SUperSYmmetry searches at LHC: Part II

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"Pure logical thinking cannot yield us any knowledge of the empirical world; all knowledge of reality starts from experience and ends in it."
A. Einstein (1933)

"I am sure we all agree that a giraffe is truly beautiful, but she doesn't seem to serve any purpose"
J. Weiss (1974)

"Theories are like fishing : only he who casts can catch"
Novalis (1772-1801)

Mandate: "Cover the broad scope of the many various SUSY searches by both CMS and ATLAS at the LHC and their possible future prospects"

Lecture Overview (1)

❑ Part II : Status of SUSY searches at LHC & Prospects

Edwin Moses, , 400 m hurdles (47s75")
Los Angeles Olympic Games 1984

1. R-Parity Conserving [RPC] inclusive searches
2. Natural RPC: stop, sbottom, EWK-inos
3. Long Lived particles
4. R-Parity Violating [RPV] signatures
5. Monojets ←→ Dark Matter production **See Dan Hooper**
6. MSSM Higgs Searches **See Vivek Sharma**
7. Future prospects

"Theories are like fishing : only he who casts can catch"
Novalis (1772-1801)

SUSY Related papers in ATLAS/CMS*

- 2010 (7 TeV, 0.03 fb^{-1}): 12 / 10+2 papers
- 2011 (7 TeV, 1-5 fb^{-1}): 16 / 8+3

SUSY Related CONF notes in ATLAS/CMS*

- 2010 (7 TeV, 0.03 fb^{-1}): 7 / 3+0
- 2011 (7 TeV, 1-5 fb^{-1}): 25 / 16+4
- 2012 (8 TeV, 4 fb^{-1}): 0 / 3+

~ 100 analyses in 2 years !

➔ Show most powerful 7 TeV, 1-5fb^{-1} searches
➔ Give general status of each topical search

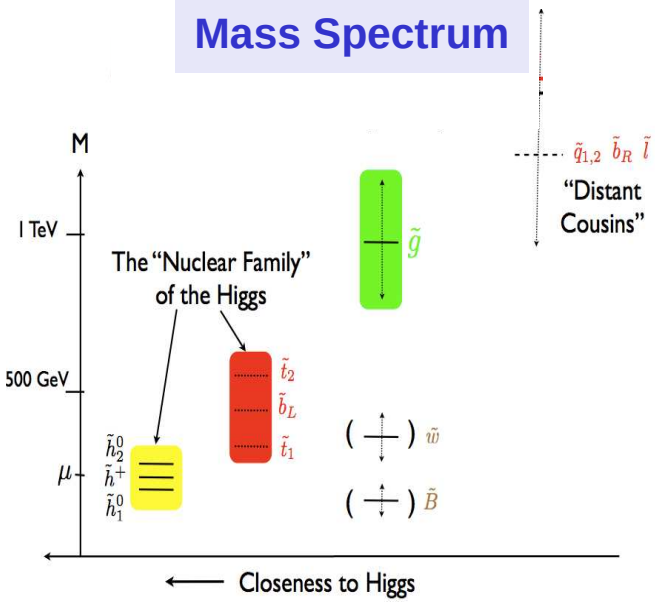
See Ulrich Heintz for 8 TeV results

All information on ATLAS/CMS Public pages:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

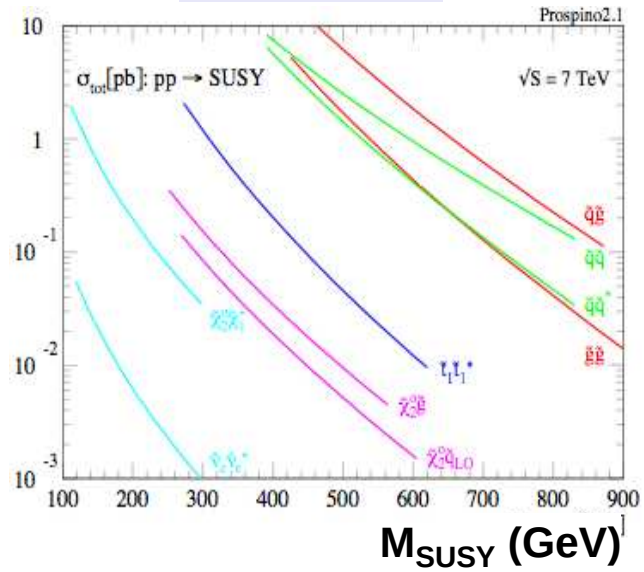
* CMS= SUSY + RPV LongLived in EXOTIC

Lecture Overview (2)

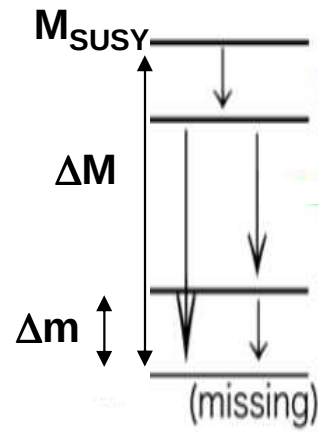
Mass Spectrum



Production



Decay

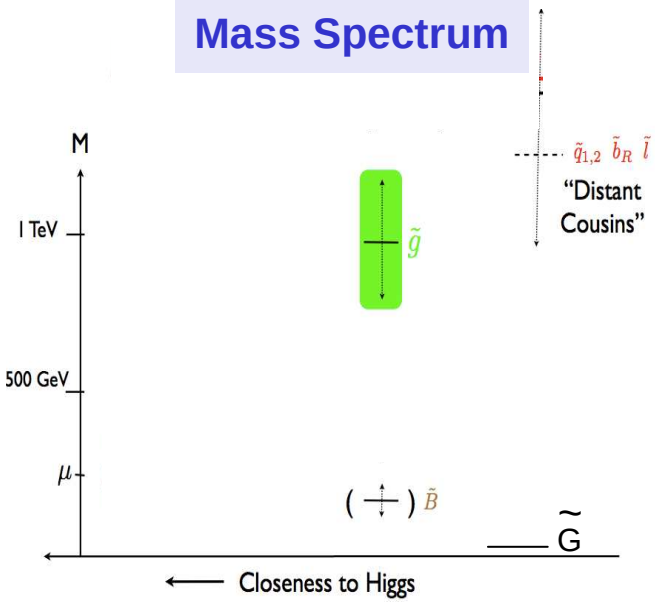


Theory guide → **Experimental side**

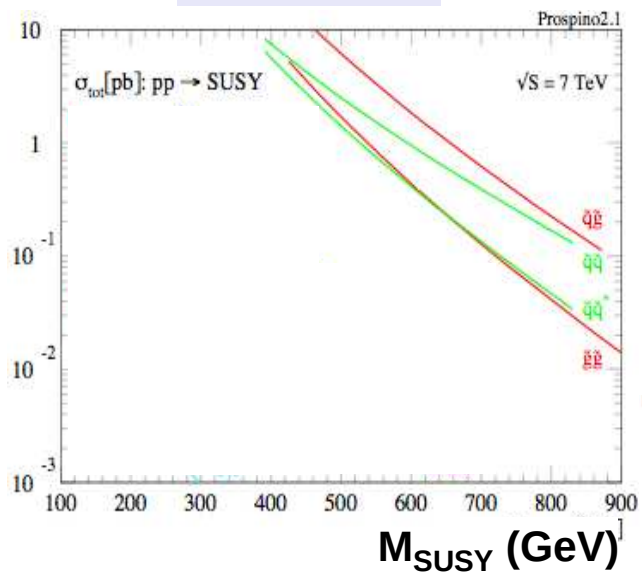
1. Strong production (low, high $\Delta M/M_{SUSY}$) — Inclusive jets+MET
2. Natural spectrum — Dedicated searches with bjets, multileptons, jet/Z veto
3. Degenerate masses (low Δm), tiny RPV — Long Lived particles, displaced vertex/Z/γ
4. 'Sizeable' RPV — Multileptons (inc. tau), No Z, jet/emu resonances
5. No hint. New SUSY Theories? — Improve analysis technics, 8 TeV, 14 TeV

Inclusive searches

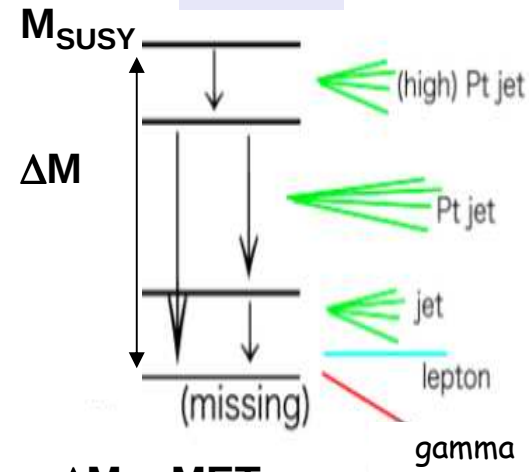
Mass Spectrum



Production



Decay



$\Delta M \sim$ MET

$H_T = \Sigma\, p_T$ (jet) [+ p_T (l,γ)]

1. Strong production dominates (low, high $\Delta M/M_{SUSY}$) ➔ **Inclusive jets+MET**

LSP=$\tilde{\chi}_1^0$
- **squarks/gluino cascade**: **0** lepton + **1-9** jets + MET
- **squark/gluino cascade + leptonic gaugino/slepton decay**:
  - 1lepton (e μ) + jets +MET
  - 2leptons (e μ) same sign + jets +MET

LSP=$\tilde{G}$
- **squark/gluino cascade in GMSB / GGM** :
  - γγ+jets +MET
  - 2 opp. Sign leptons + jets +MET (Z or non Z)
  - (1)2taus + jets +MET

Inclusive searches (1)

- **'Standard' 0lepton + jets + MET searches : Most inclusive !**
  - 0lepton : highest branching ratios generally in $\tilde{q} \rightarrow \tilde{q}\chi_1^0$ and $\tilde{g} \rightarrow q\tilde{q}\chi_1^0$
  - $\tilde{q}\tilde{q}$: **0lepton + >=2, (3, 4) jets + MET** → LO, (NLO or $\chi_1^{+/-} \rightarrow qq\chi_1^0$)
  - $\tilde{q}\tilde{g}$: **0lepton + >=3, (4, 5) jets + MET** → LO, (NLO or $\chi_1^{+/-} \rightarrow qq\chi_1^0$)
  - $\tilde{g}\tilde{g}$: **0lepton + >=4, (5, 6) jets + MET** → LO, (NLO or $\chi_1^{+/-} \rightarrow qq\chi_1^0$)

ATLAS-CONF-2012-033 (1207.1898, 1207.1798, PAS-SUS-11-022/12-005))

Requirement	Channel					
	A **2j**	A' **2j**	B **3j**	C **4j**	D **5j**	E **6j**
E_T^{miss}[GeV] >	160					
$p_T(j_1)$ [GeV] >	130					
$p_T(j_2)$ [GeV] >	60					
$p_T(j_3)$ [GeV] >	–	–	60	60	60	60
$p_T(j_4)$ [GeV] >	–	–	–	60	60	60
$p_T(j_5)$ [GeV] >	–	–	–	–	40	40
$p_T(j_6)$ [GeV] >	–	–	–	–	–	40
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$ >	0.4 ($i = \{1, 2, (3)\}$)			0.4 ($i = \{1, 2, 3\}$), 0.2 (p_T > 40 GeV jets)		
$E_T^{miss}/m_{eff}(N j)$ >	0.3 (2j)	0.4 (2j)	0.25 (3j)	0.25 (4j)	0.2 (5j)	0.15 (6j)
m_{eff}(incl.) [GeV] >	1900/1400/–	–/1200/–	1900/–/–	1500/1200/900	1500/–/–	1400/1200/900

Trigger-driven

Pile-up driven

QCD rejection -driven

Meff discriminant variable

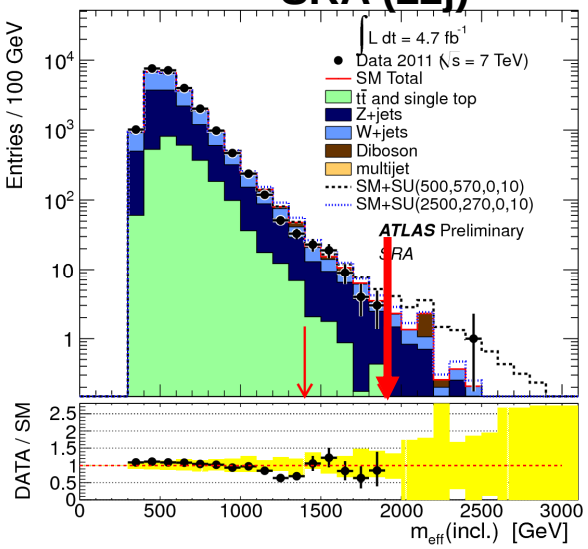
➔ 11 Signal regions split in **Tight (5)** and ***Medium/Loose (6)***

Inclusive searches (2)

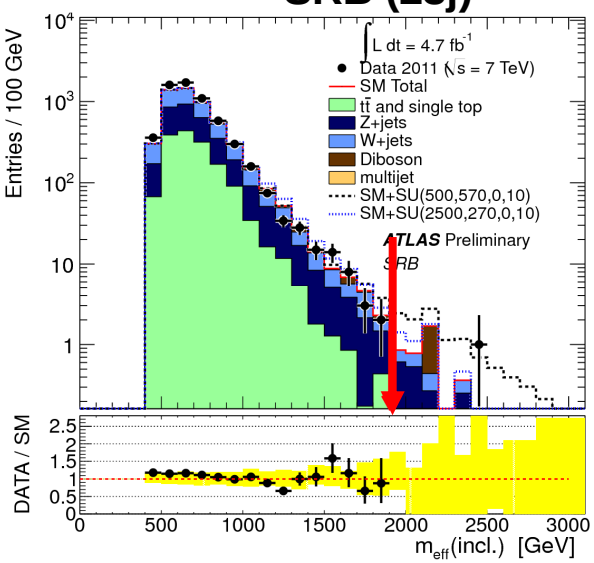
- **5 Tight Signal Regions cover highest M_{SUSY}, large $\Delta M/M_{SUSY}$**
  - Background methods detailed yesterday
  - Dominated by Z→νν +jets / ttbar / W+jets

↓ = SR above the arrow

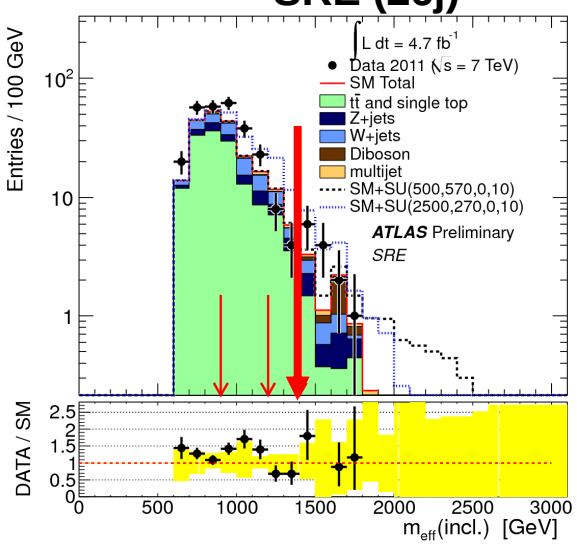
SRA (≥2j)



SRB (≥3j)



SRE (≥6j)



SR	At 2j	Bt 3j	Ct 4j	Dt 5j	Et 6j
Est. back.	7 ± 0.999 ± 2.26	5.39 ± 0.951 ± 2.01	5.68 ± 1.79 ± 1.51	6.84 ± 1.7 ± 2.1	12.1 ± 4.59 ± 3.04
Data	1	1	14	9	13
local p0 (Gaus. σ)	0.98(-2.1)	0.95(-1.7)	0.018(2.1)	0.29(0.55)	0.45(0.13)

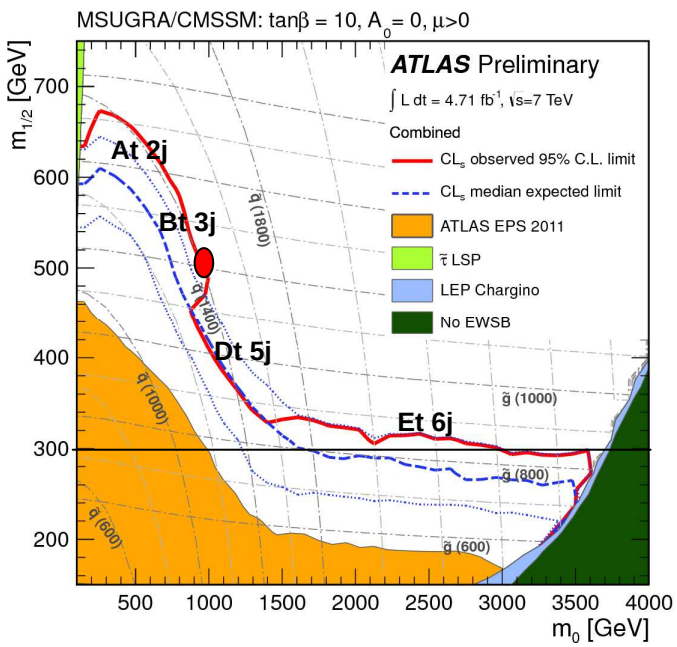
± syst ± stat

➔ Stat competes with syst

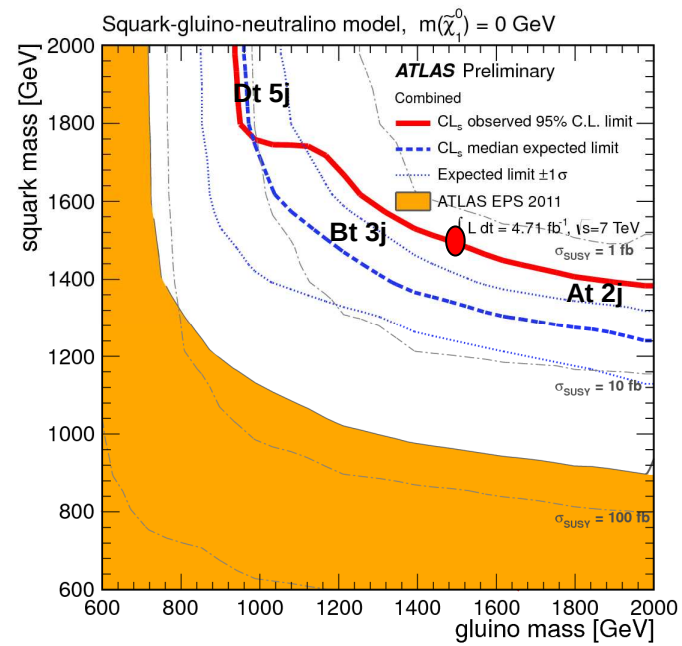
Inclusive searches (3)

- **Interpretations for high M_{SUSY}, large $\Delta M/M_{SUSY}$**
  - No significant excess → set limits in specific model
  - For each point take the signal region that gives the best expected limit

Very Constrained Model (105 parameters →5)



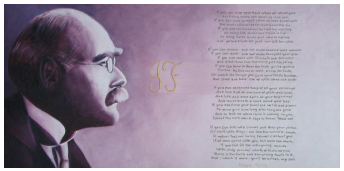
Only 3 sparticles gluino, squark 1rst,2nd gene., LSP

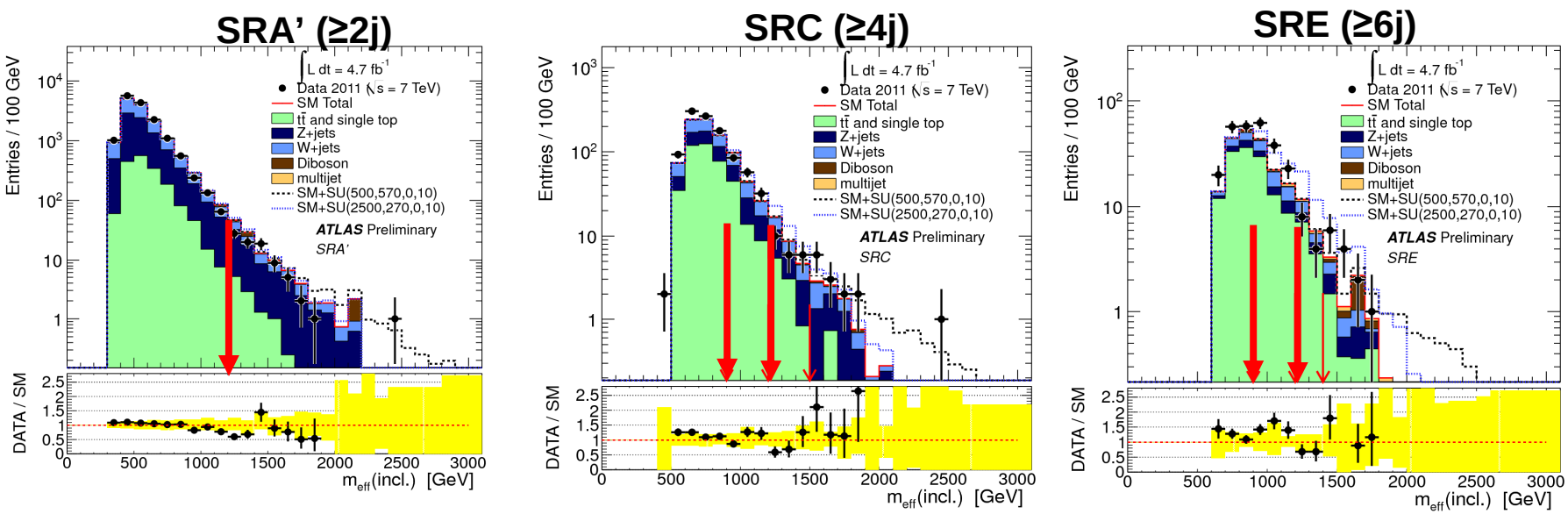


➔ For m(squarks)=m(gluinos), set limit at ~1.4 TeV

Inclusive searches (4)

- **What if low $\Delta M/M_{SUSY}$?**
  - 6 signal regions with Medium/Loose M_{Eff} also exists





Part I Example

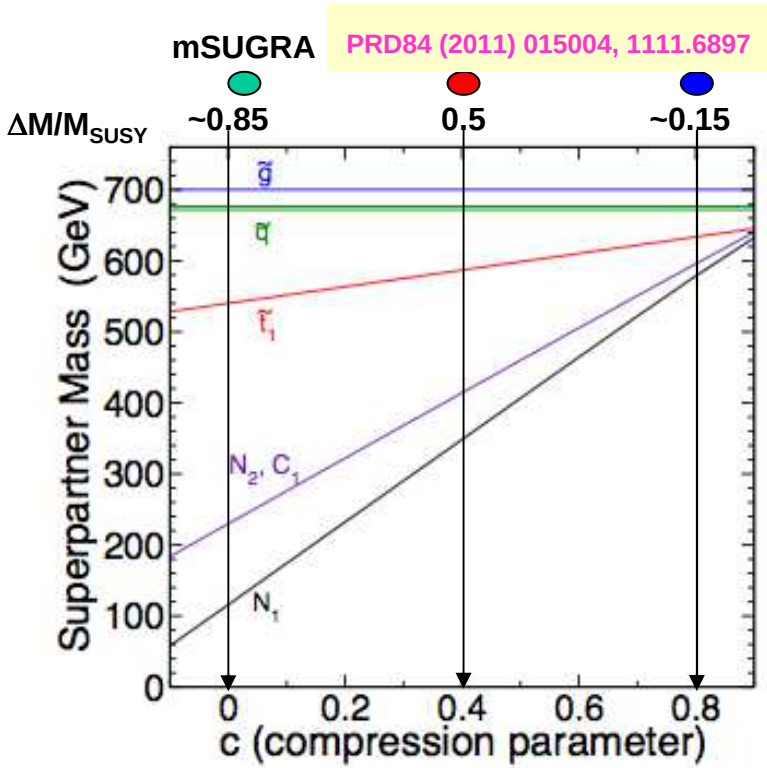
SR	Cl 4j	El 6j	A m 2j	A' 2j	C m	Em 6j
Est. back.	214 ± 24.9 ± 13	119 ± 32.6 ± 11.6	64.8 ± 10.2 ± 6.92	115 ± 19 ± 9.69	38.6 ± 6.68 ± 4.77	34 ± 4.47 ± 5.57
Data	210	148	59	85	36	25
Local p0 (Gauss. σ)	0.55(-0.14)	0.21(0.8)	0.65(-0.4)	0.9(-1.3)	0.6(-0.26)	0.85(-1)

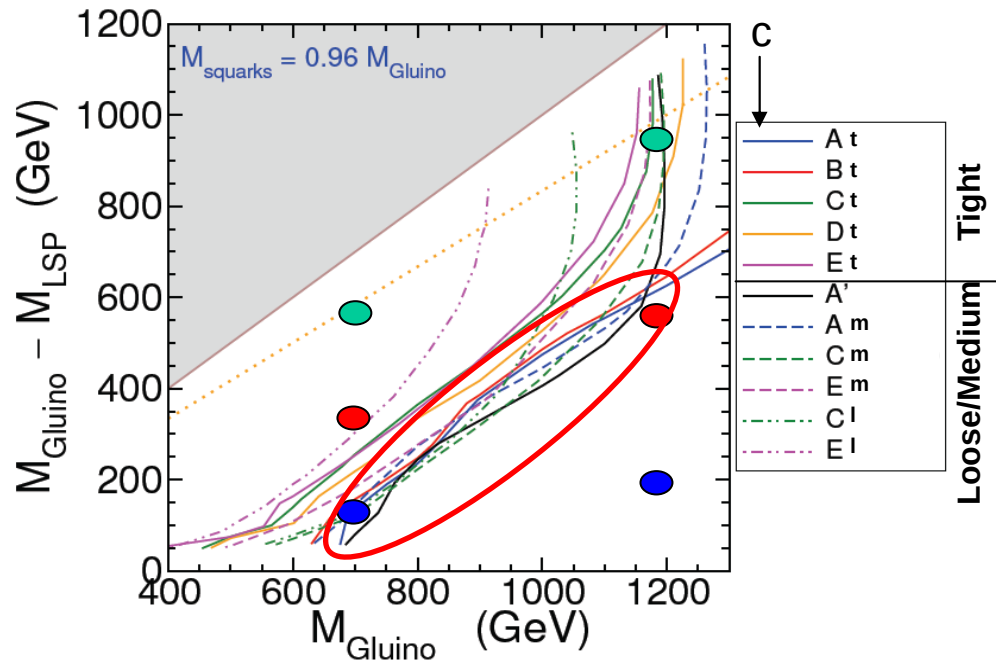
± syst ± stat

➔ Now dominated by syst

Inclusive searches (5)

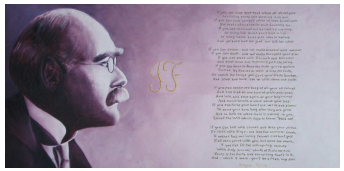
- **Interpretations for lower $\Delta M/M_{SUSY}$ ('compressed spectra')**
  - Assume for example M(squarks)= 0.96 M(gluinos), a la MSUGRA





➔ Gaining in the compressed spectra for m(gluino)<1.2 TeV

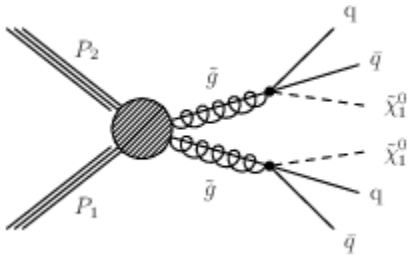
Inclusive searches (6)

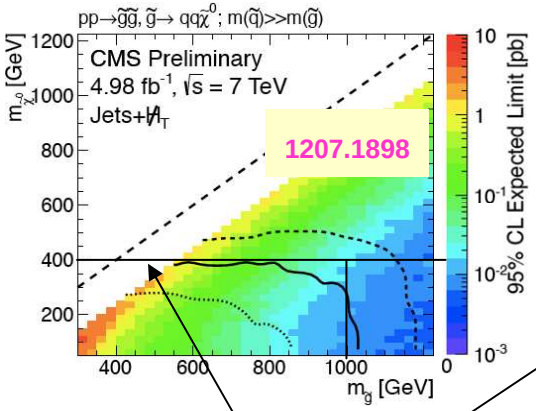


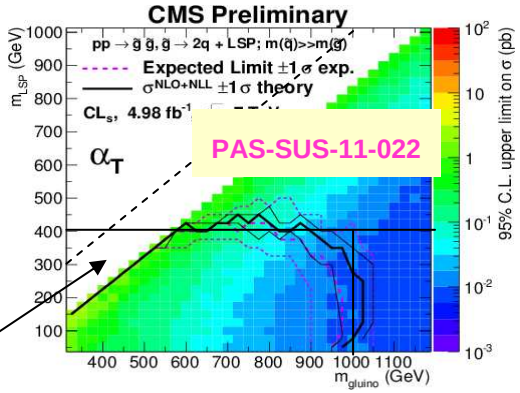
❑ What if Meff variable is not sensitive enough or biased ?

- Use different discriminating variables: cruder MET (MHT), α_T, M_{T2}

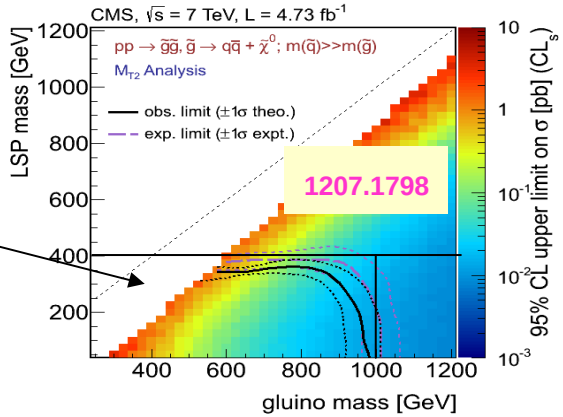
Gluino cascade (only 1rst/2nd generation of squarks)





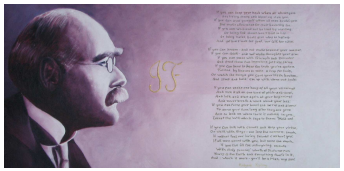


Near the diagonal high syst. from ISR ~30-40 %



➔ Similar limit : m(gluinos) < 1 TeV and m(LSP)<400 GeV

Inclusive searches (7)



❑ What if trigger is killing our SUSY signal ?

Requirement	Channel					
	A	A'	B	C	D	E
E_T^{miss}[GeV] >	160					
$p_T(j_1)$ [GeV] >	130					

Trigger-driven

0lepton + 6-9 jets, lower MET
➔ Multijet trigger

1206.1760

Signal region	7j55	8j55	9j55	6j80	7j80	8j80
Number of isolated leptons (e, μ)	$= 0$					
Jet p_T	> 55 GeV			> 80 GeV		
Jet $\lvert\eta\rvert$	< 2.8					
Number of jets	≥ 7	≥ 8	≥ 9	≥ 6	≥ 7	≥ 8
$E_T^{miss}/\sqrt{H_T}$	> 4 GeV$^{1/2}$					

0lepton + 1 jet ('Monojet')
➔ Only MET trigger

ATLAS-CONF-2012-084
(1206.5663)

Signal regions	SR1	SR2	SR3	SR4
Common requirements	Data quality + trigger + vertex + jet quality + $\lvert\eta^{jet1}\rvert < 2.0$ + $\lvert\Delta\phi(\mathbf{p}_T^{miss}, \mathbf{p}_T^{jet2})\rvert > 0.5$ + $N_{jets} \leq 2$ + lepton veto			
E_T^{miss}, p_T^{jet1} >	120 GeV	220 GeV	350 GeV	500 GeV

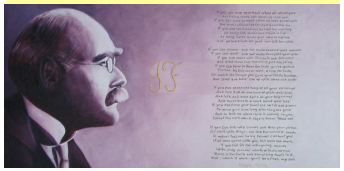
- Sensitive to compressed spectra, ISR tagged

See Dan Hooper

- QCD and ttbar all hadronic dominated
- $\tilde{g}$ med. charginos ($\chi_1^{+/-} \rightarrow qq\chi_1^0$) gives long decay chain :
  ➔ (6,7), 8 (9) jets
- Very nice complementarity with 'standard' 0lepton

Inclusive searches (8)

ATLAS-CONF-2012-041
(PAS-SUS-12-010)



❑ What if 'one' lepton (e,μ) is present in the decay chain ?

- Generate high p_T lepton when $\chi_1^{+/-} \rightarrow l\nu\chi_1^0$ or intermediate slepton
  - ✓ Single lepton trigger is sufficient
  - ✓ Lower QCD multi-jet background: can remove Δϕ(j,MET), and relax pT(jets)

	High M_{SUSY} large $\Delta M/M_{SUSY}$		Compressed $\Delta M/M_{SUSY}$
	3-jet	**4-jet**	**soft-lepton**
Trigger	Single electron or muon (+jet)		Missing E_T
N_{lep}	1	1	1
p_T^{ℓ} (GeV)	> 25 (20)	> 25 (20)	[7,25] ([6,20])
$p_T^{\ell 2}$ (GeV)	< 10	< 10	< 7 (6)
N_{jet}	≥ 3	≥ 4	> 2
p_T^{jet} (GeV)	> 100, 25, 25	> 80, 80, 80, 80	> 130,25
$p_T^{jet\ 4}$ (GeV)	< 80	—	—
E_T^{miss} (GeV)	> 250	> 250	> 250
m_T (GeV)	> 100	> 100	> 100
E_T^{miss}/m_{eff}	> 0.3	> 0.2	> 0.3
m_{eff}^{inc} (GeV)	> 1200	> 800	—

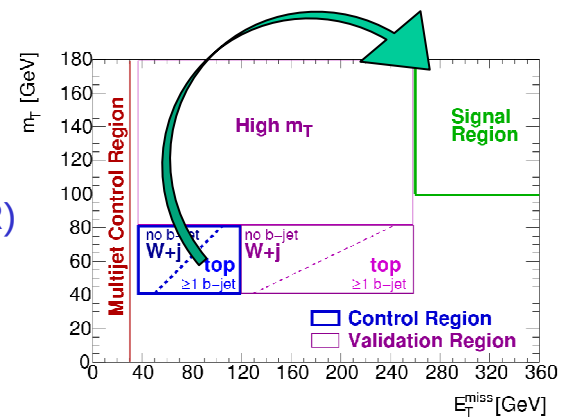
→ Only Low pT

→ 1 high pT jet (ISR)
1 low pT

→ W killer

Background **5.7±4.0(JES) 8.3±3.1(JES) 32±11 (JES)** (Dominant Syst)

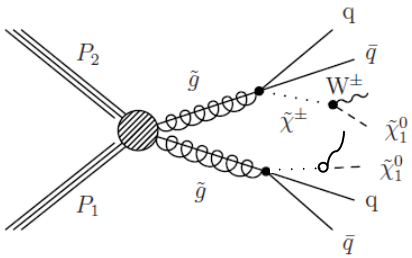
Background estimation strategy



➔ More flexibility than in 0lepton, but lower signal BR

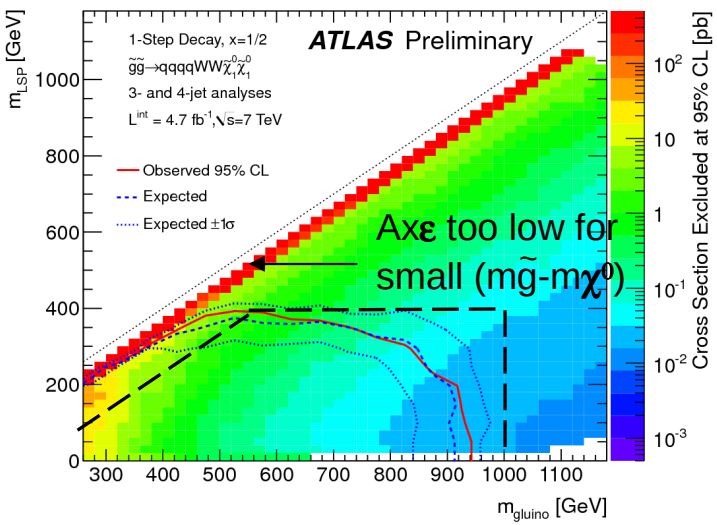
Inclusive searches (9)

Gluino cascade (only 1rst/2nd generation of squarks)

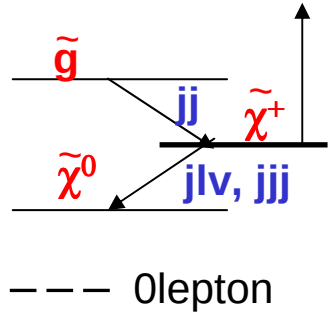


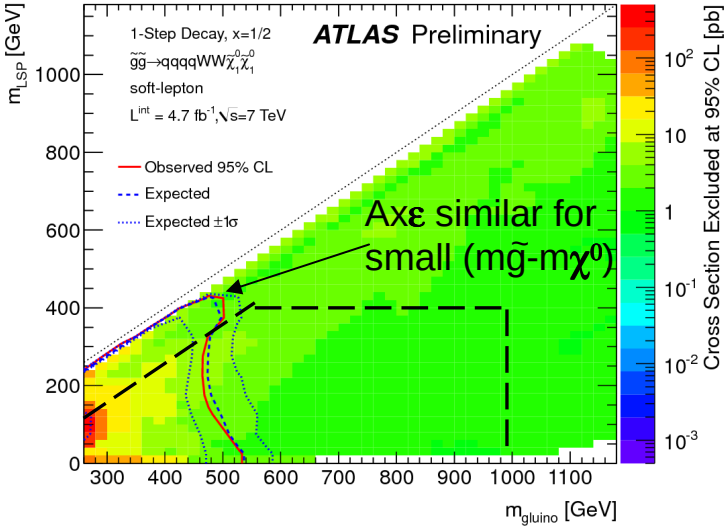
❑ Quite complementary wrt 0lepton search

- Compare by considering gluino mediated charginos



$m\chi_1^{+/-}=(m_{\tilde{g}}+m\chi_1^0)/2$

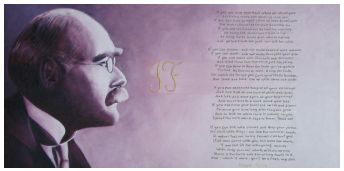




➔ Slightly below 0lepton reach but much better near the diagonal !

Inclusive searches (10)

1205.6615

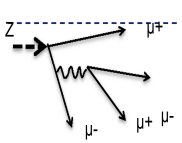


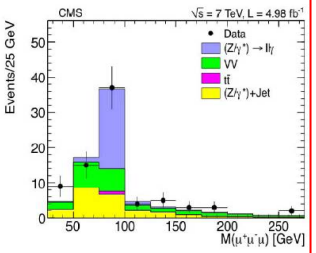
❑ What if 'two' leptons with same sign (e,μ) ?

- In MSSM, gluino are Majorana particles: gives equally q̃ and anti-q̃
  - ➔ same sign leptons from the two legs in ½ of the case + jets +MET
- SM killer which compensates for low branching ratios.

Background

Charge mis-identification



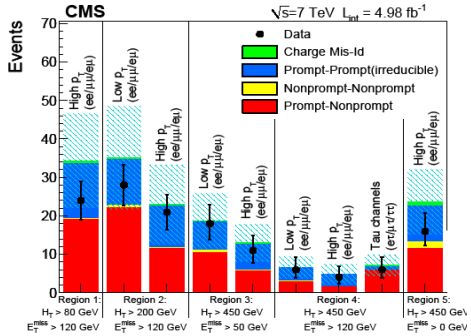


ttbar + W or Z : σ~0.1 pb

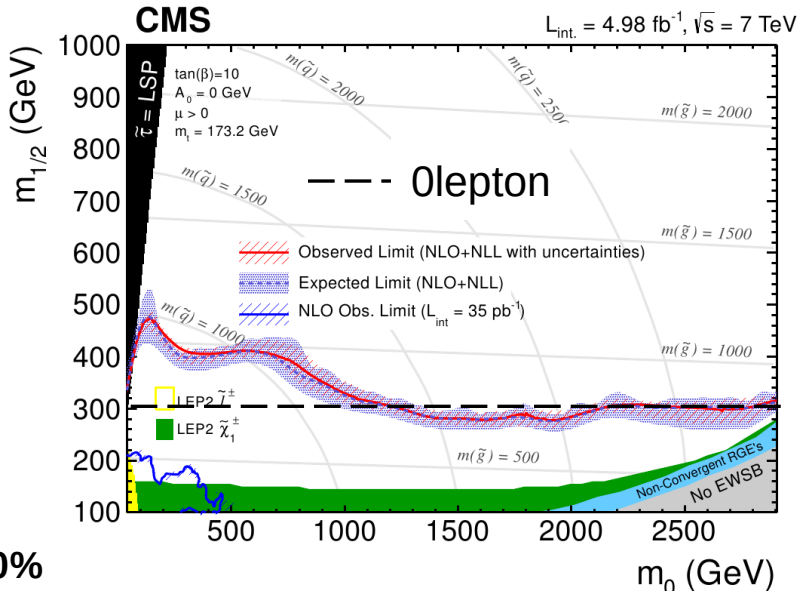
1 Real +1 Fake lepton (jets)

Selection

- Trigger: Dilepton+HT
- 2 leptons low/high pT
- MET, H_T Cuts



Background Error ~35-50%

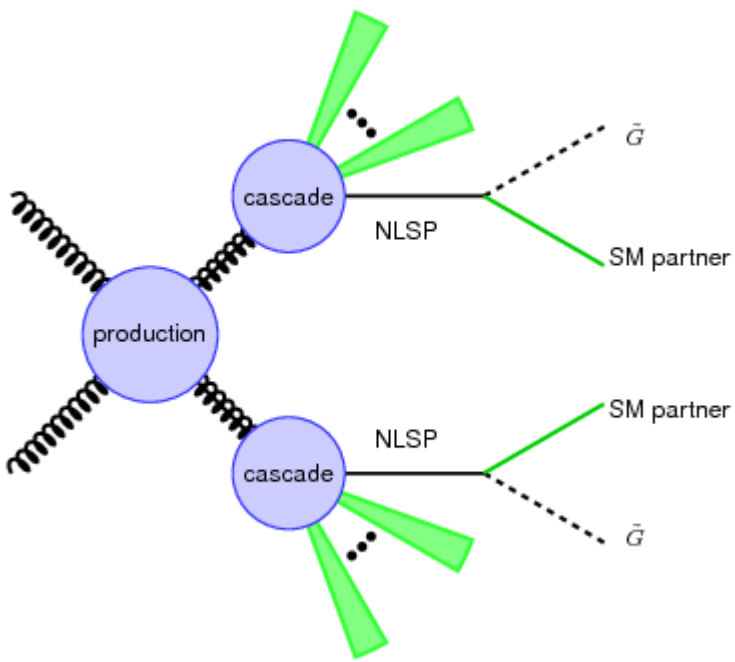


➔ Competitive with 0lepton searches at high m0 !

Inclusive searches (11)

❑ Motivation for multi-leptonic / photonic signatures

- Can not compete with inclusive 0lepton, 1lepton channels because of branching ratios
- GMSB: LSP is the gravitino and NLSP determines the event final states



JHEP 02 (2012) 115

NLSP type	Relevant final states (+MET)
bino	$\gamma\gamma$, γ+jets
wino	$\gamma\ell$, $\gamma\gamma$, γ+jets, ℓ+jets, jets
Z-rich higgsino	$Z(\ell^+\ell^-)$+jets, $Z(\ell^+\ell^-)Z(\ell'^+\ell'^-)$, SS dileptons, jets
h-rich higgsino	b-jets, SS dileptons, jets
chargino	SS dileptons, OS dileptons, ℓ+jets, jets
slepton	multileptons, SS dileptons, OS dileptons, ℓ+jets, jets
squark/gluino	jets
stop	SS dileptons, OS dileptons, b-jets, ℓ+jets, $\ell + b$-jets, $t\bar{t}$, jets
sbottom	b-jets, jets

➔ Can seriously enhanced Z+jets+MET, τ+X+jets+MET, OS ll+jets+MET, γ+X+MET

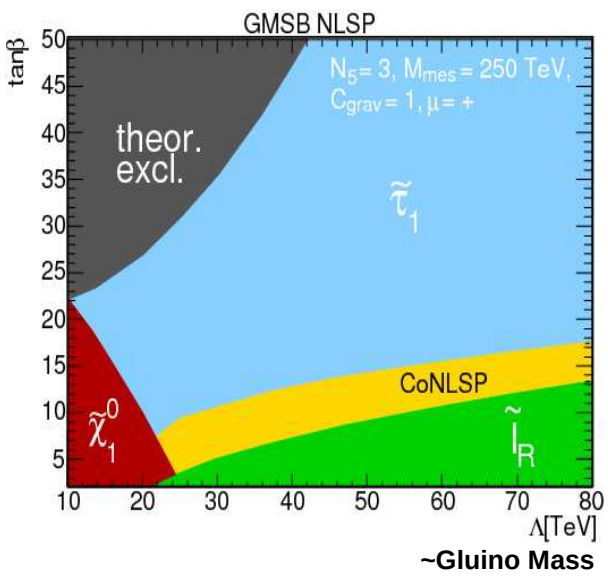
➔ Note: 0lepton, 1lepton and SS dileptons also very strong

Inclusive searches (12)

❑ Two leptons (e,μ) opposite sign + jets +MET

ATLAS-CONF-2011-156
(1206.3949)

NLSP type	Relevant final states (+MET)
slepton	multileptons, SS dileptons, OS dileptons, ℓ+jets, jets
- 3 categories: ee, μμ and eμ + jets + MET
  - ✓ Main background : ttbar dileptonic (semi data driven)



Selection

- Trigger: Single lepton
- =2 leptons pT>25 GeV
- ≥3 jets pt >80,40,40 GeV
- MET>220 GeV

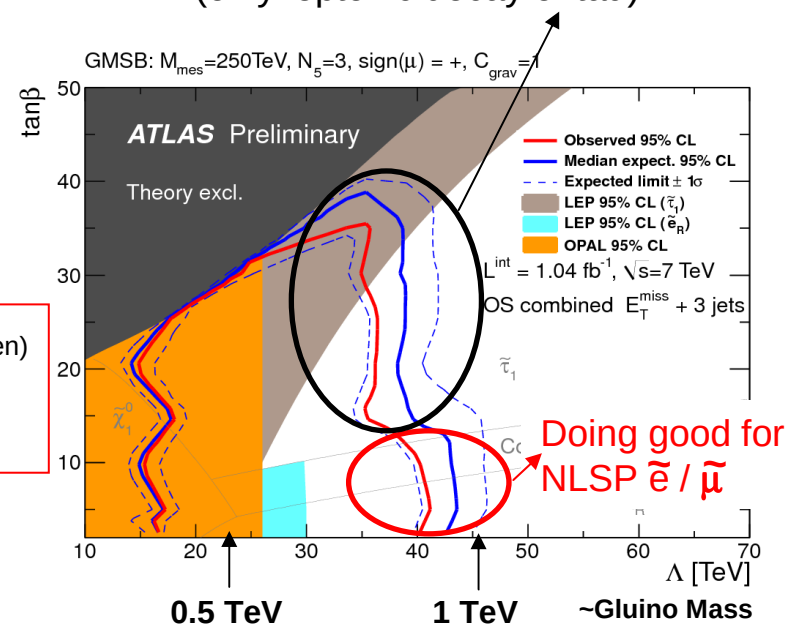
Background

~ttbar dileptonic (semi data-driven)
N_B=13±3.2(syst.)±2.4(stat)
Main Syst.= ttbar ISR/FSR

Signal

Syst is 20%/15%
exp/theo around the limit

Doing less good for NLSP stau
(only leptonic decay of tau)



Inclusive searches (13)

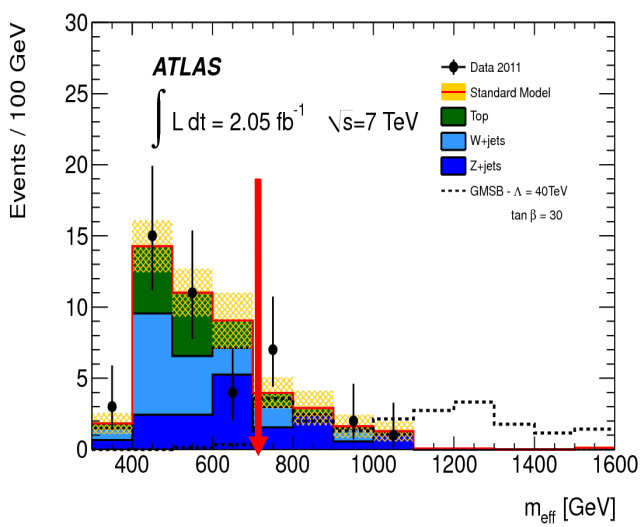
1204.3852, 1203.6580
(PAS-SUS-12-004)

❑ Two τ_{had} of opposite sign + jets + MET

- Stau can also be light if high mixing

NLSP type	Relevant final states (+MET)
slepton	multileptons, SS dileptons, OS dileptons, ℓ+jets, jets

- Experimental challenge : understand the fake τ, τ energy scale for pT(τ)>20 GeV
  - ✓ Dominate background systematics



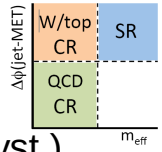
Selection

- Trigger: Jet+MET
- ≥ 2 'loose' taus pT>20 GeV
- ≥ 3 jets pt >130,30,30 GeV
- MET>160, m_{Eff}>700 GeV

Background

ttbar/W+jets: 1 fake + 1 real τ

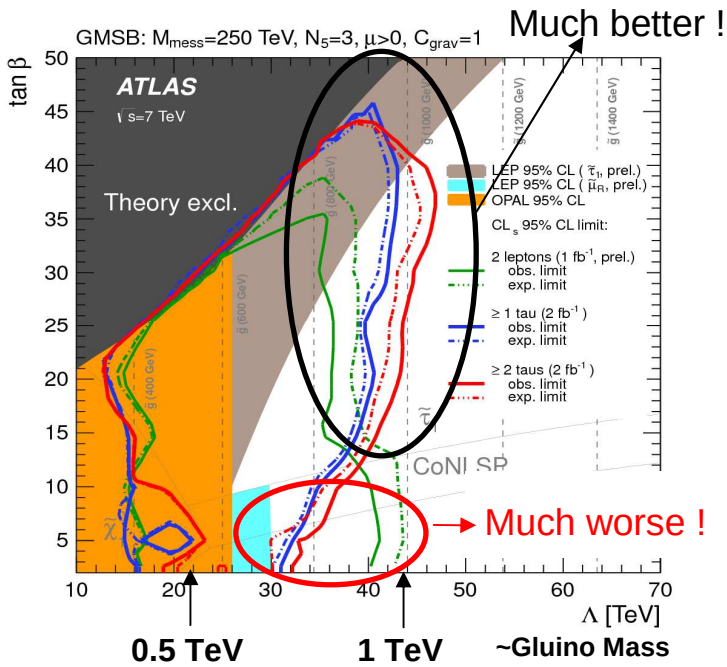
Semi data-driven



N_B=5.3±2.6 (50% syst.)

Signal

Syst is 20%/15% exp/theo around the limit



➔ More challenging but a nice addition to consider taus for SUSY !

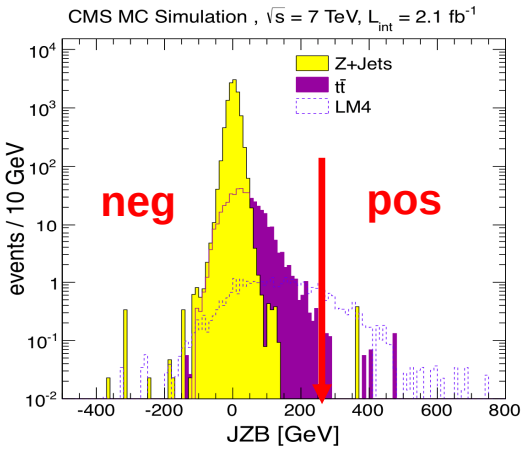
Inclusive searches (14)

1204.3774
(ATLAS-CONF-2012-046)

❑ Two leptons opposite sign from Z (ee, μμ) + jets + MET

NLSP type	Relevant final states (+MET)
Z-rich higgsino	$Z(\ell^+\ell^-)$+jets, $Z(\ell^+\ell^-)Z(\ell'^+\ell'^-)$, SS dileptons, jets

- Experimental challenge: Fake MET from SM Z+jets hard to estimate
  - ✓ JZB (data driven) = imbalance between pT(Z) and jets: symmetric around 0 for Z+jets but not for ttbar
  - ✓ Can also use MET templates (γ+jets and QCD) to estimate tails at high MET. Not shown here



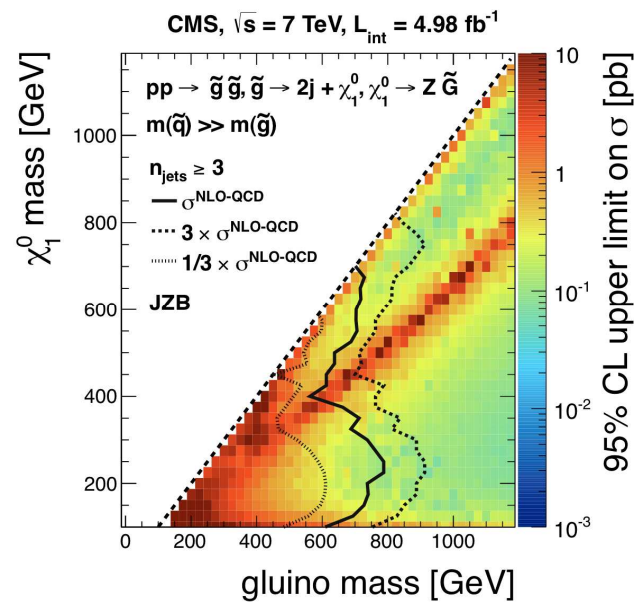
$$JZB^{\rm pred}_{\rm bkgd} = |{\rm JZB}^{\rm SFZP}_{\rm neg}| + \frac{1}{3}|{\rm JZB}^{\rm OFZP}_{\rm pos}| - \frac{1}{3}|{\rm JZB}^{\rm OFZP}_{\rm neg}| + \frac{1}{3}|{\rm JZB}^{\rm SFSB}_{\rm pos}| - \frac{1}{3}|{\rm JZB}^{\rm SFSB}_{\rm neg}| + \frac{1}{3}|{\rm JZB}^{\rm OFSB}_{\rm pos}| - \frac{1}{3}|{\rm JZB}^{\rm OFSB}_{\rm neg}|$$

Selection

- Trigger: double leptons
- 2 lep. Opp. Sign Same Flavor
- 81<M(Z)<101 GeV
- ≥2,3 jets pt >30 GeV
- JZB>250 GeV

Background

JZB method
NB=2.0±0.8 (40% stat)



➔ Sensitivity suppressed for signal with symmetric JZB

Inclusive searches (15)

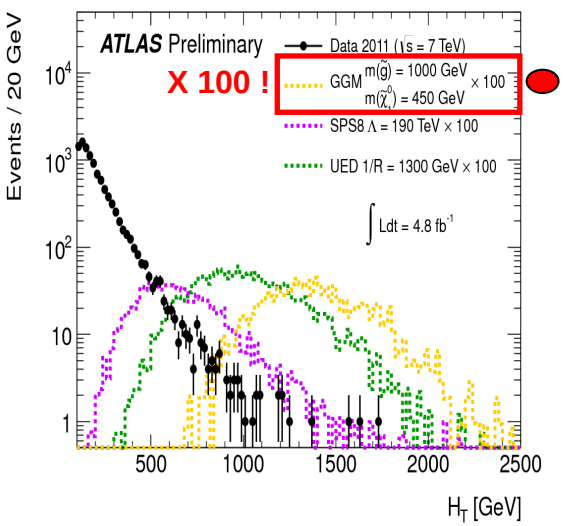
ATLAS-CONF-2012-075
(CMS-PAS-SUS-12-001/018)

NLSP type	Relevant final states (+MET)
bino	$\gamma\gamma$, γ+jets
wino	$\gamma\ell$, $\gamma\gamma$, γ+jets, ℓ+jets, jets

❑ Two photons in the final state

- Experimental Challenge : determine fake γ and tail at high MET (see Part I)
- 3 variables MET, H_T and $\Delta\phi$ (γ, MET) to increase sensitivity

After 2 γ selection



Selection (SRA/B)

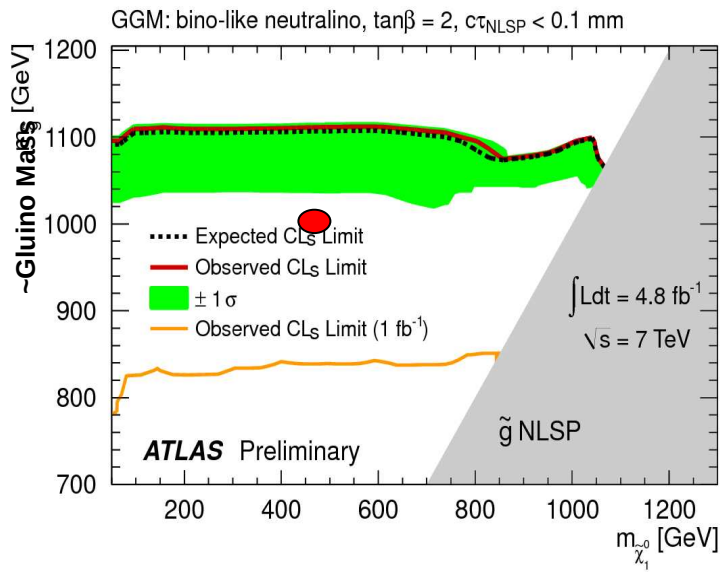
- 2 γ pT> 50 GeV
- MET>200/100 GeV
- H_T>600/1100 GeV
- $\Delta\phi(\gamma,\text{MET})$>0.5/0

Background

N_B=0.1±0.03(stat)±0.07(syst)
Syst dominated by fake γ

Signal

Syst is 10%/30 % for exp/theo around the limit

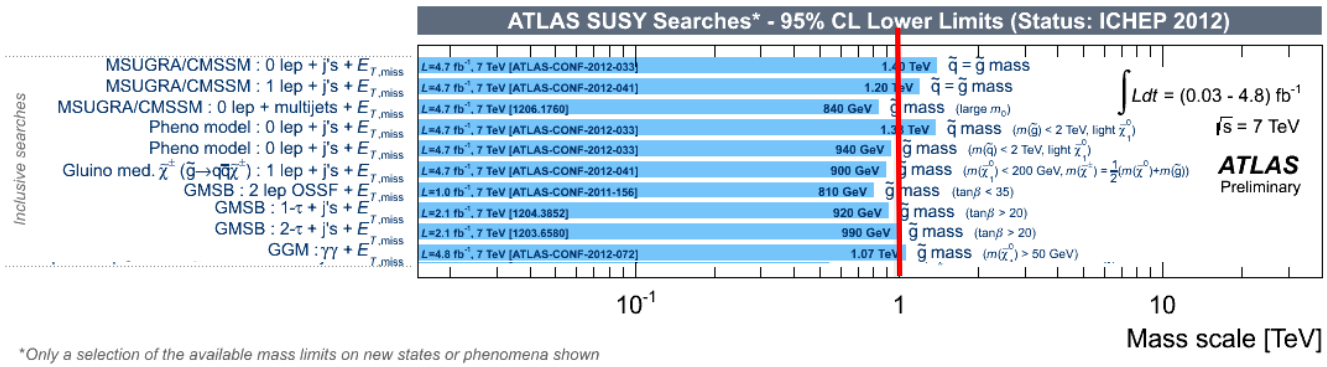


➔ Quite strong in the LSP bino case ($M_{\tilde{g}}$> 1.1 TeV). Similar for $M_{\tilde{q}}$!

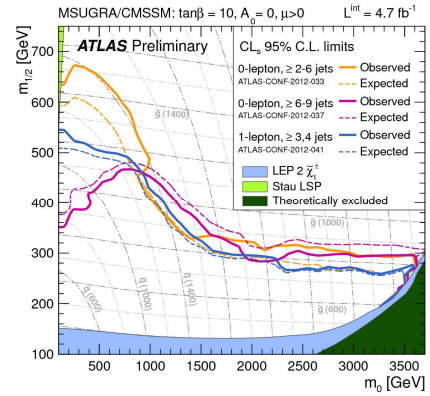
Summary on Inclusive searches

- **These searches are covering a wide range of SUSY models !**

ATLAS 2-5 fb^{-1} (CMS similar)



*Only a selection of the available mass limits on new states or phenomena shown



LSP= $\tilde{\chi}_1^0$ and pMSSM

1206.4321, 1206.5800

L [fb^{-1}]	1	5	5	20
√s [TeV]	7	7	8 (proj)	8 (proj)
% of SUSY models excluded	7	23	32	45

LSP = $\tilde{G}$ and GGM Models (1fb^{-1})

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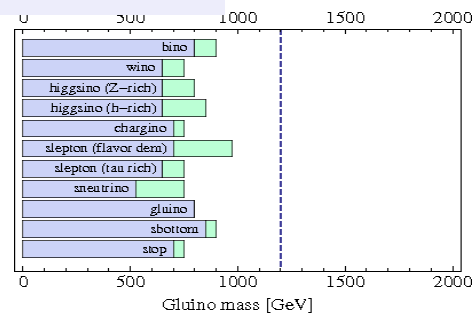
Recasting results from ATLAS/CMS with 1fb^{-1} in GGM



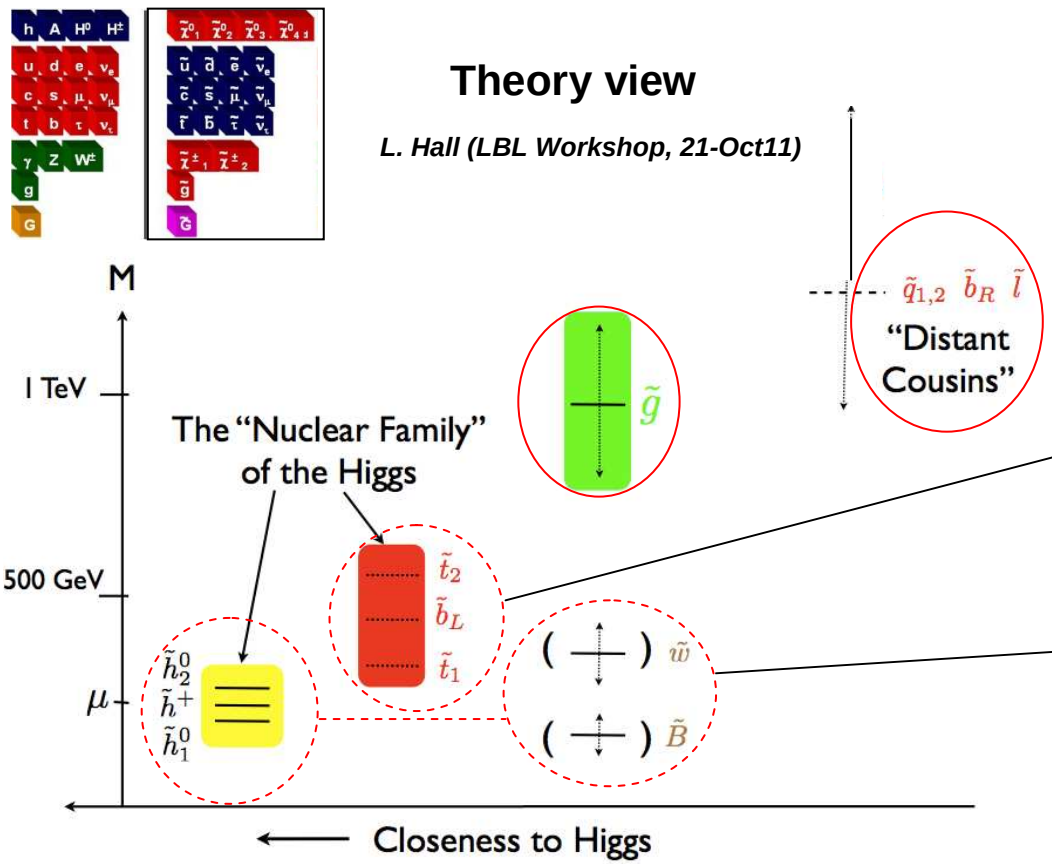
➔ $m_{\tilde{q}}$ and $m_{\tilde{g}}$ already reach the 1 TeV limit (was ~300-400 GeV before LHC !)

➔ Can cover 'all' pMSSM and GGM with LHC (14 TeV) ?

Natural SUSY

❑ A "natural" SUSY spectrum

~~Too~~ See Inclusive searches



Experimental view

Light squarks, sleptons :
«decoupled»

Gluino :
~~*Direct production*: jets + MET (+leptons) but cross-section may be low~~

3rd generation:
Direct production: bs, Ws, ts + MET
Gluino mediated: same +jets

EWK-inos=Gauginos ($\tilde{\chi}^0_1$=LSP):
Direct production: leptons, MET, Jet veto
~~*Gluino mediated*: leptons, jets, MET~~

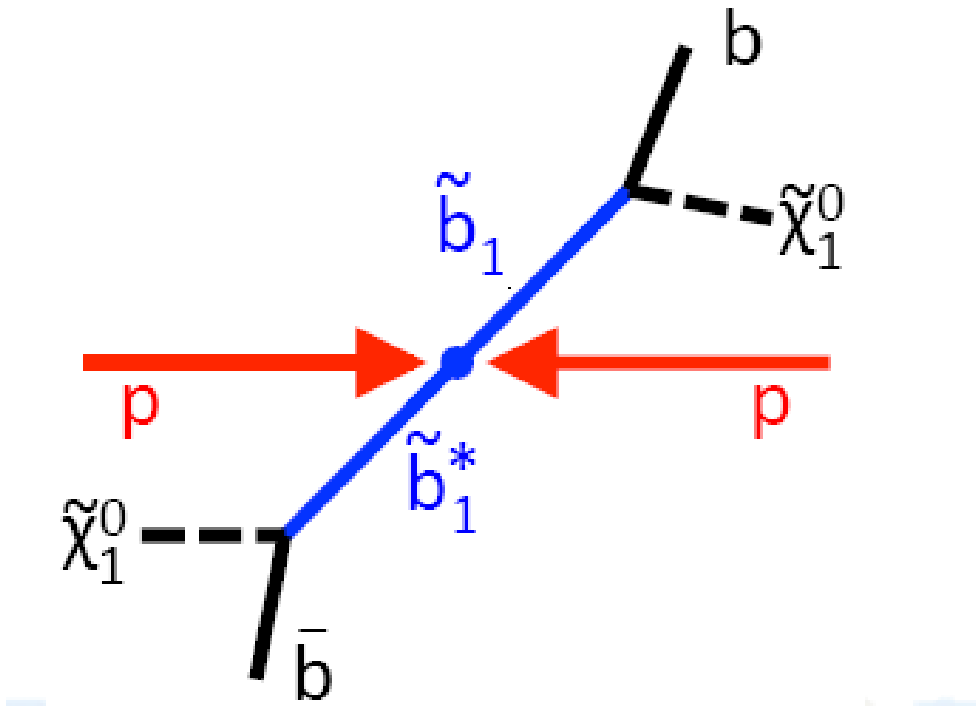
➔Dedicated b-jet, multileptons and jet veto analyses

Direct Sbottom (1)

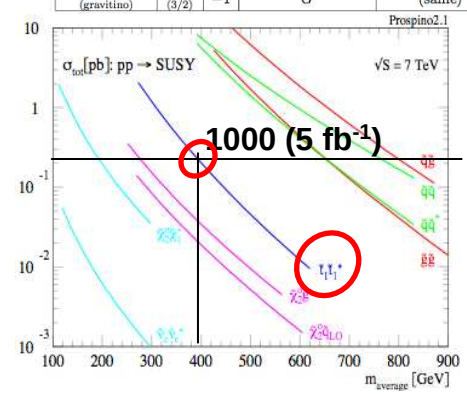
PRL 108 (2012) 181802

❑ The simplest case: direct sbottom

- Assume all other particles high mass and decoupled (Simplified Model)



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	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
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)



➔ A simple final state (though experimentally challenging): 2b +MET

Direct Sbottom (2)

❑ Design an exclusive 2b jet +MET analysis

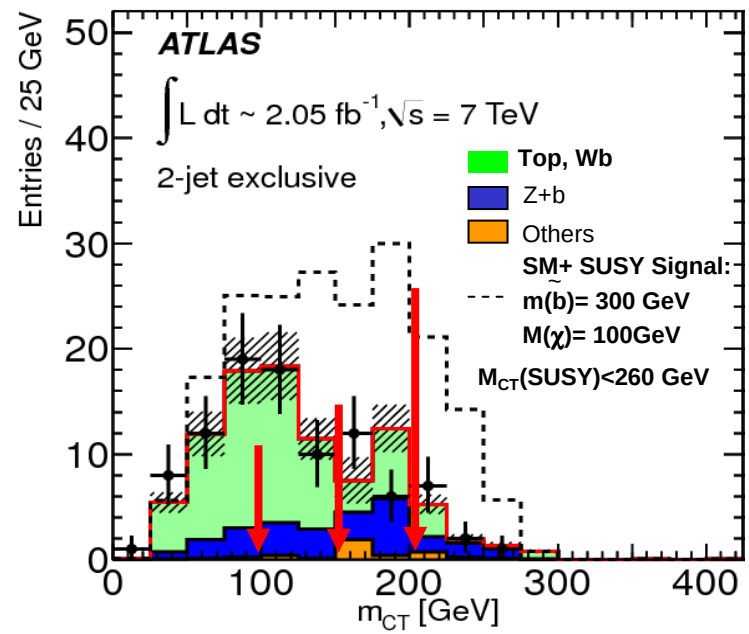
Requirements	
Etmiss [GeV] >	**130**
Pt (j1) [GeV] >	**130**
Pt (j2) [GeV] >	**50**
Lepton and 3rd jet veto	
$\Delta\phi$ (jet-MET) >	**0.4**
MET/Meff >	**0.25**
N(bjets)=	**2 Tight (ε=0.6)**
M_{CT}>	**0, 100, 150, 200**

Trigger-driven

Pile-up-driven

QCD-killers

Discriminating variables
[m_{CT}(ttbar)<135 GeV]



Background determination :

- QCD: jet smearing method (cf. 0lepton)
- top, Wb: Control Region with =1 lep + 2 bjets + MET> 80 GeV
- Z(vv)bb: Control Region with Z mass constraint + 2 b-jets

N_B [m_{CT}>200 GeV] = 8.1 ± 3.5

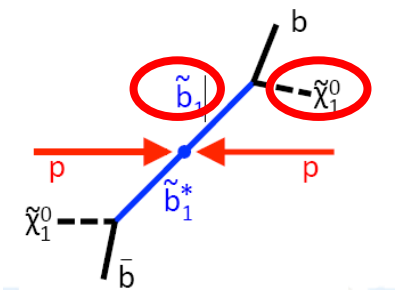
➔Error dominated by stat in Control Regions

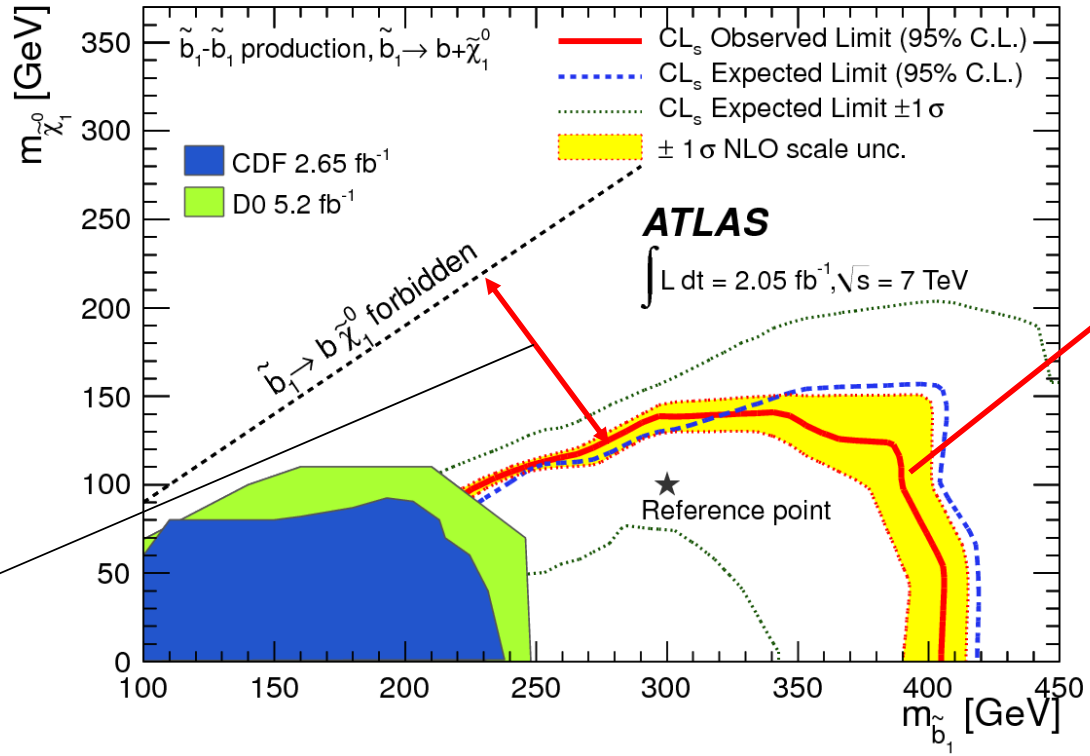
Signal :

- Systematically limited (~40%) because of b-tagging

Direct Sbottom (3)

❑ Interpretation of the results





Tighten M_{CT} cut

Compressed spectrum:

1. **Lower pT cut on jets**
2. **Move to MET trigger only**
3. **Add one more jet (ISR)**

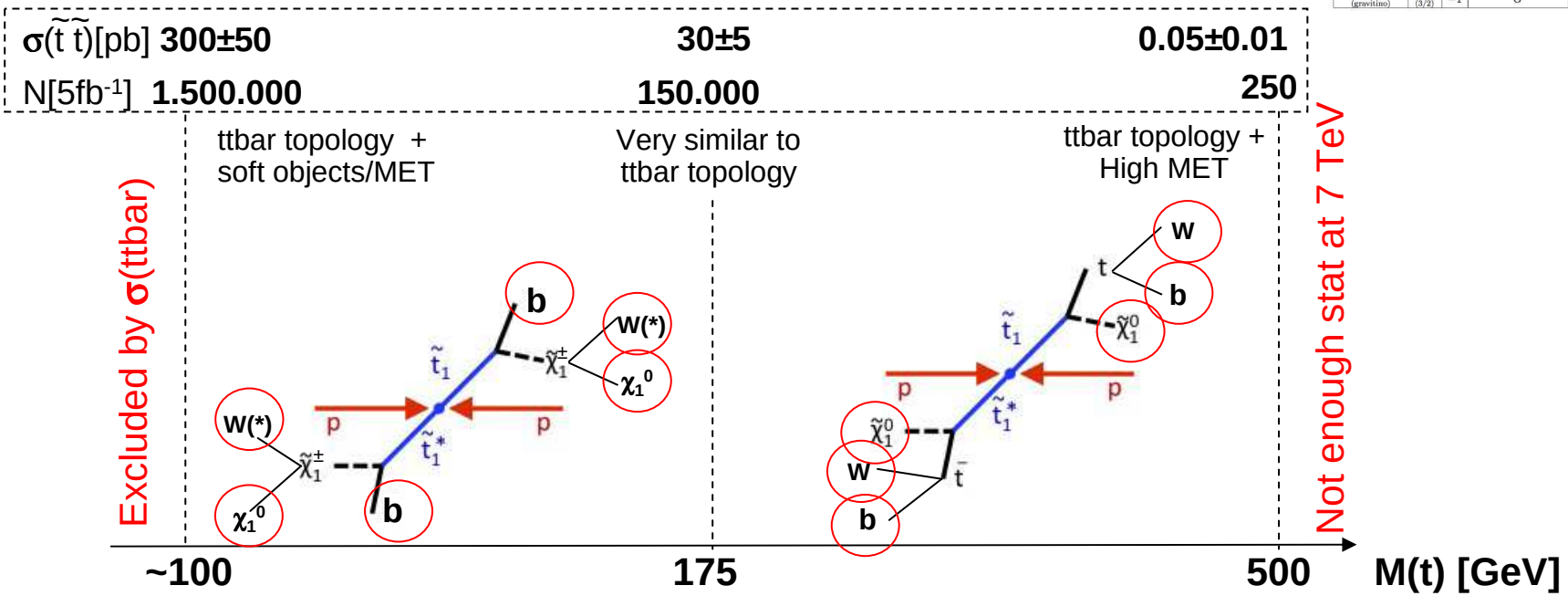
➔ Can still gain a lot in sensitivity

Direct Stop (1)

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	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$ $\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$ $\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	(same) (same) $\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$ $\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$ $\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	(same) (same) $\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
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)

❑ A bit more complicated case: direct stop

- At √s=7TeV, σ(ttbar)= 177±11 pb is measured by ATLAS
  - ➔ Exclude m(stop)<100 GeV



➔ Most promising final states 2b + 2(4)jets + 0(1)lepton + MET

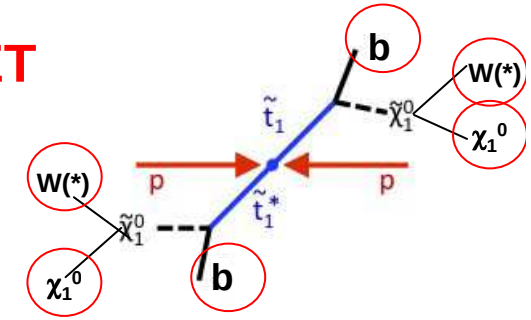
➔ Build few exclusive analyses to catch the beast !

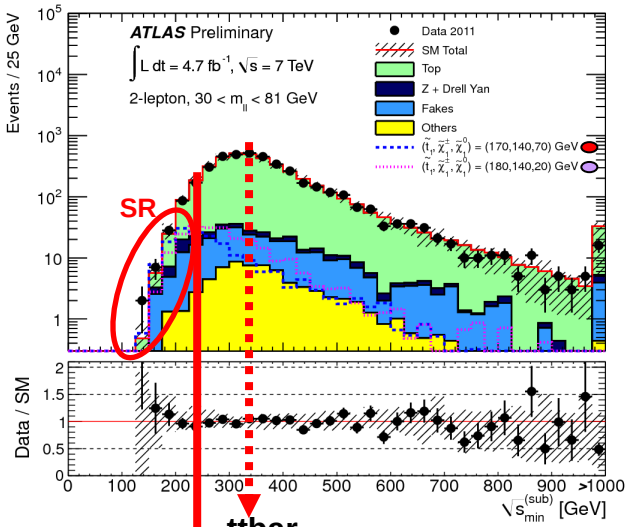
Direct Stop (2)

ATLAS-CONF-2012-070
ATLAS-CONF-2012-059

❑ Example m(stop) < m(top): =2l + ≥1b-jet + ≥1jet + MET

- Like searching for top with a lighter mass
- Background completely dominated by ttbar





ttbar

Analysis cut

Selection (2LSR2)

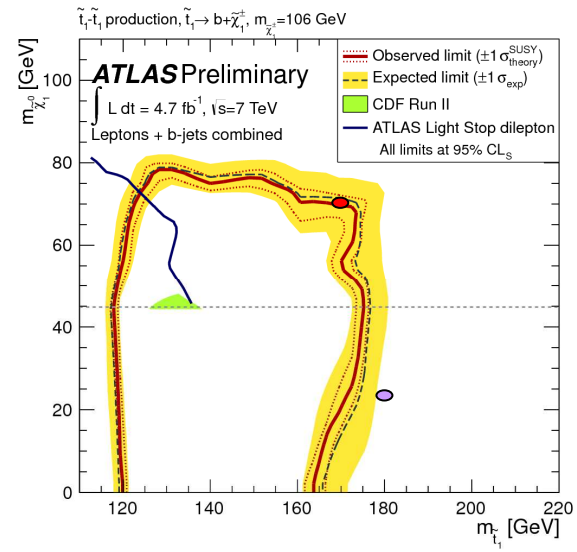
- Trigger : 1 Lepton
- Soft pTcuts on l, b, j (20), MET (40 GeV)
- Upper cuts on Z : $31<m_{ll}<80$
- Global Mass cuts: $\sqrt{s}_{min}$, $m_{lljj}^{(sub)}<140$ GeV

Background

$N_B=46\pm8$
Syst dominated (top theory)

Signal

Errors are ~15% for exp⊕theo around the limit



➔ Consider also =1l + 2 b-jet & =2l + pt(l)<30 GeV, …

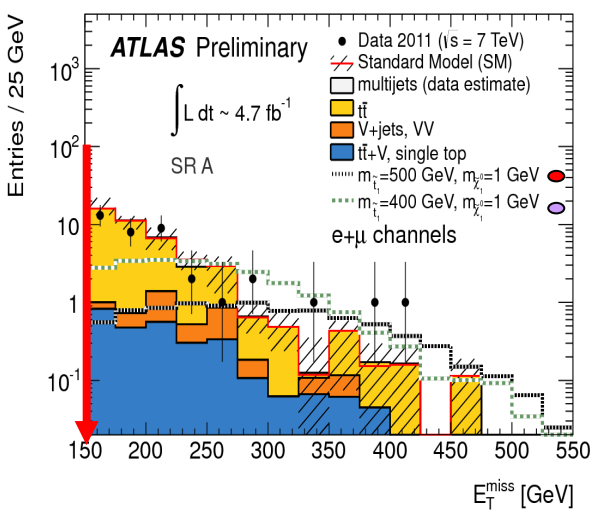
Direct Stop (3)

ATLAS-CONF-2012-073
ATLAS-CONF-2012-071
ATLAS-CONF-2012-074

❑ Example m(stop) > m(top) : =1l + ≥1b-jet + ≥4jets + MET

- Like searching for top with a high MET ➔ Design 5 Signal Regions (show only SRA here)
- Background completely dominated by ttbar

All SRA cuts but MET



Selection (SRA)

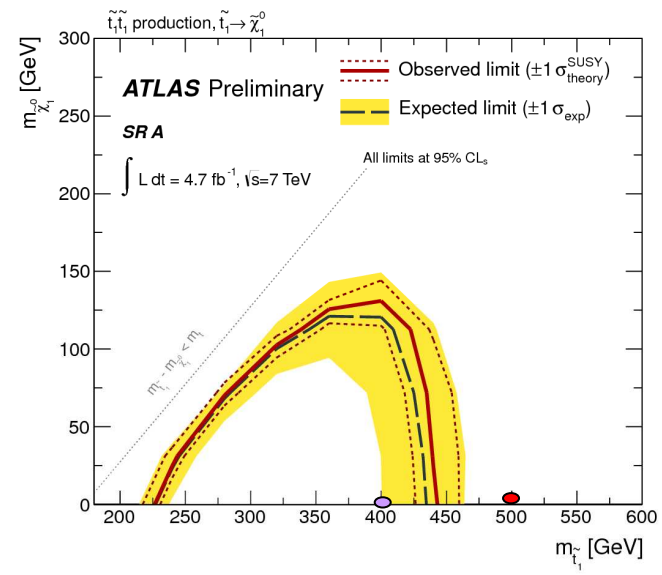
- Trigger: 1 Lepton
- pT(l)>20 + pT(j)>80,60,40,25 GeV
- $\Delta\phi(j,MET)_{min}>0.8$
- Reconstruct had. top (ΔR method)
- $m_T>120$ GeV, $MET/\sqrt{H_T}>7$ GeV$^{1/2}$
- MET>150 GeV

Background

$N_B=42\pm6$
Syst dominated (top theory)

Signal

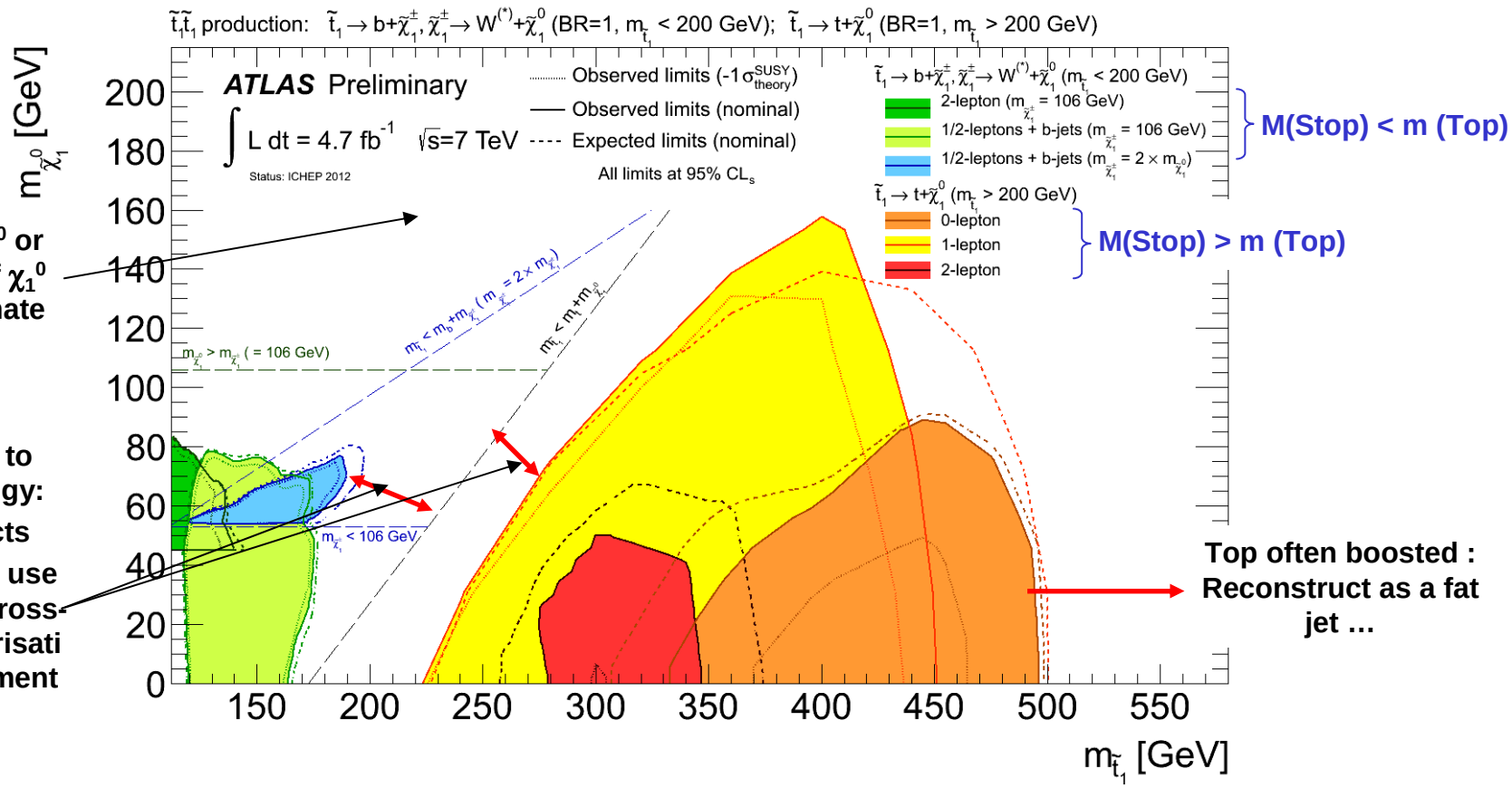
Errors are ~15% for exp⊕theo around the limit



➔ Consider also: =0 l +1-2 b-jet + ≥5-4jets & =2 l + ≥2jets

Direct Stop (4)

- **Current summary after 5 fb^{-1}**



Stop→cχ_1^0 or stop → bff χ_1^0 can dominate

Very close to ttbar topology:
-Soft objects
-Can may be use precise top cross-section/polarisation measurement

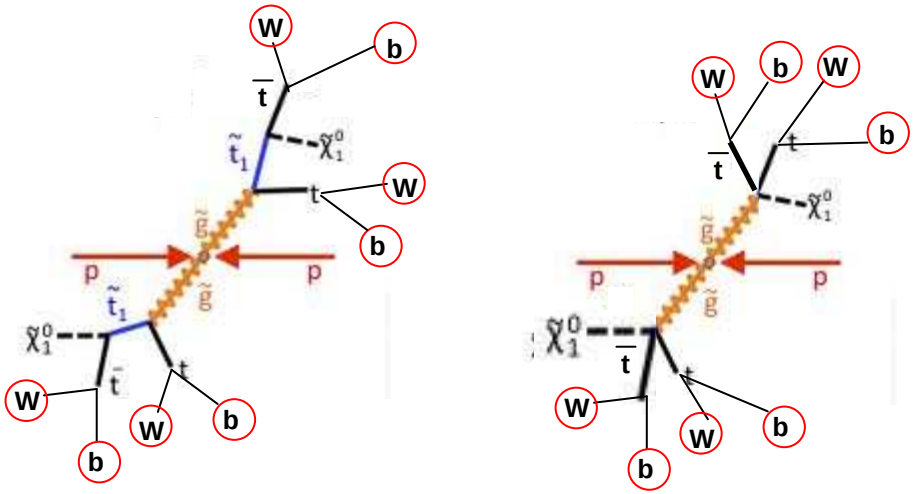
Top often boosted : Reconstruct as a fat jet …

➔ "If you cover the white then Weak scale SUSY is probably dead" R. Barbieri (ICHEP2012)

Gluino Mediated stop (1)

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	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

- **Increase again complexity: $m_{\tilde{g}}$ ~ O (1 TeV)**
  - Stop in gluino cascade dominates
  - Stop on-shell (2 body) or off-shell (3 body decay)



Final state (4 tops !!): =**4b, 4W + High MET**

➔ Need ttbar killers : 0l + ≥3b-jets + MET, Same Sign 2l (+ bjet) + MET, 0l+6-9 jets

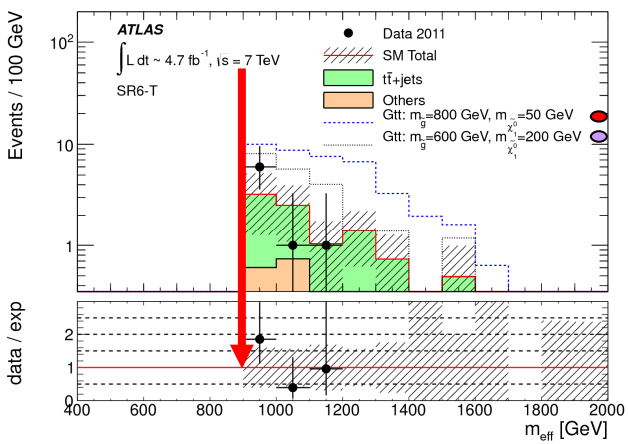
1205.3933, 1205.6615 1206.1760

Gluino Mediated stop (2)

1207.4686
(CMS-PAS-SUS-12-003)

❑ 0lepton + ≥3 bjets analyses

- Experimental challenge: Understand and measure ttbar+jets background in Signal Regions
- 2 Signal Regions w Njets≥6 jets: adjust btagging operating points, MET and M_{eff} cuts



Selection (SR6-T)

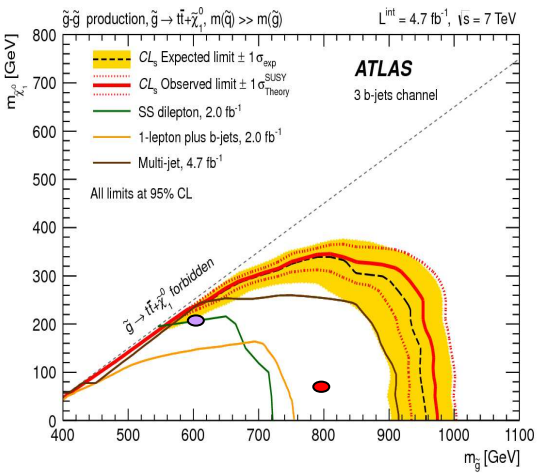
- Trigger : Jet +MET
- Jets: pT(lead.)>160 +≥5 jets pT>50 GeV
- Lepton veto
- 3 bjets Loose (ε=0.75)
- $\Delta\phi(j,MET)_{min}$>0.4, MET/Meff>0.2
- Discr.: MET>200, M_{eff}>900 GeV

Background

N_B=10±3
Syst dominated (top theory)

Signal

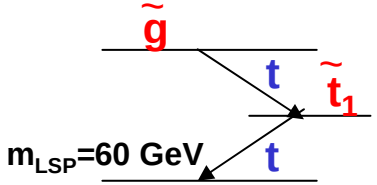
Errors are ~30-10% ⊕ 10-30%
for exp⊕theo around the limit

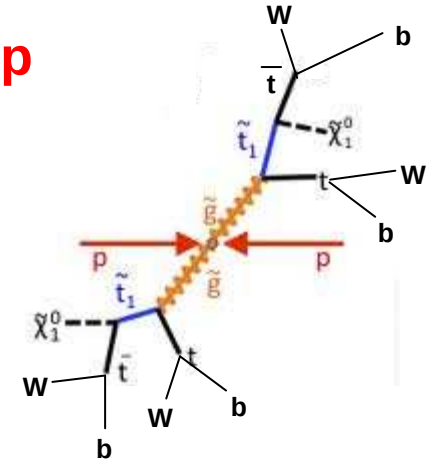


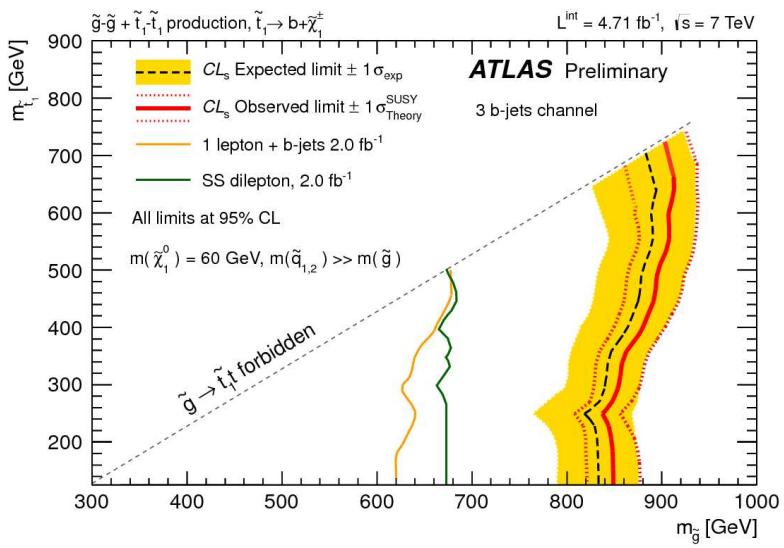
➔ The most optimised for these scenarios

Gluino Mediated stop (3)

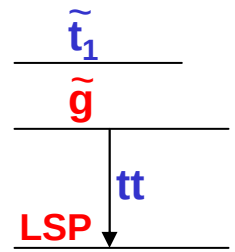
❑ On-shell stop

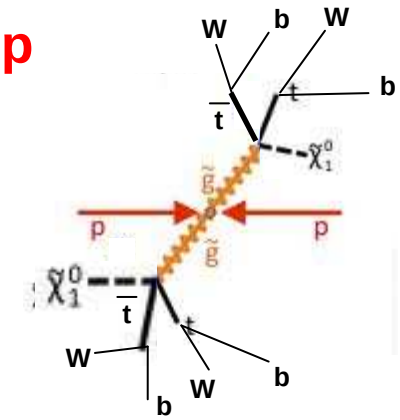


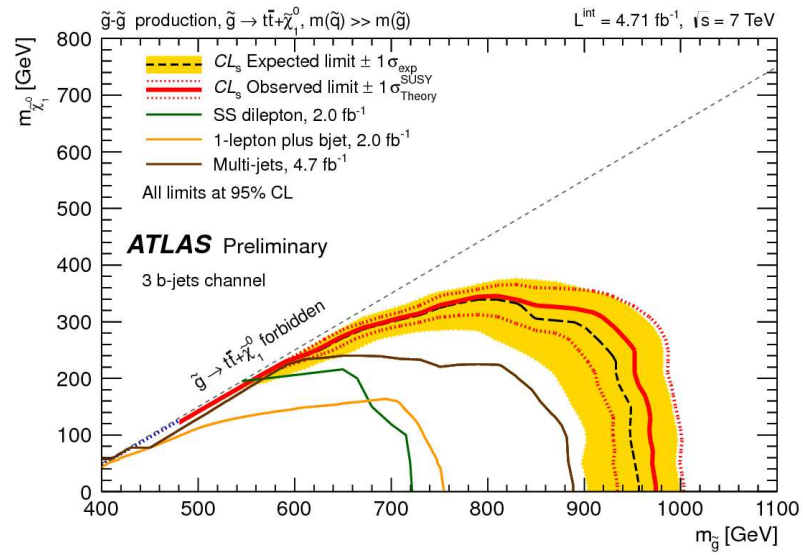




❑ Off-shell stop

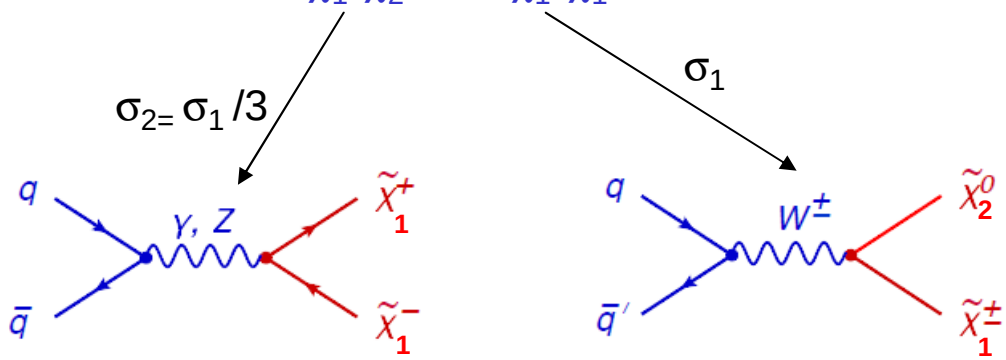




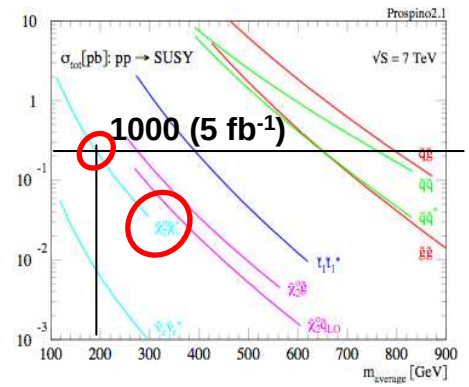


Direct Gauginos (1)

- **If $\tilde{q}$ / $\tilde{g}$ too heavy ➔ only EWK Production !**
  - Gauginos produced in s-channel mediated by γ, Z, W or $h^0/H^0/A^0$
  - Accessible @ 5 fb^{-1}: $\chi_1^{\pm}\chi_2^0$ and $\chi_1^{+}\chi_1^{-}$



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	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
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)



- Focus on gaugino leptonic decays to remove hadronic background
  - ✓ Via an intermediate lepton (BR=50%l, 50%v)
  - ✓ Via an onshell/offshell W (BR~33%) or Z(BR~10%)

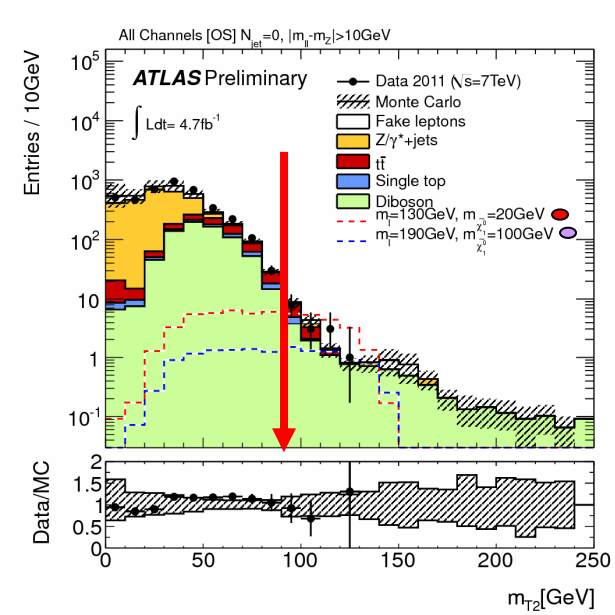
➔ 2 or 3 leptons in final states and no jets

Direct Gauginos (2)

ATLAS-CONF-2012-076

❑ Search for Direct Chargino ➔ =2 leptons + MET +jet veto

- Experimental challenge: consider low pT lepton to gain acceptance
- Dominant background: ttbar dileptonic, WW and Z+jets



Selection (SR-M_{T2})

- Trigger : Lepton OR Dilepton
- Pt (lepton) >20,10 GeV + Jet veto
- Z veto
- MET(rel)>40 GeV
- Discr.: MT2>90 GeV

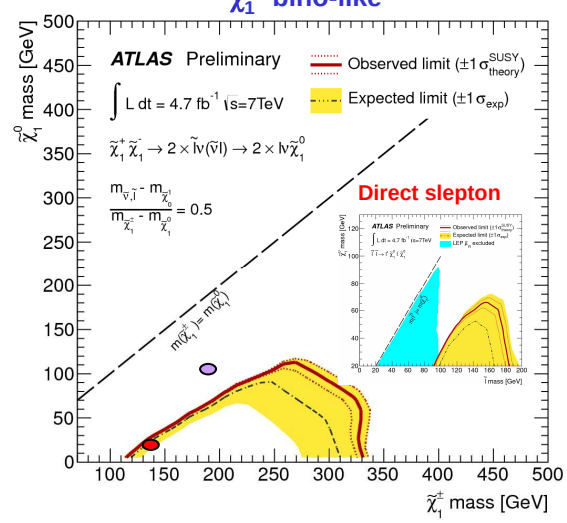
Background

N_B=33±7 (20±7 for Same flavor)
Syst dominated. Mainly from lepton energy scale/resolution + trigger eff.)

Signal

Errors are 10-20% dominated by theo. signal uncertainty

w Intermediate slepton, $\chi_1^{\pm}$ wino-like, χ_1^0 bino-like



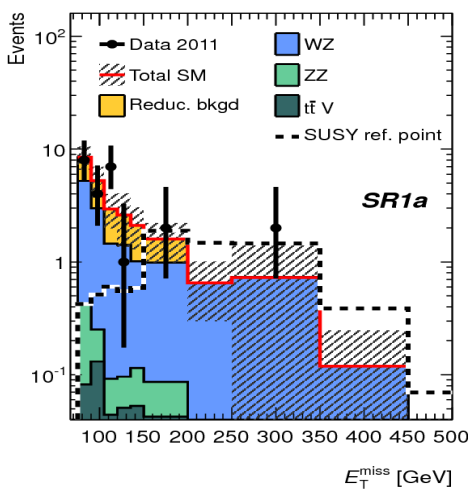
➔ Sensitive also to direct slepton production (beyond LEP!)

Direct Gauginos (3)

ATLAS-CONF-2012-077
(1204.5341)

❑ Search for $\chi_1^{\pm}\chi_2^0$ ➔ =3 leptons + MET

- Similar experimental challenge, but dominant background is now WZ !
- Consider 3 signal regions (w/wo Z veto or w/wo W veto)



Selection (SR1a)

- Trigger : Lepton OR Dilepton
- Pt (lepton) >20,10,10 GeV
- Jet veto, Z veto, bjet veto
- Discr. MET>75 GeV

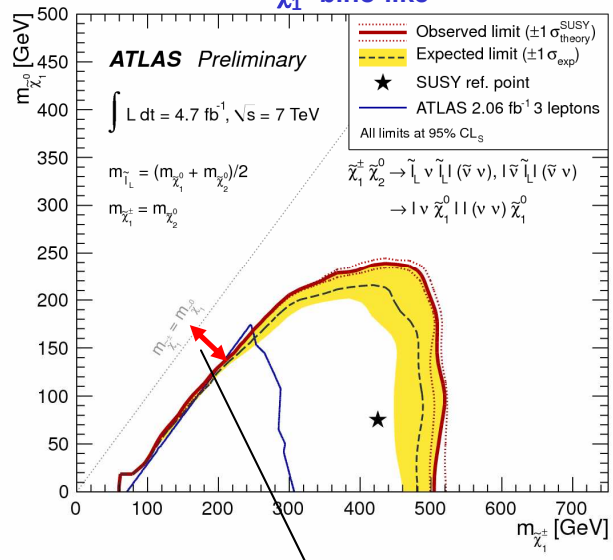
Background

N_B=25±6
Syst dominated. Mainly from WZ theo uncertainties.

Signal

Errors are 10-20% dominated by theo. signal uncertainty

w Intermediate slepton, $\chi_1^{\pm}$/ χ_2^0 wino-like, χ_1^0 bino-like



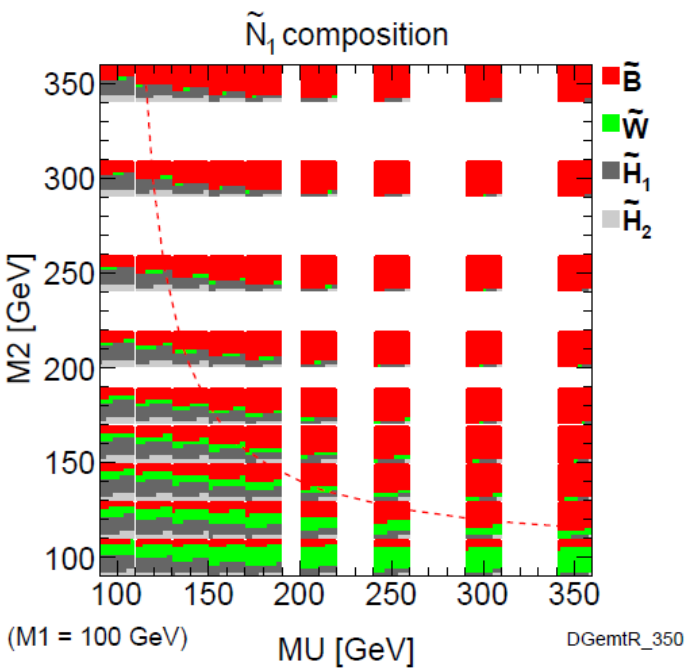
Soft objects + sleptons in the middle

➔ Exclude $m(\chi_1^{\pm})=m(\chi_2^0)$<500 GeV for massless LSP

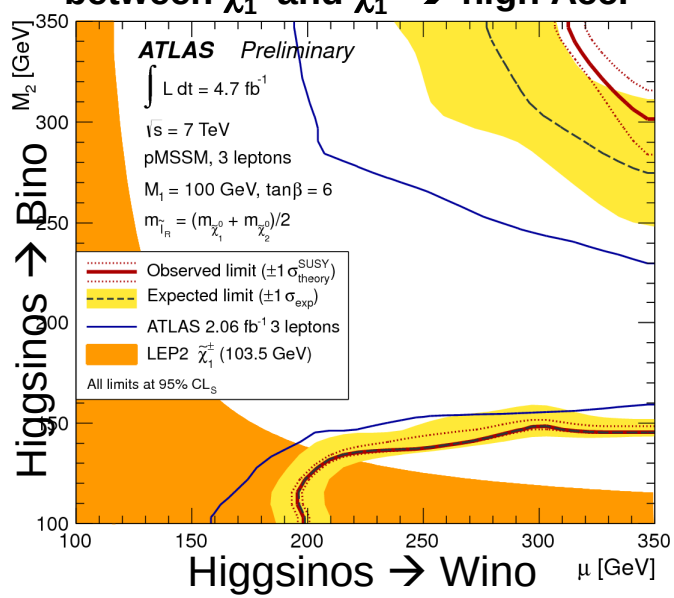
Direct Gauginos (4)

❑ Closer to a real SUSY model ~pMSSM

- Mixing of eigenstates = f(M1 [Bino Mass], M2 [Wino masses], tanβ, μ [Higgses])
- Trilinear mixing all set to 0 except for the stop
- Will benefit of the combination 2l + 3l (in the making)



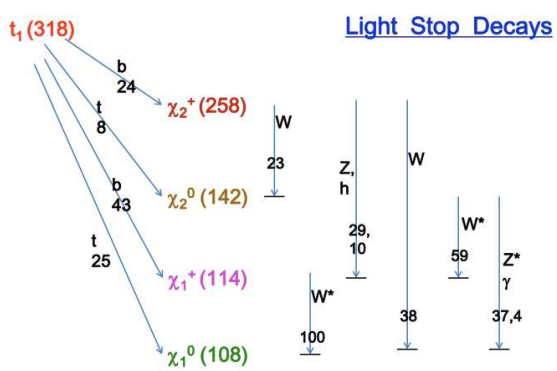
M1=100 GeV, high mass splitting between $\chi_1^{\pm}$ and χ_1^0 ➔ high Acc.

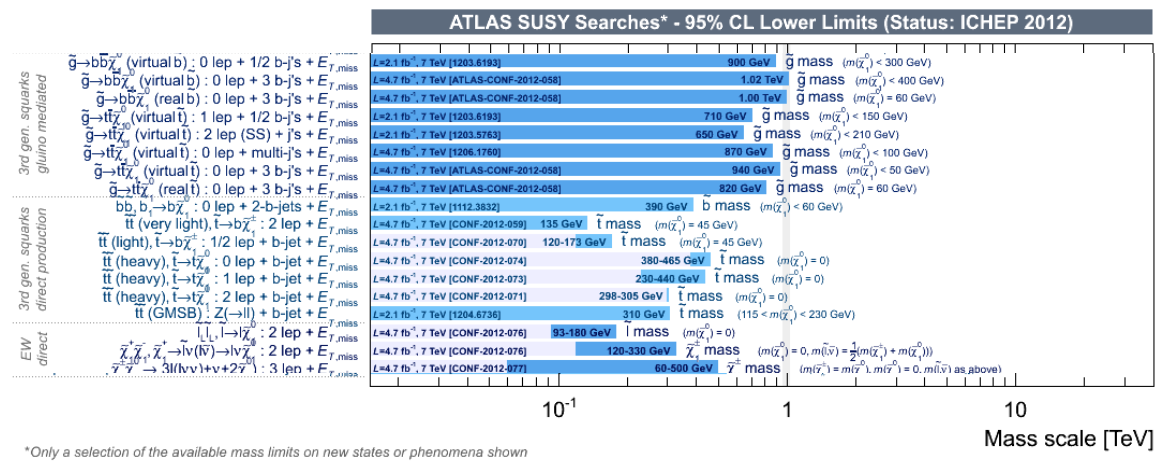


Summary on Natural searches

- **Start to bite seriously in the natural SUSY region**
  - Note: all generic searches also partially sensitive to these decays
  - Consider other LSP flavors: if higgsino-like, expect nearly degenerate $\chi_1^0, \chi_1^\pm, \chi_2^0$ masses
  - Consider other decays: stop→cLSP, Higgs, add taus

➔ Quantify robustness of present analysis wrt these more complex cases



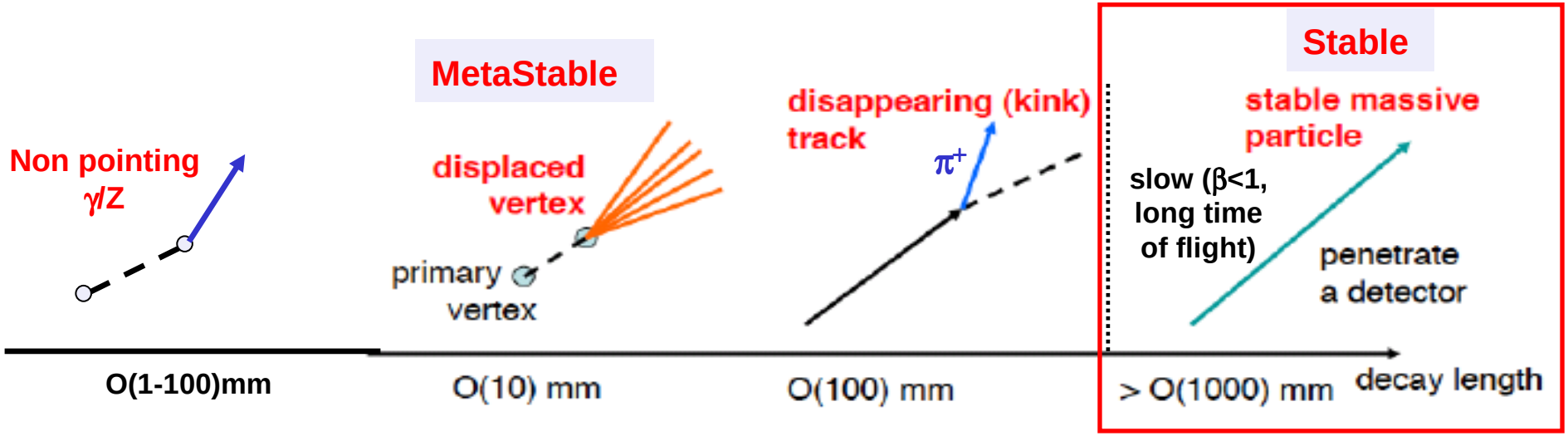


➔ Still viable (R. Sundrum ICHEP2012) !

Long-Lived particles

❑ Some examples (more in back-up)

1. Very weak coupling with $\tilde{G}$=LSP [GMSB] : ➔ Non pointing γ or Z
2. Lifetime proportional to $\lambda^2, \lambda'^2, \lambda''^2$ [R-Parity violation] ➔ Displaced vertex if $\lambda, \lambda', \lambda'' < 10^{-7}$
3. Low mass difference $\Delta M(\tilde{\chi}_1^+ - \tilde{\chi}_1^0) \sim 100$ MeV [AMSB] ➔ Low π emitted, kinked track
4. Stable Massive Particle (mix of 1 and 3) ➔ R-hadron ($\tilde{g}$ or $\tilde{q}$) or sleptons



PAS EXO-11-035, 1207.0627 | PLB 707 (2012) 47, PAS-EXO-11-001 | ATLAS-CONF-2012-034 (See Back-up for more) | ATLAS-CONF-2012-075, 1207.0106, 1205.0272

➔ A bunch of striking signatures, not present in the standard Model !!

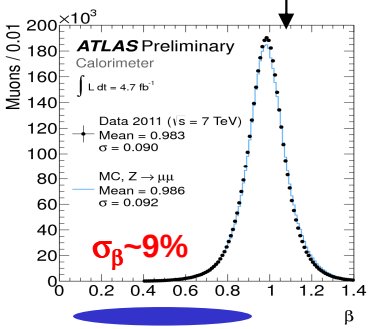
Long-Lived particles (1)

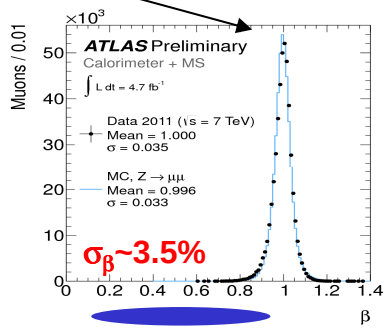
ATLAS-CONF-2012-075

❑ Mass reconstruction of pair produced stable particles

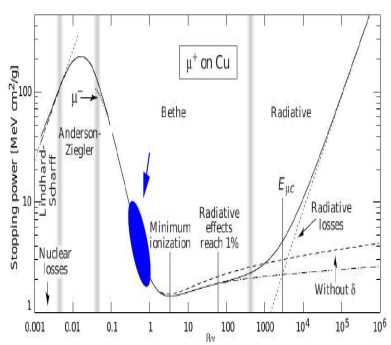
Signal

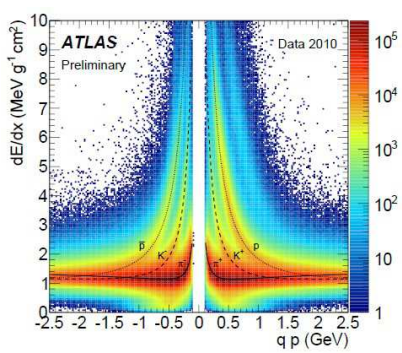
1. Start from one (or two) high pT isolated track →p
2. Measure β (calo or calo+Muon Spectrometer)

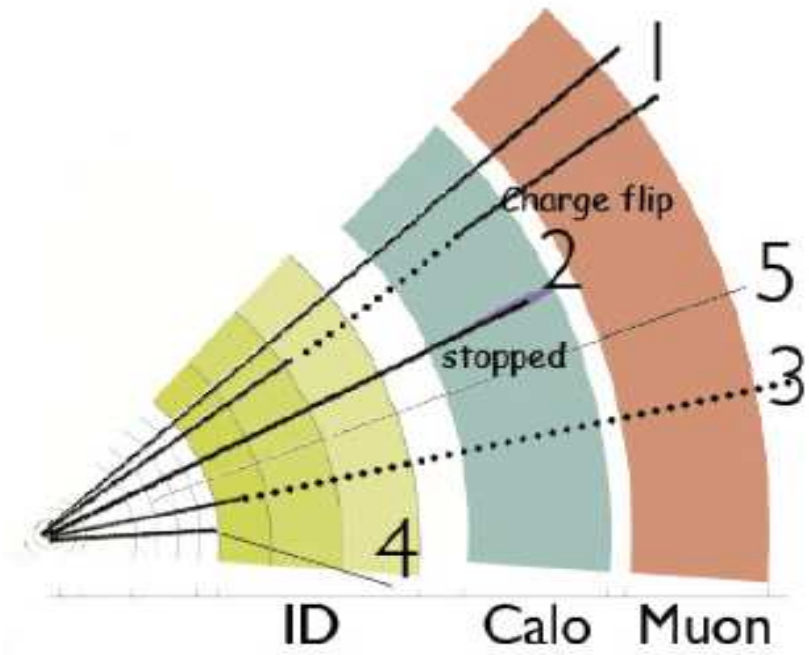




3. Measure βγ (invert Bethe-Bloch) from track clusters







➔ Add the 2 or 3 information together and compute M =p/βγ

Long-Lived particles (2)

❑ Event selection

Requirements	R-hadrons (ID-only)	Stable R-hadrons (ID+calo-only)	Stable R-hadrons (Full Detector)	Stable Sleptons (Full detector, 2 cand.)
	$(\tilde{g}+q\bar{q}$, $g+qqq$, $\tilde{b}/\tilde{t}+\bar{q}$, $qq)$ + ISR			Heavy Muon
Particle Type	Metastable or Charged→Neutral	Charged→Neutral	Charged	Charged
Trigger	MET turn-on			Slow β
Track quality	d0, z0, n (ID-hits)			
Track kinematics	pT>50, p>100 GeV			pT>70 GeV
β Consistency between detectors	No	Yes		
β < [m(g, q, l) dependent]	No	0.8-0.9		0.95
βγ > [m(g, q, l) dependent]	MIP	1.5-2.0		No
M_{β} range (TeV)	No	0.2-1.1 ; 3.0		0.1-0.3 ;
$M_{\beta\gamma}$ range (TeV)		0.2-1.1 ; 3.0		No
Signal Efficiency (%)	6 [m(g)=900 GeV]	7 [m(g)=900 GeV]	11 [m(g)=900 GeV]	40
Systematics (%)	6 (S), 13 (B)	12 (S), 15 (B)	12 (S), 15 (B)	6 (S), 13 (B)

Optimised

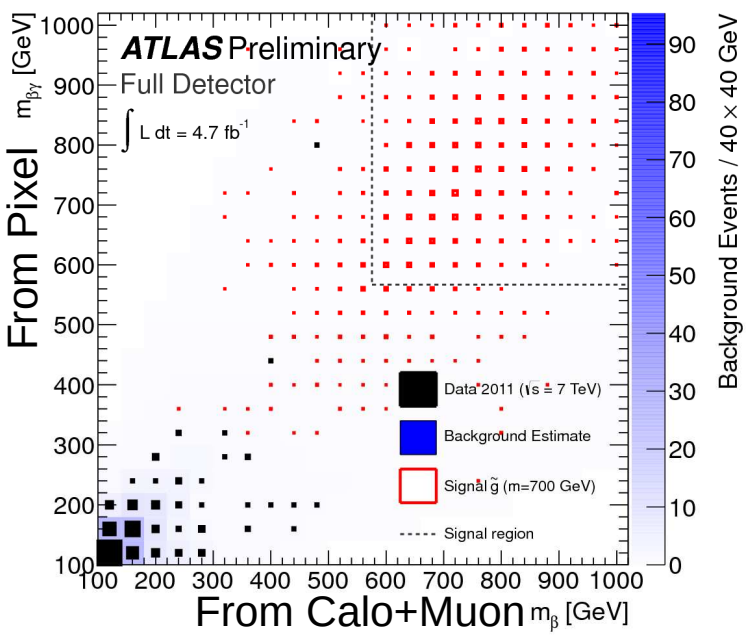
- Background type : high pT muons (tracks) with mis-measured β (dE/dx)
- Background estimate: generate mass spectrum from S/B<<1 ➔ p-templates + β (βγ)-PDF templates
- Signal: Different interaction models, gluino ball fractions (10%, 50 %, 100%).

Long-Lived particles (3)

❑ Mass distributions

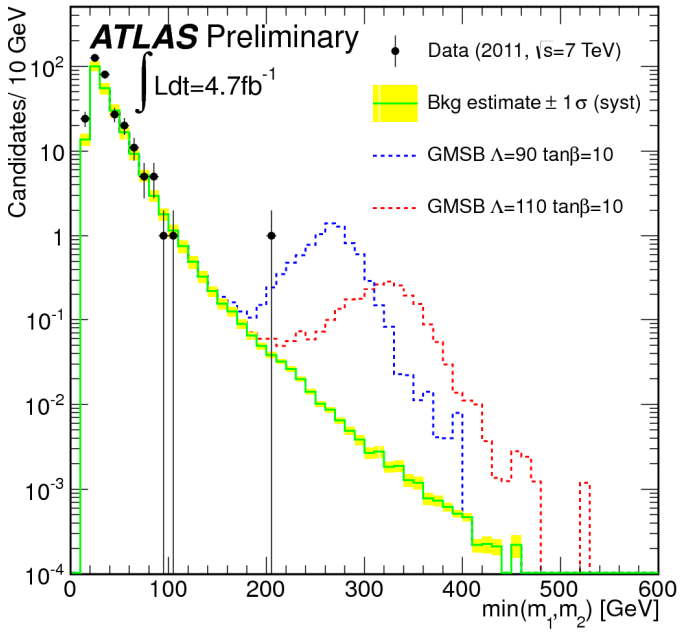
- Cut and count in mass ranges. Very low level of background

R-hadrons: Full detector



Exclude 1 TeV R-hadron (g) and ~600-700 GeV R-hadron (t, b)

Slepton searches (2 candidates)

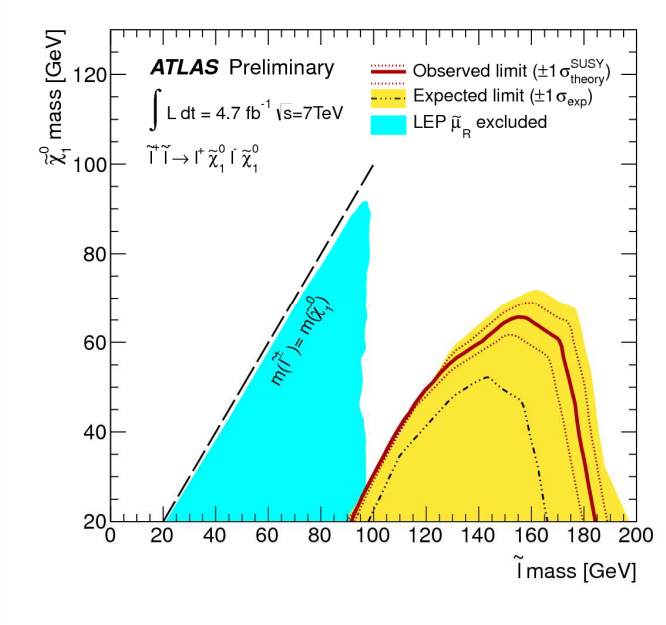


Exclude ~300 GeV sleptons (assuming direct production)

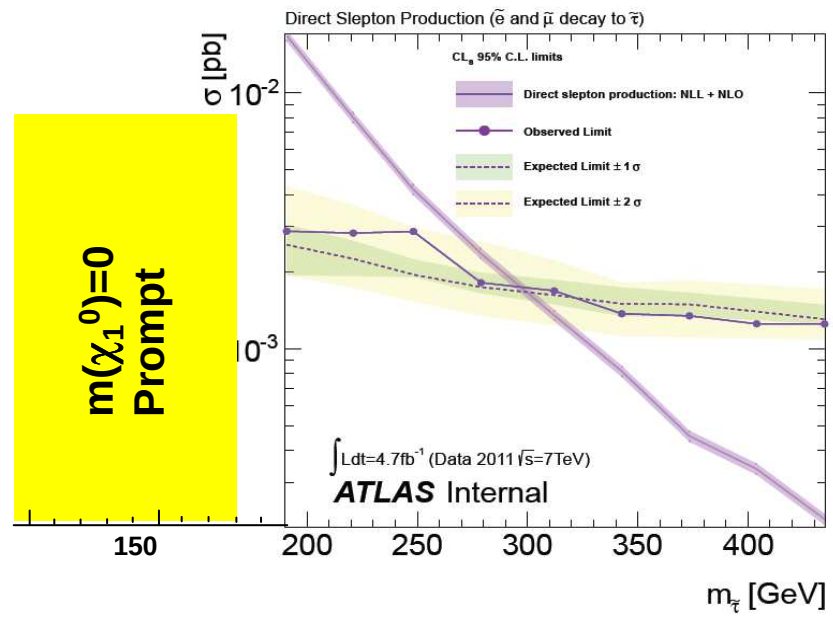
Long-Lived particles (4)

- **Direct sleptons from prompt to stable**

Slepton searches
(2 prompt candidates)



Slepton searches
(2 LLP candidates)



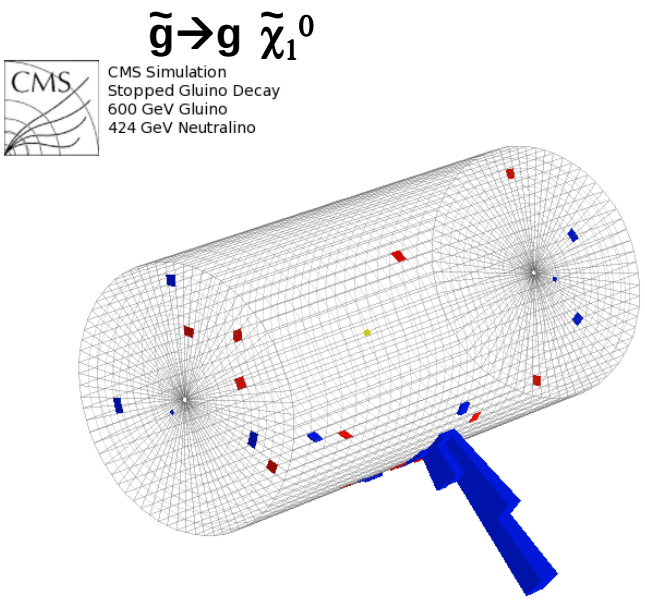
➔ Intermediate region (metastable slepton, i.e. displaced vertex w 1lepton) not covered

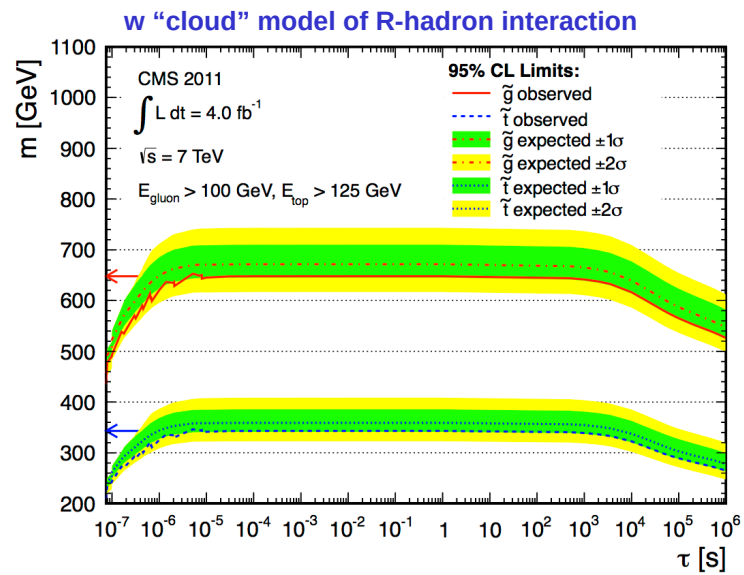
Long-Lived Particles (5)

1207.0106

❑ R-hadrons can also stop and decay later

- Very well motivated (Split SUSY) : stopped gluino only particle reachable at LHC !
- High pT jets in absence of collisions (gaps of LHC beam structure)
- Background = calorimeter noise, cosmics and beam halo not SM !
  - ➔ Control samples: 2010 low lumi run, cosmic runs, beam halo tag&probe in opposite endcaps





➔ $M_{\tilde{g}} < 640$ GeV and $M_{\tilde{t}} < 340$ GeV excluded for 10 μs < τ < 15 min

RPV

❑ R-parity violating search at LHC

$$W = W_{MSSM} + \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\text{Lepton Number Violation (LFV)}} + \kappa_i L_i H_u + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{Baryon Number Violation (BNV)}}$$

- Proton decays only forbids simultaneous violation of lepton and baryon number

From H. Dreiner

	Signature	Model
Multilepton production (including taus)	1) 4 charged leptons: $e^+e^+\mu^-\mu^-$	χ_1^0–LSP, $LL\bar{E}$, $\tilde{\tau}$–LSP, $LL\bar{E}$
	2) 2 leptons, 2 taus: $e^+e^+\tau^-\tau^-$	χ_1^0–LSP, $LL\bar{E}$, $\tilde{\tau}$–LSP, $LQ\bar{D}$
Resonances (2jets, 2x2 jets, 2x3 jets, eμ, eτ, mτ)	3) 6 jets or 2 w/ substructure	χ_1^0–LSP, $\bar{U}\bar{D}\bar{D}$
	4) like-sign dileptons + jets	χ_1^0–LSP, $LQ\bar{D}$
	5) dilepton resonance	$LL\bar{E} \otimes LQ\bar{D}$
	6) mono lepton	$LL\bar{E} \otimes LQ\bar{D}$
Note: Absence of Z and Importance of taus	7) dijet resonance	pure $LQ\bar{D}$
	8) like sign ditau's $\tau^-\tau^-$ + 6jets	$\tilde{\tau}$–LSP, $LQ\bar{D}$

➔ Generally: lower background (no LFV nor BNV in SM) and MET than RPC

RPV (1)

1204.5341

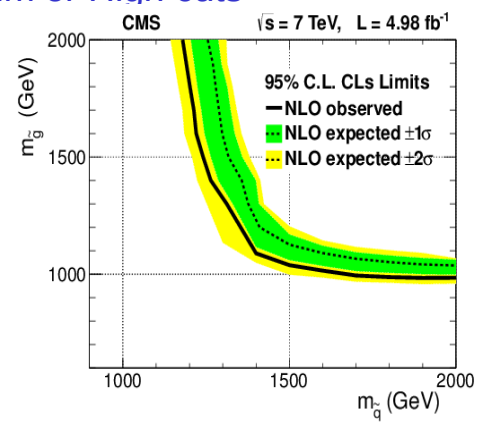
❑ Multilepton (≥3 isolated e, μ or τ_{had}) search

- General search targetting many BSM theories (not only SUSY) → 52 signal regions
- Background: lots of small contribution (ZZ, WZ, γ conversion, tt+X)
- 3 Discriminating variables: N tau, Zeto Veto (ZV), $S_T = M_{Eff}$ low / Medium or High cuts

	Selection	N(τ)=0 obs	N(τ)=0 expect	N(τ)=1 obs	N(τ)=1 expect	N(τ)=2 obs	N(τ)=2 expect
	4ℓ Lepton Results						
4 leptons	4ℓ (DY0) S_T(High)	0	0.0009 ± 0.0009	0	0.01 ± 0.09	0	0.17 ± 0.07
	4ℓ (DY0) S_T(Mid)	0	0.004 ± 0.002	0	0.27 ± 0.10	2	2.5 ± 1.1
	4ℓ (DY0) S_T(Low)	0	0.04 ± 0.02	0	2.98 ± 0.48	4	3.4 ± 1.0
	4ℓ (DY1,ZV) S_T(High)	1	0.009 ± 0.004	0	0.09 ± 0.07	0	0.11 ± 0.05
	4ℓ (DY1) S_T(High)	1	0.09 ± 0.01	0	0.48 ± 0.14	0	0.42 ± 0.15
	4ℓ (DY1,ZV) S_T(Mid)	0	0.06 ± 0.02	1	0.83 ± 0.24	1	0.92 ± 0.29
	4ℓ (DY1) S_T(Mid)	0	0.42 ± 0.10	5	3.9 ± 1.1	3	3.4 ± 0.9
	4ℓ (DY1,ZV) S_T(Low)	0	0.08 ± 0.04	7	5.4 ± 2.2	19	13.6 ± 6.4
	4ℓ (DY1) S_T(Low)	2	0.75 ± 0.32	19	16.9 ± 4.6	95	60 ± 31
	4ℓ (DY2,ZV) S_T(High)	0	0.02 ± 0.01	–	–	–	–
	4ℓ (DY2) S_T(High)	0	0.84 ± 0.32	–	–	–	–
	4ℓ (DY2,ZV) S_T(Mid)	0	0.19 ± 0.08	–	–	–	–
	4ℓ (DY2) S_T(Mid)	3	7.4 ± 3.0	–	–	–	–
	4ℓ (DY2,ZV) S_T(Low)	1	2.3 ± 1.0	–	–	–	–
	4ℓ (DY2) S_T(Low)	29	27 ± 11	–	–	–	–
	3ℓ Lepton Results						
3 leptons	3ℓ (DY0) S_T(High)	2	1.12 ± 0.43	17	11.0 ± 3.2	20	22.3 ± 6.0
	3ℓ (DY0) S_T(Mid)	5	7.3 ± 3.0	113	96 ± 31	157	181 ± 24
	3ℓ (DY0) S_T(Low)	17	13.3 ± 4.1	522	413 ± 63	1631	2016 ± 253
	3ℓ (DY1,ZV) S_T(High)	6	3.3 ± 0.9	10	13.0 ± 2.3	–	–
	3ℓ (DY1) S_T(High)	17	17.6 ± 5.6	35	39.0 ± 4.7	–	–
	3ℓ (DY1,ZV) S_T(Mid)	32	24.6 ± 6.4	159	141 ± 27	–	–
	3ℓ (DY1) S_T(Mid)	89	97 ± 29	441	462 ± 41	–	–
	3ℓ (DY1,ZV) S_T(Low)	126	147 ± 36	3721	2981 ± 418	–	–
	3ℓ (DY1) S_T(Low)	727	797 ± 189	17631	15751 ± 2452	–	–

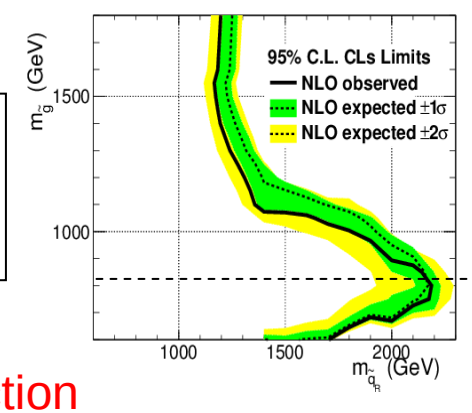
Leptonic RPV in strong production

M(LSP-Bino)=300 GeV
$\lambda_{e\mu\tau} \neq 0$



Hadronic RPV in strong production

M(bino)=500 GeV
M(sleptons)=300 GeV
M (LSP-Wino)=150 GeV
λ''≠0 :LSP→jjj



Low BR (g→Bino)

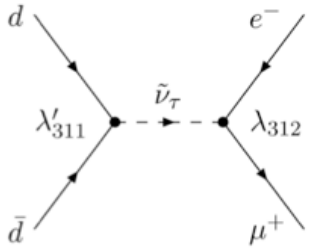
➔ Also sensitive to direct gauginos production

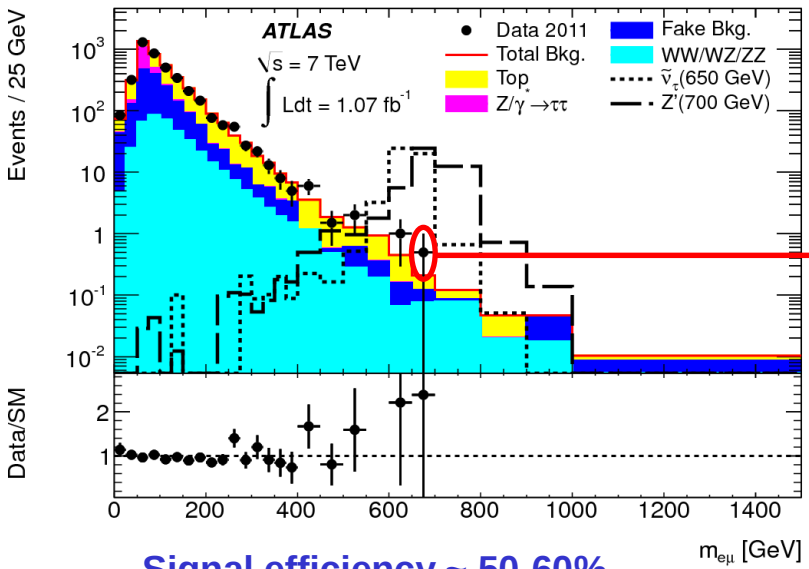
RPV (2)

EPJC 71 (2011) 1809

❑ Lepton flavor violation resonance

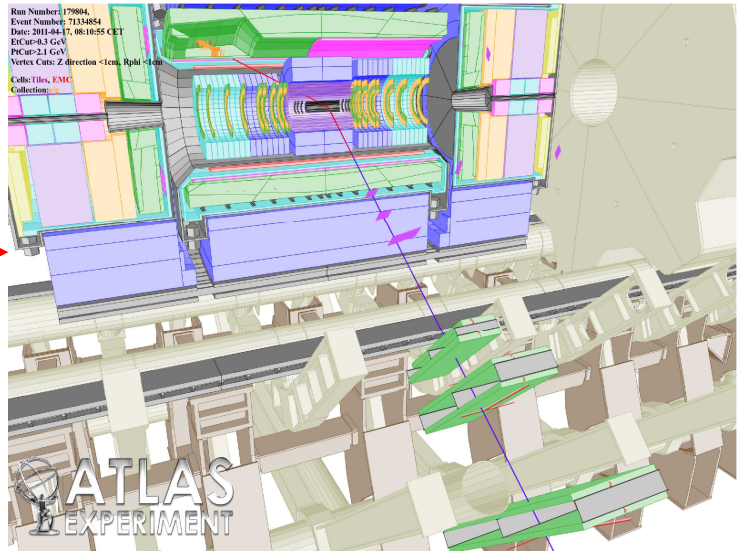
- Lepton flavor violation brought by sneutrinos decay (s-channel)
- Look in eμ spectrum inside +/-3 σ





Signal efficiency ~ 50-60%

Δϕ (e, μ)~π , MET=132 GeV, no Jet !

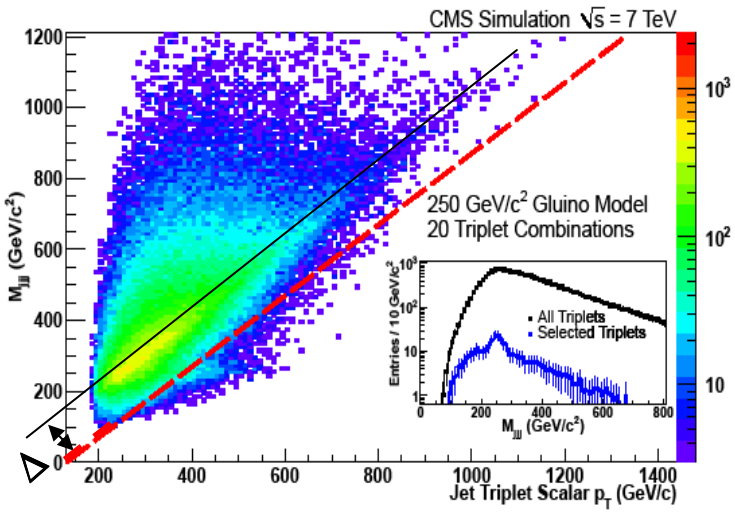


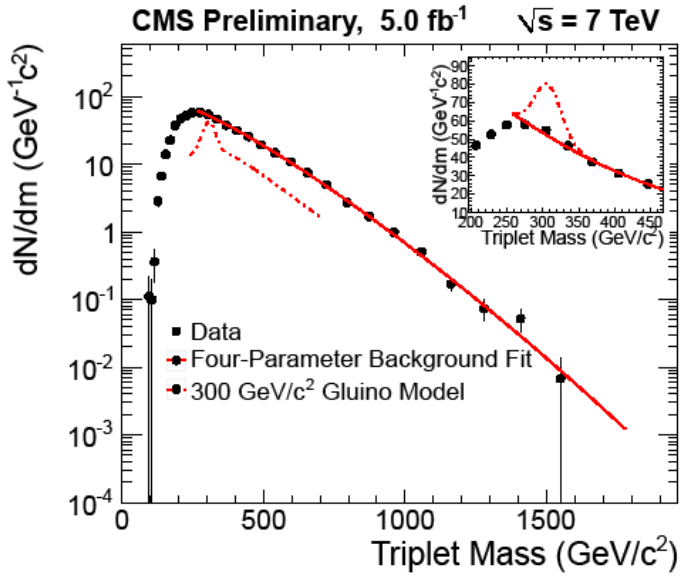
RPV (3)

EXO-11-060 (no PAS)

❑ 2x3 jets resonance

- Selection: 6 jets + Mjjj < ΣpT(jjj) - Δ: reduce combinatory (signal & background), search for a mass peak
- Interpret the results in RPV models with gluino →jjj
- Note: ISR systematics not taken into account for signal



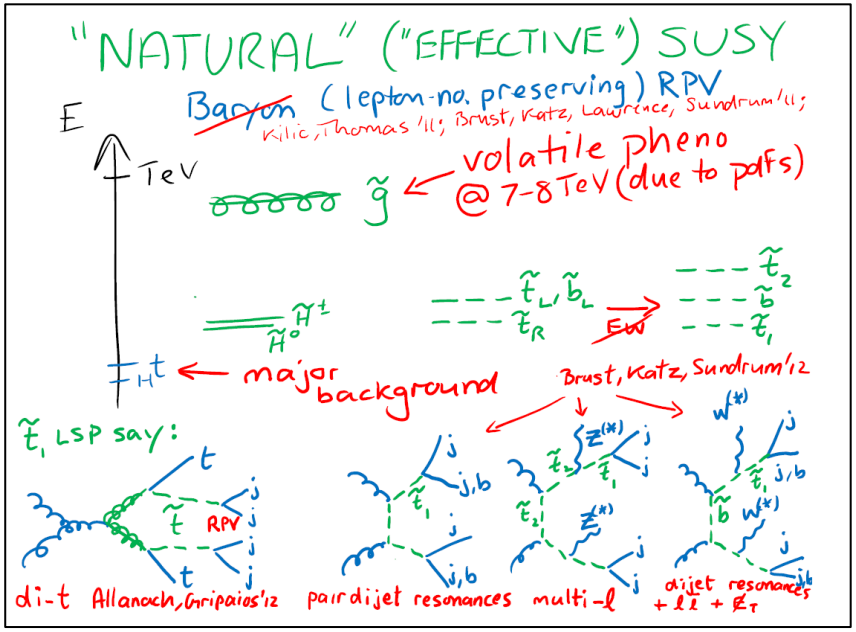


➔ Exclude Gluino masses [200;460] GeV with 35pb^{-1} and 5 fb^{-1}

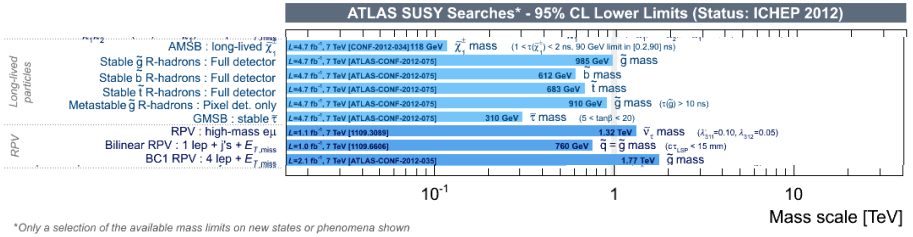
Summary on LLP/RPV searches

❑ An increasing center of interest !

- Lots of very striking signature to discover SUSY (may be hiding in the current data)
- One of the best motivated explanation to the absence of signal in inclusive/natural searches



R. Sundrum (ICHEP 2012)



➔ May be the (only) possible future of SUSY ?

LHC Future Prospects

❑ Discovery reach @ 8 and 14 TeV

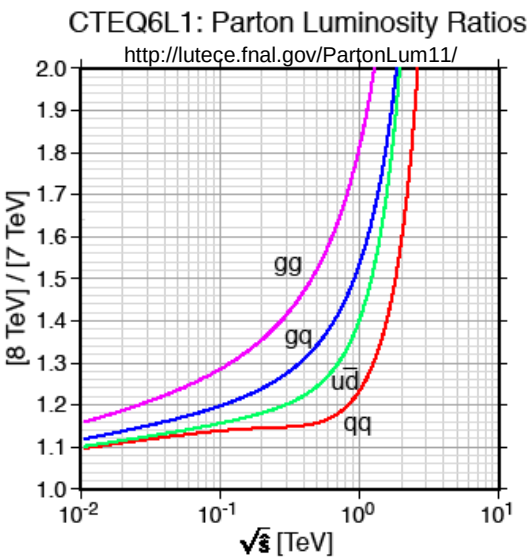
- For energy frontier (gluinos, squarks)

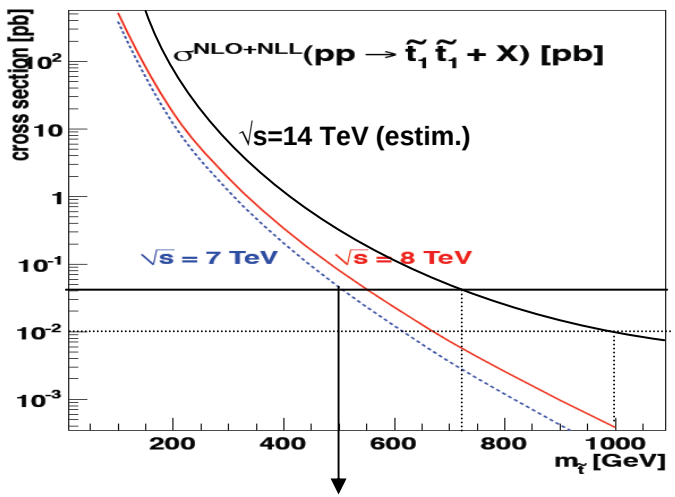
  ➔ Extend m_g by 100 GeV if $\sqrt{s}_{new}$ [TeV]= $\sqrt{s}_{orig}$ + 1 or L_{new} [fb^{-1}]=10xL_{orig}

ATL-PHYS-PUB-2011-003

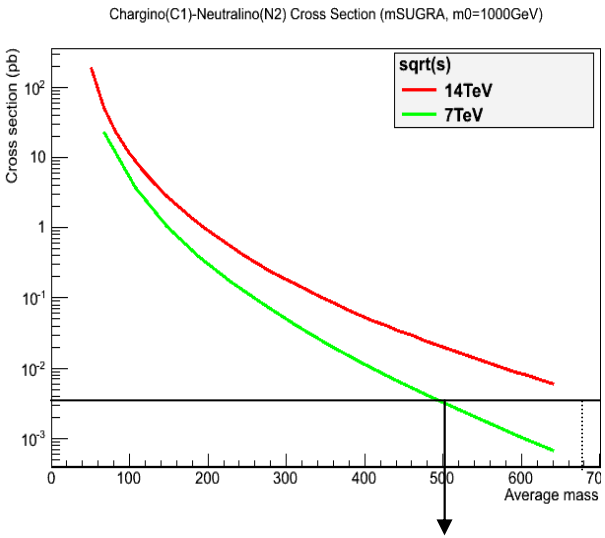
- For stop / sbottom / gauginos ~ top mass

  ➔ Generally ttbar main background : S/B constant vs $\sqrt{s}_{new}$ but S/√B increases





Limit for M(LSP)=0 @ 5 fb^{-1}



Limit for M(LSP)=0 @ 5 fb^{-1}

Conclusions (1)

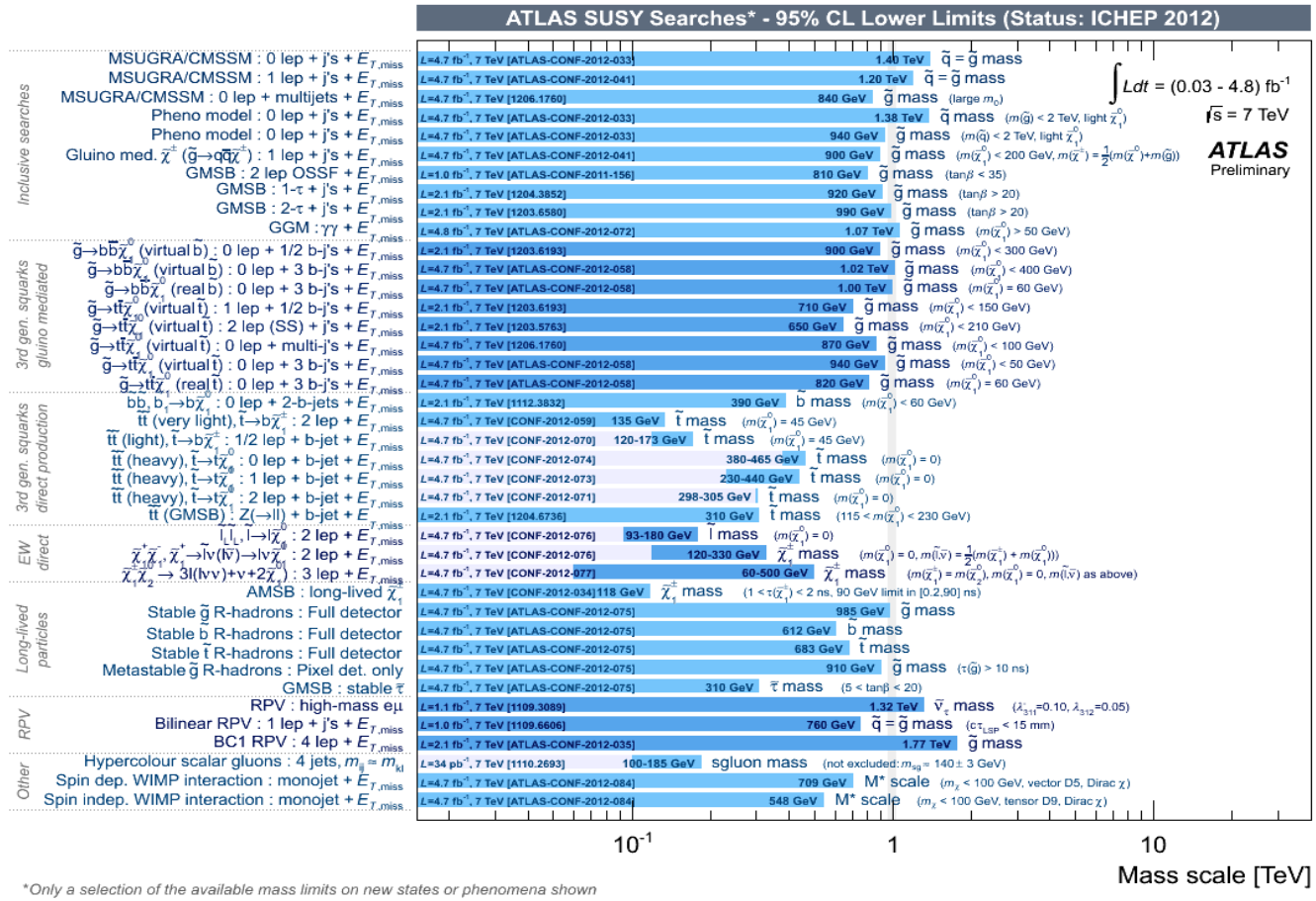
- **Very active search of Weak scale SUSY at LHC**

1.Inclusive searches

2.Natural SUSY

3.Long-Lived Particles

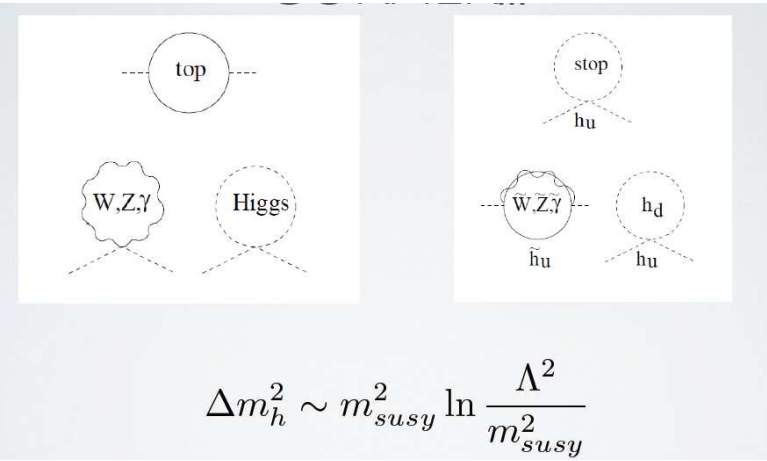
4.RPV



➔ Reach the 1 TeV limit and huge improvment compared to previous experiments !

Conclusions (2)

- **Weak scale SUSY is (still) a natural and front-runner theory beyond SM …**



- Provided it is right around the corner
- Remember that cross-sections can be quite low for many SUSY processes (lots of scalar)
  - ➔ for Higgs it took ~40 years !
  - ➔ Complicated by RPV/LLP ?

- **… But, let's be fair also, no sign of it (yet)**
  - LEP+LHC: no hint … SUSY **not** around the corner ??
    - ➔ Need a sign before the closing of LHC (presently keep all possibilities open) !
  - May be it's **not** weak-scale SUSY but **Split SUSY** (not natural) ?
  - Or may be SUSY is **not** driving beyond SM (Strong coupling to the Higgs)

Conclusions (3)

The three main scenarios

G. Altarelli
Joint EPS-ECFA meeting
July 26, EPS-HEP 2011

LHC scenarios

1 Catastrophic: No Higgs, no new physics

Can only occur if the LHC is not enough to fully probe the EW scale: unitarity violations impose one or the other (eg new vector bosons) or both

2 Theorist projection: non standard Higgs and new physics

A lot of model building in this direction

3 Pure SM: A light scalar Higgs, no new physics at the EW scale

If so, nature does not abhor fine tuning at all

This is the paradigm that experiment must try to falsify

➔ Clearly we are evading 1 and (hopefully) moving to 2 !

Some usefull links

- **Bibliography** http://pralavop.web.cern.ch/pralavop/phd.html
- **ATLAS public results** https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- **CMS public results** https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- **LHC Status** http://lhc.web.cern.ch/lhc/
- **Questions** pralavor@cppm.in2p3.fr

SPARE

Appetizers for tomorrow

- Weak-scale SUSY searches **before** first LHC SUSY results

MSSM: 29 sparticles + 5 Higgs undiscovered

Mass Limits from PDG2010 (95% CL)
$\tilde{\chi}_1^0$=LSP, RPC, degenerate squarks (except $\tilde{b}$,$\tilde{t}$), $\tilde{l}=\tilde{l}_R$, Gaugino mass unification at GUT scale

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates	
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$	**114.4 , 92.8 , 93.4 , 79.3 GeV** (m_h^{max} benchmark scenarios)
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)	**379 GeV**
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)	
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$	**95.7 , 89 GeV**
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)	**107 GeV**
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)	**94 GeV**
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$	**81.9 GeV**
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$	**46 , 62.4, 99.9 , 116 GeV**
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$	**94 GeV**
gluino	1/2	−1	$\tilde{g}$	(same)	**308 GeV**
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)	

Note: These limits are also model dependent

Covers most of SUSY production and decays ... But most in the 0-100 GeV range limited by √s

➔ Come back tomorrow to explore the 0.1-1 TeV range !

CMS Multilepton Generic Search (1)

Three or more electrons, muons or taus. Up to two tau's reconstructed.

54-channel ST table and 52 channel MET/HT results on and off Z

Signal (low-bkgnd) and control (high bkgnd) channels treated uniformly.

CMS multileptons in this talk:

a) Strong production GMSB slepton co-NLSP

b) R-parity Violation (Leptonic)

c) Sensitive to accidents of spectrum (strong production captured by lepton sector)

d) Missing MET: e.g. RPV (Hadronic): S_T comes handy

e) Electroweak Production: cut-and-count (shown), [fitting MET/MT in progress]

SURPRISES (detailed background studies)

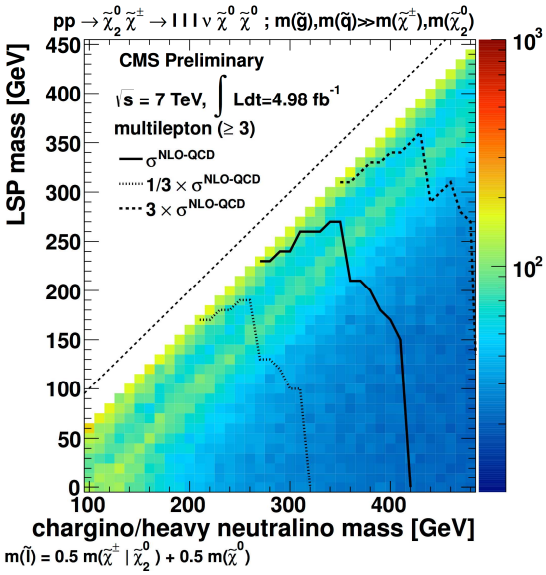
- CMS pristine di-Z event ~5/pb (2010)
- Very rare four lepton event(s) in 2011, still outstanding.
- Next: Trimuon Z (!!!???) and impact on Higgs

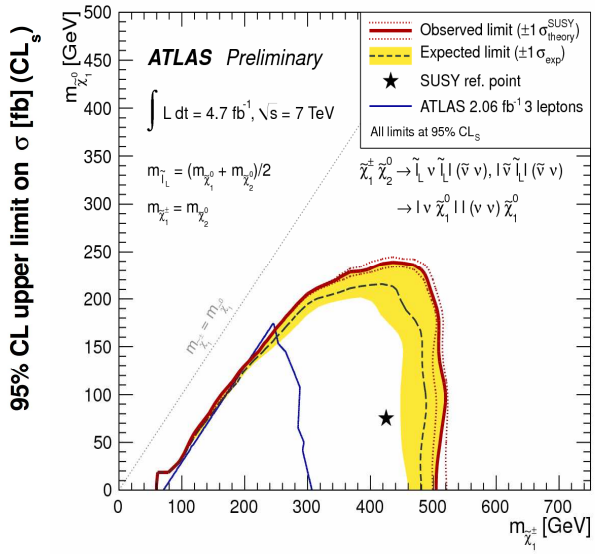
Sunil Somalwar, Rutgers, Blois 29-May-2012 37

CMS Multilepton Generic Search (2)

❑ Sensitivity to direct gauginos (=3 leptons + MET)

- $\chi_1^{\pm}/\chi_2^0$ wino-like, χ_1^0 bino-like

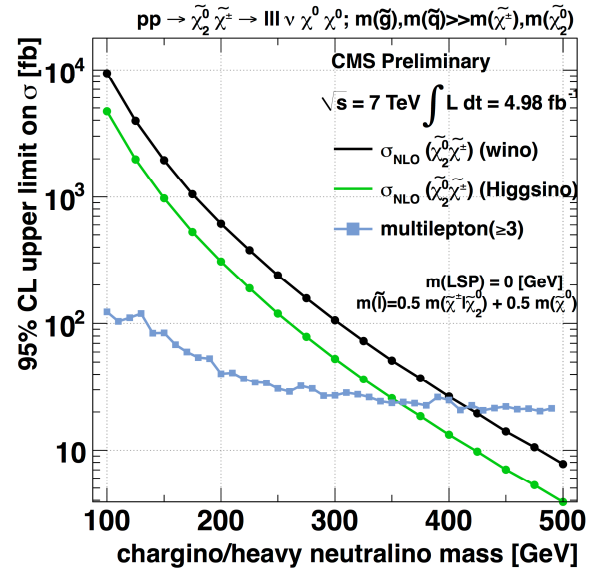




Force decay to lepton to 100 % (do not consider ν)

Force decay to lepton and ν

- $\chi_1^{\pm}\chi_2^0$ (mLSP=0)



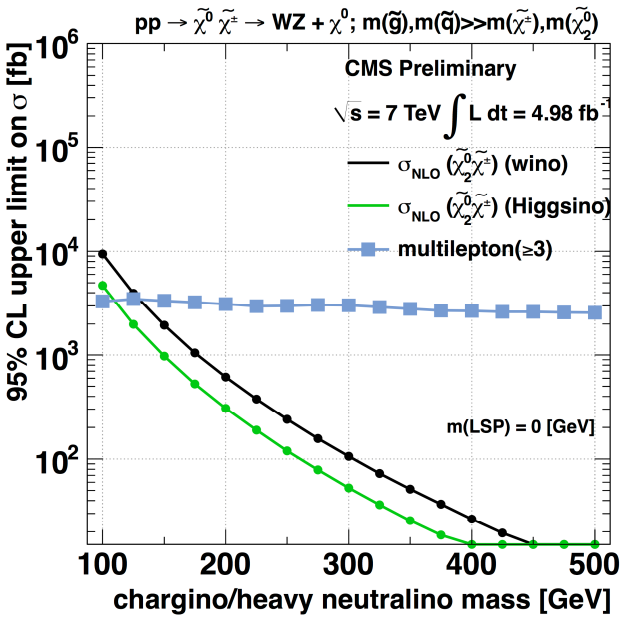
Lower sensitivity to Higgsino $\chi_1^{\pm}\chi_2^0$ case (more compressed spectra)

Dedicated search more powerful

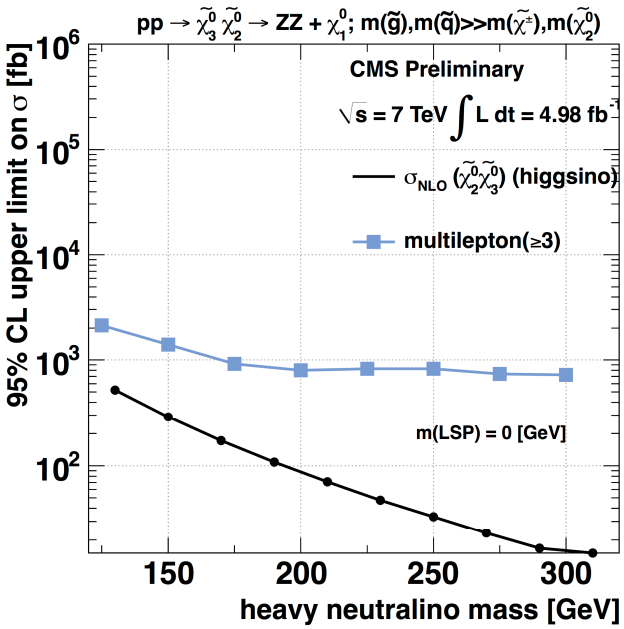
CMS Multilepton Generic Search (3)

❑ Sensitivity to direct gauginos (=3 leptons + MET)

- $\chi_1^{\pm}$/ χ_2^0 wino-like, χ_1^0 bino-like: Decay through W and Z (not intermediate lepton), M(LSP)=0



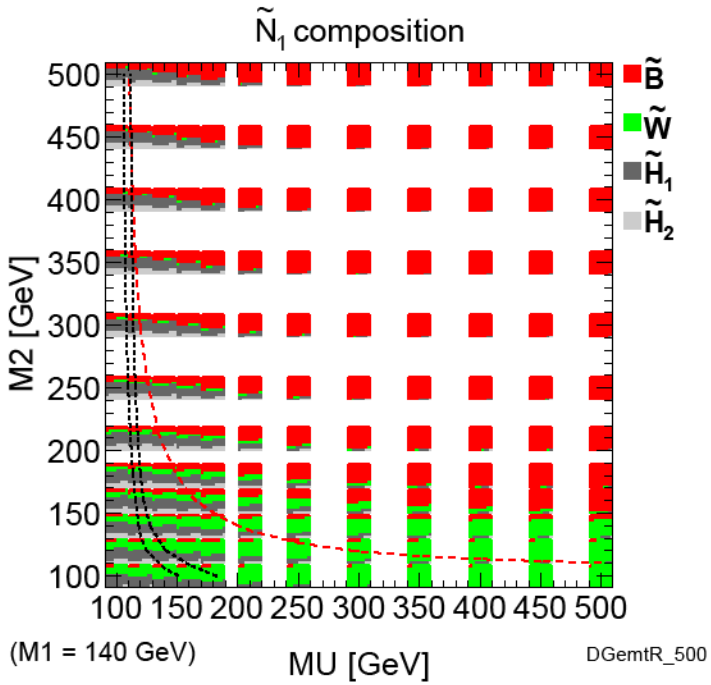
➔ Barely sensitive



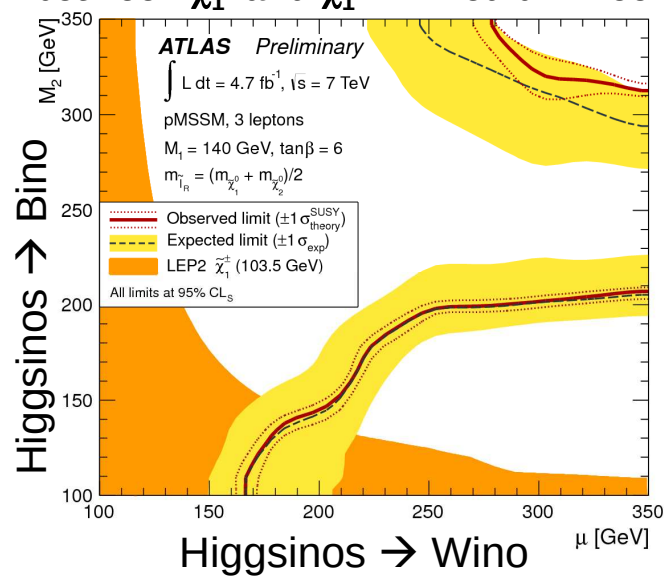
➔ No yet sensitive

Direct Gauginos (1)

- **Closer to a real SUSY model ~pMSSM**
  - Mixing of eigenstates = f(M1 [Bino Mass], M2 [Wino masses], tanβ, μ [Higgses])
  - Trilinear mixing all set to 0 except for the stop

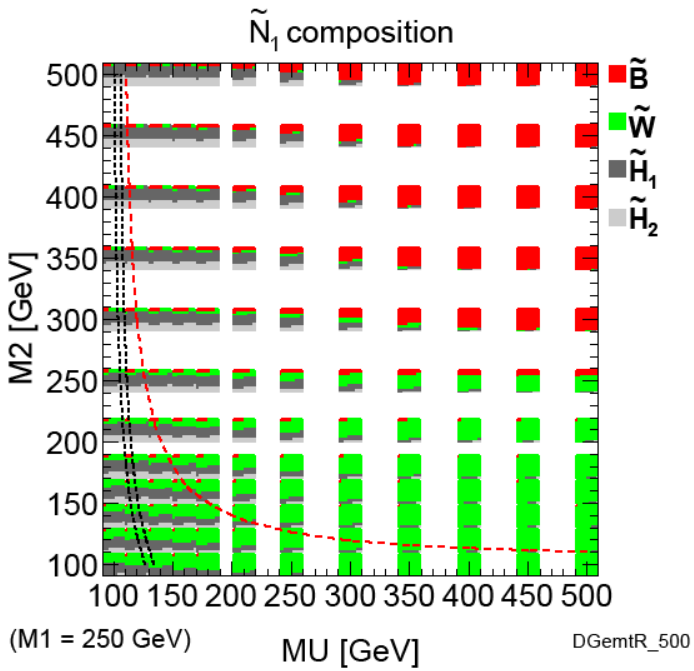


M1=140 GeV, medium mass splitting between $\chi_1^{\pm}$ and χ_1^0 ➔ medium Acc.

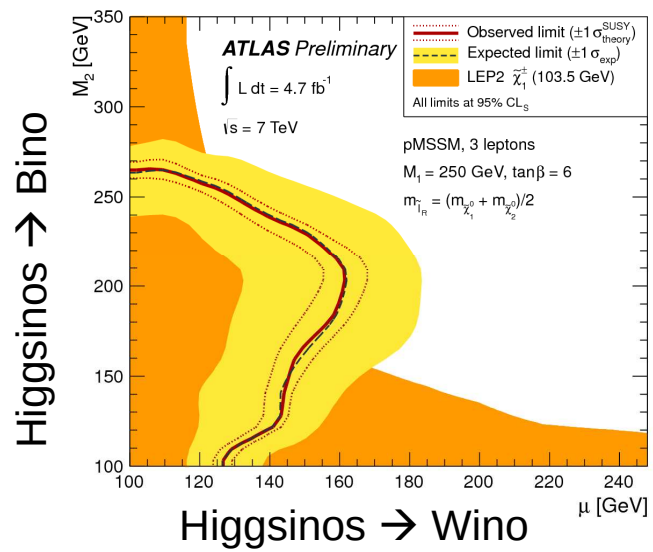


Direct Gauginos (2)

- **Closer to a real SUSY model ~pMSSM**
  - Mixing of eigenstates = f(M1 [Bino Mass], M2 [Wino masses], tanβ, μ [Higgses])
  - Trilinear mixing all set to 0 except for the stop



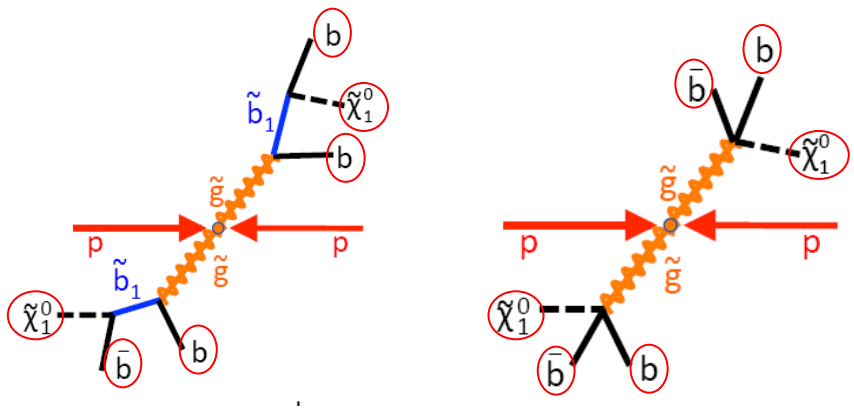
M1=250 GeV, low mass splitting between $\chi_1^{\pm}$ and χ_1^0 ➔ low Acc.



Gluino Mediated sbottom (1)

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	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
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)

- **Increase again complexity: $m_{\tilde{g}}$ ~ O (1 TeV)**
  - Stop in gluino cascade dominates
  - Stop on-shell (2 body) or off-shell (3 body decay)



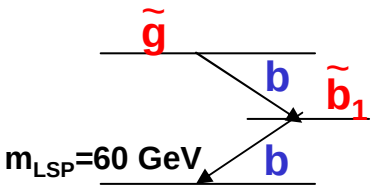
Final state: =**4 b + MET**

➔ ttbar killers should be best: 0l + ≥3b-jets + MET & Same Sign 2l + bjet + MET

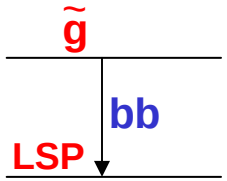
1205.3933

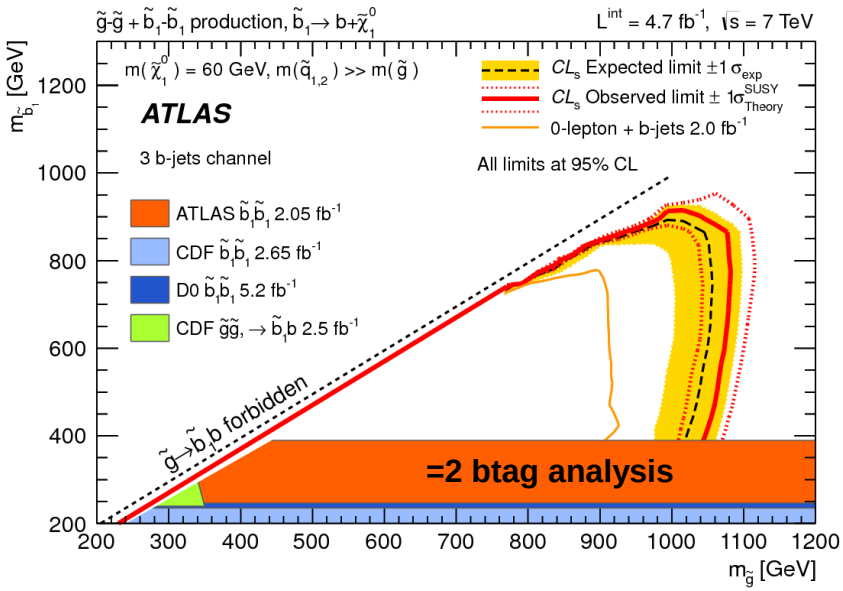
Gluino Mediated sbottom (2)

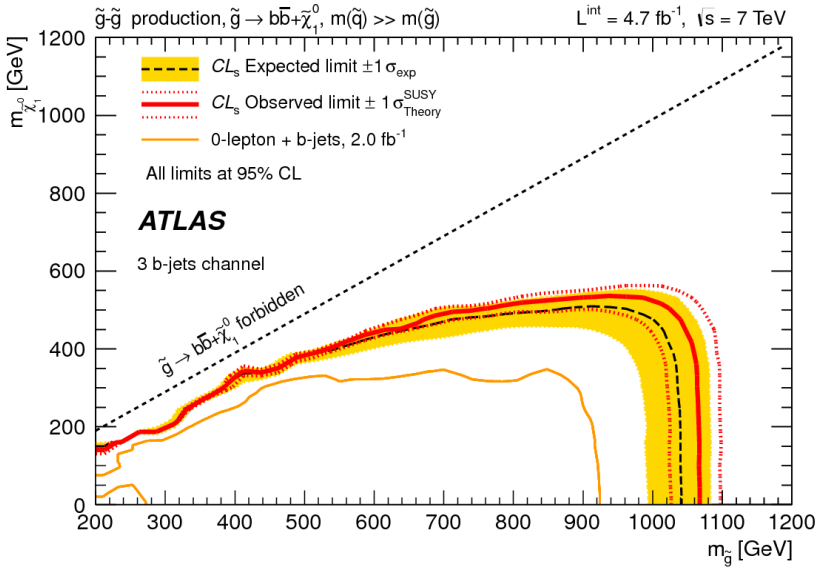
- **On-shell sbottom**



- **Off-shell sbottom**







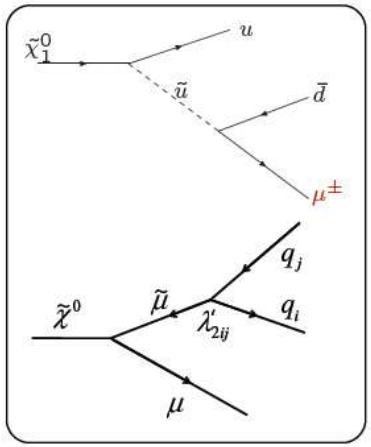
Multivariate (MVA) for SUSY ?

- Usefulness considerations …
  - MVA less useful in case of strongly varying signal predictions and inclusive search
  - MVA classification useful in presence of several not too strongly correlated variables
  - Useful in case of bad signal to background ratio in signal region
  - Less useful in case of one or two very strong variables with little correlation
  - Maybe: analyses that strongly benefit from more statistics are good use cases for MVA classification, while analyses depending mostly on highest CM energy are less so
  - MVA training requires supervision by a signal model: useful if good generic or specific signal model exists
- Looking at the current SUSY analyses …
  - Probably not much needed for: inclusive 0/1-lepton, multijet, monojet, photon/tau + jets + MET searches → driven by highest effective mass tails with good S/B ratio
  - However, compressed scenarios in these analyses might be an MVA use case
  - Potentially useful for direct stop / gaugino / slepton searches
  - Probably not so useful for RPV scenarios (?)

Andreas Hoecker – SUSY and MVA ?

LSP decay

Neutralino-LSP decay



- $\tilde{\chi}_1^0$ could decay via non-zero λ, λ' couplings:

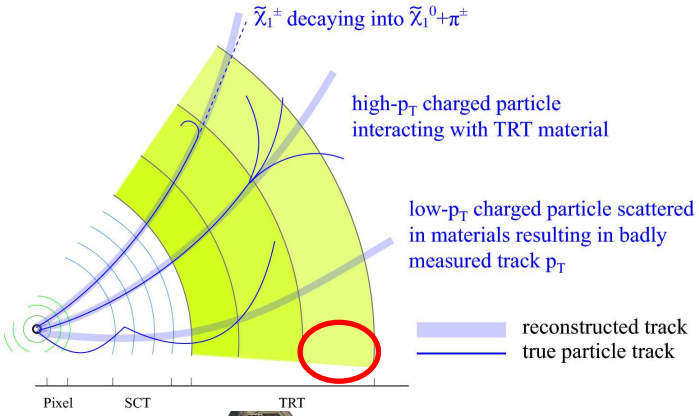
$$LL\bar{E}(\lambda): \ \tilde{\chi}_1^0 \to ll' + \nu$$

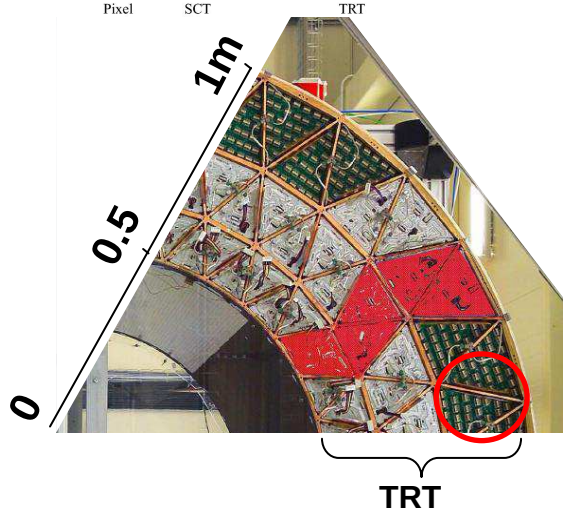
$$LQ\bar{D}(\lambda'): \ \tilde{\chi}_1^0 \to \begin{pmatrix} e, \mu, \tau \\ \nu \end{pmatrix} + 2 \text{ jets}$$

- The lifetime is proportional to $(\lambda)^{-2}$, $(\lambda')^{-2}$
  - Decay prompt for λ, λ' ≳ 10^{-5}.
  - If the RPV coupling is smaller than that (e.g. ≲ 10^{-7}), *a decay vertex with a significant distance from its production point* can be seen.
- →Perform a search using a displaced vertex (DV) reconstruction technique.
  - The result presented today is based on 2010 data, non-zero λ' with muon final states.
  - More to come using 2011 full dataset covering variety of signatures:
    - Final states including e/tau

AMSB Metastable $\chi_1^{\pm}$ (1)

❑ Layout of the analysis

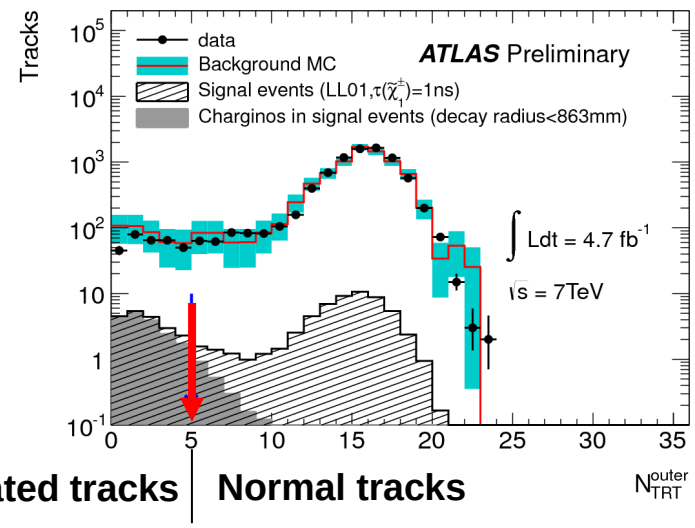




Requirements	
Etmiss [GeV] >	**130**
Pt (j1) [GeV] >	**130**
Pt (j2) [GeV] >	**60**
Pt (j3) [GeV] >	**60**
Lepton veto	
1 track pT> [GeV]	**10**
DR (track, pT>0.5 GeV) >	**0.1**
N(TRT outer)	**5**

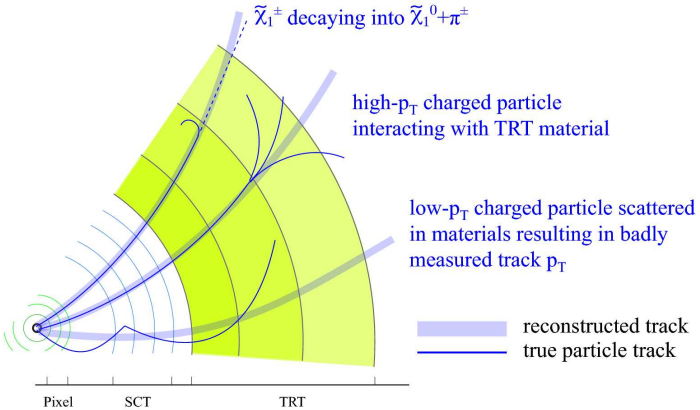
SUSY signal (LL01):AMSB model

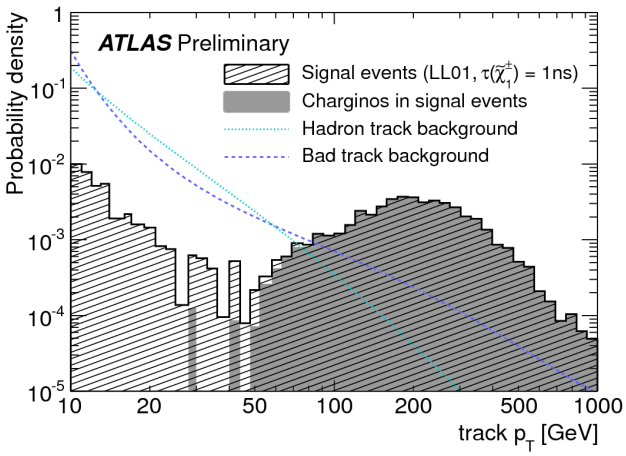
- **m_0=1.5 TeV, m3/2=32 TeV**
- **σ=0.07 pb, $\tau\chi_1^{+/-}$= 1 ns**
- **$m\chi_1^{+/-}$=90.2 GeV,**
- **BR ($\chi_1^{+}\rightarrow\chi^{0}\pi^{+}$)=100%**



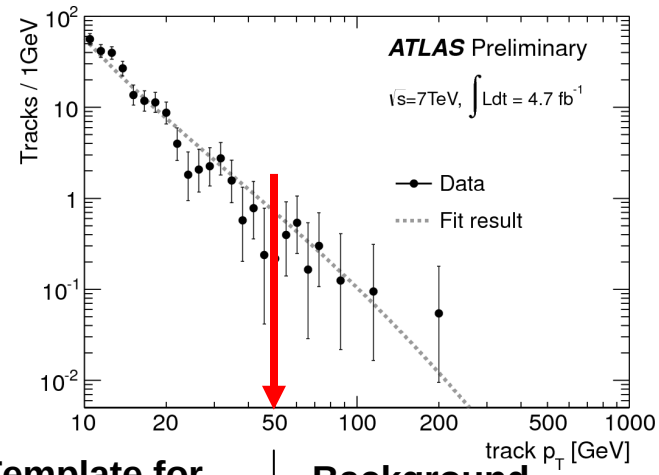
AMSB Metastable $\chi_1^{\pm}$ (2)

❑ Background estimate





Requirements	
1 track pT> [GeV]	**50**



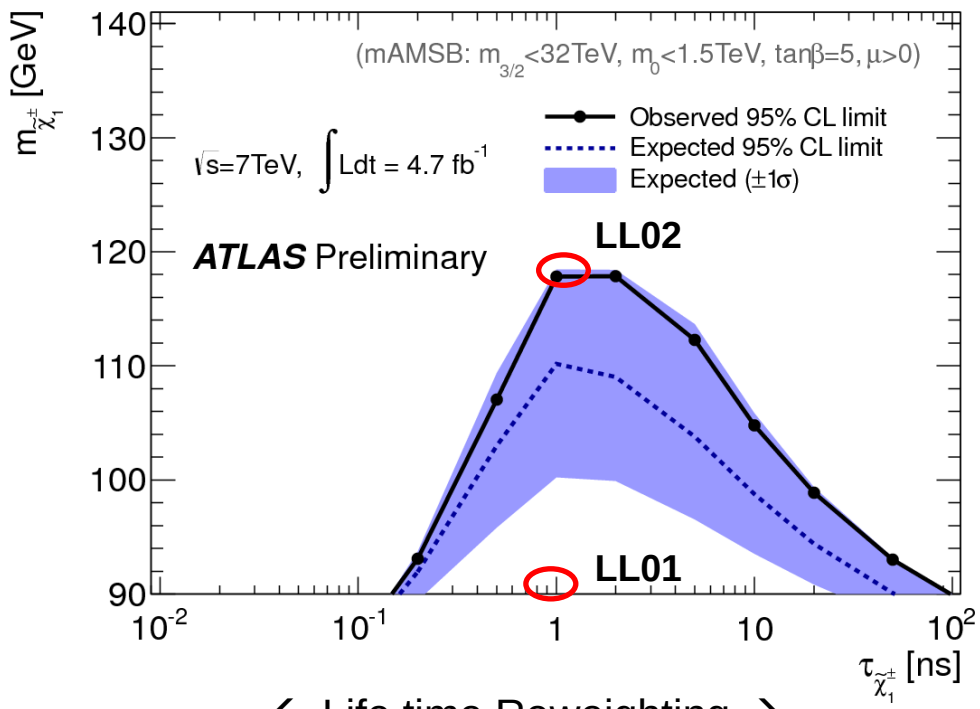
Template for background | **Background +signal**

➔ Data driven background: small uncertainties

AMSB Metastable $\chi_1^{\pm}$ (3)

- **Interpretation of the results (some examples)**

← Linear interpolation LL01, LL02 →



← Life time Reweighting →

SUSY signal (LL02):AMSB model

- **σ=0.009 pb, $\tau\chi_1^{+/-}$= 1 ns**
- **$m\chi_1^{+/-}$=117.8 GeV,**
- **BR ($\chi_1^{+}\rightarrow\chi^0\pi^+$)=100%**

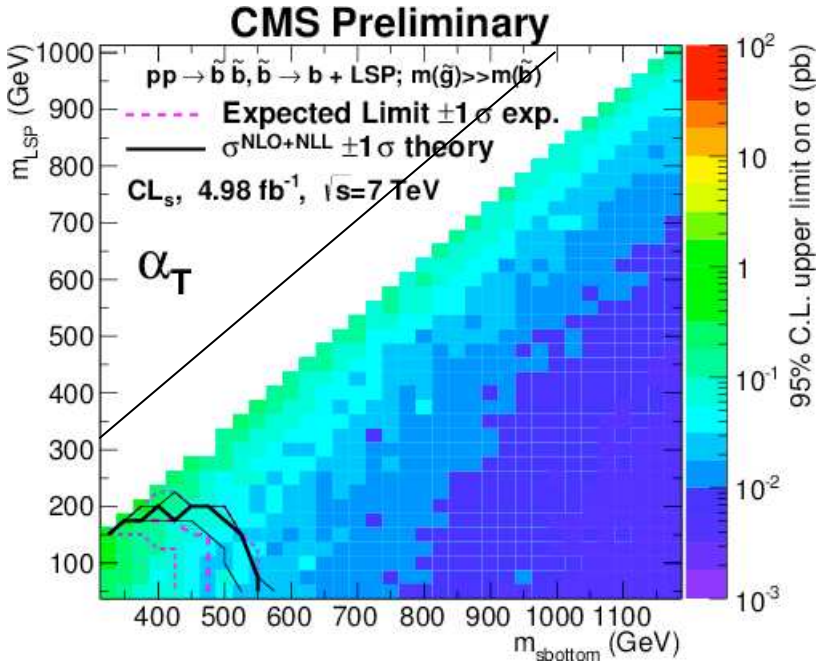
SUSY signal (LL01):AMSB model

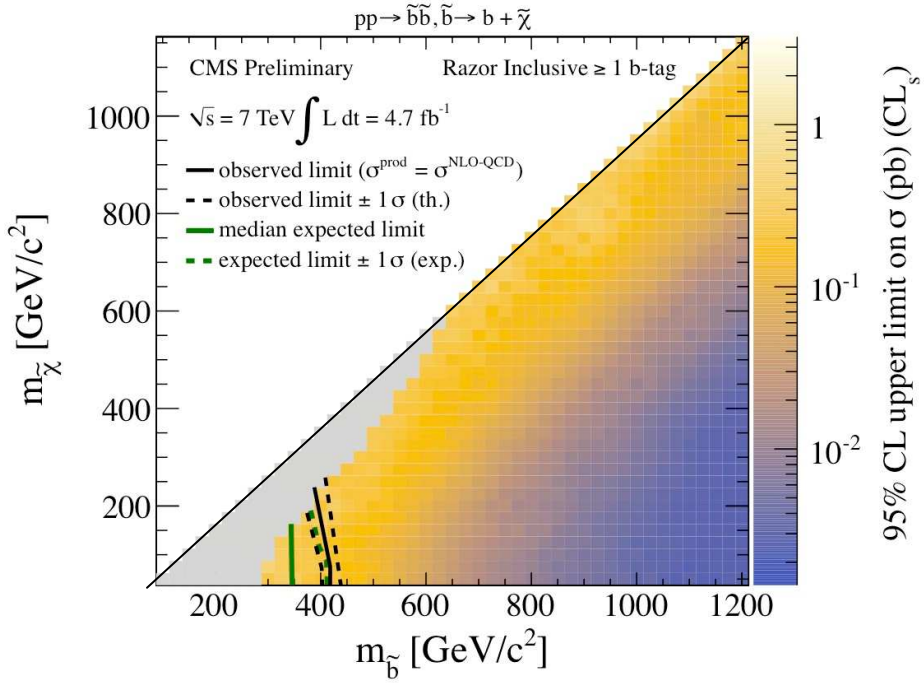
- **σ=0.07 pb, $\tau\chi_1^{+/-}$= 1 ns**
- **$m\chi_1^{+/-}$=90.2 GeV,**
- **BR ($\chi_1^{+}\rightarrow\chi^0\pi^+$)=100%**

➔ Exceed previous LEP2 limit ($m\chi_1^{\pm}$ > 92 GeV) !

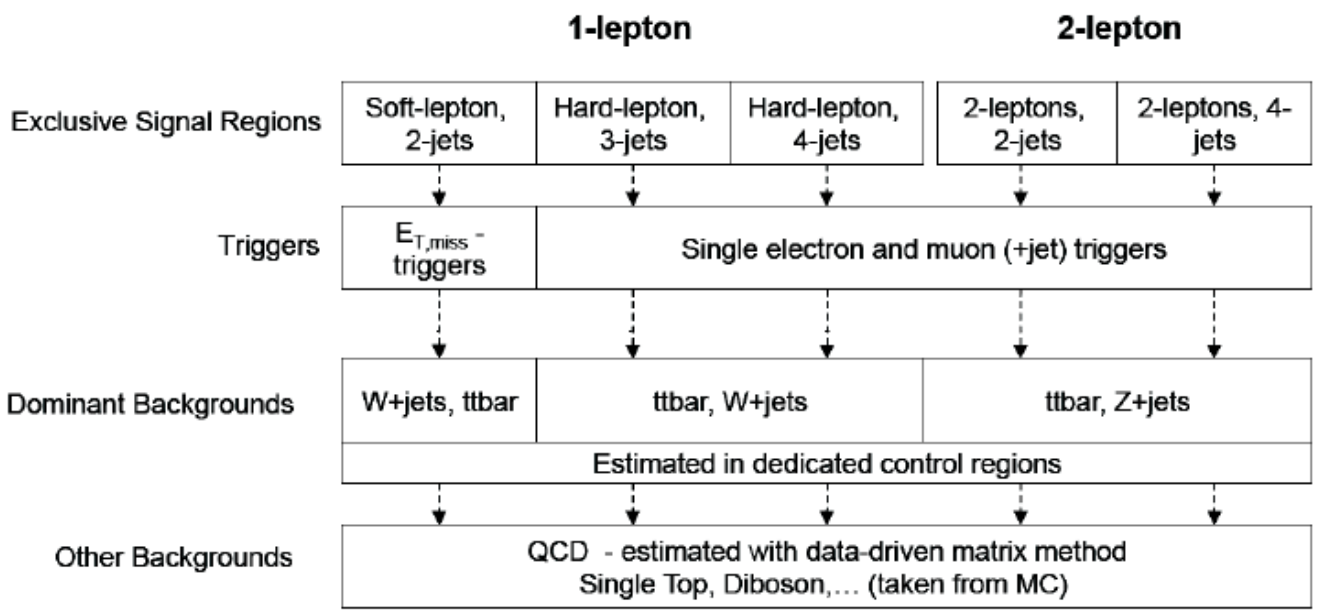
Direct Sbottom (inclusive)

- **Results from generic searches**



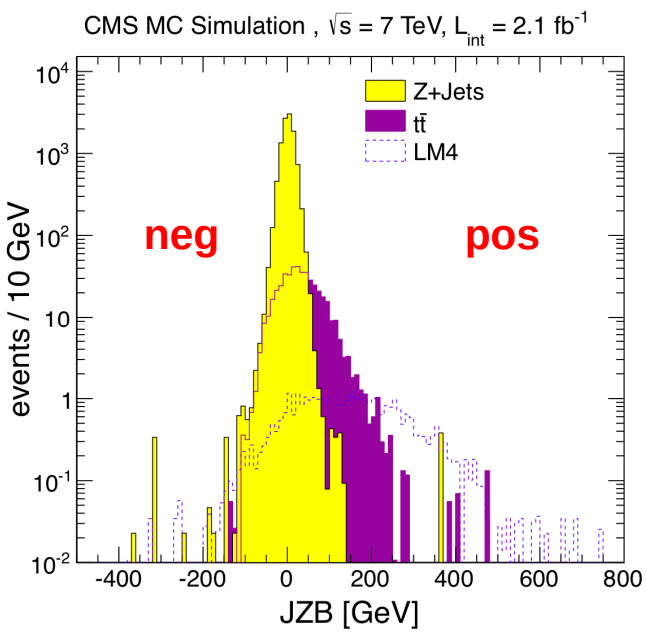


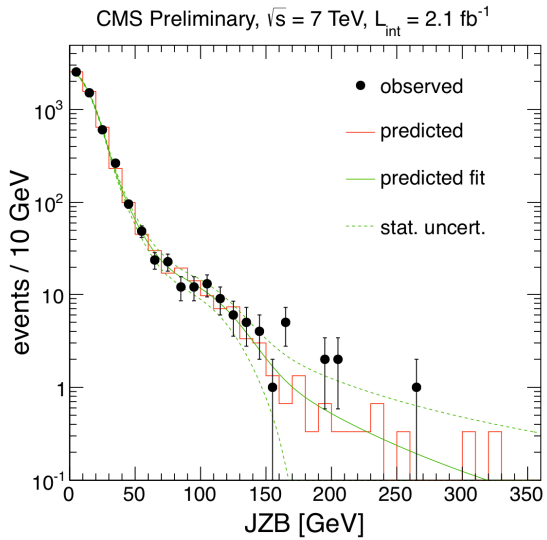
1-2 lepton (ATLAS)

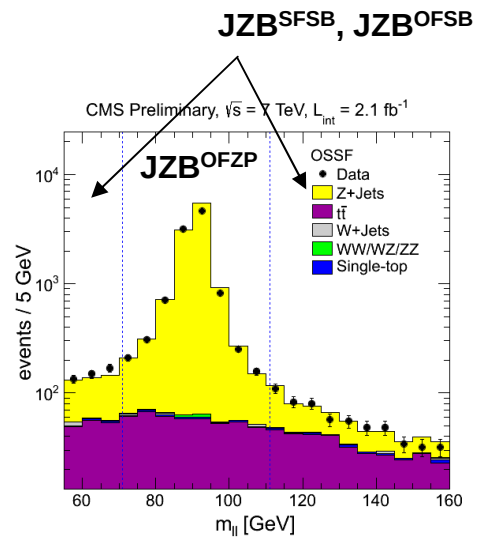


- **Transfer factors** to go from Control Regions to Signal Regions (MC-based)
- Fake background:
  - Matrix Method using fake rates measured via **relaxed** ID & isolation **cuts**, evaluating hf separately
  - Soft-lepton: Fake rates from Same-Sign Same-Flavor pairs
  - real+fake background for multilepton taken from MC and cross checked via matrix method

JZB (1)







$$JZB^{\mathrm{pred}}_{\mathrm{bkgd}} = |\mathrm{JZB}^{\mathrm{SFZP}}_{\mathrm{neg}}| + \frac{1}{3}|\mathrm{JZB}^{\mathrm{OFZP}}_{\mathrm{pos}}| - \frac{1}{3}|\mathrm{JZB}^{\mathrm{OFZP}}_{\mathrm{neg}}| + \frac{1}{3}|\mathrm{JZB}^{\mathrm{SFSB}}_{\mathrm{pos}}| - \frac{1}{3}|\mathrm{JZB}^{\mathrm{SFSB}}_{\mathrm{neg}}| + \frac{1}{3}|\mathrm{JZB}^{\mathrm{OFSB}}_{\mathrm{pos}}| - \frac{1}{3}|\mathrm{JZB}^{\mathrm{OFSB}}_{\mathrm{neg}}|$$

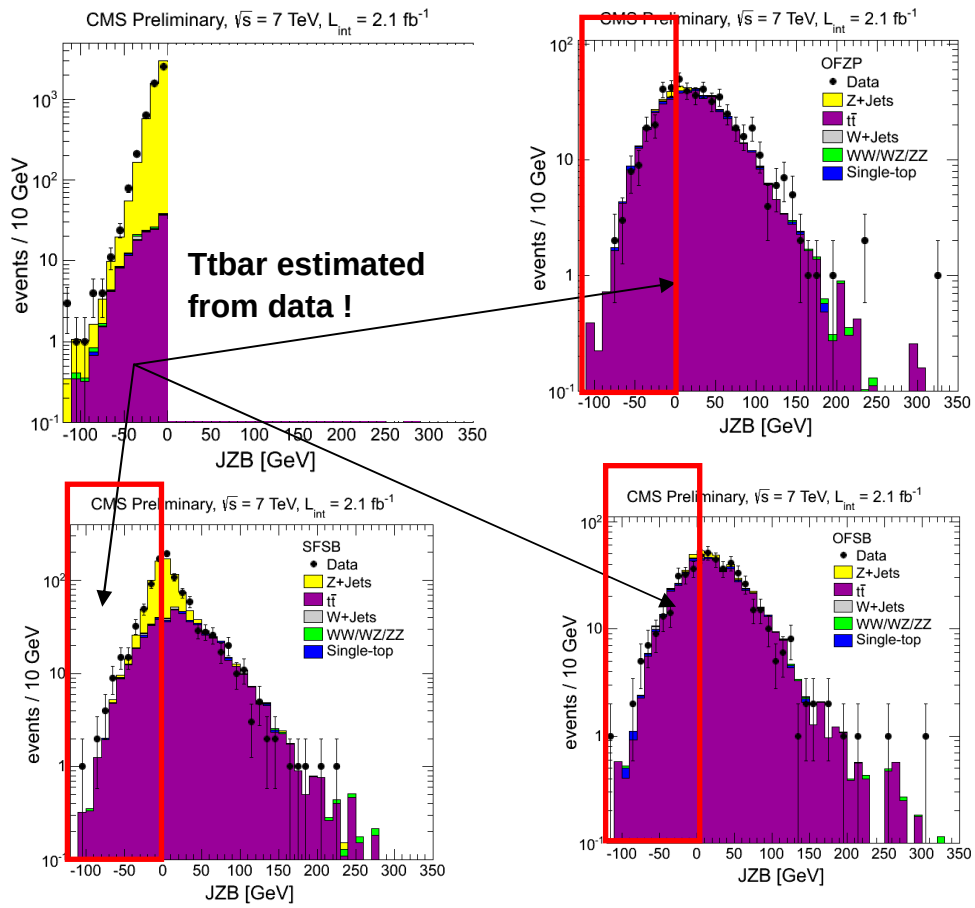
JZB (2)

SF (e+e-, m+m-)

OF (e+m-, e-m+)

Zmass

Zsideband

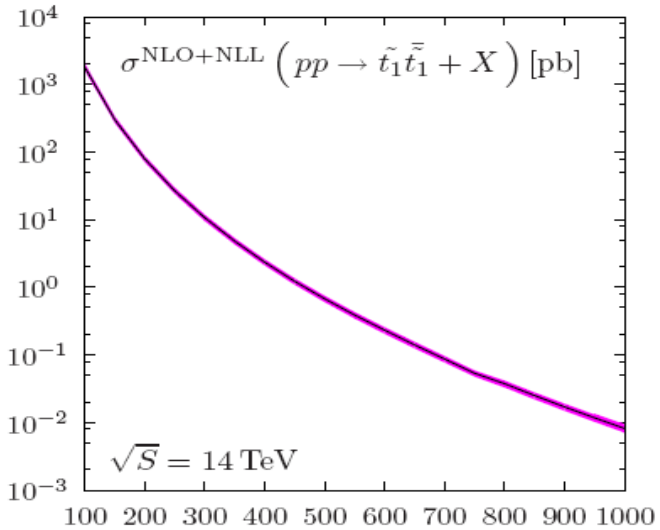


Equality of ttbar yield in OF and SF final states

$$JZB^{\mathrm{pred}}_{\mathrm{bkgd}} = |\mathrm{JZB}^{\mathrm{SFZP}}_{\mathrm{neg}}| + \frac{1}{3}|\mathrm{JZB}^{\mathrm{OFZP}}_{\mathrm{pos}}| - \frac{1}{3}|\mathrm{JZB}^{\mathrm{OFZP}}_{\mathrm{neg}}| + \frac{1}{3}|\mathrm{JZB}^{\mathrm{SFSB}}_{\mathrm{pos}}| - \frac{1}{3}|\mathrm{JZB}^{\mathrm{SFSB}}_{\mathrm{neg}}| + \frac{1}{3}|\mathrm{JZB}^{\mathrm{OFSB}}_{\mathrm{pos}}| - \frac{1}{3}|\mathrm{JZB}^{\mathrm{OFSB}}_{\mathrm{neg}}|$$

Prospects

Parton luminosity (ratio 8 to 7 TeV) : http://lutece.fnal.gov/PartonLum11/



Gtt uncertainties