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Supersymmetry after LHC Run-I: Where do we stand?

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IFIC Valencia & CERN

HEP 2015

Conference on Recent Developments
in High Energy Physics and Cosmology

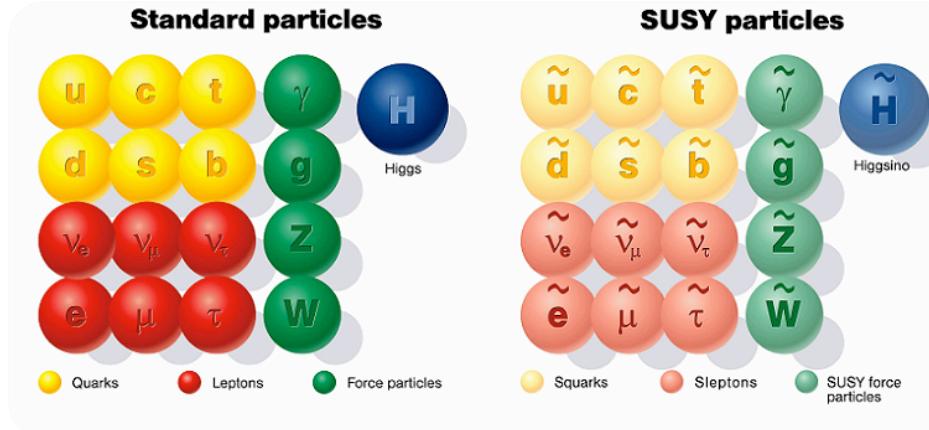
15-18 April 2015, Athens, Greece



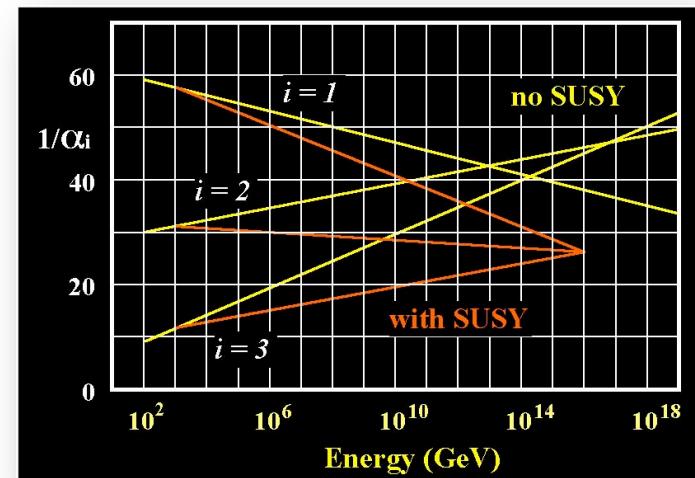
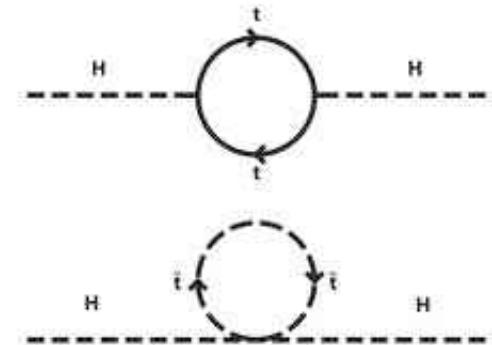
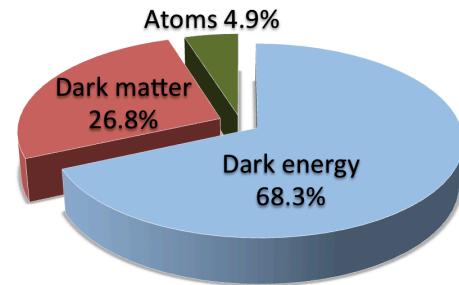
Outline

- Introduction – Supersymmetry
 - motivation
 - searches strategy @ LHC
- Run I results
 - exclusions of parameter space
 - observed deviations from SM
 - possible explanations within SUSY
- Expectations for Run-II & beyond
 - extended reach from higher \sqrt{s} & \mathcal{L}
 - R-parity violation (especially when explaining neutrino masses)
 - bilinear RPV
 - $\mu\nu$ SSM
 - dark matter
 - long-lived particles
- Summary and outlook

Supersymmetry (SUSY)

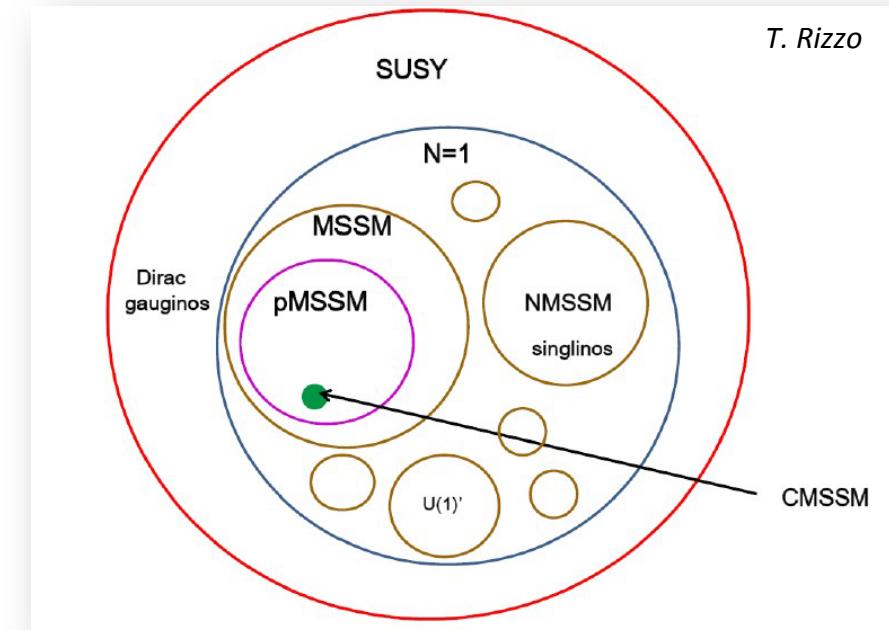


- What it is?
 - global symmetry between fermions & bosons
- Why is it attractive?
 - Higgs: predicts a below-135-GeV Higgs scalar
 - may be SM-like
 - completely solves hierarchy problem
 - unification of gauge couplings at single scale
 - dark matter candidate
 - neutrino masses can be explained, if R-parity broken



Framework versus model

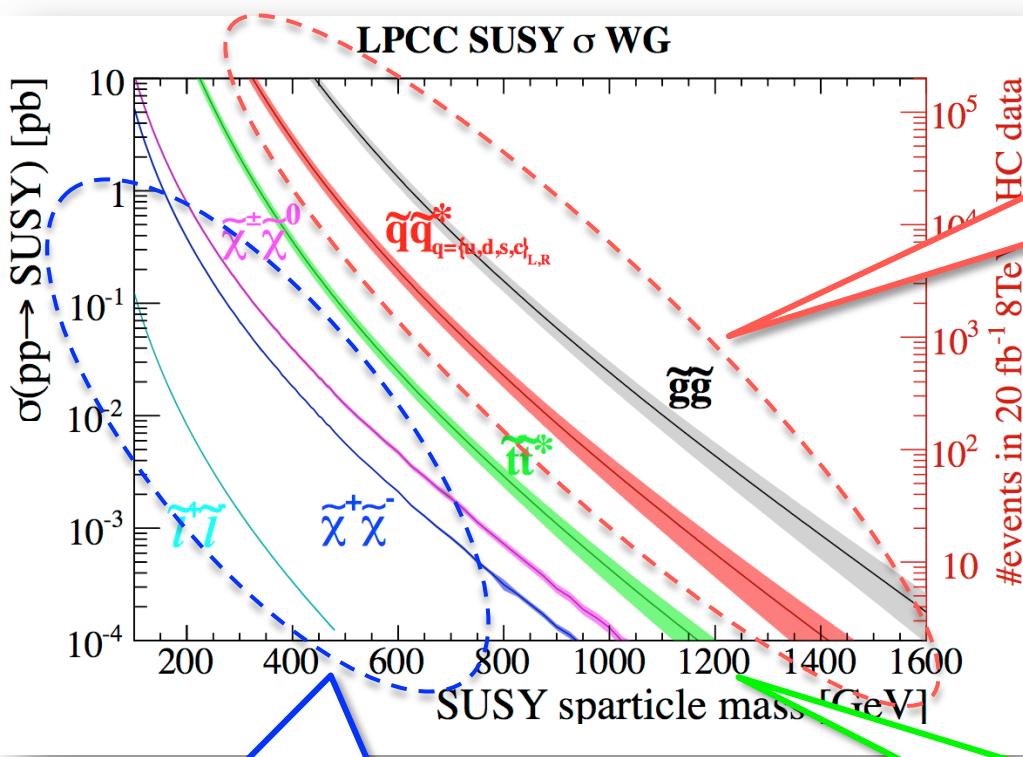
- Sparticle masses from SUSY breaking not fixed by theory
⇒ huge parameter space to explore
 - MSSM: > 100 parameters
 - pMSSM: 19 parameters
 - CMSSM: 5 parameters
- **How to test that at LHC?**
- 1. **Top-down approach**
 - SUSY breaking mechanism → different models
 - GUT scale unification → few free parameters
- 2. **Bottom-up approach**
 - Phenomenological models
 - fix masses and hierarchy
 - scan remaining parameters
 - Simplified topologies
 - specific decay chain



Searches at the LHC prioritised by integrated luminosity, trigger requirements, spectrum-calculator availability, etc.

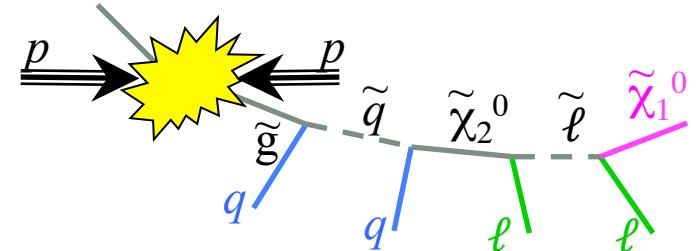
Not necessarily driven by theoretical motivations

SUSY searches @ LHC



Strong-production channels

- Copious production at hadron colliders
- MET-based generic channels (*)



- towards rarer processes
- ~ follows searches timeline

Leptons/photons searches

Colored sparticles too heavy

→ direct gaugino production

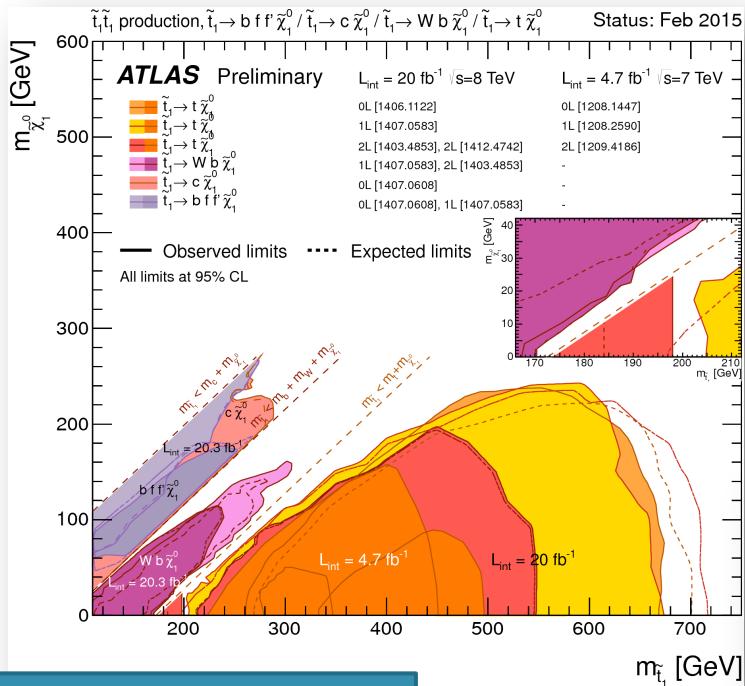
→ relevant for **Dark Matter** searches

Third-generation sparticle searches

- Expected from naturalness to be $O(<\text{TeV})$
- Expected lighter than other squarks

(*) MET = imbalance of total measured transverse momentum

Results overview from Run I



3rd generation squarks

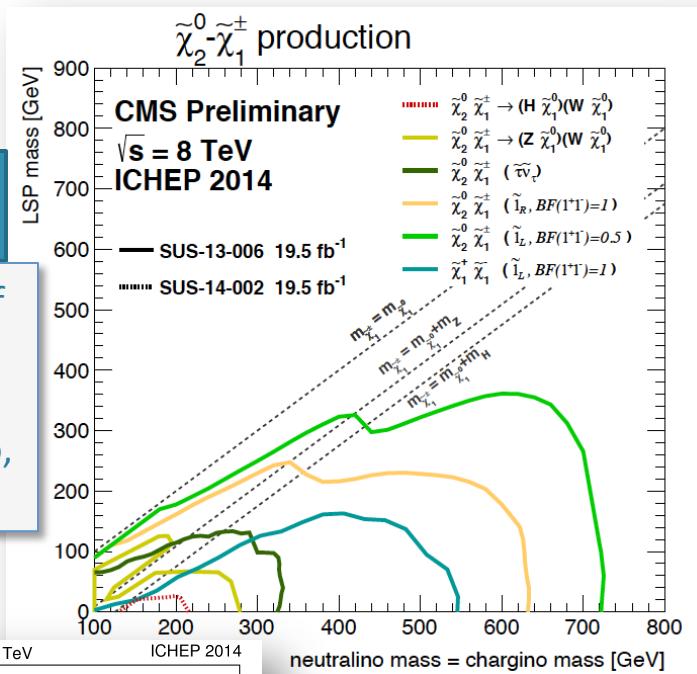
Overlaid contours belong to different stop decay channels, sparticle mass hierarchies, and simplified-decay scenarios. Care must be taken when interpreting them.



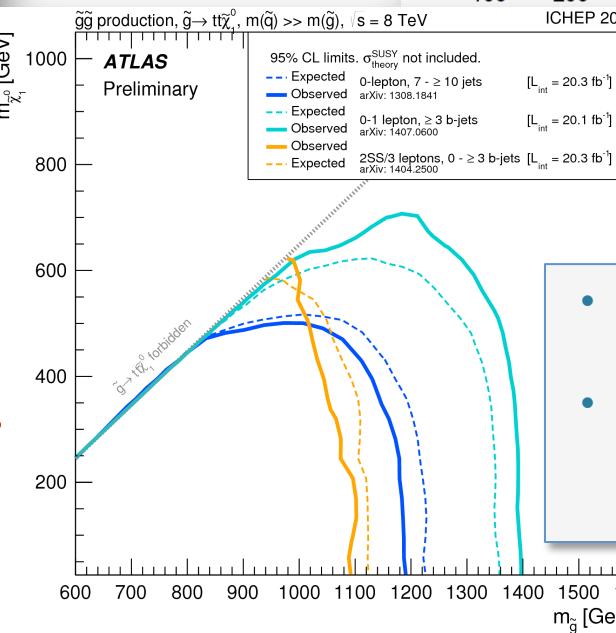
Electroweak production

Sensitive to details of scenario considered

- e.g. nature of gaugino (bino, wino, higgsino)



3rd generation squarks
– gluino mediated

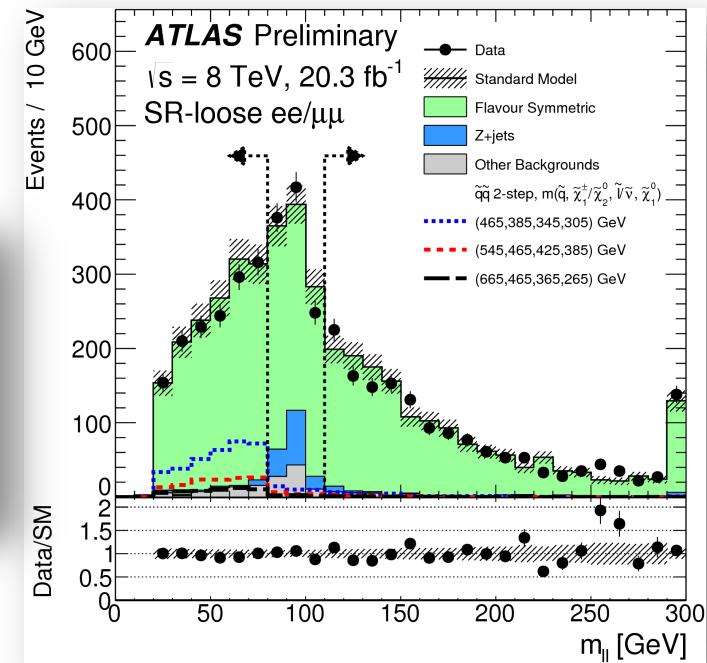
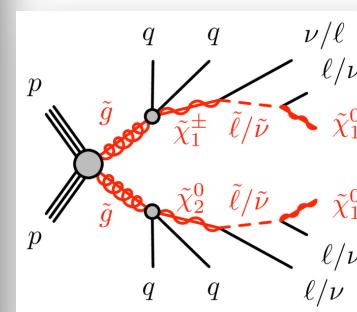
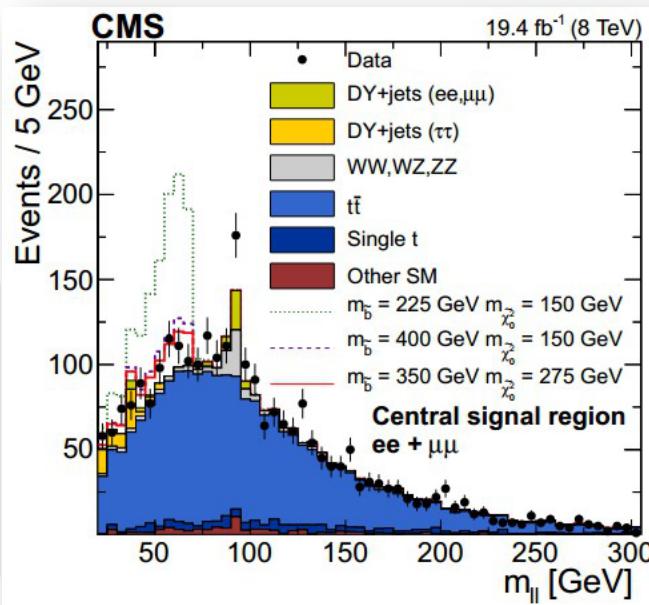


- Limits largely independent from \tilde{t} and \tilde{b} masses
- Sensitivity at large \tilde{g} masses increased by using composite jets

$2\ell + \text{jets} + \text{MET}$ channel – kinematic edge

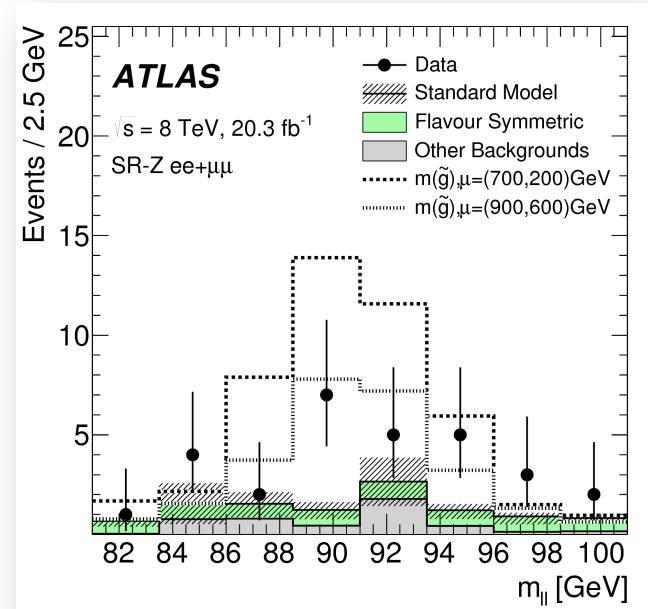
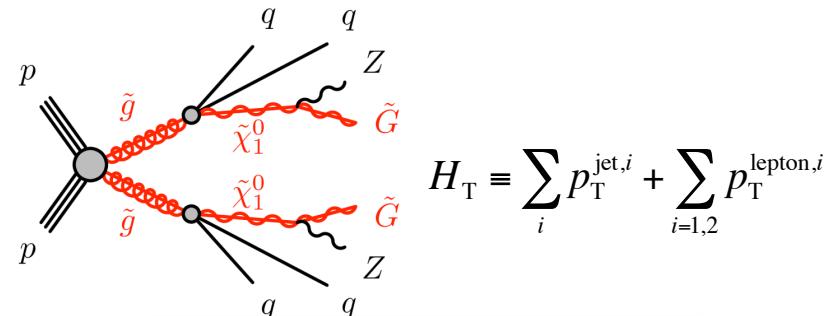
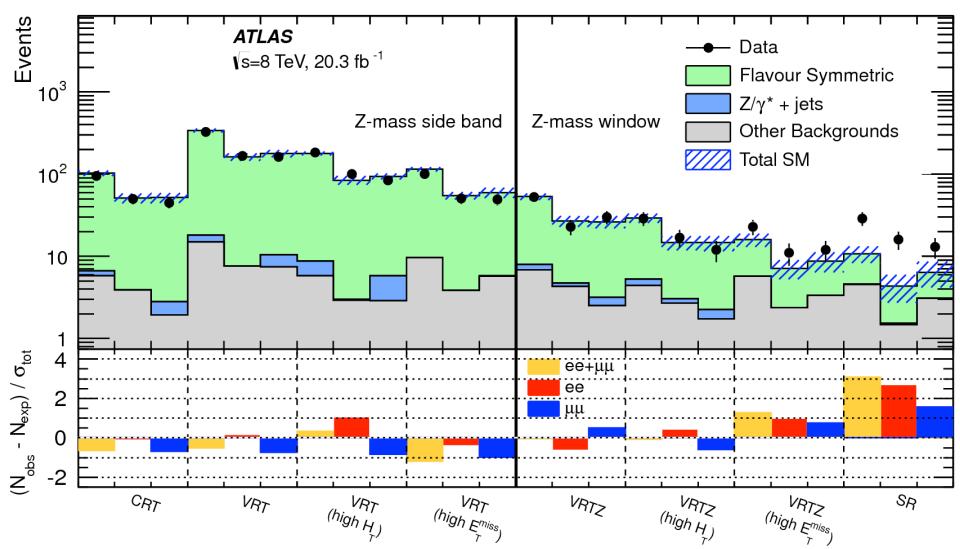
- Search in final states with 2 leptons (e, μ), 2 or 4 jets, with or without b-tags and MET
- Rising $m_{\ell\ell}$ distribution with endpoint at $m_{\max} \approx m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) = [m(\tilde{g}/\tilde{q}) - m(\tilde{\chi}_1^0)] / 2$
- Kinematic fit of backgrounds to data spectrum
- **CMS:** Excess in low $m_{\ell\ell}$ observed at **2.6σ** level for central dileptons (2.4 σ including forward)
 - roughly consistent with a 350-400 GeV sbottom with a 150-300 GeV $\tilde{\chi}_2^0$
- **ATLAS:** No excess seen in similar selection

$$\tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$$



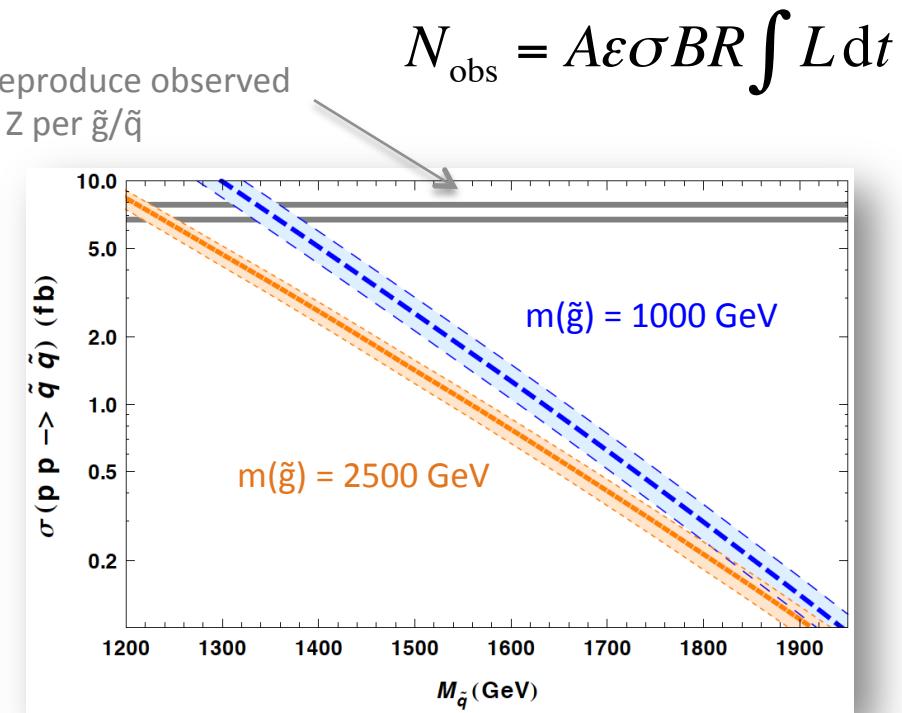
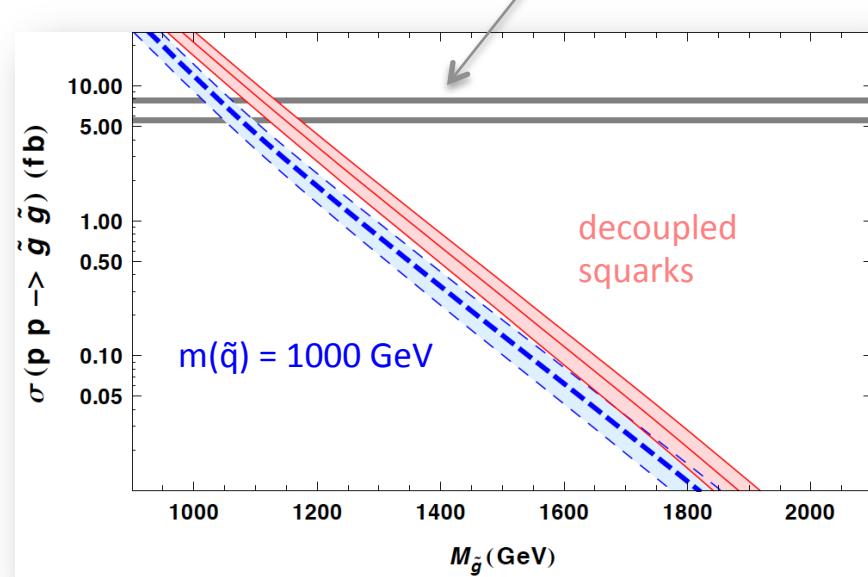
$Z (\rightarrow \ell\ell) + \text{jets} + \text{MET}$

- Selection: $\ell^\pm \ell^\mp$ pair consistent with M_Z , ≥ 2 jets with $p_T > 35$ GeV, $H_T > 600$ GeV, MET > 225 GeV
- Excess of events over expected background observed with **3σ significance**
- No such excess in CMS [arXiv:1502.06031], but $\sim 30\%$ overlap with CMS (no H_T cut) means this is **not ruled out** (yet)



Channel	$Z \rightarrow e^+ e^-$	$Z \rightarrow \mu^+ \mu^-$	Combined
Observed	16	13	29
Expected bkg.	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Significance	3σ	1.7σ	3.0

Trying to explain Z+MET excess



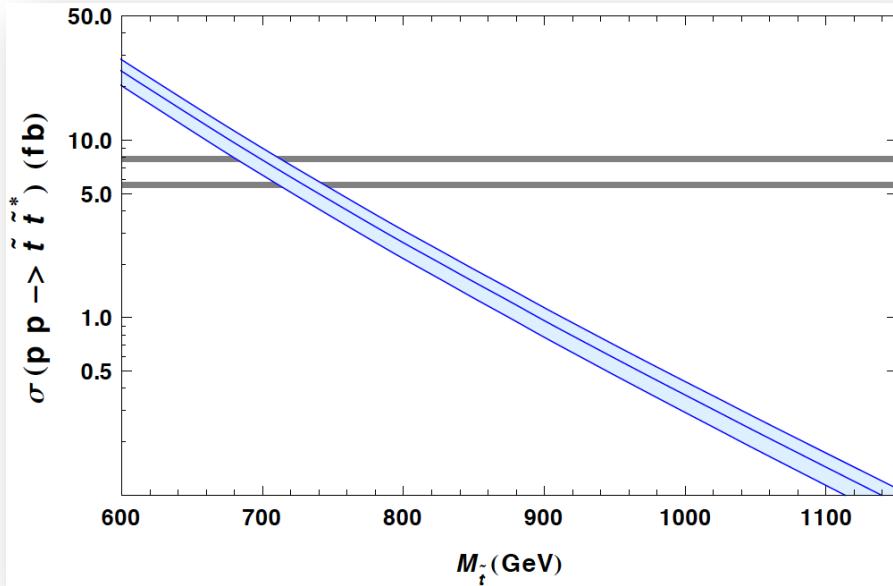
- High H_T implies heavy particles in production
 - current set limits also require heavier states
- Excess “strength” implies high cross section



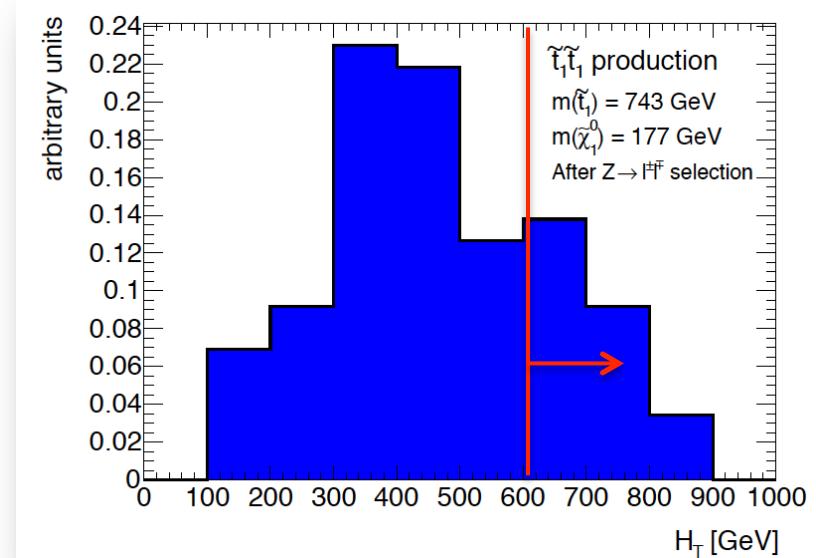
- Many Z bosons in decay chain
- to maintain high acceptance A

Z+MET & stop-stop production

- Weaker bounds on stop masses: $m(\tilde{t}_1) \gtrsim 650$ GeV



- But... for $m(\tilde{t}_1) \approx 750$ GeV
 H_T distribution “soft”
⇒ heavier stops needed

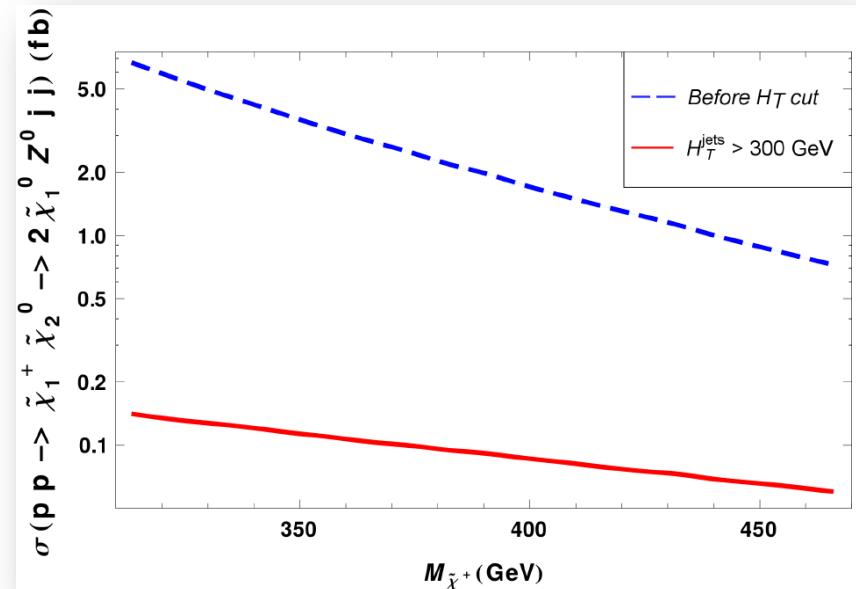


Z+MET & electroweak production

- Z-bosons expected in decays of higgsino-like charginos/neutralinos
- EW gauginos can be light with present bounds
- Large cross section for light $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$
- Could they contribute to Z production?

$$H_T^{\text{jets}} \equiv \sum_i p_T^{\text{jet},i}$$

- Large production cross section for light charginos
- But even after a mild cut on hadronic H_T , **great loss of acceptance**



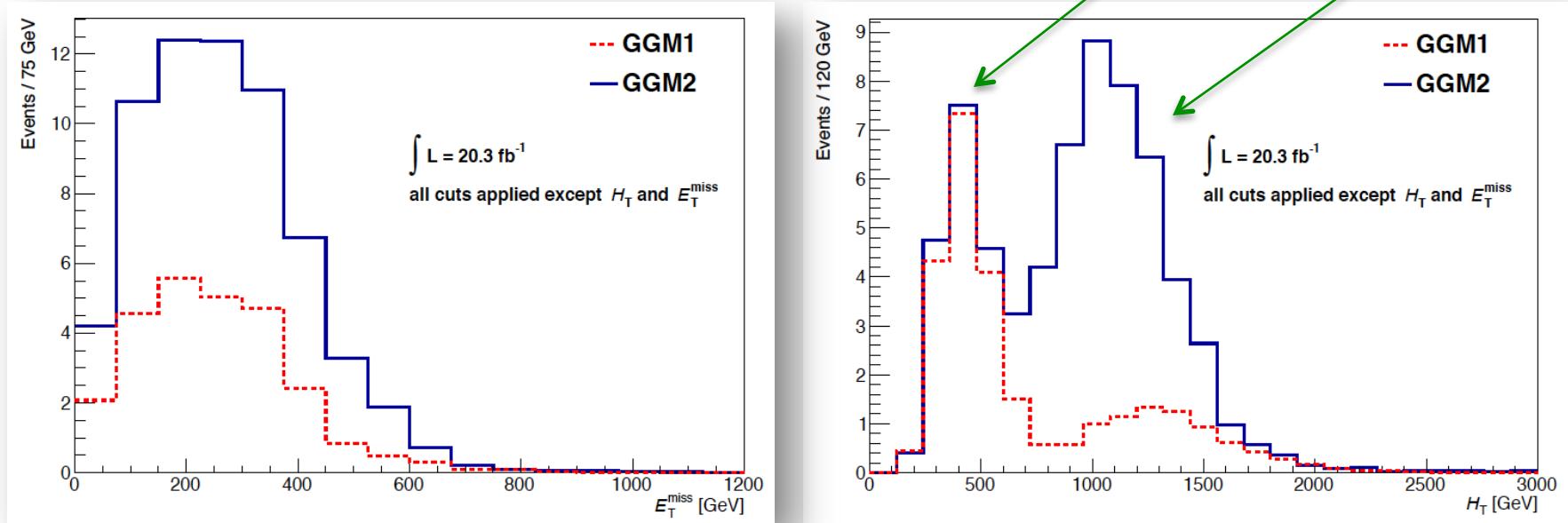
Z + MET & General Gauge Mediation

- Z-boson production not sufficient in mSUGRA under present constraints
- Instead of expecting Z production in cascade decay, produce Z in NLSP decay
- GGM: Dependence of soft-masses on hidden sector obtained from hidden sector current-current correlators
→ 6 independent parameters
- Two benchmark points considered
 - relatively light gluinos
 - Z produced in NLSP decay to gravitino: $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$
 - higgsino-like $\tilde{\chi}_1^0$, large mixing in semi-degenerate in mass 2 lightest $\tilde{\chi}^0$
 - too light Higgs (~ 120 GeV) solved by new operators or heavier squarks

	GGM1	GGM2
$m(\tilde{g})$ [GeV]	1088	911
$m(\tilde{q})$ [GeV]	3000	2500
$m(\tilde{t})$ [GeV]	2750	2350
$m(\tilde{\chi}_1^0)$ [GeV]	428	425
$m(\tilde{\chi}_2^0)$ [GeV]	431	433
$BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})$	99%	94%
$\sigma(pp \rightarrow \tilde{g}\tilde{g})$ [fb]	8.4	41.6

Z + MET & General Gauge Mediation

- Simulation with Pythia8, Prospino and Delphes



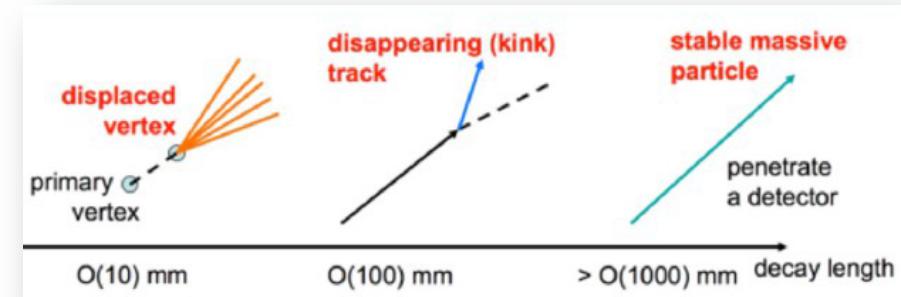
- After experimental cuts for **GGM1** (**GGM2**), 6.34 ± 1.02 (28.0 ± 4.7) leptonic pairs survive, compared with observed excess of 19.4 ± 3.2
- ↗ Possible solution somewhere between **GGM1** and **GGM2**
- Prospects at Run II: “Light” gluinos (or strongly produced particles) required
→ production cross section increased factor ~ 20 for **GGM1** or ~ 15 for **GGM2**

Prospects for future LHC run(s)

- Collider conditions
 - higher energy: 8 TeV → 13 – 14 TeV
 - more luminosity:
 - 2015: ~ 10 – 15 fb^{-1}
 - > 100 fb^{-1} for end of Run II
 - High Luminosity LHC (HL-LHC): 3000 fb^{-1}



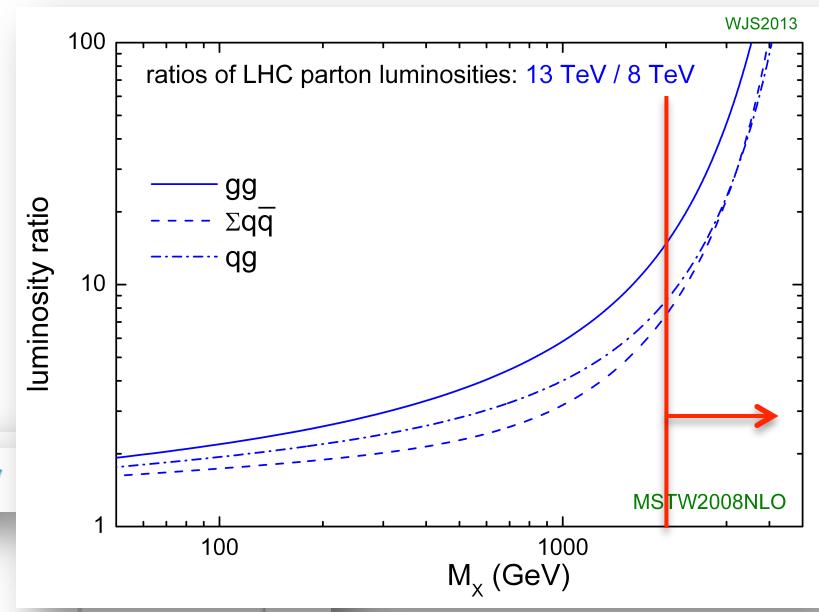
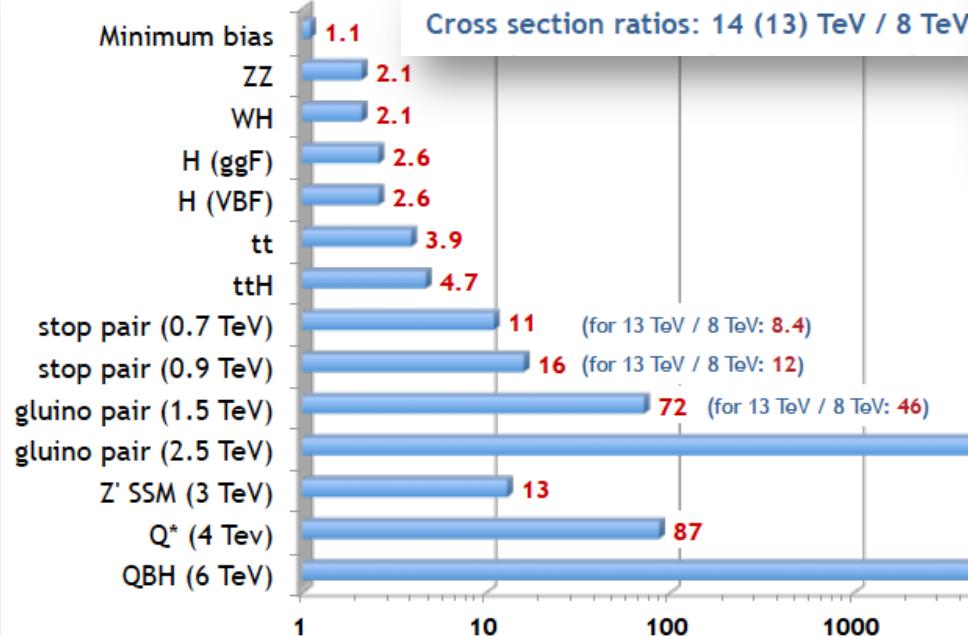
- Analysis strategy
 - cover kinematic “holes” – compressed spectra
 - boosted tops, improve background control, ...
 - [see also talks by K. Papageorgiou & A. Agapitos on Friday]
 - target less explored signatures
 - long-lived particles
 - RPV → no MET, multilepton, purely hadronic multi-jet events



What changes in Run II for SUSY?

- Rates are more than doubled
- Strong-interaction dominated processes more enhanced than EW processes

A. Höcker



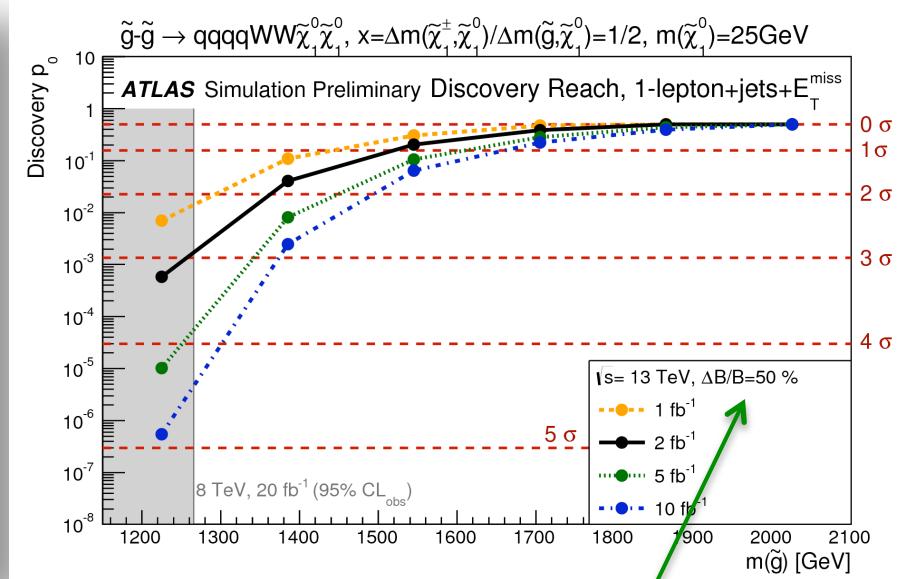
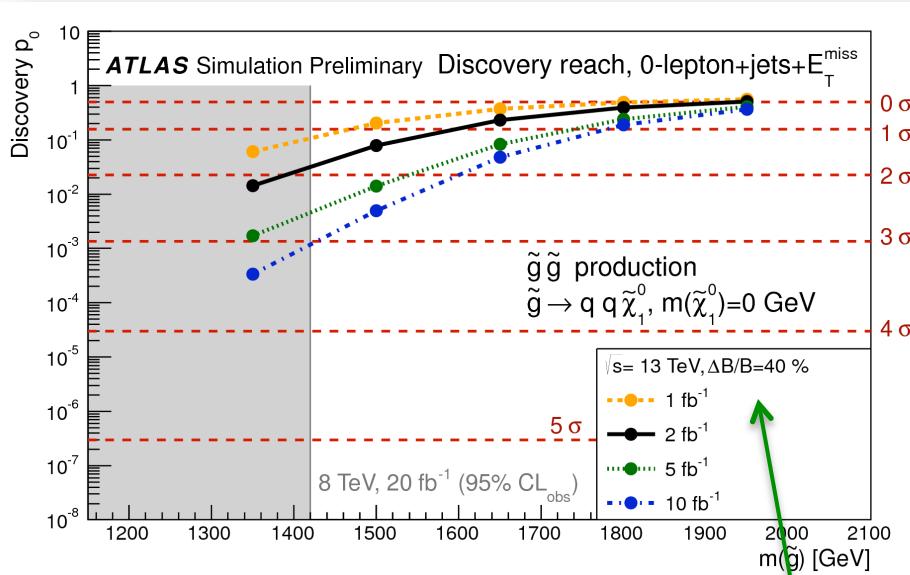
J. Stirling

Hugely increased potential for discovery of heavy particles at 13-14 TeV

- less SM background

Expectations for Run II

- Understanding when 13 TeV discovery potential will surpass 8 TeV limits for several analyses
- **Access to 3σ evidence with $2\text{-}10 \text{ fb}^{-1}$, even with poor systematics**



conservative background estimation

R-parity violation

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

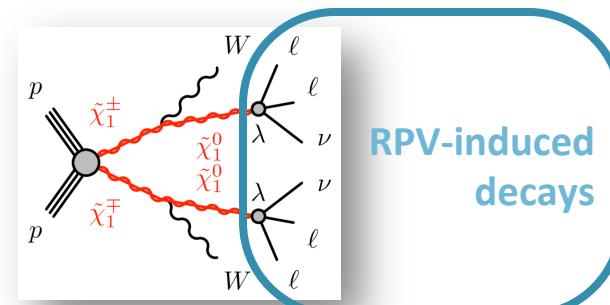
L-number violating terms

$$W_{Rp} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^C + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^C + \epsilon_i \hat{L}_i \hat{H}_u + \lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C$$

bilinear terms

B-number violating terms

- R-parity conservation hinted but *not* required by proton stability
- Phenomenological consequences:
 - LSP may be charged and/or carry color
 - LSP is not stable
 - transverse missing energy (MET) not necessarily large
 - potentially long LSP lifetime
 - LSP mass may be reconstructed



With no evidence for “standard” Rp conserving SUSY seen at LHC so far, RPV becomes a very attractive alternative

Bilinear RPV and neutrino sector

- Model parameters
 - three parameters ϵ_i in bilinear terms
 - three soft SUSY-breaking parameters B_i expressed through sneutrino vev's v_i or “alignment” parameters $\Lambda_i = \epsilon_i v_d + \mu v_i$
- Bilinear RPV introduces **neutrino masses** in an intrinsically supersymmetric way
 - EW symmetry is broken by Higgs and sneutrino VEVs
 - neutrinos mix with neutralinos $\rightarrow 7 \times 7$ mixing matrix
 - a “low-scale” seesaw mechanism renders neutrinos **massive**
 - tree level \rightarrow atmospheric scale
 - 1-loop \rightarrow solar scale
- Direct connection between model phenomenology and neutrino parameters

$$W_{\text{bRPV}} = W^{\text{MSSM}} + \epsilon_i \hat{L}_i \hat{H}_u$$

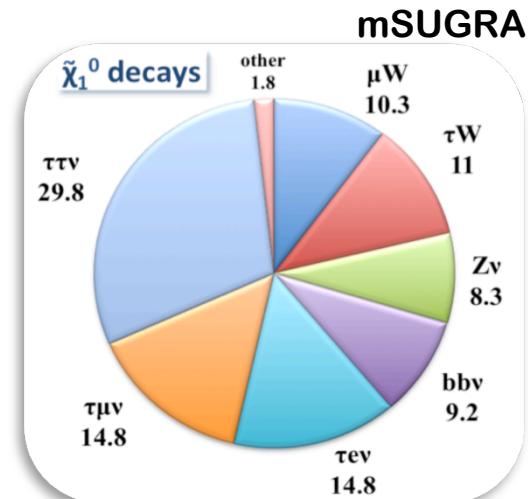
$$V_{\text{soft}} = V_{\text{soft}}^{\text{MSSM}} - B_i \epsilon_i \tilde{L}_i H_u$$

Valle, Hirsch, Porod,
Romao, Diaz, *et al.*

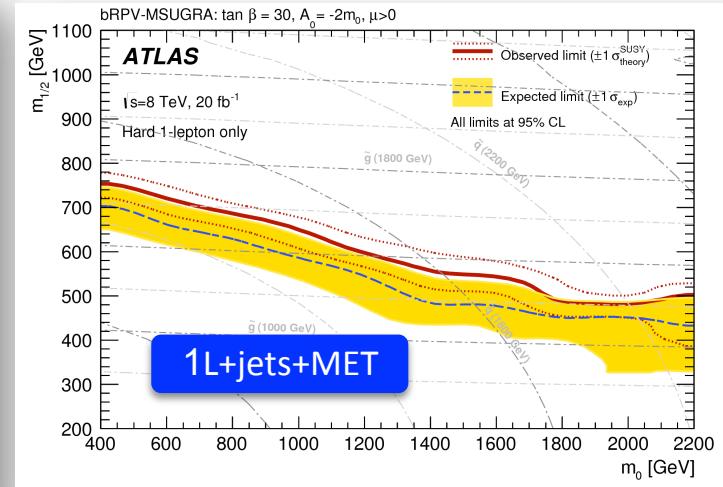
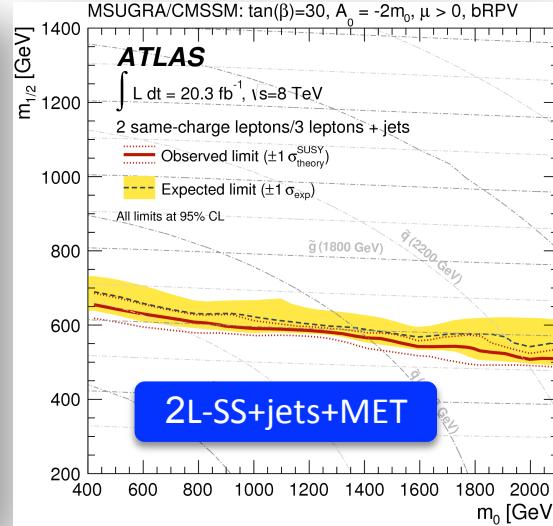
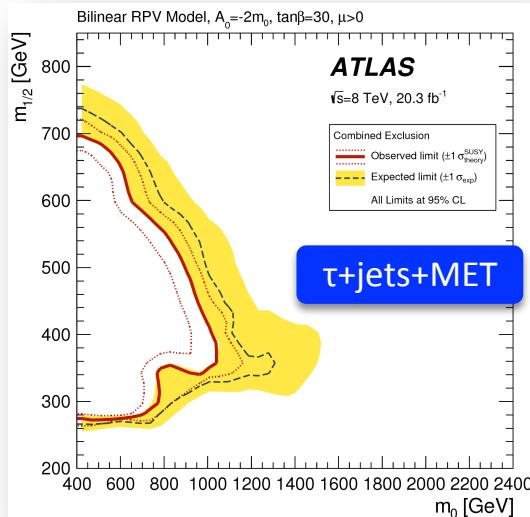
$$\tan^2 \theta_{\text{atm}} \simeq \left| \frac{\Lambda_\mu}{\Lambda_\tau} \right|^2 \simeq \frac{BR(\tilde{\chi}_1^0 \rightarrow \mu^\pm W^\mp)}{BR(\tilde{\chi}_1^0 \rightarrow \tau^\pm W^\mp)}$$

bRPV searches with ATLAS

- bRPV couplings can be embedded in various SUSY models
 - bRPV parameters constrained by neutrino parameters Δm_{atm}^2 , Δm_{sol}^2 , $\tan^2 \theta_{\text{atm}}$, $\tan^2 \theta_{\text{sol}}$, ...
 - RPV-related phenomenology fully defined
 - Moderately large MET due to copious *neutrino* production
 - LSP may have long lifetime



Run II: explore bRPV in other models, e.g. pMSSM



Beyond bilinear RPV: μ vSSM

- **μ -from-v Supersymmetric Standard Model:** introduces three singlet right-handed neutrino superfields to solve the **μ problem** and can generate **three Majorana neutrino masses** through the seesaw mechanism
 - (bilinear) RPV terms are generated after EWSB
 - combines bRPV & NMSSM features

$$W = W^{\text{MSSM}} - \epsilon_{ab} \mu \hat{H}_d^a \hat{H}_u^b + \epsilon_{ab} \left(\underbrace{Y_{\nu_{ij}} \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c}_{\epsilon_{\text{eff}}^i = Y_{\nu_{ij}} \langle \tilde{\nu}_j^c \rangle} - \underbrace{\lambda_i \hat{\nu}_i^c \hat{H}_d^a \hat{H}_u^b}_{\mu_{\text{eff}} = \lambda_i \langle \tilde{\nu}_i^c \rangle} \right) + \underbrace{\frac{1}{3} \kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c}_{m_{\nu_{ij}^c} = 2 \kappa_{ijk} \langle \tilde{\nu}_k^c \rangle}$$

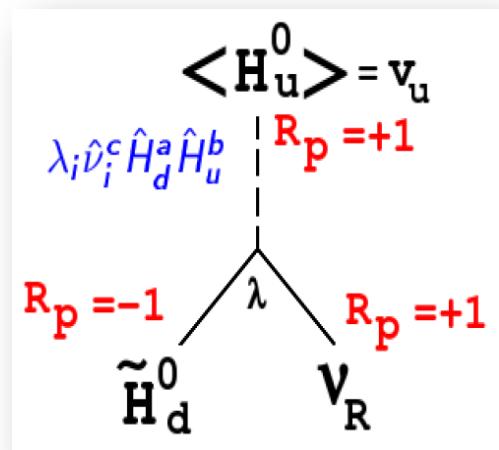
- Very rich phenomenology
 - many Higgs bosons and gauginos
 - → enlarged Higgs sector can easily accommodate a 125-GeV Higgs boson
 - long neutralino lifetimes → **(extremely) displaced vertices**
 - **multileptons / multitäus**

$\mu\nu$ SUSM phenomenology

- Particle spectrum

- 2 from MSSM + 3 $\tilde{\nu}_i^c$ + 3 $\tilde{\nu}_L^i \rightarrow$ 8 CP-even states S_α^0
 - S_4^0 lightest doublet-like Higgs; $m(S_4^0) \sim 125$ GeV
- 1 from MSSM + 3 $\tilde{\nu}_i^c$ + 3 $\tilde{\nu}_L^i \rightarrow$ 7 CP-odd states P_α^0
- 1 from MSSM + 3 \tilde{e}_L^i + 3 $\tilde{e}_R^i \rightarrow$ 7 charged states S_α^\pm
- 4 from MSSM + 3 ν_i^c + 3 $\nu_L^i \rightarrow$ 10 neutralinos $\tilde{\chi}_\alpha^0$
 - $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0 \rightarrow$ neutrinos
 - $\tilde{\chi}_4^0 \rightarrow$ “true” lightest neutralino
- 2 from MSSM + 3 $e_{L,R}^i \rightarrow$ 5 charginos $\tilde{\chi}_\alpha^\pm$
 - $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm, \tilde{\chi}_3^\pm \rightarrow e, \mu, \tau$
 - $\tilde{\chi}_4^\pm \rightarrow$ “true” lightest chargino

- Phenomenology largely defined by: $\lambda, \kappa, \mu, \tan\beta, M_1, A_\lambda, A_\kappa$
 - $\lambda \equiv \sqrt{3}\lambda$, singlet-doublet mixing parameter (universal λ_i assumed)
 - κ : common κ_{ijk} assumed
 - A_λ, A_κ : soft SUSY-breaking parameters

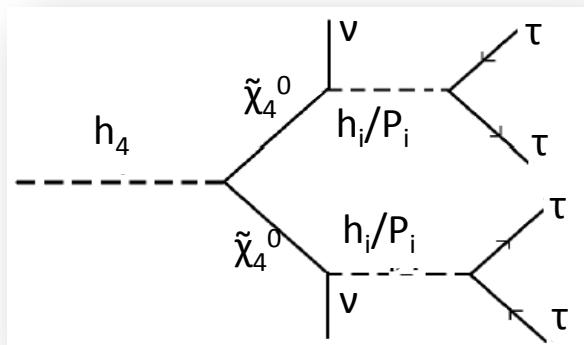


$\mu\nu$ SUSY @ LHC

- With small doublet-singlet mixing λ_i
 $\rightarrow h_i, P_i, \tilde{\chi}_{i+3}^0$ ($i = 1, 2, 3$) mostly \tilde{v}_i^C
- h_4 plays the role of the observed Higgs with $m(h_4) \approx 125$ GeV, while $\tilde{\chi}_4^0$ is the lightest neutralino with a mass of ~ 10 GeV

Ghosh, López-Fogliani, VAM, Muñoz,
Ruiz de Austri, PRD88 (2013) 015009

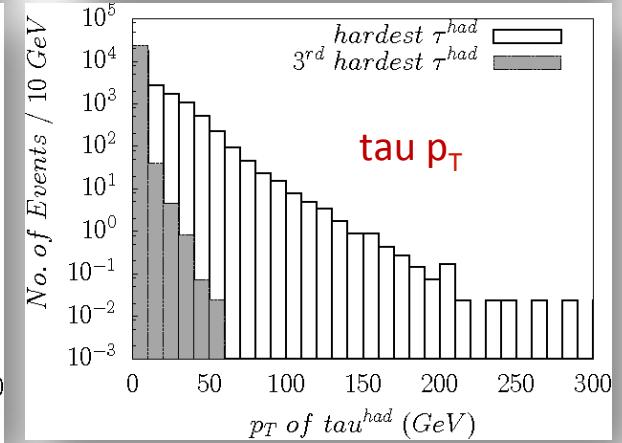
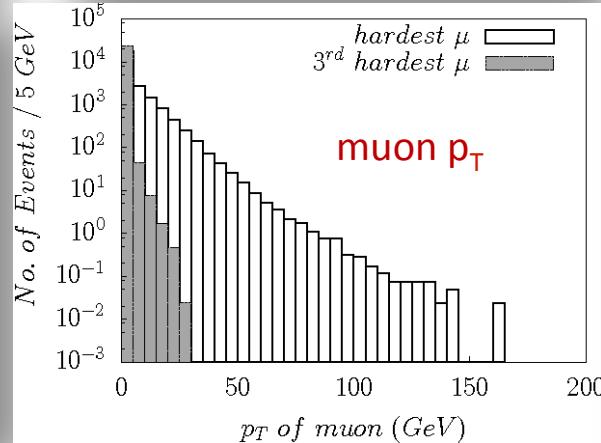
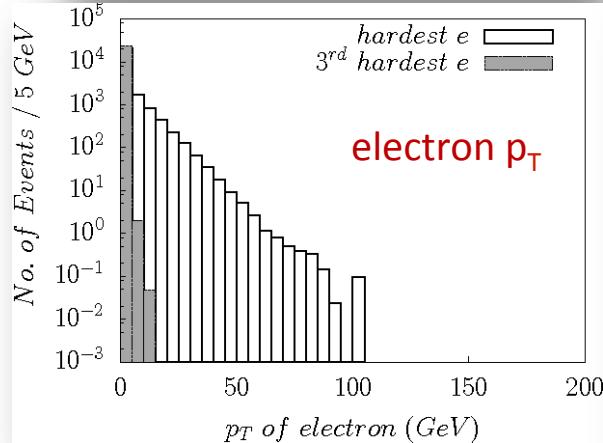
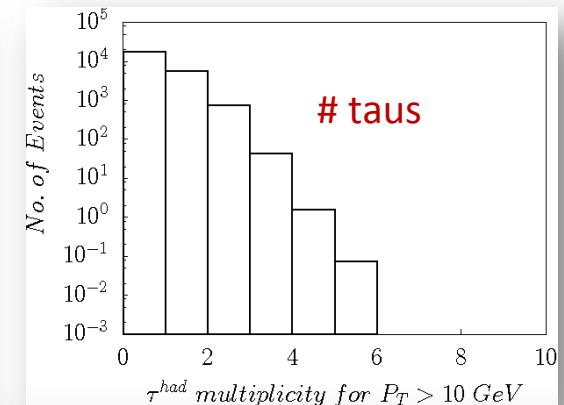
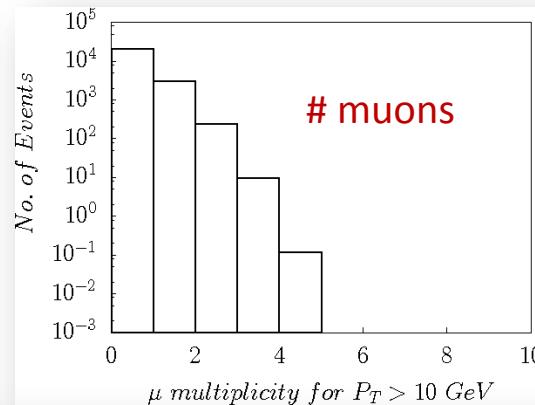
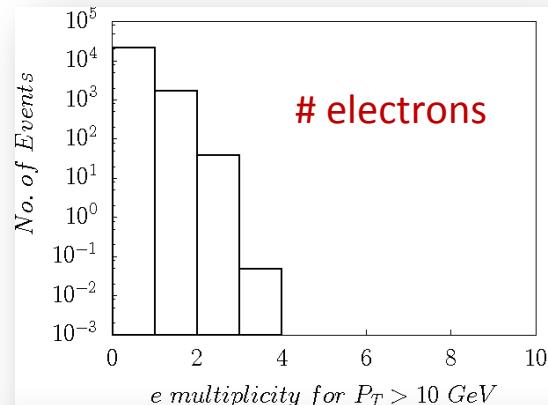
- $h/P \rightarrow bb$ dominant over a broad range of parameters
- $2m_\tau \lesssim h_i, P_i$ mass $\lesssim 2m_b$
- Small RPV \rightarrow long-lived LSP \rightarrow displaced yet detectable multi-leptons at LHC
- Multiple hadronically decaying τ 's provide signature with low SM bkg
 - τ identification efficiency relatively low and varies with p_T



- The signal: $gg \rightarrow h_4 \rightarrow \tilde{\chi}_4^0 \tilde{\chi}_4^0 \rightarrow 2 h_i/P_i + 2\nu \rightarrow 2\tau^+ 2\tau^- 2\nu$

Lepton multiplicity

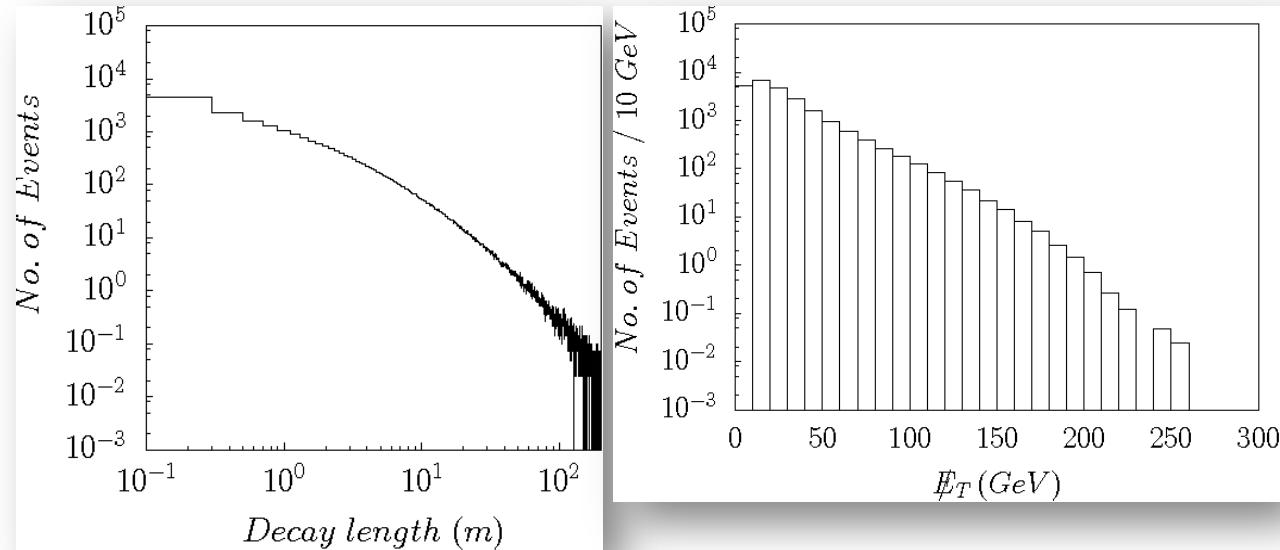
Ghosh, López-Fogliani, VAM, Muñoz,
Ruiz de Austri, PRD88 (2013) 015009



- e, μ from τ decay; $h_i/P_i \rightarrow \mu\mu$ also possible
- $(4e, 4\mu \text{ from } \tau) \sim 0.1\%$; $4\tau_{had} \sim 18\%$
- hadronic τ 's most promising; $\mu+e$ workable, too

$\sqrt{s} = 8$ TeV
 $L = 20$ fb⁻¹

Decay length, MET, H_T^ℓ



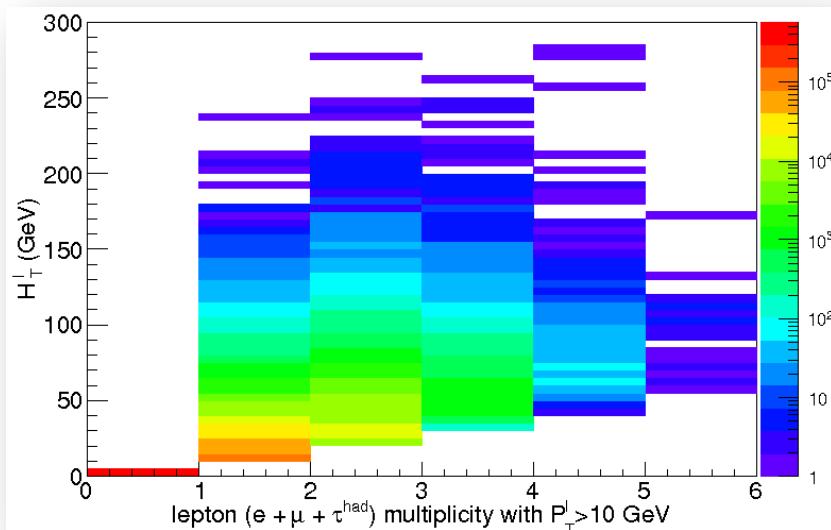
$$H_T^\ell = \sum_i p_{T,i}^\ell$$

- H_T^ℓ moderately high for large lepton multiplicity
- $H_T^\ell + \text{MET}$ may be used as discriminating variable

- 6 neutrinos from $\tilde{\chi}_4^0$ and tau decays
⇒ moderately large MET
- $c\tau(\tilde{\chi}_4^0) \approx 30 \text{ cm} \Rightarrow$ large number of tracks initiate within the inner tracker → displaced vertices (DVs)

$\sqrt{s} = 8 \text{ TeV}$
 $L = 20 \text{ fb}^{-1}$

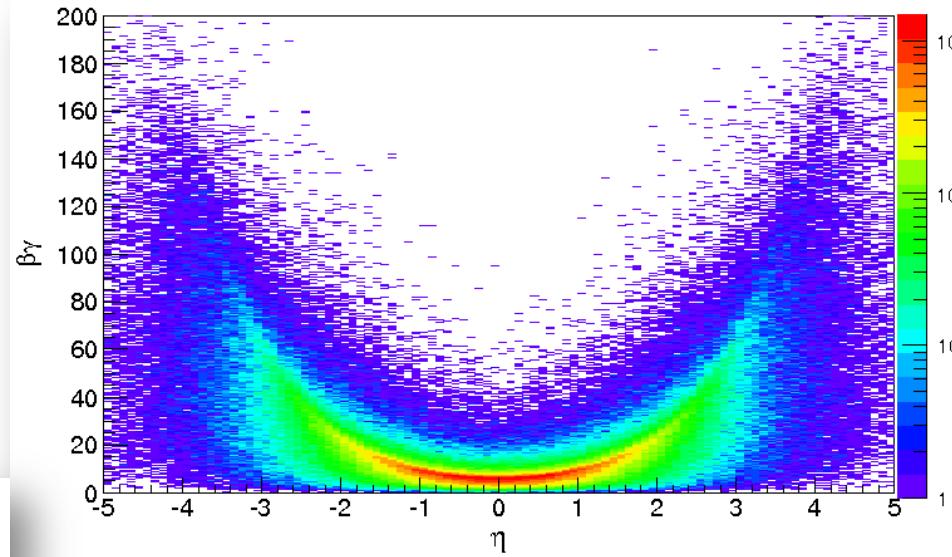
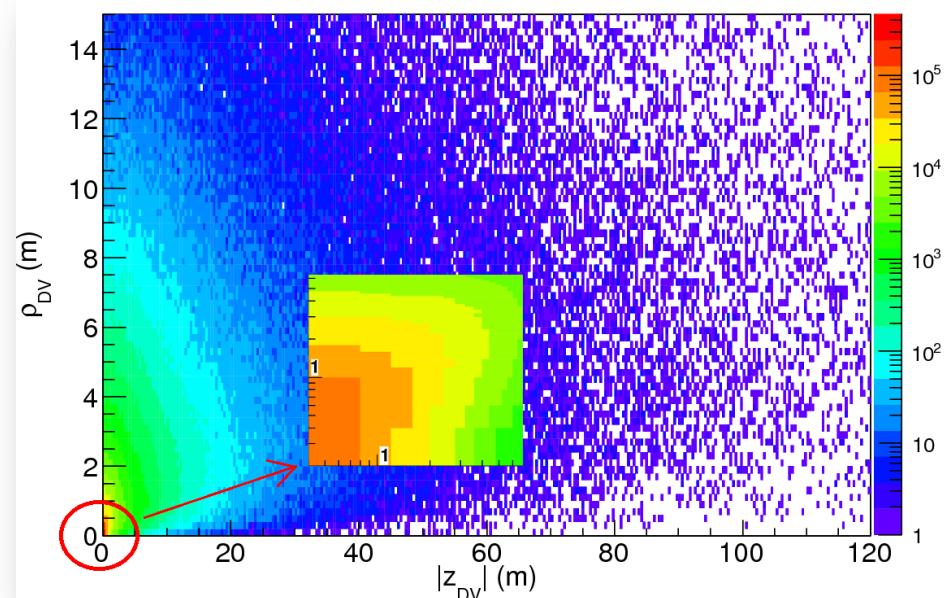
Ghosh, López-Fogliani, VAM, Muñoz,
Ruiz de Austri, PRD88 (2013) 015009



$\tilde{\chi}_4^0$ decay kinematics

- Single h_4 production at the LHC
→ low momentum in central region
- High boost leads to collimated tracks
→ hard to disentangle from primary vertex

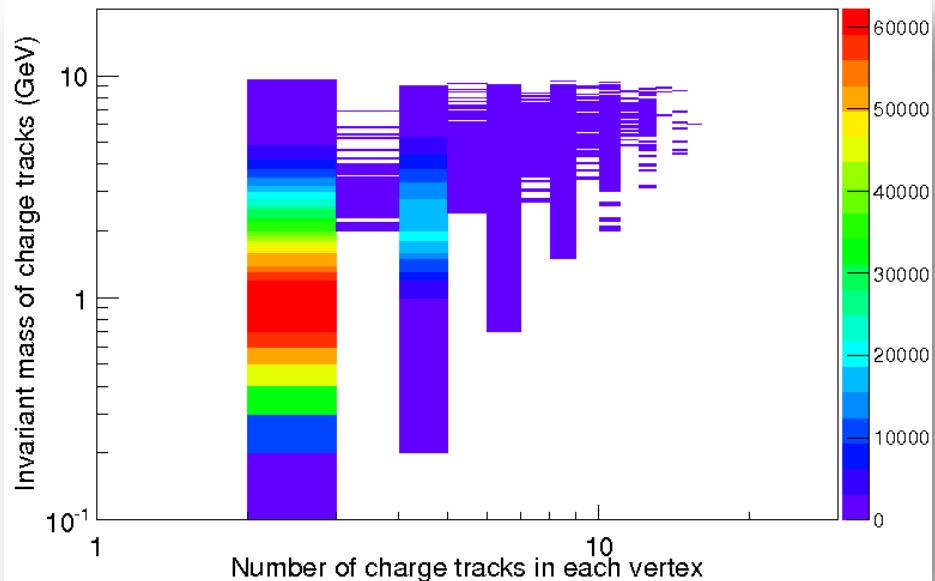
$\sqrt{s} = 8 \text{ TeV}, L = 20 \text{ fb}^{-1}$



- Large fraction of DVs occur within $|z_{\text{DV}}| \lesssim 2.5 \text{ m}$ and $\rho_{\text{DV}} \lesssim 1 \text{ m}$
→ in the volume of ATLAS and CMS inner trackers
- Possible to detect this signal

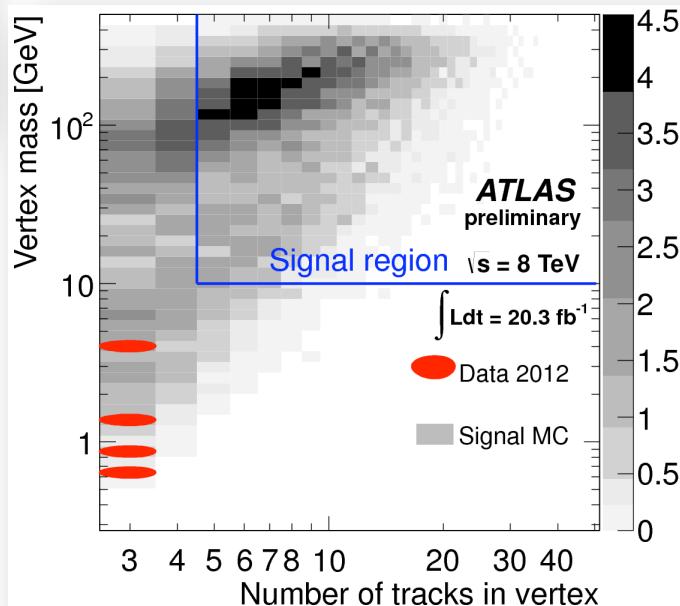
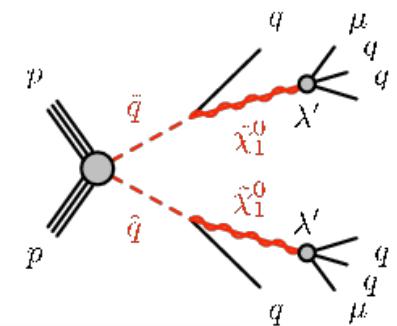
Ghosh, López-Fogliani, VAM, Muñoz,
Ruiz de Austri, PRD88 (2013) 015009

Probing displaced vertices



Ghosh, López-Fogliani, VAM, Muñoz, Ruiz de Austri, PRD88 (2013) 015009

$\sqrt{s} = 8 \text{ TeV}$
 $L = 20 \text{ fb}^{-1}$

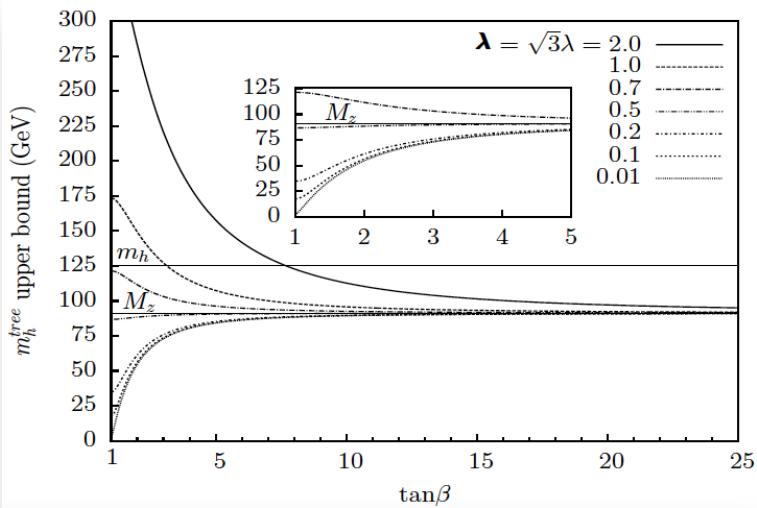


- Low DV mass and n_{trk} make delayed-tau detection challenging yet...
- ... similar analysis with (b-)jets seems promising
 - large track multiplicity
 - **already considered in ATLAS for Run-I analysis (to be published soon)**

More on Higgs decays

- A 125-GeV Higgs boson, S_4^0 , can be accommodated within a wide range of $\tan\beta$ and λ values
- S_4^0 decays to $S_i^0 S_j^0$, $P_i^0 P_j^0$, $\tilde{\chi}_{i+3}^0 \tilde{\chi}_{j+3}^0$ compatible with measured Higgs signal strengths μ_{xx}
 - $0.01 < \lambda < 0.1$: All μ_{xx} remain within 2σ of CMS measurements for $2.5 < \tan\beta < 3.9$
 - $0.1 < \lambda < 0.7$: only (invisible) S_4^0 decays to $\tilde{\chi}_{i+3}^0 \tilde{\chi}_{j+3}^0$ remain viable in whole range of λ
 - $\lambda > 0.1$: for decays to pair of binos, all μ_{xx} are within 2σ for $2.4 < \tan\beta < 3.8$
- The final states are dominated by a combination of prompt or displaced leptons taus / jets / photons plus MET due to neutrinos

Ghosh, López-Fogliani, VAM, Muñoz,
Ruiz de Austri, JHEP 11(2014)102



	Measured value	$m_{S_4^0}$ (GeV)
ATLAS	$\mu_{b\bar{b}}(S_4^0)$	$0.2^{+0.7}_{-0.6}$ ■
	$\mu_{\tau^+\tau^-}(S_4^0)$	$1.4^{+0.5}_{-0.4}$ ■
	$\mu_{\gamma\gamma}(S_4^0)$	1.17 ± 0.27 ■
	$\mu_{WW^*}(S_4^0)$	$1.0^{+0.32}_{-0.29}$ ■
	$\mu_{ZZ^*}(S_4^0)$	$1.44^{+0.40}_{-0.33}$ ■
	Combined	$1.30^{+0.18}_{-0.17}$ ■
CMS	$\mu_{b\bar{b}}(S_4^0)$	0.93 ± 0.49 ■
	$\mu_{\tau^+\tau^-}(S_4^0)$	0.91 ± 0.27 ■
	$\mu_{\gamma\gamma}(S_4^0)$	1.13 ± 0.24 ■
	$\mu_{WW^*}(S_4^0)$	0.83 ± 0.21 ■
	$\mu_{ZZ^*}(S_4^0)$	1.00 ± 0.29 ■
	Combined	1.00 ± 0.13 ■

Unusual Z and W decays

- New Z/W decays predicted leading to final states with **prompt (P)** or **displaced (D)** particles
- Partial widths respect current Z and W total and invisible widths
- Signatures with **taus** and **b-jets** preferred
- $W^\pm \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_{j+3}^0$
 - $\text{BR} < \mathcal{O}(10^{-13}) \rightarrow$ e.g. 0.05 events with $\sqrt{s} = 14 \text{ TeV}$ with 3000 fb^{-1}
 - very difficult at LHC; maybe possible at LC-MegaW and TLEP-OkuW
- $Z^0 \rightarrow \tilde{\chi}_{i+3}^0 \tilde{\chi}_{i+3}^0$ and $Z^0 \rightarrow S_i^0 P_j^0$
 - $\text{BR} \sim \mathcal{O}(10^{-5}) \rightarrow$ detection may be possible at HL-LHC, LC-GigaZ, TLEP-TeraZ

Ghosh, López-Fogliani, VAM, Muñoz,
Ruiz de Austri, PRD91 (2015) 035020

Z -decay	W^\pm -decay
$2x^D 2\bar{x}^D + \cancel{E}_T (\tilde{\chi}_{i+3}^0 \tilde{\chi}_{j+3}^0)$	$1\ell^P + x^D \bar{x}^D + \cancel{E}_T (\tilde{\chi}_i^\pm \tilde{\chi}_{j+3}^0)$
$2x^P 2\bar{x}^P (S_i^0 P_j^0)$	

x : e, μ , τ , γ , q
 P : prompt (short-lived)
 D: delayed (long-lived)

Prompt +Displaced yet detectable multi-leptons/taus/jets/photons (x) at LHC

What about dark matter?

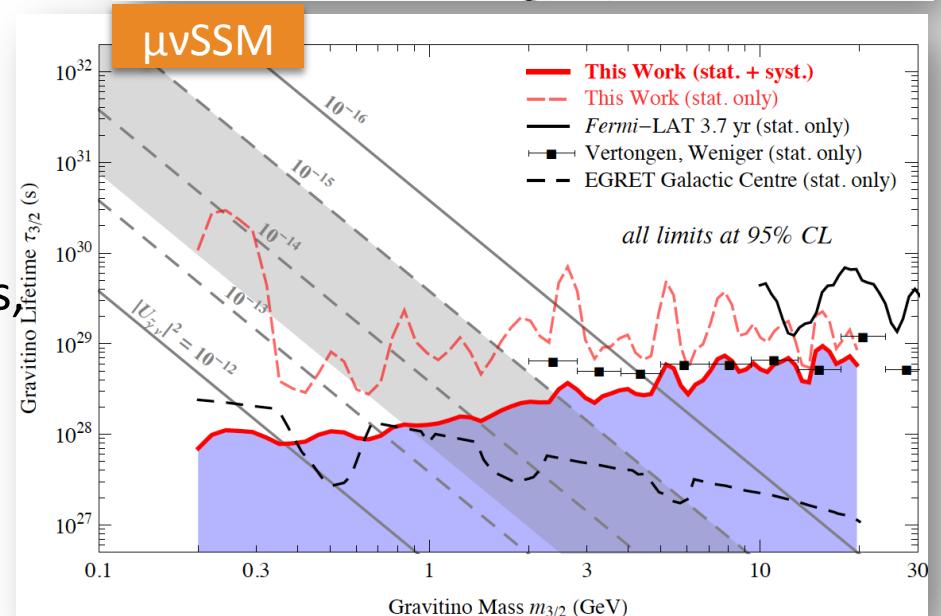
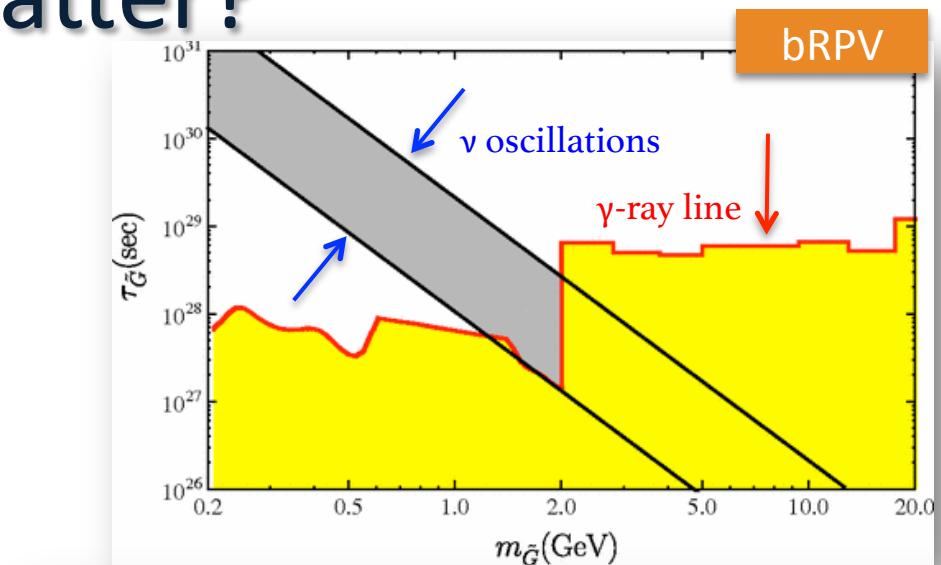
- Gravitino or axino LSP with cosmologically-long lifetime
 - signal: monochromatic gamma-rays, electrons, positrons

$$\tilde{G}, \tilde{\alpha} \rightarrow \gamma\nu, l^\pm W^\mp$$

- constrained by
 - ν -oscillations & DM relic density
- If lightest neutralino is the NLSP

$$\begin{aligned}\tilde{\chi}_1^0 &\rightarrow h^0 \nu_i, & \tilde{\chi}_1^0 &\rightarrow W^\pm l_i^\mp, \\ \tilde{\chi}_1^0 &\rightarrow \gamma \nu_i, & \tilde{\chi}_1^0 &\rightarrow Z^0 \nu_i.\end{aligned}$$

- Unlike R-parity conserving scenarios, NLSP decays occur rapidly via RPV interactions
→ do not upset Big-Bang nucleosynthesis



RPV SUSY DM & cosmic-ray anomalies

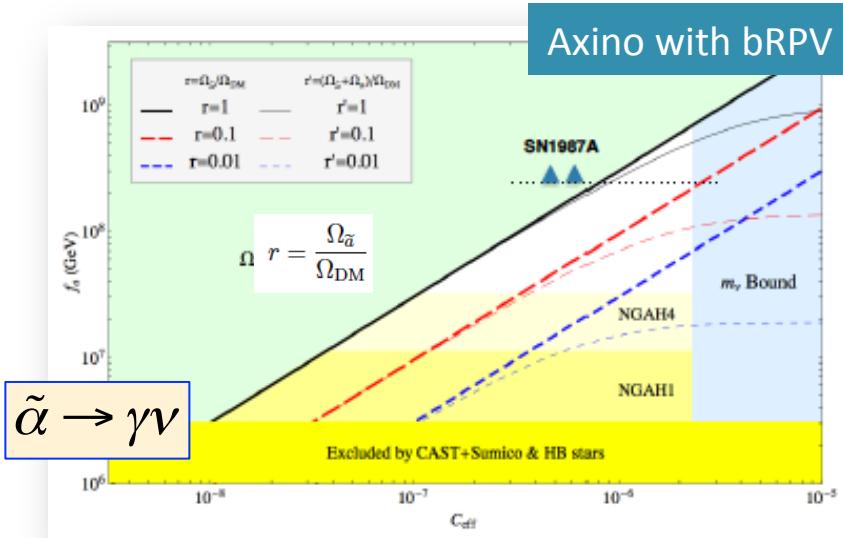
Observed cosmic-ray features

- **Fermi-LAT** 130-GeV γ -ray line in galactic centre
- **XMM-Newton** 3.5 keV X-ray line in galaxy clusters
- **AMS-02** positron fraction flattening

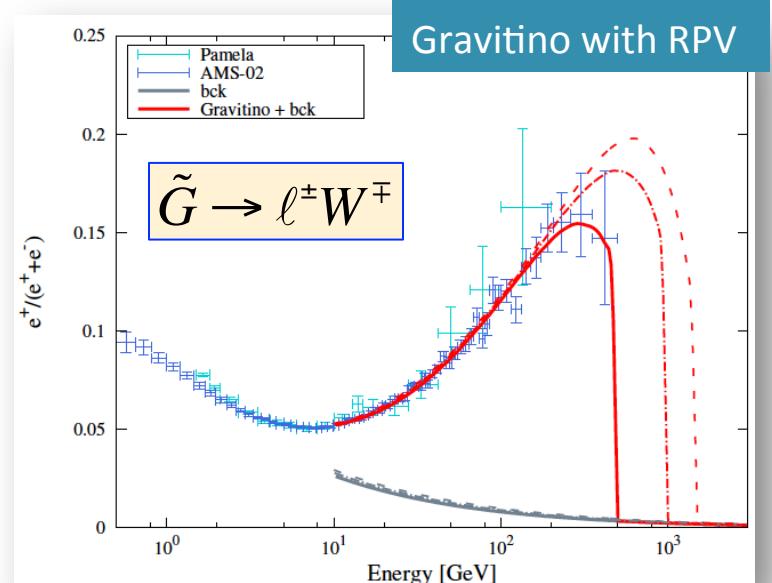
R-parity conserving SUSY cannot provide a natural explanation to these observations

may be explained by decaying or annihilating DM, in particular by (b)RPV SUSY

- **axino with (b)RPV**
- **gravitino, bino, or photino in RPV**

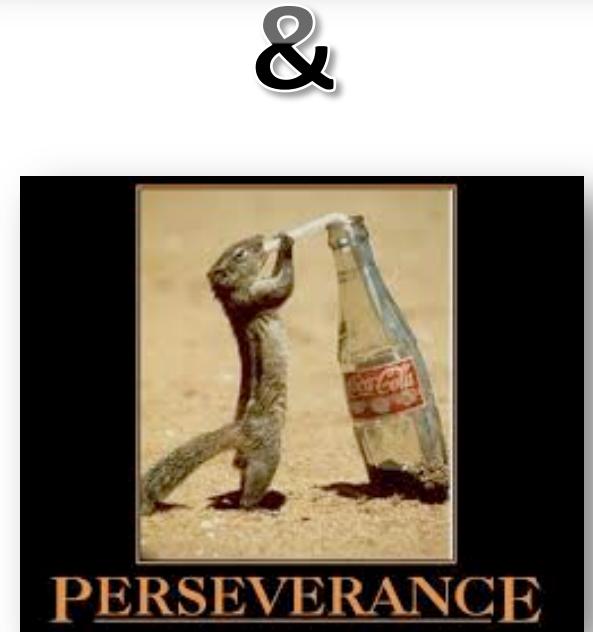


Kong, Park², PLB733 (2014) 217



Summary & outlook

- Large number of new results still being derived from LHC Run I
 - mostly in agreement with SM predictions
 - some excesses as well
- Higher energy at Run II allows probing higher mass scales fast
 - HL-LHC will allow further exploration
- Future search strategies to reinforce:
 - coverage of kinematically difficult regions in already studies topologies
 - R-parity breaking scenarios that lead to **novel signals at colliders**
 - especially when connected to neutrino masses
 - searches for **stable or meta-stable particles**
- ***Looking forward to Run II probing higher energies***

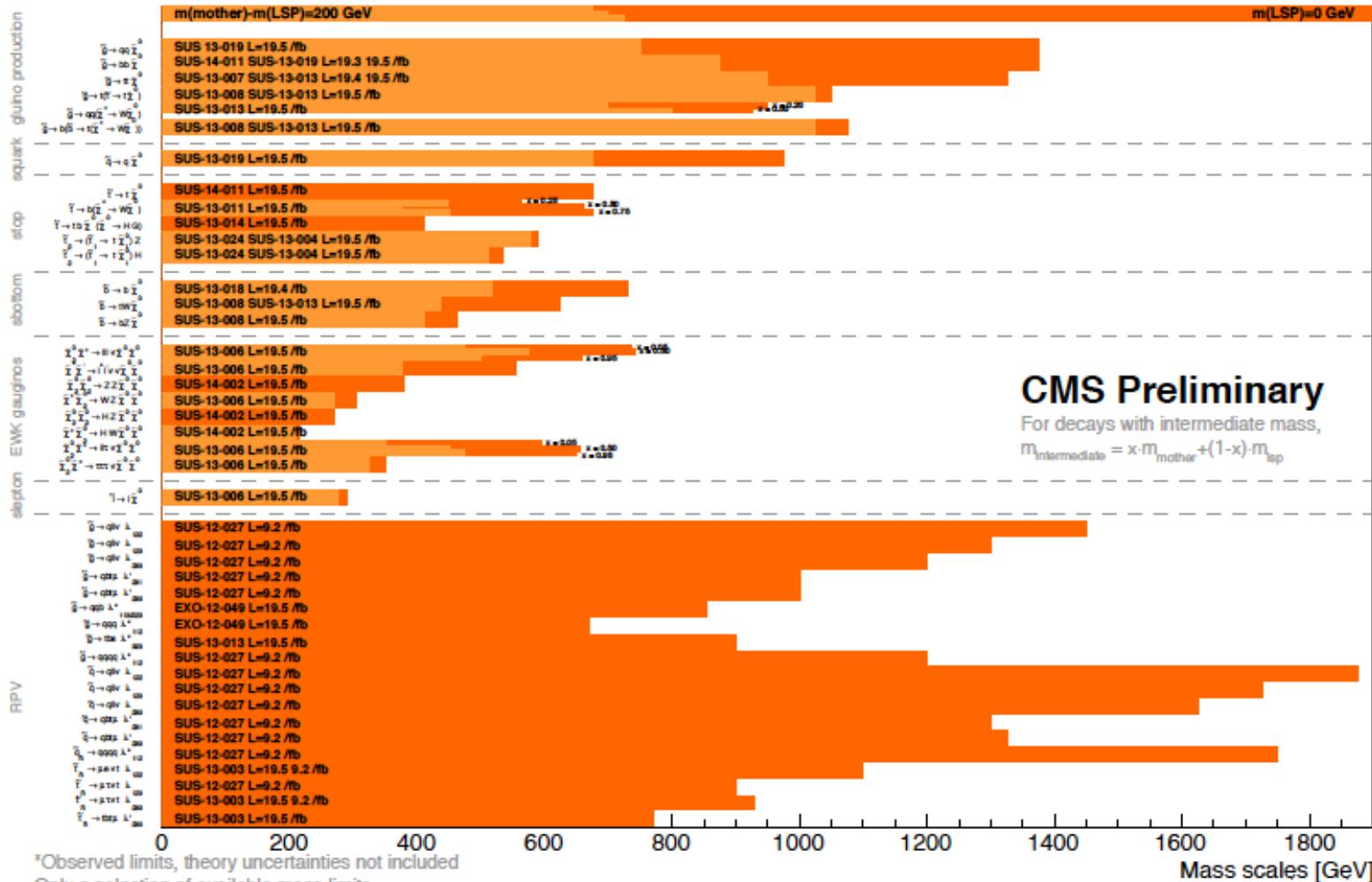


Backup

Results overview from Run I

Summary of CMS SUSY Results* in SMS framework

ICHEP 2014



Bilinear RPV phenomenology

- bRPV parameters constrained by neutrino measurements:

$$\Delta m_{\text{atm}}^2, \Delta m_{\text{sol}}^2, \tan^2 \theta_{\text{atm}}, \tan^2 \theta_{\text{sol}}, \dots$$

- If tree-level dominance is assumed...

Underlying **SUSY model**
parameters
(MSSM, mSUGRA, AMSB, ...)



Fitting to
neutrino physics
data



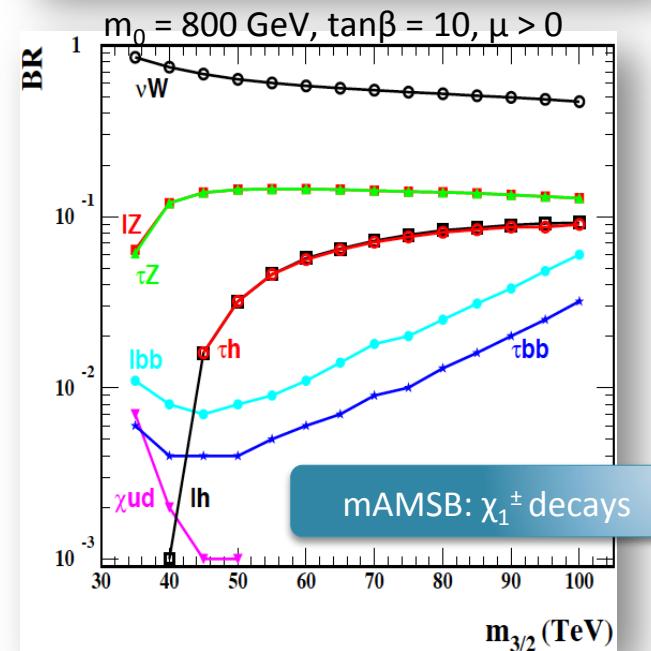
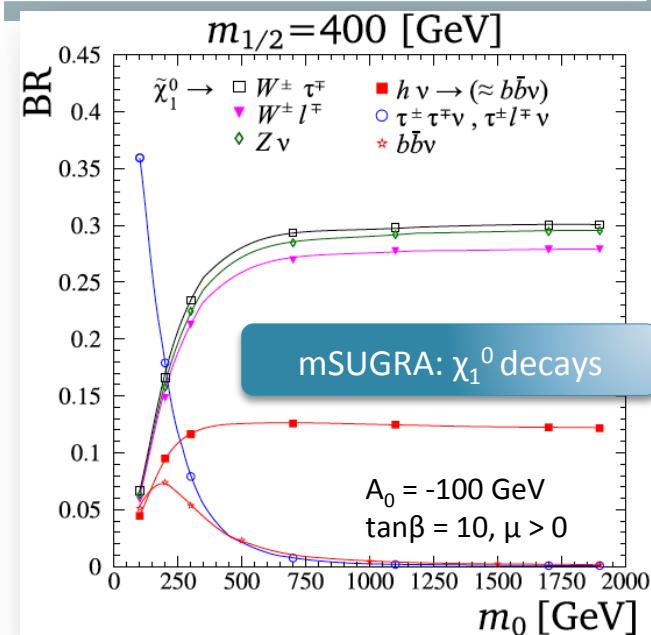
bRPV parameters
determined
unambiguously

- Sparticle mass spectra
- Sparticle decay modes
- LSP lifetime

→ Phenomenology is completely
defined for specific SUSY-model point

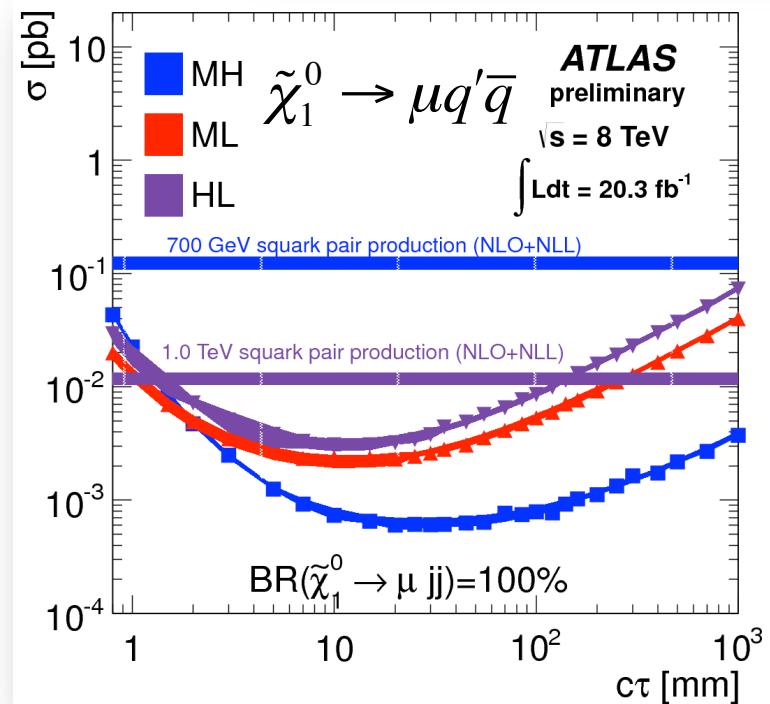
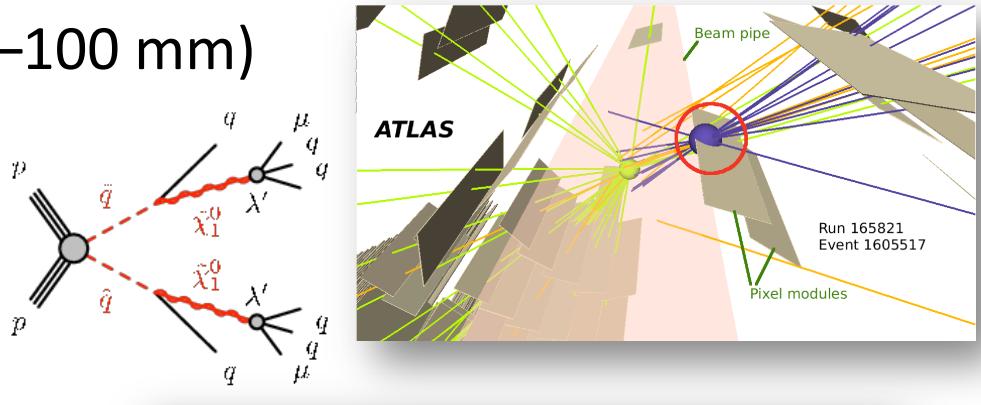
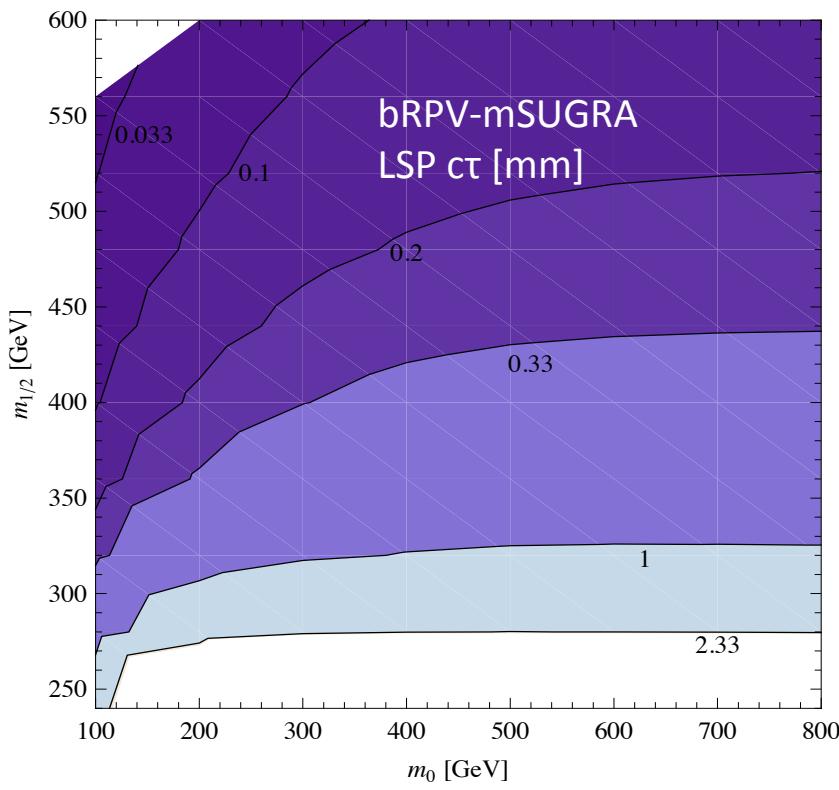
mSUGRA versus mAMSB

- Similarities:
 - same $\tilde{\chi}_1^0$ LSP decay modes
- Differences: in mAMSB
 - wino-like neutralino LSP \rightarrow its interactions are stronger hence easier to be produced at LHC
 - $m(\tilde{\chi}_1^0) \approx m(\tilde{\chi}_1^\pm) \rightarrow$ (long-lived) $\tilde{\chi}_1^\pm$ decays dominantly through RPV couplings to $\ell\ell\ell$, $\tau\ell\ell$, ℓbb , τbb , ...
 - → displaced vertices
 - wider spectrum of final states
 - enhanced cross sections

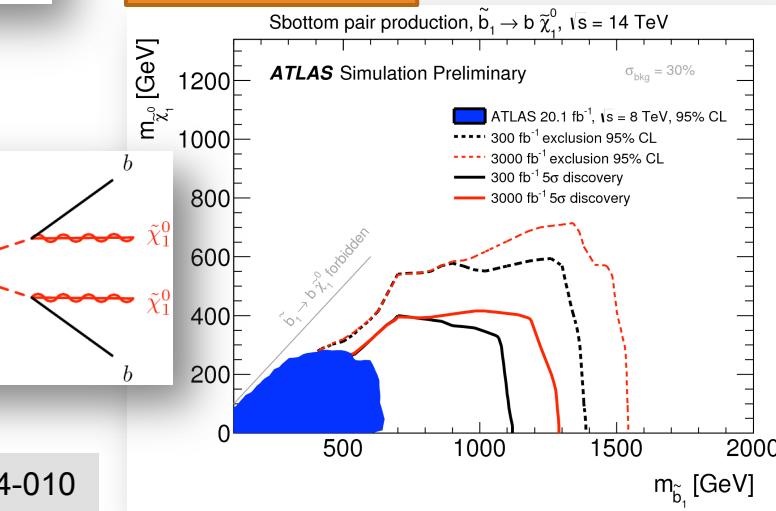
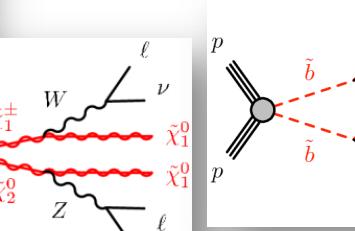
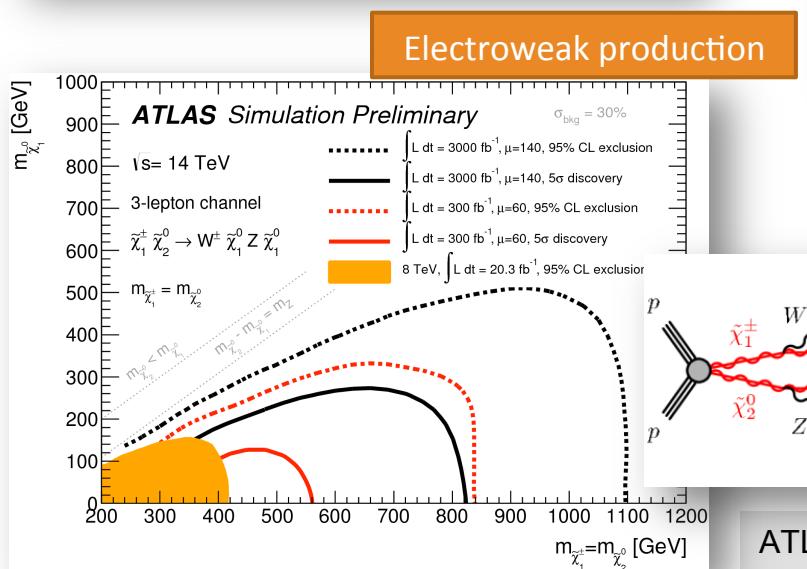
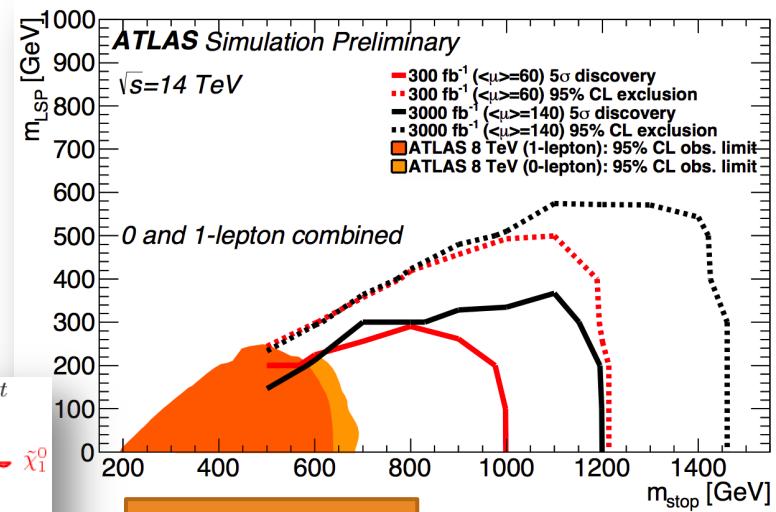
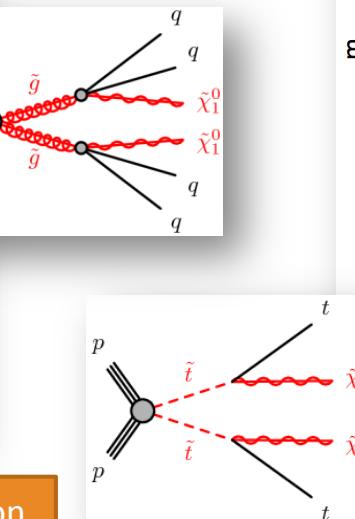
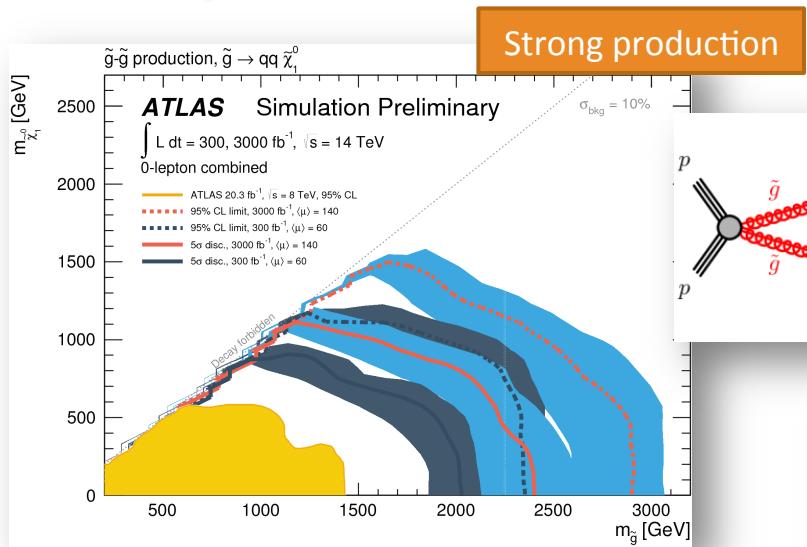


Bilinear RPV and displaced vertices

LSP lifetime may be long ($c\tau \sim 1\text{--}100 \text{ mm}$)
 → search for **displaced vertices**



Prospects for SUSY at High-Luminosity LHC



ATL-PHYS-PUB-2014-010