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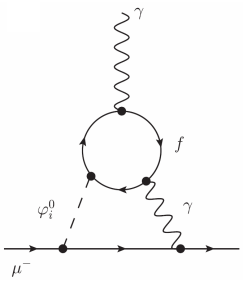
# Search for a light CP-odd Higgs boson with the ATLAS detector

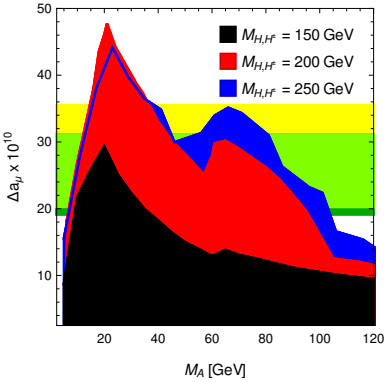
## Session T 82: Higgs, Di-Higgs II

DPG Spring Meeting Dresden, 22nd of March, 2023

# Motivation

- $4.2\sigma$ deviation in $a_\mu$ between experiment[1] and SM
- possible solution: introduce 2nd Higgs doublet
- flavour-aligned 2HDM, scaling factors $\zeta$:
  - ⇒ leptons: $\zeta_l \approx 50$
  - ⇒ up-type quarks: $\zeta_u \approx 0.5$
  - ⇒ down-type quarks: $\zeta_d \approx 0$
- analysis mass points: $m_A = 20 - 110\,\mathrm{GeV}$



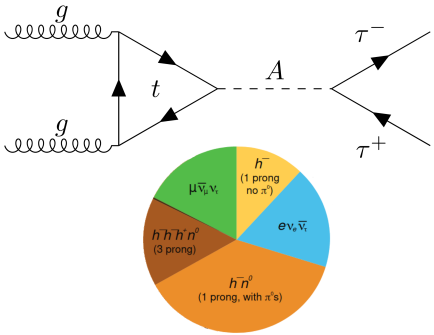

JHEP **09** (2021) 080

[1] Phys. Rev. Lett. **126** (14 2021) 141801

# Signal process

- entirely defined by couplings
  - ⇨ cross-section calculated with ggHiggs[2]
- leptonic decays due to trigger thresholds

→ $A \to \tau\tau \to e + \mu \left(+\nu_e \nu_\mu \nu_\tau \nu_\tau\right)$

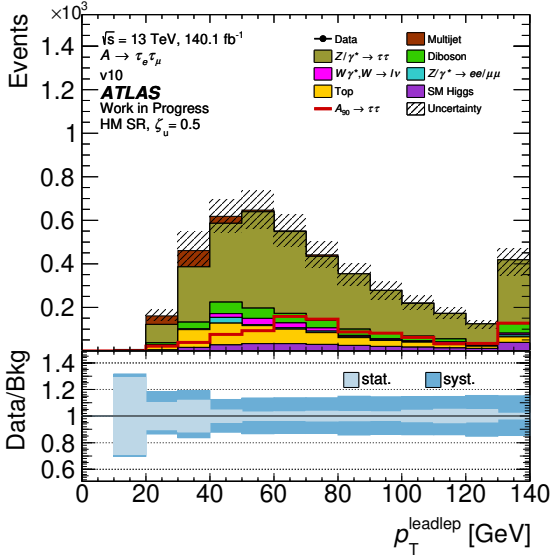



| $m_A$/GeV | 20 | 50 | 80 | 110 | 125 ($m_{h,\mathrm{SM}}$) |
|---|---|---|---|---|---|
| N$^3$LO xsec / pb | 463.5 | 128.6 | 59.7 | 34.3 | 47 ± 3 |
| exp. production for 140 fb$^{-1}$ in millions | 64.9 | 18.0 | 8.4 | 4.8 | 6.6 |
| uncertainty / % | 11.2 | 8.2 | 7.0 | 6.5 | 6.5 |

[2] https://www.ge.infn.it/~bonvini/higgs/

# Background processes

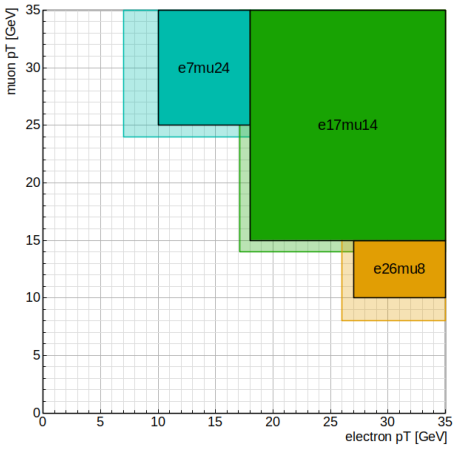
- Data
- Multijet
- $Z/\gamma^* \rightarrow \tau\tau$
- Diboson
- $W\gamma^*, W \rightarrow l\nu$
- $Z/\gamma^* \rightarrow ee/\mu\mu$
- Top
- SM Higgs
- $A_{90} \rightarrow \tau\tau$
- Uncertainty




- main background: $Z/\gamma^*$ + jets $\rightarrow \tau\tau$
- except Multijet estimated from Monte Carlo (MC) simulations
- Multijet = jets misidentified as leptons
  - ⇨ data-driven method (see next talk)

# Baseline selection and trigger

- combination of electron–muon triggers
- opposite charge
- reject events with $b$-tagged jets



# Analysis selection cuts

- two mass ranges: low-/high-mass signal region (SR)

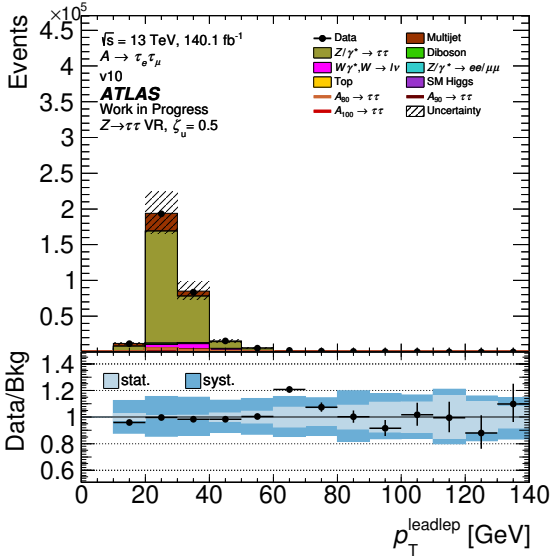
| | $m_A$ | $(20-80)$ GeV | $(80-110)$ GeV |
|---|---|---|---|
| $E_{\mathrm{T}}^{\mathrm{miss}}$ **cut** | $E_{\mathrm{T}}^{\mathrm{miss}}$ | $> 50$ GeV | $> 30$ GeV |
| | | → general background reduction | |
| **Mass cut**[3] | $m_{\mathrm{T}}^{\mathrm{tot}}$ | $< 45$ GeV | $< 65$ GeV |
| | | → reduction of Top & Diboson background | |
| **Angular cut**[4] | $\Delta R_{ll}$ | $< 0.7$ | $< 1.0$ |
| | | → reduction of $Z \to \tau\tau$ background | |

[3] $m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{\left(p_{\mathrm{T}}^{e} + p_{\mathrm{T}}^{\mu} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 + \left(\vec{p}_{\mathrm{T}}^{\,e} + \vec{p}_{\mathrm{T}}^{\,\mu} + \vec{E}_{\mathrm{T}}^{\,\mathrm{miss}}\right)^2}$

[4] $\Delta R = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2}$

# $Z \to \tau\tau$ validation region

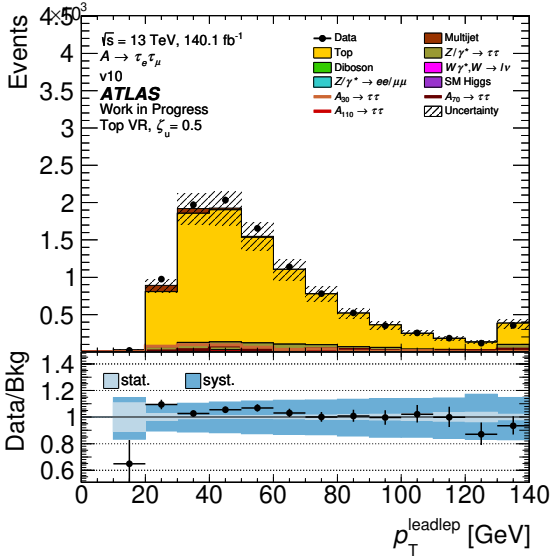
- Data
- $Z/\gamma^* \to \tau\tau$
- $W\gamma^*, W \to l\nu$
- Top
- $A_{80} \to \tau\tau$
- $A_{100} \to \tau\tau$
- Multijet
- Diboson
- $Z/\gamma^* \to ee/\mu\mu$
- SM Higgs
- $A_{90} \to \tau\tau$
- Uncertainty




- orthogonality to SR by inverting $\Delta R_{ll}$ cut:
  - ⇨ $\Delta R_{ll} > 1.4$
- $Z \to \tau\tau$ MC reweighted on basis of $n_{\text{jets}}$ distribution
  - ⇨ see following talk

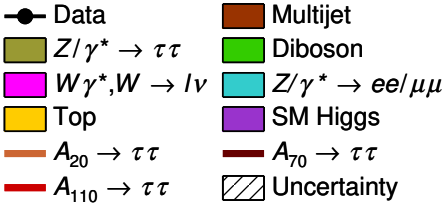
# Top validation region

- Data
- Top
- Diboson
- $Z/\gamma^* \rightarrow ee/\mu\mu$
- $A_{30} \rightarrow \tau\tau$
- $A_{110} \rightarrow \tau\tau$
- Multijet
- $Z/\gamma^* \rightarrow \tau\tau$
- $W\gamma^*, W \rightarrow l\nu$
- SM Higgs
- $A_{70} \rightarrow \tau\tau$
- Uncertainty

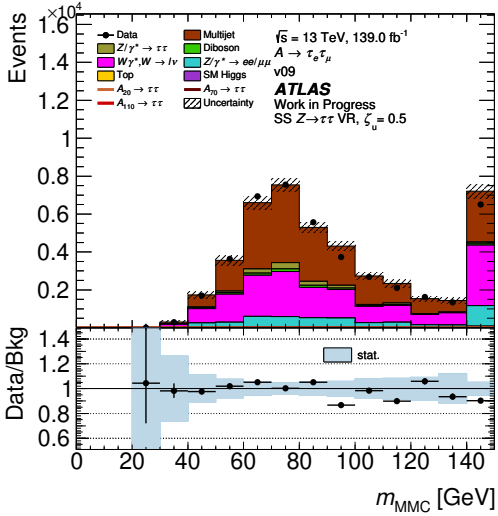



- orthogonality to SR:
  - ⇨ $n_{b-\text{jets}} > 0$
- NNLO QCD and NLO electro-weak reweighting applied
- region used to extract top generator uncertainties
  - ⇨ see following talk

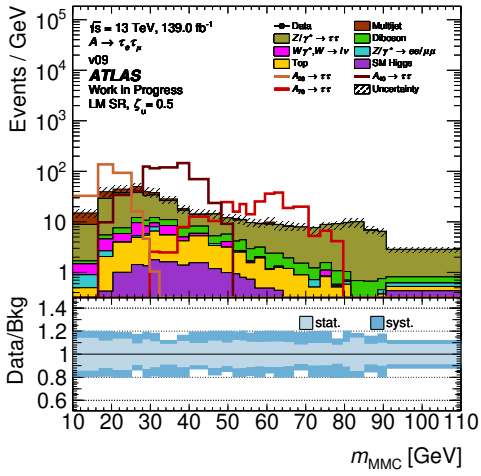
# Same-sign "$Z \to \tau\tau$ " validation region



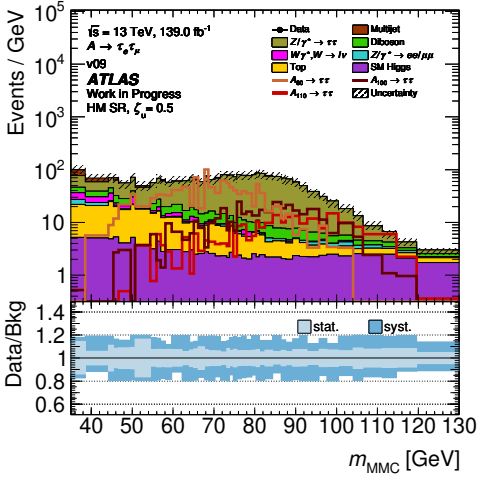

- only difference to $Z \to \tau\tau$ validation region:
  - ⇨ $q_e \cdot q_\mu = 1$
- used for validation of fake lepton background estimation
- MMC = tool to determine most probable Higgs boson mass from $E_{\mathrm{T}}^{\mathrm{miss}}$ and lepton properties



# Signal regions




low-mass SR



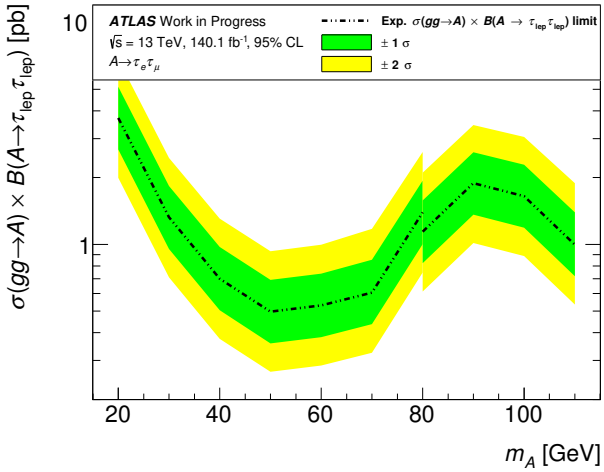

high-mass SR

# Expected cross-section limits

- final variable $m_{\text{MMC}}$
- discontinuity due to split into two SRs

Result includes systematics from:

- experimental sources
- cross-section predictions
- luminosity
- generator uncertainties
- fake lepton estimation
- $Z \to \tau\tau$ reweighting



# Expected $|\zeta_u|$ limits

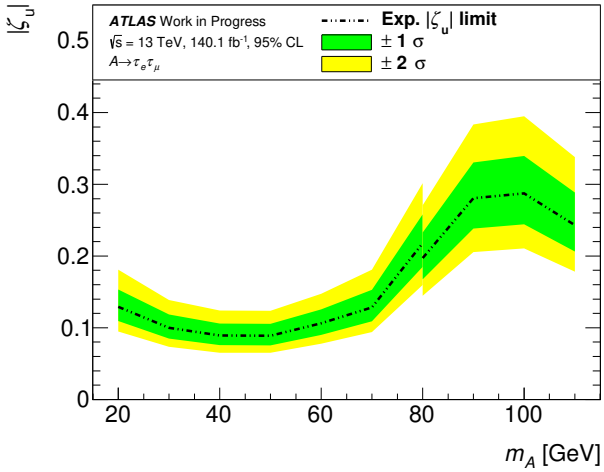
- final variable $m_{\text{MMC}}$
- discontinuity due to split into two SRs

Additional systematics included:

- signal cross-section
- signal generator uncertainties

Previous general limit[5]:

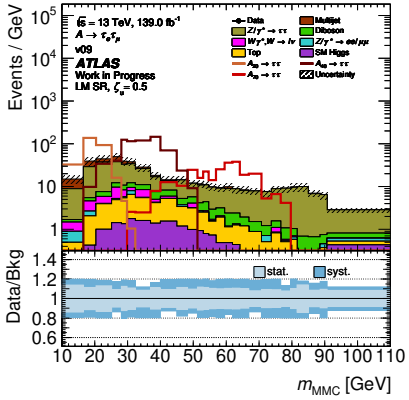
- $|\zeta_u| <\approx 0.5$
  - ⇒ large limit improvements expected




[5] JHEP **09** (2021) 080

# Summary and outlook

- deviation in $a_\mu$ explainable with low-mass CP-odd Higgs boson
- search $A \to \tau\tau \to e\mu + 4\nu$ presented
- major open point: validation of fake estimation method
  - ⇨ currently implementing matrix method
- aiming for publication in summer



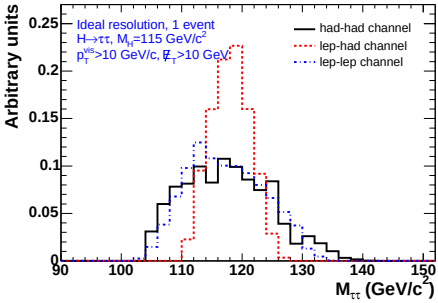
# Thank you for your attention!

Questions?

# Backup

# Backup - Missing mass calculator (MMC)

- tool to calculate most probable Higgs boson mass for decays to $\tau$-lepton pairs
  - ⇨ inputs: visible lepton kinematics, $E_{\mathrm{T}}^{\mathrm{miss}}$
  - ⇨ uses information about $\tau$-lepton decay kinematics
  - ⇨ whole possible phase space is scanned
    - ⇨ some solutions are more likely for given kinematics
  - ⇨ uses likelihood approach to find most likely Higgs mass
- note for selection: outputs $-1$ if algorithm does not converge




Nucl. Instrum. Meth. A **654** (2011) 481

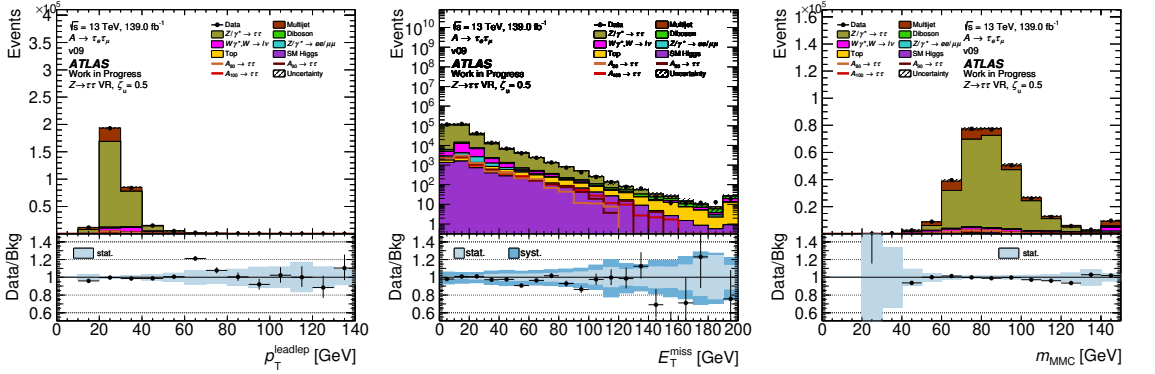
# Backup - Selection cuts

- selecting only events where lepton IDs are `Medium`, isolation `Tight` (`Tight_VarRad`)

| ***ATLAS*** Work in progress | | SR low-mass | SR high-mass | SS VR low-mass | SS VR high-mass | TVR | ZVR | SS ZVR |
|---|---|---|---|---|---|---|---|---|
| $E_{\mathrm{T}}^{\mathrm{miss}}$ **cut** | $E_{\mathrm{T}}^{\mathrm{miss}}$ | $> 50\,\mathrm{GeV}$ | $> 30\,\mathrm{GeV}$ | $> 50\,\mathrm{GeV}$ | $> 30\,\mathrm{GeV}$ | $> 30\,\mathrm{GeV}$ | – | – |
| **Mass cut**[a] | $m_{\mathrm{T}}^{\mathrm{tot}}$ | $< 45\,\mathrm{GeV}$ | $< 65\,\mathrm{GeV}$ | $< 45\,\mathrm{GeV}$ | $< 65\,\mathrm{GeV}$ | $< 65\,\mathrm{GeV}$ | $< 65\,\mathrm{GeV}$ | $< 65\,\mathrm{GeV}$ |
| **Angular cut**[b] | $\Delta R_{ll}$ | $< 0.7$ | $< 1.0$ | $< 0.7$ | $< 1.0$ | $< 1.0$ | $> 1.4$ | $> 1.4$ |
| **MMC cut** | $m_{\mathrm{MMC}}$ | $> 0\,\mathrm{GeV}$ | $> 35\,\mathrm{GeV}$ & $< 130\,\mathrm{GeV}$ | $> 0\,\mathrm{GeV}$ | $> 35\,\mathrm{GeV}$ & $< 130\,\mathrm{GeV}$ | $> 0\,\mathrm{GeV}$ | $> 0\,\mathrm{GeV}$ | $> 0\,\mathrm{GeV}$ |
| **Charge cut** | $q_e \cdot q_\mu$ | $-1$ | $-1$ | $1$ | $1$ | $-1$ | $-1$ | $1$ |
| $b$**-tag**[c] | $n_{b\text{-jets}}$ | $0$ | $0$ | $0$ | $0$ | $> 0$ | $0$ | $0$ |

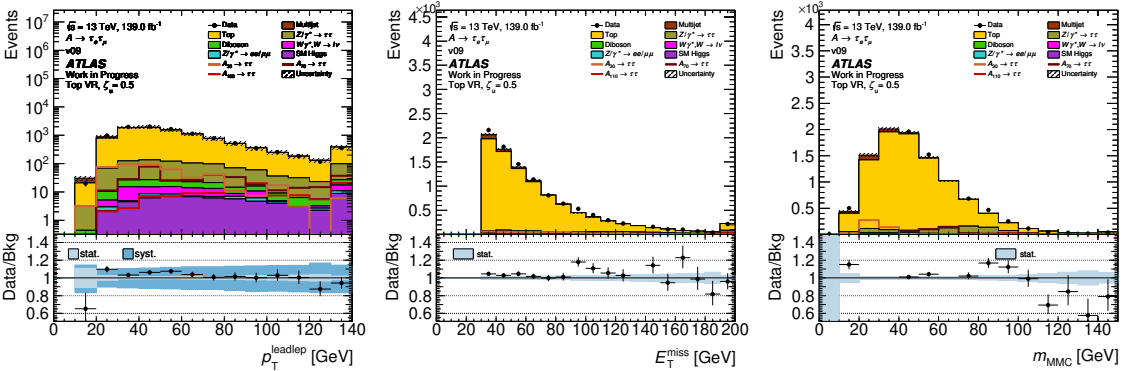
[a] $m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{\left(p_{\mathrm{T}}^{e} + p_{\mathrm{T}}^{\mu} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{\mathrm{T}}^{\,e} + \vec{p}_{\mathrm{T}}^{\,\mu} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)^2}$
[b] $\Delta R = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2}$
[c] $85\,\%$ efficiency WP

# Backup - $Z \to \tau\tau$ validation region




| Process | Data | Multijet | $Z/\gamma^* \to \tau\tau$ | Diboson | $W \to l\nu$ | $Z/\gamma^* \to \ell\ell$ | Top | SM Higgs | total Bkg |
|---|---|---|---|---|---|---|---|---|---|
| **ATLAS** Work in progress | 313216 | $37435 \pm 622$ (11.9 %) | $243552 \pm 1720$ (77.3 %) | $4294 \pm 25$ (1.4 %) | $16611 \pm 764$ (5.3 %) | $4845 \pm 235$ (1.5 %) | $3361 \pm 22$ (1.1 %) | $5101 \pm 11$ (1.6 %) | 315200 |

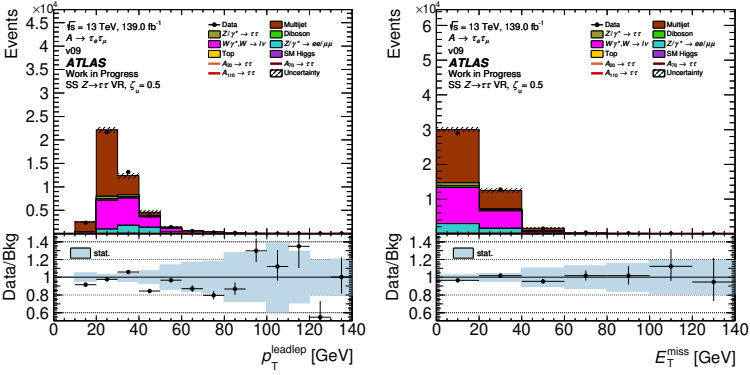
# Backup - Top validation region




| Process | Data | Multijet | $Z/\gamma^* \to \tau\tau$ | Diboson | $W\gamma*, W \to l\nu$ | $Z/\gamma^* \to \ell\ell$ | Top | SM Higgs | total Bkg |
|---|---|---|---|---|---|---|---|---|---|
| **ATLAS** Work in progress | 10361 | $201 \pm 26$ (2.0 %) | $762 \pm 24$ (7.7 %) | $87 \pm 3$ (0.9 %) | $53 \pm 12$ (0.5 %) | $12 \pm 2$ (0.1 %) | $8783 \pm 34$ (88.2 %) | $61 \pm 1$ (0.6 %) | 9959 |

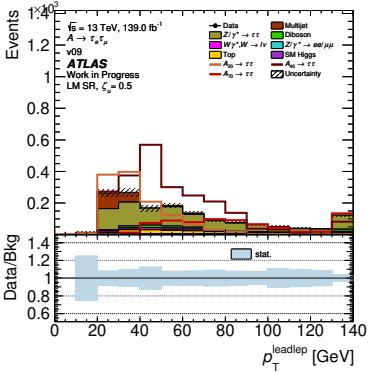
- NNLO QCD and NLO EW reweighting applied to `ttbar` samples

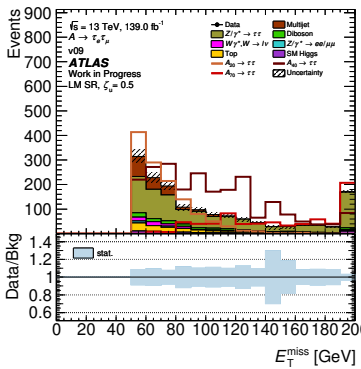
# Backup - SS "$Z \to \tau\tau$" validation region

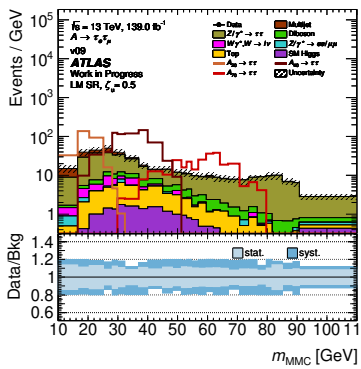



| Process | Data | Multijet | $Z/\gamma^* \to \tau\tau$ | Diboson | $W\gamma*, W \to l\nu$ | $Z/\gamma^* \to \ell\ell$ | Top | SM Higgs | total Bkg |
|---|---|---|---|---|---|---|---|---|---|
| **ATLAS** Work in progress | 43700 | $2154 \pm 411$ (48.3 %) | $1263 \pm 110$ (2.8 %) | $779 \pm 8$ (1.7 %) | $16166 \pm 725$ (36.2 %) | $4475 \pm 238$ (10.0 %) | $374 \pm 7$ (0.8 %) | $21 \pm 1$ (0.0 %) | 44624 |

# Backup - Low-mass signal region



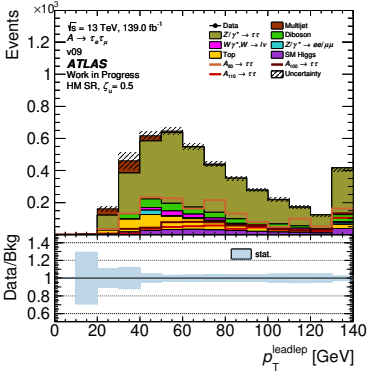



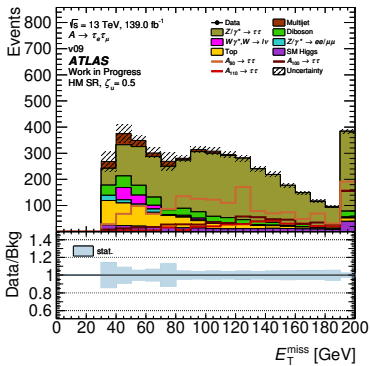



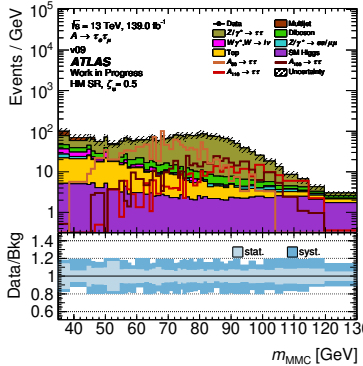

| Process | Data | Multijet | $Z/\gamma^* \to \tau\tau$ | Diboson | $W\gamma*, W \to l\nu$ | $Z/\gamma^* \to \ell\ell$ | Top | SM Higgs | total Bkg |
|---|---|---|---|---|---|---|---|---|---|
| ***ATLAS*** Work in progress | – | $191 \pm 26$ $(12.6\,\%)$ | $937 \pm 34$ $(61.7\,\%)$ | $108 \pm 2$ $(7.1\,\%)$ | $63 \pm 11$ $(4.1\,\%)$ | $16 \pm 5$ $(1.0\,\%)$ | $138 \pm 5$ $(9.1\,\%)$ | $67 \pm 1$ $(4.4\,\%)$ | 1518 |

- signal scaled with $\zeta_u = 0.5$

# Backup - High-mass signal region



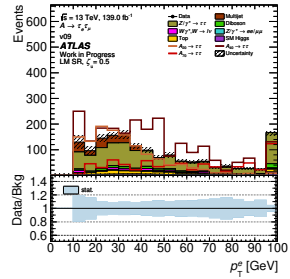

| Process | Data | Multijet | $Z/\gamma^* \to \tau\tau$ | Diboson | $W\gamma*, W \to l\nu$ | $Z/\gamma^* \to \ell\ell$ | Top | SM Higgs | total Bkg |
|---|---|---|---|---|---|---|---|---|---|
| **ATLAS** Work in progress | – | $153 \pm 26$ ($3.5\,\%$) | $2910 \pm 42$ ($65.8\,\%$) | $369 \pm 4$ ($8.3\,\%$) | $109 \pm 53$ ($2.5\,\%$) | $71 \pm 16$ ($1.6\,\%$) | $540 \pm 9$ ($12.2\,\%$) | $270 \pm 2$ ($6.1\,\%$) | 4422 |

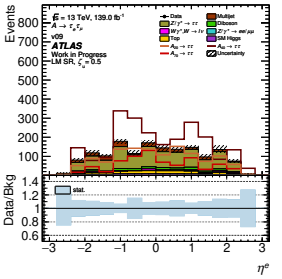
- signal scaled with $\zeta_u = 0.5$

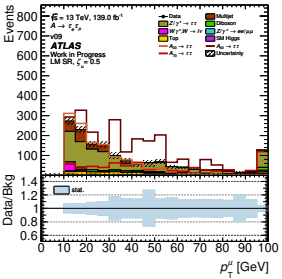
# Backup - High Level Triggers

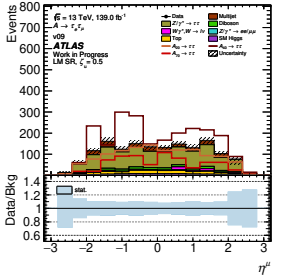
| Short version | period | trigger name |
|---|---|---|
| e7mu24 | 2015 | `HLT_e7_lhmedium_mu24` |
| e7mu24 | 2016-18 | `HLT_e7_lhmedium_nod0_mu24` |
| e17mu14 | 2015 | `HLT_e17_lhloose_mu14` |
| e17mu14 | 2016-18 | `HLT_e17_lhloose_nod0_mu14` |
| e26mu8 | 2015 | `HLT_e24_lhmedium_nod0_L1EM20VHI_mu8noL1` |
| e26mu8 | 2016 | `HLT_e26_lhmedium_nod0_L1EM22VHI_mu8noL1` |
| e26mu8 | 2017-8 | `HLT_e26_lhmedium_nod0_mu8noL1` |

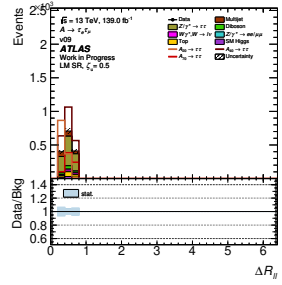
# Backup - Additional plots low-mass SR

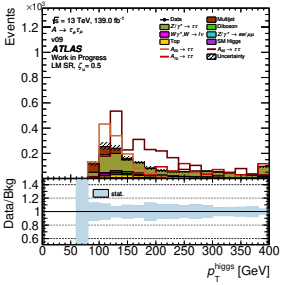

Events
Data/Bkg
$\sqrt{s}$ = 13 TeV, 139.0 fb$^{-1}$
$A \to \tau_e\tau_e$
v09
ATLAS
Work in Progress
LM SR, $\zeta_\tau$= 0.5
Data
$Z(\gamma^*\to\tau\tau$
$W\gamma^*/W\to l\nu$
Top
$A_{bb}\to\tau\tau$
$A_{tb}\to\tau\tau$
Multijet
Diboson
$Z(\gamma^*\to ee/\mu\mu$
SM Higgs
$A_{gg}\to\tau\tau$
Uncertainty
stat.
$p_T^e$ [GeV]

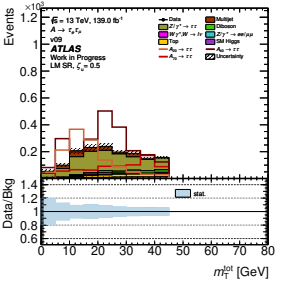

Events
Data/Bkg
$\sqrt{s}$ = 13 TeV, 139.0 fb$^{-1}$
$A \to \tau_e\tau_e$
v09
ATLAS
Work in Progress
LM SR, $\zeta_\tau$= 0.5
Data
$Z(\gamma^*\to\tau\tau$
$W\gamma^*/W\to l\nu$
Top
$A_{bb}\to\tau\tau$
$A_{tb}\to\tau\tau$
Multijet
Diboson
$Z(\gamma^*\to ee/\mu\mu$
SM Higgs
$A_{gg}\to\tau\tau$
Uncertainty
stat.
$\eta^e$

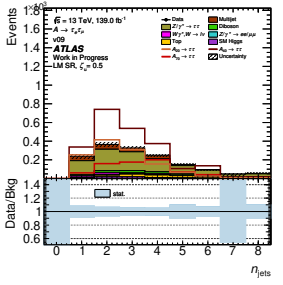

Events
Data/Bkg
$\sqrt{s}$ = 13 TeV, 139.0 fb$^{-1}$
$A \to \tau_e\tau_e$
v09
ATLAS
Work in Progress
LM SR, $\zeta_\tau$= 0.5
Data
$Z(\gamma^*\to\tau\tau$
$W\gamma^*/W\to l\nu$
Top
$A_{bb}\to\tau\tau$
$A_{tb}\to\tau\tau$
Multijet
Diboson
$Z(\gamma^*\to ee/\mu\mu$
SM Higgs
$A_{gg}\to\tau\tau$
Uncertainty
stat.
$p_T^\mu$ [GeV]


Events
Data/Bkg
$\sqrt{s}$ = 13 TeV, 139.0 fb$^{-1}$
$A \to \tau_e\tau_e$
v09
ATLAS
Work in Progress
LM SR, $\zeta_\tau$= 0.5
Data
$Z(\gamma^*\to\tau\tau$
$W\gamma^*/W\to l\nu$
Top
$A_{bb}\to\tau\tau$
$A_{tb}\to\tau\tau$
Multijet
Diboson
$Z(\gamma^*\to ee/\mu\mu$
SM Higgs
$A_{gg}\to\tau\tau$
Uncertainty
stat.
$\eta^\mu$


Events
Data/Bkg
$\sqrt{s}$ = 13 TeV, 139.0 fb$^{-1}$
$A \to \tau_e\tau_e$
v09
ATLAS
Work in Progress
LM SR, $\zeta_\tau$= 0.5
Data
$Z(\gamma^*\to\tau\tau$
$W\gamma^*/W\to l\nu$
Top
$A_{bb}\to\tau\tau$
$A_{tb}\to\tau\tau$
Multijet
Diboson
$Z(\gamma^*\to ee/\mu\mu$
SM Higgs
$A_{gg}\to\tau\tau$
Uncertainty
stat.
$\Delta R_{ll}$


Events
Data/Bkg
$\sqrt{s}$ = 13 TeV, 139.0 fb$^{-1}$
$A \to \tau_e\tau_e$
v09
ATLAS
Work in Progress
LM SR, $\zeta_\tau$= 0.5
Data
$Z(\gamma^*\to\tau\tau$
$W\gamma^*/W\to l\nu$
Top
$A_{bb}\to\tau\tau$
$A_{tb}\to\tau\tau$
Multijet
Diboson
$Z(\gamma^*\to ee/\mu\mu$
SM Higgs
$A_{gg}\to\tau\tau$
Uncertainty
stat.
$p_T^{higgs}$ [GeV]


Events
Data/Bkg
$\sqrt{s}$ = 13 TeV, 139.0 fb$^{-1}$
$A \to \tau_e\tau_e$
v09
ATLAS
Work in Progress
LM SR, $\zeta_\tau$= 0.5
Data
$Z(\gamma^*\to\tau\tau$
$W\gamma^*/W\to l\nu$
Top
$A_{bb}\to\tau\tau$
$A_{tb}\to\tau\tau$
Multijet
Diboson
$Z(\gamma^*\to ee/\mu\mu$
SM Higgs
$A_{gg}\to\tau\tau$
Uncertainty
stat.
$m_T^{tot}$ [GeV]


Events
Data/Bkg
$\sqrt{s}$ = 13 TeV, 139.0 fb$^{-1}$
$A \to \tau_e\tau_e$
v09
ATLAS
Work in Progress
LM SR, $\zeta_\tau$= 0.5
Data
$Z(\gamma^*\to\tau\tau$
$W\gamma^*/W\to l\nu$
Top
$A_{bb}\to\tau\tau$
$A_{tb}\to\tau\tau$
Multijet
Diboson
$Z(\gamma^*\to ee/\mu\mu$
SM Higgs
$A_{gg}\to\tau\tau$
Uncertainty
stat.
$n_{jets}$

# Backup - Systematic uncertainties in the low-mass SR

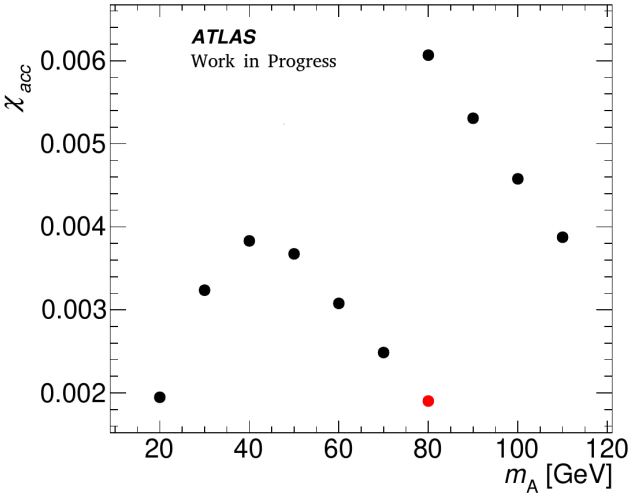
| Process | $Z \to \tau\tau$ | Multijet | Top | Diboson | $Z \to ll$ | $W\gamma*, W \to l\nu$ | SM Higgs |
|---|---|---|---|---|---|---|---|
| Systematics group | ***ATLAS*** Work in progress | | | Relative uncertainty in % | | | |
| EG | $^{+0.00}_{-0.48}$ | $^{+2.42}_{-0.64}$ | $^{+0.17}_{-0.68}$ | $^{+0.67}_{-0.17}$ | $^{+9.14}_{-1.20}$ | $^{+3.52}_{-0.04}$ | $^{+0.49}_{-0.27}$ |
| EL_EFF | $^{+0.36}_{-0.36}$ | $^{+1.66}_{-1.65}$ | $^{+0.29}_{-0.29}$ | $^{+0.29}_{-0.29}$ | $^{+0.26}_{-0.26}$ | $^{+0.92}_{-0.91}$ | $^{+0.24}_{-0.24}$ |
| MUON | $^{+0.23}_{-0.45}$ | $^{+1.17}_{-0.11}$ | $^{+0.18}_{-0.33}$ | $^{+0.31}_{-0.03}$ | $^{+1.83}_{-1.94}$ | $^{+0.45}_{-1.01}$ | $^{+0.09}_{-0.05}$ |
| MUON_EFF | $^{+1.69}_{-1.69}$ | $^{+1.60}_{-1.60}$ | $^{+1.42}_{-1.42}$ | $^{+1.33}_{-1.33}$ | $^{+4.76}_{-1.78}$ | $^{+2.00}_{-2.00}$ | $^{+1.20}_{-1.20}$ |
| JET | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ |
| JET_EFF | $^{+0.47}_{-0.42}$ | $^{+0.53}_{-0.58}$ | $^{+1.72}_{-1.64}$ | $^{+0.63}_{-0.59}$ | $^{+1.92}_{-1.95}$ | $^{+0.27}_{-0.30}$ | $^{+0.65}_{-0.61}$ |
| MET | $^{+1.30}_{-0.64}$ | $^{+3.33}_{-1.82}$ | $^{+1.79}_{-2.02}$ | $^{+1.57}_{-1.61}$ | $^{+10.25}_{-2.31}$ | $^{+3.84}_{-3.67}$ | $^{+0.33}_{-0.29}$ |
| FT_EFF | $^{+1.04}_{-1.03}$ | $^{+1.56}_{-1.59}$ | $^{+10.40}_{-9.93}$ | $^{+1.14}_{-1.13}$ | $^{+0.96}_{-0.95}$ | $^{+0.97}_{-0.96}$ | $^{+0.97}_{-0.96}$ |
| PRW | $^{+0.77}_{-0.35}$ | $^{+2.11}_{-3.34}$ | $^{+0.09}_{-0.08}$ | $^{+0.51}_{-0.71}$ | $^{+0.00}_{-0.67}$ | $^{+0.00}_{-1.93}$ | $^{+0.61}_{-0.71}$ |
| QCDFF | $^{+0.00}_{-0.00}$ | $^{+10.81}_{-10.59}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ |
| TTBar | $^{+0.00}_{-0.00}$ | $^{+1.12}_{-1.01}$ | $^{+12.27}_{-13.26}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ |
| Ztautau_MCGenSys | $^{+3.79}_{-8.55}$ | $^{+3.29}_{-1.41}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ |
| Ztautau_NJetWt | $^{+7.47}_{-7.43}$ | $^{+2.44}_{-2.46}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ |
| Diboson_MCGenSys | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+5.64}_{-6.89}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ | $^{+0.00}_{-0.00}$ |
| total systematics | $^{+8.76}_{-11.55}$ | $^{+12.87}_{-12.01}$ | $^{+16.34}_{-16.85}$ | $^{+6.21}_{-7.35}$ | $^{+14.81}_{-4.35}$ | $^{+5.76}_{-4.90}$ | $^{+1.90}_{-1.86}$ |
| statistical | $\pm 3.64$ | $\pm 13.37$ | $\pm 3.12$ | $\pm 1.94$ | $\pm 28.01$ | $\pm 17.20$ | $\pm 1.22$ |
| nominal | 937.04 | 190.69 | 137.70 | 107.94 | 15.62 | 62.63 | 66.56 |

# Backup - Cutflow for A70 in the low-mass SR

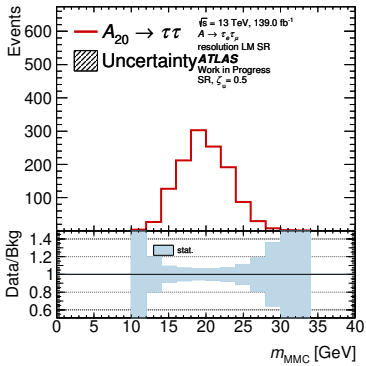
| ATLAS Work in progress | Events passed | Efficiency | Cumulative Efficiency |
|---|---|---|---|
| AOD | 203000.0 | 1.000 | 1.000 |
| DAOD HIGG3D1 | 26351.0 | 0.130 | 0.130 |
| >= 1 muon | 19230.0 | 0.730 | 0.095 |
| >= 1 electron | 6685.0 | 0.348 | 0.033 |
| E-Mu or single lepton trigger | 6002.0 | 0.898 | 0.030 |
| trigger efficiency threshold cut | 5342.0 | 0.890 | 0.026 |
| $q_e * q_\mu = -1$ | 5261.0 | 0.985 | 0.026 |
| $n_{\text{b-jets}} = 0$ | 4920.0 | 0.935 | 0.024 |
| JvT & FJvT SF | 4920.0 | 1.000 | 0.024 |

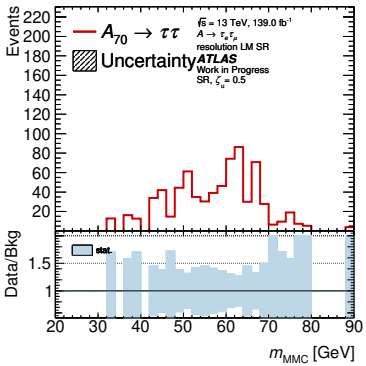
| ATLAS Work in progress | Events passed | Efficiency | Cumulative Efficiency |
|---|---|---|---|
| presel | 26098.3 | 1.000 | 1.000 |
| EMU triggers | 19397.0 | 0.743 | 0.743 |
| $n_{\text{lep}} = 2$ | 19303.3 | 0.995 | 0.740 |
| lepton ID *medium* | 17871.8 | 0.926 | 0.685 |
| lepton isolation *tight* | 12706.8 | 0.711 | 0.487 |
| $m_{\text{MMC}} > 0\,\text{GeV}$ | 12228.0 | 0.962 | 0.469 |
| $E_{\text{T}}^{\text{miss}} > 50\,\text{GeV}$ | 3603.4 | 0.295 | 0.138 |
| $m_{\text{T}}^{\text{tot}} < 45\,\text{GeV}$ | 2474.3 | 0.687 | 0.095 |
| $\Delta R_{ll} < 0.7$ | 786.2 | 0.318 | 0.030 |
| lepton SFs | 729.5 | 0.928 | 0.028 |

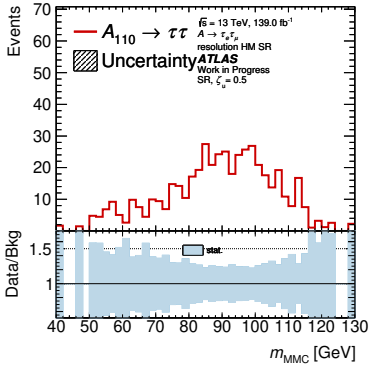
# Backup - Signal acceptance



# Backup - Signal resolution

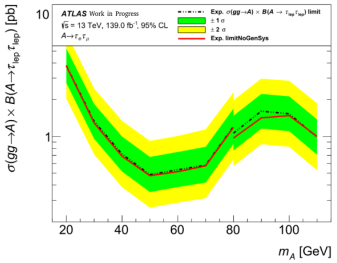


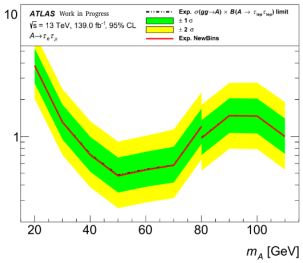



# Backup - Influence of generator systematics on expected limits

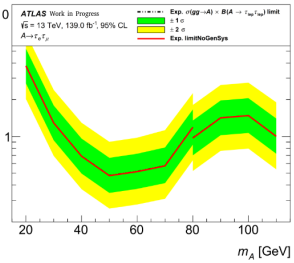
Z → ττ: max. 14%



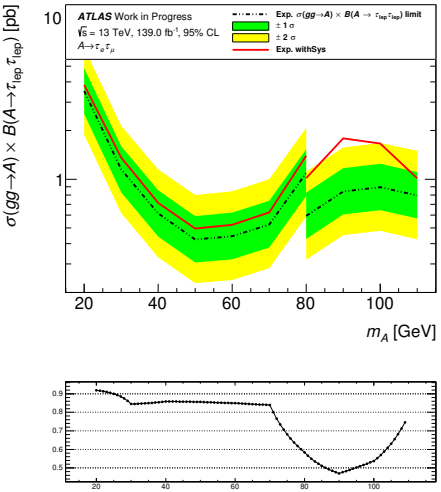

$t\bar{t}$: max. 1.4%



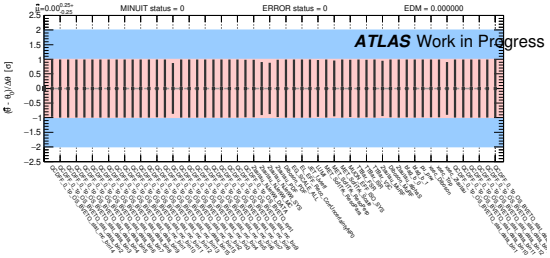

Diboson: max. 0.3%



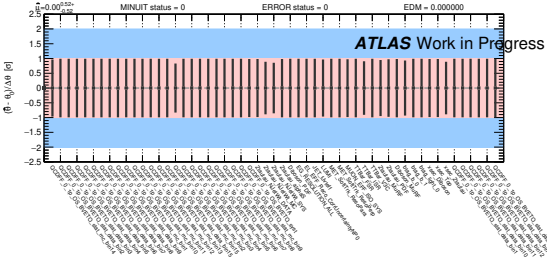
# Backup - STAT only expected limits



# Backup - Fit check - pull plots

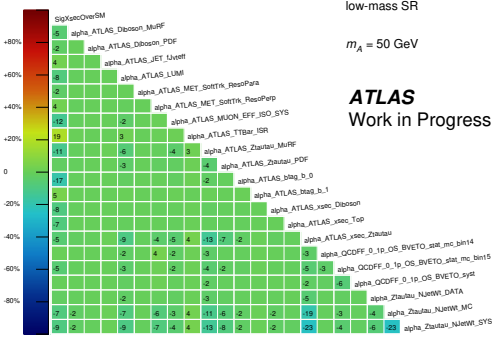


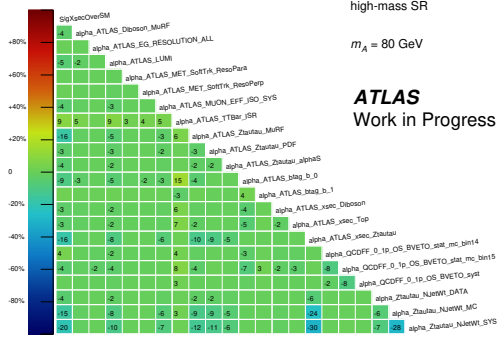

- fit with Asimov dataset for cross-section limit
- signal A50 in the low-mass SR




- fit with Asimov dataset for cross-section limit
- signal A80 in the high-mass SR

# Backup - Fit check - correlation matrices




- fit with Asimov dataset for cross-section limit
- signal A50 in the low-mass SR

- fit with Asimov dataset for cross-section limit
- signal A80 in the high-mass SR

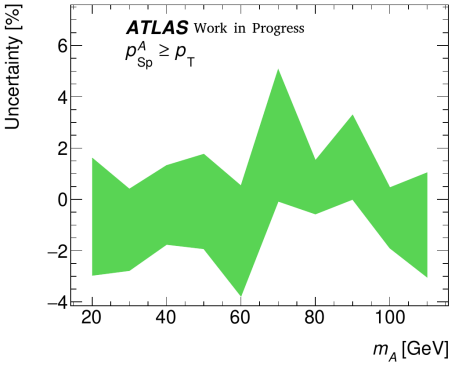
# Backup - Pruning of systematics

- following procedure from $VHbb$ Run 1 analysis:
  - ⇨ smoothing of uncertainties
  - ⇨ neglect normalization uncertainties if:
    - ⇨ variation is smaller than $1\,\%$
  - ⇨ neglect shape uncertainties if:
    - ⇨ no bin has deviation greater than $1\,\%$
- only the following experimental NPs survive pruning for at least one SR and signal:

ATLAS_btag_b_0
ATLAS_btag_b_1
ATLAS_btag_c_0
ATLAS_btag_light_0
ATLAS_EG_RESOLUTION_ALL
ATLAS_EG_SCALE_AF2
ATLAS_EG_SCALE_ALL
ATLAS_EL_EFF_ID_SIMPLIFIED_UncorrUncertaintyNP2
ATLAS_EL_EFF_ID_SIMPLIFIED_UncorrUncertaintyNP11
ATLAS_EL_EFF_ID_SIMPLIFIED_UncorrUncertaintyNP13
ATLAS_EL_EFF_Reco_CorrUncertaintyNP0
ATLAS_JET_fJvteff
ATLAS_LUMI
ATLAS_MET_SoftTrk_ResoPara
ATLAS_MET_SoftTrk_ResoPerp
ATLAS_MET_SoftTrk_Scale
ATLAS_MUON_CB
ATLAS_MUON_EFF_ISO_SYS
ATLAS_MUON_EFF_TrigStatUncertainty_e17mu14
ATLAS_MUON_SAGITTA_RESBIAS
ATLAS_MUON_SCALE
ATLAS_pu_prw

# Backup - Signal modeling systematics

- estimated uncertainties from FSR scale, ISR scale, multi-parton interactions, color reconnection, scale variations, $\alpha_s$ variations and PDF variations
- example for scale variation uncertainties in higher $p_T^A$ bin ($99\,\%$ of statistics):



# Backup - Experimental uncertainties

- following CP group recommendations for full Run 2 data
- large number of NPs for “EL_EFF” due to 3 triggers and uncertainty scheme `1NP_v1` with many NPs

| NP name | Description **ATLAS** Work in progress | NPs |
|---|---|---|
| “LUMI” | Integrated luminosity measurement | 1 |
| “MUON” | muon resolution and energy scale | 4 |
| “MUON_EFF” | muon systematics from including trigger, reconstruction, isolation and identification | 9 |
| “EG” | electron resolution and energy scale | 3 |
| “EL_EFF” | electron systematics from trigger, reconstruction, isolation and identification | 176 |
| “MET” | $E_{\mathrm{T}}^{\mathrm{miss}}$ soft term resolution and scale | 3 |
| “JET” | jet energy scale and resolution | 17 |
| “JET_EFF” | jet vertex tagging efficiency | 2 |
| “btag” | flavor-tagging | 11 |
| “PRW” | pile-up | 1 |

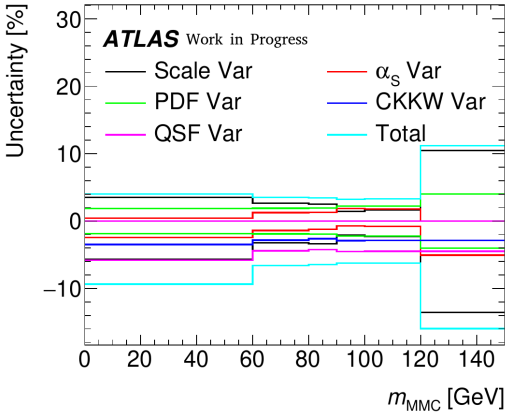
# Backup - Theoretical uncertainties

- cross-section uncertainties
  - ⇨ following PMG recommendations
- fake factor systematics
  - ⇨ taking into account statistical uncertainties on data + MC and experimental systematics
  - ⇨ smoothed by smoothing algorithm, statistical uncertainties decorrelated for each bin
- generator uncertainties for $Z \to \tau\tau$, diboson and $t\bar{t}$ samples
- $Z \to \tau\tau$ reweighting uncertainties
  - ⇨ taking into account statistical uncertainties on data + MC and experimental systematics
- signal modeling uncertainties for model-dependent search

| NP name | Description | NPs | Order |
|---|---|---|---|
| | **ATLAS** Work in progress | | |
| "xsec_Ztautau" | Cross section prediction uncertainty | 1 | 5% |
| "xsec_Diboson" | Cross section prediction uncertainty | 1 | 7.1% |
| "xsec_Top" | Cross section prediction uncertainty | 1 | 4.4% |
| "QCDFF " | Fake factor systematics | 29 | - |
| "TTBar" | Top modeling systematics | 5 | - |
| "Ztautau_MCGenSys" | $Z$+jets generator systematics | 5 | - |
| "Diboson_MCGenSys" | Diboson generator systematics | 3 | - |
| "Ztautau_NJetWt" | $Z \to \tau\tau$ $N_{\text{Jets}}$ reweighting uncertainty | 3 | - |

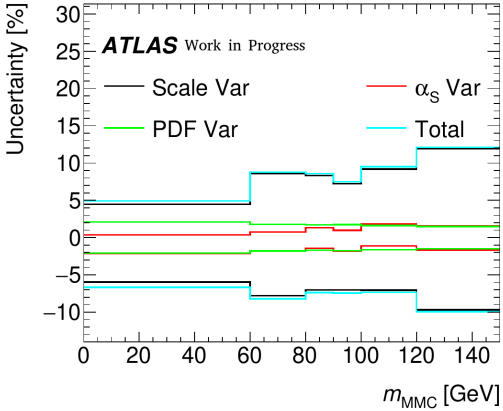
# Backup - $Z \to \tau\tau$ generator systematics

- following PMG recommendations for weak boson processes
- estimated uncertainties from scale, $\alpha_s$, CKKW, QSF and PDF variations
- insufficient statistics in SR
  - ⇨ relative uncertainties estimated in ZVR
  - ⇨ additional cut $n_{\text{jets}} > 0$ in ZVR to get closer to SR
  - ⇨ relative uncertainties applied in SR
- recently integrated in fit



# Backup - Diboson generator systematics

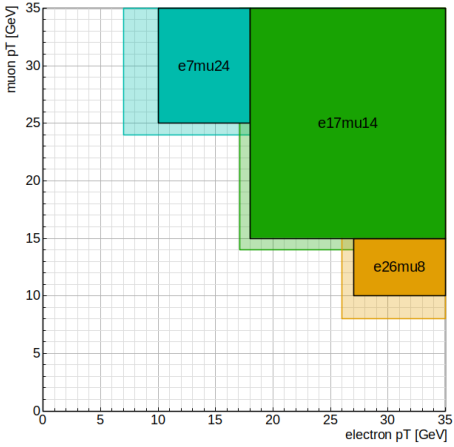
- following PMG recommendations for weak boson processes
- estimated uncertainties from scale, $\alpha_s$ and PDF variations
- CKKW & QSF need explicit variation samples that are not fully available according to PMG
  - ⇨ neglected, since Diboson is only a minor background in this analysis
- insufficient statistics in SR
  - ⇨ relative uncertainties estimated in ZVR
  - ⇨ additional cut $n_{\text{jets}} > 0$ in ZVR to get closer to SR
  - ⇨ relative uncertainties applied in SR
- recently integrated in fit



# Backup - Baseline selection and trigger

- combination of electron–muon triggers
- opposite charge
- loose lepton isolation and ID
- reject events with $b$-tagged jets
- overlap removal:

| removed object | kept object | angular separation $\Delta R$[5] |
|---|---|---|
| electron | muon | 0.2 |
| jet | electron | 0.4 |
| jet | muon | 0.4 |

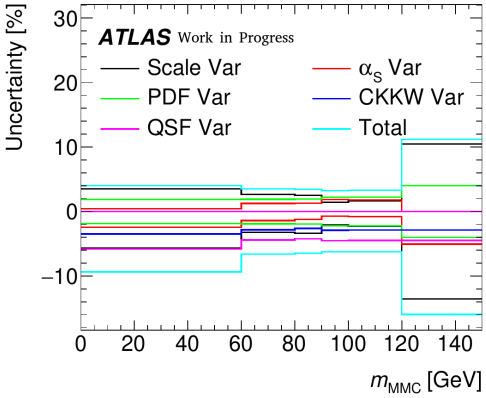



[6] $\Delta R = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2}$

# Backup - Systematic uncertainties

- experimental sources:
  - ⇨ efficiencies, detector calibration
- data-driven Multijet estimation
- generator uncertainties for $Z \to \tau\tau$, Top, Diboson and signal
  - ⇨ including scale, PDF, $\alpha_s$, CKKW and QSF variations
- $Z \to \tau\tau$ reweighting uncertainties

→ more about uncertainties in the following talks!




$Z \to \tau\tau$ generator uncertainties