Quivers in SARAH:

building a taylor made spectrum generator!

with

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DESY

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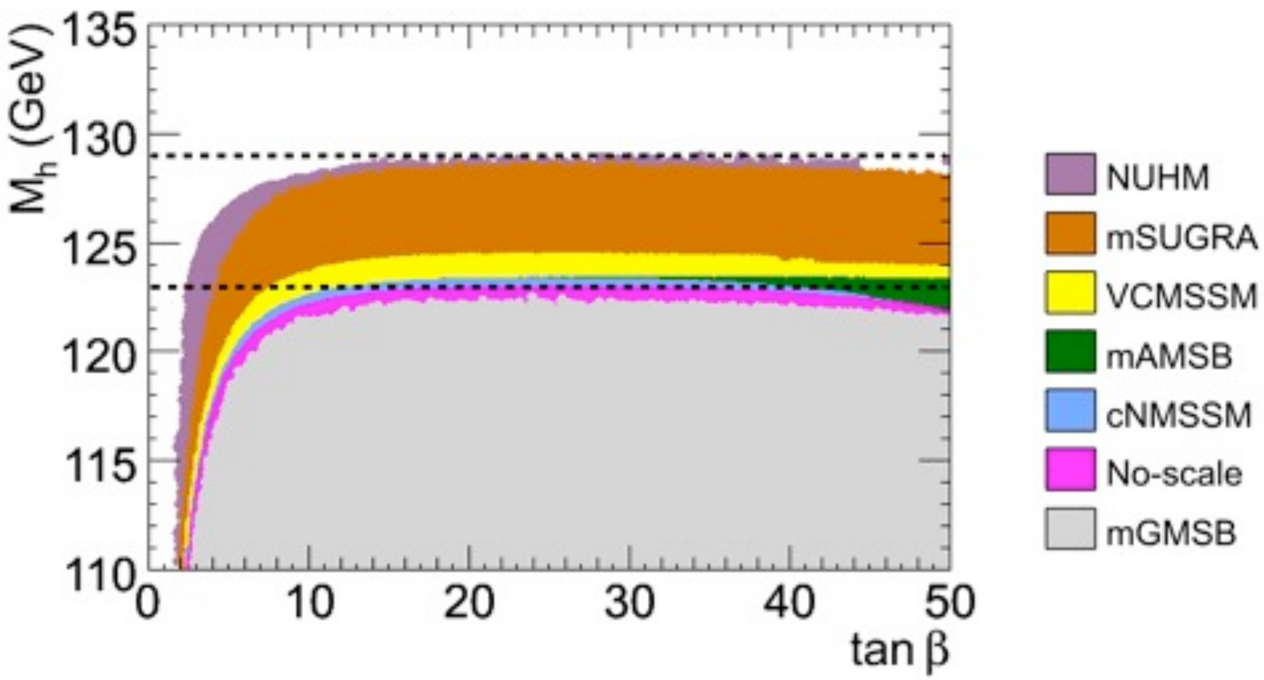
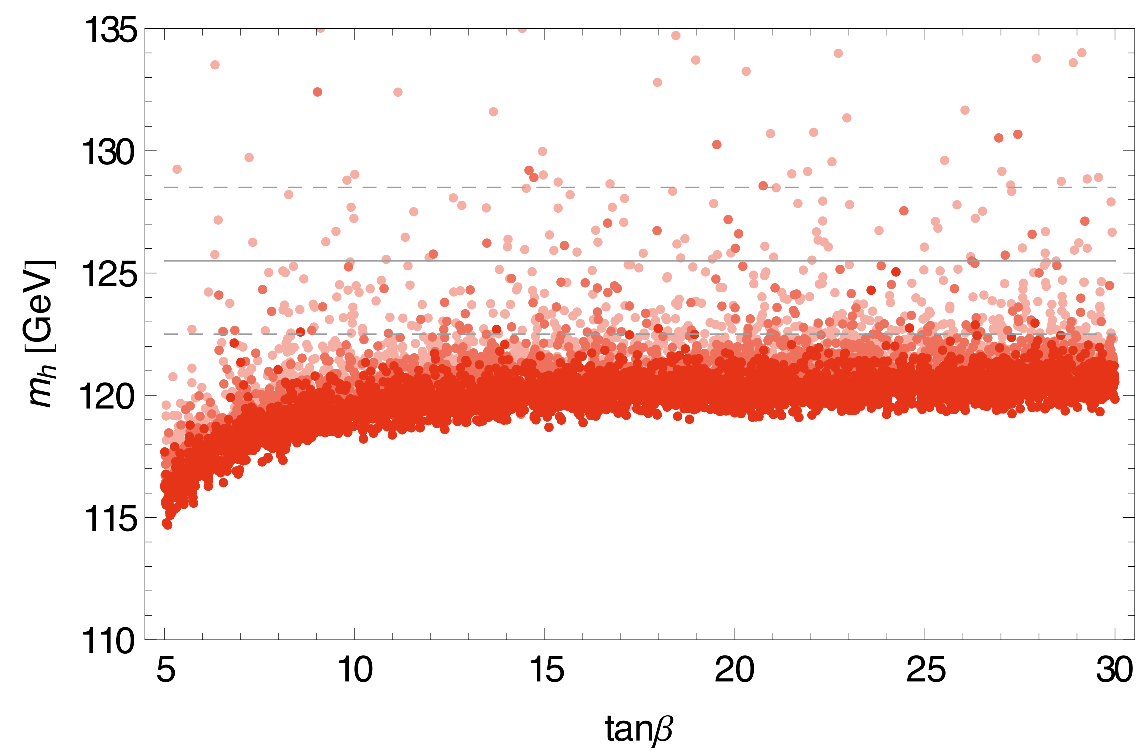
Our model vs benchmarks



1207.1348
Arbey, Battaglia, Djouadi, Mahmoudi

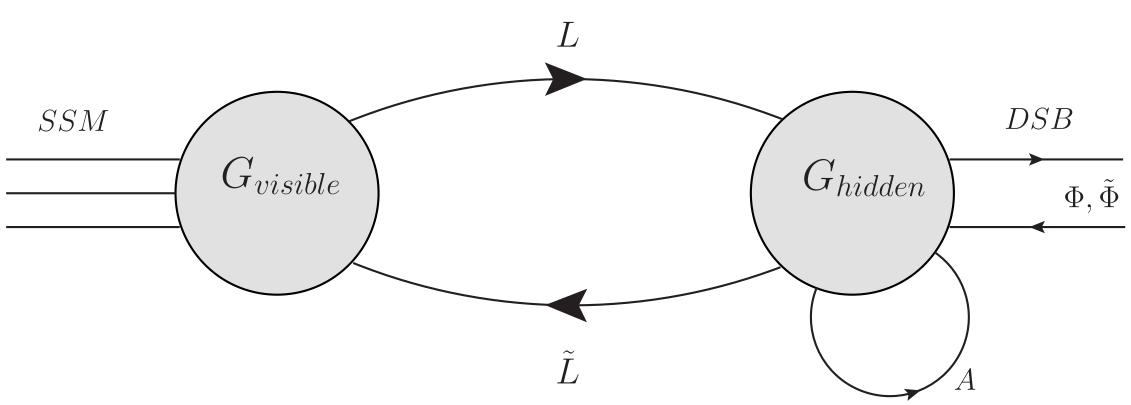


stops less than 2 TeV dark red
less than 2.3 TeV light red

A *meta* model

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)_A, \mathrm{SU}(2)_B, \mathrm{SU}(3)_c, U(1)_B, \mathrm{SU}(2)_A)$	R-Parity
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{1}, \mathbf{3}, 0, \mathbf{2})$	-1
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{1}, \mathbf{1}, 0, \mathbf{2})$	-1
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{1}, \mathbf{1}, 0, \mathbf{2})$	$+1$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{1}, \mathbf{1}, 0, \mathbf{2})$	$+1$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}}, 0, \mathbf{1})$	-1
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}}, 0, \mathbf{1})$	-1
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1}, 0, \mathbf{1})$	-1
$\hat{L}$	L	ψ_L	1	$(-\frac{1}{2}, \overline{\mathbf{2}}, \mathbf{1}, \frac{1}{2}, \mathbf{2})$	$+1$
$\hat{\tilde{L}}$	$\tilde{L}$	$\psi_{\tilde{L}}$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, -\frac{1}{2}, \overline{\mathbf{2}})$	$+1$
$\hat{K}$	K	ψ_K	1	$(0, \mathbf{1}, \mathbf{1}, 0, \mathbf{1})$	$+1$
$\hat{A}$	A	ψ_A	1	$(0, \mathbf{3}, \mathbf{1}, 0, \mathbf{1})$	$+1$

Table 2. Matter fields of the model.



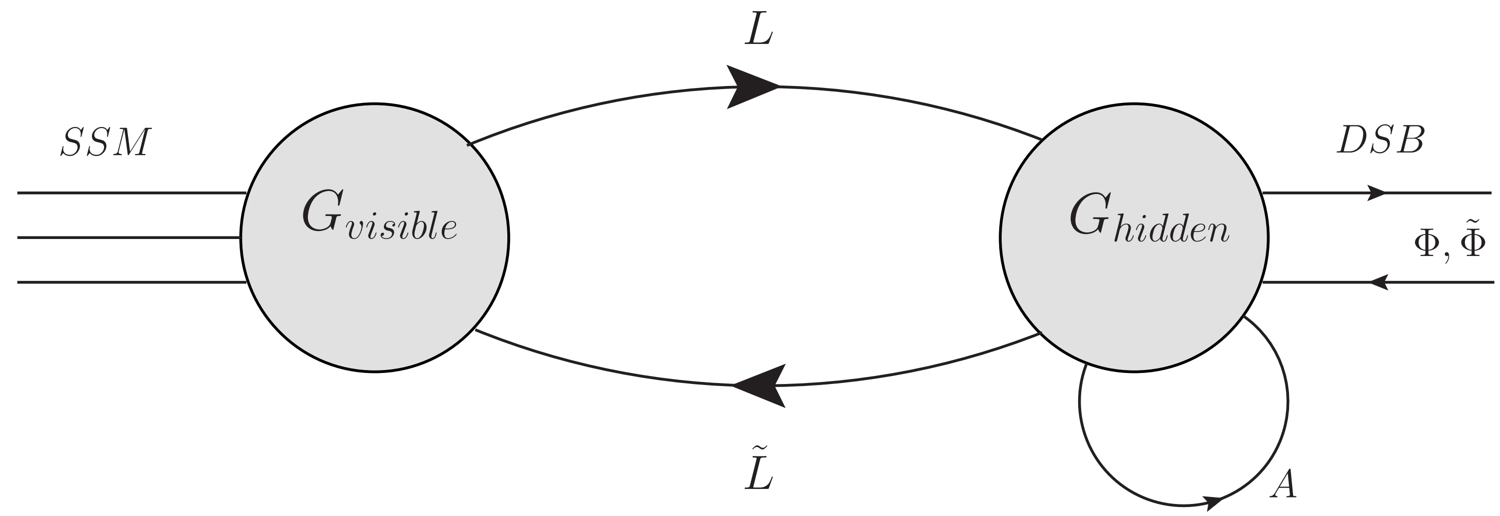
$$W_{\mathrm{SSM}} = Y_u\, \hat{u}\, \hat{q}\, \hat{H}_u - Y_d\, \hat{d}\, \hat{q}\, \hat{H}_d - Y_e\, \hat{e}\, \hat{l}\, \hat{H}_d + \mu\, \hat{H}_u\, \hat{H}_d$$

$$W_{\mathrm{Quiver}} = \frac{Y_K}{2} \hat{K}(\,\hat{L}\,\hat{\tilde{L}} - V^2) + Y_A\, \hat{L}\, \hat{A}\, \hat{\tilde{L}}$$

The most sophisticated model so far implemented into a spectrum generator (SARAH/SPHENO)
A *meta*-model i.e. *independent* of the type of supersymmetry breaking:
AMSB, mSUGRA, GMSB, phenomenological, other?

A quiver model: motivation

- non decoupled D-terms: lifts the Higgs (sometimes substantially) Batra, Delgado, Kaplan, Tait 0309149
- extra adjoints of SU(2),SU(3): lifts the Higgs
- More natural than NMSSM?
- embeds into SQCD
- Deconstructs an extra dimension



$$m_h^2 \simeq m_z^2 \cos 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v_{ew}^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2})\right]$$

$$\Delta = (\frac{g_A^2}{g_B^2})\frac{2m_L^2}{m_v^2 + 2m_L^2}$$

$$m_z^2 \to m_z^2 + \left(\frac{g_1^2\Delta_1 + g_2^2\Delta_2}{2}\right) v_{ew}^2$$

$$\delta\mathcal{L} = -g_1^2\Delta_1(H_u^\dagger H_u - H_d^\dagger H_d)^2 - g_2^2\Delta_2\sum_a (H_u^\dagger\sigma^a H_u + H_d^\dagger \sigma^a H_d)^2$$

Related works:

Csaki, Erlich, Grojean,Kribs 0106044

"GGM and Deconstruction"
M.M. 1009.0012 and 1101.5158

Auzzi, Amit Giveon, Gudnason, Shacham
1009.1714
1011.1664
+ ...

Under explored compared to NMSSM

Building a taylor made spectrum generator!

- We used SARAH mathematica package: "a spectrum generator *generator*" to write our own spectrum generator.
- We implemented 5 gauge groups with full 2-loop RGE's and one loop self energies (soon 6 and 9 gauge groups!).
- Higgsing, and breaking to the diagonal 4 gauge groups, including all mixing matrices and assignment of Goldstones, Ghosts, RGEs of *vevs*, and Bmu at 2 loop.
- All 3 and 4 vertices of all fields computed, and self energies.
- All anomalous dimensions, tadpoles and running of all *additional soft terms and Yukawas, at 2 loop level.*
- finite shifts and threshold corrections also accounted for.

Quiver @
M messenger

$\downarrow$

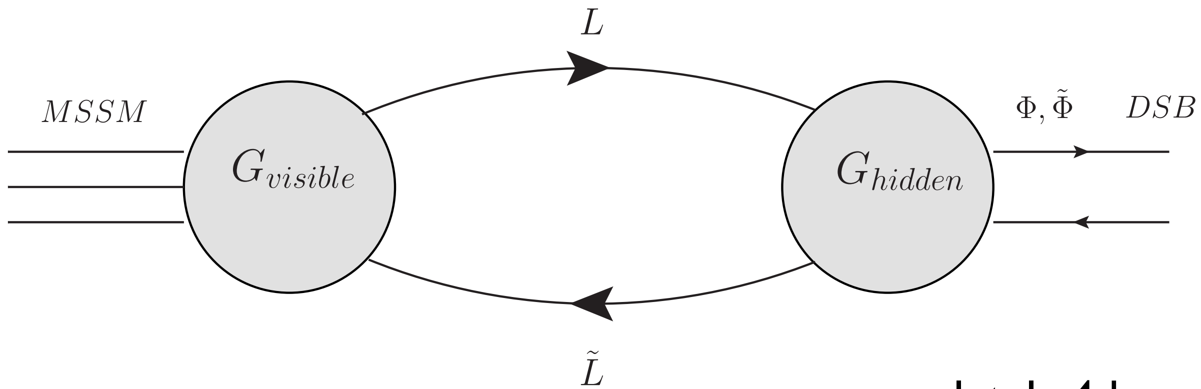
Threshold
scale:
MSSM

$\downarrow$

LHC

If we assume GMSB

Simplest case
corresponds to a 2 site quiver model



completely 4d

Form factor

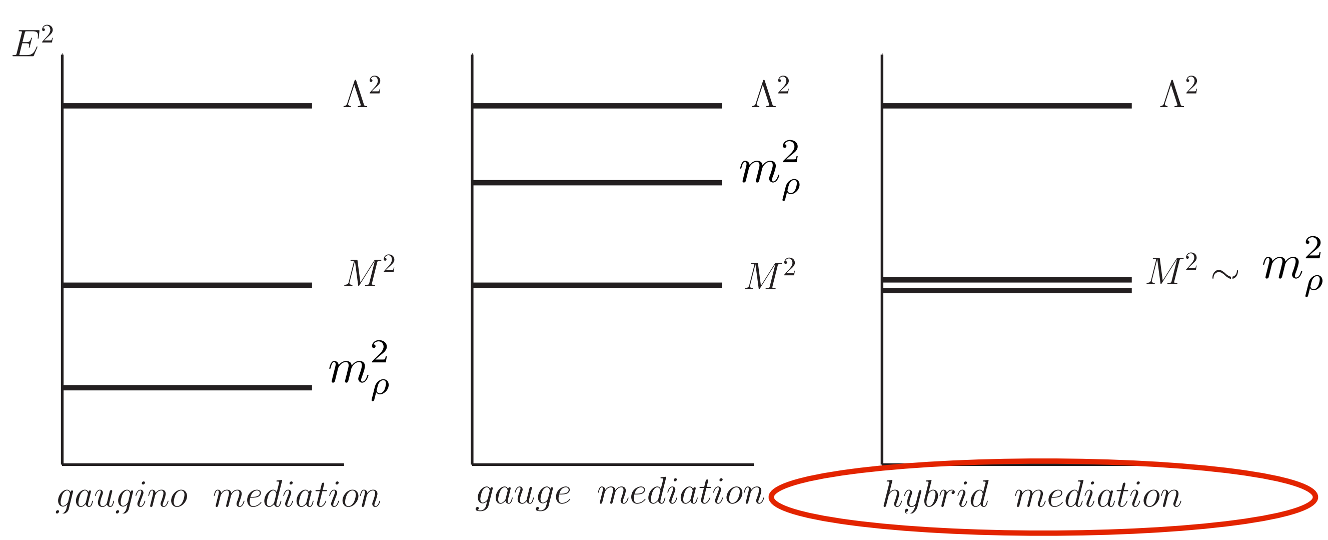
$$F(s) = \frac{m_\rho^2}{s + m_\rho^2}$$

A hidden local symmetry,
exhibits vector meson dominance

embeds into magnetic SQCD

Deconstructs an extra dimension

3 Regimes depends on ratio $y = \frac{m_\rho}{M}$



We have a new hybrid regime where

$$@M_{SUSY} : m_\lambda^2 > m_{\tilde{f}}^2$$

soft masses are analytically calculable at 2 loops!
and cross sections are now known.

soft terms:
we chose GMSB
(but we can change it)

- everything completely calculable

$$\Lambda = \frac{F}{M}$$

$$N = n_{5plets} + 3n_{10plets}$$

$$x = \frac{F}{M^2}$$

$$y = \frac{m_v}{M}$$

$$m_{\lambda,r} = N\Lambda\left(\frac{g_r^2}{16\pi^2}\right)g(x)$$

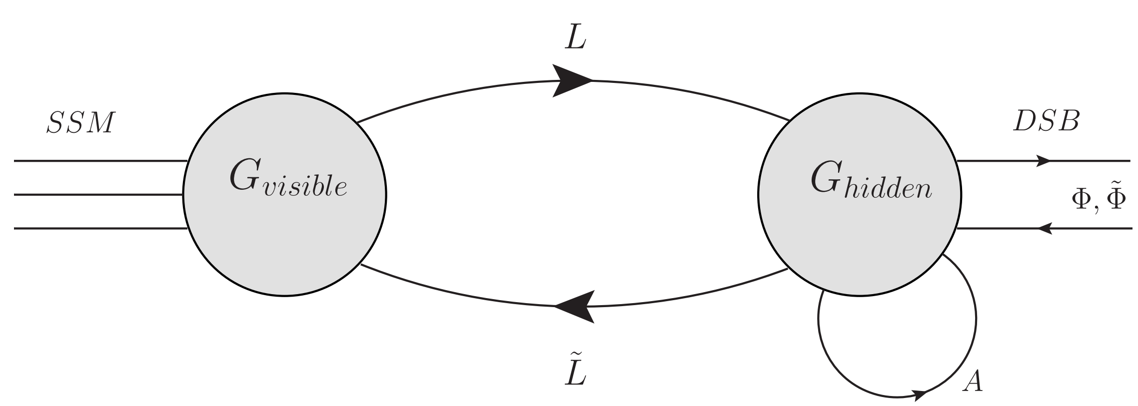
$$\mathcal{L}_{soft} \supset \frac{1}{2}\left(m_{\tilde{G}}\tilde{G}\tilde{G} + m_{B_B}\tilde{B}_B\tilde{B}_B + m_{W_B}\tilde{W}_B\tilde{W}_B\right) + h.c.$$

$$m_\lambda^{A=1,2} \equiv 0.$$

$$m_L^2 = m_{\tilde{L}}^2 = N\Lambda^2\sum_{i=1,2} 2C_L^{B,i}\left(\frac{g_{Bi}^2}{16\pi^2}\right)^2 f(x),$$

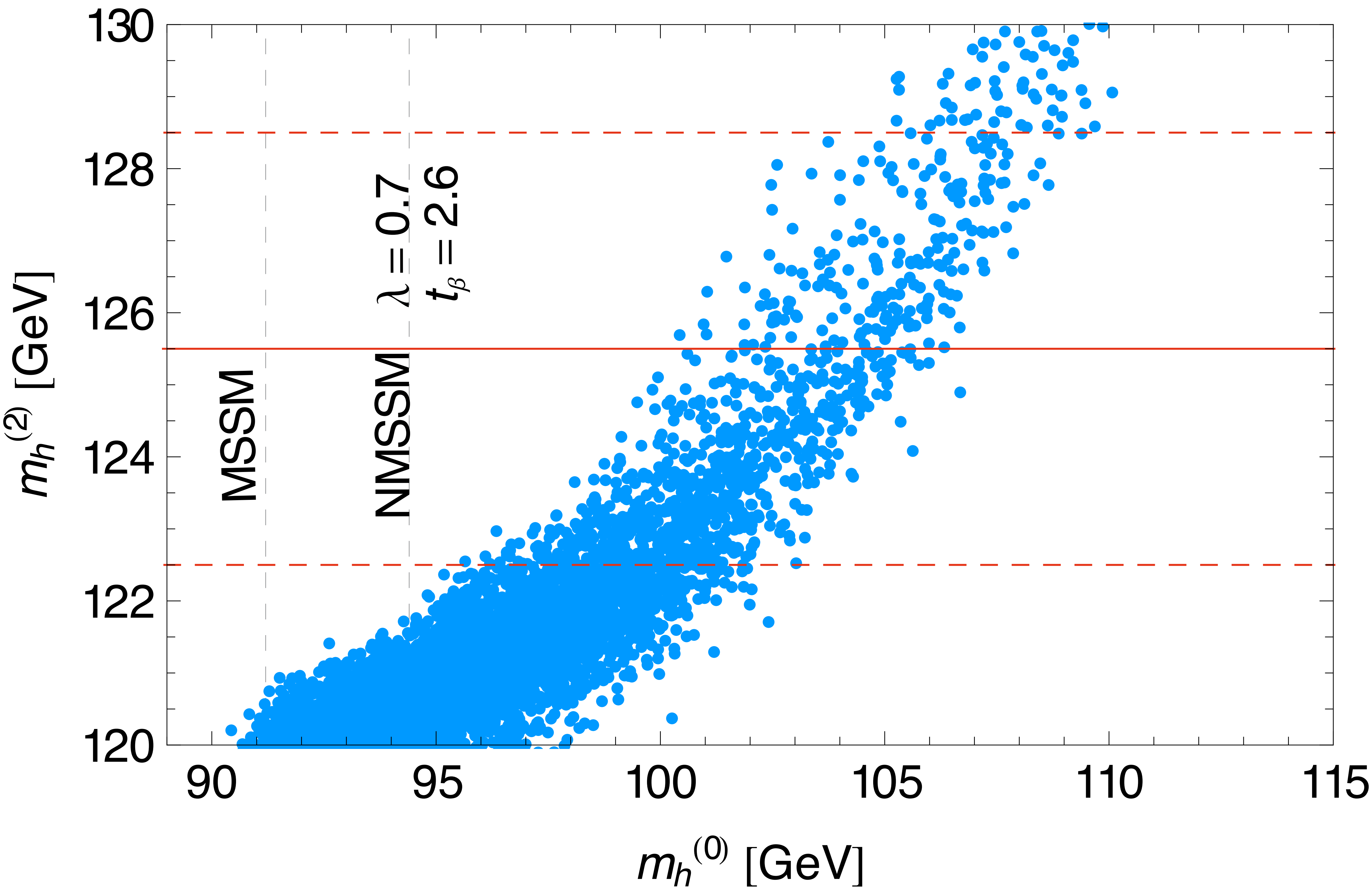
$$m_{SM}^2 = N\Lambda^2\sum_{i=1,2} 2C_{SM}^{B,i}\left(\frac{g_i^2}{16\pi^2}\right)^2 S(x,y_i),$$

A-terms are vanishing at the messenger scale

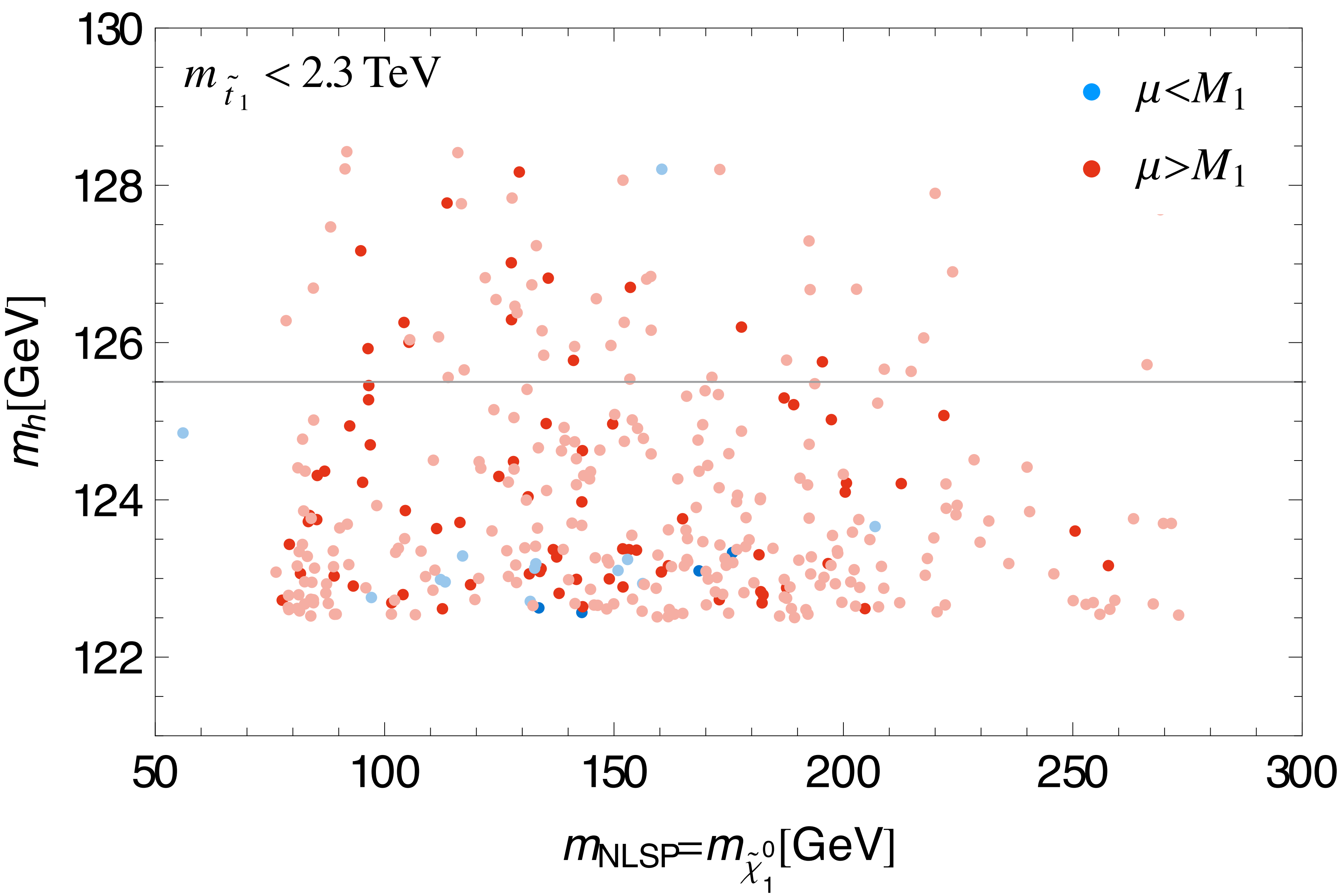


Benchmarks

Inputs	1	2
M	2.52×10^5 GeV	2.32×10^5 GeV
$\Lambda_{1,2}$	1.46×10^5 GeV	1.22×10^5 GeV
Λ_3	1.75×10^5 GeV	2.1×10^5 GeV
m_L^2	8.0×10^7 GeV^2	6.0×10^7 GeV^2
$\tan\beta$	25	25
$n_{5\text{plets}}$	1	1
$v = T_{Scale}$	2.68×10^4 GeV	2.68×10^4 GeV
θ_1, θ_2	1.21, 1.16	1.3,1.15
Δ_1, Δ_2	0.324, 0.157	0.276,0.119
Y_K, Y_A	0.8, 0.8	0.8,0.8
Colour sector		
$m_{\tilde{t}_1}$	1803 GeV	2018 GeV
$\tilde{G}$	1462 GeV	1881 GeV
$T_u(3,3)$	-352 GeV	-442 GeV
Electroweakini		
$\tilde{\chi}_1^0$	209 GeV	174 GeV
$\tilde{\chi}_1^\pm$	425 GeV	339 GeV
Higgses		
m_{h_0}	126.3 GeV	125.4 GeV
m_{H_0}	650 GeV	587 GeV
m_{A_0}	652 GeV	588 GeV
$m_{H_\pm}$	658 GeV	595 GeV
μ	630 GeV	439 GeV
$B\mu$	2.50×10^4	2.25×10^4
Quiver states		
$m_{B'}$	52 TeV	37 TeV
$m_{W'_\pm}$	38 TeV	93 TeV
$m_{\Psi_{K/A_3}}$	24 TeV	24 TeV



130
128
126
124
122
120
90
95
100
105
110
115
$m_h^{(2)}$ [GeV]
$m_h^{(0)}$ [GeV]
MSSM
NMSSM
$\lambda = 0.7$
$t_\beta = 2.6$



Within reach of LHC14

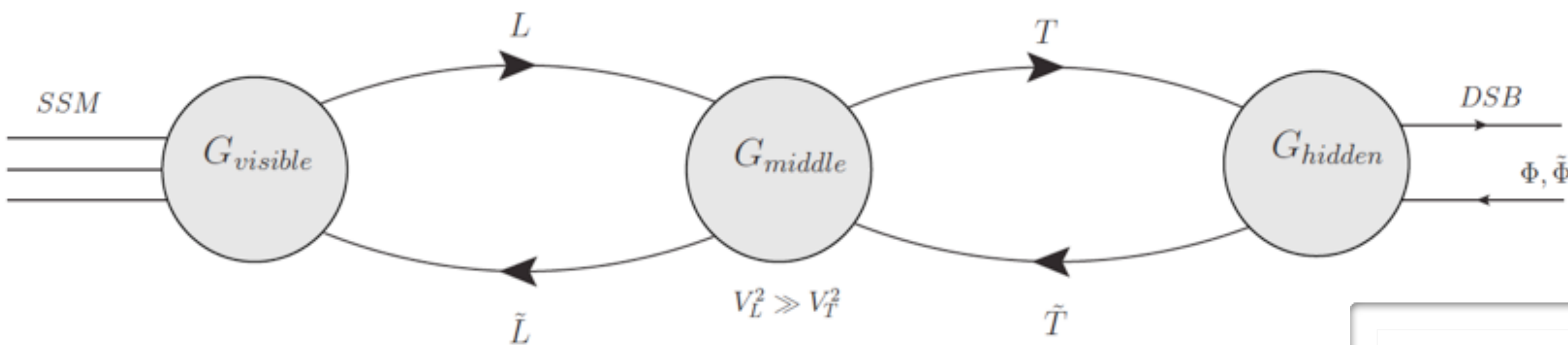
“Deconstructed Holography for Gauge Mediation”

A holographic quiver

M.M. Rodolfo Russo 1004.3305
M.M. Daniel C.Thompson 1009.4696
M.M. 1210.4935

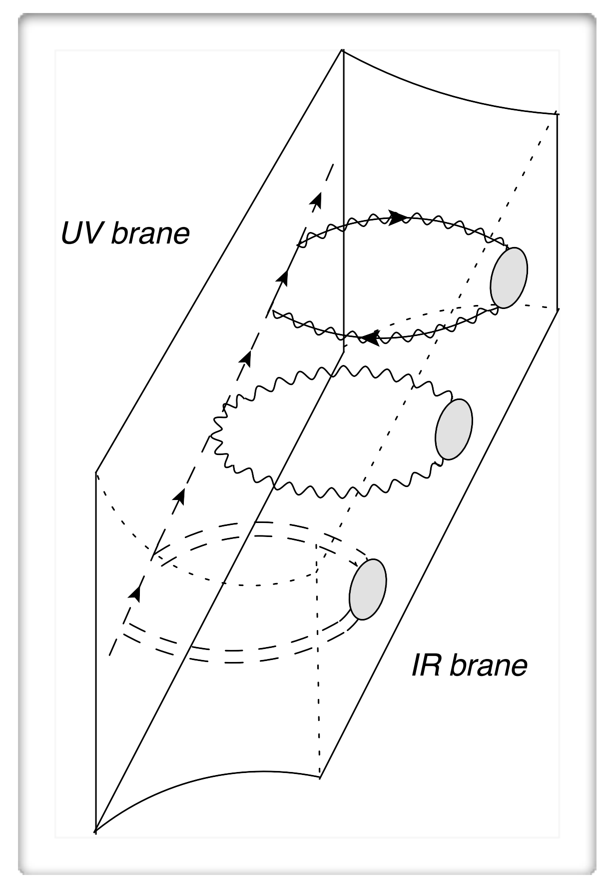
currently putting this into SARAH
(9 gauge groups, full 2 loop RGE’s)
Aoife Bharucha & Andreas Goudelis

- non decoupled D-terms
- extra adjoints of SU(2),SU(3)
- Interesting RGE’s



4D: operator		Field	Δ	m^2
$\mathcal{O}_{L,R} = \phi^\dagger \phi_{L,R}$	$\rightarrow$	$D(z,x)_{L,R}$	2	-4
$\mathcal{O}^\alpha(x)_{L,R} = -i\sqrt{2}\phi^\dagger q^\alpha_{L,R}$	$\rightarrow$	$\lambda^\alpha(z,x)_{L,R}$	5/2	1/2
$\mathcal{O}^\mu(x)_{L,R} = \bar{q}\sigma^\mu q_{L,R} - i\left(\phi^\dagger\partial^\mu\phi - \partial^\mu\phi^\dagger\phi\right)_{L,R}$	$\rightarrow$	$A^\mu(z,x)_{L,R}$	3	0

Table 1: *Operators corresponding to the bulk fields of the model.*



What next?

Single regime model

SU(3) quiver

Dirac Gauginos

Kinetic mixing

3 site quiver

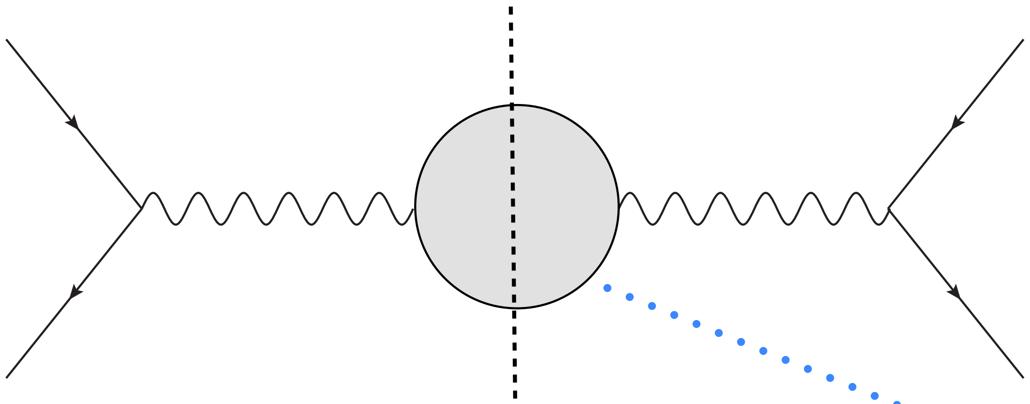
GUTS

Back up slides

Can we develop intuition with QCD?

Can QCD tell us something about the “blobs” and therefore something about the soft masses?

QCD



$$i\mathcal{M}(e^+, e^- \to e^+, e^-)$$

gives $\sigma(e^+, e^- \to hadrons)$

quark current $\mathcal{O}^\mu = \bar{q}\gamma^\mu q$

perturbative in α_{em}

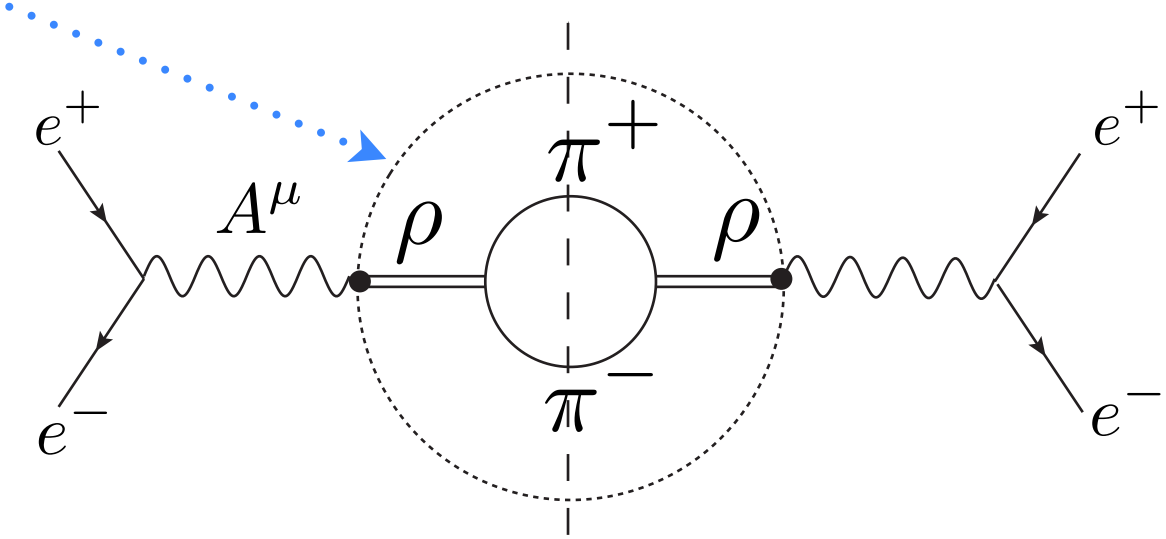
all orders in α_s

Hadronic picture

“look under the hood”

Sum of many parts

one such piece: $\sigma(e^+ e^- \to \pi^+, \pi^-)$



$$F(s) = \frac{m_\rho^2}{s + m_\rho^2}$$

perturbative in α_{em}

perturbative in α_{mag}

Summary

The key idea is to build models around scattering

ALL old GMSB models are of this type

RED

$$\sigma_a(visible \to hidden) = \frac{(4\pi\alpha)^2}{2s}\ Disc\ \tilde{C}_a(s)$$

OR

$$F(s) = \frac{m_\rho^2}{s + m_\rho^2}$$

form factor or no form factor?

BLACK?

$$\sigma_a(visible \to hidden) = \frac{(4\pi\alpha)^2}{2s}|F(s)|^2\ Disc\ \tilde{C}_a(s)$$

Similar to the hadronic world: perhaps we should take it more seriously?

$$\text{Duality in } e^+, e^- \to \text{hidden?}$$

Ideally, determine this form factor from experiment	impossible
or from computer simulations	hard
or from toy models and effective field theory	possible

String theorists know how to compute scattering amplitudes!

“Holography for General Gauge Mediation”

M.M.: 1210.4935

also $AdS/\cancel{SUSY}$
“Warped General Gauge Mediation”
M.M. Daniel C. Thompson 1009.4696

Abel & Gherghetta 1010.5655

“General Gauge Mediation in 5D”
M.M. Rodolfo Russo 1004.3305

IR hardwall/
slice of AdS

<u>Check list</u>

1. Metric: slice of AdS $\quad ds^2 = \left(\frac{R}{z}\right)^2 (\eta^{\mu\nu} dx_\mu dx_\nu + dz^2)$
2. Interval $\quad L_0 < z < L_1$
3. Flavour symmetries $\quad SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V$
4. Scale matching $\quad \frac{R}{g^2_{5d(YM)}} = \frac{N_c}{12\pi^2}$
5. Sources $\quad A^0_\mu(x), \lambda^0_\alpha(x), D^0(x)$
6. Operators $\quad \mathcal{O}_\mu(x), \mathcal{O}_\alpha(x), \mathcal{O}(x)$
7. Bulk field $\quad A^\mu(q,z) = A^\mu_0(q) K(q,z)$
8. Bulk to boundary propagator $\quad K(q,z) = \frac{V(q,z)}{V(q,L_0)}$

N=1 5d super Yang-Mills
action in the bulk

$$V(q,z) = zq\left[Y_0(qL_1)J_1(qz) - J_0(qL_1)Y_1(qz)\right]$$

compute...

“Holography for General Gauge Mediation”

IR hardwall/
slice of AdS

N=1 5d super Yang-Mills action in the bulk

$$SU(N_f)_L \times SUN(N_f)_R$$

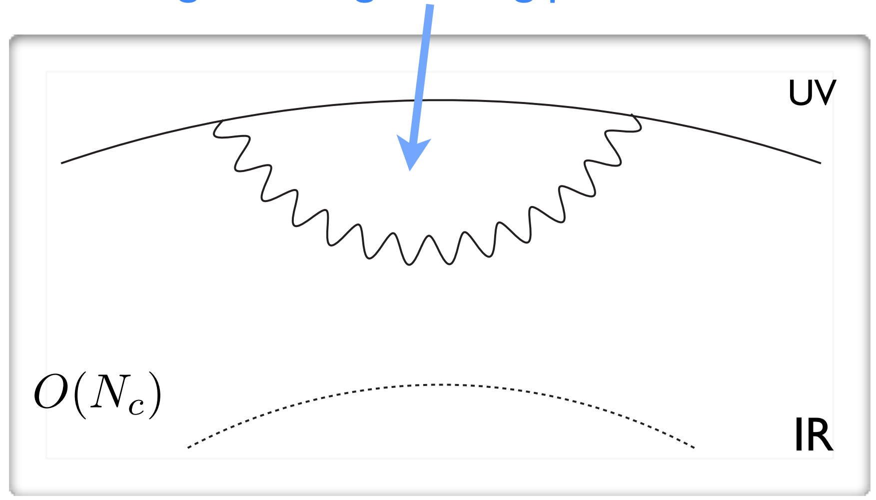
$$ds^2 = \left(\frac{R}{z}\right)^2 (\eta^{\mu\nu} dx_\mu dx_\nu + dz^2) \qquad L_0 < z < L_1 \qquad \frac{R}{g^2_{5d(YM)}} = \frac{N_c}{12\pi^2}$$

$$A^\mu(q,z) = A^\mu_0(q) \frac{V(q,z)}{V(q,L_0)}$$

$$\int d^4x e^{ip.x} \langle \mathcal{O}_\mu(x) \mathcal{O}_\nu(0) \rangle = \Pi(p^2) P^{\mu\nu}$$

$$\Pi(q^2) = \frac{1}{q} \left(\frac{R}{z} \frac{\partial_z V(q,z)}{V(q,L_0)} \right)_{z=L_0}$$

gives a log running piece



An AdS/SQCD proposal

4D: operator		Field	Δ	m^2
$\mathcal{O}(x)$	$\rightarrow$	$D(z,x)$	2	-4
$\mathcal{O}_\alpha(x)$	$\rightarrow$	$\lambda_\alpha(z,x)$	5/2	1/2
$\mathcal{O}_\mu(x)$	$\rightarrow$	$A_\mu(z,x)$	3	0

The UV operators that correspond to bulk fields

$$\mathcal{O}_{L,R} = \phi^\dagger \phi_{L,R}$$

$$\mathcal{O}^\alpha_{L,R} = -i\sqrt{2}\phi^\dagger q^\alpha_{L,R}$$

$$\mathcal{O}^\mu_{L,R} = \bar{q}\sigma^\mu q_{L,R} - i\left(\phi^\dagger \partial^\mu \phi - \partial^\mu \phi^\dagger \phi\right)_{L,R}$$

UV boundary correlators give a supersymmetric effective action

$$\left[3\Pi_1(q^2) - 4\Pi_{1/2}(q^2) + \Pi_0(q^2)\right] \equiv 0 \qquad \langle \mathcal{O}_\alpha(x) \mathcal{O}_\beta(0) \rangle \equiv 0$$

Related to the Gibbons-Hawking boundary terms of SYM

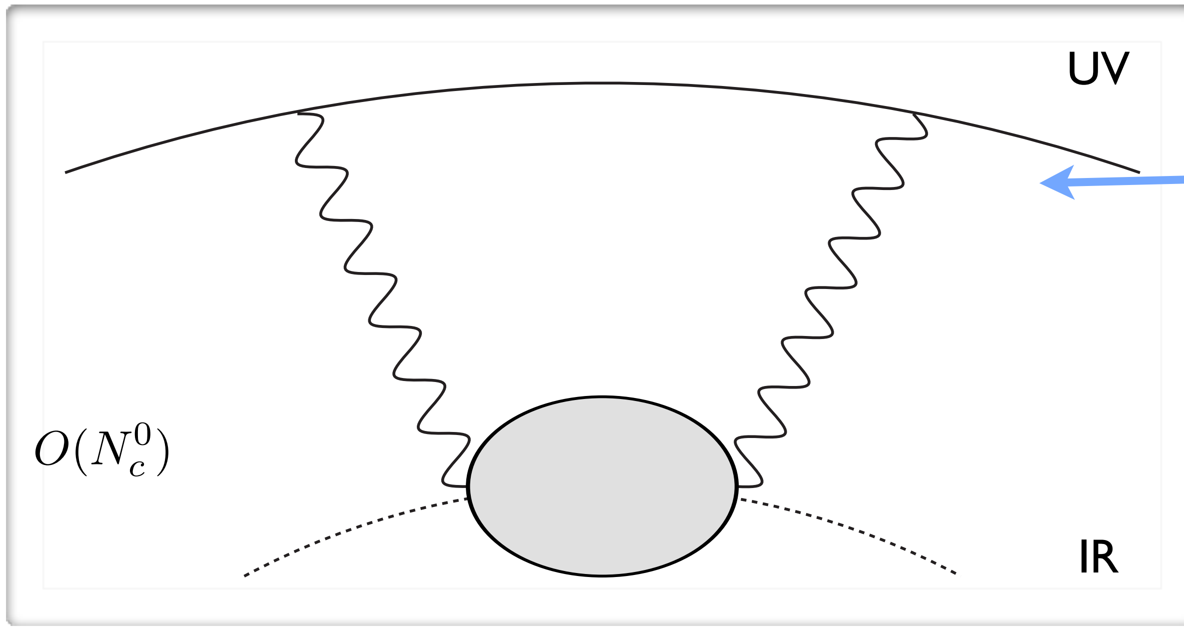
Introduce IR localised correlators that encode supersymmetry breaking

SUSY breaking currents located on an IR brane or live in the bulk

$$A_\mu J^\mu = \int dz K(p,z) A^0_\mu J^\mu = A^0_\mu J^\mu \Lambda(p)$$

An effective vertex function generated by a bulk to boundary propagator

Ignore $O(1/N_c)$ corrections



$A^0_\mu \Lambda(p) \tilde{C}(p^2/M^2) P^{\mu\nu} \Lambda(p)\ A^0_\nu$

$$\delta L^{\cancel{SUSY}}_{eff}|_{UV} = \frac{g^2_{SM}}{2}\tilde{C}_0(0) D_0^2 - i g^2_{SM} \tilde{C}_{1/2}(0)\lambda_0 \sigma_\mu \partial^\mu \bar{\lambda}_0 - \frac{g^2_{SM}}{4}\tilde{C}_1(0) F_{\mu\nu,0}F_0^{\mu\nu}$$

may be written as a boundary effective action too

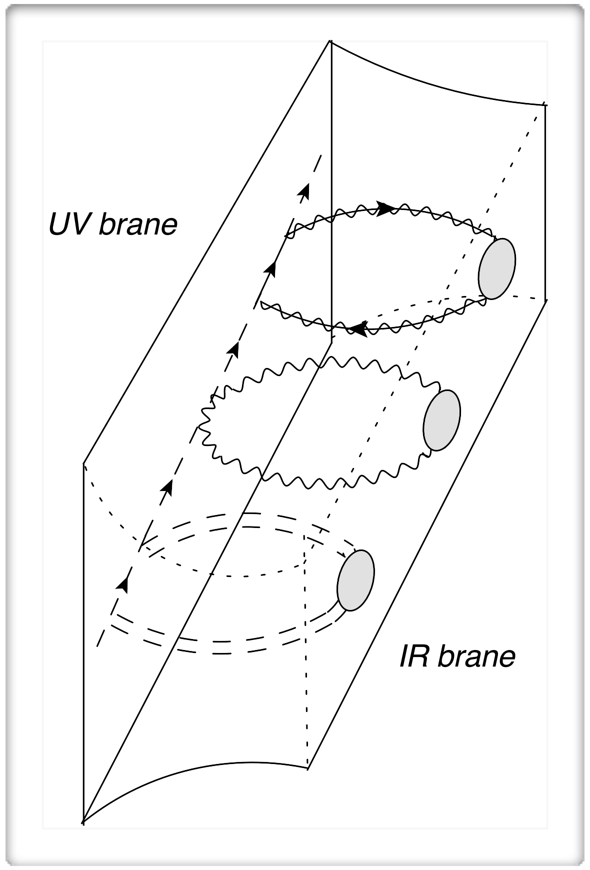
<u>If</u> you also assume a messenger sector then*

* this part is not necessary. It is a further additional assumption

$$m_\lambda = \left(\frac{\alpha_{IR}}{4\pi}\right)\left(\frac{R}{z}\right)\left[\frac{2Fg(x)}{M}\right]$$

soft masses are calculable!

$$m^2_\phi = \left(\frac{\alpha_{IR}}{4\pi}\right)^2 \left(\frac{R}{z}\right)^2 \left[\frac{F}{M}\right]^2 \left|\frac{1}{\hat{M}}\right|^2 \int dp\ p\ \Lambda^2(p)$$

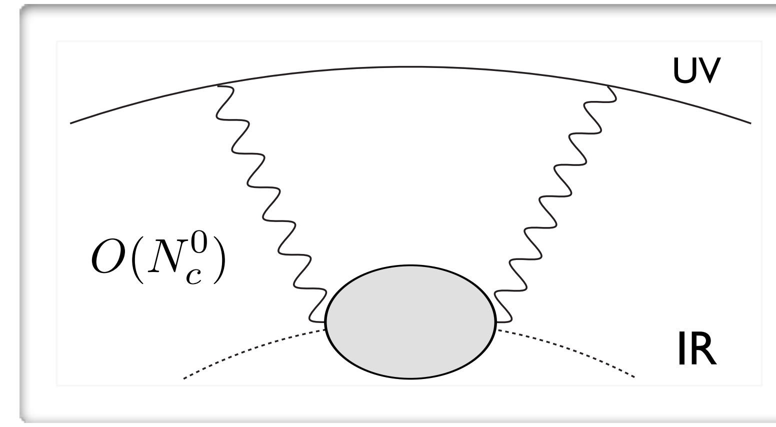


$$F_n \epsilon_\mu = \langle 0 | \mathcal{O}_\mu | \rho_n \rangle$$

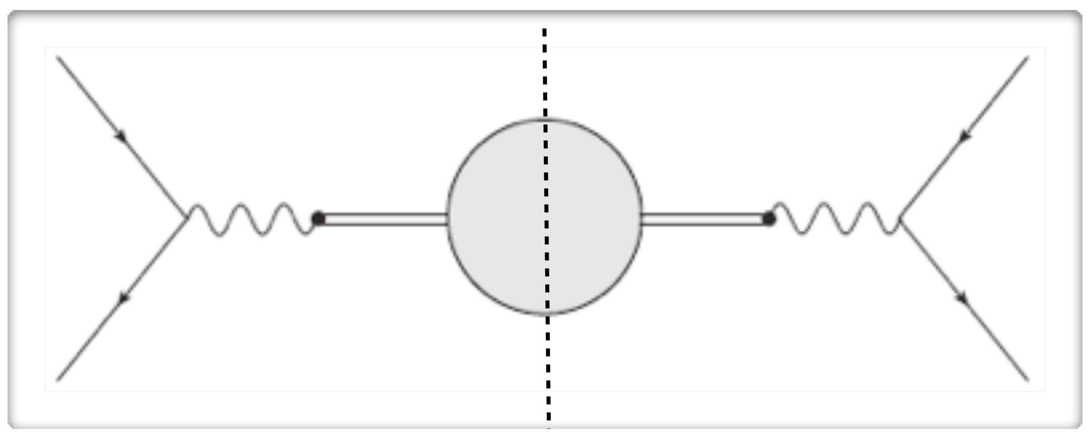
meson decay constant

Holographic Scattering

$$g_n = g_5 g_{IR} \int dz \psi_n(z) \varphi(z) \tilde{\varphi}(z) \delta(z - L_1)$$



The form factor encodes a sum of monopole contributions
of an infinite tower of vector mesons with decay constants for each meson



Final states can be taken to be messenger fields

$$\sigma_a(vis \to hid) = \frac{(4\pi\alpha_{SM})^2}{2s} (g_{IR}^2 g_5^2) \sum_{n=1} \frac{F_n \psi_n(z)}{s + m_n^2} \sum_{\hat{n}=1} \frac{F_{\hat{n}} \psi_{\hat{n}}(z)}{s + m_{\hat{n}}^2} \mathrm{Disc}\ \tilde{C}_a(s/\hat{M})$$

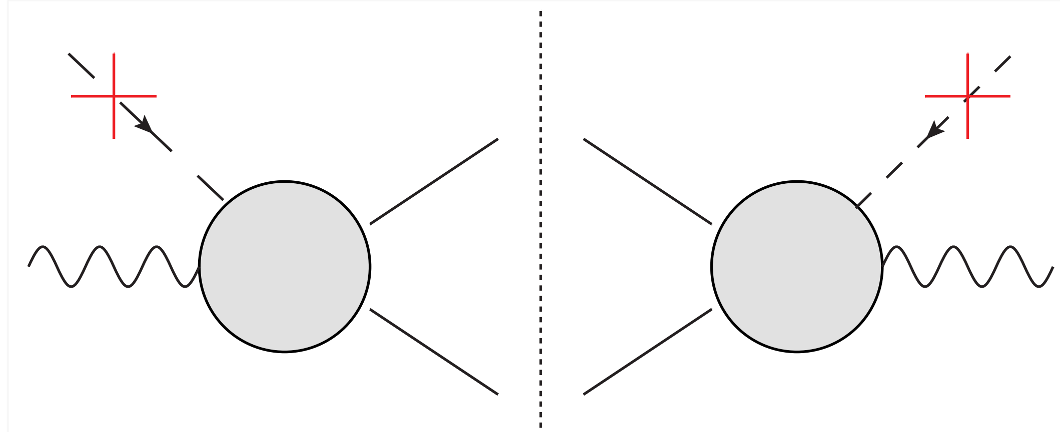
$$\boxed{\text{Duality in } e^+, e^- \to \text{hidden?}}$$

Speculative

D.Vecchia and Drago (1969)
Chua, Hama & Kiang (1970)
Frampton (1970)
Many others...

A Veneziano-like amplitude for GGM?

$$F(s) \sim \frac{\Gamma(1-\alpha(s)\Gamma(\lambda-\frac{1}{2})}{\Gamma(\lambda-\alpha(s))\Gamma(\frac{1}{2})}$$



$$\equiv \tilde{C}_a(S)$$

$A(1 \to 2)$

A fit to the pion data

$$\lambda \sim 2$$

$$\lim_{s\to\infty} F(s) \simeq 1/s^{\lambda-1}$$

$$\alpha(s) = 1/2 + s/2m_\rho^2$$

Infinitely rising linear Regge trajectories

Forward scattering amplitude

Higher spin states contribute too!

The point is that holographic models are toy models with a separation of scales between the spin 0,1/2,3/2,2 and the higher spin states.