Auxiliary Gauge Mediation: A New Route to Mini-Split Supersymmetry

Yoni Kahn, MIT

with Jesse Thaler and Matthew McCullough

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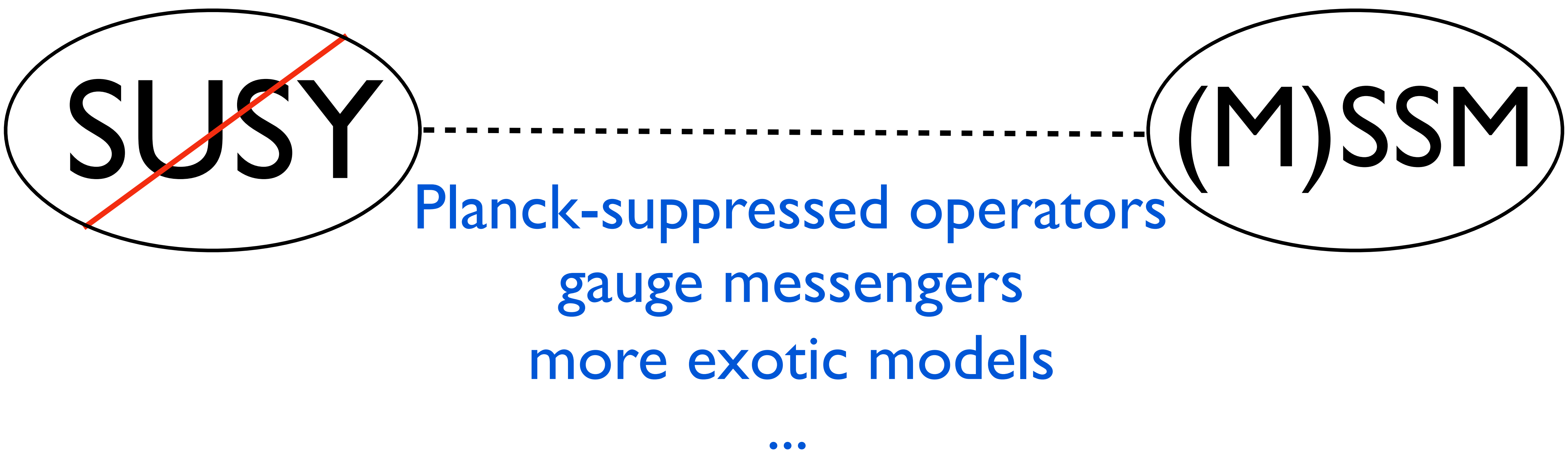
The hidden sector paradigm

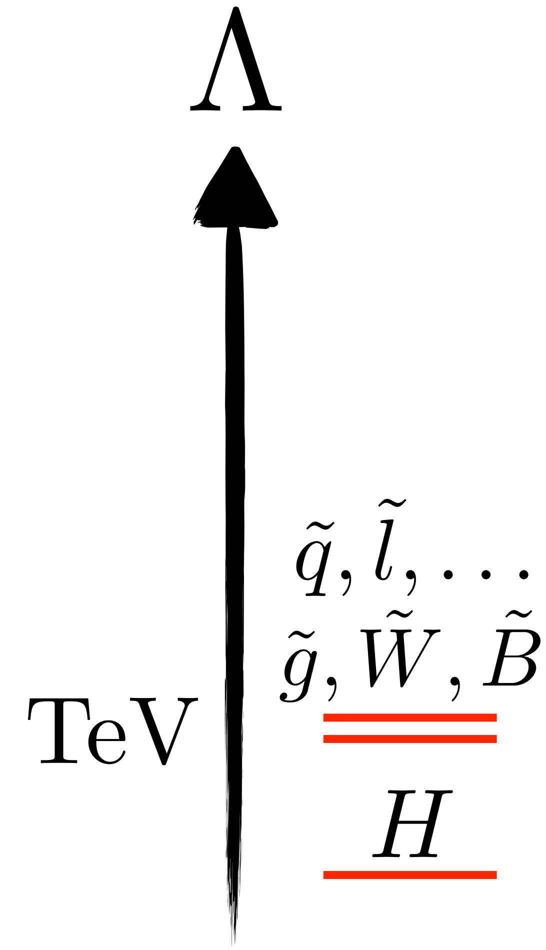
Necessitated by supertrace sum rule



Gauge mediation: successes

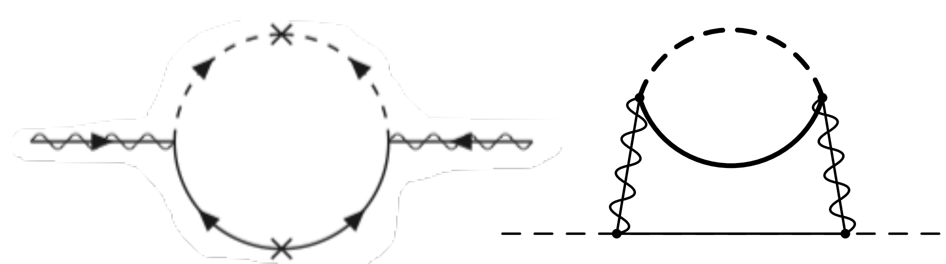
[Dine, Nelson, Shirman, 1995; hep-ph/9408384 and others]

[Giudice, Rattazzi, 1998; hep-ph/9706540]



$$\tilde{m}_{sc} \sim \tilde{m}_{\tilde{\lambda}} \sim \frac{\alpha}{4\pi}\Lambda$$

Flavor-blind



$$\mathbf{W} \supset \mathbf{X}\mathbf{\Phi}\mathbf{\Phi}^c, \ \langle \mathbf{X} \rangle = M + \theta^2 F$$

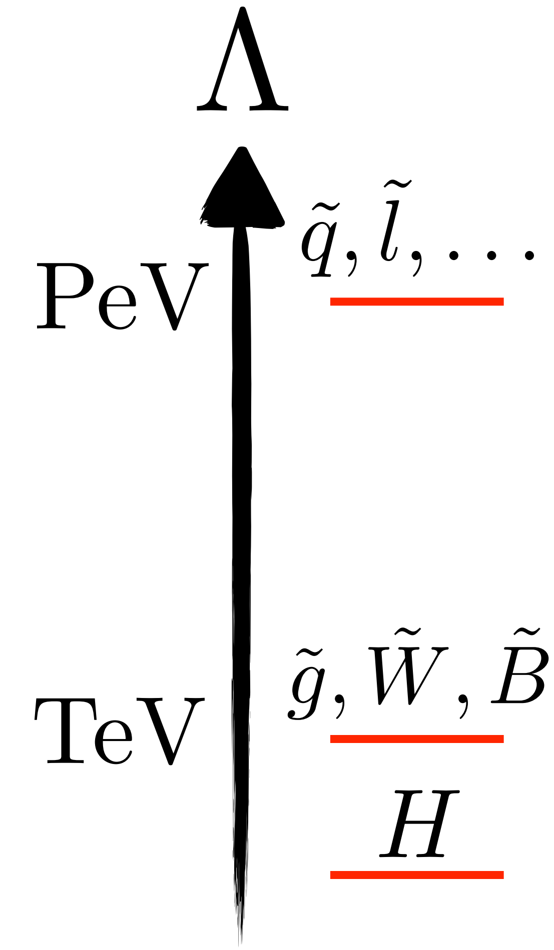
calculable!

The LHC rains on our parade

$m_H = 126 \text{ GeV}$
No superpartners yet } Heavy scalars (but not too heavy!)

however...

Gauge coupling unification (WIMP miracle) } Weak- or TeV-scale gauginos?

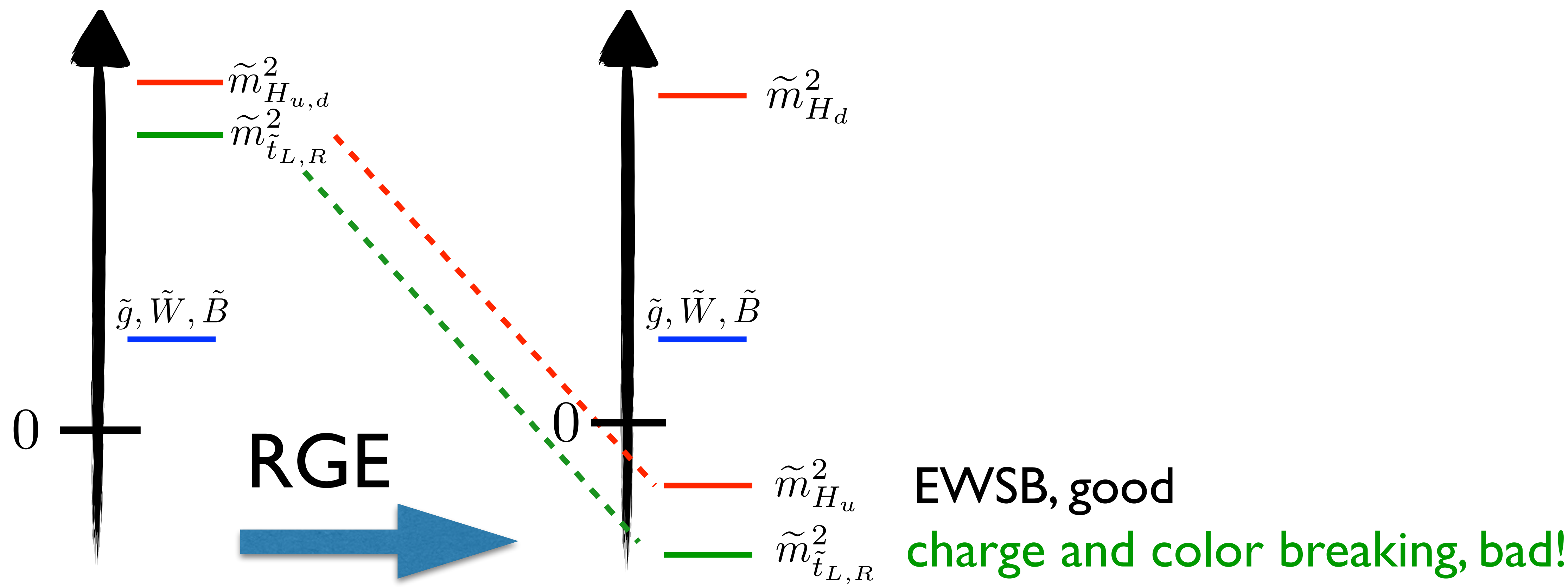


“Mini-split” or “simply unnatural” supersymmetry
[Arvanitaki et al, 2013; 1210.0555], [Arkani-Hamed et al, 2013; 1212.6971]

But what is the UV completion?
Not trivial!

Challenges of mini-split

RG stability: need $\tilde{m}^2_{H_u}(M) \lesssim \frac{3}{2}\tilde{m}^2_t(M)$



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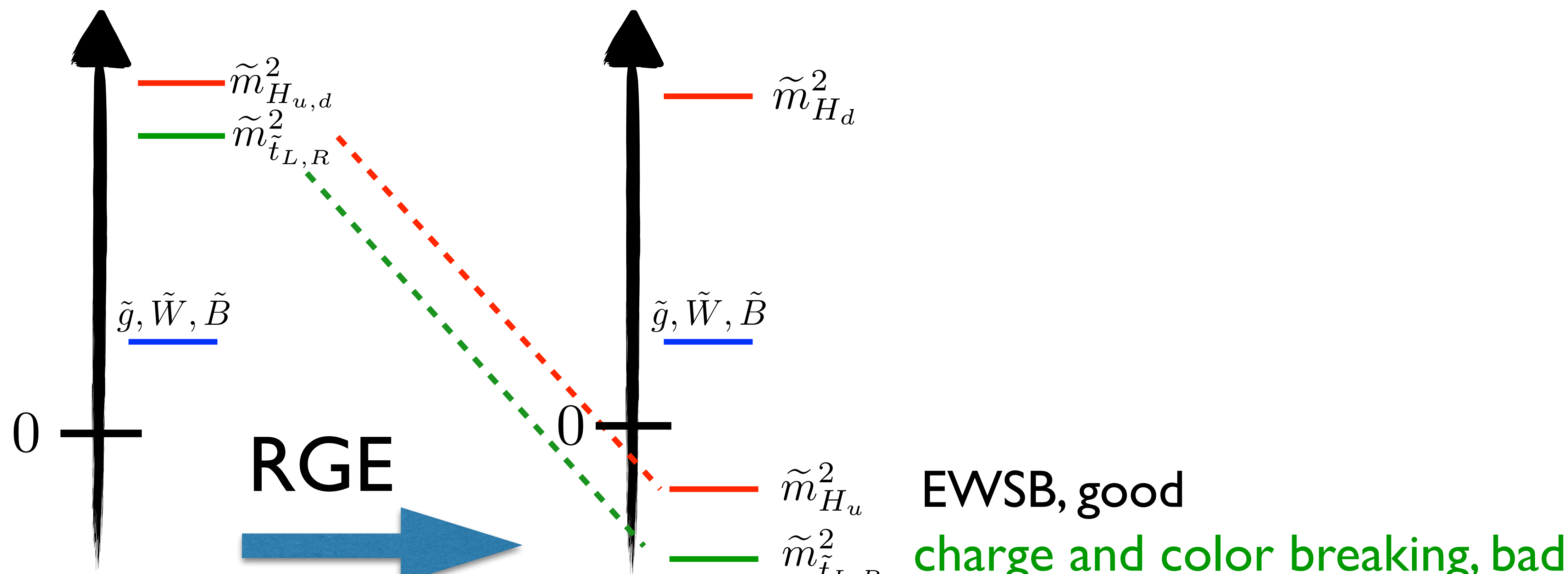
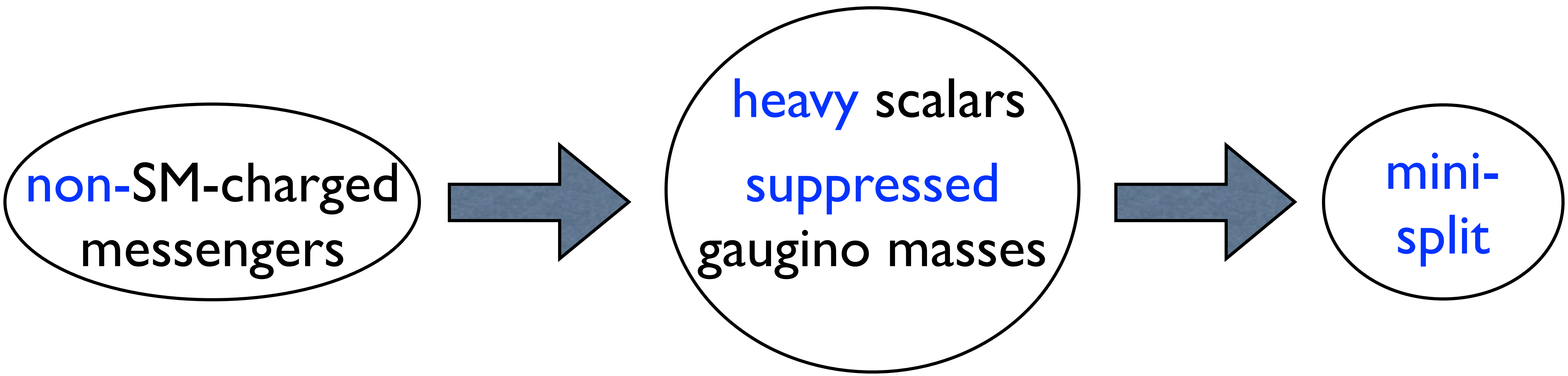


Higgs sector: How is B_μ generated?

$$\det \begin{pmatrix} \mu_H^2 + \widetilde{m}^2_{H_u} & -B_\mu \\ -B_\mu^* & \mu_H^2 + \widetilde{m}^2_{H_d} \end{pmatrix} \approx 0$$

Must be "in the ballpark": $B_\mu \sim \widetilde{m}^2_H$ or $B_\mu \sim \mu_H^2$

This talk:
Mini-split from gauge mediation



Key: new $\mathrm{U}(1)_H$

- m_H and $\widetilde{m}_{\tilde{t}}$ independent
- generates $B_\mu \sim m_H^2$

Outline

1. Construct auxiliary group

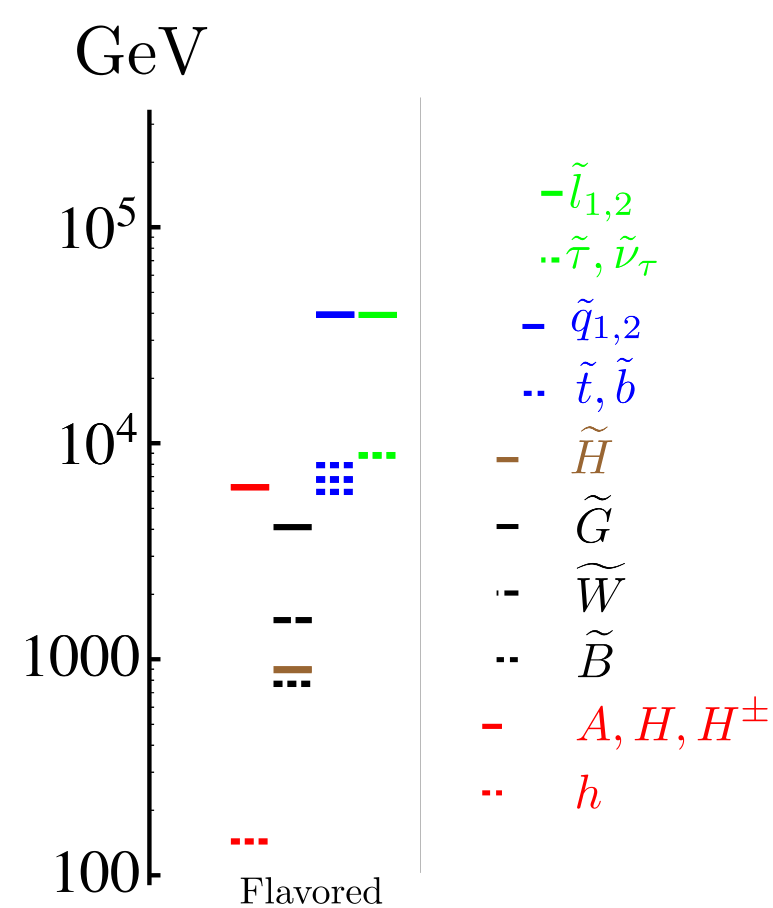
$$G_{aux} = \mathrm{SU}(3)_{\mathrm{F}} \times \mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{H}}$$

↓ gauge mediation

2. Calculate soft terms

$$\tilde{m}^2_{sc} \sim \int d^4\theta \, K_{2L}(\mathbf{X}^\dagger \mathbf{X}, \mathbf{q}^\dagger \mathbf{q})$$

3. Benchmark spectra for LHC



The Auxiliary Group

The auxiliary group

All anomaly-free* global symmetries of the MSSM in limit of vanishing Yukawas

* with respect to SM

$$G_{aux} = \mathrm{SU}(3)_F \times \mathrm{U}(1)_{B-L} \times \mathrm{U}(1)_H$$

$$W_{MSSM} = \lambda_u \mathbf{u}^c \mathbf{Q} \mathbf{H}_u - \lambda_d \mathbf{d}^c \mathbf{Q} \mathbf{H}_d - \lambda_e \mathbf{e}^c \mathbf{L} \mathbf{H}_d + \mu_H \mathbf{H}_u \mathbf{H}_d$$

Global symmetries with $\lambda_u = \lambda_d = \lambda_e = 0$:

$\mathrm{U}(1)_B$ baryon number

$\mathrm{U}(3)^5$ flavor symmetry

(3 generations, 5 matter superfields)

$\mathrm{U}(1)_L$ lepton number

$\mathrm{U}(1)_H$ "Higgs symmetry"

$q_{H_u} = -q_{H_d}$

G_{aux} is the anomaly-free subgroup

The role of G_{aux}

$$G_{aux} = \mathrm{SU}(3)_F \times \mathrm{U}(1)_{B-L} \times \mathrm{U}(1)_H$$

At leading order:

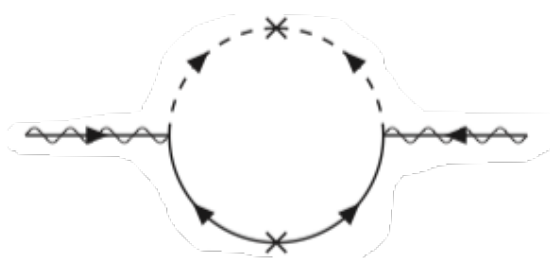
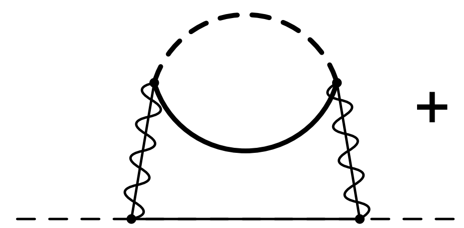
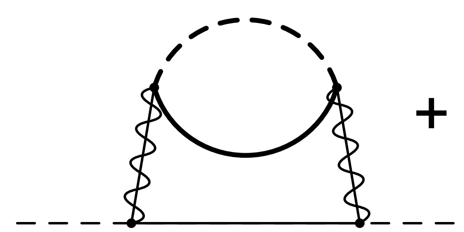
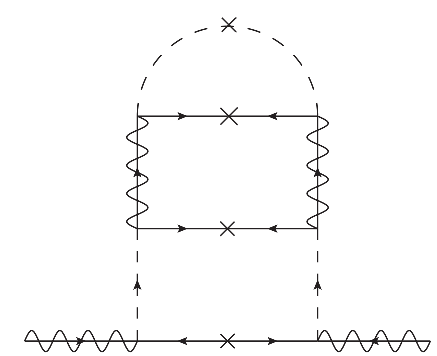
- $\mathrm{SU}(3)_F$, $\mathrm{U}(1)_{B-L}$: squark, slepton masses, A-terms
- $\mathrm{U}(1)_H$: Higgs masses, A- and B-terms

Note:

- Matter charged, but not gauginos: gaugino masses only appear at 3-loops, $\tilde{m}_{\tilde{\lambda}} \ll \tilde{m}_{sc}$
- Without $\mathrm{U}(1)_H$, no Higgs sector soft terms! Problems for EWSB and m_H

(for models that address this, see [Arvanitaki et al, 2013; 1210.0555])

Ordinary vs. auxiliary gauge mediation in Feynman diagrams

	1-loop	2-loop	3-loop
Ordinary GMSB	 Gauginos	 + 7 sim. Sfermions and Higgses	(subdominant)
Auxiliary GMSB	Nothing!	 + 7 sim. Sfermions and Higgses	 Gauginos

first computed in
[Gorbatov and Sudano, 2008; 0802.0555]

Calculating soft terms

or

“applied Higgsed gauge mediation”

Hierarchies of scale

two independent scales lead to interesting pheno

G_{aux} breaking M_V

messenger M

$\sim 10^{10} - 10^{15}\,\mathrm{GeV}$

SUSY breaking F/M — $\sim 100 - 1000\,\mathrm{TeV}$

scalars — $\sim 10 - 100\ \mathrm{TeV}$

gauginos — $\sim 1 - 5\ \mathrm{TeV}$

weak scale — $246\,\mathrm{GeV}$

Higgs

(Higgsino mass depends on choice of params.)

Analytic continuation

Example: single chiral superfield $\mathbf{q}$,

charge q_q under new spontaneously broken U(1)

vector-like messengers w/U(1) charges

SUSY-breaking spurion

$$\mathbf{W} \supset \mathbf{X}\mathbf{\Phi}\mathbf{\Phi}^c, \ \langle \mathbf{X} \rangle = M + \theta^2 F$$

$$\mathbf{M_\Phi}^2 \to \mathbf{X}^\dagger \mathbf{X}, \ \mathbf{M_V}^2 \to M_V^2 + 2g^2 q_q^2 \mathbf{q}^\dagger \mathbf{q}$$

messenger mass

U(1) vector superfield mass

Ordinary gauge mediation:

integrate out $\mathbf{\Phi}$

[Giudice, Rattazzi, 1998; hep-ph/9706540]

$$\int d^4\theta \, Z(\mathbf{M}_\mathbf{\Phi}^2) \mathbf{q}^\dagger \mathbf{q}$$

WF renorm. for **q**

Higgsed gauge mediation:

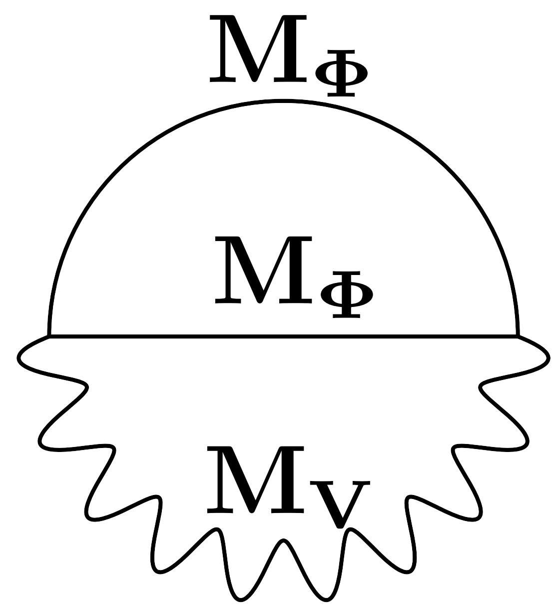
integrate out **V** too

[Craig, McCullough, Thaler, 2012; 1201.2179, 1203.1622]

$$\int d^4\theta \, K_{2L}(\mathbf{M}_\mathbf{\Phi}^2, \mathbf{M}_\mathbf{V}^2)$$

2-loop eff. Kähler potential

Scalar masses

$$K_{2L} =$$ 

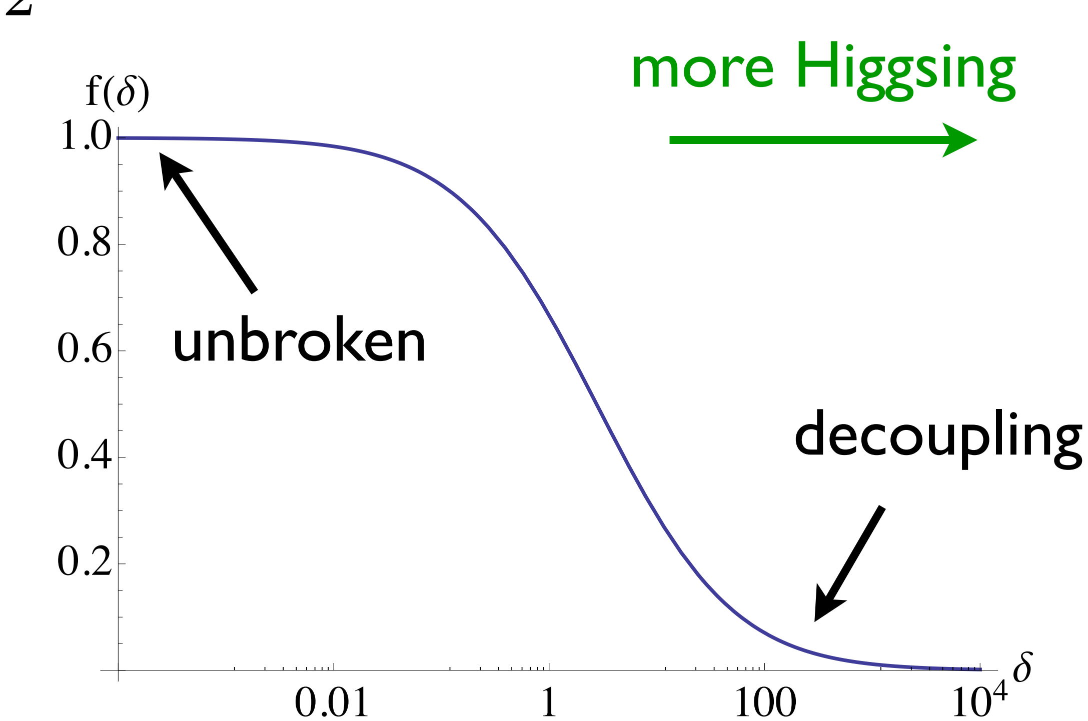
Integrate Kähler potential over superspace:

$$\delta = M_V^2/M^2$$

$$\tilde{m}_q^2 = q_q^2 q_\Phi^2 \left(\frac{\alpha}{2\pi}\right)^2 \left|\frac{F}{M}\right|^2 f(\delta)$$

ordinary gauge mediation result

Higgsing suppression factor



Varying δ gives different phenomenology

Soft terms in auxiliary gauge mediation

- Φ charges: $C(\Phi), p_\Phi, q_\Phi$
- Higgsing scales: $\delta_F, \delta_{B-L}, \delta_H$
- Auxiliary gauge couplings: $\alpha_F, \alpha_{B-L}, \alpha_H$
- SUSY-breaking parameter: F/M

all soft terms

color code: $G_{aux} = \mathrm{SU}(3)_F \times \mathrm{U}(1)_{B-L} \times \mathrm{U}(1)_H$

Soft terms in auxiliary gauge mediation

(all formulas evaluated at effective messenger scale *min*{M,M$_V$})

Squarks/sleptons:

$$(\widetilde{m}_q^2)_{ij} = \left(C(\Phi)\frac{\alpha_F^2}{(2\pi)^2}\sum_a f(\delta_F^a)\,(T_q^a T_q^a)_{\{ij\}} + \eta\, p_\Phi^2 \frac{\alpha_{B-L}^2}{(2\pi)^2} f(\delta_{B-L})\delta_{ij} \right) \left| \frac{F}{M} \right|^2$$

Stop-Higgs A-term:

$$A_{h_u \widetilde{t}_L \widetilde{t}_R} = \frac{\lambda_t}{(2\pi)^2} \left(2C(\Phi)\alpha_F^2 \sum_a h(\delta_F^a)\,(T_q^a T_q^a)_{33} + q_\Phi^2 \alpha_H^2 h(\delta_H) + \frac{2}{9} p_\Phi^2 \alpha_{B-L}^2 h(\delta_{B-L}) \right) \left(\frac{F}{M} \right)$$

Higgs sector:

$$\widetilde{m}_{H_u,H_d}^2 = q_\Phi^2 \frac{\alpha_H^2}{(2\pi)^2} f(\delta_H) \left| \frac{F}{M} \right|^2 \qquad B_\mu = 2\mu_H q_\Phi^2 \frac{\alpha_H^2}{(2\pi)^2} h(\delta_H) \frac{F}{M}$$

Gauginos:

$$\widetilde{M}_{\widetilde{g}} = \frac{\alpha_S}{4\pi^3}\frac{F}{M} \left(\frac{1}{2} C(\Phi)\alpha_F^2 \sum_a h(\delta_F^a) + \frac{1}{3} p_\Phi^2 \alpha_{B-L}^2 h(\delta_{B-L}) \right),$$

$$\widetilde{M}_{\widetilde{W}} = \frac{\alpha_W}{4\pi^3}\frac{F}{M} \left(\frac{1}{2} C(\Phi)\alpha_F^2 \sum_a h(\delta_F^a) + \frac{1}{2} q_\Phi^2 \alpha_H^2 h(\delta_H) + 4 p_\Phi^2 \alpha_{B-L}^2 h(\delta_{B-L}) \right),$$

$$\widetilde{M}_{\widetilde{B}} = \frac{\alpha_Y}{4\pi^3}\frac{F}{M} \left(\frac{5}{6} C(\Phi)\alpha_F^2 \sum_a h(\delta_F^a) + \frac{1}{2} q_\Phi^2 \alpha_H^2 h(\delta_H) + \frac{23}{9} p_\Phi^2 \alpha_{B-L}^2 h(\delta_{B-L}) \right)$$

Some parametrics

Ordinary gauge mediation:

$$\widetilde{m}_\lambda \sim \frac{\alpha}{4\pi}\frac{F}{M}, \quad \widetilde{m}^2_{sc} \sim \left(\frac{\alpha}{4\pi}\right)^2 \left|\frac{F}{M}\right|^2$$

$$\Longrightarrow \boxed{\widetilde{m}_\lambda \sim \widetilde{m}_{sc}}$$

Auxiliary gauge mediation:

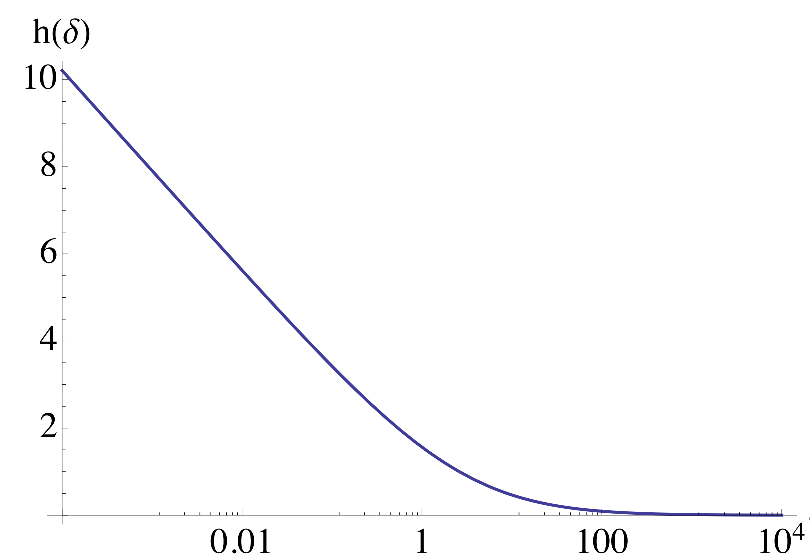
$$\widetilde{m}_\lambda \sim \frac{\alpha_{SM}}{4\pi}\left(\frac{\alpha_{aux}}{4\pi}\right)^2 \frac{F}{M}, \quad \widetilde{m}^2_{sc} \sim \left(\frac{\alpha_{aux}}{4\pi}\right)^2 \left|\frac{F}{M}\right|^2$$

$$\Longrightarrow \boxed{\widetilde{m}_\lambda \sim \frac{\alpha_{SM}\alpha_{aux}}{16\pi^2}\widetilde{m}_{sc}}$$

Also:

$$\frac{B_\mu}{\widetilde{m}^2_H} = \frac{\mu_H}{F/M}\,\frac{2h(\delta_H)}{f(\delta_H)}$$

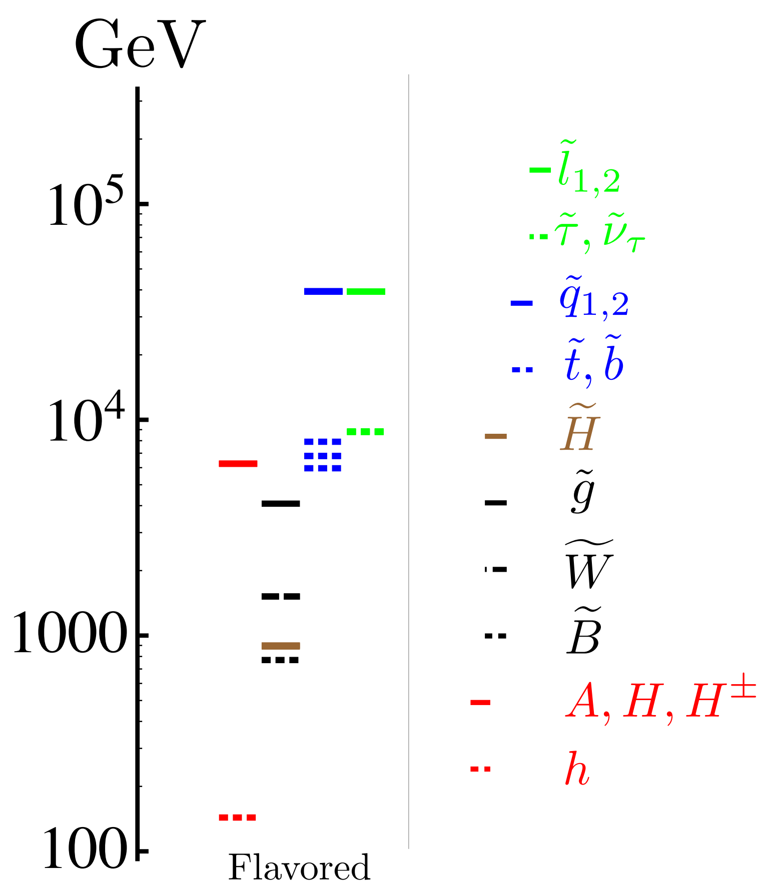
$\mathcal{O}(10)$ for $m_{V_H} \sim M/3$



Can accommodate μ_H a factor of 10 lighter than F/M and still get Higgs sector soft terms at the correct scale!

Benchmark spectra

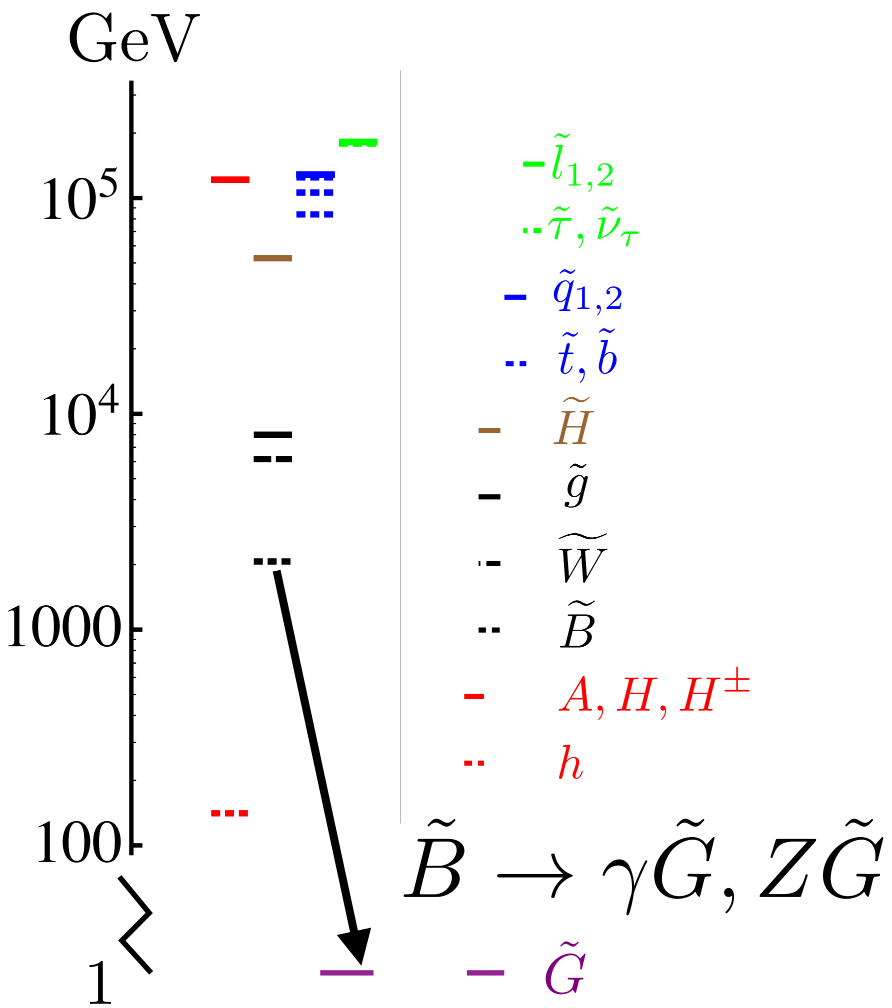
Flavored benchmark



Benchmark	Flavored
M_{eff} [GeV]	10^{10}
F/M [GeV]	1×10^5
$\sqrt{C(\Phi)}\,\alpha_F$	2.5
δ_F	260
$p_\Phi\,\alpha_{B-L}$	—
δ_{B-L}	—
$q_\Phi\,\alpha_H$	0.4
δ_H	0.1
$\tan\beta$	20.05
μ_H [TeV]	0.8
$\sqrt{B_\mu}$ [TeV]	1.5
$m_{3/2}$ [GeV]	7.6×10^{-4}

- Large δ_F gives stops and sbottoms lighter by a factor of ~6
- Gluino decay goes like $1/m_{\tilde{q}}^4$ so decays to 3rd-gen quarks are 6^4 times as likely!
- Light Higgsinos and largeish $\tan\beta$ possible by tuning messenger scale (not specific to AGMSB)

SuperWIMP benchmark



Benchmark	superWIMP
$M_{\rm eff}$ [GeV]	6×10^{12}
F/M [GeV]	1×10^6
$\sqrt{C(\mathbf{\Phi})}\,\alpha_F$	0.6
δ_F	0.1
$p_\Phi\,\alpha_{B-L}$	0.8
δ_{B-L}	0.1
$q_\Phi\,\alpha_H$	0.6
δ_H	0.0125
$\tan\beta$	3.95
μ_H [TeV]	45.8
$\sqrt{B_\mu}$ [TeV]	67.3
$m_{3/2}$ [GeV]	1.9

- Use all three factors of auxiliary group
- Bino NSLP has correct mass to decay after freeze-out to gravitino LSP, which is dark matter (superWIMP paradigm)
- Preferred parameter space in Feng et al. easily accomodated

SuperWIMPS: [Feng, Rajaraman, Takayama, 2003; hep-ph/0302215, hep-ph/0306024]

In gauge mediation: [Feng, Smith, Takayama, 2008; 0709.0297]

With 125 GeV Higgs: [Feng, Surujon, Yu, 2012; 1205.6480]

Summary

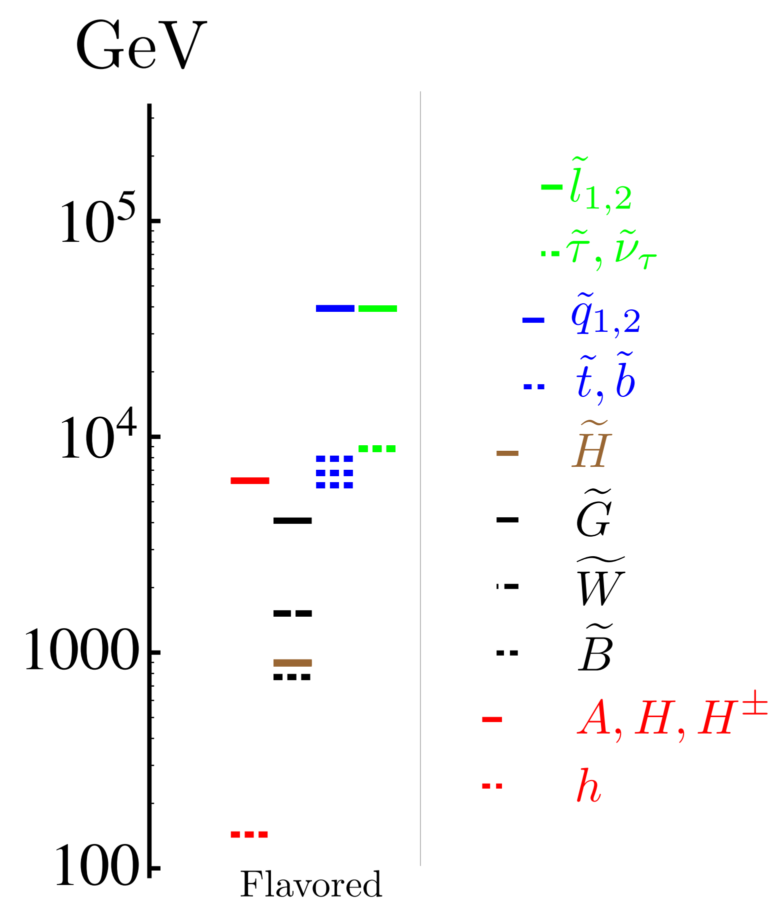
Auxiliary group used for Higgsed gauge mediation

$$G_{aux} = \mathrm{SU}(3)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{B-L} \times \mathrm{U}(1)_\mathrm{H}$$

Soft terms calculable with analytic continuation

$$\tilde{m}^2_{sc} \sim \int d^4\theta \, K_{2L}(\mathbf{X}^\dagger \mathbf{X}, \mathbf{q}^\dagger \mathbf{q})$$

Spectrum constrained by RG stability, but can find viable LHC benchmarks



Outlook

- If supersymmetry is realized, LHC seems to be pointing us toward mini-split. Need explicit, concrete models!
- Auxiliary gauge mediation is a good place to start. Some interesting and unusual phenomenology (can even get acceptable spectrum with a single U(1)!)
- Along the way, applied useful techniques, including Higgsed gauge mediation and another way to generate B-terms at messenger scale (contrary to lore)

Backup slides

Incorporating flavor

$$W \supset \frac{1}{\Lambda_u^2}\mathbf{S}^-_{\mathbf{H}}\mathbf{S}_{\mathbf{u}}\mathbf{H}_{\mathbf{u}}\mathbf{Q}\mathbf{U}^c + \frac{1}{\Lambda_d^2}\mathbf{S}^+_{\mathbf{H}}\mathbf{S}_{\mathbf{d}}\mathbf{H}_{\mathbf{d}}\mathbf{Q}\mathbf{D}^c$$

S fields are flavor spurions: $\frac{\langle \mathbf{S}^{\mp}_H \mathbf{S}_{u,d} \rangle}{\Lambda^2_{u,d}} = \lambda_{u,d}$

Also cancel anomalies

Note: G_{aux} now spontaneously broken. In particular,

$$\mathrm{SU}(3)_F \to \mathrm{SU}(2)_F \to \emptyset$$

large 3rd-gen. Yukawa → heavy flavor bosons → suppressed 3rd-gen. masses

First two generations stay heavy and degenerate (U(3) not anomaly-free)

(Original motivation of [Craig, McCullough, Thaler, 2012; 1203.1622]: natural SUSY spectrum)

Field content and reps

	G_{SM}			G_{aux}		
	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{SU}(3)_F$	$\mathrm{U}(1)_{B-L}$	$\mathrm{U}(1)_H$
$\boldsymbol{Q}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$\mathbf{3}$	$1/3$	—
$\boldsymbol{U^c}$	$\overline{\mathbf{3}}$	—	$-2/3$	$\mathbf{3}$	$-1/3$	—
$\boldsymbol{D^c}$	$\overline{\mathbf{3}}$	—	$1/3$	$\mathbf{3}$	$-1/3$	—
$\boldsymbol{L}$	—	$\mathbf{2}$	$-1/2$	$\mathbf{3}$	-1	—
$\boldsymbol{E^c}$	—	—	1	$\mathbf{3}$	1	—
$\boldsymbol{H_u}$	—	$\mathbf{2}$	$1/2$	—	—	1
$\boldsymbol{H_d}$	—	$\mathbf{2}$	$-1/2$	—	—	-1
$\boldsymbol{N_F^c}$	—	—	—	$\overline{\mathbf{3}}$	—	—
$\boldsymbol{N_{B-L}^c}$	—	—	—	—	1	—
$\boldsymbol{S_u}$	—	—	—	$\overline{\mathbf{6}}$	—	—
$\boldsymbol{S_d}$	—	—	—	$\overline{\mathbf{6}}$	—	—
$\boldsymbol{S_{B-L}^{\pm}}$	—	—	—	—	± 2	—
$\boldsymbol{S_H^{\pm}}$	—	—	—	—	—	± 1
$\boldsymbol{\Phi}/\boldsymbol{\Phi^c}$	—	—	—	$C(\boldsymbol{\Phi})$	$\pm p_\Phi$	$\pm q_\Phi$
α_i	α_S	α_W	α_Y	α_F	α_{B-L}	α_H

all matter fields fundamentals

Cancel internal $\mathrm{SU}(3)_F, \mathrm{U}(1)_{B-L}$ anomalies

KEY: Higgs only charged under $\mathrm{U}(1)_H$

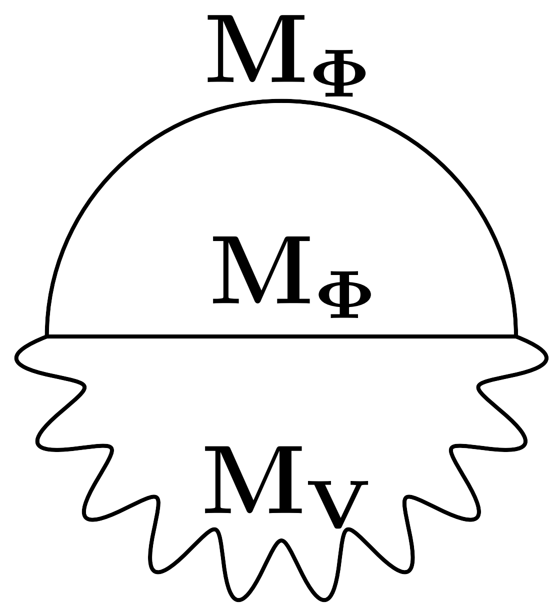
get vevs, spontaneously break all of G_{aux}

$\mathrm{N^c_{B-L}}$ can get a Majorana mass

gauge messengers

Higgsed gauge mediation

$$\mathbf{M}_{\mathbf{\Phi}}^2 \rightarrow \mathbf{X}^\dagger \mathbf{X}$$



$$\mathbf{M}_{\mathbf{V}}^2 \rightarrow M_V^2 + 2g^2 q_q^2 \mathbf{q}^\dagger \mathbf{q}$$

$$K_{2L} \supset -2q_\Phi^2 g^2 \int \frac{d^D p \, d^D q}{(2\pi)^{2D} \mu^{2(D-4)}} \frac{1}{p^2 + |\mathbf{M}_{\mathbf{\Phi}}|^2} \frac{1}{(p+q)^2 + |\mathbf{M}_{\mathbf{\Phi}}|^2} \frac{1}{q^2 + \mathbf{M}_{\mathbf{V}}{}^2}$$

Do loop integral, isolate coefficient of $|\mathbf{q}|^2$:

$$K_{2L} \supset -q_\Phi^2 q_q^2 \frac{\alpha^2}{(2\pi)^2} \left(h(\delta) \left(\frac{F}{M}\theta^2 + \frac{F^\dagger}{M^\dagger}\bar{\theta}^2 \right) + f(\delta) \left| \frac{F}{M} \right|^2 \theta^2 \bar{\theta}^2 \right) |\mathbf{q}|^2$$

$\boxed{\delta = M_V^2 / M^2}$ parameterizes Higgsing scale

Note: analytic continuation gives only lowest order result in F/M

Gaugino masses

Suppose $\mathbf{q}$ has hypercharge Y = 1

Field rescaling is anomalous, shifts kinetic term:

$$\int d^2\theta\, \mathbf{f}\, \mathbf{W}_\alpha \mathbf{W}^\alpha \to \int d^2\theta \left(\mathbf{f} - \frac{1}{8\pi^2} \log \mathbf{Z_q}(\overline{\mu}) \right) \mathbf{W}_\alpha \mathbf{W}^\alpha$$

hypercharge field-strength superfield

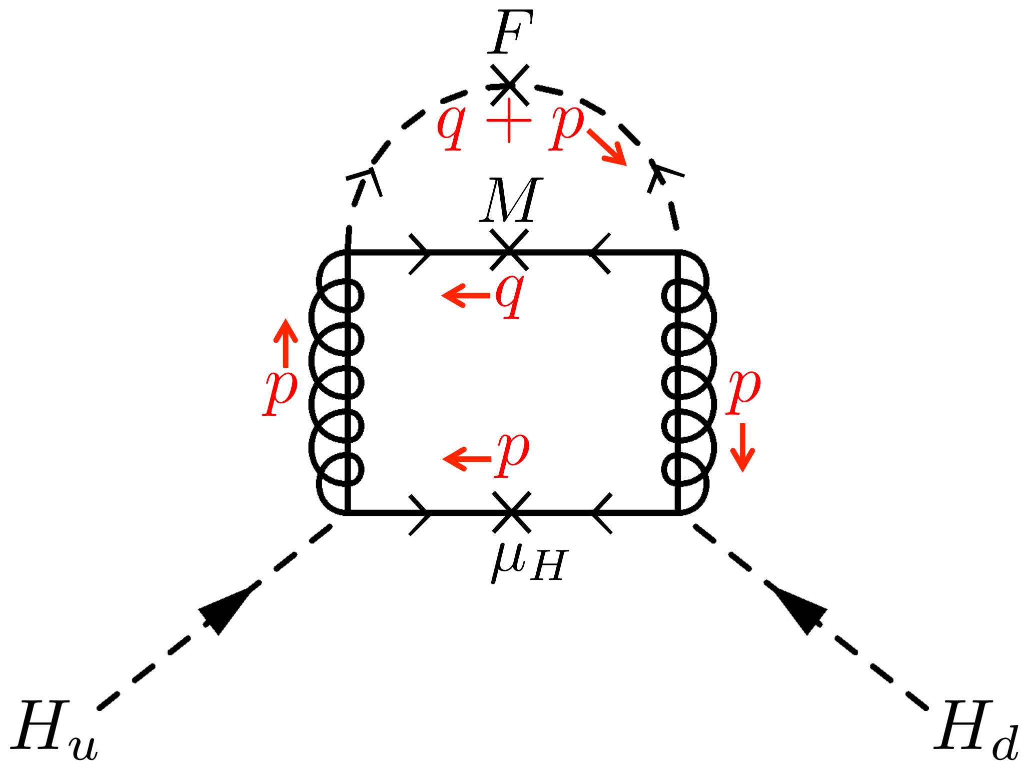
$$\Longrightarrow \quad \widetilde{M}_{\tilde{B}} = q_q^2 q_\Phi^2 \left(\frac{\alpha}{2\pi} \right)^2 \frac{\alpha_Y}{2\pi} h(\delta) \frac{F}{M}$$

Same as for A-terms!

Simple and predictive framework: all soft terms given to lowest order by two functions, $f(\delta)$ and $h(\delta)$.

For gauginos, 3-loop result from 2-loop effective potential

Aside: A- and B-terms in ordinary gauge mediation

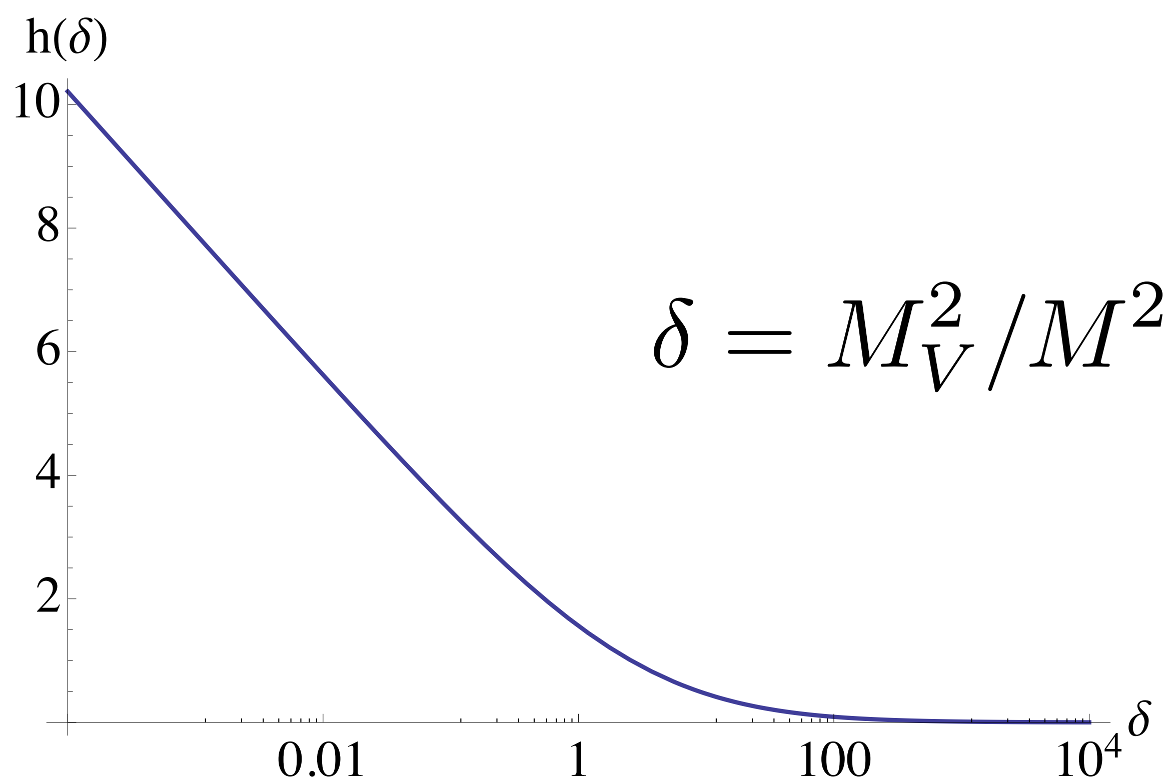


Higgsed GMSB in the unbroken limit

Higgsed gauge mediation: $A_q = q_q^2 q_\Phi^2 \left(\frac{\alpha}{2\pi}\right)^2 \frac{F}{M} h(\delta)$

Standard lore: "A-terms vanish at the messenger scale"

Not quite! $\lim_{\delta \to 0} h(\delta) = 1 - \log \delta$



Higgsed GMSB in the unbroken limit

$$\lim_{\delta \to 0} h(\delta) = 1 - \log \delta \qquad \delta = M_V^2 / M^2$$

IR cutoffs

For an unbroken gauge group, $M_V \to 0, \quad \delta \to \overline{\mu}^2 / M^2$

Log captures familiar RG running, but there remains a finite 2-loop piece even for $\overline{\mu} = M$

Same result w/component-field Feynman diagram calculation and 2-loop $\overline{DR}$

Threshold effects

[Giudice, Rattazzi, 1998; hep-ph/9706540]

$$A(\overline{\mu}) = \left. \frac{\partial \ln \mathbf{Z_q}(\mathbf{X}, \mathbf{X}^\dagger, \overline{\mu})}{\partial \ln \mathbf{X}} \right|_{\mathbf{X}=M} \frac{F}{M}$$

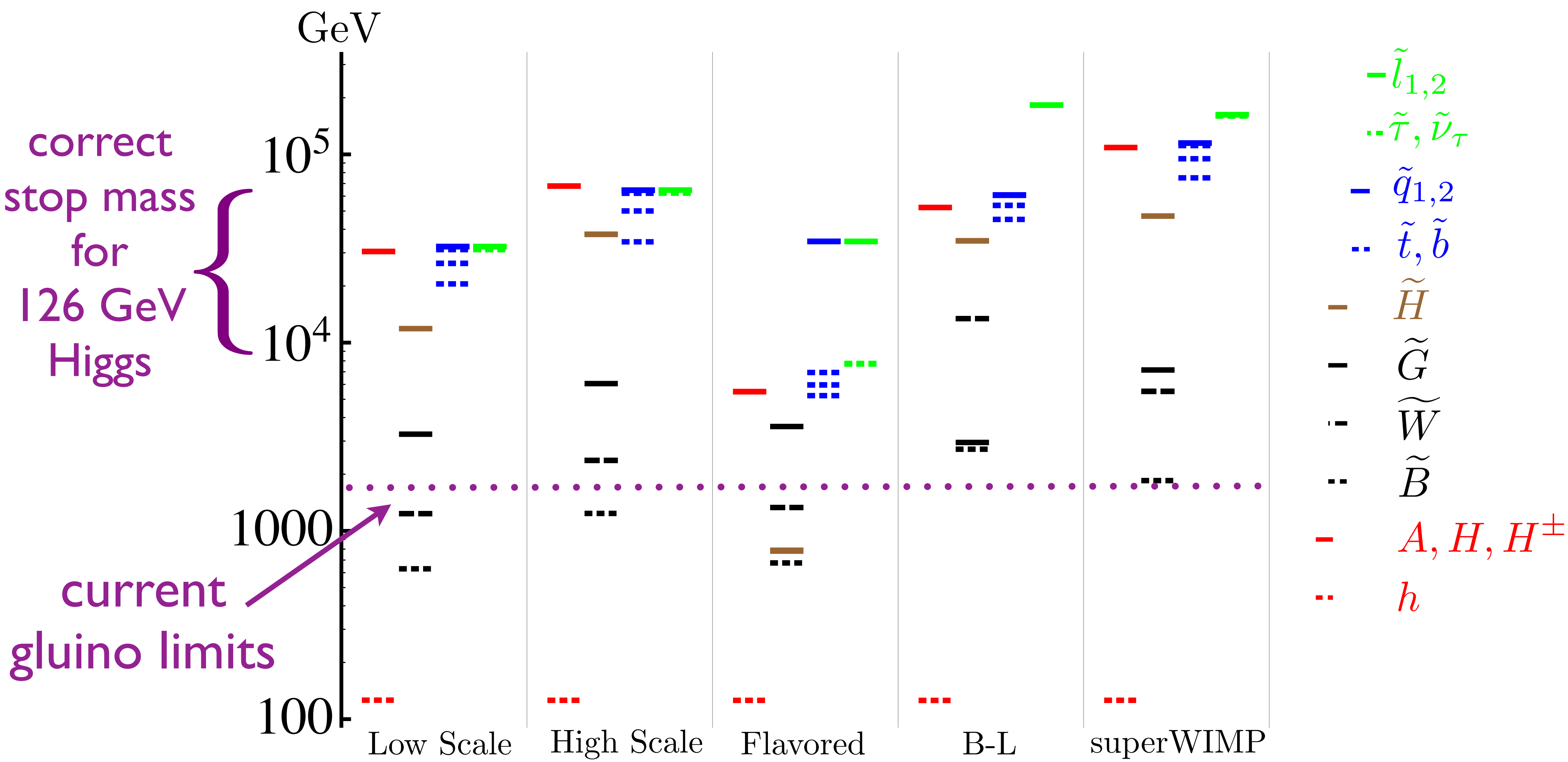
[Arkani-Hamed, Giudice, Luty, Rattazzi, 1998; hep-ph/9803290]

$$\ln \mathbf{Z_q} = \int_{\mu_0}^{\mu_X} \frac{d\mu'}{\mu'} \gamma'_{\mathbf{q}}(\mu') + \int_{\mu_X}^{\overline{\mu}} \frac{d\mu'}{\mu'} \gamma_{\mathbf{q}}(\mu') + \mathcal{O}\left(\frac{\alpha(\mathbf{X})^2}{16\pi^2}\right)$$

NNLO for scalars, but LO for A-terms!

Formalism of Higgsed gauge mediation contains 2-loop threshold effects in ordinary GMSB!

Benchmark spectra: overview

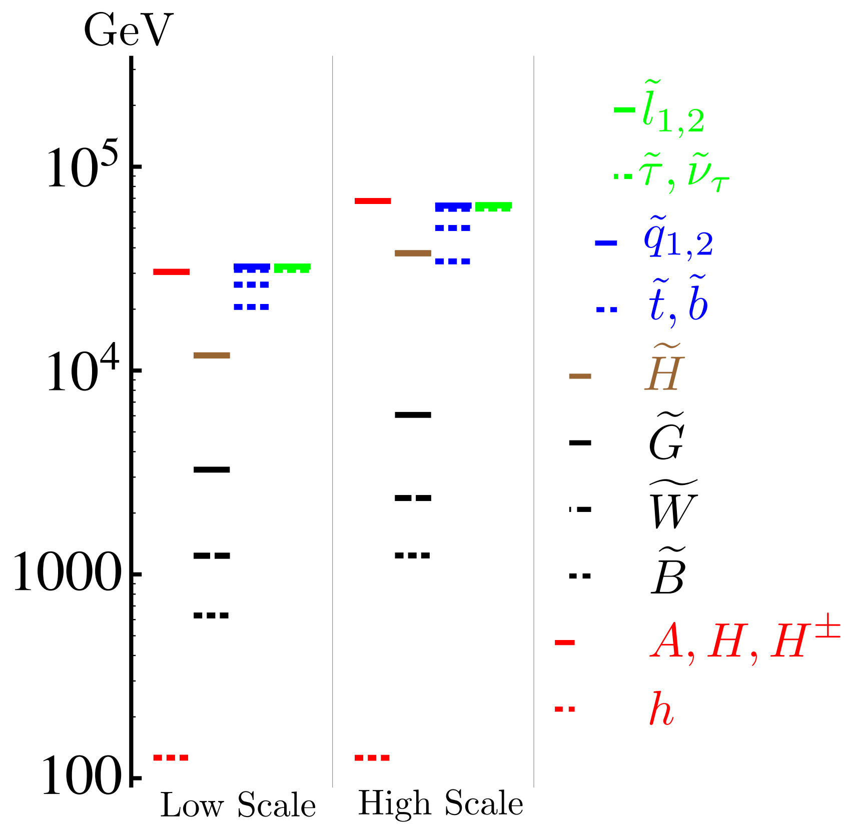


(all spectra RG-evolved with SoftSUSY)

[B. Allanach, 2002; hep-ph/0104145]

General observations: non-canonical gaugino hierarchy, Higgsinos can be heavy or light, B-L charges push sleptons heavier

Low/high scale benchmarks

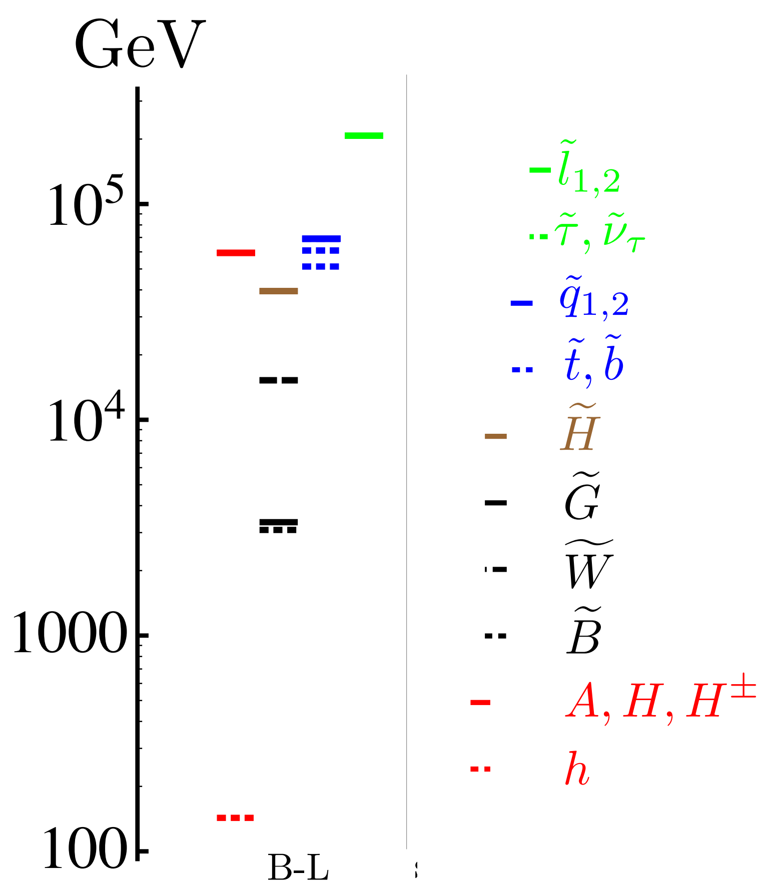


Benchmark	Low Scale	High Scale
$M_{\rm eff}$ [GeV]	10^{10}	10^{15}
F/M [GeV]	2×10^5	4×10^5
$\sqrt{C(\mathbf{\Phi})}\,\alpha_F$	0.9	0.9
δ_F	0.1	0.1
$p_\Phi\,\alpha_{B-L}$	—	—
δ_{B-L}	—	—
$q_\Phi\,\alpha_H$	0.9	0.9
δ_H	0.1	0.1
$\tan\beta$	4.469	4.396
μ_H [TeV]	11.9	36.9
$\sqrt{B_\mu}$ [TeV]	18.3	45.6
$m_{3/2}$ [GeV]	1.5×10^{-3}	300

- Small δ_F means flavor splitting almost entirely due to RG running
- All scalars out of LHC reach
- Heavy Higgsinos, need smallish $\tan\beta$ for correct Higgs mass
- Generic mini-split collider signatures:

$$\widetilde{g} \to \widetilde{q}^* q \to \cdots \to \widetilde{G} + SM$$

B-L benchmark



Benchmark	$B-L$
M_{eff} [GeV]	10^{10}
F/M [GeV]	4×10^5
$\sqrt{C(\mathbf{\Phi})}\,\alpha_F$	—
δ_F	—
$p_\Phi\,\alpha_{B-L}$	3.0
δ_{B-L}	0.1
$q_\Phi\,\alpha_H$	0.6
δ_H	0.02
$\tan\beta$	4.552
μ_H [TeV]	34.7
$\sqrt{B_\mu}$ [TeV]	35.4
$m_{3/2}$ [GeV]	6.8×10^{-3}

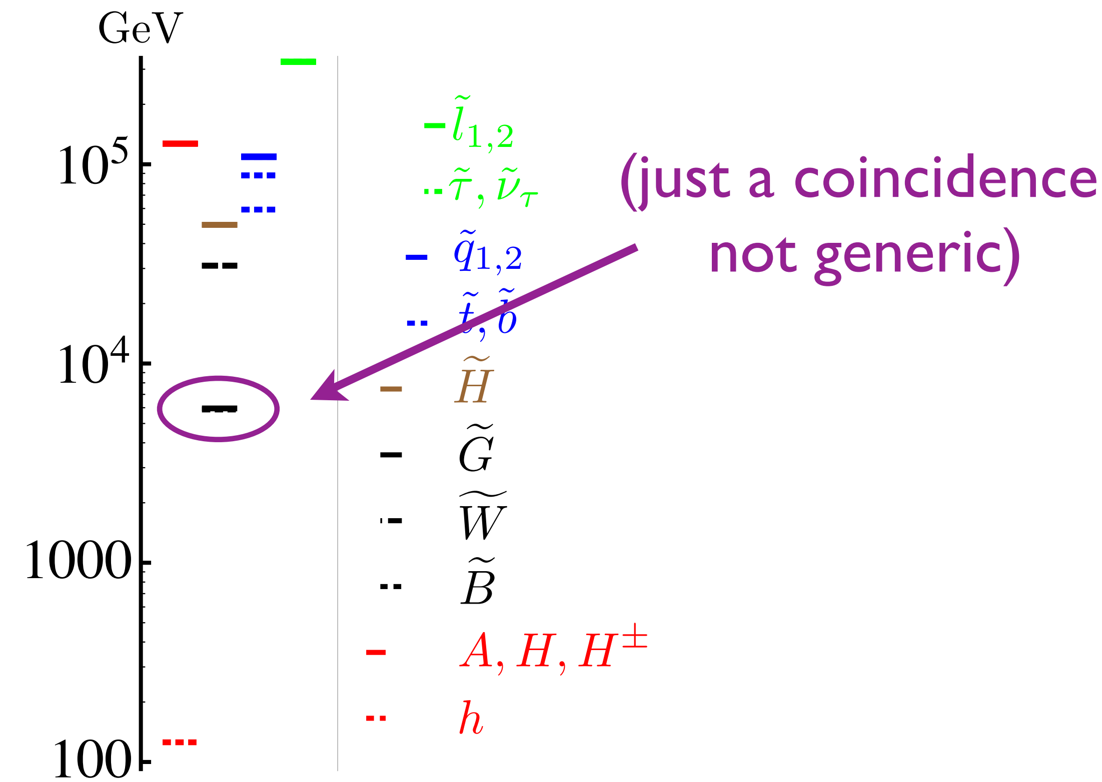
- Turn off $SU(3)_F$, mediate with $U(1)_H$ and $U(1)_{B-L}$ alone
- Sleptons ~3 times heavier than squarks from B-L charge
- Unconventional gaugino hierarchy

U(1)x benchmark

$$U(1)_{X\equiv B-L+kH} \subset U(1)_{B-L} \times U(1)_H$$

Take k = 1/3:

Benchmark	Minimal Model
$M_{\rm eff}$ [GeV]	10^{10}
F/M [GeV]	7×10^5
$q_\Phi\,\alpha_X$	3.0
δ_X	0.04
$\tan\beta$	3.045
μ_H [TeV]	51.5
$\sqrt{B_\mu}$ [TeV]	88.3
$m_{3/2}$ [GeV]	5.3×10^{-3}



Mini-split spectrum through a single U(1)!

Aux. breaking in detail

- Φ has charges $C(\Phi)\,(\mathrm{SU}(3)_F),\ p_\Phi\,(\mathrm{U}(1)_{B-L}),\ q_\Phi\,(\mathrm{U}(1)_H)$
- Independent Higgsing scale for each factor: $\delta_F,\ \delta_{B-L},\ \delta_H$
  - need to choose breaking pattern for $\mathrm{SU}(3)_F$
  - rotate $\mathrm{SU}(3)_F$ generators T^a_{ij} to mass eigenstate basis: sum over generators involves $\delta^a_F,\ a = 1, 2, \ldots, 8$ and gives a generation-dependent suppression factor

RGE's for 3rd gen. and Higgs

Assuming small flavor splitting, RGE entirely controlled by

$$X_t = |\lambda_t|^2(\widetilde{m}^2_{H_u} + \widetilde{m}^2_{\widetilde{t}_R} + \widetilde{m}^2_{\widetilde{t}_L}) + |A_{H_u\widetilde{t}_L\widetilde{t}_R}|^2$$

$$\boxed{\frac{d\widetilde{m}^2_{H_u}}{d\log\overline{\mu}} = \frac{3}{8\pi^2}X_t, \qquad \frac{d\widetilde{m}^2_{\widetilde{t}_R}}{d\log\overline{\mu}} = \frac{2}{8\pi^2}X_t, \qquad \frac{d\widetilde{m}^2_{\widetilde{t}_L}}{d\log\overline{\mu}} = \frac{1}{8\pi^2}X_t}$$

Analytic solution ignoring running of A-term and Yukawa:

$$\widetilde{m}^2_{H_u}(\overline{\mu}) = \widetilde{m}^2_{H_u}(M) - \frac{3}{8\pi^2}X_t(M)\log\frac{M}{\overline{\mu}},$$

$$\widetilde{m}^2_{\widetilde{t}_R}(\overline{\mu}) = \widetilde{m}^2_{\widetilde{t}}(M) - \frac{2}{8\pi^2}X_t(M)\log\frac{M}{\overline{\mu}}$$

$$\widetilde{m}^2_{\widetilde{t}_L}(\overline{\mu}) = \widetilde{m}^2_{\widetilde{t}}(M) - \frac{1}{8\pi^2}X_t(M)\log\frac{M}{\overline{\mu}}$$

To ensure $\widetilde{m}^2_{H_u} < 0$ and $\widetilde{m}^2_{t_{L,R}} > 0$ at weak scale, need $\widetilde{m}^2_{H_u}(M) \lesssim \frac{3}{2}\widetilde{m}^2_t(M)$

Flavor structures

Suppose $SU(3)_F$ breaking generates SM Yukawas:

$$\langle \mathbf{S_u} \rangle = \begin{pmatrix} v_{u1} & 0 & 0 \\ 0 & v_{u2} & 0 \\ 0 & 0 & v_{u3} \end{pmatrix}, \quad \langle \mathbf{S_d} \rangle = V_{\rm CKM} \begin{pmatrix} v_{d1} & 0 & 0 \\ 0 & v_{d2} & 0 \\ 0 & 0 & v_{u3} \end{pmatrix} V_{\rm CKM}^T$$

($v_{u3}/v_{u2} = m_t/m_c$, etc.)

Breaking pattern is $\mathrm{SU}(3)_F \overset{v_{u3}}{\to} \mathrm{SU}(2)_F \to \emptyset$:

$$M_V^2[\sim \mathrm{SU}(3)_F/\mathrm{SU}(2)_F] \approx 4\pi\alpha_F v_{u3}^2 \,\{2.67, 1.02, 1.00, 1.00, 0.99\}$$

$$M_V^2[\sim \mathrm{SU}(2)_F] \approx 4\pi\alpha_F v_{u3}^2 \,\{11.0, 5.60, 5.55\} \times 10^{-5}$$

large 3rd-gen. Yukawa → heavy flavor bosons → suppressed 3rd-gen. soft mass

Original motivation of gauging $SU(3)_F$ ("flavor mediation", 1201.2179 and 1203.1622) was to generate natural SUSY spectrum, with light stops: here just an added feature

Benchmark parameters

Benchmark	Low Scale	High Scale	Flavored	$B-L$	superWIMP
M_{eff} [GeV]	10^{10}	10^{15}	10^{10}	10^{10}	6×10^{12}
F/M [GeV]	2×10^5	4×10^5	1×10^5	4×10^5	1×10^6
$\sqrt{C(\mathbf{\Phi})}\,\alpha_F$	0.9	0.9	2.5	—	0.6
δ_F	0.1	0.1	260	—	0.1
$p_\Phi\,\alpha_{B-L}$	—	—	—	3.0	0.8
δ_{B-L}	—	—	—	0.1	0.1
$q_\Phi\,\alpha_H$	0.9	0.9	0.4	0.6	0.6
δ_H	0.1	0.1	0.1	0.02	0.0125
$\tan\beta$	4.469	4.396	20.05	4.552	3.95
μ_H [TeV]	11.9	36.9	0.8	34.7	45.8
$\sqrt{B_\mu}$ [TeV]	18.3	45.6	1.5	35.4	67.3
$m_{3/2}$ [GeV]	1.5×10^{-3}	300	7.6×10^{-4}	6.8×10^{-3}	1.9

single fine-tuning ($\tan\beta$ row)

same scale! (μ_H and $\sqrt{B_\mu}$ rows)