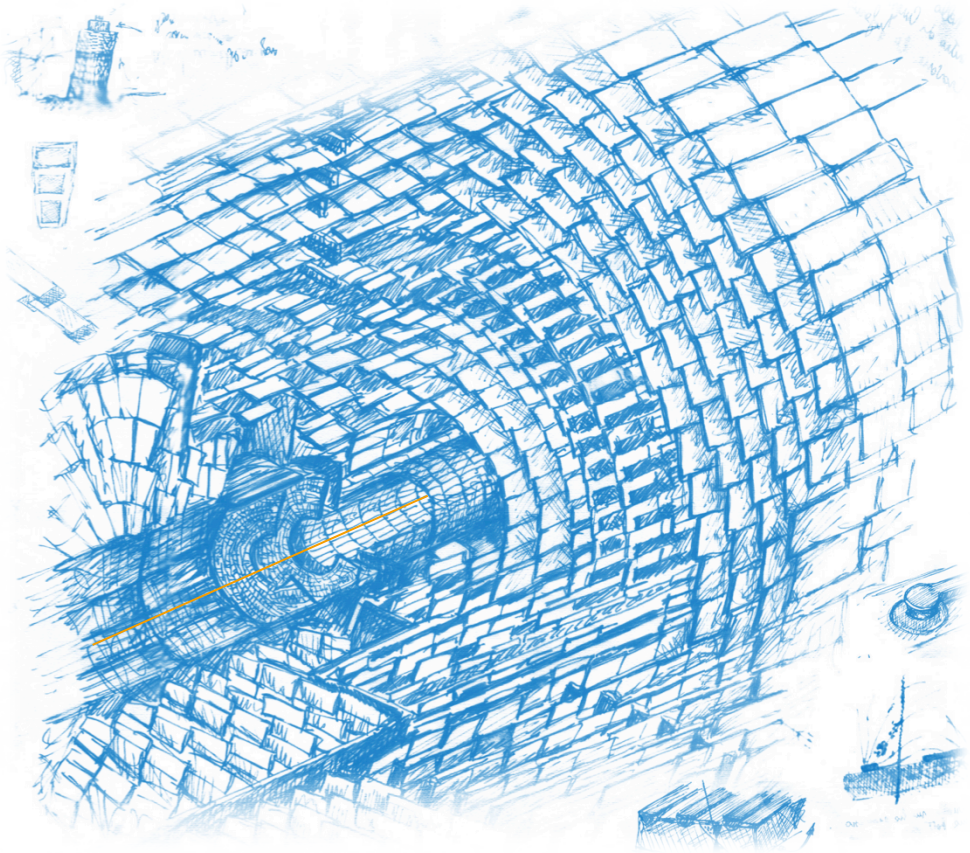
# Searches for R-parity Violated Supersymmetry at CMS

On behalf of the CMS Collaboration

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DESY

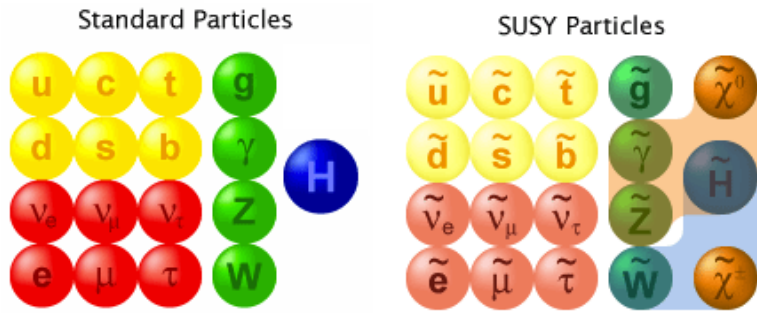

EPS-HEP 2013,
Stockholm, Sweden.

HELMHOLTZ ASSOCIATION

# Supersymmetry and R-parity

- Weak scale supersymmetry (SUSY) is one of the most studied extensions of the Standard Model (SM).

- SUSY postulates super-partners for all SM particles:




SM fermions ⇔ SUSY bosons
SM bosons ⇔ SUSY fermions

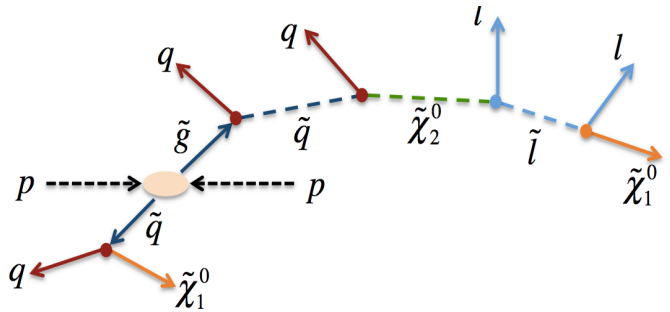
quarks leptons gauge bosons squarks sleptons gauginos

➢ **Definition: R-parity → $R_P = (-1)^{3B+L+2s}$**
**(B)aryon and (L)epton number and s for particle spin**

- **In case of a R-parity conserving *theory***
  - → SM particle fields : $R_P = +1$
  - → SUSY particle field : $R_P = -1$

***phenomenologically means:***

- → Superpartners produced in pairs
- → Lightest Supersymmetric particle (LSP) stable
- → Proton stabilized



**Generic SUSY Searches: R-parity conserved scenario**
Details can be seen in the following talks:

- Direct stop search, Hongxuan Liu
- Search for multiple W and b quarks, Keith Ulmer
- Searches for Gauginos and Sleptons, L. Schutska,
- Search for natural SUSY, S. Sekmen,
- Search for inclusive SUSY, C. Autermann

**If R-parity is not conserved?**

# R-Parity Violation in Supersymmetry?

- Proton decay involves violating both lepton and baryon number simultaneously, **no single renormalizable R-parity violating (RPV) coupling leads to proton decay.**

✓ R-parity violation → one set of the **R-parity violating couplings** are non-zero!

The most general superpotential → $W = W_{MSSM} + W_{RPV}$

$$W_{MSSM} = h^{e}_{ij} L_i H_1 \overline{E}_j + h^{d}_{ij} Q_i H_1 \overline{D}_j + h^{u}_{ij} Q_i H_2 \overline{U}_j + \mu H_1 H_2$$

$$W_{RPV} = \tfrac{1}{2} \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \tfrac{1}{2} \lambda''_{ijk} U_i D_j \overline{D}_k + \kappa_i L_i H_2 \quad ★$$

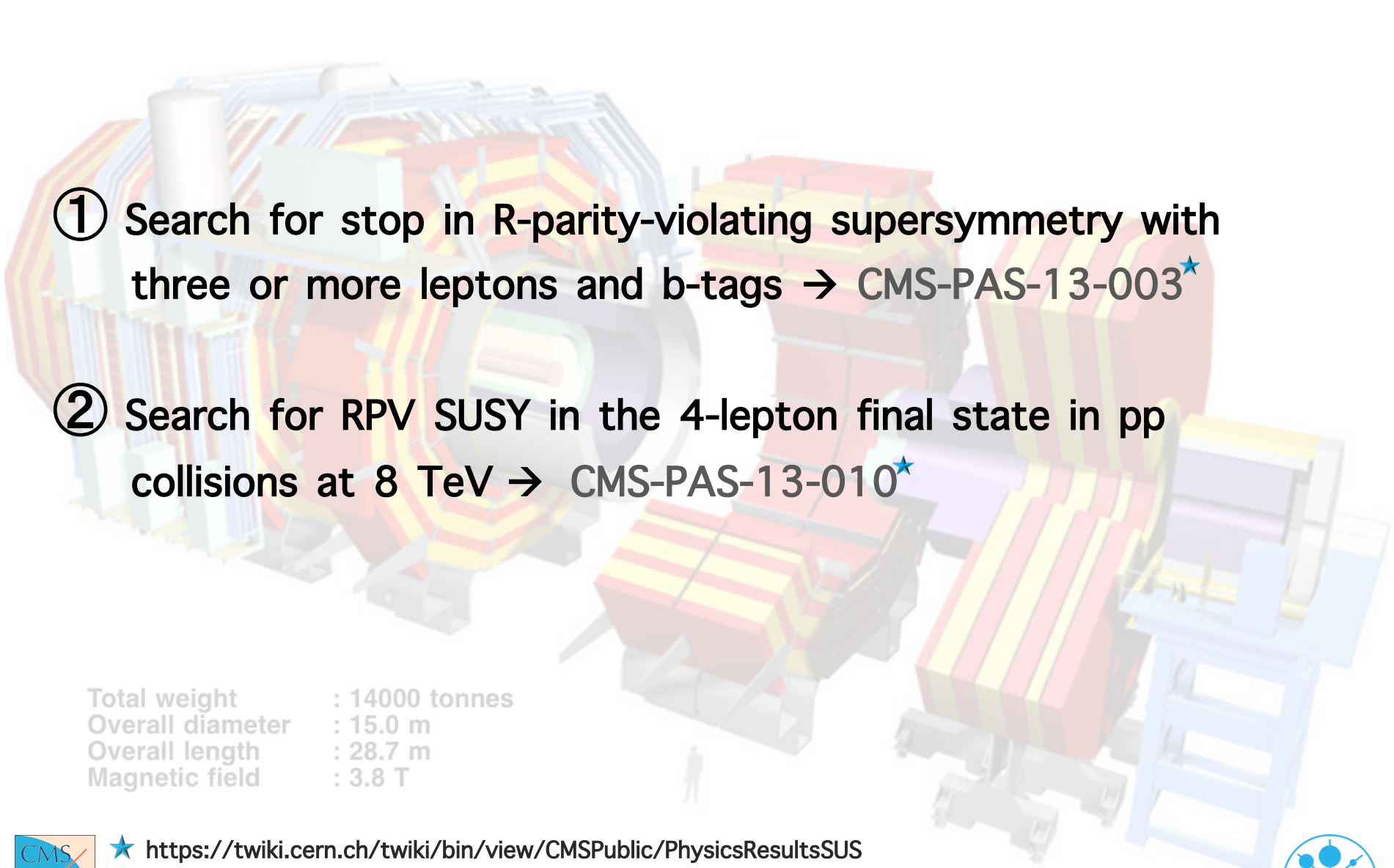
- RPV couplings can violate **lepton and baryon number conservation**
- Can result in **two, three and four body decays** of supersymmetric particles to Standard Model particles
- Couplings chosen to have **prompt decay**, and to satisfy constraints from neutrino mass and proton decay.

★ $L_i(Q_j)$ are lepton(quark) $SU(2)_L$ doublet, $\overline{E}_j(\overline{D}_j, \overline{U}_j)$ are the electron (down- and up-quark) $SU(2)_L$ singlet, $\lambda_{ijk}$, $\lambda'_{ijk}$, $\lambda''_{ijk}$ are Yukawa couplings, κ mass parameter.

# Searches for R-parity violated Supersymmetry at CMS

① Search for stop in R-parity-violating supersymmetry with three or more leptons and b-tags → CMS-PAS-13-003★

② Search for RPV SUSY in the 4-lepton final state in pp collisions at 8 TeV → CMS-PAS-13-010★




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

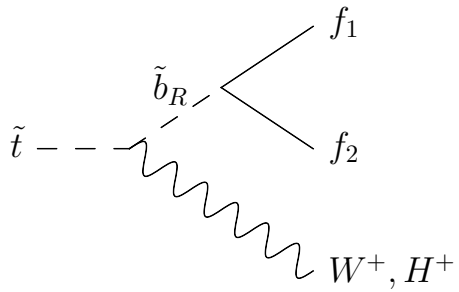
# ① Stop in RPV Supersymmetry

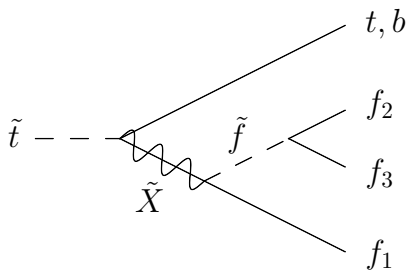
- Focus on stop pair production, where stop mass changes between 300 GeV to 1250 GeV
- Search for RPV couplings that produce **multi-lepton final states**

$$W_{RPV} = \tfrac{1}{2}\,\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \tfrac{1}{2}\,\lambda''_{ijk} U_i D_j \bar{D}_k + \kappa_i L_i H_2$$

Leptonic Mixed Hadronic

| couplings | LLE 122 | LLE 233 | LQD 233 |
|---|---|---|---|
| Decay products for stop | llvt | lTvt, TTvt | Vbbt, lbtt |
| Stop mass (GeV) | 700 - 1250 | 700 - 1250 | 300 - 1000 |
| Bino mass (GeV) | 100 - 1300 | 100 - 1300 | 200 - 850 |




arXiv:hep-ph/1209.0764

# ① Event Classification and Results

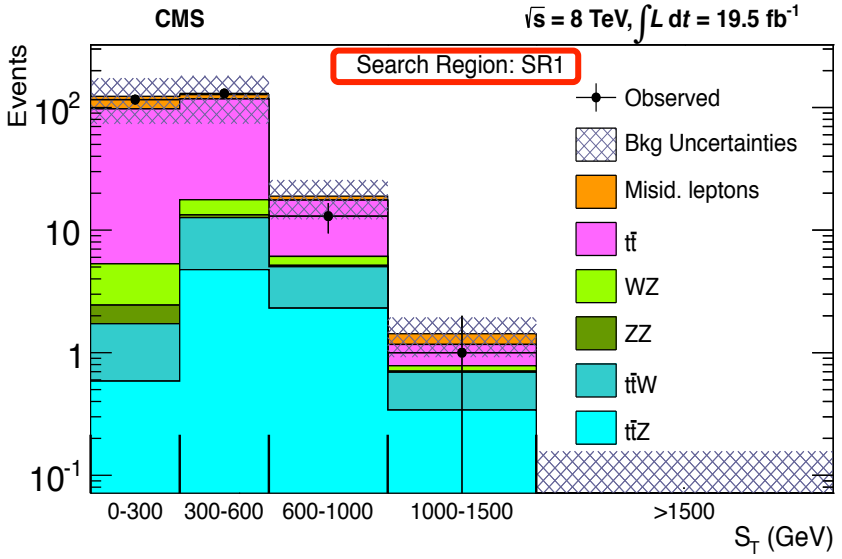
- Using **19.5/fb,** full data set from **2012 CMS data**
- Light lepton $p_T$ must pass 20/10/10(/10) GeV threshold
- Require at least one tagged b-quark jet
- Remove events with OSSF* di-lepton mass on Z and below 12 GeV J/Ψ events
- Define search regions in different **$S_T$ bins,**

$$S_T = MET + HT + P_T^{leptons}$$

**MET** = Missing Transverse Energy

**HT** = Scalar sum of all selected Jet $P_T$

$P_T^{leptons}$ = Selected leptons $P_T$




#Leptons (e, μ)

# tau lepton

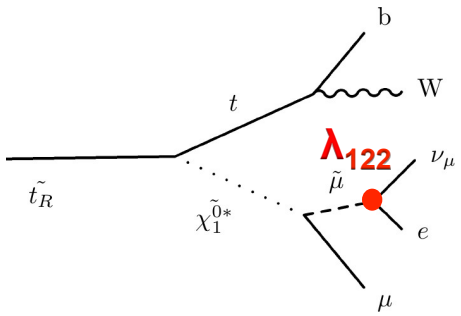
| SR | $N_L$ | $N_\tau$ | $0 < S_T < 300$ | | $300 < S_T < 600$ | | $600 < S_T < 1000$ | | $1000 < S_T < 1500$ | | $S_T > 1500$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | obs | exp | obs | exp | obs | exp | obs | exp | obs | exp |
| SR1 | 3 | 0 | 116 | $123 \pm 50$ | 130 | $127 \pm 54$ | 13 | $18.9 \pm 6.7$ | 1 | $1.43 \pm 0.51$ | 0 | $0.208 \pm 0.096$ |
| SR2 | 3 | $\geq 1$ | 710 | $698 \pm 287$ | 746 | $837 \pm 423$ | 83 | $97 \pm 48$ | 3 | $6.9 \pm 3.9$ | 0 | $0.73 \pm 0.49$ |
| SR3 | 4 | 0 | 0 | $0.186 \pm 0.074$ | 1 | $0.43 \pm 0.22$ | 0 | $0.19 \pm 0.12$ | 0 | $0.037 \pm 0.039$ | 0 | $0.000 \pm 0.021$ |
| SR4 | 4 | $\geq 1$ | 1 | $0.89 \pm 0.42$ | 0 | $1.31 \pm 0.48$ | 0 | $0.39 \pm 0.19$ | 0 | $0.019 \pm 0.026$ | 0 | $0.000 \pm 0.021$ |
| SR5 | 3 | 0 | — | — | — | — | 165 | $174 \pm 53$ | 16 | $21.4 \pm 8.4$ | 5 | $2.18 \pm 0.99$ |
| SR6 | 3 | $\geq 1$ | — | — | — | — | 276 | $249 \pm 80$ | 17 | $19.9 \pm 6.8$ | 0 | $1.84 \pm 0.83$ |
| SR7 | 4 | 0 | — | — | — | — | 5 | $8.2 \pm 2.6$ | 2 | $0.96 \pm 0.37$ | 0 | $0.113 \pm 0.056$ |
| SR8 | 4 | $\geq 1$ | — | — | — | — | 2 | $3.8 \pm 1.3$ | 0 | $0.34 \pm 0.16$ | 0 | $0.040 \pm 0.033$ |

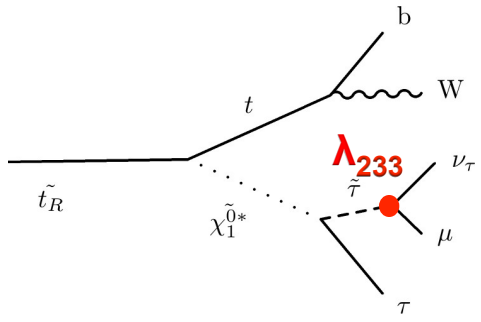
*OSSF: Opposite Sign Same Flavor

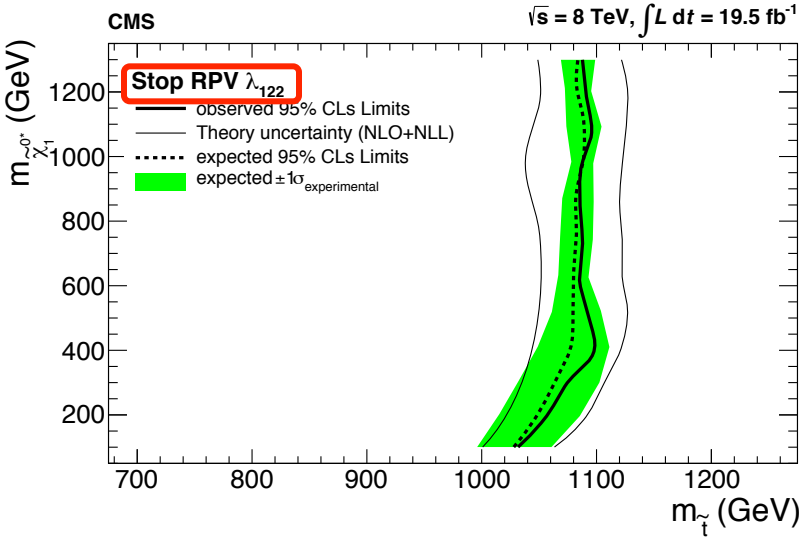
# ① Interpretation for RPV Stop SUSY Search

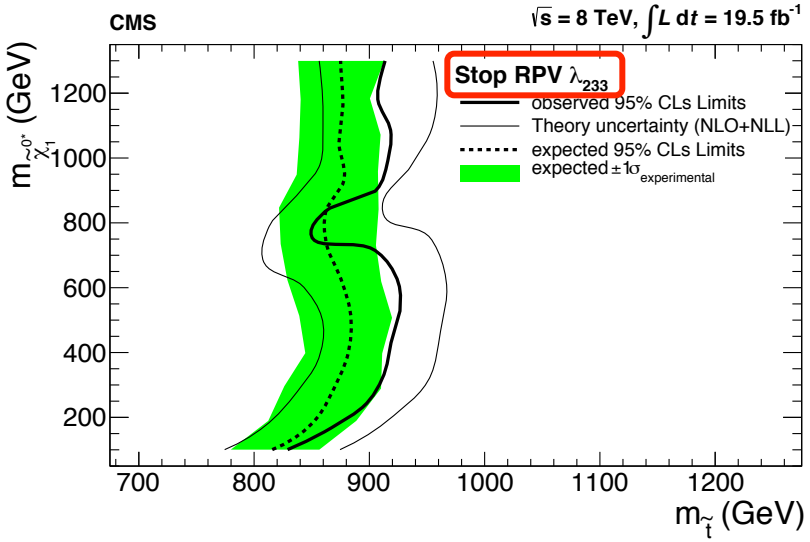
$$W_{RPV} = \tfrac{1}{2}\,\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \tfrac{1}{2}\,\lambda''_{ijk} U_i D_j \bar{D}_k + \kappa_i L_i H_2$$

**Leptonic** Mixed Hadronic



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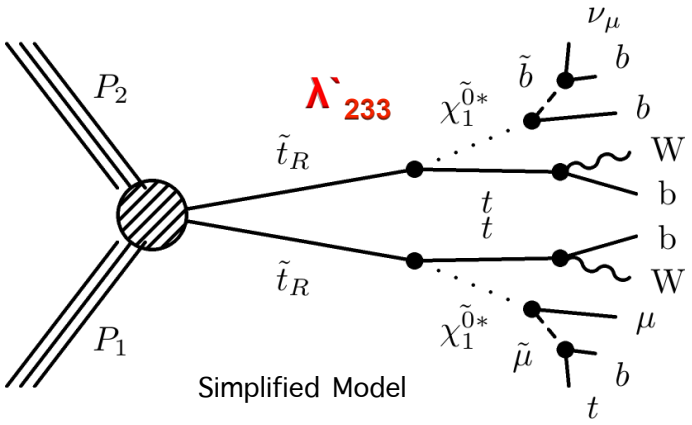
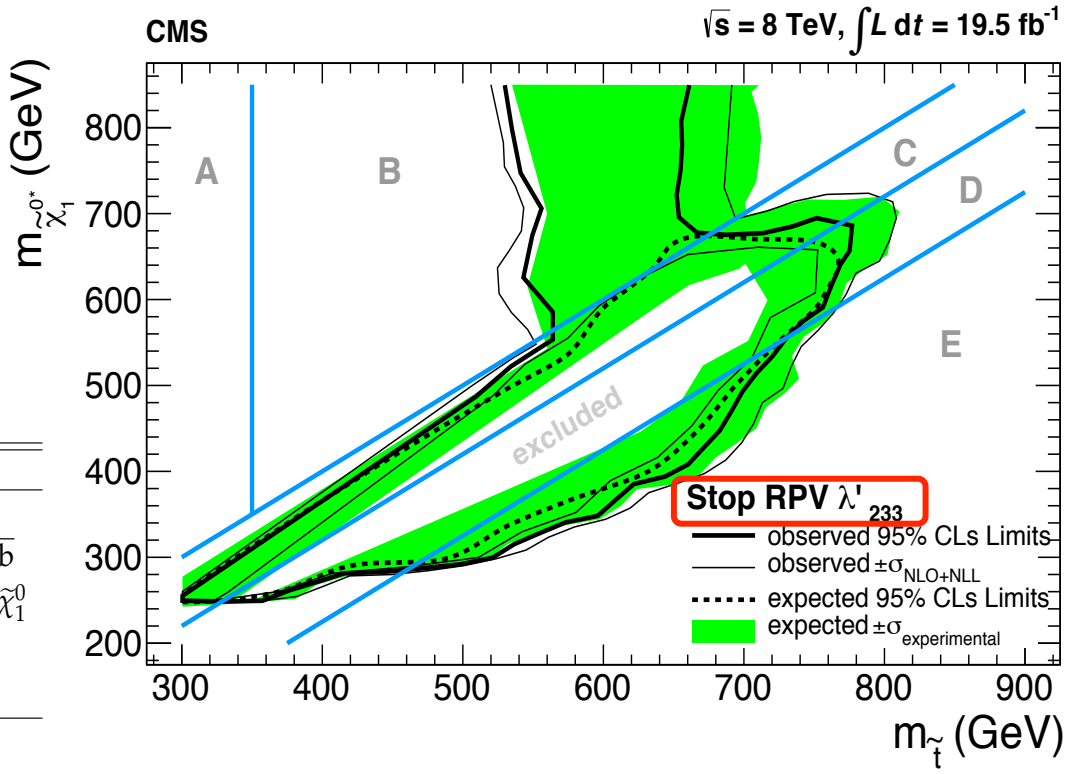
Leptonic **Mixed** Hadronic




| Label | Kinematic region | Decay mode |
|---|---|---|
| A | $m_t < m_{\tilde{t}_1} < 2m_t, m_{\tilde{\chi}_1^0}$ | $\tilde{t}_1 \to t\nu\bar{b}\bar{b}$ |
| B | $2m_t < m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0}$ | $\tilde{t}_1 \to t\mu\bar{t}\bar{b}$ or $t\nu\bar{b}\bar{b}$ |
| C | $m_{\tilde{\chi}_1^0} < m_{\tilde{t}_1} < m_{W^\pm} + m_{\tilde{\chi}_1^0}$ | $\tilde{t}_1 \to \ell\nu b\tilde{\chi}_1^0$ or $jjb\tilde{\chi}_1^0$ |
| D | $m_{W^\pm} + m_{\tilde{\chi}_1^0} < m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$ | $\tilde{t}_1 \to bW^\pm\tilde{\chi}_1^0$ |
| E | $m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}_1}$ | $\tilde{t}_1 \to t\tilde{\chi}_1^0$ |



# ② RPV in Supersymmetry in 4-lepton Final State

- Selection of **4 isolated leptons** in the event is already a strong requirement for SM processes
- 4 leptons requirement needs high lepton identification and reconstruction efficiency!
- The lepton $p_T$ must pass 20/10/10/10 GeV threshold
- No MET, $S_T$ and b-quark jet requirement – decouple from generic SUSY (RPC) searches
- ZZ production is the dominant SM background.

$$W_{RPV} = \tfrac{1}{2}\,\lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \tfrac{1}{2}\,\lambda''_{ijk} U_i D_j \overline{D}_k + \kappa_i L_i H_2$$

**Leptonic** Mixed Hadronic

| $\lambda$-term | neutralino LSP decay mode |
|---|---|
| $\lambda_{121} = -\lambda_{211}$ | $e\mu\nu_e + ee\nu_\mu$ |
| $\lambda_{122} = -\lambda_{212}$ | $\mu\mu\nu_e + \mu e\nu_\mu$ |
| $\lambda_{123} = -\lambda_{231}$ | $\tau\mu\nu_e + \tau e\nu_\mu$ |
| $\lambda_{131} = -\lambda_{311}$ | $e\tau\nu_e + ee\nu_\tau$ |
| $\lambda_{132} = -\lambda_{312}$ | $\mu\tau\nu_e + \mu e\nu_\tau$ |
| $\lambda_{133} = -\lambda_{331}$ | $\tau\tau\nu_e + \tau e\nu_\tau$ |
| $\lambda_{231} = -\lambda_{321}$ | $e\tau\nu_\mu + e\mu\nu_\tau$ |
| $\lambda_{232} = -\lambda_{322}$ | $\mu\tau\nu_\mu + \mu\mu\nu_\tau$ |
| $\lambda_{233} = -\lambda_{323}$ | $\tau\tau\nu_\mu + \tau\mu\nu_\tau$ |

→ Select OSSF pairs and find closest to $M_Z$ **$M_1$**

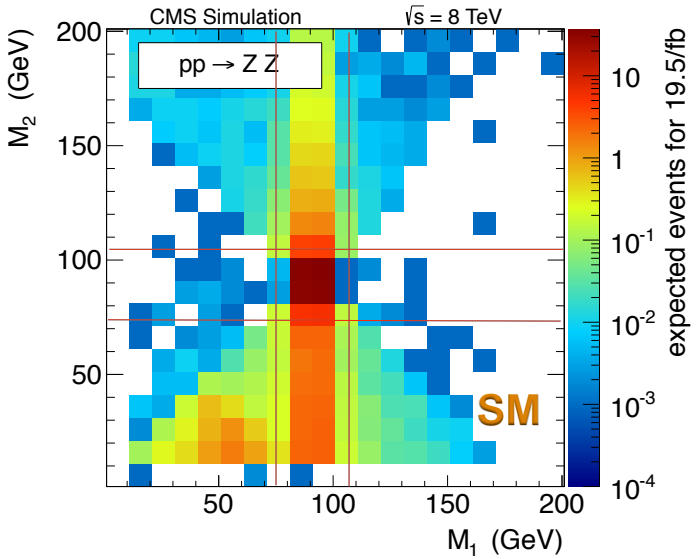
→ Another OS (OF or SF) pair **$M_2$**

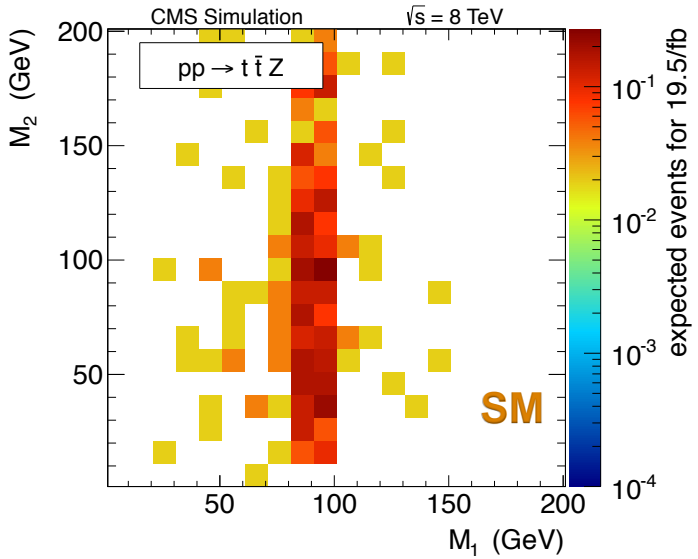
Define 2D plot ($M_1$ vs $M_2$) for different OS regions

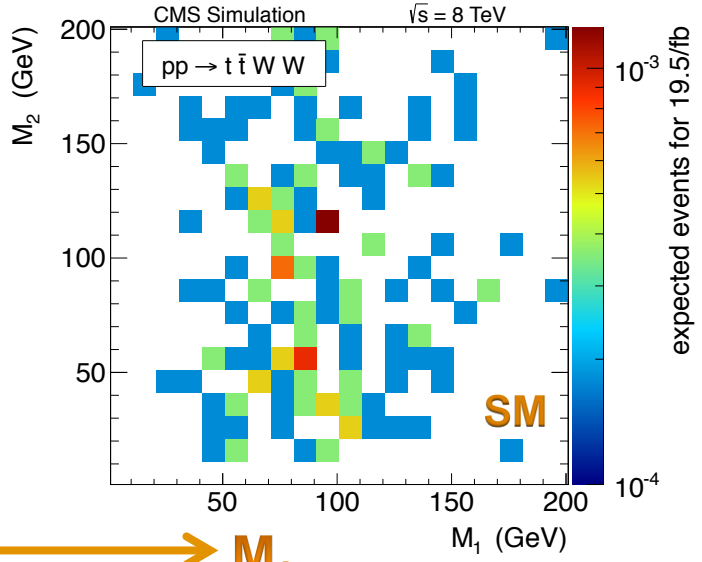
0 – 75 – 105 – Infinity

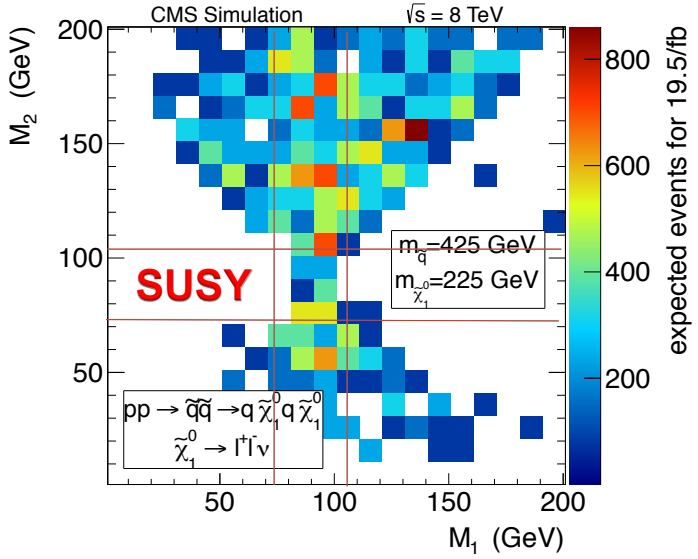
→ 9 analyses regions

# ② Backgrounds and SUSY Signal



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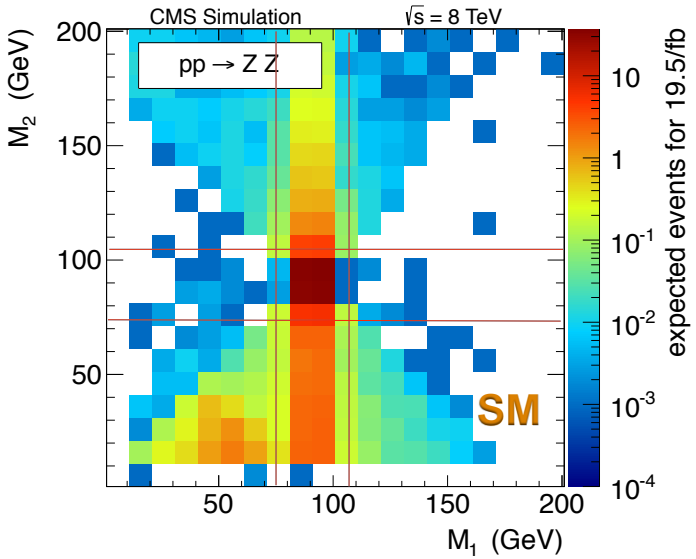
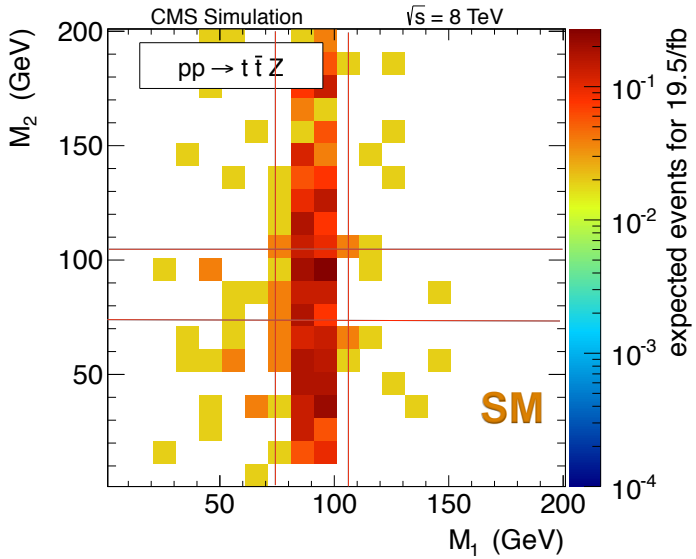
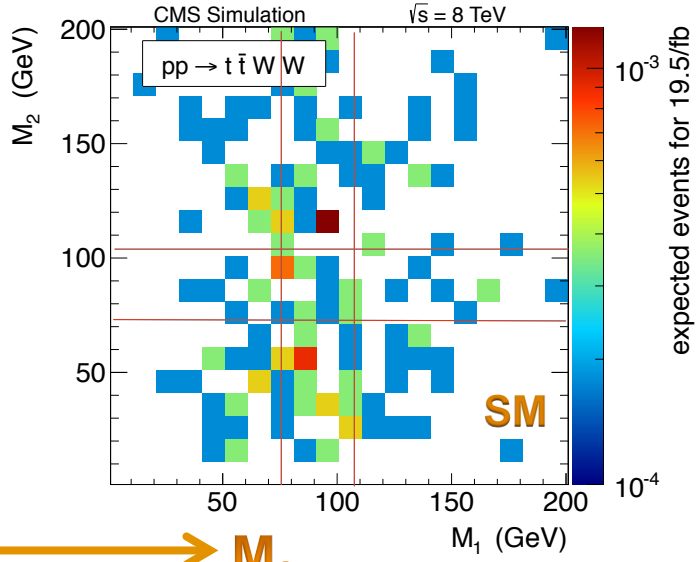
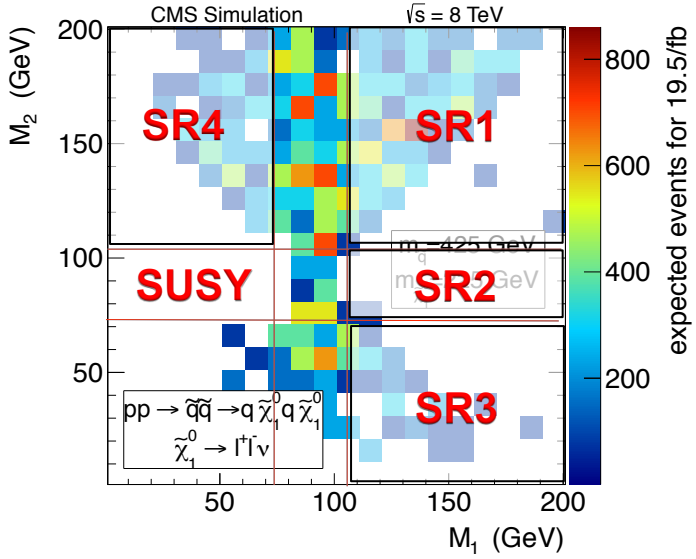


# ② Results

- Expected background contributions from different SM sources and experimentally observed events in all analysis regions.

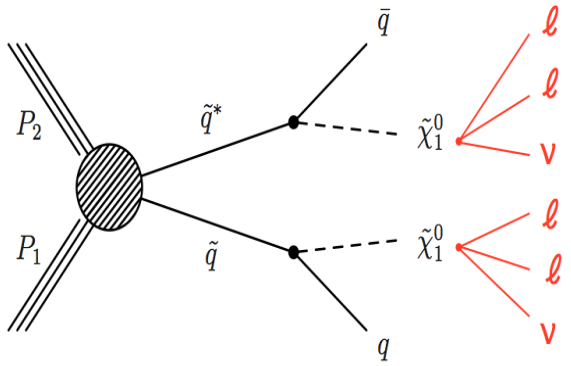
| | | $M_1 < 75\ GeV$ | $75 < M_1 < 105\ GeV$ | $M_1 > 105\ GeV$ |
|---|---|---|---|---|
| $M_2 > 105\ GeV$ | ZZ | 0.76±0.18 | 15±4 | 0.30±0.07 |
| | rare | 0.28±0.13 | 2.7±1.0 | 0.12±0.05 |
| | fakes | 0.4±0.4 | 0.7±0.7 | 0.05±0.05 |
| | all backgrounds | 1.4±0.5 | 18±4 | 0.47±0.10 |
| | observed | 0 | 20 | 0 |
| $75 < M_2 < 105\ GeV$ | ZZ | 0.10±0.03 | 150* | 0.05±0.01 |
| | rare | 0.12±0.05 | 2.5±1.2 | 0.06±0.03 |
| | fakes | 0.3±0.3 | 0.6±0.6 | 0.05±0.05 |
| | all backgrounds | 0.52±0.34 | 153* | 0.16±0.06 |
| | observed | 0 | 160 | 0 |
| $M_2 < 75\ GeV$ | ZZ | 9.8±2.0 | 32±8 | 0.98±0.20 |
| | rare | 0.31±0.14 | 2.5±1.2 | 0.011±0.005 |
| | fakes | 0.3±0.3 | 0.8±0.8 | 0.06±0.06 |
| | all backgrounds | 10.4±2.0 | 35±8 | 1.0±0.2 |
| | observed | 14 | 30 | 1 |

- Irreducible SM background → estimated from MC
- Fake leptons → data driven estimation method

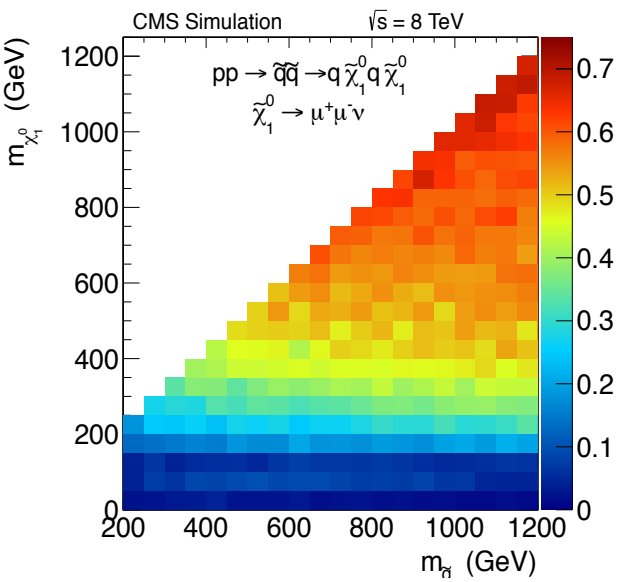
# ② 4-lepton efficiency for neutralino dynamics

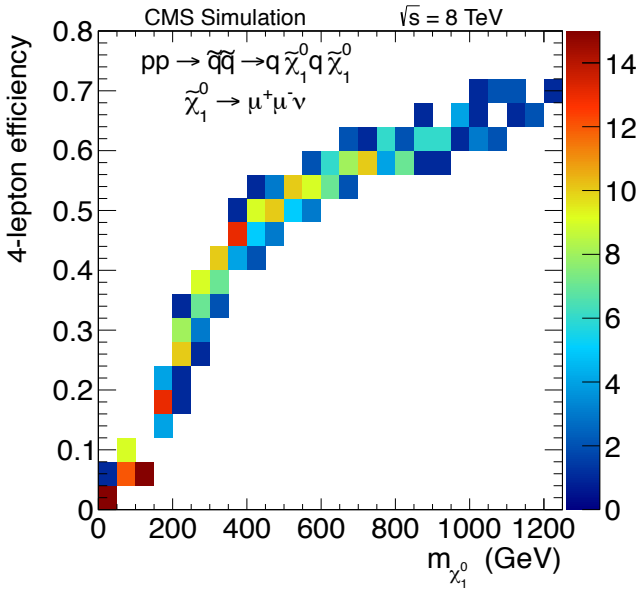
- Two extreme cases are taken into account:

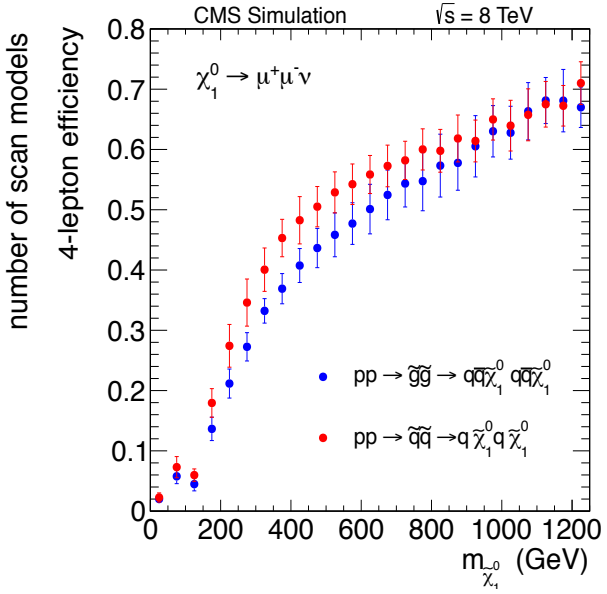
  1. Neutralino is produced in 2-body decay of a directly produced squark → **The most energetic neutralino**
  2. Neutralino produced at rest → **The most soft neutralino**




- No significant difference in efficiency for both cases



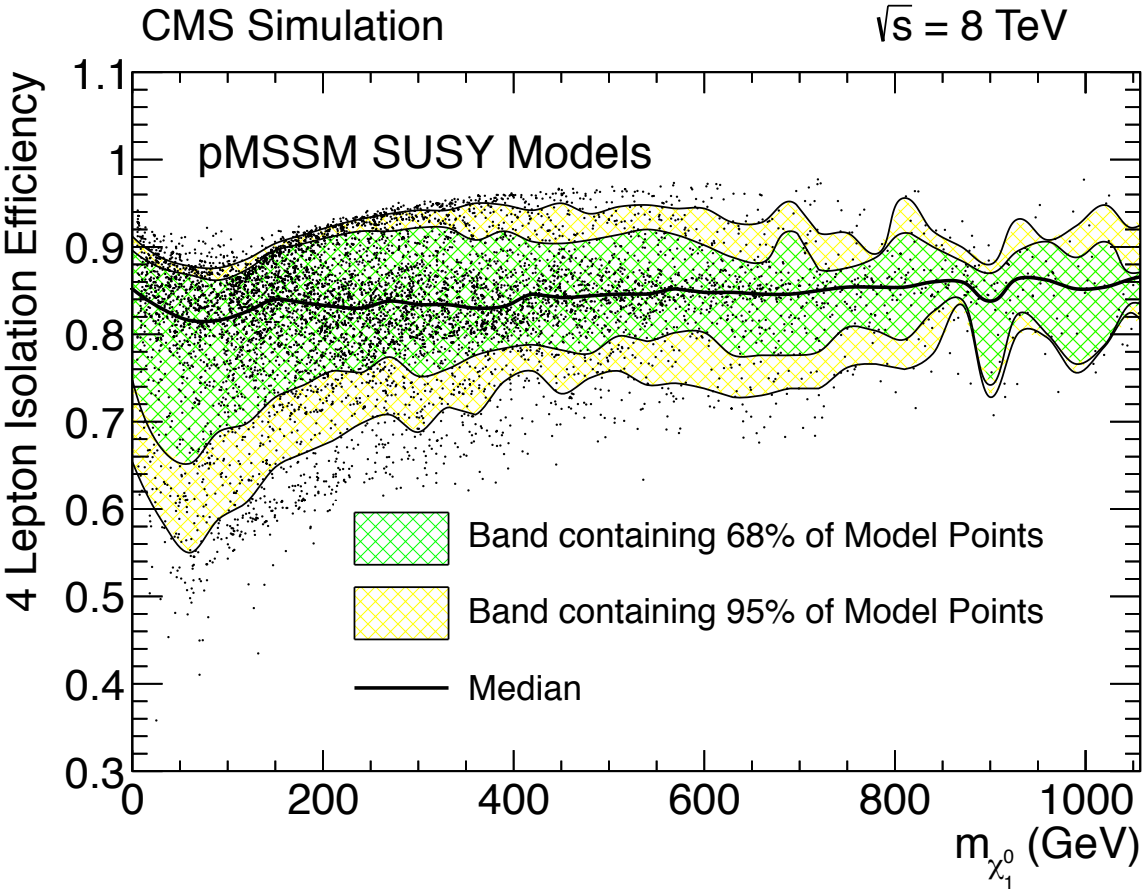




✓ Efficiency is driven by neutralino mass via signal region selection

# ② Interpretation of pMSSM Model

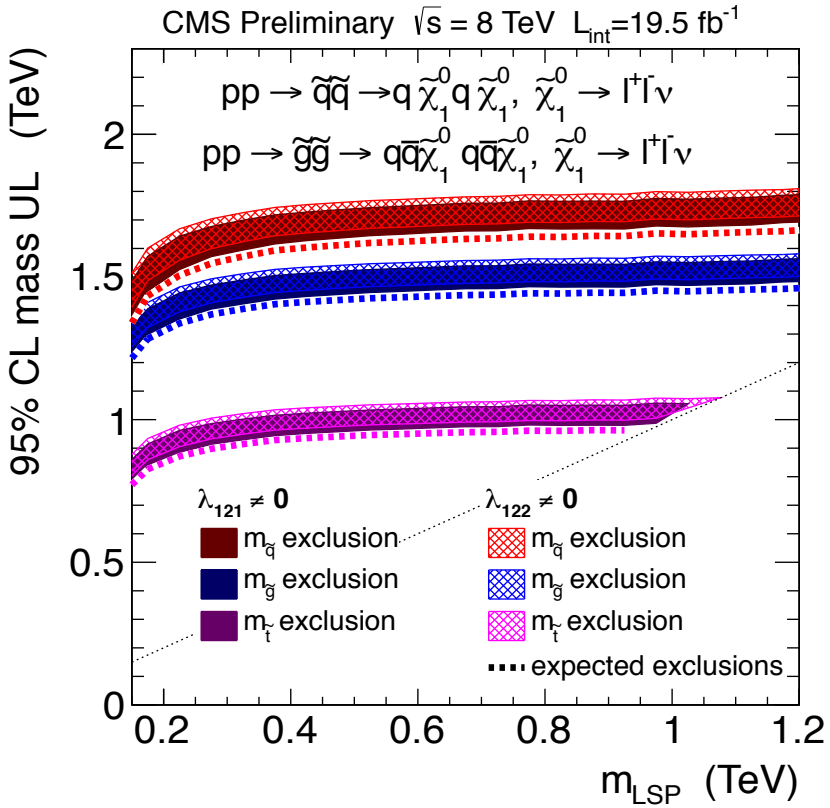
- pMSSM model points (~7300), which represents properties of generic MSSM, chosen with flat parameter priors at Electro-weak scale

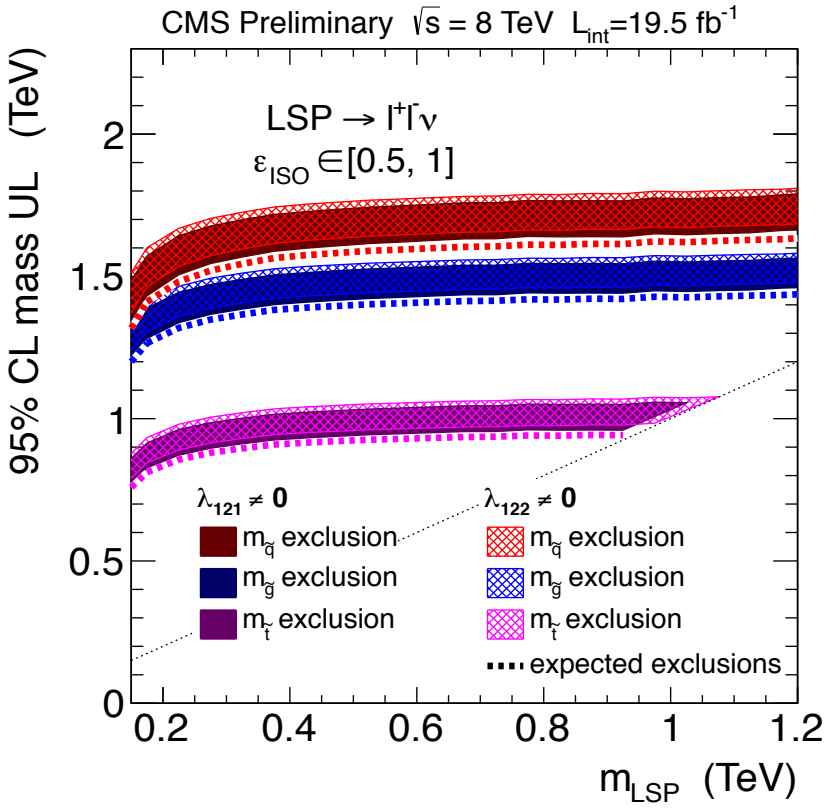


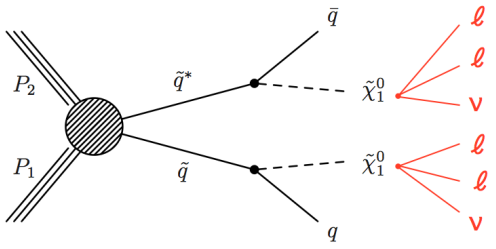

**4-lepton isolation efficiency fits very well between 0.5 and 1.**

# ② General interpretation

## Mass exclusions for different SUSY production mechanisms




Generic RPV SUSY cross section limit

# Conclusions

- **CMS** has an active program searching for **R-parity violated SUSY.**
- **No significant excess** observed over **Standard Model expectations** for multi-lepton final states

  → Both analyses are used to exclude regions of SUSY parameters space, where RPV couplings are non-zero. RPV Stop search puts limits on the **stop** and **bino** masses.

- **pMSSM model** are used to study the impact of generic component on R-parity violated term signatures

  → Results are applicable to generic set of **MSSM SUSY models** and **simplified models.**

# Backup slides

- LATER