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DEGLI STUDI  
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# PRELIMINARY STUDIES FOR A 10-TeV MUON COLLIDER DETECTOR

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# Overview

- Generator-level study to understand the characteristics of the particles to be detected at a  $\sqrt{s} = 10$  TeV muon collider.
- Comparison of the distributions of some relevant observables considering muon collisions at  $\sqrt{s} = 3$  TeV and  $\sqrt{s} = 10$  TeV for several representative channels of the future physics programme.

Special thanks to **Sergo Jindariani** and **Luciano Ristori** for all the very useful discussions and suggestions!

# Samples

Samples of 100k events generated at  $\sqrt{s} = 3$  TeV and  $\sqrt{s} = 10$  TeV.

- $\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu$   
 $H \rightarrow b \bar{b}$
- $\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu$   
 $H \rightarrow \gamma \gamma$
- $\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu$   
 $H \rightarrow ZZ, Z \rightarrow l^+ l^-$

100k events generated at  $\sqrt{s} = 10$  TeV only.

- $\mu^+ \mu^- \rightarrow Z \nu_\mu \bar{\nu}_\mu$  ( $m_Z = 5$  TeV)  
 $Z \rightarrow jj (l^+ l^-)$
- $\mu^+ \mu^- \rightarrow Z'$ , ( $m_{Z'} = 9.5$  TeV)  
 $Z' \rightarrow jj (l^+ l^-)$

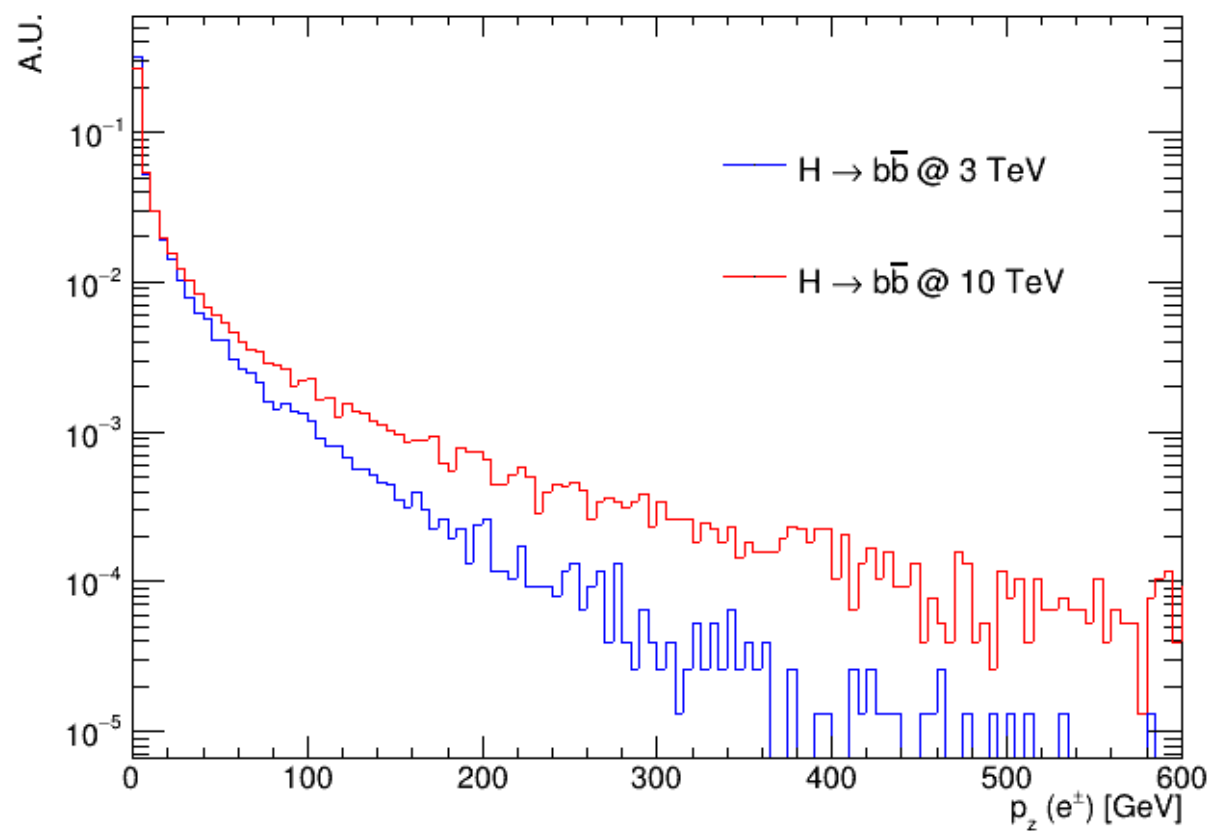
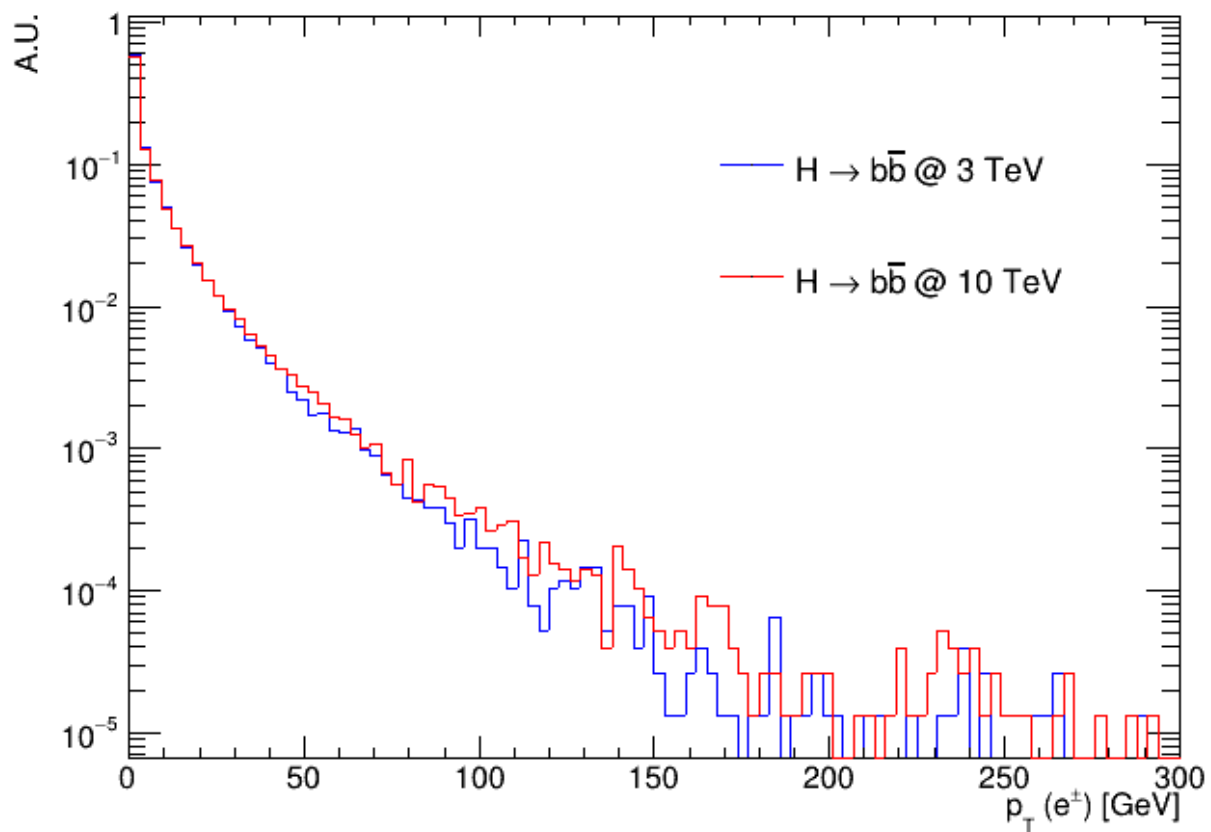
## Observables

- $p_T, p_z, \theta, E, E(\theta)$  for visible particles, decay products, Higgs boson, Z boson and b-quarks;
- b decay vertex  $\sqrt{x^2 + y^2}$  and  $\sqrt{x^2 + y^2 + z^2}$ ;
- $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$  between b-quarks and decay products.

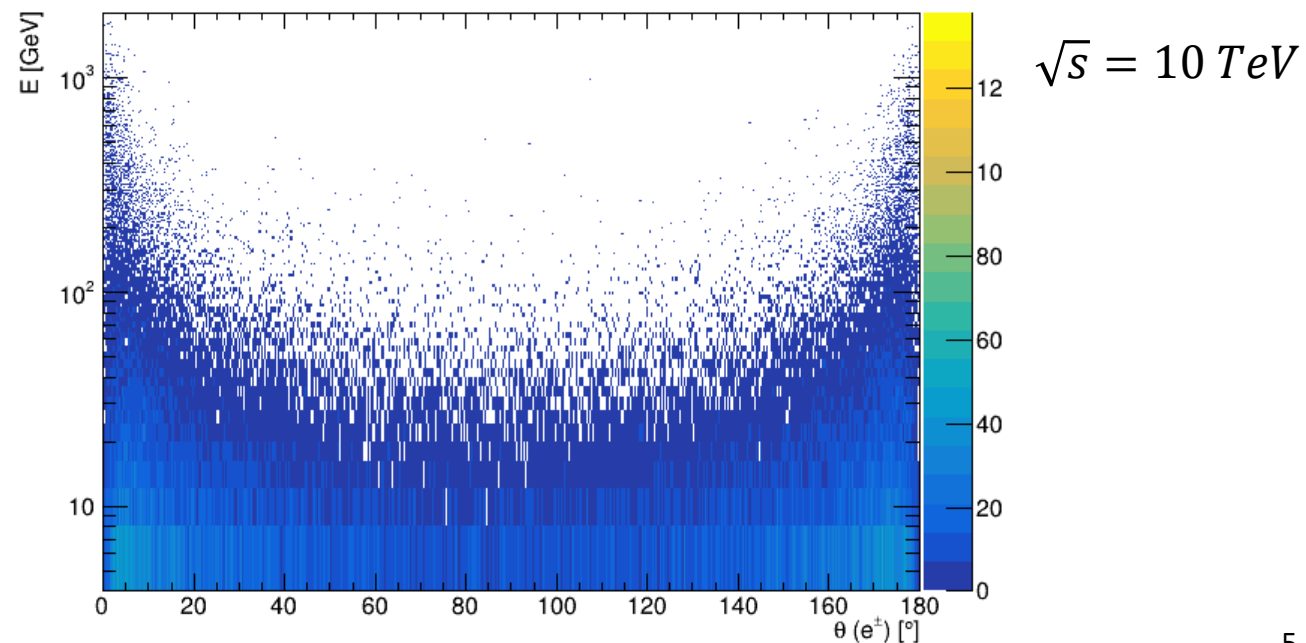
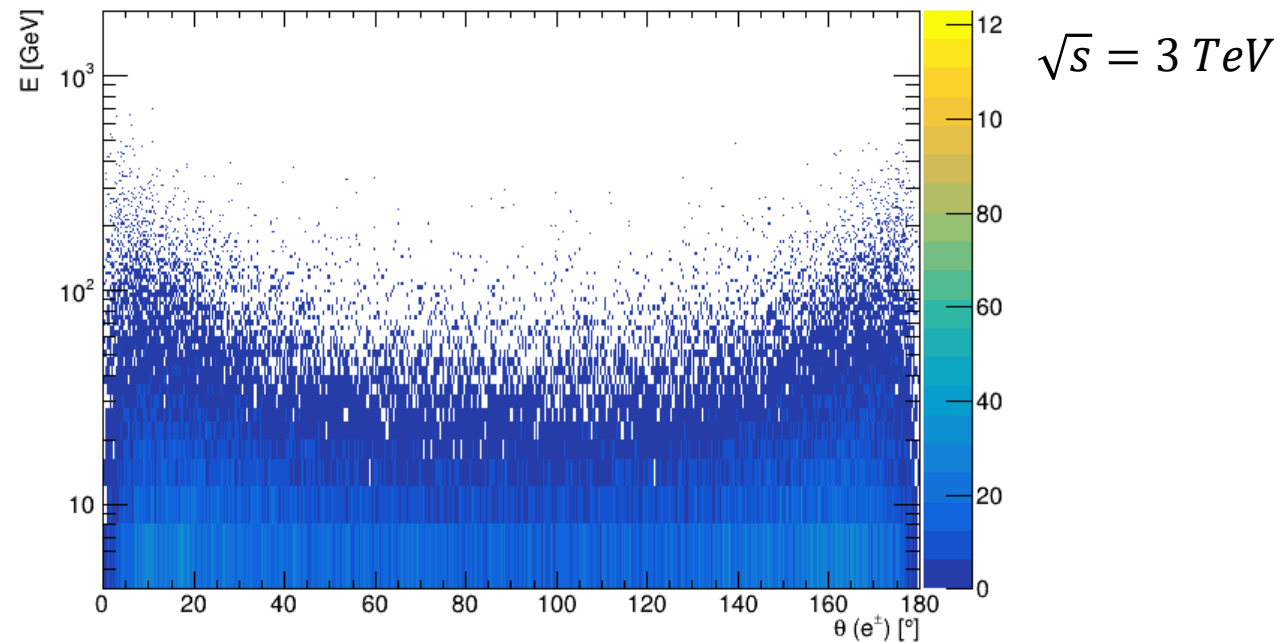
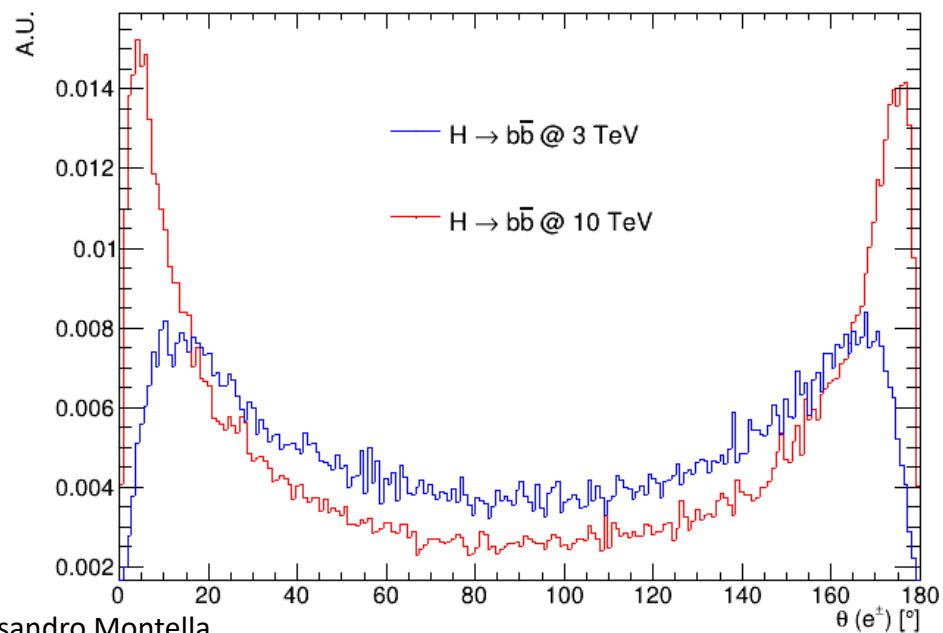
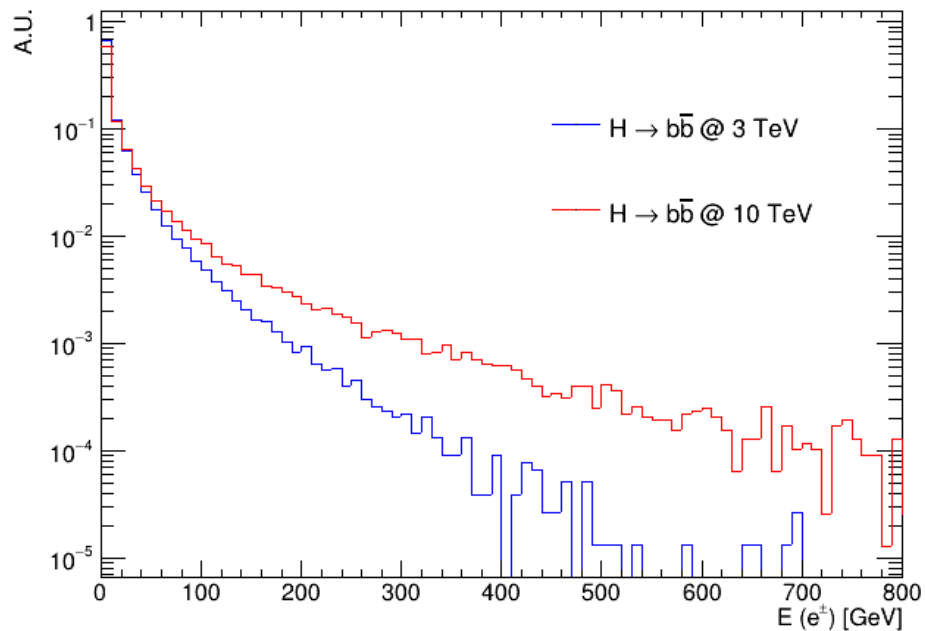
$$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu,$$
$$H \rightarrow b \bar{b}$$

$$\sqrt{s} = 3 \text{ TeV vs } \sqrt{s} = 10 \text{ TeV}$$

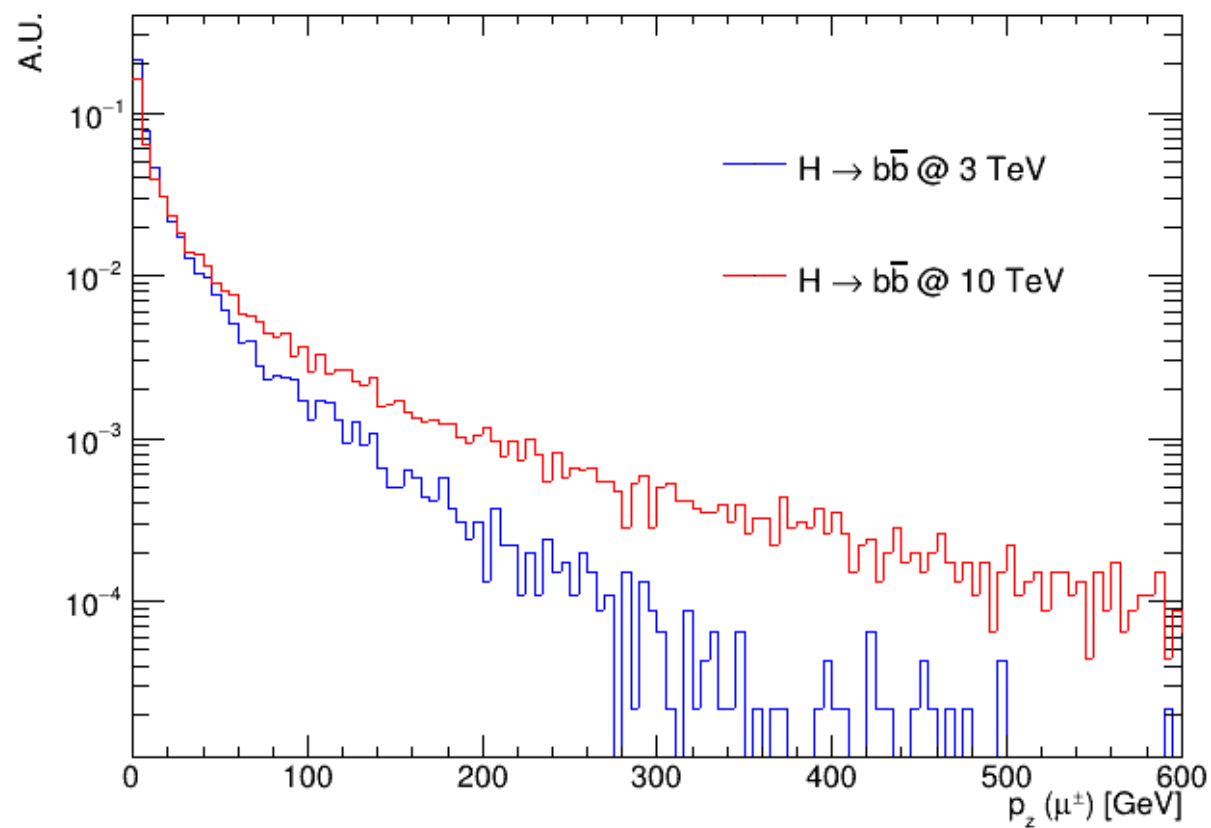
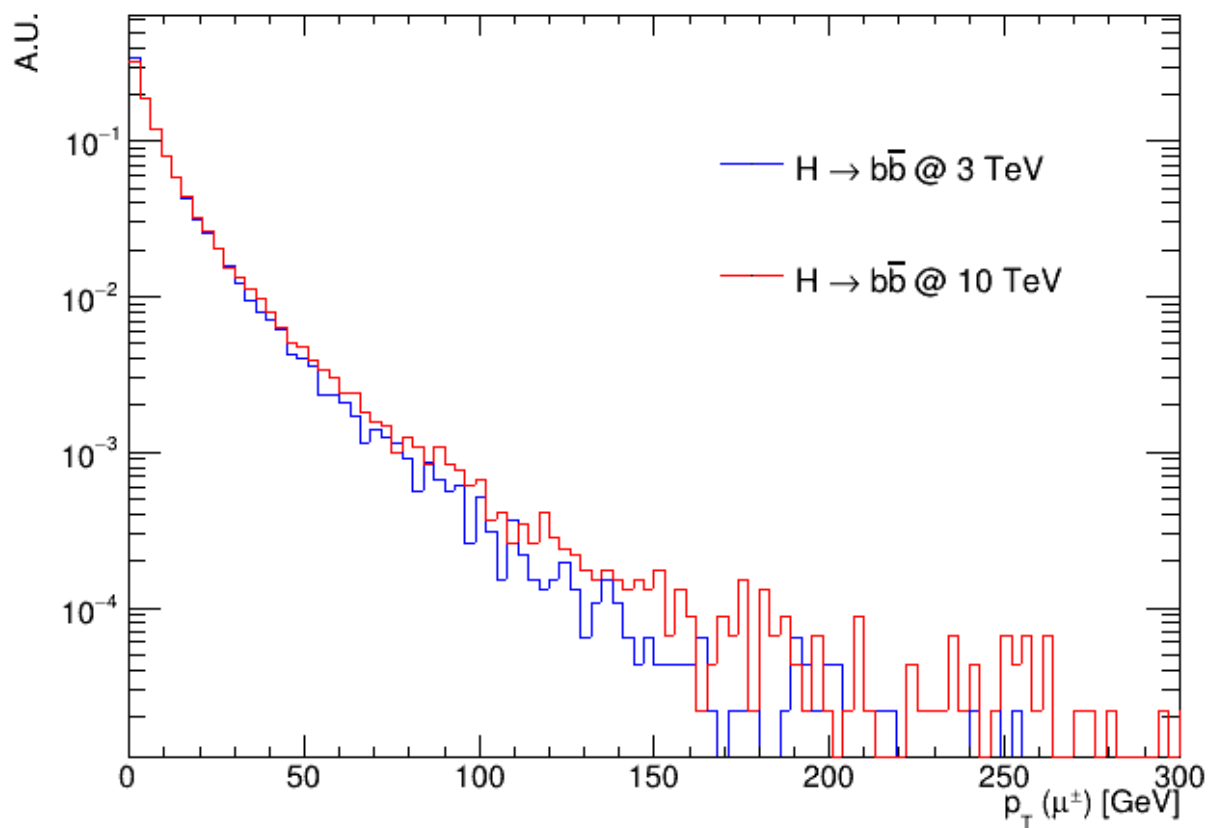
# Electrons: $p_T$ and $p_z$



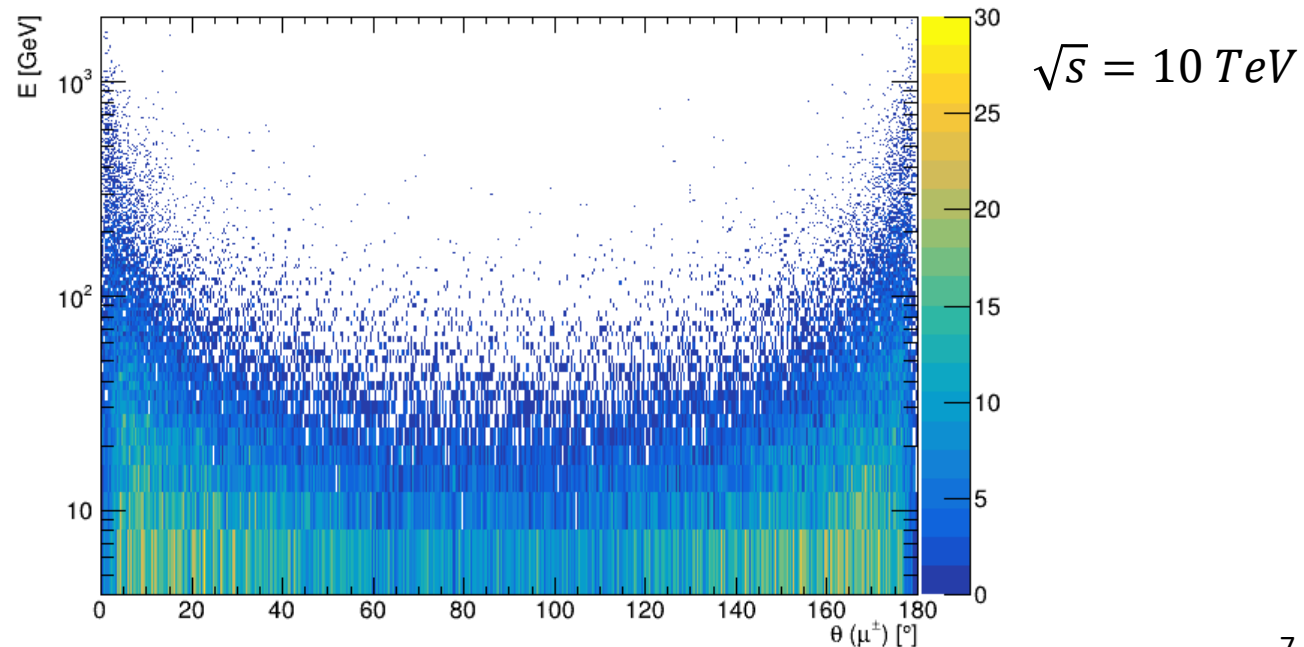
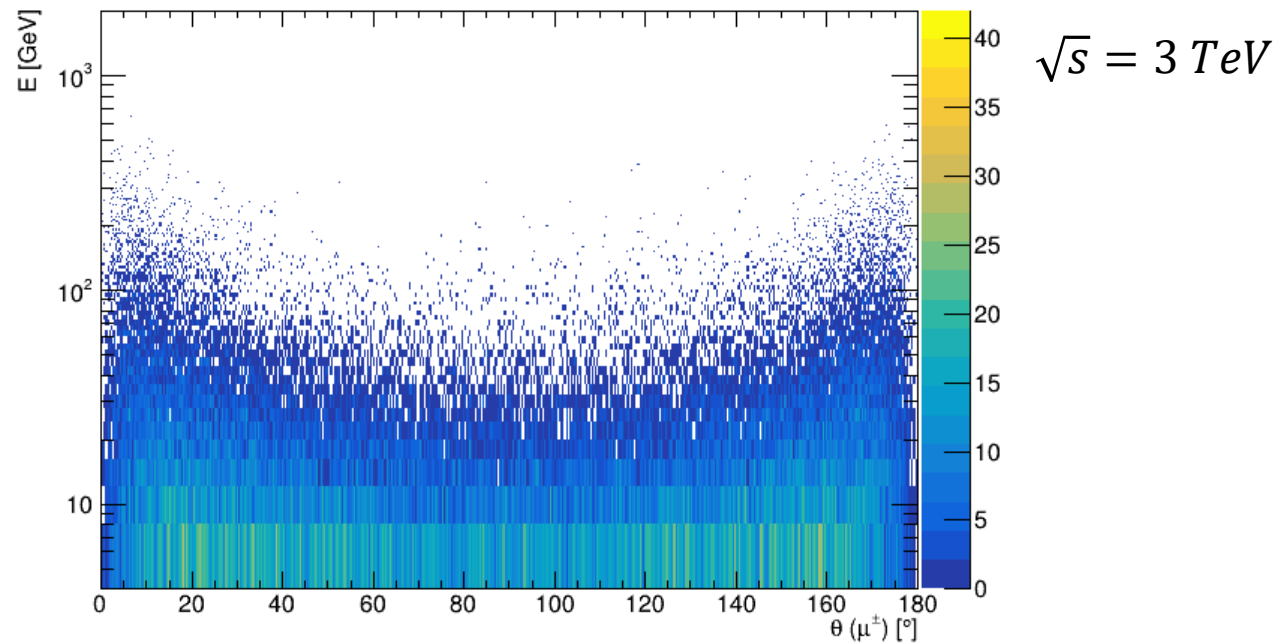
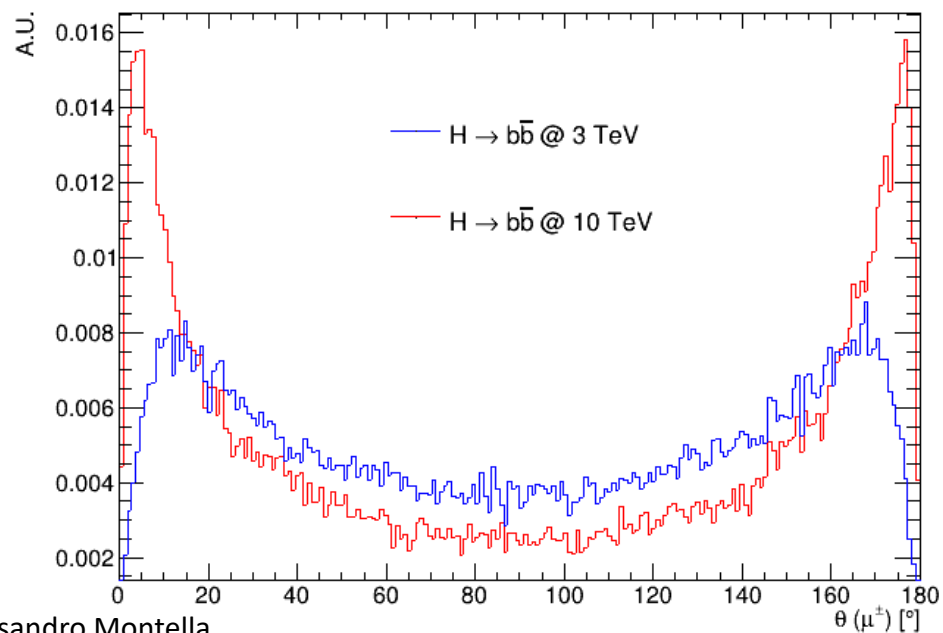
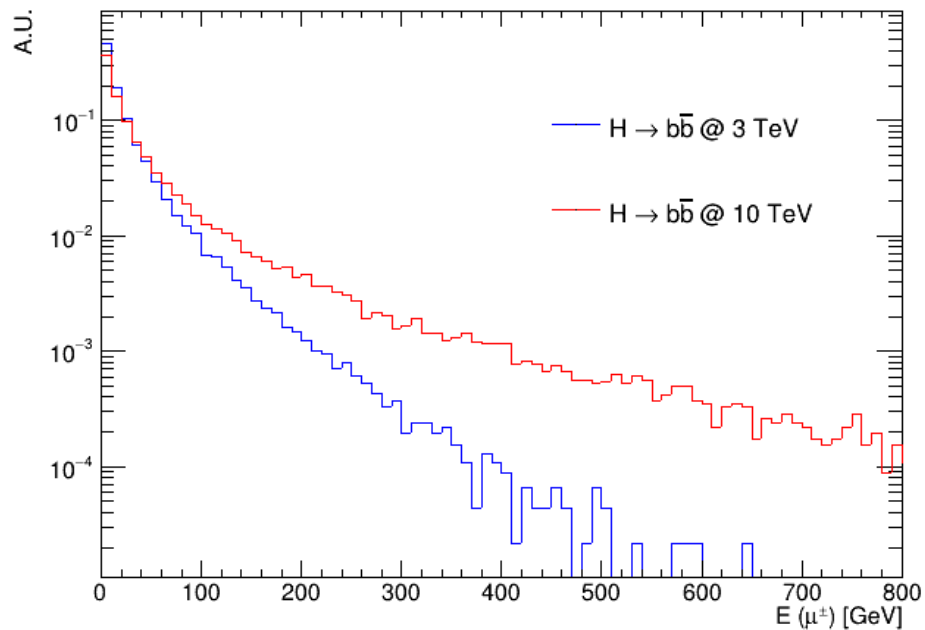
# Electrons: $E$ and $\theta$



# Muons: $p_T$ and $p_z$

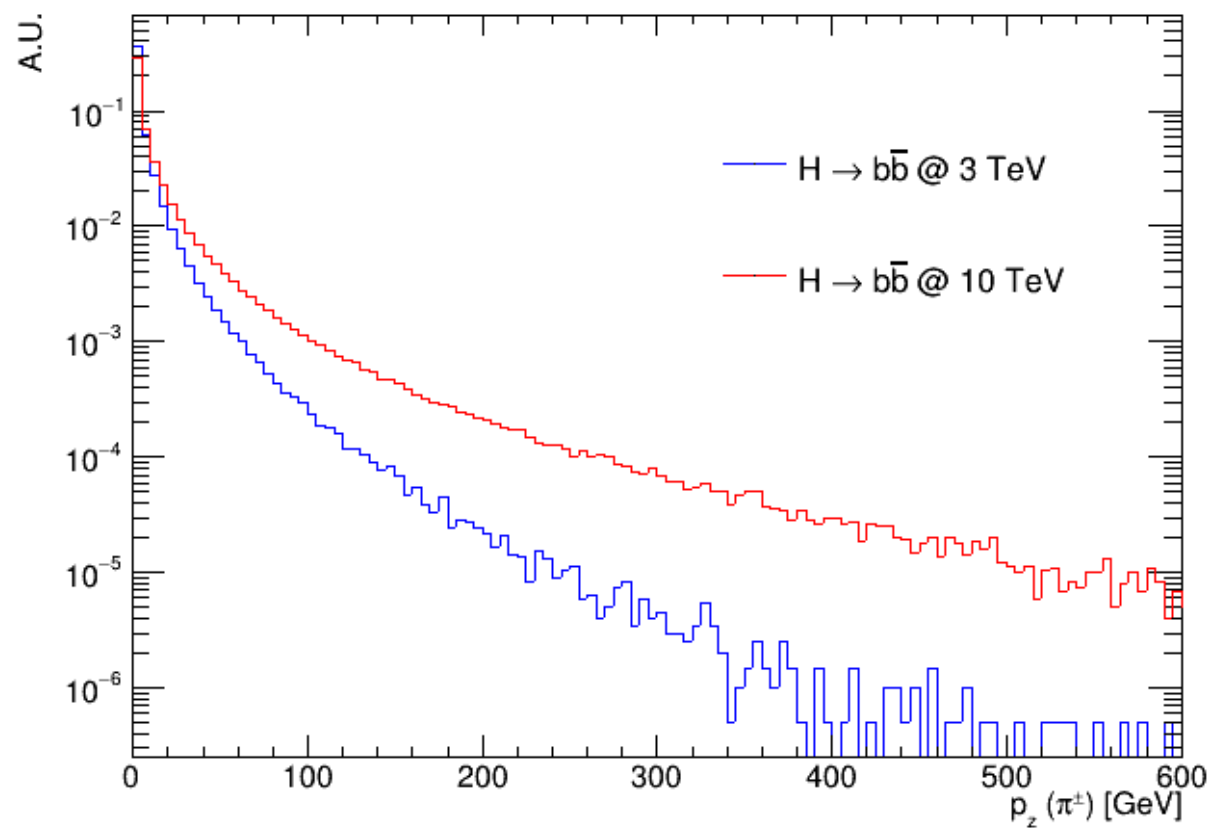
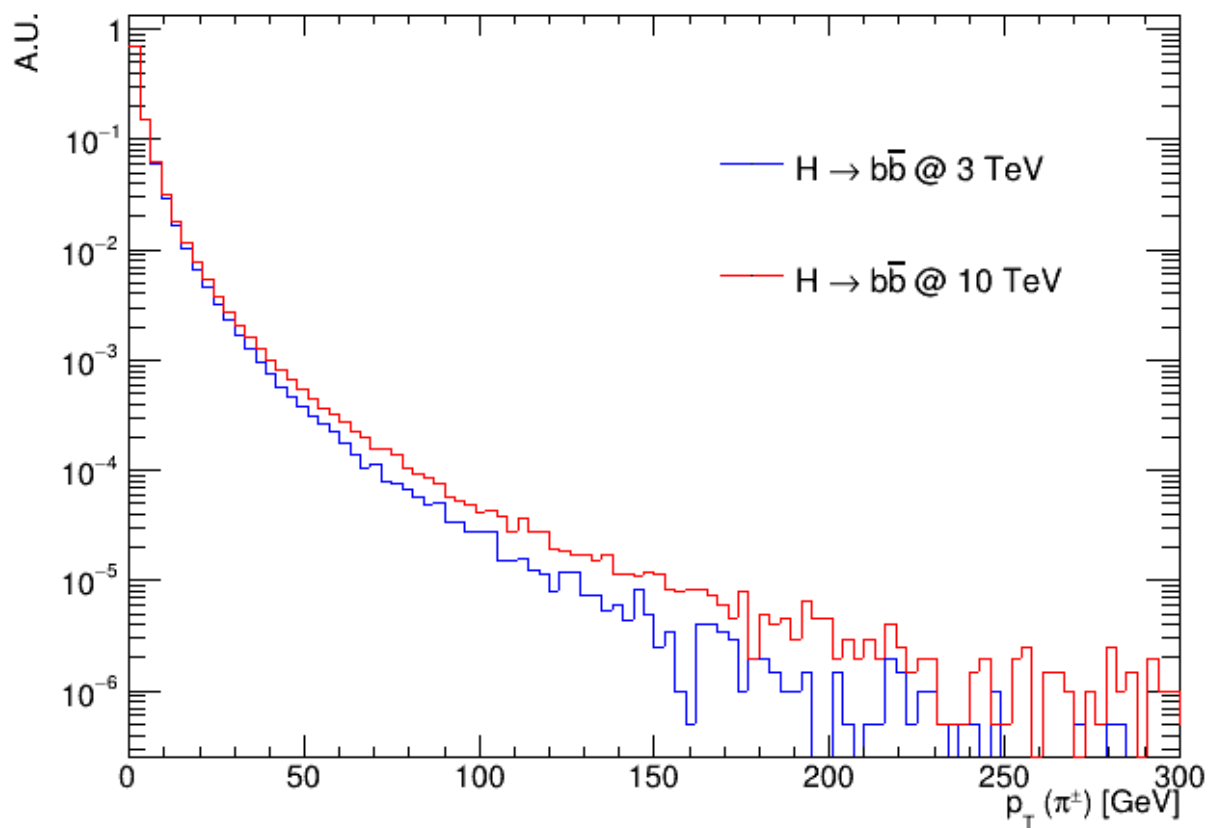


# Muons: $E$ and $\theta$

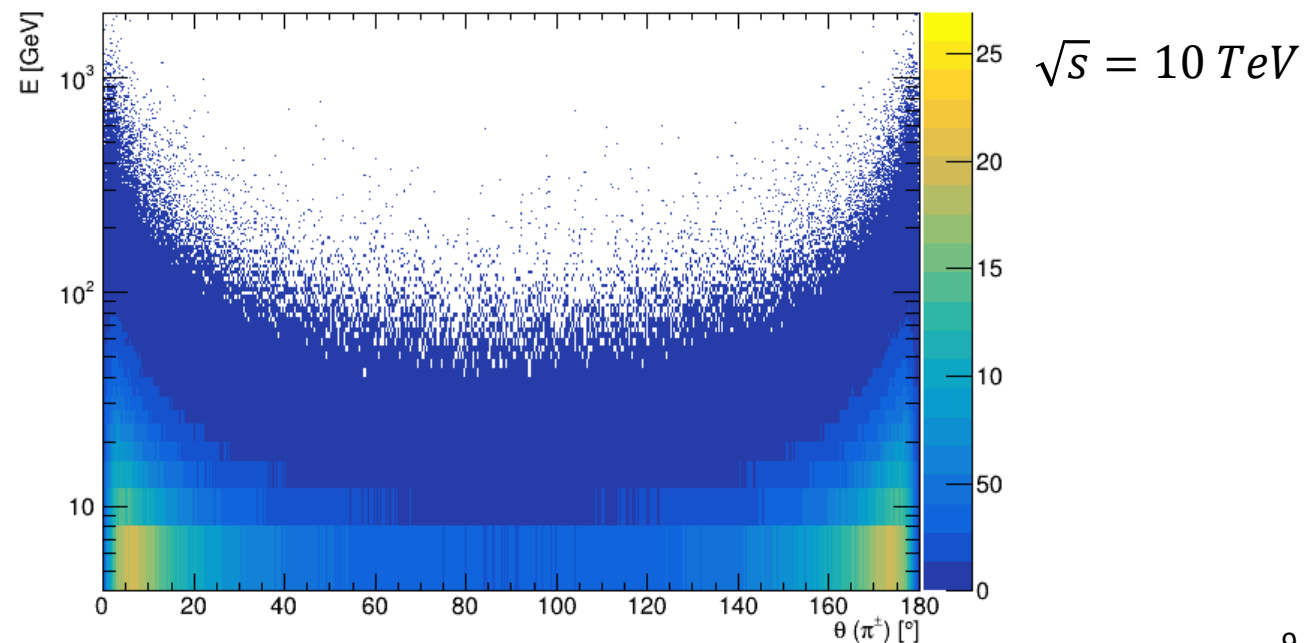
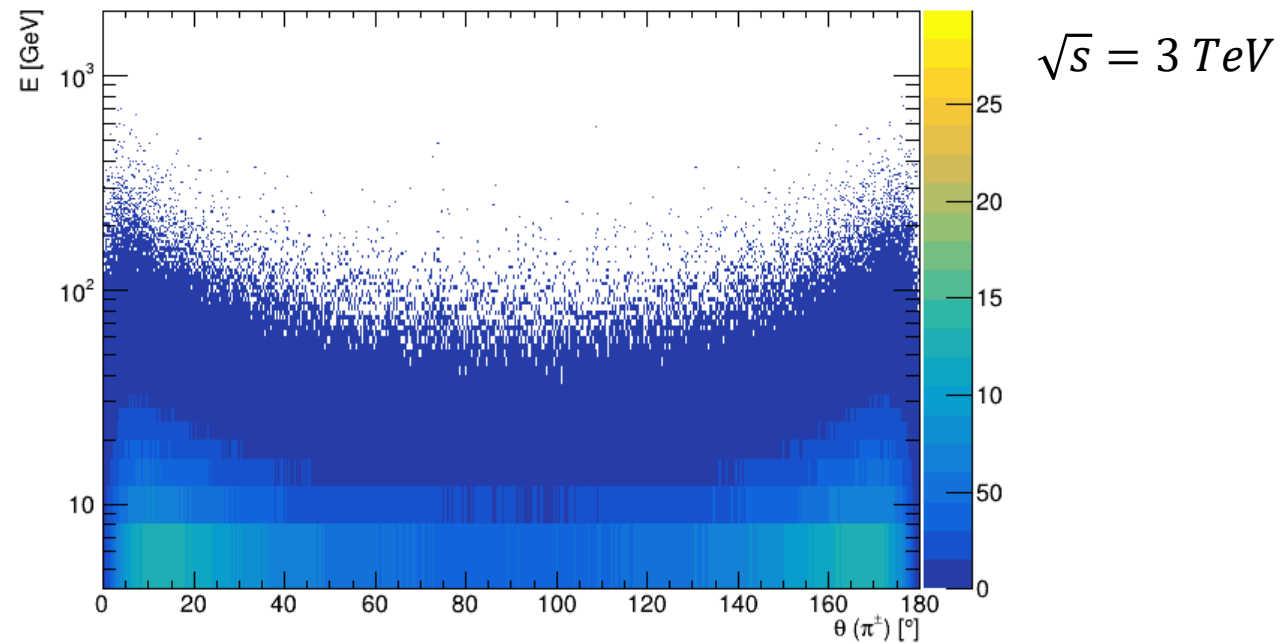
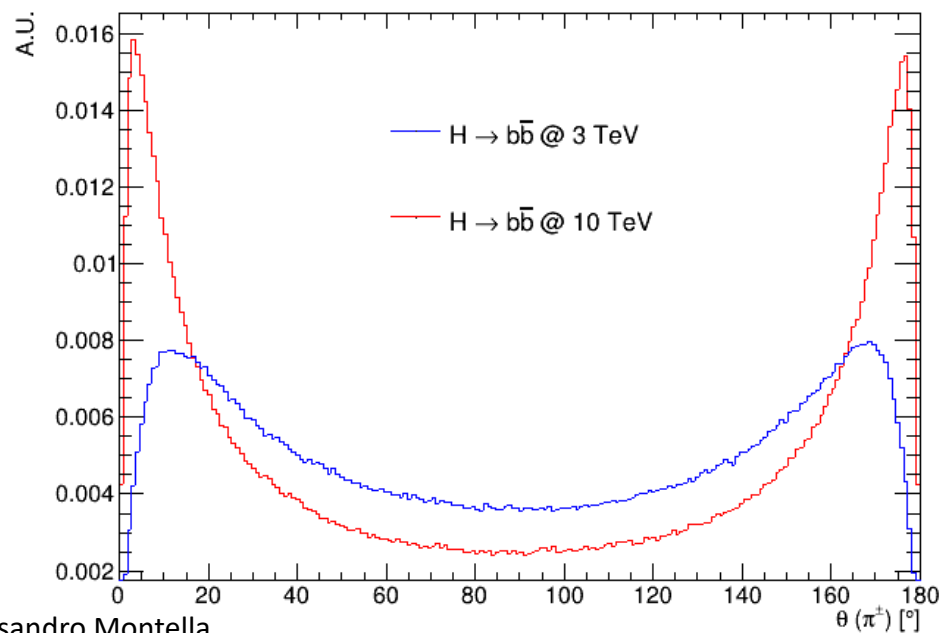
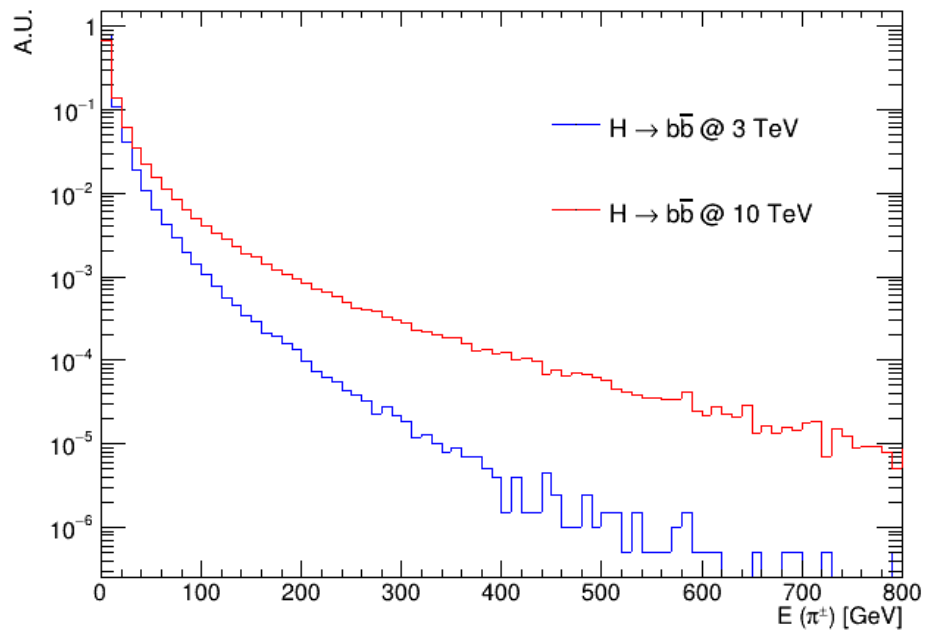




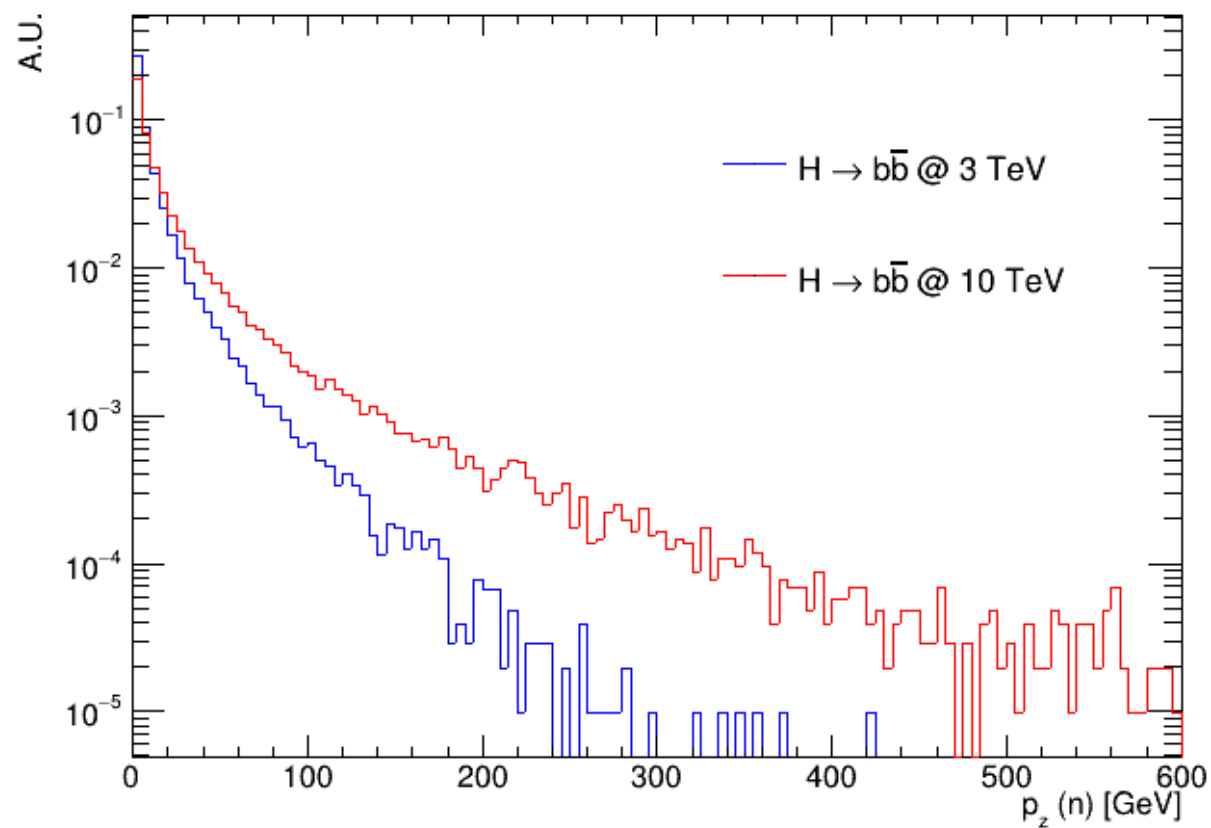
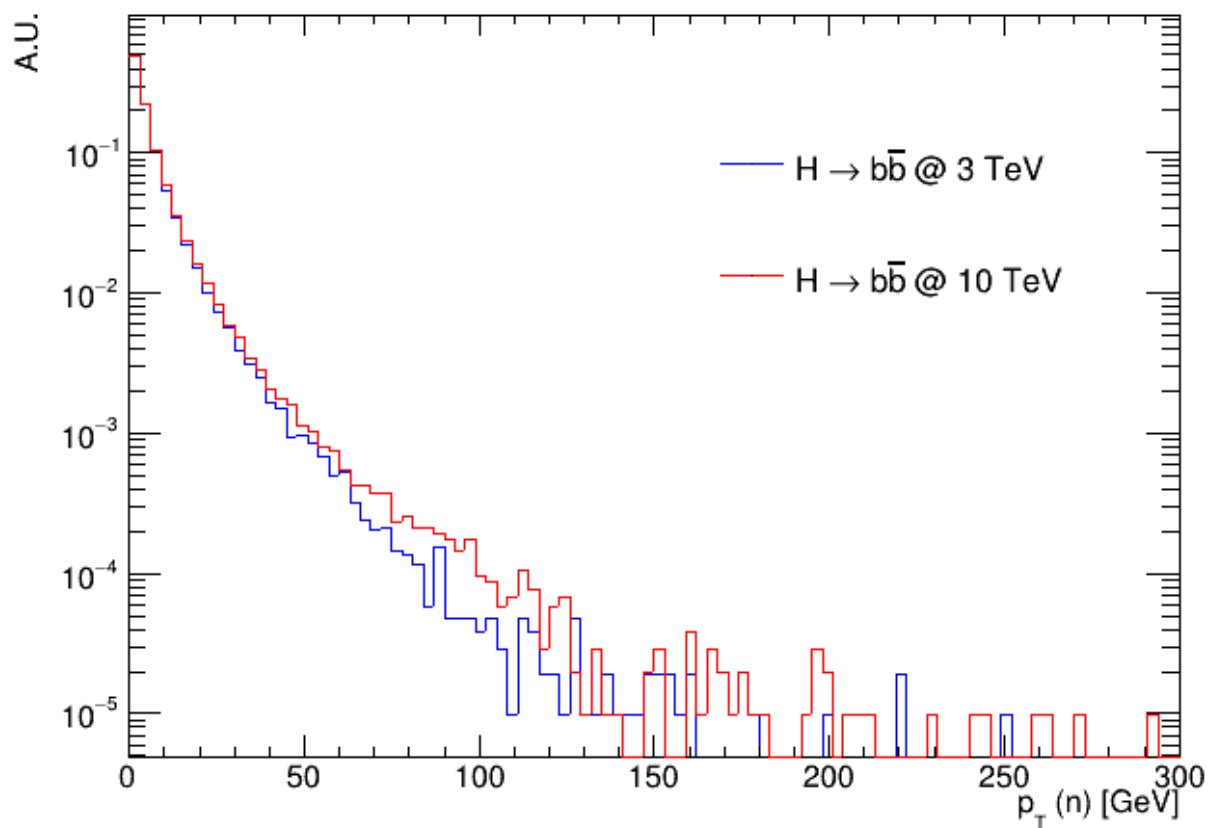
# Charged pions: $p_T$ and $p_z$



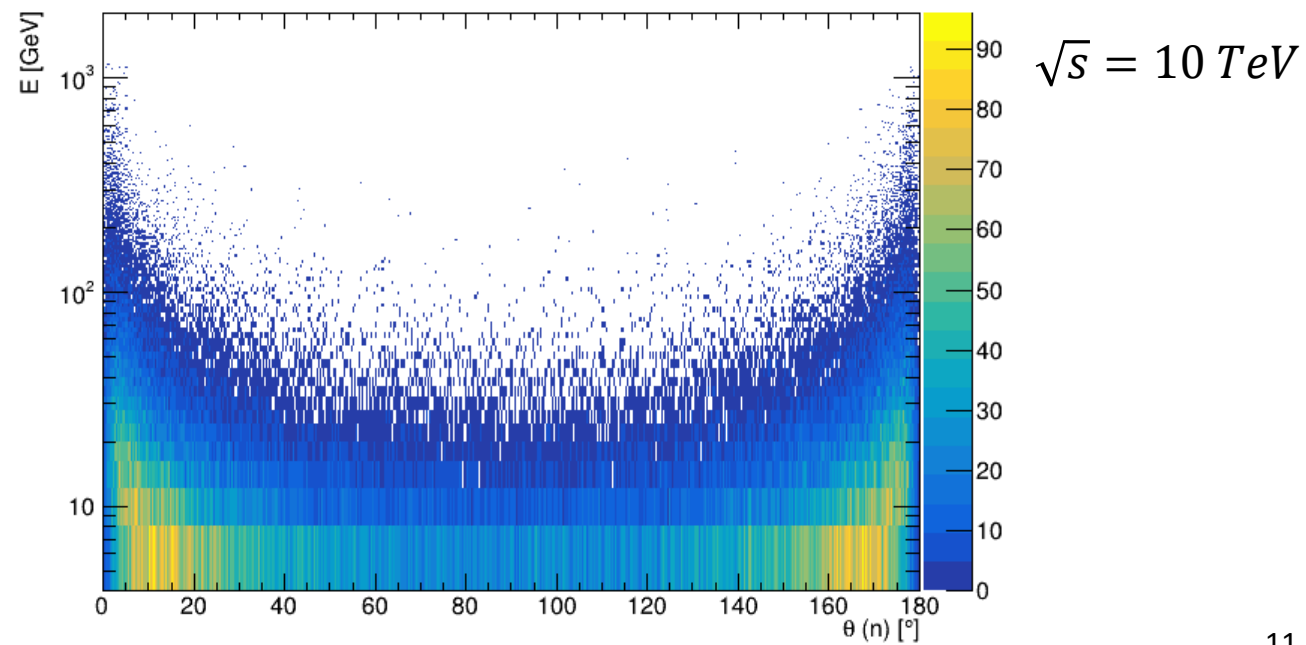
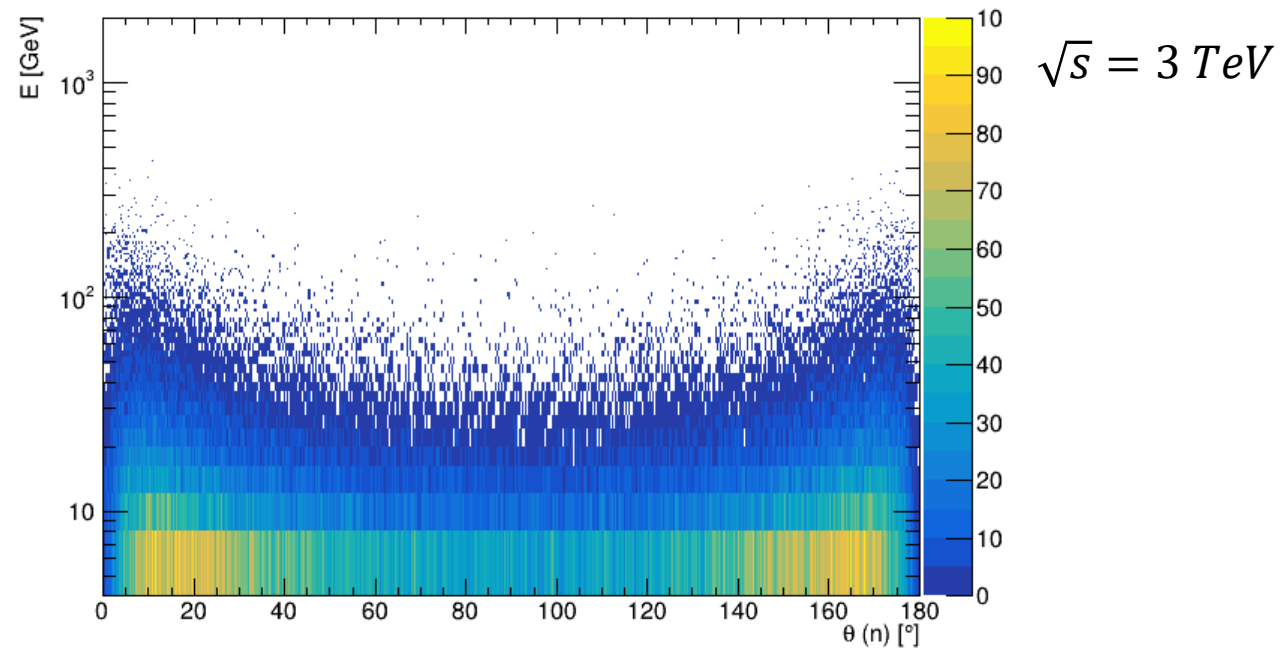
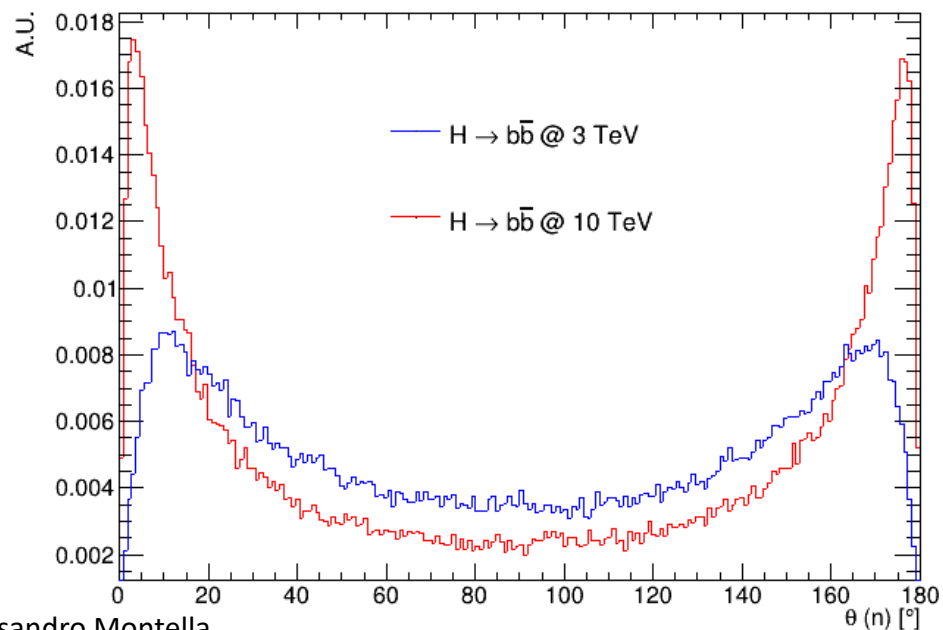
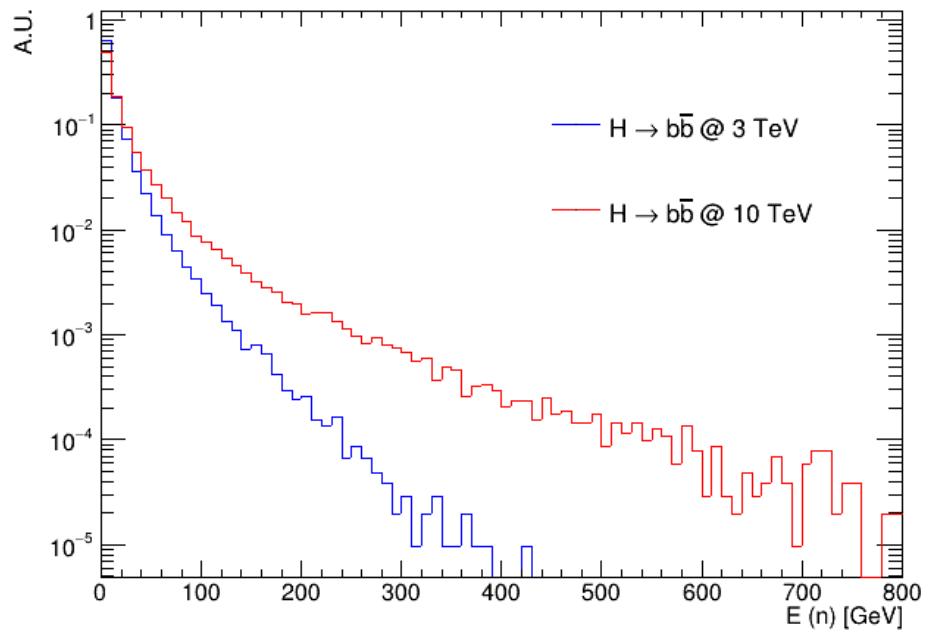
# Charged pions: $E$ and $\theta$



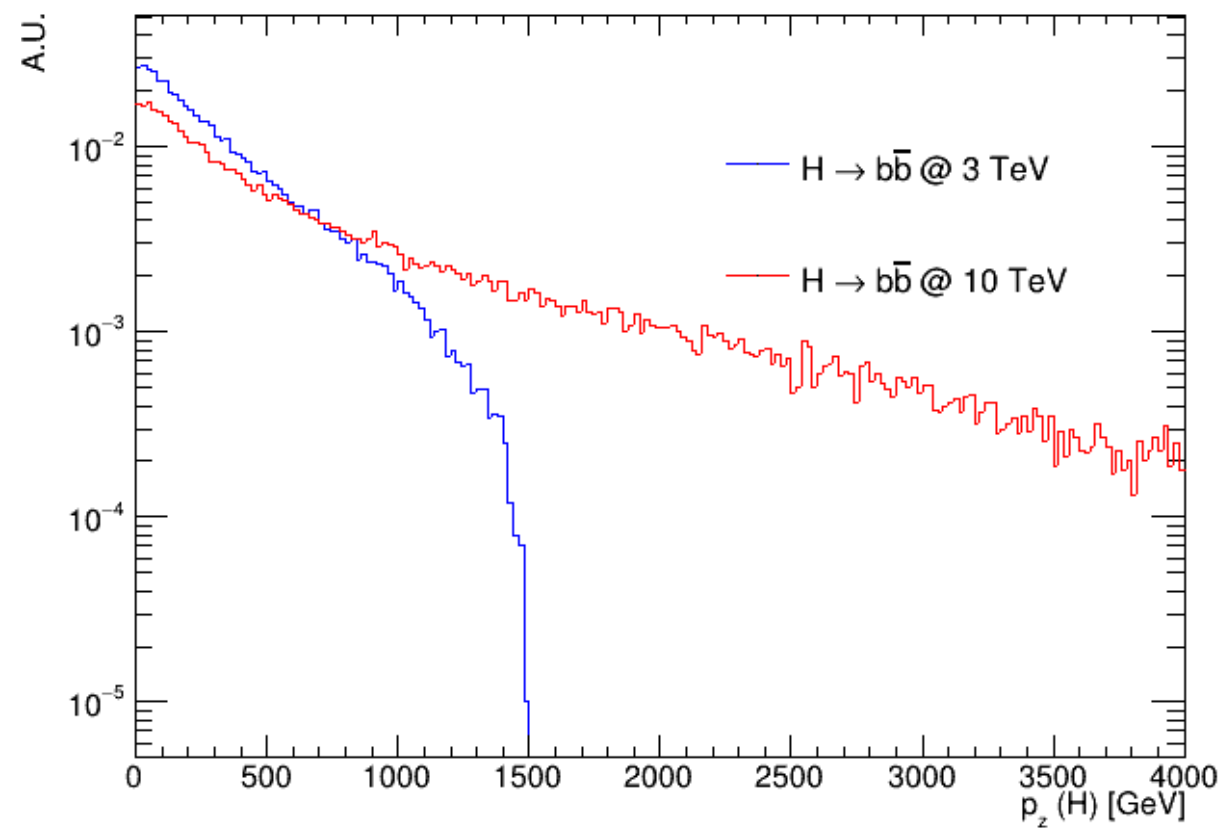
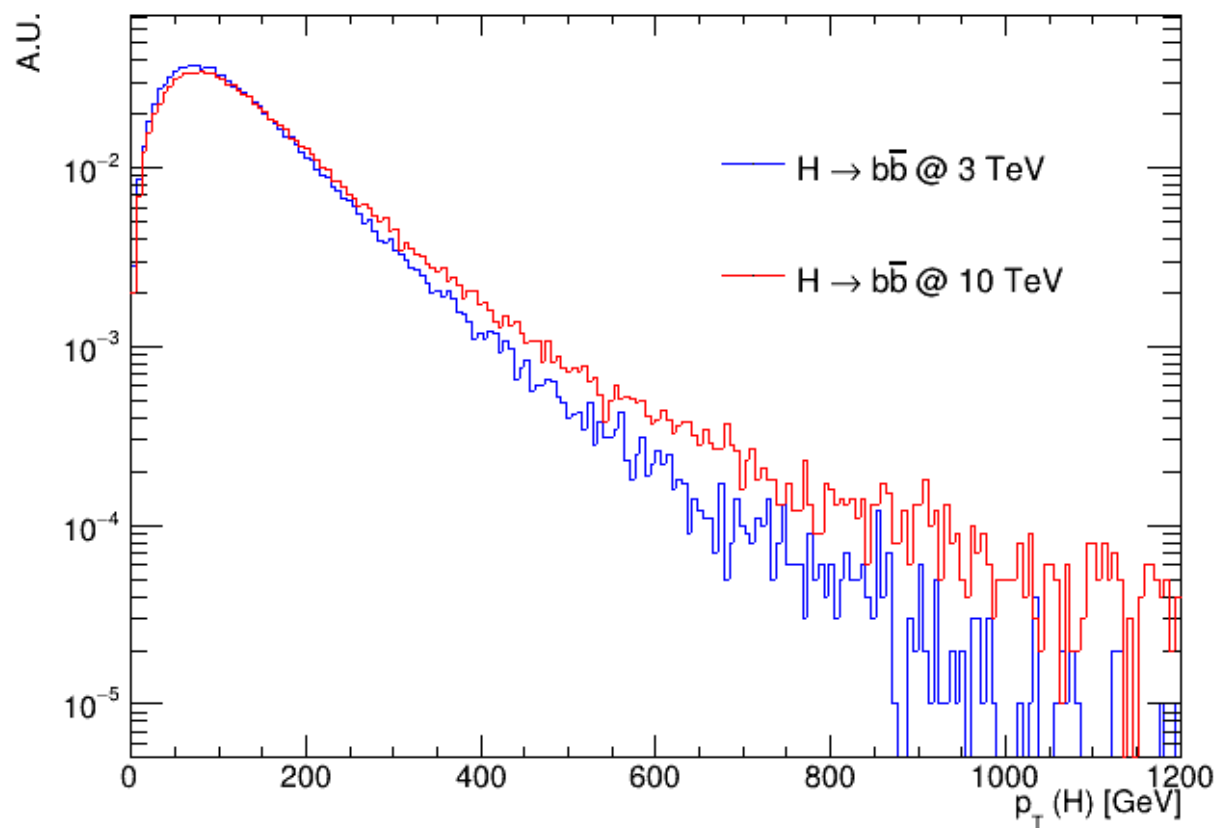
# Neutrons: $p_T$ and $p_z$



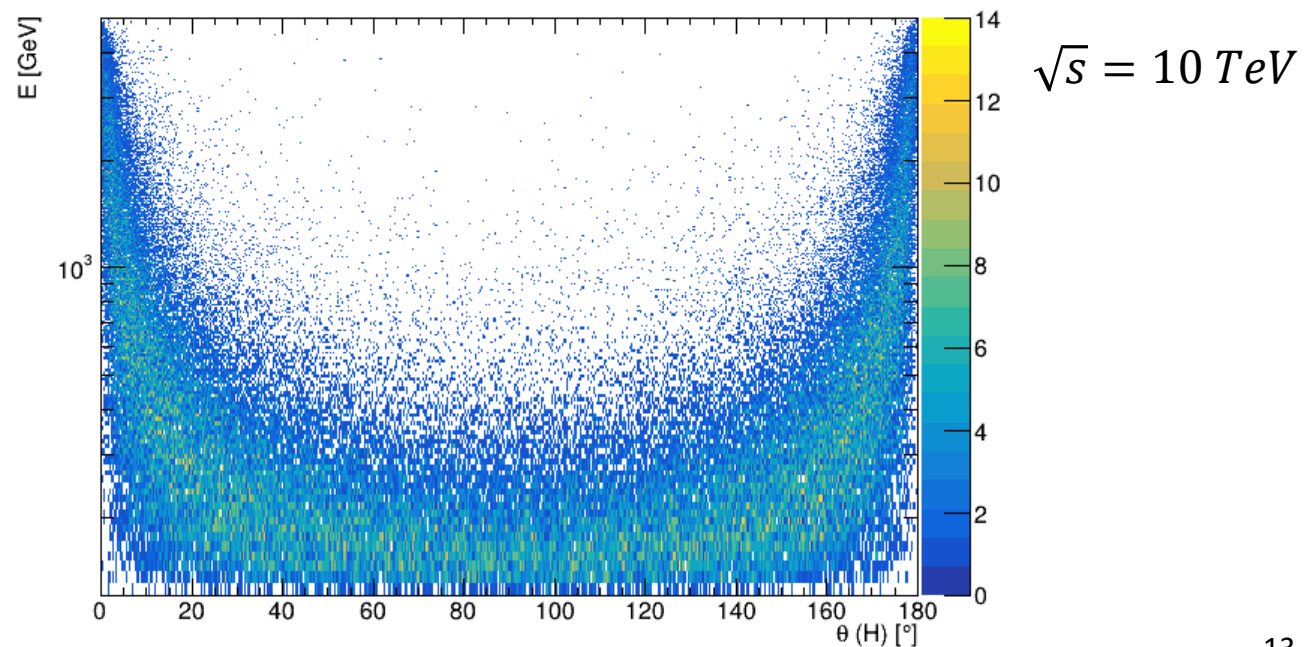
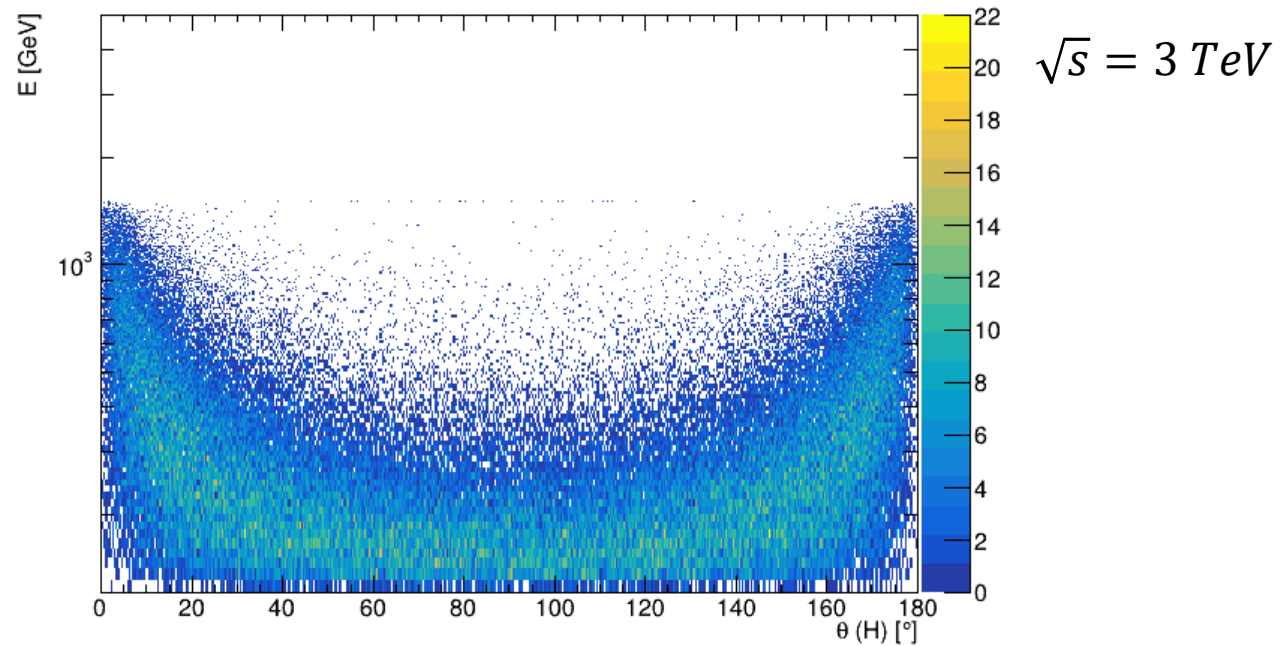
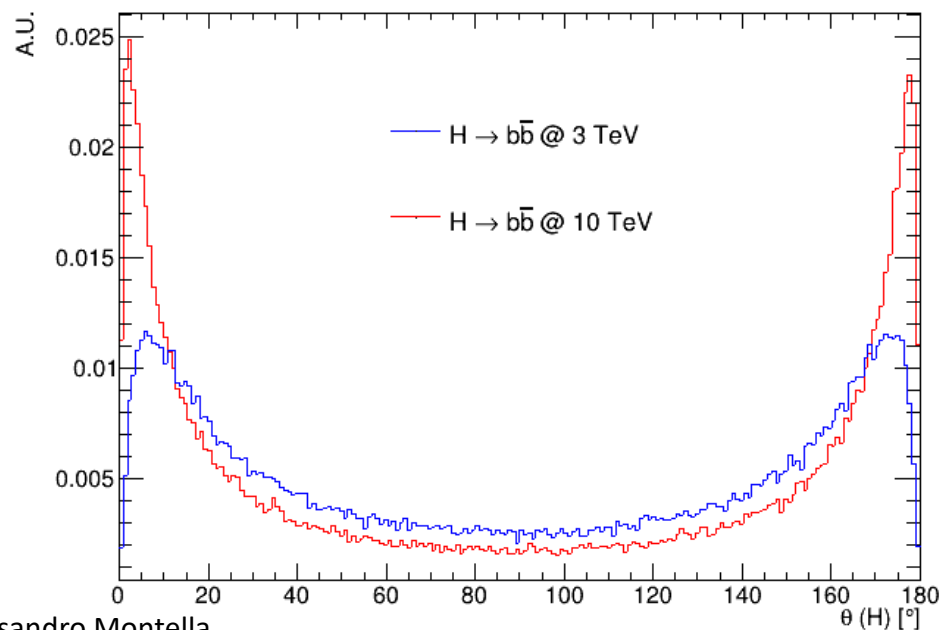
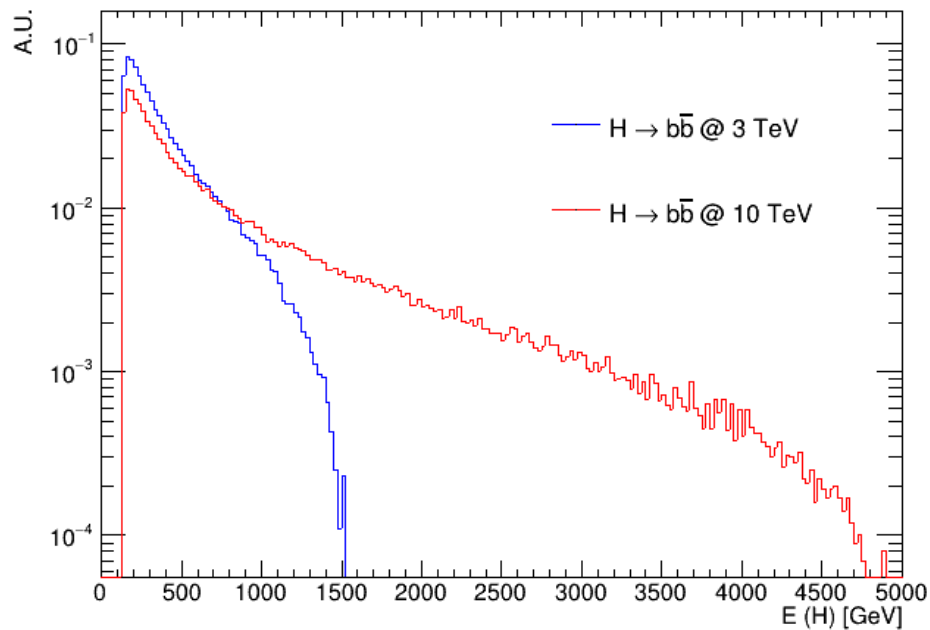
# Neutrons: $E$ and $\theta$



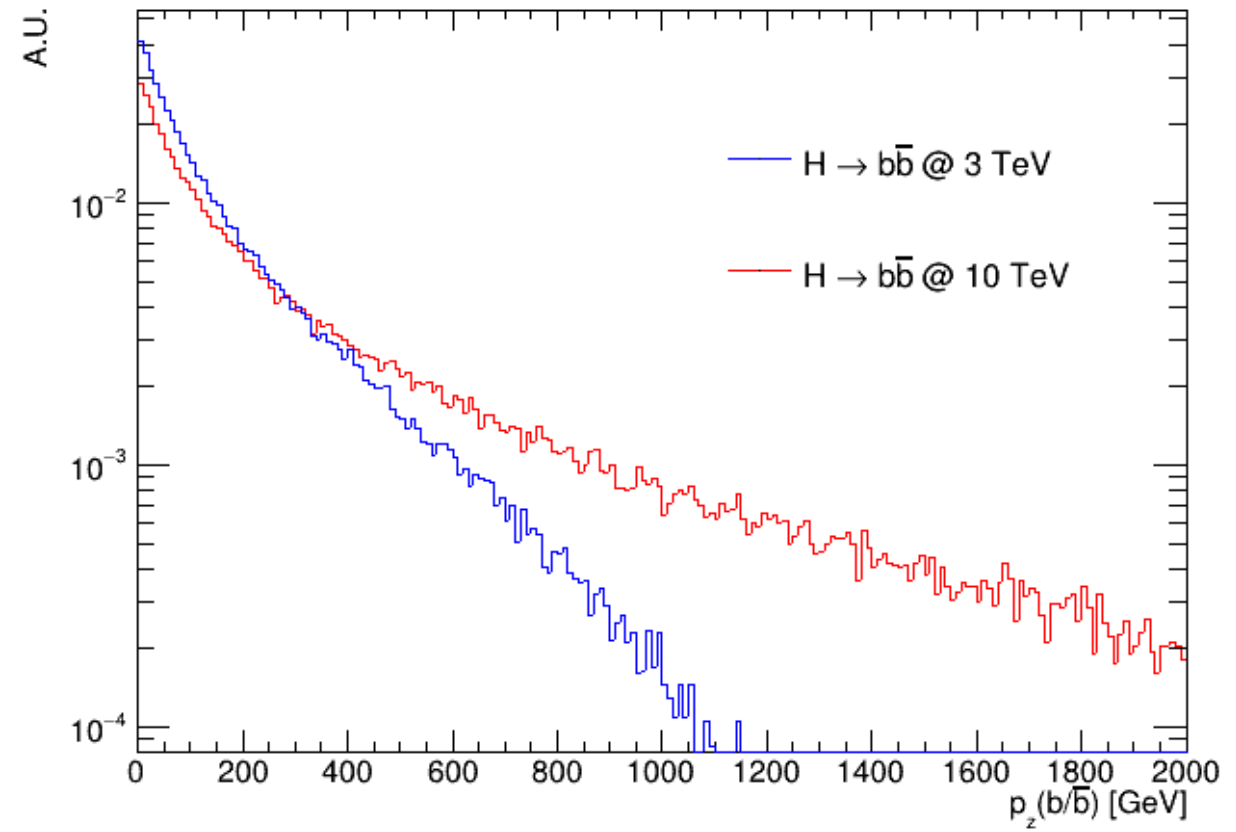
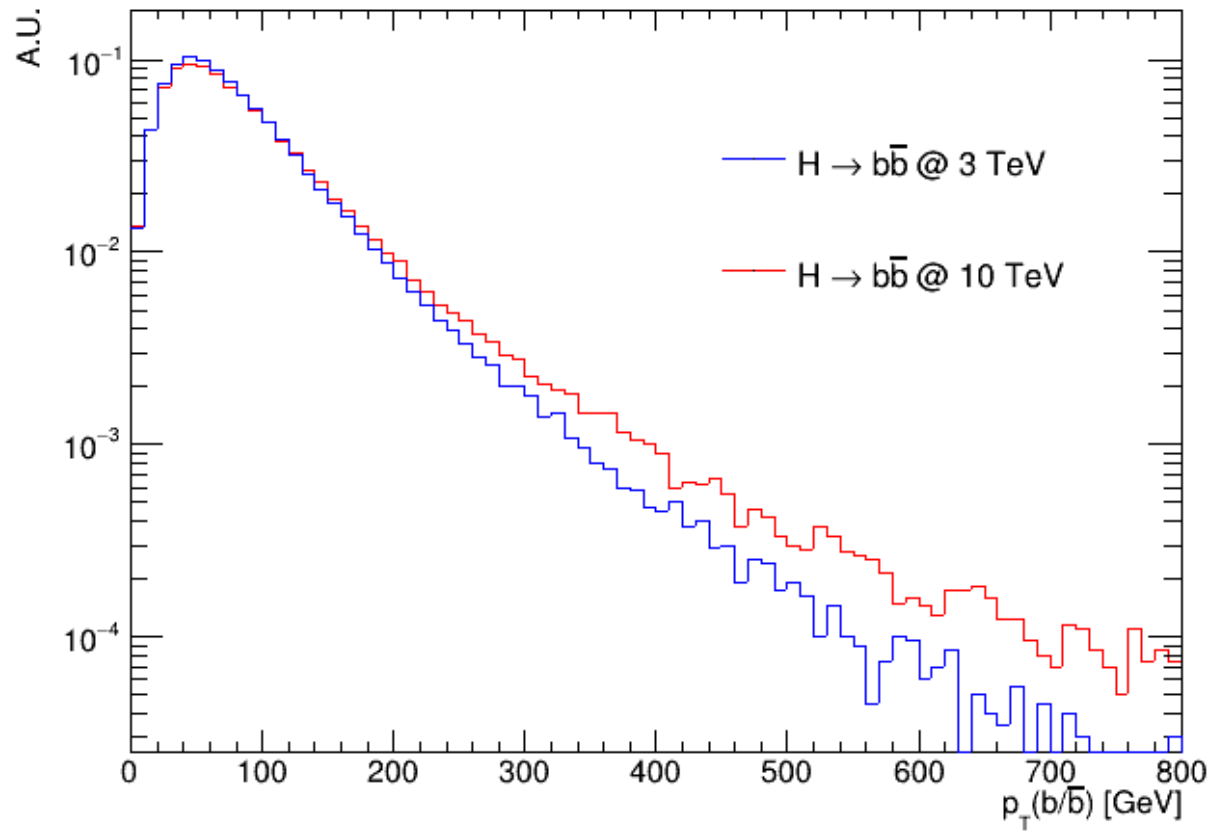
# Higgs: $p_T$ and $p_z$



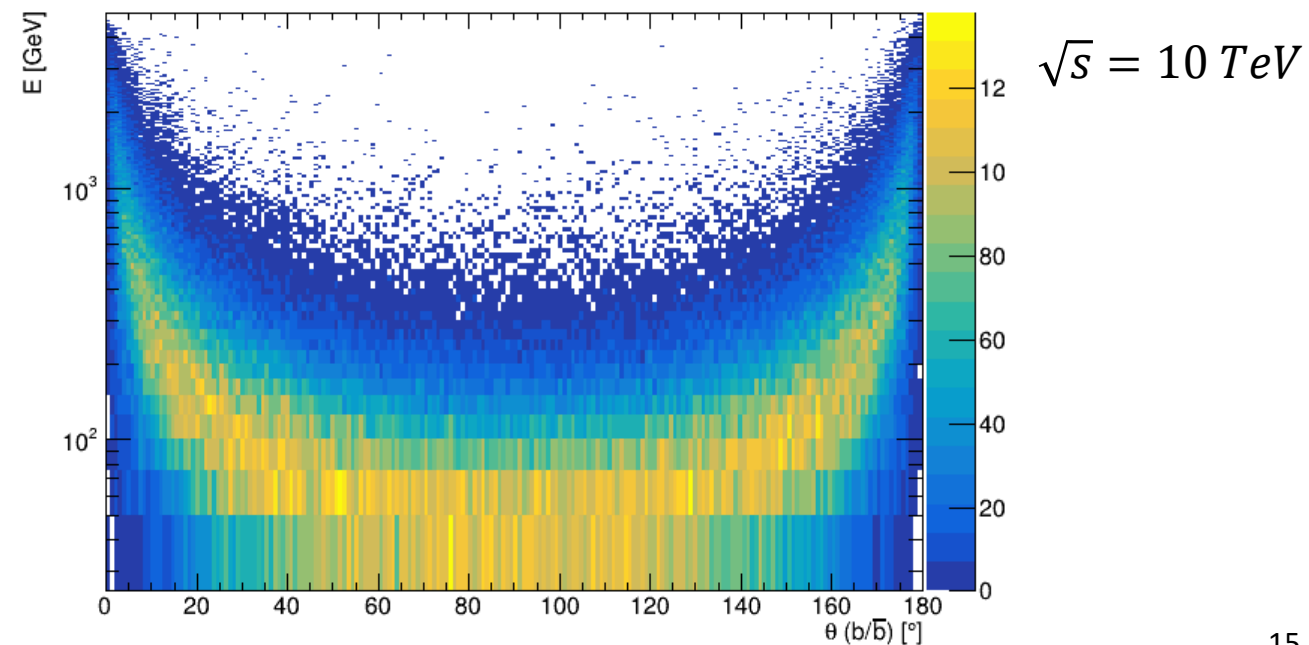
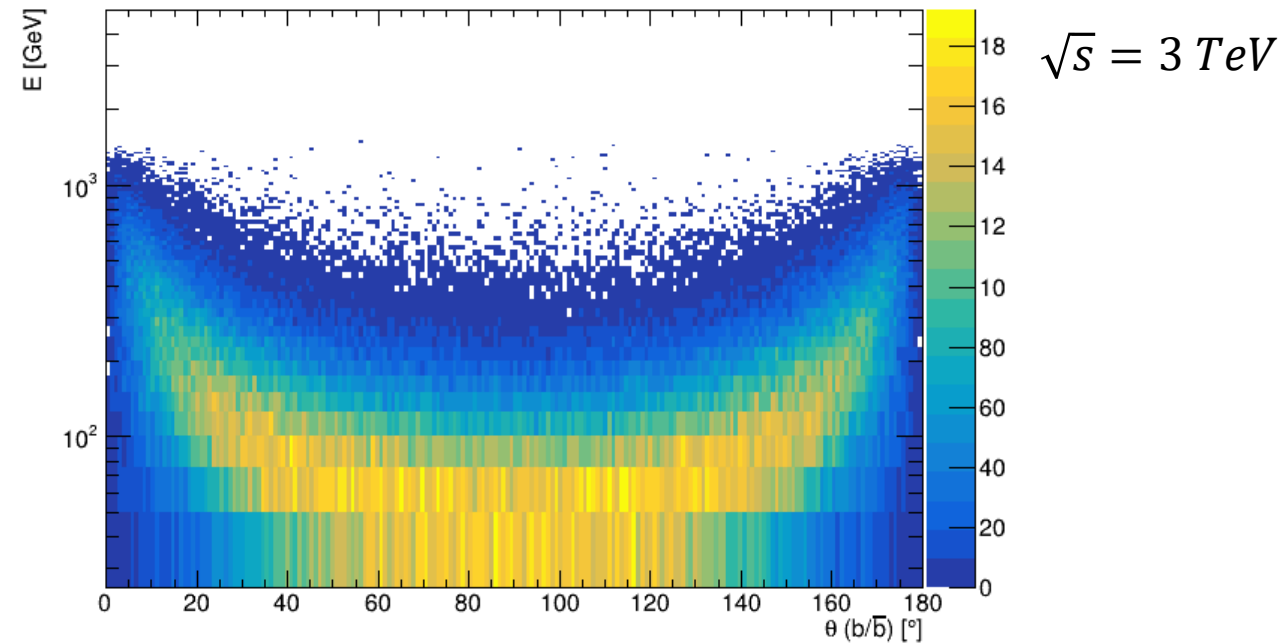
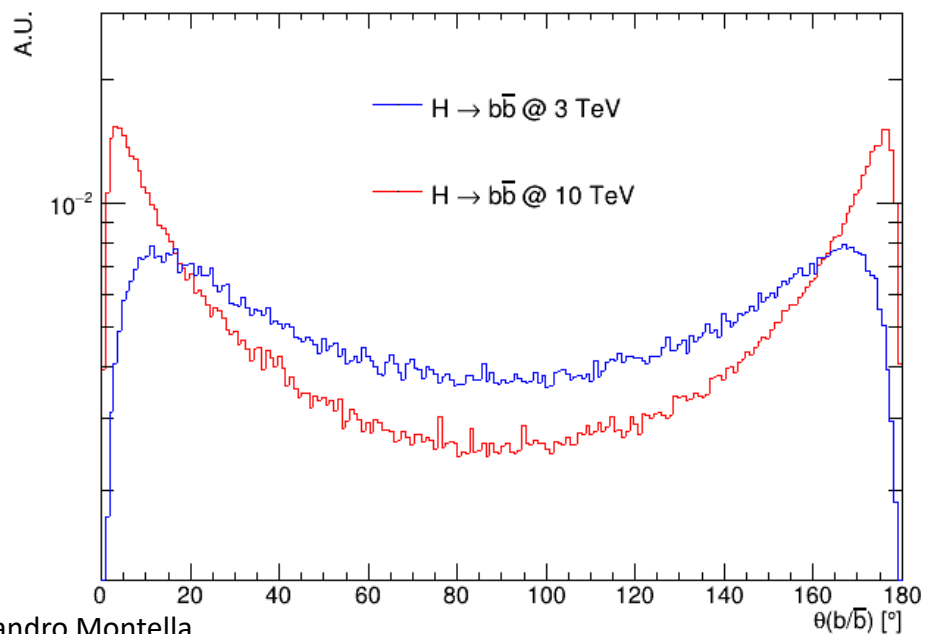
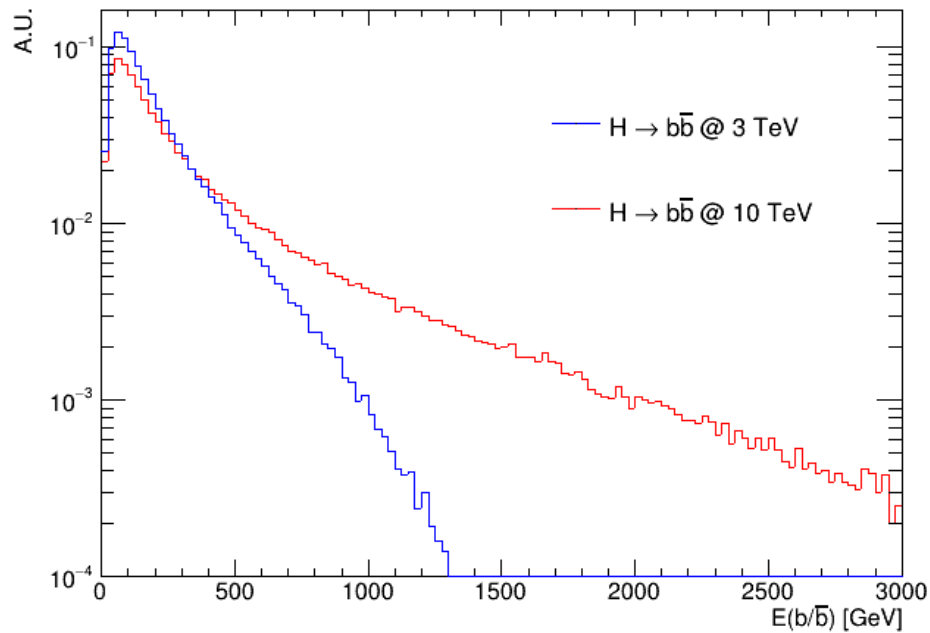
# Higgs: $E$ and $\theta$



# b-quarks: $p_T$ and $p_z$

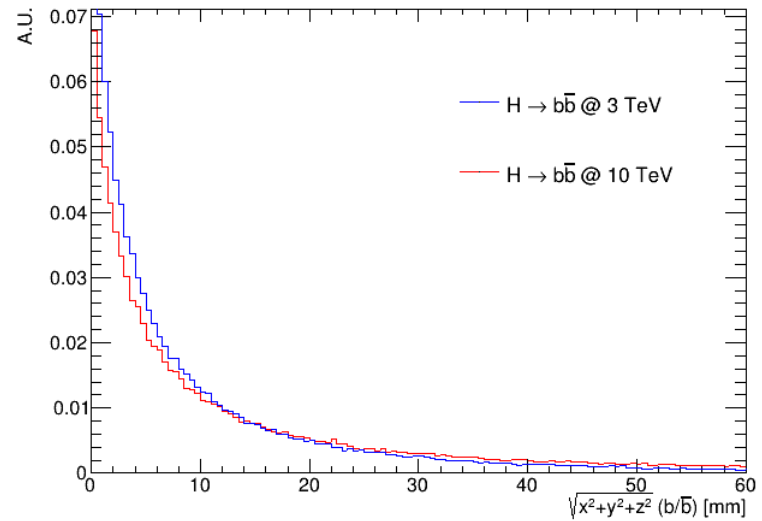
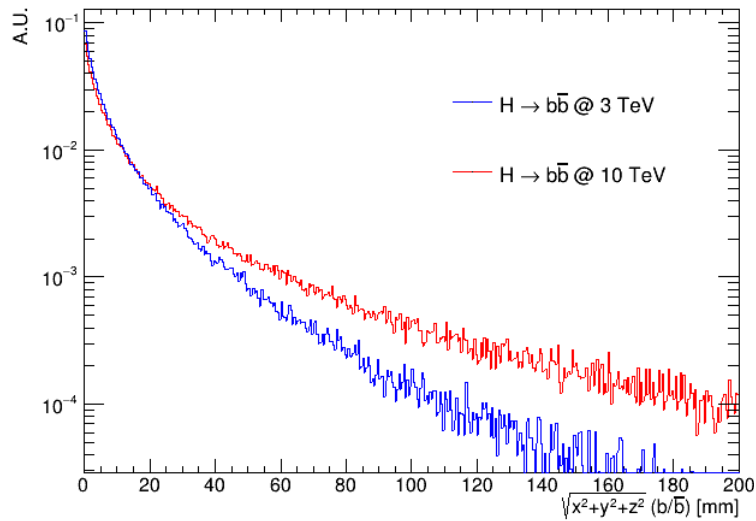
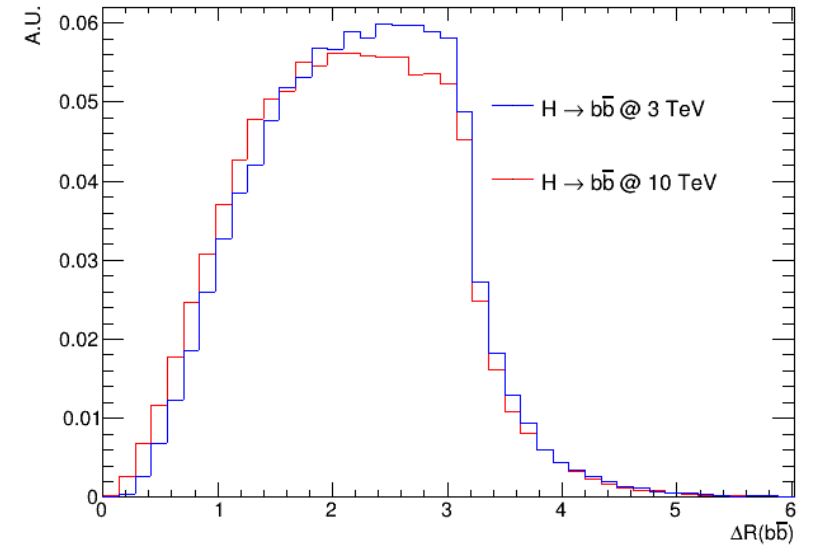
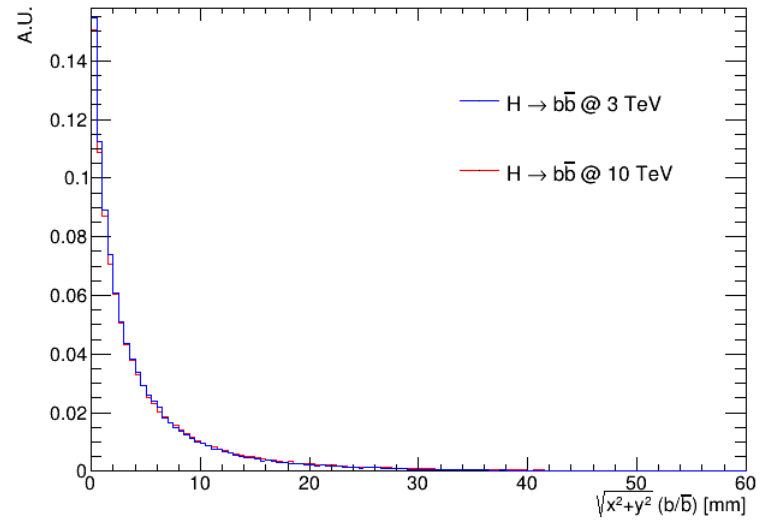
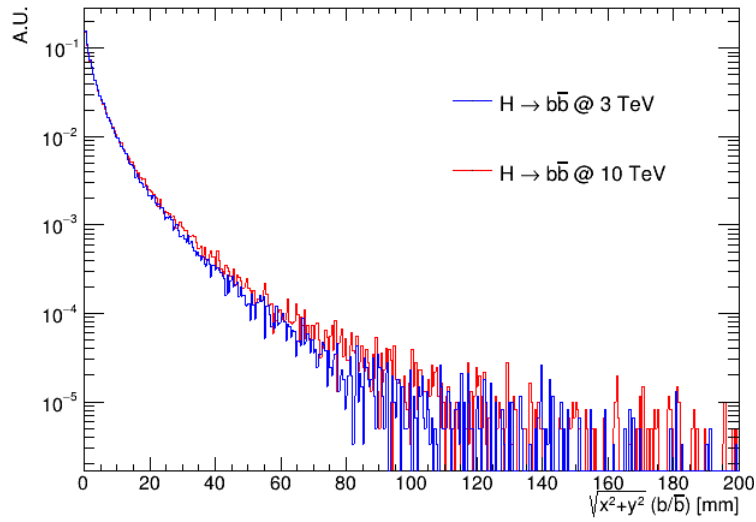


# b-quarks: $E$ and $\theta$





# b-quarks: b decay vertex and $\Delta R$



# Considerations on geometrical acceptance

% of events with at least one b-quark inside the acceptance region	$5^\circ < \theta < 175^\circ$	$10^\circ < \theta < 170^\circ$
$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu, H \rightarrow b\bar{b}$ @ $\sqrt{s} = 3$ TeV	99.99	98.75
$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu, H \rightarrow b\bar{b}$ @ $\sqrt{s} = 10$ TeV	95.78	85.31

% of events with two b-quarks inside the acceptance region	$5^\circ < \theta < 175^\circ$	$10^\circ < \theta < 170^\circ$
$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu, H \rightarrow b\bar{b}$ @ $\sqrt{s} = 3$ TeV	92.99	79.05
$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu, H \rightarrow b\bar{b}$ @ $\sqrt{s} = 10$ TeV	77.63	60.27

% of events with one b-quark inside the acceptance region	$5^\circ < \theta < 175^\circ$	$10^\circ < \theta < 170^\circ$
$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu, H \rightarrow b\bar{b}$ @ $\sqrt{s} = 3$ TeV	7.00	19.69
$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu, H \rightarrow b\bar{b}$ @ $\sqrt{s} = 10$ TeV	18.14	25.05

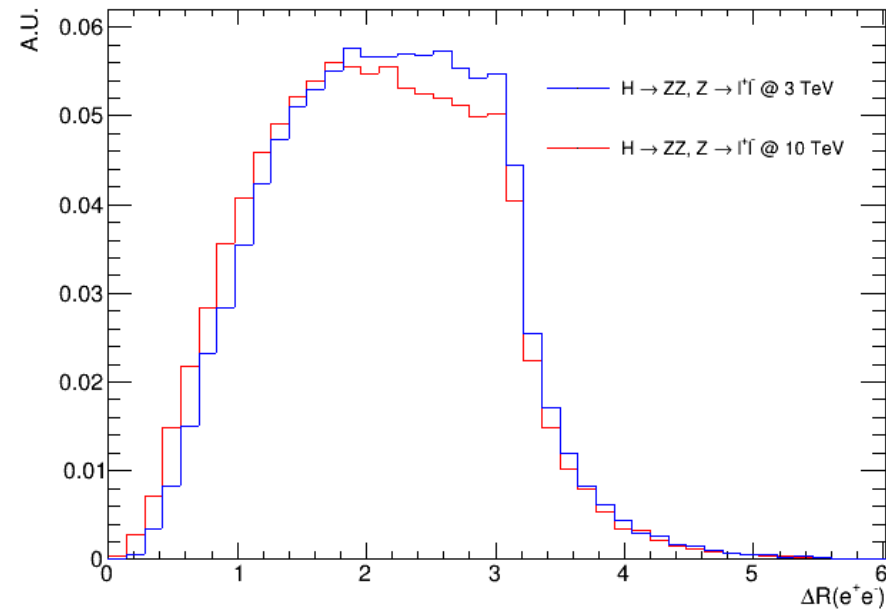
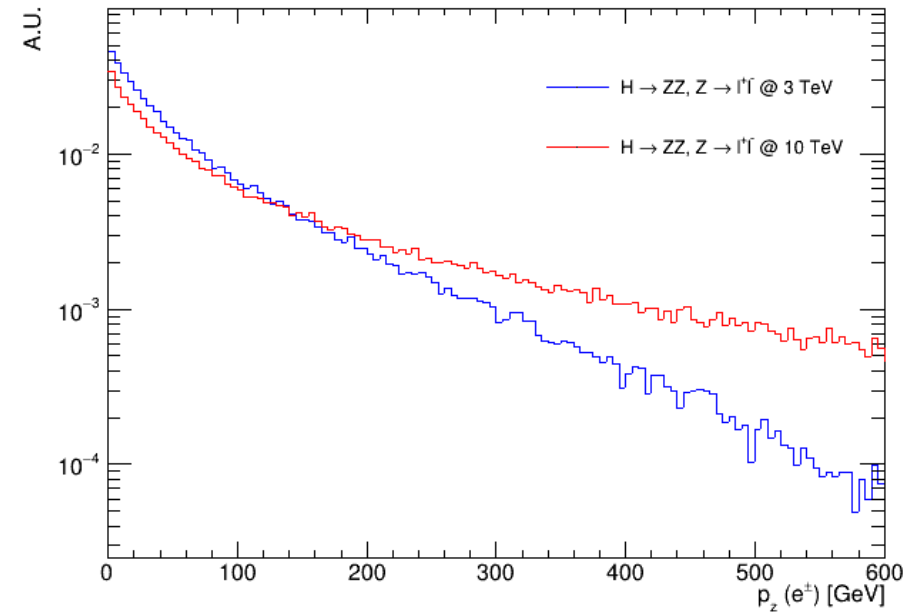
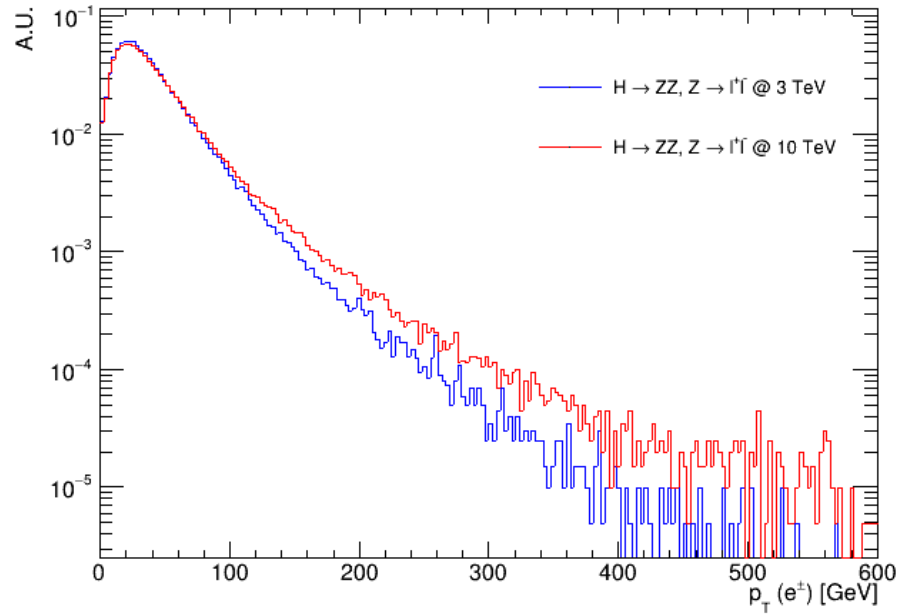
$$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu,$$

$$H \rightarrow ZZ,$$

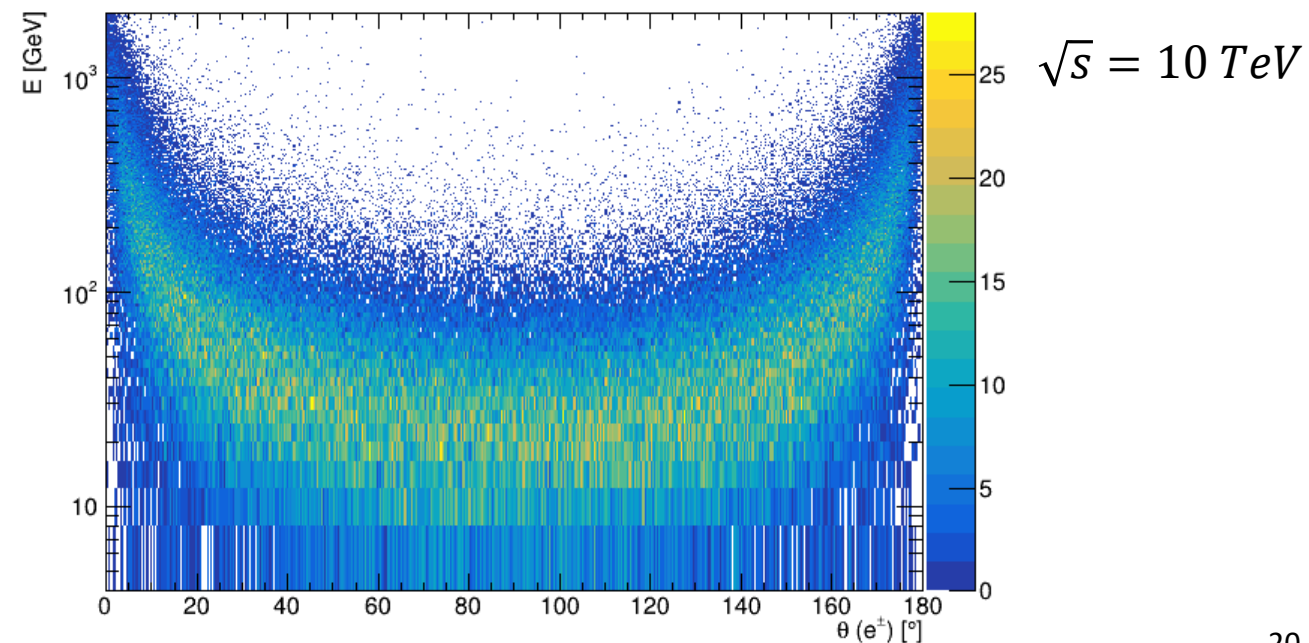
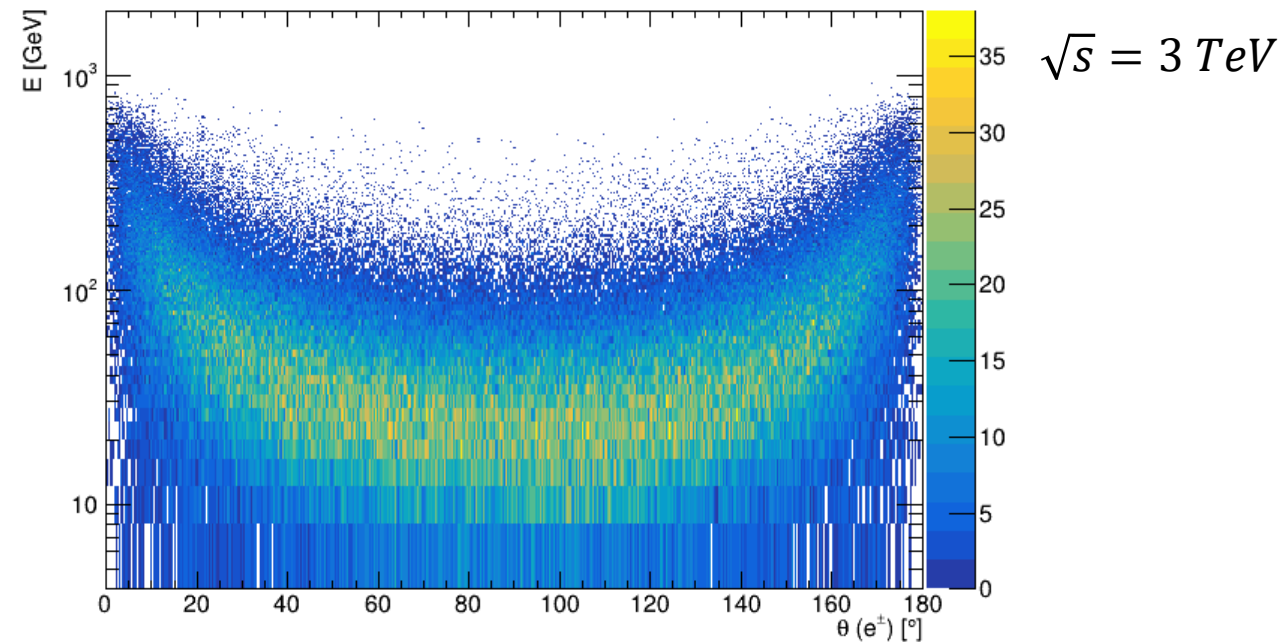
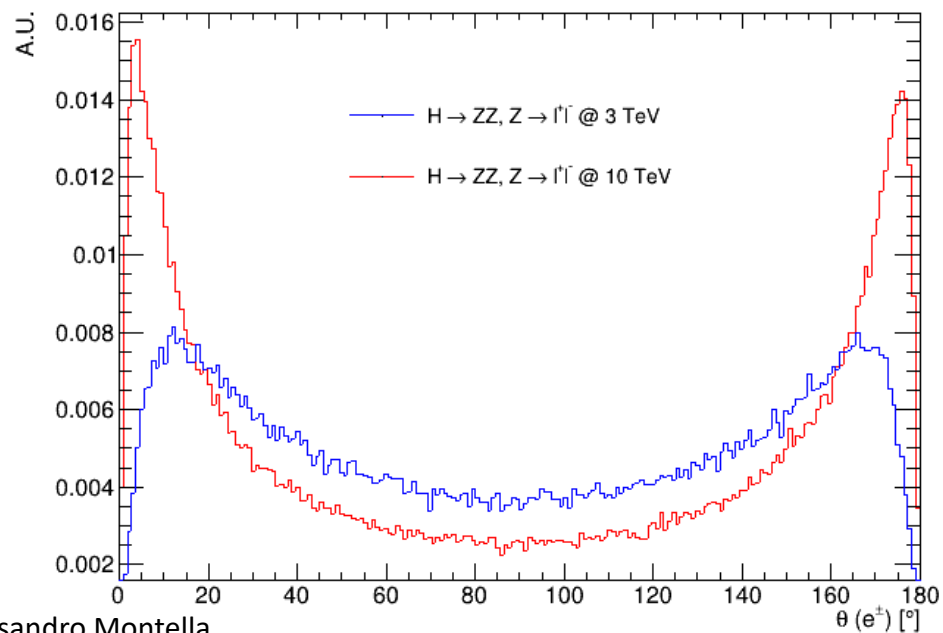
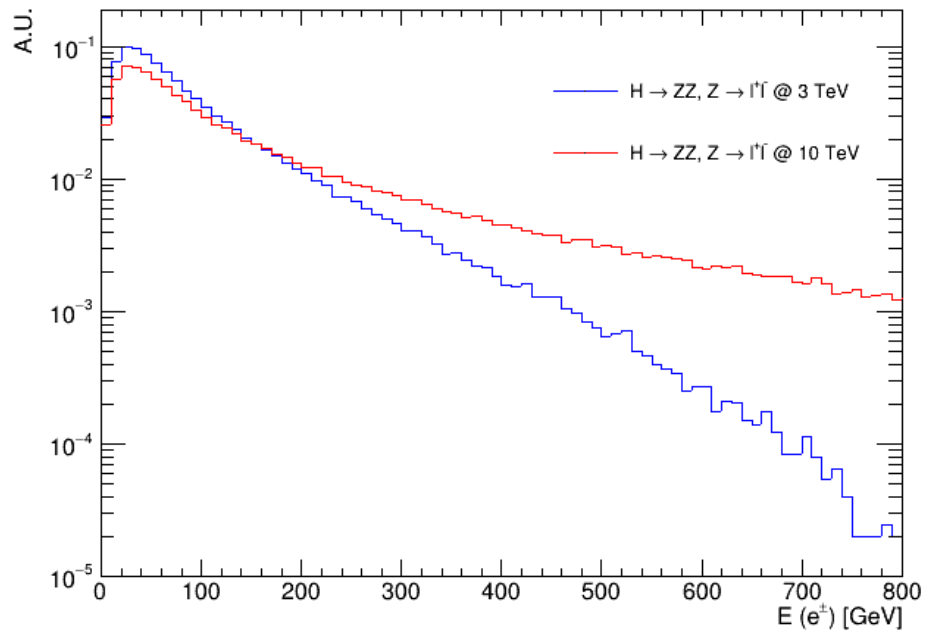
$$Z \rightarrow l^+ l^-$$

$$\sqrt{s} = 3 \text{ TeV vs } \sqrt{s} = 10 \text{ TeV}$$

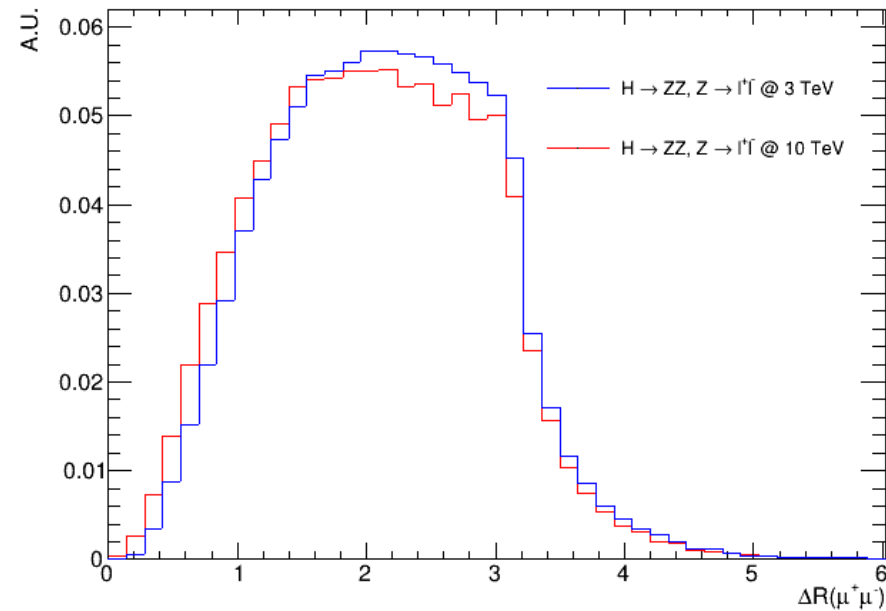
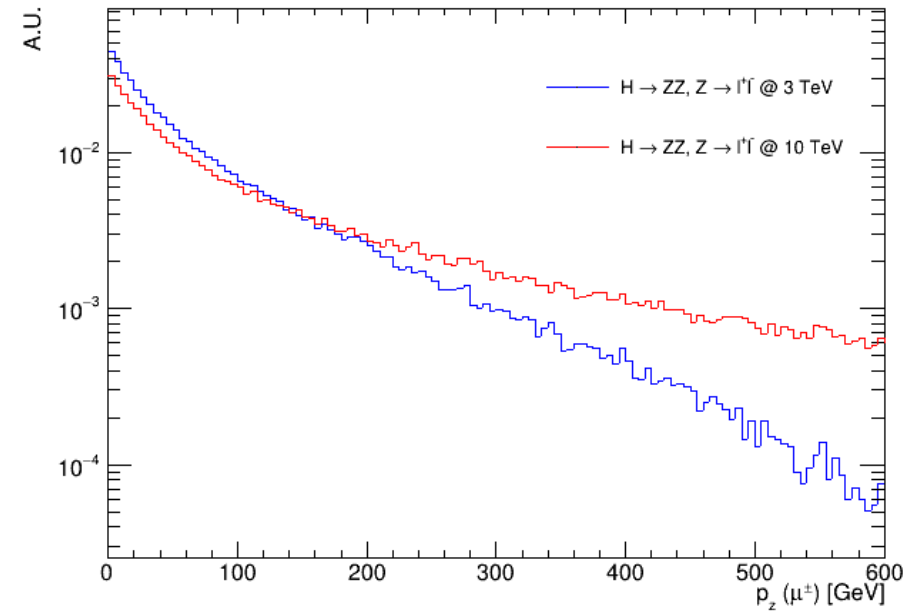
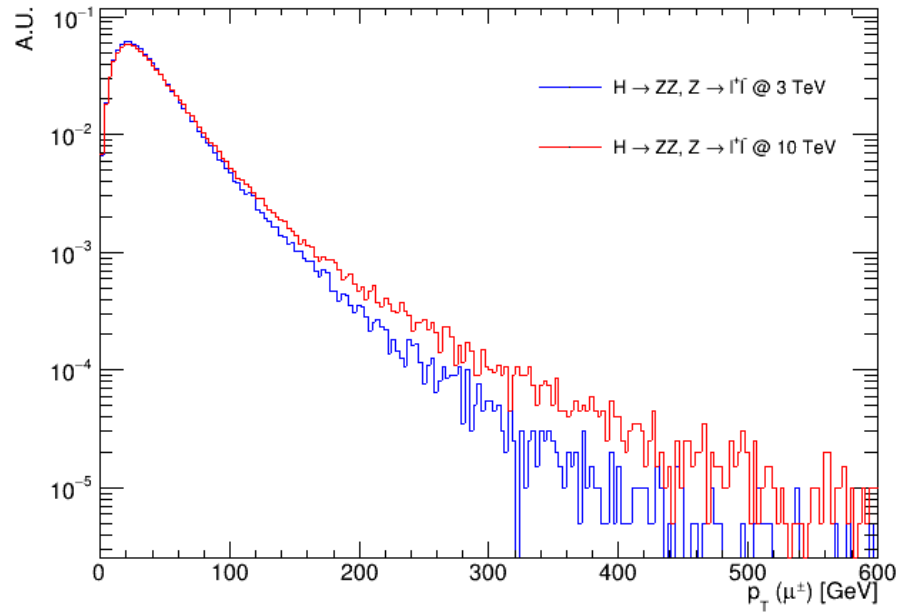
# Electrons: $p_T$ , $p_z$ and $\Delta R$



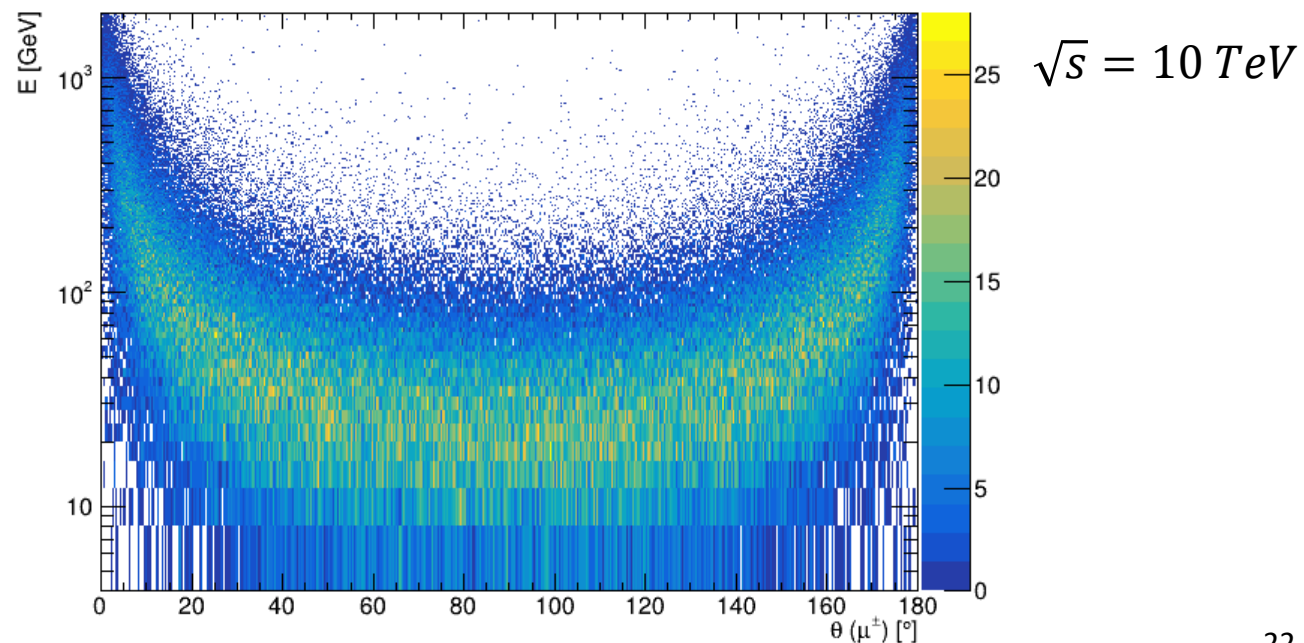
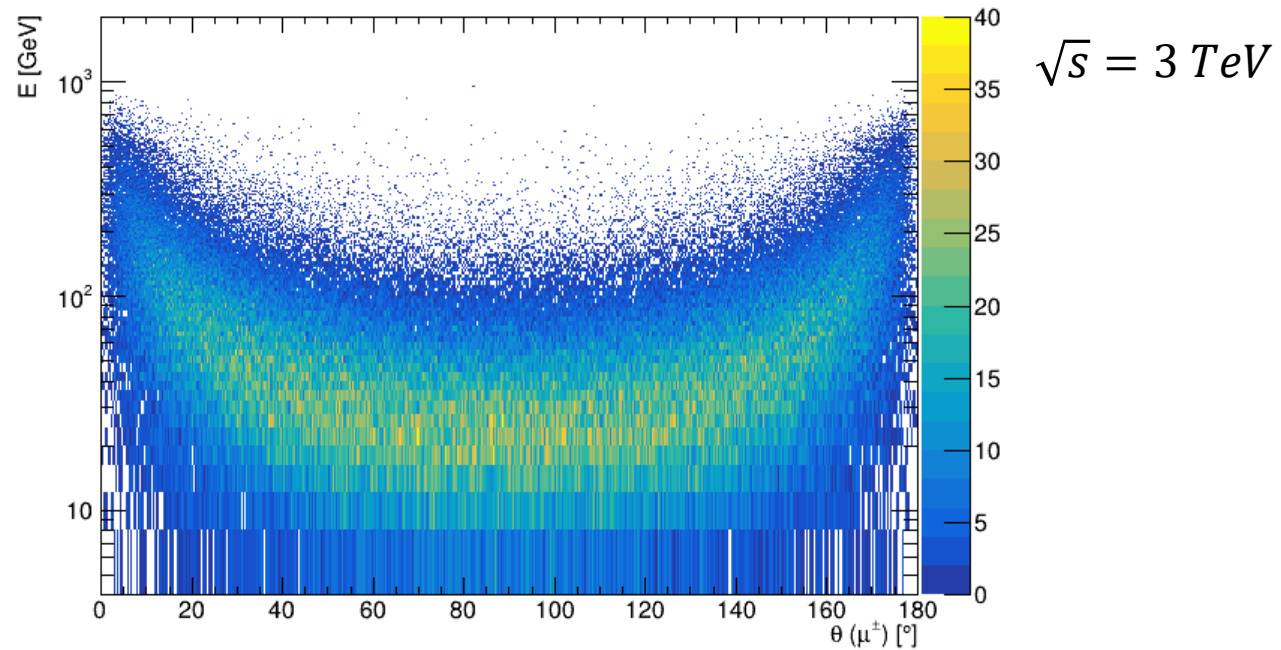
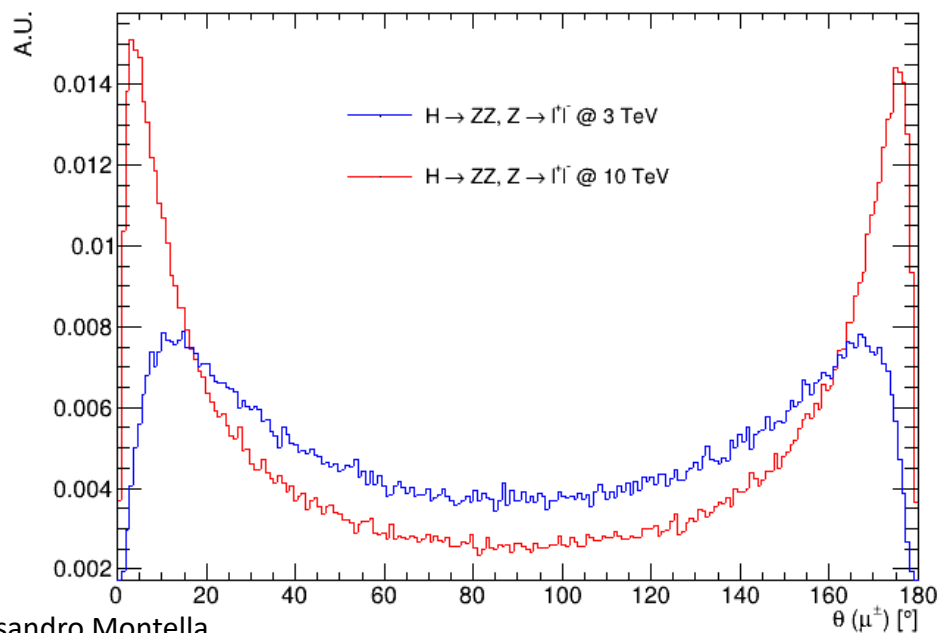
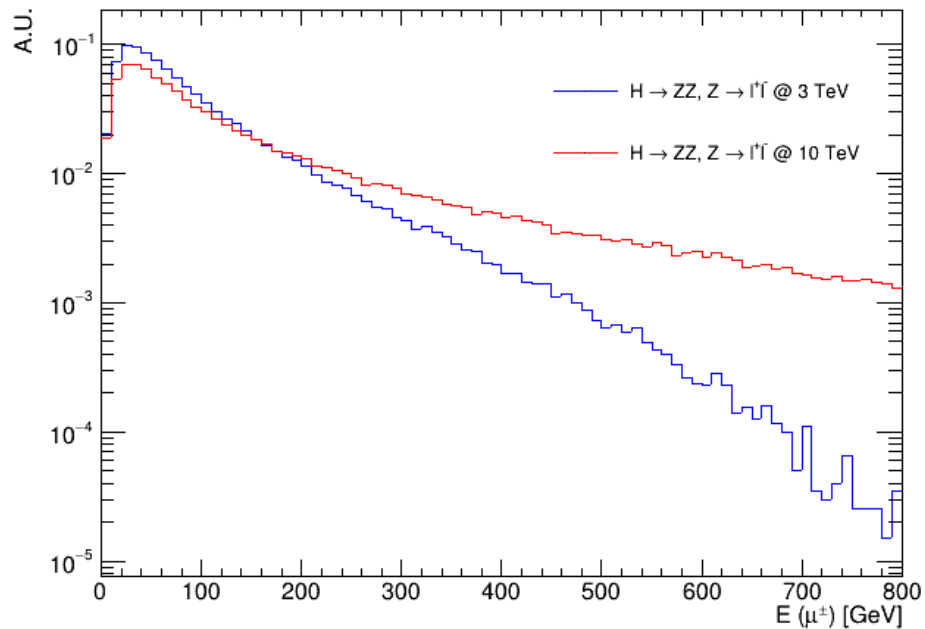
# Electrons: $E$ and $\theta$



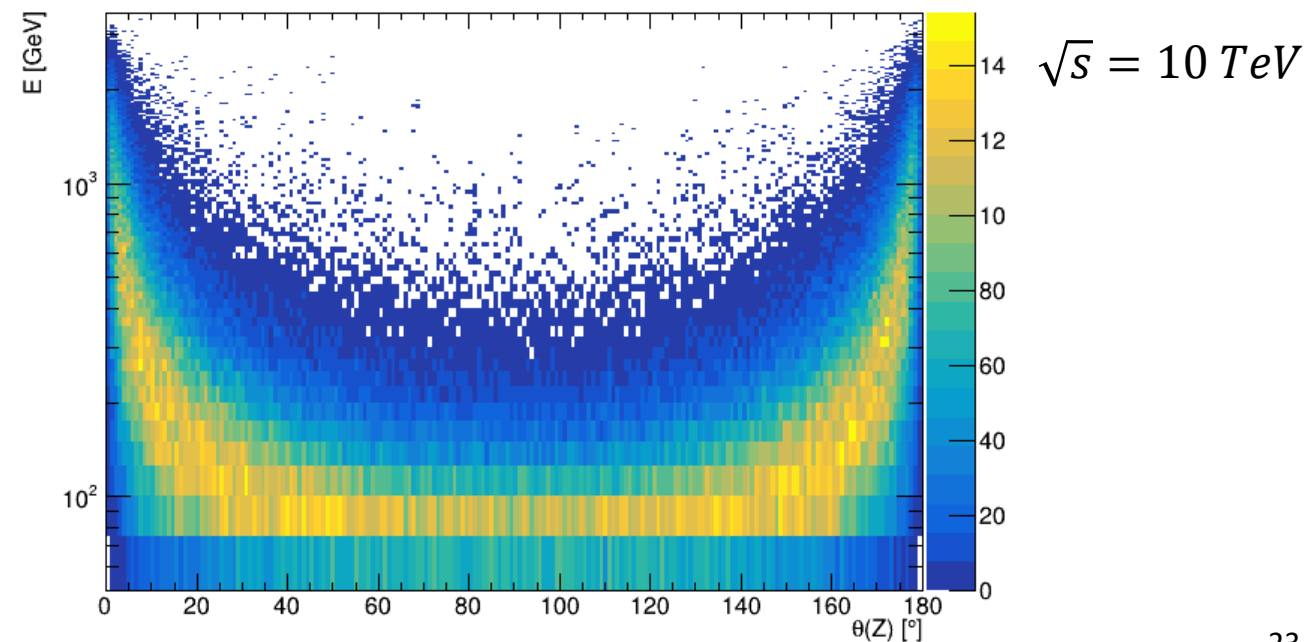
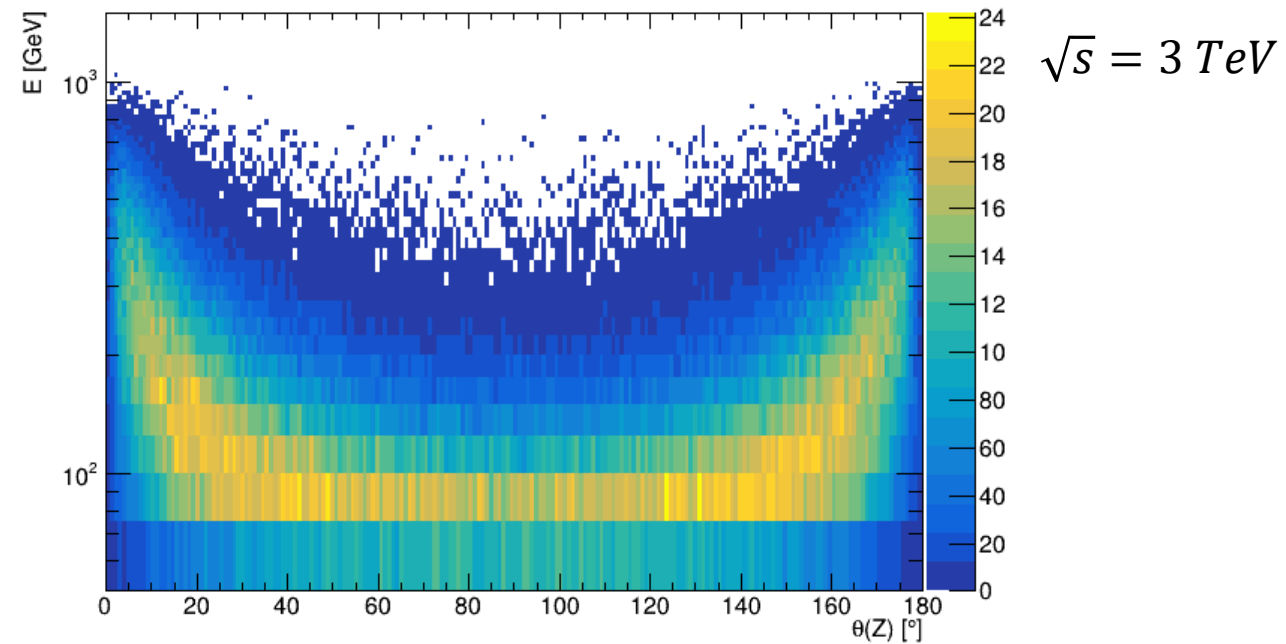
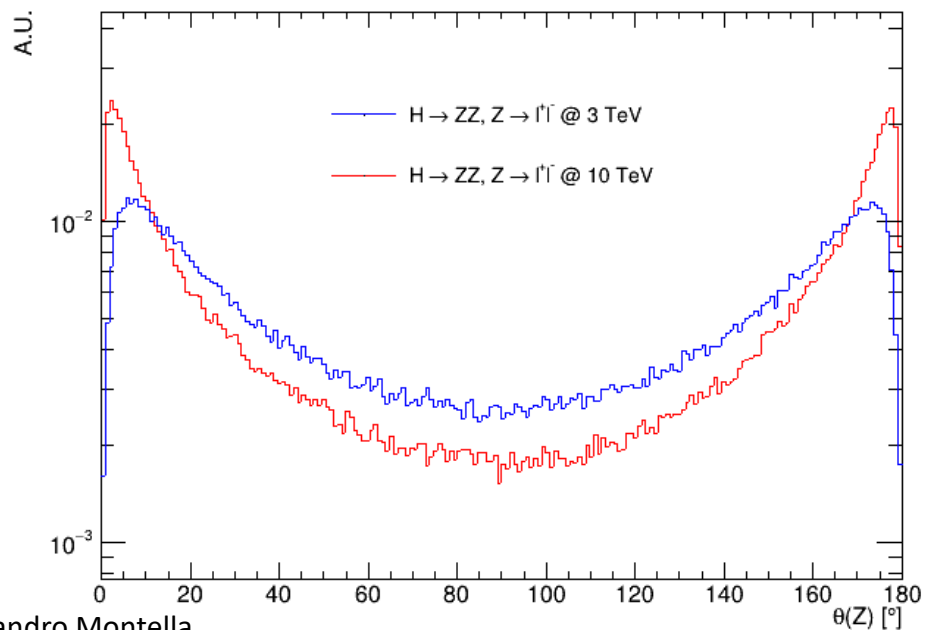
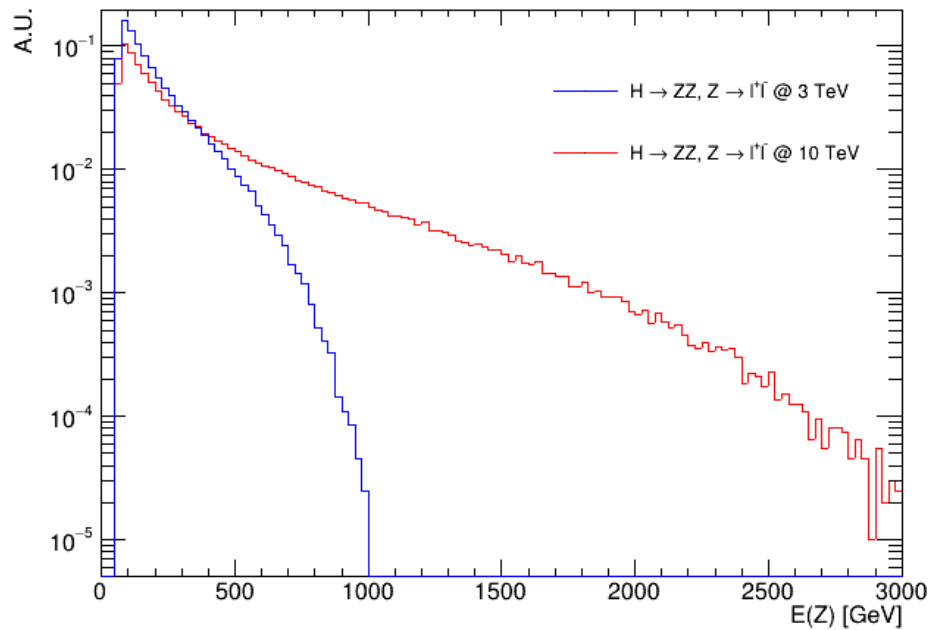
# Muons: $p_T$ , $p_z$ and $\Delta R$



# Muons: $E$ and $\theta$



# Z: $E$ and $\theta$

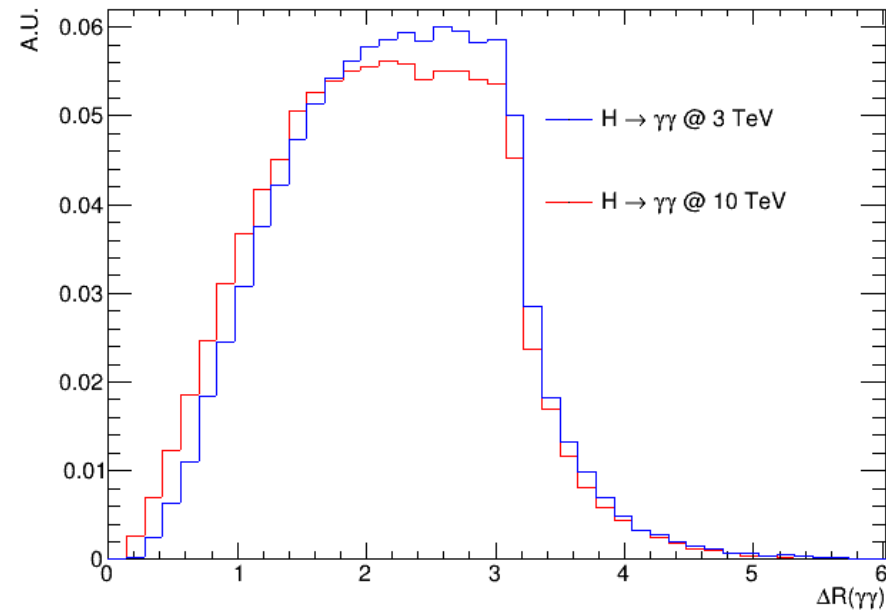
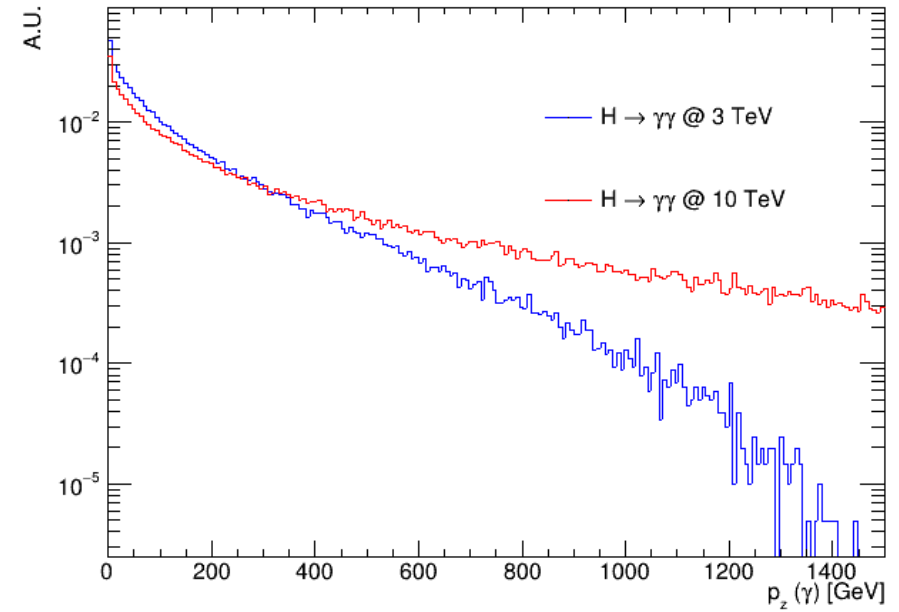
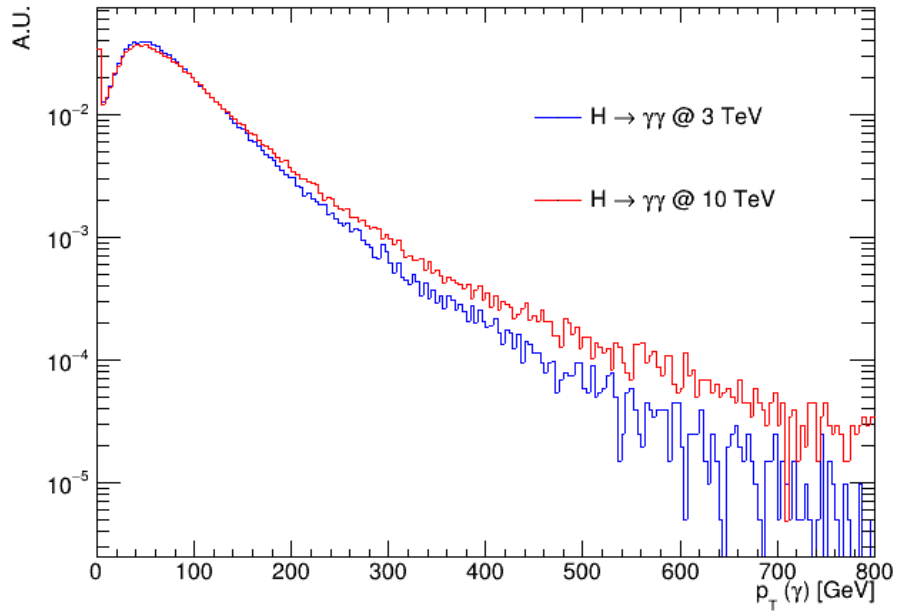




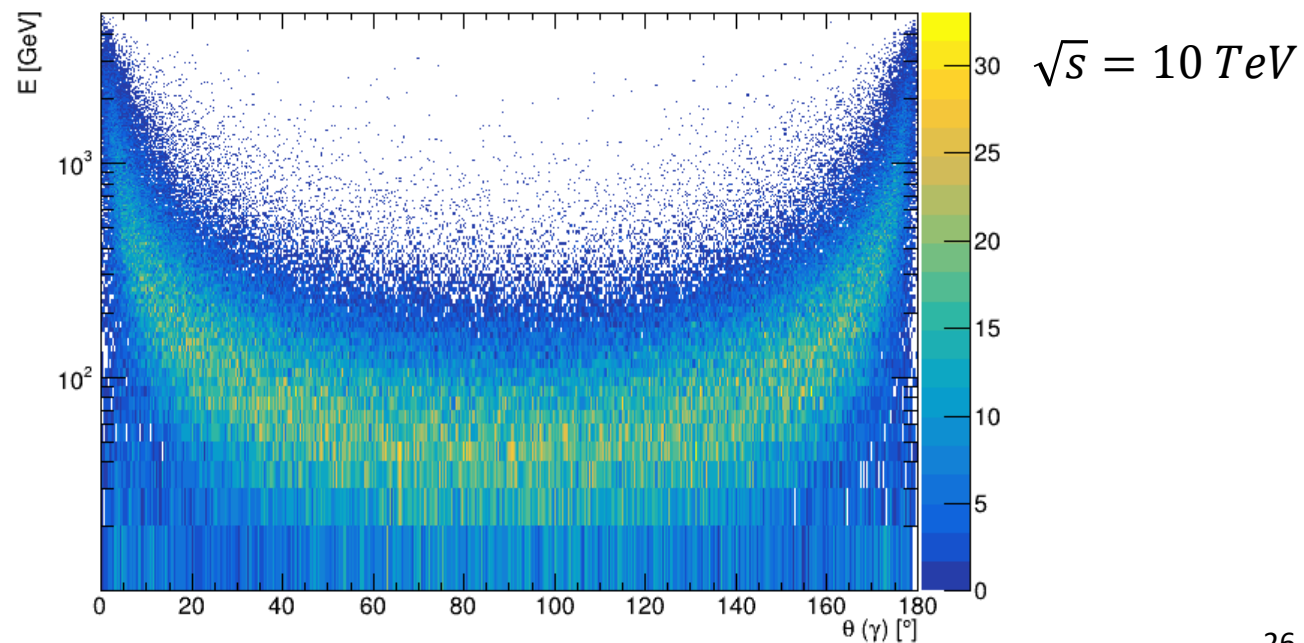
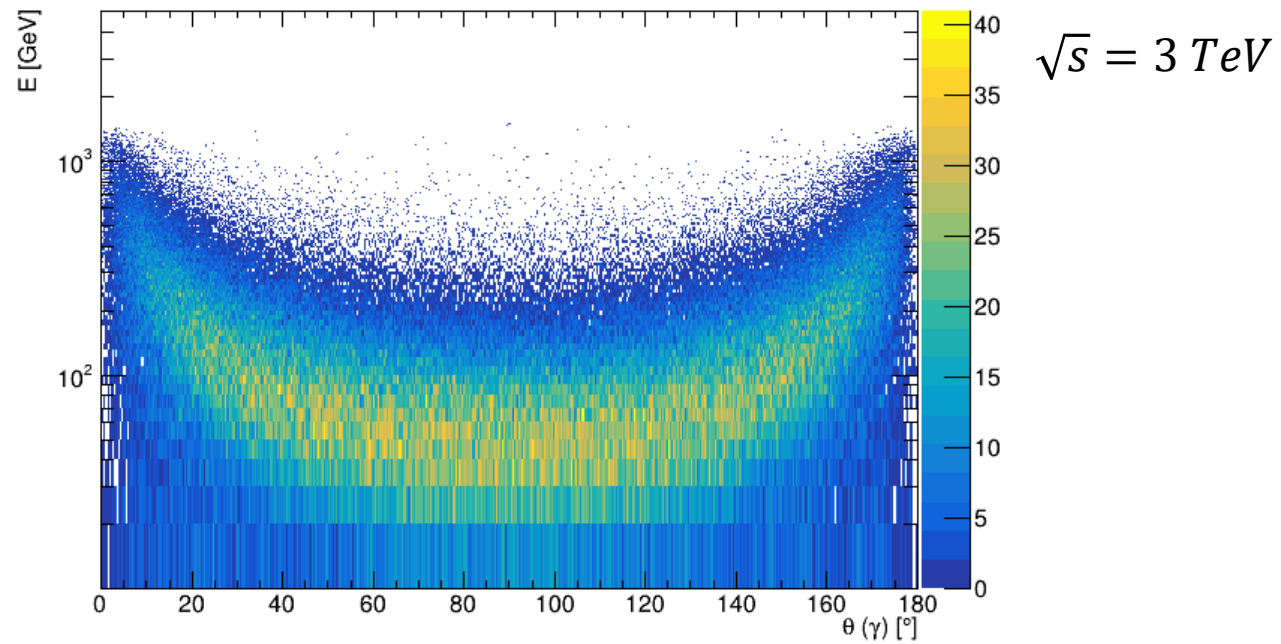
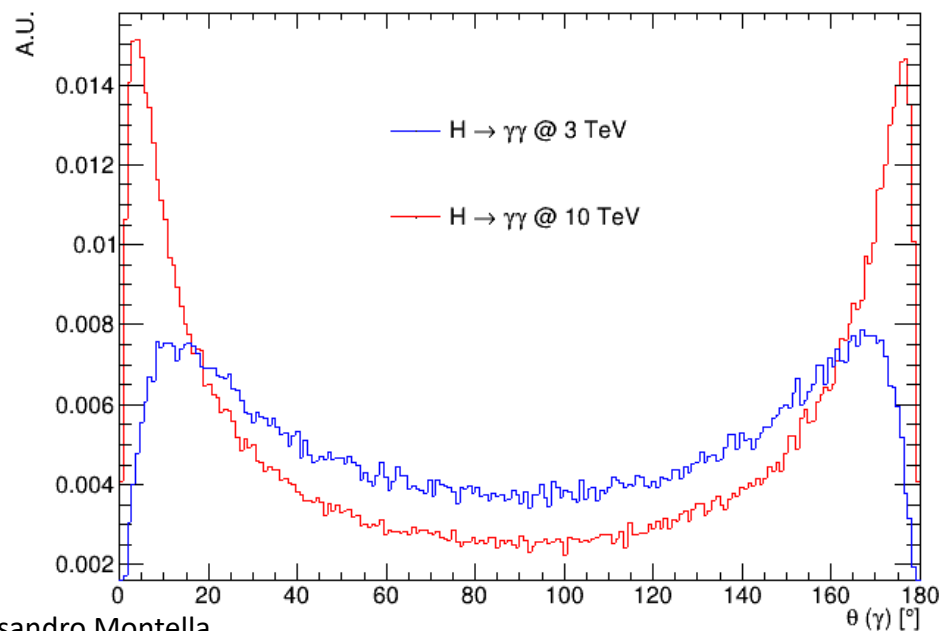
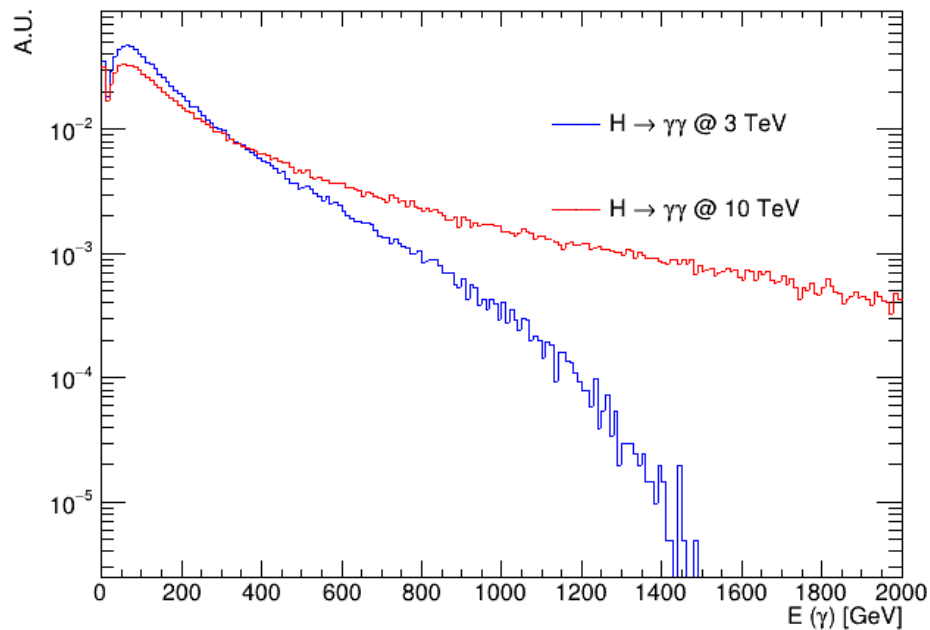
$$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu,$$
$$H \rightarrow \gamma\gamma$$

$$\sqrt{s} = 3 \text{ TeV vs } \sqrt{s} = 10 \text{ TeV}$$

# Photons: $p_T$ , $p_z$ and $\Delta R$



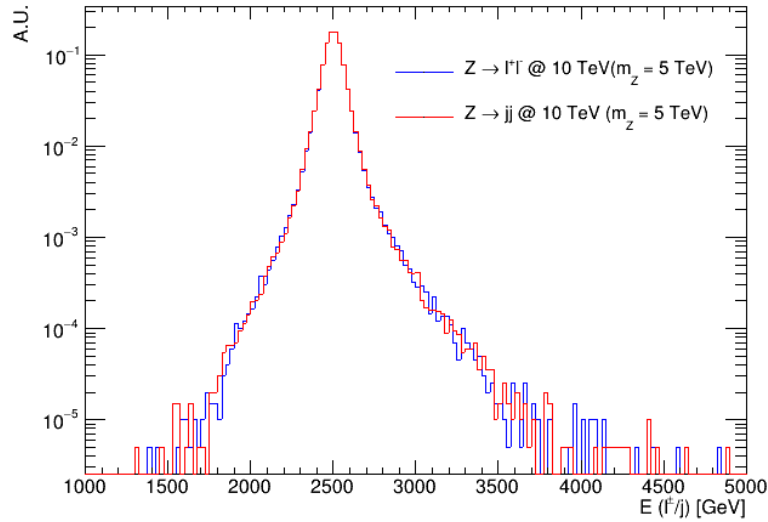
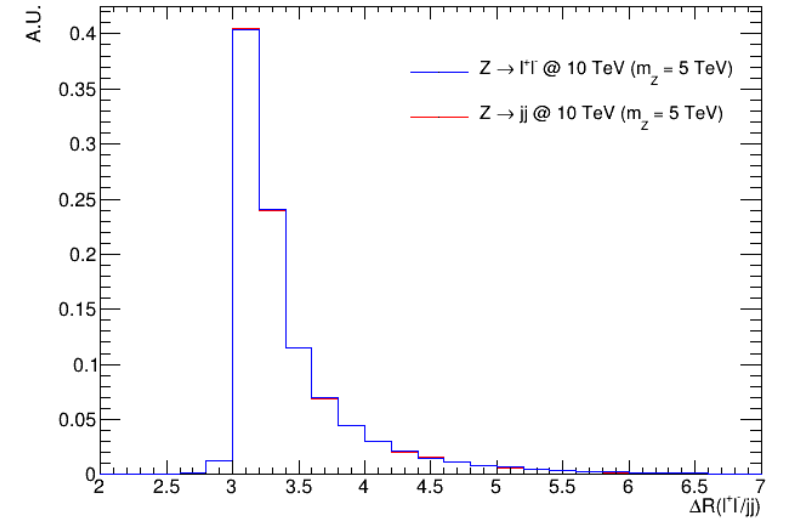
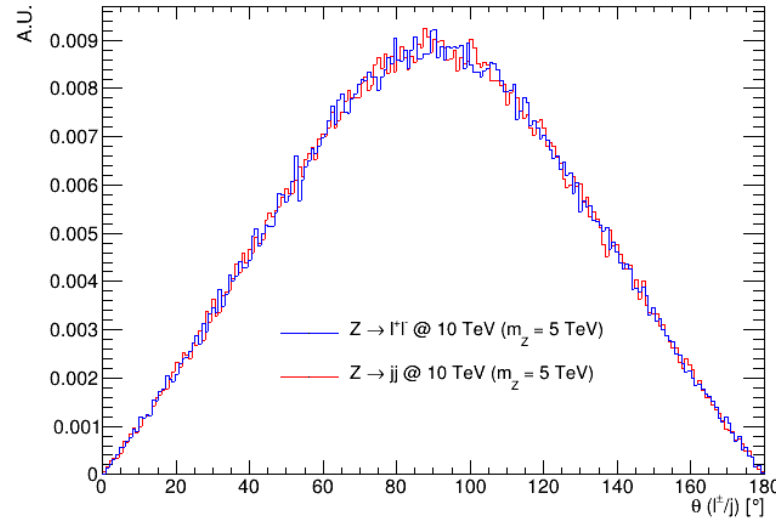
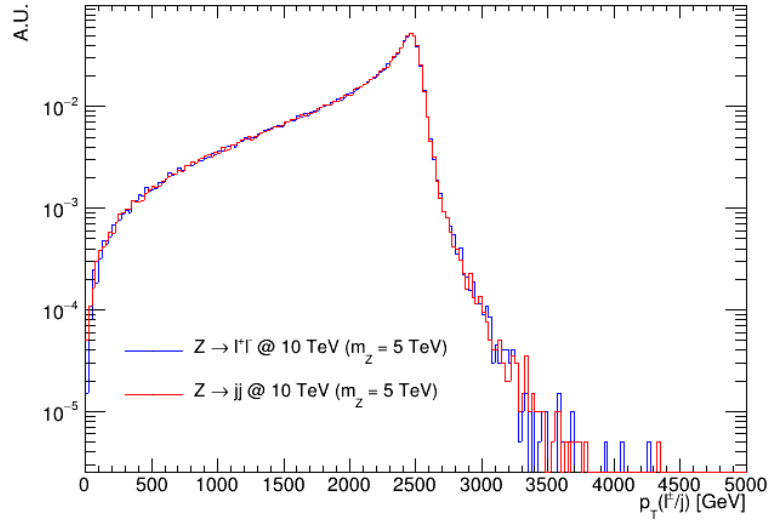
# Electrons: $E$ and $\theta$



$$\mu^+ \mu^- \rightarrow Z \nu_\mu \bar{\nu}_\mu, \quad (m_{Z'} = 5 \text{ TeV})$$
$$Z \rightarrow jj(l^+ l^-)$$

$$\sqrt{s} = 10 \text{ TeV}$$

# Jets/leptons: $p_T$ , $E$ , $\theta$ and $\Delta R$

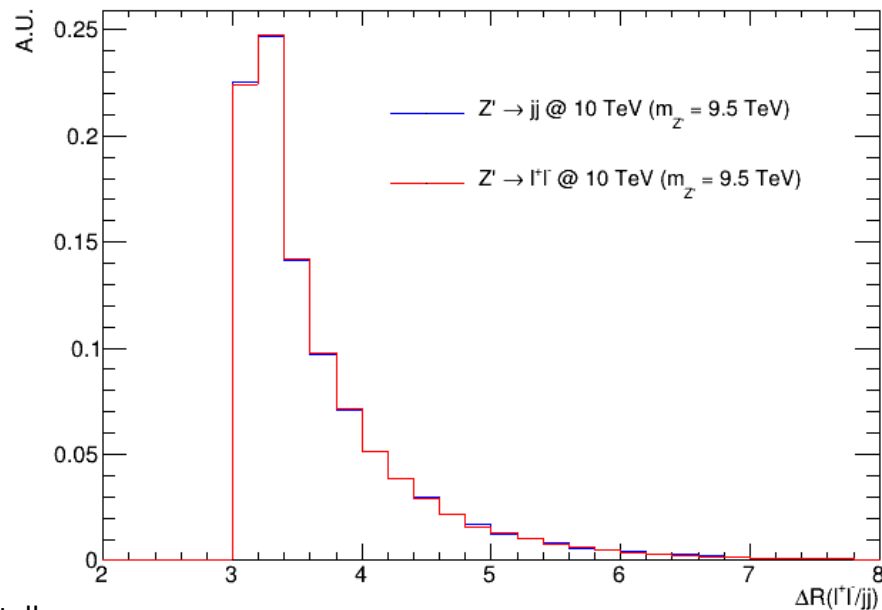
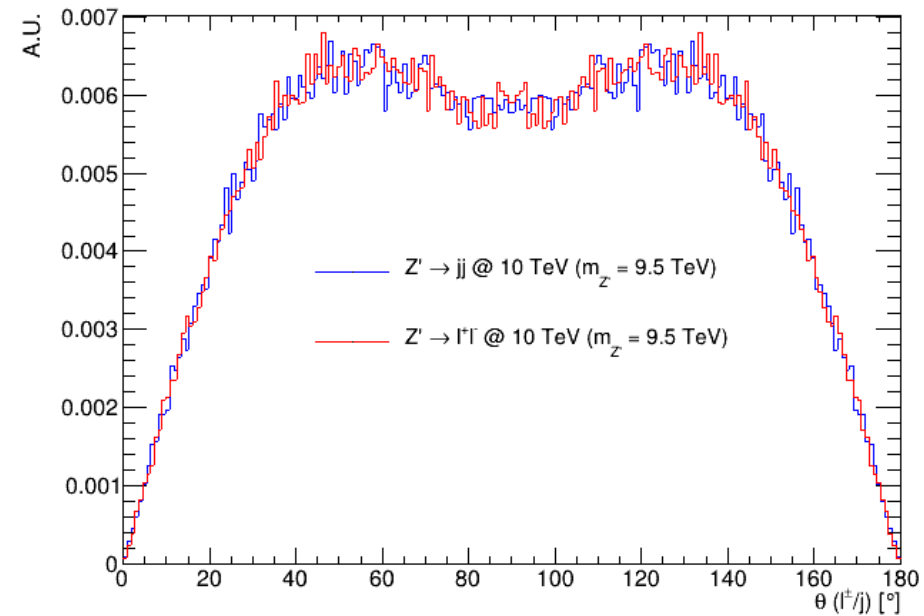
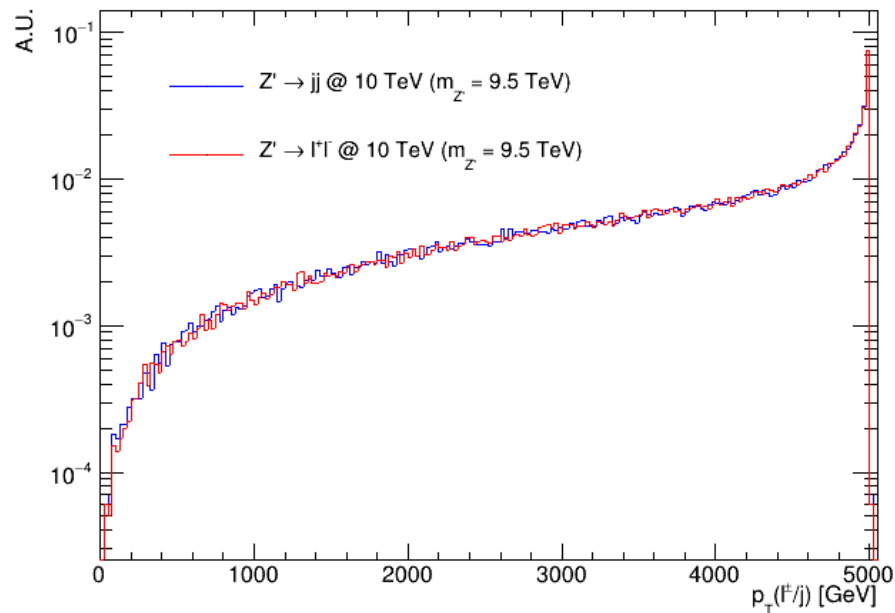


% of events with at least one jet inside the acceptance region ( $m_Z = 5$ TeV)	$5^\circ < \theta < 175^\circ$	$10^\circ < \theta < 170^\circ$
$\mu^+\mu^- \rightarrow Z\nu_\mu\bar{\nu}_\mu, Z \rightarrow l^+l^-/jj @ \sqrt{s} = 10$ TeV	99.84	99.13
% of events with two jets inside the acceptance region ( $m_Z = 5$ TeV)	$5^\circ < \theta < 175^\circ$	$10^\circ < \theta < 170^\circ$
$\mu^+\mu^- \rightarrow Z\nu_\mu\bar{\nu}_\mu, Z \rightarrow l^+l^-/jj @ \sqrt{s} = 10$ TeV	99.59	98.58
% of events with one jet inside the acceptance region ( $m_Z = 5$ TeV)	$5^\circ < \theta < 175^\circ$	$10^\circ < \theta < 170^\circ$
$\mu^+\mu^- \rightarrow Z\nu_\mu\bar{\nu}_\mu, Z \rightarrow l^+l^-/jj @ \sqrt{s} = 10$ TeV	0.25	0.55

$$\begin{aligned} \mu^+ \mu^- &\rightarrow Z', & (m_{Z'} = 9.5 \text{ TeV}) \\ Z' &\rightarrow jj(l^+ l^-) \end{aligned}$$

$$\sqrt{s} = 10 \text{ TeV}$$

# Jets/leptons: $p_T$ , $\theta$ and $\Delta R$



% of events with at least one jet inside the acceptance region ( $M_{Z'} = 9.5$ TeV)	$5^\circ < \theta < 175^\circ$	$10^\circ < \theta < 170^\circ$
$\mu^+\mu^- \rightarrow Z', Z' \rightarrow l^+l^-/jj @ \sqrt{s} = 10$ TeV	99.43	97.65
% of events with two jets inside the acceptance region ( $M_{Z'} = 9.5$ TeV)	$5^\circ < \theta < 175^\circ$	$10^\circ < \theta < 170^\circ$
$\mu^+\mu^- \rightarrow Z', Z' \rightarrow l^+l^-/jj @ \sqrt{s} = 10$ TeV	99.43	97.65
% of events with one jet inside the acceptance region ( $M_{Z'} = 9.5$ TeV)	$5^\circ < \theta < 175^\circ$	$10^\circ < \theta < 170^\circ$
$\mu^+\mu^- \rightarrow Z', Z' \rightarrow l^+l^-/jj @ \sqrt{s} = 10$ TeV	0.00	0.00

# Conclusion

- As expected, the Standard Model physics at a 10 TeV muon collider is considerably more forward than at a 3 TeV muon collider.
- Energy-related observables show very similar distributions between the 3 TeV and 10 TeV cases.
- Detectable particles produced by the decay of heavy new states are very central for both WW-fusion and s-channel production modes; however, a detector capable of measuring particles with a  $p_T$  on the order of several TeV would be needed.



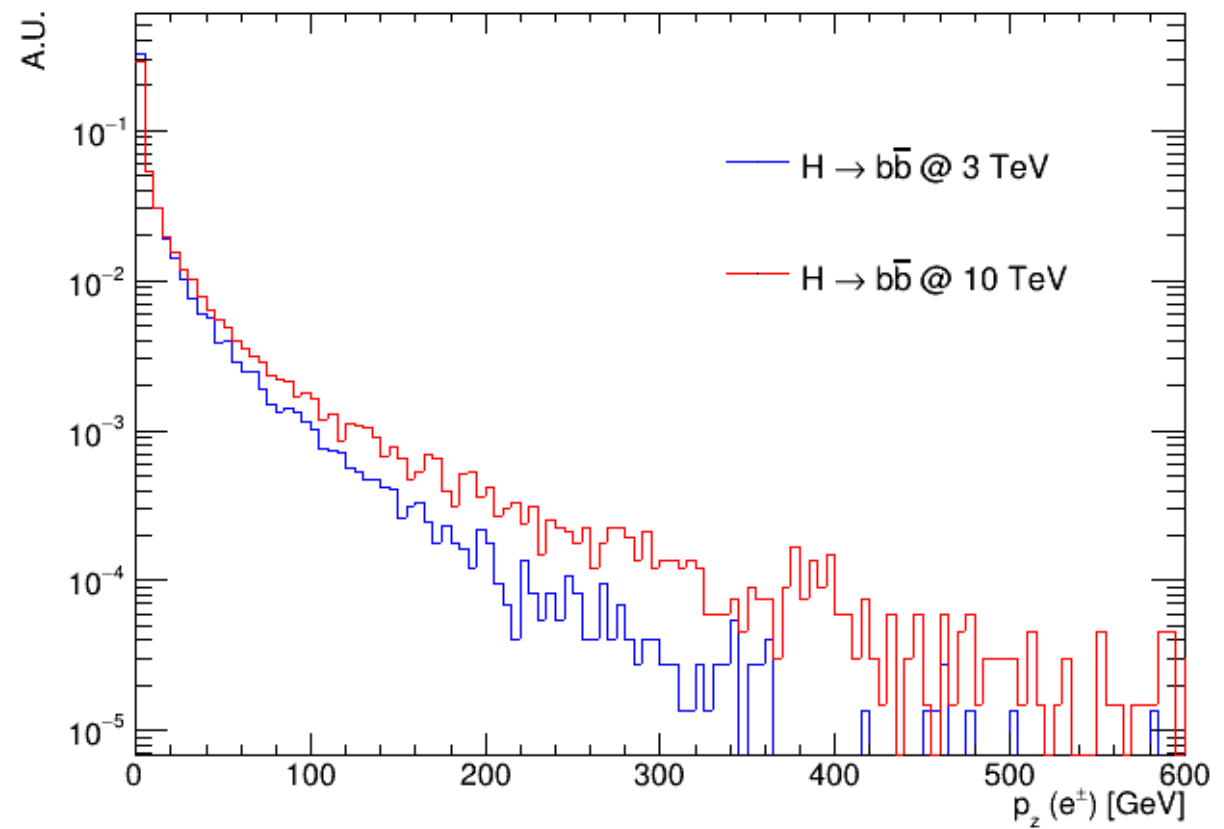
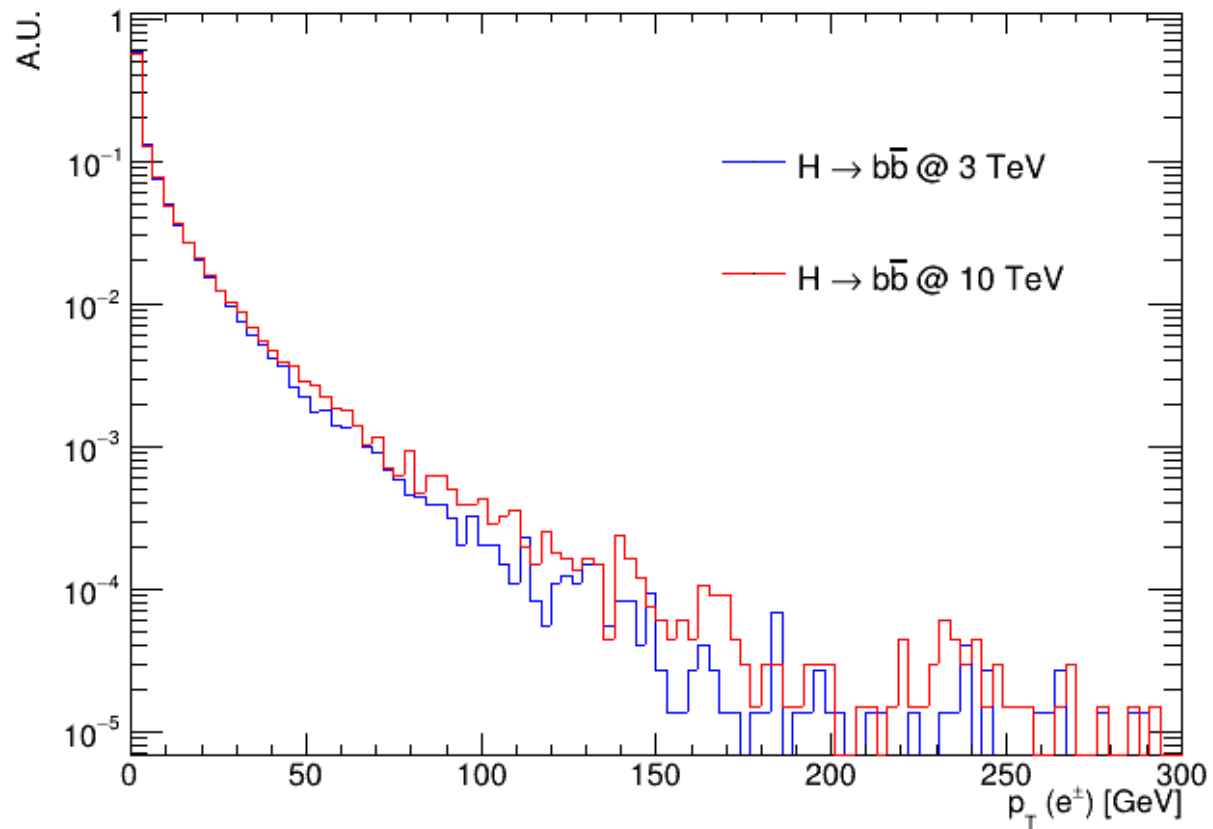
**BACKUP**

$$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu,$$
$$H \rightarrow b \bar{b}$$

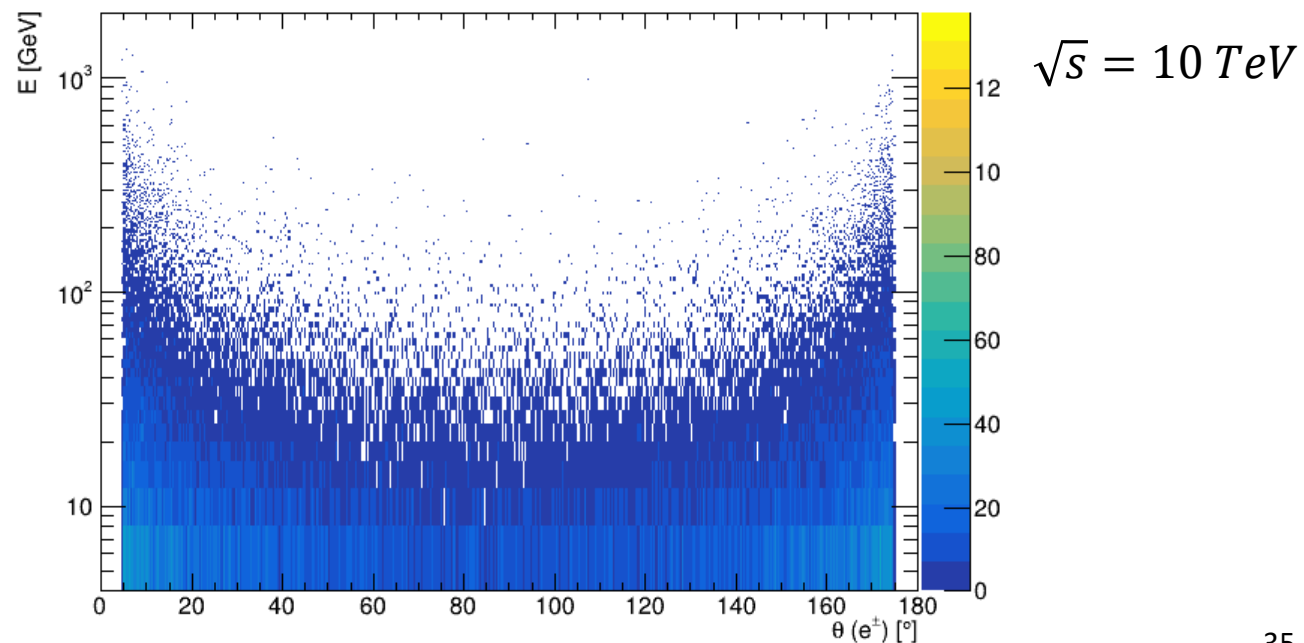
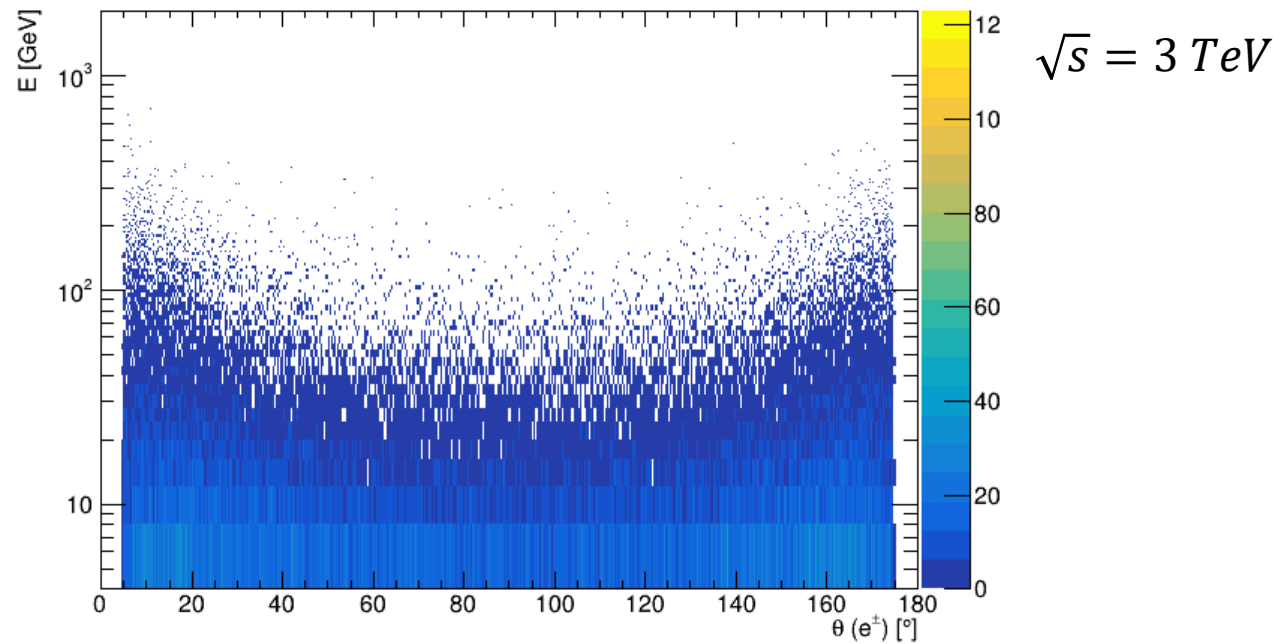
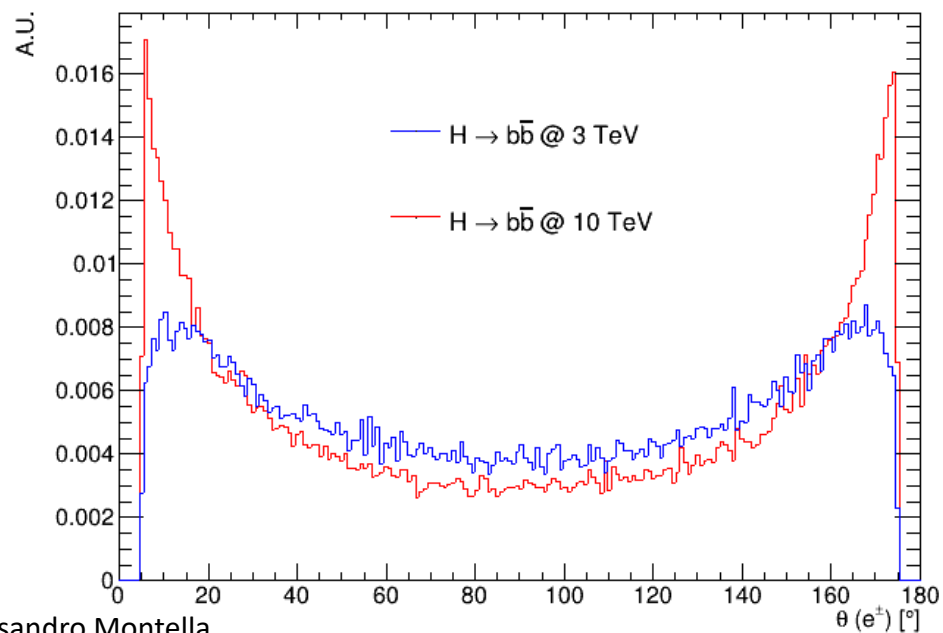
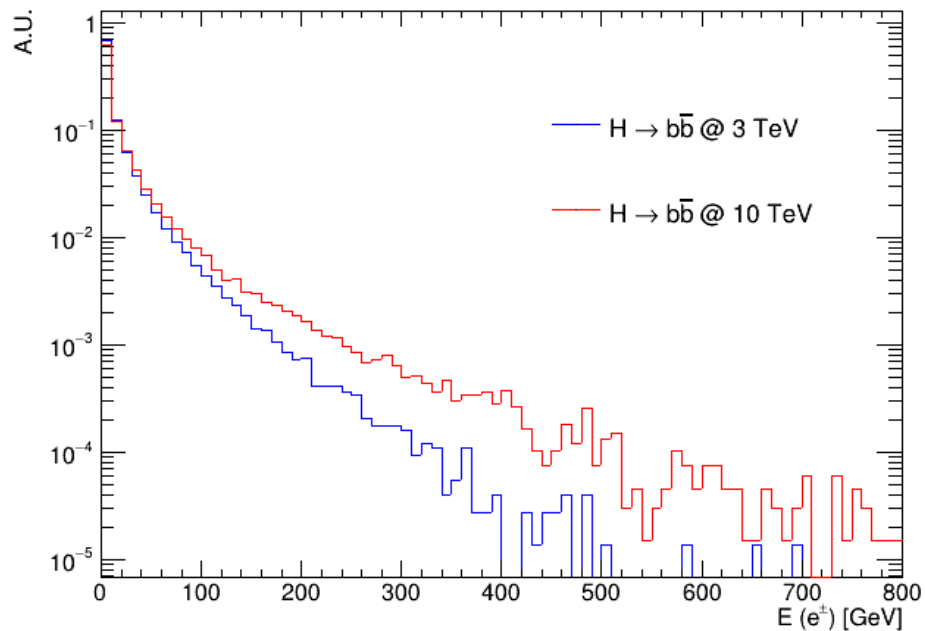
Acceptance region:  $5^\circ < \theta < 175^\circ$

$\sqrt{s} = 3 \text{ TeV}$  vs  $\sqrt{s} = 10 \text{ TeV}$

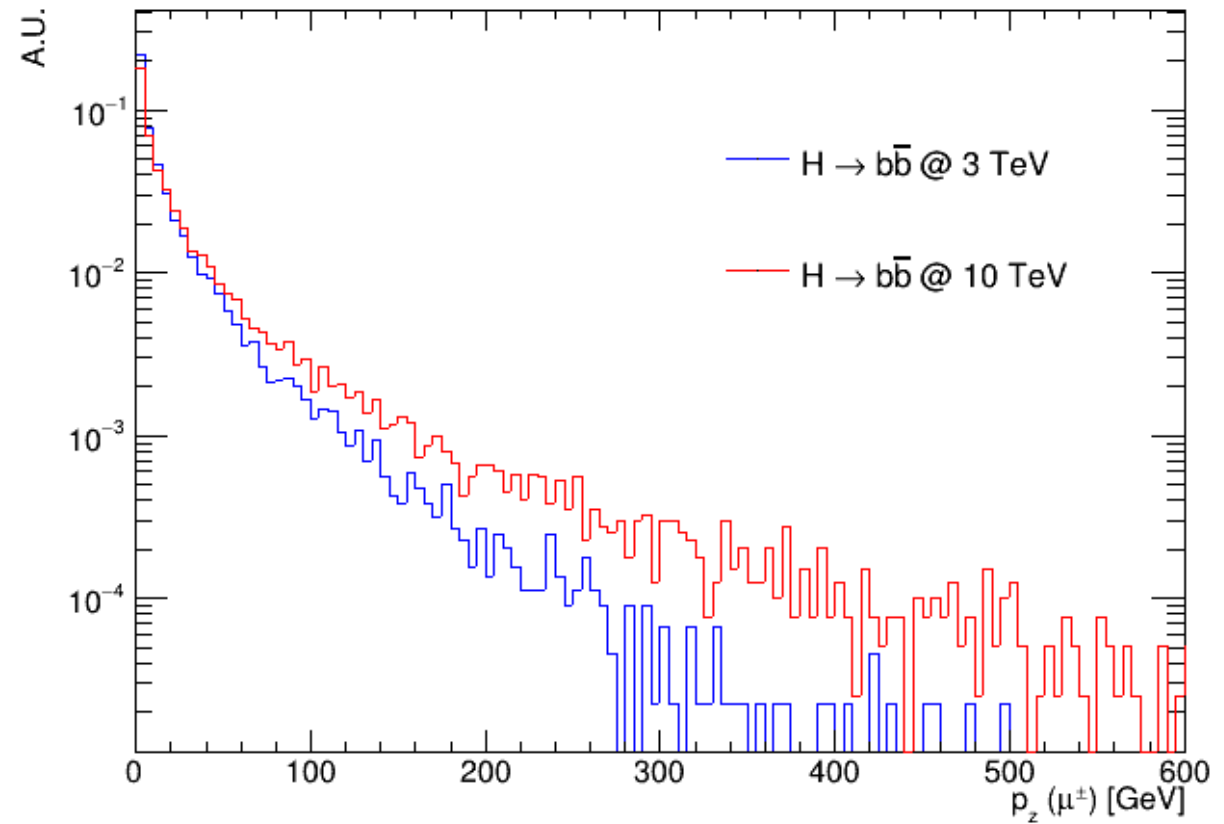
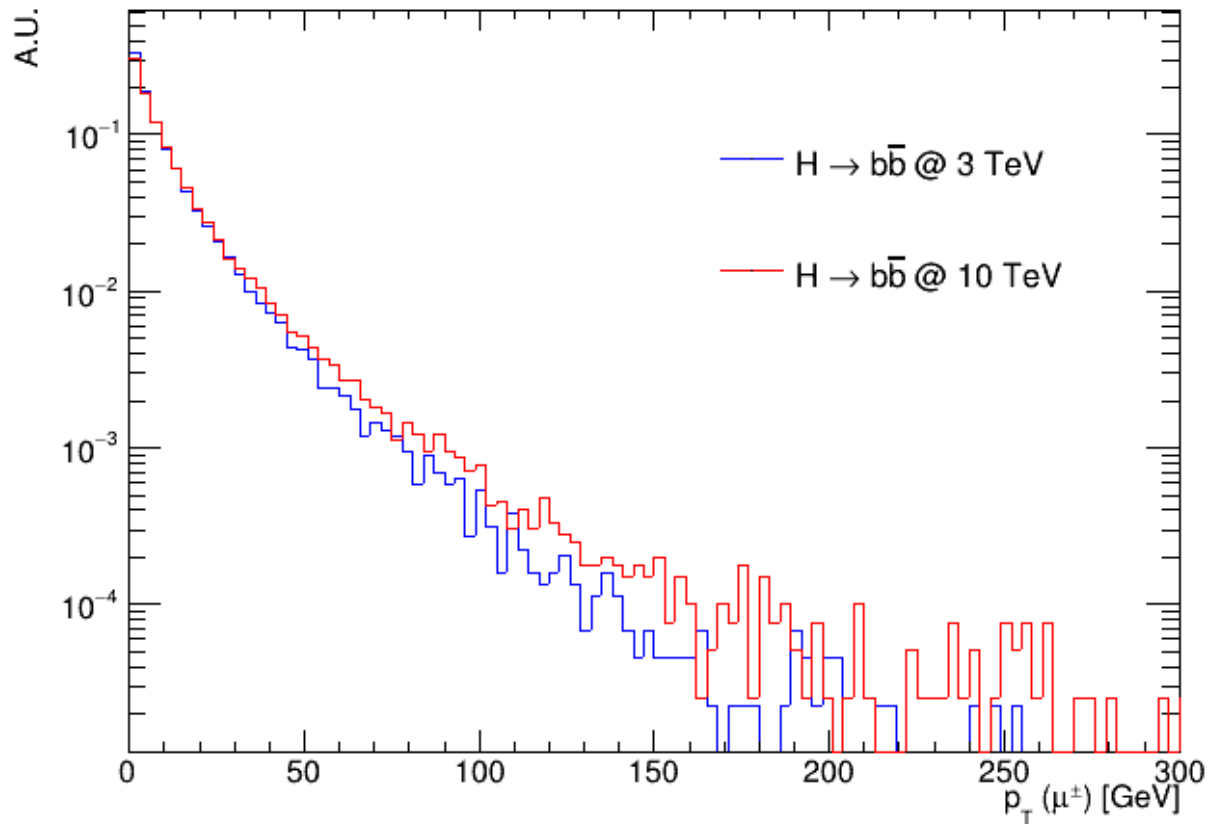
# Electrons: $p_T$ and $p_z$



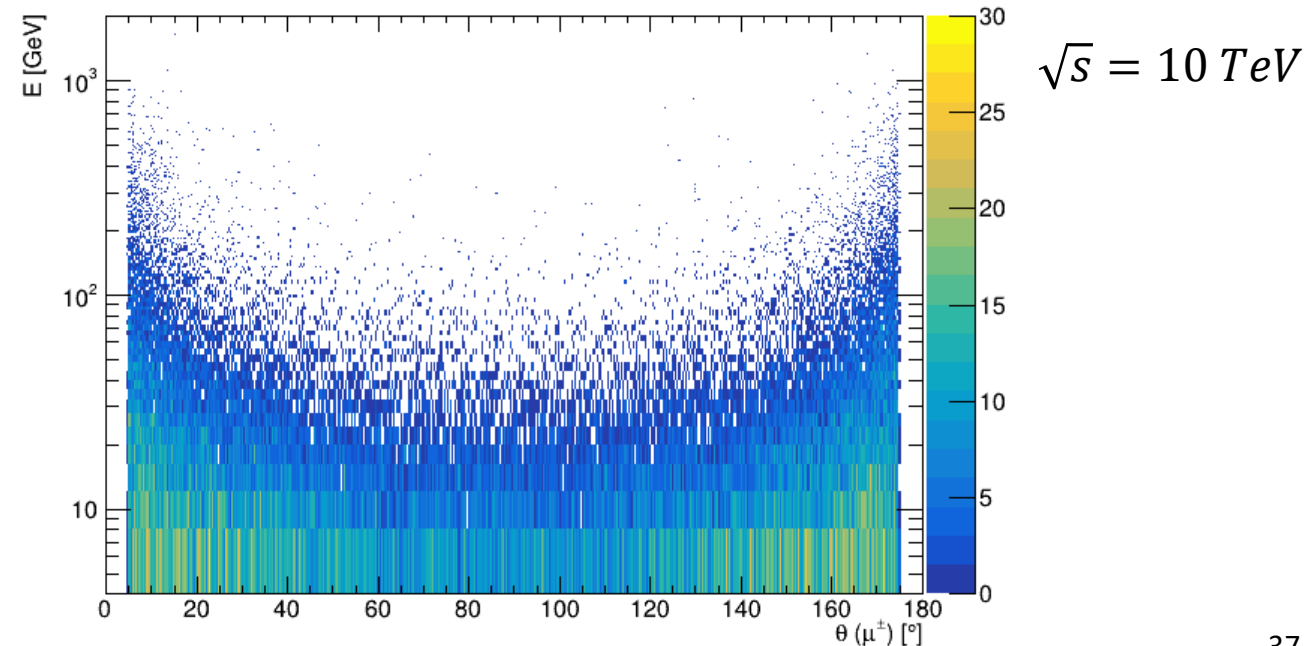
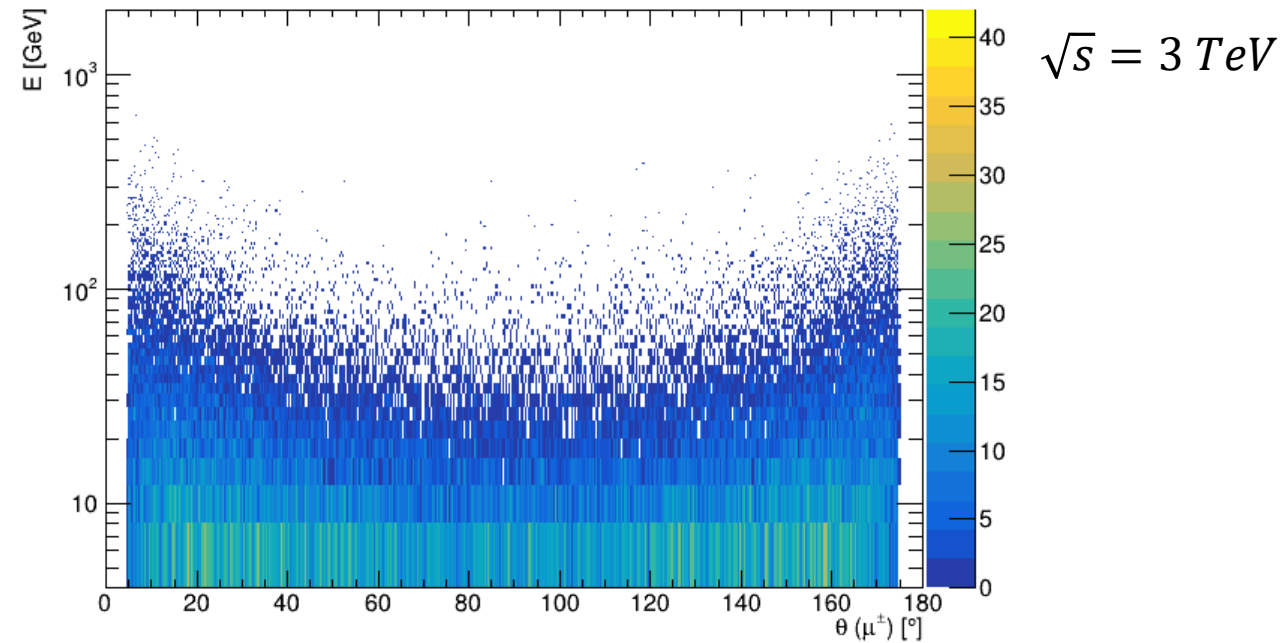
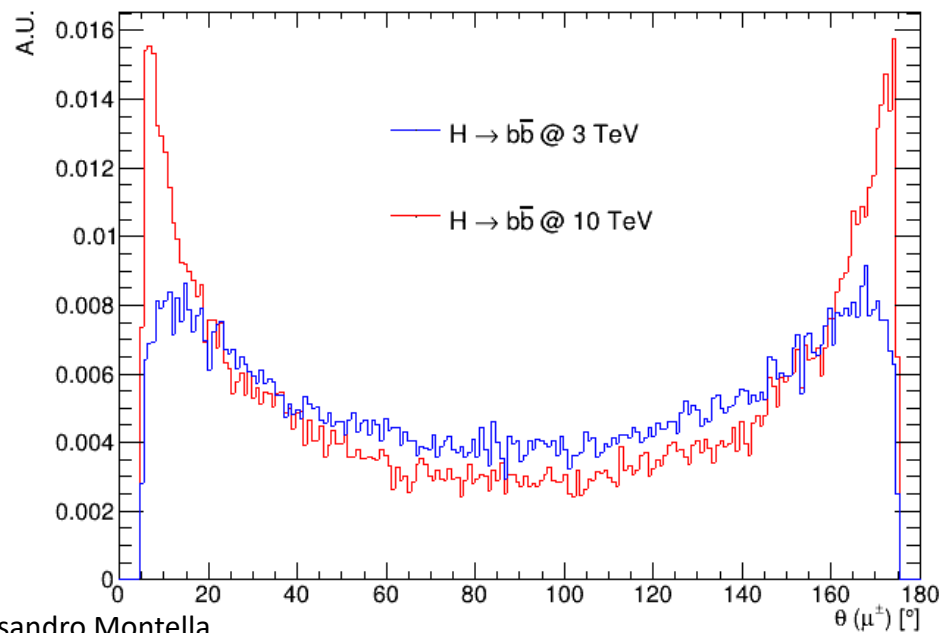
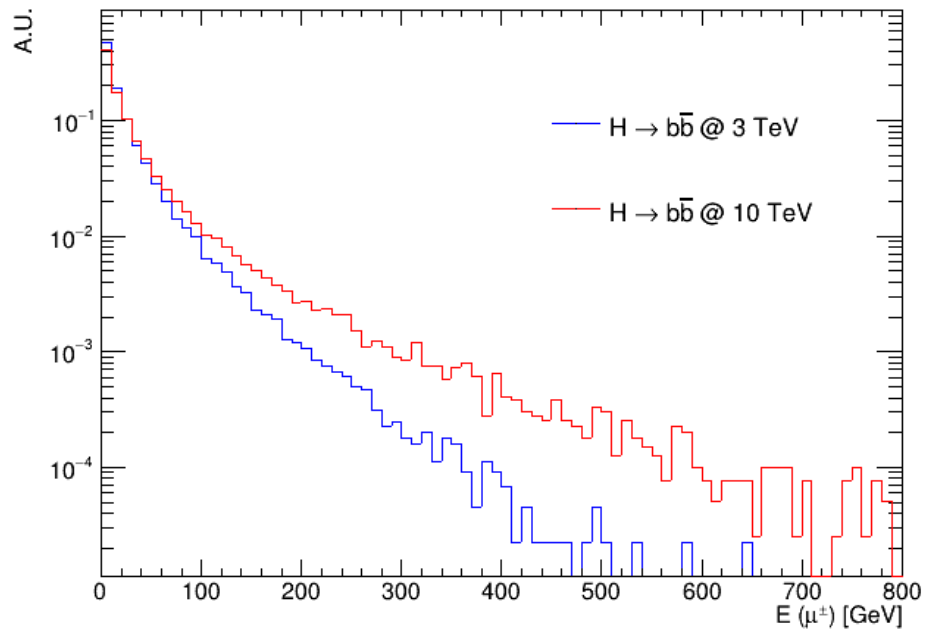
# Electrons: $E$ and $\theta$



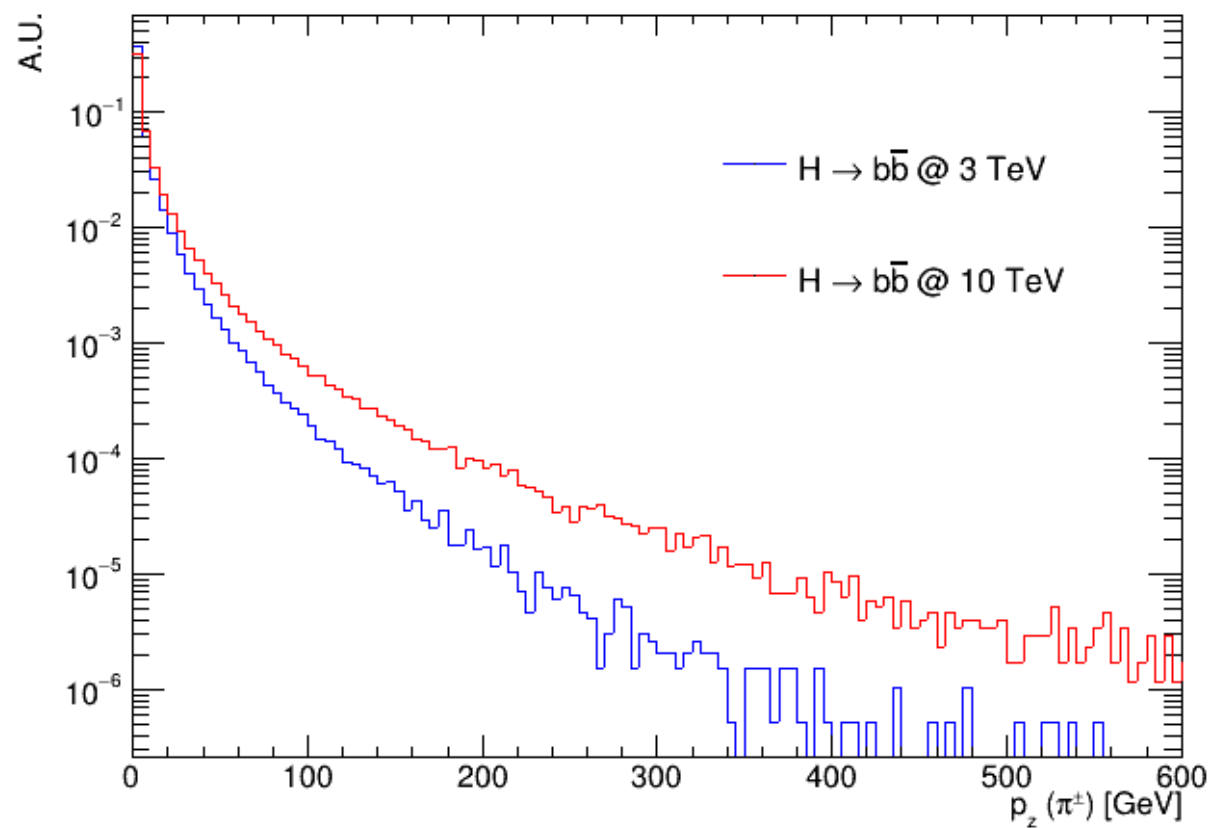
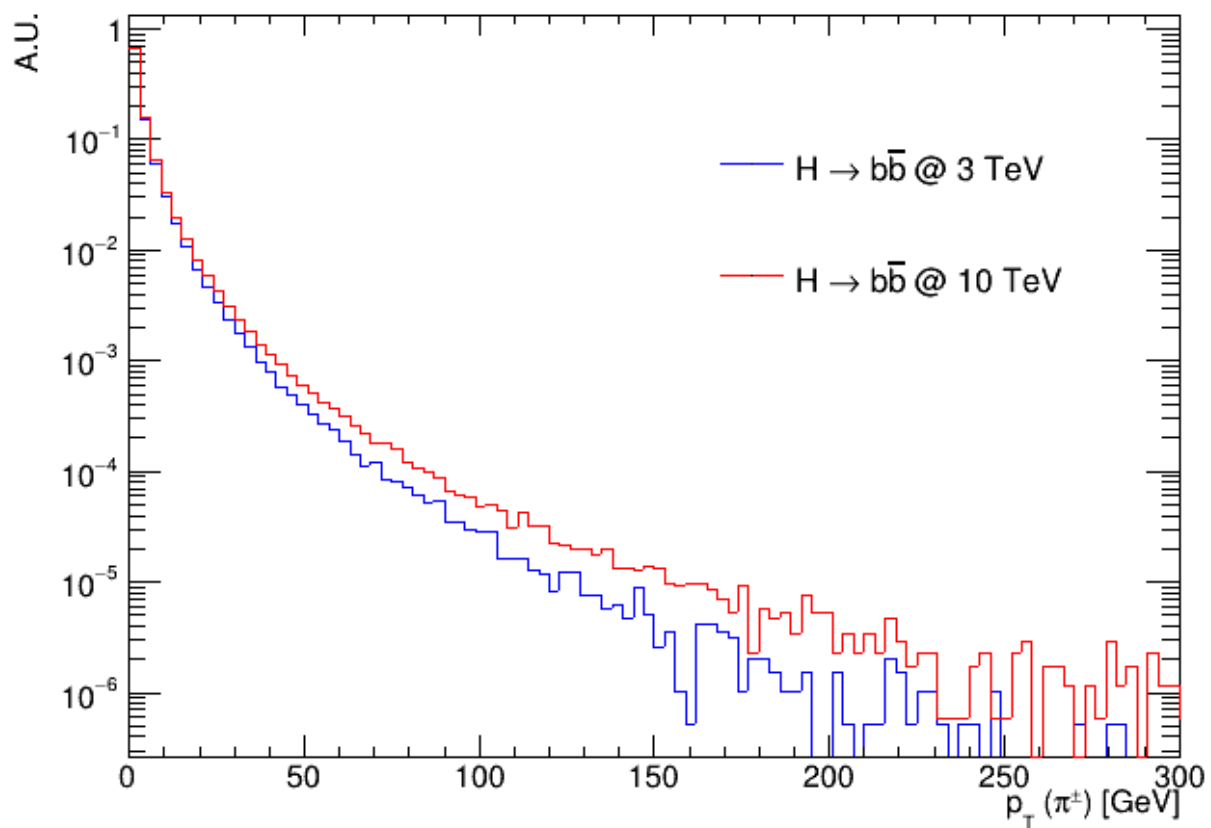
# Muons: $p_T$ and $p_z$



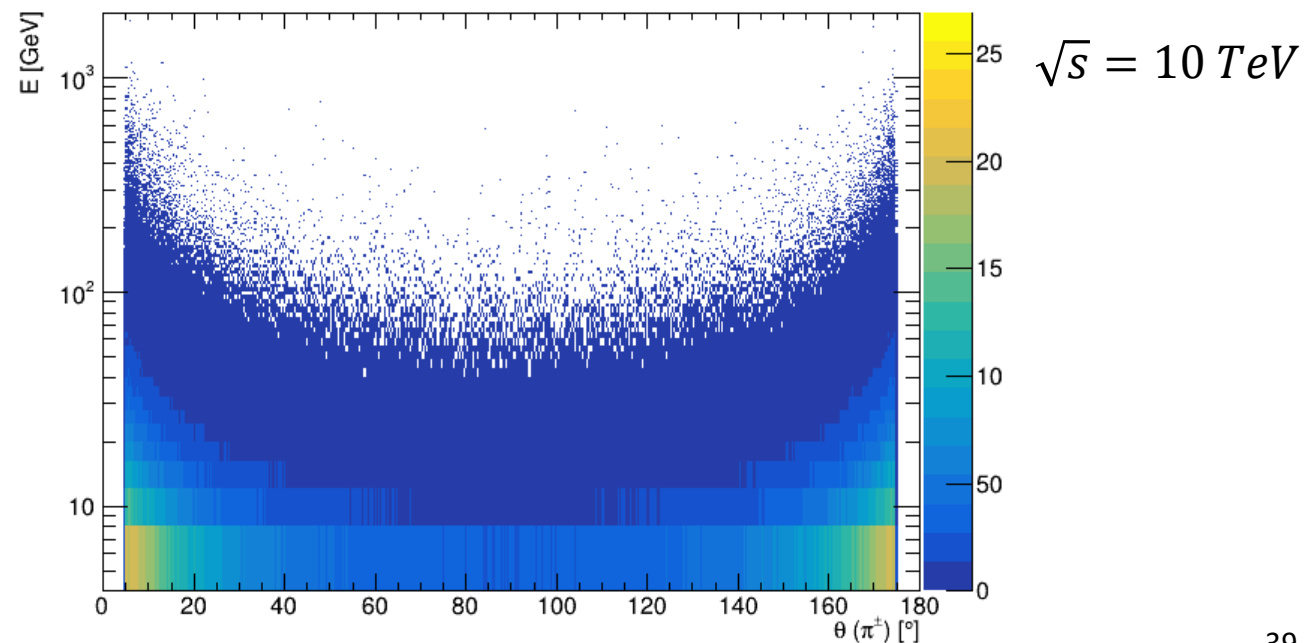
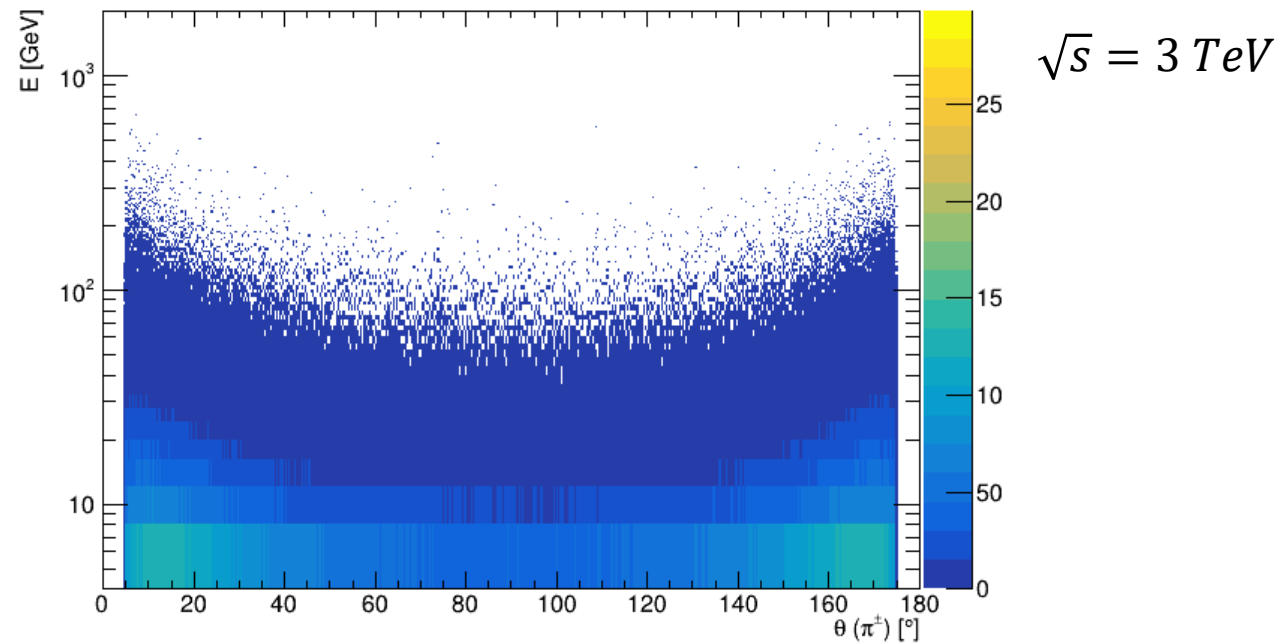
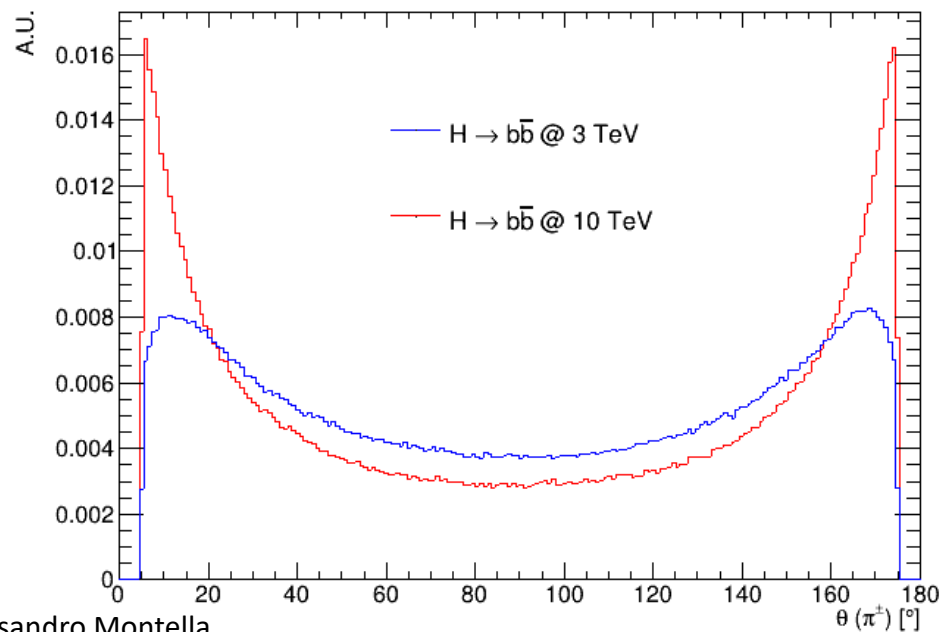
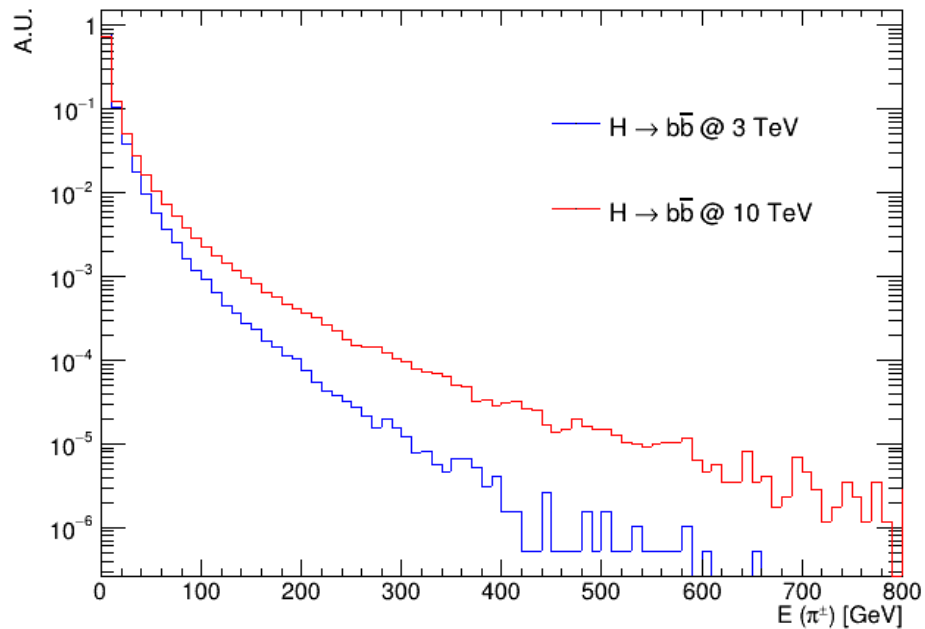
# Muons: $E$ and $\theta$



# Charged pions: $p_T$ and $p_z$

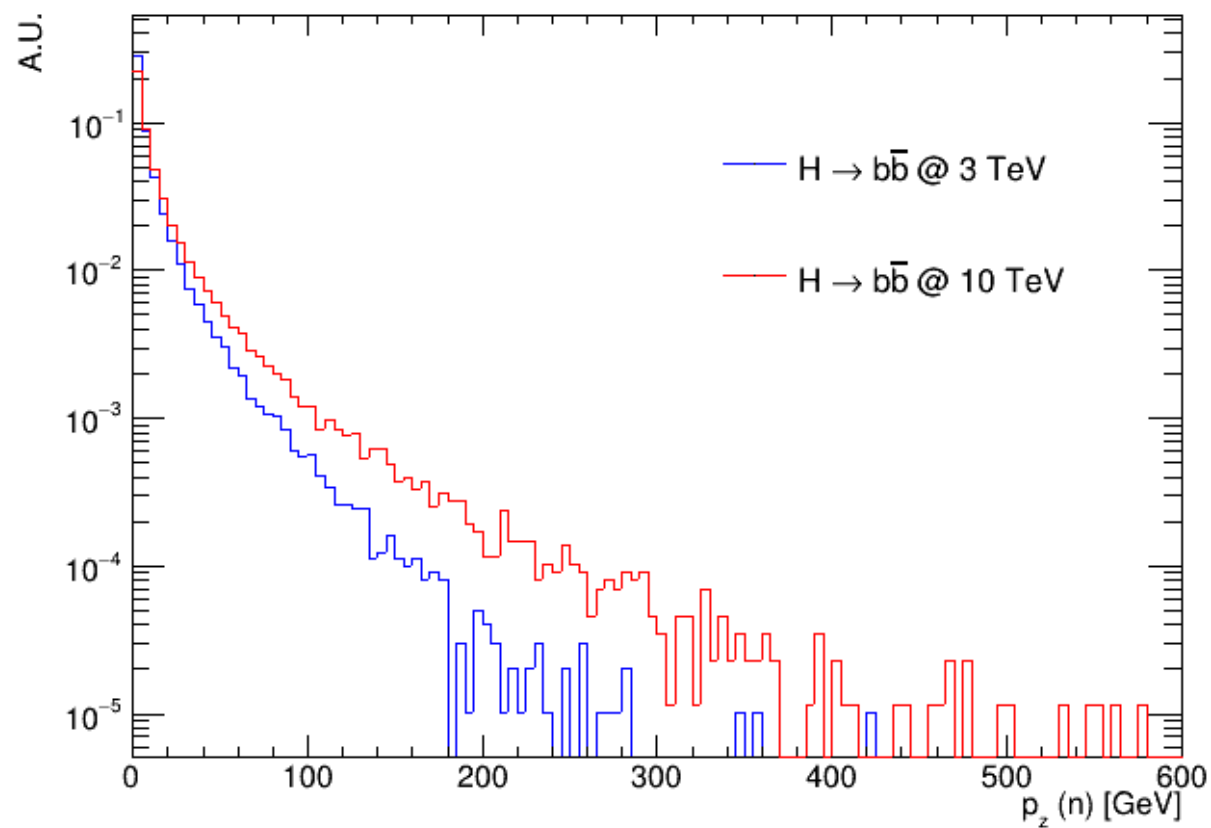
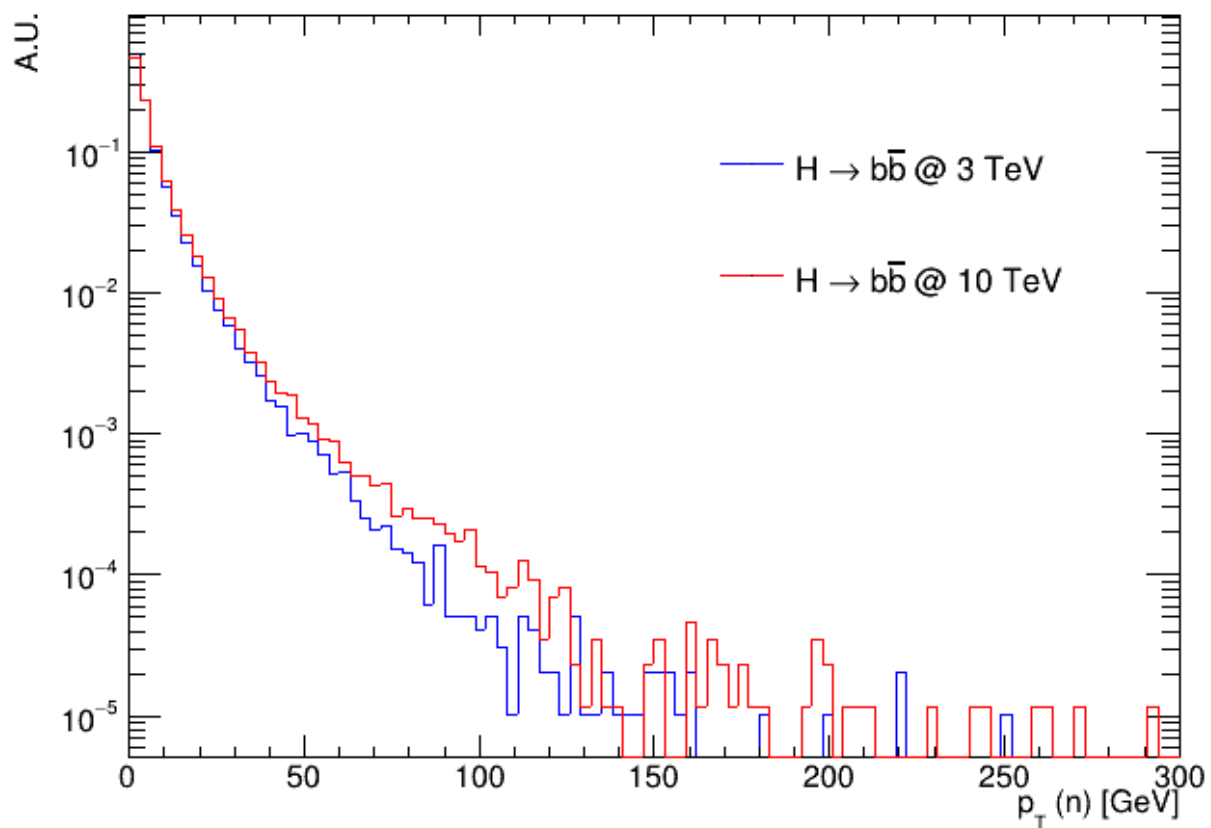


# Charged pions: $E$ and $\theta$

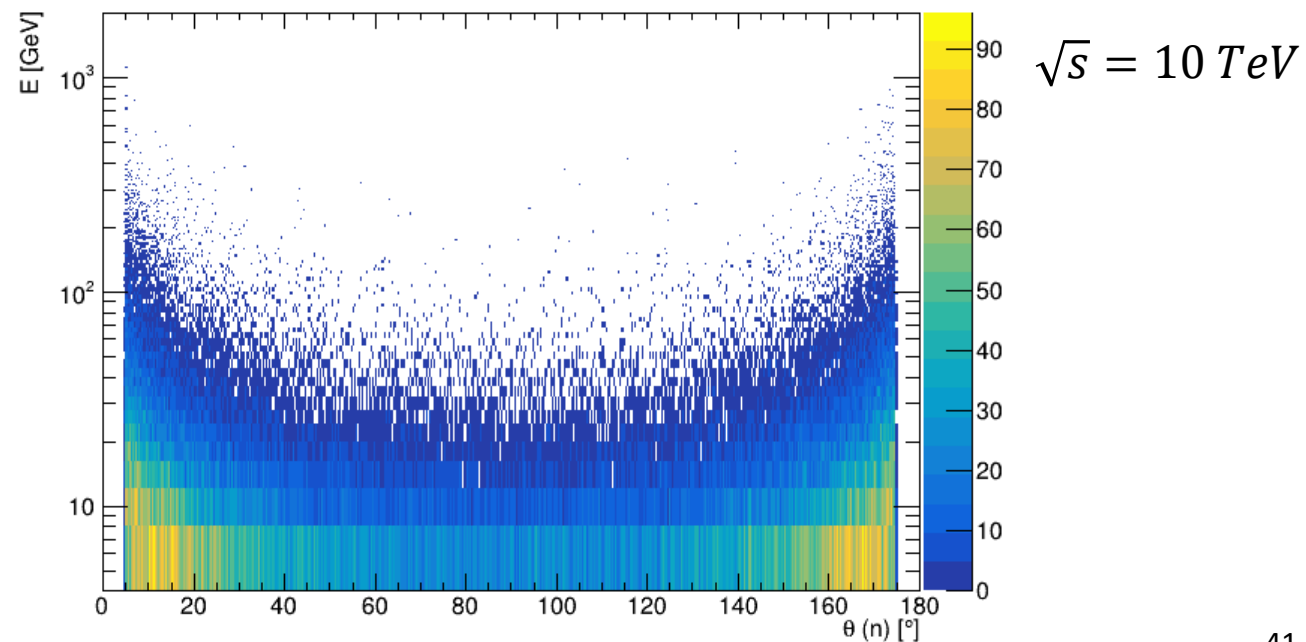
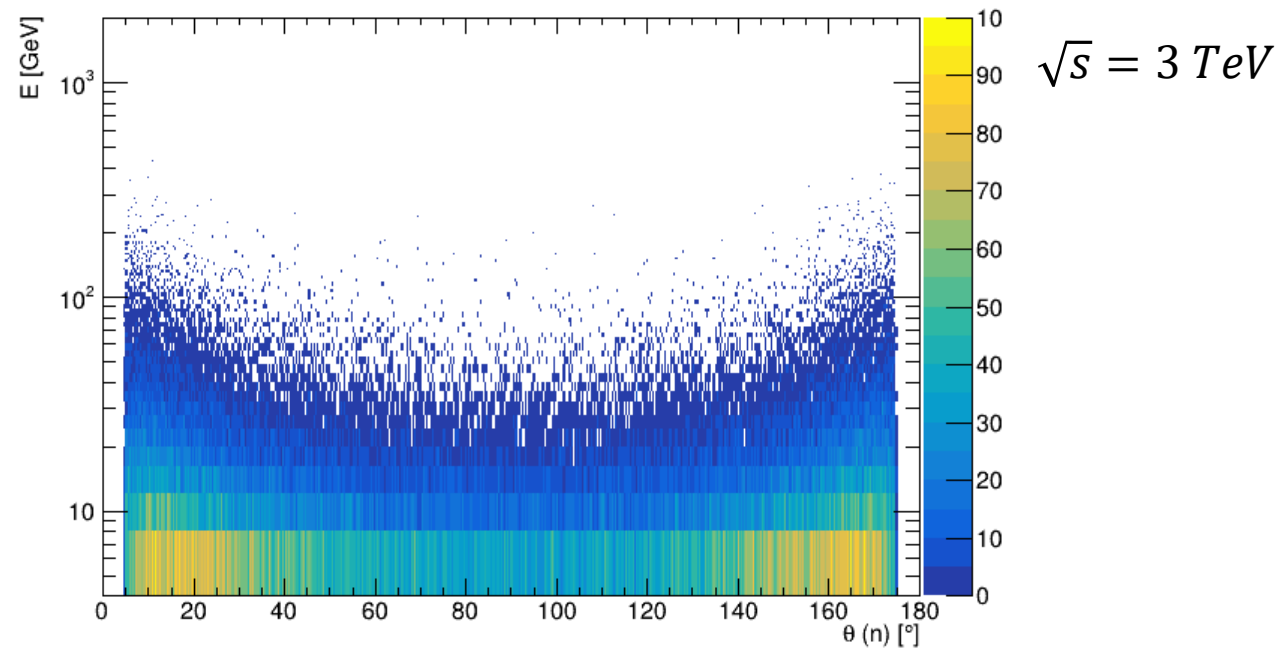
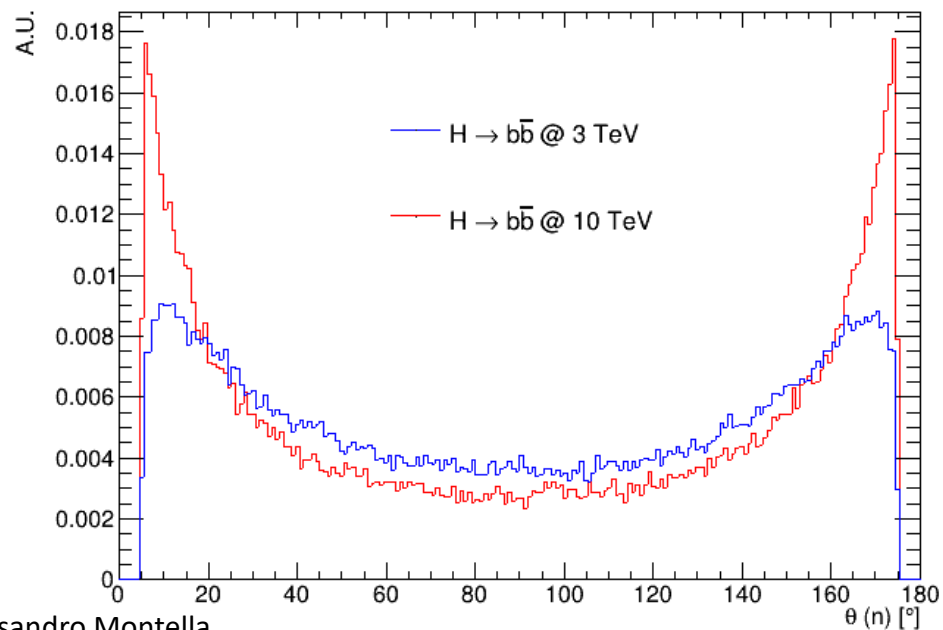
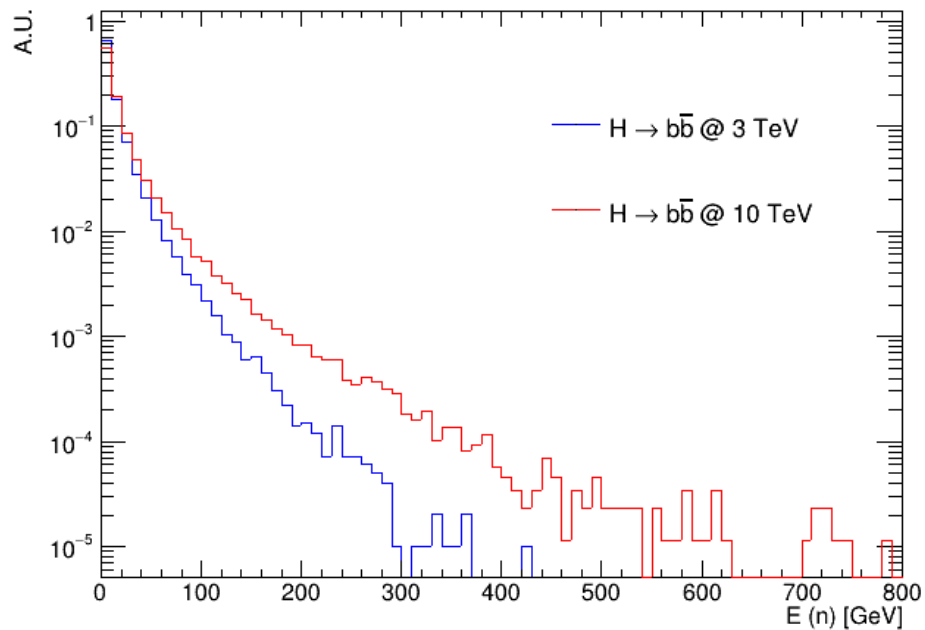




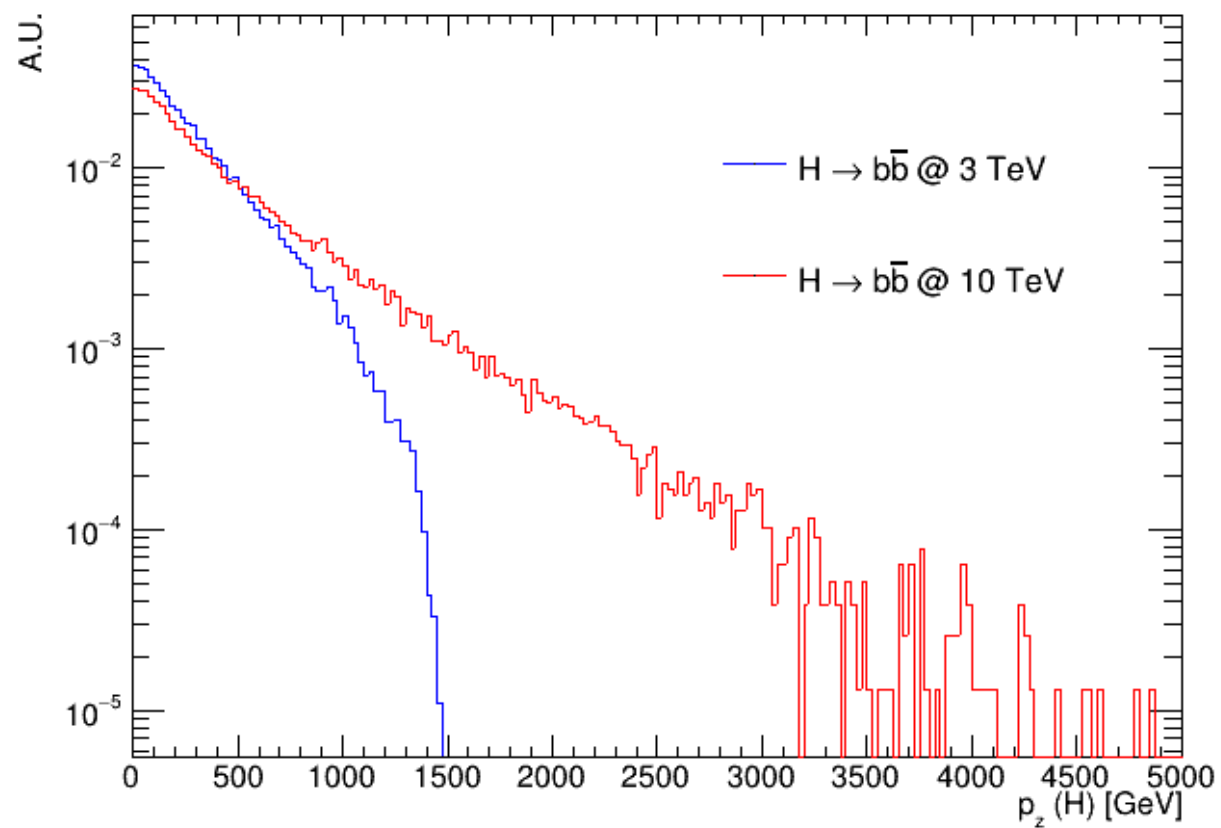
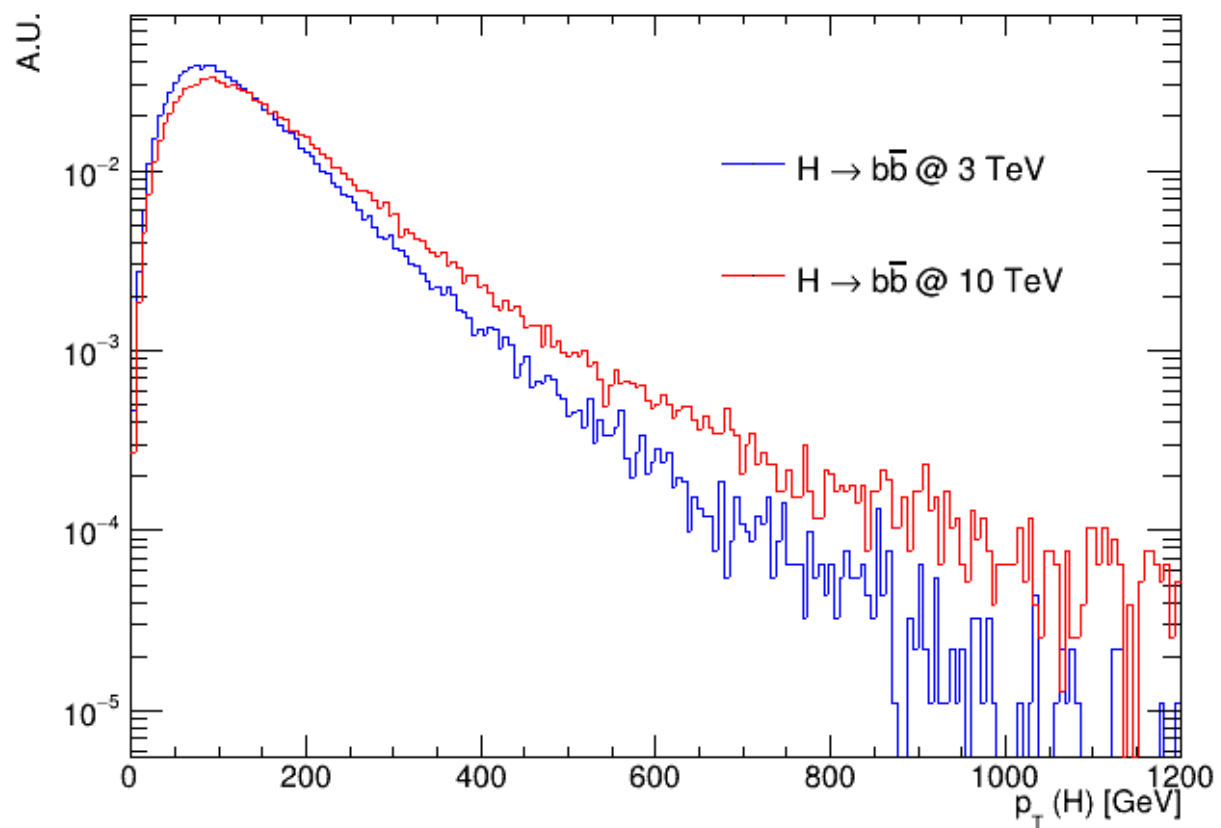
# Neutrons: $p_T$ and $p_z$



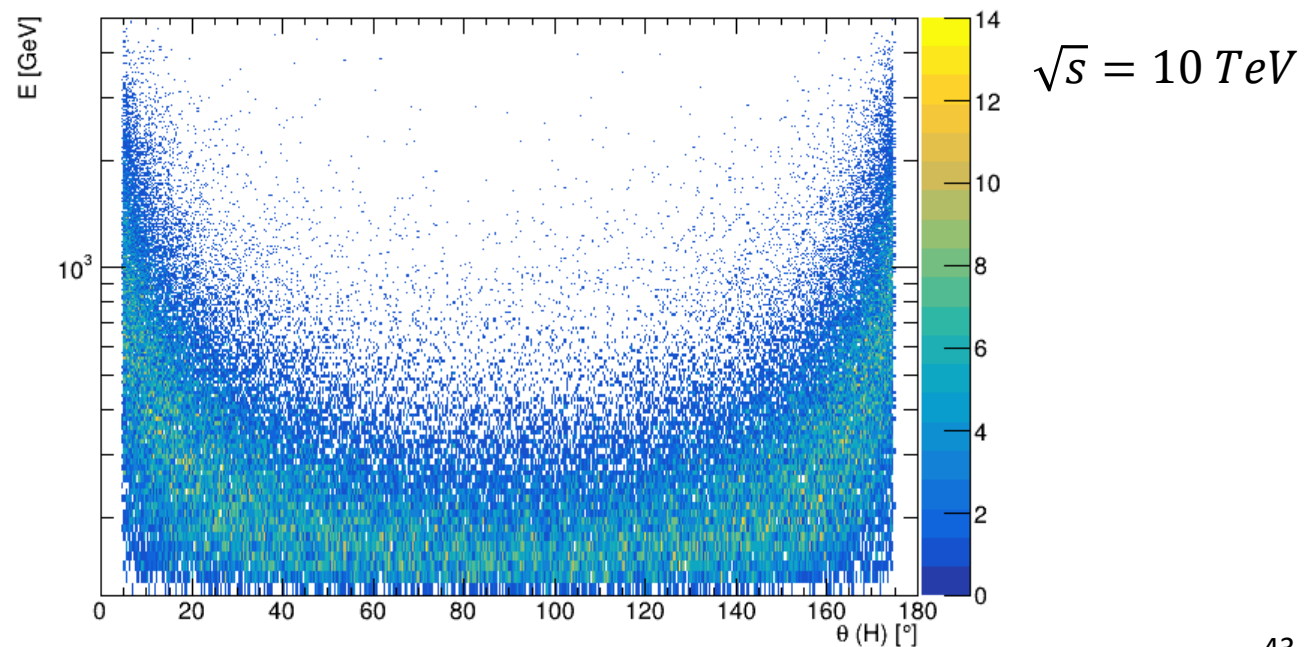
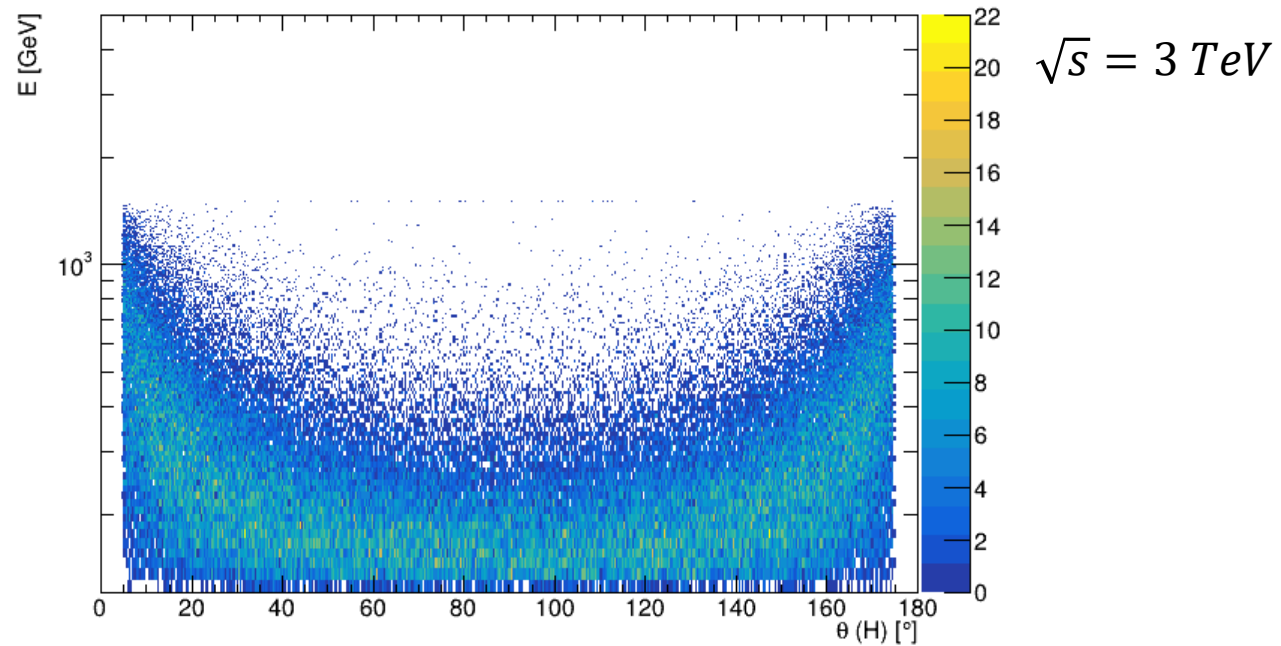
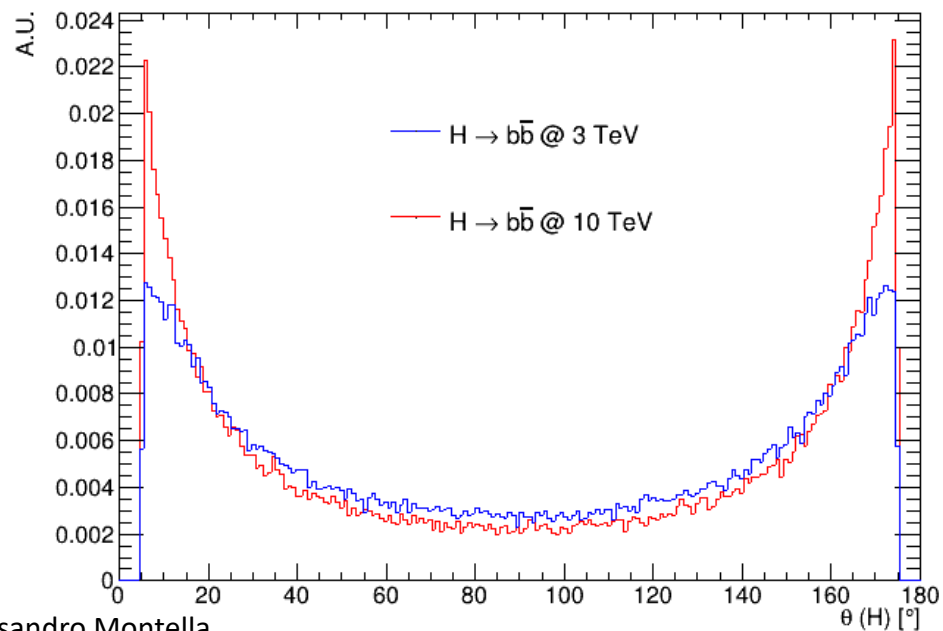
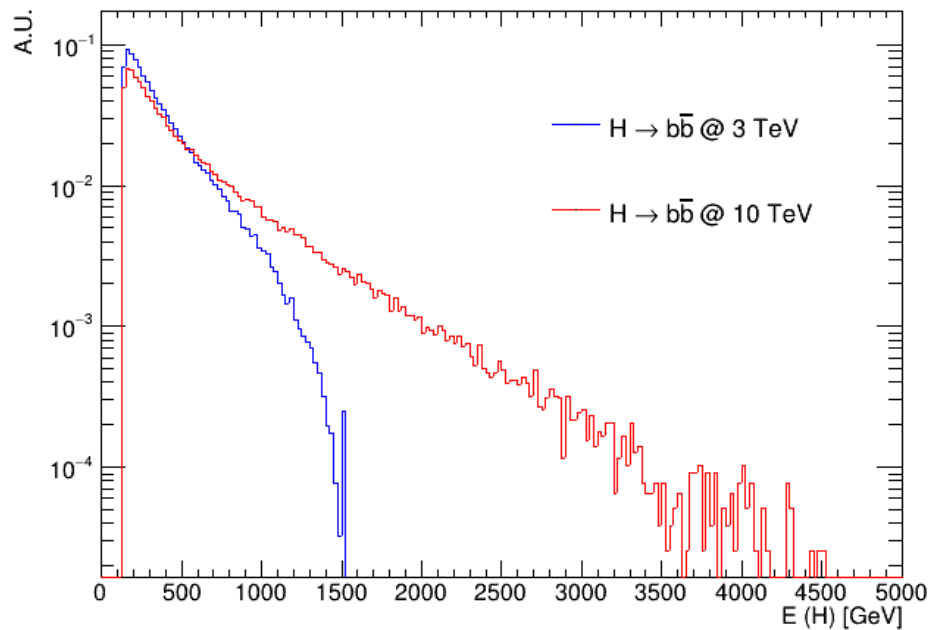
# Neutrons: $E$ and $\theta$



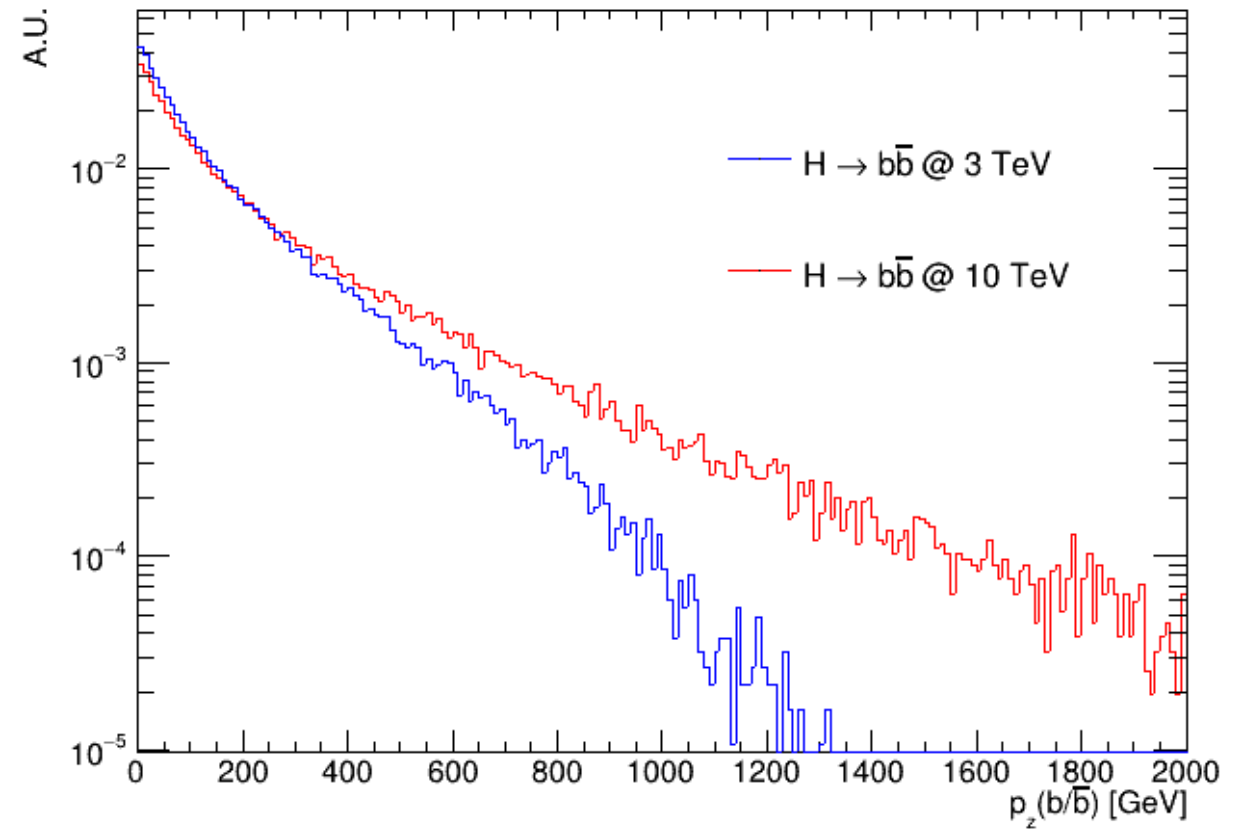
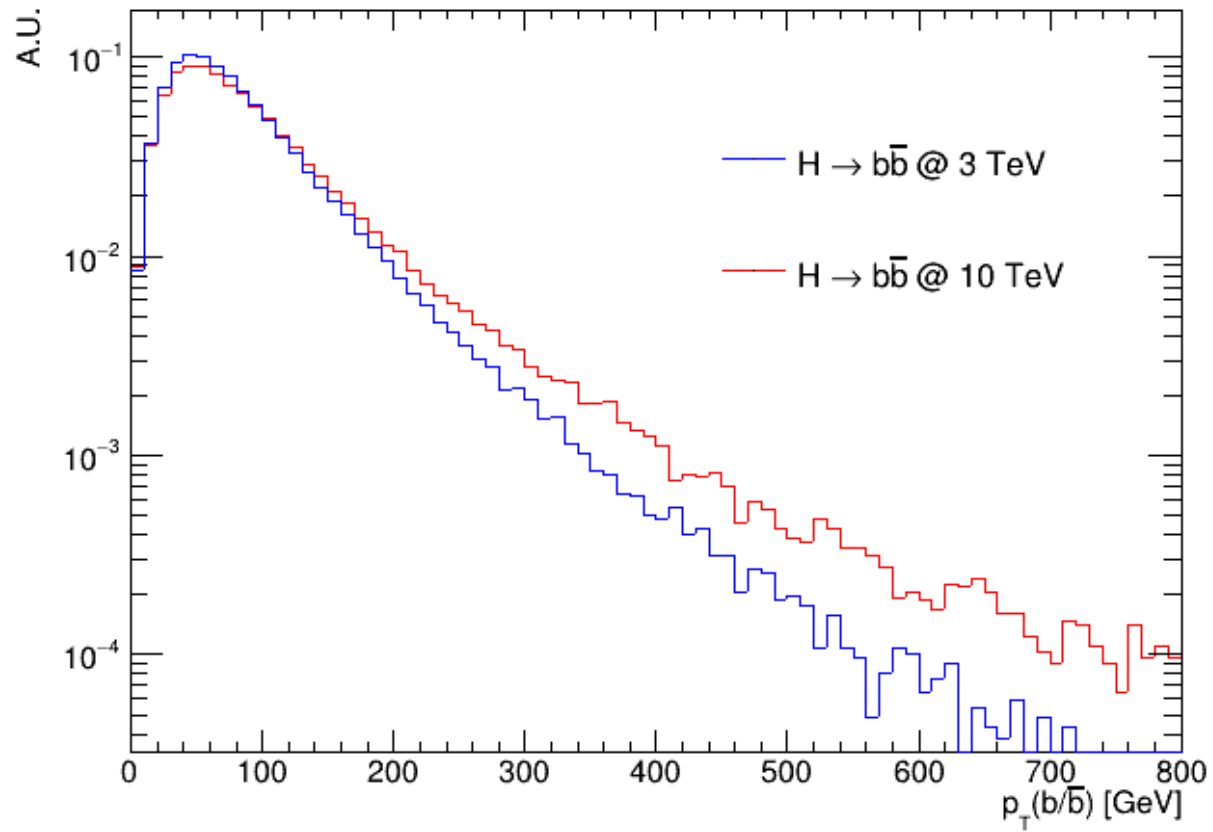
# Higgs: $p_T$ and $p_z$



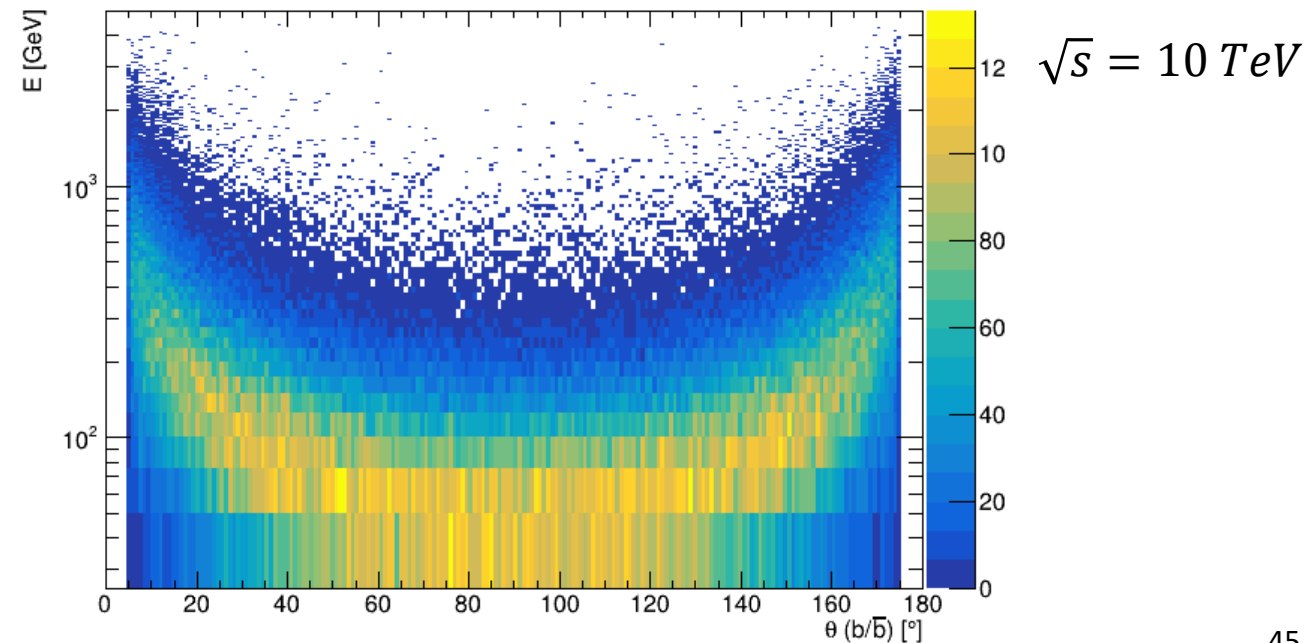
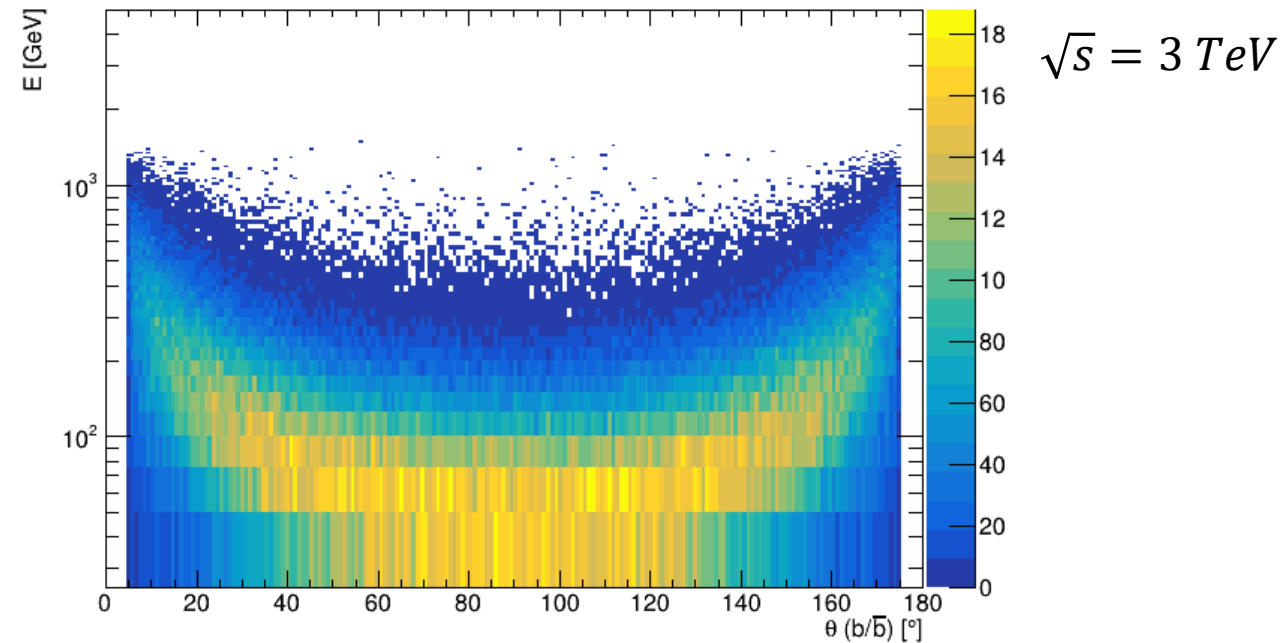
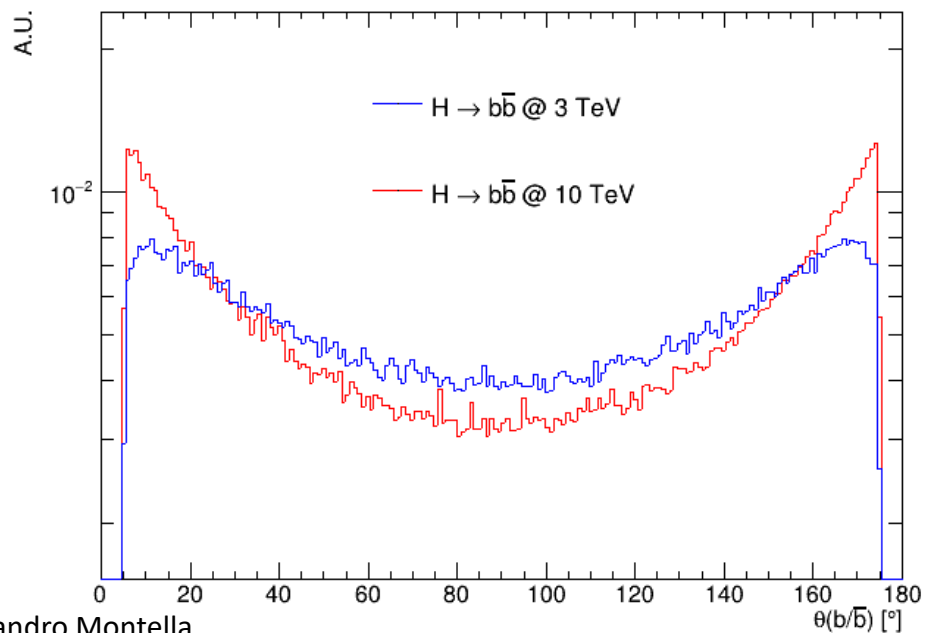
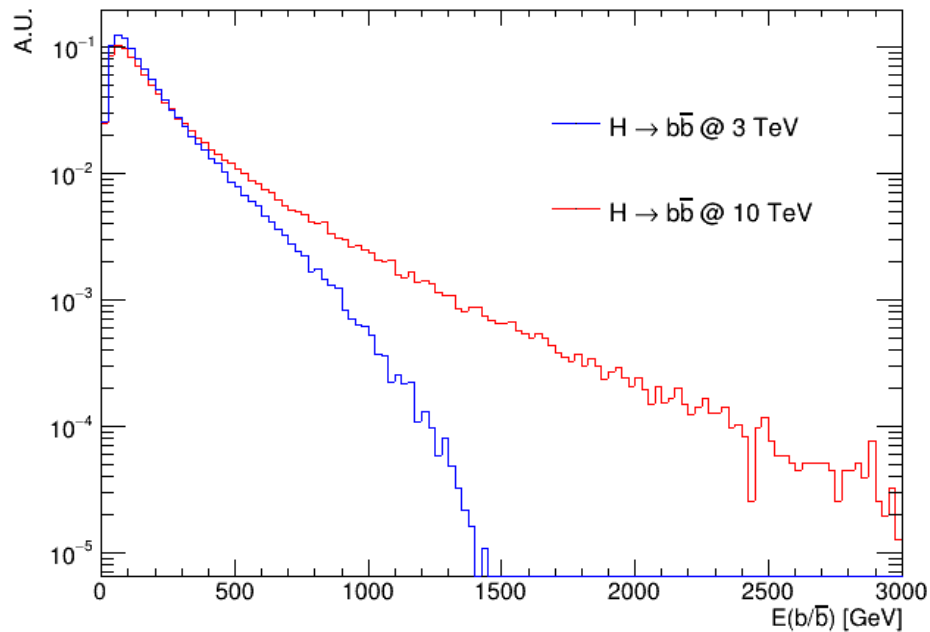
# Higgs: $E$ and $\theta$



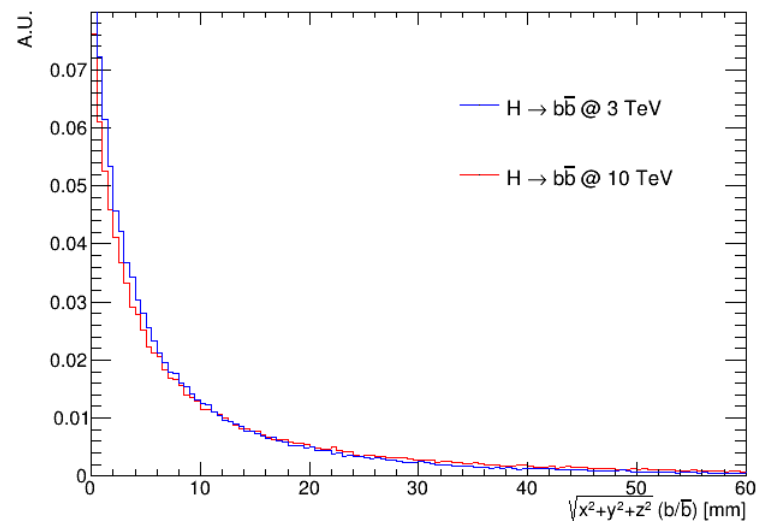
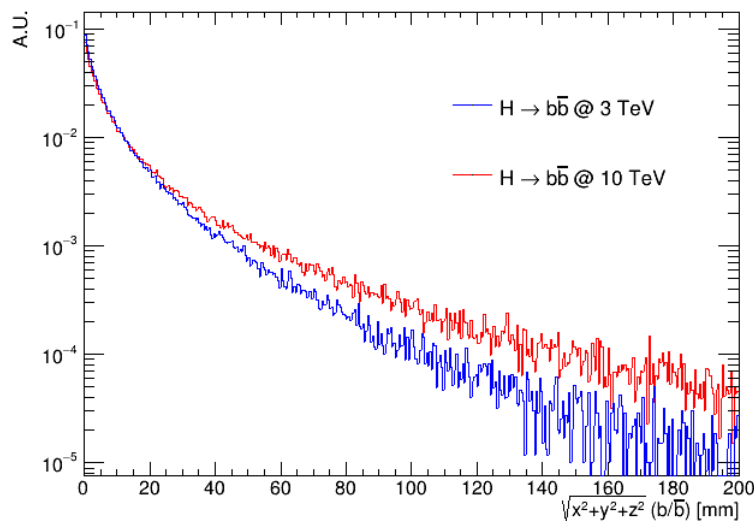
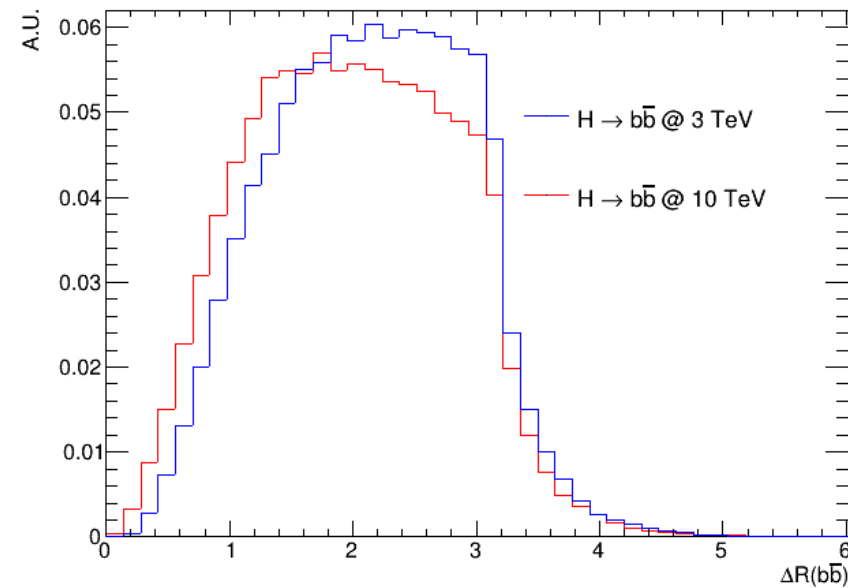
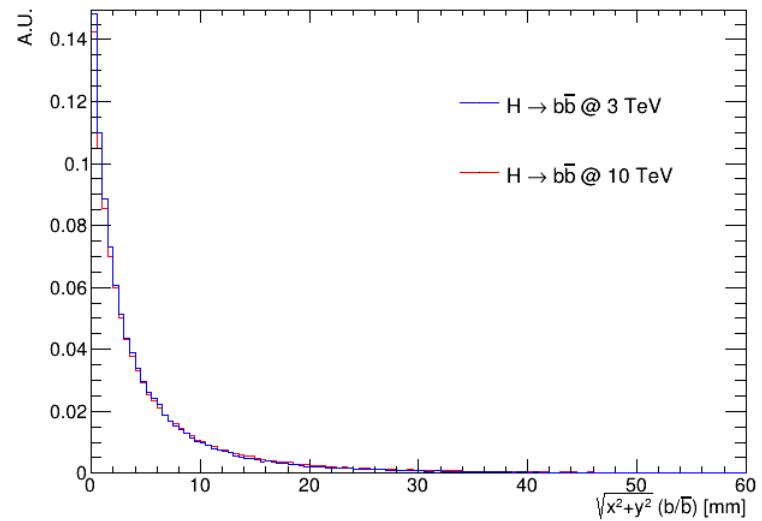
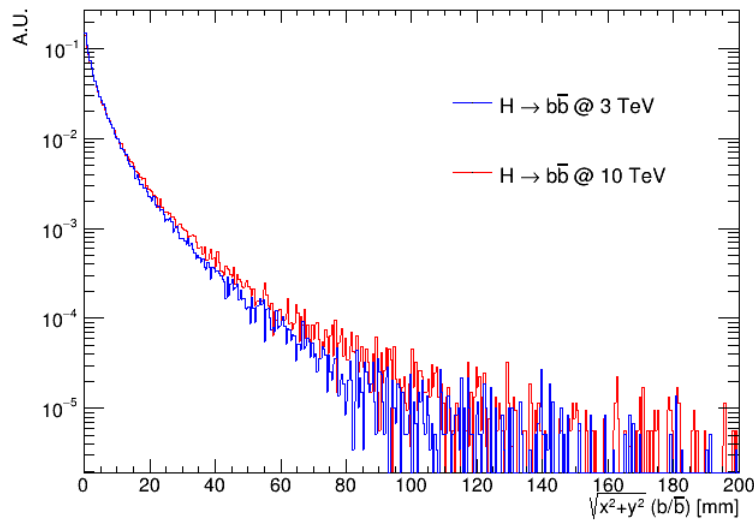
# b-quarks: $p_T$ and $p_z$



# b-quarks: $E$ and $\theta$



# b-quarks: b decay vertex and $\Delta R$



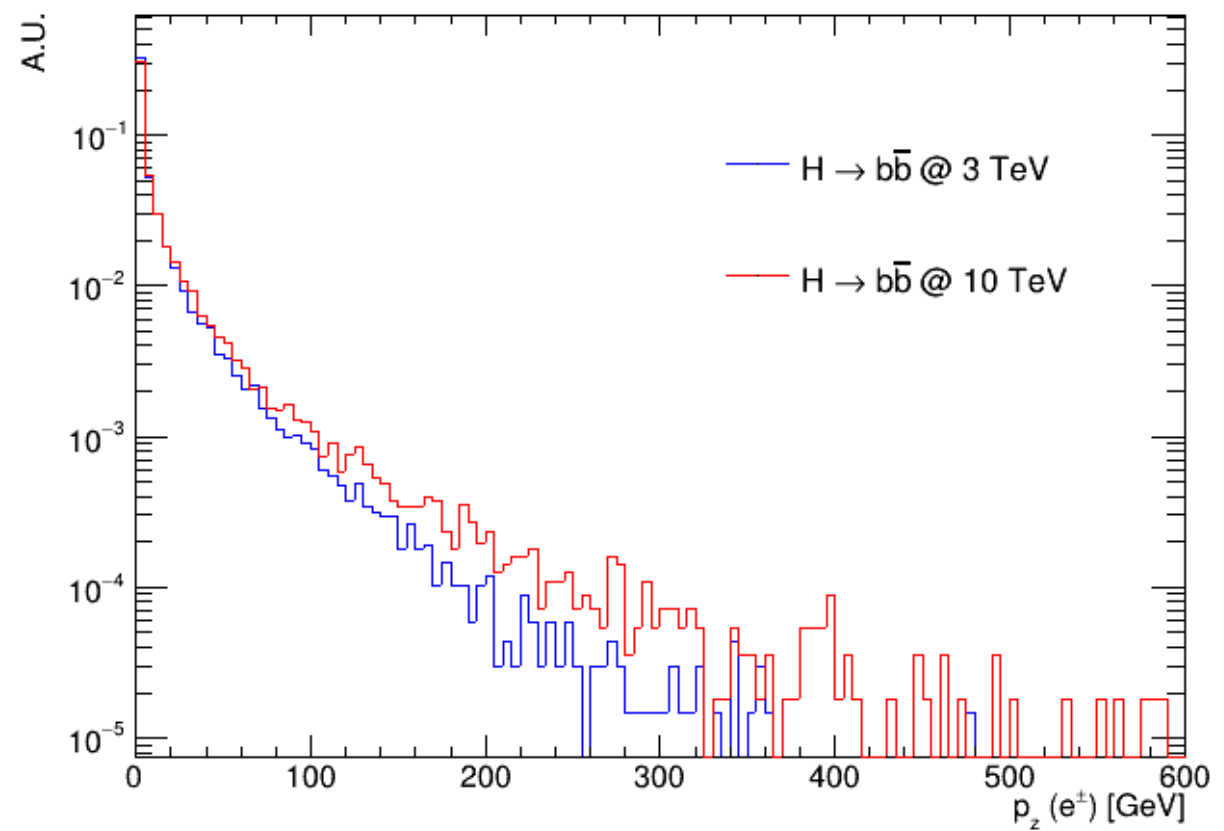
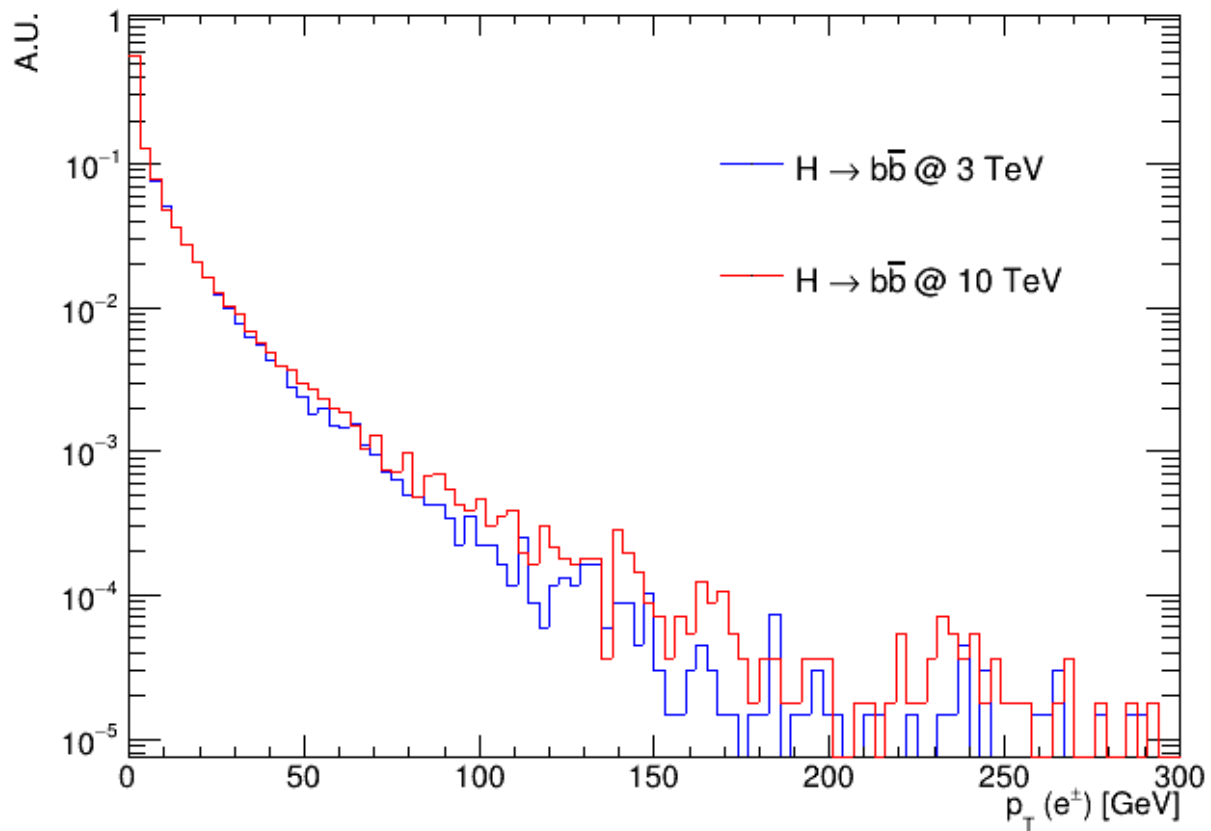
$$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu,$$
$$H \rightarrow b \bar{b}$$

Acceptance region:  $10^\circ < \theta < 170^\circ$

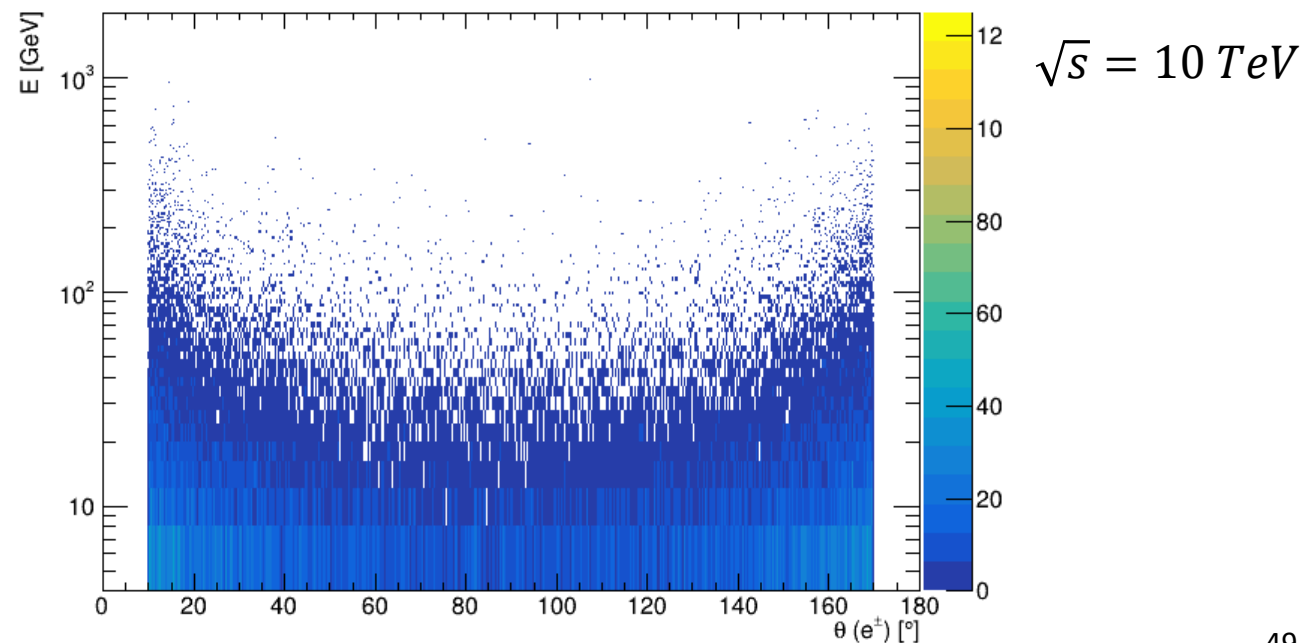
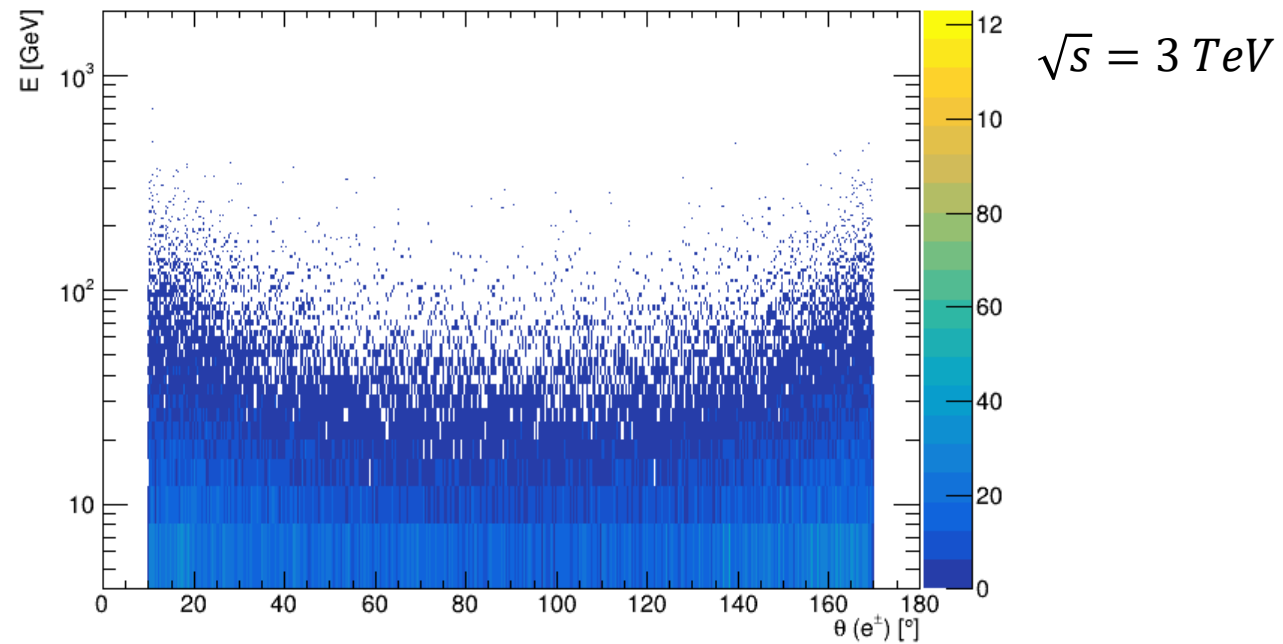
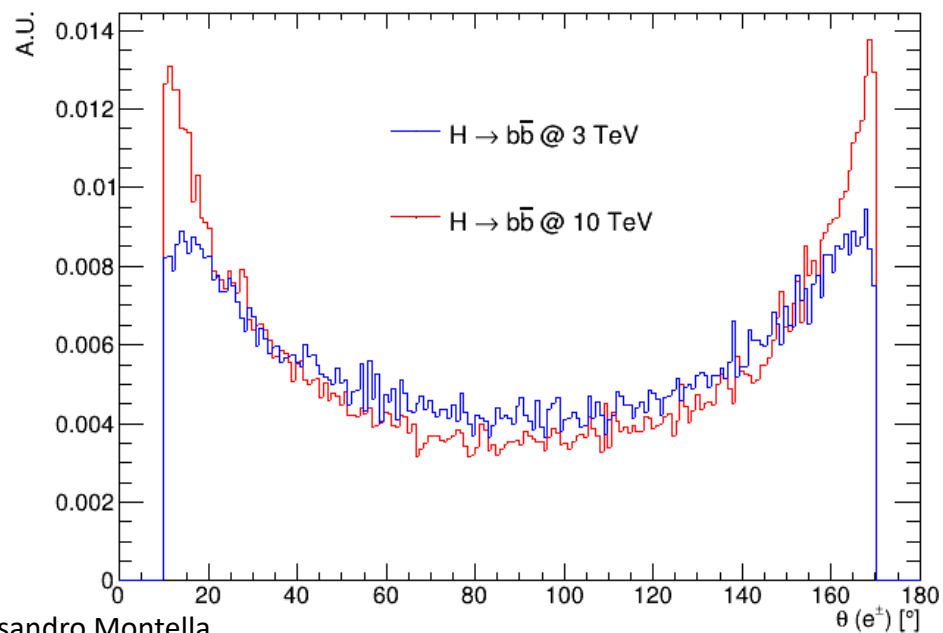
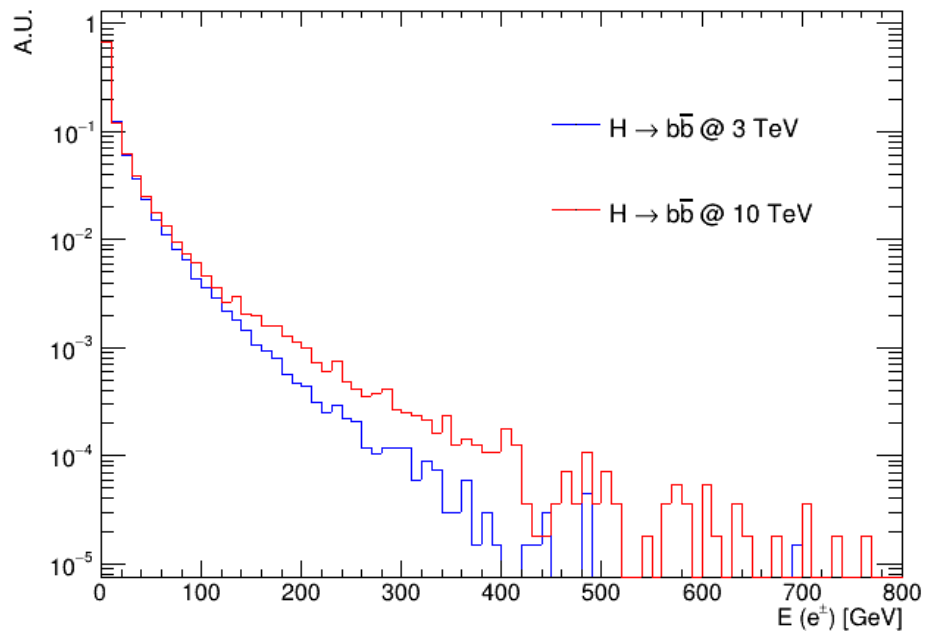
$\sqrt{s} = 3 \text{ TeV}$  vs  $\sqrt{s} = 10 \text{ TeV}$



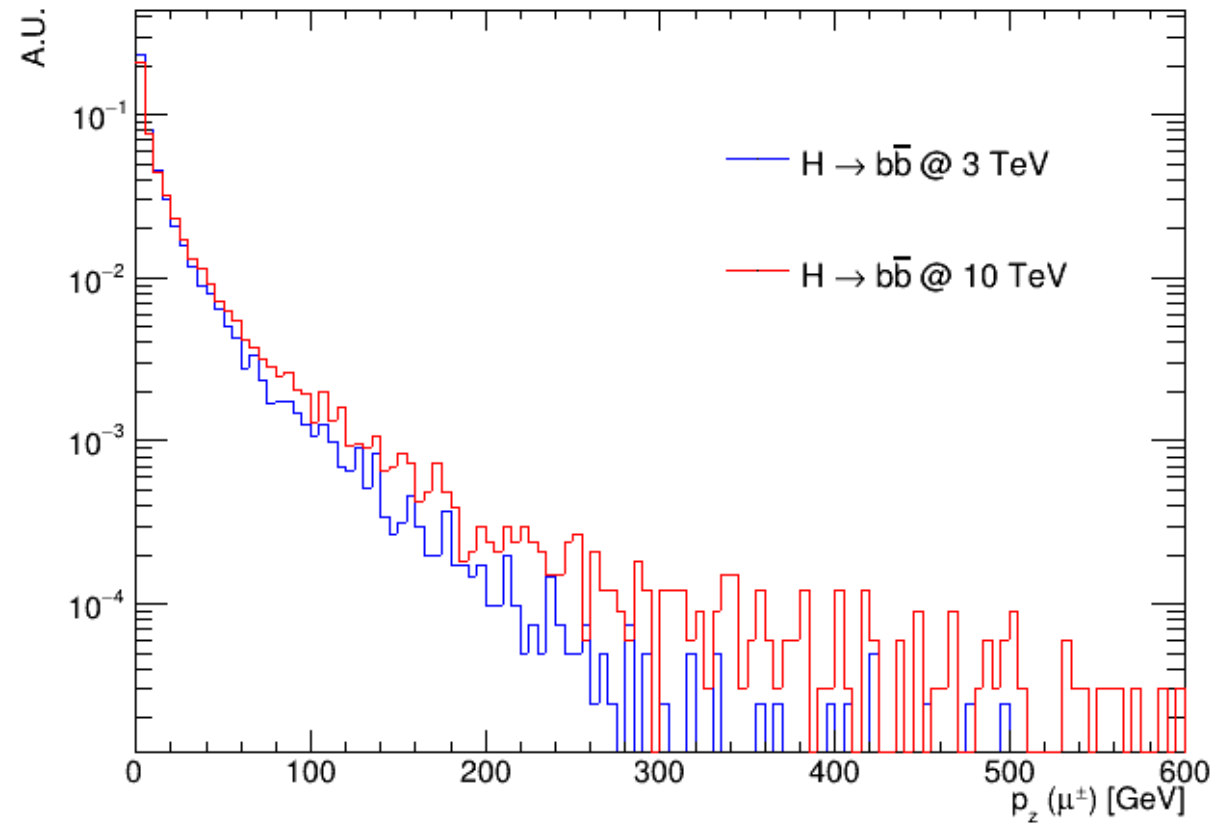
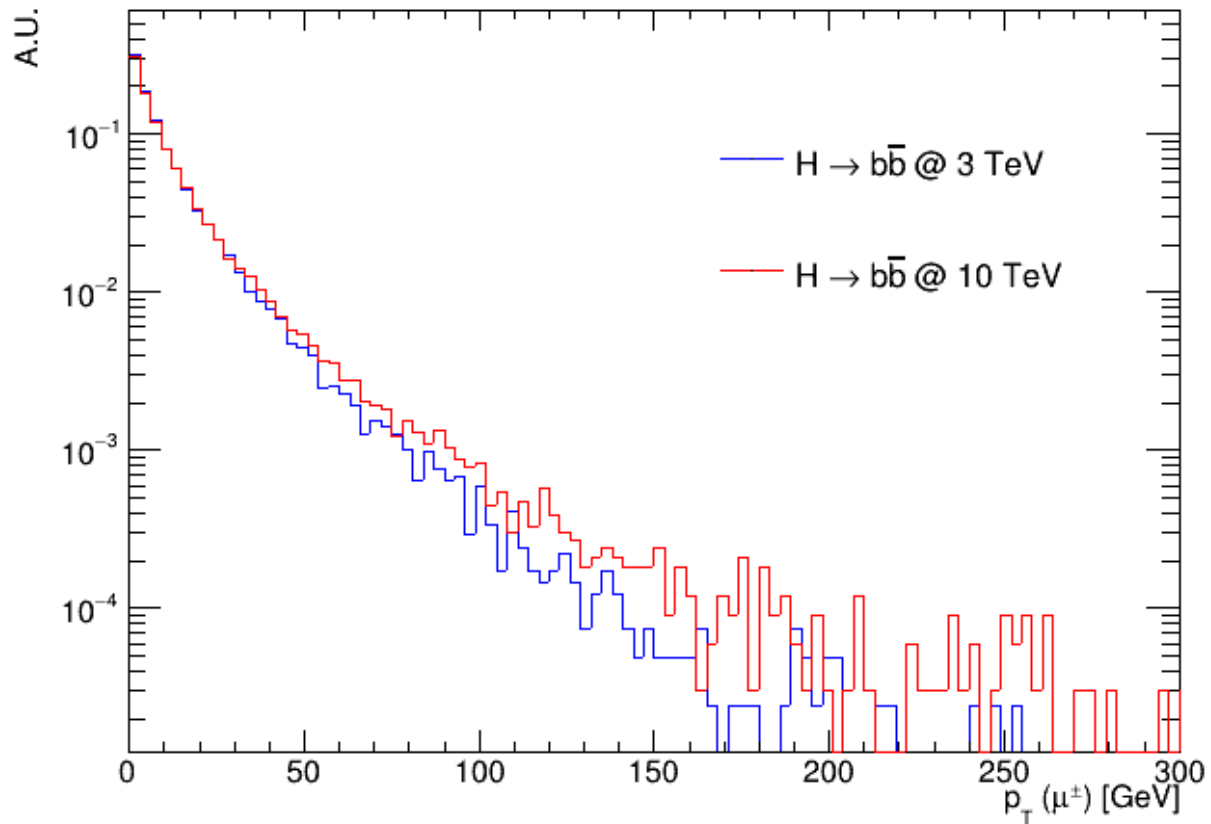
# Electrons: $p_T$ and $p_z$



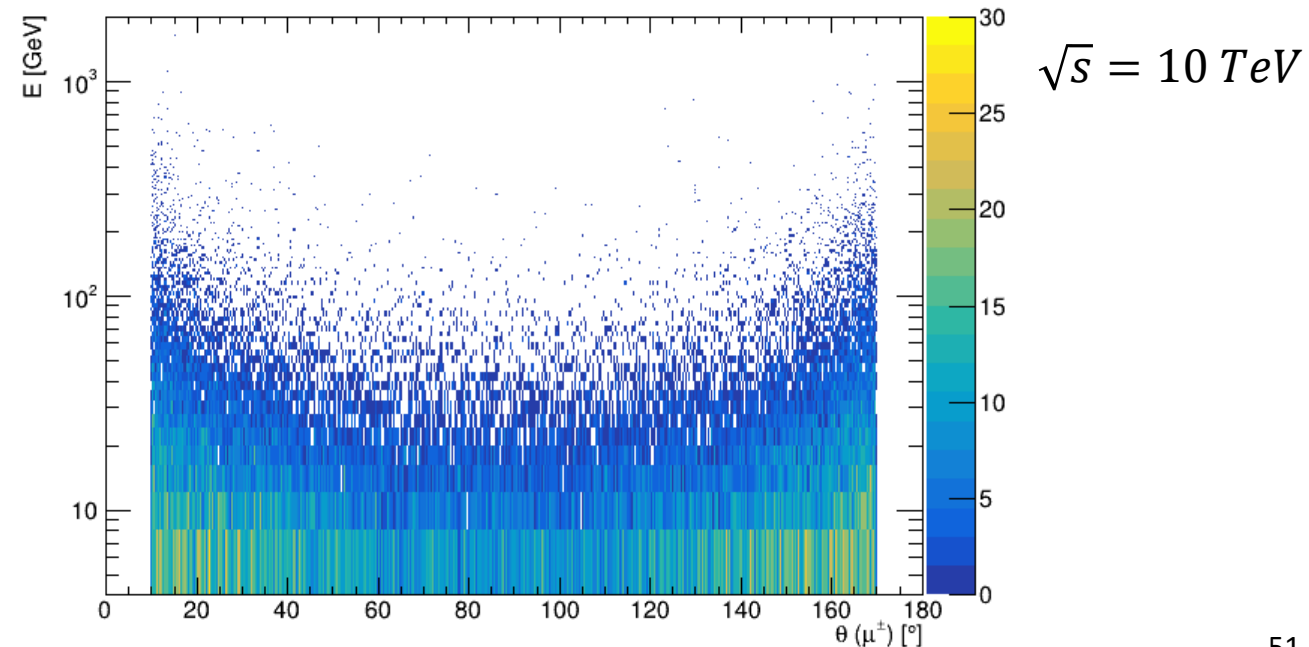
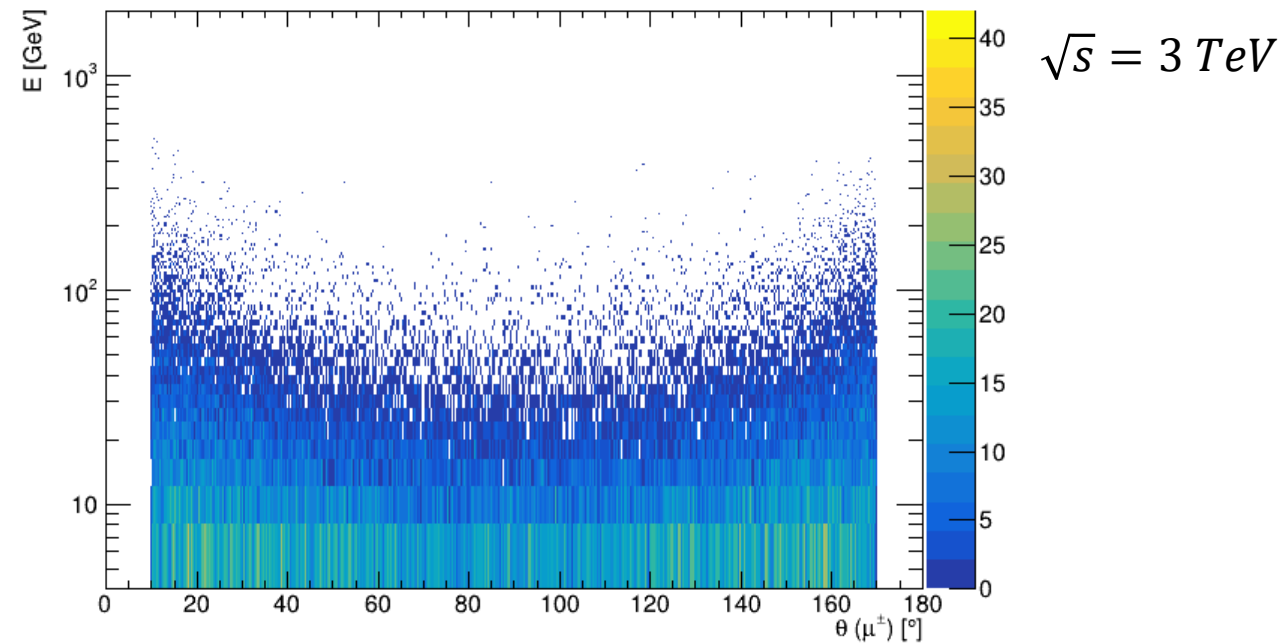
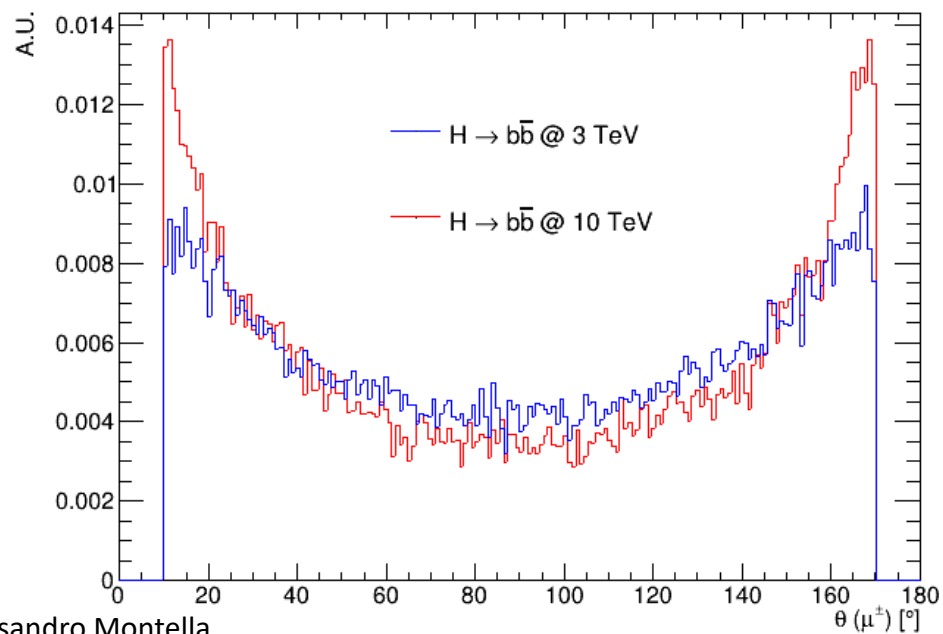
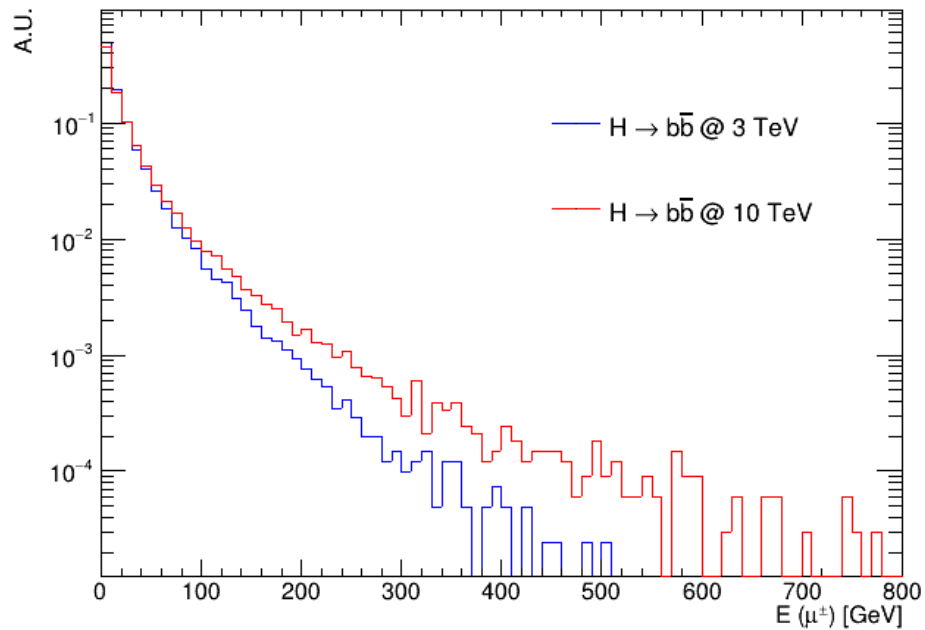
# Electrons: $E$ and $\theta$



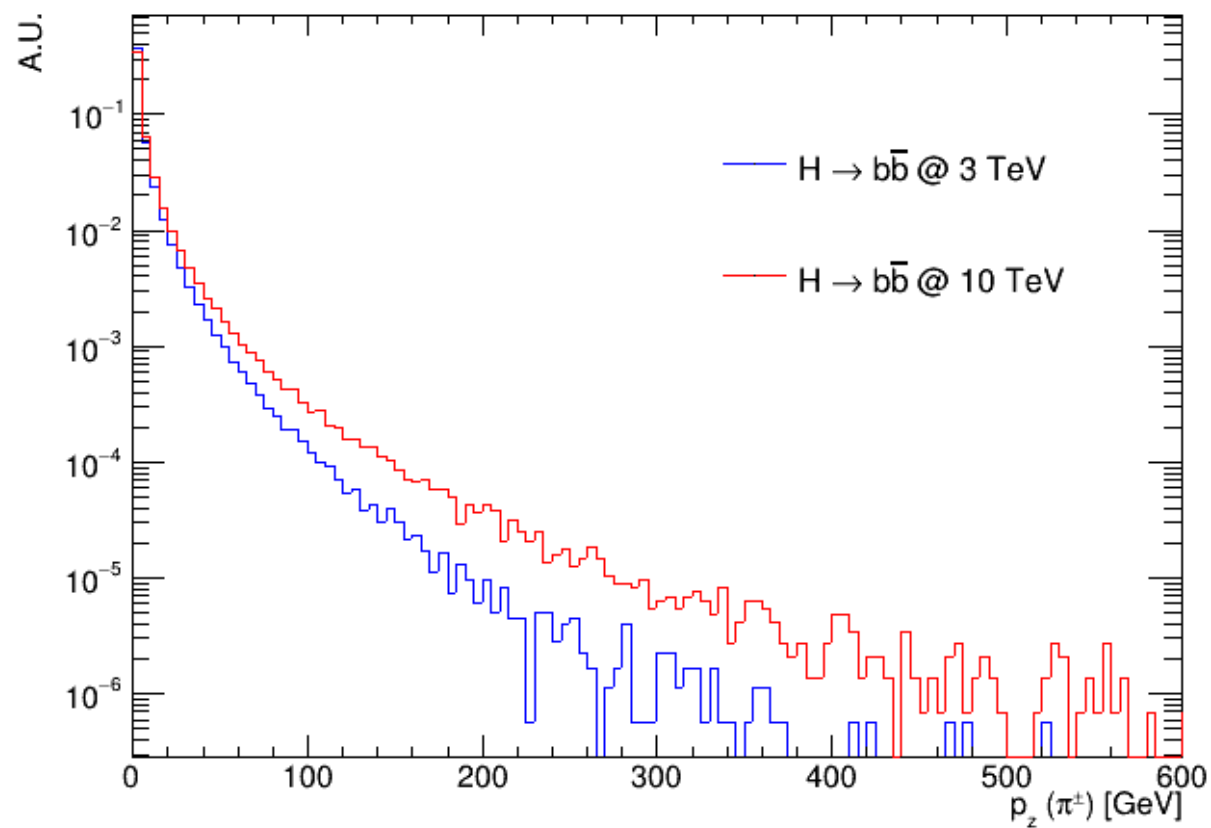
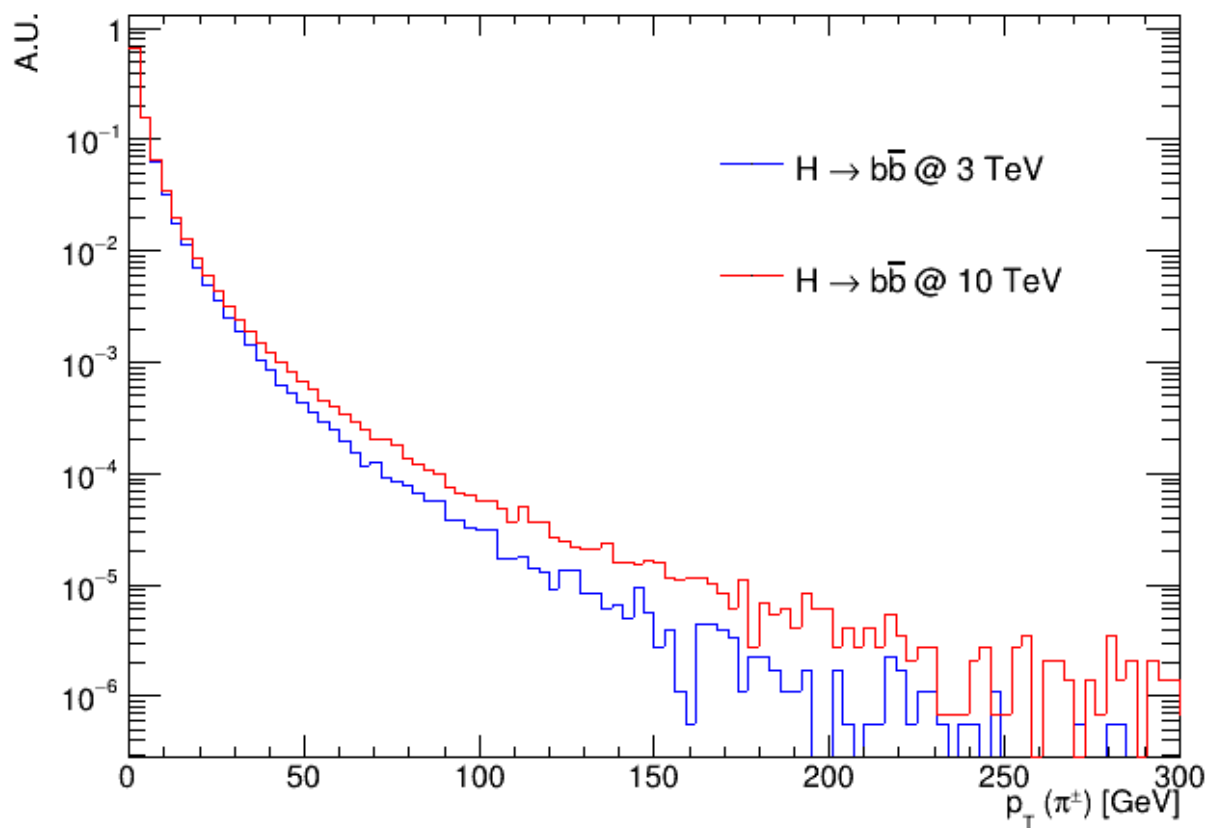
# Muons: $p_T$ and $p_z$



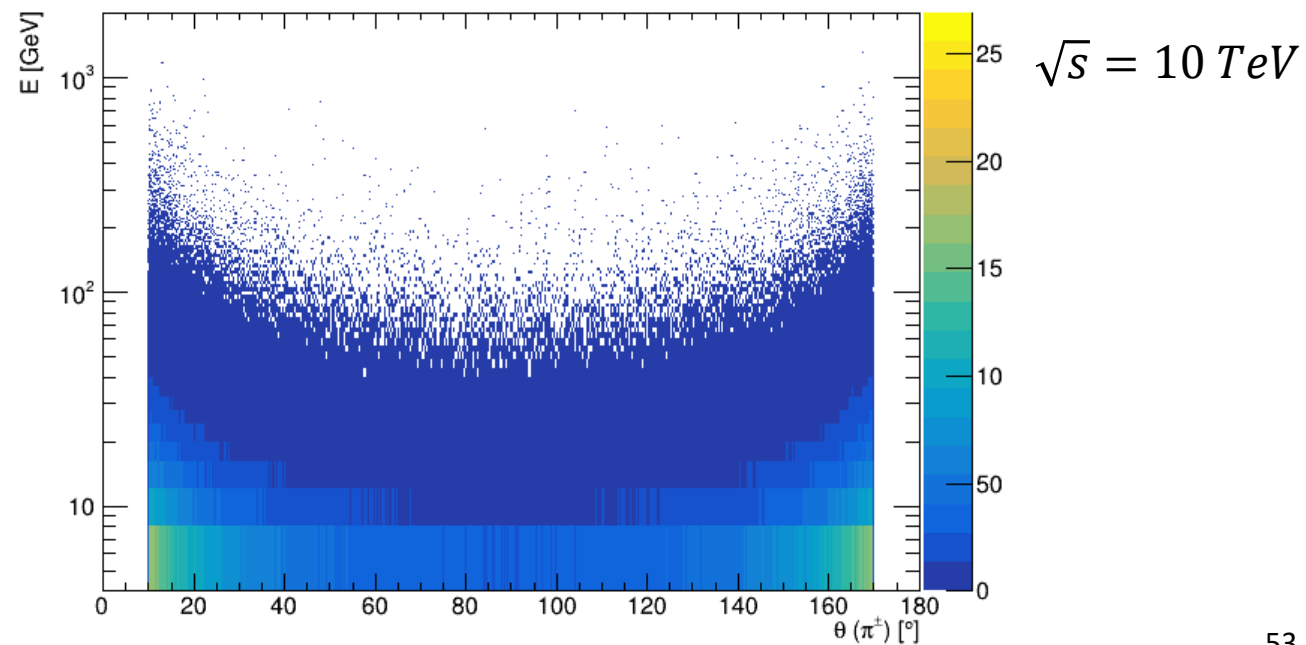
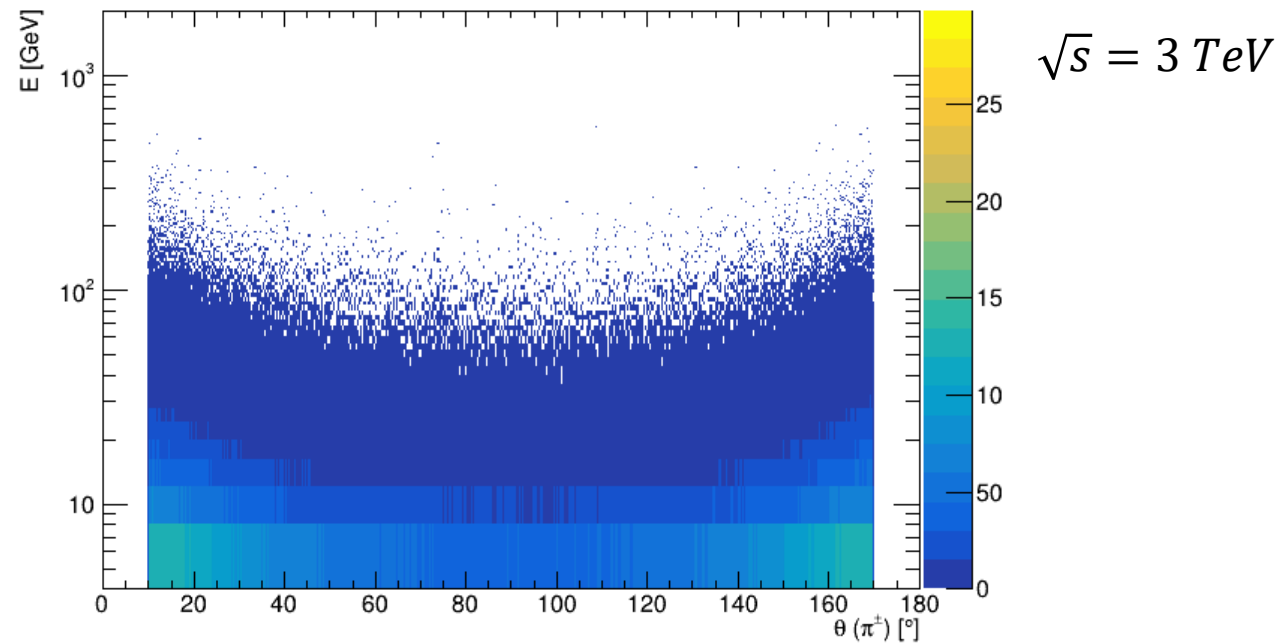
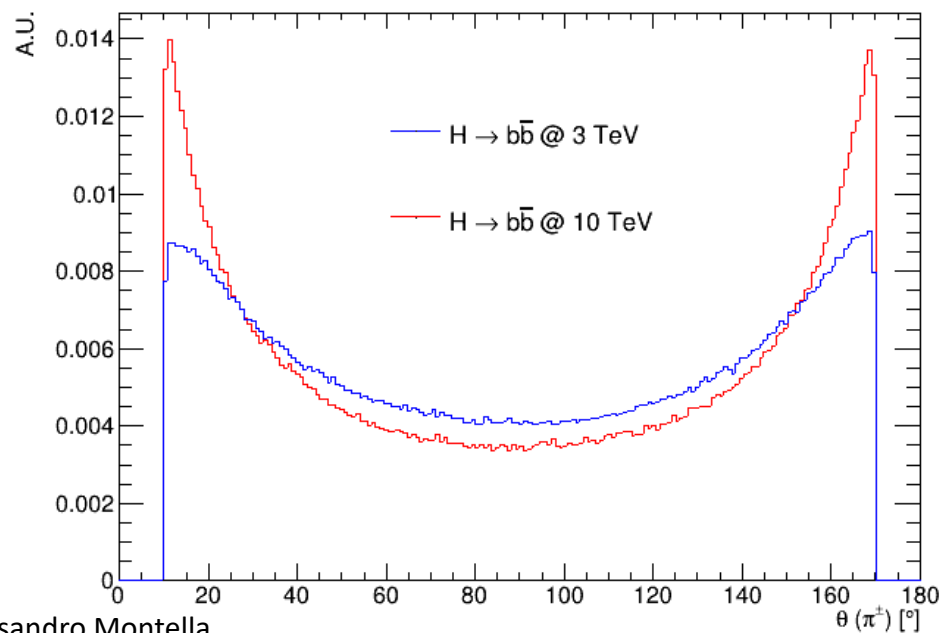
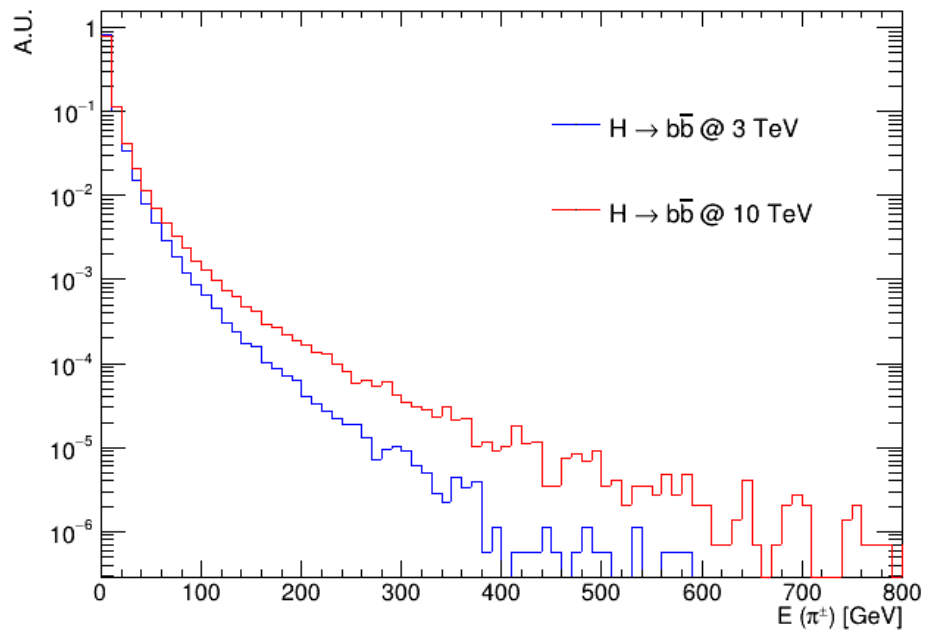
# Muons: $E$ and $\theta$



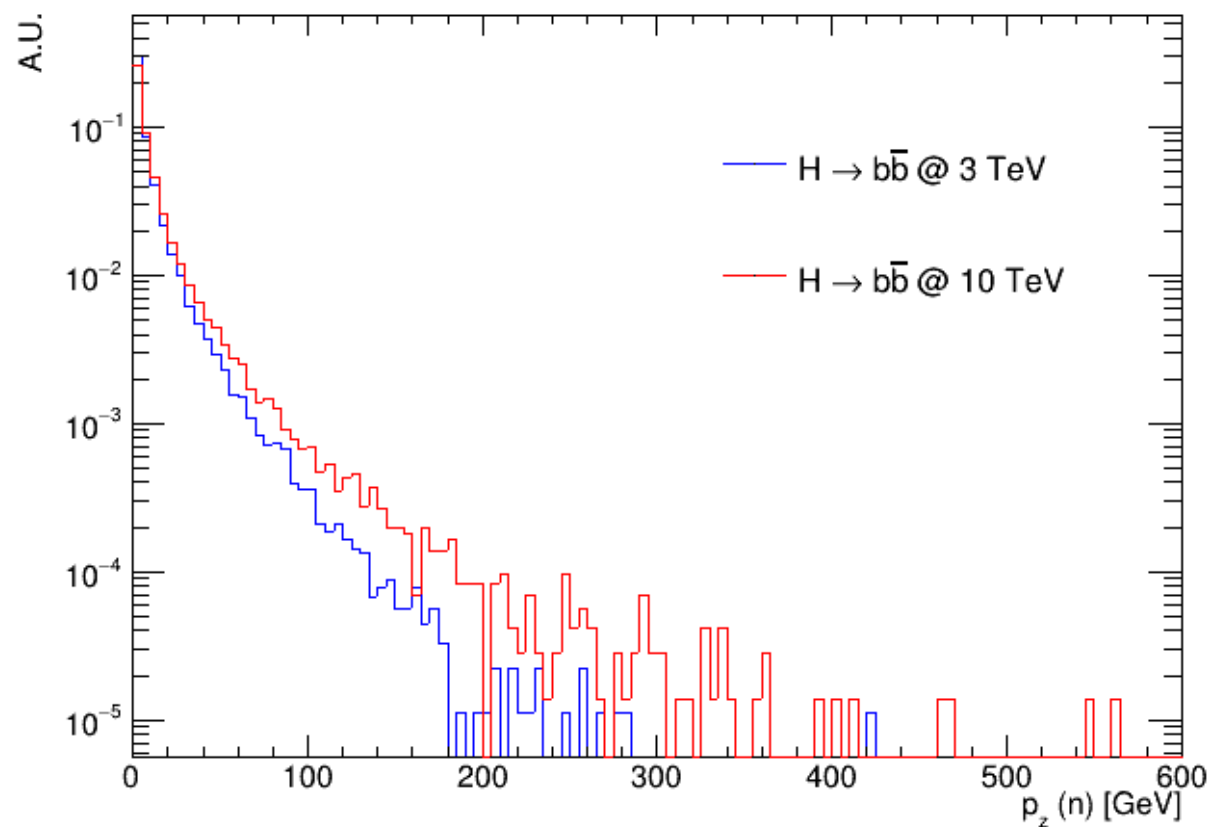
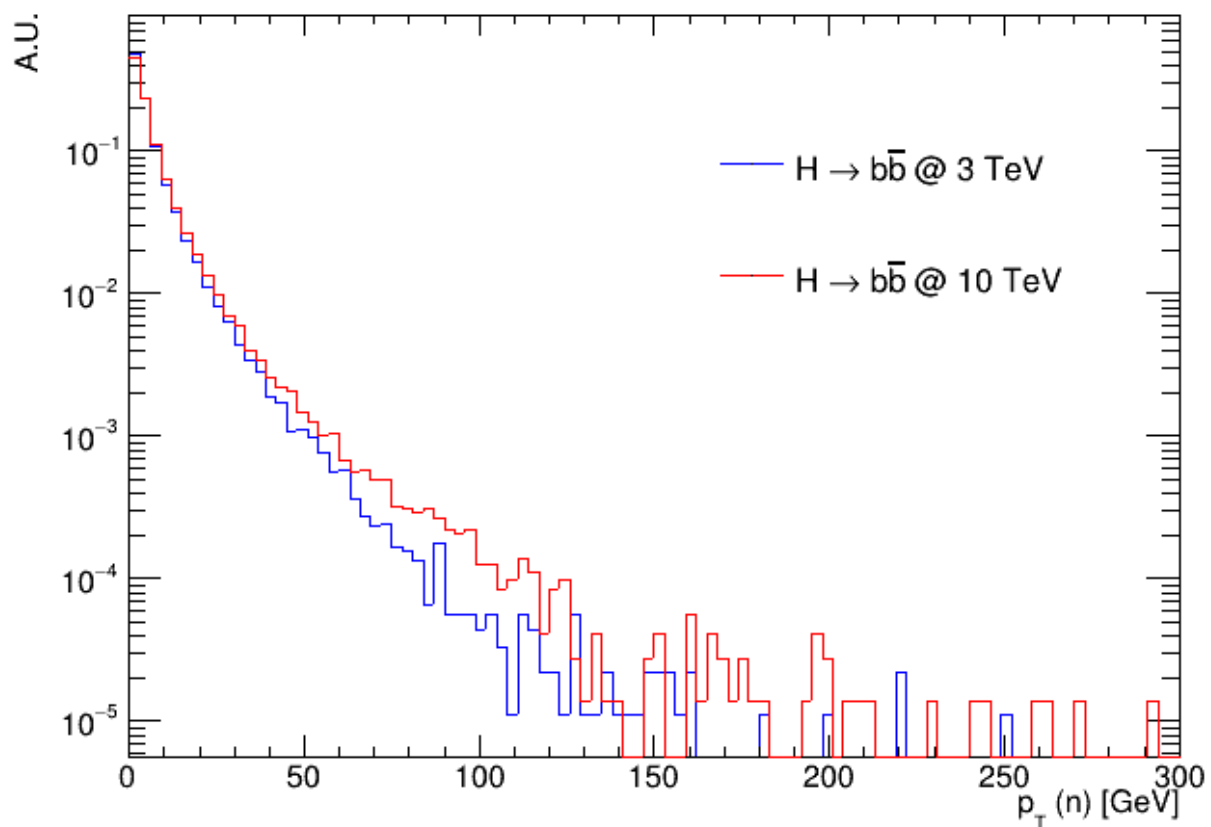
# Charged pions: $p_T$ and $p_z$



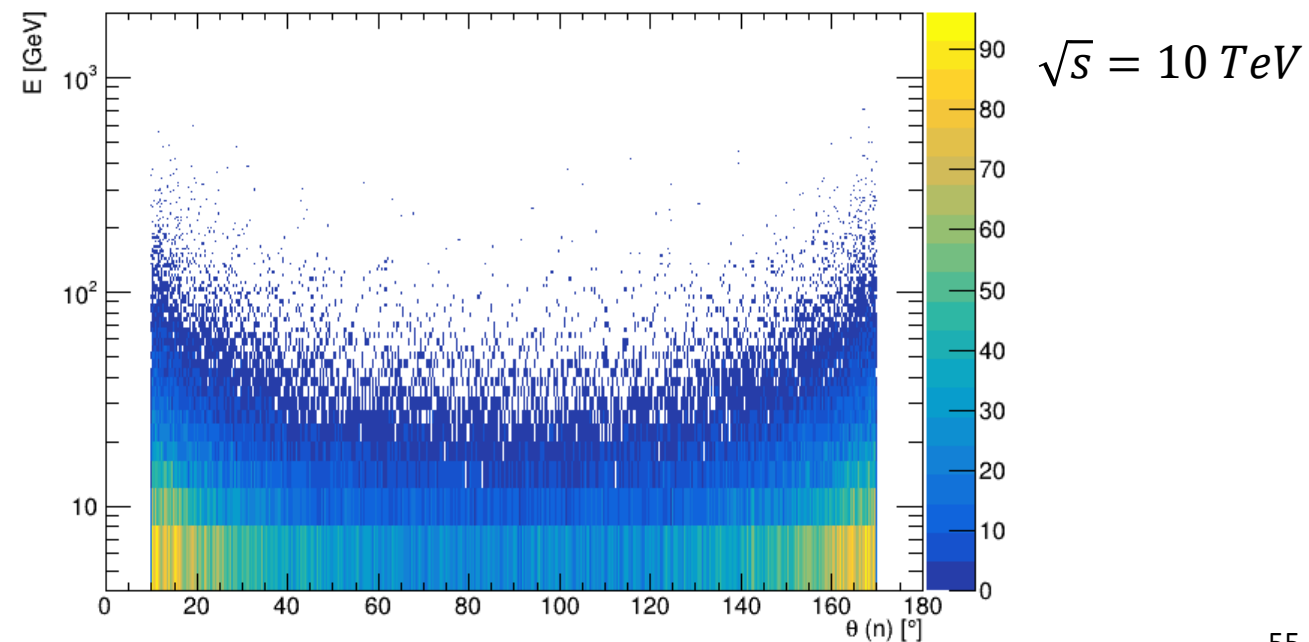
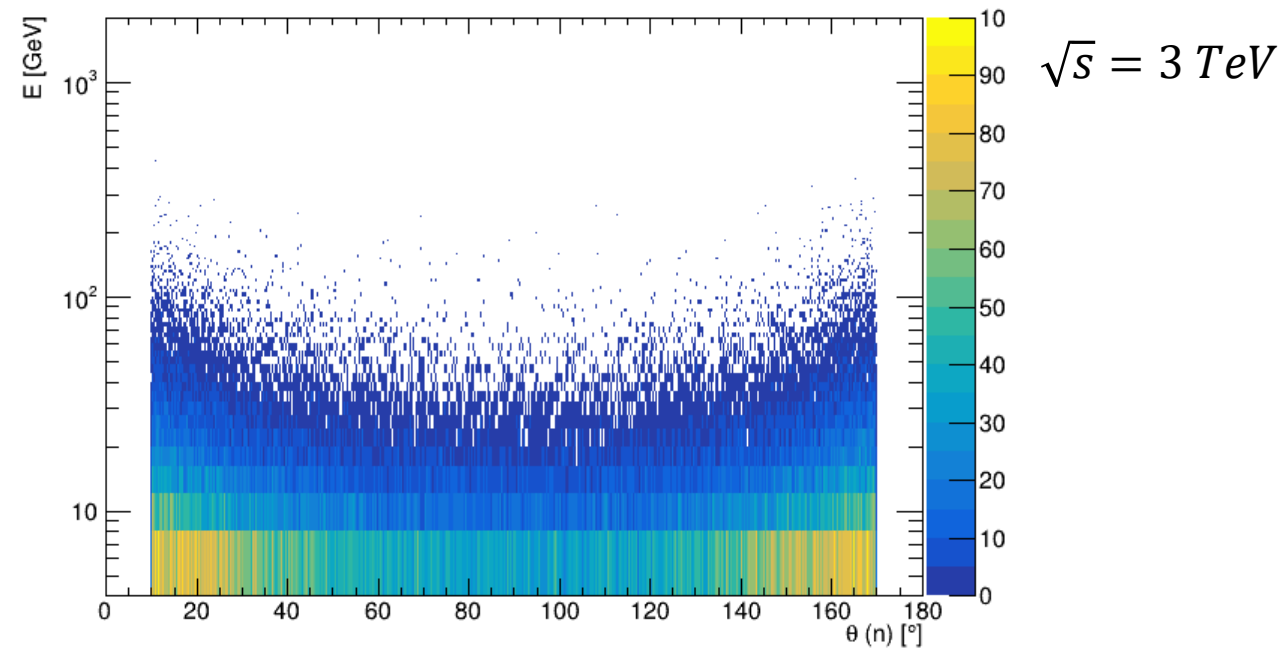
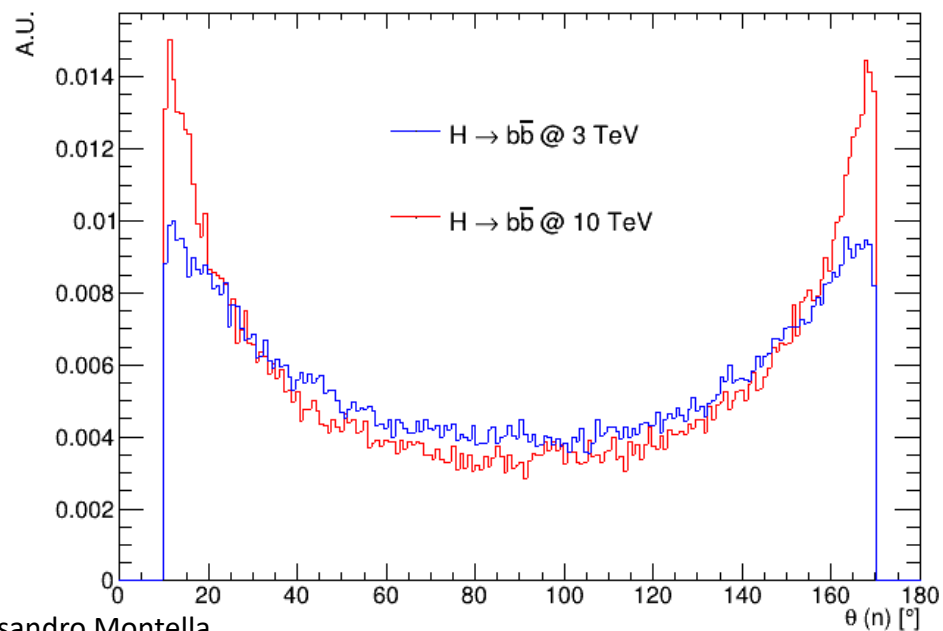
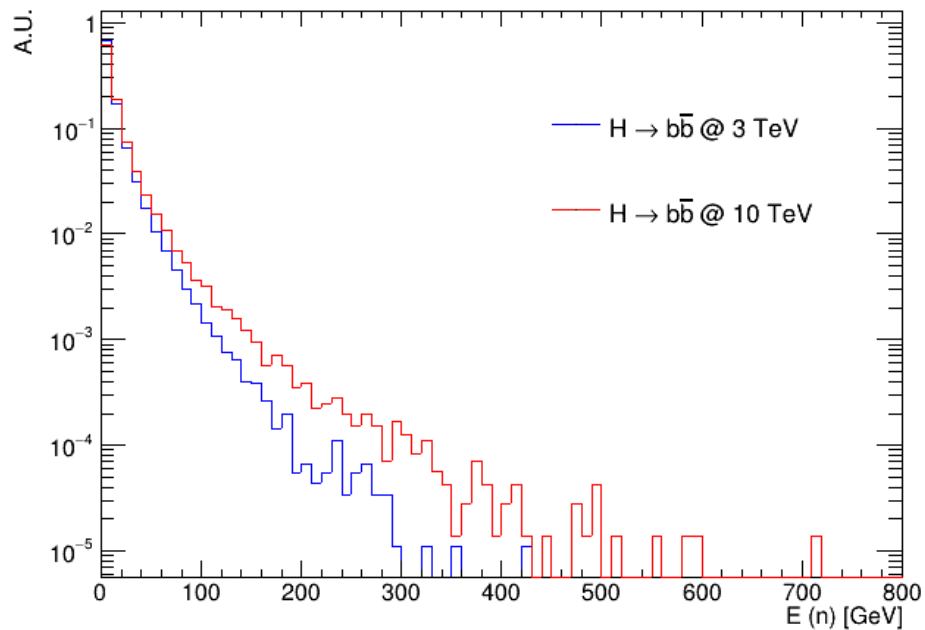
# Charged pions: $E$ and $\theta$



# Neutrons: $p_T$ and $p_z$

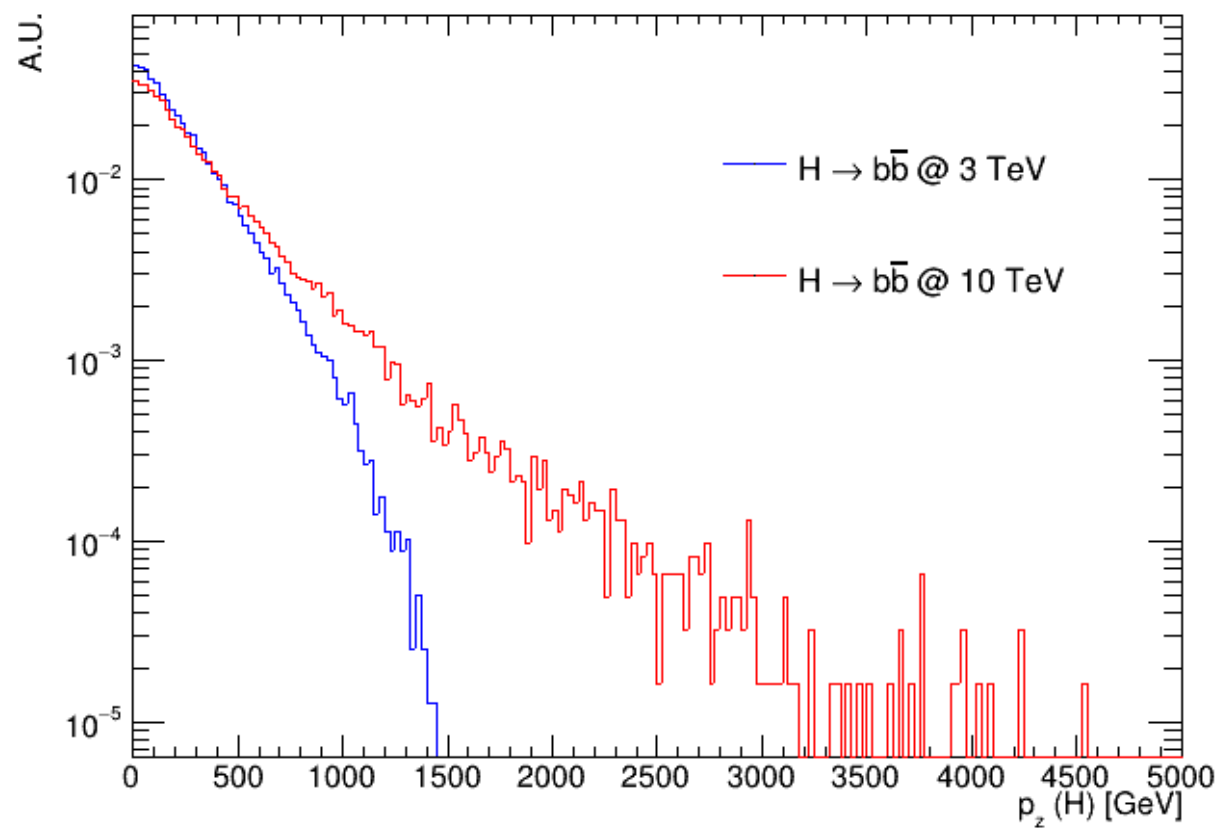
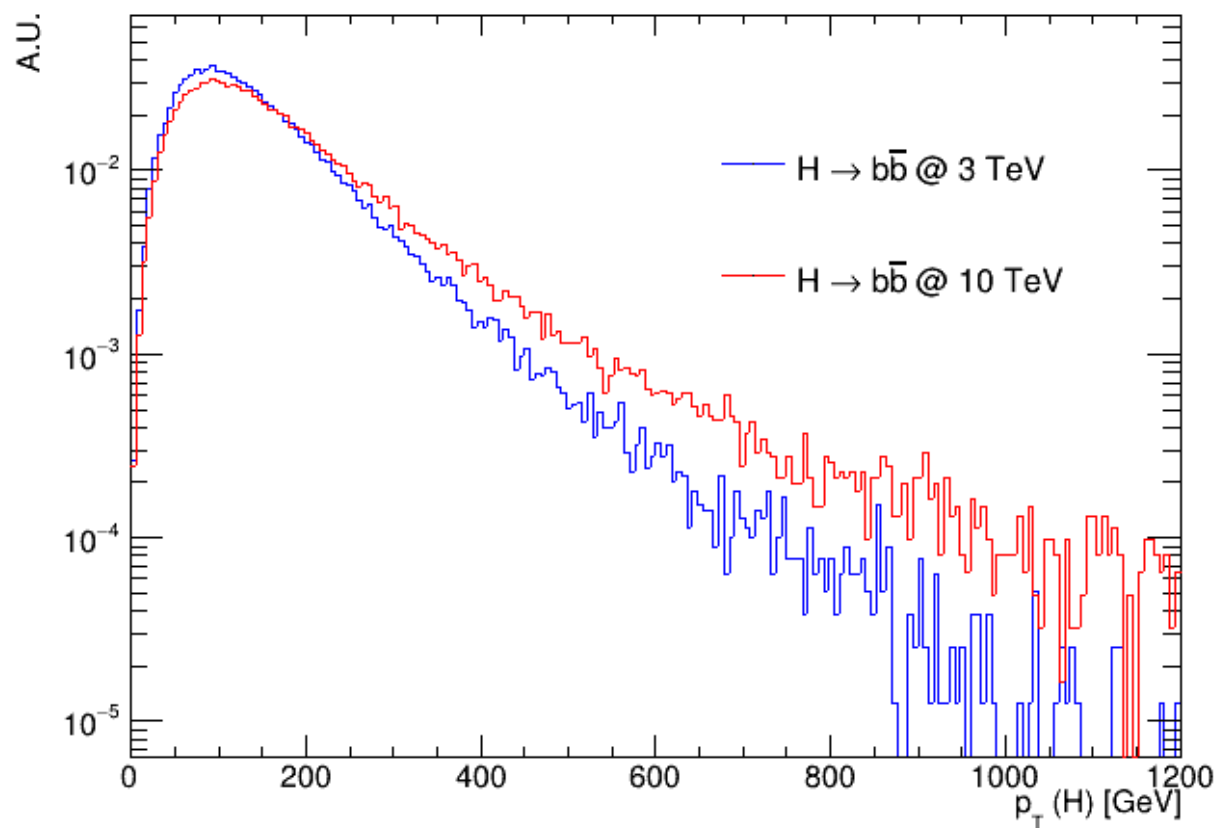


# Neutrons: $E$ and $\theta$

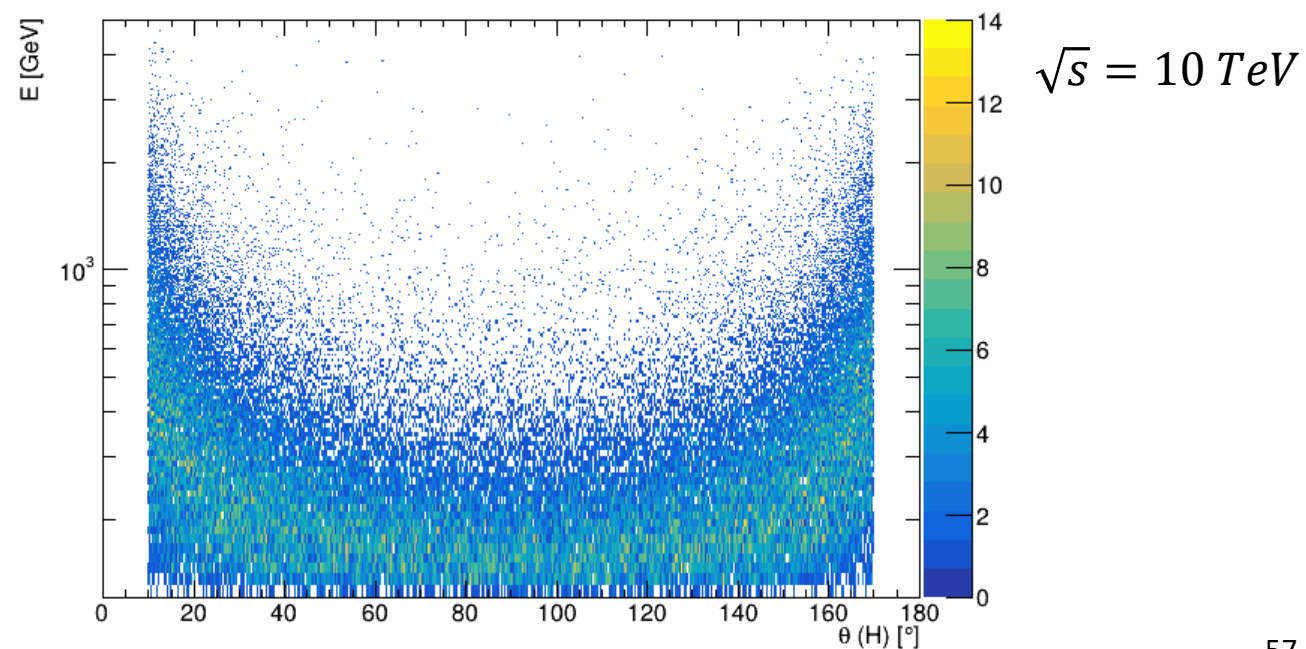
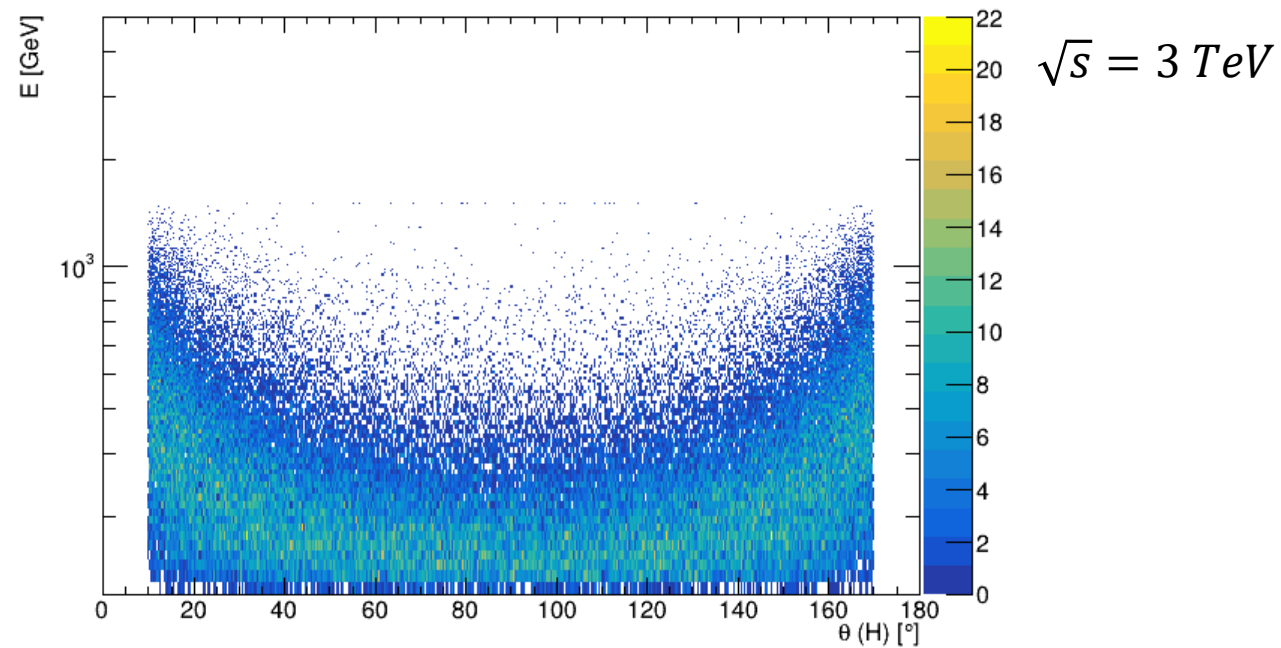
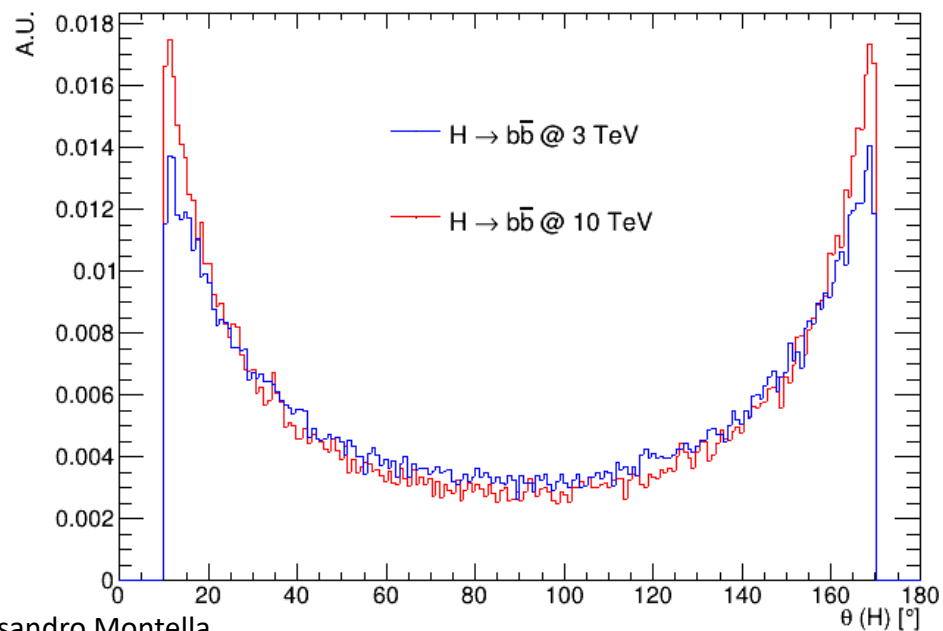
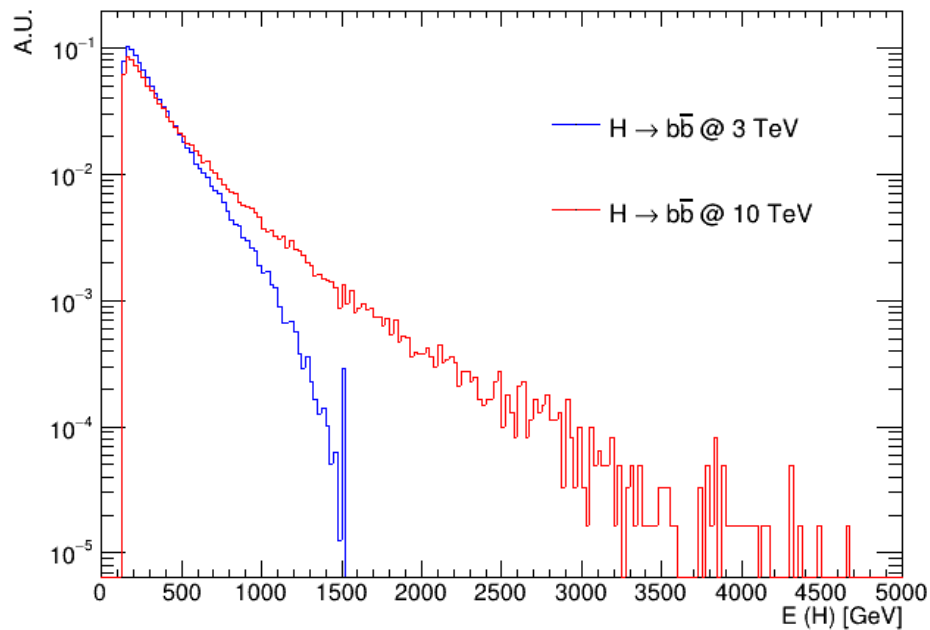




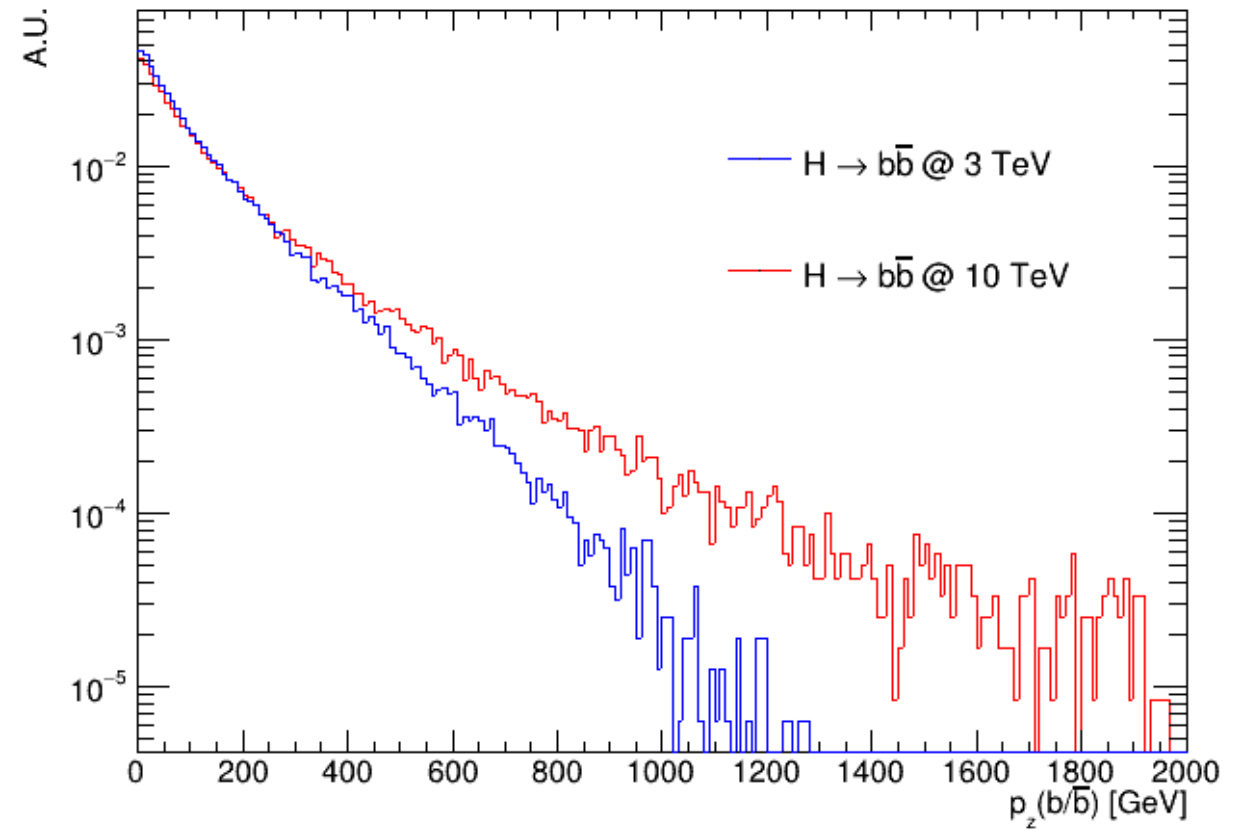
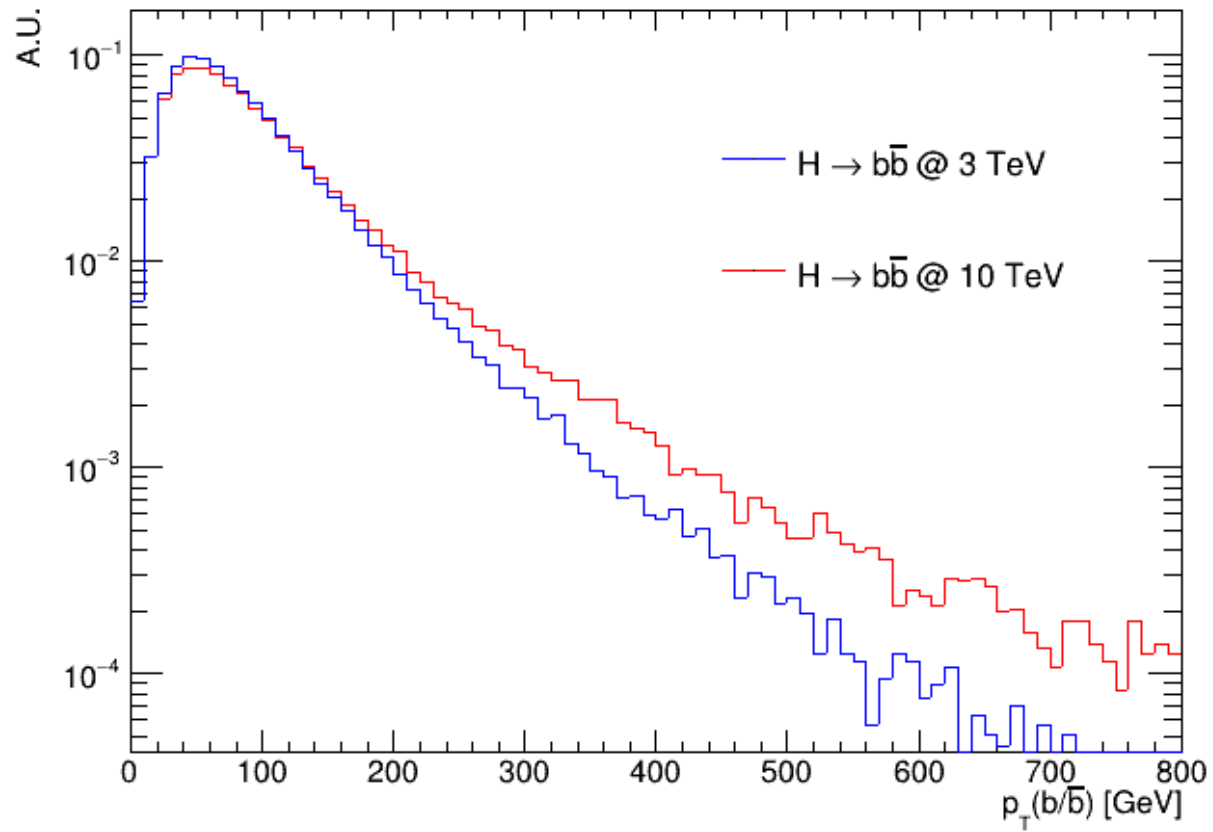
# Higgs: $p_T$ and $p_z$



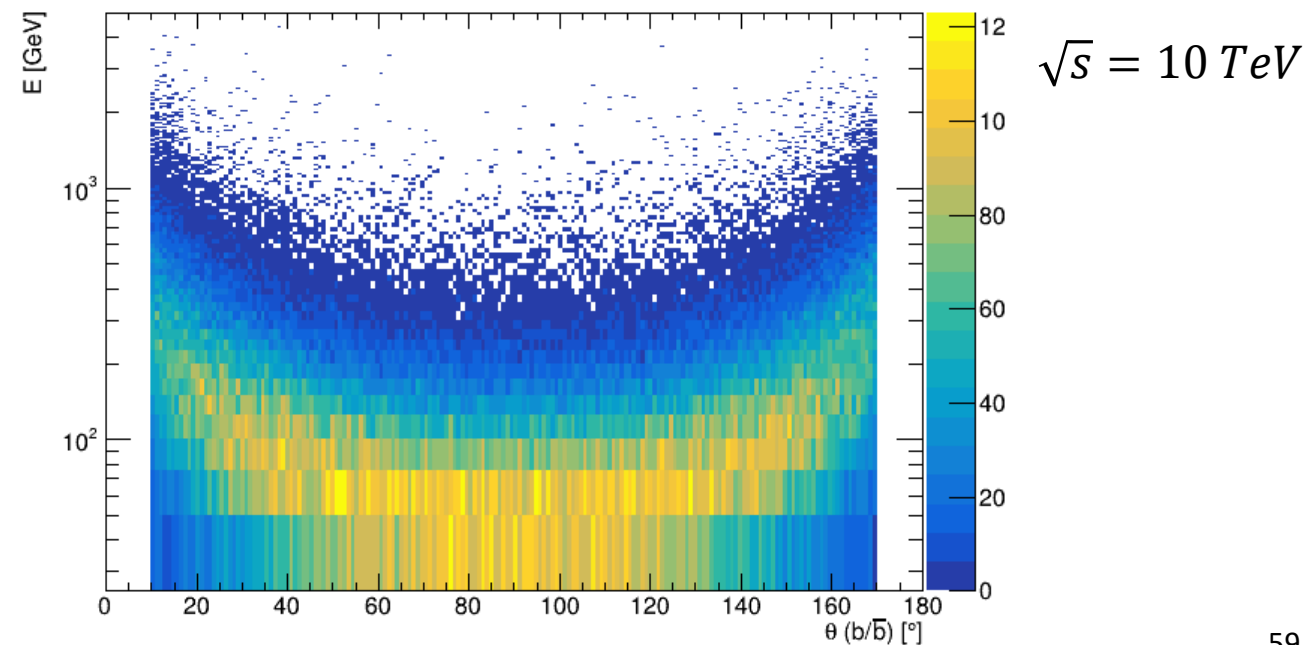
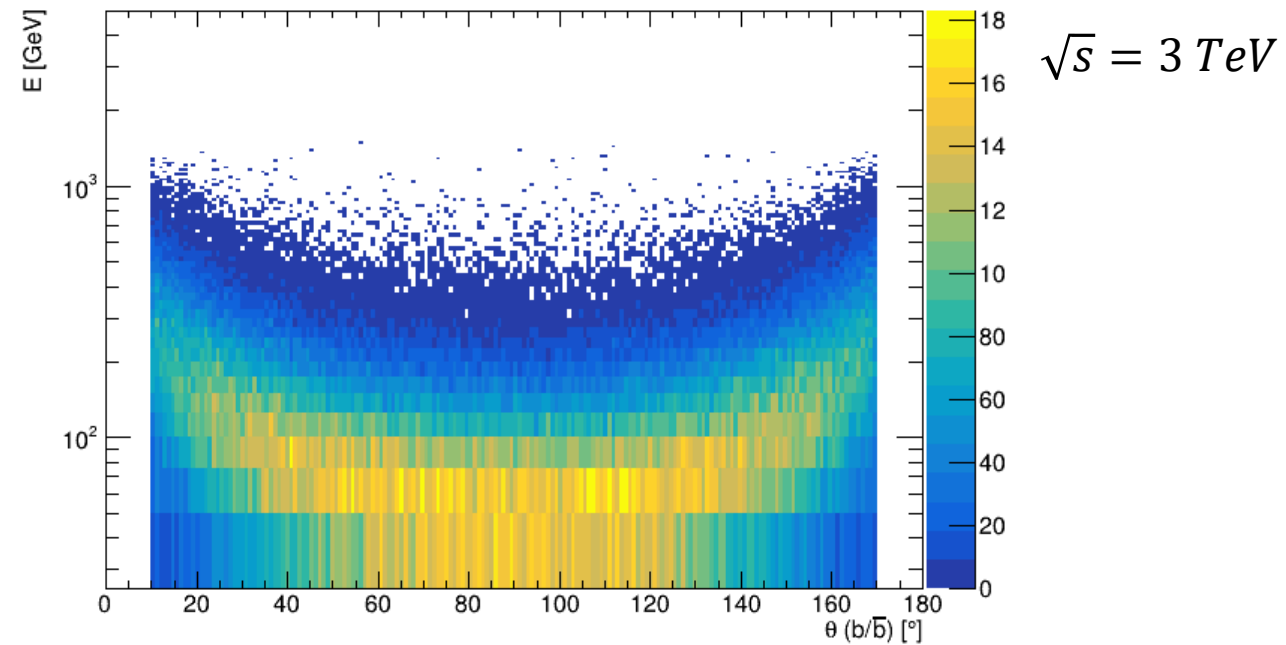
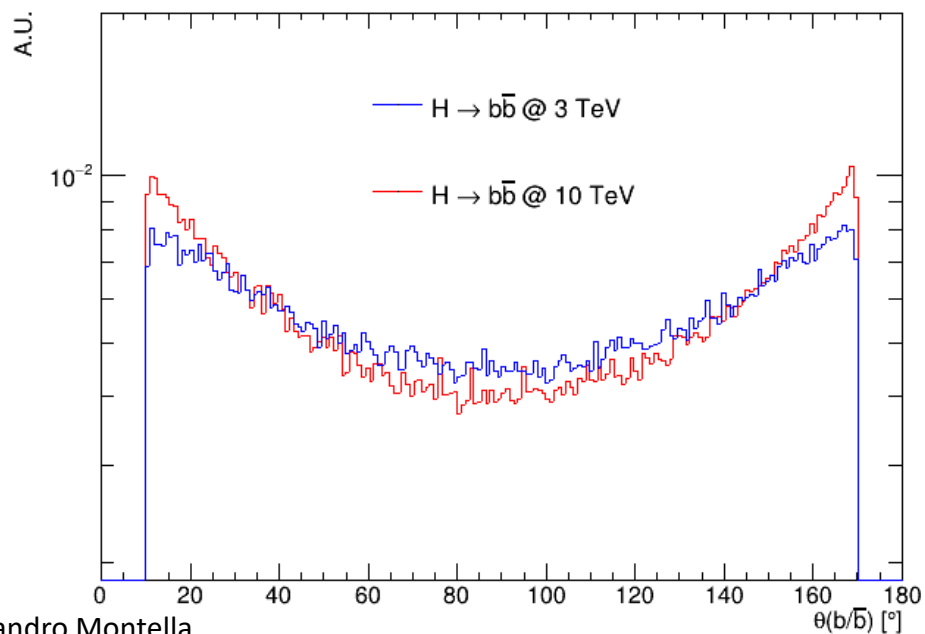
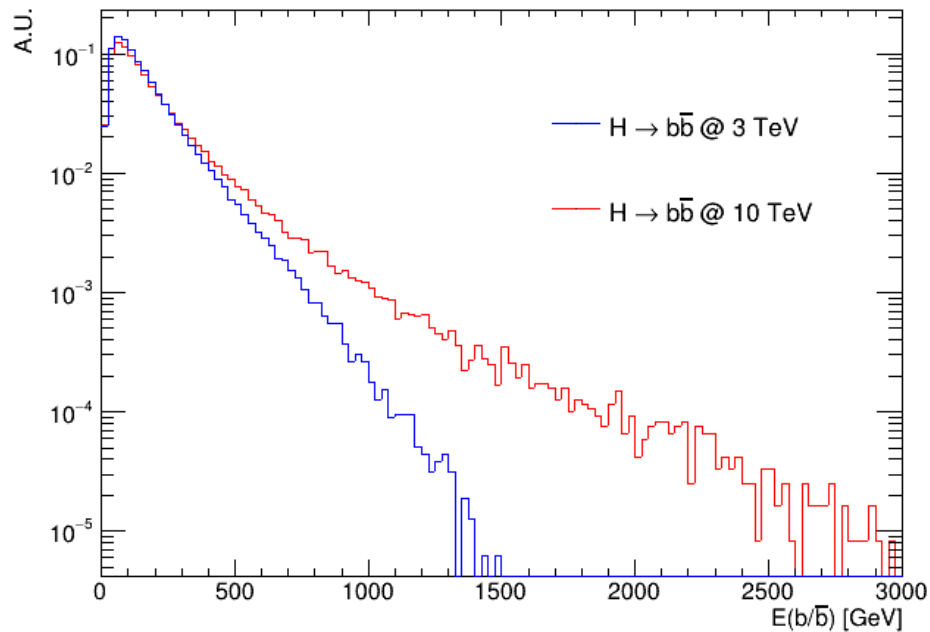
# Higgs: $E$ and $\theta$



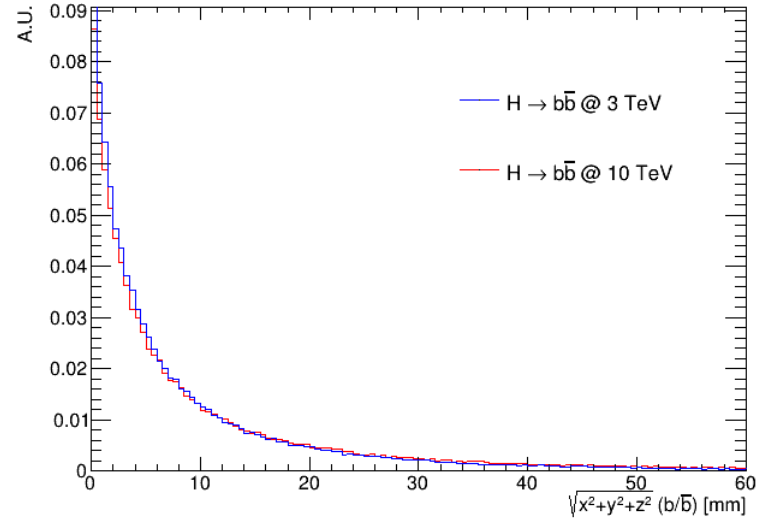
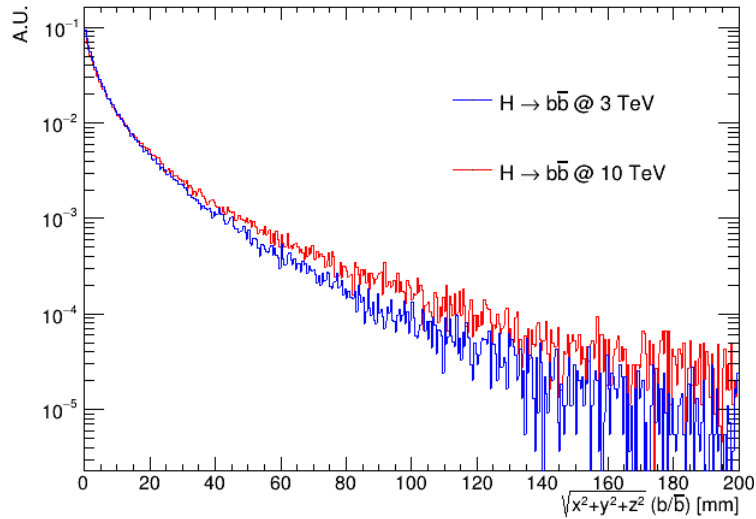
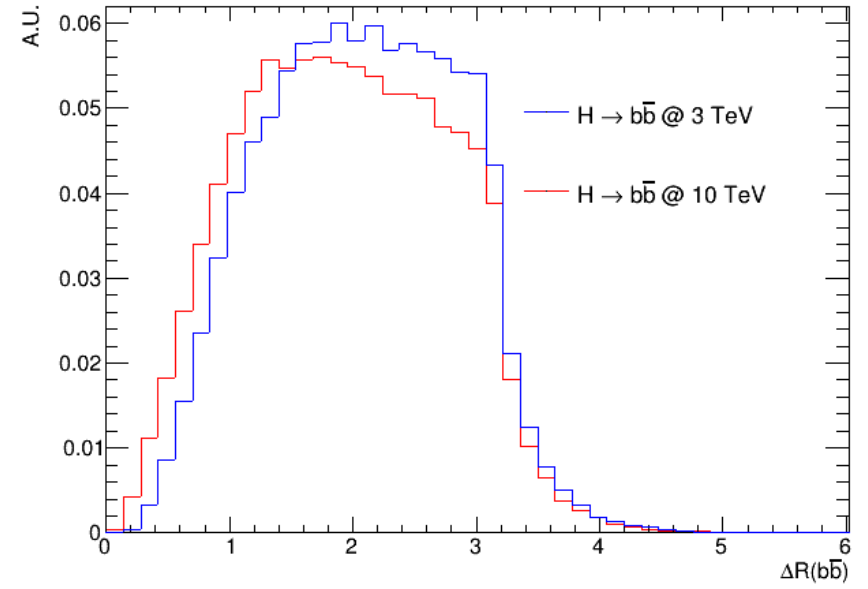
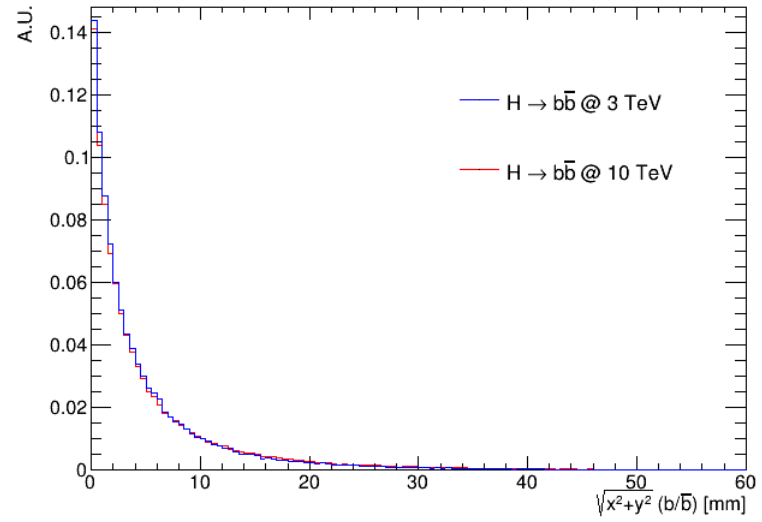
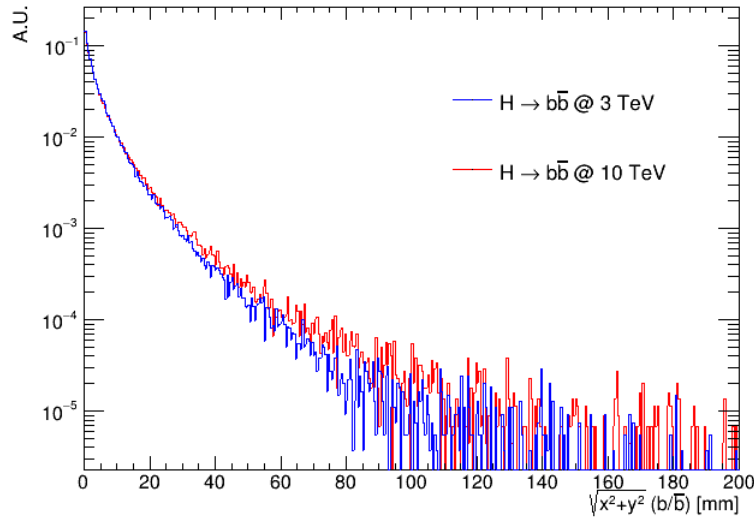
# b-quarks: $p_T$ and $p_z$



# b-quarks: $E$ and $\theta$



# b-quarks: b decay vertex and $\Delta R$

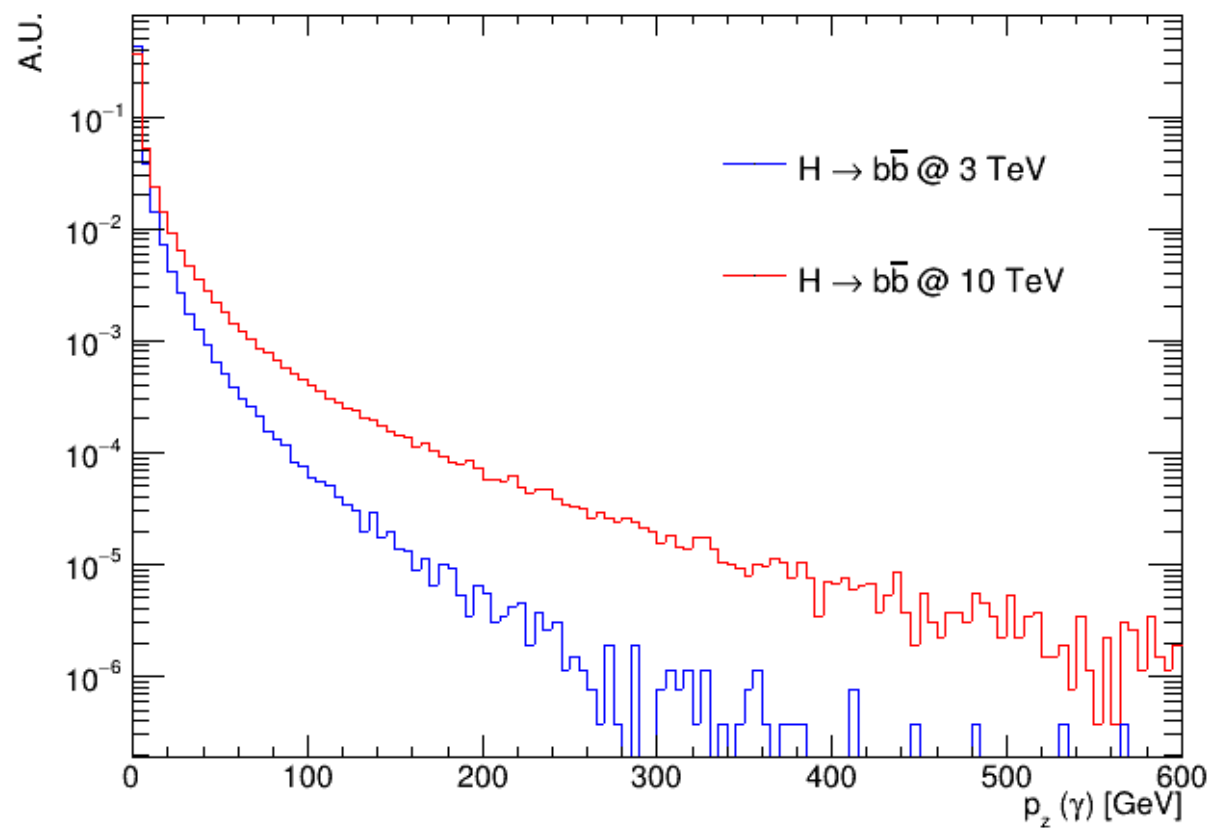
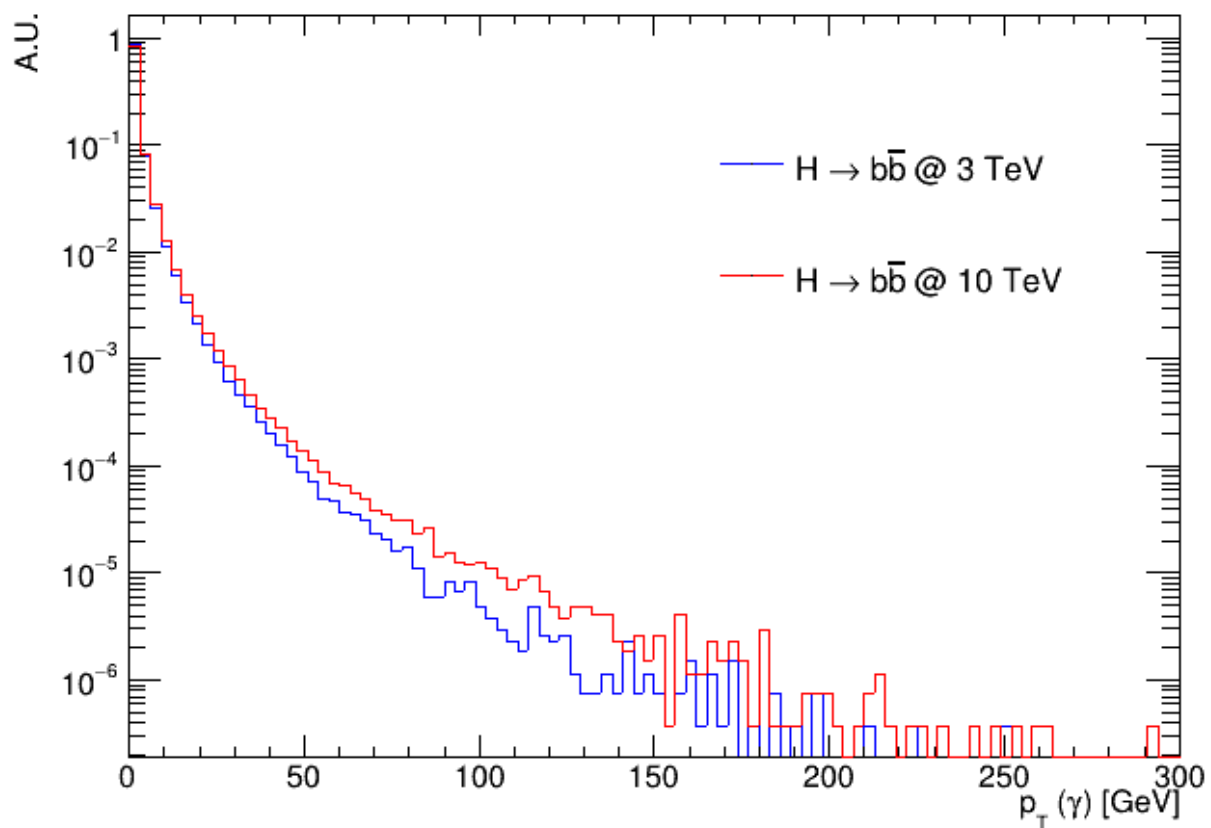


$$\mu^+ \mu^- \rightarrow H \nu_\mu \bar{\nu}_\mu,$$
$$H \rightarrow b \bar{b}$$

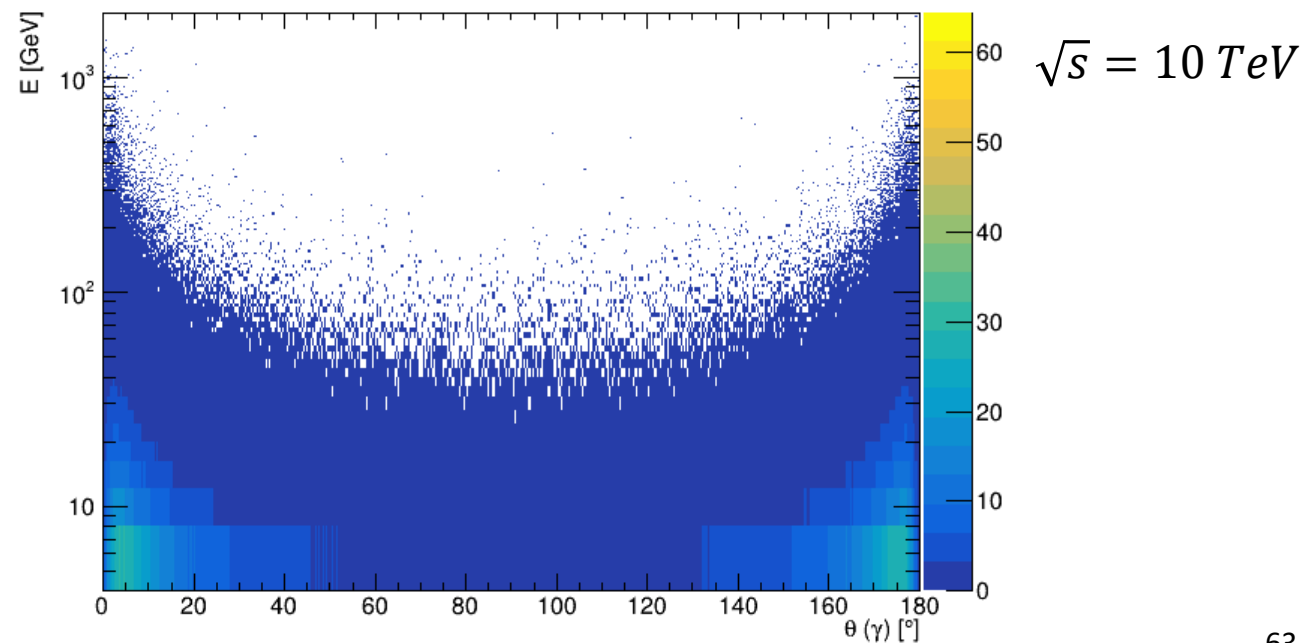
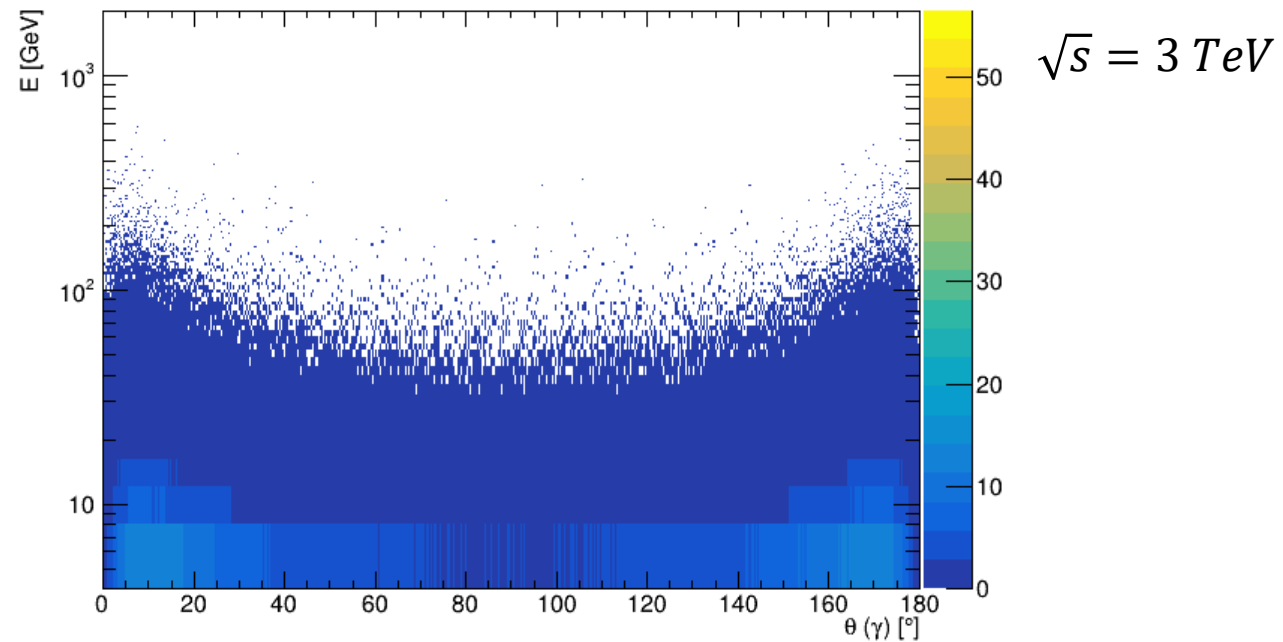
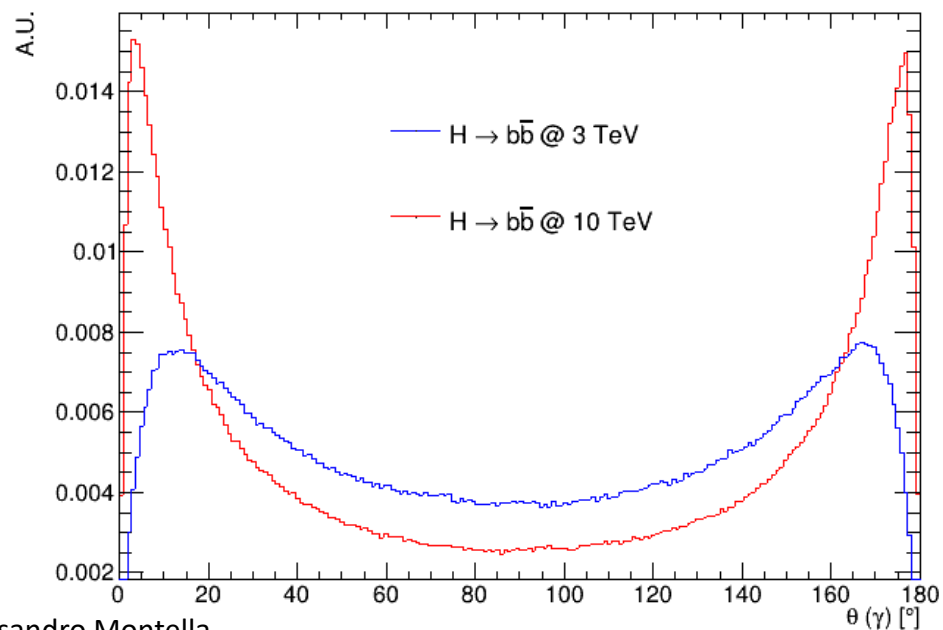
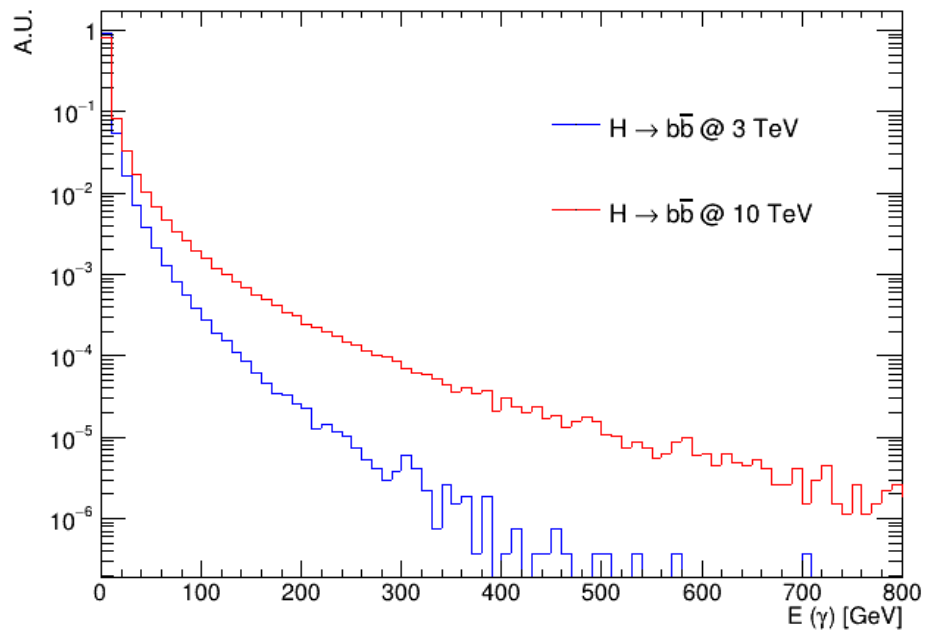
Other visible particles

$$\sqrt{s} = 3 \text{ TeV vs } \sqrt{s} = 10 \text{ TeV}$$

# Photons: $p_T$ and $p_z$

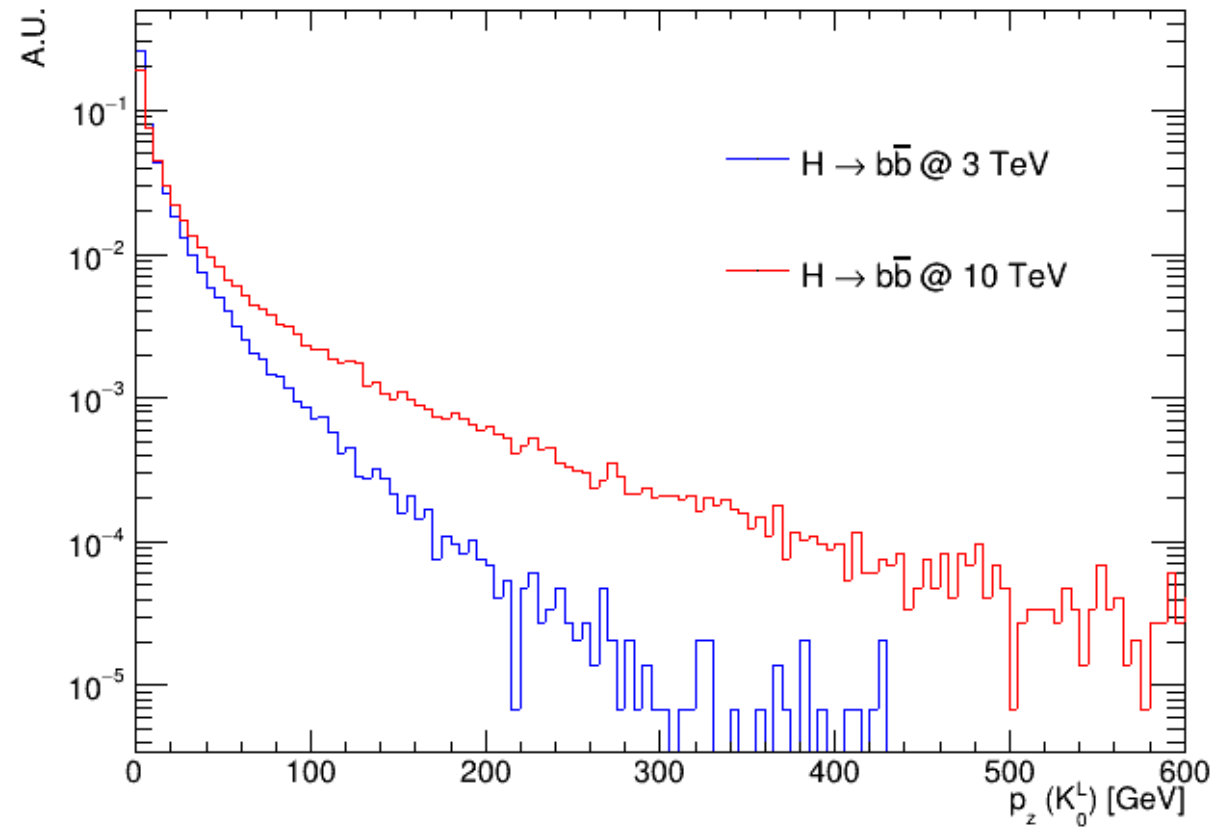
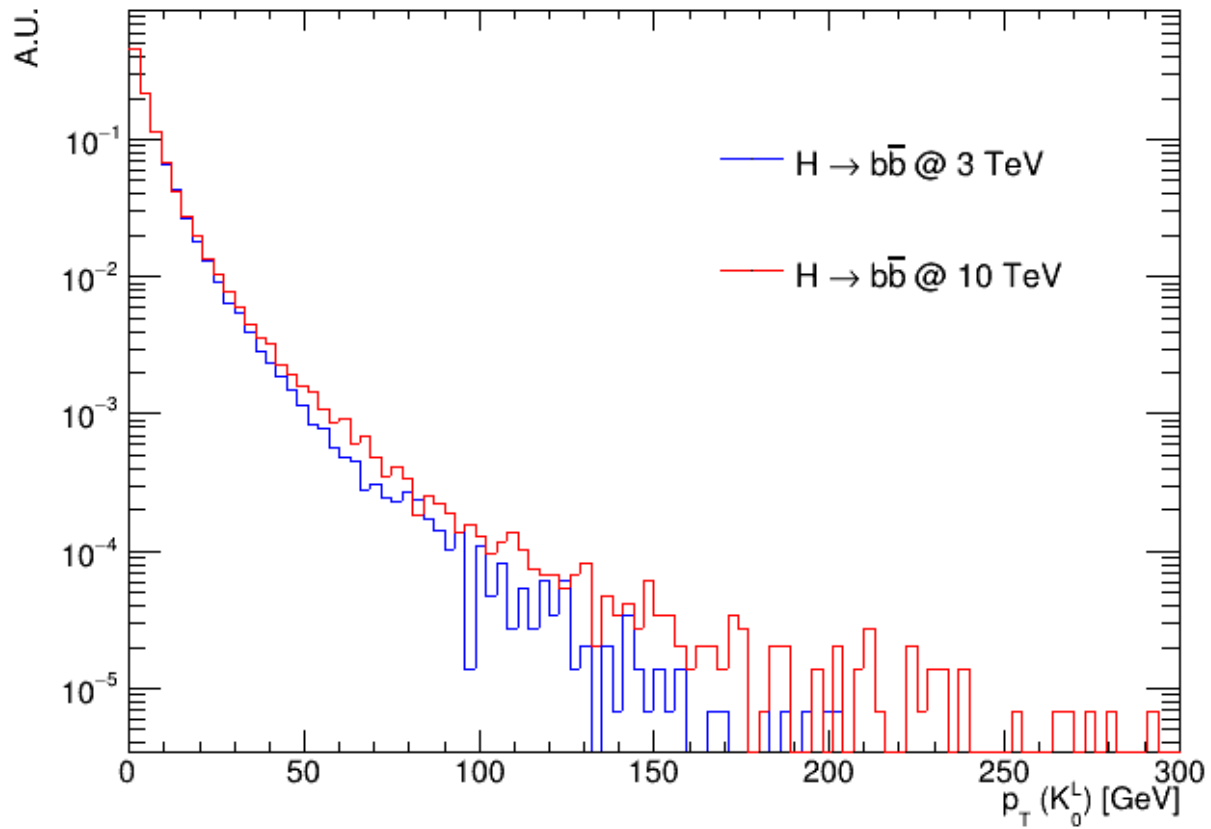


# Photons: $E$ and $\theta$

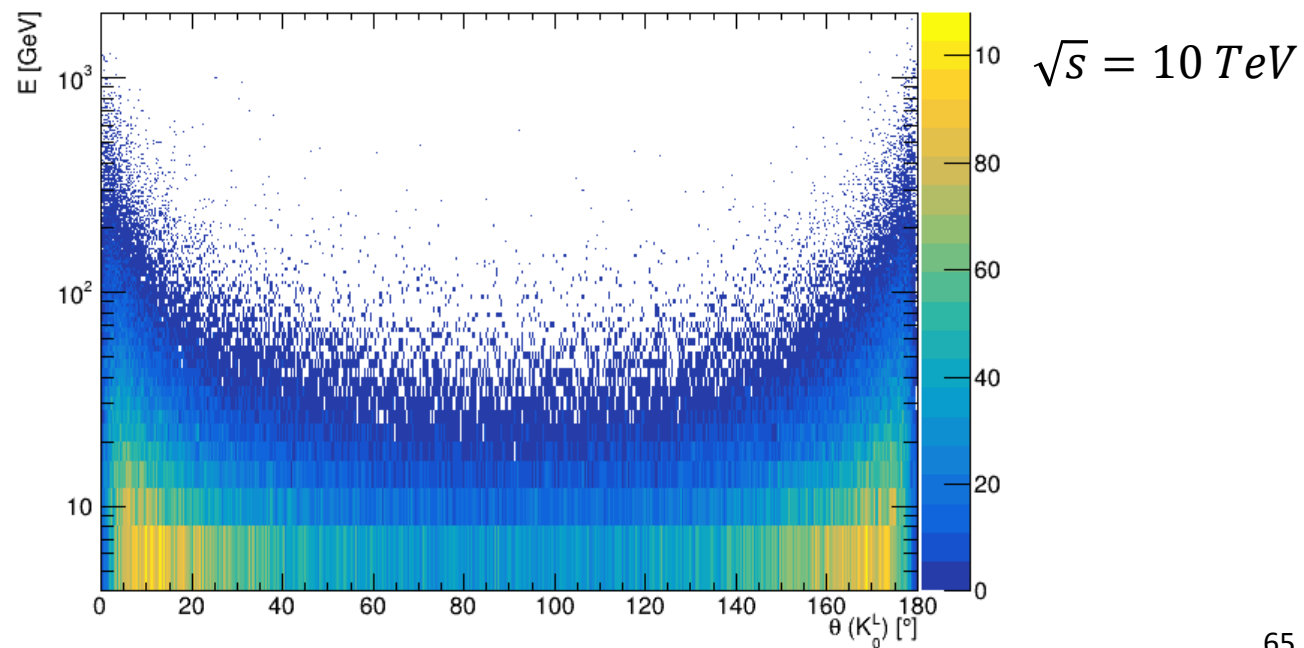
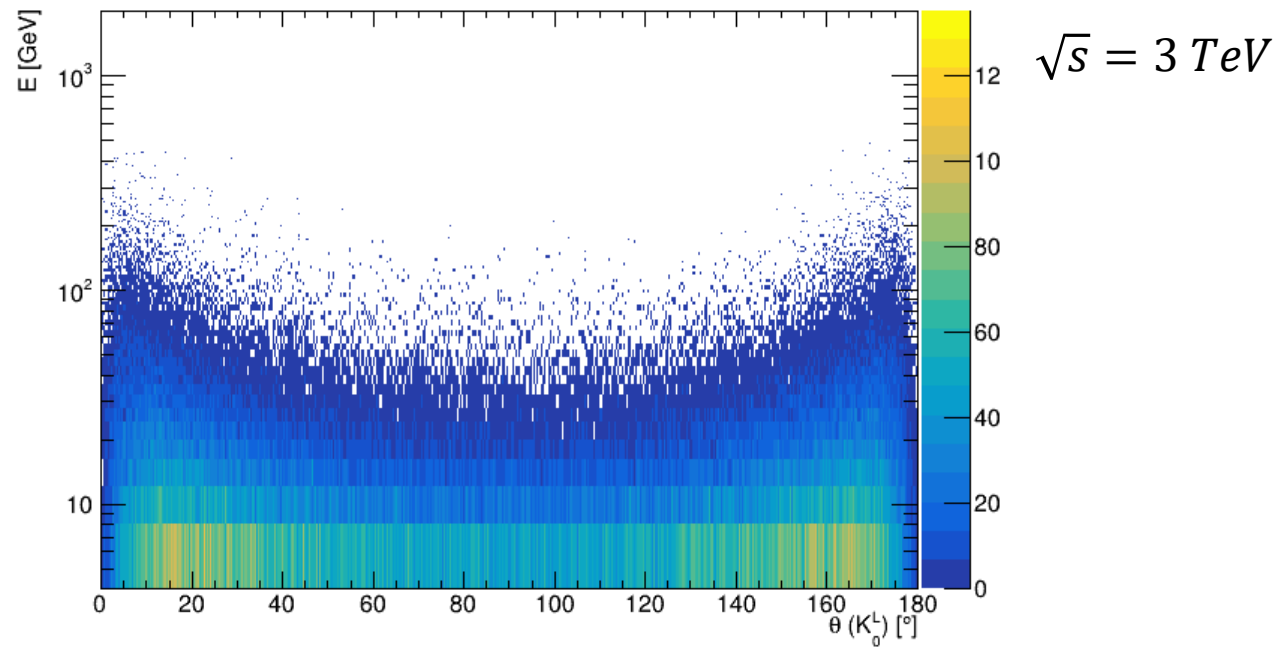
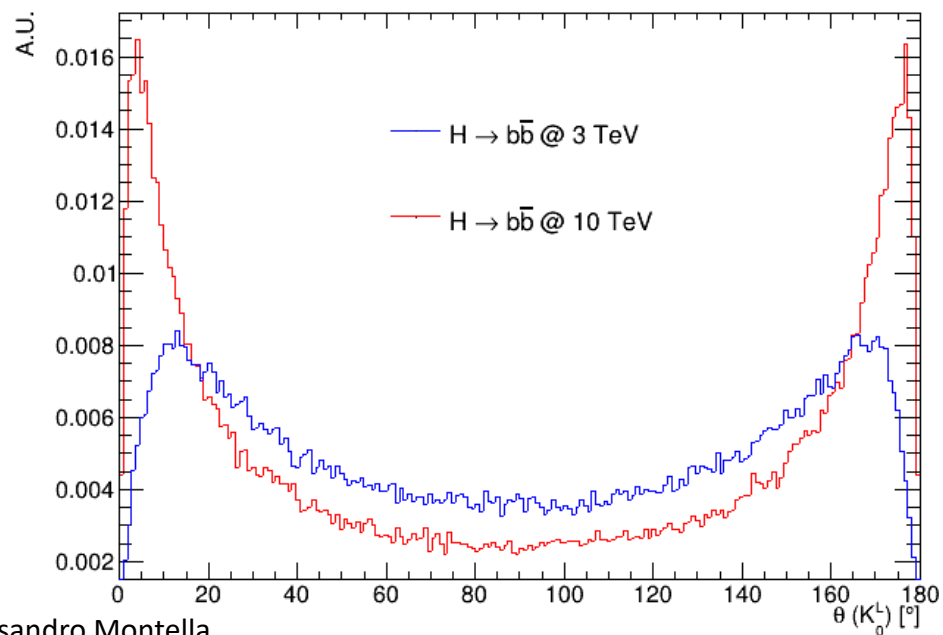
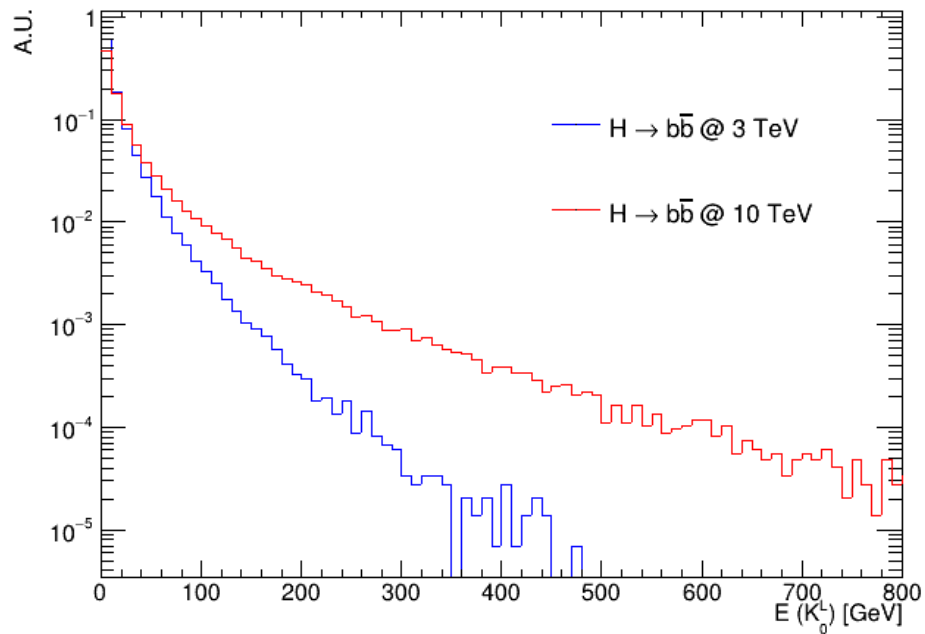




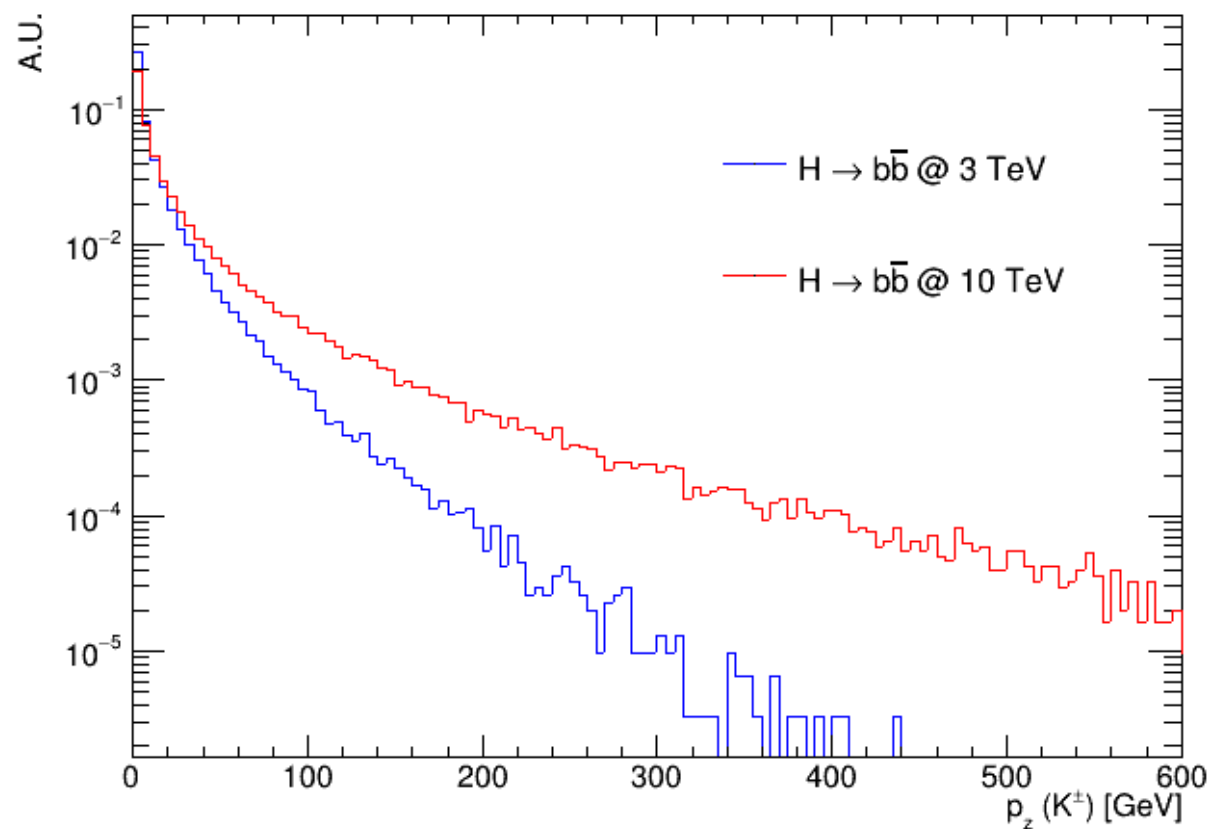
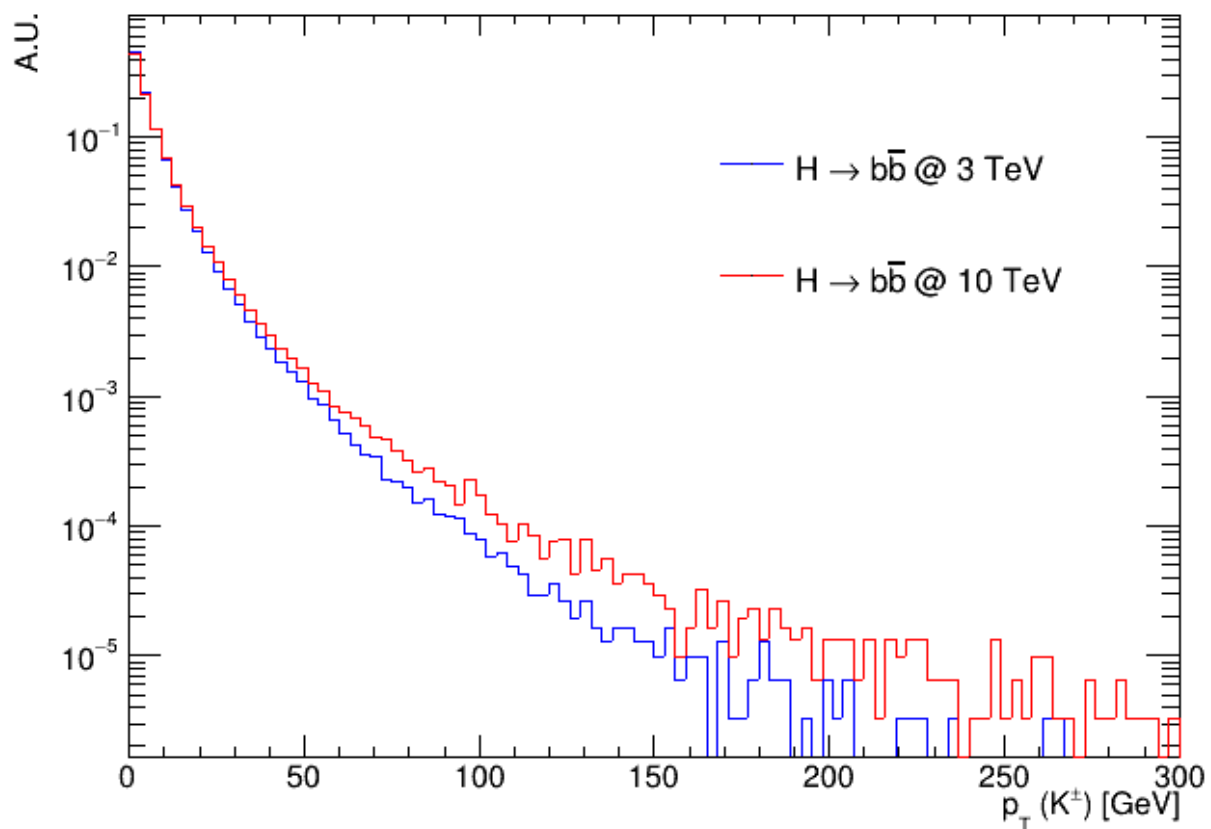
# Neutral kaons: $p_T$ and $p_z$



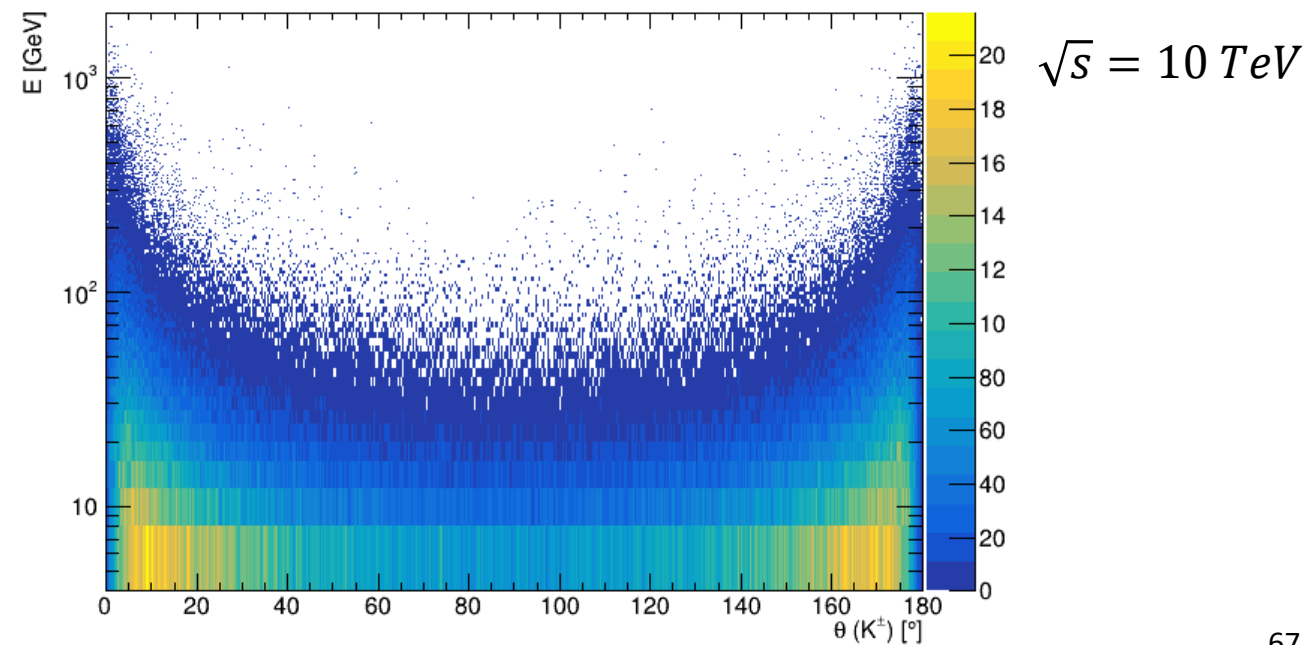
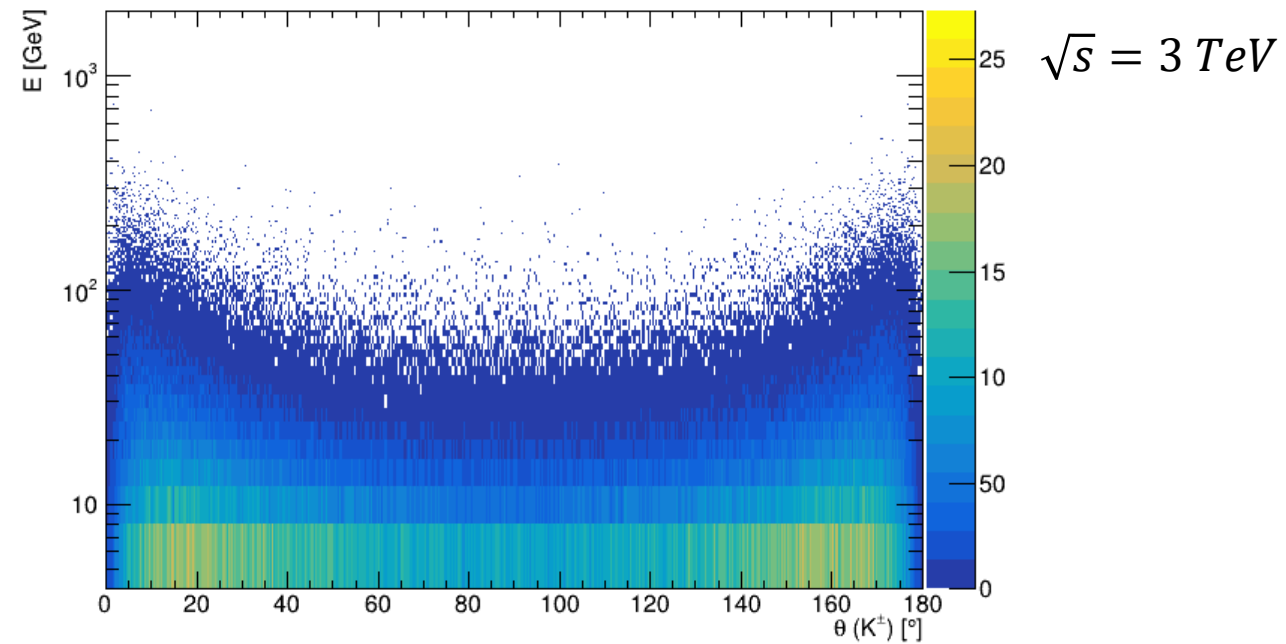
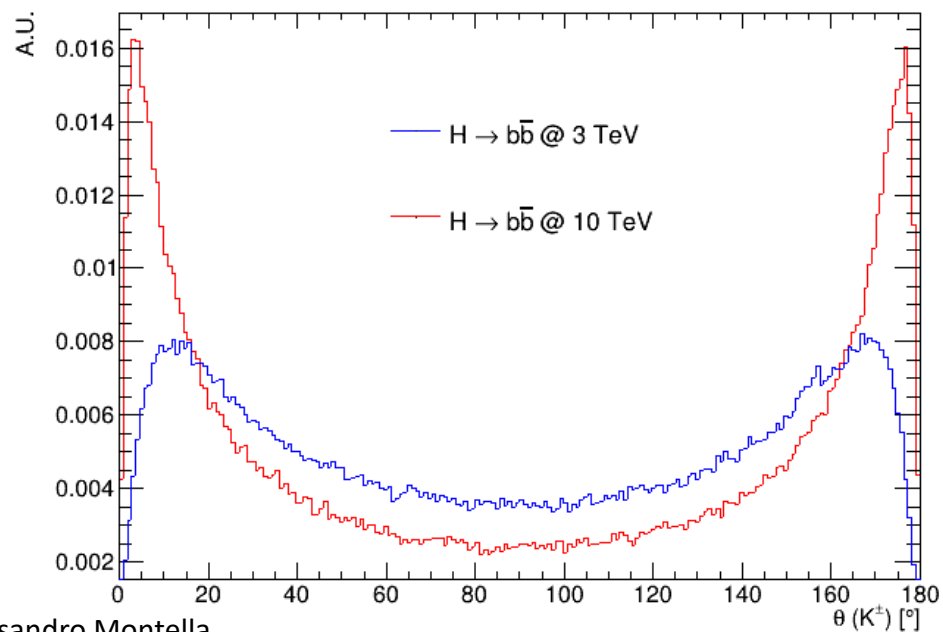
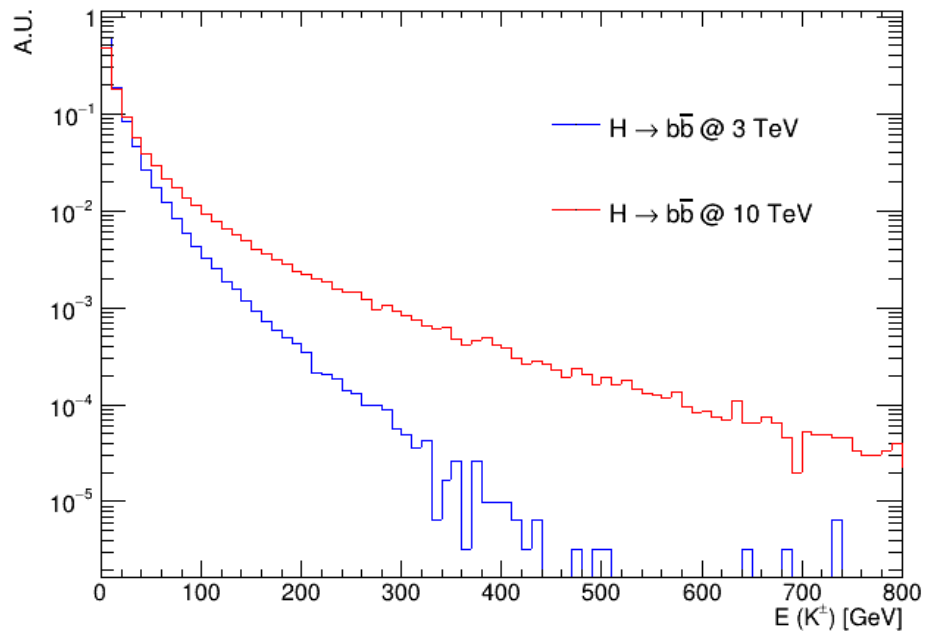
# Neutral kaons: $E$ and $\theta$



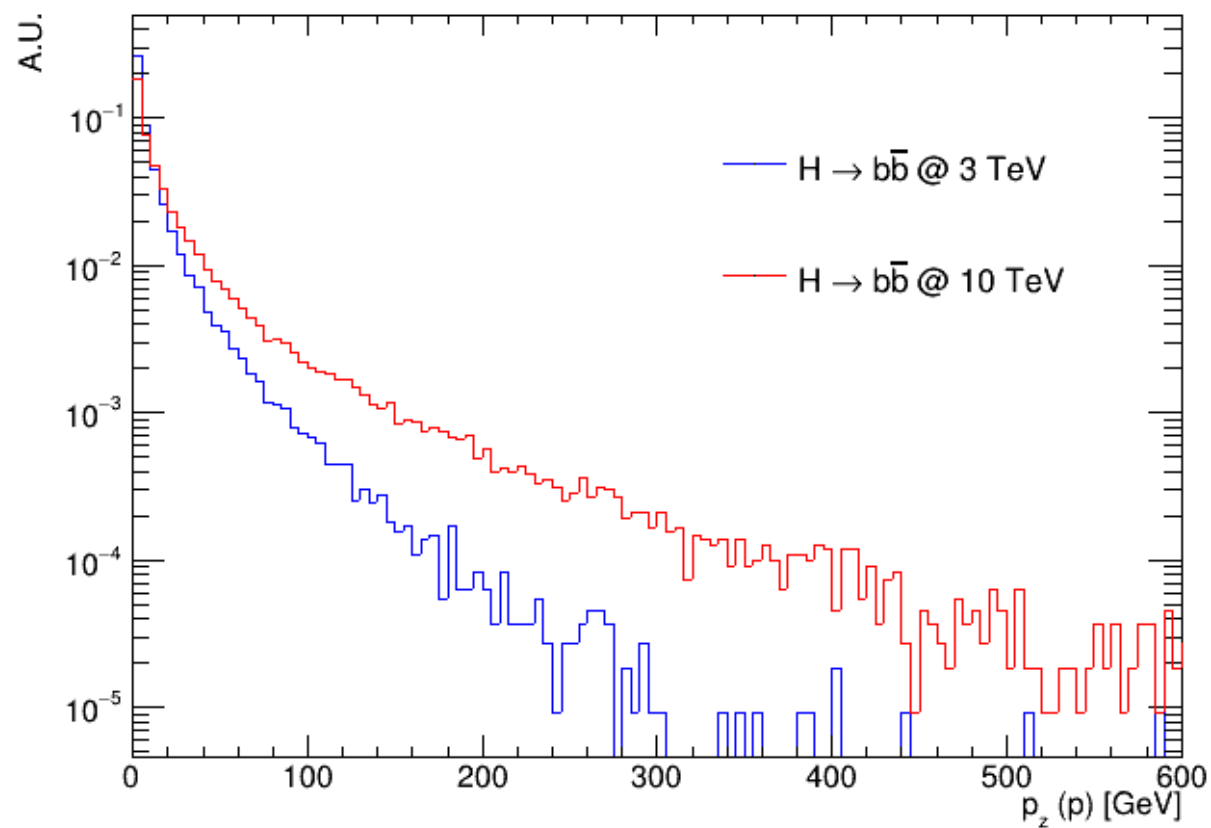
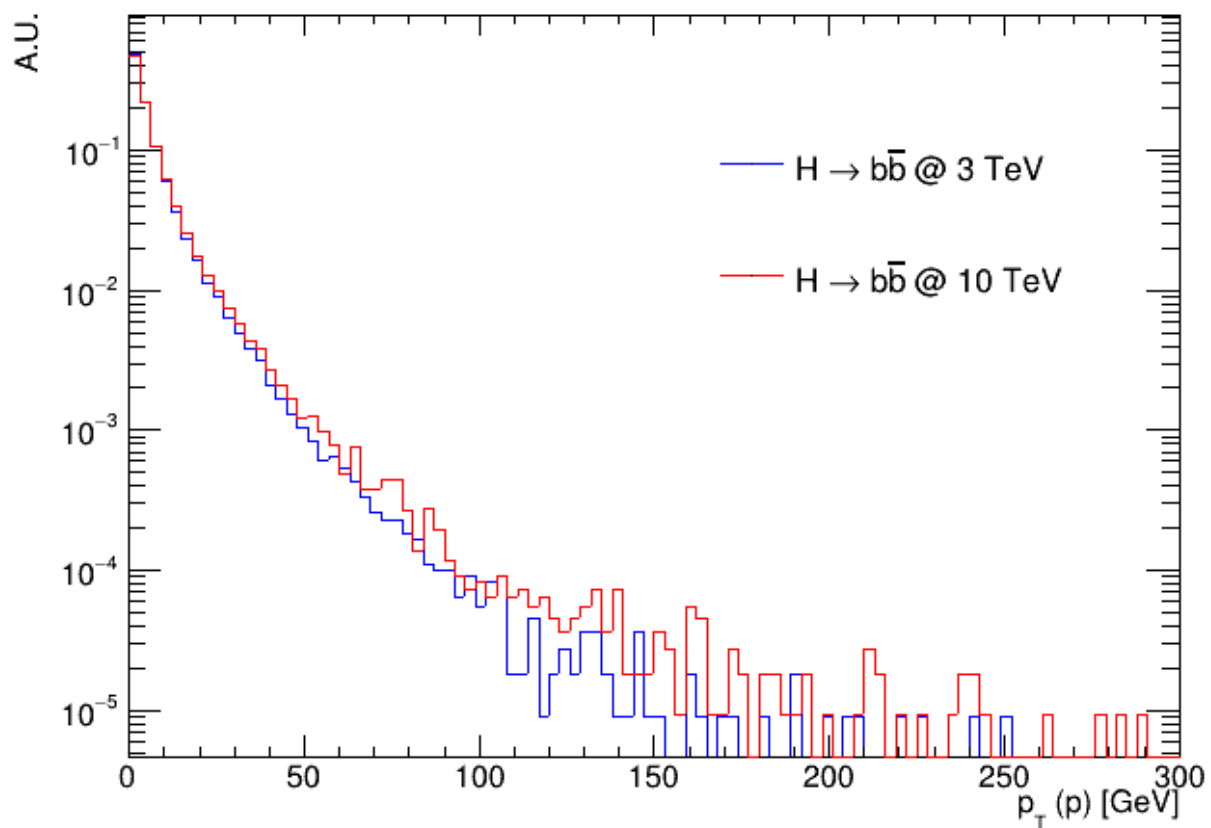
# Charged kaons: $p_T$ and $p_z$



# Charged kaons: $E$ and $\theta$



# Protons: $p_T$ and $p_z$



# Protons: $E$ and $\theta$

