Searching Supersymmetry with the ATLAS detector

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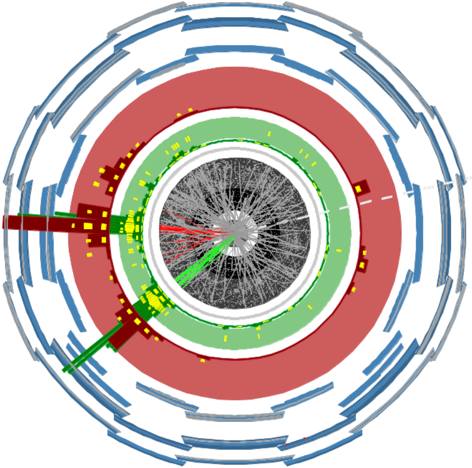
Outline

- **Theory Overview**
- **Search Strategy**
- **Reduction of QCD Background**

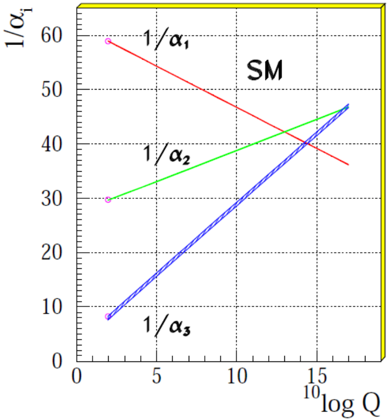


Theory Overview

Motivation

Some problems of the Standard Model:

- no high energy unification of fundamental interactions



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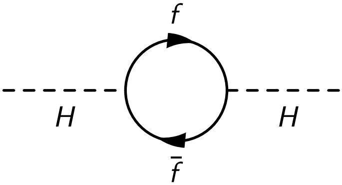
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + ...$$



The Theory of Supersymmetry

Extension of the Standard Model of particle physics.

Symmetry transformation: fermions $\Leftrightarrow$ bosons

$$Q|fermion>=|boson>, \qquad Q|boson>=|fermion>$$

fermions $\rightarrow$ **s**fermions, gauge bosons $\rightarrow$ gaug**inos**

$$s = 1/2 \;\rightarrow\; s = 0, \qquad s = 1 \;\rightarrow\; s = 1/2$$

$\Rightarrow$ changes spin of particles

The SUSY Operator

- Q groups particles in supermultiplets (chiral, vectorial and gravitational)
- Q commutes with gauge transformations
  $\rightarrow$ superpartners have same charge (el, colour, weak isospin)
- Q commutes with P^2 (mass operator)
  $\rightarrow$ superpartners have equal masses

$\Rightarrow$ Superpartners have same quantum numbers except for spin

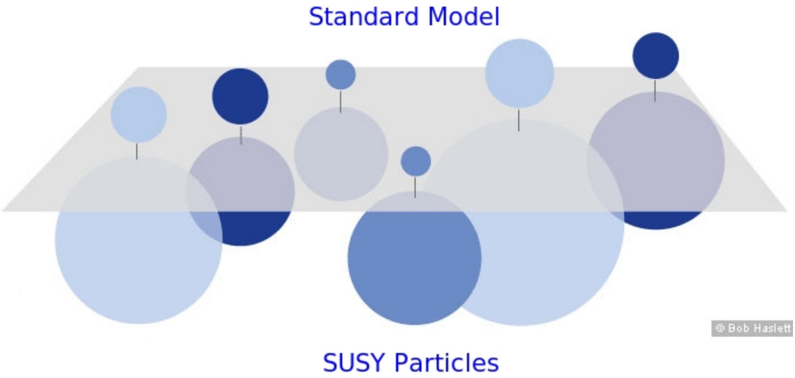
$\rightarrow$ new particles needed

$\rightarrow$ superpartners have to be heavy

$\Rightarrow$ Supersymmetry is broken

Contents of SUSY Models

Minimal **S**upersymmetric **S**tandard **M**odel:
minimal number of particles necessary for a viable SUSY model



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SM	$u_{\mathrm{R,L}}$	$s_{\mathrm{R,L}}$	$b_{\mathrm{R,L}}$	$e_{\mathrm{R,L}}$	$\mu_{\mathrm{R,L}}$	$\tau_{\mathrm{R,L}}$	g	W^+	H	Z	γ
	$d_{\mathrm{R,L}}$	$c_{\mathrm{R,L}}$	$t_{\mathrm{R,L}}$	ν_e	ν_μ	ν_τ		W^-			

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$\Downarrow$ Supersymmetry Transformation Q $\Downarrow$

SUSY	$\tilde{u}_{R,L}$	$\tilde{s}_{R,L}$	$\tilde{b}_{R,L}$	$\tilde{e}_{R,L}$	$\tilde{\mu}_{R,L}$	$\tilde{\tau}_{R,L}$	$\tilde{g}$	$\tilde{W}^+$	$\tilde{H}$[1]	$\tilde{Z}$	$\tilde{\gamma}$
	$\tilde{d}_{R,L}$	$\tilde{c}_{R,L}$	$\tilde{t}_{R,L}$	$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$		$\tilde{W}^-$			

[1] Extended Higgs Sector: 5 Higgs

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		$\Downarrow$		Supersymmetry Transformation Q						$\Downarrow$	
SUSY	$\tilde{u}_{\mathrm{R,L}}$ $\tilde{d}_{\mathrm{R,L}}$	$\tilde{s}_{\mathrm{R,L}}$ $\tilde{c}_{\mathrm{R,L}}$	$\tilde{b}_{\mathrm{R,L}}$ $\tilde{t}_{\mathrm{R,L}}$	$\tilde{e}_{\mathrm{R,L}}$ $\tilde{\nu}_e$	$\tilde{\mu}_{\mathrm{R,L}}$ $\tilde{\nu}_\mu$	$\tilde{\tau}_{\mathrm{R,L}}$ $\tilde{\nu}_\tau$	$\tilde{g}$	$\tilde{W}^+$ $\tilde{W}^-$	$\tilde{H}$[1]	$\tilde{Z}$	$\tilde{\gamma}$
		$\Downarrow$			Mixing					$\Downarrow$	
MSSM	$\tilde{u}_{1,2}$ $\tilde{d}_{1,2}$	$\tilde{s}_{1,2}$ $\tilde{c}_{1,2}$	$\tilde{b}_{1,2}$ $\tilde{t}_{1,2}$	$\tilde{e}_{1,2}$ $\tilde{\nu}_e$	$\tilde{\mu}_{1,2}$ $\tilde{\nu}_\mu$	$\tilde{\tau}_{1,2}$ $\tilde{\nu}_\tau$	$\tilde{g}$	$\tilde{\chi}^+_{1,2}$ $\tilde{\chi}^-_{1,2}$	$\tilde{\chi}^0_{1,2}$	$\tilde{\chi}^0_{3,4}$	

[1] Extended Higgs Sector: 5 Higgs

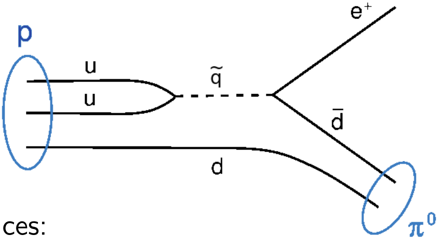
R-Parity

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

B: baryon number, L: lepton number, S: spin

$\rightarrow$ particles have positive, sparticles negative R-parity

R-Parity conservation prohibits proton decay:



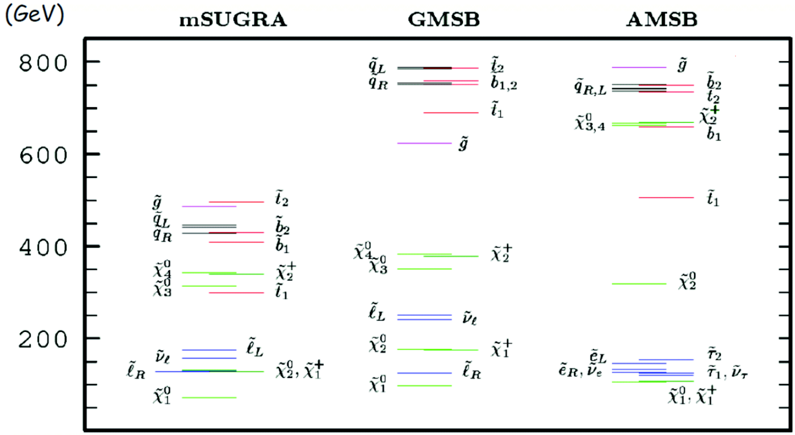
Further consequences:

- no mixing between particles and sparticles
- **l**ightest **s**upersymmetric **p**article is stable
  $\rightarrow$ good dark matter candidate, if neutral

SUSY Models

- Number of SUSY Operators defines particle content
- SUSY breaking mechanism affects phenomenology

⇒ Different scenarios possible



SUSY Models

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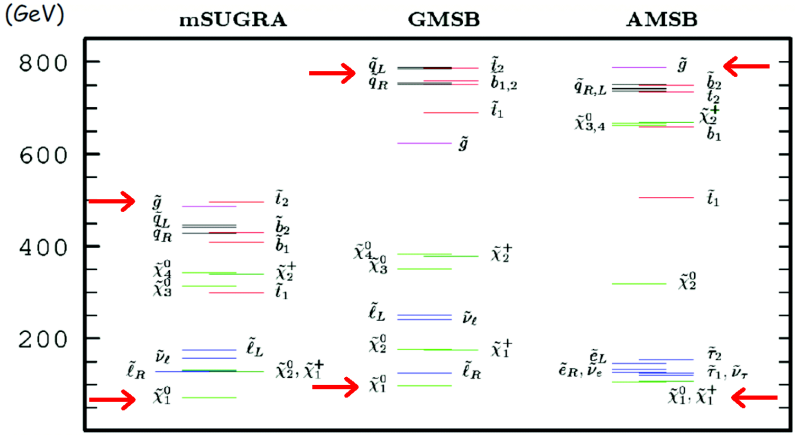

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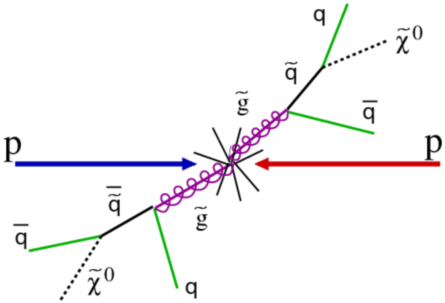
$\Rightarrow$ Different scenarios possible

Prominent Example for MSSM:

- **m**inimal **SU**per **GRA**vity, 5 free parameters:
  - universal scalar/gaugino mass: $m_0/m_{1/2}$
  - ratio of the vacuum expectation values of the Higgs fields $\tan(\beta)$
  - universal trilinear scalar coupling A_0
  - sign of the higgsino mass parameter μ

SUSY Signatures at the LHC

R-Parity conservation:
→ sparticles produced in pairs & decay to LSP via cascades



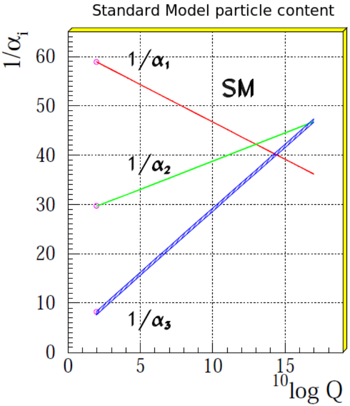
Signatures: $E_{\mathrm{T}}^{\mathrm{miss}}$ + jets + different number of leptons in final state

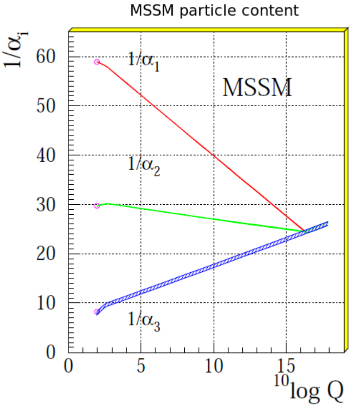
More sophisticated theories (R-Parity violation, long lived particles...) lead to further signatures.

Solutions SUSY Provides

Some problems of the Standard Model:

- no high energy unification of fundamental interactions
  → in SUSY models they unify





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- cannot explain dark matter
  $\rightarrow$ could consist of the LSP

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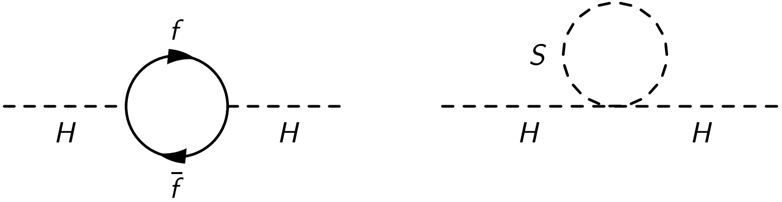
Some problems of the Standard Model:

- no high energy unification of fundamental interactions
  → in SUSY models they unify
- cannot explain dark matter
  → could consist of the LSP
- hierarchy problem: higgs mass dominated by quantum corrections
  → with SUSY these corrections cancel

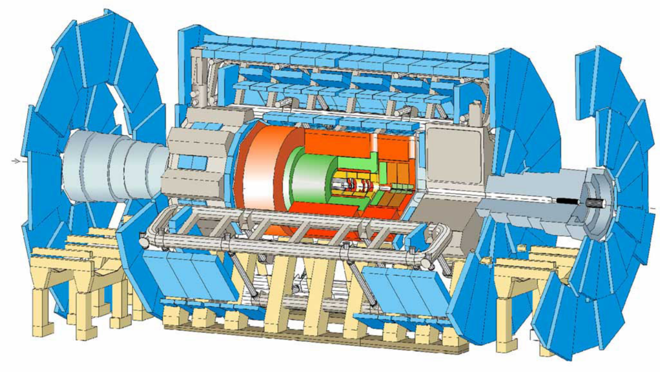
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \frac{\lambda_S}{16\pi^2}\Lambda_{UV}^2 \pm ...$$



SUSY Searches in final states with jets and E_T^{miss}

The ATLAS Detector

- located at the LHC (pp collider)
- multipurpose detector
- components: tracking, calorimeters, muon system



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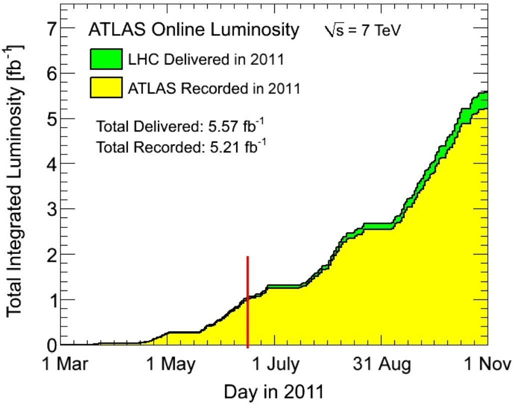
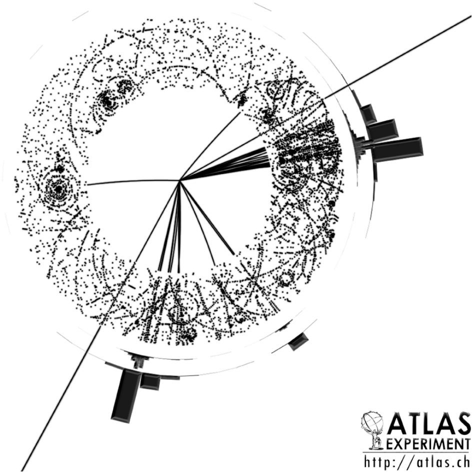


SUSY Searches at ATLAS

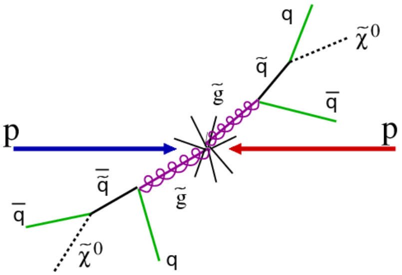
Analysis groups for different signatures:

- E_T^{miss} and monojets
- E_T^{miss}, jets and 0, 1 or 2 leptons (e, μ)
- E_T^{miss} and taus
- E_T^{miss} and b-jets
- E_T^{miss} and photons
- long lived particles and R-parity violation



Final States with Jets and E_T^{miss}

- simple signature in R-parity conserving scenarios
- stem from $\tilde{g} \rightarrow qq\tilde{\chi}_1^0$ and $\tilde{q} \rightarrow q\tilde{\chi}_1^0$
- inclusive search: model independent
- covers wide phase space

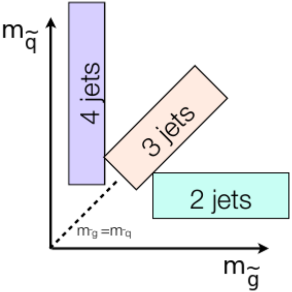


Analysis Strategy

- analyze only events without leptons in the final state
  $\rightarrow$ no overlap with other analyses
- main expected SM BG: W/Z + jets, top quarks and QCD multijets
  $\rightarrow$ optimize cuts to suppress this BG
- depending on SUSY mass hierarchy different production processes favored ($\tilde{g}\tilde{g}, \tilde{q}\tilde{g}, \tilde{q}\tilde{q}$)
  $\rightarrow$ define multiple signal regions to maximize sensitivity to each process

$$\tilde{g} \rightarrow qq\tilde{\chi}_1^0$$

$$\tilde{q} \rightarrow q\tilde{\chi}_1^0$$



Event selection (2 Jet SR)

- veto events containing leptons with $p_T > 20\,\text{GeV}$ (e^- or μ)
- p_T(leading jet) $> 180\,\text{GeV}$, p_T(subleading jet) $> 50\,\text{GeV}$
- $E_{\text{T}}^{\text{miss}} > 80\,\text{GeV}$

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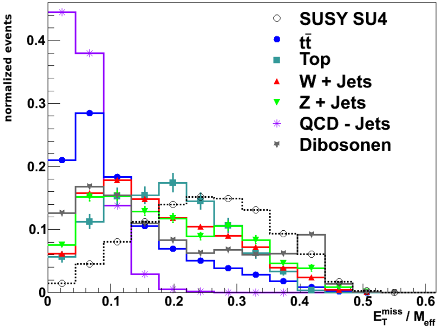
- $E_{\text{T}}^{\text{miss}} / M_{\text{eff}} > 0.3$, with $M_{\text{eff}} = \sum_{i=1}^{N_{jets}} p_T^{jet,i} + E_{\text{T}}^{\text{miss}}$



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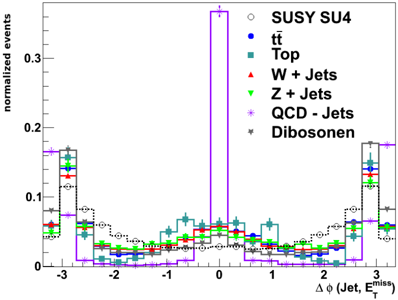
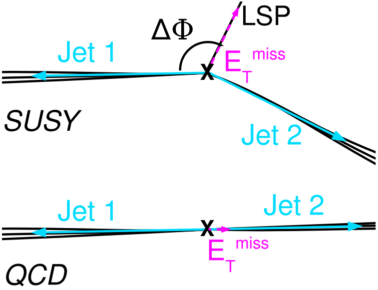
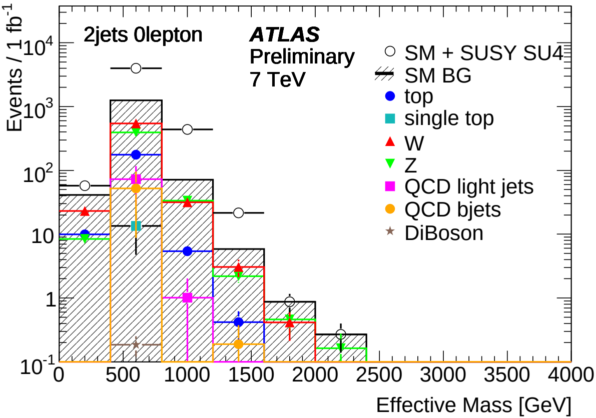
- $E_\mathrm{T}^\mathrm{miss}/M_\mathrm{eff} > 0.3$, with $M_\mathrm{eff} = \sum_{i=1}^{N_{jets}} p_T^{jet,i} + E_\mathrm{T}^\mathrm{miss}$
- $\Delta\phi(\mathrm{jet}_i, E_T^\mathrm{miss}) = \phi(\mathrm{jet}_i) - \phi(E_\mathrm{T}^\mathrm{miss}) > 0.2$





Final distribution

$M_{\mathrm{eff}} \rightarrow$ discovery or limit calculations



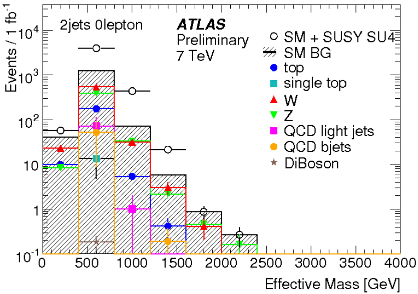
July 2010: ATLAS-PHYS-PUB-2010-010

Differences between Samples

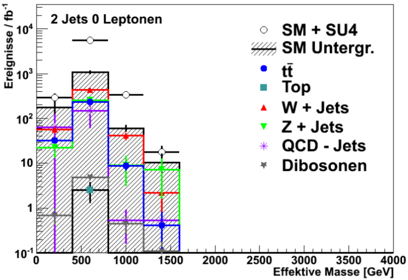
	ATL-PHYS-PUB-2010-010	My Study
Simulated $\sqrt{s}$	10 TeV(pdf reweighted)	7 TeV
Jet MC generators	ALPGEN with JIMMY/HERWIG	PYTHIA
Diboson MC generators	MC@NLO & gg2WW	HERWIG
SUSY MC generators	HERWIG	HERWIG++
Sample Size	$> 1fb^{-1}$	mostly $< 1fb^{-1}$
Jet algorithm	cone based	AntiKt
Jet algorithm input	tower cluster	topo cluster

Cross Check

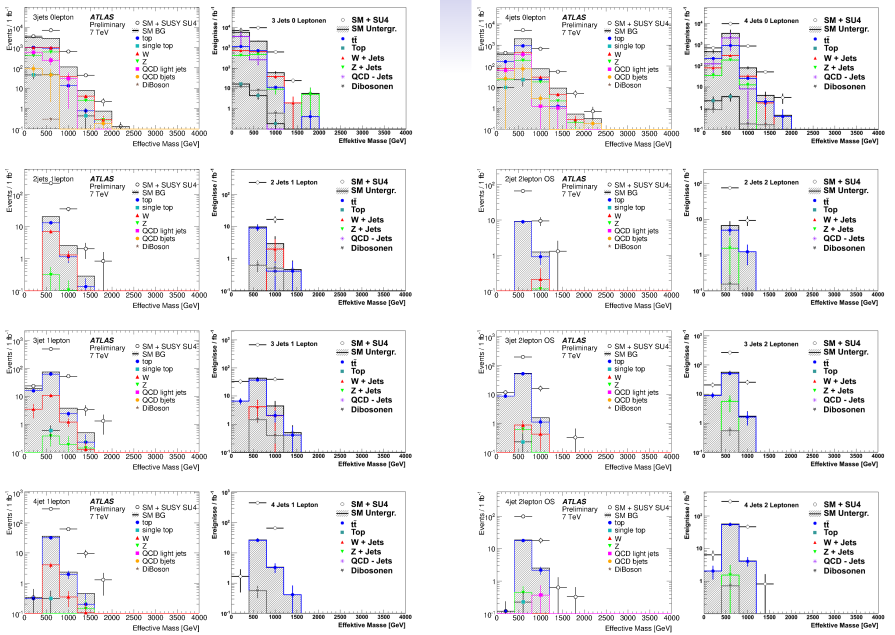
ATL-PHYS-PUB-2010-010



My Study



$\Rightarrow$ confirmation of result, discovery potential still given, no iteration of the optimization process needed


3jets 0lepton
ATLAS
Preliminary
7 TeV
SM + SUSY SU4
SM BG
top
single top
W
Z
QCD light jets
QCD bjets
DiBoson
Events / 1 fb^{-1}
Effective Mass [GeV]
3 Jets 0 Leptonen
SM + SU4
SM Untergr.
tt̄
Top
W + Jets
Z + Jets
QCD - Jets
Dibosonen
Ereignisse / fb^{-1}
Effektive Masse [GeV]
4jets 0lepton
4 Jets 0 Leptonen
2jets 1lepton
2 Jets 1 Lepton
2jet 2lepton OS
2 Jets 2 Leptonen
3jet 1lepton
3 Jets 1 Lepton
3jet 2lepton OS
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4jet 1lepton
4 Jets 1 Lepton
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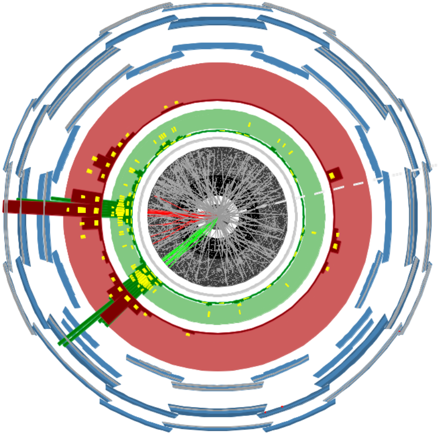
4 Jets 2 Leptonen

Reduction of QCD Background

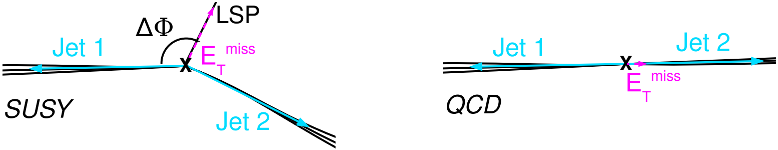
Motivation

- Hadronic jets are a major background (QCD BG)
- Suppression substantial because of high production cross section
- Cut on E_T^{miss} suppresses most events, but non negligible number left

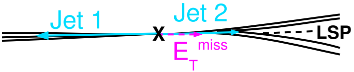


QCD Background Suppression

Currently used: $\Delta\phi(\text{jet}_i, E_T^{\text{miss}}) > 0.4$



- cuts into signal for boosted SUSY scenarios



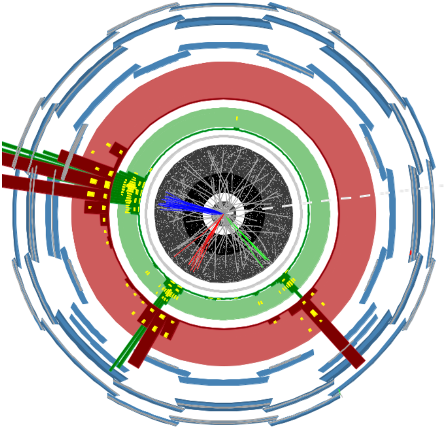
- cut also problematic for events with high jet multiplicity

$\Rightarrow$ studied alternative cut

Missing Transverse Momentum p_T^{miss}

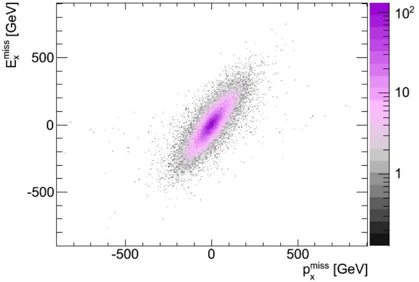
- E_T^{miss} based on information from calorimeter and muon system
- p_T^{miss} computed using only data from the inner detector

$\rightarrow$ complementary measurements, different systematic behavior

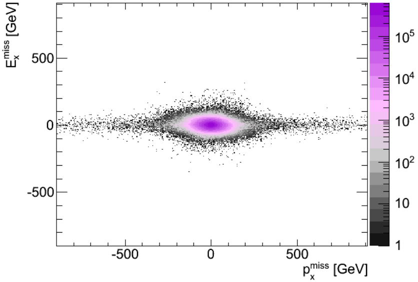


Properties of p_T^{miss}

p_T^{miss} and E_T^{miss} correlated if event contains physical E_T^{miss}



SUSY Sample (Su4)

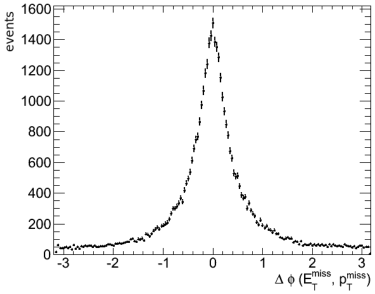


QCD Sample

→ combine these variables for suppression of fake E_T^{miss}

$\Delta\phi(E_T^{\text{miss}},\, p_T^{\text{miss}})$

measure for correlation: $\Delta\phi(E_T^{\text{miss}},\, p_T^{\text{miss}}) = \phi(E_T^{\text{miss}}) - \phi(p_T^{\text{miss}})$



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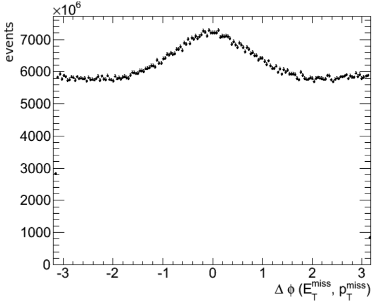


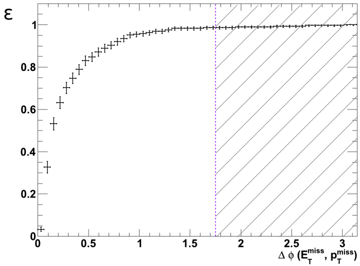
QCD Sample

→ introduction of cut on $\Delta\phi(E_T^{\text{miss}},\, p_T^{\text{miss}})$ possible

Cut Efficiency after standard cuts

dependent of $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})$ cut value

$$\epsilon = \frac{\text{events after cut}}{\text{events before cut}}$$



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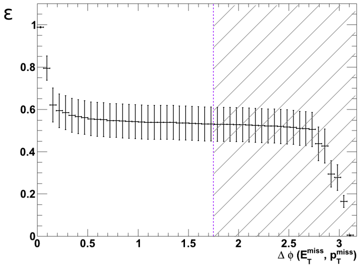


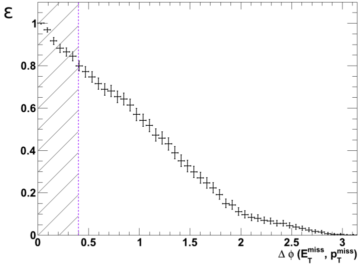
QCD Sample

$\longrightarrow$ stable cut for SUSY and QCD

Cut Efficiency of the $\Delta\phi(\text{jet}_i, E_T^{\text{miss}})$ Cut

dependent of $\Delta\phi(\text{jet}_i, E_T^{\text{miss}})$ cut value

$$\epsilon = \frac{\text{events after cut}}{\text{events before cut}}$$



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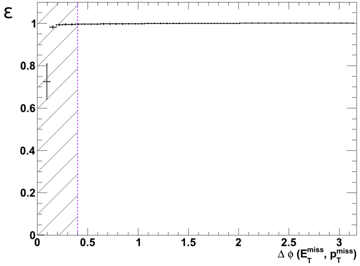


QCD Sample

→ only stable for QCD

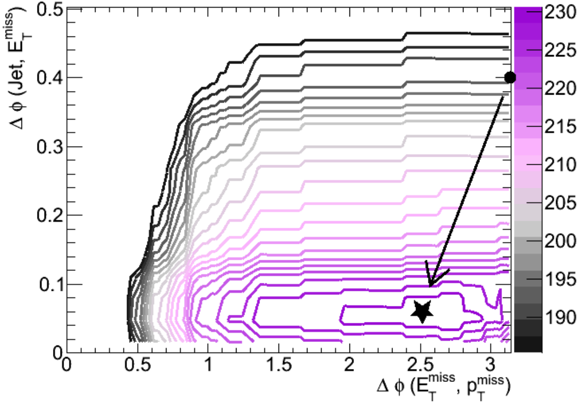
$\Delta\phi(\text{jet}_i, E_T^{\text{miss}})$ vs. $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})$

	$\Delta\phi(\text{jet}_i, E_T^{\text{miss}})$	$\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})$
signal acceptance	$79{,}8\pm^{2.3}_{2.4}$	$98{,}61\pm^{0.59}_{0.82}$
BG rejection	99.47 ± 0.23	53.0 ± 8.0
stability	low for signal	high for signal and BG

$\rightarrow$ both cuts have advantages and disadvantages

Cut Combination

studied in terms of the significance: $s^2 = \frac{(\text{signal events})^2}{\text{signal events} + \text{BG events}}$

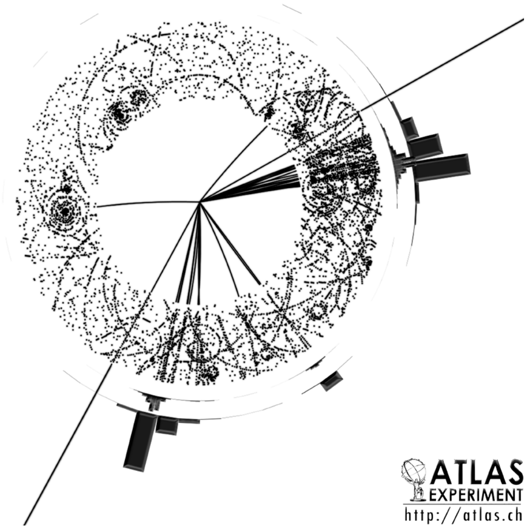


$\rightarrow$ 16 % improvement

Conclusion

- SUSY is able to solve some problems of the SM
  $\rightarrow$ prominent extension
- Outlined basic search strategy in final states with jets and E_T^{miss}
- Cross checked MC study
  $\rightarrow$ confirmed previous result
- Studied potential of cut on $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})$ to suppress QCD BG
  $\rightarrow$ found good performance for single and combined cut
- Hoping to join the IRTG

Thanks!



Backup

Object Definitions

- Jets: AntiKt4 with $p_T > 20\,\text{GeV}$ and $|\eta| < 2.5$
- Electrons: $p_T > 10\,\text{GeV}$ and $|\eta| < 2.5$
- Muons: $p_T > 10\,\text{GeV}$ and $|\eta| < 2.5$
- $E_{\text{T}}^{\text{miss}}$: vectorial sum of all jets, leptons and not matched clusters

Overlap Removal: $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

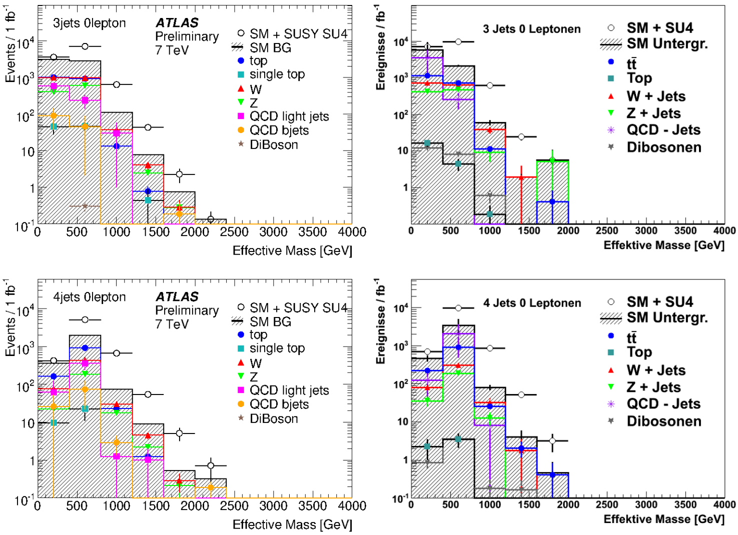
- remove jets within $\Delta R < 0.2$ of an electron
- remove muons within $\Delta R < 0.4$ of a jet
- remove electron within $0.2 \leq \Delta R < 0.4$ of a jet

Full Event selection

- veto events containing leptons with $p_T > 20\,\text{GeV}$ (e^- or μ)
- jet p_T cuts see table
- $E_{\text{T}}^{\text{miss}} > 80\,\text{GeV}$
- $E_{\text{T}}^{\text{miss}}/M_{\text{eff}} = \text{f}$ with $M_{\text{eff}} = \sum_{i=1}^{N_{jets}} p_T^{jet,i} + E_{\text{T}}^{\text{miss}}$,
  cuts see table
- $\Delta\phi(\text{jet}_i, E_T^{\text{miss}}) = \phi(\text{jet}_i) - \phi(E_{\text{T}}^{\text{miss}})$, cuts see table

Number of jets	≥ 2 jets	≥ 3 jets	≥ 4 jets
Leading jet P_T (GeV)	> 180	> 100	> 100
Other jets P_T (GeV)	> 50 (Jet 2)	> 40 (Jet 2-3)	> 40 (Jet 2-4)
$\Delta\phi(jet_i, E_T^{miss})$	$[> 0.2, > 0.2]$	$[> 0.2, > 0.2, > 0.2]$	$[> 0.2, > 0.2, > 0.2, > 0.0]$
$E_T^{miss} > f \times M_{\text{eff}}$	$f = 0.3$	$f = 0.25$	$f = 0.2$

Cross Check of Further Signal Regions



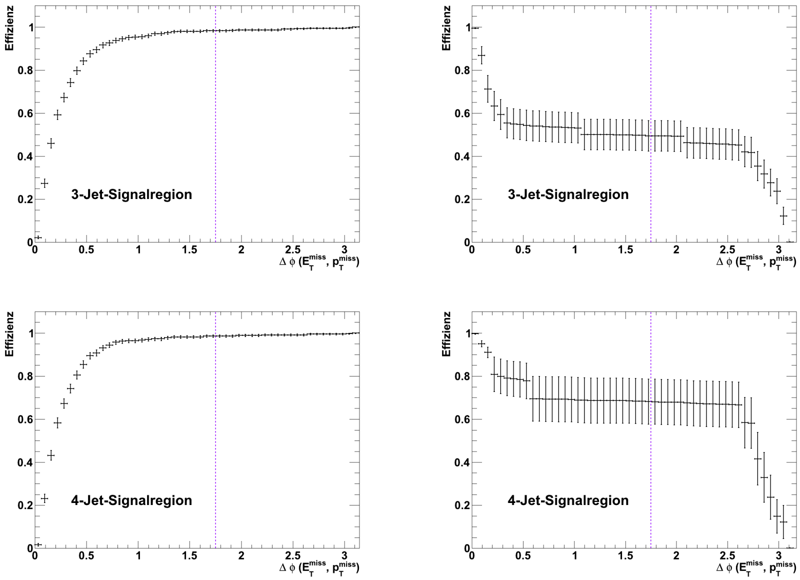
Computation of p_T^{miss}

$$p_{x,y}^{miss} = -\sum_{tracks} p_{x,y}$$

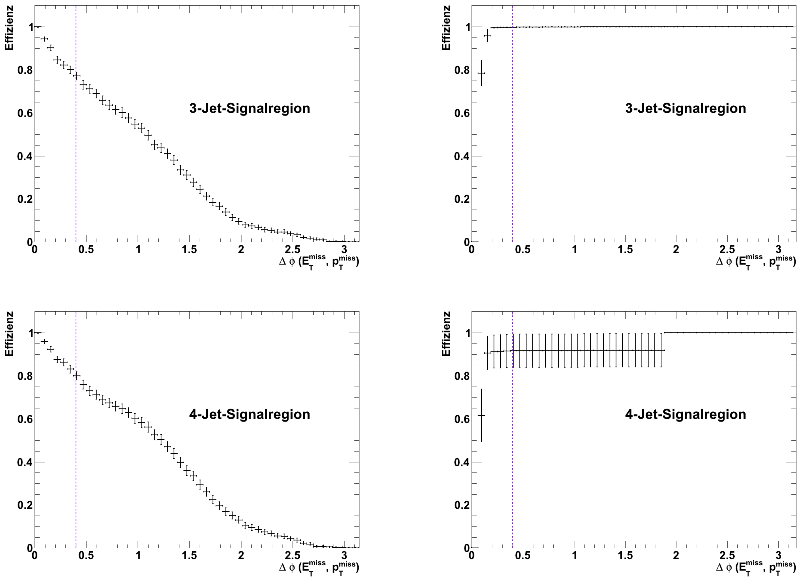
Requirements for tracks:

- $p_t > 500$ MeV
- $|\eta| < 2.5$
- ≥ 1 hit in the pixel detector
- ≥ 6 hits in the SCT
- $|d_0| < 1.5$ mm (wrt primary vertex)
- $|z_0 * sin(\theta)| < 1.50$ mm (wrt primary vertex)

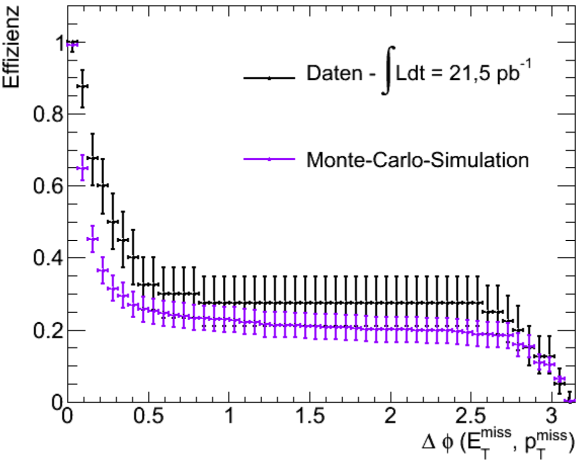
Cut Efficiency of $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})$ in other SR



Cut Efficiency of $\Delta\phi(\text{jet}_i, E_T^{\text{miss}})$ in other SR



Comparison with Collision Data



→ agreement within error bars