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

DPG Spring Meeting 2024, T 21: BSM Higgs 1

Manuel Gutsche, Asma Hadef, Tom Kresse, Christian Schmidt, Arno Straessner
Institute of Nuclear and Particle Physics, TU Dresden

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INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS
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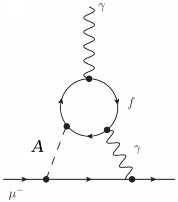
ATLAS EXPERIMENT

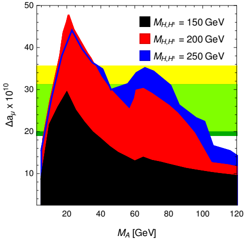
Motivation

- Motivation: up to $5\,\sigma$ deviation in anomalous magnetic moment of the muon a_μ between experiment and Standard Model (SM)

- flavour-aligned two-Higgs-doublet model (2HDM)
- 4 new Higgs bosons, one of them being the CP-odd A boson
- free parameters such as masses and scaling factors ζ:
  - $\Rightarrow$ leptons: $\zeta_l \approx 50$
  - $\Rightarrow$ up-type quarks: $\zeta_u \approx 0.5$
  - $\Rightarrow$ down-type quarks: $\zeta_d \approx 0$

- deviation explained for large ζ_l & light A
  - $\Rightarrow$ this search: $m_A = 20, 30, \ldots 110\,\mathrm{GeV}$



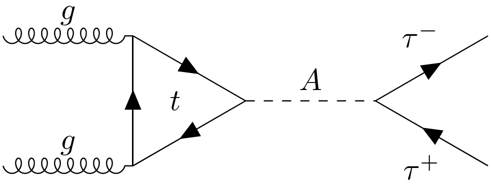


https://arxiv.org/pdf/2104.03691.pdf

Signal Process

- production of A via ggF and top quark loop
- cross-section calculated via ggHiggs
- decay 100 % to τ pairs
- only leptonic channels because of trigger thresholds

  $\Rightarrow$ mainly boosted topology
- restriction to electron-muon final state to reject $Z \to ll$ events



$\Rightarrow A \to \tau\tau \to e + \mu\,(+\nu_e\nu_\mu\nu_\tau\nu_\tau)$

Background Processes

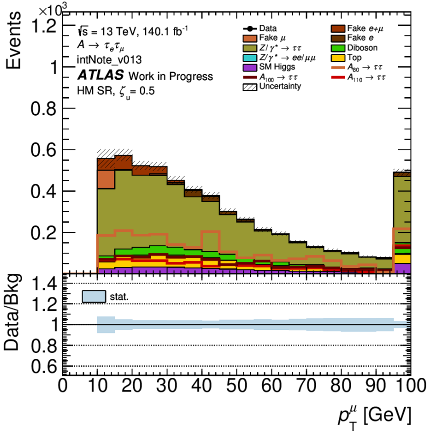
- largest background is $Z/\gamma^* + \text{jets} \to \tau\tau$
- fake lepton background(s)

  $\Rightarrow$ particles reconstructed as prompt leptons, but are e.g. misidentified jets

  $\Rightarrow$ deficiently modeled by Monte Carlo

  $\Rightarrow$ estimated via data-driven matrix method
- other MC backgrounds

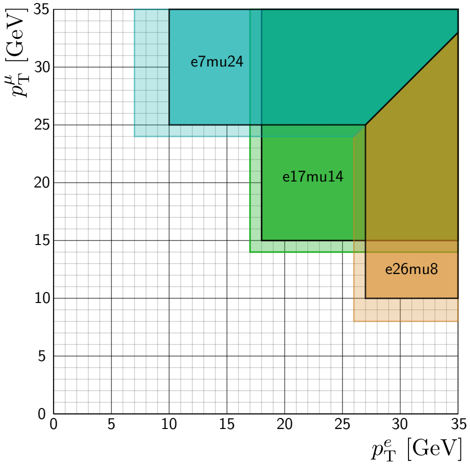
Fake μ | Fake e+μ
$Z/\gamma^* \to \tau\tau$ | Fake e
$Z/\gamma^* \to ee/\mu\mu$ | Diboson
SM Higgs | Top



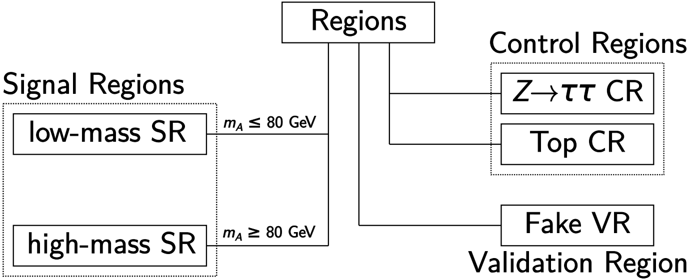
Selection Criteria

- 1 electron and 1 muon, opposite charge
- `Medium` ID and `Tight` isolation
- electron:
  $p_{\mathrm{T}} > 7\,\mathrm{GeV}$, $|\eta| < 2.47$, $|\eta| \notin (1.37, 1.52)$
  muon:
  $p_{\mathrm{T}} > 7\,\mathrm{GeV}$, $|\eta| < 2.7$
- overlap removal prioritizing muons over electrons over jets

3 electron-muon triggers



Selection Cuts Defining Regions



- high missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $\Rightarrow$ expecting neutrinos
- low transverse mass[a] $m_{\mathrm{T}}^{\mathrm{tot}}$
  - $\Rightarrow$ diboson & top suppression
- low angular separation[b] $\Delta R_{\ell\ell}$
  - $\Rightarrow$ $Z \to \tau\tau$ suppression
- no b-tagged jets
  - $\Rightarrow$ top suppression

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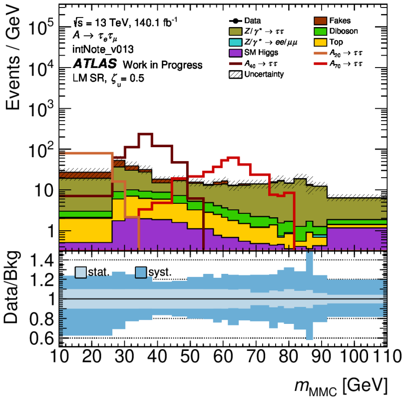
[a] $m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{\left(p_{\mathrm{T}}^{e} + p_{\mathrm{T}}^{\mu} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{\mathrm{T}}^{\,e} + \vec{p}_{\mathrm{T}}^{\,\mu} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)^2}$

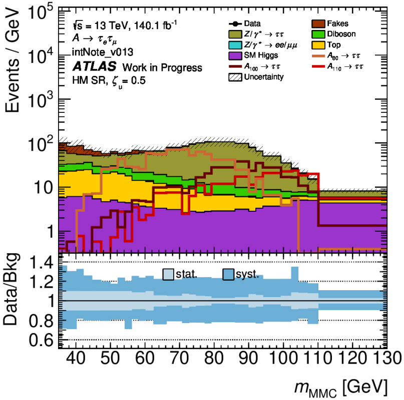
[b] $\Delta R_{\ell\ell} = \sqrt{(\Delta\Phi_{\ell\ell})^2 + (\Delta\eta_{\ell\ell})^2}$

Signal regions

low-mass SR



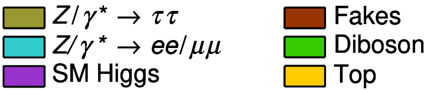
high-mass SR

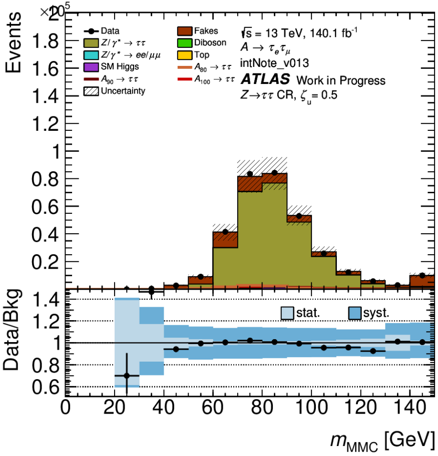


⇒ m_{MMC} is Higgs mass reconstructed via Missing Mass Calculator, which estimates neutrino energy with likelihood approach

$Z \to \tau\tau$ CR

- separated from SRs by inverted $\Delta R_{\ell\ell}$ cut
- validate (main) background modeling
- reweight $Z \to \tau\tau$ MC in dependence on n_{jets}
- used as control region for fit

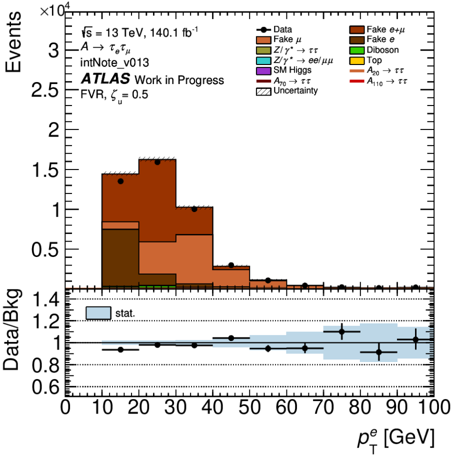




Fake (Lepton) VR

- same cuts as $Z \to \tau\tau$ CR, except $q_e \cdot q_\mu = 1$
- calculation of fake lepton efficiencies for matrix method
- validate fake lepton background modeling

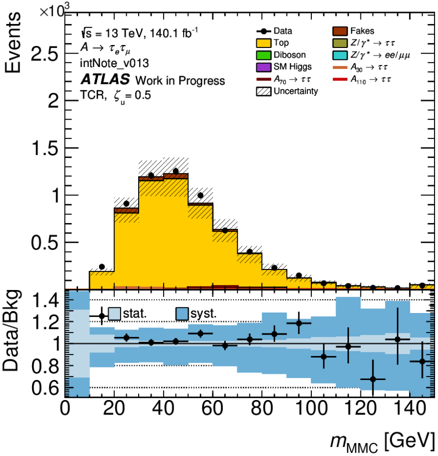
Fake μ | Fake e+μ
$Z/\gamma^* \to \tau\tau$ | Fake e
$Z/\gamma^* \to ee/\mu\mu$ | Diboson
SM Higgs | Top



Top CR

- separated from SRs by requiring at least 2 b-jets
- validate Top background modeling
- used as control region for fit

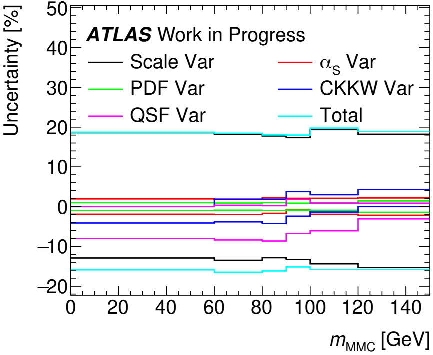
$Z/\gamma^* \to \tau\tau$ | Fakes
$Z/\gamma^* \to ee/\mu\mu$ | Diboson
SM Higgs | Top



Systematics

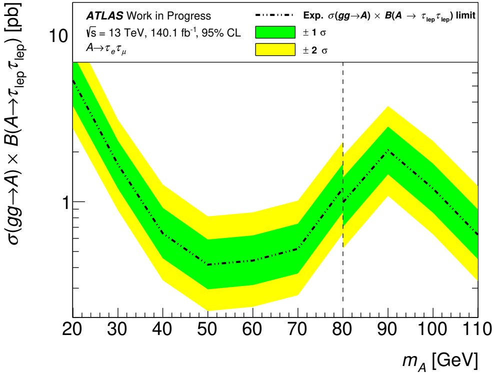
- experimental systematics on efficiencies, detector calibration, missing transverse momentum, pileup reweighting, luminosity
- uncertainties of MC samples
  - ⇒ cross-section uncertainties
  - ⇒ generator uncertainties for $Z \to \tau\tau$, Top, Diboson, Signal
- uncertainties of fake background modeling
  - ⇒ statistical uncertainty of efficiencies, parametrizations, composition
- uncertainties of $Z \to \tau\tau$ reweighting

$Z \to \tau\tau$ generator systematics



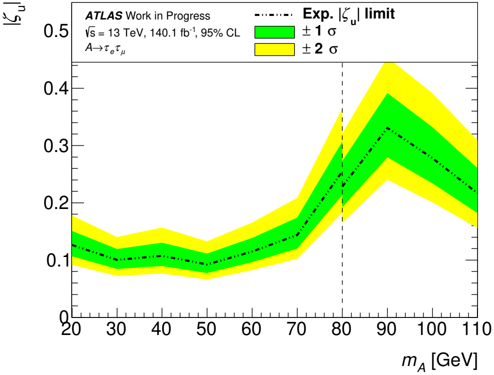
Expected Cross-section Limits

- binned likelihood fit of m_{MMC} distribution for each mass hypothesis
- fit and limit calculation done via TRExFitter
- pruning and smoothing applied
- asymptotic CLs method
- discontinuity at 80 GeV due to transition from low-mass to high-mass SR



Expected $|\zeta_u|$ Limits

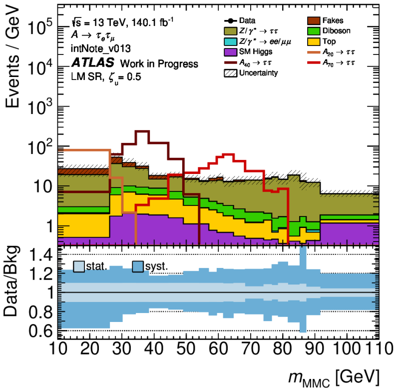
- binned likelihood fit of m_{MMC} distribution for each mass hypothesis
- fit and limit calculation done via TRExFitter
- pruning and smoothing applied
- asymptotic CLs method
- discontinuity at 80 GeV due to transition from low-mass to high-mass SR
- signal cross-section uncertainties only considered for $|\zeta_u|$ limits
- current $|\zeta_u|$ limit at ≈ 0.5



Summary

- a_μ deviation could be resolved by CP-odd Higgs boson A
- low-mass $A \to \tau\tau$ search in $e - \mu$ channel
- selection criteria finalized
- all systematics evaluated
- fake estimation via matrix method implemented
- expected exclusion limits presented

  $\Rightarrow$ analysis almost complete, currently in unblinding approval process



Outlook:

- unblinding
- aiming for ATLAS publication in summer

BACKUP

Selection Criteria

		SR low-mass 20 to 80 GeV	SR high-mass 80 to 110 GeV	Top CR	$Z \to \tau\tau$ CR	Fake VR
E_T^{miss} **cut**	E_T^{miss}	> 50 GeV	> 30 GeV	> 30 GeV	–	–
Mass cut[1]	m_T^{tot}	< 45 GeV	< 65 GeV	< 65 GeV	< 65 GeV	< 65 GeV
Angular cut[2]	ΔR_{ll}	< 0.7	< 1.0	< 1.0	> 1.4	> 1.4
MMC cut	m_{MMC}	> 0 GeV	> 35 GeV & < 130 GeV	> 0 GeV	> 0 GeV & < 130 GeV	> 0 GeV & < 130 GeV
b-**tag**	n_{b-jets}	0	0	> 1	0	0
Charge cut	$q_e \cdot q_\mu$	-1	-1	-1	-1	1

[1] $m_T^{tot} = \sqrt{\left(p_T^e + p_T^\mu + E_T^{miss}\right)^2 - \left(\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{E}_T^{miss}\right)^2}$, [2] $\Delta R = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2}$

Matrix method in the low-mass $A \to \tau\tau$ search

for 1 electron (1st index) and 1 muon (2nd index):

$$\begin{pmatrix} N^{\mathrm{TT}}_{\mathrm{XX}} \\ N^{\mathrm{T\bar{T}}}_{\mathrm{XX}} \\ N^{\mathrm{\bar{T}T}}_{\mathrm{XX}} \\ N^{\mathrm{\bar{T}\bar{T}}}_{\mathrm{XX}} \end{pmatrix} = \begin{pmatrix} r_e r_\mu & r_e f_\mu & f_e r_\mu & f_e f_\mu \\ r_e \bar{r}_\mu & r_e \bar{f}_\mu & f_e \bar{r}_\mu & f_e \bar{f}_\mu \\ \bar{r}_e r_\mu & \bar{r}_e f_\mu & \bar{f}_e r_\mu & \bar{f}_e f_\mu \\ \bar{r}_e \bar{r}_\mu & \bar{r}_e \bar{f}_\mu & \bar{f}_e \bar{r}_\mu & \bar{f}_e \bar{f}_\mu \end{pmatrix} \cdot \begin{pmatrix} N^{\mathrm{LL}}_{\mathrm{RR}} \\ N^{\mathrm{LL}}_{\mathrm{RF}} \\ N^{\mathrm{LL}}_{\mathrm{FR}} \\ N^{\mathrm{LL}}_{\mathrm{FF}} \end{pmatrix}$$

$\rightarrow$ inverting matrix gives 3 fake backgrounds:

$$N^{\mathrm{TT}}_{\mathrm{RF,\,est}} = \frac{r_e f_\mu}{(r_e - f_e)(r_\mu - f_\mu)} \left[-\bar{f}_e \bar{r}_\mu N^{\mathrm{TT}}_{\mathrm{XX}} + \bar{f}_e r_\mu N^{\mathrm{T\bar{T}}}_{\mathrm{XX}} + f_e \bar{r}_\mu N^{\mathrm{\bar{T}T}}_{\mathrm{XX}} - f_e r_\mu N^{\mathrm{\bar{T}\bar{T}}}_{\mathrm{XX}} \right],$$

$$N^{\mathrm{TT}}_{\mathrm{FR,\,est}} = \frac{f_e r_\mu}{(r_e - f_e)(r_\mu - f_\mu)} \left[-\bar{r}_e \bar{f}_\mu N^{\mathrm{TT}}_{\mathrm{XX}} + \bar{r}_e f_\mu N^{\mathrm{T\bar{T}}}_{\mathrm{XX}} + r_e \bar{f}_\mu N^{\mathrm{\bar{T}T}}_{\mathrm{XX}} - r_e f_\mu N^{\mathrm{\bar{T}\bar{T}}}_{\mathrm{XX}} \right],$$

$$N^{\mathrm{TT}}_{\mathrm{FF,\,est}} = \frac{f_e f_\mu}{(r_e - f_e)(r_\mu - f_\mu)} \left[+\bar{r}_e \bar{r}_\mu N^{\mathrm{TT}}_{\mathrm{XX}} - \bar{r}_e r_\mu N^{\mathrm{T\bar{T}}}_{\mathrm{XX}} - r_e \bar{r}_\mu N^{\mathrm{\bar{T}T}}_{\mathrm{XX}} + r_e r_\mu N^{\mathrm{\bar{T}\bar{T}}}_{\mathrm{XX}} \right].$$

- can be converted to event weights via IFF Fake Bkg Tools

Calculation of Efficiencies

- Normally: measure assumingly independent $\text{efficiency} = \frac{\#\text{tight leptons}}{\#\text{loose leptons}}$ of each lepton
  $\Rightarrow$ IFF Fake Efficiency Tool
- Here: parametrize probe lepton's efficiencies in tagged lepton's tightness
  $\Rightarrow$ leptons no longer assumed to be independent!
- real efficiencies calculated in signal region using MC only

$$\Rightarrow r_e(\mu) = \begin{cases} \frac{N^{\text{TT}}_{\text{RX}}}{N^{\text{LT}}_{\text{RX}}}, & \mu \text{ tight} \\ \frac{N^{\text{T}\overline{\text{T}}}_{\text{RX}}}{N^{\text{L}\overline{\text{T}}}_{\text{RX}}}, & \mu \text{ not tight} \end{cases} \qquad r_\mu(e) = \begin{cases} \frac{N^{\text{TT}}_{\text{XR}}}{N^{\text{TL}}_{\text{XR}}}, & e \text{ tight} \\ \frac{N^{\overline{\text{T}}\text{T}}_{\text{XR}}}{N^{\overline{\text{T}}\text{L}}_{\text{XR}}}, & e \text{ not tight} \end{cases}$$

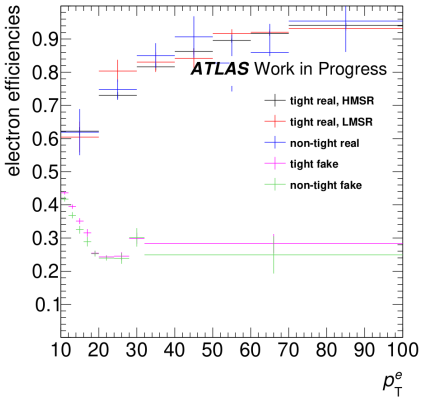
- fake efficiencies from same-sign ZVR, using data, subtracting MC with real lepton

$$\Rightarrow f_e(\mu) = \begin{cases} \frac{N^{\text{TT}}_{\text{Data}} - N^{\text{TT}}_{\text{RX}}}{N^{\text{LT}}_{\text{Data}} - N^{\text{LT}}_{\text{RX}}}, & \mu \text{ tight} \\ \frac{N^{\text{T}\overline{\text{T}}}_{\text{Data}} - N^{\text{T}\overline{\text{T}}}_{\text{RX}}}{N^{\text{L}\overline{\text{T}}}_{\text{Data}} - N^{\text{L}\overline{\text{T}}}_{\text{RX}}}, & \mu \text{ not tight} \end{cases} \qquad f_\mu(e) = \begin{cases} \frac{N^{\text{TT}}_{\text{Data}} - N^{\text{TT}}_{\text{XR}}}{N^{\text{TL}}_{\text{Data}} - N^{\text{TL}}_{\text{XR}}}, & e \text{ tight} \\ \frac{N^{\overline{\text{T}}\text{T}}_{\text{Data}} - N^{\overline{\text{T}}\text{T}}_{\text{XR}}}{N^{\overline{\text{T}}\text{L}}_{\text{Data}} - N^{\overline{\text{T}}\text{L}}_{\text{XR}}}, & e \text{ not tight} \end{cases}$$

Calculation of efficiencies

Best agreement with:

- same combined e-μ-triggers as in analysis
- loose ID & loose isolation vs. medium ID & tight isolation
- efficiencies binned in p_{T} and tightness of tagged lepton



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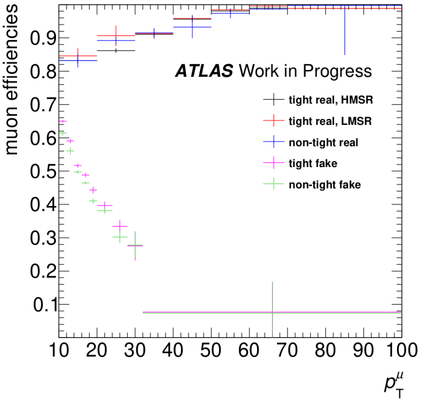
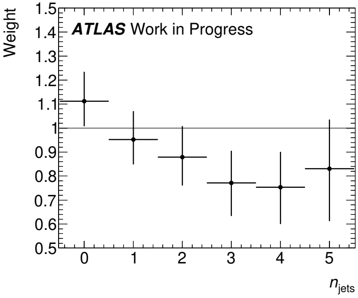


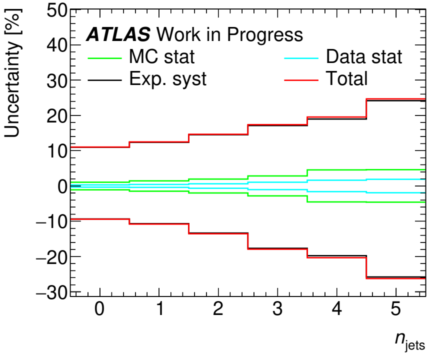
$Z \to \tau\tau$ Reweighting

calculated weights in ZCR, in n_{jets} distribution:

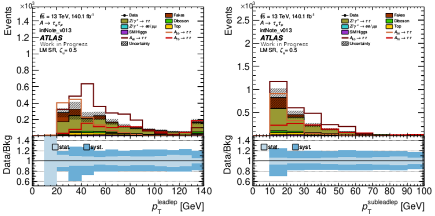
$$\text{weight} = \frac{(\text{Data} - \sum_{i \neq Z_{\tau\tau}} \text{Bkg}_i)}{\text{Bkg}_{Z_{\tau\tau}}}$$



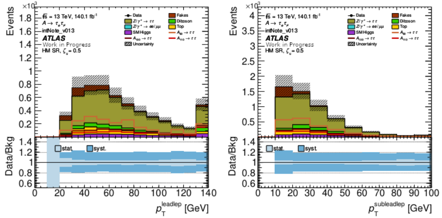
systematics:



Distributions



(a) (b)



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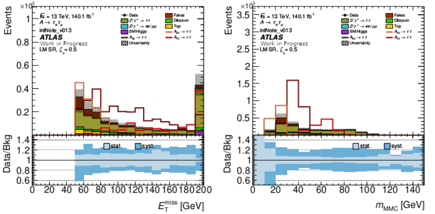

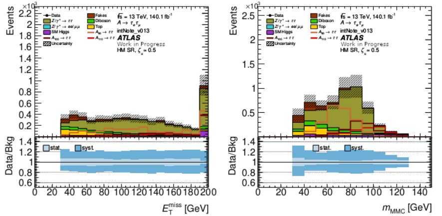

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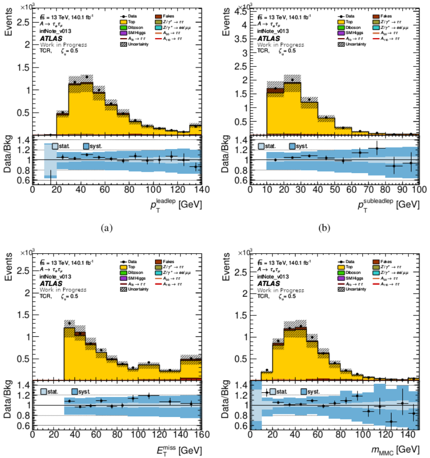

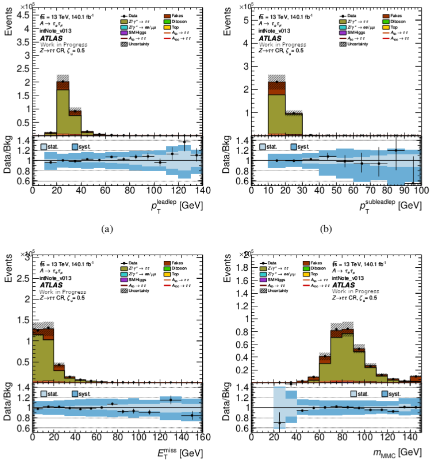

Distributions