

# VBS at the muon collider

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UNIVERSITY



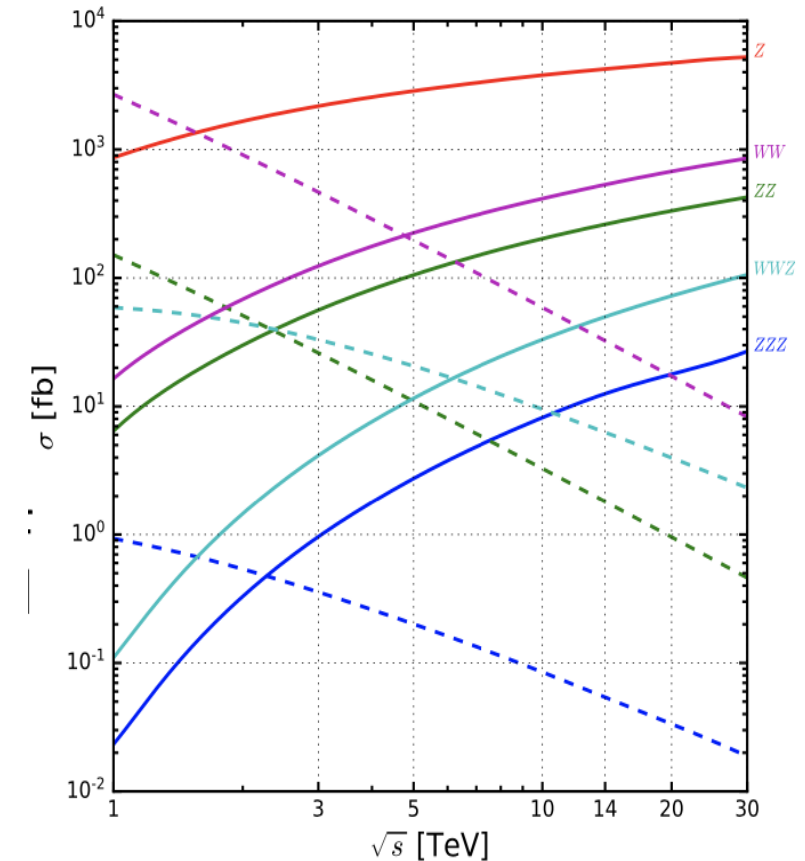
*The* UNIVERSITY of OKLAHOMA

 **Fermilab**

# Introduction

- VBS at high energy muon collider
  - Muon collider at few  $\sim$ TeV is a high luminosity boson collider
  - Production cross sections grow as logs while the corresponding s-channel decreases as  $1/s$

arXiv:2005.10289v2



Solid = VBF , Dashed = s-channel

# Objective

- To study aQGC in dimension-8 EFT framework.

|                                                                                                                                              | WWWW | WWZZ | WW $\gamma$ Z | WW $\gamma\gamma$ | ZZZZ | ZZZ $\gamma$ | ZZ $\gamma\gamma$ | Z $\gamma\gamma\gamma$ | $\gamma\gamma\gamma\gamma$ |
|----------------------------------------------------------------------------------------------------------------------------------------------|------|------|---------------|-------------------|------|--------------|-------------------|------------------------|----------------------------|
| <b>S</b> : Pure Higgs field, pure longitudinal<br>$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}$                                                     | ✓    | ✓    |               |                   | ✓    |              |                   |                        |                            |
| <b>M</b> : Mixed Higgs-field-strength, mixed long-transverse<br>$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,6}, \mathcal{O}_{M,7}$ | ✓    | ✓    | ✓             | ✓                 | ✓    | ✓            | ✓                 |                        |                            |
| $\mathcal{O}_{M,2}, \mathcal{O}_{M,3}, \mathcal{O}_{M,4}, \mathcal{O}_{M,5}$                                                                 |      | ✓    | ✓             | ✓                 | ✓    | ✓            | ✓                 |                        |                            |
| <b>T</b> : Pure field-strength tensor, pure transverse<br>$\mathcal{O}_{T,0}, \mathcal{O}_{T,1}, \mathcal{O}_{T,2}$                          | ✓    | ✓    | ✓             | ✓                 | ✓    | ✓            | ✓                 | ✓                      | ✓                          |
| $\mathcal{O}_{T,5}, \mathcal{O}_{T,6}, \mathcal{O}_{T,7}$                                                                                    |      | ✓    | ✓             | ✓                 | ✓    | ✓            | ✓                 | ✓                      | ✓                          |
| $\mathcal{O}_{T,8}, \mathcal{O}_{T,9}$                                                                                                       |      |      |               |                   | ✓    | ✓            | ✓                 | ✓                      | ✓                          |

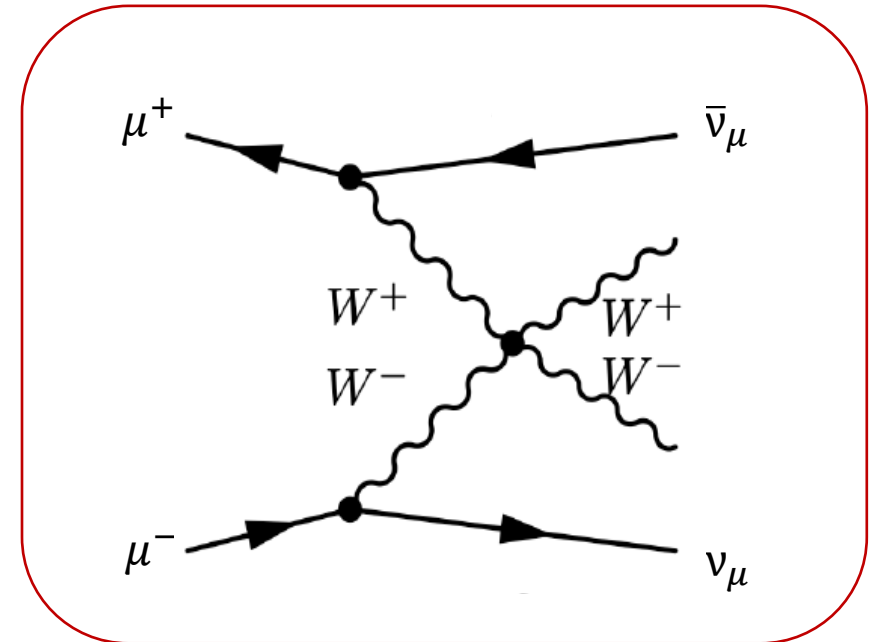
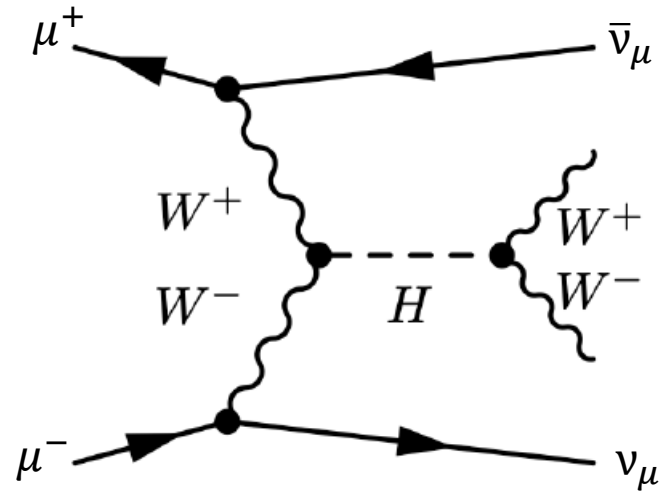
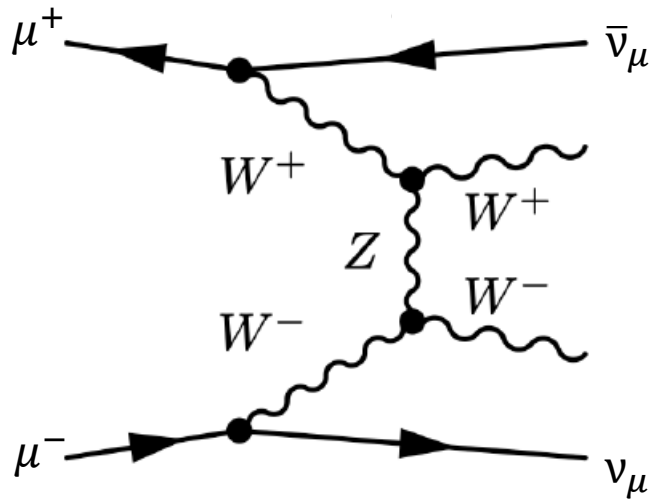
Allowed by SM

Image taken from: <https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/DIM8EFT>

# Sample Generation

- We have produced aQGC and SM background samples using both MadGraph and Whizard for 6 TeV and are working on validating.
- Used the latest muon-collider Delphes card:  
<https://github.com/delphes/delphes/tree/master/cards/MuonCollider>

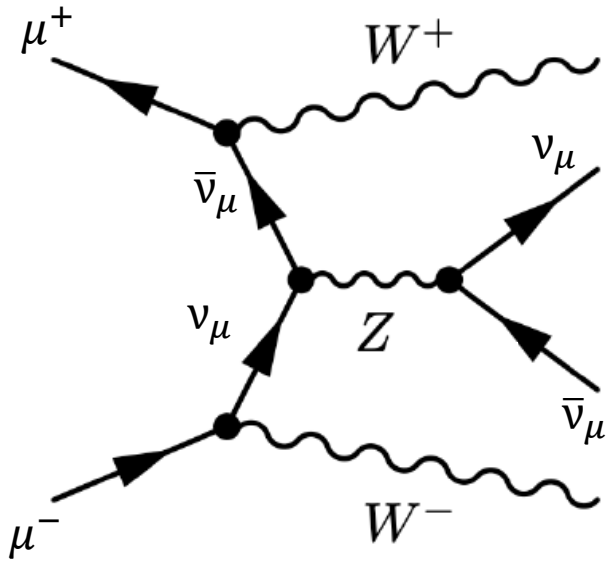
# VBS processes: $W^+W^- \nu \nu$



SM cross-section: 257.7 fb at  
6 TeV

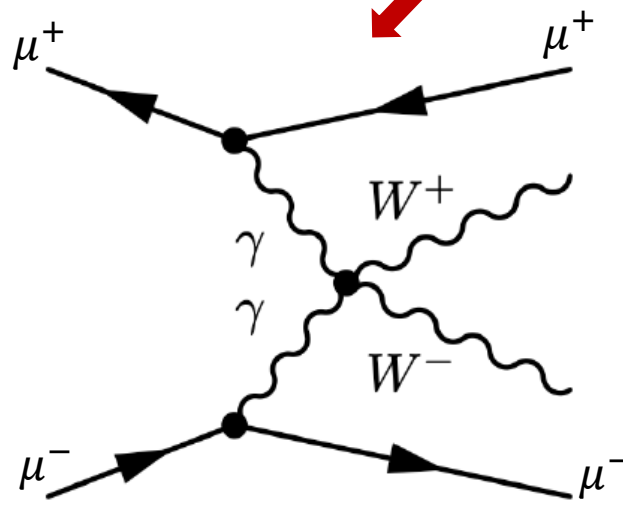
# Background processes:

photon-induced production



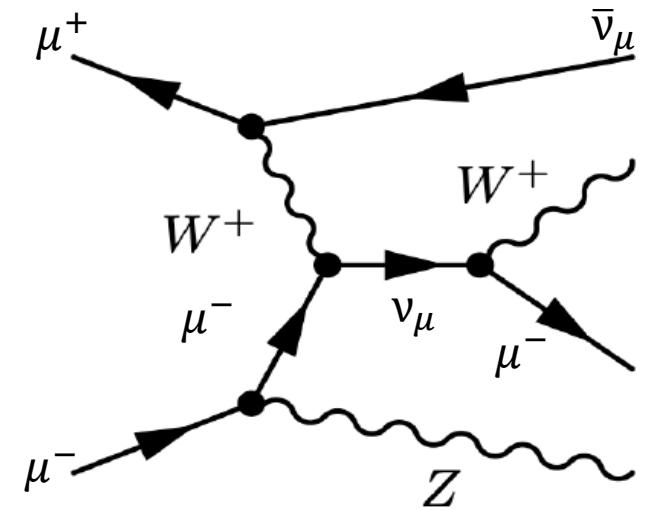
$W^+W^-(Z \rightarrow \nu \bar{\nu})$

Cross-section at 6 TeV: 3.6 fb



$W^+W^- \mu^+ \mu^-$

Cross-section at 6 TeV: 2795.3 fb



$W^+Z \mu^- \bar{\nu}_\mu$

Cross-section at 6 TeV: 283.2 fb

# SM Background Samples

- Generated using Whizard at 6 TeV
- Samples are in the Snowmass area ([login.snowmass21.io:/work/arapyan](https://login.snowmass21.io:/work/arapyan))
  - wpwm\_vbs\_6tev.root, 257.7 fb
  - wpwmz\_ztonunu\_6tev.root, 3.6 fb
  - wzmunu\_6tev.root, 283.2 fb
  - zzmumu\_6tev.root, 0.83 fb
  - ggwpwm\_6tev.root, 2795.3 fb

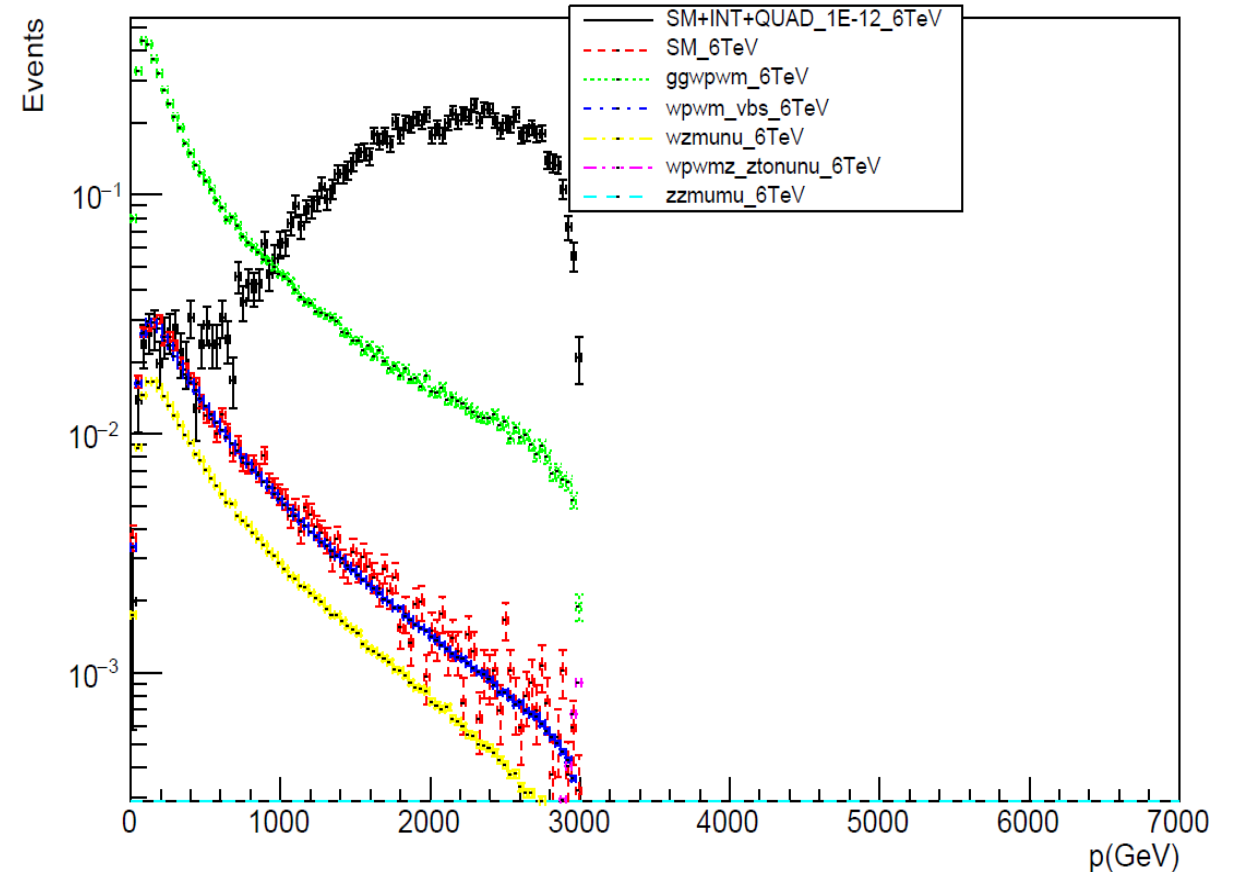
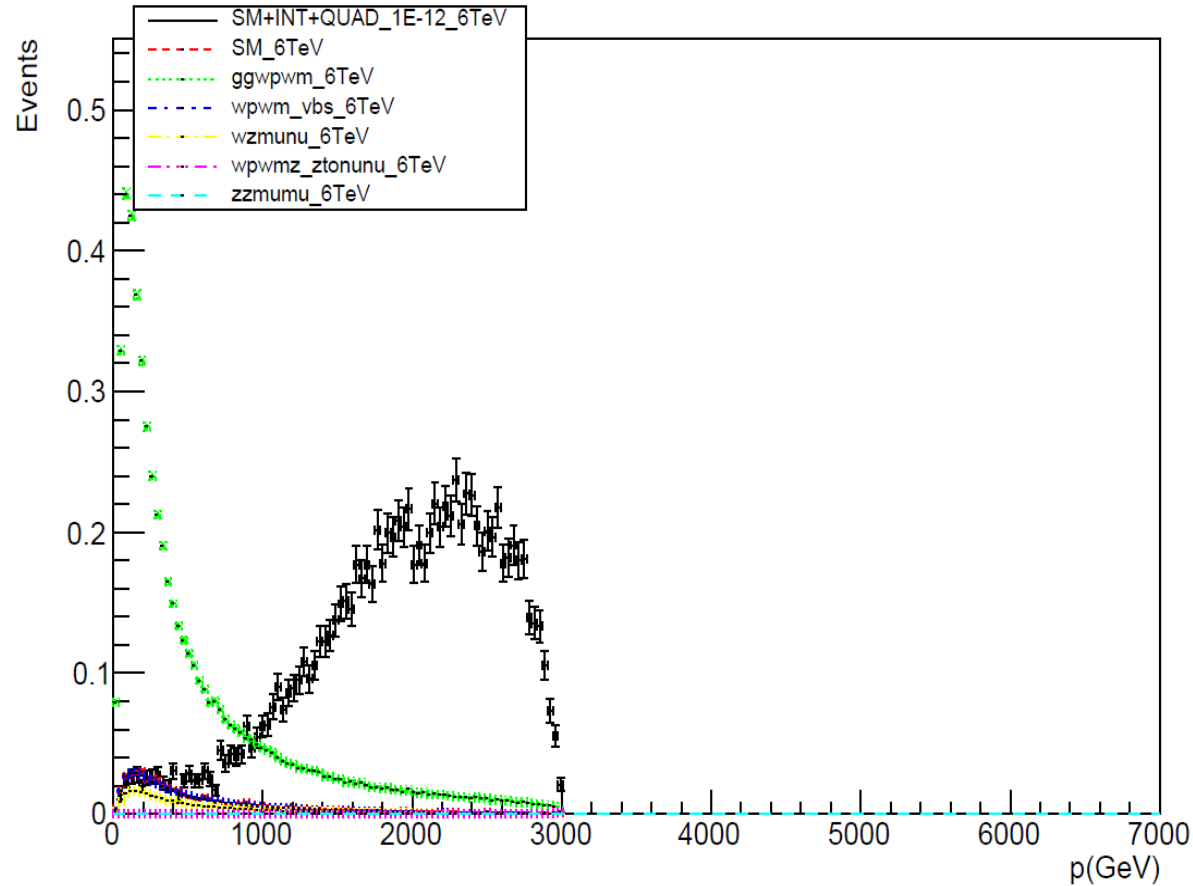
# Truth level plots

- We will first look at 6 TeV samples at truth level
- No selection applied
- Events are normalized using cross-section (pb) and assuming luminosity as  $1 \text{ pb}^{-1}$



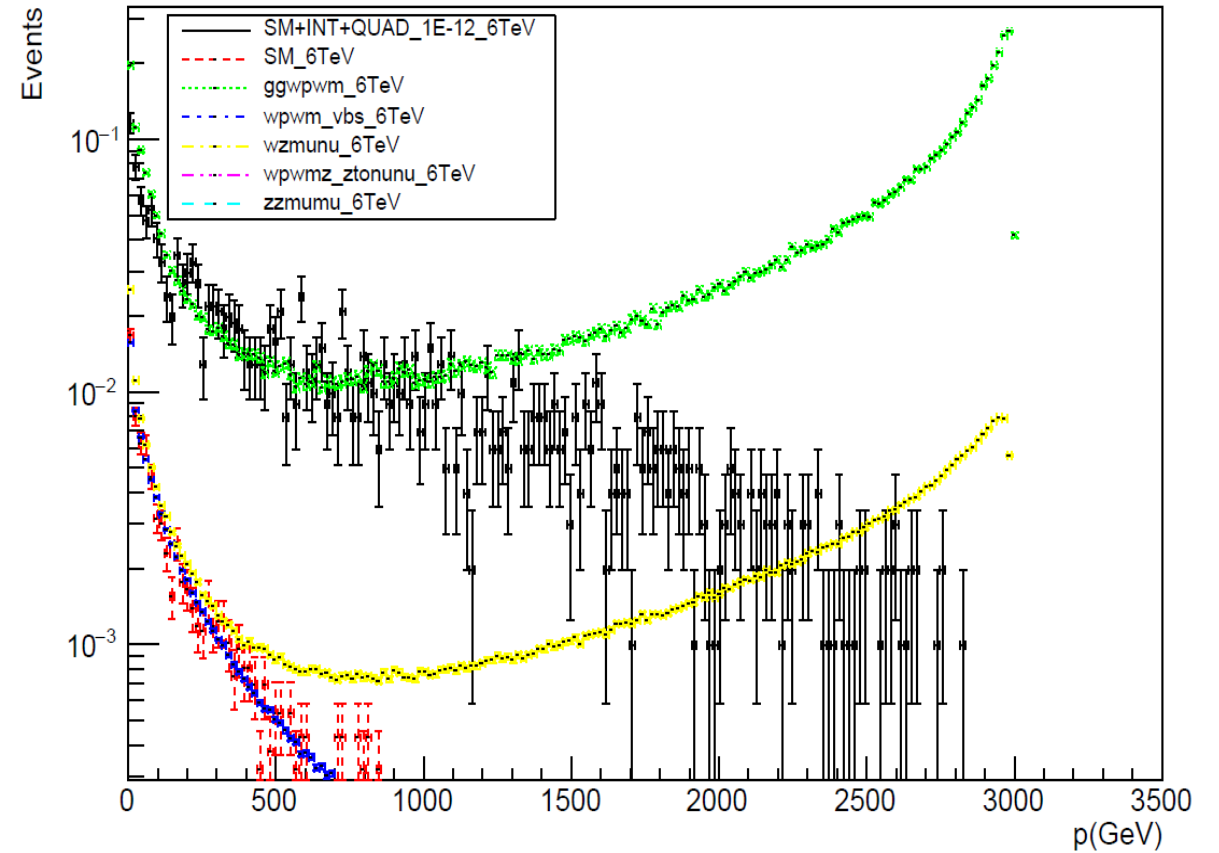
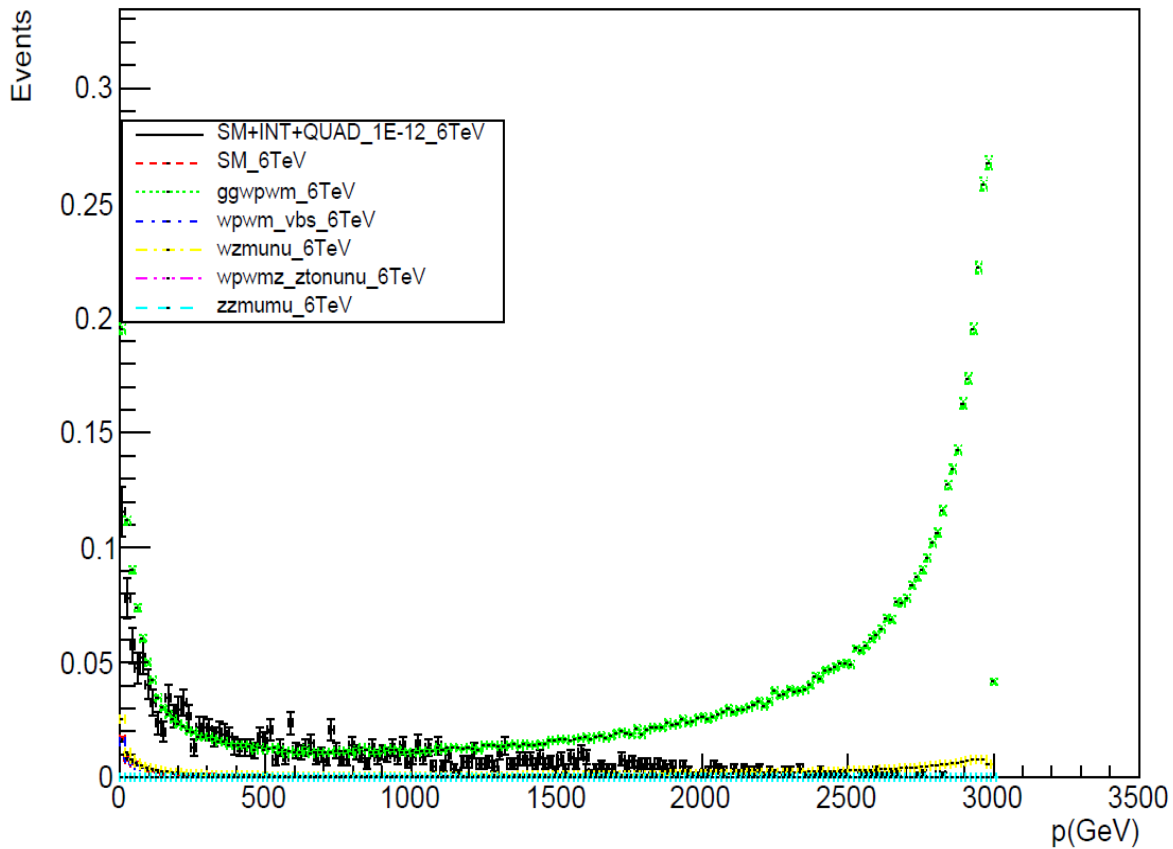
# Truth level momentum plot at 6 TeV

## W boson



# Truth level momentum plot at 6 TeV

## Muon



# Future work:

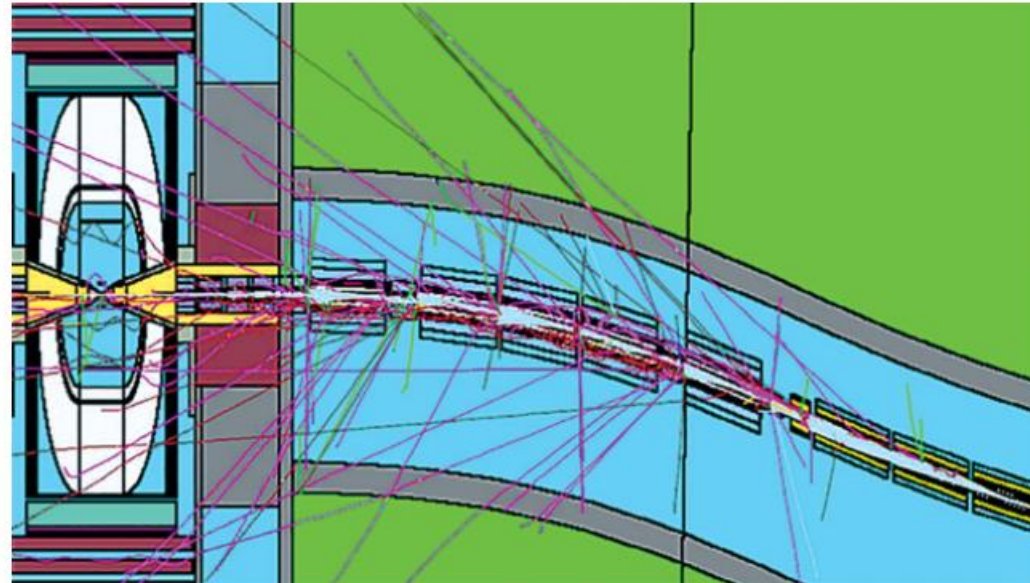
- Apply selections and look at both leptonic and hadronic final states.
- The hadronic final states will probably be more sensitive to the aQGCs we are studying here.
- To repeat the studies for 3 TeV, 10 TeV and 30 TeV.

# Backup slides

# Beam induced backgrounds

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- Large amount of beam induced backgrounds from muon decays
  - Depends on beam energy and on the design of interaction region
  - High occupancy in the first layers of detector tracking system->need to asses the detector performance
    - Dedicated LOI #234 to study the performance of reconstructed objects in the presence of beam induced backgrounds



# Sample generation using MadGraph

- **Generated samples for the WWWW vertex using the following commands for 3, 6 and 10 TeV using MadGraph.**

**1) SM: Did not load the aQGC model.**

```
generate mu+ mu- > w+ w- vm~ vm
```

**2) INT+QUAD:**

```
generate mu+ mu- > w+ w- vm~ vm QED=2 QCD=0 T1^2==1 S0=0 S1=0 M0=0 M1=0  
M6=0 M7=0 T0=0 T2=0
```

```
add process mu+ mu- > w+ w- vm~ vm QED=2 QCD=0 T1^2==2 S0=0 S1=0 M0=0 M1=0  
M6=0 M7=0 T0=0 T2=0
```


**3) FULL :**

```
generate mu+ mu- > w+ w- vm~ vm T1=1 S0=0 S1=0 M0=0 M1=0 M6=0 M7=0 T0=0  
T2=0
```


- **The parameters used in the commands above are those affecting to the WWWW vertex.**

# Final States

aQGCs

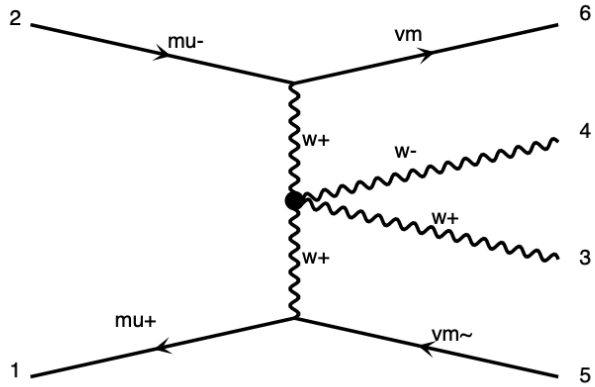


|           | WWWW        | WWZZ        | WWZ $\gamma$     | WW $\gamma\gamma$    |  | N_Z | N_centralLeptons | N_forwardMuons | N_ $\gamma$ | missing p                      |
|-----------|-------------|-------------|------------------|----------------------|--|-----|------------------|----------------|-------------|--------------------------------|
| VBS       | WW $\nu\nu$ |             |                  |                      |  | 0   | 2                | 0              | 0           | p<br><br><br><br><br><br><br>✓ |
|           |             | WW $\mu\mu$ | WW $\mu\mu$      | WW $\mu\mu$          |  | 0   | 2                | 2              | 0           |                                |
|           |             | WZ $\mu\nu$ | WZ $\mu\nu$      |                      |  | 1   | 3                | 1              | 0           |                                |
|           |             |             | W $\gamma\mu\nu$ | W $\gamma\mu\nu$     |  | 0   | 1                | 1              | 1           |                                |
|           |             | ZZ $\nu\nu$ |                  |                      |  | 2   | 4                | 0              | 0           |                                |
|           |             |             | Z $\gamma\nu\nu$ |                      |  | 1   | 2                | 0              | 1           |                                |
|           |             |             |                  | $\gamma\gamma\nu\nu$ |  | 0   | 0                | 0              | 2           |                                |
| s-channel |             | WWZ         | WWZ              |                      |  | 1   | 4                | 0              | 0           |                                |
|           |             |             | WW $\gamma$      | WW $\gamma$          |  | 0   | 2                | 0              | 1           |                                |

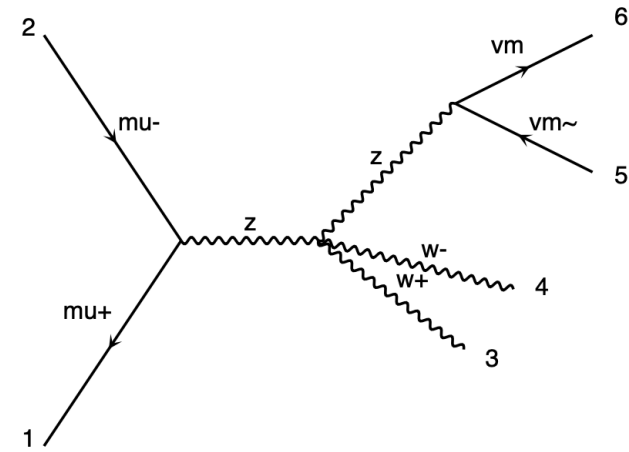


each row unique

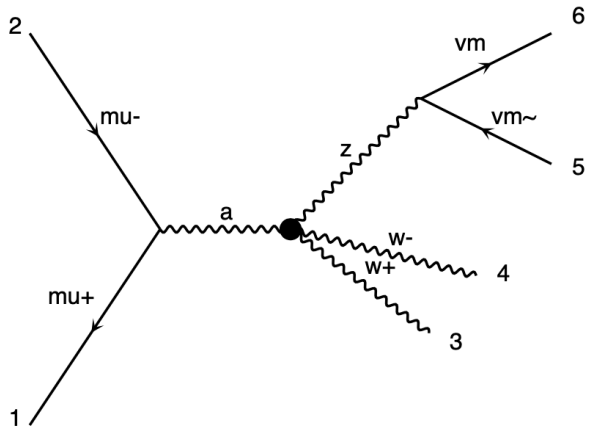
# Feynman Diagrams



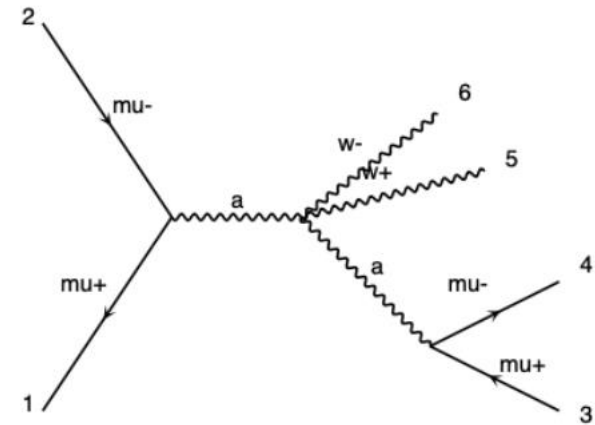
WWWW



WWZZ



WWγZ

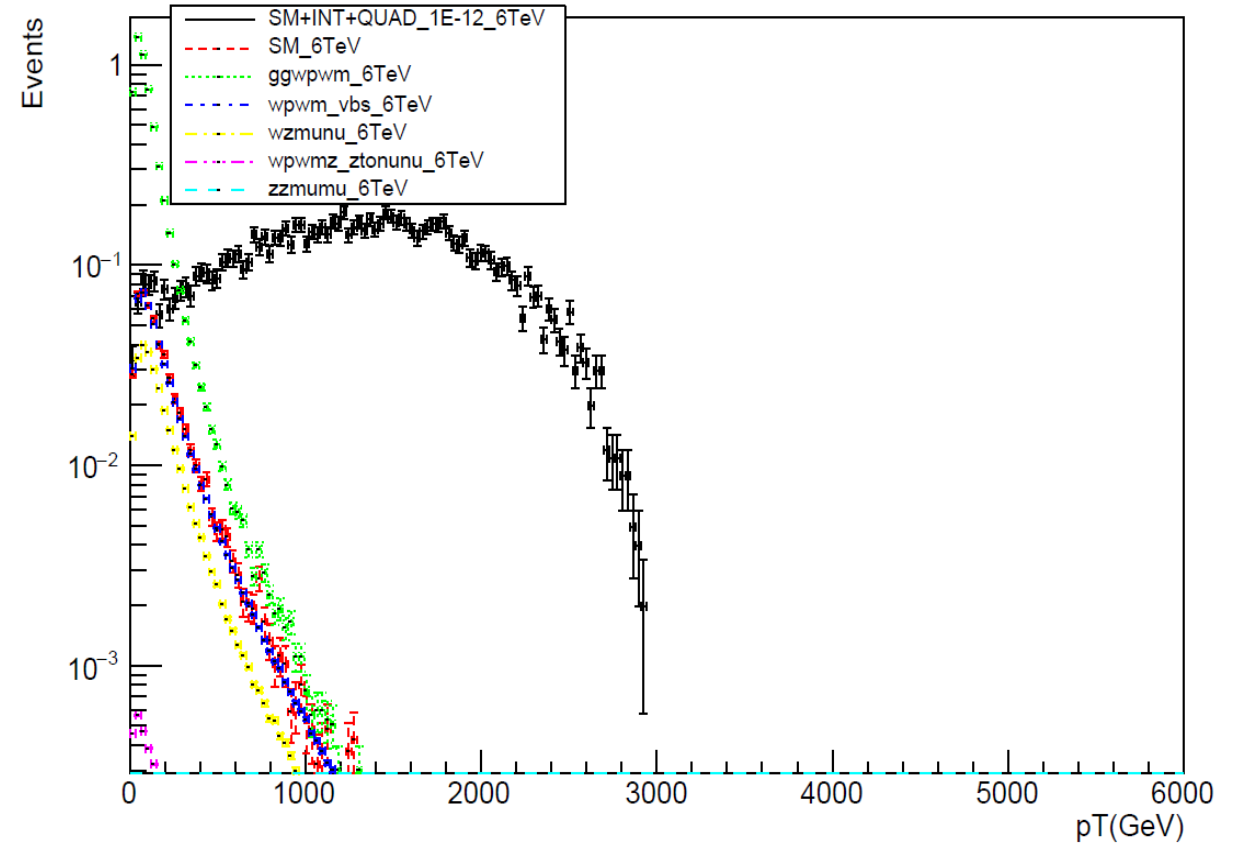
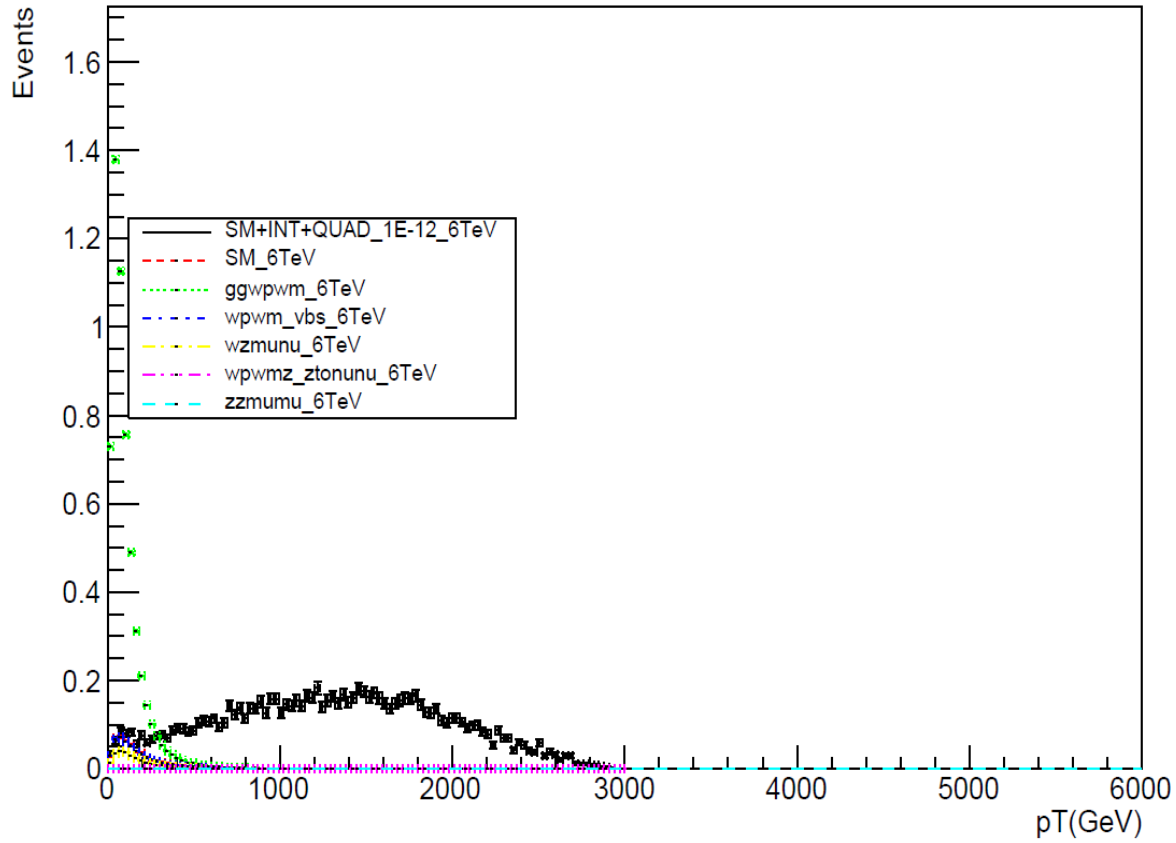


WWγγ



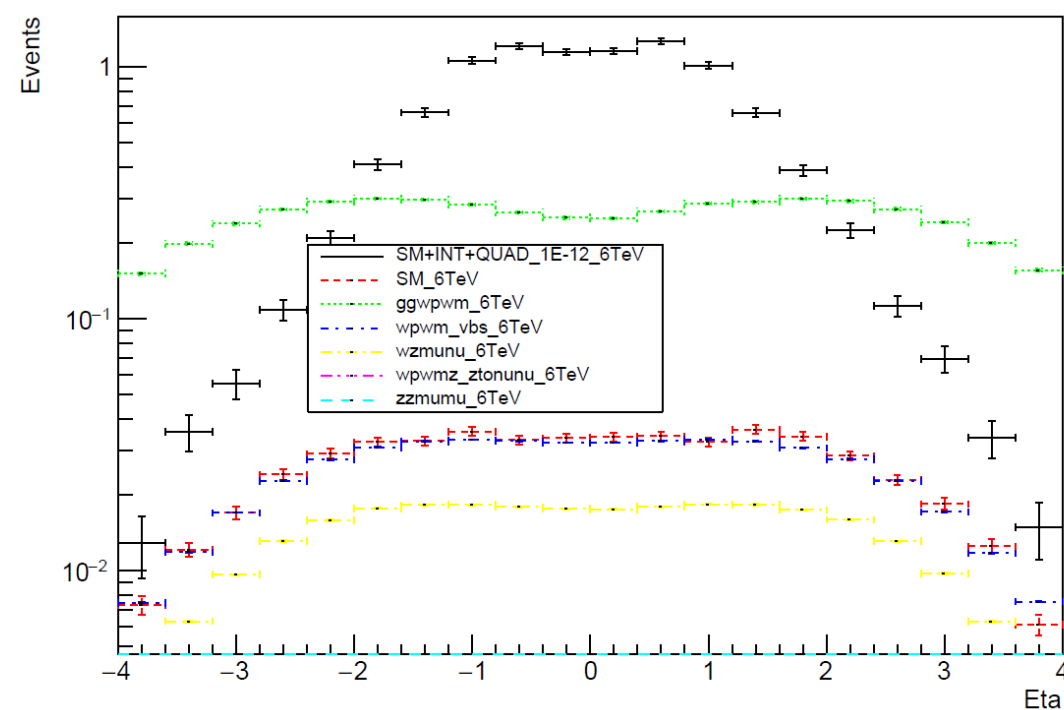
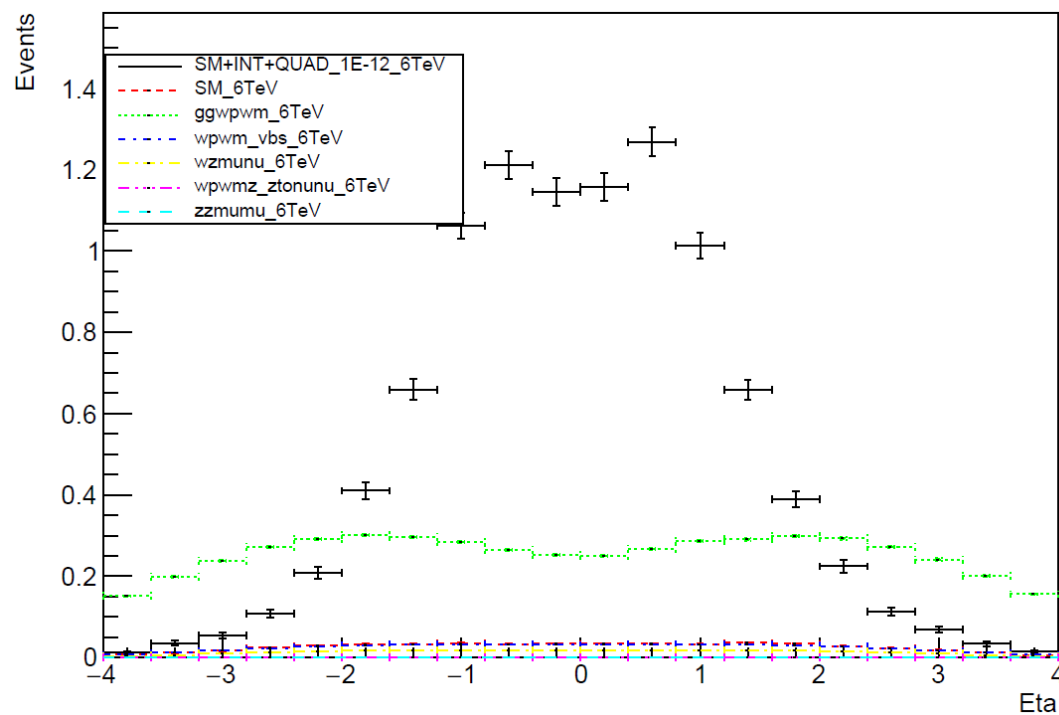
# Truth level pT plots

## W boson



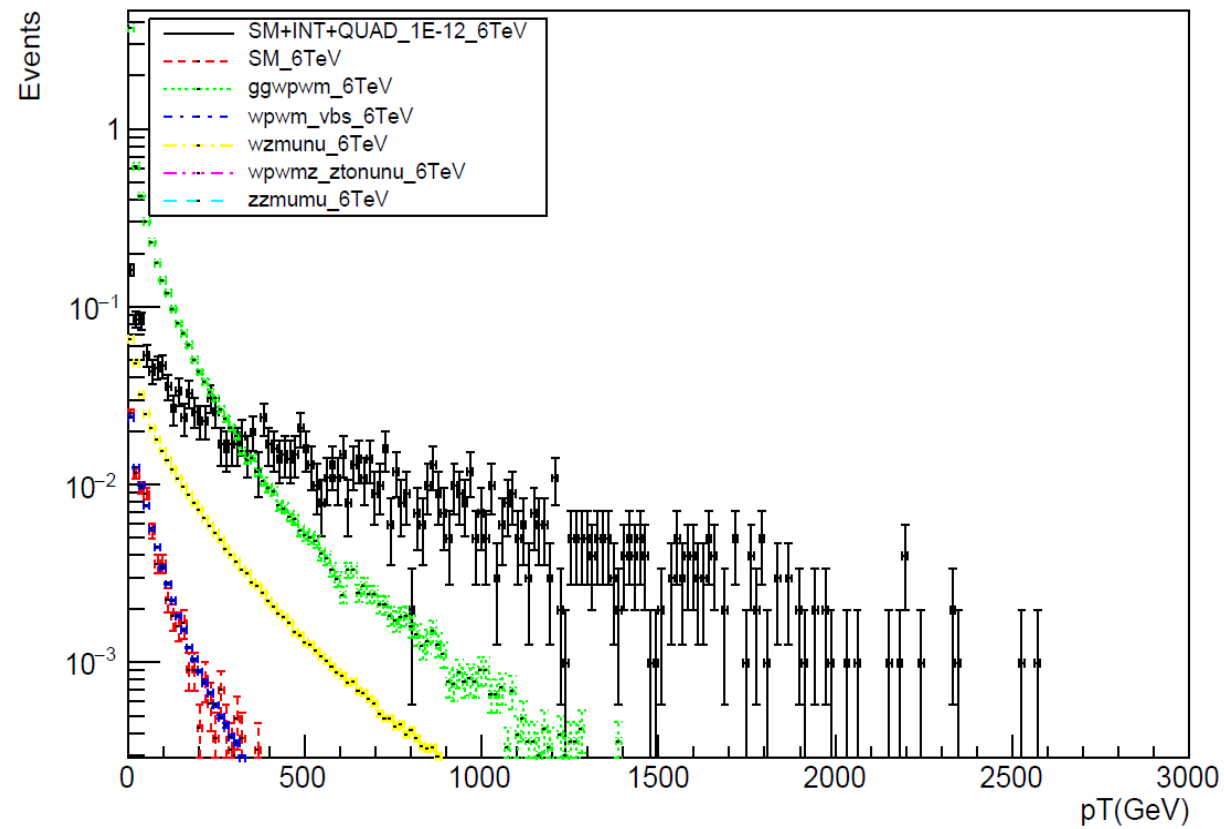
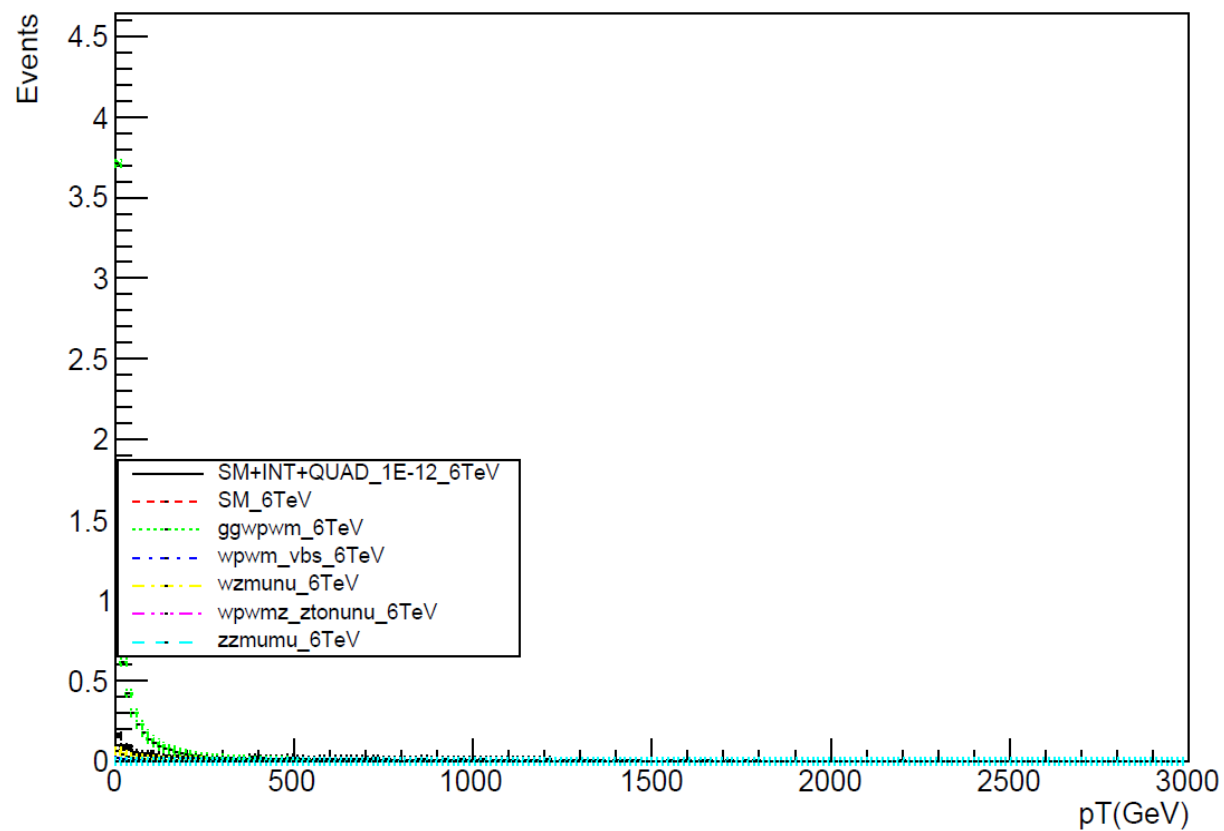
# Truth level eta plots

## W boson



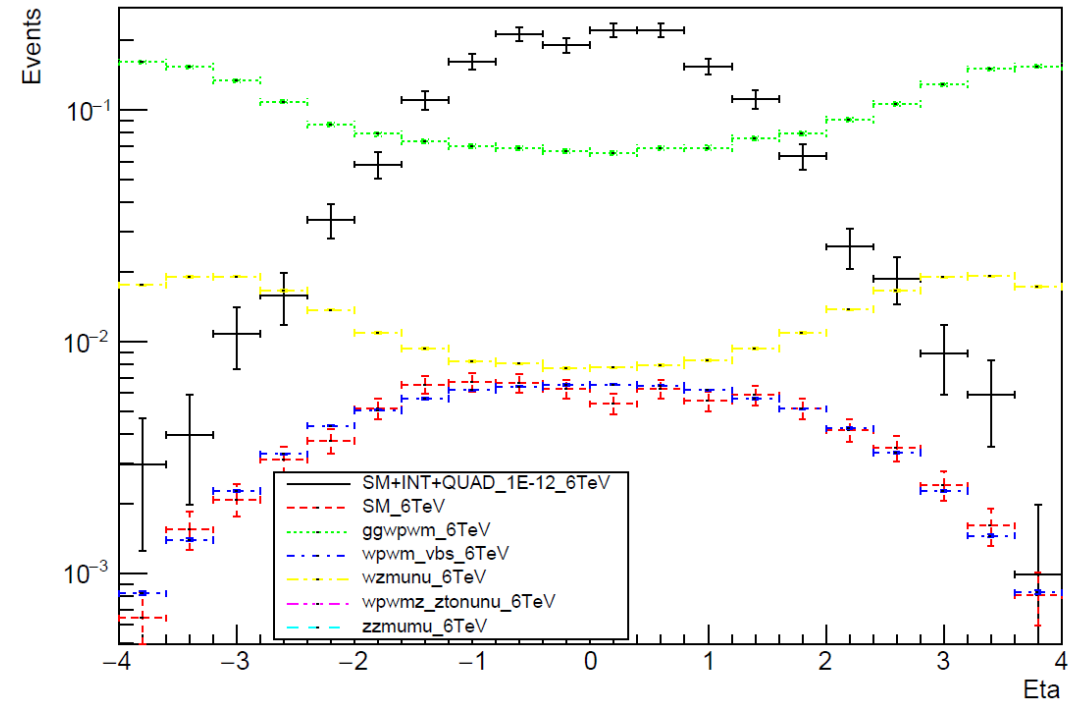
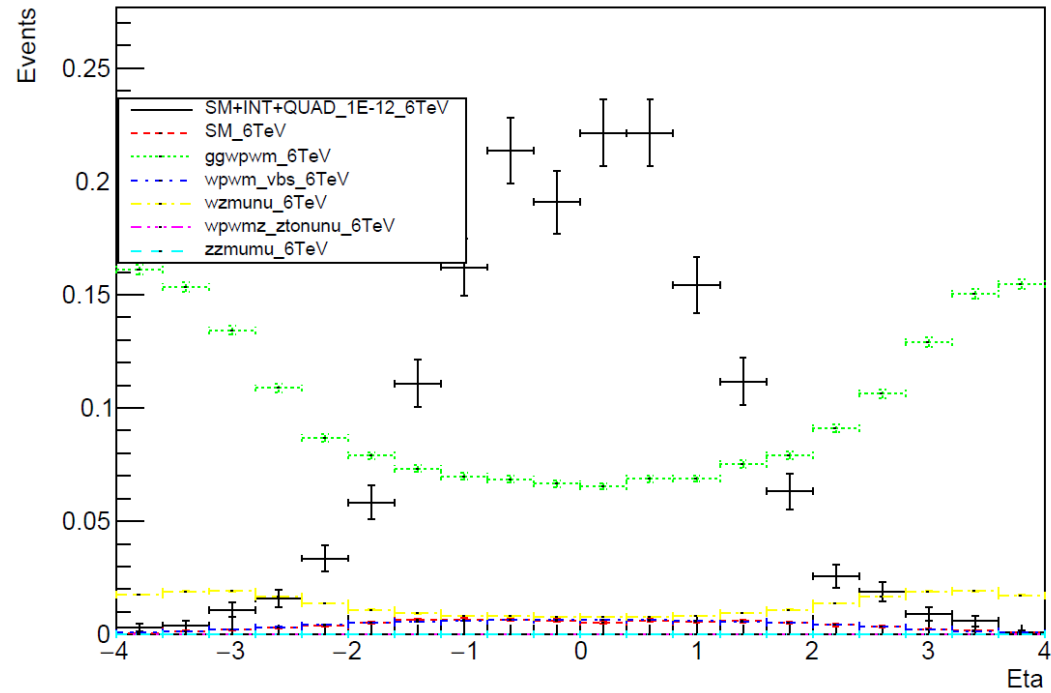
# Truth level pT plots

## Muon



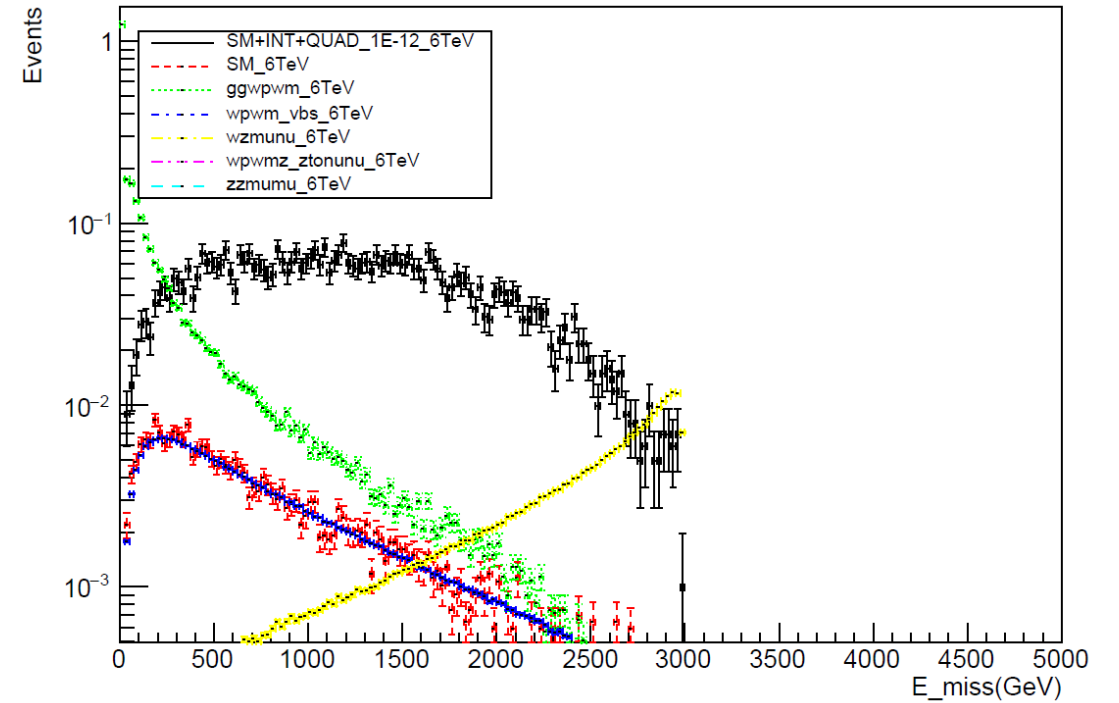
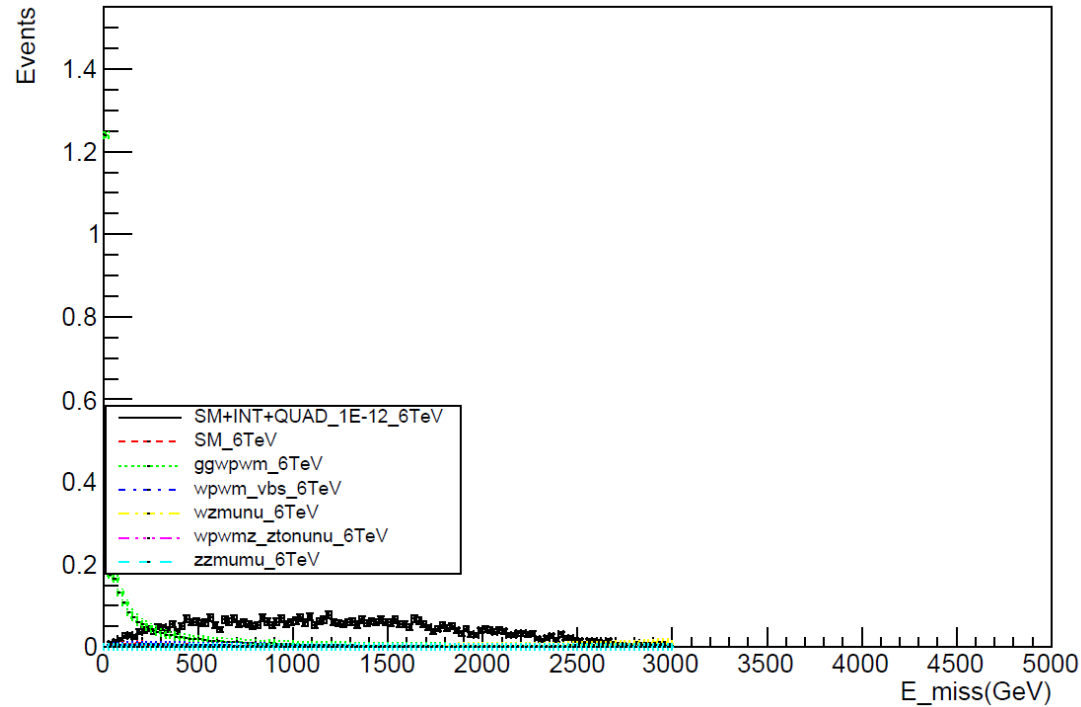
# Truth level eta plots

## Muon



# Truth level plots

## Missing E



# Truth level plots

## Missing Et

