Searches for supersymmetric higgsinos with the ATLAS detector

End of the Year Workshop

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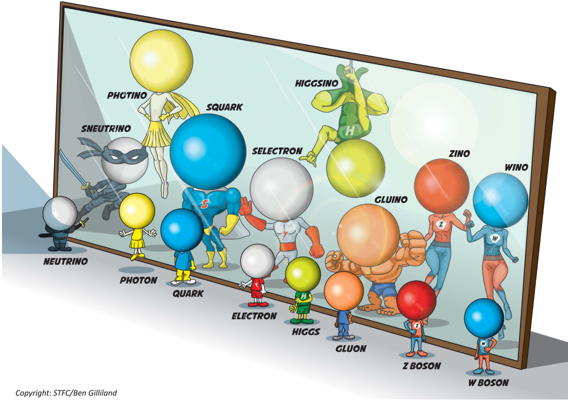
October 11, 2017

Outline

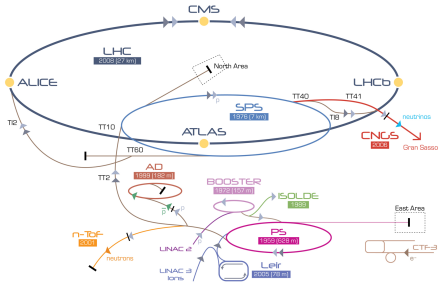
- LHC and the ATLAS detector
- ATLAS pixel detector
- Beyond standard model: Supersymmetry and naturalnes
- Compressed Electroweak spectra analysis: first results



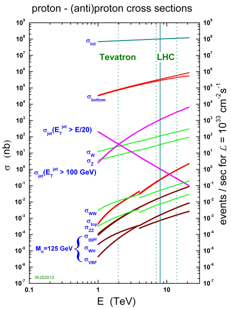
LHC

The Large Hadron Collider is the largest and most powerful accelerator ever built. It provides proton-proton collisions at an energy in the center of mass of $\sqrt{s} = 13$ TeV.

- run 1: 2010 and 2012 data taken period at 7 and 8 TeV
- run 2: 2015 and 2016 data taken period at 13 TeV



- $\approx 10^{11}$ protons per bunch
- 25 ns bunch spaching
- four main experiments: **ATLAS**, ALICE, CMS, LHCb



- More data recorded in 2015, 2016, and 2017 (run 2) than ever: $\mathcal{L}_{int} = \int \mathcal{L} dt = 62.9$ fb^{-1}
- Number of events $= \sigma_{\text{process}} \times \mathcal{L}_{int}$

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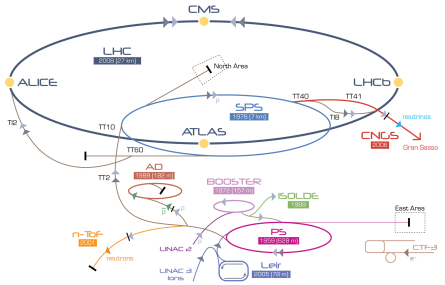

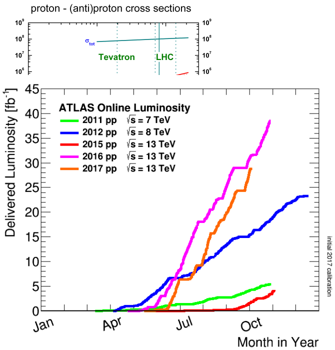

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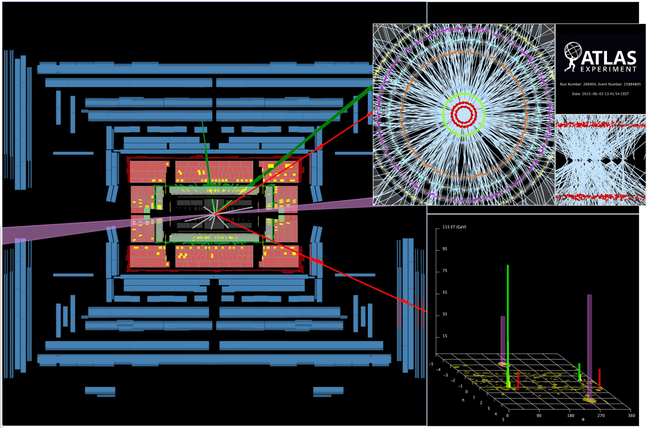
ATLAS Detector

ATLAS detector is divided in sub-detector with a specialized purpose
Detector Parts:

- Inner Detector;
- Calorimeters;
  - Electromagnetic
  - Hadronic
- Muon spectrometer;



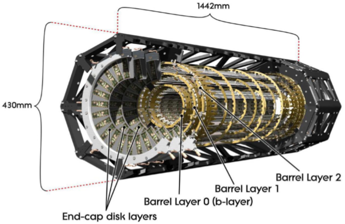
- Transverse quantity are conserved: p_T, m_T, and E_T.
- E_T^{miss} is the negative vectorial sum of all the visible quantities $\rightarrow$ invisible contributions (e.g. neutrinos)

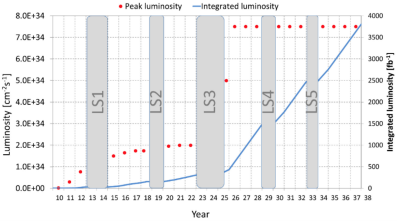
ATLAS Pixel Detector

Pixel detector is the innermost layer of the ATLAS detector → highest flux of particles

Pixel based on silicon p-n junction technology

- 4 main layers with different geometry
  - IBL (planar and 3D technology)
  - B-layer
  - Layer 1
  - Layer 2
- Must be able to distinguish all the different tracks
  - High granularity
  - High precision
- Upgraded (IBL layer) between run 1 and run 2 to account for increasing instantaneous luminosity
- Before run 4 it will be replaced by ITk
  - New design and new technology
  - Even higher instantaneous luminosity

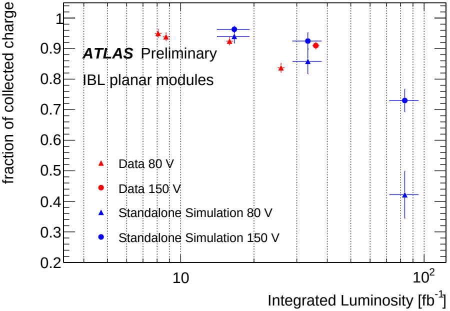




Radiation Damage in the ATLAS Pixel Detector

High rate of particles means high dose of radiation → loss of performance due to radiation damage in the sensors

- MonteCarlo simulation doesn't account for Rad Damage
- Part of my work: Implement Radiation Damage in simulation and validate them on run 2 data
    - Plot: charge collection efficiency of the IBL as a function of integrated luminosity
    - Increase in Bias Voltage reduce effect of Rad Damage



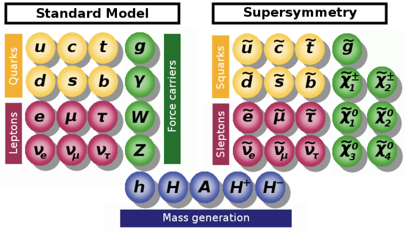
- Use simulation to predict loss of efficiency in run 4
    - work on going
    - Technical Design Report due in December

Beyond the Standard Model

Standard Model current framework. Still different (important) open questions:

- No Dark Matter candidate
- Higgs boson mass divergence

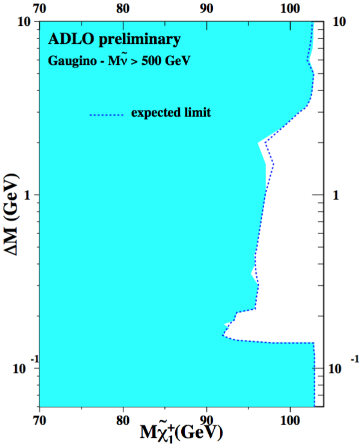
Super Symmetry (SUSY) could solve these problems → one superpartner for each SM particle, with 1/2 difference in spin

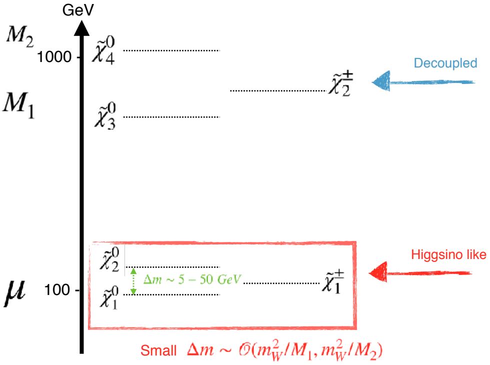


- New set of particles!
  - allows to cancel out higgs boson divergence
  - symmetry broken → different masses
- $\tilde{\chi}^0$ and $\tilde{\chi}^\pm$ mass eigenstates
  - SM: B^0 and $W^3 \to \gamma$ and Z^0
  - SUSY: $\tilde{B}$, $\tilde{W}$, and $\tilde{H} \to \tilde{\chi}^0$ $\tilde{\chi}^\pm$
- If $\tilde{\chi}^0$ is stable → lightest SUSY particle might be DM candidate

Naturalness and Higgsinos

- μ is the tree level higgs mass, must be light for naturalness



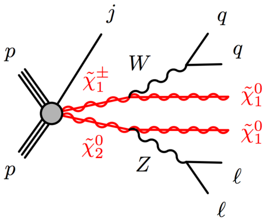


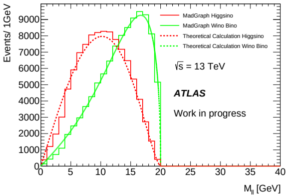
- Soft decay products from higgsino decays, challenging to detect
- Only LEP limits available
- For reference: Papucci et. al., "Natural SUSY endures", 35 JHEP 2012

Higgsino signals

Processes considered: production of $\tilde{\chi}_2^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_1^{\pm}$

- Signature:
  - ISR jet to boost the invisible system
  - Rely on $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
  - 2 very soft leptons OS
- l^+l^- invariant mass bounded by the mass difference of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ ($m_{ll} < \Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$)
- m_{ll} distribution depends on the nature of the $\tilde{\chi}^0$ $\rightarrow$ different shape for Wino-Bino and Higgsino case
- Main strategy:
  - Look at low m_{ll} region
  - Shape fit (separately for ee and $\mu\mu$) the m_{ll} distribution





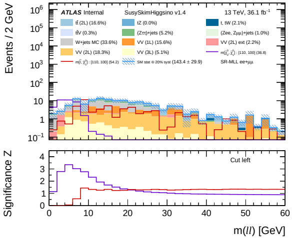
Signal Region definition

Signal Region (SR) defined by maximising the ratio signal / background

- Optimization refined and harmonised with careful analysis.
- Defined a common SR definition
- Then define m_{ll} bins to maximise the exclusion potential

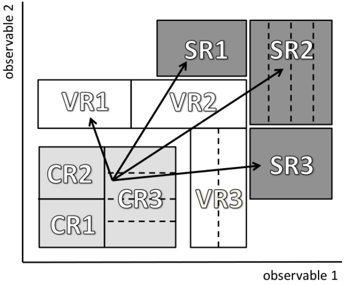
Variable	Requirement
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV
N_{jets}^{30}	$\geq 1, \leq 4$
Leading jet $p_{\mathrm{T}}(j_1)$	> 100 GeV, $\|\eta\| < 2.8$
Sub-leading jets $p_{\mathrm{T}}(j_{2,3,4})$	> 30 GeV, $\|\eta\| < 2.8$
$\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	> 2.0
$N_{b-\mathrm{jet}}^{30}$, 85% WP	Exactly zero
N_{leptons}	Exactly two baseline and two signal
Nature of leptons	SFOS ($e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$)
Leading electron (muon) $p_{\mathrm{T}}^{\ell_1}$	$> 5(5)$ GeV
Subleading electron (muon) $p_{\mathrm{T}}^{\ell_2}$	$> 4.5(4)$ GeV
$m_{\tau\tau}$	Veto [0, 160] GeV
$m_{\ell\ell}$	$> 1, < 60$ GeV

Variable	Selections optimised for Higgsinos						
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{leptons}}$	$>$ Max (5.0, 15 – 2 · $m_{\ell\ell}$/ GeV)						
$\Delta R_{\ell\ell}$	< 2.0						
$m_{\mathrm{T}}^{\ell_1}$	< 70 GeV						
SRee-, SRmm-	eMLLa	eMLLb	eMLLc	eMLLd	eMLLe	eMLLf	eMLLg
$m_{\ell\ell}$ [GeV]	[1, 3]	[3.2, 5]	[5, 10]	[10, 20]	[20, 30]	[30, 40]	[40, 60]
SRSF-	iMLLa	iMLLb	iMLLc	iMLLd	iMLLe	iMLLf	iMLLg
$m_{\ell\ell}$ [GeV]	< 3	< 5	< 10	< 20	< 30	< 40	< 60



Background Estimation

Main irreducible backgrounds are estimated from MC. $\rightarrow$ need to check validity of prediction. Typical approach is:



- Define high background purity region (CR)
  - One region for every main background
  - Define normalisation factors (Scale Factors) for backgrounds: $SF = N_{obs}/N_{\mathbf{MC}}$
- Test normalisation in VR
  - built in the middle between CRs and SRs
  - check sanity of estimation near the SRs
- Extrapolate normalisation in SRs
  - Scale background in SRs
  - Look at data! Excess or not?

- This procedure helps to reduce uncertainties on:
  - cross section
  - integrated luminosity
- Used also Data-Driven technique to describe some of the background not well described by MC

Standard Model Background

Signal region is characterized by very soft leptons with very low m_{ll}. Main background comes mainly from:

- fake leptons
- QCD resonances
- Low mass offshell dibosons
- Low mass Drell-Yan process

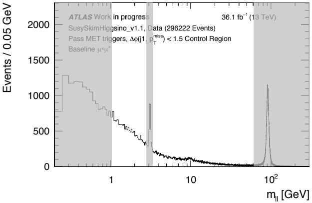
Different background with different strategy relying on either MC, Control Region (CR), and Data driven technique and Validation Region.

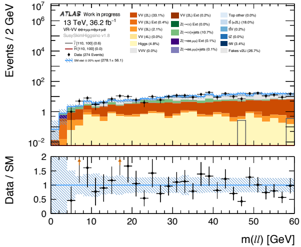
Background process	Origin in signal region	Estimation strategy
$t\bar{t}$, tW	b-jet fails identification	CR using b-tagging
Diboson	Irreducible leptonic decays	CR using $E_{\mathrm{T}}^{\mathrm{miss}} / \left(p_{\mathrm{T}}^{\ell_1} + p_{\mathrm{T}}^{\ell_2} \right)$
$(Z \to \tau\tau)$ + jets	Irreducible fully leptonic taus	CR using $m_{\tau\tau}$
$(W \to \ell\nu)$ + jets	Jet fakes second lepton	Fake factor, same sign VR
$(Z \to ee, \mu\mu)$ + jets	Instrumental $E_{\mathrm{T}}^{\mathrm{miss}}$	Monte Carlo
Low mass Drell-Yan	Instrumental $E_{\mathrm{T}}^{\mathrm{miss}}$	VR and Monte Carlo
Other rare processes	Irreducible leptonic decays	Monte Carlo

low m_{ll} background

At very low m_{ll} there are contributions from resonance (J/ψ) and non resonant processes (DY)

- Resonance:
  - $E_{\mathrm{T}}^{\mathrm{miss}}$ based trigger prevent much of this contribution to be significant
  - veto J/ψ peak ($m_{J/\psi} = 3.096$ GeV) $\rightarrow$ 3.0-3.2 GeV range
  - Υ enough small contribution to be ignored
  - Top plot: data distribution m_{ll} for di-muon channel, after applying trigger
- Non resonant
  - check with Different Flavor Validation Region (VR-DF) and Same Flavor Validation region (VR-VV,bottom plot plot) but with $E_{\mathrm{T}}^{\mathrm{miss}}/HT_{lep}$ reversed
  - data driven estimate to check MC prediction





Background Systematic Uncertainties

Two kind of systematic uncertainties affect the Monte Carlo simulation:

- Experimental systematic uncertainties
  - Jet energy scale and resolution
  - E_T^{miss} modelling
  - Object identification efficiency
- Theoretical systematic uncertainties
  - PDF scale variation
  - Diboson and top modelling

Uncertainty of SRSF-iMLL	[1, 3] GeV	[1, 5] GeV	[1, 10] GeV	[1, 20] GeV	[1, 30] GeV	[1, 40] GeV	[1, 60] GeV
Total background expectation	1.70	3.13	11.65	36.25	46.21	49.69	52.35
Total statistical ($\sqrt{N_{exp}}$)	±1.31	±1.77	±3.41	±6.02	±6.80	±7.05	±7.24
Total background systematic	±1.01 [59.22%]	±1.34 [43.02%]	±2.75 [23.57%]	±7.40 [20.42%]	±8.31 [17.99%]	±8.54 [17.18%]	±8.57 [16.37%]
MC statistical uncertainties	±1.51	±0	±0	±0	±0	±0	±0
Jet Energy Resolution	±0.42	±0.4	±0.15	±1.77	±1.81	±1.81	±1.77
Jet Energy Scale	±0.09	±0.04	±0.14	±0.78	±0.81	±0.75	±0.84
Fake Leptons Estimate uncertainties	±0.26	±0.3	±1.94	±7.43	±9.01	±9.26	±9.24
Theoretical uncertainties	±0.14	±0.45	±0.76	±1.19	±1.65	±1.89	±2.23
Normalization	±0.08	±0.11	±0.09	±0.86	±1.22	±1.38	±1.5
Flavour tagging	±0.16	±0.31	±0.6	±1.55	±2.39	±2.73	±3.15
E_T^{miss} Modelling	±0.05	±0.07	±0.15	±1.48	±1.36	±1.45	±1.4
Muon Reconstraction Efficiency	±0.06	±0.1	±0.13	±0.33	±0.37	±0.49	±0.46
Electron Reconstruction Efficiency	±0.03	±0.05	±0.21	±0.47	±0.39	±0.41	±0.33

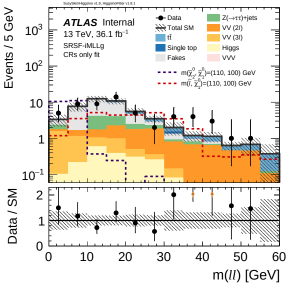
ATLAS Work in progress

Main source of uncertainties comes from fakes leptons estimate → main background

Observed Results

Un-blinded results: no excess observed → Set limits at 95% Confidence Level on higgsinos masses

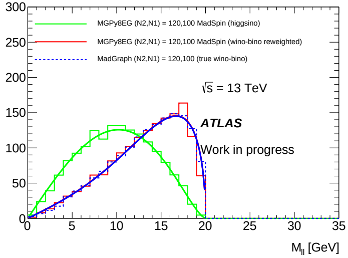
- Plot: m_{ll} distribution in inclusive SR
- No significant excess
- **model dependent** limits:
  - Signal + Background hypothesis vs Only Background hypothesis for every signal considered
- Possible also to evaluate **model independent limits**:
  - limits on the number of possible signal events present compatible with the observed data
  - No assumption on the signal



Different interpretation of the results

Higgsino is not the only interpretation considered for this analysis, could use Wino-Bino scenario

- Wino-Bino production have higher cross section
  - but different m_{ll} shape (plot)
  - Events peaked at higher m_{ll} value $\rightarrow$ slightly different kinematics
- possibility to reweight event by event to the Wino-Bino distribution and scale up the cross section
- Need also to account for different mass of $\tilde{\chi}_1^{\pm}$



Conclusion

Compressed Electroweak analysis have been presented

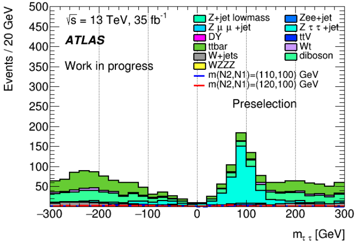
- Very low m_{ll} and p_{T} region
- Background estimation:
  - Data driven techniques to estimates Fakes and low m_{ll} DY
  - CR for top, VV and $Z \to \tau\tau$ events
  - Good agreement data/MC
- No excess observed
  - higgsino scenario: up to $\tilde{\chi}_2^0 \sim 120\ \mathrm{GeV}$ and mass splitting from 2 to 20 GeV
  - wino-bino scenario: up to $\tilde{\chi}_2^0 \sim 150\ \mathrm{GeV}$ and mass splitting from 2 to 40 GeV
- LEP limits extended
- New interesting results

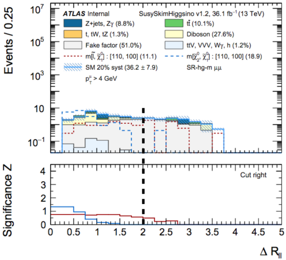
BACK-UP

Useful variables

Some of the variables used in the SR definition

- $E_{\mathrm{T}}^{\mathrm{miss}} / HT_{lep}$
  - $E_{\mathrm{T}}^{\mathrm{miss}}$ over the **scalar** sum of the leptons p_{T}
  - helpful for small Δm signals
- $m_{\tau\tau}$ (top plot)
  - Reconstruct the $Z \to \tau\tau$ peak.
  - Different definition in literature
- $\Delta\phi(p_{\mathrm{T}}^{jet1}\ ,\ E_{\mathrm{T}}\ )$
  - $\Delta\phi$ between leading jet and $E_{\mathrm{T}}^{\mathrm{miss}}$
  - all the signal is peaked at $\Delta\phi(p_{\mathrm{T}}^{jet1}, E_{\mathrm{T}}) > 2$
- ΔR_{ll}
  - $\sqrt{(\phi_{l1} - \phi_{l2})^2 + (\eta_{l1} - \eta_{l2})^2}$
  - Higgsino decays have small value





$m_{\tau\tau}$ definition

$m_{\tau\tau}$ try to reconstruct the 2 τs system from the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the two leptons p_{T}
It is defined by

$$m_{\tau\tau}^2 = (p_{\tau_1} + p_{\tau_2})^2 \sim 2p_{l1} \cdot p_{l2}(1+\zeta_1)(1+\zeta_2)$$

where $\zeta_{1/2}$ are defined such as

$$p_T^{miss} = \zeta_1 p_T^{l1} + \zeta_2 p_T^{l2}$$

$m_{\tau\tau}^2$ can be either positive and negative, and the two part aren't symmetrical.
$m_{\tau\tau}$ defined as

$$m_{\tau\tau} = sign(m_{\tau\tau}^2)\sqrt{|m_{\tau\tau}^2|}$$