SPLIT SUSY RADIATES FLAVOR

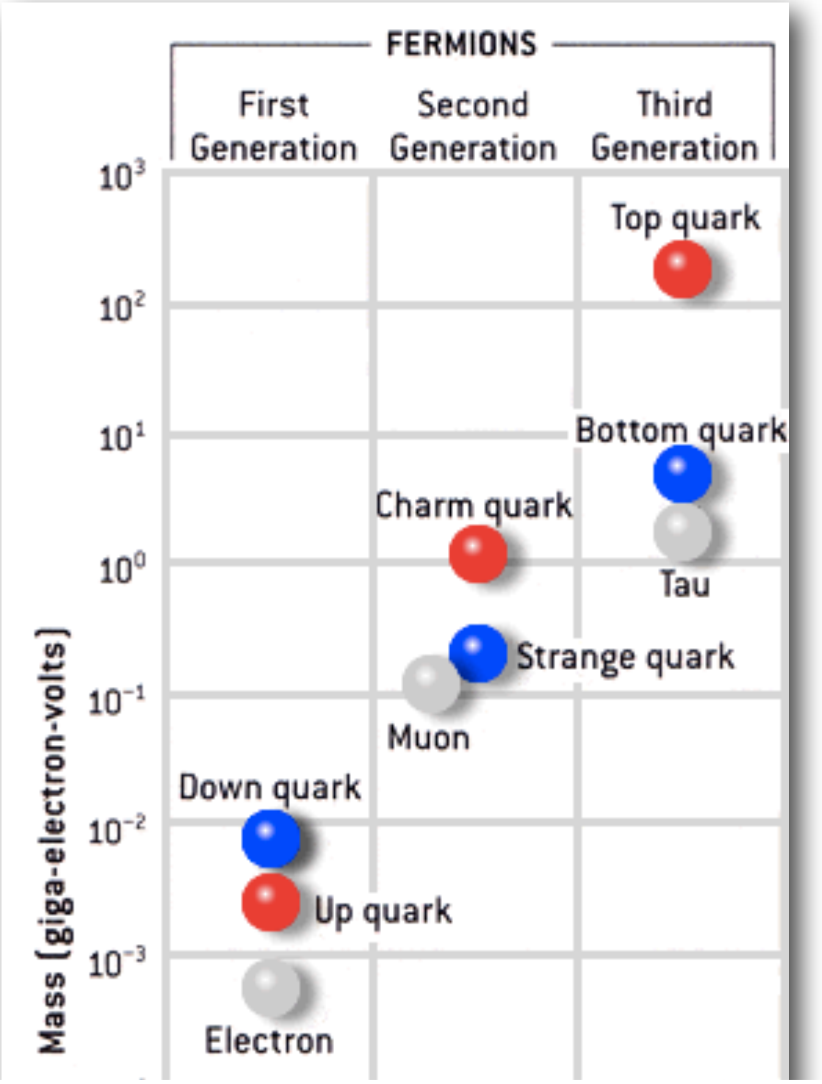
DANIEL STOLARSKI

MATTHEW BAUMGART, DS, TOM ZORAWSKI, arXiv:140?.????

OUTLINE

- Flavor motivation
- Mini-split SUSY motivation
- A model for the up quarks
- Down and leptons + CKM matrix
- Constraints and (austere) phenomenology
- Conclusions

SM FLAVOR STRUCTURE



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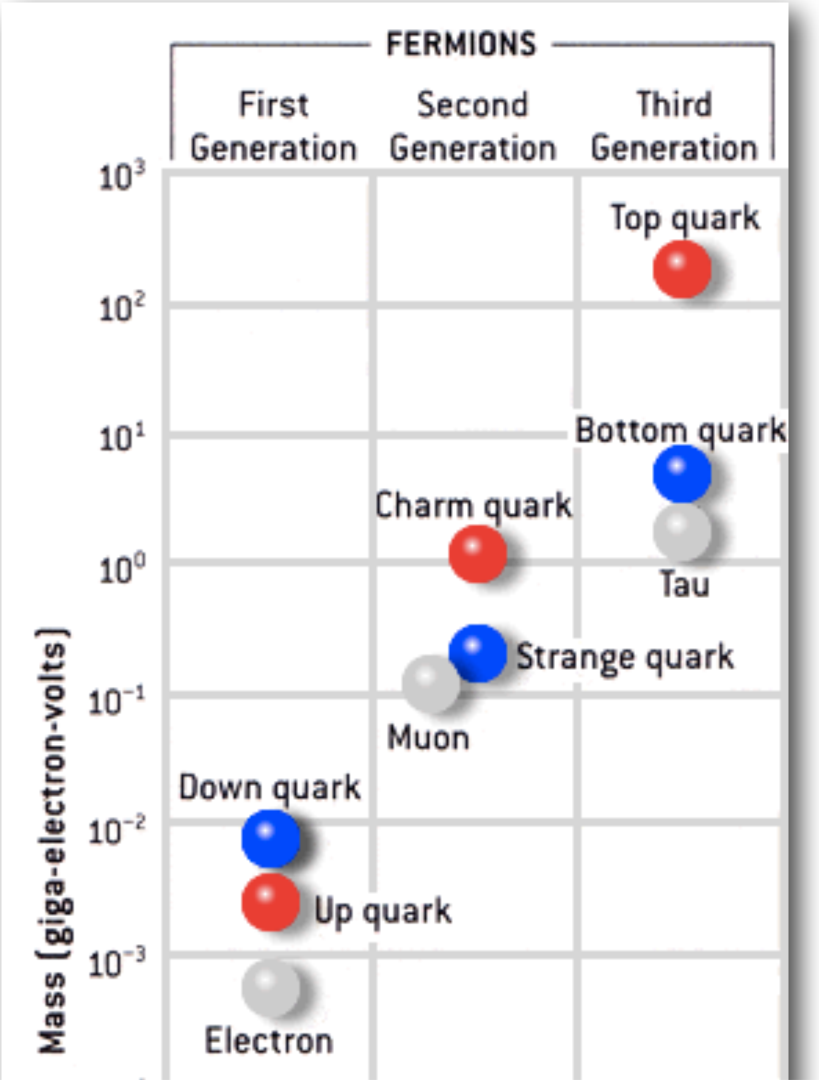
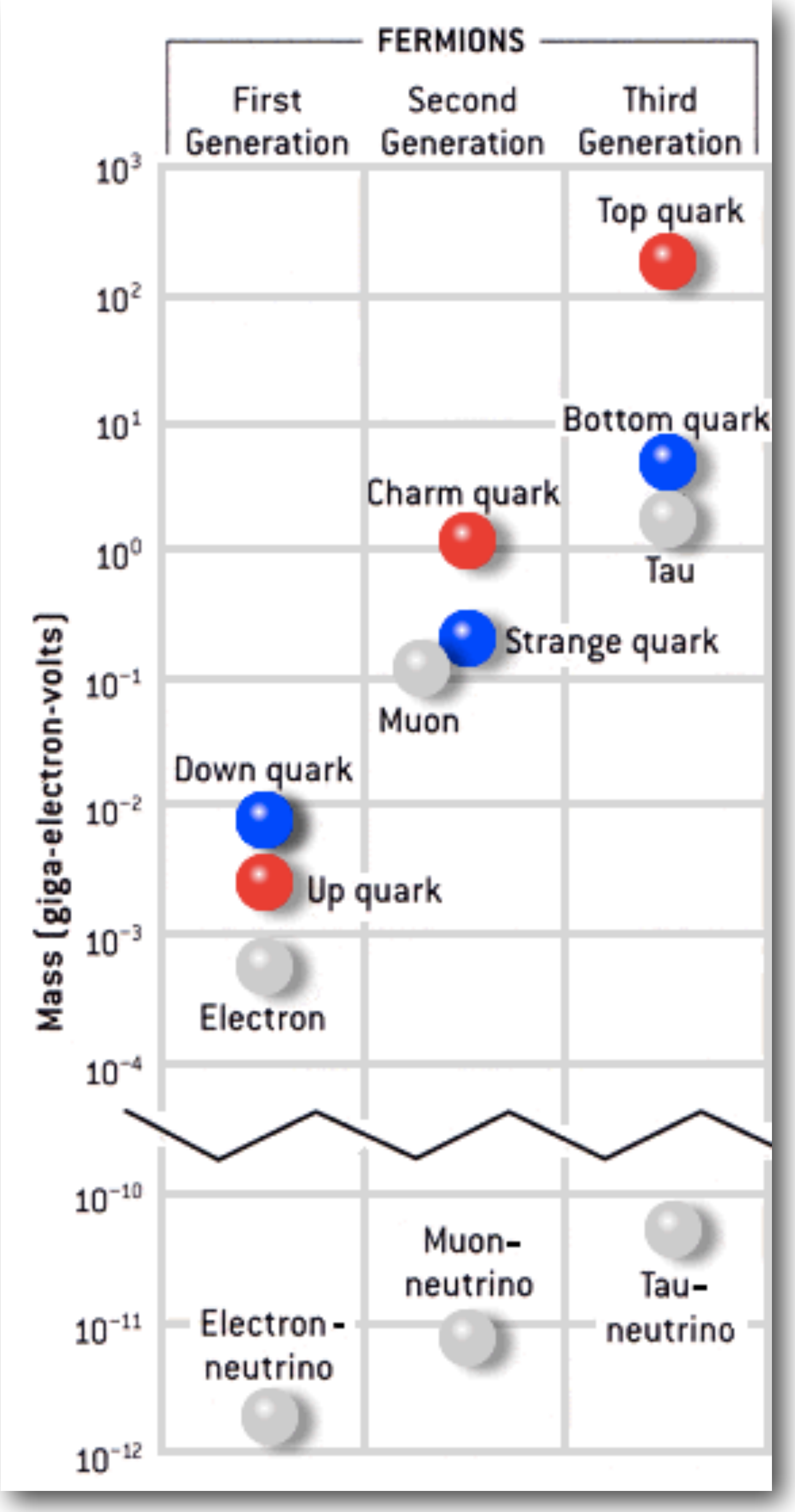


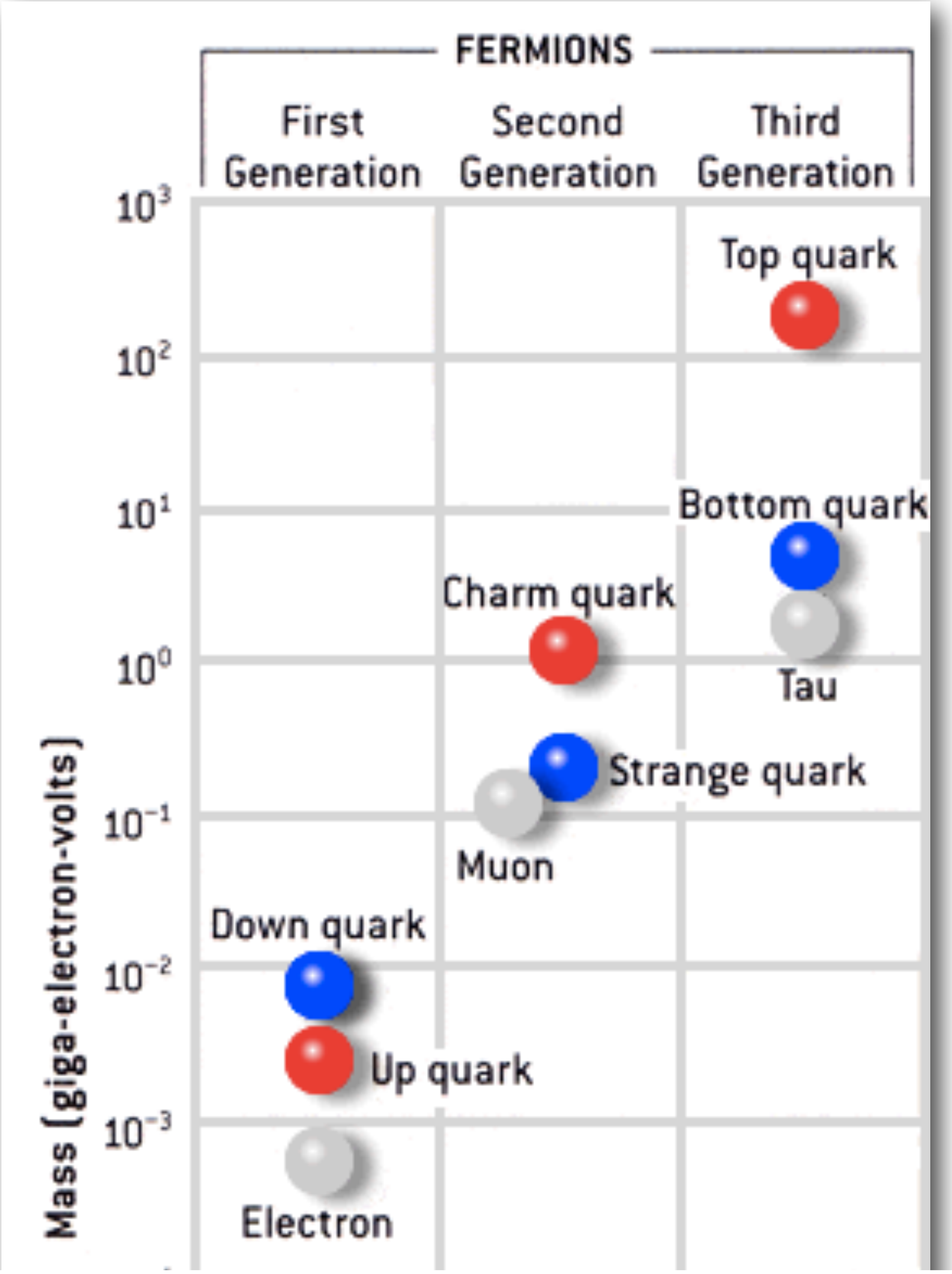
- Masses vary by orders of magnitude
- Three generations, each much heavier than the previous
- Seems to be a regular pattern between mass ratios

SM FLAVOR STRUCTURE



- Masses vary by orders of magnitude
- Three generations, each much heavier than the previous
- Seems to be a regular pattern between mass ratios
- Neutrinos are completely different

SM FLAVOR STRUCTURE



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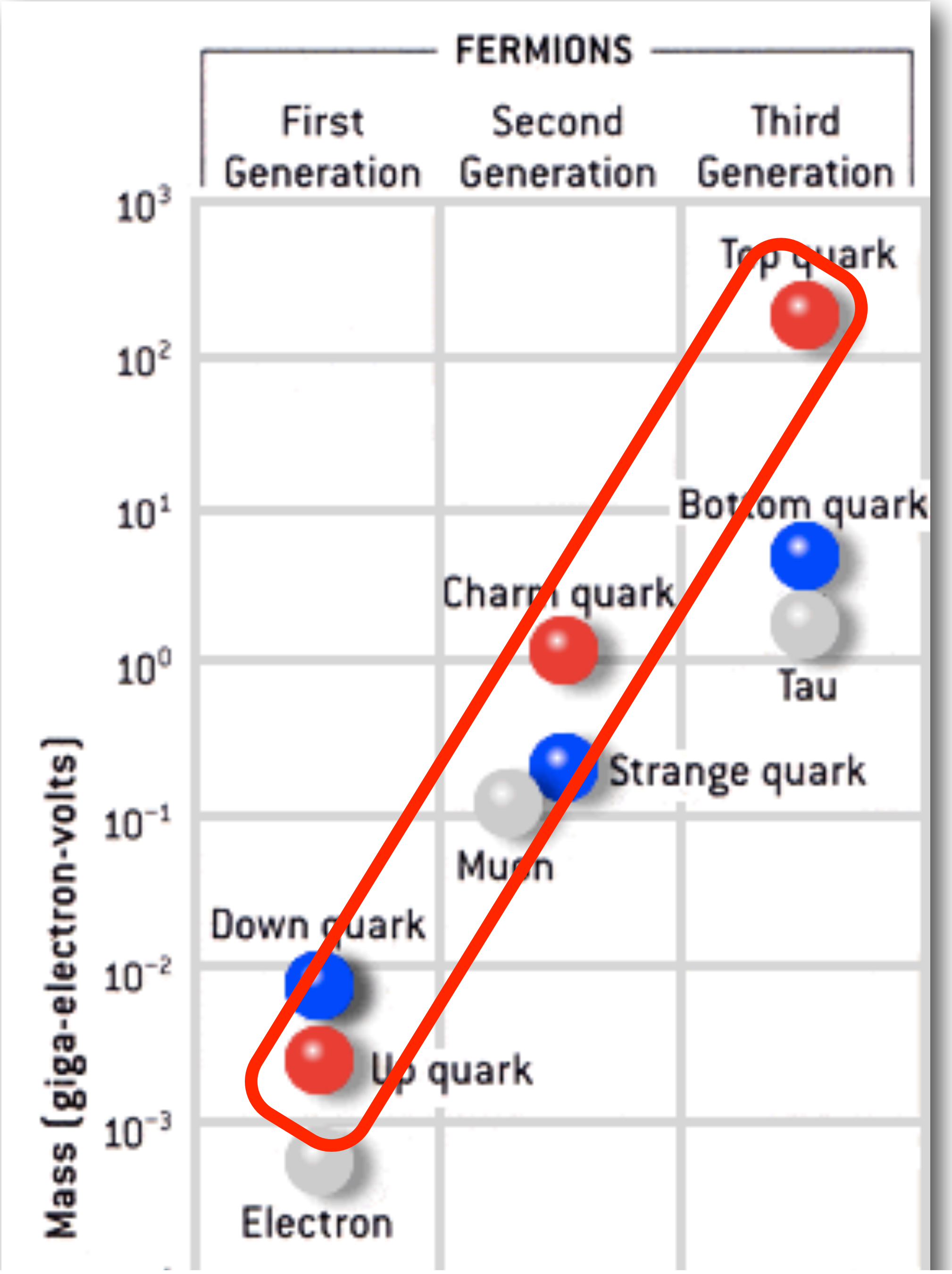

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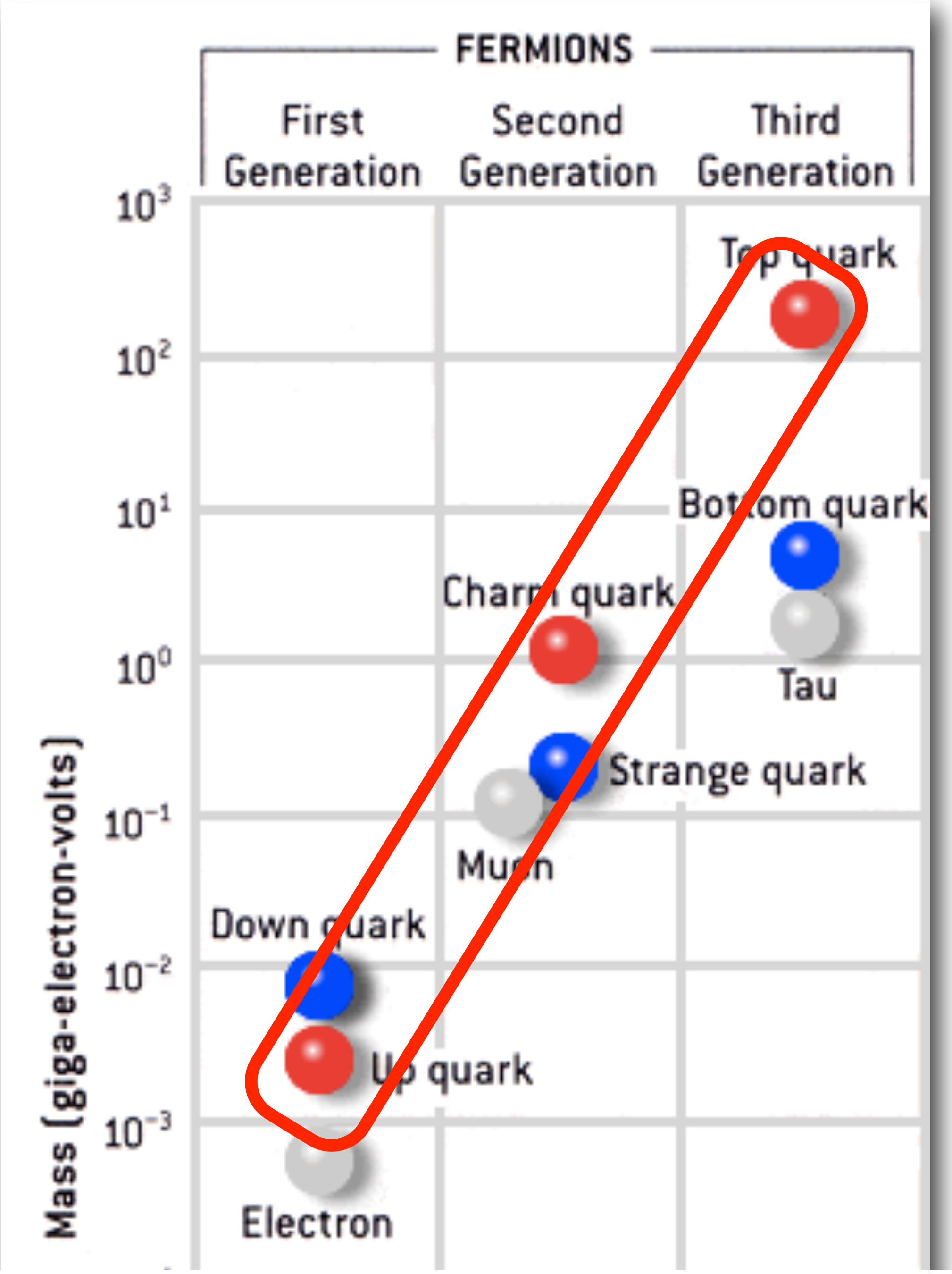

$$\frac{m_c}{m_t} \approx 0.007$$

$$\frac{m_u}{m_c} \approx 0.002$$

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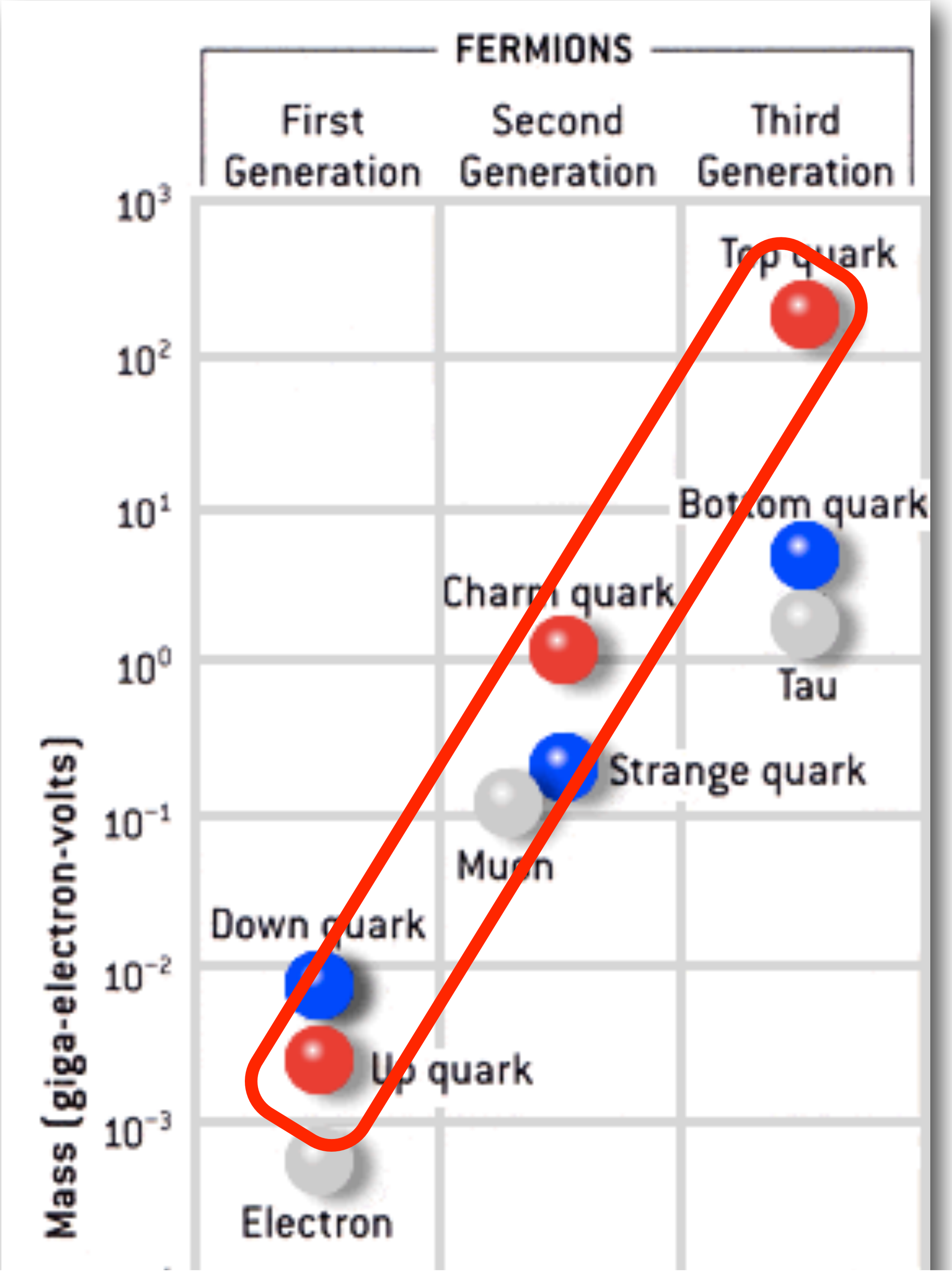
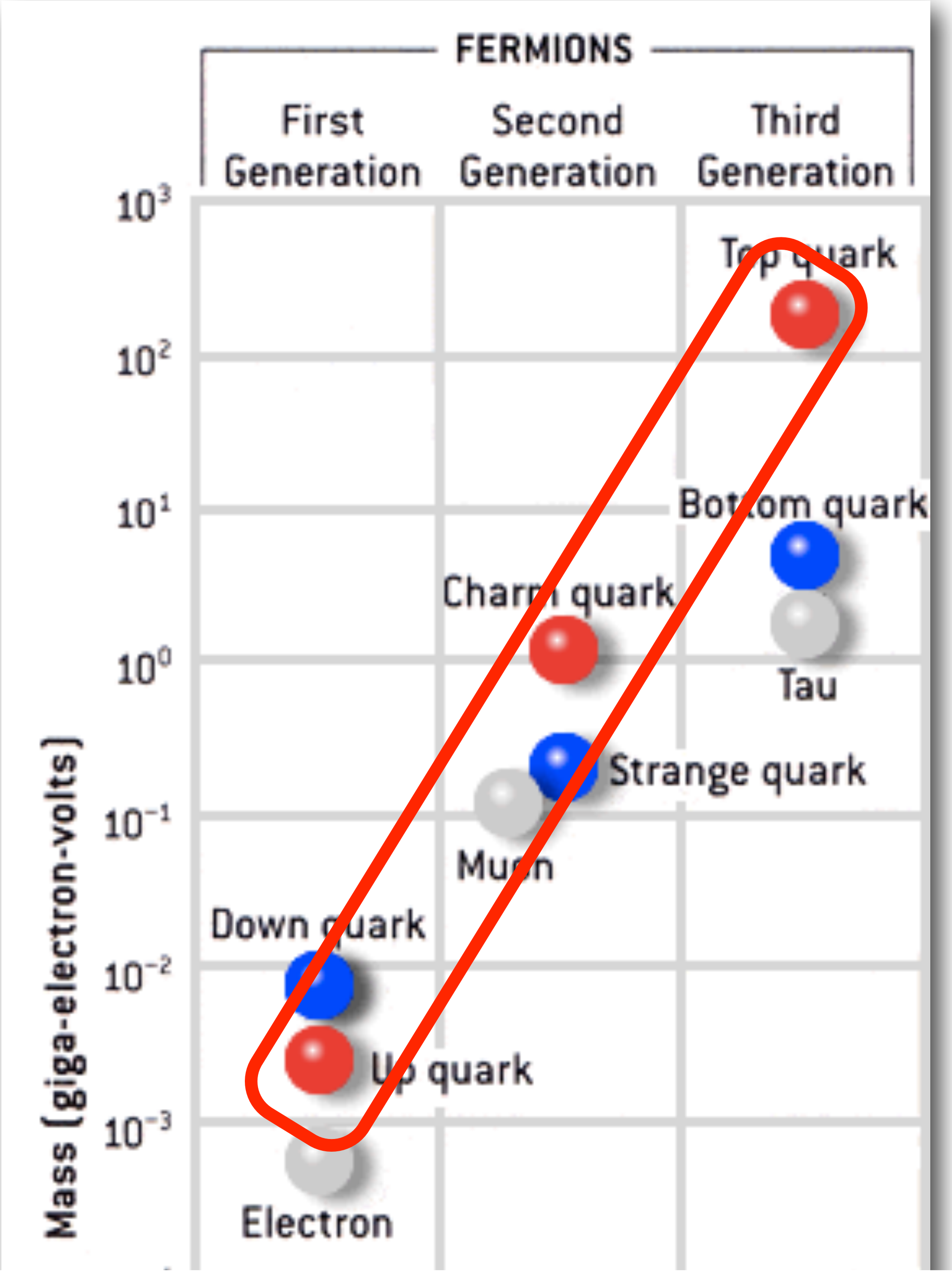


$$\frac{m_c}{m_t} \approx 0.007$$

$$\frac{m_u}{m_c} \approx 0.002$$

$$\frac{1}{16\pi^2} \approx 0.006$$

SM FLAVOR STRUCTURE



$$\frac{m_c}{m_t} \approx 0.007$$

$$\frac{m_u}{m_c} \approx 0.002$$

$$\frac{1}{16\pi^2} \approx 0.006$$

Radiative flavor generation?

Top mass : tree level

Charm mass : 1-loop

Up mass : 2-loop

RADIATIVE FLAVOR GENERATION

Old idea:

- Derive electron mass from muon mass

  Glashow, Georgi '72. Weinberg '72. Barr, Zee '77.

- Many other works including

  Ibanez '81. Balakrishna, Kagan, Mohapatra '88. Babu, Ma '89. Dobrescu, Fox '08.

- Also SUSY versions

  Ibanez '82. Banks '88. Babu, Balakrishna, Mohapatra '90. Arkani-Hamed, Cheng, Hall '96. Graham, Rajendran '09.

MIXING MATRICES

$$\mathbf{V}_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

MIXING MATRICES

$$\mathbf{V}_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & \lambda & 0 \\ \lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

MIXING MATRICES

$$\mathbf{V}_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & 0 \\ \lambda & 1 & \lambda^2 \\ 0 & \lambda^2 & 1 \end{pmatrix}$$

MIXING MATRICES

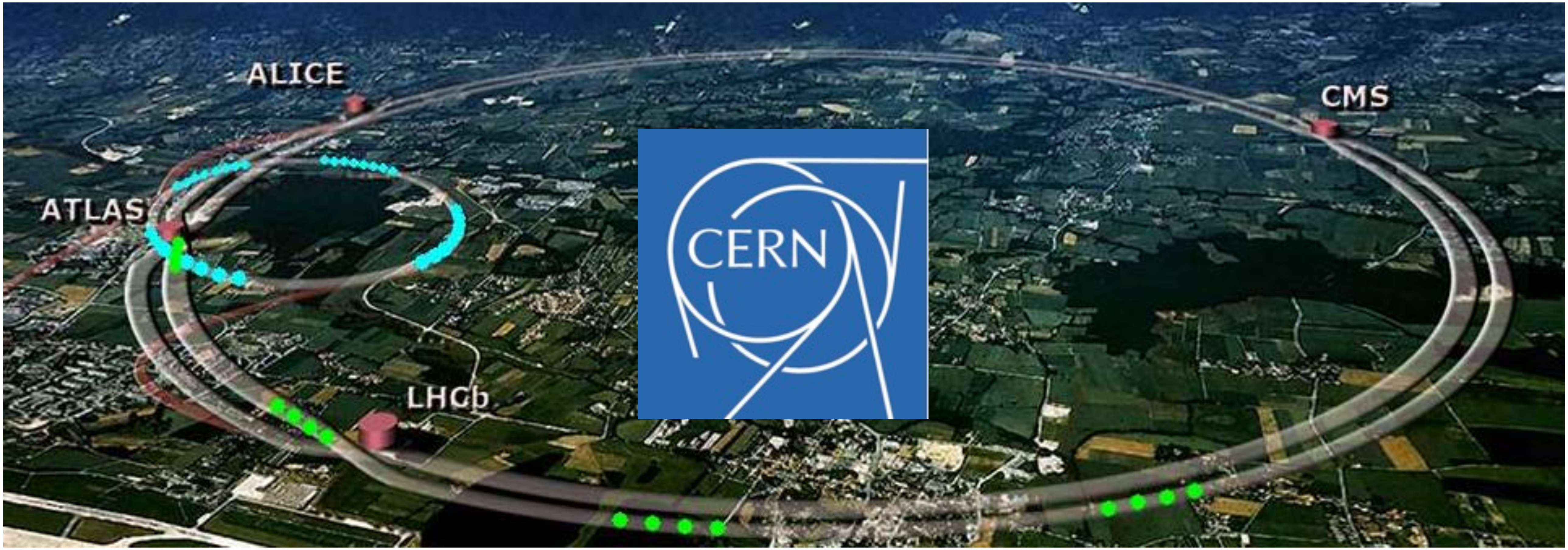
$$\mathbf{V}_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

MIXING MATRICES

$$\mathbf{V}_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

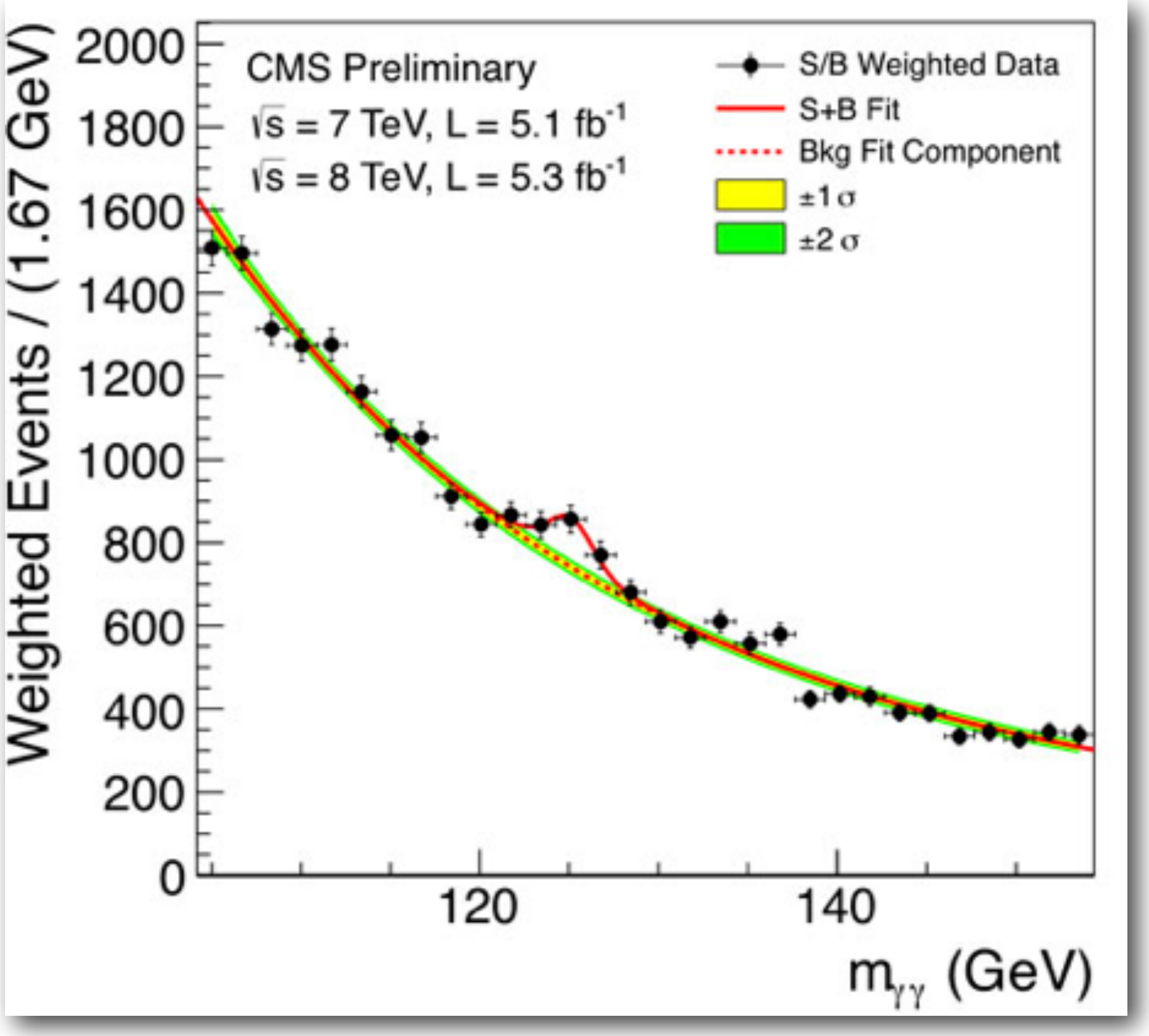
$$\mathbf{V}_{\mathrm{MNS}} \sim \begin{pmatrix} 1 & 1 & \lambda \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

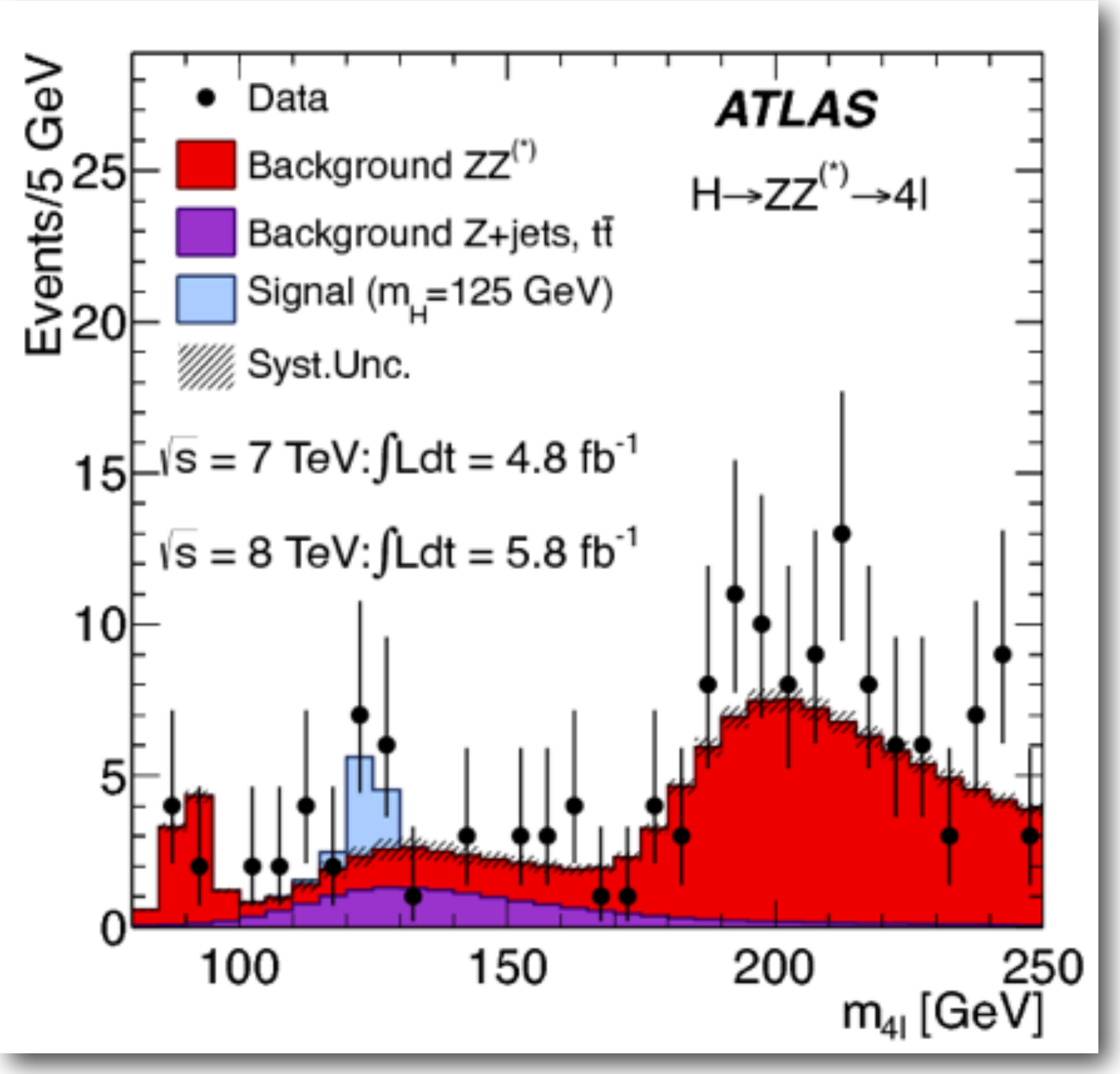
LARGE HADRON COLLIDER



LHC is exploring the TeV scale.

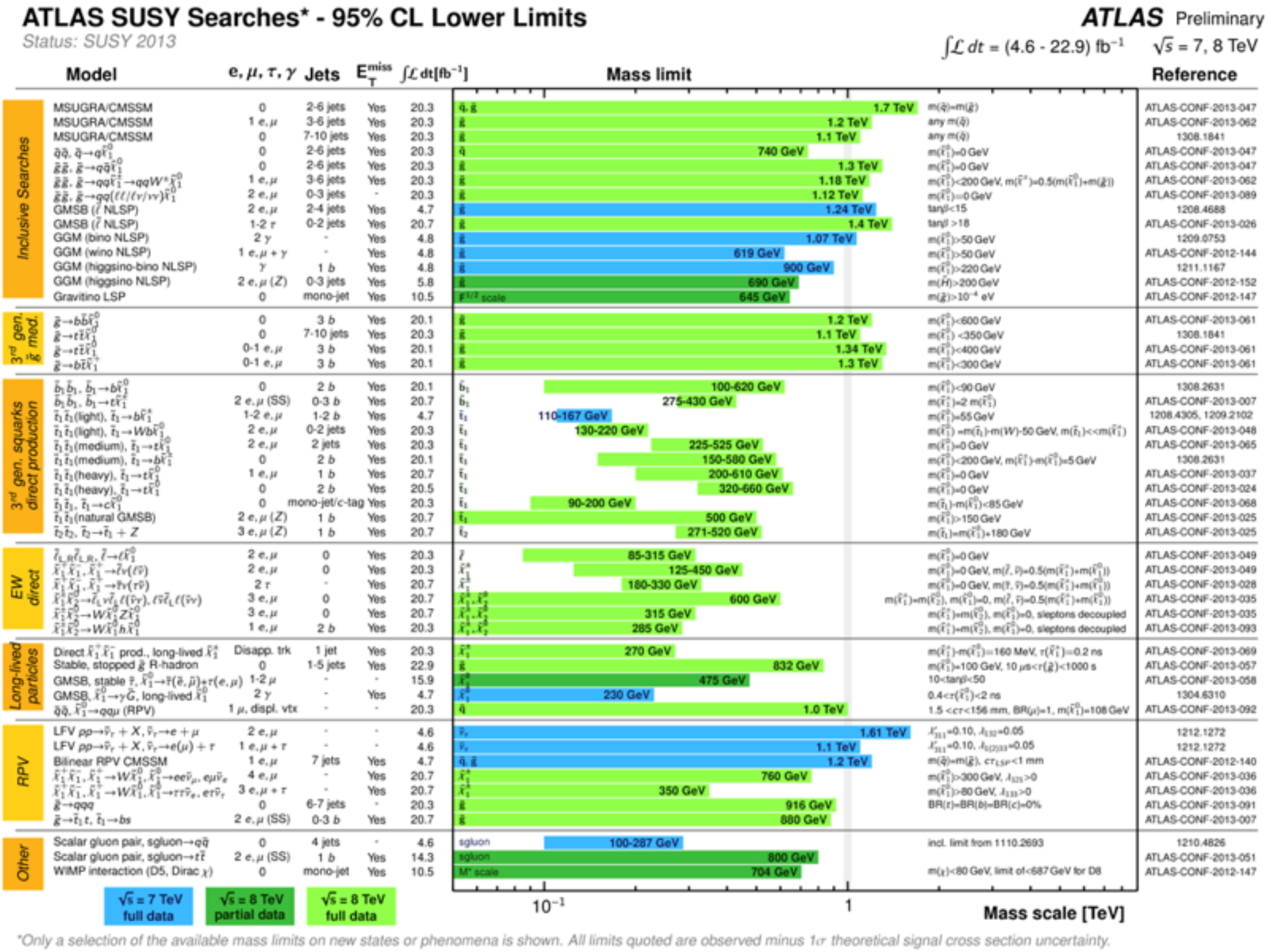
HIGGS DISCOVERY





Higgs-like particle discovered with mass around 126 GeV!

NO BSM PHYSICS



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int\mathcal{L}\,dt = (4.6 - 22.9)\ \text{fb}^{-1}$ $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	$m(\tilde{\chi}_1^{\pm})=2\,m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^{\pm})$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	315 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	285 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e+\mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon	800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

🟦 $\sqrt{s}$ = 7 TeV full data

🟩 $\sqrt{s}$ = 8 TeV partial data

🟩 $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

WHAT NOW?

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Run I of the LHC has sharpened the hierarchy problem

We appear to have an elementary scalar, yet no sense of how its radiative corrections are tamed

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Nature could be fine-tuned to the Planck scale...

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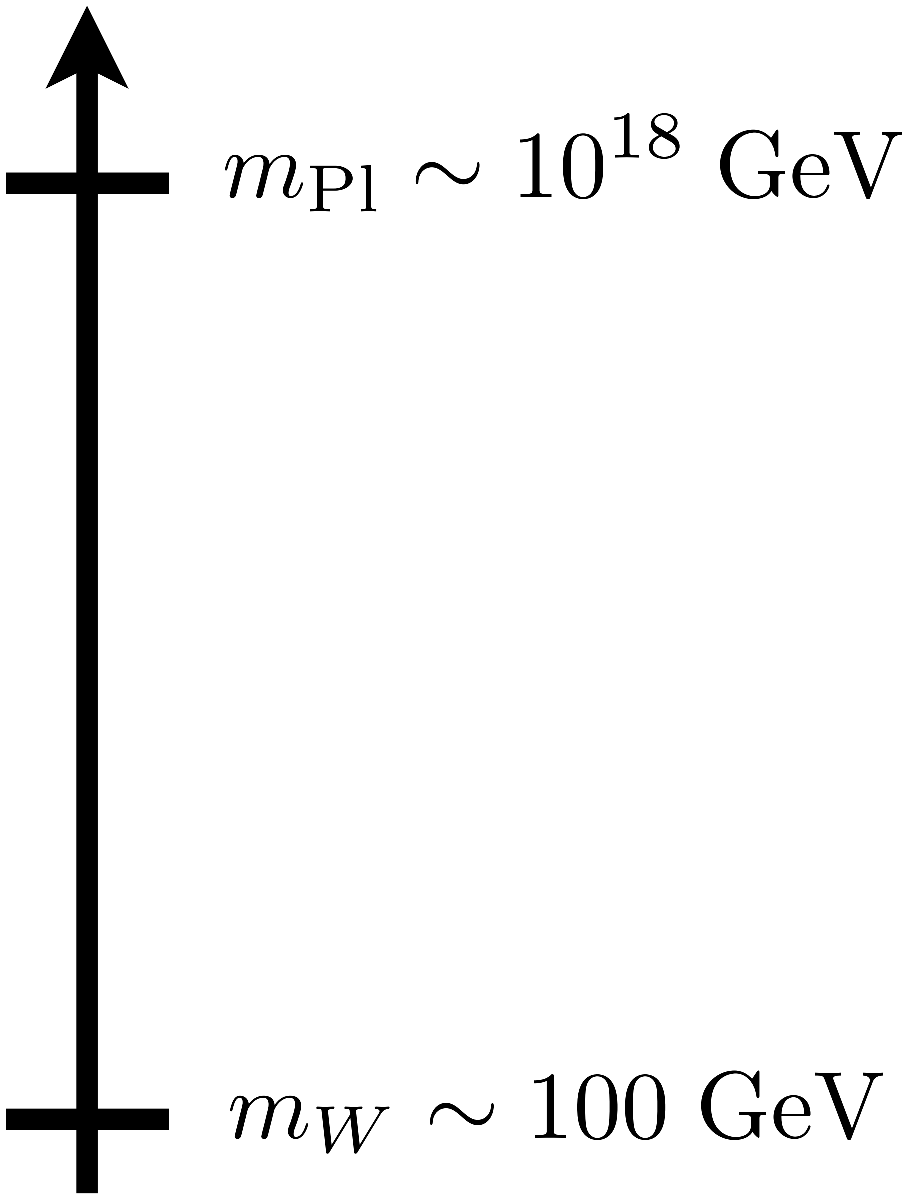
Run I of the LHC has sharpened the hierarchy problem

We appear to have an elementary scalar, yet no sense of how its radiative corrections are tamed

Nature could be fine-tuned to the Planck scale...

...or we could live in a meso-tuned world.

MESO-TUNING

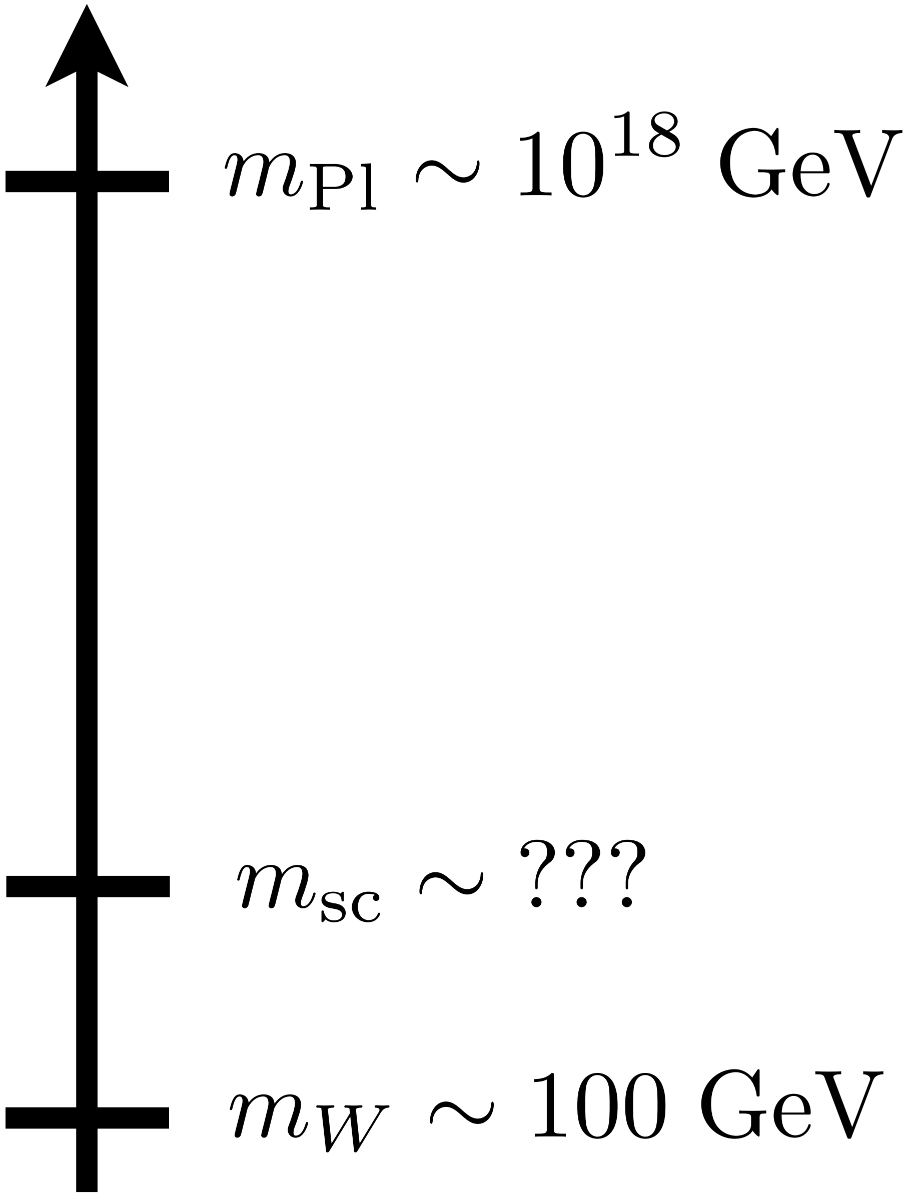


$m_{\rm Pl} \sim 10^{18}$ GeV

$m_W \sim 100$ GeV

SM tuning: $\left(\frac{m_W}{m_{\rm Pl}}\right)^2 \sim 10^{-32}$

MESO-TUNING



$m_{\rm Pl} \sim 10^{18}$ GeV

$m_{\rm sc} \sim ???$

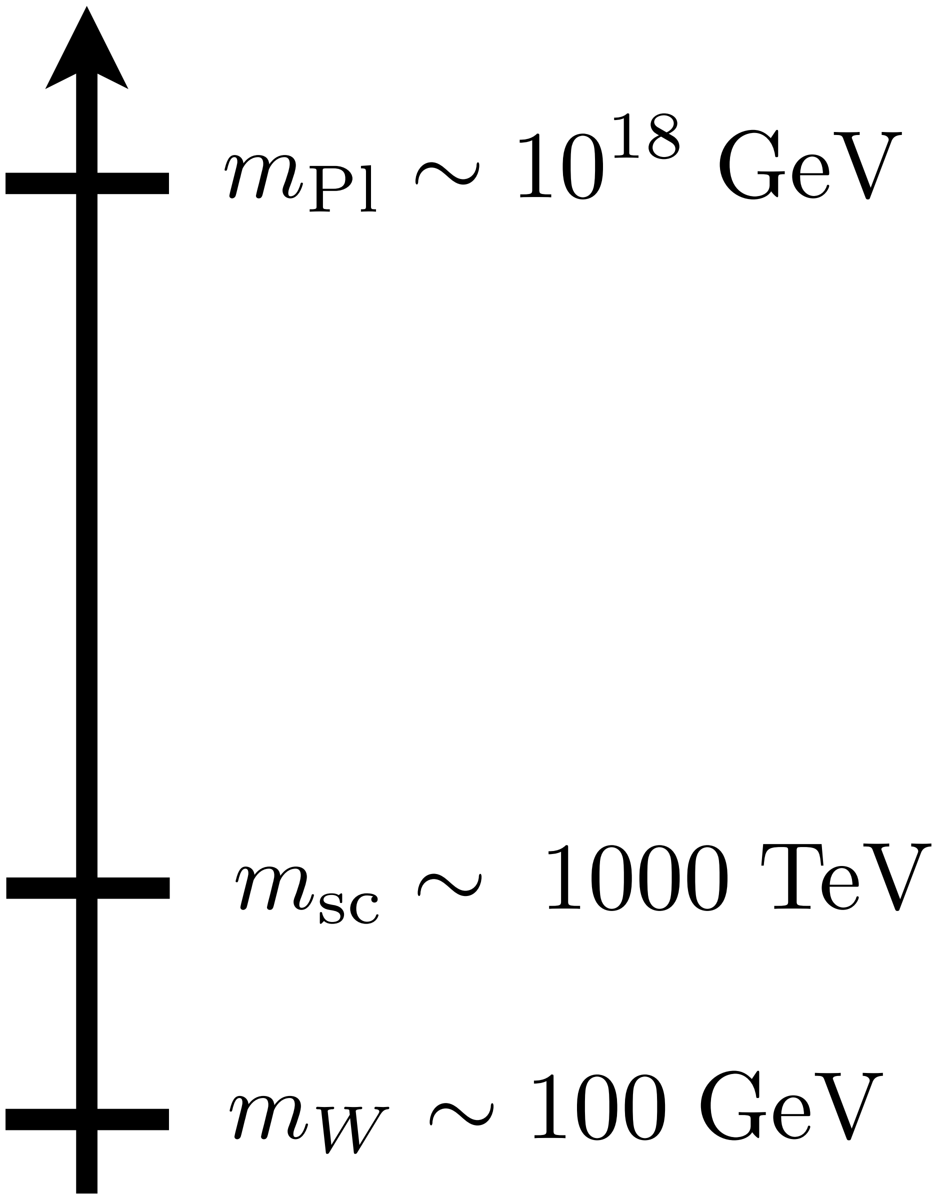
$m_W \sim 100$ GeV

SM tuning: $\left(\frac{m_W}{m_{\rm Pl}}\right)^2 \sim 10^{-32}$

Can reduce tuning to

$$\left(\frac{m_W}{m_{\rm sc}}\right)^2$$

MESO-TUNING



$m_{\rm Pl} \sim 10^{18}$ GeV

$m_{\rm sc} \sim$ 1000 TeV

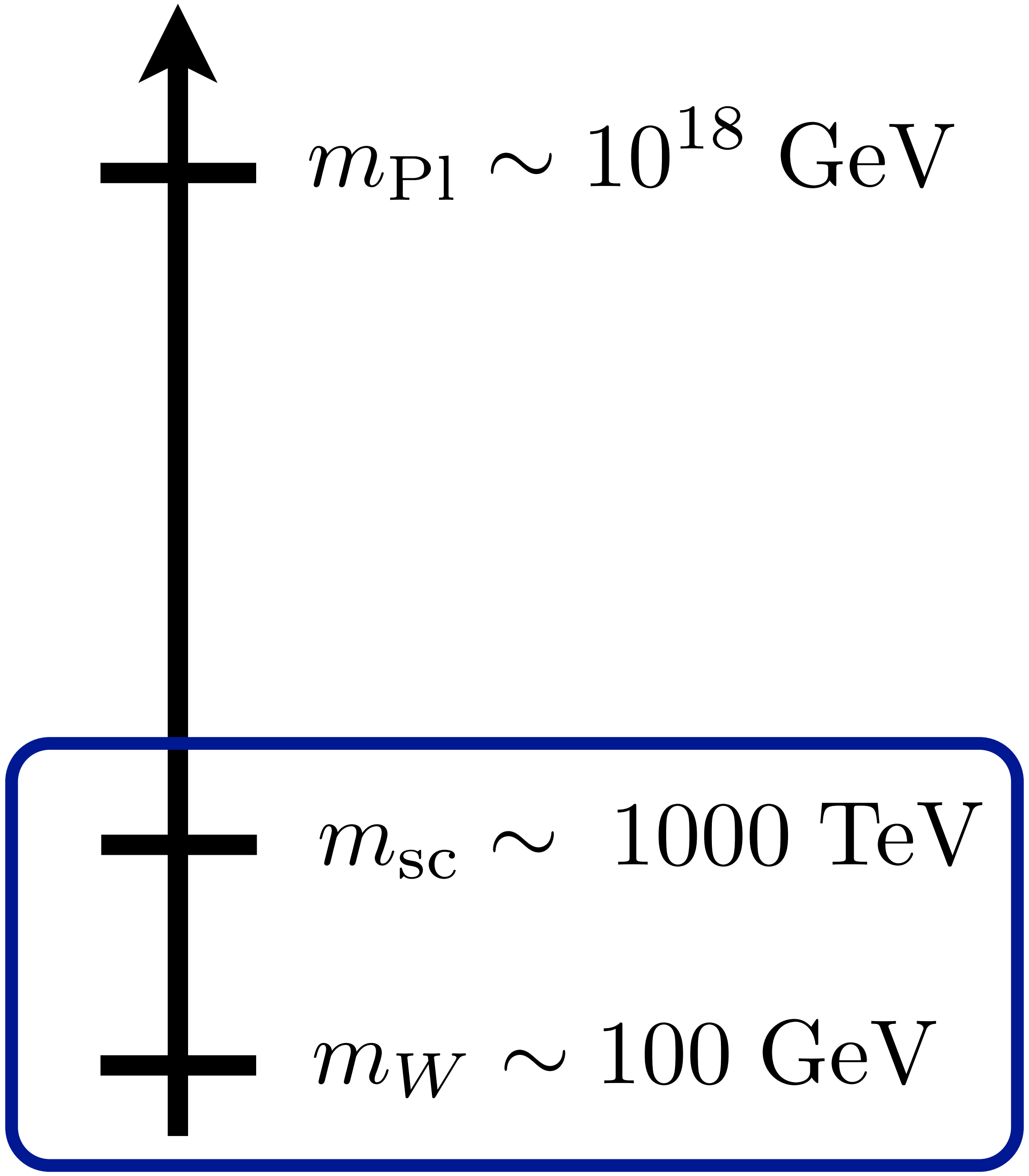
$m_W \sim$ 100 GeV

SM tuning: $\left(\frac{m_W}{m_{\rm Pl}}\right)^2 \sim 10^{-32}$

Can reduce tuning to

$$\left(\frac{m_W}{m_{\rm sc}}\right)^2 \sim 10^{-8}$$

MESO-TUNING



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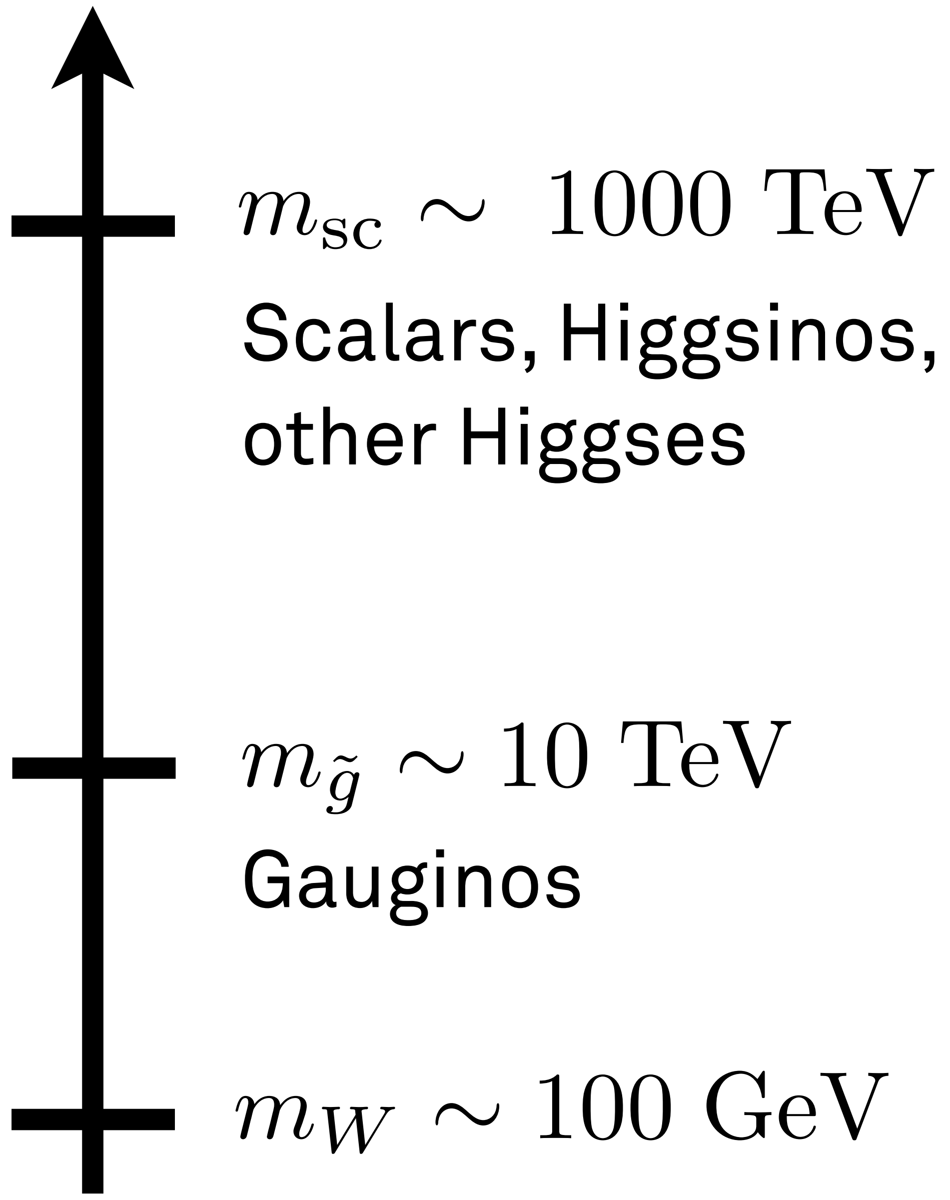
Can reduce tuning to

$$\left(\frac{m_W}{m_{\rm sc}}\right)^2 \sim 10^{-8}$$

MINI-SPLIT SUPERSYMMETRY



$m_{\rm sc} \sim \; 1000 \text{ TeV}$

Scalars, Higgsinos, other Higgses

$m_{\tilde{g}} \sim 10 \text{ TeV}$

Gauginos

$m_W \sim 100 \text{ GeV}$

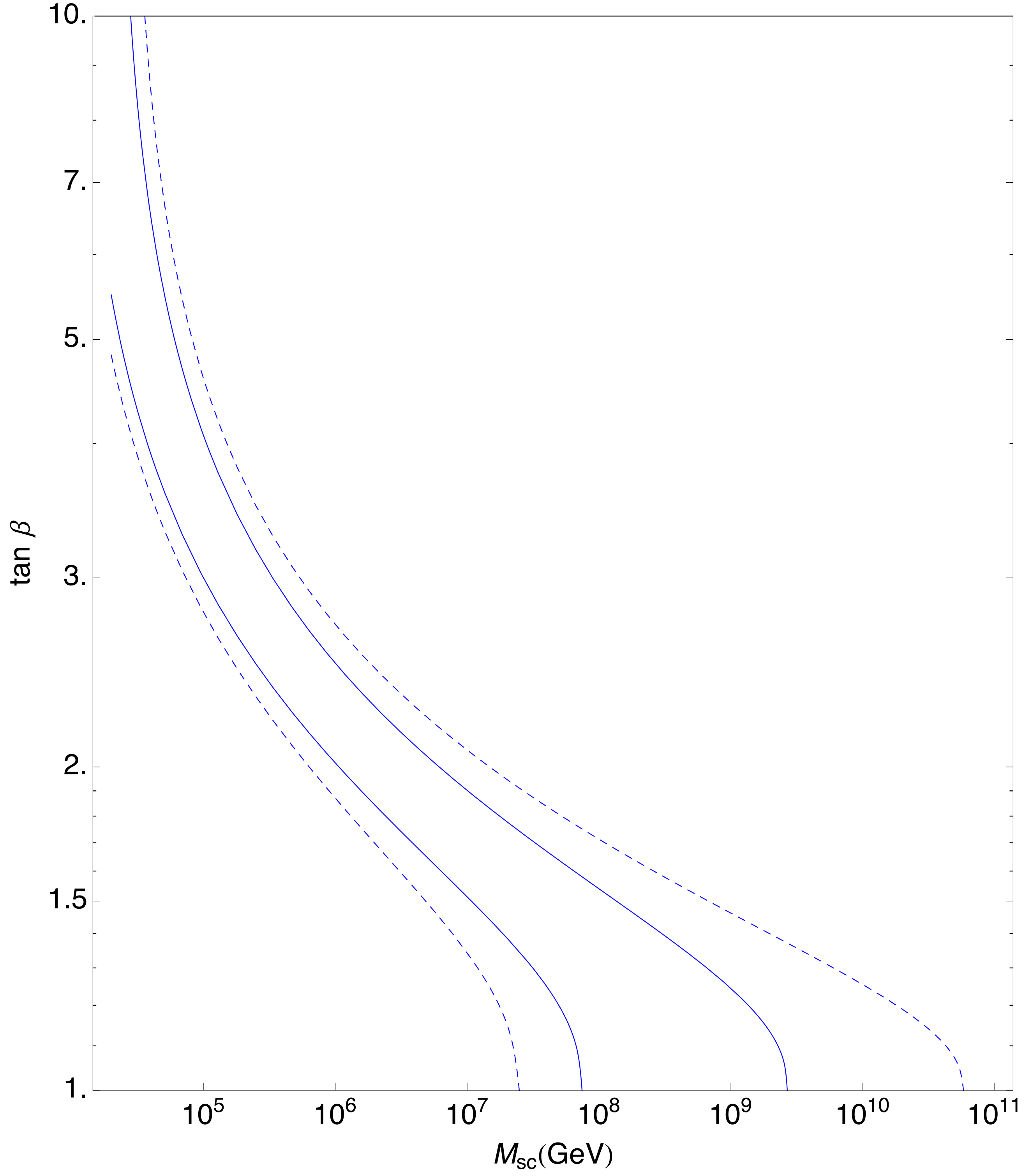
Implement meso-tuning in the context of Split Supersymmetry

Wells '04. Arkani-Hamed, Dimopoulos '04. Giudice, Romanino '04.

Mini-split SUSY has received a great deal of attention recently

Hall, Nomura '11. Kane, Kumar, Lu, Zheng '11. Ibe, Matsumoto, Yanagida, '12. Arvanitaki, Craig, Dimopoulos, Villadoro, '12, Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski, '12.

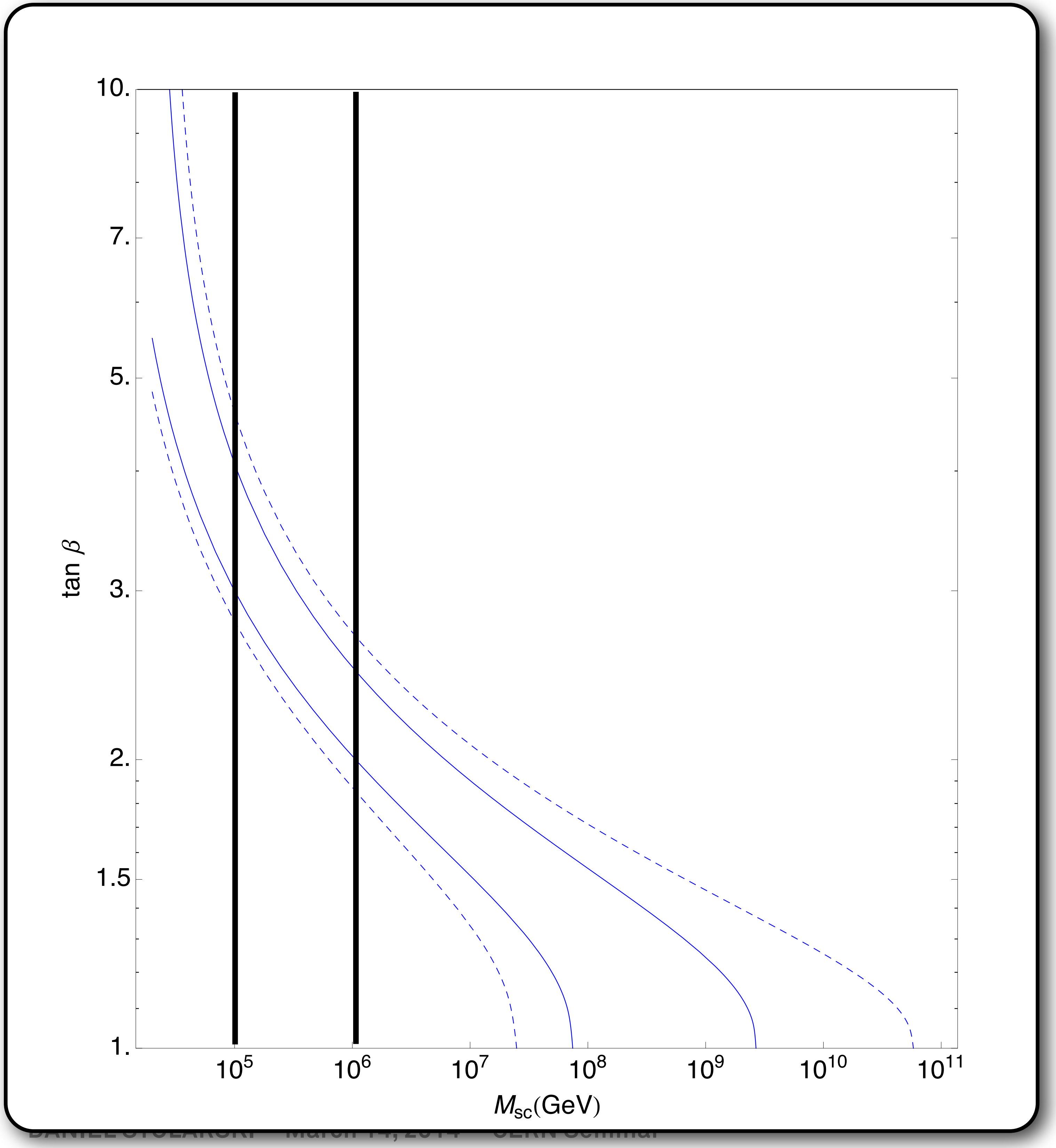
HIGGS MASS



$$m_h = 125.7 \pm 0.8 \text{ GeV}$$

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski, '12.

HIGGS MASS



$$m_h = 125.7 \pm 0.8 \text{ GeV}$$

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski, '12.

SUSY BREAKING

Naive gravity mediated SUSY breaking

Scalar masses: $\int d^4\theta \frac{X^\dagger X}{M_{\rm Pl}^2}\Phi^\dagger\Phi \;\Rightarrow\; m_0 \simeq m_{3/2}$

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SUSY breaking field

MSSM matter field

SUSY BREAKING

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If *X* has some charge, gaugino mass forbidden at tree level $\int d^2\theta \frac{X}{M_{\rm Pl}} W^\alpha W_\alpha$

SUSY BREAKING

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$$\xcancel{\int d^2\theta \frac{X}{M_{\rm Pl}} W^\alpha W_\alpha}$$

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If *X* has some charge, gaugino mass forbidden at tree level

$$\cancel{\int d^2\theta \frac{X}{M_{\rm Pl}} W^\alpha W_\alpha}$$

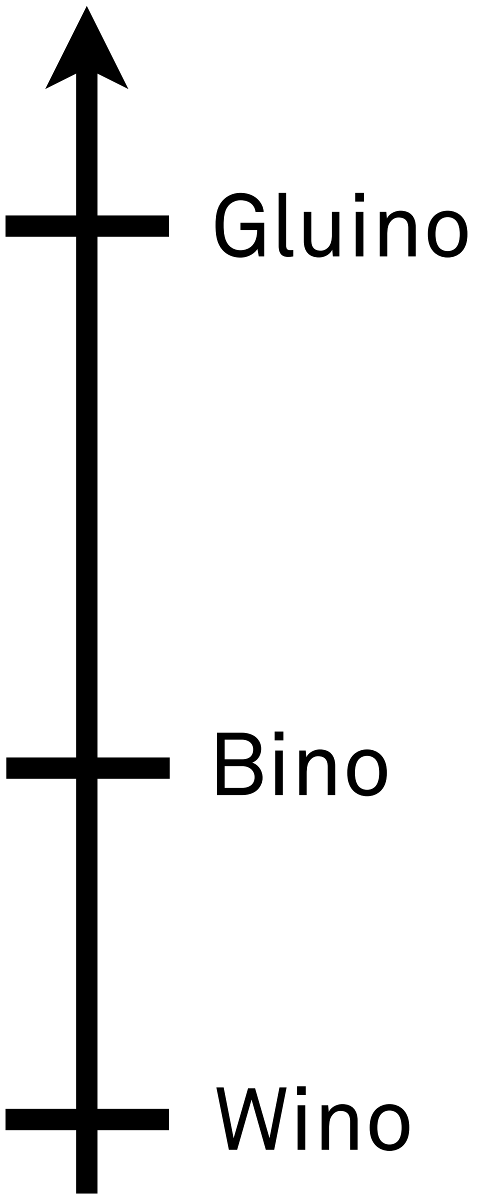
Gaugino masses at one loop from anomaly mediation

$$m_{1/2} \simeq \frac{g^2}{16\pi^2} m_{3/2}$$

Giudice, Luty, Murayama, Rattazzi '98.

Randall, Sundrum '98.

DARK MATTER

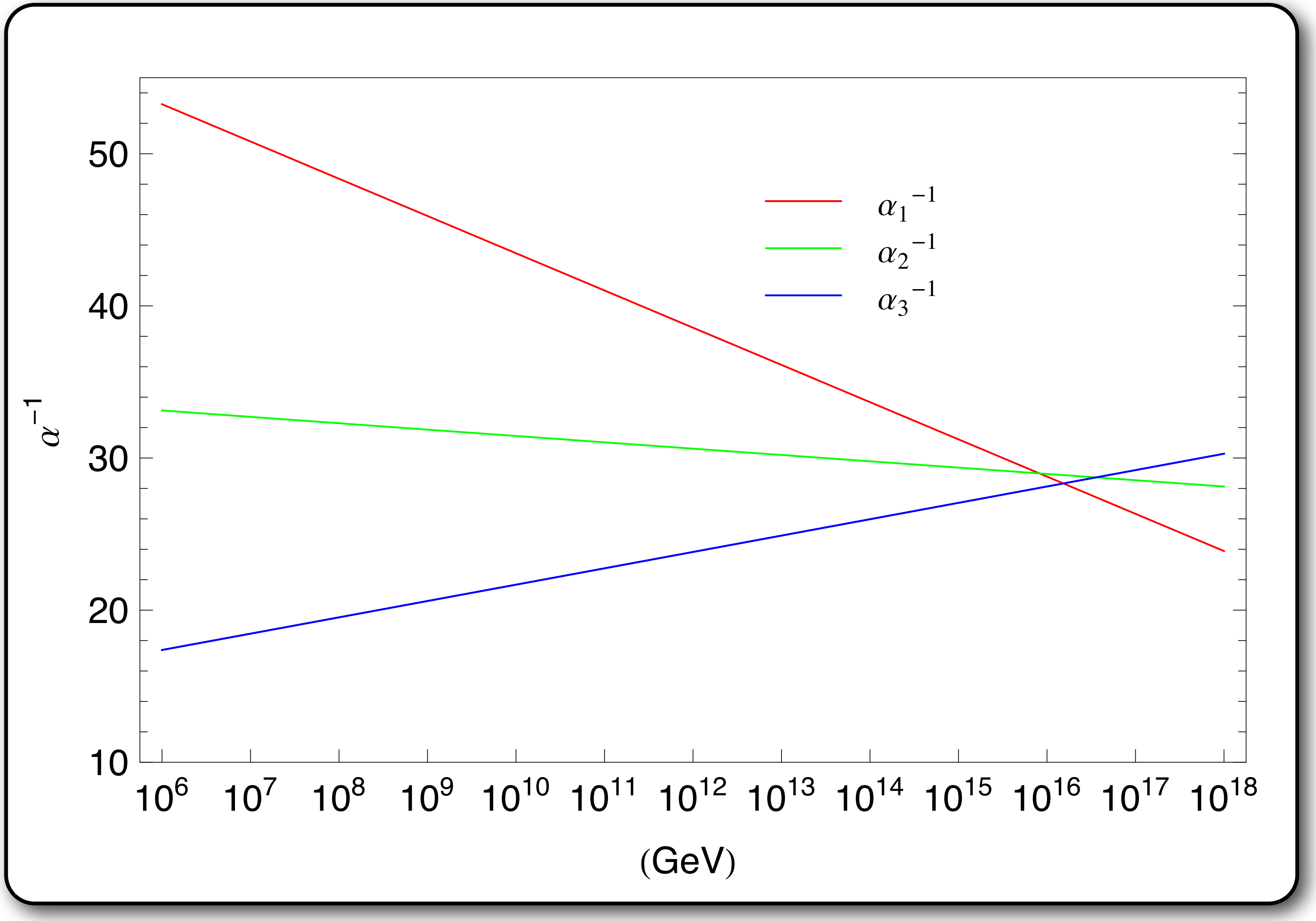


Anomaly mediation predicts Wino LSP

Wino LSP with mass ~ 3 TeV gives correct WIMP dark matter density

Hisano, Matsumoto, Nagai, Saito, Senami, '06.

GAUGE UNIFICATION



$$m_{\tilde{g}} = 14.4 \text{ TeV}$$

$$m_{\tilde{W}} = 2.6 \text{ TeV}$$

$$m_{\text{sc}} = \mu = 1000 \text{ TeV}$$

$$\tan\beta = 2.2$$

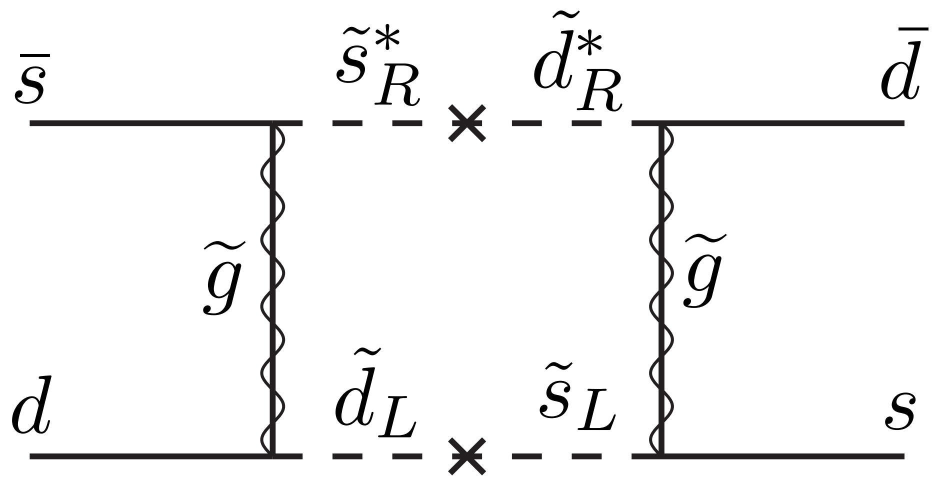
Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski, '12.

SUSY FLAVOR PROBLEM

Scalar masses generically change flavor:

$$\int d^4\theta \frac{X^\dagger X}{M_{\mathrm{Pl}}^2} Q_i^\dagger Q_j$$

Ruled out for TeV scale squarks:

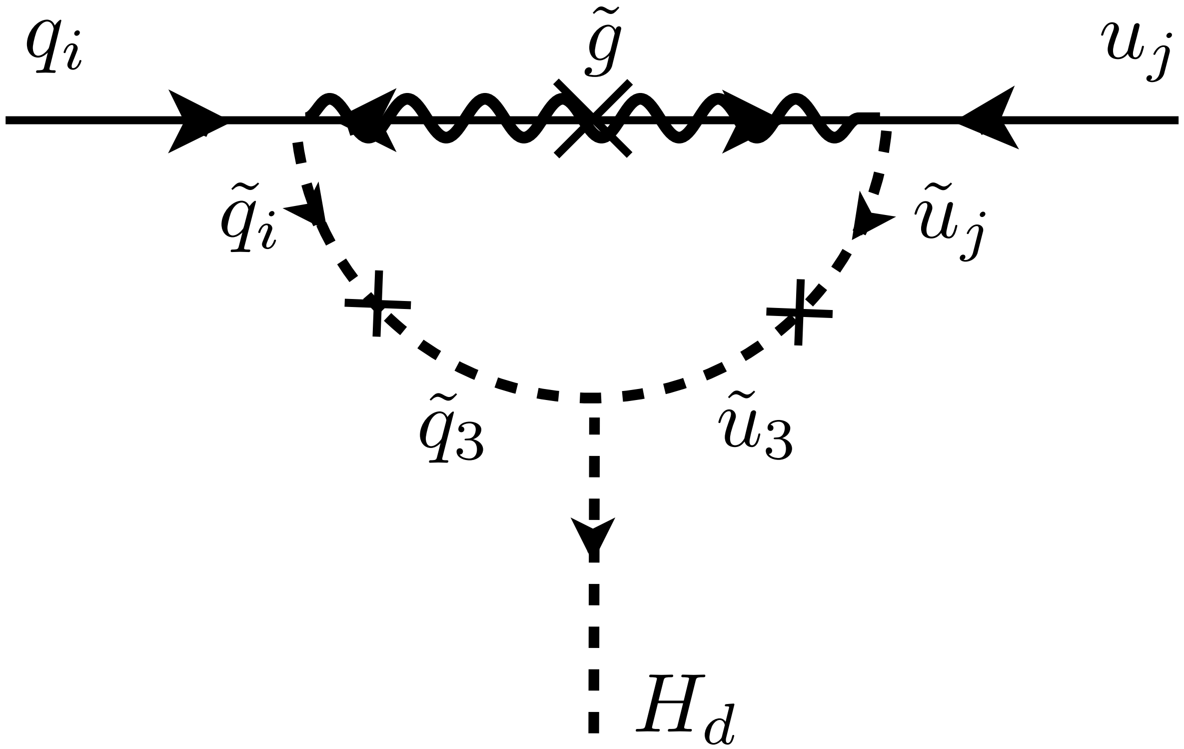


Kaon mixing motivates choice of 1000 TeV squark mass

SUSY FLAVOR FEATURE

Scalar masses generically change flavor: $\int d^4\theta \frac{X^\dagger X}{M_{\rm Pl}^2} Q_i^\dagger Q_j$

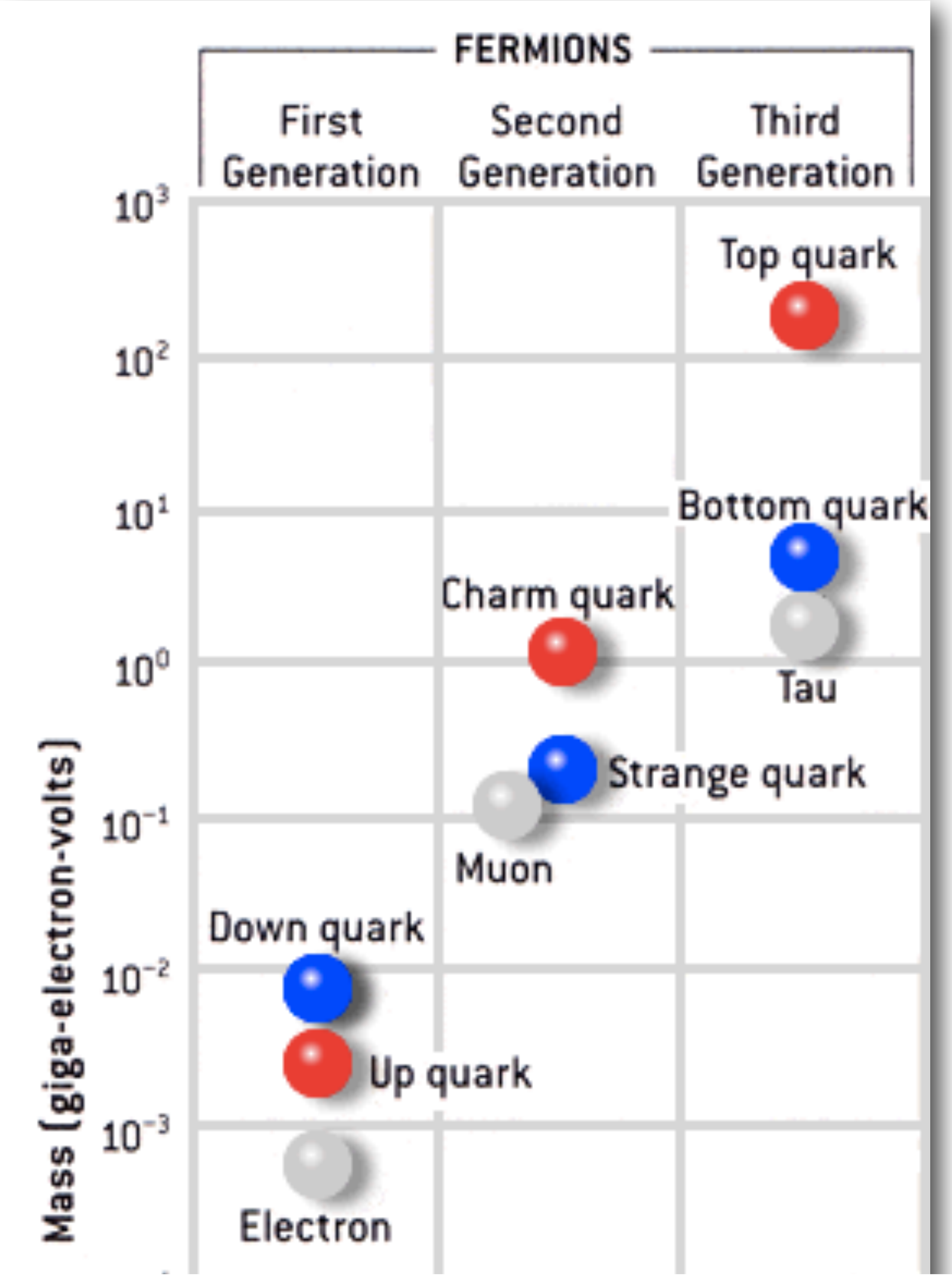
Flavor anarchy can be used to generate SM Yukawa couplings

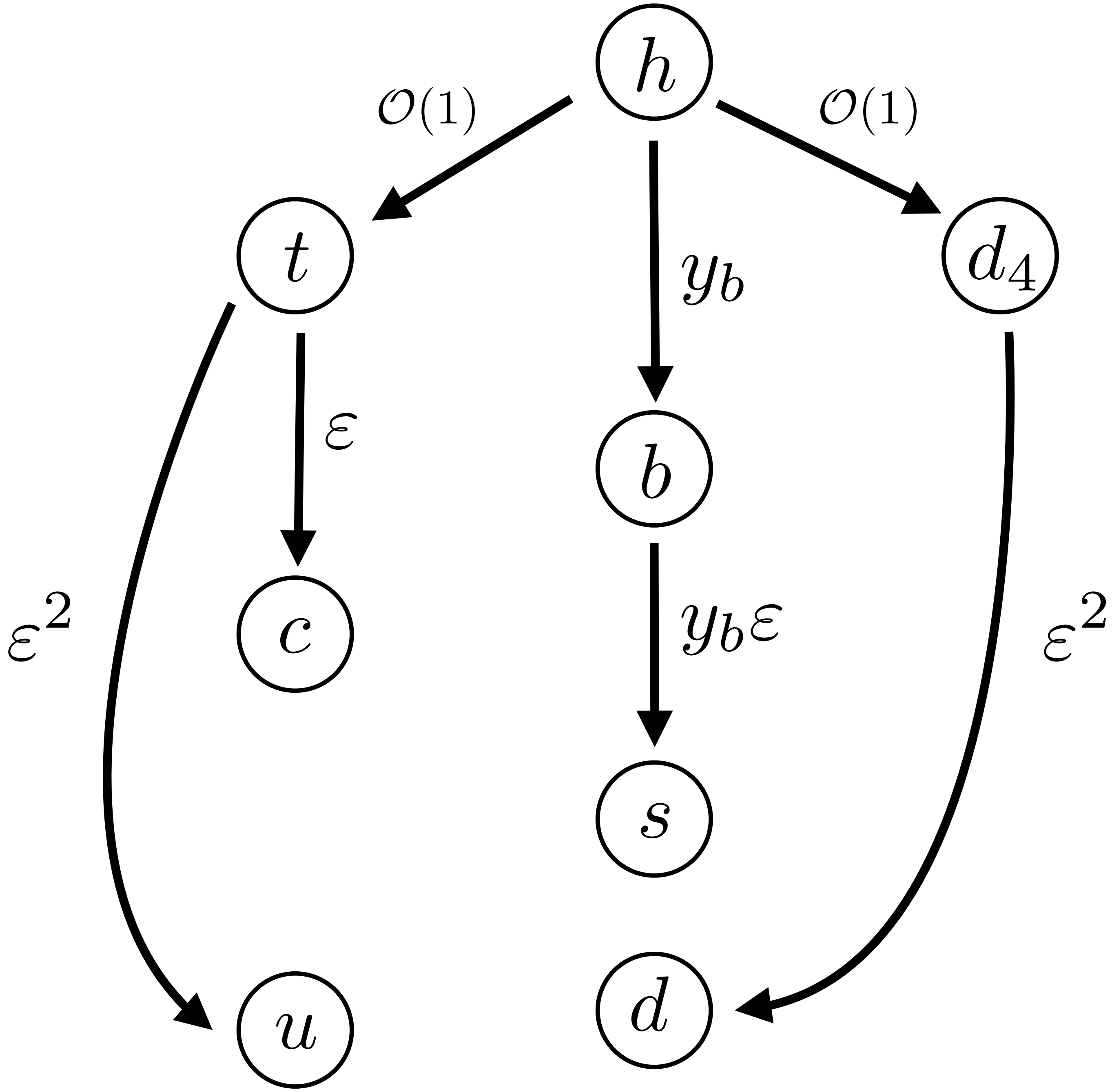


ADVANTAGES OF MINI-SPLIT

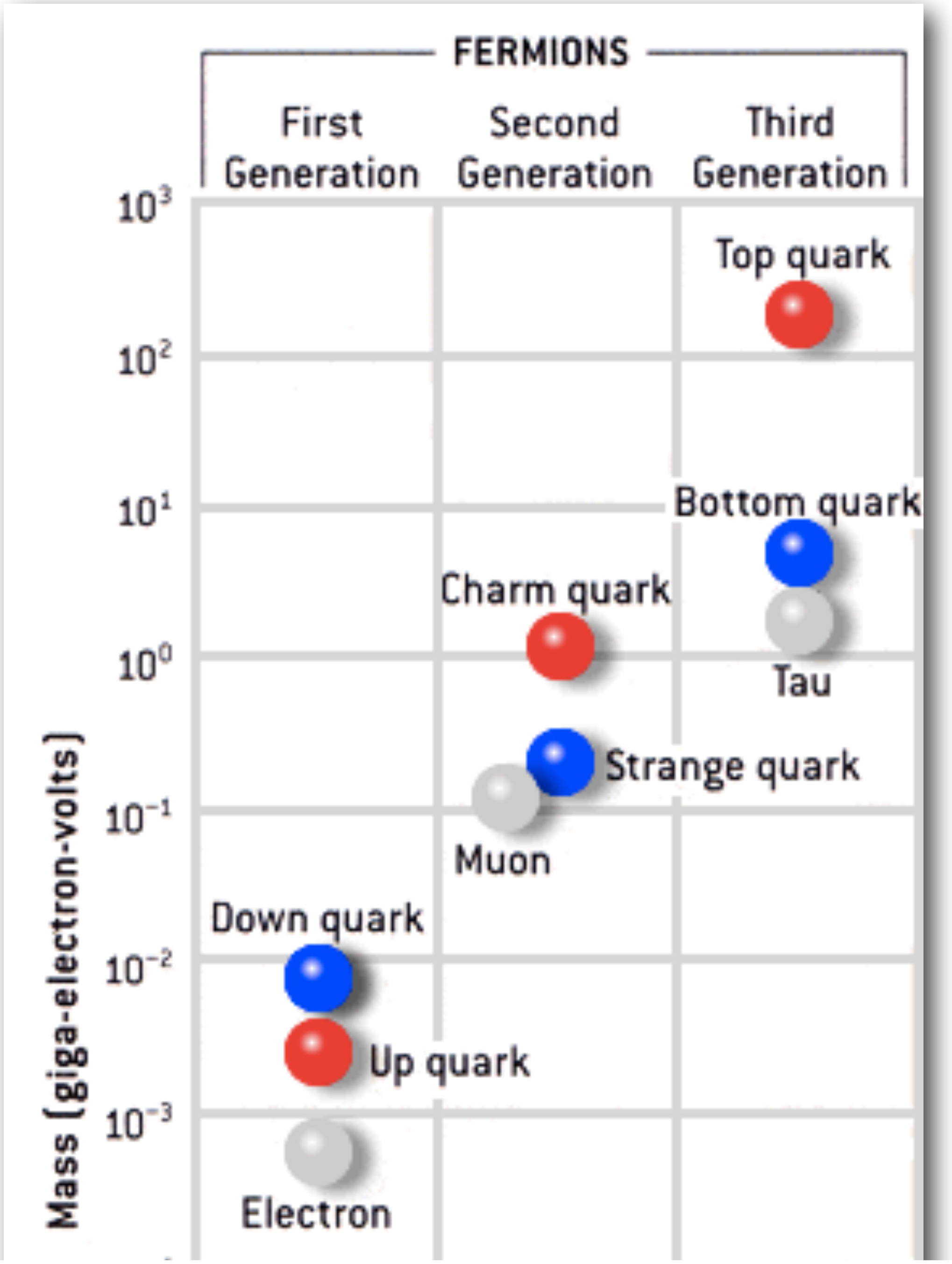
- Generate superpotential Yukawa operators by loops, can only be done in conjunction with SUSY breaking
- Scalars do some of the work, need fewer new fields than previous models
- Requires flavor anarchy in soft mass, a natural consequence of the simplest gravity mediation

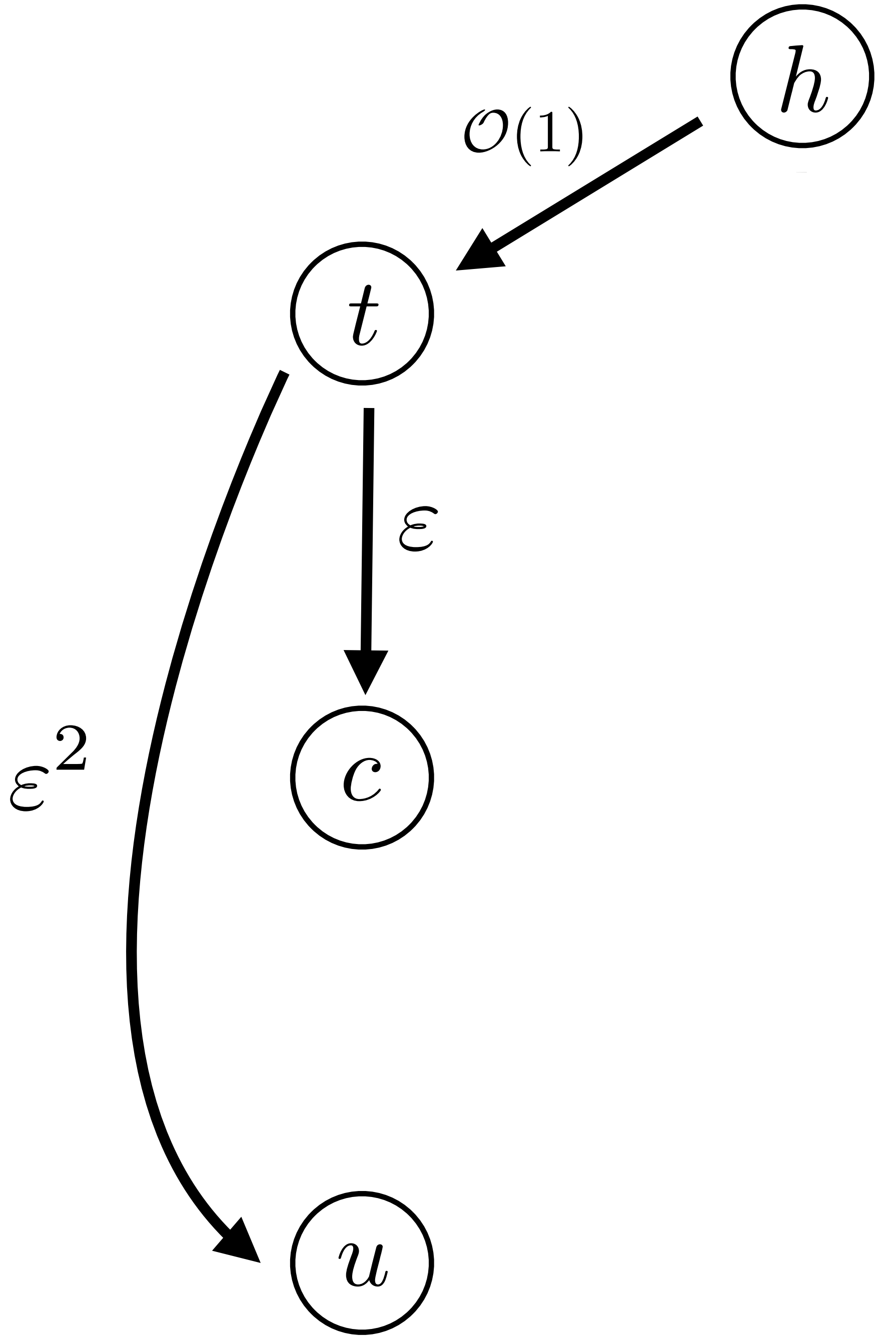
STRUCTURE OF MODEL



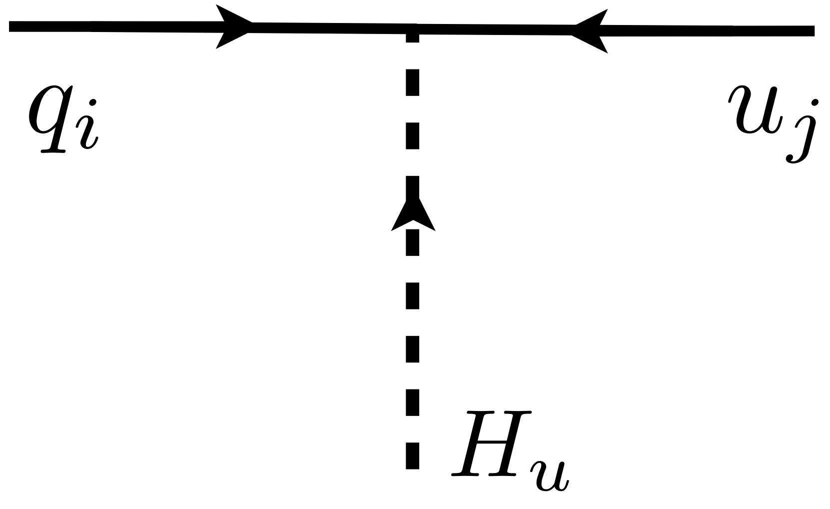


STRUCTURE OF MODEL



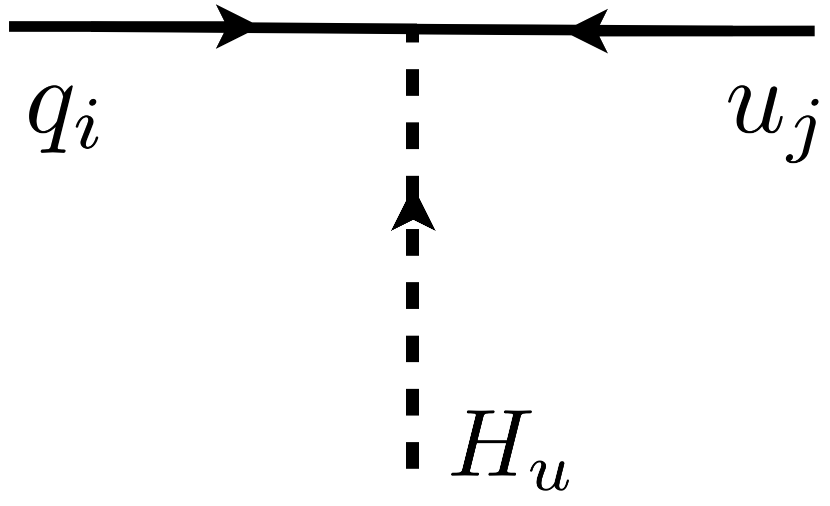


TREE LEVEL TOP MASS



TREE LEVEL TOP MASS

1. Introduce U(1) symmetry which forbids SM Yukawa coupling



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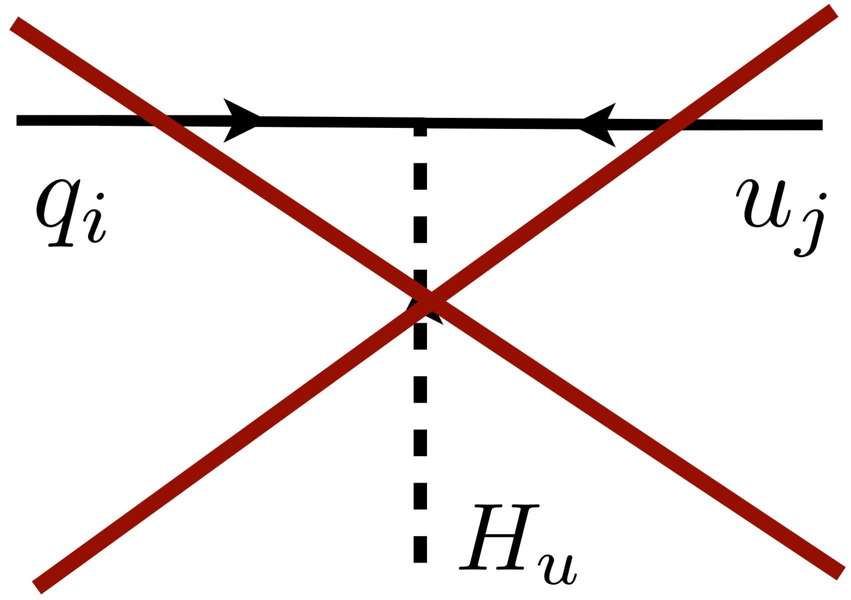

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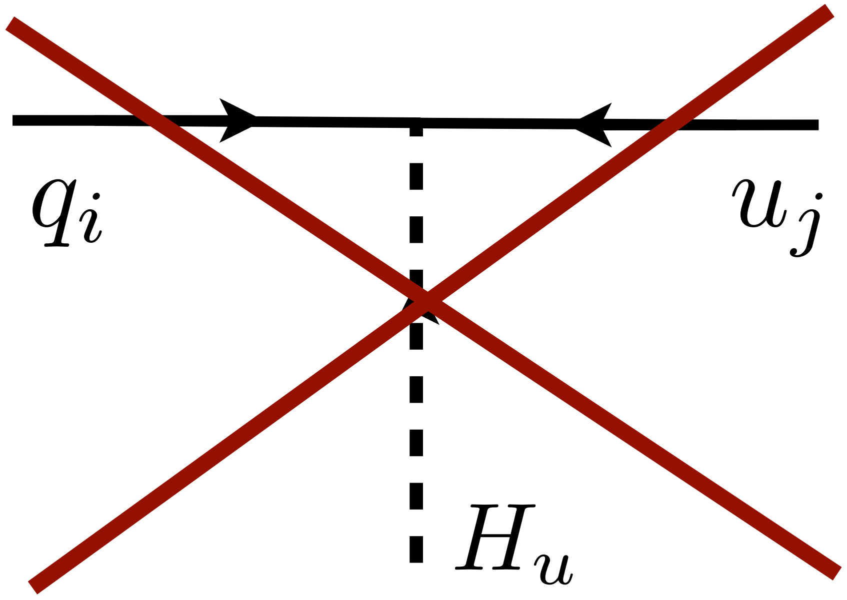
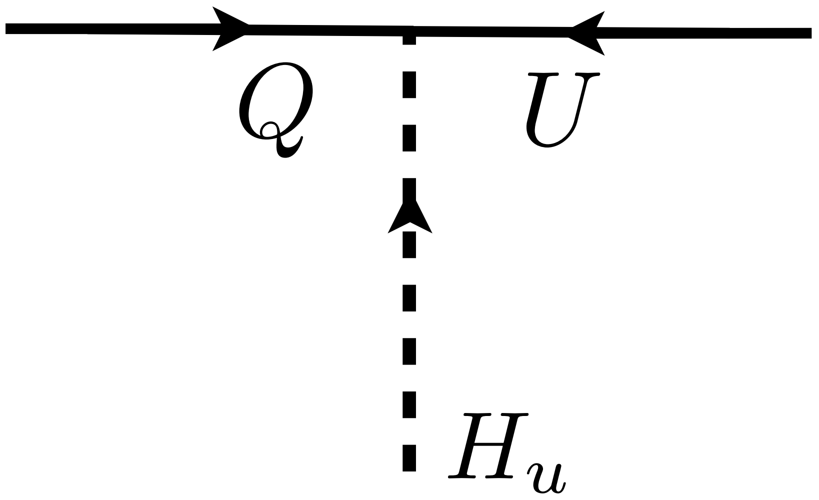
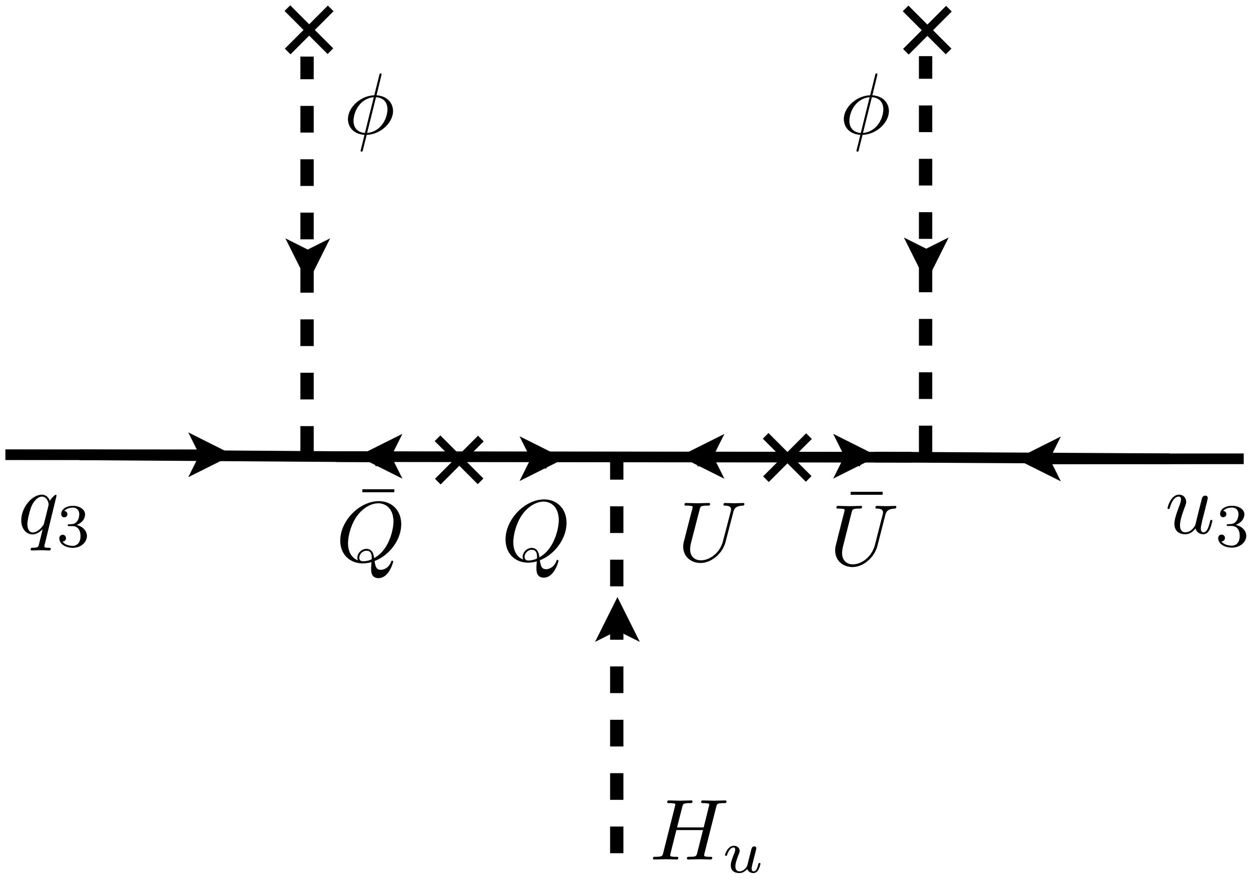


2. Add vectorlike *Q* and *U* which couple to Higgs but don’t have flavor



TREE LEVEL TOP MASS

Mix SM fields into new fermions via U(1) breaking



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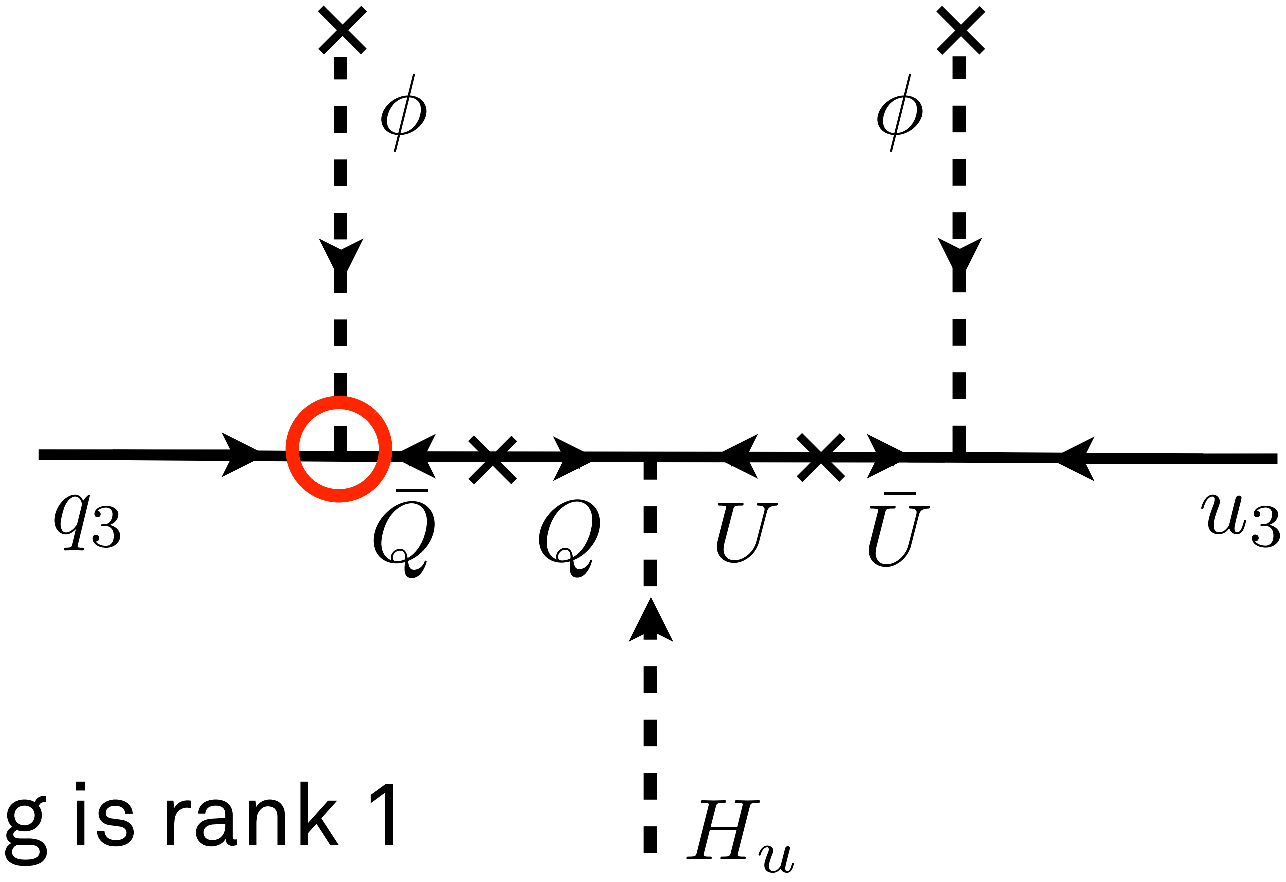

$q_i\bar{Q}$ coupling is rank 1

TREE LEVEL TOP MASS

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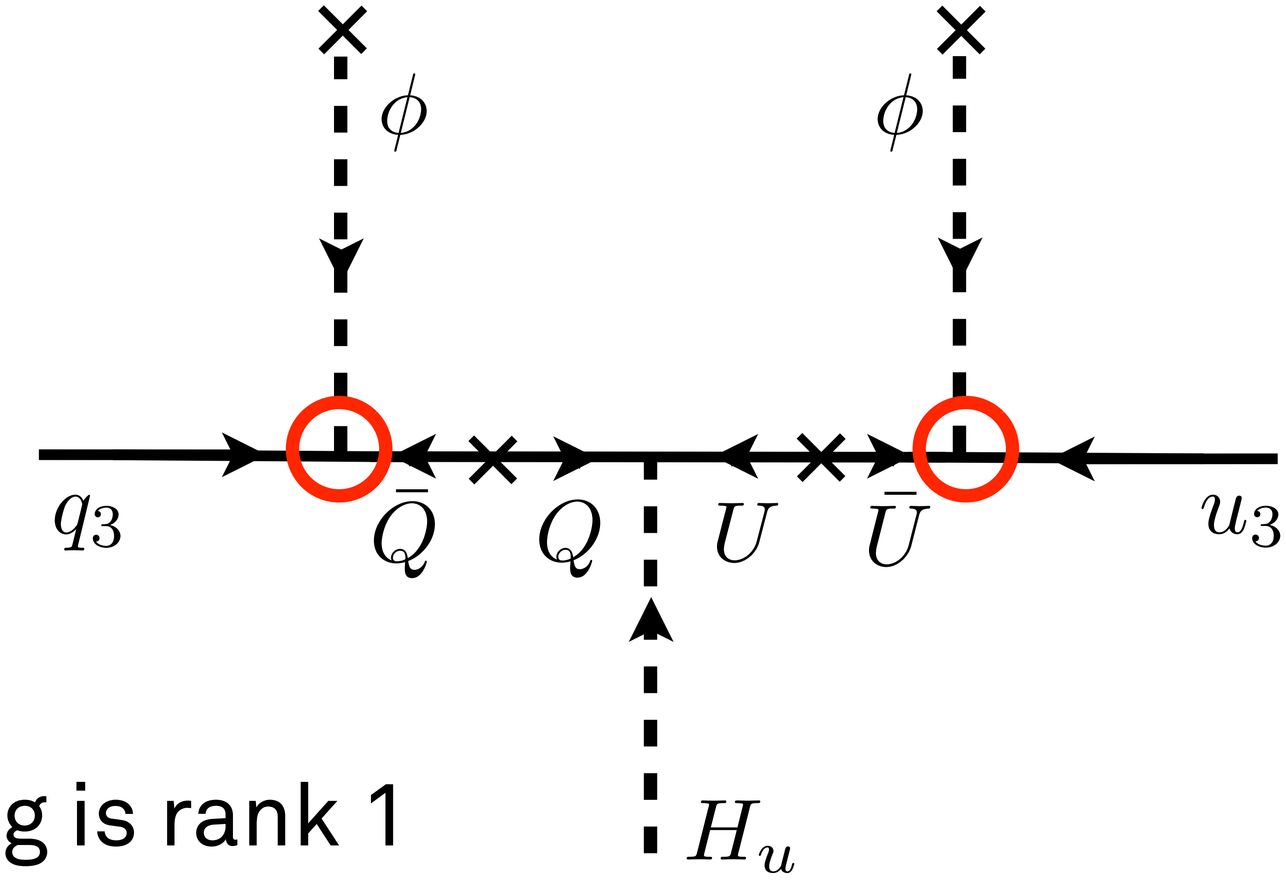

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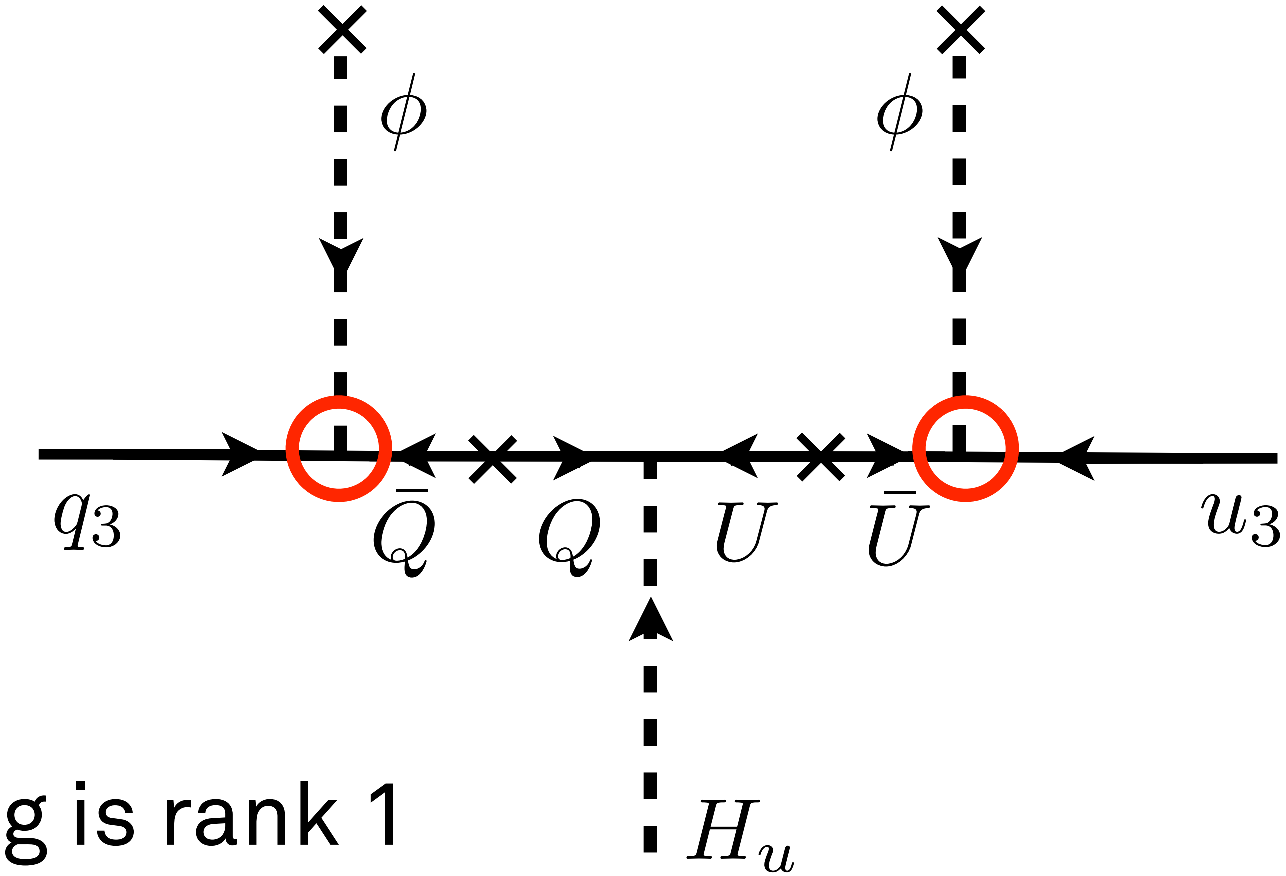
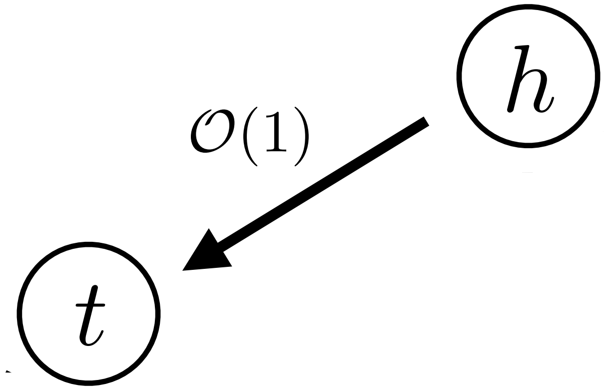


$q_i\bar{Q}$ coupling is rank 1

Only top gets mass at tree level

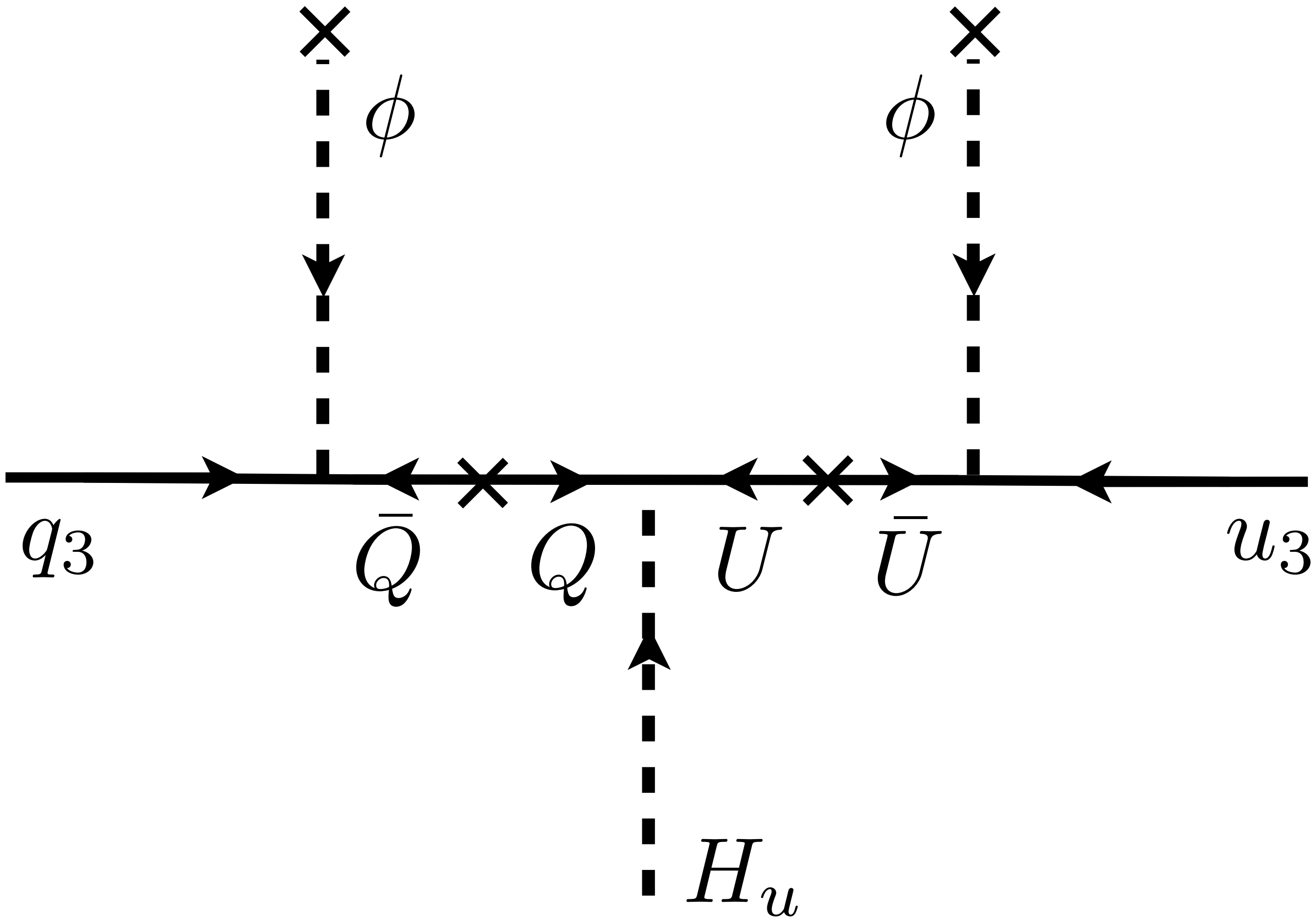
TREE LEVEL TOP MASS

$$\mathbf{y_u} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



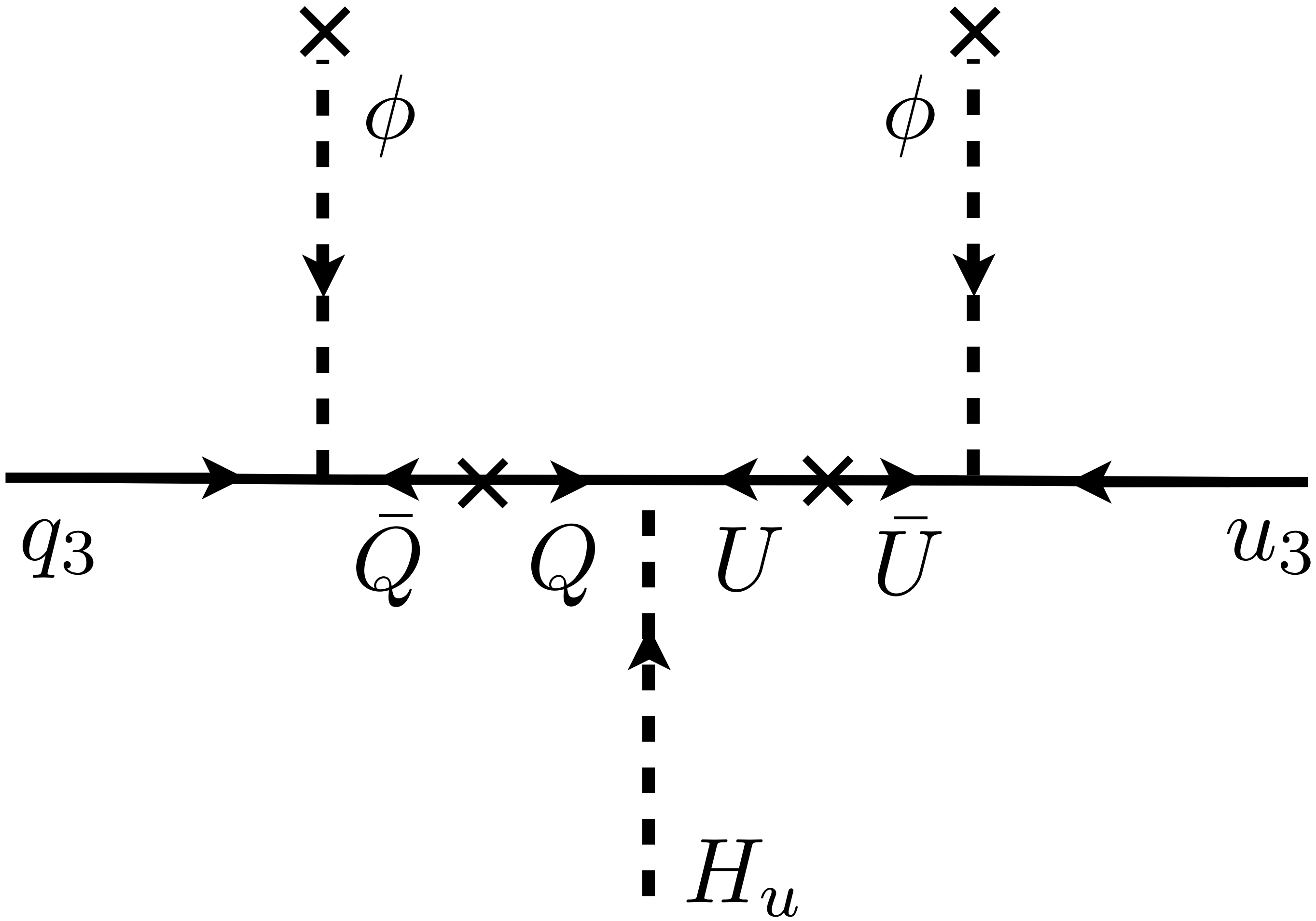
ONE LOOP CHARM MASS

ϕ



ONE LOOP CHARM MASS

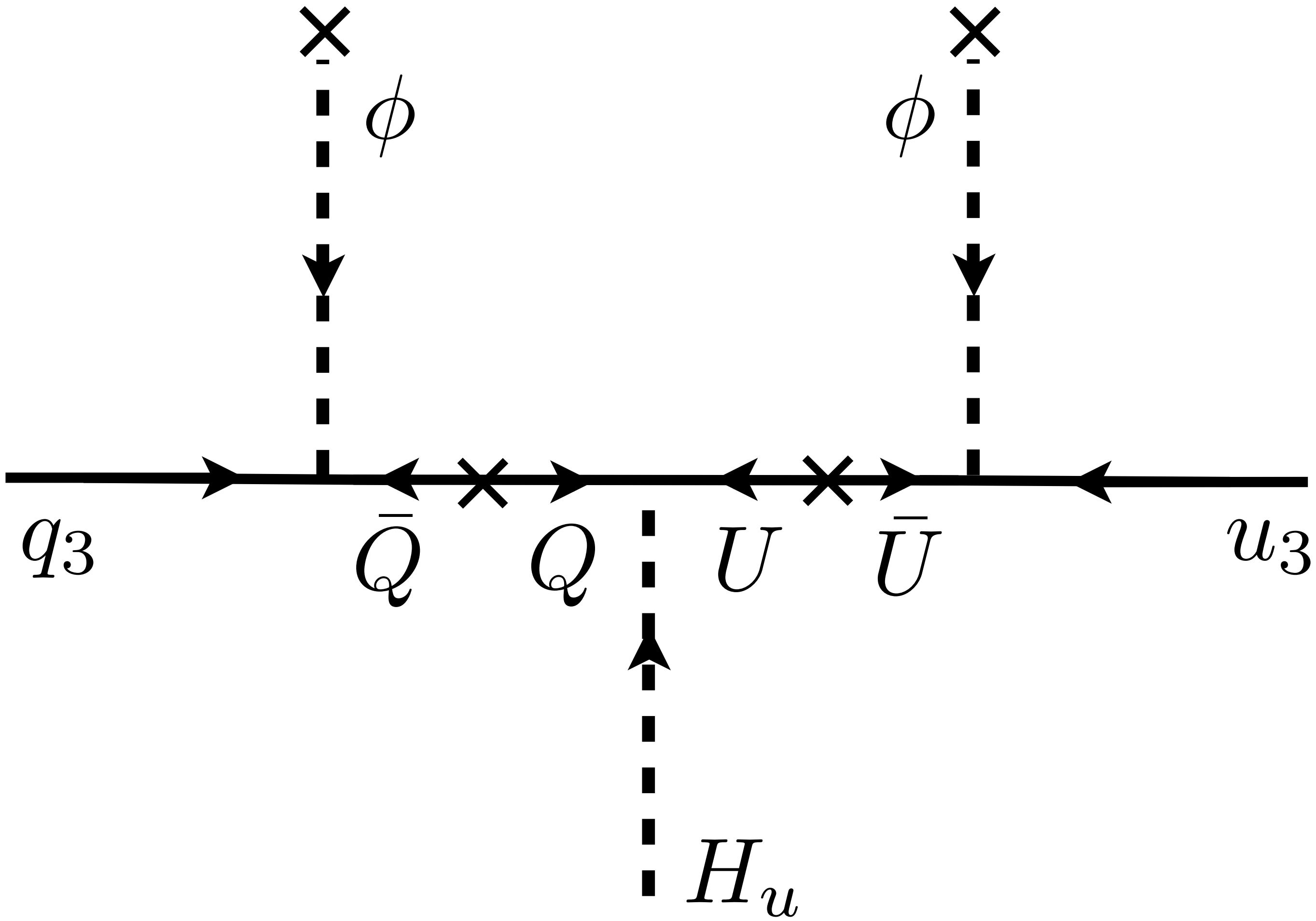
Make ϕ a doublet:



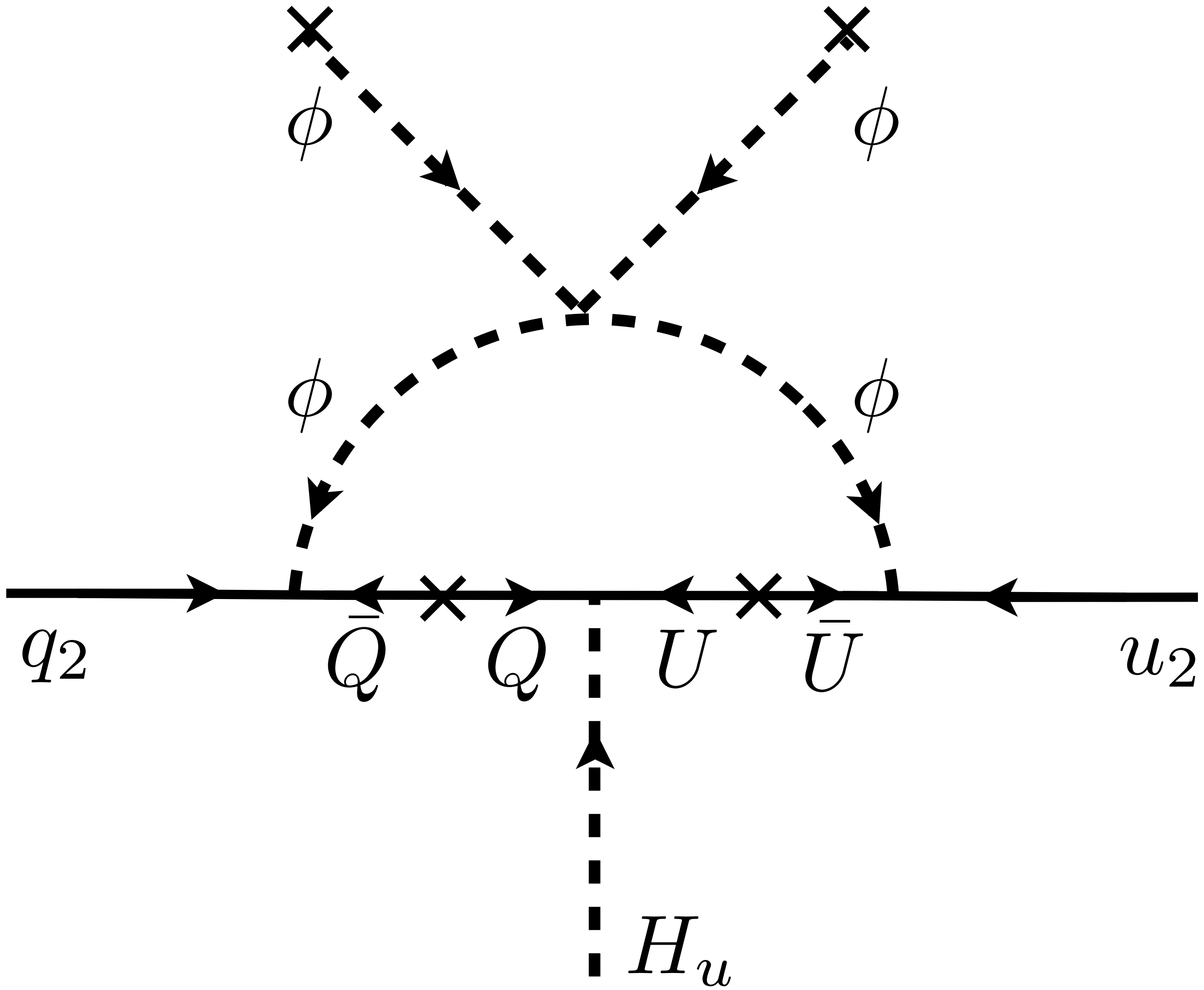
ONE LOOP CHARM MASS

Make ϕ a doublet:

Propagating ϕ couples to second generation



ONE LOOP CHARM MASS



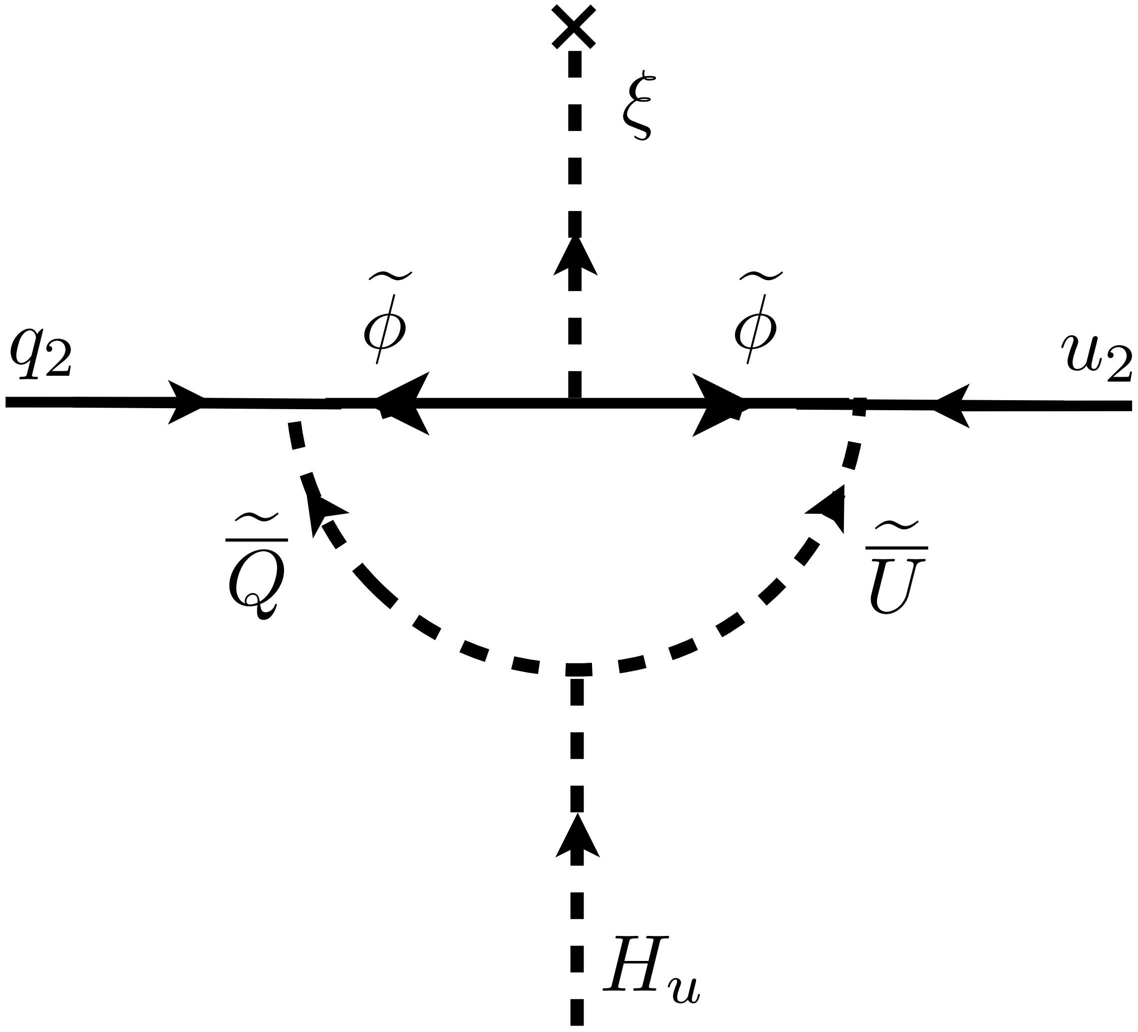
Make ϕ a doublet:

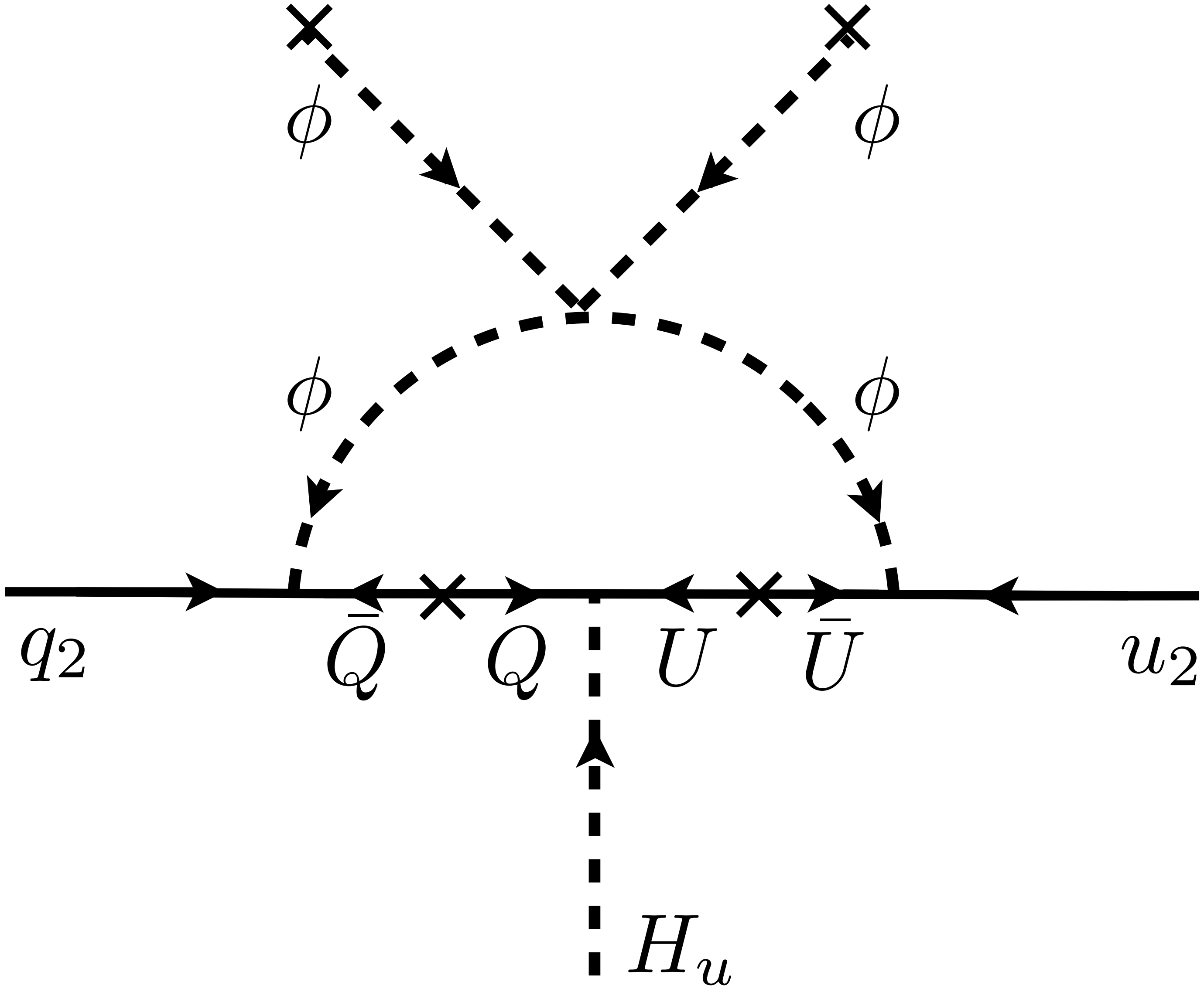
Propagating ϕ couples to second generation

Make loop of ϕ

Top mass dynamics contains one loop charm mass!

ONE LOOP CHARM MASS

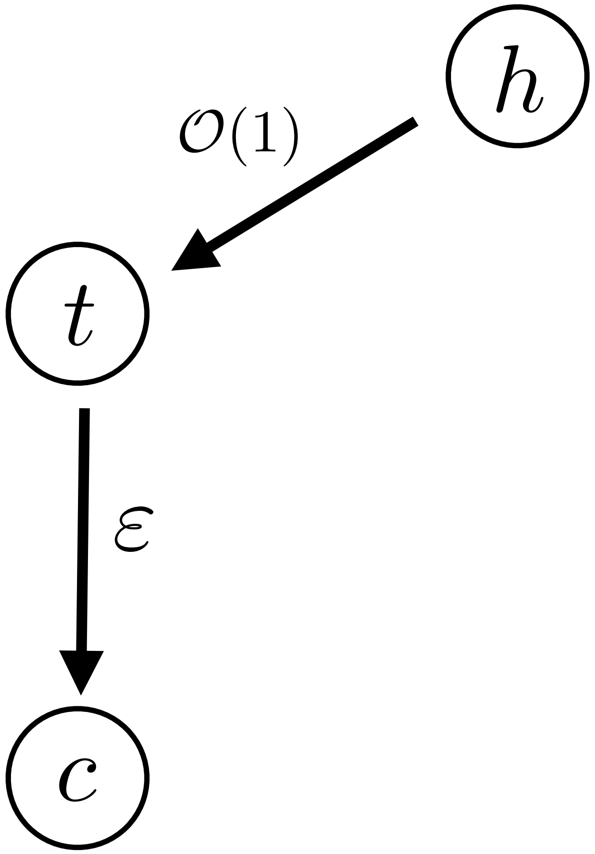




Need SUSY-rotated diagram as well

ONE LOOP CHARM MASS

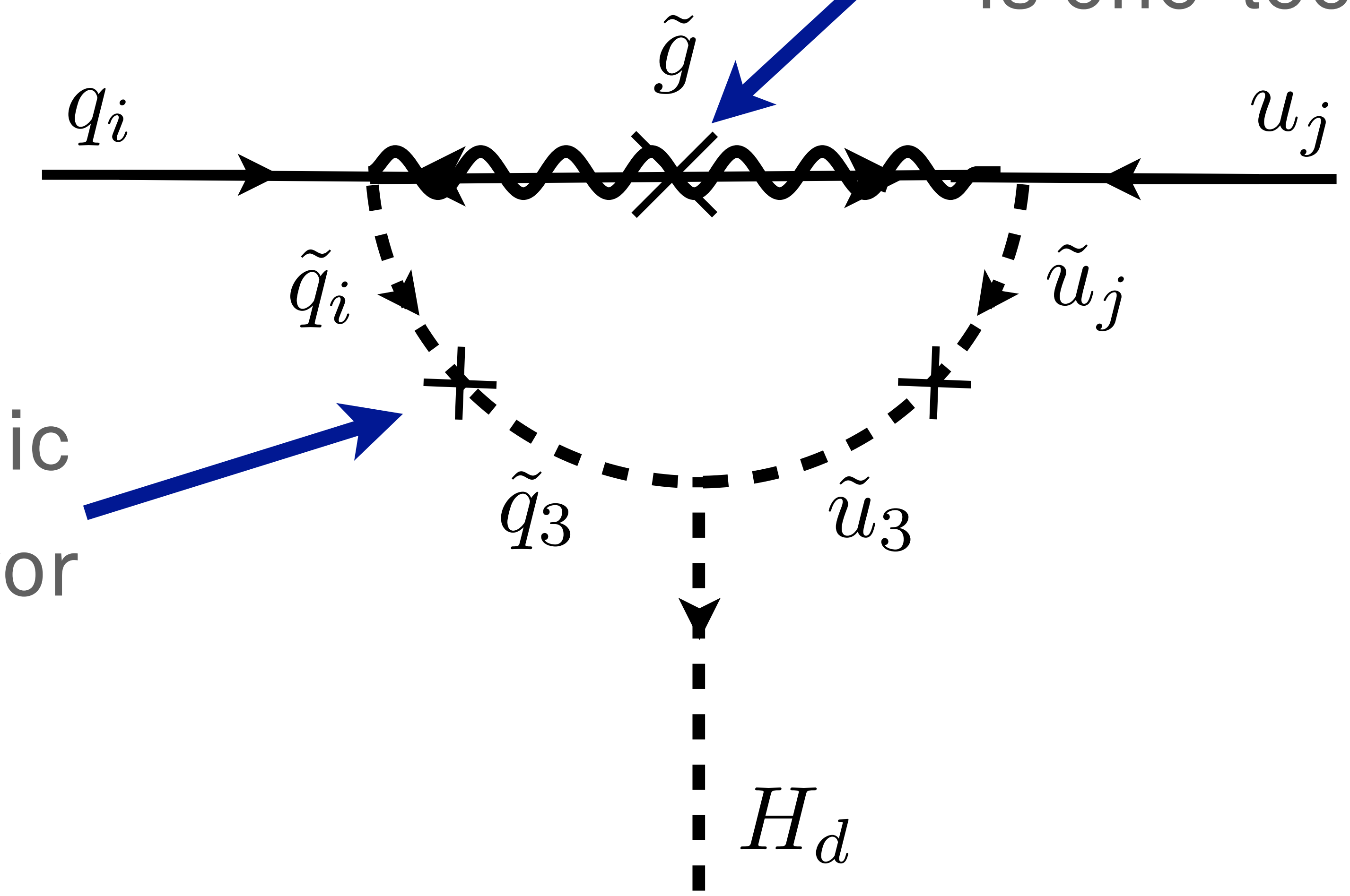
$$\mathbf{y_u} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \varepsilon & \varepsilon \\ 0 & \varepsilon & 1 \end{pmatrix}$$



$$\varepsilon \simeq \frac{1}{16\pi^2}$$

TWO LOOP UP MASS

Use squark mixing to seed two loop up mass

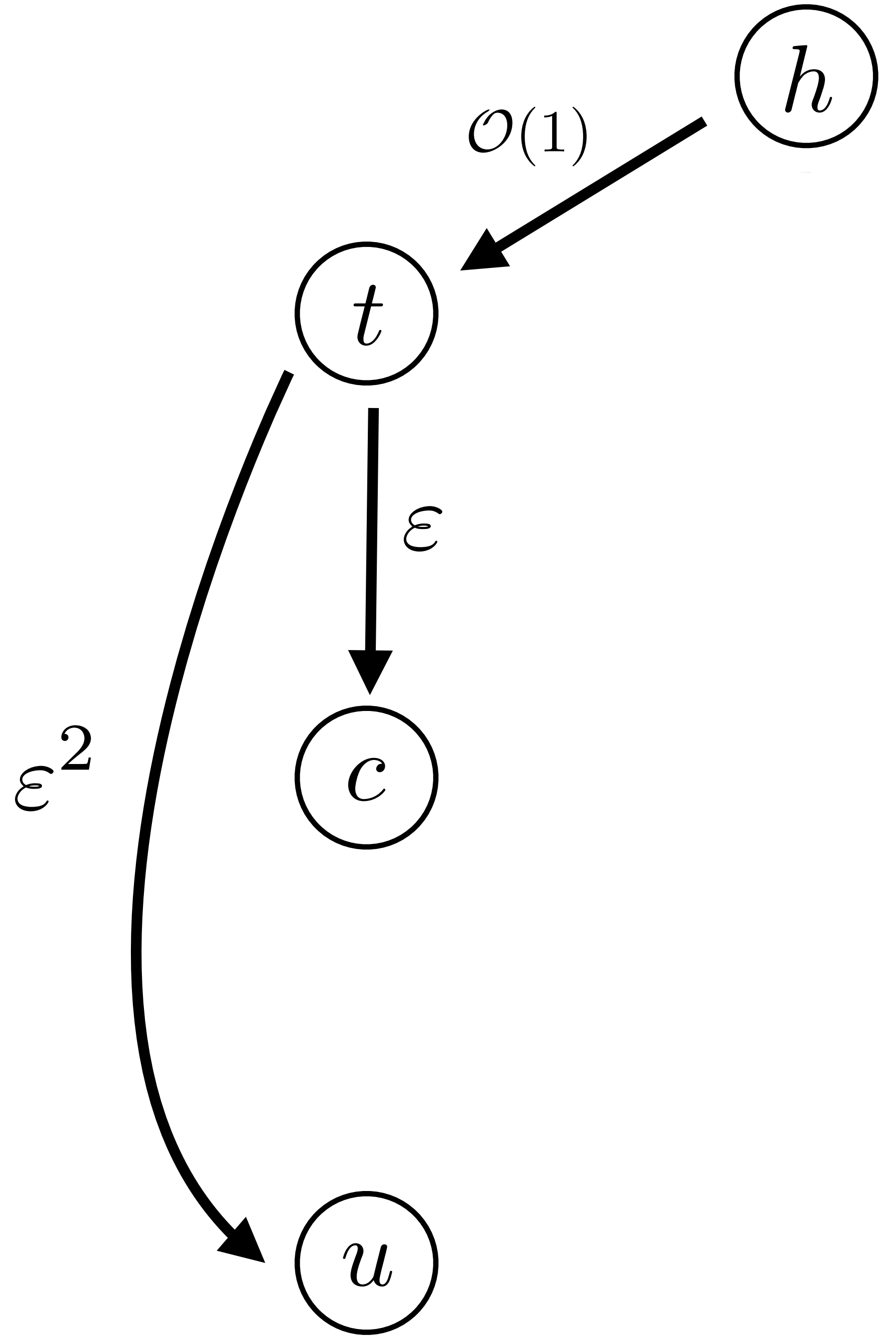


Gluino mass insertion is one-loop

Use anarchic squark flavor structure

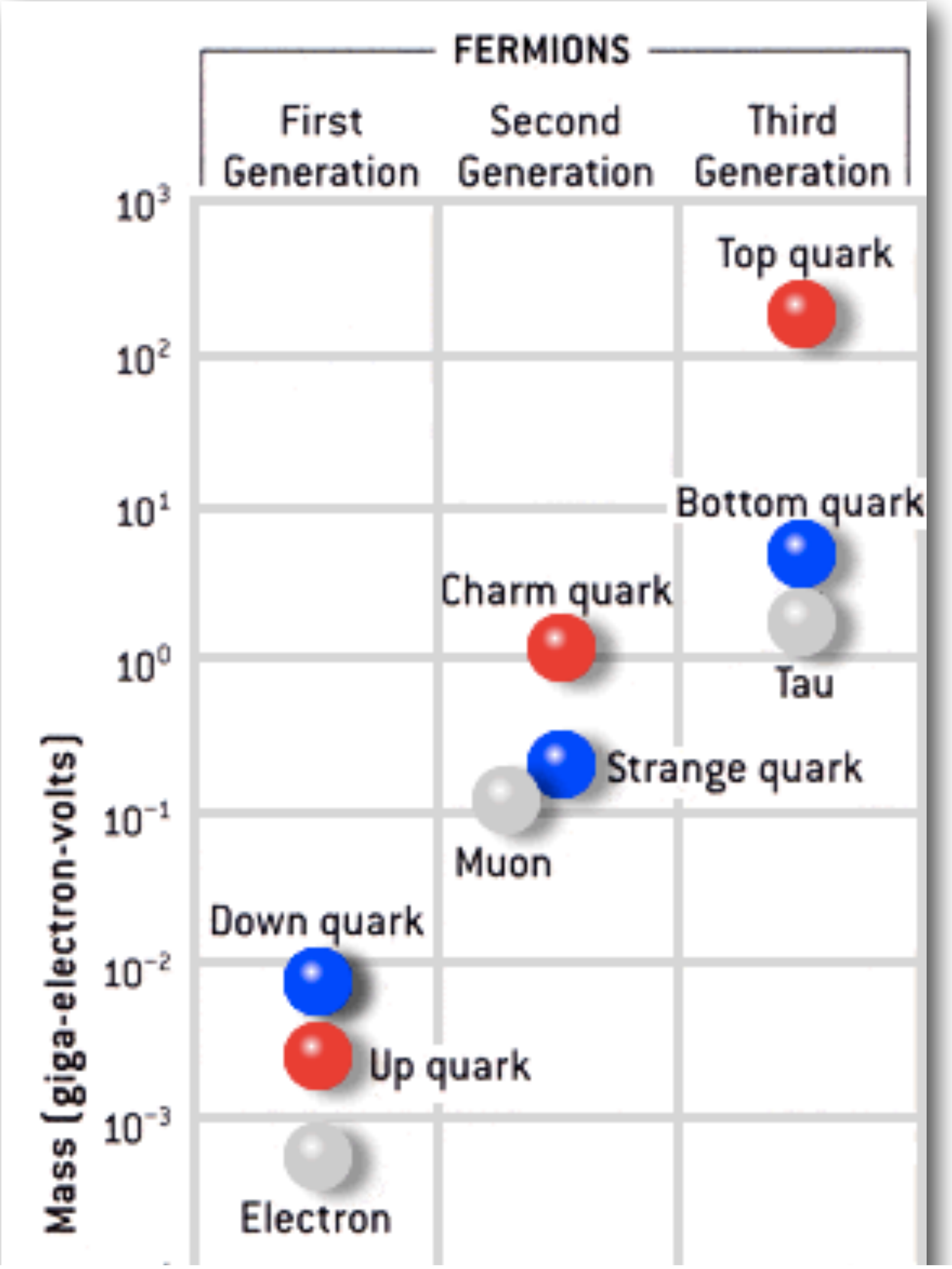
TWO LOOP UP MASS

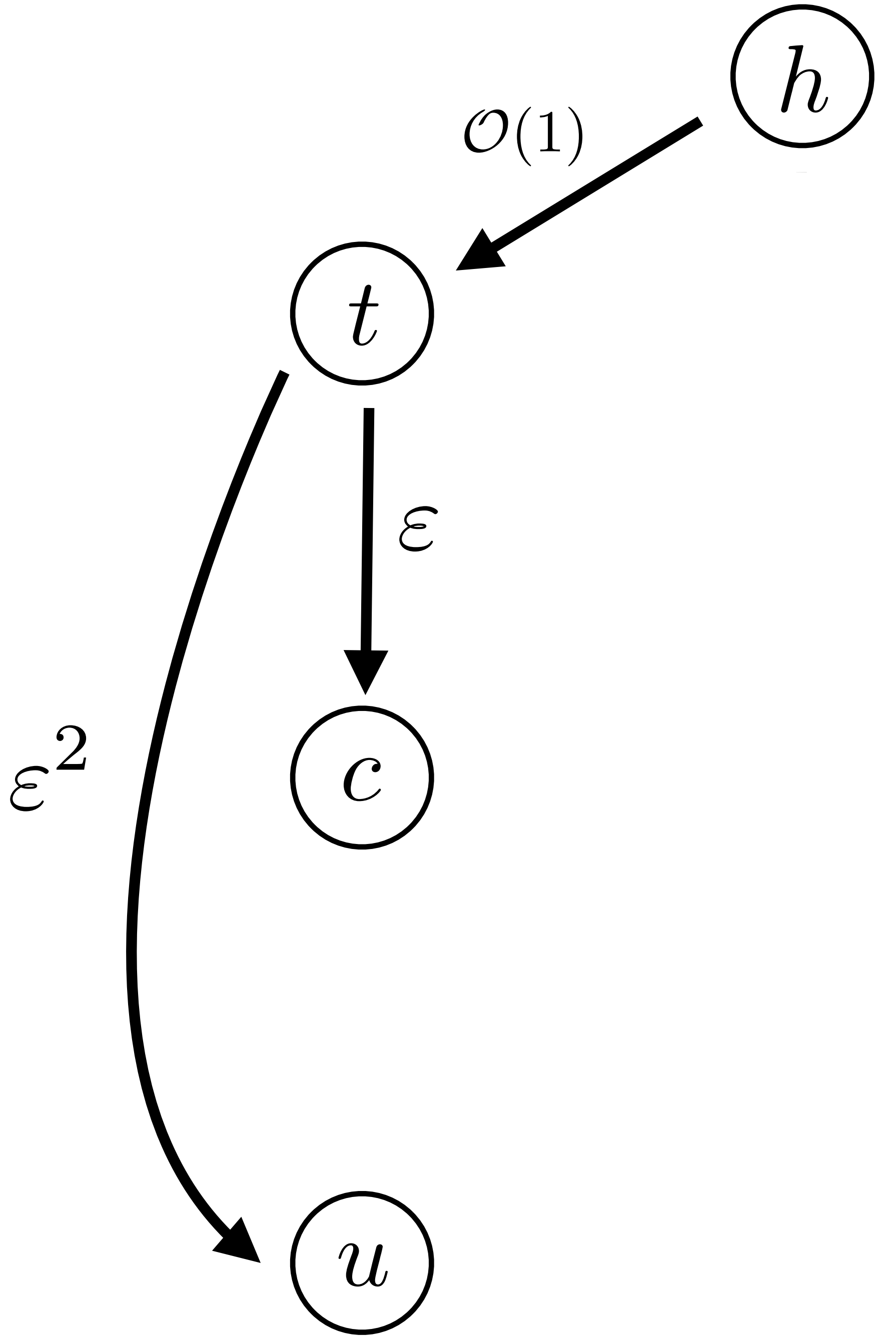
$$\mathbf{y_u} \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^2 & \varepsilon & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix}$$



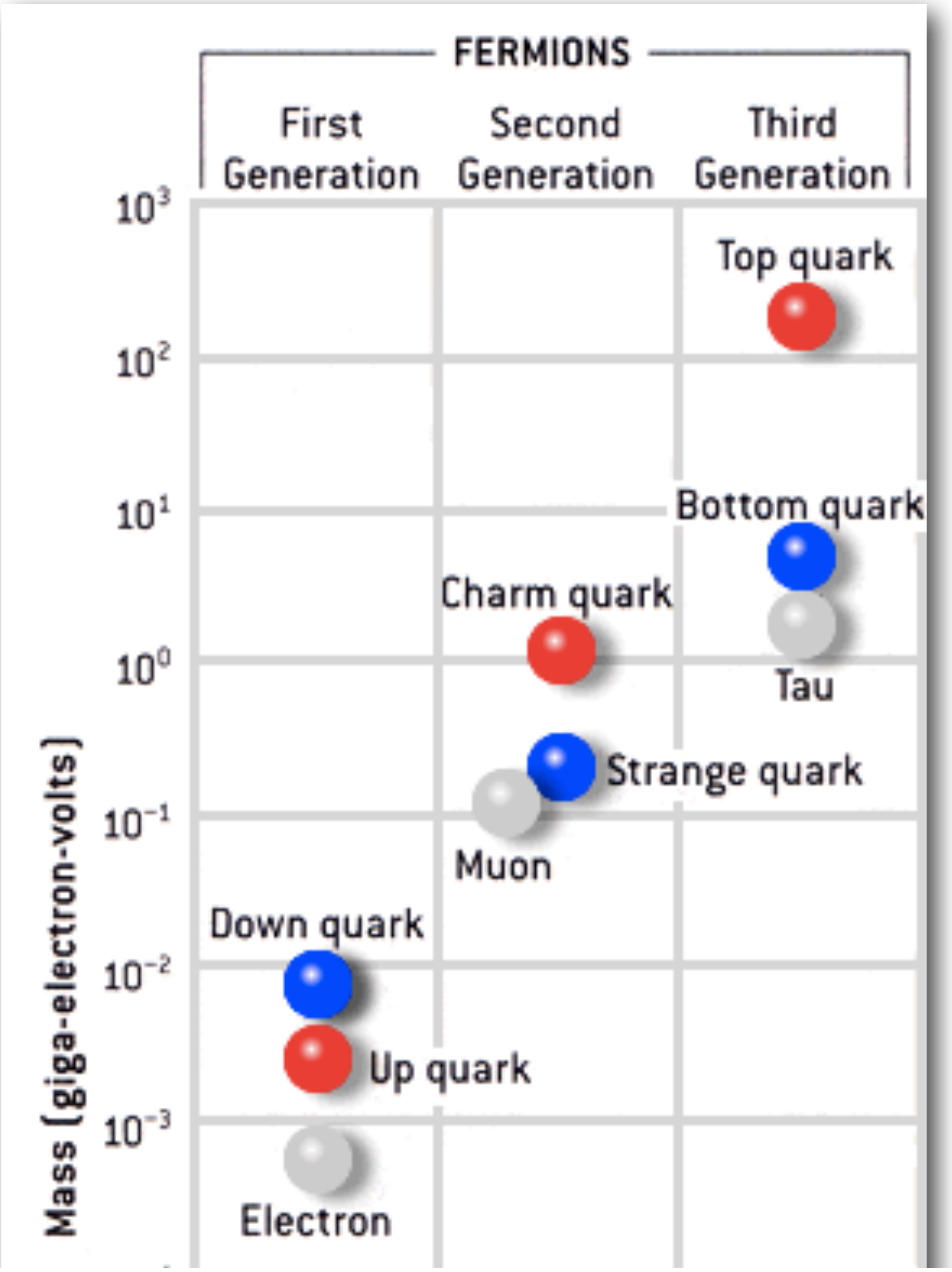
Masses: $(\varepsilon^2, \varepsilon, 1)$

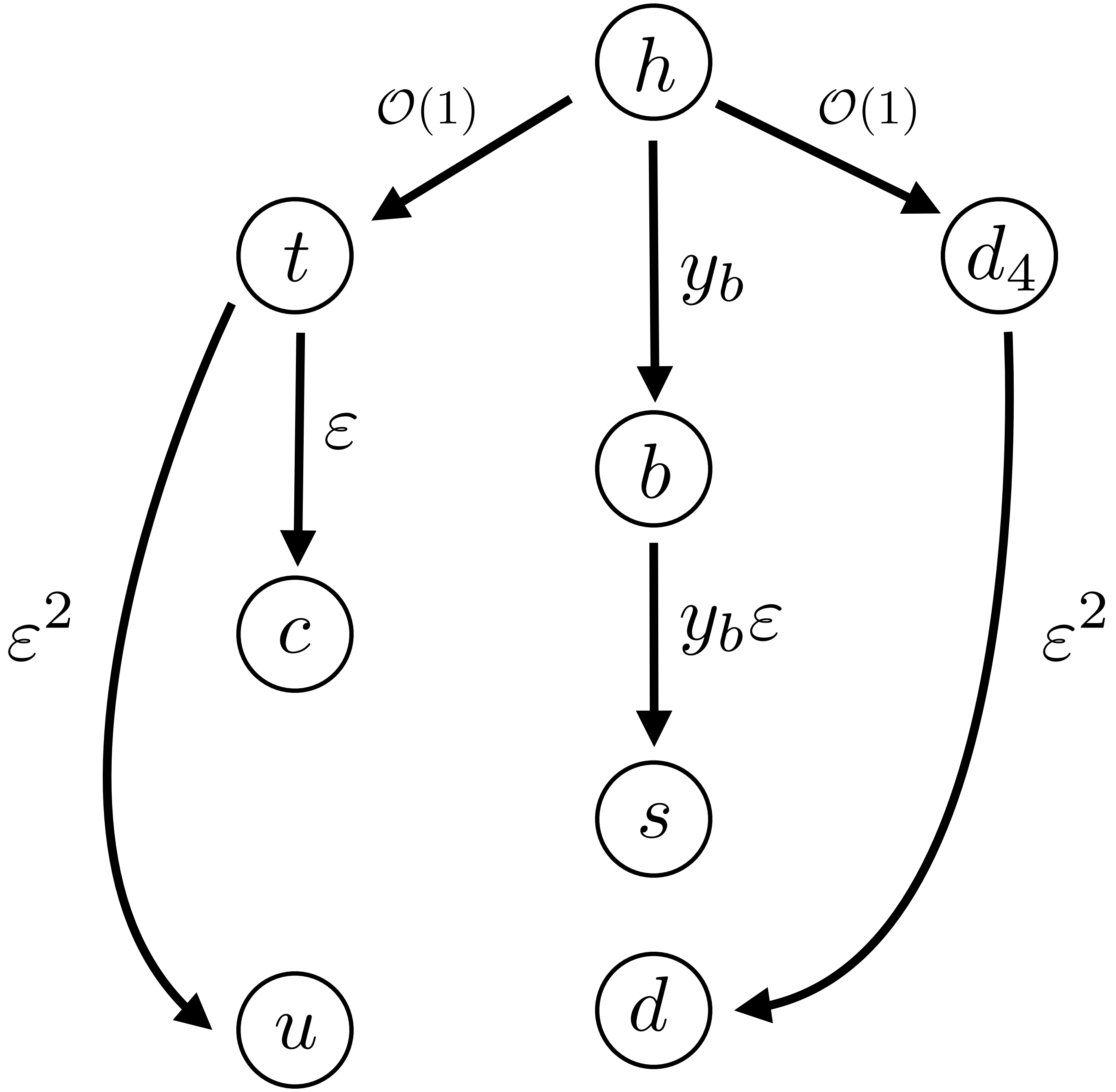
STRUCTURE OF MODEL





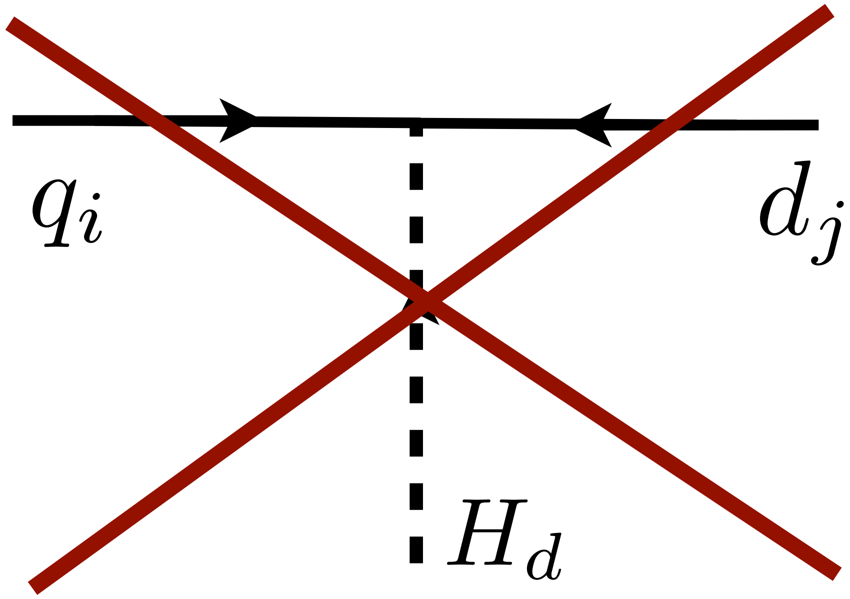
STRUCTURE OF MODEL

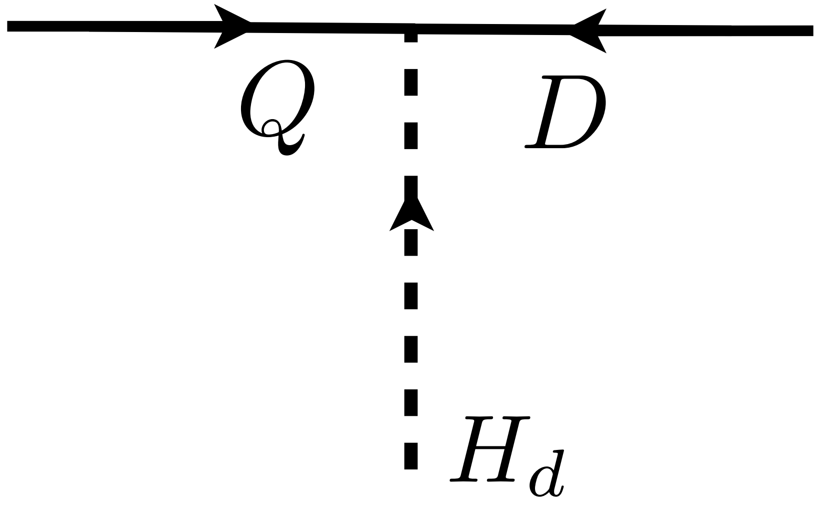




DOWN TYPE MASSES

As before, forbid Yukawa coupling, but allow coupling to new vectorlike pair





EXTRA VECTORLIKE PAIR

$$W = \mu_D D\bar{D} + QDH_d$$

EXTRA VECTORLIKE PAIR

Add additional vectorlike pair which cannot get Yukawa coupling

$$W = \mu_D D\bar{D} + QDH_d + \mu_i \, d_i \bar{d} + f_i^d \, d_i \, \bar{D} \, \chi$$

$$i = 1, ..., 4$$

EXTRA VECTORLIKE PAIR

Add additional vectorlike pair which cannot get Yukawa coupling

$$W = \mu_D D\bar{D} + QDH_d + \mu_i\, d_i\bar{d} + f_i^d\, d_i\, \bar{D}\, \chi$$

$$i = 1, ..., 4$$

Can choose basis such that $\mu_i = (0, 0, 0, \mu)$

leaving 3 massless and one heavy down.

EXTRA VECTORLIKE PAIR

Add additional vectorlike pair which cannot get Yukawa coupling

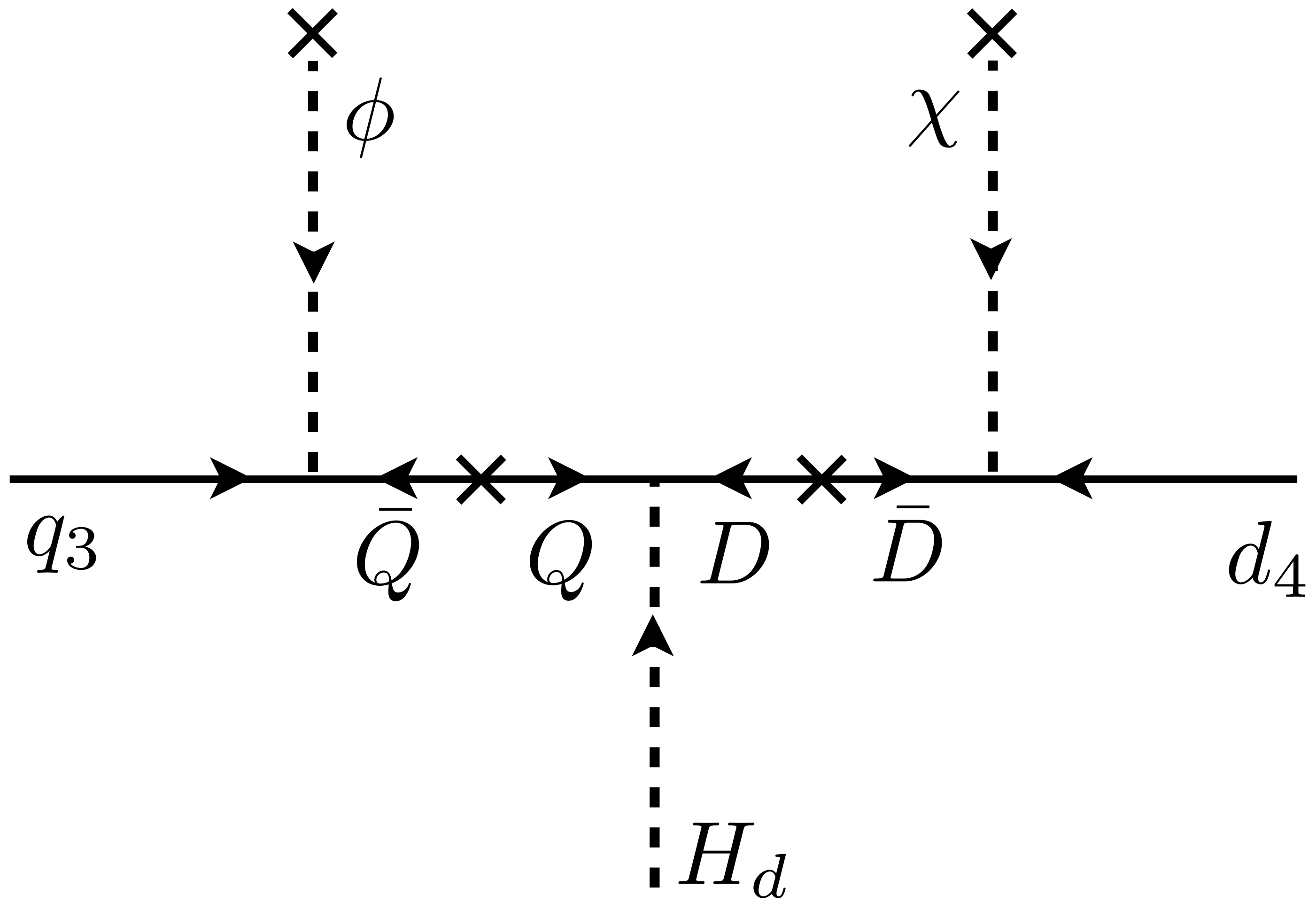
$$W = \mu_D D\bar{D} + QDH_d + \mu_i\, d_i\bar{d} + f_i^d\, d_i\, \bar{D}\,\chi$$

$$i = 1, ..., 4$$

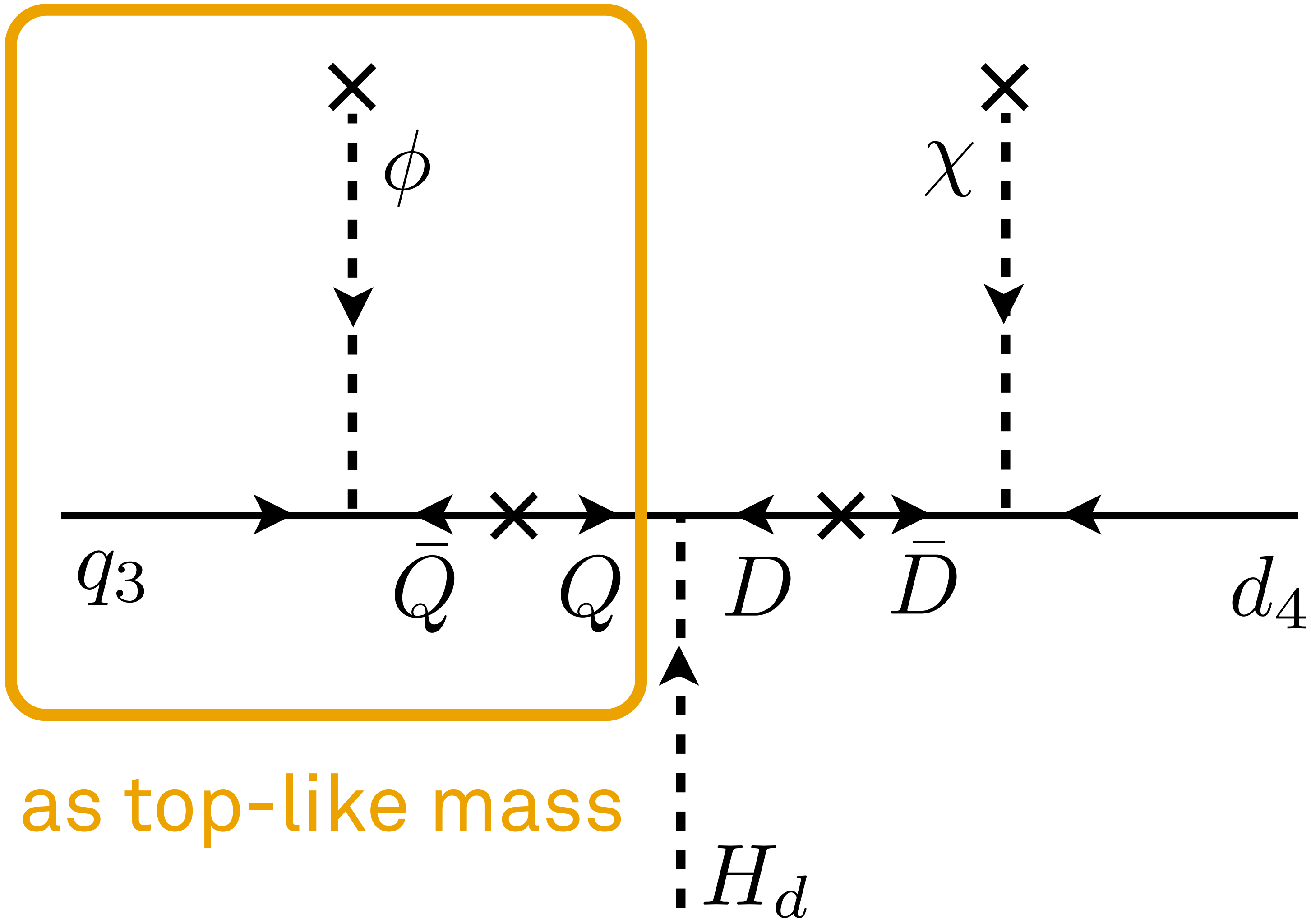
Make all remaining *f* couplings somewhat smaller than 1, a technically natural tuning.

$$f^d \sim \begin{pmatrix} y_b \\ y_b \\ y_b \\ 1 \end{pmatrix}$$

TREE LEVEL BOTTOM MASS

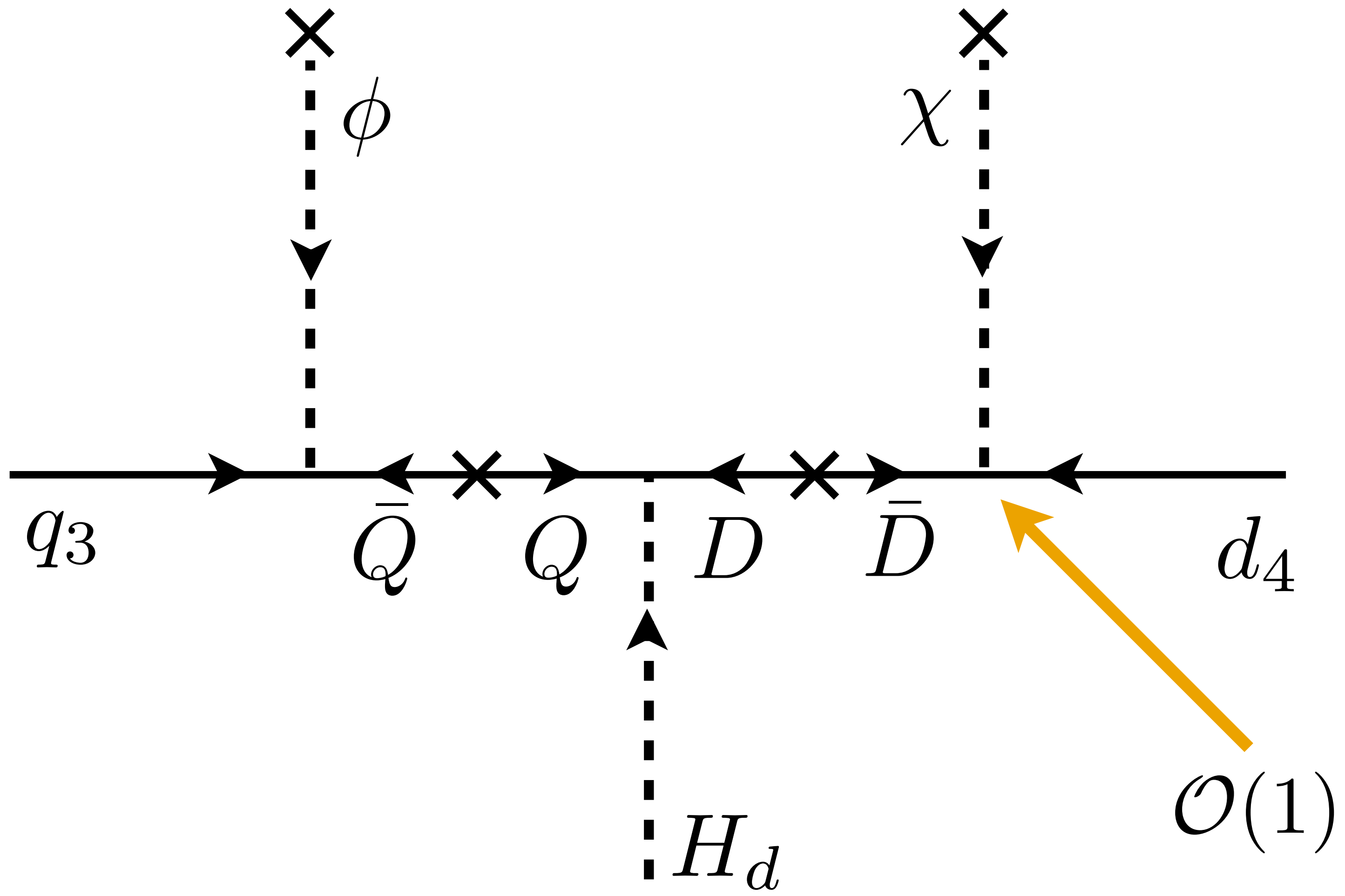


TREE LEVEL BOTTOM MASS

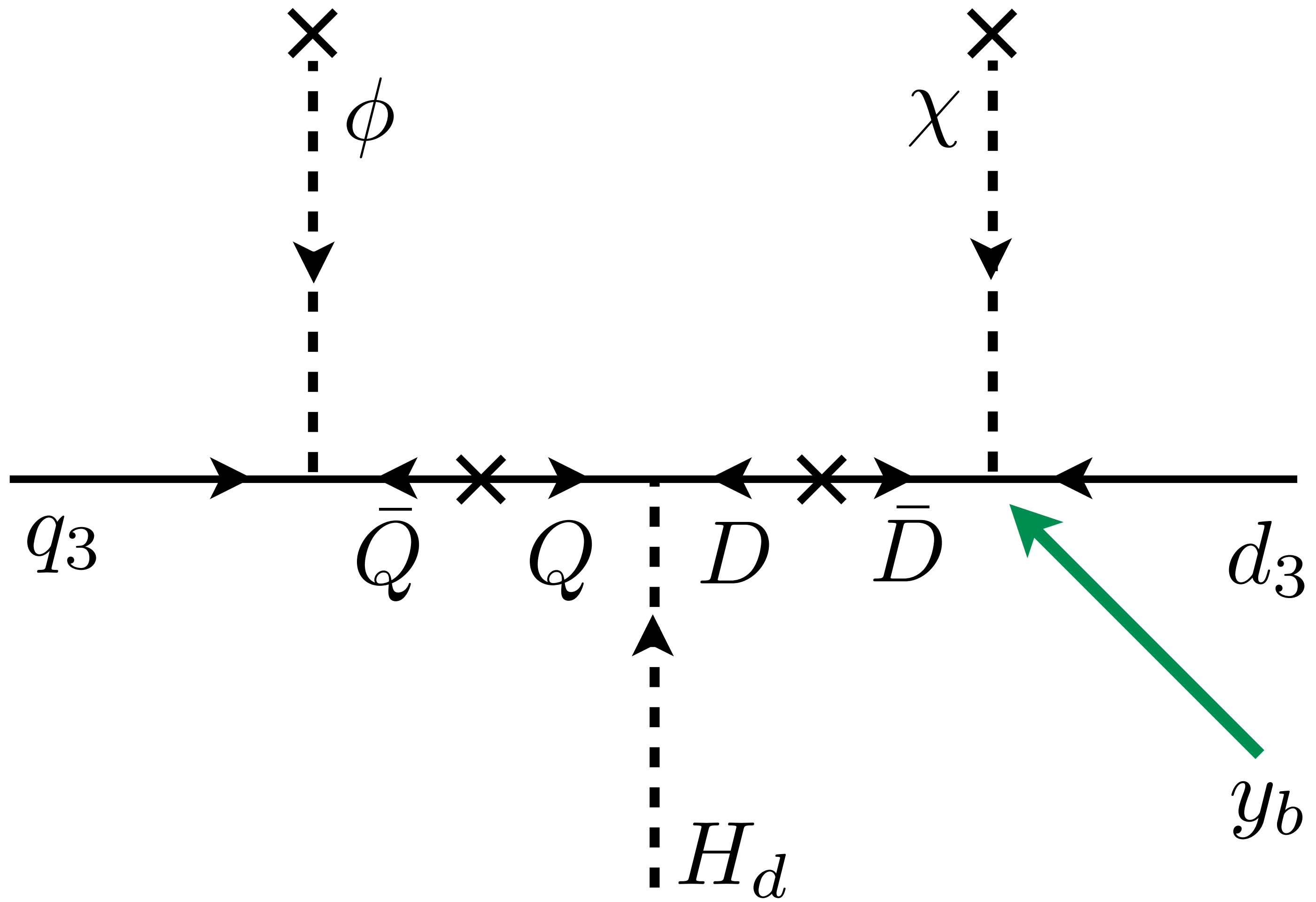


same as top-like mass

TREE LEVEL BOTTOM MASS

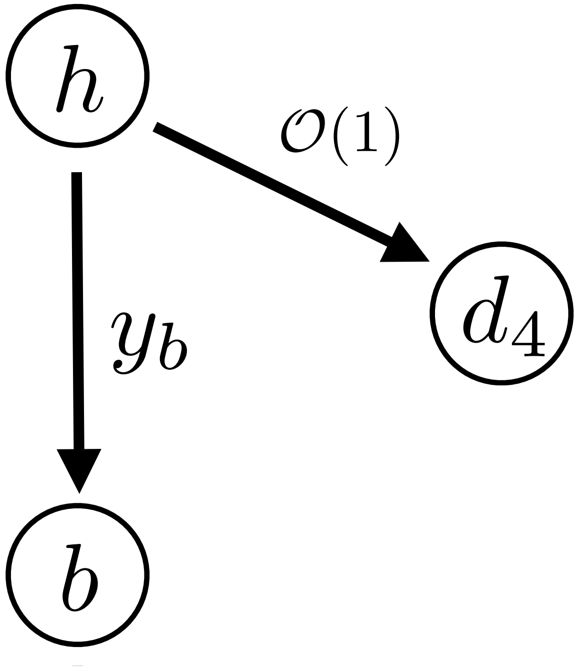


TREE LEVEL BOTTOM MASS



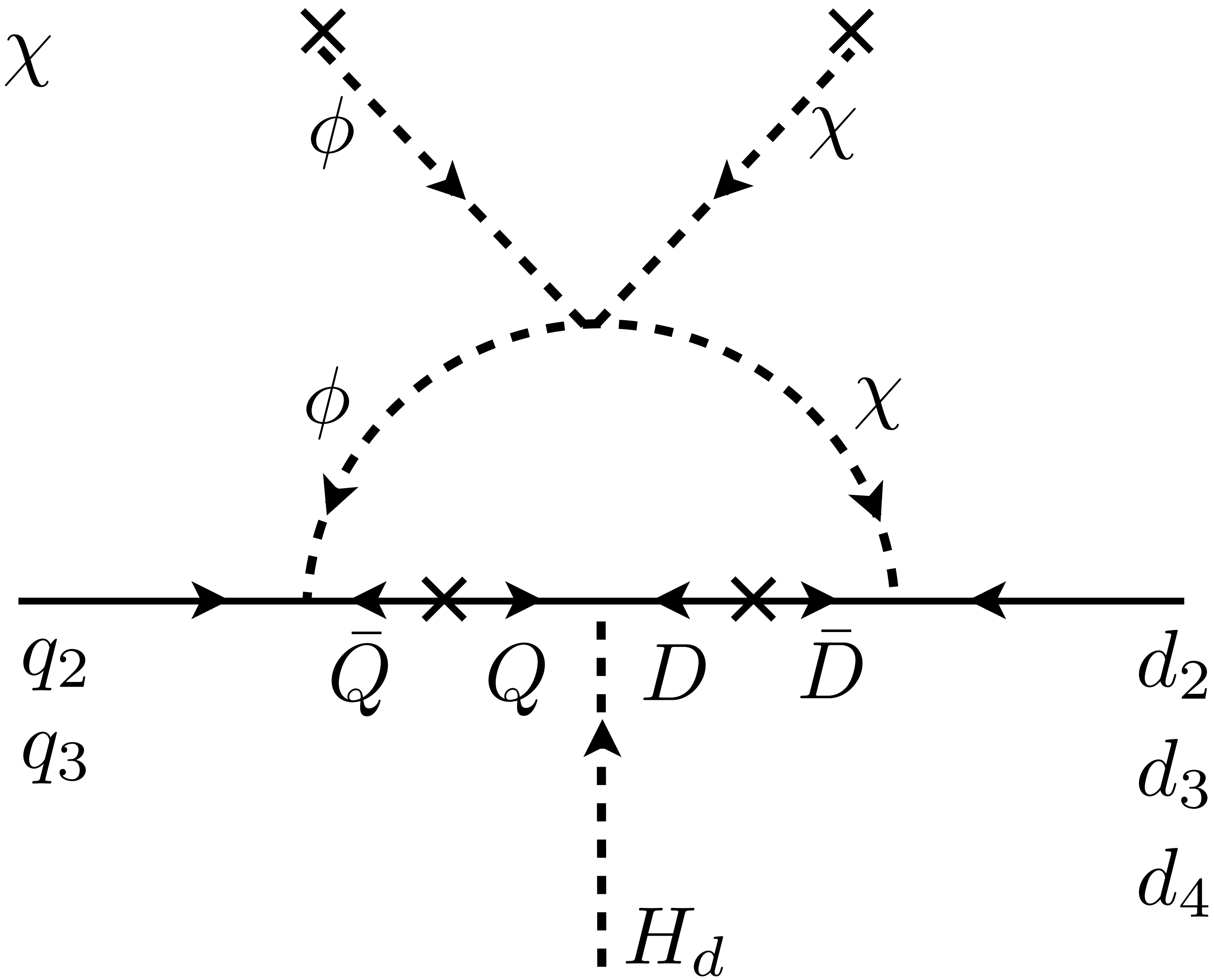
TREE LEVEL BOTTOM MASS

$$\mathbf{y_d} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_b \\ 0 & 0 & 1 \end{pmatrix}$$



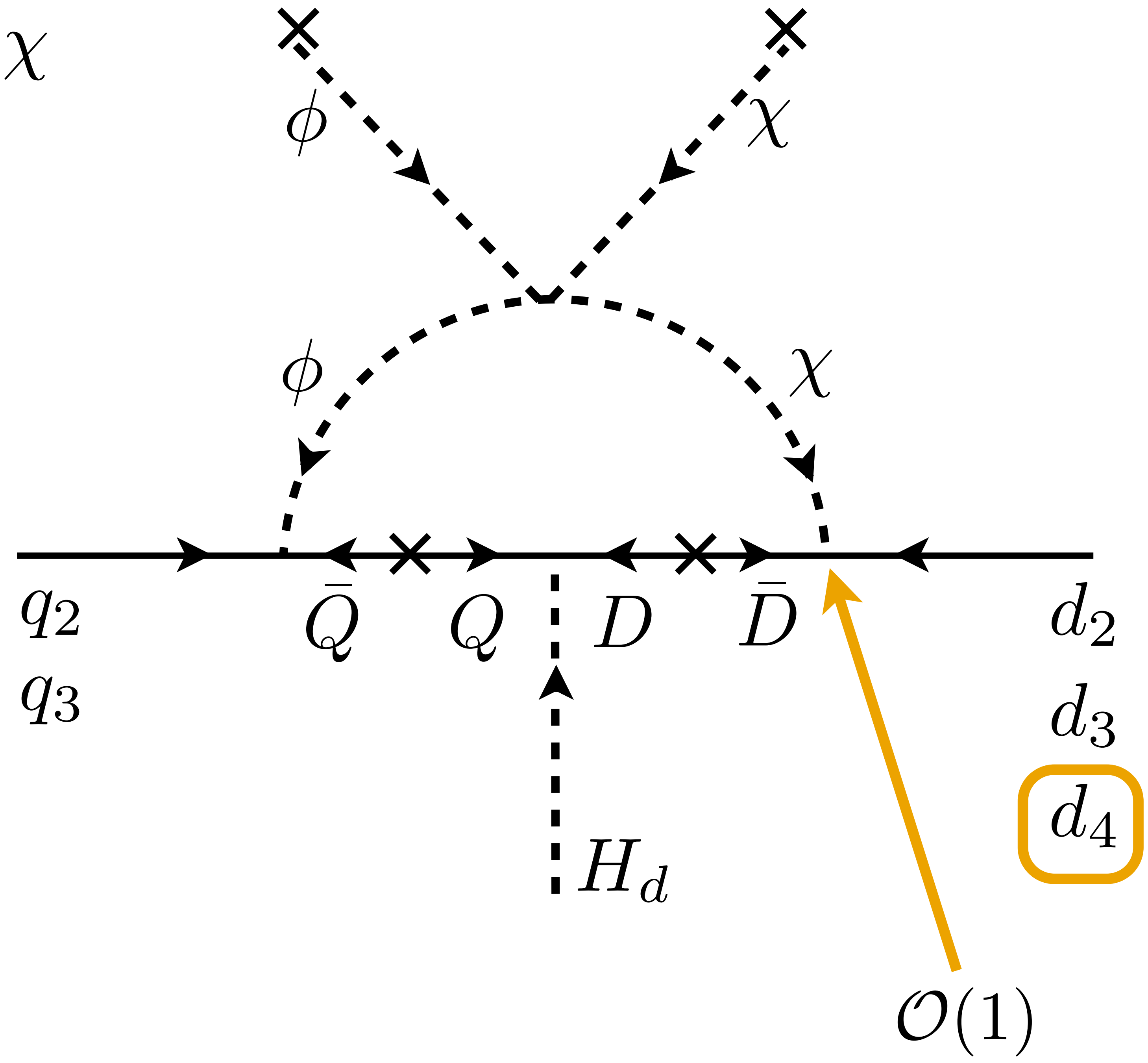
ONE LOOP STRANGE MASS

Make ϕ and χ doublets



ONE LOOP STRANGE MASS

Make ϕ and χ doublets



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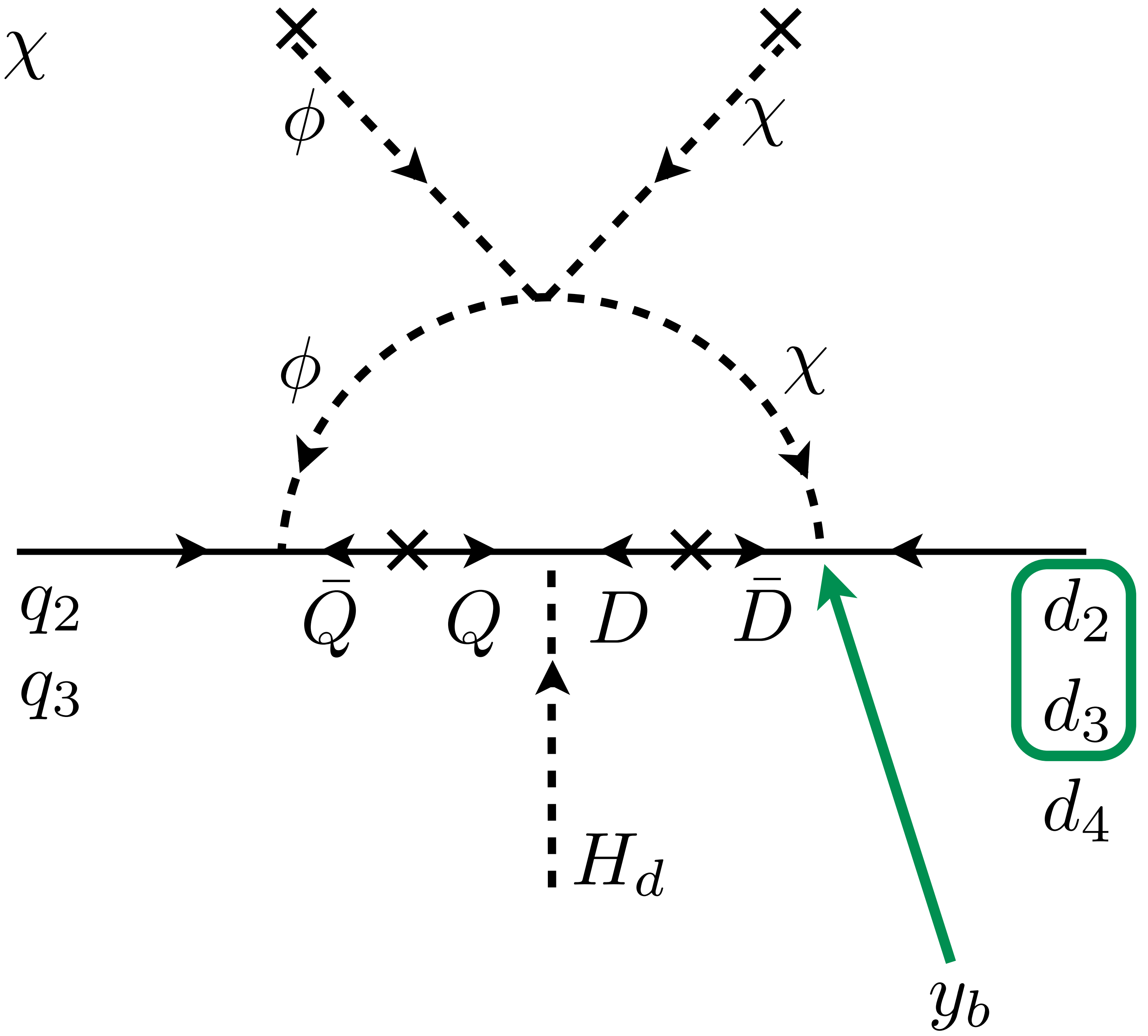
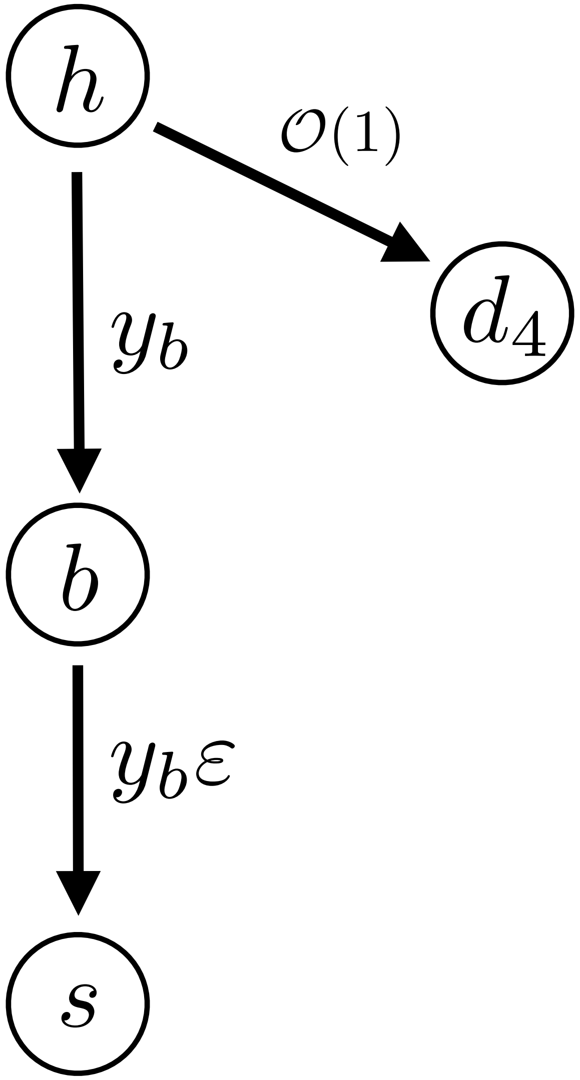


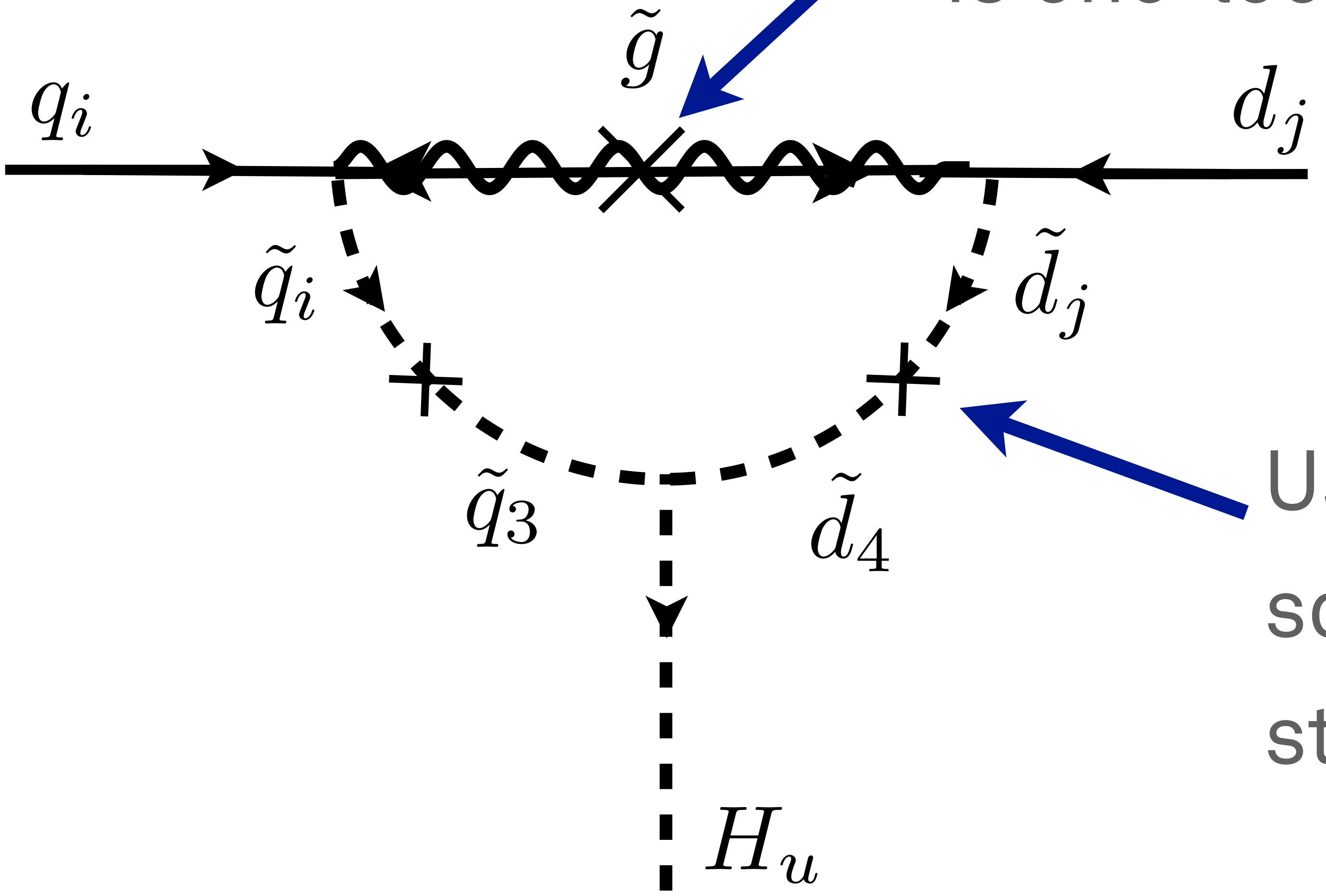
ONE LOOP STRANGE MASS

$$\mathbf{y_d} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_b\mathcal{E} & y_b\mathcal{E} \\ 0 & y_b\mathcal{E} & y_b \\ 0 & \mathcal{E} & 1 \end{pmatrix}$$



TWO LOOP DOWN MASS

Same two loop mass as up

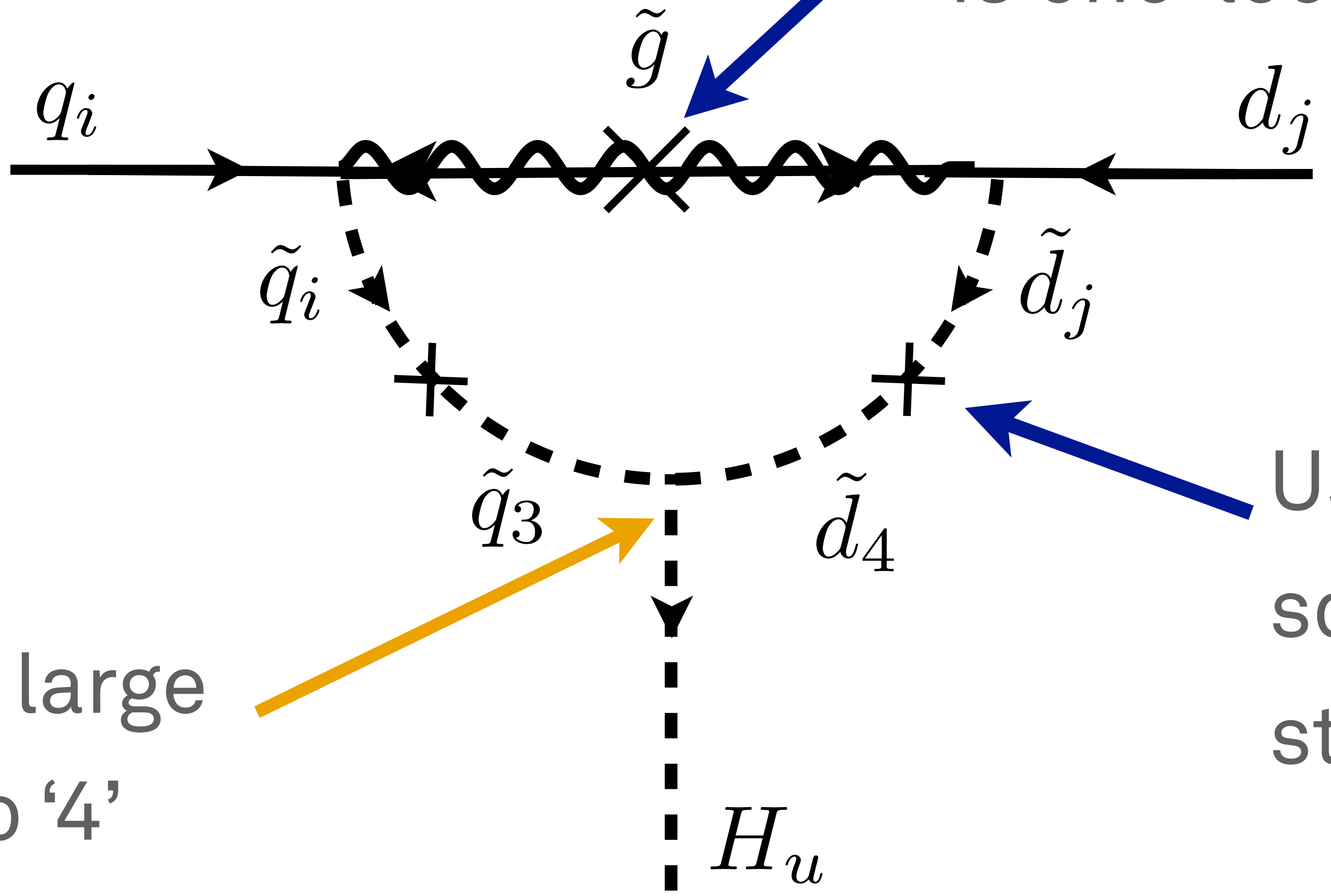


Gluino mass insertion is one-loop

Use anarchic squark flavor structure

TWO LOOP DOWN MASS

Same two loop mass as up



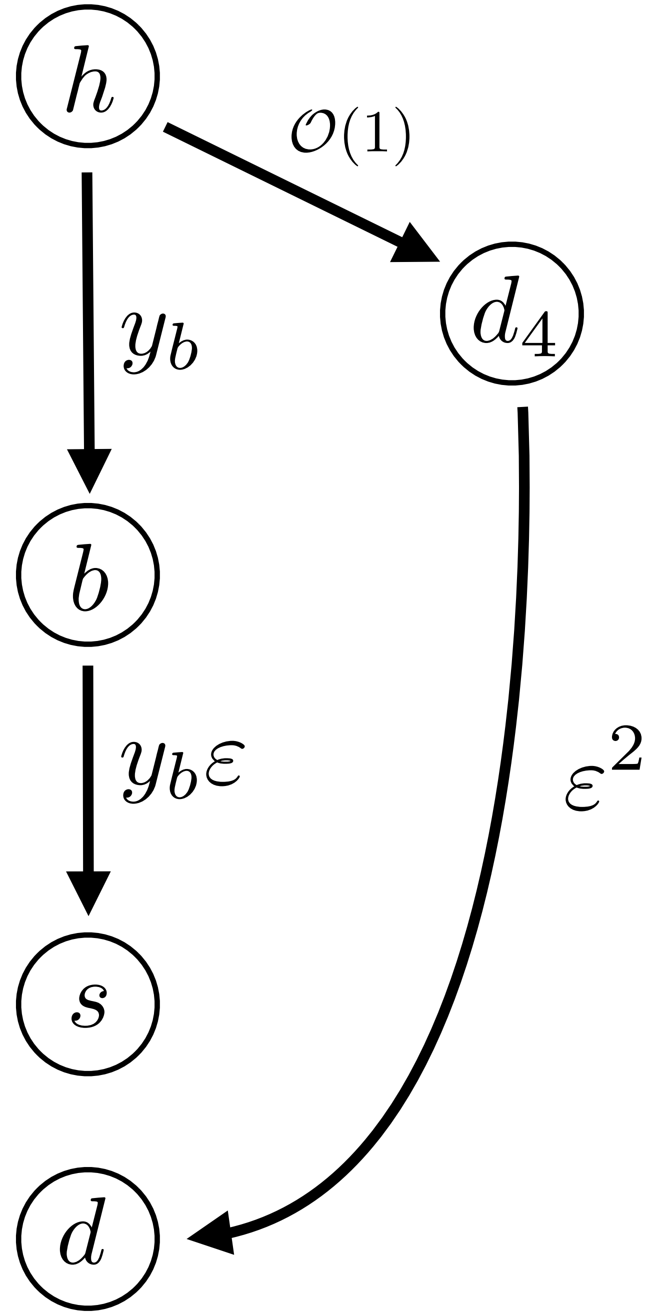
Gluino mass insertion is one-loop

Use anarchic squark flavor structure

Seeded by large coupling to ‘4’

TWO LOOP DOWN MASS

$$\mathbf{y_d} \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^2 & y_b\varepsilon & y_b\varepsilon \\ \varepsilon^2 & y_b\varepsilon & y_b \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix}$$



TWO LOOP DOWN MASS

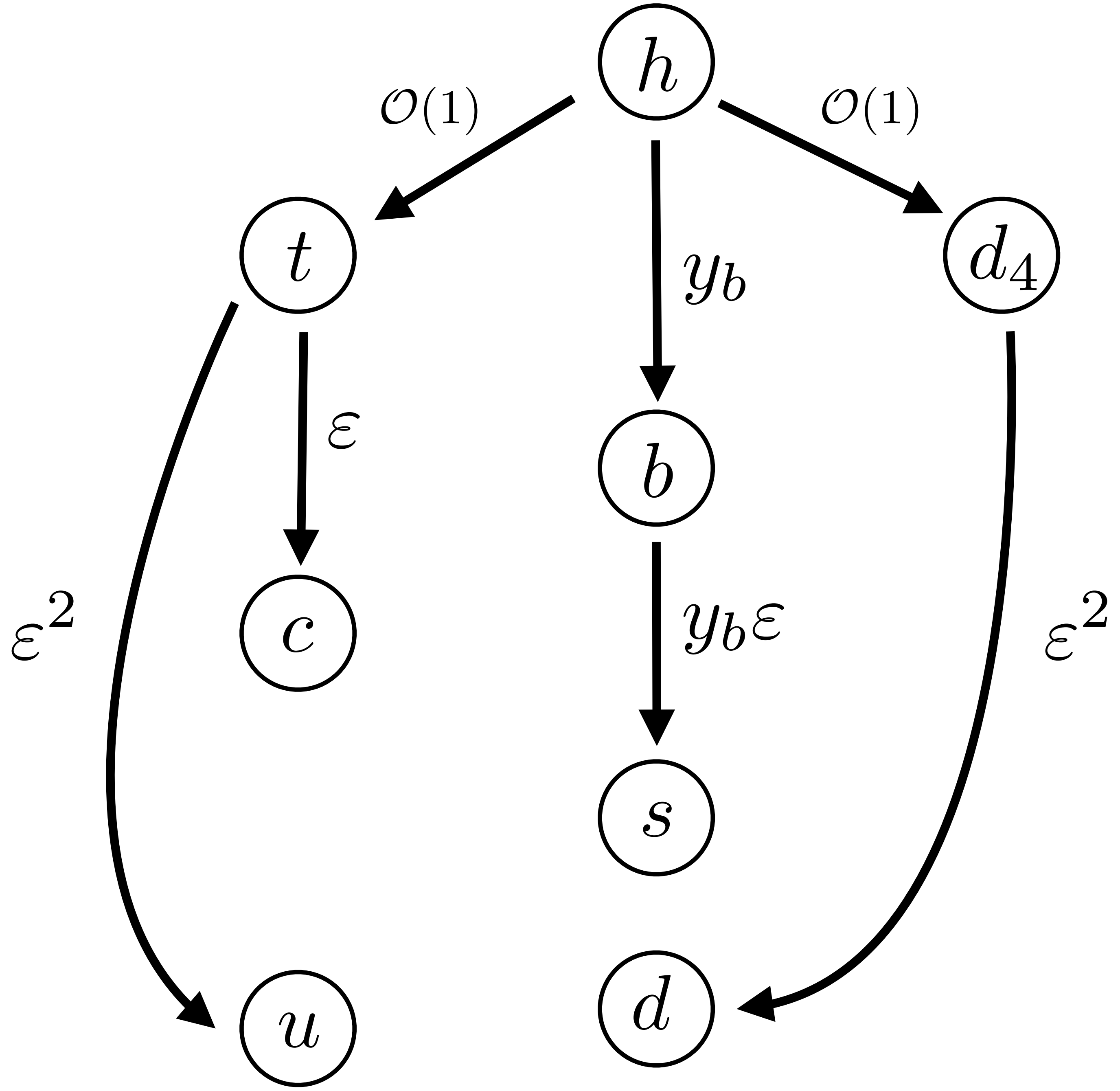
Fourth generation has vectorlike mass $\mu\, d_4 \bar{d}$

At scales well below μ

$$\mathbf{y_d} \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^2 & y_b \varepsilon & y_b \varepsilon \\ \varepsilon^2 & y_b \varepsilon & y_b \end{pmatrix}$$

Masses: $(\varepsilon^2, y_b \varepsilon, y_b)$

WHY ALL THE FUSS?



If up and down sectors were the same, then

$$\frac{m_u}{m_t} \simeq \frac{m_d}{m_b} \Rightarrow m_d \ll m_u$$

If we want a proton that is lighter than the neutron, need more structure

Current setup gives

$$\frac{m_u}{m_t} \simeq \frac{m_d}{m_t} \Rightarrow m_d \simeq m_u$$

CKM MATRIX

$$\mathbf{y_u} \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^2 & \varepsilon & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix} \qquad \mathbf{y_d} \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^2 & y_b\varepsilon & y_b\varepsilon \\ \varepsilon^2 & y_b\varepsilon & y_b \end{pmatrix}$$

$$\mathbf{V_u} \sim \begin{pmatrix} 1 & \varepsilon & \varepsilon^2 \\ \varepsilon & 1 & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix} \qquad \mathbf{V_d} \sim \begin{pmatrix} 1 & \varepsilon/y_b & \varepsilon^2/y_b \\ \varepsilon/y_b & 1 & \varepsilon \\ \varepsilon^2/y_b & \varepsilon & 1 \end{pmatrix}$$

CKM MATRIX

$$\mathbf{y_u} \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^2 & \varepsilon & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix} \qquad \mathbf{y_d} \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^2 & y_b\varepsilon & y_b\varepsilon \\ \varepsilon^2 & y_b\varepsilon & y_b \end{pmatrix}$$

$$\mathbf{V_u} \sim \begin{pmatrix} 1 & \varepsilon & \varepsilon^2 \\ \varepsilon & 1 & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix} \qquad \mathbf{V_d} \sim \begin{pmatrix} 1 & \varepsilon/y_b & \varepsilon^2/y_b \\ \varepsilon/y_b & 1 & \varepsilon \\ \varepsilon^2/y_b & \varepsilon & 1 \end{pmatrix}$$

$$\mathbf{V}_{\mathrm{CKM}} = \mathbf{V_u^\dagger V_d} \sim \begin{pmatrix} 1 & \varepsilon/y_b & \varepsilon^2/y_b \\ \varepsilon/y_b & 1 & \varepsilon \\ \varepsilon^2/y_b & \varepsilon & 1 \end{pmatrix}$$

CKM MATRIX

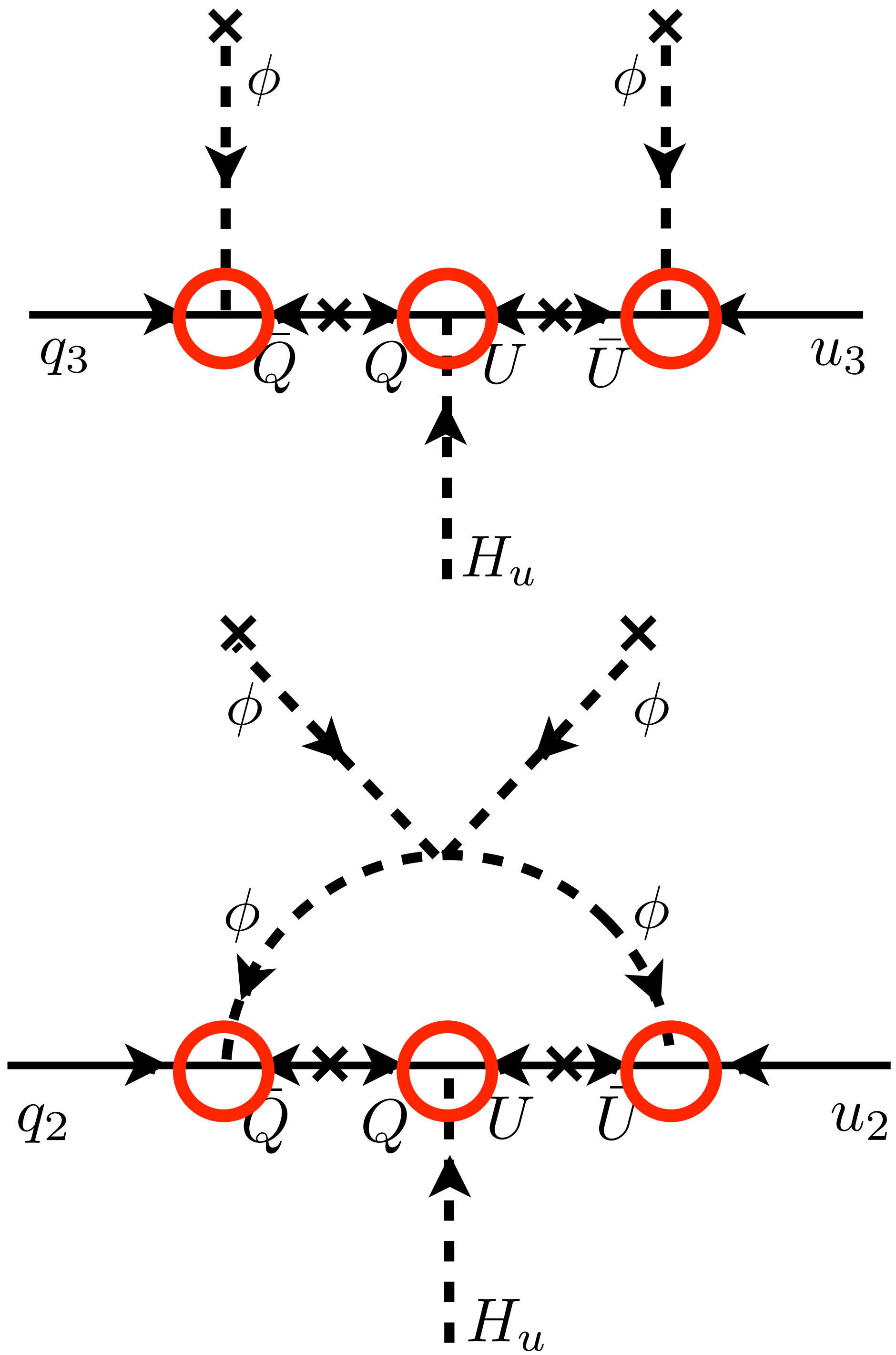
$$\mathbf{y_u} \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^2 & \varepsilon & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix} \qquad \mathbf{y_d} \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^2 & y_b\varepsilon & y_b\varepsilon \\ \varepsilon^2 & y_b\varepsilon & y_b \end{pmatrix}$$

$$\mathbf{V_u} \sim \begin{pmatrix} 1 & \varepsilon & \varepsilon^2 \\ \varepsilon & 1 & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix} \qquad \mathbf{V_d} \sim \begin{pmatrix} 1 & \varepsilon/y_b & \varepsilon^2/y_b \\ \varepsilon/y_b & 1 & \varepsilon \\ \varepsilon^2/y_b & \varepsilon & 1 \end{pmatrix}$$

$$\mathbf{V}_{\text{CKM}} = \mathbf{V_u^\dagger V_d} \sim \begin{pmatrix} 1 & \varepsilon/y_b & \varepsilon^2/y_b \\ \varepsilon/y_b & 1 & \varepsilon \\ \varepsilon^2/y_b & \varepsilon & 1 \end{pmatrix}$$

$$\mathbf{V}_{us} = \lambda \simeq \sin\theta_c \sim \varepsilon/y_b$$

CKM PHASE



Diagrams that generate Yukawa’s have complex couplings

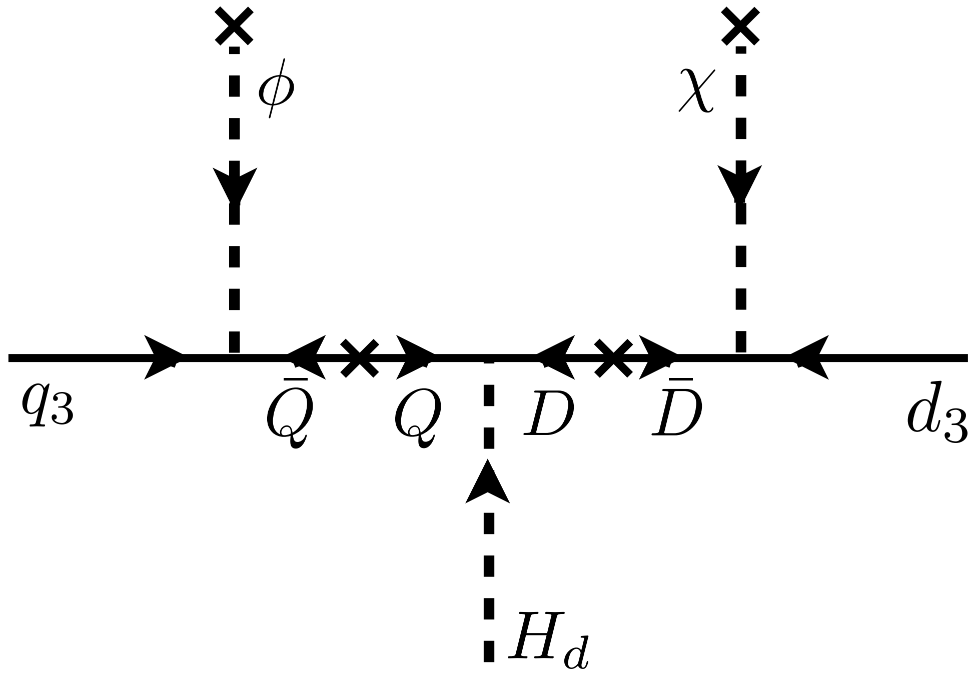
Different couplings go into different Yukawa entries

CKM matrix will have O(1) phase

LEPTON SECTOR

Model consistent with *SU*(5) unification:

Leptons like downs $d \to \ell \quad q \to e$

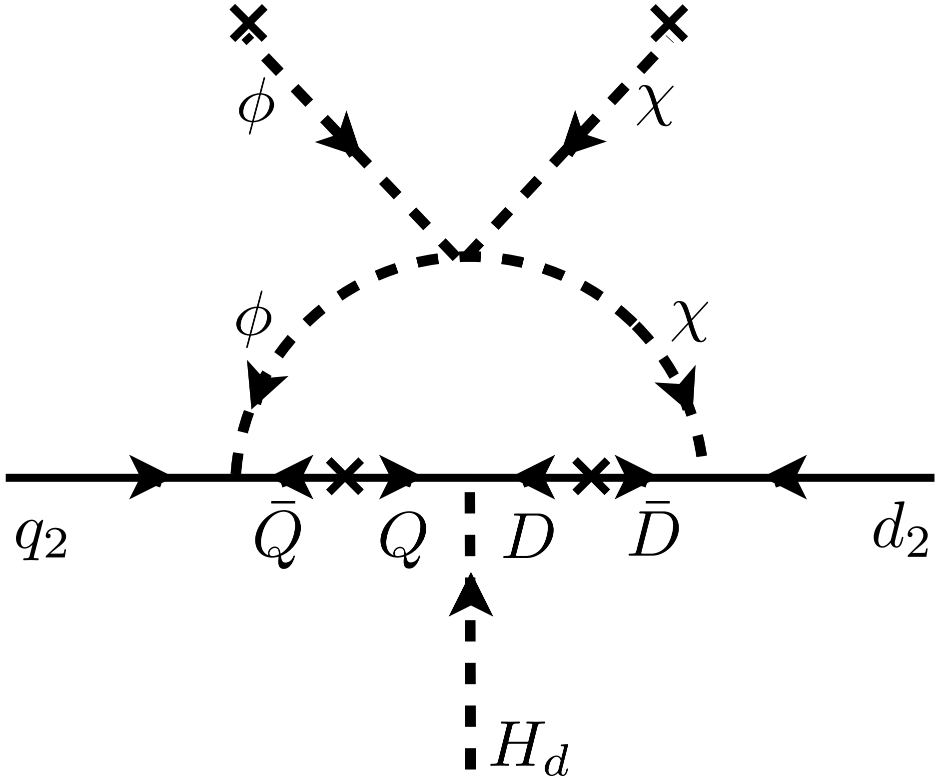


$$m_\tau \simeq m_b$$

LEPTON SECTOR

Model consistent with *SU*(5) unification:

Leptons like downs $d \to \ell \quad q \to e$

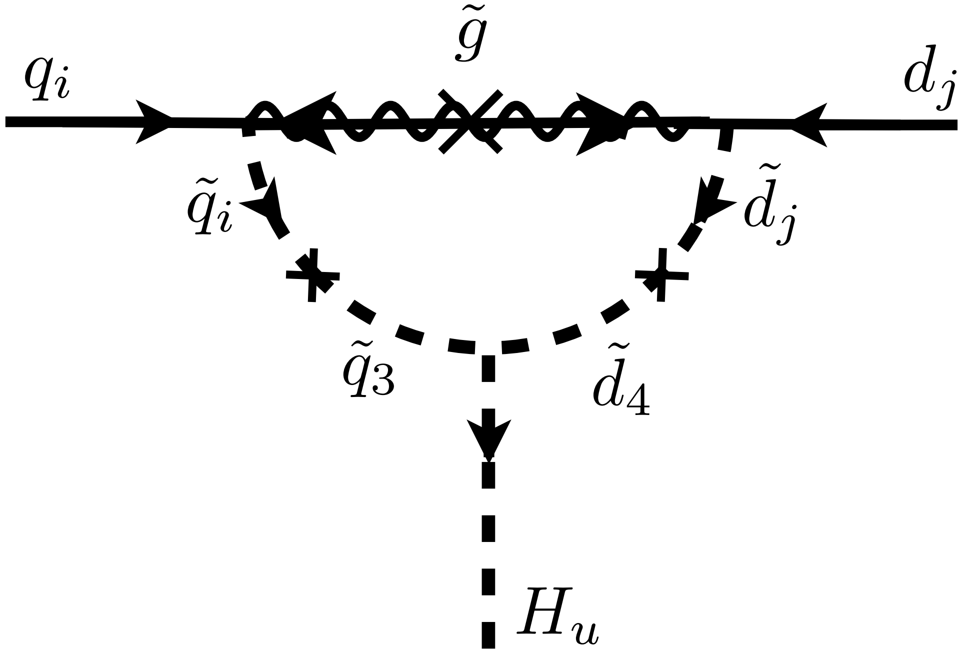


$$m_\mu \simeq m_s$$

LEPTON SECTOR

Model consistent with *SU*(5) unification:

Leptons like downs $d \to \ell \quad q \to e$



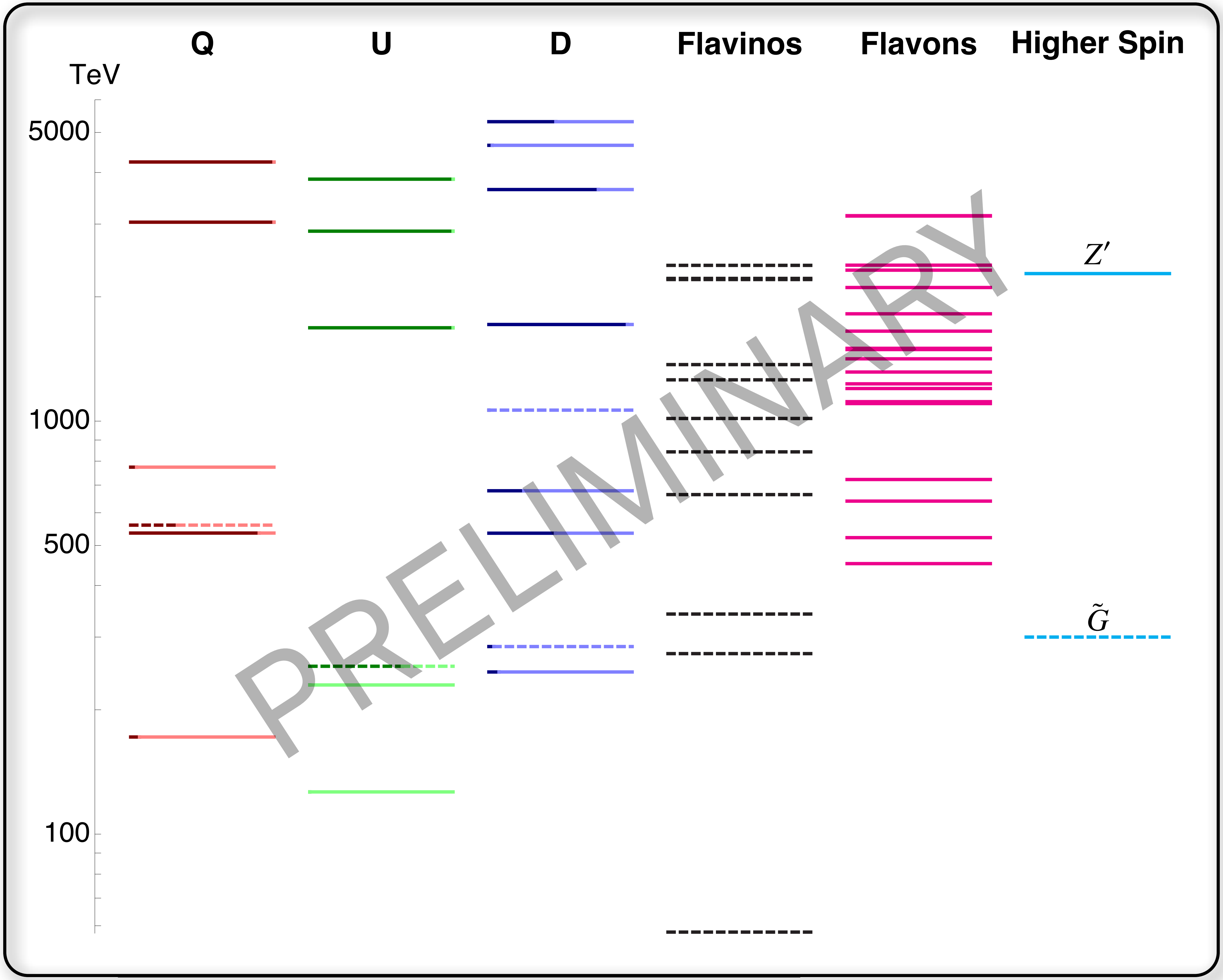
$$m_e \simeq \frac{g_1^4}{g_3^4} m_d$$

SUMMARY OF FIELD CONTENT

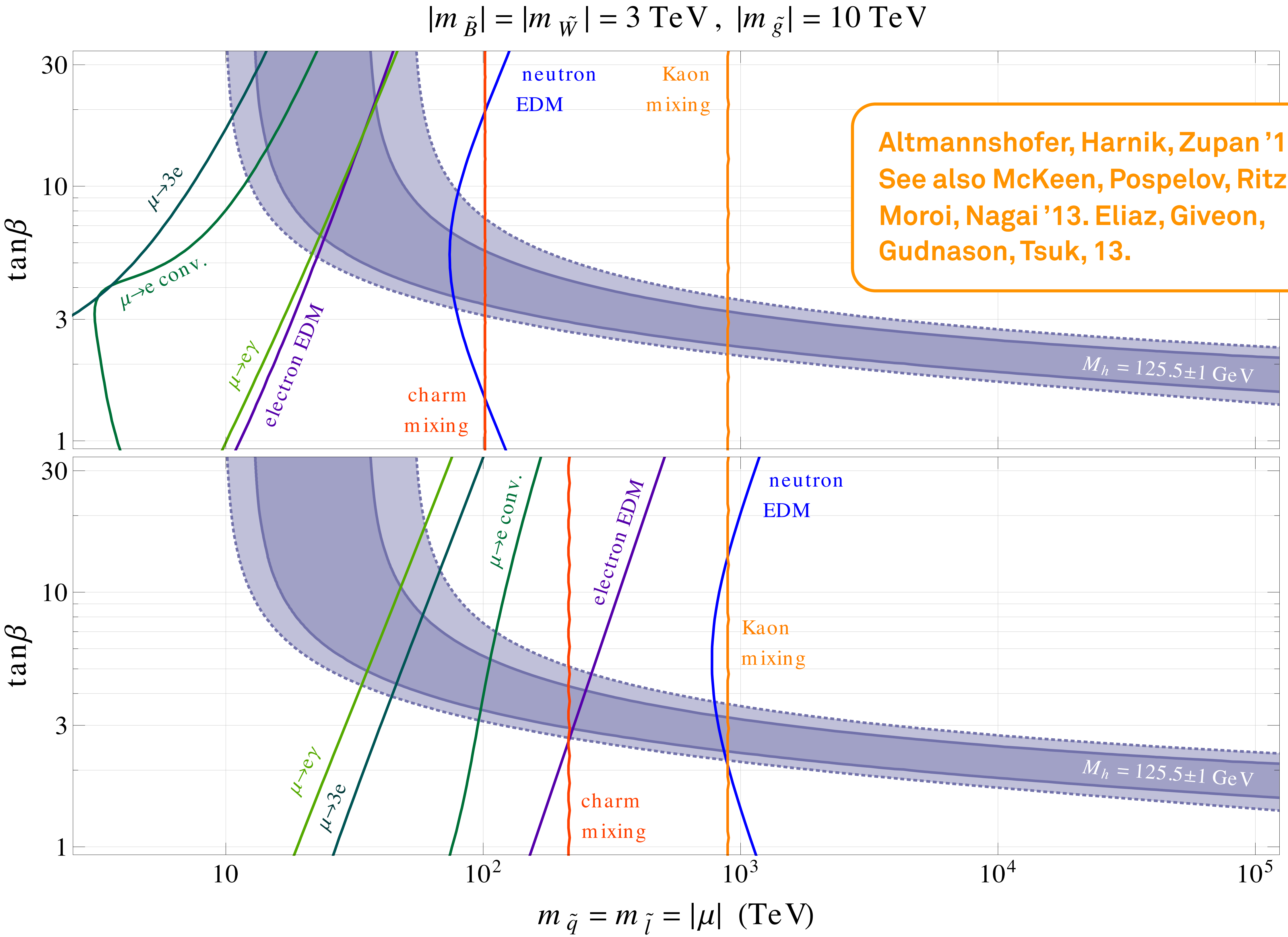
Field	$\mathrm{U}(1)_F$	$SU(3) \times SU(2) \times U(1)$	R_p
$H_u,\, H_d$	∓ 2	$(\mathbf{1},\mathbf{2})_{1/2} + (\mathbf{1},\mathbf{2})_{-1/2}$	$+$
$Q,\, \bar{Q}$	± 1	$(\mathbf{3},\mathbf{2})_{1/6} + (\bar{\mathbf{3}},\mathbf{2})_{-1/6}$	$-$
$U,\, \bar{U}$	± 1	$(\bar{\mathbf{3}},\mathbf{1})_{-2/3} + (\mathbf{3},\mathbf{1})_{2/3}$	$-$
$E,\, \bar{E}$	± 1	$(\mathbf{1},\mathbf{1})_{1} + (\mathbf{1},\mathbf{1})_{-1}$	$-$
$D,\, \bar{D}$	∓ 3	$(\bar{\mathbf{3}},\mathbf{1})_{1/3} + (\mathbf{3},\mathbf{1})_{-1/3}$	$-$
$L,\, \bar{L}$	∓ 3	$(\mathbf{1},\mathbf{2})_{-1/2} + (\mathbf{1},\mathbf{2})_{1/2}$	$-$
$\ell_4,\, \bar{\ell}$	0	$(\mathbf{1},\mathbf{2})_{-1/2} + (\mathbf{1},\mathbf{2})_{1/2}$	$-$
$d_4,\, \bar{d}$	0	$(\bar{\mathbf{3}},\mathbf{1})_{1/3} + (\mathbf{3},\mathbf{1})_{-1/3}$	$-$
$\phi_{1,2},\, \bar{\phi}_{1,2}$	± 1	$(\mathbf{1},\mathbf{1})_{0}$	$+$
$\chi_{1,2},\, \bar{\chi}_{1,2}$	∓ 3	$(\mathbf{1},\mathbf{1})_{0}$	$+$
$\xi,\, \bar{\xi}$	∓ 2	$(\mathbf{1},\mathbf{1})_{0}$	$+$

- Field content is consistent with SU(5) unification and *R*-parity
- SM matter neutral under *U(1),* all other matter vectorlike
- Anomalies cancel trivially, everybody gets supersymmetric mass
- Flavon sector slightly complicated

EXAMPLE SPECTRUM



MSSM CONTRAINTS



Altmannshofer, Harnik, Zupan '13.
See also McKeen, Pospelov, Ritz '13.
Moroi, Nagai '13. Eliaz, Giveon,
Gudnason, Tsuk, 13.

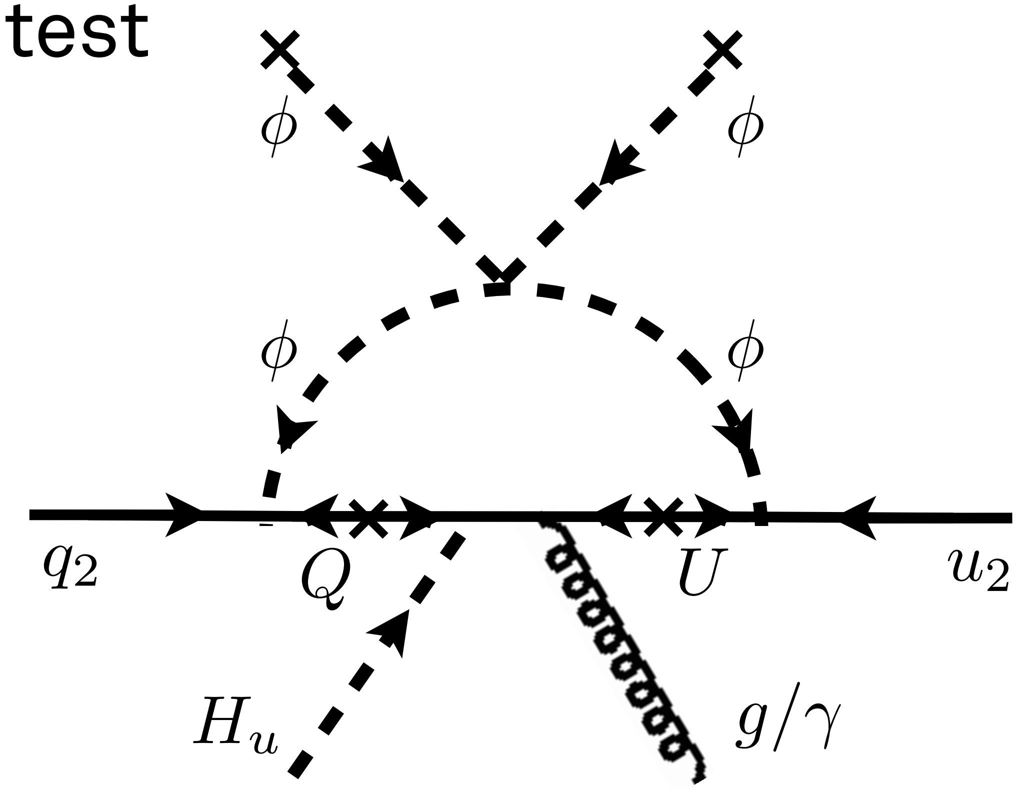
MODEL PHENO

Model has messengers and flavons (+inos) which couple to second and third generation

Precision flavor observables involving second and third generation provide in principle test

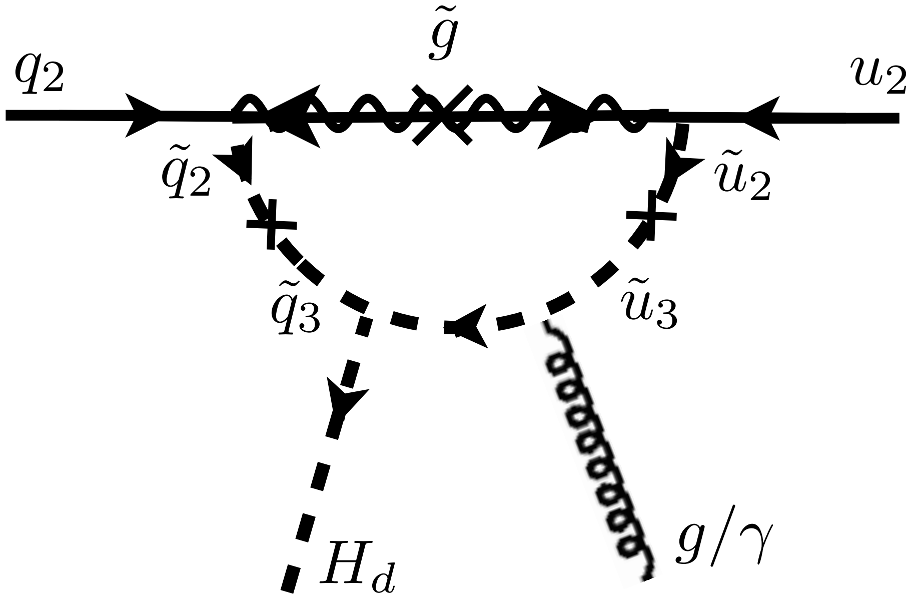
- Charm (C)EDM
- $\tau \to \mu\gamma$
- B_s mixing

Need order of magnitude improvement in experimental precision for discovery

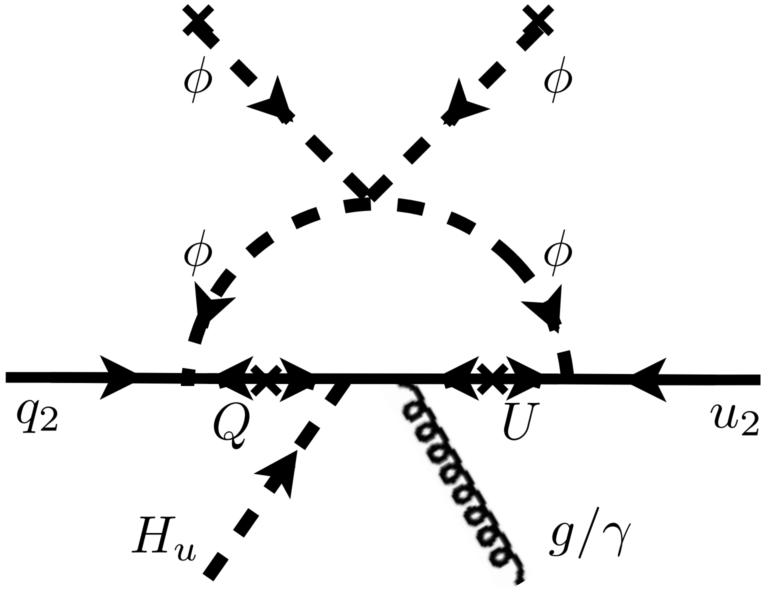


MODEL PHENO

Charm (C)EDM



MSSM



Model

Flavon contribution does not have gaugino mass insertion

Model contribution is one loop enhanced

CONCLUSIONS

- LHC discoveries (and lack of) make mini-split SUSY an intriguing framework with unification and dark matter accommodated

- Dumbest form of SUSY breaking gives anarchic flavor structure in soft masses, fine for mini-split

- Anarchic structure can be used to build radiative flavor model and give elegant explanation of structure of SM parameters

- Use of one small parameter for *b* Yukawa gives right Cabibbo angle and CKM matrix

- Model presented here all the hierarchies of the SM quark and charged lepton sector

THANK YOU