SUSY searches – Part II

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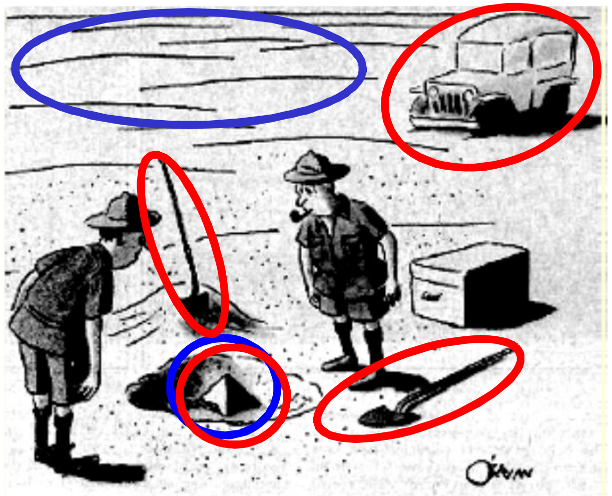
Terascale School on BSM Physics (DESY)



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

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

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

Lecture Organization

Ia - Ingredients for a SUSY search @ LHC

"What drives the sensitivity to SUSY at LHC ?"

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

~35 slides → 50'

Ib - SUSY ElectroWeak

"Exploring the bottom part of the SUSY spectrum"

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

~25 slides → 40'

IIa – 3rd gene. SUSY

"Best natural candidates"

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

~20 slides → 30'

IIb – Strong SUSY

"Inclusive searches"

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

~15 slides → 25'

IIc – Beyond MSSM

"Last hopes (!) and conclusions"

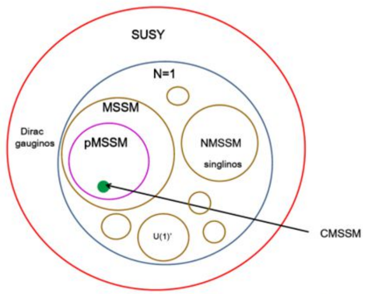
1. Long lived (10)
2. RPV (8)
3. Other SUSY realization (3)
4. Overall conclusions (3)

~20 slides → 30'

Recap from lecture I

1404.7191

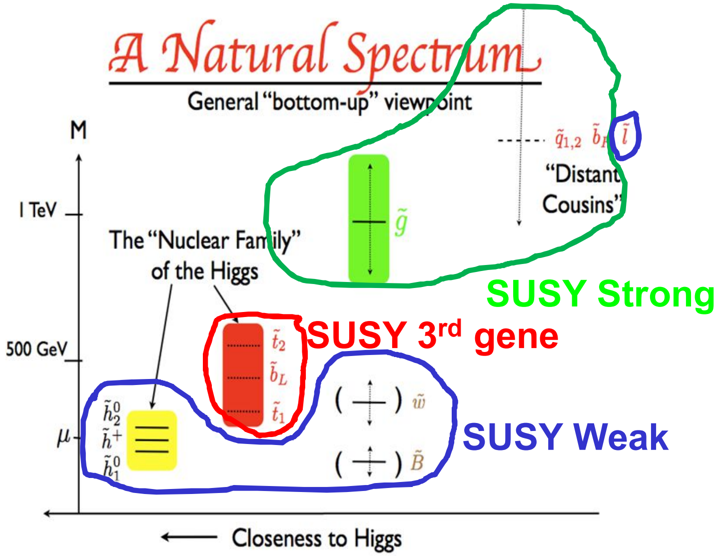
Theory guidance



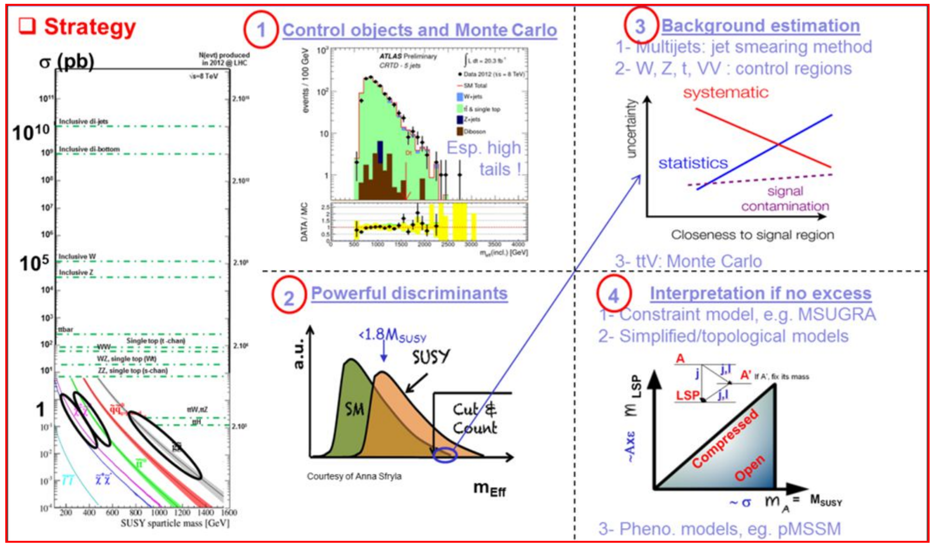
A: MSSM
B: Natural >10%
C1: **RPC**
C2: LSP nature
C3: Spectra opening

N=1 supermultiplet $\left| \begin{array}{c} g \\ \tilde{g} \end{array} \right|$

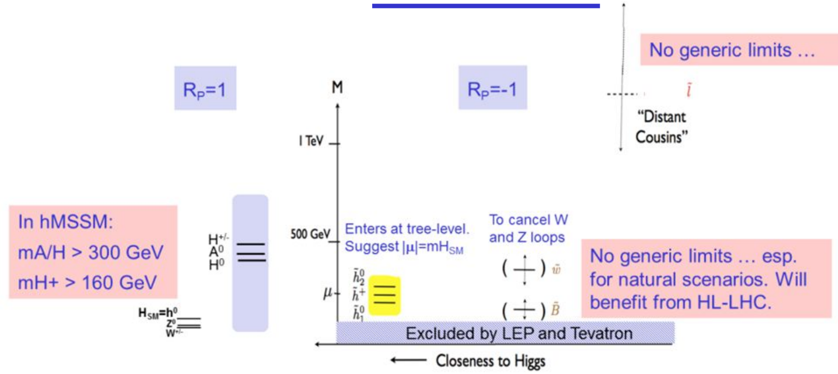
$\tilde{g} \rightarrow g\, \tilde{\chi}$



Experimental work

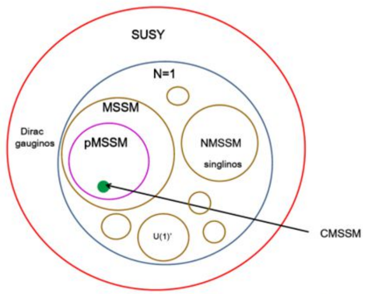


EWK SUSY



Preparation for lecture II

Theory guidance



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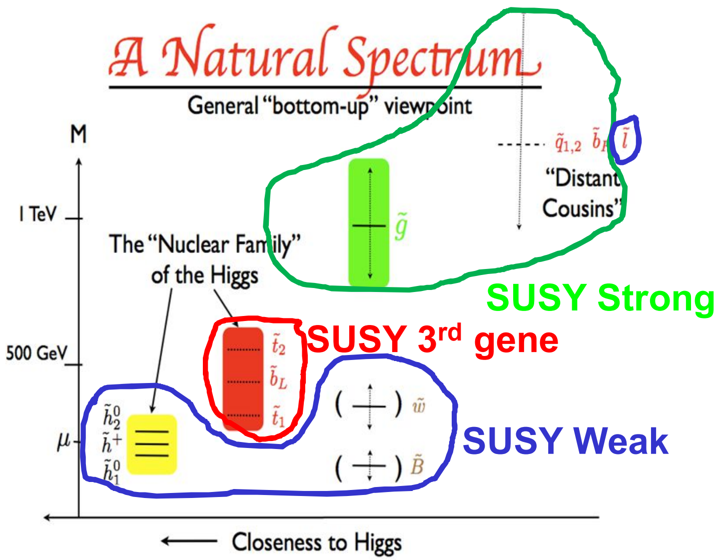

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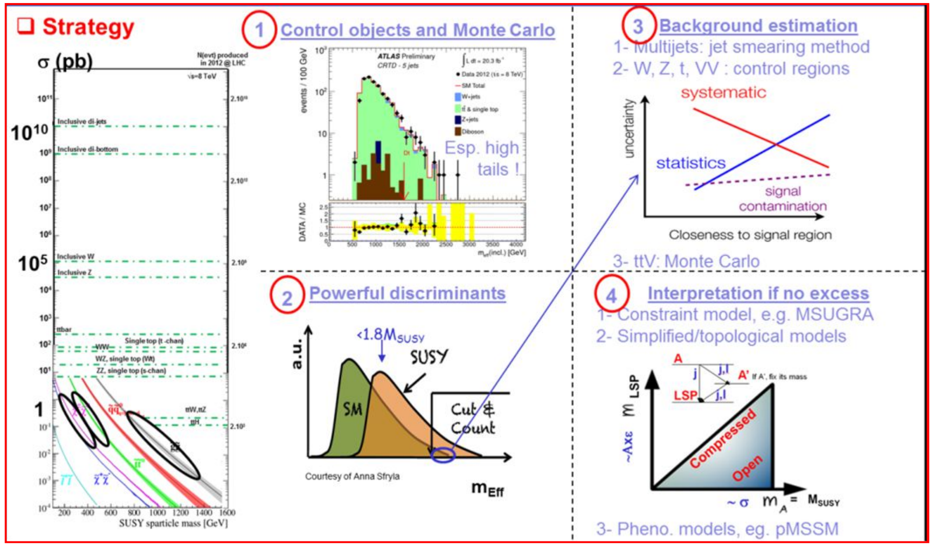


Sbottom search:

1) main decay channel ?

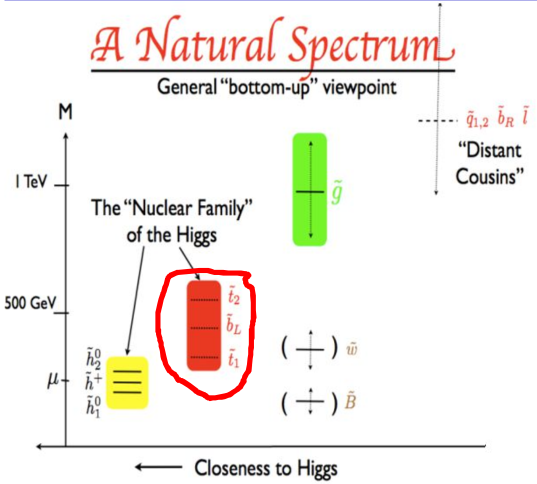
2) Final state ?

3) main backgrounds ?

4) main discriminant variable ?

5) How to control the background ?

Lecture Part IIa



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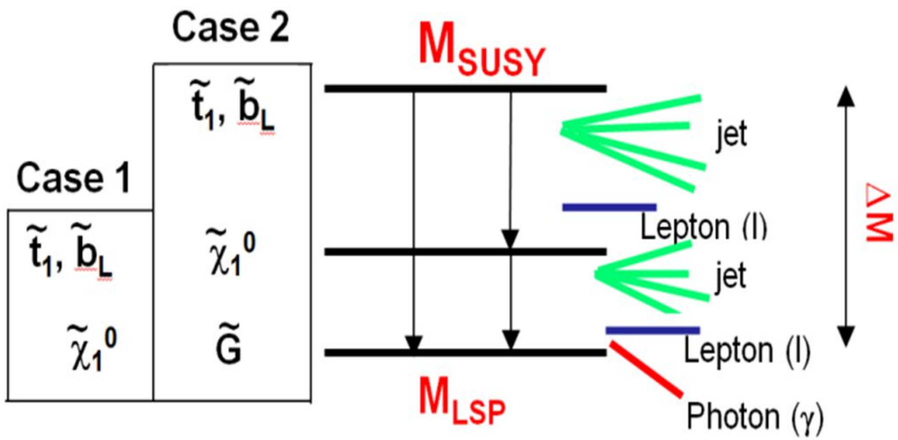
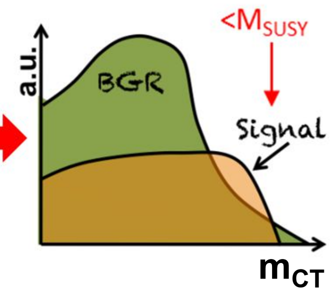


Multi b-jets
+ E_T^{miss}
+ 0/**1**/2 lepton
+ 0/1/2 photon

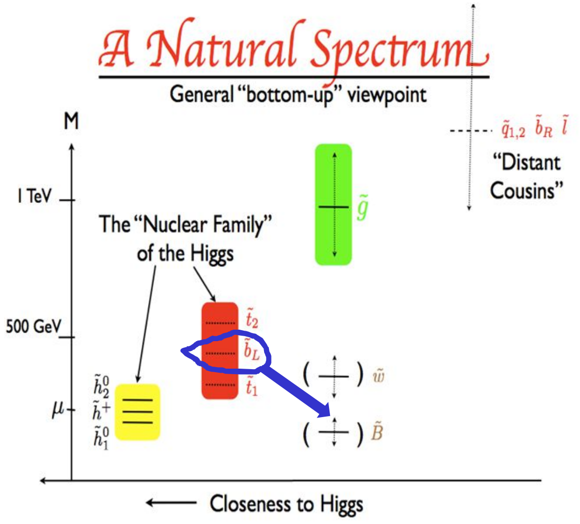
- Absolute value of vectorial sum: $E_T^{miss} \sim \Delta M$
- Number of b-jets
- Endpoint at $m_{CT} \sim (M_{SUSY}^2 - M_{LSP}^2)/M_{SUSY}$ [0802.2879,0910.0174]



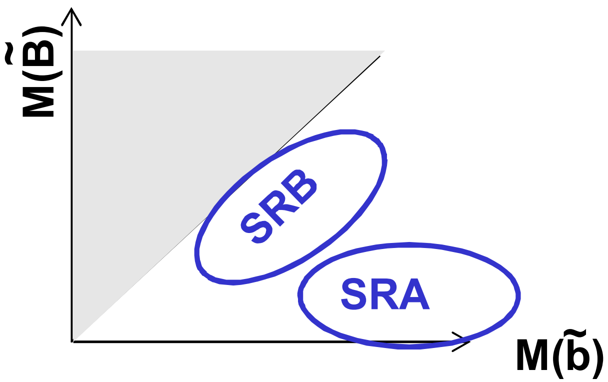
Before LHC start ~no constraints on stop and sbottom !

Sbottom (1)

ATLAS: 1308.2631



Simpliest decay $\tilde{b} \rightarrow b\tilde{\chi}_1^0$
Signature: 2 b-jets + MET



- **SRA for large sbottom mass:**

Requirements	SRA
Etmiss [GeV] >	**150**
Pt (j1) [GeV] >	**130**
Pt (j2) [GeV] >	**50**
Lepton and 3rd jet veto	
MET/Meff >	**0.25**
$\Delta\phi$ (jet-MET) >	**0.4**
N(bjets)=	**2 Tight (ε=0.6)**
M_{CT} [GeV] >	**150,200,250,300,350**
m_{bb}[GeV] >	**200**

Trigger-driven

Pile-up-driven

QCD-killer

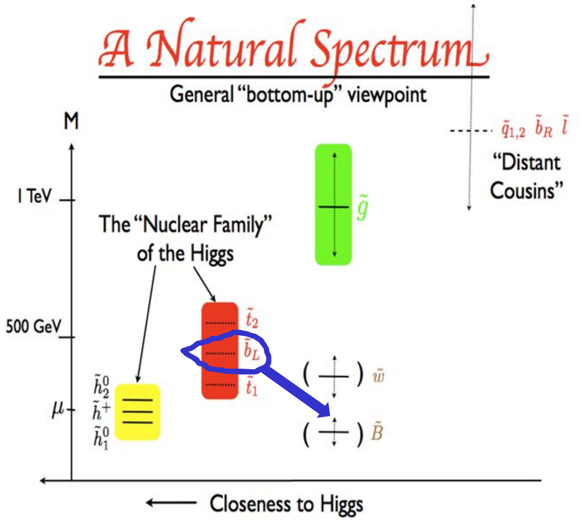
Discriminating var.
[m_{CT}(ttbar)<135 GeV]

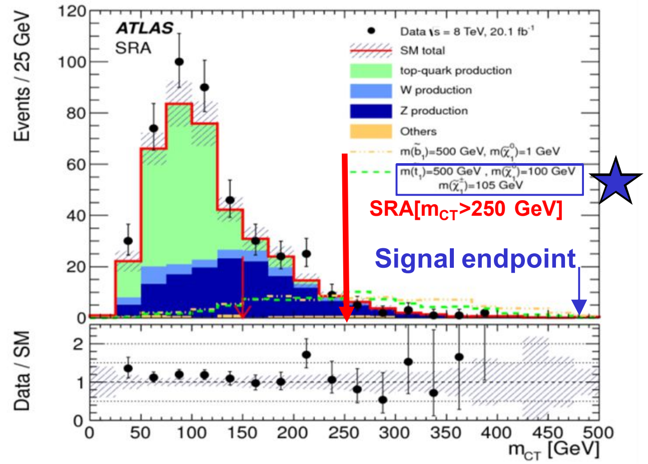
- **Background** : **N_B [m_{CT}>250 GeV] = 15.8 ± 2.8 (14 obs)**
  - ✓ Z(vv)bb: Control Region with Z→ll mass constraint + 2 b-jets
  - ✓ top, Wb: Control Region with =1 lep + 2 bjets + MET> 100 GeV
  - ✓ QCD: jet smearing method
- **SRB for compressed spectrum:**
  - ✓ m_{CT} & m_{bb} cuts → 3rd jet (ISR) & H_T(wo 3 leading jets)<50 GeV

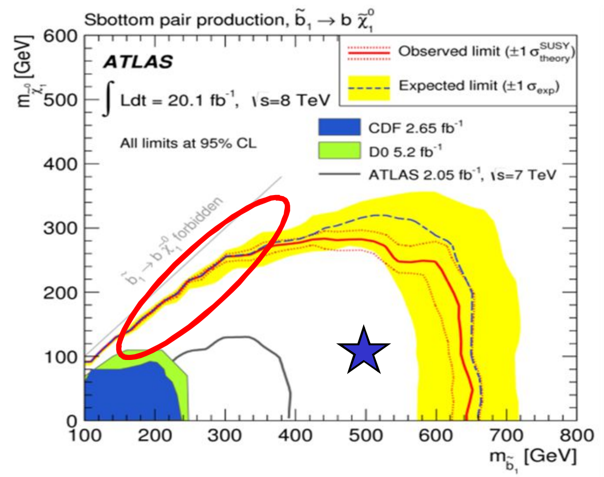
Sbottom (2)

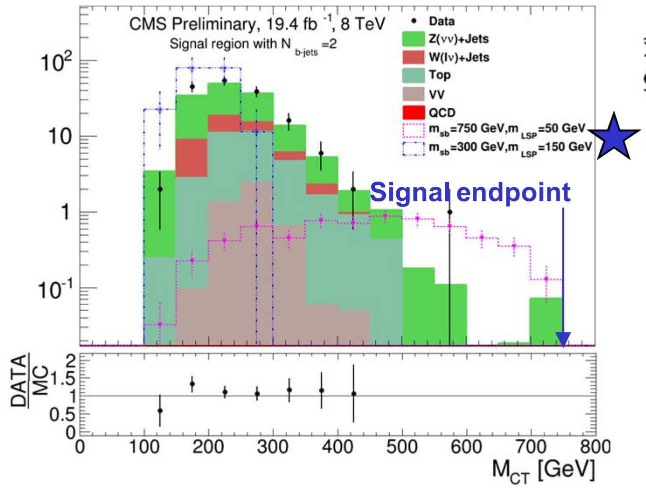
ATLAS: 1308.2631
CMS-PAS-SUS-13-018

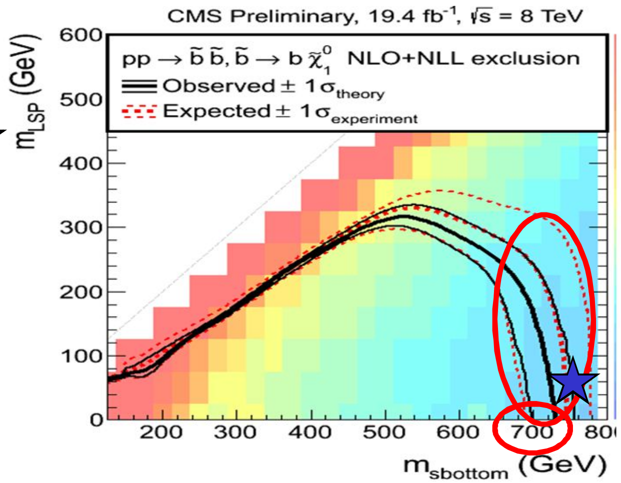
$\tilde{b}_L\tilde{b}_L \rightarrow bb\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow$ 2b+MET











Cover both large mass and compressed spectra

Sbottom (3)

ATLAS: 1112.3832, ATL-CONF-2012-006, ATL-CONF-2012-165, 1308.2631

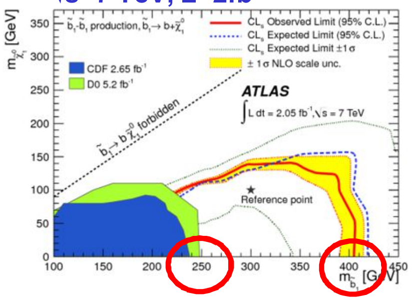
$\tilde{b}_L\tilde{b}_L \rightarrow bb\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow$ 2b+MET

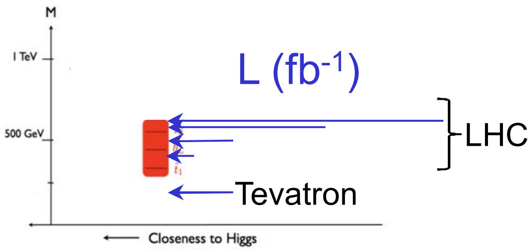
❑ Gradually improve mass limits with luminosity …

- Reoptimise the signal regions for each luminosity

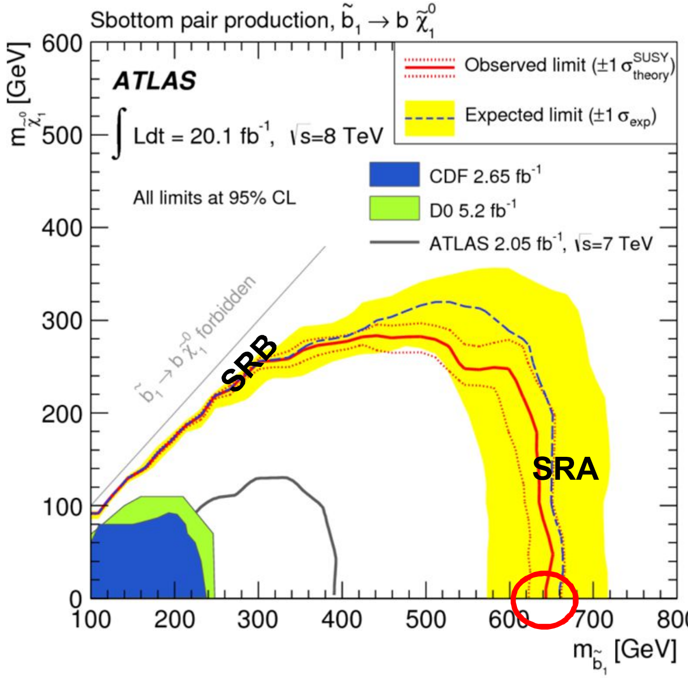
Only 2 sparticles: sbottom, LSP

√s=7 TeV, L=2fb^{-1}

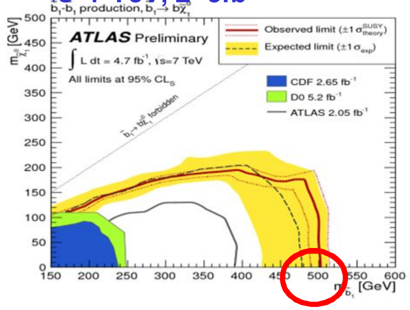




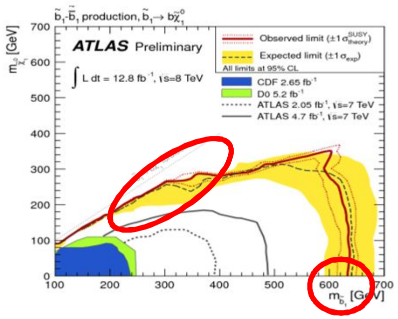
Final LHC Run I: √s=8 TeV, L=20fb^{-1}



√s=7 TeV, L=5fb^{-1}



√s=8 TeV, L=12fb^{-1}



Reaching upper mass limits of the natural SUSY spectrum for m(N1)<250 GeV

Sbottom (4)

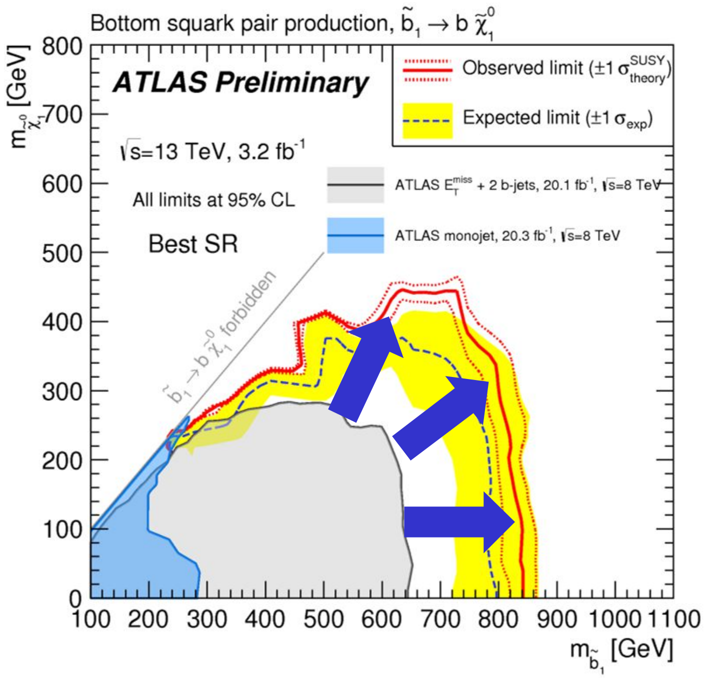
ATLAS-CONF-2015-066
CMS-PAS-SUS-16-001

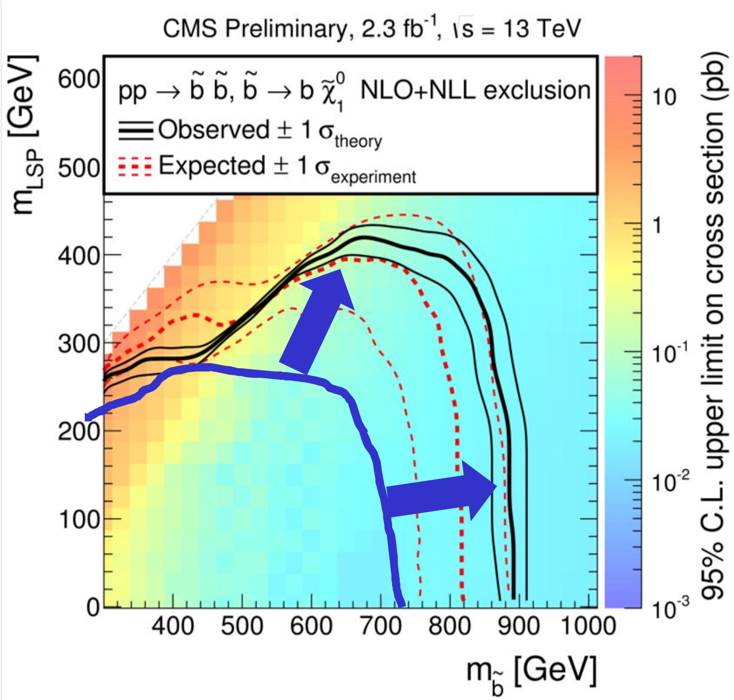
❑ … and center-of-mass energy

$\tilde{b}_L\tilde{b}_L \rightarrow bb\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow$ 2b+MET

- ATLAS: improves over 8 TeV because of b-tagging performance (one more layer)
- CMS: improves over 8 TeV because of increase numbers of Signal Regions for exclusion

First Results @LHC Run II: √s=13TeV, L=3fb^{-1}

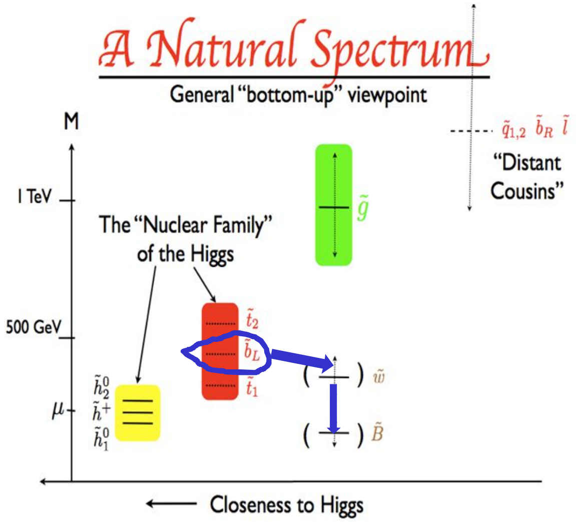




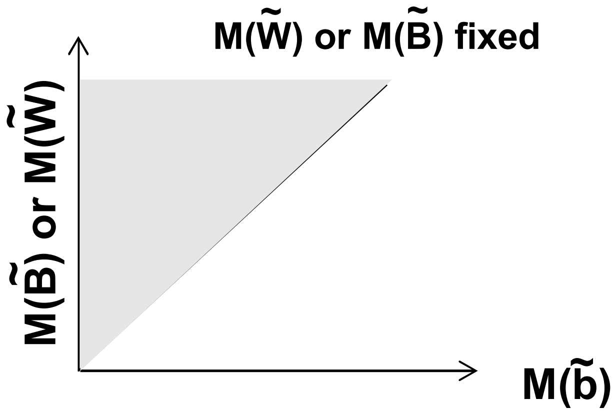
Reaching upper masses of the natural SUSY spectrum

Sbottom (5)

ATLAS: 1602.09058



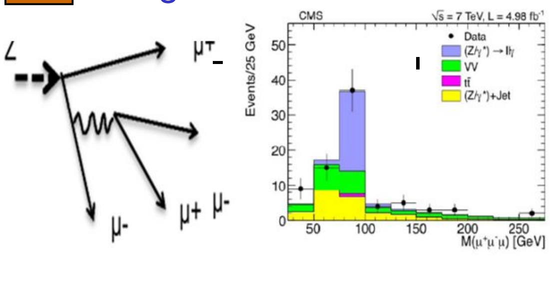
$\tilde{b}_L\tilde{b}_L \to tt\,\tilde{\chi}_1^+\tilde{\chi}_1^- \to 2b+4W+\tilde{\chi}_1^0$



- ≥2 leptonic W : a high probability of 2 same-sign lepton
  - ✓ Multipurpose final state for RPC Strong SUSY (see later)
- ~no SM background compensate for BR(W→lv)=0.1
  - ✓ Low stat channels !

Remaining background

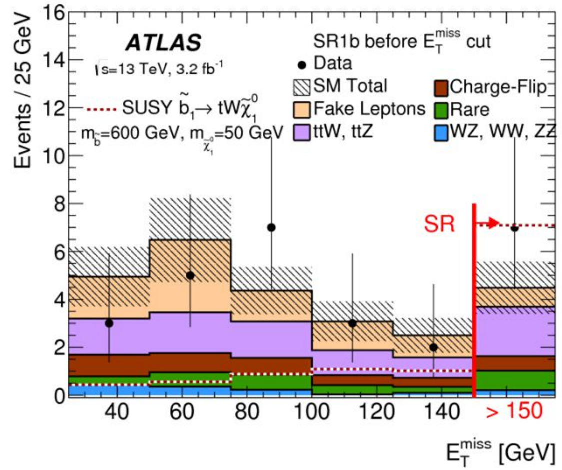
Charge mis-identification



ttbar + W or Z : σ~0.5 pb

1 Real +1 Fake lepton (jets)

$N_{\mathrm{lept}}^{\mathrm{signal}}$	$N_{b-\mathrm{jets}}^{20}$	N_{jets}^{50}	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	m_{eff} [GeV]
≥2	≥1	≥4	>150	>550



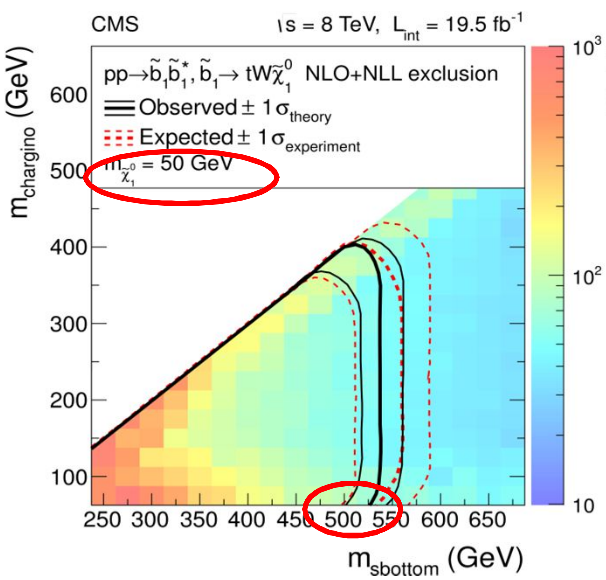
N_B [SR1b] = 4.5 ± 1.0 (7 obs)

Sbottom (6)

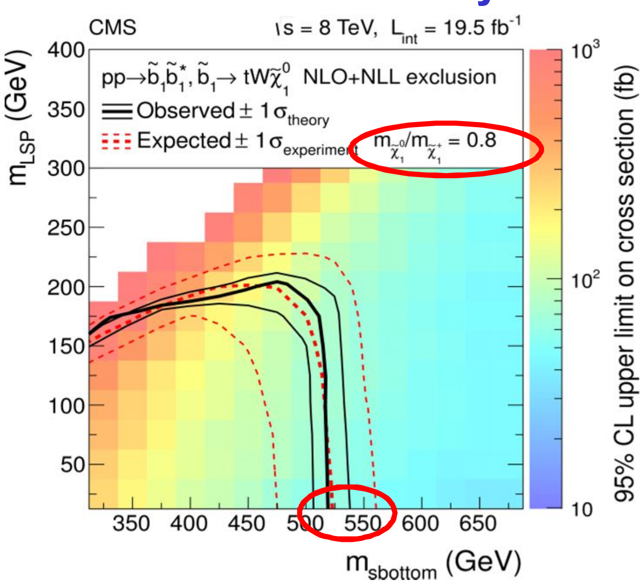
ATLAS: 1404.2500
CMS: 1311.6736

- **Results depends on χ_1^0 and $\chi_1^{+/-}$ masses** — $\tilde{b}_L\tilde{b}_L \rightarrow tt\,\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow 2b+4W+\tilde{\chi}_1^0$
  - Several assumptions are chosen
  - Limits quite robust at $m(\tilde{b})$<500 GeV … Not much change at 13 TeV yet …

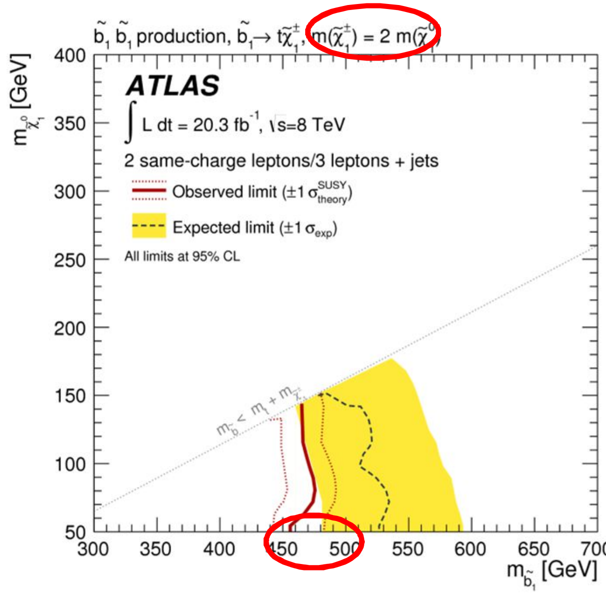
Fixed N1 mass



C1-N1 close-by



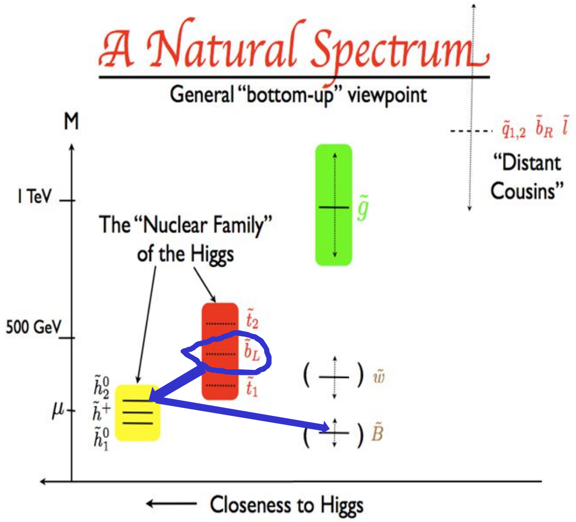
C1-N1 far



Reaching upper masses of the natural SUSY spectrum

Sbottom (7)

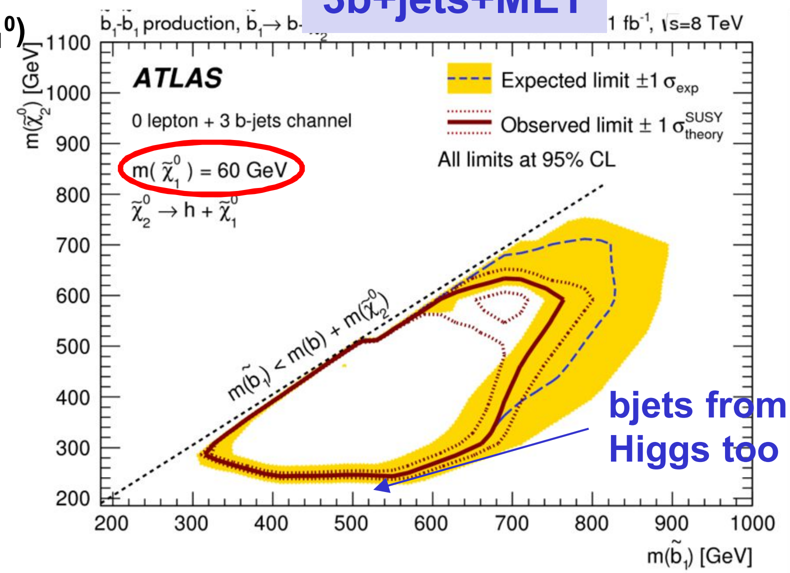
ATLAS: 1407.0600,1506.08616



ΔM
$(\chi_2^0-\chi_1^0)$

340
240
140

3b+jets+MET

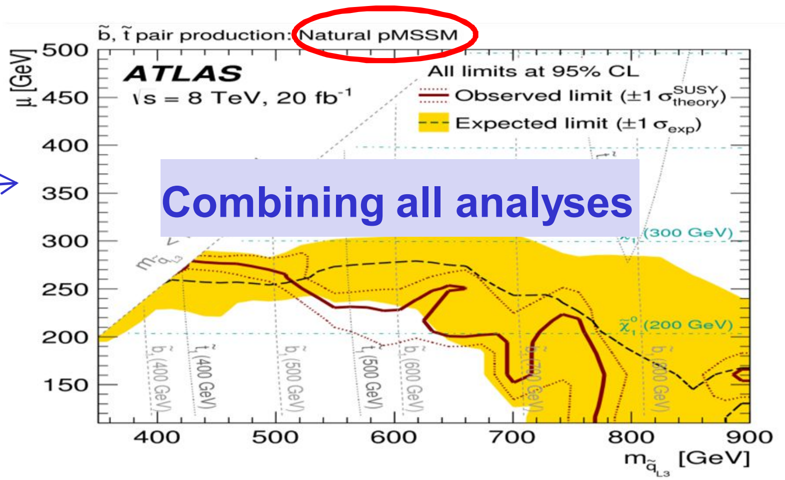


bjets from Higgs too soft

$\tilde{b}_L\tilde{b}_L \rightarrow bb\ \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow 2b+2H(bb,WW)+2\tilde{\chi}_1^0$

Natural pMSSM

(BR not fixed to 100%)



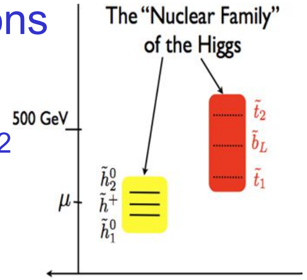
Combining all analyses

Seems quite model independent !

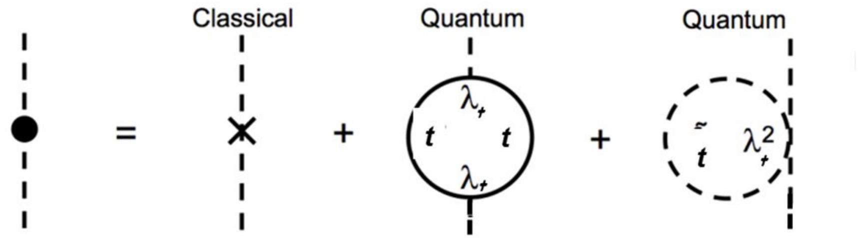
Stop (1)

Higgs mass in SM

- Want **low** radiative corrections



$m_h^2 = (m_h^2)_0 - \Delta m_h^2 = 125^2\ \text{GeV}^2$



$$m_h^2 = (m_h^2)_0 \underbrace{- \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2)\Lambda_{NP}^2 + \frac{3G_F}{4\sqrt{2}\pi^2}(4m_{\tilde{t}}^2)\Lambda_{NP}^2}$$

$$+ \frac{6G_F}{2\sqrt{2}\pi^2} m_t^2 (m_t^2 - m_{\tilde{t}}^2) \ln(\Lambda_{NP}^2/m_{\tilde{t}}^2)$$

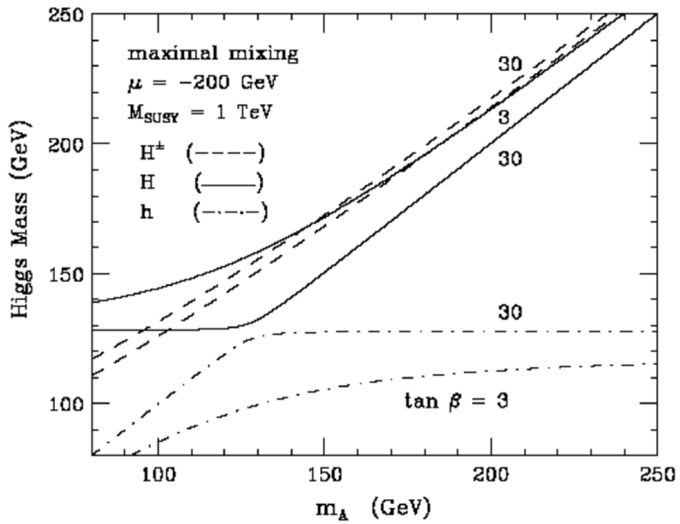
Small fine tuning ➔ light $\tilde{t}_1$

Lightest Higgs in SUSY

- Want **high** rad. corrections to reach 125 GeV

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3g^2 \boxed{m_t^4}}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{SUSY}^2} - \frac{1}{12}\frac{X_t^4}{M_{SUSY}^4}\right]$$

$125^2 = 91^2 + 86^2$ $\quad M_{SUSY}^2 = (m_{t1}^2 + m_{t2}^2)/2$



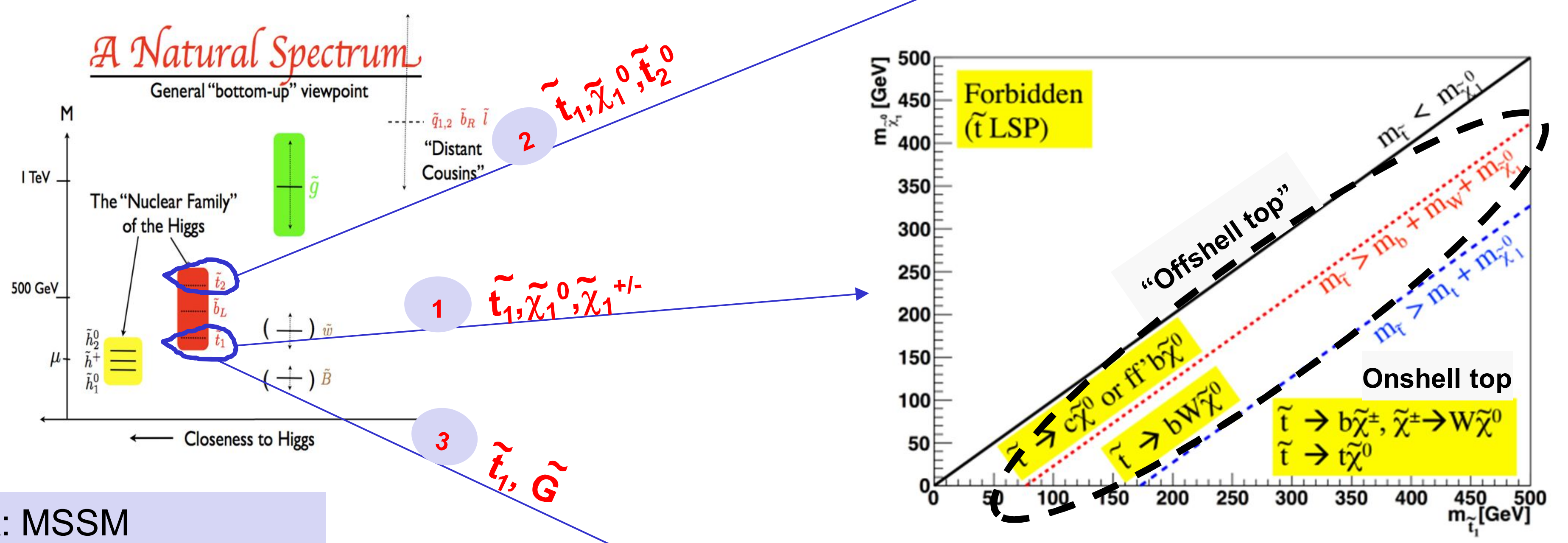
With $m(h^0)$=125 GeV ➔ heavy $\tilde{t}_1$ or large X_t

➔ Some tension in MSSM … not fully natural anymore

Stop (2)

- **Search strategy @LHC: 3 possible roads**

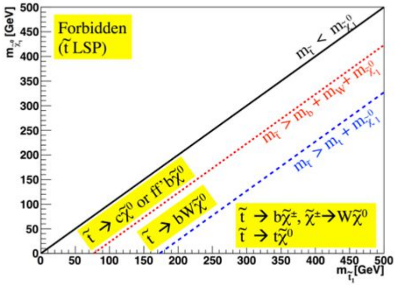
- $t_2 \to t\chi_1^0$ or $t_2 \to Z/H\ t_1 \to Z/H\ t\ \chi_1^0$



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

- NLSP=Higgsino-like : $\tilde{t}_1 \to b\tilde{\chi}_1^+ \to bff'\tilde{\chi}_1^0 \to bff'h^0(\to\gamma\gamma,bb)\tilde{G}$ 1312.3310 (CMS)
- NLSP=Higgsino-like : $\tilde{t}_1 \to b\tilde{\chi}_1^+ \to bff'\tilde{\chi}_1^0 \to bff'h^0(\to ZZ)/Z\ (\to ll)\ \tilde{G}$ 1404.5801 (CMS), 1403.5222 (ATLAS)
- Other NLSP scenario also looked at, e.g. $\tilde{\tau}_1$ NLSP: $t_1 \to b\nu_\tau\tilde{\tau}_1 \to b\nu_\tau\nu_\tau\tau\tilde{G}$ 1509.04976 (ATLAS)

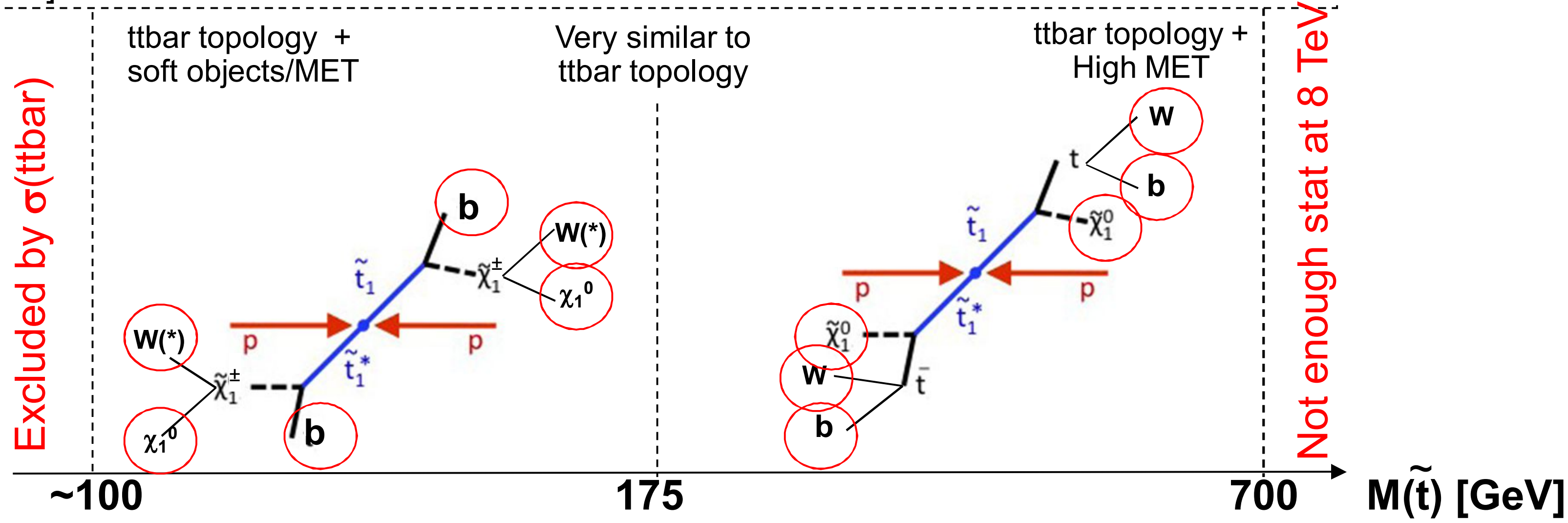
Stop (3)



❑ Main experimental challenge

- Remove ttbar σ~240pb
- Not too many handle (mainly MET is different)

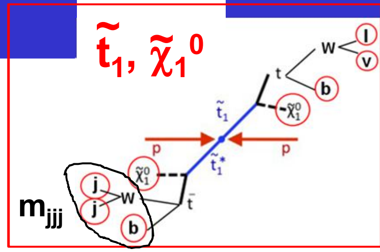
$\sigma(\tilde{t}\,\tilde{t})$[pb]	**800±100**	**40±8**	**0.008±0.002**
N[20fb^{-1}]	**16.000.000**	**800.000**	**160**



Stop (4)

ATLAS: 1407.0583

CMS: 1308.1586



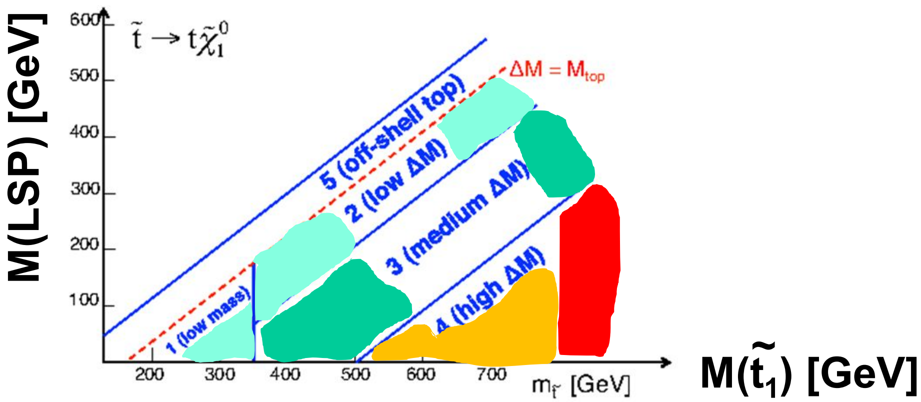
- **1l + 4j + ≥1b-jet analysis most powerful for $\tilde{t} \rightarrow t\tilde{\chi}_1^0$**
  - Similar strategy for ATLAS and CMS

ATLAS

	2(low)	3(low)	4(high)	4(high-boosted)
large-R jet	–			≥ 1, $p_T > 270$ GeV and $m > 75$ GeV
$\Delta\phi(\mathrm{jet}_2^{\mathrm{large}\text{-}R}, \vec{p}_T^{\mathrm{miss}})$	–			> 0.85
E_T^{miss}	> 100 GeV	> 200 GeV	> 320 GeV	> 315 GeV
m_T	> 60 GeV	> 140 GeV	> 200 GeV	> 175 GeV
am_{T2}	–	> 170 GeV	> 170 GeV	> 145 GeV
m_{T2}^{τ}	–	–	> 120 GeV	–
topness	–	–	–	> 7
$m_{\mathrm{had-top}}$	$\in [130, 205]$ GeV	$\in [130, 195]$ GeV	$\in [130, 250]$ GeV	
τ-veto	tight	–	–	modified, see text.
$\Delta R(b\text{-jet}, \ell)$	< 2.5	–	< 3	< 2.6
$E_T^{\mathrm{miss}}/\sqrt{H_T}$	> 5 GeV$^{1/2}$	–		
$H_{T,\mathrm{sig}}^{\mathrm{miss}}$	–	> 12.5		> 10
$\Delta\phi(\mathrm{jet}_i, \vec{p}_T^{\mathrm{miss}})$	> 0.8 $(i=1,2)$	> 0.8 $(i=2)$	–	$> 0.5, 0.3$ $(i=1,2)$

CMS

Selection	$\tilde{t} \rightarrow t\tilde{\chi}_1^0$ BDT	Cut-based Low ΔM	Cut-based High ΔM
E_T^{miss} (GeV)	yes	$> 150, 200, 250, 300$	$> 150, 200, 250, 300$
M_{T2}^{W} (GeV)	yes		>200
min $\Delta\phi$	yes	>0.8	>0.8
H_T^{ratio}	yes		
Hadronic top χ^2	(on-shell top)	<5	<5
Leading b-tagged jet p_T (GeV)	(off-shell top)		
$\Delta R(\ell$,leading b-tagged jet)			
Lepton p_T (GeV)			

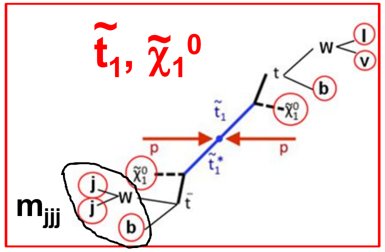


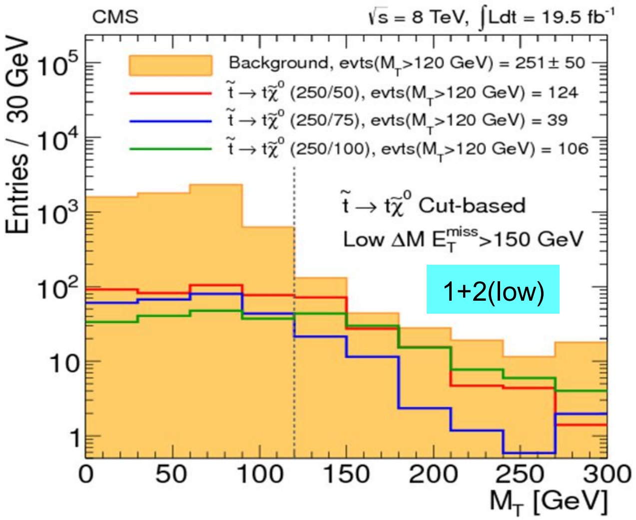
Stop (5)

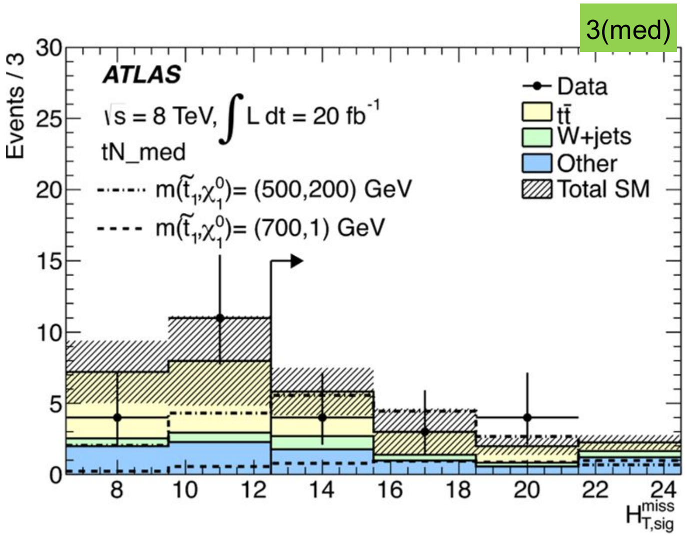
ATLAS: 1407.0583
CMS: 1308.1586

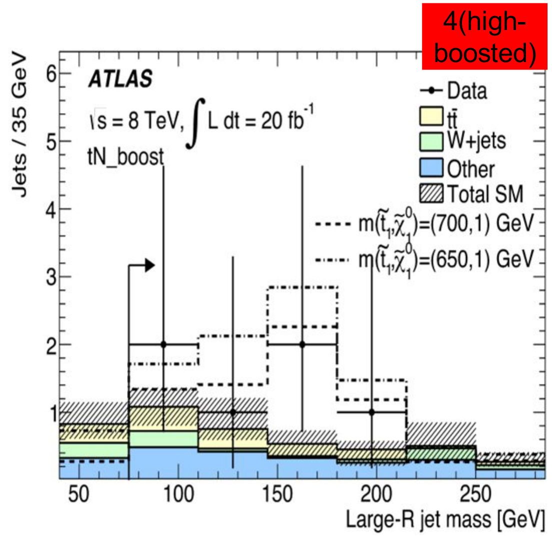
❑ Look at the results in Signal Regions

- Dominated by tt→WWbb→lνlνbb events
  - ✓ where one lepton is τ_{had} or is not rec./identified









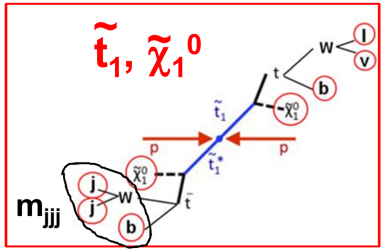
Exp. (Obs)	Low ΔM 1+2(low)	Med ΔM 3(med)	High ΔM 4(high)
ATLAS	Shape fit	13+/-2 (12)	5+/-1 (5)
CMS: Cut-based, Higher MET	11.5+/-3.6 (9)		4.7+/-1.4 (2)

Stop (6)

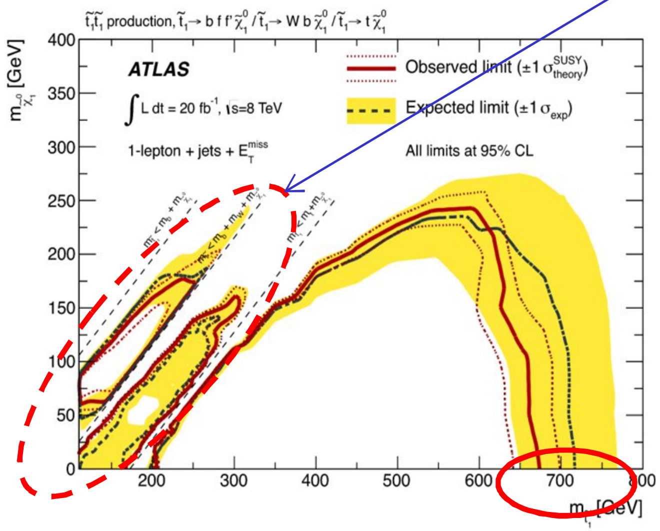
ATLAS: 1407.0583
CMS: 1308.1586

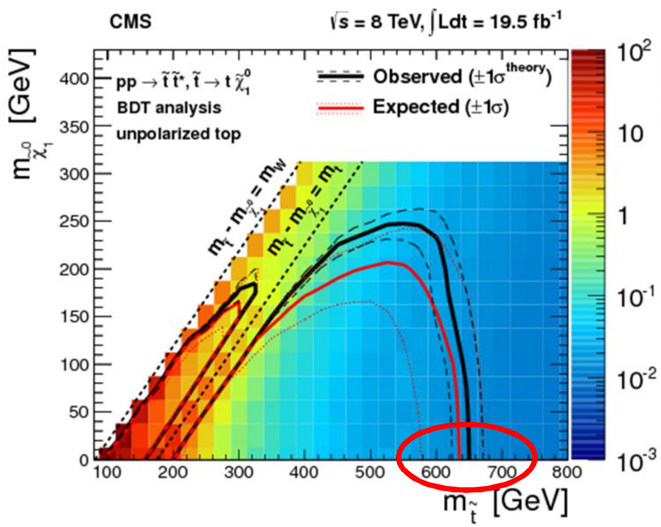
❑ Set limits on the $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$ scenario

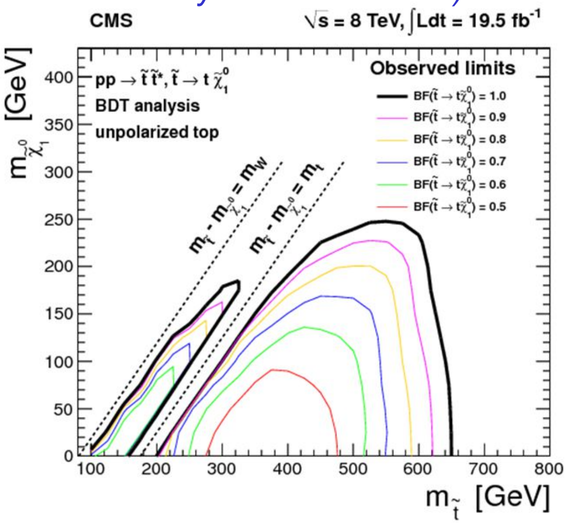
- Cover nicely the allowed phase space
- ATLAS and CMS obtain very similar limits
- Sensitive to other models at low $\Delta M(\tilde{t}-\tilde{\chi}_1^0)<m(t)$ [offshell top]



Impact of BR(t→tN1) hypothesis *(assume the other decay mode is invisible)*







Cover a wide range of the region allowed by naturalness

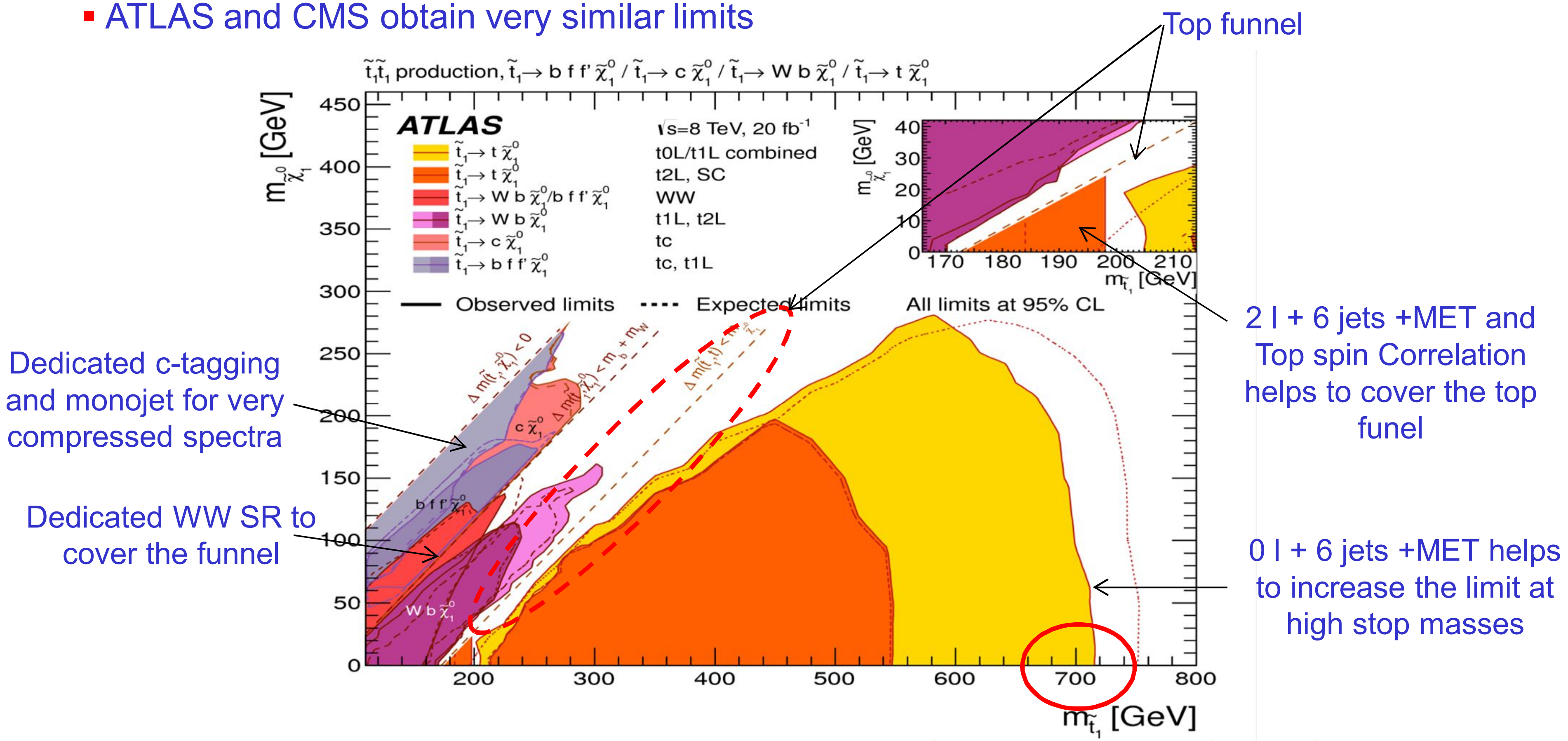
Stop (6)

ATLAS: 1506.08616

CMS: 1602.03169, 1603.00765

❑ General limit on $\tilde{t}_1 \rightarrow t/Wb/c + \tilde{\chi}_1^0$

- Combining all final states : 0 lepton, 1lepton, 2leptons
- ATLAS and CMS obtain very similar limits



Very strong constraint on naturalness (apart from Top funnel)

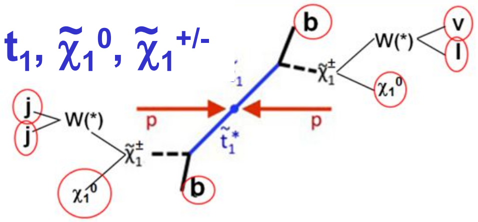
Stop (7)

ATLAS: 1407.0583
CMS: 1308.1586

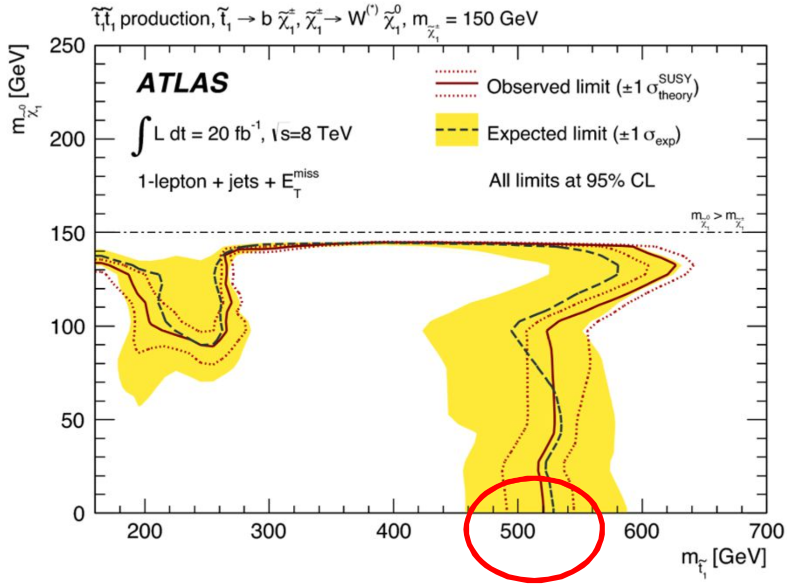
❑ Can reuse the analysis 1l + 4j + ≥1b-jet …

- Similar signal regions but with lower cuts and wo mjjj requirement
- Results interpretation depends on $(\tilde{t}_1)$, m(C1) and m(N1)
  - ✓ Need an hypothesis on m(N1) or m(C1).

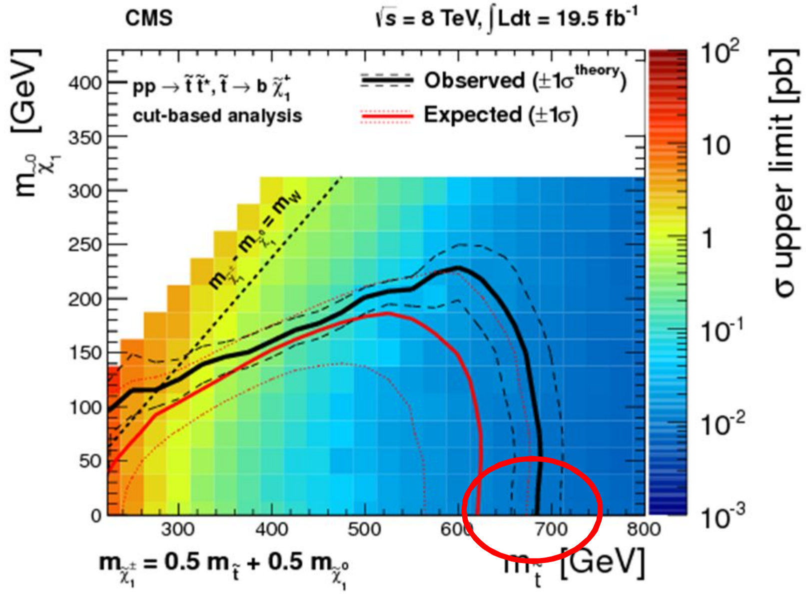
$t_1, \tilde{\chi}_1^0, \tilde{\chi}_1^{+/-}$



m(C1)=150 GeV fixed



m(C1) half way from $m(\tilde{t}_1)$ and m(N1)



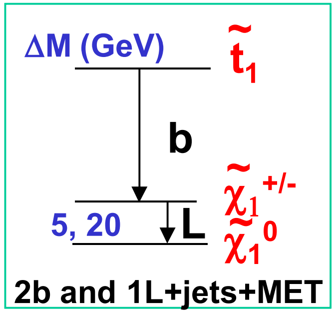
Also quite strong limit on stop masses

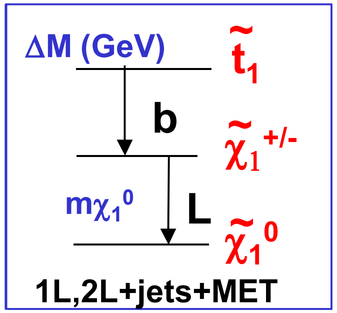
Stop (8)

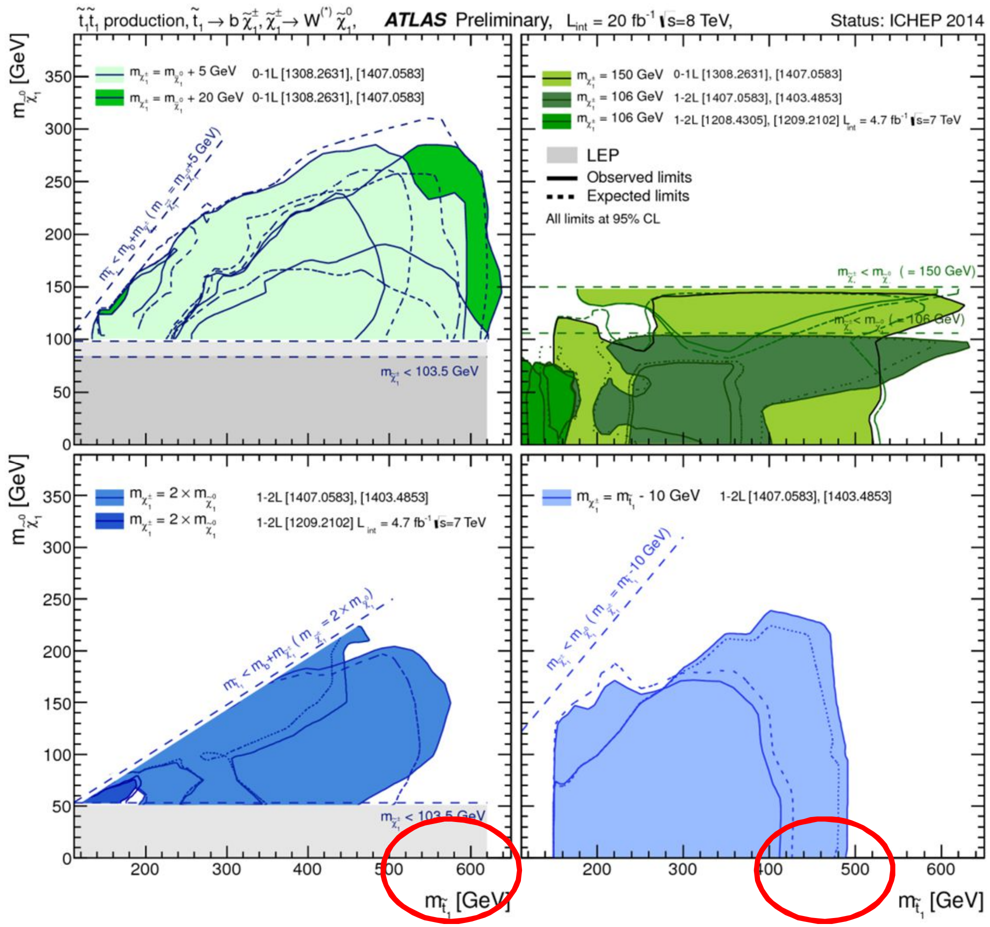
ATLAS: 1506.08616

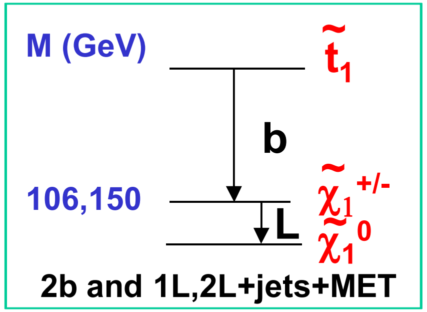
CMS: 1602.03169, 1603.00765

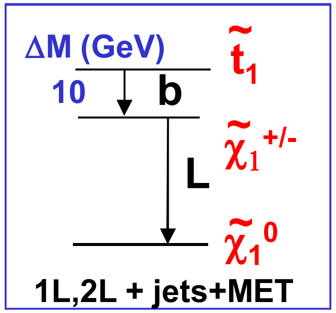
- … and combine with other channels for $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^{+/-} \rightarrow W^{(*)}\,\tilde{\chi}_1^0$









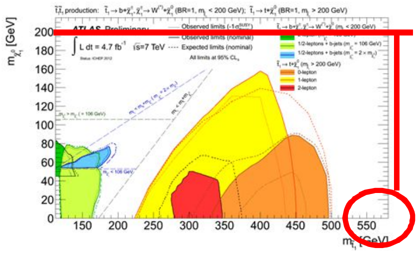


Not too much dependent on $\chi_1^{+/-}$ position

Stop (9)

❑ Lot of progress in three years !

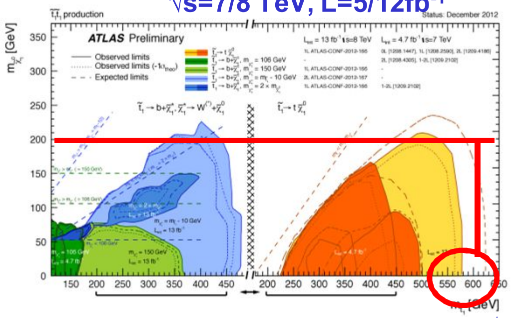
FIRST LIMITS (July2012) ! $\sqrt{s}$=7 TeV, L=5fb^{-1}



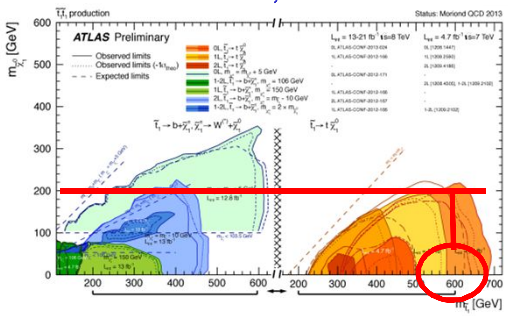
M(LSP)=200 GeV

M(t1)=600 GeV

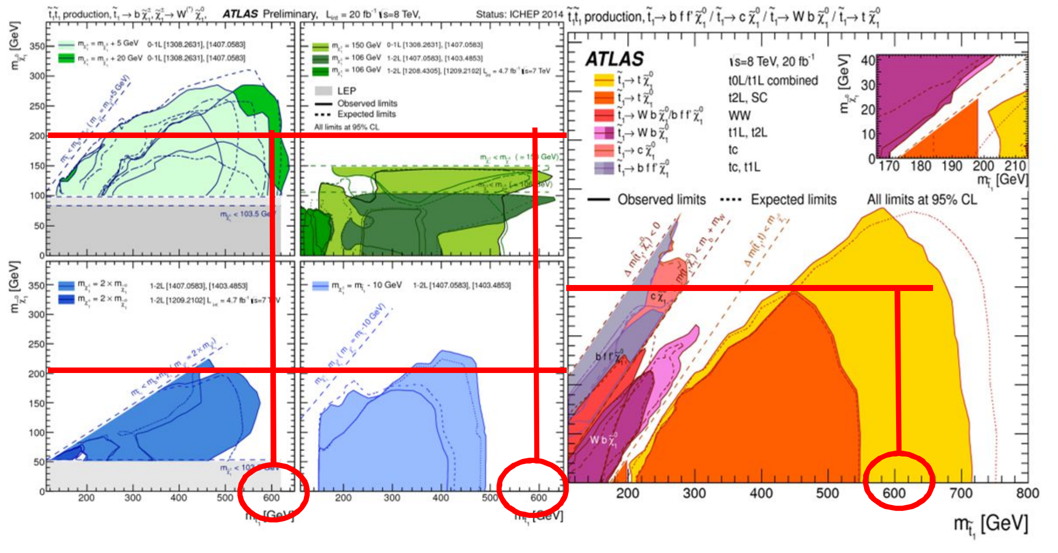
$\sqrt{s}$=7/8 TeV, L=5/12fb^{-1}



$\sqrt{s}$=8 TeV, L=20 fb^{-1}



Final LHC Run I: $\sqrt{s}$=8 TeV, L=20fb^{-1}



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

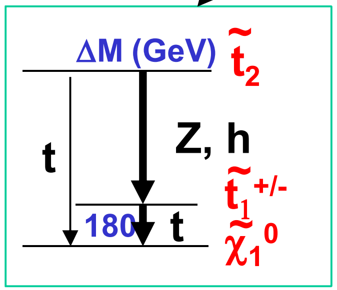
→ Almost there thanks to huge exp. Efforts ?

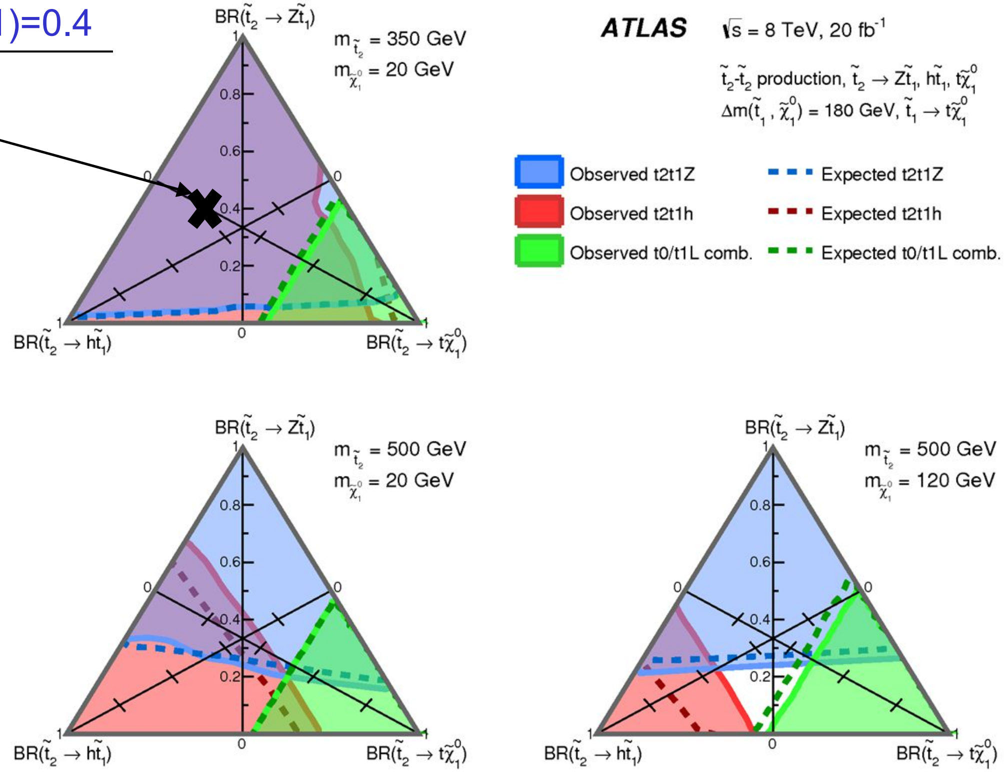
Stop (10)

ATLAS: 1403.5222
CMS: 1405.3886

❑ A word on $\tilde{t}2$

- A way to access the uncovered phase space of stop1: $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = 180$ GeV, $\tilde{t}_1 \to t\tilde{\chi}_1^0$
- Vary Branching ratio of stop2 to Z, h, t coherently
  - ✓ BR(t2->tχ_1^0)=0.2, BR(t2->Zt1)=BR(t2->ht1)=0.4





➔ Develop new analyses (ZZtt, hhtt)

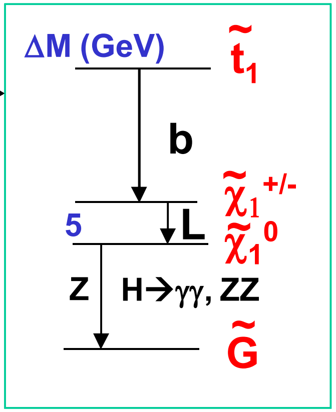
Stop (11)

ATLAS: 1403.5222

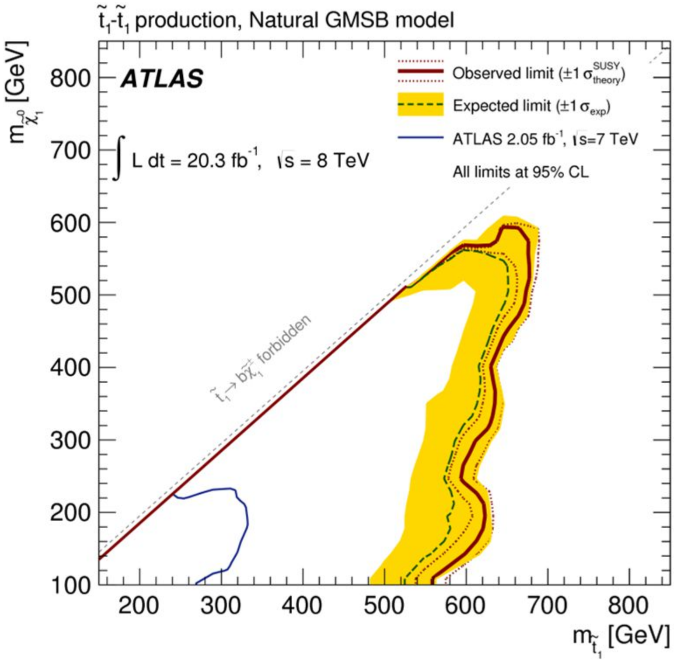
CMS: 1404.5801

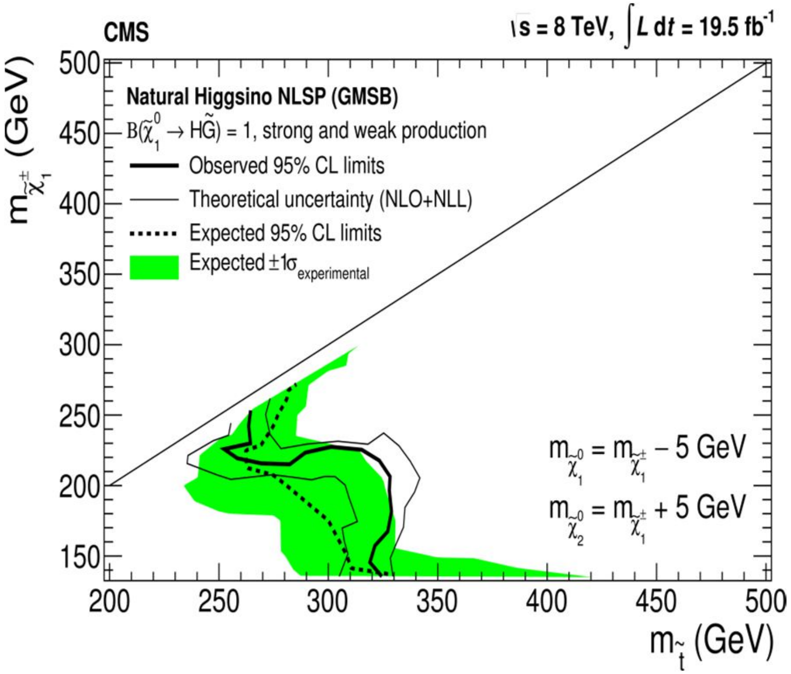
A word on Gravitino LSP

- If χ_1^0 is NLSP and Higgsino-like it will decay via Z, H



$t \to t\tilde{\chi}_1^0$ and $b\tilde{\chi}_1^{+/-}$ rates fixed by the model

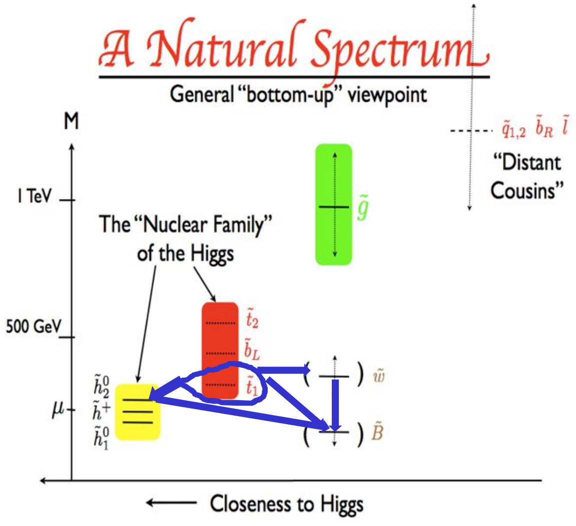




Limit a bit weaker: m(stop)> 300 GeV

Stop (12)

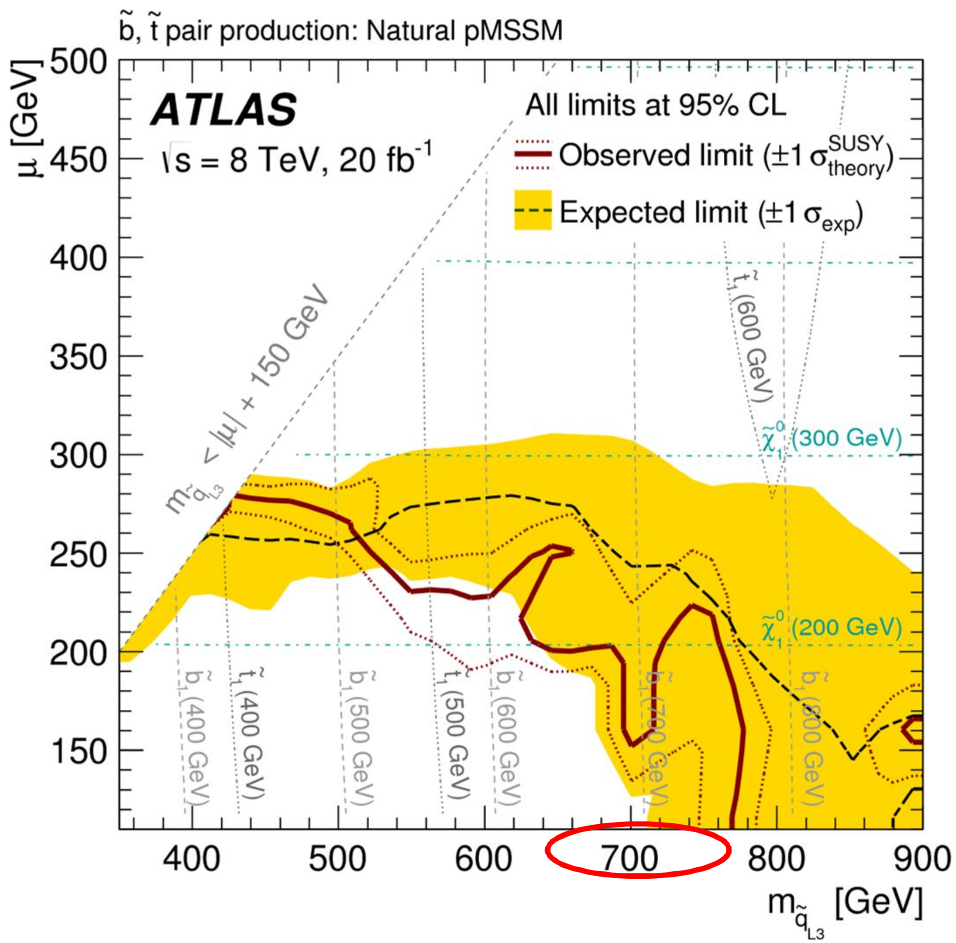
ATLAS: 1407.0600,1506.08616



Natural pMSSM

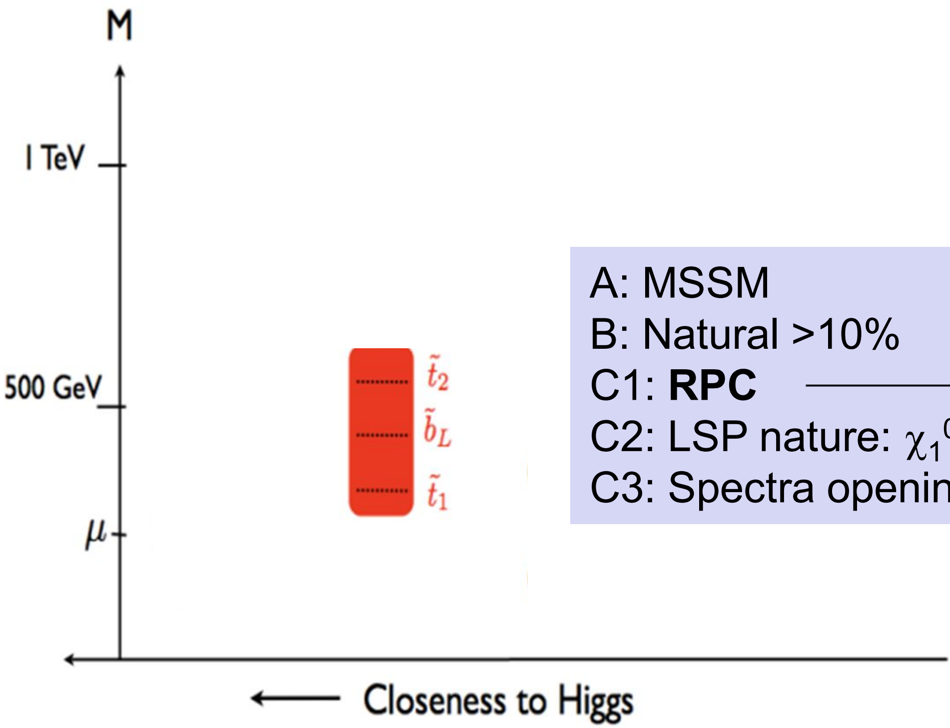
(BR not fixed to 100%)

Combining all analyses



Seems quite model independent !

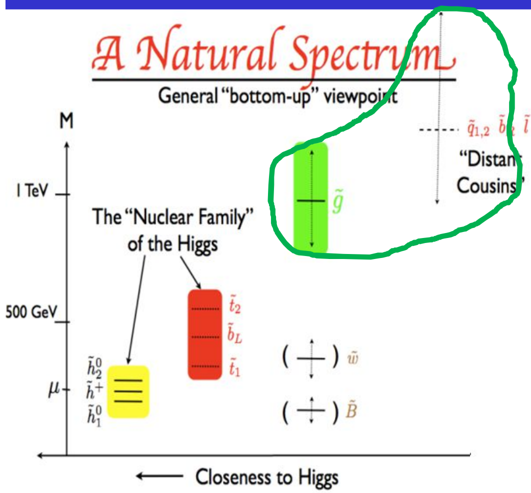
Summary on 3rd generation squark

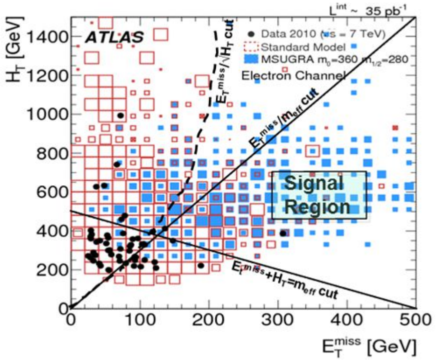


A: MSSM
B: Natural >10%
C1: **RPC** → **RPV ? (see later)**
C2: LSP nature: χ_1^0, G
C3: Spectra opening → Very compressed ? Intricate decays ?

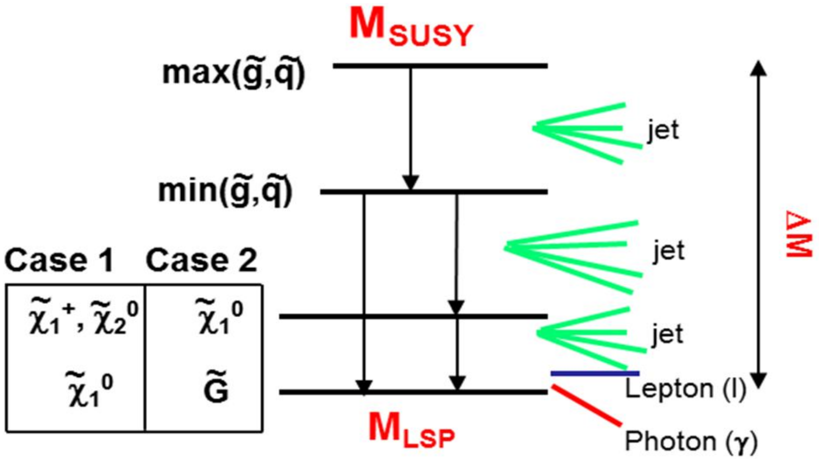
Seriously cornered in vanilla framework !?

Lecture Part IIb



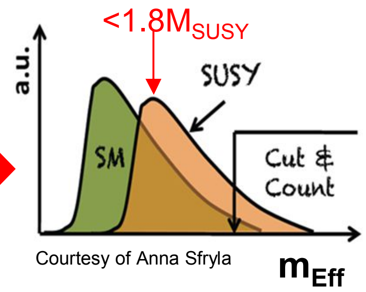


A: MSSM
B: Natural >10%
C1: **RPC**
C2: LSP nature
C3: Spectra opening



1-10 jets
+ E_T^{miss}
+ **0**/1/2 lepton
+ 0/1/2 photon

- Absolute value of vectorial sum: $E_T^{miss} \sim \Delta M$
- Scalar sum: $H_T = \Sigma\ p_T(\text{jet})\ [+\ p_T(l,\gamma)] \sim \Delta M$
- $m_{eff} = E_T^{miss} + H_T \sim 1.8(M_{SUSY}^2 - M_{LSP}^2)/M_{SUSY}$ [hep-ph/0006276]



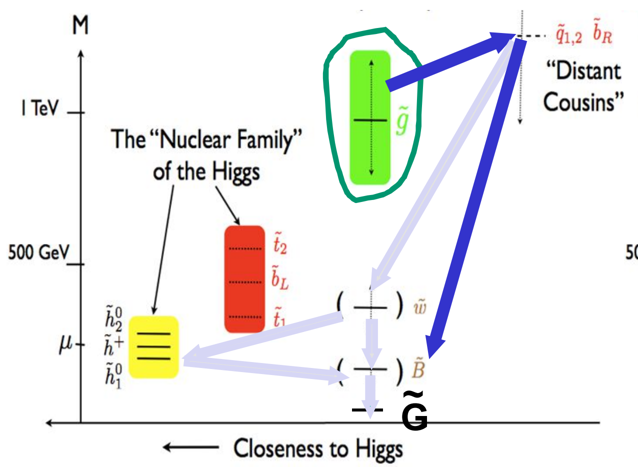
Courtesy of Anna Sfryla

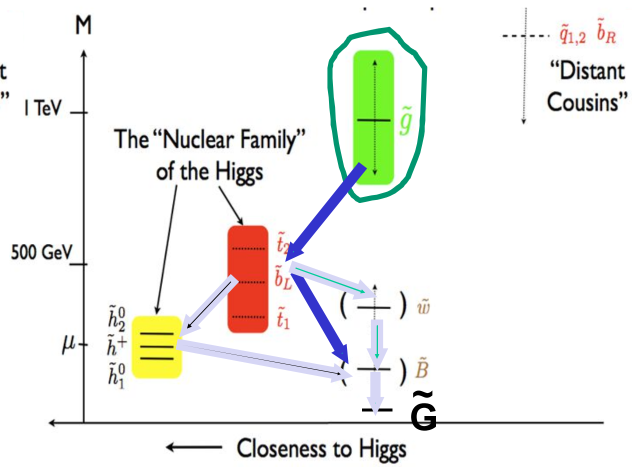
Gluino (1)

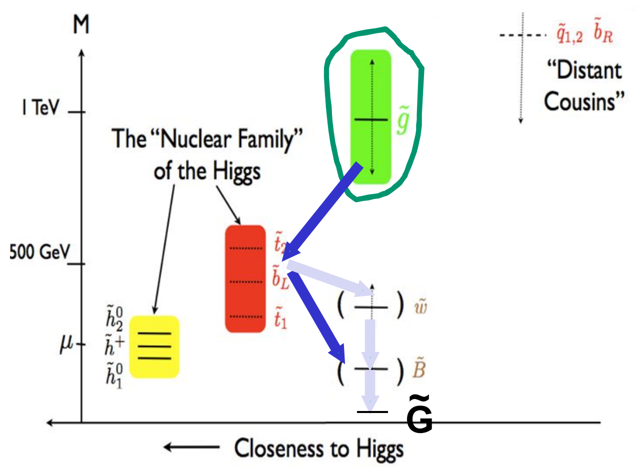
- **Gluino mass govern by one parameter (M3)** — **2-steps, 3/4-steps**
  - Can decay via offshell squarks (1rst/2nd gene) or onshell stop, sbottom

Multiple light jets + MET

Multiple light and b-jets + MET







Gluino (2)

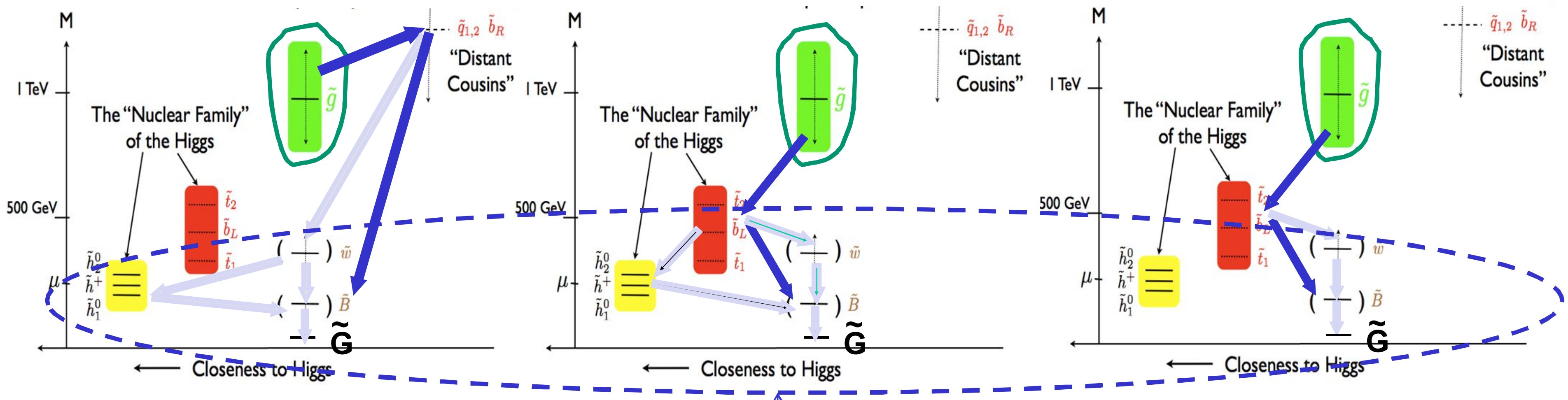
❑ Gluino mass govern by one parameter (M3)

2-steps, 3/4-steps

- Can decay via offshell squarks (1rst/2nd gene) or onshell stop, sbottom

Multiple light jets + MET

Multiple light and b-jets + MET



Complexity of the final state depends on the EWK sector
(see Lecture Ib)

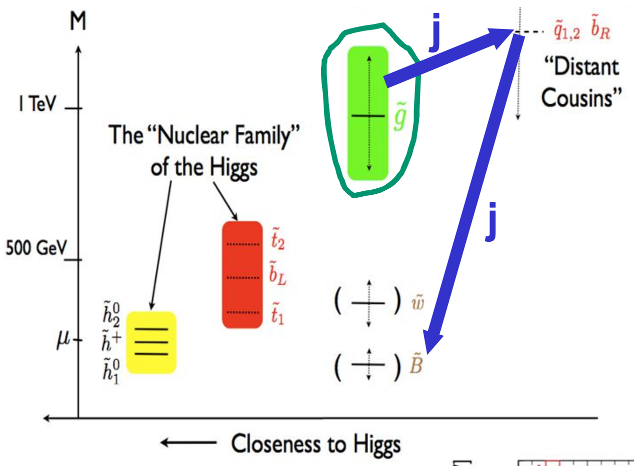
Gluino (3)

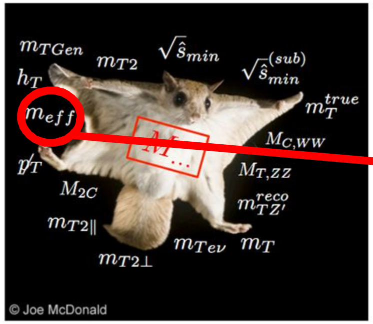
ATLAS-CONF-2015-062

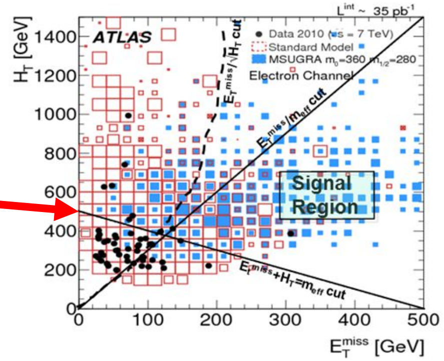
❑ ATLAS: 2-step via 1rst/2nd gene squarks

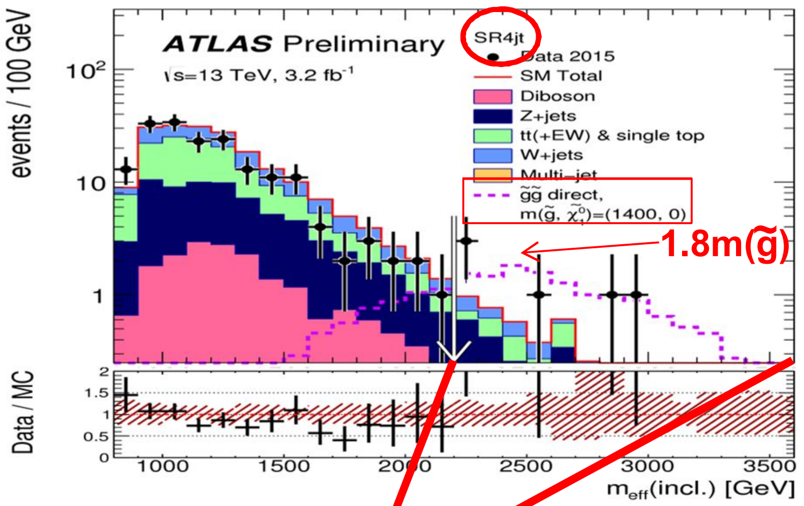
- Inclusive searches with lepton veto

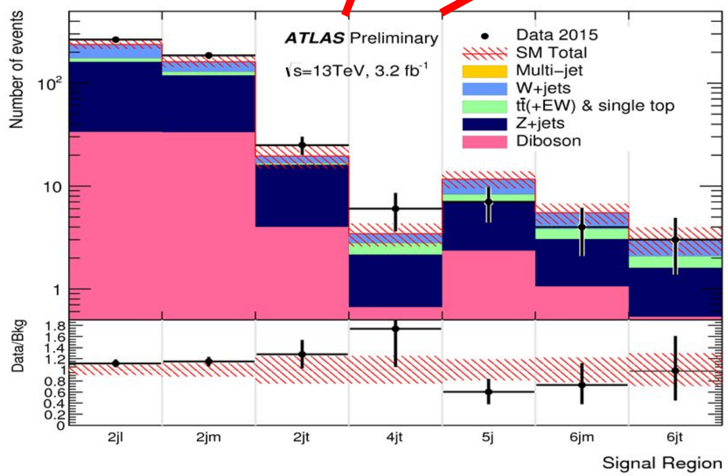
2-6 jets + MET











7 SRs

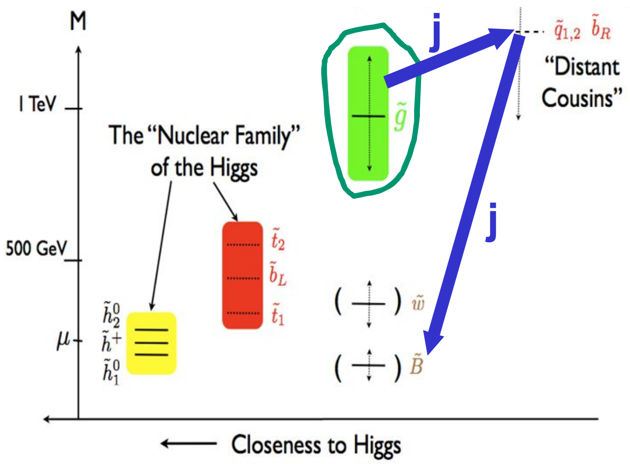
Gluino (4)

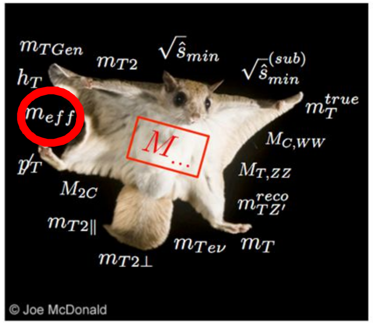
ATLAS-CONF-2015-062

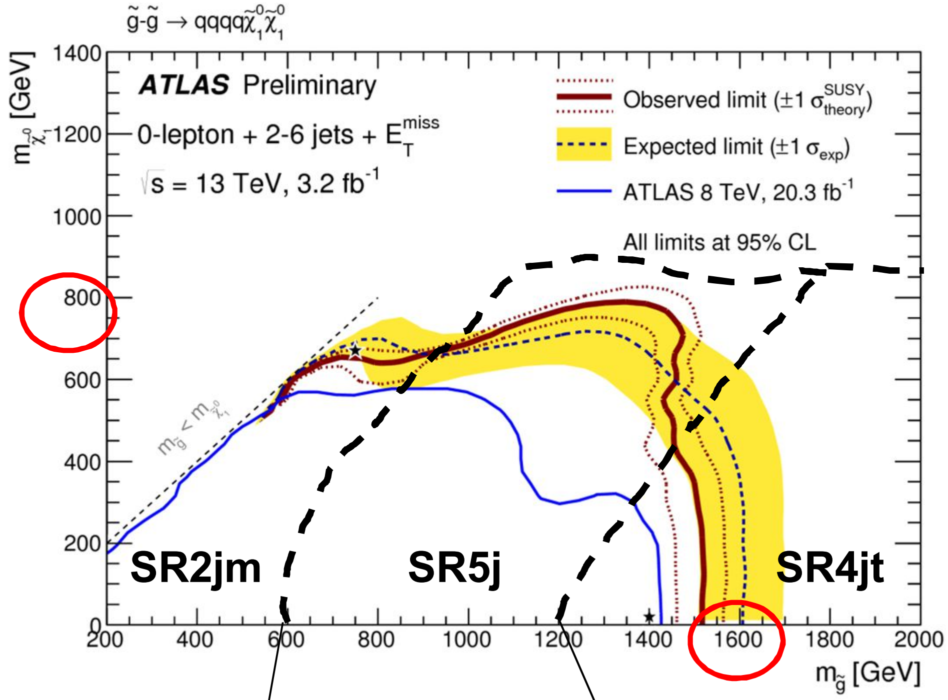
❑ ATLAS: 2-step via 1rst/2nd gene squarks

- Inclusive searches with lepton veto

2-6 jets + MET







Compressed region
→ Most sensitive SR has 2 jets (others too low pT)

Medium mass
→ Most sensitive SR has 5 jets (one from ISR)

High mass
→ Most sensitive SR has 4 very high pT jets

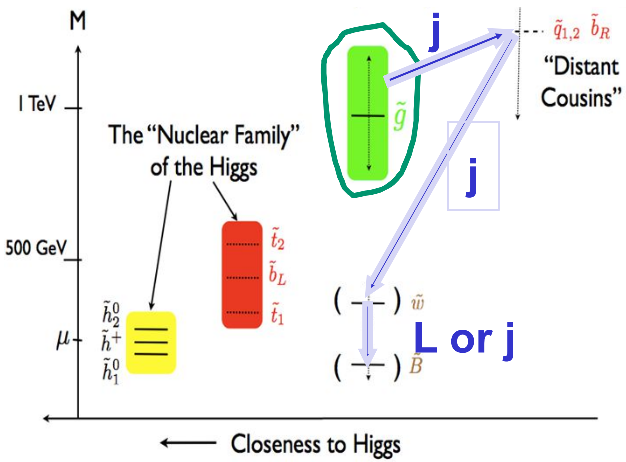
Gluino (5)

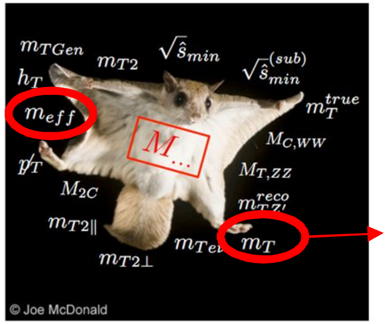
ATLAS-CONF-2015-076

❑ 3-step via 1rst/2nd gene squarks

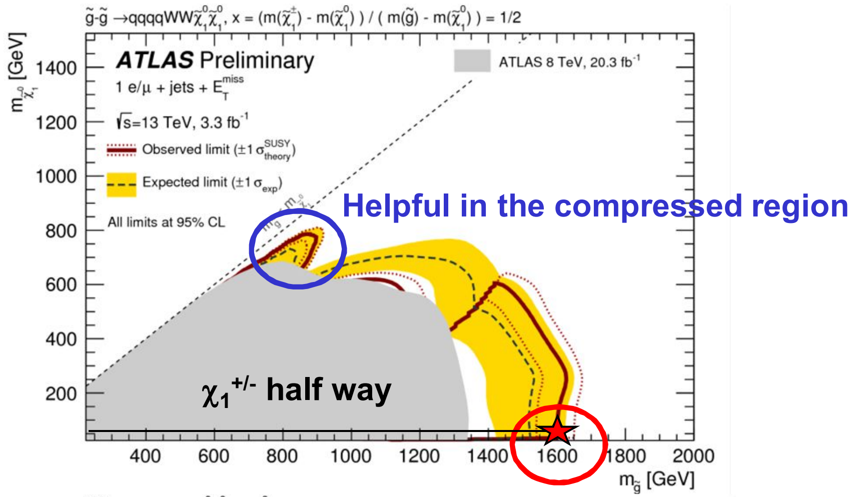
- Inclusive searches with =1 lepton

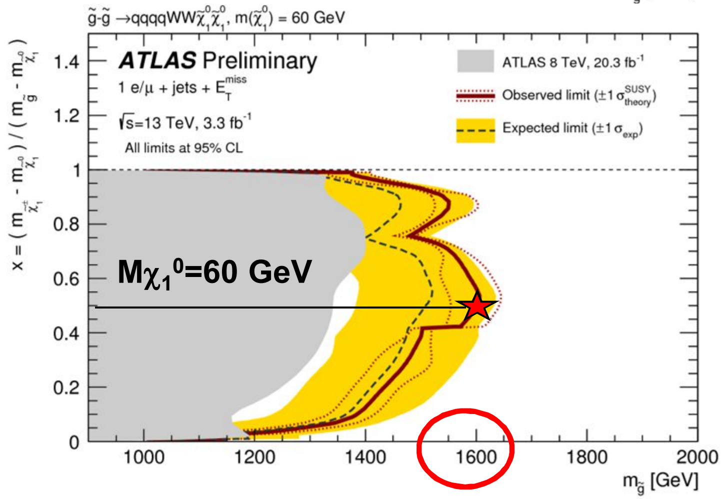
=1lepton+ 2-6 jets + MET





To remove W+jets





Also quite competitive. Can be combined with 0lepton

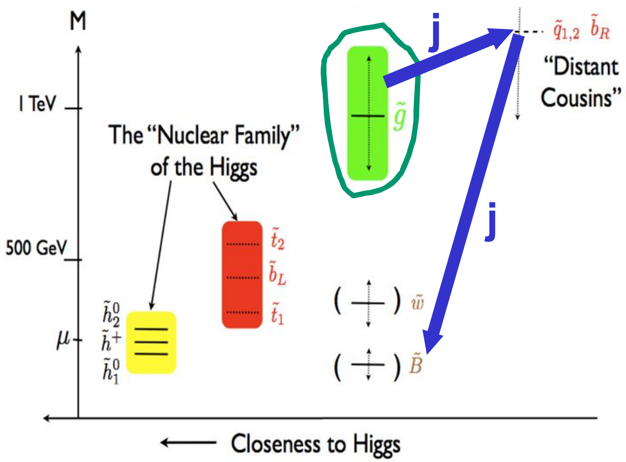
Gluino (6)

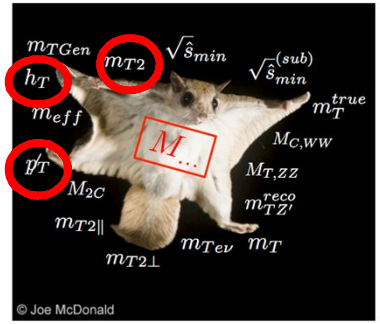
CMS-PAS-SUS-15-002/3/4/5

❑ CMS: 2-step via 1rst/2nd gene squarks

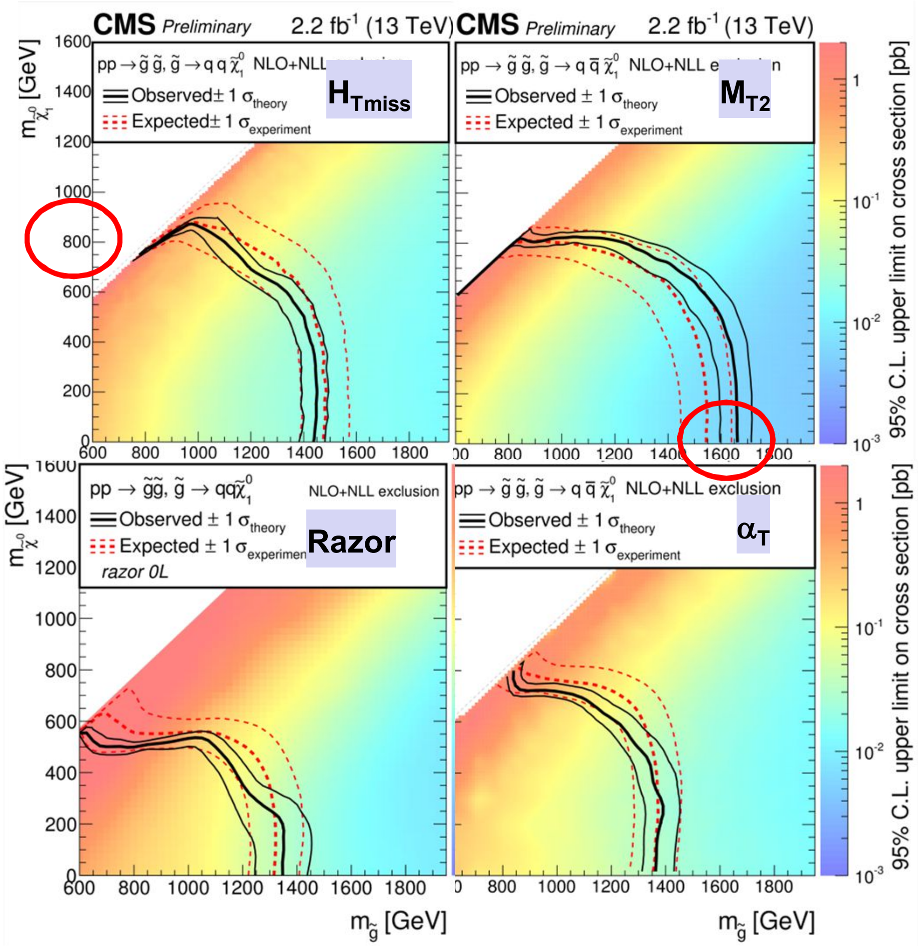
- Inclusive searches with lepton veto

2-7 jets + MET





+ *Razor*
+ α_T



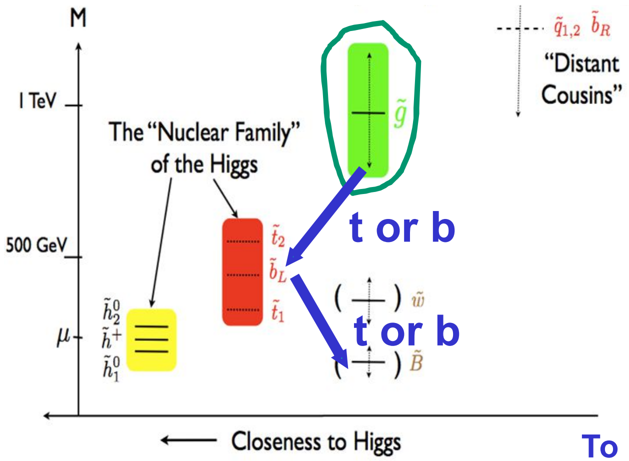
MT2 variable most powerful (and similar to ATLAS) !

Gluino (7)

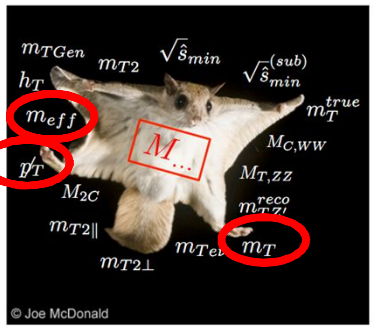
ATLAS-CONF-2015-076

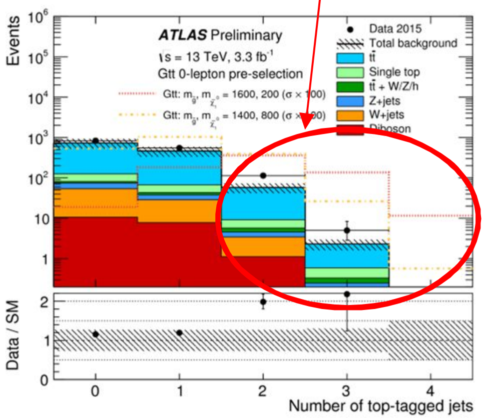
❑ 3-step via 3rd gene squarks

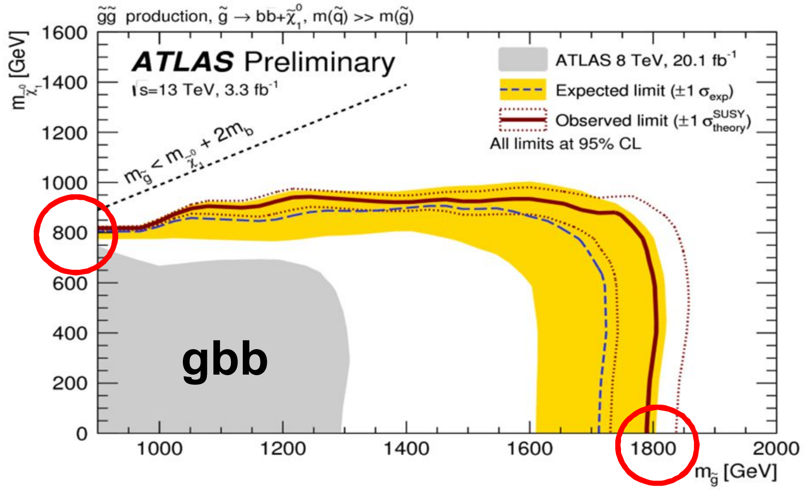
0-1lepton+ ≥3 b-jets + MET

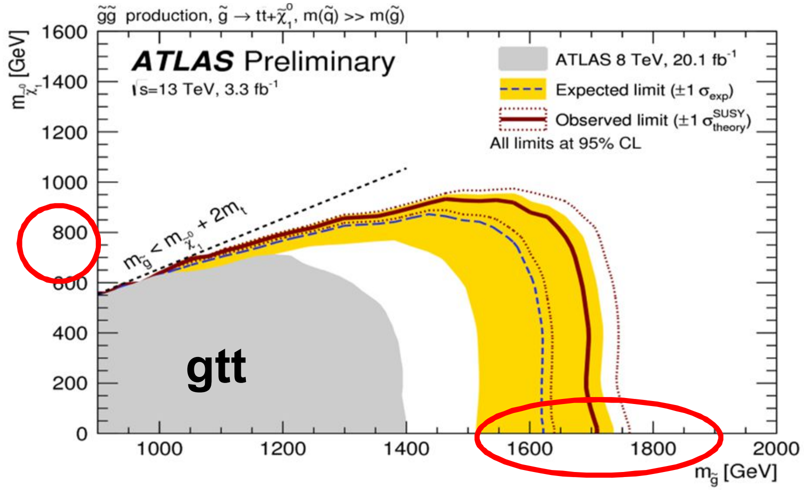


To remove ttbar









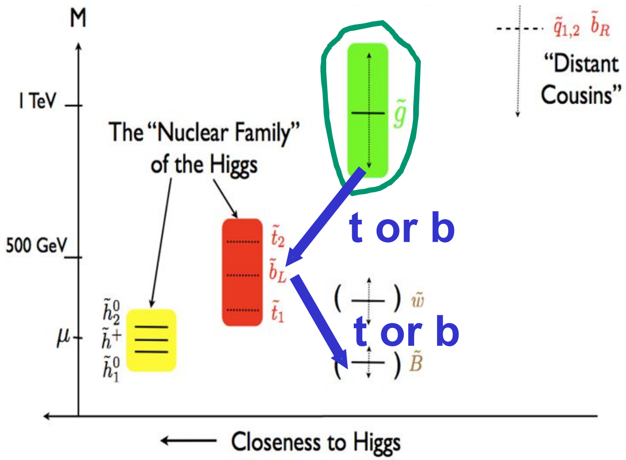
Strongest limits on gluino masses !

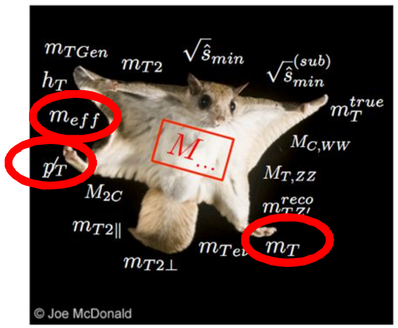
Gluino (8)

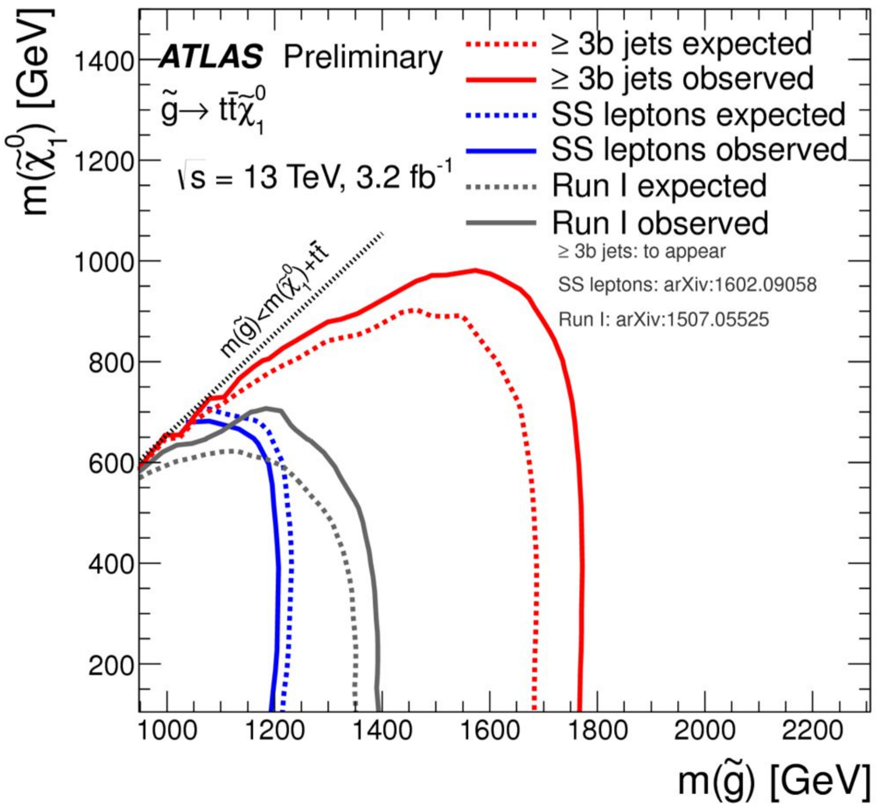
ATLAS-CONF-2015-076

- 3-step via 3rd gene squarks

0-1lepton+ ≥3 b-jets + MET







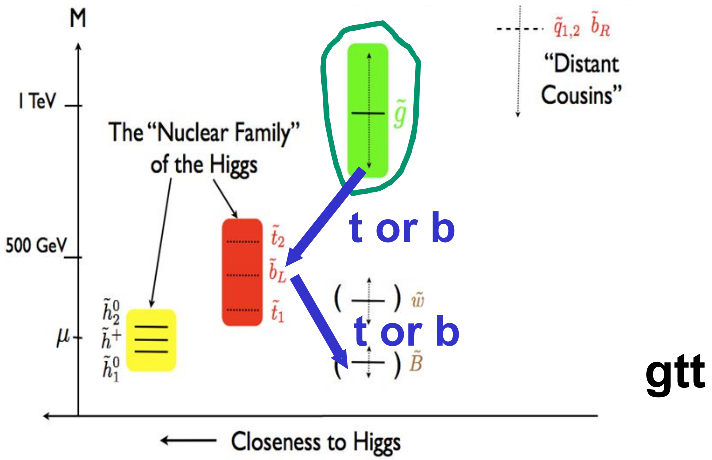
Other top-killer analyses can not compete

Gluino (9)

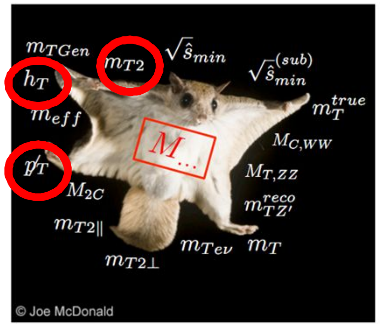
CMS-PAS-SUS-15-002/3/4/7

❑ 3-step via 3[rd] gene squarks

0-1lepton+ ≥3 b-jets + MET

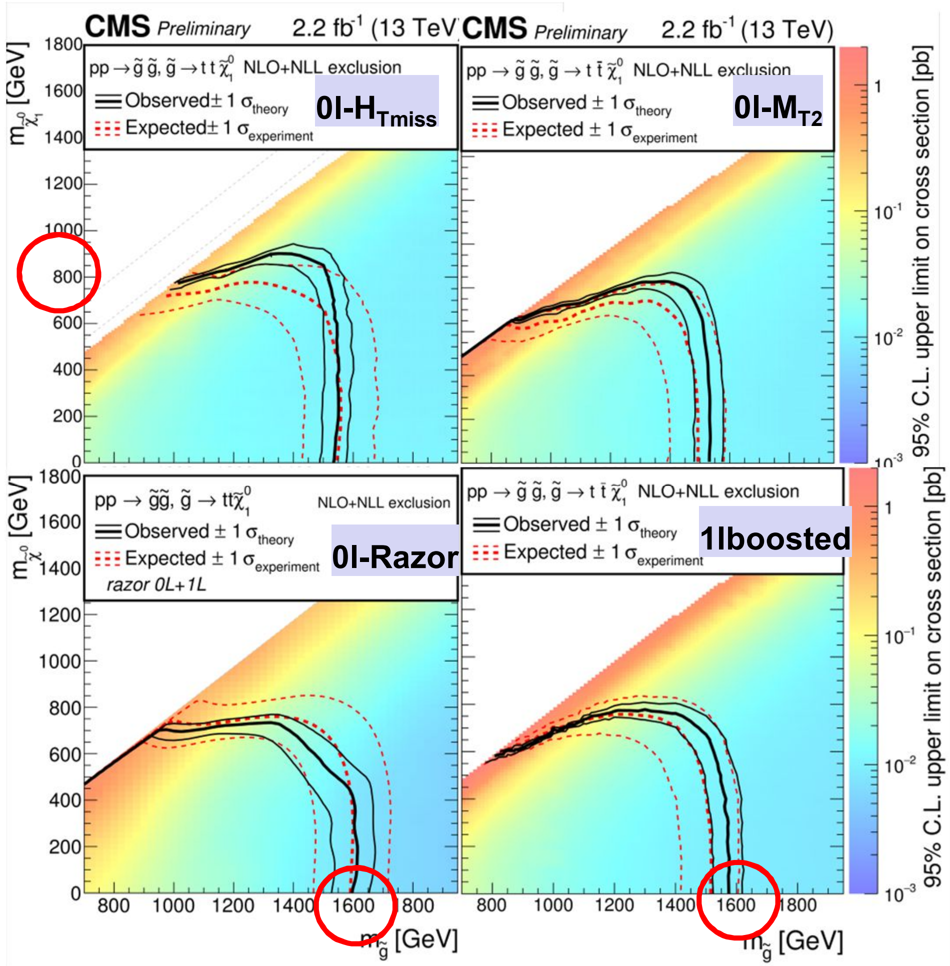


gtt



+ *Razor*

+ α_T



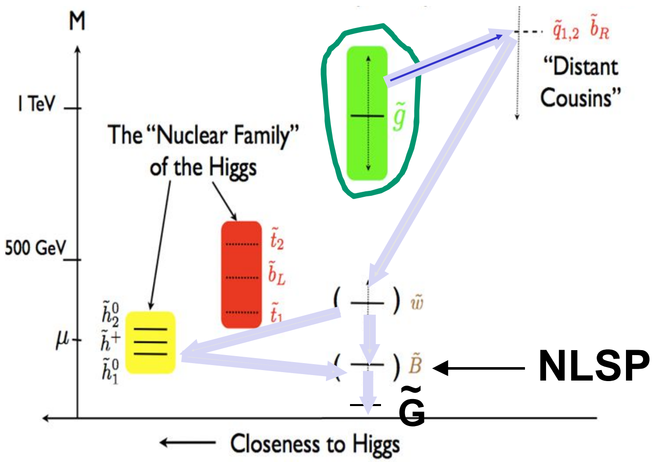
Very similar limits (since dominated by Nb cut)

Gluino (10)

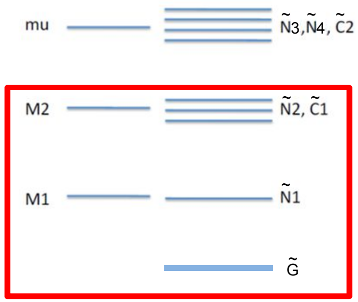
❑ Assume now LSP is the gravitino

- Next-to-Lighest LSP (NLSP) determines the event final states
- Enhance multi-leptonic / photonic signature (0/1 leptons +jets +MET analyses also strong)

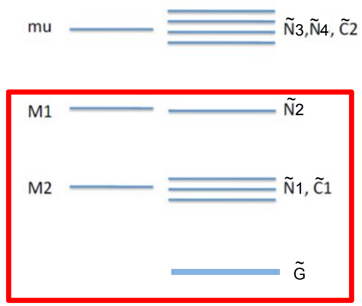
Multiple light jets + MET



Bino case
Open Spectra



Wino co-NLSP case
ΔM(C1-N1)<1GeV



Higgsino case
Compressed spectra

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

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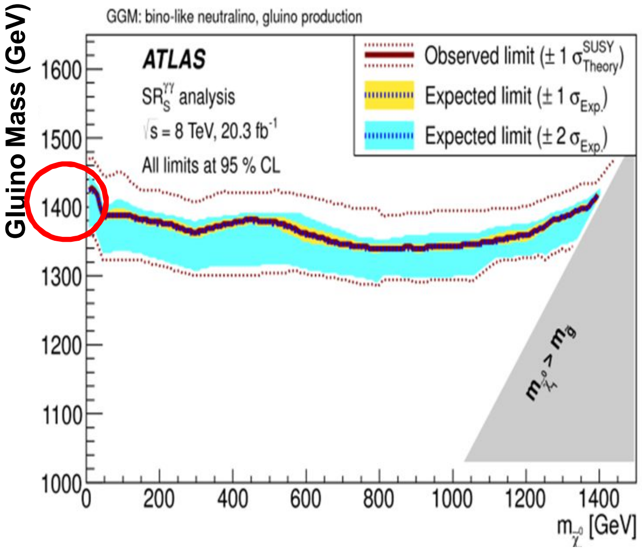
Gluino (11)

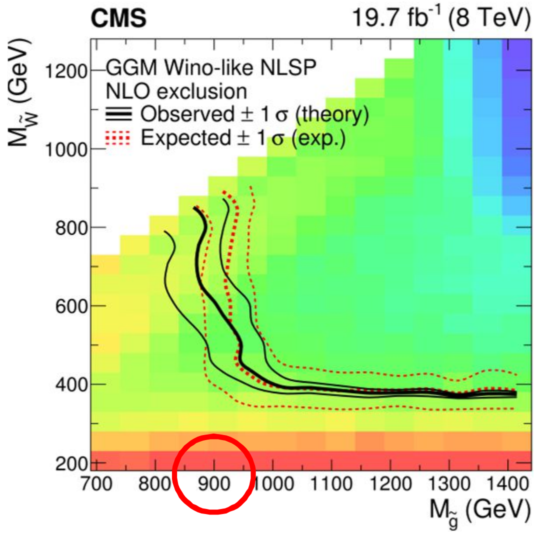
ATLAS: 1507.05493
CMS: 1507.02898,1508.01218

- **NLSP = $\tilde{\chi}_1^0$**
  - Add MET to all signature in brackets

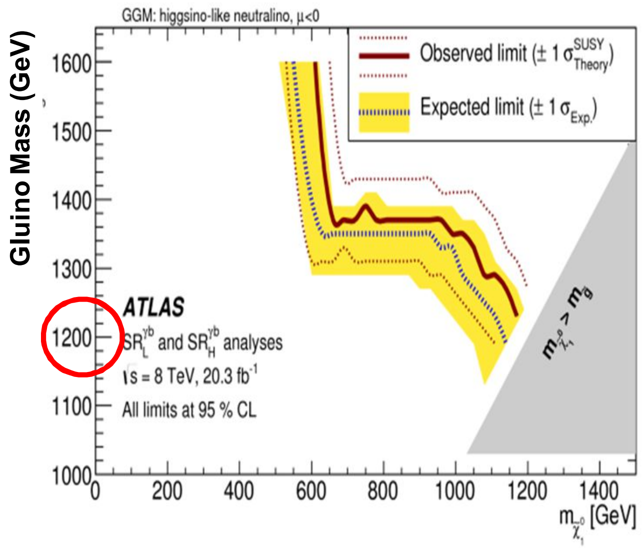
χ_1^0-bino like ($\gamma\gamma$)



χ_1^0-wino like degenerate with $\chi_1^{+/-}$ (γ + e)



χ_1^0-Higgsino like (Z+jets, H→bb+jets)



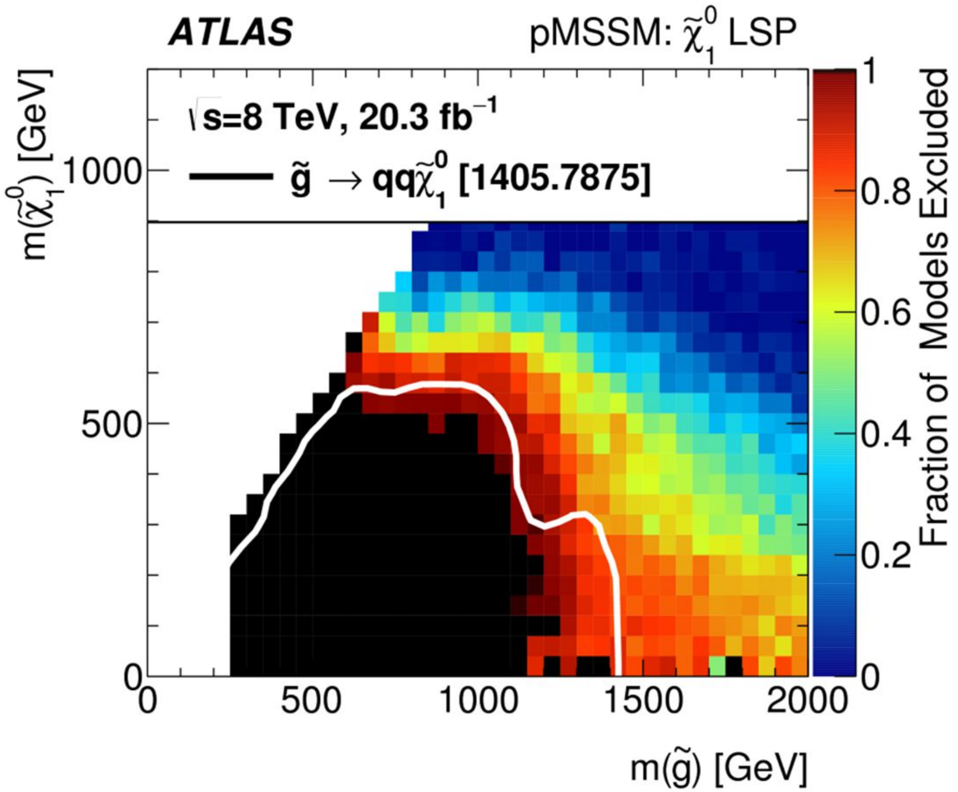
M(gluino) above 1 TeV

Gluino (12)

ATLAS: 1508.06608
CMS-PAS-SUS-15-010

❑ pMSSM

- Not assuming 100% BR …



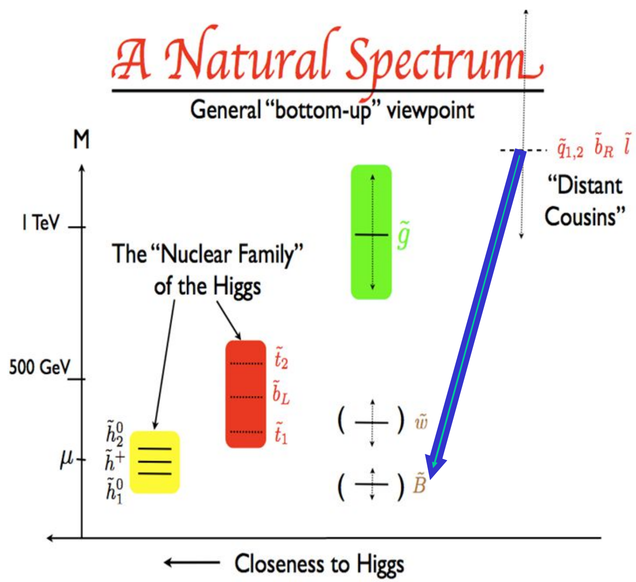
Close-by limit wrt Simplified Model for gluinos

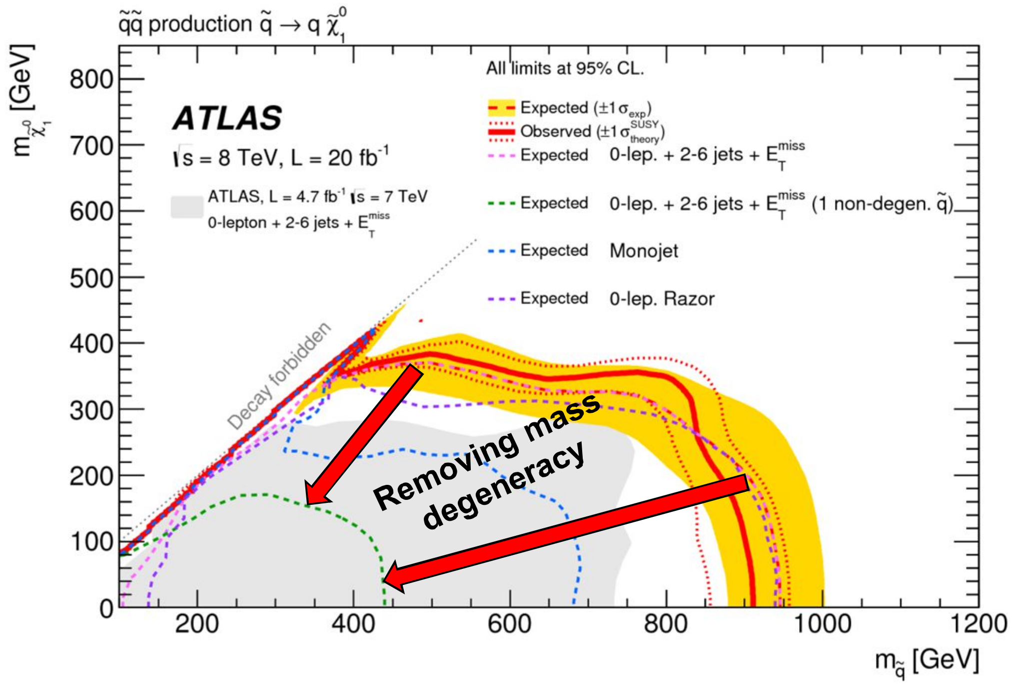
1rst/2nd gene squarks (1)

ATLAS: 1508.06608
CMS-PAS-SUS-15-010

❑ By products of gluino-like analyses

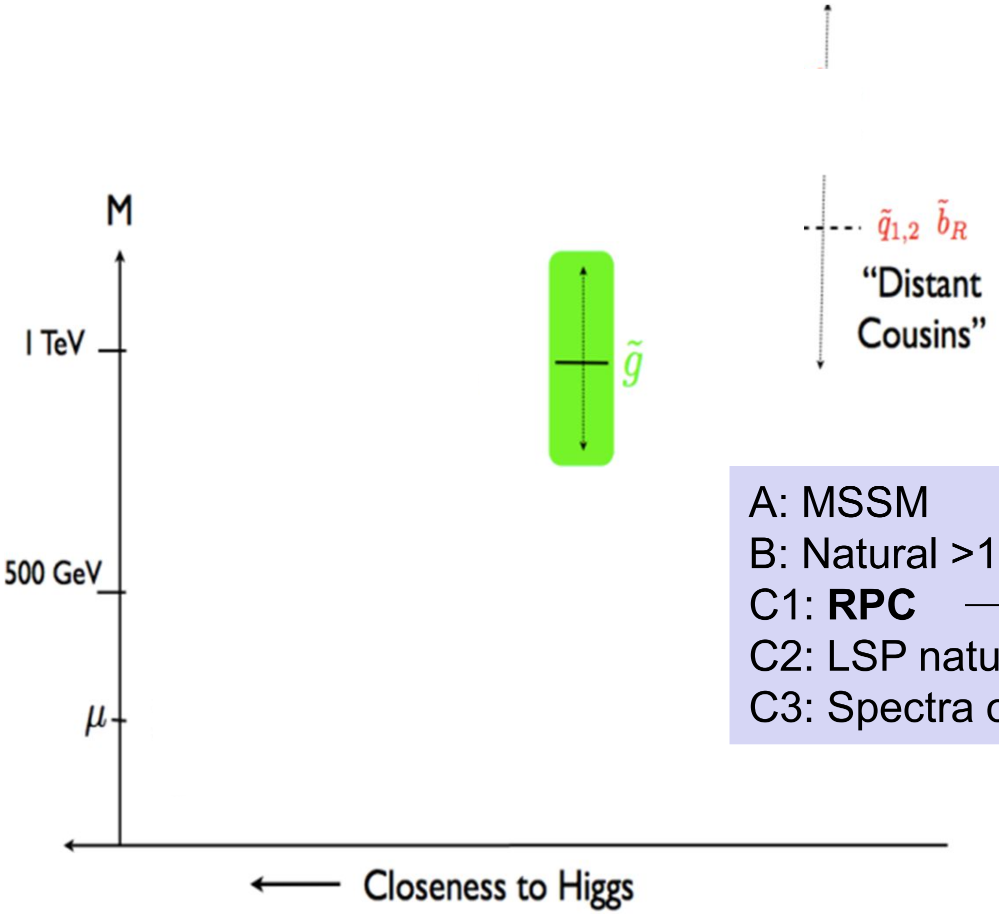
- But not constraint by naturalness: can be anywhere !
- Generally mass degeneracy across squarks families, for left and right-handed. Not generic !





Quite weak generic limits

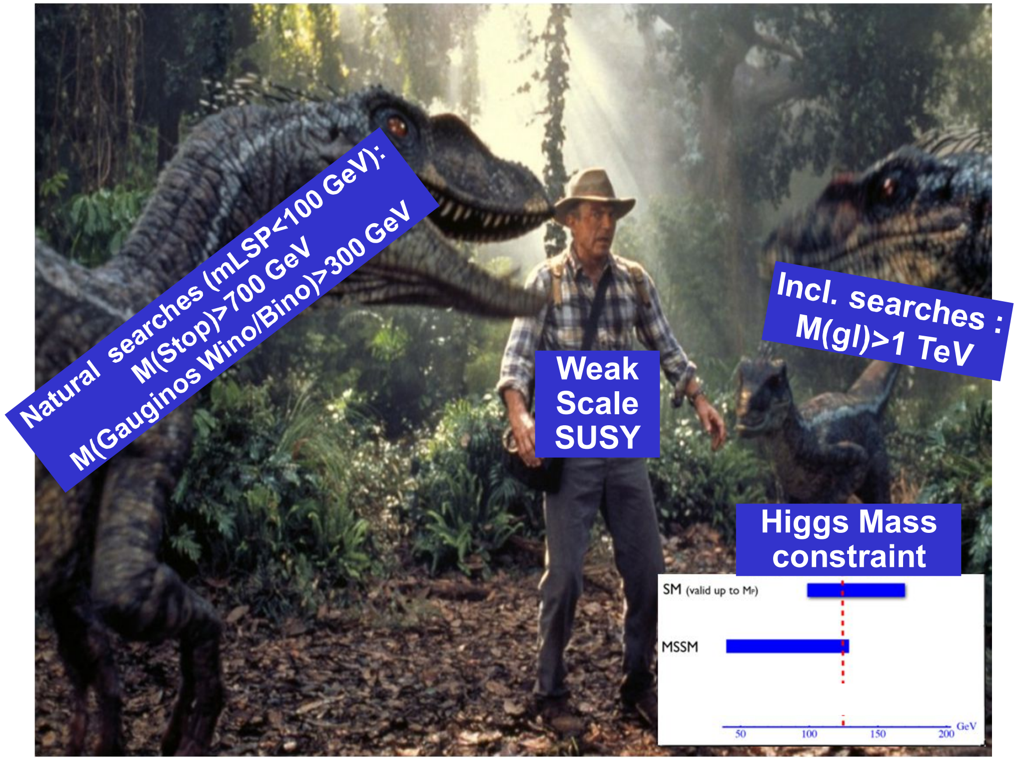
Summary on Strong SUSY



A: MSSM
B: Natural >10%
C1: **RPC** → **RPV ? (see later)**
C2: LSP nature: χ_1^0, G
C3: Spectra opening

Limits on gluino mass very strong: >1 TeV in 'all' vanilla cases

Conclusions on Vanilla framework



Still viable if :

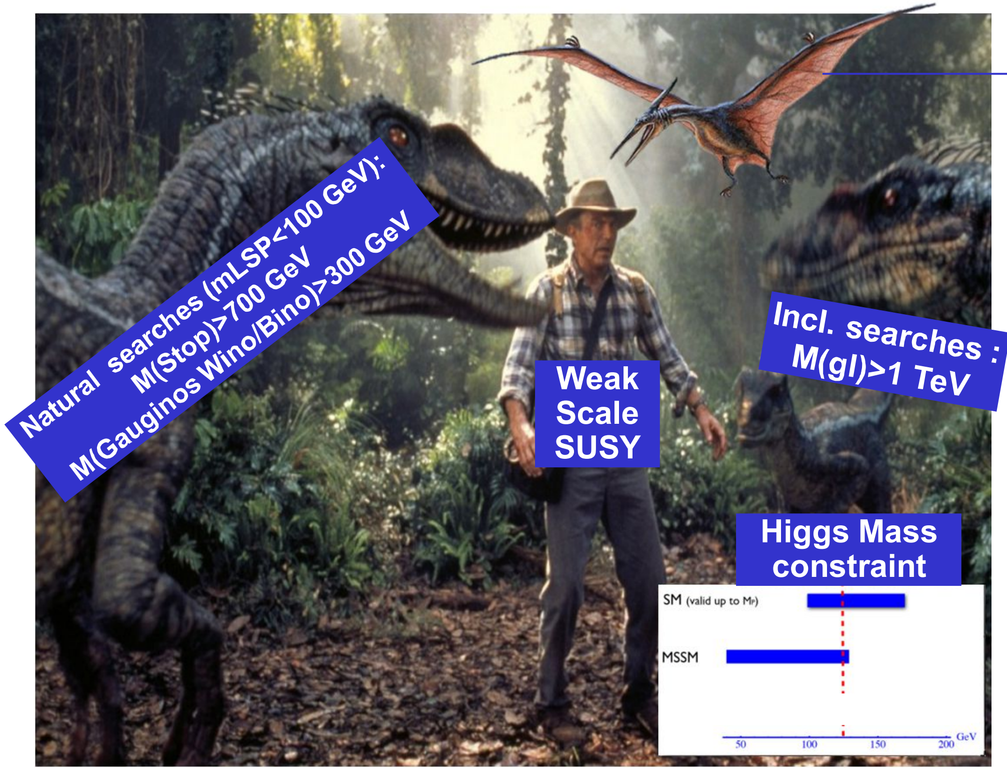
-- very compressed scenario: limits are weaker but will come

-- complicated SUSY spectrum: intricate decay chains especially due to EWK sector

-- a new electroweak singlet is added : relax Higgs constraints and complexify more the EWK sector

-- hard accessible process at low luminosity ($\chi_1^+\chi_1^- \rightarrow WW$), ...

Conclusions on Vanilla framework

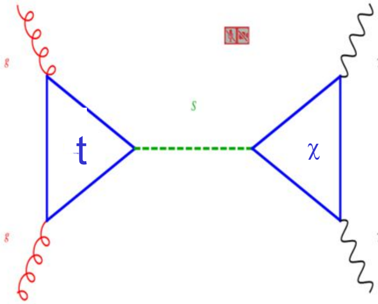


And a recent newcomer !!
S(750 GeV) if it turns out to be true

Max σxBR(A+H→$\gamma\gamma$)~10^{-2} fb vs 6fb obs.

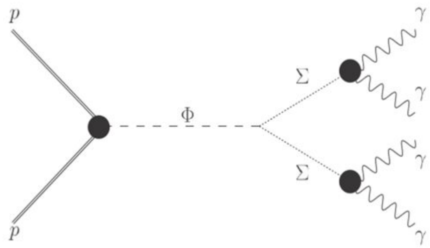
→ Factor 500 too low *1512.05332*

→ Only known possibility but extremely contrived *1603.04464*



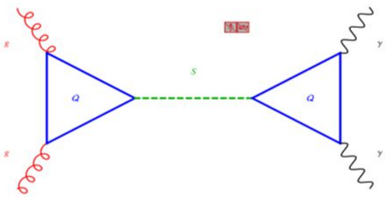
Chargino enhancement
mχ~350 GeV, $\Gamma\chi$<5 keV
tanβ ≈ 1 and μ ≈ M2 ≈ M1

→ Adding one more Σ scalar [NMSSM], could be possible by generating a new final state



1602.03344
m_Σ~ GeV → 2 photons in one cluster ! Should be possible to confirm or not experimentally

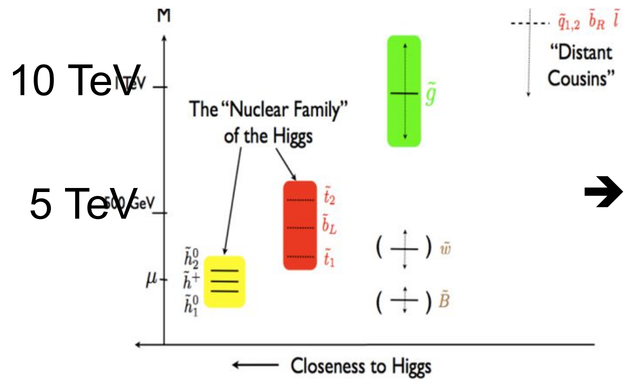
→ Add to MSSM new families of Vector-like Fermions Q to enhance ϕ→$\gamma\gamma$ rate *1601.03696*



Lecture Part IIc

MSSM Extensions?
Scalar Gluon, another scalar (NMSSM)

Fine-tuning is 1% or 0.1 % …
~ sparticles can be above TeV !



➔ HL-LHC, FCC

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

SUSY has no role in hierarchy problem
~ No mass constraints on sparticles or particular spectrum (long-lived particles)

RPV
Targeting gluino and stop + Spectacular signatures (multileptons, no Z, resonances, LFV, Long-lived particles)

(Very) Compressed spectrum
Low pT objects + eventually Long-lived or meta-stable particles

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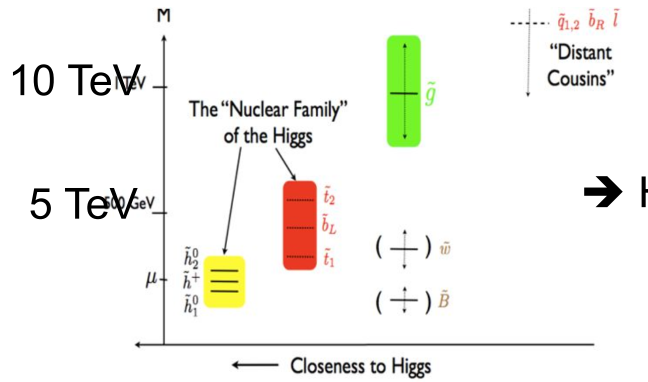

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long-lived particles

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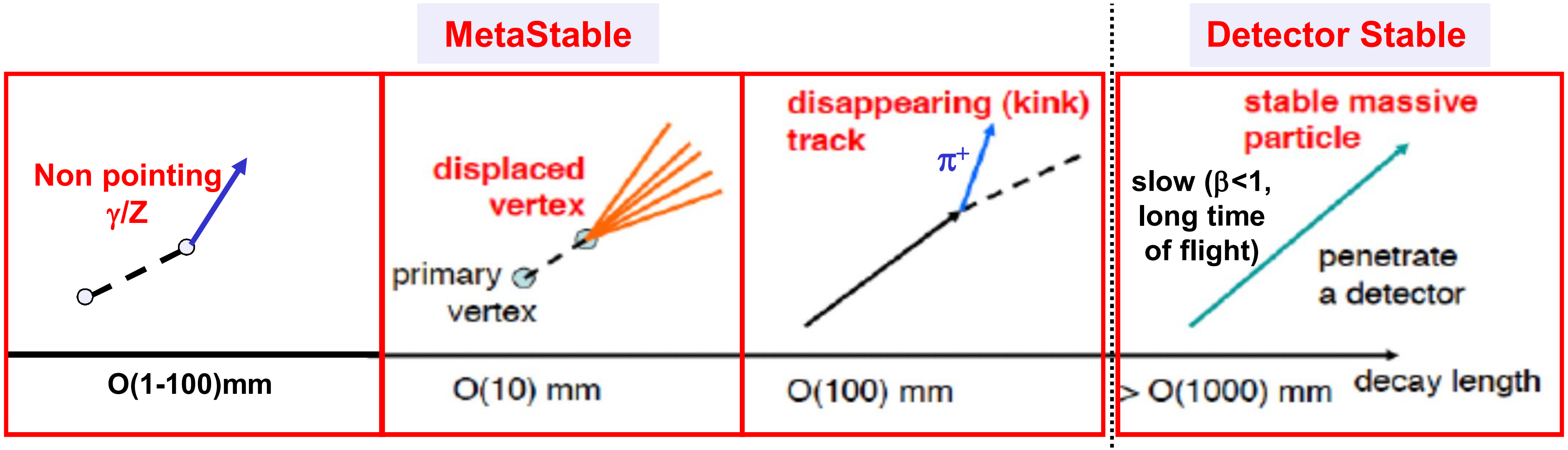
Long-Lived Particles

See also Loic Quertenmont

❑ Apart from LSP other particle could be long-lived :

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 $\lambda, \lambda', \lambda'' \sim 0(10^{-5})$
3. Low mass difference, e.g $\Delta M(\tilde{\chi}_1^+ - \tilde{\chi}_1^0) \sim 100$ MeV [AMSB] ➔ Low **p** emitted, kinked track
4. Stable Massive Particle (mix of 1 and 3) ➔ Stable R-hadron ($\tilde{g}$ or $\tilde{q}$), sleptons



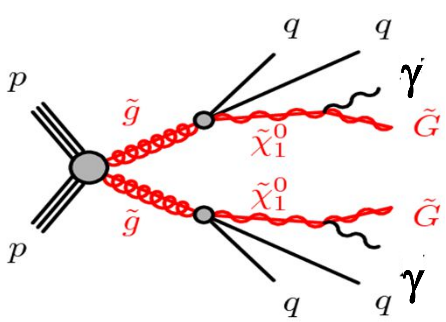
Generic limits on life-time vs mass plane !

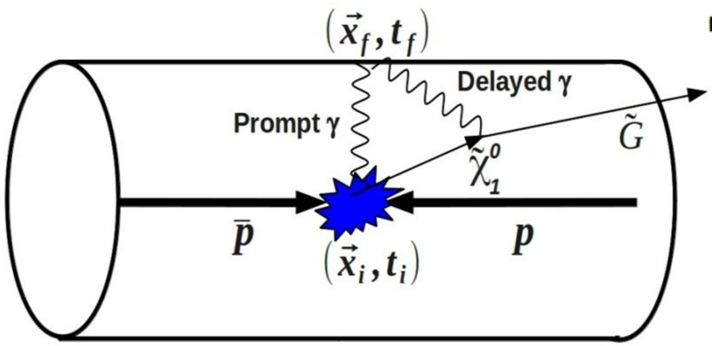
Long-Lived Particles (1)

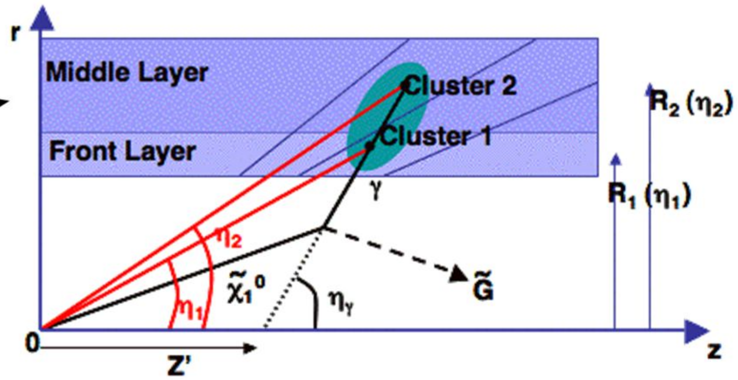
ATLAS: 1409.5542

❑ Non pointing photon could have several striking signatures

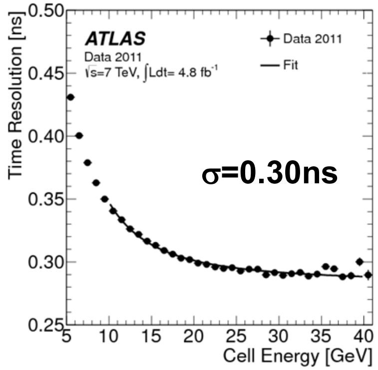
- LSP=G and long-lived bino-NLSP = $\chi_1^0 \to \gamma G$

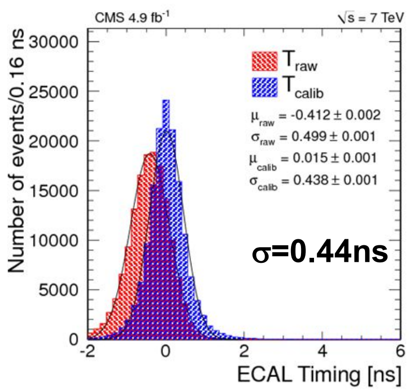






- Late Timing arrival in the EM calorimeter (t_γ)
  → Need excellent calorimeter timing reso.





- No pointing to the primary vertex

1. Stand-alone pointing capabilities of the calorimeter → $\tau(\chi_1^0) < 50$ ns
2. Impact parameter of the converted photons → $\tau(\chi_1^0) < 1$ ns

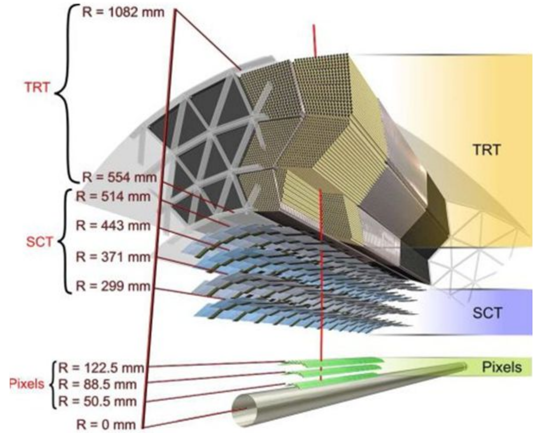
Need a deep understanding of the detector !

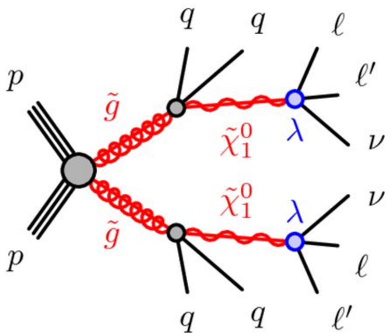
Long-Lived Particles (2)

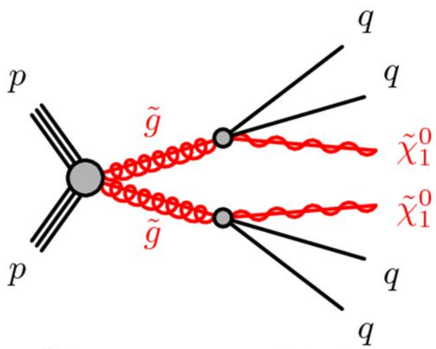
ATLAS: 1504.05162
CMS: 1411.6530

❑ High mass displaced vertex with 5 tracks or lepton

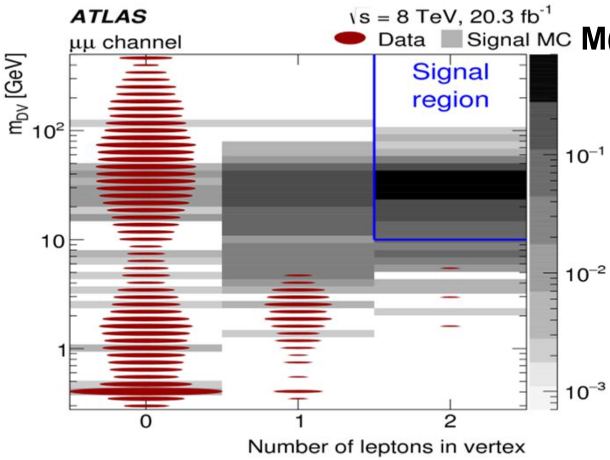
- Design a background-free analysis in $M_{vertex} – N_{track}$ plane
- Build up a dedicated tracking to increase signal efficiency
- Could come from e.g. RPV with $\lambda_{ijk}\neq0$ or Long-lived gluinos



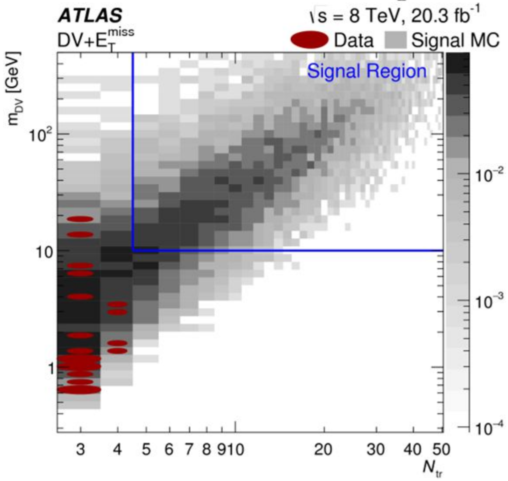




M(gl)=0.6 TeV



M(gl)=1.4 TeV

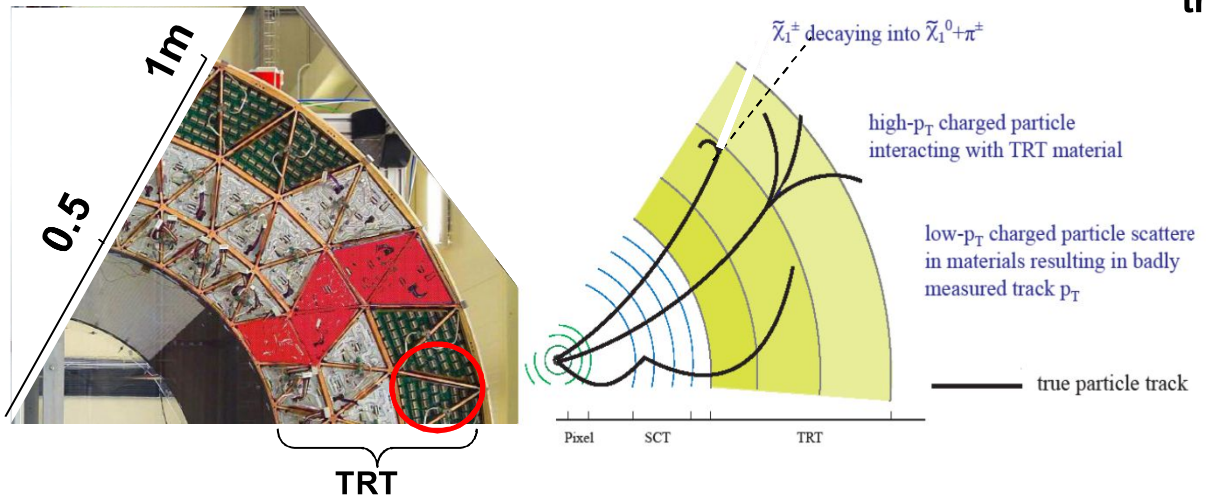


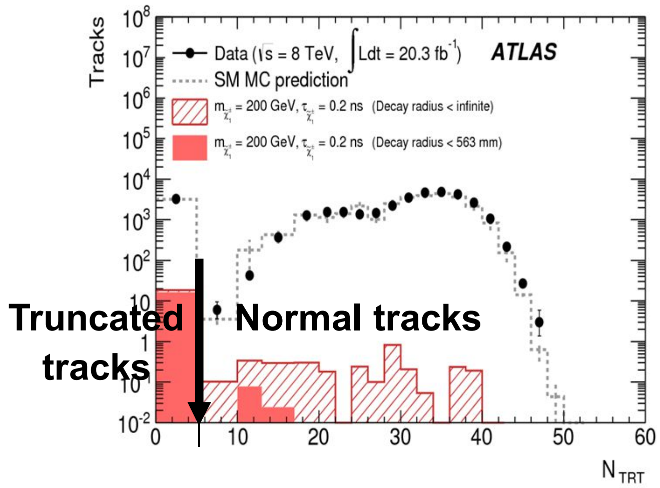
Long-Lived Particles (3)

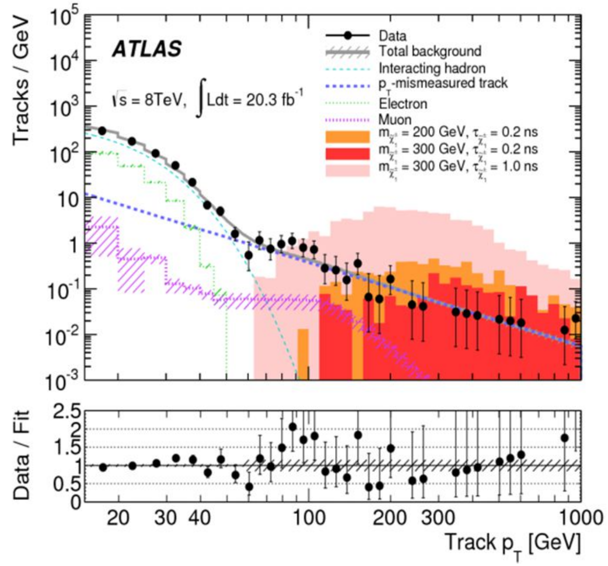
ATLAS: 1310.3675
CMS: 1411.6006

❑ Direct production of a metastable $\chi_1^{\pm}$ *

- Motivated by AMSB, but model independent results
  - ✓ $\chi_1^{\pm} \rightarrow$ soft $\pi^+ + \chi_1^0$: Disapearing track in the TRT
- Remove background : N_{TRT} + highest p_T isolated track







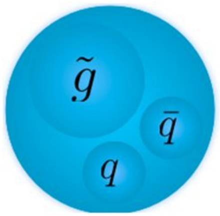
* σ (C1N1,C1C1) ~ 15/ 1pb for m=100/200 GeV @ 8TeV

Long-Lived Particles (4)

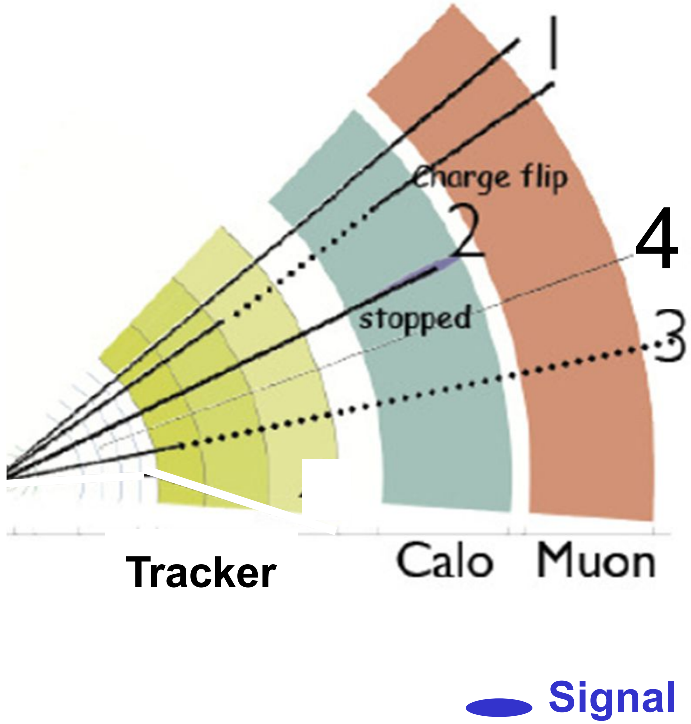
1211.1597, ATLAS-2013-058

❑ Slowly moving particles

- Can be colored (*gluinos*)
  - ✓ If lifetime > hadronization time scale ~O(10^{-24})s then gluino R-hadrons or gluinoballs can form



  - ✓ Can flip sign (1, 2 times) or not 1, 3
  - ✓ Can stop and decay later 2
- Can be non-colored (*sleptons, charginos*) 4
  - ✓ Manifest as a heavy muon, charged and penetrating

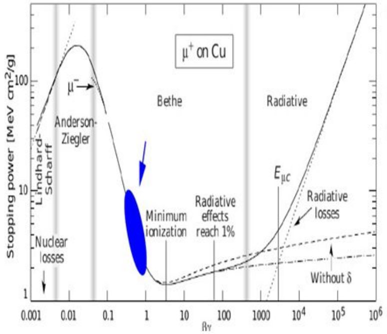


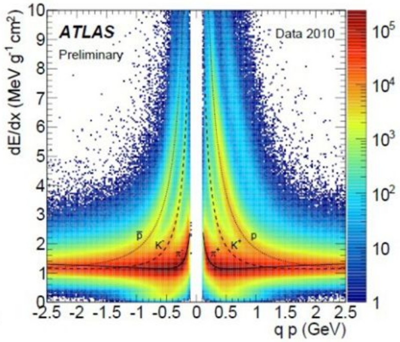
➔ Important to combine all detector information to cover all cases

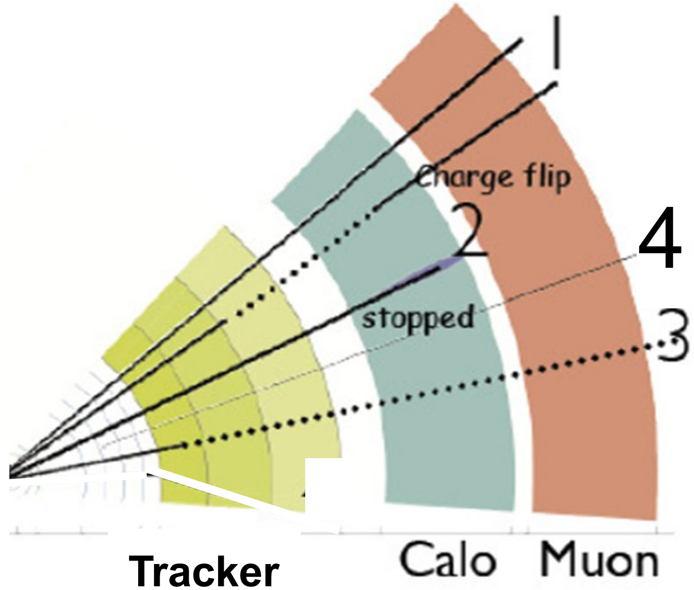
Long-Lived Particles (5)

❑ Possible to reconstruct its mass !

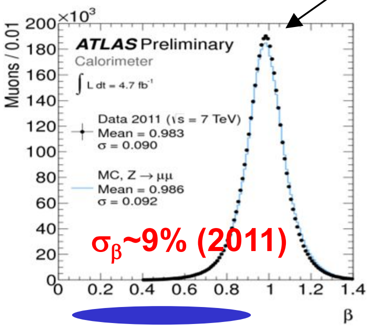
- Start from one (or two) high pT isolated track →p
- Measure $\beta\gamma$ (invert Bethe-Bloch) from **Si-track** clusters

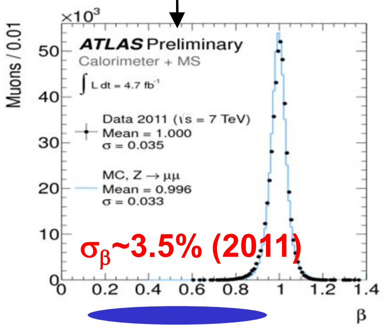


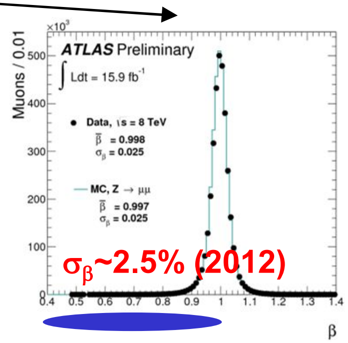




- Measure β (**calo** or **calo+Muon Spectrometer**)







Signal

➔ Add the 2 or 3 information together and compute $M=p/\beta\gamma$

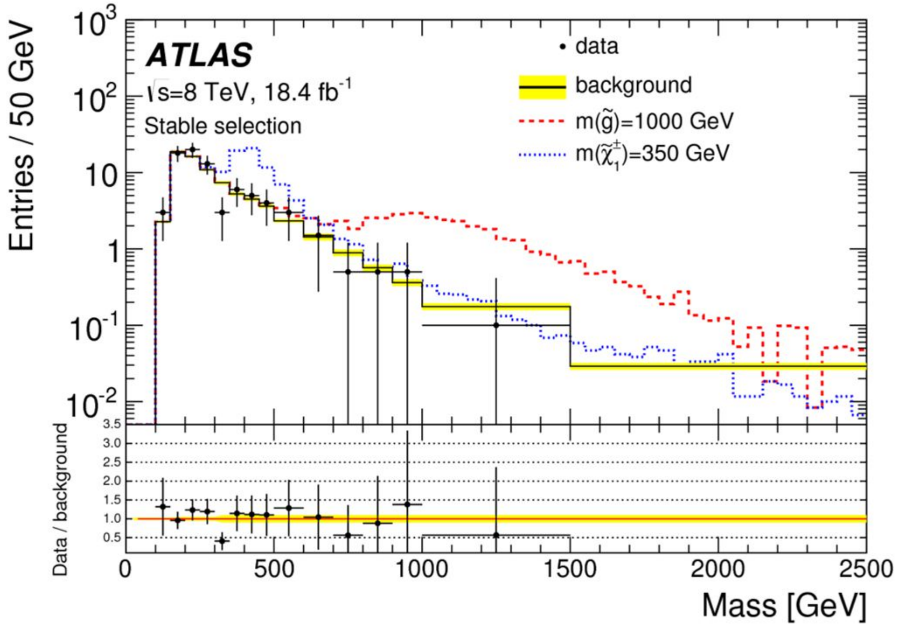
Long-Lived Particles (6)

ATLAS: 1411.6795, 1506.05332, CMS: 1305.0491

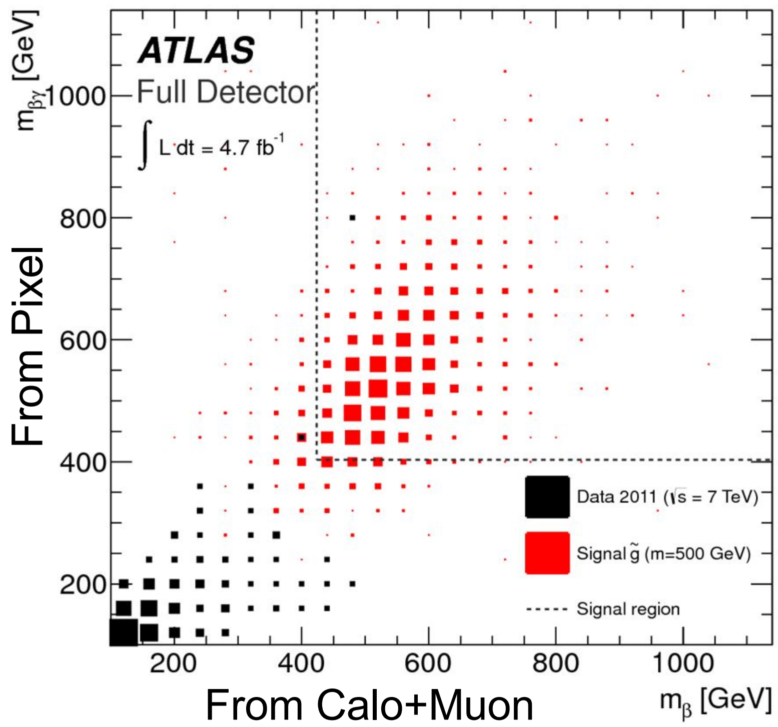
❑ Look at the Mass distributions

- And search for a peak !
- Good S/B in general

Pixel only



Full detector

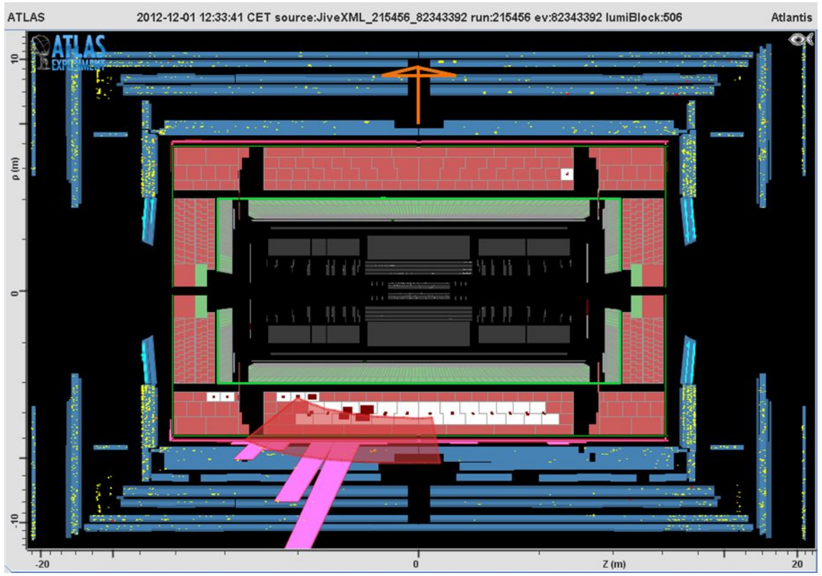


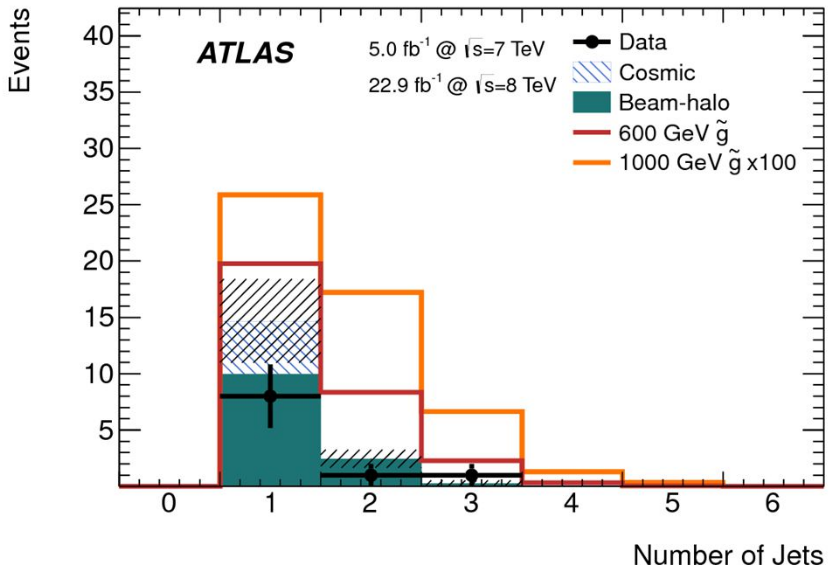
Long-Lived Particles (7)

ATLAS: 1310.6584
CMS: 1501.05603

R-hadrons can also stop in the calo and decay later

- In Split SUSY (unnatural model), the stopped gluino only particle reachable at LHC
- High energetic jets in absence of collisions
- Background = calorimeter noise, cosmics and beam halo not SM !



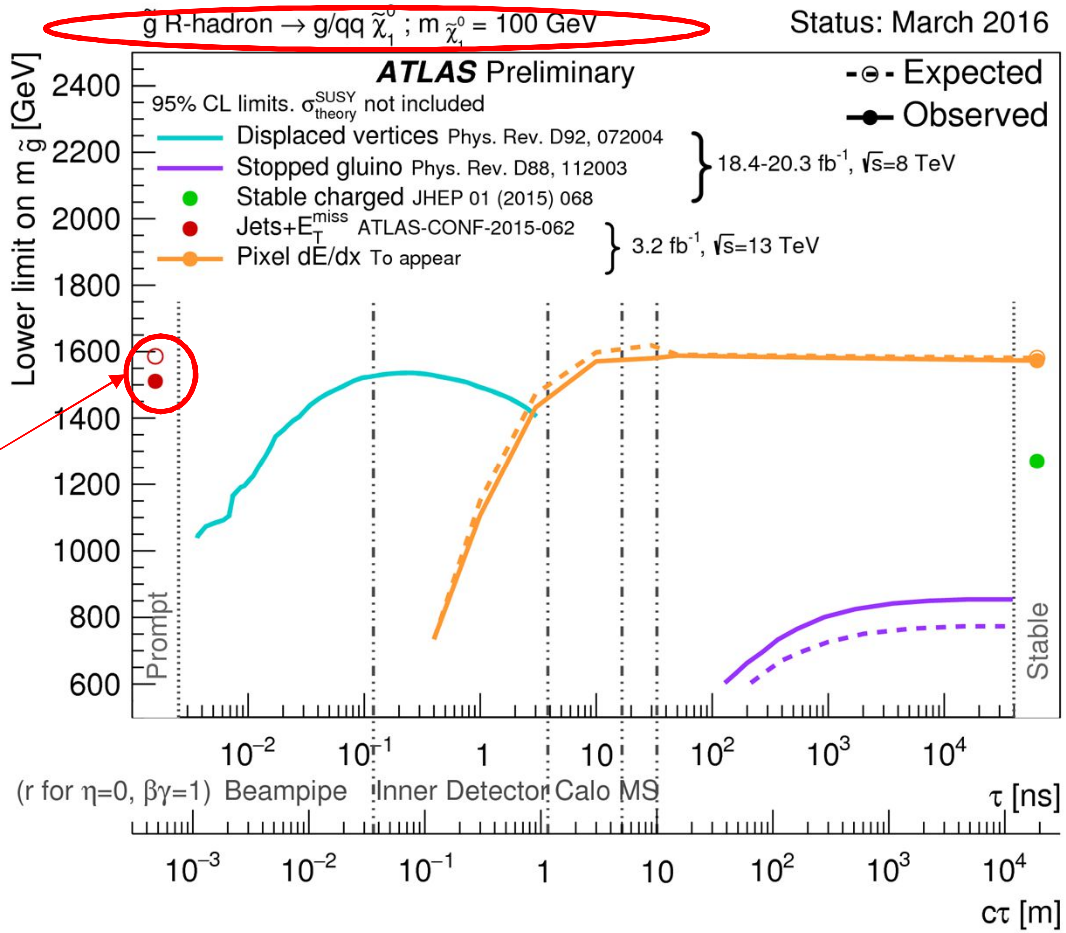


Can look for it in a window 1 μs < t < 300 hours !!

Summary Long-Lived Particles (1)

- Combining all, very strong on gluino mass limit !

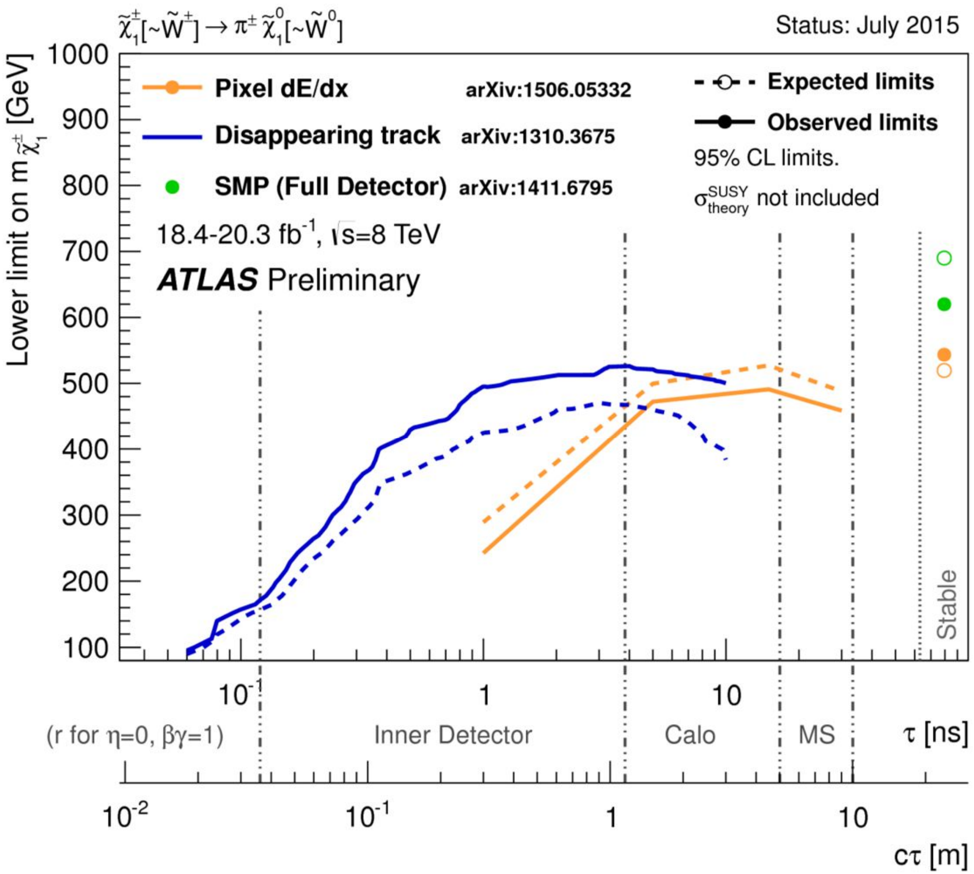
0lepton analysis !



Exclude m(gluino) >1 TeV whatever the lifetime !

Summary Long-Lived Particles (2)

- Combining all, very strong on chargino mass limit !

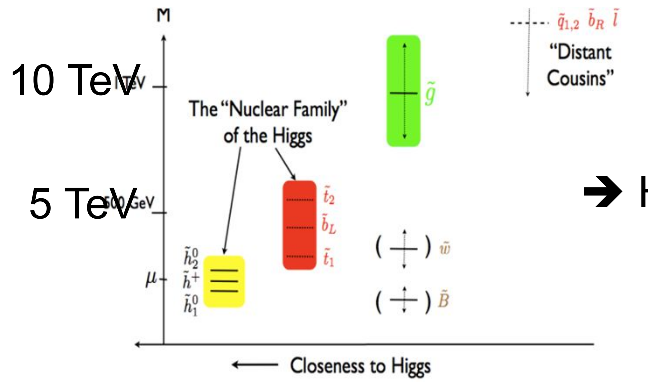


Exclude m(chargino) >100 GeV whatever the lifetime !

Lecture Part IIc

MSSM Extensions?
Scalar Gluon, another scalar (NMSSM)

Fine-tuning is 1% or 0.1 % …
~ sparticles can be above TeV !



➔ HL-LHC, FCC

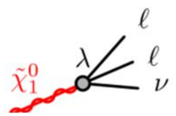
A: MSSM
B: Natural >10%
C1: **RPC**
C2: LSP nature
C3: Spectra opening

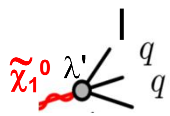
SUSY has no role in hierarchy problem
~ No mass constraints on sparticles or particular spectrum (long-lived particles)

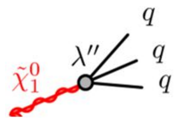
RPV
Targeting gluino and stop + Spectacular signatures (multileptons, no Z, resonances, LFV, Long-lived particles)
RPV … can not be systematically check !

(Very) Compressed spectrum
Low pT objects + eventually Long-lived or meta-stable particles

RPV







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

- Add **48** new Yukawa couplings and **96** complex parameters
- Proton decay only forbids simultaneous violation of lepton and baryon number
  - ✓ … but not one **or** the other
- Allow the LSP to decay
- Can change other sparticle decay

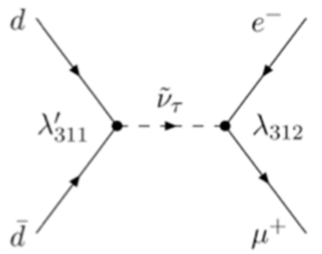
RPV (1)

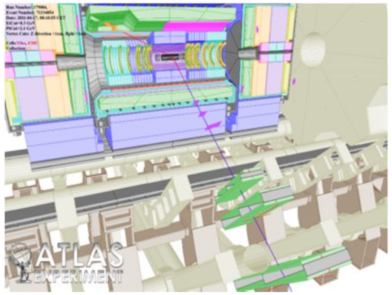
ATLAS: 1503.04430

❑ New signature: Lepton flavor violation in the production / decay

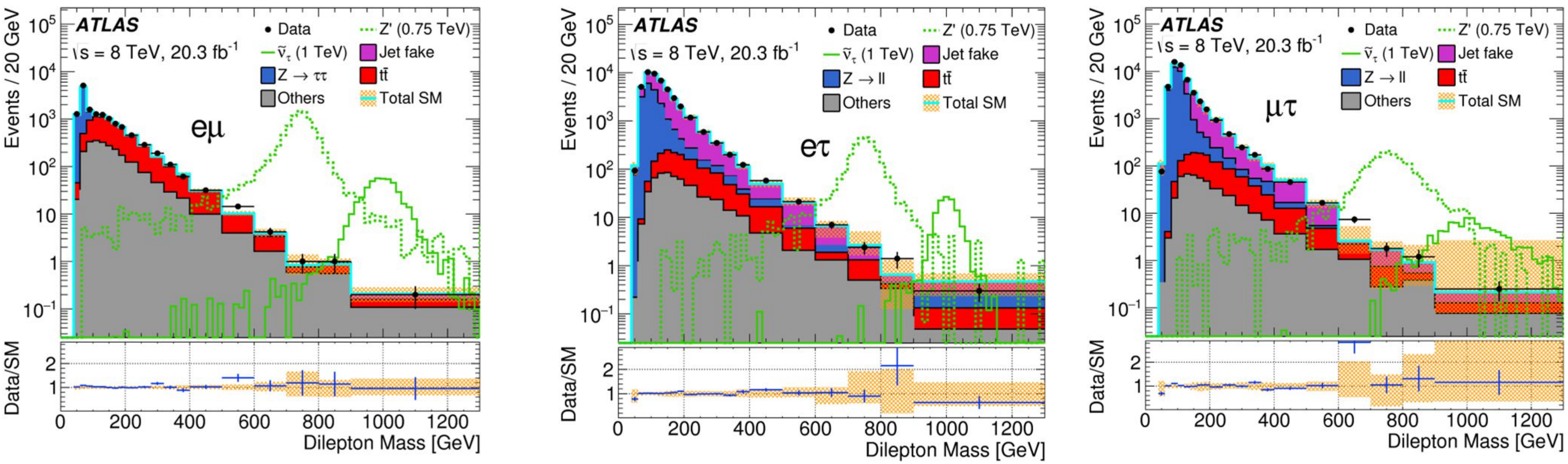
7 TeV

- λ'_{311}, $\lambda_{i32} \neq 0$ and pp $\rightarrow \tilde{\nu}_\tau \rightarrow e\mu$, $e\tau$, $\mu\tau$ resonance $W = W_{MSSM} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$





$\Delta\phi$ (e, μ)~π , MET=132 GeV, no Jet !



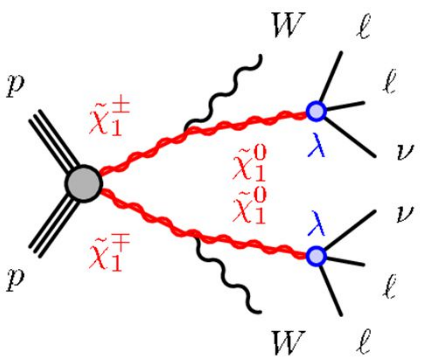
RPV (2)

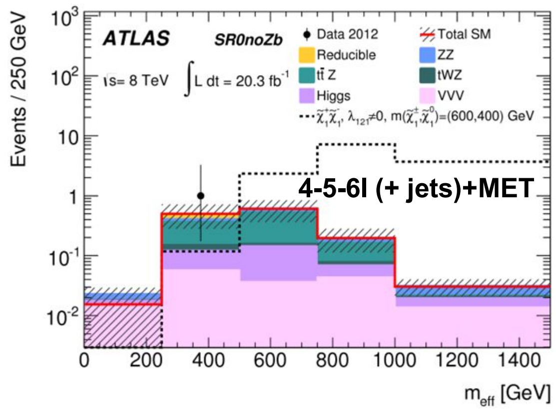
ATLAS: 1405.5086

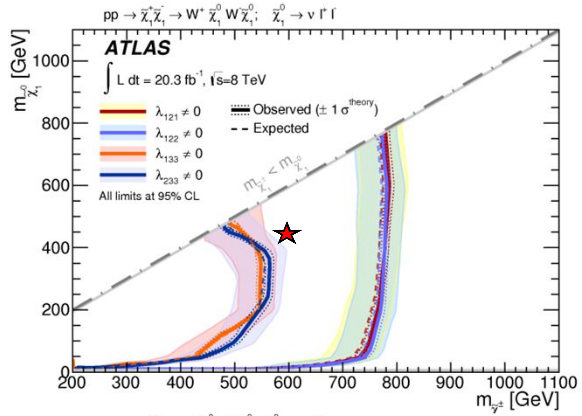
❑ New signature: lepton but no Z

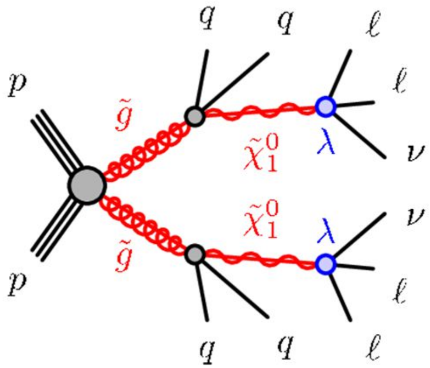
$$W = W_{MSSM} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

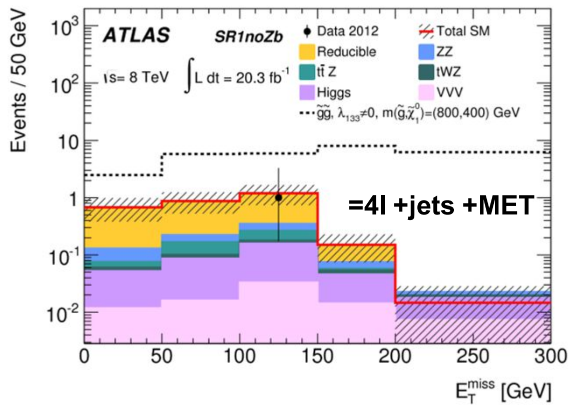
- χ_1^0 LSP, $\lambda_{ijk} \neq 0$ implies $\chi_1^0 \rightarrow ll'\nu$ with $l=e,\mu,\tau$

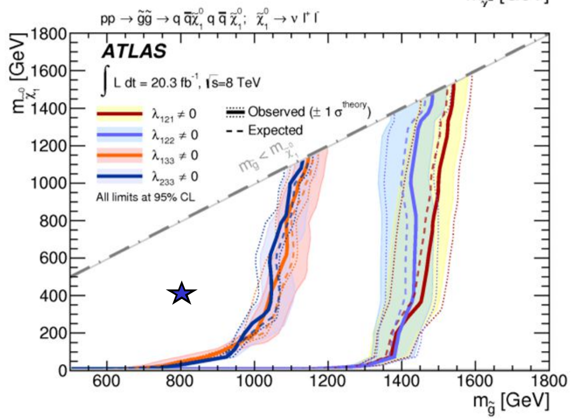












Now limit on direct charginos production (*not possible in RPC*) !

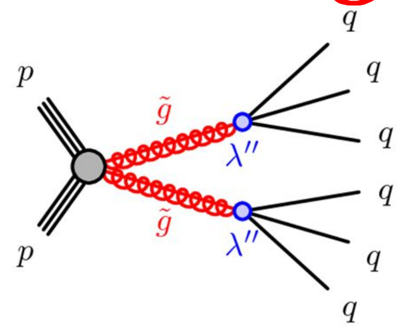
RPV (3)

ATLAS: 1502.05686
CMS: 1311.1799

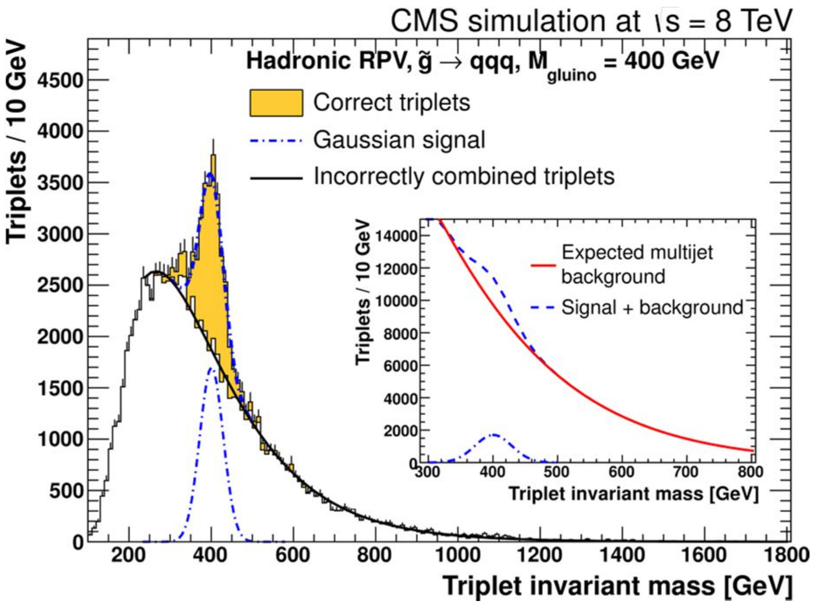
$$W = W_{MSSM} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

❑ New signature: 2x3 jet resonance

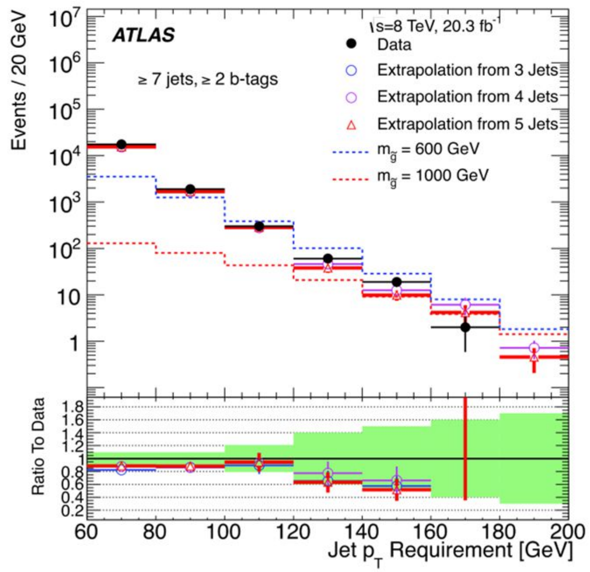
- Motivated by g→qqq and g→qqχ_1^0→qqqqq
- Multi-jets background data driven and differentiates 0, 1, 2 btag …
- 2 different strategies pursued by CMS and ATLAS



Reconstruct 6jet invariant mass



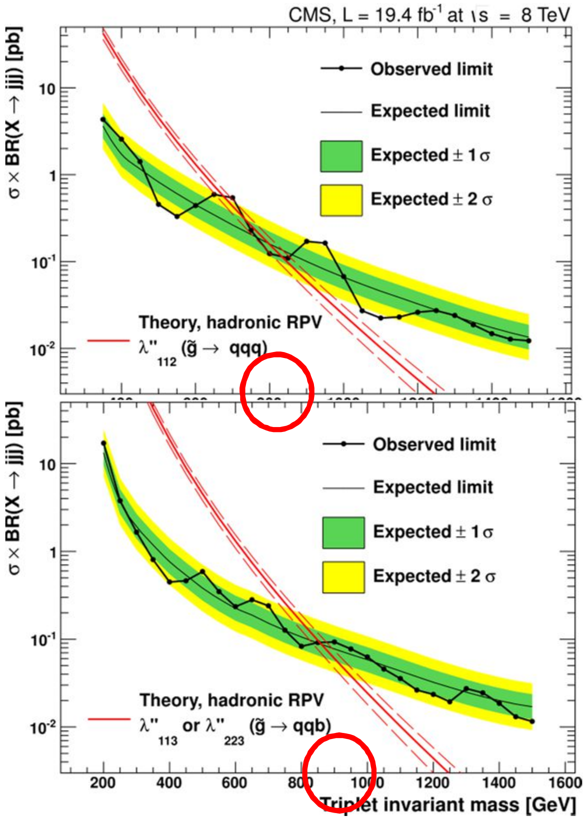
Resolve 6-10jet evts with a lower p_T cut

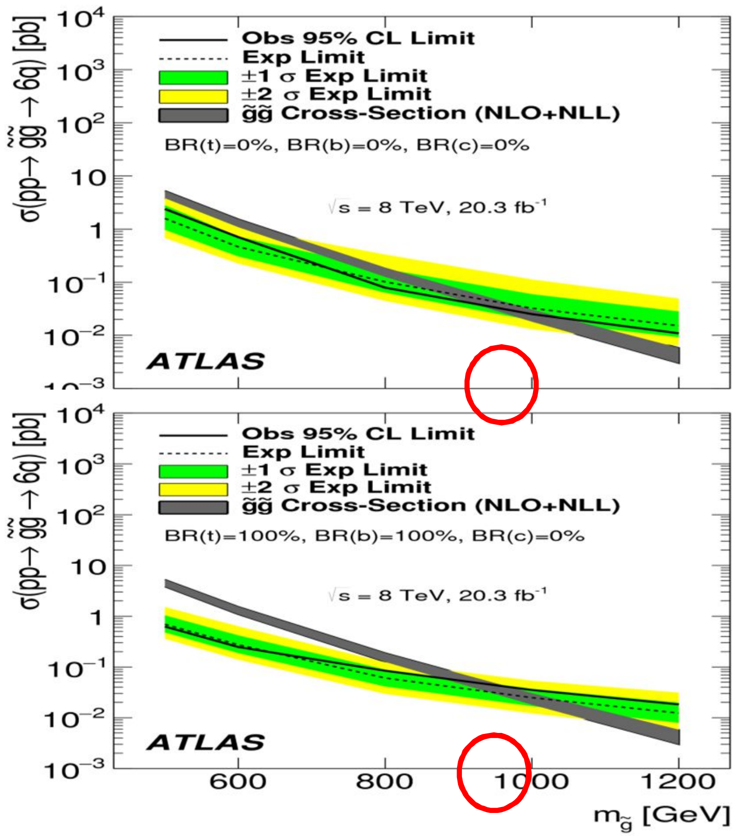


RPV (4)

❑ Results for 2x3 jets resonance

- Show for light flavor (top) and heavy flavor (bottom)





➔ Exclude Gluino masses < 1 TeV. ATLAS above CMS

RPV (5)

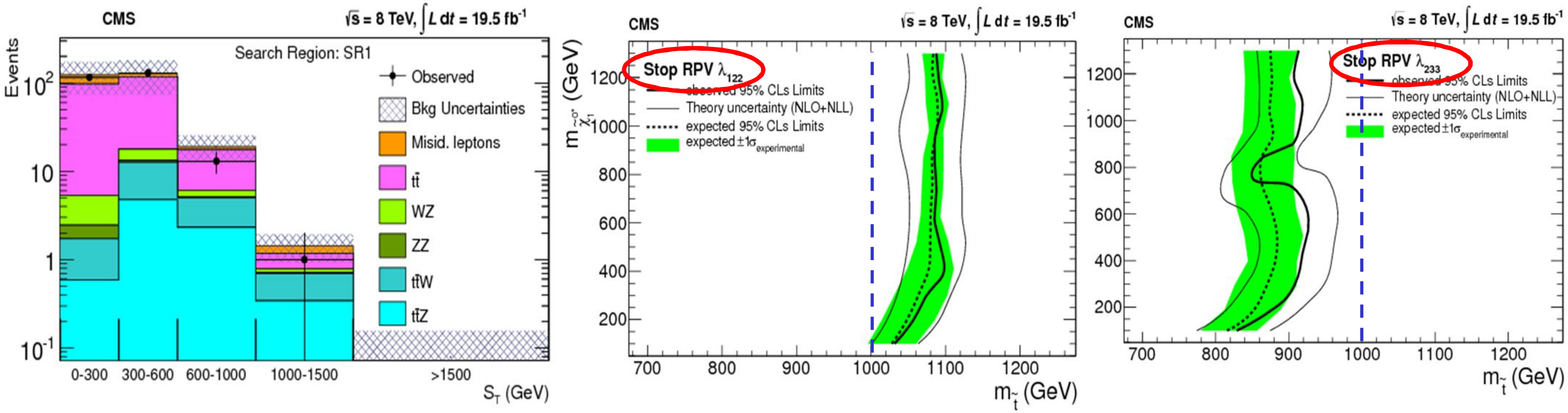
CMS: 1306.6643

❑ Stop RPV (λ)

$$W = W_{MSSM} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

- χ_1^0 LSP, consider two possible combinations
- pp $\rightarrow \tilde{t}\tilde{t} \rightarrow t\chi_1^0 t\chi_1^0 \rightarrow$ >4l (+ jets)+MET
- Assume χ_1^0 bino-like

λ-term	neutralino LSP decay mode
$\lambda_{122} = -\lambda_{212}$	$\mu\mu\nu_e + \mu e \nu_\mu$
$\lambda_{233} = -\lambda_{323}$	$\tau\tau\nu_\mu + \tau\mu\nu_\tau$



Very strong limits for direct stop, w or wo taus (independent of LSP mass)

RPV (6)

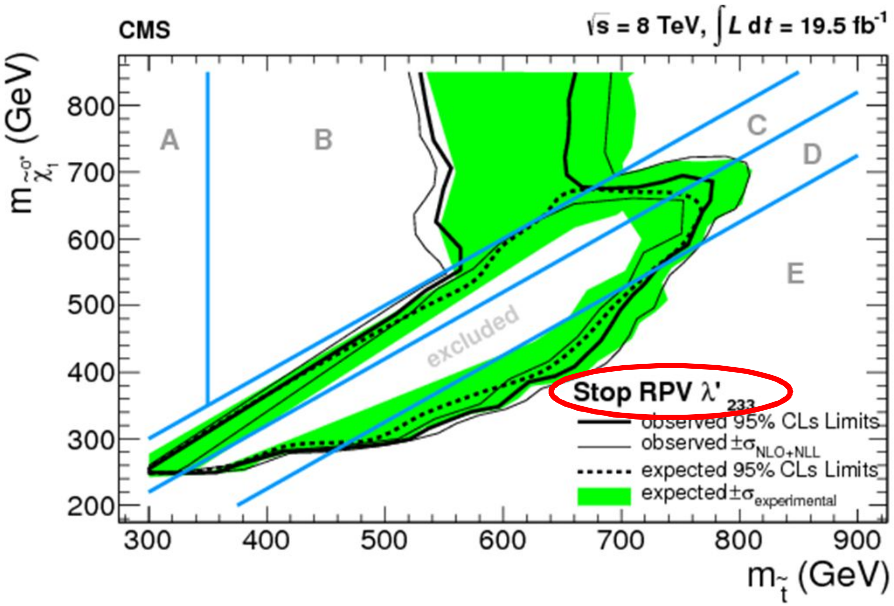
CMS: 1306.6643

❑ Stop RPV (λ')

$$W = W_{MSSM} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

- χ_1^0 LSP, consider several decay modes
- Final states: 2μ + 2t + 2b
- Assume χ_1^0 bino-like

region label	kinematic region	stop decay mode(s)
A	$m_t < m_{\tilde{t}} < 2m_t, m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\nu b\bar{b}$
B	$2m_t < m_{\tilde{t}} < m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\mu t\bar{b} + t\nu b\bar{b}$
C	$m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_W + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to \ell\nu b\tilde{\chi}_1^0 + jjb\tilde{\chi}_1^0$
D	$m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_t + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to Wb\tilde{\chi}_1^0$
E	$m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}}$	$\tilde{t} \to t\tilde{\chi}_1^0$



Weaker limits dependent of LSP mass

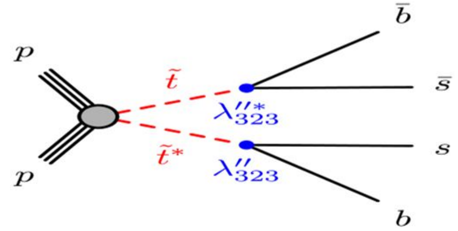
RPV (7)

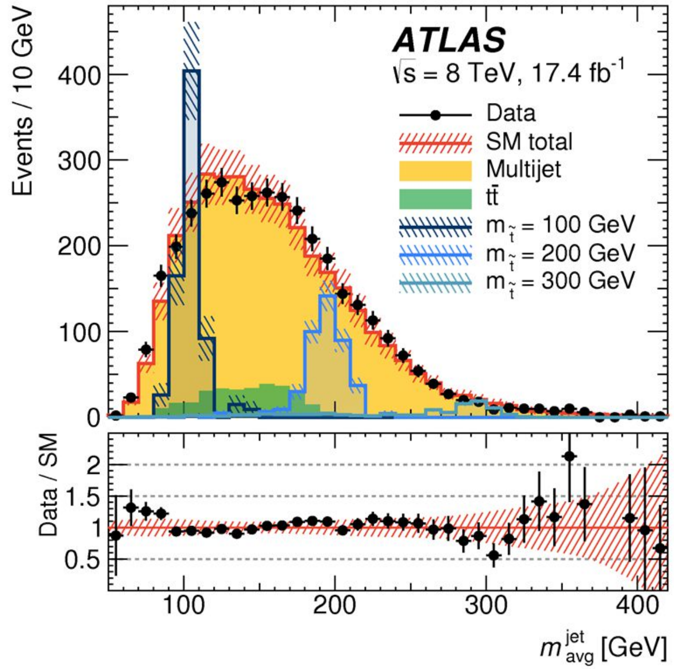
ATLAS: 1306.6643

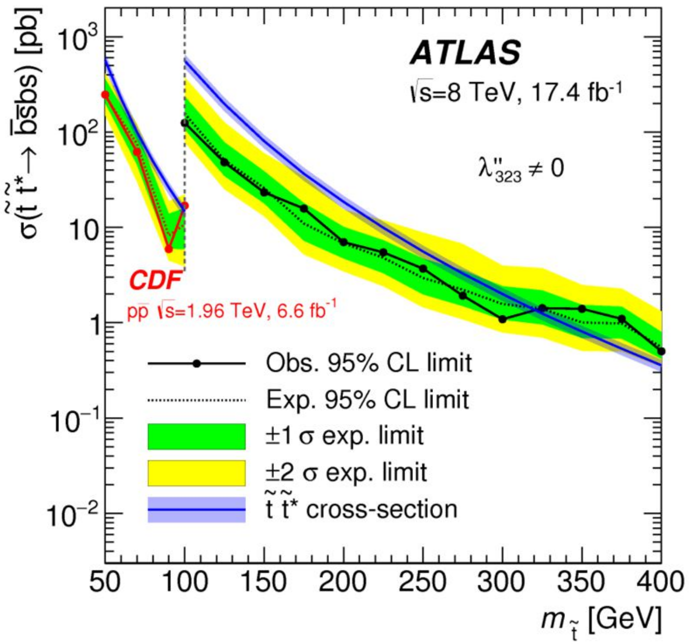
❑ Stop RPV (λ“)

- Stop direct decay to bs
- Final states 2x2 resonant jets

$$W = W_{MSSM} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$







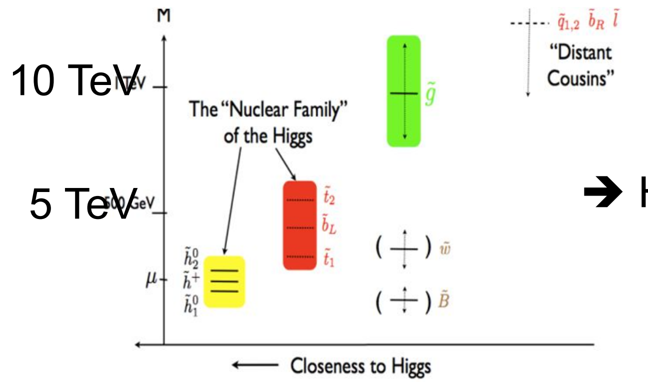
Lecture Part IIc

MSSM Extensions?

Scalar Gluon, another scalar (NMSSM)

Fine-tuning is 1% or 0.1 % …

~ sparticles can be above TeV !



➔ HL-LHC, FCC

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C1: **RPC**
C2: LSP nature
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SUSY has no role in hierarchy problem

~ No mass constraints on sparticles or particular spectrum (long-lived particles)

RPV

Targeting gluino and stop + Spectacular signatures (multileptons, no Z, resonances, LFV, Long-lived particles)

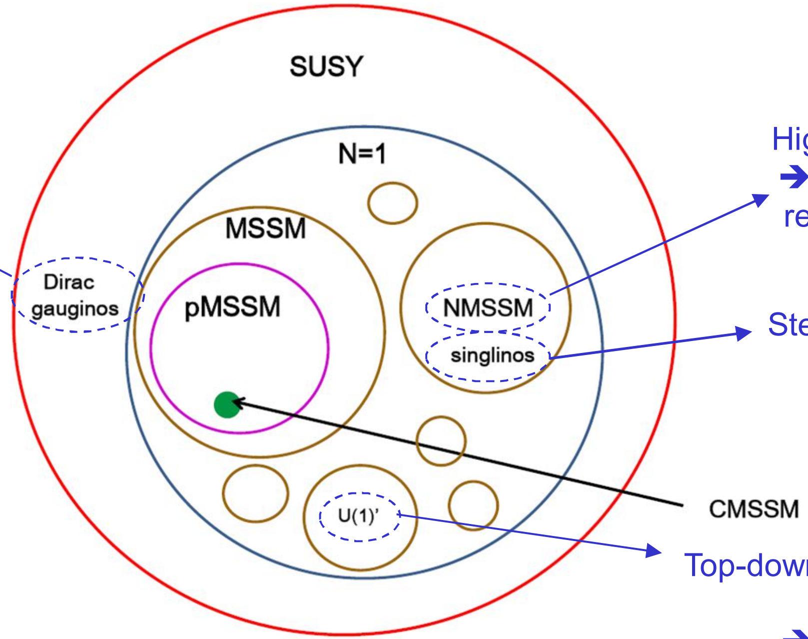
(Very) Compressed spectrum

Low pT objects + eventually Long-lived or meta-stable particles

Beyond MSSM

SUSY Theory phase space

N=2/N=1 models [**0812.3586**] where for example gluinos are not Majorana particles. Similar if R is a continuous symmetry instead of discrete [RMSSM, **0712.2039, 0810.3919**].
➔lower σ, 2x2 jet resonance



A new scalar singlet is added [2 more Higgs and one more neutralino, **0910.1785**]
➔ Relax constraints from Higgs mass (i.e. reduce fine-tuning) and provide a solution to the μ problem

Stealth SUSY. Invisible singlet added.
➔ Relax MET cuts **[1105.513]**

Top-down. Mediation of SUSY breaking via U(1)'. [**0910.2480**]
➔ Generally predicts wino-like LSP

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

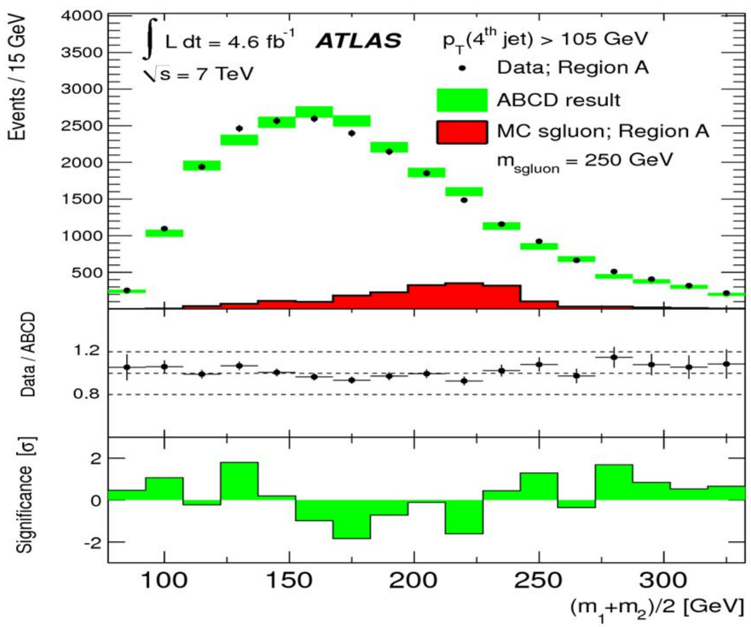
Loose simplicity, can generally evade part of the LHC limits – but not for long

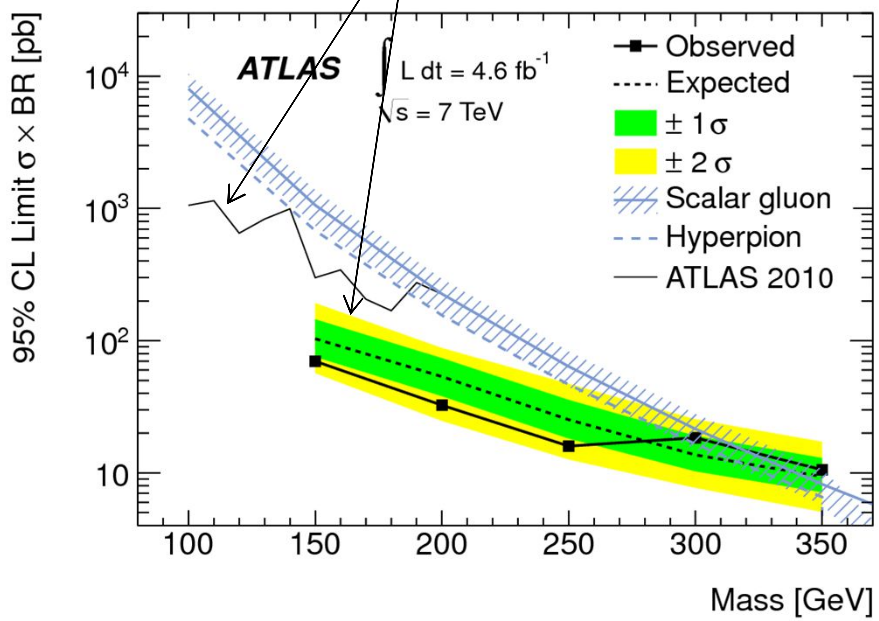
Beyond MSSM (1)

1210.4826

❑ Dirac Gluino: 2x2 jets final states

- sgluon (→ gg) pair produced: 2 resonances M_1, M_2 reconstructed with ≥4 jets pT>80 GeV
- Reduce combinatorics by minimizing $|\Delta R_1-1|+|\Delta R_2-1|$
- Note: @LHC lower masses are hardly accessible because of trigger threshold !





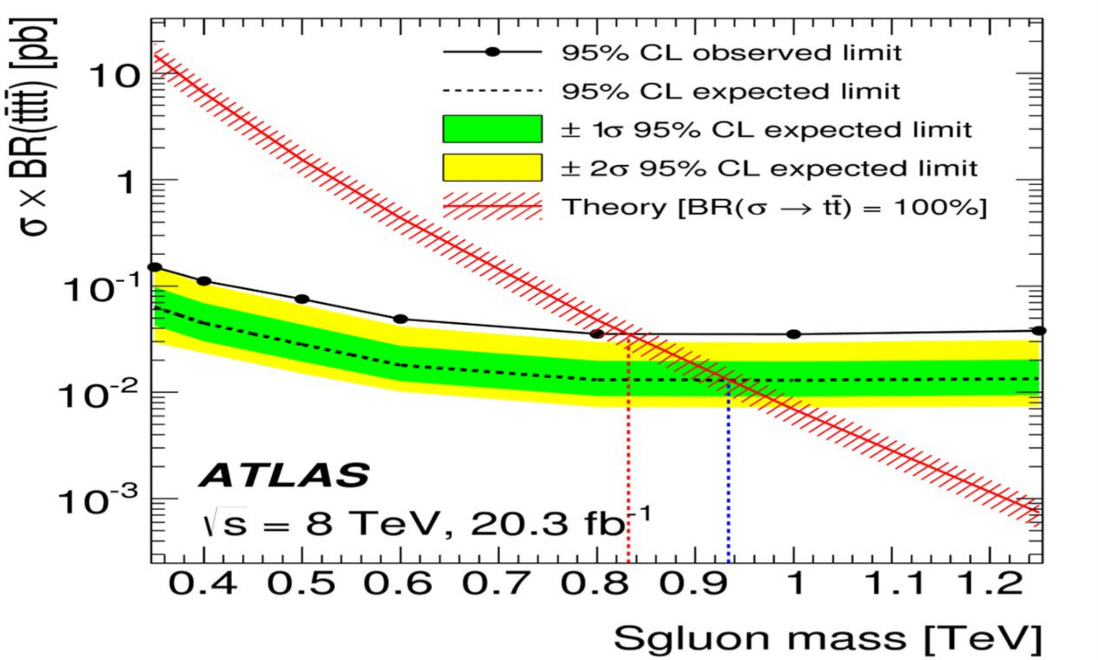
➔ Exclude scalar gluons for masses below 300 GeV

Beyond MSSM (2)

ATLAS: 1504.04605

❑ Dirac Gluinos: 4 top final states

- For more massive sgluon (M>350 GeV), sgluon→tt dominates ➔ 4 top final states
- Can be accessed by asking 2 same-sign leptons



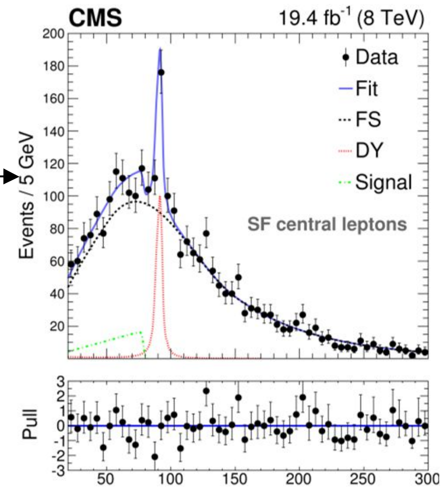
➔ Exclude scalar gluons for masses below 800 GeV

Conclusions (1)

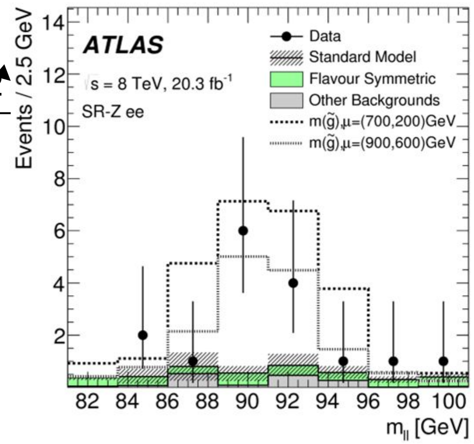
What we have seen in Run1 (beg. Of Run2) ? nothing except from few small effect

CMS	1407.3683	2.8σ	2l + 2j	RPV SUSY?
	1502.06031	2.6σ	jets plus dilepton plus MET	SUSY?
ATLAS	1503.03290	3.0σ	jets plus on-shell Z plus MET	SUSY?
	1506.00962	3.4σ	WW/WZ/ZZ resonance at ~ 2 TeV	Z'?

Not seen by ATLAS

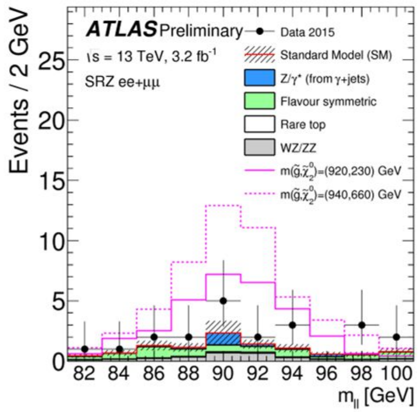


Not seen by CMS



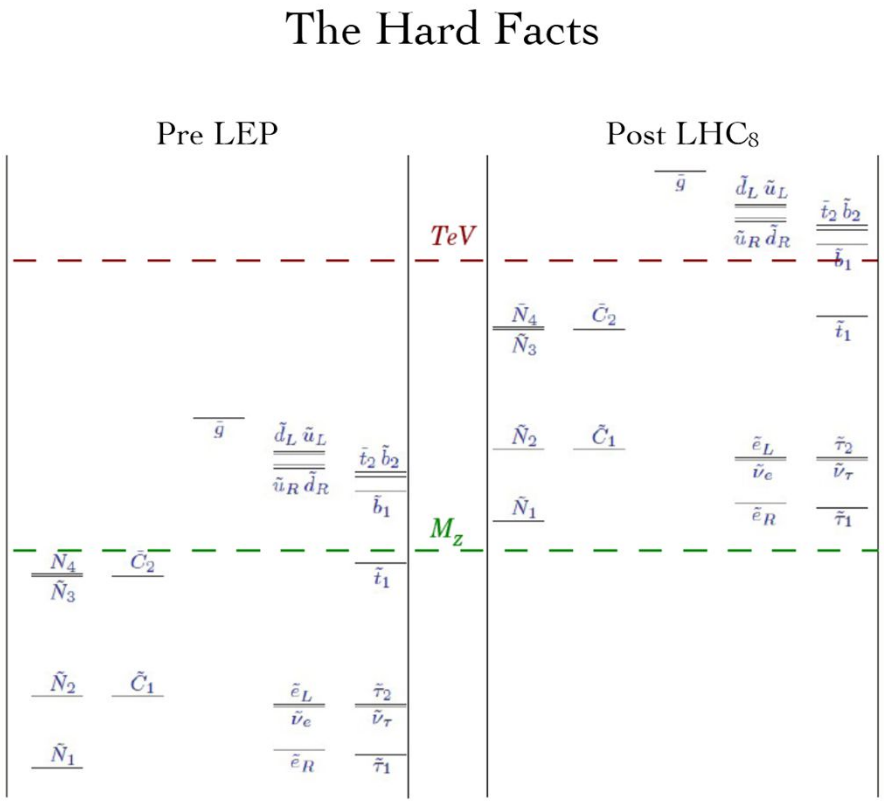
Still an excess in Run2

(still nothing for CMS)



Conclusions (2)

What we conclude ?



S. Dimopoulos, SUSY13

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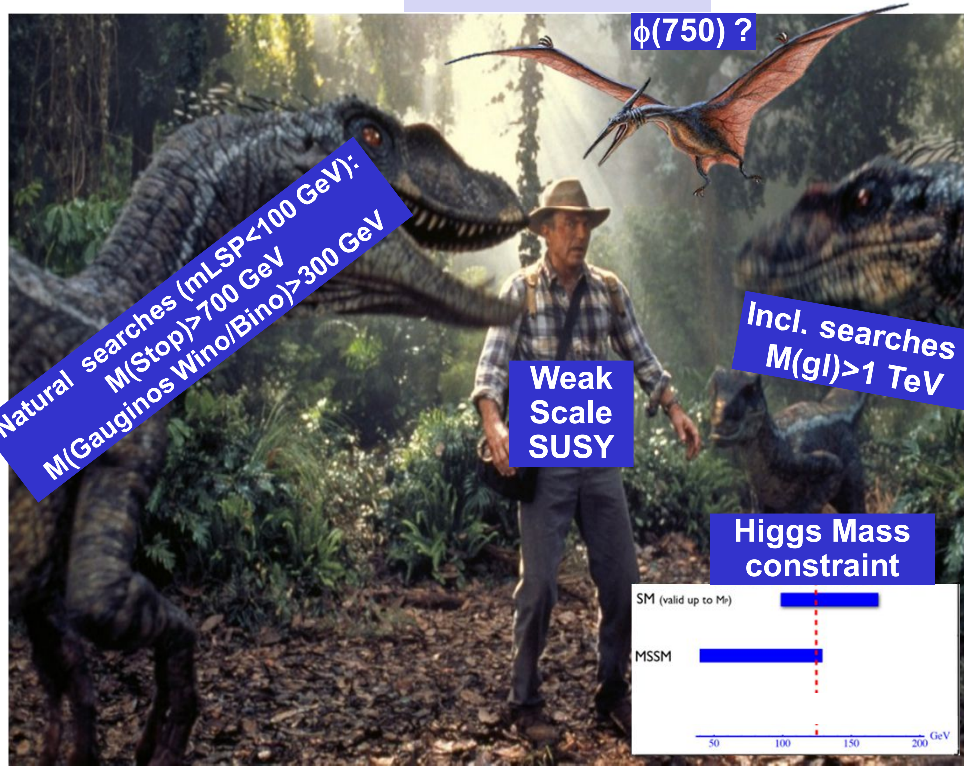
C1: **RPC**
C2: LSP nature: χ_1^0, G
C3: Spectra opening



Connection of MSSM with the hierarchy problem diminished

Conclusions (3)

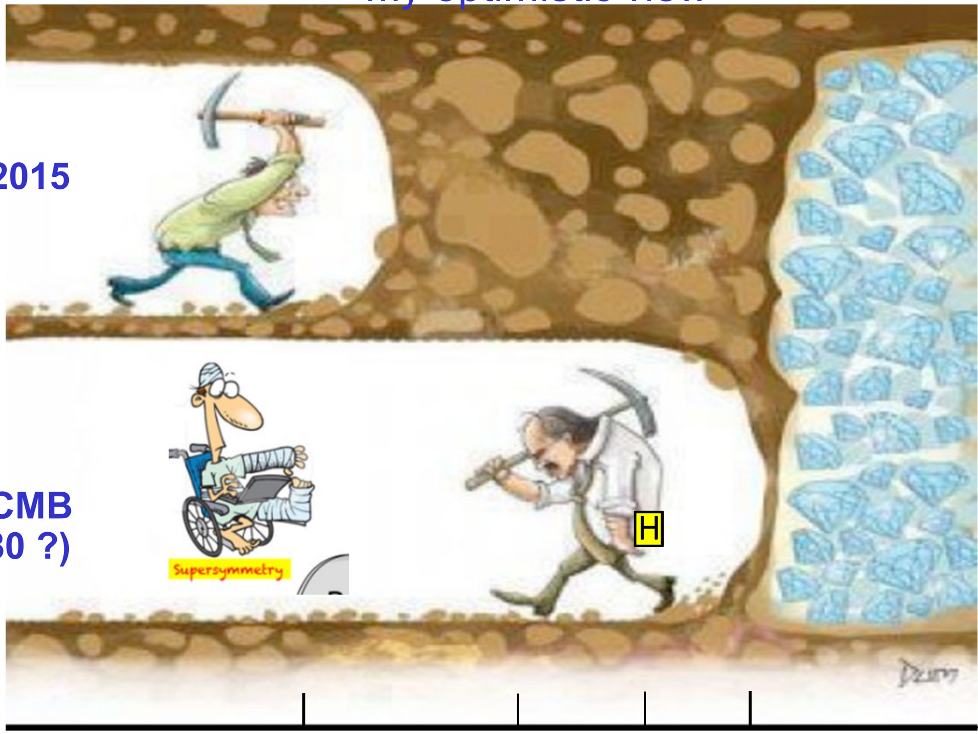
- ❑ **Particle Physicists continue to dig hard …**

My optimistic view

ReStart in 2015

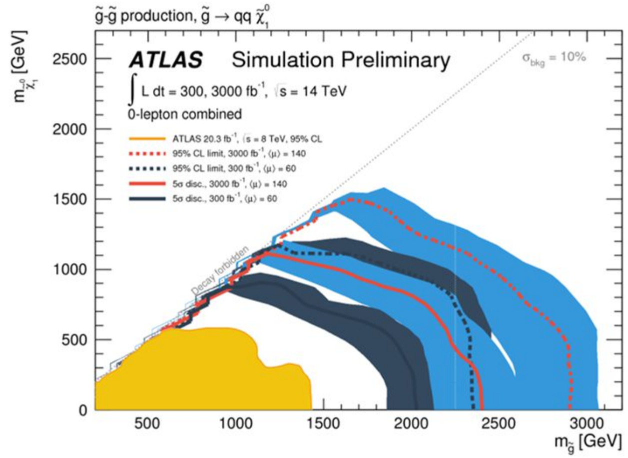
LHC-8

(Similar to CMB Searches '80 ?)



10^{-4} 10^{-10} 10^{-15} 10^{-18} 10^{-35}? *L (m)*

Vacuum(Λ) *strong* *weak* *GUT* *Gravitation?*



SPARE