Anatomizing exotic production the Higgs boson

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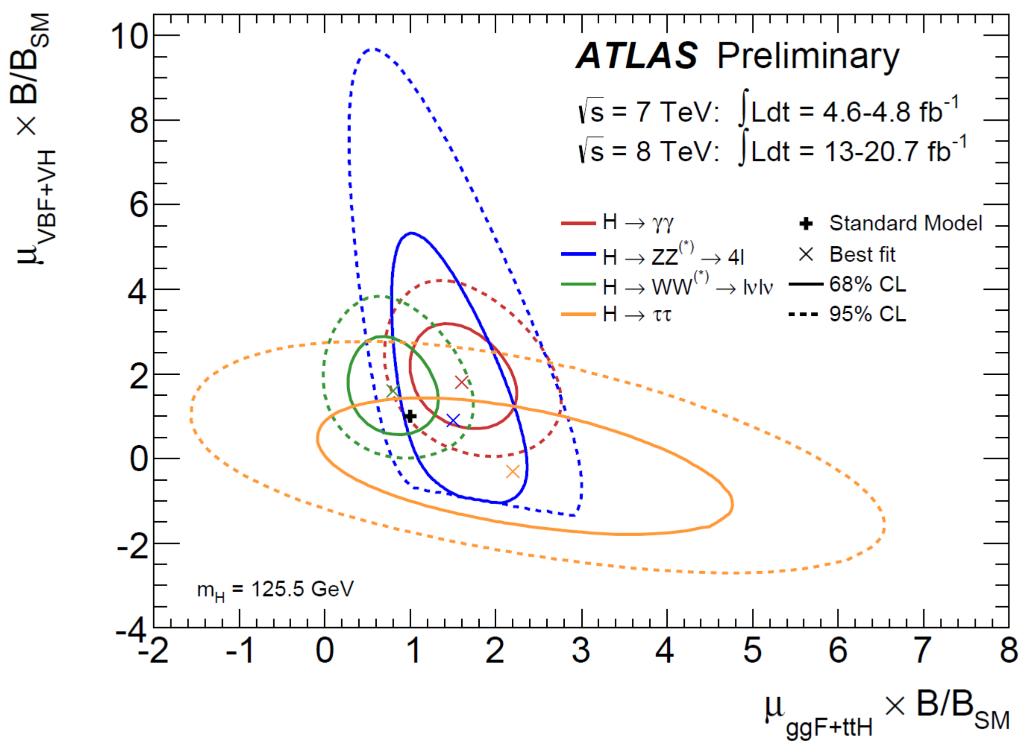
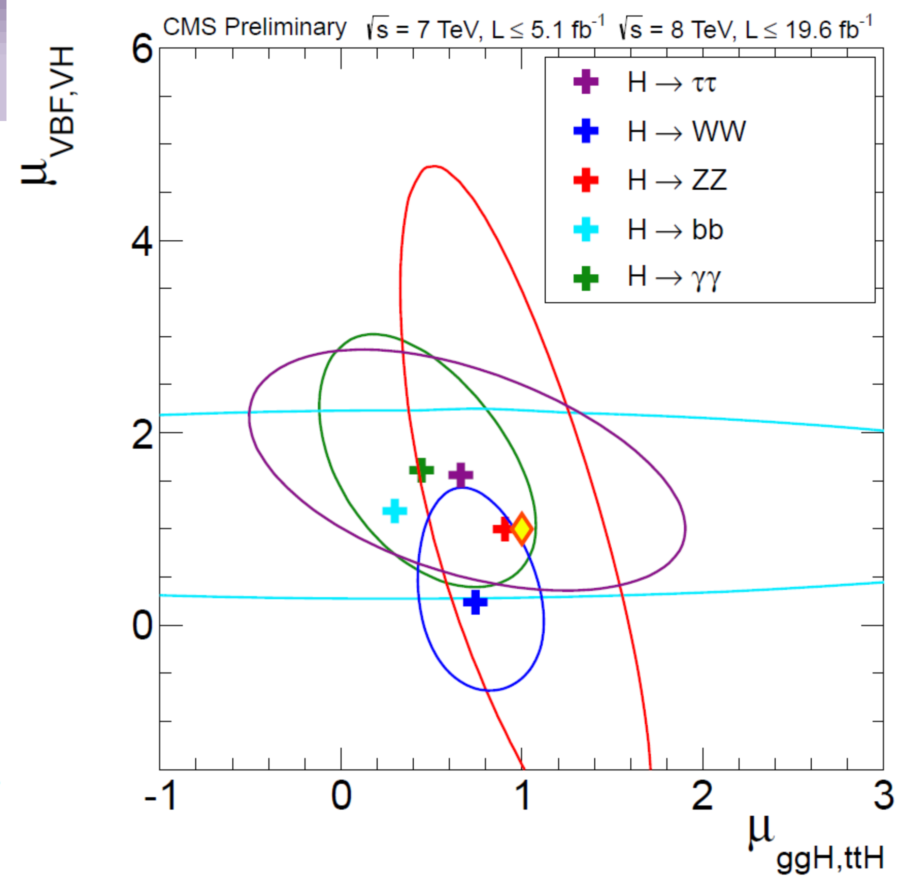
Higgs Couplings





- Signal strength defined as $\mu_i = \sigma_i / \sigma_{i,\mathrm{SM}}$
- Cannot combine separate search channels without an underlying model assumption (*e.g.* SM)

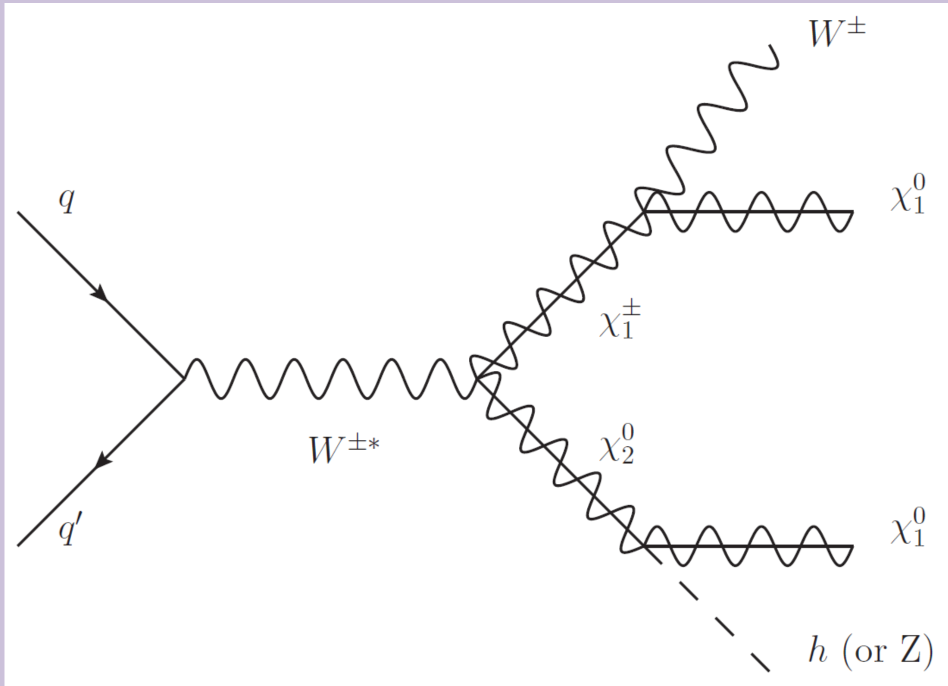
ATLAS-CONF-2013-034, CMS PAS HIG-13-005

Making assumptions

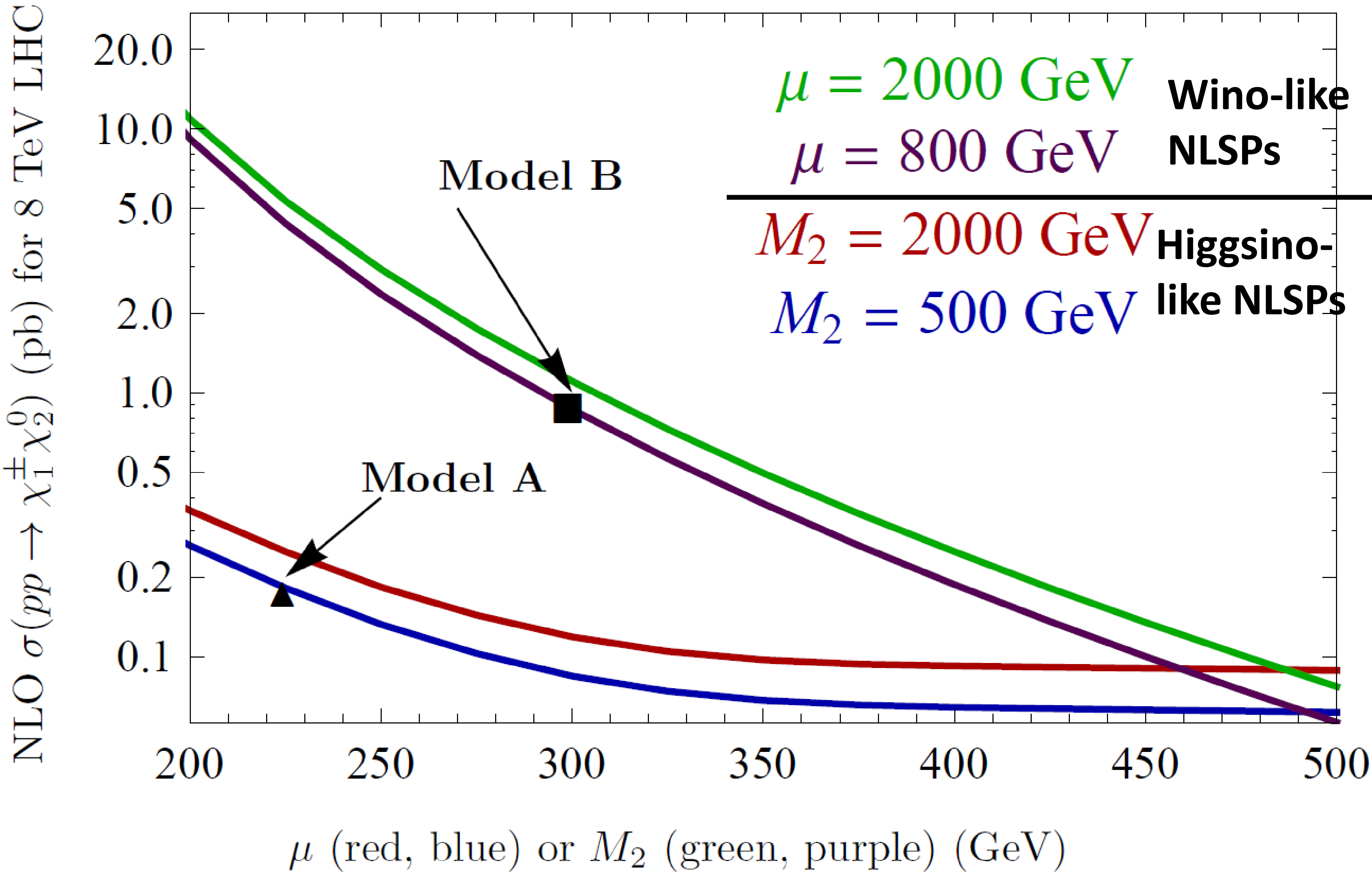
- Thus far, coupling fits have all assumed **no new production modes** for the Higgs
  - A signal strength different from 1 ***is*** New Physics
  - Variation away from 1 assumes NP only manifests as a rescaling of a SM production rate with SM kinematics (*i.e.* known efficiencies)
  - Moreover, effective Lagrangians involving only SM fields necessarily do not include possibilities for on-shell NP states
- Exploring the possibility of exotic production is feasible with current and upcoming data

Testing exotic production

- Consider the concrete case of chargino-neutralino production at LHC
  - Gives final states of $W^{\pm}Z$ + MET or $W^{\pm}h$ + MET (kinematically forbid intermediate sleptons)
  - Controlled by Drell-Yan production, not Higgs couplings

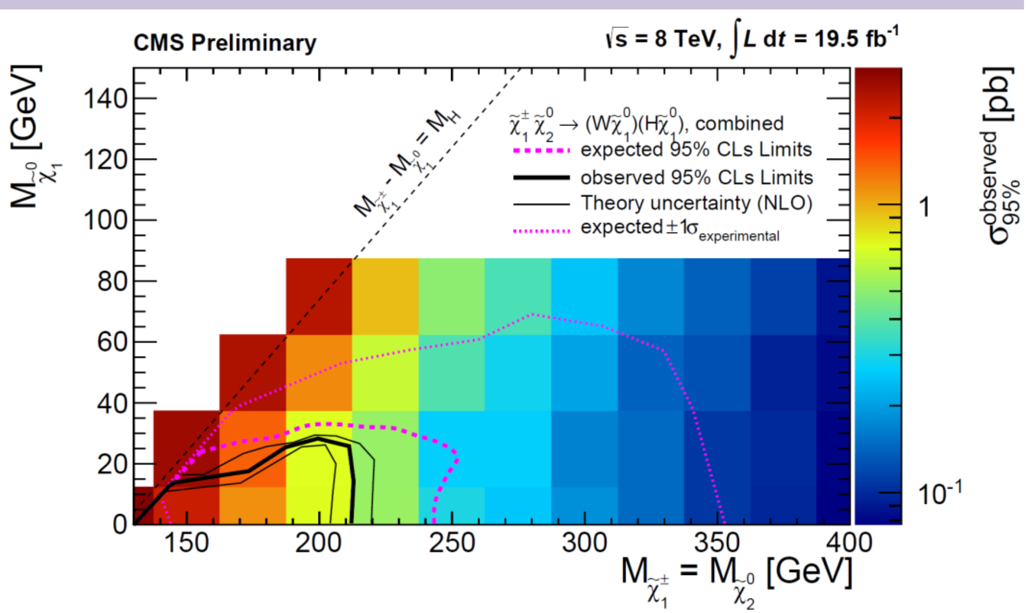


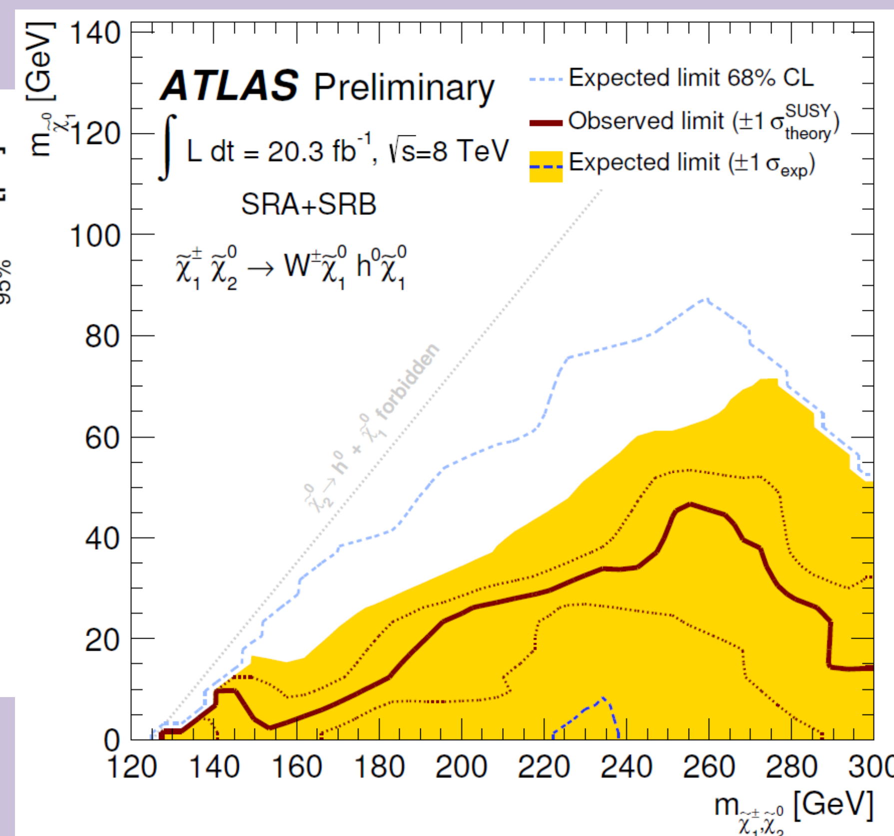
Exotic production rates



Electroweakino searches: $W^{\pm}h$ + MET

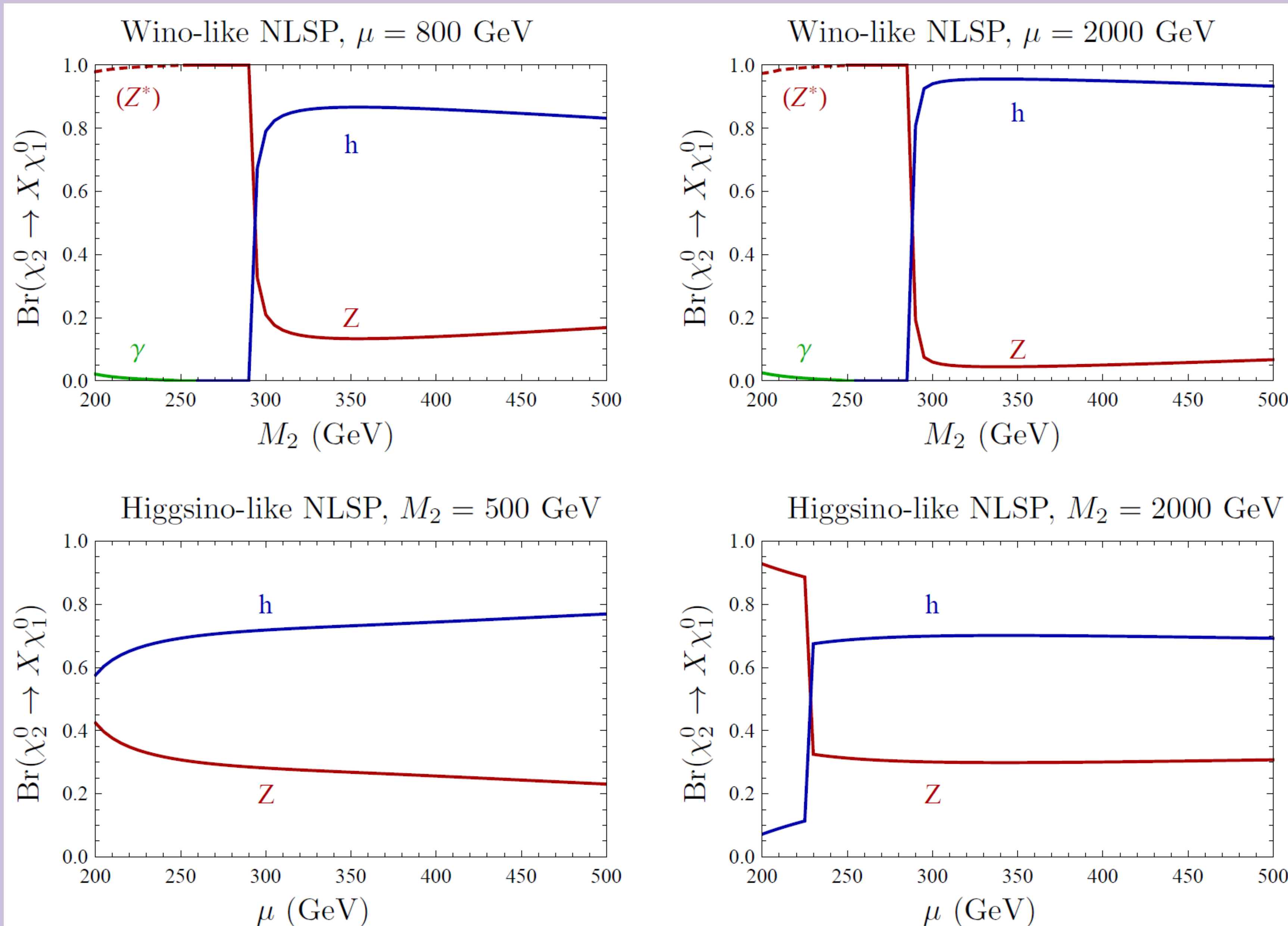
- Current limits in lν(bb)+MET, SS dileptons + jj(j) + MET remove SM Wh production via hard m_T cut – no sensitivity near the Higgs mass splitting line





CMS SUS-13-017, ATLAS-CONF-2013-093

Chargino-neutralino BRs



Two benchmark models

Parameter	Model A	Model B
M_0	2000	2000
$\tan\beta$	10	10
m_A	2000	2000
trilinear A_0	2500	2500
M_1	200	200
M_2	500	300
M_3	2000	2000
μ	225	800
$\chi_1^\pm$ mass	213 GeV	191 GeV
χ_2^0 mass	215 GeV	191 GeV
χ_1^0 mass	57.8 GeV	61.5 GeV

$\mathrm{BR}(\chi_2^0 \to h\chi_1^0)$	66.2%	79.1%
$\mathrm{BR}(\chi_2^0 \to Z\chi_1^0)$	33.8%	20.9%
$\mathrm{BR}(\chi_2^\pm \to W^\pm\chi_1^0)$	100%	100%
$\sigma(\chi_1^+\chi_2^0)$	0.126	0.622
$\sigma(\chi_1^-\chi_2^0)$	0.058	0.295
Ωh^2	0.0211	0.117
$\sigma_{SI,p}$	7.3×10^{-10}	2.2×10^{-11}
$\sigma_{SD,p}$	5.9×10^{-5}	3.3×10^{-7}
$\sigma_{SI,n}$	7.4×10^{-10}	2.3×10^{-11}
$\sigma_{SD,n}$	4.5×10^{-5}	2.6×10^{-7}
$\mathrm{Br}(h \to \chi_1^0\chi_1^0)$	0.035	3.6×10^{-5}

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Can have large exotic production rates

Mass difference between NLSPs and LSP is close to m_h

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MSSM illustration: chargino-neutralino production

- Use MadGraph 5 for signal generation
- Implement ATLAS and CMS diphoton, ZZ and WW analyses
  - Important to use high-resolution final states in order to distinguish possible contamination from NP production processes
    - The ττ and bb analyses are usually MVA/BDT and intractable for theorists to reproduce
- Illustrate how this exotic production mode is categorized under current search strategy
  - Other analyses dedicated to single subleading SM production modes are not as useful in disentangling exotic production

ATLAS categorization efficiencies

Analysis	Category	Model A	Model B
$\gamma\gamma$	Lepton	6.3%	6.6%
	MET significance	28.2%	22.7%
	Low-mass two-jet	1.4%	1.9%
	High-mass two-jet	0.2%	0.2%
	Untagged	9.1%	14.0%
ZZ^*	ggF-like	21.5%	21.4%
	VBF-like	0.2%	0.2%
	VH-like	7.1%	7.1%
WW^*	$N_{\text{jet}} = 0$	1.6%	1.7%
	$N_{\text{jet}} = 1$	3.4%	3.1%
	$N_{\text{jet}} \geq 2$	<0.1%	<0.1%

Before cuts: Expect about
8 (41) γγ events for Model A (B)
0 (2) ZZ* to 4l events,
86 (429) events for h → lνlν,
347 (1730) events for h→lνjj

	ggF	VBF	WH	ZH	$t\bar{t}H$
N_{events} for 20.7 fb^{-1}	888.2	73.5	31.9	18.9	5.9
Lepton	0.0%	0.0%	5.3%	2.2%	8.5%
E_T miss significance	0.0%	0.0%	1.3%	3.0%	2.4%
Low-mass two-jet	0.2%	0.0%	2.9%	2.9%	0.0%
Tight high-mass two-jet	0.2%	8.0%	0.0%	0.0%	0.0%
Loose high-mass two-jet	0.3%	3.7%	0.0%	0.0%	0.0%
Untagged	36.0%	25.8%	21.9%	22.2%	17.0%

Extracted ATLAS γγ efficiency

CMS categorization efficiencies

Analysis	Category	Model A	Model B
$\gamma\gamma$	Muon	5.2%	5.1%
	Electron	5.1%	5.1%
	Dijet tight	0.1%	0.1%
	Dijet loose	0.3%	0.3%
	E_T miss	26.7%	16.8%
	Untagged	20.2%	32.5%
ZZ^*	Category 1, $N_{\text{jet}} \leq 1$	22.1%	22.9%
	Category 2, $N_{\text{jet}} \geq 2$	11.6%	10.8%
WW^*	0−jet	0.3%	0.4%
	1−jet	1.0%	1.2%

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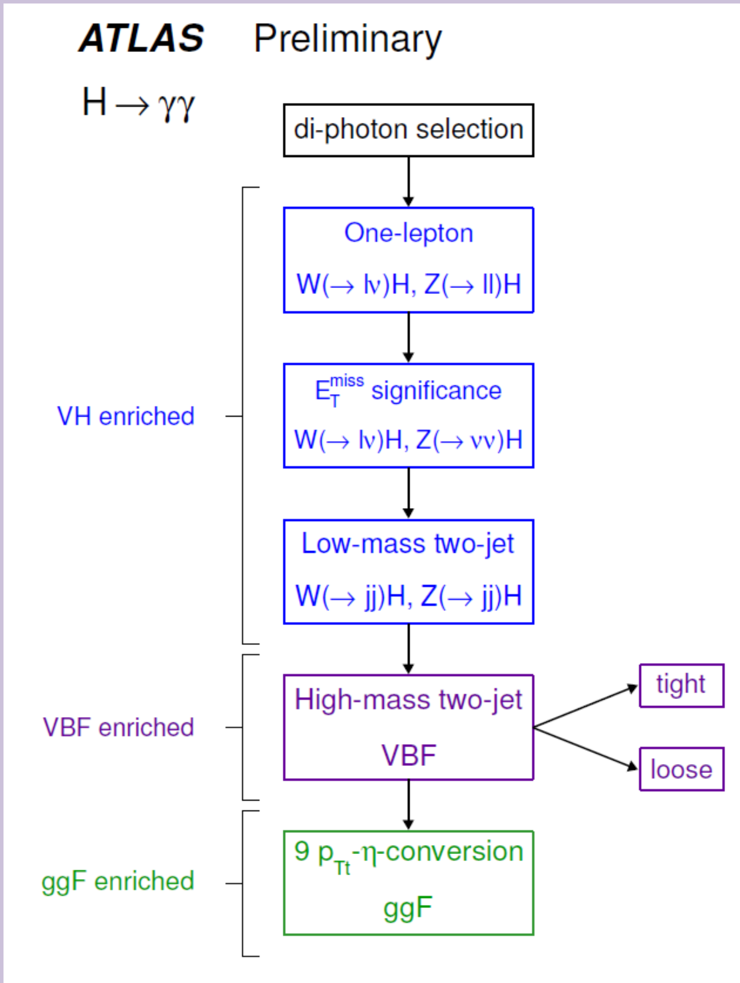
	ggF	VBF	VH	$t\bar{t}H$
N_{events} for 19.6 fb^{-1}	861.1	70.5	50.0	5.8
Muon	0.0%	$< 0.1\%$	2.2%	5.0%
Electron	$< 0.1\%$	$< 0.1\%$	1.4%	3.1%
Dijet tight	0.2%	10.3%	$< 0.1\%$	0.2%
Dijet loose	0.6%	8.3%	0.4%	1.0%
E_T miss	$< 0.1\%$	$< 0.1\%$	2.2%	3.4%
Untagged combined	38.3%	25.7%	31.1%	32.9%

Extracted CMS γγ efficiency

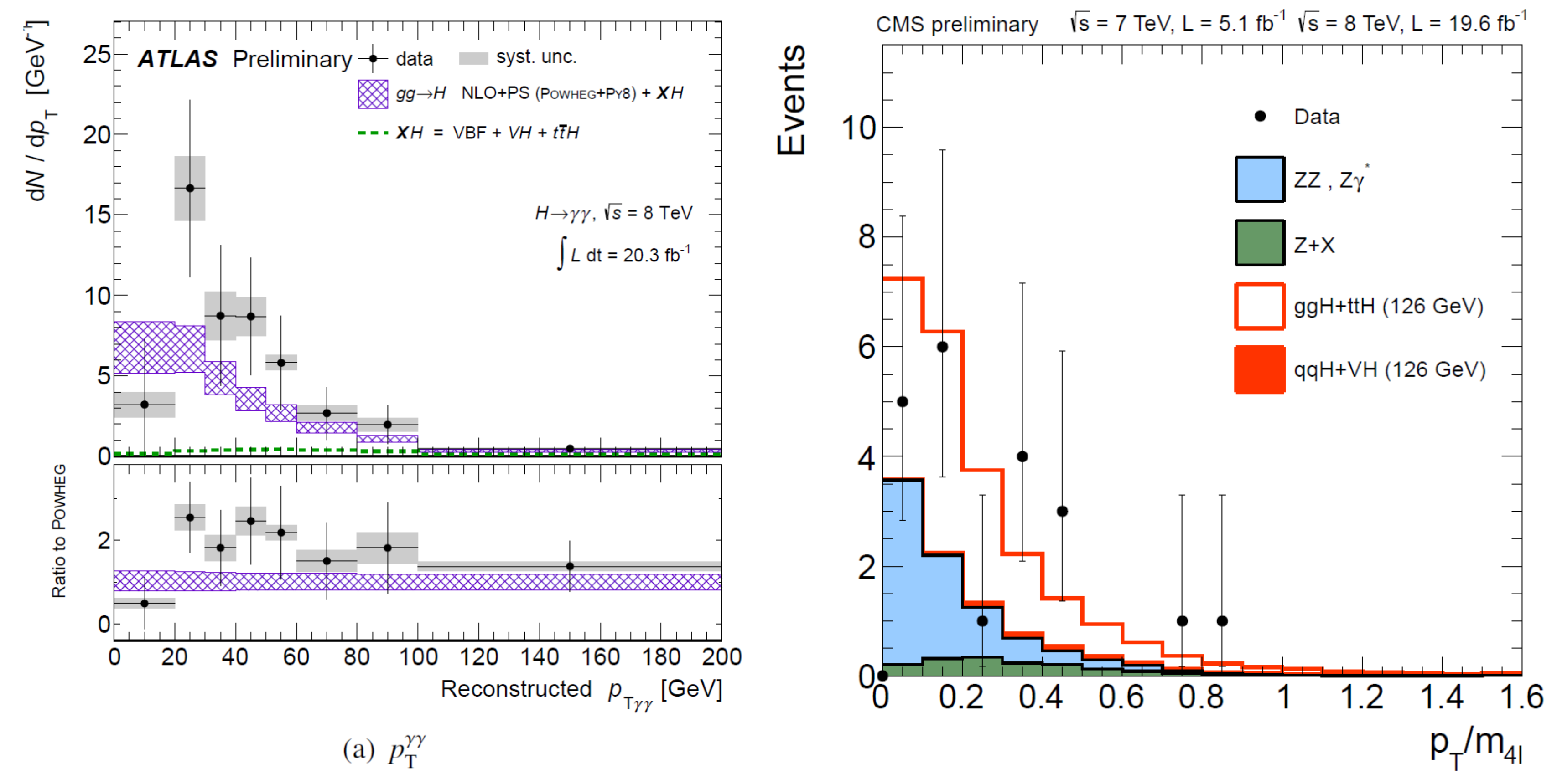
Inclusive/exclusive $\gamma\gamma$ rates

- Categorizing by multiplicities still leaves ambiguities in identifying production modes
  – Gluon fusion is catch-all
  – Contamination by NP can be significant
- Cannot use a rescaling of a SM production mode to capture the NP effects
- Need shapes to disentangle



Tests for exotic production

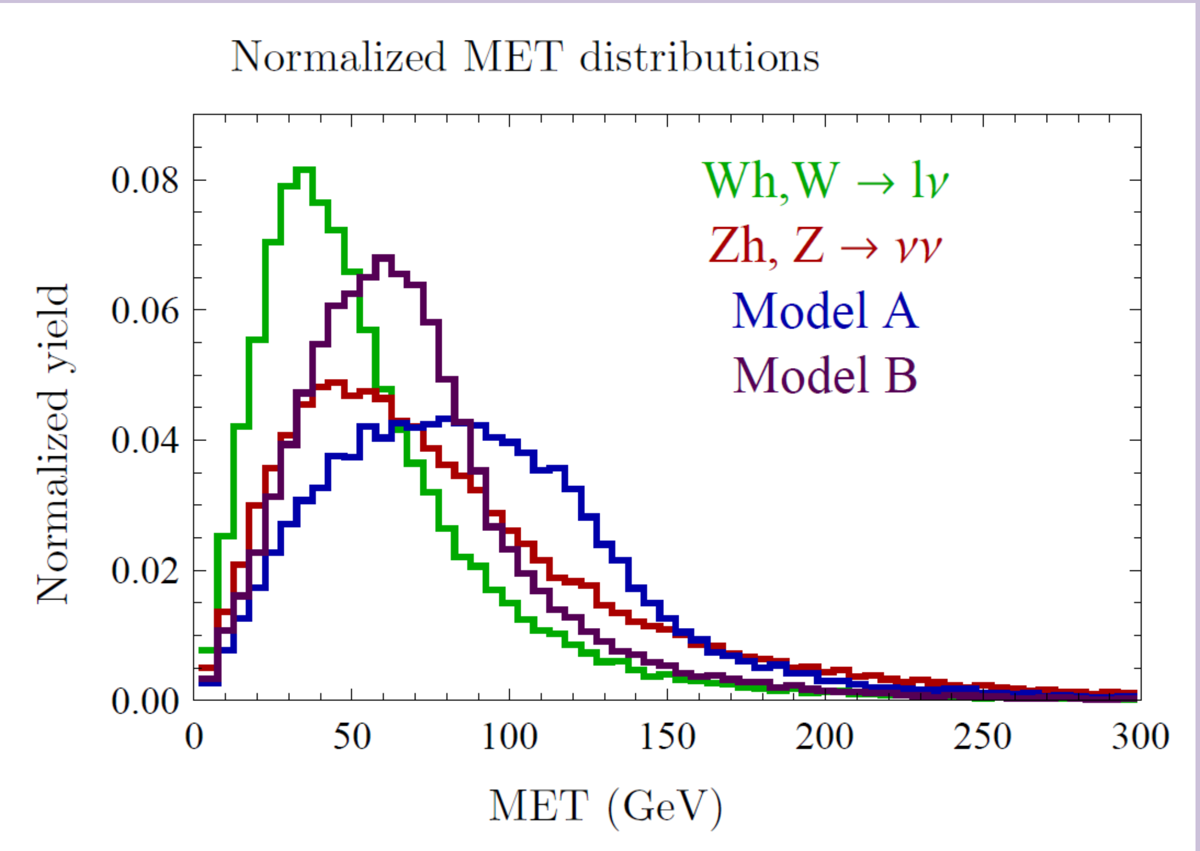
- Need counts and kinematics of associated objects
- Also should probe the p_T of the Higgs candidates



(a) $p_T^{\gamma\gamma}$

Testing for exotic production

- Also should look at MET distributions
- Disentangling these shapes requires high-resolution final states (*e.g.* 4l or γγ)



Summary

- The current suite of tests for the presence of new physics in Higgs data is incomplete
- Exotic Higgs production is a new class of models to probe with current and future data
- Advocate experiments to publish differential distributions of Higgs candidates and kinematics of associated objects
- Exotic production of the Higgs could be the initial signature of new physics present in current data

Negative signal strength

- Negative signal strength corresponds to observing fewer events than the background expectation
- Still require that the "negative signal" contribution give a non-negative number of events (equivalently, a positive probability density function)

$$\tilde{\lambda}(\mu) = \begin{cases} \dfrac{L(\mu, \hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})} & \hat{\mu} \geq 0, \\ \dfrac{L(\mu, \hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(0, \hat{\hat{\boldsymbol{\theta}}}(0))} & \hat{\mu} < 0. \end{cases}$$

ATLAS, 1207.0319

Higgs Measurements – introducing NP

- Alternatively, can consider higher dimension operators and fit for coefficients
- As an illustration: light Higgs as a Goldstone boson

$$\begin{aligned}\Delta\mathcal{L}_{SILH} =& \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\ &+ \left(\left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right) \\ &+ \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\ &+ \frac{i\bar{c}_{HW}\,g}{m_W^2}\left(D^\mu H\right)^\dagger\sigma^i\left(D^\nu H\right)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\left(D^\mu H\right)^\dagger\left(D^\nu H\right)B_{\mu\nu} \\ &+ \frac{\bar{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,,\end{aligned}$$

Giudice, Grojean, Pomarol, Rattazzi (hep-ph/0703164)
Contino, Ghezzi, Grojean, Muhlleitner, Spira (1303.3876)
Azatov, Contino, Iura, Galloway (1308.2676) + more

Expanding to more models

- Other models with similar kinematics and cascade decay objects will give similar efficiencies
  - Rate is largely controlled by mass scale of SUSY parents
- RPC SUSY will be typically limited by MET significance bin of the diphoton analysis

Diphoton 8 TeV counts: expected background and SM signal contributions

Can constrain chargino-neutralino production along Higgs mass splitting line

Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV) Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37	1.7 ± 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27	22.1 ± 0.5
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39	94.3 ± 1.0
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54	570.5 ± 2.6
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14	1060.9 ± 3.5
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50	3.4 ± 0.2
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60	12.4 ± 0.4
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52	0.7 ± 0.1
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54	0.7 ± 0.1
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64	1.8 ± 0.1

CMS PAS HIG-13-001

Extracted ATLAS ZZ* and WW* effs.

	ggF+$t\bar{t}H$	VBF	WH+ZH
N_{events} for 20.7 fb^{-1}	50.8	4.1	2.8
ggF-like	26.6%	19.3%	23.0%
VBF-like	0.6%	10.5%	0.4%
VH-like	0.1%	0.0%	5.0%

	Signal
N_{events} for 20.7 fb^{-1}	11029
0-jet	0.907%
1-jet	0.372%
$\geq$ 2-jet	0.099%

Extracted CMS ZZ* and WW* effs.

N_{events} for 5.1 fb^{-1} + 19.6 fb^{-1}	ggF 60.9	VBF 5.0	WH 2.2	ZH 1.3	$t\bar{t}H$ 0.4
0/1-jet	25.3%	14.0%	12.6%	16.1%	0.0%
Dijet	2.6%	17.3%	9.5%	12.3%	20.3%

N_{events} for 19.4 fb^{-1}	ggF 8852	VBF+VH 1212
0-jet	1.62%	0.27%
1-jet	0.60%	0.79%

Electroweakino searches: $W^{\pm}Z$ + MET

- Current limits in multilepton final state (assuming 100% branching fraction to WZ + MET)