

#### DISCOVERING LIGHT STOPS IN RPV SUSY

#### RICCARDO TORRE SISSA & PADOVA U. & INFN PADOVA







SUPPORTED BY THE ERC ADVANCED GRANT "DAMESYFLA" (ELECTROWEAK SYMMETRY BREAKING, FLAVOUR AND DARK MATTER: ONE SOLUTION FOR THREE MYSTERIES)

based on R. Franceschini and RT, 1212.3622 [hep-ph]



#### ... 48 WAYS TO LEAVE THE MSSM ...

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# OUTLINE

- Introduction & Natural SUSY
- R-parity and its breaking
- Or Pair production of stops: signal vs background
- Occursion

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- Introduction & Natural SUSY
- R-parity and its breaking
- O Pair production of stops: signal vs background
- Occurrence Conclusions

#### Left out

Model building for R-parity violation

#### THE HEALTH OF SUSY ATLAS Preliminary

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: LHCP 2013

searches nclusive

gen. 3'<sup>d</sup> gen. ğ med.

direct production

3<sup>rd</sup> gen. squarks

EW

Long-lived

PL

Other

1s = 7 TeV

full data

particles

MSUGALACMSM         1 $\mu$ $\mu$ $\mu$ $\mu$ $\mu$ $\mu$ $\mu$ $\pi$	Model	e, μ, τ, γ	Jets	ET	Lat [tb"]	Mass limit			Reference
MSUDUACONSM       0       7-10 phs       Yes       23.3       9       1.1 TW       av m <sup>2</sup> ATLASCONF.201         GG = -dr2       0       2 6 phs       Yes       23.3       9       Yes       23.3       9       AtLASCONF.201       <		0				õ	1.8 TeV		ATLAS-CONF-2013-047
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $		1 e, µ	4 jets			<u>j</u>	1.24 TeV		ATLAS-CONF-2012-104
Sig         Sig <td></td> <td></td> <td>7-10 jets</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>ATLAS-CONF-2013-054</td>			7-10 jets						ATLAS-CONF-2013-054
Gluin ome (2)         Te, μ         2.4 μo         4.7 μo		0	2-6 jets	Yes		740 GeV	1		ATLAS-CONF-2013-047
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	99-9→9 <b>4</b> X,	0							ATLAS-CONF-2013-047
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $			2-4 jets			900	GeV		
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $							1.1 TeV		ATLAS-CONF-2013-007
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $							1.24 TeV		
OLOM [mot NLSP]         1         0         Yes         4.8         9         9         9         9         0         ATLAS-CONF-201 (21:1167)           OLOM [higgsho NLSP)         2         0         0.3         10         Yes         5.8         600 GeV         m0(2):>0 GeV         ATLAS-CONF-201 (21:1167)           2									ATLAS-CONF-2013-026
GGM Inggano Ann NLSP)         r         1         Vis         4.8         Image: Control of the second cont	GGM (bino NLSP)	2 Y	0				1.07 TeV		
OGM Inspire NLSP         2.e. μ (2)         0.4 jess         Ves         5.8         0         400 GeV         ATLAS CONF-201 ATLAS CONF-201 ATL	GGM (wino NLSP)	1 θ, μ + γ	0	Yes	4.8	619 GeV		m(χ <sup>2</sup> ) > 50 GeV	ATLAS-CONF-2012-144
Gravita         0         mano-jet         Yes         10.5         Interaction         state	GGM (higgsino-bino NLSP)	Y				900	) GeV		
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	GGM (higgsino NLSP)	2 e, µ (Z)	0-3 jets	Yes	5.8	690 GeV		m(H) > 200 GeV	ATLAS-CONF-2012-152
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $		0	mono-jet	Yes	10.5	<sup>22</sup> scale 545 GeV		$m(\overline{G}) > 10^{-6} eV$	ATLAS-CONF-2012-147
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	ğ→bbx		Зb	Yes	12.8		1.24 TeV	m( $\chi^{2}_{-}) < 200 \; GeV$	ATLAS-CONF-2012-145
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	9-+0x1	2 e, µ (SS)	0-3 b	No		900	GeV	m(x <sup>2</sup> ) < 500 GeV	ATLAS-CONF-2013-007
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	g-xdx <sup>0</sup>	0	7-10 jets	Yes	20.3		1.14 TeV	m(χ <sup>2</sup> ) <200 GeV	ATLAS-CONF-2013-054
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	9-HX1	0	3 b	Yes	12.8		1.15 TeV	m(χ <sup>†</sup> ) < 200 GeV	ATLAS-CONF-2012-145
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	D.D. D>DX.	0	2 b	Yes		100-630 GeV		m( $\chi^2$ ) < 100 GeV	ATLAS-CONF-2013-053
$ \begin{array}{c} \frac{1}{12} \left( \frac{1}{10} (\eta, 1, -W) \overline{L}_{1}^{2} & 2 e, \mu \\ 1 & 0 & 2 e e e \\ \frac{1}{11} \left( \frac{1}{10} (\eta, 1, -W) \overline{L}_{1}^{2} & 2 e, \mu \\ 1 & 0 & 2 e e \\ \frac{1}{11} \left( \frac{1}{10} (\eta, 1, -W) \overline{L}_{1}^{2} & 2 e, \mu \\ 0 & 2 e e \\ \frac{1}{11} \left( \frac{1}{10} (\eta, 1, -W) \overline{L}_{1}^{2} & 1 e \\ 1 & 1 & 1 & 1 \\ \frac{1}{10} (\eta, 1, -W) \overline{L}_{1}^{2} & 1 e \\ \frac{1}{11} & 1 & 1 & 1 \\ \frac{1}{10} (\eta, 1, -W) \overline{L}_{1}^{2} & 1 e \\ \frac{1}{11} & 1 & 1 & 1 \\ \frac{1}{10} (\eta, 1, -W) \overline{L}_{1}^{2} & 1 e \\ \frac{1}{11} & 1 & 1 & 1 \\ \frac{1}{10} (\eta, 1, -W) \overline{L}_{1}^{2} & 1 e \\ \frac{1}{$	$b_1b_2, b_1 \rightarrow t\chi_1^2$	2 e, µ (SS)	0-3 b	Yes	20.7	430 GeV		$m(\overline{\chi}^{\circ}) = 2 m(\overline{\chi}^{\circ})$	ATLAS-CONF-2013-007
$ \begin{array}{c} \hline \begin{array}{c} \hline \mbox{$1$} \hline \mbox{$1$} \hline \mbox{$2$} \hline \$	1,1, (light), 1,-+bx1	1-2 e, µ	1-2 b	Yes	4.7	167 GeV		m(χ?) = 55 GeV	1208.4305, 1209.2102
$ \frac{1}{24} (medun) \frac{1}{2} - b\overline{\chi}_{1}^{2} & 2  \mu & 0  2  bds & Yes & 20.3 \\ \frac{1}{2}, \frac{1}{10} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  2  b & Yes & 20.3 \\ \frac{1}{2}, \frac{1}{10} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  2  b & Yes & 20.5 \\ \frac{1}{2}, \frac{1}{10} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  2  b & Yes & 20.5 \\ \frac{1}{2}, \frac{1}{10} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  2  b & Yes & 20.5 \\ \frac{1}{2}, \frac{1}{10} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  Yes & 20.5 \\ \frac{1}{2}, \frac{1}{10} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  Yes & 20.7 \\ \frac{1}{2}, \frac{1}{10} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  Yes & 20.7 \\ \frac{1}{2}, \frac{1}{10} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  Yes & 20.7 \\ \frac{1}{2}, \frac{1}{10} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  Yes & 20.7 \\ \frac{1}{2}, \frac{1}{10} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  Yes & 20.7 \\ \frac{1}{2}, \frac{1}{2} (medun) \frac{1}{2}, -b\overline{\chi}_{1}^{2} & 2  \mu & 0  Yes & 20.3 \\ \frac{1}{2}, \frac{1}{2}$	t,t, (light), t,→Wbχ <sup>o</sup>	2 e, µ	0-2 jets	Yes	20.3	220 GeV		$m(\widetilde{\chi}_1^0) = m(\widetilde{L}_1) - m(W) - 50 \text{ GeV}, m(\widetilde{L}_1) \leftrightarrow m(\widetilde{\chi}_1^0)$	ATLAS-CONF-2013-048
$ \frac{1}{14} \left( \frac{1}{16} (-\frac{1}{16} + \frac{1}{16} + \frac{1}{16$		2 e, µ	0-2 jets	Yes	20.3	150-440 GeV		$m(\tilde{\chi}_{1}^{2}) = 0 \text{ GeV}, m(\tilde{\chi}_{1}) - m(\tilde{\chi}_{1}^{2}) = 10 \text{ GeV}$	ATLAS-CONF-2013-048
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$		0	2 b	Yes	20.1	150-580 GeV			ATLAS-CONF-2013-053
$\begin{split} \begin{array}{c} \frac{1}{2} \int_{1}^{2} (\operatorname{peary}), \frac{1}{4} - \frac{4}{2} \int_{1}^{2} & 0 & 2 \ b & \mathrm{Yes} & 20.5 \\ \frac{1}{4} \int_{1}^{2} (\operatorname{peary}), \frac{1}{4} - \frac{4}{4} \int_{1}^{2} 0 & \mathrm{GeV} & \mathrm{m}(\frac{1}{2}) = 0 \ \mathrm{GeV} & \mathrm{m}(\frac{1}{2}) = 0 \ \mathrm{GeV} & \mathrm{m}(\frac{1}{2}) = 0 \ \mathrm{GeV} & \mathrm{m}(\frac{1}{2}) = 160 \ \mathrm{GeV} & \mathrm{m}(\frac{1}{2}) = 0 \ \mathrm{GeV} $		1 e, µ	1 b	Yes	20.7			$m(\tilde{\chi}^{\dagger}) = 0 \text{ GeV}$	ATLAS-CONF-2013-037
$ \begin{array}{c} \frac{1}{2} \left( \frac{1}{2} \operatorname{charmal} (\operatorname{MSBB}) \\ \frac{1}{2} e, \mu(Z) $		0	2 b	Yes	20.5				ATLAS-CONF-2013-024
$ \frac{1}{\sqrt{2}} \int_{0}^{\infty} \int_$	L1, (natural GMSB)	2 e. u (Z)	1 b	Yes	20.7				ATLAS-CONF-2013-025
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$\overline{i_2 i_2}, \overline{i_2 \rightarrow i_1 + Z}$		1 b	Yes					ATLAS-CONF-2013-025
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	AN AN AN	2 e. µ	0	Yes	20.3	85-315 GeV	_	m(x?) = 0 GeV	ATLAS-CONF-2013-049
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			0	Yes	20.3				ATLAS-CONF-2013-049
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			0	Yes	20.7			and the second s	ATLAS-CONF-2013-028
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\overline{y}^{-}\overline{y}^{0} \rightarrow L y L ((\overline{y}y), (\overline{y}) L ((\overline{y}y))$		0				mixile		ATLAS-CONF-2013-035
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\tilde{\chi}_1 \tilde{\chi}_2^0 \rightarrow W^0 \tilde{\chi}_1^0 Z^{(1)} \tilde{\chi}_1^0$		0						ATLAS-CONF-2013-035
Stable 9, H-hadrons       0-2 e, $\mu$ 0       Yes       4.7       90       905 GeV       5 < tan\$ < 20       1211.1597         GMSB, stable 1, low $\beta$ 2 e, $\mu$ 0       Yes       4.7       1       300 GeV       5 < tan\$ < 20		0	1 jet	Yes	4.7			1 < 1121) < 10 ns	1210.2852
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $							85 GeV		
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$			0	Yes	4.7		and the second sec	5 < tanp < 20	1211.1597
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	GMSB, vo wGlong-lived v.		0	Yes	4.7				1304.6310
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$			0						
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	LFV pp -> v +X, v -> e+u	2.0. 4	0		4.6		1.61 TeV	ki=0.10. k=0.05	1212.1272
$\begin{array}{c c c c c c c c c c c c c c c c c c c $				1.5					
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$				Yes		ā .			ATLAS-CONF-2012-140
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$									ATLAS-CONF-2013-036
$\tilde{g} \rightarrow qq\bar{q}$ 0 6 jets - 4.6 $\tilde{g}$ 668 GeV 1210.4813 $\tilde{g} \rightarrow \tilde{K}_{\mu} \tilde{I}_{\mu} \rightarrow bs$ 2 e, µ (SS) 0-3 b Yes 20.7 $\tilde{g}$ 880 GeV ATLAS-CONF-201	2'2 2' - W20 20 - 100 - 000								ATLAS-CONF-2013-036
ḡ→κ̃μ l̄ <sub>1</sub> →bs 2 e, μ (SS) 0-3 b Yes 20.7 g 880 GeV ATLAS-CONF-201								The second secon	
	g-HJ. L-+bs		-	Yes			GeV		ATLAS-CONF-2013-007
V 4 pra - 4/2 agravit 12/201/201/ 12/201/ 12/201/ 12/201/ 12/201/			d lots					and 2008 from 1110 2602	
									ATLAS-CONF-2012-147

Mass scale [TeV]

1

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 or theoretical signal cross section uncertainty.

10-1

1s = 8 TeV

full data

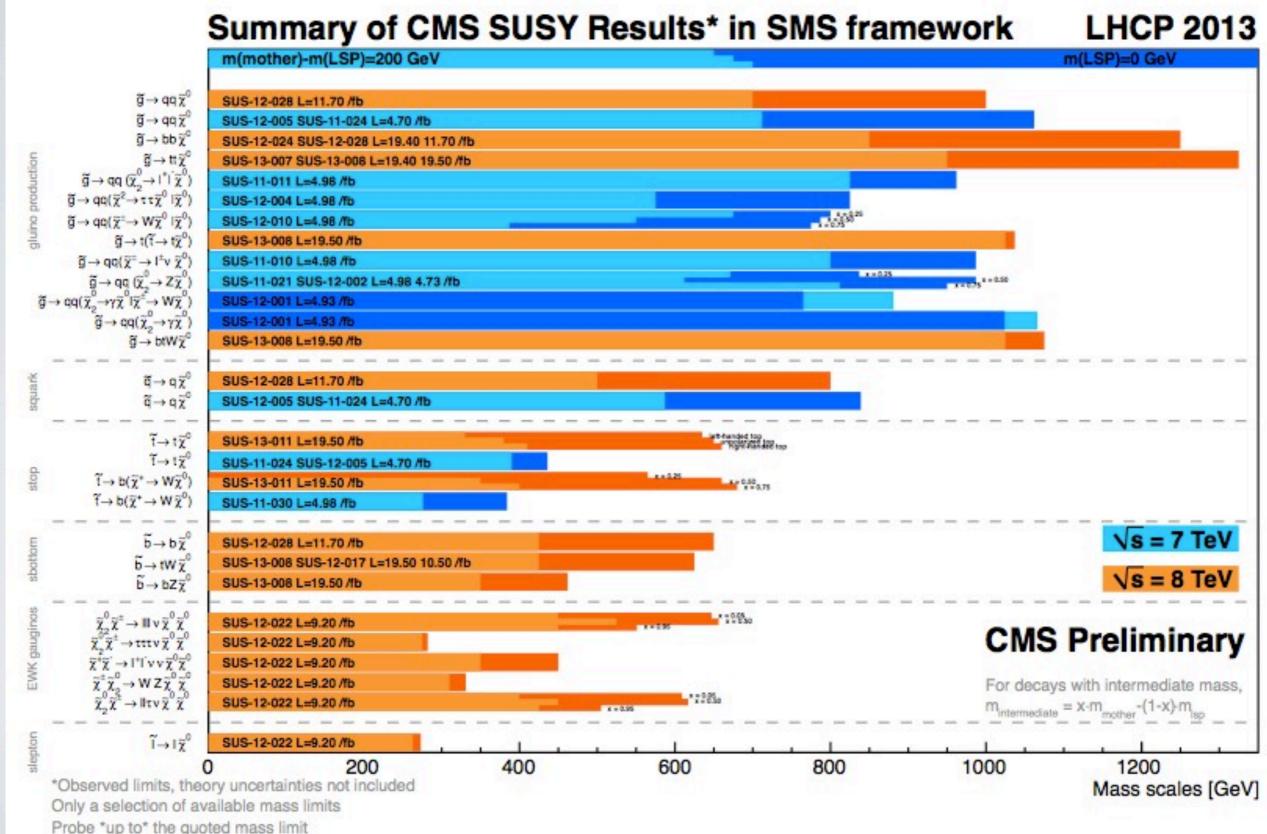
1s = 8 TeV

partial data

#### **Riccardo Torre**

#### Light RPV stops hiding in the LHC data

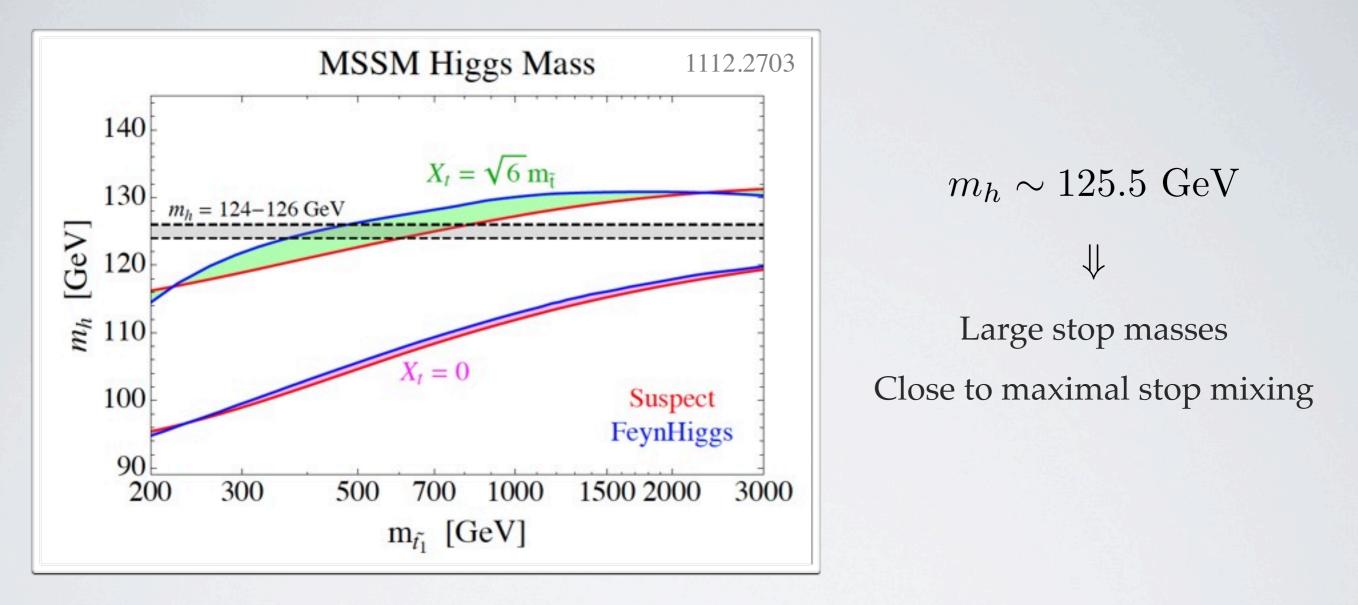
# THE HEALTH OF SUSY



#### Riccardo Torre

#### Light RPV stops hiding in the LHC data

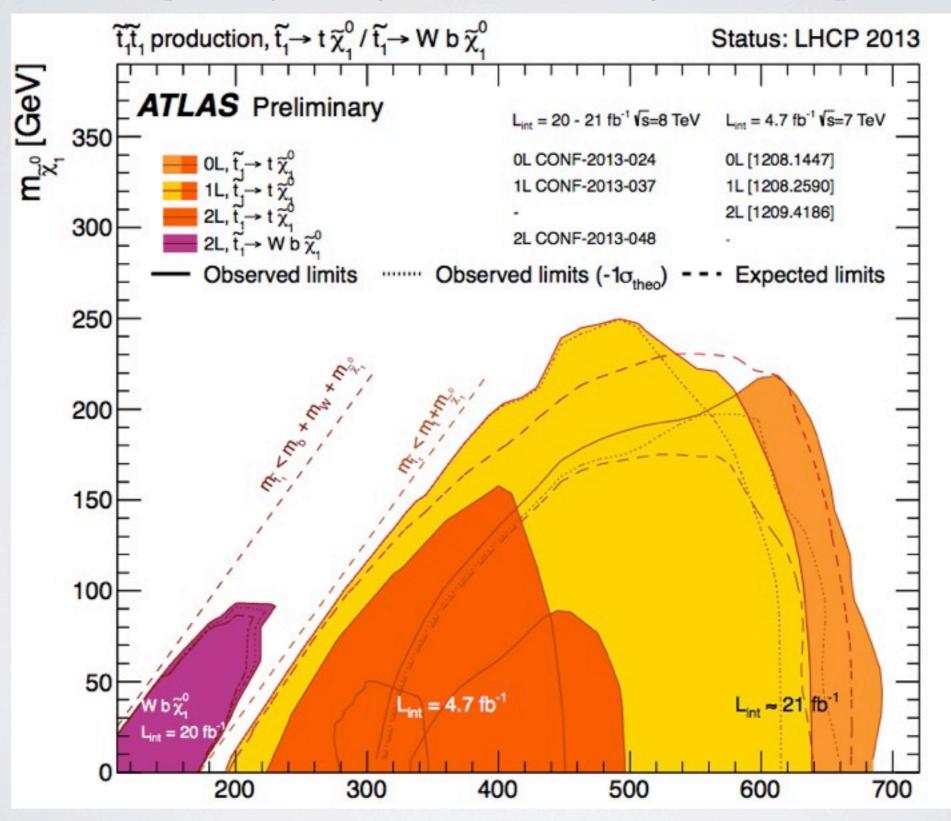
#### THE HIGGS VS THE MSSM



- The light Higgs boson and the negative results in the searches for superpartners point toward a non-minimal scenario
- A plethora of possible models, so which criterion to follow?

### **STOP SEARCHES**

The LHC7/8 has put very strong bounds on third generation squarks

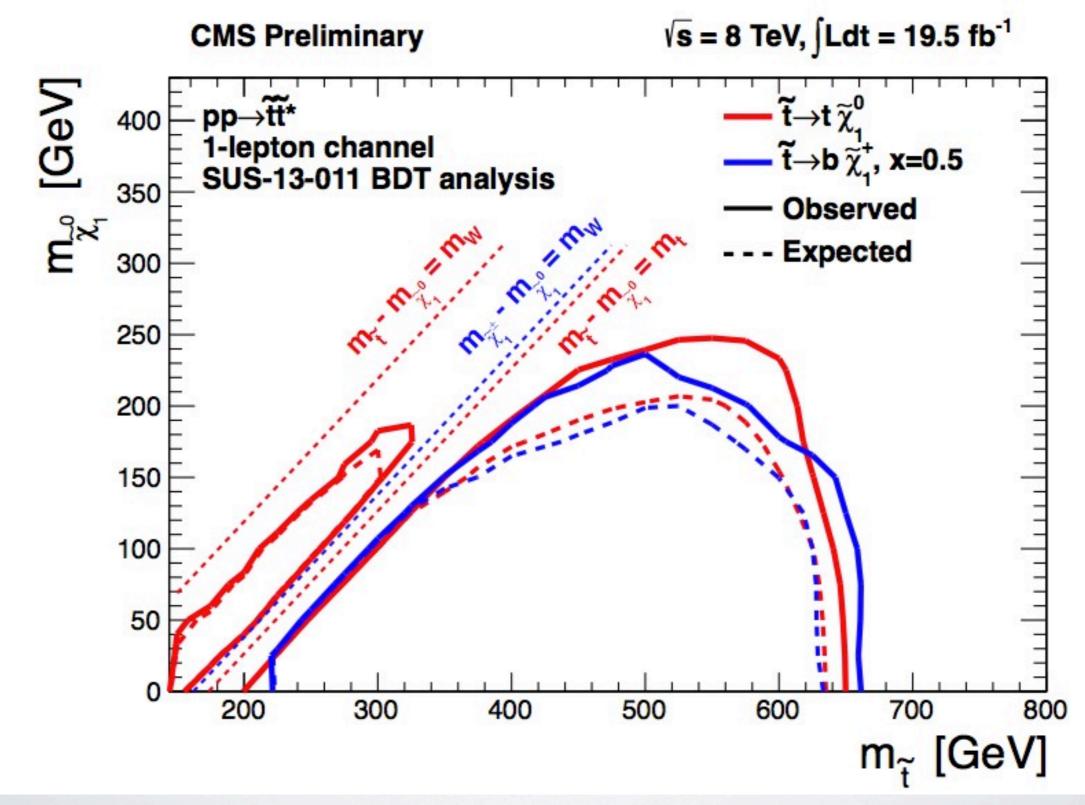


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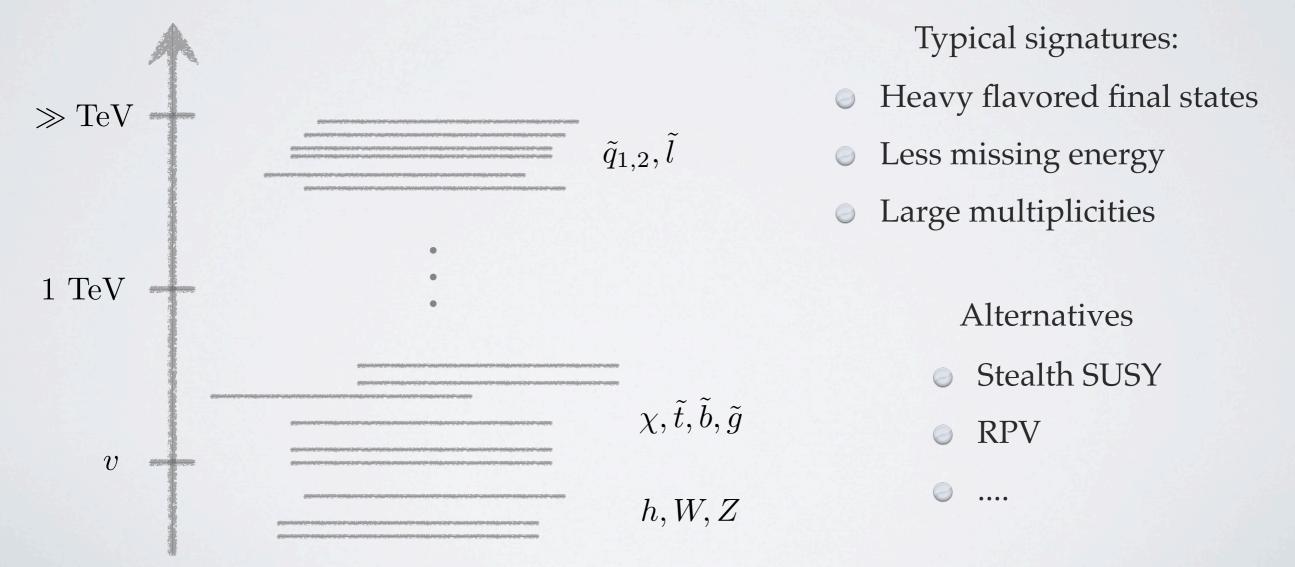
## **STOP SEARCHES**

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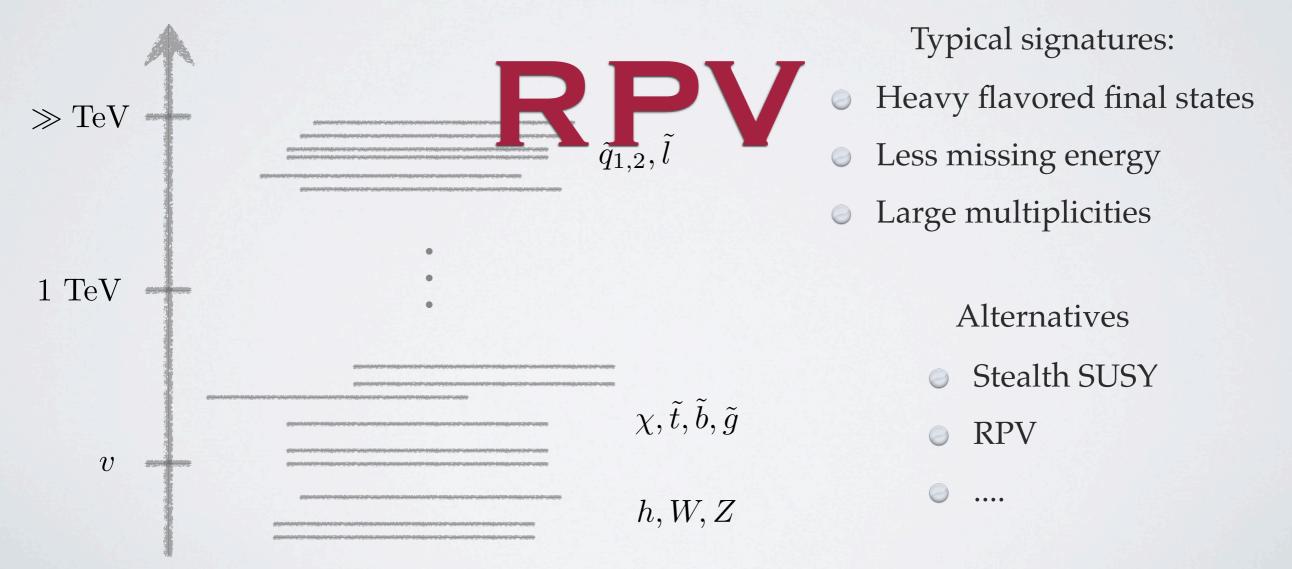
## MSSM --> NATURAL SUSY

- We still want to insist on naturalness and on supersymmetry
- We are interested in an effective SUSY model describing only the physics relevant for the LHC
- These ingredients require only a part of the SUSY spectrum to be at the TeV scale and possible new physics to become relevant at some scale  $\Lambda_{\rm UV}$  not far above the TeV scale



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## WHY RPV?... WHY NOT?

In the SM B and L conservation is accidental while in the MSSM gauge invariant, local operators that violate B and L can be written at the renormalizable level

$$W_{\not\!B} = \frac{1}{2} \lambda_{ijk}^{\prime\prime} U_i^c D_j^c D_k^c$$
$$W_{\not\!L} = \mu_i H_u L_i + \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \frac{1}{2} \lambda_{ijk}^\prime L_i Q_j D_k^c$$

Dreiner hep-ph/9707435 Barbier et al. hep-ph/0406039

- There is a total of 9+27+9 new Yukawas  $(\lambda, \lambda', \lambda'')$  and 3 new mass parameters  $(\mu_i)$
- The mixings µ<sub>i</sub> can be diagonalized away with a suitable field redefinition and is unphysical if no soft terms are present
- When SUSY is broken however, the mixing will reappear in the dim=2 SUSY soft terms generating RPV mass terms
- To forbid these operators a symmetry called *R*-parity is required, where

$$R_P = (-1)^{2S+3(B-L)}$$

 SM particles have even *R*-parity while superpartners, i.e. squarks, sleptons, higgsinos and gauginos have odd *R*-parity

### WHY RPV?... WHY NOT?

#### • Giving up with *R*-parity generates a lot of problems

- **1.** *B* and *L* violation
- **2.** Proton decay (  $\lambda'' \cdot \lambda' < 10^{-24}$  )
- **3.** Experimental constraints (charged current universality, masse of  $\nu_e$ ,  $0\nu 2\beta$  decay, atomic parity violation,  $\Gamma(\tau \to e\nu\bar{\nu}) / \Gamma(\tau \to \mu\nu\bar{\nu})$ ,  $D^0 \bar{D}^0$  mixing,  $n \bar{n}$  oscillation, di-nucleon decay,  $\Gamma(\pi \to e\bar{\nu}) / \Gamma(\pi \to \mu\bar{\nu})$ , BR  $(D^+ \to \bar{K}^{0*}\mu^+\nu_{\mu}) / BR(D^+ \to \bar{K}^{0*}e^+\nu_e)$ , BR $(\tau \to \pi\nu_{\tau})$ ,  $\nu_{\mu}$  DIS)
- However *R*-parity is not enough to forbid *B* and *L* violating HDO and in effective SUSY models one could expect the scale that suppresses these operators to be lower than the GUT scale

$$W_{\rm HDO} \supset \frac{k}{\Lambda_{p-{\rm decay}}} UUDE$$

- In this case proton decay becomes an issue even with *R*-parity for  $\Lambda_{RPV} < M_{GUT}$
- In the framework of Natural SUSY RPV is less constrained than RPC
- RPV provides very peculiar phenomenology (due to the absence of MET)
- However, some model building to predict the couplings and the flavor structure is necessary (e.g. MFV, gauged flavor symmetry, partial compositeness, etc.) *Berenzhiani* 1985, Grinstein, Redi, Villadoro 1009.2049, Krnjaic, Stolarski 1212.4860, Csaki, Grossman, Heidenreich 1111.1239, Karen-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi 1205.5803, Franceschini, Mohapatra 1301.3637, Csaki, Heidenreich 1302.0004

### WHY RPV?... WHY NOT?

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Onsidering only B breaking but not L breaking the main bounds are the following

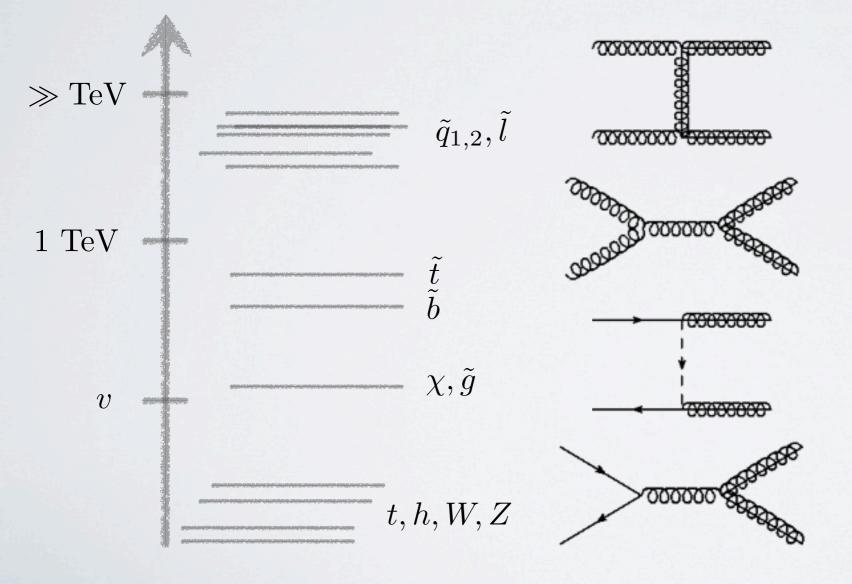
$ \lambda_{uds}^{\prime\prime}  < O(10^{-5})$	$NN \to K^+K^+$	$ \lambda_{cdb}^{\prime\prime}\lambda_{csb}^{\prime\prime}  < O($	$(10^{-3})$	$K - \bar{K}$ oscillation
$ \lambda_{udb}^{\prime\prime}  < O(10^{-2})$	$n-\bar{n}$ oscillation	$\left \lambda_{tdb}^{\prime\prime}\lambda_{tsb}^{\prime\prime}\right  < O($	$(10^{-3})$	$K - \bar{K}$ oscillation
$ \lambda_{tds}^{\prime\prime}  < O(10^{-1})$	$n-\bar{n}$ oscillation		$(10^{-1})$	$B^+ \to K^0 \pi^+$
$ \lambda_{tdb}^{\prime\prime}  < O(10^{-1})$	$n-\bar{n}$ oscillation			$B^- \to \phi \pi^-$
$\lambda'' < 3 \times 10^{-7}$ for	$m z \sim 1 { m TeV}$	cosmological bound	Barbier et al. h	
			Di Luzio, Nara	lecchia, Romanino 1305.7034

- Unification has been usually considered an issue but recently a natural solution has been presented in the context of SO(10) with an adjoint vev along  $T_{3R}$  or B L (*Di Luzio, Nardecchia, Romanino* 1305.7034)
- The absence of a stable LSP also implies the lack for a WIMP DM candidate but solutions are possible (axions)

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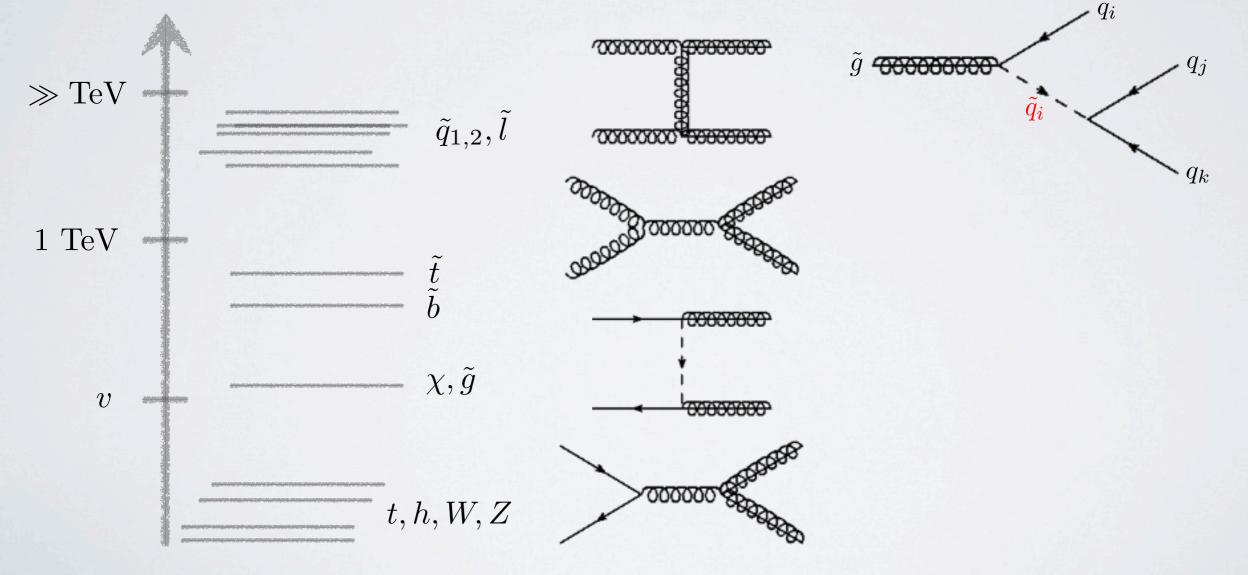
#### Light RPV stops hiding in the LHC data

- Collider signatures of RPV strongly depend on the spectrum (light states and LSP)
- Leptonic RPV more constrained due to many leptons in final states
- Hadronic RPV gives more "jetty" final states and therefore is less constrained
- We focus on hadronic RPV (*L* conservation can still protect proton decay)
- QCD pair production of colored superpartners  $(\tilde{g}\tilde{g}, \tilde{b}\tilde{b}, \bar{\tilde{t}}\tilde{t})$  main prod. mechanism



Light RPV stops hiding in the LHC data

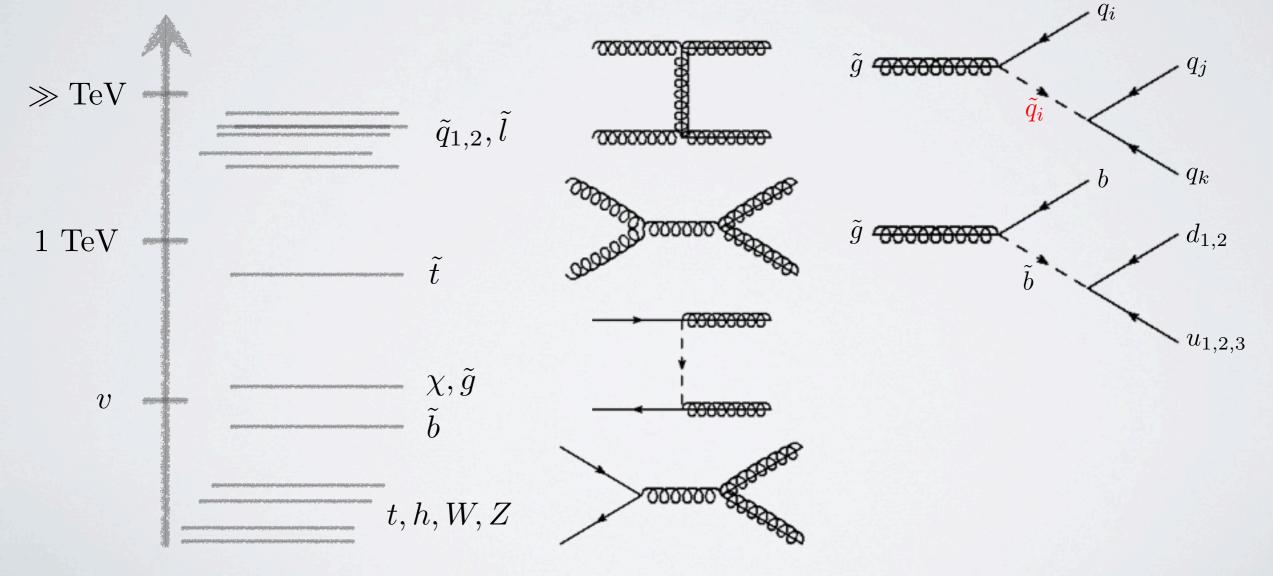
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Light RPV stops hiding in the LHC data

Han, Katz, Son, Tweedie 1211.4025

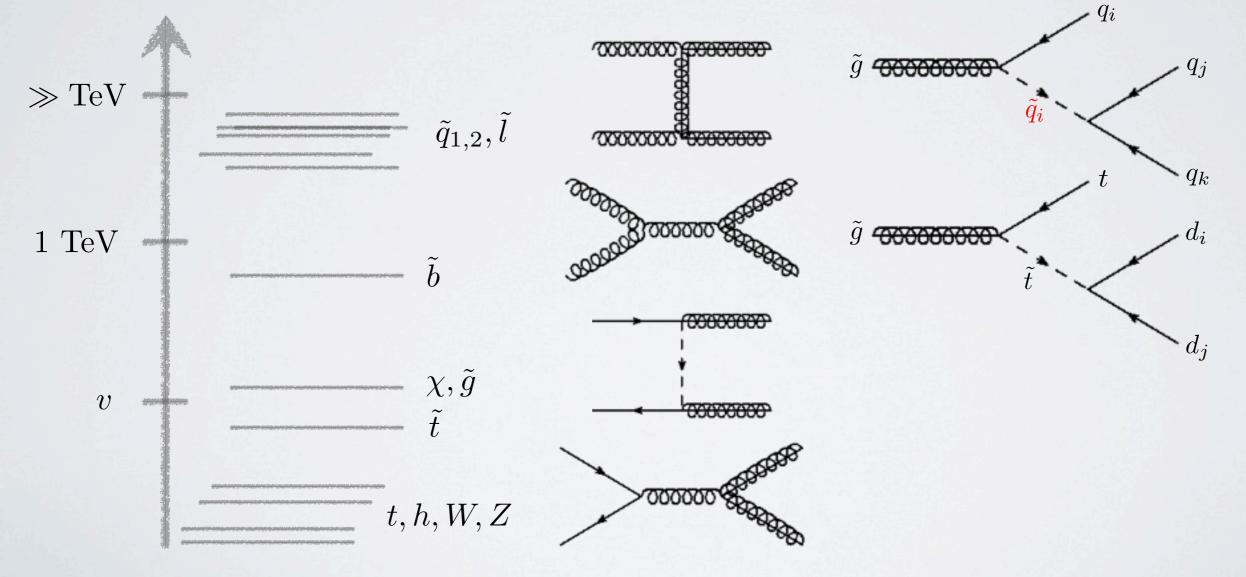
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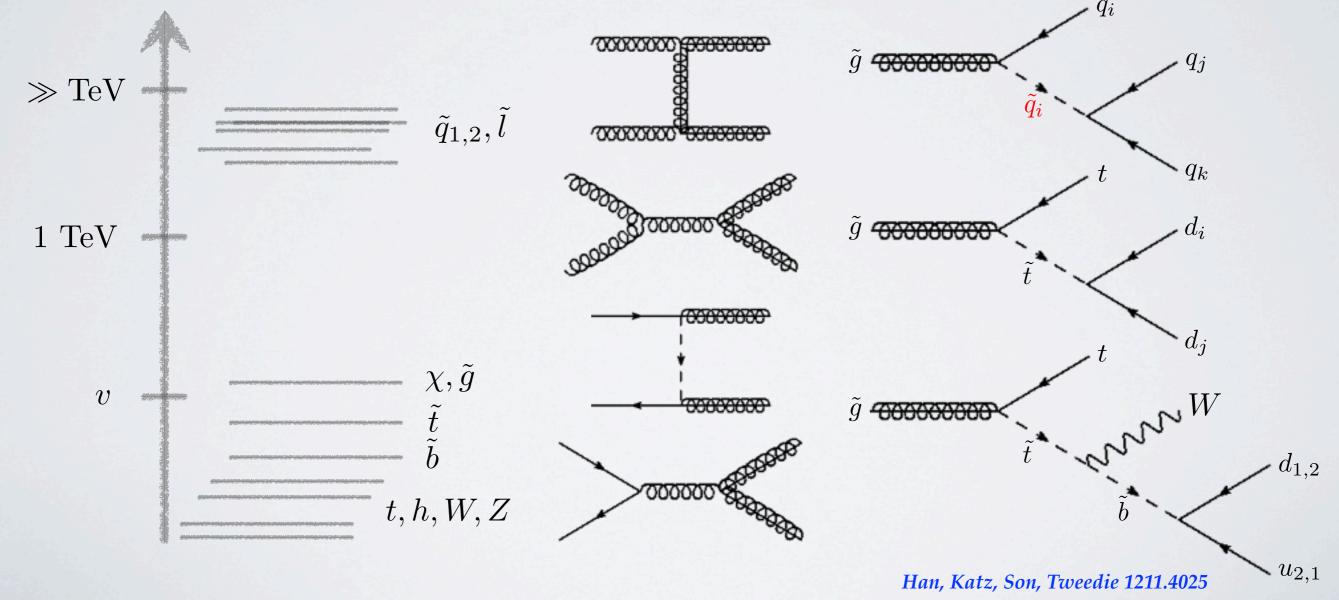
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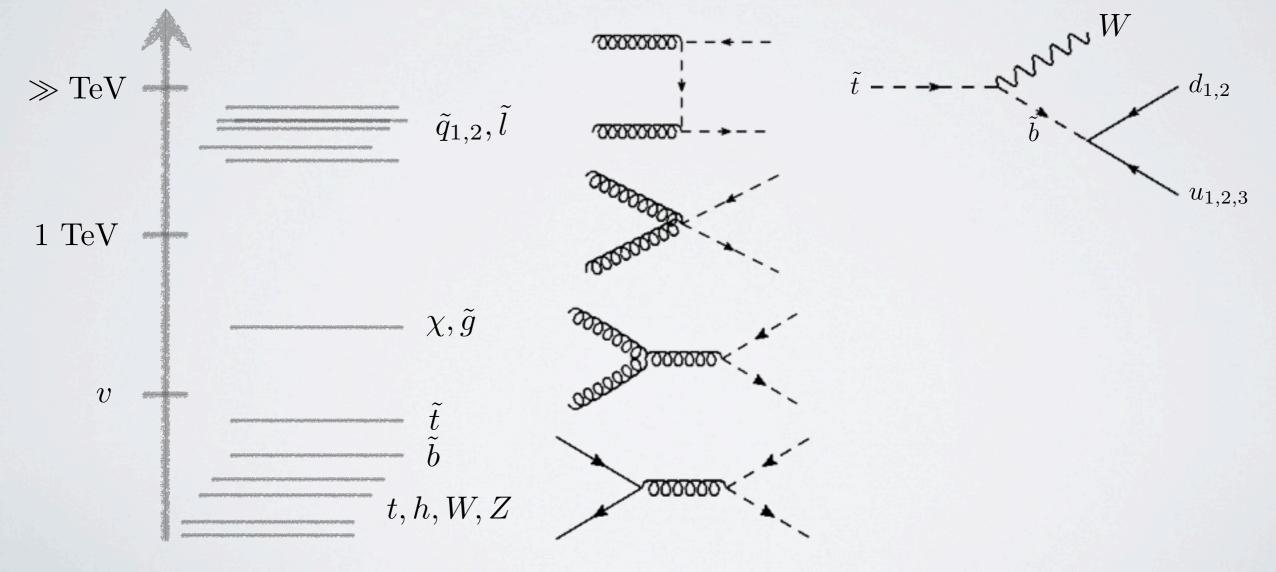
Light RPV stops hiding in the LHC data

Han, Katz, Son, Tweedie 1211.4025

- Collider signatures of RPV strongly depend on the spectrum (light states and LSP)
- Leptonic RPV more constrained due to many leptons in final states
- Hadronic RPV gives more "jetty" final states and therefore is less constrained
- We focus on hadronic RPV (*L* conservation can still protect proton decay)
- QCD pair production of colored superpartners  $(\tilde{g}\tilde{g}, \bar{\tilde{b}}\tilde{b}, \bar{\tilde{t}}\tilde{t})$  main prod. mechanism



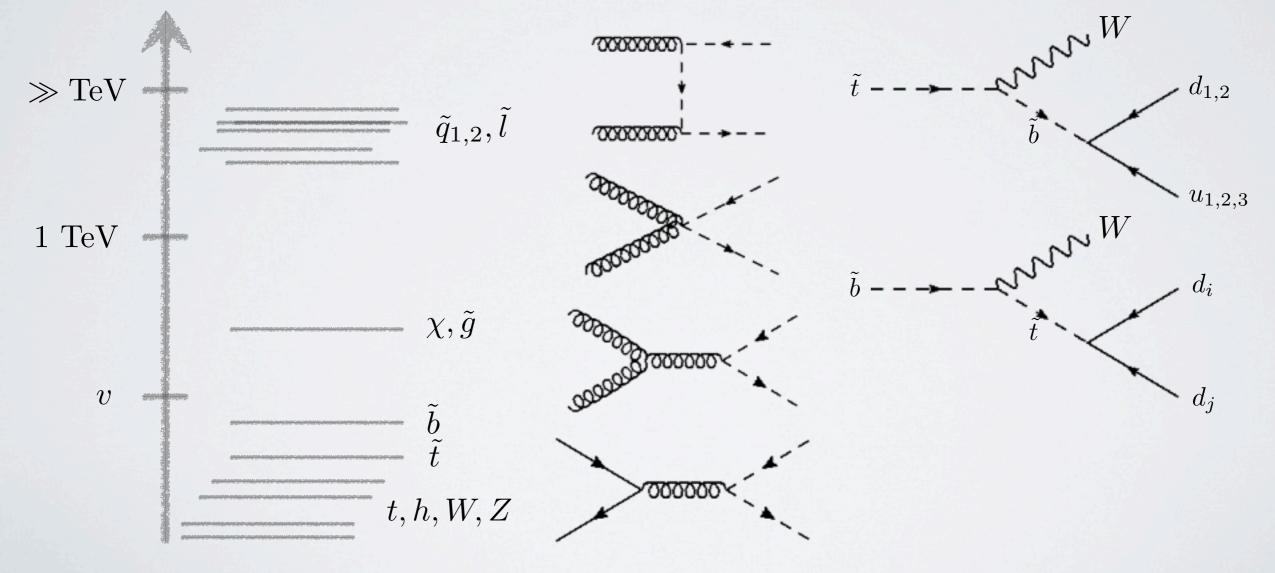
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Light RPV stops hiding in the LHC data

Brust, Katz, Sundrum 1206.2353

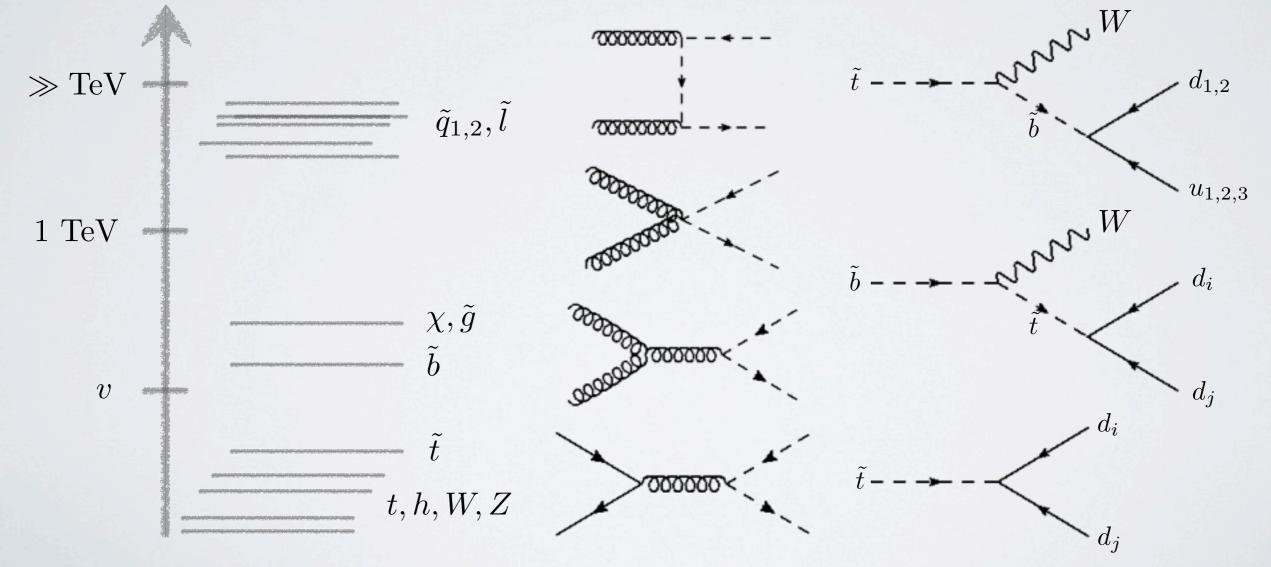
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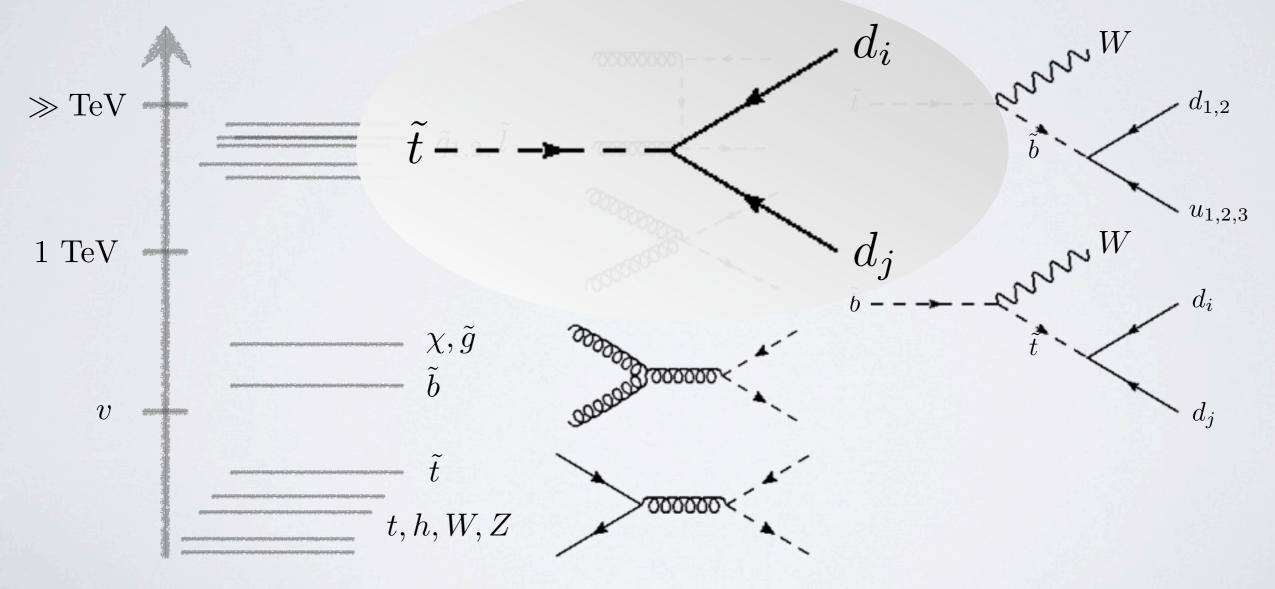
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Light RPV stops hiding in the LHC data

Choudhury, Datta, Maity 1106.5114 Franceschini, RT 1212.3622

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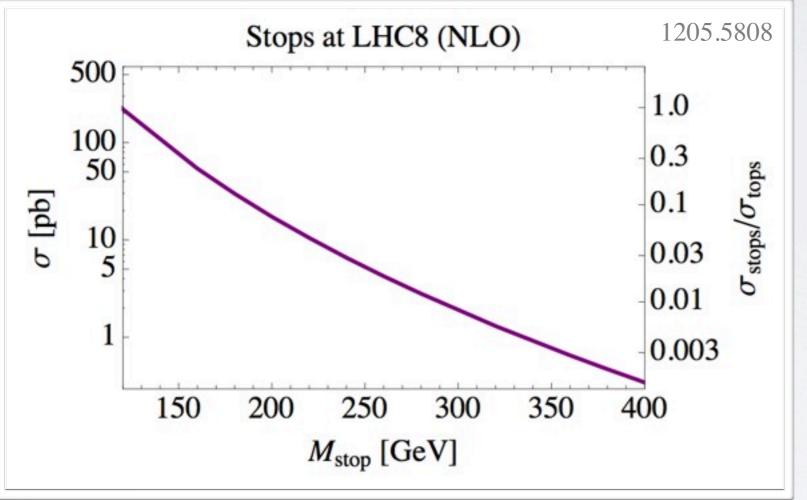
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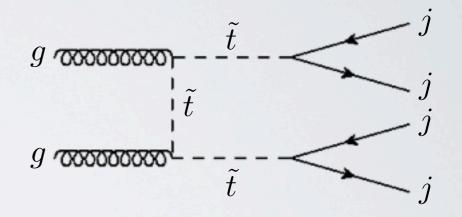
Choudhury, Datta, Maity 1106.5114 Franceschini, RT 1212.3622

## **STOP PAIR PRODUCTION**

Choudhury, Datta, Maity 1106.5114 Franceschini, RT 1212.3622

- We have seen that RPV couplings are bounded to be very small Single production of superpartners is therefore strongly suppressed C
- Pair production however depends only on QCD interactions and it's fixed by the 0 strong quantum numbers





- The LHC is not yet sensitive to 0 the stop pair production CS in the present analyses
- The background is huge, and 0 heavy flavor tagging is crucial in this case

0

## **STOP DECAY**

- The stop BRs into different flavor di-quark final states are model dependent
- The structure of the baryon number violating couplings  $\lambda''$  is given, in explicit constructions (MFV, gauged flavor symmetry, partial compositeness, etc) by the expression

$$\lambda'' \sim V_{il}^{\text{CKM}} \left( \frac{m_{u_i} m_{d_j} m_{d_k}}{m_t^3} \right)^{\mu} \epsilon_{ljk}$$

This expression depends only on CKM matrix elements, quark masses and a model dependent parameter  $\mu$  (the overall factor is a free parameter)

$\mu = 1$	$\mathrm{BR}\left(\tilde{t} \to bd + bs\right) \approx 99\%$	$SU(3)_{Q,L,d,u,e, u}$ $SU(3)_{Q,Q^c,L,L^c}$ MFV Partial Comp.	Csaki, Grossman, Heidenreich 1111.1239 Krnjaic, Stolarski 1212.4860 Karen-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi 1205.5803
$\mu = \frac{1}{2}$	$BR\left(\tilde{t} \to bd + bs\right) \approx 14\%$	$SU(3)_{V,q,l}$	Franceschini, Mohapatra 1301.3637

 For small BRs into heavy flavors searches are very difficult, but assuming large BRs into heavy flavors stop pair production can be observed at the LHC

Riccardo Torre

#### **STOP DECAY**

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 $\bigcirc$  For  $\mu = 1$  we get (low tan  $\beta$ )

• So all the bounds on hadronic RPV can be easily satisfied

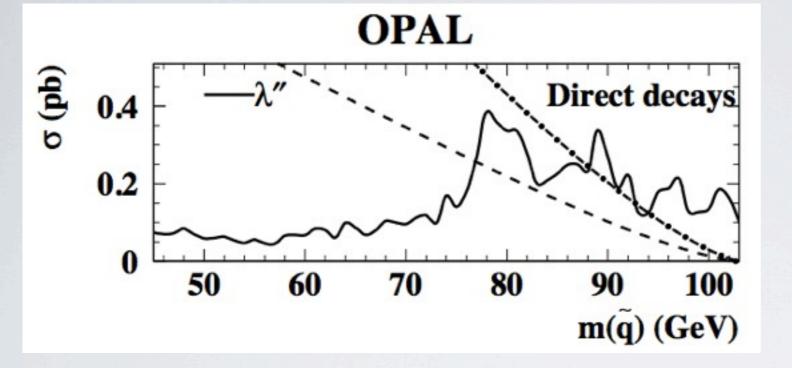
• The decay length is given by

$$L = 2 \operatorname{mm}(\beta\gamma) \left(\frac{500 \text{ GeV}}{m_{\tilde{q}}}\right) \left(\frac{0.9 \times 10^{-7}}{\lambda''}\right)^2$$

• So that prompt decay requires  $\lambda'' \gtrsim 10^{-7}$ 

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#### **CURRENT LIMITS: LEP + TEVATRON**



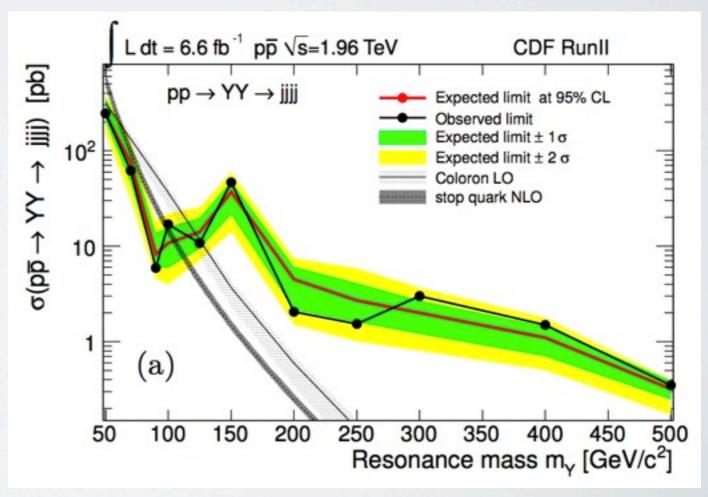
 Searches at LEP have set a bound (OPAL Collaboration hep-ex/ 0310054)

$$m_{\tilde{t}}(\theta_{\tilde{t}} = 0.98) \ge 77 \text{ GeV}$$
$$m_{\tilde{t}}(\theta_{\tilde{t}} = 0) \ge 88 \text{ GeV}$$

 Tevatron (CDF) has an analysis setting a stronger bound (CDF Collaboration 1303.2699 hep-ex)

 $m_{\tilde{t}} \leq 50 \,\,\mathrm{GeV}$ 

$$m_{\tilde{t}} \ge 100 \text{ GeV}$$

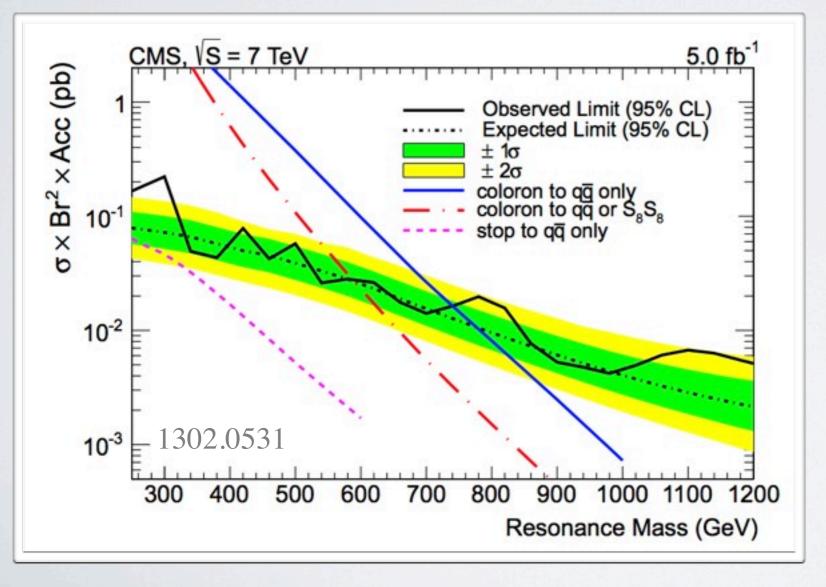


# **CURRENT LIMITS: LHC**

Together, LEP and Tevatron have set a bound

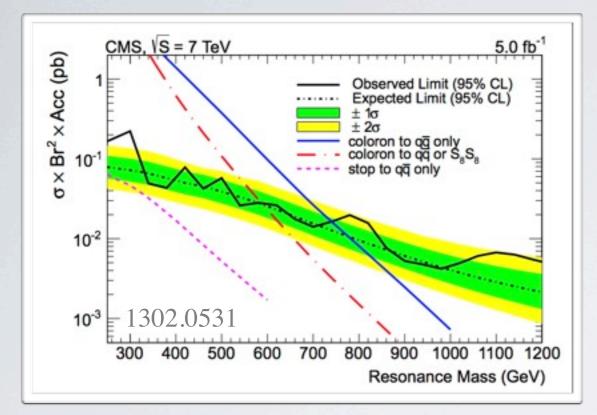
 $m_{\tilde{t}} \geq 100~{\rm GeV}$ 

 ATLAS and CMS have presented searches for pair produced colored resonances decaying to 4j (colorons and sgluons) and recently have also focused on stops



- The LHC is not yet sensitive to the stop pair production CS in the present analyses
- The background is huge, and heavy flavor tagging is crucial in this case
- We will show that with btagging techniques LHC data can already exclude stops in the very light mass region (at the hearth of naturalness)

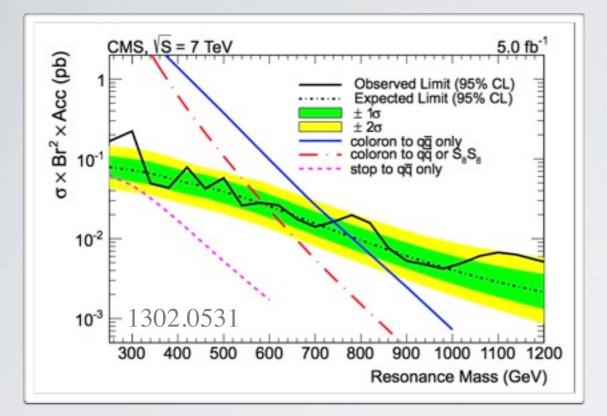
## SKETCH OF THE ANALYSES



Mass pairing: 
$$\delta_m = \frac{|m_{ab} - m_{cd}|}{m_{ab} + m_{cd}}$$
  
Main cuts: at least 4j with  
 $p_{T\,j} > 110 \text{ GeV}$   
 $|\eta_j| < 2.5$   
 $\Delta R_{jj} = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \ge 0.7$   
 $\delta_m < 0.075$   
 $\Delta = \sum_{i=1,2} (p_T)_i - |m_{ab} - m_{bc}| > 25$ 

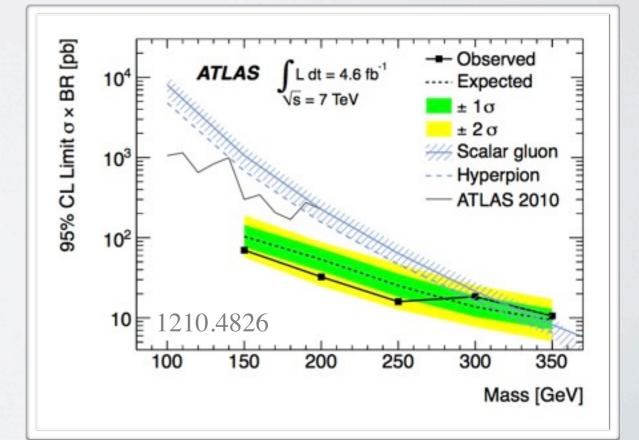
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N



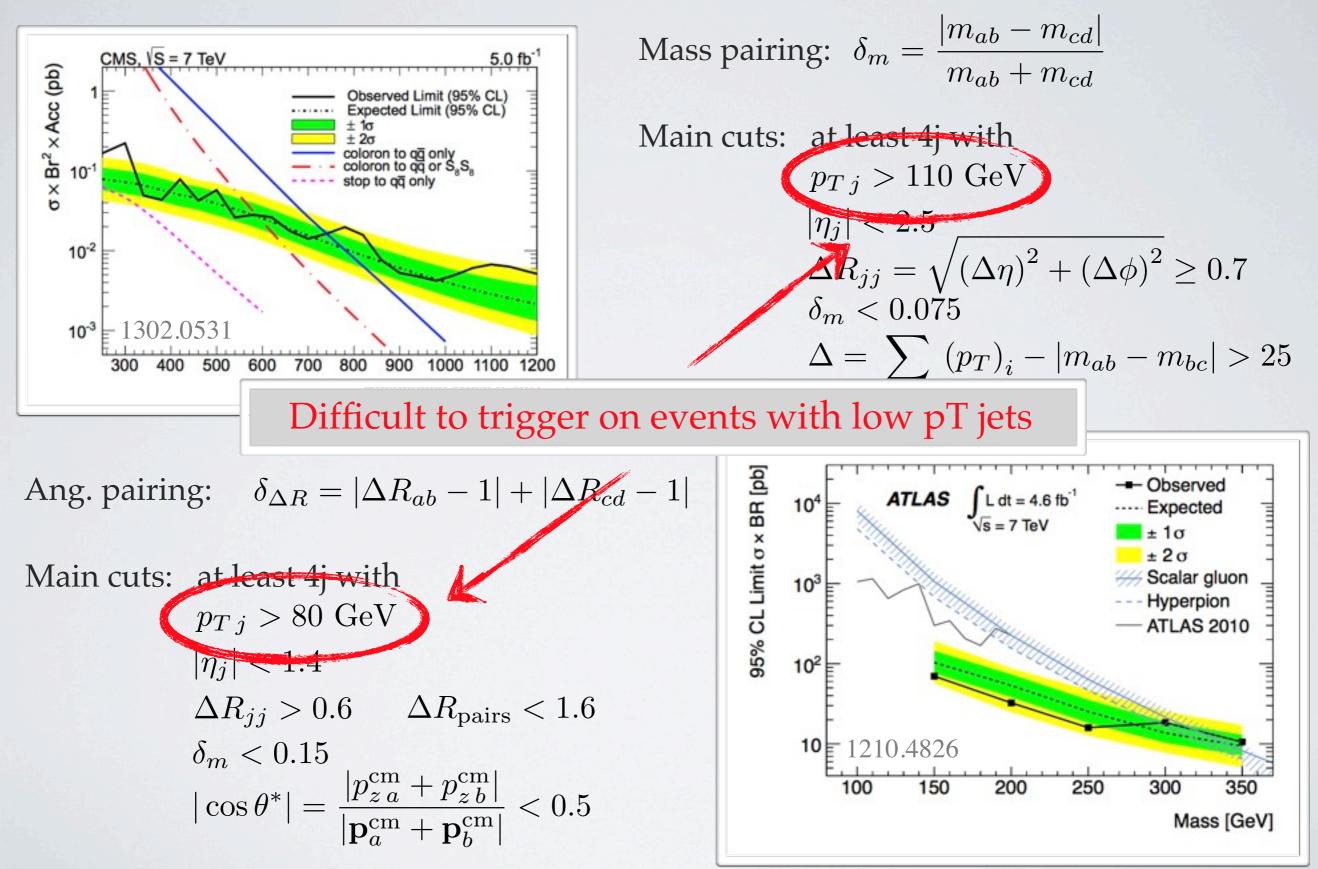
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Ang. pairing: 
$$\delta_{\Delta R} = |\Delta R_{ab} - 1| + |\Delta R_{cd} - 1|$$
  
Main cuts: at least 4j with  
 $p_{T j} > 80 \text{ GeV}$   
 $|\eta_j| < 1.4$   
 $\Delta R_{jj} > 0.6$   $\Delta R_{\text{pairs}} < 1.6$   
 $\delta_m < 0.15$   
 $|\cos \theta^*| = \frac{|p_{z a}^{\text{cm}} + p_{z b}^{\text{cm}}|}{|\mathbf{p}_a^{\text{cm}} + \mathbf{p}_b^{\text{cm}}|} < 0.5$ 



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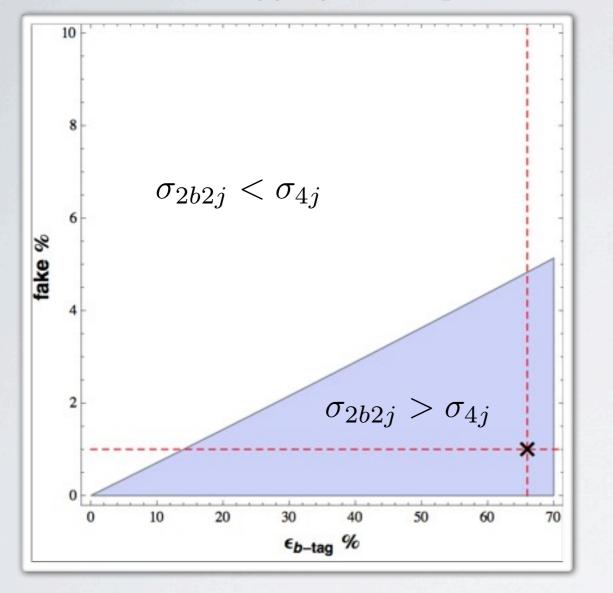
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Riccardo Torre

#### **B-TAGGING**

○ Online *b*-tagging can help in reducing the pT threshold for the recorded jets!



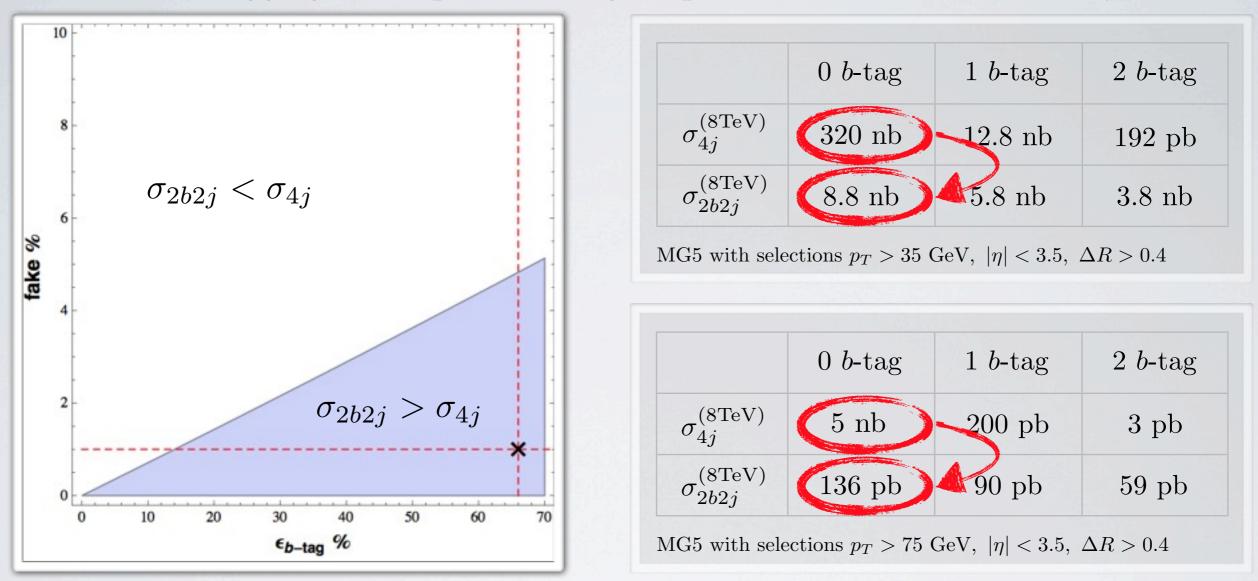
	0 <i>b</i> -tag	1 <i>b</i> -tag	2 b-tag
$\sigma_{4j}^{(8{\rm TeV})}$	320  nb	12.8 nb	192 pb
$\sigma^{(8{\rm TeV})}_{2b2j}$	8.8 nb	5.8  nb	$3.8 \mathrm{~nb}$

MG5 with selections  $p_T > 35$  GeV,  $|\eta| < 3.5$ ,  $\Delta R > 0.4$ 

	0 b-tag	1 <i>b</i> -tag	2 b-tag
$\sigma^{(8{ m TeV})}_{4j}$	5  nb	$200 \mathrm{~pb}$	$3 \mathrm{~pb}$
$\sigma^{(8{ m TeV})}_{2b2j}$	136 pb	$90~{\rm pb}$	$59 \mathrm{~pb}$

#### **B-TAGGING**

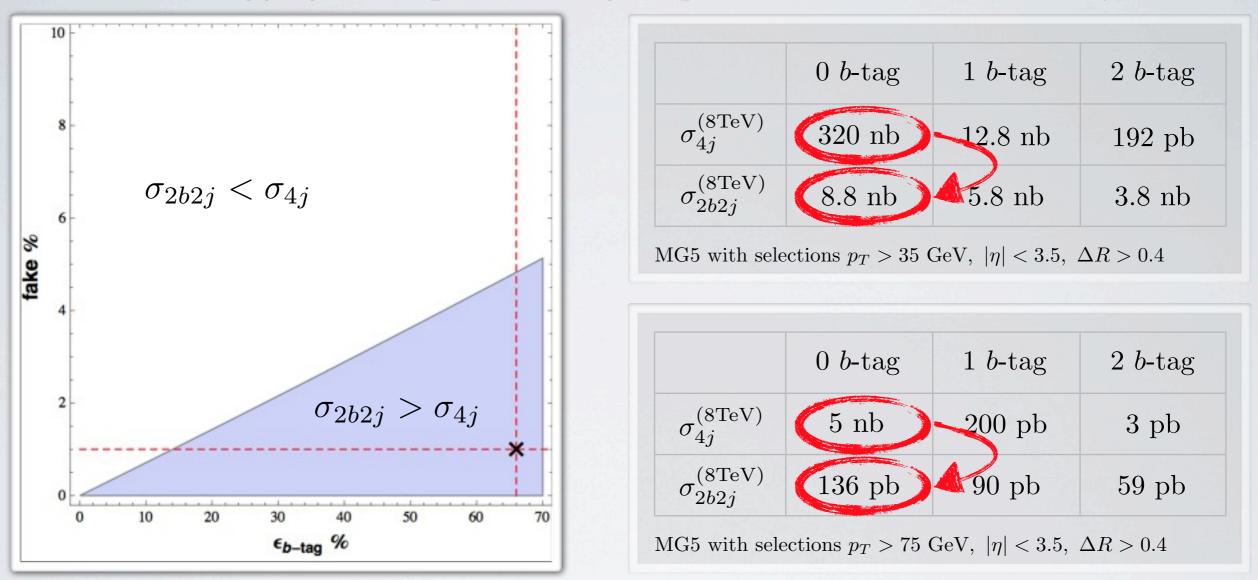
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### **B-TAGGING**

Online *b*-tagging can help in reducing the pT threshold for the recorded jets!



• We can reduce main background from the 4j to the 2b2j, i.e. a factor of 36 smaller

 Assuming the interesting events have been recorded with the ATLAS and CMS 2012 triggers, then using (offline) *b*-tagging the relevant backgrounds for our final state are

$$pp \to 2b2j$$
  $pp \to t\bar{t} \left(\sigma_{t\bar{t}}^{(8\text{TeV})} = 135 \text{ pb}\right)$ 

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## **OUR ANALYSIS**

- $\bigcirc$  We aim at identify the stops signal as a bump in the  $m_{\text{best}}$  distribution
- After studying the effect of a cut based analysis using all the different kinematic variables defined by the CMS and ATLAS collaborations, we identify the following kinematic variables as the most relevant to optimize S/B

$$\delta_{\Delta R} = |\Delta R_{ab} - 1| + |\Delta R_{cd} - 1|$$
$$m_{\text{best}} = \frac{m_{ab} + m_{cd}}{2}$$
$$\cos \theta^* = \frac{p_{za}^{\text{cm}} + p_{zb}^{\text{cm}}}{|\mathbf{p}_a^{\text{cm}} + \mathbf{p}_b^{\text{cm}}|} = \frac{p_{zc}^{\text{cm}} + p_{zd}^{\text{cm}}}{|\mathbf{p}_c^{\text{cm}} + \mathbf{p}_d^{\text{cm}}|}$$

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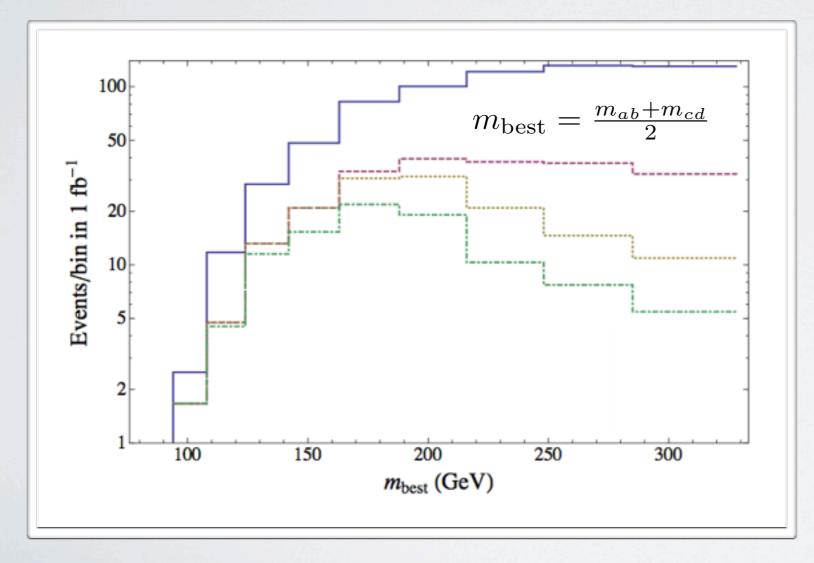
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Validated vs ATLAS analysis (4j) 1110.2693 with 30% level agreement after all selections!

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For very boosted jets we have

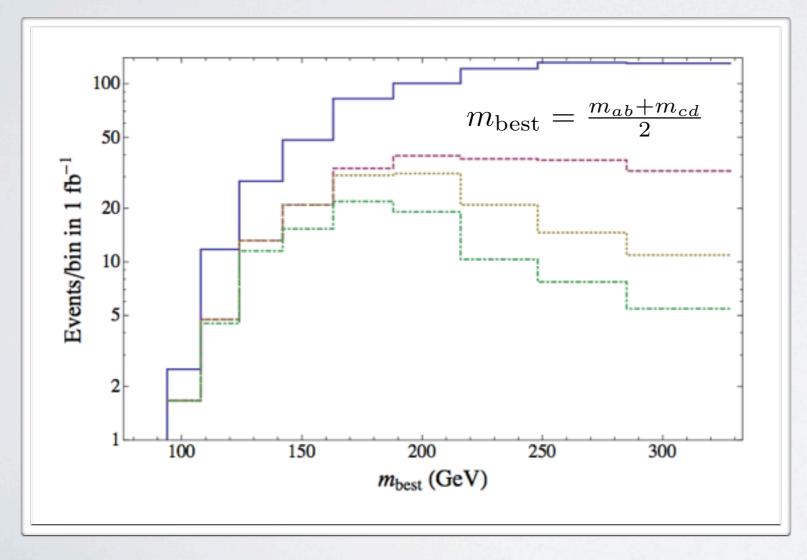
 $m_{\tilde{t}}^2 \approx p_{T_{j_1}} p_{T_{j_2}} \Delta R_{j_1 j_2}^2$ 



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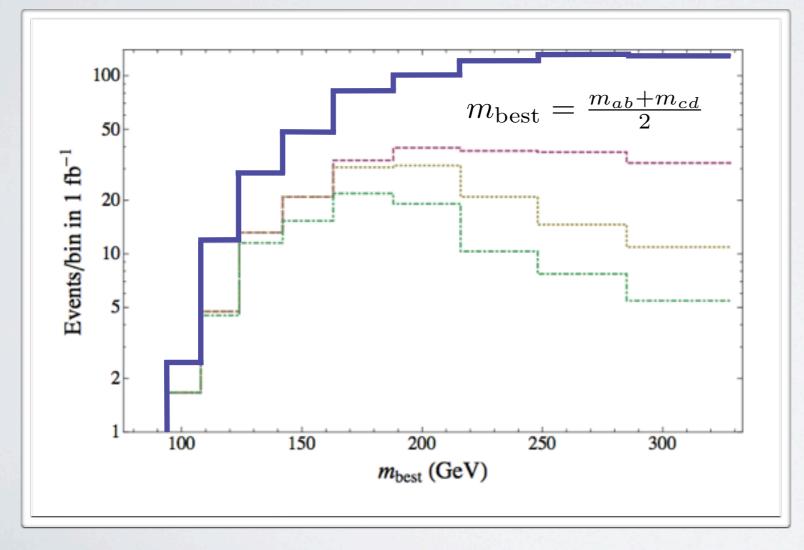
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We identify these selections to optimize S/B

$$p_{T\,j} > \frac{m_{\tilde{t}}}{2} \qquad |\eta| < 2.8 \qquad \Delta R_{jj} > 0.7$$
  
$$\delta m < 0.075$$



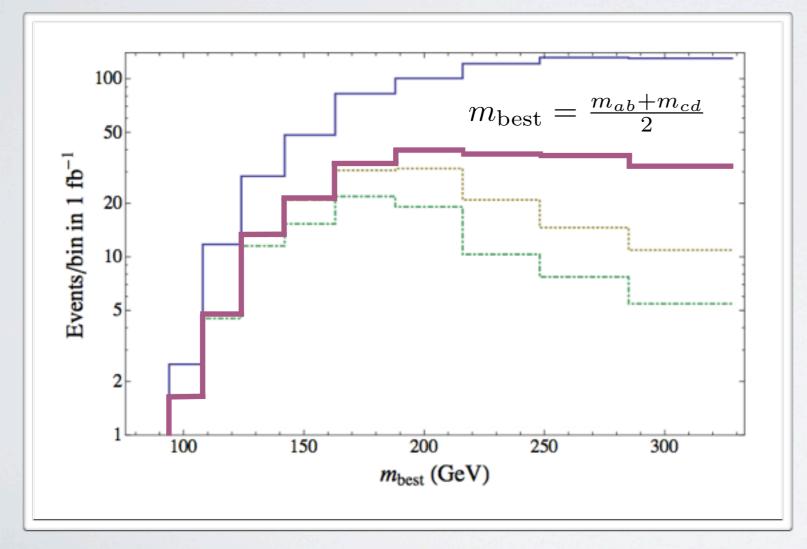
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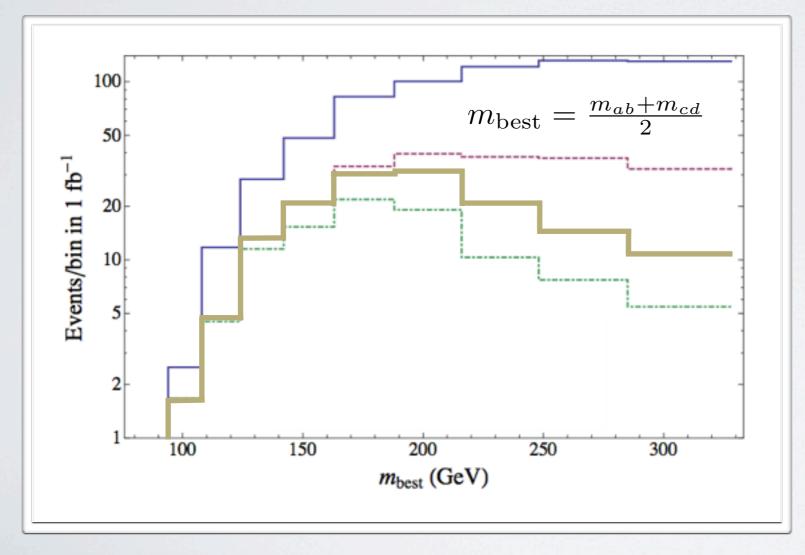


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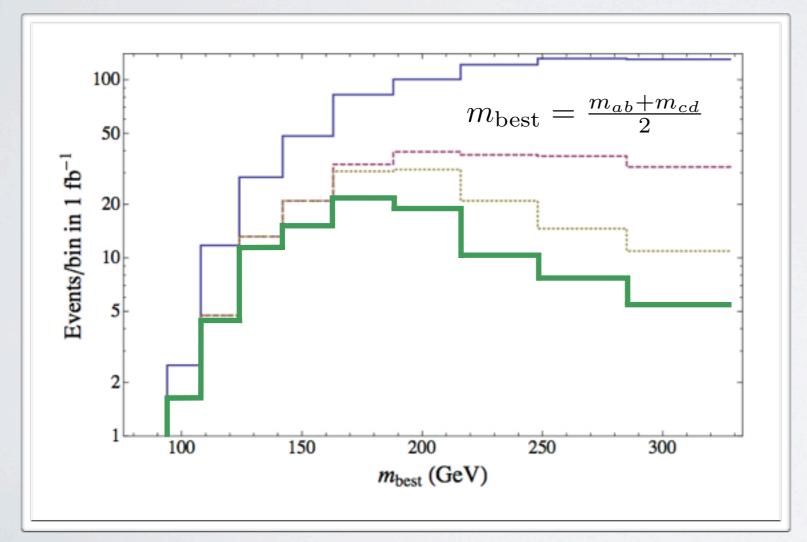
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$$\delta m < 0.075 \qquad |\cos \theta^*| < 0.4 \quad \Delta R_{\text{best}} < 1.5$$
  
$$\Delta \eta_{\text{best}} < 0.8$$



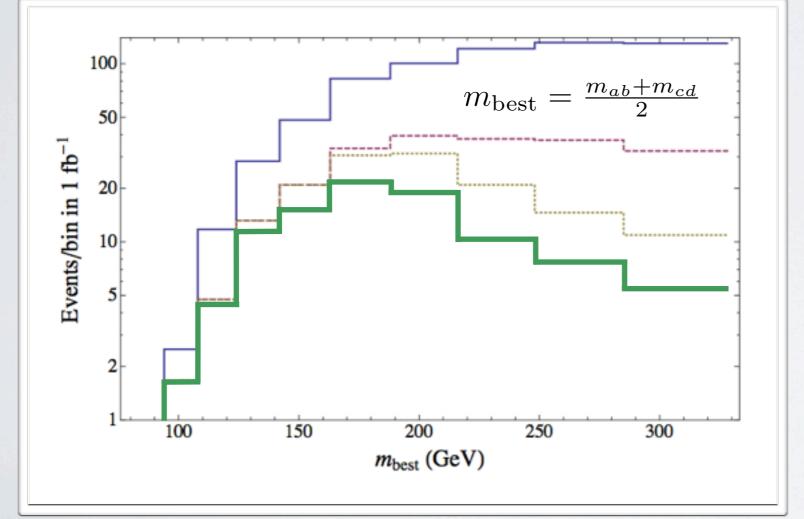
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The combined effect of the  $\Delta R_{\text{best}}$ and  $\Delta \eta_{\text{best}}$  cuts is to move the peak of the background distribution toward smaller values of  $m_{\text{best}}$ 

Therefore using these angular variables we can hope to see the stop signal as a bump on a smoothly falling background

#### CUT EFFICIENCIES LHC@8TEV

	$m_{\tilde{t}} = 100  { m GeV}$ - $\Delta R  pairing$									
	$\tilde{t}\tilde{t}$ (314 pb)			QCD $b\bar{b}jj$ (8826 pb) <sup>a</sup>			$t\bar{t}(135 \text{ pb})$			
Selection	$\epsilon^{(1)}$	E	$\epsilon_{i \rightarrow i+1}$	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	
$\eta < 2.8$	0.81	0.81	-	0.82	0.82	-	0.88	0.88	-	
$p_T > 50 \text{ GeV}$	0.16	0.16	0.19	0.15	0.15	0.18	0.38	0.38	0.43	
$\Delta R > 0.7$	0.78	0.15	0.95	0.79	0.14	0.96	0.85	0.36	0.94	
b-tags = 2	0.44	0.064	0.44	0.44	0.062	0.44	0.44	0.15	0.44	
$\delta_m < 0.075$	0.13	0.010	0.16	0.11	0.0085	0.14	0.15	0.026	0.17	
$ \cos \theta^*  < 0.4$	0.33	0.0047	0.46	0.19	0.0021	0.24	0.36	0.026	0.45	
$\Delta \eta_{\rm best} < 0.8$	0.31	0.0030	0.64	0.23	0.00077	0.38	0.37	0.0069	0.60	
$\Delta R_{\rm best} < 1.5$	0.25	0.0025	0.85	0.19	0.00063	0.82	0.31	0.0056	0.81	
$\Delta R_{\rm best} < 1$	0.031	0.00080	0.32	0.030	0.00020	0.32	0.043	0.0016	0.28	

<sup>a</sup>This QCD cross section is computed taking  $p_T > 35$  GeV,  $|\eta| < 3.5$  and  $\Delta R > 0.4$  for the matrix element computation.

#### CUT EFFICIENCIES LHC@8TEV

	$m_{\tilde{t}} = 100  { m GeV}$ - $\Delta R  pairing$									
	$\tilde{t}\tilde{t}$ (314 pb)			QCD $b\bar{b}jj$ (8826 pb) <sup>a</sup>			$t\bar{t}(135 \text{ pb})$			
Selection	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	
$\eta < 2.8$	0.81	0.81	-	0.82	0.82	-	0.88	0.88	-	
$p_T > 50 \text{ GeV}$	0.16	0.16	0.19	0.15	0.15	0.18	0.38	0.38	0.43	
$\Delta R > 0.7$	0.78	0.15	0.95	0.79	0.14	0.96	0.85	0.36	0.94	
b-tags = 2	0.44	0.064	0.44	0.44	0.062	0.44	0.44	0.15	0.44	
$\delta_m < 0.075$	0.13	0.010	0.16	0.11	0.0085	0.14	0.15	0.026	0.17	
$ \cos \theta^*  < 0.4$	0.33	0.0047	0.46	0.19	0.0021	0.24	0.36	0.026	0.45	
$\Delta \eta_{ m best} < 0.8$	0.31	0.0030	0.64	0.23	0.00077	0.38	0.37	0.0069	0.60	
$\Delta R_{\rm best} < 1.5$	0.25	0.0025	0.85	0.19	0.00063	0.82	0.31	0.0056	0.81	
$\Delta R_{\rm best} < 1$	0.031	0.00080	0.32	0.030	0.00020	0.32	0.043	0.0016	0.28	

		$m_{\tilde{t}} = 200 \text{ GeV} - \Delta R \text{ pairing}$								
		$\overline{t}\overline{t}$ (9.1 pb)		QCD $b\bar{b}jj$ (136 pb) <sup>b</sup>			$t\bar{t}(135 \text{ pb})$			
Selection	$\epsilon^{(1)}$	e	$\epsilon_{i \rightarrow i+1}$	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	
$\eta < 2.8$	0.16	0.16	-	0.94	0.036	-	0.88	0.88	-	
$p_T > 100 \text{ GeV}$	0.026	0.026	0.16	0.13	0.13	0.14	0.0031	0.31	0.035	
$\Delta R > 0.7$	0.15	0.035	0.95	0.88	0.12	0.93	0.85	0.027	0.87	
b-tags = 2	0.44	0.011	0.44	0.44	0.52	0.44	0.44	0.012	0.44	
$\delta_m < 0.075$	0.036	0.0031	0.29	0.12	0.0072	0.14	0.15	0.0015	0.13	
$ \cos \theta^*  < 0.4$	0.096	0.0018	0.57	0.25	0.0021	0.29	0.36	0.00066	0.45	
$\Delta \eta_{ m best} < 0.8$	0.078	0.0013	0.73	0.29	0.00084	0.41	0.38	0.00044	0.66	
$\Delta R_{\rm best} < 1.5$	0.075	0.0011	0.85	0.26	0.00071	0.84	0.31	0.00038	0.86	
$\Delta R_{\rm best} < 1$	0.012	0.00031	0.29	0.046	0.00025	0.35	0.043	0.00019	0.49	

<sup>b</sup>This QCD cross section is computed taking  $p_T > 75$  GeV,  $|\eta| < 3.5$  and  $\Delta R > 0.4$  for the matrix element computation.

#### CUT EFFICIENCIES LHC@8TEV

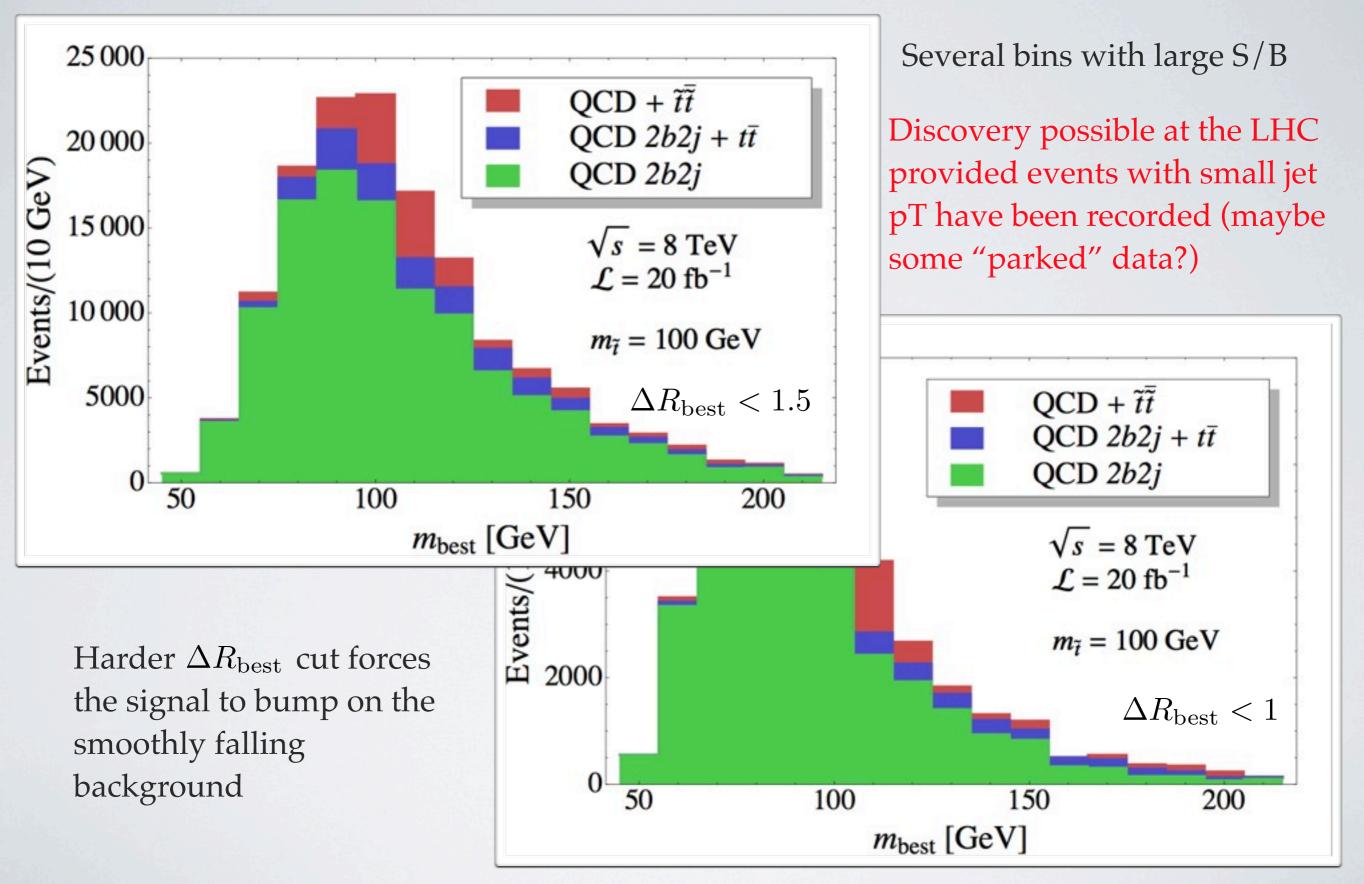
	$m_{\tilde{t}} = 100  { m GeV}$ - $\Delta R  pairing$									
	NC 1	$\tilde{t}\bar{\tilde{t}}$ (314 pb)		QCD $b\bar{b}jj$ (8826 pb) <sup>a</sup>			$t\bar{t}(135 \text{ pb})$			
Selection	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	
$\eta < 2.8$	0.81	0.81	-	0.82	0.82	-	0.88	0.88	-	
$p_T > 50 \text{ GeV}$	0.16	0.16	0.19	0.15	0.15	0.18	0.38	0.38	0.43	
$\Delta R > 0.7$	0.78	0.15	0.95	0.79	0.14	0.96	0.85	0.36	0.94	
b-tags = 2	0.44	0.064	0.			0.44	0.44	0.15	0.44	
$\delta_m < 0.075$	0.13	0.010	0. 🧲	$/\mathbf{P}$	190%	0.14	0.15	0.026	0.17	
$ \cos \theta^*  < 0.4$	0.33	0.0047	0. D/	$D \sim$	$\perp \angle /0$	0.24	0.36	0.026	0.45	
$\Delta \eta_{\rm best} < 0.8$	0.31	0.0030	0.			0.38	0.37	0.0069	0.60	
$\Delta R_{\rm best} < 1.5$	0.25	0.0025	0.85	0.19	0.00063	0.82	0.31	0.0056	0.81	
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Selection		$m_{\tilde{t}} = 200 \text{ GeV} - \Delta R \text{ pairing}$								
		$\overline{t}\overline{t}$ (9.1 pb)		QC	CD bbjj (136		$t\bar{t}(135 \text{ pb})$			
	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	$\epsilon^{(1)}$	ε	$\epsilon_{i \rightarrow i+1}$	
$\eta < 2.8$	0.16	0.16	-	0.94	0.036	-	0.88	0.88	-	
$p_T > 100 \text{ GeV}$	0.026	0.026	0.16	0.13	0.13	0.14	0.0031	0.31	0.035	
$\Delta R > 0.7$	0.15	0.035	0.95	0.88	0.12	0.93	0.85	0.027	0.87	
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$ \cos \theta^*  < 0.4$	0.096	0.0018	0. <i>D</i>	$D \sim$		0.29	0.36	0.00066	0.45	
$\Delta \eta_{\rm best} < 0.8$	0.078	0.0013	0.			0.41	0.38	0.00044	0.66	
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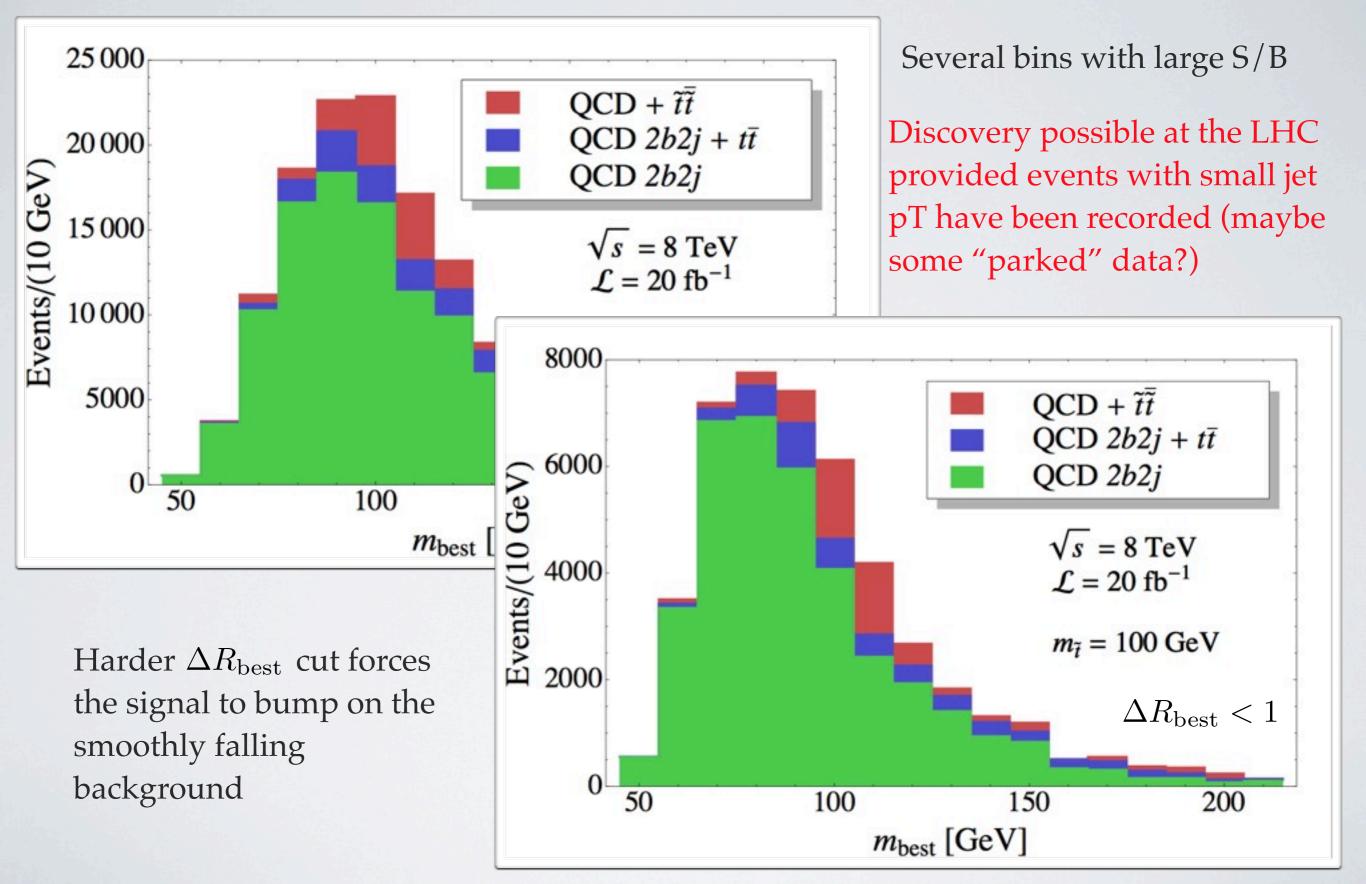
<sup>b</sup>This QCD cross section is computed taking  $p_T > 75$  GeV,  $|\eta| < 3.5$  and  $\Delta R > 0.4$  for the matrix element computation.

# **RESULTS: 100 GEV STOPS**

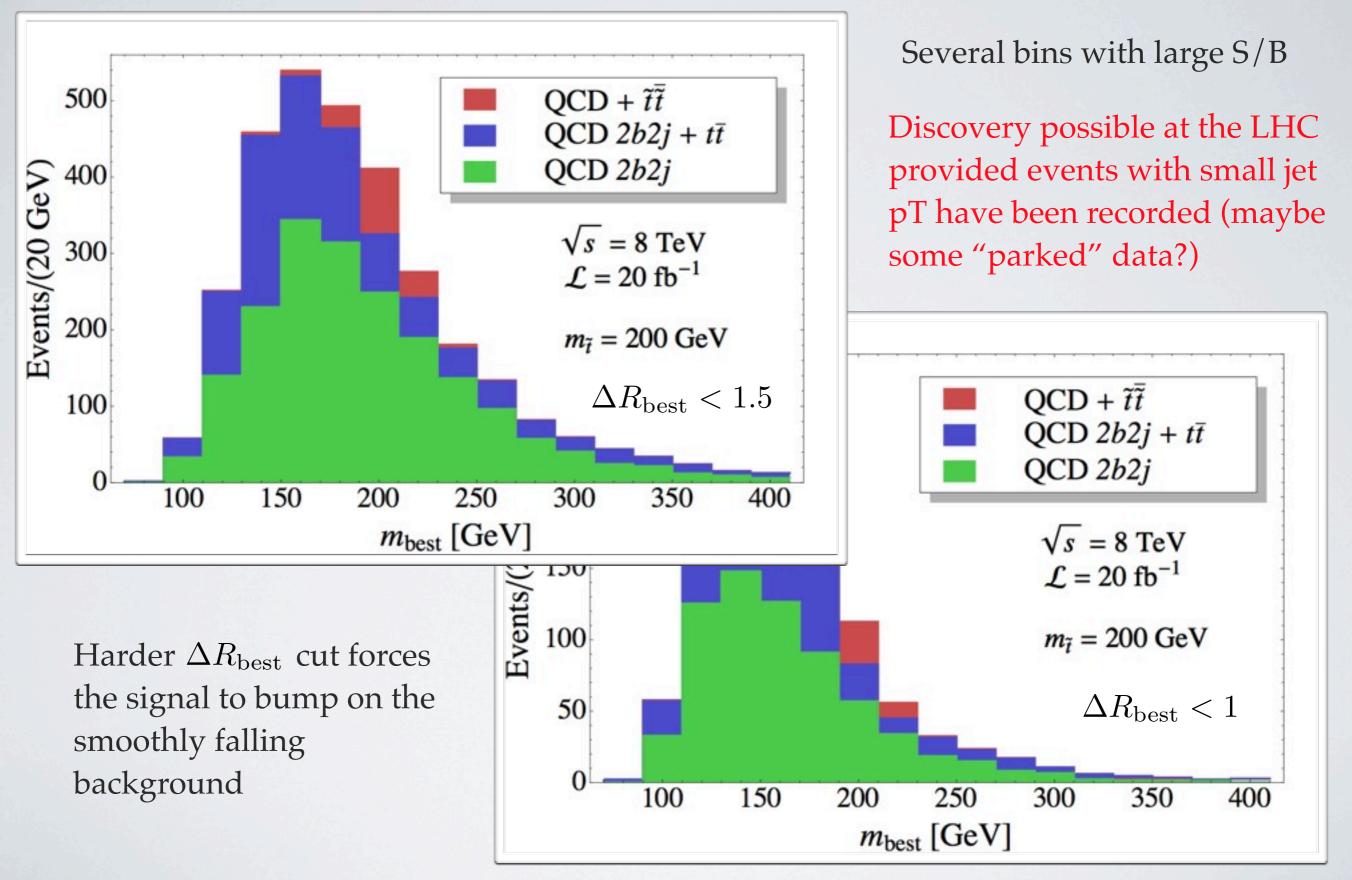


Light RPV stops hiding in the LHC data

# **RESULTS: 100 GEV STOPS**

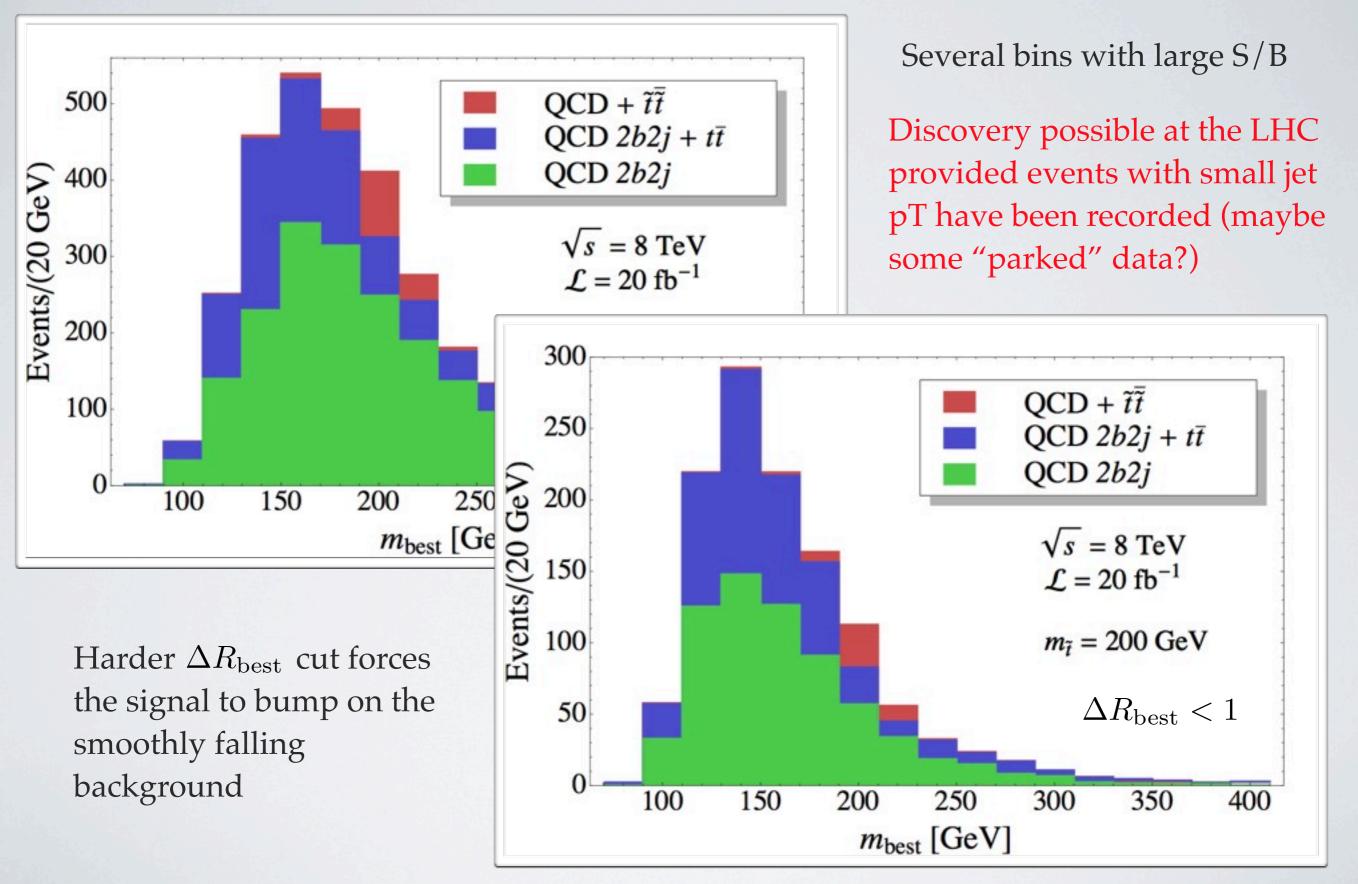


#### **RESULTS: 200 GEV STOPS**



Light RPV stops hiding in the LHC data

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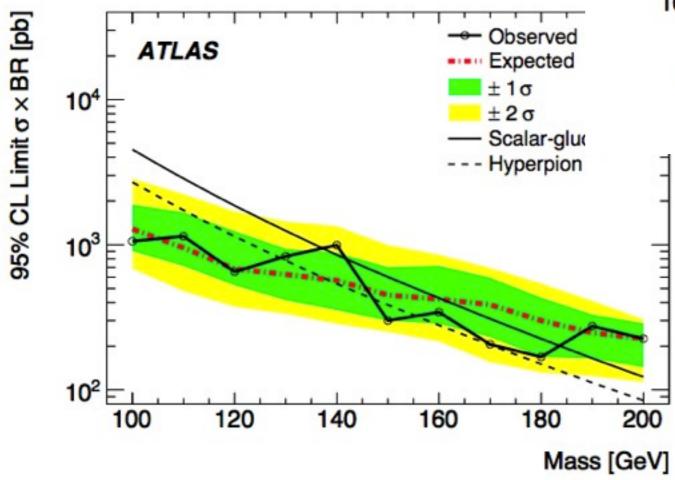


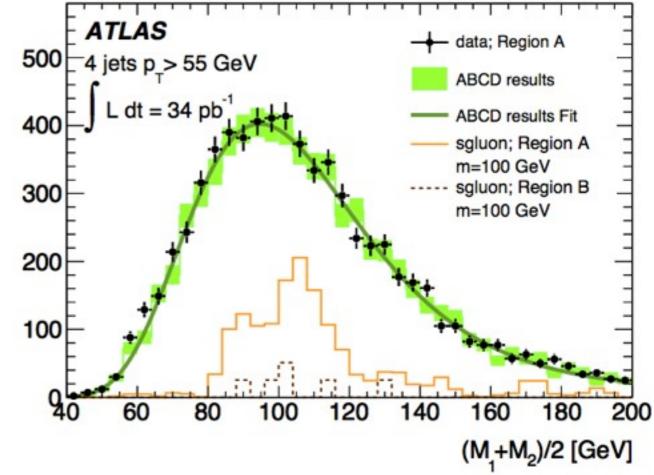
Light RPV stops hiding in the LHC data

#### HOW ROBUST IS OUR PREDICTION?

Events / 4.0 GeV

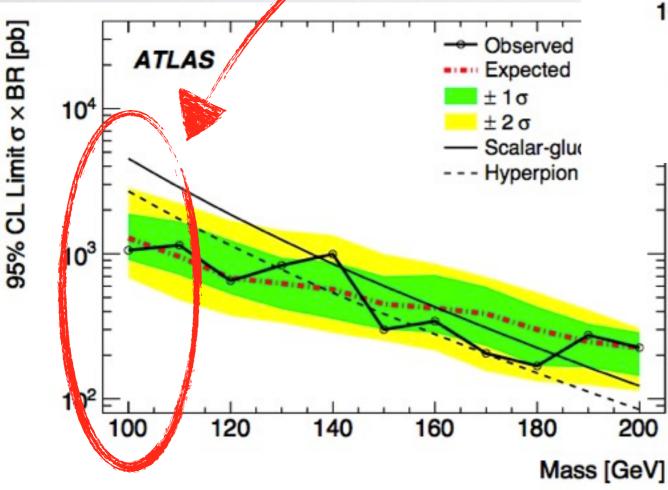
- One may argue that the signal can hardly been extracted from the BG for our S/B
- We can simply check the S/B
   which allows discovery/exclusion
   by comparing with experimental
   analyses

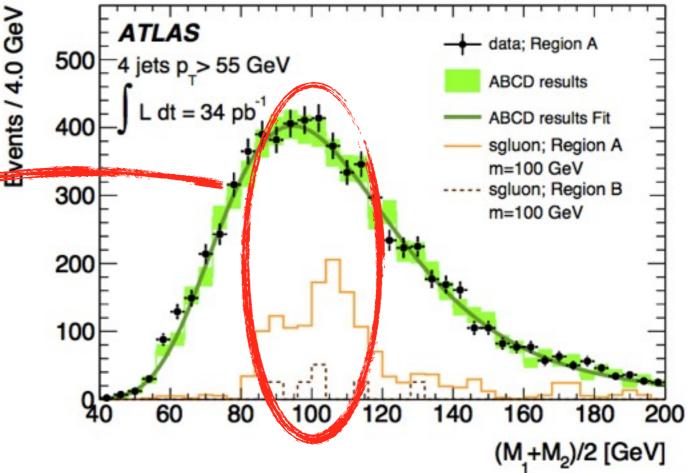




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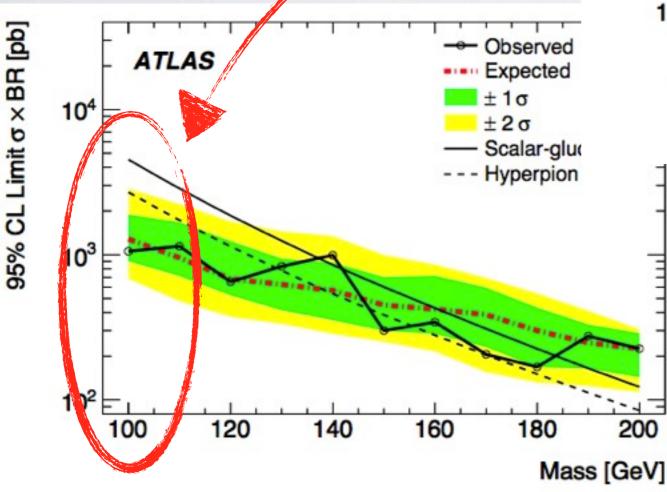


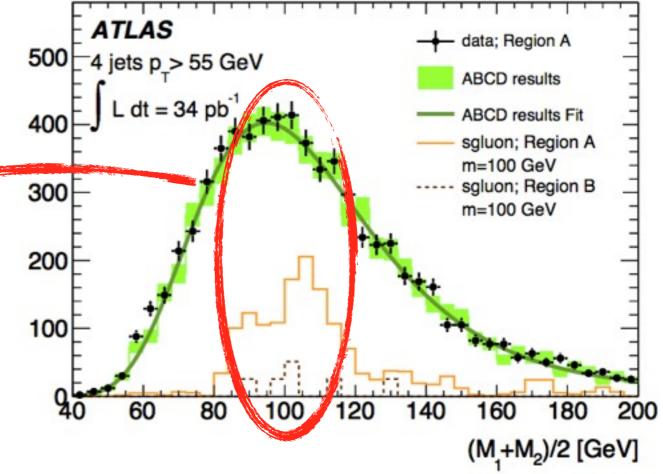
With S/B~0.5 they can exclude the sgluon CS by a factor of 4/5

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vents / 4.0 GeV

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With S/B~0.5 they can exclude the sgluon CS by a factor of 4/5

They are sensitive to S/B~0.1 with an analysis very similar to ours!

# CONCLUSION

- If we take Naturalness as a driving principle, then a new "LHC paradox" adds up to the "LEP paradox" to require non-minimal models
- Insisting on Naturalness and Supersymmetry and in the attempt of building an effective SUSY model, *R*-parity is probably not enough to guarantee proton stability and looking for RPV physics can be motivated (in effective SUSY models)
- RPV SUSY is characterized by the absence of large MET and its phenomenology is strikingly different from the RPC one
- We studied the pair production of stops in the Natural region (where the stop mass is very close to the top-quark one) assuming large BR into heavy flavor final states (motivated by RPV model building)
- We pointed out the importance of using online b-tagging to keep low pT thresholds in the trigger for multi-jet final states in order to cover all the region down to the present bound on RPV stops
- Using b-tagging and suitable angular selections we concluded that light RPV stops can be discovered even with the data already collected in the first run of the LHC

#### THANK YOU