CMS SUSY Searches with Higgs in the Final States

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Texas A&M University
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Outline

- "Why SUSY?" by analogy (theorists can ignore this)
- SUSY battle, the higgsino frontier →h+X searches
  - Strong production (very briefly)
  - Strong vs weak production:
    - "Natural" higgsino: higgsino + 3rd generation
  - Electroweak ("ElectroHiggs") production

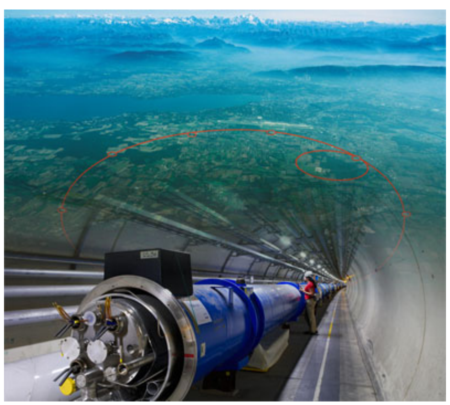
    Higgs is the best EWSB exploration tool we have.
  - Omnibus ElectroHiggs search scheme
- BSM (SUSY/non-SUSY) with higgs in the final state
  - 2HDM, t→ch (If time permits) (See A. Perieanu, Tuesday)
- Speculation: SUSY, if alive, is well.
  - Stau (N)NLSP

Searching for SUSY

Latest results from CMS:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

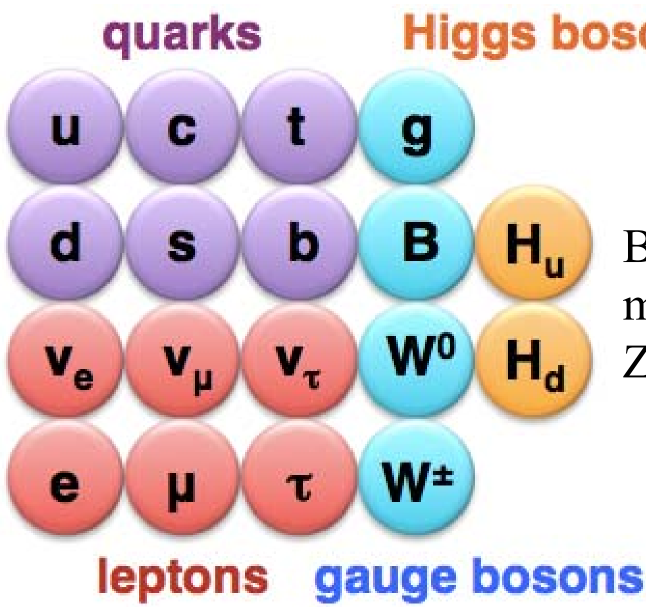
(or search for “cms susy results”)



Conventional “SUSY 101”

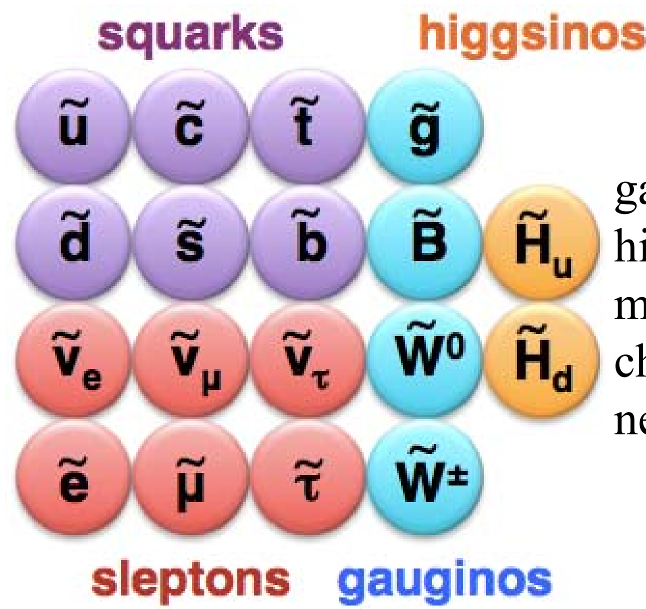
New spin-based symmetry relating fermions and bosons

SM Particles



B & W^0 mix to give Z & γ

SUSY Particles



gauginos & higgsinos mix to give charginos & neutralinos

If R-Parity is conserved, provides Dark Matter Candidate (Lightest Supersymmetric Particle or LSP)

- R-parity = $(-1)^{3(B-L)+2s}$ → R = +1 (-1) for SM (SUSY) particles

Supersymmetry Motivation by Analogy

Doubling the spectrum (particle → sparticle) is a big price!

→Worked once before: Assembling the electron (Murayama, TASI Lectures)

Electron q=1.6x10^{-19} Coul , radius < 10^{-19}m

[200GeV ~ 10^{-18}m ➔ r_e < 10^{-18}m (from g_e), LEP 2006: 10 TeV contact interaction ➔ r_e < 10^{-20}m]

$E_{assembly}$ ~ +q^2/r_e ~ 10,000 MeV but m_e~ 0.5 MeV

➔Large *negative* correction

m_e = 0.5 MeV = -9999.5 MeV + 10,000 MeV

FIX: Double the particle spectrum! positron i.e., new physics at ~2m_e ~1MeV~200fm

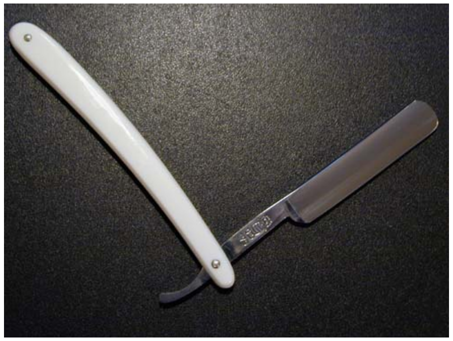
Weisskopf (1939): $E_{assembly}$ ~ +q^2/r_e cancelled by $E_{vacuum\ pair}$ ~ -q^2/r (e^+ from vacuum)

$$(m_e c^2)_{obs} = (m_e c^2)_{bare} \left[1 + \frac{3\alpha}{4\pi} \log \frac{\hbar}{m_e c r_e} \right]$$

Occam's Razor: Particle Physics Version

We like doubling the particle spectrum.

Single Blade (electron)

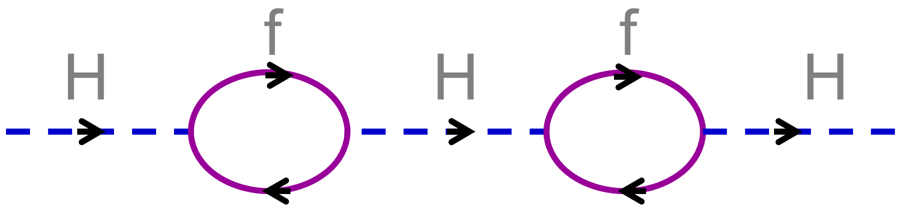


Twin Blade
(electron & positron)

Multiple Blades
(electron, positron, selectron?...)

SUSY: Why?

Today: Higgs has the same “hierarchy problem”.



Radiative loops: $M_H \sim 10^{15}$ GeV, but Higgs at 100 GeV (EW scale)

Delicate cancellations at high energy

OR

SUSY at TeV scale

- hierarchy problem solution → stop loops cancel the top loops

But SUSY is badly broken. m(selectron) >> 0.5MeV

SUSY-Breaking Defines Phenomenology

- **Signatures depend on SUSY breaking, mass hierarchy and mixing**

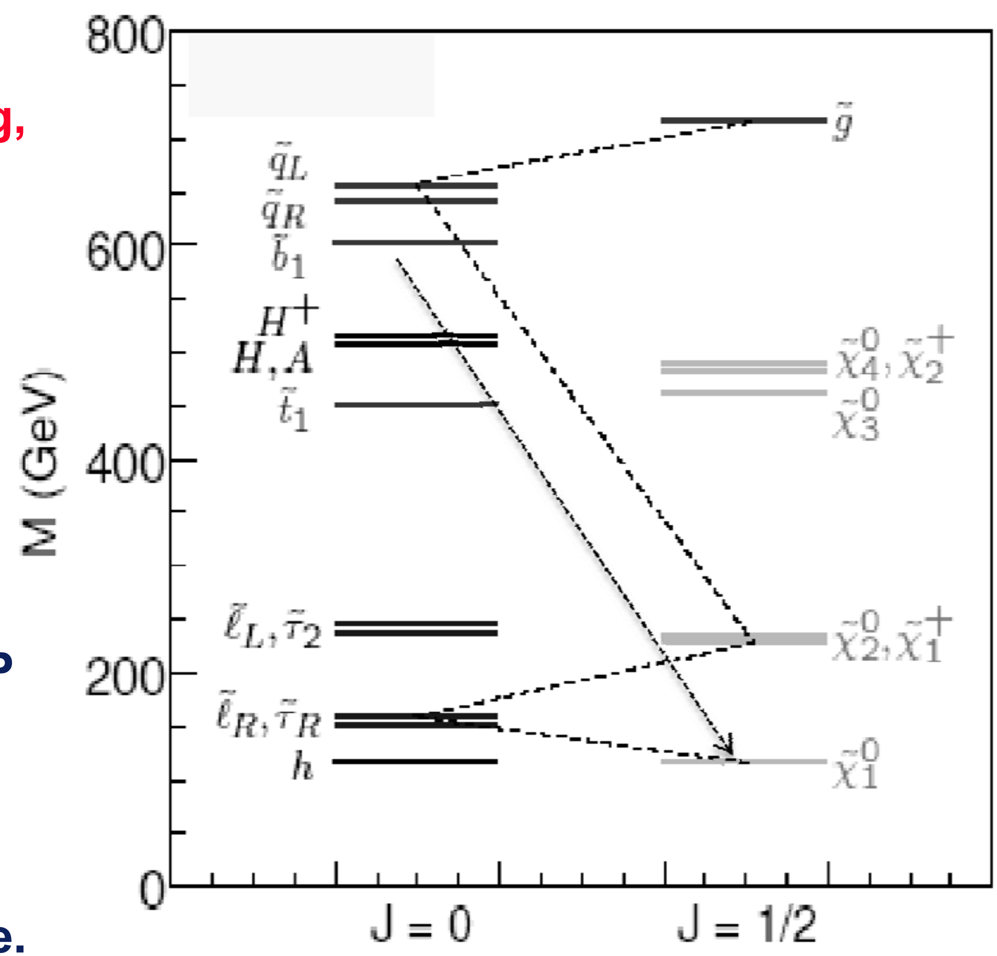
General prejudice:
RGE running →

- **Strongly interacting particles heavy**
- **Weakly interacting (middle)**

e.g. with R-parity, Stable Lightest Supersymmetric Particle (LSP)

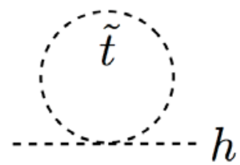
→ Missing E_T (MET) signature (from LSP and neutrinos)

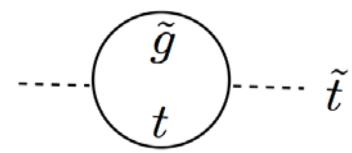
→ BUT many mass spectrum variations leading to rich search topology space.



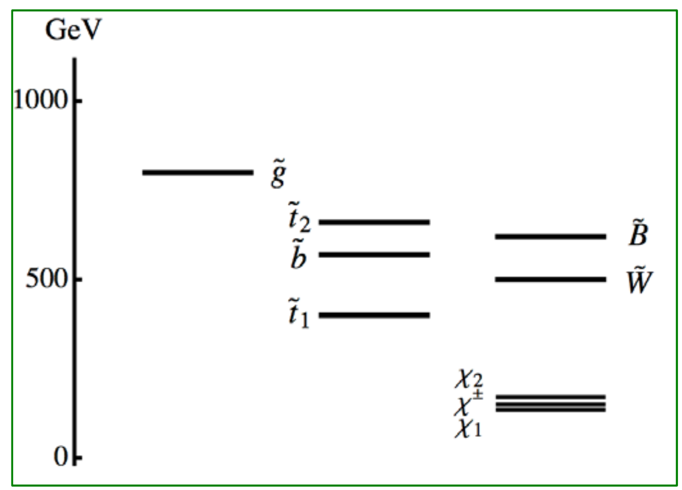
“Natural” SUSY Scenarios

- Hierarchy problem:
  - Higgs mass at the weak scale despite divergent corrections from top loops
  - Large cancelations are unnatural
- Solution:
  - SUSY could make this natural
  - top squark adds canceling terms
  - gluino mass should not be too large also so its contributions to the top squark are controlled.



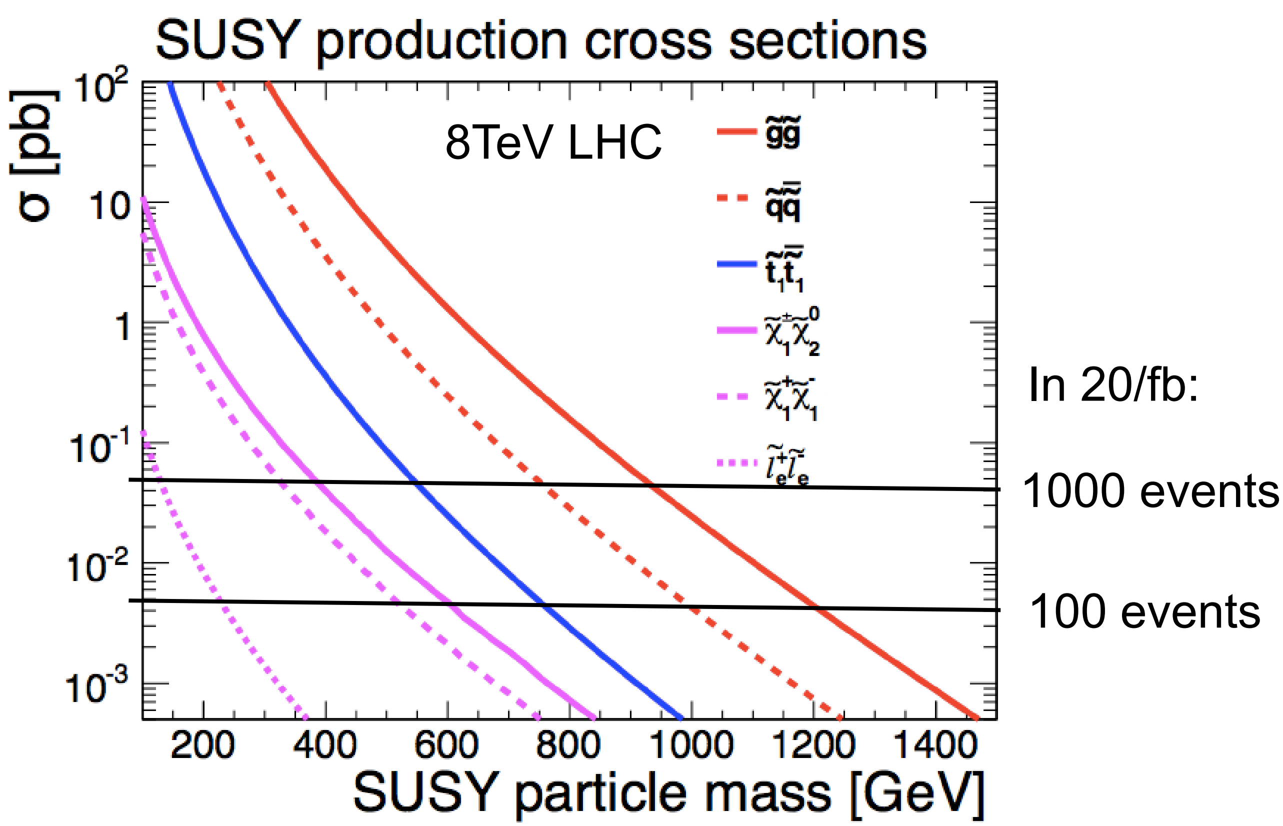


- Leads to “natural” SUSY spectrum:
  - 3rd generation squarks part of “nuclear family”, while the other generations can be heavy and decoupled
  - Some charginos and neutralinos (the higgsinos) at ~ the weak scale.



R.Barbieri & D.Pappadopulo JHEP 0910:061,2009

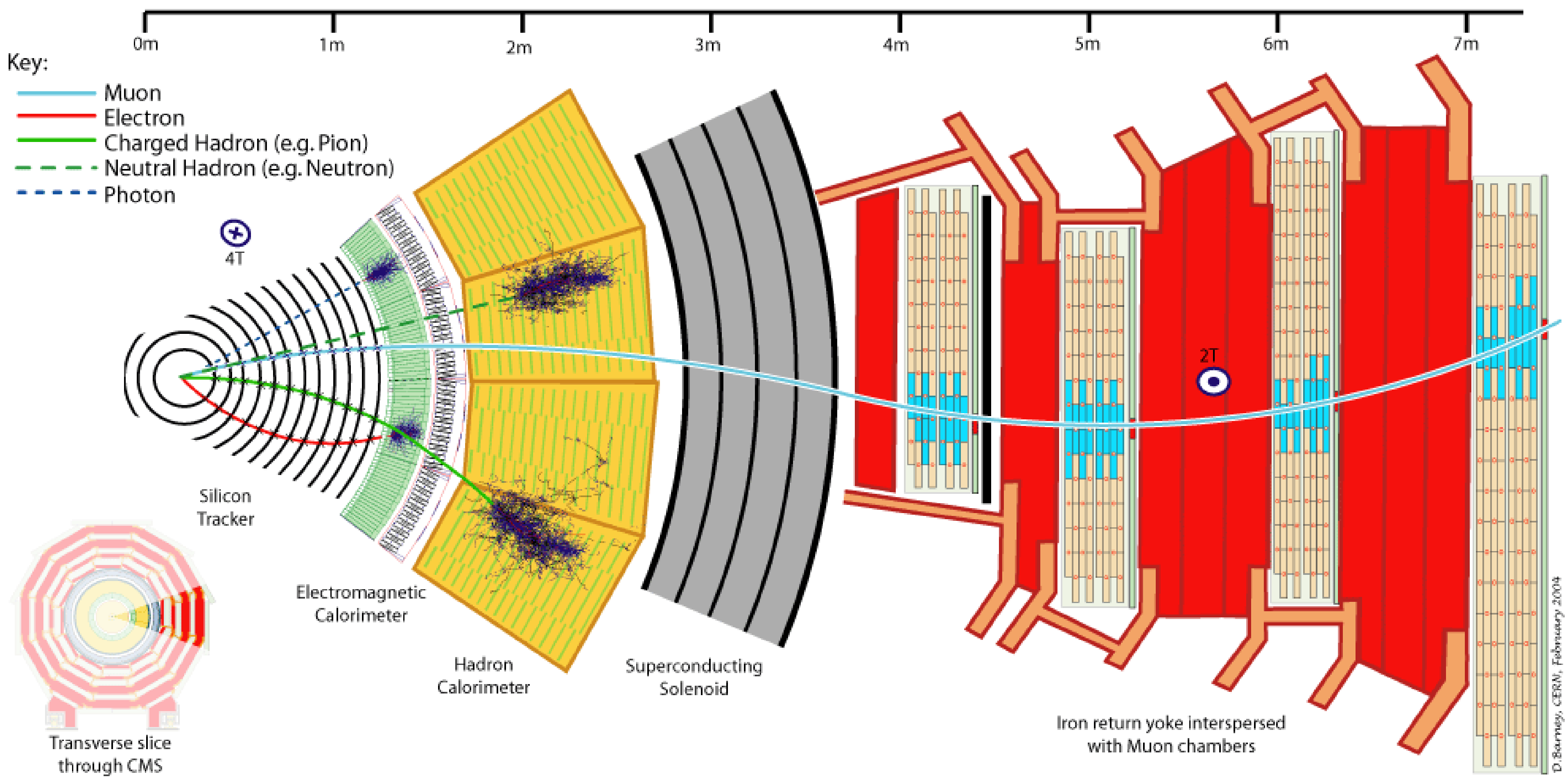
SUSY Particle Production at the LHC



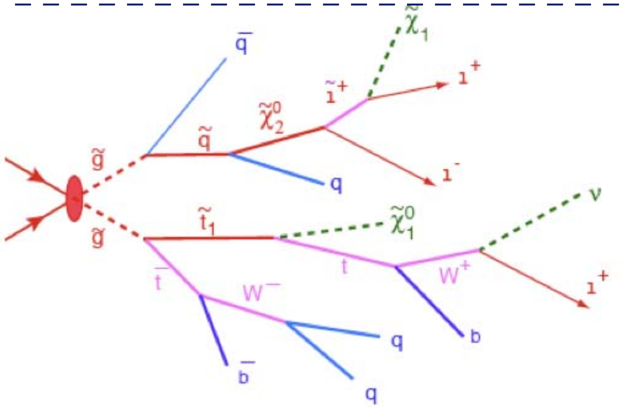
[arXiv:1206.2892]

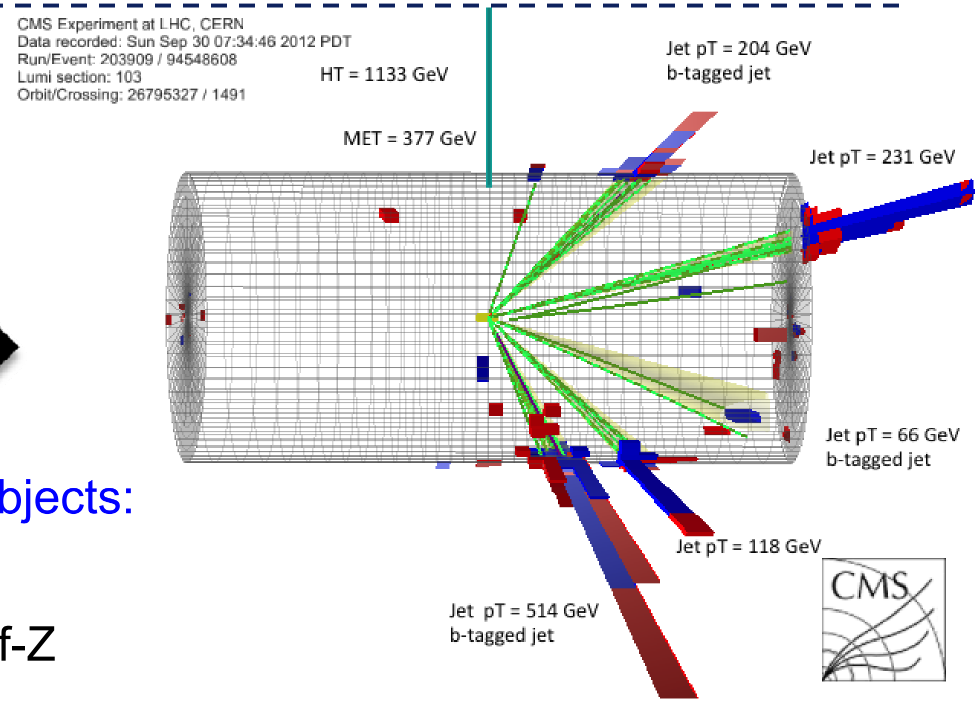
- Gluinos, 1st & 2nd generation squarks
  - High cross sections
  - *Thermal Detection ☺*
- 3rd generation squarks (stops, sbottoms)
  - Moderate cross sections
- Charginos, neutralinos, sleptons (higgsinos)
  - Small cross sections, but less SM background.

CMS = Compact MUON solenoid



SUSY hypotheses → signatures





CMS-PAS-SUS-12-024

Topology oriented signatures with these objects:

- Jets: N-jets, N-b-jets, jet p_T
- Leptons: e, mu, tau-had, SS, OS, on/off-Z
- Photons

→Map onto:

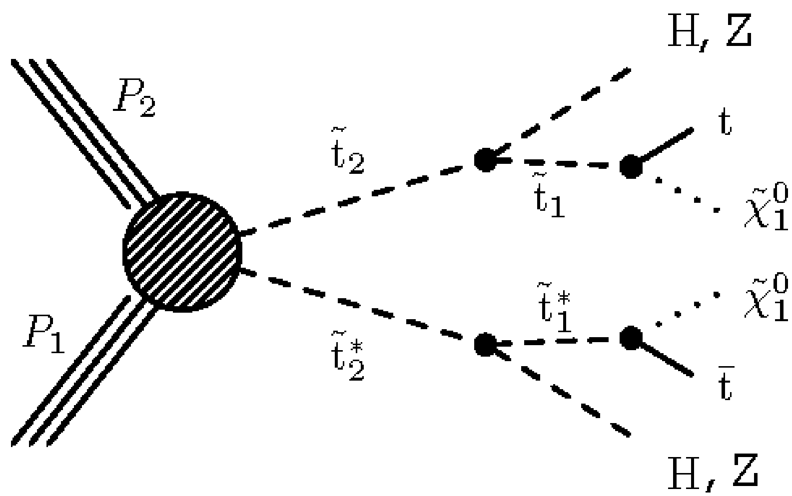
- HT, MET, ST
- Clever variables (Razr etc),
- Opaque variables (Neural Networks,…)

Next

SUSY strong production → higgs + X

(very briefly)

Strong production: stop2 → stop1 + H/Z ("Natural")



CMS SUS-13-024

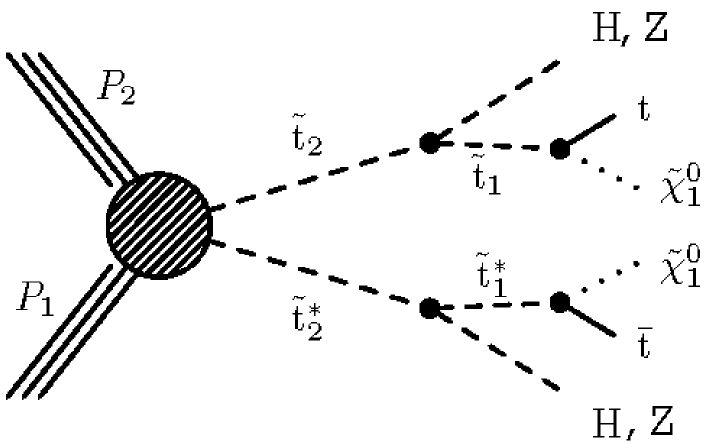
Very specific signature
→ Rich final state!

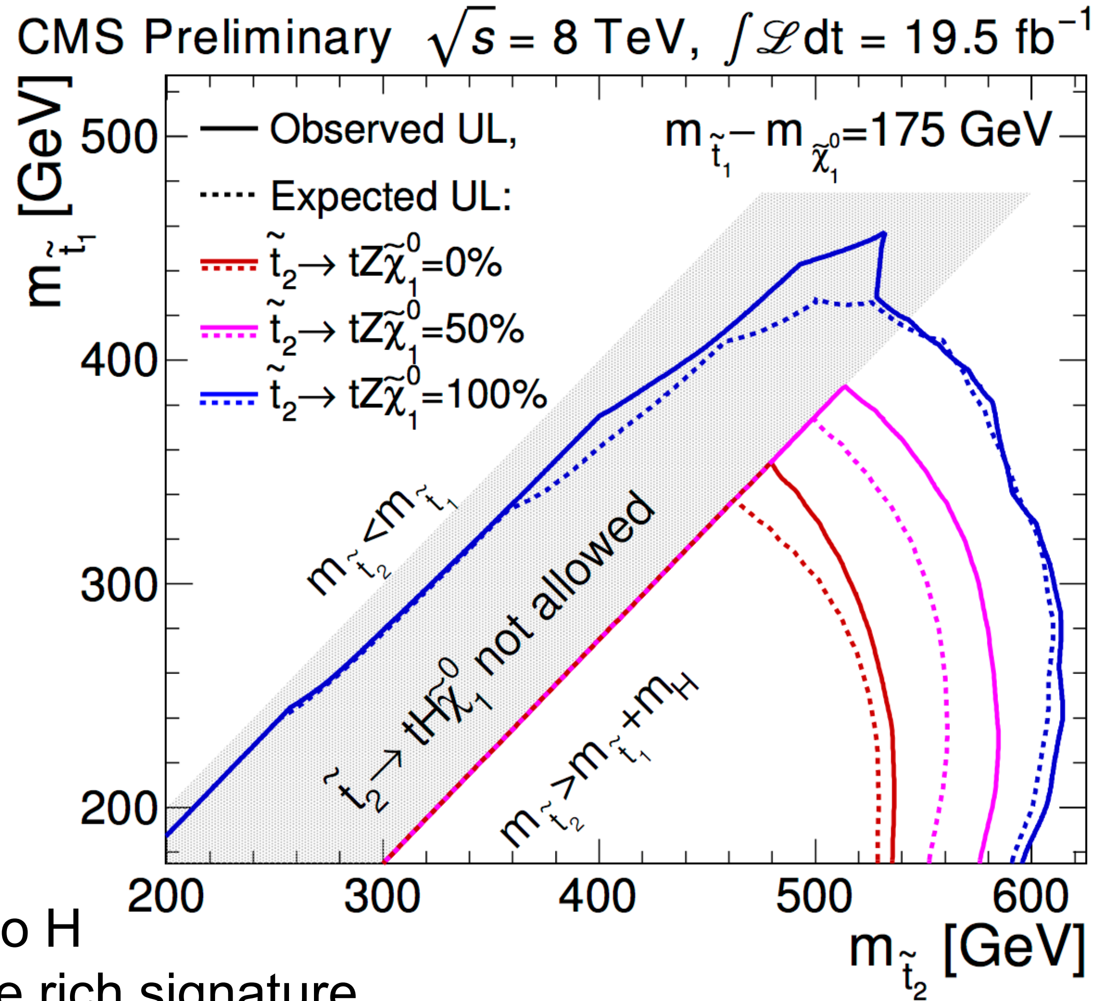
N_ℓ	Veto	$N_{\text{b jets}}$	N_{jets}	E_T^{miss} [GeV]	Additional requirements [GeV]
1	track or τ_h	$= 3$	≥ 5	≥ 50	$m_T > 150$
		≥ 4	≥ 4		$m_T > 120$
2 OS	extra e/μ	$= 3$	≥ 5	≥ 50	($N_{bb} = 1$ with $100 \leq m_{bb} \leq 150$), $N_{bb} \geq 2$
		≥ 4	≥ 4		
2 SS	extra e/μ	$= 1$	$[2,3], \geq 4$	$[50,120], \geq 120$	for low/high-p_T: $H_T \in [200,400], \geq 400$
		≥ 2			
≥ 3	—	$= 1$	$[2,3], \geq 4$	$[50,100], [100,200], \geq 200$	for on/off-Z: $H_T \in [60,200], \geq 200$
		$= 2$			
		≥ 3	≥ 3		

CMS

CMS SUS-13-024

Stop1 vs stop2 exclusion





Loss in sensitivity going from Z to H
Still a strong exclusion due to the rich signature
(cf: ewk later)

Next

Natural higgsino (3rd gen), strong vs weak.

(In detail, then pure electroweak-electroHiggs.)

BUT

First introduce the CMS inclusive multilepton search. It forms the backbone of these searches.

CMS Inclusive Multilepton Search

CMS SUS-13-002 submitted to PRD

- Three or more e/μ/τ, at least two (e/μ)
- Bin in lepton number, flavor (e/μ or $\tau_{hadronic}$), b-jets, opposite-sign same-flavor pairs, MET, HT and dilepton pair mass (on-above-below Z).
- SM backgrounds using data-driven methods for Z+jets, τ and internal γ conversions, validated MC for ttbar, WZ and rare SM such as ttV.
- Many SUSY interpretations including natural Higgsino, GMSB, SMS and also top → charm+higgs, 2HDM etc

τ's in CMS (This is τexas A&M!)

- Leptonic - BR(τ → e/mu) ~1/3 ->Comes automatically (but softer leptons)
- Hadronic ~2/3
  - ~1/3 "Single prong" - Isolated track with or w/o π^0
  - ~1/3 "Three prong" - (also) like a pencil jet

• Use "particle flow" reconstruction of jets etc (HPS algorithm) to reconstruct hadronic tau's with ~40% efficiency (pt > 20 GeV)

• But ~1% of jets (which are ubiquitous) still show up as fake tau's. This is a hard business.

• Especially useful for tau-dominated new physics and also when S/B is high (e.g. high MET, ST etc)

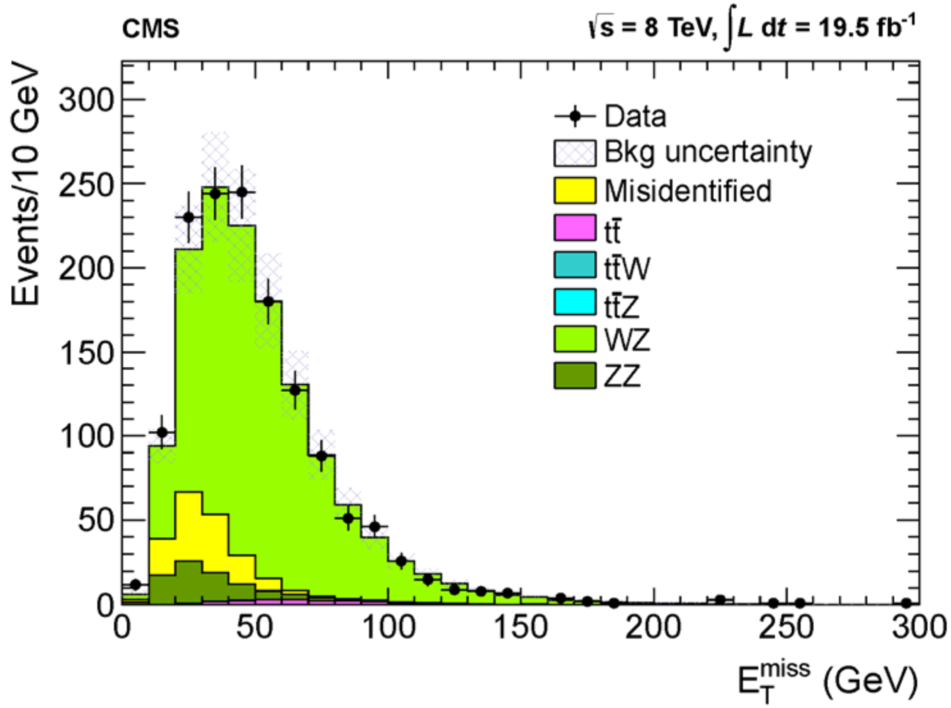
Multilepton SM Bkgnds (Leptonic BR's) (Clean but the odds are still pretty bad!)

Process pp → X	**σ*B (8 TeV)**	**Events (20 fb^{-1})**	**"Objects"**
W (→ **ℓ=e,μ,τ**)	38 nb	750M	one lepton + MET
Z/γ^* (→ $\ell^+\ell^-$) ($m_{\ell\ell}$>20GeV)	6 nb (~60% pole)	110M	Two leptons
ttbar (→bWbW, W → $\ell\nu$)	24 pb	500K	Two leptons + MET
WZ(→ $\ell\nu\ell^+\ell^-$)	1 pb	20K	Three leptons + MET
New physics	10 fb (say)	200	3 leptons+? or 2 leptons + ?? or 1 lepton + ???

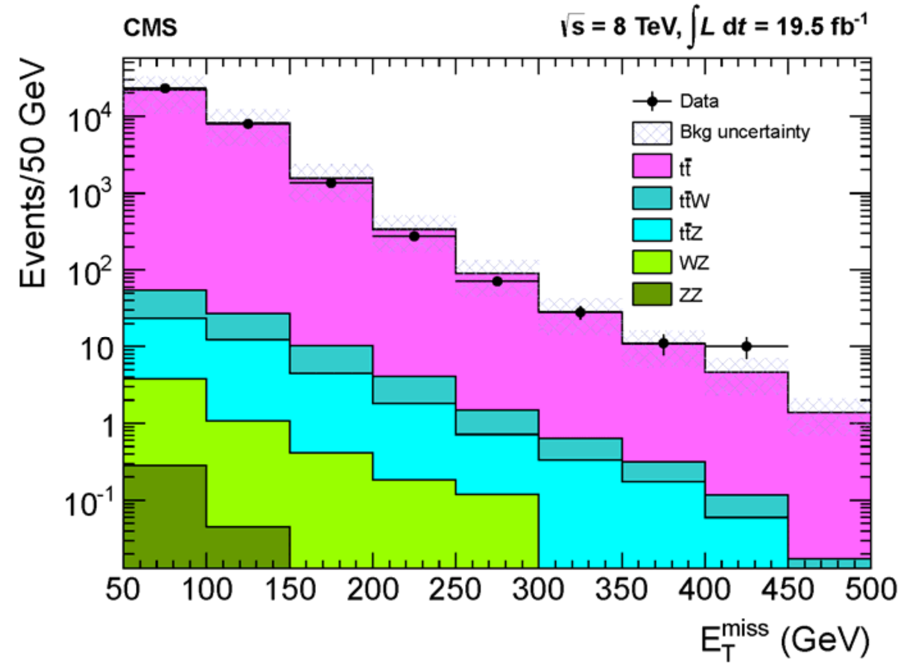
From CMS results, internal CMS twiki etc

Multilepton SM Background estimation

Do lots of data-driven and MC and hybrid backgrounds, look at zillion control plots….



WZ trilepton control region

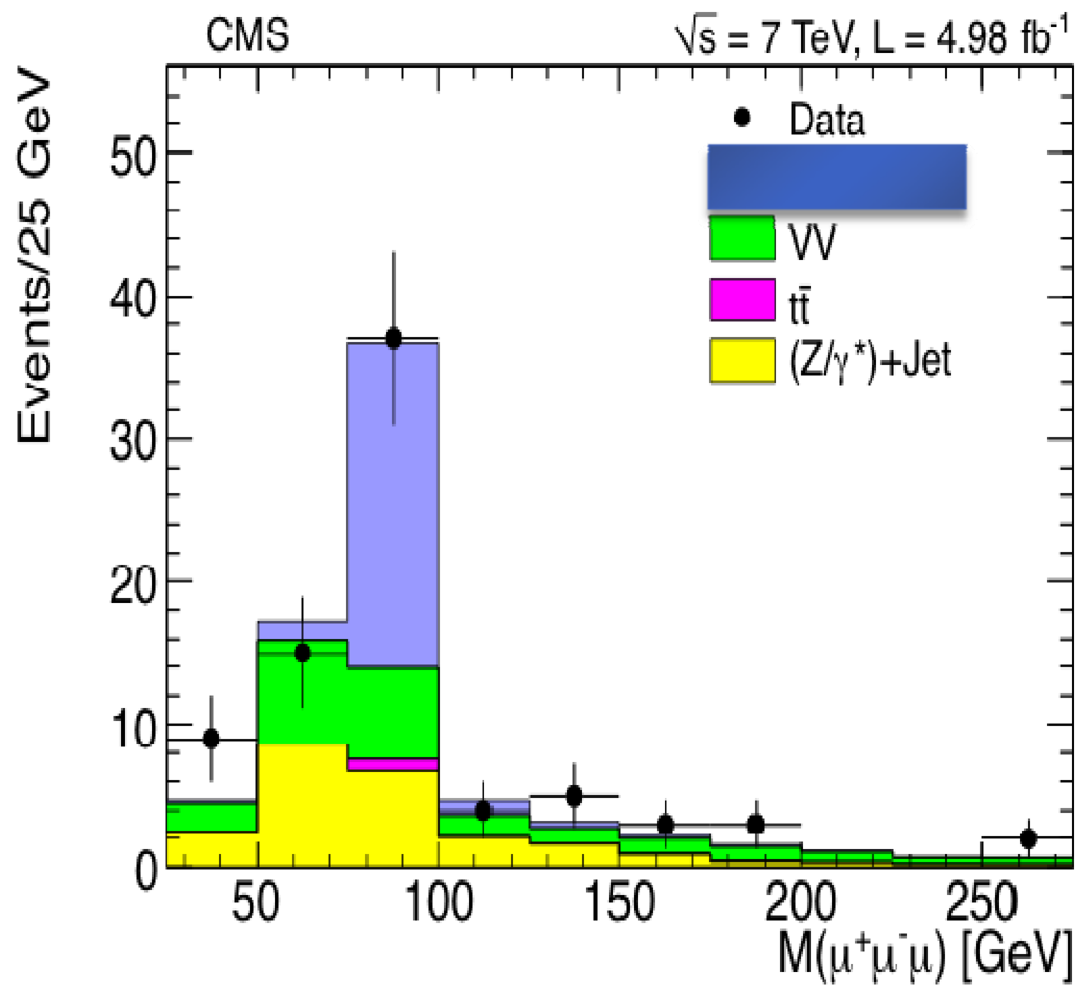


Ttbar dilepton control region

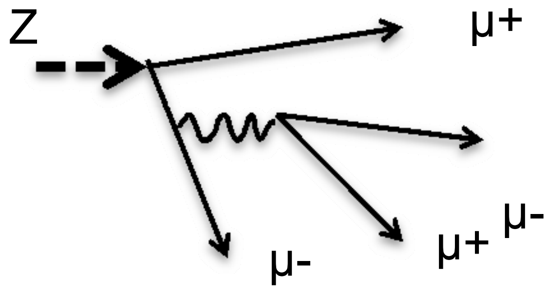
Before results: a small surprising detour from 2011 archives….

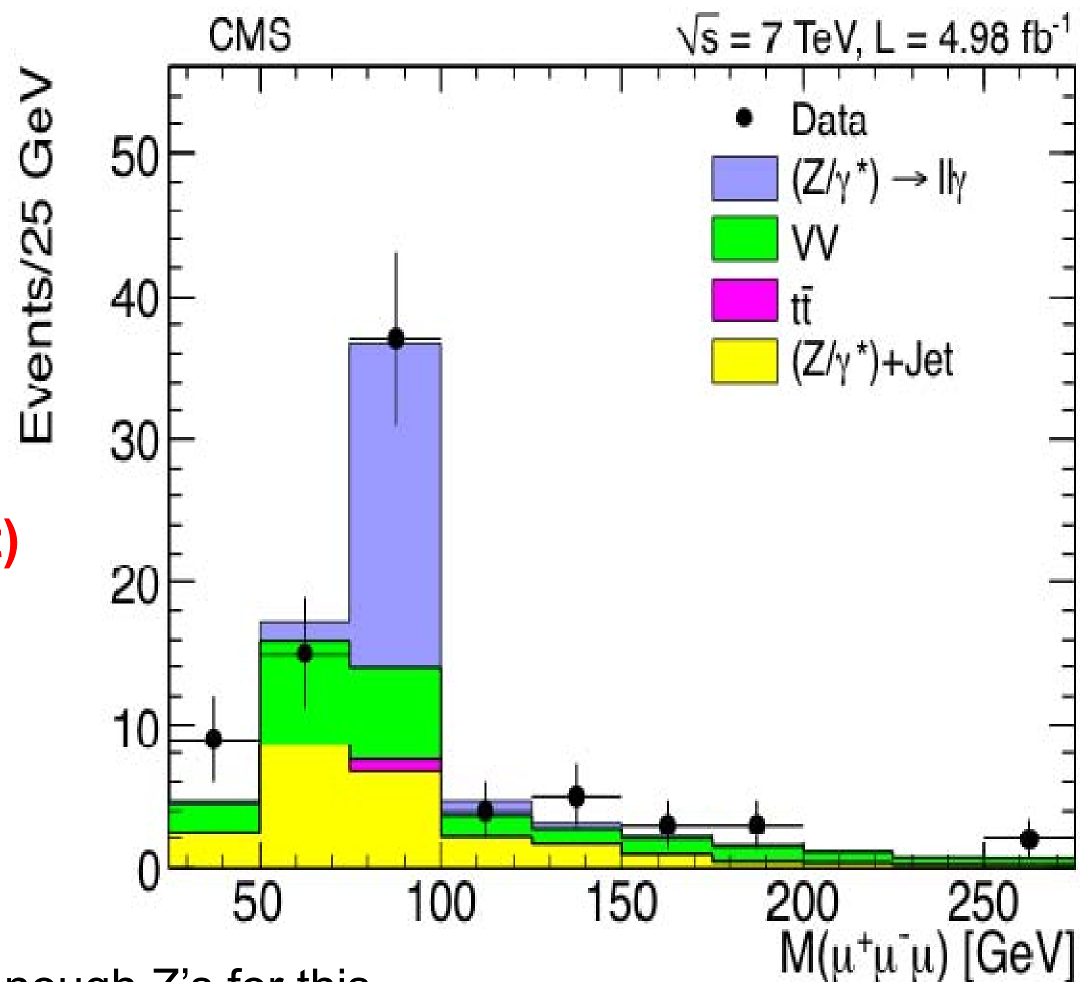
Note: Muons!

Note again: 3 muons!!



$Z \to 3\mu$ - Asymmetric Internal (Dalitz) Photon Conversions





$Z \to (3)4\mu$

Feynman level (γ*) (NOT γ)

gives e+e- and μ+μ-

Observe 3μ Z peak (4th μ soft)

BUT

Also W→2μ (Higgs!)

Wg* was not in Higgs WW searches

arXiv:1110.1368 R. C. Gray et. al.

LEP-I did not produce enough Z's for this

Multilepton Results: 3 leptons

CMS-SUS-13-002

number of opposite-sign same flavor (OSSF) dilepton pair

presence of τ-had

OSSF pair invariant mass is in Z mass window?

presence of b tagged jets

HT

MET (HT>200)

Selection 3 Lepton Results			E_T^{miss}	$N(\tau_h)=0$, $N_{b-jets}=0$ obs	exp	$N(\tau_h)=1$, $N_{b-jets}=0$ obs	exp	$N(\tau_h)=0$, $N_{b-jets}\geq1$ obs	exp	$N(\tau_h)=1$, $N_{b-jets}\geq1$ obs	exp
OSSF0	$H_T > 200$	NA	(100,∞)	5	3.7 ± 1.6	35	33 ± 14	1	5.5 ± 2.2	47	61 ± 30
OSSF0	$H_T > 200$	NA	(50,100)	3	3.5 ± 1.4	34	36 ± 16	8	7.7 ± 2.7	82	91 ± 46
OSSF0	$H_T > 200$	NA	(0,50)	4	2.1 ± 0.8	25	25 ± 9.7	1	3.6 ± 1.5	52	59 ± 29
OSSF1	$H_T > 200$	above-Z	(100,∞)	5	3.6 ± 1.2	2	10 ± 4.8	3	4.7 ± 1.6	19	22 ± 11
OSSF1	$H_T > 200$	below-Z	(100,∞)	7	9.7 ± 3.3	18	14 ± 6.4	8	9.1 ± 3.4	21	23 ± 11
OSSF1	$H_T > 200$	on-Z	(100,∞)	39	61 ± 23	17	15 ± 4.9	9	14 ± 4.4	10	12 ± 5.8
OSSF1	$H_T > 200$	above-Z	(50,100)	4	5 ± 1.6	14	11 ± 5.2	6	6.8 ± 2.4	32	30 ± 15
OSSF1	$H_T > 200$	below-Z	(50,100)	10	11 ± 3.8	24	19 ± 6.4	10	9.9 ± 3.7	25	32 ± 16
OSSF1	$H_T > 200$	on-Z	(50,100)	78	80 ± 32	70	50 ± 11	22	22 ± 6.3	36	24 ± 9.8
OSSF1	$H_T > 200$	above-Z	(0,50)	3	7.3 ± 2	41	33 ± 8.7	4	5.3 ± 1.5	15	23 ± 11
OSSF1	$H_T > 200$	below-Z	(0,50)	26	25 ± 6.8	110	86 ± 23	5	10 ± 2.5	24	26 ± 11
OSSF1	$H_T > 200$	on-Z	(0,50)	*135	127 ± 41	542	543 ± 159	31	32 ± 6.5	86	75 ± 19

Multilepton Results for Three Leptons

CMS SUS-13-002

Selection 3 Lepton Results		E_T^{miss}	$N(\tau_h)=0$, $N_{b-jets}=0$ obs	exp	$N(\tau_h)=1$, $N_{b-jets}=0$ obs	exp	$N(\tau_h)=0$, $N_{b-jets}\geq1$ obs	exp	$N(\tau_h)=1$, $N_{b-jets}\geq1$ obs	exp
OSSF0 $H_T < 200$	NA	(100,∞)	7	11 ± 4.9	101	111 ± 54	13	10 ± 5.3	87	119 ± 61
OSSF0 $H_T < 200$	NA	(50,100)	35	38 ± 15	406	402 ± 152	29	26 ± 13	269	298 ± 151
OSSF0 $H_T < 200$	NA	(0,50)	53	51 ± 11	910	1035 ± 255	29	23 ± 10	237	240 ± 113
OSSF1 $H_T < 200$	above-Z	(100,∞)	18	13 ± 3.5	25	38 ± 18	10	6.5 ± 2.9	24	35 ± 18
OSSF1 $H_T < 200$	below-Z	(100,∞)	21	24 ± 9	41	50 ± 25	14	20 ± 10	42	54 ± 28
OSSF1 $H_T < 200$	on-Z	(100,∞)l	150	152 ± 26	39	48 ± 13	15	14 ± 4.8	19	23 ± 11
OSSF1 $H_T < 200$	above-Z	(50,100)	50	46 ± 9.7	169	139 ± 48	20	18 ± 8	85	93 ± 47
OSSF1 $H_T < 200$	below-Z	(50,100)	142	125 ± 27	353	355 ± 92	48	48 ± 23	140	133 ± 68
OSSF1 $H_T < 200$	on-Z	(50,100)	*773	777 ± 116	1276	1154 ± 306	56	47 ± 13	81	75 ± 32
OSSF1 $H_T < 200$	above-Z	(0,50)	178	196 ± 35	1676	1882 ± 540	17	18 ± 6.7	115	94 ± 42
OSSF1 $H_T < 200$	below-Z	(0,50)	510	547 ± 87	9939	8980 ± 2660	34	42 ± 11	226	228 ± 63
OSSF1 $H_T < 200$	on-Z	(0,50)	*3869	4105 ± 666	*50188	50162 ± 14984	*148	156 ± 24	906	925 ± 263

HT < 200

Multilepton Results for Four Leptons

CMS-SUS-13-002

HT < 200

Selection 4 Lepton Results		E_T^{miss}	N(τ_h)=0, N_{b-jets}=0 obs	exp	N(τ_h)=1, N_{b-jets}=0 obs	exp	N(τ_h)=0, $N_{b-jets}\geq1$ obs	exp	N(τ_h)=1, $N_{b-jets}\geq1$ obs	exp
OSSF0 $H_T < 200$	NA	(100,∞)	0	0.11 ± 0.08	0	0.17 ± 0.1	0	0.03 ± 0.04	0	0.04 ± 0.04
OSSF0 $H_T < 200$	NA	(50,100)	0	0.01 ± 0.03	2	0.7 ± 0.33	0	0 ± 0.02	0	0.28 ± 0.16
OSSF0 $H_T < 200$	NA	(0,50)	0	0.01 ± 0.02	1	0.7 ± 0.3	0	0.001 ± 0.02	0	0.13 ± 0.08
OSSF1 $H_T < 200$	off-Z	(100,∞)	0	0.06 ± 0.04	3	0.6 ± 0.24	0	0.02 ± 0.04	0	0.32 ± 0.2
OSSF1 $H_T < 200$	on-Z	(100,∞)	1	0.5 ± 0.18	2	2.5 ± 0.5	1	0.38 ± 0.2	0	0.21 ± 0.1
OSSF1 $H_T < 200$	off-Z	(50,100)	0	0.18 ± 0.06	4	2.1 ± 0.5	0	0.16 ± 0.08	1	0.45 ± 0.24
OSSF1 $H_T < 200$	on-Z	(50,100)	2	1.2 ± 0.34	9	9.6 ± 1.6	2	0.42 ± 0.23	0	0.5 ± 0.16
OSSF1 $H_T < 200$	off-Z	(0,50)	2	0.46 ± 0.18	15	7.5 ± 2	0	0.09 ± 0.06	0	0.7 ± 0.31
OSSF1 $H_T < 200$	on-Z	(0,50)	4	3 ± 0.8	41	40 ± 10	1	0.31 ± 0.15	2	1.5 ± 0.47
OSSF2 $H_T < 200$	off-Z	(100,∞)	0	0.04 ± 0.03	-	-	0	0.05 ± 0.04	-	-
OSSF2 $H_T < 200$	on-Z	(100,∞)	0	0.34 ± 0.15	-	-	0	0.46 ± 0.25	-	-
OSSF2 $H_T < 200$	off-Z	(50,100)	2	0.18 ± 0.13	-	-	0	0.02 ± 0.03	-	-
OSSF2 $H_T < 200$	on-Z	(50,100)	4	3.9 ± 2.5	-	-	0	0.5 ± 0.21	-	-
OSSF2 $H_T < 200$	off-Z	(0,50)	7	8.9 ± 2.4	-	-	1	0.23 ± 0.09	-	-
OSSF2 $H_T < 200$	on-Z	(0,50)	*156	159 ± 34	-	-	4	2.9 ± 0.8	-	-

Multilepton Results for Four Leptons

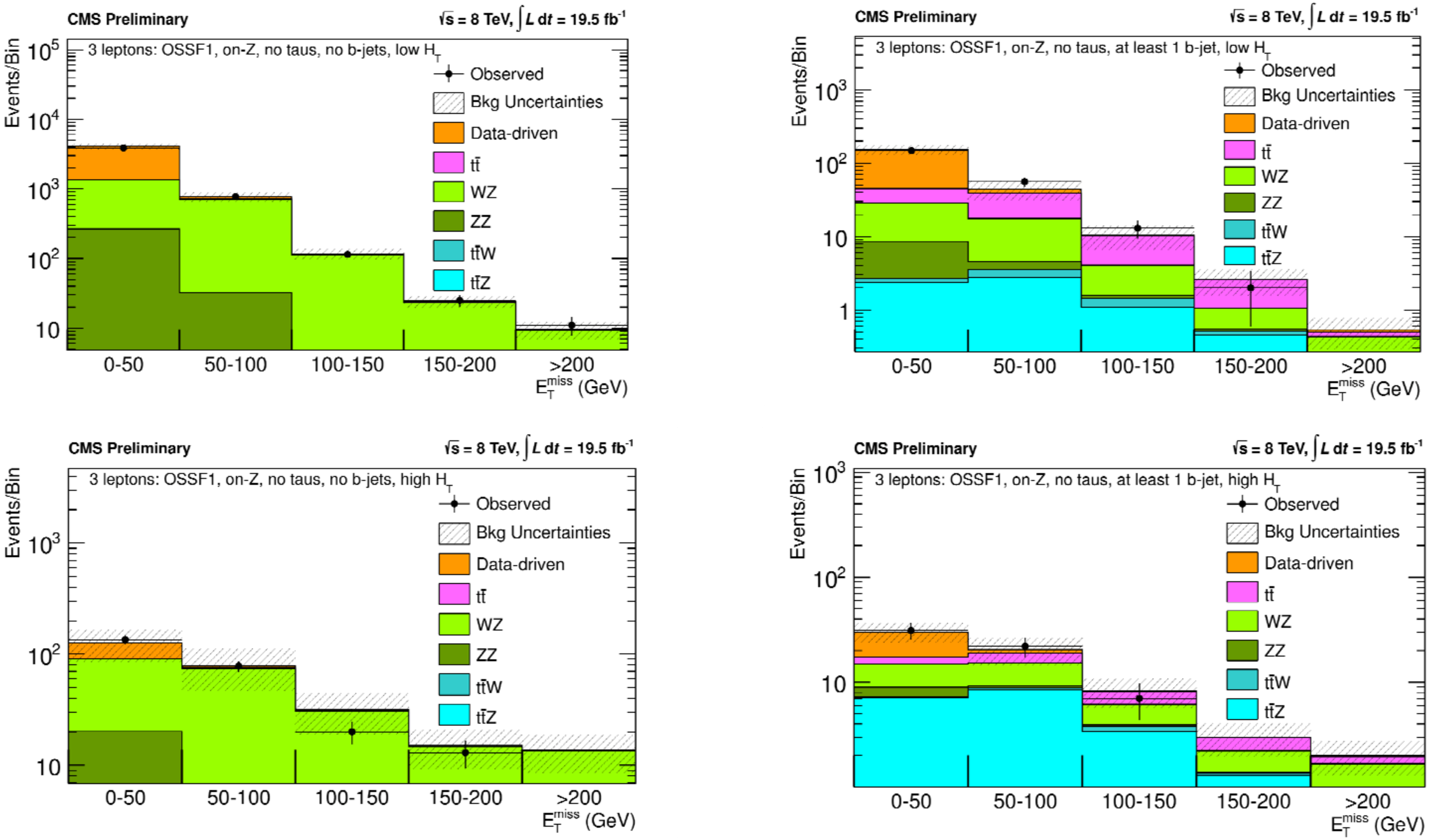
CMS-SUS-13-002

HT > 200

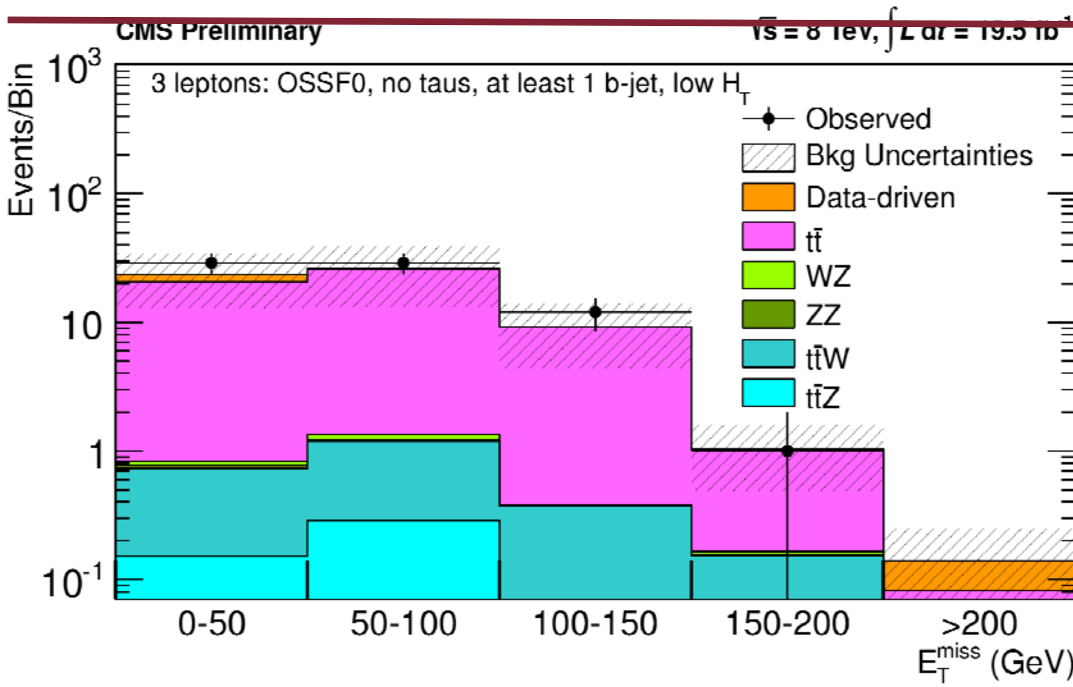
Selection 4 Lepton Results		E_T^{miss}	N(τ_h)=0, N_{b-jets}=0 obs	exp	N(τ_h)=1, N_{b-jets}=0 obs	exp	N(τ_h)=0, $N_{b-jets}\geq$1 obs	exp	N(τ_h)=1, $N_{b-jets}\geq$1 obs	exp
OSSF0 $H_T > 200$	NA	(100,∞)	0	0.01 ± 0.03	0	0.01 ± 0.06	0	0.02 ± 0.04	0	0.11 ± 0.08
OSSF0 $H_T > 200$	NA	(50,100)	0	0 ± 0.02	0	0.01 ± 0.06	0	0 ± 0.03	0	0.12 ± 0.07
OSSF0 $H_T > 200$	NA	(0,50)	0	1e-05 $\pm$ 0.02	0	0.07 ± 0.1	0	0 ± 0.02	0	0.02 ± 0.02
OSSF1 $H_T > 200$	off-Z	(100,∞)	0	0.005 ± 0.02	1	0.25 ± 0.11	0	0.13 ± 0.08	0	0.12 ± 0.12
OSSF1 $H_T > 200$	on-Z	(100,∞)	1	0.1 ± 0.06	0	0.5 ± 0.27	0	0.42 ± 0.22	0	0.42 ± 0.19
OSSF1 $H_T > 200$	off-Z	(50,100)	0	0.07 ± 0.06	1	0.29 ± 0.13	0	0.04 ± 0.04	0	0.23 ± 0.13
OSSF1 $H_T > 200$	on-Z	(50,100)	0	0.23 ± 0.11	1	0.7 ± 0.31	0	0.23 ± 0.13	1	0.34 ± 0.16
OSSF1 $H_T > 200$	off-Z	(0,50)	0	0.02 ± 0.03	0	0.27 ± 0.12	0	0.03 ± 0.04	0	0.31 ± 0.15
OSSF1 $H_T > 200$	on-Z	(0,50)	0	0.2 ± 0.08	0	1.3 ± 0.47	0	0.06 ± 0.04	1	0.49 ± 0.19
OSSF2 $H_T > 200$	off-Z	(100,∞)	0	0.01 ± 0.02	-	-	0	0.01 ± 0.06	-	-
OSSF2 $H_T > 200$	on-Z	(100,∞)	1	0.15 ± 0.16	-	-	0	0.34 ± 0.18	-	-
OSSF2 $H_T > 200$	off-Z	(50,100)	0	0.03 ± 0.02	-	-	0	0.13 ± 0.09	-	-
OSSF2 $H_T > 200$	on-Z	(50,100)	0	0.8 ± 0.4	-	-	0	0.36 ± 0.19	-	-
OSSF2 $H_T > 200$	off-Z	(0,50)	1	0.27 ± 0.13	-	-	0	0.08 ± 0.05	-	-
OSSF2 $H_T > 200$	on-Z	(0,50)	5	7.4 ± 3.5	-	-	2	0.8 ± 0.4	-	-

Results with Background Breakdown

CMS-SUS-13-002



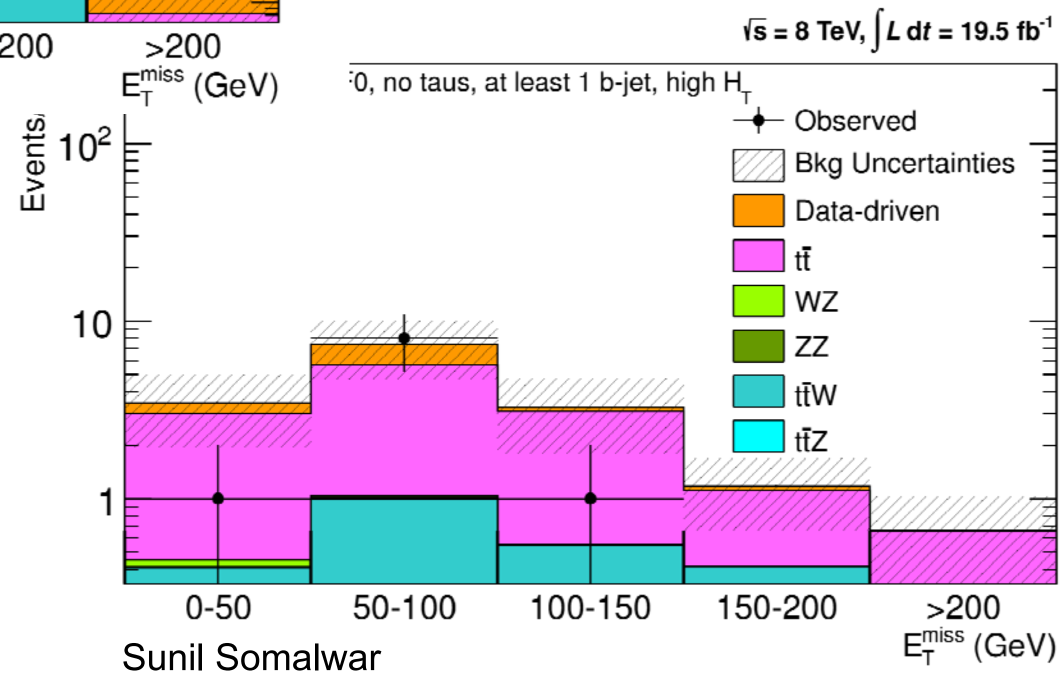
More Background Breakdown examples (b-tag)



HT<200

CMS SUS-13-002

HT>200



What to do with these huge multilepton tables?

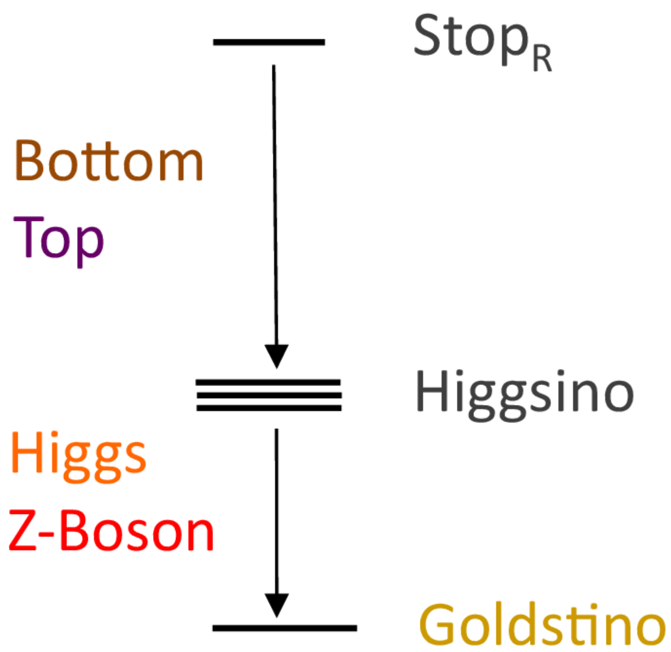
CMS SUS-13-002

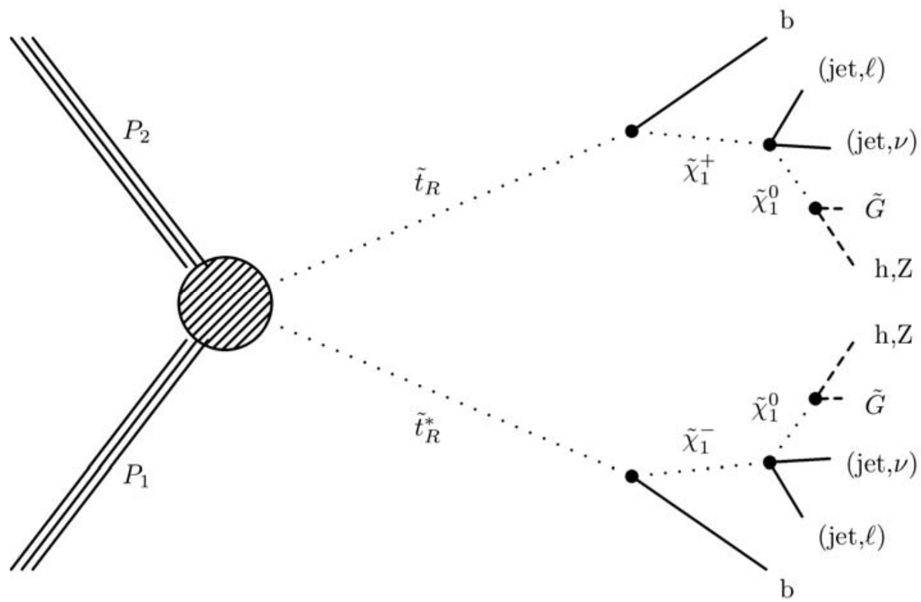
- Tables ARE the principle results. Several pheno papers for specific models using these detailed binned results for specific models.

- Several CMS results (not all mentioned in this talk):
  - Generate the signal in detail (typically 2-d masses etc)
  - Throw the signal at the tables and calculate exclusions/deviations.
  - Include all channels that contribute to 90% signal acceptance (90% not important – S/B low at that point)
  - Contributing channels vary as the signal parameters are scanned. e.g. going from Z to H in the final state, on-Z channels get replaced by off-Z channels (H→WW, say)
  - A lot of channels – fluctuations can be picked up by specific signals. ("lucky" or "unlucky" depending on viewpoint.)(An example later)

Natural Higgsino NLSP

Gauge Mediated Supersymmetry Breaking (GMSB)
Strong and weak production, third generation (“natural”)





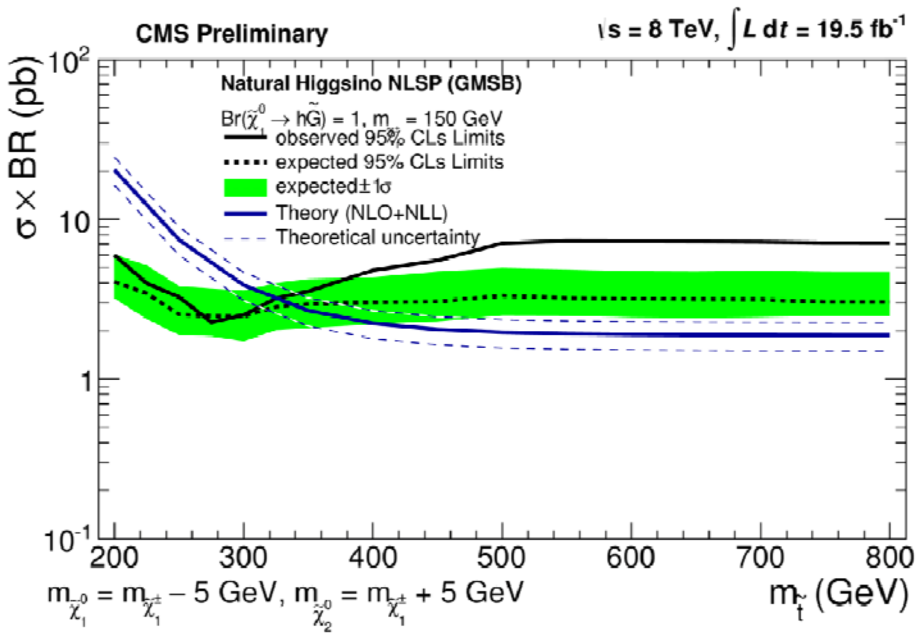
Natural Higgsino-NLSP

& direct ewk production

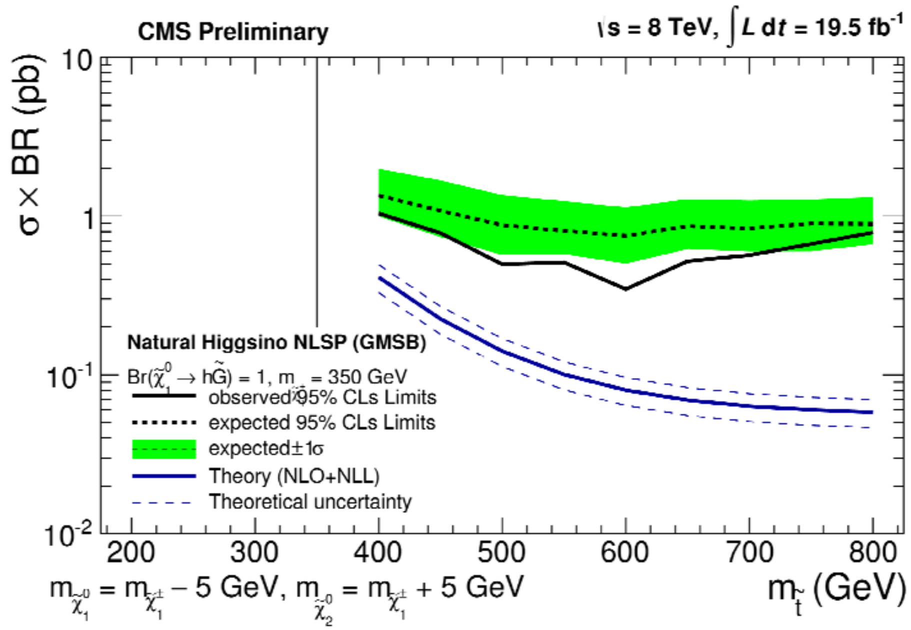
Interpretations: Natural Higgsino NLSP

Gauge Mediated Supersymmetry Breaking (GMSB) model
Strong and weak production

CMS-SUS-13-002



150 GeV Chargino



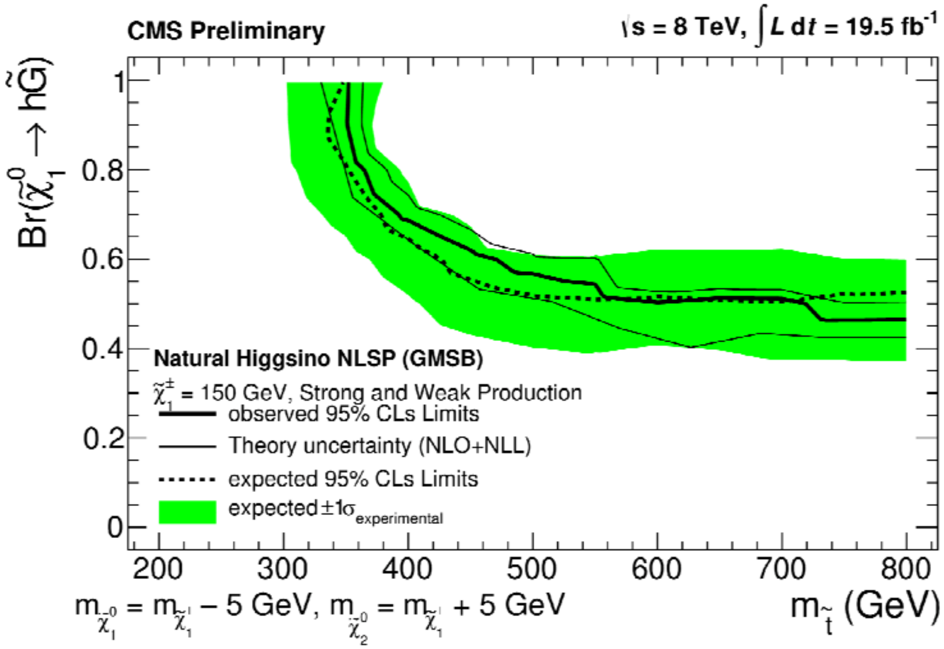
350 GeV Chargino

100% Higgs (=no Z) assumed: hardest to detect
High stop masses: only ewk production
Right: Higher chargino mass ➔ much lower ewk production

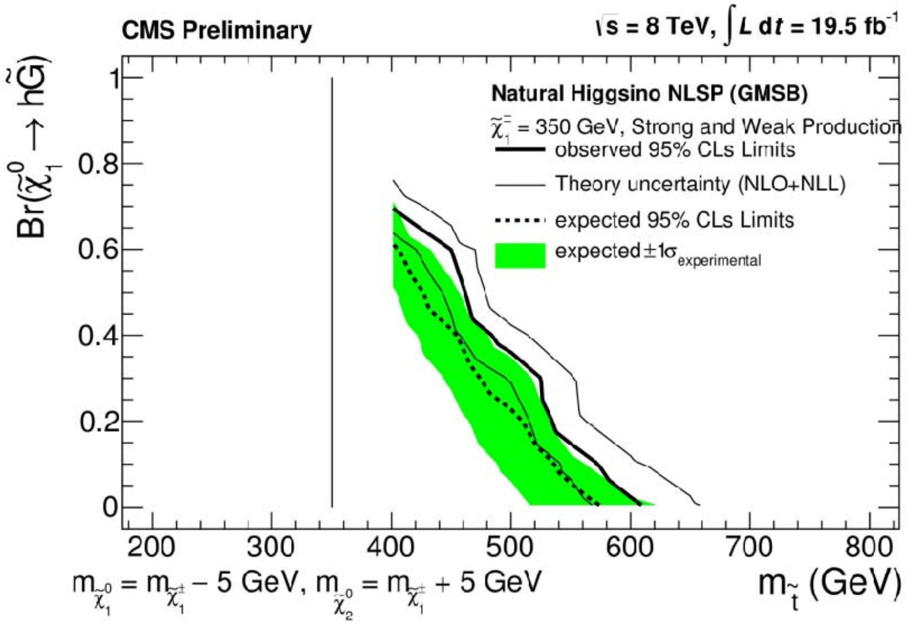
Natural Higgsino NLSP scenario

Gauge Mediated Supersymmetry Breaking (GMSB) model

CMS-SUS-13-002



150 GeV Chargino



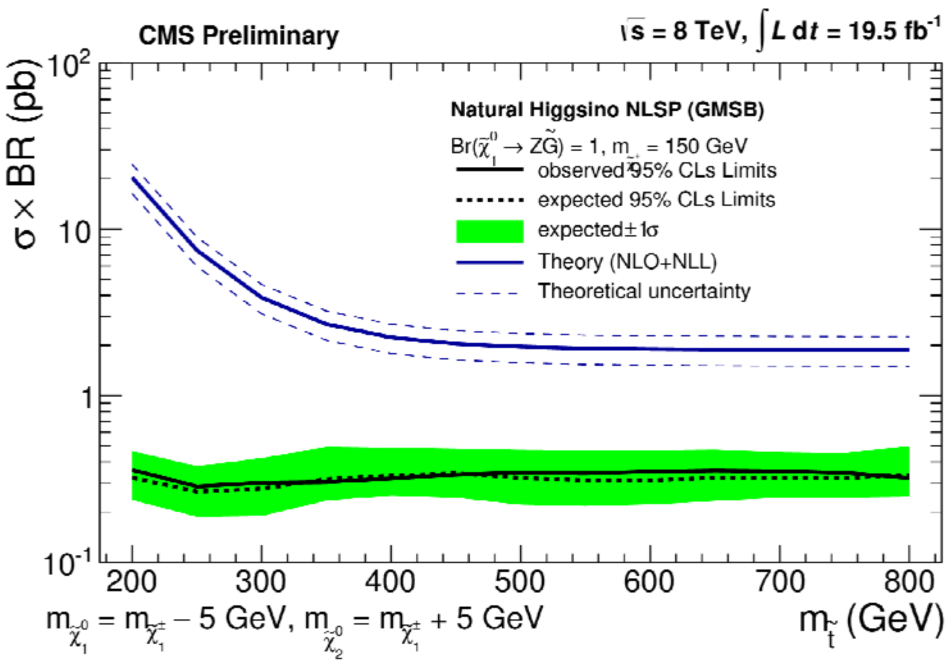
350 GeV Chargino

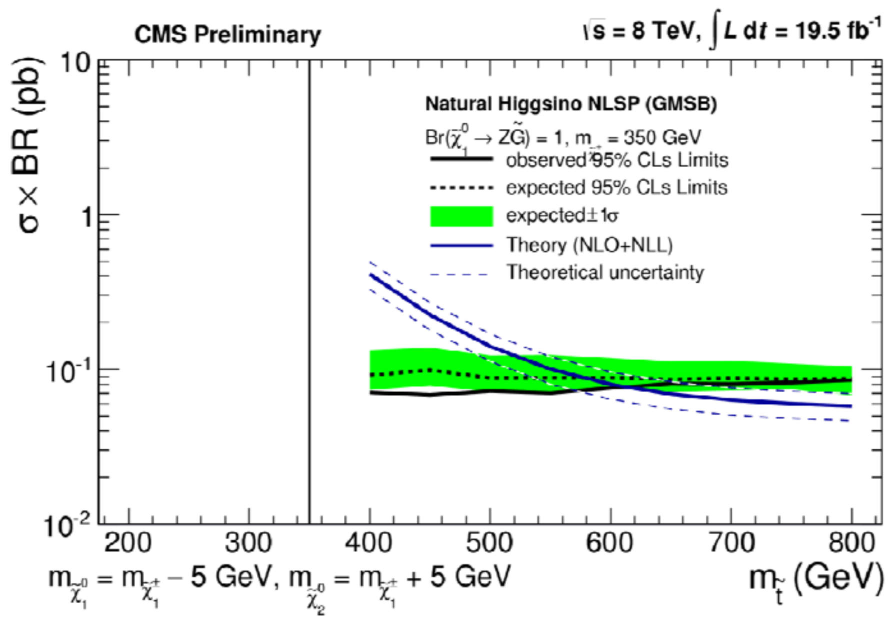
Variable higgs BR (100% higgs is the hardest).
Strong vs weak production
e.g. Left: 700 GeV stop: All weak, 100% higgs not excluded
~350 GeV stop: strong+weak, 100% higgs excluded.
Right: chargino too heavy, ewk small, do what you can with strong production

Natural Higgsino NLSP scenario

Gauge Mediated Supersymmetry Breaking (GMSB) model

CMS-SUS-13-002



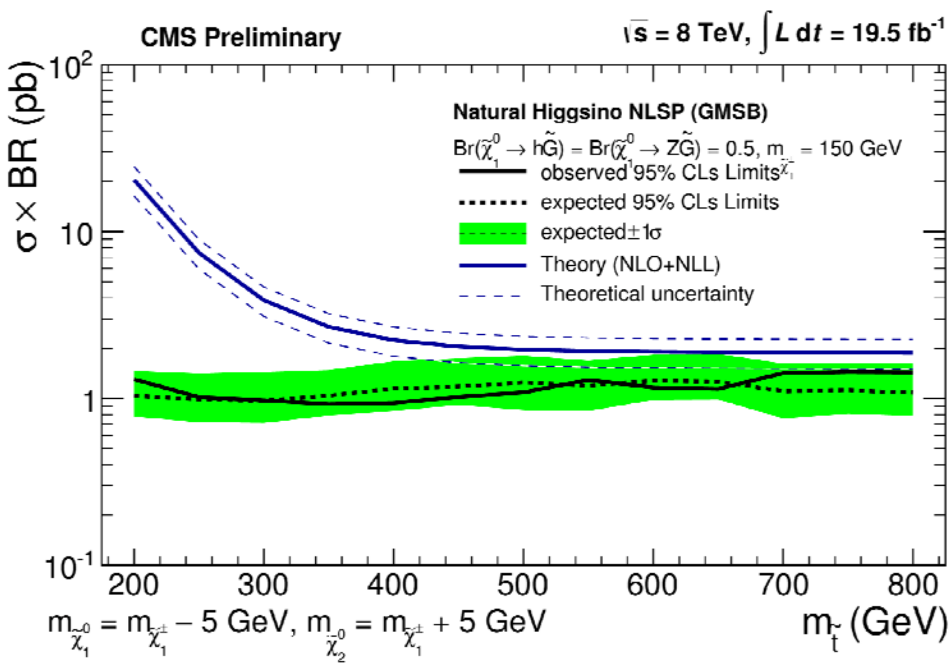


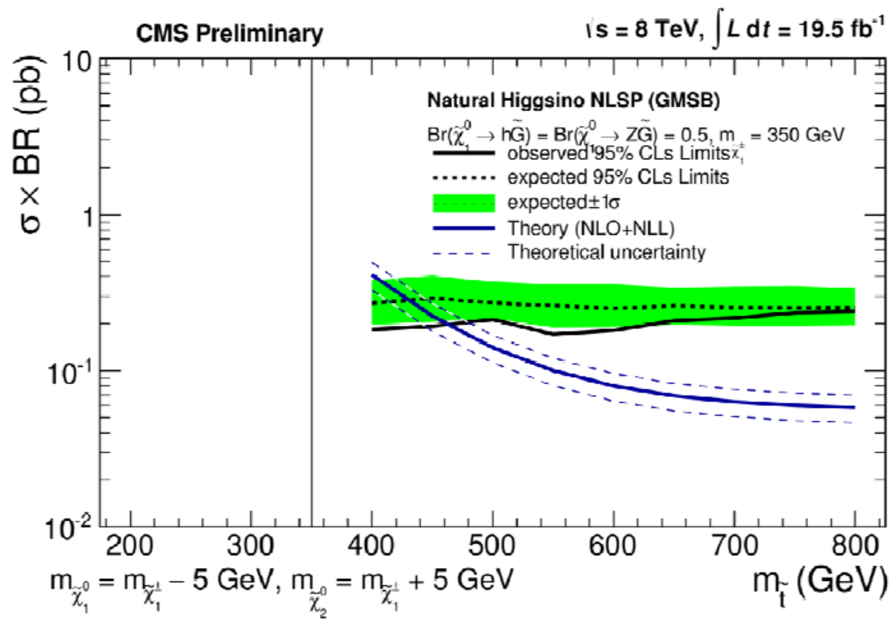
Now all Z (no Higgs), different chargino masses
Better exclusion

Natural Higgsino NLSP scenario

Gauge Mediated Supersymmetry Breaking (GMSB) model

CMS-SUS-13-002

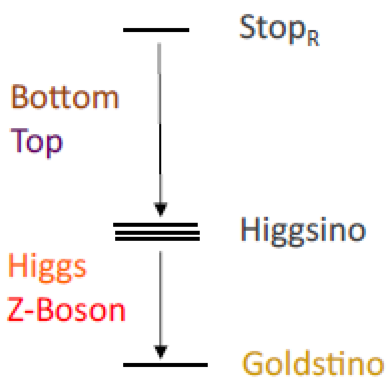


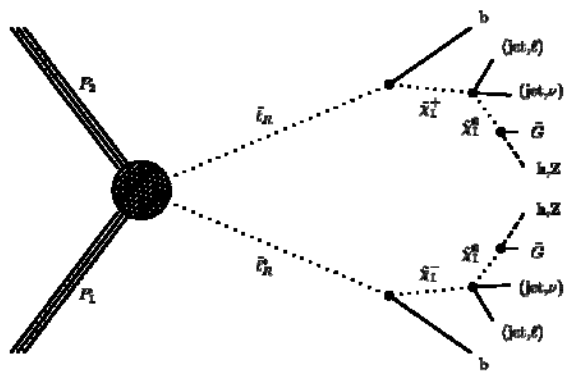


One side to Higgs, other to Z (unphysical), different chargino masses

Natural Higgsino NLSP (GMSB, strong vs weak)

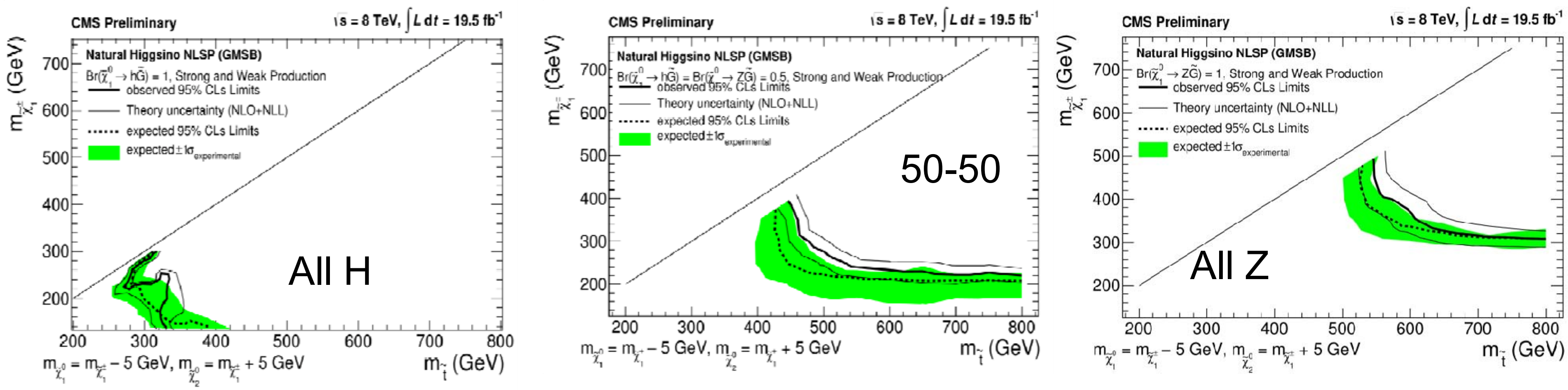
CMS-SUS-13-002





Top squark production with decays to neutral di-boson pair

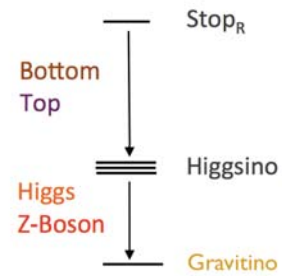
Finally: Put H and Z BR's together properly



Natural Higgsino with Diphotons(+b-jets)

Same model, now with diphotons.

Most powerful for 100% Higgs BR.



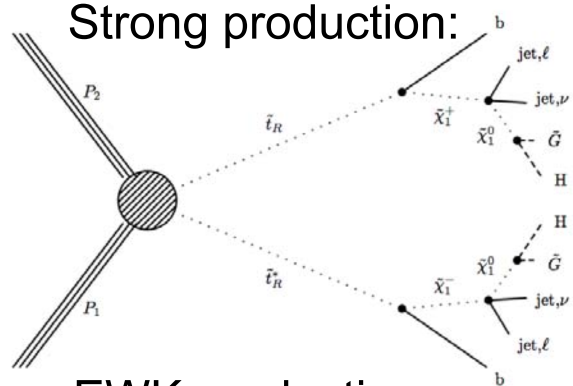
Signature:

- ≥2 photons (p_T > 40, 25 GeV)
- ≥2 *b*-tags (p_T > 30 GeV)

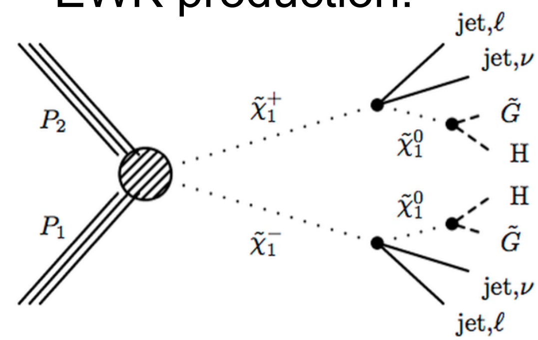
Backgrounds:

- QCD: γγbbbar+ γbbbar +jet (with γ-fakes from jets)
- Small bkg from electrons (faking a photon)

Strong production:

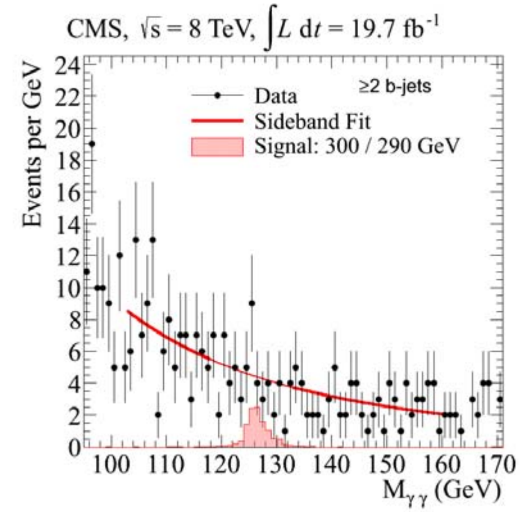


EWK production:

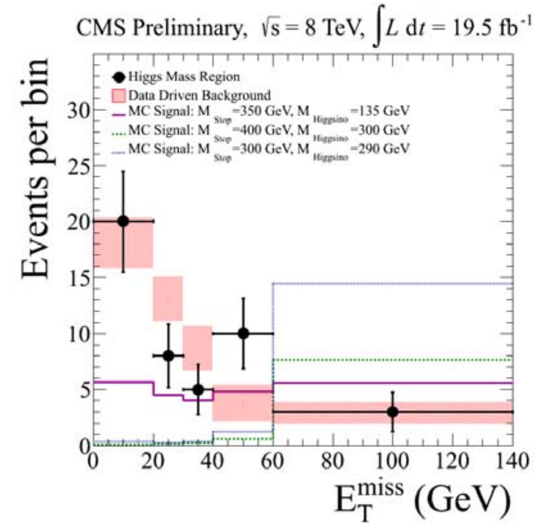


Natural SUSY GMSB (diphotons)

- **Strategy:**
  - Require 1 Higgs to decay to γγ
  - Higgs →γγ allows us to use Higgs mass sidebands for data-driven background estimate
  - Take MET shape from sidebands
- **3 search regions ($M_{\gamma\gamma}$ 118-133 GeV):**
  - bb pair in the Higgs mass window of 95 to 155 GeV
  - Not consistent with Higgs mass
  - ≥ 3 btags
- **Combine 3 signal regions**



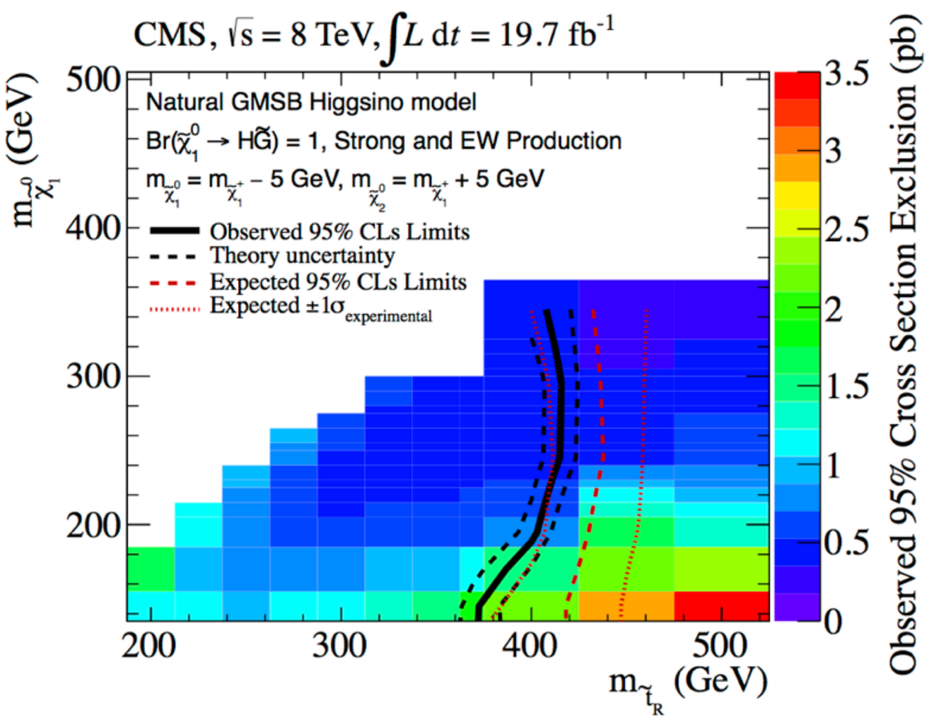
$M_{\gamma\gamma}$



MET

Natural SUSY (with diphotons)

E_T^{miss} (GeV)	2 b-jets on h mass		2 b-jets off h mass		3+ b-jet		Total	
	Data	Bkg	Data	Bkg	Data	Bkg	Data	Bkg
0-20	3	5.0 ± 1.3	15	11.0 ± 1.8	2	1.77 ± 0.73	20	18.1 ± 2.3
20-30	2	3.4 ± 1.3	4	7.9 ± 1.7	1	1.8 ± 1.1	7	13.1 ± 2.0
30-40	0	1.39 ± 0.71	5	6.3 ± 1.3	1	0.73 ± 0.84	6	8.7 ± 2.0
40-60	1	0.58 ± 0.68	7	2.2 ± 1.7	2	0.73 ± 0.84	10	3.8 ± 1.6
60+	1	0.19 ± 0.28	2	1.35 ± 0.73	0	1.3 ± 1.0	3	2.8 ± 1.0



- ← higgsino vs stop mass exclusion
- Exclude stop mass below ~ 360 to 410 GeV, depending on the higgsino mass.

Next

➔Pure Electroweak production.

➔No strong production, hence electroweak searches are a hard business

➔ First pure Electroweak without higgs in the final state (quickly)

Electroweak Production

- Squarks and gluinos getting heavier in simple scenarios
- What if weak production beats strong production?

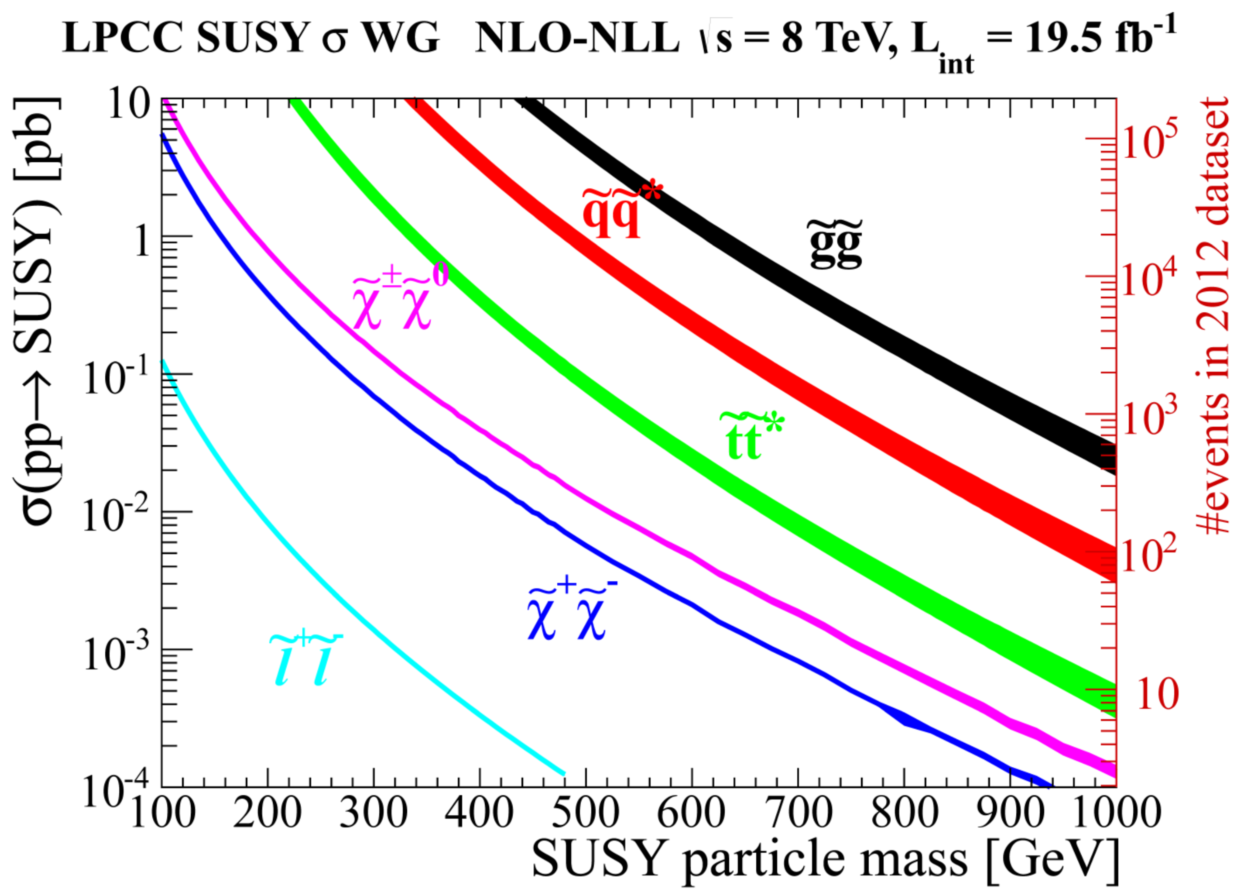
→Electroweak production to the rescue?

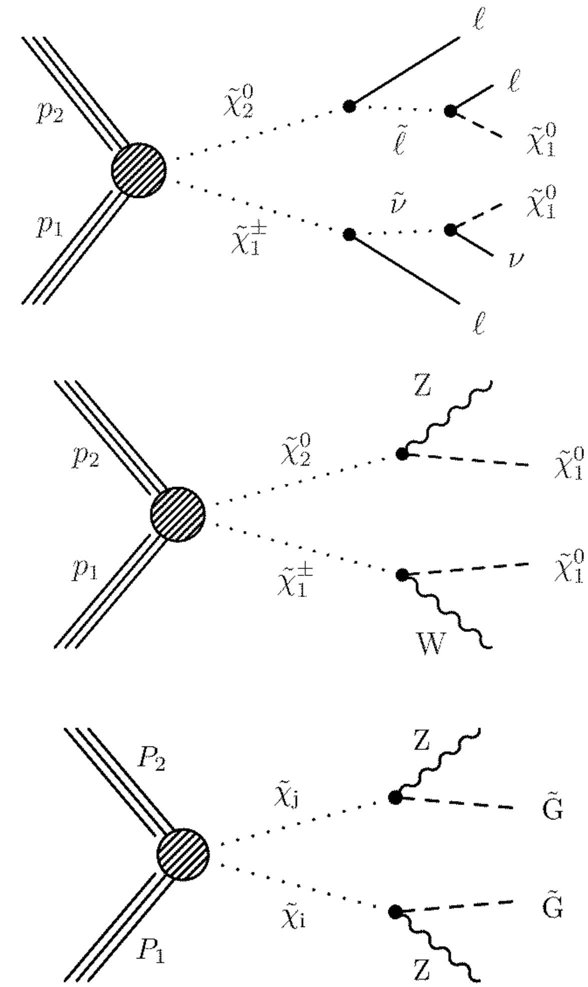
- Less copious, so lesser reach in mass
- *Less* hadronic activity

  cf: classic trilepton SUSYsignature from Tevatron Run II. mSUGRA limits were mostly due to EWK production.

  (CDF: We got grief for cutting on jets → LHC: bin, don't cut.)

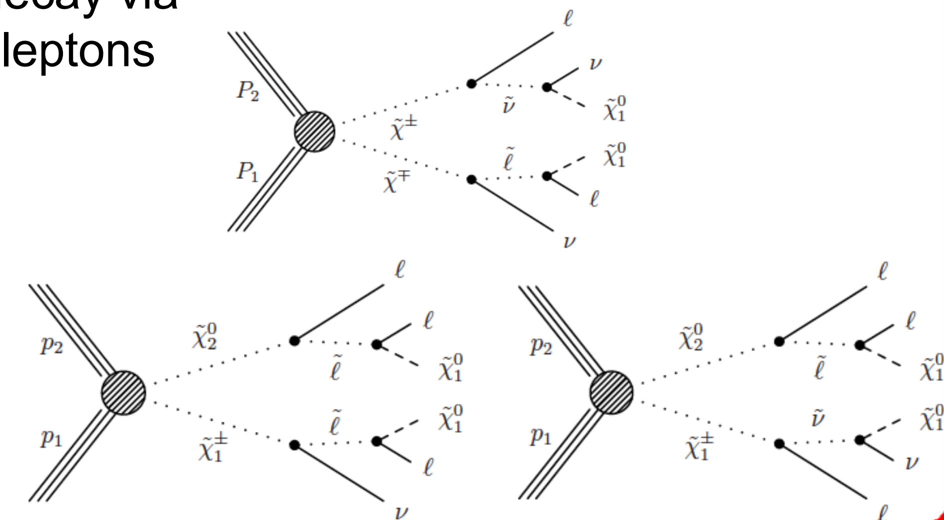
The Leftward March





Searches for Production of EWKinos

decay via sleptons

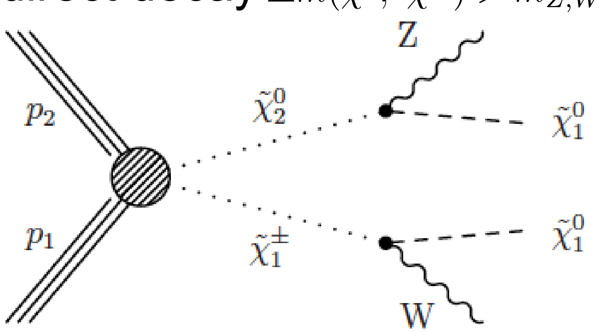


- Extensive set of searches for chargino and neutralino production
- Final states and search strategy depends on assumption of sleptons masses: e.g. all light, only stau light, all heavy
- Signatures:

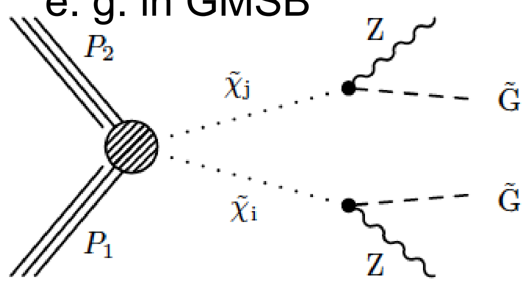
  2 (opposite and same sign),

  3, 4 leptons + MET

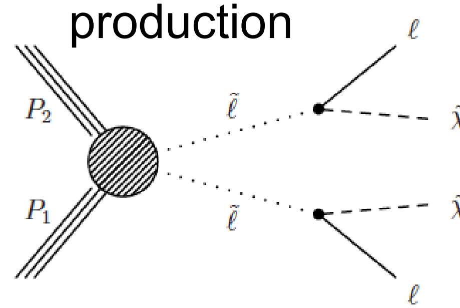
direct decay $\Delta m(\tilde{\chi}^0,\ \tilde{\chi}^{\pm}) > m_{Z,W}$



ZZ enriched models: e. g. in GMSB

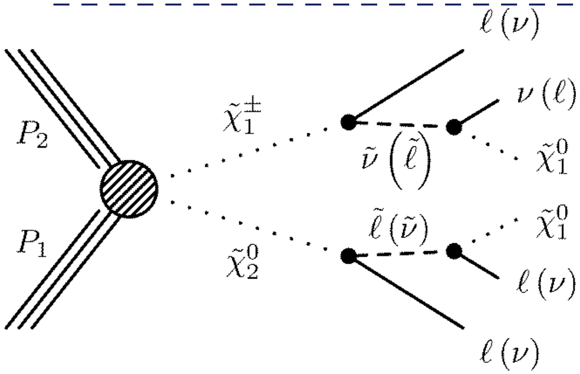


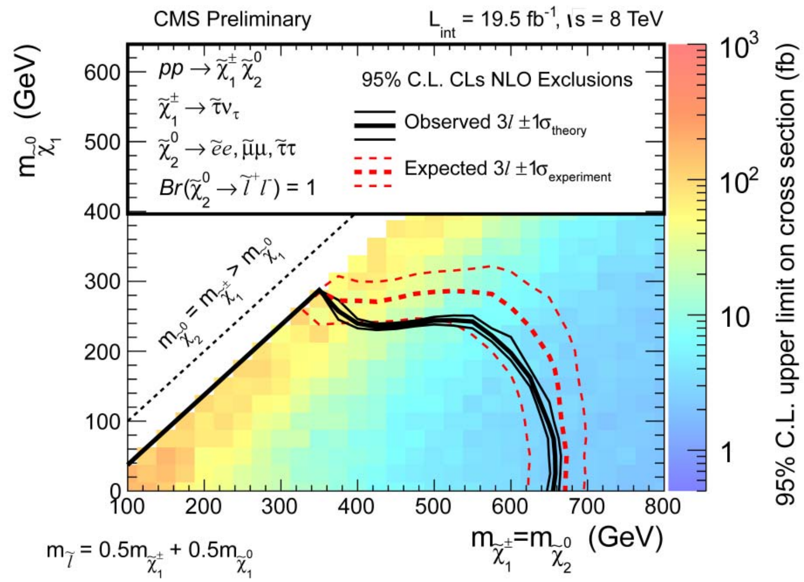
Direct slepton production



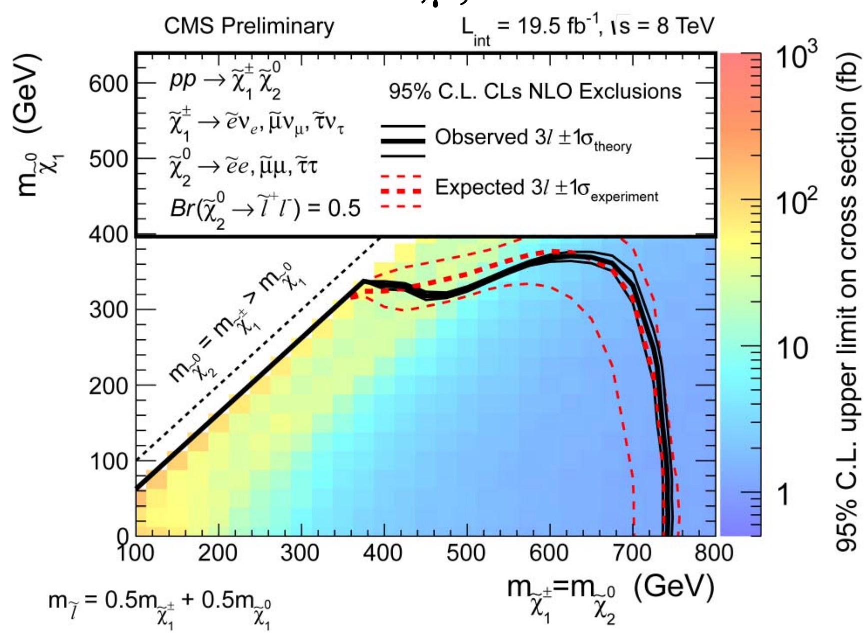
EWKino results (CMS-SUS-13-006)

Multileptons, on-Z and off-Z and SS dileptons

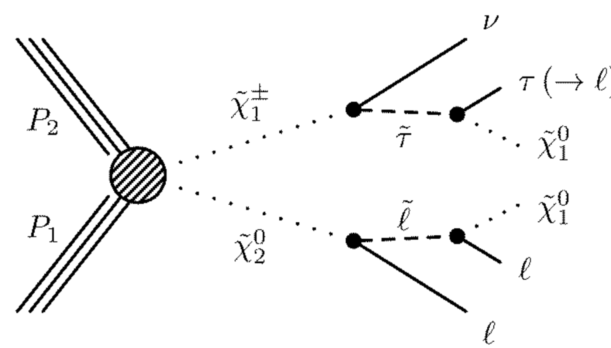




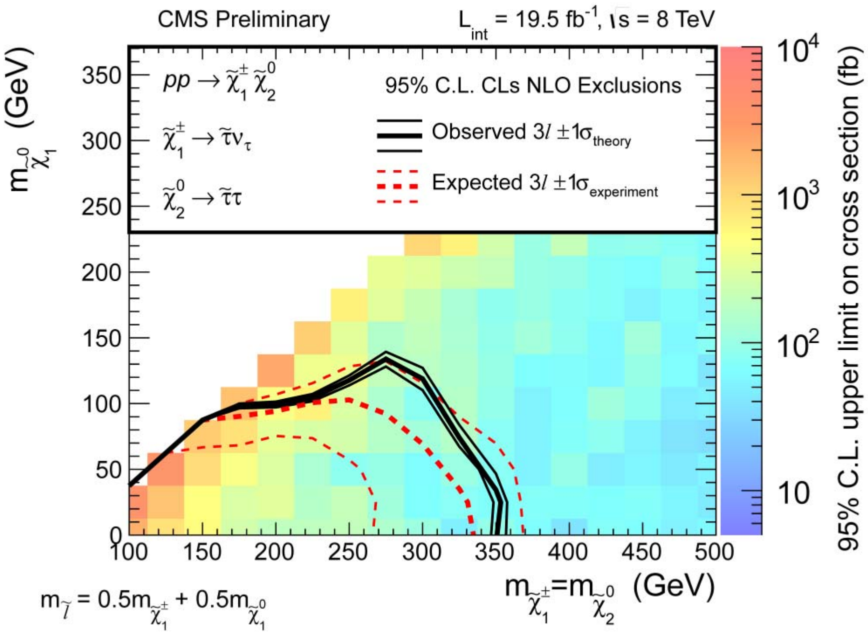
Democratic e,μ,τ



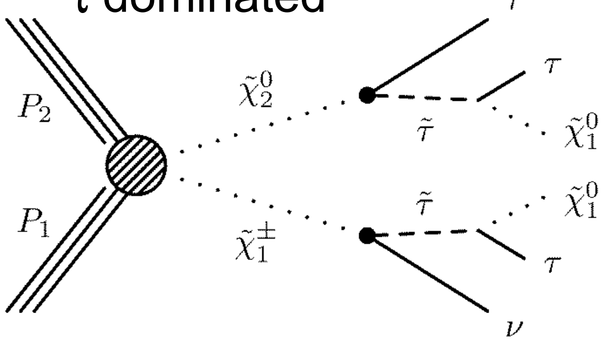
τ enriched

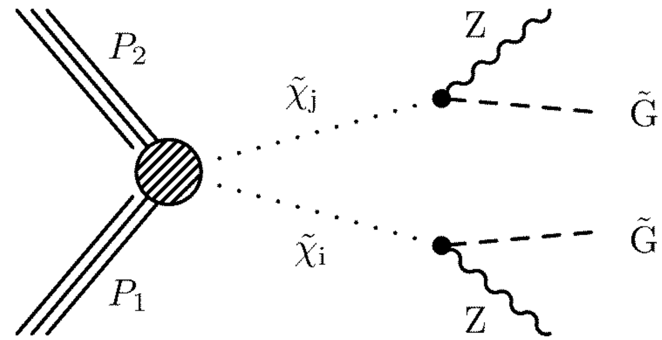


EWKino results (contd)

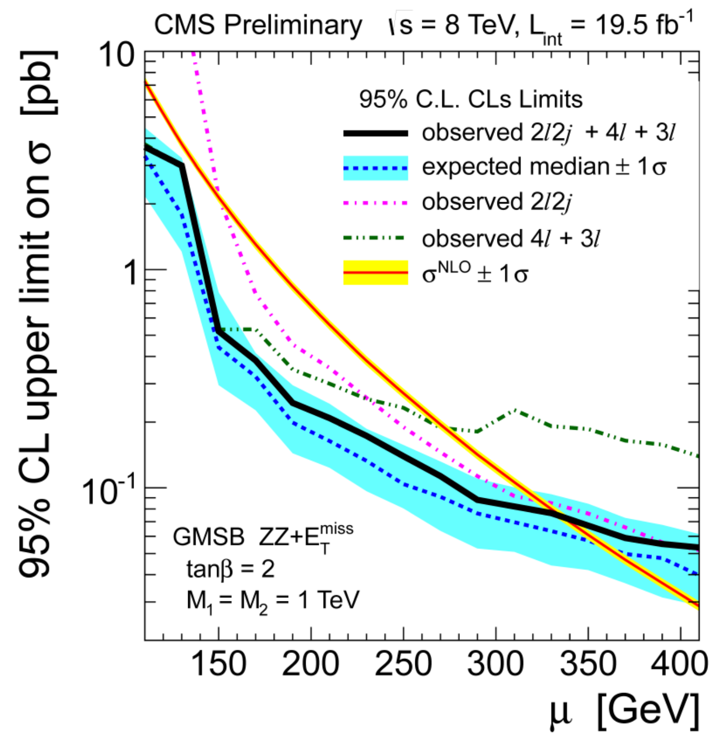


τ dominated

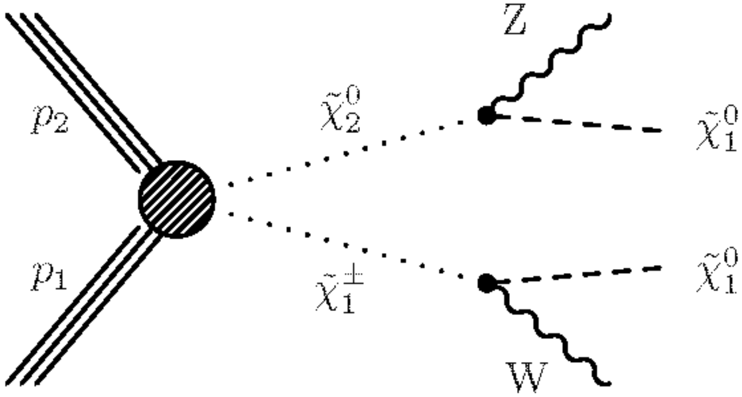




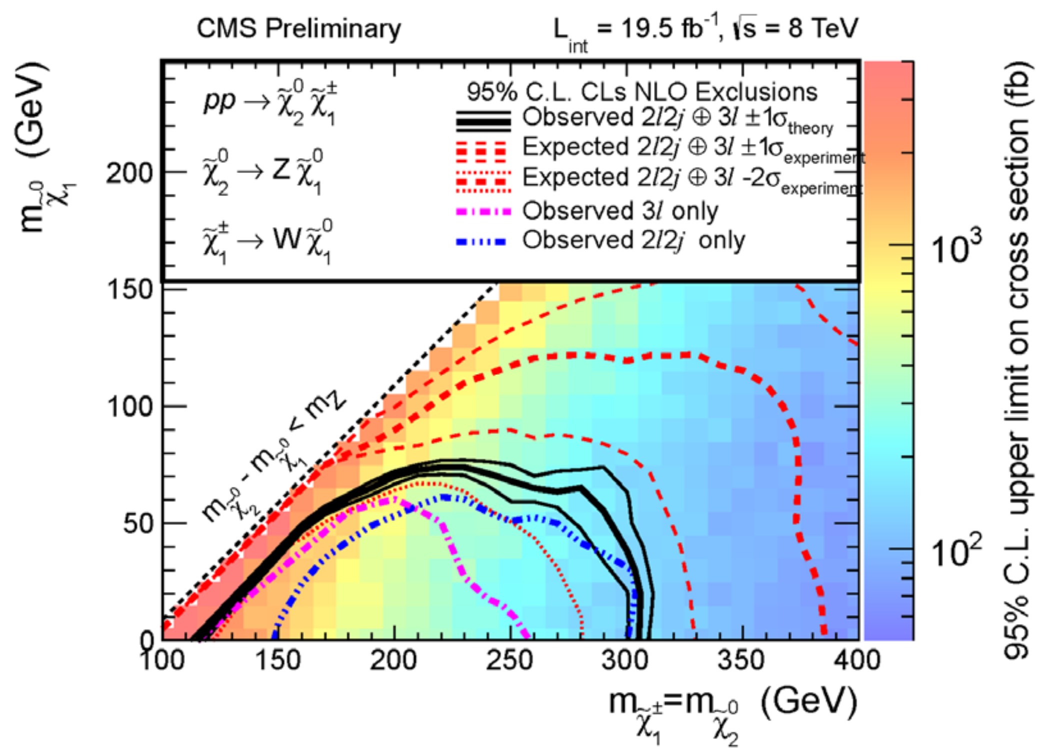
GMSB SUSY ZZ - includes Z(ll)+Z(jj)



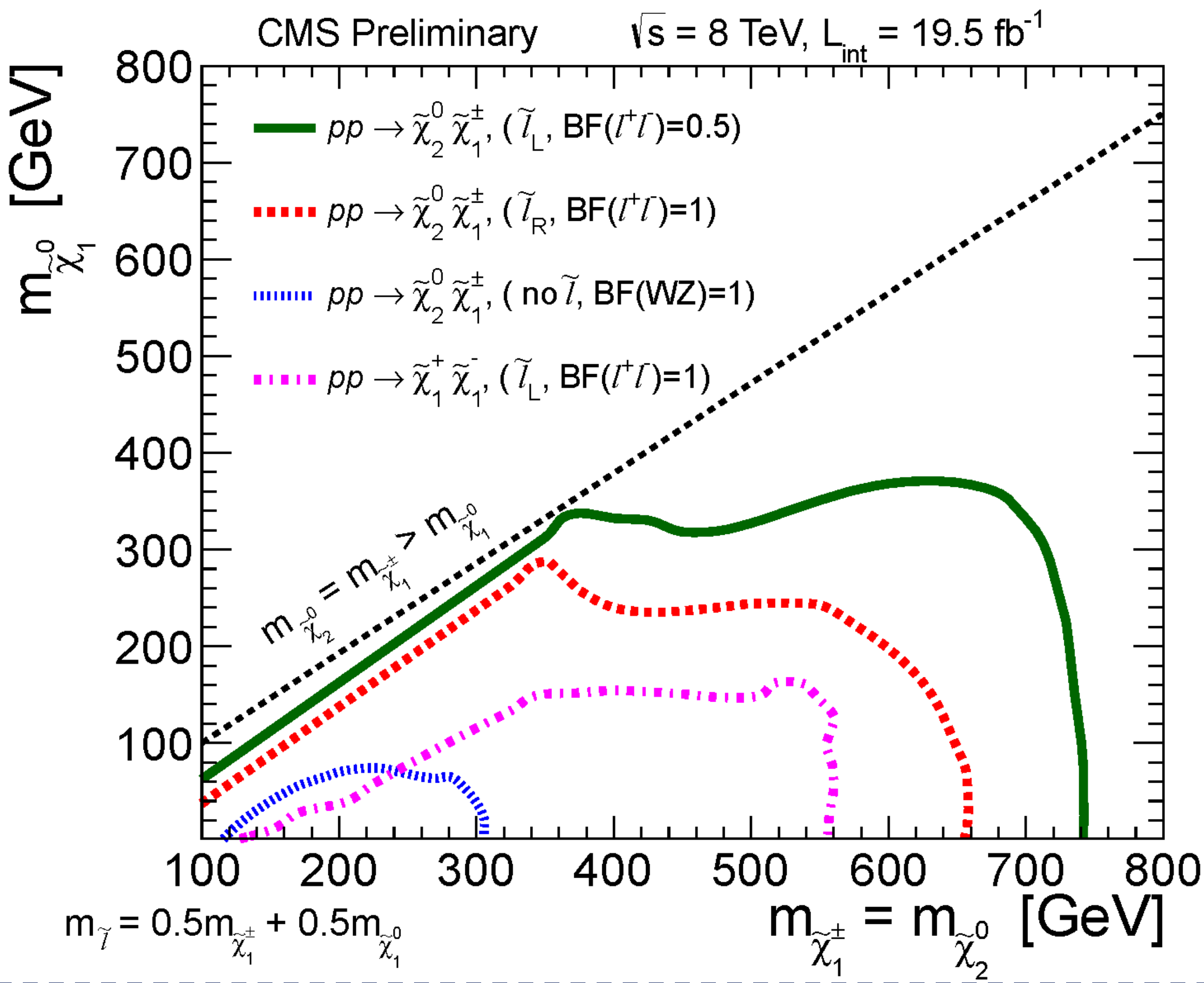
EWKino results (contd)



Sleptons heavy/decoupled
WZ+ MET signature
trileptons on Z & Z(ll)+Z(jj)



EWKino Summary (no Higgs)

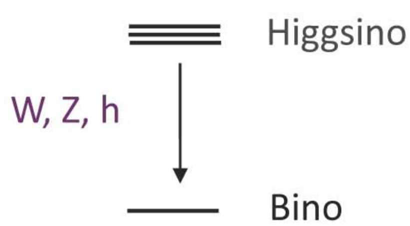


Next

- ➔Pure Electroweak production with higgs in the final state.
- ➔No strong production and higgs is difficult to detect.
- ➔ Electroweak with higgs in the final state is the most difficult of such searches. Not just a fetish. Higgs is the best EWSB exploration tool we have.
- ➔Multi-binned and multi-signature approach essential.

EWKino with Higgs

Higgsino-Bino:



"Draining the swamp"
(Scott Thomas)

Higgs – multibinned approach essential !!

Production Mode		Di-boson Channel
Chargino-Chargino	->	WW
Chargino-Neutralino	->	WZ, Wh
Neutralino-Neutralino	->	ZZ, Zh, hh

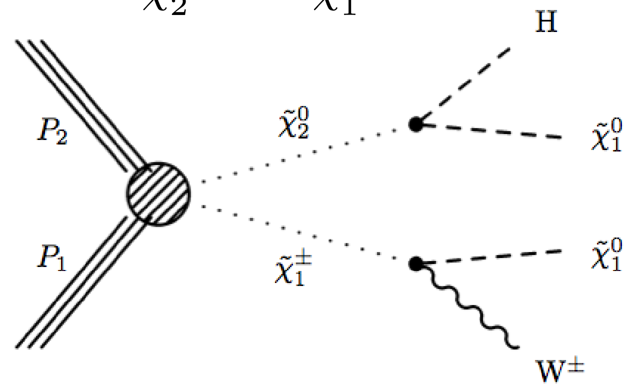
Dominates if Open

Neutralino$_{\text{Higgsino}}$ -> Neutralino$_{\text{Bino}}$ + h 0th order in mixing
Neutralino$_{\text{Higgsino}}$ -> Neutralino$_{\text{Bino}}$ + Z 1st order in mixing

Now with Higgs in the final state (WH + MET)

Novel approaches: **“Higgs tagging” in SUSY searches**

$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > m_H$

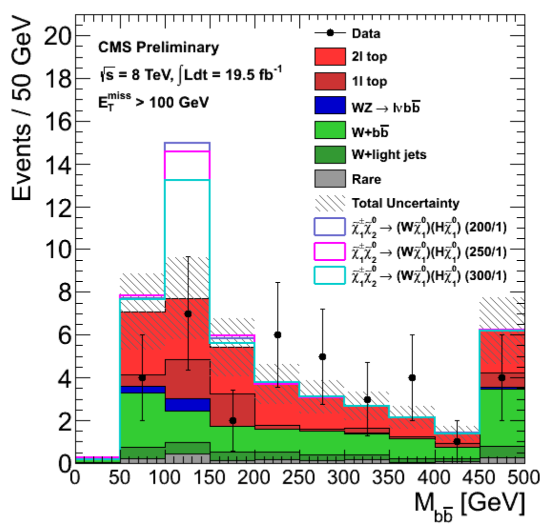


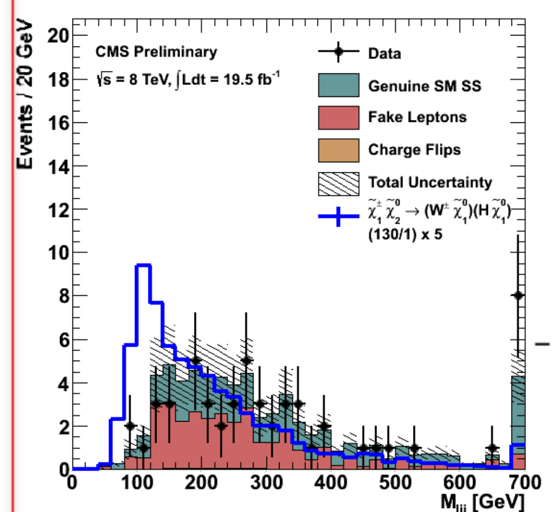
H decay modes considered:

- $H \to b\bar{b}$: 1ℓ + 2 b-tags
- $H \to W(\to l\nu)W(\to q\bar{q})$: 2ℓ (SS)
- $H \to W^+W^-/\tau^+\tau^-/ZZ$: 3ℓ

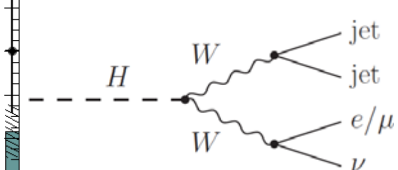
Combination of 1ℓ + 2 b-tags, 2ℓ (SS) and 3ℓ

1ℓ + 2 b-tags
Uses M_{bb}



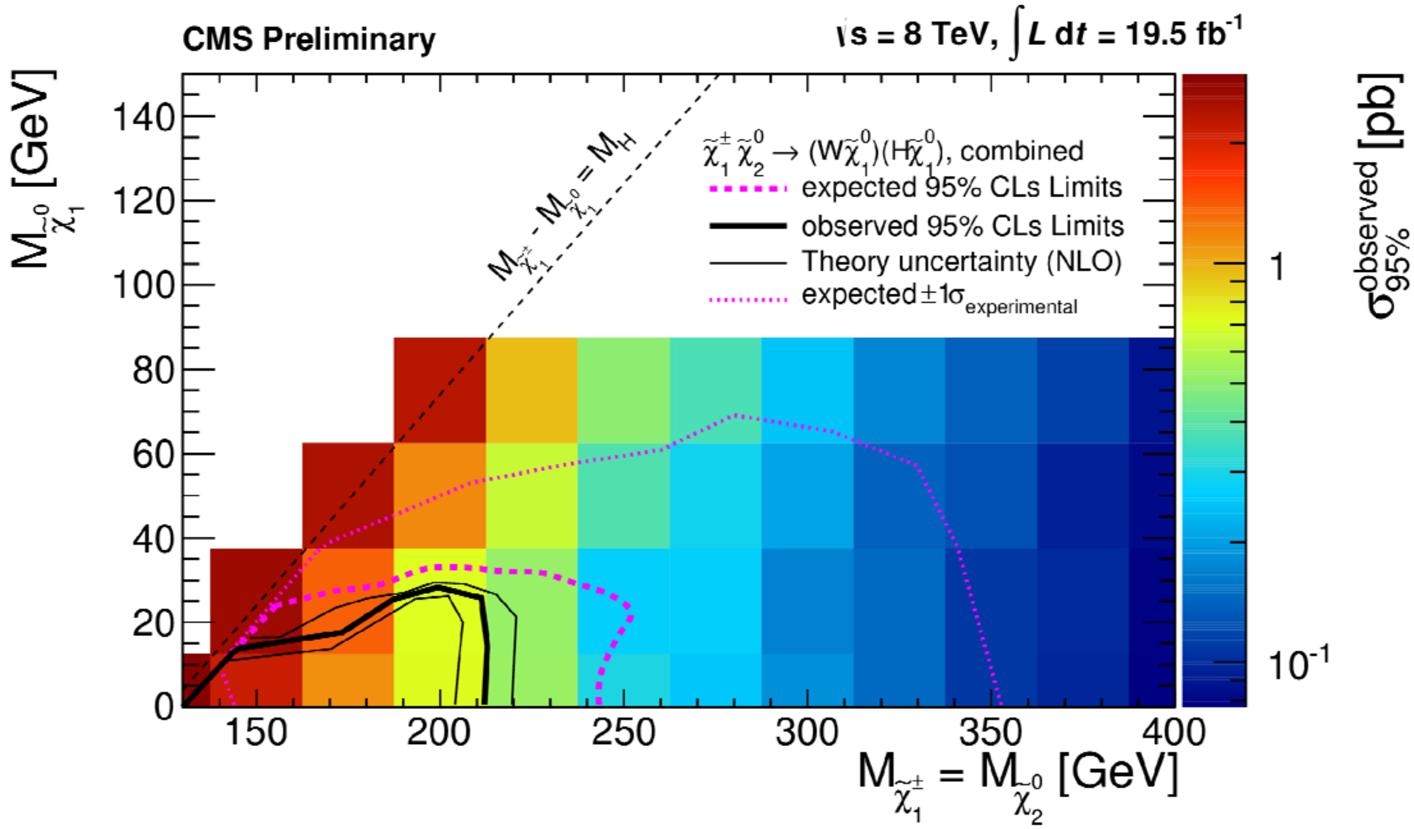


2ℓ (SS)
Uses M_{ljj}



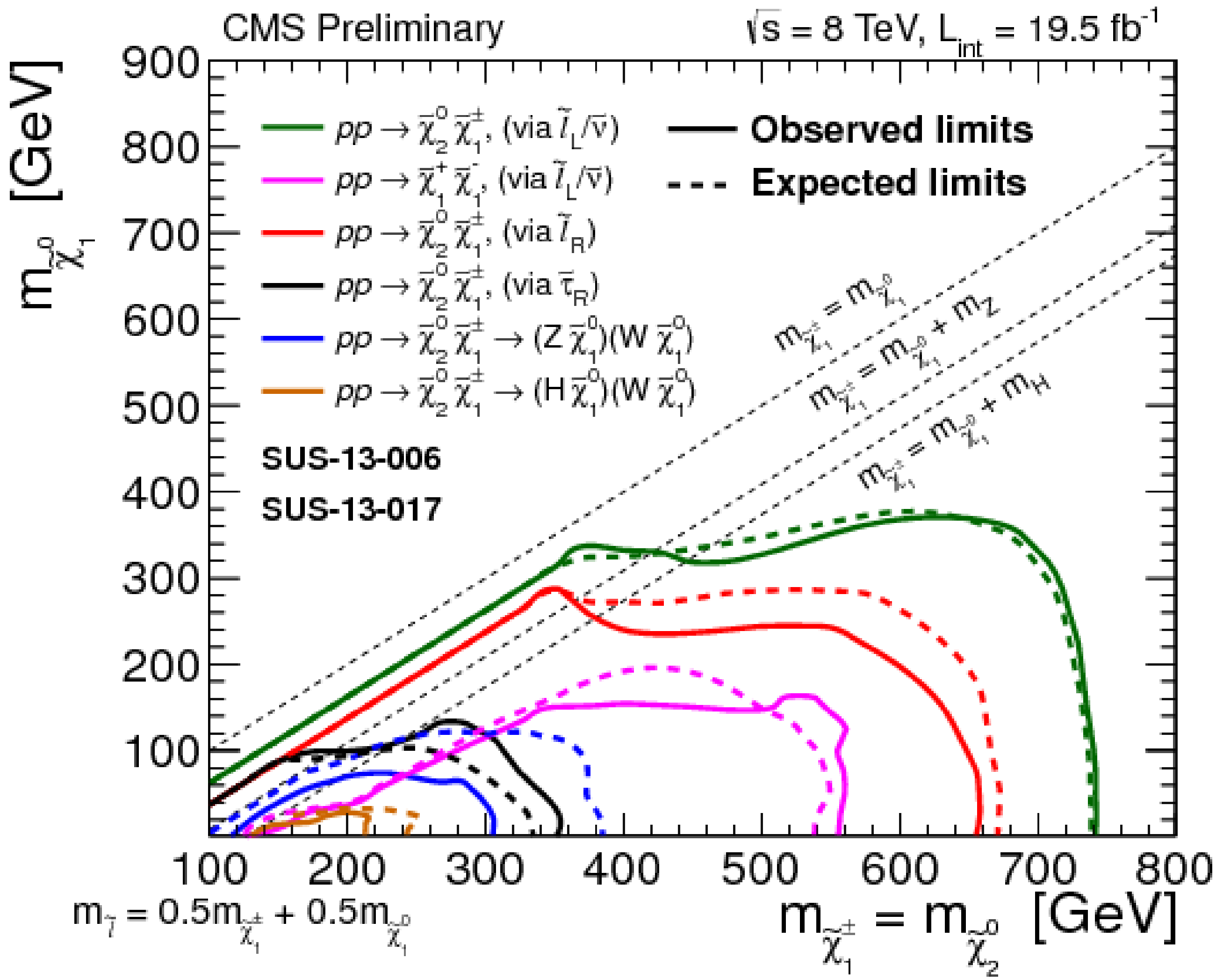
EWKinos with Higgs in the final state

Probing neutralino/chargino masses up to ~ 204 GeV



CMS-PAS-SUS-13-006
CMS-PAS-SUS-13-017

EWKino Summary (including WH)

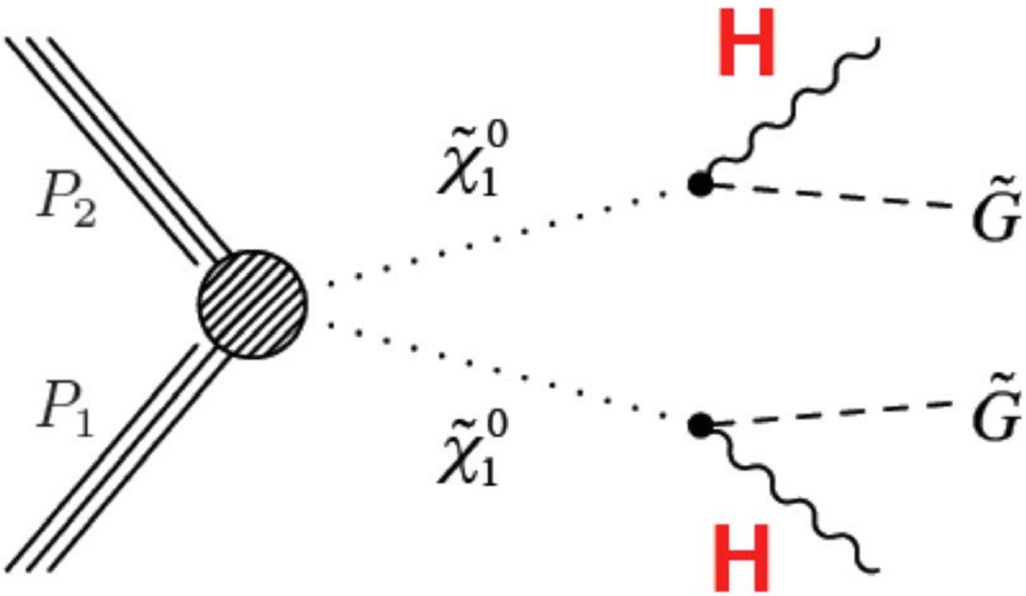


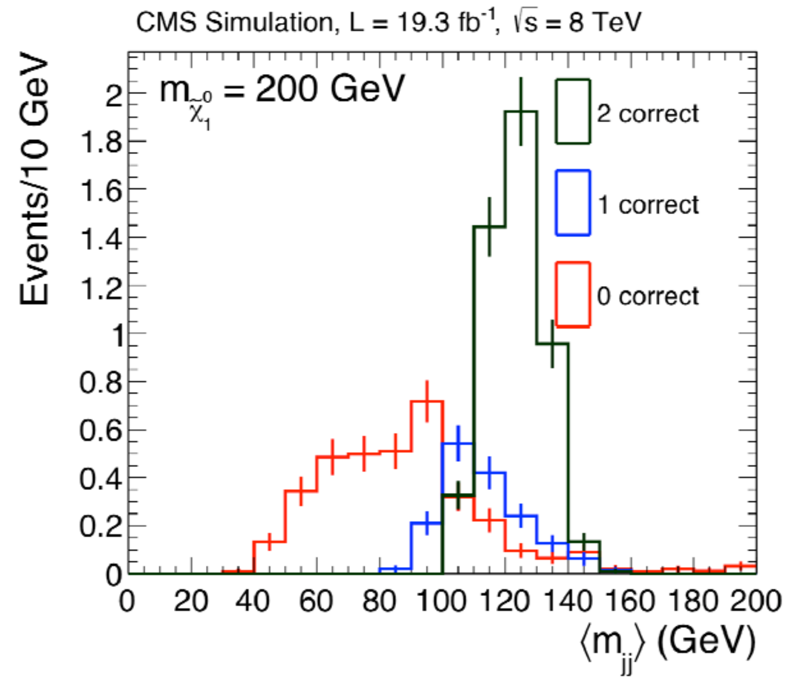
Next: and independently….

➔All hadronic ElectroHiggs

CMS hh → 4b

CMS SUS-13-022

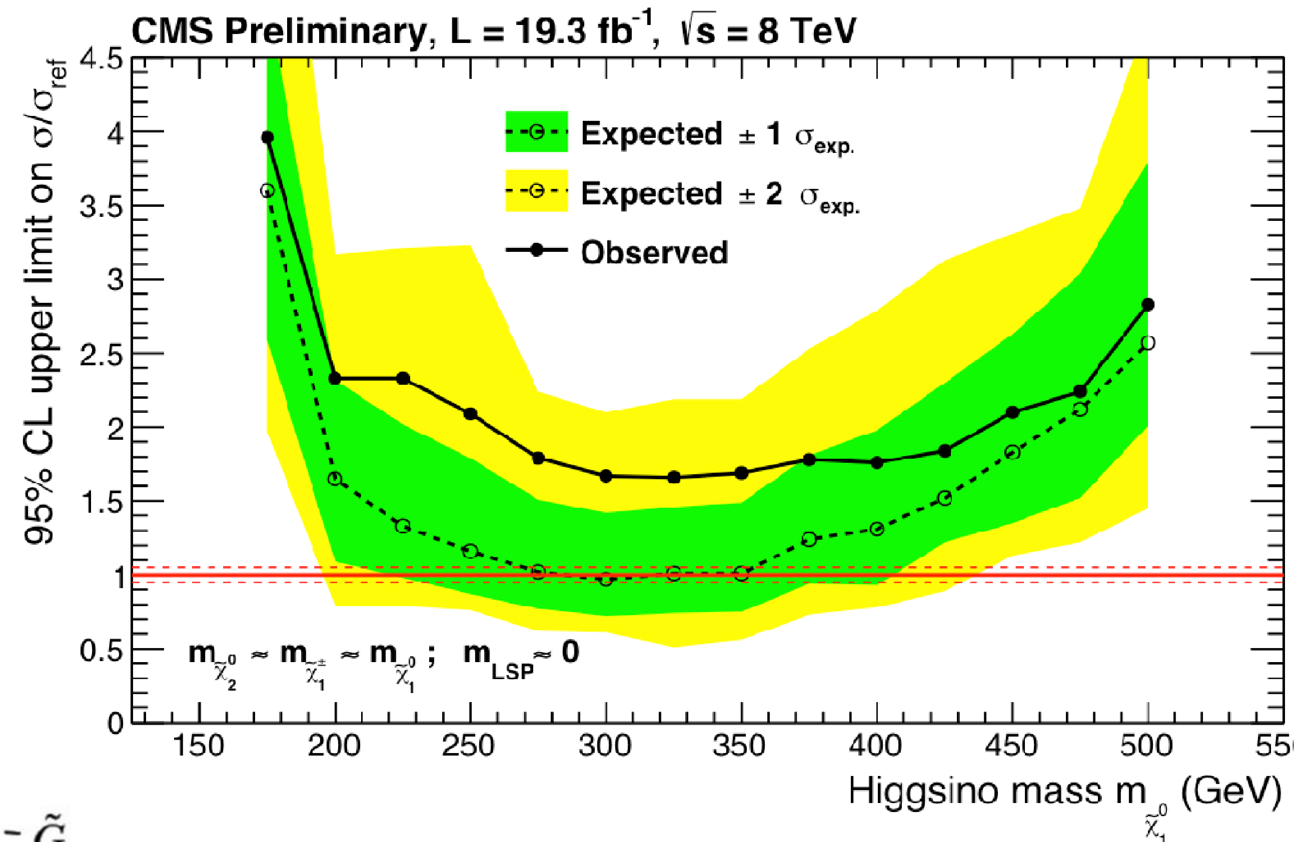


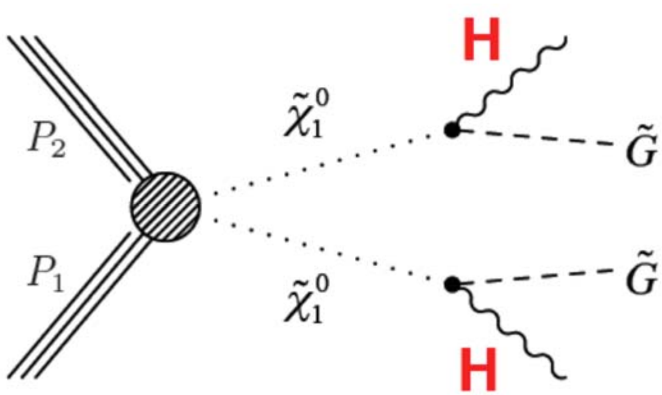


4/5 jets, top jets > 50GeV
Veto: leptons, tracks, hadronic tau
MET significance and jet-met angle
Signal: 4b, 3b in MET significance bins
Bkgnd: 2b, 3b sideband, 4b sideband

CMS hh → 4b

CMS SUS-13-022





Final word at 8 TeV

Showed ElectroHiggs so far with:

1,2,3,4 leptons: on-Z, off-Z etc etc

Diphotons + X

3b/4b

➔Grand ElectroHiggs omnibus combination

Topologies: hh, hZ and ZZ and admixture

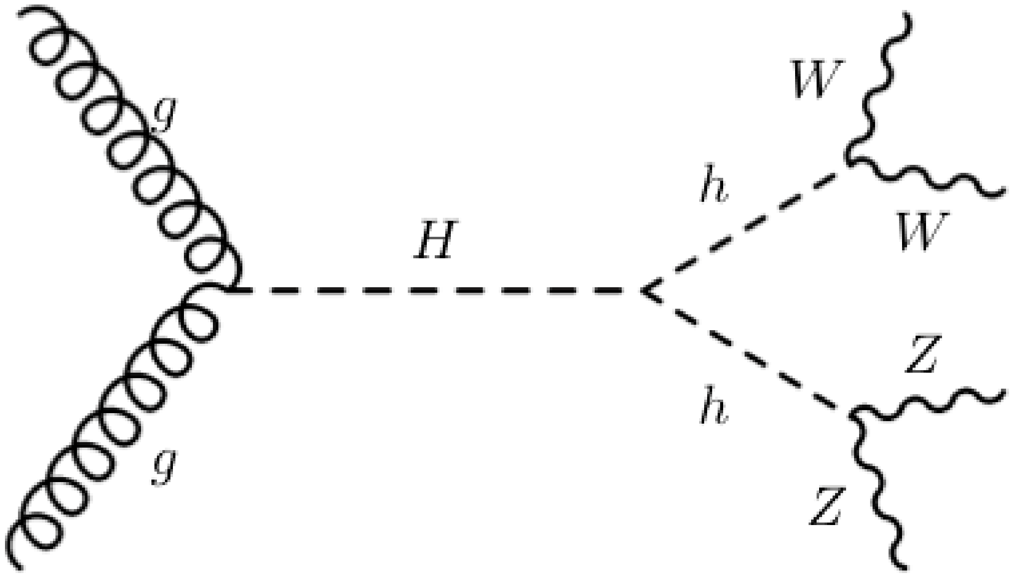
& hW

Next: Not necessarily SUSY

SUSY or non-SUSY BSM searches with Higgs in the final state (multileptons and diphotons)

Heavy Higgs - Extended Higgs Sector(2HDM)

CMS-HIG-13-025

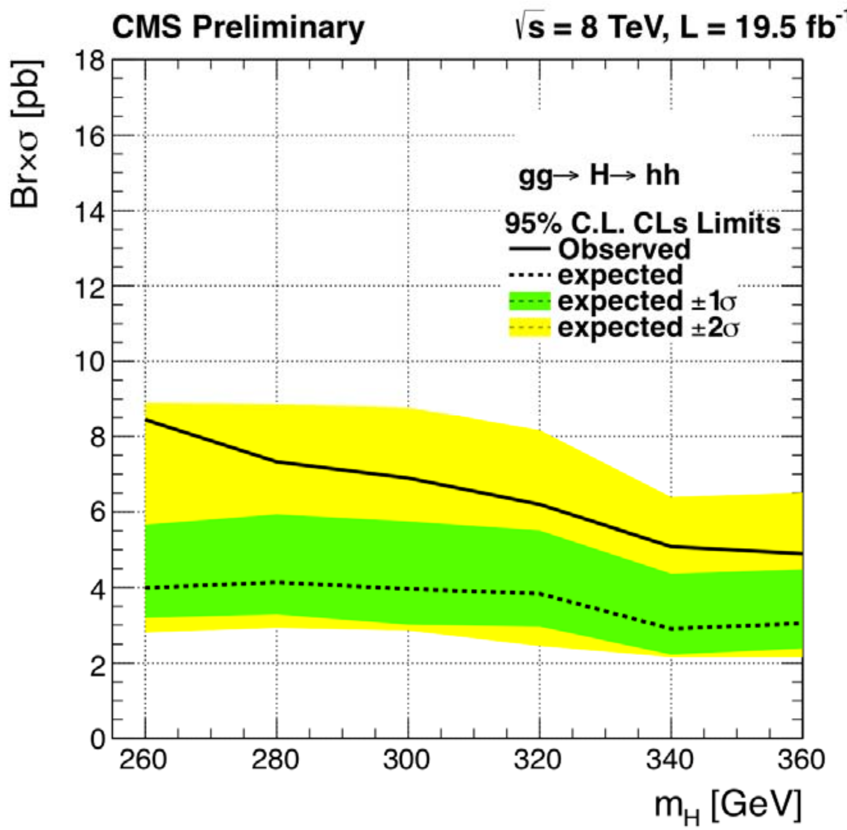


Nathaniel Craig et. al hep-ph:arXiv:1210.0559 & 1305.2424

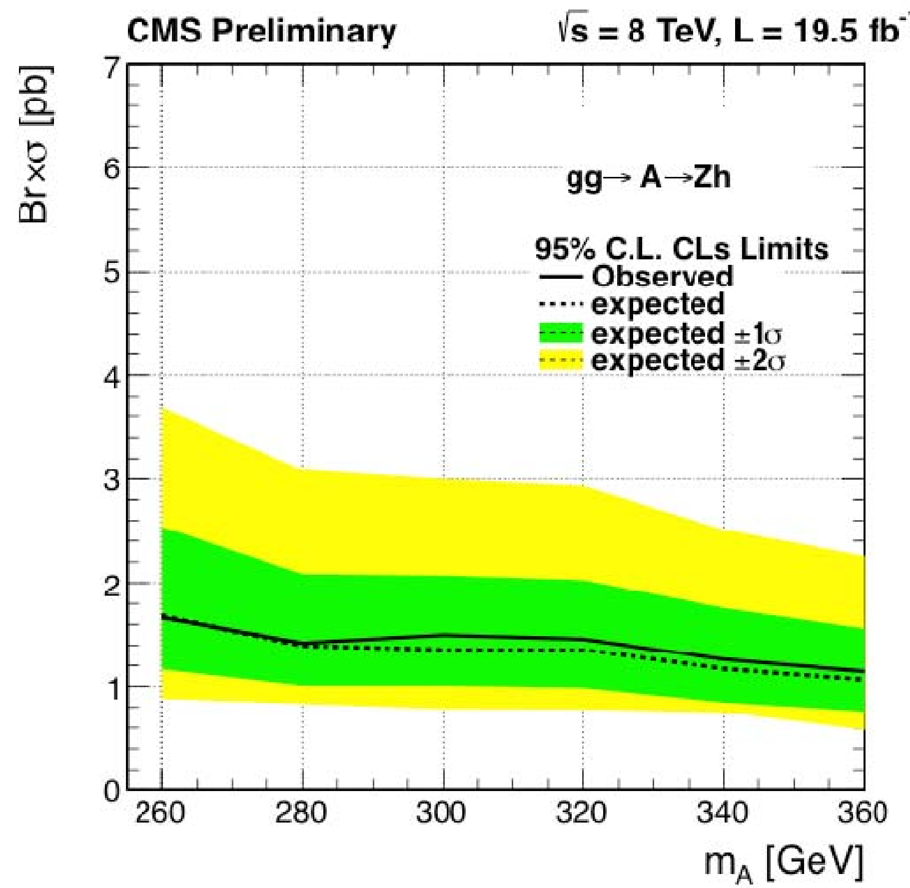
- Heavy Higgs H→hh) and
- pseudo scalar Higgs A→Zh
- Signature: multileptons and diphoton+leptons

H→hh and A→Zh Model Independent Limits

CMS-HIG-13-025



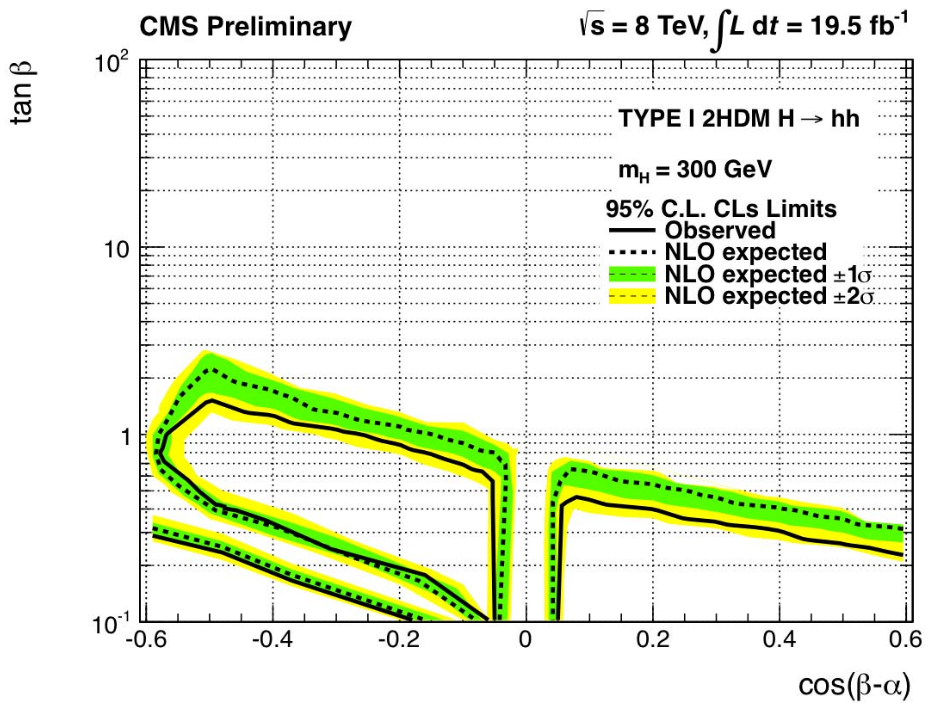
σ.BR(gg-H->hh)

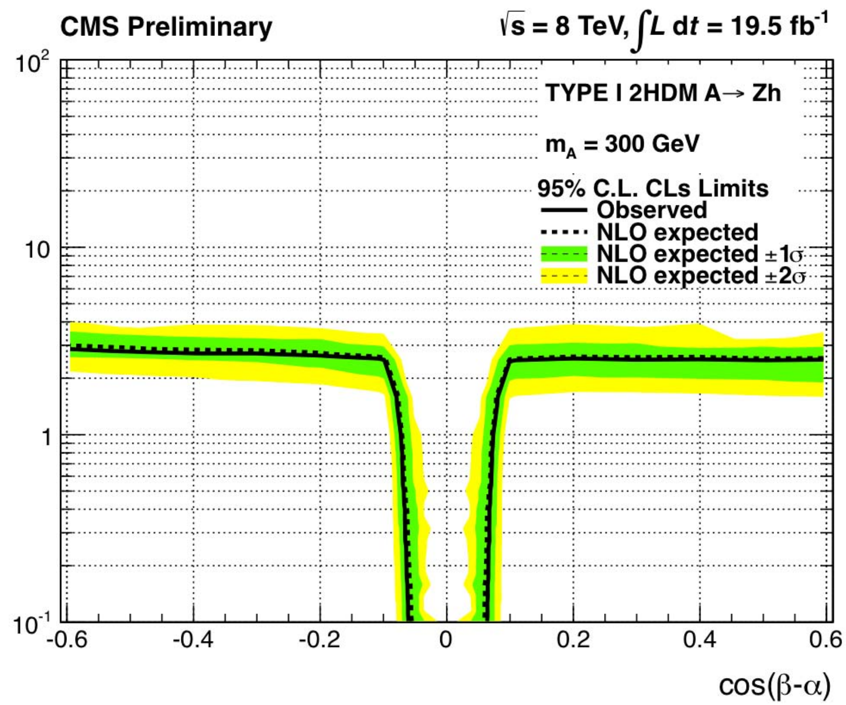


σ.BR(gg->A->Zh)

H→hh and A→Zh in 2HDM

CMS-HIG-13-025



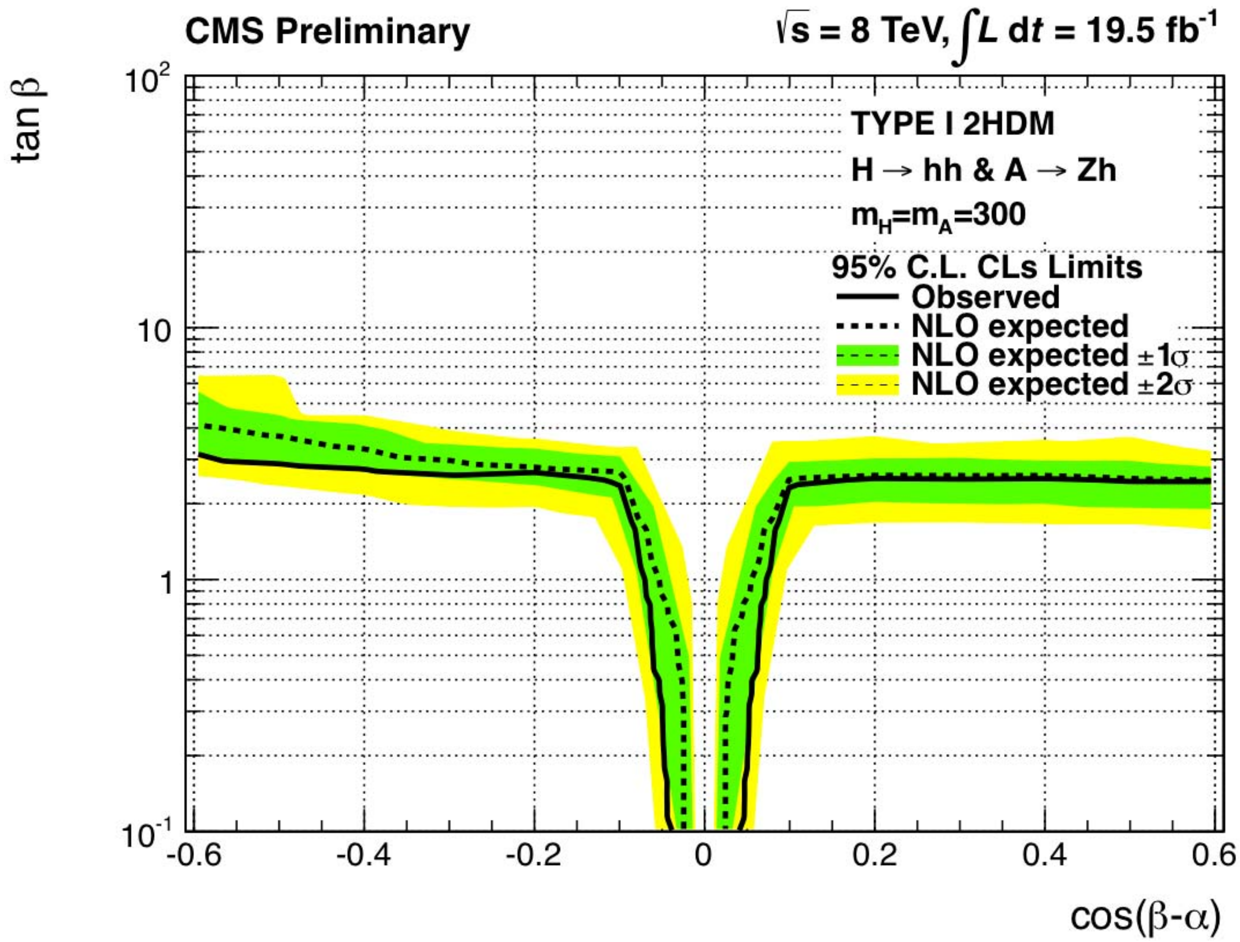


gg-H->hh

gg->A->Zh

H→hh and A→Zh COMBINED in 2HDM

CMS-HIG-13-025



t → ch FCNC coupling

CMS-HIG-13-034

Multileptons combined with diphoton+leptons

Higgs Decay Mode	observed	expected	1σ range
$H \to WW^*$ ($\mathcal{B} = 23.1\,\%$)	1.58 %	1.57 %	(1.02–2.22) %
$H \to \tau\tau$ ($\mathcal{B} = 6.15\,\%$)	7.01 %	4.99 %	(3.53–7.74) %
$H \to ZZ^*$ ($\mathcal{B} = 2.89\,\%$)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)	1.28 %	1.17 %	(0.85–1.73) %
$H \to \gamma\gamma$ ($\mathcal{B} = 0.23\,\%$)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons	0.56 %	0.65 %	(0.46–0.94) %

$$\sqrt{|\lambda_{tc}^{H}|^2 + |\lambda_{ct}^{H}|^2} < 0.14$$

Next

➔SUSY is dead. Long live SUSY!

SUSY Search Criteria (are very loose)

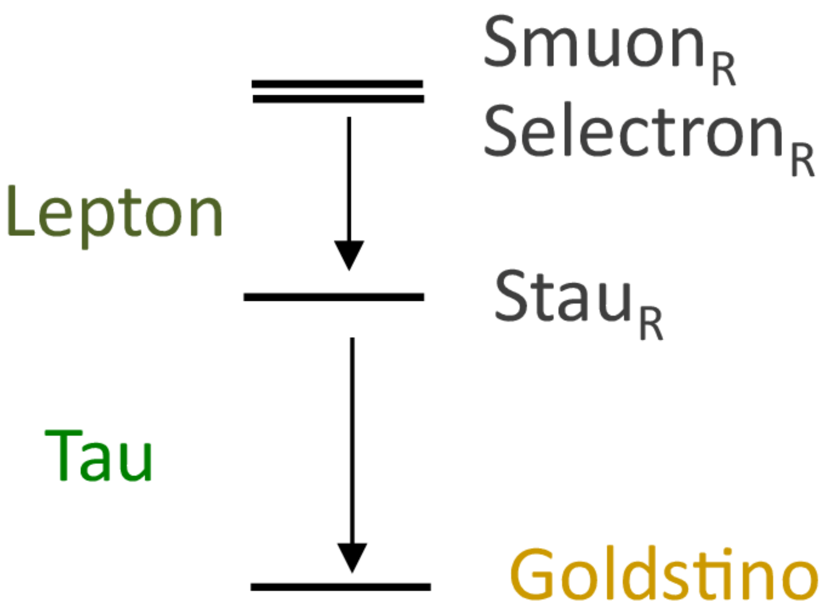
- Prompt vs non-prompt (lifetime=?)
- R-Parity conserved? RPV? (nonprompt?)
- Infinite mass spectra variations
- Production: Strong or Weak?
- Strong: Squark, gluinos, 3rd Generation (stop/sbottom),
  Cascades to higgs final states
- Electroweak: Sleptons, gauginos,natural higgs, “ElectroHiggs”

→We clearly have not fully spanned the very interesting electroHiggs sector…… AND….

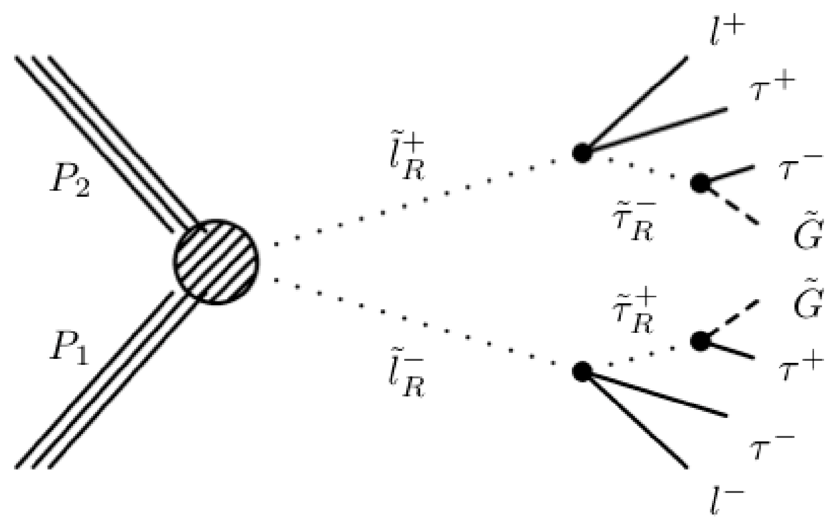
→ Have we really seen nothing so far?

(What follows comes with a strong disclaimer!!)

Stau (N)NLSP with multileptons



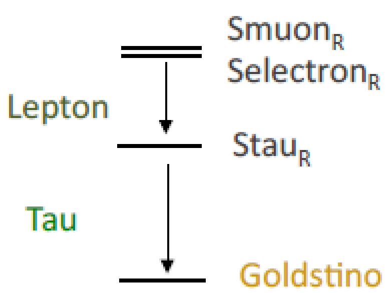
Stau (N)NLSP

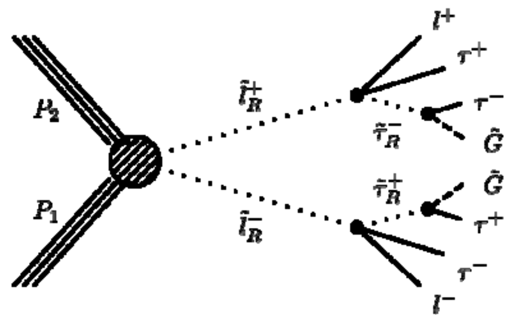


Stau (N)NLSP scenario

Gauge Mediated Supersymmetry Breaking (GMSB) model

CMS-SUS-13-002



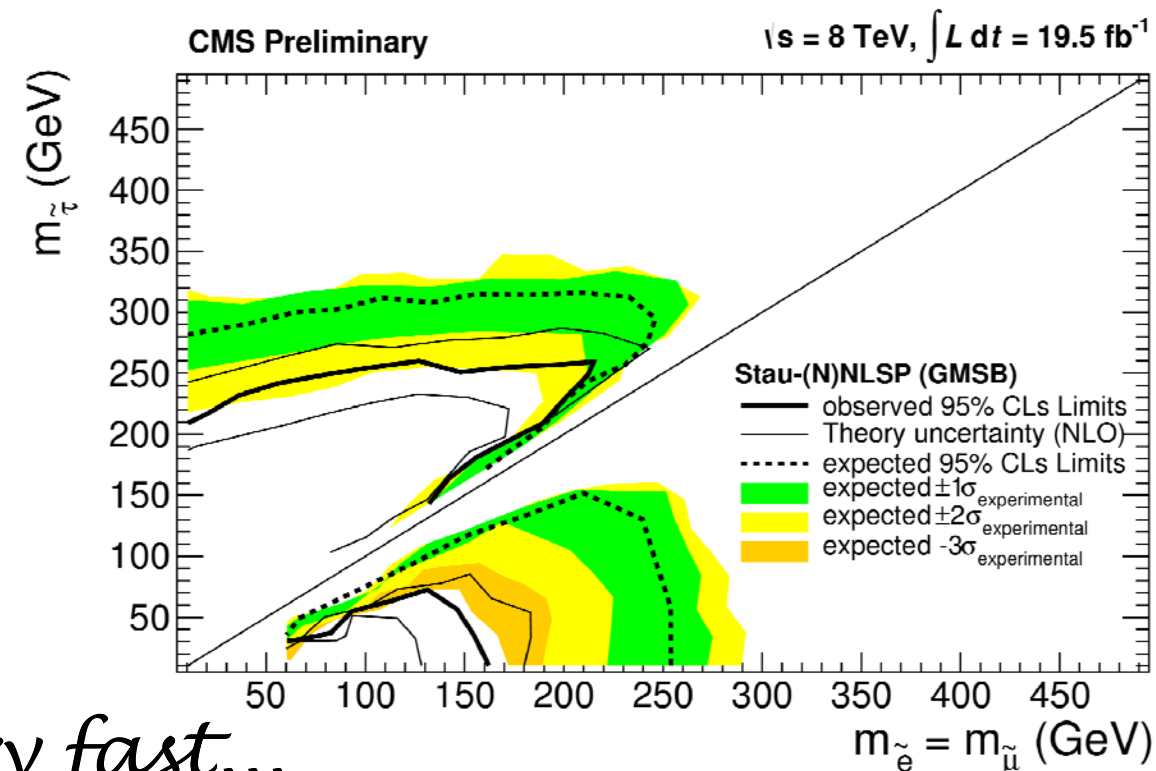


Electroweak production of right-handed sleptons

Signal populates high MET and τ channels.

Exclusion limits in the degenerate smuon- and selectron-stau mass plane

Next slide more on discrepancy



Say "τ excess" very fast...

Origin & significance of discrepancy

CMS-SUS-13-002

Most significant contributing channel:

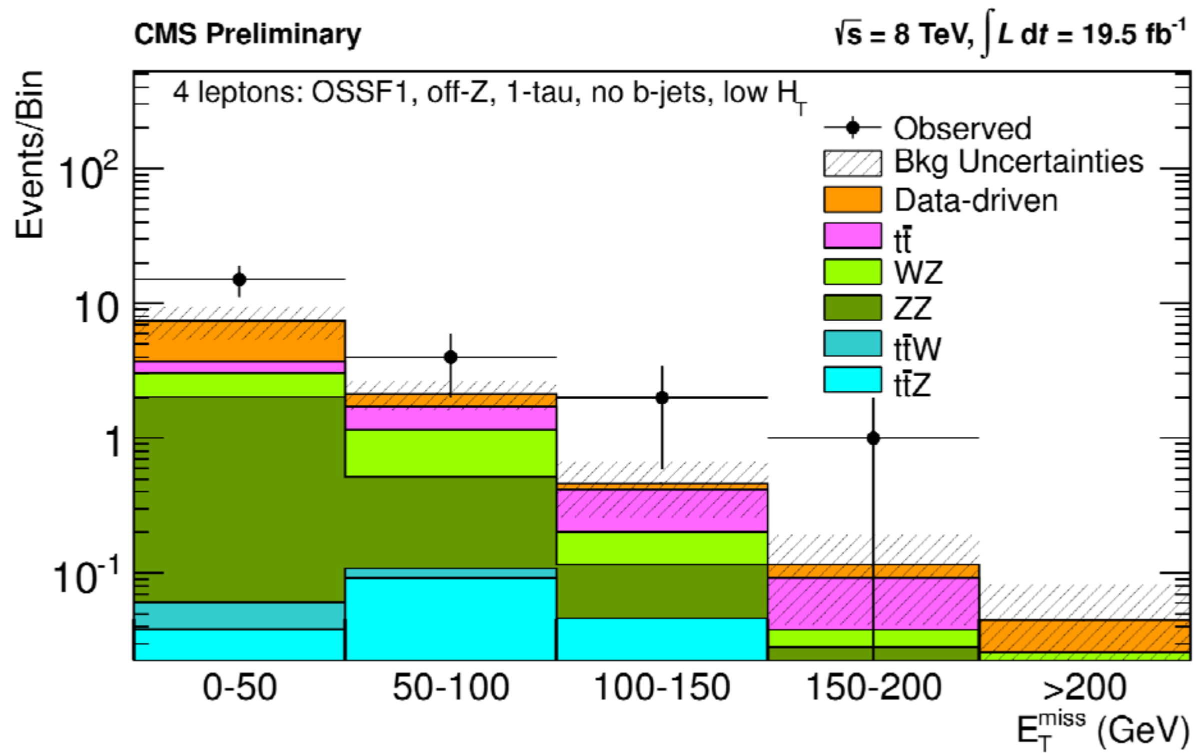
4 leptons, OSSF1, off-Z,

including 1 τ,

no b-tags, HT< 200 GeV

Observe = 22 events

Expected = 10 ± 2.4



Discrepancy studies

CMS-SUS-13-002

Category:

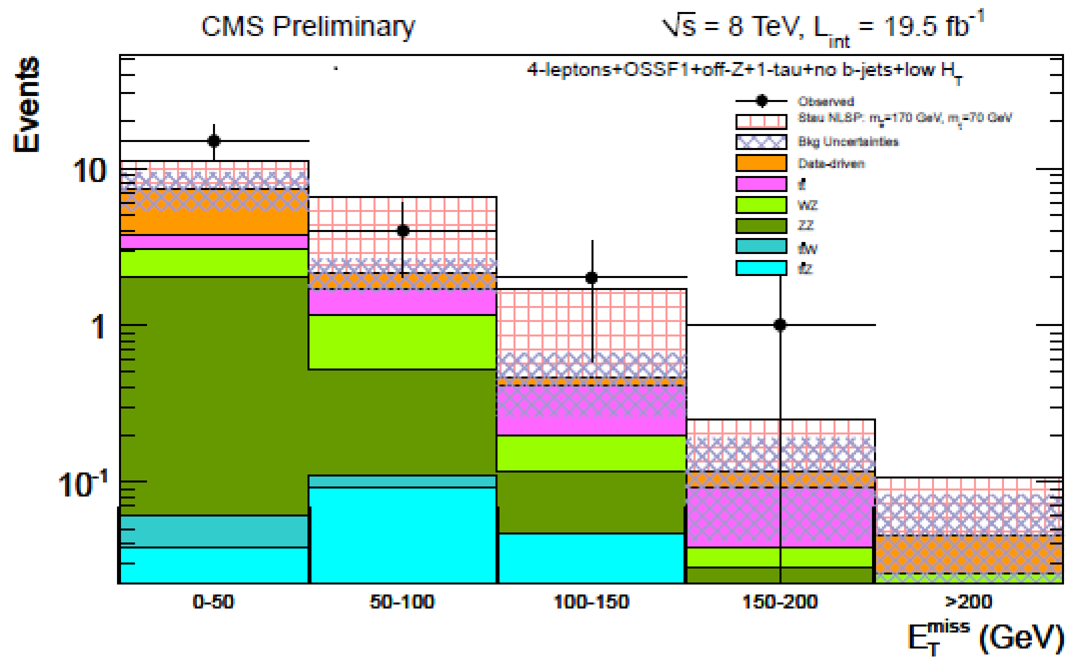
4 leptons, including 1 τ,

OSSF1, off-Z,

no b-tags, HT< 200 GeV

Observe = 22 events

Expected = 10 ± 2.4 events



Same plot, with stau NLSP signal filling the SM void.

There are 64 different categories of met-binned multi-lepton events.
BUT: One of the first to-do for 2015

SUSY searches with higgs conclusions

- **Masses heavy in simple (hadronic) schemes, but many foxholes left. The hunt continues.**

- The obvious hierarchy is squark/gluino, 3rd generation, electroweak and electrohiggs. (RPV etc separate). Higgs is our best EWSB probe.
- A new energy regime in 2015. Let us hope for a quick hadronic find. If not, back to the electroweak and electrohiggs chase.
- 2015 should see significant advances with electroHiggs.
- A word to the experimentalist: If a search team discovers an excess, it will NOT be the physics model they were looking for → open (inclusive) searches important.
- SUSY is a sly cat with nine lives.
  →Rumors of SUSY's demise are greatly exaggerated.

Thanks/Credits

- Mitchell workshop organizers
- LHC staff.
- CMS collaborators, conveners and management.

Interpretations: GMSB scenarios

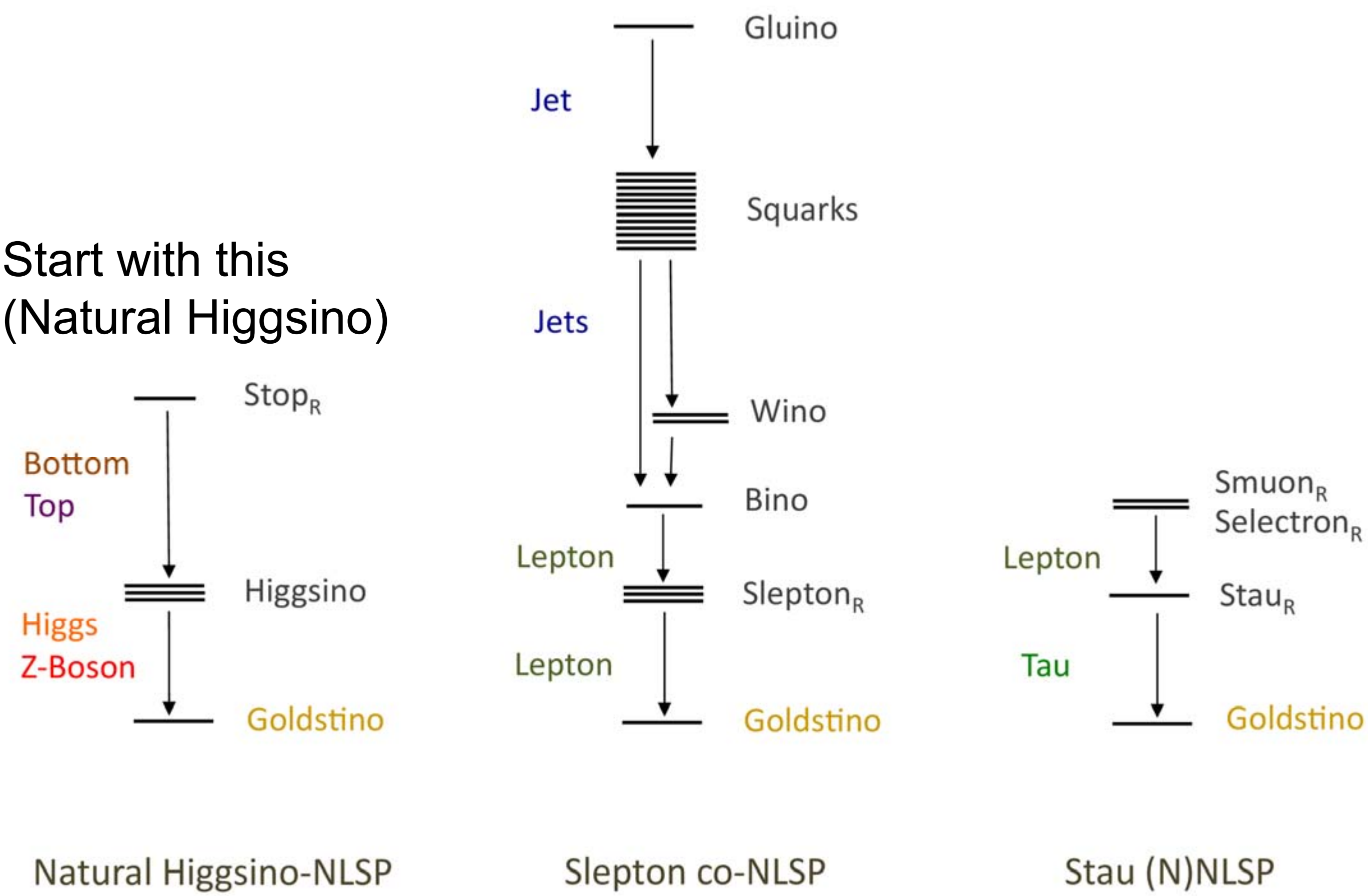
GMSB = Gauge Mediated Supersymmetry Breaking

CMS-SUS-13-002

Mass spectra in 3 models

Gravitino is the lightest SUSY particle (LSP).

Start with this (Natural Higgsino)



GMSB scenarios

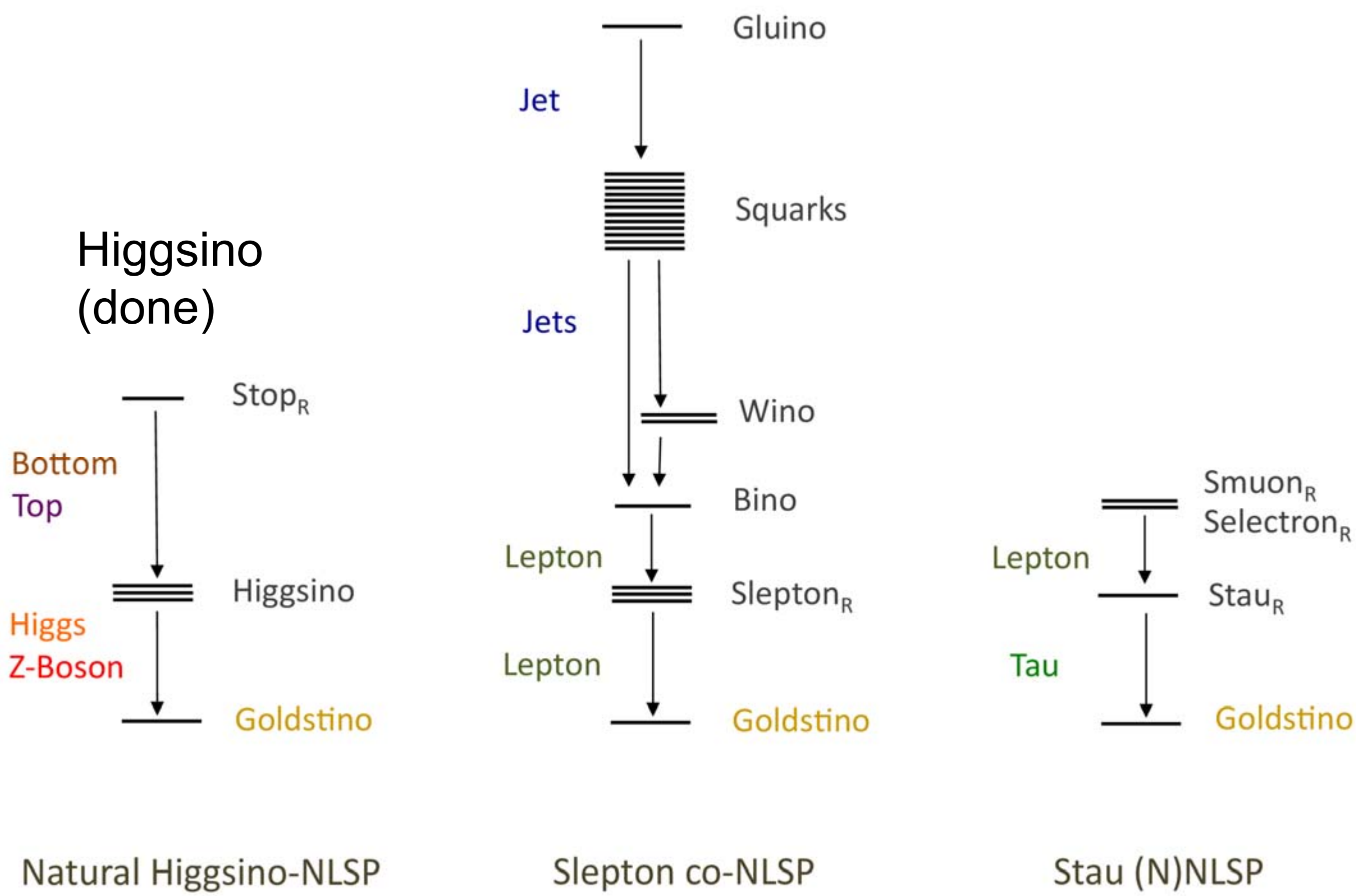
CMS-SUS-13-002

GMSB = Gauge Mediated Supersymmetry Breaking

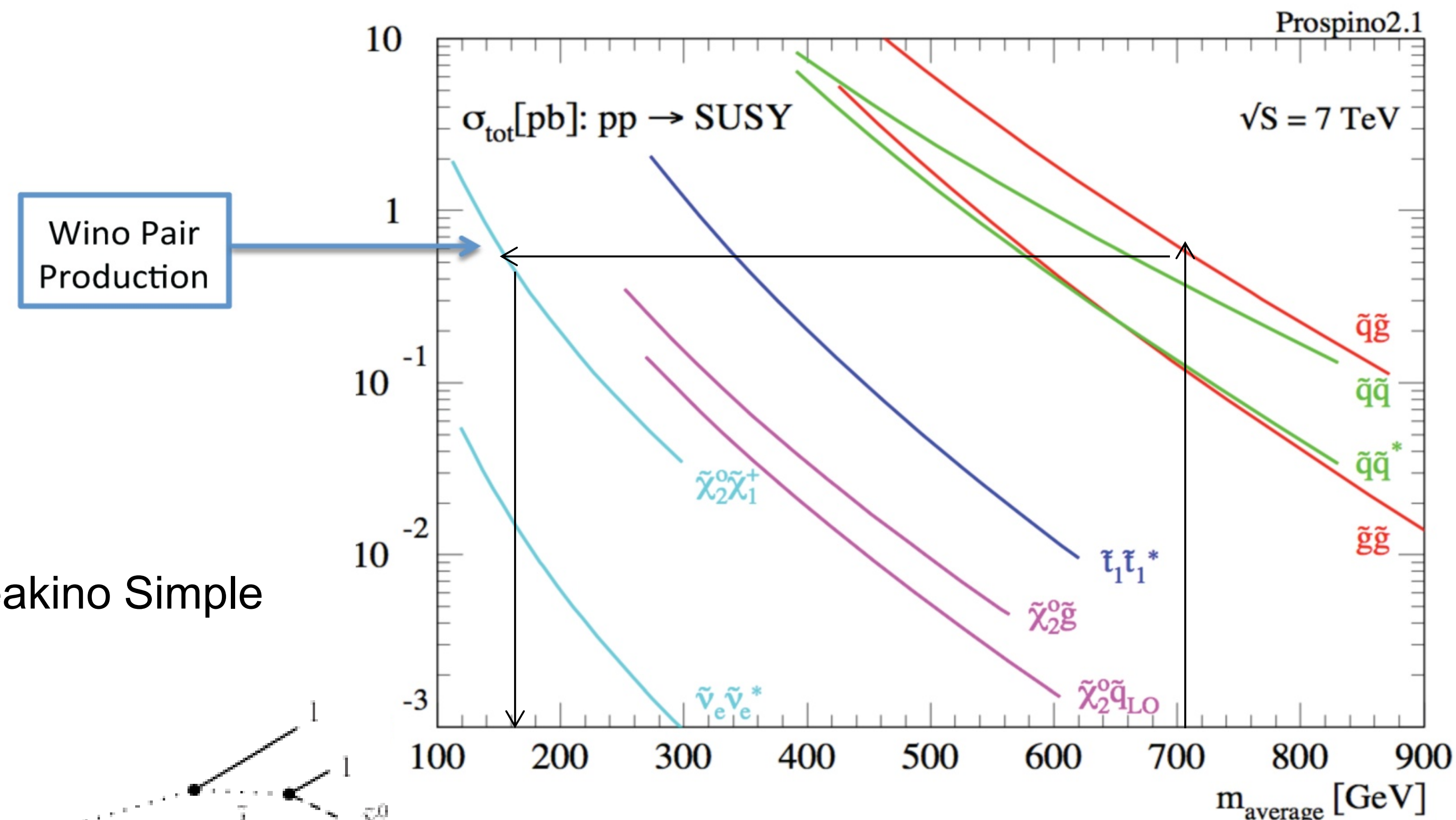
Gravitino is the lightest SUSY particle (LSP).

Mass spectra in 3 models

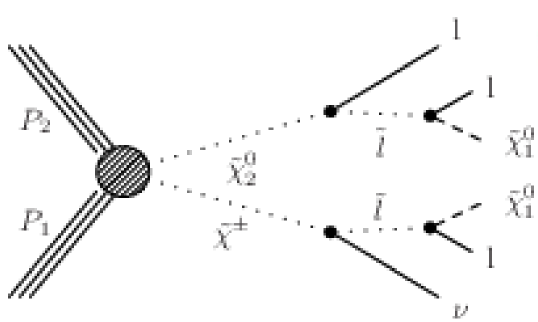
Higgsino (done)



Strong vs Weak Super-Partner Production



Electroweakino Simple topology



Search: Require *less* hadronic activity (CDF trileptons, ~2008)