SUGRA Inflation in the light of LHC constraints

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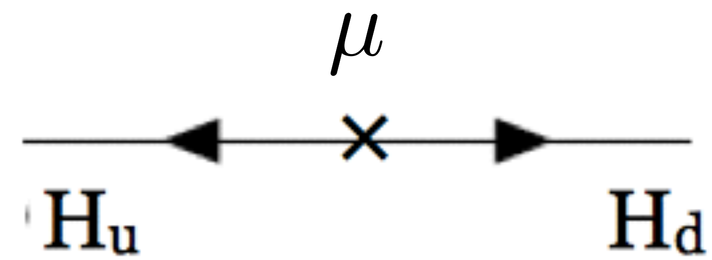
Natural SUSY

$$\delta m_H^2 = \mu^2$$

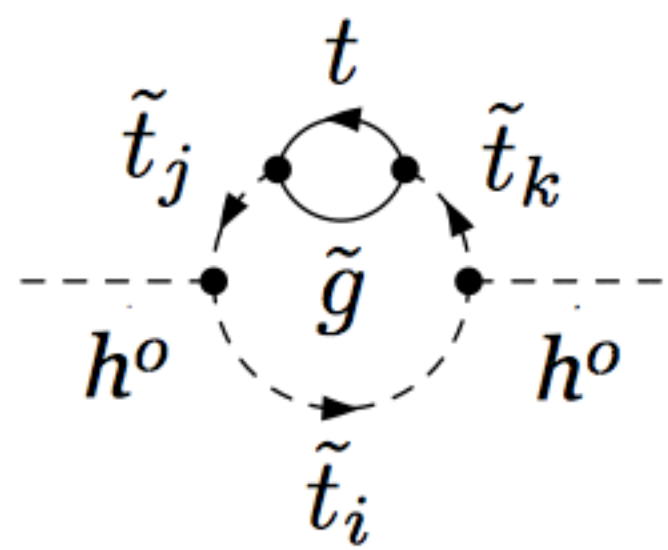


Higgsino mass < 250 GeV

$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{\mathrm{stop}}^2 \log\frac{\Lambda}{Q}$$

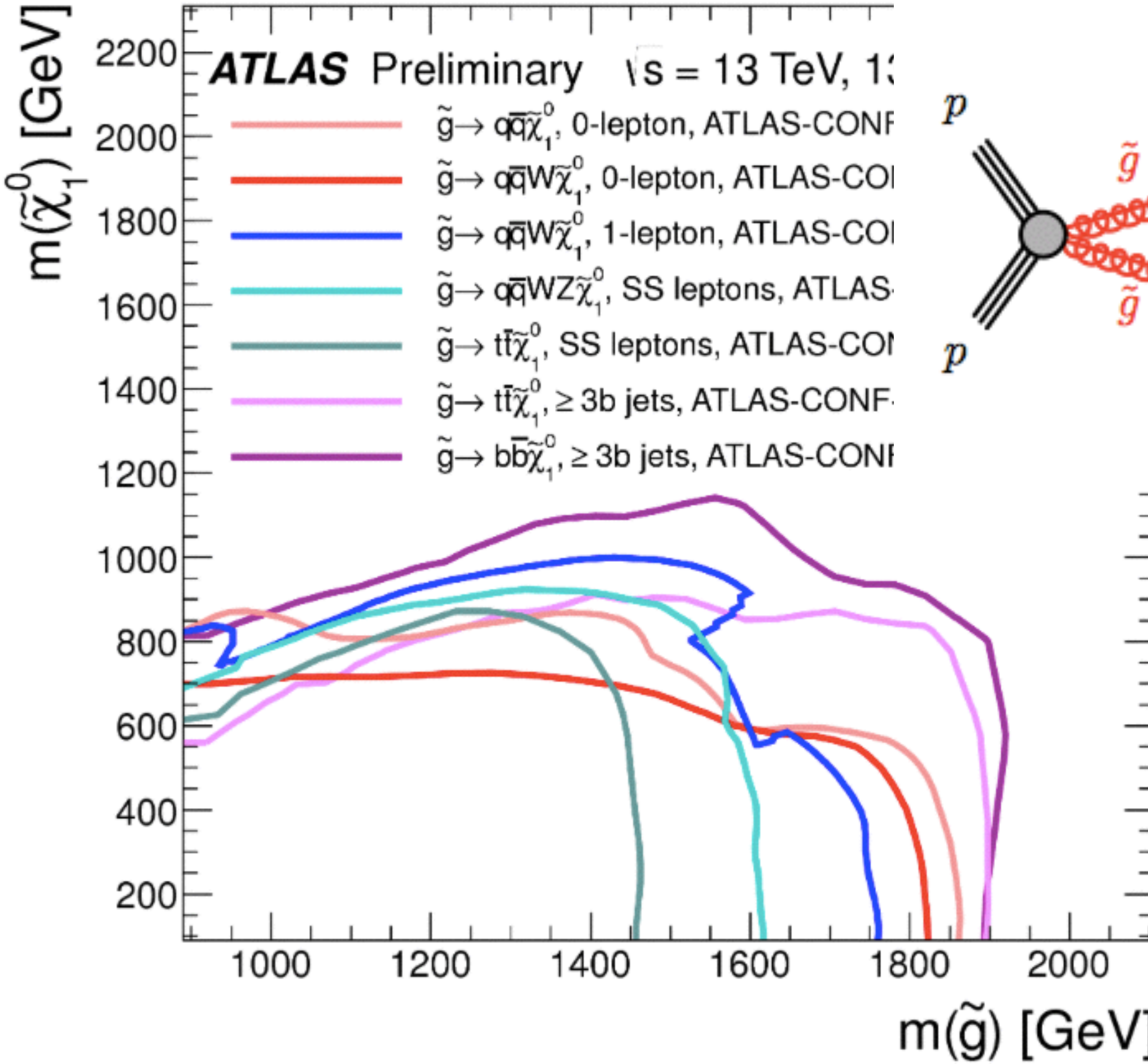
Stop mass < 600 GeV

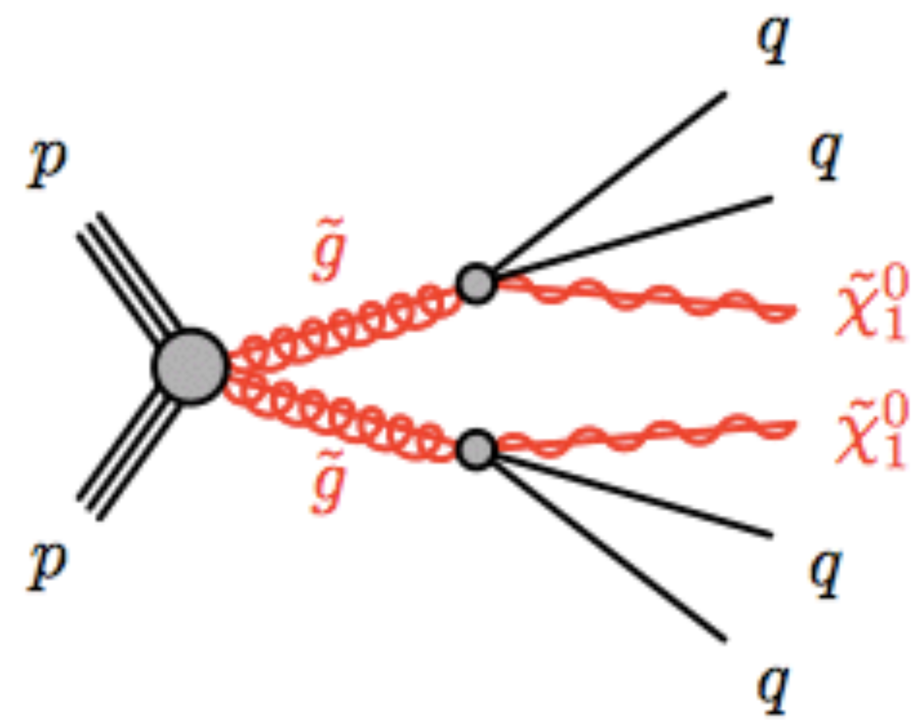
$$\delta m_H^2 \sim -\frac{g_3^2 y_t^2}{4\pi^4} |M_3|^2 \left(\log\frac{\Lambda}{Q}\right)^2$$

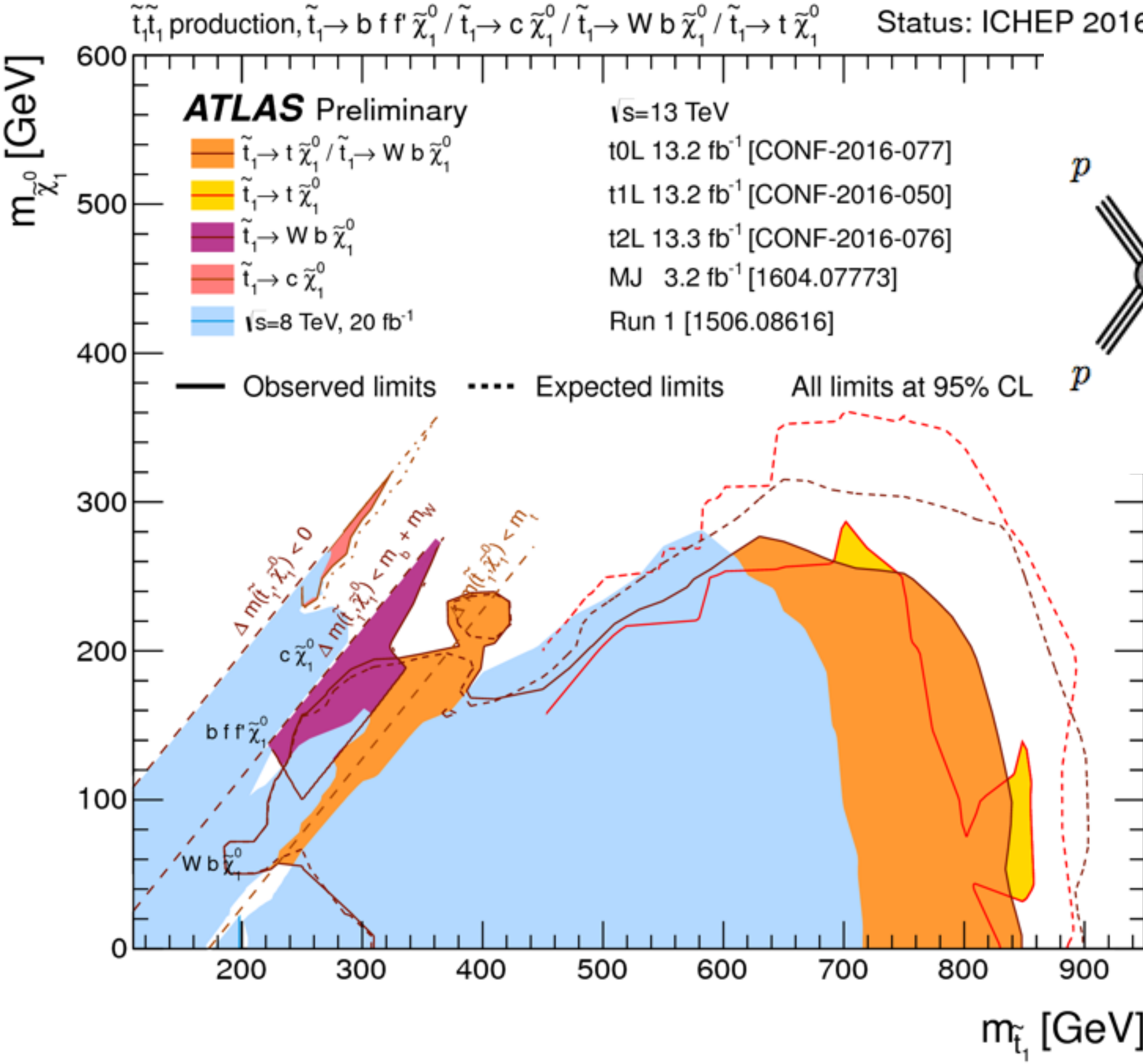


Gluino mass < 1.4 TeV

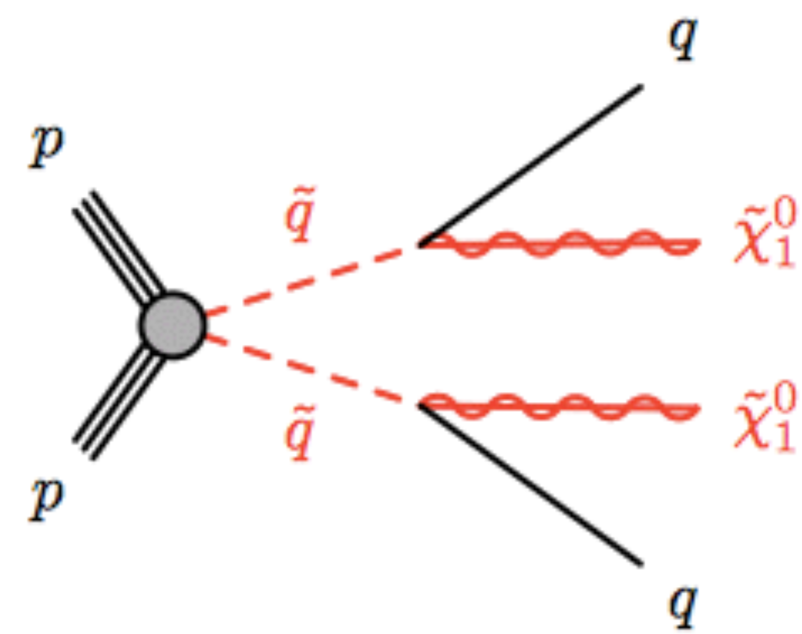
https://atlas.web.cern.ch







$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$
Status: ICHEP 2016
ATLAS Preliminary
$\sqrt{s}$=13 TeV
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$
t0L 13.2 fb^{-1} [CONF-2016-077]
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$
t1L 13.2 fb^{-1} [CONF-2016-050]
$\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$
t2L 13.3 fb^{-1} [CONF-2016-076]
$\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$
MJ 3.2 fb^{-1} [1604.07773]
$\sqrt{s}$=8 TeV, 20 fb^{-1}
Run 1 [1506.08616]
Observed limits
Expected limits
All limits at 95% CL
$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0) < 0$
$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0) < m_b + m_W$
$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0) < m_t$
$c \tilde{\chi}_1^0$
$b f f' \tilde{\chi}_1^0$
$W b \tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
100
200
300
400
500
600
200
300
400
500
600
700
800
900



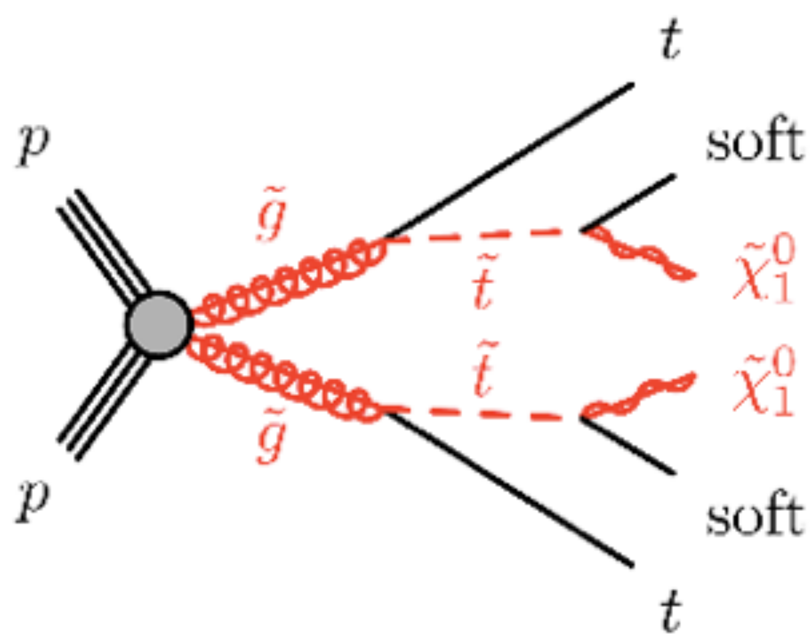
p
p
$\tilde{q}$
$\tilde{q}$
q
q
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$

Ways of evading the LHC bounds on Natural MSSM

1. R-parity violating MSSM
2. Compressed or degenerate spectrum
3. Split SUSY
4. …

1. R-Parity violating MSSM

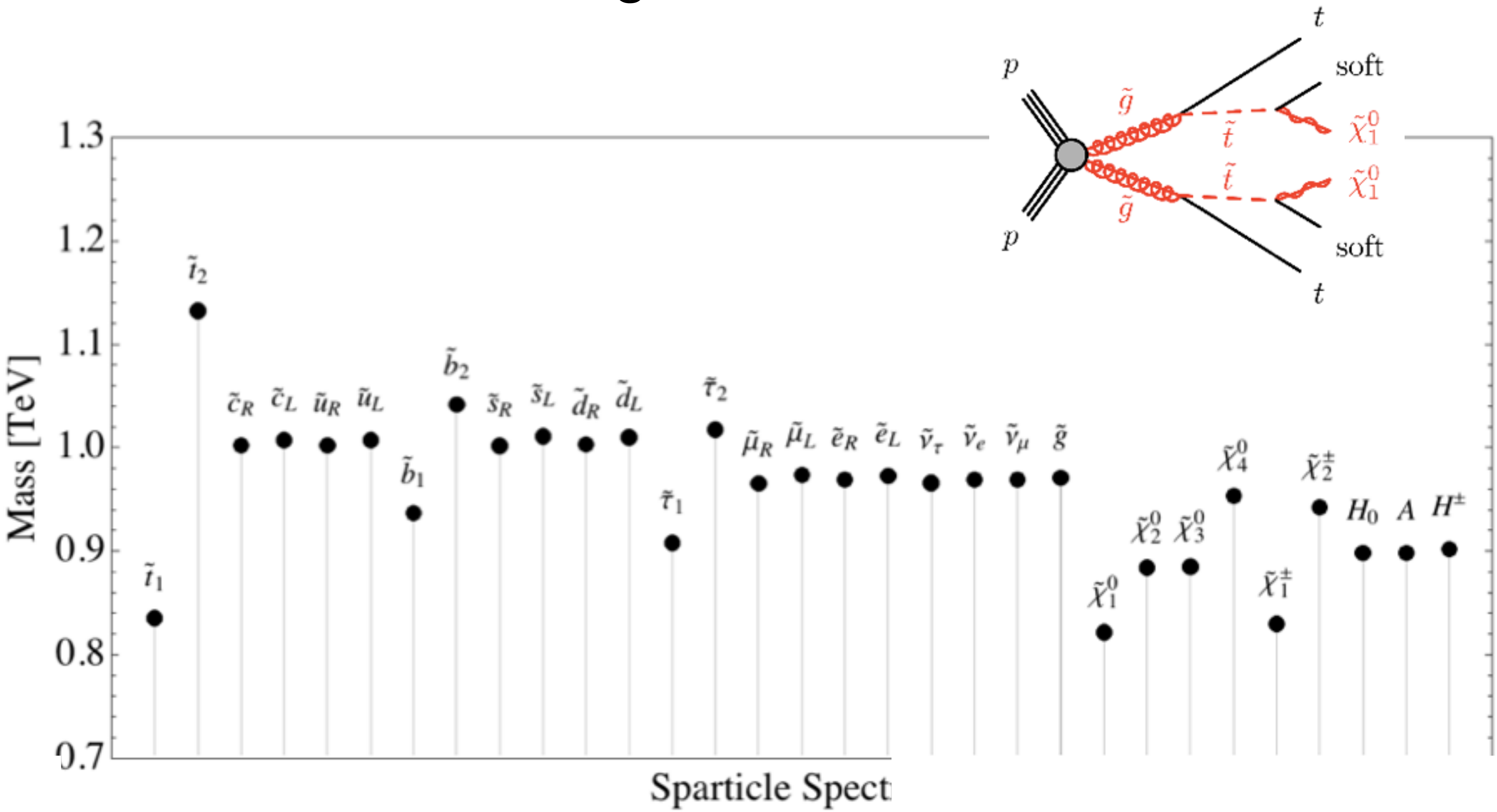
$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c.$$



Squarks can decay to 2-jets due to UDD term and be hidden in the QCD background

Biplob Bhattacherjee, Amit Chakraborty, 2014

2. Degenerate MSSM

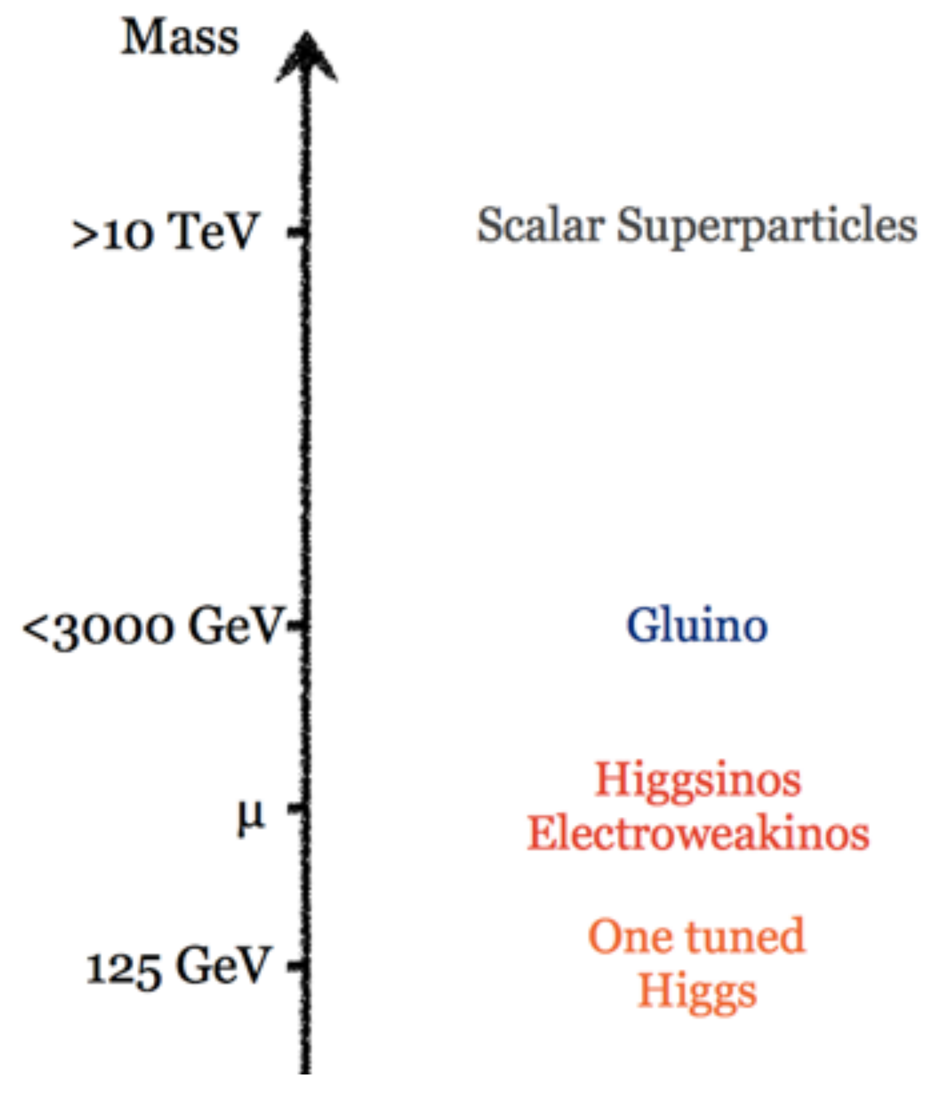


Typical spectrum in the case of $M_D \simeq 975$ GeV

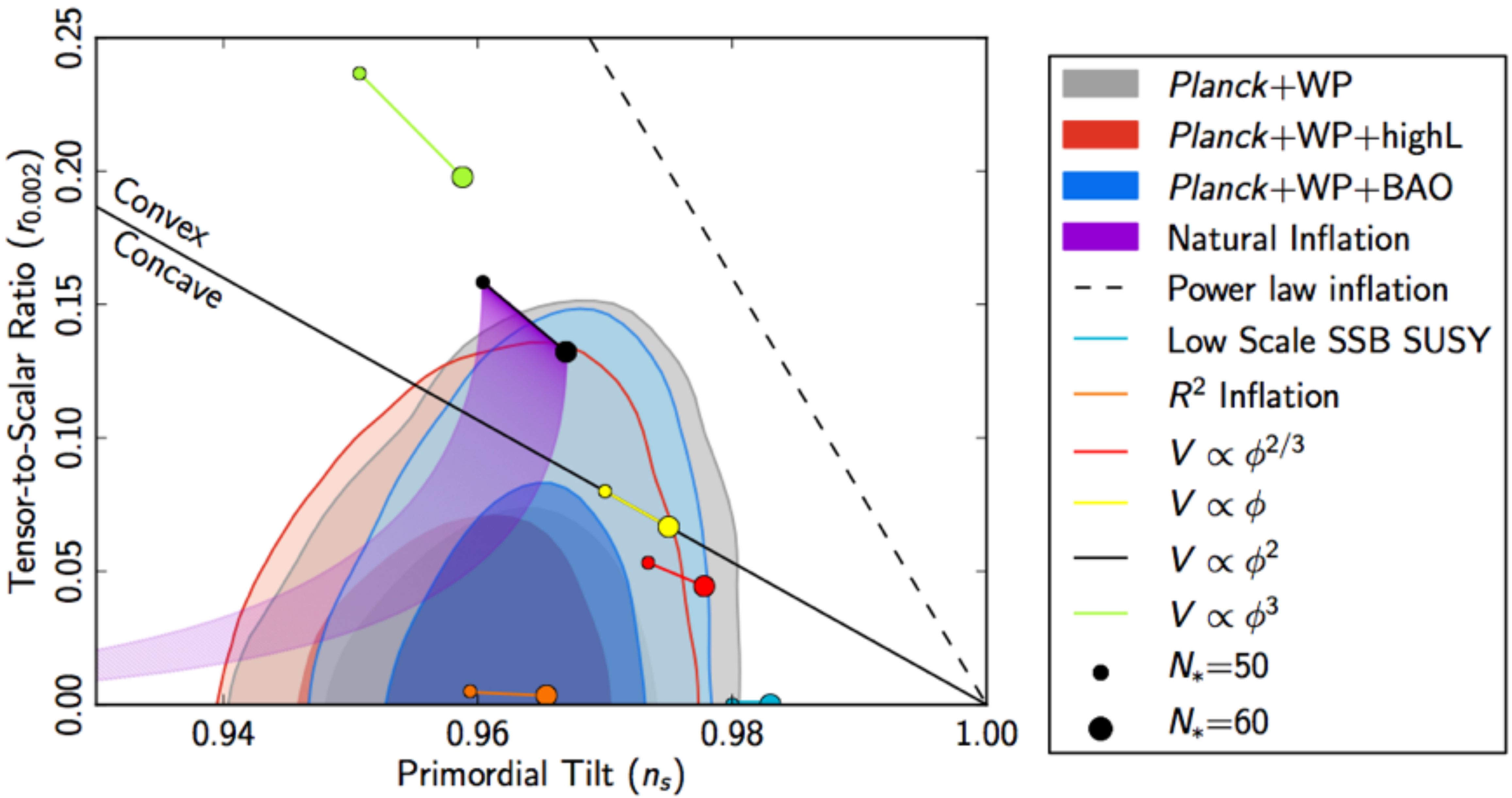
D.Chowdhuri, K.M.Patel, X.Tata, S.K. Vempati 1612.06471

3. Split SUSY

- WIMP Dark Matter
- Coupling constant unification
- Fine tuned Higgs mass



Inflation models compatible with CMB data



f(R) theories

$$S = \frac{1}{8\pi G}\int d^4x\sqrt{-g}\,f(R) + S_{(m)}$$

Jordan frame

Make a conformal transformation to go to Einstein frame

$$\tilde{g}_{\mu\nu} = e^{2\chi} g_{\mu\nu}$$

$$\chi = \frac{1}{2}\ln|f'(R)| \; = \frac{1}{\sqrt{6}}\varphi$$

$$\sqrt{-g}f(R) = \sqrt{-\tilde{g}}\left(-\frac{1}{2}\tilde{R} + \frac{1}{2}\nabla_\mu\varphi\nabla^\mu\varphi - V\right)$$

Einstein frame

$$V(\varphi) \; = \frac{f - Rf'}{2f'^{\,2}}$$

Starobinsky model

$$S_{\mathrm{S}} = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\,\left(M_{\mathrm{p}}^2 R + \frac{1}{6M^2}R^2\right)$$

Jordan frame

$$S_{\mathrm{S}} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{p}}^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{3}{4}M_{\mathrm{p}}^4 M^2\left(1 - e^{-\sqrt{\frac{2}{3}}\phi/M_{\mathrm{p}}}\right)^2\right]$$

Einstein frame

$$n_s - 1 \approx -\frac{2}{N},\ \ r \approx \frac{12}{N^2}$$

$$M \simeq 10^{-5}\,, \quad N = 55$$

Higgs Inflation

$$S_J = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}f(\phi)R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

conformal transformations with $\Omega^2 = f(\phi)$.

$$S_E = \int d^4x\sqrt{-\tilde{g}}\left[\frac{M_p^2}{2}\tilde{R} - \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\tilde{\phi}\partial_\nu\tilde{\phi} - \tilde{V}(\tilde{\phi})\right]$$

$$\tilde{V}(\tilde{\phi}) = \frac{V(\phi(\tilde{\phi}))}{f(\phi(\tilde{\phi}))^2}$$

$$\frac{\partial\tilde{\phi}}{\partial\phi} = \sqrt{\frac{3M_p^2}{2f^2}\left(\frac{\partial f}{\partial\phi}\right)^2 + \frac{1}{f}}$$

Higgs Inflation

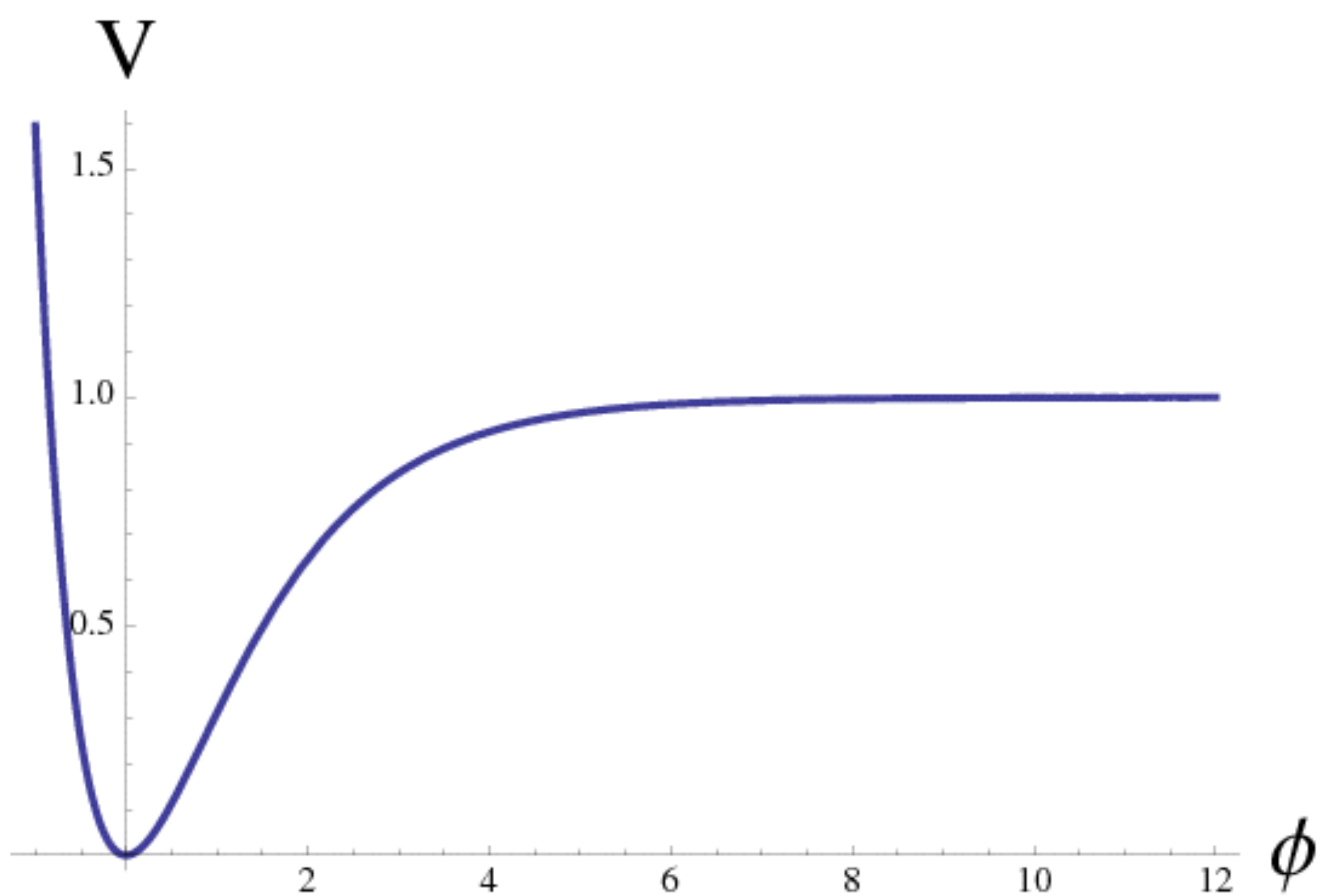
$$S_{\rm HI} = \int d^4x\sqrt{-g}\left(\frac{M_{\rm p}^2}{2}R + \frac{1}{2}\xi h^2 R - \frac{\lambda}{4}h^4\right)$$ Jordan frame

Potential in the Einstein frame

$$V(\phi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi/M_{\rm p}}\right)^2$$

$$\xi \sim 49000$$

Plateau potential



SUGRA Inflation

Kahler potential $K(\phi_i, \phi_i^*)$

Superpotential $W(\phi_i)$

$$\mathcal{L}_{kin} = -K_{ij^*} g^{\mu\nu} \partial_\mu \phi^i \partial_\nu \phi^{*j}$$

$$K_{ij^*} = \frac{\partial^2 K}{\partial \phi^i \partial \phi^{*j}},$$

Scalar potential

$$V(\phi_i, \phi_i^*) = V_F(\phi_i, \phi_i^*) + V_D(\phi_i, \phi_i^*),$$

F term potential

$$V_F = e^K \left[D_{\phi_i} W K^{ij^*} D_{\phi_j^*} W^* - 3|W|^2 \right]$$

$$M_P = 1$$

$$K^{ij^*} \equiv K^{-1}_{ij^*}$$

$$D_{\phi_i} W = \frac{\partial W}{\partial \phi_i} + \frac{\partial K}{\partial \phi_i} W.$$

D-term potential

$$V_D = \frac{1}{2} \left[Ref^{-1}_{ab}(\phi_i) \right] D^a D^b$$

$$D^a = -g \frac{\partial G}{\partial \phi_k} (\tau^a)^l_k \phi_l$$

$$G(\phi_i, \phi_i^*) \equiv K(\phi_i, \phi_i^*) + \ln W(\phi_i) + \ln W^*(\phi_i^*)$$

SUGRA Model of Starobinsky potential

Ellis, Nanopoulos, Olive , PRL, 2013

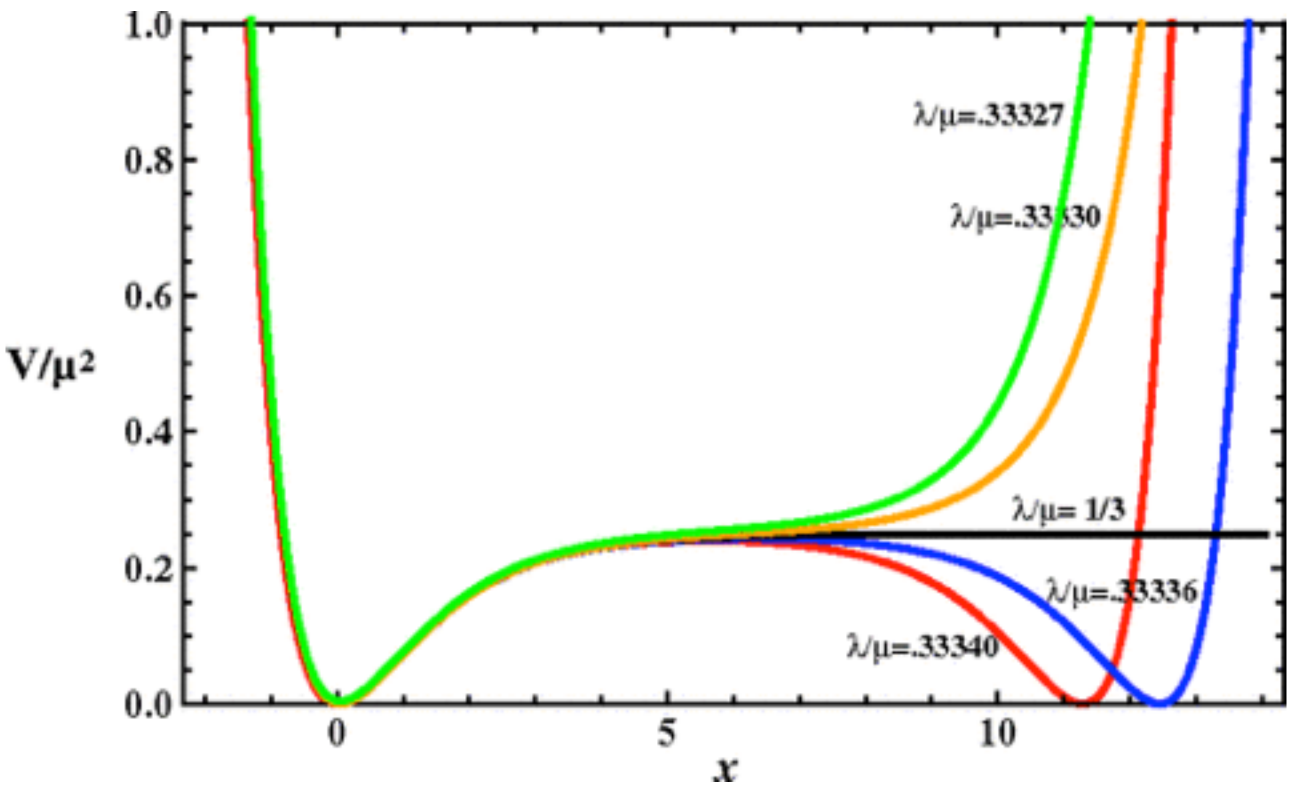
$$K = -3\ln\left[T + T^* - \frac{\phi\phi^*}{3}\right]$$

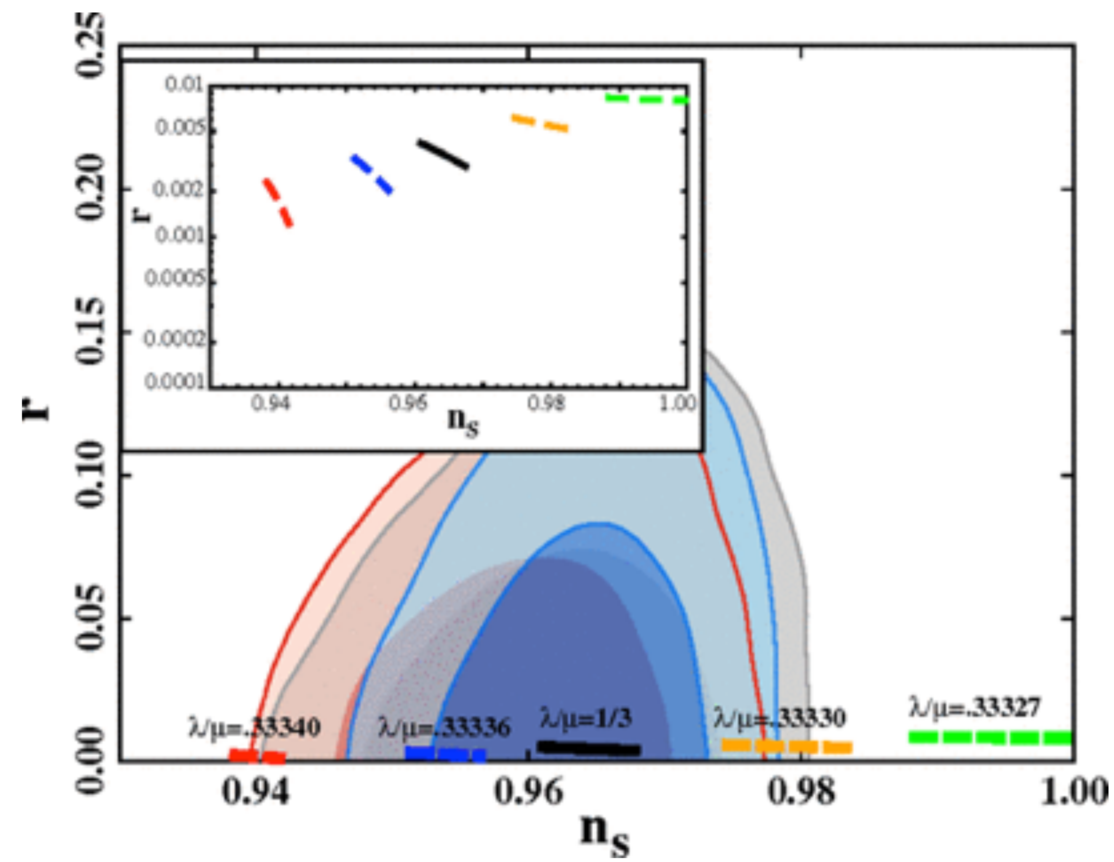
$$W = \frac{\hat{\mu}}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$$

$$\mathcal{L}_{eff} = \frac{1}{(c - |\phi|^2/3)^2}\left[c|\partial_\mu\phi|^2 - \hat{V}\right]$$

$$\phi = c\sqrt{3}\tanh\frac{\chi}{\sqrt{3}}$$

$$V_F = \frac{\mu^2}{4}\left(1 - e^{-\sqrt{\frac{2}{3}}x}\right)^2$$





Plateau inflation in SUGRA- MSSM

G.K.Chakravarty, G. Gupta, G. Lambiase, S.M., PLB 2015

$$K = 3M_p^2 \ln\left[1 + \frac{1}{3M_p^2}\left(H_u^\dagger H_u + H_d^\dagger H_d\right)\right]$$

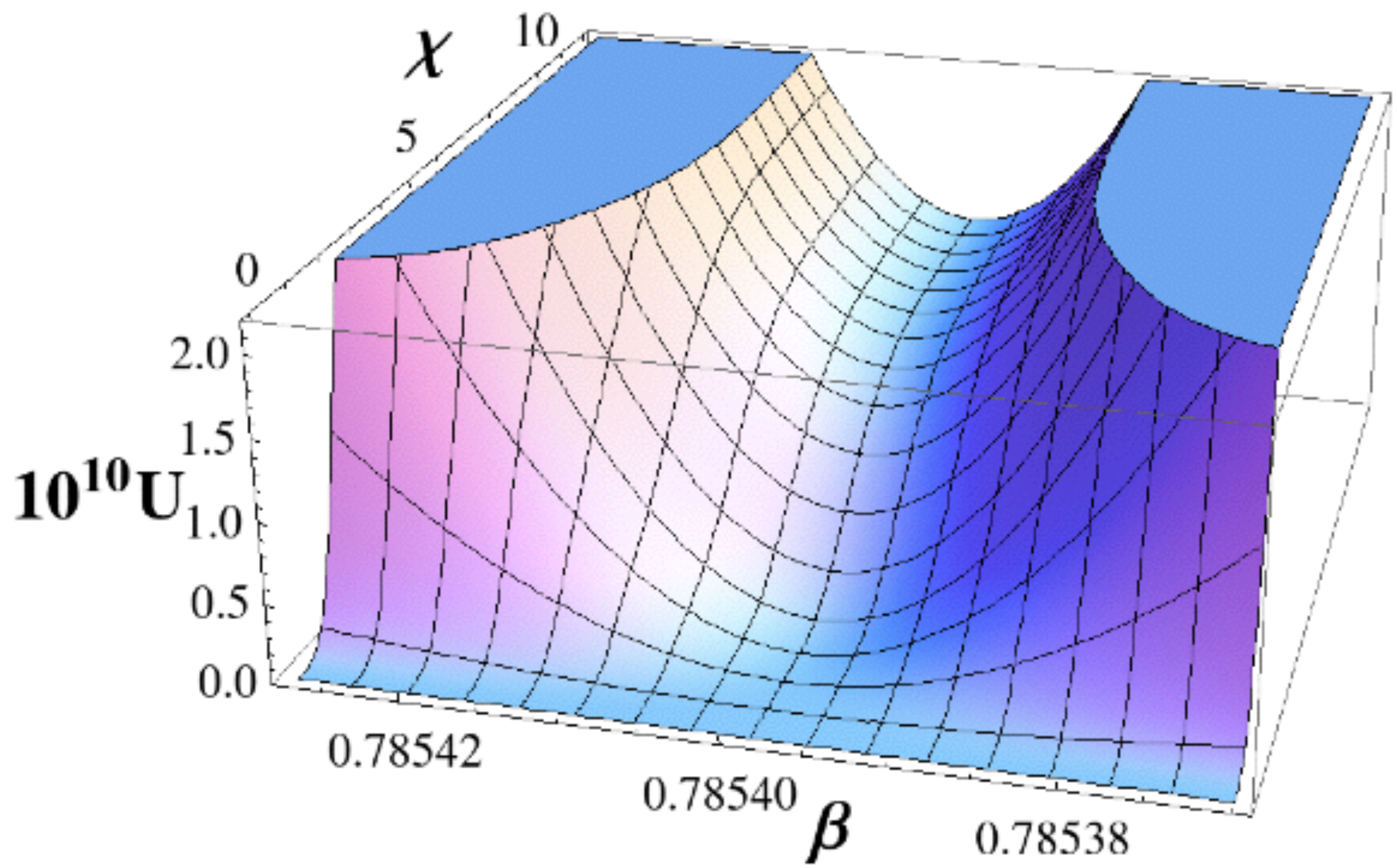
$$W = \mu(H_u \cdot H_d) + \lambda \frac{(H_u \cdot H_d)^2}{M_p} \exp\left(\frac{H_u \cdot H_d}{M_p^2}\right)$$

$$H_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}$$

$$V_D = \frac{9}{8}(g_1^2 + g_2^2)\,|\phi|^4\,\frac{\cos(2\beta)^2}{(3+|\phi|^2)^2}$$

$$\begin{aligned}
V_F \;=\;& \frac{\lambda^2}{31104}\sin(2\beta)^2 \exp\left(-(\phi^2+\phi^{*2})\sin(2\beta)/2\right) \\
& |\phi|^6\,(3+|\phi|^2)^3 \Big[1152 + |\phi|^2 \Big\{756 + |\phi|^2\,[232 \\
& +3\,|\phi|^2\,(7+9\,|\phi|^2)]\Big\} - 4\,|\phi|^2\Big\{93 + |\phi|^2\,[58 \\
& +|\phi|^2\,(6+|\phi|^2)]\Big\}\cos(4\beta) + (3+|\phi|^2)\Big\{\,|\phi|^6 \\
& \cos(8\beta) - 8(\phi^2+\phi^{*2})\,[12 + 7\,|\phi|^2\sin(2\beta)^2]\Big\} \\
& \sin(2\beta)\Big]\,.
\end{aligned}$$

$$\mathcal{L}_{KE} = \frac{9}{(3+|\phi|^2)^2}|\partial_\mu\phi|^2$$



$$\lambda \simeq 3.8 \times 10^{-8}$$

$$r \simeq 0.00337, \; n_s \simeq 0.966$$

Plateau Inflation in R-parity Violating MSSM

G.K. Chakravarty, U. K. Dey, G. Lambiase, S.M., PLB 2016

$$K = 3\ln\left[1 + \frac{1}{3M_p^2}\Big(L^\dagger L + H_u^\dagger H_u + H_d^\dagger H_d + H_d^\dagger L + L^\dagger H_d\Big)\right] + ZZ^* - \frac{(ZZ^*)^2}{\Lambda^2}$$

$$W = \mu_1 L\cdot H_u + \mu_2 H_u \cdot H_d + \Delta M_p^2 + \mu_z^2 Z + \frac{\lambda_1}{M_p}(L\cdot H_u)^2 \exp\left(\frac{-L\cdot H_u}{M_p^2}\right) + \frac{\lambda_2}{M_p}(H_u\cdot H_d)^2 \exp\left(\frac{H_u\cdot H_d}{M_p^2}\right)$$

$$L = \begin{pmatrix} \phi_\nu \\ 0 \end{pmatrix}, \qquad H_u = \begin{pmatrix} 0 \\ \phi_u \end{pmatrix}, \qquad H_d = \begin{pmatrix} \phi_d \\ 0 \end{pmatrix}$$

$$V_D = \frac{9}{8}\left(g_1^2 + g_2^2\right) \times \frac{\left(-|\phi_u|^2 + |\phi_d|^2 + |\phi_\nu|^2 + (\phi_d \phi_\nu^* + \phi_d^* \phi_\nu)/2\right)^2}{\left(3 + |\phi_u|^2 + |\phi_d|^2 + |\phi_\nu|^2 + (\phi_d \phi_\nu^* + \phi_d^* \phi_\nu)/2\right)^2}.$$

D-flat direction

$$\phi_\nu = \phi_u = \phi, \ \phi_d = 0$$

$$
\begin{aligned}
V_F(\chi) =& \frac{9}{32}\lambda_1^2 \exp\left(3\tanh\left(\chi/\sqrt{6}\right)^2\right)\tanh\left(\chi/\sqrt{6}\right)^6 \\
&\times \left[1+\tanh\left(\chi/\sqrt{6}\right)^2\right]^3 \left[112 + 466\tanh\left(\chi/\sqrt{6}\right)^2\right. \\
&\quad + 777\tanh\left(\chi/\sqrt{6}\right)^4 + 369\tanh\left(\chi/\sqrt{6}\right)^6 \\
&\quad \left. + 54\tanh\left(\chi/\sqrt{6}\right)^8\right].
\end{aligned}
$$

$$\lambda_1 \simeq 3.7 \times 10^{-8}$$

$$r \simeq 0.0033$$

$$n_s \simeq 0.9664$$

SUSY breaking by Polonyi field and soft masses

$$m_{3/2}^2 = \Delta^2\,,$$
$$m_Z^2 = \frac{12\Delta^2}{\Lambda^2} = \frac{12m_{3/2}^2}{\Lambda^2} \gg m_{3/2}^2\,,$$

$m_{3/2} \sim 1$ TeV and $m_z \sim \mathcal{O}(100 \text{ TeV})$.

$$m_{\phi_\nu}^2 = \Delta^2 + \mu_1^2\,,$$
$$m_{\phi_\tau}^2 = \Delta^2\,,$$
$$m_{\phi_u}^2 = \Delta^2 + \frac{4}{3}(\mu_1^2 + \mu_1\mu_2 + \mu_2^2)$$
$$m_{\phi_d}^2 = \Delta^2 + \mu_2^2\,.$$

Soft SUSY bilinear and trilinear couplings

$$\frac{1}{3}A_{ijk}\phi^i\phi^j\phi^k + \frac{1}{2}B_{ij}\phi^i\phi^j + \text{h.c.}$$

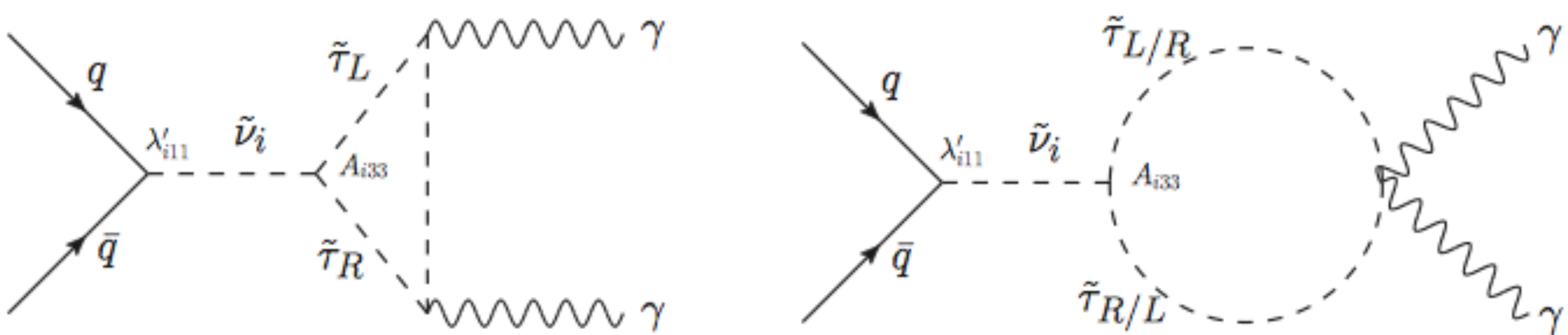
$$A_{ijk} = F^I\partial_I Y_{ijk} + \frac{1}{2}F^I(\partial_I\hat{K})Y_{ijk}\,,$$

$$B_{ij} = F^I\partial_I\mu_{ij} + \frac{1}{2}F^I(\partial_I\hat{K})\mu_{ij} - m_{3/2}\mu_{ij}$$

$$F^I = e^{\hat{K}/2}\hat{K}^{IJ^*}\left(\partial_{J^*}\hat{W}^* + \hat{W}^*\partial_{J^*}\hat{K}\right)$$

Soft gauging masses by appropriate choice of gauge kinetic function $f_{ab}(z)$

SUGRA Inflation models can be tested at LHC



Thank You