Search for $T' \longrightarrow t + H^0$ in the trilepton channel

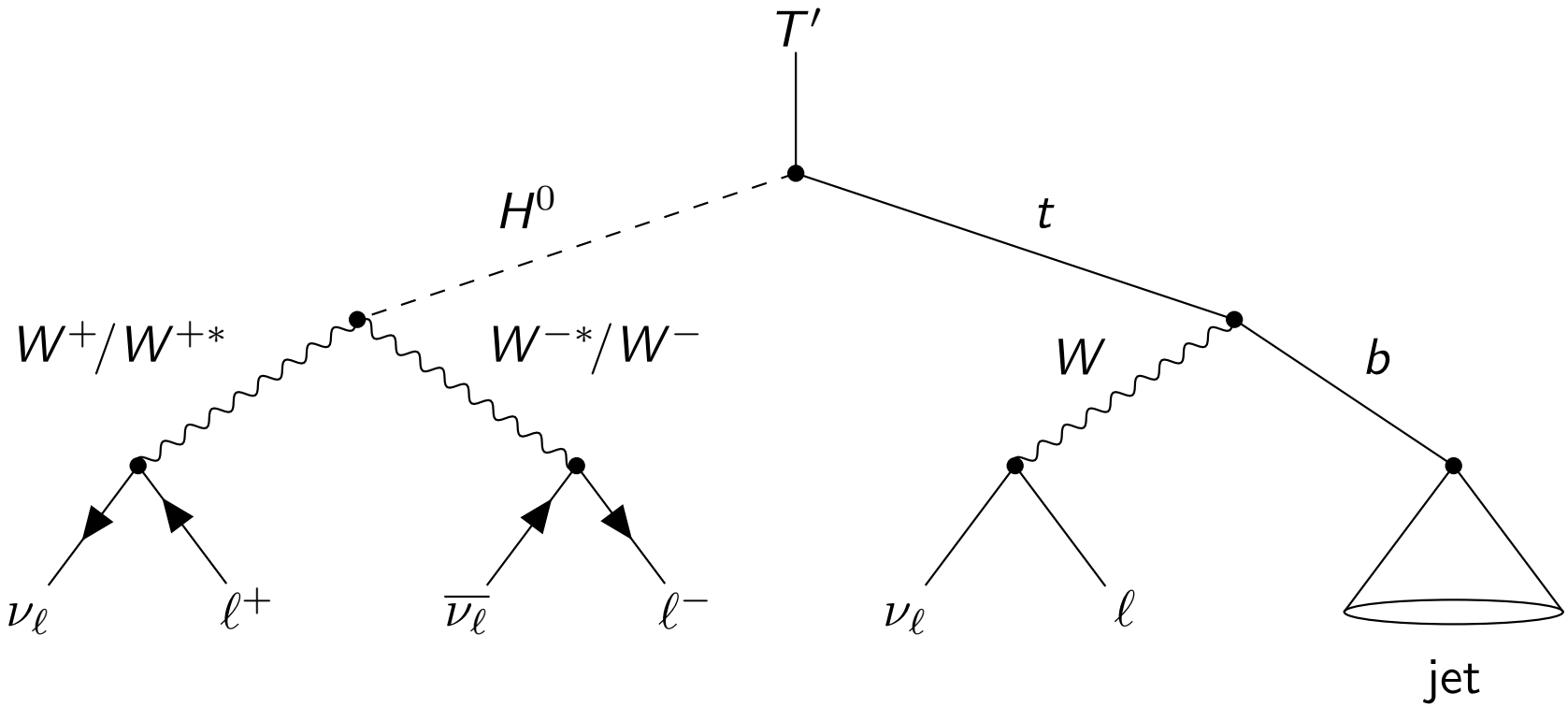
Status report #2 (weeks 4, 5)

Bastien Voirin

June 3, 2022

Signal

$\sigma\left(T' \longrightarrow t + H^0\right) = 89\,\text{fb}$

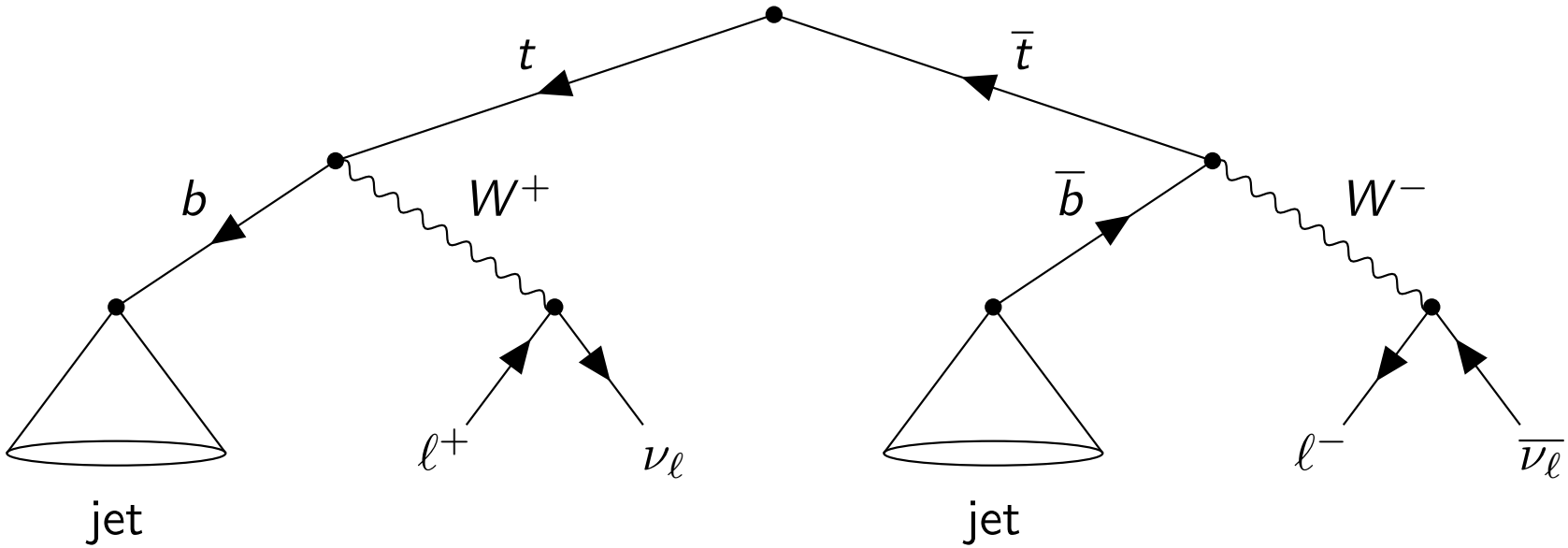


Final state: $\ell^+\ell^-\ell^\pm\nu\nu\nu$ + b-tagged jet

Unless the Higgs boson is sufficiently boosted, one the two intermediate W bosons is off-shell ($m_{H^0} = 125\,\text{GeV}$, $m_{W^\pm} = 80.4\,\text{GeV}$)

$t\bar{t}$ background

$\sigma(t\bar{t} \longrightarrow \text{dilepton}) = 87.315\,\text{pb}$

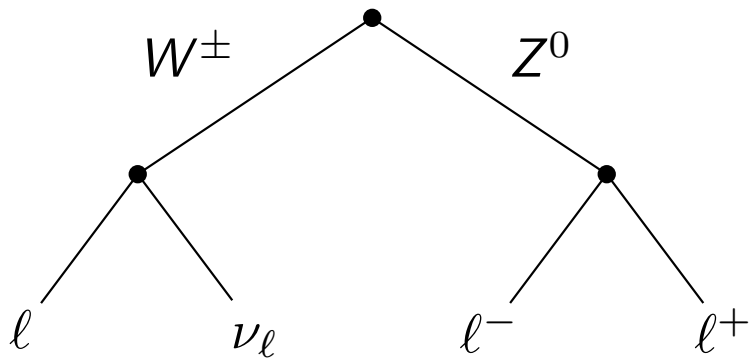


Final state: $\ell^+\ell^-\nu\nu + 2$ b-tagged jets

The top quarks are heavy enough compared to the bottom quarks for the intermediate W bosons to be on-shell ($m_t = 173\,\text{GeV}$, $m_b = 4.2\,\text{GeV}$)

WZ background

$\sigma(WZ) = 4.4297\,\text{pb}$ in Benjamin's dataset



Final state: $\ell^+\ell^-\ell^{\pm}\nu$ (no b-tagged jet for $\ell \in \{\mu, e\}$)

Export of plots as individual images (`Compare.cc`)

- Simplified the legend
- Labeled the X and Y axes
- Removed an unnecessary plot

`pyrootplots`: ROOT files visualisation using Python

- Repository: `https://github.com/bastienvoirin/pyrootplots`
- Documentation: `https://pyrootplots.readthedocs.io/en/latest/`
- Classes:
  - `Condition` ($<$, $\leqslant$, $>$, $\geqslant$, $\in$, $\notin$)
  - `Criterion` (variable, condition, values/thresholds)
  - `Cut` (criterion, sig. before, sig. after, bkg. before, bkg. after...)
  - `CutEffVsVal` (#after/#before vs. cut value)
  - `Histogram1D` (`THIF`, `TH1D`)
  - `Histogram2D` (`TH2F`, `TH2D`)
  - `ROCCurve`
  - `ROOTDataLoader`

Feel free to contribute!

pyrootplots: ROOT files visualisation using Python

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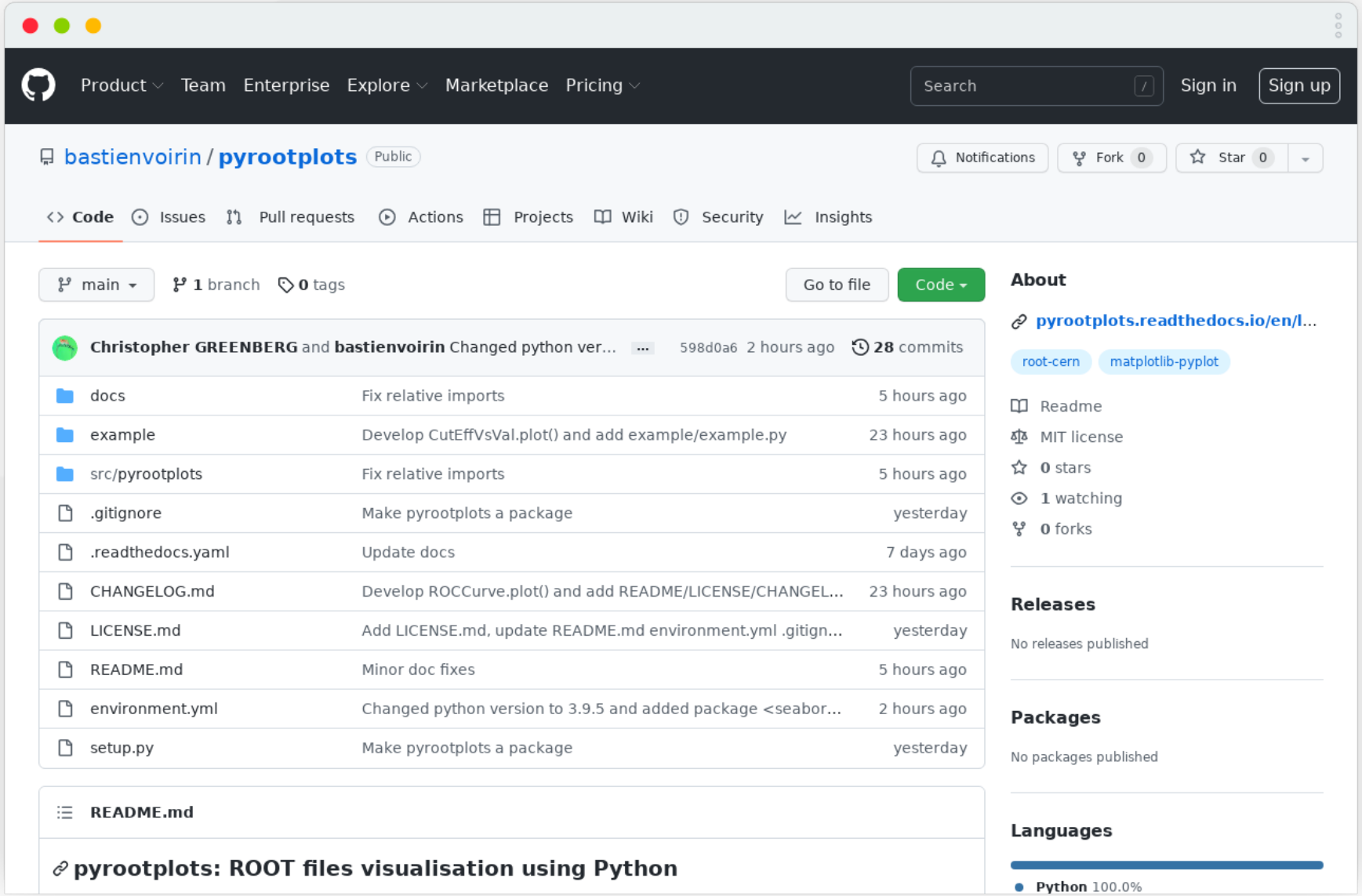

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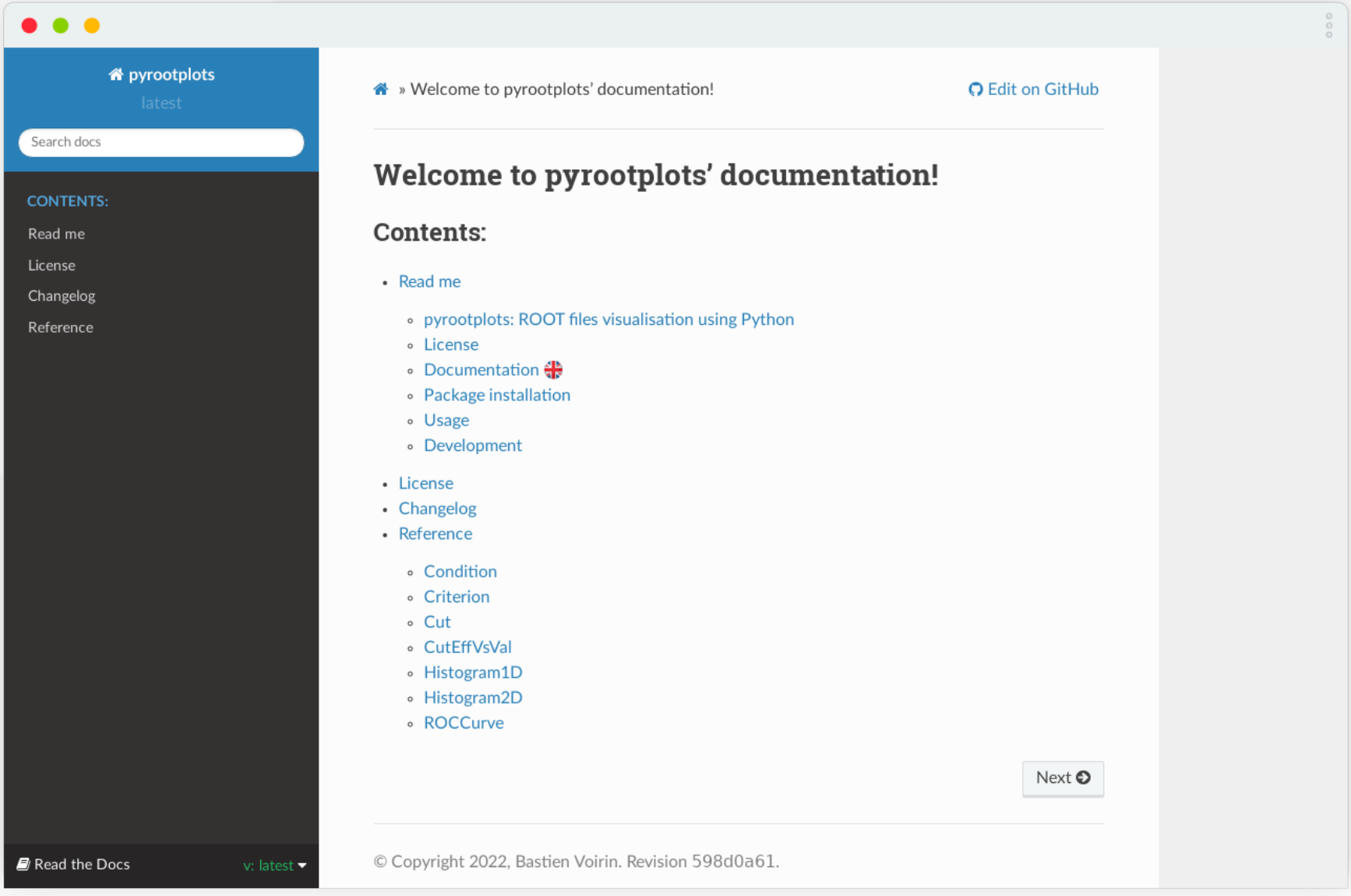


$\Delta R_{\min}$ between two muons of opposite charges

$$\begin{aligned}
\Delta R_{\min} &= \min(\Delta R_{01}, \Delta R_{02}) \quad \text{if } \text{charge}(1) = \text{charge}(2) \\
\Delta R_{\min} &= \min(\Delta R_{02}, \Delta R_{12}) \quad \text{if } \text{charge}(0) = \text{charge}(1) \\
\Delta R_{\min} &= \min(\Delta R_{12}, \Delta R_{01}) \quad \text{if } \text{charge}(0) = \text{charge}(2)
\end{aligned}$$

Let

$$v_{ab} \equiv \frac{\text{charge}(a)\,\text{charge}(b) + 1}{2} = \begin{cases} v_{ab} = 0 & \text{if } \text{charge}(a) \neq \text{charge}(b) \\ v_{ab} = 1 & \text{if } \text{charge}(a) = \text{charge}(b) \end{cases}$$

Then

$$\begin{aligned}
\Delta R_{\min} &= \min(\Delta R_{01}, \Delta R_{02}) \quad \text{if } v_{12} = 1, v_{01} = 0, v_{02} = 0 \\
\Delta R_{\min} &= \min(\Delta R_{02}, \Delta R_{12}) \quad \text{if } v_{01} = 1, v_{02} = 0, v_{12} = 0 \\
\Delta R_{\min} &= \min(\Delta R_{12}, \Delta R_{01}) \quad \text{if } v_{02} = 1, v_{12} = 0, v_{01} = 0
\end{aligned}$$

$$\begin{aligned}
\Delta R_{\min} = \min(&\Delta R_{01} v_{12} + \Delta R_{02} v_{01} + \Delta R_{12} v_{02}, \\
&\Delta R_{02} v_{12} + \Delta R_{12} v_{01} + \Delta R_{01} v_{02})
\end{aligned}$$

ΔR_{min} between two muons of opposite charges

$$v_{ab} \equiv \frac{\text{charge}(a)\,\text{charge}(b)+1}{2} = \begin{cases} v_{ab}=0 & \text{if charge}(a) \neq \text{charge}(b) \\ v_{ab}=1 & \text{if charge}(a) = \text{charge}(b) \end{cases}$$

$$\begin{aligned} \Delta R_{\text{min}} = \min(&\Delta R_{01} v_{12} + \Delta R_{02} v_{01} + \Delta R_{12} v_{02}, \\ &\Delta R_{02} v_{12} + \Delta R_{12} v_{01} + \Delta R_{01} v_{02}) \end{aligned}$$

```
("dR01", "ROOT::VecOps::DeltaR(Selected_muon_eta[0],
↪  Selected_muon_eta[1], Selected_muon_phi[0], Selected_muon_phi[1])")
("dR02", "ROOT::VecOps::DeltaR(Selected_muon_eta[0],
↪  Selected_muon_eta[2], Selected_muon_phi[0], Selected_muon_phi[2])")
("dR12", "ROOT::VecOps::DeltaR(Selected_muon_eta[1],
↪  Selected_muon_eta[2], Selected_muon_phi[1], Selected_muon_phi[2])")
("Selected_muon_deltaR_min", "min(min(dR01, dR02), dR12)")
("v01", "(1 + Selected_muon_charge[0]*Selected_muon_charge[1]) / 2")
("v02", "(1 + Selected_muon_charge[0]*Selected_muon_charge[2]) / 2")
("v12", "(1 + Selected_muon_charge[1]*Selected_muon_charge[2]) / 2")
("Selected_muon_deltaR_min_neutral", "min(dR01*v12 + dR02*v01 +
↪  dR12*v02, dR02*v12 + dR12*v01 + dR01*v02)")
```

Signal vs. $t\bar{t}$ comparison ($L_{\text{int}} = 300\,\text{fb}^{-1}$)

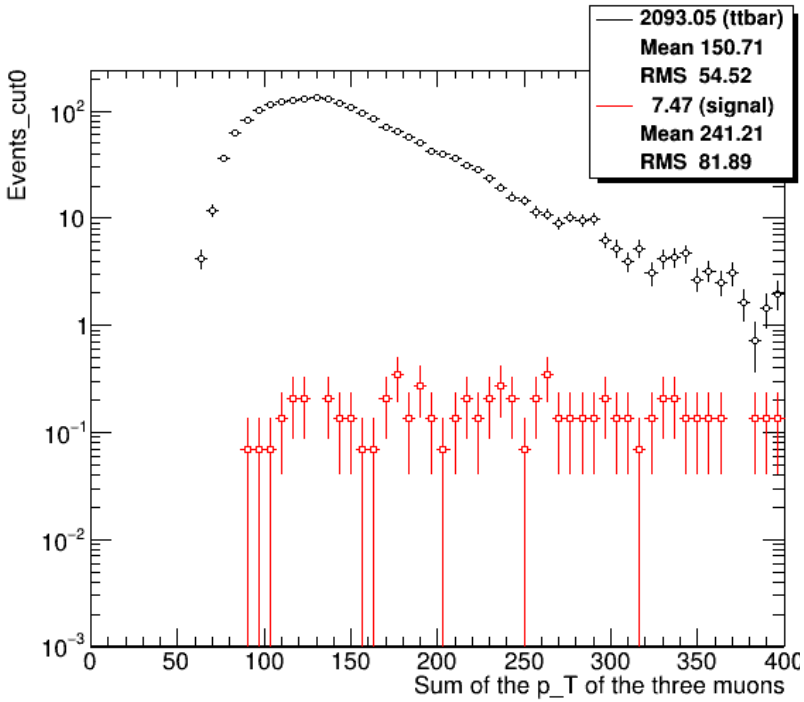
`Selected_muon_sum_all_muons_pt`

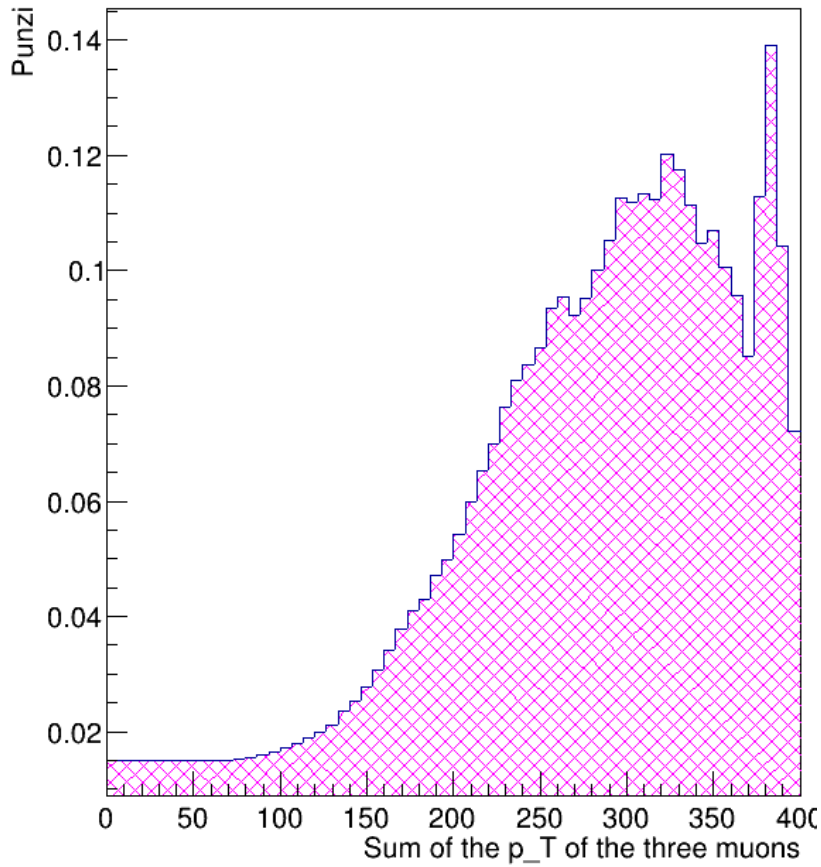
Cut 1: `Selected_muon_number == 3 && abs(Selected_muon_charge_sum) == 1`

~~Cut 2:~~ `Selected_bjet_number >= 1` (relevant for some backgrounds but not $t\bar{t}$)

Cut 2: `Selected_muon_sum_all_muons_pt >= 130.0`

Cut 3: `Selected_muon_deltaR_min_neutral <= 1`





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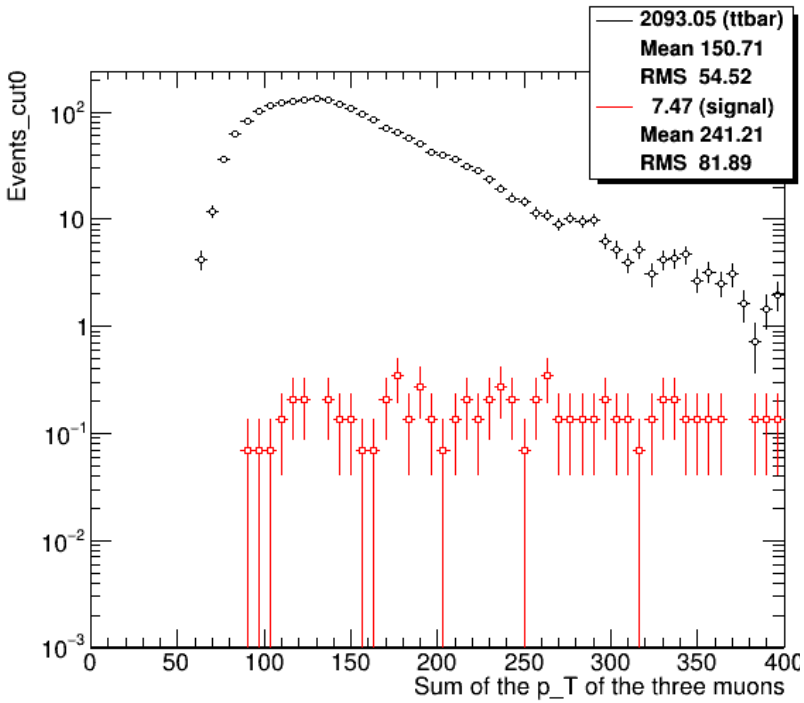

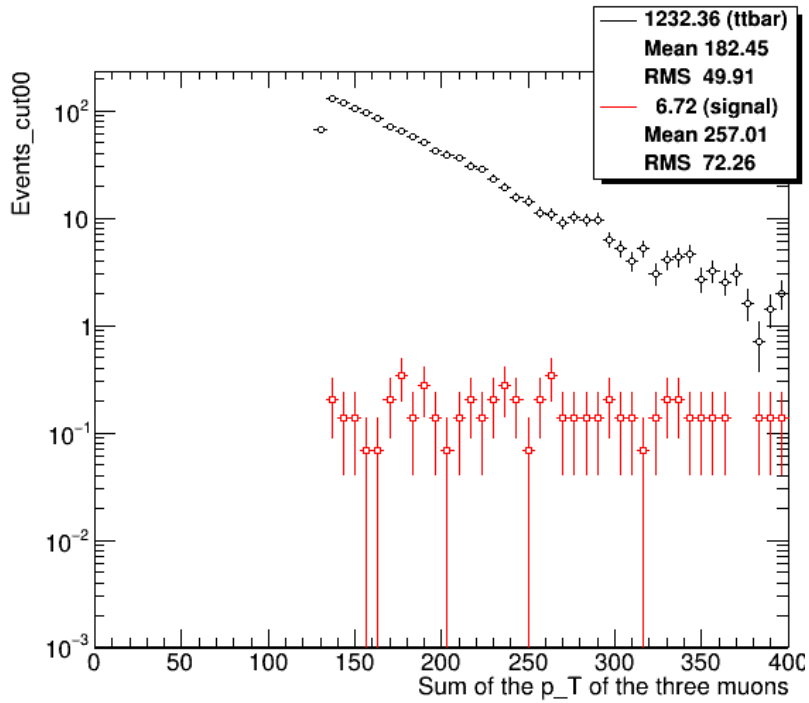

Signal vs. $t\bar{t}$ comparison ($L_{\text{int}} = 300\,\text{fb}^{-1}$)

`Selected_muon_deltaR_min_neutral`

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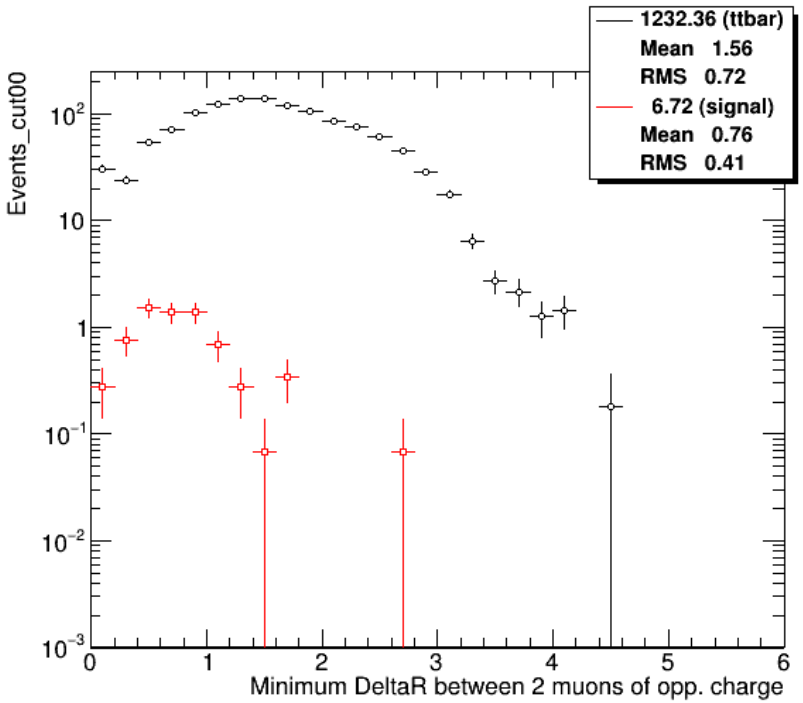

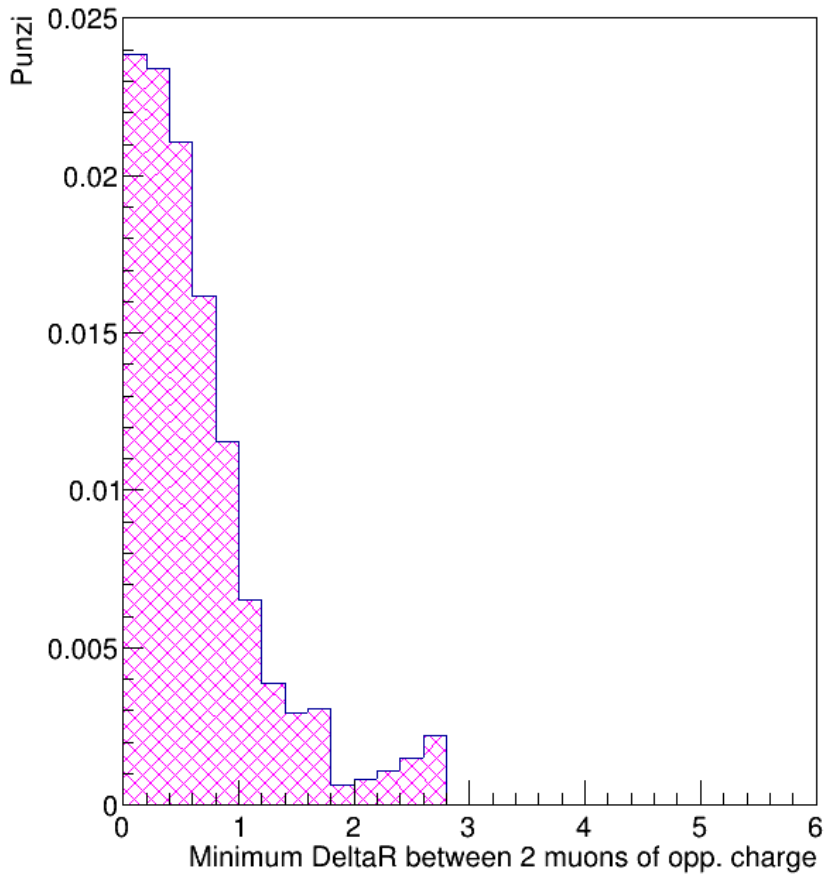

Signal vs. $t\bar{t}$ comparison ($L_{\text{int}} = 300\,\text{fb}^{-1}$)

`Selected_muon_deltaR_min_neutral`

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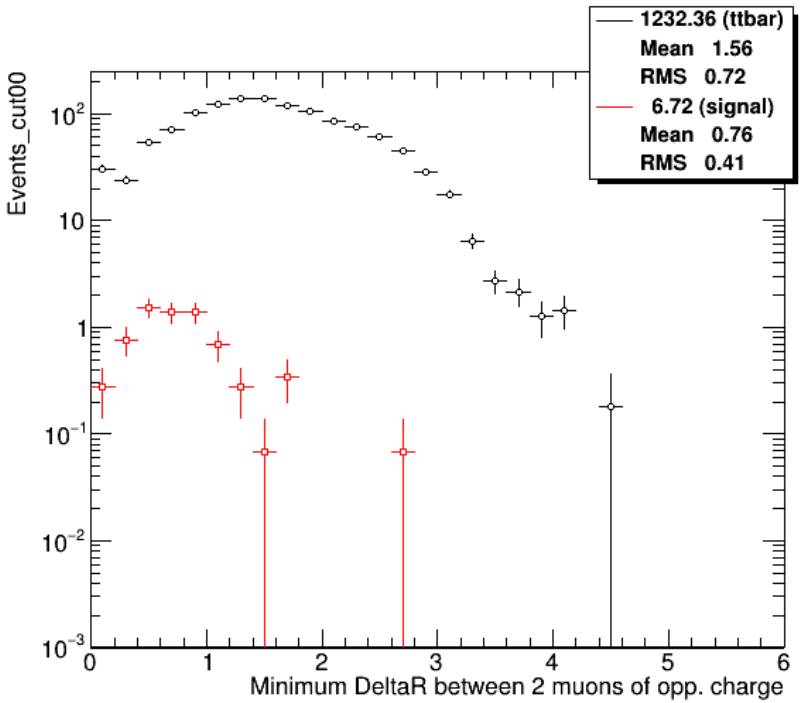

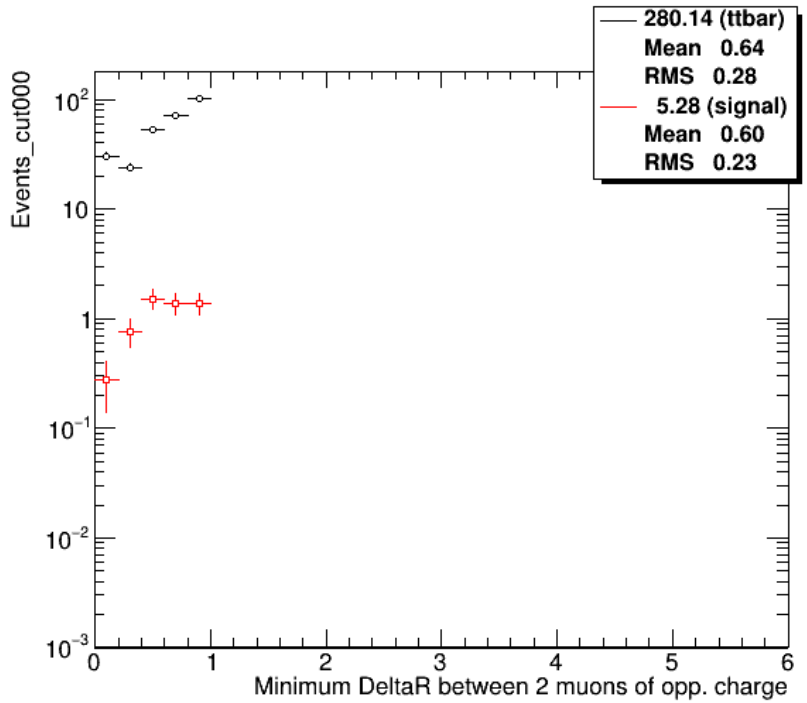

Signal vs. $t\bar{t}$ comparison ($L_{\text{int}} = 300\,\text{fb}^{-1}$)

Summary/results

Cut 1: `Selected_muon_number == 3 && abs(Selected_muon_charge_sum) == 1`
~~Cut 2:~~ `Selected_bjet_number >= 1` (relevant for some backgrounds but not $t\bar{t}$)
Cut 2: `Selected_muon_sum_all_muons_pt >= 130.0`
Cut 3: `Selected_muon_deltaR_min_neutral <= 1`

	Events (sig.)	Events ($t\bar{t}$ bkg.)	Cut (sig.)	Cut ($t\bar{t}$ bkg.)	S/B
Before	1184	2 728 521			0.0434 %
After Cut 1	7.47	2093	−99.4 %	−99.9 %	0.357 %
After Cut 2	6.72	1232	−10.0 %	−41.1 %	0.545 %
After Cut 3	5.28	280	−21.4 %	−77.3 %	**1.89 %**

ROC curve

Cut 1: `Selected_muon_number == 3 && abs(Selected_muon_charge_sum) == 1`
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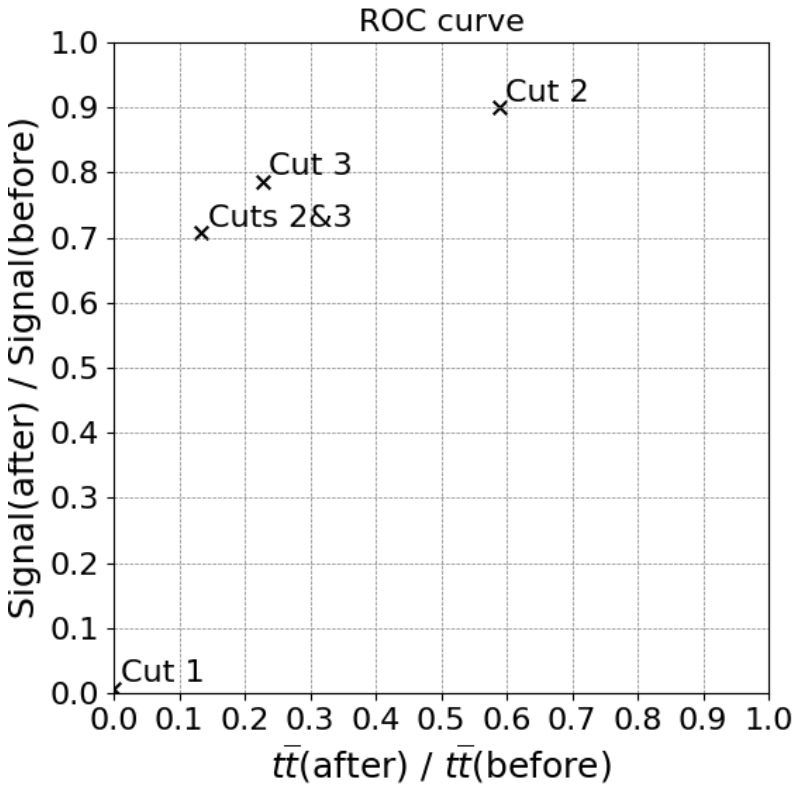
Cut 2: `Selected_muon_sum_all_muons_pt >= 130.0`
Cut 3: `Selected_muon_deltaR_min_neutral <= 1`



- Cut 2 and Cut 3 are quite interesting but I should be able to find better ones
- To be compared with *actual* signal events: are these cuts still relevant?

Selecting actual signal events from generator particles

- Define a flag: `Is_signal`
- If `Is_signal == 1`, select signal events:
  - H^0 from a T'
    - W^+W^- from a H^0 from a T'
      - $\ell^+\ell^-$ **from a W^+W^- from a H^0 from a T'**
  - t from a T'
    - Wb from a t from a T'
      - ℓ from a $W^\pm$ from a t from a T'
      - b-tagged jet from a **b from a t from a T'**

```
addCuts("Is_signal == 0 || (Is_signal == 1 && ... && ... && ...)", "0");
```

What's next

- **Select actual signal events from generator particles (WIP)**
- Study $\mu\mu e$, μee, eee final states
- WZ background which should be filtered out by `Selected_bjet_number >= 1`
- Invariant mass of the nearest muons (corresponding to $\Delta R_{\min}$)
- Invariant mass $m(b\ell)$ of the $b\ell$ from the t, where ℓ is the most distant lepton from the two others (corresponding to $\Delta R_{\min}$) or the closest to the b: we should find 1 m_t for the signal and 2 for the $t\bar{t}$ background
- Plot $s_T \equiv \sum_{\text{leptons}} p_T + \sum_{\text{jets}} p_T$ for signal and $t\bar{t}$ to compare the distributions
- $\Delta\phi_{\min}$ should be more stable for H^0 than $\Delta R_{\min}$ (which includes η/the boost)
- Define and compare many variables to determine relevant cuts

Appendix

$$N_{\text{data set}}(\text{sig.}) = 389\,500 \tag{1}$$

$$N_{\text{data set}}(t\bar{t}) = 145\,962\,000 \tag{2}$$

$$N_{\text{expected}}(\text{sig.}) = \underbrace{L_{\text{int}} \times \sigma(\text{sig.})}_{26\,700} \times \underbrace{\text{BR}\left(H^0 \longrightarrow WW\right)}_{21\ \%} \times \underbrace{\text{BR}\left(t \longrightarrow Wb\right)}_{\approx 100\ \%} \times \text{BR}\left(W \longrightarrow \ell\nu\right)^3 \tag{3}$$

$$= 7.46\ (\ell = \mu) \tag{4}$$

$$= 12.32\ (\ell = \mu)\ \text{(intermediate } \tau \text{ leptons allowed)} \tag{5}$$

$$= 59.70\ (\ell = e, \mu) \tag{6}$$

$$= 98.55\ (\ell = e, \mu)\ \text{(intermediate } \tau \text{ leptons allowed)} \tag{7}$$

$$N_{\text{expected}}(t\bar{t}) = \underbrace{L_{\text{int}} \times \sigma(t\bar{t})}_{26\,194\,500} \times \underbrace{\text{BR}\left(t \longrightarrow Wb\right)}_{\approx 100\ \%} \times \text{BR}\left(W \longrightarrow \ell\nu\right)^2 \tag{8}$$

$$= 316\,953\ (\ell = \mu) \tag{9}$$

$$= 442\,687\ (\ell = \mu)\ \text{(intermediate } \tau \text{ leptons allowed)} \tag{10}$$

$$= 1\,267\,814\ (\ell = e, \mu) \tag{11}$$

$$= 1\,770\,748\ (\ell = e, \mu)\ \text{(intermediate } \tau \text{ leptons allowed)} \tag{12}$$

$$N_{\text{scaled}}(\text{sig.}) = N_{\text{unscaled}} \times \frac{\sigma(\text{sig.}) \times L_{\text{int}}}{N_{\text{data set}}} = N_{\text{unscaled}} \times \frac{26\,700}{389\,500} = N_{\text{unscaled}} \times 0.068\,55 \tag{13}$$

$$N_{\text{scaled}}(t\bar{t}) = N_{\text{unscaled}} \times \frac{\sigma(t\bar{t}) \times L_{\text{int}}}{N_{\text{data set}}} = N_{\text{unscaled}} \times \frac{26\,194\,500}{145\,962\,000} = N_{\text{unscaled}} \times 0.179\,46 \tag{14}$$