STASHING THE STOPS IN MULTI b-JETS EVENTS AT THE LHC

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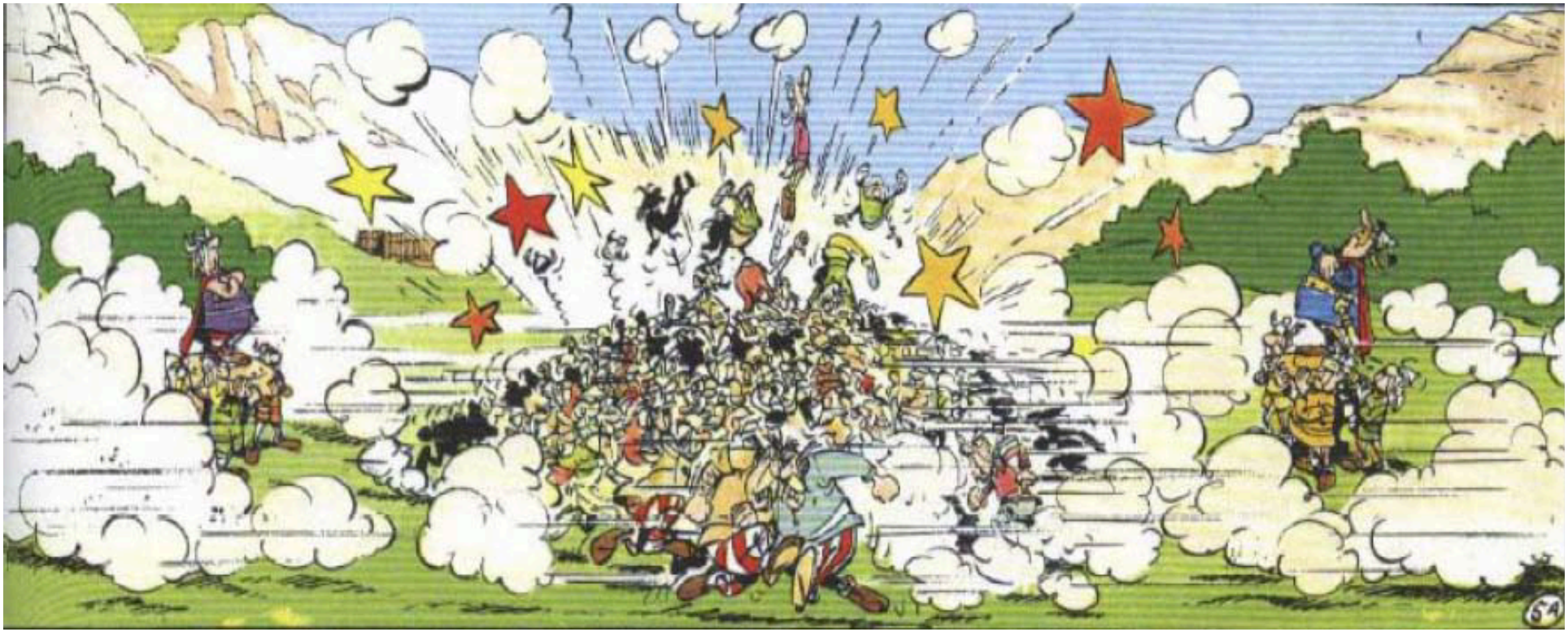
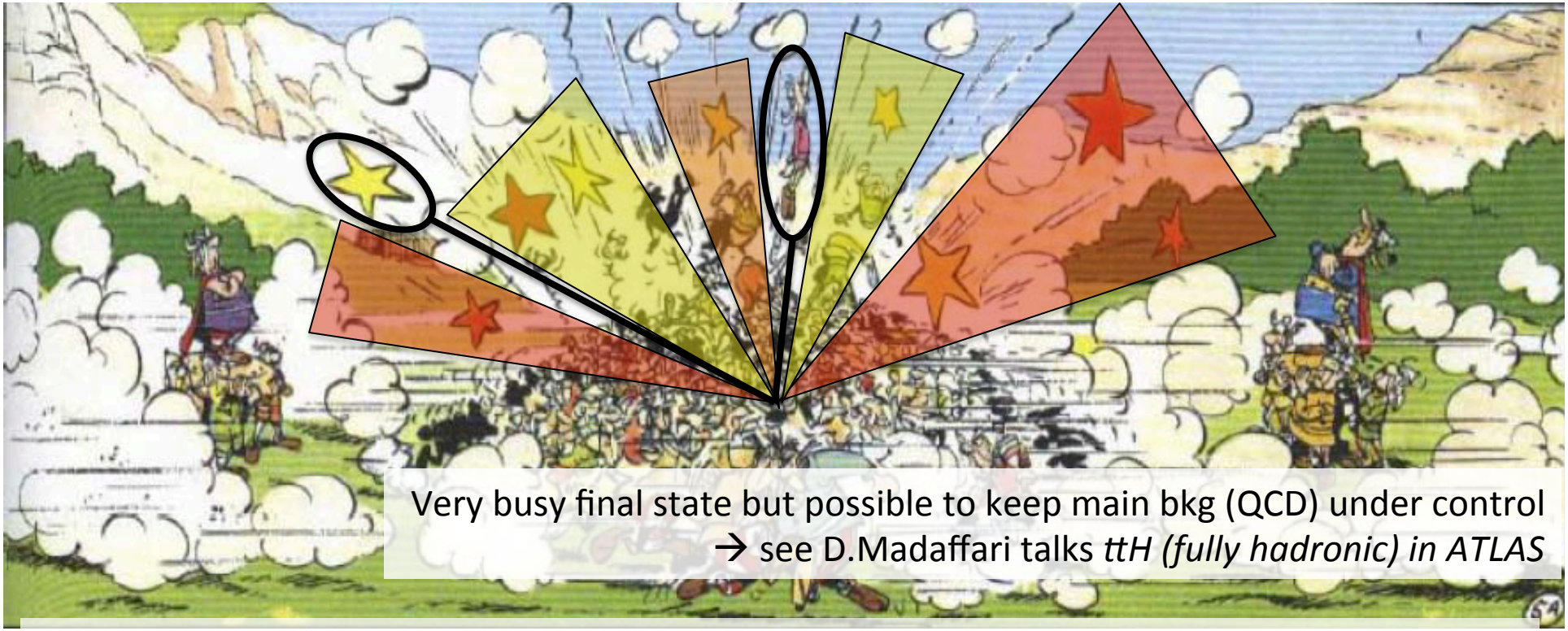
PROTON – PROTON COLLISION



PROTON – PROTON COLLISION

Multi b-jet final states



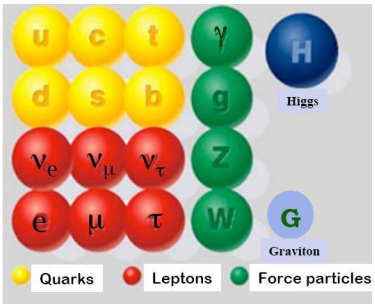
In some parts of the SUSY parameter space, decays with
high b-jet multiplicities and **very low missing energy** become relevant

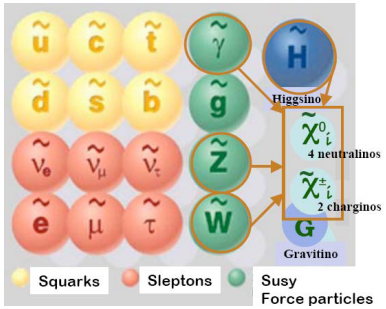
→ Focus on **R-Parity Violating (RPV) supersymmetric signatures**
originating from **top squarks decaying hadronically** at the LHC

QUICK FLASH ON SUSY AND R-PARITY

SUSY extends the SM by predicting a new symmetry:

Spin 1/2 matter particles (fermions) ⟺ Spin 1 force carriers (bosons)





SM and SUSY partners can be distinguished by a discrete quantum number : **R-Parity**

$$R = (-1)^{3(B-L)+2s} \rightarrow R = \begin{cases} +1, \text{ for SM particles} \\ -1, \text{ for superpartners} \end{cases}$$

B: baryon number, L: lepton number, S: spin

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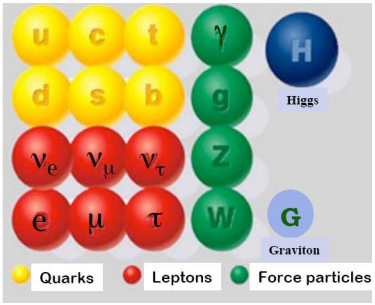

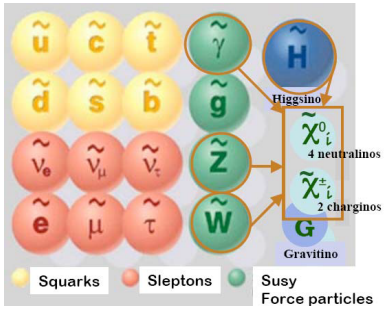

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R-Parity Conserving (RPC) model	R-Parity Violating (RPV) model
Sparticles produced in pairs	**Single Sparticle production is possible**
Neutral stable Lightest MSSM Particle behaving like a neutrino ← escaping detection	**Lightest MSSM Particle not necessary neutral and/or stable → possibility for new signals**
Large missing transverse energy	**Missing transverse energy not necessary large**
Conservation of L and B	**Violation of L and/or B**

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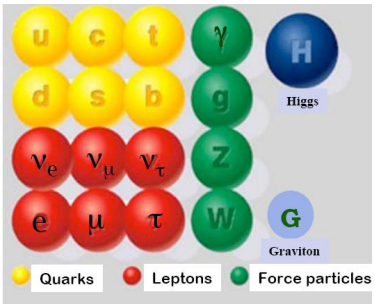

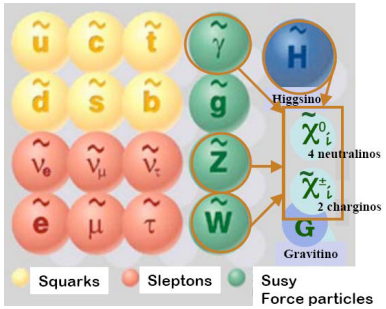

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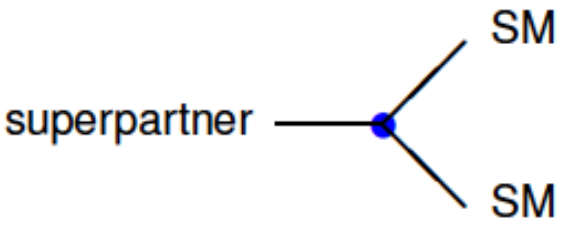
- Strong experimental constraints for many RPC models
- SUSY breaking typically accompanied by R-symmetry breaking
  → the residual R-Parity could be also spontaneously broken
- RPV is a "signature generator" less explored by experiments

RPV INTERACTIONS

Super potential

B-number violating term

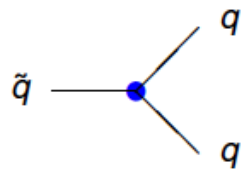


$$W = \frac{1}{2}\lambda_{ijk}\, L_i L_j E^c_k + \lambda'_{ijk}\, L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk}\, U^c_i D^c_j D^c_k + \mu_i L_i H_u$$

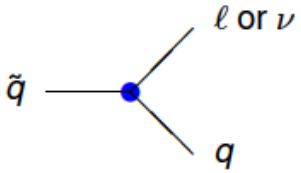
i, j, k = generation indices

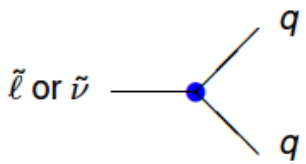
Tri linear couplings

UDD

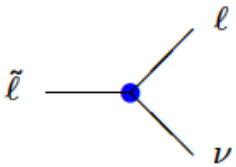


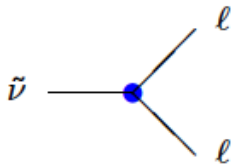
LQD





LLE





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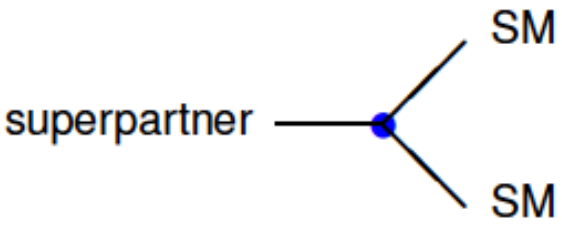

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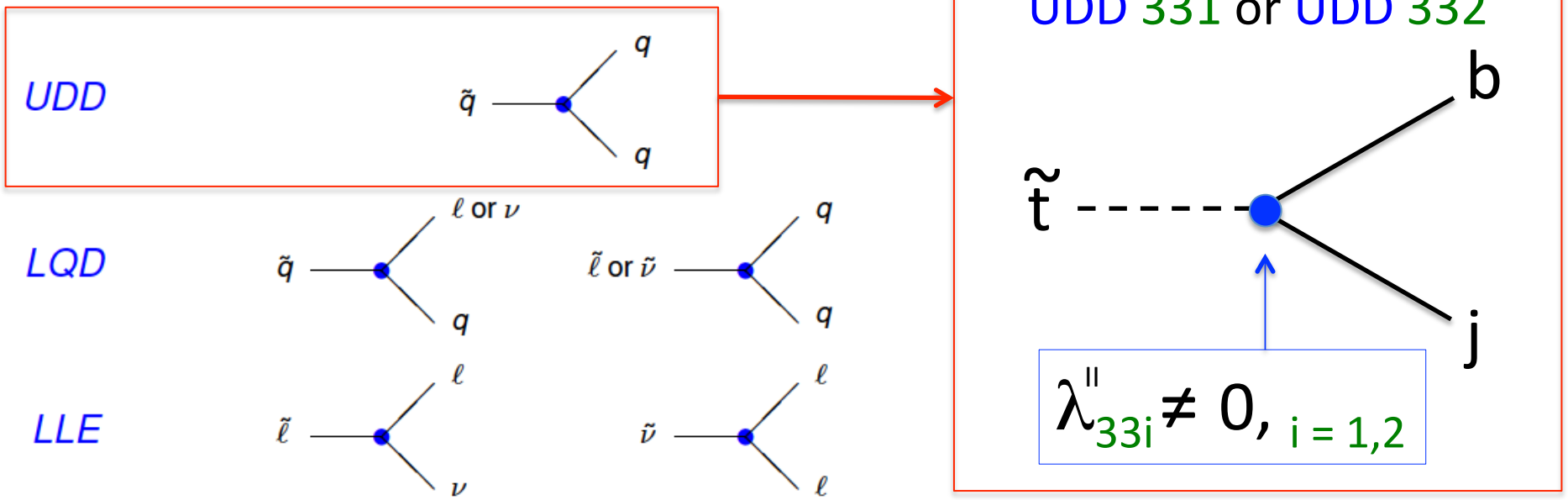
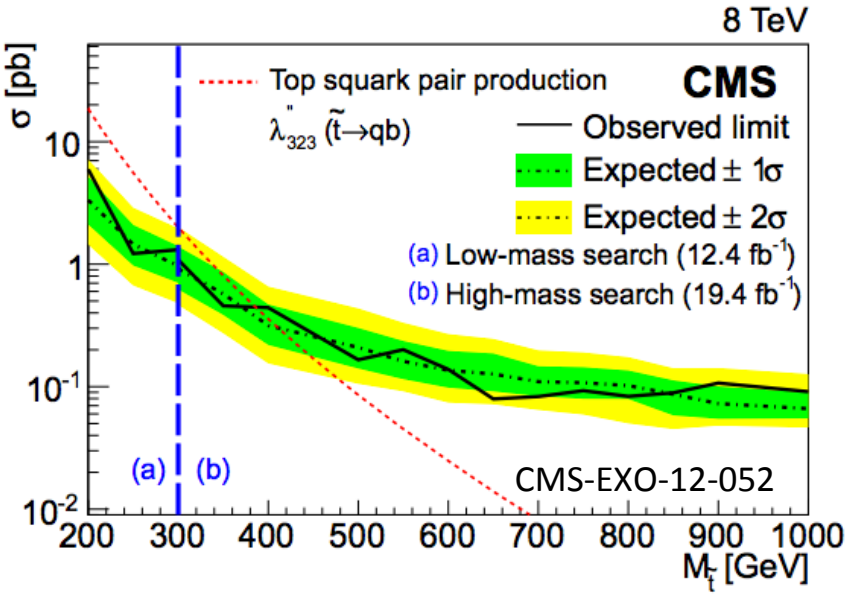
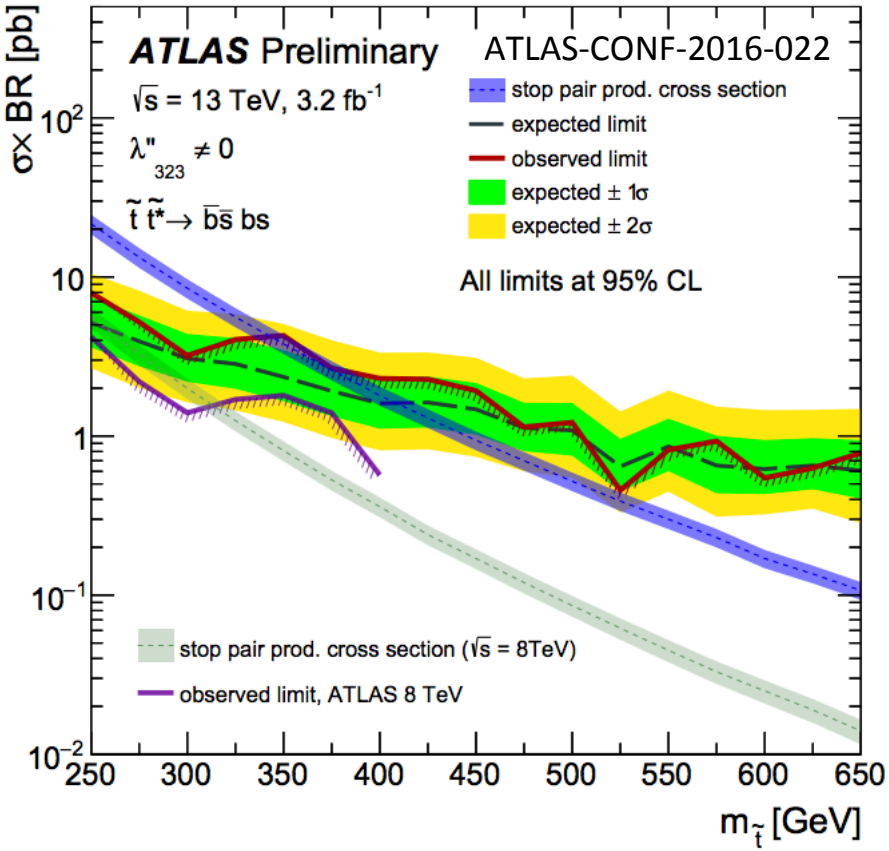


DIRECT RPV $\tilde{t} \rightarrow b\,j$ SEARCHES AT THE LHC

- Model assumptions
  - BR($\tilde{t} \rightarrow b\,j$) = 100%
  - top squark as LSP





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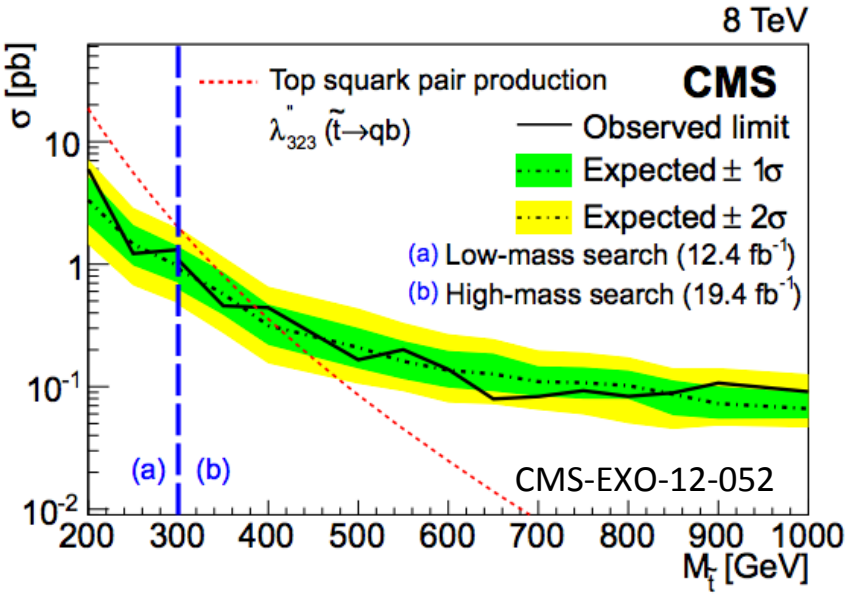

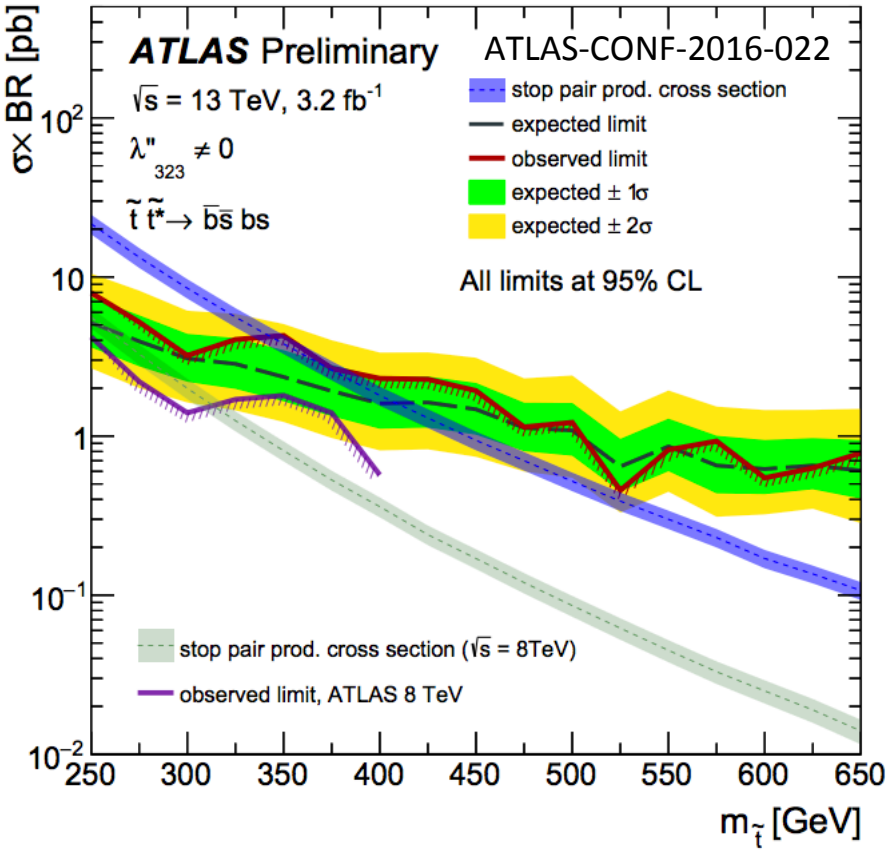

What if the stop is NOT the RPV-MSSM-LSP ?
To which stop decay channels do we have access ?
Are the decay branching ratios independent of the RPV coupling?

MODEL ASSUMPTIONS & BENCHMARK POINTS

We want to test a region where the **stop** is **NOT** the **RPV-MSSM-LSP**

Low scale parameters	1st benchmark	2nd benchmark
$\tan\beta$	10	
M_1, M_2, M_3	1-3 TeV	
$(m_{\tilde{U}})_{33}$	570 GeV	964 GeV
μ	400-600 GeV	750-1000 GeV
λ''_{33i}	$10^{-1} - 10^{-7}$	

SARAH/SPheno codes used **calculate the mass spectrum** and other low energy observables

- λ''_{33i} is the only non-vanishing RPV coupling

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Mass spectra	1st benchmark	2nd benchmark
$m_{\tilde{t}}$	**~ 600 GeV**	**~1 TeV**
m_{χ^0}	~ 400-600 GeV	~750-1000 GeV
$m_{\tilde{t}} - m_{\chi^+}$	**~ 5-200 GeV**	**~ 1-250 GeV**
$m_{\chi^+} - m_{\chi^0}$	~ 1.5-2.5 GeV	
m_{h^0}	~ 125 GeV	

SARAH/SPheno codes used **calculate the mass spectrum** and other low energy observables

- λ''_{33i} is the only non-vanishing RPV coupling
- **The RPV-MSSM-LSP is the lightest neutralino χ^0**
- The **light part of the SUSY spectrum** is composed of
  - one stop: $\tilde{t}$
  - one chargino and two neutralinos higgsino-like almost degenerate: χ^+, χ^0 and χ_2^0
  - the lightest CP-even Higgs: h^0

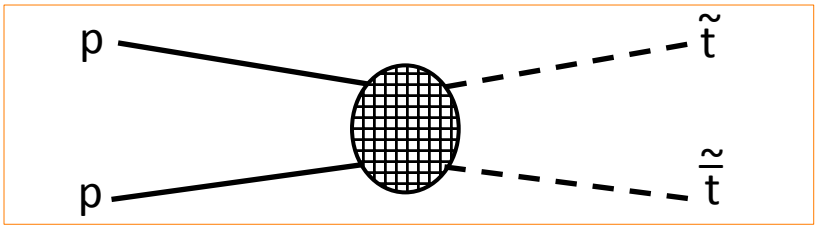
  → Spectrum motivated by **Natural SUSY**
- Mass configuration:

$$m_{\tilde{t}} \geq m_{\chi^+} \gtrsim m_{\chi^0} > m_t$$

- All other SUSY particles are assumed to be too heavy to be produced at the LHC
- Benchmark points consistent with electroweak precision observables and B physics observables

STOP PRODUCTION AND DECAYS

Stop production



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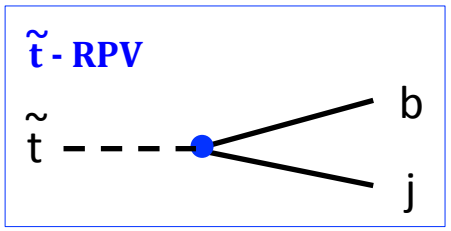

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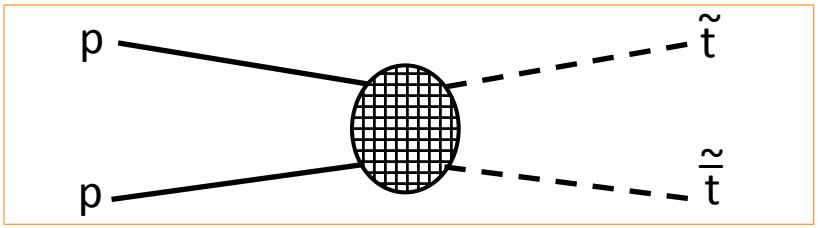

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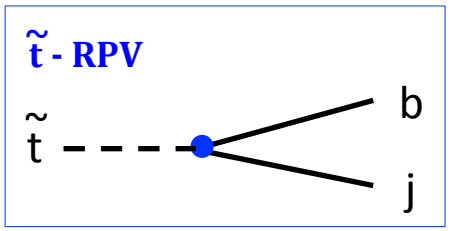

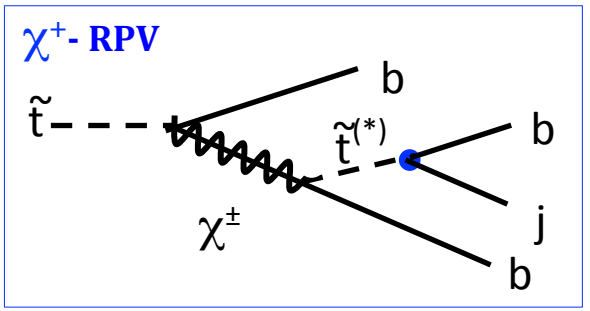

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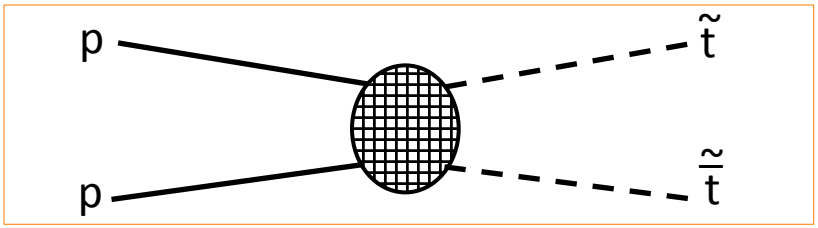
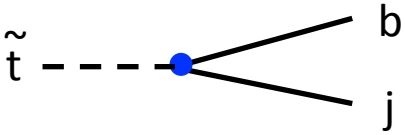
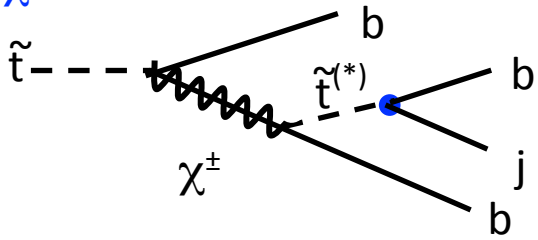


Stop decays

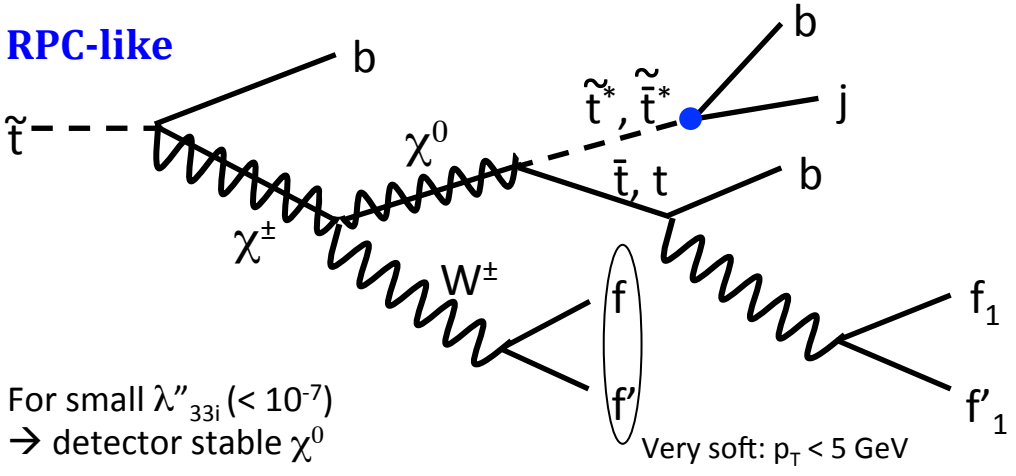
$\tilde{t}$ - RPV



χ^+- RPV



RPC-like



For small λ''_{33i} ($< 10^{-7}$)
→ detector stable χ^0

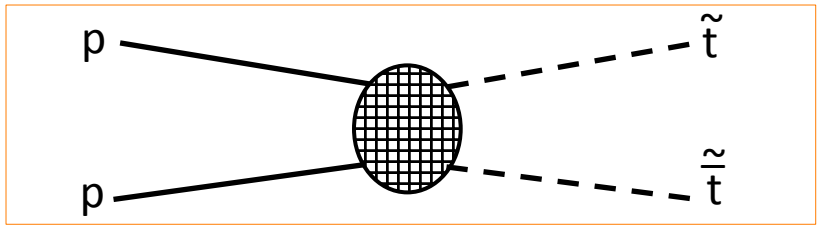
Very soft: $p_T < 5$ GeV

STOP PRODUCTION AND DECAYS

SPheno mass spectra → **SARAH/MadGraph5** full matrix element

We investigate the **sensitivity of the processes** to different values of RPV λ''_{33i} coupling and stop-chargino mass splitting in p-p collisions at 14 TeV

Stop production



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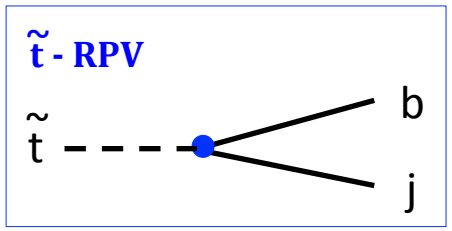
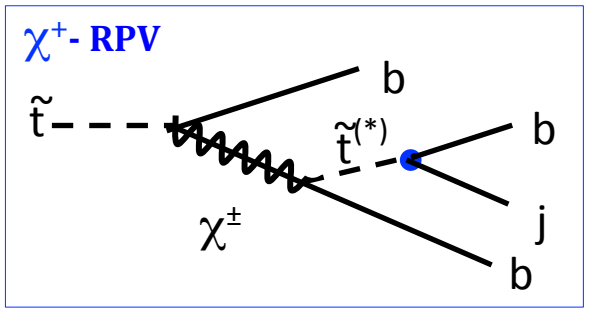
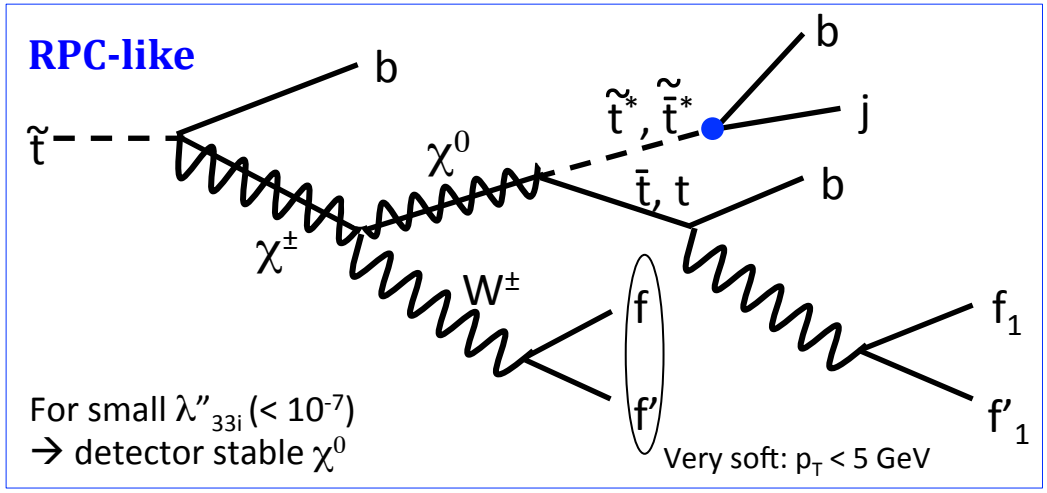
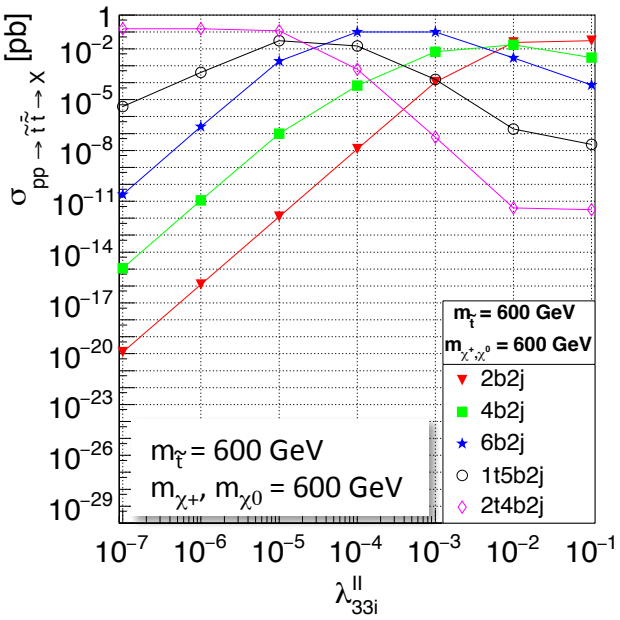


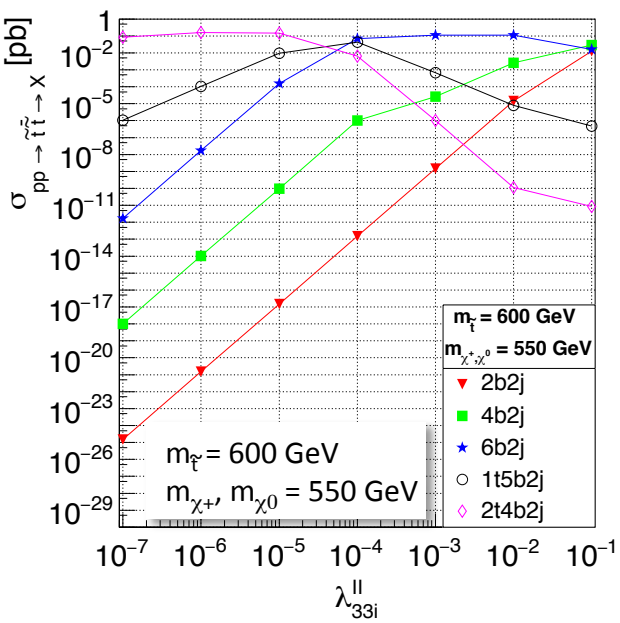


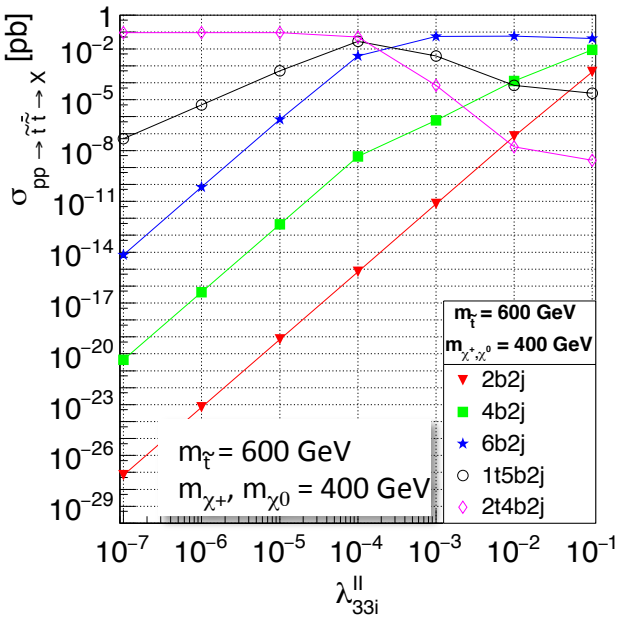
$\tilde{t}$ / $\bar{\tilde{t}}$	$\tilde{t}$ - RPV	χ^+ - RPV	RPC-like
$\tilde{t}$ - RPV	▼ 2b2j	■ 4b2j	1t3b2j
χ^+ - RPV		★ 6b2j	◯ 1t5b2j
RPC-like			◇ 2t4b2j



SENSITIVITY TO $m_{\tilde{t}} - m_{\chi^+}$ AND λ''_{33i} (I)







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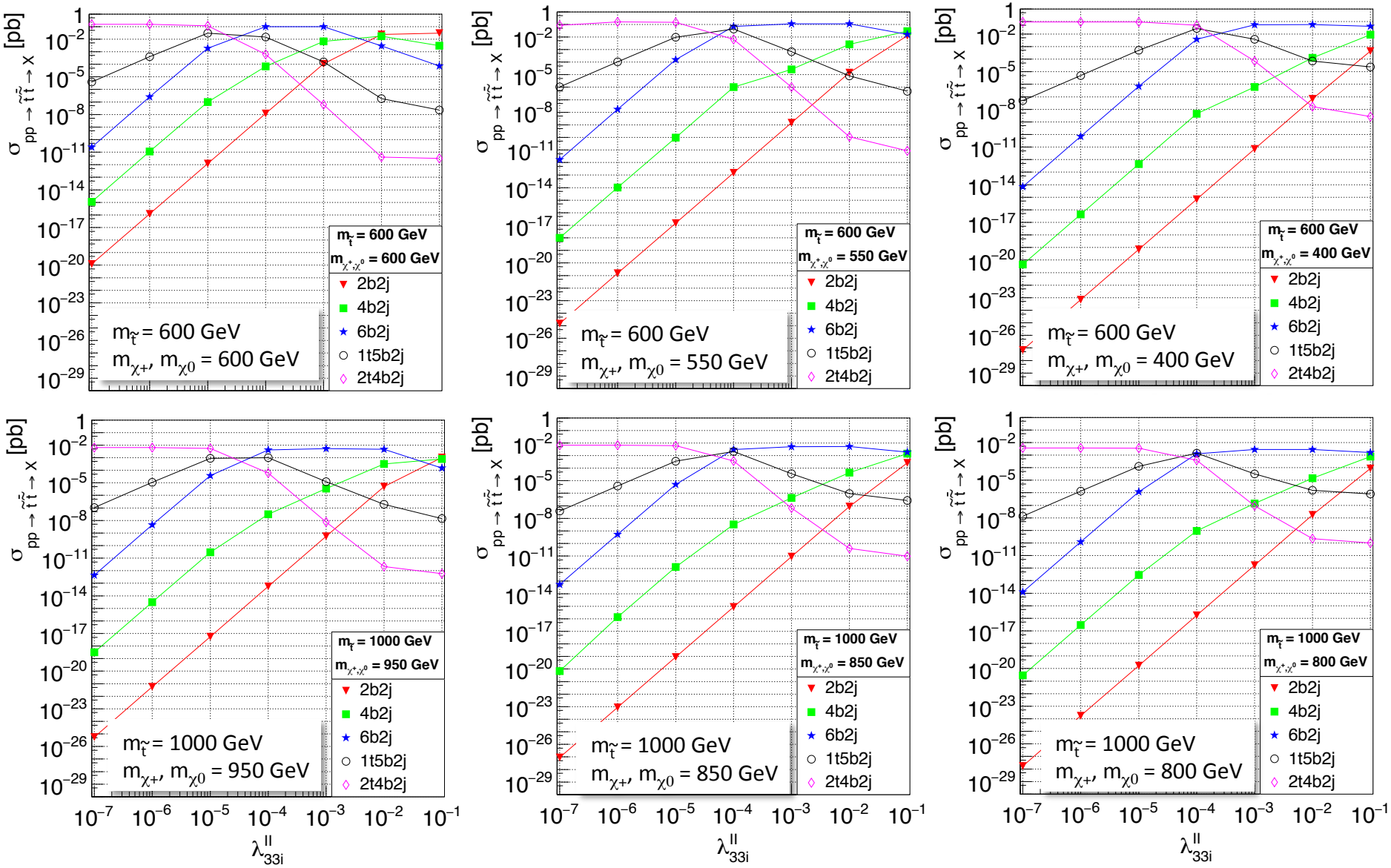

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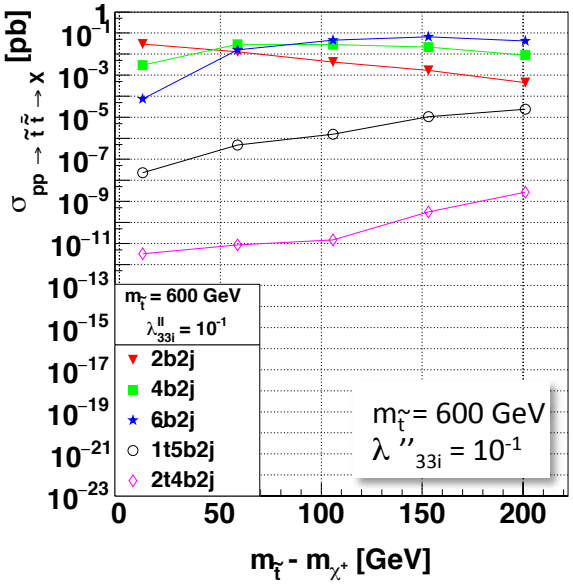
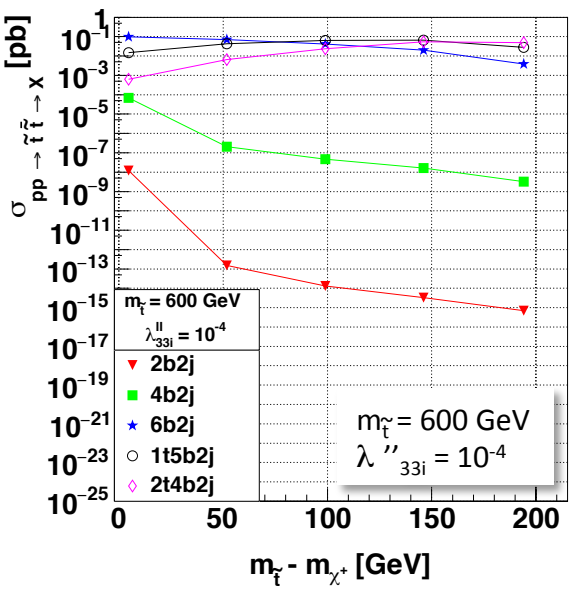
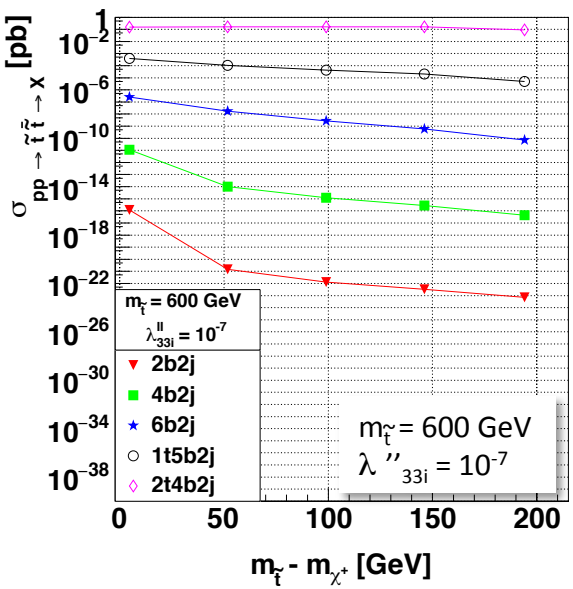






- Dependences of the various decay branching ratios on stop-chargino mass splitting and on λ''_{33i}
- Decay channels with different jet multiplicity probe different ranges of the RPV couplings
  → Higher jet multiplicity probe smaller RPV couplings
- For values of $\lambda''_{33i} < 10^{-7}$ the RPC LHC limits apply

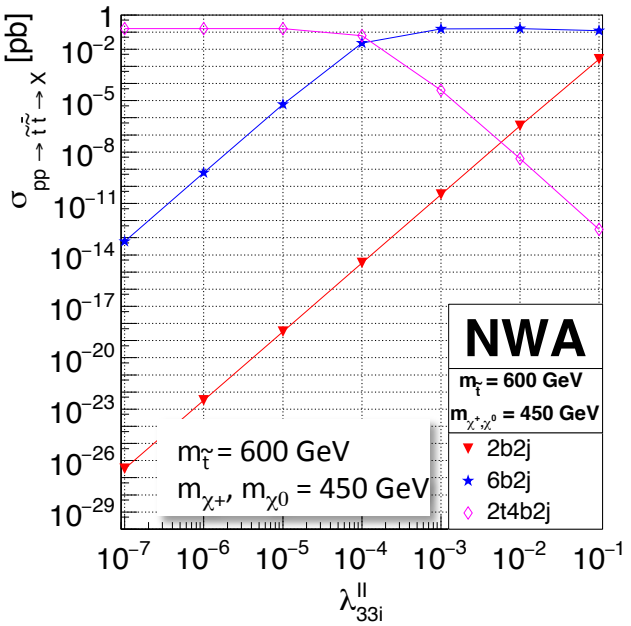
TESTING THE NARROW WIDTH APPROXIMATION

$$\sigma(2b2j) \simeq \sigma(pp \to \tilde{t}\bar{\tilde{t}}) \times \frac{r_1^2 \times (\lambda''_{33i})^4}{\left(1 + r_1 \times (\lambda''_{33i})^2\right)^2}$$

$$\sigma(6b2j) \simeq \sigma(pp \to \tilde{t}\bar{\tilde{t}}) \times \frac{r_2^2 \times (\lambda''_{33i})^4}{\left(1 + r_1 \times (\lambda''_{33i})^2\right)^2 \left(1 + r_2 \times (\lambda''_{33i})^2\right)^2}$$

$$\sigma(2t4b2j) \simeq \sigma(pp \to \tilde{t}\bar{\tilde{t}}) \times \frac{1}{\left(1 + r_1 \times (\lambda''_{33i})^2\right)^2 \left(1 + r_2 \times (\lambda''_{33i})^2\right)^2}$$

$$r_1 \equiv \frac{\Gamma_1(\tilde{t} \to \bar{b}\bar{q})}{\Gamma(\tilde{t} \to \chi^+ b)} \qquad r_2 \equiv \frac{\Gamma_1(\chi^+ \to \bar{b}\bar{q}\bar{b})}{\Gamma(\chi^+ \to \bar{b}\bar{q}\bar{b} f_1 \bar{f}'_1 f'_2 \bar{f}_2)} = \frac{\Gamma_1(\chi^+ \to \bar{b}\bar{q}\bar{b})}{\Gamma(\chi^+ \to \chi^0 f'_2 \bar{f}_2)} \qquad \Gamma_1 \equiv \Gamma_{|\lambda''_{33i}=1}$$



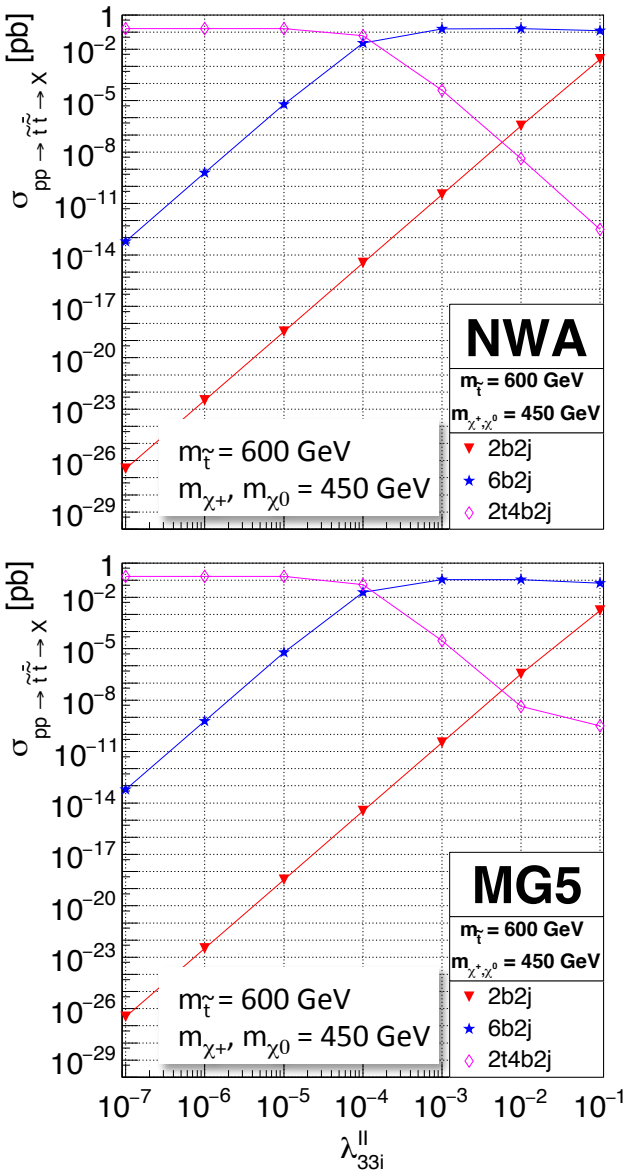
Testing the Narrow Width Approximation

$$\sigma(2b2j) \simeq \sigma(pp \to \tilde{t}\bar{\tilde{t}}) \times \frac{r_1^2 \times (\lambda''_{33i})^4}{\left(1 + r_1 \times (\lambda''_{33i})^2\right)^2}$$

$$\sigma(6b2j) \simeq \sigma(pp \to \tilde{t}\bar{\tilde{t}}) \times \frac{r_2^2 \times (\lambda''_{33i})^4}{\left(1 + r_1 \times (\lambda''_{33i})^2\right)^2 \left(1 + r_2 \times (\lambda''_{33i})^2\right)^2}$$

$$\sigma(2t4b2j) \simeq \sigma(pp \to \tilde{t}\bar{\tilde{t}}) \times \frac{1}{\left(1 + r_1 \times (\lambda''_{33i})^2\right)^2 \left(1 + r_2 \times (\lambda''_{33i})^2\right)^2}$$

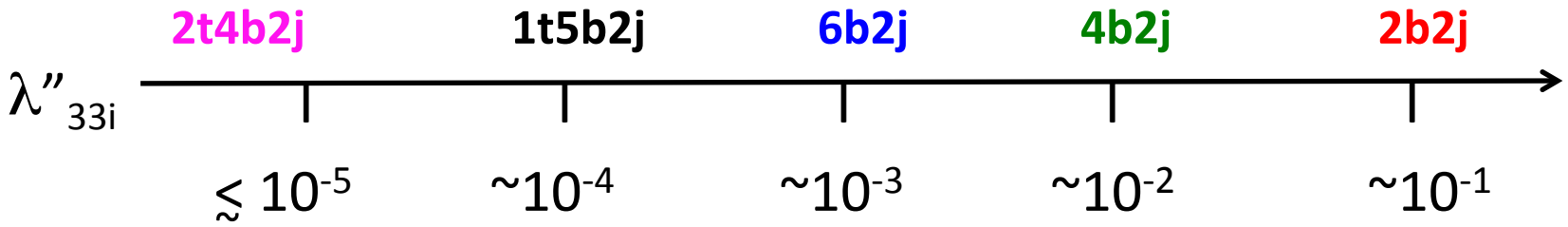
$$r_1 \equiv \frac{\Gamma_1(\tilde{t} \to \bar{b}\bar{q})}{\Gamma(\tilde{t} \to \chi^+ b)} \qquad r_2 \equiv \frac{\Gamma_1(\chi^+ \to \bar{b}\bar{q}\bar{b})}{\Gamma(\chi^+ \to \bar{b}\bar{q}\bar{b} f_1 \bar{f}'_1 f'_2 \bar{f}_2)} = \frac{\Gamma_1(\chi^+ \to \bar{b}\bar{q}\bar{b})}{\Gamma(\chi^+ \to \chi^0 f'_2 \bar{f}_2)} \qquad \Gamma_1 \equiv \Gamma_{|\lambda''_{33i}=1}$$



- The general trend of the sensitivity to λ''_{33i} can be understood qualitatively from the NWA expressions
- An agreement between full matrix element (MG5) and analitical (NWA) calculation within 5% is observed in ~80% of the cases
- Disagreement in cases of long decay chains in region of large λ''_{33i}

SIGNALS AND BACKGROUNDS

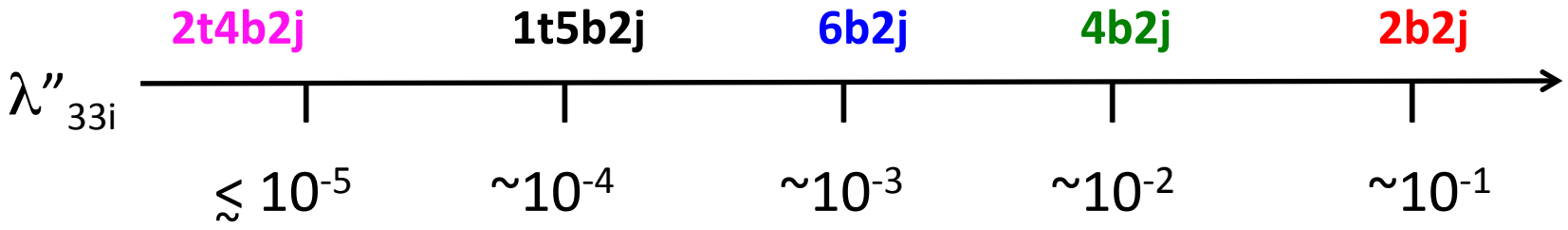
The value of λ''_{33i} determines which signal channel(s) is(are) dominant



The channels sensitivity to λ''_{33i} might slightly move depending on $m_{\tilde{t}}$ and $m_{\tilde{t}} - m_{\chi^+}$

SIGNALS AND BACKGROUNDS

The value of λ''_{33i} determines which signal channel(s) is(are) dominant



The channels sensitivity to λ''_{33i} might slightly move depending on $m_{\tilde{t}}$ and $m_{\tilde{t}} - m_{\chi^+}$

Can we look for these processes at the LHC?

- **2b2j**
  - boosted topology → large sized back to back jets
- **4b2j**, **6b2j**
  - high energetic events with high (b)-jet multiplicity
- **1t5b2j**, **2t4b2j**
  - high energetic events with high (b)-jet multiplicity
  - trigger: lepton from top decay

SIGNALS AND BACKGROUNDS

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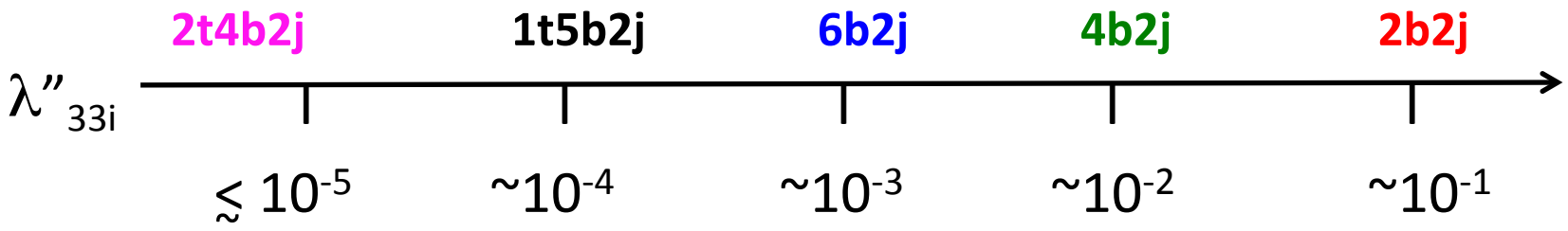


The channels sensitivity to λ''_{33i} might slightly move depending on $m_{\tilde{t}}$ and $m_{\tilde{t}} - m_{\chi+}$

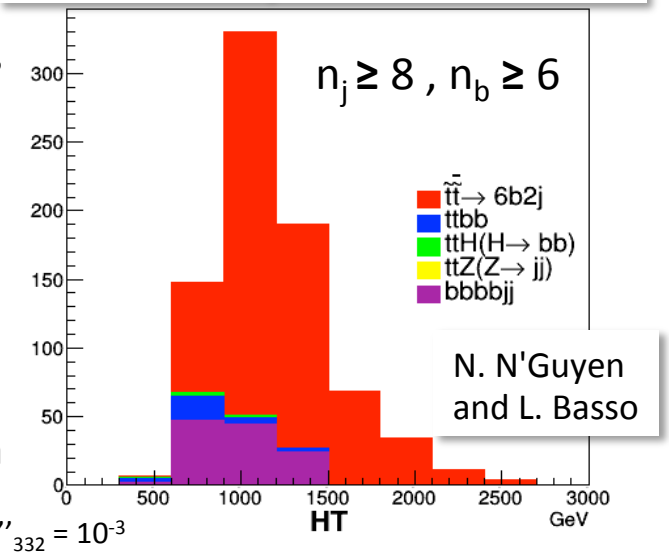
6b2j

pp @ 13 TeV in 100 fb^{-1}

MG5+Pythia+Delphes

- FastJet Reconstruction
- Flat Jet Tagging efficiency:
  - b-tag: 77%,
  - c-tag : 5%,
  - light-jet: 0.5%
- Offline jets p_T selection

Scalar sum of the transverse mass of all the jets in the event



$m_{\tilde{t}}$ = 600 GeV, $m_{\chi+} = m_{\chi0}$ = 500 GeV, $\lambda''_{332} = 10^{-3}$

Can we look for these processes at the LHC?

- **2b2j**
  - boosted topology → large sized back to back jets
- **4b2j, 6b2j**
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- **1t5b2j, 2t4b2j**
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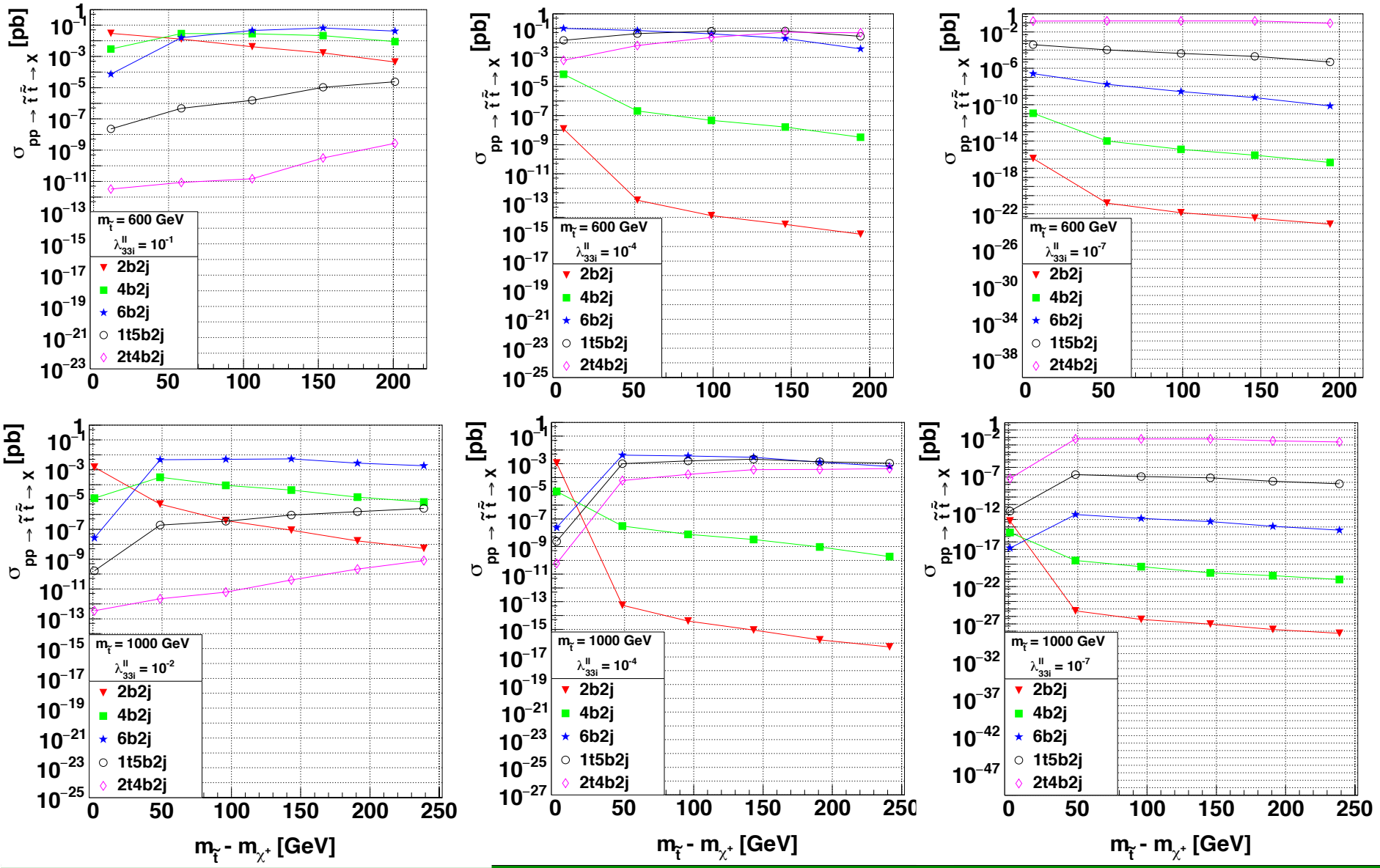
SUMMARY

- The RpV SUSY model offers a variety of interesting final states not yet explored by experiments
- RPV opens the possibility of light SUSY spectrum
- Depending on the spectrum and the (likely) small magnitude of RPV couplings, SUSY can be hiding in high multiplicity final states
- Possible reinterpretation of ATLAS and CMS results in cases where the stop is NOT the LSP
- The strong sensitivity to different channels apply more generally than the case we presented

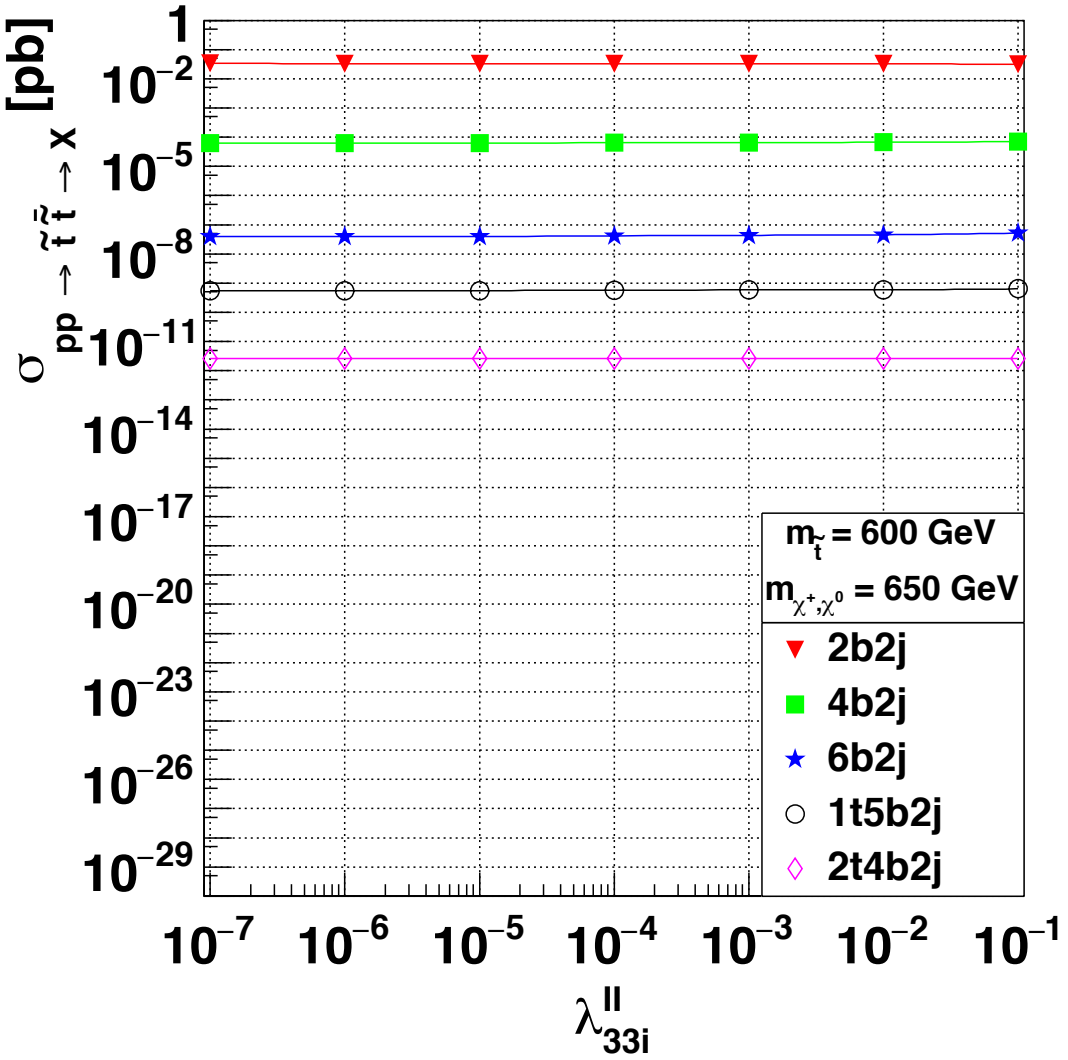
Thanks for your attention!

BACKUP

SENSITIVITY TO $m_{\tilde{t}} - m_{\chi^+}$



SENSITIVITY TO $m_{\tilde{t}} - m_{\chi^+}$ AND λ''_{33i}



1T5B2J

$p\,p \rightarrow \tilde{t}\,\tilde{t}$

$\tilde{t} \rightarrow b\,\chi^+$

$\chi^+ \rightarrow b\,\tilde{t}$

$\tilde{t} \rightarrow b\,s$

$\tilde{t} \rightarrow b\,\chi^-$

$\chi^- \rightarrow \chi^0\,W^-$

$W^- \rightarrow f\,f'$

$\chi^0 \rightarrow t\,\tilde{t}$

$\tilde{t} \rightarrow b\,s$

$t \rightarrow b\,W^-$

$W^- \rightarrow f\,f'$

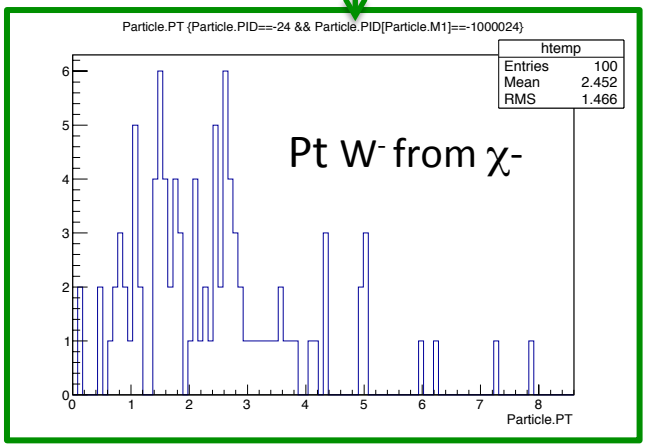
Similar final state as ttH (H→bb) both fully-hadronic and semi-leptonic, depending from f and f' flavours

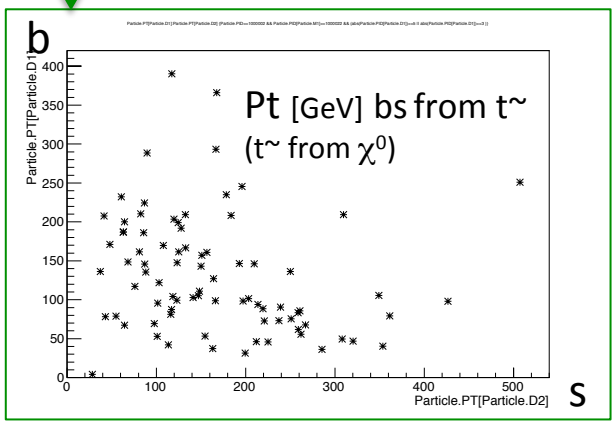
100 events

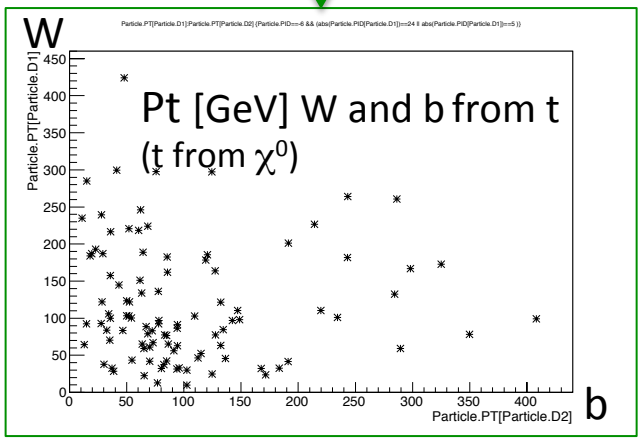
$m_{\tilde{t}} \sim 600$ GeV

$m_{\chi^0} \sim m_{\chi^+} \sim 400$ GeV

Too soft to be reconstructed







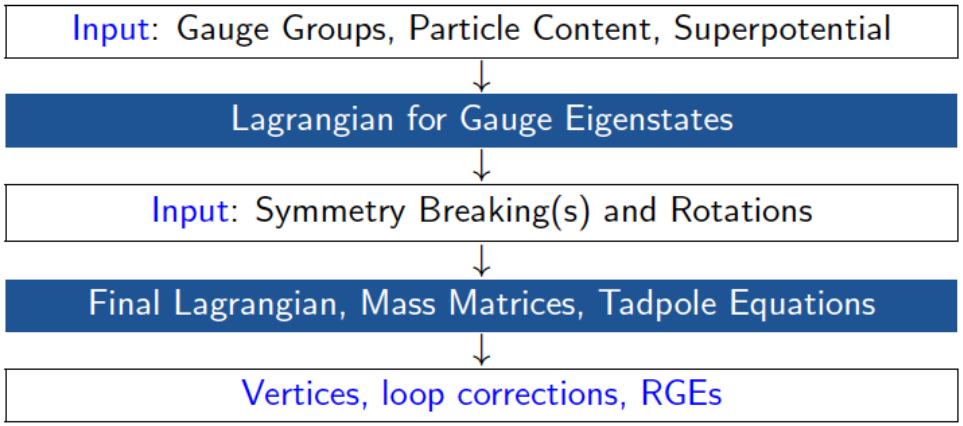
SARAH

http://sarah.hepforge.org/

- How to generate the interesting processes?
  - Does it exist an implementation of the Tri-linear RpV model?
  - Is it interfaced with any MC generator?

SARAH

- is a Mathematica package for **building SUSY and non-SUSY models,** including **RpV**
- writes **model files in the UFO format** which is supported by **MadGraph 5**
- creates **source code for SPheno** (see next slide)



- **We generated the model files for Tri-linear RpV SUSY model**
- **We created source code for SPheno**
- **We included the model in last version of MadGraph 5**

SPHENO

https://spheno.hepforge.org/

- How to generate different mass spectra?

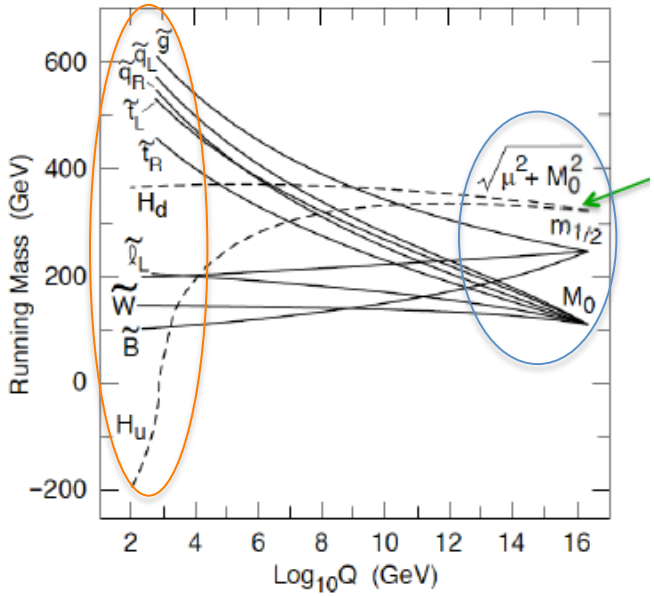
SPheno: S(upersymmetric) Pheno(menology)

Code to **calculate the mass spectrum and other low energy observables** of a given model using some low energy data and a user supplied **high or low scale parameters as input**

Mass eigenstates (physical masses) $m_{\chi^+}, m_{\tilde{t}}, m_{\chi^0}$ … and other low energy observables

Low scale SUSY masses (parameters)

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \\ \chi_4^0 \end{pmatrix} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$



High scale SUSY masses (parameters)

bottom-bottom approach

Top-bottom approach

SPHENO

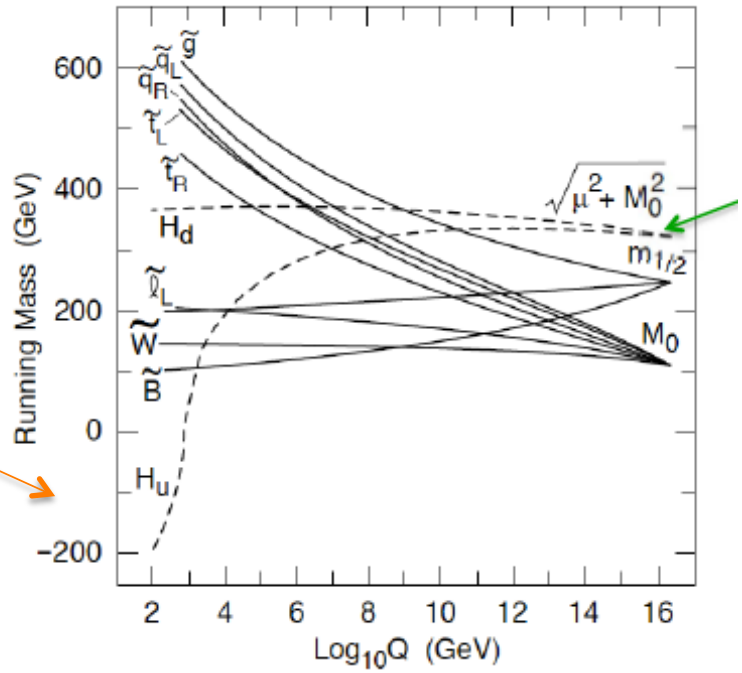
https://spheno.hepforge.org/

- How to generate different mass spectra?

SPheno: S(upersymmetric) Pheno(menology)
Code to **calculate the mass spectrum and other low energy observables** of a given model using some low energy data and a user supplied high or **low scale parameters as input**

Low scale input parameters (bottom-bottom approach)

M_1, M_2, M_3	Bino, Wino, gluino masses
m_A	mass of the pseudoscalar Higgs
Tanβ	ratio of the vev of the 2 Higgs doublets
μ	Higgs mass term
	Soft masses couplings terms
λ, λ', λ"	RpV couplings



- **We studied different combination of the low scale input parameters in order to generate several spectra**
- **Those spectra are used as an input in the event generator code: aMC@NLO**

- How to generate events/how to evaluate x- sec?

MadGraph5_aMC@NLO

- is a framework that aims at providing all the elements necessary for SM and BSM phenomenology
  - computations of cross sections,
  - generation of hard events
  - their matching with event generators
  - use of a variety of tools relevant to event manipulation and analysis (including interface with PYTHIA and pgs simulators)
- Processes can be simulated to LO accuracy for any user-defined Lagrangian (and the NLO accuracy in the case of QCD corrections to SM processes)

- **We generated events and evaluate cross sections of processes of interest for different spectra generated with SPheno**