Physics Beyond Standard Model

(mostly supersymmetry)

Asia-Europe-Pacific High Energy Physics School

Chinese Academy of Sciences, Beijing

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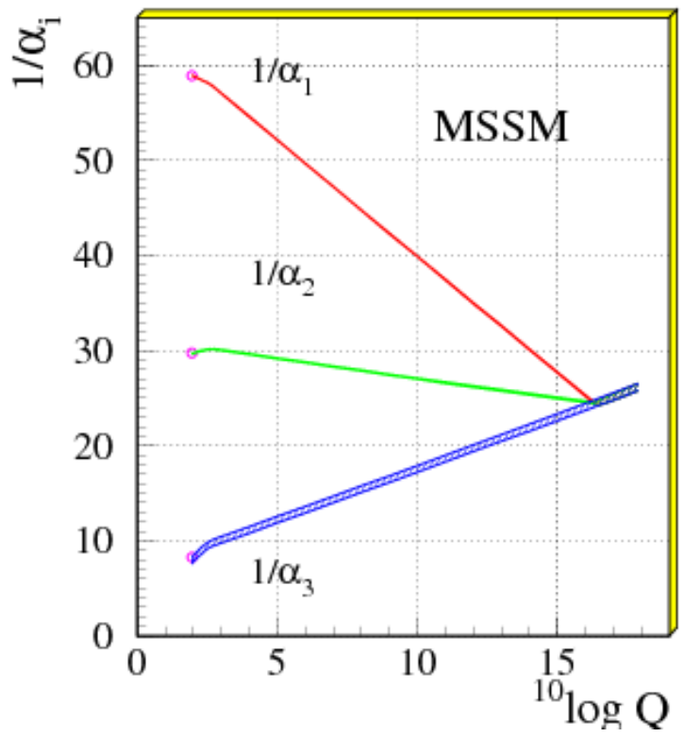
Outline

1) Three paths to supersymmetry
2) LHC Results
3) Flavour Constraints
4) Dark Matter Constraints
5) Escaping LHC and other search strategies
6) Famous SUSY breaking models and their status
7) A small introduction to Extra Dimensions

Other advantages of SUSY

- Its calculable and thus in principle, predictable. It has nice Quantum field theory properties (non-renormalisable theorems etc)
- Dark Matter candidate if R-parity is conserved.
- Gauge coupling unification (GUTs with neutrino masses and mixing)
- Lightest Higgs boson can be SM -like in regions of parameter space.

Then, where can we find it ?



Model
of
SUSY

lecture 2

LHC

DM

Flavour and
CP violation

Some SUSY CODES

Spectrum Generators

SPHENO
SOFTSUSY
ISASUSY
SUSPECT
SUSEFLAV
FLEXISUSY

Dark Matter

ISADM
SuperISoRelic
MicroOmegas
Dark SUSY

Flavour Physics

SuperIso
SUSYFLAVOR
SuperLFV
ISABSMU
SUSEFLAV

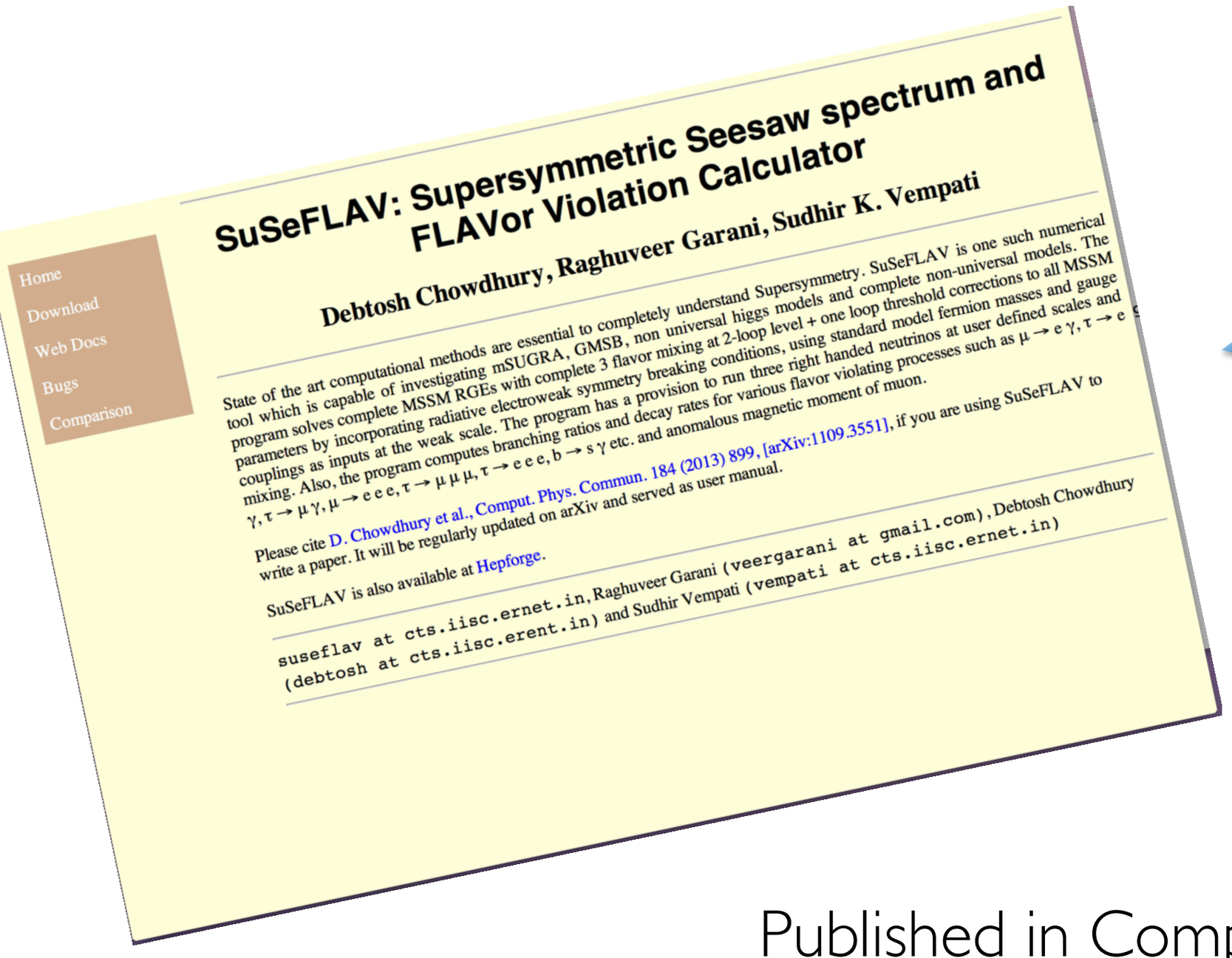
Collider Physics

ISAJET
Prospino
Higlu
SUSHI
MADGRAPH
CHECKMATE

http://www.hepforge.org

SuSeFLAV

SUpersymmetric SEesaw and Flavour Violation



Our Webpage

Published in Computer Physics Communications 184 (2013) 899

Searches at LHC

(1) squarks and gluinos

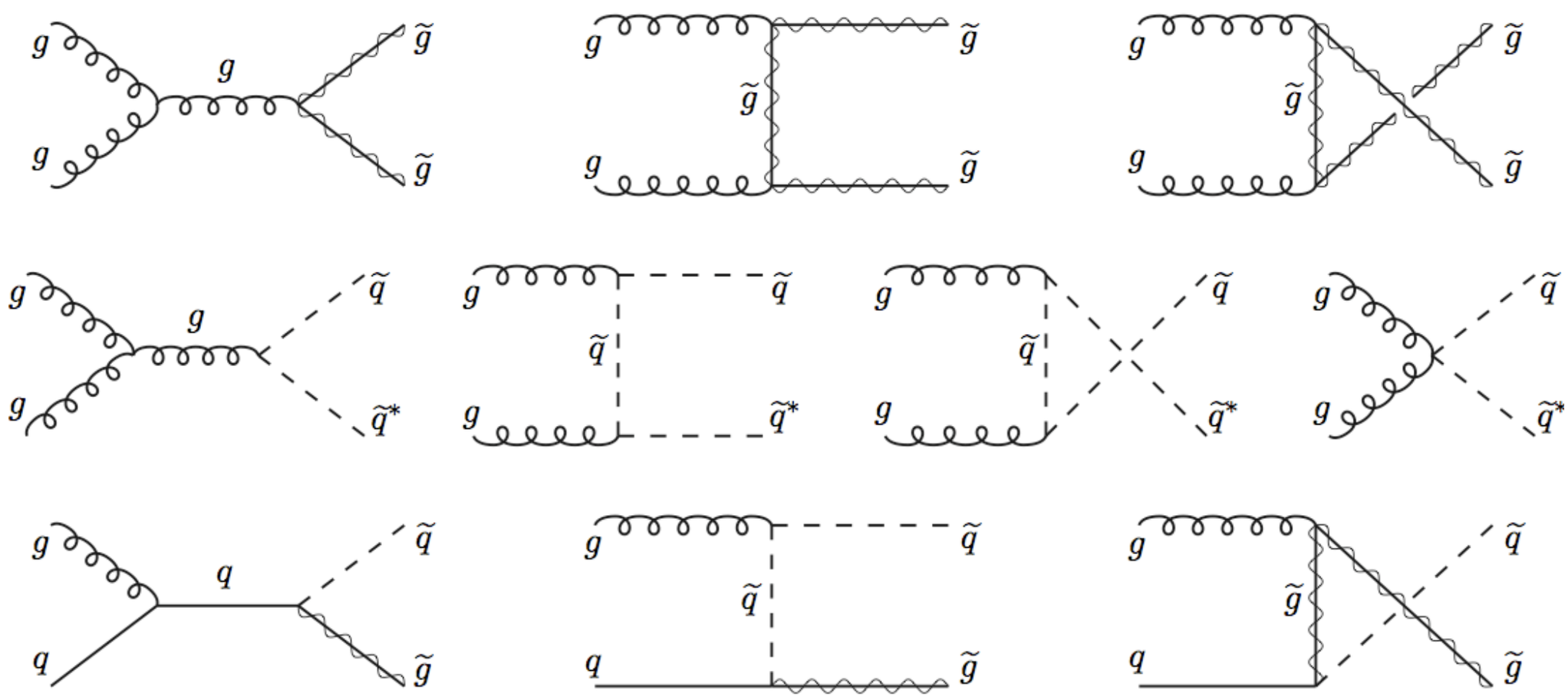
(2) Direct Production of stops and Bottoms

(3) Direct Electroweak production

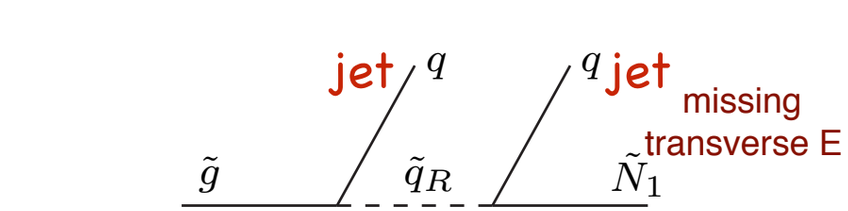
Searches at LHC

Coloured particles are produced more copiously at the LHC

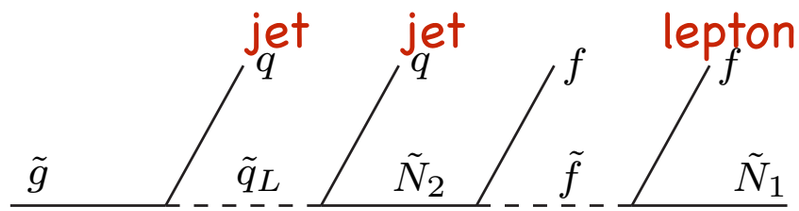
So squarks and gluinos have the strongest constraints



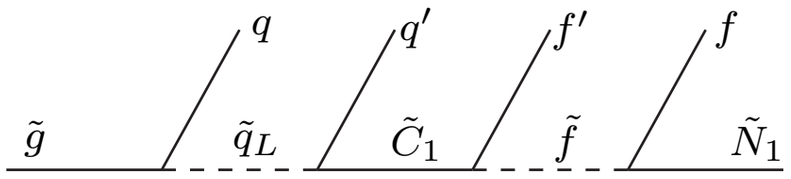
Some cascade decays of gluinos



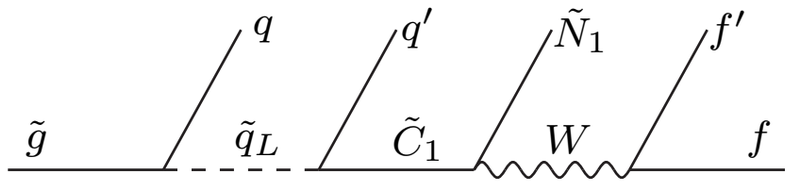
(a)



(b)

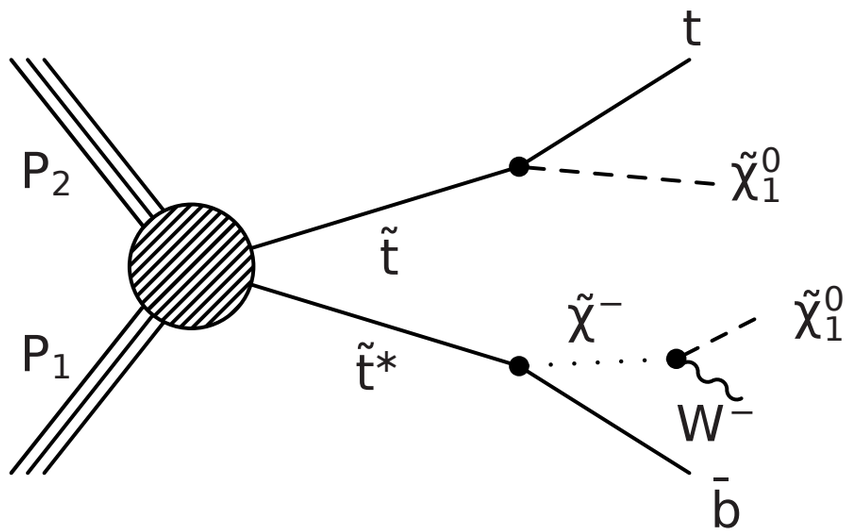


(c)



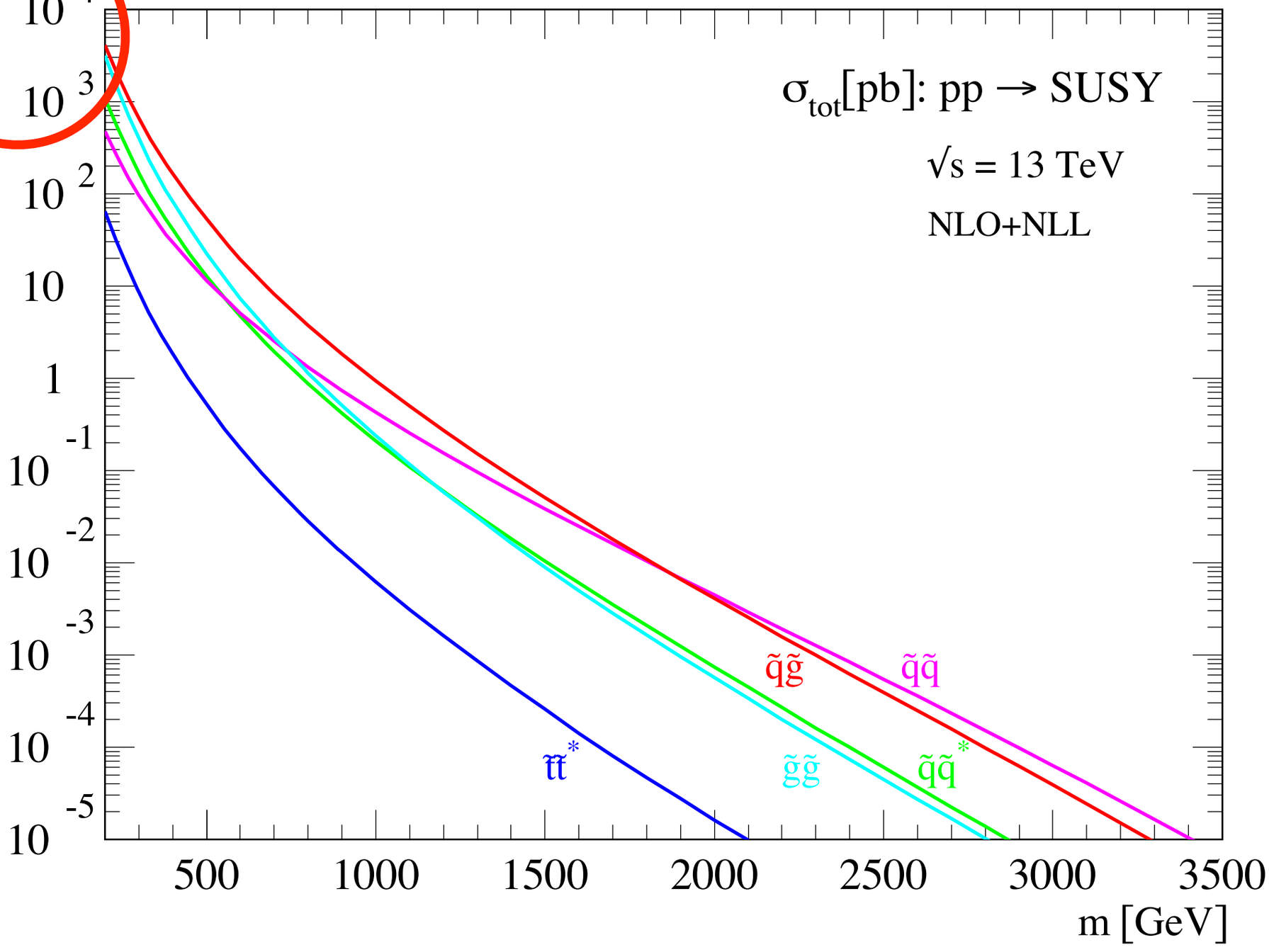
(d)

sample stop decays



SUSY production cross-sections

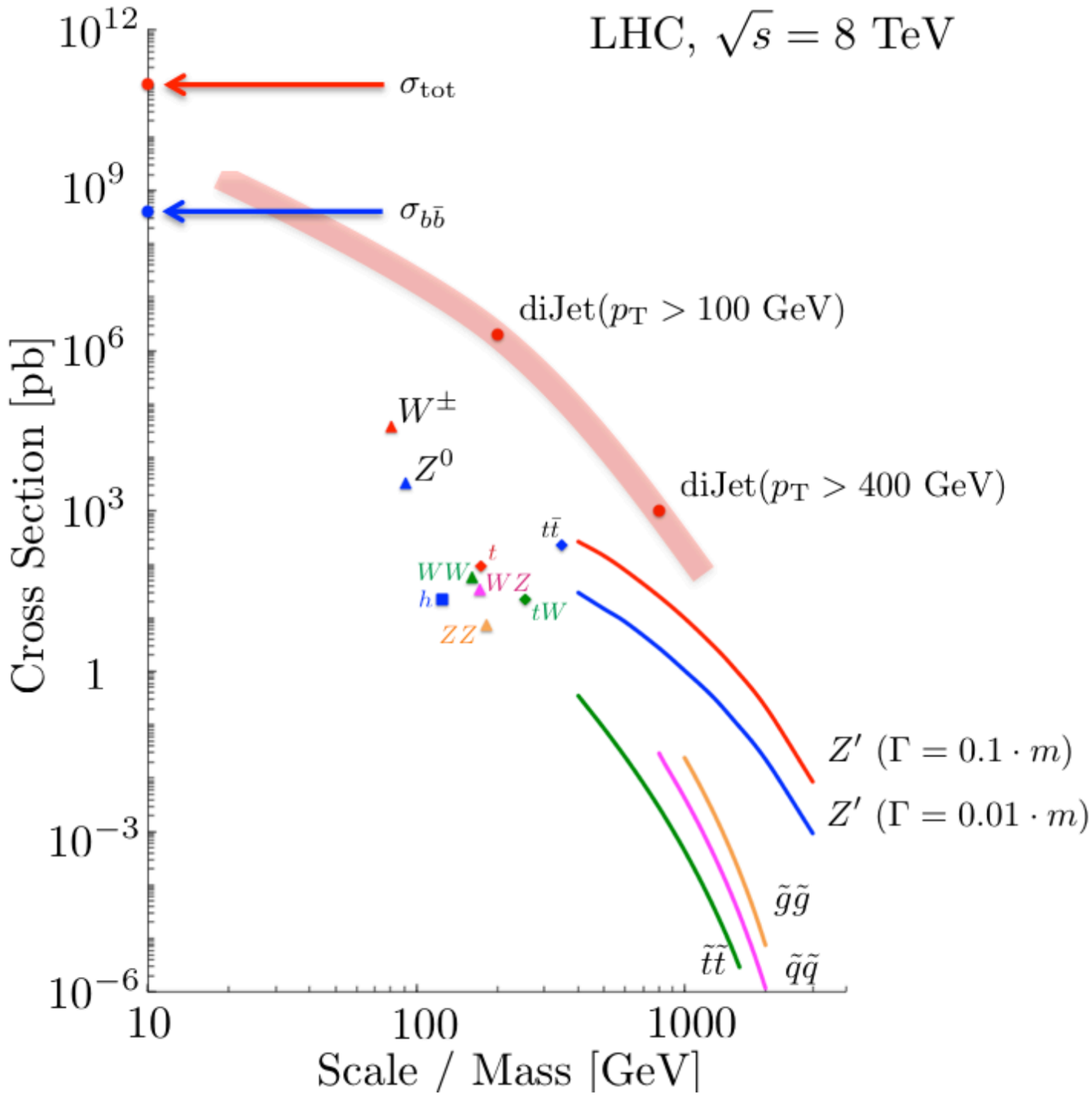
arxiv : 1407.5066



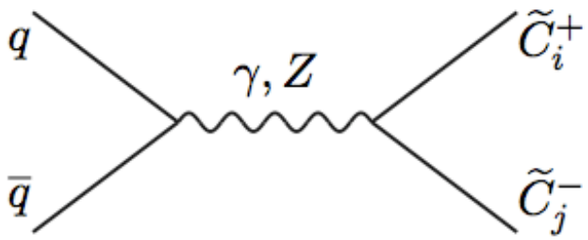
fall rapidly with mass

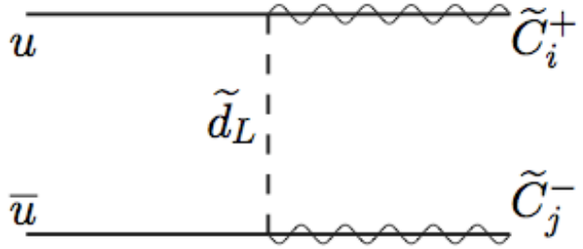
Review : 1105.1110

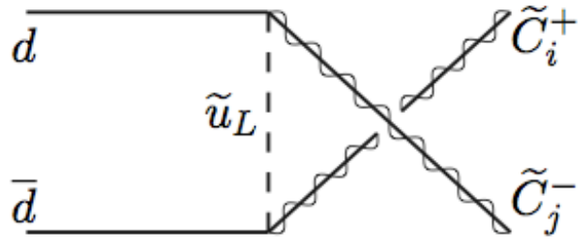
Christian Sanders, For CMS,
Talk at SUSY 2015

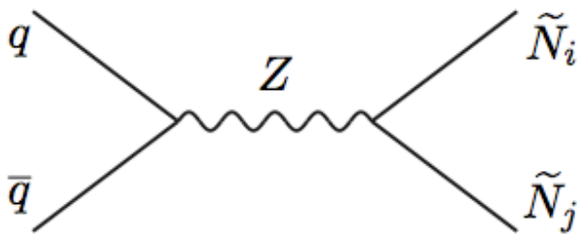


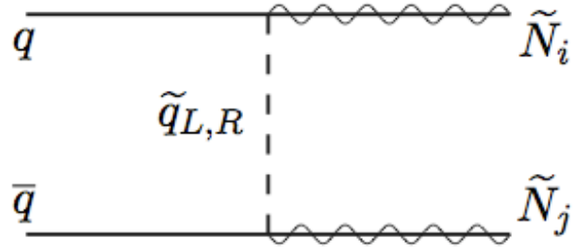
backgrounds are typically large

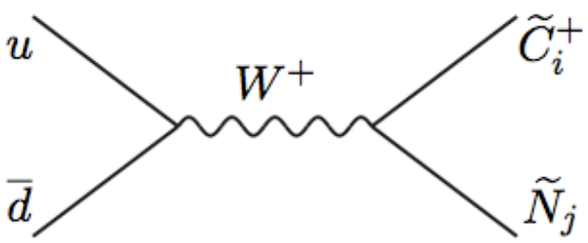


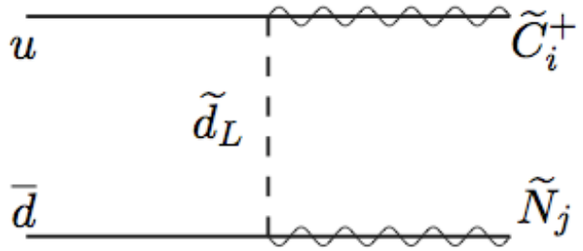


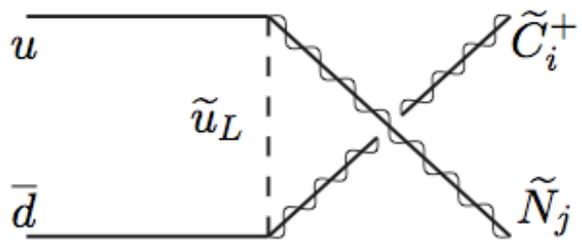


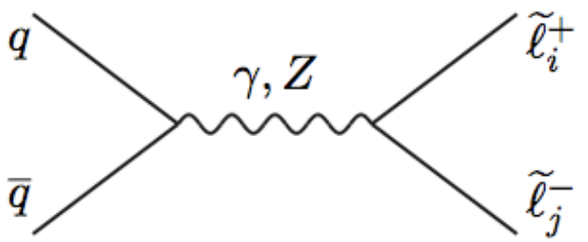


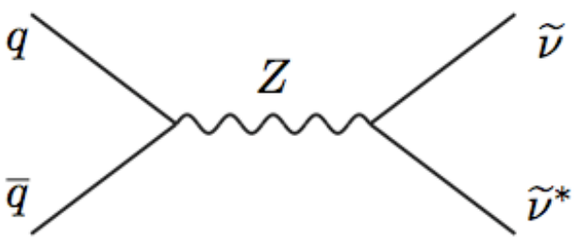


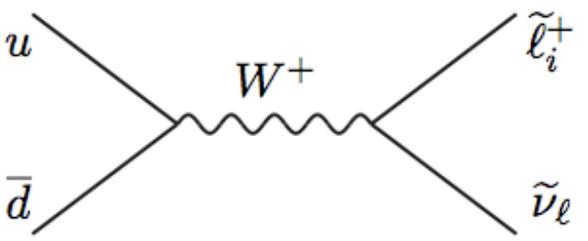






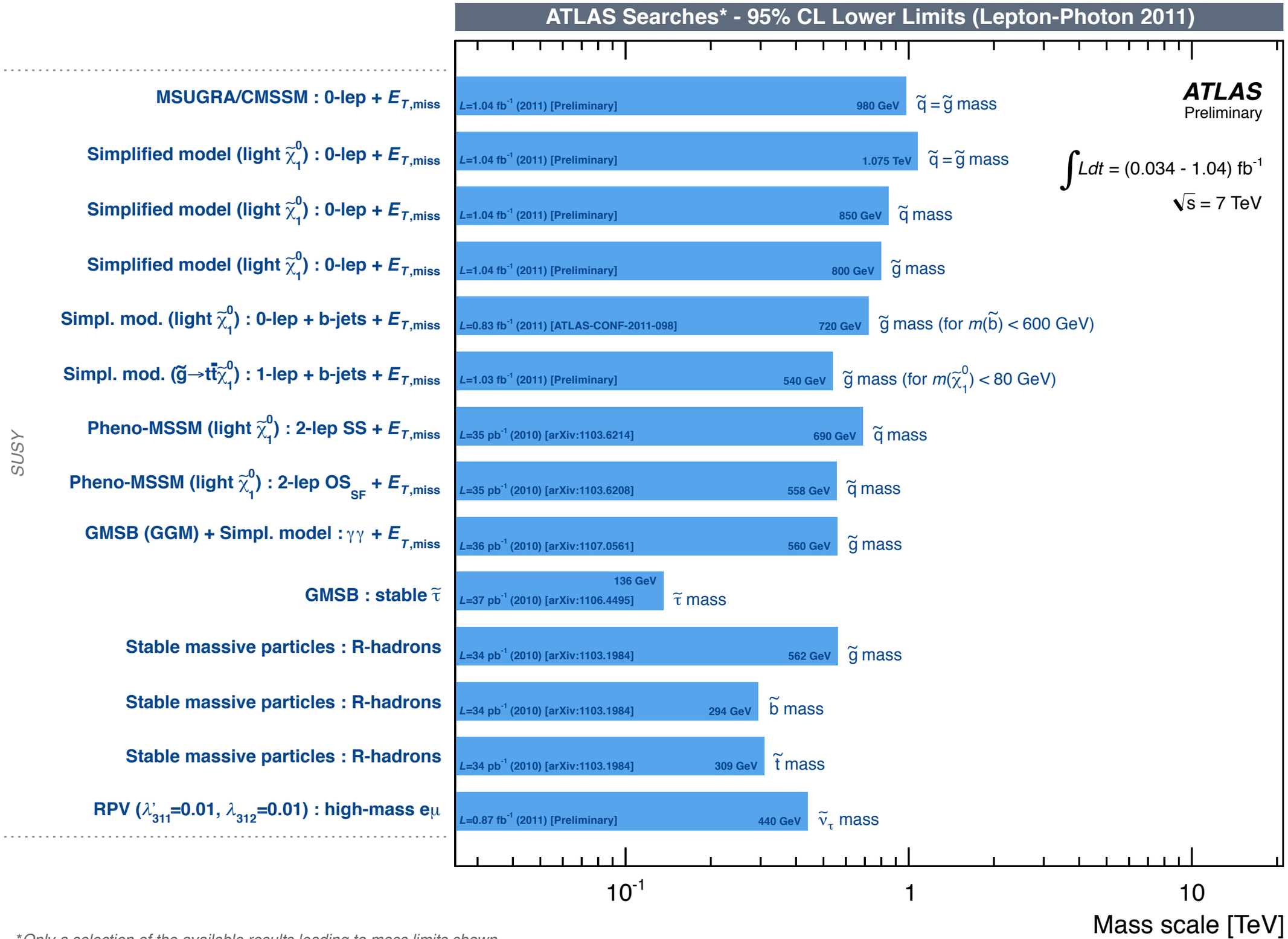






production of charginos neutralinos,sleptons etc.

Early Results from LHC



*Only a selection of the available results leading to mass limits shown

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

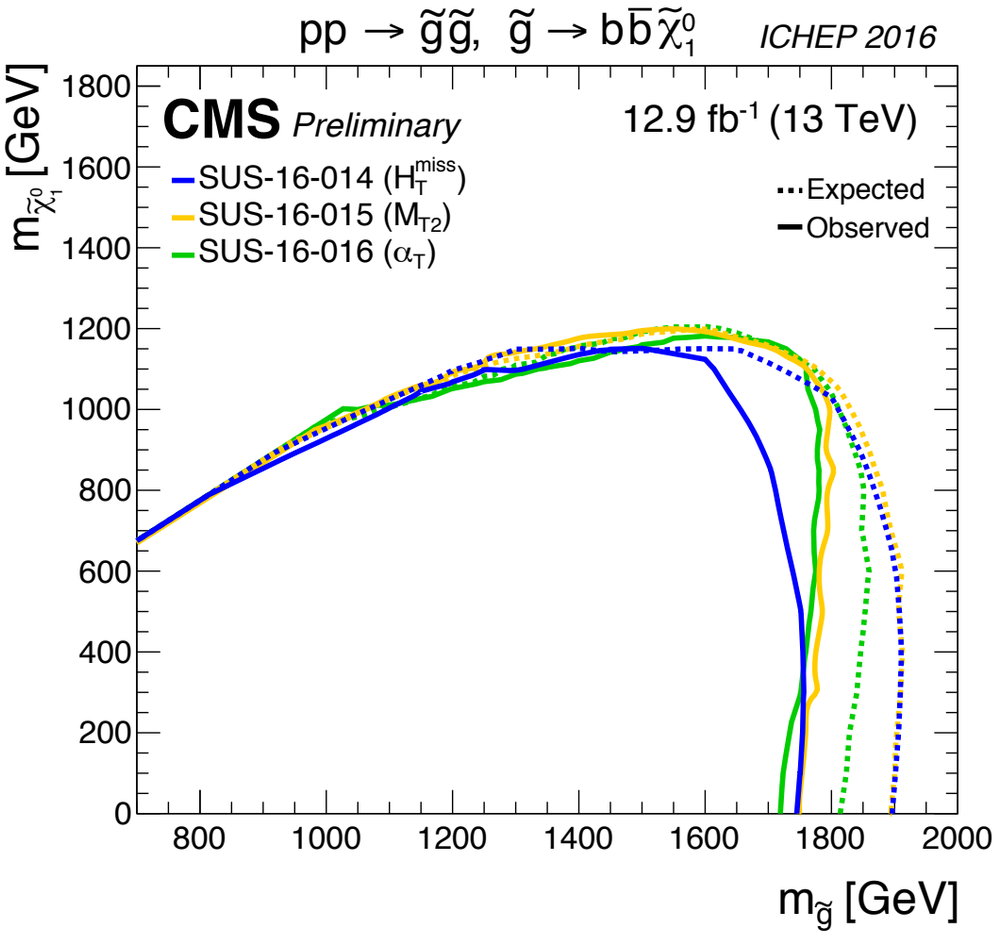
ATLAS Preliminary

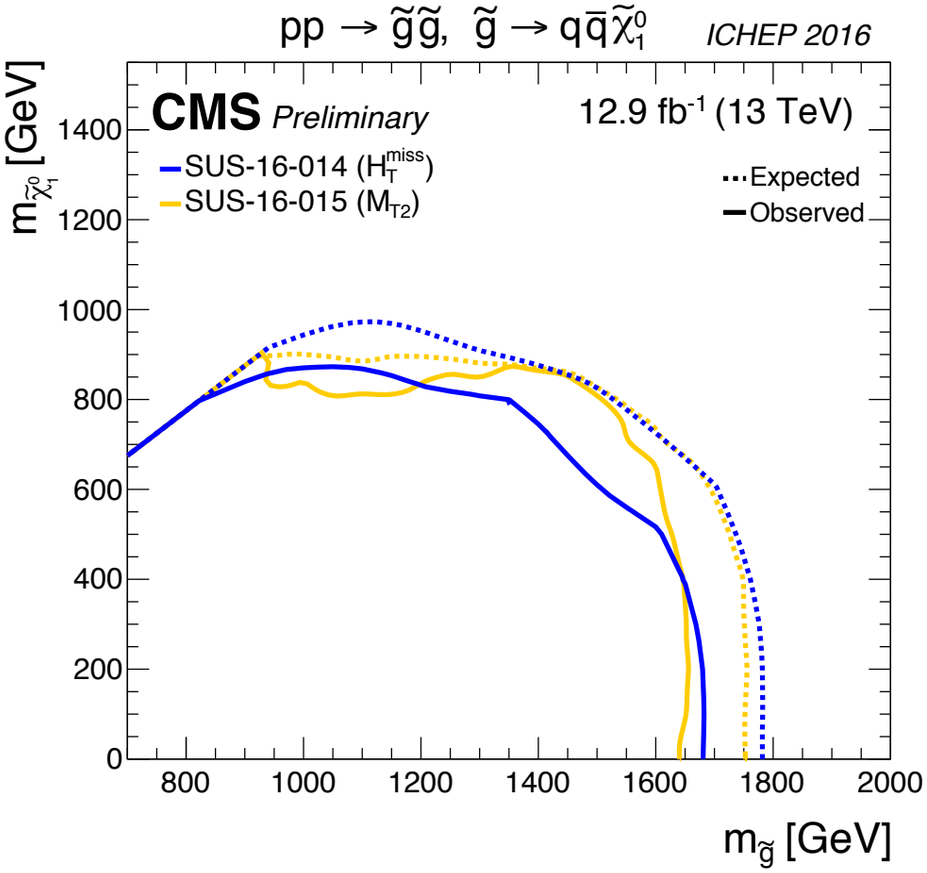
$\sqrt{s}$ = 7, 8, 13 TeV

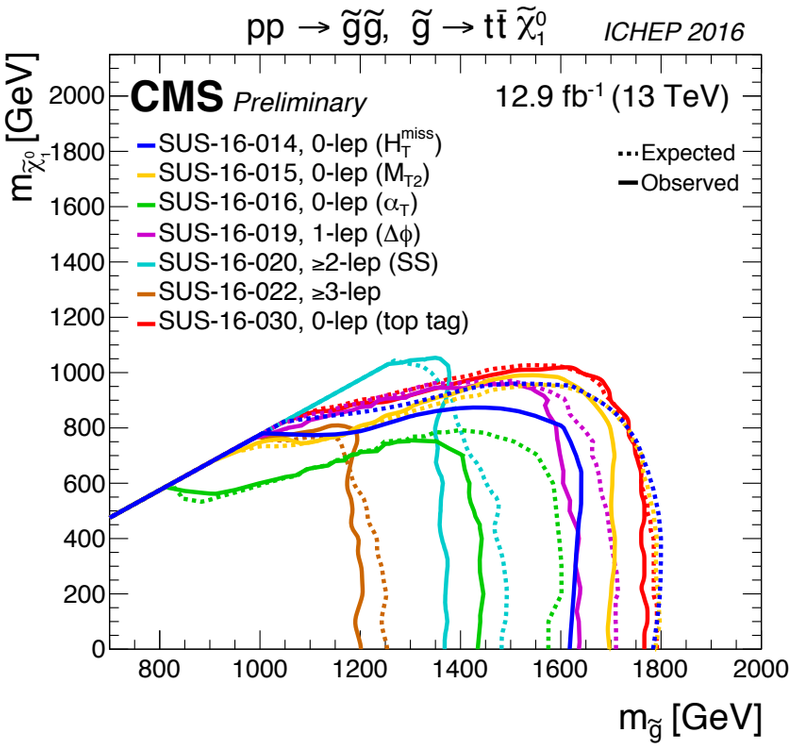
	Model	e, μ, τ, γ	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit ($\sqrt{s}$ = 7, 8 TeV / $\sqrt{s}$ = 13 TeV)		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{q}$ 1.35 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(1^{\mathrm{st}}\ \mathrm{gen.}\ \tilde{q})=m(2^{\mathrm{nd}}\ \mathrm{gen.}\ \tilde{q})$	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 608 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{g}$ 1.86 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{g}$ 1.83 TeV	$m(\tilde{\chi}_1^0)$<400 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	13.2	$\tilde{g}$ 1.7 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$ 1.6 TeV	$m(\tilde{\chi}_1^0)$ <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	14.8	$\tilde{g}$ 1.89 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	14.8	$\tilde{g}$ 1.89 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}, \tilde{g}\to bt\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	$\tilde{b}_1$ 840 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	1 b	Yes	13.2	$\tilde{b}_1$ 325-685 GeV	$m(\tilde{\chi}_1^0)$<150 GeV, $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_1^0)$+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 117-170 GeV, 200-720 GeV	$m(\tilde{\chi}_1^\pm)=2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 90-198 GeV, 205-850 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$ 90-323 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-600 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	13.3	$\tilde{t}_2$ 290-700 GeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$	1 e, μ	6 jets + 2 b	Yes	20.3	$\tilde{t}_2$ 320-620 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 90-335 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	13.3	$\tilde{\chi}_1^\pm$ 640 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-2016-096
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	14.8	$\tilde{\chi}_1^\pm$ 580 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-2016-093
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_{\mathrm{L}}\nu\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	13.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 1.0 TeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2016-096
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 425 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 270 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_{\mathrm{R}}\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 635 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
	GGM (wino NLSP) weak prod.	1 e, μ + γ	-	Yes	20.3	$\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	$\tilde{W}$ 590 GeV	$c\tau$<1 mm	1507.05493
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	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$ 495 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 850 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 1.57 TeV	$m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 440 GeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.45 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^\pm$ 1.14 TeV	$m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ ($k=1,2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e, μ + τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.55 TeV	$m(\tilde{\chi}_1^0)$=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	1 e, μ	8-10 jets/0-4 b	-	14.8	$\tilde{g}$ 1.75 TeV	$m(\tilde{\chi}_1^0)$=700 GeV	ATLAS-CONF-2016-094
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e, μ	8-10 jets/0-4 b	-	14.8	$\tilde{g}$ 1.4 TeV	625 GeV<$m(\tilde{t}_1)$<850 GeV	ATLAS-CONF-2016-094
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$ 410 GeV, 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 510 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

**Only a selection of the available mass limits on new states or phenomena is shown.*

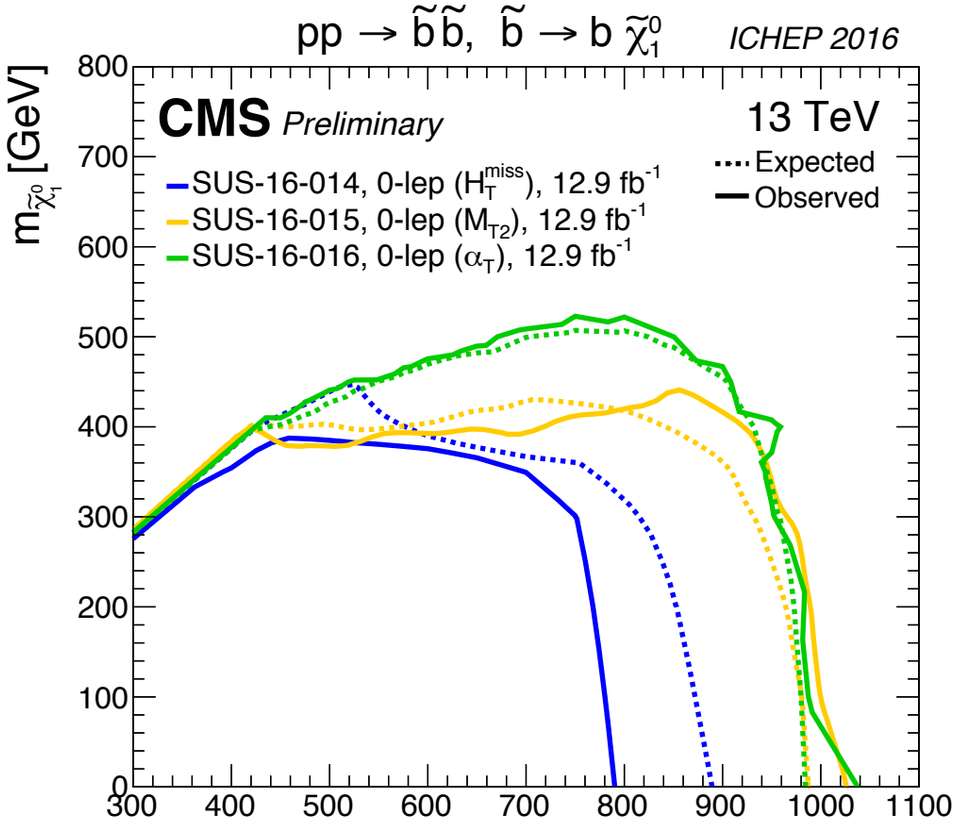
10^{-1} 1 **Mass scale [TeV]**

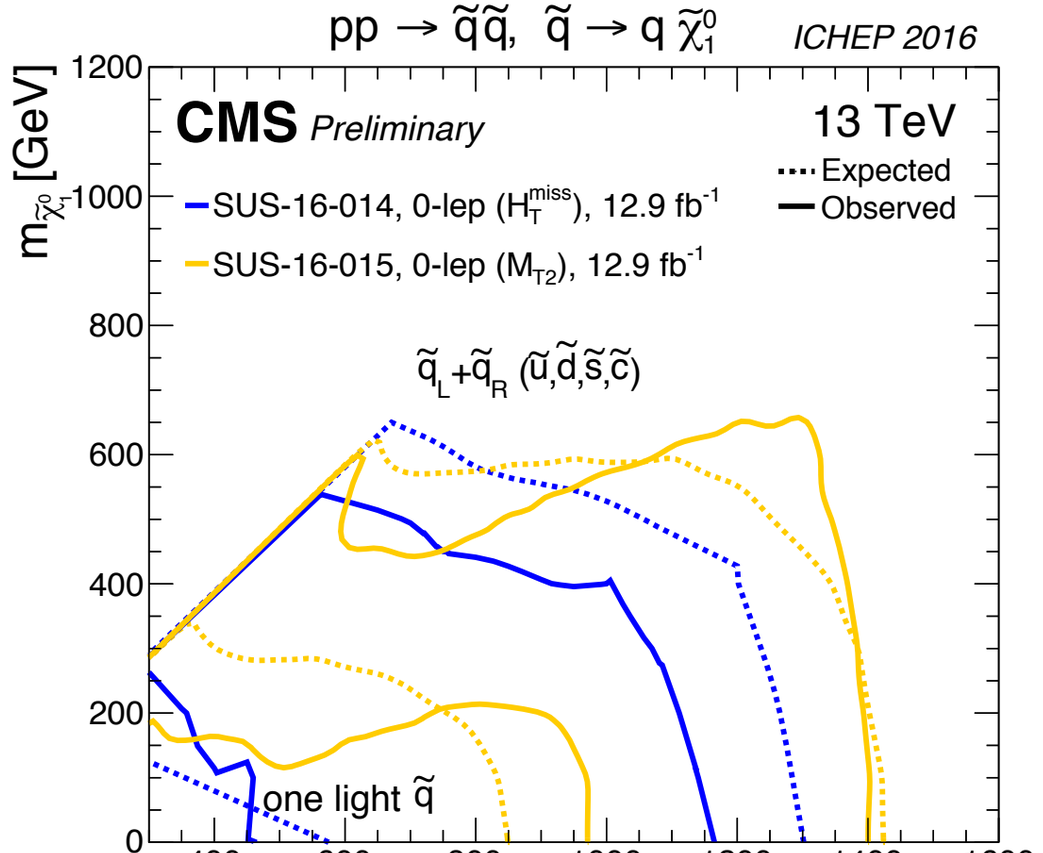


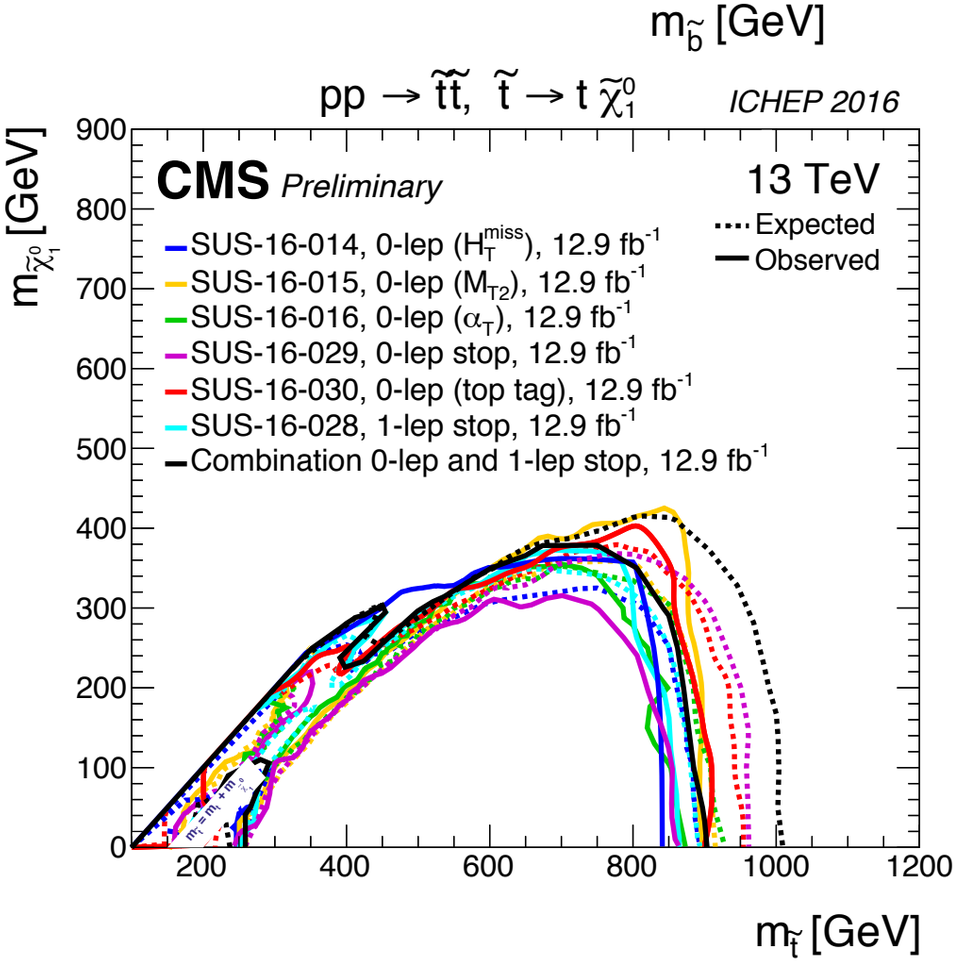




Limits on Gluino mass from CMS







limits on sbottoms, squarks and stops

Summary of the data

Gluinos are ruled out up to masses 1- 1.8 TeV

First two generations should be greater than 1-1.2 TeV

third generation limits reaching 0.8 TeV in some cases

Weakly coupled particles limits becoming stronger reaching 0.5 TeV in some cases

limits obtained typically in simplified models and thus there could be variation

Flavour

flavour violation in soft susy breaking terms.

$$
\begin{aligned}
-\mathcal{L}_{\text{soft}} &= m^2_{Q_{ii}} \tilde{Q}^\dagger_i \tilde{Q}_i + m^2_{u^c_{ii}} \tilde{u^c}^\star_i \tilde{u^c}_i + m^2_{e^c_{ii}} \tilde{e^c}^\star_i \tilde{e^c}_i + m^2_{d^c_{ii}} \tilde{d^c}^\star_i \tilde{d^c}_i + m^2_{L_{ii}} \tilde{L}^\dagger_i \tilde{L}_i \\
&+ m^2_{H_1} H^\dagger_1 H_1 + m^2_{H_2} H^\dagger_2 H_2 + A^u_{ij}\, \tilde{Q}_i \tilde{u^c}_j H_2 + A^d_{ij}\, \tilde{Q}_i \tilde{d^c}_j H_1 \\
&+ A^e_{ij}\, \tilde{L}_i \tilde{e^c}_j H_1 + (\Delta^l_{ij})_{\text{LL}} \tilde{L}^\dagger_i \tilde{L}_j + (\Delta^l_{ij})_{\text{RR}} \tilde{e^c}^\star_i \tilde{e^c}_j \\
&+ (\Delta^e_{ij})_{\text{LR}} \tilde{e}^\star_{Li} \tilde{e^c}_{Rj} + \ldots \qquad (1)
\end{aligned}
$$

Define :

$$\delta^l_{ij} \equiv \Delta^l_{ij} / m^2_{\tilde{l}} \qquad (2)$$

Ratio of flavour violating terms with flavour conserving ones.

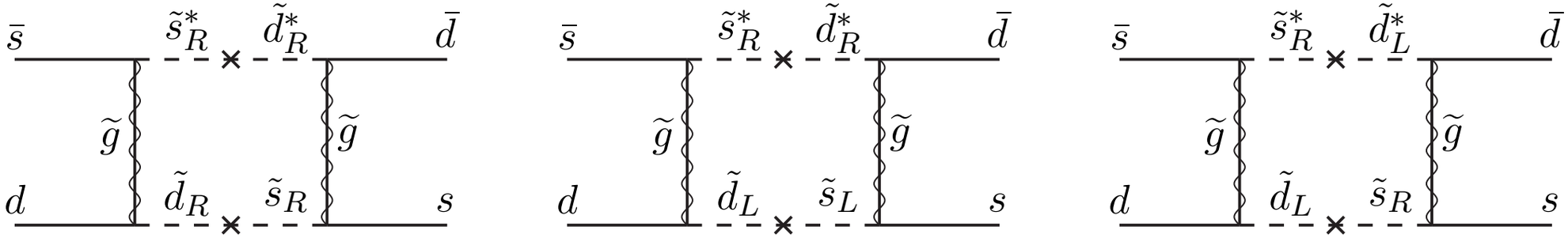
similar parameterisation can be done for squarks

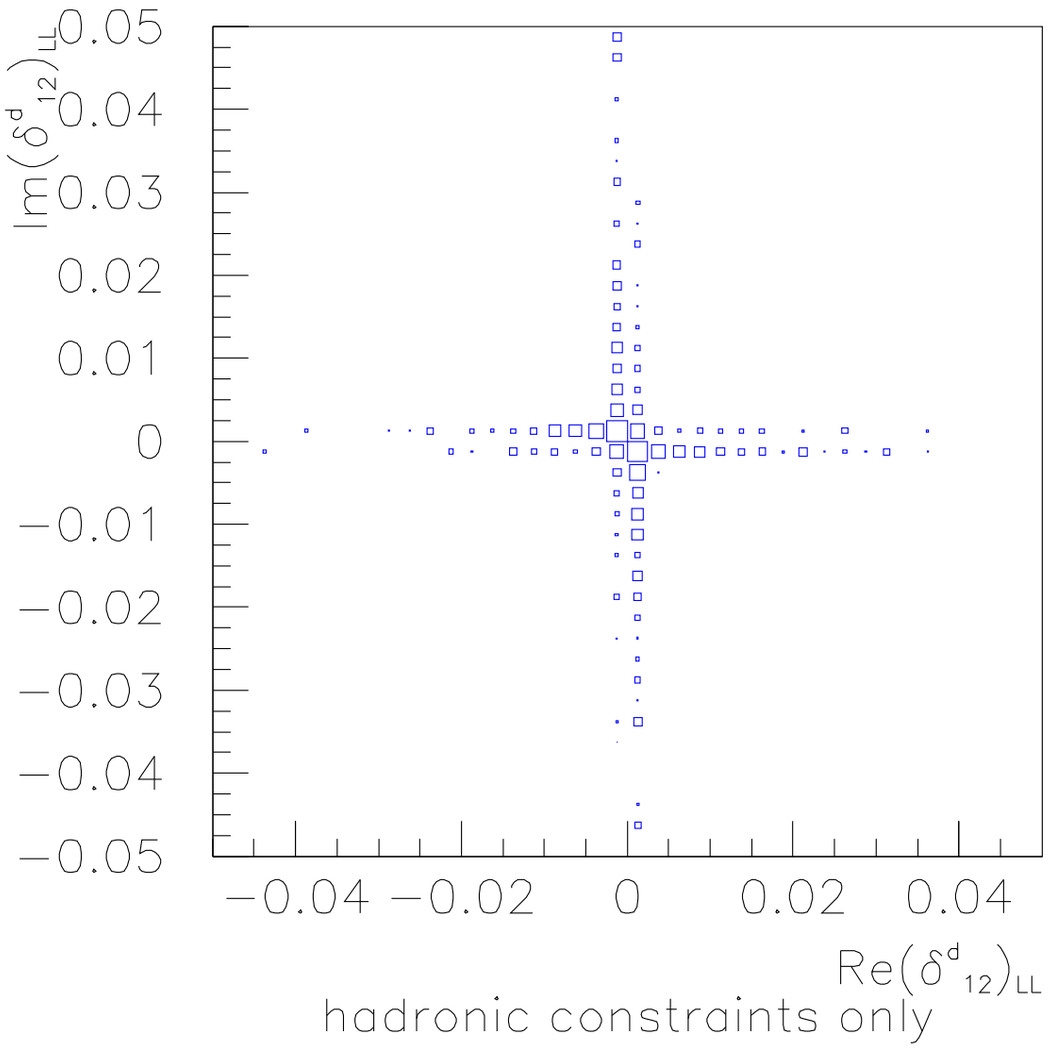
Flavour and CP violation limits

process	current exp.	future exp.
K^0 mixing	$\epsilon_K = (2.228 \pm 0.011) \times 10^{-3}$ [22]	—
D^0 mixing	$A_\Gamma = (-0.02 \pm 0.16)\%$ [23]	$\pm 0.007\%$ LHCb [24] $\pm 0.06\%$ Belle II [25]
B_d mixing	$\sin 2\beta = 0.68 \pm 0.02$ [23]	± 0.008 LHCb [24] ± 0.012 Belle II [25]
B_s mixing	$\phi_s = 0.01 \pm 0.07$ [26]	± 0.008 LHCb [24]
$d_{\rm Hg}$	$< 3.1 \times 10^{-29}$ $e$cm [27]	–
$d_{\rm Ra}$	–	$\lesssim 10^{-29}$ $e$cm [28]
d_n	$< 2.9 \times 10^{-26}$ $e$cm [29]	$\lesssim 10^{-28}$ $e$cm [28]
d_p	–	$\lesssim 10^{-29}$ $e$cm [28]
d_e	$< 1.05 \times 10^{-27}$ $e$cm YbF [30, 31] $< 8.7 \times 10^{-29}$ $e$cm ThO [32]	$\lesssim 10^{-30}$ $e$cm YbF, Fr [28]
$\mu \to e\gamma$	$< 5.4 \times 10^{-13}$ MEG [33]	$\lesssim 6 \times 10^{-14}$ MEG upgrade [34]
$\mu \to 3e$	$< 1.0 \times 10^{-12}$ SINDRUM I [35]	$\lesssim 10^{-16}$ Mu3e [36]
$\mu \to e$ in Au	$< 7.0 \times 10^{-13}$ SINDRUM II [37]	–
$\mu \to e$ in Al	–	$\lesssim 6 \times 10^{-17}$ Mu2e [38]

TABLE I: Summary of current and selected future expected experimental limits on CP violation in meson mixing, EDMs and lepton flavor violating processes.

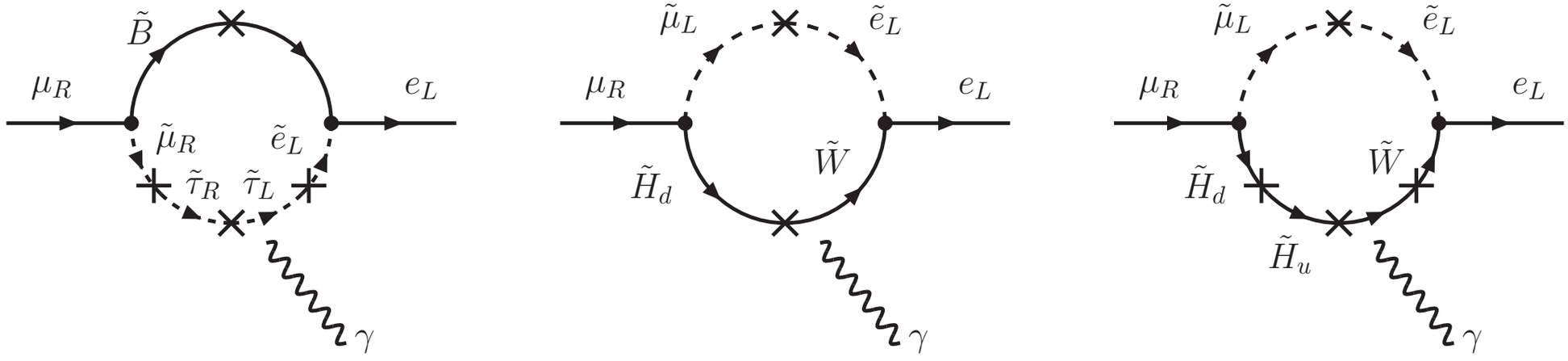
from Altmannhosfer, Harnik, Zupan, 1308.3653





for squark masses
up to 500 GeV

$$\frac{M^2_{\tilde{L}}}{m^2_{\tilde{L}}} \simeq \begin{pmatrix} 1 & \left(\delta^l_{12}\right)_{\rm LL} & \left(\delta^l_{13}\right)_{\rm LL} & \left(\delta^l_{11}\right)_{\rm LR} & \left(\delta^l_{12}\right)_{\rm LR} & \left(\delta^l_{13}\right)_{\rm LR} \\ \left(\delta^l_{12}\right)^*_{\rm LL} & 1 & \left(\delta^l_{23}\right)_{\rm LL} & \left(\delta^l_{21}\right)_{\rm LR} & \left(\delta^l_{22}\right)_{\rm LR} & \left(\delta^l_{23}\right)_{\rm LR} \\ \left(\delta^l_{13}\right)^*_{\rm LL} & \left(\delta^l_{23}\right)^*_{\rm LL} & 1 & \left(\delta^l_{31}\right)_{\rm LR} & \left(\delta^l_{32}\right)_{\rm LR} & \left(\delta^l_{33}\right)_{\rm LR} \\ \left(\delta^l_{11}\right)^*_{\rm LR} & \left(\delta^l_{21}\right)^*_{\rm LR} & \left(\delta^l_{31}\right)^*_{\rm LR} & 1 & \left(\delta^l_{12}\right)_{\rm RR} & \left(\delta^l_{13}\right)_{\rm RR} \\ \left(\delta^l_{12}\right)^*_{\rm LR} & \left(\delta^l_{22}\right)^*_{\rm LR} & \left(\delta^l_{32}\right)^*_{\rm LR} & \left(\delta^l_{12}\right)^*_{\rm RR} & 1 & \left(\delta^l_{23}\right)_{\rm RR} \\ \left(\delta^l_{13}\right)^*_{\rm LR} & \left(\delta^l_{23}\right)^*_{\rm LR} & \left(\delta^l_{33}\right)^*_{\rm LR} & \left(\delta^l_{13}\right)^*_{\rm RR} & \left(\delta^l_{23}\right)^*_{\rm RR} & 1 \end{pmatrix}$$



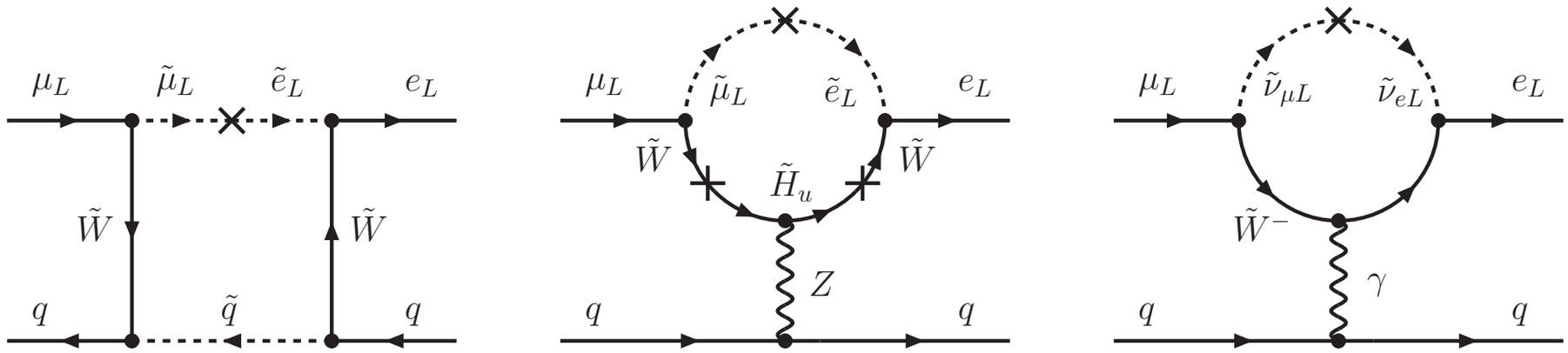
mu to e gamma diagrams

Type of δ^l_{12}	$\mu \to e\,\gamma$	$\mu \to e\,e\,e$	$\mu \to e$ conversion in Ti
LL	6×10^{-4}	2×10^{-3}	2×10^{-3}
RR	-	0.09	-
LR/RL	1×10^{-5}	3.5×10^{-5}	3.5×10^{-5}

for slepton masses close to 400 GeV and tan beta = 10

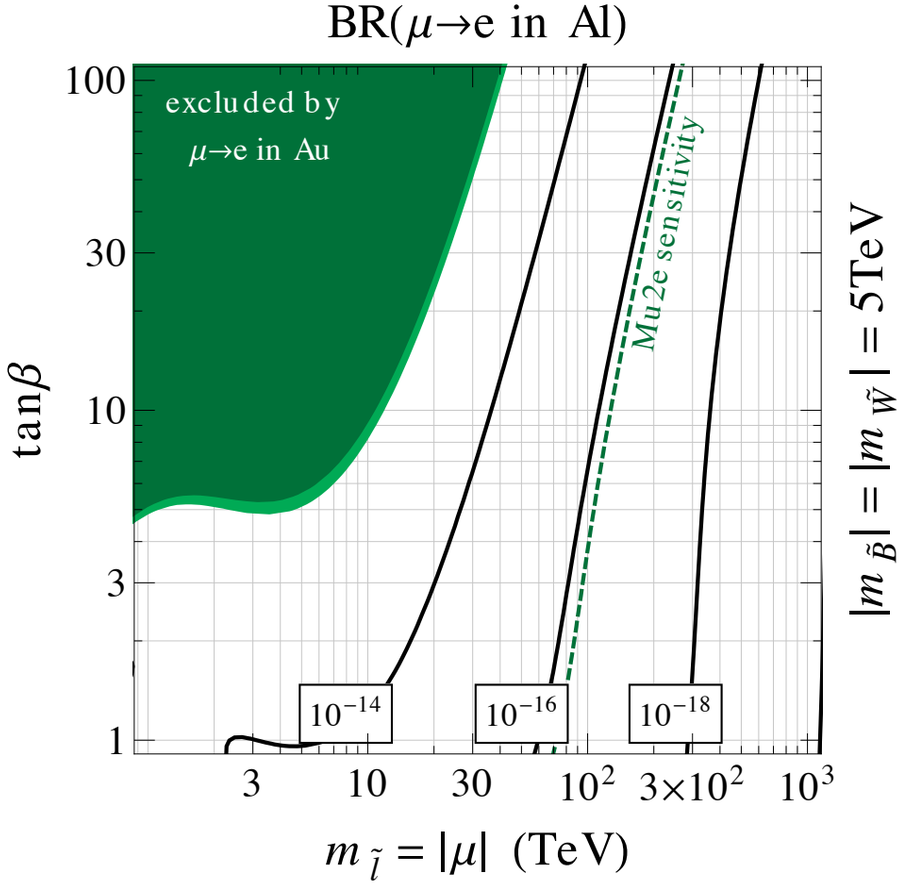
Type of δ^l_{23}	$\tau \to \mu\,\gamma$	$\tau \to \mu\,\mu\,\mu$	$\tau \to \mu\,e\,e$
LL	0.12	-	-
RR	-	-	-
LR/RL	0.03	-	0.5

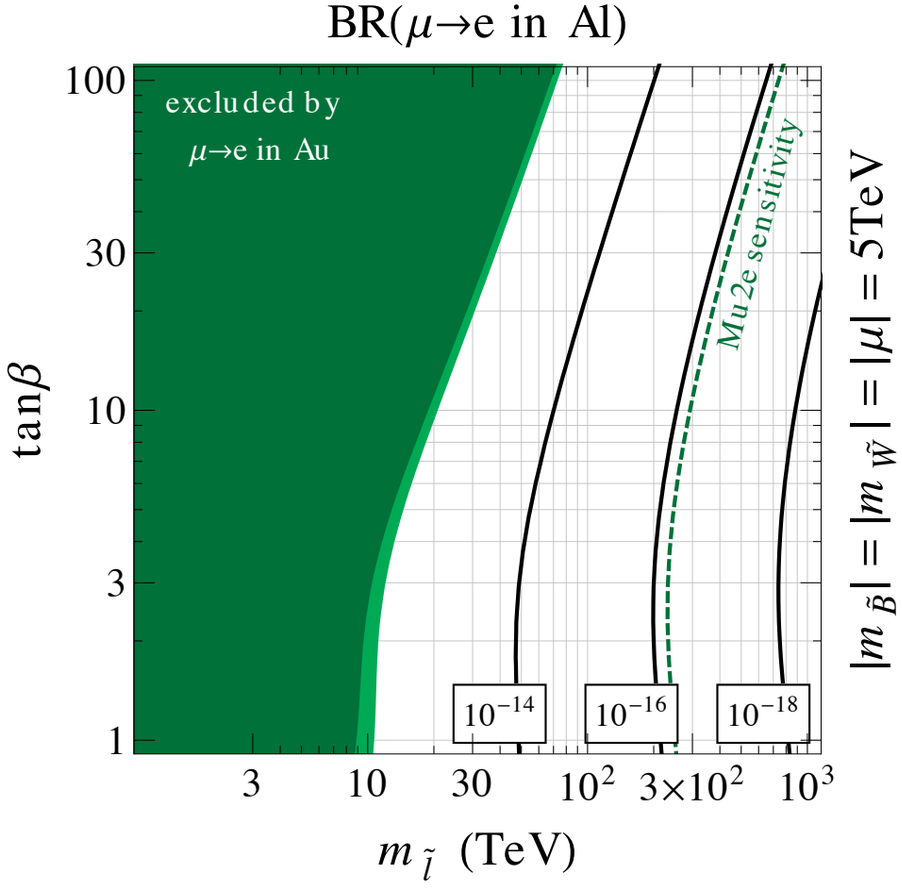
for third generation, bounds are weaker



mu-e conversion diagrams

The strongest limits on flavour violating entries of soft terms





Minimal Flavour Violation with SUSY

Even if all the flavour violating terms are set to zero supersymmetry can still contribute to flavour violation through CKM vertices

Misiak et.al, 1503.01789

The most famous example is $B \to X_s\gamma$

which is measured very accurately and computed in SM up to four loops in QCD

$$\mathcal{B}^{\rm exp}_{s\gamma} = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4},$$

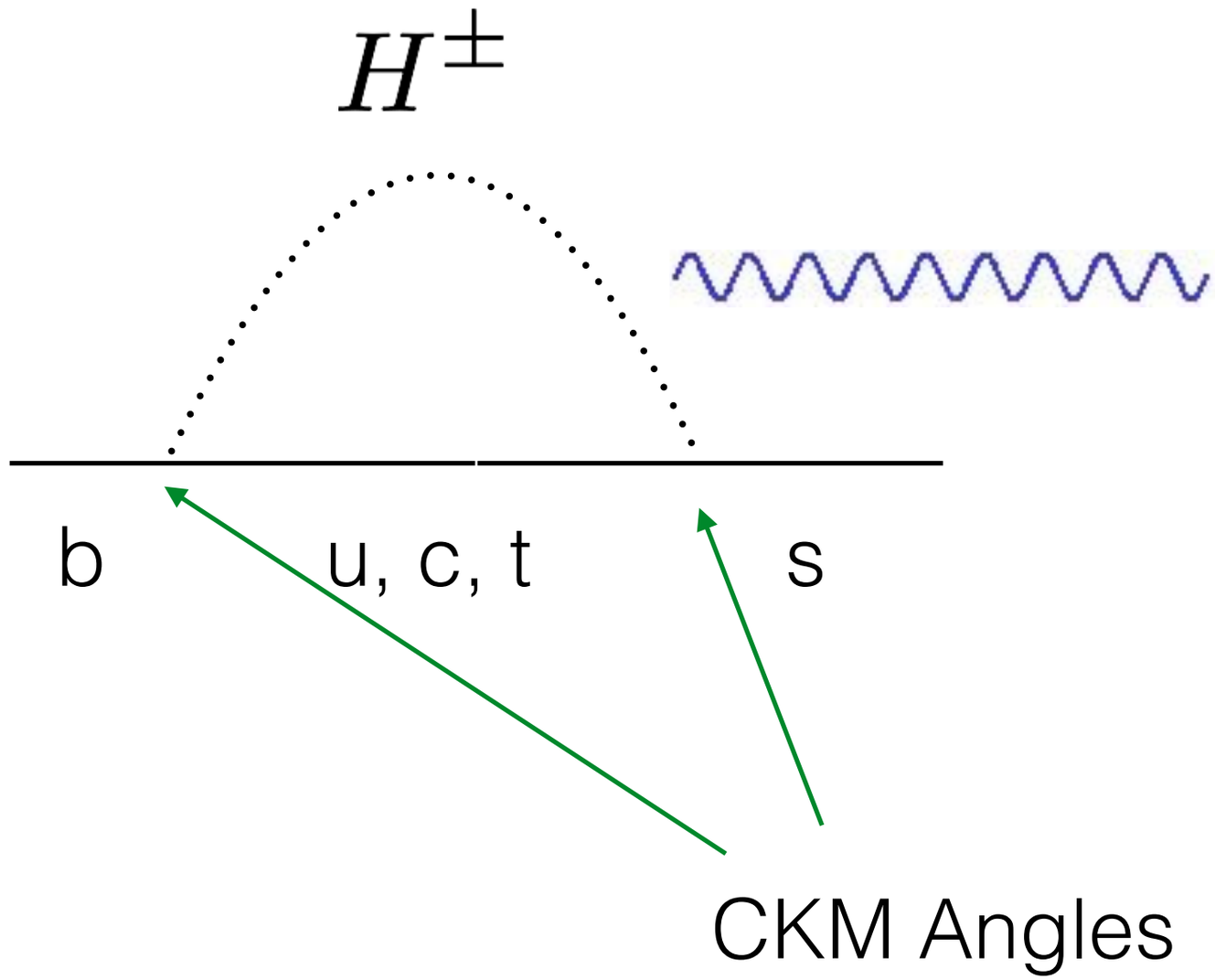
$$\mathcal{B}_{s\gamma} = (3.36 \pm 0.23) \times 10^{-4}$$

In MSSM, contributions from Standard Model diagrams,

Charged Higgs, Chargino and Neutralino diagrams

Large regions of various model parameter spaces are ruled out by this.

MFV charged Higgs diagram



Dark Matter

$$\mathcal{L} \supset \frac{1}{2}\,\Psi_N \mathcal{M}_N \Psi_N^T + H.c \qquad\qquad \Psi_N = \{\tilde{B},\ \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0\}$$

Neutralino Mass matrix

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -M_Z c\beta\ s\theta_W & M_Z s\beta\ s\theta_W \\ 0 & M_2 & M_Z c\beta\ c\theta_W & M_Z s\beta\ c\theta_W \\ -M_Z c\beta\ s\theta_W & M_Z c\beta\ c\theta_W & 0 & -\mu \\ M_Z s\beta\ s\theta_W & -M_Z s\beta\ c\theta_W & -\mu & 0 \end{pmatrix}$$

Diagonalising $\quad N^* \cdot M_{\tilde{N}} \cdot N^\dagger = \mathrm{Diag.}(m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}, m_{\chi_4^0})$

$$M_{\chi_1^0} = N_{\tilde{B}1} + N_{\tilde{W}1} + N_{\tilde{H}_1 1} + N_{\tilde{H}_2 1}$$

The composition of the lightest neutralino determines the regions where the relic density is satisfied

arxiv:0601041

Pure Higgsino

$$\langle \sigma_{eff} v \rangle = \frac{g^4}{512\pi\mu^2}\left(21 + 3\tan^2\theta_W + 11\tan^4\theta_W\right),$$

$$\Omega_{\tilde{H}} h^2 = 0.10\left(\frac{\mu}{1\,\mathrm{TeV}}\right)^2,$$

around 1 TeV !!

(too less if otherwise)

Pure Wino

$$\langle \sigma_{eff} v \rangle = \frac{3g^4}{16\pi M_2^2},$$

$$\Omega_{\tilde{W}} h^2 = 0.13\left(\frac{M_2}{2.5\,\mathrm{TeV}}\right)^2.$$

around 2.5 TeV !!

(too less if otherwise)

Pure Bino

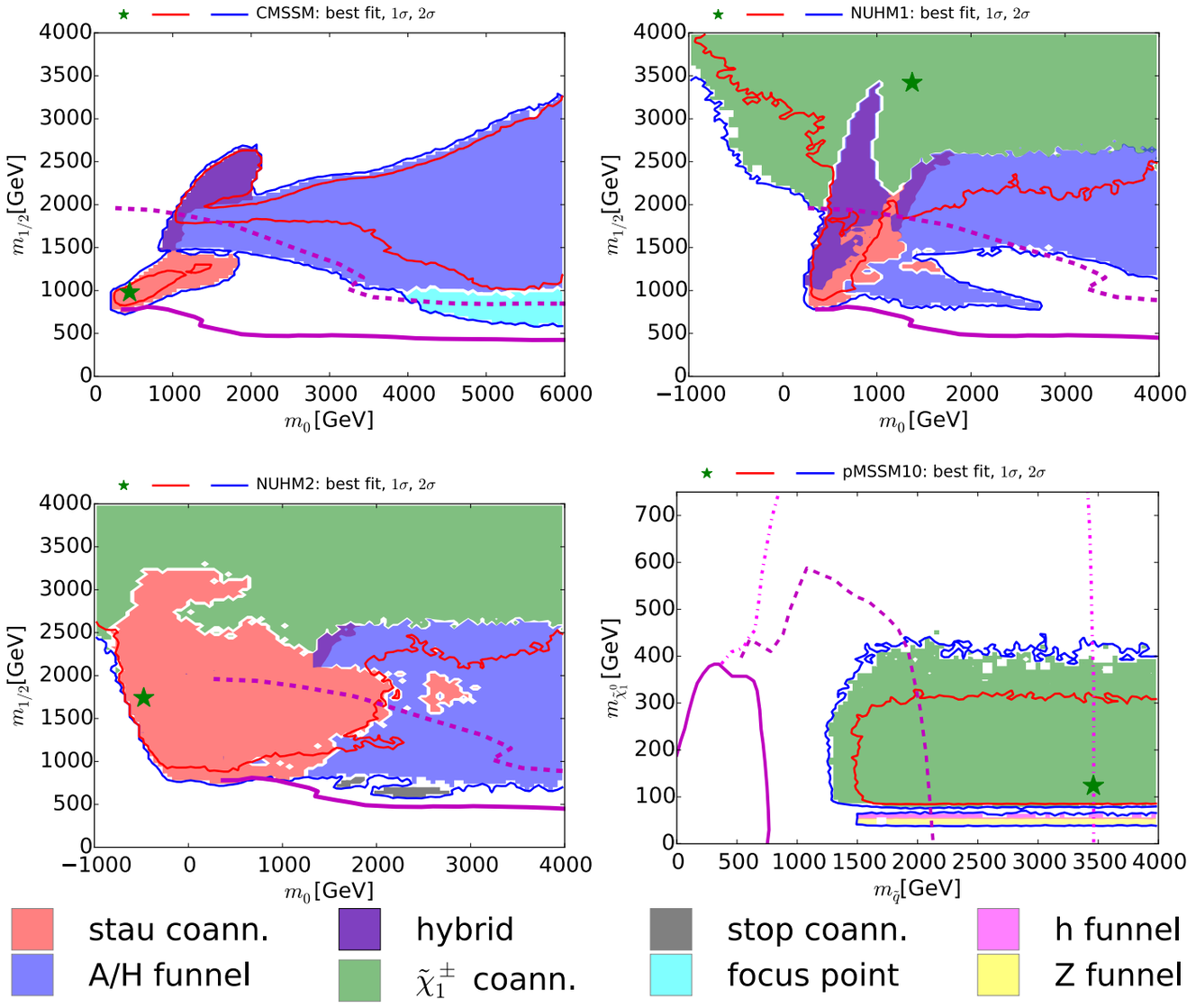
$$\langle \sigma_{\tilde{B}} v \rangle = \frac{3g^4\tan^4\theta_W r(1+r^2)}{2\pi m_{\tilde{e}_R}^2 x(1+r)^4}, \quad x \equiv \frac{M_1}{T}, \quad r \equiv \frac{M_1^2}{m_{\tilde{e}_R}^2},$$

$$\Omega_{\tilde{B}} h^2 = 1.3\times 10^{-2}\left(\frac{m_{\tilde{e}_R}}{100\,\mathrm{GeV}}\right)^2 \frac{(1+r)^4}{r(1+r^2)}\left(1 + 0.07\log\frac{\sqrt{r}100\,\mathrm{GeV}}{m_{\tilde{e}_R}}\right).$$

(too large !! unless..)

An admixture of these states (Wino-Bino, Bino-Higgsino etc.. is a good candidate for dark matter

Supersymmetric DM summary



1508.011173

Figure 1. *The $(m_0, m_{1/2})$ planes in the CMSSM (upper left), the NUHM1 (upper right) and the NUHM2 (lower left), and the $(m_{\tilde{q}}, m_{\tilde{\chi}_1^0})$ plane in the pMSSM10. Regions in which different mechanisms bring the CDM density into the allowed range are shaded as described in the legend and discussed in the text. The red and blue contours are the $\Delta\chi^2 = 2.30$ and 5.99 contours found in global fits to these models, corresponding approximately to the 68 and 95% CL contours, with the green stars indicating the best-fit points, and the solid purple contours show the current LHC 95% exclusions from $\not{E}_T$ searches. In the CMSSM, NUHM1 and NUHM2 cases, the dashed purple contours show the prospective 5-σ discovery reaches for $\not{E}_T$ searches at the LHC with 3000/fb at 14 TeV, corresponding approximately to the 95% CL exclusion sensitivity with 300/fb at 14 TeV. In the pMSSM10 case, the dashed purple contour shows the 95% CL exclusion sensitivity of the LHC with 3000/fb assuming $m_{\tilde{g}} \gg m_{\tilde{q}}$, and the dash-dotted lines bound the corresponding sensitivity region assuming $m_{\tilde{g}} = 4.5$ TeV.*

Phenomenological MSSM

- Do not consider a specific model of Supersymmetric Breaking
- Intelligent choice of parameters
- For ex: flavor violating and CP violating parameters set to zero. Degenerate first two generations etc.
- 15-20 remaining parameters determine the entire weak scale spectrum.

Jo Anne Hewett, T. Rizzo et. al
N. Mahmoudi et.al
Carena, Wagner et. al
Buchmuller et. al

Degenerate Supersymmetry

(at weak scale)

murayama et. al

Chowdhury, Patel, Vempati, Tata

compressed spectra can escape detection at LHC

Are there any indirect ways to search for such supersymmetric models other than monojets ?

$$M_1 \approx M_2 \approx M_3 \equiv M_D, \quad m^2_{\tilde{Q}} \approx m^2_{\tilde{U}} \approx m^2_{\tilde{D}} \approx m^2_{\tilde{L}} \approx m^2_{\tilde{E}} \equiv M_D^2 \ .$$

$$|\mu|^2 = k_\mu \ M_D^2, \quad \text{and} \quad m_A^2 = k_A \ M_D^2,$$

motivated from extra dimensional theories

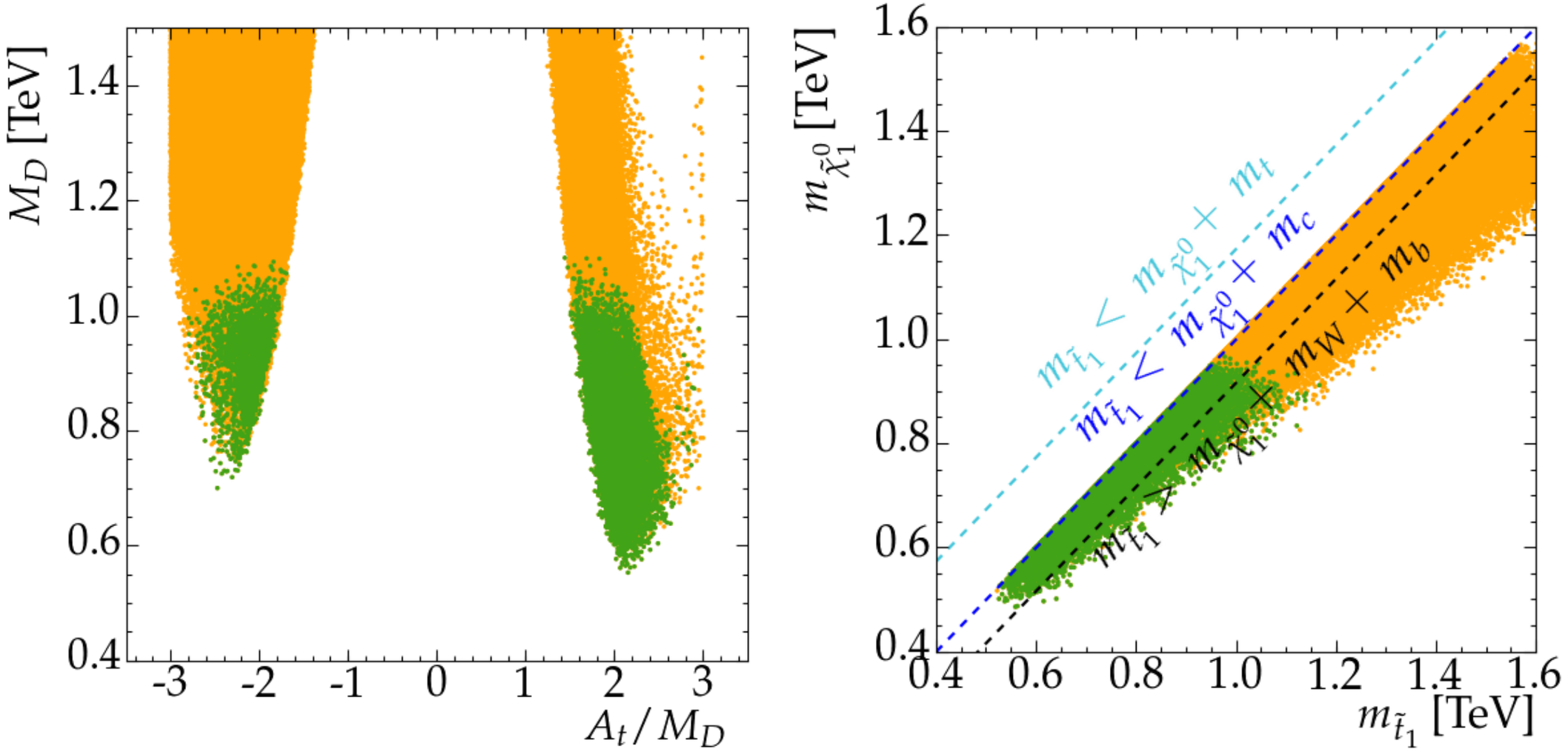
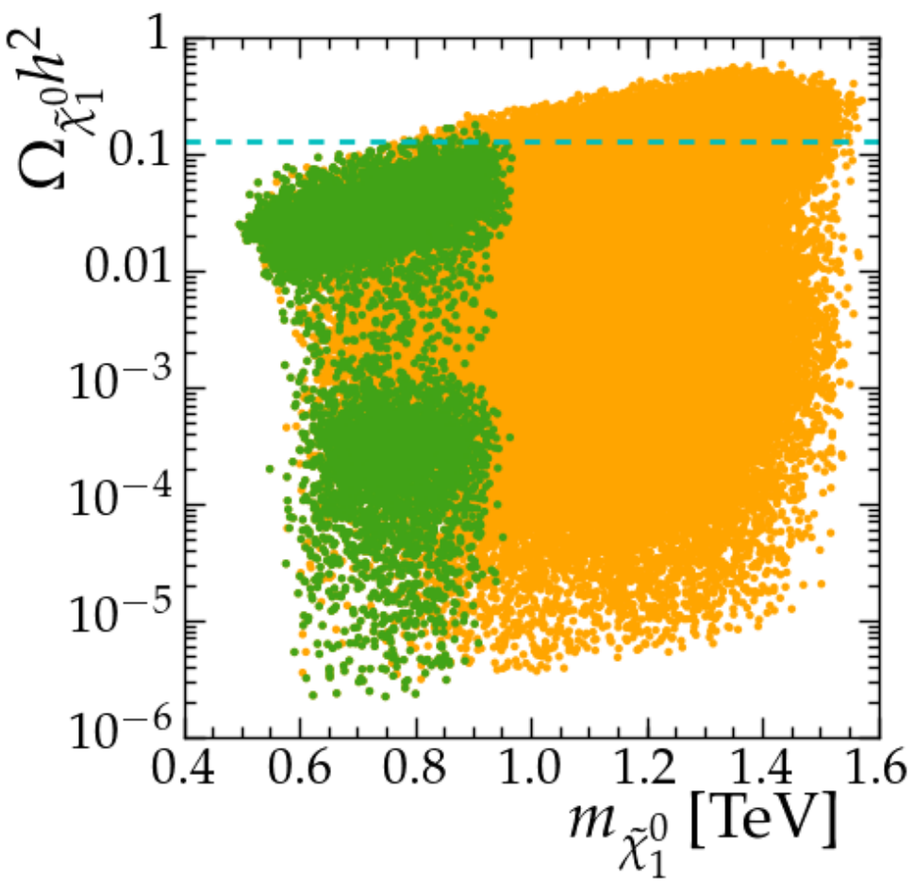


FIG. 3. The regions allowed in $A_t - M_D$ plane (left panel) and correlation between the lightest stop and neutralino masses (right panel) for $\pm 10\%$ deviation in the soft masses around the degenerate scale and after imposing the constraints in Eq. (21). The green (orange) points are consistent with the experimental value of $(g-2)_\mu$ at 2σ (3σ).



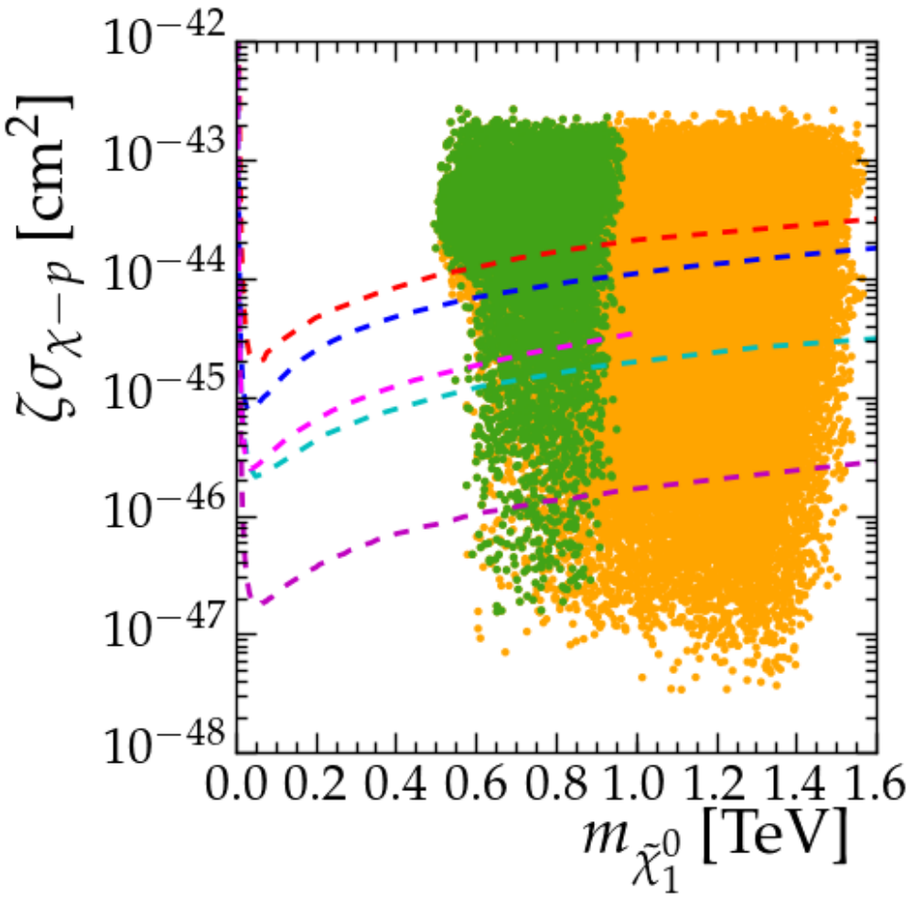


FIG. 6. Left: The neutralino relic density with respect to its mass for $M_D \in [0, 1500]$ GeV with $\pm 10\%$ deviation in the soft masses from the exact degeneracy and it satisfies all the bounds in Eq. (21). Right: For the same points, the scaled neutralino-nucleon spin-independent cross-section with respect to the lightest neutralino mass. In both the panels, the green (orange) points are in agreement with the experimental value of the muon $g-2$ at 2σ (3σ). The red-dashed and blue-dashed line correspond to the bounds by the XENON100 [94] and LUX [96] collaborations. The pink-dashed (cyan-dashed) line represents the latest limit from PandaX-II [95] (LUX-2016 [97]) experiment. The magenta dashed line shows the projected reach of the XENON1T [98] collaboration. The horizontal dashed line on the left panel shows the upper bound on the dark matter relic density given in Eq. (22).

Relic density with degenerate susy

One can in a similar way escape limits from flavour violation in some regions of the parameter space.

Supergravity

local supersymmetry transformations
gravitational interactions come in `*automatically*'

$$K = S^\dagger S + \Phi^\dagger \Phi + \frac{1}{M_{Pl}^2}(\Phi^\dagger \Phi)^2 + \dots$$

$$W = \Phi_i \Phi_j \Phi_k + \frac{1}{M_{Pl}} \Phi_i \Phi_j \Phi_k \Phi_l + \dots$$

$$G = K + \ln |W|^2$$

$$< V > = < e^G (G^M \ G_M - 3) + \frac{1}{2} \sum_A g_A^2 D_A^2 > = \ 0 \ .$$

Can derive the most general set of soft terms

Brignole Ibanez etc.
Dudas Vempati

$$m^2_{i\bar{j}} = m^2_{3/2}\,(G_{i\bar{j}} - R_{i\bar{j}\alpha\bar{\beta}}G^{\alpha}G^{\bar{\beta}}\,) - \frac{1}{2}\sum_A g^2_A D^2_A G_{i\bar{j}} + \sum_A g^2_A D_A \partial_i \partial_{\bar{j}} D_A\ ,$$

$$m^2_{ij} = m^2_{3/2}\,(2\nabla_i G_j + G^{\alpha}\nabla_i\nabla_j G_{\alpha}) - \frac{1}{2}\sum_A g^2_A D^2_A(\nabla_i G_j + \frac{g^2_A}{2}\partial_i\partial_j f_A) + \sum_A g^2_A D_A \nabla_i\nabla_j D_A$$

$$A_{ijk} = m^2_{3/2}\,(3\nabla_i\nabla_j G_k + G^{\alpha}\nabla_i\nabla_j\nabla_k G_{\alpha}) - \frac{1}{2}\sum_A g^2_A D^2_A \nabla_i\nabla_j G_k + \sum_A g^2_A D_A \nabla_i\nabla_j\nabla_k D_A\ ,$$

$$\mu_{ij} = m_{3/2}\,\nabla_i G_j \quad , \quad M^A_{1/2} = \frac{1}{2}(Ref_A)^{-1} m_{3/2} f_{A\alpha} G^{\alpha}\ ,$$

applicable to any Kahler potential
and/or superpotential

However, if the Kahler potential is in canonical form we have:

(kinetic terms are diagonal)

mSUGRA / CMSSM soft terms

$$m^2_{\tilde{Q}} = m^2_{\tilde{U}} = m^2_{\tilde{D}} = m^2_{\tilde{L}} = m^2_{\tilde{E}} = m^2_{H_u} = m^2_{H_d} = m^2_0$$

(degenerate matrices in flavour space)

$$M_1 = M_2 = M_3 = M_{1/2}$$

$$A^u_{ij} = A^d_{ij} = A^e_{ij} = A_0 \delta_{ij}$$

$$B_\mu$$

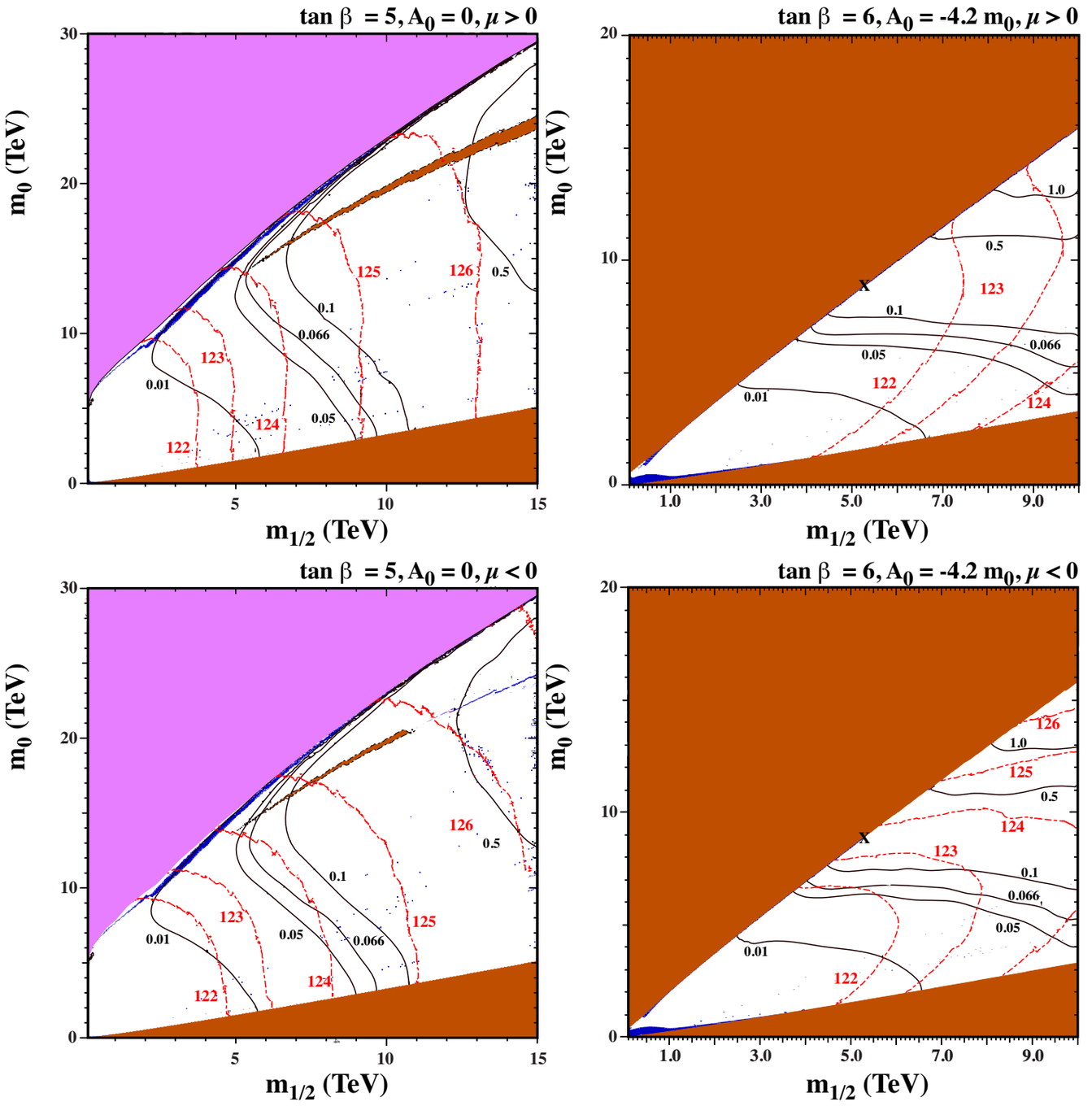


Figure 3: *Sample CMSSM* $(m_{1/2}, m_0)$ *planes showing the focus-point strip for* $\tan\beta = 5$ *and* $A_0 = 0$ *(left) with* $\mu > 0$ *(upper) and* $\mu < 0$ *(lower), and the stop coannihilation strip with* $\tan\beta = 6$ *and* $A_0 = -4.2\, m_0$ *(right). In the light mauve shaded regions, it is not possible to satisfy the electroweak symmetry breaking (EWSB) conditions. In the brown shaded regions, the LSP is charged and/or colored. The dark blue shaded strips show the areas where* $0.06 < \Omega_\chi h^2 < 0.2$ *in the left panels and the further enlarged range of* $0.01 < \Omega_\chi h^2 < 2.0$ *in the right panels. The red dot-dashed contours indicate the Higgs mass, labeled in GeV, and the solid black contours indicate the proton lifetime in units of* 10^{35} *yrs.*

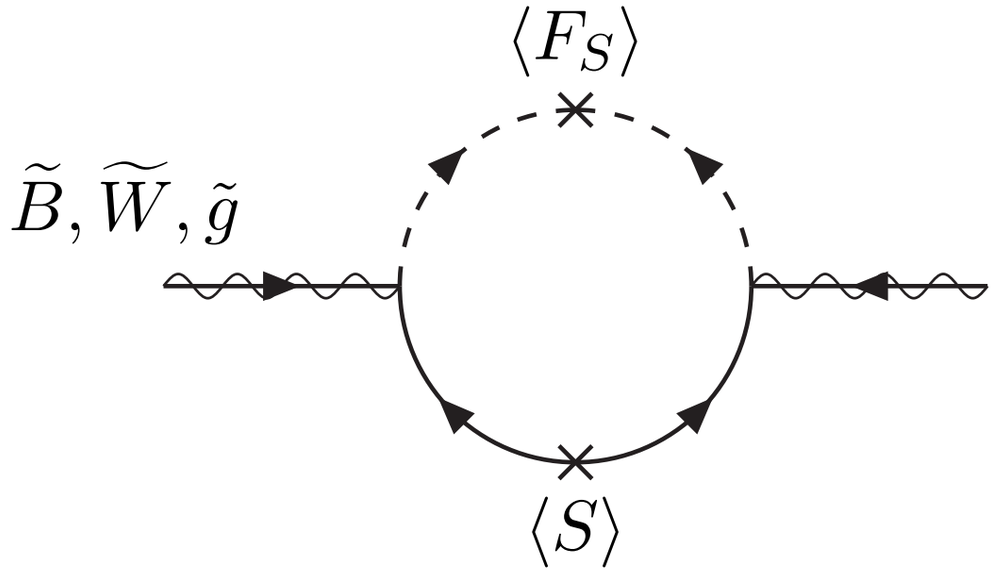
Gauge Mediation and Higgs Mass

$$W_{\rm mess} = \lambda S \bar{\Phi} \Phi$$

X is a spurion field which parameterises supersymmetry breaking in the hidden sector in terms of a F -VEV

$\Phi, \bar{\Phi}$ are set of superfields (typically) transforming as fundamentals under SU(5)

so they have SM gauge interactions



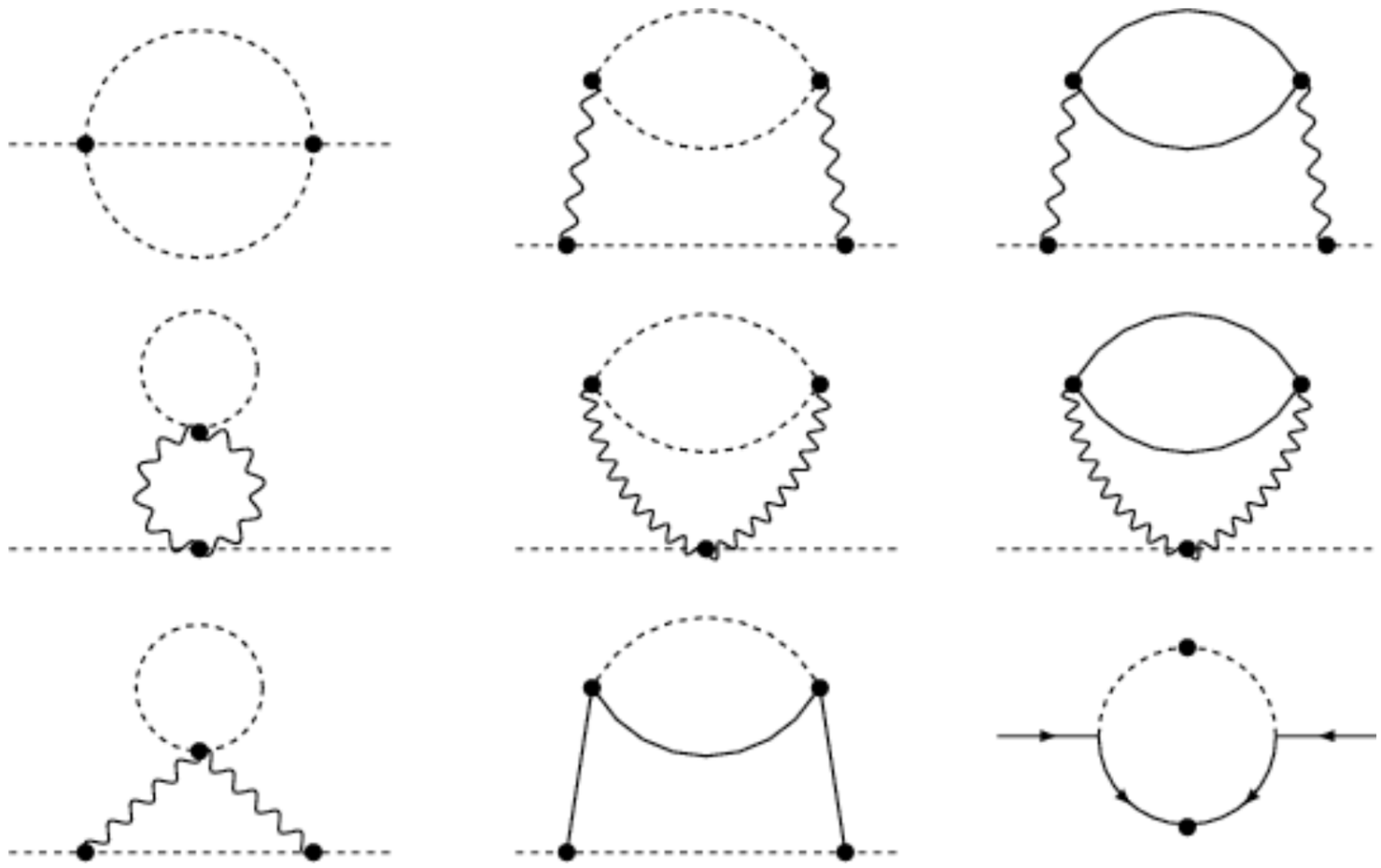
Gaugino Masses are generated at 1-loop

diagrams are finite

$$M_a = \frac{\alpha_a}{4\pi}\Lambda$$

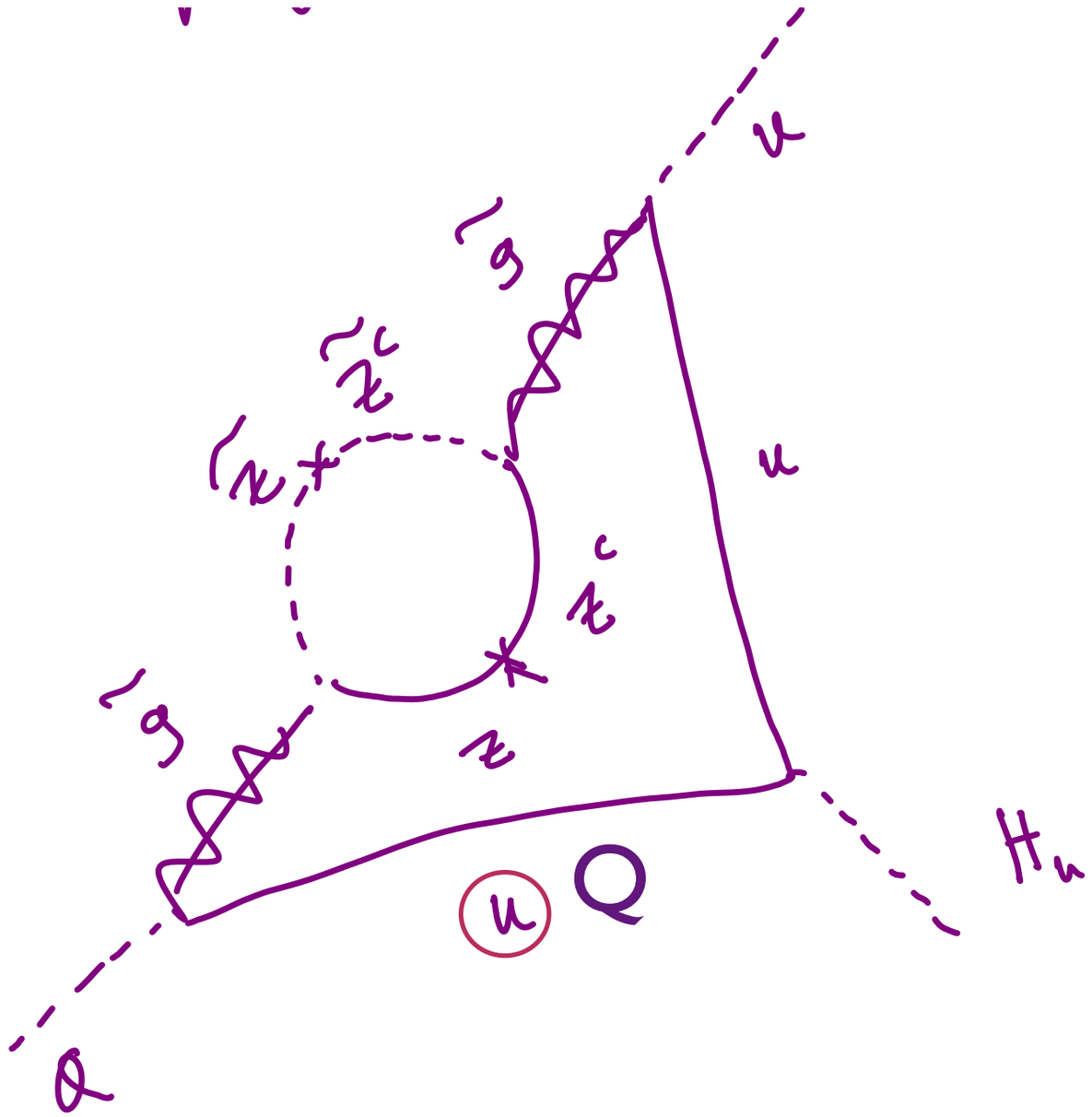
$$\Lambda \equiv \frac{< F_S >}{< S >}$$

Two loop diagrams contributing to soft masses



$$m_{\phi_i}^2 \;=\; 2\Lambda^2 \left[\left(\frac{\alpha_3}{4\pi} \right)^2 C_3(i) + \left(\frac{\alpha_2}{4\pi} \right)^2 C_2(i) + \left(\frac{\alpha_1}{4\pi} \right)^2 C_1(i) \right] .$$

Trilinear Couplings



additional coupling suppression

A-terms are essentially zero !!!

Draper, Meade, Shih et.al 1112.3068

Gauge Mediation and light higgs mass

the A-terms in the gauge mediation are very small !!

So a 125 GeV Higgs is very difficult unless we have a very heavy stop spectrum (beyond LHC)

Draper, Meade, Shih et.al 1112.3068

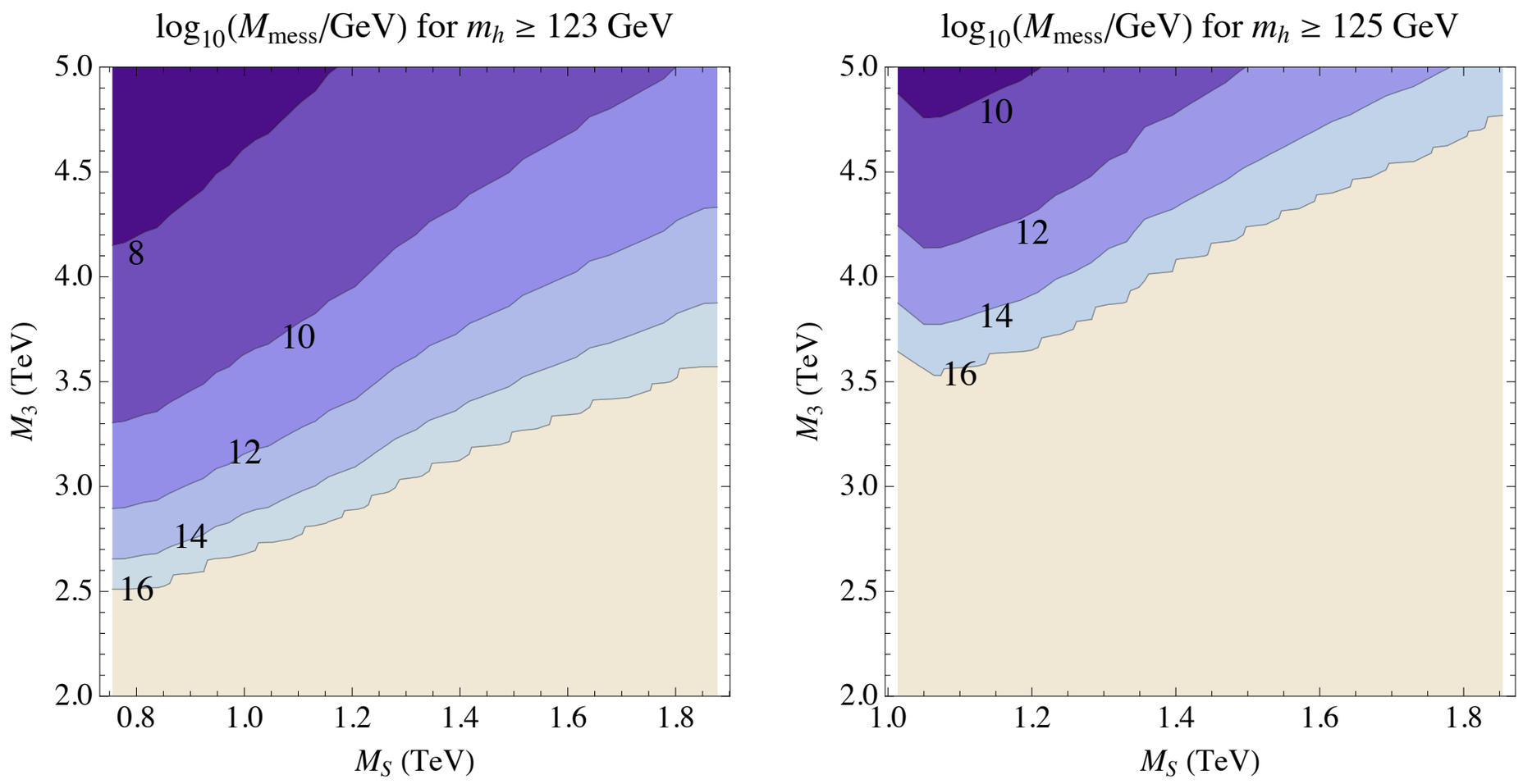


FIG. 5. Messenger scale required to produce sufficiently large $|A_t|$ for $m_h = 123$ GeV (left) and $m_h = 125$ GeV (right) through renormalization group evolution.

The change required in the messenger scale is a bit too large : almost up to GUT scale

Some Ways out for Gauge Mediation

(1) Have Yukawa mediation in addition to gauge mediation. This can be achieved by having matter-messenger fields mixing.

Delgado, Giudice, Rattazzi et. al, Yanagida et.al

review: Shih et.al, 1303.0228

(2) Have additional matter in the higgs sector with or without an extra U(1)

Langacker et. al, Yanagida et. al, Soori and Vempati

(3)Large additional radiative corrections to the Higgs through inverse seesaw and heavy sleptons

Soori and Vempati

(4)Large additional radiative corrections to the Higgs through inverse seesaw and heavy sleptons

Chun, Vempati et.al, Byakti et.al

(5)Increase gravity contributions without spoiling the nice features of gauge mediation.

Iyer, Soori and Vempati

SUSY Scorecard

5 3

For SUSY

1) Higgs at 126 GeV Updated calculations
2) electroweak baryogenesis, leptogenesis etc.
3) Gauge Coupling Unification
4) Hierarchy Problem : GUTS -> SUSY GUTS
5) Dark Matter

Against SUSY

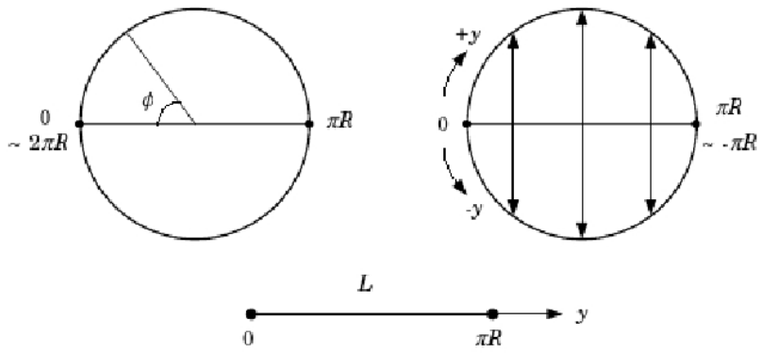
1) No indication of it at LHC so far
2) No indication of it in Loop effects (Electroweak)
3) No indication of it in Flavour effects (Loop effects)

Extra Space Dimensions and hierarchy Problem

Assumes the presence additional space dimensions in addition to the three visible ones.

Additional dimensions must be compact- For example a extra-dimensional co-ordinate $y \in [0, 2\pi R]$ - S_1 compactification

Imposition of reflection symmetries $y \to -y$ implies $y \in [0, \pi R]$ - Z_2 orbifolding



Consider extra-dimensions of size R

Gravitational potential felt by two test masses m_1 and m_2 separated by r in a $4+n$ dimensional theory

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}} \qquad r << R$$

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2} R^n} \frac{1}{r} \qquad r >> R$$

At large distances ($r >> R$) the effective Planck scale $M_{PL}^2 = M_{Pl(4+n)}^{n+2} R^n \sim (10^{18})^2\ GeV^2$

Choosing $M_{Pl(4+n)}^{n+2} \sim 1$TeV then $R \sim 10^{\frac{30}{n}-17}$cm

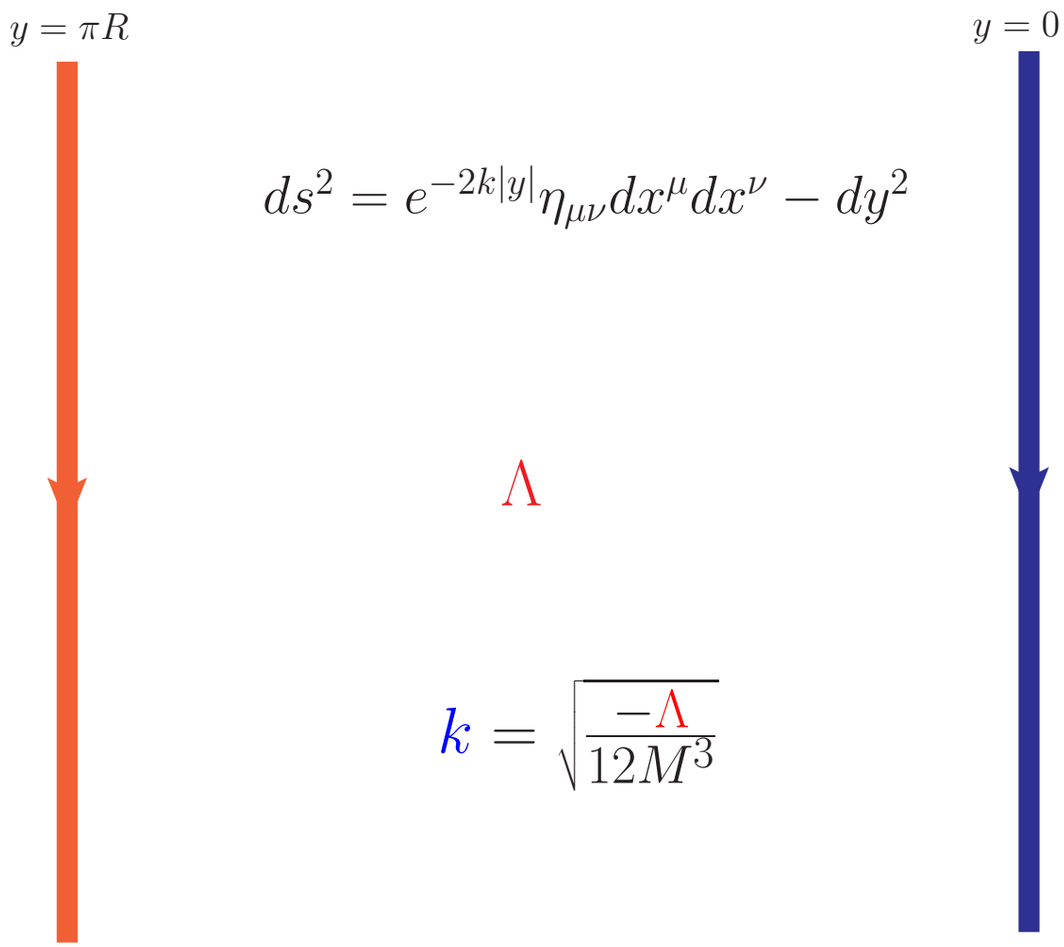
$n = 1 \implies R \sim 10^{13}$ cm - ✗

$n \geq 2 \implies R \leq 10^{-2}$ cm - ✓

Pro: Hierarchy Problem Solved

Con: Reintroduction of hierarchy between the Compactification scale and the Electroweak scale

Randall Sundrum model



S1/Z2 Compactification

Large Energy Density- Warped Bulk

Non-factorizable metric

Zero Brane Cosmological constant

Flat metric induced at y=0

Non-trivial metric Induced at y=π R

Randall Sundrum Model

Assume the scale of physics at the $y = 0$ is the $M_{PL} \sim 10^{18}$GeV

The scale induced at the $y = \pi R$ is $M_{y=\pi R} = e^{-kR\pi} M_{PL}$

For $kR \sim 11$, $e^{-kR\pi} \sim 10^{-16} \rightarrow M_{y=\pi R} \sim M_{weak}$

Thus to solve hierarchy problem Higgs fields must be very close or on IR brane.

The effective 4D planck scale and the 5D Planck scale are same.

Extra Dimension Theories: Some comments

- Strong constraints from Electroweak precision observables.

- Can act as theories of flavour, have strong constraints from flavour observables

- Some of them can lead to unification of couplings closer to weak scale

- Many of them predict extra vector like particles or gravitons, KK partners to be discovered at LHC and bigger machines.