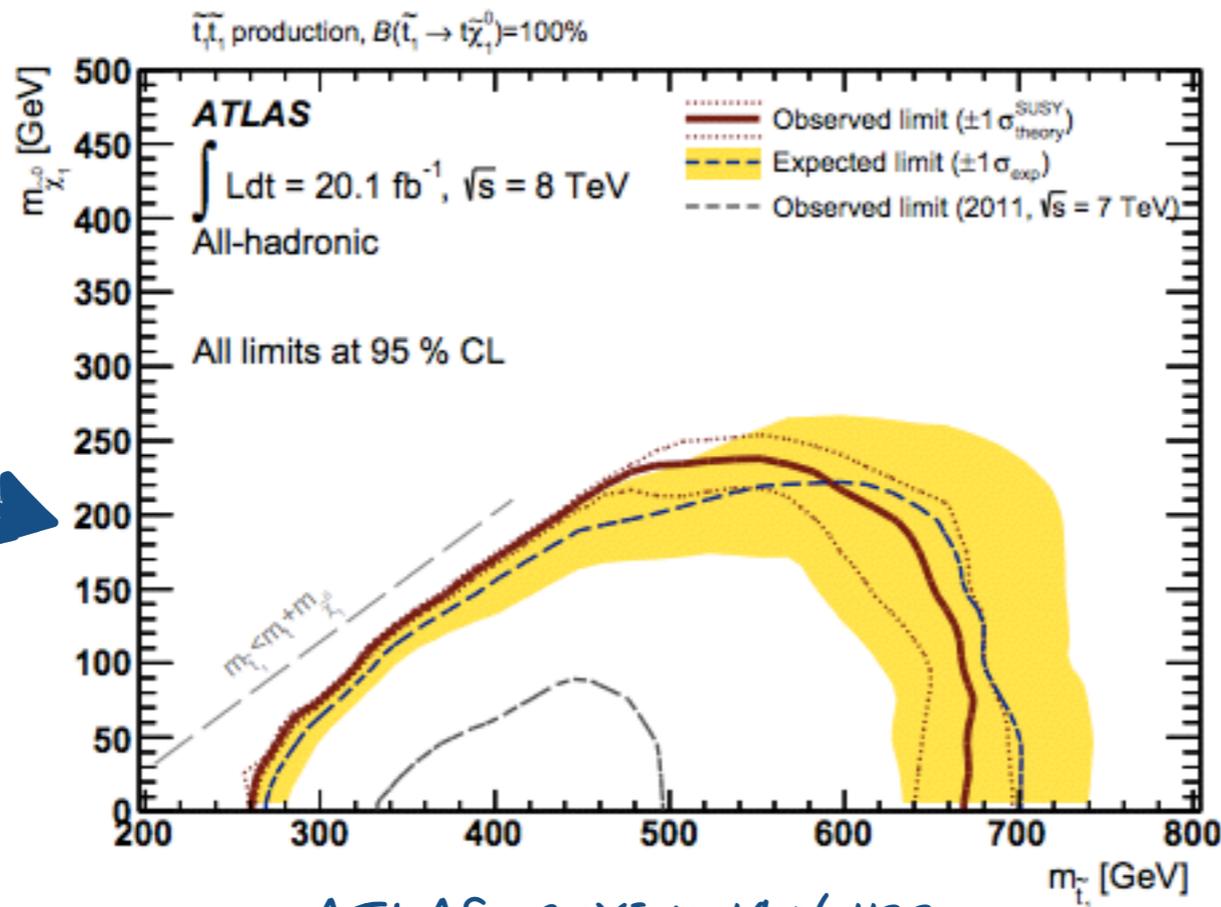
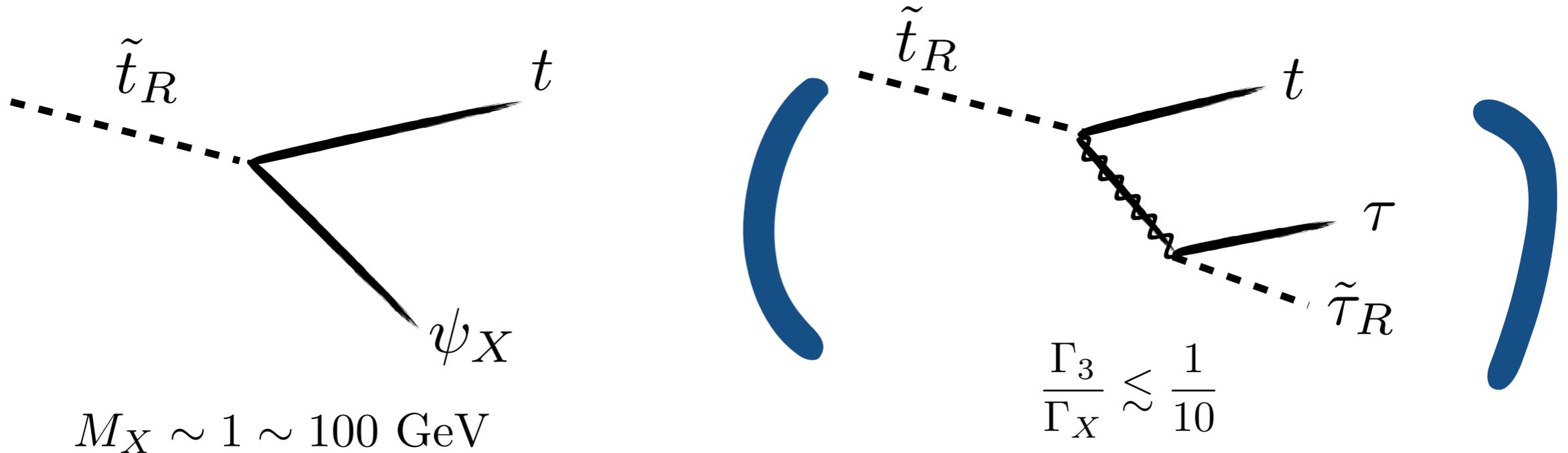


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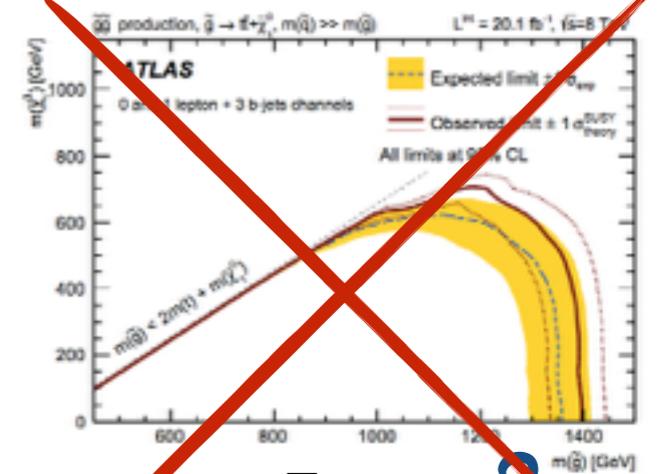


$\tilde{g} \rightarrow t\bar{t} + X?$

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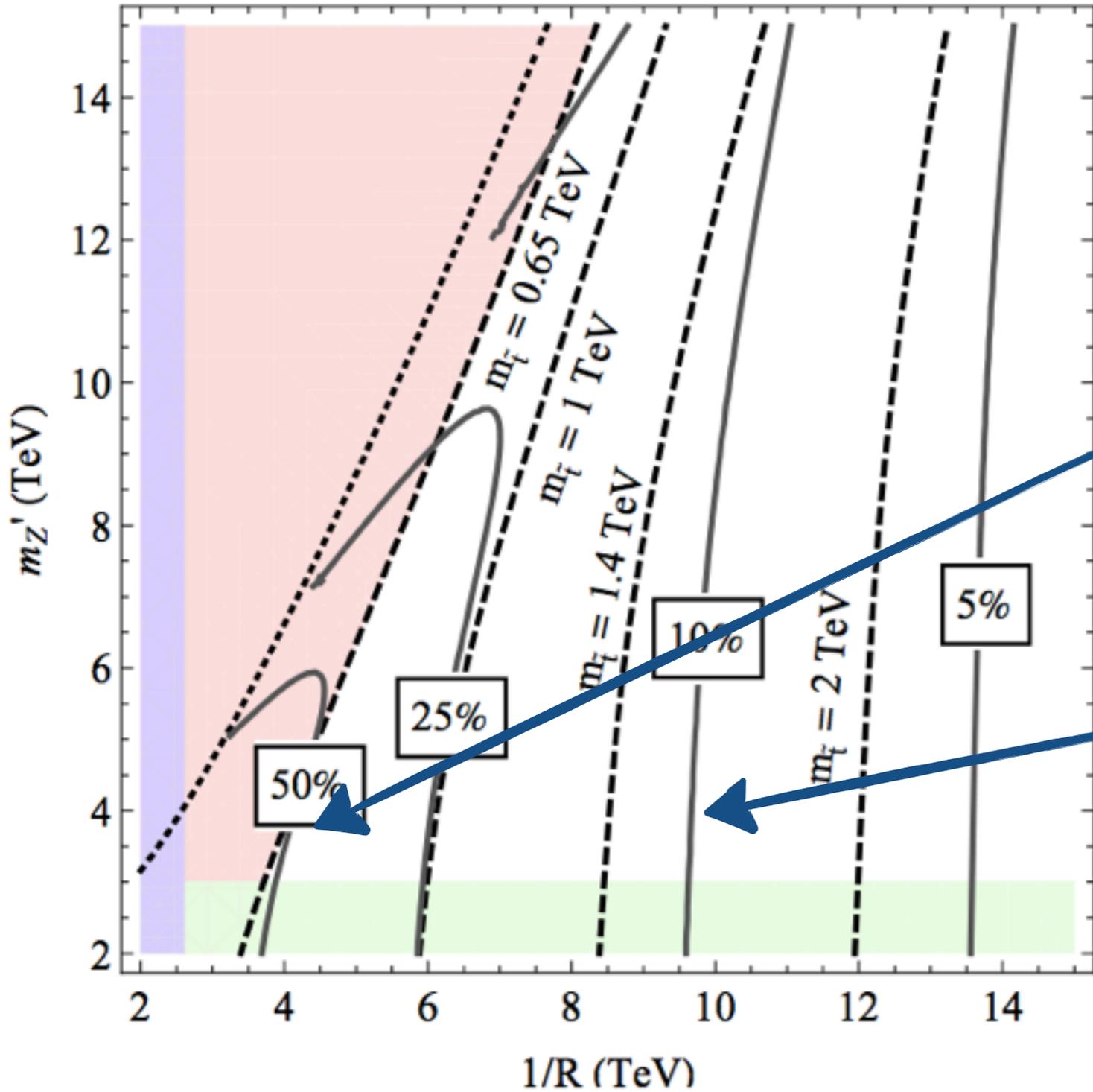
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$\tilde{g} \rightarrow t\bar{t} + X?$

“vanilla” simplified model captures full UV complete model!

Tuning [U(1)' variation]



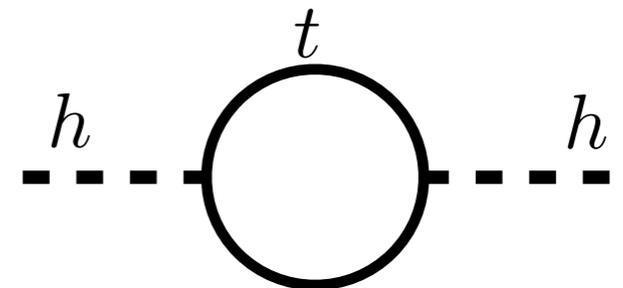
$$\Delta = \sqrt{\left(\frac{\partial \ln v^2}{\partial \ln m_{\tilde{t}}^2}\right)^2 + \left(\frac{\partial \ln v^2}{\partial \ln m_{Z'}^2}\right)^2}$$

NO TUNING(!)
 For ~ 700 GeV Stop &
 2 TeV Gluinos/Squarks

$\sim 10\%$ Tuned
 within LHC13 Reach

“Maximal” \sim saturates one-loop tuning

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



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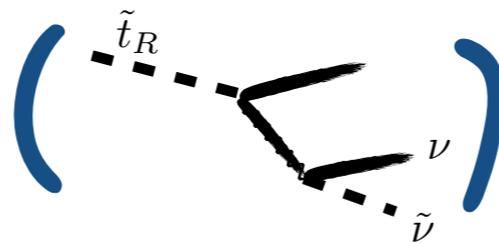
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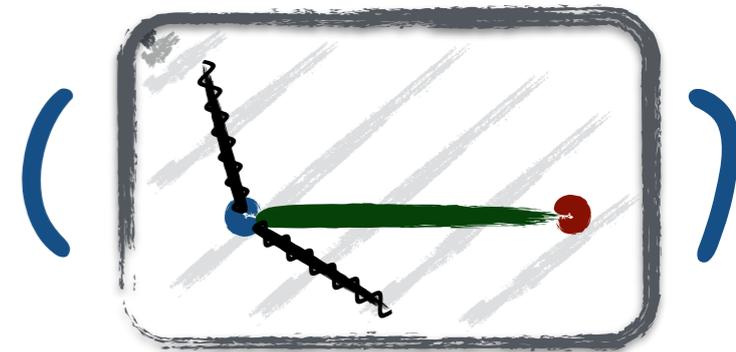
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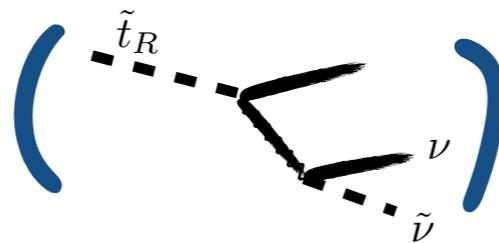
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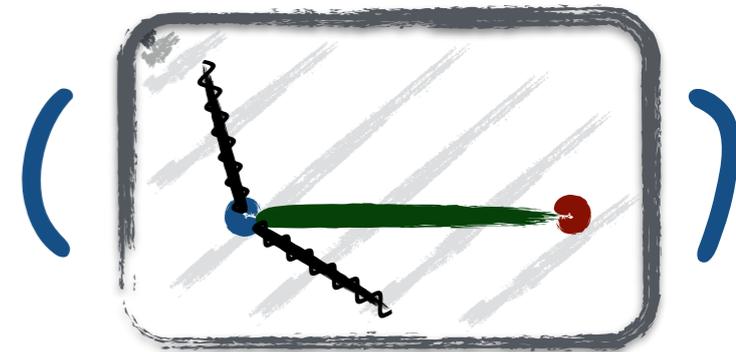
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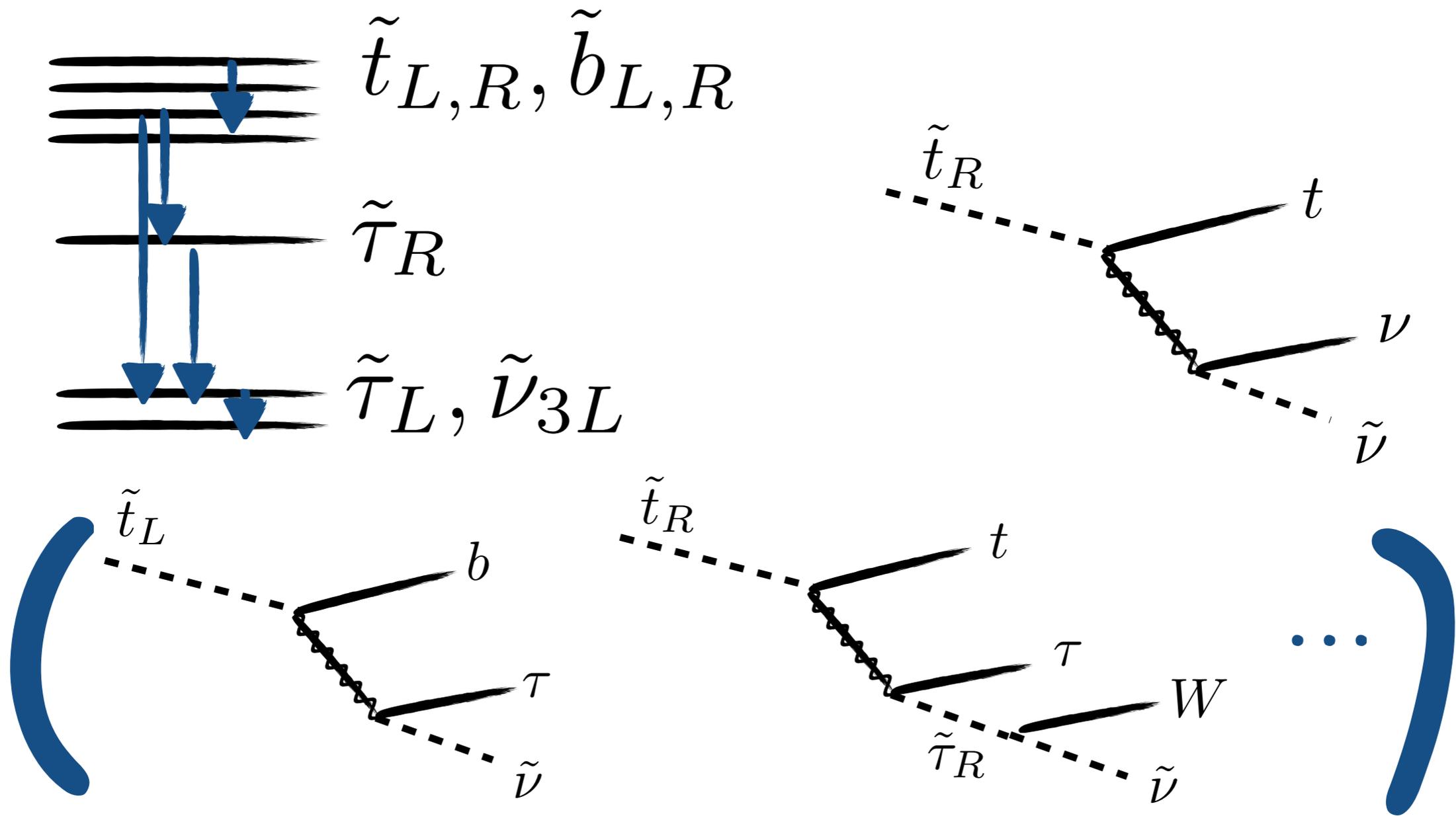
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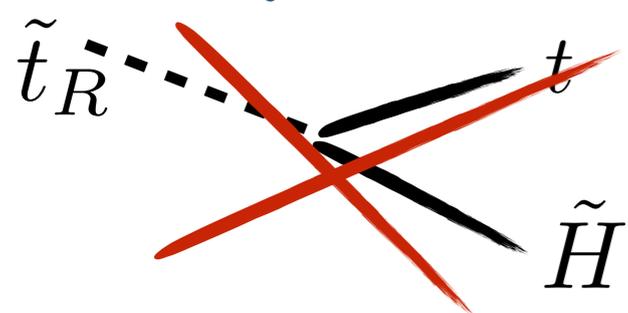


(bulk decay kinematics,
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$\tilde{\nu}_3$ LSP: New Signatures of Naturalness?



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



Reduced MET?
Alves et. al. arXiv:1312.4965

ATLAS-CONF-2014-014
ATLAS-CONF-2013-026

[(3) Bulk LHC Pheno]

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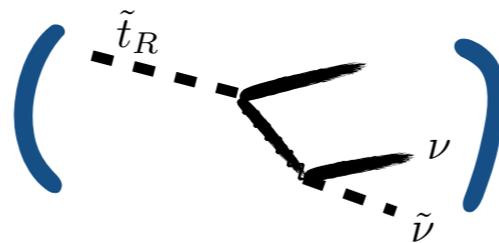
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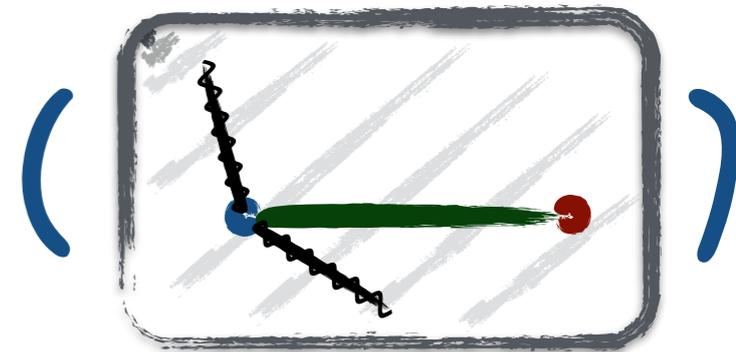
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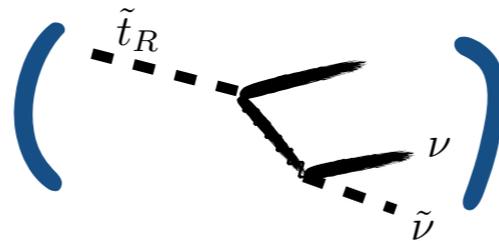
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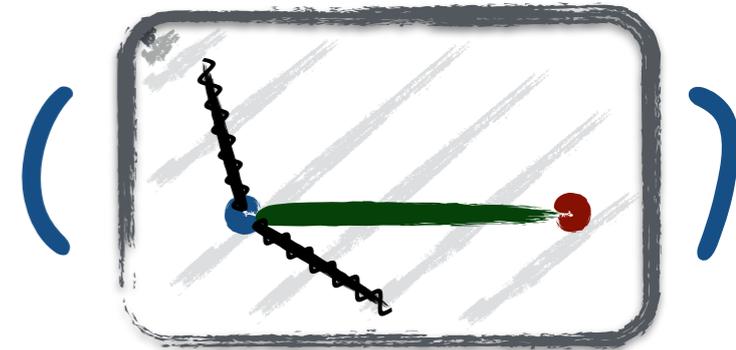
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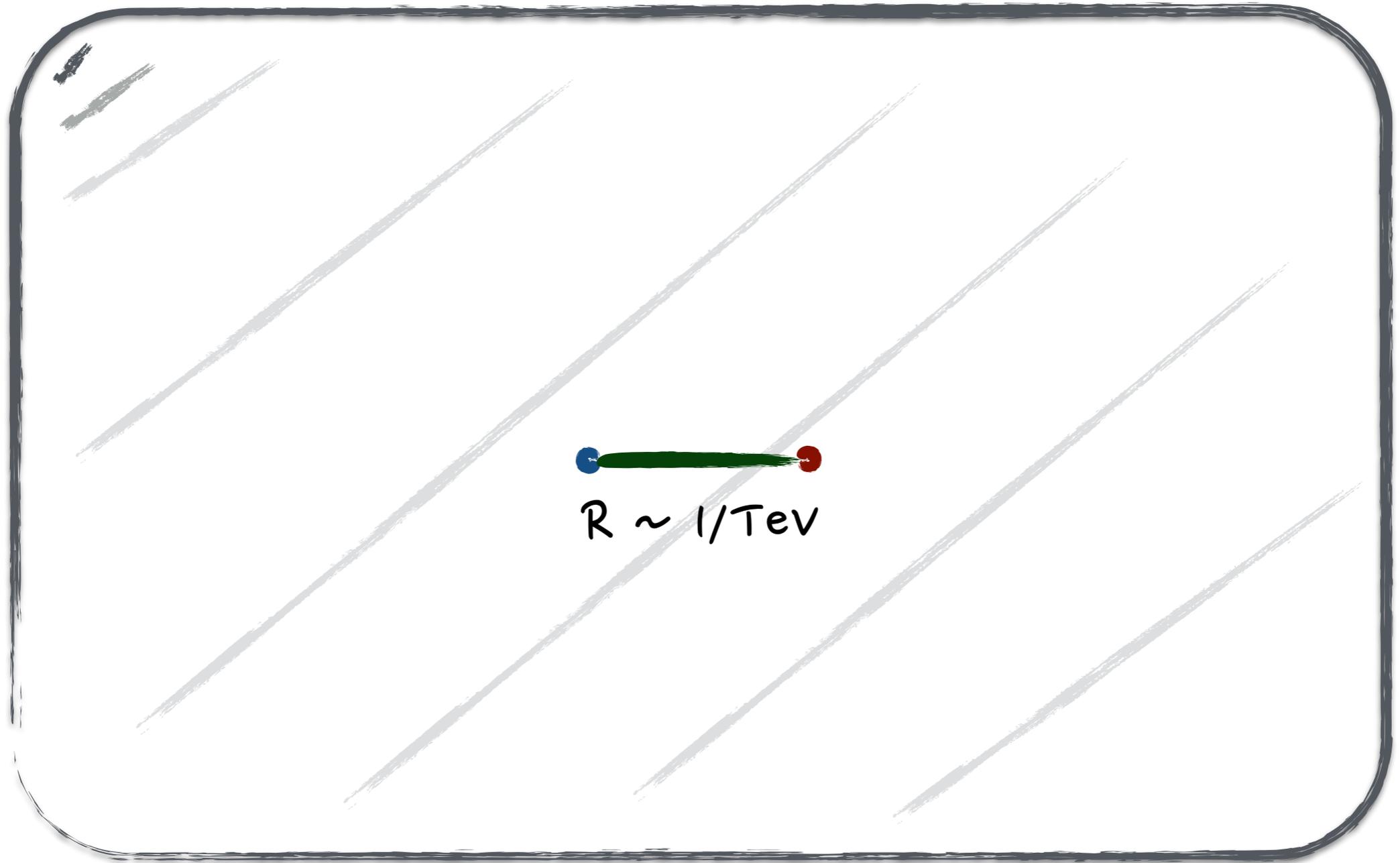
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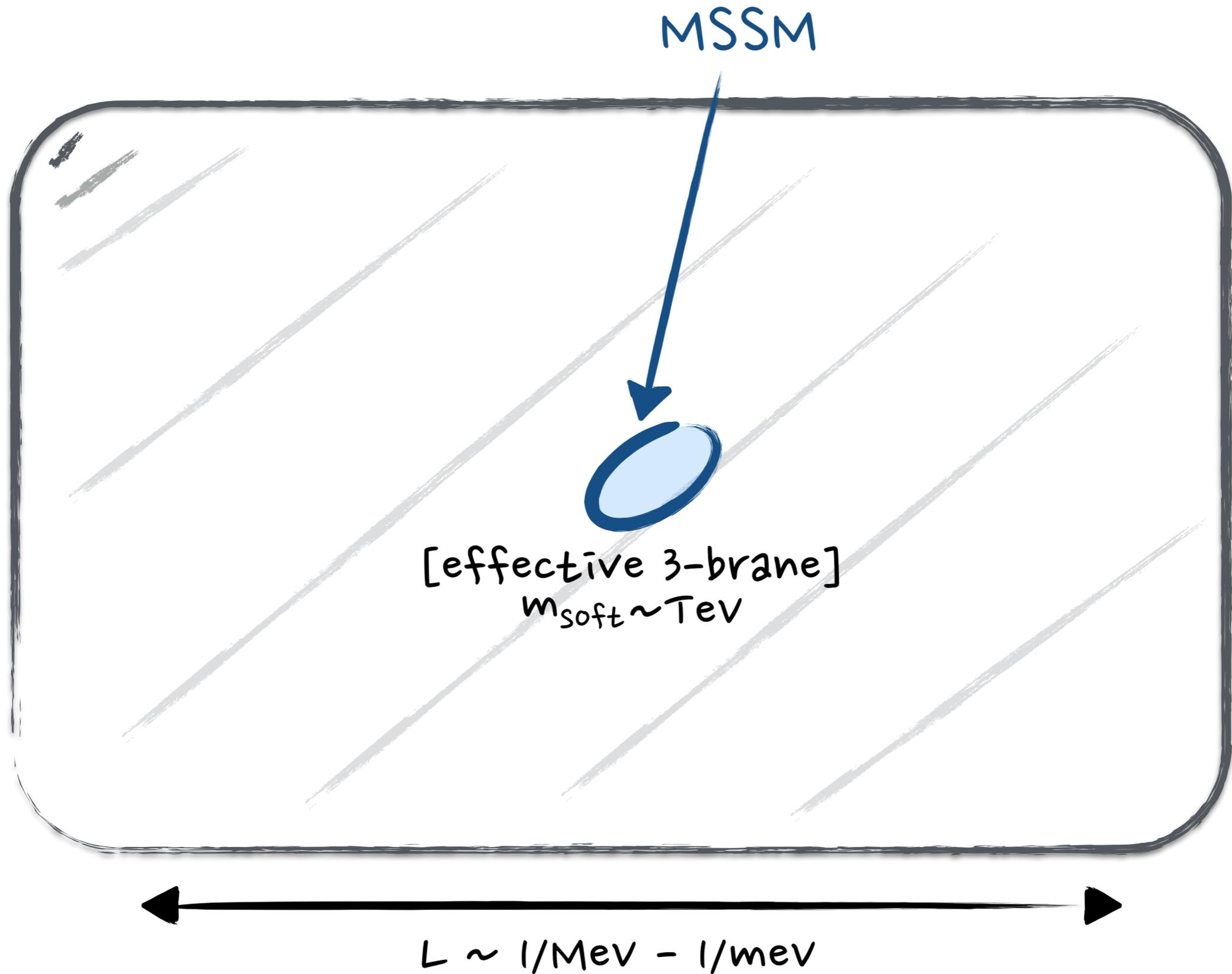
(bulk decay kinematics,
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Decaying to the Bulk

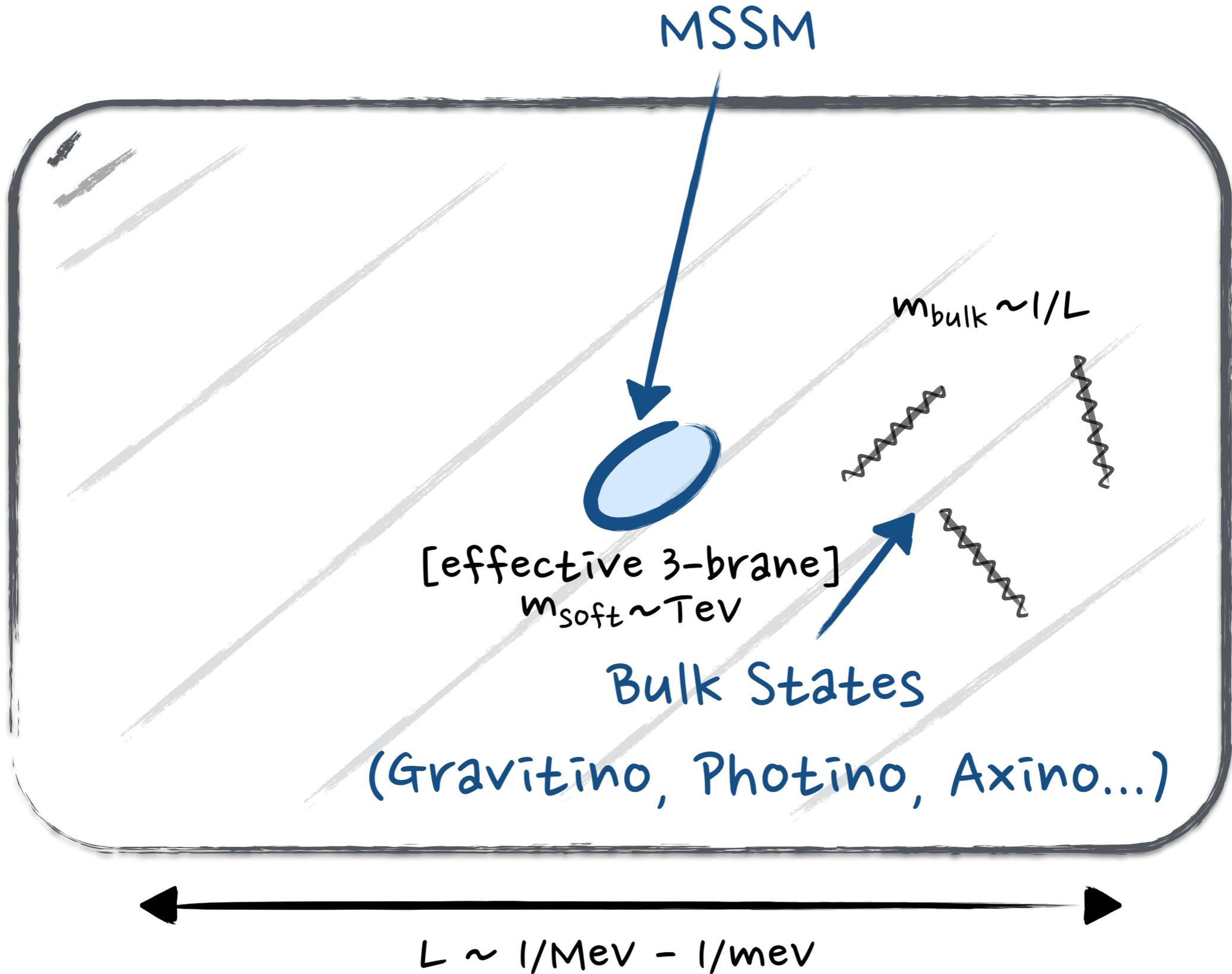


$$L \sim 1/\text{GeV} - 1/\text{meV}$$

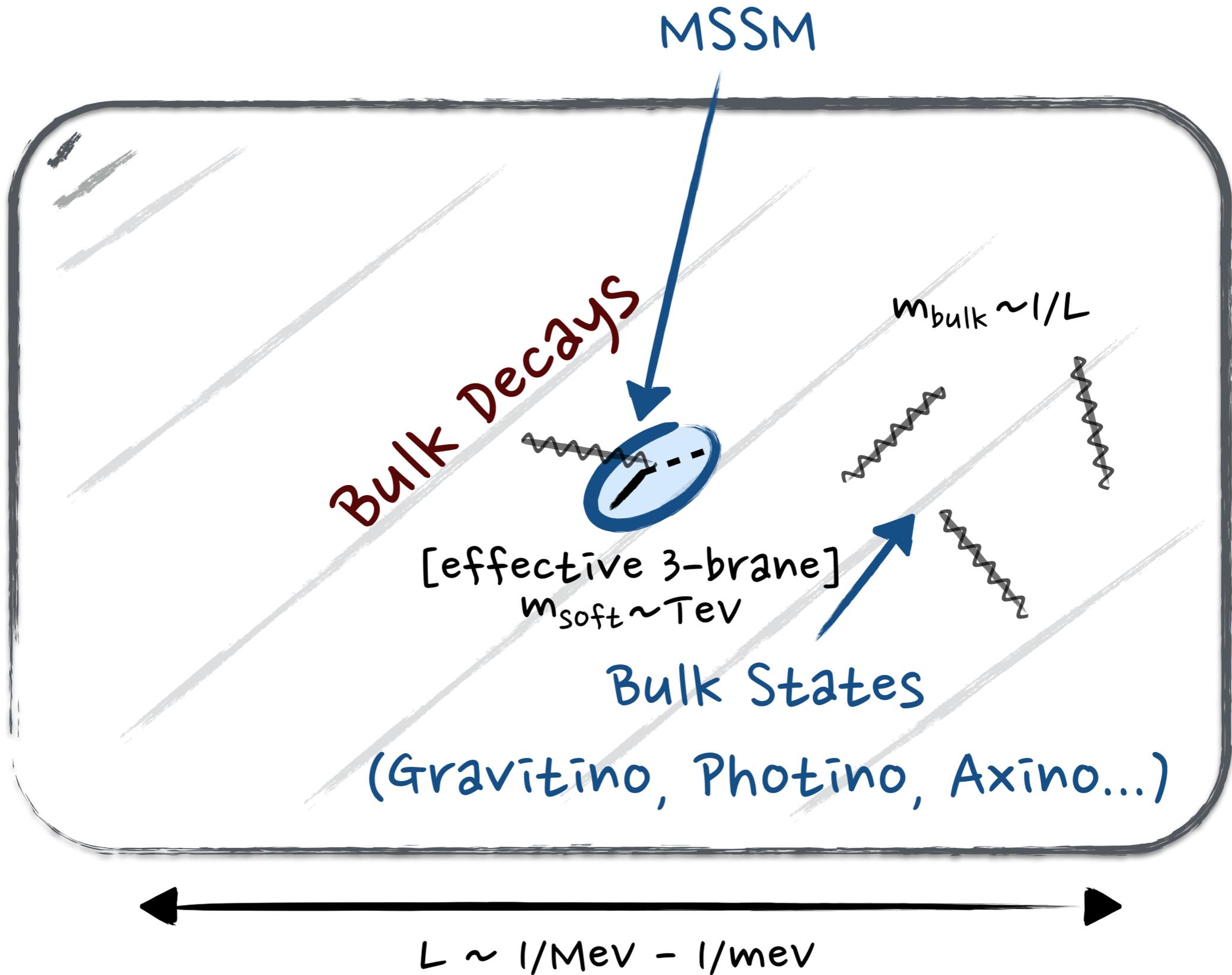
Decaying to the Bulk



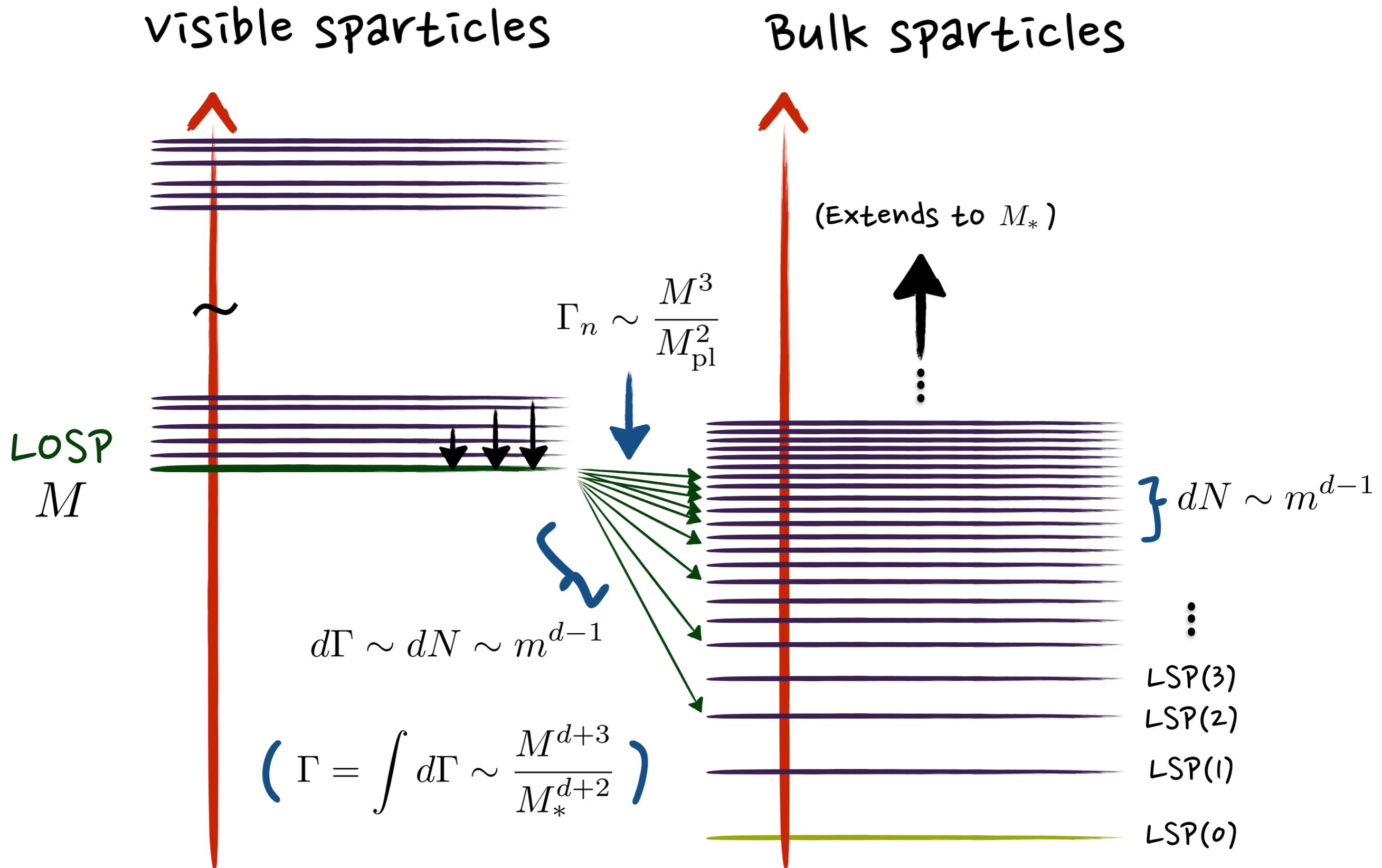
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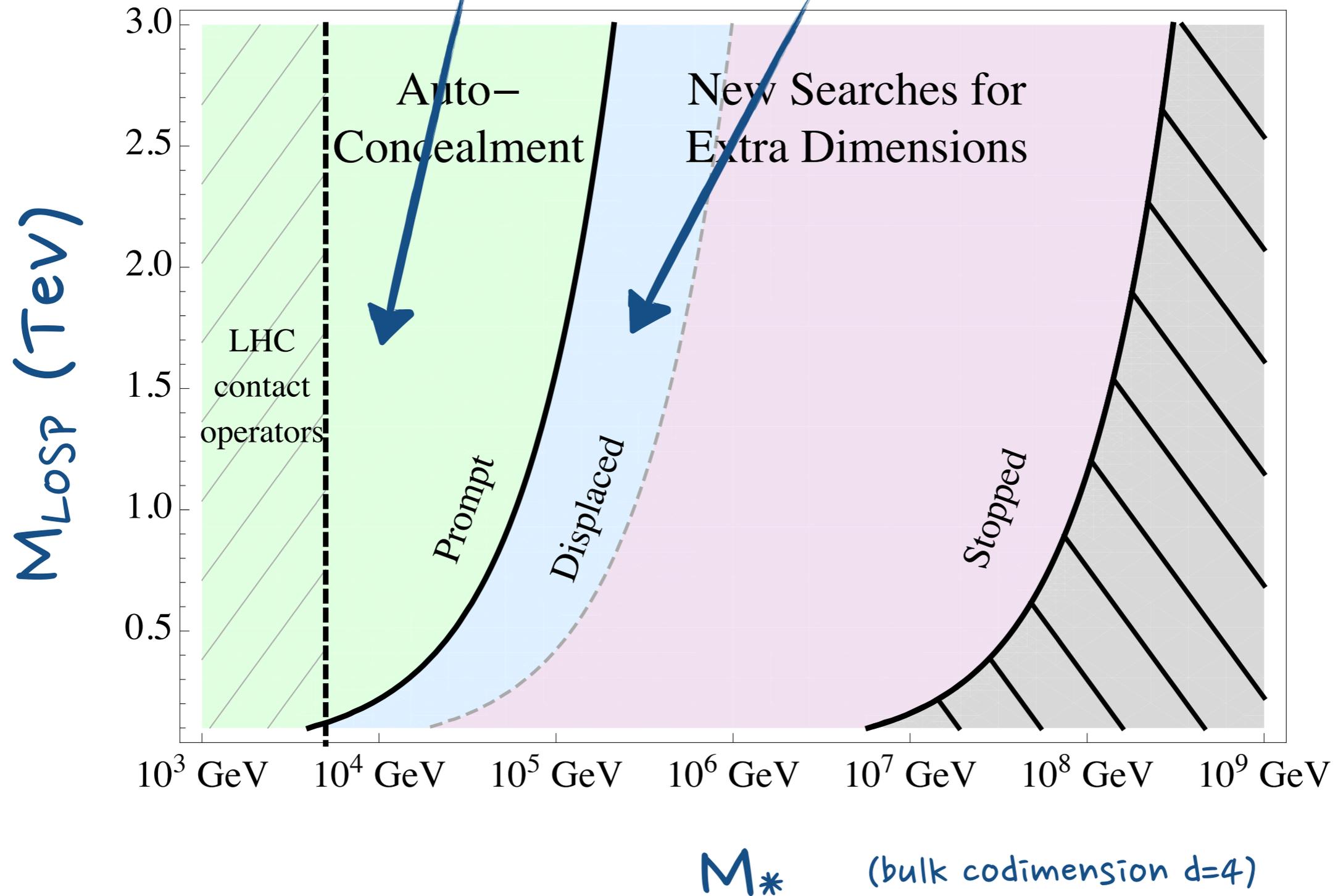


Auto-concealment?

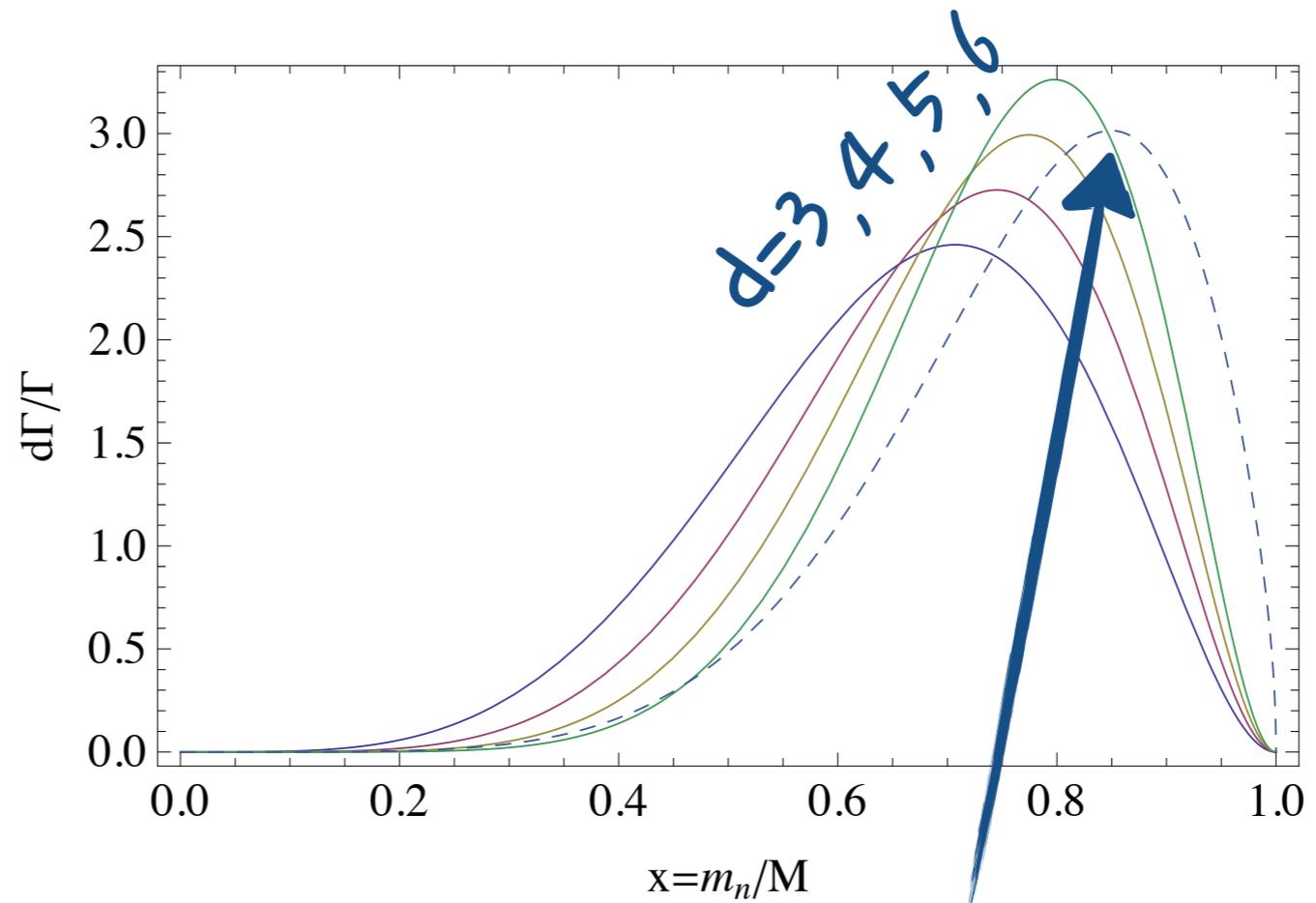
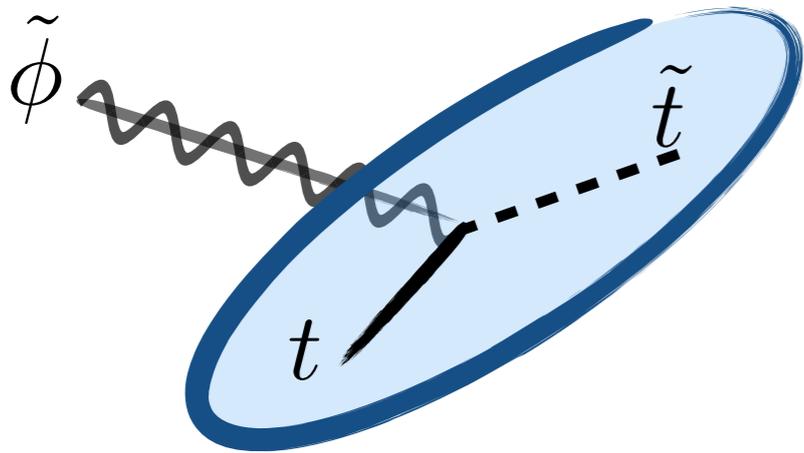


Decay length

(1) Prompt (2) Displaced

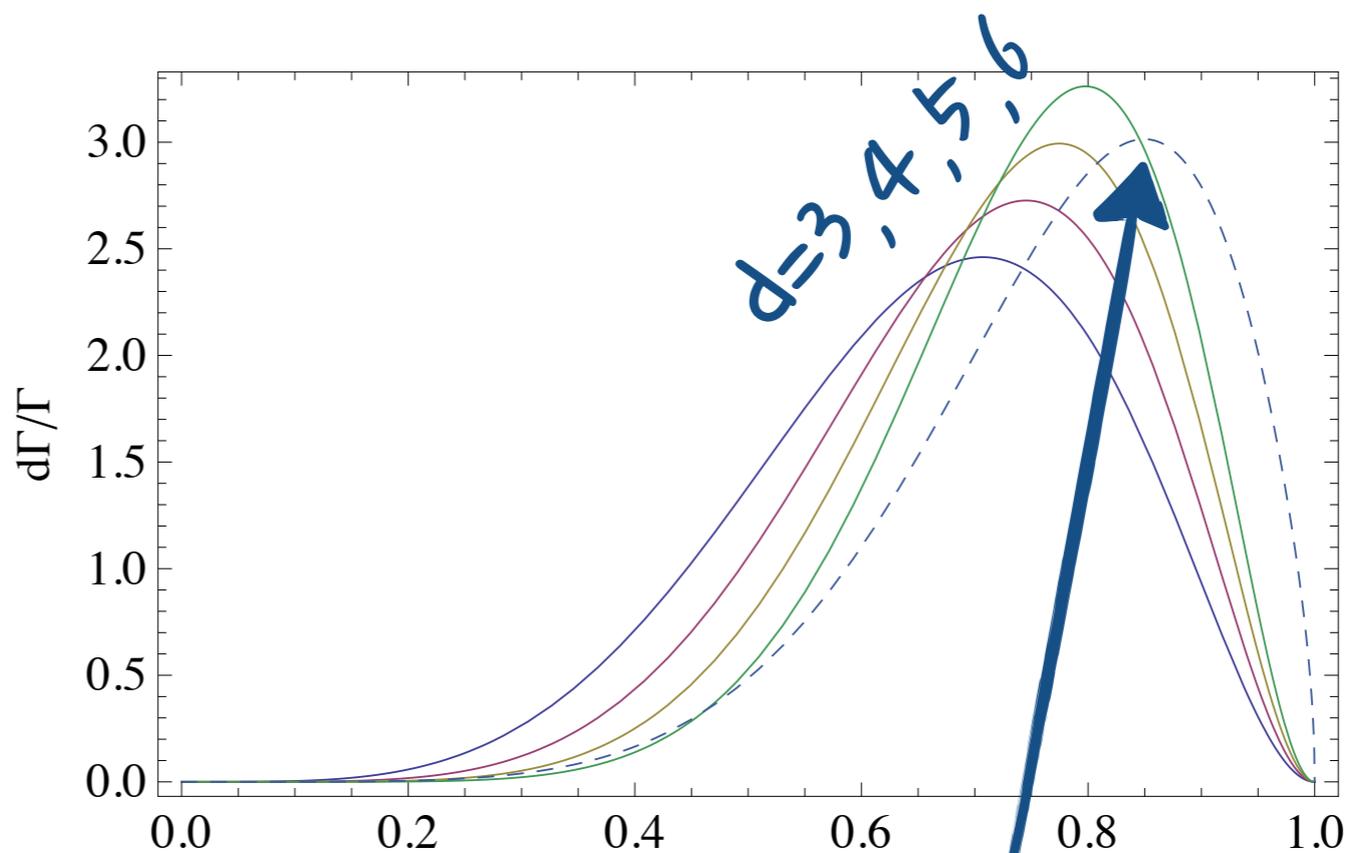
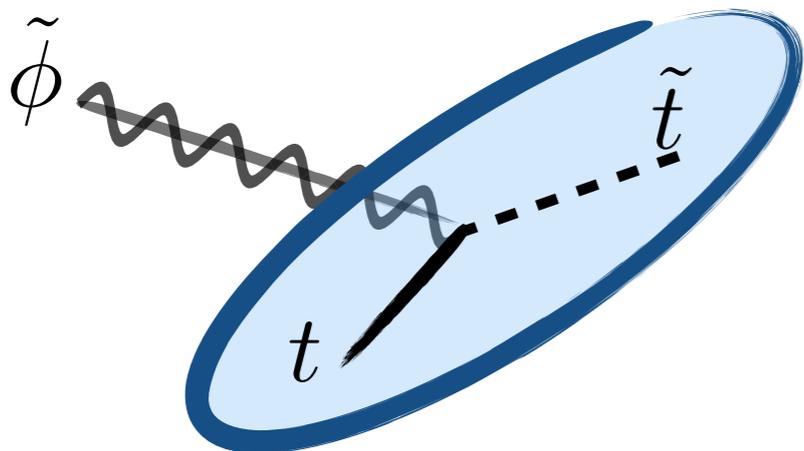


Prompt Auto-concealment?



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

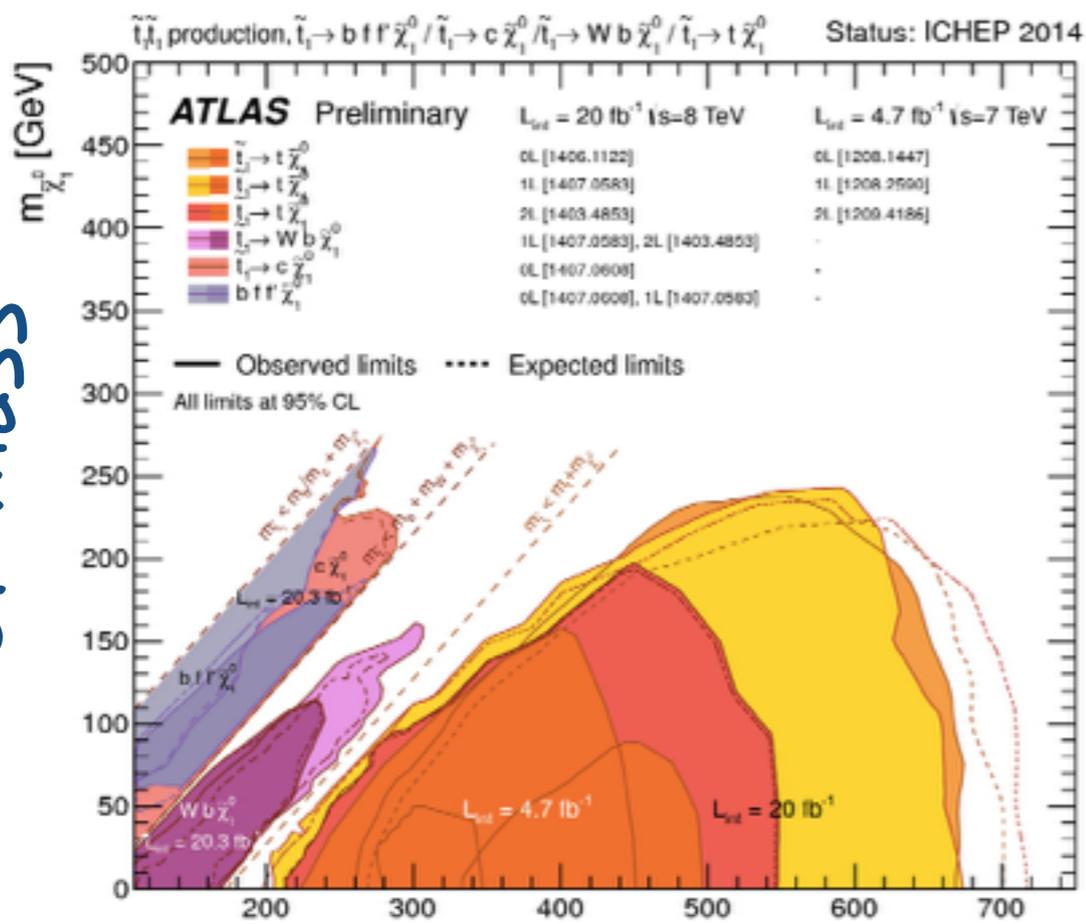
Prompt Auto-concealment?



$x = m_n/M$

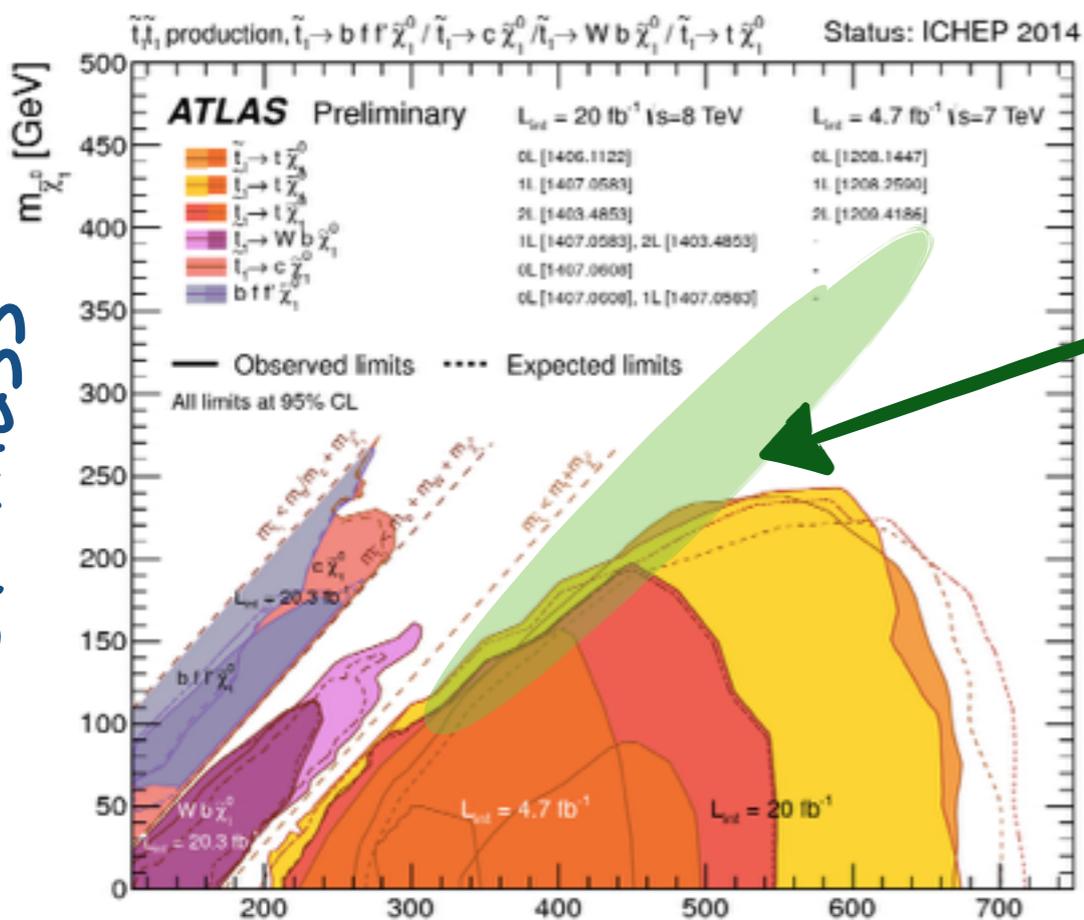
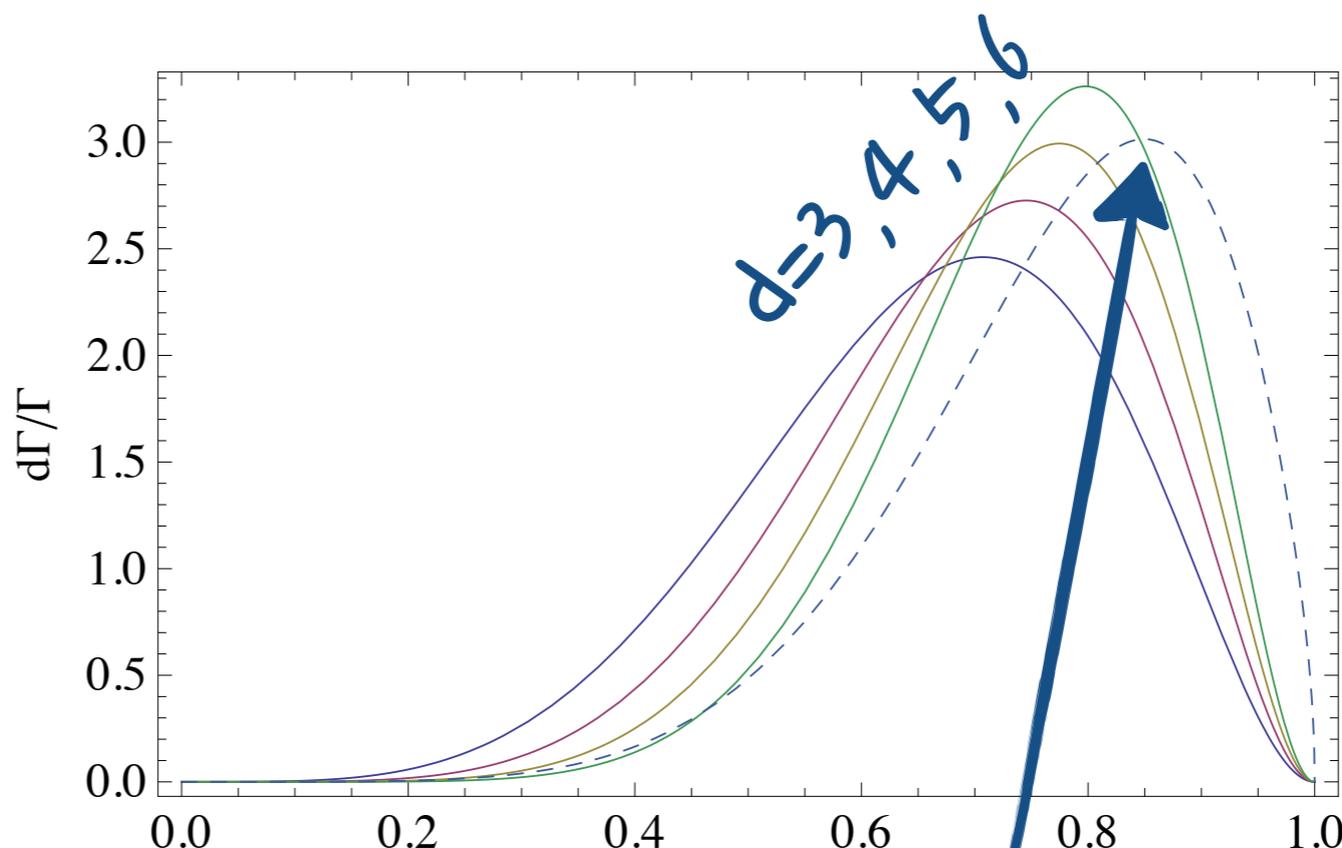
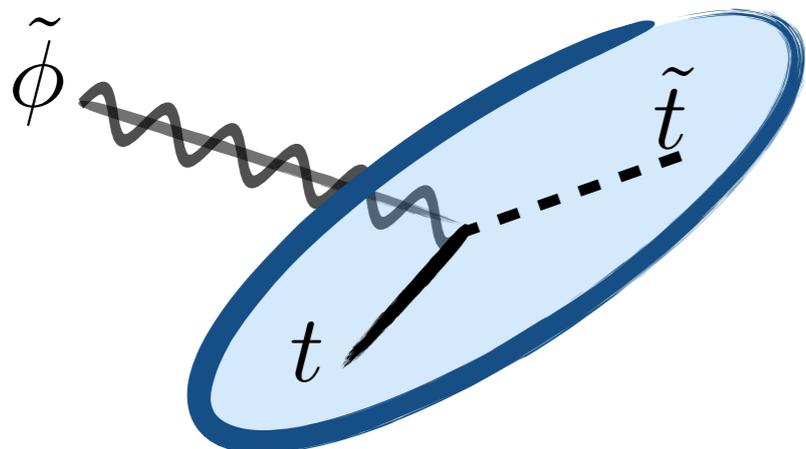
$\langle m \rangle \sim 0.8 (m_{\text{stop}} - m_t)$

LSP mass



m_{stop}

Prompt Auto-concealment?

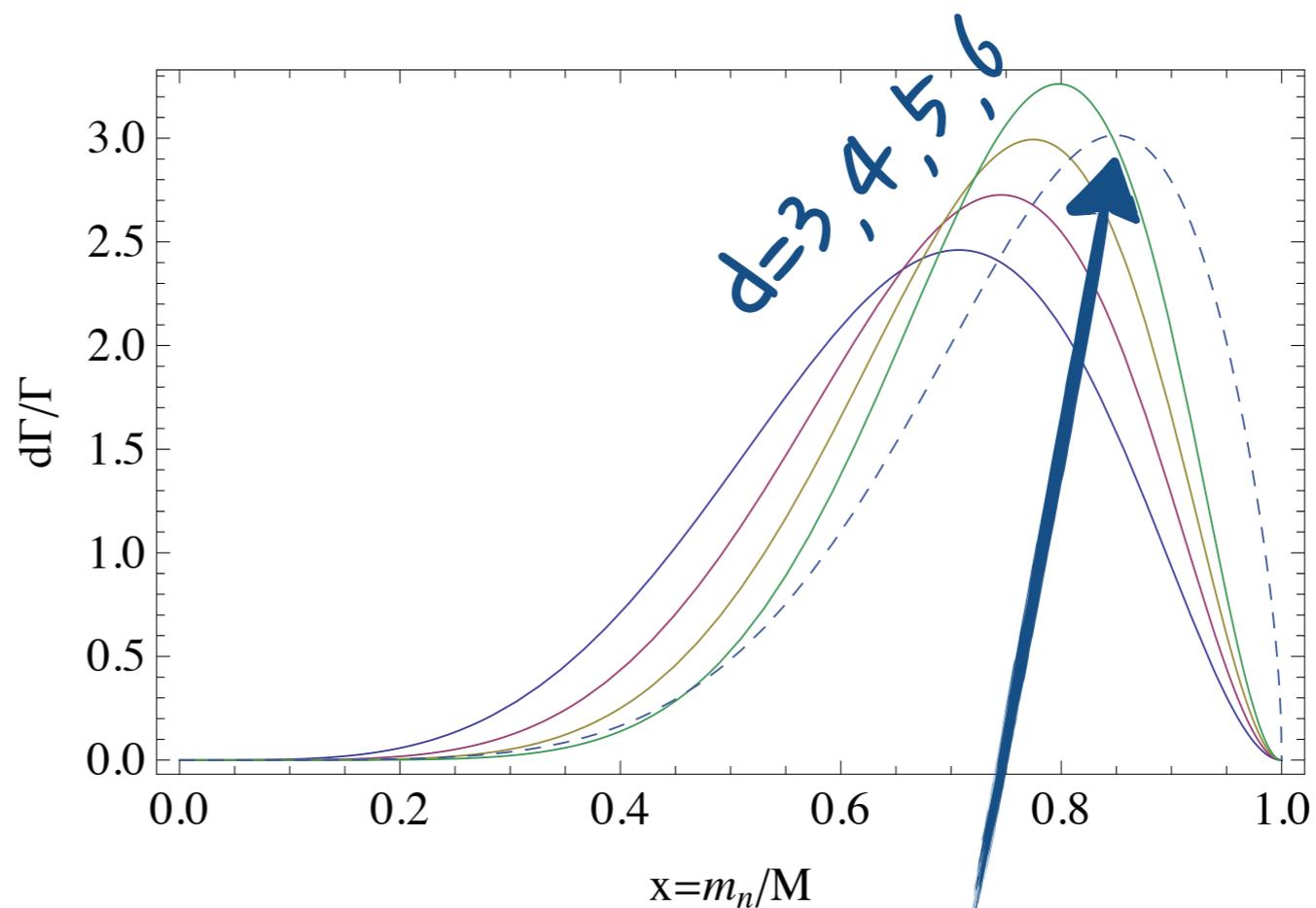
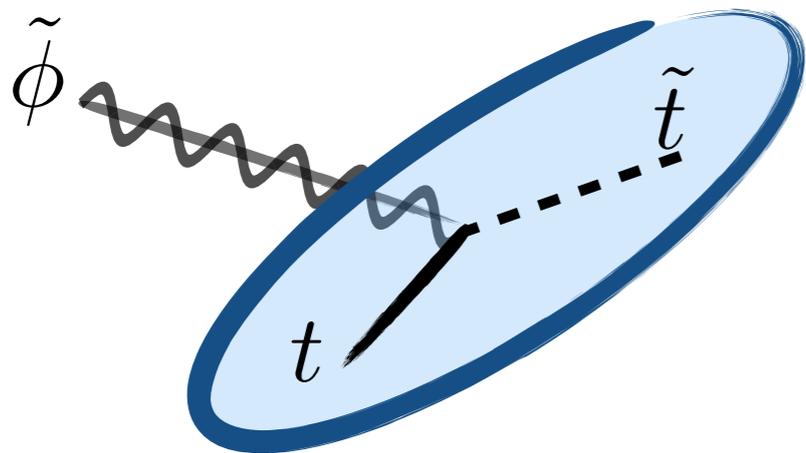


LSP mass

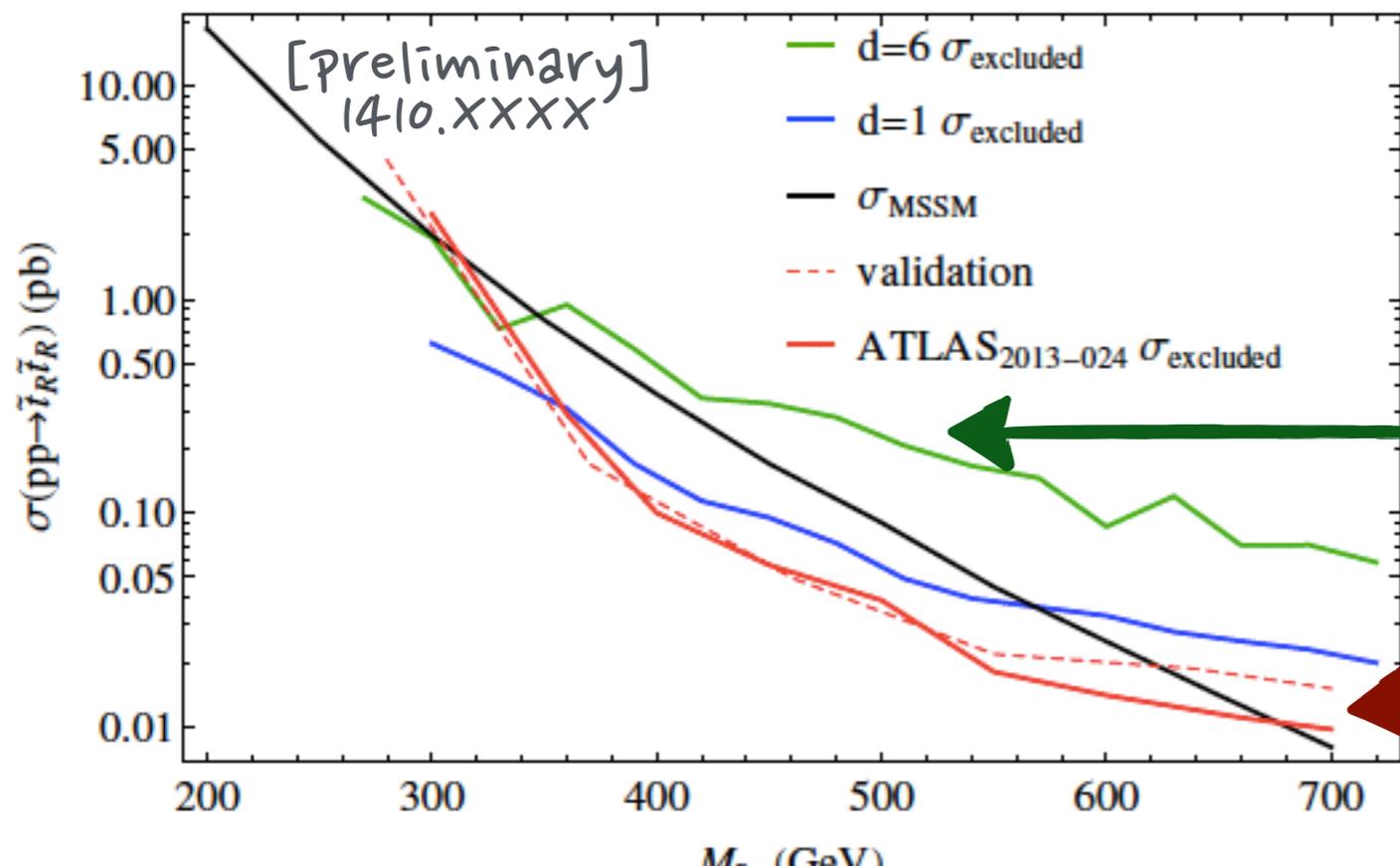
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m_{stop}

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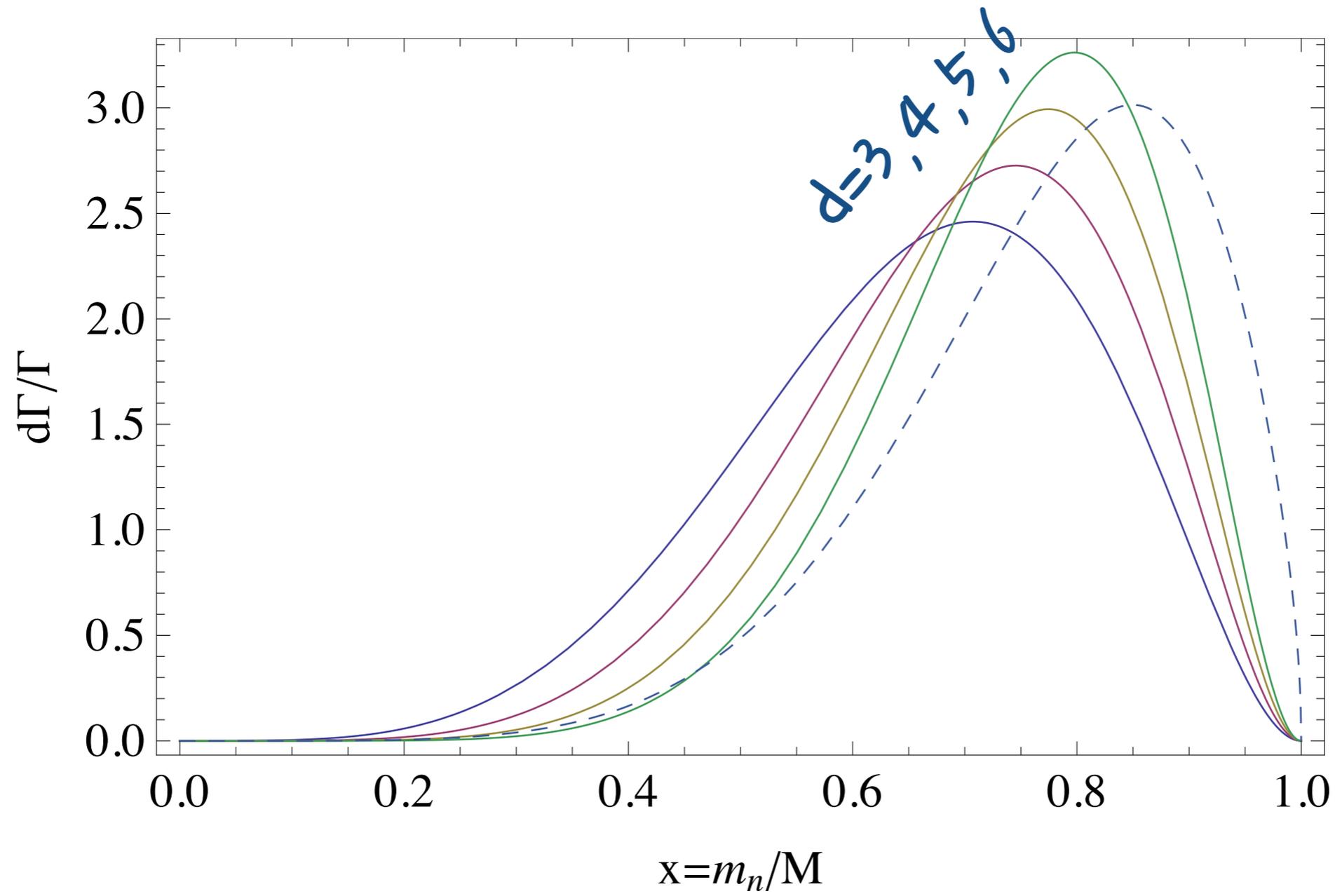
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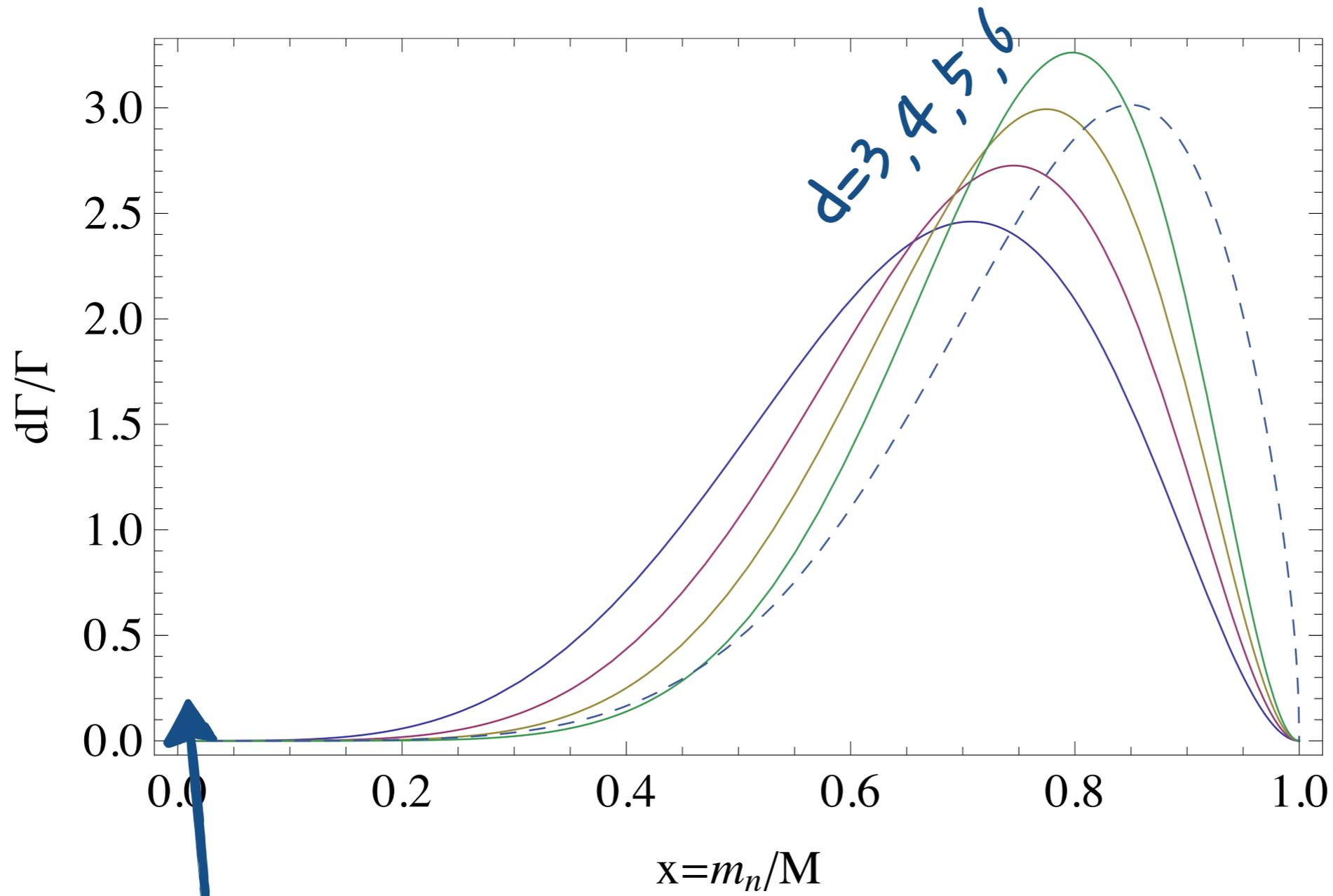
$d=6, m_{\text{stop}} > \sim 400 \text{ GeV}$

validation

Displaced Signatures?

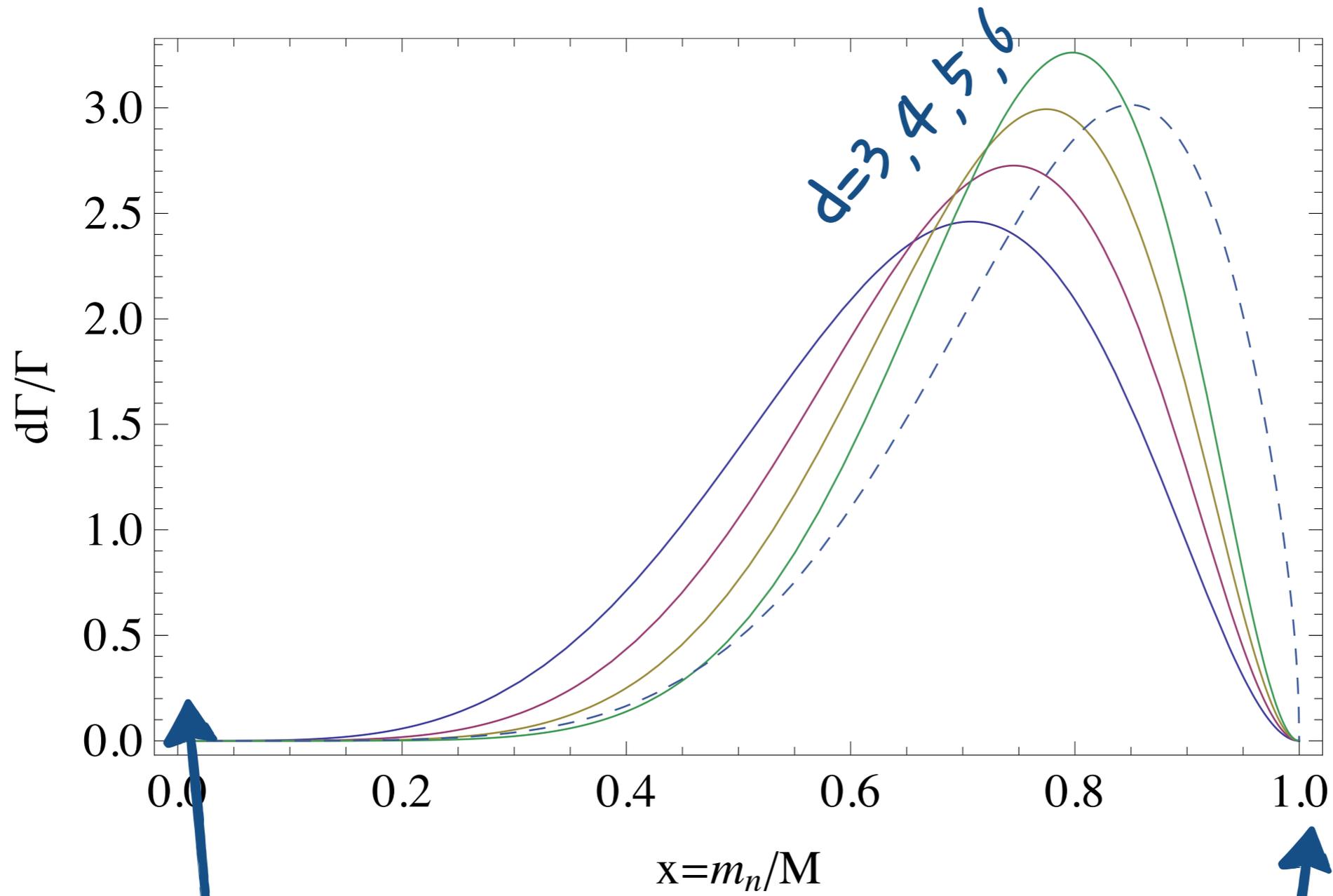


Displaced Signatures?



Low-scale GMSB

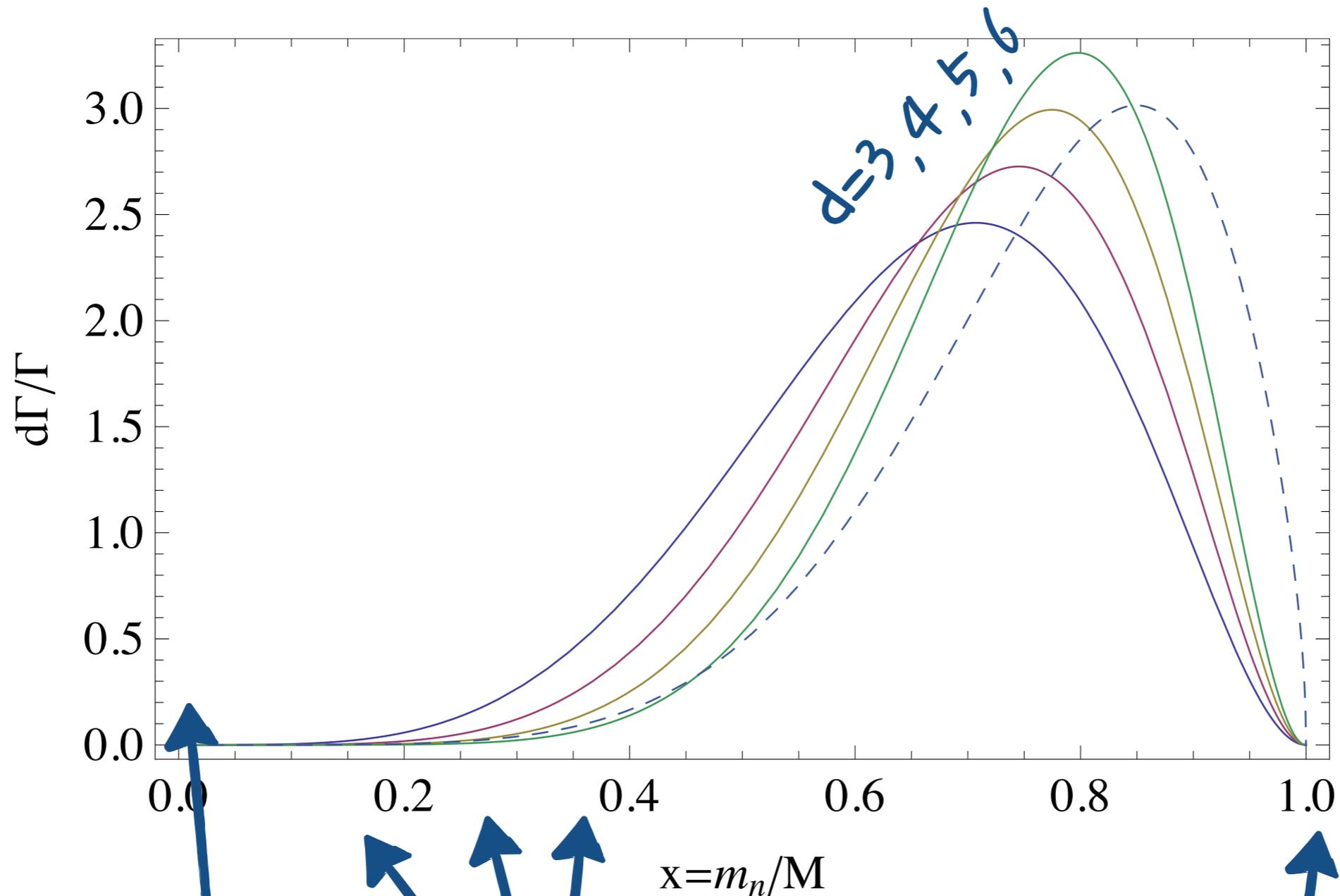
Displaced Signatures?



Low-scale GMSB

Wino LSP

Displaced Signatures?



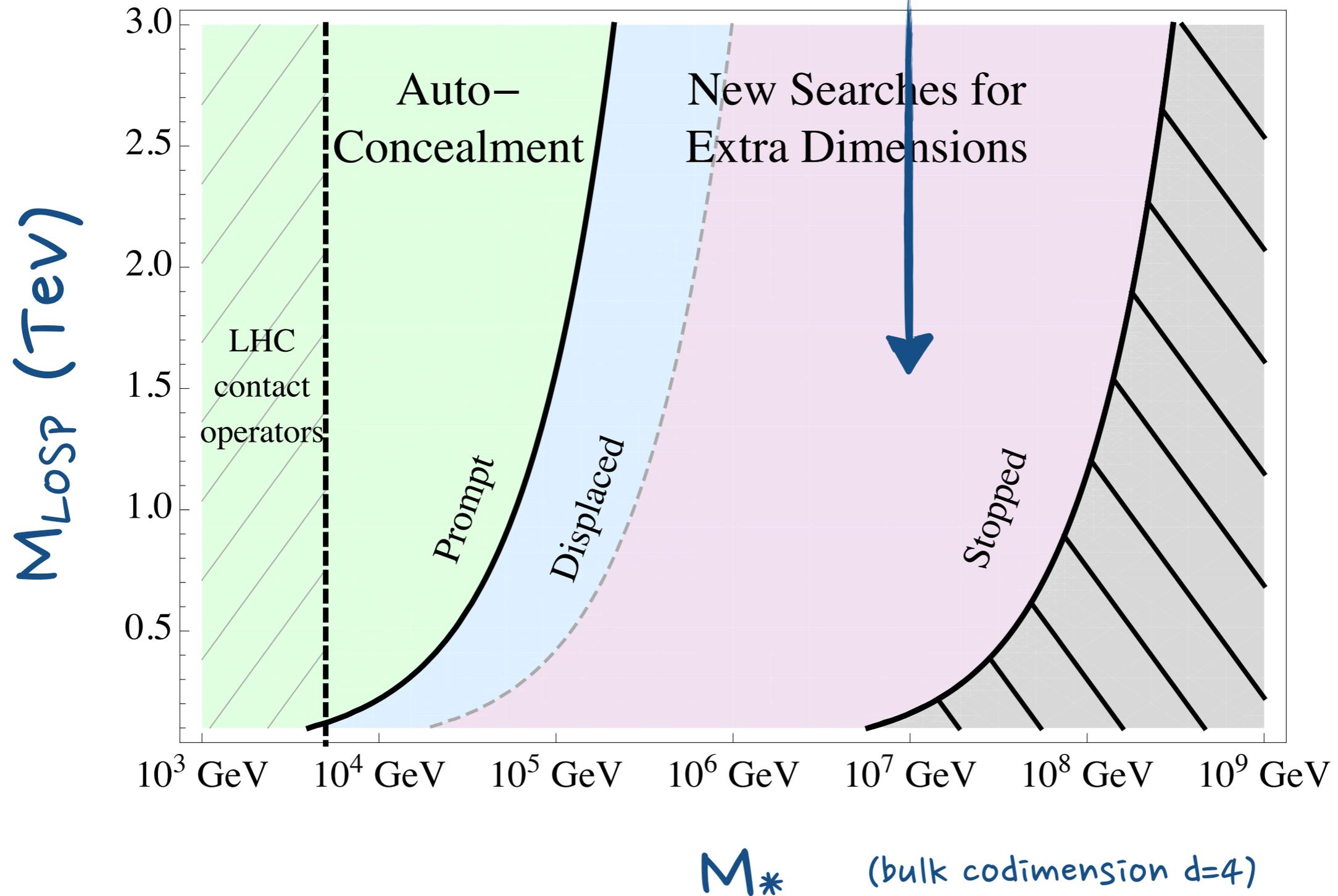
Low-scale GMSB

~Split SUSY Gluino

Wino LSP

Discovering extra dimensions?

Stopped in Detector?



Conclusions

n-dimensional bulk

4D SUSY



3rd Gen

5D SUSY



Gauge, Higgs,
1st + 2nd Gen



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

Conclusions

n-dimensional bulk

1) Locality + Low-scale of SSSB
Protects natural Spectrum

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2) 3rd Gen Sfermions
(i) untuned Simplified
Model
(ii) heavy higgsinos:
3-body decays

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n-dimensional bulk

1) Locality + Low-scale of SSSB
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3) decays to bulk
(i) auto-concealment
(ii) new displaced and stopped signatures

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Spectra variations

Bulk States

Higgs Mass
=>Pheno

Gauge unification

...

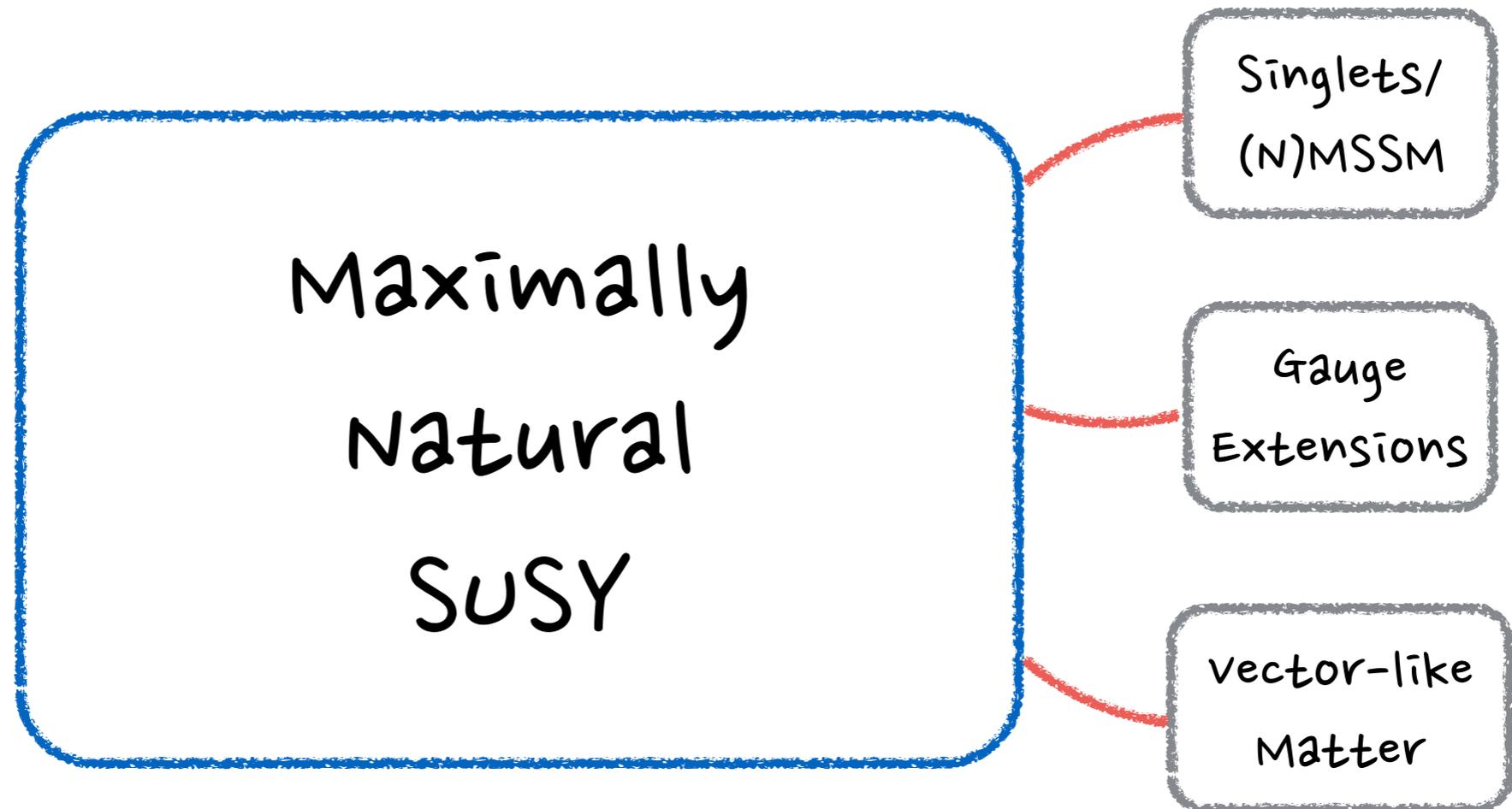
work in progress w/
I. Garcia-Garcia, J. Huang, J. Scoville,
S. Dimopoulos, J. March-Russell

Questions?

[Back-ups]

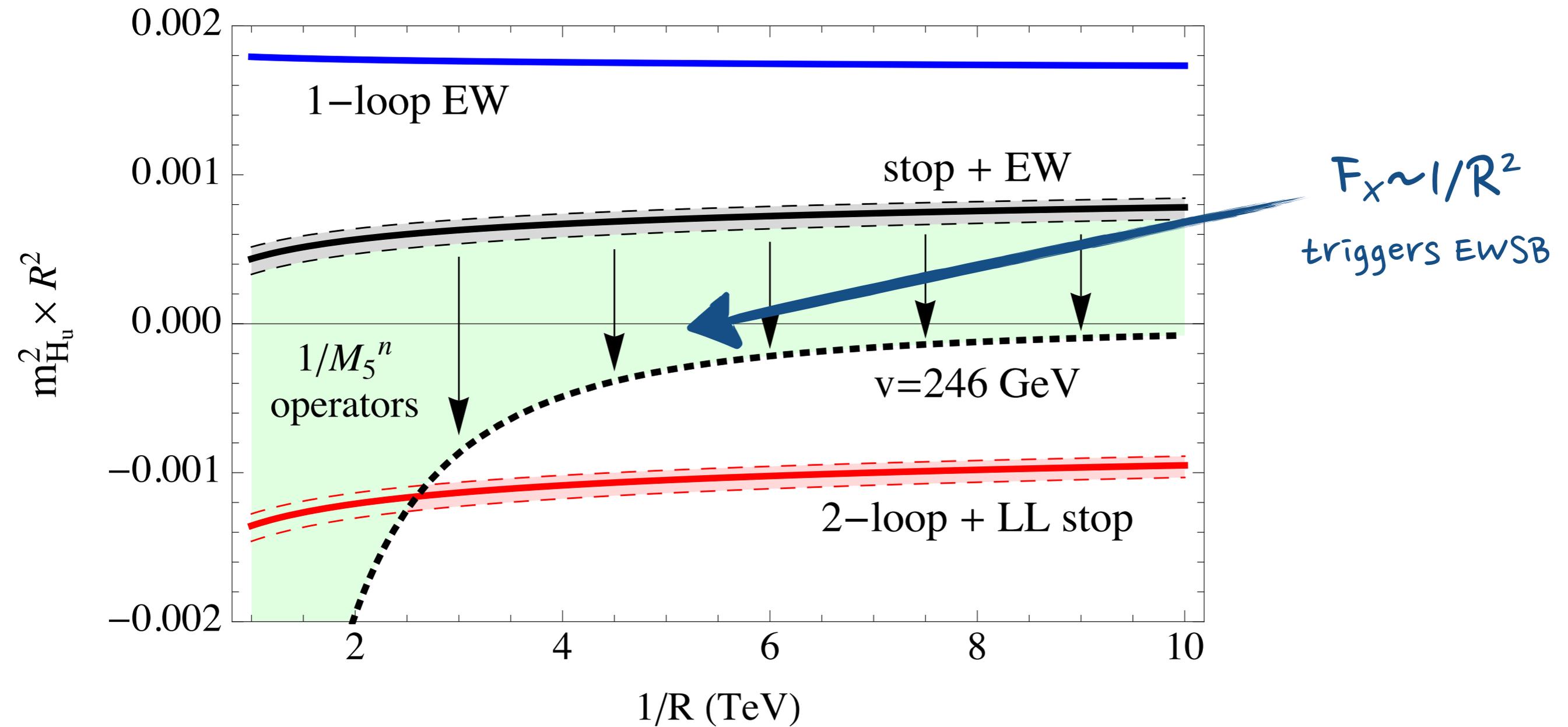
125 GeV Higgs?

Higgs Mass



(...or stops $> \sim 3$ TeV?)

EW/SB?



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



Brane-localized x ,
 $F_x \sim 1/R^2$



Extra Contributions to Soft Mass?

Radius stabilization?

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(comparable to 1-loop)

Brane-localized x ,
 $F_x \sim 1/R^2$

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

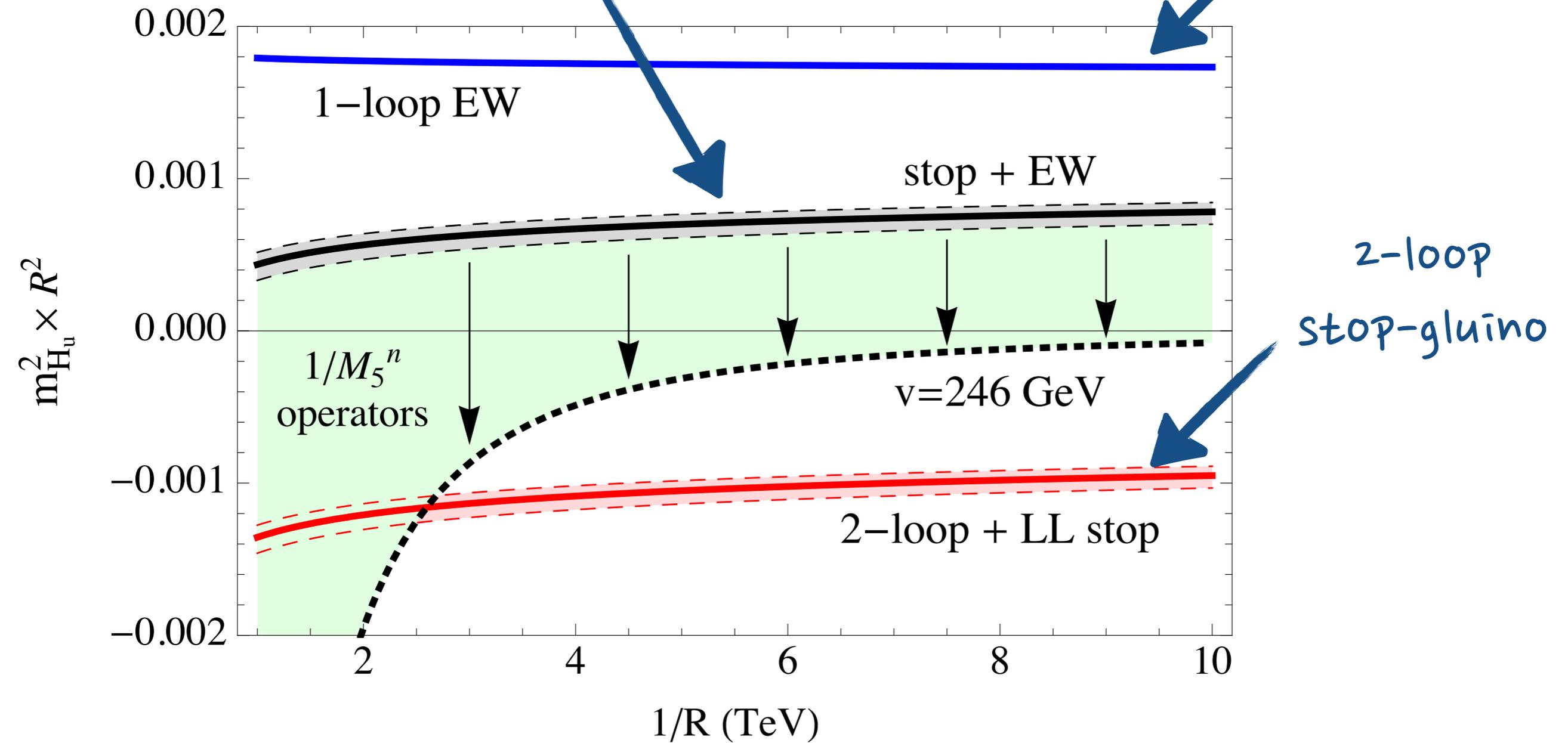
($\pi M_* R \sim 20$ fixed by perturbativity)

EWSB?

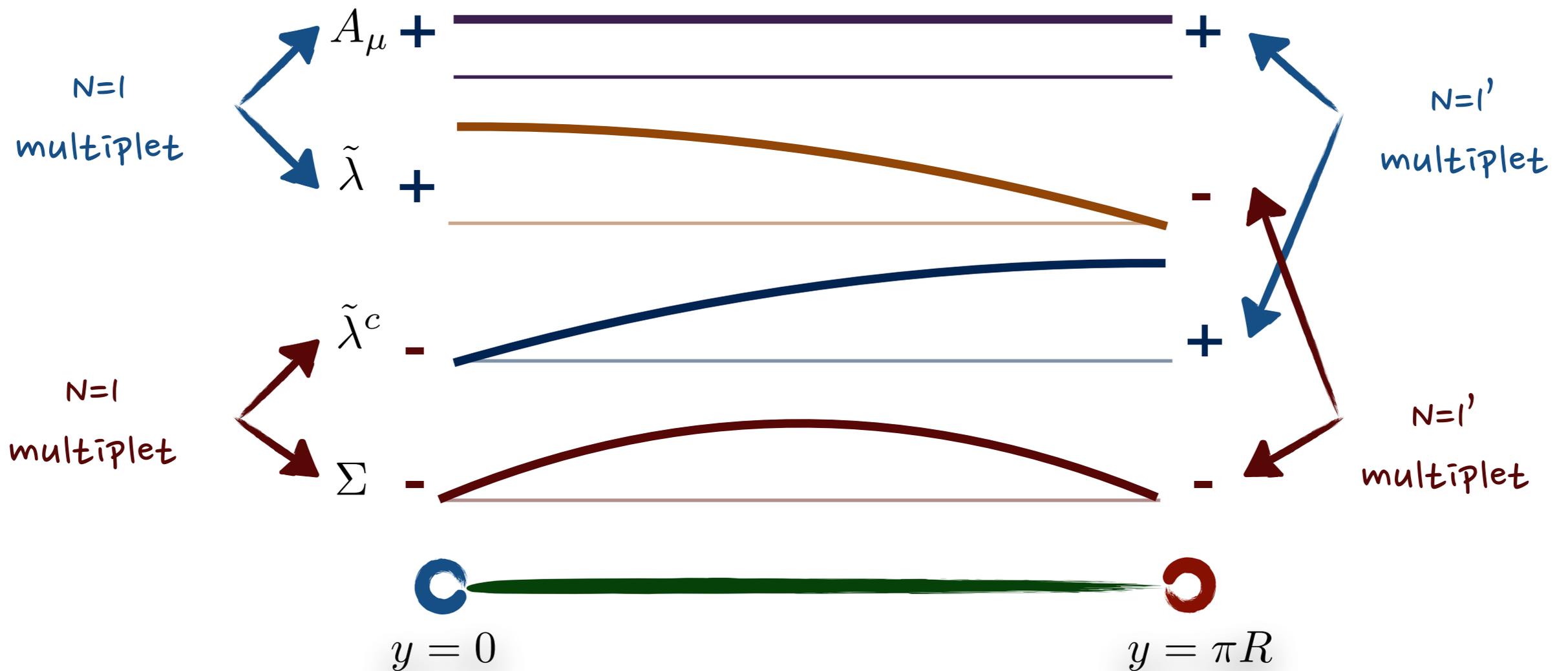
Total Scherk-Schwarz contribution:

1-loop electroweak

NO EWSB

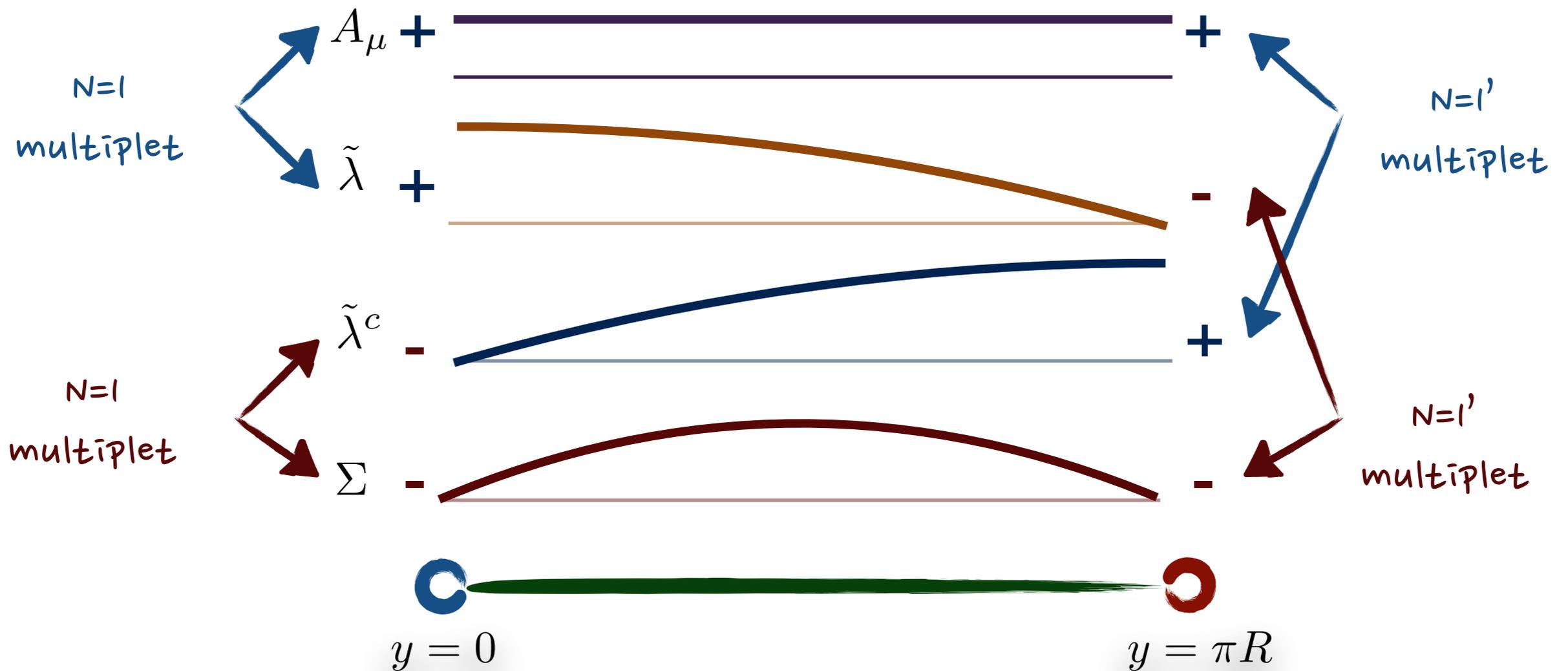


Softness of Scherk Schwarz



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

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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 : ~ 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

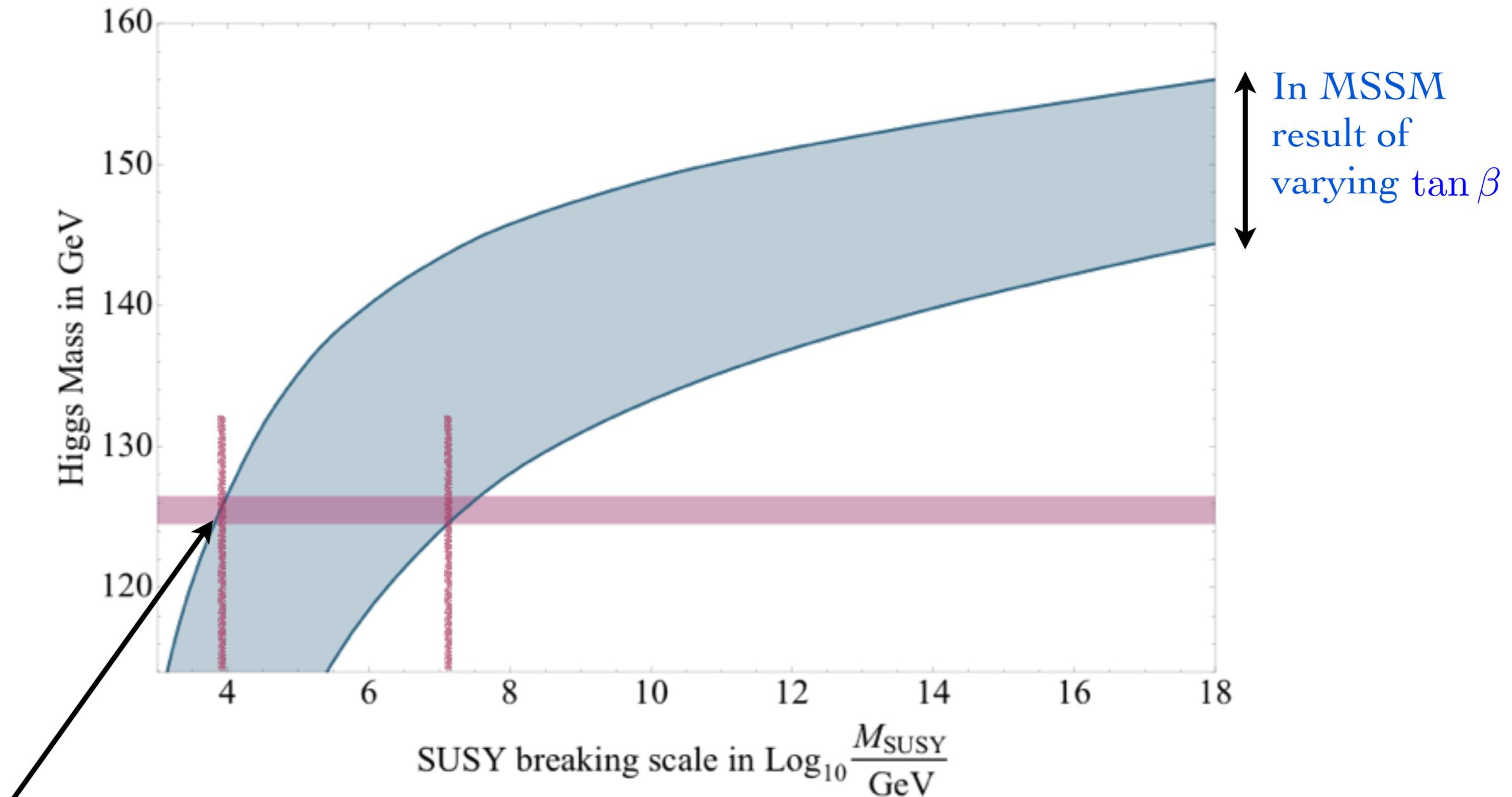
$$\Delta\mathcal{K}_{m_H^2} = \delta(y) \frac{c_H}{M_5^3} X^\dagger X H_u^\dagger H_u$$

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

leading HDOs in our range of parameters

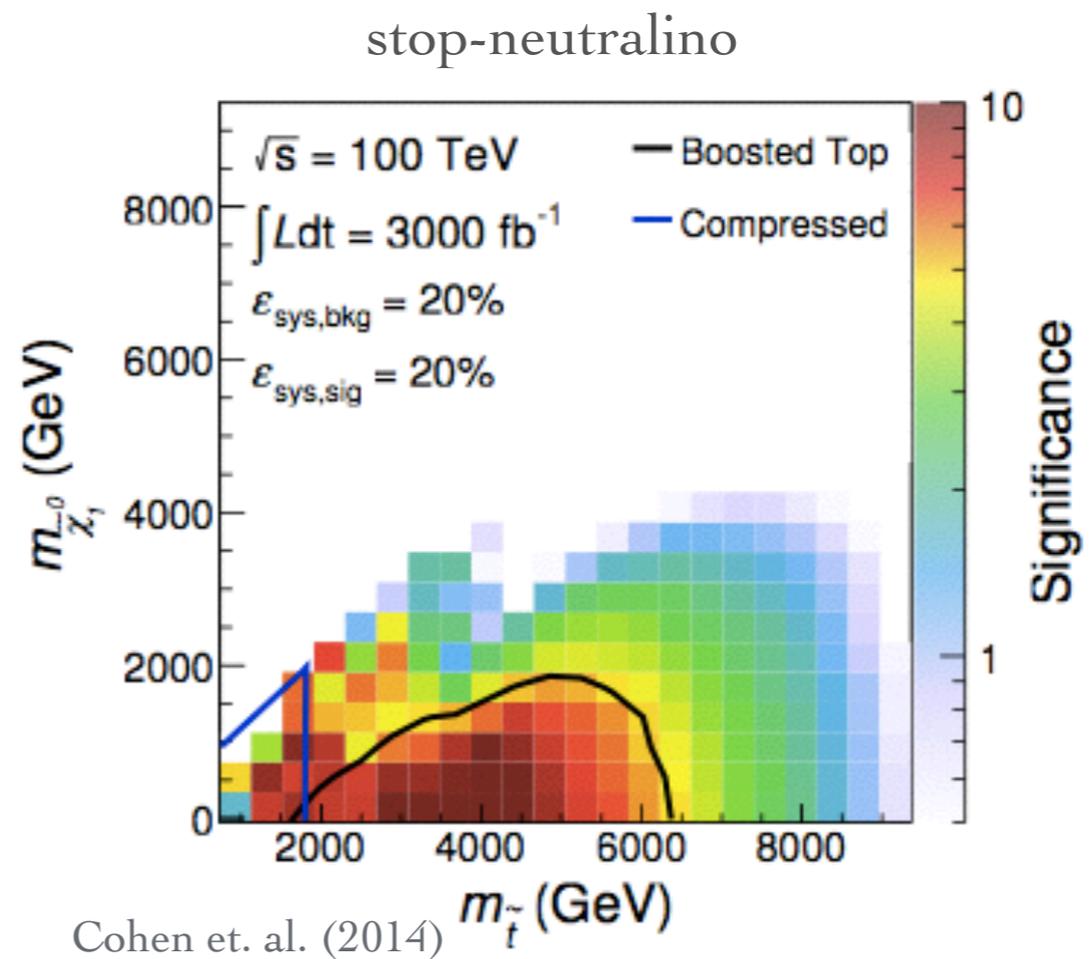
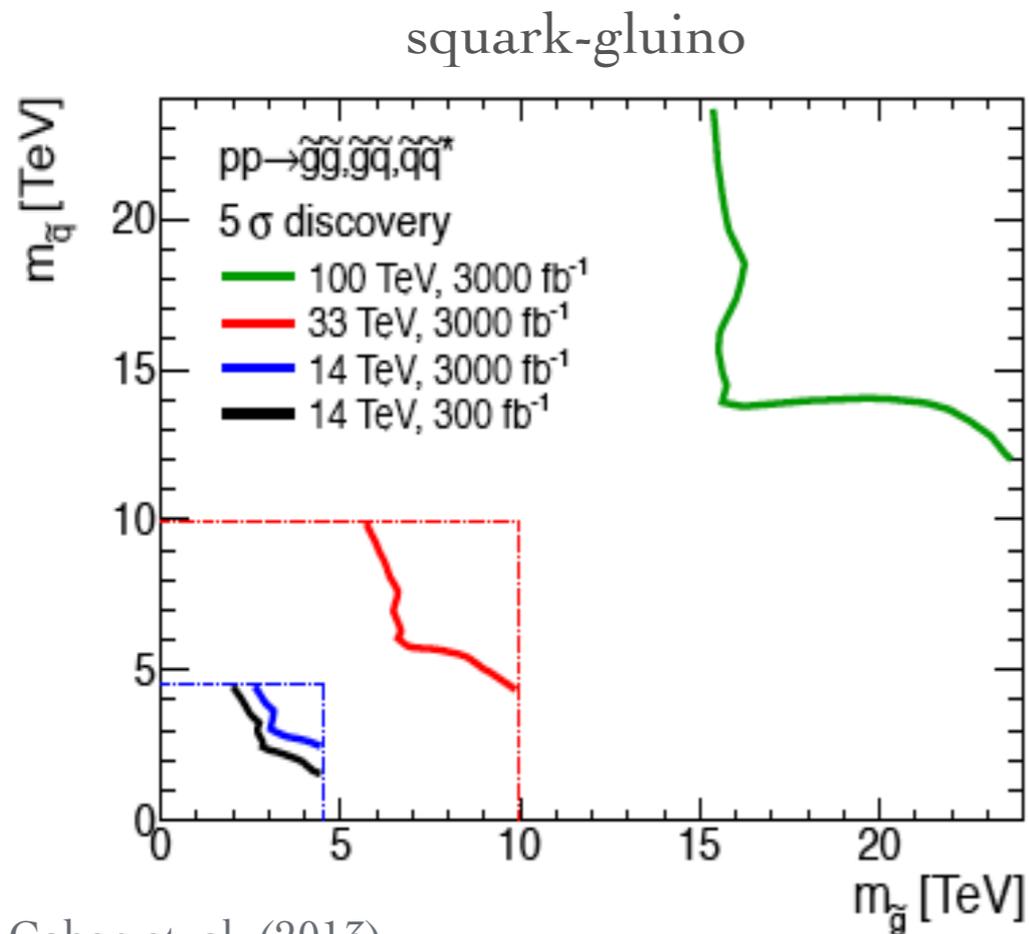
down-like Yukawas: $\delta(y) (H_u(y)^\dagger X^\dagger) \left(\frac{\tilde{y}_b}{M_5^{5/2}} Q_3 D_3^c + \dots \right).$

Amusing Possibility for 126 GeV Higgs



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

Discovery Reach of 100 TeV



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 126 GeV higgs at $\sim 3\%$ tune