Search for a resonance decaying to 4-lepton final state in association with missing energy

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For Yaquan's group

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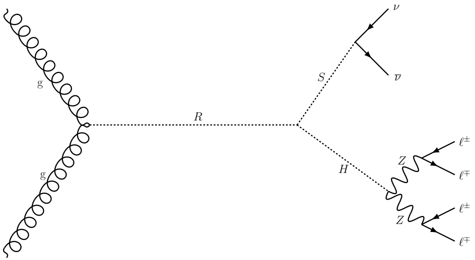
Contents

What's good about Higgs to four-lepton (*HZZ*)?

- Provides good sensitivity for the Higgs properties measurement[1];
- Because of the high signal to background ration, for instance;
- About 2.2-2.3 for the 4μ, $4e$, $2e2\mu$ and $2\mu2e$ channels;
- Fully reconstructed final states, and good signal mass resolution ($1 - 2\% \times m_H$); and
- Can similar thing be achieved within th physics BSM interpretation?

[1] Event Selection and background estimation for the measurement of the properties of the Higgs particle in the four lepton decay channel with the ATLAS detector.

Objectives



- Explores the presence of a heavy scalar boson, *R*;
- Produced in gluon-gluon fusion in association with Met;
- The resonance decays to lighter scalar *H* and *S* bosons;
- *H* decays into four leptons through *ZZ* bosons; and
- *S* decays to a pair of neutrinos.

Objectives

$$gg \to R \to SH \to 4\ell + \text{Met} \Leftrightarrow \text{RSH-model}$$

The search looks at the region where the invariant mass of the four leptons greater than 200 GeV ($m_{4\ell} > 200$ GeV). In the phase space of RSH model, we consider the mass of R to be between $(m_S + m_H) < m_R < 1500$ GeV.

Advantages for this channel

- The missing transverse energy background is very small; and
- It can be controlled by varying the masses of R, H, and S.

RSH-model interpretation

- RSH-model can be embedded into 2HDM+S or 2HDM+a

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(will be inserted by the editor)

Phenomenological signatures of additional scalar bosons at the LHC

Stefan von Buddenbrock[a,1], Nabarun Chakrabarty[b,2], Alan S. Cornell[c,1], Deepak Kar[d,1], Mukesh Kumar[e,3], Tanumoy Mandal[f,4], Bruce Mellado[g,1], Biswarup Mukhopadhyaya[h,2], Robert G. Reed[i,1] and Xifeng Ruan.[j,1]

[1]School of Physics, University of the Witwatersrand, Johannesburg, Wits 2050, South Africa.
[2]Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad - 211 019, India.
[3]National Institute for Theoretical Physics, School of Physics and Mandelstam Institute for Theoretical Physics, University of the Witwatersrand, Johannesburg, Wits 2050, South Africa.
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The N2HDM under Theoretical and Experimental Scrutiny

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[4]*Centro de Física Teórica e Computacional, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, Edifício C8 1749-016 Lisboa, Portugal*
[5]*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany*

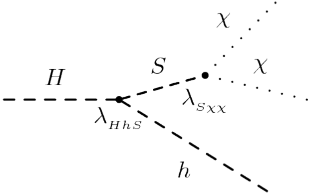
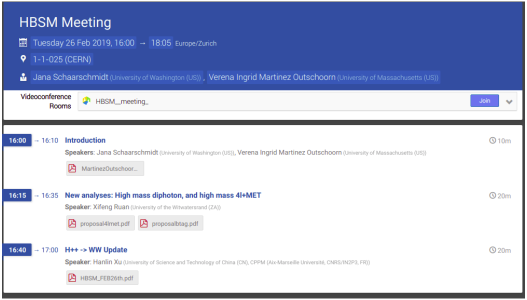


Figure: Changing $H \to R$, $h(125) \to H$; a theory study is going on.

Analysis group

- ☐ The analysis will be in HBSM under HDBS; and
- ☐ Report to *HZZ*-group as the analysis uses their framework.



Manpower

- ☐ One senior (Fang Yaquan) and myself from IHEP. And two seniors from Wits University (Xifeng Ruan and Bruce Mellado).

Signal samples

RSH-signal

Signal samples have already been produced, JIRA, as follows:

- The mass of S is fixed to 160 GeV;
- The masses of R are 390 GeV, 450 GeV, 800 GeV and 1500 GeV:
  - $m_R = 390$ GeV: $m_H = 220$ GeV
  - $m_R = 450$ GeV: $m_H = 220$ GeV and 250 GeV
  - $m_R = 800$ GeV: $m_H = 220$ GeV, 300 GeV and 500 GeV
  - $m_R = 1500$ GeV:$m_H = 220$ GeV, 250 GeV and 1000 GeV
- Is this overlap with DiHiggs $X \to SH$? Neither S nor H in the RSH-signal has a mass of 125 GeV.
- Requested HIGG2D1 derivation with cache: 21.2.55 and p-tag: p3782. It's done, you can see it here; and
- The mini-trees production using HZZAnalRun2Code is nearly done.

Background samples

Considered background for *RSH*

- We consider similar background as *HZZ*, mainly:
  - $q\bar{q} \to ZZ^*$
  - gg $\to ZZ^*$
  - ttZ
  - $Z +$ jets
  - $t\bar{t}$
- The main contribution coming from the first two background;
- Refere to as continuum background, while the rest reducible; and
- We can also look at *VVV*-bosons background as we move on.

Event selection

- Using the nominal selection, *HZZ*-group , for the four-lepton;

Physics Objects
ELECTRONS
Loose Likelihood quality electrons with hit in innermost layer, $E_\mathrm{T} > 7$ GeV and $\lvert\eta\rvert < 2.47$
Interaction point constraint: $\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm (if ID track is available)
MUONS
Loose identification with $p_\mathrm{T} > 5$ GeV and $\lvert\eta\rvert < 2.7$
Calo-tagged muons with $p_\mathrm{T} > 15$ GeV and $\lvert\eta\rvert < 0.1$, segment-tagged muons with $\lvert\eta\rvert < 0.1$
Stand-alone and silicon-associated forward restricted to the $2.5 < \lvert\eta\rvert < 2.7$ region
Combined, stand-alone (with ID hits if available) and segment-tagged muons with $p_\mathrm{T} > 5$ GeV
Interaction point constraint: $\lvert d_0\rvert < 1$ mm and $\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm (if ID track is available)
JETS
anti-k_T jets with *bad-loose* identification, $p_\mathrm{T} > 30$ GeV and $\lvert\eta\rvert < 4.5$
Jets with $p_\mathrm{T} < 60$ GeV and $\lvert\eta\rvert < 2.4$ are required to pass the pile-up jet rejection at the 92% working point (JVT score > 0.59).
Jets with $p_\mathrm{T} < 50$ GeV and $\lvert\eta\rvert > 2.5$ are required to pass the forward pile-up jet rejection at the 90% working point.
b-TAGGING
Previously selected jets with $\lvert\eta\rvert < 2.5$ passing the `MV2_c10` algorithm at its 70% working point
OVERLAP REMOVAL
Jets within $\Delta R < 0.2$ of an electron or $\Delta R < 0.1$ of a muon are removed

Event Selection	
QUADRUPLET SELECTION	- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements: - p_T thresholds for three leading leptons in the quadruplet: 20, 15 and 10 GeV - At most 1 calo-tagged, stand-alone or silicon-associated muon per quadruplet - Leading di-lepton mass requirement: $50 < m_{12} < 106$ GeV - Sub-leading di-lepton mass requirement: $m_\mathrm{threshold} < m_{34} < 115$ GeV - $\Delta R(\ell, \ell') > 0.10$ for all lepton pairs in the quadruplet - Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} < 5$ GeV - Keep all quadruplets passing the above selection
ISOLATION NEEDS UPDATING	- Contribution from the other leptons of the quadruplet is subtracted - Muon track isolation ($\Delta R = 0.30$): $\Sigma p_\mathrm{T}/p_\mathrm{T} < 0.15$ - Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_\mathrm{T}/p_\mathrm{T} < 0.30$ - Electron track isolation ($\Delta R = 0.20$) : $\Sigma E_\mathrm{T}/E_\mathrm{T} < 0.15$ - Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.20$
IMPACT PARAMETER SIGNIFICANCE	- Apply impact parameter significance cut to all leptons of the quadruplet - For electrons: $d_0/\sigma_{d_0} < 5$ - For muons: $d_0/\sigma_{d_0} < 3$
BEST QUADRUPLET	- If more than one quadruplet has been selected, choose the quadruplet with highest Higgs decay ME according to channel: 4μ, $2e2\mu$, $2\mu2e$ and $4e$
VERTEX SELECTION	- Require a common vertex for the leptons: - χ^2/ndof < 5 for 4μ and < 9 for others decay channels

- B-veto to reject $ttZ \rightarrow 4\ell$ background;
- Events categorized into two categories:
  - $N_{jet}^{Central} = 0$
  - $N_{jet}^{Central} \geq 1$
- We do 2D scan using $p_\mathrm{T}^{4\ell}$ and $E_\mathrm{T}^\mathrm{miss}$ for the first category; and
- 1D scan, cutting on $E_\mathrm{T}^\mathrm{miss}$ for the second category.

Work in progress

Signal optimization

Zero-central jet category

- ☐ $N_{jet}^{Central} = 0$

Table: The $qq \rightarrow ZZ^*$ MC is normalised to the data while the non $qq \rightarrow ZZ^*$ are normalised to cross section for the $m_{4\ell} > 190$ GeV.

	Data17	Signal	$qqZZ^*$	$ggZZ^*$	ttZ	$Z+jet$	$t\bar{t}$	$s/\sqrt{s+b}$	$0.1 \times s/\sqrt{0.1 \times s+b}$	$s/\sqrt{b}$
4ℓ	2119.00±46.03	55.87±0.75	2119.00±4.62	127.55±0.24	33.28±0.48	20.32±0.44	8.13±0.28	3.30	0.36	3.68
B-veto	2026.00±45.01	54.48±0.74	2071.96±4.59	125.26±0.24	7.77±0.23	19.65±0.43	6.44±0.24	3.27	0.36	3.65
$N_{Cjet} = 0$	1406.00±37.50	24.49±0.49	1416.90±4.03	81.10±0.19	1.22±0.08	15.41±0.39	3.07±0.16	1.84	0.20	1.99
$(p_T^{4\ell} > 20$ & $E_T^{miss} > 10)$ GeV	490.00±23.17	19.91±0.46	416.55±2.70	40.08±0.14	1.16±0.08	7.25±0.27	2.85±0.16	2.44	0.29	2.91

	Data17	Signal	$qqZZ^*$	$ggZZ^*$	ttZ	$Z+jet$	$t\bar{t}$	$s/\sqrt{s+b}$	$0.1 \times s/\sqrt{0.1 \times s+b}$	$s/\sqrt{b}$
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$N_{Cjet} = 0$	1406.00±37.50	24.49±0.49	1416.90±4.03	81.10±0.19	1.22±0.08	15.41±0.39	3.07±0.16	1.84	0.20	1.99
$(p_T^{4\ell} > 30$ & $E_T^{miss} > 0)$ GeV	312.00±17.66	17.44±0.42	248.93±1.79	25.63±0.11	1.14±0.08	3.84±0.19	2.54±0.15	2.58	0.32	3.28

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$N_{Cjet} = 0$	1406.00±37.50	24.49±0.49	1416.90±4.03	81.10±0.19	1.22±0.08	15.41±0.39	3.07±0.16	1.84	0.20	1.99
$(p_T^{4\ell} > 30$ & $E_T^{miss} > 10)$ GeV	290.00±17.03	16.10±0.40	223.95±1.67	23.52±0.10	1.12±0.08	3.66±0.19	2.53±0.15	2.50	0.31	3.19

- ☐ $m_R = 390$ GeV, $m_H = 200$ GeV and $m_S = 160$ GeV.

Signal optimization

One or more central jet category

- ☐ $N_{jet}^{Central} \geq 1$

Table: The $qq \to ZZ^*$ MC is normalised to the data while the non $qq \to ZZ^*$ are normalised to cross section for the $m_{4\ell} > 190$ GeV.

	Data17	Signal	$qqZZ^*$	$ggZZ^*$	ttZ	$Z+jet$	$t\bar{t}$	$s/\sqrt{s+b}$	$0.1 \times s/\sqrt{0.1 \times s + b}$	$s/\sqrt{b}$
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B-veto	2026.00±45.01	54.48±0.74	2071.96±4.59	125.26±0.24	7.77±0.23	19.65±0.43	6.44±0.24	3.27	0.36	3.65
$N_{\text{Cjet}} \geq 1$	620.00±24.90	29.99±0.55	655.06±2.19	44.16±0.14	6.56±0.22	4.25±0.19	3.38±0.18	2.98	0.35	3.55
$E_{\text{T}}^{\text{miss}} > 20$ GeV	377.00±19.42	28.07±0.53	426.38±1.75	30.17±0.12	6.35±0.21	3.01±0.16	3.18±0.17	3.24	0.40	4.10

	Data17	Signal	$qqZZ^*$	$ggZZ^*$	ttZ	$Z+jet$	$t\bar{t}$	$s/\sqrt{s+b}$	$0.1 \times s/\sqrt{0.1 \times s + b}$	$s/\sqrt{b}$
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$N_{\text{Cjet}} \geq 1$	620.00±24.90	29.99±0.55	655.06±2.19	44.16±0.14	6.56±0.22	4.25±0.19	3.38±0.18	2.98	0.35	3.55
$E_{\text{T}}^{\text{miss}} > 30$ GeV	250.00±15.81	26.15±0.51	276.48±1.40	20.17±0.10	6.04±0.21	2.20±0.14	3.05±0.17	3.47	0.45	4.71

	Data17	Signal	$qqZZ^*$	$ggZZ^*$	ttZ	$Z+jet$	$t\bar{t}$	$s/\sqrt{s+b}$	$0.1 \times s/\sqrt{0.1 \times s + b}$	$s/\sqrt{b}$
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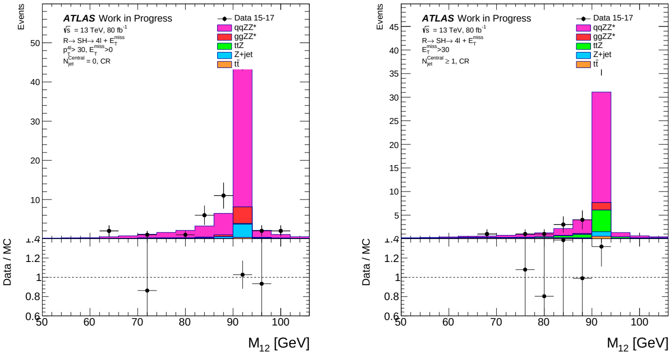
$N_{\text{Cjet}} \geq 1$	620.00±24.90	29.99±0.55	655.06±2.19	44.16±0.14	6.56±0.22	4.25±0.19	3.38±0.18	2.98	0.35	3.55
$E_{\text{T}}^{\text{miss}} > 40$ GeV	162.00±12.73	23.63±0.49	165.72±1.07	12.29±0.08	5.57±0.20	1.36±0.11	2.70±0.16	3.63	0.51	5.46

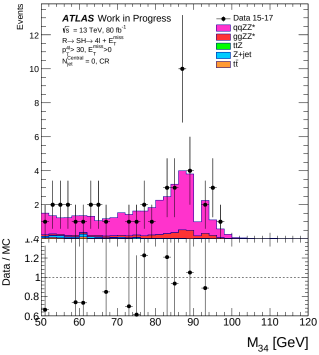
- ☐ $m_R = 390$ GeV, $m_H = 200$ GeV and $m_S = 160$ GeV.

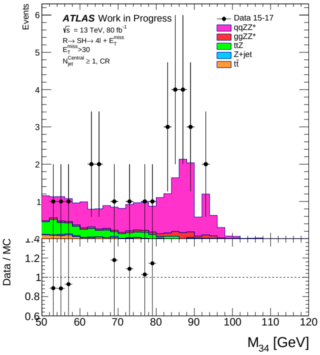
Control plots comparing data and background



- The invariant mass of the first lepton pairs: zero-central jet category (left), and one or more central jet category (right). Control region defined by $130 < m_{4\ell} < 190$.

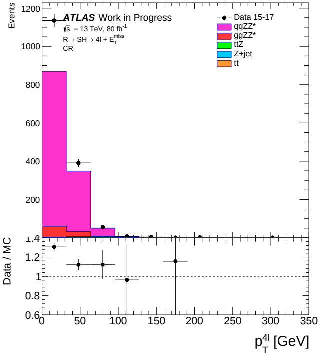
Control plots comparing data and background

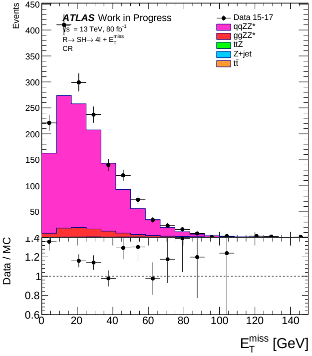




- The invariant mass of the second lepton pairs: zero-central jet category (left), and one or more central jet category (right). Control region defined by $130 < m_{4\ell} < 190$.

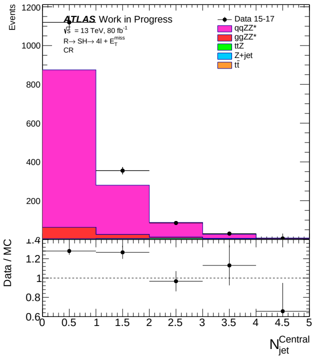
Control plots comparing data and background





- The $p_T^{4\ell}$ (left) and missing transverse energy (right) of the 4-lepton. Control region defined by $130 < m_{4\ell} < 190$.

Control plots comparing data and background



- Number of central jets; $p_T^{jet} > 30$ GeV with $|\eta| < 2.5$. Control region defined by $130 < m_{4\ell} < 190$.

Other 4-lepton from a different process

Other 4-lepton from a different process

- Four-lepton coming from Di-Higgs process:

$$HH \rightarrow \begin{bmatrix} ZZZZ \\ WWZZ \\ WWWW \\ WW\tau\tau \\ \tau\tau\tau\tau \end{bmatrix} \rightarrow 4\ell/4\ell + \text{(Met, jets, etc...)}$$

Timeline

Tasks / Year	2019				2020				2021			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. **Preparing of Proposal**												
1.1 *Literature review*												
1.2 *Opening report & submission*												
2. **Monte Carlo validation**												
3. **Analysis Crafts**												
3.1 *Signal optimisation*												
3.2 *Signal parameterisation*												
3.3 *Background studies*												
3.3.1 Background estimation												
3.3.2 Background shape modelling												
3.4 *Experimental and theoretical systematic*												
3.5 **Statistical studies**												
4. **Result interpretation**												
5. **Writing the supporting note (ATLAS)**												
5.1 *Contributing on writing the paper*												
6. **Writing up**												
7. **Thesis Examination & Defence**												

Thank you!

Additional slides

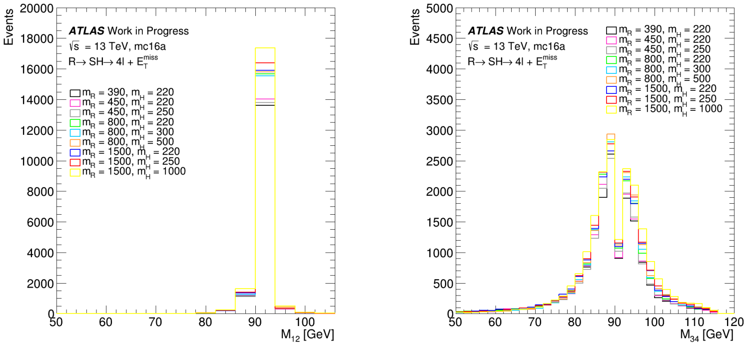


Figure: The invariant mass of the first (left) and the second (right) lepton pairs.

Additional slides

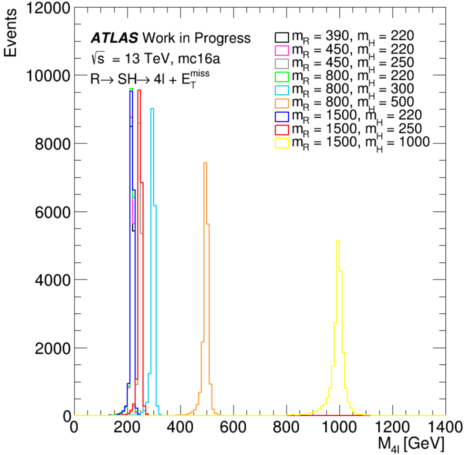
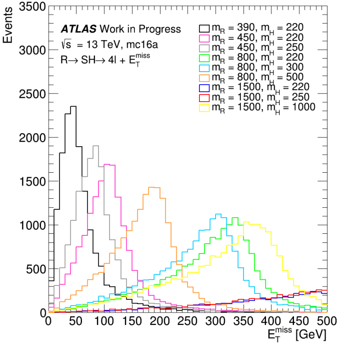


Figure: The invariant mass of the four leptons final state.

Additional slides



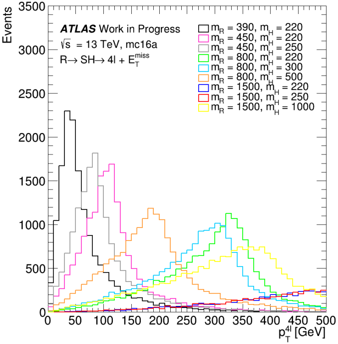


Figure: The missing transverse energy (left), and $p_T^{4\ell}$ of the 4-lepton (right).

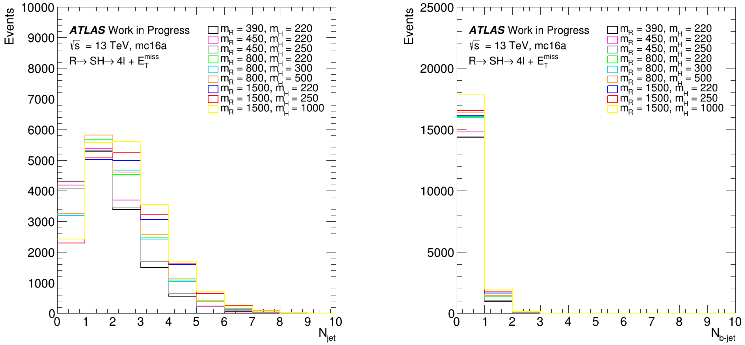


Figure: Number of the jet multiplicity (left), and number of b-jet (right).

Additional slides

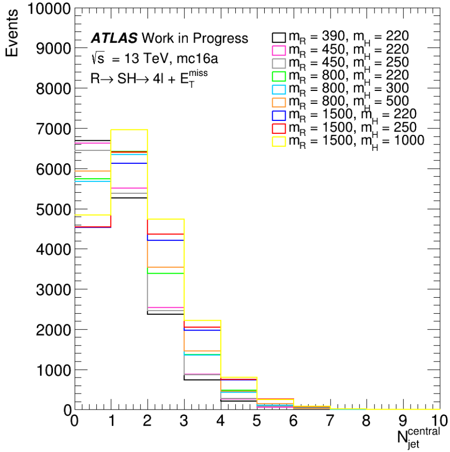


Figure: Number of central jets; $p_{\mathrm{T}}^{jet} > 30$ GeV with $|\eta| < 2.5$.

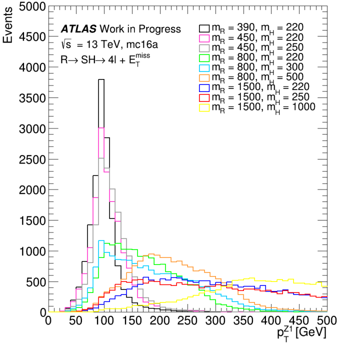


Figure: The $p_{\mathrm{T}}^{4\ell}$ of the first (left) and second (right) lepton pairs.

General MET data/MC and topology studies - MET (QT)

Missing transverse momentum reconstruction is important for many different analyses – both searches and measurements. This qualification concerns evaluating the pile-up and topology dependence of the reconstructed MET and the modelling of this in simulation. A variety of data-to-MC plots will be produced in Z+jet, gamma+jet, ttbar and di-jet events using the METPerformance package. Cases where large spurious MET is reconstructed will be investigated to determine the source of this miss-measurement, whether it be pile-up jets, poorly performing overlap removal, or poorly measured objects. The results will inform how MET is reconstructed and fixes for edge cases will be implemented in the analysis software and provided to the collaboration. The full set of physics results will be documented internally in note(s), while a subset of the results will be used in the precision MET paper.