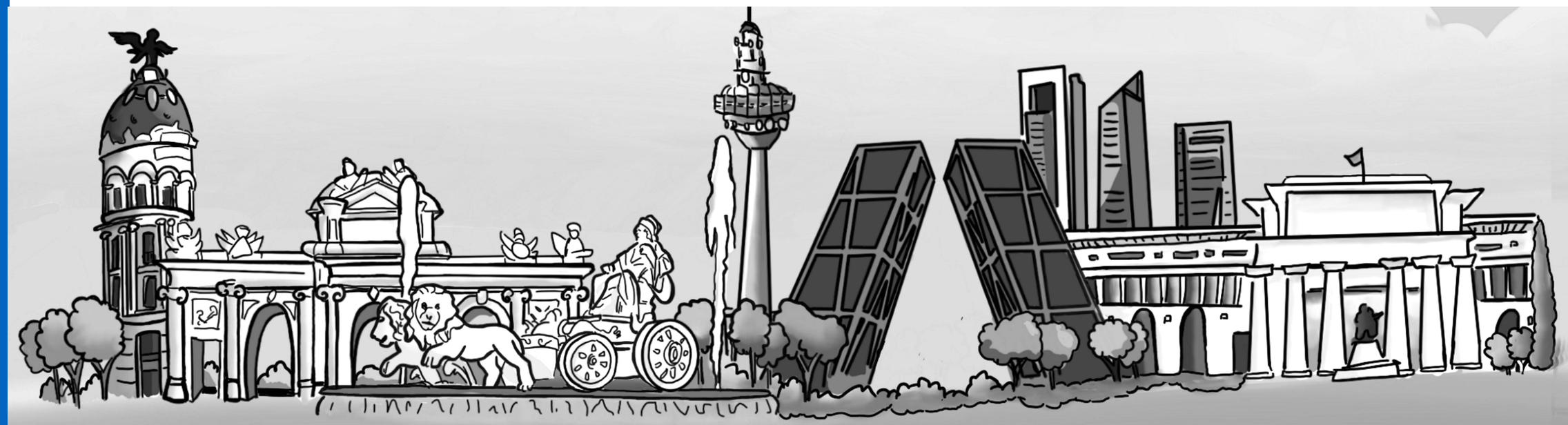
rcarney@slac.stanford.edu

Searches for RPV SUSY at the LHC

Rebecca Carney

On behalf of the ATLAS and CMS collaborations



rcarney@slac.stanford.edu

Supersymmetry intro

- Supersymmetry (SUSY) extends the Standard Model (SM) to include a fermion-boson symmetry.

$$g\ (s=1) \leftrightarrow \widetilde{g}(s=\frac{1}{2}) \qquad t\ (s=\frac{1}{2}) \leftrightarrow \widetilde{t}(s=0)$$

rotation transforms SM vector boson into ‘gaugino’, e.g. gluon to gluino

rotation transforms SM fermion into ‘sparticle’, e.g. top quark to ‘stop’

- Not a perfect symmetry, mass degeneracy between SM & SUSY broken, additional Higgs bosons & their superpartners.

$$(\tilde{H}_u^0, \tilde{H}_d^0, \tilde{B}, \tilde{W}^0) \rightarrow \{\tilde{\chi}_i^0\}_{i\in 1:4} \qquad (\tilde{H}_u^+, \tilde{H}_d^-, \tilde{W}^+, \tilde{W}^-) \rightarrow \{\tilde{\chi}_i^\pm\}_{i\in 1:2}$$

Four neutralinos, ordered in decreasing mass

Two charginos, ordered in decreasing mass

- Superpartners to the electroweak bosons mix with higgsinos, result in six mass eigenstates: neutralinos and charginos.

- **Well motivated: Radiative corrections suppressed (solution to the hierarchy problem w/o fine-tuning), a means for gauge coupling unification, neutralino is excellent dark matter candidate.**

rcarney@slac.stanford.edu

R-parity violation

- Minimal Supersymmetric Standard Model (MSSM) superpotential conserves baryon & lepton number. Can describe in terms of R-parity:

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

B = baryon number
L = lepton number
S = spin

- SM particles have R_p = 1, SUSY particles R_p = -1

- The R-parity violating (RPV) addition to MSSM superpotential defined as:

Lepton number violating terms

$$W_{\not{R}_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \mu'_i L_i H_u$$
$$+ \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Baryon number violating term

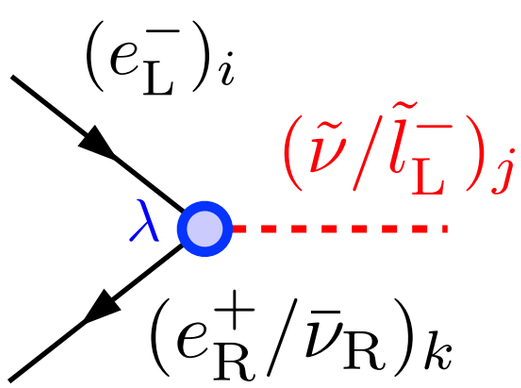
not covered in this talk

- Many searches for new physics assume that R-parity Conserved (RPC), which is a special case of the more generic RPV SUSY.

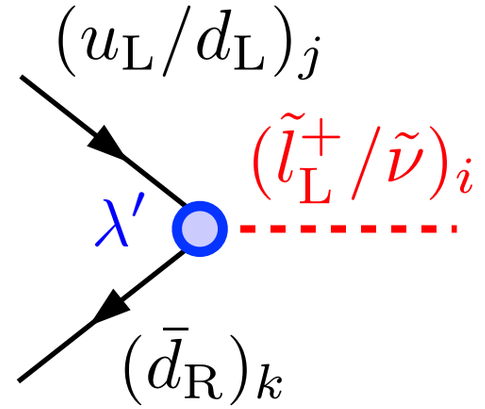
rcarney@slac.stanford.edu

RPV couplings & proton decay

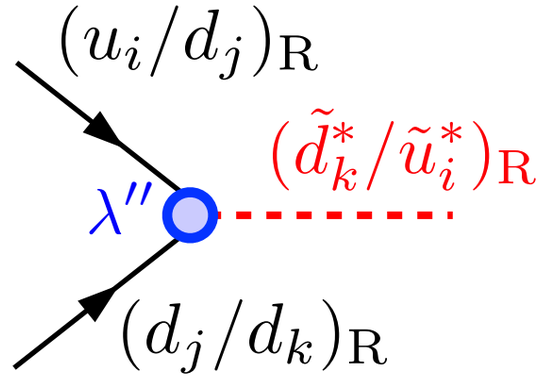
- Terms* in the RPV superpotential introduce additional interaction vertices with associated coupling constants, e.g. :



$$\lambda_{ijk} L_i L_j \bar{E}_k$$



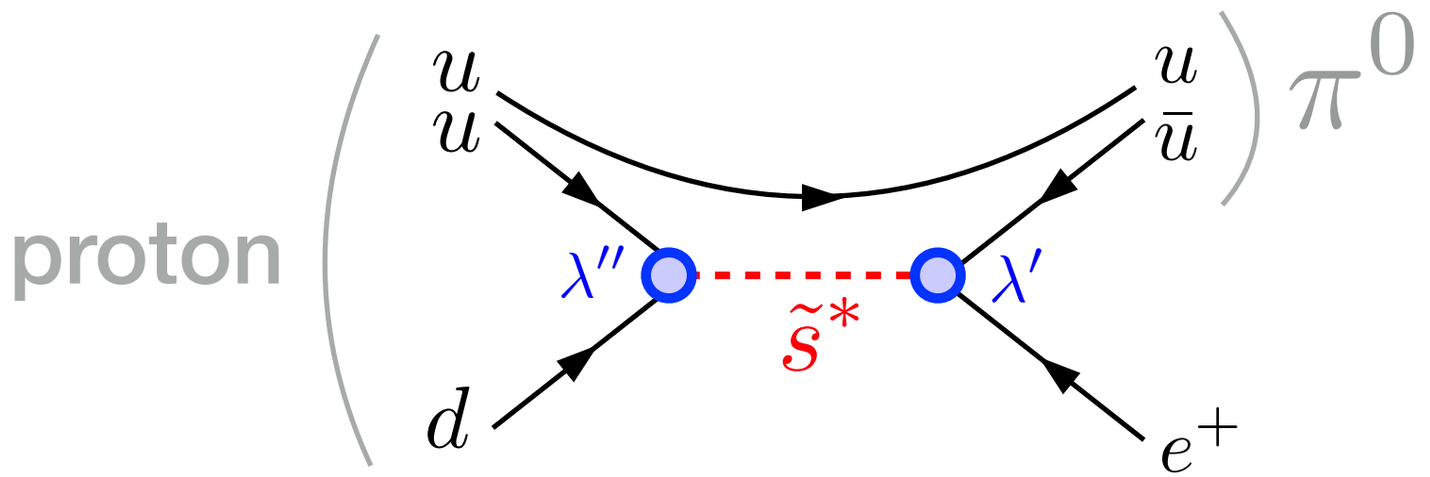
$$\lambda'_{ijk} L_i Q_j \bar{D}_k$$



$$\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

*not including bilinear LH coupling in this presentation

- Rapid proton decay requires **both** lepton and baryon numbers violation. So either baryon violating or lepton violating terms can have non-zero coupling strengths, but not both.



rcarney@slac.stanford.edu

RPV consequences

With the addition of the **RPV** term to the MSSM:

- Well motivated: Radiative corrections suppressed (solution to the hierarchy problem w/o fine-tuning), a means for gauge coupling unification, ~~neutralino is excellent dark matter candidate.~~

- Neutralino can decay and so no longer viable DM candidate. However, other DM candidates still exist depending on which variant of SUSY being considered, e.g. tau sneutrino, gravitino, axino, etc.

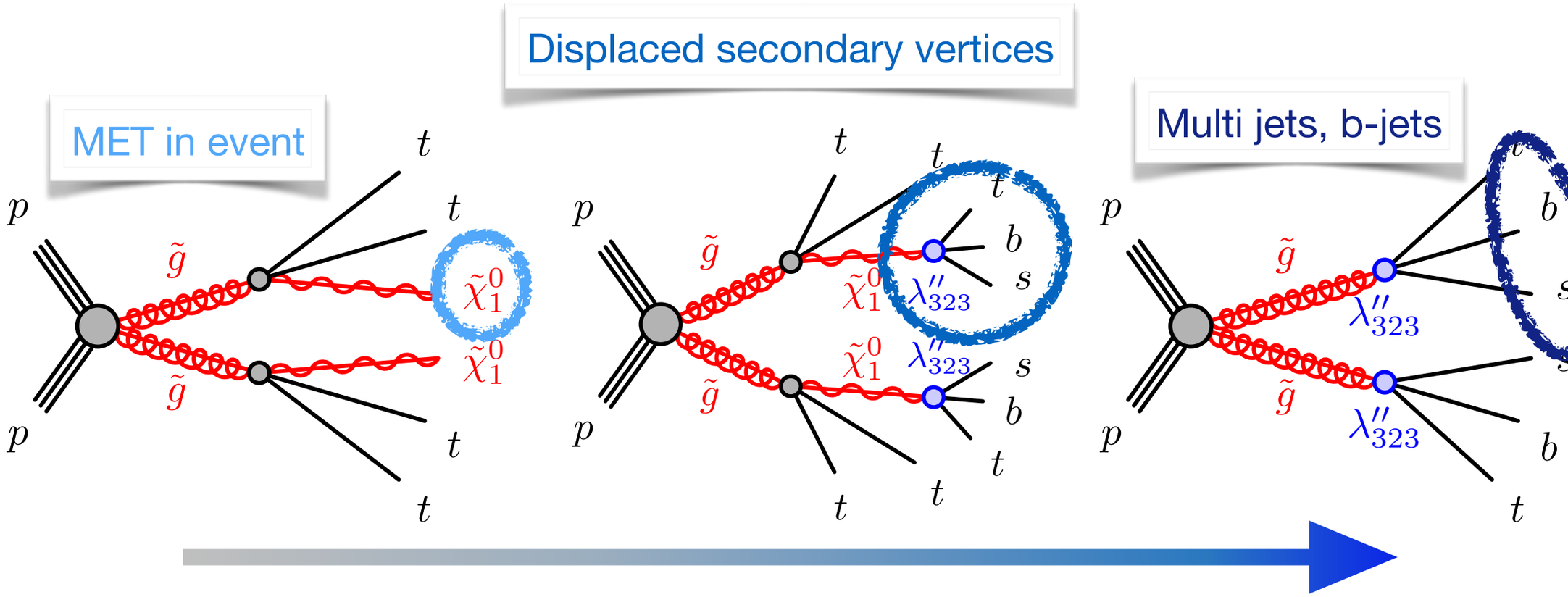
- Light neutrino masses arise from the lepton number violating terms.

- SUSY particles do not need to be pair produced, resonant production possible too.

rcarney@slac.stanford.edu

RPV signatures

As the RPV coupling strength varies, so too does the topology of the event.



- If the RPV coupling is small but non-zero, decay is suppressed which can result in LLP signatures, recall Andrew Hart's talk in yesterday's session: https://indico.cern.ch/event/754031/contributions/3522749/.
- **This talk will focus on prompt decays.**

rcarney@slac.stanford.edu

This talk

- RPV SUSY has a rich and varied topology so only a **limited selection** of results from ATLAS & CMS shown today. Some are dedicated searches for RPV SUSY whilst some are interpretations of a different exotic search.
- Results presented here grouped by RPV coupling and signature.
- Complete list of ATLAS and CMS public results available **here**, **here**, **here**, **here**, **here**.

List of results mentioned today

CMS

- Search for lepton flavour violating decays of heavy resonances and quantum black holes to an eμ pair in proton-proton collisions at sqrt(s)=13 TeV: **CMS-EXO-16-058**
- Search for resonant production of second-generation sleptons with same-sign dimuon events in proton-proton collisions at sqrt(s) = 13 TeV: **CMS-SUS-17-008**
- Search for pair production of first-generation scalar leptoquarks at sqrt(s)=13 TeV: **CMS-EXO-17-009**
- Search for new phenomena in events with high jet multiplicity and low missing transverse momentum in proton-proton collisions at 13 TeV: **CMS-EXO-17-030**
- Search for physics beyond the standard model in events with two same-sign leptons or at least three leptons and jets in proton-proton collisions at sqrt(s) = 13 TeV: **CMS-PAS-SUS-19-008**

ATLAS

- Search for supersymmetry in events with four or more leptons in sqrt(s)=13 TeV *pp* collisions with ATLAS: **SUSY-2016-21**
- Search for lepton-flavor violation in different-flavor, high-mass final states in *pp* collisions at sqrt(s)=13 TeV with the ATLAS detector: **EXOT-2016-09**
- A search for B–L R-parity-violating top squarks in sqrt(s)=13 TeV *pp* collisions with the ATLAS experiment: **SUSY-2016-029**
- Search for R-parity-violating SUSY particles in multi-jet final states in *pp* collisions at sqrt(s)=13 TeV: **SUSY-2016-22**
- Search for new phenomena in a lepton plus high jet multiplicity final state with the ATLAS experiment using sqrt(s) = 13 TeV *pp* collision data: **SUSY-2016-11**
- Search for squarks and gluinos in final states with same-sign leptons and jets using 139 fb–1 of data collected with the ATLAS detector: **SUSY-2018-09**
- Reinterpretation of searches for supersymmetry in models with variable R-parity-violating coupling strength and long-lived R-hadrons: **https://cds.cern.ch/record/2308391**

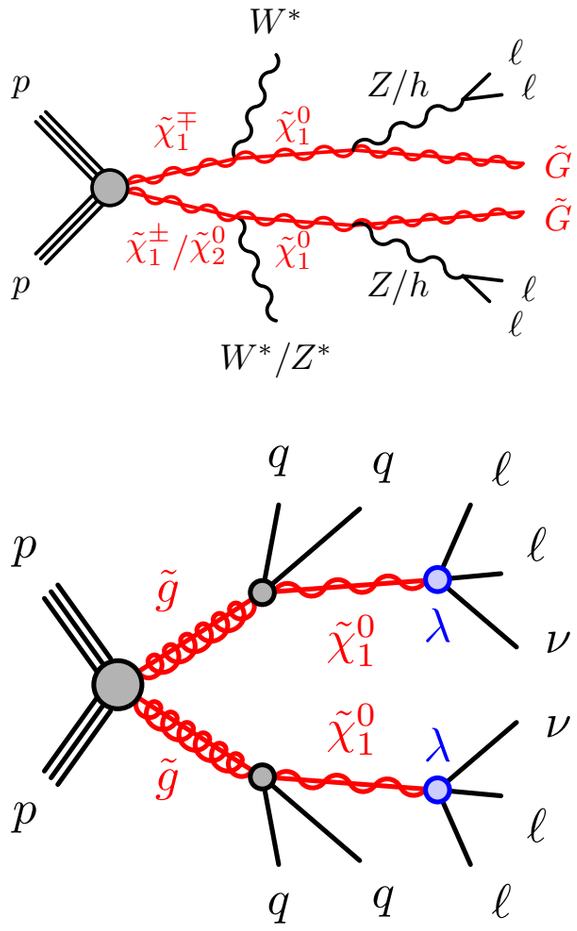
rcarney@slac.stanford.edu

$\lambda_{ijk} L_i L_j \bar{E}_k$

Four charged leptons

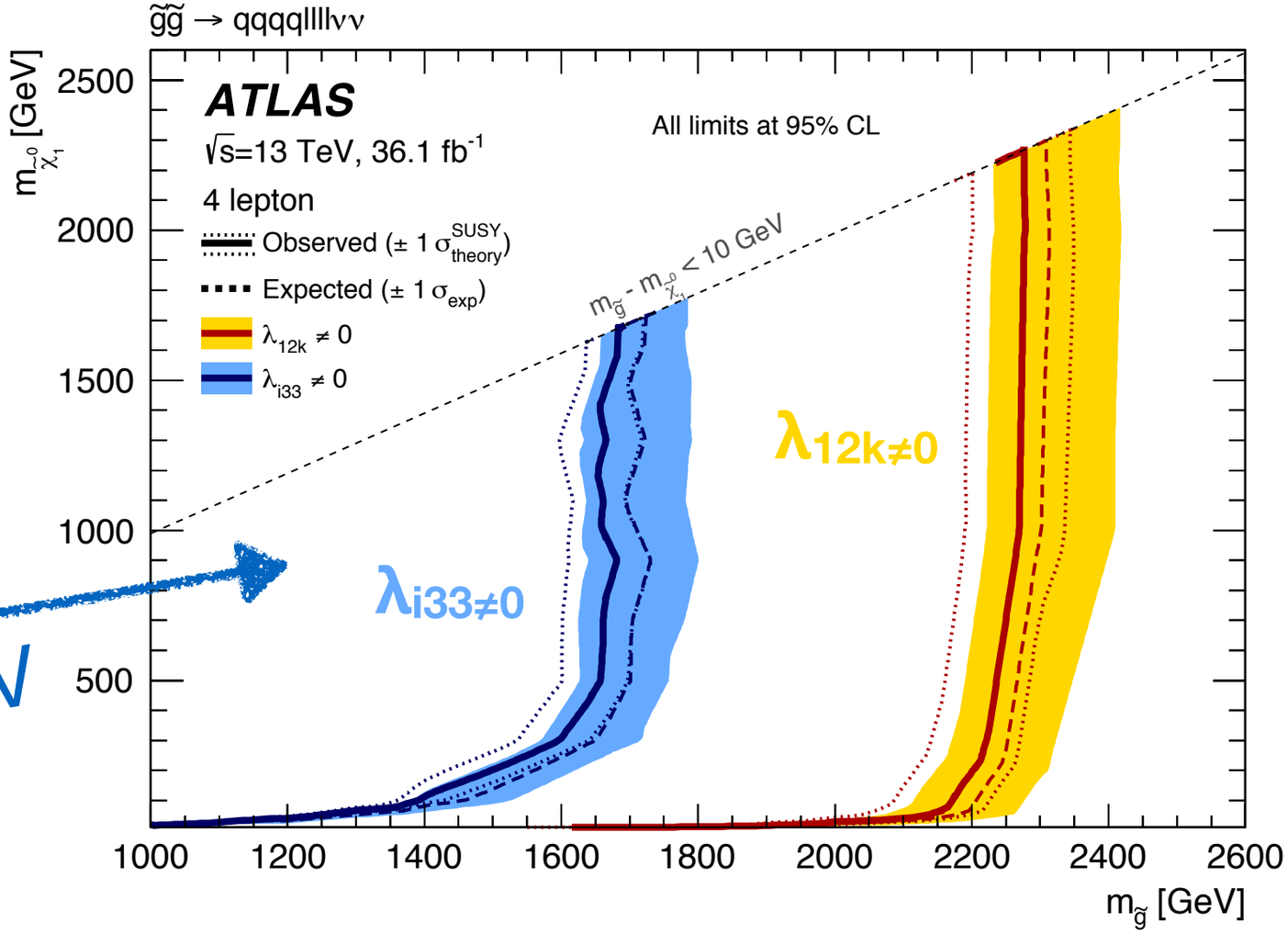
36.1 fb-1 data collected by the ATLAS experiment in 2015 + 2016, 04/17

- Search events containing **4 isolated, charged leptons.**
- Reconstructed Z, presence of hadronically decaying tau, and MET to define different regions of sensitivity.



RPC

RPV



- Signal regions designed to explore two RPV decays. Sensitivity to other couplings not explicitly covered, e.g. λ_{ijk} =123 falls in between.
- **A common signature can be interpreted as a search for either RPC and RPV SUSY models when combined with additional constraints, e.g. low or high MET.**

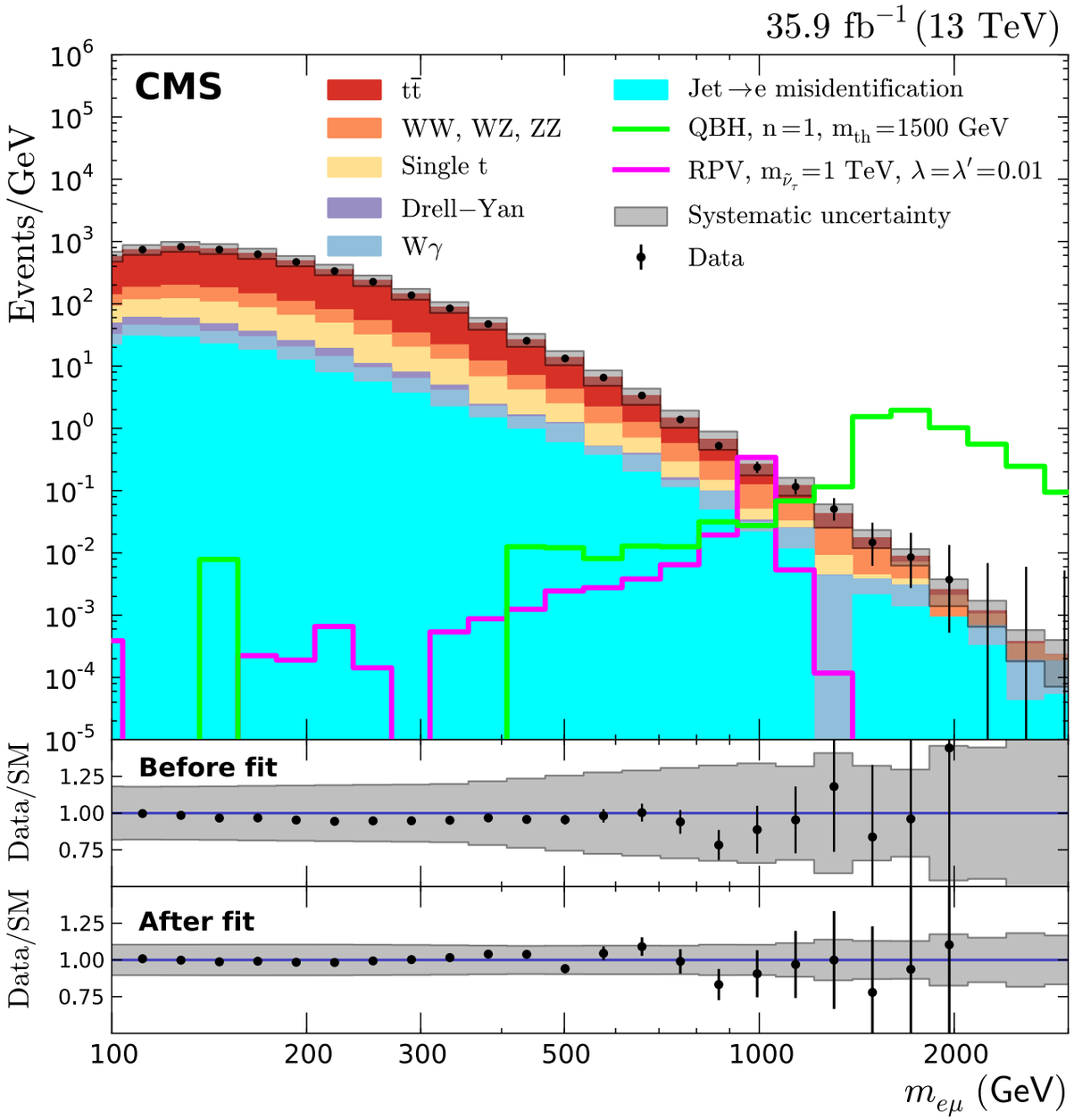
rcarney@slac.stanford.edu

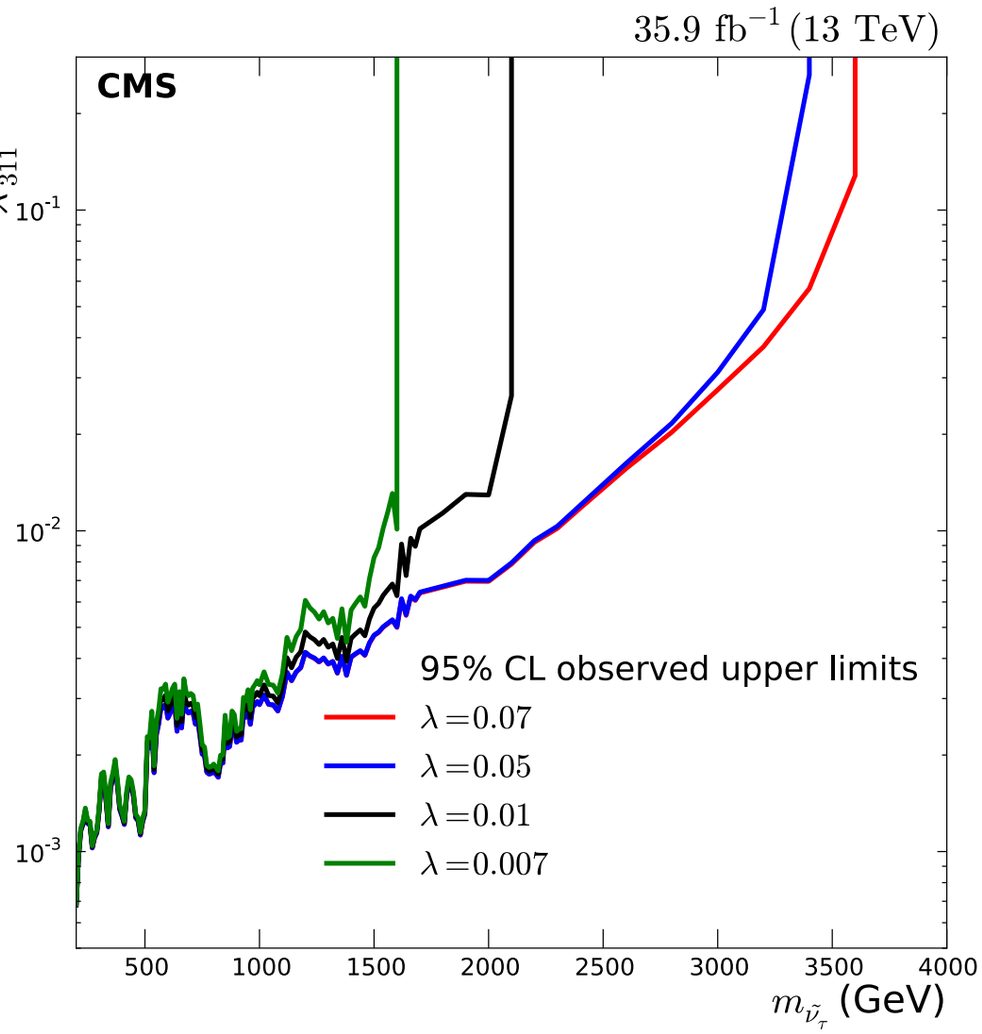
$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k$

Resonances

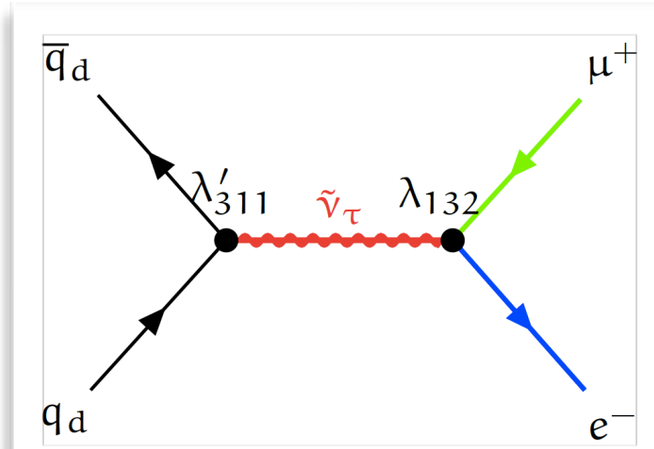
LLE =132 & LQD = 311

35.9 fb-1 data collected by the CMS experiment in 2016, 02/18





- Focusing on the mu-e decay here, obviously dd-bar also possible. ATLAS analysis also released in 2018 includes Tau in final states.
- **RPV allows for resonant production, but requires assumptions about both production and decay couplings!**

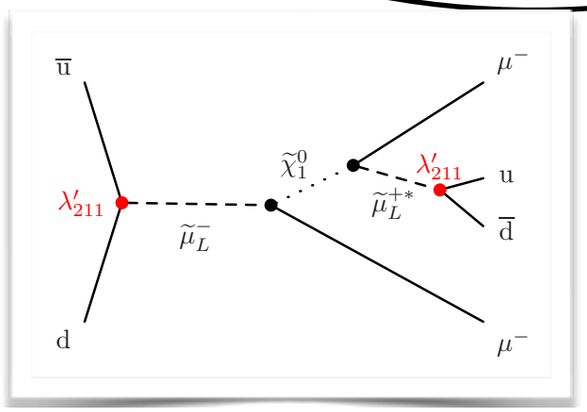


rcarney@slac.stanford.edu

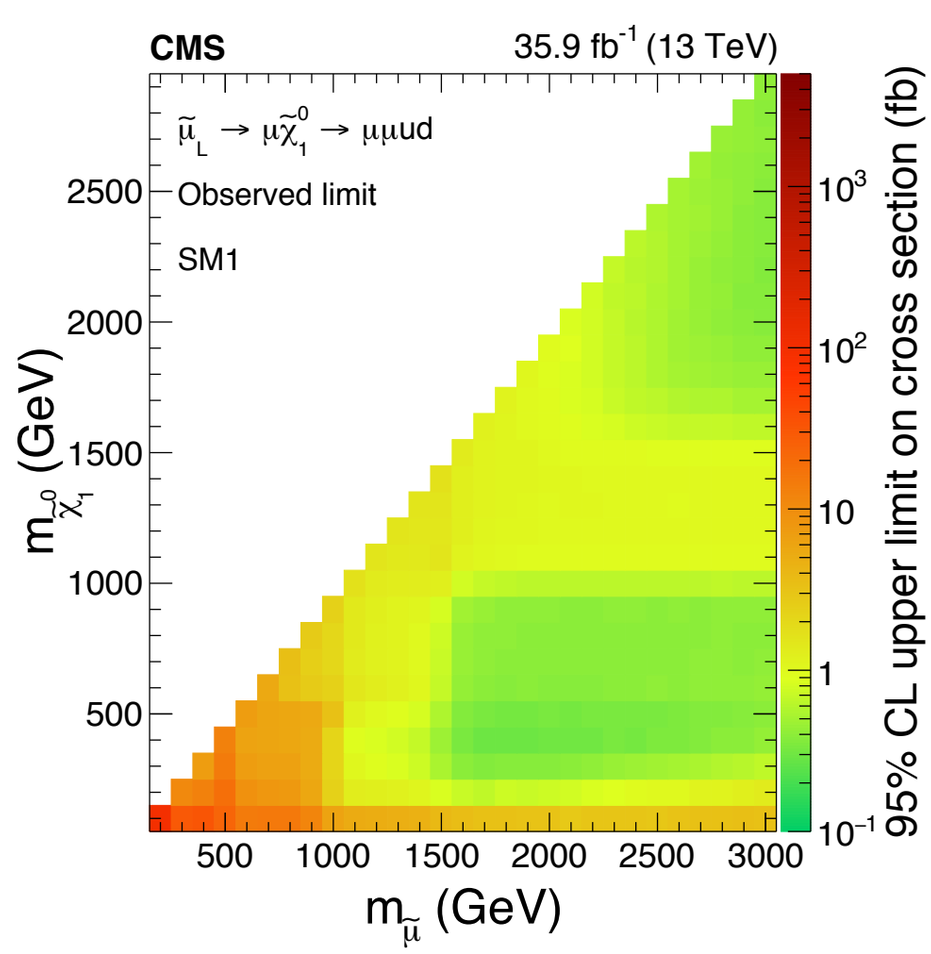
$\lambda'_{ijk} L_i Q_j \bar{D}_k$

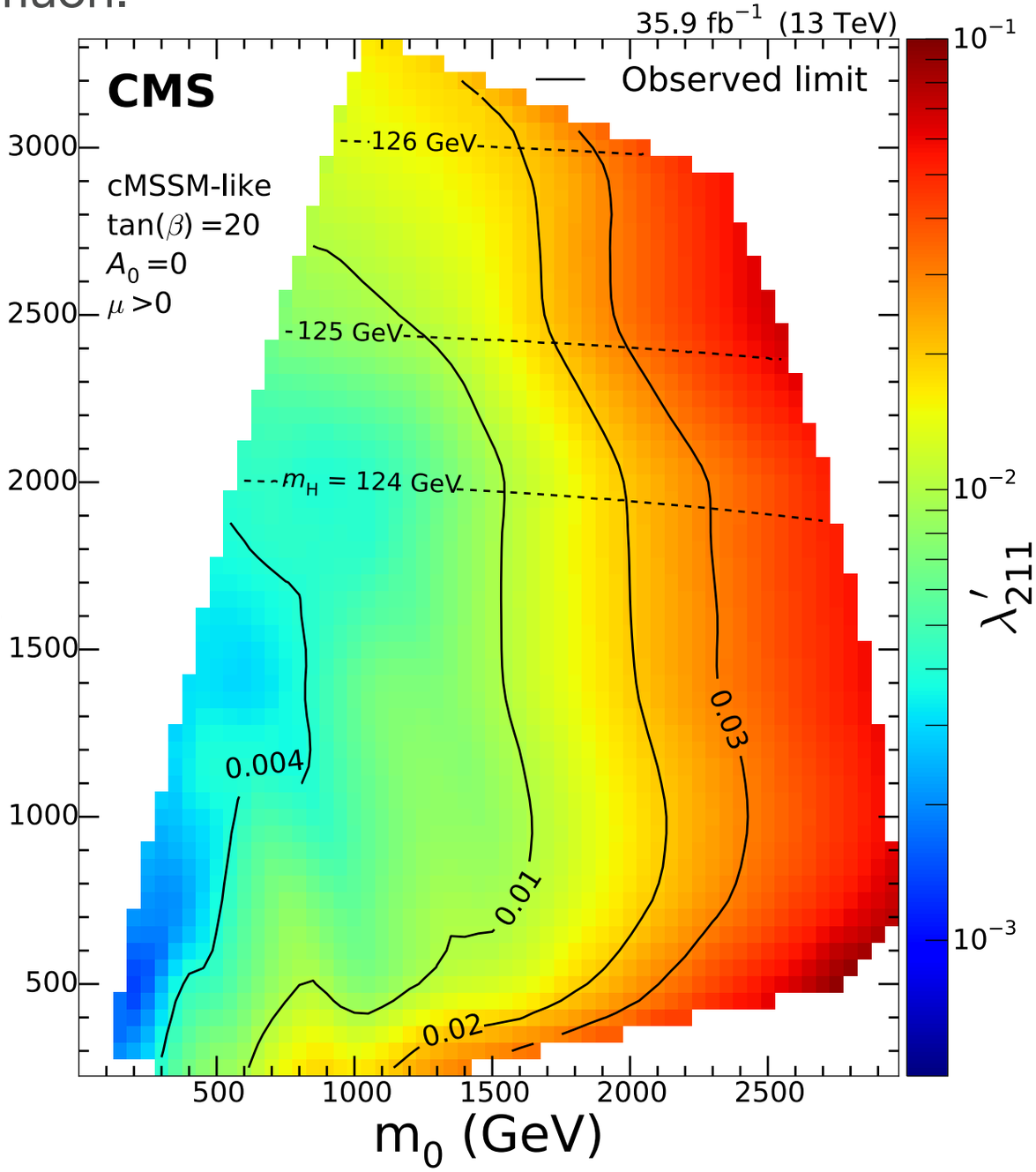
Resonances II

35.9 fb-1 data collected by the CMS experiment in 2016, 11/18



- Resonant smuon production, same RPV coupling at production and decay vertices.
- Same-sign di-muon events, small SM background.
- Sets limits on prod. cross section of smuon.
- Also sets limits on the RPV coupling constant, as a function of cMSSM mass terms.





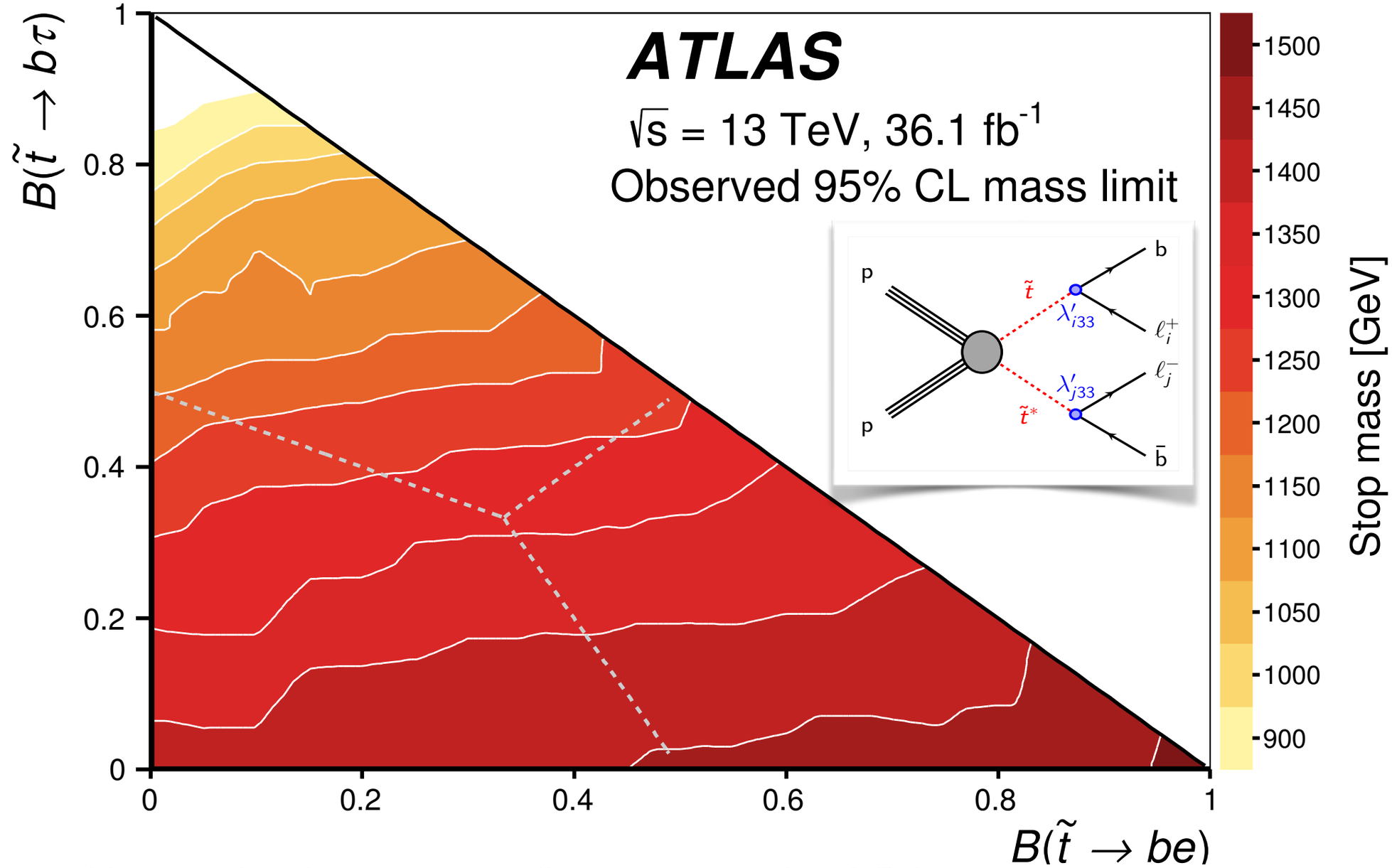
rcarney@slac.stanford.edu

$\lambda'_{ijk} L_i Q_j \bar{D}_k$

B-L & leptoquarks

LQD = i33

36.1 fb-1 data collected by the ATLAS experiment in 2015+2016, 10/17



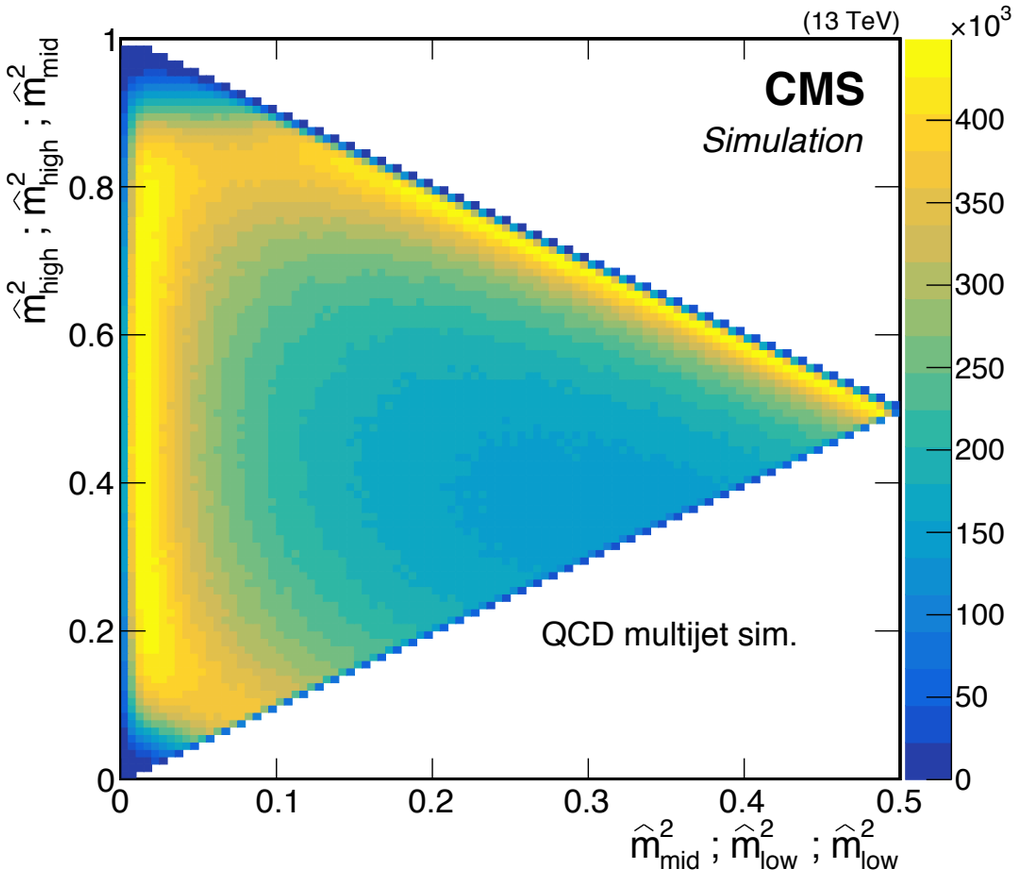
- Events with opposite sign e or muon flavor lepton pair + 2 B-jets.
- Reco b-hadron and lepton paired to minimize mass difference between pairs.
- Result scans stop branching ratio between leptons.
- CMS recently released a search for leptoquarks. Similar strategy and signature. Recast for RPV stop decay production cross-section.
- **RPV SUSY can be investigated in non-RPV dedicated searches too!**

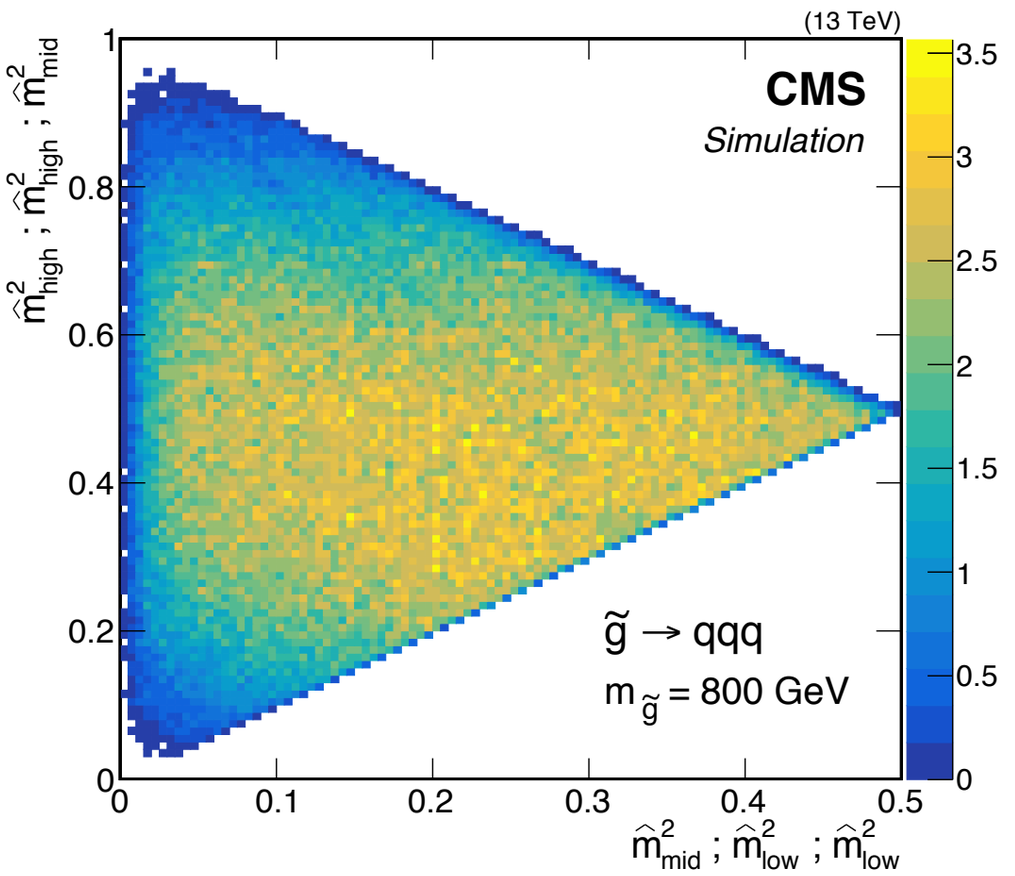
rcarney@slac.stanford.edu

$\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$

Multi-jet 1

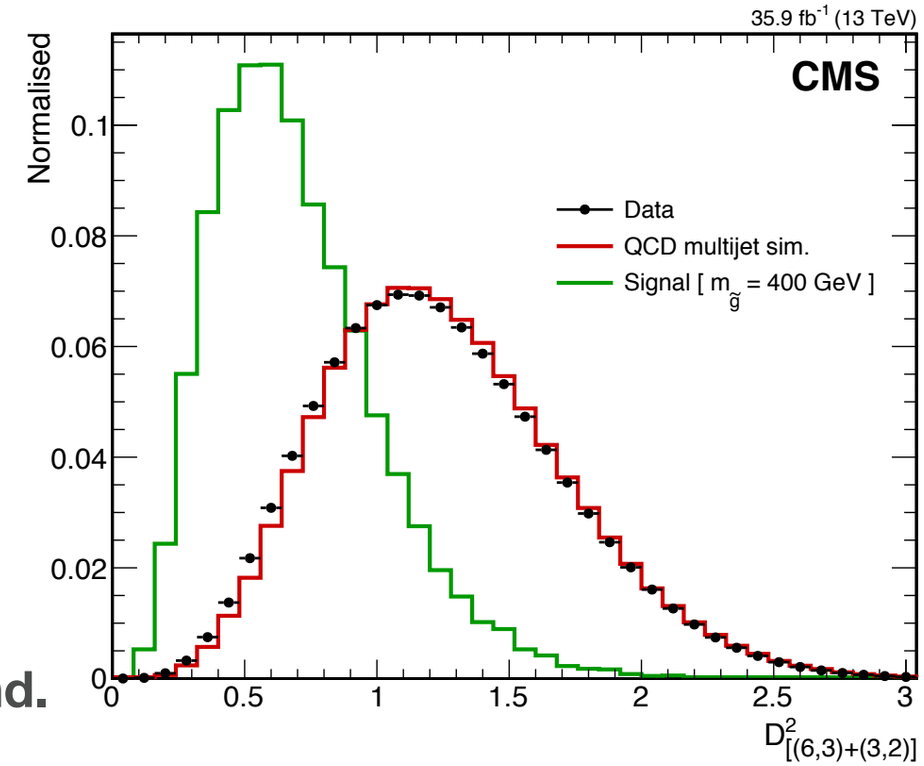
35.9 fb-1 data collected by the CMS experiment in 2016, 10/18





- Take 6 highest pT jets in event and arrange into combinations of triplets to make Dalitz vars.

$$D^2_{[(6,3)+(3,2)]} = \sum_{i<j<k} \left(\sqrt{\hat{m}(6,3)^2_{ijk} + D^2_{[3,2],ijk}} - \frac{1}{\sqrt{20}} \right)^2 .$$



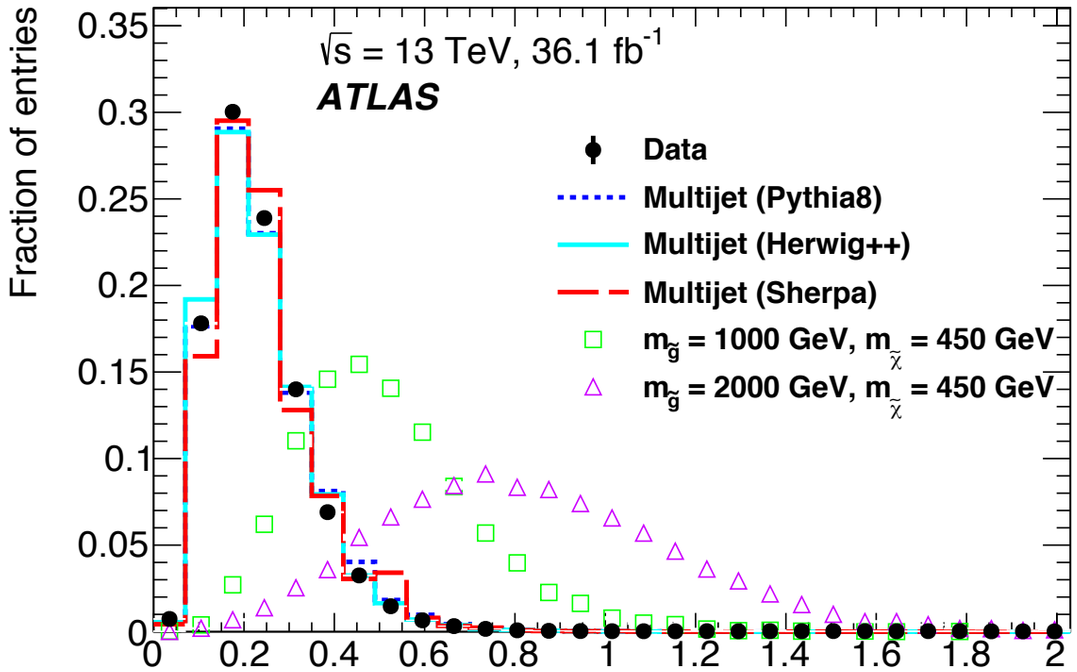
- Excludes gluinos decaying to 3 jets via RPV < 1.5 TeV.
- **This analysis uses a detailed understanding of jet properties and kinematics used as to discriminate between a signal event and the multi-jet background.**

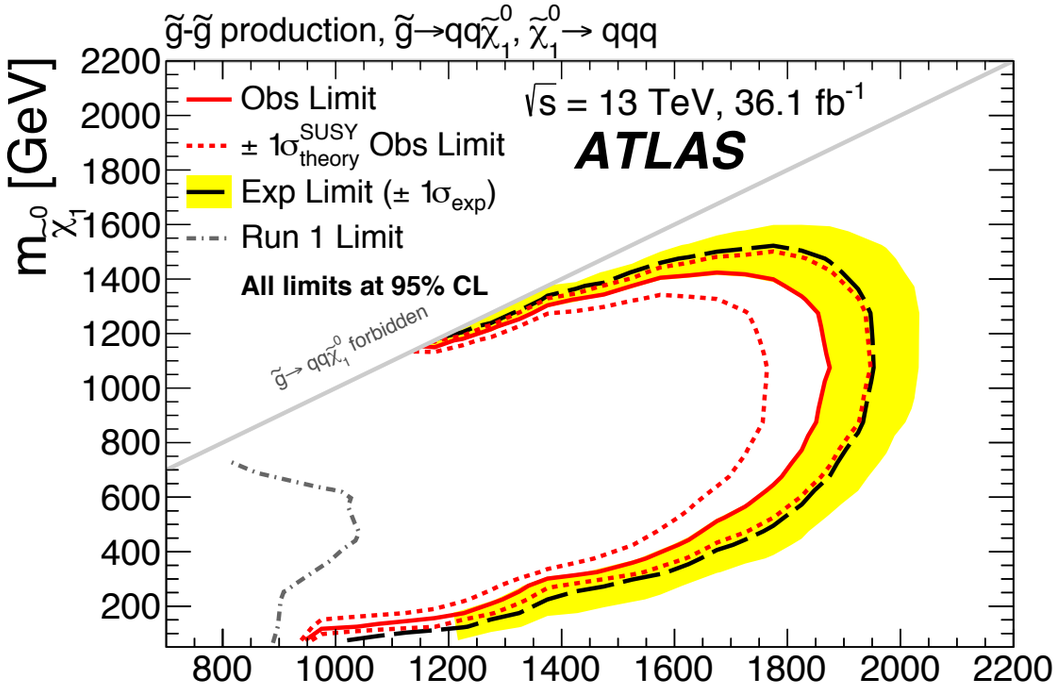
rcarney@slac.stanford.edu

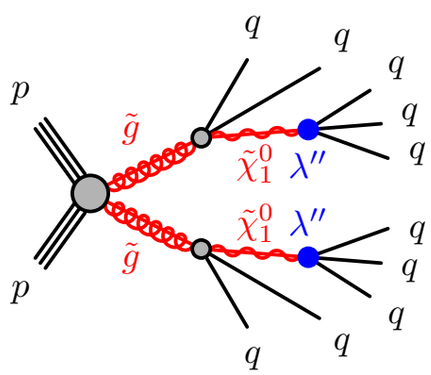
$\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$

Multi-jet 2

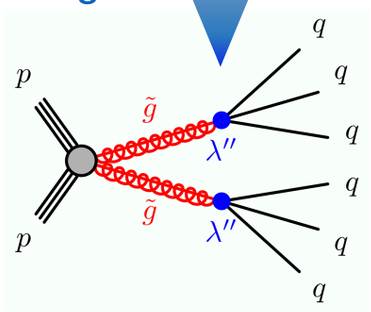
36.1 fb-1 data collected by the ATLAS experiment in 2015+2016, 04/18







Increasing RPV coupling strength



- Events selected with at least 4 jets.
- Scalar sum of 4 leading pT large-R jets as a discriminating variable.
- Use >120 templates to discriminate against background. Also allow b-tagged jets.
- Complimentary to the CMS search, they set a mass limit on cascade gluino decay in addition to the direct decay: probing a range of coupling strengths.
- **Same final state, different approach to background estimation, different sensitivity to models give optimizations.**

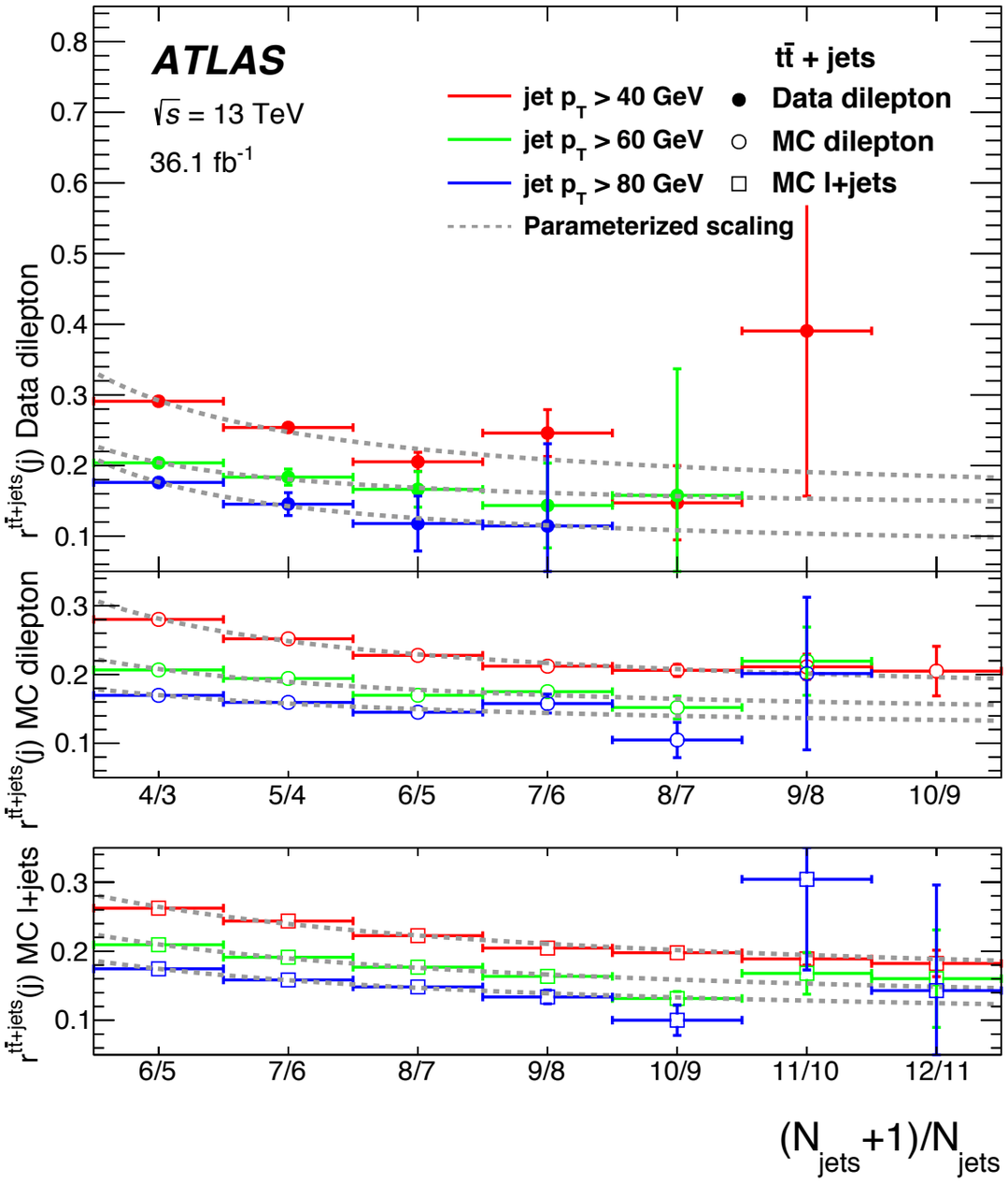
UDD λ''_{ijk}

rcarney@slac.stanford.edu

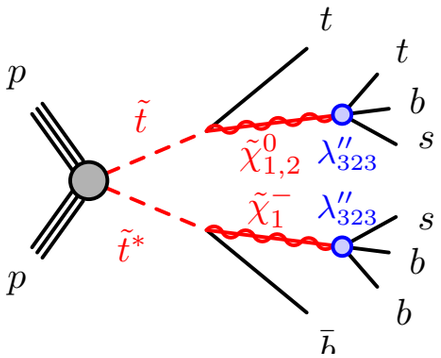
$\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k\ \lambda'_{ijk}L_iQ_j\bar{D}_k$

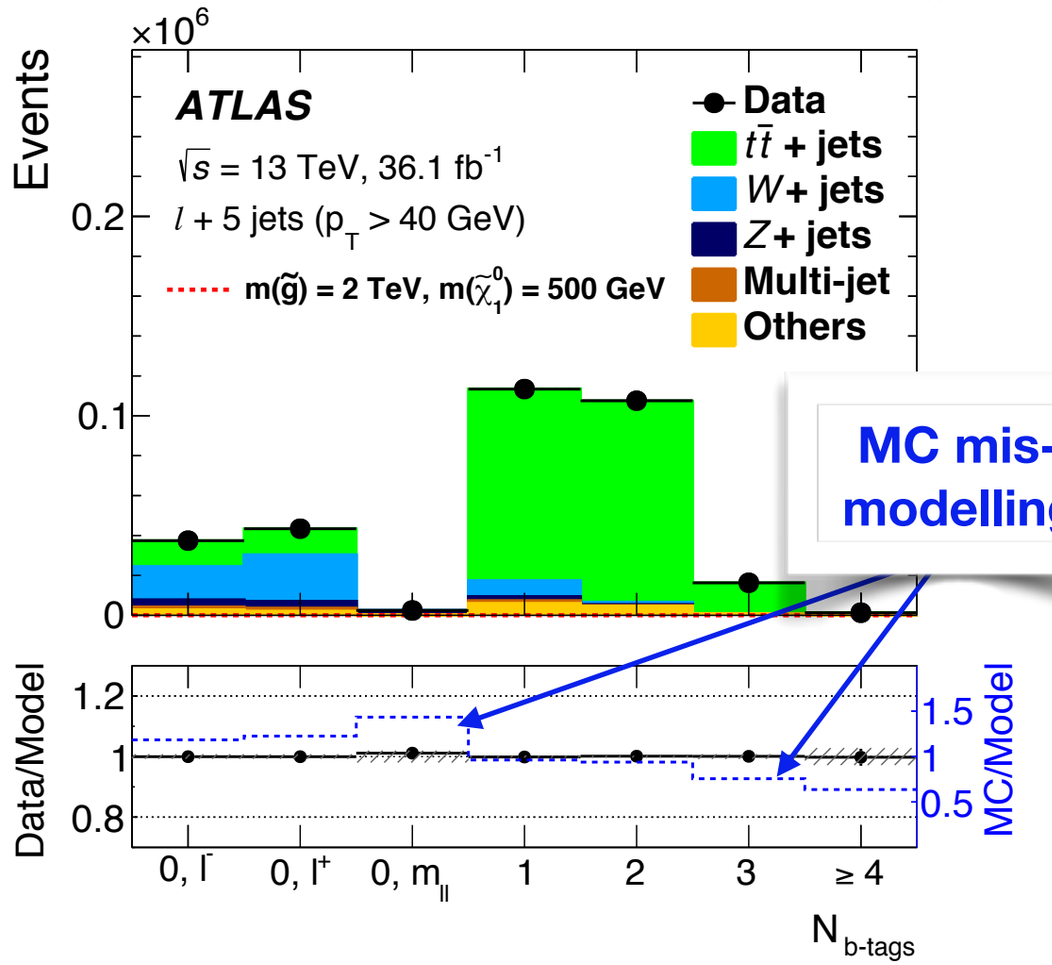
1L + jets

LQD = ijk, UDD = ijk



36.1 fb-1 data collected by the ATLAS experiment in 2015+2016, 04/17





- Requires isolated e or muon, 8-12 jets, 0-many b-jets; multiple signal regions.
- Theoretical modeling of ttbar, V+jet uncertainties dominate systematics, instead estimate background from parameterized extrapolations at low-multiplicity jet regions. Mismatch can be seen by comparing MC/model to data/model in results.
- **Improved background estimation technique helps set stringent limit on gluino and stop production as well as SM 4-top production.**

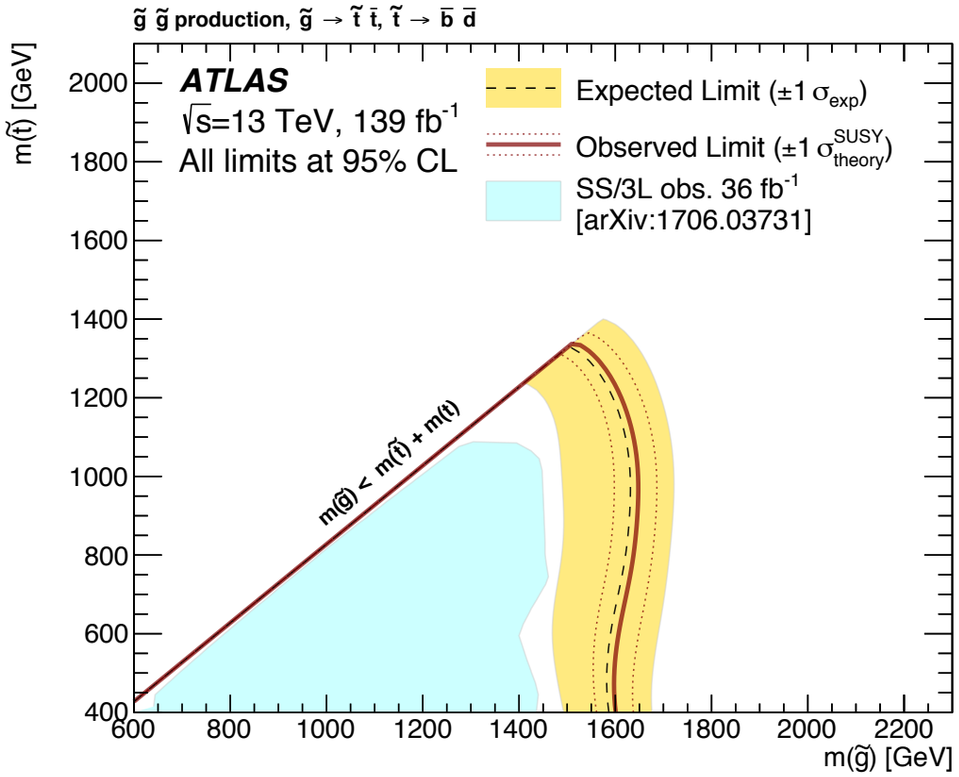
rcarney@slac.stanford.edu

$\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k\ \lambda'_{ijk}L_iQ_j\bar{D}_k$

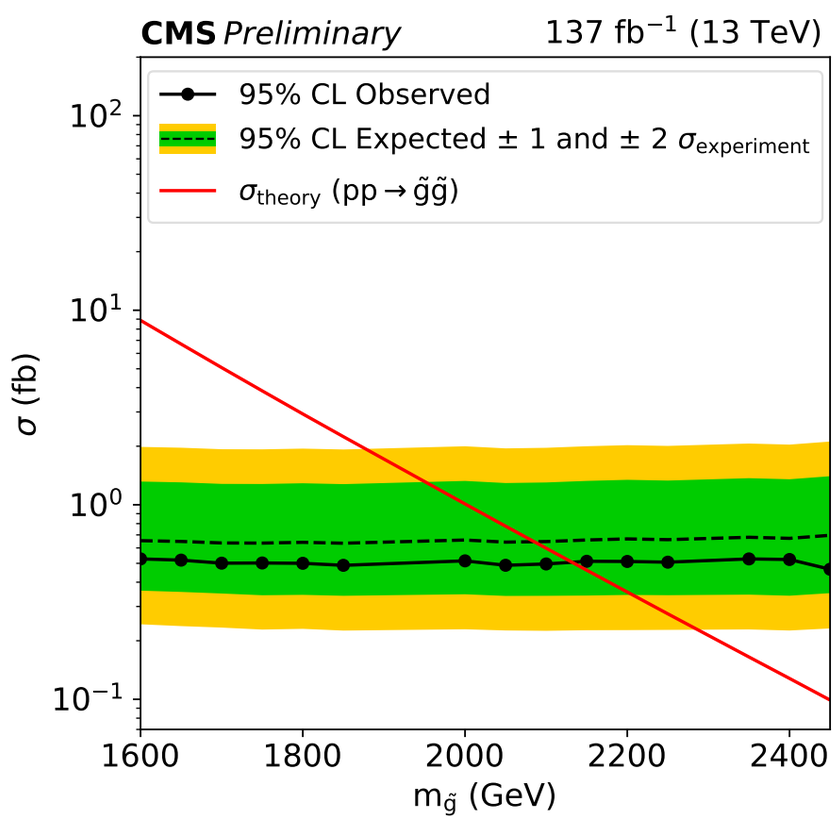
SS lep + jets

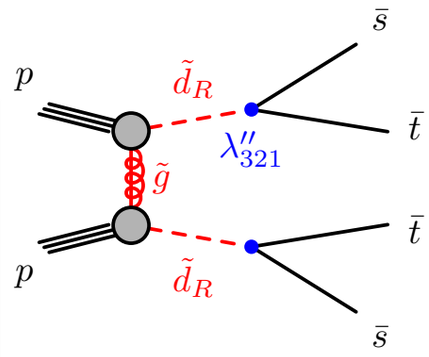
LQD = ijk, UDD

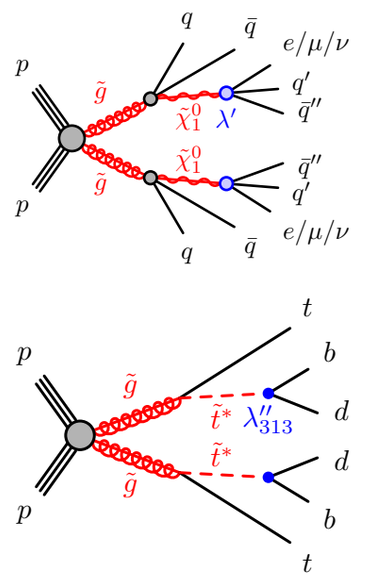
139 fb-1 data collected by the ATLAS experiment in 2015-2018, 09/19



139 fb-1 data collected by the CMS experiment in 2016-2018, 03/19



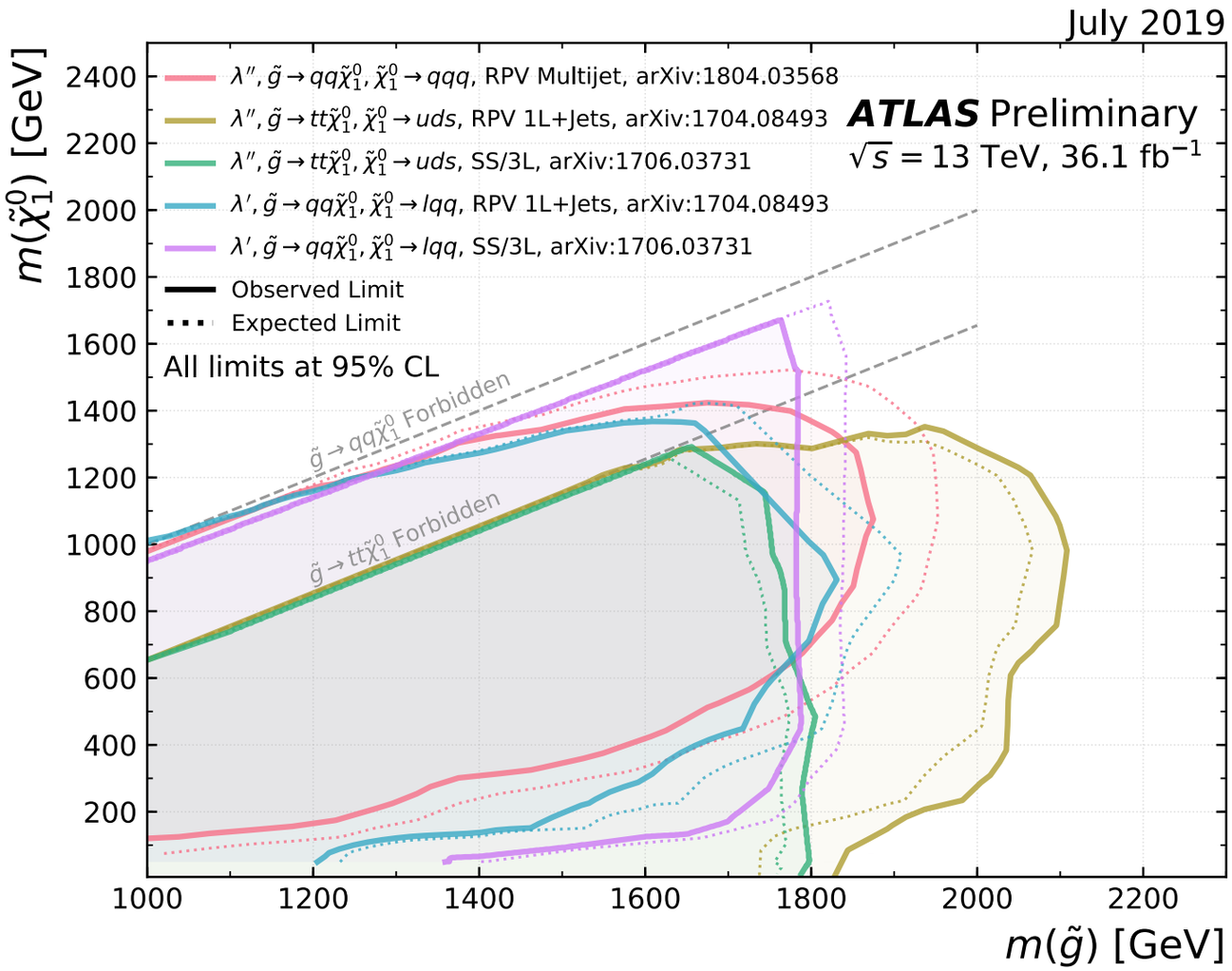


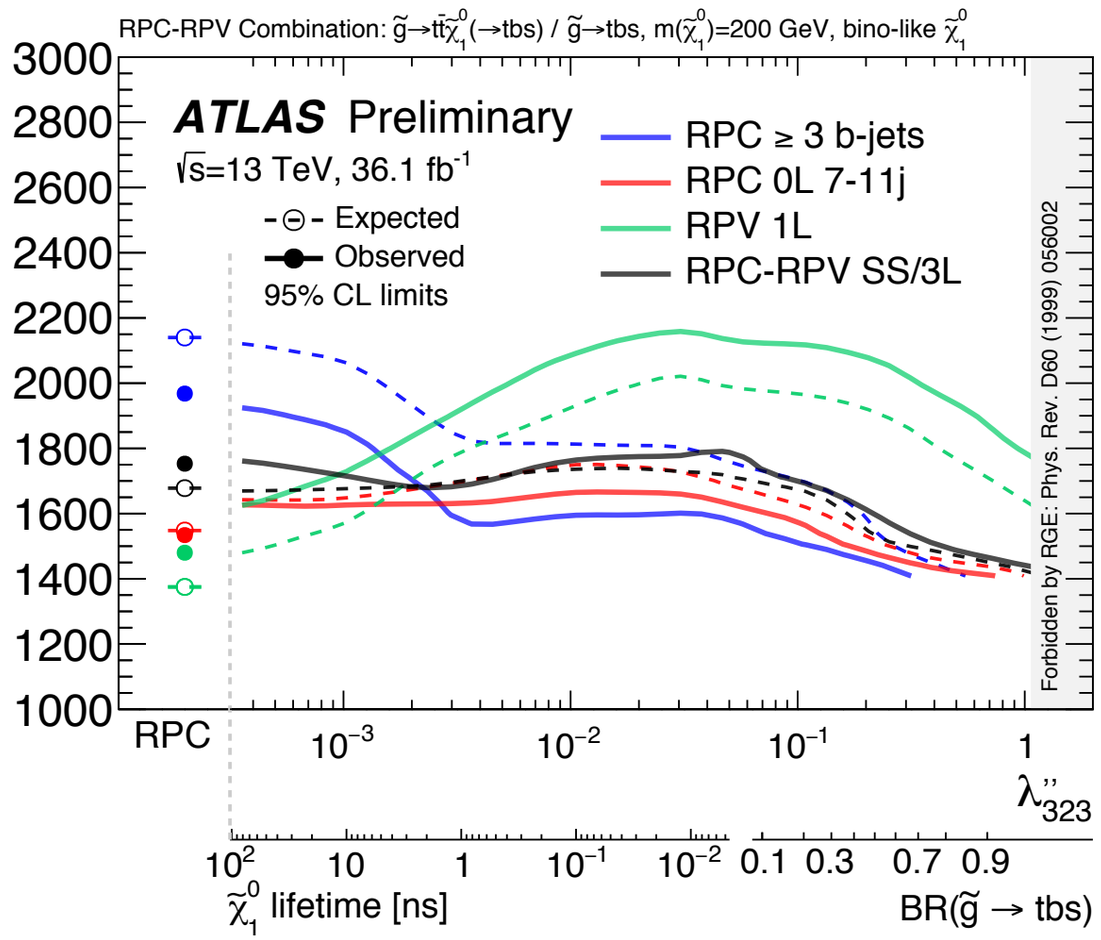


- **Full Run 2 dataset** analysis for both ATLAS and CMS.
- RPV decays have an increased likelihood of an event containing pairs of same-sign leptons compared to SM. So able to probe smaller sparticle masses.
- Search can be reinterpreted for RPV LQD or UDD, setting production cross-section limits on various masses of sparticles.
- Dominant uncertainty in both cases is charge-sign mis-ID.
- **Searches that take advantage of unique signatures with highly suppressed SM, such as same-sign leptons and jets can be interpreted for a wide range of models.**

rcarney@slac.stanford.edu

Summary and outlook





- The ATLAS and CMS programs are exploring a wide range of RPV signatures. In addition, **ATLAS has begun the process** of systematically studying our sensitivity to a range of RPV couplings using both prompt RPV search reinterpretations and dedicated long-lived analyses.
- Through extensive search program that bridges exotic physics searches, reinterpretations, and SUSY RPV dedicated searches and explore resonant production modes, multi-jet, same-sign and opposite sign leptonic final states, R-parity violating SUSY is being thoroughly explored at the LHC.

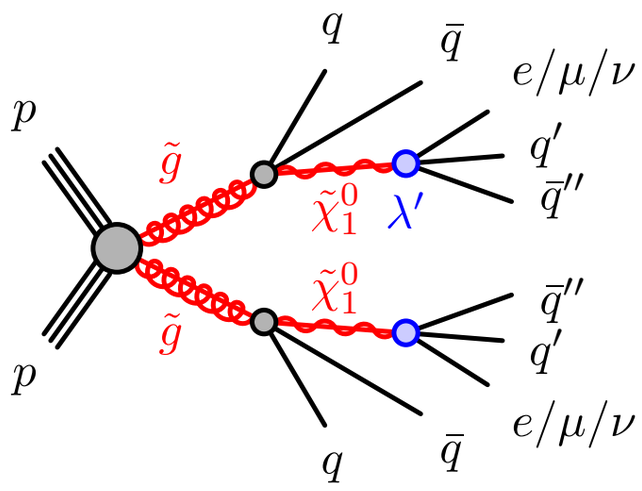
Thanks for your attention!

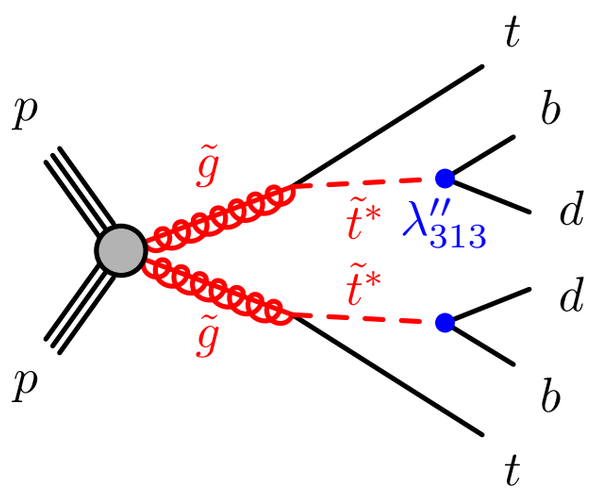
rcarney@slac.stanford.edu

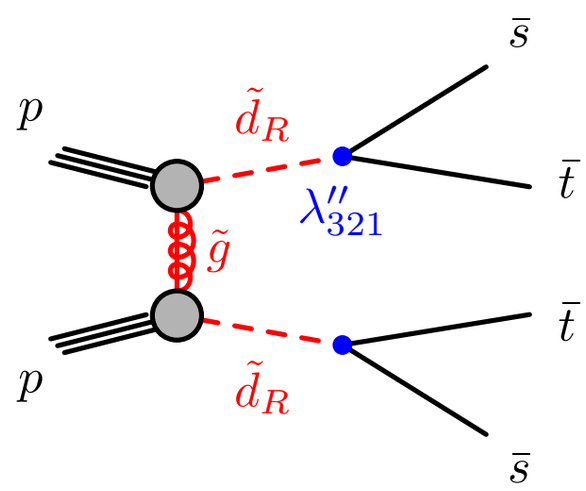
Backup

rcarney@slac.stanford.edu

$\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$ $\lambda'_{ijk}L_iQ_j\bar{D}_k$ **Same-sign** leptons







- In both LQD and UDD decays that include stop-top production, there is an increased likelihood of an event containing pairs of same-sign leptons.

$$\tilde{g} \to \tilde{t}\bar{t}, \quad \tilde{t} \to \bar{b}\bar{s} \quad \text{or} \quad \tilde{g} \to \tilde{t}^* t, \quad \tilde{t}^* \to bs$$

- e.g. If gluino decays to stops-top pairs, 50% of the time the tops will be same-sign. Then ~55% of the time, both tops will decay leptons. So ~27% of events with gluinos decaying to stop-top pairs have 2 SS leptons.
- Compared to other BSM searches, analyses based on these signatures therefore allow the use of looser kinematic requirements allowing us to probe smaller masses in RPV and RPC scenarios.
- Because initial event selection is quite generic there is sensitivity to a wide range of BSM physics processes, hence both papers interpret the results for many different models.