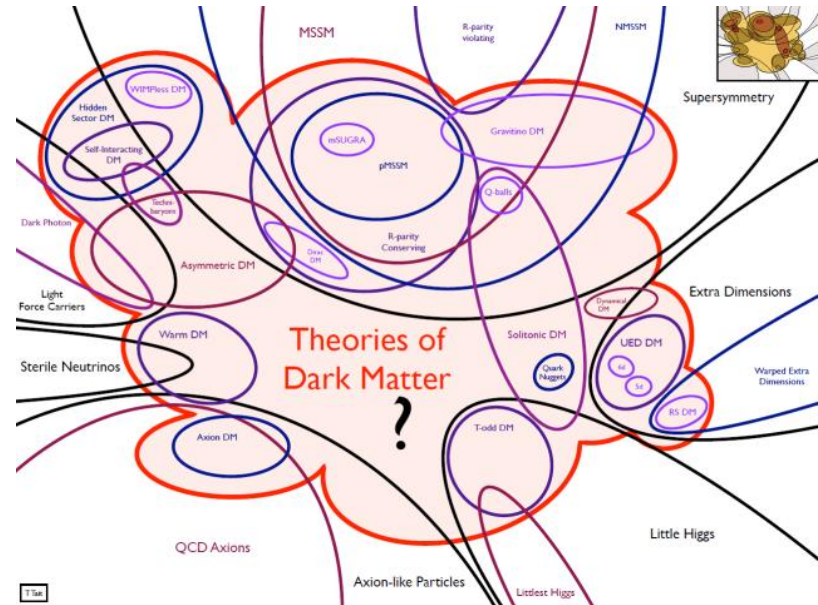# Physics Beyond the Standard Model

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L1. Introduction. EFT (SMEFT, EFT for DM)

L2. UV complete theories (SUSY, Extra Dimensions)

L3. Simplified models. Concluding remarks

EFT for Dark Matter

$$L_{DMEFT} \sim O_{SM} \cdot O_{DM}$$

EFT (a mediator is very heavy)

Operators coupling DM particles to the SM particles

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

$$\sigma_0^{D1} = 1.60 \times 10^{-37}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{20\text{GeV}}{M_*}\right)^6,$$

$$\sigma_0^{D5,C3} = 1.38 \times 10^{-37}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{300\text{GeV}}{M_*}\right)^4,$$

$$\sigma_0^{D8,D9} = 9.18 \times 10^{-40}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{300\text{GeV}}{M_*}\right)^4,$$

$$\sigma_0^{D11} = 3.83 \times 10^{-41}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{100\text{GeV}}{M_*}\right)^6,$$

$$\sigma_0^{C1,R1} = 2.56 \times 10^{-36}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{10\text{GeV}}{m_\chi}\right)^2 \left(\frac{10\text{GeV}}{M_*}\right)^4,$$

$$\sigma_0^{C5,R3} = 7.40 \times 10^{-39}\text{cm}^2 \left(\frac{\mu_\chi}{1\text{GeV}}\right)^2 \left(\frac{10\text{GeV}}{m_\chi}\right)^2 \left(\frac{60\text{GeV}}{M_*}\right)^4$$

$$\mu_{n\chi} = m_n m_{\text{DM}}/(m_n + m_{\text{DM}})$$

EFT (a mediator is very heavy)

$$L_{int} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$$

couplings to light quarks are suppressed

Signal Signature: tt+MET

perturbative limit $g \equiv \sqrt{g_\chi g_t} = 4\pi$ (m$_t$/M$_*^3$ = g²/M², M>2M$_{\chi\chi}$)

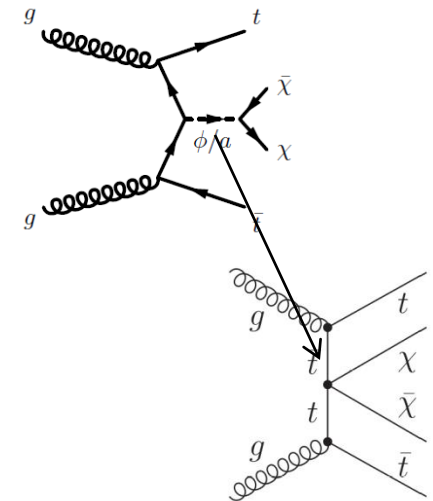**EFT approximation is valid if** $M_{\chi\bar{\chi}} < g\sqrt{M_*^3/m_t}$

Requirement R – number of events with $M_{\chi\bar{\chi}} < g\sqrt{M_*^3/m_t}$

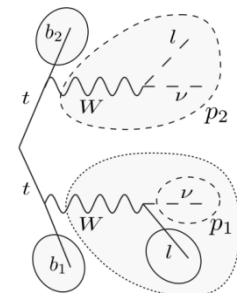| Source	Yield ($\pm$stat $\pm$syst)
t$\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.8 \pm 2.1$
Single top	$2.3 \pm 1.1 \pm 1.1$
Diboson	$0.5 \pm 0.2 \pm 0.2$
Drell–Yan	$0.3 \pm 0.3 \pm 0.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.9$
Data	18

Dominating background

Observed exclusion limits, the region below the solid curve is excluded at a 90% CL.
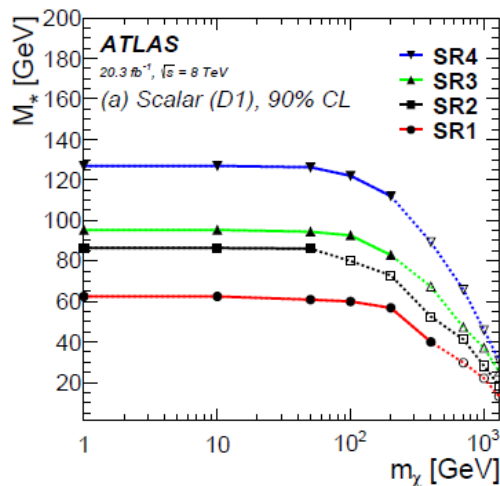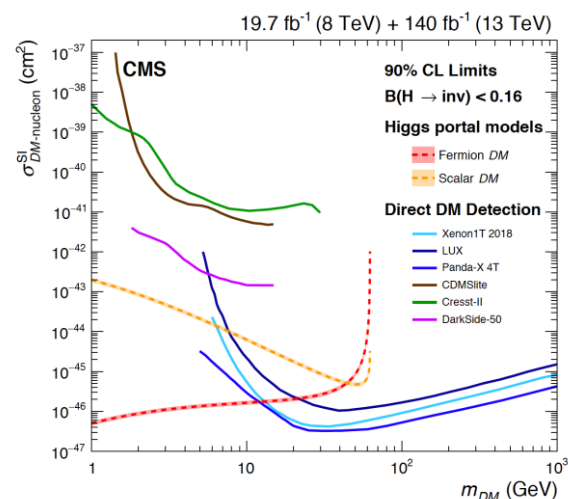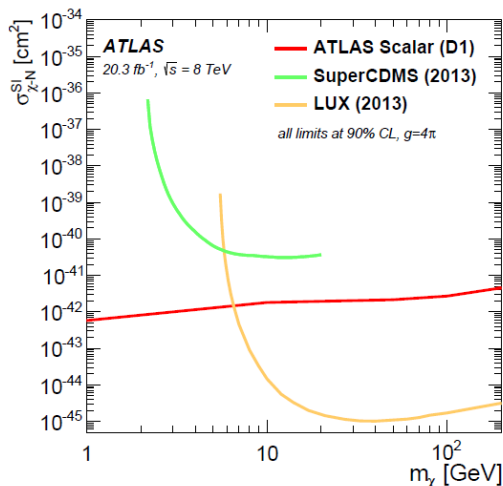
$$\mathcal{O}_{scalar} = \sum_q \frac{m_q}{M_*^N} \bar{q}q\bar{\chi}\chi$$

N=3 for D1, N=2 for C1
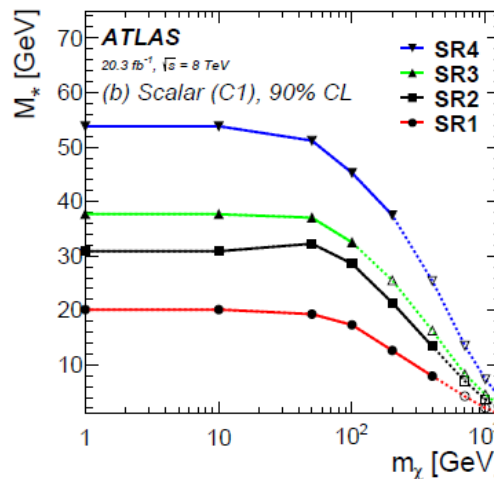
Lower limits on M* at 90% CL for verious signal regions as a function of m_χ for the operators D1 (Dirac fermion) and C1 (complex scalar)

Comparison with direct detection for D1

L2

Supersymmetry

Main steps to SUSY Lagrangians

• **Poincare transformation and algebra of the generators**

$$x^\mu \;\mapsto\; x'^\mu \;=\; \Lambda^\mu{}_\nu\, x^\nu \;+\; a^\mu$$

$$\left[P^\mu , P^\nu \right] = 0$$

$$\left[M^{\mu\nu} , P^\sigma \right] = i\left(P^\mu \eta^{\nu\sigma} - P^\nu \eta^{\mu\sigma} \right)$$

$$\left[M^{\mu\nu} , M^{\rho\sigma} \right] = i\left(M^{\mu\sigma} \eta^{\nu\rho} + M^{\nu\rho} \eta^{\mu\sigma} - M^{\mu\rho} \eta^{\nu\sigma} - M^{\nu\sigma} \eta^{\mu\rho} \right)$$

• **No-go theorem by Coleman-Mandula – most general symmetry of the S-matrix is Poincare $\otimes$ internal, that can not mix different spins**

• **The way out – extended the Poincare algebra by spinor generators $Q_\alpha{}^N$ (α=1,2) (Golfand, Lihtman). We consider only the case N=1 (N=1 SUSY)**

History of the sypersymmetry – see M.Shifman talk at CERN "Fifty Years of Supersymmetry"

- **The algebra of extended Poincare group:**

$$\left[Q_\alpha \,,\, M^{\mu\nu} \right] \;=\; (\sigma^{\mu\nu})_\alpha{}^\beta \, Q_\beta$$

$$\left[Q_\alpha \,,\, P^\mu \right] \;=\; \left[\bar{Q}^{\dot\alpha} \,,\, P^\mu \right] \;=\; 0$$

$$\left\{ Q_\alpha \,,\, \bar{Q}_{\dot\beta} \right\} \;=\; 2 \, (\sigma^\mu)_{\alpha\dot\beta} \, P_\mu$$

- **Comutators with generators of internal symmetries all vanish except one called R-symmetry**

$$Q_\alpha \;\mapsto\; \exp(i\lambda)\, Q_\alpha \,, \qquad \bar{Q}_{\dot\alpha} \;\mapsto\; \exp(-i\lambda)\, \bar{Q}_{\dot\alpha}$$

$$\left[Q_\alpha \,,\, R \right] \;=\; Q_\alpha \,, \qquad \left[\bar{Q}_{\dot\alpha} \,,\, R \right] \;=\; -\bar{Q}_{\dot\alpha}$$

- **Spinor generators change the spin of the states**

$$Q_\alpha \, |F\rangle \;=\; |B\rangle \,, \qquad \bar{Q}_{\dot\beta} \, |B\rangle \;=\; |F\rangle$$

- **In any supersymmetric multiplet, the number of boson states in equal to the number of fermion states $n_B = n_F$.**

• Superspace and superfields

Grassman coordinates (two Weil spinors) in addition to x_μ

$$S(x^\mu, \theta_\alpha, \bar\theta_{\dot\alpha})$$

Ralization of generators in superspace in accord with the algebra (c=1)

$$\mathcal{Q}_\alpha = -i\frac{\partial}{\partial\theta^\alpha} - c\,(\sigma^\mu)_{\alpha\dot\beta}\,\bar\theta^{\dot\beta}\,\frac{\partial}{\partial x^\mu}$$

$$\bar{\mathcal{Q}}_{\dot\alpha} = +i\frac{\partial}{\partial\bar\theta^{\dot\alpha}} + c^*\,\theta^\beta\,(\sigma^\mu)_{\beta\dot\alpha}\,\frac{\partial}{\partial x^\mu}$$

$$\mathcal{P}_\mu = -i\partial_\mu\,,$$

$\mathcal{Q}_\alpha$ **is a representation of the spinor generator** Q_α

Superfield transforms as

$$S(x^\mu, \theta_\alpha, \bar\theta_{\dot\alpha}) \;\mapsto\; \exp\!\big(i\,(\epsilon\mathcal{Q} + \bar\epsilon\bar{\mathcal{Q}})\big)\,S(x^\mu, \theta_\alpha, \bar\theta_{\dot\alpha}) \;=\; S\big(x^\mu - ic(\epsilon\sigma^\mu\bar\theta) + ic^*(\theta\sigma^\mu\bar\epsilon),\, \theta + \epsilon,\, \bar\theta + \bar\epsilon\big)$$

S1·S2 – is a superfield, S1+S2 – is a superfield, $\partial_\alpha S$ – is NOT a superfield

Covariant derivatives give superfields

$$\mathcal{D}_\alpha := \partial_\alpha + i(\sigma^\mu)_{\alpha\dot\beta}\,\bar\theta^{\dot\beta}\,\partial_\mu\,, \qquad \bar{\mathcal{D}}_{\dot\alpha} := -\bar\partial_{\dot\alpha} - i\theta^\beta\,(\sigma^\mu)_{\beta\dot\alpha}\,\partial_\mu$$

• Two special cases – Chiral and Vector Superfields

Chiral superfield and its mode decomposition

$$\bar{\mathcal{D}}_{\dot{\alpha}}\Phi = 0$$

$$\Phi(x^{\mu}, \theta^{\alpha}, \bar{\theta}^{\dot{\alpha}}) = \varphi(x) + \sqrt{2}\,\theta\psi(x) + \theta\theta\,F(x) + i\theta\,\sigma^{\mu}\,\bar{\theta}\,\partial_{\mu}\varphi(x)$$
$$- \frac{i}{\sqrt{2}}\,(\theta\theta)\,\partial_{\mu}\psi(x)\sigma^{\mu}\,\bar{\theta} - \frac{1}{4}\,(\theta\theta)\,(\bar{\theta}\bar{\theta})\,\partial_{\mu}\partial^{\mu}\varphi(x)$$

Scalar field (Higgses, squarks, sleptons)   **Fermion fields (quarks, leptons, higgsinos)**

Vector superfield and its mode decomposition

$$V(x, \theta, \bar{\theta}) = V^{\dagger}(x, \theta, \bar{\theta})$$

$$V_{\mathrm{WZ}}(x, \theta, \bar{\theta}) = (\theta\,\sigma^{\mu}\,\bar{\theta})\,V_{\mu}(x) + (\theta\theta)\,(\bar{\theta}\bar{\lambda}(x)) + (\bar{\theta}\bar{\theta})\,(\theta\lambda(x)) + \frac{1}{2}\,(\theta\theta)\,(\bar{\theta}\bar{\theta})\,D(x)$$

Gauge vector fields   **Fermion fields - Gaugions**

$$[\theta] = m^{-1/2} \rightarrow [F] = [D] = m^2 \rightarrow \textbf{F and D fields are the auxiliary,}$$
do not propagate and can be integrated out

• Two special cases – Chiral and Vector Superfields

Vector superfield strength tensor is a chiral superfield

$$W_\alpha \ := \ -\frac{1}{8q} \, (\bar{\mathcal{D}}\bar{\mathcal{D}}) \left(\exp(-2qV) \, \mathcal{D}_\alpha \, \exp(2qV) \right)$$

Decomposition in Wess-Zumino gauge

$$W_\alpha^a(y,\theta) \ = \ -\frac{1}{4} \, (\bar{\mathcal{D}}\bar{\mathcal{D}}) \, \mathcal{D}_\alpha \left(V^a(y,\theta,\bar{\theta}) \ + \ i \, V^b(y,\theta,\bar{\theta}) \, V^c(y,\theta,\bar{\theta}) \, f^a{}_{bc} \right)$$

$$= \ \lambda_\alpha^a(y) \ + \ \theta_\alpha \, D^a(y) \ + \ (\sigma^{\mu\nu}\theta)_\alpha \, F_{\mu\nu}^a(y) \ - \ i(\theta\theta) \, (\sigma^\mu)_{\alpha\dot\beta} \, D_\mu \bar{\lambda}^{a\dot\beta}(y)$$

$$F_{\mu\nu}^a \ := \ \partial_\mu V_\nu^a \ - \ \partial_\nu V_\mu^a \ + \ q \, f^a{}_{bc} \, V_\mu^b \, V_\nu^c$$

$$D_\mu \bar{\lambda}^a \ := \ \partial_\mu \bar{\lambda}^a \ + \ q \, V_\mu^b \, \bar{\lambda}^c \, f_{bc}{}^a$$

Simple Example

$$L(x) = \int d^2\theta d^2\bar{\theta} \; \Phi^\dagger \Phi + \int d^2\theta W(\Phi) + h.c.$$

W(Φ) – superpotential depending on chiral superfield Φ but not on Φ⁺

After integration over supercoordinates:

$$L(x) = \partial_\mu \phi^\dagger \partial^\mu \phi + i\bar{\psi}\sigma_\mu \partial^\mu \psi + F^\dagger F + \frac{\partial W}{\partial \phi} F - \frac{1}{2}\frac{\partial^2 W}{\partial \phi^2}\psi\psi + h.c.$$

Potential for the scalar field (scalar part of supermultiplet):

$$V(\phi) = -F^\dagger F - \frac{\partial W}{\partial \phi} F - \frac{\partial W^\dagger}{\partial \phi^\dagger} F^\dagger$$

Equations of motion

$$\frac{\partial L}{\partial F} = 0 \; \Rightarrow \; F^\dagger + \frac{\partial W}{\partial \phi} = 0$$

$$\frac{\partial L}{\partial F^\dagger} = 0 \; \Rightarrow \; F + \frac{\partial W^\dagger}{\partial \phi^\dagger} = 0$$

Potential is always positive:

$$V(\phi) = -\frac{\partial W^\dagger}{\partial \phi^\dagger}\frac{\partial W}{\partial \phi} + \frac{\partial W^\dagger}{\partial \phi^\dagger}\frac{\partial W}{\partial \phi} + \frac{\partial W^\dagger}{\partial \phi^\dagger}\frac{\partial W}{\partial \phi} = |\frac{\partial W}{\partial \phi}|^2 \geq 0$$

Simple Example

$$W(\Phi) = 1/2 \; m \; \Phi^2 \; + 1/3! \; g \; \Phi^3$$

The potential for the scalar component takes the form:

$$V(\phi) = m^2|\phi|^2 \; + \; \frac{g}{2}m(\phi|\phi|^2 \; + \; |\phi|^2\phi^\dagger) \; + \; \frac{g^2}{4}(|\phi|^2)^2$$

Quartic $(|\phi|^2)^2$ **term follows from the interaction!**

• MSSM field content

Vector superfieds

Chiral superfieds

Superfields	Quantum			Spin	
	SU(3)	SU(2)	U(1)	S=1	S=1/2
$\hat{G}^a$	8	1	0	G_μ^a	$\tilde{g}^a$
$\hat{W}^i$	1	3	0	W_μ^i	$\tilde{W}^i$
$\hat{B}$	1	1	0	B_μ	$\tilde{B}$
				S=1/2	S=0
$\hat{Q} = \begin{pmatrix} \hat{u} \\ \hat{d} \end{pmatrix}$	3	2	1/3	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$
$\hat{u}^c$	$\bar{3}$	1	-4/3	$\bar{u}_R$	$\tilde{u}_R^*$
$\hat{d}^c$	$\bar{3}$	1	2/3	$\bar{d}_R$	$\tilde{d}_R^*$
$\hat{L} = \begin{pmatrix} \hat{v} \\ \hat{e} \end{pmatrix}$	1	2	-1	$\begin{pmatrix} v_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \tilde{v}_L \\ \tilde{e}_L \end{pmatrix}$
$\hat{e}^c$	1	1	2	$\bar{e}_R$	$\tilde{e}_R^*$
$\hat{H}_1$	1	2	-1	$\tilde{H}_1$	H_1
$\hat{H}_2$	1	2	1	$\tilde{H}_2$	H_2

• MSSM Lagrangian

$$L_{MSSM}^{SUSY} = \sum_{A=SU_c(3),SU_L(2),U_Y(1)} \frac{1}{4} \int d^2\theta \, Tr(W^A W^A) + h.c.$$

$$+ \sum_{i=1}^{3} \sum_{f_i} \int d^2\theta d^2\bar{\theta} \, \Phi_{f_i}^\dagger \, e^{-g_3 V_3 - g_2 V_2 - g_1 V_1} \, \Phi_{f_i}$$

$$+ \sum_{i=1}^{3} \sum_{f_i} \int d^2\theta \, W_{MSSM}(\Phi_{f_i}) + h.c.$$

$$W_{MSSM} = W_{MSSM}^{R} + W_{MSSM}^{\not R}$$

$$W_{MSSM}^{R} = \sum_{i,j=1}^{3} \left[\Gamma_{ij}^u \hat{Q}_i^T \hat{u}_j^c \hat{H}_2 + \Gamma_{ij}^d \hat{Q}_i^T \hat{d}_j^c \hat{H}_1 + \Gamma_{ij}^l \hat{L}_i^T \hat{l}_j^c \hat{H}_1 \right] + \mu \hat{H}_1^T \hat{H}_2$$

$$W_{MSSM}^{\not R} = \sum_{i,j,k=1}^{3} \Gamma_{ijk}^l \hat{L}_i^T \hat{Q}_j \hat{d}_k^c + \dots$$

• R-parity

+ **for particles (antiparticles)**

$$R = (-1)^{3B+L+2s}$$

- **for superpartners**

If the R-parity is conserved:

-Lightest superpartner is stable – good candidate for Dark Matter

-Superparticles are produced in particle collisions only in pairs

SUSY must be broken

$$L_{MSSM} = L_{MSSM}^{SUSY} + L_{MSSM}^{\cancel{SUSY}}$$

Soft SUSY breaking:

$$L_{MSSM}^{\cancel{SUSY}} = -\sum_s (m_s^0)^2 |\phi_s|^2 - \frac{1}{2}\sum_g M_g \tilde{\lambda}_g \tilde{\lambda}_g$$

$$-\sum_{i,j=1}^{3}\left[A_{ij}^u \Gamma_{ij}^u \tilde{Q}_i^T \tilde{u}_j^c H_2 + A_{ij}^d \Gamma_{ij}^d \tilde{Q}_i^T \tilde{d}_j^c H_1 + A_{ij}^l \Gamma_{ij}^l \tilde{L}_i^T \tilde{l}_j^c H_1\right]$$

$$+B\mu H_1^T H_2$$

Scalar mass parameters   **Gaugino mass parameters**   **Trilinear couplings**

Higgsino mass parameter

105 model parameters

Physical states – states with definite masses

Photino

$$\tilde{\gamma} = \tilde{W}^3 sin\theta_W + \tilde{B} cos\theta_W$$

Wino $\quad \tilde{W}^\pm = \dfrac{\tilde{W}^1 \mp \tilde{W}^2}{\sqrt{2}}$

Zino

$$\tilde{Z} = \tilde{W}^3 cos\theta_W - \tilde{B} sin\theta_W$$

Higgs doublets and corresponding Higgsinos

$$H_1(x) = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \longrightarrow \begin{pmatrix} \tilde{\psi}_1^0 \\ \tilde{\psi}_1^- \end{pmatrix} \qquad\qquad H_2(x) = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \longrightarrow \begin{pmatrix} \tilde{\psi}_2^+ \\ \tilde{\psi}_2^0 \end{pmatrix}$$

Chargino – mixture of corresponding winos and charged Higgsinos

$$\begin{pmatrix} \tilde{\psi}_2^+ \\ \tilde{W}^+ \end{pmatrix} \longrightarrow \begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \end{pmatrix} \qquad\qquad \begin{pmatrix} \tilde{\psi}_1^- \\ \tilde{W}^- \end{pmatrix} \longrightarrow \begin{pmatrix} \tilde{\chi}_1^- \\ \tilde{\chi}_2^- \end{pmatrix}$$

Neutralino

$$\begin{pmatrix} \tilde{\gamma} \\ \tilde{Z}^0 \\ \tilde{\psi}_1^0 \\ \tilde{\psi}_2^0 \end{pmatrix} \xrightarrow{\hspace{2cm}} \begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix}$$

-mixture of photino, zino and neutral xiggsinos

Sfermions (Squarks, Sleptons) 1,2

$$\begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix} \xrightarrow{\hspace{1cm}} \begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix}$$

-mixture of left -and right sfermions

Relevant only for the third generation of sfermions (stop, sbottom, stau)

All the vertexes and decay widths follow from the Lagrangian

$$\mathcal{L}_I = g \sum_{\substack{f=\nu_\tau,t \\ f'=\tau,b}} \left[\bar{f} \left(k_{ij}^{\tilde{f}'} P_L + l_{ij}^{\tilde{f}'} P_R \right) \tilde{\chi}_j^+ \tilde{f}_i + \bar{f}' \left(k_{ij}^{\tilde{f}} P_L + l_{ij}^{\tilde{f}} P_R \right) \tilde{\chi}_j^- \tilde{f}_i + h.c. \right]$$

$$+ g \sum_{f=\tau,\nu_\tau,b,t} \left[\bar{f} \left(b_{ki}^f P_L + a_{ki}^f P_R \right) \tilde{\chi}_i^0 \tilde{f}_k + h.c. \right]$$

$$- g \left[W_\mu^+ \overline{\tilde{\chi}_k^0} \left(O'_{L_{kj}} P_L + O'_{R_{ki}} P_R \right) \gamma^\mu \tilde{\chi}_j^+ + h.c. \right]$$

$$- g \left[H^+ \overline{\tilde{\chi}_k^0} \left(Q'_{R_{kj}} P_L + Q'_{L_{ki}} P_R \right) \tilde{\chi}_j^+ + h.c. \right]$$

$$- \frac{g}{\sqrt{2}} \left[W_\mu^+ \bar{t} \gamma^\mu P_L b + h.c. \right]$$

$$- g \left[i W_\mu^+ \left(\sum_{i,j=1,2}^{2} A_{\tilde{t}_i \tilde{b}_j}^W \overline{\tilde{t}_i} \overleftrightarrow{\partial_\mu} \tilde{b}_j + \sum_{i=1,2}^{2} A_{\tilde{\nu}_\tau \tilde{\tau}_i}^W \overline{\tilde{\nu}_\tau} \overleftrightarrow{\partial_\mu} \tilde{\tau}_i \right) + h.c. \right]$$

$$+ \frac{g}{\sqrt{2}\, m_W} \left[H^+ \bar{t} \left(m_b \tan\beta \, P_R + m_t \cot\beta \, P_L \right) b + h.c. \right]$$

$$- g \left[H^+ \left(\sum_{i,j=1,2}^{2} C_{\tilde{t}_i \tilde{b}_j}^H \overline{\tilde{t}_i} \tilde{b}_j + \sum_{i=1,2}^{2} C_{\tilde{\nu}_\tau \tilde{\tau}_i}^H \overline{\tilde{\nu}_\tau} \tilde{\tau}_i \right) + h.c. \right]$$

$$- \frac{i\,g}{2\cos\theta_W} Z_\mu \left[\cos\theta_{\tilde{t}} \sin\theta_{\tilde{t}} \left(\overline{\tilde{t}_1} \overleftrightarrow{\partial_\mu} \tilde{t}_2 - \overline{\tilde{t}_2} \overleftrightarrow{\partial_\mu} \tilde{t}_1 \right) \right.$$

$$\left. - \sum_{f=\tau,b} \cos\theta_{\tilde{f}} \sin\theta_{\tilde{f}} \left(\overline{\tilde{f}_1} \overleftrightarrow{\partial_\mu} \tilde{f}_2 - \overline{\tilde{f}_2} \overleftrightarrow{\partial_\mu} \tilde{f}_1 \right) \right]$$

$$- g\, h^0 \left(\sum_{f=\tau,b,t} B_{h^0}^{\tilde{f}} \tilde{f}_1 \overline{\tilde{f}_2} + h.c. \right) - g\, H^0 \left(\sum_{f=\tau,b,t} B_{H^0}^{\tilde{f}} \tilde{f}_1 \overline{\tilde{f}_2} + h.c. \right)$$

$$+ i\, g\, A^0 \left[\sum_{f=\tau,b,t} B_{A^0}^{\tilde{f}} \left(\tilde{f}_1 \overline{\tilde{f}_2} - \tilde{f}_2 \overline{\tilde{f}_1} \right) \right]$$

$$- \sqrt{2}\, g_s T_{jk}^a \left[\sum_{q=b,t} \left(\bar{q}_j (\cos\theta_{\tilde{q}} P_R - \sin\theta_{\tilde{q}} P_L) \tilde{g}_a \tilde{q}_1^k \right. \right.$$

$$\left. \left. - \bar{q}_j (\sin\theta_{\tilde{q}} P_R + \cos\theta_{\tilde{q}} P_L) \tilde{g}_a \tilde{q}_2^k \right) + h.c. \right]$$

2 complex Higgs doublets in MSSM

$$H_1(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 + H_1^0 + iP_1^0 \\ H_1^- \end{pmatrix}$$

$$v^2 \equiv v_1^2 + v_2^2 \qquad \tan\beta \equiv \frac{v_2}{v_1}$$

$$\begin{pmatrix} P_1^0 \\ P_2^0 \end{pmatrix} \longrightarrow \begin{pmatrix} G_0 \\ A \end{pmatrix} \qquad \begin{pmatrix} H_1^\pm \\ H_2^\pm \end{pmatrix} \longrightarrow \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

$$H_2(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} H_2^+ \\ v_2 + H_2^0 + iP_2^0 \end{pmatrix}$$

G^0, $G^\pm$ - **Goldstone bosons**

2 complex scalar doublets => 8 degrees of freedom

As in the SM 3 Goldstone bosons are absorbed ("eaten") by W$^\pm$ and Z

h, H – CP even scalars,

5 physics degrees of freedom

A - CP odd scalar,

H$^\pm$ - sharged scalars

$$V_H = V_F + V_D^{U(1)} + V_D^{SU(2)} + V_{soft}$$

MSSM

MSSM potential after supersymmetry breaking

$$V(H_1, H_2) = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_3^2 (H_1^T i\tau_2 H_2 + h.c.) +$$

$$\frac{\lambda_1}{2} \left(H_1^\dagger H_1 \right)^2 + \frac{\lambda_2}{2} \left(H_2^\dagger H_2 \right)^2 + \lambda_3 \left(H_1^\dagger H_1 \right) \left(H_2^\dagger H_2 \right) + \lambda_4 \left| (H_1^T i\tau_2 H_2) \right|^2$$

2HDM type II with quartic couplings fixed due to the gauge nature

$$\lambda_1 = \lambda_2 = \frac{g_1^2 + g_2^2}{4}, \qquad \lambda_3 = \frac{g_2^2 - g_1^2}{4}, \qquad \lambda_4 = -\frac{g_2^2}{2}$$

8-3=5 physics states

h, H – CP even scalars,
A - CP odd scalar,
H± - charged scalars

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$	$g_{\Phi AZ}/g_{\Phi H^+W^-}$
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$	$\propto \cos(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$	$\propto \sin(\beta-\alpha)$
A	$\cot\beta$	$\tan\beta$	0	$\propto 0/1$

Couplings are shared between the Higgses:
$$\sum_i g_{H_i VV}^2 = \left(g_{HVV}^{\mathrm{SM}} \right)^2$$

At tree level there are only two parameters: tanβ and M_A

$$M_{h,H}^2 = \tfrac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

$$M_h \leq \min(M_A, M_Z)\cdot|\cos 2\beta| \leq M_Z \quad M_{H^\pm} > M_W, M_H > M_A$$

Why MSSM is not ruled out yet?   **Fortunately, top quark is very heavy!**

$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{\left(M_A^2 + M_Z^2\right) - 4M_A^2 M_Z^2 \cos^2(2\beta)} \right]$$

At tree level $\qquad M_h \le \min\left(M_A, M_Z\right)\cdot|\cos(2\beta)| \le M_Z$

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\text{SUSY}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\text{SUSY}}^2}\left(1 - \frac{X_t^2}{12M_{\text{SUSY}}^2}\right) \right]$$

$$M_{\text{SUSY}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$$X_t = A_t - \mu \cot \beta$$

(X$_t$ = √6 M$_{\text{SUSY}}$ Maximal mixing scenario)
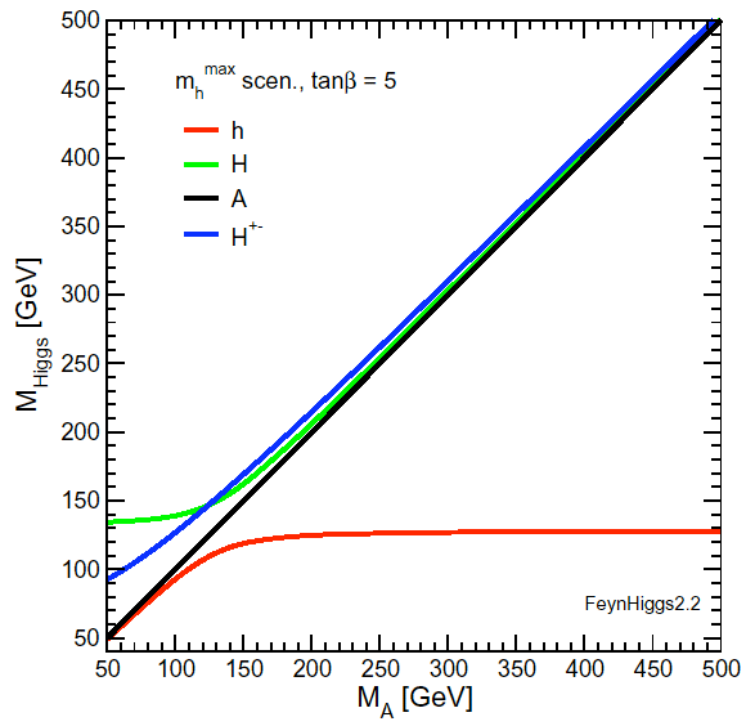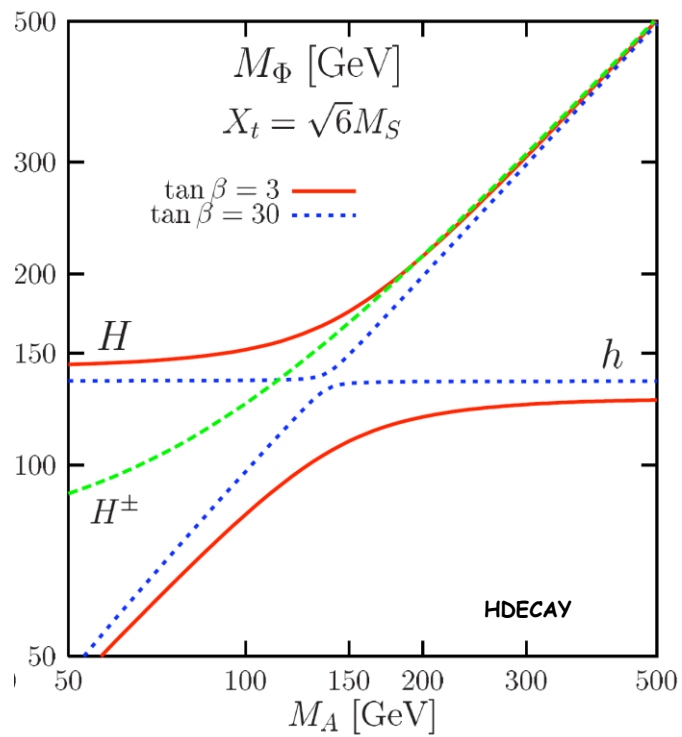
Only two parameters at tree level $\qquad \tan\beta \equiv \dfrac{v_2}{v_1}$ **, M$_A$**

But large loop correction

M$_h$² ≤ M$_Z$² + Δm$_h$²

125 GeV²   **91 GeV²**   **86 GeV²**

Available parameter range after all constrains ?

Left panel:

M_Φ [GeV]

$X_t = \sqrt{6}M_S$

tan $\beta = 3$
tan $\beta = 30$

H

h

$H^\pm$

HDECAY

M_A [GeV]

Right panel:

M_{Higgs} [GeV]

m_h^{max} scen., tan$\beta = 5$

h
H
A
H^{+-}

FeynHiggs2.2

M_A [GeV]

Search strategies

- measuring deviations on couplings of the discovered state h
- new particles, new decays such as
  $H \to hh$ and $A \to Zh$ (if kinematically accessible)

Φ	$g_{\Phi \bar{u} u}$	$g_{\Phi \bar{d} d}$	$g_{\Phi VV}$	$g_{\Phi AZ}/g_{\Phi H^+ W^-}$
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$	$\propto \cos(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$	$\propto \sin(\beta-\alpha)$
A	$\cot\beta$	$\tan\beta$	0	$\propto 0/1$

Djouadi, Maiani, Moreau, Polosa, Quevillon, Rique (1502.05653)

hMSSM

M_h is fixed to be 125 GeV

Carena, Heinemeyer, Stal, Wagner, Weiglein'13

Parameter	$m_h^{\max}$	$m_h^{\mathrm{mod}+}$	$m_h^{\mathrm{mod}-}$	light stop	light stau	τ-phobic	low-M_H
m_t	173.2	173.2	173.2	173.2	173.2	173.2	173.2
M_A	varied	varied	varied	varied	varied	varied	110
$\tan\beta$	varied	varied	varied	varied	varied	varied	varied
M_{SUSY}	1000	1000	1000	500	1000	1500	1500
$M_{\tilde{l}_3}$	1000	1000	1000	1000	245 (250)	500	1000
$X_t^{\mathrm{OS}}/M_{\mathrm{SUSY}}$	2.0	1.5	-1.9	2.0	1.6	2.45	2.45
$X_t^{\overline{\mathrm{MS}}}/M_{\mathrm{SUSY}}$	$\sqrt{6}$	1.6	-2.2	2.2	1.7	2.9	2.9
A_t			Given by $A_t = X_t + \mu\cot\beta$				
A_b	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$
A_τ	$= A_t$	$= A_t$	$= A_t$	$= A_t$	0	0	$= A_t$
μ	200	200	200	350	500 (450)	2000	varied
M_1			Fixed by GUT relation to M_2				
M_2	200	200	200	350	200 (400)	200	200
$m_{\tilde{g}}$	1500	1500	1500	1500	1500	1500	1500
$M_{\tilde{q}_{1,2}}$	1500	1500	1500	1500	1500	1500	1500
$M_{\tilde{l}_{1,2}}$	500	500	500	500	500	500	500
$A_{f\neq t,b,\tau}$	0	0	0	0	0	0	0

$$M_H^2 = \frac{(M_A^2 + M_Z^2 - M_h^2)(M_Z^2\cos^2\beta + M_A^2\sin^2\beta) - M_A^2 M_Z^2\cos^2 2\beta}{M_Z^2\cos^2\beta + M_A^2\sin^2\beta - M_h^2}$$
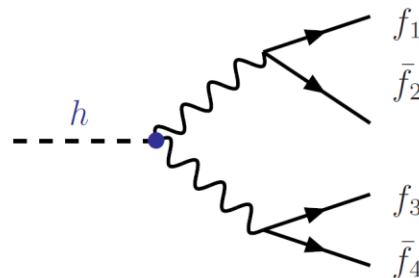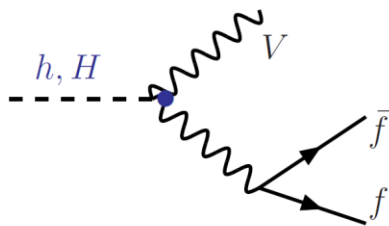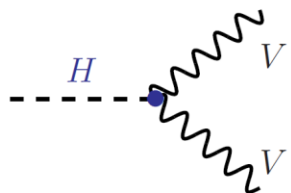
$$\alpha = -\arctan\left(\frac{(M_Z^2 + M_A^2)\cos\beta\sin\beta}{M_Z^2\cos^2\beta + M_A^2\sin^2\beta - M_h^2}\right)$$

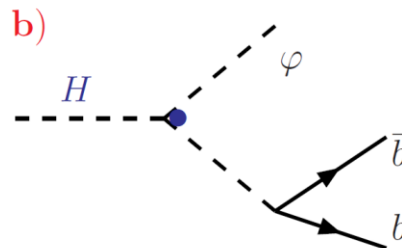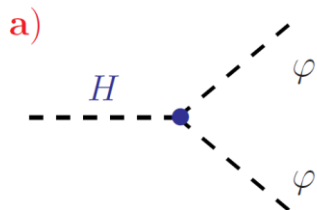Good approximate formulas at loop level with only same 2 parameters as at tree level
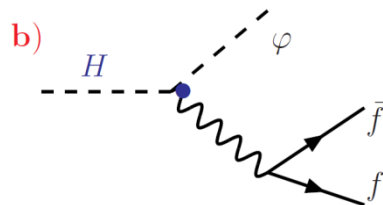
Decay modes depend on Higgs masses and couplings:

a) $h, H, A \to f \bar{f}$

b) $H/A \to t \bar{t} \to t\, W^- \bar{b}$

To fermions

$H \to V V$

$h, H \to V \bar{f} f$

$h \to f_1 \bar{f}_2\, f_3 \bar{f}_4$
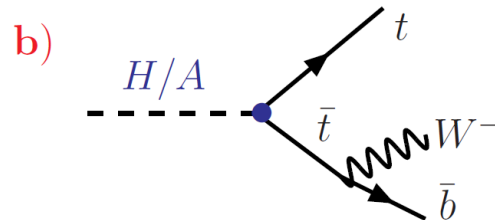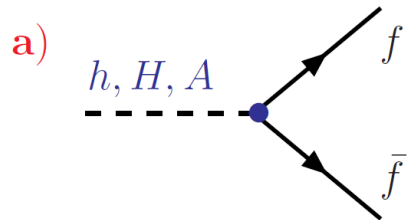
To W,Z vector bosons

a) $H \to \varphi \varphi$

b) $H \to \varphi\, \bar{b}\, b$

To lighter Higgses

a) $H \to \varphi\, V$

b) $H \to \varphi\, \bar{f}\, f$

. . .
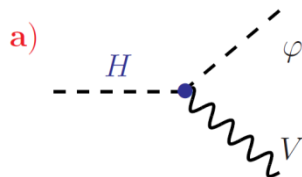
Loop decays for neutral Higgses
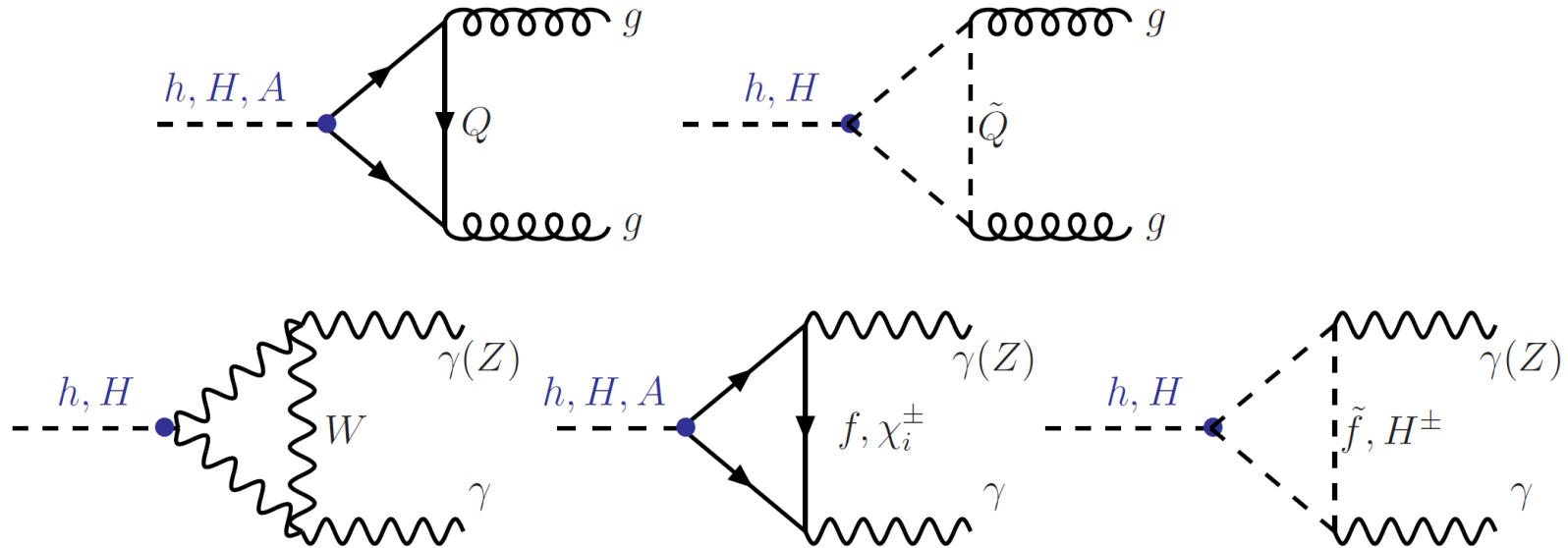
Decays and production for charged Higgs

$$g_{H^+\bar{t}b} \propto m_b \, \mathrm{tg}\,\beta(1+\gamma_5) + m_t \, \mathrm{ctg}\,\beta(1-\gamma_5)$$
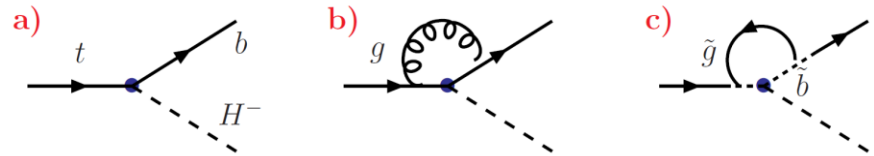
$$\Gamma_{\mathrm{LO}} = \frac{G_\mu m_t}{8\sqrt{2}\pi}|V_{tb}|^2 \lambda(x_H^2, x_b^2; 1)^{\frac{1}{2}}\left[(m_t^2 \cot^2\beta + m_b^2 \tan^2\beta)(1+x_b^2-x_H^2)+4m_t^2 m_b^2\right]$$

$$x_H = M_{H^\pm}/m_t, \, x_b = m_b/m_t$$
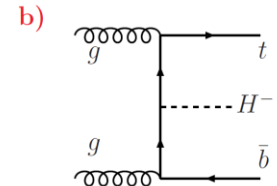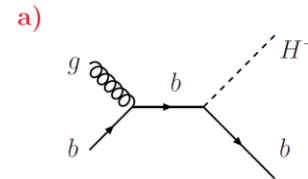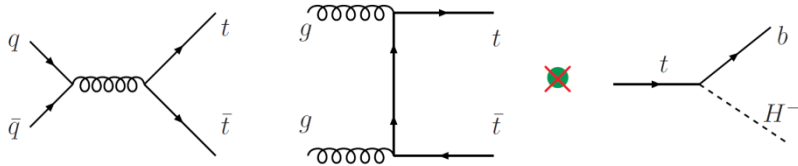
Neutral Higgses
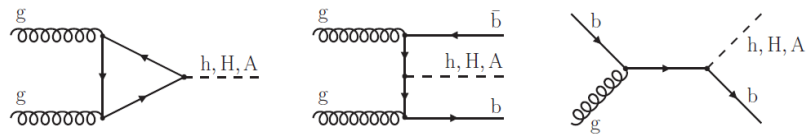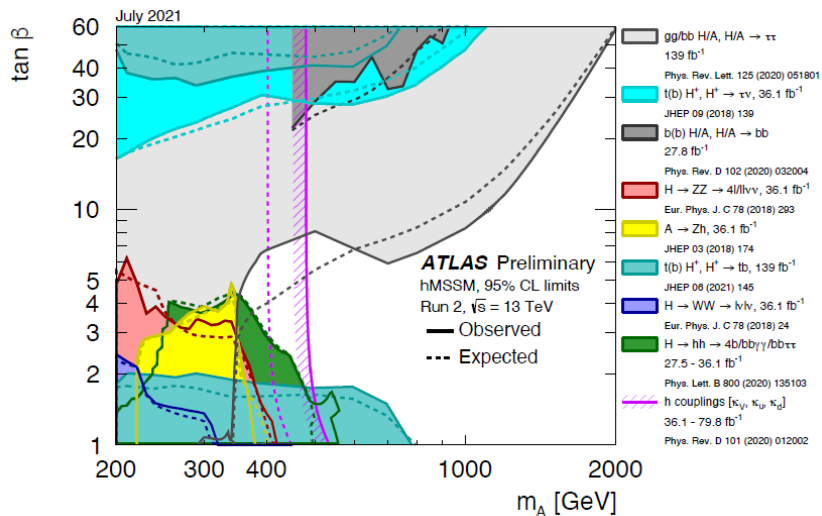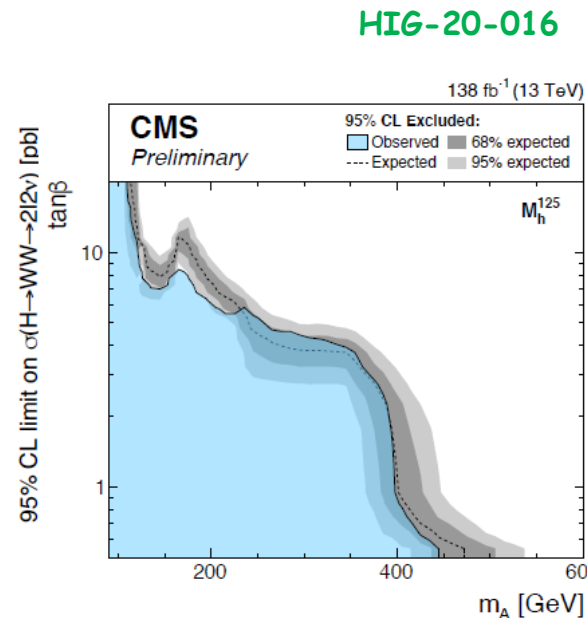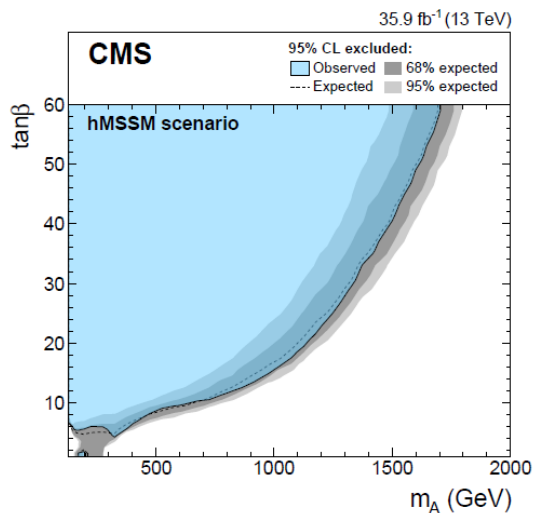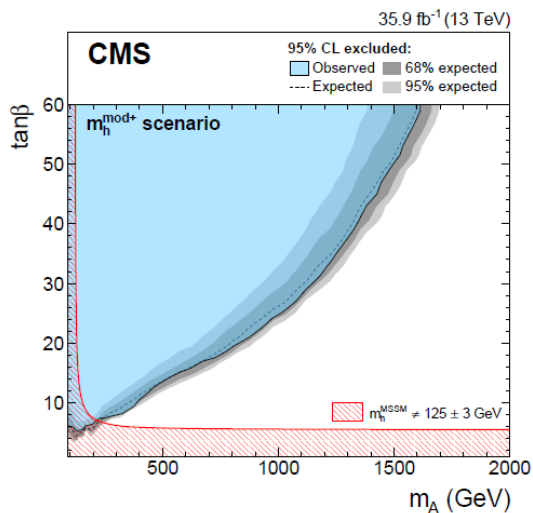
Searches for charged Higgs

Charged Higgses are predicted in many BSM (2HDM, MSSM, NMSSM...)
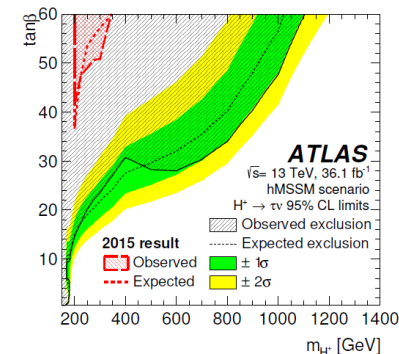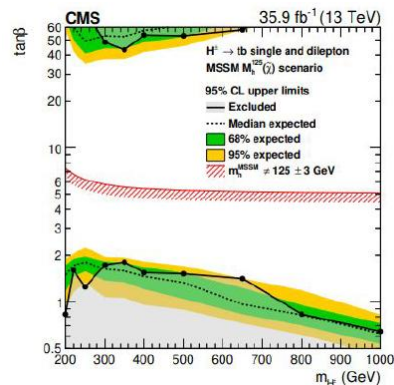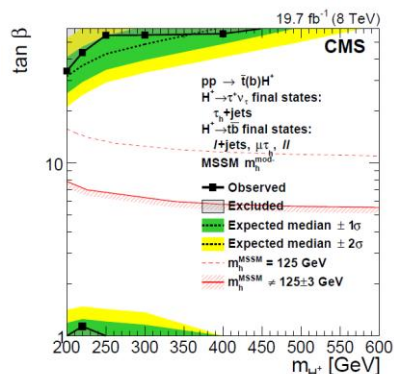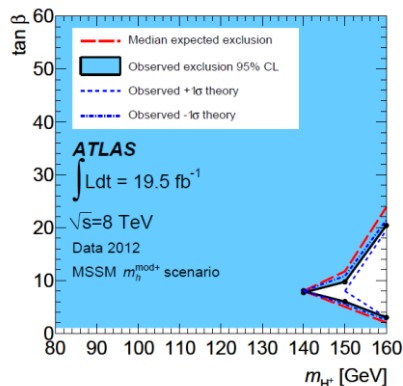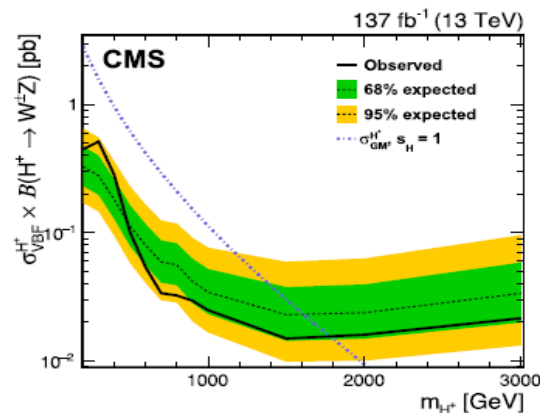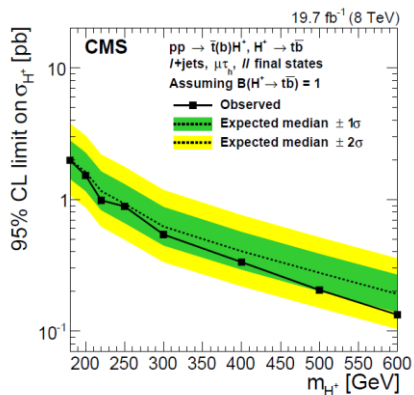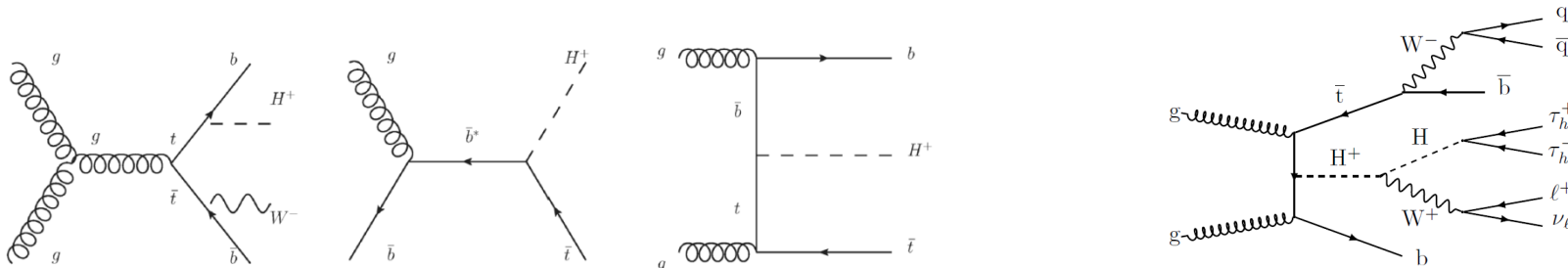
Charged Higgs
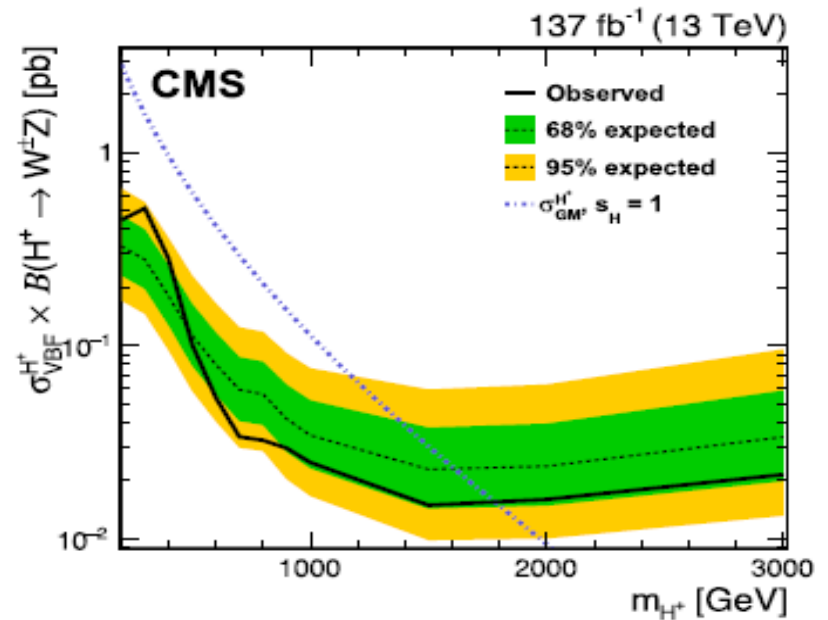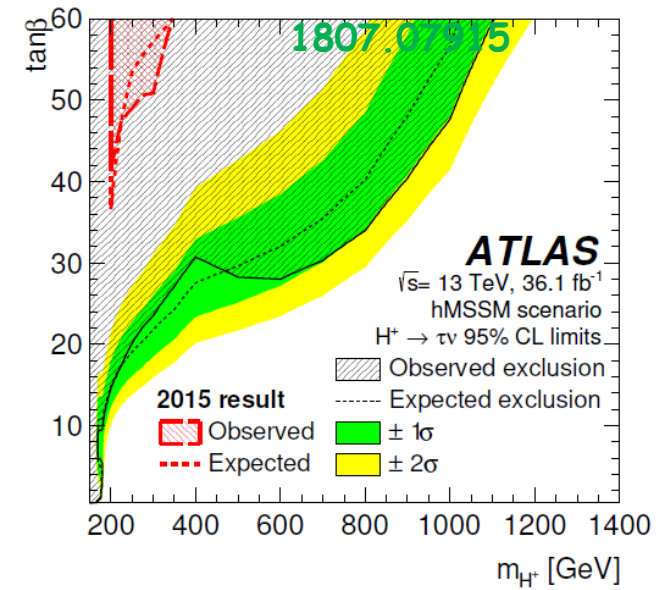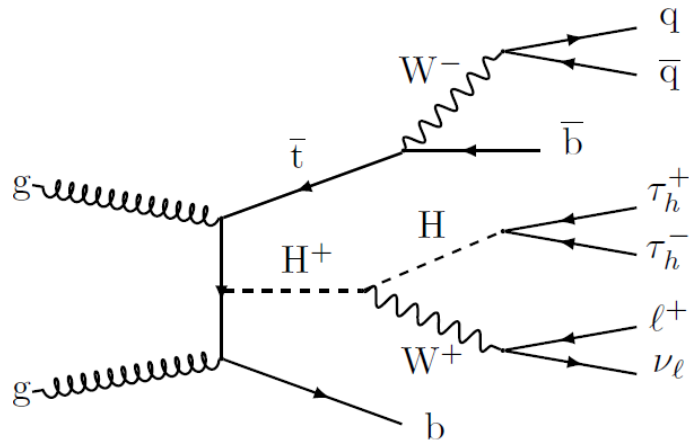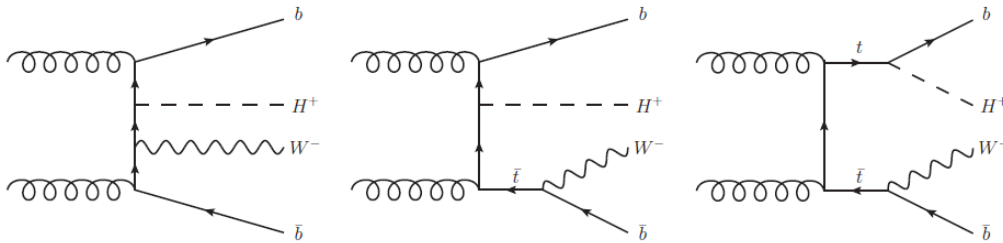
Searches for heavy H in WW
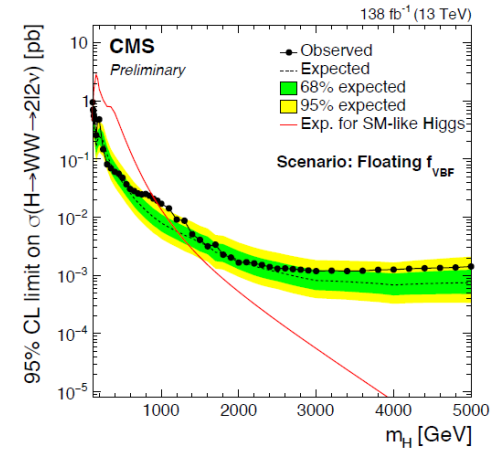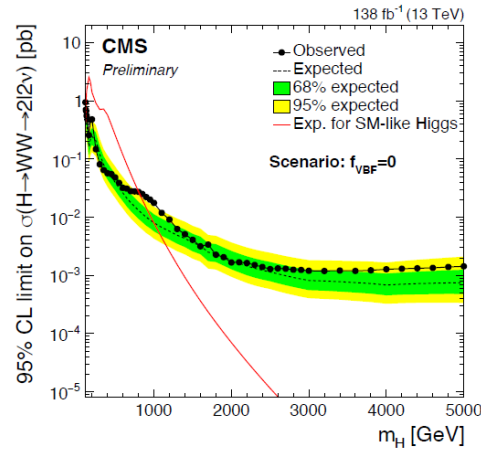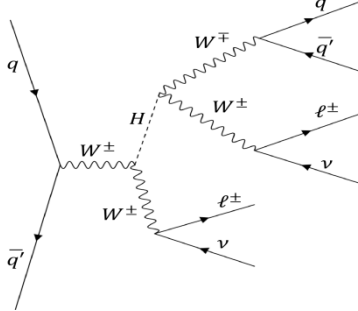
Searches for A/H in 4 tops
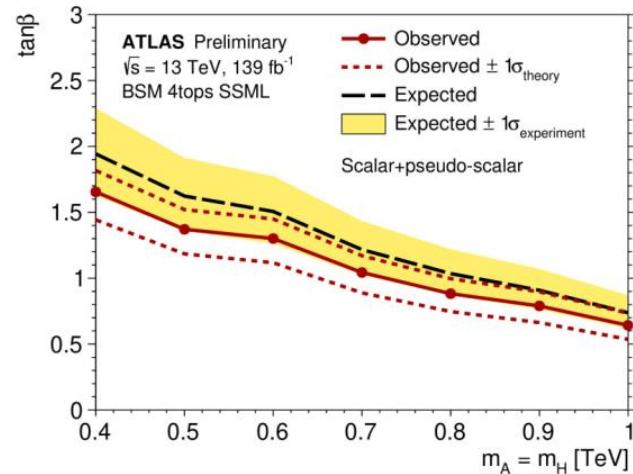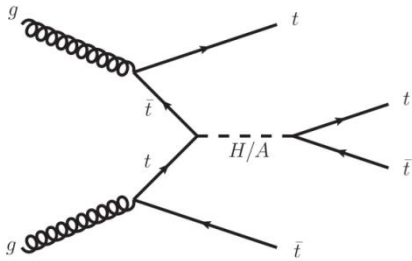
Exotic Higgs: 95 GeV excess

[LEP: hep-ex/0306033]
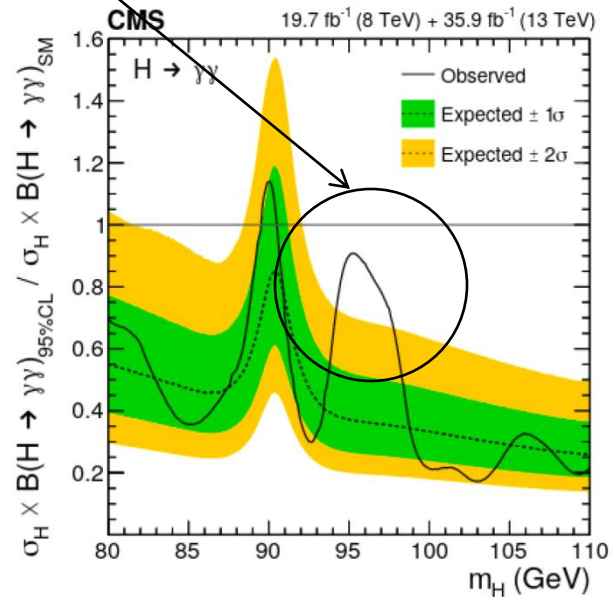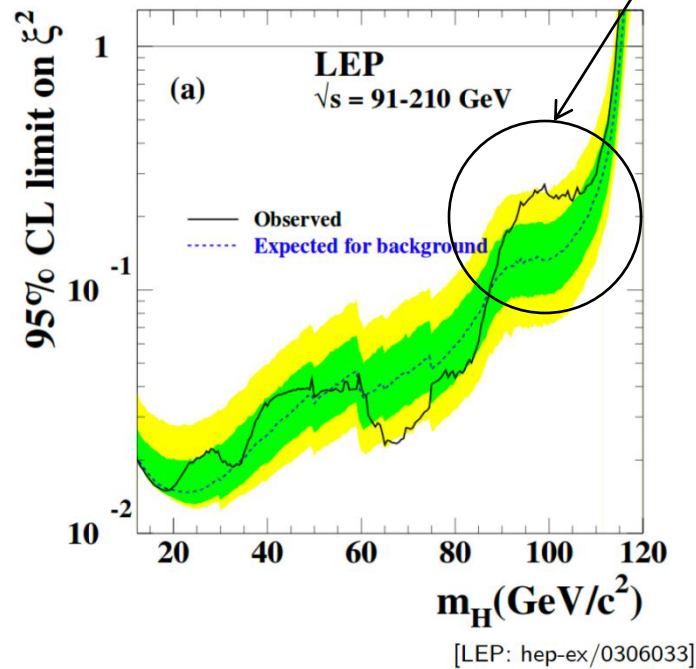
Can be accommodated into N2HDM (S.Heinemeyer, G.Weiglein)

Minimal particle content

☐ Gauge / Gaugino Sector

Standard Bosons	Supersymmetric Partners
$W^{\pm}$ $H^{\pm}$	Charginos $\chi_1^{\pm}$ $\chi_2^{\pm}$
g Z h H A	Neutralinos χ_1^0 χ_2^0 χ_3^0 χ_4^0
g_i	Gluinos $\tilde{g}_i$

[Two Higgs doublets]   [All fermions]

And also …

Graviton G	Gravitino $\tilde{G}$

☐ Particle / Sparticle Sector

Standard Particles	Supersymmetric Partners
Leptons ℓ	Sleptons $\tilde{\ell}_{R,L}$
Neutrinos ν_ℓ	Sneutrinos $\tilde{\nu}_\ell$
Quarks q	Squarks $\tilde{q}_{R,L}$

[All scalars]

Existing particles

SUSY particles (MSSM model)
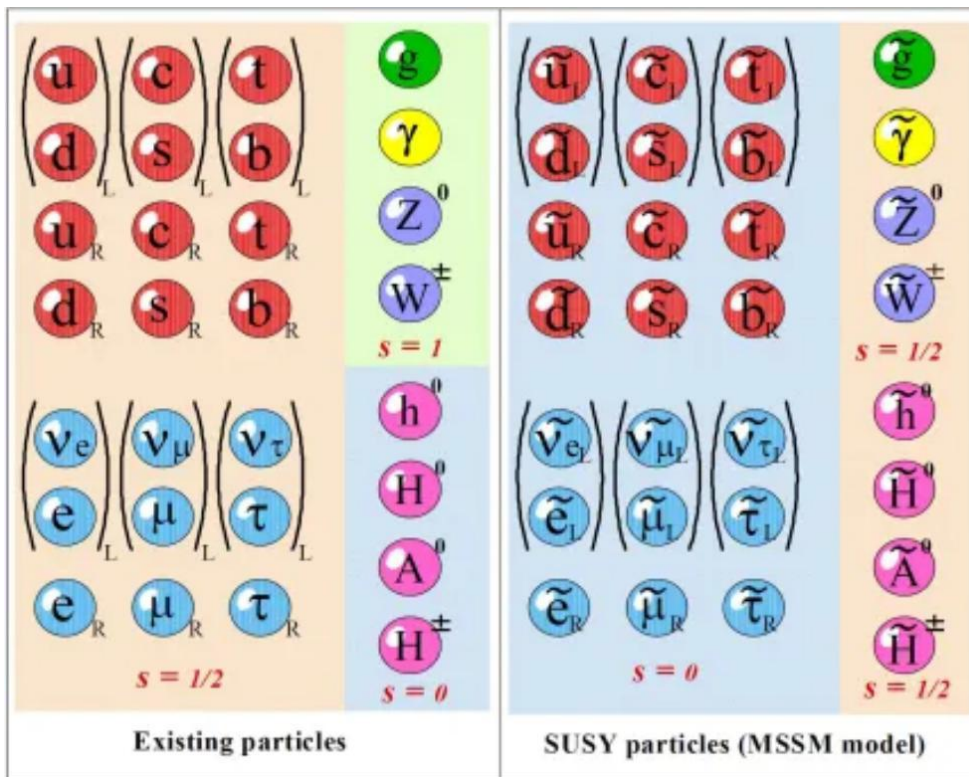
$$W = W_{\text{MSSM}} + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

Higgs sector

MSSM

h
H
A
H+
H−

SM
Higgs Boson
h

NMSSM

H1
H2
H3
A1
A2
H+
H−

physical fileds(CP-even)
pseudoscalar (CP-odd)
charge scalar

NMSSM

Fayet '75;
Dine, Fischler, Srednicki '81;
Nilles, Srednicki, Wyler '83;
Ellis, Gunion, Haber,
Roszkowski, Zwirner '85
Vysotsky, ter-Martirosian '86
...
King, Mühlleitner, Nevzorov '12
Beskidt, de Boer, Kazakov '13
King, Mühlleitner, Nevzorov, Walz '14
...
...
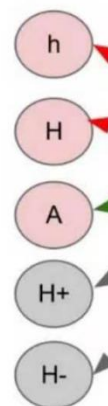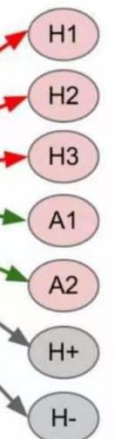
MSSM + a singlet chiral superfield

Physical Higgses:

SM   4 – 3 = 1   h

MSSM   2*4 – 3 = 5   CP-even H1, H2; CP-odd A; charged $H^{\pm}$
(2HDM)

NMSSM   2*4 + 2 – 3 = 7   CP-even H1, H2, H3; CP-odd A1, A2; charged $H^{\pm}$
(2HDM + complex scalar)

- **μ-problem is solved dynamically** $\mu\left(H_u^{\mathrm{T}} \epsilon H_d\right) \longrightarrow \lambda S\left(H_u^{\mathrm{T}} \epsilon H_d\right) + \frac{1}{3}\kappa S^3$

- **less fine tunning** $m_Z^2 \cos^2(2\beta) \longrightarrow m_Z^2\left(\cos^2(2\beta) + \frac{2|\lambda|^2 \sin^2(2\beta)}{g_1^2 + g_2^2}\right)$
compared to MSSM
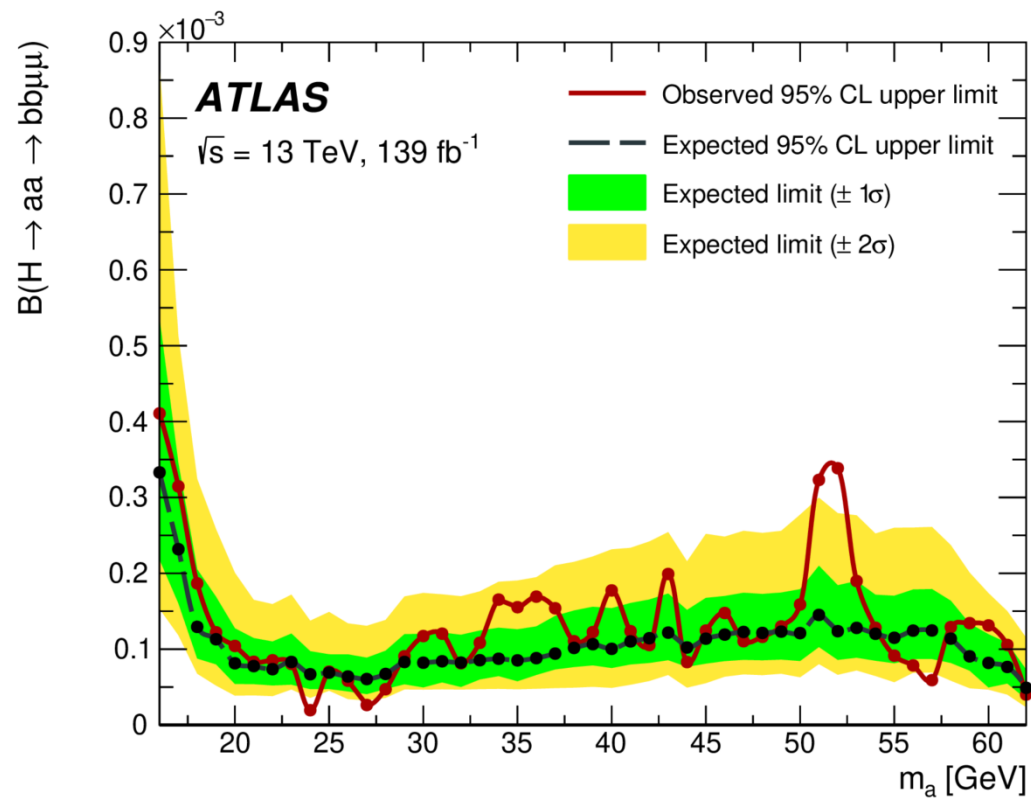
SUSY

1. Cancellation of the leading scale dependence
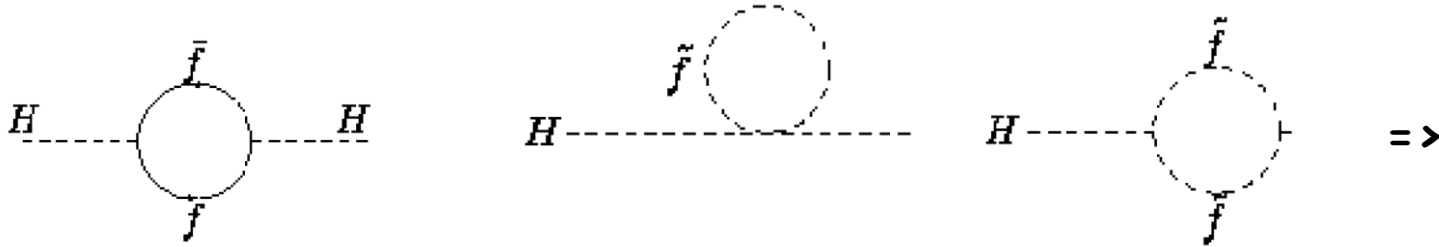
M_H is protected!

2. Lightest SUSY particle is stable (if R-parity) – Dark Matter candidate

3. Unification of couplings in contrast to SM
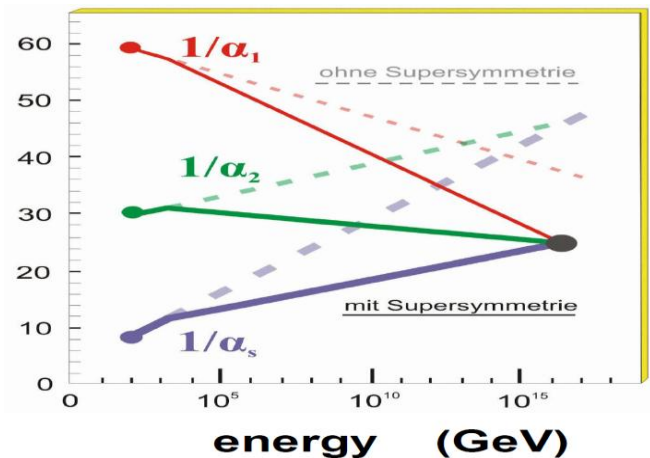
4. Fit of EW precision data
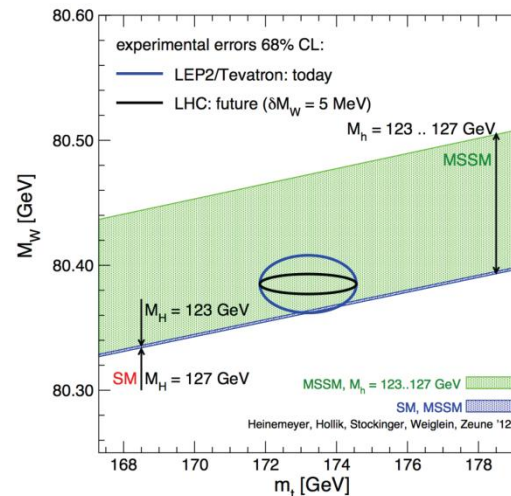
SUSY searches

In order to establish SUSY one needs:

-find superpartners
-measure spins which should differ by ½
-demonstrate their couplings are the same
-their quantum numbers are the same
…

SUSY searches

In order to establish SUSY one needs:

-find superpartners
-measure spins which should differ by ½
-demonstrate their couplings are the same
-their quantum numbers are the same

…

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^\pm, H^\pm} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \qquad \tilde{\chi}_{1,2}^\pm \qquad\qquad \tilde{\chi}_{1,2,3,4}^0 \qquad\qquad \text{Spin } \tfrac{1}{2}$$

Searches for strongly interacting superpartners

Gluino and squark signatures:
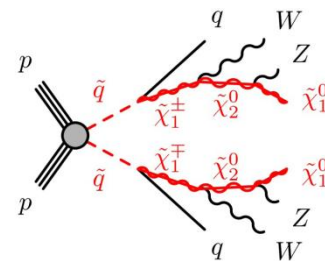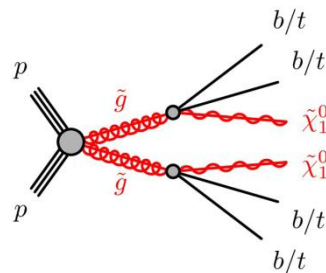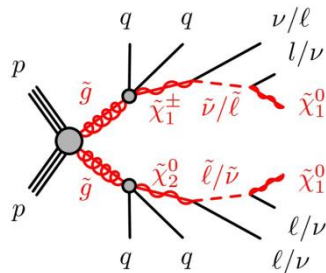
$$i\, g_s\, \tilde{g}^a \gamma^\mu \tilde{g}^b G_\mu^c f^{abc}$$

$$-\sqrt{2}\, g_s \sum_{q=u,d,c,s} \left[\bar{q} P_R t^a \tilde{g}^a \tilde{q}_L - \bar{q} P_L t^a \tilde{g}^a \tilde{q}_R \right] + h.c.$$
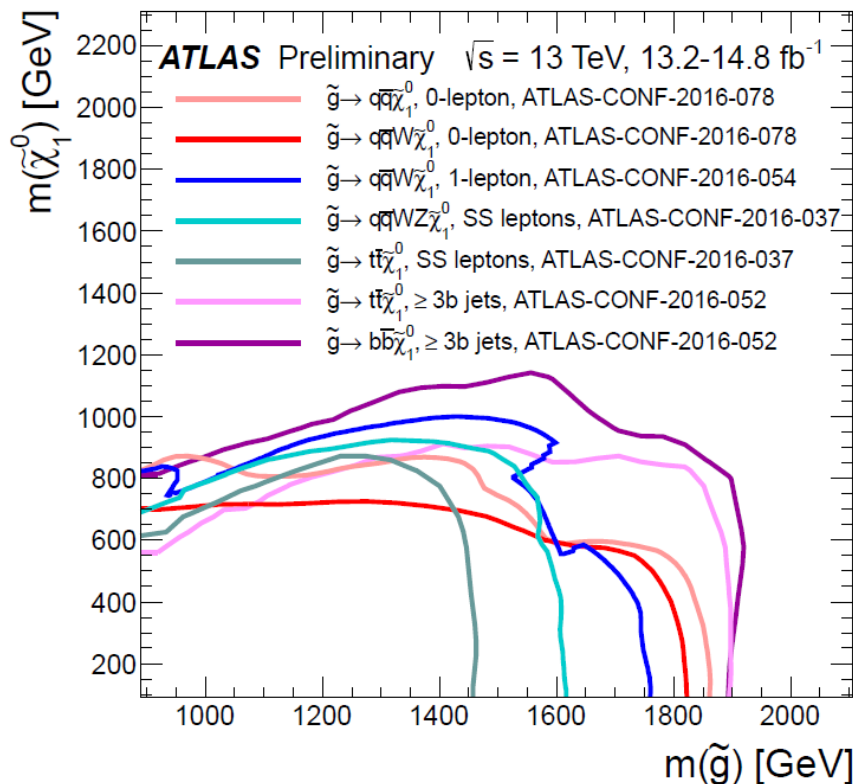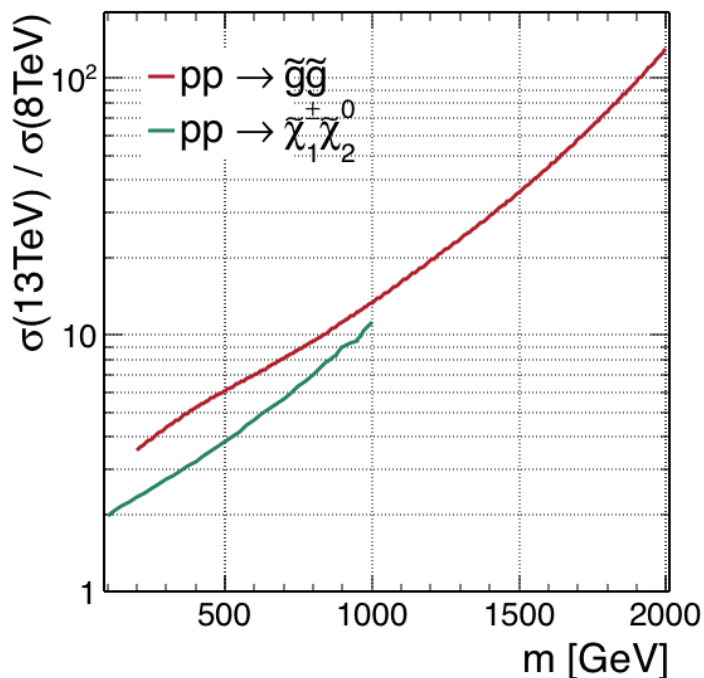
Gluino decays to tt+LSP
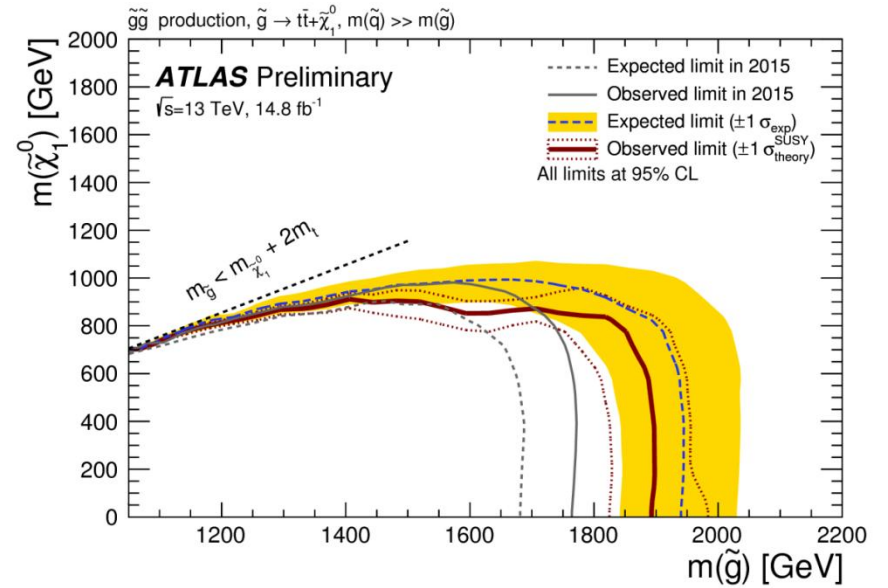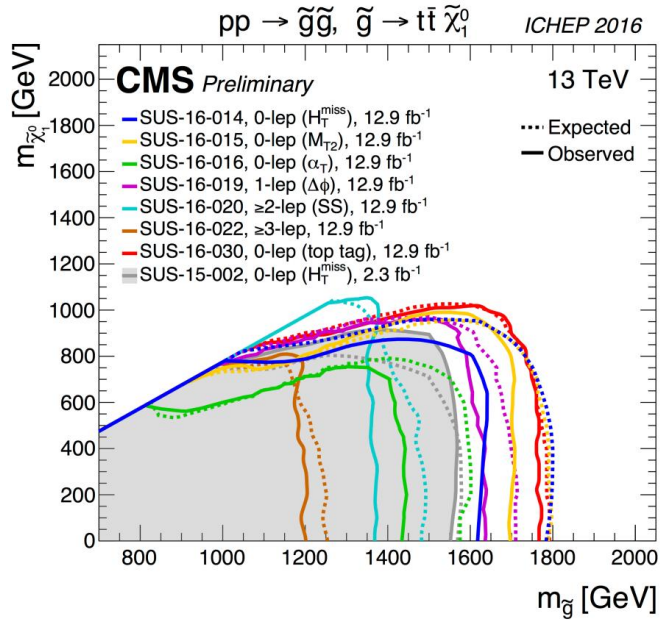
$$-\sqrt{2}g_s T_{jk}^a \left[\sum_{q=b,t} \left(\overline{q}_j \left(\cos\theta_{\tilde{q}} P_R - \sin\theta_{\tilde{q}} P_L \right) \tilde{g}_a \tilde{q}_1^k - \overline{q}_j \left(\sin\theta_{\tilde{q}} P_R + \cos\theta_{\tilde{q}} P_L \right) \tilde{g}_a \tilde{q}_2^k \right) + \\ +h.c. \right]$$

$$+g \sum_{f=\tau,\nu_\tau,b,t} \left[\overline{f} \left(b_{ki}^f P_L + a_{ki}^f P_R \right) \tilde{\chi}_i^0 \tilde{f}_k + h.c \right]$$

$pp \rightarrow \tilde{g}\tilde{g}, \ \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ *Moriond 2021*

CMS $137 \ \text{fb}^{-1} \ (13 \ \text{TeV})$

$m_{\tilde{\chi}_1^0}$ [GeV]

— 1908.04722, 0-lep (H_T^{miss})
— 1909.03460, 0-lep (M_{T2})
— 2103.01290, 0-lep (stop)
— 1911.07558, 1-lep (M_J)
— 2001.10086, ≥2-lep (same-sign)
— 1710.11188, 0-lep (stop), 36 fb^{-1}

····· Expected
— Observed

$m_{\tilde{g}}$ [GeV]
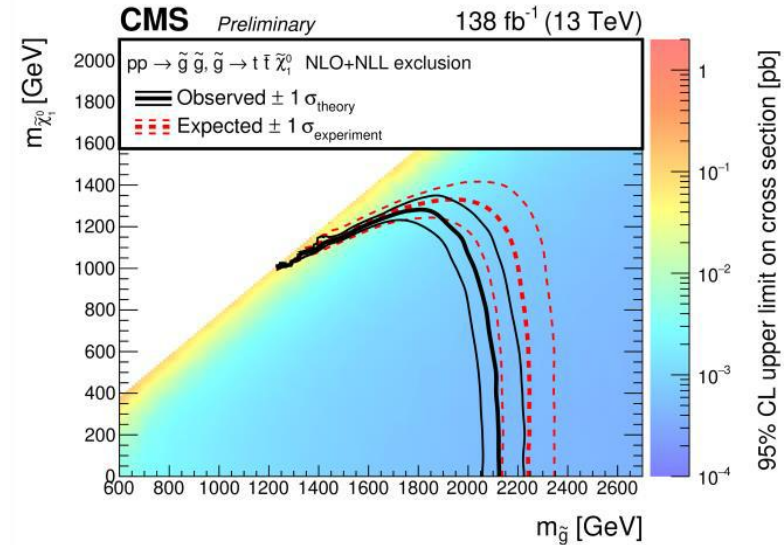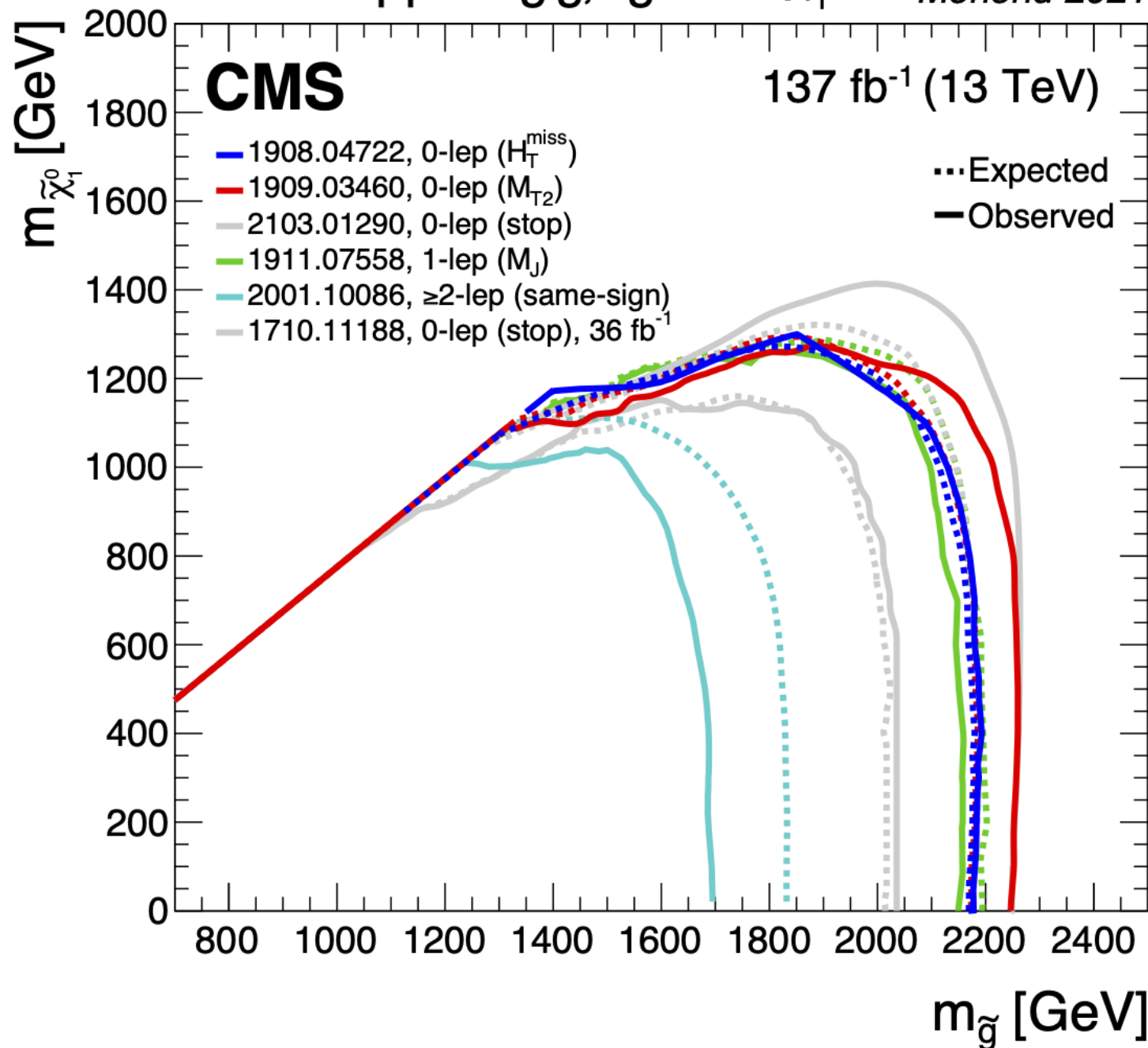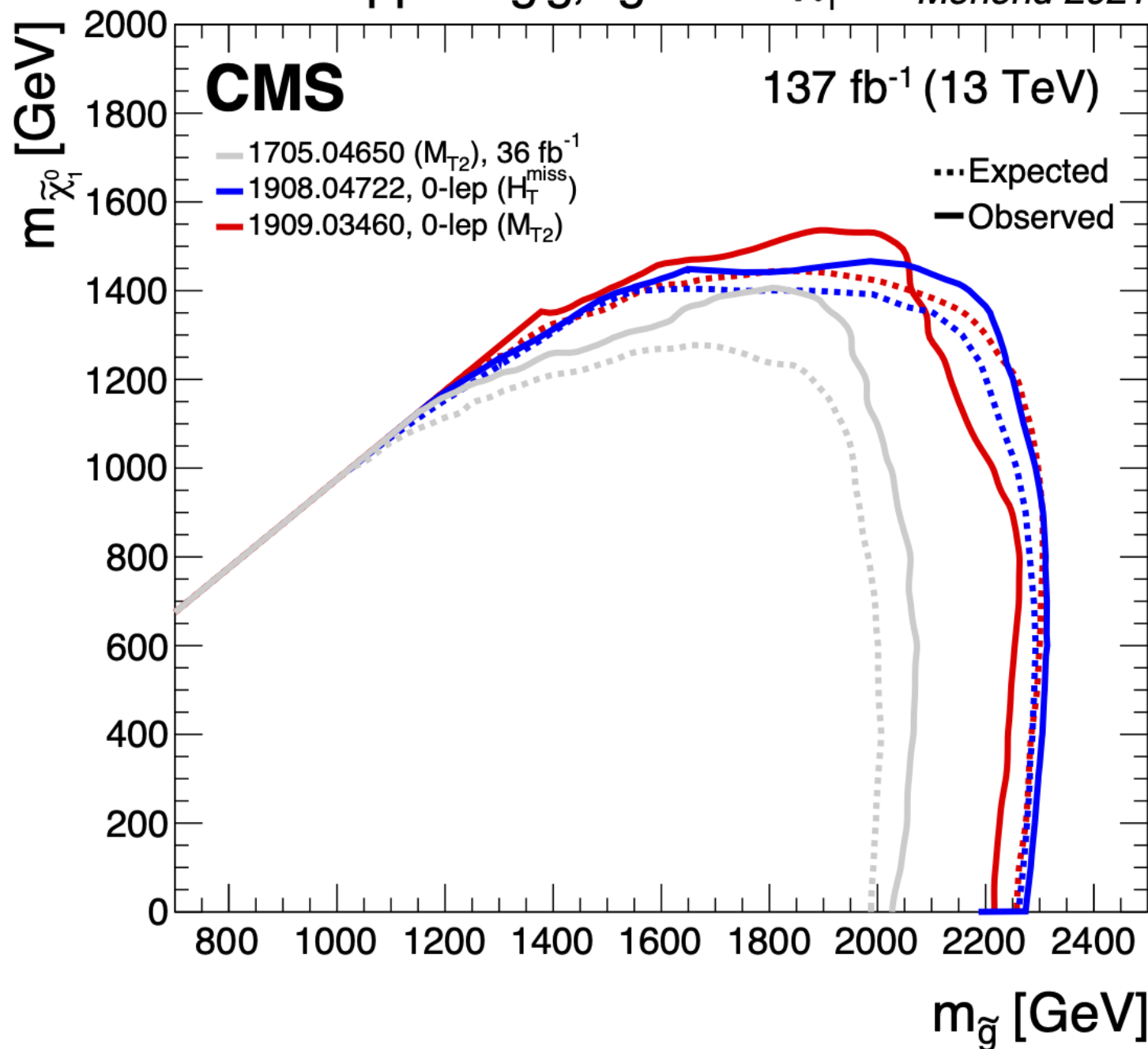
$pp \rightarrow \tilde{q}\bar{\tilde{q}}, \ \tilde{q} \rightarrow q \ \tilde{\chi}_1^0$ *Moriond 2021*

CMS   137 fb^{-1} (13 TeV)

— 1705.04650, 0-lep (M$_{T2}$), 36 fb^{-1}

— 1909.03460, 0-lep (M$_{T2}$)

— 1908.04722, 0-lep (H$_T^{miss}$)

$\cdots\cdots$ Expected

—— Observed

$\tilde{q}_L + \tilde{q}_R \ (\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c})$

one light $\tilde{q}$

m$_{\tilde{\chi}_1^0}$ [GeV]

m$_{\tilde{q}}$ [GeV]
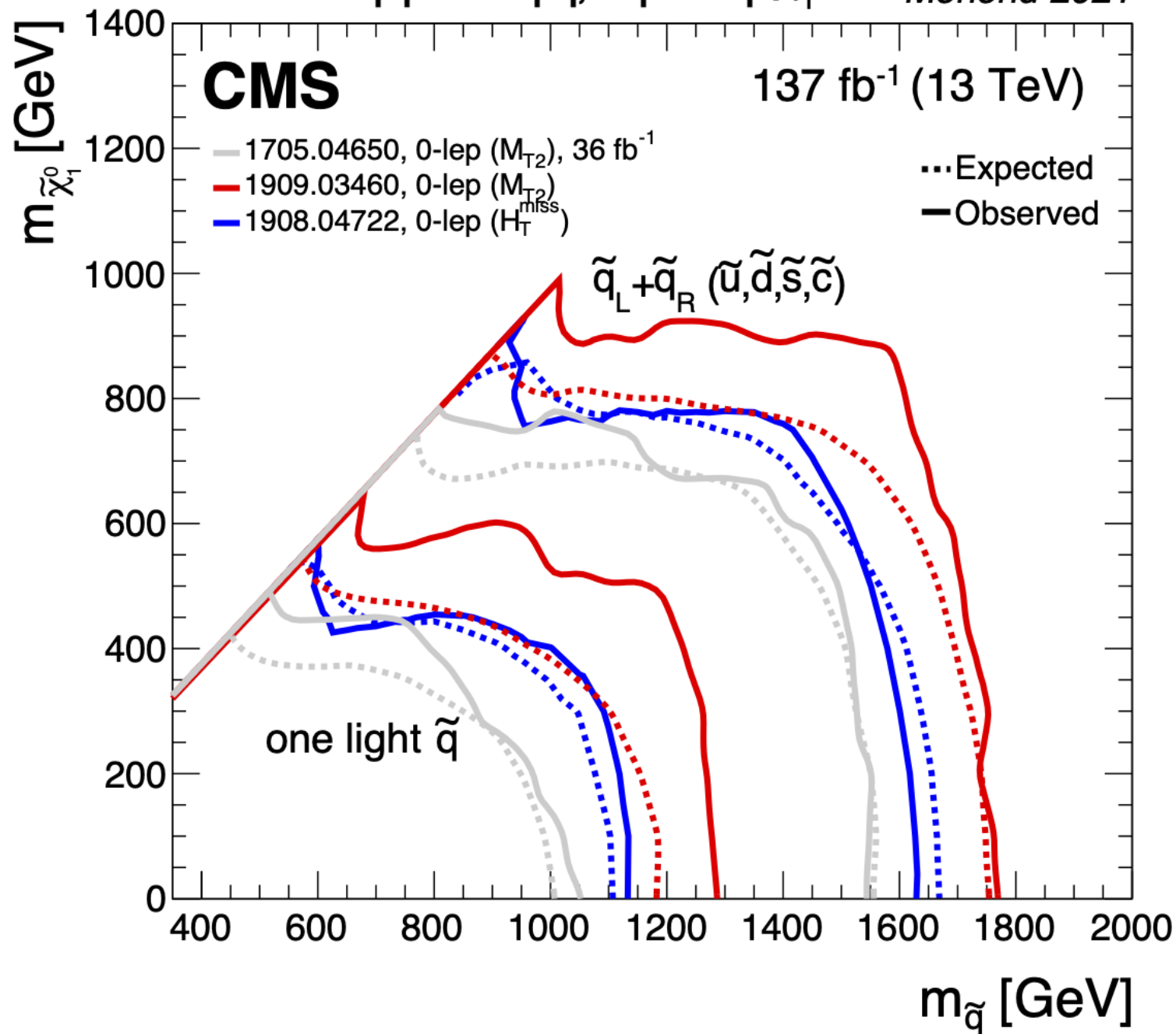
CMS Moriond 2021

Overview of SUSY results: gluino pair production

137 fb^{-1} (13 TeV)

pp → g̃g̃

$\tilde{\mathbf{g}} \to \mathbf{tt}\tilde{\chi}_1^0$ — **0ℓ:** arXiv:1909.03460;1908.04722,2103.01290

1ℓ: arXiv:1911.07558

2ℓ same-sign and ≥ 3ℓ: arXiv:2001.10086

$\tilde{\mathbf{g}} \to \mathbf{bb}\tilde{\chi}_1^0$ — **0ℓ:** arXiv:1909.03460;1908.04722

$\tilde{\mathbf{g}} \to \mathbf{qq}\tilde{\chi}_1^0$ — **0ℓ:** arXiv:1909.03460;1908.04722

$\tilde{\mathbf{g}} \to \mathbf{qq}(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) \to \mathbf{qq}(\mathbf{W/Z})\tilde{\chi}_1^0$ — **0ℓ:** arXiv:1908.04722   BF($\tilde{\chi}_1^\pm$:$\tilde{\chi}_2^0$) = 2:1, x = 0.5

2ℓ same-sign and ≥ 3ℓ: arXiv:2001.10086   BF($\tilde{\chi}_1^\pm$:$\tilde{\chi}_2^0$) = 2:1, x = 0.5

mass scale [GeV]: 0 — 500 — 1000 — 1500 — 2000

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Searches for Stops

$$\tilde{t}\tilde{t} \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

$$\tilde{t}\tilde{t} \rightarrow b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

$$\tilde{t}\tilde{t} \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

$$\tilde{t}\tilde{t} \rightarrow b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

CMS *Supplementary*   137.0 fb^{-1} (13 TeV)

pp → $\tilde{t}\,\tilde{t}$ Approx. NNLO+NNLL exclusion — Observed   --- Expected

$\tilde{t} \rightarrow t\,\tilde{\chi}_1^0$ [BR($\tilde{t} \rightarrow t\,\tilde{\chi}_1^0$) = 100%]

$\tilde{t} \rightarrow t\,\tilde{\chi}_1^0/\tilde{t} \rightarrow b\,\tilde{\chi}_1^\pm$ [$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ = 5 GeV, BR($\tilde{t} \rightarrow t\,\tilde{\chi}_1^0$) = 50%]

$\tilde{t} \rightarrow b\,\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \rightarrow W^\pm\,\tilde{\chi}_1^0$ [$m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} + m_{\tilde{\chi}_1^0})/2$, BR($\tilde{t} \rightarrow b\,\tilde{\chi}_1^\pm$) = 100%]

$\tilde{t} \rightarrow b\,\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \rightarrow W^{\pm(*)}\,\tilde{\chi}_1^0$ [$m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} + m_{\tilde{\chi}_1^0})/2$, BR($\tilde{t} \rightarrow b\,\tilde{\chi}_1^\pm$) = 100%]

$\tilde{t} \rightarrow b\,f\,\bar{f}'\,\tilde{\chi}_1^0$ [BR($\tilde{t} \rightarrow b\,f\,\bar{f}'\,\tilde{\chi}_1^0$) = 100%]

$\tilde{t} \rightarrow c\,\tilde{\chi}_1^0$ [BR($\tilde{t} \rightarrow c\,\tilde{\chi}_1^0$) = 100%]   arXiv:2103.01290

CMS Preliminary $\sqrt{s}$ = 8 TeV, $\int$Ldt = 19.5 fb^{-1}

pp → $\tilde{t}\overline{\tilde{t}}$*
1-lepton channel
SUS-13-011 BDT analysis
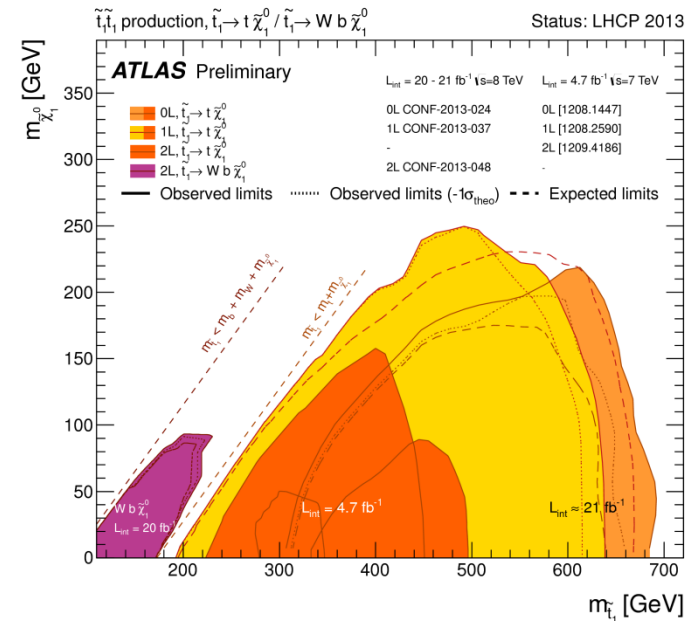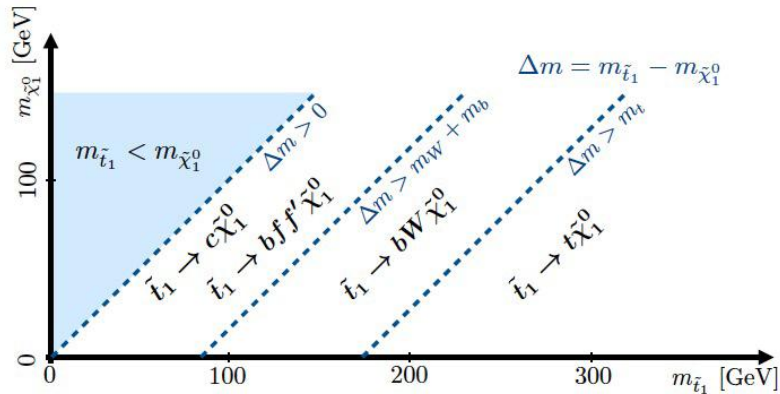
$\tilde{t} \rightarrow t\,\tilde{\chi}_1^0$
$\tilde{t} \rightarrow b\,\tilde{\chi}_1^+$, x=0.5
Observed
Expected
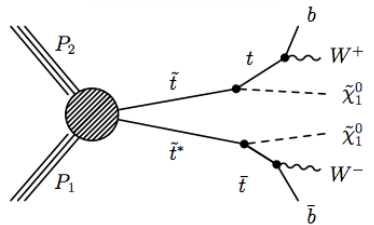
Neutralino LSP
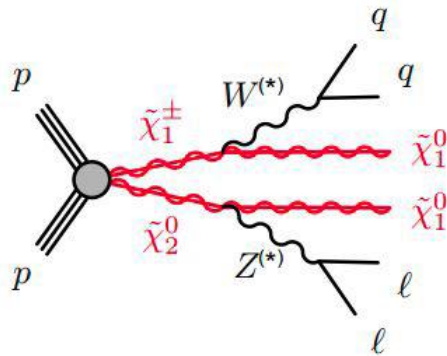
Gauge-mediated SUSY breaking

$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \to 2 \times \tilde{\tau}\nu(\tilde{\nu}\tau) \to 2 \times \tau\nu\tilde{\chi}_1^0$

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \tilde{\tau}\nu\tilde{\tau}\tau(\tilde{\nu}\nu),\tilde{\tau}\nu\tilde{\tau}\tau(\tilde{\nu}\nu) \to \tau\nu\tilde{\chi}_1^0\tau\tau(\nu\nu)\tilde{\chi}_1^0$ $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \to 2\times \tilde{\tau}\nu(\tilde{\nu}\tau) \to 2 \times \tau\nu\tilde{\chi}_1^0$

ATLAS Preliminary

SR-C1C1-combined

$\sqrt{s}$=13 TeV, 139 fb^{-1}

$m_{\tilde{\tau}}=(m_{\tilde{\chi}_1^0}+m_{\tilde{\chi}_1^{\pm}})/2$

All limits at 95% CL

Expected Limit ($\pm 1\,\sigma_{exp}$)

Observed Limit ($\pm 1\,\sigma_{theory}^{SUSY}$)

$m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_1^{\pm}}$

ATLAS Preliminary

$\sqrt{s}$=13 TeV, 139 fb^{-1}

$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$

$m_{\tilde{\tau}} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_1^{\pm}})/2$

All limits at 95 % CL

Expected comb. limit ($\pm 1\,\sigma_{exp}$)

Combined observed ($\pm 1\,\sigma_{theory}^{SUSY}$)

SS observed

SS expected

OS observed

OS expected

$m_{\tilde{\chi}_1^{\pm}} < m_{\tilde{\chi}_2^0}$
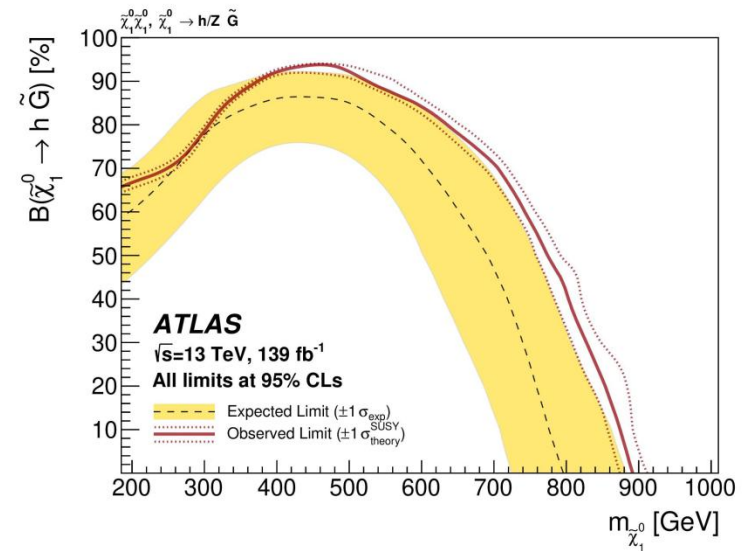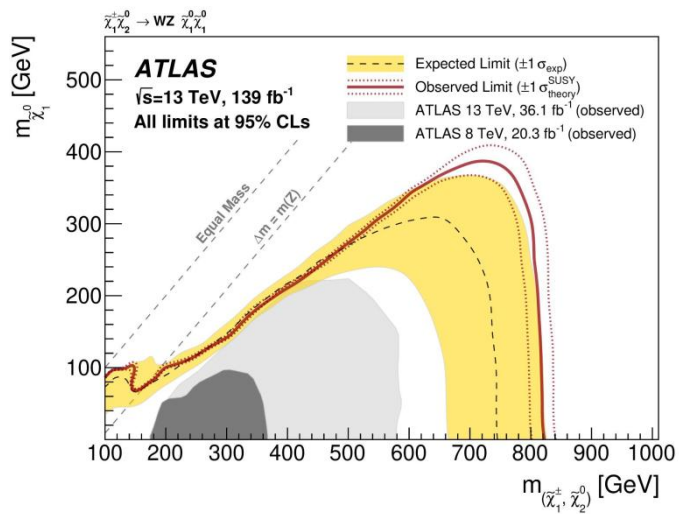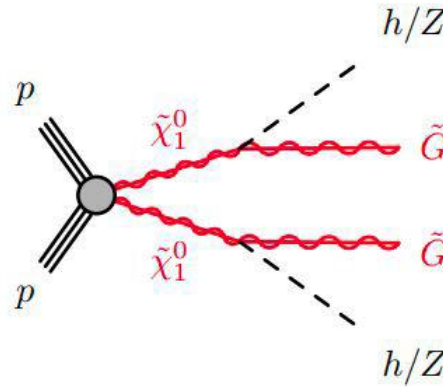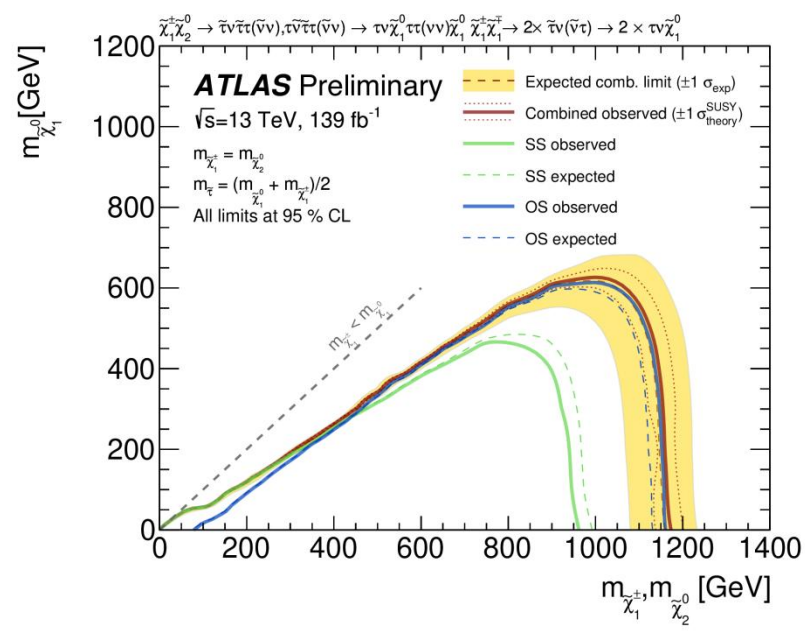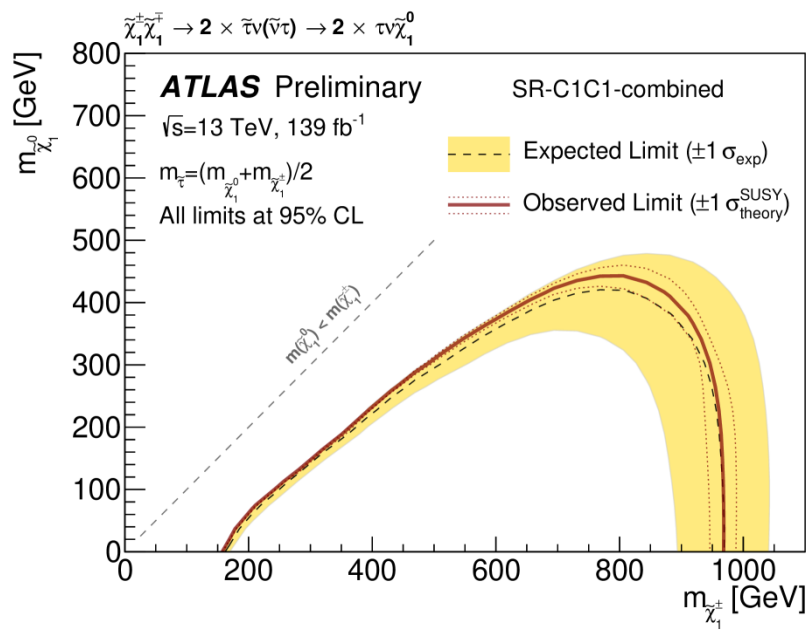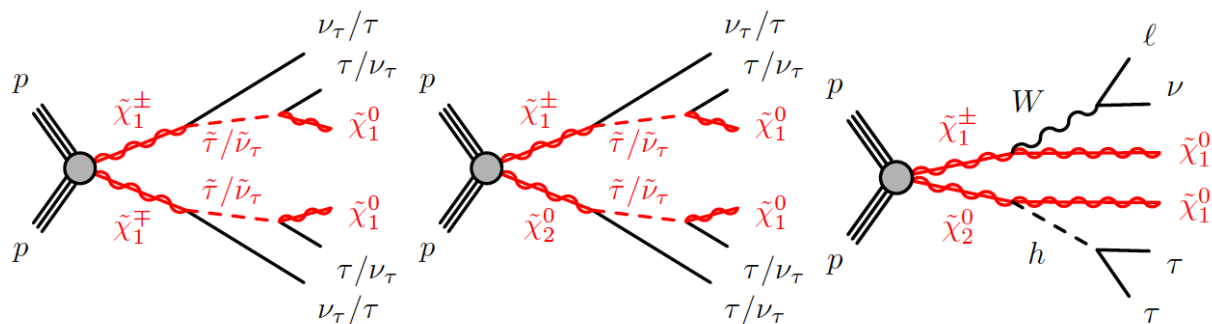
Many other searches for superpartners

R-parity conserving scenarios

Gauge mediated scenarios

R-parity violating scenarios

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2022

ATLAS Preliminary

$\sqrt{s} = 13$ TeV

Model	Signature	$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit		Reference

Inclusive Searches

Model	Signature	$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit	Conditions	Reference
$\tilde{q}\tilde{q}$, $\tilde{q} \to q\tilde{\chi}_1^0$	$0\ e,\mu$ 2-6 jets E_T^{miss}	139	$\tilde{q}$ [1×, 8× Degen.] 1.0 / 1.85	$m(\tilde{\chi}_1^0)<400$ GeV	2010.14293
	mono-jet 1-3 jets E_T^{miss}	139	$\tilde{q}$ [8× Degen.] 0.9	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)=5$ GeV	2102.10874
$\tilde{g}\tilde{g}$, $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	$0\ e,\mu$ 2-6 jets E_T^{miss}	139	$\tilde{g}$ 2.3	$m(\tilde{\chi}_1^0)=0$ GeV	2010.14293
		139	$\tilde{g}$ Forbidden 1.15-1.95	$m(\tilde{\chi}_1^0)=1000$ GeV	2010.14293
$\tilde{g}\tilde{g}$, $\tilde{g} \to q\bar{q}W\tilde{\chi}_1^0$	$1\ e,\mu$ 2-6 jets E_T^{miss}	139	$\tilde{g}$ 2.2	$m(\tilde{\chi}_1^0)<600$ GeV	2101.01629
$\tilde{g}\tilde{g}$, $\tilde{g} \to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$ 2 jets E_T^{miss}	139	$\tilde{g}$ 2.2	$m(\tilde{\chi}_1^0)<700$ GeV	CERN-EP-2022-014
$\tilde{g}\tilde{g}$, $\tilde{g} \to q qWZ\tilde{\chi}_1^0$	$0\ e,\mu$ 7-11 jets E_T^{miss}	139	$\tilde{g}$ 1.97	$m(\tilde{\chi}_1^0)<600$ GeV	2008.06032
	SS e,μ 6 jets	139	$\tilde{g}$ 1.15	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)=200$ GeV	1909.08457
$\tilde{g}\tilde{g}$, $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ 3 b E_T^{miss}	79.8	$\tilde{g}$ 2.25	$m(\tilde{\chi}_1^0)<200$ GeV	ATLAS-CONF-2018-041
	SS e,μ 6 jets	139	$\tilde{g}$ 1.25	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)=300$ GeV	1909.08457

3rd gen. squarks direct production

Model	Signature	$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit	Conditions	Reference
$\tilde{b}_1\tilde{b}_1$	$0\ e,\mu$ 2 b E_T^{miss}	139	$\tilde{b}_1$ 1.255	$m(\tilde{\chi}_1^0)<400$ GeV	2101.12527
		139	$\tilde{b}_1$ 0.68	10 GeV$<\Delta m(\tilde{b}_1,\tilde{\chi}_1^0)<20$ GeV	2101.12527
$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1 \to b\tilde{\chi}_2^0 \to bh\tilde{\chi}_1^0$	$0\ e,\mu$ 6 b E_T^{miss}	139	$\tilde{b}_1$ Forbidden 0.23-1.35	$\Delta m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)=130$ GeV, $m(\tilde{\chi}_1^0)=100$ GeV	1908.03122
	$2\ \tau$ 2 b E_T^{miss}	139	$\tilde{b}_1$ 0.13-0.85	$\Delta m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)=130$ GeV, $m(\tilde{\chi}_1^0)=0$ GeV	2103.08189
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to t\tilde{\chi}_1^0$	0-1 e,μ ≥ 1 jet E_T^{miss}	139	$\tilde{t}_1$ 1.25	$m(\tilde{\chi}_1^0)=1$ GeV	2004.14060,2012.03799
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to Wb\tilde{\chi}_1^0$	$1\ e,\mu$ 3 jets/1 b E_T^{miss}	139	$\tilde{t}_1$ Forbidden 0.65	$m(\tilde{\chi}_1^0)=500$ GeV	2012.03799
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to \tilde{\tau}_1 b\nu$, $\tilde{\tau}_1 \to \tau\tilde{G}$	1-2 τ 2 jets/1 b E_T^{miss}	139	$\tilde{t}_1$ Forbidden 1.4	$m(\tilde{\tau}_1)=800$ GeV	2108.07665
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}$, $\tilde{c} \to c\tilde{\chi}_1^0$	$0\ e,\mu$ 2 c E_T^{miss}	36.1	$\tilde{c}$ 0.85	$m(\tilde{\chi}_1^0)=0$ GeV	1805.01649
	$0\ e,\mu$ mono-jet E_T^{miss}	139	$\tilde{t}_1$ 0.55	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}_1^0)=5$ GeV	2102.10874
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \to Z/h\tilde{\chi}_1^0$	1-2 e,μ 1-4 b E_T^{miss}	139	$\tilde{t}_1$ 0.067-1.18	$m(\tilde{\chi}_2^0)=500$ GeV	2006.05880
$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2 \to \tilde{t}_1 + Z$	3 e,μ 1 b E_T^{miss}	139	$\tilde{t}_2$ Forbidden 0.86	$m(\tilde{\chi}_1^0)=360$ GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)=40$ GeV	2006.05880

EW direct

Model	Signature	$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit	Conditions	Reference
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.96	$m(\tilde{\chi}_1^0)=0$, wino-bino	2106.01676, 2108.07586
	$ee,\mu\mu$ ≥ 1 jet E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.205	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)=5$ GeV, wino-bino	1911.12606
$\tilde{\chi}_1^+\tilde{\chi}_1^-$ via WW	2 e,μ E_T^{miss}	139	$\tilde{\chi}_1^\pm$ 0.42	$m(\tilde{\chi}_1^0)=0$, wino-bino	1908.08215
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ Forbidden 1.06	$m(\tilde{\chi}_1^0)=70$ GeV, wino-bino	2004.10894, 2108.07586
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ E_T^{miss}	139	$\tilde{\chi}_1^\pm$ 1.0	$m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1908.08215
$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau} \to \tau\tilde{\chi}_1^0$	2 τ E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$] 0.16-0.3 / 0.12-0.39	$m(\tilde{\chi}_1^0)=0$	1911.06660
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell} \to \ell\tilde{\chi}_1^0$	2 e,μ 0 jets E_T^{miss}	139	$\tilde{\ell}$ 0.7	$m(\tilde{\chi}_1^0)=0$	1908.08215
	$ee,\mu\mu$ ≥ 1 jet E_T^{miss}	139	$\tilde{\ell}$ 0.256	$m(\tilde{\ell})$-$m(\tilde{\chi}_1^0)=10$ GeV	1911.12606
$\tilde{H}\tilde{H}$, $\tilde{H} \to h\tilde{G}/Z\tilde{G}$	$0\ e,\mu$ ≥ 3 b E_T^{miss}	36.1	$\tilde{H}$ 0.13-0.23 / 0.29-0.88	BR$(\tilde{\chi}_1^0 \to h\tilde{G})=1$	1806.04030
	4 e,μ 0 jets E_T^{miss}	139	$\tilde{H}$ 0.55	BR$(\tilde{\chi}_1^0 \to Z\tilde{G})=1$	2103.11684
	$0\ e,\mu$ ≥ 2 large jets E_T^{miss}	139	$\tilde{H}$ 0.45-0.93	BR$(\tilde{\chi}_1^0 \to Z\tilde{G})=1$	2108.07586

Long-lived particles

Model	Signature	$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit	Conditions	Reference
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk 1 jet E_T^{miss}	139	$\tilde{\chi}_1^\pm$ 0.66	Pure Wino	2201.02472
		139	$\tilde{\chi}_1^\pm$ 0.21	Pure higgsino	2201.02472
Stable $\tilde{g}$ R-hadron	pixel dE/dx E_T^{miss}	139	$\tilde{g}$ 2.05		CERN-EP-2022-029
Metastable $\tilde{g}$ R-hadron, $\tilde{g} \to qq\tilde{\chi}_1^0$	pixel dE/dx E_T^{miss}	139	$\tilde{g}$ [$\tau(\tilde{g})=10$ ns] 2.2	$m(\tilde{\chi}_1^0)=100$ GeV	CERN-EP-2022-029
$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell} \to \ell\tilde{G}$	Displ. lep E_T^{miss}	139	$\tilde{e},\tilde{\mu}$ 0.7	$\tau(\tilde{\ell})=0.1$ ns	2011.07812
		139	$\tilde{\tau}$ 0.34	$\tau(\tilde{\ell})=0.1$ ns	2011.07812
	pixel dE/dx E_T^{miss}	139	$\tilde{\tau}$ 0.36	$\tau(\tilde{\ell})=10$ ns	CERN-EP-2022-029

RPV

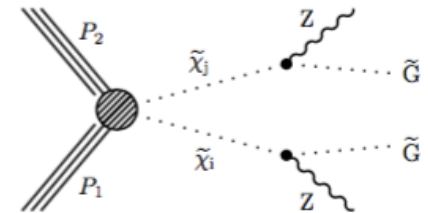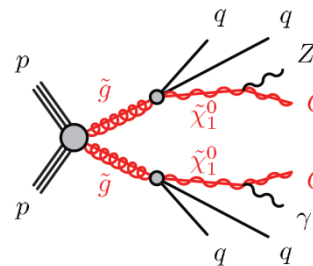| Model	Signature	$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit	Conditions	Reference
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm \to Z\ell \to \ell\ell\ell$	3 e,μ	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [BR$(Z\tau)=1$, BR$(Ze)=1$] 0.625 / 1.05	Pure Wino	2011.10543
$\tilde{\chi}_1^+\tilde{\chi}_1^-/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ 0 jets E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$] 0.95 / 1.55	$m(\tilde{\chi}_1^0)=200$ GeV	2103.11684
$\tilde{g}\tilde{g}$, $\tilde{g} \to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to qqq$	4-5 large jets	36.1	$\tilde{g}$ [$m(\tilde{\chi}_1^0)=200$ GeV, 1100 GeV] 1.3 / 1.9	Large λ''_{112}	1804.03568
$\tilde{t}\tilde{t}$, $\tilde{t} \to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to tbs$	Multiple	36.1	$\tilde{t}$ [$\lambda''_{323}=2e{-}4$, 1e-2] 0.55 / 1.05	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003
$\tilde{t}\tilde{t}$, $\tilde{t} \to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to bbs$	$\geq 4b$	139	$\tilde{t}$ Forbidden 0.95	$m(\tilde{\chi}_1^0)=500$ GeV	2010.01015
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to bs$	2 jets + 2 b	36.7	$\tilde{t}_1$ [qq, bs] 0.42 / 0.61		1710.07171
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to q\ell$	2 e,μ 2 b	36.1	$\tilde{t}_1$ 0.4-1.45	BR$(\tilde{t}_1 \to be/b\mu)>20\%$	1710.05544
	$1\ \mu$ DV	136	$\tilde{t}_1$ [1e-10$<\lambda'_{23k}<$1e-8, 3e-10$<\lambda'_{23k}<$3e-9] 1.0 / 1.6	BR$(\tilde{t}_1 \to q\mu)=100\%$, $\cos\theta_t=1$	2003.11956
$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0 \to tbs$, $\tilde{\chi}_1^\pm \to bbs$	1-2 e,μ ≥ 6 jets	139	$\tilde{\chi}_1^0$ 0.2-0.32	Pure higgsino	2106.09609

Mass scale [TeV]

10^{-1} 1

Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

CMS (preliminary)   Moriond 2021

Overview of SUSY results: electroweak production
137 fb^{-1} (13 TeV)

$\mathbf{pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm}$

$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \ell\tilde{\nu}\ell\tilde{\ell} \to \ell\nu\ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$

2ℓ same-sign and 3ℓ: SUS-19-012   flavour democratic, $x = 0.5$
2ℓ same-sign and $\geq$ 3ℓ: SUS-19-012   flavour democratic, $x = 0.05$
2ℓ same-sign and $\geq$ 3ℓ: SUS-19-012   flavour democratic, $x = 0.95$

$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\tau}\nu\ell\tilde{\ell} \to \tau\nu\ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$

2ℓ same-sign and 3ℓ/τ$_\mathbf{h}$: SUS-19-012   τ enriched, $x = 0.5$
3ℓ/τ$_\mathbf{h}$: SUS-19-012   τ enriched, $x = 0.05$
3ℓ/τ$_\mathbf{h}$: SUS-19-012   τ enriched, $x = 0.95$

$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\tau}\nu\tau\tilde{\tau} \to \tau\nu\tau\tau\tilde{\chi}_1^0\tilde{\chi}_1^0$

$\geq$ 3ℓ/τ$_\mathbf{h}$: SUS-19-012   τ dominated, $x = 0.5$

$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \mathbf{WH}\tilde{\chi}_1^0\tilde{\chi}_1^0$

2ℓ same-sign and $\geq$ 3ℓ/τ$_\mathbf{h}$: SUS-19-012
1ℓ+jets: SUS-20-003

$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \mathbf{WZ}\tilde{\chi}_1^0\tilde{\chi}_1^0$

2ℓ opposite-sign: arXiv:2012.08600
2ℓ same-sign and 3ℓ: SUS-19-012
2ℓ and 3ℓ soft: SUS-18-004 $\Delta M = 5$–10 GeV

$pp \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm/\tilde{\chi}_1^0\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm/\tilde{\chi}_2^0 \to (\mathbf{W}^*/\mathbf{Z}^*)\tilde{\chi}_1^0$

2ℓ and 3ℓ soft: SUS-18-004   higgsino simplified model, $\Delta M = 5$–10 GeV

$\mathbf{pp \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm}$

$pp \to \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \to \mathbf{W}\tilde{\chi}_1^0$

2ℓ opposite-sign: arXiv:1807.07799 $M_{\tilde{\chi}_1^0} = 1$ GeV

$pp \to \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \to (\tilde{\ell}\nu/\ell\tilde{\nu}) \to \ell\nu\tilde{\chi}_1^0$

2ℓ opposite-sign: arXiv:1807.07799   BF($\tilde{\ell}\nu$) = 50%, $x = 0.5$

$\mathbf{pp \to \tilde{\ell}\tilde{\ell}}$

$pp \to \tilde{\ell}_{\mathbf{L/R}}\tilde{\ell}_{\mathbf{L/R}}, \tilde{\ell} \to \ell\tilde{\chi}_1^0$

e$^+$e$^-$, μ$^+$μ$^-$: arXiv:2012.08600

mass scale [GeV]

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise.
The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate
sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

SUSY is one of the most attractive idea for BSM physics

SUSY, if exists, is broken, and there are many possibilities:

Gravity mediation
Gauge madiation
Gaugino mediation
Anomaly mediation
Hidden sector mediation

...

In general the unconstrained MSSM has 105 parameters
(22 with reasonable assumptions)
(many parameter space points of are rulled out already)

Many nice SUSY feaches are due to additional global symmetry-
R-parity. Tiny deviations of R-parity possible leading to processes
with FCNC, lepton/barion number violation, proton decay…
But what is an origin of R-parity?...

Supersymmetry Parameter Analysis:
SPA Convention and Project

0511344
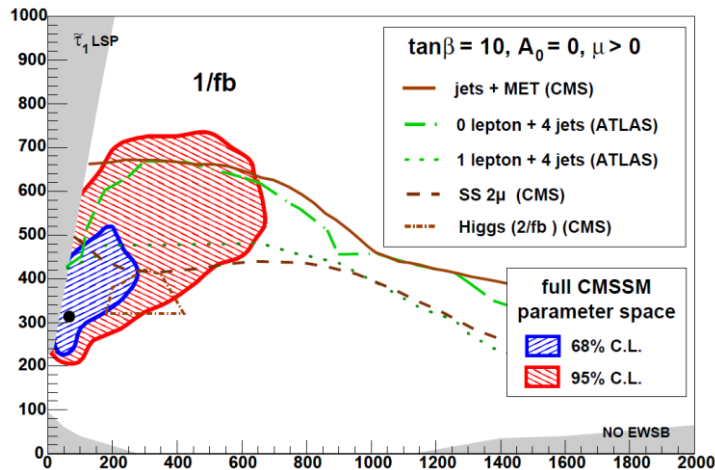
The 65% and 95% CL regions favoured by b→sγ, (g$_\mu$ - 2), WMAP data.
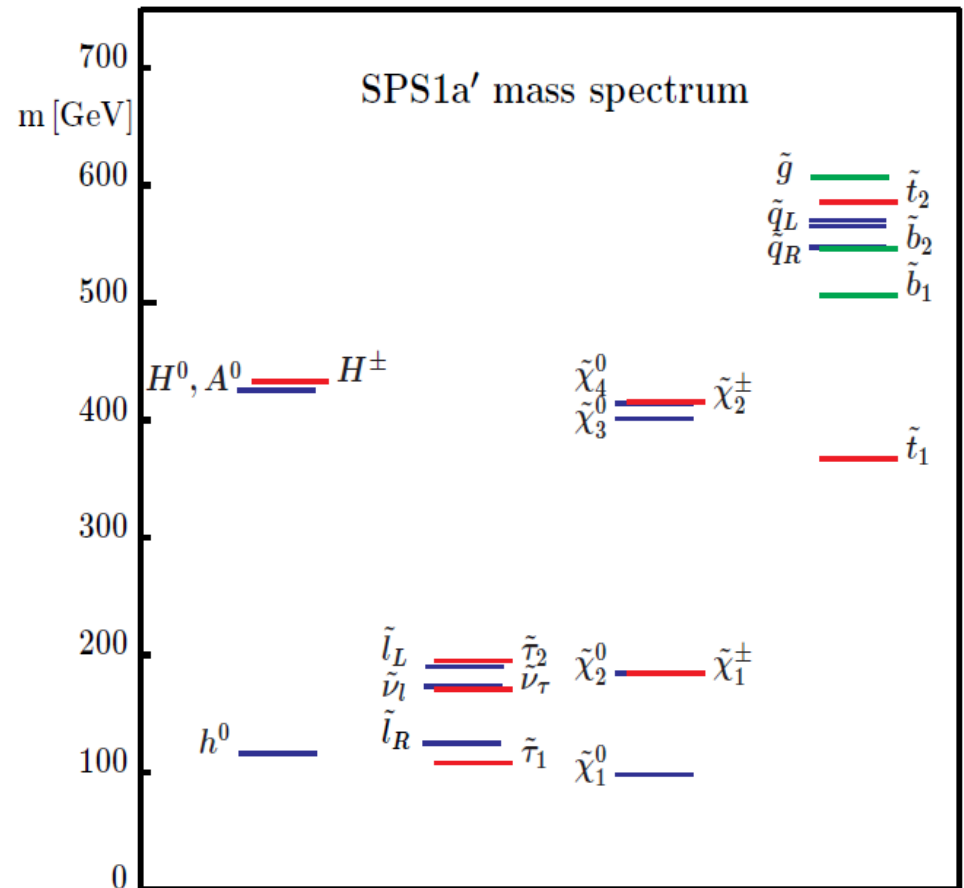
Extra Dimensions

5D massless scalar field, M=0,1,2,3,4
Dimension $x_4 = y$ defines the circle with radios r : y = y + 2πr
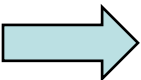
$$\mathcal{S}_{5D} = \int d^5x \, \partial^M \varphi \, \partial_M \varphi$$

Fourier expansion:
$$\varphi(x^\mu, y) = \sum_{n=-\infty}^{\infty} \varphi_n(x^\mu) \exp\left(\frac{iny}{r}\right)$$

Equation of motion gives:

$$\partial^M \partial_M \varphi = 0 \implies \sum_{n=-\infty}^{\infty} \left(\partial^\mu \partial_\mu - \frac{n^2}{r^2}\right) \varphi_n(x^\mu) \exp\left(\frac{iny}{r}\right) = 0$$

$$\implies \partial^\mu \partial_\mu \varphi_n(x^\mu) - \frac{n^2}{r^2} \varphi_n(x^\mu) = 0$$

Kaluza-Klien tower, KK modes with masses $\qquad m_n^2 = \frac{n^2}{r^2}$

Models with extra space dimensions

we are confined on some 4-dim. brane imbedded into higher dim. bulk

ADD type models
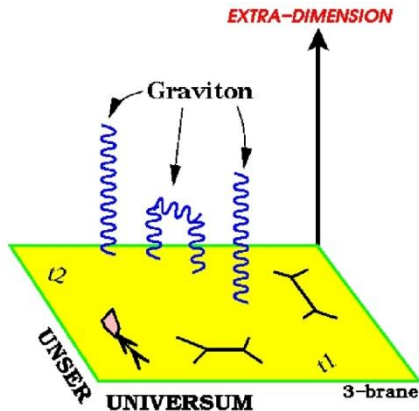
RS type models

UED type scenarios

with SM fields in ADD or RS bulk

**KK-parity ->
LKKP is a good DM candidate**
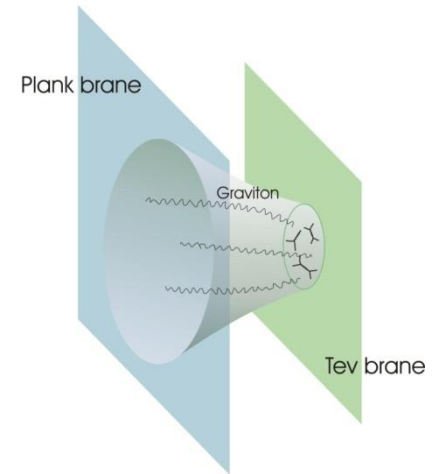
Many KK modes with small splitting.
It may give coherently an effect of the EW order

The 1st KK mode may interact
with the SM particles at EW level

$$M_{\text{pl}}^2 = M_*^{D-2} V_{D-4}$$

**Can unify the forces
Can explain why gravity is weak (solve hierarchy problem)
Contain Dark Matter Candidates
Can generate neutrino masses**

Signature jet + MET

ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
95% CL Limits, E_T^{miss} > 400 GeV
— Observed limit
···· Observed limit ± 1σ
·-· Expected limit
■ Expected limit ± 1σ
■ Expected limit ± 2σ
— ATLAS $\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}

Lower limit on M_D [TeV] vs Number of extra dimensions
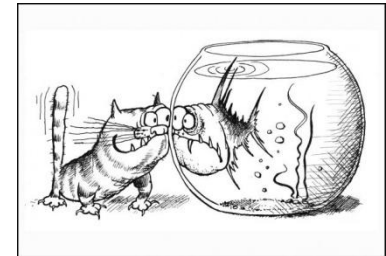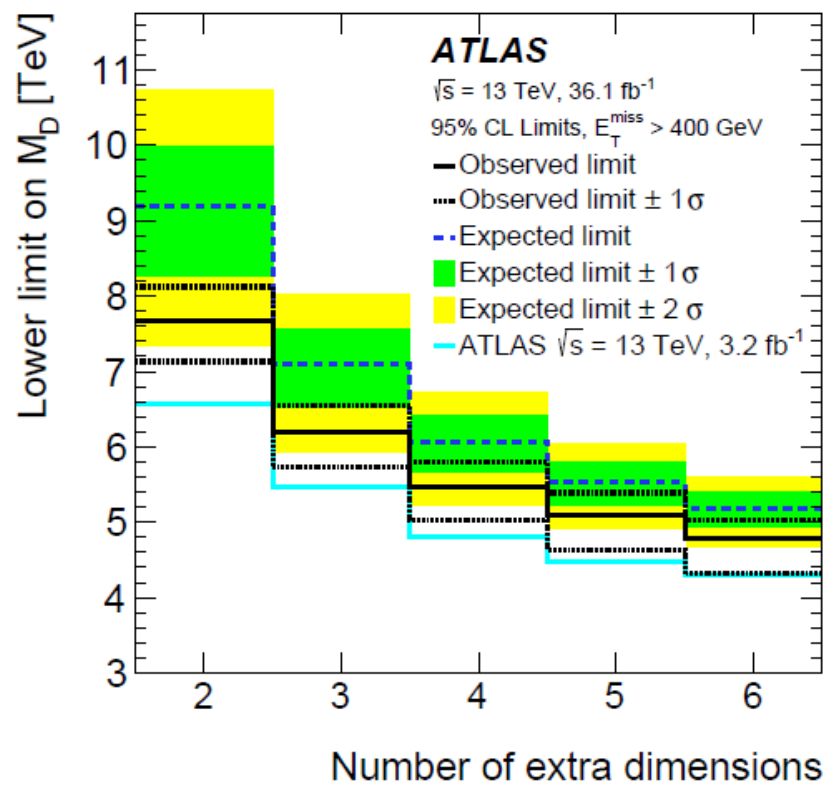
D = 4 + n

9811350

$$D(s) \approx \frac{-i}{4\pi} R^2 \log(M_S^2/s) \quad (n = 2),$$

$$\approx \frac{-2i}{(n-2)\Gamma(n/2)} \frac{R^n M_S^{(n-2)}}{(4\pi)^{n/2}} \quad (n > 2).$$

ADD Model Limits on M_D (95% CL)

	Expected [TeV]	Observed [TeV]	Observed (damped) [TeV]
$n = 2$	$9.2^{+0.8}_{-1.0}$	$7.7^{+0.4}_{-0.5}$	7.7
$n = 3$	$7.1^{+0.5}_{-0.6}$	$6.2^{+0.4}_{-0.5}$	6.2
$n = 4$	$6.1^{+0.3}_{-0.4}$	$5.5^{+0.3}_{-0.5}$	5.5
$n = 5$	$5.5^{+0.3}_{-0.3}$	$5.1^{+0.3}_{-0.5}$	5.1
$n = 6$	$5.2^{+0.2}_{-0.3}$	$4.8^{+0.3}_{-0.5}$	4.8
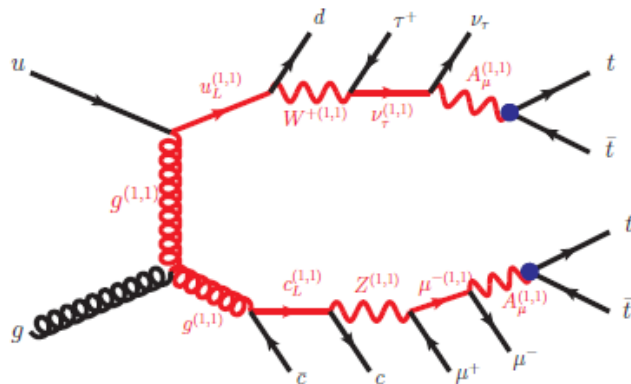
2UED model

$$m^2 = k^2/R_4{}^2 + l^2/R_5{}^2$$

$$m_{kk} = 1/R_4; \quad \xi = R_4/R_5$$

$$\xi = 1$$
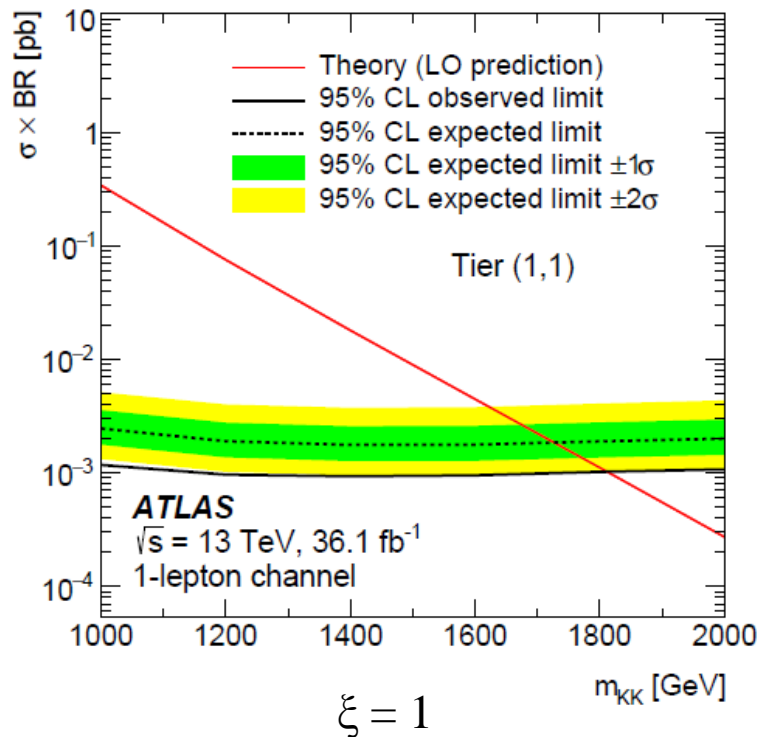
The Randall-Sundrum model

Two branes with tension at the fixed points of the orbifold S^1/Z_2:

$$S = \int d^4x \int_{-L}^{L} dy \left(2M^3 R - \Lambda\right)\sqrt{-g} -$$
$$- \lambda_1 \int_{y=0} \sqrt{-\tilde{g}} d^4x - \lambda_2 \int_{y=L} \sqrt{-\tilde{g}} d^4x.$$

The solution for the background metric:

$$ds^2 = \gamma_{MN} dx^M dx^N = e^{-2\sigma(y)} \eta_{\mu\nu} dx^\mu dx^\nu + (dy)^2, \quad \sigma(y) = k|y| + c.$$

Plank brane

Graviton

Tev brane

The parameters k, и $\lambda_{1,2}$ satisfy the fine tuning condition

$$\Lambda = -24M^3 k^2, \quad \lambda_1 = -\lambda_2 = 24M^3 k.$$

The hierarchy problem is solved if kL~ 35:

at TeV brane $M \sim M_{Pl} \cdot e^{-kL}$
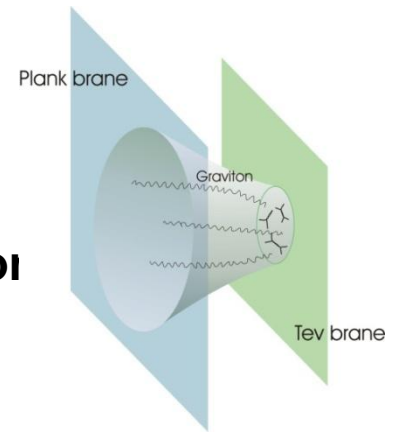
The linearized gravity is ob solution for the metric

$$g_{MN} = \gamma_{MN} + \frac{1}{\sqrt{2M^3}} h_{MN}$$

In the unitary gauge $\boxed{h_{\mu 4} = 0}$ $h_{44} = \phi(x).$

The distance between the branes along the geodesic

$$l = \int_0^L \sqrt{ds^2} \simeq \int_0^L \left(1 + \frac{1}{2\sqrt{2M^3}} h_{44}\right) dy = L\left(1 + \frac{1}{2\sqrt{2M^3}} \phi(x)\right).$$

The field φ(x) (when canonically normalized) is called the radion field

C. Csaki, M. Graesser, L. Randall and J. Terning,
Phys. Rev. D 62, 045015 (2000)
C. Charmousis, R. Gregory and V. A. Rubakov,
Phys. Rev. D 62, 067505 (2000)
C. Csaki, M. L. Graesser and G. D. Kribs,
Phys. Rev. D 63, 065002 (2001)
G. F. Giudice, R. Rattazzi and J. D. Wells,
 Nucl. Phys. B 595, 250 (2001)
K. -M. Cheung, Phys. Rev. D 63, 056007 (2001)

- The radion is massless.
- The coupling of the radion to matter on the brane is too strong and violates 4D gravity.
- Interbrane distance is not fixed.

The Randall-Sundrum model must be stabilized!

Stabilized Randall-Sundrum model

Stabilization mechanisms – extra scalar field W. D. Goldberger and M.B. Wise, Phys. Rev. Lett. 83 (1999) 4922

Solution of coupled Eqs for the 5d warped metric and for stabilizing scalar field O. DeWolfe, D.Z. Freedman, S.S. Gubser, and A. Karch, Phys. Rev. D 62 (2000) 046008

The physical degrees of freedom of the model in the linear approximation

- tensor fields $b_{\mu v}^n(x)$, n=0,1, … with masses m_n ($m\_0 = 0$) and wave functions in the space of extra dimension $\psi_n(y)$,
- scalar fields $\varphi_n(x)$, n=1,2, … with masses μ_n and wave functions in the space of extra dimension $g_n(y)$.

Effective Lagrangian of the model E. B., Y.S. Mikhailov, M.N. Smolyakov, and I.P. Volobuev, Mod. Phys. Lett. A 21 (2006) 1431
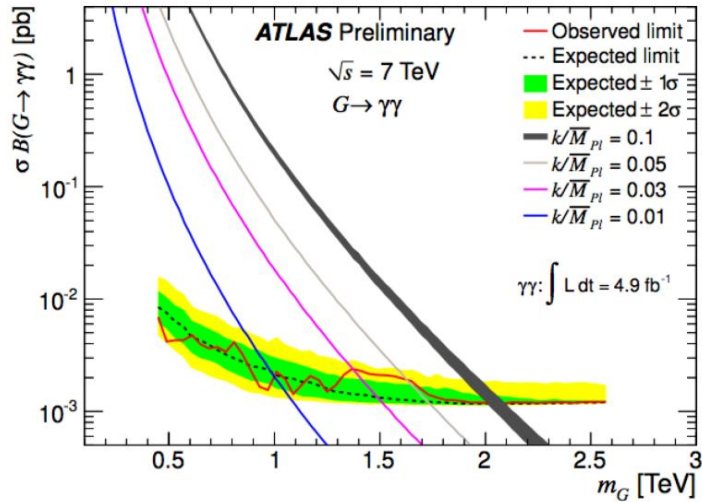
$$L_{int} = -\frac{1}{\sqrt{8M^3}}\left(\psi_0(L)b_{\mu\nu}^0(x)T^{\mu\nu} + \sum_{n=1}^{\infty}\psi_n(L)b_{\mu\nu}^n(x)T^{\mu\nu} + \frac{1}{2}\sum_{n=1}^{\infty}g_n(L)\varphi_n(x)T_\mu^\mu\right),$$

$\sim 1/M_{Pl}$

$\sim 1/(M_{Pl}\cdot e^{-kL}) \equiv 1/\Lambda_r$

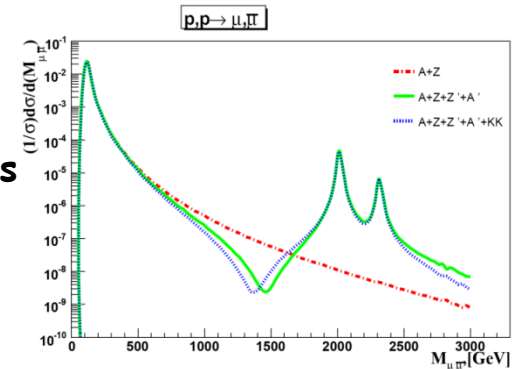$T_{\mu v}$ - the energy-momentum tensor of the SM

The lowest scalar mode is the radion of the stabilized RS

Searches for RS gravitons
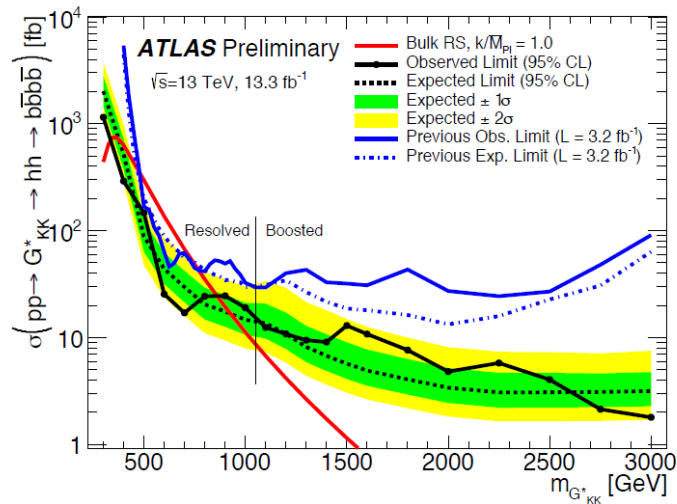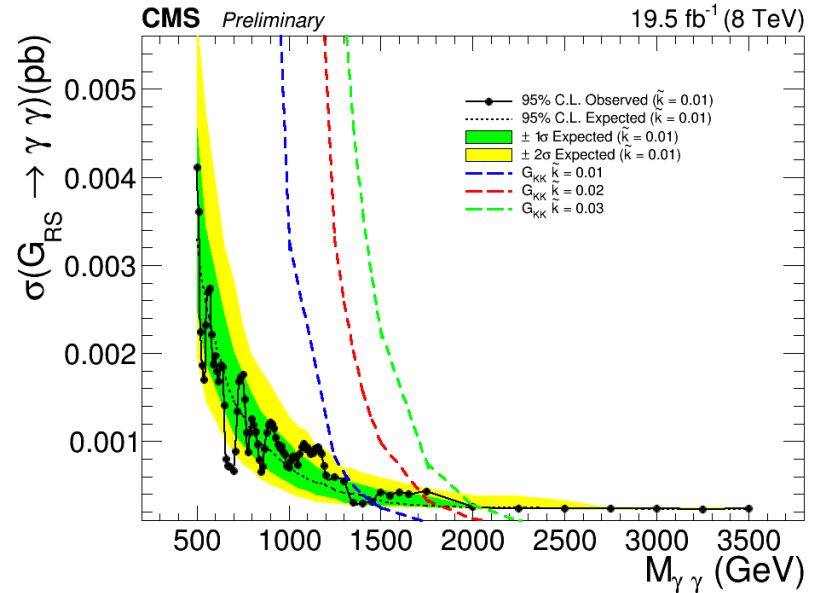
E.B., Bunichev, Smolyakov, Volobuev

Interferences

BACKUP SLIDES

$$\lambda_{ijk}\ L_L^i L_L^j \overline{E}_R^k\ +\ \lambda'_{ijk}\ L_L^i Q_L^j \overline{D}_R^k\ +\ \lambda''_{ijk}\ \overline{U}_R^i \overline{D}_R^j \overline{D}_R^k$$

L_L, Q_L left-handed lepton and quark doublets

E_R right-handed lepton singlets

U_R, D_R right-handed Up and Down quark singlets
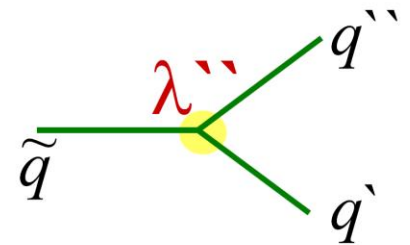
i,j,k family indices

$\lambda, \lambda', \lambda''$: Yukawa couplings
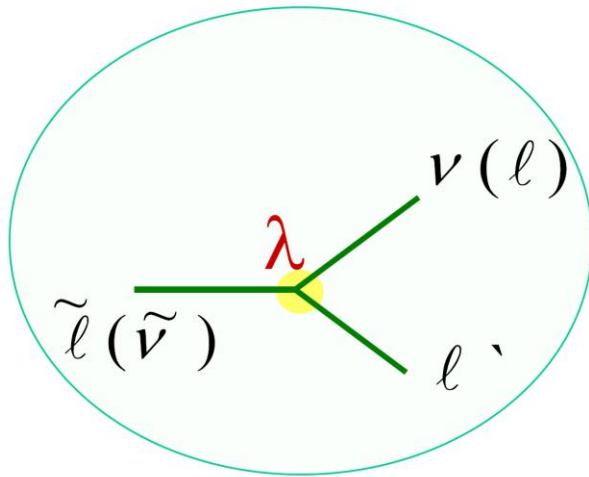
L violation

B violation

9 couplings (i≠j)   **27 couplings**   **9 couplings (j≠k)**