Loop-induced Higgs couplings as a portal to new physics

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KITP Conference: LHC - The First Part of the Journey

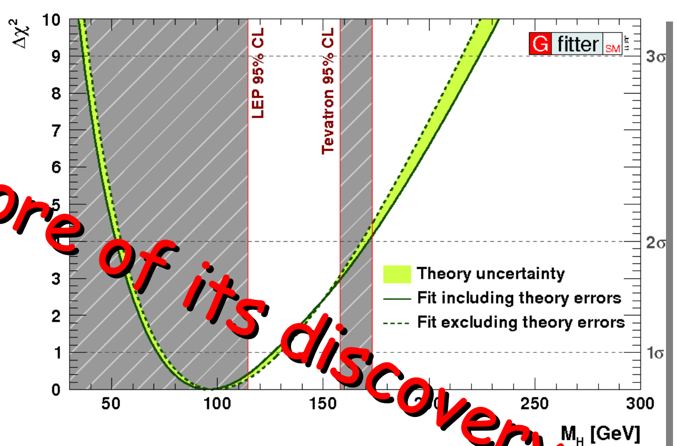
S. Barbara,
July 8th 2013

Main Idea

Precision Electroweak Measurements

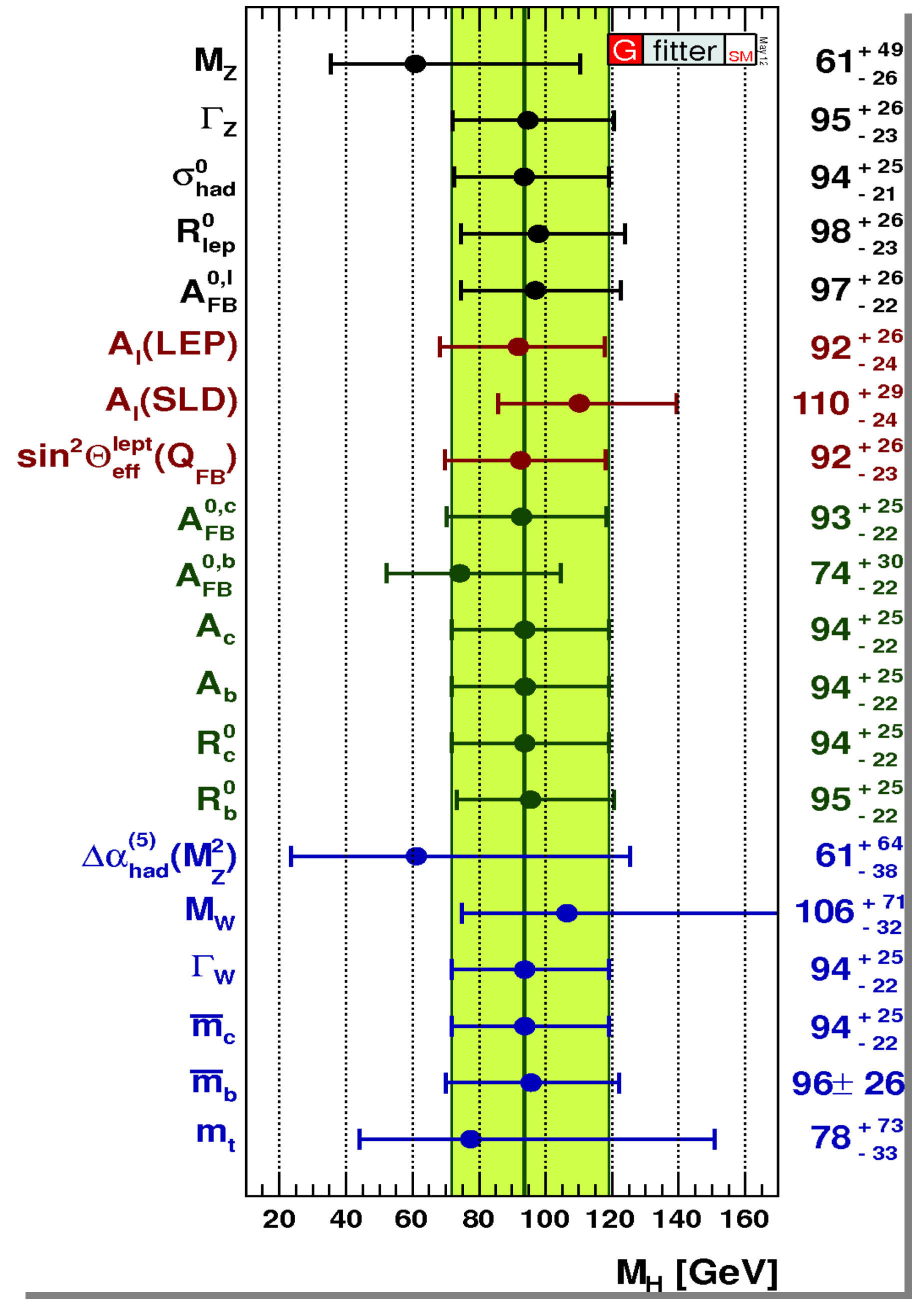
⭐ $$m_h = 91^{+30}_{-20}\,\mathrm{GeV}$$

GFitter-1107.0975



Before of its discovery

⭐ constraints on NP models



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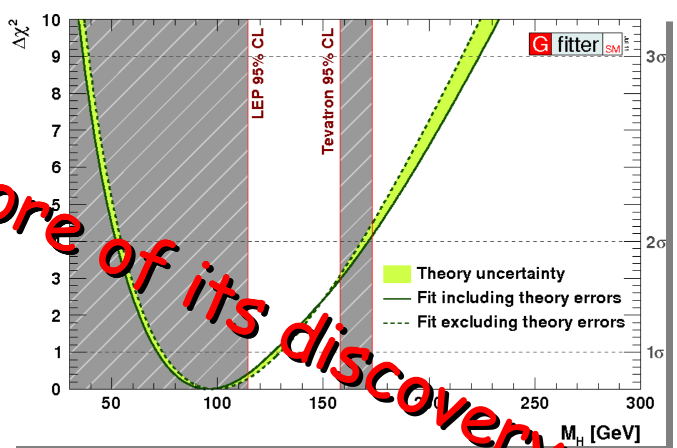

Before of its discovery

- **constraints on NP models**

Precision **measurement of the Higgs couplings**

?

Overconstraining New Physics

1. Direct production of new particles

   Probe for m_{NP}, decay mode, mass of the daughter particles, ...

2. Precision measurement of the hgg and hγγ couplings

   Probe for m_{NP}, hPP coupling

3. Decays of these new particles into a Higgs + X

$$pp \to (\mathrm{NP})(\mathrm{NP}) \to (hX)(hX)$$

   Probe for m_{NP}, hPP coupling, ...

See for example
Giddings, Liu, Low, Mintun, 1301.2324

Different assumptions

Overconstraining New Physics

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For this talk

2. Precision measurement of the hgg and hγγ couplings

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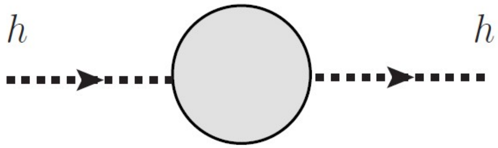
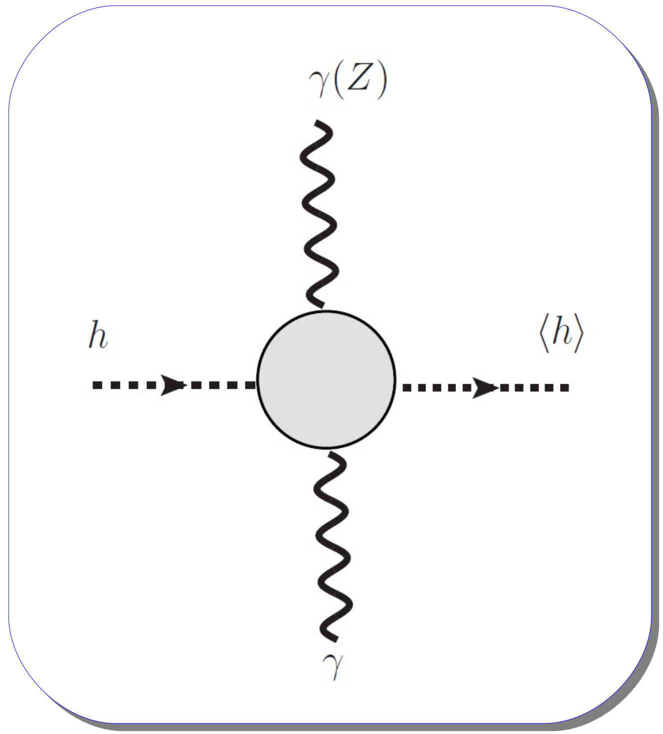
Different assumptions

„Higgs oblique corrections“

Why do we expect them?





Naturalness → Higgs pheno

Indirect probe of Naturalness

recent studies:

Farina, Perelstein, Rey-Le Lorier, 1305.6068

Craig, Englert, McCullough, 1305.5251

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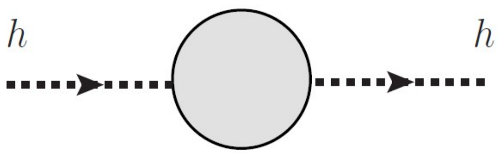

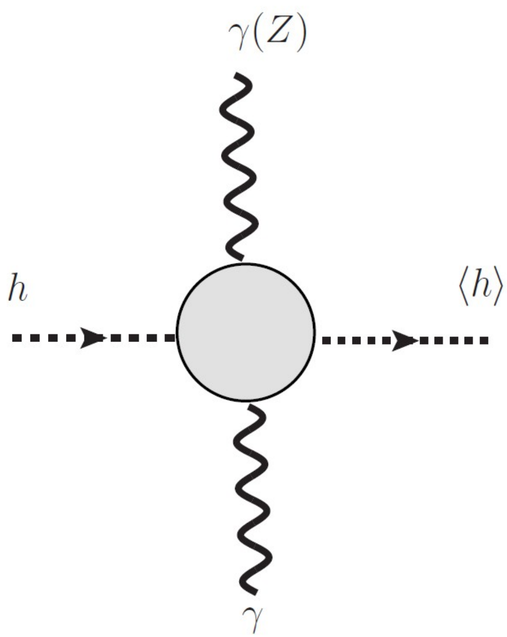

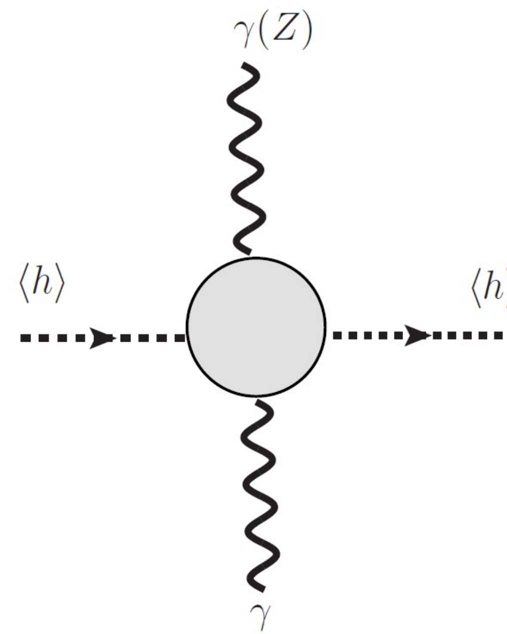

Naturalness → Higgs pheno ↔ QED (QCD) beta functions

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Low energy Higgs theorem

Ellis, Gaillard, Nanopoulos, 1976

Shifman, Vainshtein, Voloshin, Zakharov, 1979

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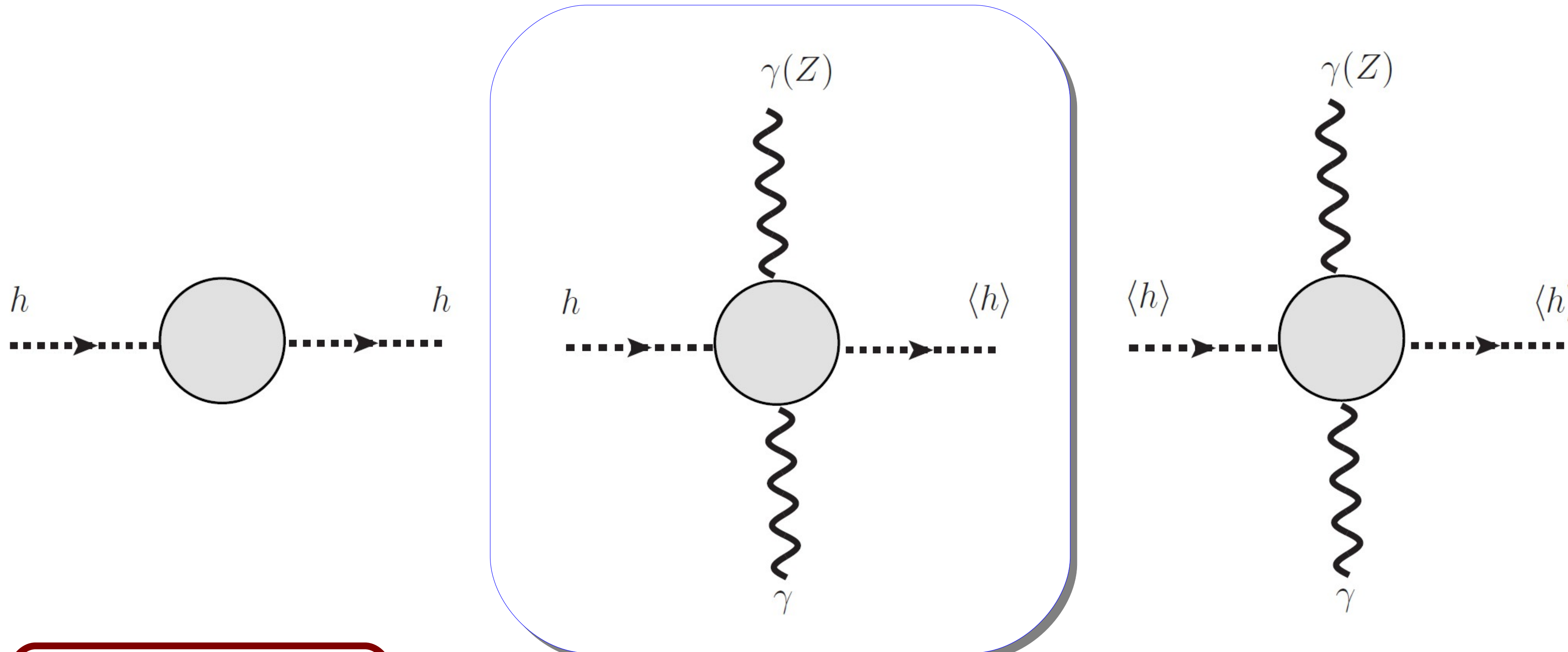


Naturalness → Higgs pheno ↔ QED (QCD) beta functions

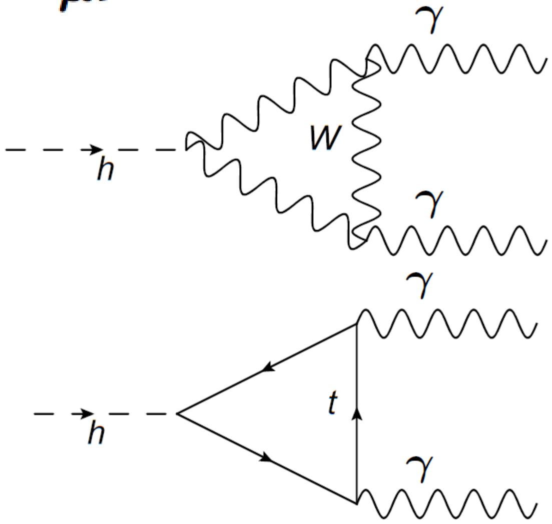
Low energy Higgs theorem

Ellis, Gaillard, Nanopoulos, 1976
Shifman, Vainshtein, Voloshin, Zakharov, 1979

Size of the corrections: $\mathcal{O}\left(\frac{v^2}{m_{\rm NP}^2}\right) \sim 5\%$ (dimension 6 effective operators)

Loop induced couplings in the SM

$$c_G \frac{\alpha_s}{12\pi v} h G^a_{\mu\nu} G^{\mu\nu a} + c_\gamma \frac{\alpha_{\rm em}}{8\pi v} h F_{\mu\nu} F^{\mu\nu}$$



At the LO:

$$c_g^{(\rm SM)} = \frac{3}{4}\left(A_{1/2}(\tau_t) + A_{1/2}(\tau_b)\right)$$
$$c_\gamma^{(\rm SM)} = A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t)$$
$$\tau_i \equiv 4m_i^2/m_h^2$$

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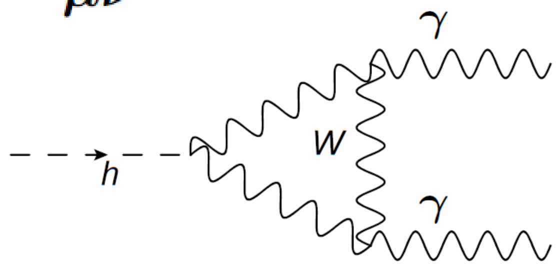

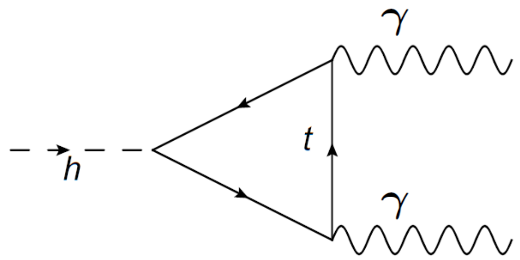

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$$\tau_i \equiv 4m_i^2/m_h^2$$

Sizable higher order corrections (computed at N[3]LO)

$$c_{g,\text{NLO}}^{(\text{SM})} = 1 + \frac{11}{4}\frac{\alpha_s}{\pi} + \left[\frac{2777}{288} - N_f \frac{67}{96} + \left(\frac{19}{16} + \frac{N_f}{3}\right)\log\frac{\mu^2}{m_t^2}\right]\left(\frac{\alpha_s}{\pi}\right)^2 + \cdots$$

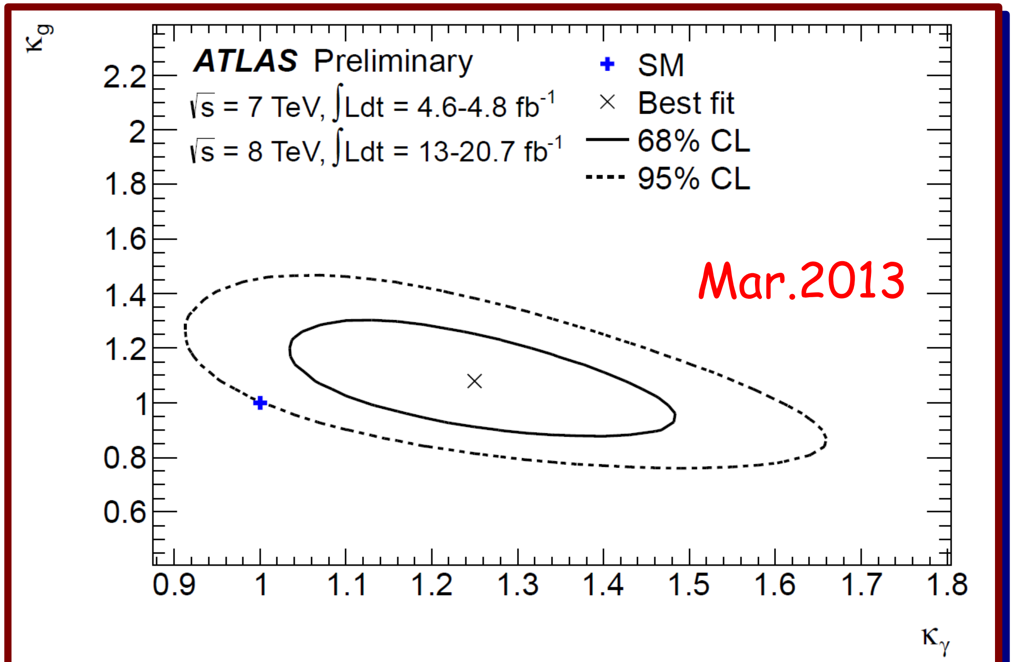
$$= 1 + 0.09891 + 0.00796 + \cdots$$

Djouadi, Spira, Zerwas, 1991
Dawson, 1991
Spira, Dawson, Graudenz, Zerwas, 1995
Kramer, Laenen, Spira, 1998
Chetyrkin, Kniel, Steinhauser, 1998, ...

Smaller NLO corrections to hγγ coupling

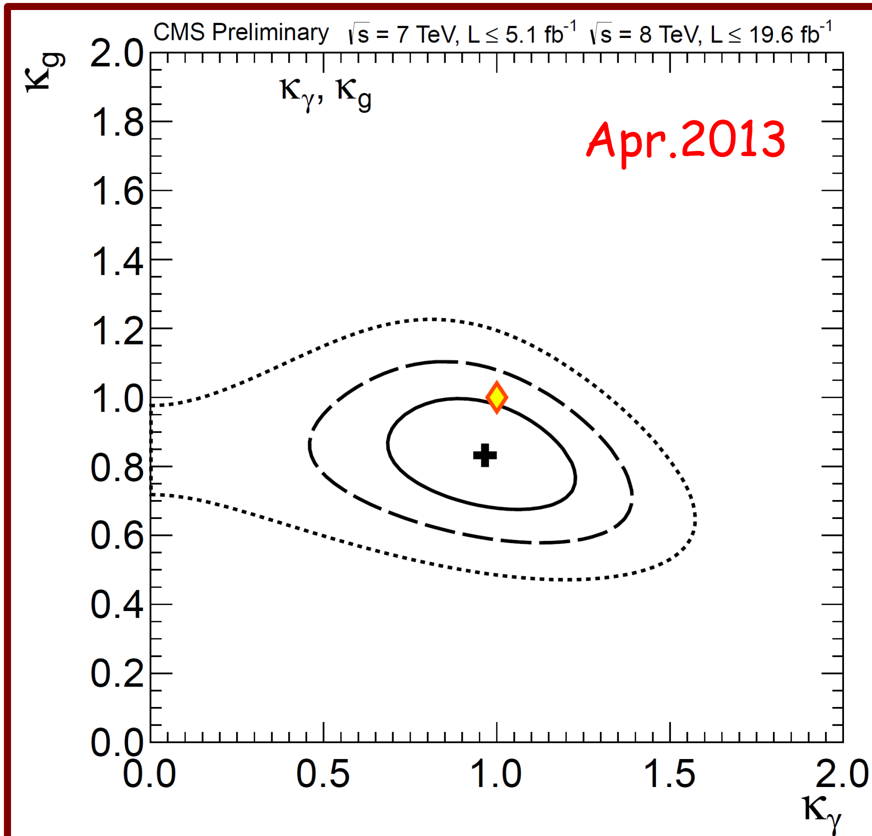
Where do we stand today?

Assuming no exotic Higgs decay, contributing to the Higgs width



ATLAS-CONF-2013-034

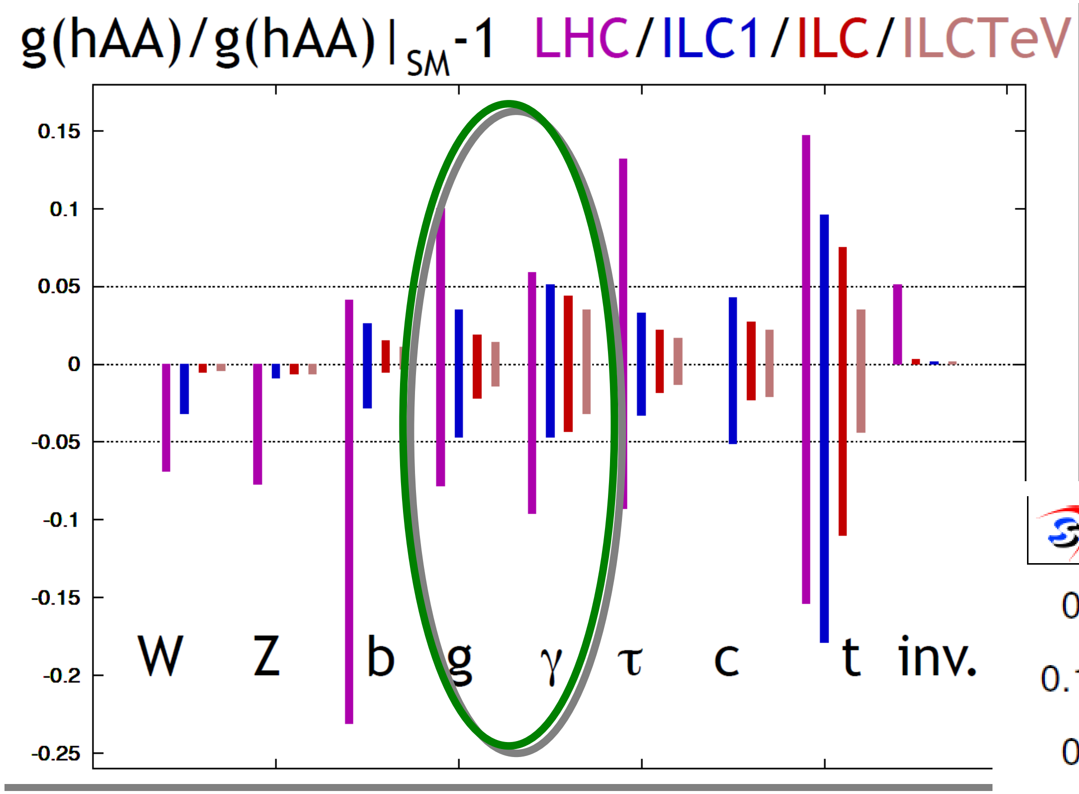
$$k_g = 1.08 \pm 0.14$$
$$k_\gamma = 1.23^{+0.16}_{-0.13}$$



CMS-PAS-HIG-13-005

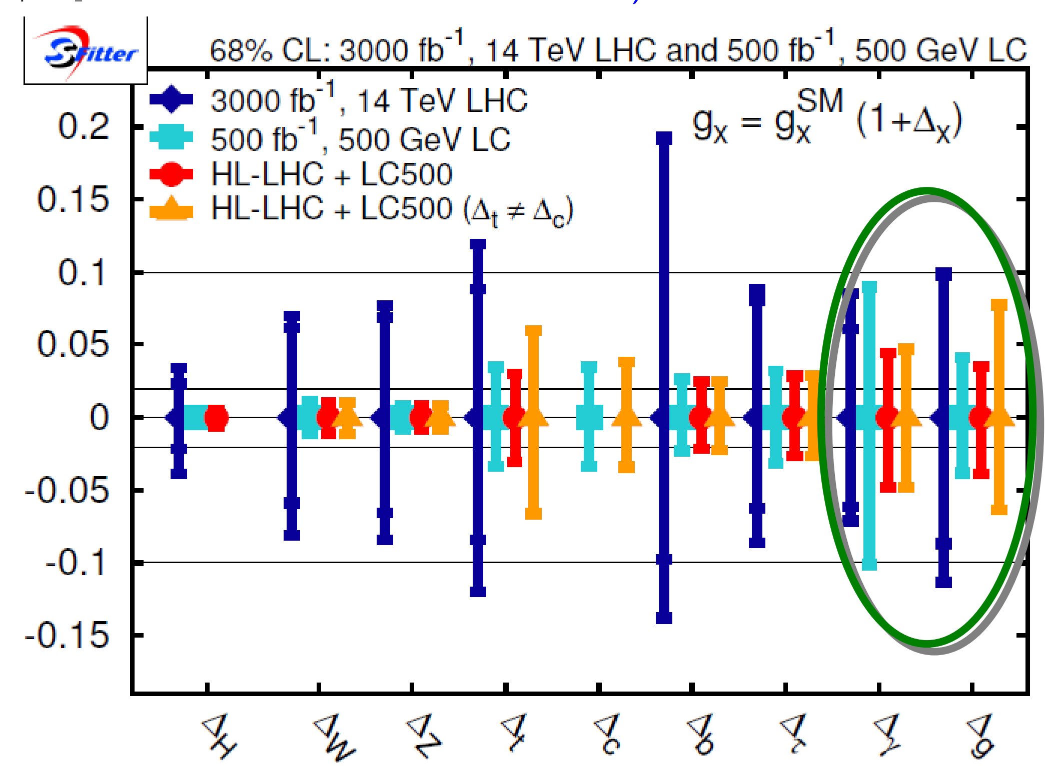
$$k_g = (0.73 - 0.94)$$
$$k_\gamma = (0.79 - 1.14)$$

Where we might stand in the future?



Peskin, 1207.2516

Klute, Lafaye, Plehn, Rauch, Zerwas, 1301.1322



NP effects

- Low energy Higgs theorem at 2-loops

Kniehl, Spira, 1995

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(5)} + \frac{h}{8v} G^a_{\mu\nu} G^{a\,\mu\nu} \frac{\beta_{\alpha_s}}{\alpha_s} \frac{1}{1+\gamma_m} \frac{\partial}{\partial \log v} \log m(v)^2$$

$$\frac{\beta^{(f)}_{\alpha_s}}{\alpha_s} = \delta_R \, b_{1/2} \frac{\alpha_s}{2\pi} T(f) \left\{ 1 + \frac{\alpha_s}{4\pi} \left[5C_2(G) + 3C_2(f) \right] \right\}$$

$$\frac{\beta^{(S)}_{\alpha_s}}{\alpha_s} = \delta_R \, b_0 \frac{\alpha_s}{2\pi} T(S) \left\{ 1 + \frac{\alpha_s}{2\pi} \left[C_2(G) + 6C_2(S) \right] \right\}$$

QCD beta function

$$\beta_{\alpha_s} = \partial \alpha_s / \partial \log \mu$$

$$\gamma_m = -\partial \log m / \partial \log \mu$$

Mass anomalous dimension

$$A_{1/2}(\tau) \to b_{1/2} = \frac{4}{3}\,,$$

$$A_0(\tau) \to b_0 = \frac{1}{3}$$

- Keeping only LO corrections to the hγγ coupling

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(5)} + \frac{h}{8v} F_{\mu\nu} F^{\mu\nu} \frac{\beta_{\alpha_{em}}}{\alpha_{em}} \frac{\partial}{\partial \log v} \log m(v)^2$$

Example scenarios (hgg)

$$\Gamma_{hgg} = \frac{\alpha_s^2 m_h^3}{128\pi^3} \kappa_{soft}^{NLO} \left| \delta_R\, T(V)\, \frac{g_{hVV}}{m_V^2} A_1(\tau_V)\, c_{g,V}^{NLO} + T(f)\, \frac{2 g_{hf\bar{f}}}{m_f} A_{1/2}(\tau_f)\, c_{g,f}^{NLO} + \delta_R\, T(R)\, \frac{g_{hSS}}{m_S^2} A_0(\tau_S)\, c_{g,S}^{NLO} \right|^2$$

$$\kappa_{soft}^{NLO} = 1 + \frac{\alpha_s}{\pi}\left(\frac{73}{4} - \frac{7}{6} N_f\right) = 1 + 0.427$$

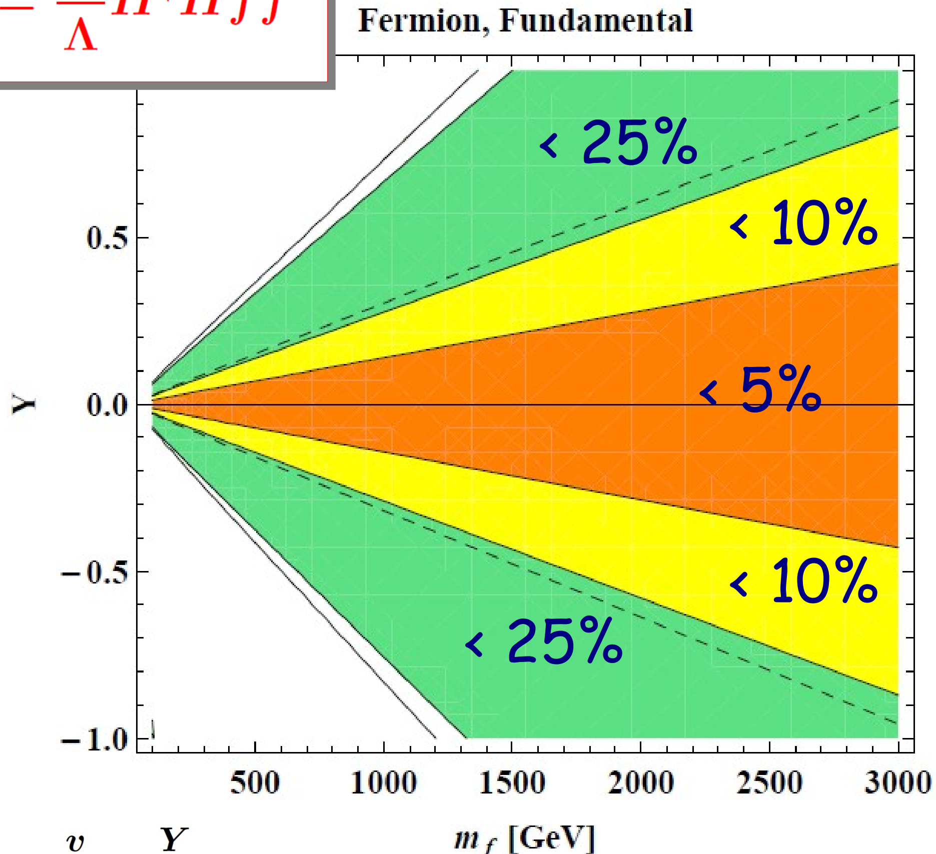
SG, Low, 1307.0496

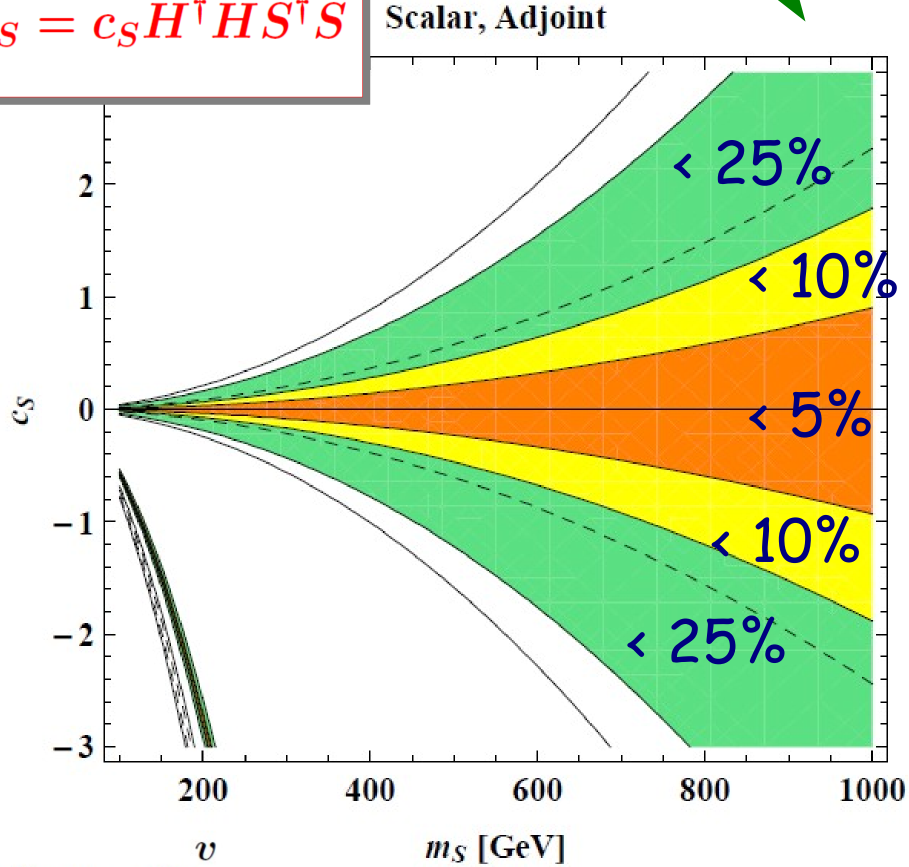
Example scenarios (hgg)

$$\Gamma_{hgg} = \frac{\alpha_s^2 m_h^3}{128\pi^3}\kappa_{soft}^{NLO}\left|\delta_R T(V)\frac{g_{hVV}}{m_V^2}A_1(\tau_V)\,c_{g,V}^{NLO} + \underbrace{T(f)\frac{2g_{hf\bar f}}{m_f}A_{1/2}(\tau_f)\,c_{g,f}^{NLO}} + \underbrace{\delta_R T(R)\frac{g_{hSS}}{m_S^2}A_0(\tau_S)\,c_{g,S}^{NLO}}\right|^2$$

$$\mathcal{O}_f = \frac{c_f}{\Lambda}H^\dagger H\bar f f$$

$$\mathcal{O}_S = c_S H^\dagger H S^\dagger S$$





$$g_{hf\bar f} = c_f\frac{v}{\Lambda} \equiv \frac{Y}{\sqrt{2}}$$

$$c_{g,f,(3)}^{NLO} = 1 + \frac{11}{4}\frac{\alpha_s}{\pi}$$

$$g_{hSS} = c_S\frac{v}{2}$$

$$c_{g,S,(8)}^{NLO} = 1 + \frac{33}{4}\frac{\alpha_s}{\pi}$$

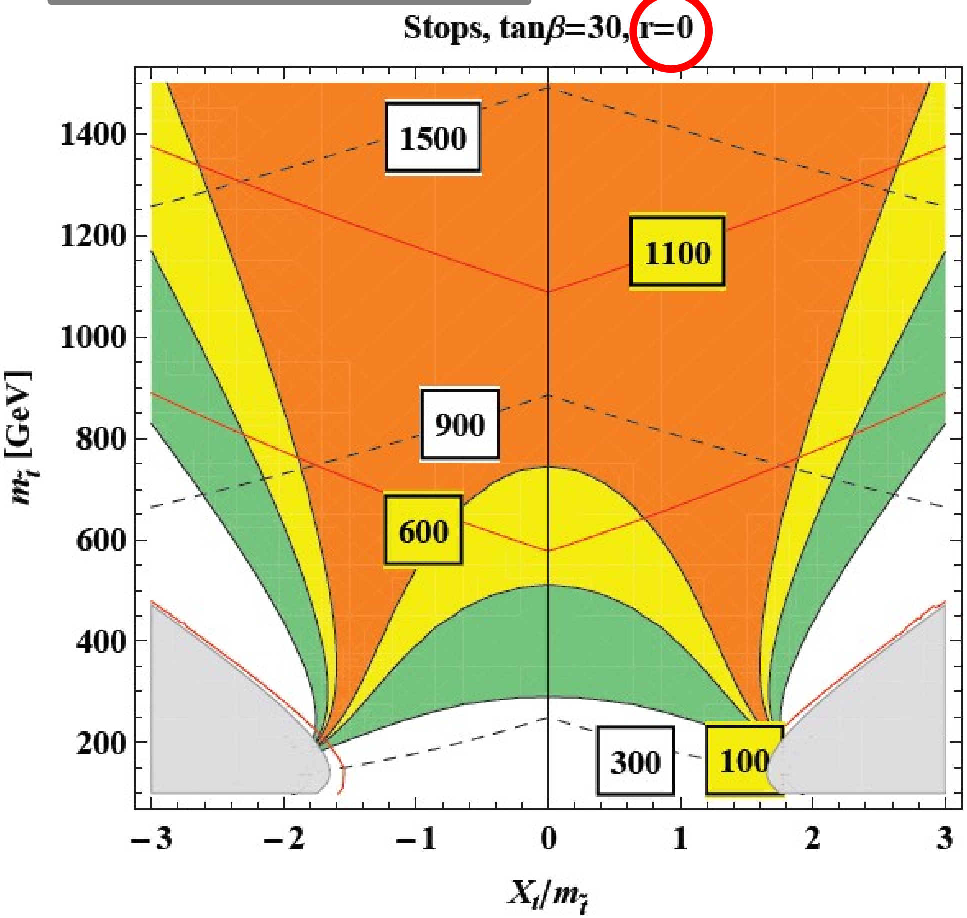
SG, Low, 1307.0496

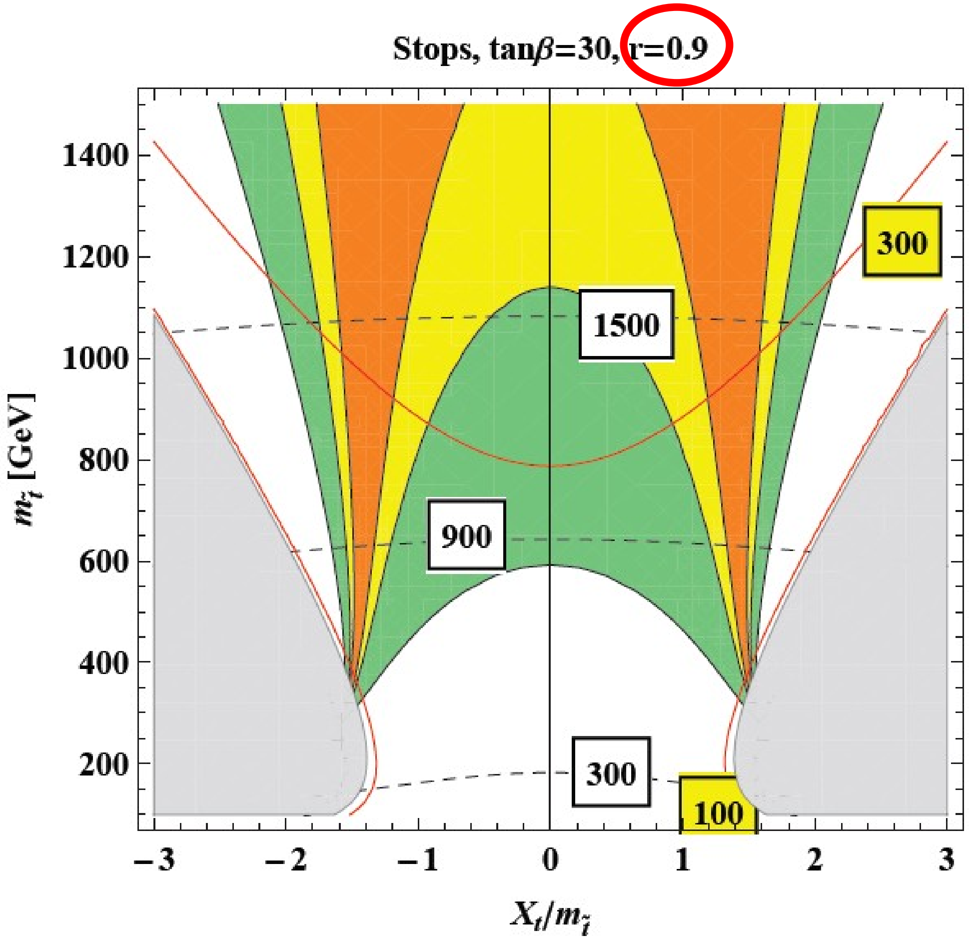
(neglecting the scalar quartic coupling)

Specific NP models (hgg)

Susy, stops

SG, Low, 1307.0496





$$m_{\tilde t}^2 \equiv \frac{m_{Q_3}^2 + m_{U_3}^2}{2}, \; r \equiv \frac{m_{Q_3}^2 - m_{U_3}^2}{m_{Q_3}^2 + m_{U_3}^2}$$

$$\mathcal{M}^2_{stop} = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_{u_3}^2 + m_t^2 + D_R \end{pmatrix}$$

See also Carena, SG, Shah, Wagner, Wang, 1303.4414

Specific NP models (hgg)

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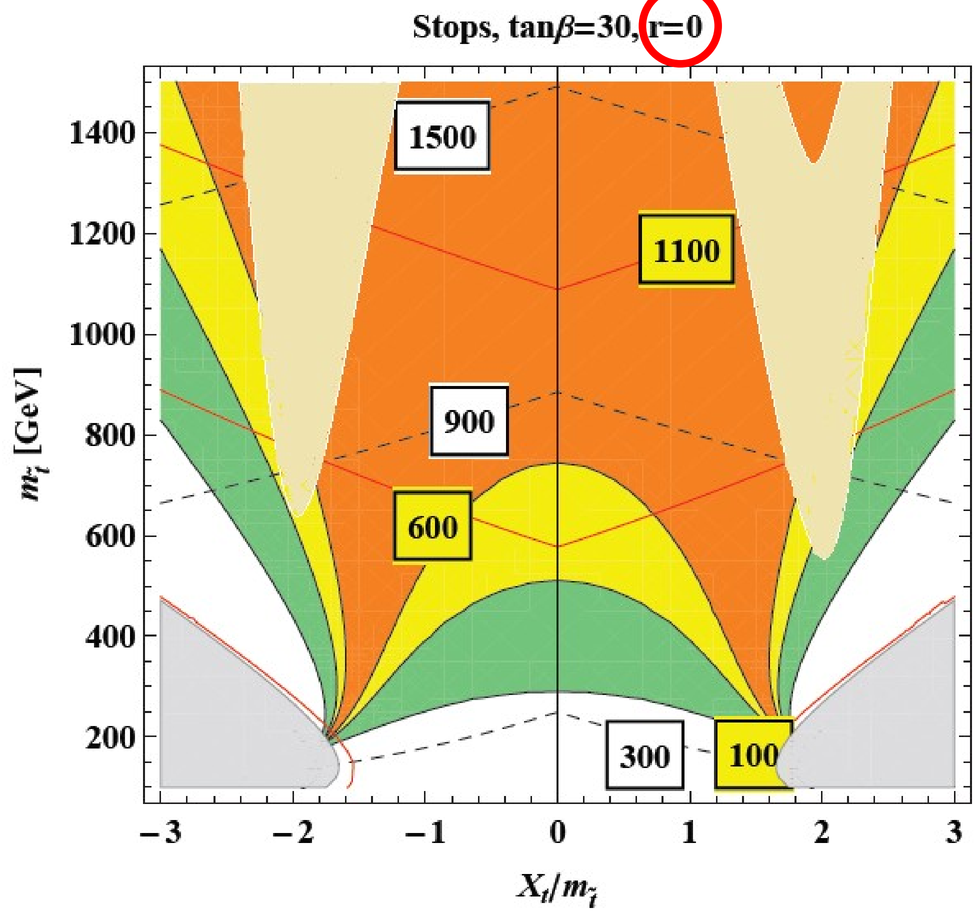

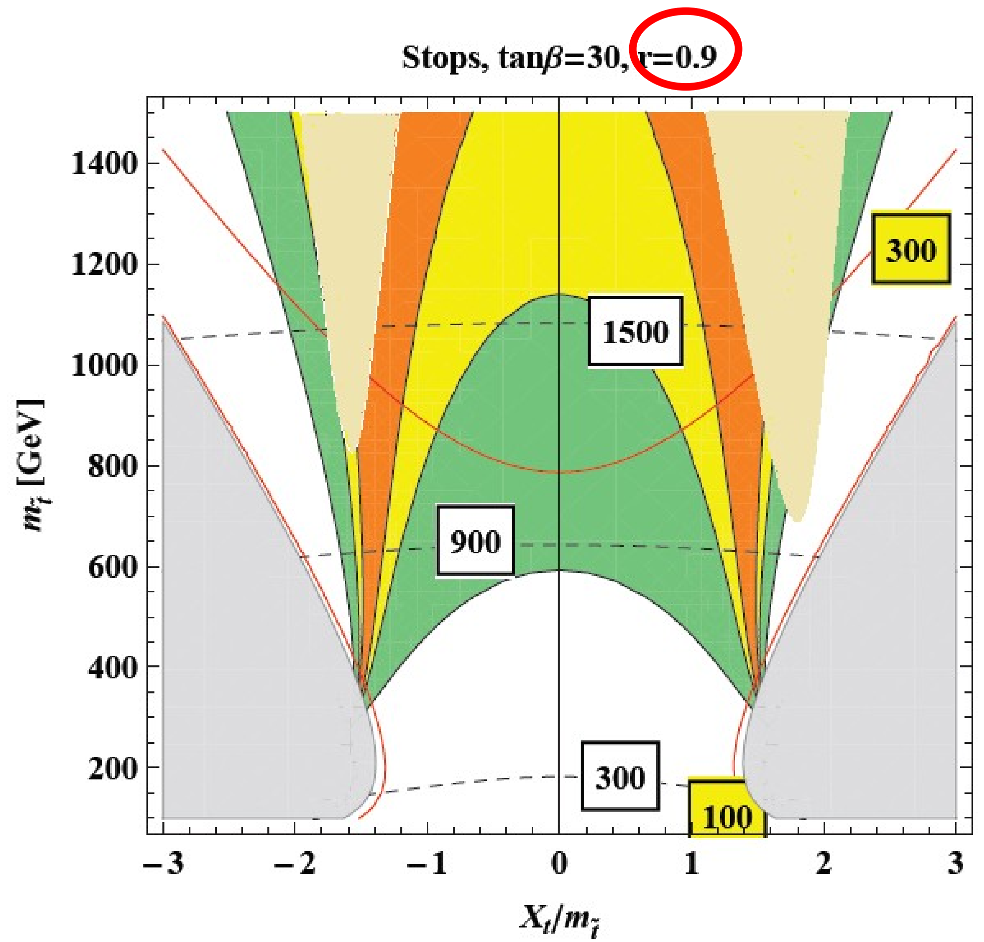

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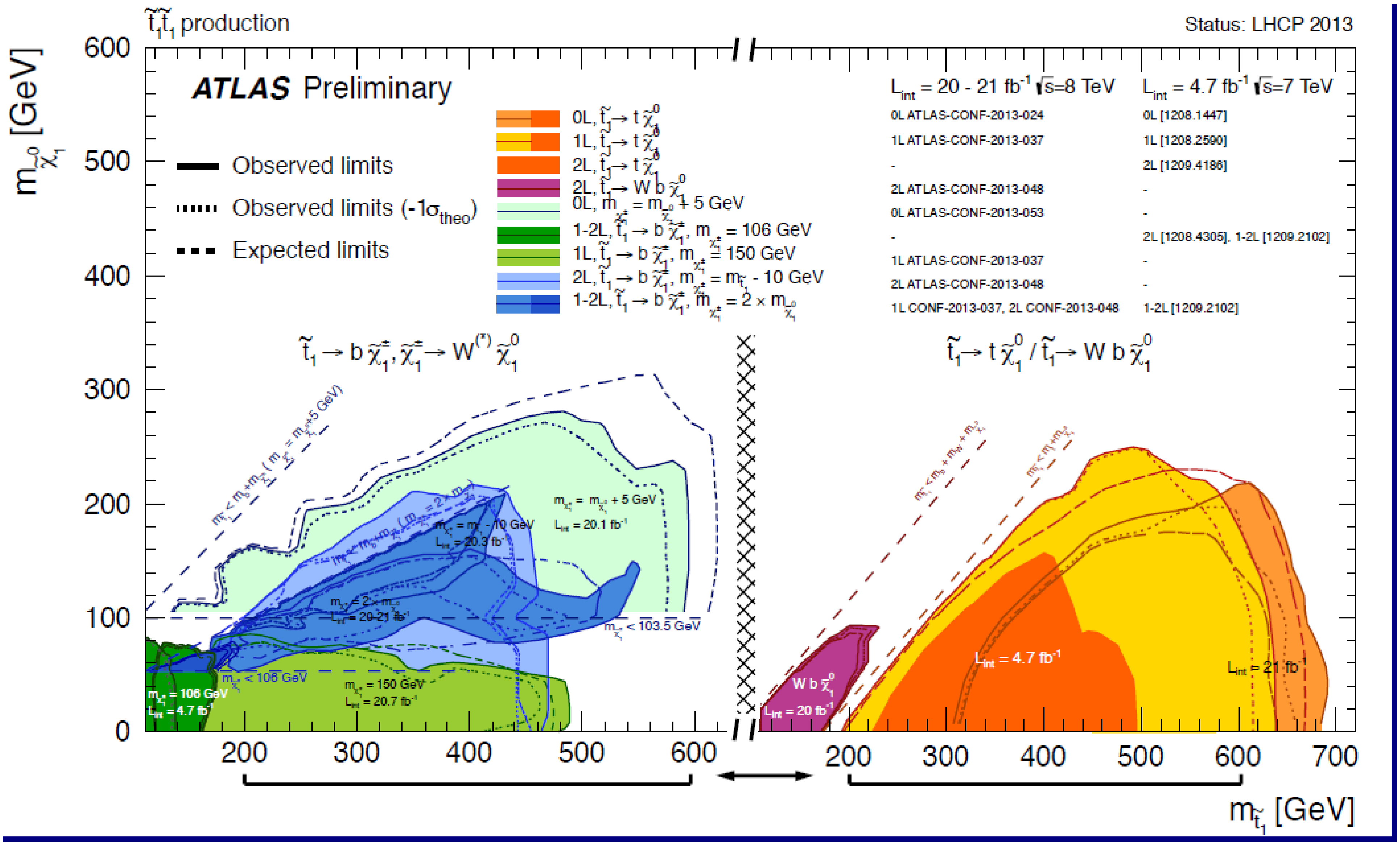
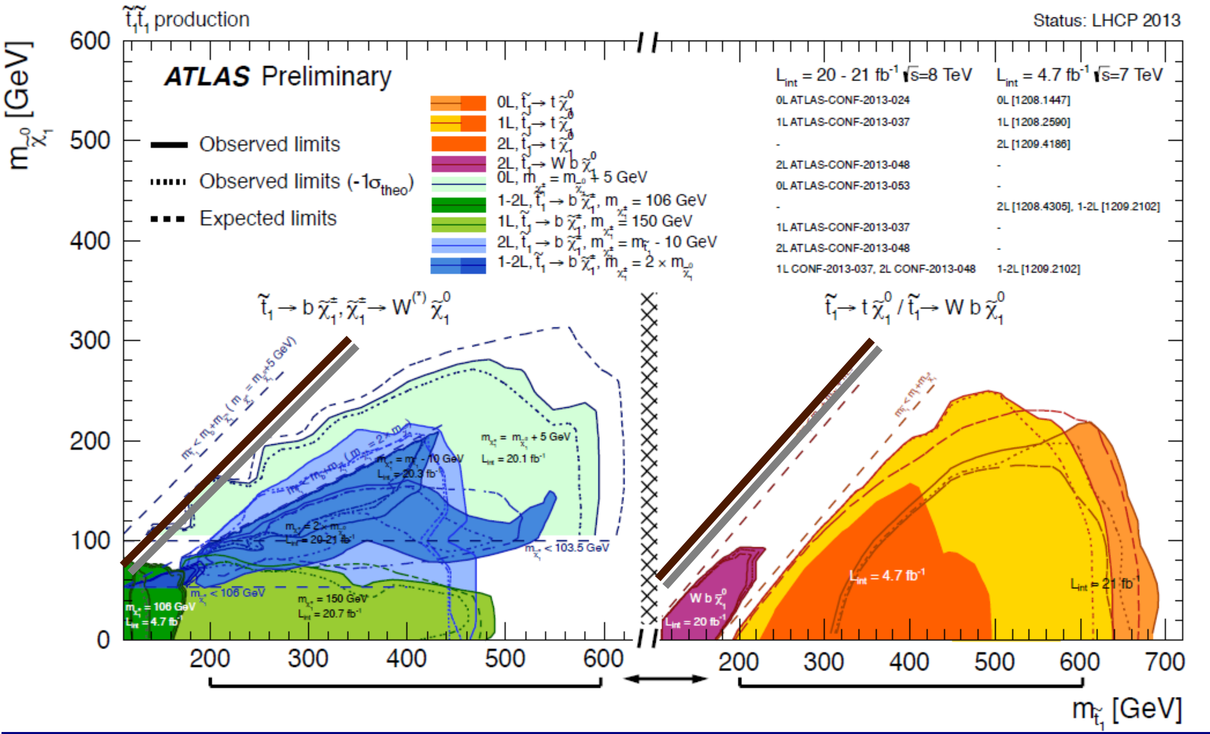
LHC stop searches



LHC stop direct searches



- Squeezed scenarios difficult for the LHC

$$m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \lesssim 25\,\mathrm{GeV}$$

See however
Alves, Buckley, Fox, Lykken, Yu, 1205.5805
Han, Katz, Krohn, Reece, 1205.5808
Kilic, Tweedie, 1211.6106

- Possible exotic stop decays not yet studied by the ATLAS and CMS collaborations

Example: $\tilde{t}_1 \to \tilde{\tau}_1 \nu_\tau b$

First bounds come from recasting the Tevatron/LHC measurement of $\sigma(pp \to t\bar{t})$ with (τ+l) and (τ+jets) final state

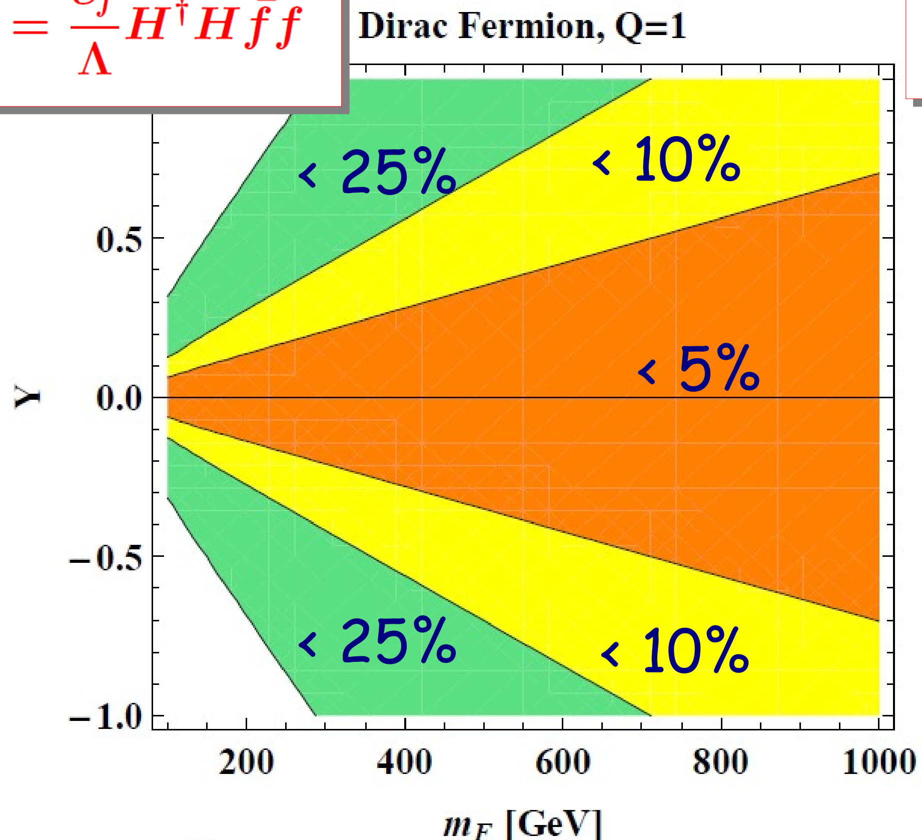
≥80% branching ratios are already excluded if $m_{\tilde{t}_1} \sim m_t$

Carena, SG, Shah, Wagner, Wang, 1303.4414

Example scenarios (hγγ)

$$\Gamma_{h\gamma\gamma} = \frac{\alpha_{\rm em}^2 m_h^3}{1024\pi^3}\left| \frac{g_{hVV}}{m_V^2} Q_V^2 A_1(\tau_V) + \underbrace{\frac{2 g_{hf\bar f}}{m_f} N_{c,f} Q_f^2 A_{1/2}(\tau_f)} + \underbrace{N_{c,S} Q_S^2 \frac{g_{hSS}}{m_S^2} A_0(\tau_S)} \right|^2$$

$$\mathcal{O}_f = \frac{c_f}{\Lambda} H^\dagger H \bar f f$$



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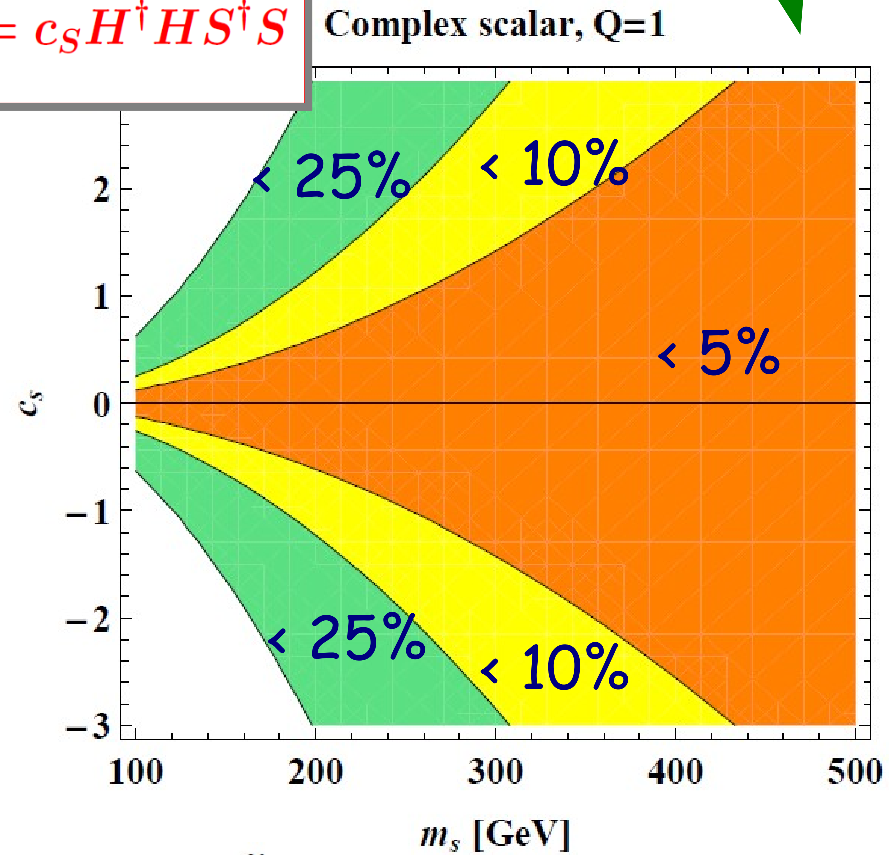


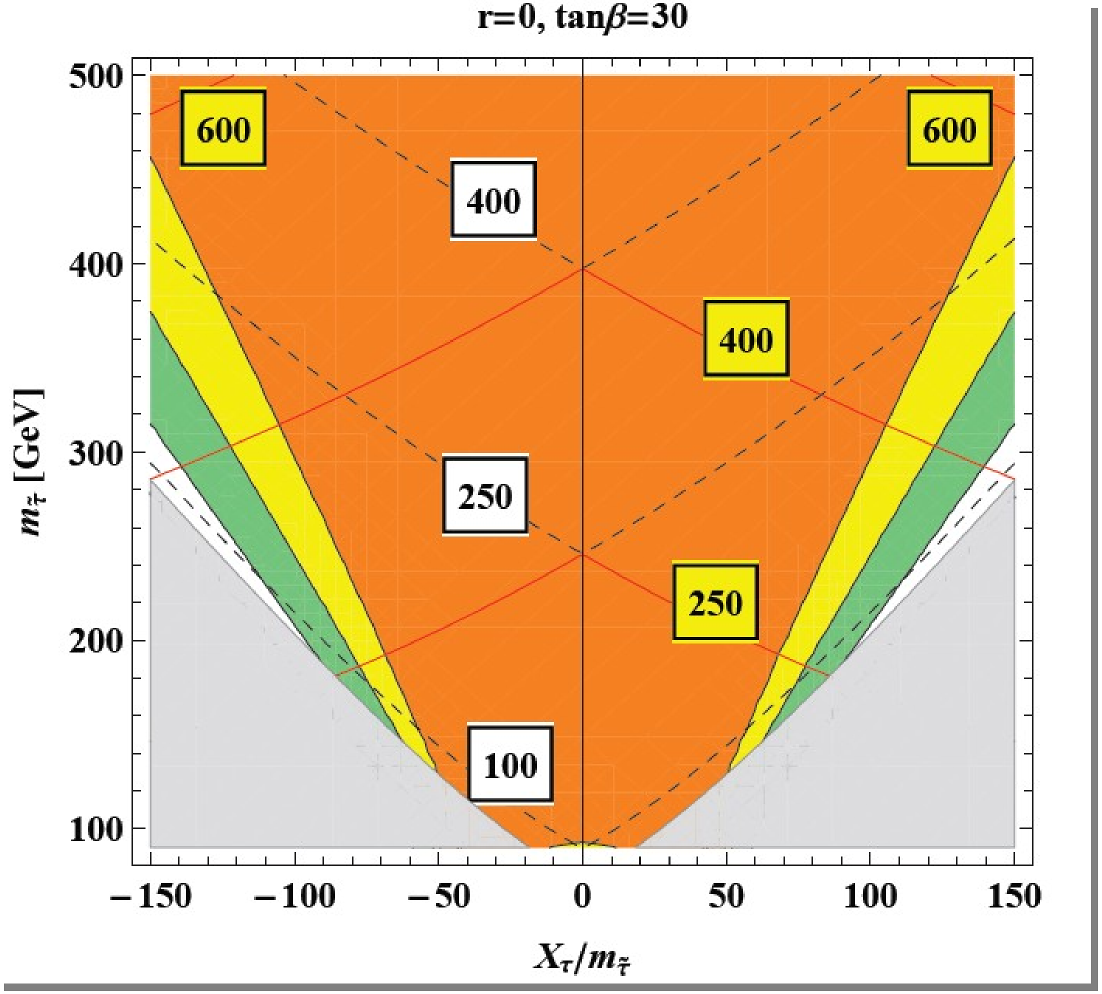
$$g_{hSS} = c_S \frac{v}{2}$$

SG, Low, 1307.0496

Specific NP models 1 (hγγ)

Susy, staus

See also
Carena, SG, Shah, Wagner,
1112.3336



Important constraints on the stau parameter space

$$\mathcal{M}^2_{\tilde{\tau}} \simeq \begin{pmatrix} m^2_{L_3} + m^2_\tau + D^\tau_L & m_\tau \overbrace{(A_\tau - \mu\tan\beta)}^{X_\tau} \\ m_\tau (A_\tau - \mu\tan\beta) & m^2_{E_3} + m^2_\tau + D^\tau_R \end{pmatrix}$$

SG, Low, 1307.0496

LHC staus direct searches

- LEP bound on the stau mass: Aleph, 0112011
  ~ 90 GeV in the case of no degeneracy with the lightest neutralino

- CMS bound on long lived staus: 339 GeV
  1305.0491 (7 TeV, 5 fb^{-1} + 8 TeV, 18.8 fb-1)

- ATLAS: searches for staus NLSP produced from gluino & squark cascade decays.
  Up to 4 leptons (at least one τ), jets and missing energy signature. ATLAS-CONF-2013-026

- CMS & ATLAS multilepton searches
  ≥ 2 leptons + MET final states

$$\tilde{\chi}^{\pm} \to \tilde{\chi}^0 W, \ell\tilde{\nu}, \tilde{\ell}\nu, \quad \tilde{\chi}^0_2 \to \tilde{\chi}^0_1 Z, \ell\tilde{\ell}$$

And also limits on sleptons produced in cascade decays

  CMS: SUS-12-022, SUS-12-026, SUS-12-027 (old @7TeV: 1204.5341)
  ATLAS: ATLAS-CONF-2013-035 (old @7TeV 1208.3144)

- ATLAS 2τ + MET search
  ATLAS-CONF-2013-028

$$\tilde{\chi}^{\pm} \to \tilde{\tau}\nu, \tau\tilde{\nu}, \quad \tilde{\chi}^0_2 \to \tilde{\tau}\tau$$

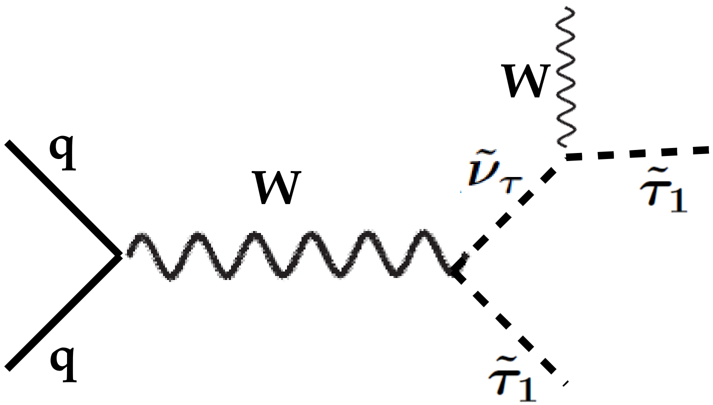
$$\tilde{\tau}\tilde{\tau} \to (\tau\tilde{\chi}^0_1)(\tau\tilde{\chi}^0_1)$$

Improved strategies to look for light staus?

Associated production

$$pp \to \tilde{\tau}_1[\tilde{\nu}_\tau(\to W\tilde{\tau}_1)] \to \ell\tau\bar{\tau} + \text{MET}$$

Carena, SG, Shah, Wagner, Wang, 1205.5842



Production cross section for staus at ~ **95 GeV**, sneutrino ~ **270 GeV**:
~15 fb (8TeV), ~40 fb (14TeV)

Main backgrounds:

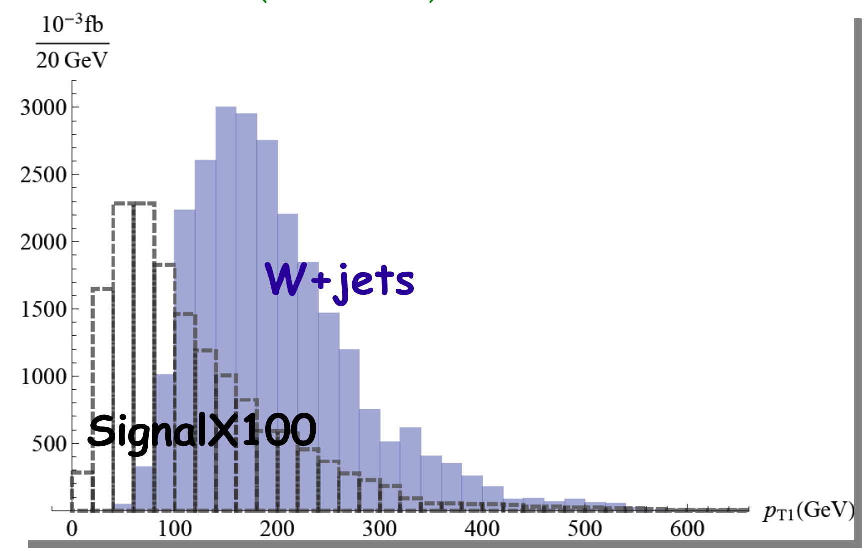
- W+ Z/γ*
- W+jets (with jets faking taus)

jet rejection factor 20-50 for loose hadronic taus (id~60%)

Basic cuts for the 8TeV LHC:

$$p_T^{\tau\,(j)} > 10\,\text{GeV},\ \Delta R > 0.4,\ |\eta| < 2.5$$

$$p_T^\ell > 70\,\text{GeV},\ \not{E}_T > 70\,\text{GeV}$$

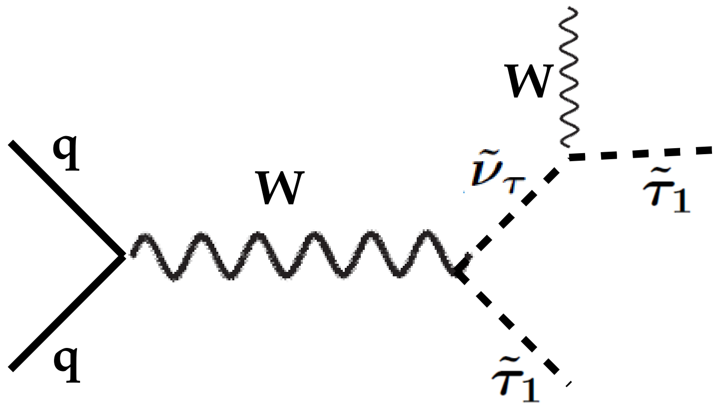


 S.Gori

Associated production

$$pp \to \tilde{\tau}_1[\tilde{\nu}_\tau(\to W\tilde{\tau}_1)] \to \ell\tau\bar{\tau} + \text{MET}$$

Carena, SG, Shah, Wagner, Wang, 1205.5842



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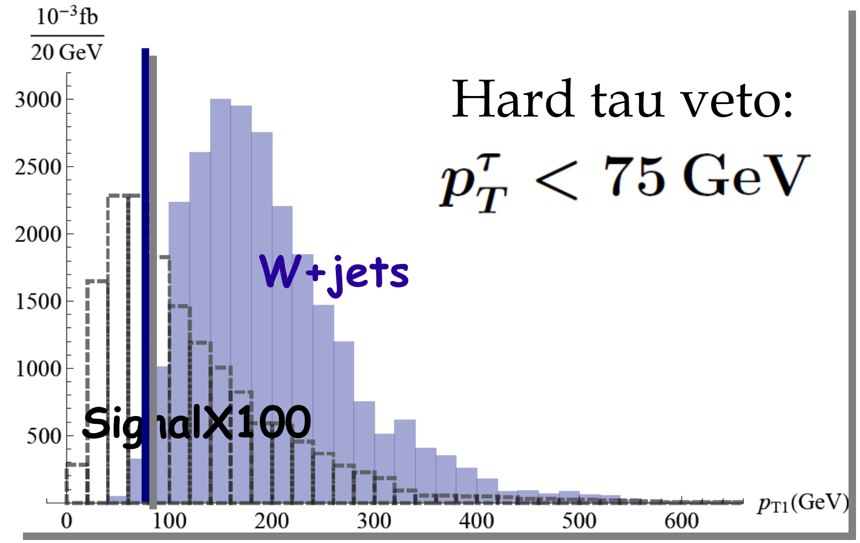


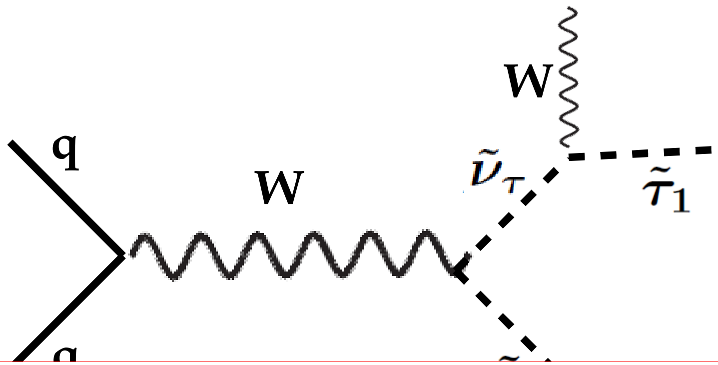
Hard tau veto:

$$p_T^\tau < 75\text{ GeV}$$

Associated production

$$pp \to \tilde{\tau}_1[\tilde{\nu}_\tau(\to W\tilde{\tau}_1)] \to \ell\tau\bar{\tau} + \text{MET}$$

Carena, SG, Shah, Wagner, Wang, 1205.5842



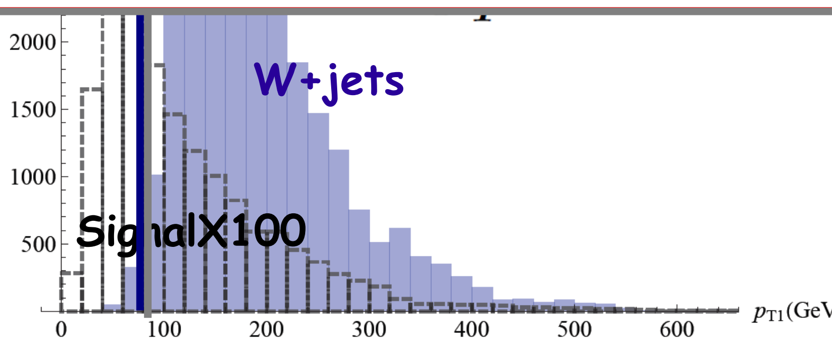
Production cross section for staus at ~ **95 GeV**, sneutrino ~ **270 GeV**:
~15 fb (8TeV), ~40 fb (14TeV)

LHC 14TeV

	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	1.6	0.26	0.11
Physical background, $W + Z/\gamma^*$	27	0.32	$\lesssim 10^{-3}$
$W+$ jets background	10^4	39	0.25

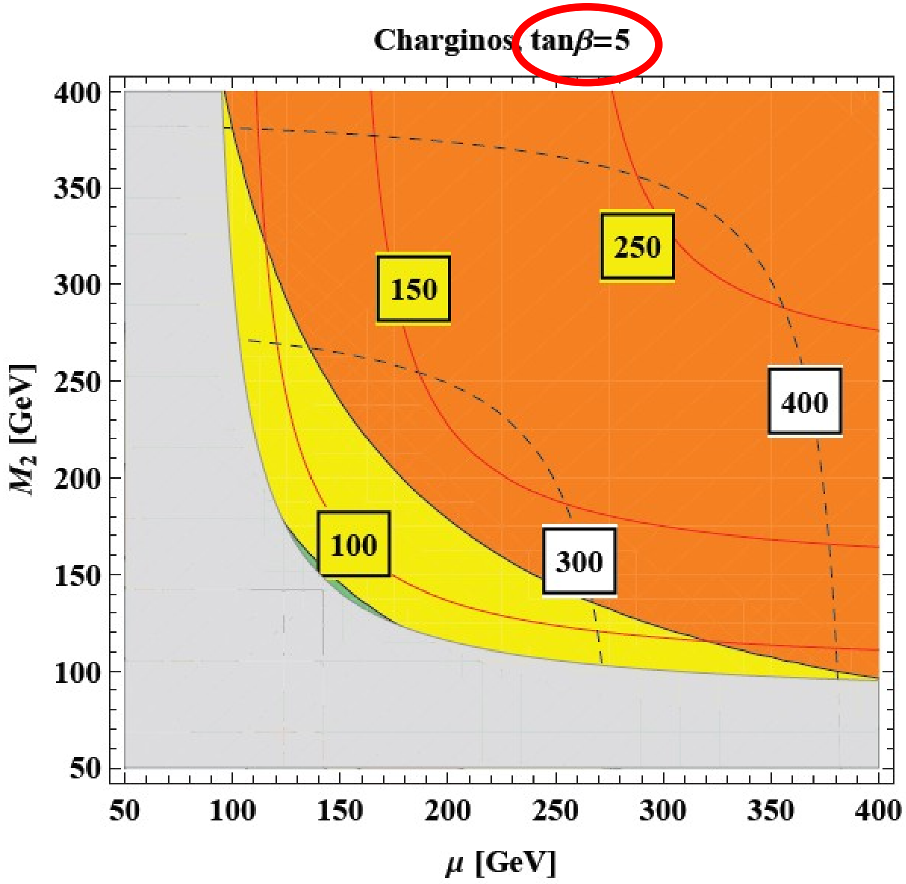
$$p_T^{\tau\,(j)} > 10\,\text{GeV},\ \Delta R > 0.4,\ |\eta| < 2.5$$

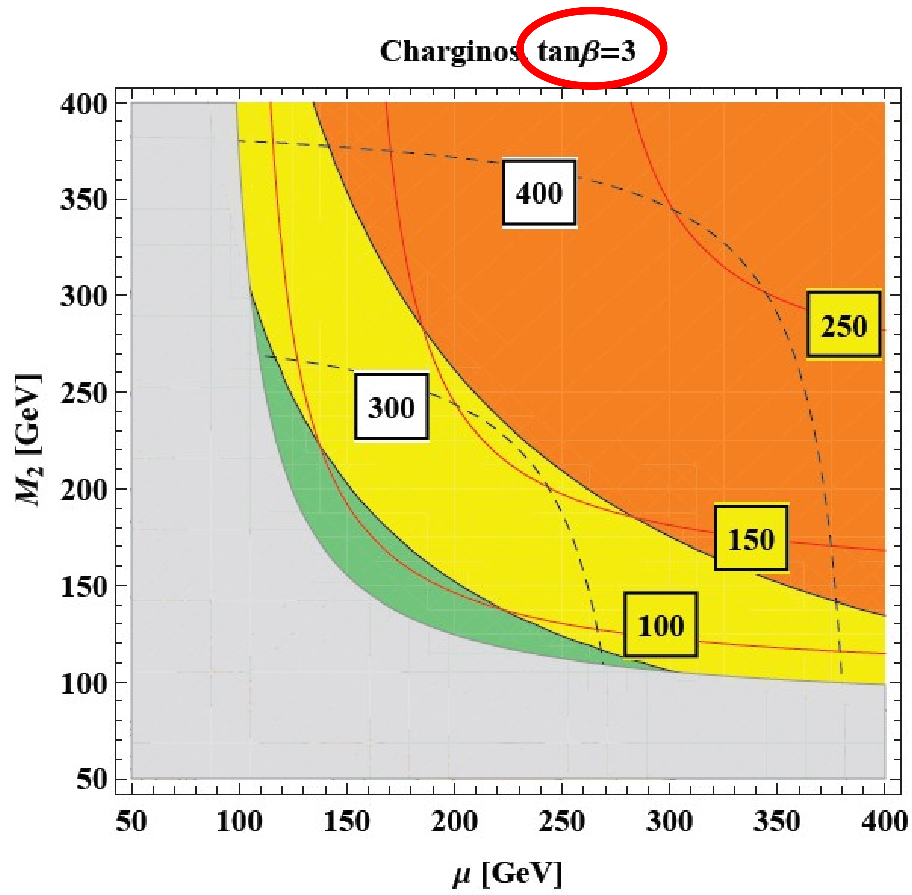
$$p_T^{\ell} > 70\,\text{GeV},\ \not{E}_T > 70\,\text{GeV}$$



Specific NP models 2 (hγγ)

Susy, charginos



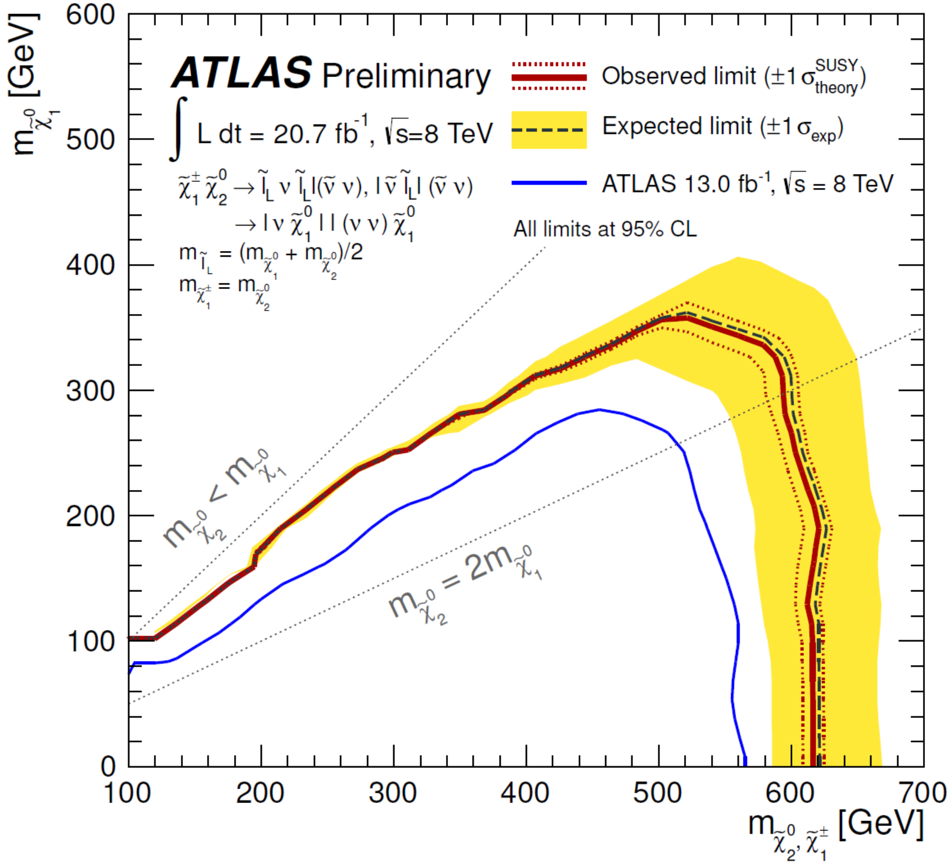


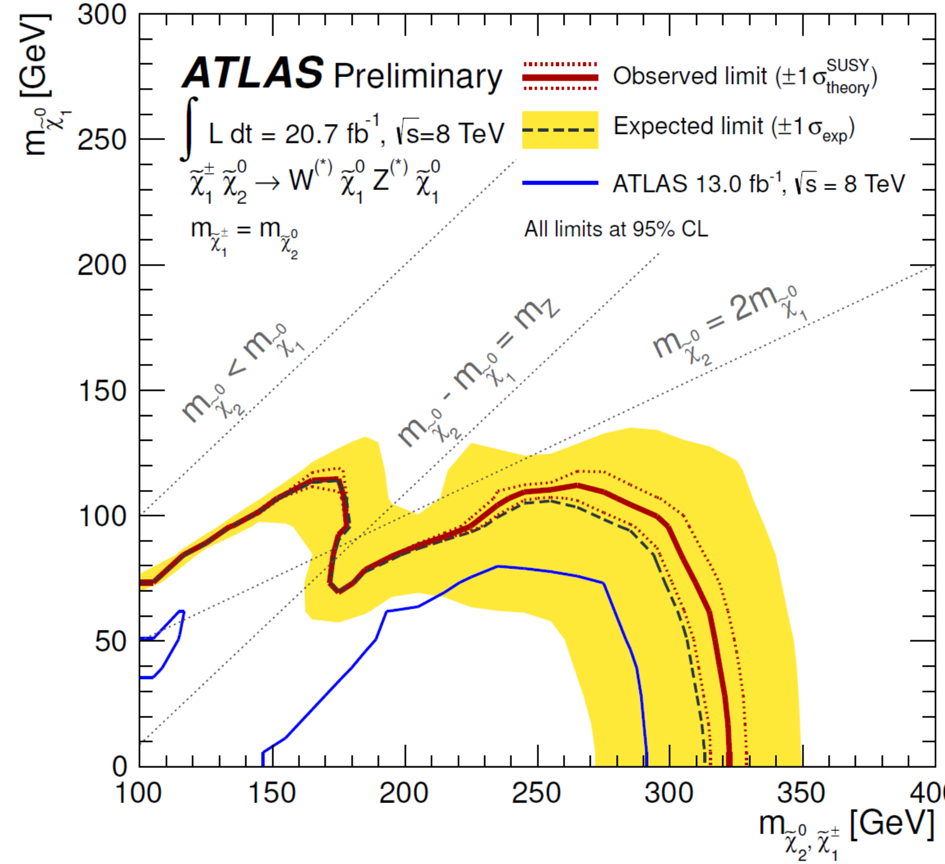
See also
Diaz, Perez, 0412066
Blum, D'Agnolo, Fan, 1206.5303

$$\mathcal{M}_{\chi^\pm} = \begin{pmatrix} M_2 & gv\sin\beta \\ gv\cos\beta & \mu \end{pmatrix}$$

LHC chargino direct searches

$$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to 3\ell + \mathrm{MET}$$





<u>Light sleptons</u>

$$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\ell}_L \ell\, (\tilde{\nu}\nu) \tilde{\ell}_L \nu,\ \tilde{\ell}_L \ell\, (\tilde{\nu}\nu) \ell \tilde{\nu}$$

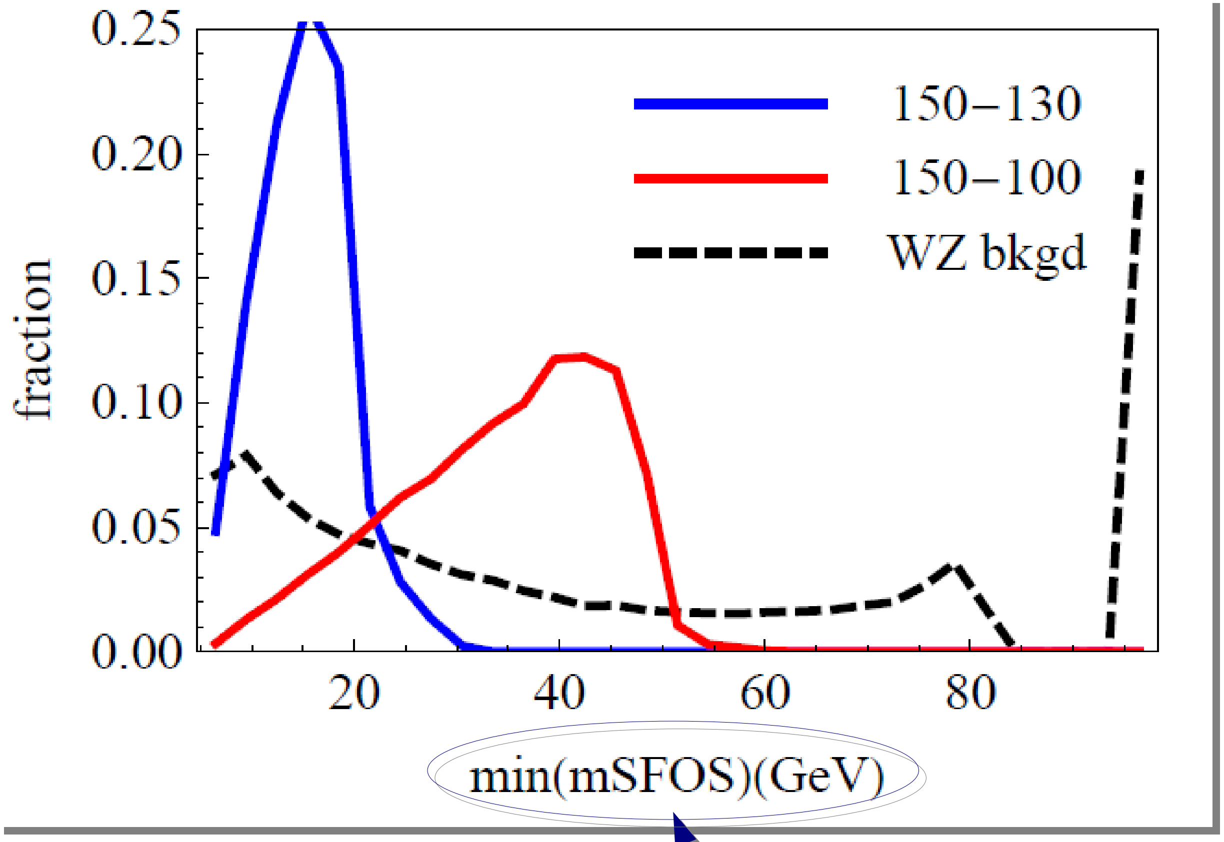
<u>Heavy sleptons</u>

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

What about squeezed scenarios?

Kinematic of the small gap region

SG, Jung, Wang, 1307.xxxx



Minimum of the invariant masses between same flavor opposite sign (SFOS) leptons

Preliminary

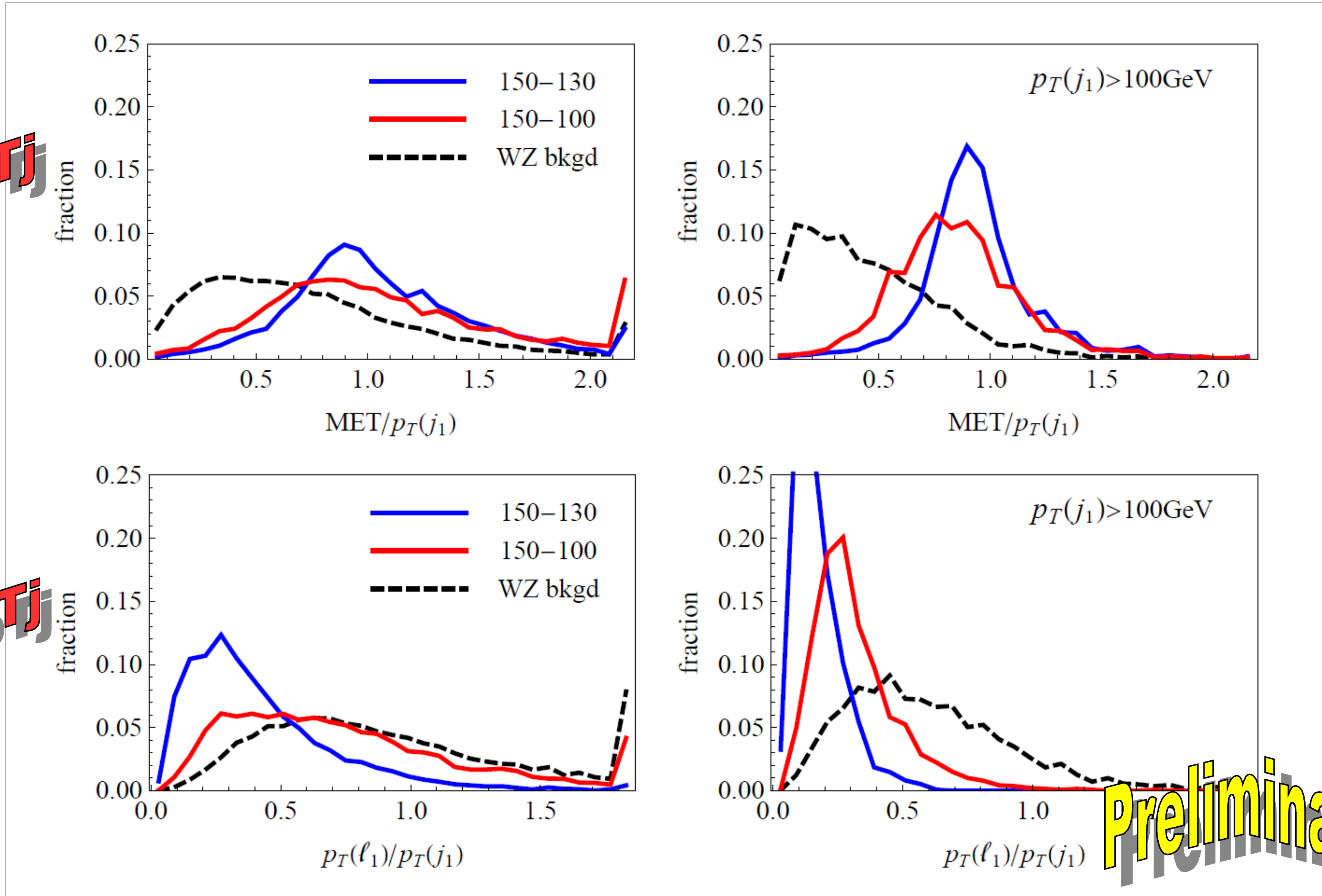
Kinematic of the small gap region

Adding a boosted ISR jet

SG, Jung, Wang, 1307.xxxx

MET/pTj

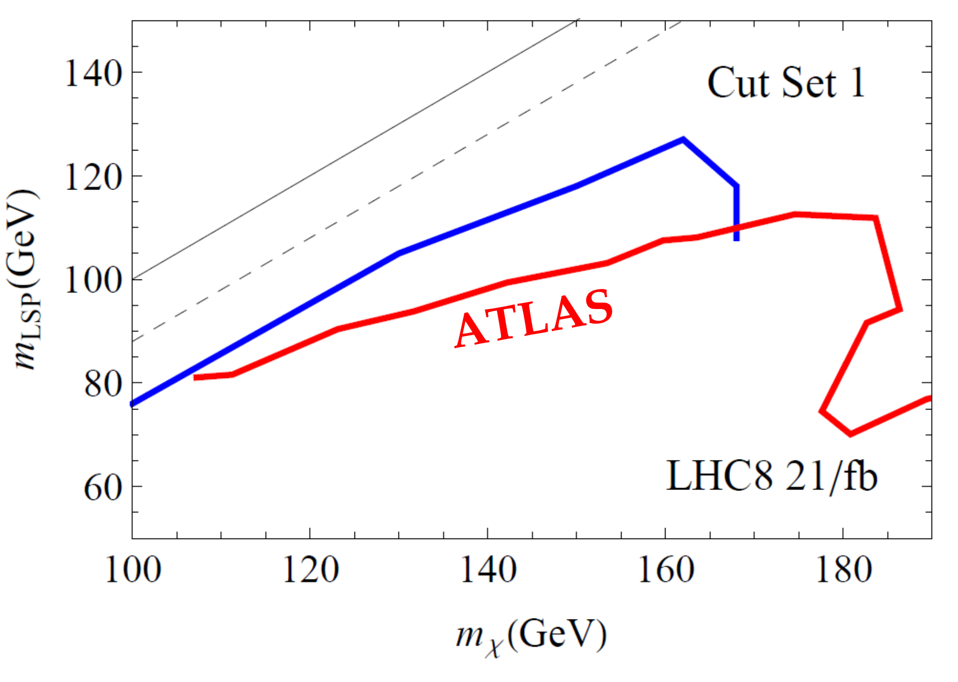
pTl1/pTj



Preliminary

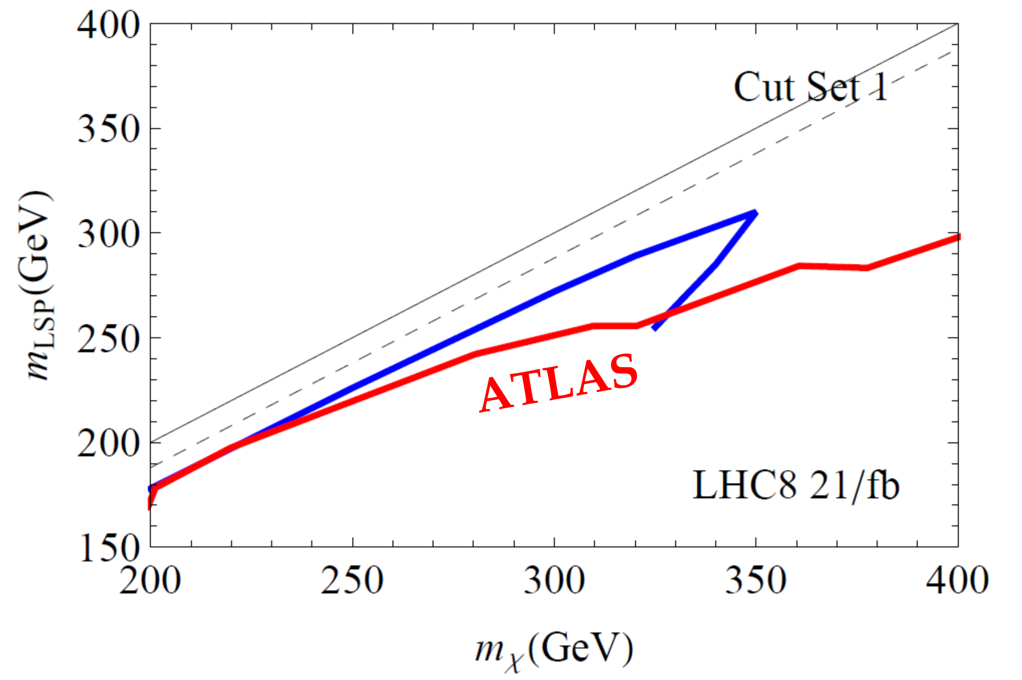
Exclusion plots

SG, Jung, Wang, 1307.xxxx



<u>Heavy sleptons</u>

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



<u>Light sleptons</u>

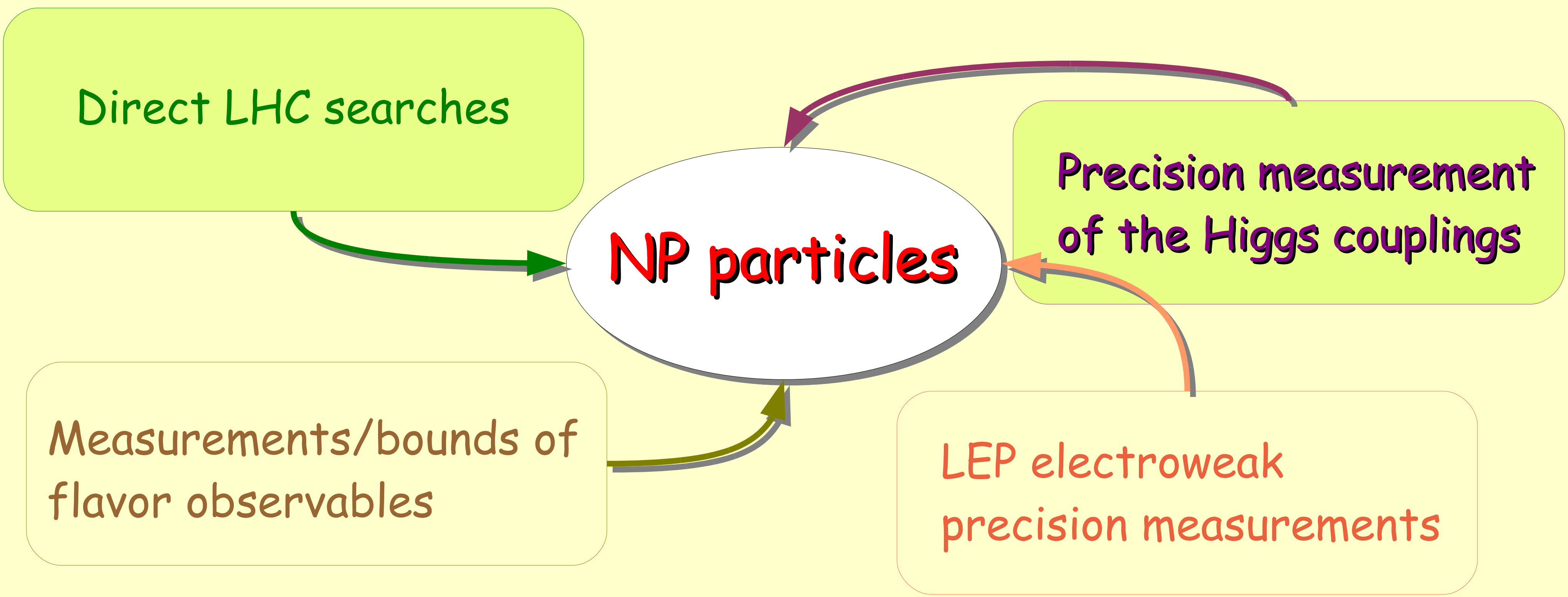
$$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\ell}_L \ell \, (\tilde{\nu}\nu) \tilde{\ell}_L \nu, \; \tilde{\ell}_L \ell \, (\tilde{\nu}\nu) \ell \tilde{\nu}$$

Preliminary

Conclusions

A lot of physics can be learned from the precision measurement of the Higgs (loop induced) couplings

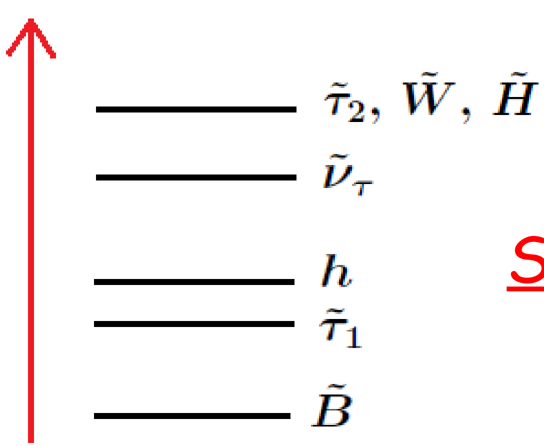
The strength of the complementarity



Staus signals at the LHC

Ex. $m_{\tilde{\tau}_1} \sim 95\,\mathrm{GeV},\ m_{\tilde{\tau}_2} \sim 390\,\mathrm{GeV},\ m_{\tilde{\nu}_\tau} \sim 270\,\mathrm{GeV},\ m_{\chi_0} \sim 35\,\mathrm{GeV}$

	Signature	8 TeV LHC (fb)	14 TeV LHC (fb)
$pp \to \tilde{\tau}_1\tilde{\tau}_1$	$2\tau,\ \not{E}_T$	55.3	124.6
$pp \to \tilde{\tau}_1\tilde{\tau}_2$	$2\tau,\ Z,\ \not{E}_T$	1.0	3.2
$pp \to \tilde{\tau}_2\tilde{\tau}_2$	$2\tau, 2Z,\ \not{E}_T$	0.15	0.6
$pp \to \tilde{\tau}_1\tilde{\nu}_\tau$	$2\tau, W,\ \not{E}_T$	14.3	38.8
$pp \to \tilde{\tau}_2\tilde{\nu}_\tau$	$2\tau, W, Z,\ \not{E}_T$	0.9	3.1
$pp \to \tilde{\nu}_\tau\tilde{\nu}_\tau$	$2\tau, 2W,\ \not{E}_T$	1.6	5.3



Signature: multileptons+missing energy

Chargino searches

(150-120)	cuts	S	$\frac{S}{B}$	$\frac{S}{\sqrt{B}}$	$\frac{S}{\sqrt{B+(0.15\cdot B)^2}}$	sig ratio
baseline	$(p_T(\ell)>10,\ p_T(j)>30,$ $\min(m\mathrm{SFOS})>18,$ $m\mathrm{SFOS}(Z)<81)$	18	0.28	2.2	1.41	–
Tight-p_T cuts	$\min(m\mathrm{SFOS})<\Delta=30$	17	0.76	3.5	2.90	–
	$E_T^{\mathrm{miss}}/p_T(j_1)>0.56$	15	1.2	4.3	3.78	–
	$E_T^{\mathrm{miss}}>30,\ p_T(\ell_1)<50$	12	1.8	4.7	4.36	–
	$p_T(\ell_1)/p_T(j_1)<0.72$	10	2.5	5.0	4.74	0.95
ATLAS	SRnoZa	17	0.52	3.0	2.24	0.45