Measurement of the Background for MSSM $A \to \mu^+\mu^-$ Higgs Searches with ATLAS

Sebastian Stern

sebastian.stern@cern.ch

Max-Planck-Institut für Physik
München

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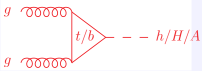
The Higgs Sector in the MSSM

Higgs Bosons in the Minimal Supersymmetric Extension of the Standard Model

- Two Higgs doublets resulting in five physical Higgs bosons: A, h, H, $H^{\pm}$.
- At tree level, the Higgs sector is determined by only two free parameters: M_A and $\tan\beta = \frac{v_1}{v_2}$ ($v_{1,2}$: VEVs for two Higgs doublets).
- Tevatron results exclude $\tan\beta > 40$ for Higgs bosons with $M_A > 100$ GeV.
  $\Rightarrow$ Presented studies assume $\tan\beta = 40$ to probe the exclusion in $A \rightarrow \mu^+\mu^-$ channel with early ATLAS data (with $\sqrt{s} = 10$ TeV p-p collsions).

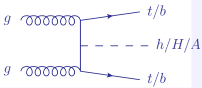
Dominant Production Modes at the LHC

Direct production



(dominant for $\tan\beta < 10$)

Associated b-quark production



(dominant for large $\tan\beta$)

Important Decay Channels

- $h/H/A \rightarrow b\bar{b}$: Largest branching ratio ($\sim 90\,\%$) but large QCD background.
- $h/H/A \rightarrow \tau\tau$: Branching ratio $\sim 10\,\%$, but neutrino contribution in final state.
- $h/H/A \rightarrow \mu\mu$: Low branching ratio ($0.04\,\%$) but excellent muon reconstruction.

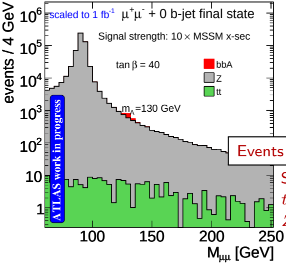
$A \to \mu^+\mu^-$ Higgs Searches at $\sqrt{s} = 10$ TeV

Challenge in the $A \to \mu^+\mu^-$ channel:

- low production cross section: $\sim 10\,\text{fb}$
- large SM backgrounds: Z (+ jets) ($1.2\,\text{nb}$), $t\bar{t}$ ($0.4\,\text{nb}$)

Event Pre-Selection: $\mu^+\mu^-$-pair, $p_T^{\mu} > 20$ GeV, low missing transverse energy

0 reconstructed b-jets in final state



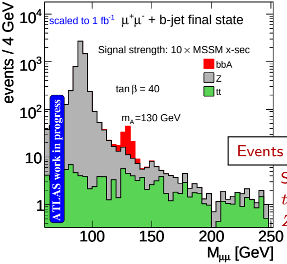
Events in mass window:

Signal: 33

$t\bar{t}$: 13

Z/γ: 1750

> 0 reconstructed b-jets in final state



Events in mass window:

Signal: 6

$t\bar{t}$: 12

Z/γ: 22

$\Rightarrow$ **Reliable background estimation is essential.**

- Monte Carlo predictions sensitive to detector-related & theoretical uncertainties.
- Background can be extracted from side-bands of the signal region.
- Alternatively signal-free control data samples can be used.

Background Estimation from Control Samples

Concept (valid on particle level)

- $BR(A \rightarrow e^+e^-) = 10^{-8}$
- $BR(Z \rightarrow e^+e^-) = BR(Z \rightarrow \mu^+\mu^-)$
- $BR(t\bar{t} \rightarrow e^+e^-) = BR(t\bar{t} \rightarrow \mu^+\mu^-) = BR(t\bar{t} \rightarrow \; e^\pm\mu^\mp) \times 0.5$
- Kinematic properties of $\mu^+\mu^-$, e^+e^- and $e^\pm\mu^\mp$ final states are equal at leading order.

$\Rightarrow$ $\boxed{ee \text{ and } \mu\mu \text{ invariant mass distributions of background processes are identical!}}$

Strategy:

1. Measure events with $\mu^+\mu^-$, e^+e^- and $e^\pm\mu^\mp$ final states
2. Estimate $\mu^+\mu^-$ background from e^+e^- final state (sum of Z and $t\bar{t}$)
3. Additionally: $t\bar{t}$ contribution from $e^\pm\mu^\mp$

Fact or Fiction: The reconstruction level

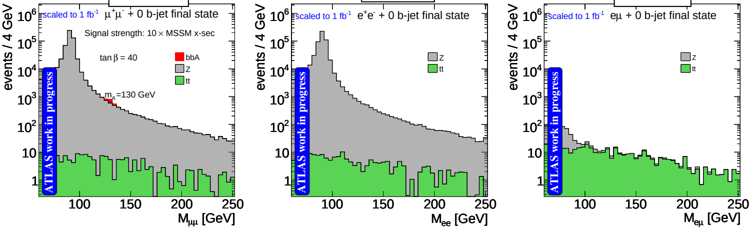
Impact of detector and higher order physics effects on invariant mass distributions need to be studied!

Dilepton Final States

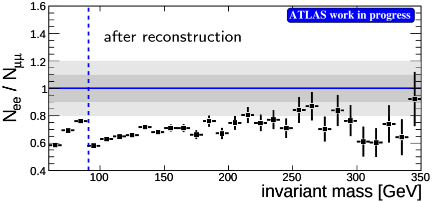
Invariant mass distributions after same selection cuts on electron and muon events

(for example: 0 b-jet final state)

$\mu^+\mu^-$ e^+e^- $e^\pm\mu^\mp$

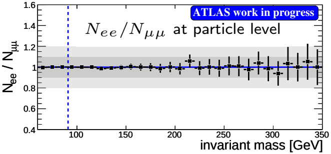


Quantitative comparision of e^+e^- and $\mu^+\mu^-$ distributions:



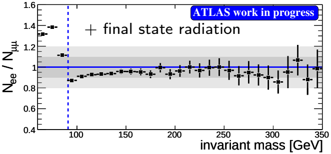
Agreement of Invariant Mass Distributions

Particle Level
(lowest order perturbation theory)
Invariant mass distributions in perfect agreement.

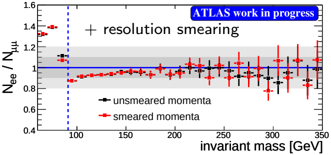


Effect I: Lepton Energy Losses

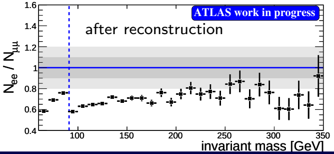
- Electrons loose more energy due to photon radiation compared to muons.
- Radiated photons cannot be reconstructed $\Rightarrow$ No correction of invariant mass spectra possible.
- BUT: Only small effect for $M_{ll} > 120$ GeV



Effect II: Lepton Momentum Resolution
Difference in lepton momentum resolutions can be neglected.

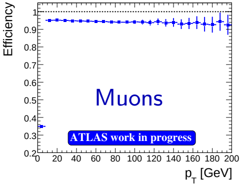


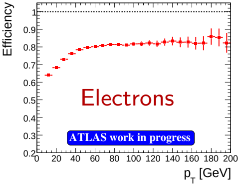
Effect III: Lepton Reconstruction Efficiency
Main effect $\Rightarrow$ Compared to muons, there are significantly less electrons reconstructed.
Effect needs to be corrected!



Correction for Lepton Reconstruction Efficiencies

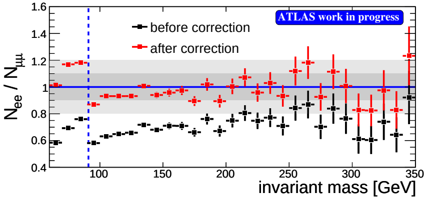
Efficiency for muons $\sim 20\,\%$ higher than for electrons:
$\Rightarrow$ Significant effect on the normalization of the invariant mass distributions.





Efficiency Correction

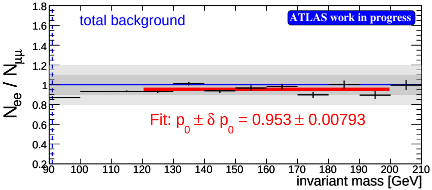
- Measure efficiency for isolated leptons using inclusive Z events.
- Parametrize efficiencies in p_T and η bins.
- Re-weight every reconstructed event with: $\frac{1}{\epsilon_1(p_{T1},\eta_1)} \times \frac{1}{\epsilon_2(p_{T2},\eta_2)}$



Clear improvement after correction procedure.
$\Rightarrow$ Correction applied for all further results.

Control Samples: Results in 0 b-jet Final State

reconstruction level @ 4 fb^{-1}:



Characteristics of the 0 b-jet final state

- Huge contribution of Z background.
- Good statistics even for low integrated luminosities.

For a quantitative comparision...

...of control samples and acctual background:

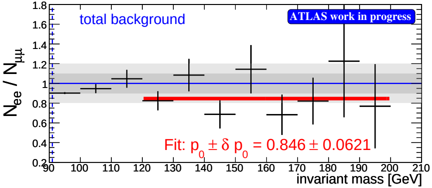
- Fit a constant (p_0) to $e^+e^-/\mu^+\mu^-$ ratio
- Normalization given by $1 - p_0$ (p_0: fit parameter)
- Shape accuracy given by relative error on fit parameter: $\delta p_0/p_0$

Results:

- maximum accuracy achievable with integrated luminosity ≥ 1 fb^{-1}.
- very good results already with ≥ 0.2 fb^{-1}.
- very precise prediction of background shape ($\sim 2-4\%$).
- background normalization $\sim 5\%$ too low.

Control Samples: Results in b-jet Final State

reconstruction level @$4\ \text{fb}^{-1}$



Characteristics of the b-jet final state

- Good suppression of the dominant Z background.
- ~ 100 times lower statistics compared to 0 b-jet final state.

Results:

- "reasonable" results for integrated luminosities $\geq 4\ \text{fb}^{-1}$.
- background normalization $(1 - p_0) \sim 15\%$ too low.
- shape accuracy $(\delta p_0 / p_0)$ of e^+e^- control sample: $\sim 7\%$.
- shape accuracy $(\delta p_0 / p_0)$ of $e^{\pm}\mu^{\mp}$ control sample: $\sim 15\%$ due to even less statistics.

BUT: With looser event selection in this final state the performance of the background estimation can be doubled!

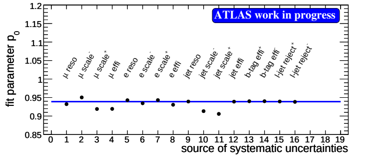
Detector-Related Uncertainties

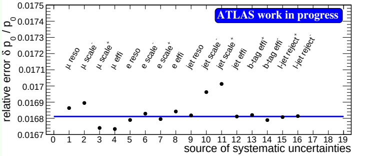
Detector-related sources of uncertainties:

- muon, electron, jet reconstruction and
- b-tagging performance

Example: Impact of different error sources in 0 b-jet final state @ $1\ \text{fb}^{-1}$

Fitting $N_{ee}/N_{\mu\mu}$ distributions with a constant $p_0 \pm \delta p_0$:





$\Rightarrow$ **only small variations of $N_{ee}/N_{\mu\mu}$ distributions observed:**
Dominant source of systematic errors: jet energy scale

- background normalization degrades to at most 10% (compared to 5% in case of no systematics).
- shape accuarcy changes from original 1.6% to at most 1.7%.

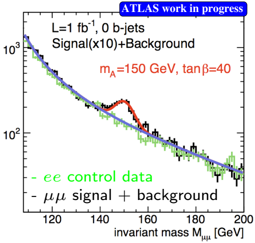
Control samples provide very accurate and robust prediction of background shape!

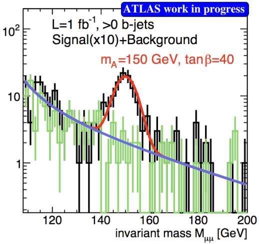
Exclusion Limits

Exclusion limits used to evaluate performance of background estimation.

- Exclusion limits obtained from fit of (signal + background) parametrization to invariant mass distributions.
- Calculated with the profile likelihood method. (CERN-OPEN-2008-020)

- Fit $f_{SB} = f_S + f_B$ to data
- Two scenarios for determination of f_B:
  A: Fit to side-bands only
  B: Fit side-bands + control samples





Signal strength with respect to MSSM cross section for exclusion at 95% CL

		0 b-jet final state			>0 b-jet final state		
M_A		0.2 fb^{-1}	1.0 fb^{-1}	4.0 fb^{-1}	0.2 fb^{-1}	1.0 fb^{-1}	4.0 fb^{-1}
130 GeV	A	1.98	0.91	0.49	×	×	0.57
	B	1.93	0.88	0.47	2.52	0.95	0.54
150 GeV	A	1.68	0.62	0.22	×	×	0.80
	B	1.67	0.61	0.21	4.24	1.31	0.75
200 GeV	A	4.48	2.00	0.99	×	×	0.50
	B	4.23	1.80	0.88	×	1.25	0.50

Conclusions & Plans

- Signal-free control samples from electron final states can be used for the background estimation in $A \to \mu^+\mu^-$ searches.
- Control samples provide good information on the background shape, even with low statistics.
- Information from control samples is crucial for evaluation of exclusion limits for early data!

Plans for early ATLAS data (≥ 200 pb^{-1} $\widehat{=}$ end of 2010)

$\Rightarrow$ Set first exclusion limits.

Plans for very early ATLAS data (≥ 10 pb^{-1} $\widehat{=}$ after few months operation)

$\Rightarrow$ Test the performance of the method with $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ events.

BACKUP

Cut Evolution

cross section $\times$ selection efficiency for $1\ fb^{-1}$ @ 10 TeV

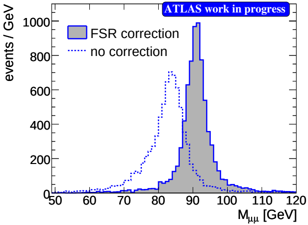
Cuts	bbA*	Z incl.	Z+jets	Zbb	ttbar
no cut	38	$1.1 \cdot 10^6$	$1.2 \cdot 10^6$	$20 \cdot 10^3$	$374 \cdot 10^3$
preselection	29	$477 \cdot 10^3$	$473 \cdot 10^3$	$10 \cdot 10^3$	$5.4 \cdot 10^3$
MET	29	$477 \cdot 10^3$	$472 \cdot 10^3$	$10 \cdot 10^3$	$1.3 \cdot 10^3$
		0 b-jet analysis			
b-jet veto	23	$470 \cdot 10^3$	$467 \cdot 10^3$	$7.3 \cdot 10^3$	219
$\Delta m = 150 \pm 7$ GeV	20	$8.6 \cdot 10^2$	$8.9 \cdot 10^2$	9.9	13
		>0 b-jet analysis			
b-jet requirement	6	$7.1 \cdot 10^3$	$5.0 \cdot 10^3$	$2.6 \cdot 10^3$	$1.1 \cdot 10^3$
$\cos \Delta\phi_{\mu\mu}$	6	$6.6 \cdot 10^3$	$4.6 \cdot 10^3$	$2.4 \cdot 10^3$	870
jet p_T sum	4	$5.2 \cdot 10^3$	$3.0 \cdot 10^3$	$1.4 \cdot 10^3$	125
$\Delta m = 150 \pm 7$ GeV	4	12	2.7	1.7	9

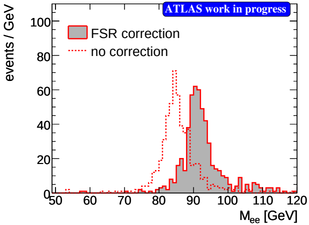
* $M_A = 150$ GeV, $\tan\beta = 40$: A resonance only, H not added

FSR Correction at Reconstruction Level

FSR correction in principle easy: $(M_{ll})^2 = (\boldsymbol{p}_1 + \boldsymbol{p}_2)^2 \Rrightarrow (M_{ll}^{corr})^2 = [(\boldsymbol{p}_1 + \boldsymbol{p}_\gamma) + \boldsymbol{p}_2]^2$

$\Rightarrow$ Profit depends on FSR photon reconstruction performance.





FSR photon selection:

- **Truth level:** Photons from a Z decay with small angular distance to mother lepton ($\Delta R < 0.5$).
- **Reconstruction level:** Photons with small angular distance to reconstructed lepton ($\Delta R < 0.25$).

$Z \to \mu^+\mu^-$	truth	reconstruction
Total	4547602	4547602
$N_\gamma = 0$	4056220	4538465
$N_\gamma = 1$	460509	9066
$N_\gamma > 1$	30873	71

$Z \to e^+e^-$	truth	reconstruction
Total	4547602	4547602
$N_\gamma = 0$	3683440	4546761
$N_\gamma = 1$	763699	827
$N_\gamma > 1$	100133	14

FSR correction performs well on reconstruction level!
But only very few photons are reconstructed.

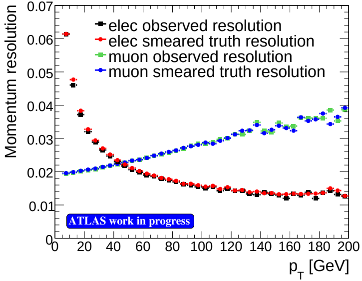
The Effect of Lepton Momentum Resolution

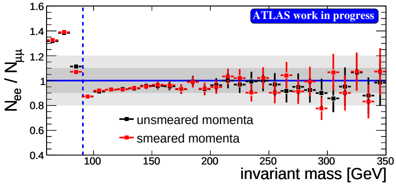
Correction of a limited detector resolution is difficult.

But: Effects of limited momentum resolution can be studied on MC truth.

1. Calculate momentum resolution using MC
2. Smear out truth momenta according to this resolution in p_T bins
3. Reconstruct Z mass with smeared 4-momenta

$\Rightarrow$ Effect on agreement of invariant mass distributions due to different electron and muon momentum resolutions negligible!

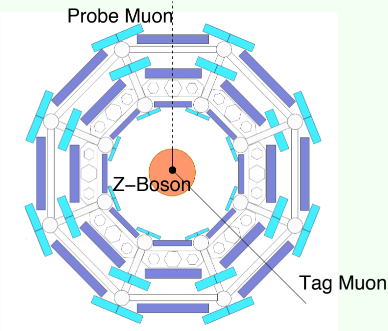




The Tag & Probe Method

Method to measure detector performance parameters directly from data.

Example: Muon Reconstruction Efficiency



1. Select Z events with high purity:
   - two isolated tracks
   - opposite charge
   - same vertex
   - $M_{tracks} \approx M_Z$
2. One track reconstructed as muon
   $\longrightarrow$ "tag"-muon
   $\longrightarrow$ identifies $Z \rightarrow \mu^+\mu^-$ decay
3. Second track ("probe") used to calculate muon rec. efficiency.

$$\text{Efficiency} = \frac{\text{number of probes reconstructed as muons}}{\text{number of all probes}}$$

Looser Event Selection in b-jet Final State

Early data analysis of > 0 b-jet final state difficult due to very low statistics.
$\rightarrow$ gain events by loosening the event selection.

Standard Event Selection @ 1 fb^{-1}

- 6 signal events
- 22 Z events
- 12 $t\bar{t}$ events

Looser Event Selection @ 1 fb^{-1}

- 8 signal events
- 30 Z events
- 63 $t\bar{t}$ events

	0 b-jet total background		b-jet total background		b-jet $t\bar{t}$ background	
	norm.	shape	norm.	shape	norm.	shape
truth level @ 4 fb^{-1}	$< 6\%$	$< 1\%$	9%	$< 3\%$	6%	3%
standard selection @ 4 fb^{-1}	$< 6\%$	$< 1\%$	15%	7%	16%	17%
standard selection @ 1 fb^{-1}	6%	2%	16%	19%	45%	50%
standard selection @ 0.2 fb^{-1}	7%	$< 5\%$	–	–	–	–
loose selection @ 4 fb^{-1}	–	–	9%	$< 4\%$	15%	$< 6\%$

Fit Performance

Fit Functions

- Background parametrization:
  $$f_B(x) = \frac{p_0}{x}\left[\frac{1}{(x^2-M_Z^2)^2+M_Z^2\Gamma_Z^2} + p_1 \cdot \exp\left(-p_2 \cdot x\right)\right]$$
- Signal + background parametrization:
  $$f_{SB}(x) = f_B + p_3 \cdot \frac{1}{\sqrt{2\pi}p_4} \cdot \exp\left(-\frac{(x-p_5)^2}{2p_4^2}\right)$$

Success rate of the fit

A: Fit to side-bands only

B: Fit to side-bands and control samples

M_A		0 b-jet final state 0.2 fb^{-1}	0 b-jet final state 1.0 fb^{-1}	0 b-jet final state 4.0 fb^{-1}	>0 b-jet final state 0.2 fb^{-1}	>0 b-jet final state 1.0 fb^{-1}	>0 b-jet final state 4.0 fb^{-1}
130 GeV	A	60%	61%	83%	0.6%	4%	15%
	B	97%	95%	89%	86%	82%	76%
150 GeV	A	50%	64%	78%	0.6%	3%	15%
	B	88%	94%	87%	86%	81%	79%
200 GeV	A	52%	65%	82%	0.5%	5%	18%
	B	84%	94%	86%	61%	74%	87%