SUSY searches – Part I

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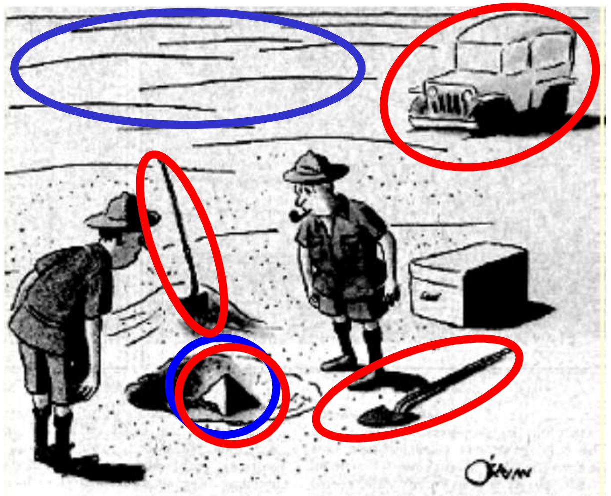
Terascale School on BSM Physics (DESY)



"This could be the discovery of the century. Depending, of course, on how far down it goes"

Part I
Motivation, the tools to dig, EW SUSY
Part II
3rd gene and Strong SUSY, Beyond MSSM

Th 7-Apr	Fr 8-Apr
	Part II
Part I	

Who am I ?

❑ **Member of ATLAS since 1998** http://www.cern.ch/pralavop/

1998: CNRS Permanent Research position at CPPM (Marseille, FRANCE)

1998-2010: Building, qualification and commissioning of the ATLAS Electromagnetic liquid argon calorimeter with cosmics and first data. Co-editor of the paper summarizing the performance of the ATLAS Liquid Argon Calorimeter [EPJ **C70** (2010) 723].

2005-2010: Preparation of analysis in top and beyond the Standard Model (W', Z' and Supersymmetry) physics. Prospects on top/W polarisation [EPJ **C44S2** (2005) 13].

2010: Co-editor of W/Z cross-section paper [JHEP **1012** (2010) 060].

2010-2012: Co-convenor of the ATLAS Supersymmetry Working group. 50 articles submitted to journals ($\sim$ 20% of ATLAS articles by 2012).

2013: CNRS research director

2013-2015: 2 SUSY Searches (JHEP **1406** (2013) 035, JHEP **1405** (2014) 071). "Lessons for SUSY from the LHC" in "SUSY after the Higgs discovery" book, "Particle Physics and Cosmology" in "100^{th} Summer School Les Houches Proc."

2015-: Co-convener of ATLAS Top Yukawa coupling measurement group

- **"Lessons for SUSY from the LHC after the first run"**, EPJ C74 (2014) 2801, 1404.7191
  - Lectures will be largely based on this – updated with latest results …
- Bibliography page : **http://www.cern.ch/pralavop/phd.html**

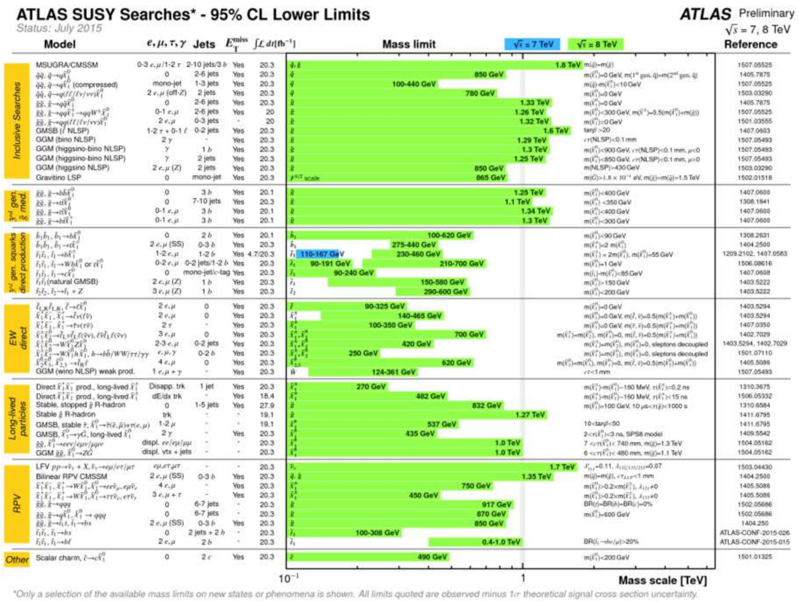
What I will talk about ?

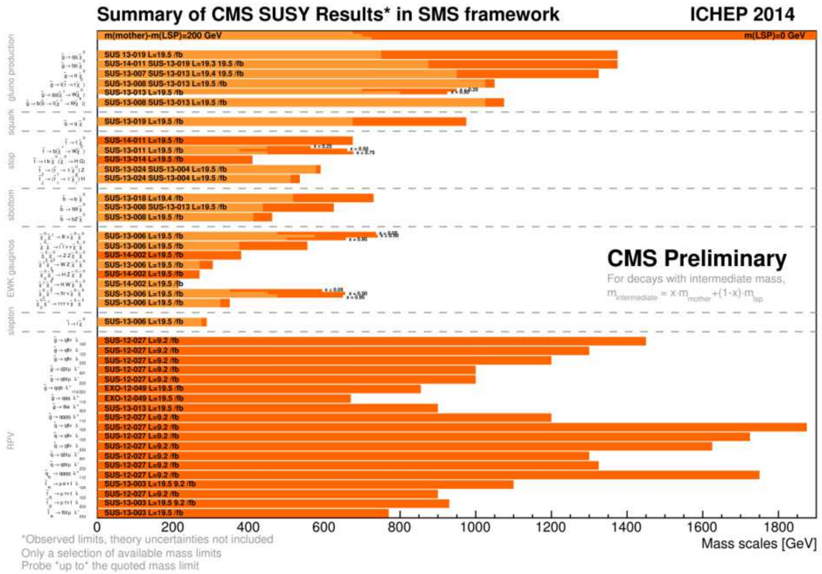
❑ ATLAS / CMS SUSY results

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS/index.html

+ http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html





88 papers for LHC Run-1 [Final !]

2 papers and 7 CONF notes for LHC Run-2

67=58+9 papers for LHC Run-1 [Final ?]

1 paper and 7 CONF note for LHC Run-2

>150 papers !!!

Lecture Organization

Ia - Ingredients for a SUSY search @ LHC

"What drives the sensitivity to SUSY at LHC ?"

1. Teaser (1)
2. SUSY Framework @LHC (11)
3. Objects and Monte Carlo (3)
4. Discriminating variables (5)
5. Background Estimation (7)
6. Fit Results (7)
7. Result Interpretation (3)

~35 slides → 50'

Ib - SUSY ElectroWeak

"Exploring the bottom part of the SUSY spectrum"

1. Parameters of the EWK sector (2)
2. SUSY Higgses (8)
3. ElectroWeakinos (12)
4. Sleptons (1)
5. Summary (1)

~25 slides → 40'

IIa – 3rd gene. SUSY

"Best natural candidates"

1. Sbottom (7)
2. Stop (12)
3. Summary (1)

~20 slides → 30'

IIb – Strong SUSY

"Inclusive searches"

1. Gluinos (12)
2. 1/2nd generation squarks (1)
3. Summary (1)
4. Overall MSSM summary (2)

~15 slides → 25'

IIc – Beyond MSSM

"Last hopes (!) and conclusions"

1. Long lived (10)
2. RPV (8)
3. Other SUSY realization (3)
4. Overall conclusions (3)

~20 slides → 30'

Part Ia - Teaser

EW Neutral Current (Z^0)

Can we **discover** (at least) one super-partner **or invalidate** the ~~Natural version of MSSM ?~~

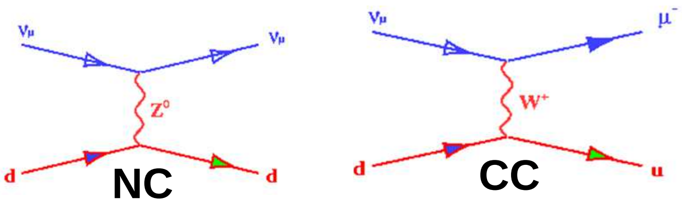
1- Need to be sure of your tools (background estimate, stat, …)

The results that were obtained from this small CERN chamber (Block *et al.* 1964) included a limit on the ratio of "elastic" neutral-current (NC) events to charged-current (CC) events: $\sigma(\nu_\mu + p \rightarrow \nu_\mu + p)/\sigma(\nu_\mu + n \rightarrow \mu^- + p) < = 0.03$ for events with proton momentum above 250 MeV/c. The accepted ratio is about 0.12. The CERN result was just wrong, following a book-keeping error (the actual 90% confidence limit was < 0.09). As is often the case in physics, the error was uncovered by a graduate student, Michel Paty from Strasbourg, who found a limit < = 0.20 and put this number in his thesis (Paty, 1965). The CERN group intended to publish an erratum, but (since there seemed to be little interest in our limit) we decided to wait for the results from a forthcoming propane run, since that would measure scattering from free as well as bound protons, and we could exploit the better kinematic constraints. However, the propane run was delayed by more than two years and the corrected limit for the ratio of < 0.12 ± 0.06 was not published until 1970 (Cundy *et al.* 1970).

2- Need to have a well designed search strategy

Gargamelle's priorities

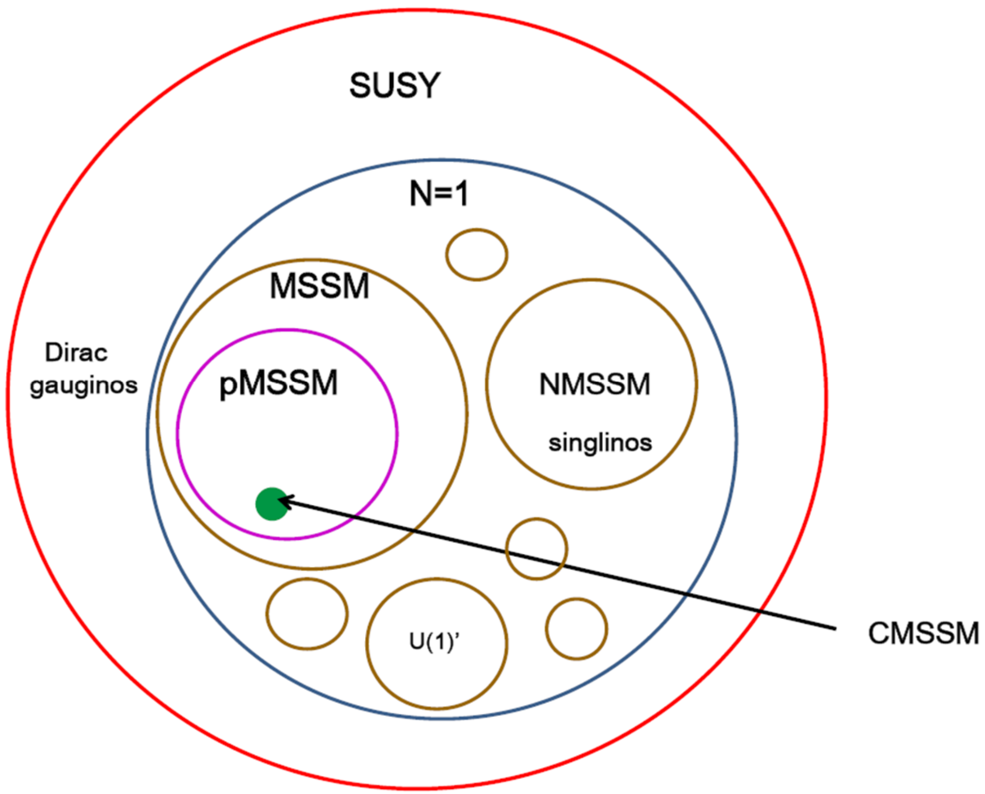
1. W search
2. deep inelastic scattering, scaling
3. current algebra sum rules, CVC, PCAC
4. Diagonal Model
5. $\Delta S = 1$ processes, inverse hyperon decay, $\overline{\nu_\mu} + p \rightarrow \Lambda + \mu^+$
6. inverse muon decay, $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$
7. electron–muon universality
8. neutral-current search
9. form factors in exclusive reactions
10. search for heavy leptons



That's why we will spend some time on understanding carefully all our tools today

SUSY Framework @LHC (1)

SUSY Theory phase space



T. Rizzo (SLAC Summer Institute, 01-Aug-12)

Many SUSY realizations are possible …
Mainly focus on MSSM

SUSY Framework @LHC (2)

A- MSSM, the larger SUSY framework we can test systematically at LHC …

- For neutralino and charginos I'll use Greek or Capital Roman letter.
- LSP = Lightest Supersymmetric Particle. In this lecture LSP will be $\tilde{G}$ or $\tilde{\chi}_1^0$

MSSM a.k.a Weak Scale SUSY : → *MSSM=Minimal Supersymmetry Standard Model (i.e. based on parsimony principle)*

29 sparticles + 4 Higgs undiscovered

	Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
SUSY Higgses	Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
Strong SUSY	squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
				$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
				$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
Weak SUSY	sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
				$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
				$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
	neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$ — $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
	charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$ — $\tilde{\chi}_1^{+/-}\ \tilde{\chi}_2^{+/-}$
	gluino	1/2	−1	$\tilde{g}$	(same)
	goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

R-parity (P_R or R_P)= -1 SUSY, +1 SM

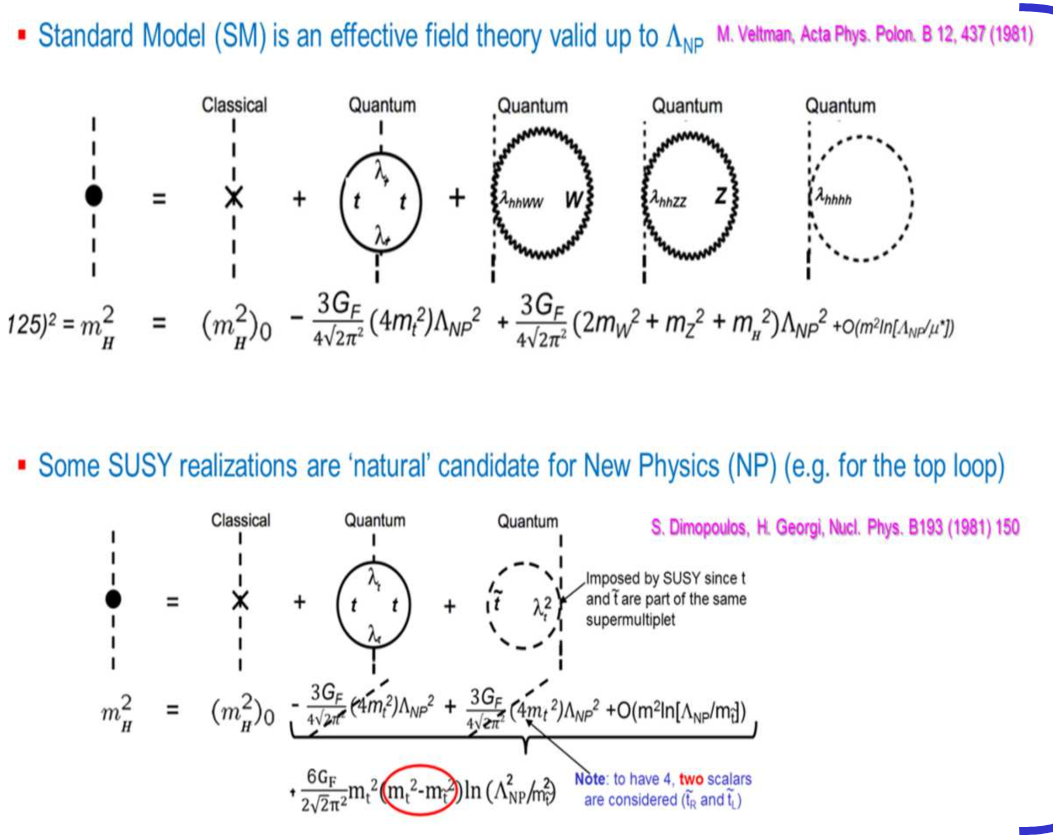
S. Martin, SUSY Primer, hep-ph/9709356

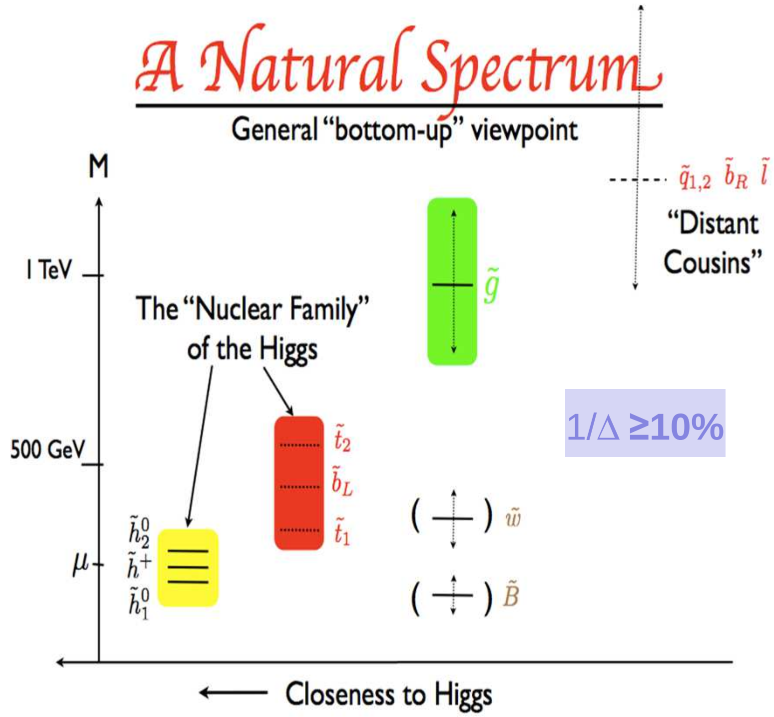
SUSY Framework @LHC (3)

See also Andreas Weiler

B- … assuming ~no fine-tuning …

- Range of MSSM particle masses can be predicted imposing ~no fine tuning ($\Delta \approx \delta m_h^2/m_h^2$)





1/Δ ≥10%

L. Hall, BNL SUSY Workshop, Oct 2011 + 1110.6926

Note: no constraints on M(H^0,$H^\pm$,A^0) and M($\tilde{G}$)

SUSY Framework @LHC (4)

C- … and make three more assumptions

1. The nature of R-Parity (RP) :
   a. RPC: SUSY particles are pair-produced at LHC and the lightest one is stable
   b. RPV, including also long-lived if $\lambda < O(10^{-5})$.

2. The nature of the stable Lightest SUSY particle (LSP) :
   a. χ_1^0 with M_{LSP} > GeV
   b. G with M_{LSP} << GeV

3. The value of $\Delta M = M_{SUSY}$ [highest particle produced at LHC] - M_{LSP}
   a. Open spectra [$\Delta M > O(100)$ GeV]: high energetic objects, generic searches
   b. Compressed spectra [$\Delta M < O(100)$ GeV]: dedicated searches (monojet …) + long-lived

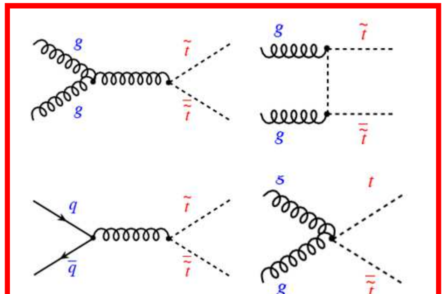
Vanilla framework used for **systematic** searches: **A, B, C1a, C2a, C3a***
Other combinations are searched for but not systematically.

* Default assumption in the following

SUSY Framework @LHC (5)

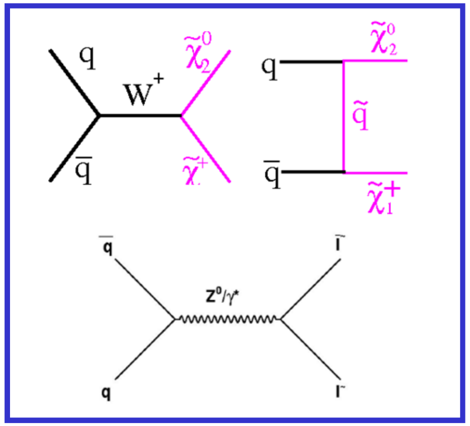
❑ **Sparticles are pair produced at LHC** (R-Parity conserved)

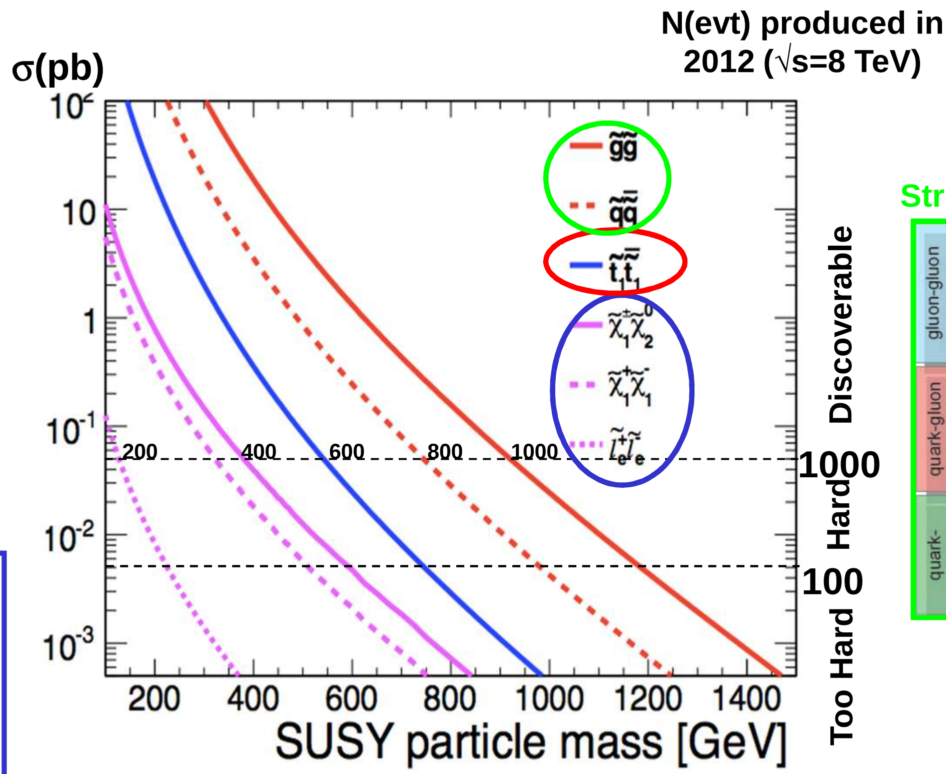
SUSY 3rd gene



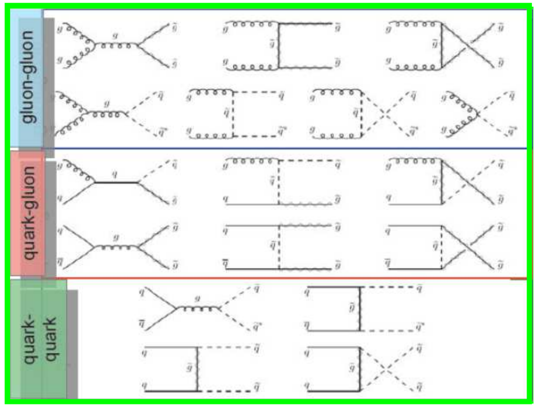
Note: no t channel, σ lower

Weak SUSY



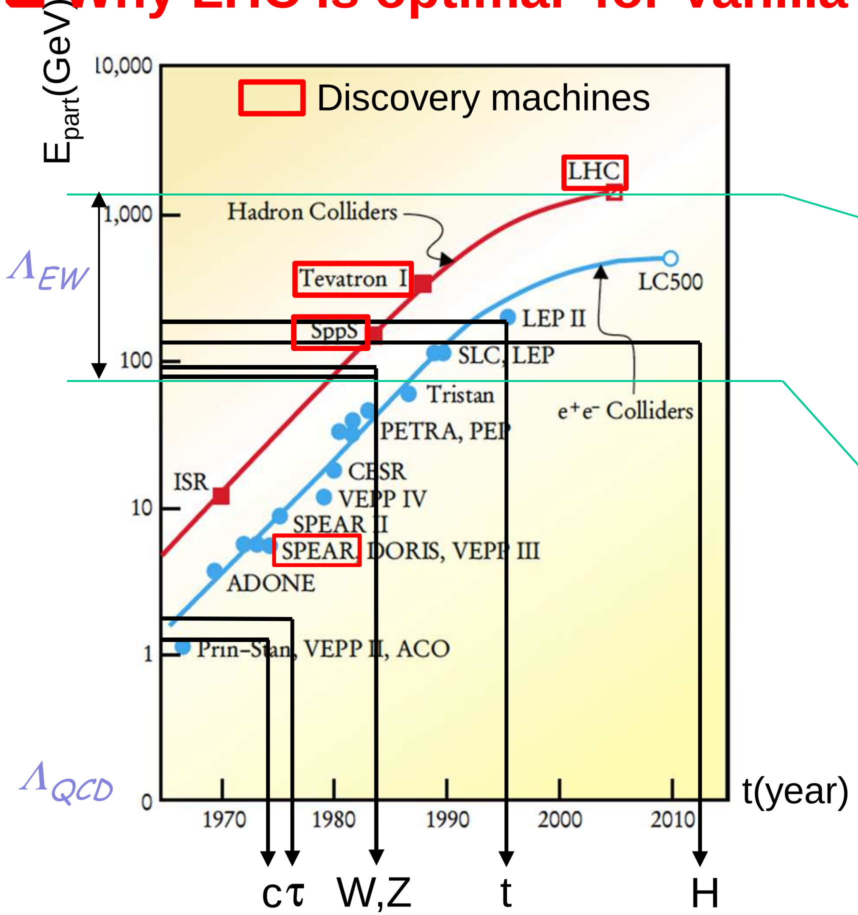


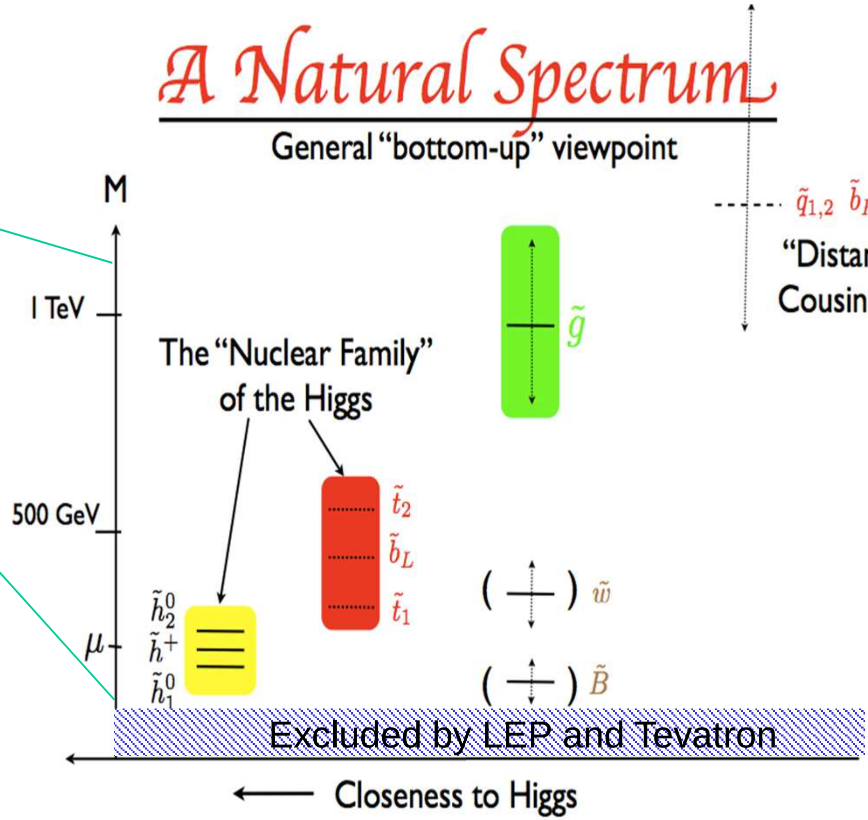
Strong SUSY



SUSY Framework @LHC (6)

❑ Why LHC is optimal for Vanilla SUSY ?



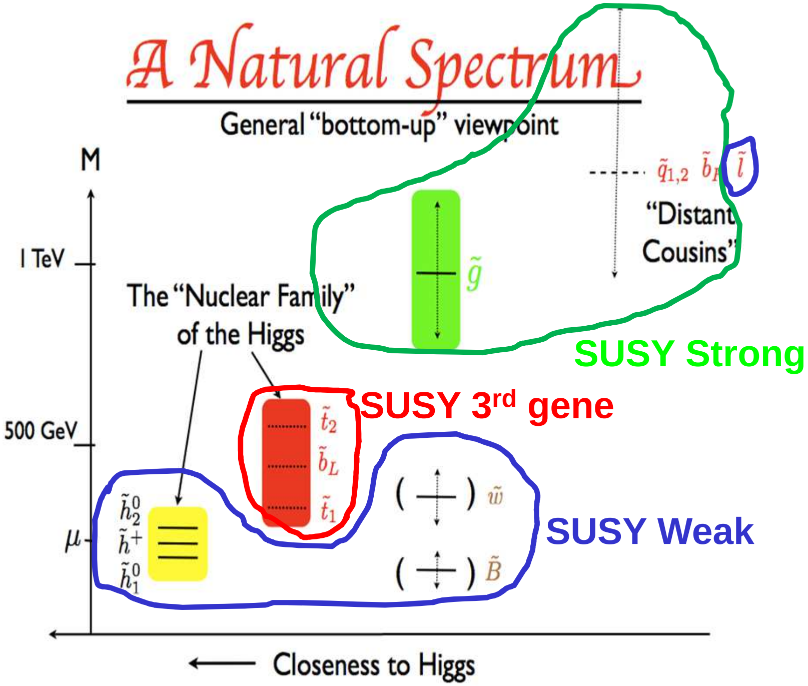


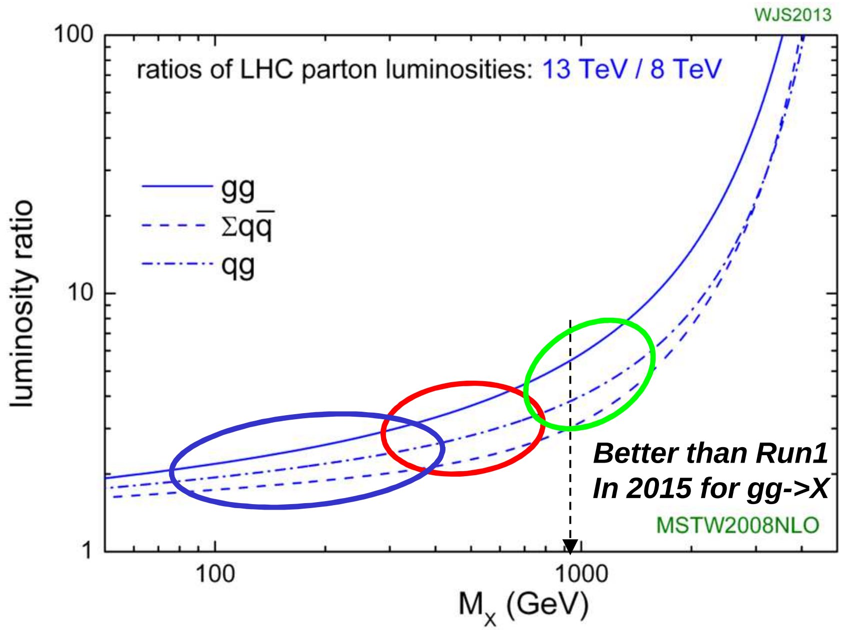
LHC* can cover the **best motivated** SUSY phase space **for the first time** !!

*The largest and the most complex machine ever constructed by humans (From Nobel Prize 2013 Press release)

SUSY Framework @LHC (7)

❑ SUSY searches at 8 and 13 TeV





- SUSY Weak: Lecture Ib
- SUSY 3rd gene.: Lecture IIa
- SUSY Strong: Lecture IIb

- SUSY Weak: No results at 13 TeV
- SUSY 3rd gene.: ~Almost no results at 13 TeV
- SUSY Strong: Many results at 13 TeV

SUSY Framework @LHC (8)

A very predictive theory !

- Once mass spectrum known theoretically computable decay rate
- Mix of on-shell (2 body decay) and off-shell (3-body decay)

MSSM: 29 sparticles + 4 Higgs undiscovered

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0$ (Bino) $\tilde{W}^0$ (Wino) $\tilde{H}_u^0\ \tilde{H}_d^0$ (Higgsino)	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm$ (Wino) $\tilde{H}_u^+\ \tilde{H}_d^-$ (Higgsino)	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

Main decay channels in MSSM

$h \to bb, WW, \tau\tau$; $H^0 \to hh, WW, tt, bb$; $A^0 \to tt, bb$; $H^{+/-} \to \tau\nu, tb$

$\tilde{q} \to q\tilde{g}, q\tilde{\chi}_1^0, q'\tilde{\chi}_1^{+/-}, q'W^{(*)}\tilde{\chi}_1^0$ — $\tilde{q}_L \to q\tilde{\chi}_{1(2)}^0, q'\tilde{\chi}_1^{+/-}$ ($\tilde{\chi}_2^0$ wino); $\tilde{q}_R \to q\tilde{\chi}_1^0$ ($\tilde{\chi}_1^0$ bino)

$\tilde{g} \to q\tilde{q}, qq\tilde{\chi}_1^0, qq'\tilde{\chi}_1^{+/-}, g\tilde{\chi}_1^0$

STRONG, 3[rd] gene

$\tilde{l} \to l\tilde{\chi}_{1(2)}^0, \nu\tilde{\chi}_1^{+/-}$ — $\tilde{l}_L \to l\tilde{\chi}_{1(2)}^0, \nu_l\tilde{\chi}_1^{+/-}$ ($\tilde{\chi}_2^0$ wino)

$\tilde{\nu} \to \nu\tilde{\chi}_{1(2)}^0, l\tilde{\chi}_1^{+/-}$ — $\tilde{l}_R \to l\tilde{\chi}_1^0$ ($\tilde{\chi}_1^0$ bino)

$\tilde{\chi}_2^0 \to W^{(*)}\tilde{\chi}_1^{+/-}, Z^{(*)}\tilde{\chi}_1^0, \tilde{l}l, \tilde{\nu}\nu, \tilde{q}q$

$\tilde{\chi}_{1(2)}^{+/-} \to W^{(*)}\tilde{\chi}_1^0, Z^{(*)}\tilde{\chi}_1^{+/-}, l\tilde{\nu}, \nu\tilde{l}, qq'$

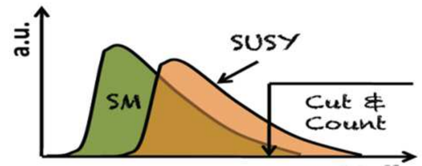
Weak

➔ Huge combinatorics: Need to look at lots of final states !

SUSY Framework @LHC (9)

❑ Main characteristics of Vanilla SUSY events at LHC

- SUSY appears as excess in tails



MSSM: 29 sparticles + 4 Higgs undiscovered

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
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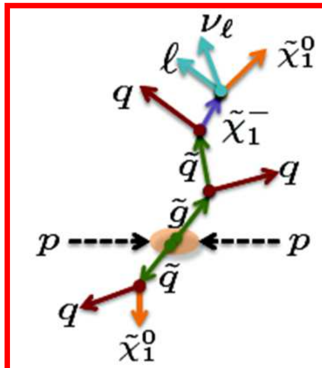
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

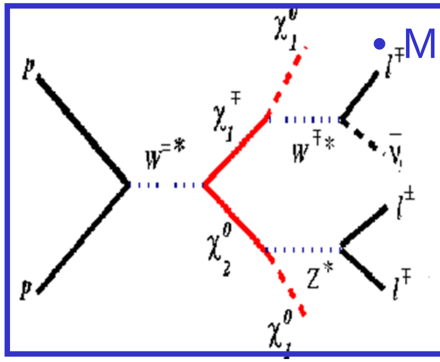
@ LHC



- Missing Energy=MET ($\tilde{\chi}_1^0$)
- "Jetty" (some from b)
- Eventually leptons
- Eventually γ

ε≈1%

STRONG, 3rd gene



- Missing Energy=MET ($\tilde{\chi}_1^0$)
- Jet veto
- 2 or 3 leptons

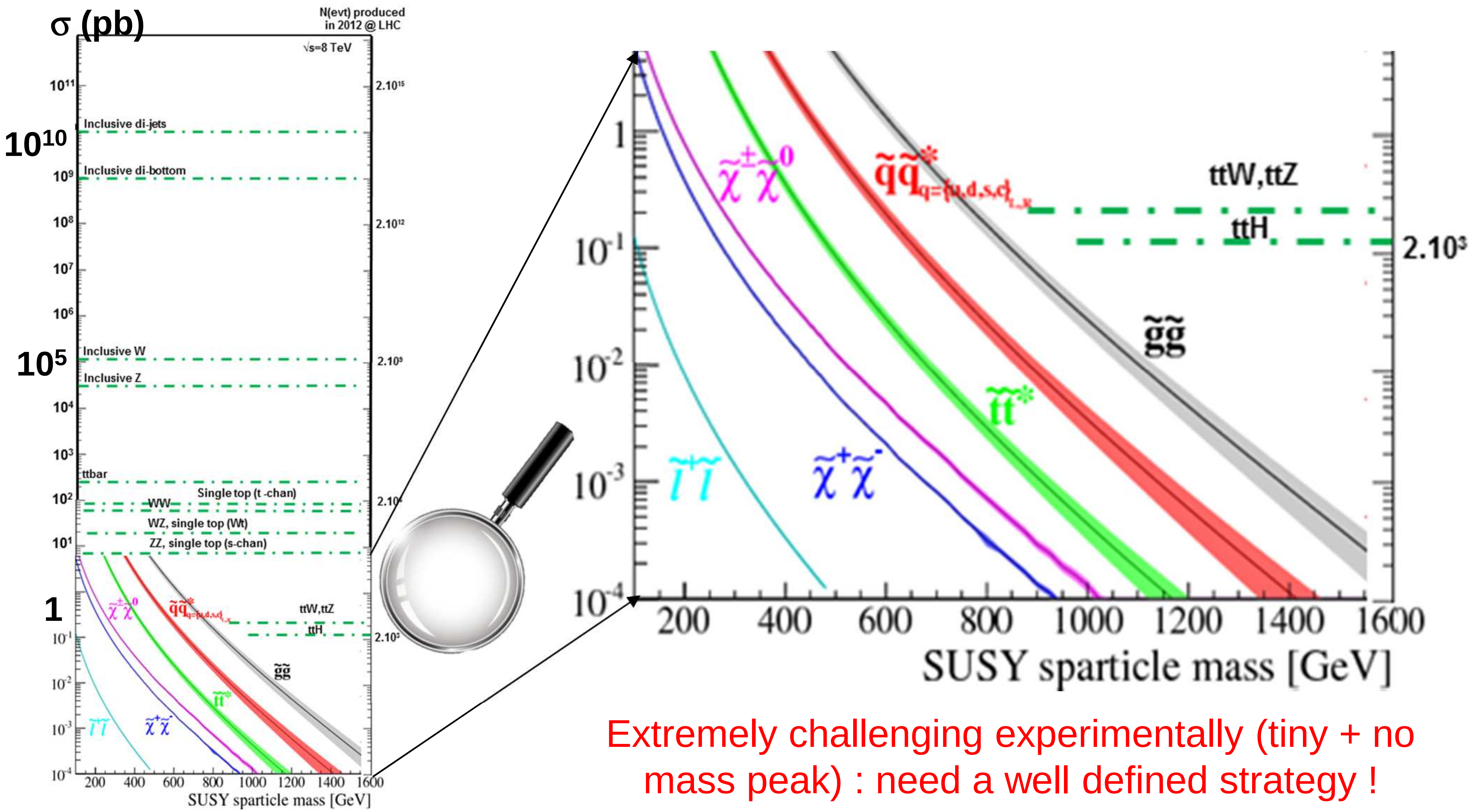
ε≈10%

Electro-Weak (EWK)

➔ Critical to master well the reconstruction of all objects (esp. MET) !

SUSY Framework @LHC (10)

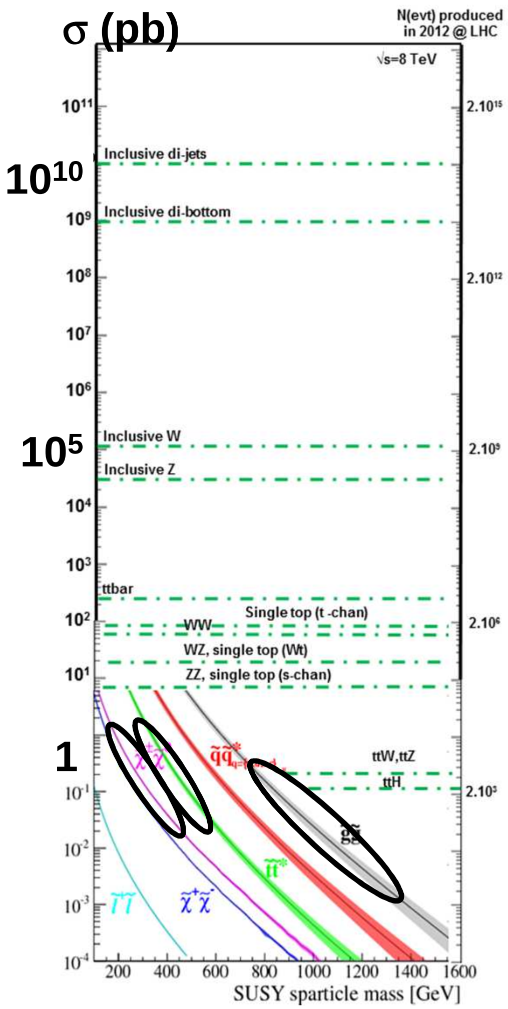
- But SUSY is tiny compared to SM processes !



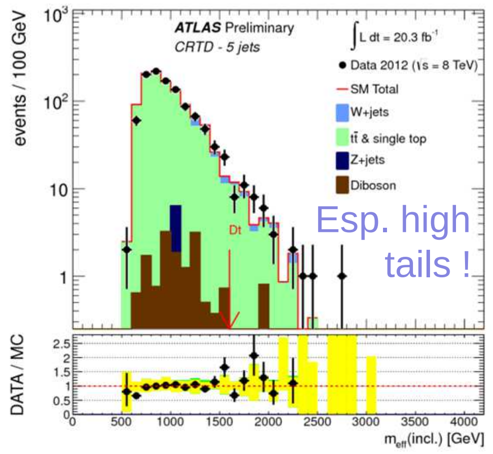
Extremely challenging experimentally (tiny + no mass peak) : need a well defined strategy !

SUSY Framework @LHC (11)

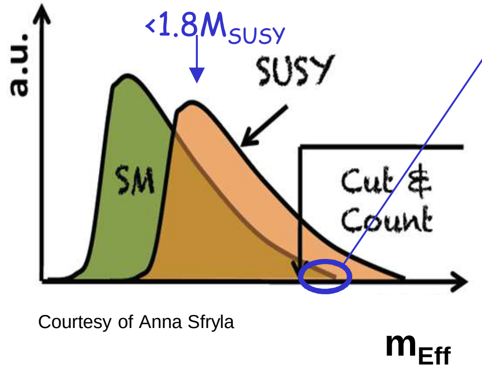
❑ Strategy



1 Control objects and Monte Carlo



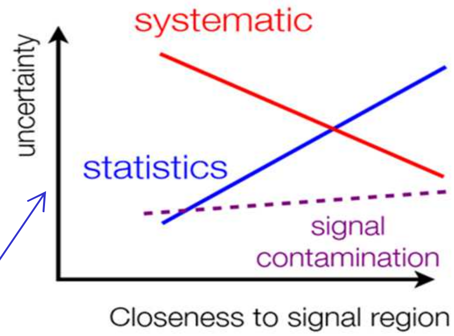
2 Powerful discriminants



Courtesy of Anna Sfryla

3 Background estimation

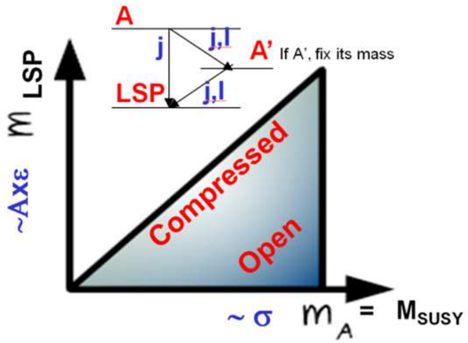
1- Multijets: jet smearing method
2- W, Z, t, VV : control regions



3- ttV: Monte Carlo

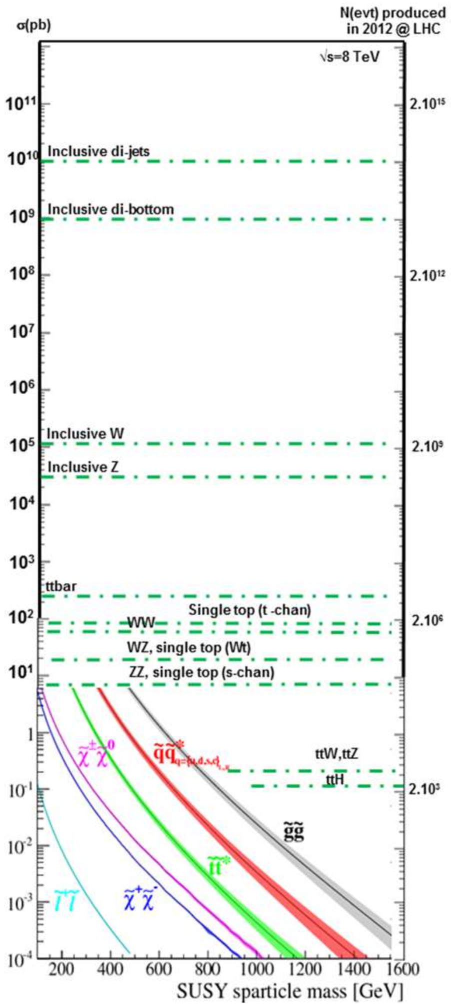
4 Interpretation if no excess

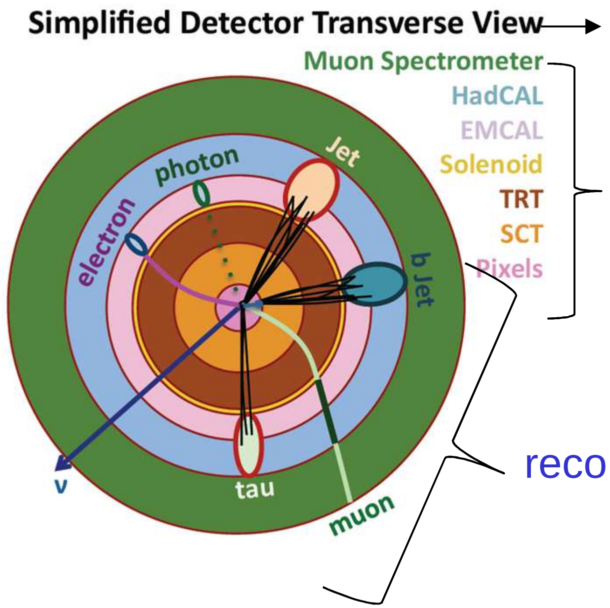
1- Constraint model, e.g. MSUGRA
2- Simplified/topological models



3- Pheno. models, eg. pMSSM

Objects and Monte-Carlo

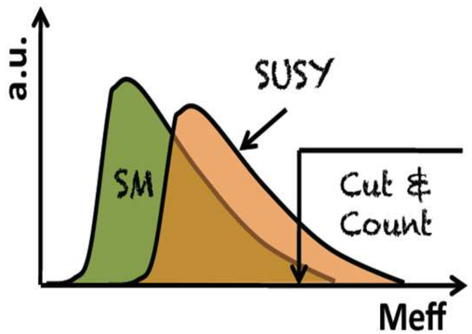




No access to total energy

Detectors crucial for **Long-Lived particle** searches

All objects (Identification, reconstruction, systematics) crucial for **RPC/RPV** searches
→ data/MC agreement ?

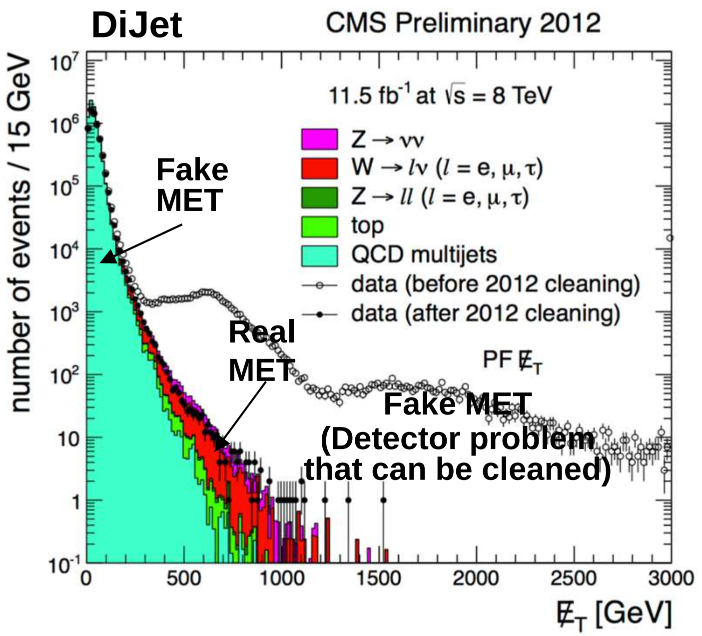


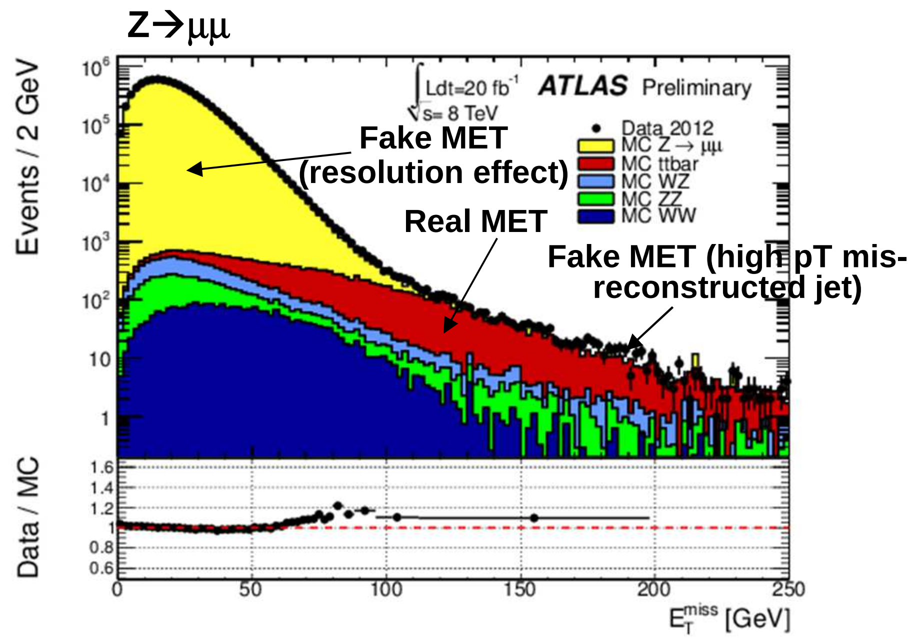
Very challenging to describe ttbar/W+jets in the tails
→ Huge effort from the theory community

Objects and Monte-Carlo (1)

❑ Transverse Missing Energy crucial for all SUSY searches

- Energy conservation (transverse plane) : $\overrightarrow{MET} = \vec{E}_T^{\text{non-int}} = -\Sigma\, \vec{E}_T$ (calo) $- \Sigma\, \vec{E}_T$ (muon)
  - ✓ If calorimeter not enough use also tracker (Particle Flow a la CMS)
- Real MET : Presence of a neutral weakly interacting particle in the event (i.e. ν)
- Fake MET : Mismeasurement + detector malfunctions, poorly instrumented regions





➔ Agreement data – Monte Carlo key for SUSY searches (systematics not dominant)

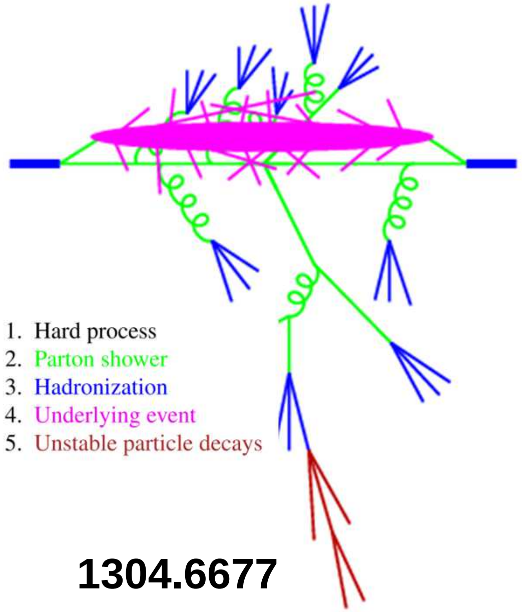
Objects and Monte-Carlo (2)

❑ Challenging to model SM processes with high jet mulitplicities

- Parton Shower (PS) : PYTHIA, HERWIG
- Matrix Element (ME) + PS : MADGRAPH, ALPGEN

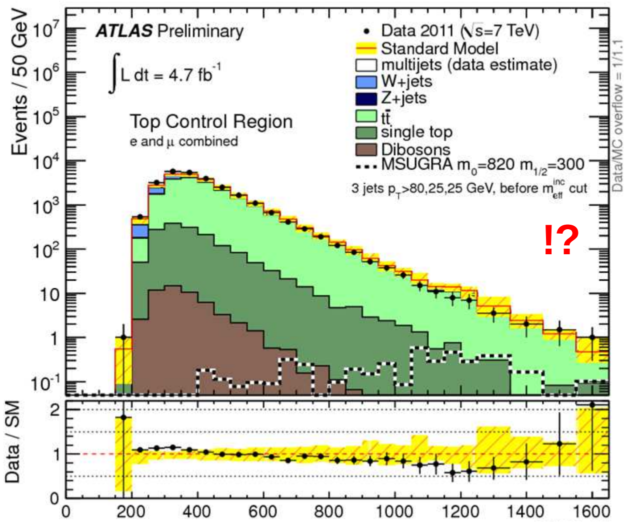
Note: SHERPA, HERWIG++, NLO+PS (MC@NLO, POWHEG) also used

➔'Best' to describe large-angle emissions beyond the hardest jet (jets well separated)

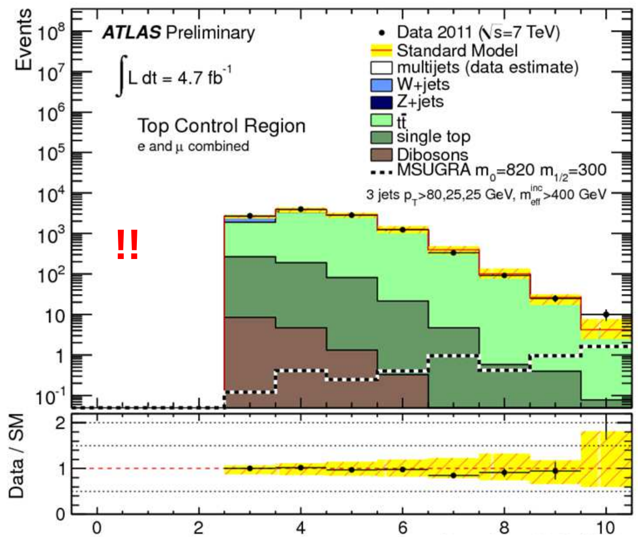


1304.6677

SUSY -1lepton Top Control Region



Meff=MET+Σp_T^{jets} (GeV



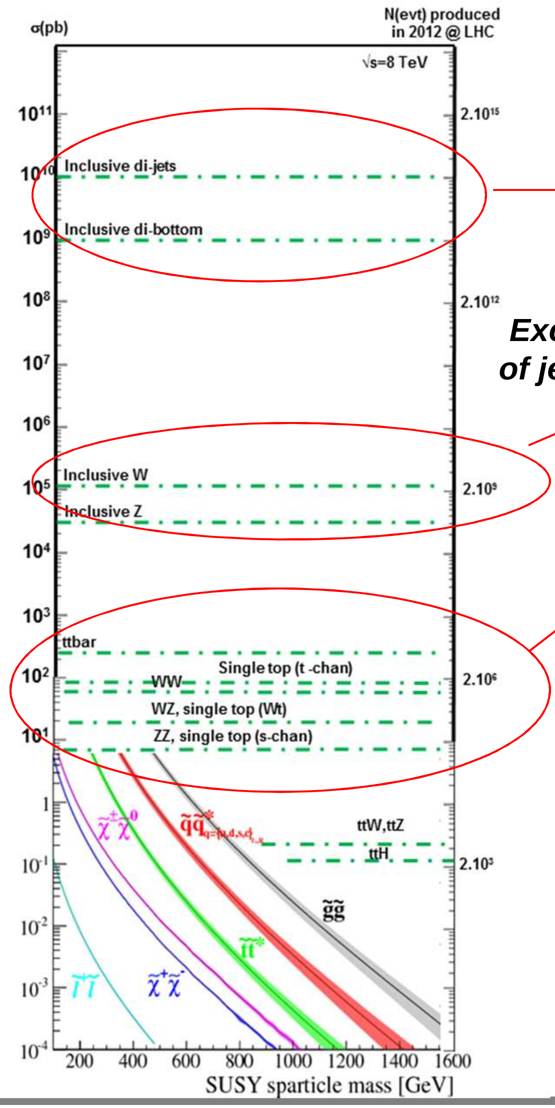
N(jets) with p_T^{jets} >25 GeV

Objects and Monte-Carlo (3)

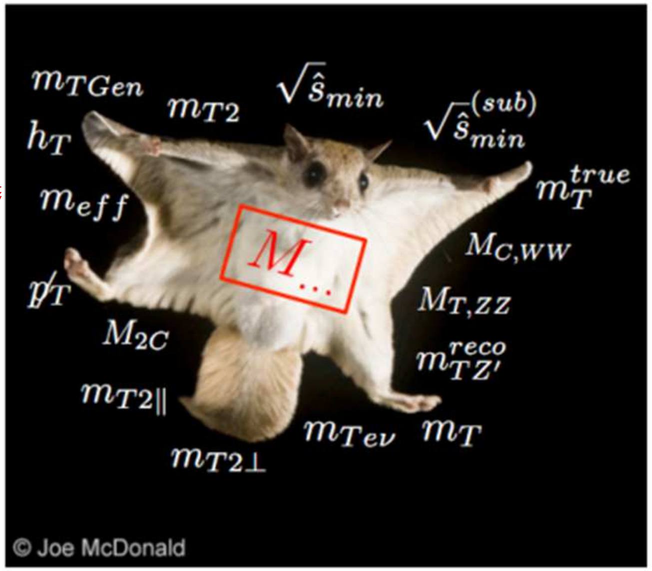
- **They drive the sensitivity of the searches !**

	Systematics	SM background estimate	SUSY Signal <1 TeV	Comments	
Experimental	Pile-up			Negligible or Small	
Experimental	Trigger			Small	
Experimental	Jet Energy scale (JES)	Dominant.	Dominant	Generally dominates exp	Fully **correlated** between signal & backgrd
Experimental	Jet Energy resolution (JER)	Less than JES (apart Z+jets)	Less than JES		Fully **correlated** between signal & backgrd
Experimental	b/τ-tagging	Could dominate	Could dominate	Take over for ≥ 2 b/τ	Fully **correlated** between signal & backgrd
Experimental	Lepton/γ energy scale			Small (even for multilep.) except τ	Fully **correlated** between signal & backgrd
Experimental	Lepton/γ energy resolution			negligible	Fully **correlated** between signal & backgrd
Theory	Scale, PDF uncertainties	Not for data-driven methods	~20% for NLO+NLL	Depend on many parameters	
Theory	Generators+Showering	Poor man's method	N.A.		
Theory	ISR/FSR	Generally important for ttbar	Up to 30% for Compressed spectra		
	MC stat			Depend on grid computing !	
	Total (indicative)	**~10-100%**	**~20-50%**		

Discriminant variables



Excellent providers of jets+MET+(lepton) signature



1) Need to suppress QCD / W,Z / top by ~ 10^{10} / 10^{5} / 10^{2}

2) Estimate small remaining quantities

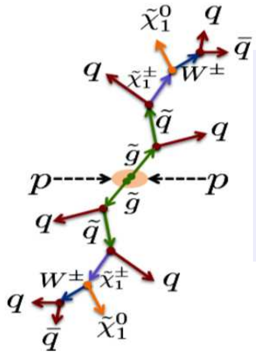
3) Fit results

4) Interpret the results if no excess

Discriminant variables (1)

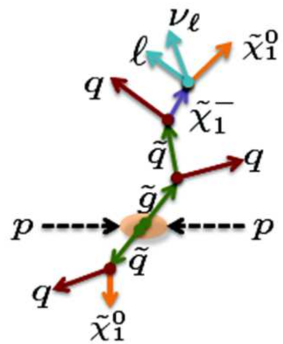
❑ First need hard kinematic cuts

- To reduce "difficult" background (Fake MET/ lepton, pile-up)



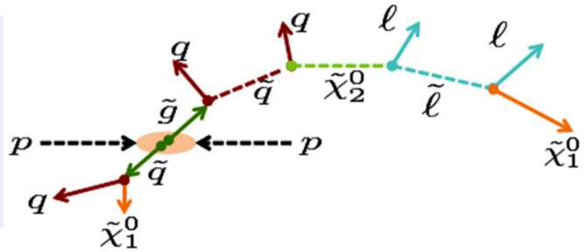
SM Background
1.Z(→νν)+jets
2.ttbar/W+jets
3.QCD

0lepton+jets+MET:
- ✓ Jet+MET trigger
- ✓ Ask several high pT jets
- ✓ High MET cuts to kill QCD



SM Background
1.ttbar
2.W+jets
(3.Fake lepton)

1lepton+jets+MET:
- ✓ Lepton trigger
- ✓ Ask several high pT jets
- ✓ Lower MET cuts than 0lep
- ✓ m_T(W) >m(W)



≥2lepton+jets+MET:
- ✓ Dilepton trigger
- ✓ MET and/or high pT jets
- ✓ 2l Opp. sign: Z or non Z
- ✓ 2l Same sign
- ✓ 3, 4leptons

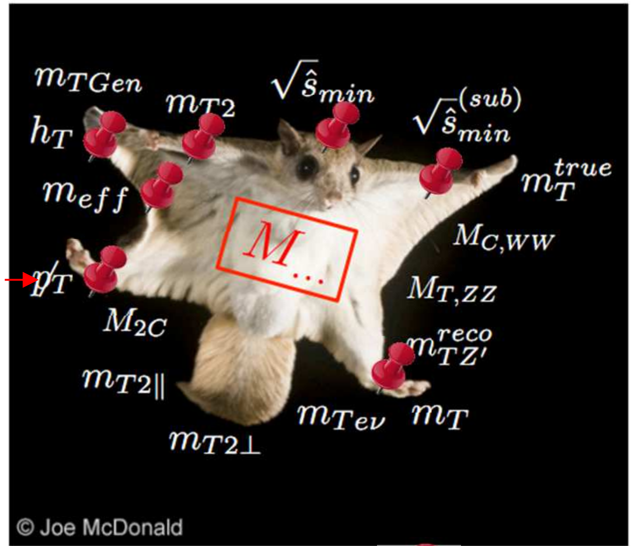
Discriminant variables (2)

❑ Then add powerful discriminant variables

- LHC: unknown momentum along the beams
- SUSY: Sparticles pair produced + Presence of invisible (massive) particles

Assume knowledge of SUSY decay chain
➔ Transverse mass-like variables

MET →



PRD 84 (2011) 095031  =used in SUSY analyses

Other approaches w/o this assumption:

- Reconstruction of 2 megajets: Razor, α_T
- QCD killers: $\Delta\phi$(jets, MET)
- QCD+EWK killers: b-jets
- ttbar killers : 2lepton Same sign, 3 bjets, 3leptons, >6 jets
- Z veto

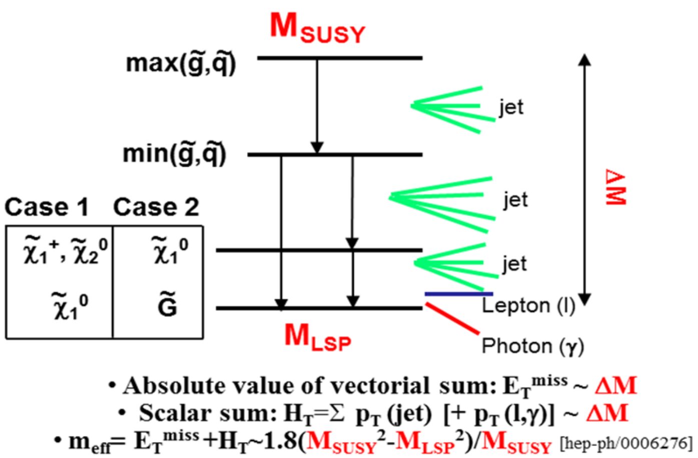
➔ Optimal choice of variable(s)/method(s) is analysis dependent

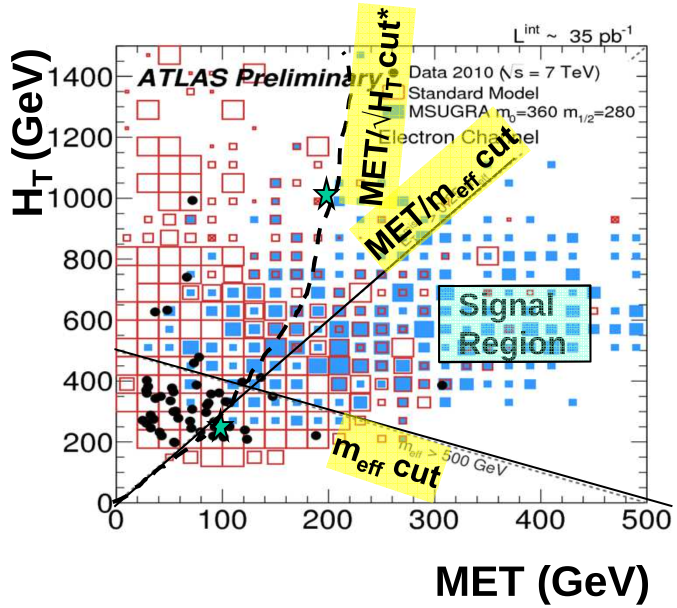
Discriminant variables (3)

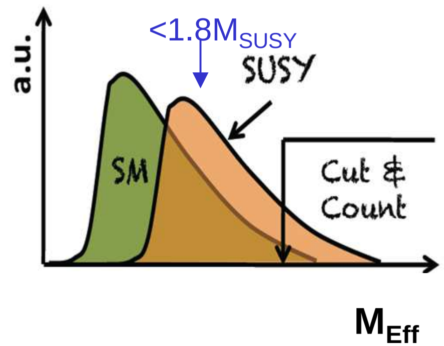
Exemple1: <u>Effective mass</u> (M_{Eff})

used w or w/o leptons in final states

- Profit from the correlation between H_T and MET in SUSY (absent in SM)





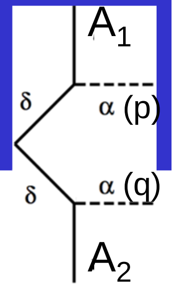


arXiv:hep-ph/9610554

➔ Hard M_{Eff} and MET cuts: signal efficiency ~0.1-10 %, high purity for signal

* Useful for lower MET SUSY signal (here cut~6 $GeV^{1/2}$)

Discriminant variables (4)



Example 2: M_{T2}, m_{CT}

- Generate end-point at different position than SM because of massive LSP*

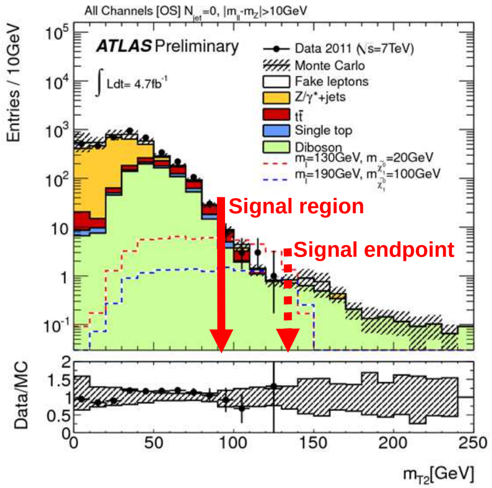
$$M^2_{T2} = \min_{\vec{p}_T + \vec{q}_T = MET} [\max\{M^2_T(A_1,p),\ M^2_T(A_2,q)\}]$$

- Min.: most 'consistent' missing momentum sharing between invisibles
- Max.: Better of the 2 lower bounds

$$M^2_{CT} = [E_T(A_1) + E_T(A_2)]^2 - [\vec{p}_T(A_1) - \vec{p}_T(A_2)]^2$$

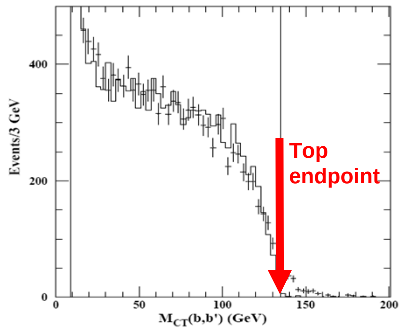
For ttbar, endpoint $[M(t)^2 - M(W)^2] / M(t)$ ~ 135 GeV, m(b,ν)~0

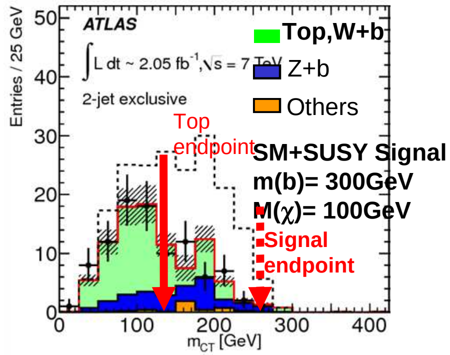
For $\tilde{b} \rightarrow b\tilde{\chi}$ endpoint $[M(\tilde{\mathbf{b}})^2 - M(\tilde{\chi})^2] / M(\tilde{\mathbf{b}})$ ~260 GeV, m(b)~0



For $\tilde{l} \rightarrow l\chi$ endpoint $[M(\tilde{\mathbf{l}})^2 - M(\tilde{\chi})^2] / M(\tilde{\mathbf{l}})$ ~130 GeV for m(l)~0

JP G29 (2003) 2343



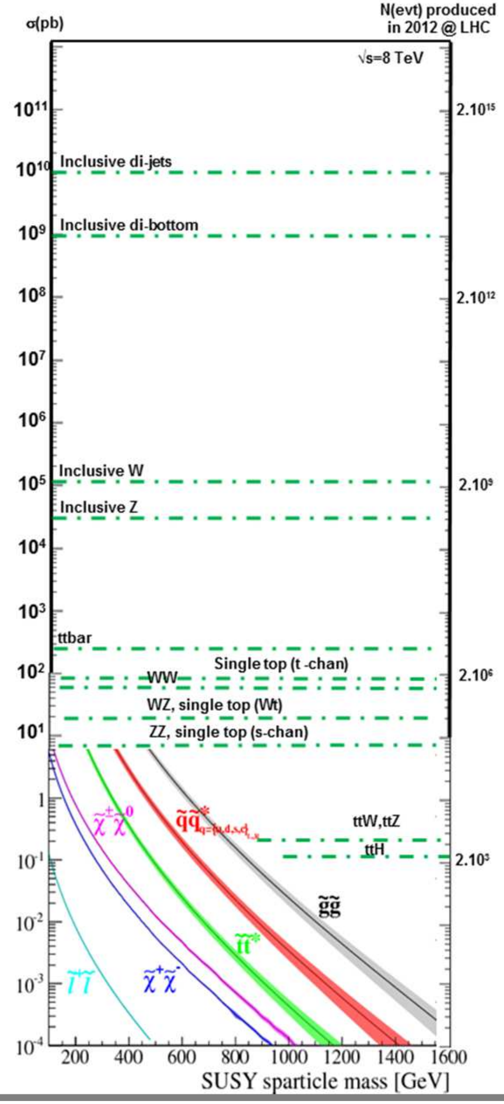


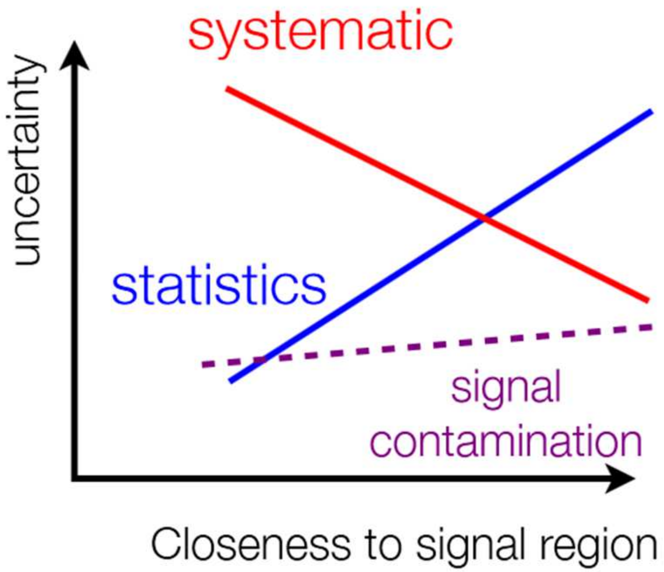
JHEP 0804 (2008) 034, JHEP 1003 (2010) 030

➔ Powerfull to reject SM background but need to assume value of endpoint to cut !

*Originally designed to measure SUSY masses

Background estimation





1) Need to suppress QCD / W,Z / top by ~ 10^{10} / 10^{5} / 10^{2}

2) Estimate small remaining quantities

3) Fit results

4) Interpret the results if no excess

Background estimation (1)

❑ Different strategies for different background

- Note: out of the box Data-Monte Carlo agreement is generally very good at LHC

Pure MC

Methods : none !

Pros: Easy, helpful to start and design Signal Regions

Cons: Suffer from large syst and/or statistical errors

Targets: Well suited for small backgrounds

Semi data-driven

Methods : i) isolate a pure background sample, ii) normalise MC iii) assume MC shape to transfer it to Signal Region

Pros: Main systematics cancel in the transfer factor

Cons: full study of possible theory systematics

Targets: Main irreducible background (top, W/Z+jets)

Fully data-driven

Methods : a lot !

Pros: i) Don't rely on potential failures in simulation, ii) Suited for large σ

Cons: Rely strongly on simplifying assumptions ➔ systematics

Targets: Fake MET (QCD, Z+jets), fake leptons, long-lived particle (high pT muons with mis-measured β)

➔ Precision in background determination drives the SUSY sensitivity

Background estimation (2)

ATLAS-CONF-2012-033

❑ Take the example of 0lepton + ≥4jets + MET channel

- Production : $\tilde{g}\tilde{g}$
- Decay : $\tilde{g} \rightarrow \tilde{q}q$ with $\tilde{q} \rightarrow q\tilde{\chi}$ dominates ➔ **0lepton + ≥4 jets + MET**
- Discriminant variable : **M_{Eff} >1200 GeV**

Signal Region (SR) Definition: Lepton veto pT (e/μ)>20/10 GeV

Requirement	Channel C 4j	
E_T^{miss}[GeV] >	160	**Trigger**-driven
$p_T(j_1)$ [GeV] >	130	
$p_T(j_2)$ [GeV] >	60	**Pile-up** driven
$p_T(j_3)$ [GeV] >	60	
$p_T(j_4)$ [GeV] >	60	
$p_T(j_5)$ [GeV] >	–	
$p_T(j_6)$ [GeV] >	–	
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$ >	0.4 ($i = \{1, 2, 3$	**QCD rejection** -driven
$E_T^{miss}/m_{eff}(Nj)$ >	0.25 (4j)	
m_{eff}(incl.) [GeV] >	1200	**Discriminating variable**

➔ 3 main backgrounds: QCD, Z→νν +jets, [ttbar→bWbW→blνbjj&W→lν]

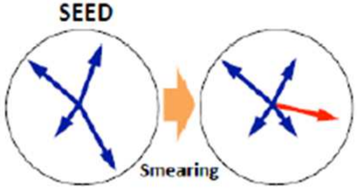
Background estimation (3)

ATLAS-CONF-2012-033

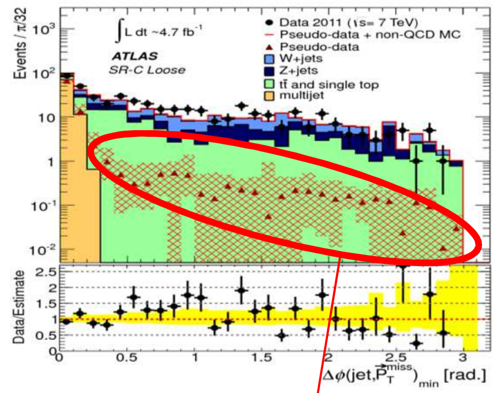
❑ QCD/Multijets background (Data driven)

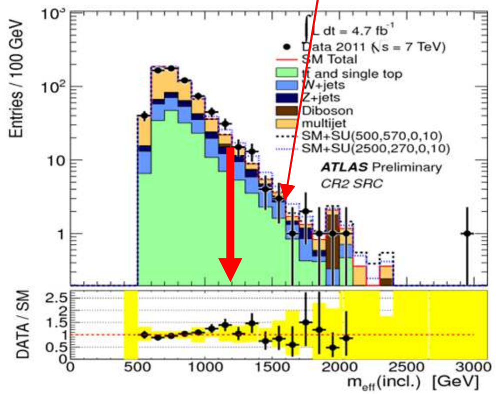
- Enter Signal Region because of fake MET or ν inside jet
- Can not trust MC + limited by MC stat
  - ✓ Compute jet response R=pT(jet reco)/pT(jet true) and generate pseudo data to populate SR

1. Determine the jet response function R from dijet balance and 3-jets mercedes events **(1jet aligned with MET)**
2. Take a control sample of multijets events with small MET.
3. Smear each jet by its response R ➔ **Pseudo-data**



4. Normalize the shape obtained in a QCD enhanced region with low $\Delta\phi(\text{jet},E_T^{miss}) < 0.4$
5. Propagate to signal region





Background estimation (4)

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❑ Z→νν +jets (Data Driven)

- Enter SR because it is exactly signal like: Irreducible background !

1. Use a close-by SM process: γ+jets

✓Similar kinematic at pT~400 GeV>>m_Z

➔Obtain a very pure sample

✓Force the photon as MET

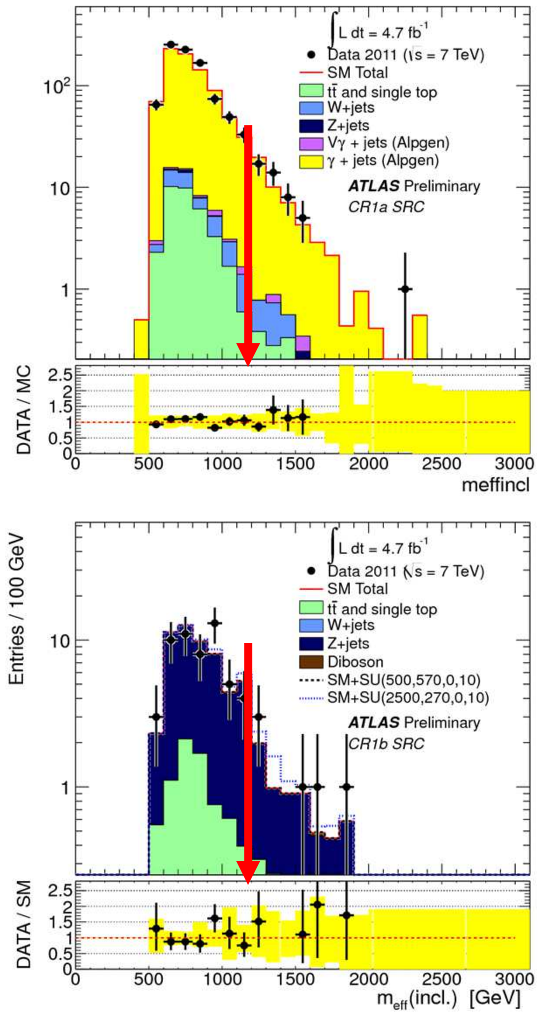
✓Gain a factor **~3** in stat: R=σ(Z+jets)/σ(γ+jets)~0.3

2. Use a close-by SM process: Z→ll+jets

✓More statistically limited (~10 times less than γ+jets)

✓Will not consider it in the following

γ+4jets Control Region



Background estimation (5)

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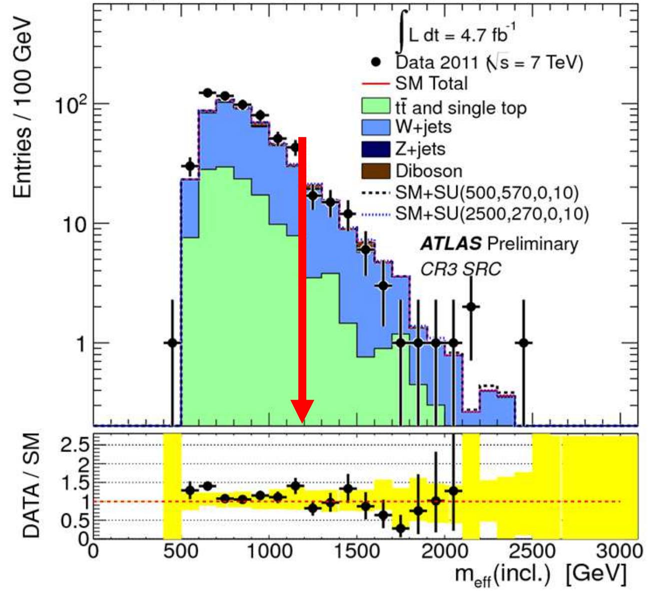
❑ W→lν +jets and ttbar→blνbqq (Semi Data-driven)

- Enter Signal Region because lepton is reconstructed as a jet, is τ, out of acceptance
- Have ν (real MET): can trust MC
  - ✓ Define enriched background "control" region (CR) by **reverting a cut** (Ex: ask 1lepton for 0lepton ch.)
  - ✓ Force the lepton as a jet (acceptable approximation)
- Look in the Control Region:
  - ✓ Monte Carlo should reproduce the data
  - ✓ High **Purity** (N_{MC}^{oth}~small), small Signal contamination
- Estimate N_{SR}^{bkg} **Transfer factor** (**c**) relying on MC shape:

W+4jets CR
1 lepton, 0 bjet, 30<m_T(lν)<100 GeV



$$N_{SR}^{Bkg} = \frac{N_{SR}^{MC}}{N_{CR}^{MC}}\left(N_{CR}^{data} - N_{CR}^{MC,others}\right) = N_{SR}^{MC}\,\frac{\left(N_{CR}^{data} - N_{CR}^{MC,others}\right)}{N_{CR}^{MC}}$$

Transfer Factor $c_{CR \to SR}$ **Scale factor** (k~1)

➔ Systematics partially cancel in the ratio, but need small extrapolation (c~0.1-1)

Background estimation (6)

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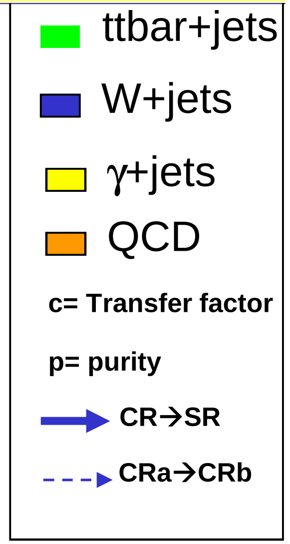
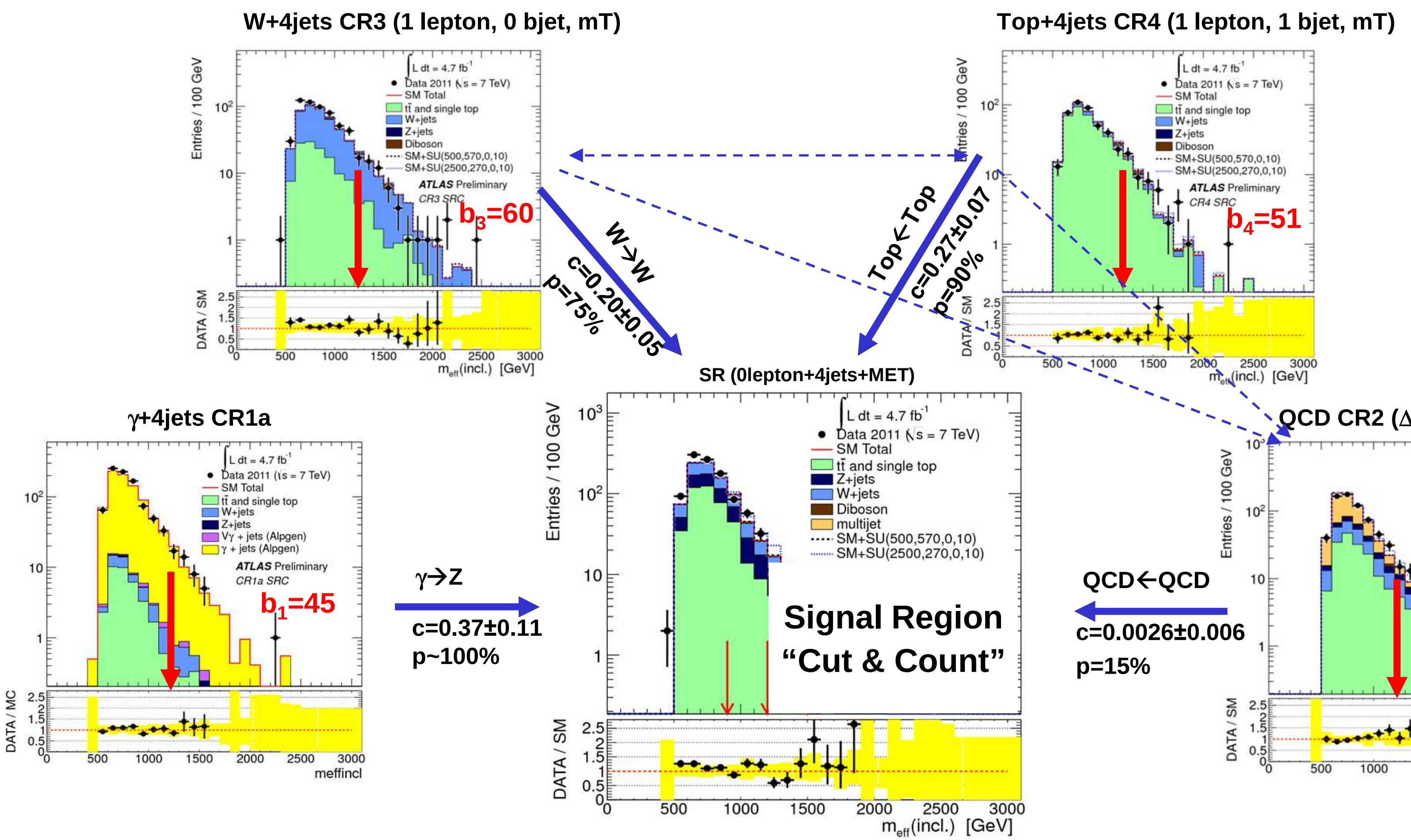
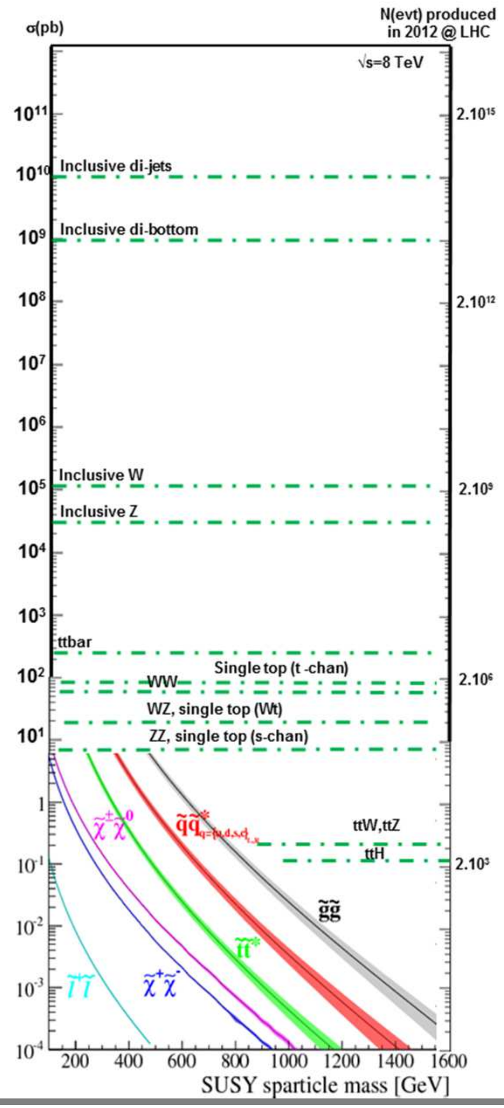
❑ **Summary: SR=0lepton + ≥4jets + MET + M_{eff} (incl.) >1200 GeV**



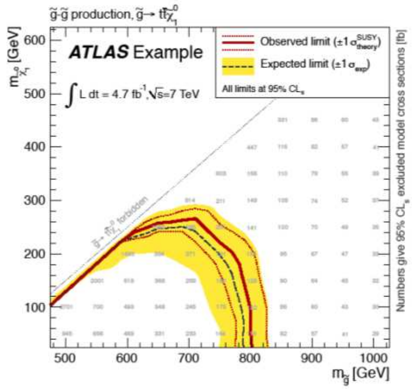


➔ Errors contains exp. (Jet Energy scale, btagging) and theo. (PDF, scale) syst.

Fit Results



OR



1) Need to suppress QCD / W,Z / top by ~ 10^{10} / 10^{5} / 10^{2}
2) Estimate small remaining quantities

3) Fit results

4) Interpret the results if no excess

Fit Results (1)

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❑ Building the likelihood

- **Likelihood function** : products of Poisson pdf* for SR and CR (as mutually exclusive) & syst.

$$L(n \mid \mu, b, \theta) = P_{SR} \times P_Z \times P_W \times P_{Top} \times P_{QCD} \times C_{syst}$$

n = Number of observed events in data
μ = SUSY signal strength to be tested
b = background
θ = systematics treated with Gaussian **Nuisance param.**

Free param.

- **Inputs**: Transfer factors** (**c**), data events in SR (**s**) and CR_j ($\mathbf{b_j}$)

$$P_{SR} = P(n \mid \lambda_S(\mu, b, \theta)) = \mu \bullet c_{sR->SR}(\theta) \bullet s + \sum_j c_{jR->SR}(\theta) \bullet \mathrm{b}_j$$

$$P_i = P(n \mid \lambda_i(\mu, b, \theta)) = \mu \bullet c_{sR->iR}(\theta) \bullet s + \sum_j c_{jR->iR}(\theta) \bullet \mathrm{b}_j$$

λ (μ, **b**, θ) = expected number of events

$c_{CR,SR \rightarrow SR}$

Region	Main CR/Process			
	CR1a / Z/γ+jets	CR2 / QCD jets	CR4 / $t\bar{t}$+ Single Top	CR3 / W+jets
CR1a	1	0	0	0
CR2	0.1	1	0.39	0.2
CR4	0.0034	0	1	0.093
CR3	0.0078	0	0.32	1
SR	0.37	0.0026	0.27	0.2

➔ Can correctly take the systematic correlation and cross-contamination into account by doing a simultaneous fit of all regions

*pdf=probability density function **can be replaced by scale factor

Fit Results (2)

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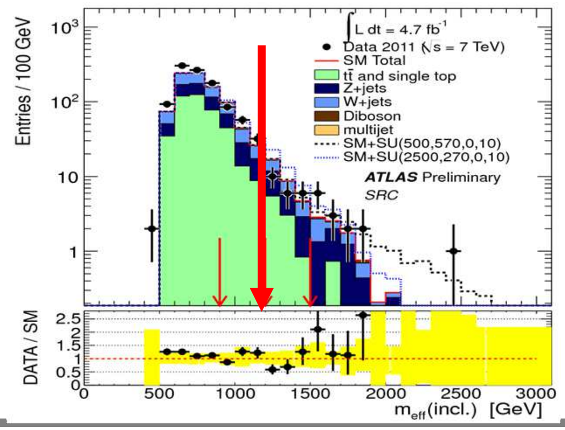
❑ Background-only fit (μ=0)

- Predict the background in the Signal Region (SR) by maximizing the likelihood
  - ✓ Give value to **free** and **nuisance** parameters [including statistical error]
  - ✓ Cross-checks of the extrapolation are done in ``validation'' region, close to SR
- Data in SR not in the fit + no signal contamination in CR (can be reproduced by theorists)

	Background in SR $c_{jR->SR}(\theta) \bullet b_j$				Others	Total Background in SR
	Zνν+jets	QCD	W+jets	Top	Dibosons	SR
MC	16	0.01	11	10	1.7	39
Fit Output	17±6	0.02±0.03	8±3	12±5	1.7±0.9	**39±9 [±5(stat)±7(syst)]**

➔ **25% error** (mainly from γ/Z acceptance, CR stat)

➔ Observed **36** evts in Data. No Excess ! Now let's quantify it (discovery fit).



Fit Results (3)

ATLAS-CONF-2012-033

❑ Discovery fit: background fit + N(data) in the signal region

- **Goal**: Test the compatibility of data with background-only hypothesis in the signal region
- **Test statistic:** based on one-sided profile log likelihood ratio (a la Higgs)

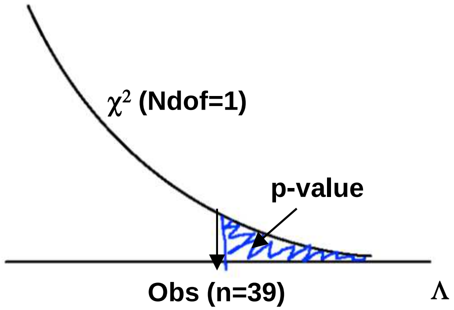
$$\Lambda(\mu) = -2 \times [L(n \mid \mu, \hat{\hat{b}}, \hat{\hat{\theta}}) - L(n \mid \hat{\mu}, \hat{b}, \hat{\theta})] \sim \chi^2 \text{ dist with Ndof} = 1^* \; (\mu \geq 0)$$

Maximise L for a choice of μ (here μ=0)

Maximise L for μ floating

***In practice this approximation works well for sufficient stat (n>5). If not the case, use toys**

- Compute a p-value :
  - ✓ Evaluate the probabilty for the observation to be signal-like



- In 0lepton+≥4jets+MET + M_{eff} (incl.) >1200 GeV:

Predict 39+/-9 and observe 36

p-value=0.6 (-0.2 σ). Compatible !

Fit Results (4)

ATLAS-CONF-2012-033

❑ From discovery fit, can derive a model independent limit

- Limit on visible cross-section of non-SM process: $\sigma_{vis} = \sigma \times A \times \varepsilon$
- In 0lepton+≥4jets+MET + M_{eff} (incl.) >1200 GeV:

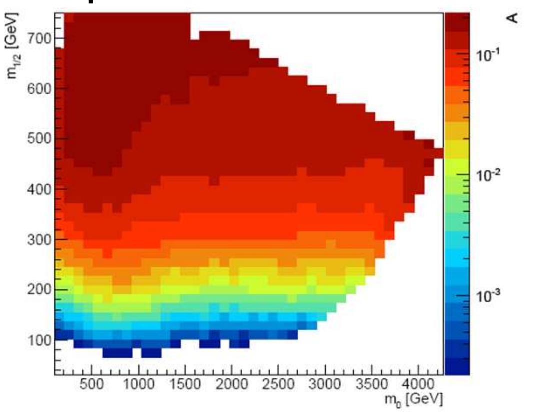
Predict 39+/-9, observe 36 ➔

➔ **Exclude at 95%CL N(BSM)≥ 18 and N/L = σ_{vis} > 3.7 fb**

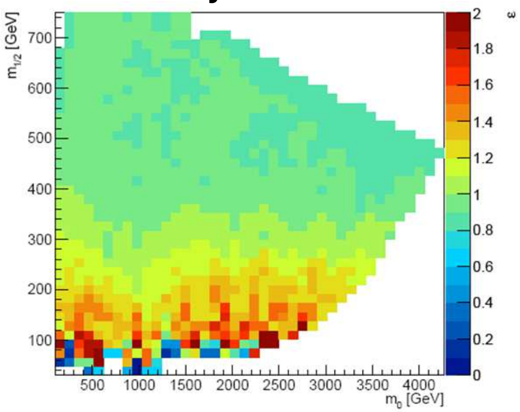
➔ *Expected to exclude N(BSM)≥ 19 and N/L=σ_{vis} > 4.1 fb*

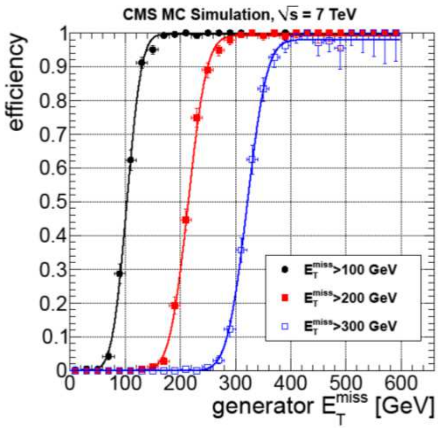
- A and ε given for a well-defined SUSY model : Examples below

Acceptance of Truth cuts~0.1-10%



Efficiency wrt Truth ~ 1





➔ Result can be recasted in other models than the one considered

Fit Results (5)

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❑ Exclusion fit : discovery fit with μ=1 and a given SUSY Model

- Exclude (or not) a given SUSY model (with well defined cross-section).
- **Test statistic:** based on one-sided profile log likelihood ratio (a la Higgs)

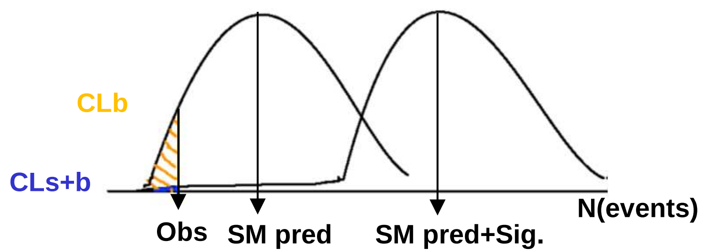
$$\Lambda(\mu) = -2\times[L(n\,|\,\mu,\hat{\hat{b}},\hat{\hat{\theta}}) - L(n\,|\,\hat{\mu},\hat{b},\hat{\theta})] \sim \chi^2 \text{ dist with Ndof} = 1^* \,(\mu \geq 0)$$

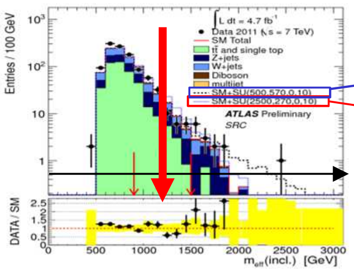
Maximise L for a choice of μ (here μ=1)

Maximise L for μ floating

***In practice this approximation works well for sufficient stat. (n>5). If not the case, use toys**

- Use CLs=CLs+b/CLb prescription (a la Higgs):
  - ✓ Protection from a down-fluctuation of the SM background
- In 0lepton+≥4jets+MET + M_{eff} (incl.) >1200 GeV:
  - ✓ CLs **p-value**<0.05 → exclude the model at 95 % CL





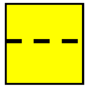
NS=5 → CLs p-value=0.4. Not excluded

NS=14 → CLs p-value=0.1. Not excluded

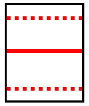
Fit Results (6)

❑ Exclusion limits : a new standard ATLAS/CMS procedure (>June 2012)

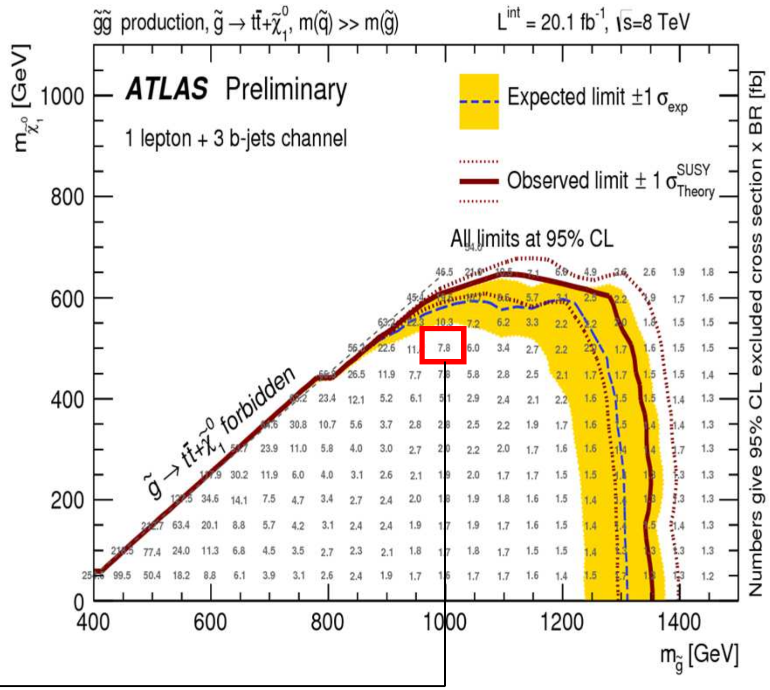
- Ease the life of theorist by separating the signal theoritical and experimental systematics

Expected limit: 

- **Central value:** all uncertainties included in the fit as nuisance parameters, except theoretical signal uncertainties (PDF,scales)
- **±1σ band** : ±1σ results of the fit

Observed limit: 

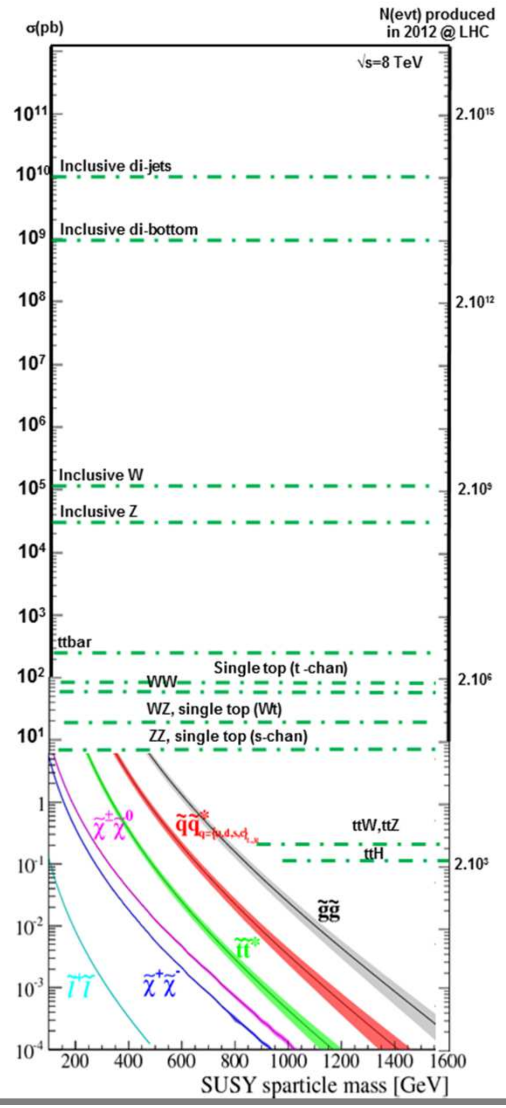
- **Central value**: Idem as for expected limit
- **±1σ band** : re-run and increase/decrease the signal cross section by the theoretical signal uncertainties (PDF, scales)

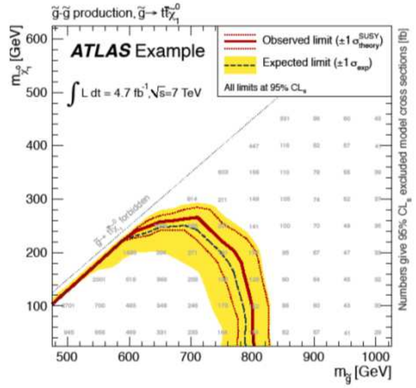


Excluded Model Production Cross section (σ_{excl})

e.g M($\tilde{g}$)=1 TeV σ($\tilde{g}\tilde{g}$)~30 fb If σ_{excl} <σ($\tilde{g}\tilde{g}$)

Interpretation





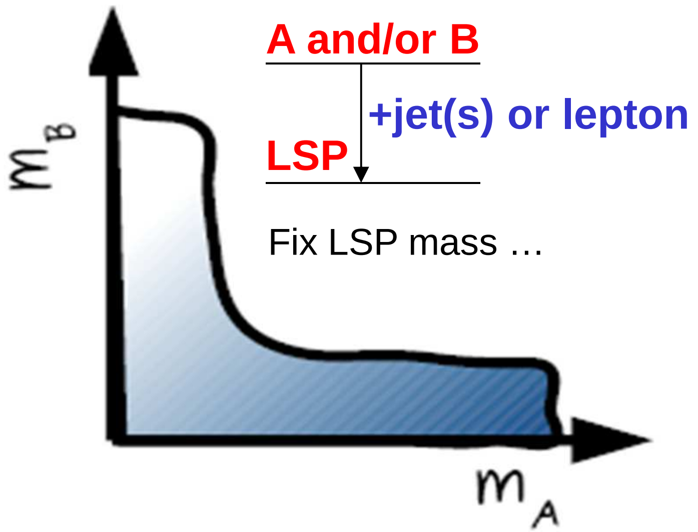
1) Estimate small remaining quantities
2) Need to suppress QCD / W,Z / top by ~ 10^{10} / 10^{5} / 10^{2}
3) Fit results

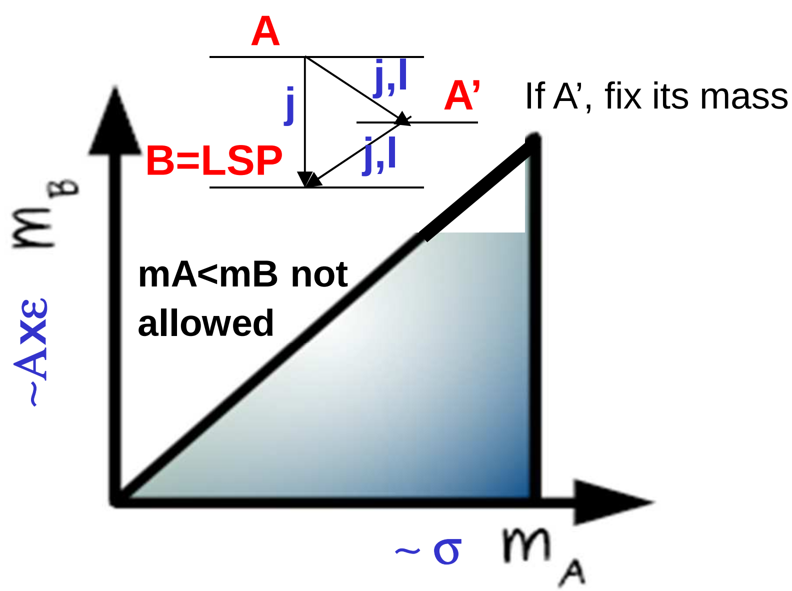
4) Interpret the results if no excess

Interpretation (1)

❑ Derive a limit in a simplified decay chain Model (SMS)

- Well suited for **natural SUSY** and **direct production** (not a SUSY model !):
  - ✓ 29 sparticles → 2 or 3, **decoupled** all other particles, force a specific decay mode (BR=100% !)
- Assumptions on the chirality and nature of particle "arbitrary"





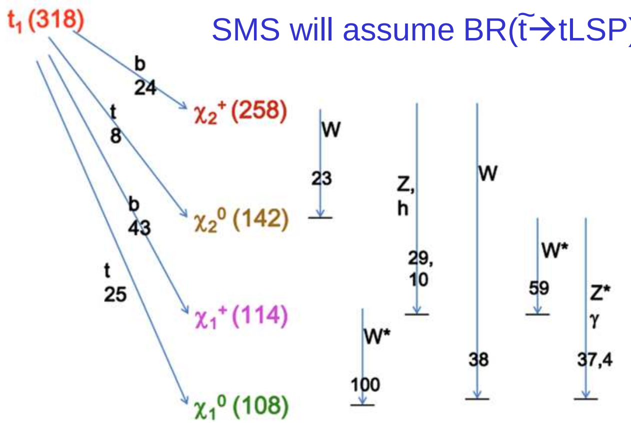
➔ Very helpful also to design analyses. Possible to recast in other models

Interpretation (2)

❑ Derive a limit in a simplified MSSM

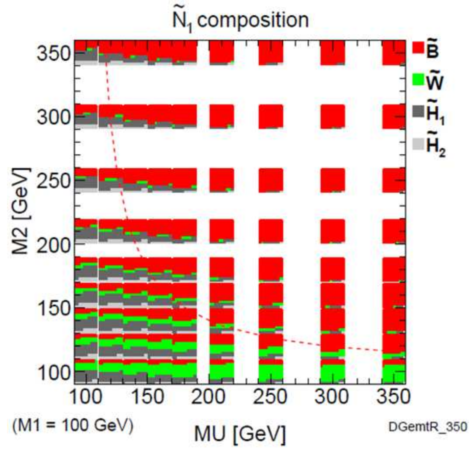
- Reduce number of SUSY parameters from 105 (MSSM) to 19, i.e. "manageable":
  - ✓ Well justified assumptions → no arbitrary fixing of the BR decay
  - ✓ "Standard" exp. constraints
- Recover the SUSY complexity ➔ can track missing features of SMS in "simple" cases

Direct Stop production



SMS will assume BR($\tilde{t}$→tLSP)=100%

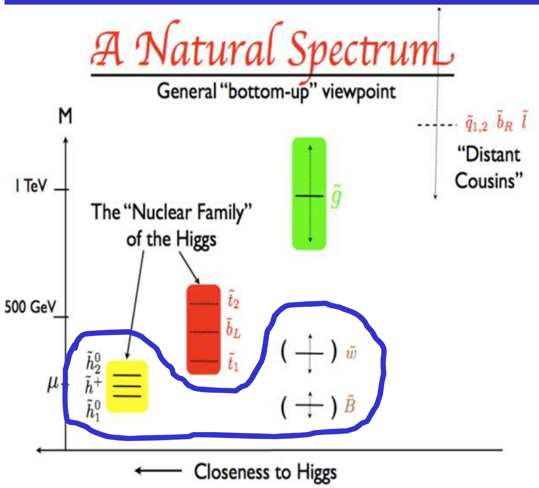
Direct Gaugino production



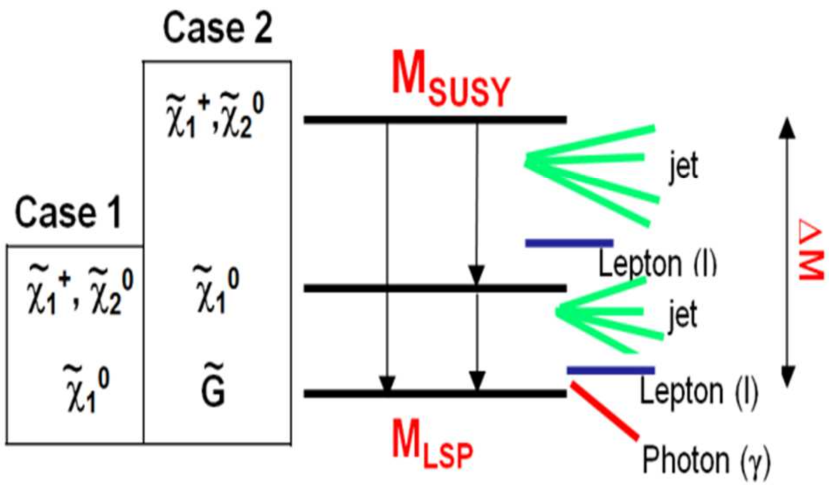
SMS will assume χ bino or higgsino-like

➔ Complementary approach to Simplified Model

Lecture Part Ib

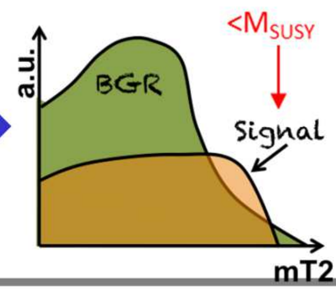


A: MSSM
B: Natural >10%
C1: **RPC**
C2: LSP nature
C3: Spectra opening



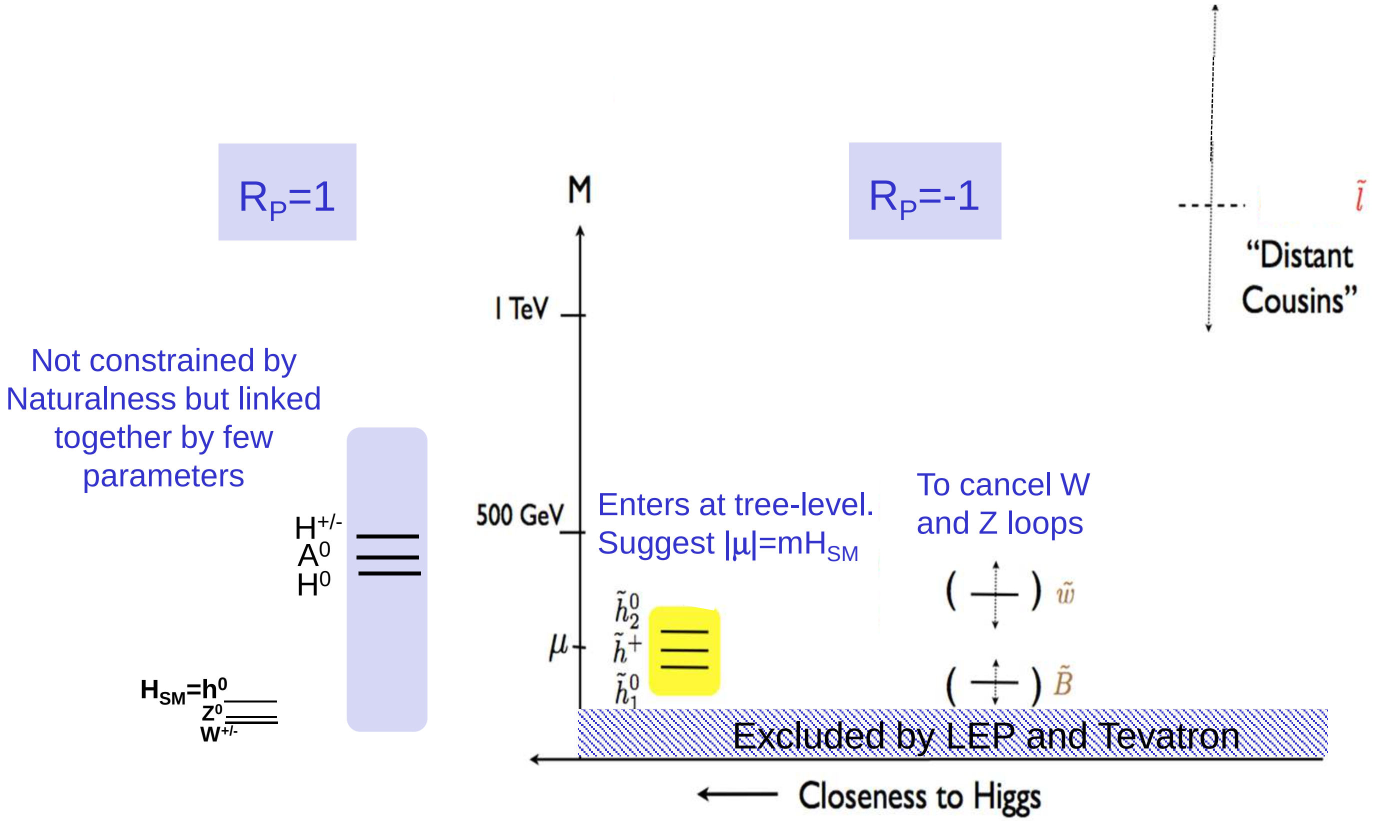
0/1/2 jets
+ E_T^{miss}
+ 1/**2**/**3**/4 lepton
+ 0/1/2 photon

- Absolute value of vectorial sum: $E_T^{miss} \sim \Delta M$
- Number of jets (can be jet-veto !)
- Endpoint at $m_{T2} \sim (M_{SUSY}^2 - M_{LSP}^2)/M_{SUSY}$ [hep-ph/9906349,0304226]



Parameters of the EW sector (1)

Before looking for SUSY particles, let's look at the EW sector at large



Parameters of the EW sector (2)

$R_P=1$

1- Standard Model $\phi_{Higgs} = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v+H^0+iH^0) \end{pmatrix}$

$$W^0, B, \mathrm{Im}(H^0) \longrightarrow \gamma, Z \quad (\theta_W \sim 30^0)$$
$$W^+, W^-, H^+, H^- \xrightarrow{\text{EWSB}} W^+, W^-$$
$$\mathrm{Re}H^0 \longrightarrow H$$

1 param. (m_H)

$$V(\phi^\dagger\phi) = -\frac{m_H^2}{2}\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$
$$v = \sqrt{m_H^2/(2\lambda)} = (\sqrt{2}G_F)^{-1/2} \simeq 246\ \mathrm{GeV}$$

2- SUSY $H_d = \begin{pmatrix} (v_d + \phi_d^0 + i\chi_d^0)/\sqrt{2} \\ \phi_d^- \end{pmatrix}$ $H_u = \begin{pmatrix} \phi_u^+ \\ (v_u + \phi_u^0 + i\chi_u^0)/\sqrt{2} \end{pmatrix}$

EWSB

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Gauge Bosons	1	+1	W^+, W^-, W^0, B	W^+, W^-, Z^0, γ
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$

θ_W + 2 angles α, β $\cos^2(\beta-\alpha) = \frac{m_{h^0}^2(m_Z^2 - m_{h^0}^2)}{m_A^2(m_{H^0}^2 - m_{h^0}^2)}$, $\tan\beta = v_u/v_d$

mH+ 1 mass m_A Masses of other Higgses are related to m_A at tree-level

$R_P=-1$

2- SUSY: Each **gauge** field has a partner with S-1/2 in the vector multiplet

$c_W = \cos\theta_W$
$s_W = \sin\theta_W$
$c_\beta = \cos\beta$
$s_\beta = \sin\beta$

$$\begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}$$

Mixing

Bino, Wino, Higgsino → Neutralinos

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$

Charginos

$$\begin{pmatrix} M_2 & \sqrt{2}s_\beta m_W \\ \sqrt{2}c_\beta m_W & \mu \end{pmatrix}$$

Masses of Gauge Eigenstates

Bino	Wino	Higgsino
↑	↑	↑

4 param. M1, M2, μ, $\tan\beta$

SUSY Higgses

$R_P=1$

1- Standard Model:

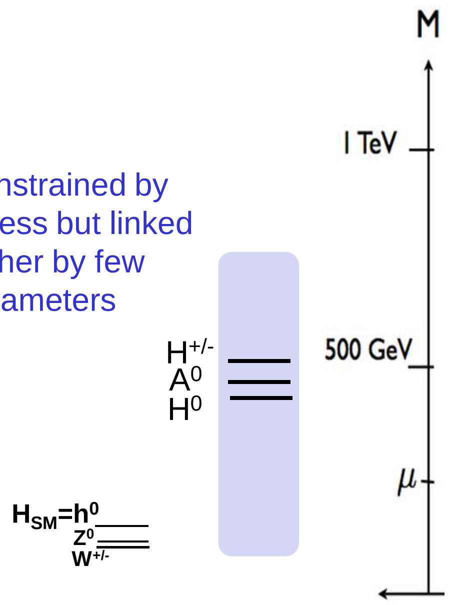
- m_H=125 GeV.
- Assume h^0 Higgs discovered *(most probable)*

2- SUSY $H_d = \begin{pmatrix} (v \quad + i\chi_d^0)/\sqrt{2} \\ \phi_d^- \end{pmatrix}$ $H_u = \begin{pmatrix} \phi_u^+ \\ (v_u + \phi_u^0 + i\chi_u^0)/\sqrt{2} \end{pmatrix}$

EWSB

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Gauge Bosons	1	+1	W^+, W^-, W^0, B	W^+, W^-, Z^0, γ
Higgs bosons	0	+1	H_u^0 H_d^0 H_u^+ H_d^-	h^0 H^0 A^0 $H^\pm$

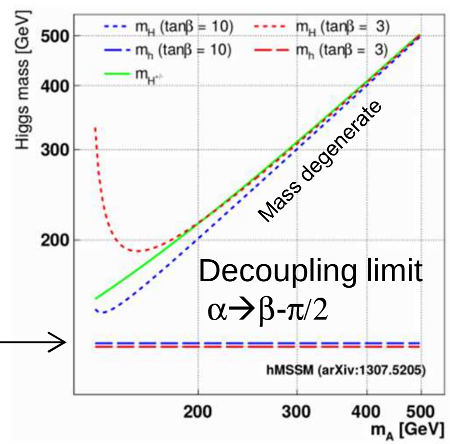
Not constrained by Naturalness but linked together by few parameters



m_A*, $\tan\beta = v_u/v_d$

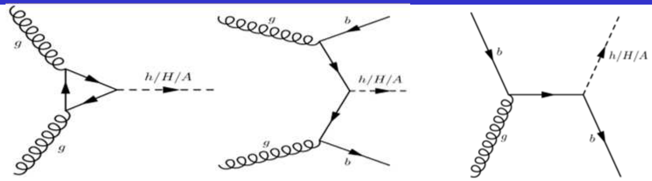
hMSSM, 1307.5205

m_{h0}=125 GeV →



SUSY Higgses (1)

ATLAS-CONF-2015-061

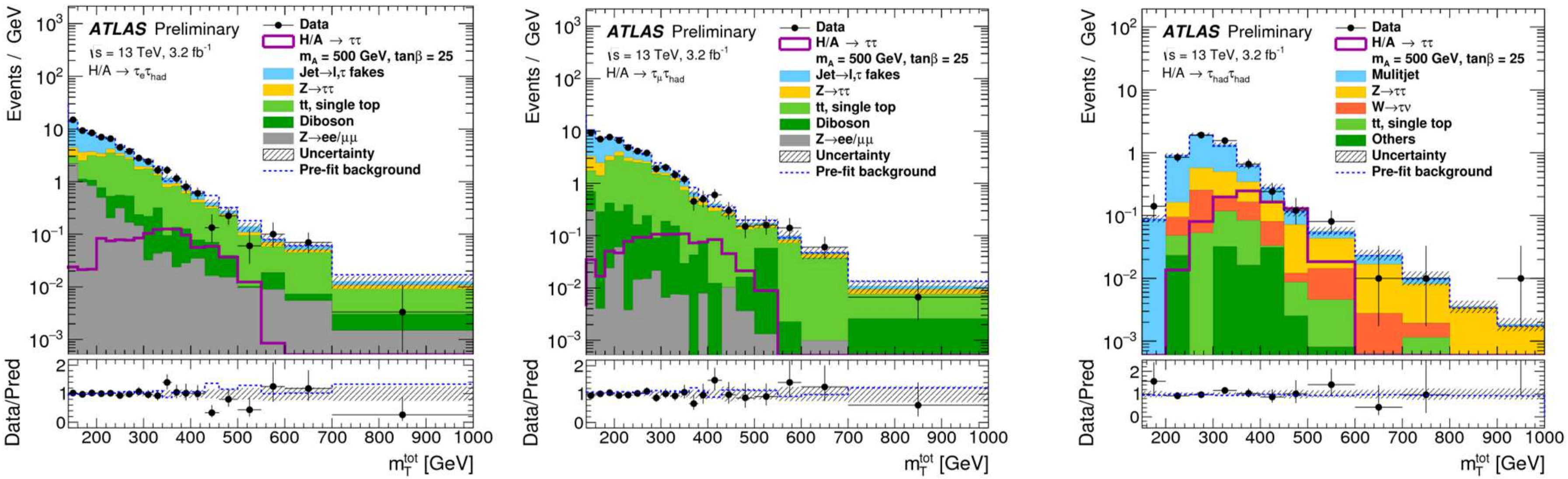


❑ Neutral Higgs searches : ϕ=A/H

- Production: gg→ϕ or gg→bϕ,bbϕ
- Coupling *(prefer down-type fermions)* : $\phi\to\tau\tau$ (10%), bb (90%)
  - ✓ Choose $\tau\tau$ since bb more challenging experimentally
- Fit discriminant variable m_T ($\tau\tau$ system) in 3 channels (could be further split in b-tag and bjet in principle)

$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)},$$

$\tau_e\tau_{had}$ $\tau_\mu\tau_{had}$ $\tau_{had}\tau_{had}$

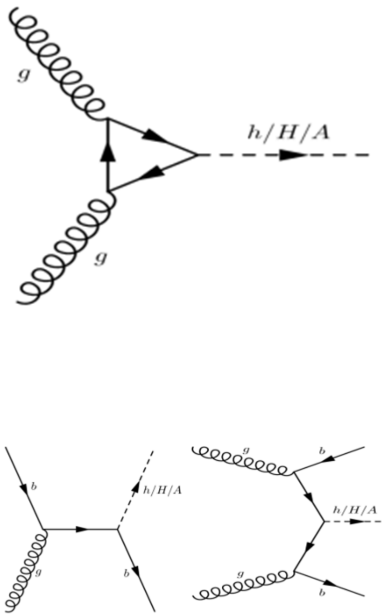


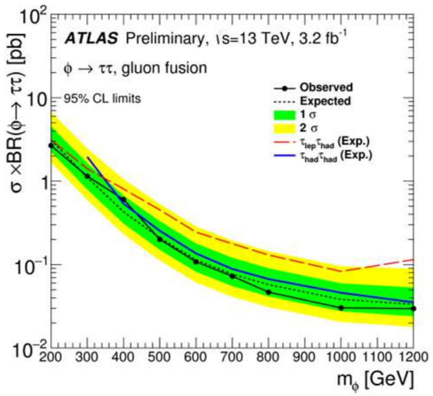
SUSY Higgses (2)

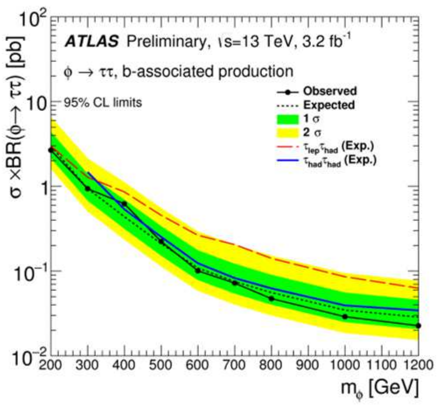
ATLAS-CONF-2015-061

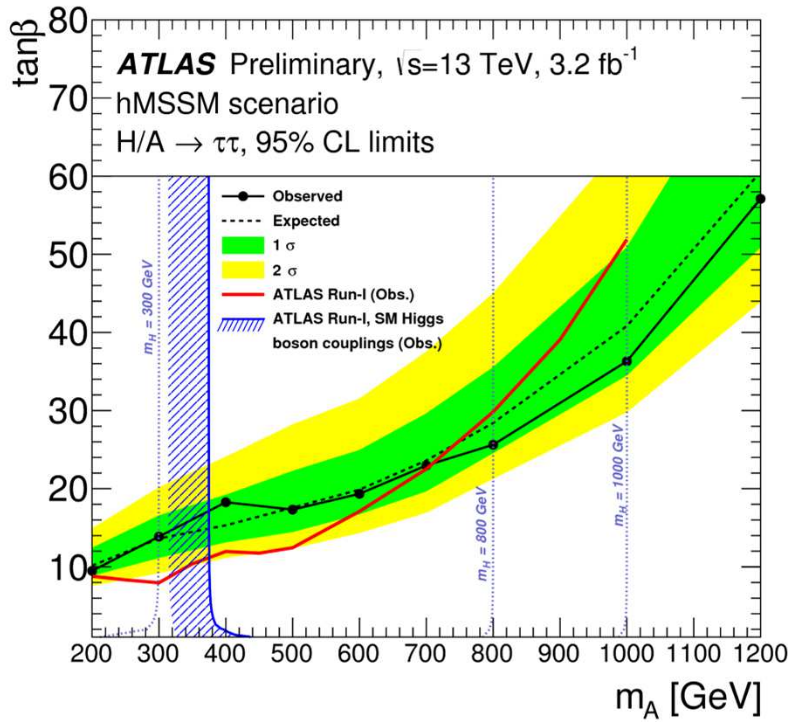
- **Combine all channels ϕ=A/H → $\tau_{had}\tau_{had}$, $\tau_{had}\tau_{lep}$**
  - $\tau_{had}\tau_{had}$ more sensitive at high ϕ mass (>400 GeV)

R_P=1









Clearly favor high mass neutral SUSY Higgses in hMSSM

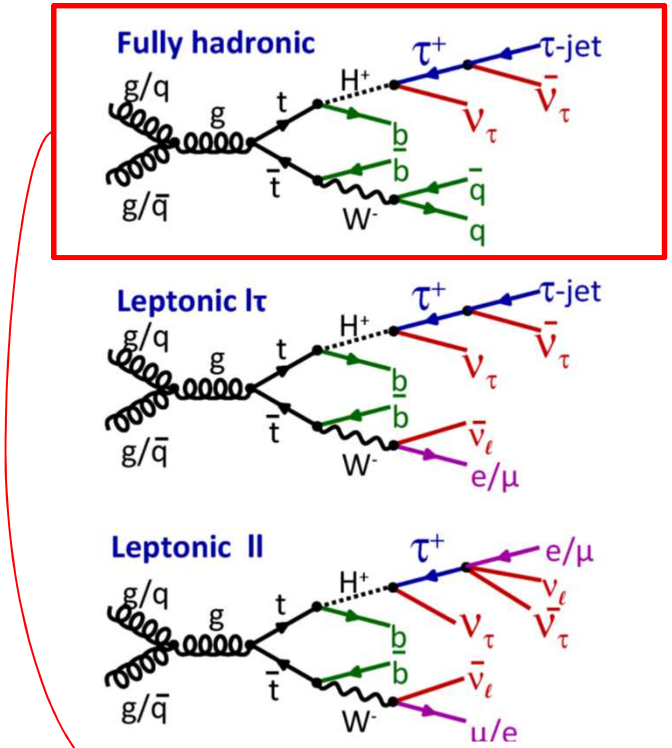
SUSY Higgses (3)

R$_P$=1

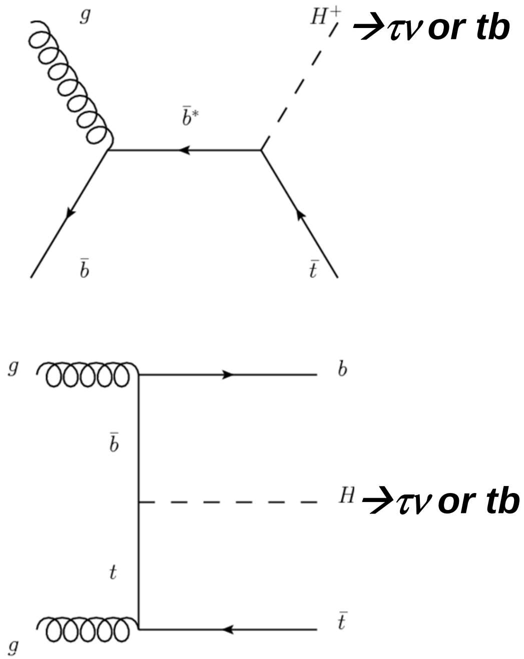
❑ Charged Higgs : $H^{+/-}$

- An elementary **charged scalar** particle : clearly indicate new physics beyond SM !
- Coupling *(prefer down-type fermions)* : BR ($H^{+/-}\rightarrow bt$) if opened, BR ($H^{+/-}\rightarrow \tau\nu$) for $\tan\beta > 1$
- Production: $m_H+/- < m_t$: ttbar events

  $m_H+/- > m_t$: Associated prod. with b,t



Most powerful mode (see 1204.2760)



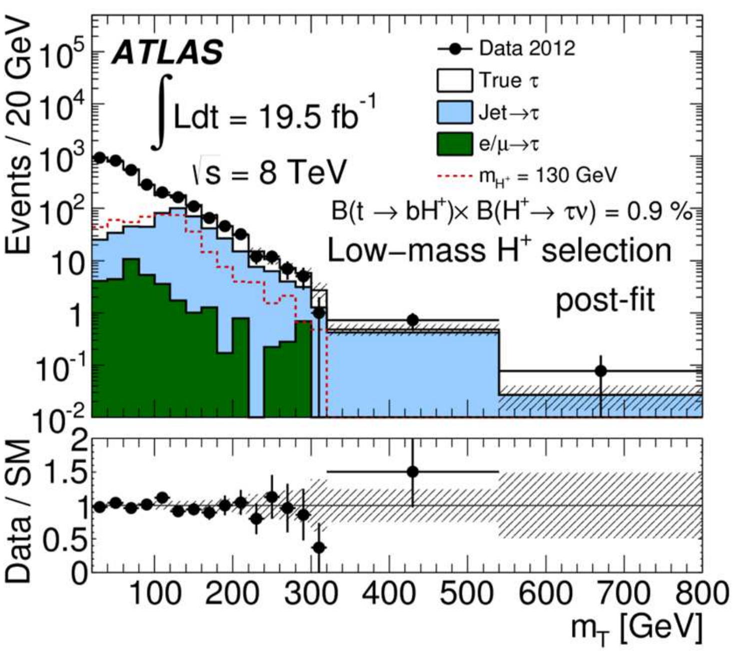
SUSY Higgses (4)

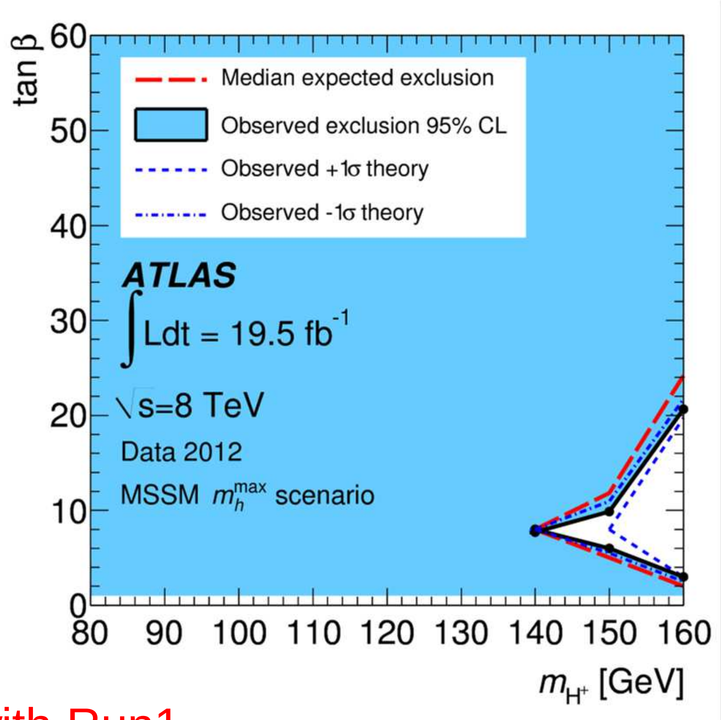
ATLAS: 1412.6663
CMS: 1508.07774

❑ Charged Higgs ($H^{+/-} \rightarrow \tau\nu$) and $m_H < m_t$

R_P=1

- =1 hadronic tau, ≥1b-jet, ≥ 4 jets [W→jj], MET>65 GeV : veto on electron/muon
- Background dominated by fake taus [Data-driven fake factor method]
- Fit discriminant variable $m_T(\tau\nu$ system) : signal will appear as a broad excess





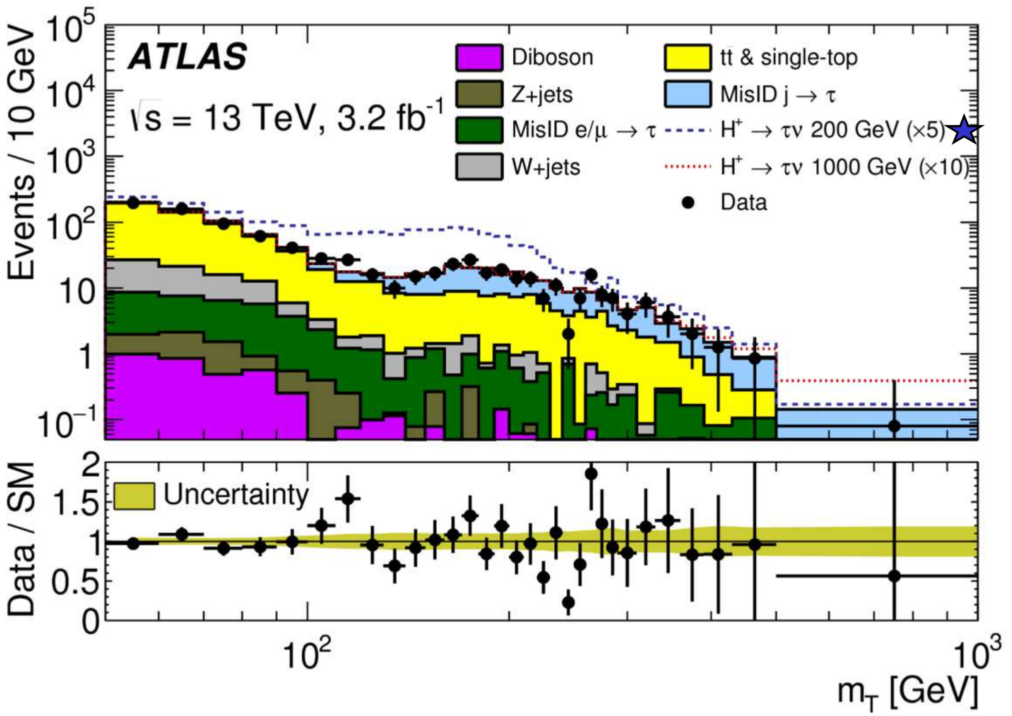
Close the low mass region with Run1 …

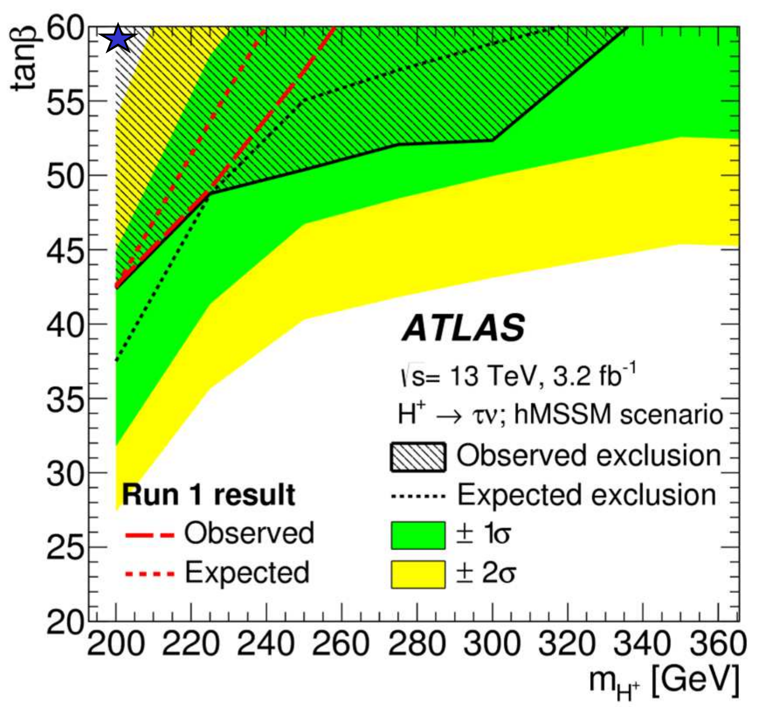
SUSY Higgses (5)

ATLAS: 1603.09203

R_P=1

- **Charged Higgs ($H^{+/-} \rightarrow \tau\nu$) and $m_H > m_t$**
  - =1 hadronic tau, ≥1b-jet, ≥ 3 jets [W→jj], MET>150 GeV : veto on electron/muon
  - Background dominated by fake taus [Data-driven fake factor method]
  - Fit discriminant variable mT ($\tau\nu$ system) : signal will appear as a broad excess





… and start to be sensitive to higher mass with Run2

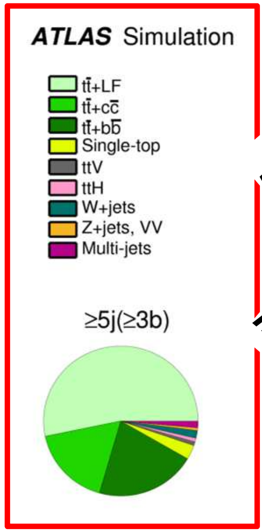
SUSY Higgses (6)

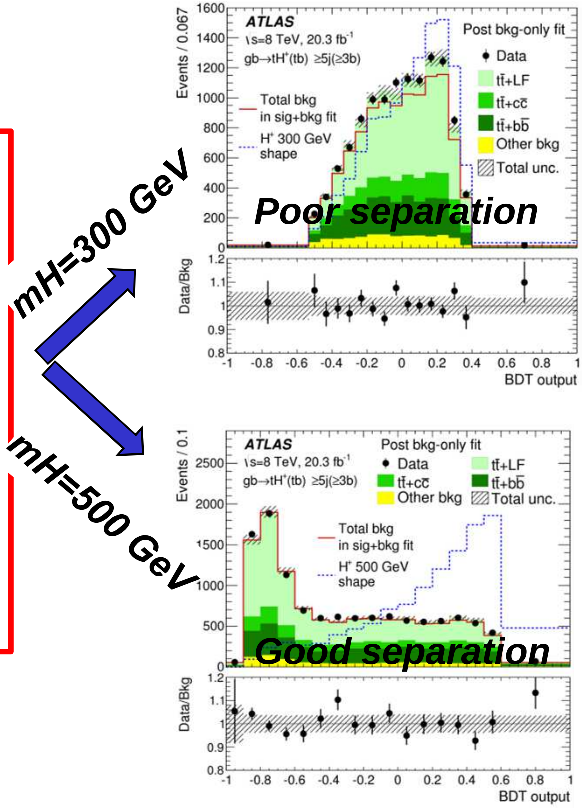
ATLAS: 1512.03704
CMS: 1508.07774

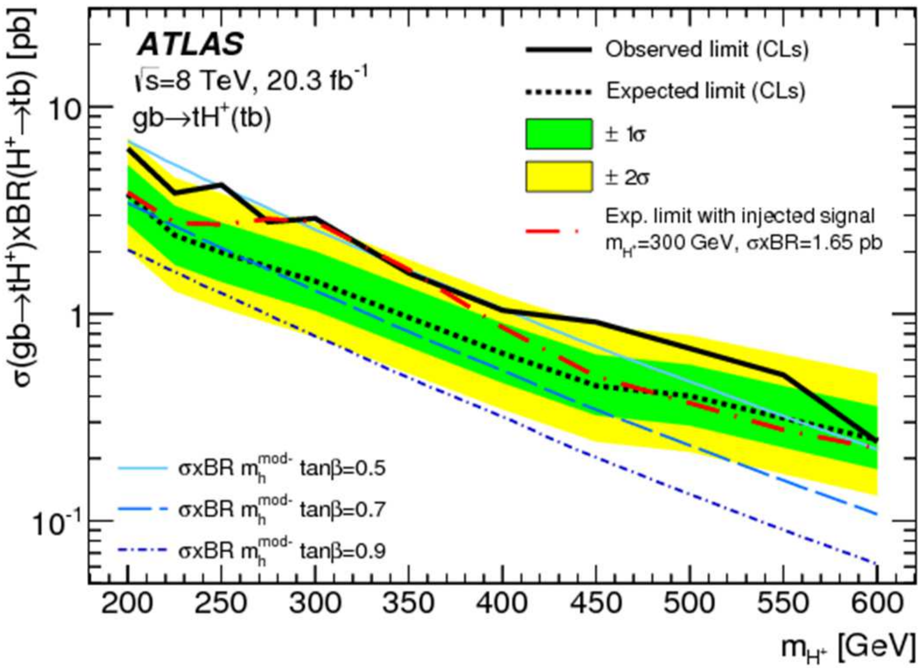
❑ Charged Higgs ($H^{+/-}$ → tb) and $m_H > m_t$

R_P=1

- Very poor signal over background around 300 GeV (even with BDT) …
- Systematic dominated (by unknowns on ttbar modelling)







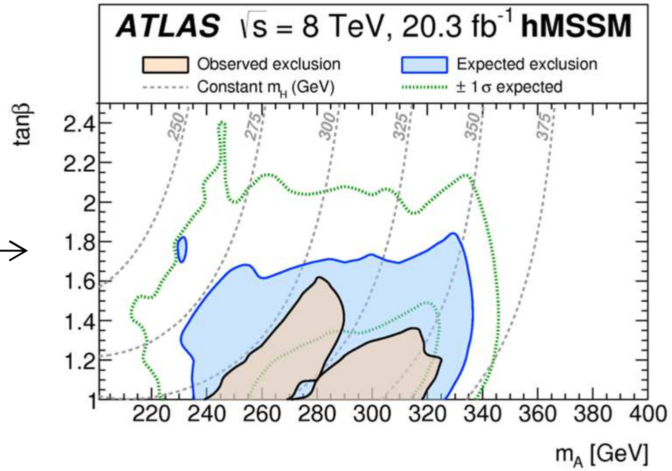
SUSY Higgses (7)

R_P=1

❑ Summary

- Reasonable to assume that h^0 is the boson discovered (even if a bit heavy for MSSM)
- SUSY Higgses excluded at low masses and typically $m(A^0/H^0, H^{+/-})$>200-300 GeV
- Other related searches :
  - ✓VBF H+
  - ✓Add another neutral scalar **a** like in NMSSM:
    - o $h \rightarrow 2a \rightarrow 2b2\mu$ [CMS-PAS-HIG-14-041]
    - o $h \rightarrow 2a \rightarrow 4\mu$ [1506.00424]
    - o $h \rightarrow 2a \rightarrow 2\mu 2\tau$ [CMS-PAS-HIG-15-011, 1505.01609]
    - o $h \rightarrow 2a \rightarrow 4\tau$ [CMS-PAS-HIG-14-022]
    - o $h \rightarrow 2a \rightarrow 4\gamma$ [1509.05051]
  - ✓diHiggs production, e.g. $H \rightarrow hh \rightarrow bb\tau\tau$

1509.04670



In the following, I assume $A^0/H^0/H^{+/-}$ decoupled

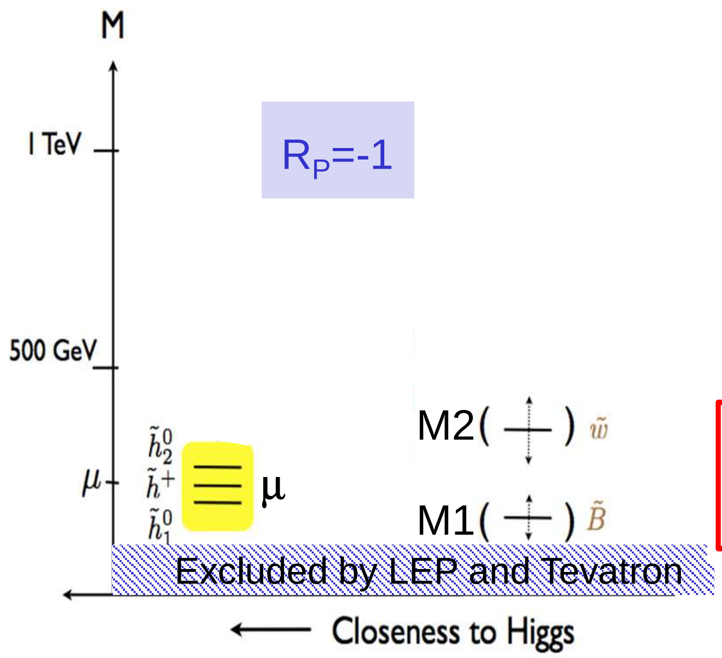
✓ It is conservative: If they happen to be lighter EWKinos cross-section will increase.

EWKinos

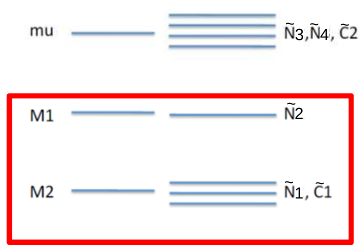
A: MSSM
B: Natural >10%
B1: **RPC**
B2: **LSP nature=N1**
B3: Unspecified Spectra

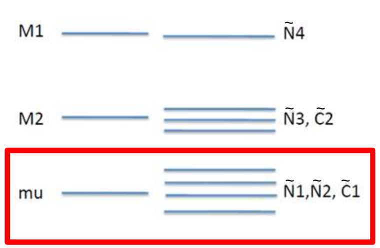
Will mainly focus on lightest states ($\tilde{C}1$, $\tilde{N}1$, $\tilde{N}2$)

R_P=-1



Bino case	**Wino case**	**Higgsino case**
Open Spectra	Degenerate spectra	Compressed spectra





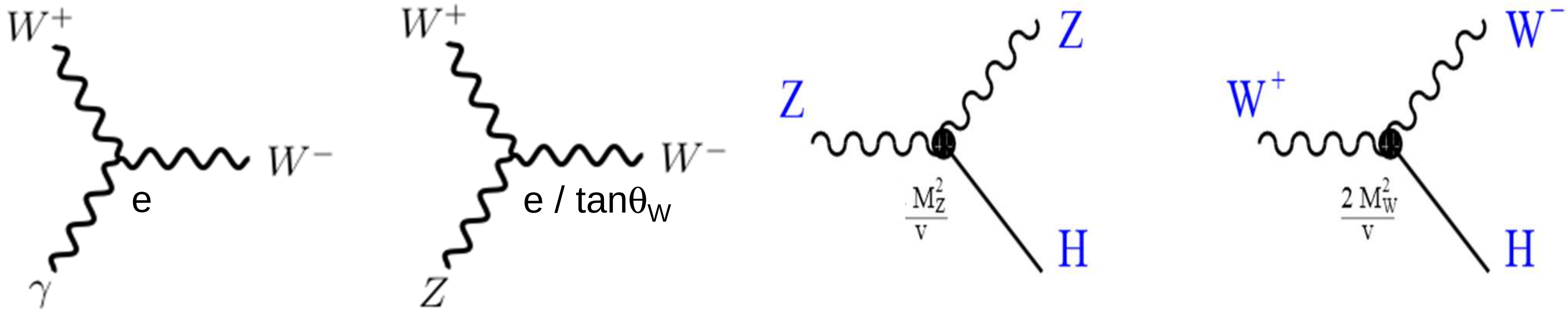
Most studied
→ See later

M(C1)~M(N1)
Long-lived chargino
→ See tomorrow

Impossible at LHC
unless use N3 decay
→Not discussed here

EWKinos (1)

❑ **Reminder : Triple Gauge coupling in the SM EWK sector**



- $\lambda_{WW\gamma} \sim 0.6\ \lambda_{WWZ}$
- Neutral gauge coupling forbidden at tree level

- $\lambda_{ZZH} \sim 0.5\ \lambda_{WWH}$
- $H\gamma\gamma$ forbidden at tree level

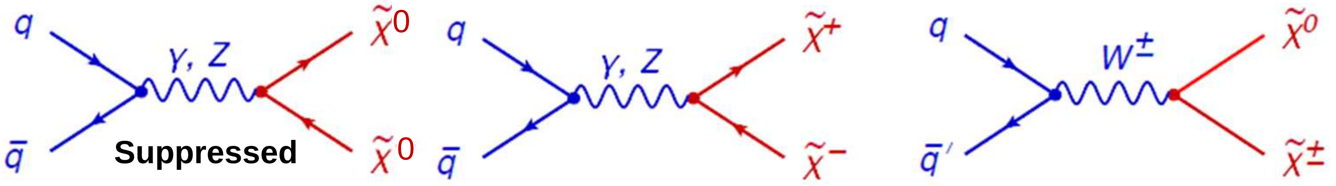
Simple rule: Keep one SM particle and change the 2 others with
W↔ $\tilde{C}$1, γ (H) ↔ $\tilde{N}$1, Z (H)↔ $\tilde{N}$2 can get a feel for SUSY couplings

EWKinos (2)

Bino case
Open Spectra

❑ How to produce them ?

- Gauginos mediated by γ, Z, W (marginally via $h^0/H^0/A^0/H^{+/-}$)



Note: Coupling depends on Ewkino flavor: (W-Bino, Z/γ-Wino)~0, (W/Z/γ-Higgsino)~small, (W-Wino, Z/γ-Bino)~large

❑ How they decay (and assumptions) ?

- Most natural is via Gauge bosons and Higgses → **1- Only decay via W/Z**
- On shell or off-shell depends ΔM=M(N2,C1)-M(N1) → **2- On-shell W/Z ΔM>M(Z,W)**
- LHC = hadronic collider → **3- W/Z leptonic decays (l=e,μ)**

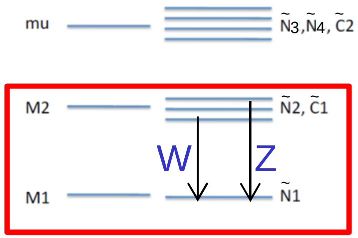
	N1	N2	C1
N1	N1N1		
N2	ZN1N1	ZZN1N1	
C1	WN1N1	WZN1N1	WWN1N1

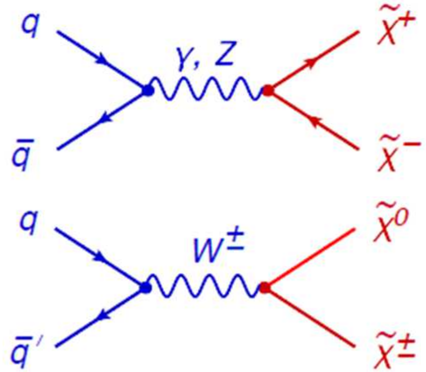
➡

	N1	N2	C1
N1	**ISR-jet**		
N2	**2l+MET**	**4l+MET**	
C1	**1l+MET**	**3l+MET**	**2l+MET**

EWKinos (3)

Bino case
Open Spectra





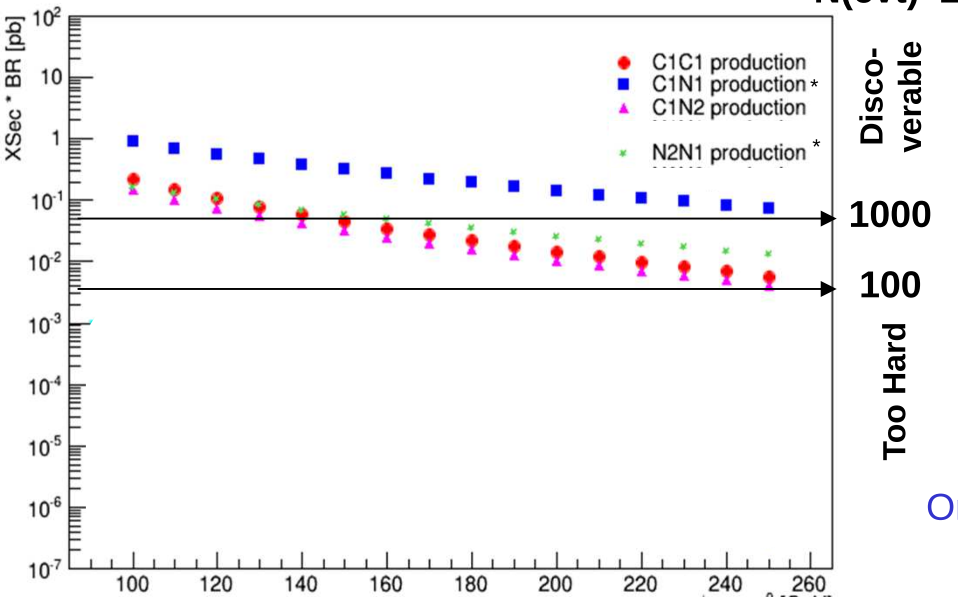
Decay via Leptonic on-shell W and Z

BR (W→lν)=0.21
BR (Z→ll)=0.07

No neutralino mass limit @LHC!

	N1	N2	C1
N1	~~**ISR-jet**~~ ▼		
N2	~~**2l+MET**~~ ★	~~**4l+MET**~~ ✚	
C1	~~**1l+MET**~~ ■	**3l+MET** ▲	**2l+MET** ●

N(evt) 2012



* Assume m(N1)=1 GeV

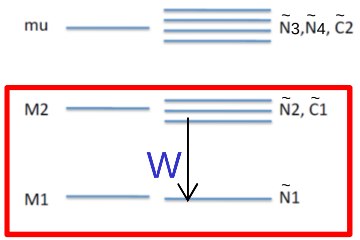
	Main EW Background		
	Type	**σ xBR (pb)**	**σ/σ$_{SUSY}$@100 GeV**
N2N1*	**Z→ll**	**2200**	2200/0.17 ~ **13000**
C1N1*	**W→lν**	**25000**	25000/1 ~ **25000**
C1N2	**WZ→lνll**	**0.3**	0.3/0.12 ~ **2.5**
C1C1	**WW→lνlν**	**2.6**	2.6/0.25 ~ **10**

Only C1C1 and C1N2 can be probed at LHC-8 (20 fb^{-1})

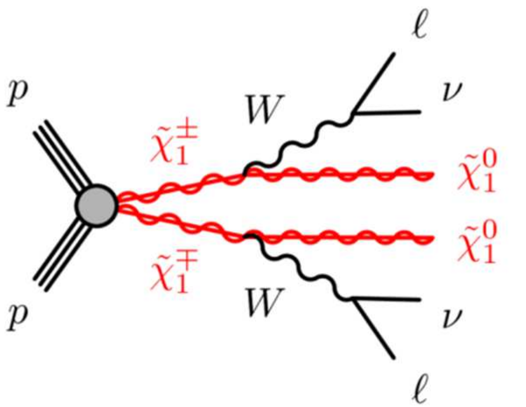
EWKinos (4)

ATLAS: 1403.5294

Bino case
Open Spectra

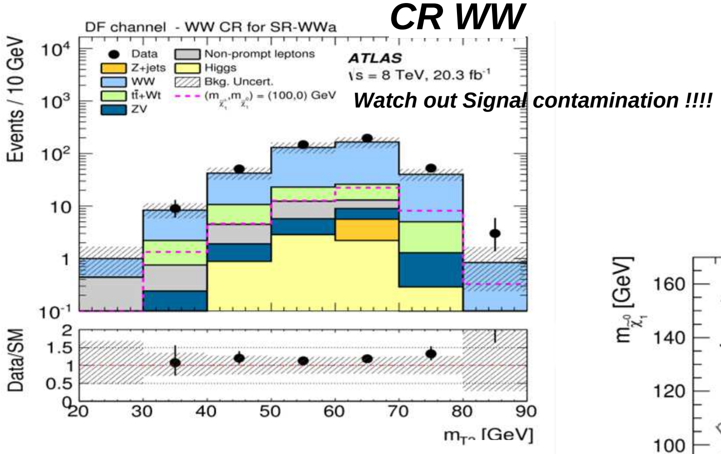


❑ Search for Direct Chargino (C1C1)

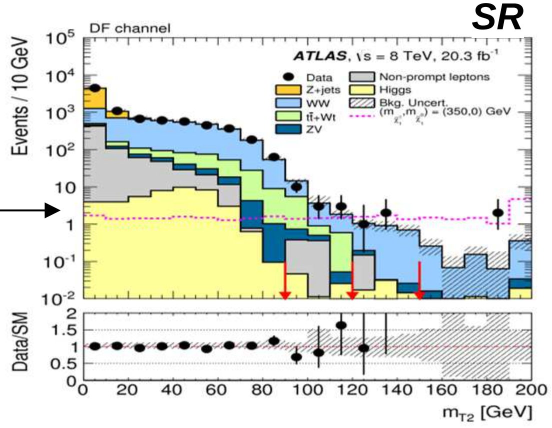


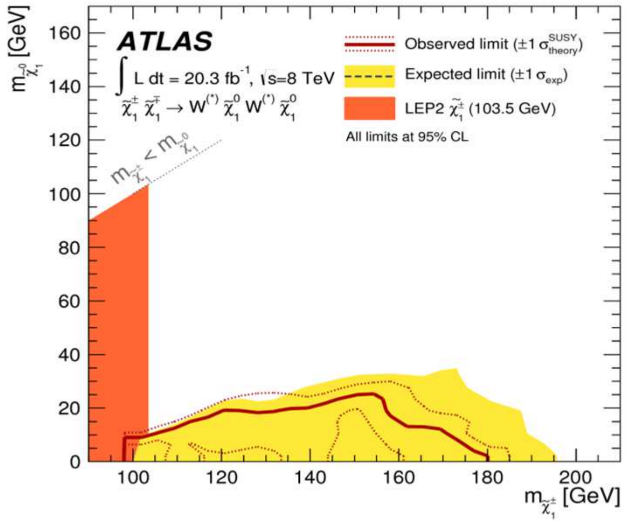
- *Expected signal is flat !*
- *WW steeply falling after 90 GeV*

CR WW



SR



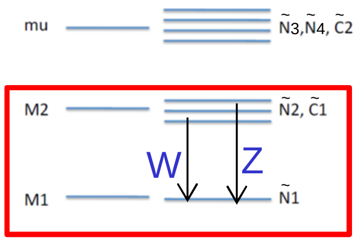


Can barely exclude SUSY models !

EWKinos (5)

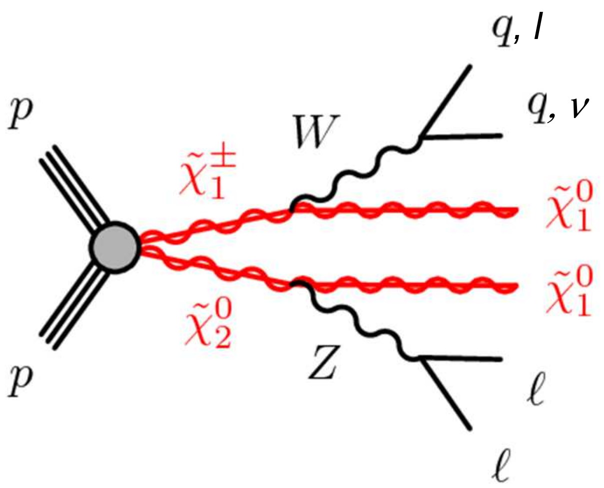
ATLAS: 1402.7029+1403.5294
CMS:1405.7570

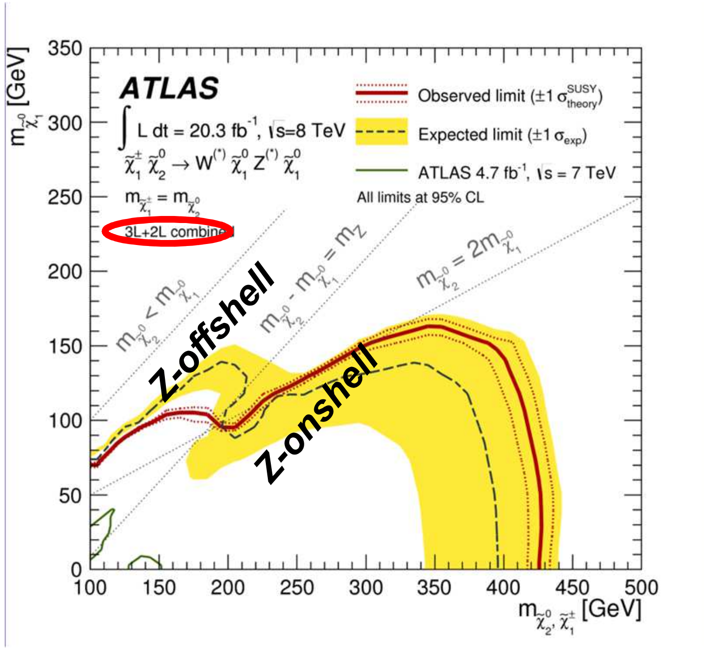
Bino case
Open Spectra



❑ Search for associate production (C1N2)

- Similar experimental challenge, but dominant background is now WZ
- Consider 3-lepton signal regions: w/wo Z veto, w/wo W veto, w/wo taus
- Can combine with 2l+2j



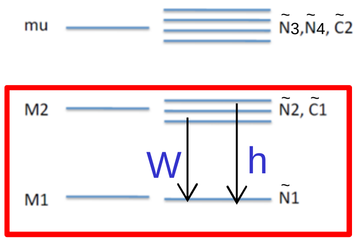


➔ Exclude $m(\chi_1^{\pm})=m(\chi_2^0)$<420 GeV for m(LSP)<80 GeV

EWKinos (6)

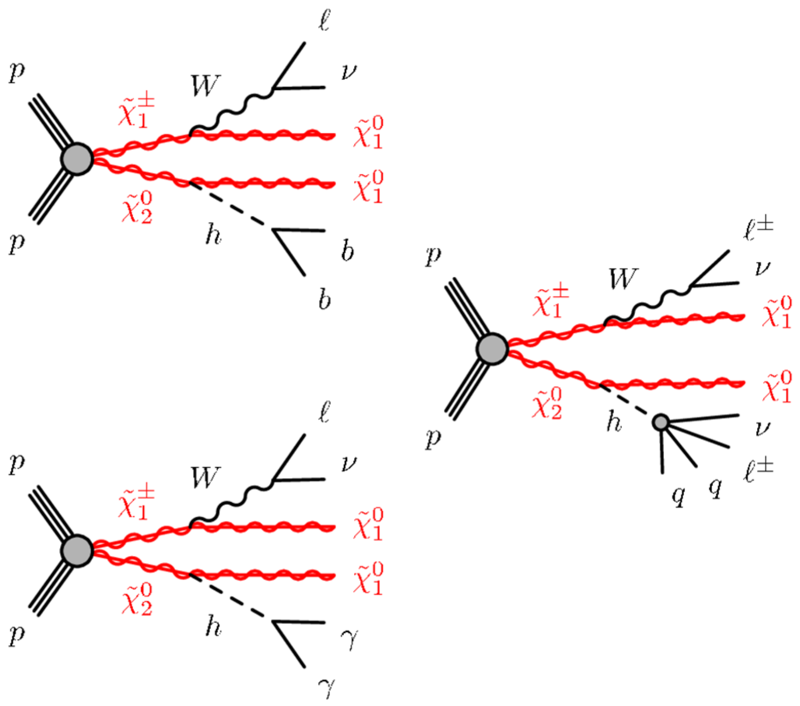
ATLAS: 1501.07110
CMS: 1409.3168

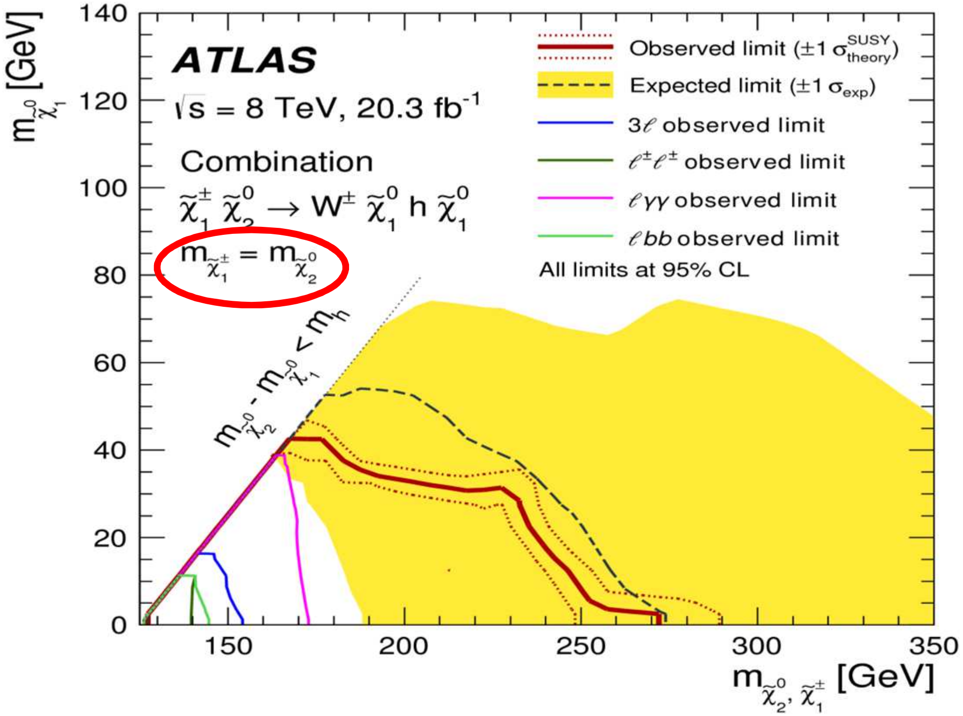
Bino case
Open Spectra



❑ EWKinos production with Higgs in the cascade

- 3 signal regions considered, with very different final states
- 1l +γγ is stronger

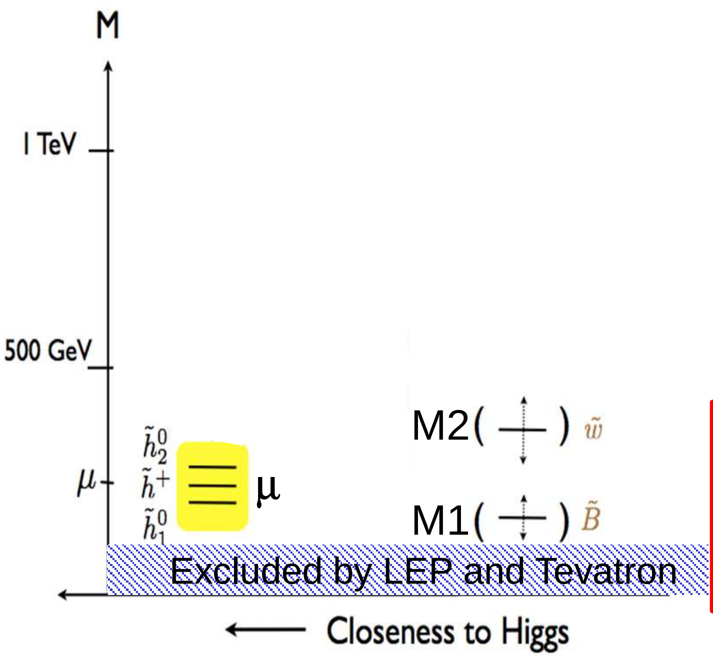




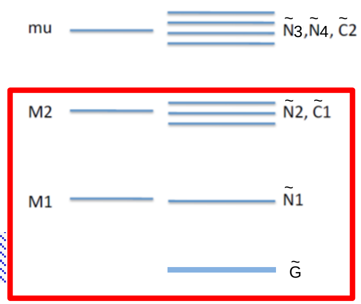
EWKinos (7)

A: MSSM
B: Natural >10%
C1: **RPC**
C2: **LSP nature=G**
C3: Unspecified Spectra

Main change →

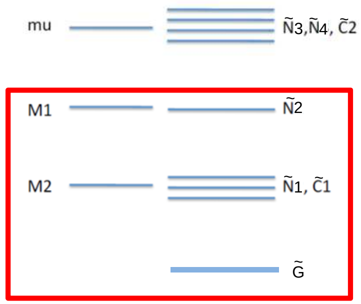


Bino case
Open Spectra



May be only way to access N1N1?

Wino co-NLSP case
ΔM(C1-N1)<1GeV



C1→WG
N1→Z/γG

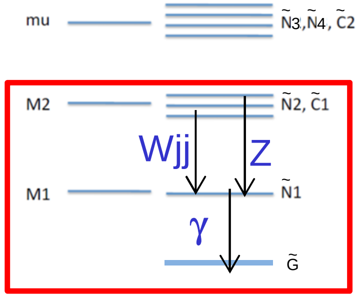
Higgsino case
Compressed spectra

N1→ZG for low tanβ
N1→HG for high tanβ

EWKinos (8)

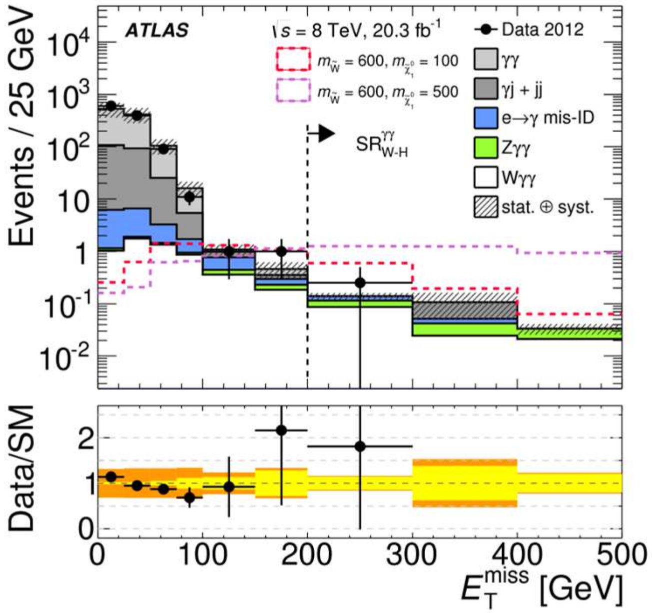
ATLAS: 1507.05493
CMS: 1602.08772

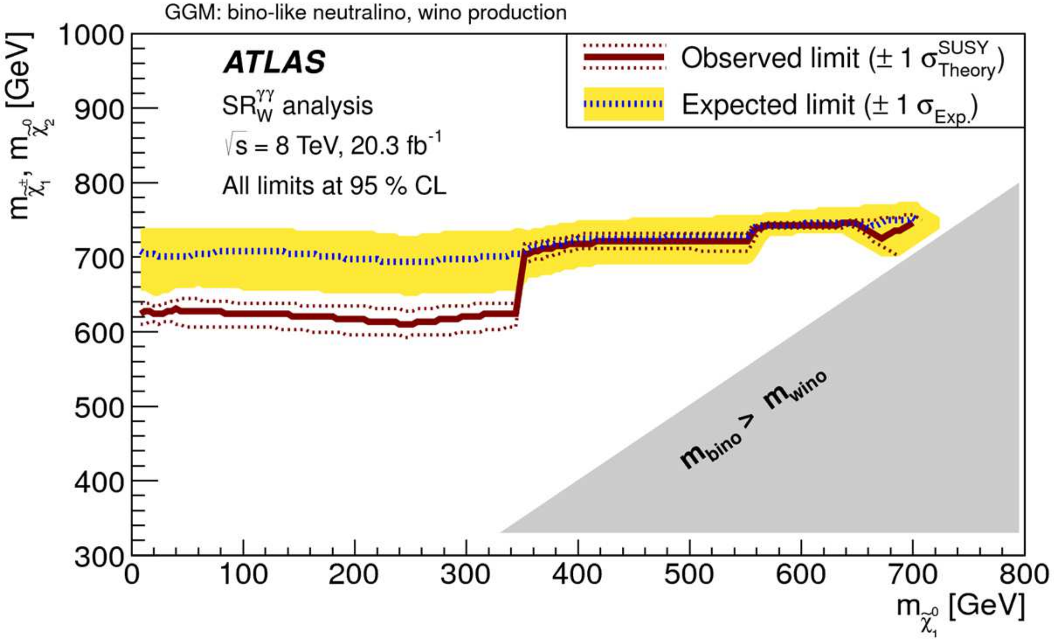
Bino case
Open Spectra



❑ A plethora of new final states for Bino case

- Pure Bino NLSP → Adding 2γ in final state kill the background





Quite strong limits for electroweak production !

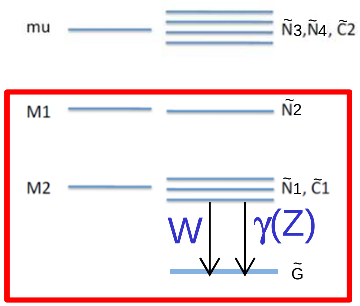
EWKinos (9)

ATLAS: 1507.05493

Wino co-NLSP case
ΔM(C1-N1)<1GeV

❑ Can access the Wino co-NLSP case

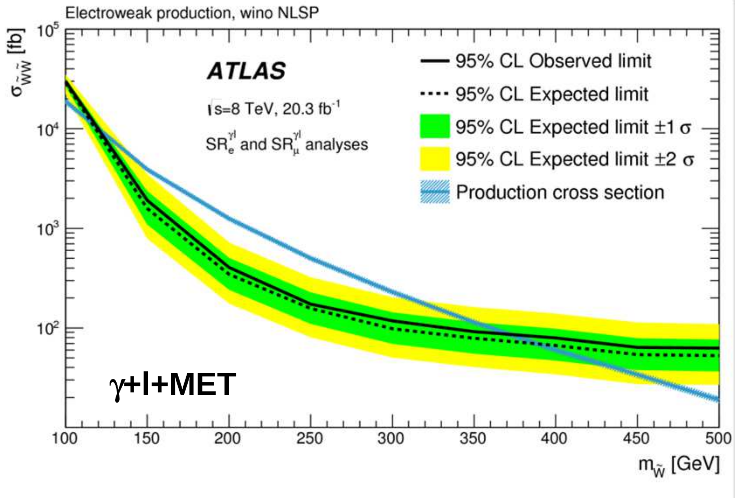
- C1N2 has very low cross-section
- Decay C1→W*N1 is longer than ~0.1 mm … and C1→WG dominates !



	N1	C1
C1	WγGG	WWGG
Final states	**1l+1γ+MET**	**2l+MET**
Bkg type	**Wγ→lvγ**	**WW→lvlv**
σ xBR (pb)	**12**	**2.6**
σ/σ_{SUSY}@100 GeV	12/1~**12**	2.6/0.25~**10**
For LSP=χ_1^0 was	25000	10

See LSP=N1 (p.54)

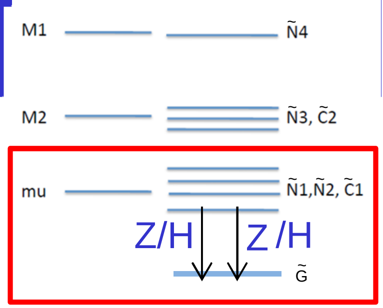
Now possible to cover it!



EWKinos (10)

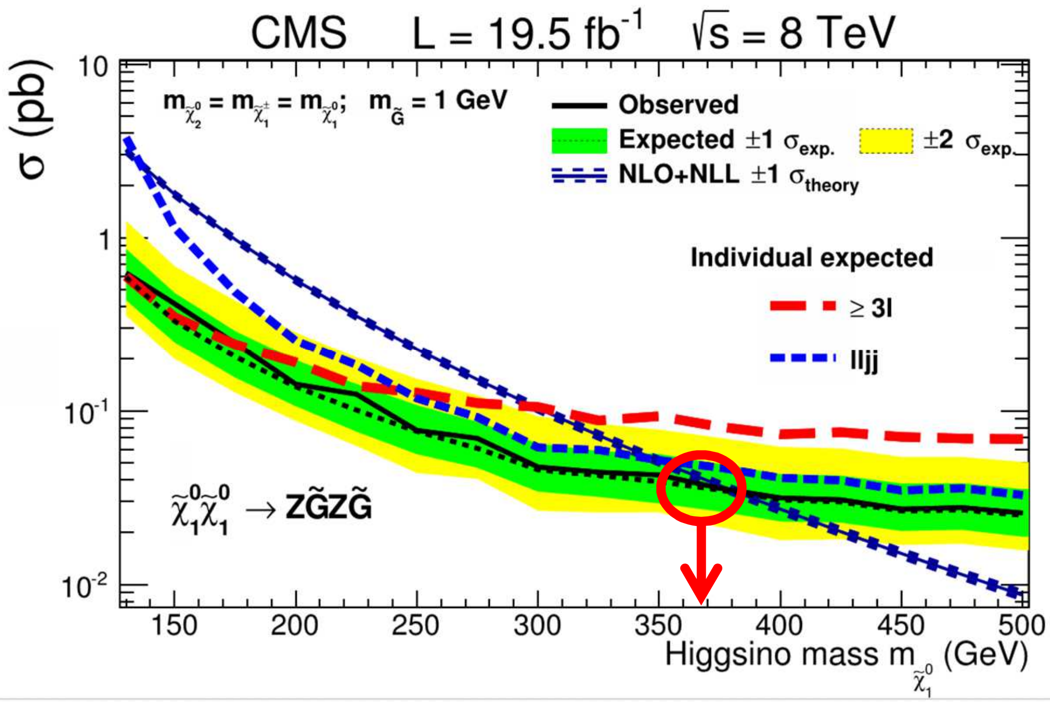
CMS: 1409.3168

Higgsino case
Compressed spectra

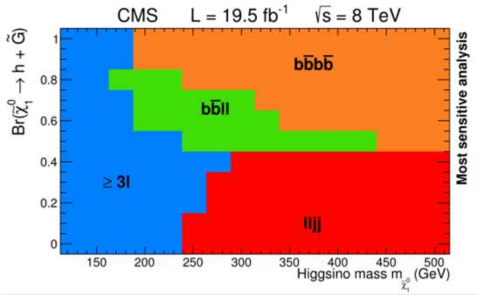


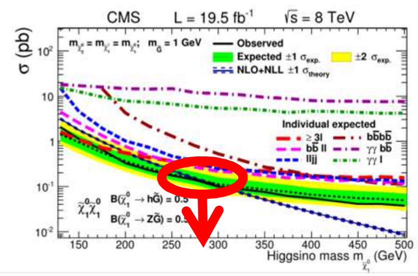
❑ Have sensitivity to the Higgsino case !

- N1, C1, N2 degenerate. Assume N1 is still the NLSP
- Can combine several channel to gain sensitivity

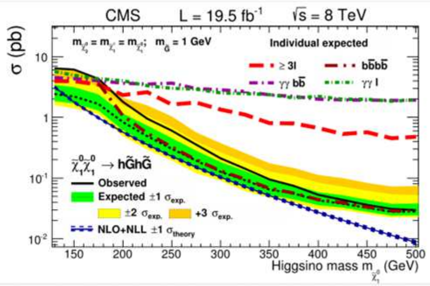


ZZ





ZH



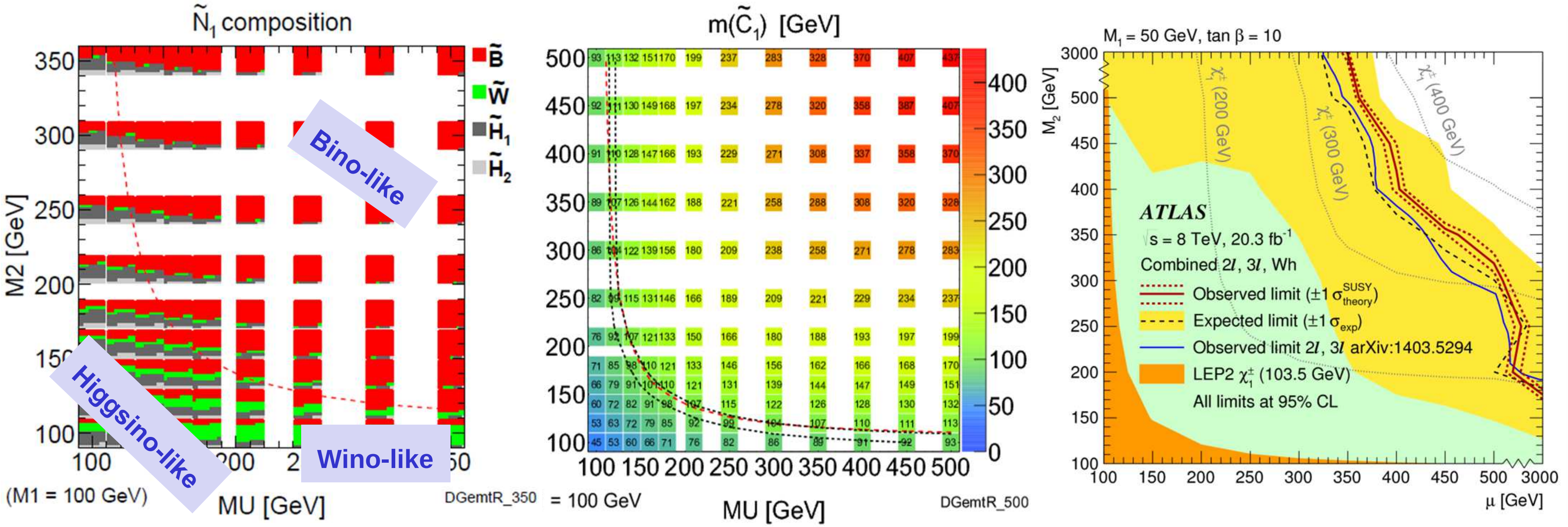
HH (no limit)

A strong constraint for naturalness

EWKinos (11)

❑ pMSSM = systematic scan of 19 parameters MSSM

- We have treated 3 extreme cases: Bino, Wino, Higgsino with BR=100%
  - ✓Sometimes even SUSY impossible models ! *(N1 Higgs decay in Bino models)*
- Can consider SUSY-motivated case and all the intermediate cases with pMSSM



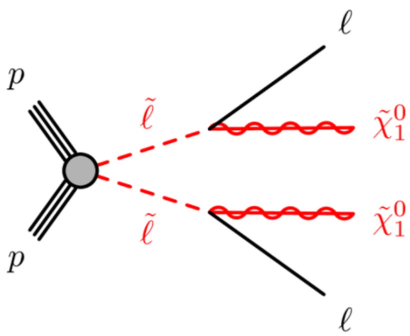
But not always easy to have a clear picture because of 4D !

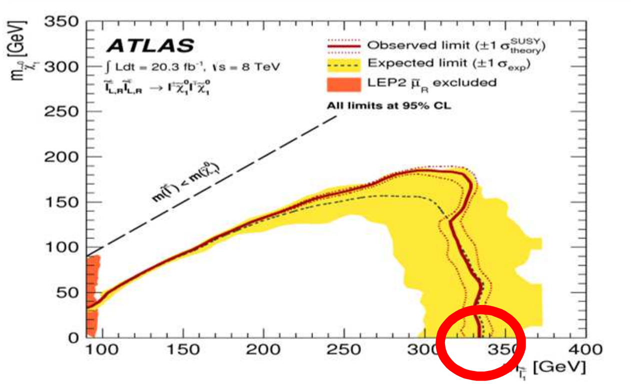
Sleptons

ATLAS: 1403.5294
CMS: 1405.7570
ATLAS-SUSY-2013-028

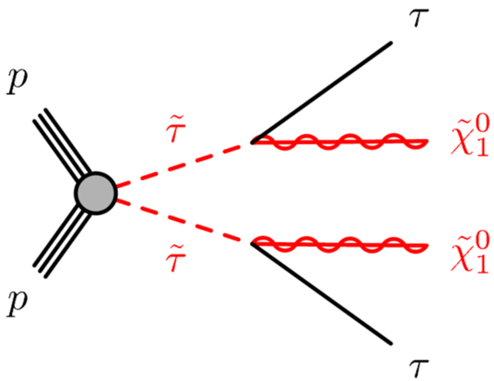
❑ Charged sleptons govern by 5 parameters ($m_{\tilde{e}R}=m_{\tilde{e}L}$, $m_{\tilde{\mu}R}=m_{\tilde{\mu}L}$, $m_{\tilde{\tau}R}$, $m_{\tilde{\tau}L}$, θ_{τ})*

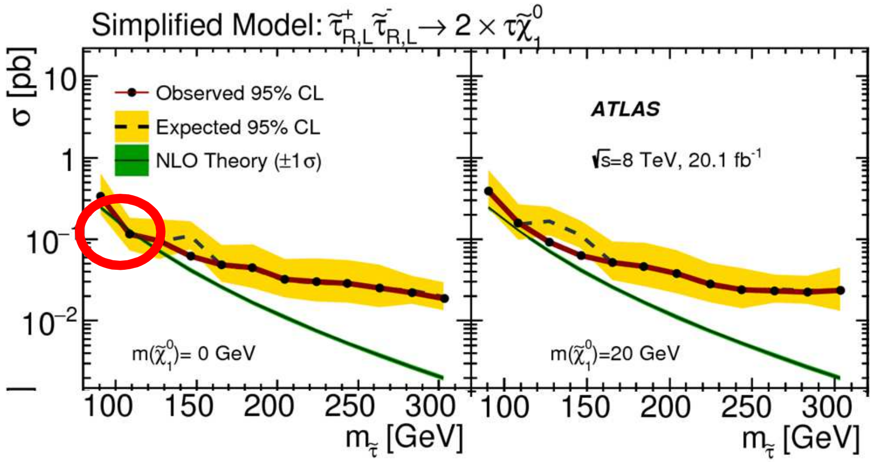
- Have same final states as C1C1→WWN1N1 so can be exclude beyond LEP





- m(tau)~1.8 GeV heavy, low mass stau conceivable but extremely challenging experimentally !





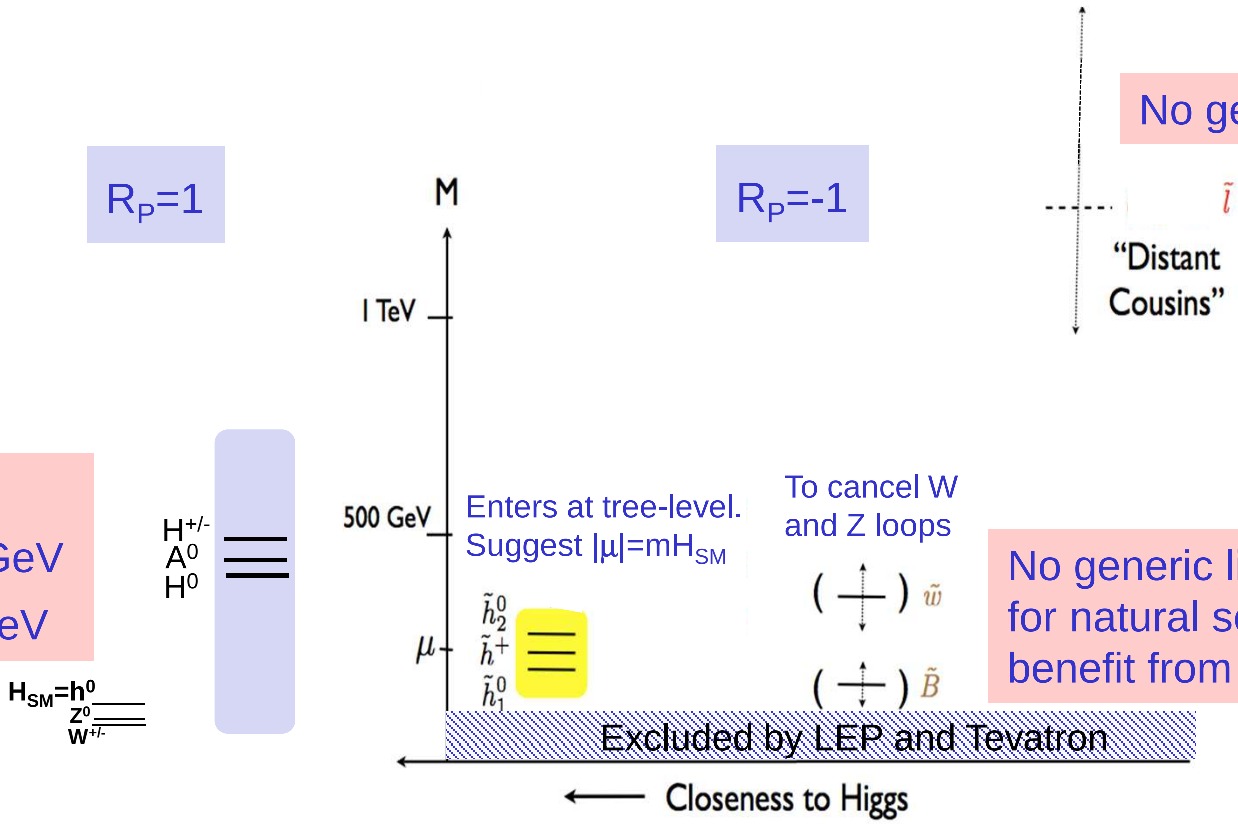
*Sneutrinos in RPC not directly accessible at LHC

Summary of Part Ib

No generic limits …

$R_P=1$

$R_P=-1$



Enters at tree-level. Suggest $|\mu|=mH_{SM}$

To cancel W and Z loops

In hMSSM:

mA/H > 300 GeV

mH+ > 160 GeV

No generic limits … esp. for natural scenarios. Will benefit from HL-LHC.

SPARE