

Searching for R-parity violating supersymmetry at the ATLAS detector

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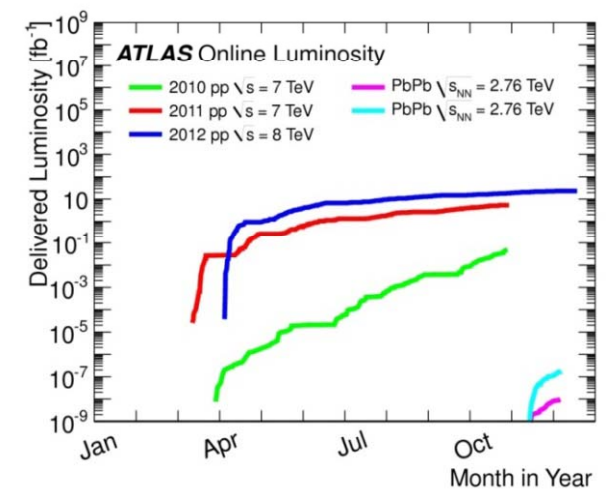
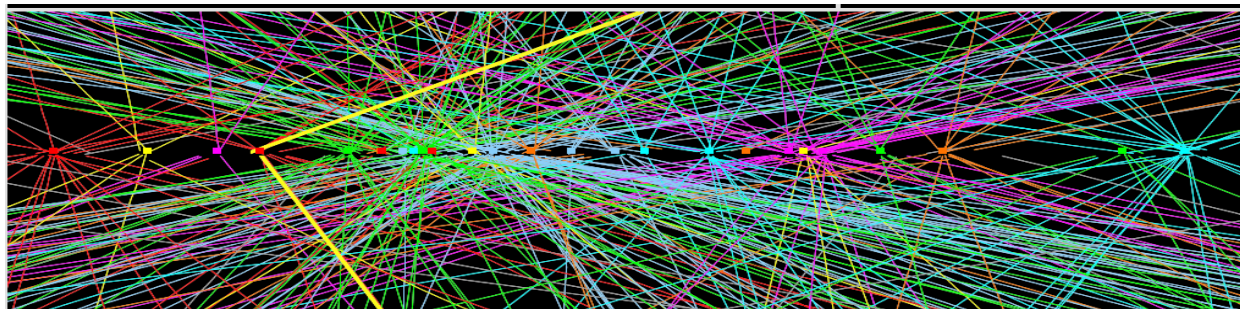
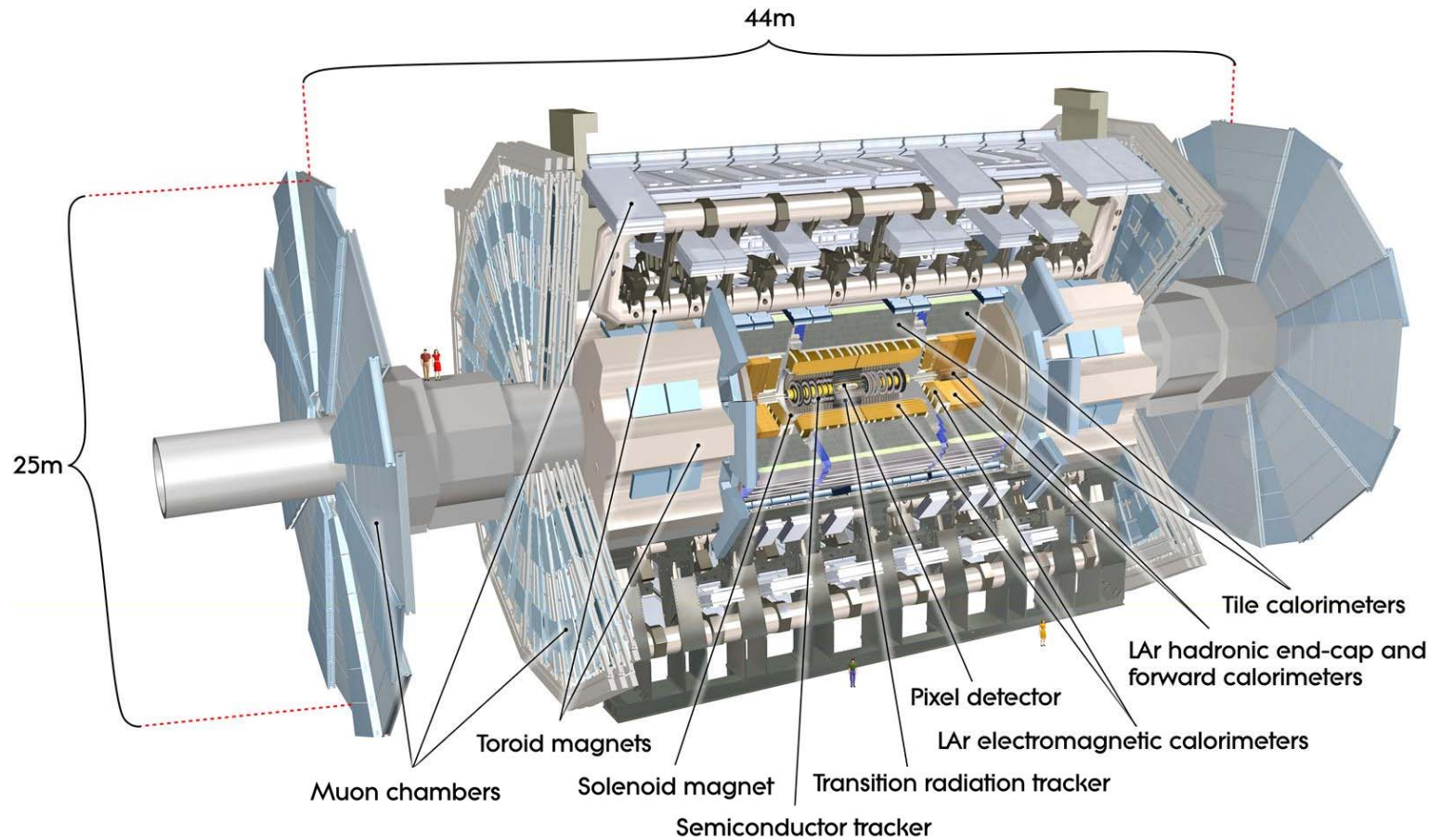
February 25 2014



Outline

- SUSY phenomenology
- Analysis example:
Search for squarks/gluinos in final states with jets + E_t^{miss}
- Phenomenology and constraints for RPV models
- Analysis example: *Search for massive particles in multi-jet signatures*
- Analysis example: *Search for SUSY with four or more leptons*
- Analysis example: *Search for long-lived particles in final states with a muon and a multi-track displaced vertex*
- Status and strategies for searches for bRPV SUSY
- Conclusions

ATLAS Detector

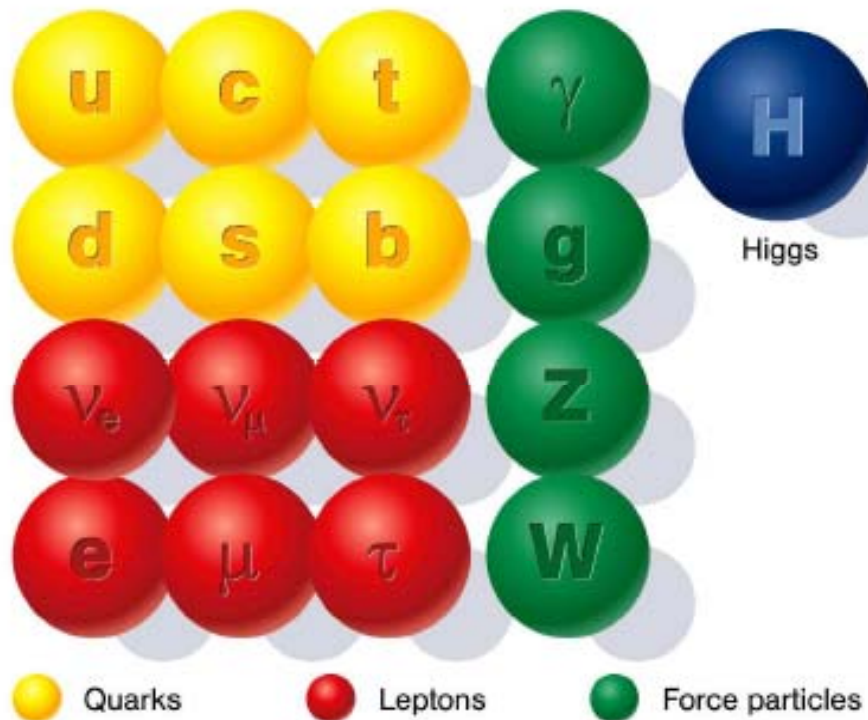


SUSY particles

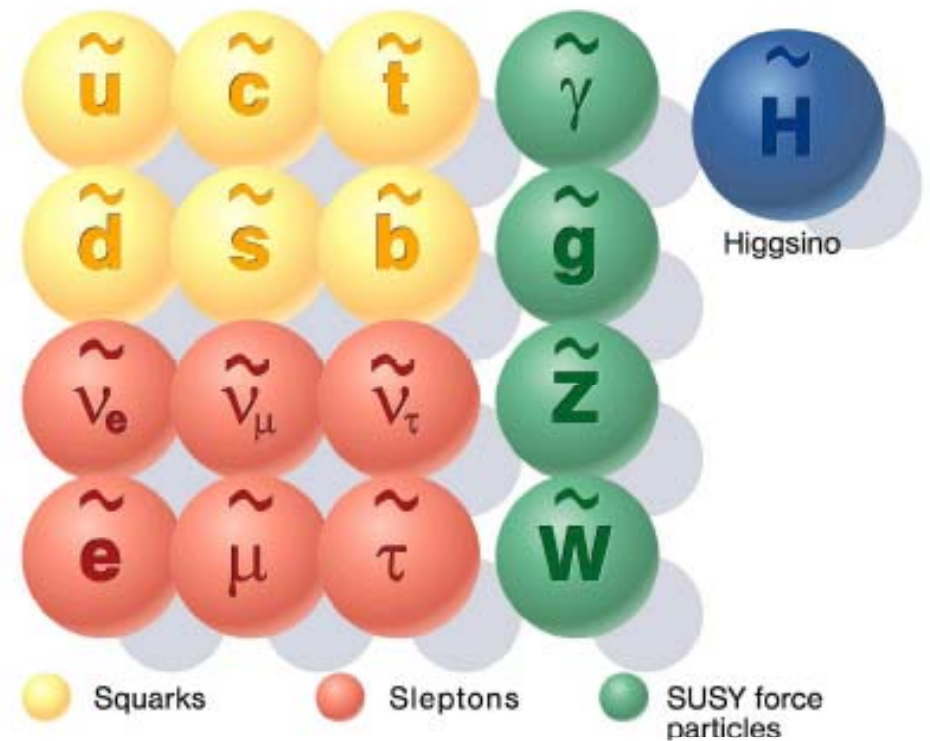
|Fermion> $\longleftrightarrow$ |Boson>

MSSM

Standard particles



SUSY particles

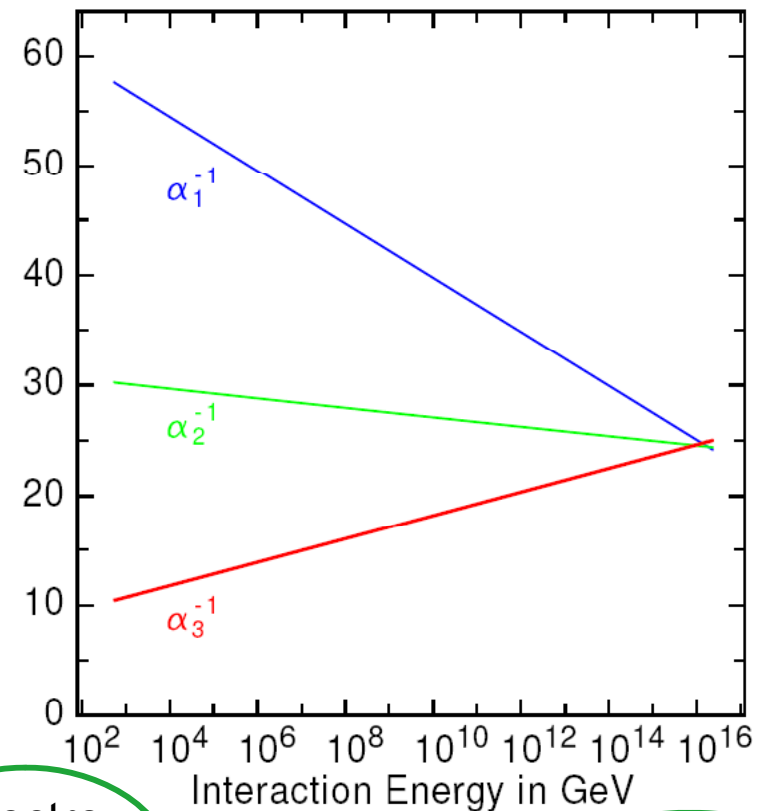


$$Z \rightarrow \mu\mu$$

$$\tilde{Z} \rightarrow \tilde{\mu}\mu \quad Z \rightarrow \tilde{\mu}\tilde{\mu}$$

SUSY extension of Standard Model

- Unification of gauge couplings
- Hierarchy problem / fine tuning
 - Natural SUSY spectrum
 - Dominant contributions to Higgs mass of the order of 100 GeV – 1 TeV
- Electroweak symmetry breaking through RGE evolution
- Combination with gravity for local supersymmetry
- Candidates for Dark Matter



electro
weak
scale

GUT scale

SUSY Masses

Sparticles in MSSM:

- 12 squarks (2 stops, 2 sbottoms,...)
- 9 sleptons (2 selectrons, 1 el. sneutrino,...)
- 5 Higgs (h_0 , H_0 , A_0 , $H^{+/-}$)
- 1 gluino
- 4 charginos $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$
- 4 neutralinos $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

LSP (lightest SUSY particle): Candidate for Dark Matter

Definition of SUSY mass values:

- „High-scale“ Unified masses at high energies (mSUGRA, GMSB, AMSB...)
- „Low-scale“ masses at electroweak scale (pMSSM, simplified models)

Experimental mass limits (pre-LHC):

- Low energy processes ($b \rightarrow s \gamma$, $g_{\mu} - 2$)
- Astrophysical constraints (Dark Matter)
- Results from high energy colliders (LEP, Tevatron)

SUSY Masses

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**SUSY models
consistent
with Higgs mass
at 125 GeV?**

LSP (lightest SUSY particle): Candidate for Dark Matter

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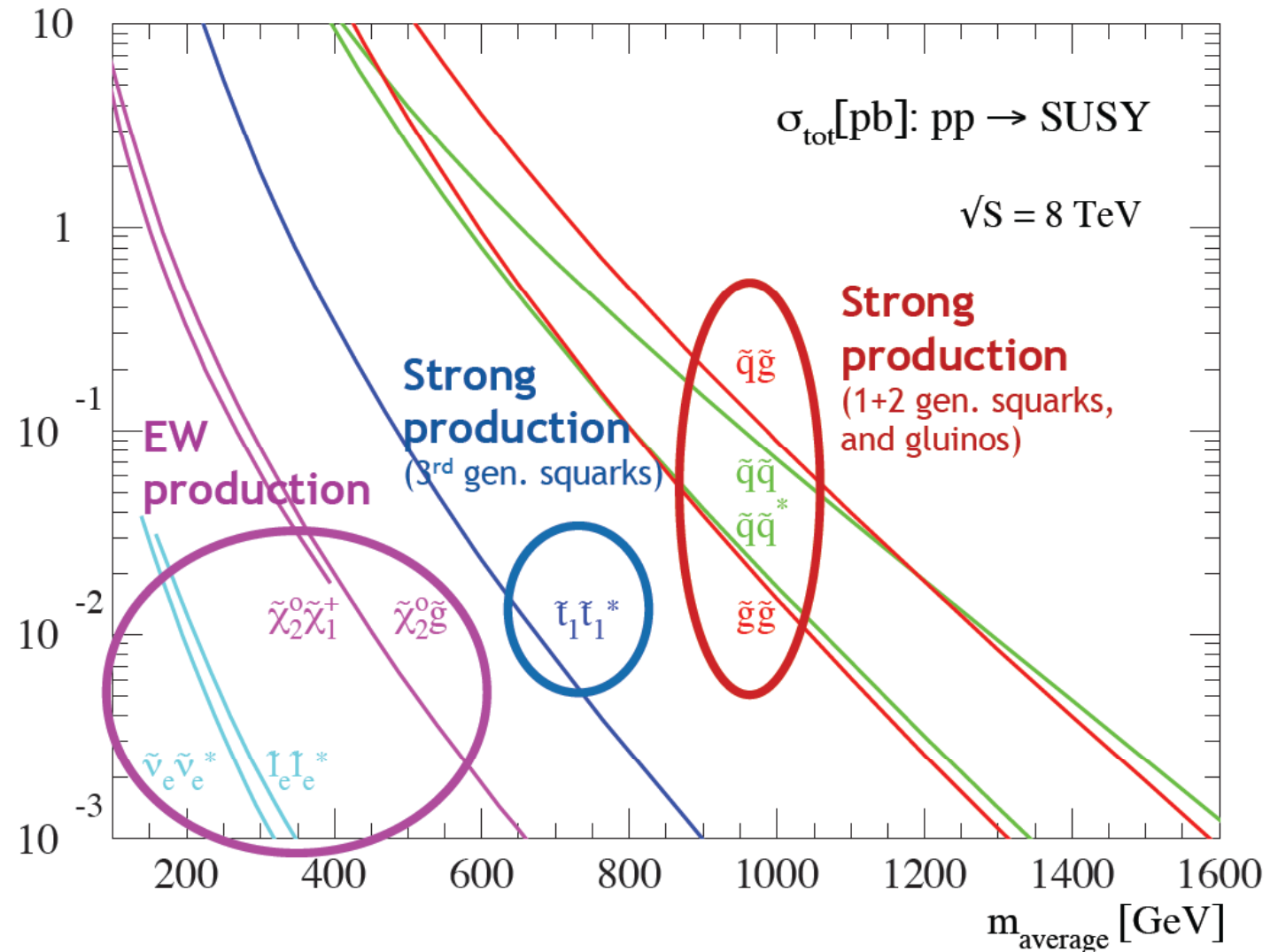
Experimental mass limits (pre-LHC):

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SUSY production mechanisms

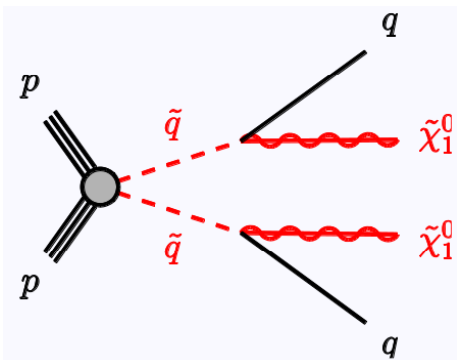
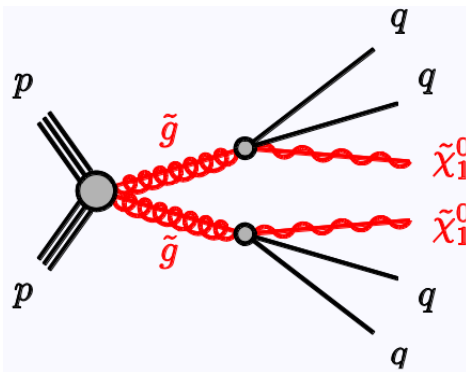
Total cross-sections for sparticle production at 8 TeV

Production mechanism as category for classifying results

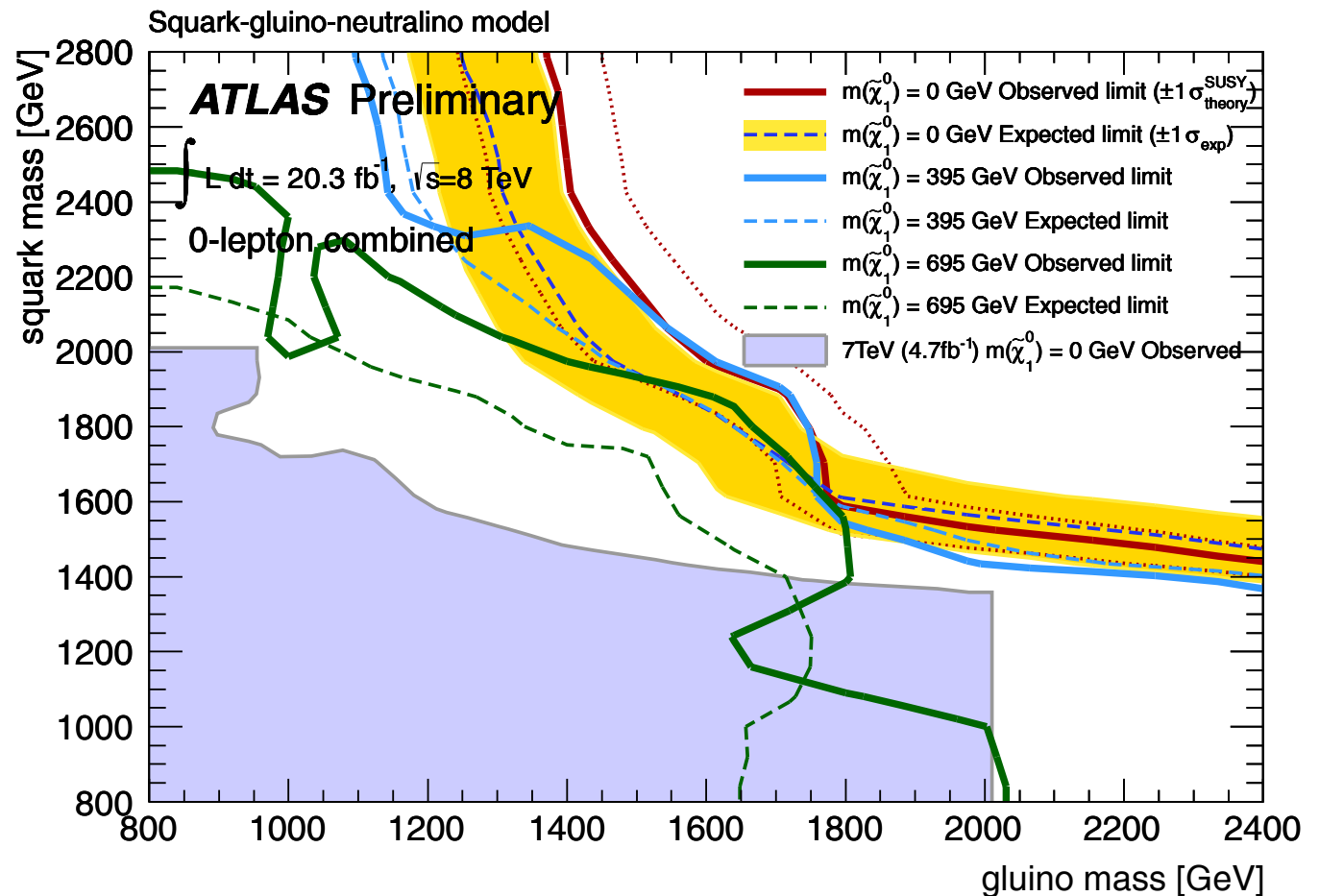


Results for jets + E_t^{miss}

- Generic signature for **strong production** of SUSY particles
- Stable LSPs at the end of decay chains resulting in **large E_t^{miss}**
- Simplified model with production of gluinos / degenerate 1st / 2nd gen. squarks
- direct decays to jets and LSPs



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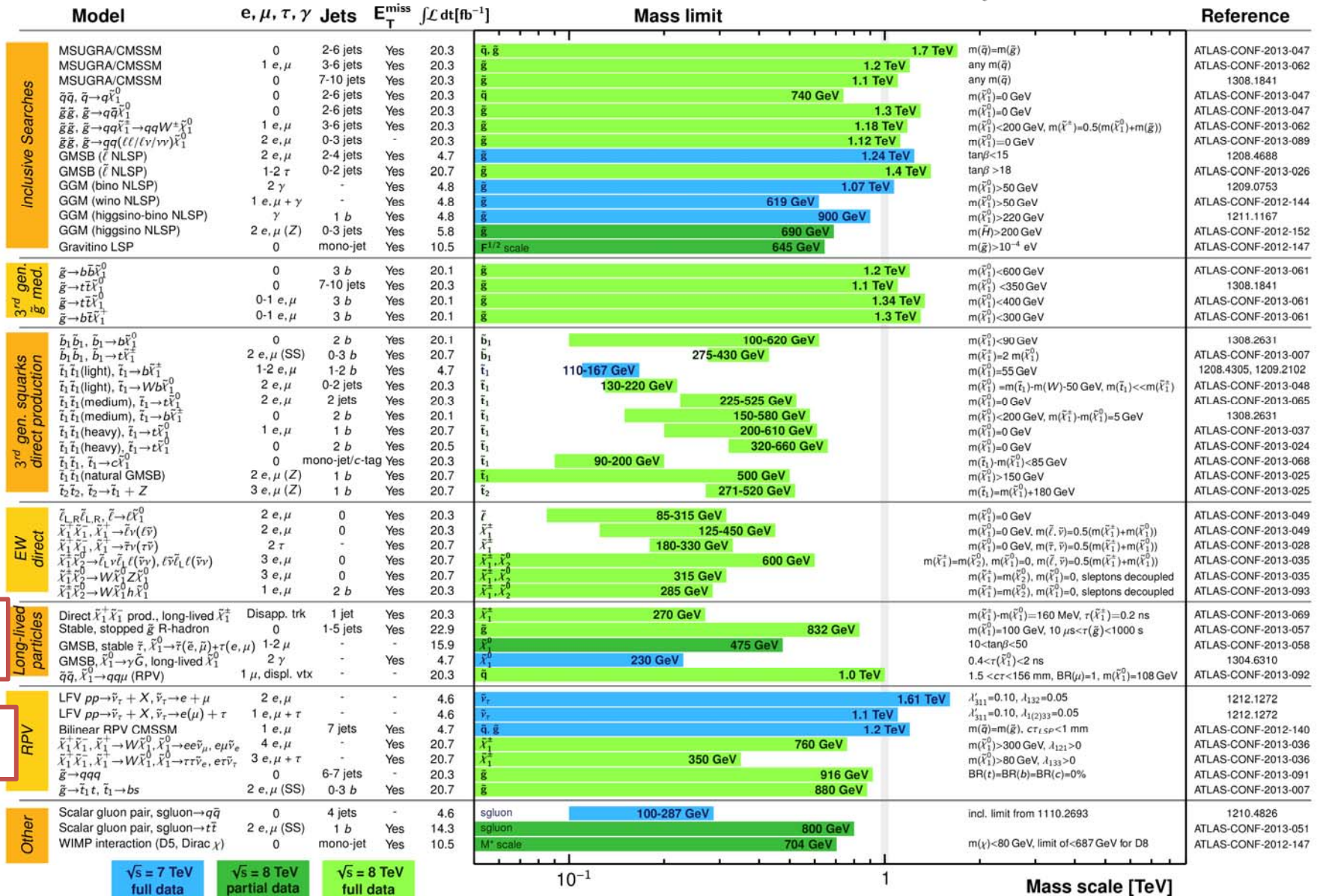
Overview plot of ATLAS-SUSY results

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1}$ $\sqrt{s} = 7, 8 \text{ TeV}$



Long-lived

Prompt RPV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/ATLAS_SUSY_Summary/ATLAS_SUSY_Summary.pdf

RPV SUSY phenomenology

- Definition of R-parity

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

- Generic phenomenological consequences
 - Violation of L and/or B
 - Decays of LSP into SM particles allowed
 - Single sparticle production possible
- Motivations for R-parity violation
 - RPC SUSY not yet found
 - Strong constraints of the order of TeV for many RPC models
 - Sparticle masses below 1 TeV more attractive from fine-tuning / naturalness point of view
 - Lepton number violation terms and baryon number violation terms allowed in the superpotential in contrast to a SM Lagrangian
 - Very rich phenomenology with various “exotic” signatures

RPV SUSY Parameters

R-Parity: $R = (-1)^{3(B-L)+2S}$ (Non-)conservation of *B* and *L*

Superpot. $W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2$

- Most constraints only assume one (or product of two) coupling(s)
 - Neutrino masses, neutrinoless double beta decay
 - Proton decay, di-nucleon or meson decays (related to $\lambda'^*\lambda$)
 - Lepton Flavor violating decays (related to $\lambda^*\lambda$)
 - Electric / anomalous magnetic dipole moments
 - Collider limits
- Number of parameters
 - $9 \lambda_{ijk}$ ($\lambda_{ijk} = -\lambda_{jik}$)
 - $27 \lambda'_{ijk}$
 - $9 \lambda''_{ijk}$ ($\lambda''_{ijk} = -\lambda''_{ikj}$)
 - 3 dimensionful κ_i

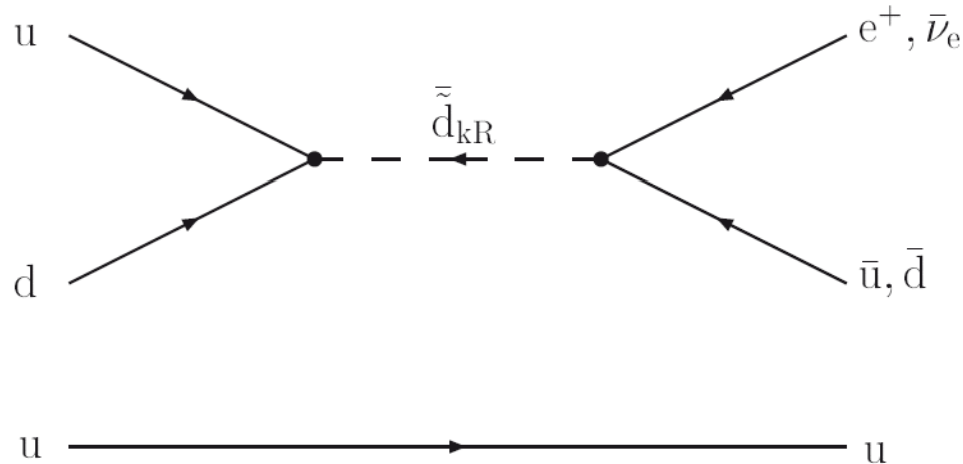
RPV SUSY phenomenology

- Constraints on R-parity couplings
 - Single / double coupling dominance
 - Either B or L violation
 - Constraints relaxed for higher sparticle masses
 - Typically weaker limits on couplings involving third generation
- Signatures from prompt RPV
 - Enhanced lepton and/or jet multiplicities from LSP decays
 - More candidates for LSP
 - Resonances from single sparticle production / subsequent decay
 - Reduction of E_t^{miss} (in many scenarios)
- Long-lived particles
 - Displaced vertices due to small RPV-couplings
 - Mass-degeneracy (also for RPC scenarios)
 - Hadronic states from heavy mediator sparticles (squarks)

Experimental constraints on RPV SUSY

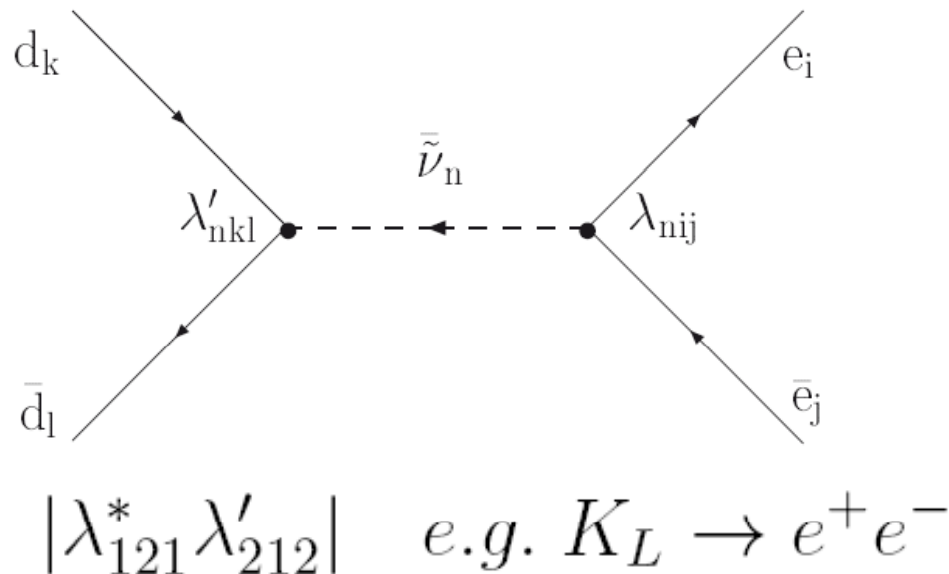
Proton decay

$$|\lambda'_{l1k} \lambda''_{11k}|$$

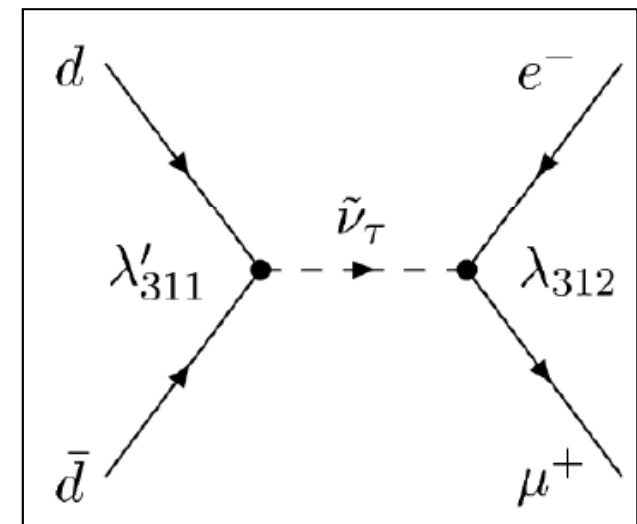


See summaries e.g.
 Phys. Rev. D 69 (2004) 115002
 Phys. Rept. 420 (2005) 1

Meson decays



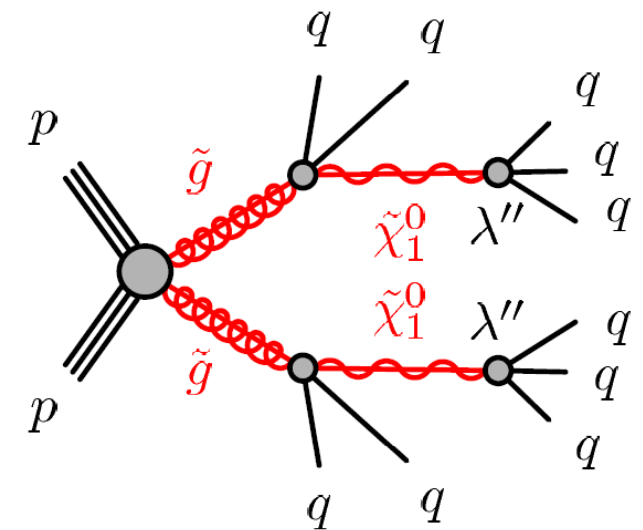
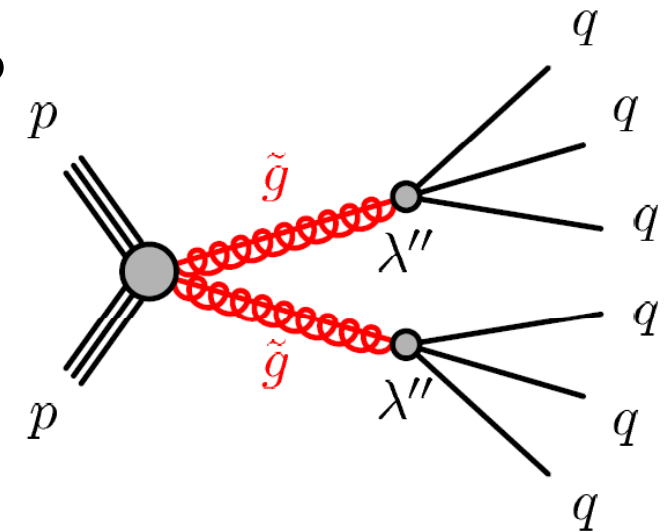
Single sneutrino production



See PLB 723 (2013) 15

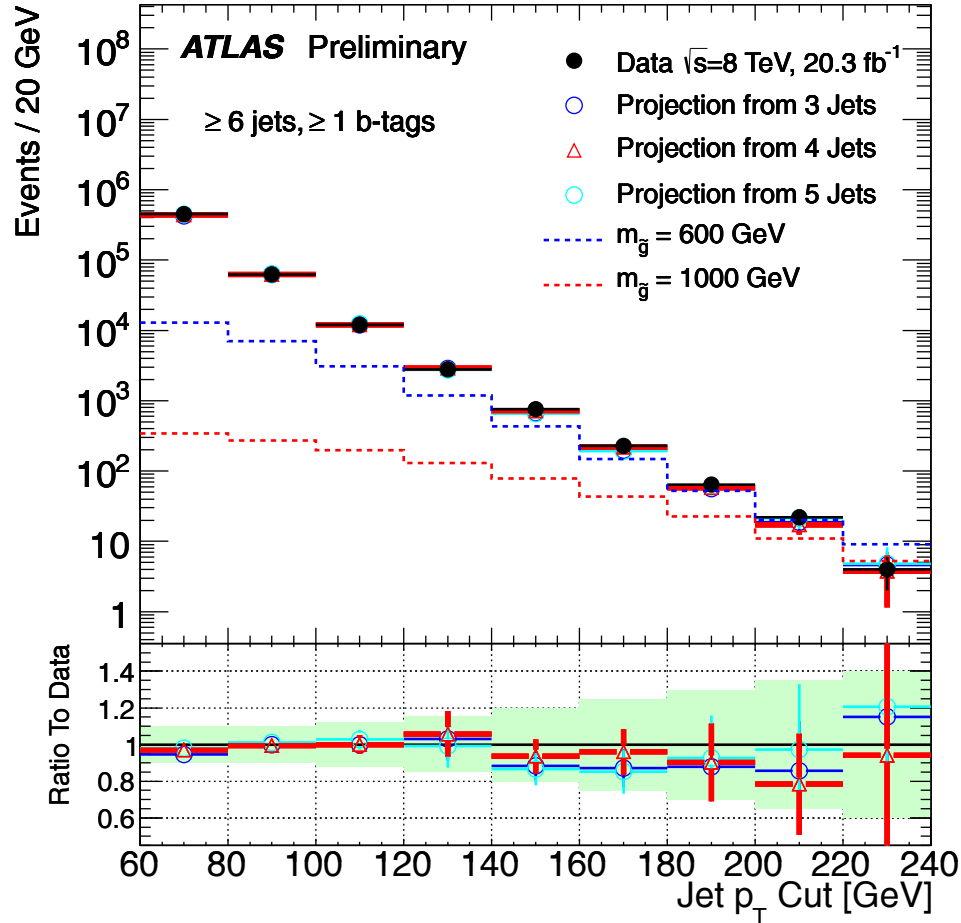
Multi-jets [RPV]- Overview

- Gluino pair-production
- RPV prompt decays of gluino / neutralino LSP
- Final state
 - Multi-jets (high p_T)
 - b -jets
 - Significant E_t^{miss}
- Main backgrounds: Multi-jets, fully hadronic t - t bar production
- Discrimination of backgrounds with jet p_T , b -tagging, number of jets
- Validation of BG predictions in various CRs for data-driven BG (within uncertainties)
- Scenarios for interpretations:
 - 6 / 10-quark model
 - Prob. for RPV decay to produce t, c, b quark: $\text{BR}(t)$, $\text{BR}(c)$, $\text{BR}(b)$

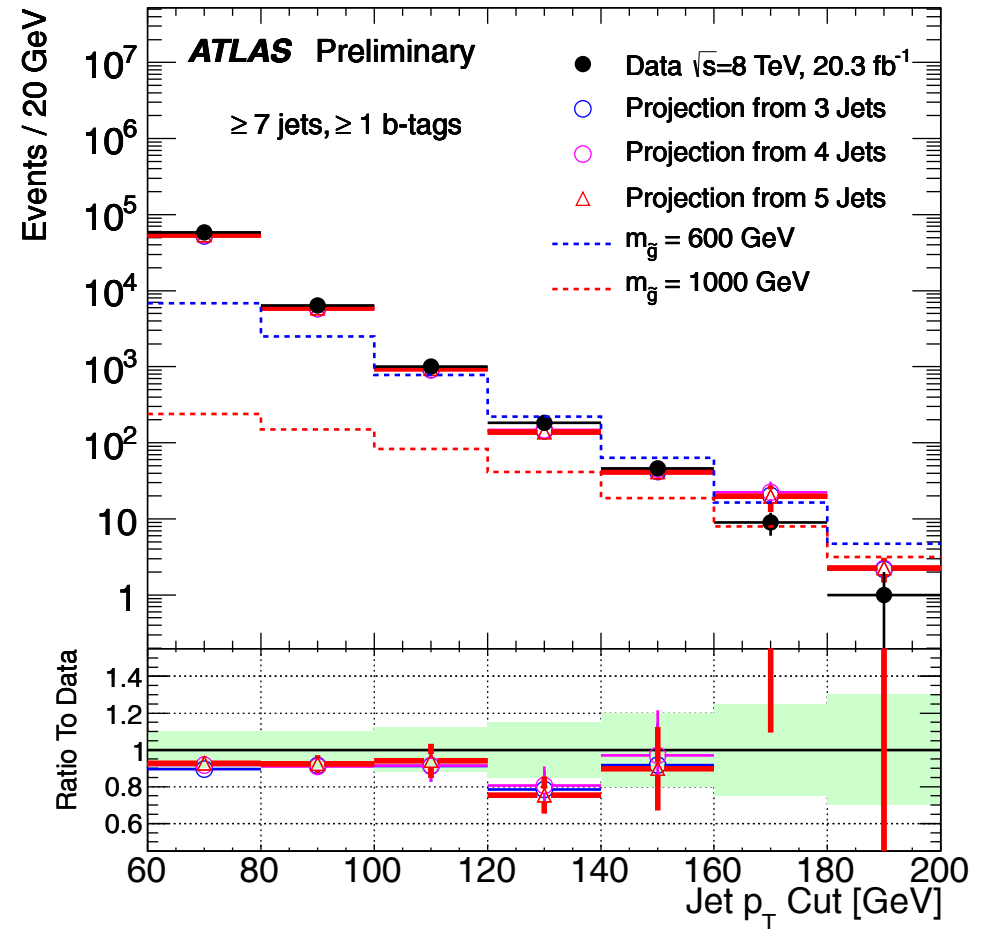


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Multi-jets [RPV]- Background



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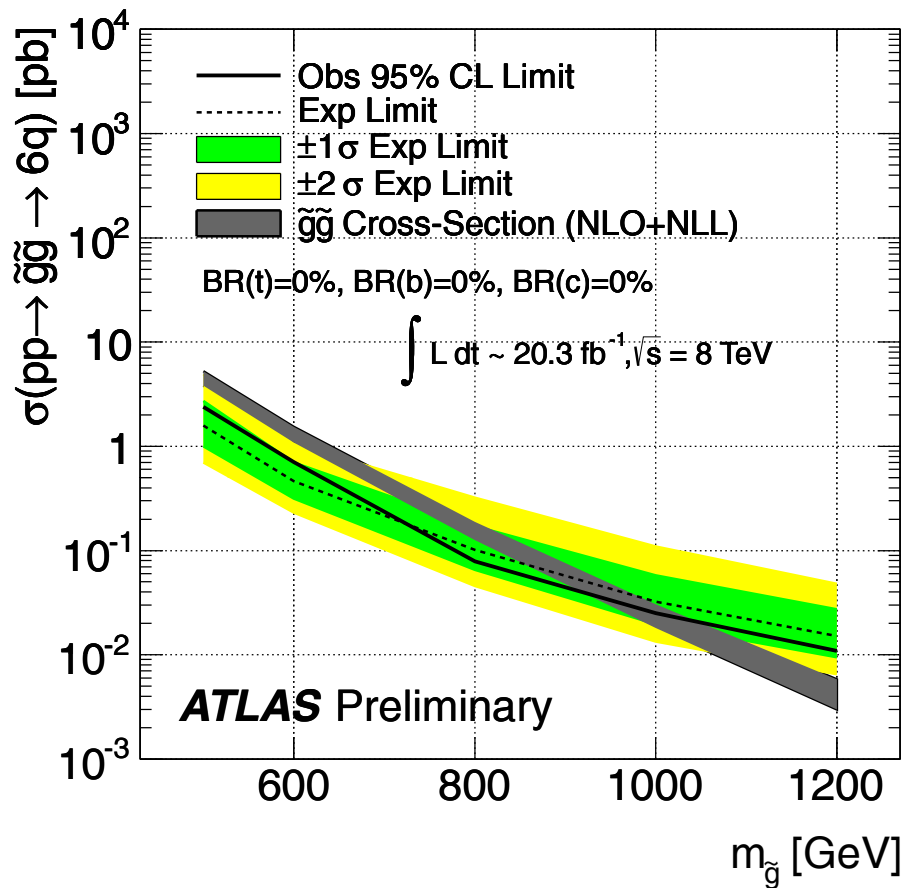


Comparison of data with background expectations from projections
green bands for systematic uncertainties.

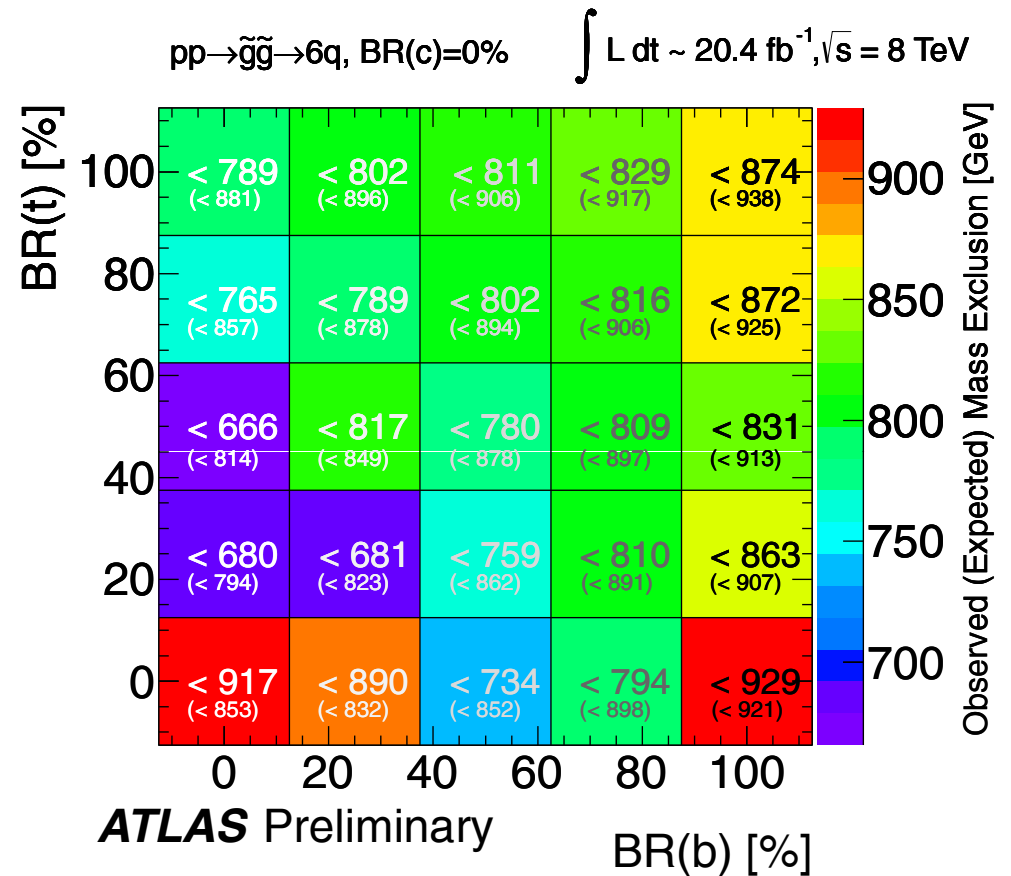
Pythia for projection of number of obs. events from low-jet multiplicity CR

$$N_{n-jet}^{data} = \left(N_{m-jet}^{data} - N_{m-jet, OtherBGs}^{MC} \right) \times \left(\frac{N_{n-jet}^{MC}}{N_{m-jet}^{MC}} \right) + N_{n-jet, OtherBGs}^{MC}$$

Multi-jets [RPV]- Results



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Expected and observed cross-section limits
 for 6-quark gluino models
 No gluinos decay into heavy-flavour quarks

Exp. and obs. mass exclusions at the 95% CL in
 BR(t) vs BR(b) space for BR(c)=0%
 Each point individually optimized and fit
 Bin centers correspond to evaluated models

4 leptons + E_t^{miss} - Overview

- Single coupling dominance λ_{121} or λ_{133}
- RPC pair production
- Prompt Neutralino-LSP decays $\rightarrow$ Large lepton multiplicities
- NLSP: Wino-chargino or gluino
- Decoupling limit of other sparticles (masses at 4.5 TeV)
- $\lambda > (0.3-1) \cdot 10^{-4}$ depending on masses
- Discrimination of backgrounds with m_{eff} , E_t^{miss} , veto on Z

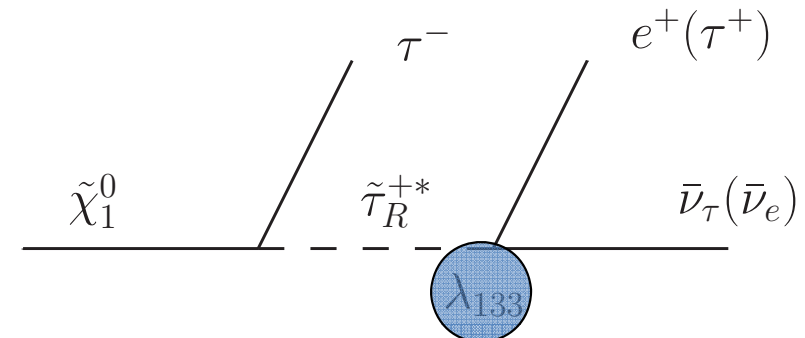
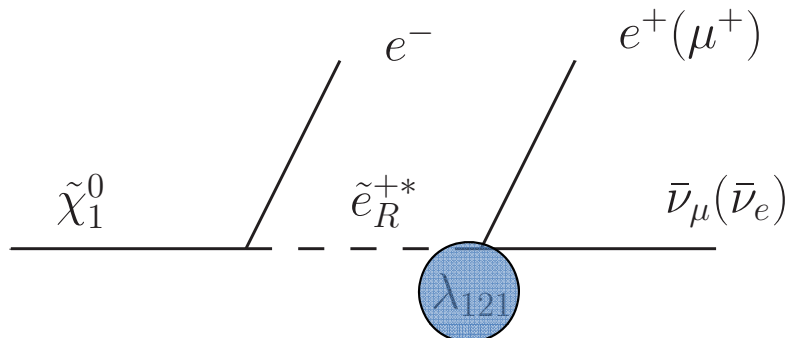
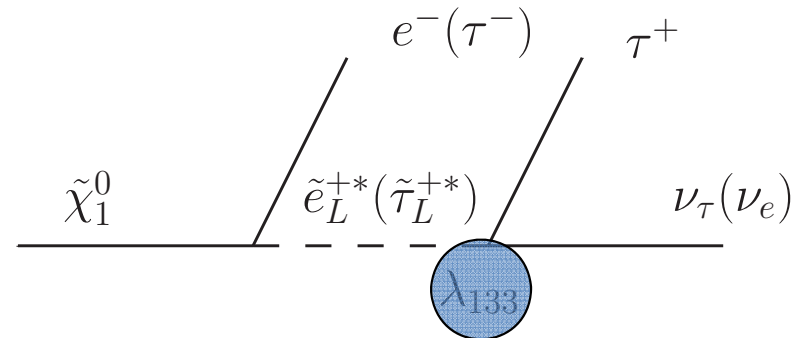
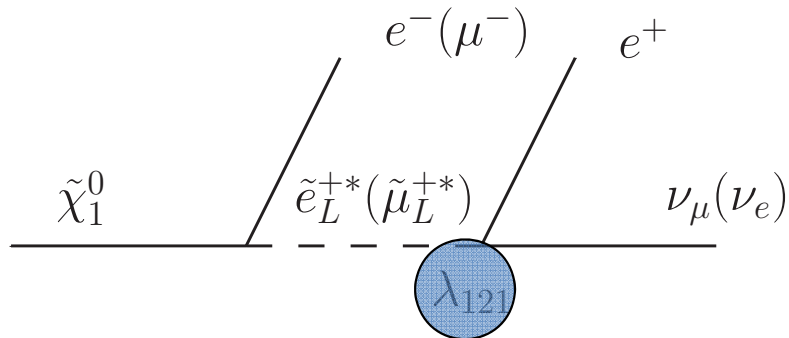
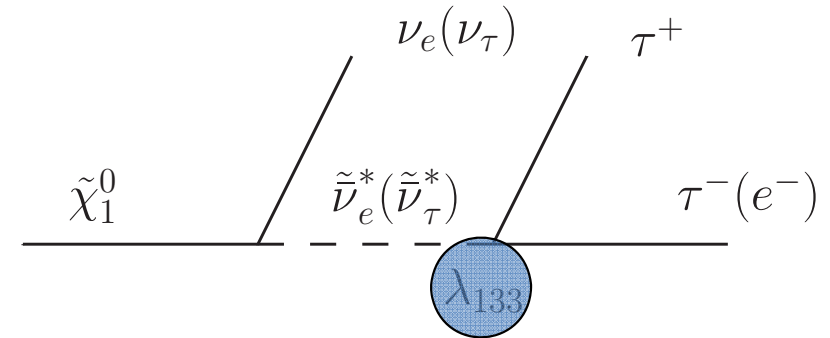
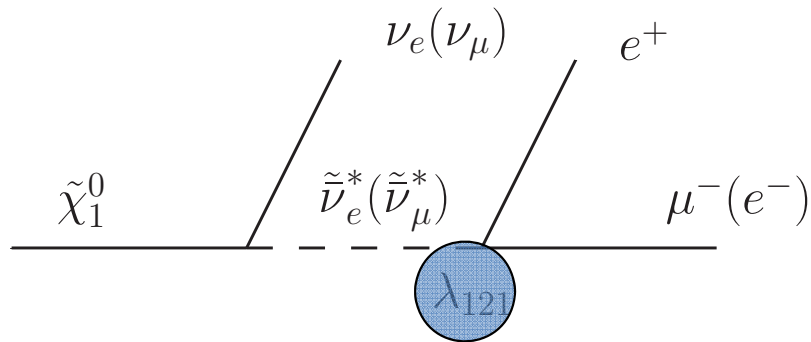
Wino-NLSP:

- $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production
- decay $\tilde{\chi}_1^\pm \rightarrow W^{\pm(*)} \tilde{\chi}_1^0$

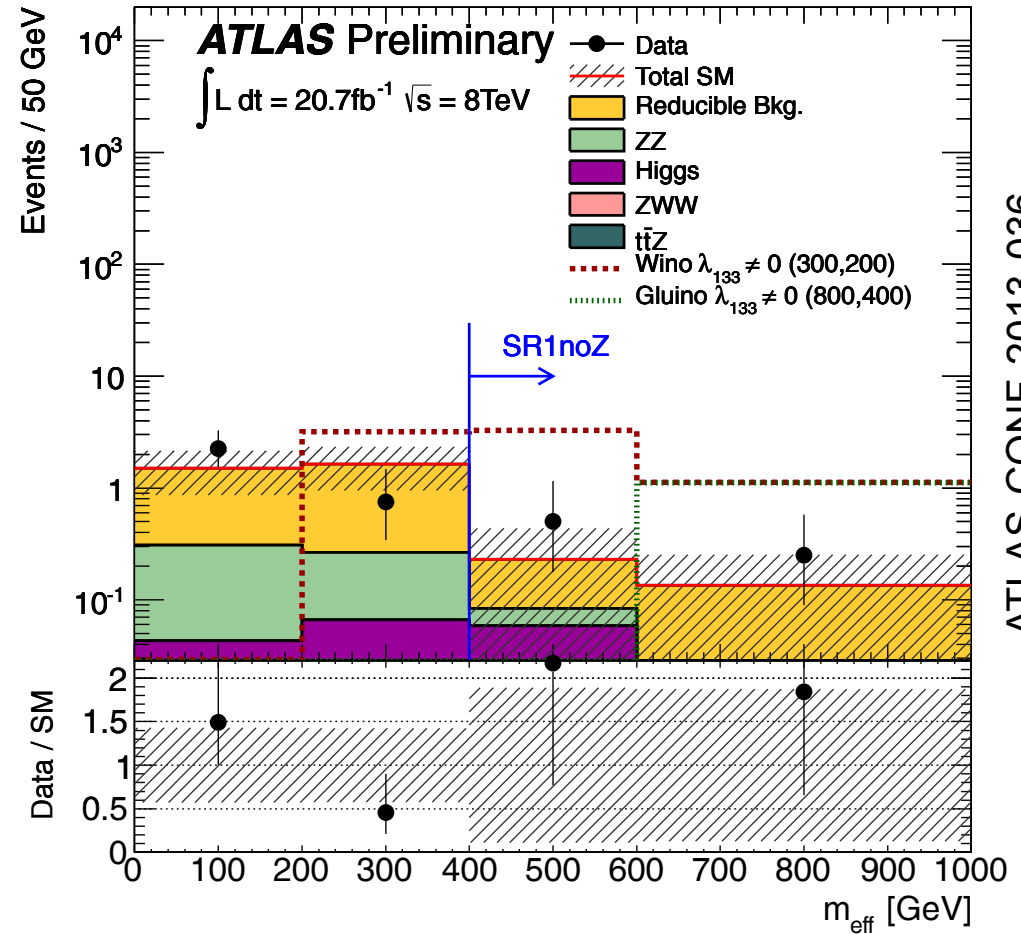
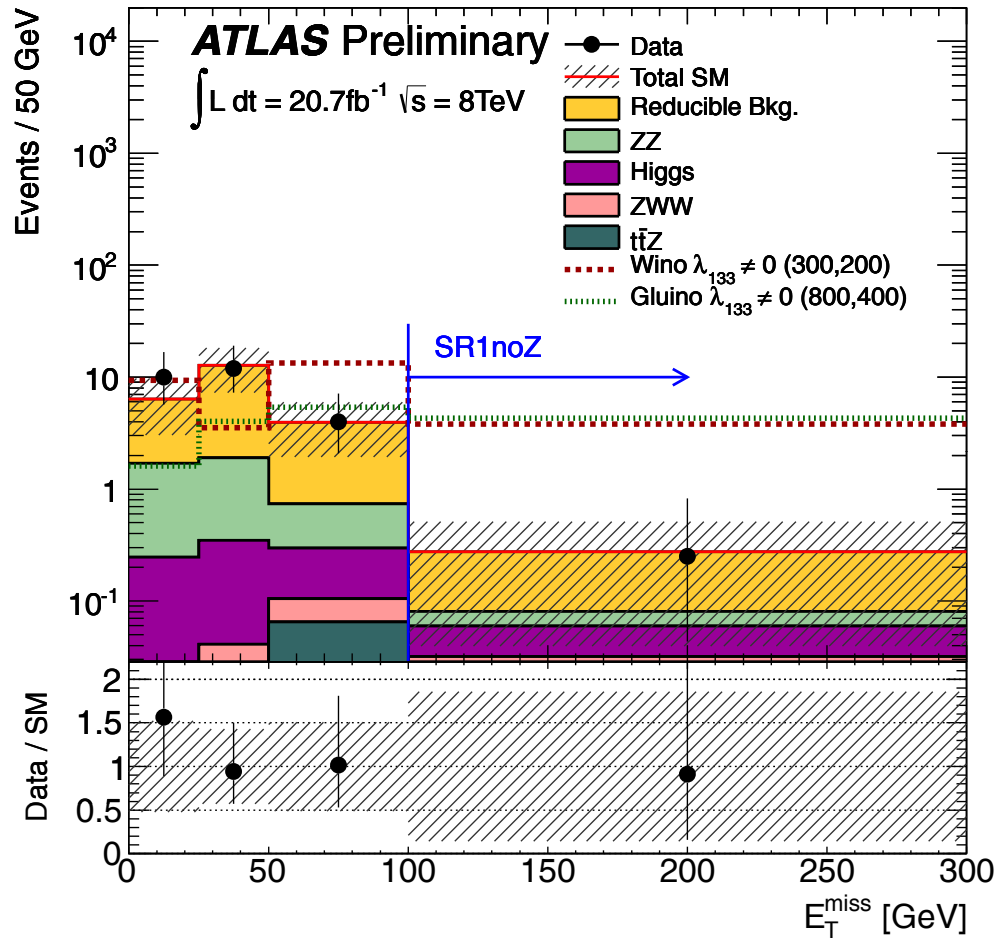
Gluino-NLSP:

- $\tilde{g}\tilde{g}$ production
- decay $\tilde{g} \rightarrow q\bar{q}' \tilde{\chi}_1^0$ ($q, q' \in u, d, s, c$)

4 leptons + E_t^{miss} – LSP decays



4 leptons + E_t^{miss} - Backgrounds

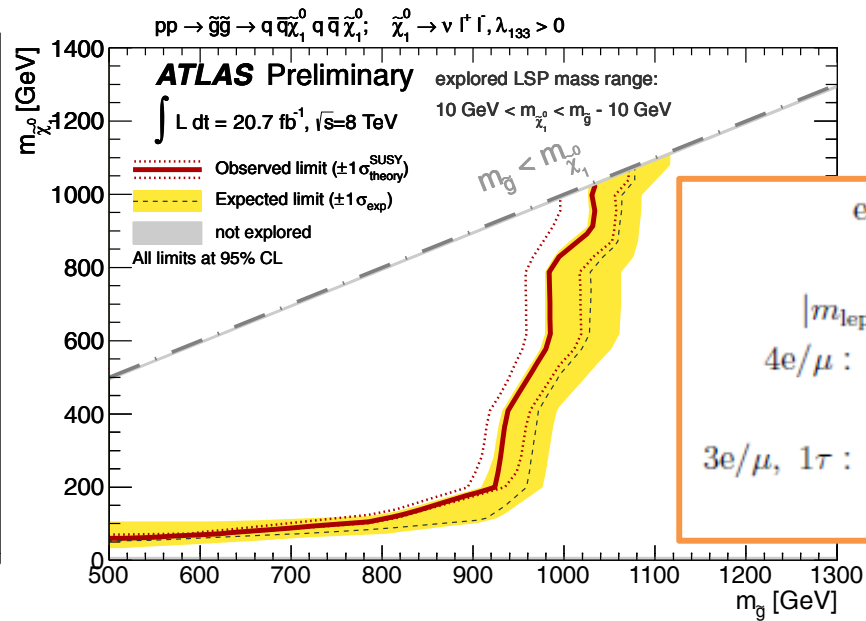
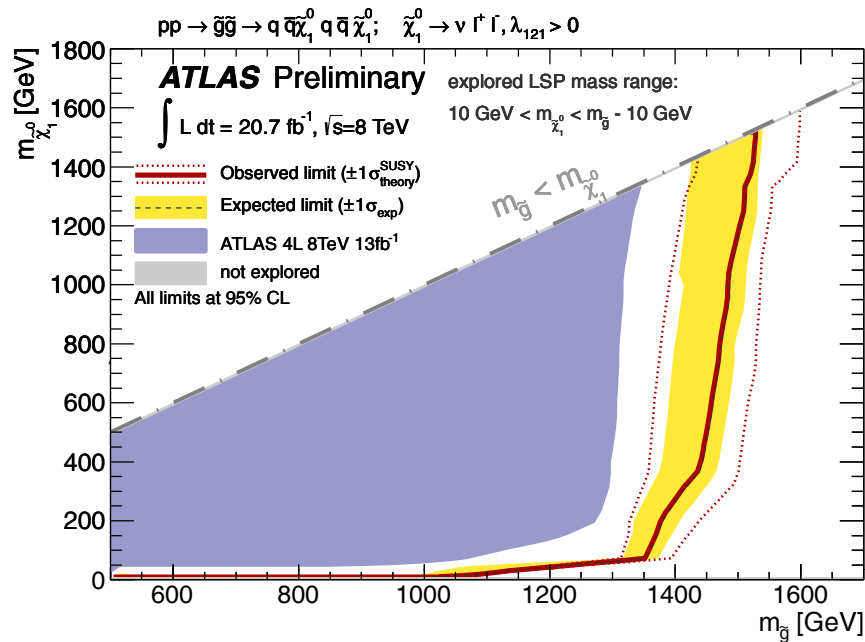
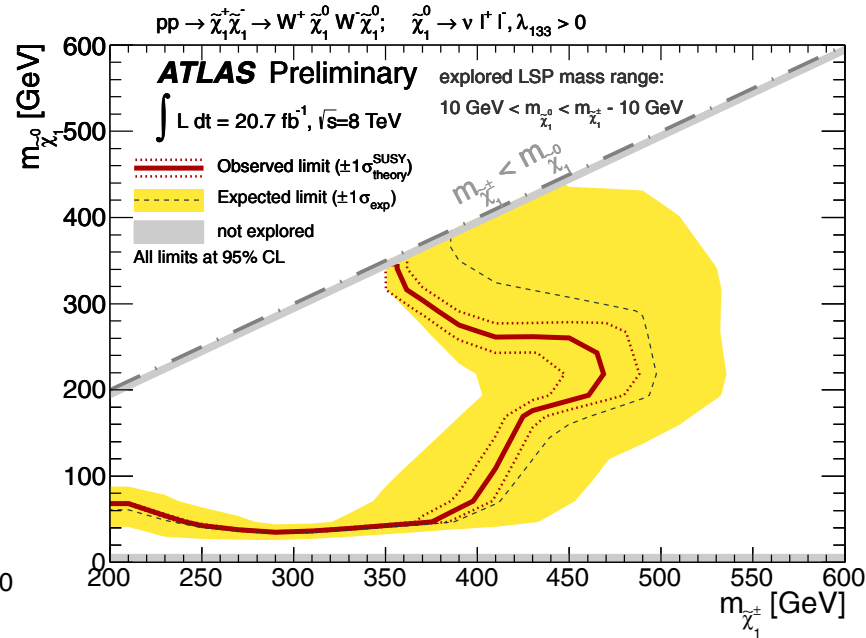
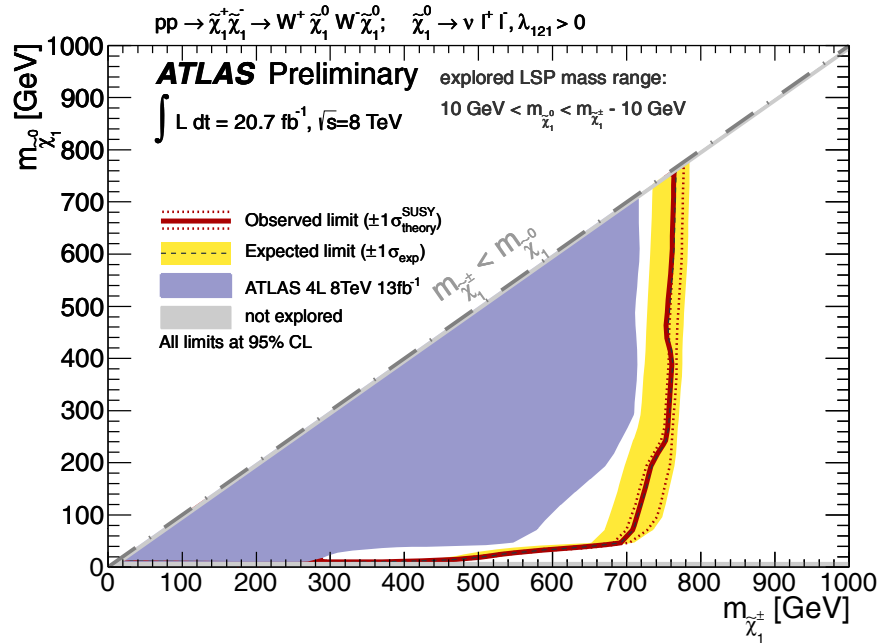


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events with $=3\ell \geq 1\tau$ and a **Z veto**

uncertainty band includes statistical and systematic uncertainties.

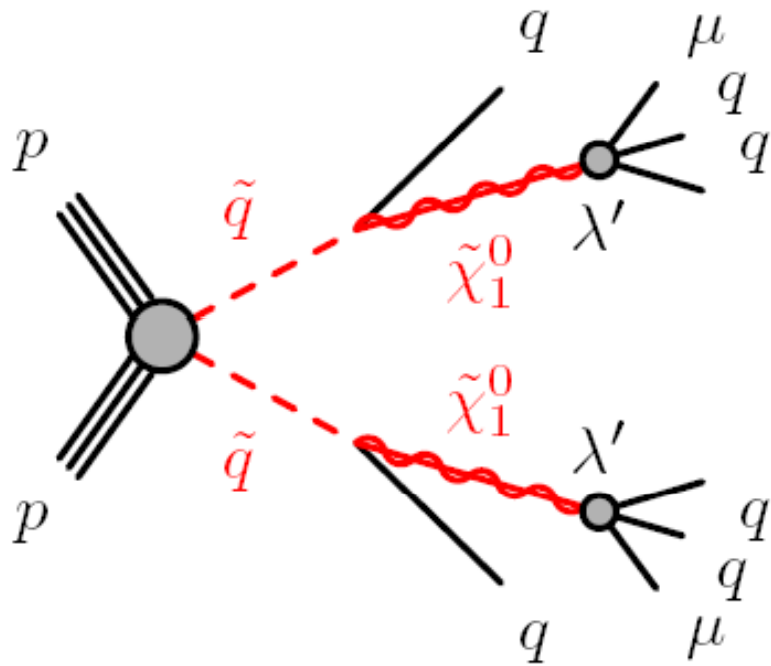
4 leptons + E_t^{miss} - Results



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2013-036

$e, \mu \quad p_T > 10 \text{ GeV}$
 $\tau \quad p_T > 20 \text{ GeV}$
 $|m_{\text{lep}} - m_Z| > 10 \text{ GeV}$
 $4e/\mu: \text{MET} > 75 \text{ GeV or}$
 $m_{\text{eff}} > 600 \text{ GeV}$
 $3e/\mu, 1\tau: \text{MET} > 100 \text{ GeV or}$
 $m_{\text{eff}} > 400 \text{ GeV}$

Displaced Vertices - Overview



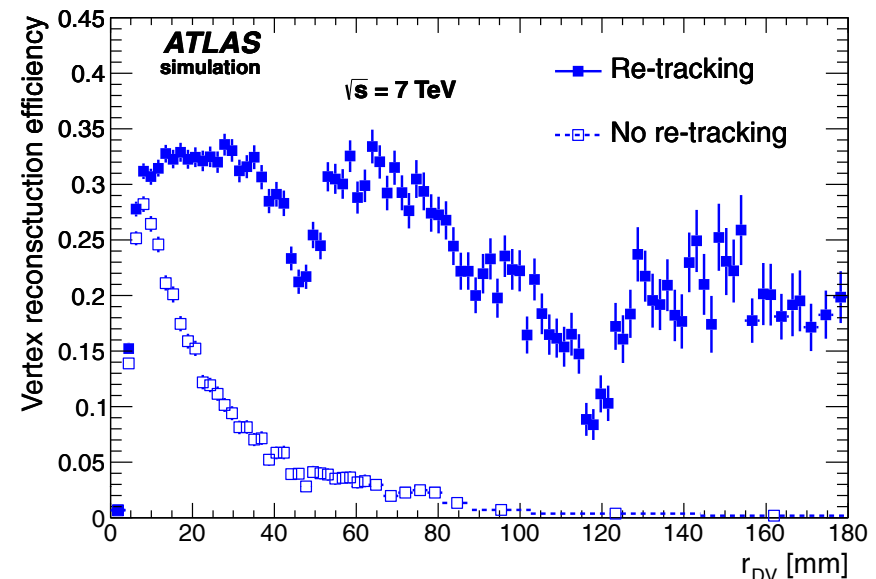
- Production of first/second generation (anti-)squarks
- RPV decay of long-lived neutralino LSP
 - 2 jets plus muon
 - within Inner Detector

Sample	$m_{\tilde{q}}$ [GeV]	$m_{\tilde{\chi}_1^0}$ [GeV]	σ [fb]	$\langle\gamma\beta\rangle_{\tilde{\chi}_1^0}$	$c\tau_{\text{MC}}$ [mm]	λ'_{211}
MH	700	494	124.3	1.0	175	0.2×10^{-5}
ML	700	108	124.3	3.1	101	1.5×10^{-5}
HL	1000	108	11.9	5.5	220	20.0×10^{-5}

ATLAS-CONF-2013-092

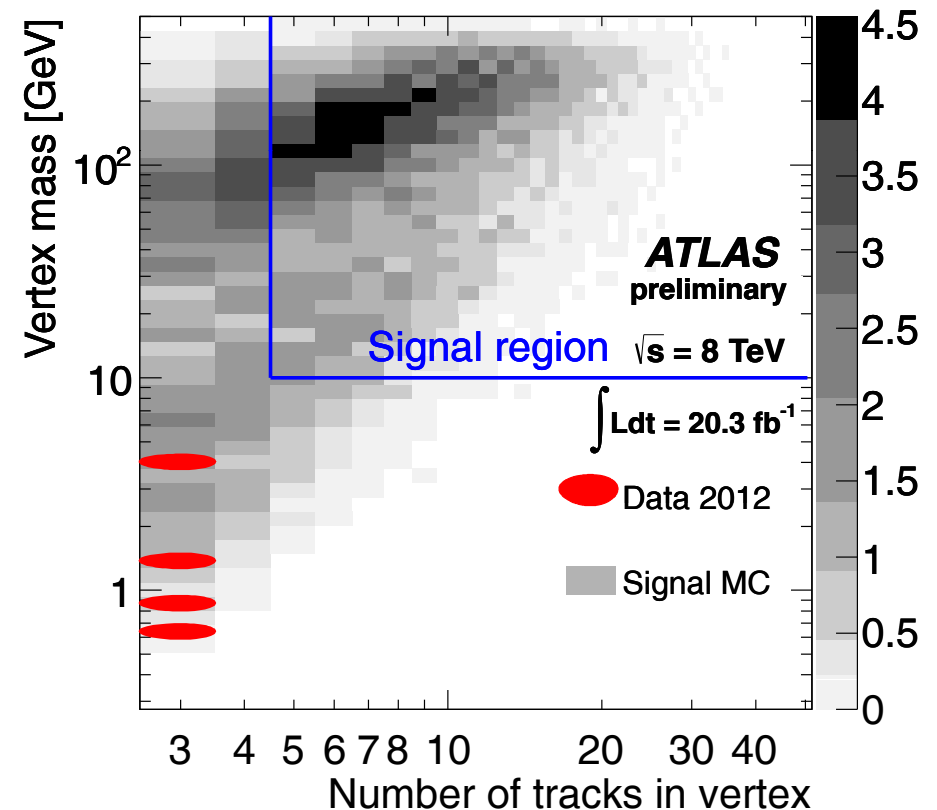
Displaced Vertices – Data Selection

- Muon trigger $p_T > 50$ GeV and $|\eta| < 1.05$
- Muon reconstruction in MS and ID with $p_T > 55$ GeV
- Rejection of cosmic ray events (2 muons back-to-back)
- Vertex requirements:
 - $2 \text{ mm} < |z_{DV}| < 300 \text{ mm}$ and $r_{DV} < 180 \text{ mm}$
 - Transverse distance PV to DV: $\sqrt{(x_{DV} - x_{PV})^2 + (y_{DV} - y_{PV})^2} \geq 4 \text{ mm}$
 - Vertex mass $m_{DV} > 10 \text{ GeV}$
 - Number of tracks associated with DV > 4
- Re-tracking:
Re-run tracking algorithm on ID hits
with looser requirements
(not used for tracks
from standard tracking)



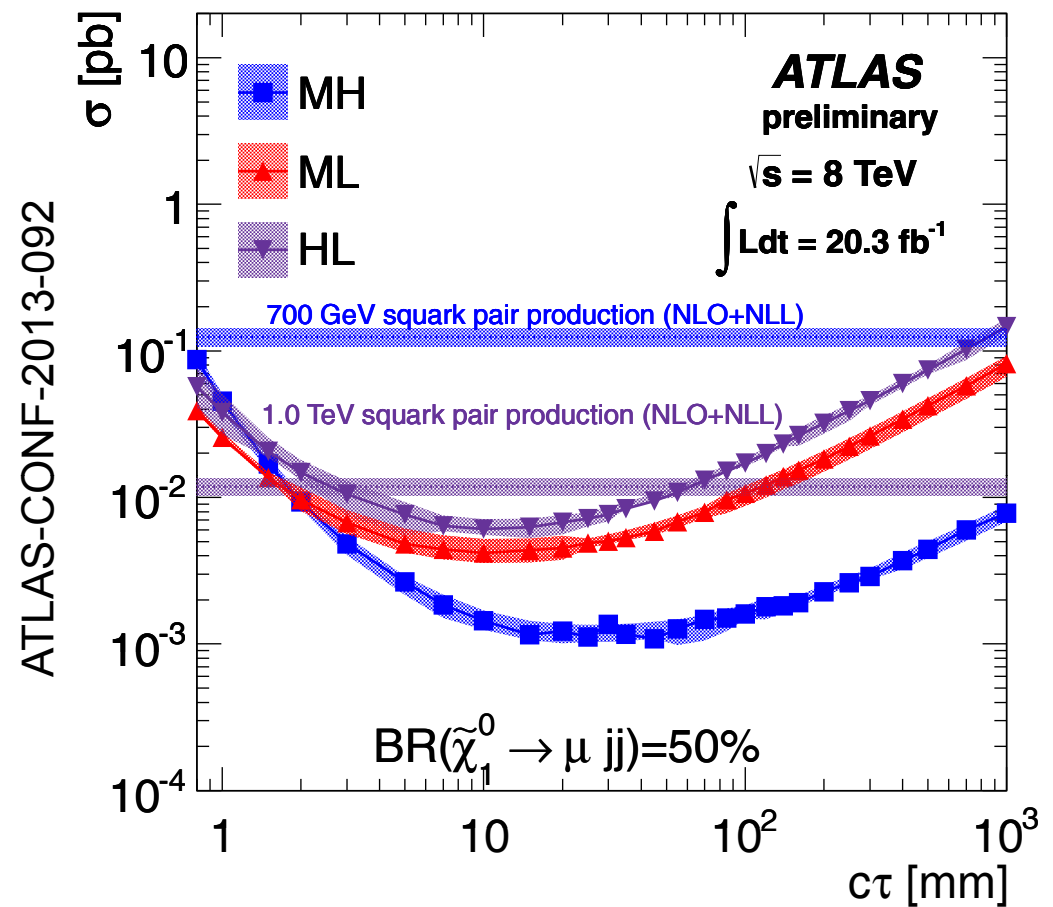
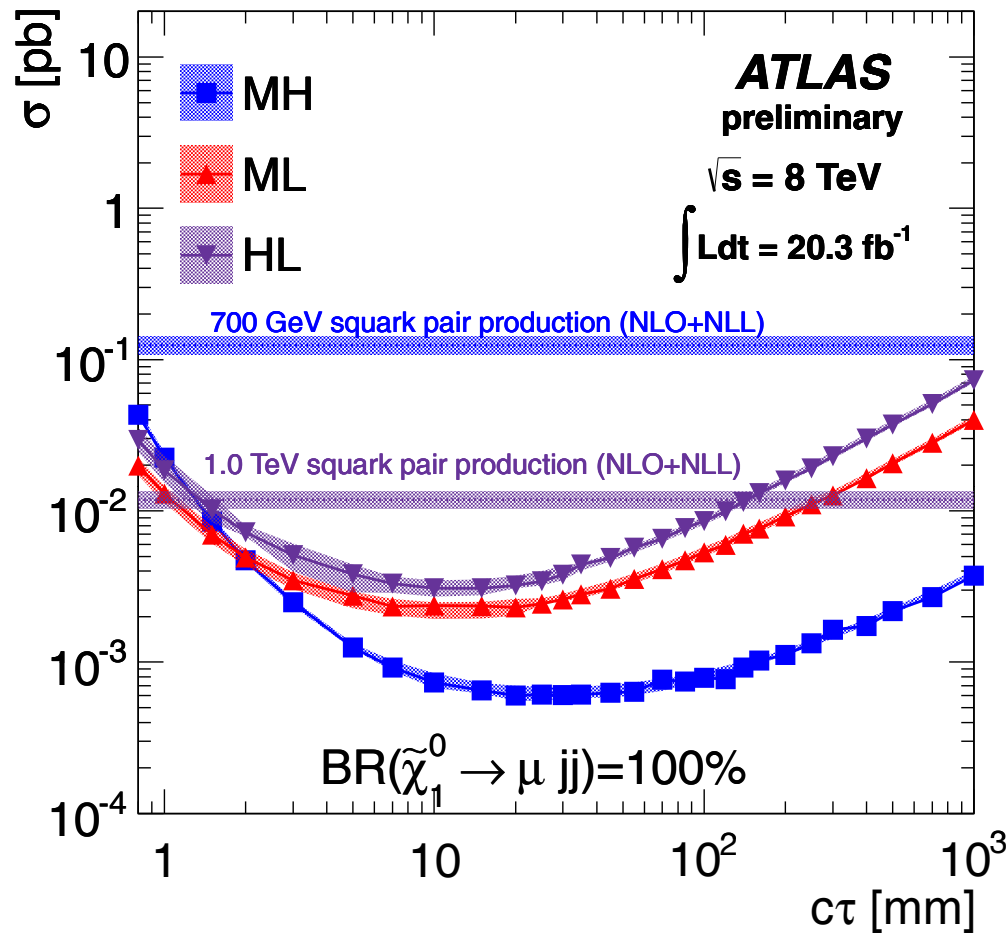
Displaced Vertices – Results

- Potential background sources
 - Random combination of tracks (inside beam pipe, negligible)
 - Hadronic interactions with gas (outside beam pipe)
- Systematic uncertainties:
 - Monte Carlo statistics
 - Muon reconstruction efficiency
 - Tracking / trigger efficiencies
 - Pile-up
 - Luminosity uncertainty
- Total background:
 0.2 ± 0.2 vertices



ATLAS-CONF-2013-092

Displaced Vertices – Results



Upper limits at 95% CL on cross-sections vs neutralino lifetime
 observation of 0 events satisfying all selection criteria

(left) BR for decay chain from squark to neutralino to muon-plus-jets 100%,

(right) this branching ratio 50%.

Shaded areas around exclusion curves ± 1 sigma uncertainty bands on expected limits.

Bilinear R-parity violation

- Phenomenological studies by J. Valle, W. Porod et al.
- L -violating couplings (in superpotential and soft SUSY breaking terms)

$$W \propto \varepsilon_i H L_i$$

- **Mixing of leptonic and Higgs superfields**

- Neutrinos and neutralinos
- Charged leptons and charginos
- Higgs and sneutrinos

- Parameters for **bRPV model and neutrino oscillations**

- ν mixing parameter consistent with ν data
- bRPV parameters determined by ν data in conjunction with electroweak symmetry breaking
- Calculation of bRPV parameters and spectrum: SPheno (W. Porod)

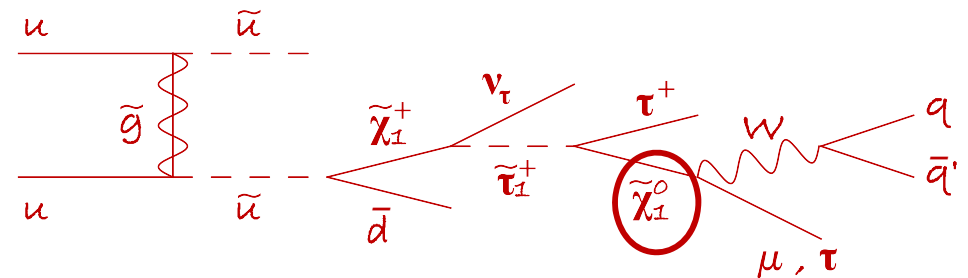
- Relation of **LSP decays to neutrino parameters**

$$\frac{BR(\tilde{\chi}_1^0 \rightarrow \mu W)}{BR(\tilde{\chi}_1^0 \rightarrow \tau W)} \approx \tan^2 \theta_{atm}$$

Generic bRPV-Signatures

- Other exp. results / constraints:
 - Processes at low energies and neutrino oscillations
 - No search results at Tevatron or CMS
- Detector signatures:
 - For $m(\text{LSP}) > 82/92/125$ GeV: Two-body decays into boson+lepton
 - Significant increase of lepton numbers (muon and tau)
 - Slight increase of jet numbers, in particular b -jets
 - Reduction of E_t^{miss} (from ν only)
 - Equal prob. for OS/SS leptons from Majorana-LSP decays
 - Prompt vs. late **LSP decays**

$\text{BR}(\tilde{\chi}_1^0 \rightarrow W\mu)$	$\text{BR}(\tilde{\chi}_1^0 \rightarrow \tau\tau\nu)$
$\text{BR}(\tilde{\chi}_1^0 \rightarrow W\tau)$	$\text{BR}(\tilde{\chi}_1^0 \rightarrow \tau\mu\nu)$
$\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\nu)$	$\text{BR}(\tilde{\chi}_1^0 \rightarrow jj'\nu)$
$\text{BR}(\tilde{\chi}_1^0 \rightarrow h\nu)$	



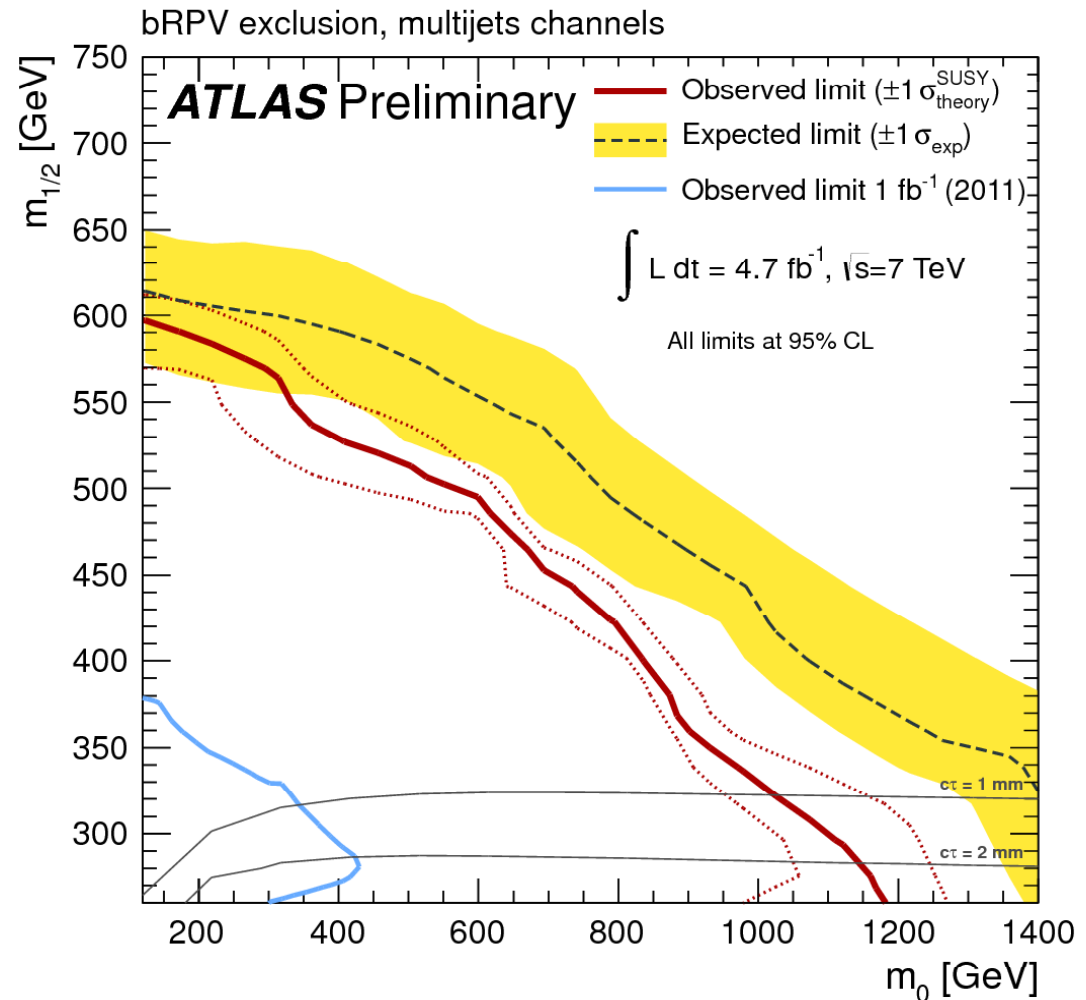
bRPV exclusion (7 TeV / 4,7 fb⁻¹)

Selection (SR):

- 1 lepton and ≥ 7 jets
- $p_T > 25$ GeV electron or $p_T > 20$ GeV muon
- Jets $p_T > 80$ (25) GeV
- $m_T > 120$ GeV
- $E_T^{\text{miss}} > 180$ GeV
- $m_{\text{eff}} > 750$ GeV

Signal grid (7 TeV)

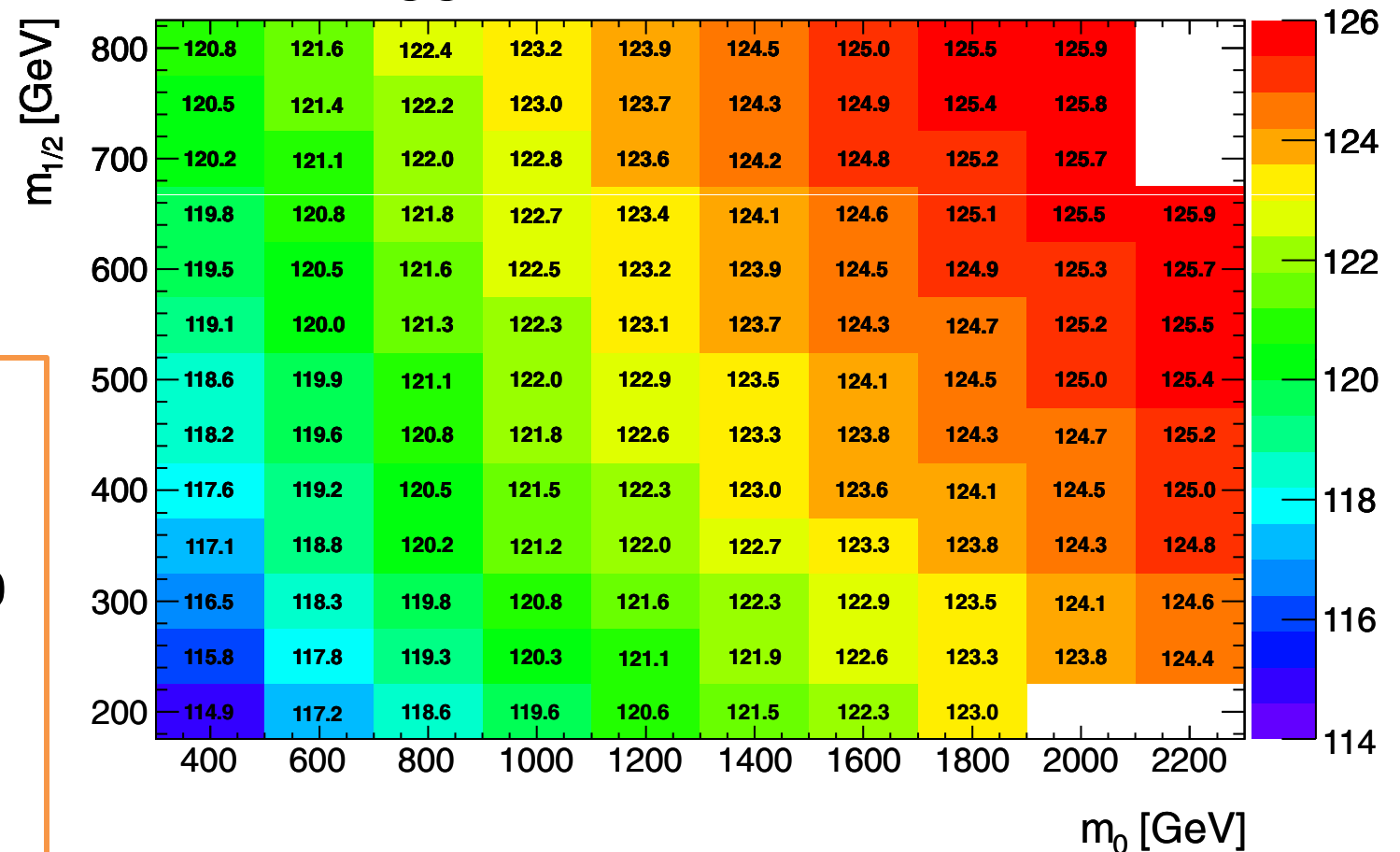
- $A_0 = 0$, $\tan\beta = 10$, $\text{sign}(\mu) = +1$
- $100 \text{ GeV} \leq m_0 \leq 800 \text{ GeV}$
- $200 \text{ GeV} \leq m_{1/2} \leq 600 \text{ GeV}$
- Prompt decays ($c\tau < 5 \text{ mm}$)



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bRPV mSUGRA: Higgs aware grid

Higgs mass in GeV

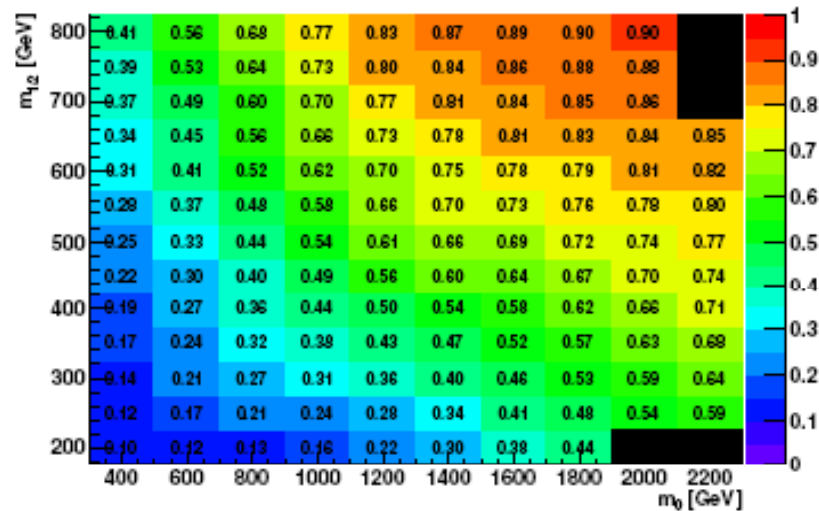


Signal grid

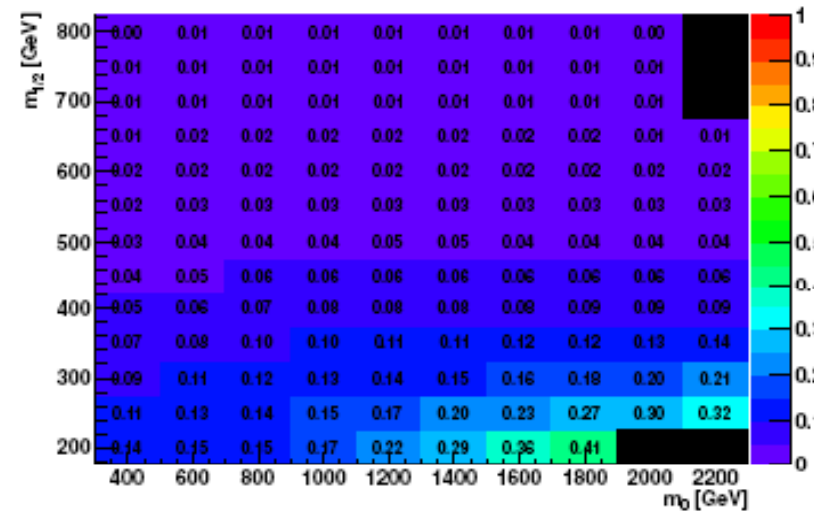
- $A_0 = -2 m_0$, $\tan\beta = 30$, $\text{sign}(\mu) = +1$
- $400 \leq m_0$ [GeV] ≤ 2200
- $200 \leq m_{1/2}$ [GeV] ≤ 800
- Focus on prompt LSP decays
- Higgs mass approx. 123 GeV

bRPV mSUGRA: Production

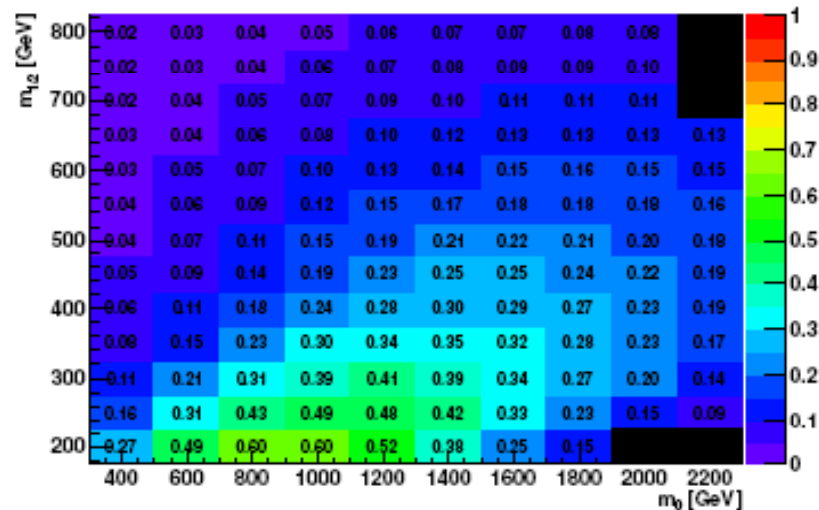
$qq \rightarrow \chi \chi$



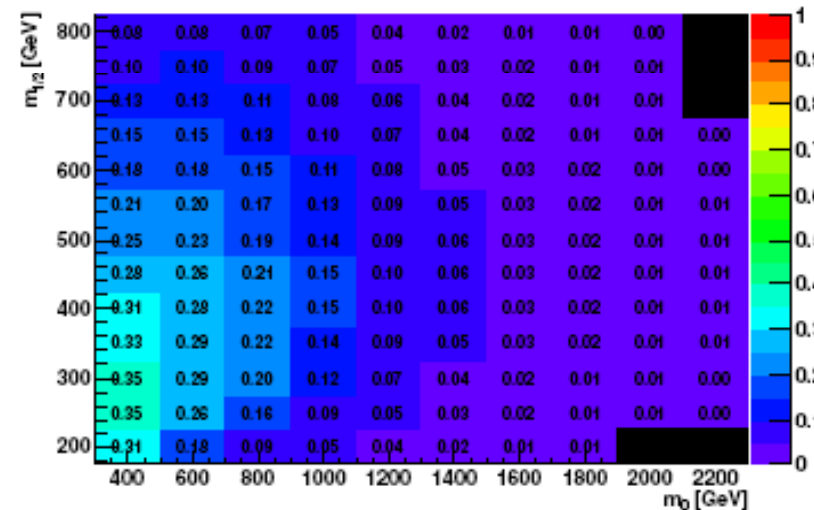
$qq \rightarrow \tilde{g} \tilde{g}$



$qq \rightarrow \tilde{t} \tilde{t}^* \rightarrow \tilde{t} \tilde{t}^* b \bar{b}$



$qq \rightarrow \tilde{q} \tilde{q}^* \rightarrow \tilde{q} \tilde{q}^* g$

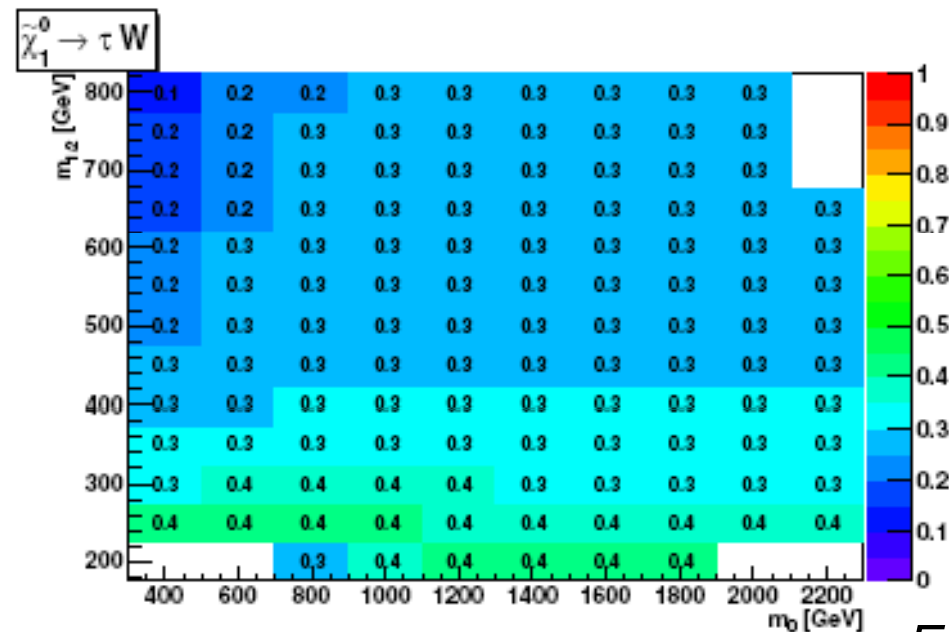
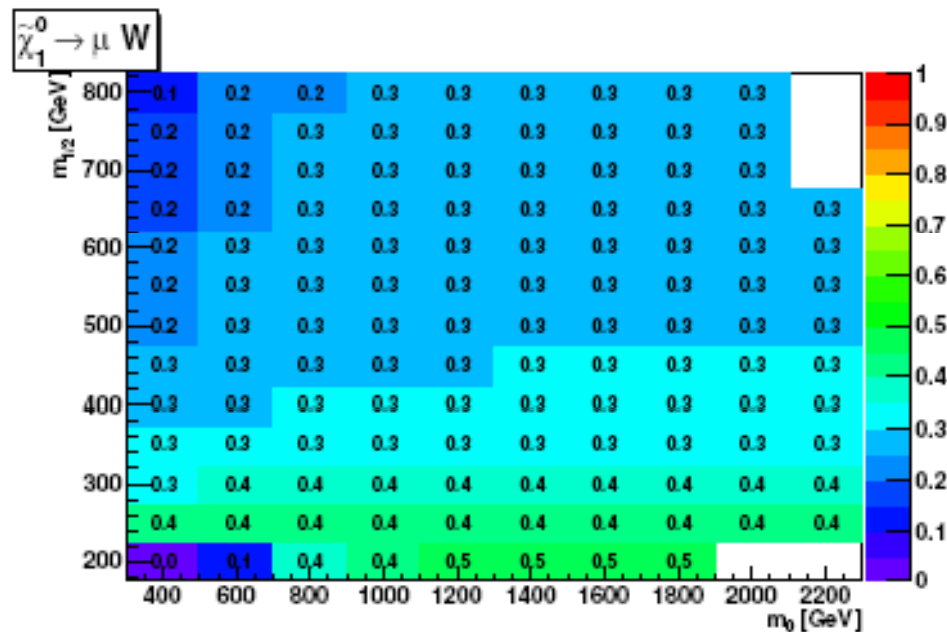
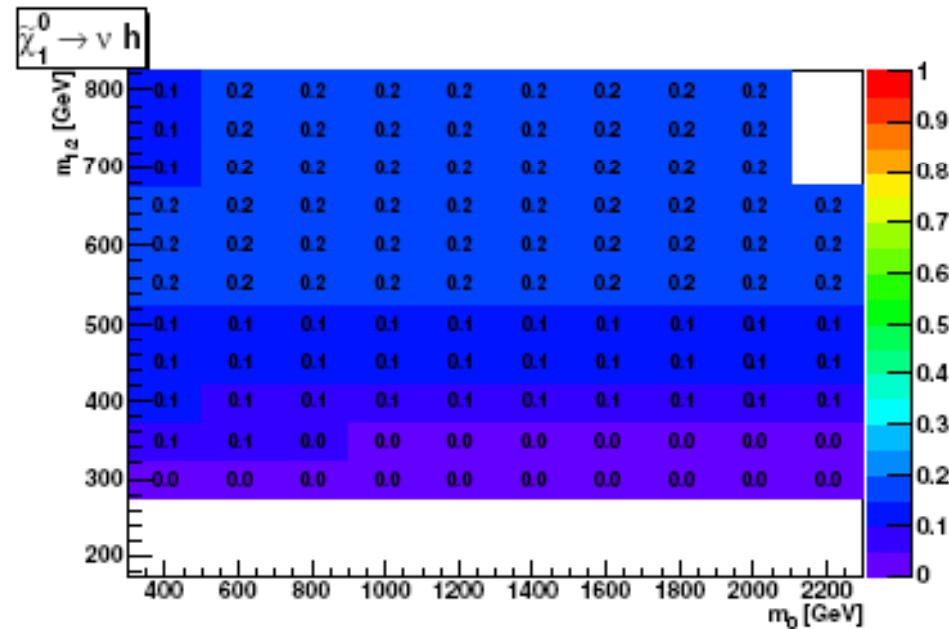
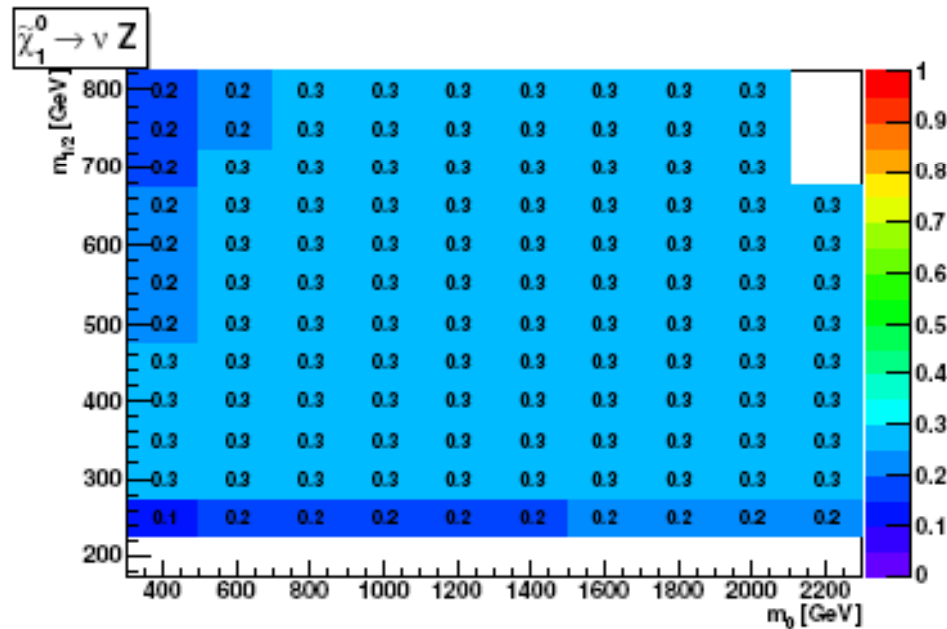


Fraction of cross-section per SUSY subprocess w.r.t *total* prod. cross-section
Similar to RPC production contributions

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bRPV mSUGRA: LSP decays



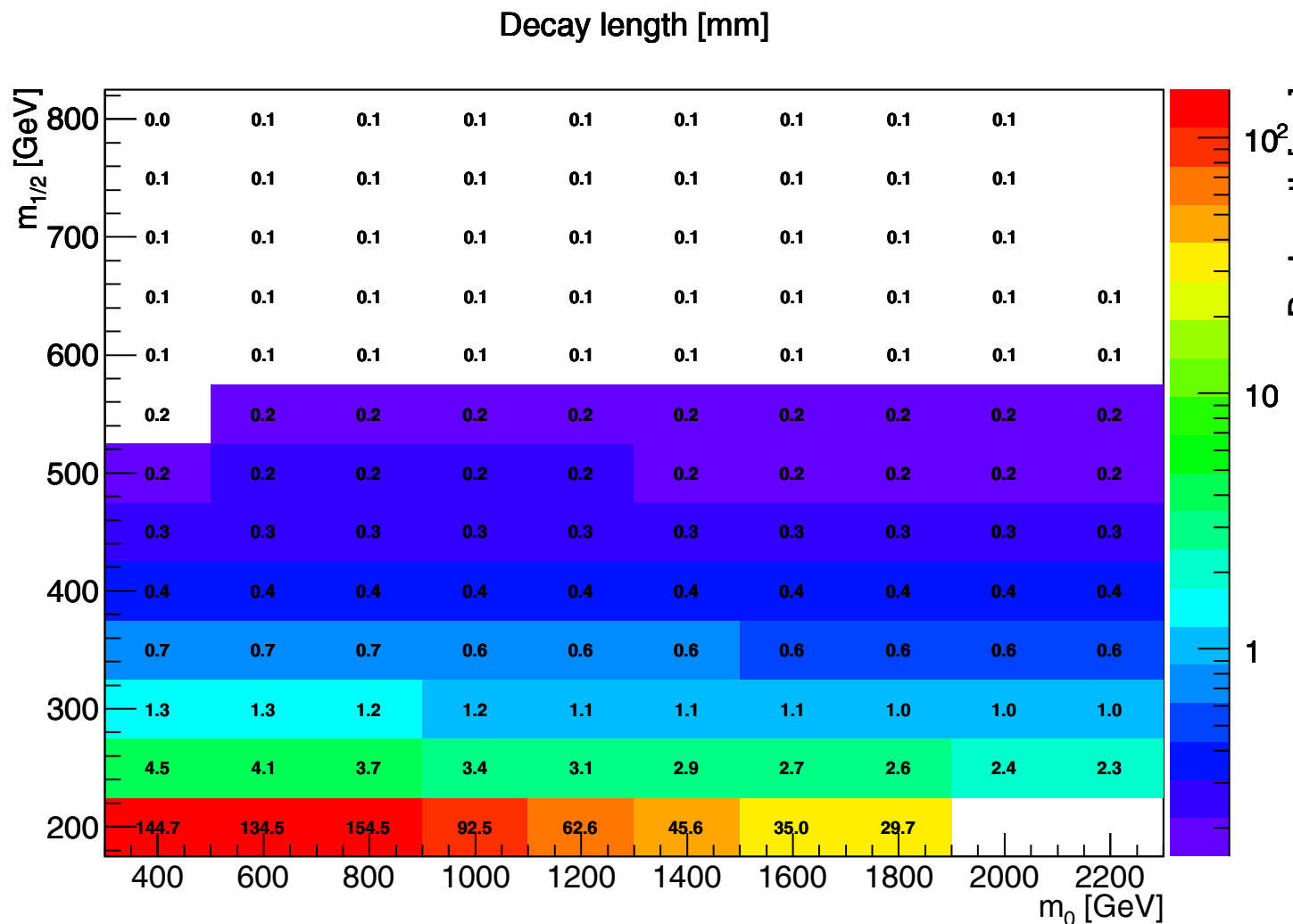
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LSP decay length in bRPV mSUGRA

Signal grid

- $A_0 = -2 m_0$, $\tan\beta = 30$, $\text{sign}(\mu) = +1$
- $400 \leq m_0 [\text{GeV}] \leq 2200$
- $200 \leq m_{1/2} [\text{GeV}] \leq 800$
- Focus on prompt LSP decays
- Higgs mass approx. 123 GeV

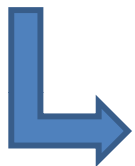


Status of searches for prompt bRPV

- Spectra files from SPheno
 - mSUGRA parameters
- Event generation based on Pythia6
 - Production of all SUSY sub-processes
 - Focus on prompt decays
- Exclusions
 - **1 Lepton + 3 (4) Jets** (Phys. Rev. D85 (2012) 012006)
 - **1 Lepton + multi-Jets** (ATLAS-CONF-2012-140)
- New Results soon
 - Dominant contributions from strong production
 - High sensitivity for several LSP decay modes
 - Combinations of analyses

Beyond prompt bRPV at ATLAS

- Take into account existing / upcoming results
- **Models**
 - Alternative high-scale models
 - Low-scale (simplified) models with bRPV LSP decays
- **Production processes** with reduced cross-sections
 - Natural spectra
 - Electroweak production channels only
- **Displaced vertices**
 - Analysis of light LSPs with late decays ($c\tau > 5$ mm)
 - Suppressed 3-body decay
- **LHC at high luminosities**
- **ILC** (see arXiv:1307.4074 [hep-ex])



Potential to search for bRPV phenomenology in detail

Conclusions

- Large amount of SUSY limits based on 2012 8 TeV data (ATLAS and CMS)
- Several analyses to be finished, **current focus on combinations**
- Search for TeV-scale SUSY in various areas of parameter space including R-parity violation
- Efforts to improve / generalize over-simplified models
- Strong constraints on SUSY parameter space from combination of LHC searches with other exp. results (rare decays, dark matter etc.)
- Experimental constraints from SUSY set **also limits for other models beyond the Standard Model**
- **Open for discussions** on strategies for (bRPV) SUSY searches

Extra material

Variables for event selection

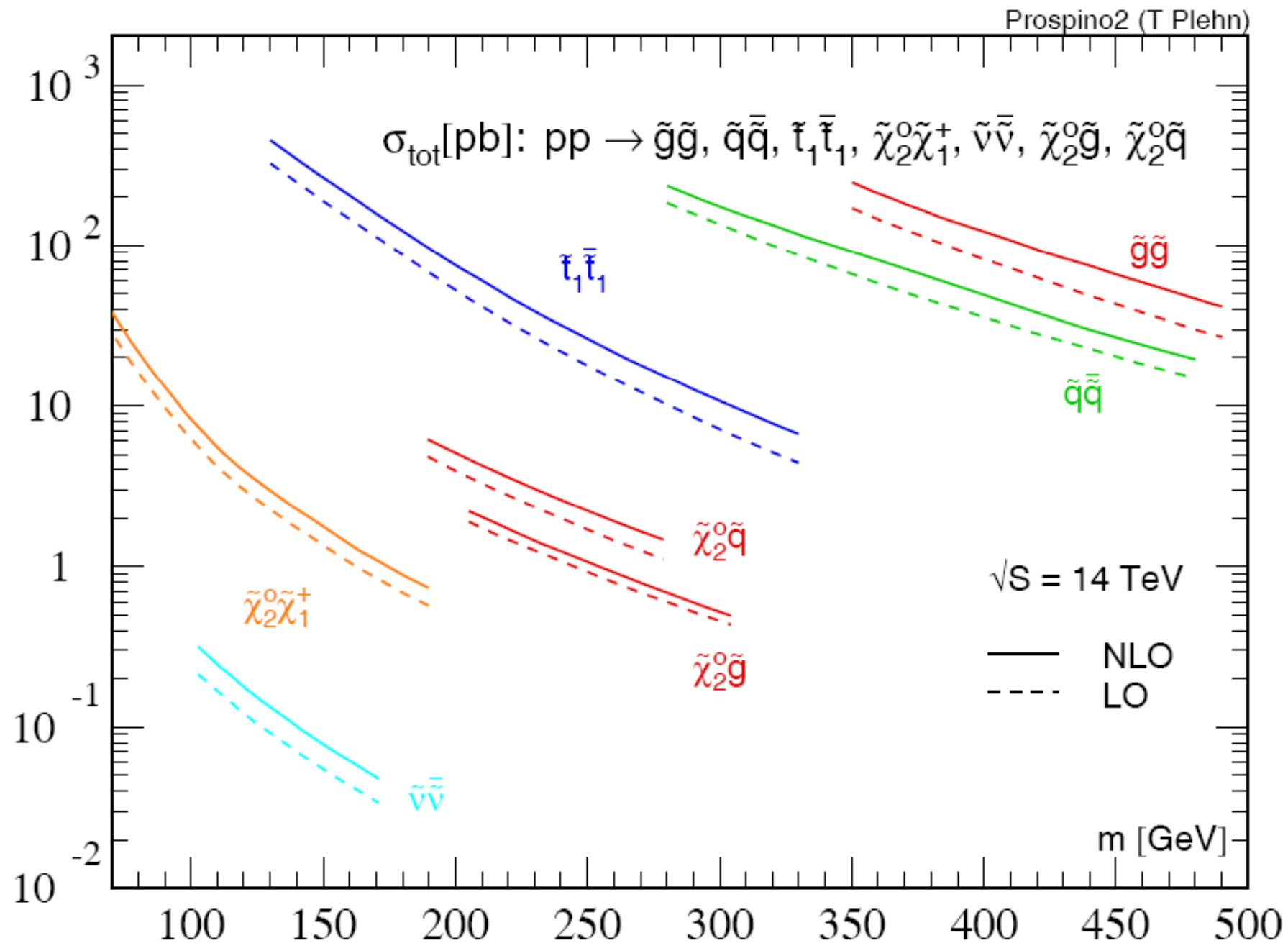
$$m_T = \sqrt{2p_T^{\text{lep}} E_T^{\text{miss}} - 2\mathbf{p}_T^{\text{lep}} \cdot \mathbf{p}_T^{\text{miss}}}$$

$$m_{\text{CT}}^2 = \left(E_T^{b_1} + E_T^{b_2}\right)^2 - \left|\mathbf{p}_T^{b_1} - \mathbf{p}_T^{b_2}\right|^2$$

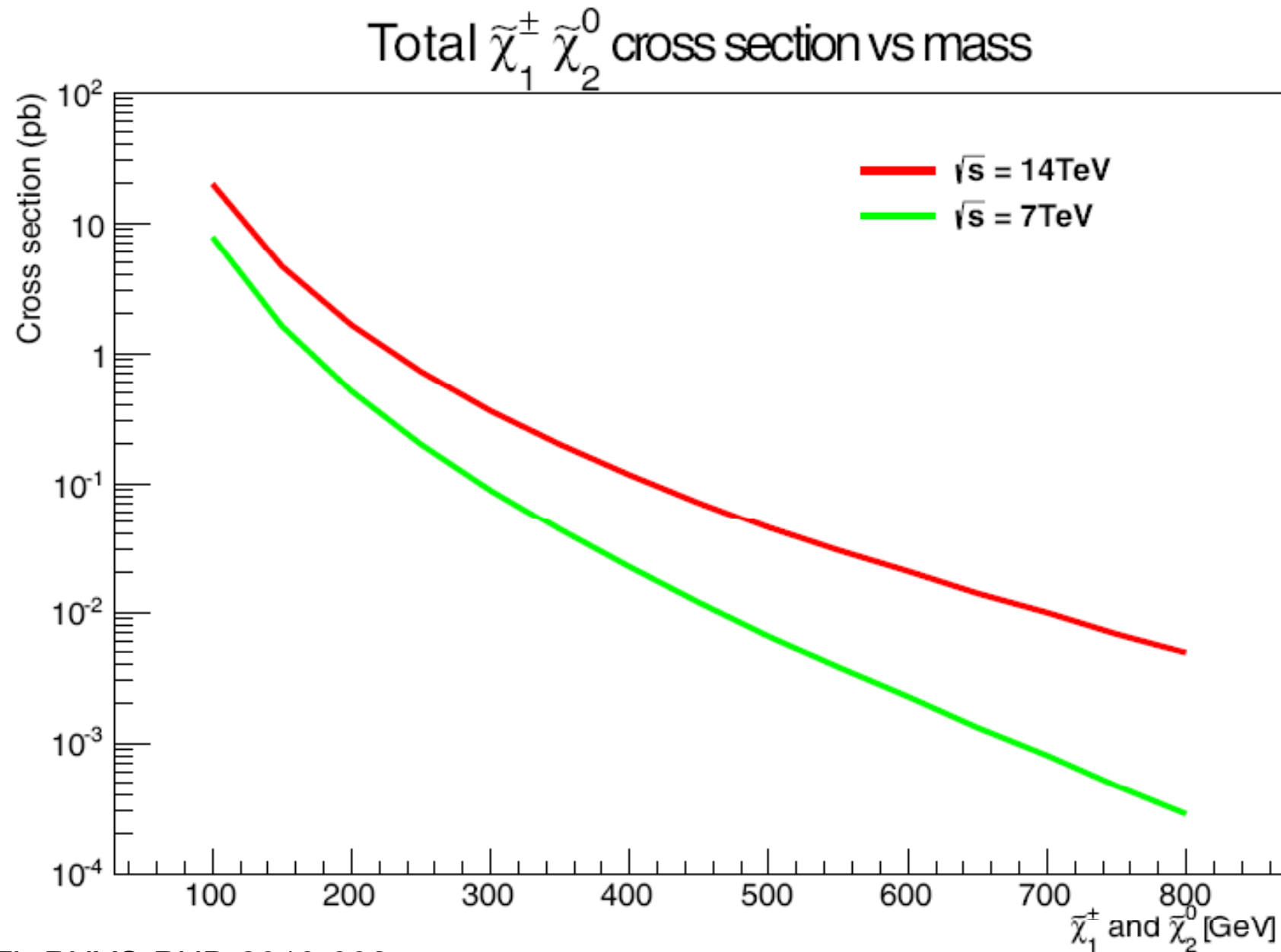
$$m_{\text{CT}}^2 \approx 2p_T^{b_1} p_T^{b_2} (1 + \cos \Delta\phi_{bb})$$

$$m_{\text{CT}}^{\text{max}} \approx \frac{m_{\text{heavy}}^2 - m_{\text{invisible}}^2}{m_{\text{heavy}}}$$

SUSY cross-sections at 14 TeV

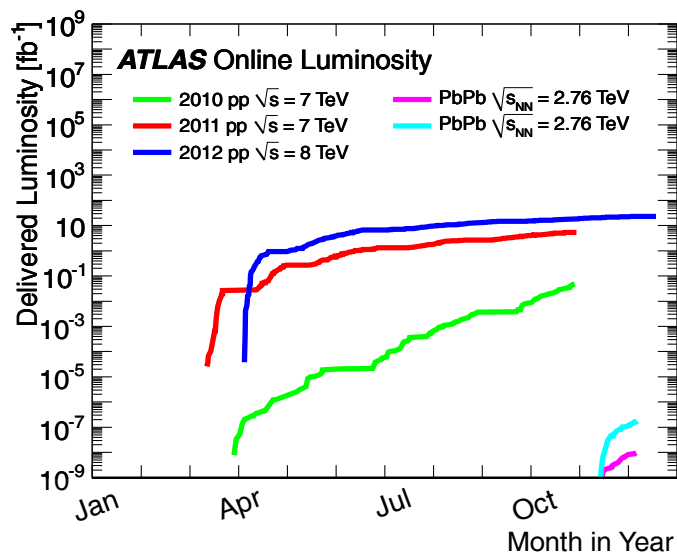
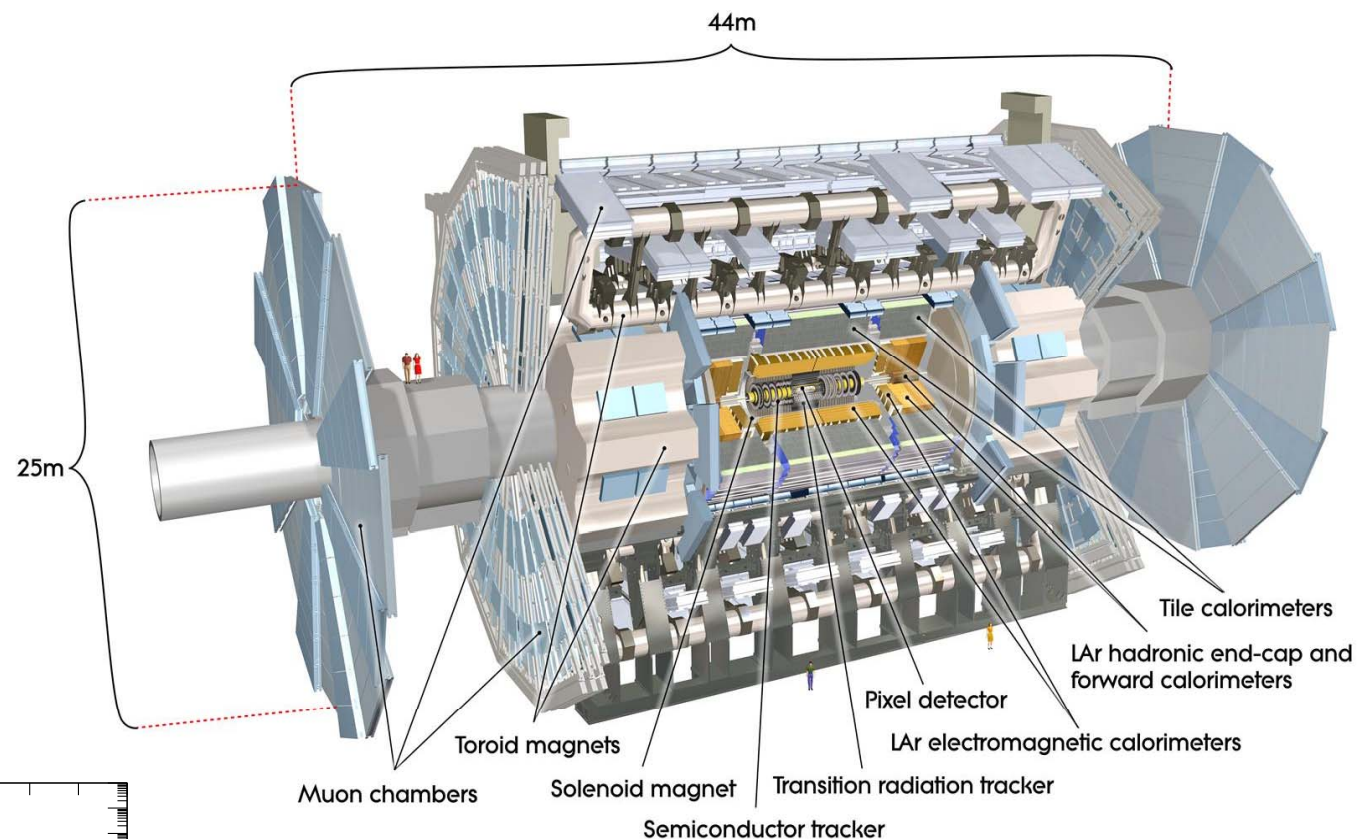


Electroweak production at 14 TeV



ATL-PHYS-PUB-2013-002

ATLAS detector and upgrade



- Higher beam energies: $\sqrt{s} = 13 / 14$ TeV
- Instant. Lumi: $2 / 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Integrated Lumi: $300 / 3000 \text{ fb}^{-1}$
- Trigger upgrade

(Phenomenological) MSSM

Parameter	Description
M_1	Bino mass
M_2	Wino mass
M_3	Gluino mass
$m_{\tilde{e}_L} = m_{\tilde{\mu}_L}$	1st / 2nd gen. L_L slepton
$m_{\tilde{\tau}_L}$	3rd gen. L_L slepton
$m_{\tilde{e}_R} = m_{\tilde{\mu}_R}$	1st / 2nd gen. E_R slepton
$m_{\tilde{\tau}_R}$	3rd gen. E_R slepton
$m_{\tilde{u}_L} = m_{\tilde{d}_L} = m_{\tilde{c}_L} = m_{\tilde{s}_L}$	1st / 2nd gen. Q_L squark
$m_{\tilde{t}_L} = m_{\tilde{b}_L}$	3rd gen. Q_L squark
$m_{\tilde{u}_R} = m_{\tilde{c}_R}$	1st / 2nd gen. U_R squark
$m_{\tilde{t}_R}$	3rd gen. U_R squark
$m_{\tilde{d}_R} = m_{\tilde{s}_R}$	1st / 2nd gen. D_R squark
$m_{\tilde{b}_R}$	3rd gen. D_R squark
A_t	Trilinear coupling t -quark
A_b	Trilinear coupling b -quark
A_τ	Trilinear coupling τ -lepton
m_{H_1}	u -type Higgs doublet mass
m_{H_2}	d -type Higgs doublet mass
$\tan \beta$	Ratio scalar doublet VEVs

e.g. Phys.Rev.D81:095012,2010

General structure
of superpotential

$$\mathcal{W}_{gen} = \frac{1}{2} M_{ij} \Phi_i \Phi_j + \frac{1}{6} y_{ijk} \Phi_i \Phi_j \Phi_k$$

Structure of soft-SUSY
breaking Lagrangian

$$\begin{aligned} \mathcal{L}_{soft}^{gen} = & -\frac{1}{2} \left(\tilde{M}_{\lambda_a} \lambda_a \lambda_a + h.c. \right) \\ & - m_{ij}^2 \phi_i^* \phi_j \\ & - \left(\frac{1}{2} b_{ij} \phi_i \phi_j + \frac{1}{6} a_{ijk} \phi_i \phi_j \phi_k + h.c. \right) \end{aligned}$$