Probing flavor-violating decays of squarks at the LHC

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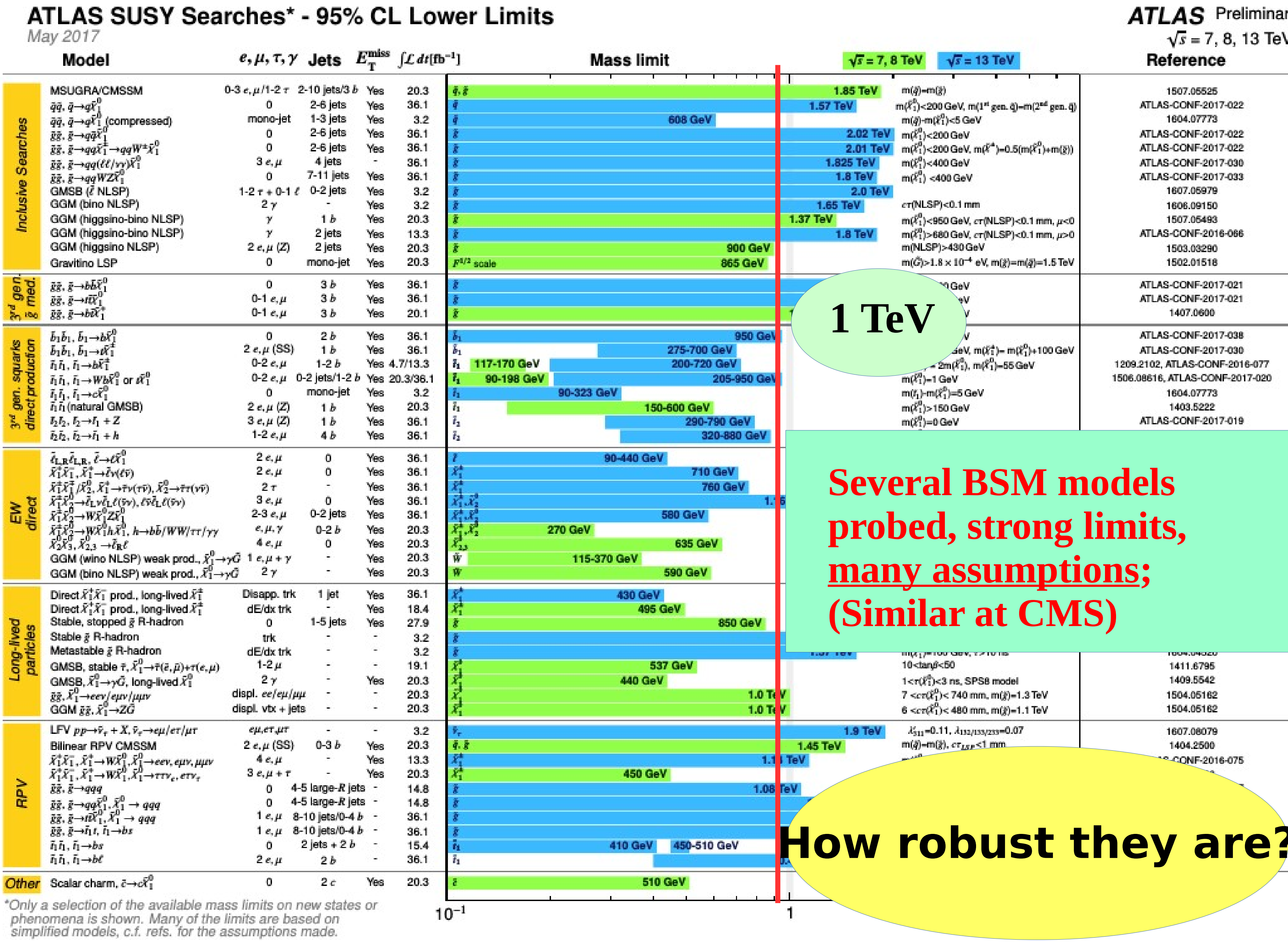
Ref: AC, M. Endo, B. Fuks, B. Herrmann, M. M. Nojiri, P. Pani and G. Polesello (for LH-2017)

Post-Higgs discovery era



1 TeV

Several BSM models probed, strong limits, many assumptions; (Similar at CMS)

How robust they are?

Agenda

Flavor mixing:

Generation mixing (squark) in MSSM w/o adding new fields/complexity

- **Direct search: Production and Decay changes significantly, limits reduces!**

- **Additional sources of FV, large contributions to various FCNC process, constraints from low energy physics data.**

In tension!

But, certain mixing (RR-type) bounds are weak too!

Goal:

1. Can we constrain these RR-type couplings with updated LHC data?

2. Sensitivity of 300 ifb or, say HL-LHC ?

Outline

- Flavor violation: SM and Beyond

- A Bottom-up approach (i.e., Simplified Model)

- Phenomenology, LHC sensitivity (high lumi)

Flavor in SM

- **Yukawa interaction: only source of FV in the SM**

$$\mathscr{L}_Y = \sum_{i,j=1}^{3} (y^e_{ij}\bar{L}_{Li}\Phi e_{Rj} + y^u_{ij}\bar{Q}_{Li}\tilde{\Phi} u_{Rj} + y^d_{ij}\bar{Q}_{Li}\Phi d_{Rj}) + \text{h.c}$$

$$Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L \sim (3,2,1/3) \qquad U_i = u_{Ri} \sim (3,1,4/3)$$

$$D_i = d_{Ri} \sim (3,1,-2/3) \qquad G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$L_i = \begin{pmatrix} \nu_{e_i} \\ e^-_i \end{pmatrix}_L \sim (1,2,-1) \qquad E_i = e_{Ri} \sim (1,1,-2)$$

- Quark flavour violating (i.e. charged current) interactions...

$$\Gamma_{W^+ d_i \bar{u}_j} \propto \frac{g_2}{\sqrt{2}}\gamma^\mu \frac{1-\gamma_5}{2} (V_{\text{CKM}})_{ij}$$

... proportional to Cabbibo-Kobayashi-Maskawa (CKM) matrix

Highly suppressed Off-diagonal terms

$$V_{\text{CKM}} = V_u^\dagger V_d \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad \lambda \sim 0.2$$

Flavor in MSSM

- Same flavor structure as in SM
- Super-CKM basis: squarks undergo same rotation as quarks
- All FV effects are proportional to CKM elements

Minimal Flavor Violation

- New sources of FV appears
- Mostly from Soft-SUSY breaking terms (e.g.: gravity mediation, gauge mediation with messenger mixing, …) [Porod et. al.,
- No direct relation with CKM
- Generation mixing at EW scale
- Independent parameters

Non-Minimal Flavor violation

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} \mathcal{M}^2_{uLL} & (\mathcal{M}^2_{uRL})^\dagger \\ \mathcal{M}^2_{uRL} & \mathcal{M}^2_{uRR} \end{pmatrix}_{6\times 6}$$

Basis:

$$\begin{cases} (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R) \\ (\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R) \end{cases}$$

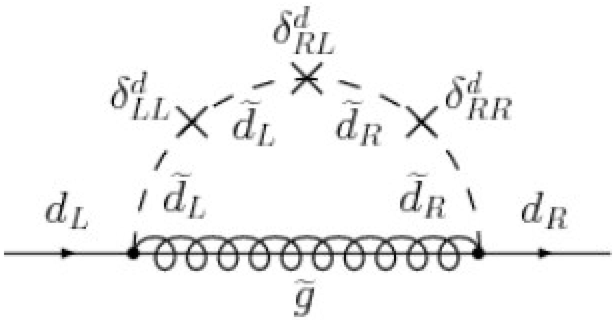
$$\delta^{uLL}_{\alpha\beta} = M^2_{Q,\alpha\beta} \Big/ \sqrt{M^2_{Q,\alpha\alpha} M^2_{Q,\beta\beta}}$$

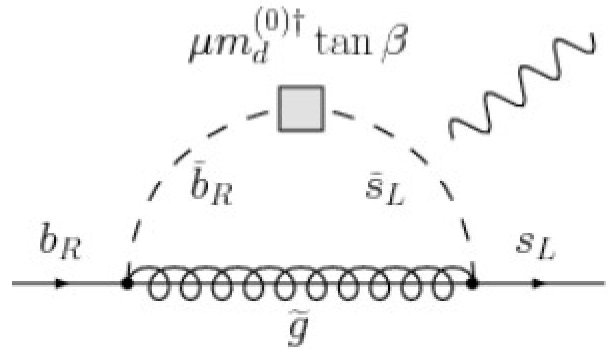
$$\delta^{uRR}_{\alpha\beta} = M^2_{U,\alpha\beta} \Big/ \sqrt{M^2_{U,\alpha\alpha} M^2_{U,\beta\beta}}$$

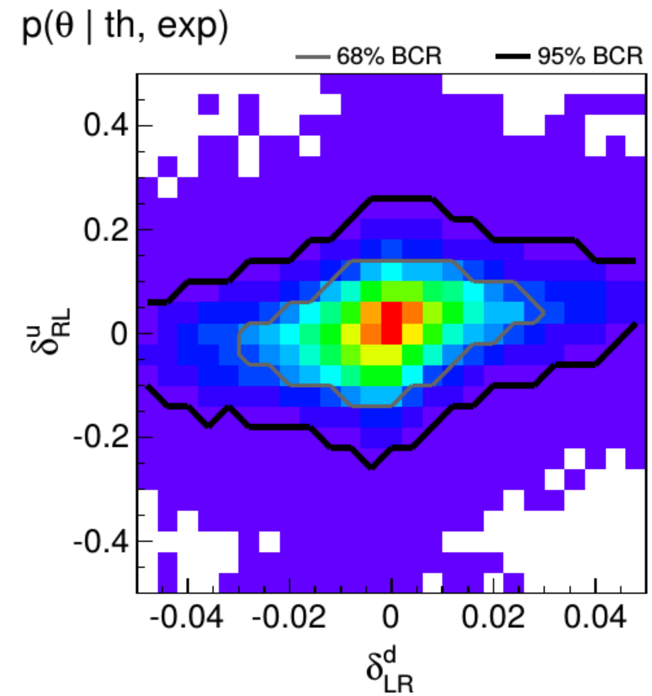
$$\delta^{uRL}_{\alpha\beta} = \frac{v_2}{\sqrt{2}} A_{U,\alpha\beta} \Big/ \sqrt{M^2_{U,\alpha\alpha} M^2_{Q,\beta\beta}}$$

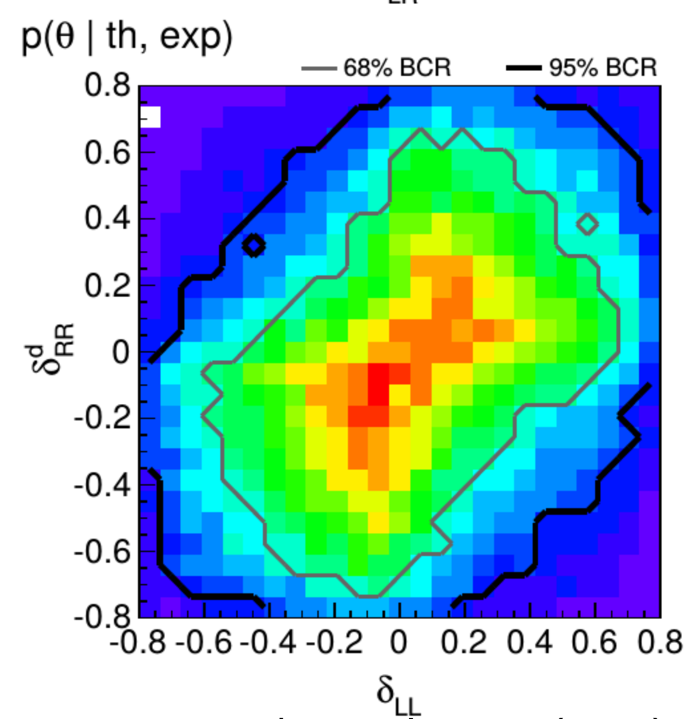
[Gabbini, Masiero (1989); Gabbiani, Gabrieli, Masiero, Silvestrini (1996); Ciuchino, Degrassi, Gambino, Giudice (1998), Lari, Pape, Porod et al. (2008), Fuks et al (2012), ...]

Consequences of Generation mixing









Fuks et. al. JHEP (2015)

- **Potential effects to low energy processes; K, B, D-physics, Meson mixing, …**
  ➡ **Precise measurements; strong constraints**
- **Higgs data also puts limits on LR-type mixing**
  ➡
- **Production and Decay of SUSY particles**, change significantly
  Relatively weaker bounds at LHC
- The RR-sector (up-type) with the mixing

Focus:
Impact of Stop search and also scharm search on
RR(c-t) mixing parameter

Simplified Model

Model: SM + right-handed stop + right-handed scharm + Gluino + Neutralino (bino)

Production & Decay

- Squarks are admixtures of different flavors
- Simplified model: right stop-scharm mixing

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{tc} & \sin\theta_{tc} \\ -\sin\theta_{tc} & \cos\theta_{tc} \end{pmatrix} \begin{pmatrix} \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}$$

- 3D parameter space (2 masses, one mixing angle)

$m_{\tilde{u}_1}, m_{\tilde{u}_2}, \theta_{tc}$

- Possible flavor-violating decays: $\tilde{u}_i \to t + \not{E}_T \quad \text{or} \quad c + \not{E}_T$

- Signatures

$t\bar{t} + E_T^{miss}$ ➢ 1407.0583 (replaced with new 13 TeV)

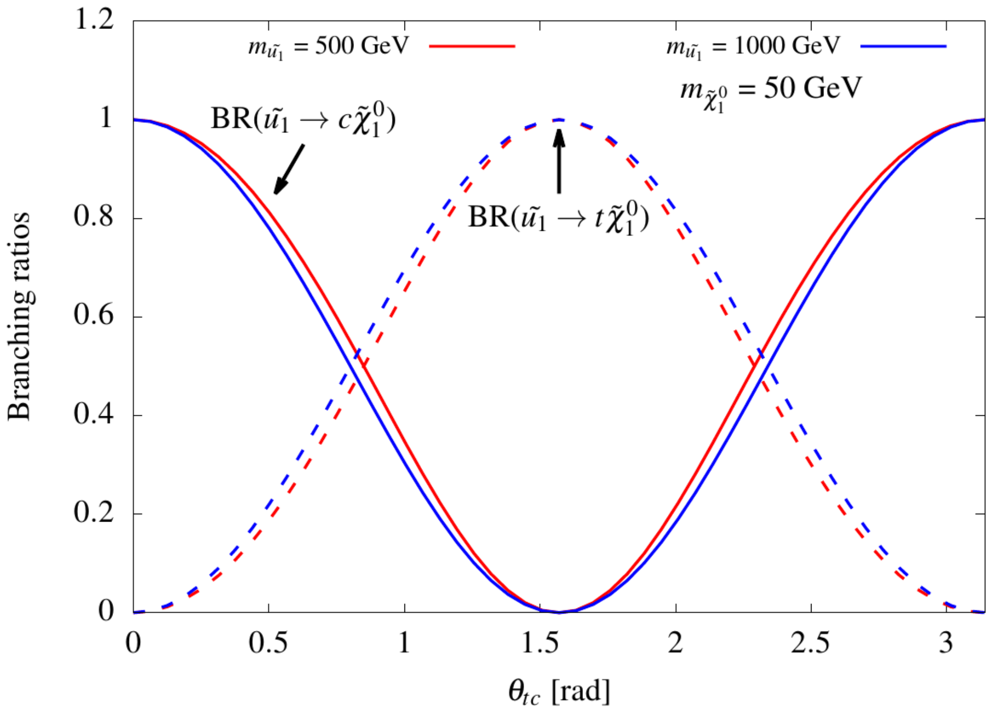
$c\bar{c} + E_T^{miss}$ ➢ 1501.01325 (8 TeV available)

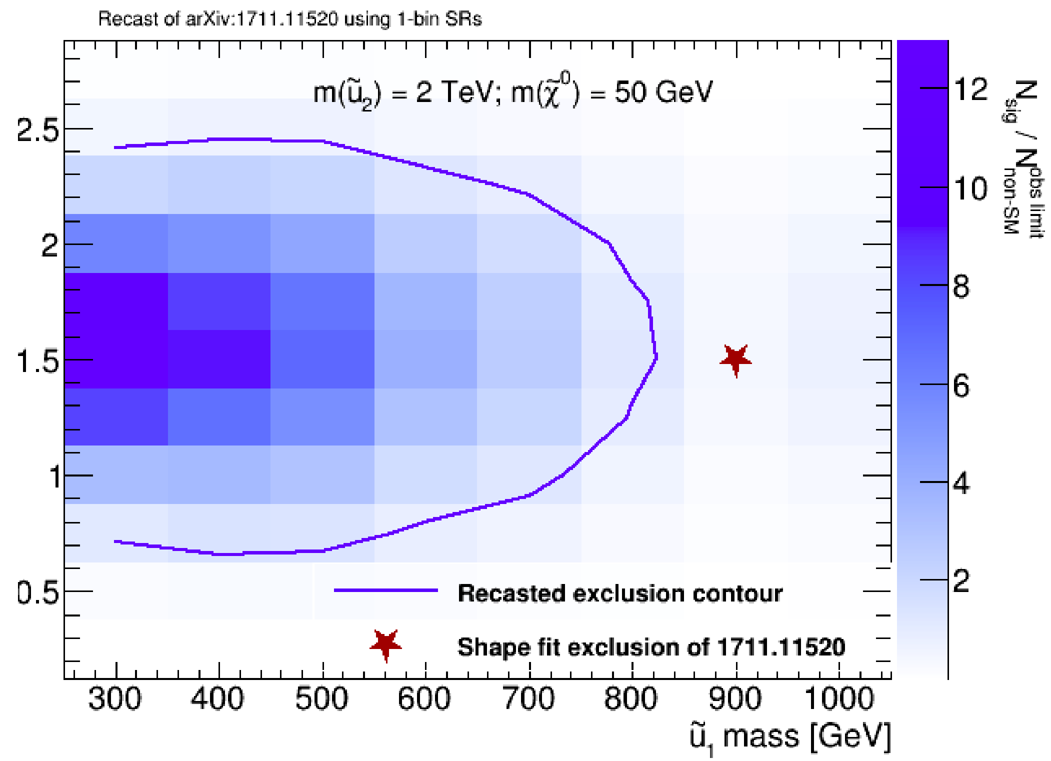
$c + t + E_T^{miss}$ ➢ Monotops?

Objectives:

- Coverage of current searches ?
- Potential of a dedicated top-charm analysis

Recast of LHC 13 TeV data



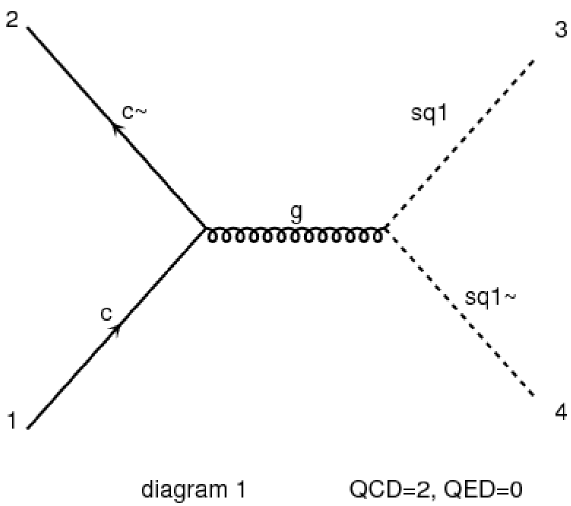


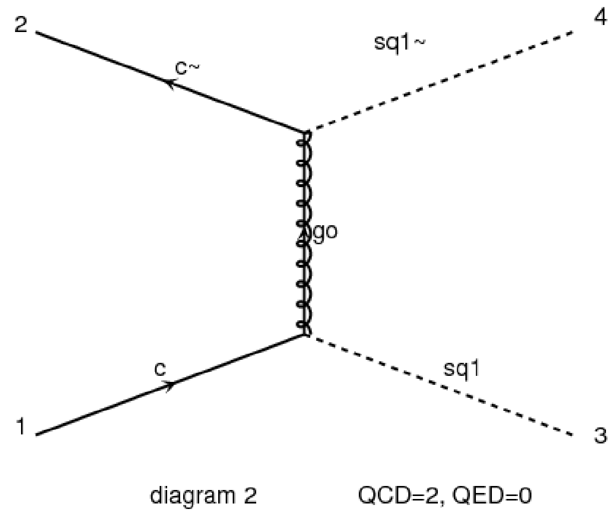
- **<u>Scharm search</u>**: ~ 500 GeV @ 8 TeV
- **<u>Stop search</u>**: **1-lepton, jets + MET search at 13 TeV**
- Translate to 3-parameter plane: m(u1), m(u2) and θ (tc).

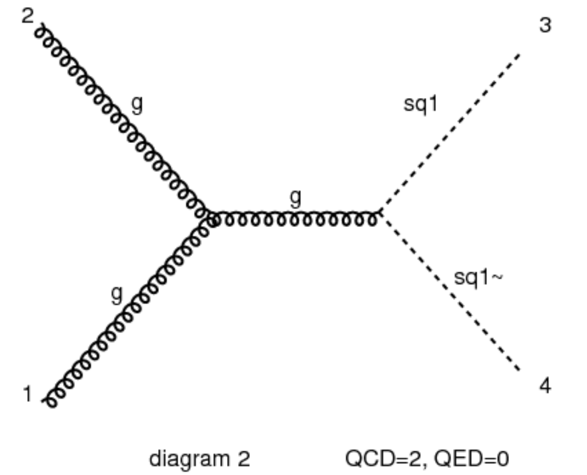
- **Recast**: compare signal yields with Model independent limits on non-SM contributions from the observed data.

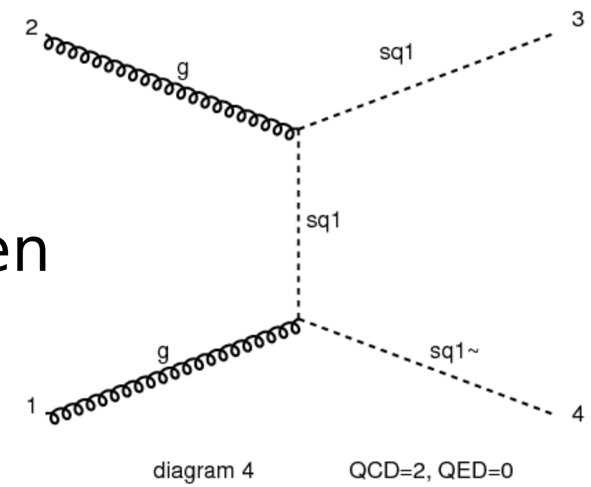
Define: $\mathbf{R = N_{sig} / N_{non\text{-}SM(obs)}}$; R > 1 => **Excluded!**

Monte-Carlo set-up









- **Signal:** LO using MG5, passed to PY8 and then Delphes; normalized using NLO+NLL xsec
- **Bkg:** ttbar, signal top @NLO, ttbarZ, ttbarW, W+jets, Z+jets @LO; PY8 + Delphes; normalized with NNLO/NLO xsecs
- **Squark pair-production:** m(u1) = [600,1400] GeV, m(chi) = 50 GeV, mixing angle fixed at θ(tc) = pi/4.
- **Jets:** Fastjet with R=0.4, anti-kT, ATLAS card.

Event selection

Aim : top + charm + MET topology

- Exactly **one lepton** with pT>25 GeV, |η|<2.5.
- Exactly **one b-tagged jet** with pT>30 GeV; Veto additional b-jets (ε_b = 77%).
- At least **one light jet** with pT>100 GeV (jet failing b-tagging criteria).
- **m_T(lep,MET)** > 90

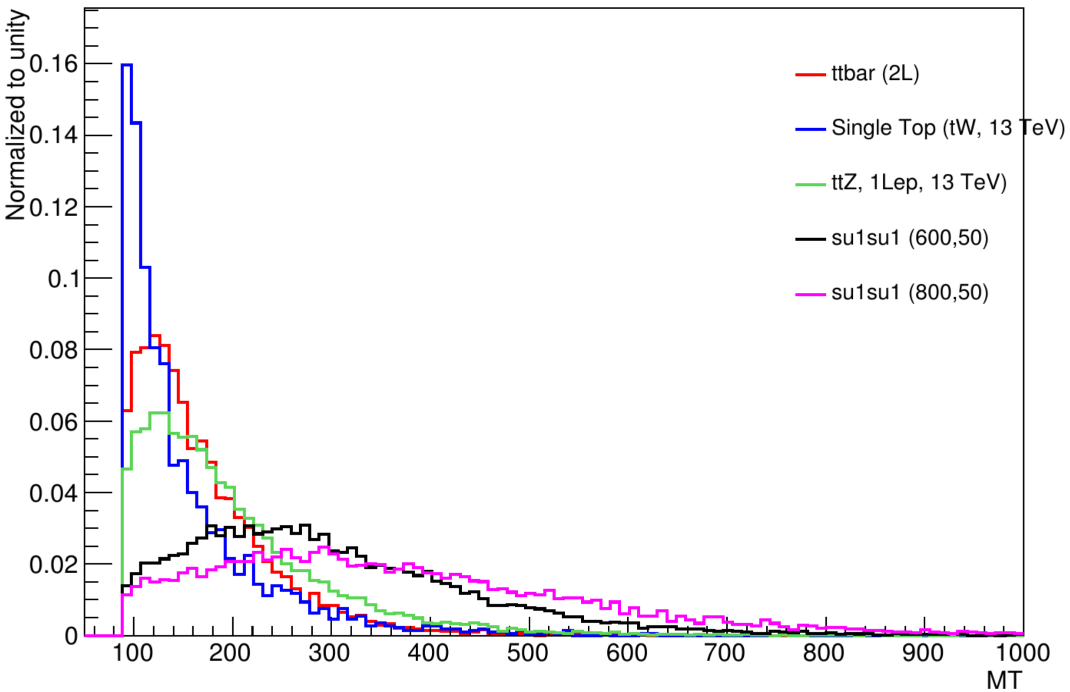
  & **MET** > 80 GeV.

$$m_{\mathrm{T}}^{lep} \equiv \sqrt{2\,|\vec{p}_{\mathrm{T}}^{\,\ell}|\,|\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}|\,(1-\cos\Delta\phi_{\vec{p}_{\mathrm{T}}^{\,\ell}\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}})}$$

- Further,

  m_T(lep,MET) > 160 GeV

  m(lep,b-jet) < 160 GeV



Event selection - II

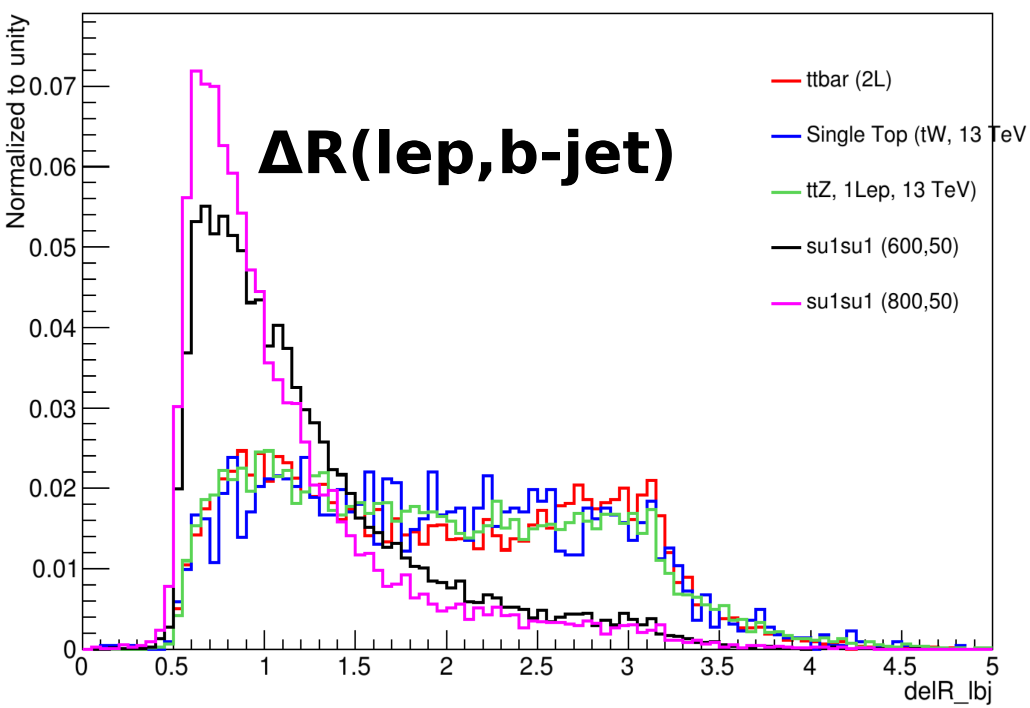
- **$|\Delta\varphi_{min}|$ > 0.6**, between MET and jets.
- **ΔR(lep,b-jet) < 1.**

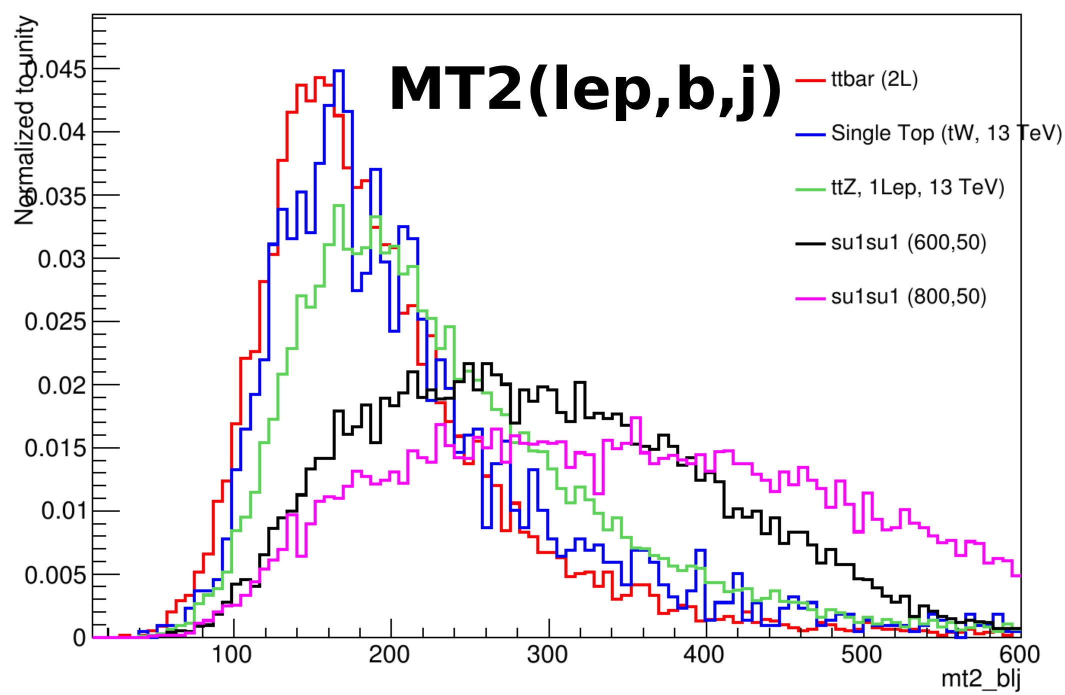
$$M_{T2}(\vec{p}_T^{\,\ell1},\vec{p}_T^{\,\ell2},\vec{\not{p}}_T) = \min_{\vec{\not{p}}_T=\vec{\not{p}}_T^{\,1}+\vec{\not{p}}_T^{\,2}}\left[\max\{M_T(\vec{p}_T^{\,\ell1},\vec{\not{p}}_T^{\,1}), M_T(\vec{p}_T^{\,\ell2},\vec{\not{p}}_T^{\,2})\}\right],$$

- **Asym MT2**: aMT2 > 200 GeV (reduce di-lep ttbar)

  (V1 = lepton, b-jet; V2 = leading non-btagged jet or c-jet or light-jet; MET system = (0,80 GeV)

- Vary **MT2(lep,b-jet,light-jet)** for optimization: **Squark mass dependent end-point**





Note: No charm tagging used, use of b-veto helps better for estimating exclusion limits.

Reach @ 14 TeV

$m_{\tilde{u}_1}$ (GeV)	$m_{\tilde{\chi}_1^0}$ (GeV)	$m_{T2_{blj}}$ cut (GeV)	N_s	N_b	$\sigma^{excl}/\sigma^{SUSY}$	
600	50	400	124.9	63.0	0.23	
700	50	450	55.6	31.5	0.30	5σ
800	50	500	25.8	15.3	0.41	
900	50	500	17.0	15.3	0.63	
1000	50	550	8.3	7.6	0.89	2σ
1100	50	600	4.0	4.4	1.41	

Likelihood Analysis; 95% CL Upper Limit on the Ratio of Signal yields to the same for the Simplified model

- **Mass ~ 1 TeV can be probed at LHC-14 at 300 ifb, ~1.3 TeV at 3000 ifb.**
- **Increased sensitivity with significant mixing in the stop-scharm sector**

- **How to know the "mixed stop" is originating from t-c mixing or t-u mixing?**
- **Charm tagging is important; Amount of c-jets in signal events can be estimated by <u>changing the b-tagging working point</u>!**

[Higgs coupling: Perez et. al. 2015].