Study of anomalous gauge couplings using $W^{\pm}Z$ channel in ATLAS

Study of dim-6 effective field theory in vector boson scattering

Lilly Wüst

March 25, 2019

Searching for new physics at the LHC

- since there is nothing new found in direct searches

$\rightarrow$ indirect searches become important

$\rightarrow$ searching for deviations of the SM and parametrizing them with an effective field theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{i,j} \left[\frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{f_j}{\Lambda^4} \mathcal{O}_j^{(8)} \right]$$ *with* Λ scale of new physics

Effective field theory

Expand the standard model Lagrangian with operators of higher dimension:

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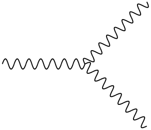
dim-6 operators:



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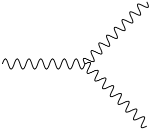

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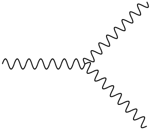

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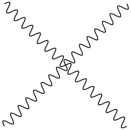

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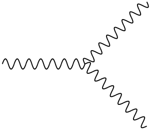

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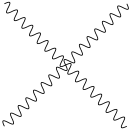

- $\rightarrow$ introduce additional interactions between the gauge bosons
- $\rightarrow$ anomalous triple and quartic gauge couplings
- $\rightarrow$ will modify the cross section and kinematic distribution

Current status of dim-6 limits

- LEP, Tevatron, ATLAS and CMS already provided limits on dim-6 operators
- as a reference I will use 13 TeV ATLAS limits with 13.3 fb^{-1} [arXiv:1603.02151v1]:

EFT coupling	Observed $\left[TeV^{-2}\right]$
c_{WWW}/Λ^2	$[-3.6; 3.4]$
c_W/Λ^2	$[-4.1; 7.6]$
c_b/Λ^2	$[-261.0; 193.0]$

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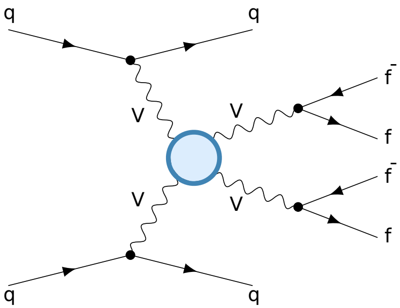
- as comparison 13 TeV CMS limits with 35.9 fb^{-1} [arXiv:1901.03428v1]:

EFT coupling	Observed $\left[TeV^{-2}\right]$
c_{www}/Λ^2	$[-2.0; 2.1]$
c_w/Λ^2	$[-4.1; 1.1]$
c_b/Λ^2	$[-100.0; 160.0]$

Vector boson scattering at the LHC



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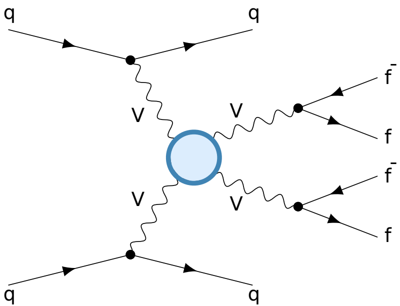
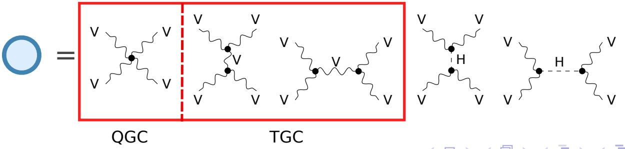
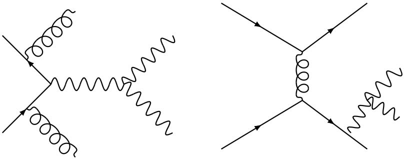


with



The $VVjj$ production:



and a lot more

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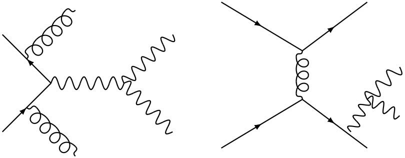

and a lot more

$$\propto \alpha_w^4 \alpha_s^2$$

$\rightarrow$ *QCD* mediated production

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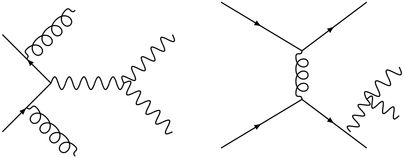

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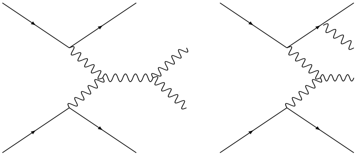

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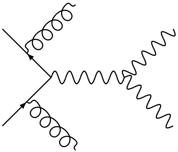

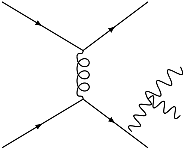

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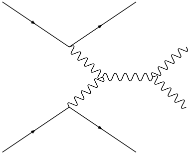
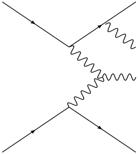


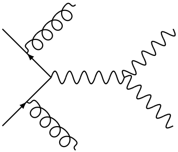
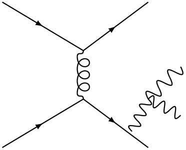


and a lot more

$\propto \alpha_w^6$

$\rightarrow$ *EW* mediated production

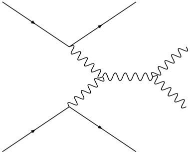
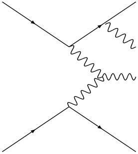
The *VVjj* production:

and a lot more

$\propto \alpha_w^4 \alpha_s^2$

$\rightarrow$ *QCD* mediated production

and a lot more

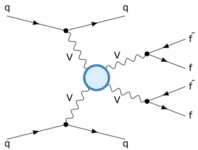
$\propto \alpha_w^6$

$\rightarrow$ *EW* mediated production

$\rightarrow$ classify *VVjj* production in two kinds

The VBS phase space

since we want to study VBS we add criteria to the jets on top of typically diboson cuts:



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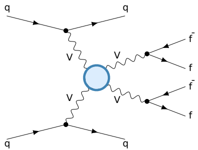
since we want to study VBS we add criteria to the jets on top of typically diboson cuts:

- at least two jets
- the two jets with highest p_T and opposite hemisphere are the tagging jets
- no b-jets
- $M_{inv}^{jj} > 500\ GeV$



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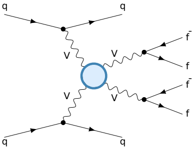


$\rightarrow$ reduce many QCD and EW mediated production of $VVjj$

Motivation of my study

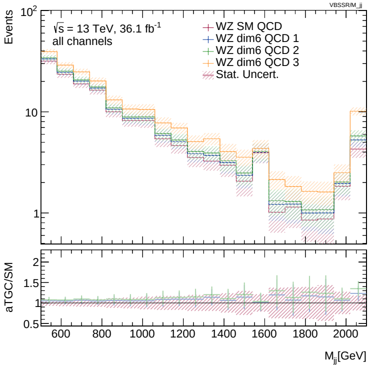
- ideally calculate limits on dim-6 and dim-8 operators together
- strong dim-6 limits LEP and LHC already produced using inclusive $W^{\pm}Z$
- to set limits on the dim-8 operators VBS was typically used at the LHC
- assuming that dim-6 operators have a negligible impact

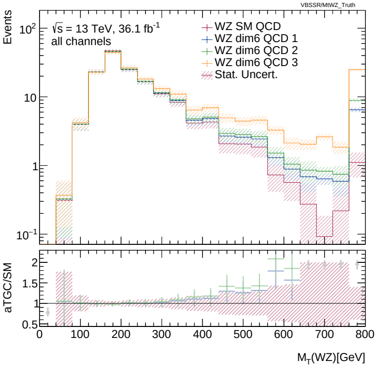
$\rightarrow$ I want to study the impact of dim-6 in the VBS phase space for dim-8 operators

Simulation of $W^{\pm}Z$ production

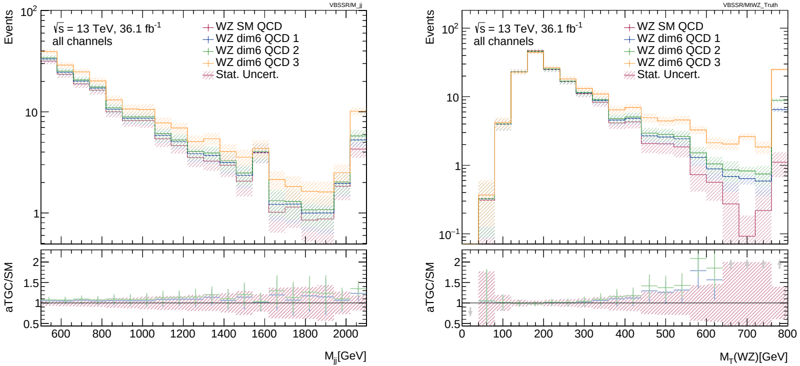
I simulated $W^{\pm}Z$ in the fully leptonic decay channel with madgraph on truth level for the SM and dim-6 operators:

- for $W^{\pm}Z$ with QCD mediated production:
  $pp \to W^{\pm}Z \to \ell\ell\ell\nu$
  with up to two jets in the matrix element
- for $W^{\pm}Z$ with EW mediated production:
  $pp \to W^{\pm}Z \to \ell\ell\ell\nu jj$


VBSSR/M_jj
√s = 13 TeV, 36.1 fb-1
all channels
WZ SM QCD
WZ dim6 QCD 1
WZ dim6 QCD 2
WZ dim6 QCD 3
Stat. Uncert.
Events
aTGC/SM
M_jj[GeV]


VBSSR/MtWZ_Truth
√s = 13 TeV, 36.1 fb-1
all channels
WZ SM QCD
WZ dim6 QCD 1
WZ dim6 QCD 2
WZ dim6 QCD 3
Stat. Uncert.
Events
aTGC/SM
M_T(WZ)[GeV]

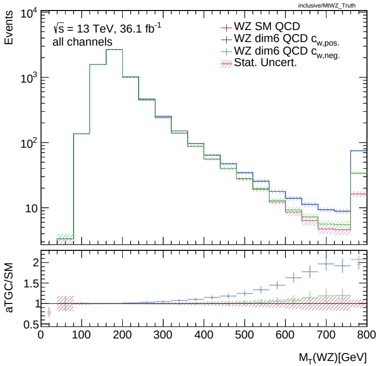
The Distributions

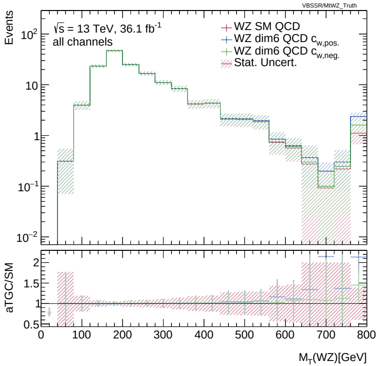


since M_T^{WZ} is the most sensitive distribution I will use it

M_T^{WZ} in the limits

M_T^{WZ} distribution in the limit of c_w of aTGC for QCD mediated production of $W^{\pm}Z$:





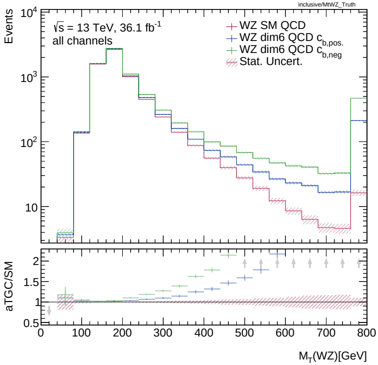
→ calculate the sum of number events and take the ratio $N_{aTGC}^{QCD}/N_{SM}^{QCD}$ to get an idea of the dim-6 operators impact

M_T^{WZ} in the limits

- without VBS cuts: $N_{SM}^{QCD} = 6497\ events$
- with VBS cuts: $N_{SM}^{QCD} = 153\ events$

	without VBS cuts	with VBS cuts
	$N_{aTGC}^{QCD}/N_{SM}^{QCD}$	$N_{aTGC}^{QCD}/N_{SM}^{QCD}$
$c_{www,neg.}$	1.011	1.022
$c_{www,pos.}$	1.013	1.028
$c_{w,neg.}$	1.003	1.011
$c_{w,pos.}$	1.026	1.012
$c_{b,neg.}$	1.383	1.739
$c_{b,pos.}$	1.232	1.322

M_T^{WZ} distribution in the limit of c_b of aTGC for QCD mediated production of $W^{\pm}Z$:



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- have a look on the impact of dim-8 operators in the VBS phase space
- compare the dim-6 and dim-8 operators impact
- calculate the uncertainty of the dim-8 limits and the cross section σ with the impact of dim-6 operators

Thank you for your attention!

Dim-6 operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Dim-6 operators

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

The inclusive $W^{\pm}Z$ phase space:

- less than four leptons passing the baseline selection*
- three leptons passing the Z lepton selection*
- leading lepton $p_T > 27\ GeV$
- two leptons with same flavour and opposite charge passing the Z lepton selection*
- mass window: $|M_{\ell\ell} - M_Z| < 10\ GeV$
- remaining lepton passing W lepton selection*
- W-lepton and p_T^{miss} have $m_T^W > 30\,GeV$

* [ATLAS-Note STDM-2018-03]