Overview of SUSY searches at the LHC

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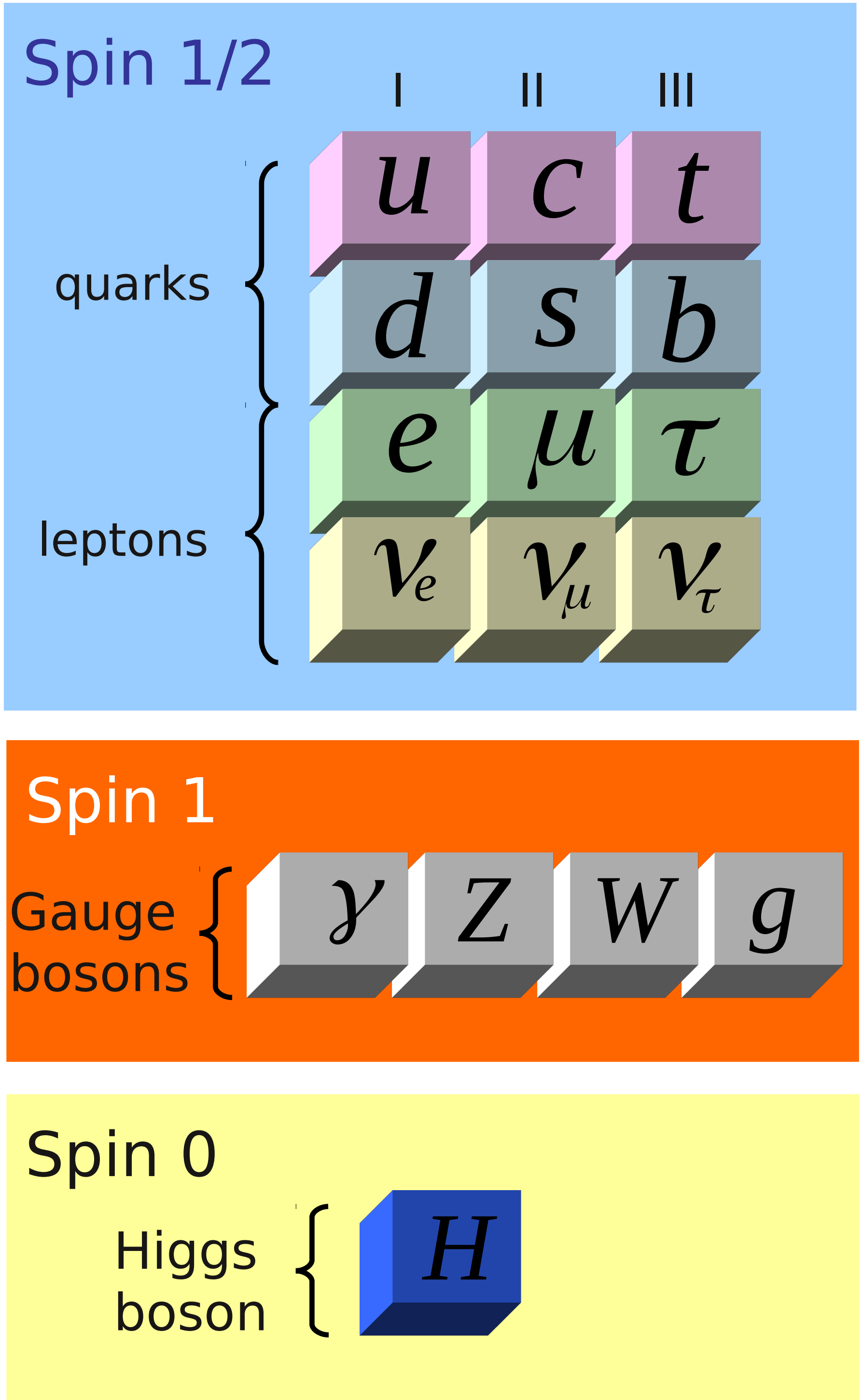
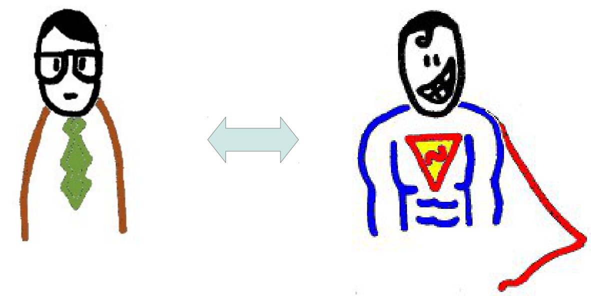
CNRS IN2P3 Les deux infinis

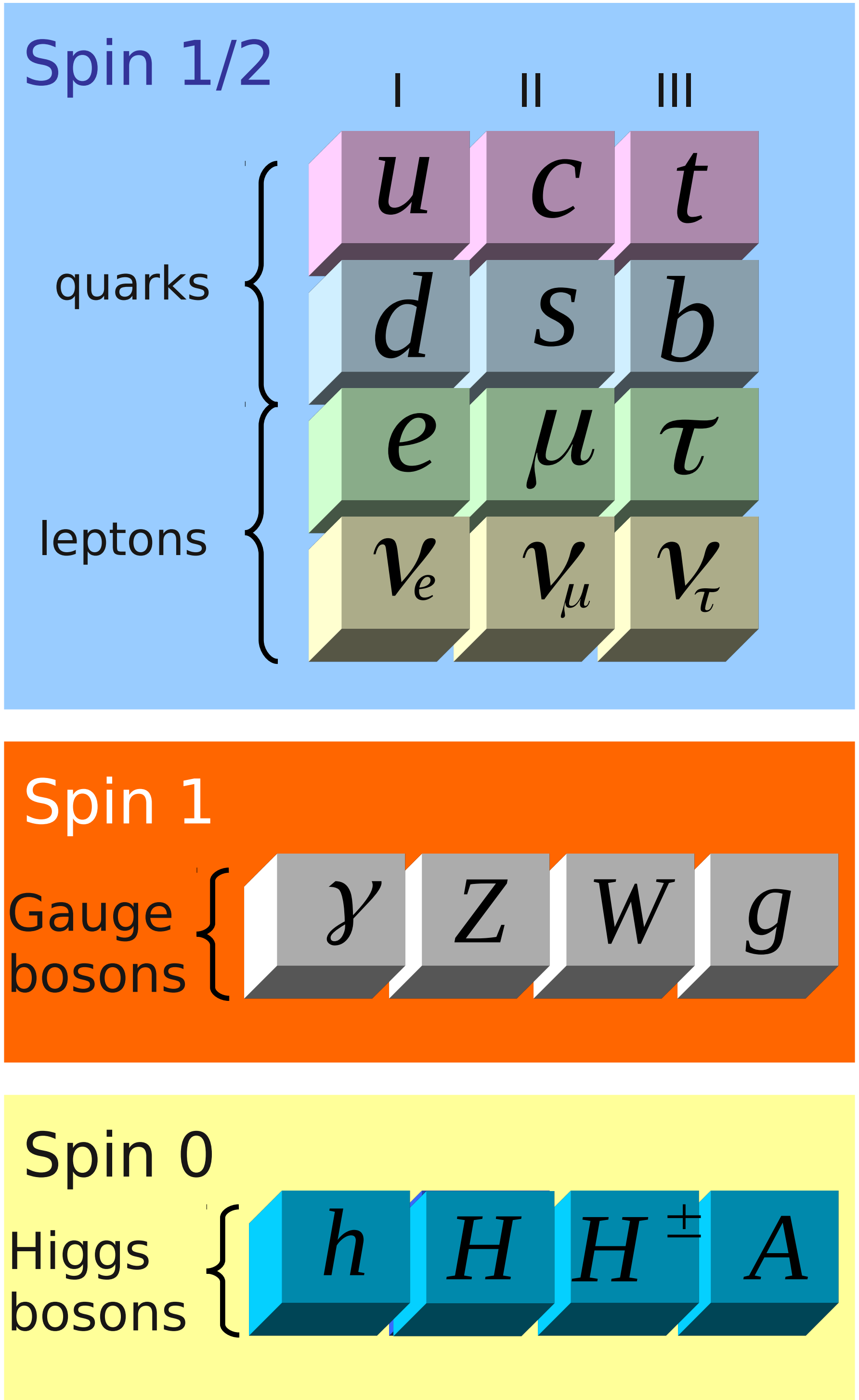
A brief reminder of SUSY



In supersymmetry, each Standard Model particle has a supersymmetric partner, called a sparticle



A brief reminder of SUSY



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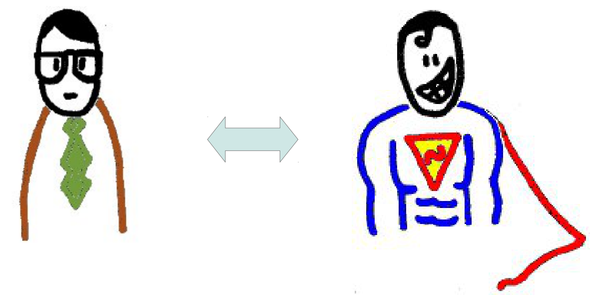
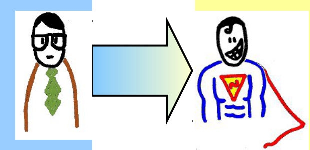


And the Higgs sector is larger

A brief reminder of SUSY

Spin 1/2

	I	II	III
quarks	u	c	t
	d	s	b
leptons	e	μ	τ
	ν_e	ν_μ	ν_τ



Spin 0

	I	II	III
squarks	$\tilde{u}$	$\tilde{c}$	$\tilde{t}$
	$\tilde{d}$	$\tilde{s}$	$\tilde{b}$
sleptons	$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$
	$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$

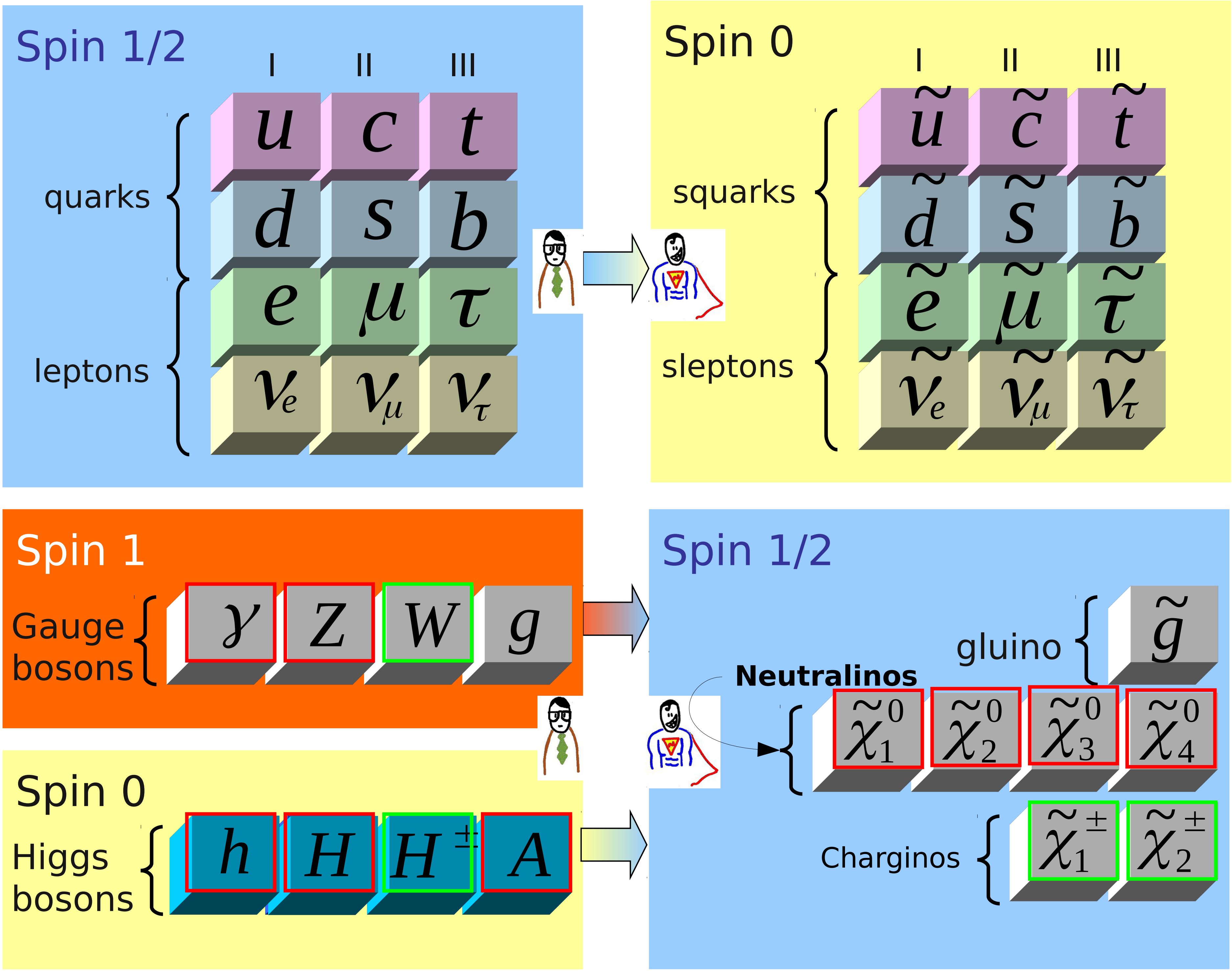
Spin 1

Gauge bosons: γ Z W g

Spin 0

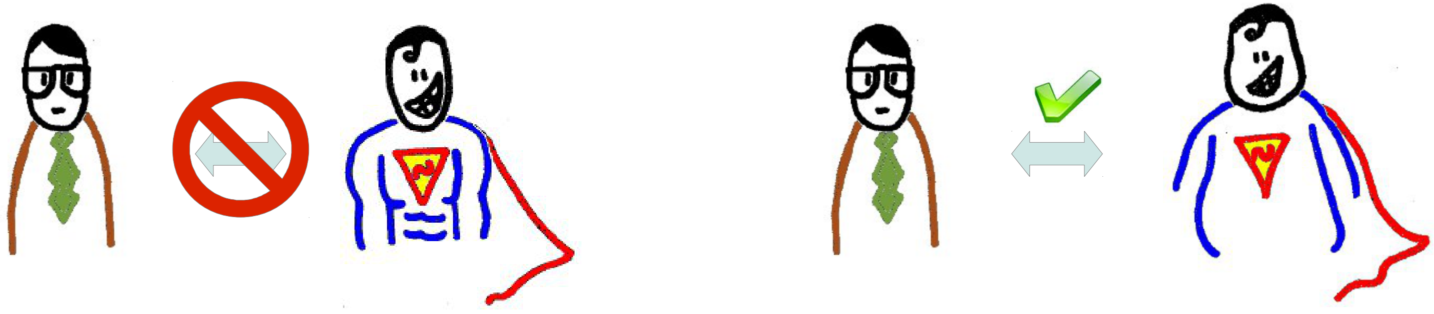
Higgs bosons: h H $H^\pm$ A

A brief reminder of SUSY



A brief reminder of SUSY

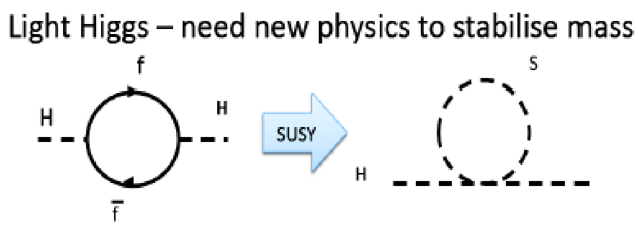
- SUSY is broken by an unknown mechanism



  - This introduces many free parameters in the theory
  - One usually presents the results for a given model / using some phenomenological assumptions in order to reduce the number of free parameters
  - Most limits shown today are given in terms of Simplified Models: consider a single decay chain assuming 100% branching ratio, vary the masses of the sparticles involved, decouple all other sparticles.

A brief reminder of SUSY

- Why introduce SUSY?
  - Stabilizes Higgs boson mass



  - Possibility of a dark matter candidate

$$R=(-1)^{(L+3B+2J)} \quad \text{where} \quad \begin{cases} L=\text{leptonic number} \\ B=\text{baryonic number} \\ J=\text{spin} \end{cases}$$

R = -1 for sparticles
R = +1 for SM particles

- Lightest sparticle (LSP) stable (WIMP candidate)
- Pair produced sparticles
- Cascade decay down to the LSP

  - Allows unification of gauge couplings

SUSY searches @ the LHC

ATLAS :

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

- **Full 2011 data (4.8 fb^{-1}, 7 TeV) :**
  - 24 papers
  - 7 conference notes
- **2012 Data Analyses (5.8 up to 20.5 fb^{-1} (full 2012 data), 8 TeV) :**
  - 22 conference notes

CMS :

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

- **Full 2011 data (4.7-4.9 /fb, 7 TeV) :**
  - 18 papers
  - 5 conference notes
- **2012 Data Analyses (4.0 up to 19.5 fb^{-1} (full 2012 data), 8 TeV) :**
  - 2 papers
  - 8 conference notes

SUSY searches @ the LHC

Broadly and deeply cover the SUSY signature space

General strategy to search for SUSY, based on phenomenology oriented searches :

1. Strong production in a R-parity conserving (RPC) scenario
2. Natural spectrum in a RPC scenario
3. Low effective couplings leading to long-lived SUSY particles
4. Prompt R-parity violating (RPV) scenarios
5. MSSM extensions
6. Higgs searches

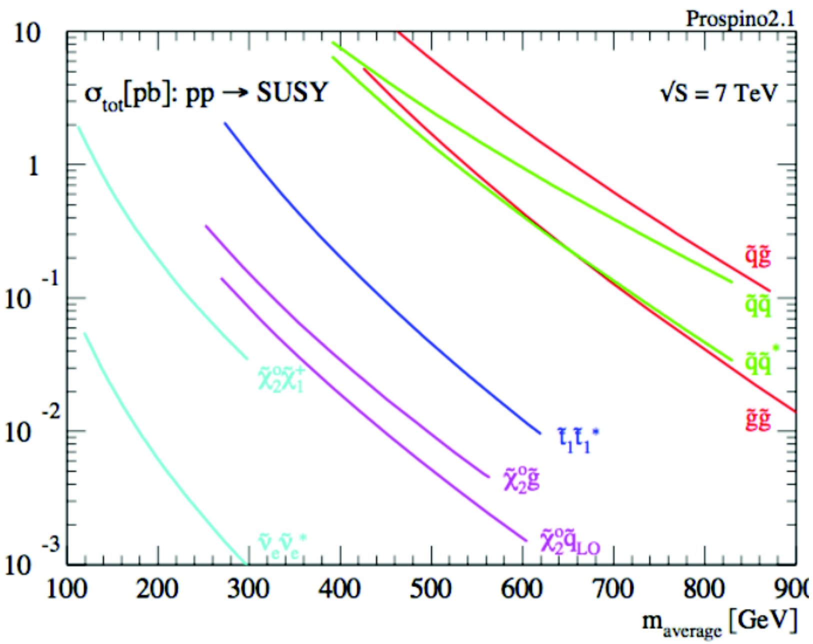
SUSY searches : strategy

Broadly and deeply cover the SUSY signature space

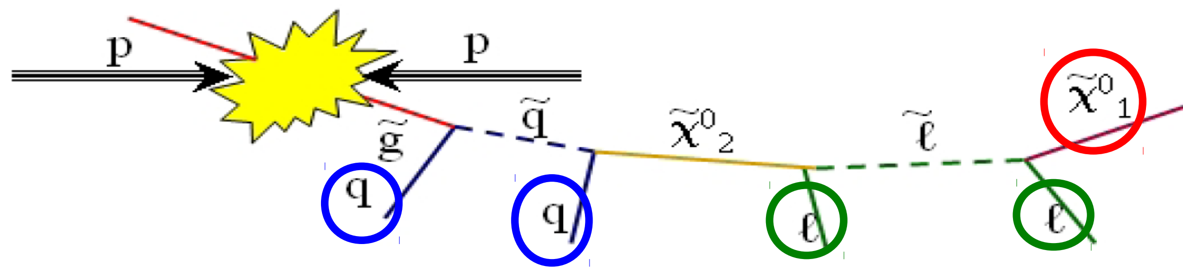
1. Strong production in a R-parity conserving (RPC) scenario

Strong production in RPC

Inclusive jets + E_T^{miss} + X (γ, ℓ, more jets... depending on NLSP)

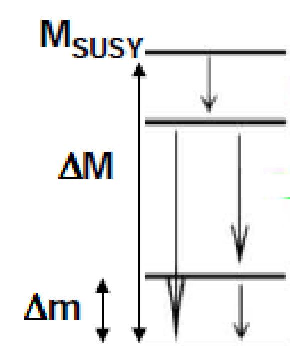


For a given mass, the production of strongly interacting sparticles would dominate



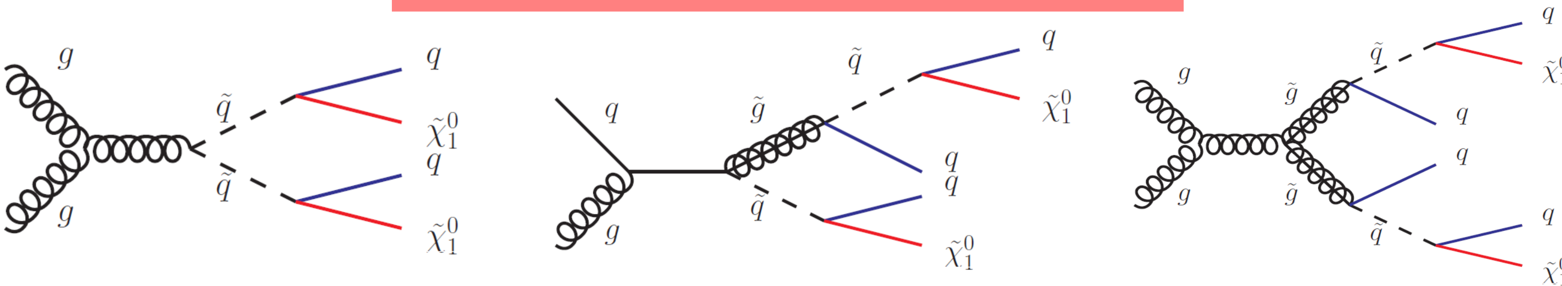
Search for large and small ΔM

$MET \sim \Delta M$
$H_T = \Sigma\, p_T(\text{jet})\ [+\ p_T(l,\gamma)]$
$M_{Eff} = MET + H_T = 2\, M_{SUSY}$



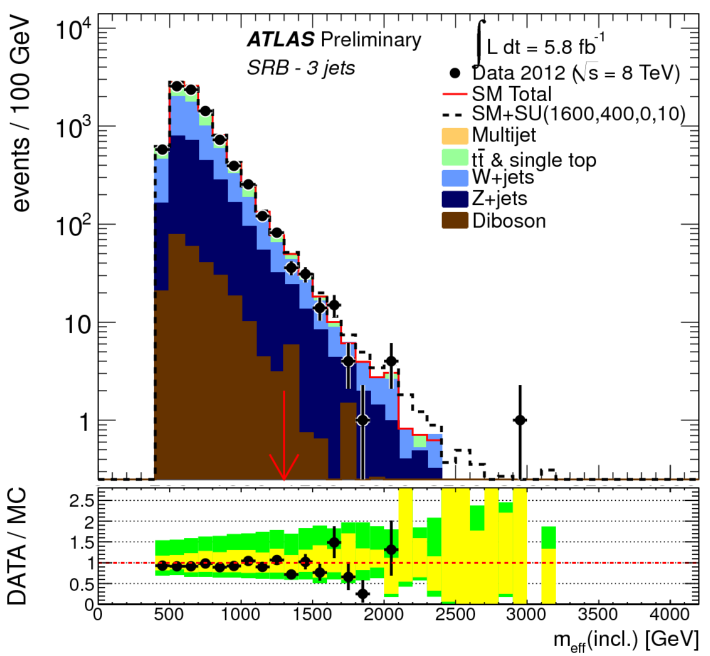
Inclusive gluino and squarks @ 8 TeV

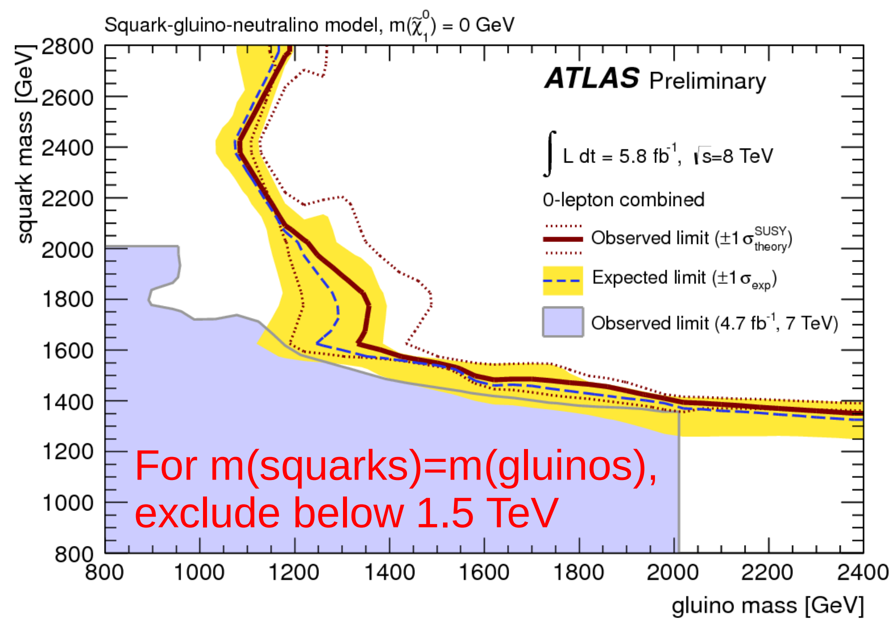
jets + E_T^{miss} signature (veto e, μ)

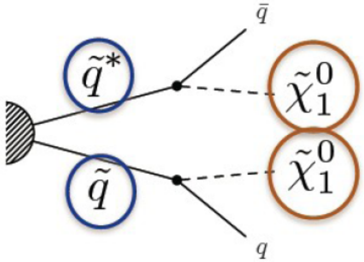


- 12 signal regions to probe different production mechanisms and SUSY mass scales
- Main background: leptonic W+jets/ttbar, Z(νν)+jets, Multijets

The 3-jet medium SR as example :

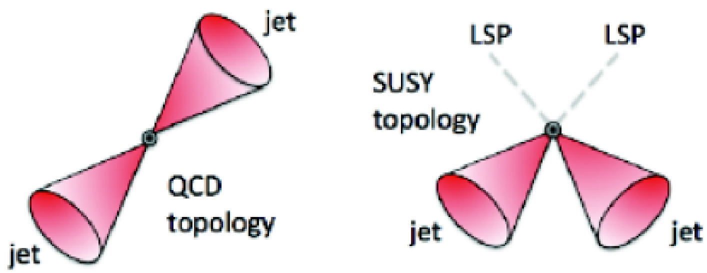


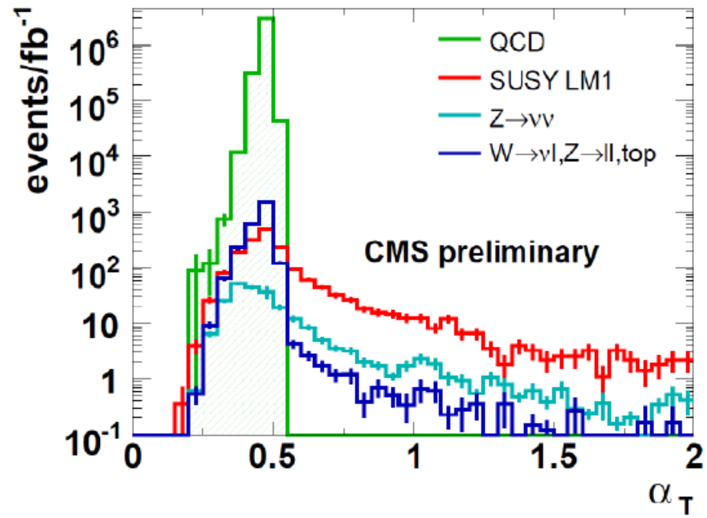


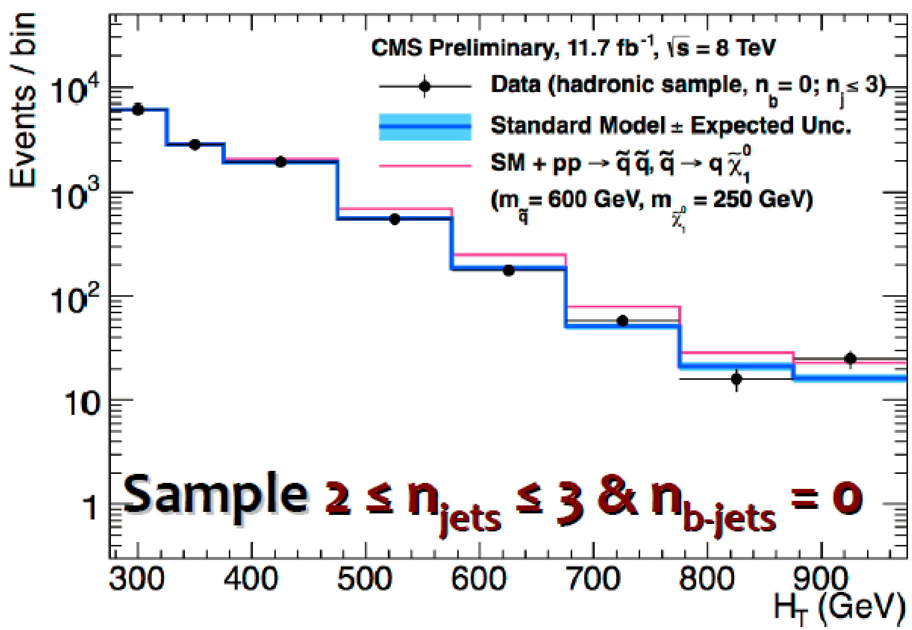


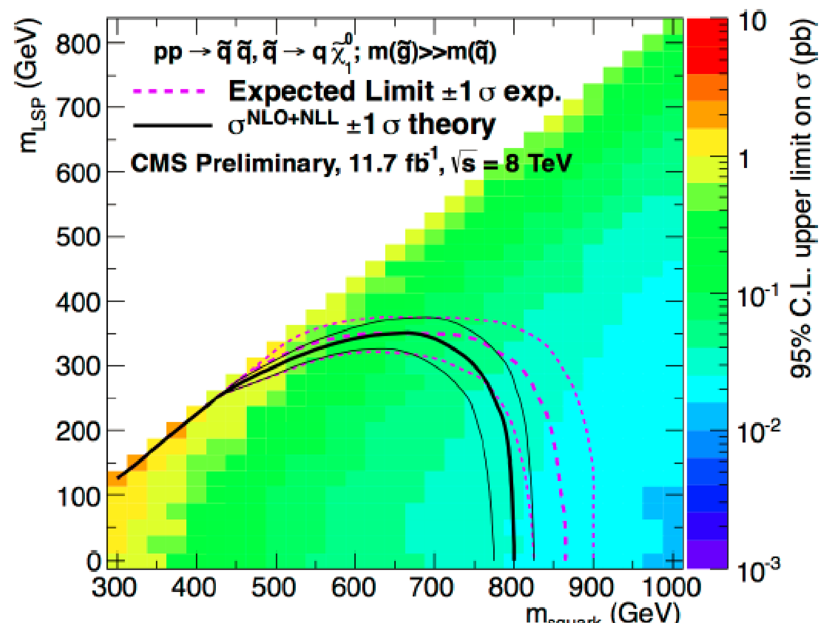
Using α_T

$$\alpha_T = \frac{E_T^{j2}}{\sqrt{2E_T^{j1}E_T^{j2}(1-\cos\Delta\phi)}} = \frac{\sqrt{E_T^{j2}/E_T^{j1}}}{\sqrt{2(1-\cos\Delta\phi)}}$$





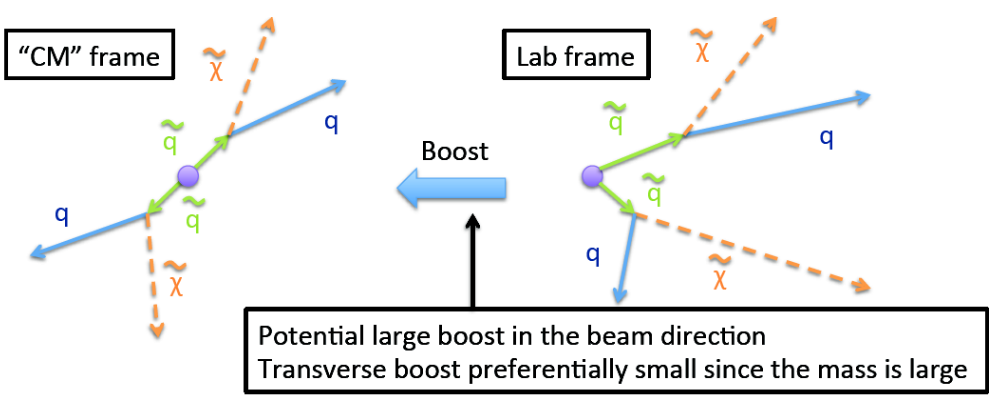




Probed squark up to ~ 800 GeV

Using the razor

- Used in the search for the pair production of two heavy particles, each decaying to an unseen particle plus a visible one
- Idea: move from the lab frame to the CM frame by looking for the boost that makes two jets to be of equal momentum and use this momentum to estimate the mass scale



$$M_R = \sqrt{(|\vec{p}_{j_1}| + |\vec{p}_{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

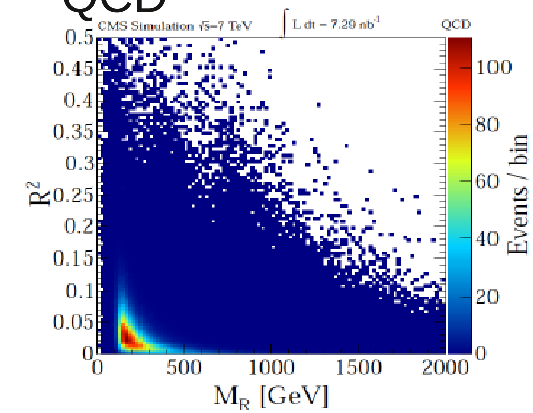
$$R = \frac{M_T^R}{M_R}$$

Peaks at

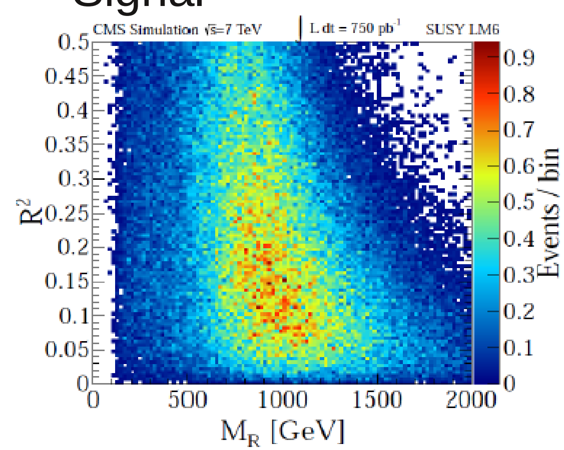
$$M_\Delta = \frac{M_S^2 - M_{LSP}^2}{M_S}$$

Edge at M_Δ

QCD



Signal



Using the razor

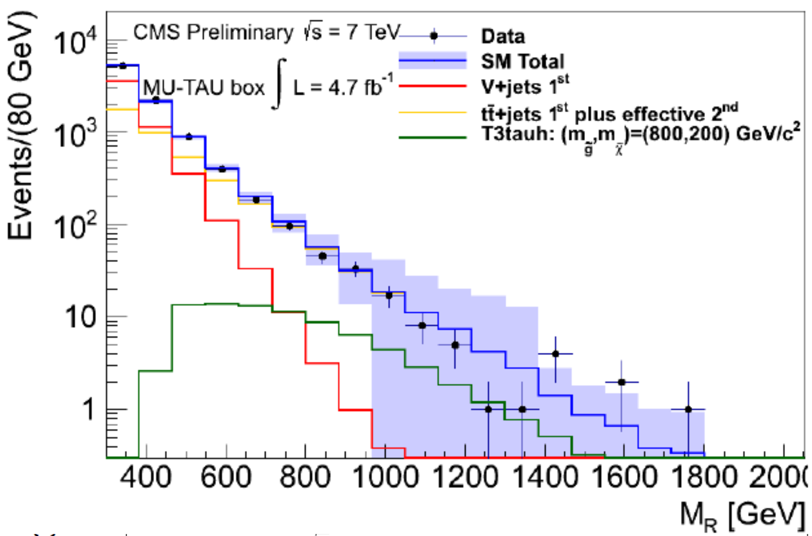
4 exclusive boxes:

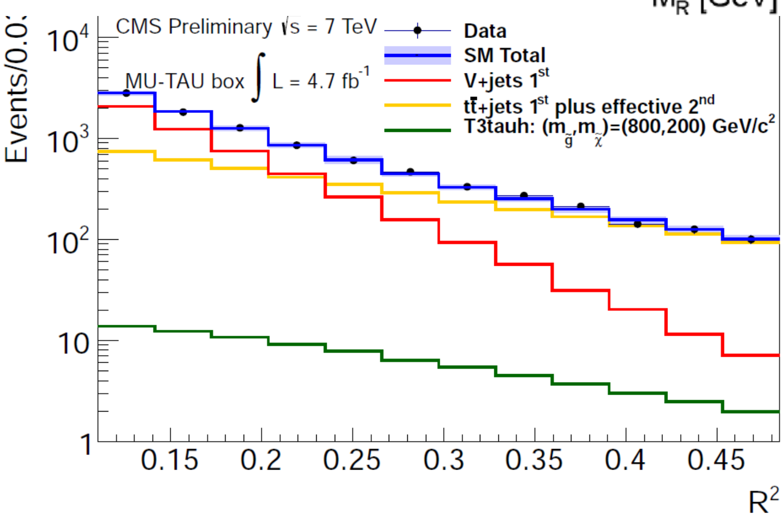
1^{st} : MU-TAU $\tau \geq 1$ & $\mu \geq 1$ & 0 e

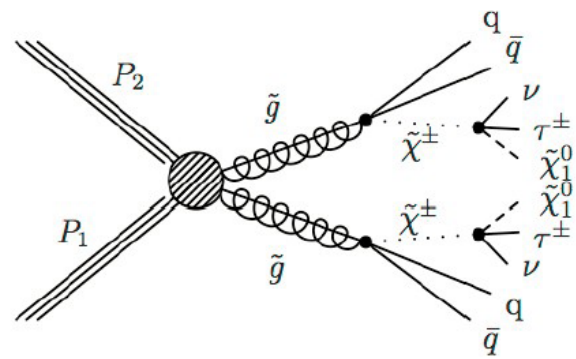
2^{nd}: MU all the other events w/ $\mu \geq 1$

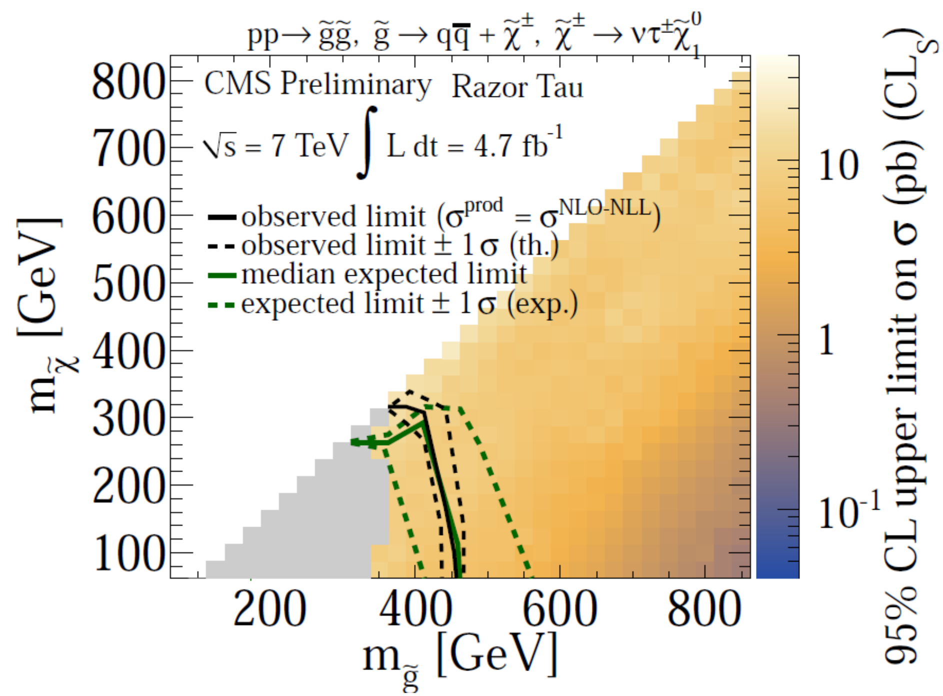
3^{rd} : ELE-TAU $\tau \geq 1$ & e ≥ 1 & 0 μ

4^{th} : ELE all the other events w/ e ≥ 1









Limit for tau-enriched SUSY events

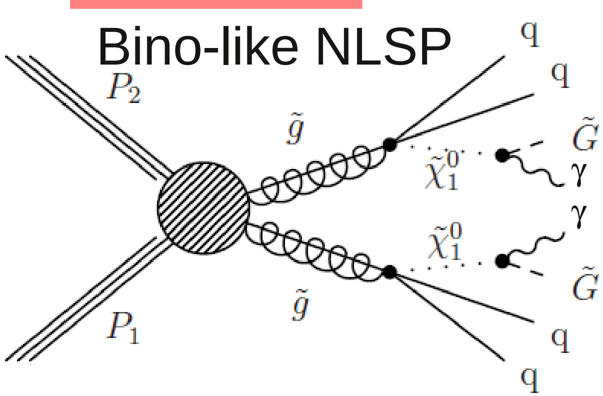
Gauge-mediated SUSY breaking (GGM)

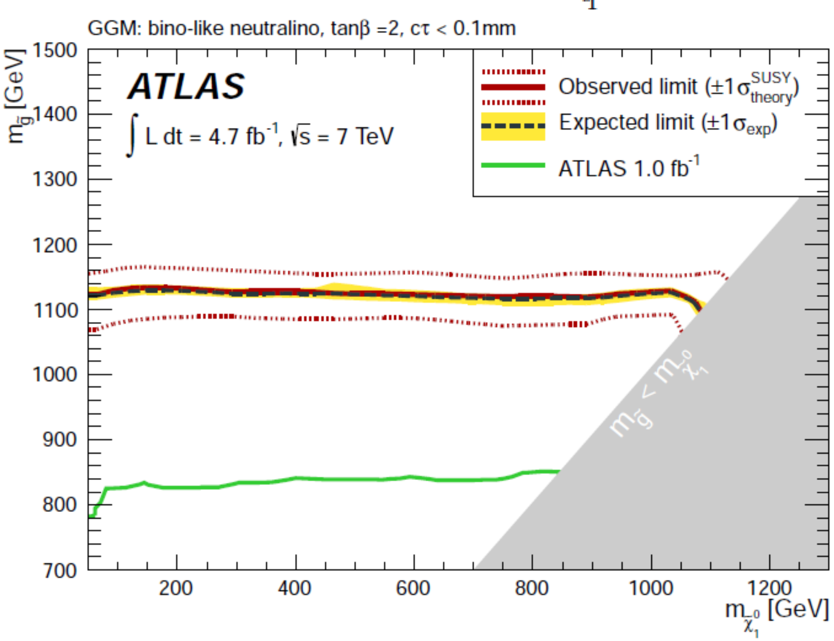
Neutralino NLSP (bino or admixture) : photon-based signature

PLB 718 (2012) 411

$2\gamma + E_T^{miss}$

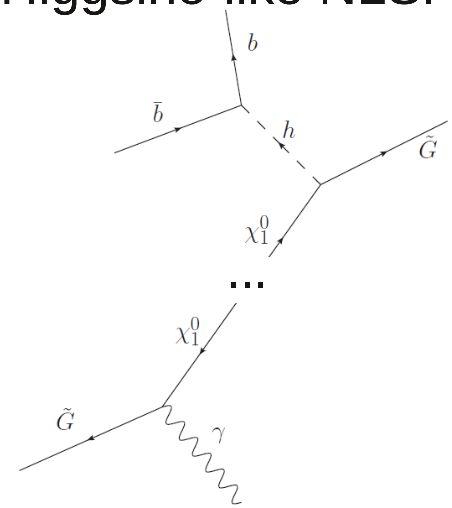
Bino-like NLSP



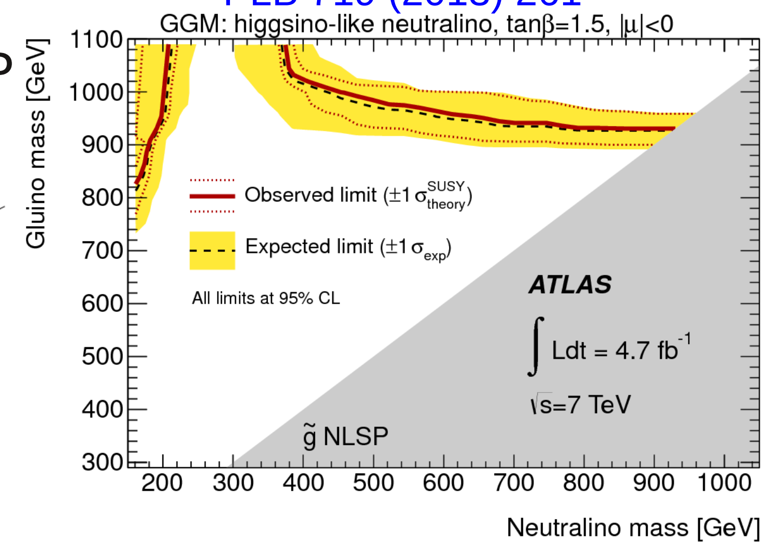


γ + b-jets + E_T^{miss}

Higgsino-like NLSP

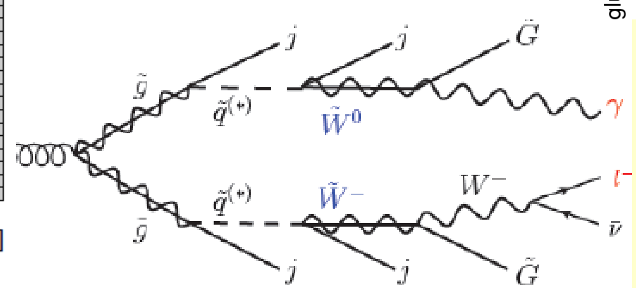


PLB 719 (2013) 261

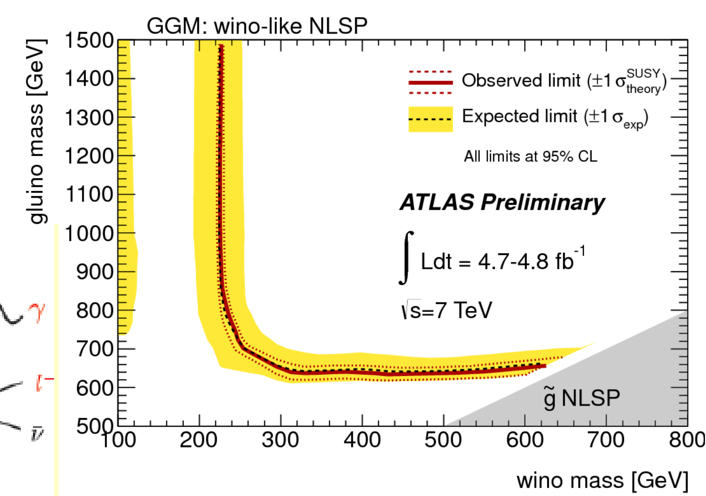


γ + lepton + E_T^{miss}

Wino-like NLSP



ATLAS-CONF-2012-144



SUSY searches : strategy

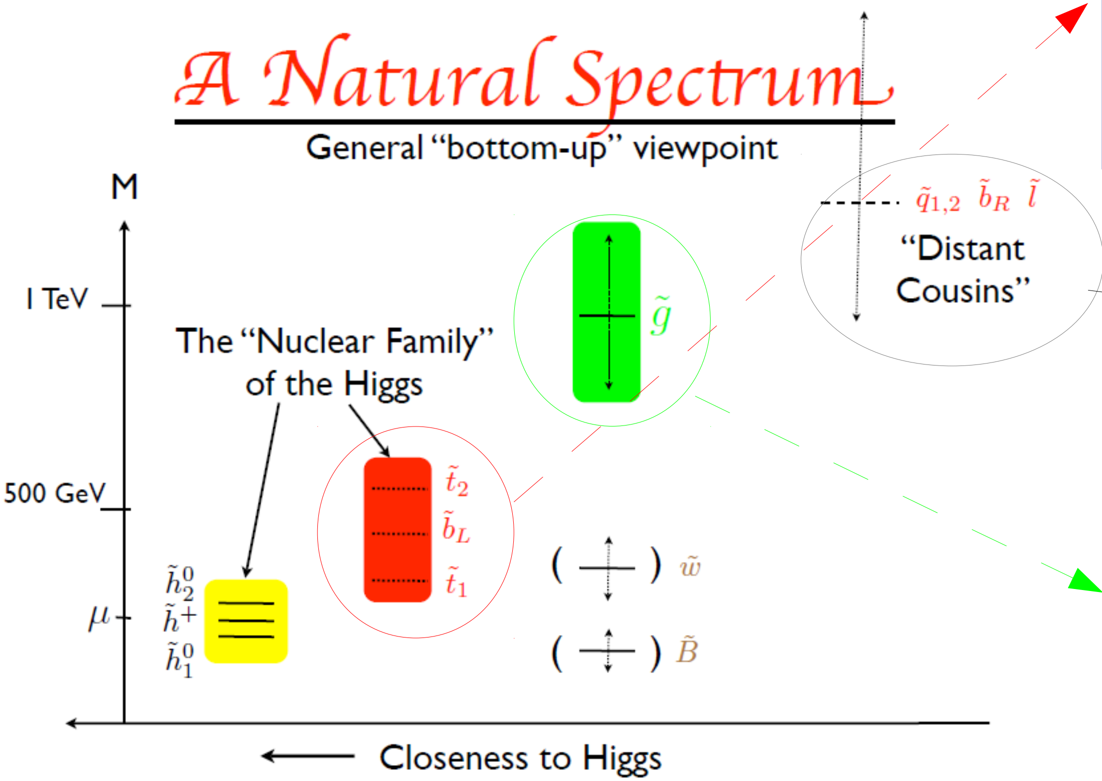
Broadly and deeply cover the SUSY signature space

1. Strong production in a R-parity conserving (RPC) scenario

Inclusive searches have set stringent limits on strongly produced sparticles (1st, 2nd generation squarks, gluinos) [less stringent in case of very compressed scenarios]

2. Natural spectrum in a RPC scenario

2- Natural SUSY



L. Hall, LBL workshop 10/2011

The Higgs boson mass is regularized by the scalar top mass and it is still possible to have a natural SUSY with a relatively light stop (and a consequently light sbottom)

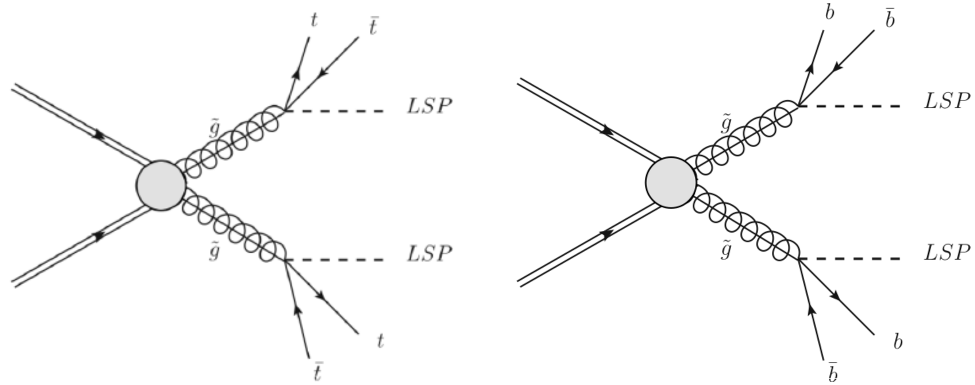
The naturalness of the theory can be achieved even if the first two generations squarks have masses around the TeV scale

The gluino should not be too heavy

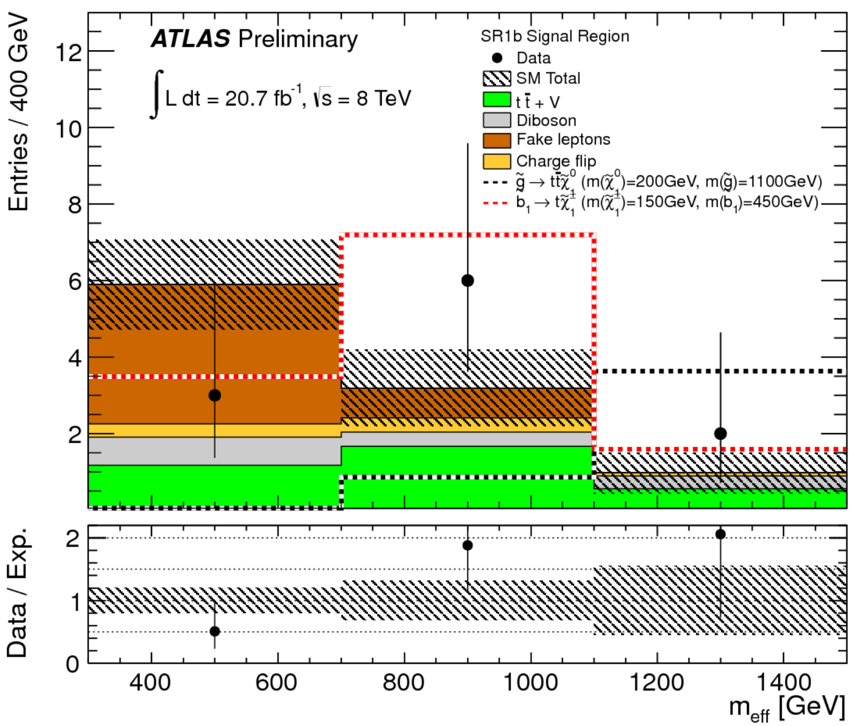
Dedicated search program for "3rd generation SUSY": direct production or gluino-mediated production of sbottom/stop pairs

Gluino-mediated 3rd generation

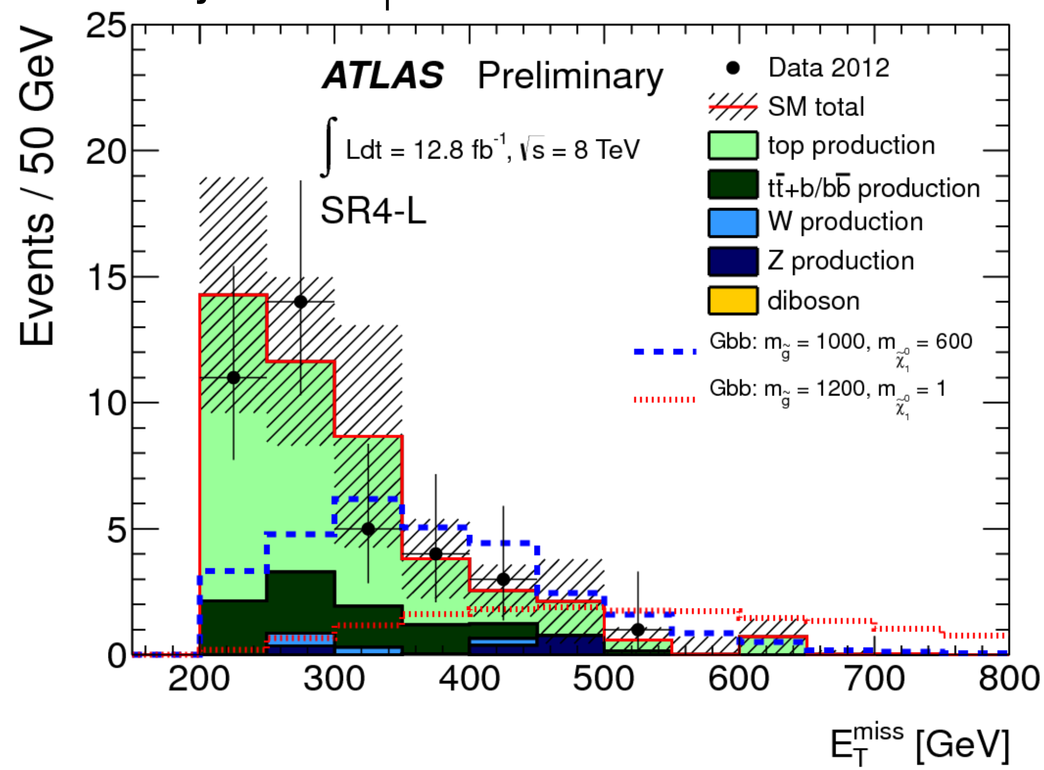
Full 8 TeV dataset



2 same-sign leptons + 0-3 b-jets + E_T^{miss}

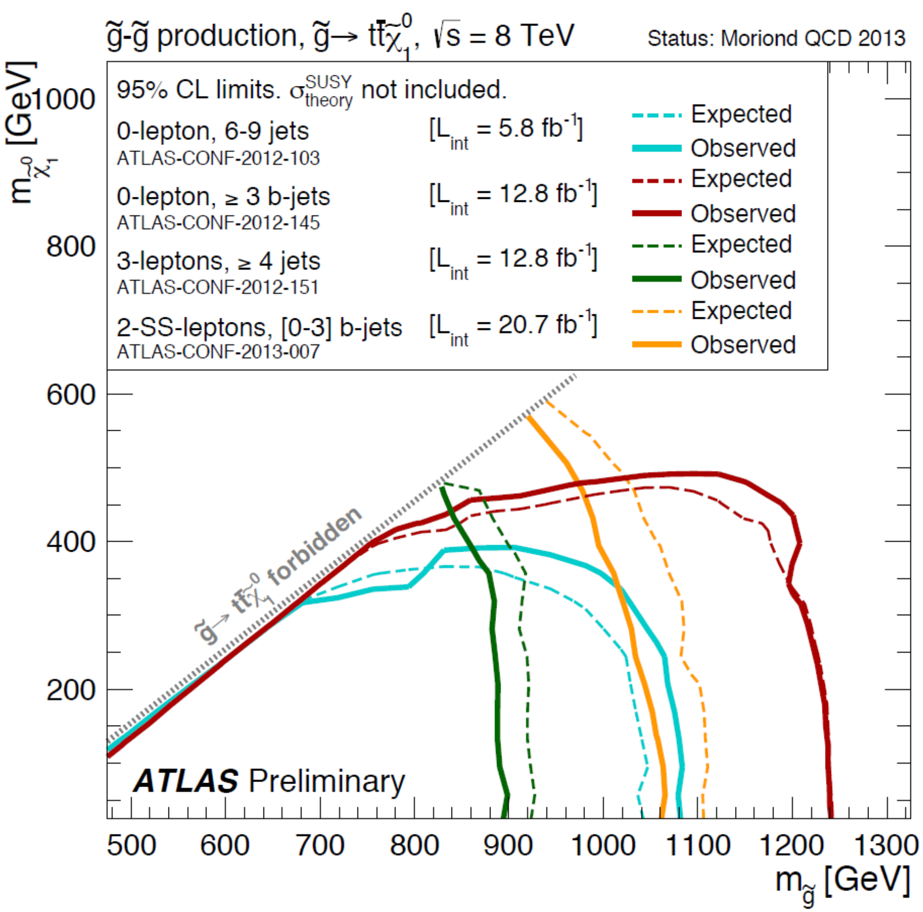


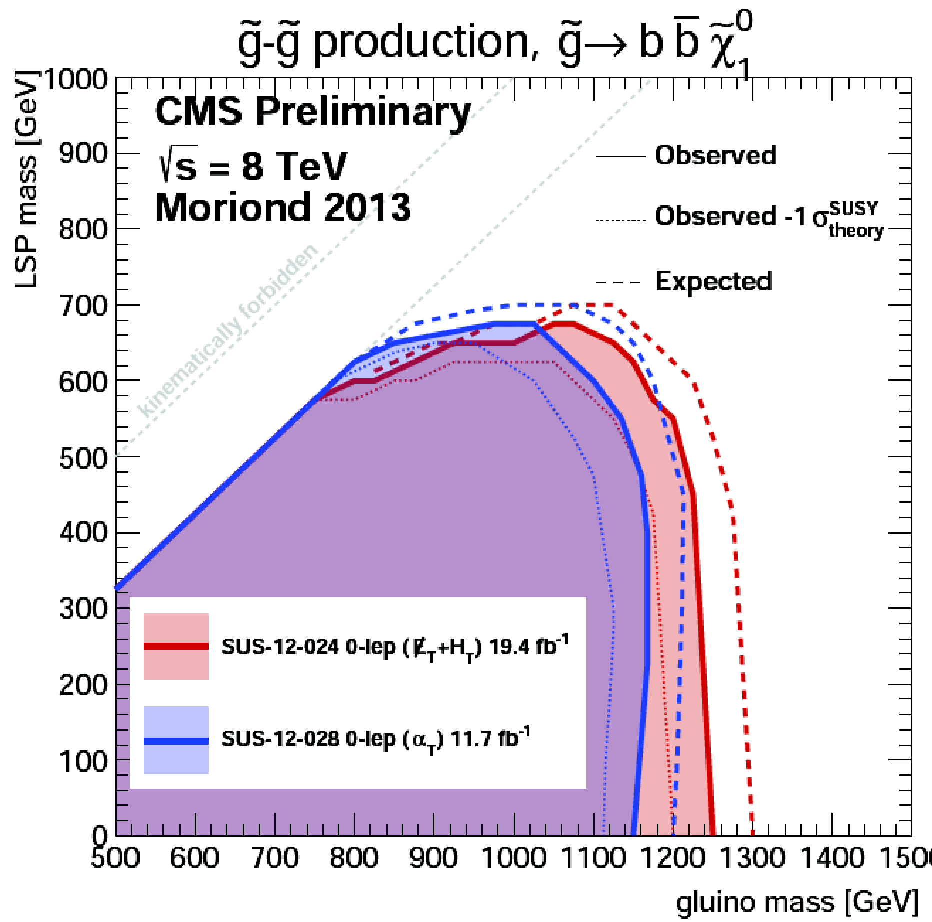
3 b-jets + E_T^{miss}



More details in J. Maurer's talk

Gluino-mediated 3rd generation





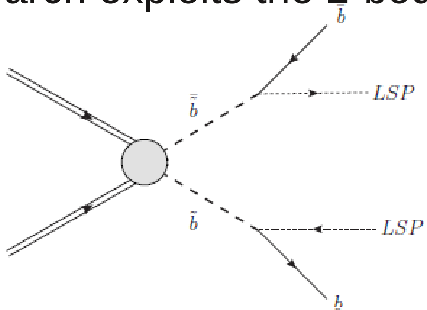
ATLAS-CONF-2012-165

ATLAS-CONF-2013-007

Direct sbottom @ 8 TeV

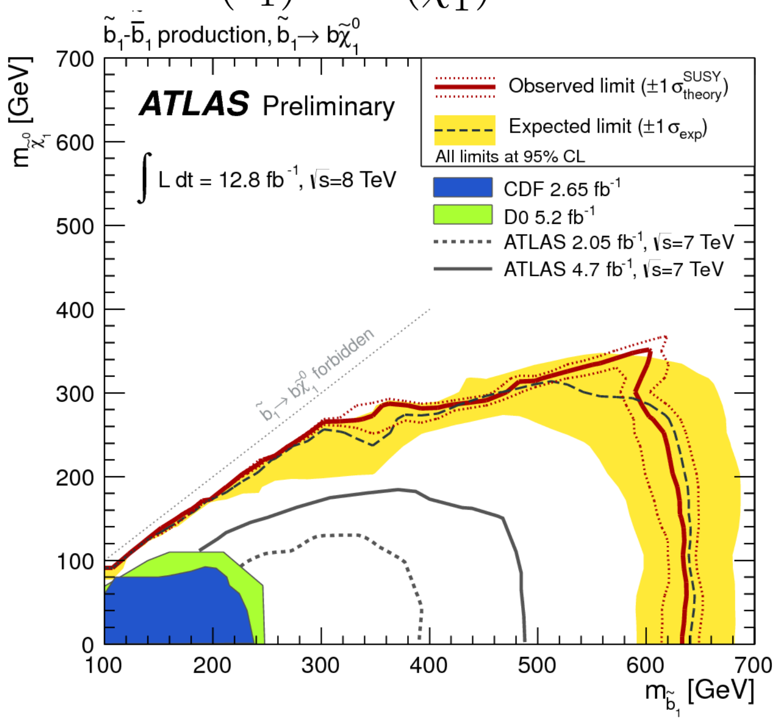
2 b-jets + E_T^{miss}

The search exploits the 2-body kinematics

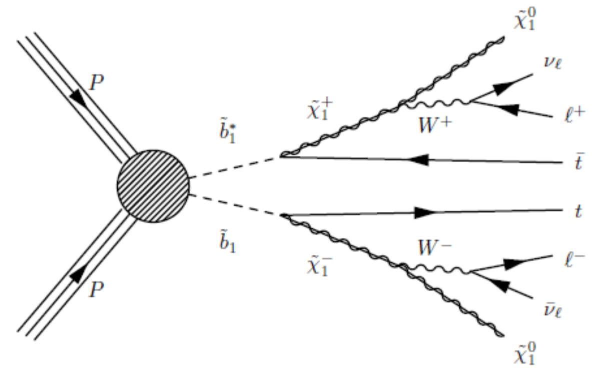


Different signal regions for different Δm

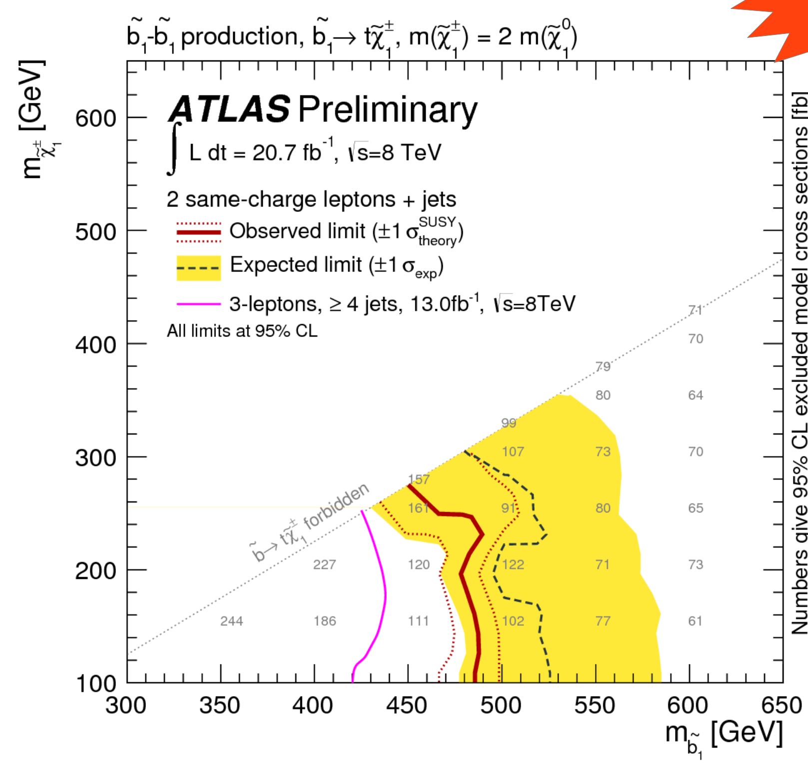
$$\Delta m = m(\tilde{b}_1) - m(\tilde{\chi}_1^0)$$



2 same-sign leptons + b-jets + E_T^{miss}



Full 8 TeV dataset



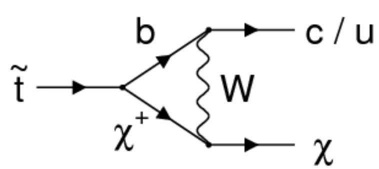
Direct stop searches

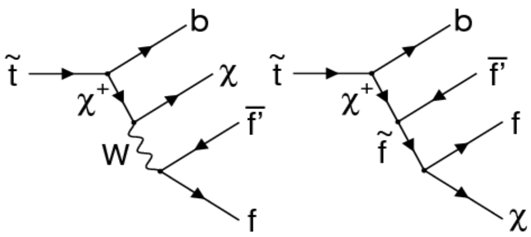
Several decay modes are possible, depending on the couplings and the SUSY particle mass hierachy

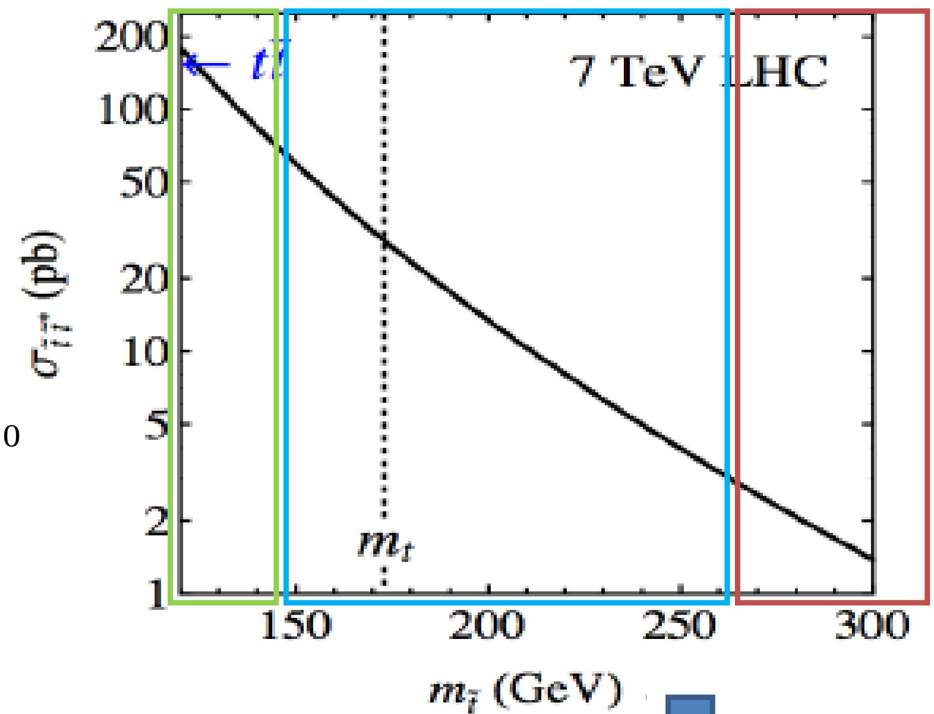
High cross sections, very similar to SM background

$$\tilde{t}_1 \to b\,\tilde{\chi}_1^{\pm} \to bW^{\pm}\tilde{\chi}_0$$

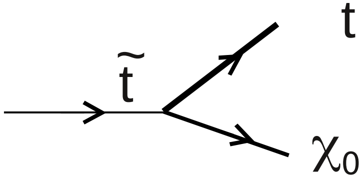
$$\tilde{t}_1 \to c\,\tilde{\chi}_0$$







Low cross section (2 pb or less), high mass: Mostly stop → top +LSP



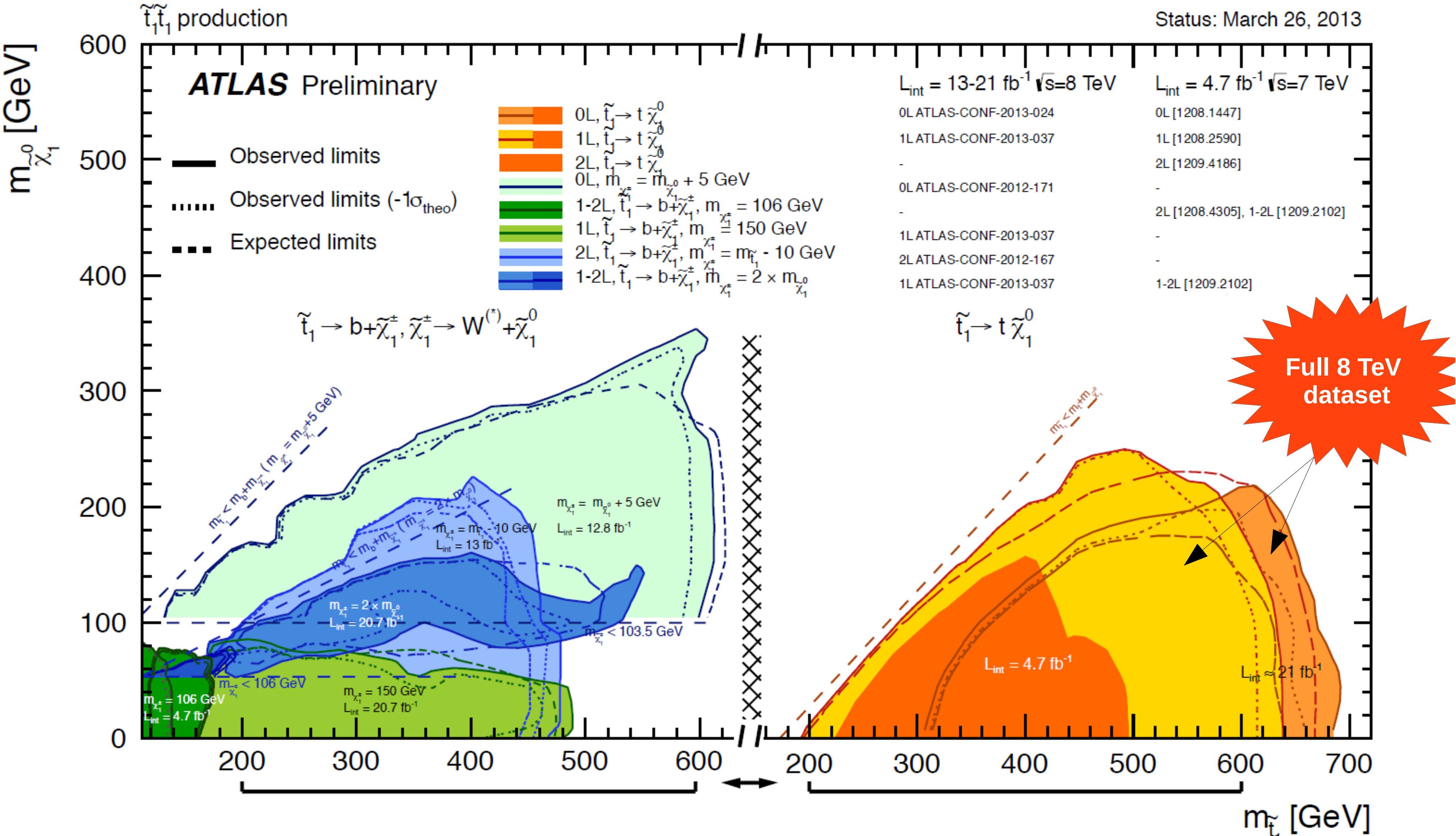
$b + \tilde{\chi}^{\pm}$ and, where kinematically allowed, $t + \tilde{\chi}^0$

Need powerful discriminating variables to reject top BG

Mass ranges , ΔM (stop – neutralino), ΔM (stop-chargino), ΔM(chargino-neutralino) all play a crucial role in the search optimization

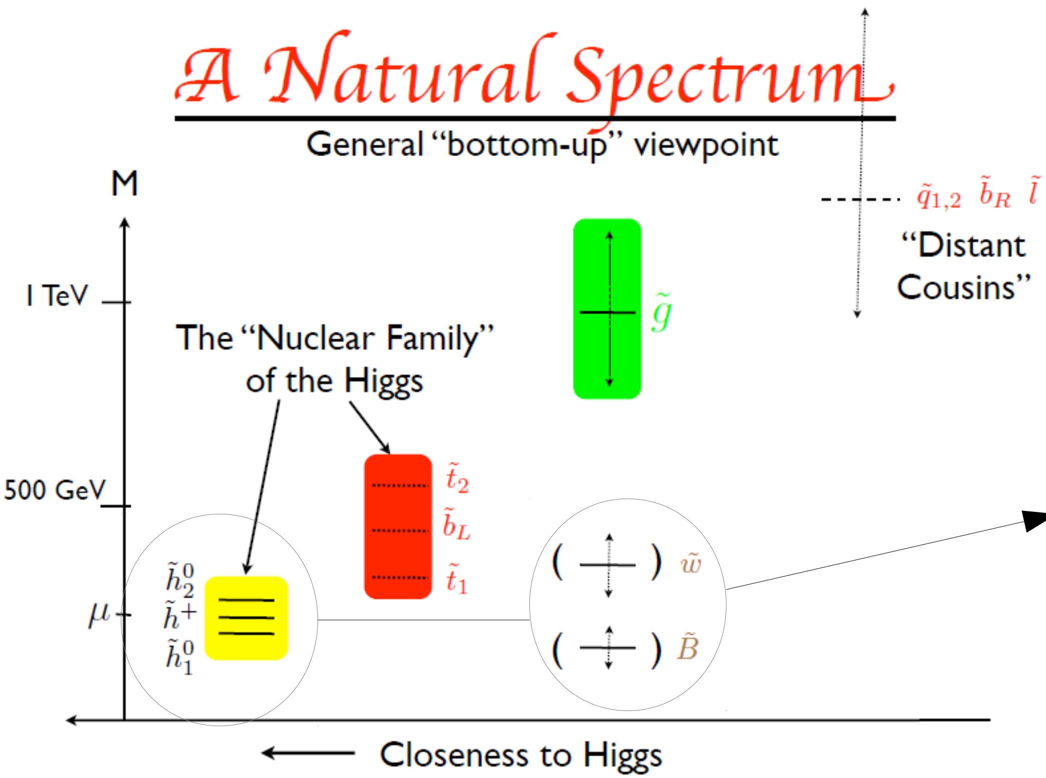
Direct stop searches

[1] arxiv:1208.1447 (0-lepton 7 TeV)
[2] arxiv:1208.2590 (1-lepton 7 TeV)
[3] arxiv:1209.4186 (2-lepton 7 TeV)
[4] ATLAS-CONF-2013-037 (1-lepton 8 TeV, 21 fb−1)
[5] ATLAS-CONF-2013-024 (0-lepton 8 TeV, 21 fb−1)
[6] arxiv:1208.4305 (very light stop: 2-lepton 7 TeV)
[7] arxiv:1209.2102 (light stop: 1/2-lepton, bjets 7 TeV)
[8] ATLAS-CONF-2012-167 (2-lepton 8 TeV, 13 fb−1)
[9] ATLAS-CONF-2013-001 (0-lepton, bb+MET 8 TeV, 13 fb−1)



Searches for stop in CMS : see J. Chasserat's talk

2- Natural SUSY



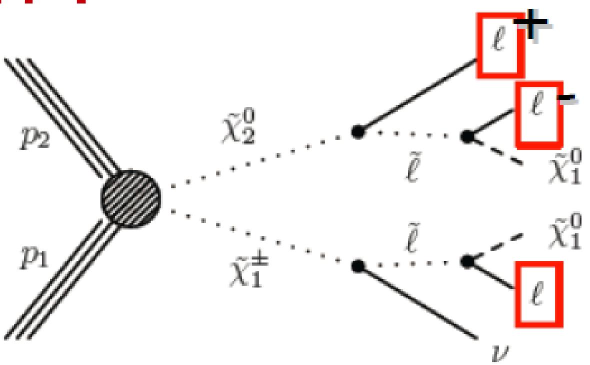
L. Hall, LBL workshop 10/2011

The electroweak sector should also be light

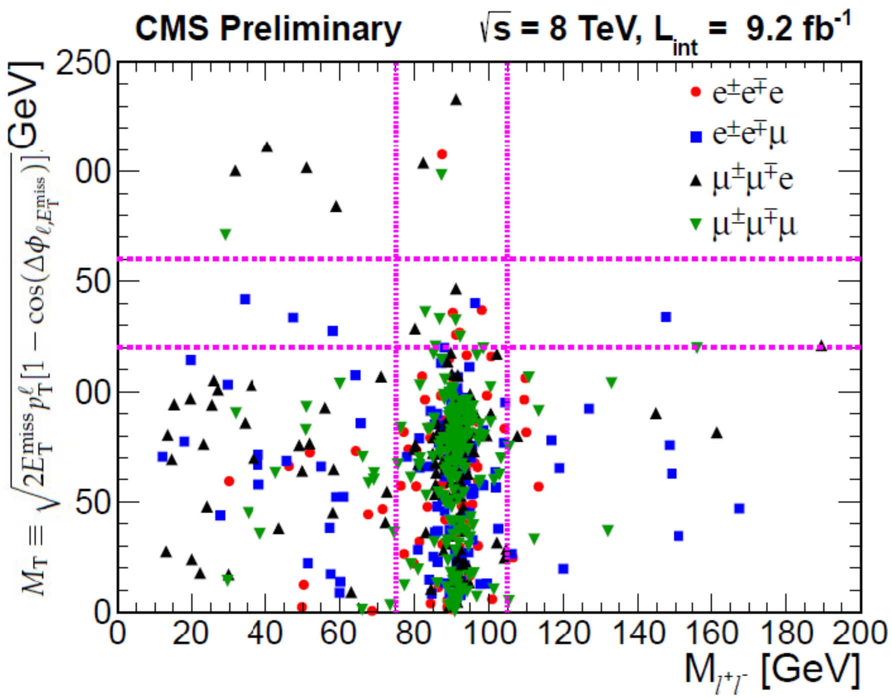
Dedicated search program for "Electroweak SUSY": direct production neutralinos, charginos, sleptons

Electroweak production : chargino/neutralino

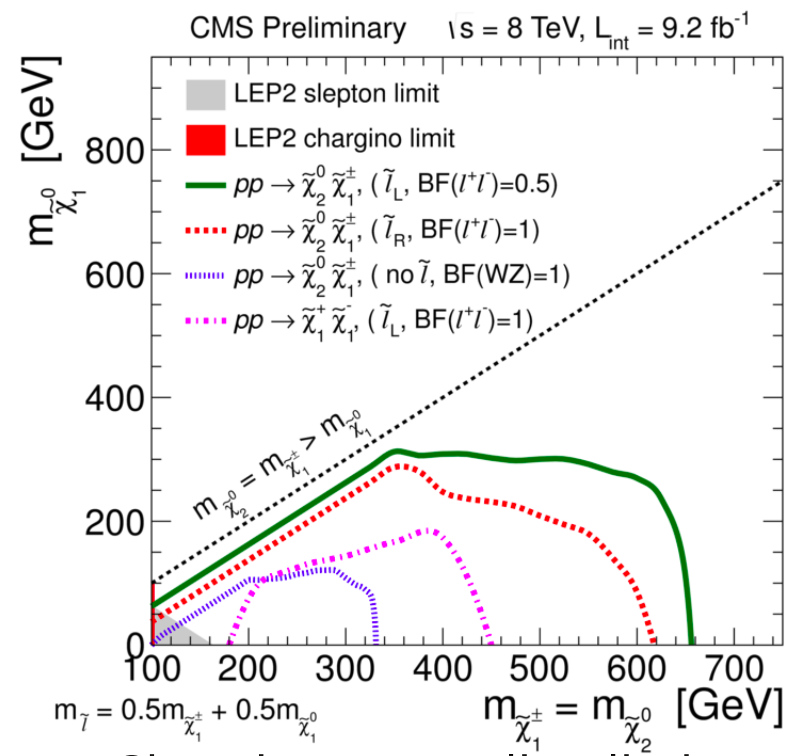
3 leptons + E_T^{miss}



Three-lepton events with an ee or μμ OSSF dilepton pair, where the third lepton is either an electron or a muon



M_T (GeV)	E_T^{miss} (GeV)	$M_{\ell\ell} < 75$ GeV		75 GeV $< M_{\ell\ell} <$ 105 GeV	
		total bkg	observed	total bkg	observed
> 160	50 – 100	2.1±0.5	4	3.3±0.5	3
	100 – 150	1.7±0.4	0	1.8±0.2	1
	150 – 200	0.8±0.3	1	0.63±0.16	1
	> 200	0.25±0.20	0	0.58±0.19	1



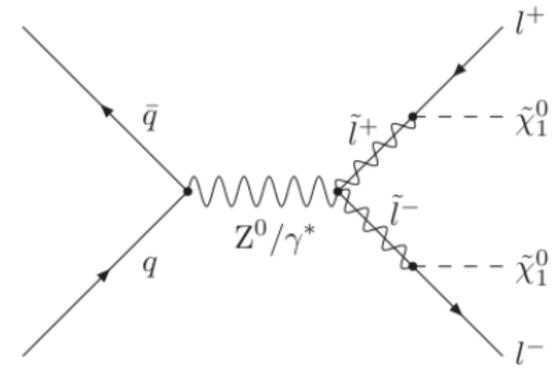
Chargino-neutralino limits extended up to ~ 650 GeV

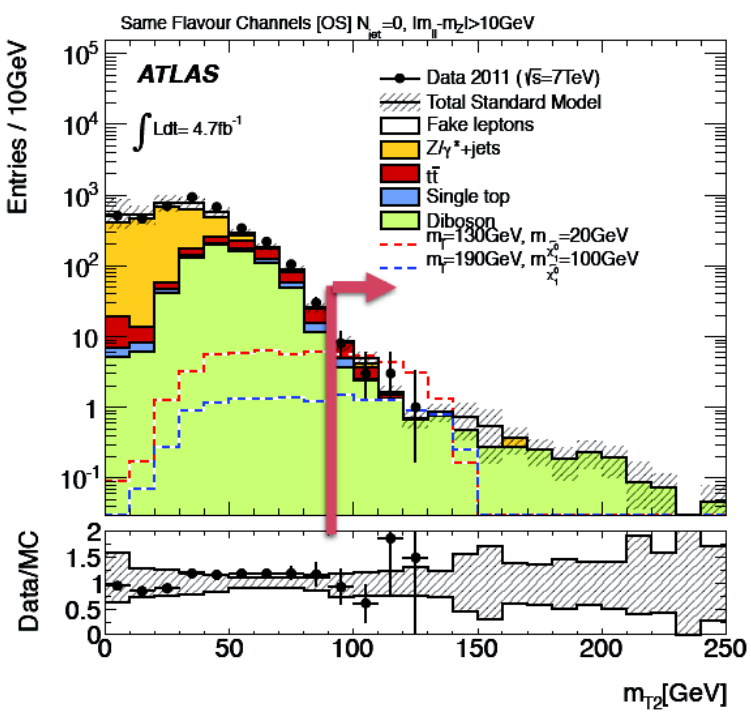
Electroweak production : sleptons

2 leptons + E_T^{miss}

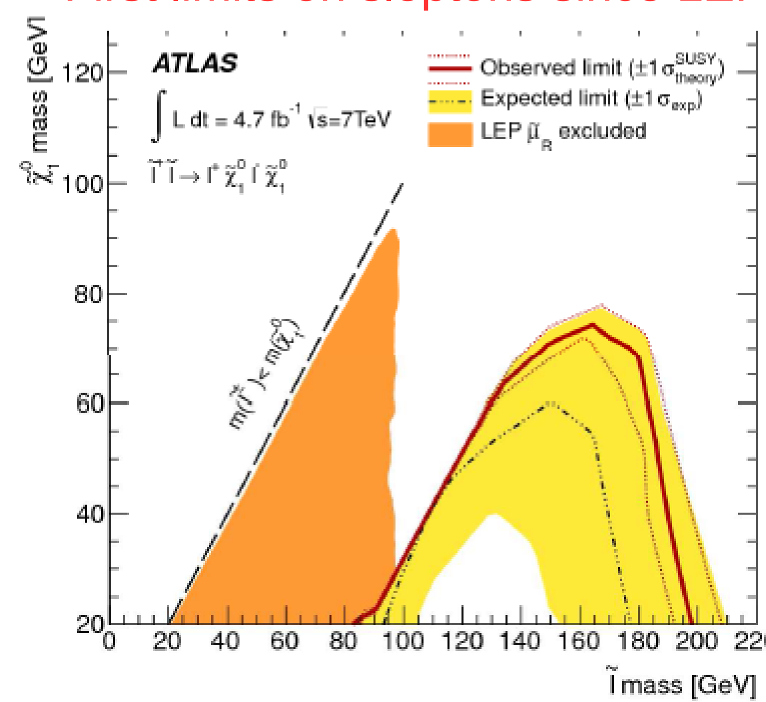
- Reduce the WW background by using its endpoint in stranverse mass, m_{T2} (at ~90 GeV)

$$m_{\mathrm{T2}} = \min_{\vec{q}_T^{\,(1)} + \vec{q}_T^{\,(2)} = \not{E}_T} \left(\max\left(m_{\mathrm{T}}(\vec{p}_T^{\,(1)}, \vec{q}_T^{\,(1)}), m_{\mathrm{T}}(\vec{p}_T^{\,(2)}, \vec{q}_T^{\,(2)}) \right) \right)$$





First limits on sleptons since LEP



SUSY searches : strategy

Broadly and deeply cover the SUSY signature space

1. Strong production in a R-parity conserving (RPC) scenario

2. Natural spectrum in a RPC scenario

Comprehensive program for the third generation sector in place with limits starting to bite into naturalness – need to continue to cover the full phase space. EW searches also underway with first limits on direct slepton since LEP.

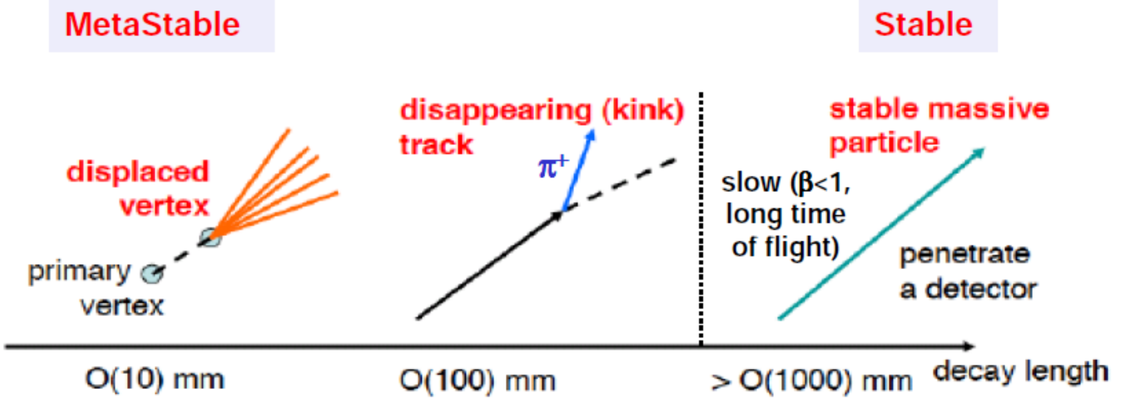
3. Low effective couplings leading to long-lived SUSY particles

R-parity violation and long-lived sparticles

- R-parity violation (RPV): $W = W_{MSSM} + \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\text{Lepton Number Violation (LFV)}} + \kappa_i L_i H_u + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{Baryon Number Violation (BNV)}}$
- RPV can lead to a displaced vertex if λ, λ', λ'' is very small
- A long-lived (LL) particle can also occur in RPC :
  - $\Delta M(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ ~100 MeV (eg. in AMSB) : disappearing track
  - *LL gluino due to the very heavy squarks mediating its decay : R-hadron*

    (See the exotics review by Samuel Calvet for an example)
  - *Weak coupling NLSP-gravitino in GMSB : LL slepton*

Challenging analyses requiring dedicated developments (re-tracking, trigger, ...)



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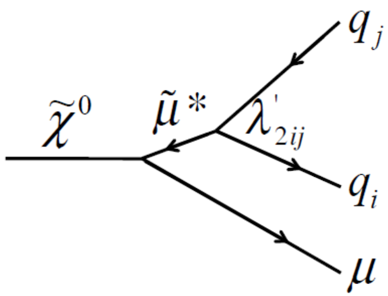
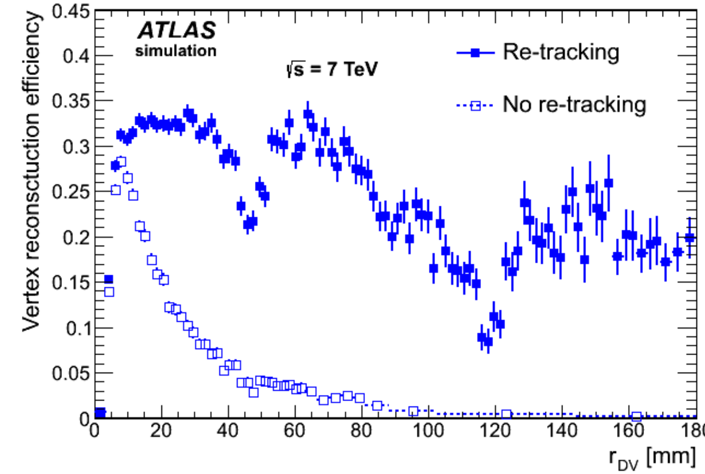
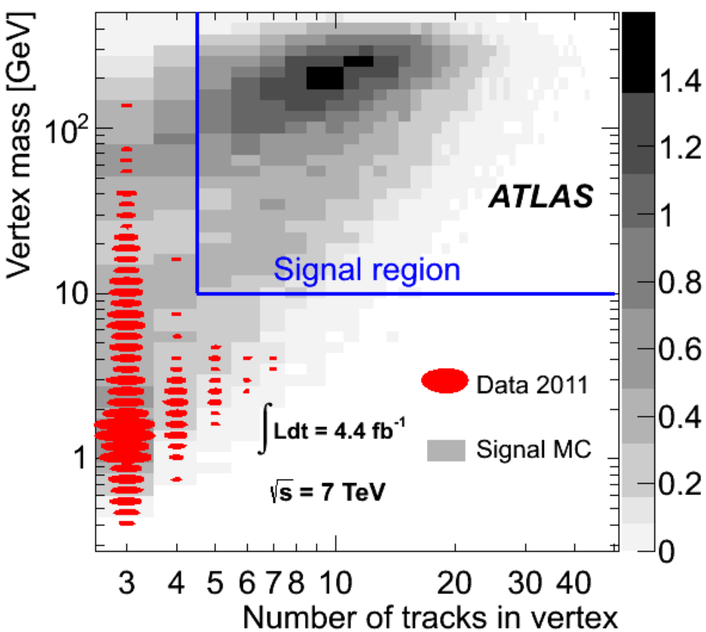
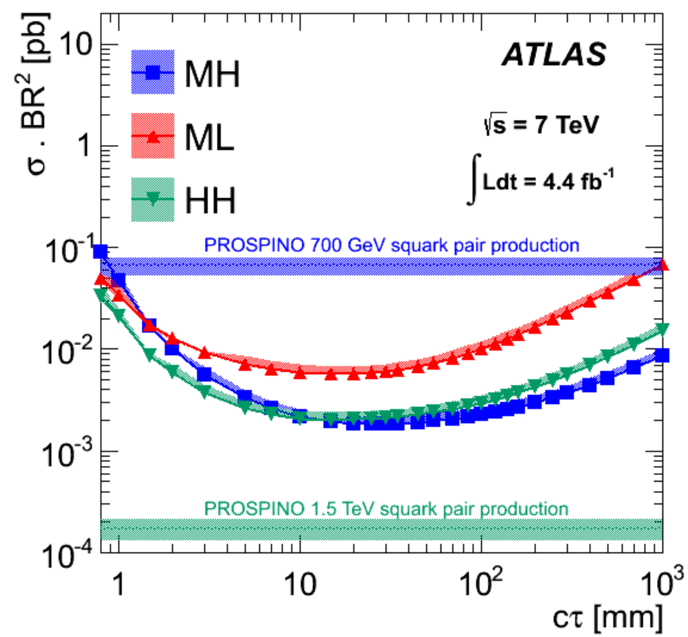


Displaced vertex

- RPV with $\lambda'_{2ij} \neq 0$: sparticle decay gives a multi-track vertex with a high-p_T muon, a few mm to ~10 cm from the IP
- Dedicated tracking to increase signal efficiency
- Remove vertices reco'ed in regions of high-density material
- Background-free analysis in M_{vertex} / N_{track} plane







Sample	$m_{\tilde{q}}$ [GeV]	$m_{\tilde{\chi}_1^0}$ [GeV]
MH	700	494
ML	700	108
HH	1500	494

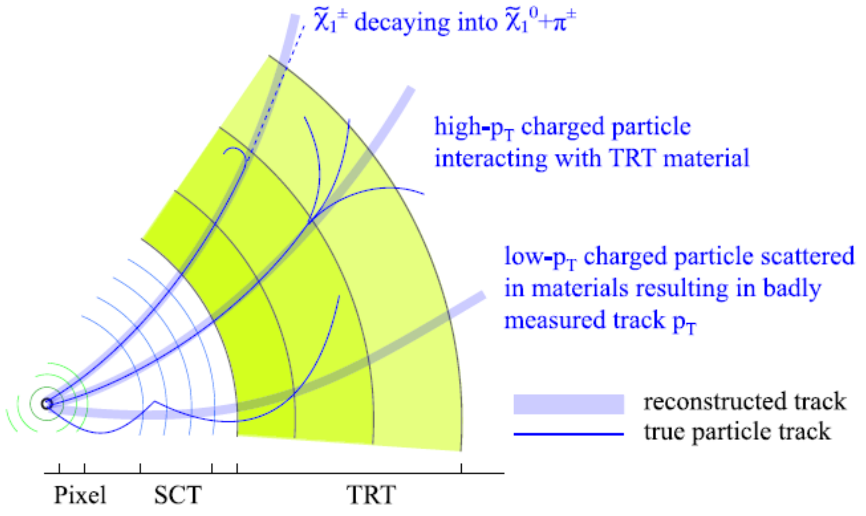
A displaced vertex analysis is also available in CMS, see : JHEP02(2013)085

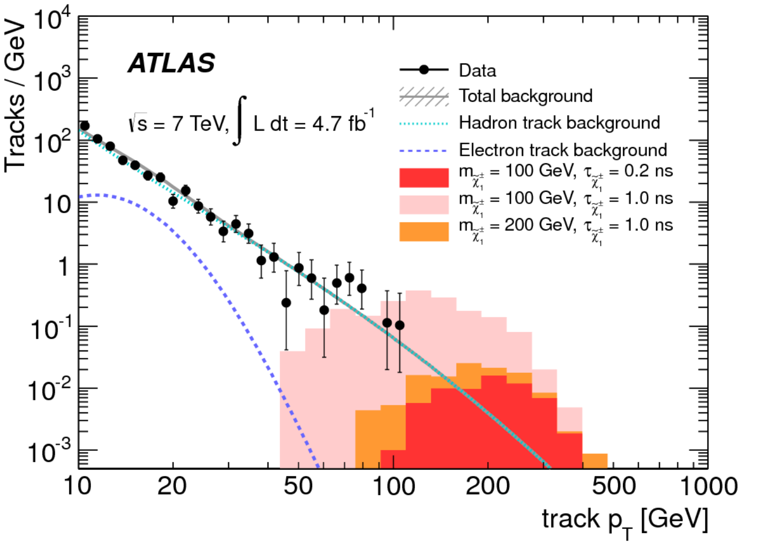
LL chargino : disappearing track

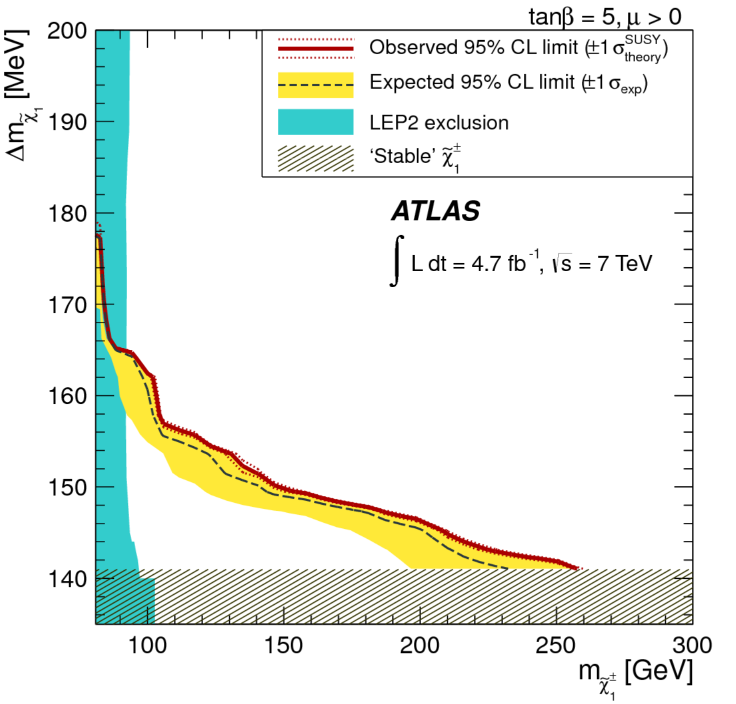
- In jet (from ISR) + E_T^{miss} events, search for high-p_T isolated tracks that stop in outer TRT

$$pp \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{0} j, \quad pp \rightarrow \tilde{\chi}_1^{+}\tilde{\chi}_1^{-} j$$

$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^{0}\pi^{\pm}$ branching ratio set to 100%







For Δm = 160 (170) MeV, the chargino mass limit is set at 103 (85) GeV

SUSY searches : strategy

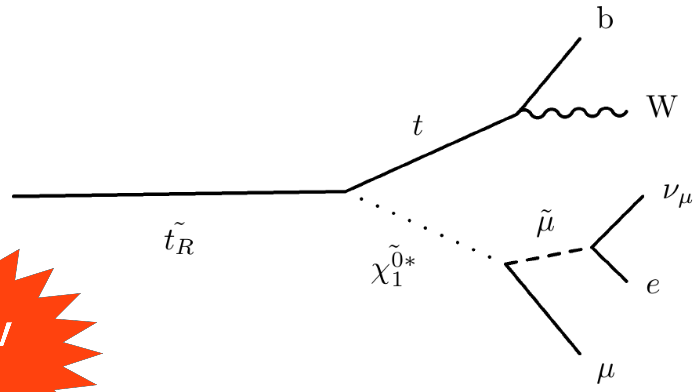
Broadly and deeply cover the SUSY signature space

There is a well-defined strategy to search for SUSY, based on phenomenology oriented searches :

1. Strong production in a R-parity conserving (RPC) scenario
2. Natural spectrum in a RPC scenario
3. Low effective couplings leading to long-lived SUSY particles
4. Prompt RPV scenarios
5. MSSM extensions

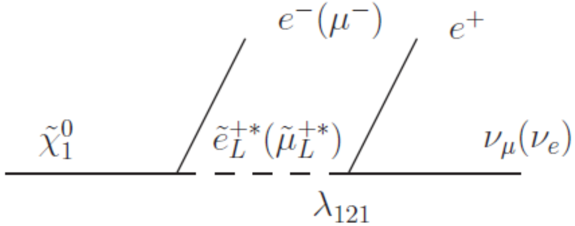
Leptonic RPV

Full 8 TeV dataset

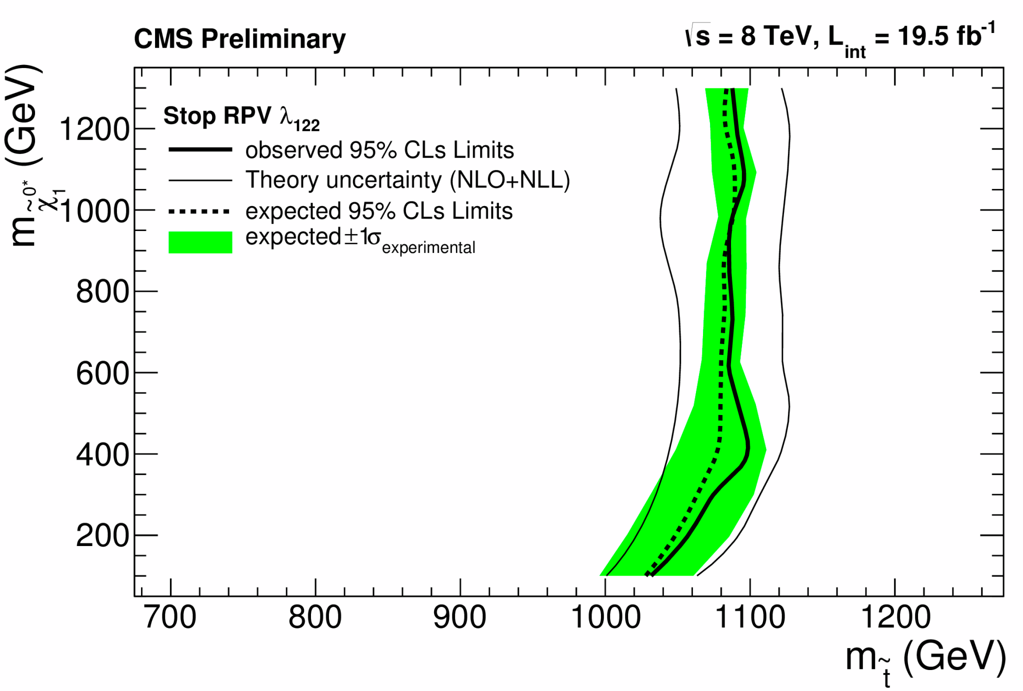


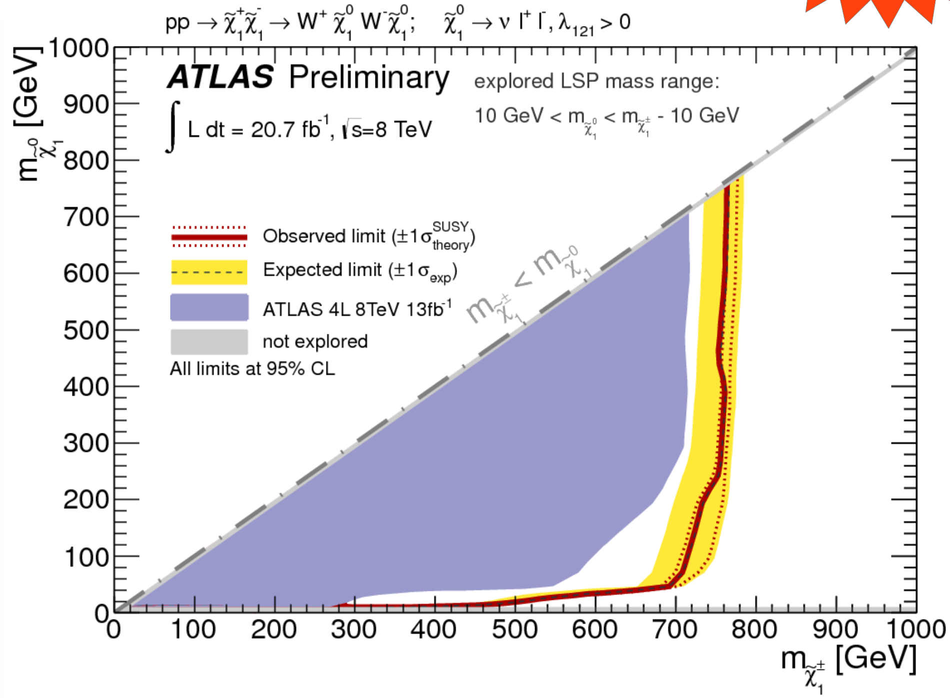
3 leptons + 1 b-jet

- 4 leptons + E_T^{miss} or m_{eff}
- $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production
- $\tilde{\chi}_1^\pm \rightarrow W^{\pm(*)}\tilde{\chi}_1^0$



Full 8 TeV dataset

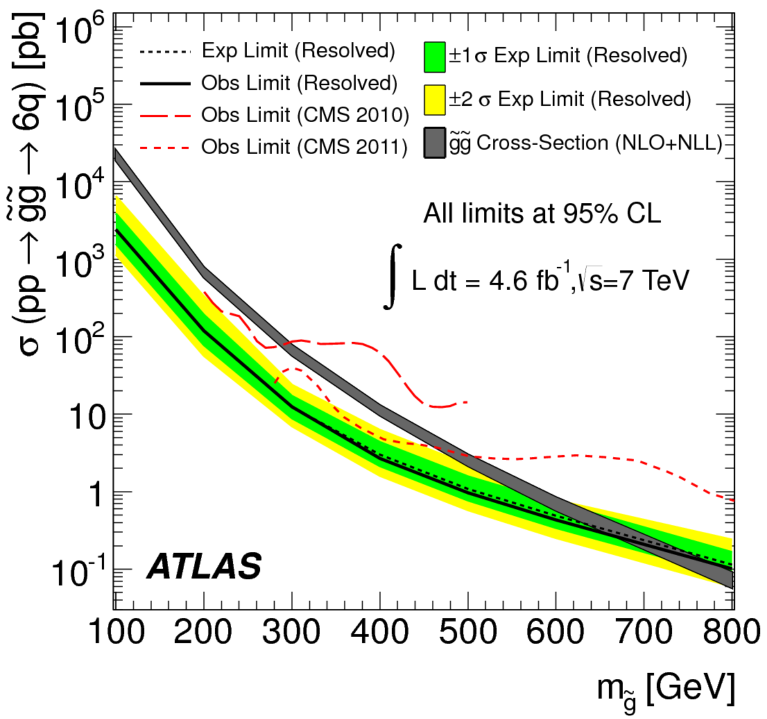




JHEP 12 (2012) 086
EPJC 73 (2013) 2263

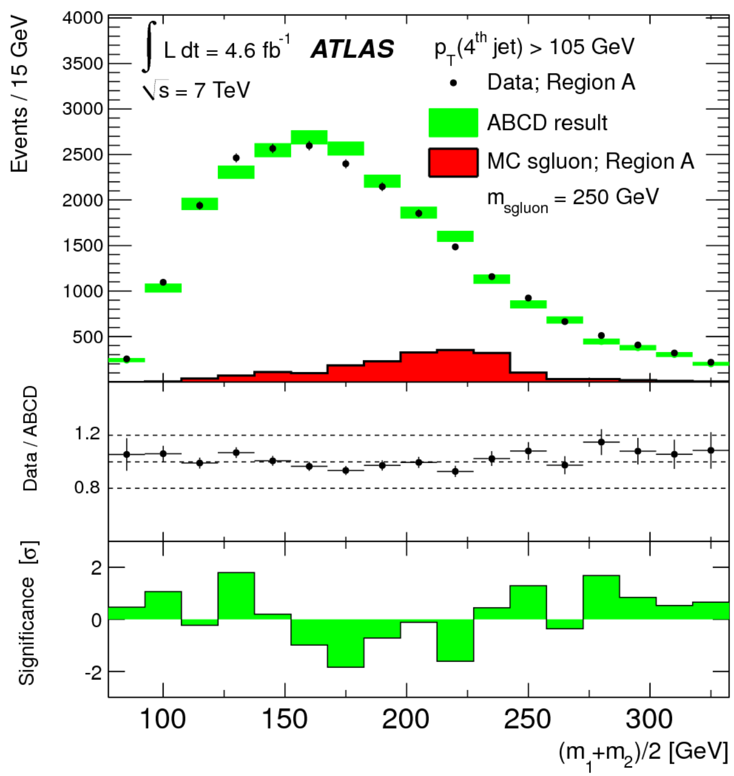
Hadronic RPV & scalar gluon

- RPV gluino decay into three quarks
- Resolved analysis with 6 jets
- Boosted analyses for low-mass gluinos



Resolved analysis : exclude up to 666 GeV
Boosted analysis : exclude up to 255 GeV

- Massive coloured scalar (sgluon) with R=1 (beyond MSSM)
- Pair production: 2 resonances M1, M2 reconstructed with ≥4 high-p_T jets



Exclude scalar gluons for masses from 150 to 287 GeV

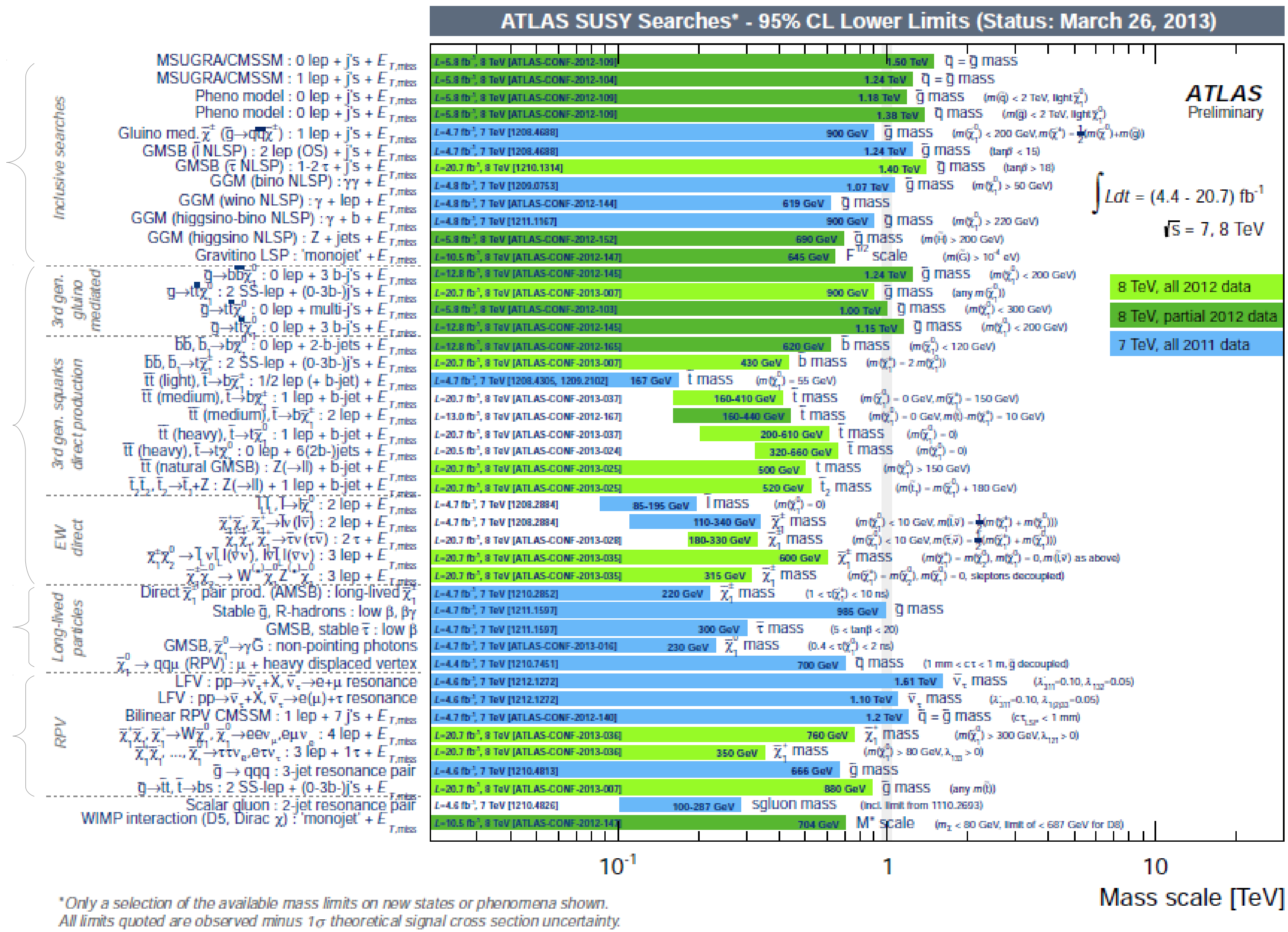
1. Inclusive search

2. Natural spectrum

3. Long-lived sparticles

4. Prompt RPV

5. MSSM extension



SUSY searches @ the LHC

Broadly and deeply cover the SUSY signature space

General strategy to search for SUSY, based on phenomenology oriented searches :

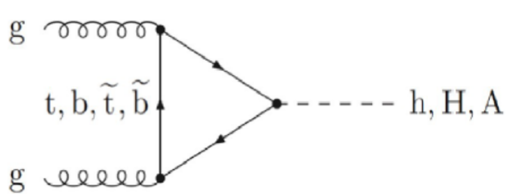
1. Strong production in a R-parity conserving (RPC) scenario
2. Natural spectrum in a RPC scenario
3. Low effective couplings leading to long-lived SUSY particles
4. Prompt R-parity violating (RPV) scenarios
5. MSSM extensions
6. Higgs searches :

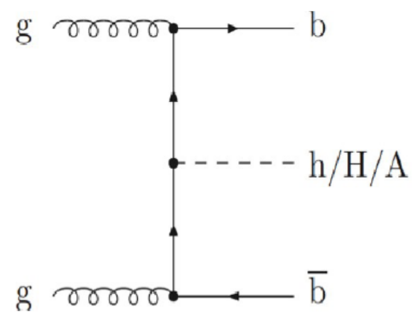
   Extended Higgs sector in SUSY : look for H,A,$H^{\pm}$

Neutral Higgs

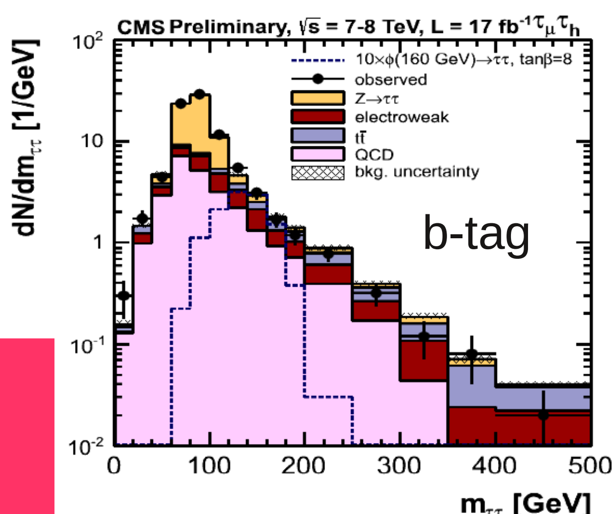
$\phi \rightarrow \tau\tau$ searches:

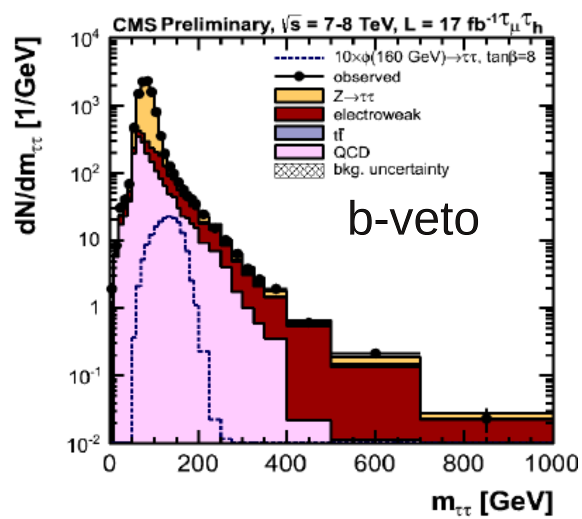
- searches in b-tag and b-veto final states
- subdivided into tau lepton final states : $\tau_e\tau_\mu$, $\tau_\mu\tau_\mu$, $\tau_l\tau_h$

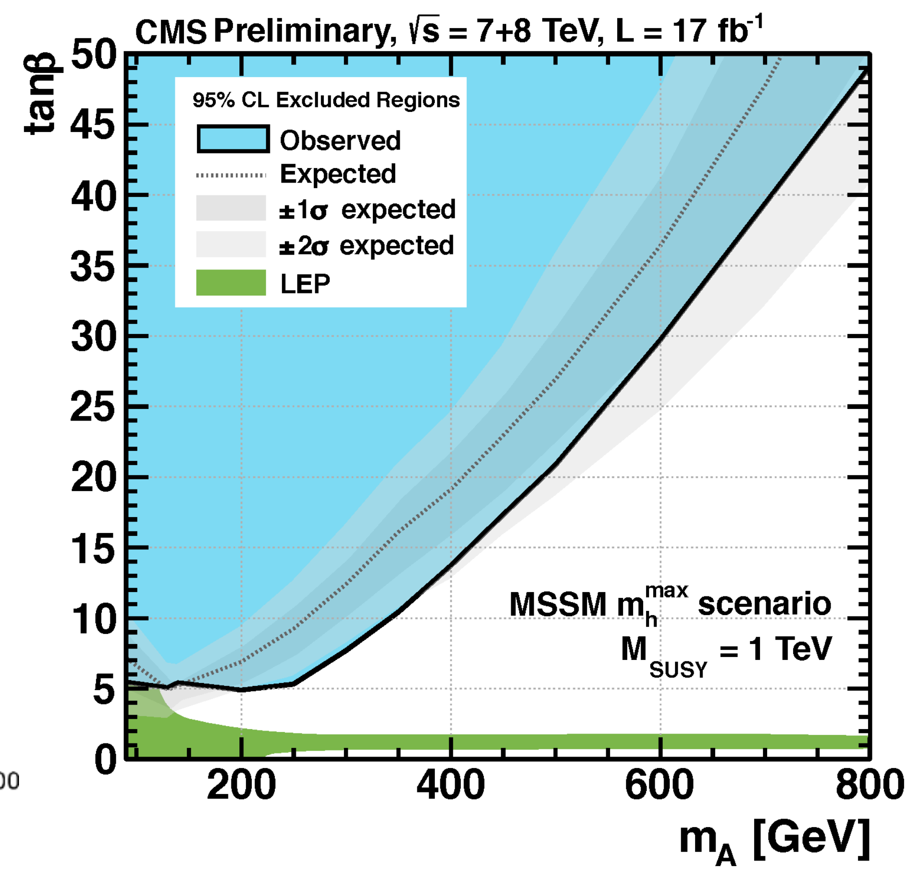




$\tau_\mu\tau_h$:







Conclusion

- Strong and diverse program for SUSY searches
- 2012 data analyses are well under way, some results already out with the complete dataset
- Goals :
  - Extend inclusive searches, also for compressed spectra
  - Continue the stop search, covering all signatures
  - Expand gaugino/slepton searches
  - Continue developing innovative searches for RPV & long-lived signatures

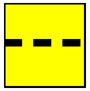
Additional material

What do the various lines mean ?

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

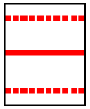
- Ease the life of theorist by separating the signal theoritical and experimental systematics

Expected limit:

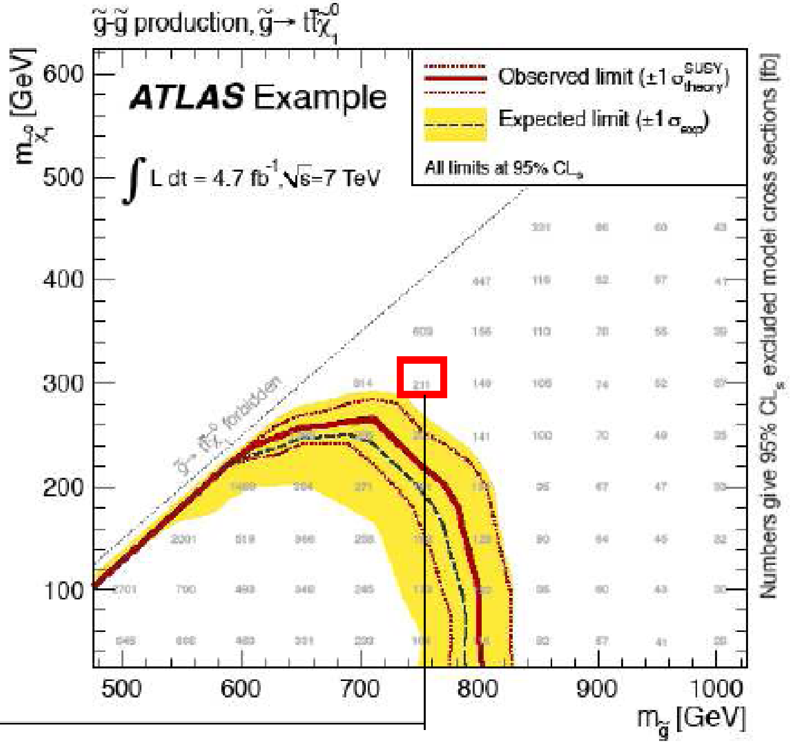


- **Central value:** all uncertainties included in the fit as nuisance parameters, except theoretical signal uncertainties (PDF,scales)
- **±1σ band** : ±1σ results of the fit

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)



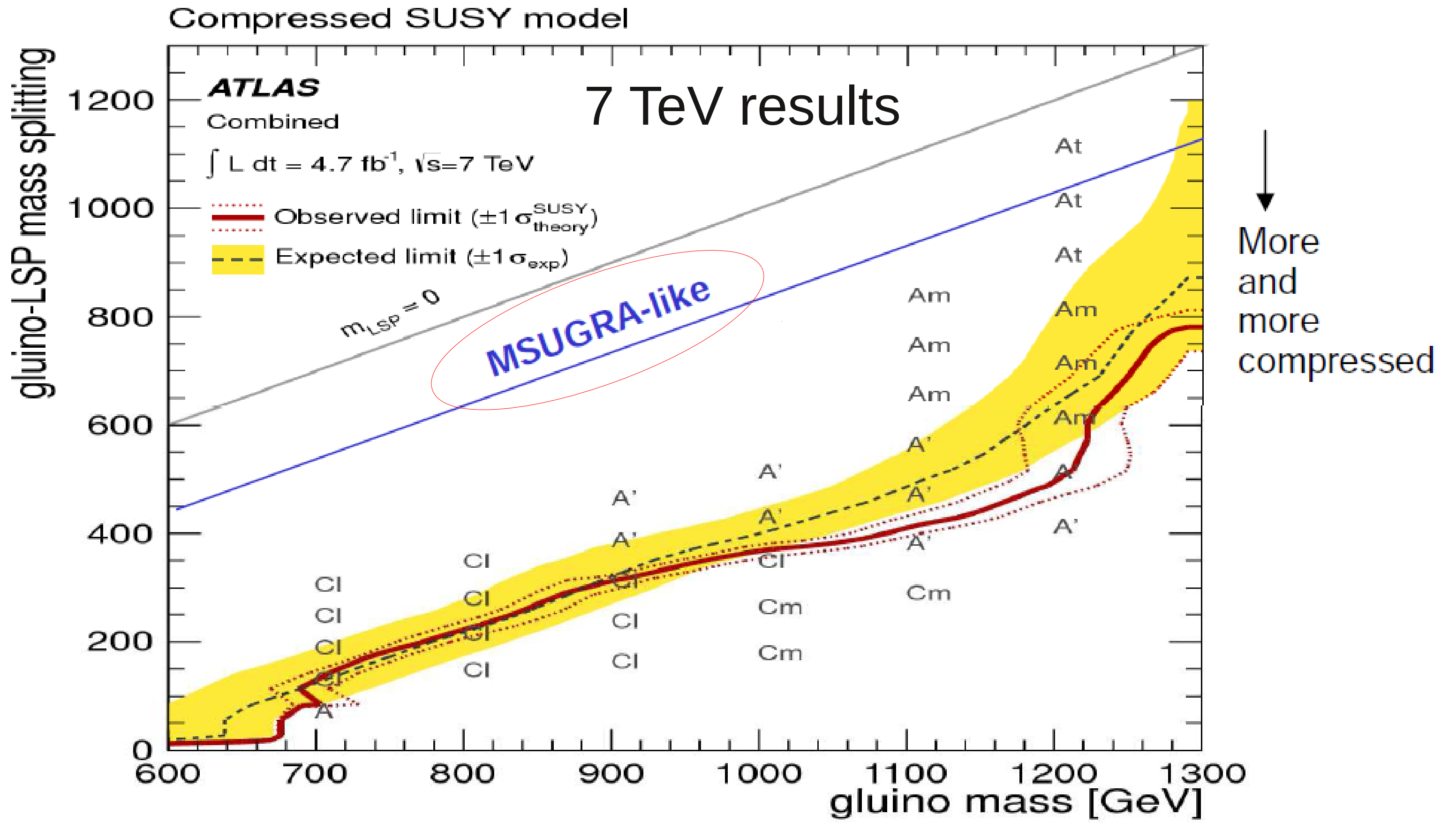
Excluded Model Cross section (SMS)

➔ Number quoted in paper correspond to observed -1 σ observed (conservative)

PRD84 (2011) 015004

A more compressed scenario

Models with compressed MSUGRA scenarios ΔM/MSUSY from 0.85 to 0.15



→The signal regions with the softer cuts allow to go to lower ΔM/MSUSY

R-hadron / long-lived slepton

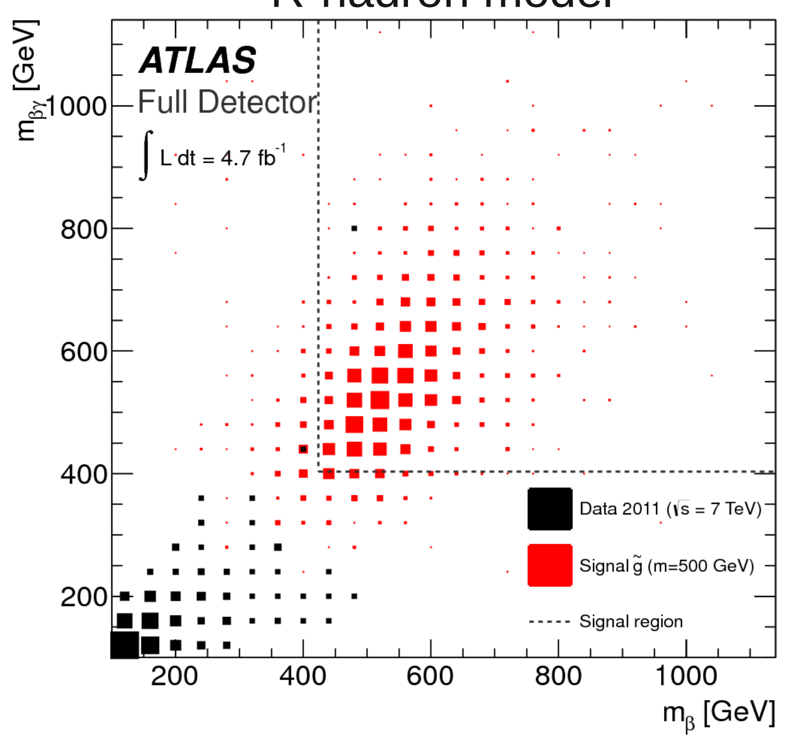
- Selection based on good quality, isolated high-p_T track
- Use the time of flight and dE/dx measurement to get β, βγ

Three analyses :

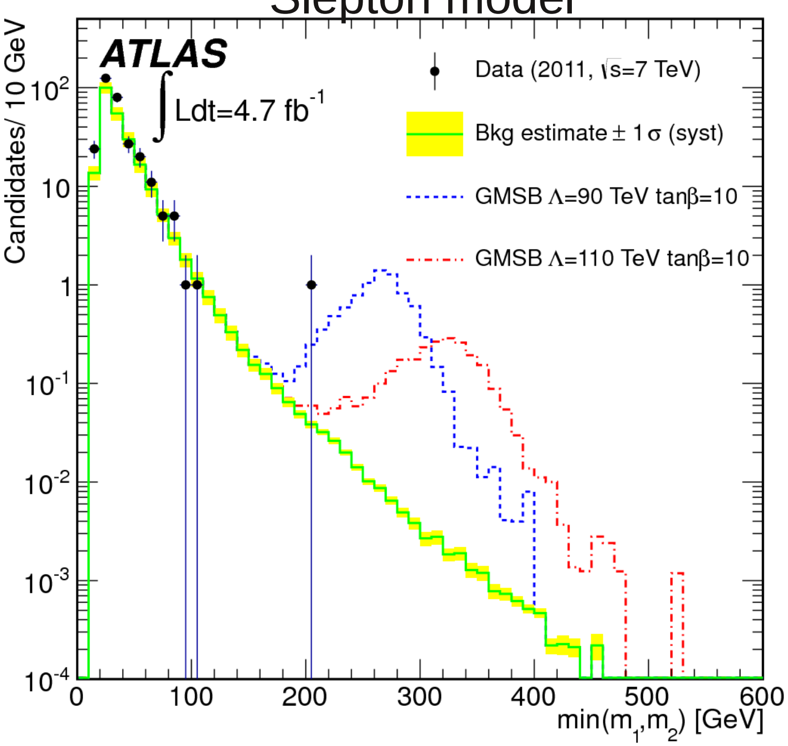
- Full-detector
- MS-agnostic (ignore MS)
- ID-only

cover the lack of knowledge of R-hadron interactions with the detector and the lifetimes for which they would not reach the calorimeters

R-hadron model



Slepton model

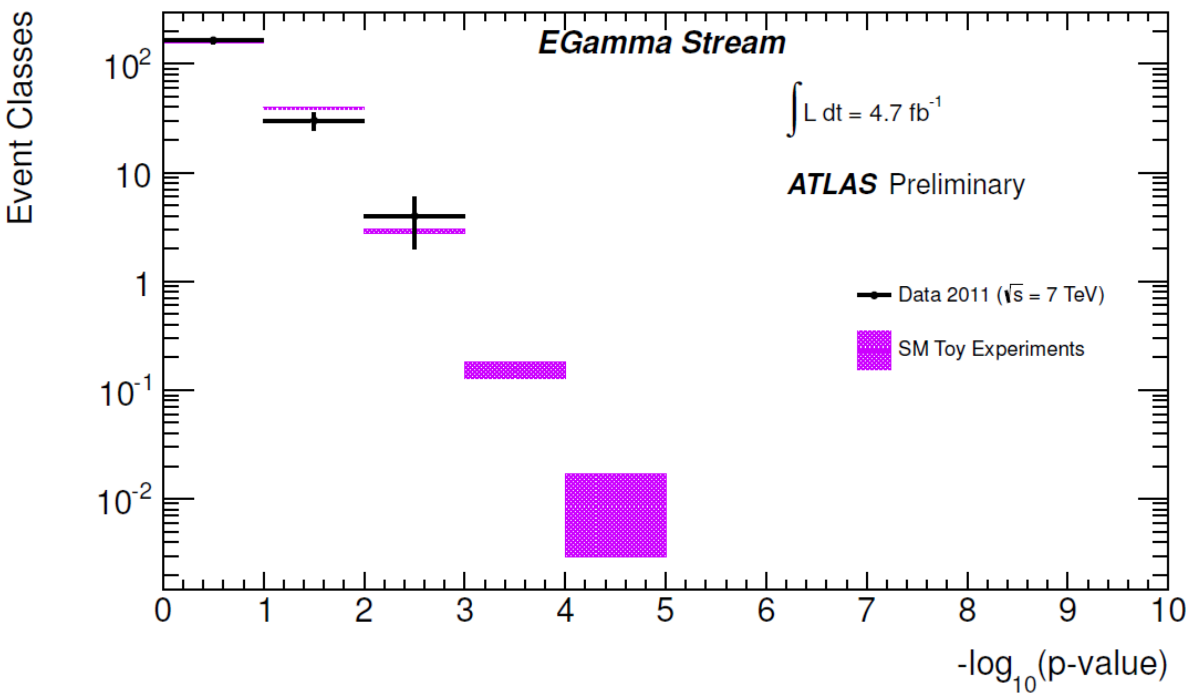


Exclude directly produced LL sleptons up to 278 GeV and R-hadrons containing a gluino up to 985 GeV (generic interaction model)

General search

- Did we miss anything? Clean up with a general search for new physics
- All event topologies involving electrons, photons, muons, jets, b-tagged jets and missing transverse momentum in a single analysis (655 channels defined)
- Scan the effective mass distribution of each final state for deviations from the Standard Model prediction (note : BG from MC only)

Distribution of the p-values :

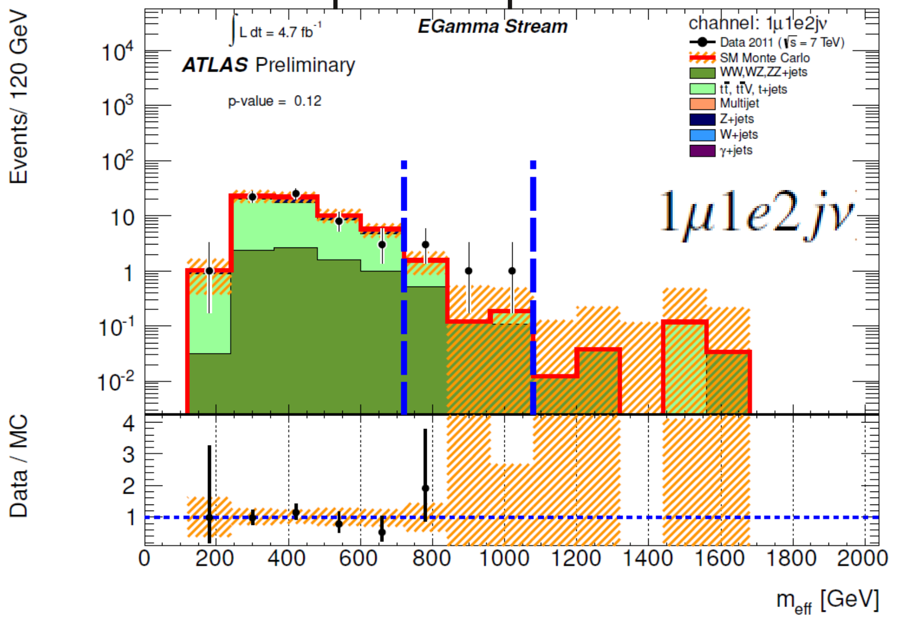


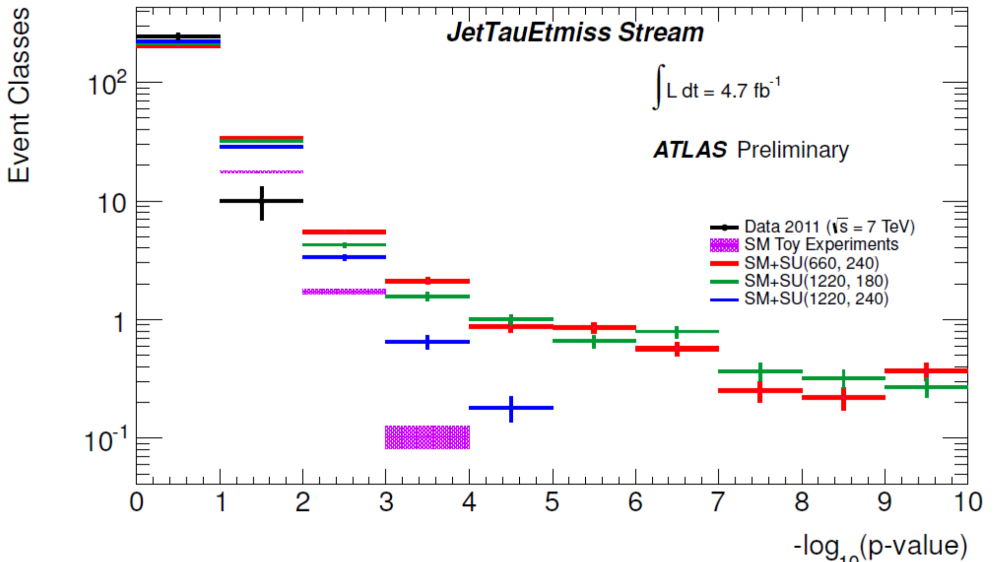
- Consistent with the expectation from toy experiments
- No event class found with a p-value smaller than 10^{-3}
- No big signal hidden in the previously unexplored channels

General search

$$p = A \int_0^\infty \mathrm{d}b\, G(b; N_{SM}, \delta N_{SM}) \sum_{i=N_{obs}}^{\infty} \frac{e^{-b} b^i}{i!}$$

An example with p=0.12



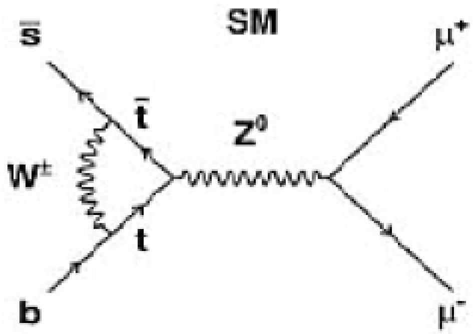


With SUSY, many event classes with small p-value would be expected.

Phys. Rev. Lett. 110, 021801 (2013)

Indirect search : $B_s \to \mu^+\mu^-$

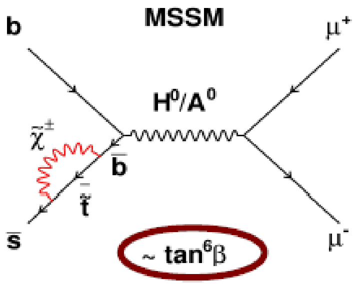
SM prediction:



SM $B(B_s \to \mu\mu) = (3.2 \pm 0.2) \times 10^{-9}$

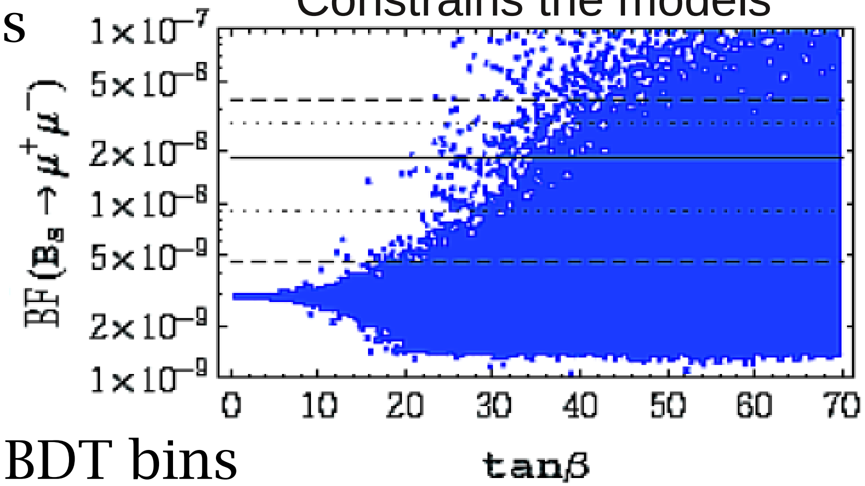
Buras et al. arXiv:1012.1447

Branching ratio very sensitive to new physics

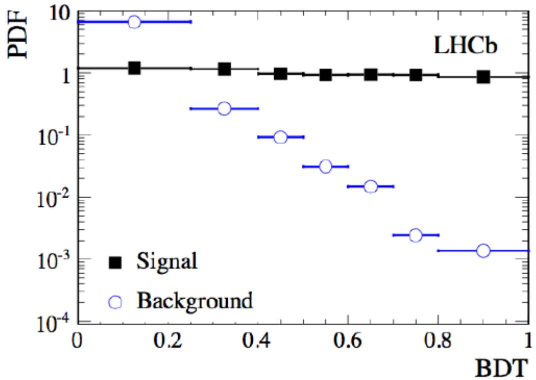


$$BR(B_s \to \mu^+\mu^-) \propto \tan^6\beta / m_A^4$$

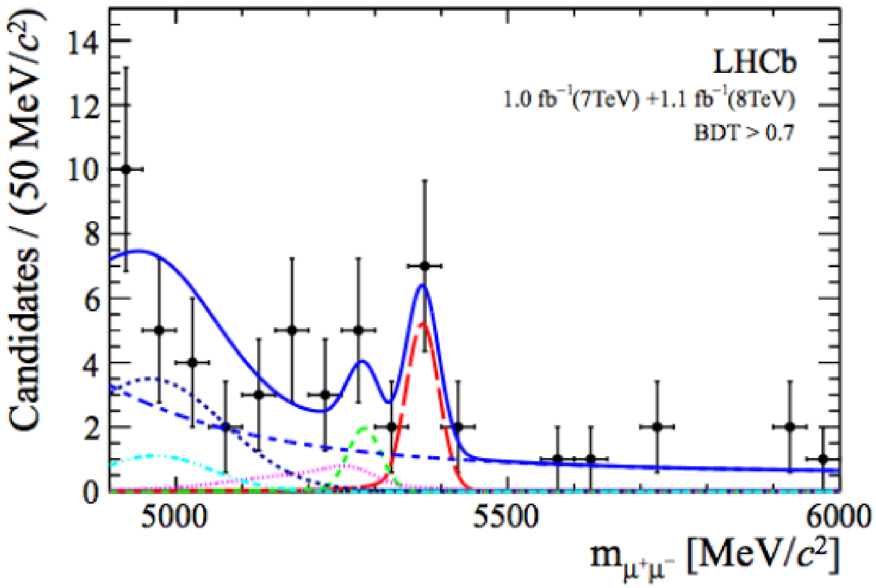
Constrains the models

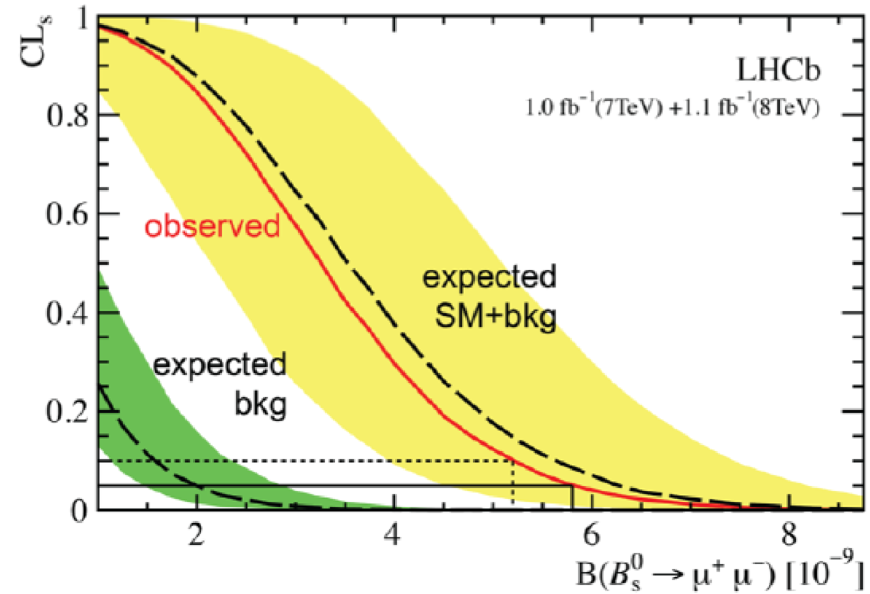


Fit performed in 8 (for 2011) + 7 (for 2012) BDT bins



Indirect search $B_s \to \mu^+\mu^-$





Combining 2011+2012 data

Bkg only hypothesis p-value is 5×10^{-4} corresponding to 3.5 σ

$\mathcal{B}(B_s \to \mu^+\mu^-) = 3.2^{+1.4}_{-1.2}(stat)^{+0.5}_{-0.3}(syst) \times 10^{-9}$

First evidence of the decay $B_s \to \mu^+\mu^-$

Consistent with the SM!