Search for Beyond the Standard Model phenomena in $e\mu$ final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

Luis Roberto Flores Castillo

The Chinese University of Hong Kong

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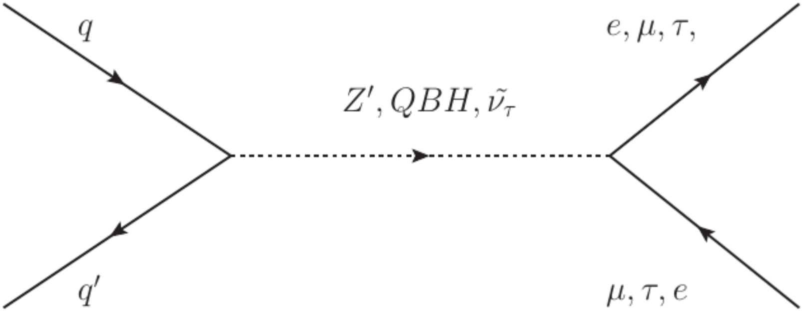
Outline

- Motivation and models
- Analysis strategy
- Object and event selection
- Background estimation
- Results

Strong participation from SJTU, USTC, HK Cluster

Introduction: Motivation

- SM processes are expected to conserve lepton flavour
- Lepton-flavour violating (LFV) decays would be a clear indication of New Physics
- Many extensions to the SM include LFV decays:



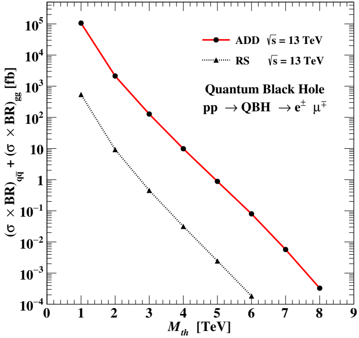
Introduction: Beyond Standard Model (BSM) theories

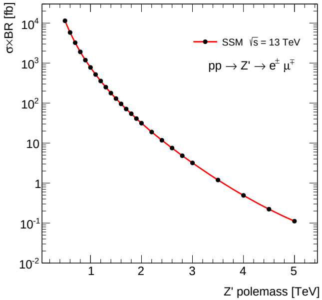
Quantum Black Hole

- Produce QBHs when the extra-dimensional Planck scale is reached (ADD: 6 lrg xD, RS: 1 warped xD)
- Quantum Gravity might violate lepton flavour conservation $\rightarrow e\mu$, $e\tau$ and $\mu\tau$ final states

Extended Z' SSM

- Heavy gauge boson with the same couplings as the SM Z
- Model can be extended to allow for LFV couplings ($\mathcal{Q}_{12}$, $\mathcal{Q}_{13}$ and $\mathcal{Q}_{23}$)
- Cross section takes the form $\sigma(Z' \rightarrow l_i l_j^{'}) \sim \frac{Q_{ij}^2 M_{ll'}^2}{(M_{ll'}^2 - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$





Introduction: Analysis Strategy

i) Select events from data with exactly one good electron and one muon

ii) Compare observed yields to SM expectation

iii) Look for deviations from SM expectation in the $m_{e\mu}$ spectrum

iv) In case deviations are found, quantify them

v) If none are found, extract limits on the models being searched for

Object and Event Selection

Electrons

- $p_T > 65$ GeV, $|\eta| < 2.47$
- Identification: *Tight* ($p_T < 125$ GeV), *Medium* ($p_T > 125$ GeV)
- Impact parameter: $|d_0/\sigma_{d_0}| < 5$ and $|\Delta z_0 \sin\theta| < 0.5$ mm
- Isolation: Loose (tracks and cells)

Muons

- $p_T > 65$ GeV, $|\eta| < 2.5$
- Identification: *HighPT* requirements
- Impact parameter: $|d_0/\sigma_{d_0}| < 3$ and $|\Delta z_0 \sin\theta| < 0.5$ mm
- Isolation: Loose with only tracks

Event Selection

- Trigger: HLT_mu50 || HLT_e60_lhmedium || HLT_e120_lhloose
- 3rd lepton veto: events with an additional 'loose' muon[1] or electron[2] rejected
- At least one trigger-matched lepton
- Back-to-back requirement: $\Delta\phi_{e\mu} > 2.7$
- No opposite charge requirement (reduces 5-6% signal, but only fake e bg)

[1] muon: standard selection cuts, except isolation
[2] electron: LH-Medium for $p_T < 125$ GeV, LH-Loose for $p_T > 125$ GeV, no isolation cut

Data, background and signal samples

SM Backgounds

Background	Estimation Method	Generator
Top ($t\bar{t}$, single t w/assoc W)	MC Simulation and Extrapolation	Powheg
Diboson (WW, ZZ, WZ)	MC Simulation and Extrapolation	Sherpa
Multi-Jet & W+jets	Data-driven (Matrix Method)	-
Drell-yan $\tau\tau$ ($Z/\gamma^* \to \tau\tau$)	MC Simulation	Pythia8

Signal processes

Process	Generator
QBH	QBH
Z'	Pythia8

Data

Currently using 3.2 fb^{-1} at $\sqrt{s} = 13$ TeV

Background processes: Multi-jets and W+jets

Data-driven estimation based on Matrix Method (2×2)[1]

$$\begin{bmatrix} N_{\mathrm{TT}} \\ N_{\mathrm{LT}} \end{bmatrix} = \begin{bmatrix} r_e & f_e \\ 1 & 1 \end{bmatrix} \begin{bmatrix} N_{\mathrm{RR}} \\ N_{\mathrm{FR}} \end{bmatrix}$$

- $\boldsymbol{r_e}$: probability of an electron to be identified $\rightarrow$ evaluated from simulation
- $\boldsymbol{f_e}$: probability of a jet to be misidentified as an electron $\rightarrow$ evaluated from data in multi-jets enriched control region

'Tight' electron: if fullfilling all selection cuts
'Loose' Electron: as above, but looser identification and no isolation requirement

Multi-jets control sample

$E_T^{\mathrm{miss}} < 25$ GeV and $m_T < 50$ GeV

Contamination from W+jets and other SM EW processes substracted using MC predictions.

Estimate

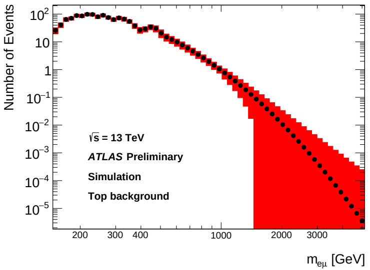
Expect $\sim$ **85 events** with a luminosity of 3.2 fb^{-1}

Background processes: Top Quarks and Diboson

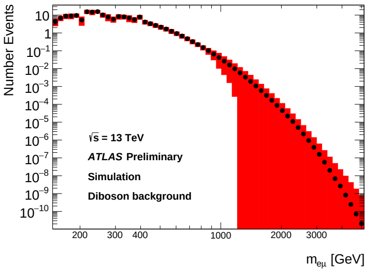
MC simulation has very limited statistic above 1 TeV in $m_{e\mu}$ → extrapolation

Functional forms: $e^{-a} \cdot x^{b} \cdot x^{c\ln(x)}$ and $a/(x+b)^{c}$

- Chosen for their stability when varying the fit range and for the quality of the fit
- *Nominal* → the median of all the tested fit ranges using both functional forms.
- *Systematic uncertainty* → fit parameter uncertainty $\oplus$ RMS of all fit variations



Top Quarks simulation up to 600 GeV



Diboson simulation up to 400 GeV

Systematics Uncertainties

Sources of systematic uncertainties are divided in two categories:

Theoretical → uncertainties on the predicted cross section times branching ratio

Experimental → uncertainties relating to detector limitations or simulation of the detector response

Source	$m_{e\mu}$=1.0 TeV		$m_{e\mu}$=2.0 TeV		$m_{e\mu}$=3.0 TeV	
	Signal	Background	Signal	Background	Signal	Background
PDF uncertainties	N/A	11.0%	N/A	27%	N/A	41%
Luminosity	5%	5%	5%	5%	5%	5%
Electron Trigger Efficiency	5%	5%	5%	5%	5%	5%
Electron ID	5%	5%	5%	5%	5%	5%
Muon Reconstruction Efficiency	1%	1%	2%	2%	3%	3%
Electron energy scale and resolution	1%	1%	4%	4%	5%	5%
Muon scale and resolution	7%	7%	15%	15%	20%	20%
Muon Trigger Efficiency	2%	2%	2%	2%	2%	2%
Instrumental backgrounds	N/A	1%	N/A	1%	N/A	1%
Background Extrapolation	N/A	25%	N/A	90%	N/A	400%
MC Statistics	2%	N/A	2%	N/A	2%	N/A
Total	12%	32%	17%	100%	23%	400%

N/A → represents cases where the uncertainty is not applicable

N.B.: The background expectation beyond 2 TeV is < 0.1 events

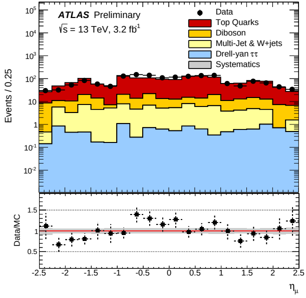
Results: yields

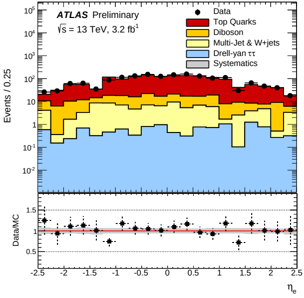
Process	$m_{e\mu} < 300$ GeV	$300 < m_{e\mu} < 600$ GeV
Top	900 ± 80	404 ± 50
Diboson	116 ± 13	52 ± 7
QCD and W+jets	67 ± 10	17 ± 4
$Z/\gamma^* \to \tau\tau$	9.3 ± 1.3	1.79 ± 0.21
Total background	1092 ± 90	476 ± 50
Data	1164	475

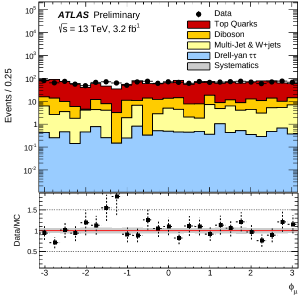
Process	$600 < m_{e\mu} < 1200$ GeV	$1200 < m_{e\mu} < 2000$ GeV
Top	36 ± 4	0.55 ± 0.31
Diboson	2.6 ± 0.4	$(7 \pm 5) \cdot 10^{-3}$
QCD and W+jets	1.0 ± 0.9	0.12 ± 0.35
$Z/\gamma^* \to \tau\tau$	0.13 ± 0.01	$(3.5 \pm 1.4) \cdot 10^{-3}$
Total background	40 ± 4	0.67 ± 0.34
Data	36	0

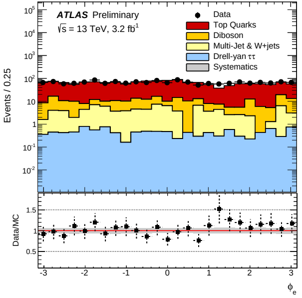
Process	$2000 < m_{e\mu} < 3000$ GeV	$m_{e\mu} > 3000$ GeV
Top	$(1.7 \pm 3.4) \cdot 10^{-2}$	$(0.3 \pm 2.6) \cdot 10^{-3}$
Diboson	$(4 \pm 6) \cdot 10^{-5}$	$(0.3 \pm 1.5) \cdot 10^{-7}$
QCD and W+jets	0	0
$Z/\gamma^* \to \tau\tau$	$(1.9 \pm 2.6) \cdot 10^{-4}$	$(2 \pm 10) \cdot 10^{-5}$
Total background	$(1.7 \pm 3.4) \cdot 10^{-2}$	$(0.3 \pm 2.7) \cdot 10^{-3}$
Data	1	0

Results: Lepton η and ϕ

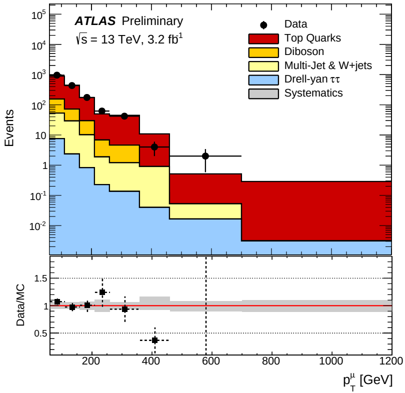


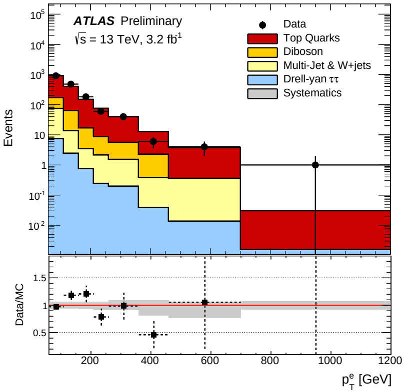




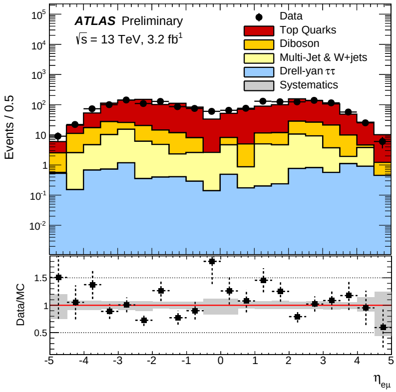


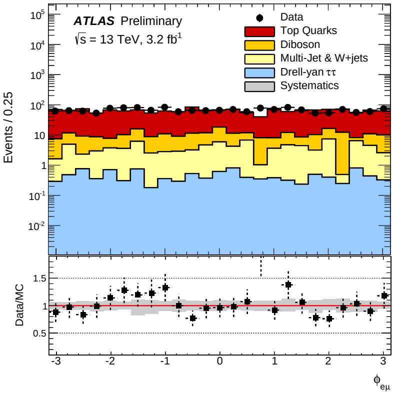
Resuts: Lepton p_T



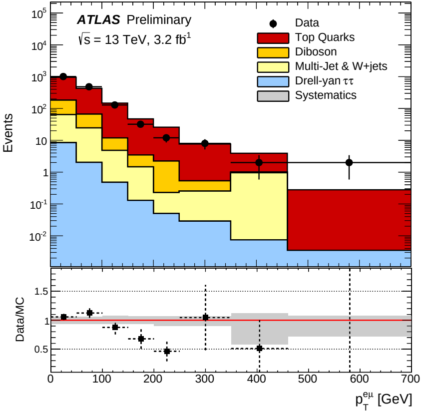


Results: $\eta_{e\mu}$, $\phi_{e\mu}$





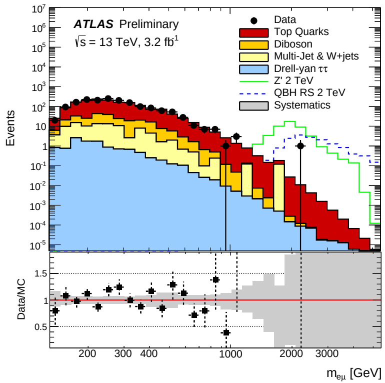
Results: $p_T^{e\mu}$

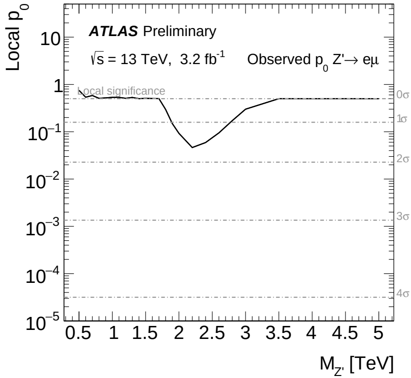


Potential $p_T^{e\mu}$ mis-modelling; its effect is incorporated into the $m_{e\mu}$ uncertainty:

1. $p_T^{e\mu}$ distribution in MC is weighted to match data
2. bg extrapolation redone from reweighted mass spectrum → larger uncertainty
3. adopted as nominal uncertainty; accounts for both $p_T^{e\mu}$ modelling & extrapolation

Results: $m_{e\mu}$ and p-value





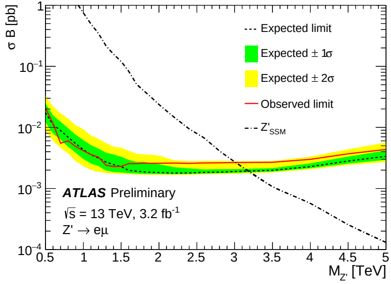
Largest local significance: 1.7σ from an event with $m_{e\mu} = 2.1$ TeV

No significant excess observed

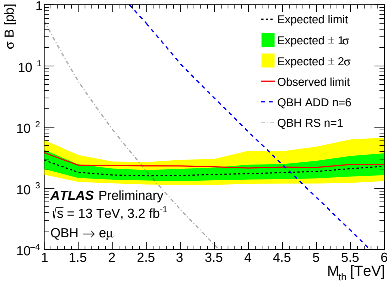
Results: Mass limits setting

- Bayesian inference using the Bayesian Analysis Toolkit (BAT)
- Template shape method employed
- Sources of systematic uncertainty incorporated in terms of nuisance parameters

Z' SSM



QBH



Model	Expected Limit [TeV]	Observed Limit [TeV]
Z' SSM	3.19	3.01
QBH ADD n=6	4.62	4.54
QBH RS n=1	2.56	2.44

Conclusions

- Presented the search for BSM phenomena decaying into $e\mu$ final states using 3.2 fb^{-1} at $\sqrt{s} = 13$ TeV
- **No significant excess observed**:
  Limit set to 3.01 TeV for Z' and 4.54 (2.44) TeV for QBH ADD (RS)
- Results published as ATLAS Conference Note (ATLAS-CONF-2015-072)
- Aim to add $e\tau$ and $\mu\tau$ decay channel in the near future

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BACKUP

Introduction: Beyond Standard Model theories

R-Parity Violating SUSY

- R-Parity introduced to avoid the decay of the proton
- SUSY particles have an R-parity of -1 while SM particles have $+1$
- Can violate either lepton or baryon number but not both at the same time (which would lead to proton decay)

[not included in this analysis]

Statistical Analysis

- Cross section and mass limits:

In the absence of any significant signal, we set cross section and model dependent exclusion limits at 95 % C.L.

- Make use of well established procedures:

✓ Bayesian inference using the Bayesian Analysis Toolkit (BAT)
✓ Sources of systematic uncertainty incorporated in terms of nuisance parameters

$$L\left(data \mid \sigma B_{Z'}, \theta_i\right) = \prod_{k=1}^{N} \frac{\mu_k^{n_k} e^{-\mu_k}}{n_k!} \prod_{i}^{Sys} G(\theta_i, 0, 1) \qquad \mu_k = \sum_j N_j T_{jk} \left(1 + \theta_i \varepsilon_{ijk}\right)$$

where, $N_1 = (A\varepsilon)(\sigma B)_{Z'}$xLumi $\quad N_2 = N_{bkg} \quad \sum_{k=1}^{N} T_k = 1$

$\sigma B_{Z'}$ normalization parameter of signal ($j=1$)
Θ_i nuisance parameter for each systematic effect
T_{jk} fractional template shape expectation of template j in bin k
ε_{ijk} systematic uncertainty in bin k due to source i on template j

Limit Setting

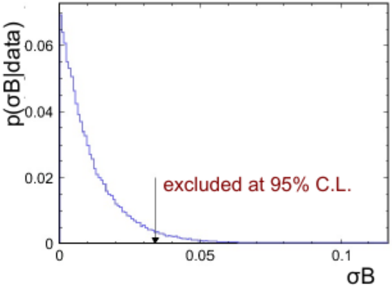
The parameter dependence of the likelihood function is reduced to *one parameter* of interest by marginalizing (using *Markov Chain MC*)

$$\mathcal{L}'(data|\sigma B) = \int \mathcal{L}(\sigma B, \theta_1, ..., \theta_N) d\theta_1, ..., d\theta_N$$

In Bayesian statistics, all knowledge about the parameter of interest is summarized by the posterior p.d.f.
Obtained through Bayes' theorem:

$$p(\boldsymbol{\theta}|\boldsymbol{x}) = \frac{L(\boldsymbol{x}|\boldsymbol{\theta})\pi(\boldsymbol{\theta})}{\int L(\boldsymbol{x}|\boldsymbol{\theta}')\pi(\boldsymbol{\theta}')\, d\boldsymbol{\theta}'}$$

here, $\theta = \sigma B$ *(parameter of interest)*



Integrate p.d.f. to obtain exclusion limits