SuperSymmetry at the LHC and LHeC

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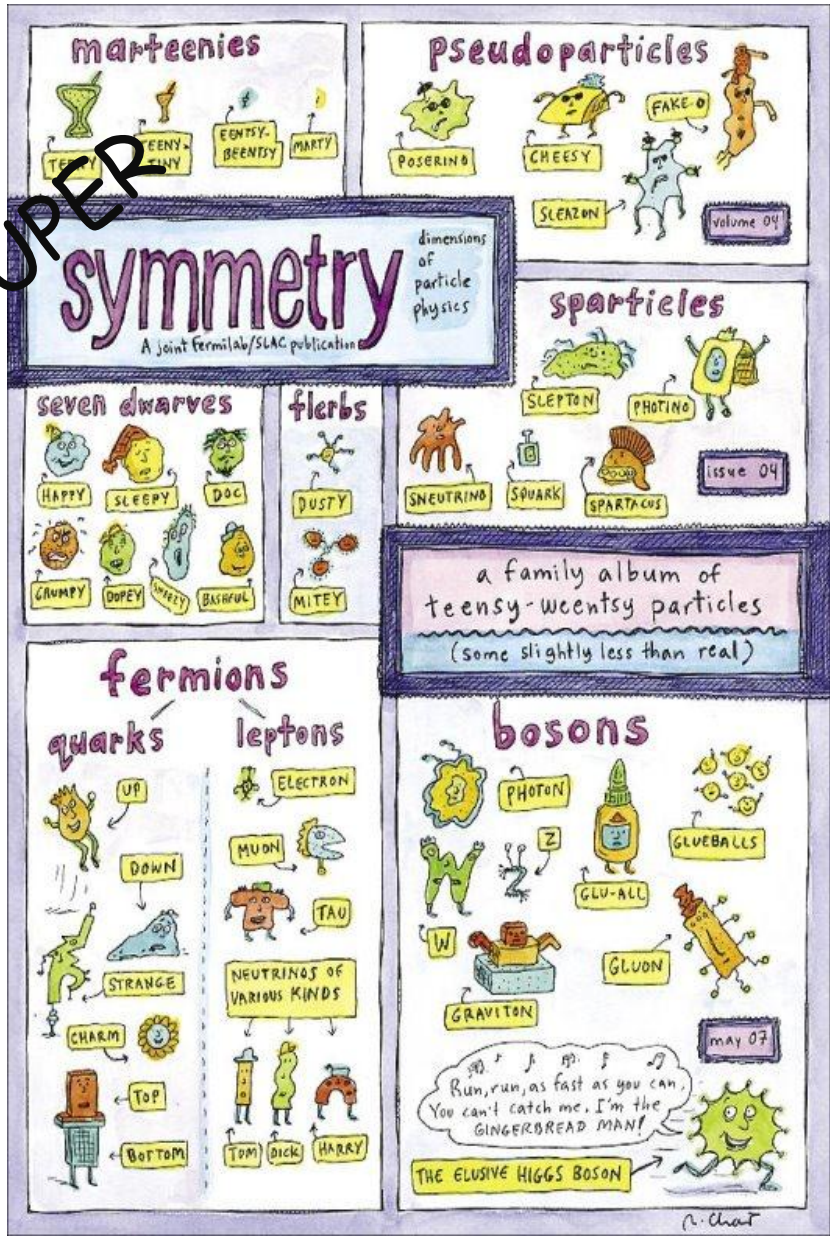


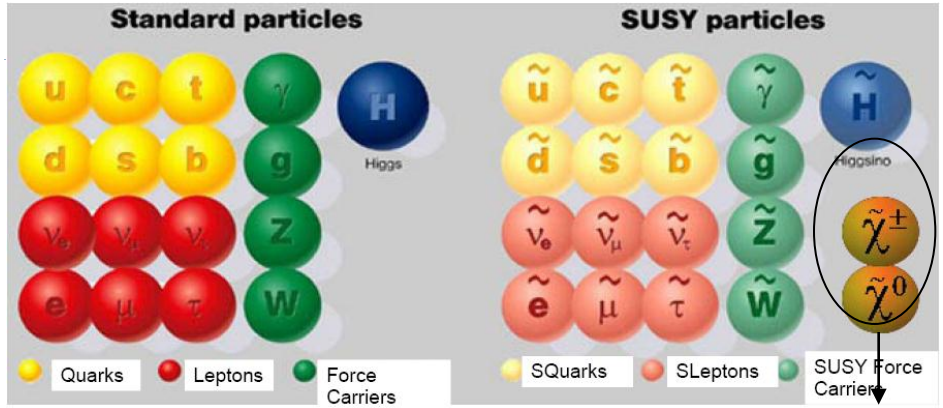
LHeC Workshop, Chavannes-de-Bogis, Switzerland
June 15th 2012

Supersymmetry in 30”

New spin-based symmetry relating fermions and bosons

Q|Boson> = Fermion

Q|Fermion> = Boson



gaugino/higgsino mixing

- Minimal SuperSymmetric SM (MSSM):
  - Mirror spectrum of particles
  - Enlarged Higgs sector: two doublets with 5 physical states

$$H_U, H_D \longrightarrow h, H, A, H^{\pm}$$

No SUSY particles found yet!

→ SUSY must be broken

$$L = L_{SUSY} + L_{Soft}$$

- Higgs mass stabilisation against loop corrections (fine-tuning problem)
- unification of gauge couplings at single scale
- possible dark matter candidate

SUSY breaking (hidden sector) → gravity *or* → MSSM (visible sector)

Gauge fields, loop effects….

R-parity

- Define R-parity = $(-1)^{3(B-L)+2s}$
  - R = 1 for SM particles
  - R = -1 for MSSM partners

If conserved (RPC), sparticles pair produced and Lightest SUSY Particle is stable (MET signatures)

If not conserved (RPV) → different terms, couplings constraint by proton decay

L-number violating terms

$$W_{\not R p} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k$$

bilinear terms

B-number violating terms

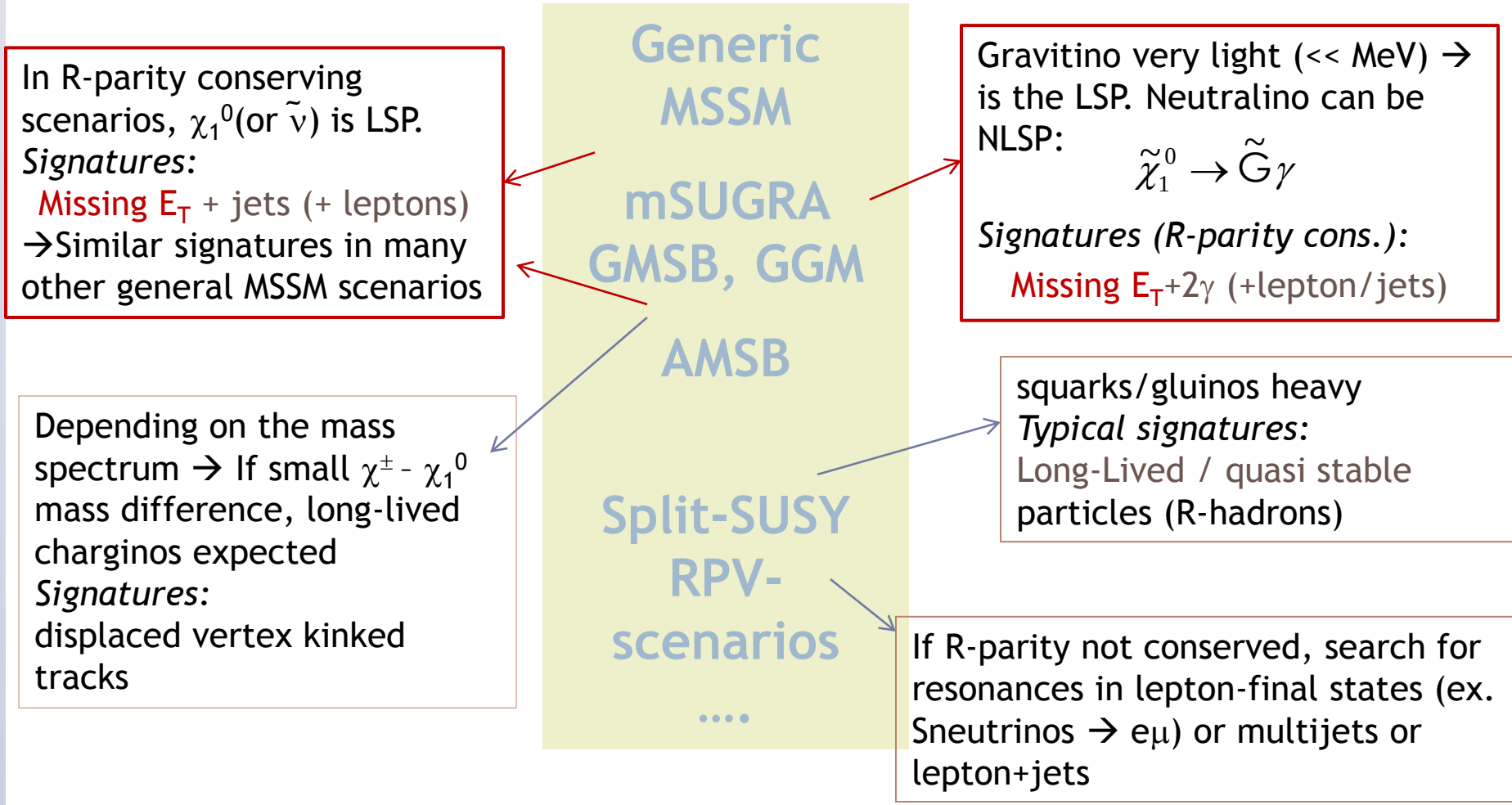
$\Delta L = 1$, 9 λ couplings, 27 λ' couplings

Pletora of new couplings, only partially constraints (m/100 GeV)

	$\lambda_{ijk}L_iL_j\bar{E}_k$	$\lambda'_{1jk}L_1Q_j\bar{D}_k$	$\lambda'_{2jk}L_2Q_j\bar{D}_k$	$\lambda'_{3jk}L_3Q_j\bar{D}_k$
weakest	0.07	0.28	0.56	0.52
strongest	0.05	$5.\cdot 10^{-4}$	0.06	0.11

SUSY phenomenology

R-parity but also breaking mechanism determine phenomenology and the search strategy at colliders



Outline

" The LHC is the primary machine to search for physics beyond the SM at the TeV scale. The role of the LHeC is to complement and possibly resolve the observation of new phenomena…"

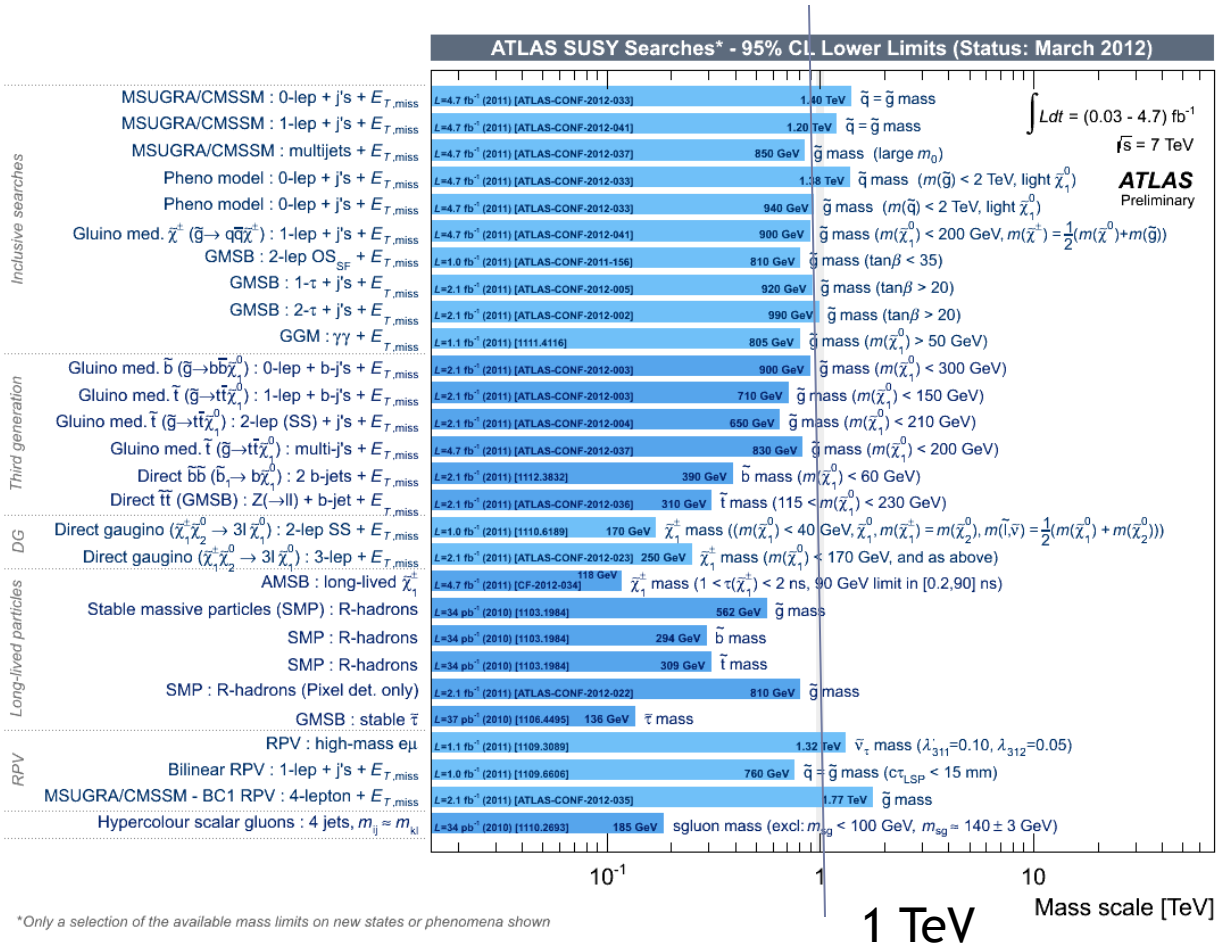
LHeC CDR

In this talk

- Brief overview of current LHC results in RPC and RPV SUSY
- Perspective for High Luminosity LHC (> 2020)
- **SUSY @ LHeC**
  - Possible searches in R-parity violation SUSY scenarios
  - complementarities with LHC:
    - Implication of LHC findings for LHeC reach
    - Implication of LHeC PDF constraints on SUSY for the LHC
    - New uncharted scenarios

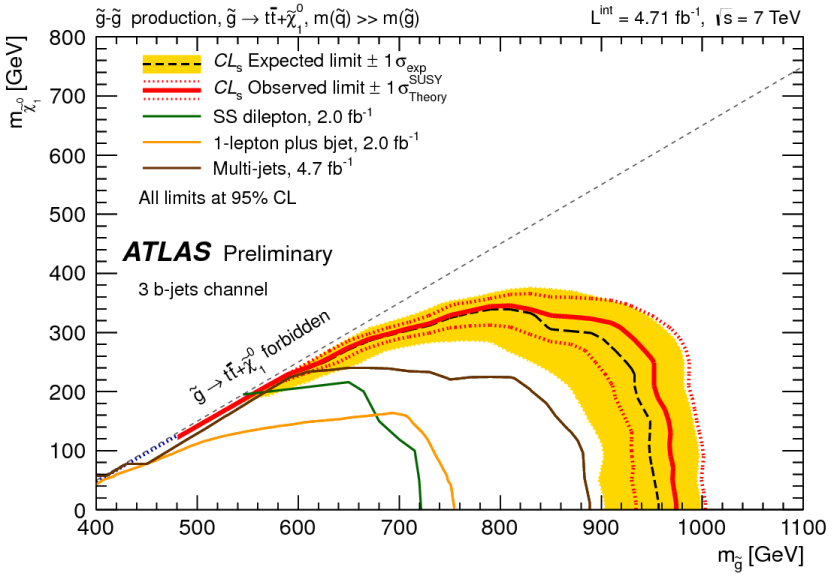
Current SUSY reach: a summary

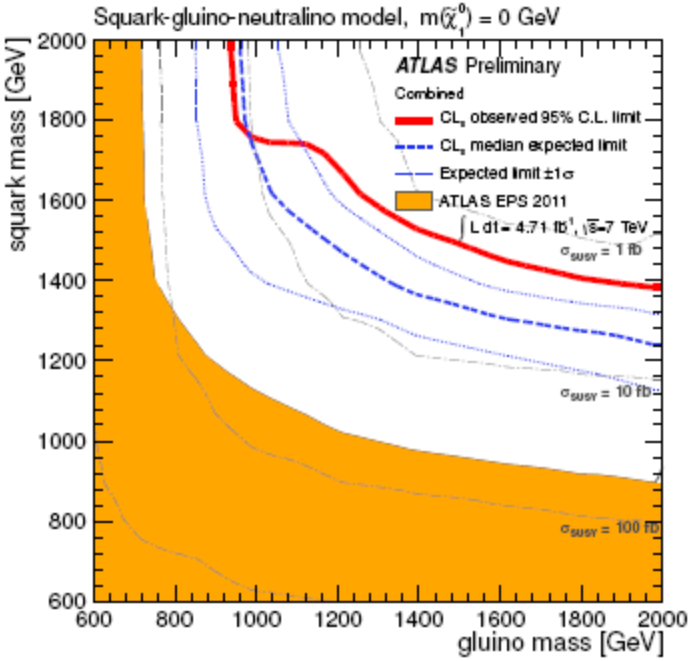
- SUSY has not been found so far, although we still have a long way to go:
  - Have excluded the easy scenarios (1st, 2nd generation squark, gluinos with mass up to 1 TeV for LSP masses ~ 300 GeV or below)



RPC scenarios: strong production

- Strong constraints on gluino (1 TeV) and squark masses (up to 1.4 TeV) under certain assumptions
  - 1st and 2nd generation squarks degenerate (limits on 3rd gen. squarks are much weaker)
  - Low LSP mass



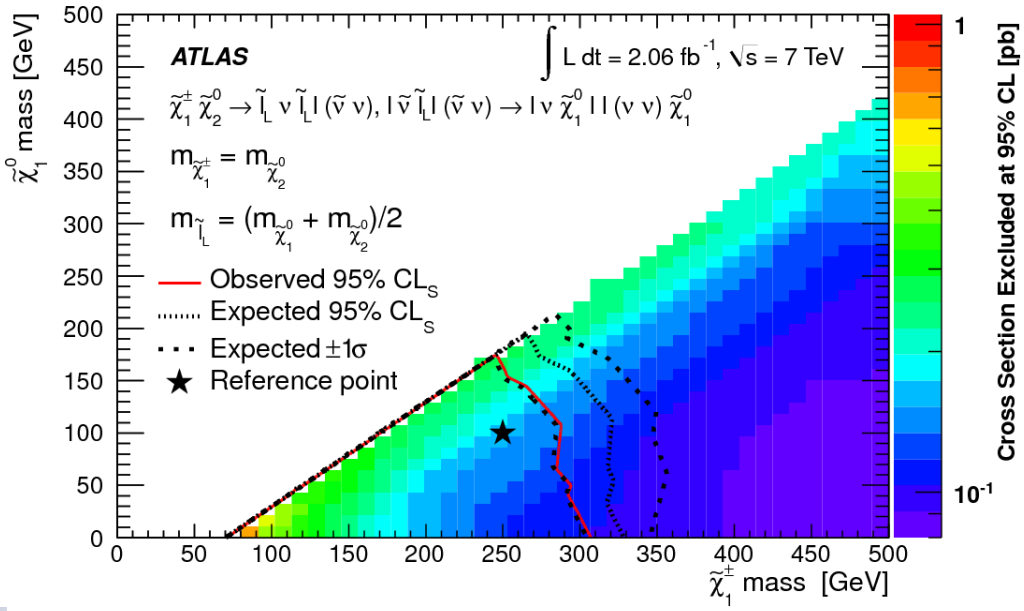


PDG Summary (2012)

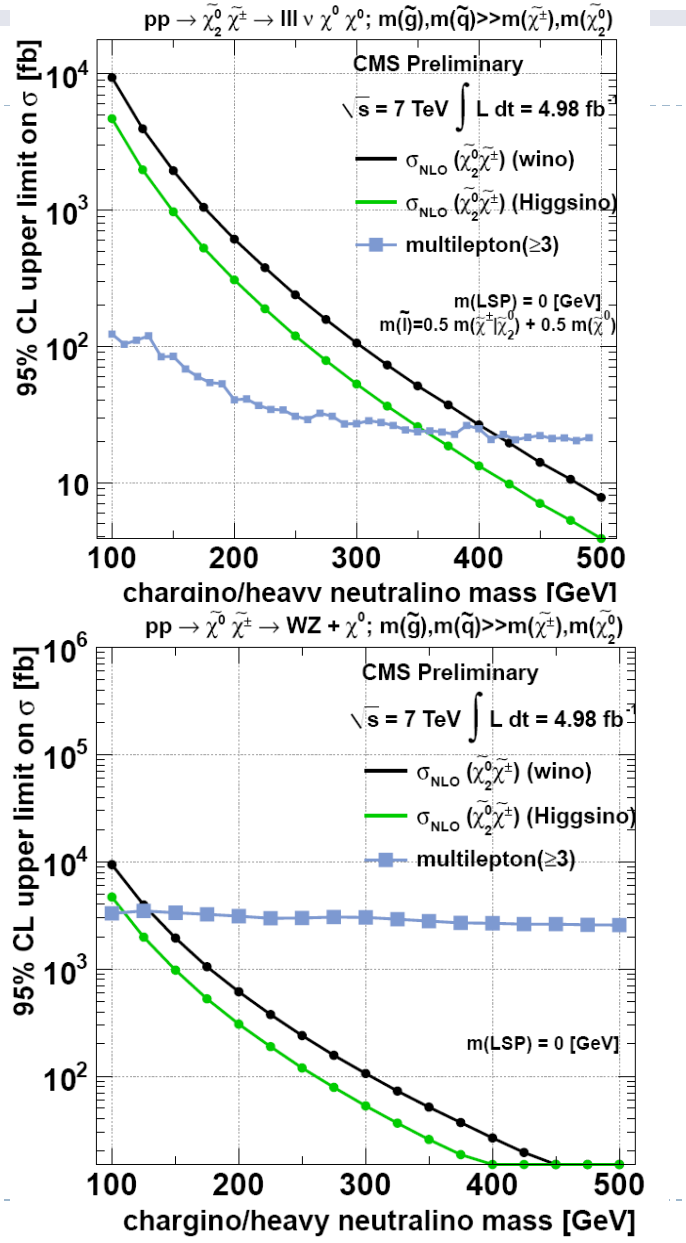
Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
CMSSM	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
	all $m_{\tilde{q}}$	-	800
	all $m_{\tilde{g}}$	1300	-
Simplified model $\tilde{g}\tilde{g}$	$m_{\tilde{\chi}_1^0}$ =0	-	900
	$m_{\tilde{\chi}_1^0} > 300$	-	no limit
Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\tilde{\bar{q}}$	$m_{\tilde{\chi}_1^0}$= 0, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0}$= 0, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0}$= 0, all $m_{\tilde{q}}$	-	900

RPC scenarios: weak production

- constraints on chargino-neutralino pair production with and without sleptons:
  - And starting to exclude low mass scenarios



- No (yet) constraints on slepton masses
  - although indirect exclusion can be inferred by lepton-based strong production searches under specific assumptions



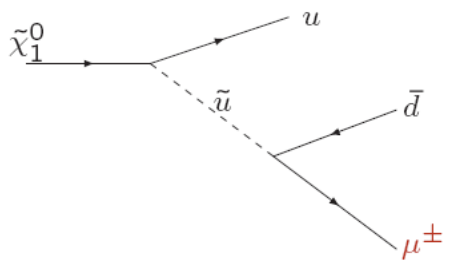
RPV scenarios

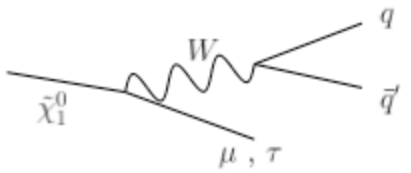
- Much more final states to explore and not yet searched for:
  - LSP no longer stable
  - Can be something like

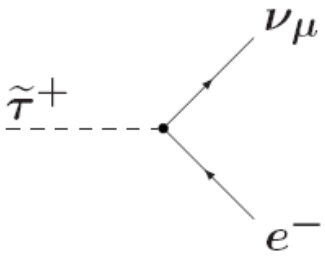
  > 700 possibilities + bilinear couplings!

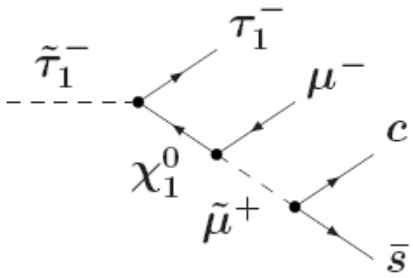
H. Dreiner (18/4/12)

$$\begin{pmatrix} \text{pair production: } \tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g} \\ \text{resonant } \tilde{\ell} \text{ production} \end{pmatrix} \otimes \begin{pmatrix} \underline{\text{LSP}} \\ \tilde{\chi}_1^0 \\ \tilde{\chi}_1^+ \\ \tilde{\nu}_L \\ \tilde{\ell}_{L,R}^{\pm} \\ \tilde{\tau}_1^{\pm} \\ \tilde{q}_{L,R} \\ \tilde{t}_1 \\ \tilde{g} \end{pmatrix} \otimes \begin{pmatrix} \underline{\text{Operator}} \\ L_1 L_2 \bar{E}_1 \\ \vdots \\ L_2 L_3 \bar{E}_3 \\ L_e Q_1 \bar{D}_1 \\ \vdots \\ L_\mu Q_1 \bar{D}_1 \\ \vdots \\ L_\tau Q_3 \bar{D}_3 \\ \bar{U}_i \bar{D}_j \bar{D}_k \end{pmatrix}$$







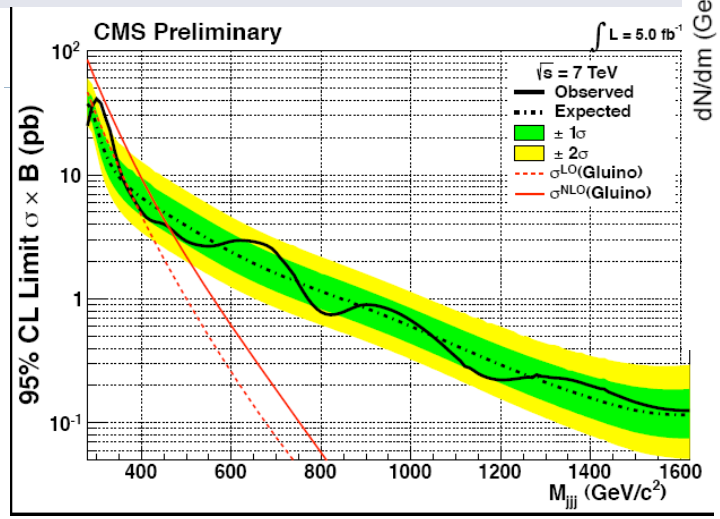


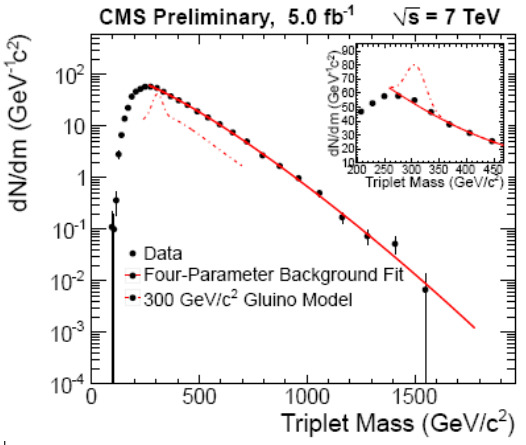
Result:
-- RPV SUSY under-constraint
-- limits depend on couplings assumptions

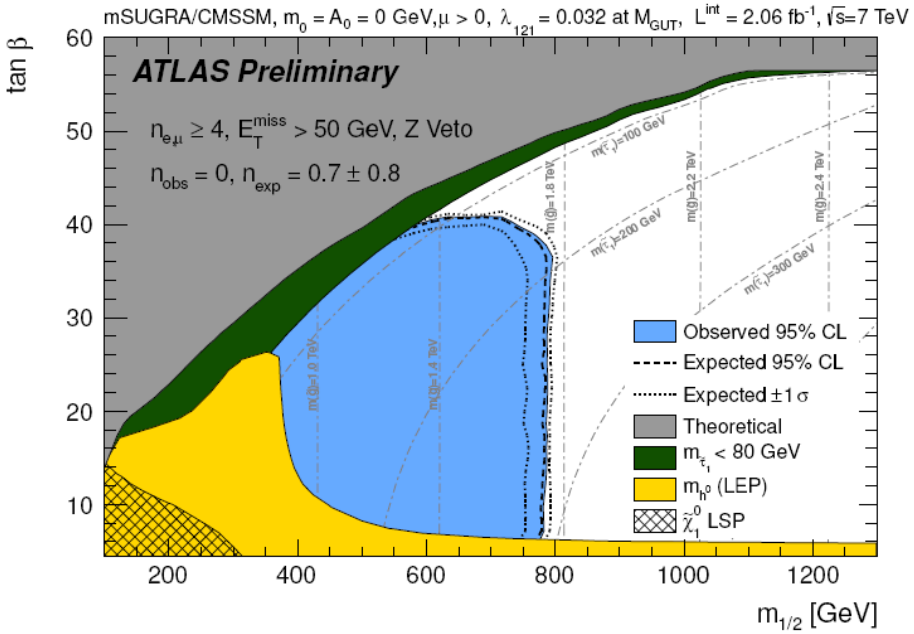
Few examples:

- Gluinos:
- Sleptons:

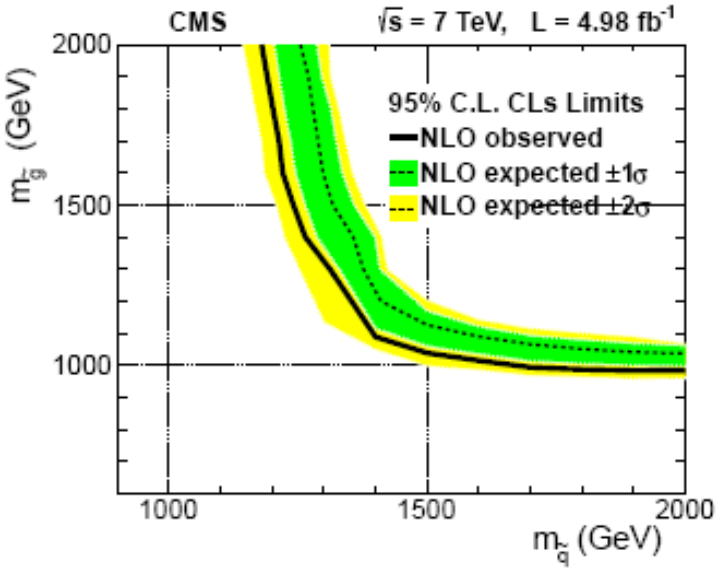
Gluinos → 3 jets





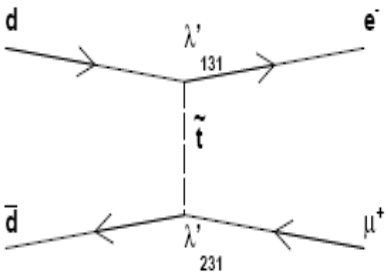


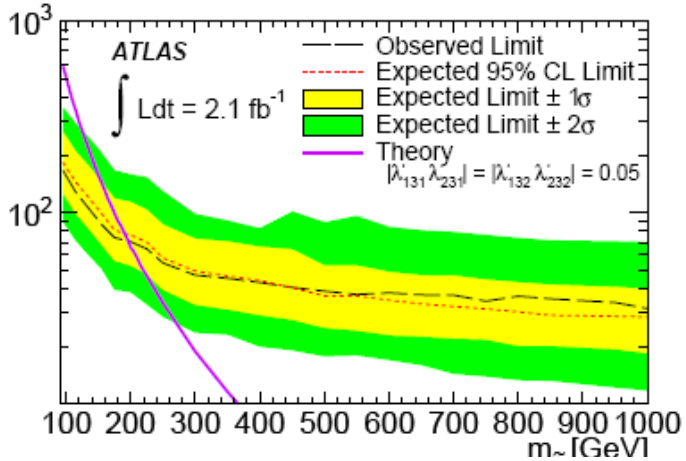
Lepton term: multilepton (λ_{123})

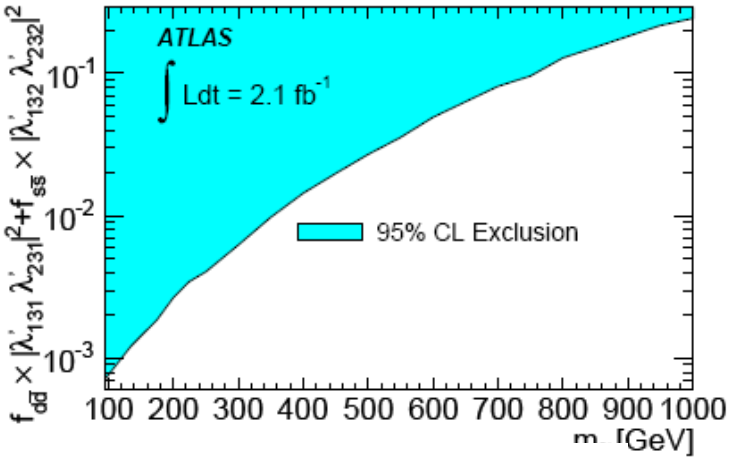


Other RPV SUSY searches

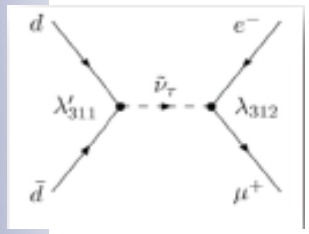
- Stop-mediated e-mu production



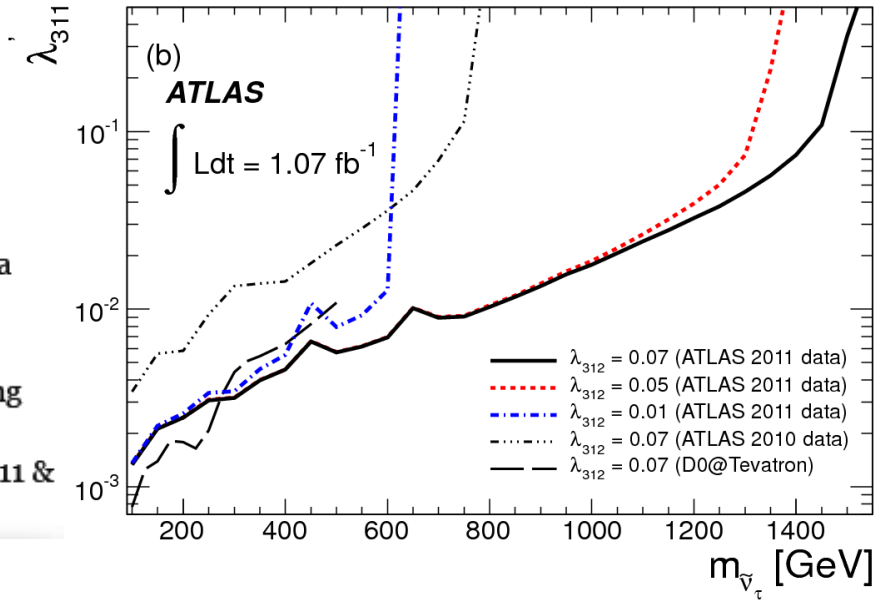




- Sneutrino e-mu



- 95% CL upper limits on $\sigma(pp \rightarrow \tilde{\nu}_\tau) \times BR(\tilde{\nu}_\tau \rightarrow e\mu)$ as a function of $m_{\tilde{\nu}}$
- Tau sneutrinos with a mass below 1.32 (1.45) TeV are excluded, assuming coupling values $\lambda'_{311} = 0.10$ & $\lambda_{312} = 0.05$ ($\lambda'_{311} = 0.11$ & $\lambda_{312} = 0.07$)



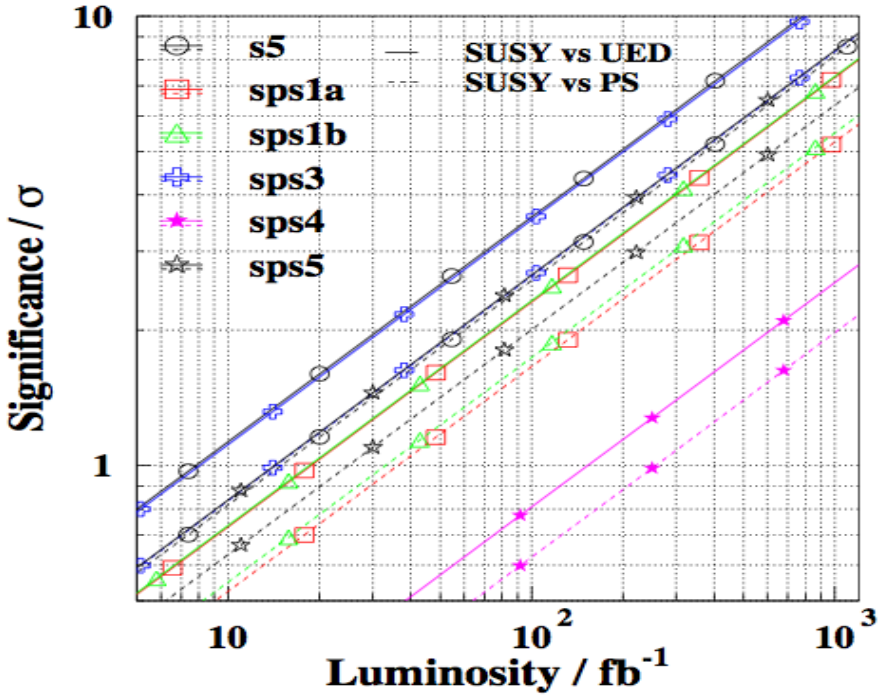
What can happen in 2020 ?

Let's assume we have *at least* seen the higgs ☺

- **Deviations from the SM observed in 300/fb**
  - Signal characterization with **3000/fb**
- **No deviations from the SM observed in 300/fb**
  - Extension of sensitivity (mass reach, xs reach) with 3000/fb

- *300 fb^{-1} @ 14 TeV: LHC Phase I*
- *3000 fb^{-1} @ 14 TeV: LHC Phase II*

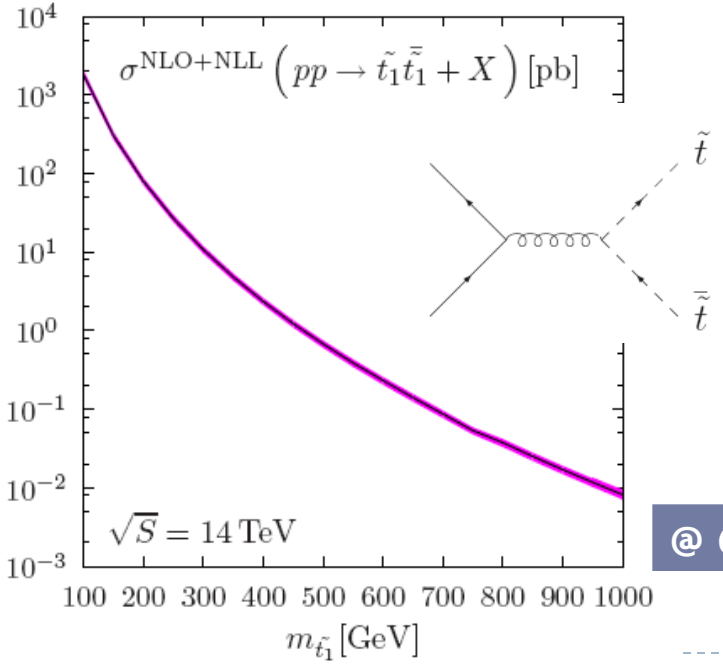
- Reconstruction of the mode at the bottom of the decay chain
- Determination of masses by measuring the endpoint of the visible mass distributions
- Measurement of couplings and spin (via angular analysis)

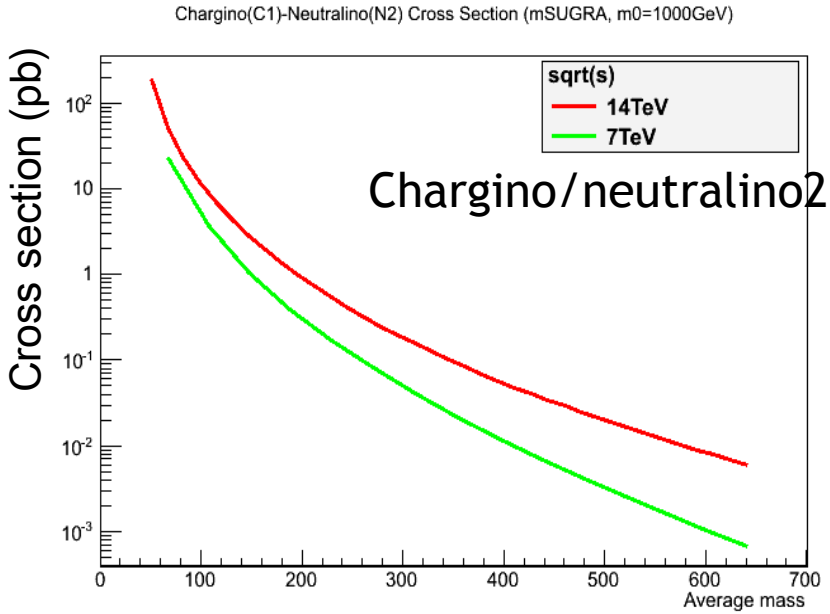


Main focus for 2020 plans

Mostl RPC SUSY:

- **Strong Production**
  - Squark-gluino, squark-squark, gluino-gluino
- **Third Generation Production**
  - Direct stop
- **Weak Production**
  - Weak gauginos [Sleptons] [Higgsinos]

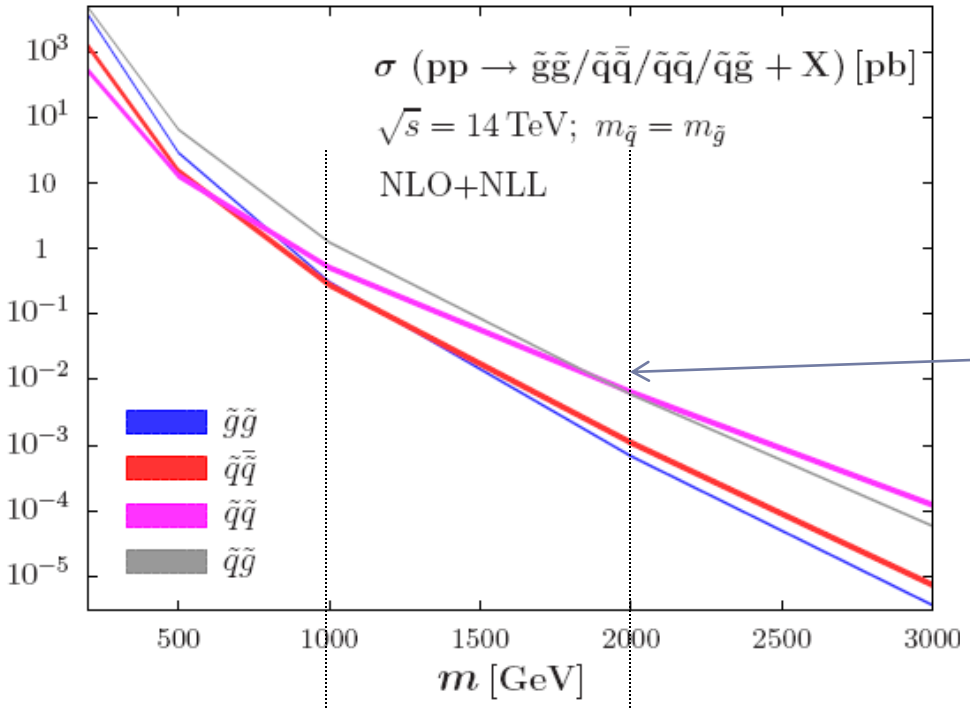




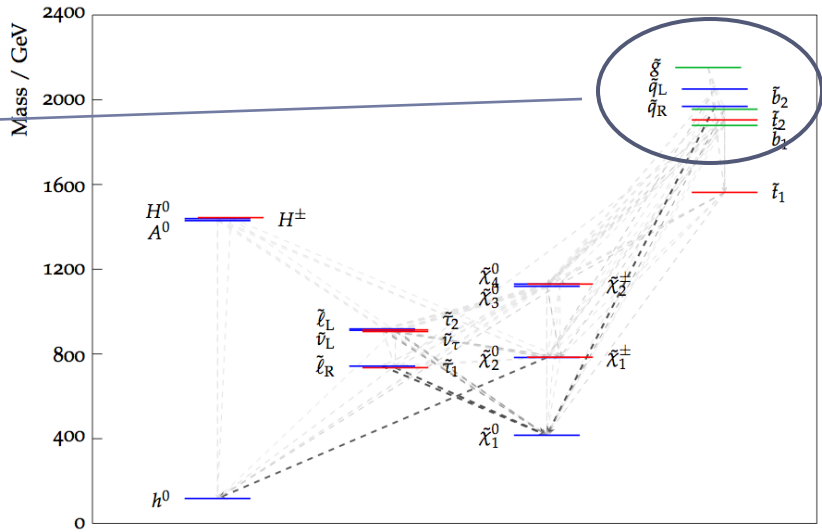
@ 600 GeV	0.24 pb

Strong production

- xsection ~ 2.5 pb for m = 1000 GeV, ~ 0.01 pb for m(squark, gluino) = 2 TeV → clearly, high stats samples are needed.



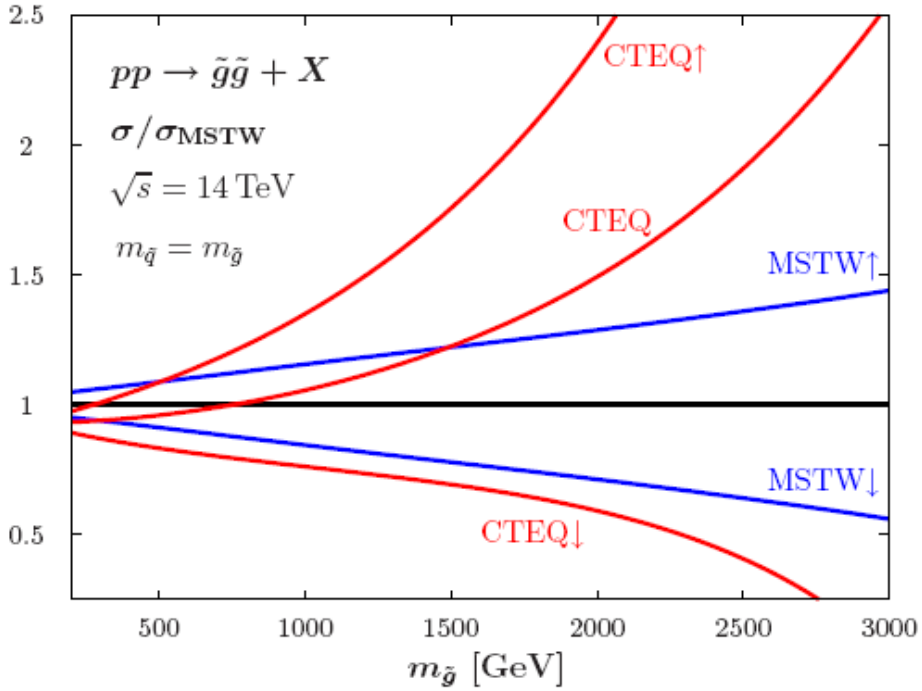
mSUGRA reference point:
m0=650, m1/2=975, xs 1.1E-05 nb

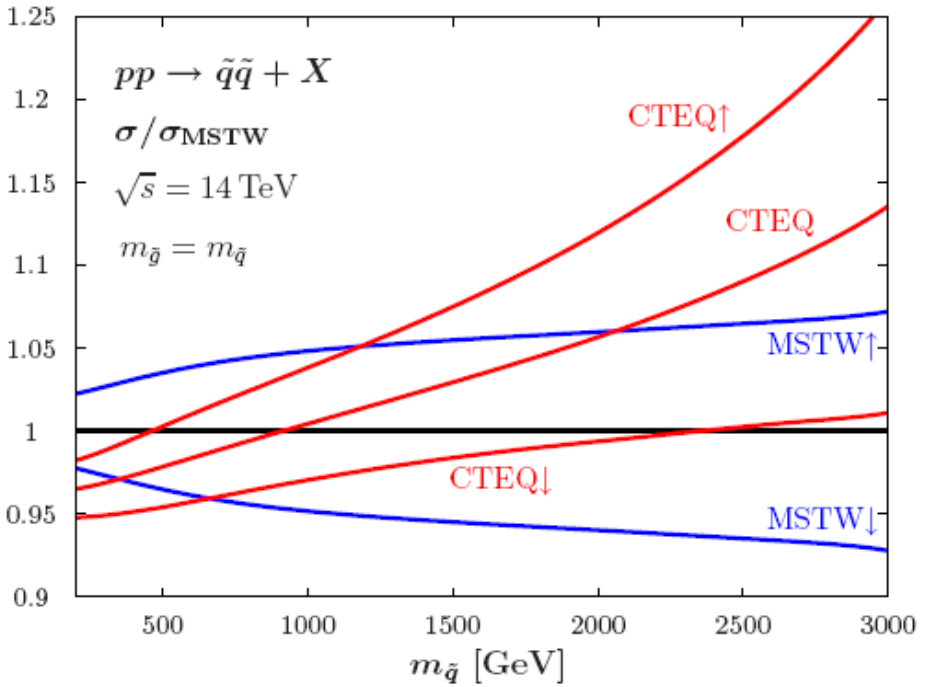


Decay chain might be complex, including Z or Higgs

Importance of PDF

- If we see deviations from SM, will be important to characterize the physics underneath
- The case of strong production:





→ driven by gluon pdf at large x

→ sizeable uncertainty $\approx \pm 25\%$ for $m \approx 1$ TeV

→ driven by valence quark pdfs at large x

→ small uncertainty $\approx \pm 5\%$ for $m \approx 1$ TeV

Gluon distributions

now

then

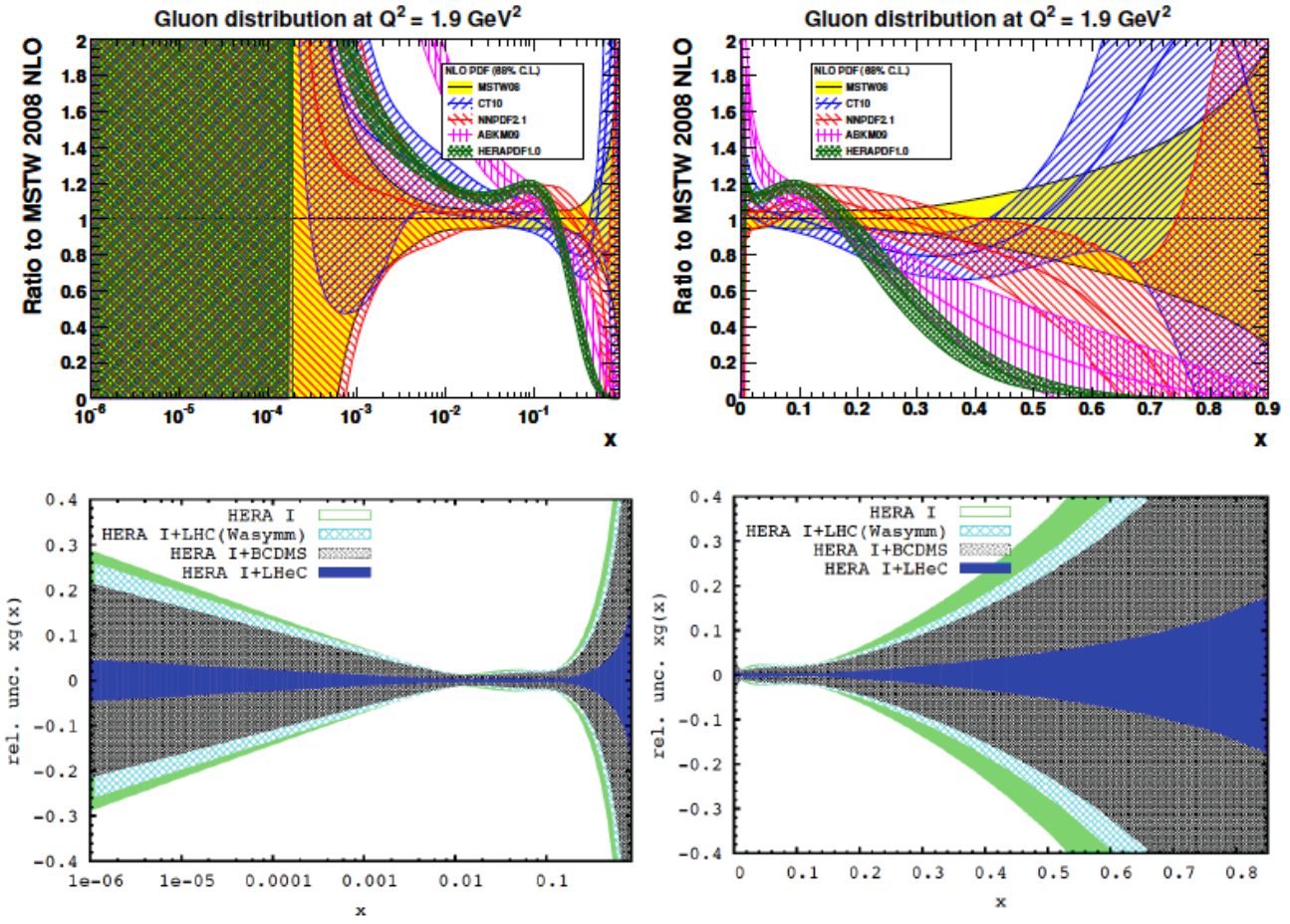


Figure 4.17: Relative uncertainty of the gluon distribution at $Q^2 = 1.9\,\mathrm{GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x, right: linear x.

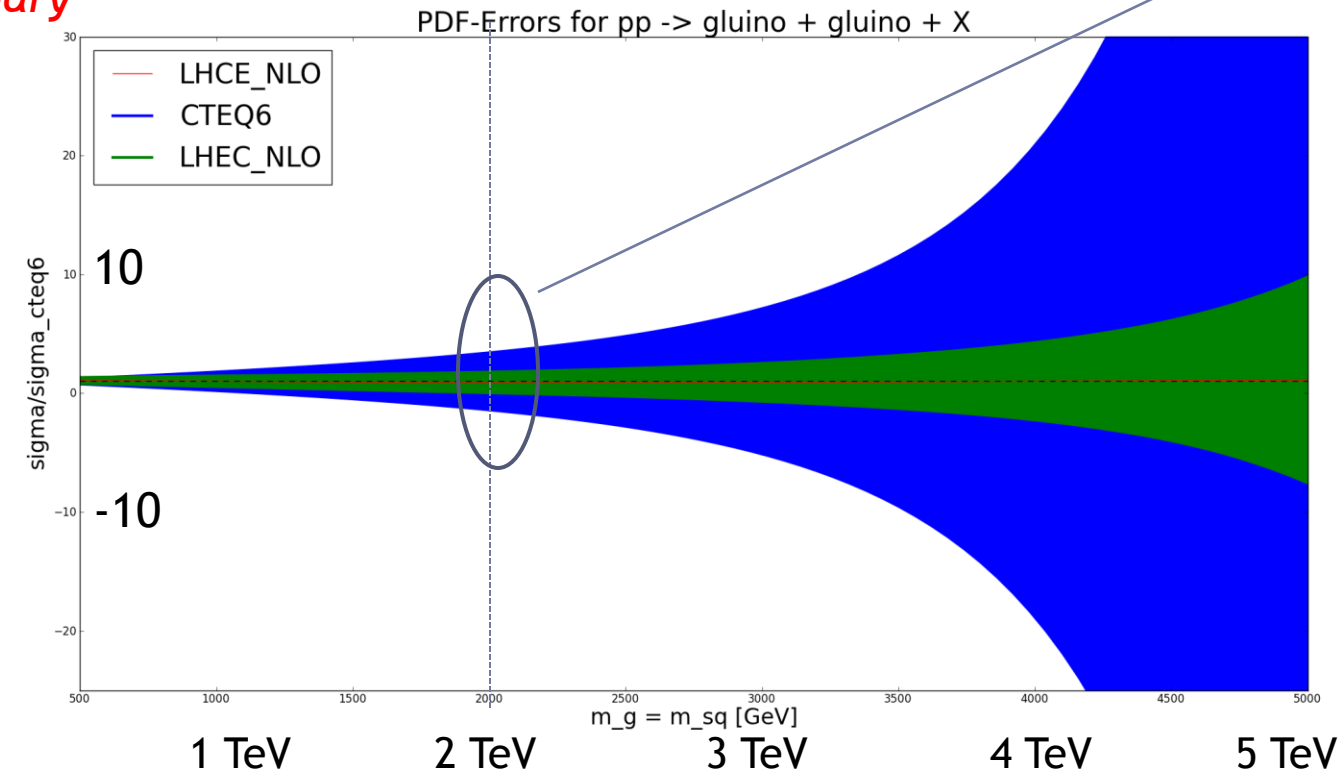
High x: xg and valence quarks: resolving new high mass states!

What the LHeC can do

- M.Kramer and R.Klees working on impact of improved PDF fits on theoretical predictions for SUSY process:
  - Example: gl-gl production (assuming m_gl = m_sq)
  - without(blue, CTEQ6) and with (green) LHeC PDF

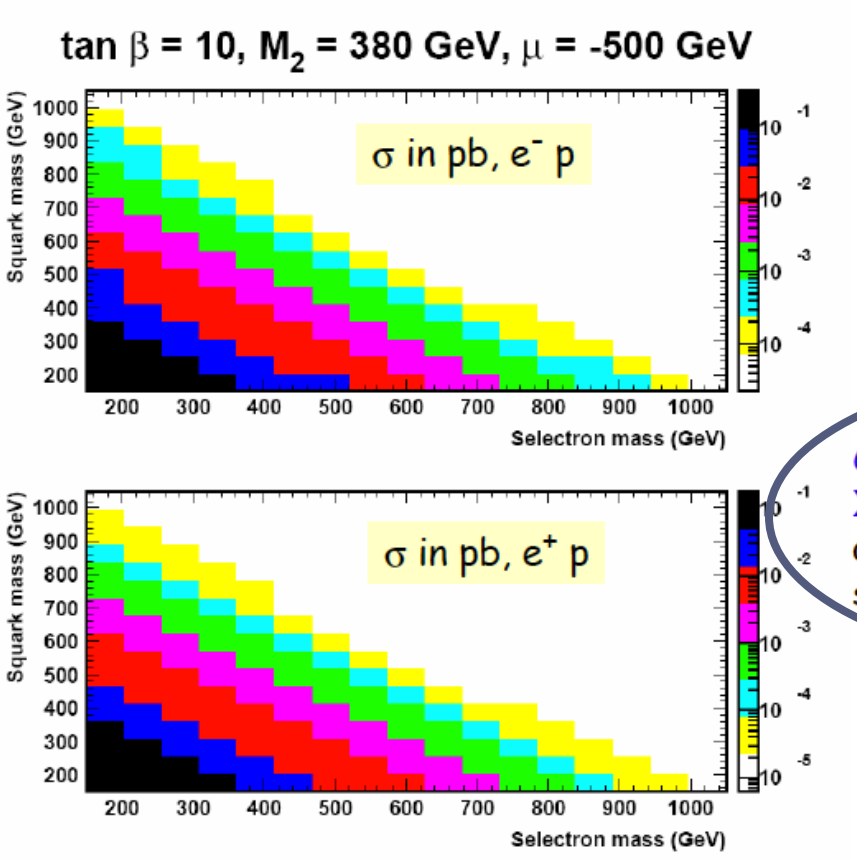
Improve of
factor of 2-3 @ 2 TeV
factor of 10 at 3.5 TeV

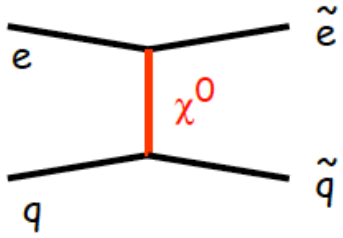
preliminary



SUSY @ LHeC: RPC scenarios

- Selectron-squark pair production
- From last workshop:





Pair production via t-channel exchange of a neutralino.

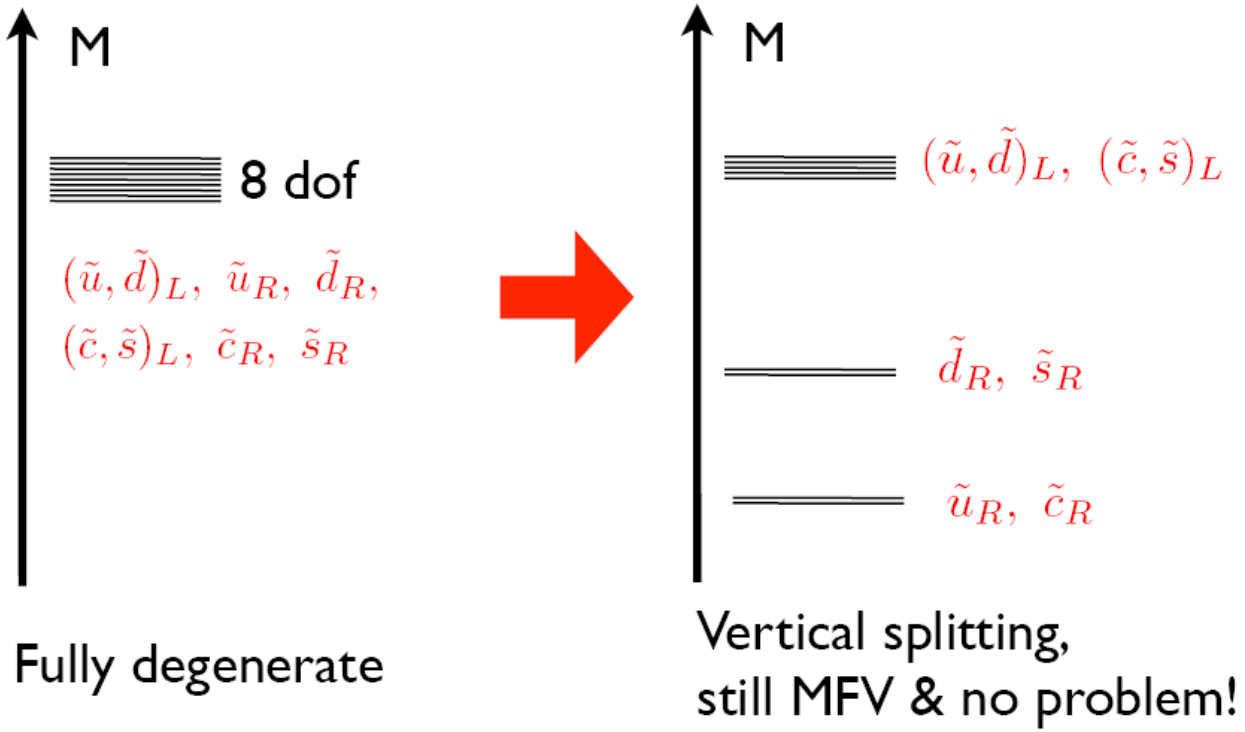
Cross-section sizeable when $\Sigma M < 1$ TeV i.e. if squarks are "light", could observe selectrons up to ~ 500 GeV.

- Could extend a bit over the LHC slepton sensitivity
- Possible information on couplings by playing with e+ / e- / L / R

Are the current constraints really strong enough?

Non-degenerate 1st and 2nd generation squarks

- Review of current constraints on usual assumption on mass degenerate of 1st and 2nd generation squarks in progress:
  - Andy Weiser, with M. Papucci, J. Ruderman (LBL Berkely), Gilad Perez, Rakhi Mahbubani (CERN) work in progress, presented at Blois



Squark mass splitting

- From Andy's talk: large splitting is possible

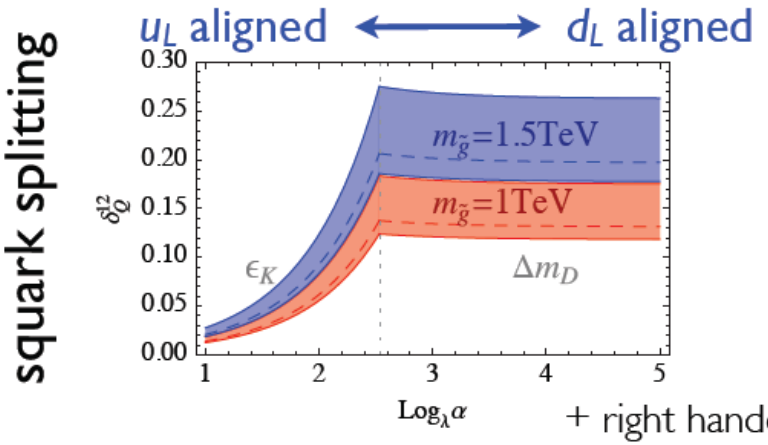
Seiberg & Nir

$$(\delta^q_{ij})_{MM} = \frac{1}{\tilde{m}^2_q} \sum_\alpha (K^q_M)_{i\alpha} (K^q_M)^*_{j\alpha} \Delta\tilde{m}^2_{q_\alpha}$$

mixing / misalignment between
SM Yukawas and squark mass matrices

If by symmetry: K_{ij} ~ diagonal => O(1) mass splitting allowed!

Gedalia et. al



Example:
m_{gluino} = 1.3 TeV
m_{Q1} = 550 GeV
m_{Q2} = 950 GeV

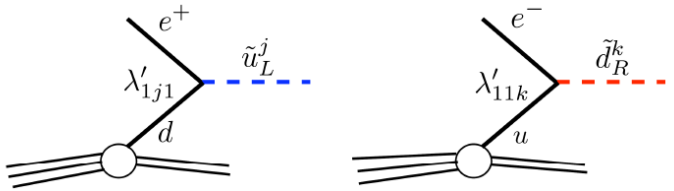
+ right handed squarks split by arbitrary amount

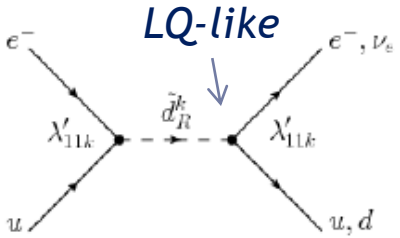
- Will depend on LHC boundaries on these scenarios, still might be worth to have a second look

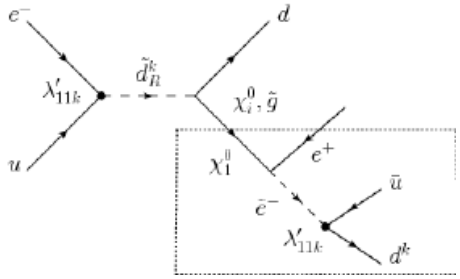
SUSY @ LHeC: RPV scenarios

$$\lambda_{ijk} L_i L_j \overline{E}_k + \underbrace{\lambda'_{ijk} L_i Q_j \overline{D}_k}_{} + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k$$

- For squark production:
  - λ' couplings relevant in e-p production
- Decays: direct or via cascade

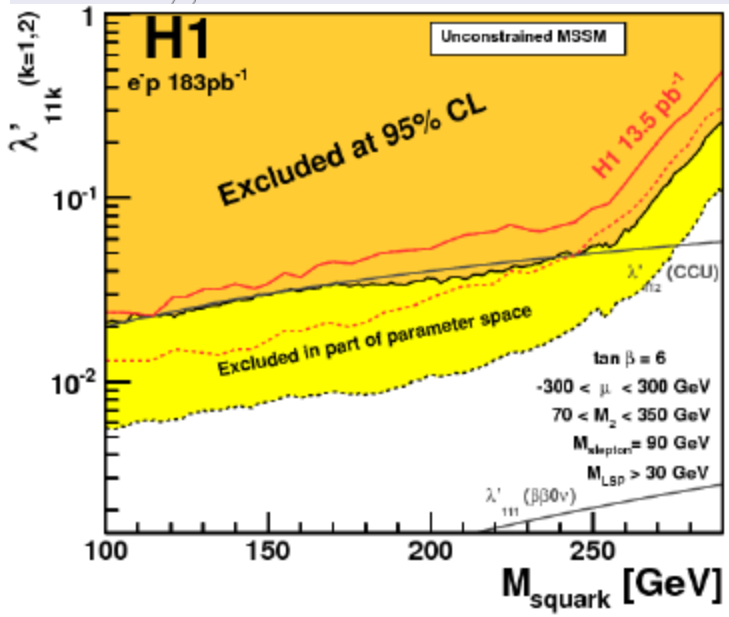






- Current limits up to HERA mass-bound
  - Strong lepto-quark constraints from LHC to be taken into account if RPV~100%
  - Cascade decays (via RPC vertex) lead to more complex and under-constrained signatures
- Reach up to 1 TeV with LHeC
  - Feasibility of these searches will depend on LHC findings (useful in case of evidence ☺)

- For couplings of em. strength ($\lambda'_{1j1}, \lambda'_{11k} \simeq 0.3$)
  - $M_{\tilde{u},\tilde{c},\tilde{t}} \geq 275$ GeV at 95% CL.
  - $M_{\tilde{d},\tilde{s},\tilde{b}} \geq 290$ GeV at 95% CL.



Summary and outlook

- We haven't seen evidence of SUSY @ LHC so far
  - Excluded most 'obvious' RP-conserving scenarios
  - Still large portion of uncharted territory for RPV SUSY
    - Hard to make predictions at this stage
- LHeC provides complementarities to the LHC SUSY search program in the twenties
  - Constraints on PDF crucial for model testing in case of observed deviations
  - Non-standard RPC scenarios with non-degenerate squarks might leave a window of so-far unexplored possibilities → eventually LHC will shed some light on this by 2020
  - RPV scenarios very complex:
    - Clearly e-p collider allow probing of important scenarios
    - Review of implication of current results needed