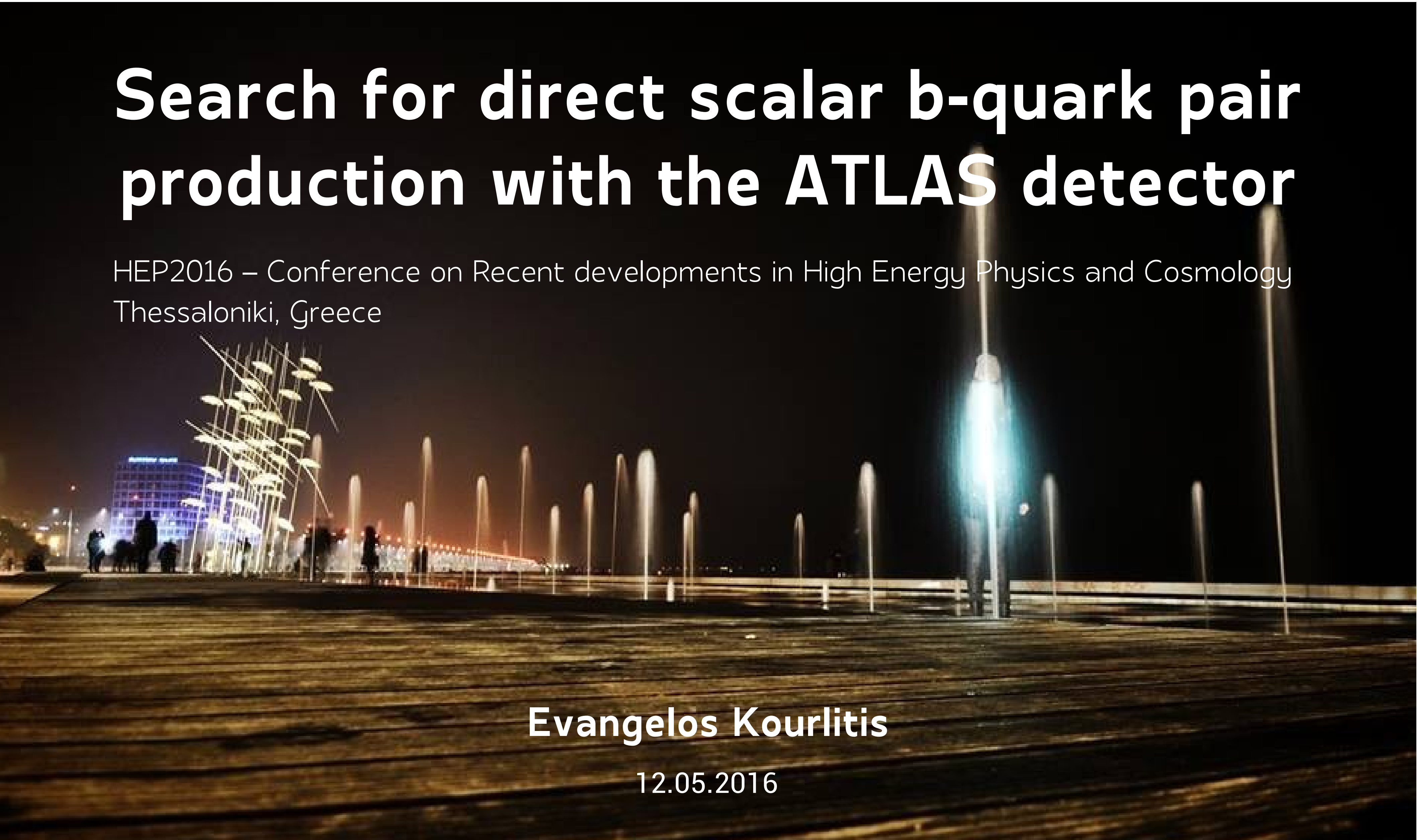
The University Of Sheffield.

ATLAS EXPERIMENT

Search for direct scalar b-quark pair production with the ATLAS detector

HEP2016 – Conference on Recent developments in High Energy Physics and Cosmology
Thessaloniki, Greece



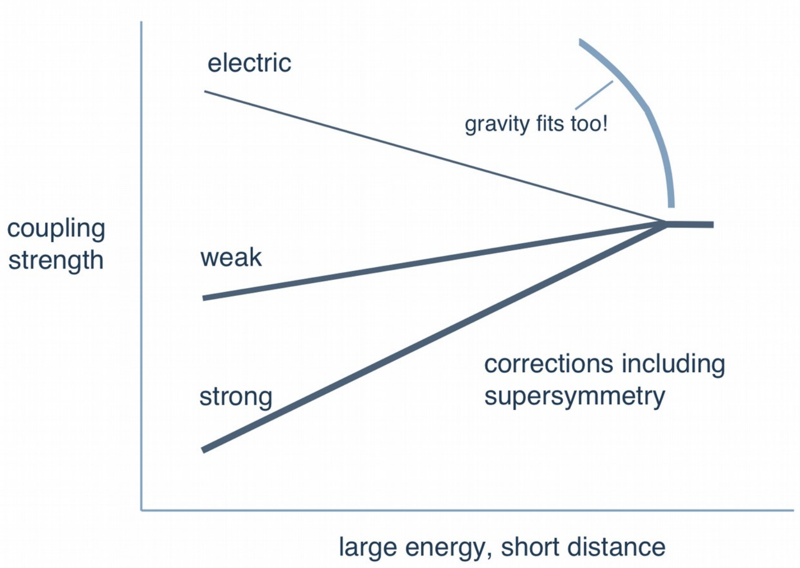
Evangelos Kourlitis

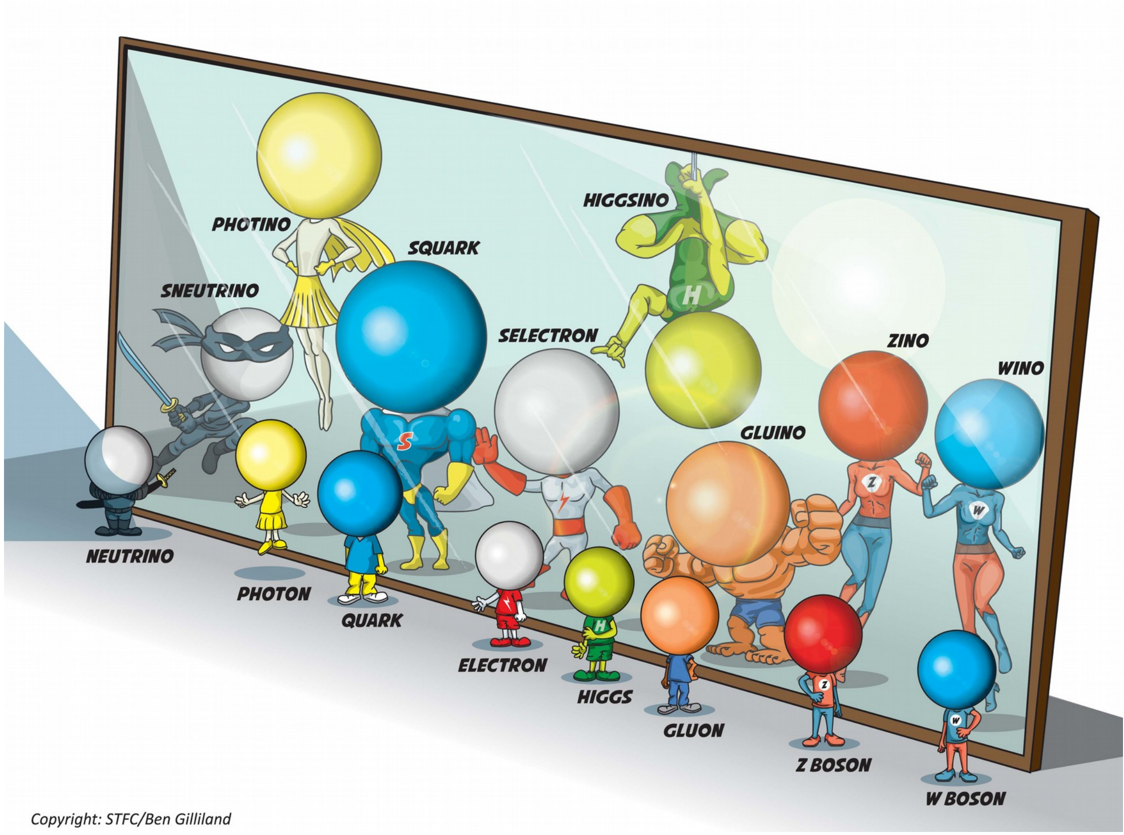
12.05.2016

Supesymmetry Overview

- Theoretical framework beyond the Standard Model
  - Predicts superpartners of the known particles – Spin differs by 1/2

- Offers solutions to known physics problems:
  - Hierarchy problem
  - Dark Matter candidate
  - Unification of forces

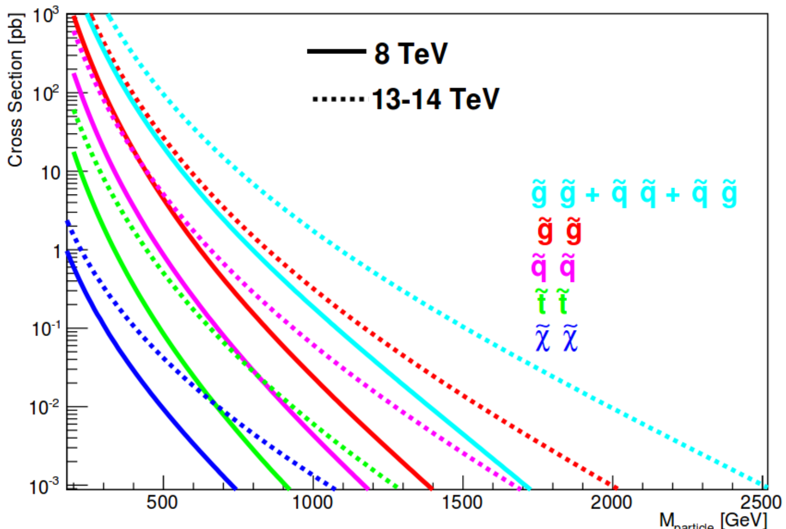




3rd Generation SUSY

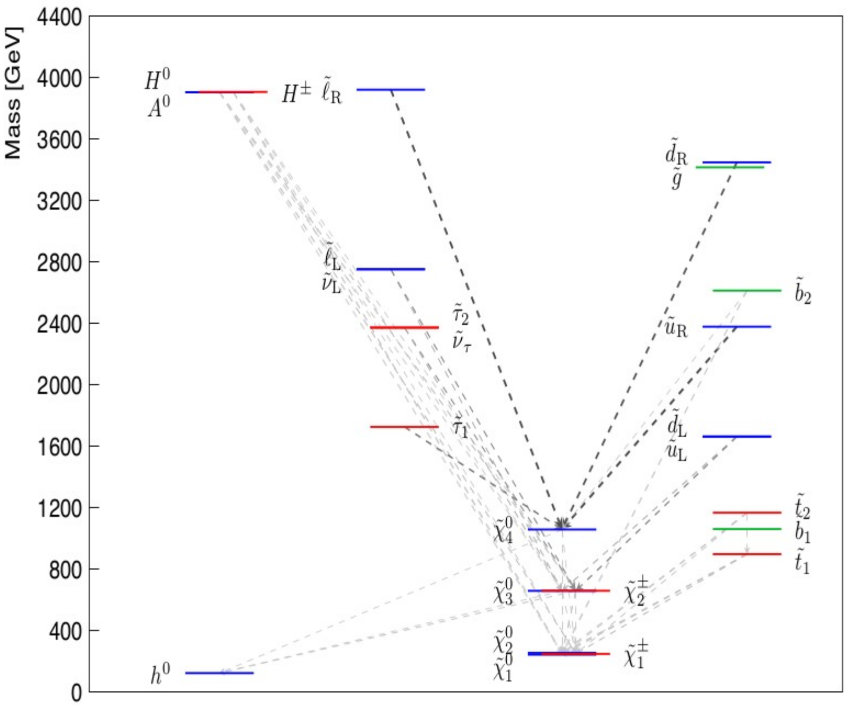
- To protect Higgs sector from unnatural loop corrections the scalar partners of top and bottom quark should have mass *O* (TeV)

- Reachable by the LHC!
  - Enhanced production cross-section, Run 2 might be a game changer



arXiv: 1411.1427

A natural (and viable) SUSY mass spectrum



arXiv: 1508.06608

The pMSSM

- The **M**inimal **S**upersymmetric **S**tandard **M**odel implies 120 parameters
- Well motivated assumptions reduce the number of parameters to 19 → **phenomenological MSSM**

Assumptions

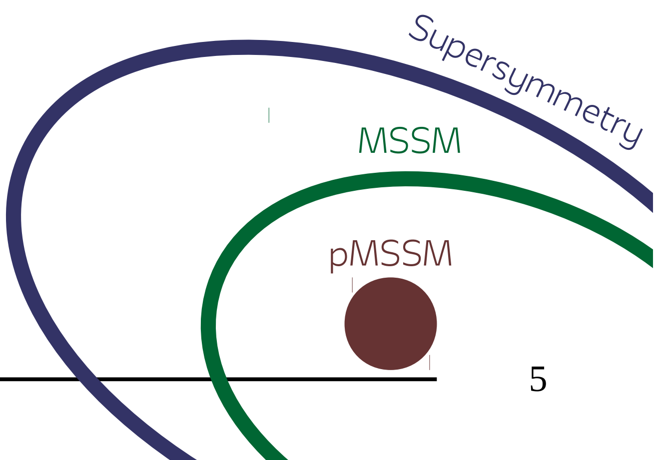
Experimental Constrains
R-parity* Conservation
No additional FCNC
Parameters ∈ ℝ
1st and 2nd Generation mass degeneracy

Experimental Constrains →
- EW measurements
- Collider constrains on mass (LEP, Tevatron)
- Dark Matter constrains ($\Omega_{CDM}h^2$ from Plank)

R-parity* Conservation →
- Sparticles produced in *pairs*
- The lightest (LSP) is *stable* ($\tilde{\chi}_0^1$)

$$\tilde{\chi}_0^1 = N_{11}\tilde{B} + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_d^0 + N_{14}\tilde{H}_u^0$$

Parameters ∈ ℝ → No new ~~CP~~



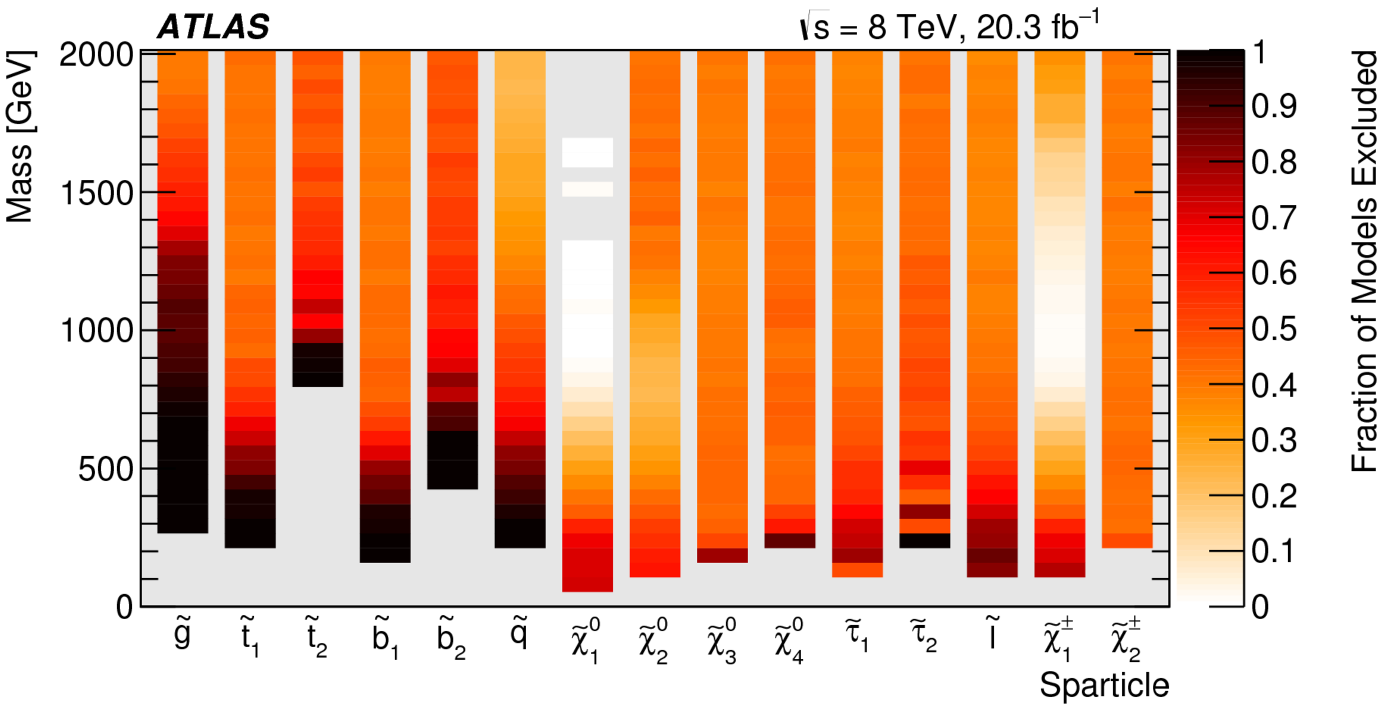
$^{*}\,P_R = (-1)^{3B+L+2s}$

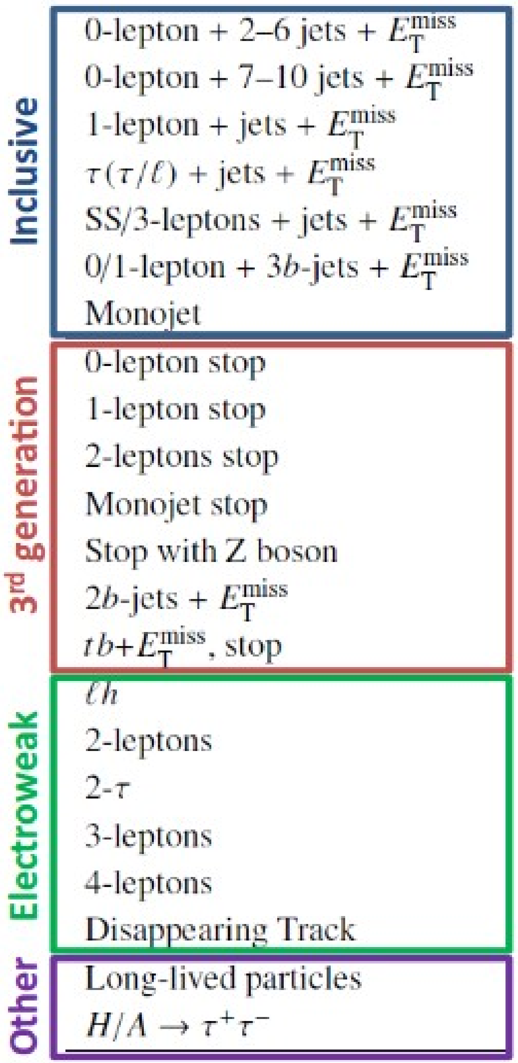
Where do we stand on pMSSM?

- After the assumptions, ATLAS generated >300k model-points
  - Random set of parameters selection
  - Interpreted by 22 Run I analyses

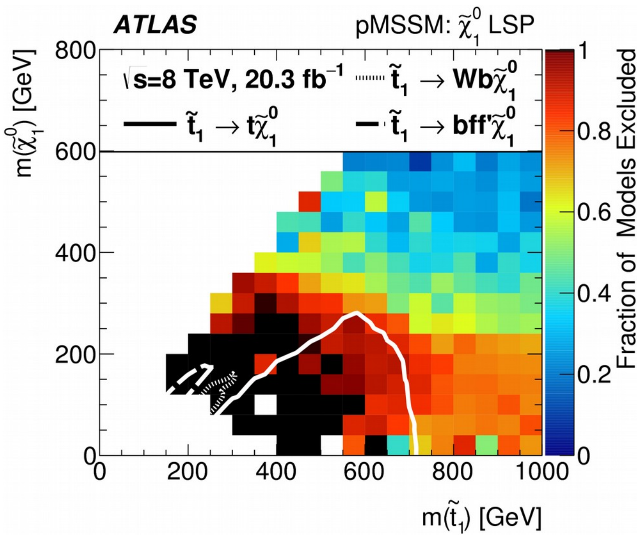
arXiv: 1508.06608

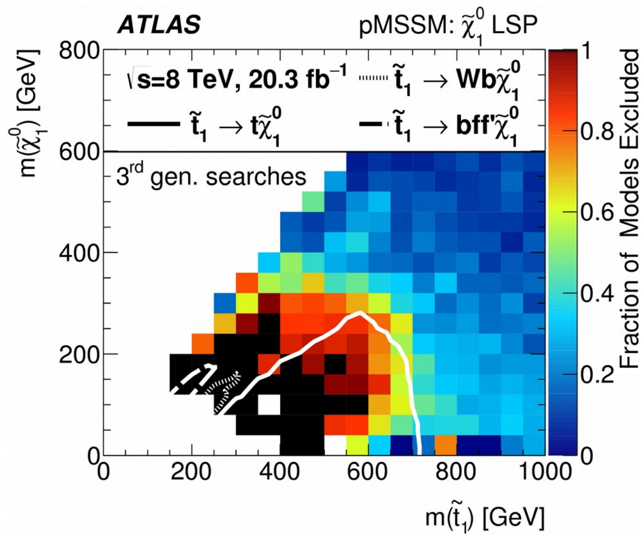
Search summary:





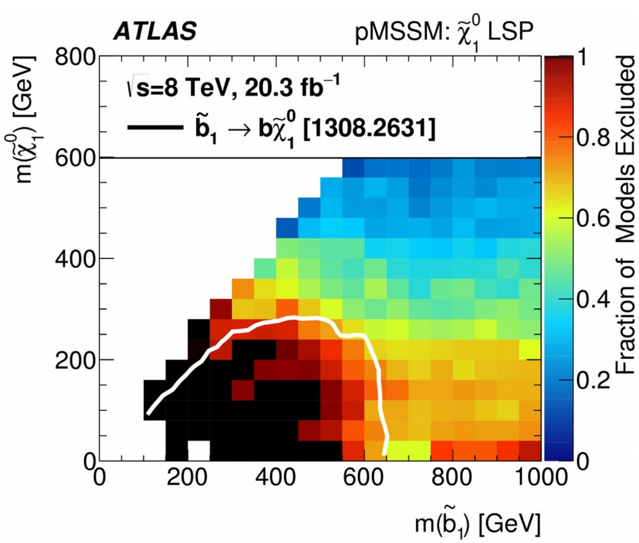
3rd Generation on pMSSM

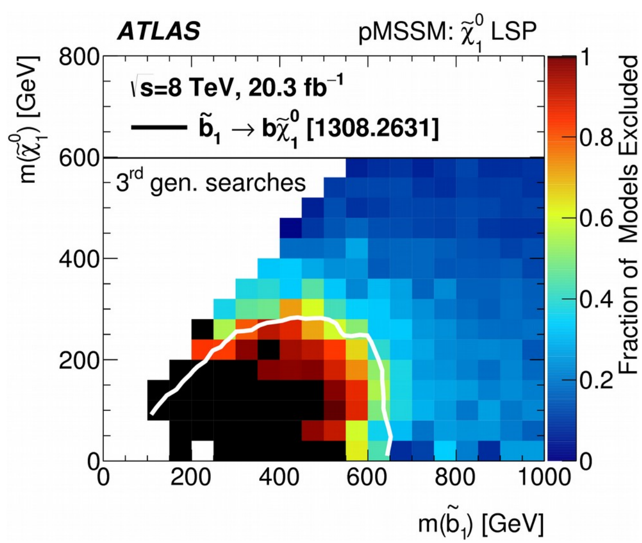




Most points excluded for **stop** mass bellow 600 GeV

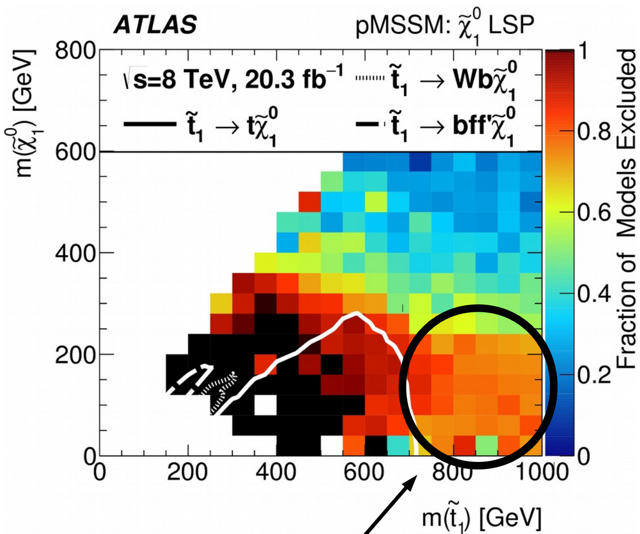
Well captured sensitivity by simplified models

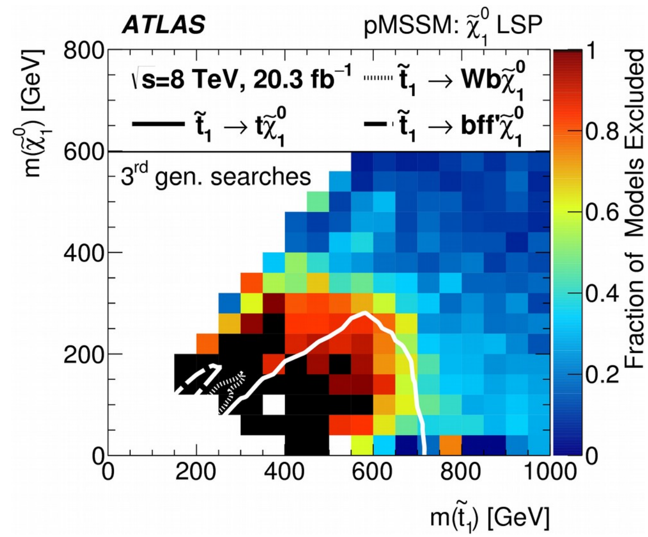




For **sbottom** this limit drops to 550 GeV

3rd Generation on pMSSM



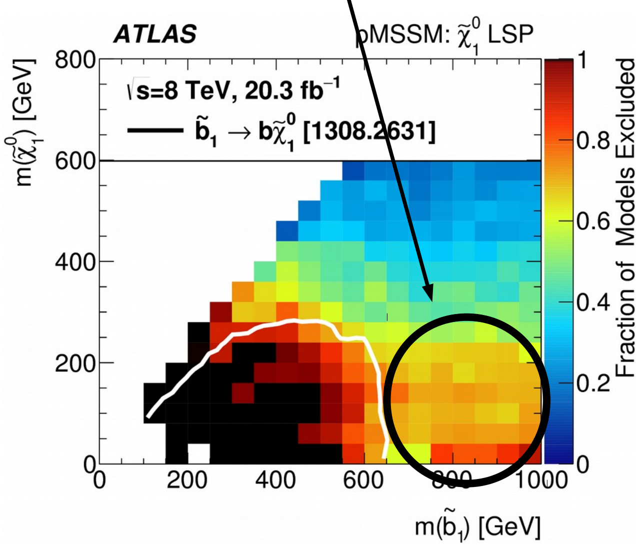


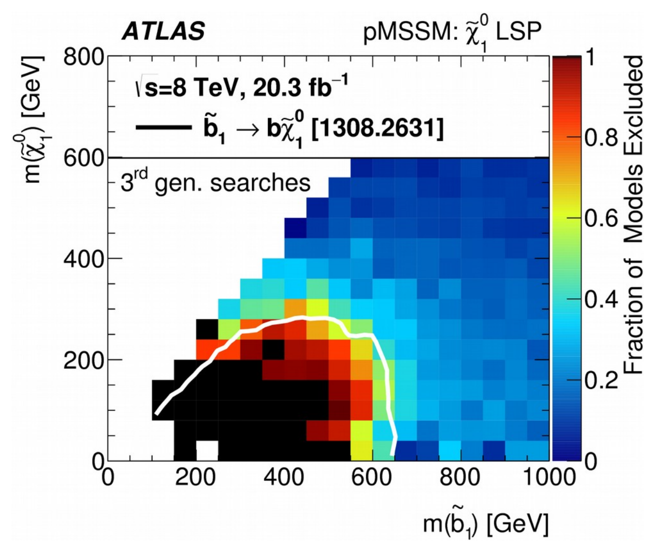
Most points excluded for **stop** mass bellow 600 GeV

Disappearing Tracks from long-lived charginos searches

Cases with wino-like LSP

and: $\Delta m(\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}) < 200\, GeV$

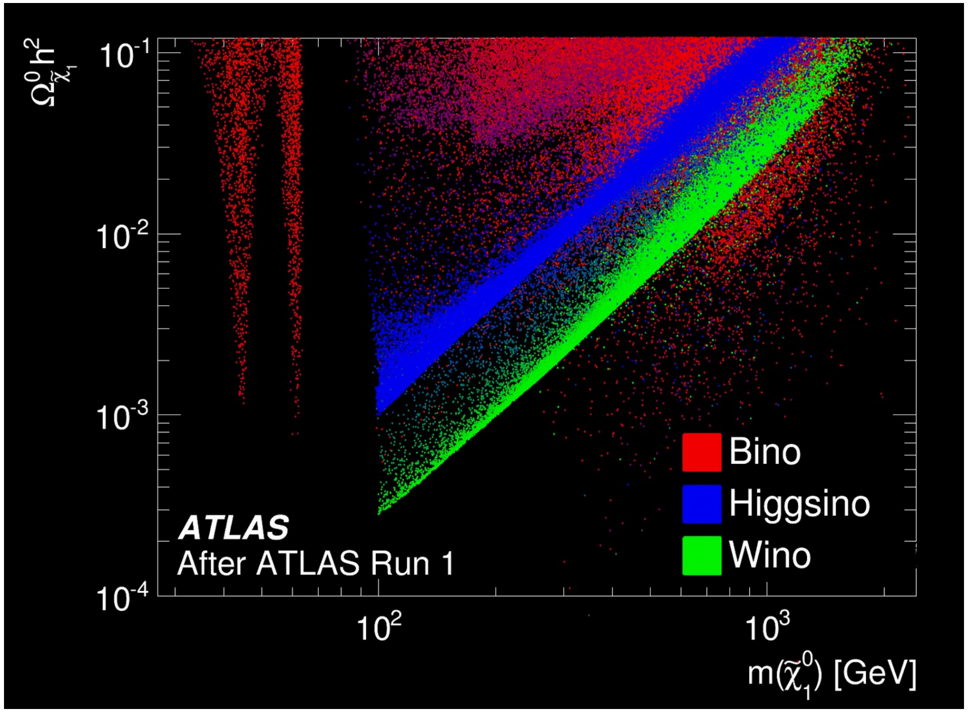




For **sbottom** this limit drops to 550 GeV

Dark Matter and other fancies

Z and h funnels: $\chi_1^0\chi_1^0 \to Z \to SM$ predicts $m_\chi \approx m_Z/2 \sim 45$ GeV
$\chi_1^0\chi_1^0 \to h \to SM$ predicts $m_\chi \approx m_h/2 \sim 63$ GeV

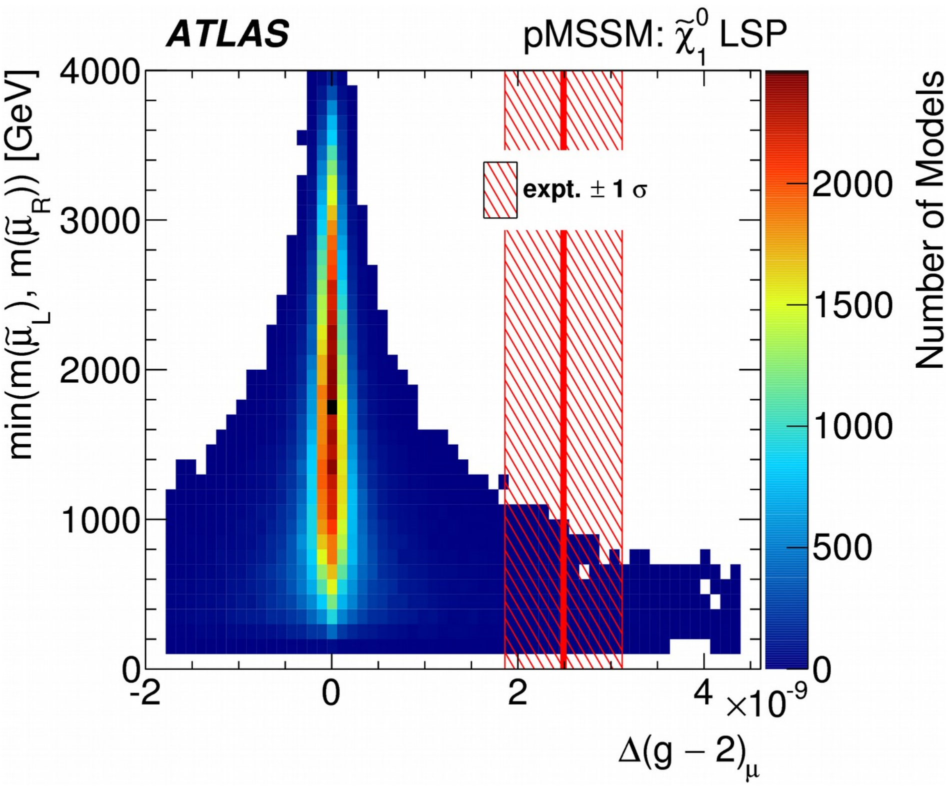


Low mass $\widetilde{H}$ or $\widetilde{W}$-like LSP predicts low mass NLSP ($\tilde{\chi}_1^{\pm}$)

Excluded by **LEP**

Muon anomalous magnetic moment: 3.4σ tension with SM

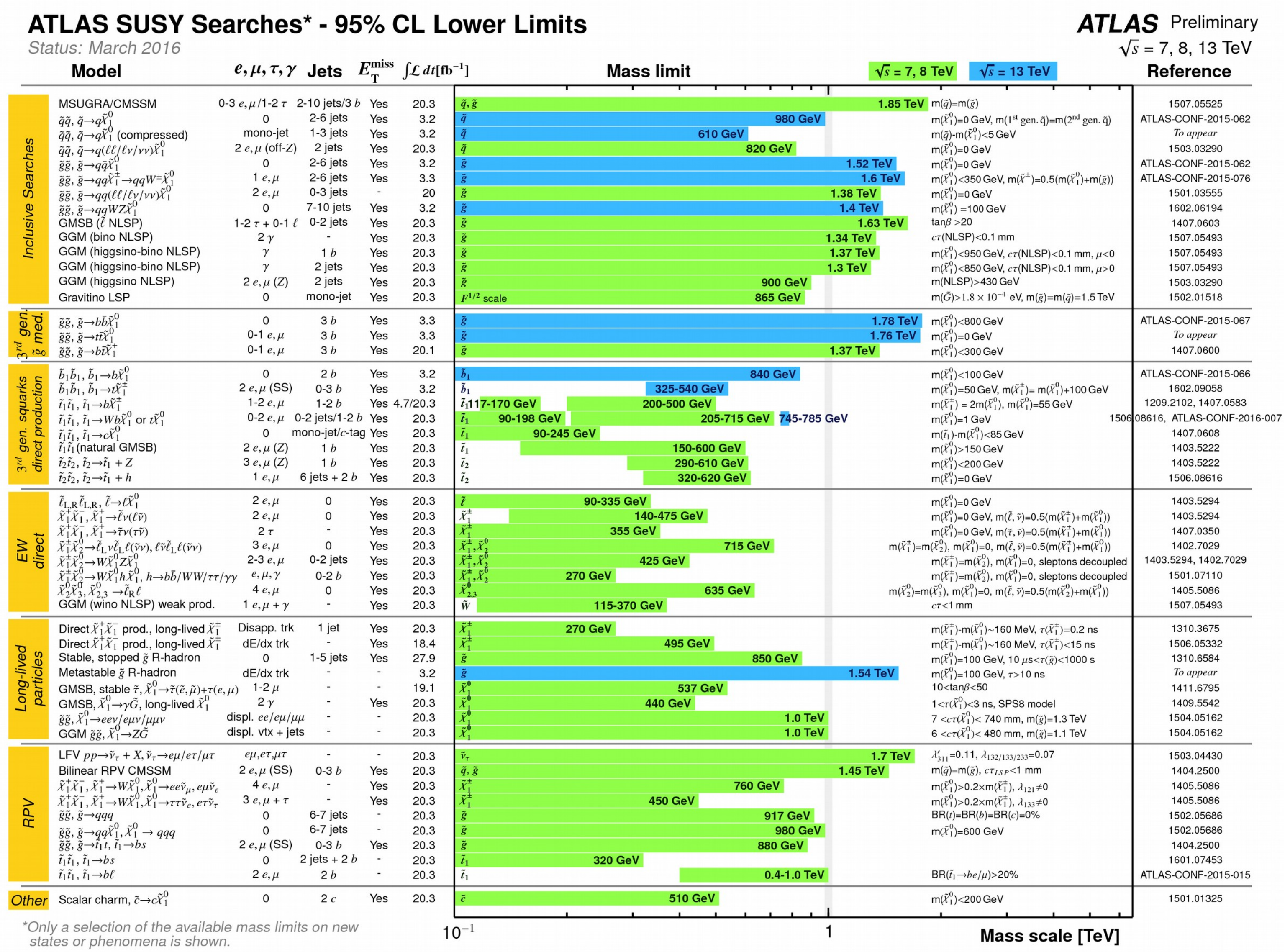
arXiv: hep-ph/0611102



- Generally small SUSY contribution
- Larger sensitivity on tails as lighter sparticles are predicted

Towards Run II

- Even with only 3.2 fb^{-1} Run II was able to surpass important Run I limits



Towards Run II

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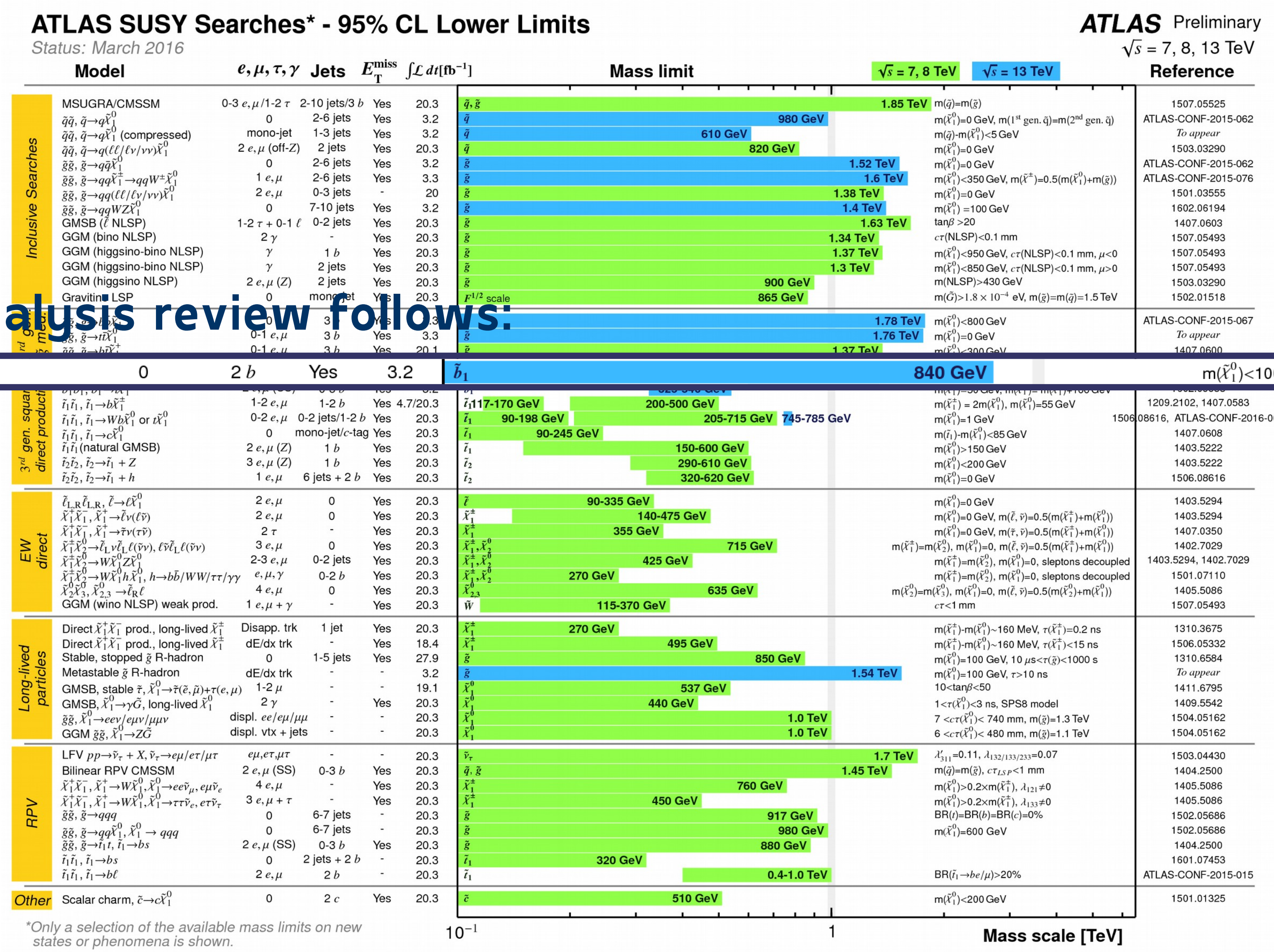
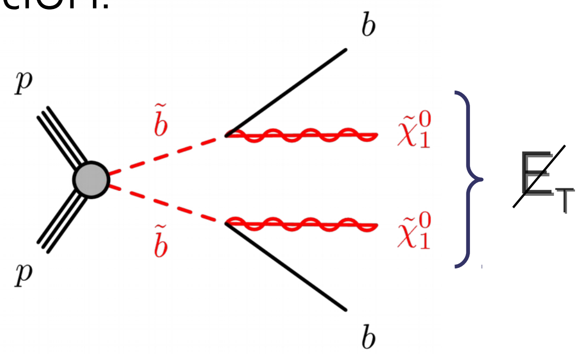


Run II analysis review follows:

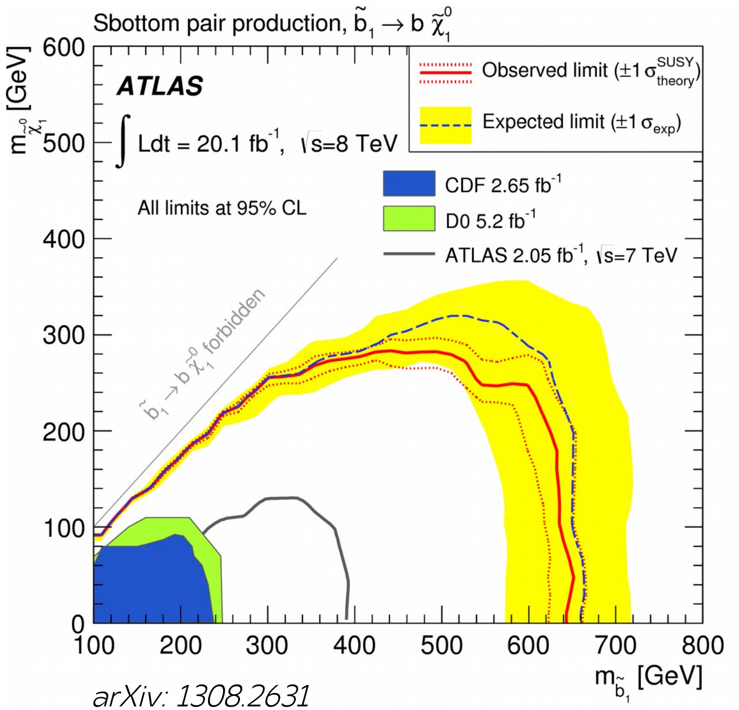
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	$\tilde{b}_1$ 840 GeV	$m(\tilde{\chi}_1^0)$<100 GeV

Overview *(ATLAS-CONF-2015-066)*

- Search for direct scalar bottom quark pair production:
  - Final state consist of 2 b-jets and large missing transverse momentum



Analysis based on Run I strategy, targeting the exclusion of large sbottom masses

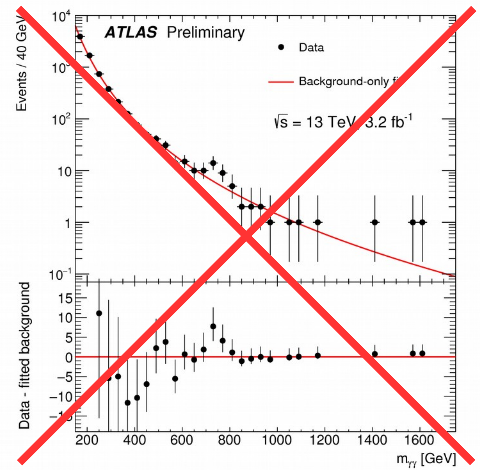


arXiv: 1308.2631

- Run II analysis sensitivity gain by E_{CMS}, 8 → 13 TeV:
  - Signal $\sigma_{\tilde{b}\,(800GeV)}$ increase by factor of ~10
  - Major background σ_{Z+Jets} increase by factor of ~2

Analysis Strategy

- The decay products manifest themselves as E_T^{miss}
  - Invariant mass reconstruction impossible



- Simple and robust *Cut 'n' Count* approach employed

1. Define Signal Regions based on a model
- Aiming to reduce background – Discriminating variables used
- Optimized to provide maximum discovery significance

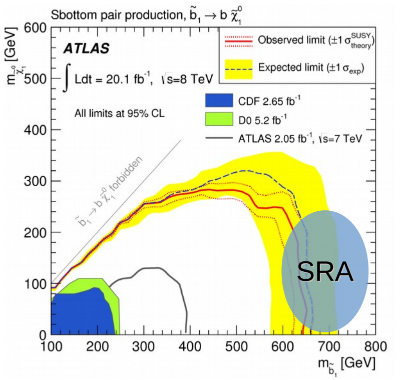
2. Define Control Regions each targeting a specific background
- Normalize the MC prediction to match the yield
- Extrapolate the normalization factors using a combined likelihood fit

3. Validation Regions to verify the prediction
- Intermediate step between CR and SR
- Kinematically close but orthogonal to SR

4. Open Pandora's box
- Compare the yield in SR with the SM prediction
- If no excess observed, derive exclusion limits on the model

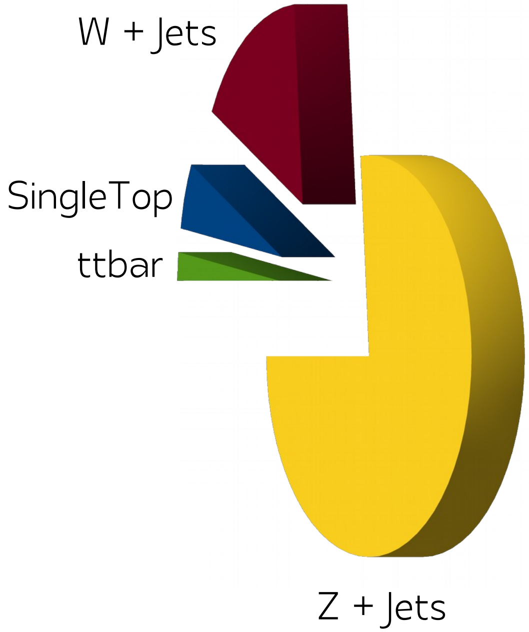
Signal Region A – Bulk Region

- Class of regions targeting large mass splitting between $\tilde{b}$ and $\tilde{\chi}_1^0$
- Containing: 0 leptons, 2 b-jets, large E_T^{miss}
  - 0 leptons → p_T > 10 GeV
  - 2 b-jets → 77% efficiency
  - large E_T^{miss} → Ensure fully efficient E_T^{miss} trigger



- Main discriminating variable, contransverse mass:
  - For the decay of two identical massive particles to two visible (v_1,v_2) and two invisible: $m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p}_T(v_1) - \mathbf{p}_T(v_2)]^2$
  - Kinematic end-point for ttbar m_{CT} = 135 GeV

Major Backgrounds



Event Selection

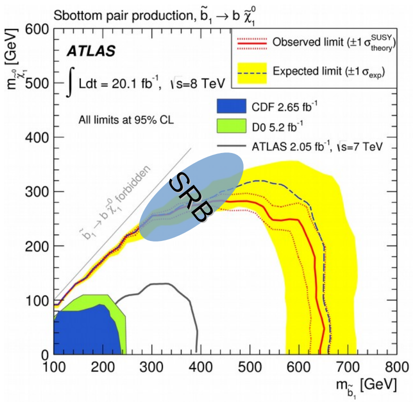
SRA250	SRA350	SRA450
No baseline electron or muon		
Leading (in p_T) two jets b-tagged		
p_T > 130 GeV for the leading jet		
m_{bb} > 200 GeV		
E_T^{miss} > 250 GeV		
Veto on 4^{th} jet with p_T > 50 GeV		
m_{CT} > 250 GeV	m_{CT} > 350 GeV	m_{CT} > 450 GeV

+ Multijet "killers"

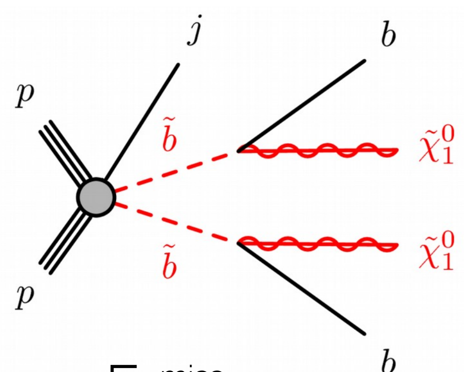
- $\Delta\varphi(j_1, E_T^{miss})$>0.4
- E_T^{miss}/m_{eff}>0.25

Signal Region B – Compressed Scenarios

- Scenarios with small mass splitting between $\tilde{b}$ and $\tilde{\chi}_1^0$ lead to softer b-jets, SRA is no more sensitive

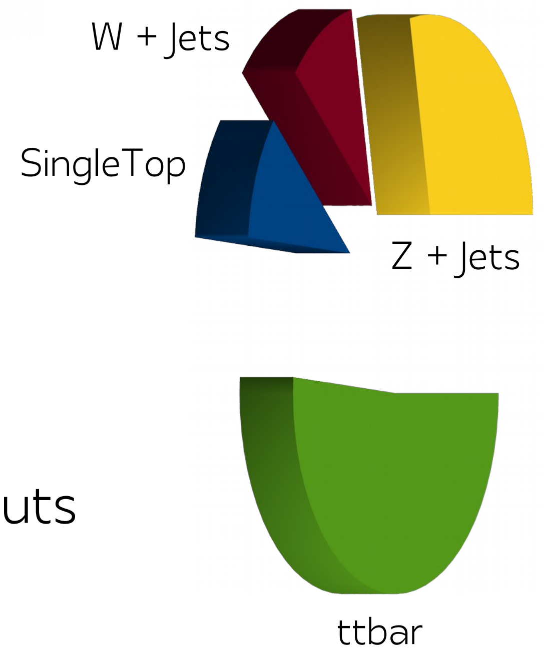


- Initial State Radiation recoiling against the sbottom system exploited to discriminate the potential signal



- Containing a high-p_T non-b-tagged jet, large E_T^{miss} and additional b-jets

Major Backgrounds



Event Selection

Lepton selection	No baseline electron or muon
Leading-p_T jet	not b-tagged, $p_T > 300$ GeV
SubLeading-p_T jet	b-tagged
$\Delta\phi(1^{st}$ jet, $E_T^{miss})$	> 2.5
JetVeto	$p_T(4^{th}$ jet$) < 50$ GeV
E_T^{miss}	> 400 GeV

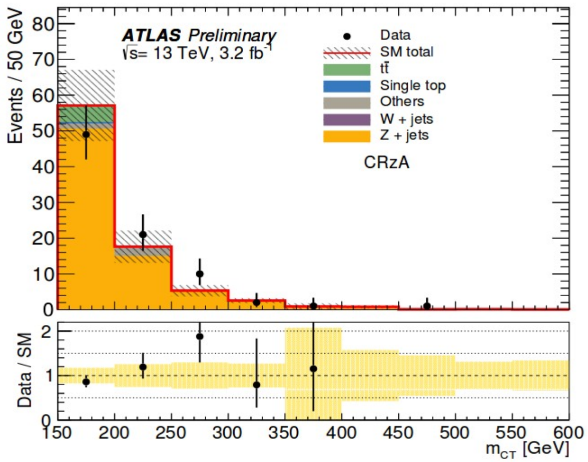
+ same Multijet cuts

Control Regions

- Dedicated Control Regions for each dominant background
- Due to kinematics, different CRs correspond to each SR type
  - **SRA**: Z+Jets, W+Jets, SingleTop, ttbar – **SRB**: ttbar, Z+Jets
- The rest of them are calculated using pure MC prediction

Alternative estimation:
Data-driven using γ+Jets events

CRAs



CRBs

2Leptons

CRz (CRAs)
- SFOS leptons, $p_T^{ll} > 100$ GeV
- Z mass window
- $E_T^{miss} < 100$ GeV

CRz (CRBs)
- SFOS leptons, $p_T^{ll} > 100$ GeV
- Z mass window
- $E_T^{miss} < 70$ GeV

1Lepton

CRtt (CRAs)
- $m_{bb} < 200$ GeV
- $E_T^{miss} > 100$ GeV

CRst
- $m_{bb} > 200$ GeV
- $E_T^{miss} > 100$ GeV

CRw
- 1 b-taged jet
- $m_{bj} > 200$ GeV
- $E_T^{miss} > 100$ GeV

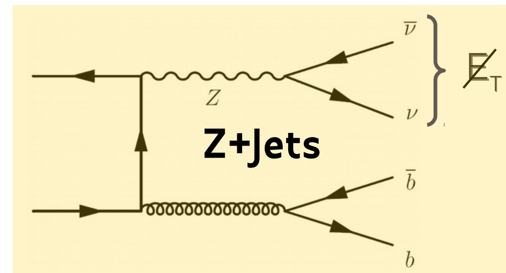
CRtt (CRBs)
- $E_T^{miss} > 200$ GeV

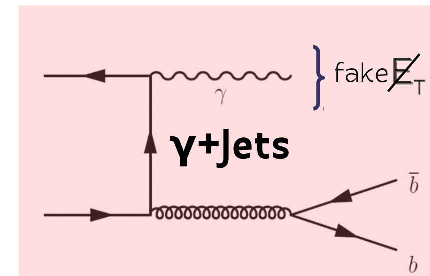
Alternatively: Z from Photons

- Data-driven technique developed for cross-checking purposes
  - Exploiting the similar properties of the vector bosons Z and γ

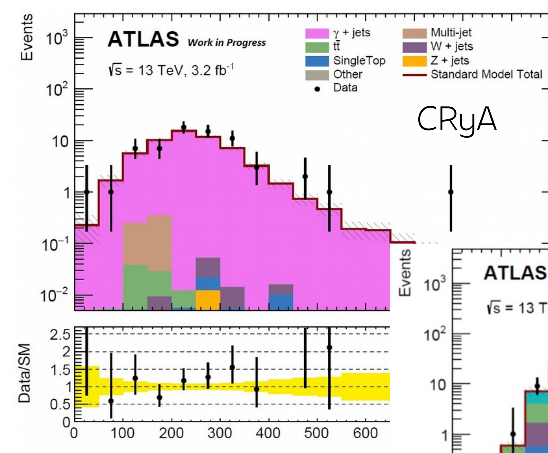
- Photons mimic the Z → νν decays:

faking E_T^{miss} by vectorially adding the photon to real E_T^{miss}

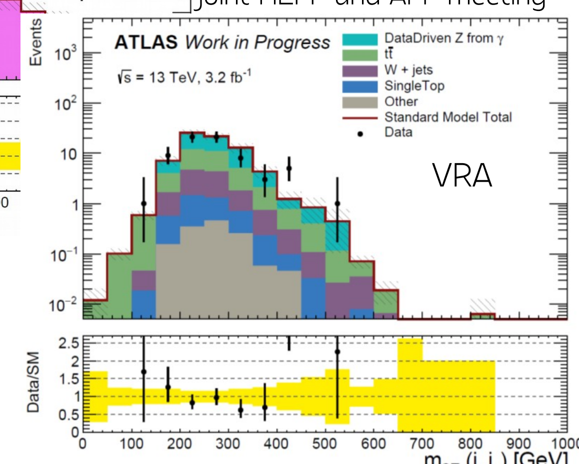




- Yield is measured in photon dominated CR
- Re-weighted, using simulations, to account for Z and γ mass difference
- Corrected for any MC miss-modeling using Z → ll events



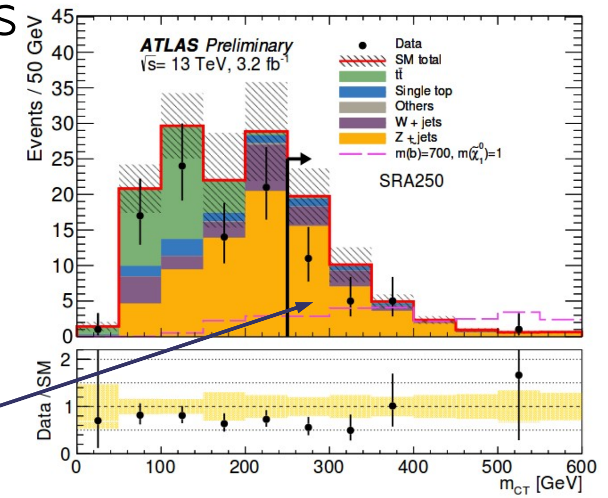
Calum Macdonald @ IOP2016
Joint HEPP and APP meeting



$$N_{SR}^{Z\nu\nu} = \int_X^{\infty} \left(f_{CR\gamma}^{\text{data}} - f_{CR\gamma}^{\text{non-}\gamma\text{ MC}}\right) \cdot \frac{1}{\kappa} \cdot R_{Z/\gamma}(p_T(\gamma))\ dm_{CT}$$

Results

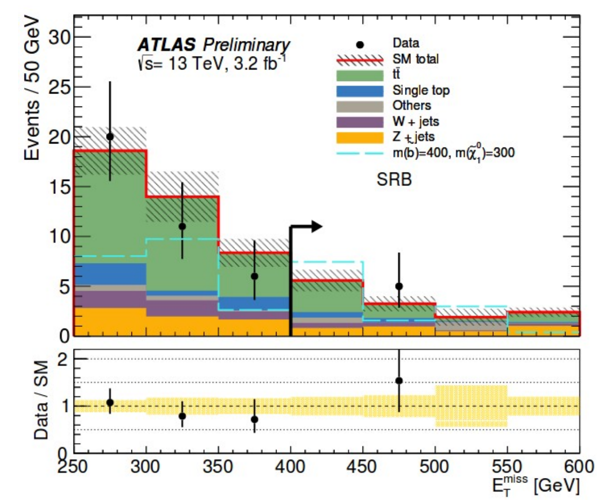
- The observed number of events in each CR is used in a combined likelihood fit to determine the SM background in SRs
- Dominant sources of systematic uncertainties:
  - Experimental: JES (SRA), JER (SRB), b-tagging (both)
  - Theoretical: Z+Jets (25-50% of the total SRA unc.), ttbar (~70% of the total SRB unc.)



small deficit
<2σ

Resulted Yields

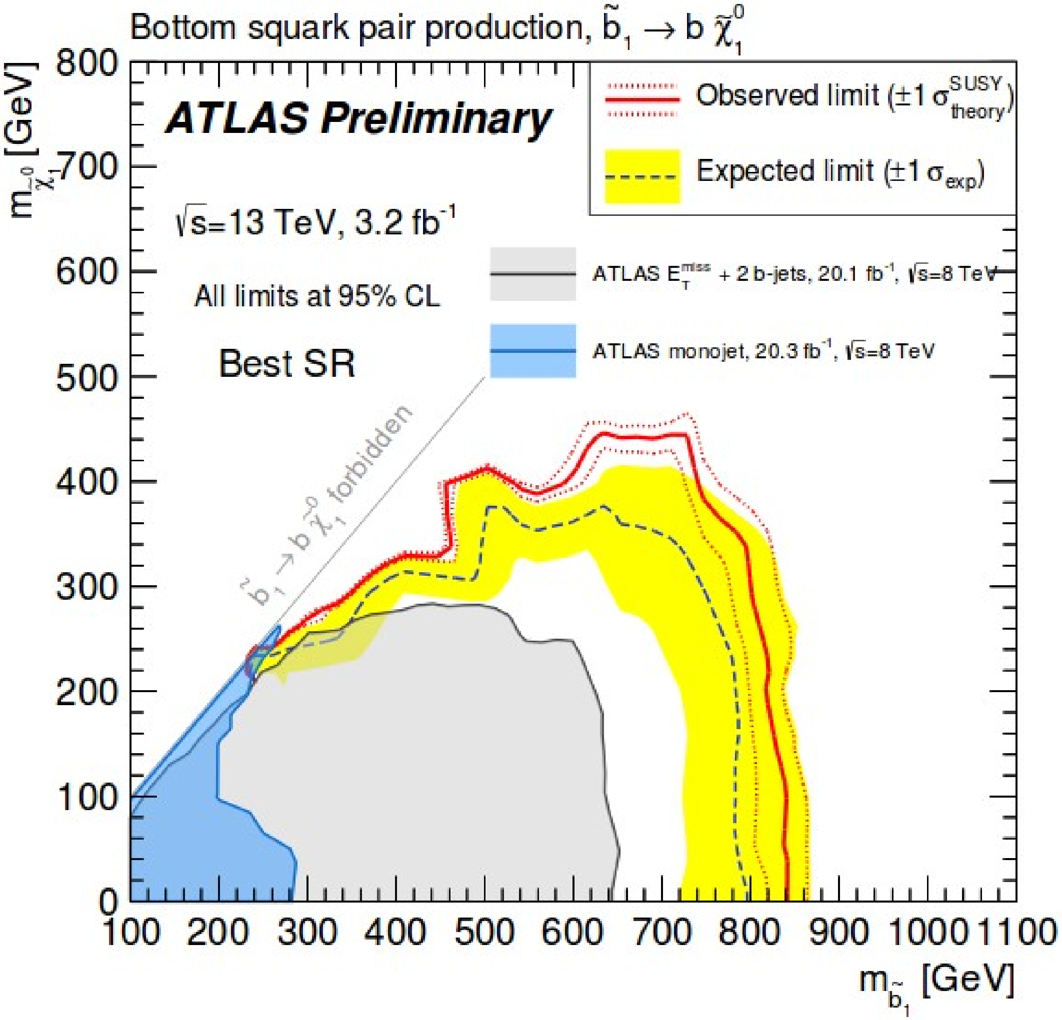
Signal region channels	SRA250	SRA350	SRA450	SRB
Observed events	22	6	1	5
Fitted bkg events	40 ± 8	9.5 ± 2.6	2.2 ± 0.6	13.1 ± 3.2
Fitted $t\bar{t}$ events	0.9 ± 0.4	0.37 ± 0.16	0.06 ± 0.03	5.9 ± 2.4
Fitted single top events	2.1 ± 1.3	0.54 ± 0.37	0.15 ± 0.10	1.2 ± 0.8
Fitted W+jets events	6.3 ± 2.4	1.3 ± 0.6	0.41 ± 0.23	1.2 ± 0.6
Fitted Z+jets events	30 ± 7	7.1 ± 2.4	1.5 ± 0.5	3.3 ± 1.4
Fitted “Other” events	0.7 ± 0.6	0.1 ± 0.1	0.02 ± 0.02	1.4 ± 0.4



No excess observed

Interpretation

- The results are used to place exclusion limits at 95% CL on the supersymmetric mass plane



- Simplified model used:
  - Only the sbottom quark and the LSP are kinematically accessible
  - $BR(\tilde{b} \rightarrow b + \tilde{\chi}_1^0) = 1$

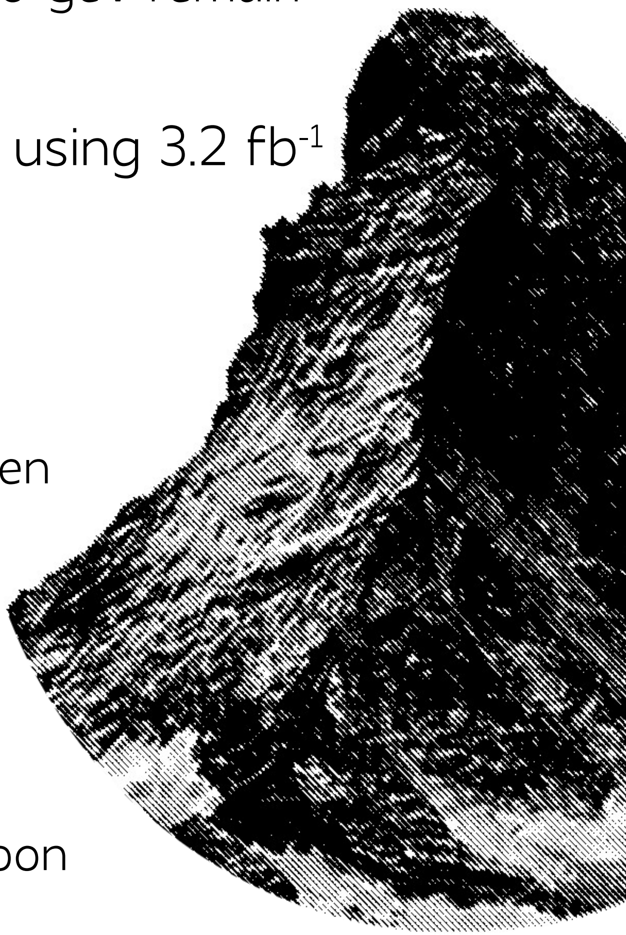
- Limit on sbottom mass stands at 800-840 GeV

- Almost 200 GeV higher than Run I

Conclusions

- Impact of ATLAS Run I searches on pMSSM
  - Few models with 3rd generation squarks lighter than 550-600 GeV remain

- Run II searches for direct bottom squark pair production using 3.2 fb^{-1}
  - Final states containing 2 b-jets and E_T^{miss}
  - A *cut'n'count* analysis shows no excess above expected background → exclusion limits on a simplified model have been placed
  - $\tilde{b}$ masses up to 840 GeV have been excluded for $\tilde{\chi}_1^0$ masses bellow 100 GeV
  - New paper investigating the SRA deficit is being published soon



Backup Slides

Object Definitions

BASELINE OBJECTS

BASELINE ELECTRONS:
- $|\eta|<2.47$, $P_T > 10$ GeV
- LooseAndBLayerLLH ID

BASELINE MUONS:
- $|\eta|<2.4$, $P_T > 10$ GeV
- Medium Track ID

BASELINE JETS:
- $|\eta|<2.8$, $P_T > 20$ GeV
- AntiKt4EMTopo, R=0.4

OVERLAP REMOVAL

SIGNAL OBJECTS: baseline + passOR + extra

ELECTRONS
- $d_0/\sigma(d_0)<5$
- $z_0 \sin(\theta)<0.5$
- TightLLH ID
- GradientLoose iso
- $P_T > 20$ GeV

MUONS
- $d_0/\sigma(d_0)<3$
- $z_0 \sin(\theta)<0.5$
- Cosmic veto
- GradientLoose iso
- $P_T > 20$ GeV

JETS
- JVT>0.59 (if P_T<50 GeV)
- $P_T > 35$ GeV

B-JETS
- Signal jets
- $|\eta|<2.5$
- MV2c20, 77% WP, FixedCut

Signal Regions

Variable	SRA	SRB
Event cleaning	Common to all SR	
Lepton veto	No e/μ with $p_{\mathrm{T}} > 10$ GeV after overlap removal	
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 250 GeV	> 400 GeV
Leading jet $p_{\mathrm{T}}(j_1)$	> 130 GeV	> 300 GeV
2nd jet $p_{\mathrm{T}}(j_2)$	> 50 GeV	> 50 GeV
Fourth jet $p_{\mathrm{T}}(j_4)$	vetoed if > 50 GeV	
$\Delta\phi^{j}_{\mathrm{min}}$	> 0.4	> 0.4
$\Delta\phi(j_1,)$	-	> 2.5
b-tagging	j_1 and j_2	j_2 and (j_3 or j_4)
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	> 0.25	> 0.25
m_{CT}	$> 250, 350, 450$ GeV	-
m_{bb}	> 200 GeV	-

VRB ← $E_{\mathrm{T}}^{\mathrm{miss}}$: $250 < E_{\mathrm{T}}^{\mathrm{miss}} < 300$

VRmctA ← m_{CT}

VRmbbA ← m_{bb}

Control Regions

Variable	CRzA	CRttA	CRstA	CRwA	CRzB	CRttB
Number of lep.	2 SFOS	1	1	1	2 SFOS	1
Lead. lep. p_T [GeV]	> 26	> 26	> 26	> 26	> 26	> 26
2nd lep. p_T [GeV]	> 20	-	-	-	> 20	-
$m_{\ell\ell}$ [GeV]	$[76 - 106]$	-	-	-	$[76 - 106]$	-
m_T [GeV]	-	-	-	> 30	-	-
Lead. jet $p_T(j_1)$ [GeV]	-	> 130	-	> 130	50	130
4th jet $p_T(j_4)$	vetoed if > 50 GeV					
b-tagged jets	j_1 and j_2	j_1 and j_2	j_1 and j_2	j_1	j_2 and (j_3 or j_4)	j_2 and (j_3 or j_4)
E_T^{miss} [GeV]	< 100	> 100	> 100	> 100	< 70	> 200
$E_T^{miss,cor}$ [GeV]	> 100	-	-	-	> 100	-
m_{bb} [GeV]	-	< 200	> 200	$(m_{bj}) > 200$	-	-
m_{CT} [GeV]	> 150	> 150	> 150	> 150	-	-
$m_{b\ell}^{min}$ [GeV]	-	-	> 170	-	-	-
$\Delta\phi(j_1, E_T^{miss})$	-	-	-	-	> 2.0	> 2.5
Observed events	84	255	54	540	55	181
Fitted bkg events	84 ± 9	255 ± 16	54 ± 7	540 ± 23	55 ± 7	181 ± 13
Fitted $t\bar{t}$ events	4.7 ± 1.4	169 ± 25	8.3 ± 3.8	123 ± 29	14 ± 4	150 ± 15
Fitted single top events	0.4 ± 0.4	27 ± 13	22 ± 8	49 ± 25	0.4 ± 0.2	16.8 ± 2.9
Fitted W+jets events	-	52 ± 17	23 ± 6	350 ± 47	-	12.6 ± 4.9
Fitted Z+jets events	75 ± 9	2.3 ± 0.5	-	5.0 ± 1.6	41 ± 8	0.3 ± 0.1
Fitted "Other" events	3.6 ± 1.3	4.4 ± 0.9	0.8 ± 0.4	11.7 ± 2.1	-	1.3 ± 0.6
MC exp. SM events	54	283	56	491	49	196
MC exp. $t\bar{t}$ events	5.7	204	10	148	15	166
MC exp. single top events	0.5	34	28	62	0.4	17
MC exp. W+jets events	-	40	17	266	-	12.6
MC exp. Z+jets events	45	1.4	-	3.0	33	0.2
MC exp. "Other" events	3.6	4.4	0.8	11.7	-	1.3

Alternative Z+Jets from γ+Jets

1. Define high-purity photon regions to emulate SRs and VRs:

		CRγAx *SRAx emulation*	CRγA-mbb *VRAmbb emulation*	CRγB *SRB emulation*
Pre-selection		✓	✓	✓
Trigger		HLT_g120_loose	HLT_g120_loose	HLT_g120_loose
Photons		1 signal	1 signal	1 signal
Leading photon	GeV	> 130	> 130	> 130
Leptons (e or μ)		0 baseline	0 baseline	0 baseline
Leading jet p_{T}	GeV	> 130	> 130	> 300
$\left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^{\gamma}$	GeV	> 250	> 250	> 400
m_{bb}	GeV	> 200	< 200	-
m_{CT}	GeV	$> x$	> 150	-
b-jets (MV2c20 77%)		(1,2)	(1,2)	(2,3) or (2,4)

* The emulation of VRAmct is made with CRγAx; $x = 0$; with an upper cut on $m_{\mathrm{CT}} < 150$.

2. Reweight P_γ^T to P_Z^T to correct Z mass effects :

$$R_{Z/\gamma}\, dp_T(B) = \frac{f_{\mathrm{SR}}^{Z\nu\nu+\mathrm{jets\ MC}}\, dp_T(\mathrm{truth}\ B)}{f_{\mathrm{CR}\gamma}^{\gamma+\mathrm{jets\ MC}}\, dp_T(\mathrm{reco}\ B)}$$

- Final computation of the expected Z events in SRs (and VRs):

$$N_{\mathrm{SRAx}}^{Z\nu\nu} = \int_x^\infty \left(f_{CR\gamma A}^{\mathrm{data}} - f_{CR\gamma A}^{\mathrm{non}\text{-}\gamma\ \mathrm{MC}}\right) \cdot \frac{1}{\kappa} \cdot R_{Z/\gamma}(p_{\mathrm{T}}(\gamma))\ dm_{\mathrm{CT}}$$

$$N_{\mathrm{SRB}}^{Z\nu\nu} = \int_0^\infty \left(f_{CR\gamma B}^{\mathrm{data}} - f_{CR\gamma B}^{\mathrm{non}\text{-}\gamma\ \mathrm{MC}}\right) \cdot \frac{1}{\kappa} \cdot R_{Z/\gamma}(p_{\mathrm{T}}(\gamma))\ dm_{\mathrm{CT}}$$

3. Define an additional κ-factor based on loose CRs to measure the γ-Z normalisation:

$$\kappa = \frac{\mu_{\gamma,\mathrm{loose}}}{\mu_{Z,\mathrm{loose}}} = \frac{N_{\mathrm{CR}\gamma\mathrm{L}}^{\gamma+\mathrm{jets,data}}}{N_{\mathrm{CRzL}}^{Z+\mathrm{jets,data}}} \cdot \frac{N_{\mathrm{CRzL}}^{Z+\mathrm{jets,MC}}}{N_{\mathrm{CR}\gamma\mathrm{L}}^{\gamma+\mathrm{jets,MC}}} = \frac{N_{\mathrm{CR}\gamma\mathrm{L}}^{\mathrm{data}} - N_{\mathrm{CR}\gamma\mathrm{L}}^{\mathrm{non}\text{-}\gamma\ \mathrm{MC}}}{N_{\mathrm{CRzL}}^{\mathrm{data}} - N_{\mathrm{CRzL}}^{\mathrm{non}\text{-}Z\ \mathrm{MC}}} \cdot \frac{N_{\mathrm{CRzL}}^{Z+\mathrm{jets,MC}}}{N_{\mathrm{CR}\gamma\mathrm{L}}^{\gamma+\mathrm{jets,MC}}}$$

Model Independent Limits

Table 5: Left to right: 95% CL upper limits on the visible cross-section ($\langle\epsilon A\sigma\rangle^{95}_{\rm obs}$) and on the number of signal events ($S^{95}_{\rm obs}$). The third column ($S^{95}_{\rm exp}$) shows the 95% CL upper limit on the number of signal events, given the expected number (and $\pm 1\sigma$ excursions on the expectation) of background events.

Signal channel	$\langle\epsilon A\sigma\rangle^{95}_{\rm obs}$[fb]	$S^{95}_{\rm obs}$	$S^{95}_{\rm exp}$
SRA250	2.74	8.8	$15.8^{+6.3}_{-4.4}$
SRA350	1.90	6.1	$8.1^{+3.7}_{-2.3}$
SRA450	1.16	3.7	$4.4^{+2.6}_{-1.0}$
SRB	1.57	5.0	$8.5^{+3.9}_{-2.4}$