

Low scale SUSY breaking and its LHC signatures

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Based on

Nucl. Phys. B841, 157 - hep-ph/1006.1662 (with I. Antoniadis, E. Dudas, D. Ghilencea)

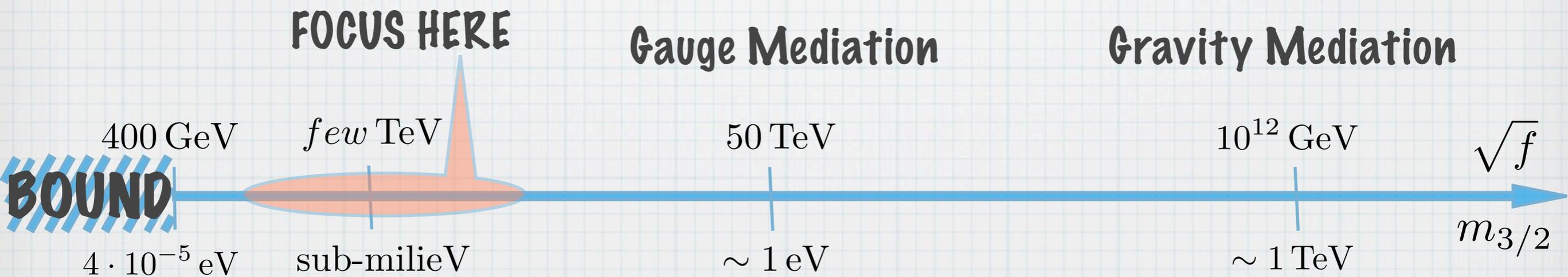
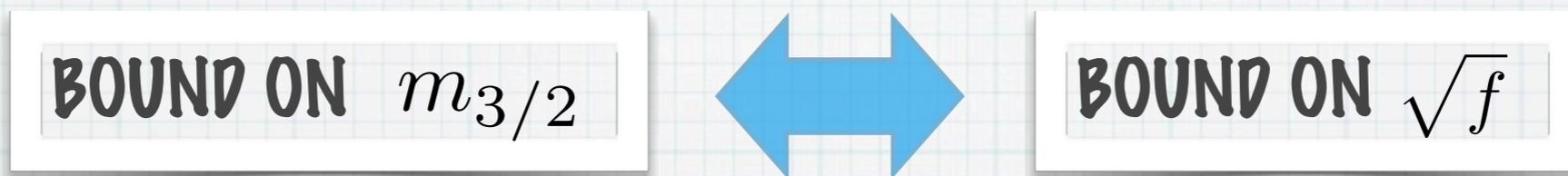
Nucl. Phys. B870, 353 - hep-ph/1211.5609 (with E. Dudas, C. Petersson)

Current work (with E. Dudas, Mark Goodsell)

MOTIVATION

- * Even if no SUSY particles yet at LHC, SUSY is still one of the most popular BSM candidates
- * What can LHC tell us about the SUSY breaking scale?
- * Higgs mass = 125 GeV \rightarrow (Relatively) good agreement with SUSY
Naturally raised Higgs mass?
- * Have we explored all final states?

SPONTANEOUS SUSY BREAKING



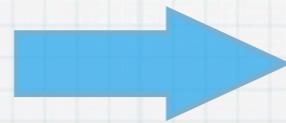
GOLDSTINO SUPERFIELD

$$X = x + \sqrt{2}\theta G + \theta\theta F_X$$

↓
↓
↓

sgoldstino
goldstino
 $\langle F_X \rangle = -f$

Zero momentum limit
of the sgoldstino



Nonlinear SUSY
(Supersymmetry realized on a single fermion)

$$X^2 = 0 \quad \longrightarrow \quad x = \frac{GG}{2F_X}$$

$$\delta_\eta G_\alpha = f\eta_\alpha - \frac{i}{f}(G\sigma^\mu\bar{\eta} - \eta\sigma^\mu\bar{G})\partial_\mu G_\alpha$$

$$(\delta_\eta\delta_{\eta'} - \delta_{\eta'}\delta_\eta)G_\alpha = -2i(\eta\sigma^\mu\bar{\eta}' - \eta'\sigma^\mu\bar{\eta})\partial_\mu G_\alpha$$

Rocek '78
Komargodski, Seiberg '09

Volkov Akulov Lagrangian ('73)

$$\mathcal{L} = X^\dagger X|_D + (fX|_F + h.c.)$$

EFFECTIVE LAGRANGIAN ANALYSIS

1) Replace spurion $S = \theta^2 m_{SUSY} \rightarrow X(x, G, F_X)$
(eg $SW^\alpha W_\alpha \rightarrow -\frac{m_{\tilde{g}}}{f} XW^\alpha W_\alpha$)

2) Add effective operators $\mathcal{L} = \mathcal{L}_4 + \sum_n \frac{1}{\Lambda^n} \alpha_{\mathcal{O}} \mathcal{O}^{(4+n)}$
(eg $\frac{1}{\Lambda^2} X(H_1 H_2)^2|_F + h.c.$)

3) Choose irreducible basis

➔ New couplings eg $\frac{1}{\Lambda^2} X^\dagger H^\dagger Q U^c|_D + h.c.$

➔ Corrections to existing ones: $\lambda = \lambda_{MSSM} \left[1 + \sum_n c_n \left(\frac{m_{SUSY}}{\sqrt{f}} \right)^n \right]$

Antoniadis, Dudas, Ghilencea, P.T. '10
Dudas, Petersson, P.T. '12

PHENO OF
LOW \sqrt{f}

NONLINEAR MSSM

Operators in Nonlinear MSSM

$$\begin{aligned} \mathcal{L} = & \int d^4\theta \left[X_{nl}^\dagger X_{nl} + \left(1 - \frac{m_i^2}{f^2} X_{nl}^\dagger X_{nl} \right) \Phi_i^\dagger e^{V_i} \Phi_i \right] \\ & + \int d^2\theta \left[f X_{nl} + W(\Phi_i) + \frac{B_{ij}}{2f} X_{nl} \Phi_i \Phi_j + \frac{A_{ijk}}{6f} X_{nl} \Phi_i \Phi_j \Phi_k + \frac{1}{4} \left(1 + \frac{2m_\lambda}{f} X_{nl} \right) \text{Tr}[W^\alpha W_\alpha] \right] + h.c. \end{aligned}$$

➔ Goldstino couplings are set by the soft terms (Goldberger Treiman relation)

➔ New **non** Goldstino couplings

$$\left(1 - \frac{m_i^2}{f^2} |\phi_i|^2 \right) F_X^\dagger = - \left(f + \frac{B_{ij}}{2f} \phi_i \phi_j + \frac{A_{ijk}}{6f} \phi_i \phi_j \phi_k + \frac{m_\lambda}{2f} \lambda \lambda + \dots \right)$$

HIGGS POTENTIAL

Even without sgoldstino or higher dimensional operators:

MSSM

$$V = \tilde{m}_1^2 |h_1|^2 + \tilde{m}_2^2 |h_2|^2 + (B h_1 \cdot h_2 + h.c.) + \frac{g_1^2 + g_2^2}{8} (|h_1|^2 - |h_2|^2)^2 + \frac{g_2^2}{2} |h_1^\dagger h_2|^2$$
$$+ f^2 + \frac{1}{f^2} |m_1^2 |h_1|^2 + m_2^2 |h_2|^2 + B h_1 \cdot h_2|^2 + \mathcal{O}(f^{-3})$$

+ NONLINEAR MSSM

$$m_h^2 = [m_Z^2 + \mathcal{O}(\tan^{-2} \beta)] + \frac{v^2}{2f^2} [(2\mu^2 + m_Z^2)^2 + \mathcal{O}(\tan^{-2} \beta)] + \mathcal{O}(f^{-3})$$

$$m_h = 125 \text{ GeV at tree level}$$

(for $\mu \simeq 1 \text{ TeV}$ & $\sqrt{f} \simeq 2 \text{ TeV}$)

HIGGS COUPLINGS

$$\mathcal{L} = -c_t \frac{m_t}{v} h t \bar{t} - c_c \frac{m_c}{v} h c \bar{c} - c_b \frac{m_b}{v} h b \bar{b} - c_\tau \frac{m_\tau}{v} h \tau \bar{\tau} + c_Z \frac{m_Z^2}{v} h Z^\mu Z_\mu + c_W \frac{2m_W^2}{v} h W^{+\mu} W_\mu^-$$

MSSM

$$c_t^{\text{MSSM}} = c_c^{\text{MSSM}} = \frac{\cos\alpha}{\sin\beta}$$

$$c_b^{\text{MSSM}} = c_\tau^{\text{MSSM}} = -\frac{\sin\alpha}{\cos\beta}$$

$$c_Z^{\text{MSSM}} = c_W^{\text{MSSM}} = \sin(\beta - \alpha)$$

decoupling limit
($m_A \gg m_Z$)

$$\alpha \rightarrow \beta - \frac{\pi}{2}$$

$$c_i^{\text{SM}} = 1$$

5-dimensional (loop) couplings

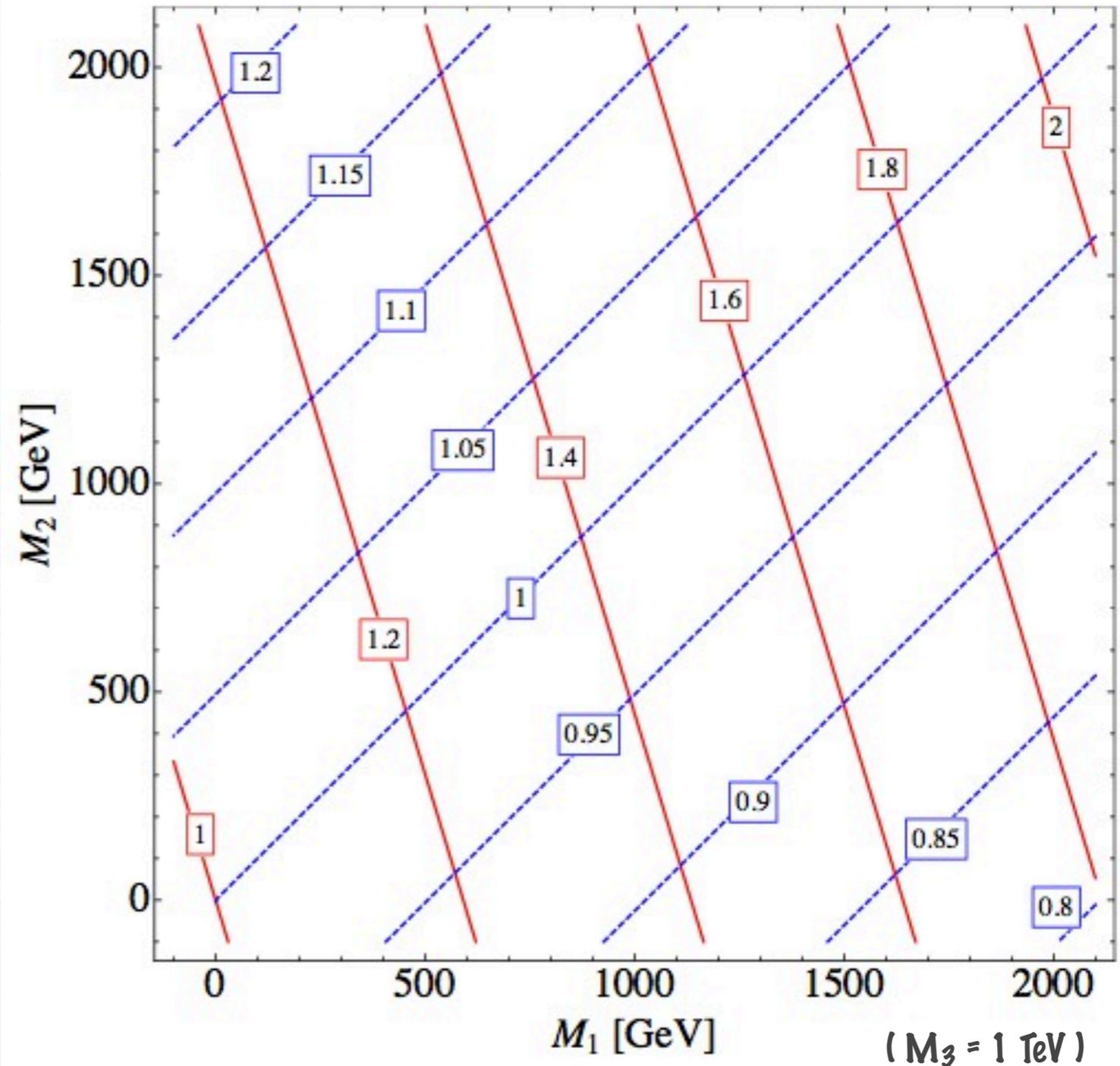
$$\mathcal{L}_{hVV} = c_\gamma \frac{\alpha_{EM}}{8\pi v} h F^{\mu\nu} F_{\mu\nu} + c_{Z\gamma} \frac{\alpha_{EM}}{4\pi v \sin\theta_w} h Z^{\mu\nu} F_{\mu\nu} + c_g \frac{\alpha_S}{12\pi v} h \text{Tr}[G^{\mu\nu} G_{\mu\nu}]$$

HIGGS - GAUGE BOSONS (gg - $\gamma\gamma$ - $Z\gamma$)

For $|c_g^{\text{sgold}}| \lesssim 0.14 \cdot |c_g^{\text{SM}}|$:

$$\frac{\Gamma_{h\gamma\gamma}}{\Gamma_{h\gamma\gamma}^{\text{SM}}} = \frac{|c_\gamma|^2}{|c_\gamma^{\text{SM}}|^2} \lesssim \left| 1 + 0.21 \frac{M_1 c_w^2 + M_2 s_w^2}{M_3} \right|^2$$

$$\frac{\Gamma_{hZ\gamma}}{\Gamma_{hZ\gamma}^{\text{SM}}} = \frac{|c_{Z\gamma}|^2}{|c_{Z\gamma}^{\text{SM}}|^2} \lesssim \left| 1 + 0.05 \frac{M_2 - M_1}{M_3} \right|^2$$



HIGGS - FERMIONS

$$\mathcal{L} = \boxed{-c_t \frac{m_t}{v} h t \bar{t} - c_c \frac{m_c}{v} h c \bar{c} - c_b \frac{m_b}{v} h b \bar{b} - c_\tau \frac{m_\tau}{v} h \tau \bar{\tau}} + c_Z \frac{m_Z^2}{v} h Z^\mu Z_\mu + c_W \frac{2m_W^2}{v} h W^{+\mu} W_\mu^-$$

“Wrong-Higgs” Yukawas eg $\frac{s'_u}{M^2} X^\dagger H_1^\dagger Q U^c|_D \supset \frac{s'_u f}{M^2} h_1^\dagger q u^c$

$$\text{eg } m_d = \left(y_d \cos\beta + \frac{s'_d f}{M^2} \sin\beta \right) \frac{v}{\sqrt{2}} \quad ; \quad g_{hdd} = \frac{1}{\sqrt{2}} \left(-y_d \sin\alpha + \frac{s'_d f}{M^2} \cos\alpha \right)$$

(same for the up and the lepton sectors)

* Disentangle mass vs Yukawa coupling relation

* Introduce flavor structure -> Constraints from FCNC $s'_i \propto y_i$

* $\tan\beta$ enhanced effects $\left(\text{eg } m_b = \frac{v \cos\beta}{\sqrt{2}} \left(y_b + \delta y_b + \frac{s'_b f}{M^2} \tan\beta \right) \right)$

* Sgoldstino - Higgs mixing eg $\frac{A_u}{f} X H_2 Q U^c|_F \supset \frac{A_u}{f} x \langle h_2 \rangle q u^c$

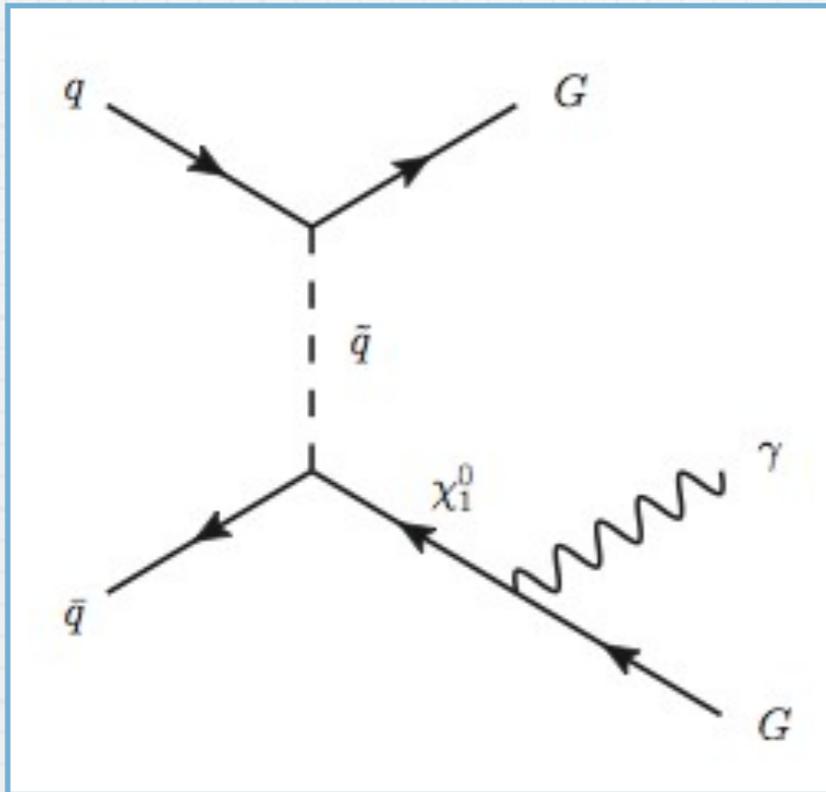
➡ They don't affect the fermion masses

➡ Splitting between c_b and c_τ (not possible in usual MSSM)

Petersson, Romagnoni, Torre '12

$\gamma + \cancel{E}_T$ SIGNATURES ($p_T^\gamma \gtrsim 100 \text{ GeV}$)

$$q \bar{q} \rightarrow G \chi_1^0 \rightarrow GG\gamma \quad (m_\chi < m_h, m_Z)$$

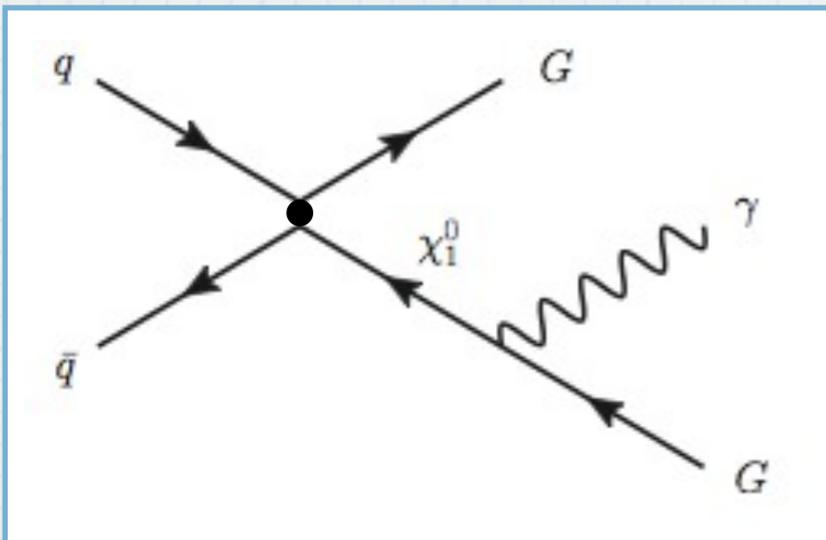


➔ Main background: $pp \rightarrow Z \rightarrow \gamma\nu\nu$

➔ If the lightest neutralino is higgsino-like, this process is suppressed within MSSM.

(gauge coupling \gg Yukawa coupling)

➔
$$\frac{s'_u}{M^2} X^\dagger H_1^\dagger Q U^c|_D \supset \frac{s'_u f}{M^2} \bar{G} \bar{\psi}_1 u u^c$$

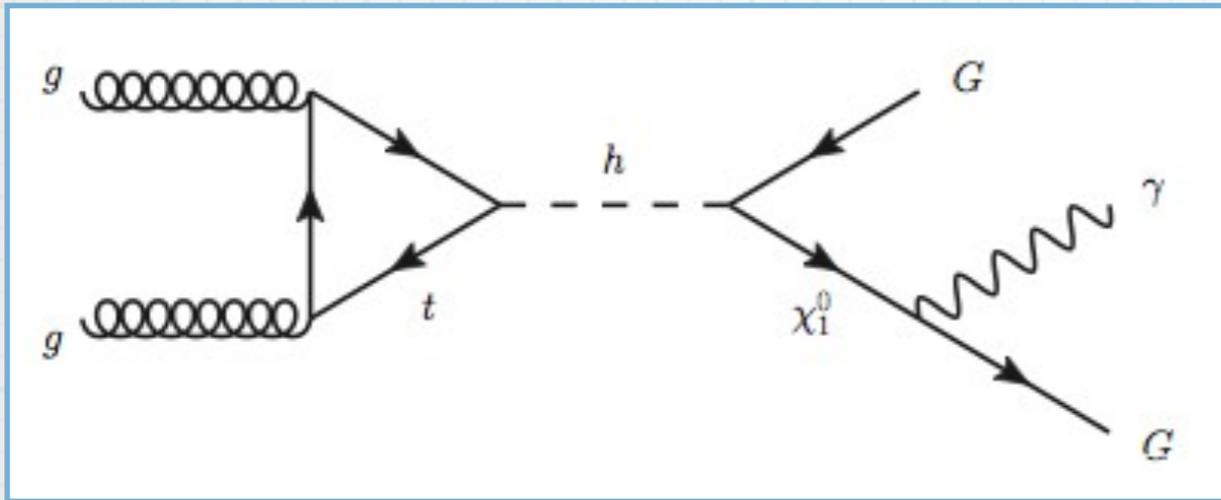


➔ Maximized for χ_1^0 higgsino.

➔ Decays to $\gamma + G$ within collider time.

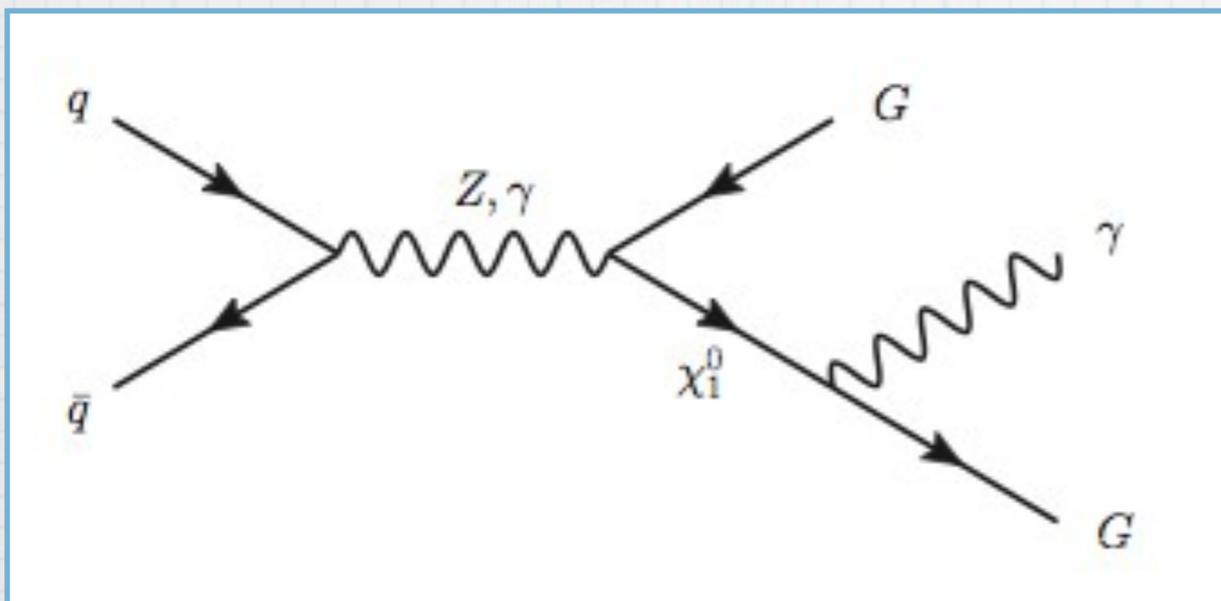
$\gamma + \cancel{E}_T$ SIGNATURES ($p_T^\gamma \lesssim m_h/2$)

$$g g \rightarrow h \rightarrow G \chi_1^0 \rightarrow G G \gamma$$



➔ **Main background:**
 $pp \rightarrow \gamma j$ (j not reconstructed)

Contributes in $p_T^\gamma \lesssim m_Z/2 \simeq 45 \text{ GeV}$

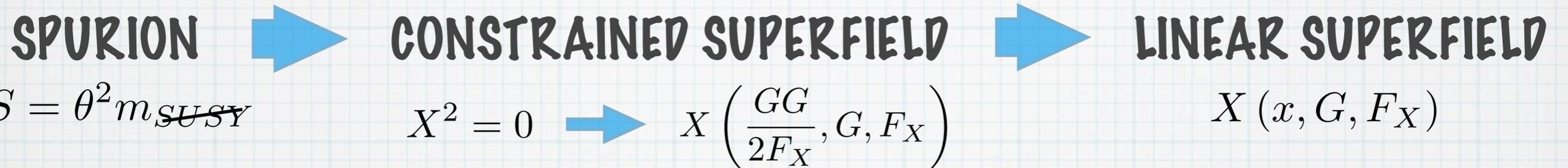


➔ **Signal significance optimized for**
 $45 \text{ GeV} < p_T^\gamma < 65 \text{ GeV}$, $|\eta_\gamma| < 1.44$

➔ **CMS & ATLAS "data parking" ?**

SUMMARY

* Effective Lagrangian analysis of Low Scale SUSY Breaking



+ Effective operators \rightarrow Important pheno

* Modified Higgs sector \rightarrow Can obtain 125 GeV mass at tree level.

* $h \rightarrow \gamma\gamma$, $Z\gamma$ couplings are affected.

* $\gamma + \text{MET}$ signals are modified (also jet +MET signals)

FUTURE PROJECTS

* Explicit SUSY breaking models?

* LHC analysis of the bound of SUSY breaking scale

* Dirac gauginos?