CSI Presentation

Measurement of the Vector Boson Scattering process in the $W^{\pm}Z$ channel, with the ATLAS detector at LHC

Panagiotis Ziakas

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  - The VBS process
  - Why is VBS important?
  - VBS topology
- **QCD Background Modelling**
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- **Qualification Project**
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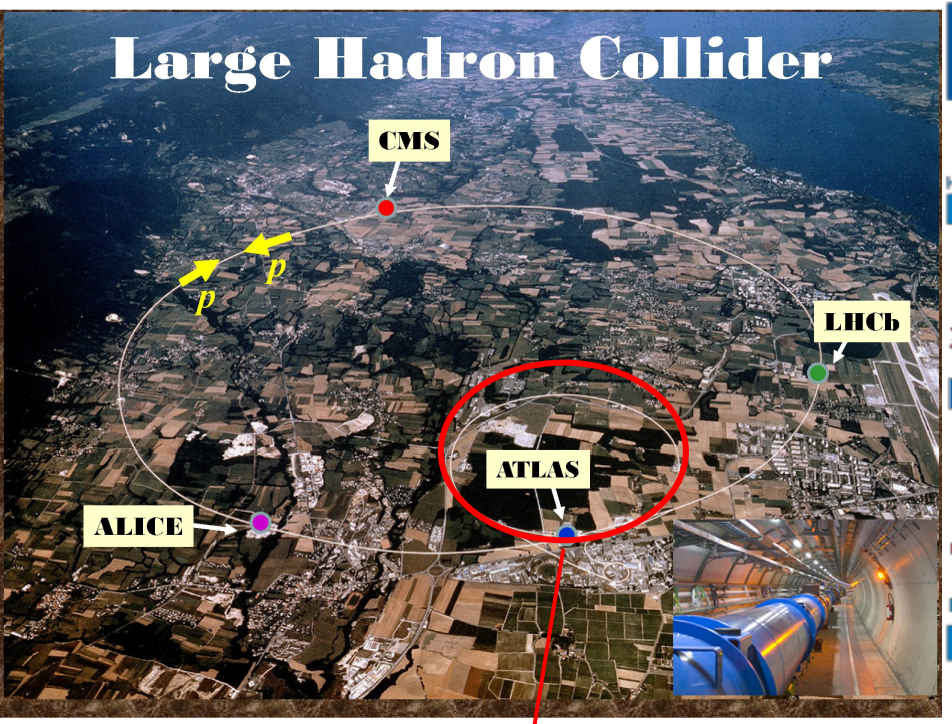
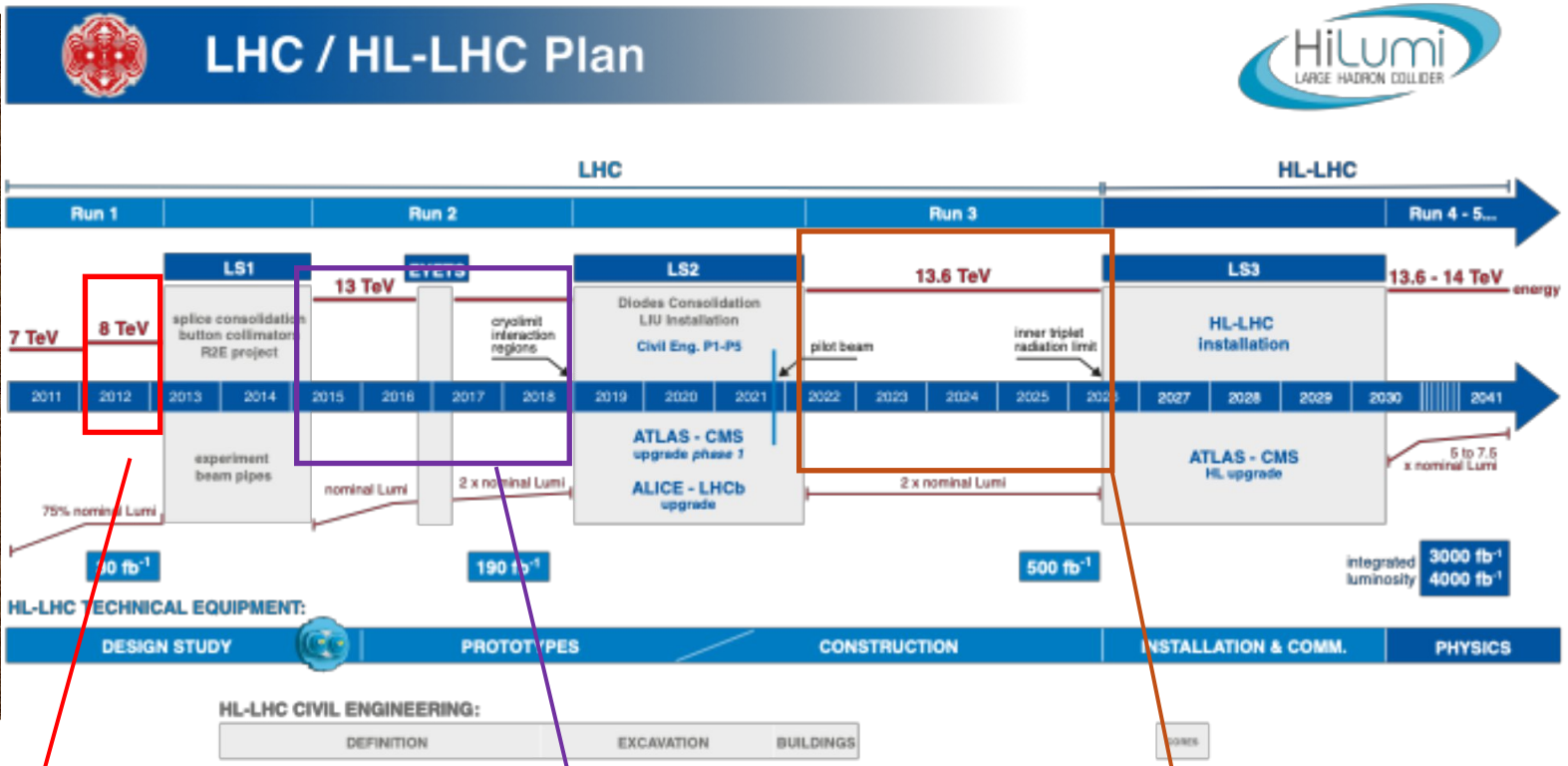
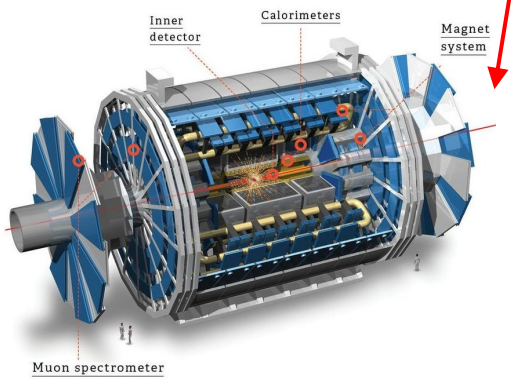
- **Prospectives and next steps**
  - Preliminary results
- **Doctoral School Training**

Introduction

Large Hadron Collider & ATLAS experiment







Higgs boson Discovery

Observation and precise measurements of rare processes

Deeper understanding of the existing processes & exploration of New Physics

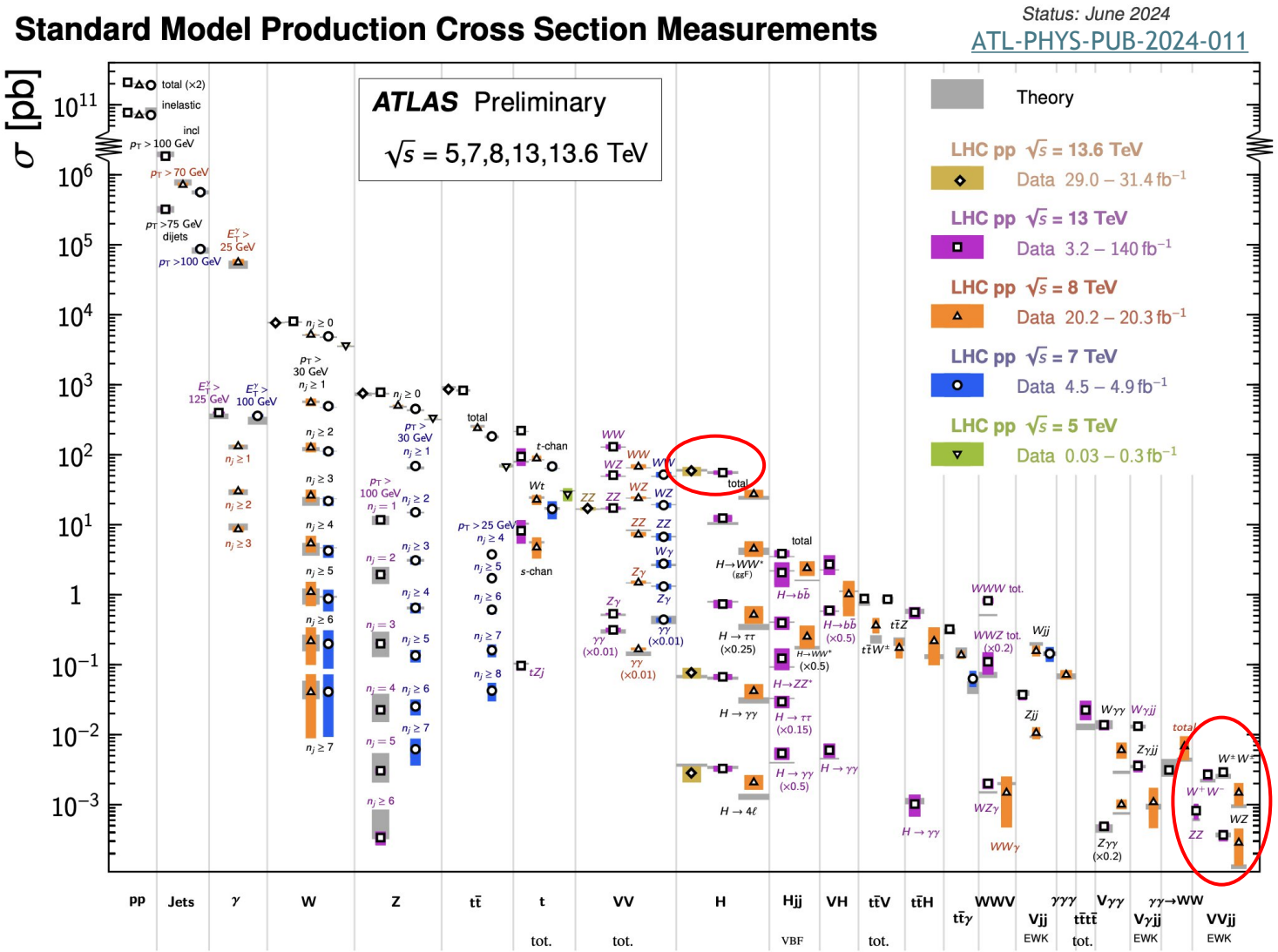
VBS as a rare process

Vector Boson Scattering (VBS)

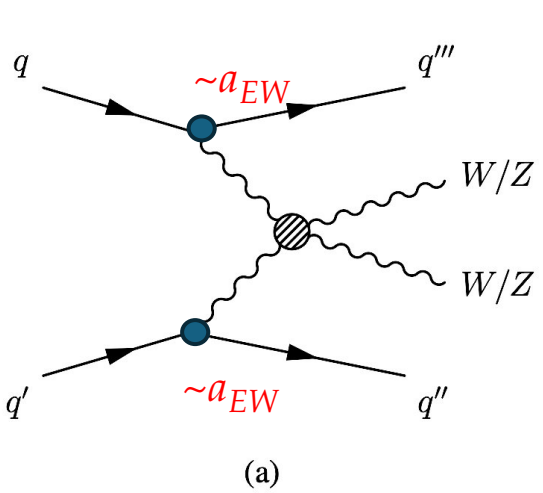
Rare but very important process!

EW symmetry breaking

Vector boson self -couplings

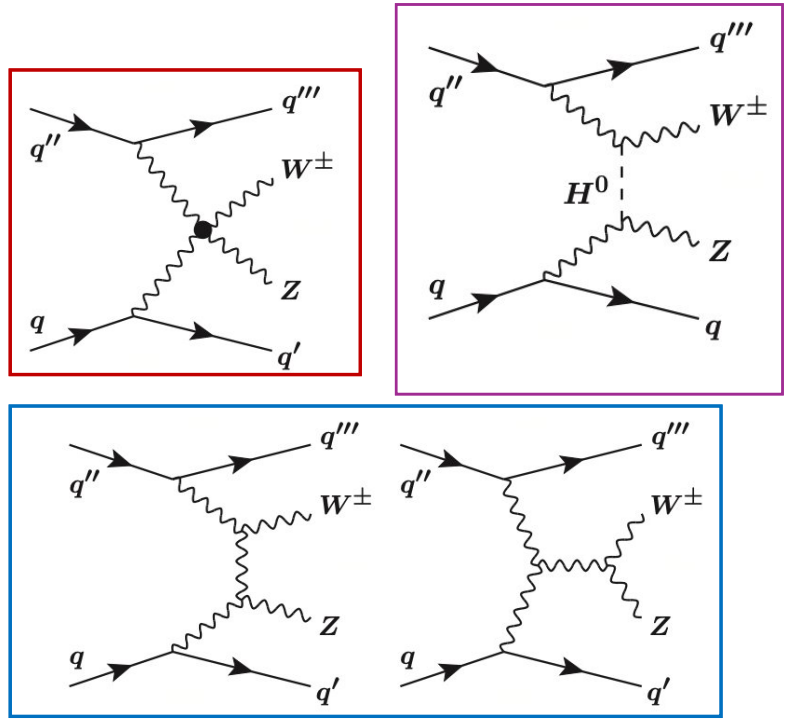


The Vector Boson Scattering process



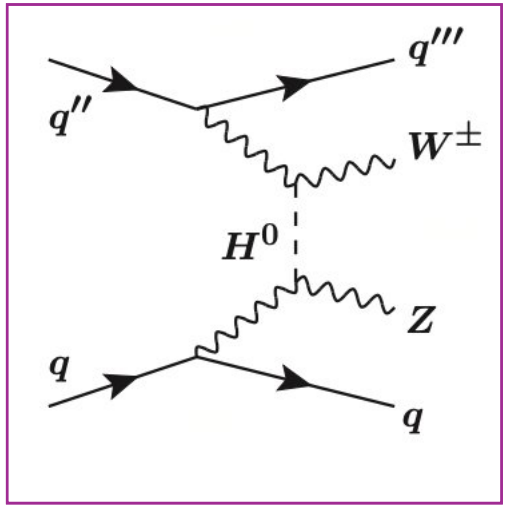
(a)

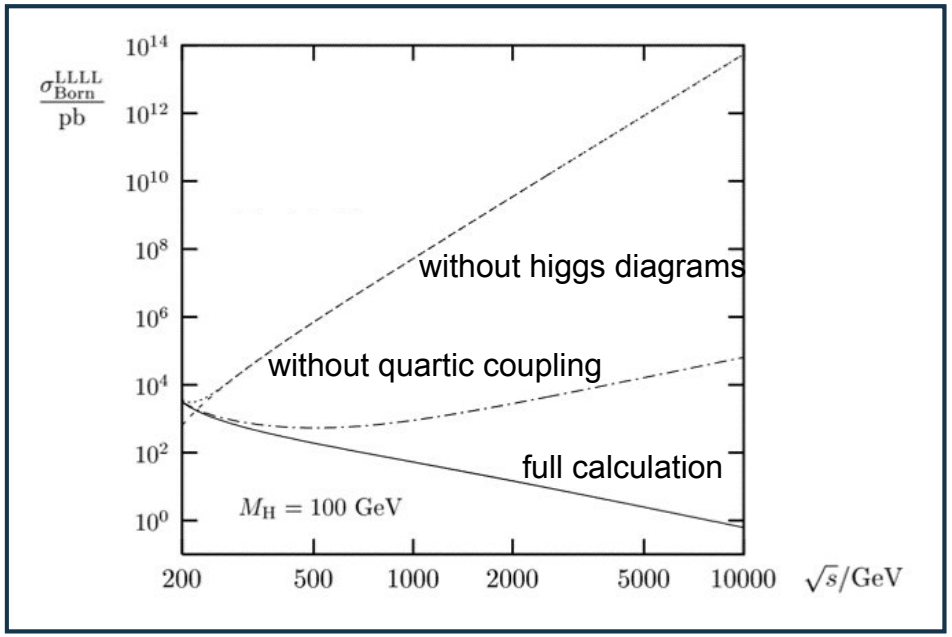
EWK VVjj via VBS



Polarized WZ production

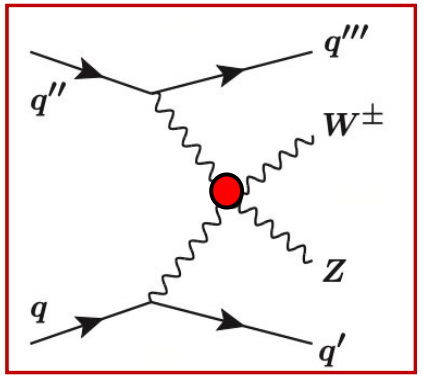
Longitudinaly polarized boson prodcuction offers an excellent test of the electroweak symmetry breaking!



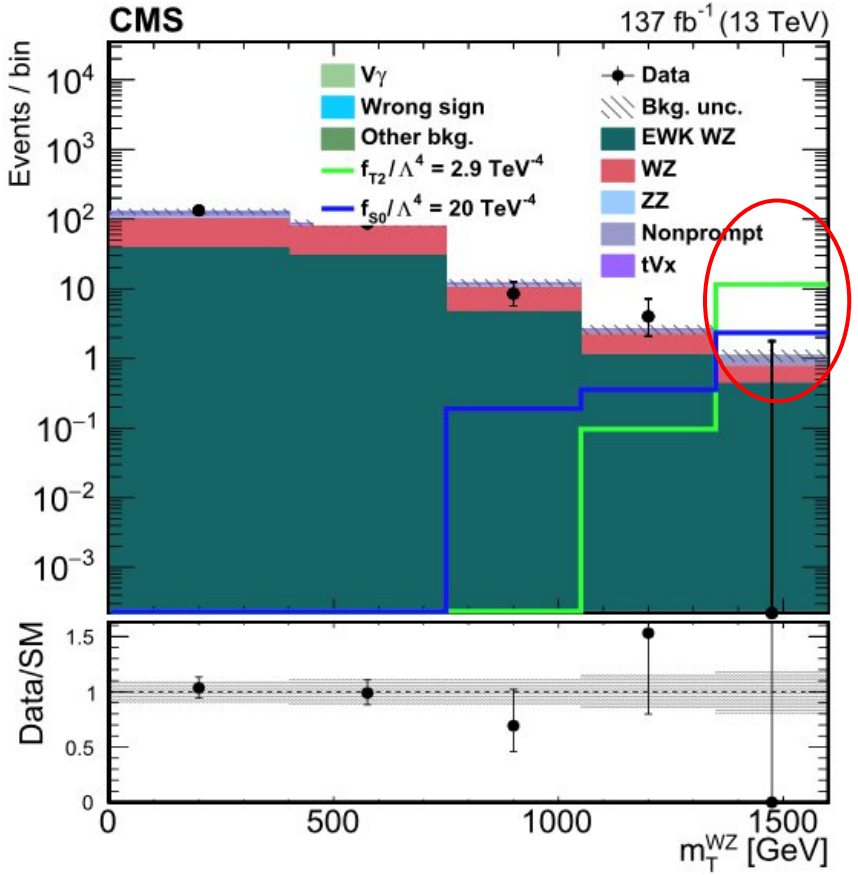


Unitarity violation if Higgs coupling deviates from SM!

Quartic Gauge Coupling measurement



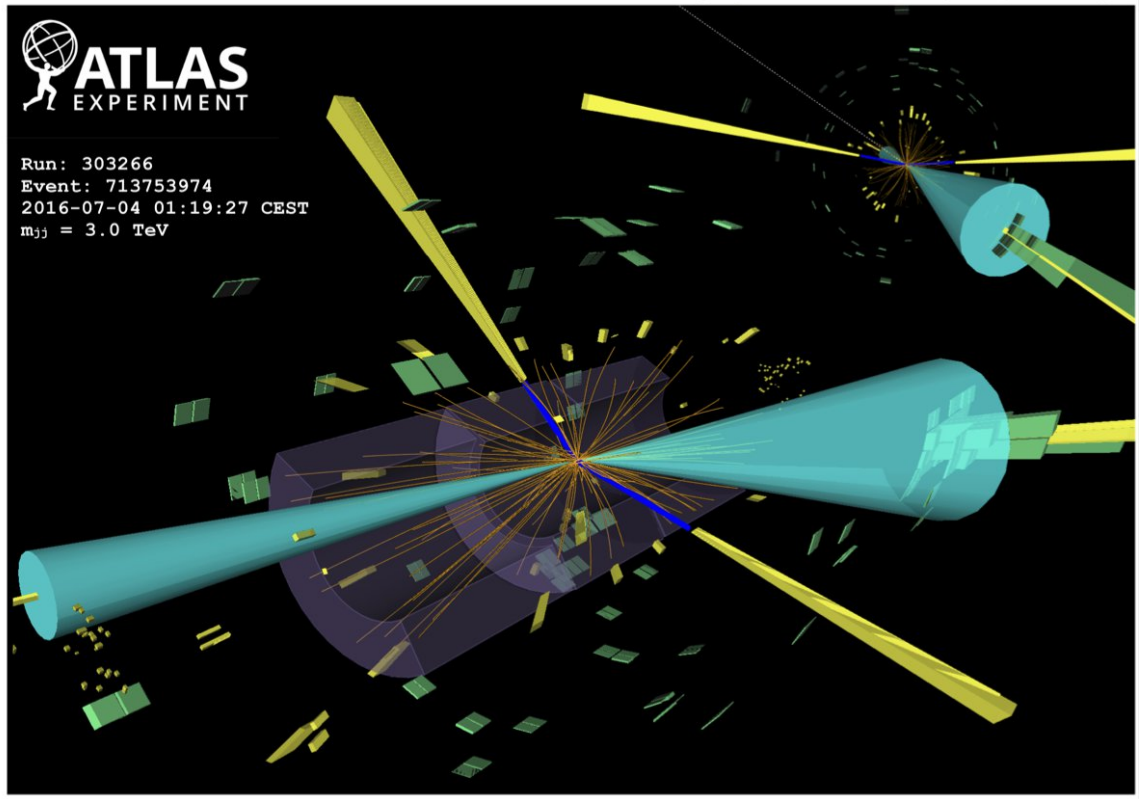
Quartic Gauge Coupling (QGCs)



- Beyond SM theories predict enhanced couplings!
- Any deviation might signal the existence of new physics!

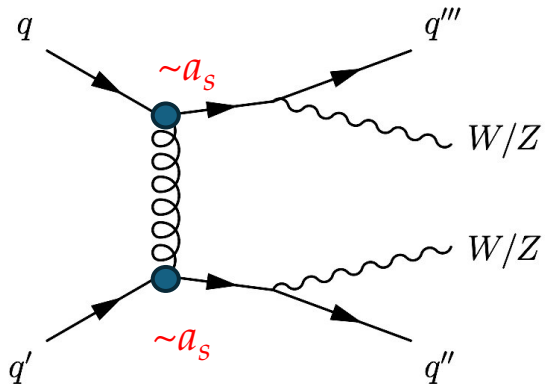
→ Sensitivity to the presence of new Physics!

VBS event topology



- Two oppositely charged leptons from Z (yellow)
- One lepton and one neutrino from W (yellow)
- Two high energy forward jets (blue)
- Additional jets due to higher order effects

WZ VBS Signal Region



(c)

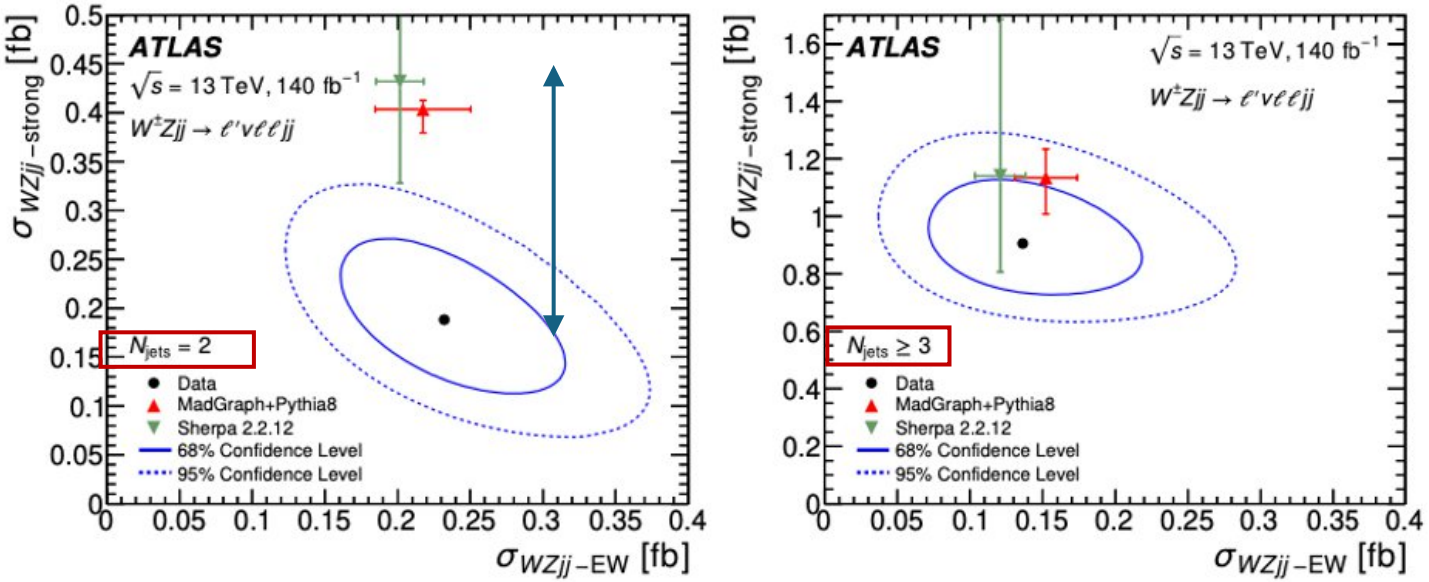
QCD VVjj

- Major background source!
- Fortunately, different topology!

QCD background modeling

QCD background mismodeling

- VBS (WZ) first observed by the ATLAS LAPP group at 2018
- EW-QCD simulataneous measurement in different subregions



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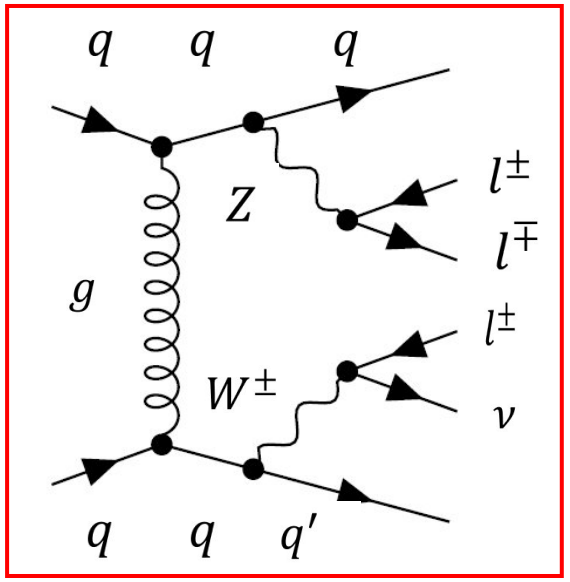
- More than 2σ discrepancy in the phase space with exactly two jets!
- Presence of mismodelling in the QCD production!
- Starting point of the PhD

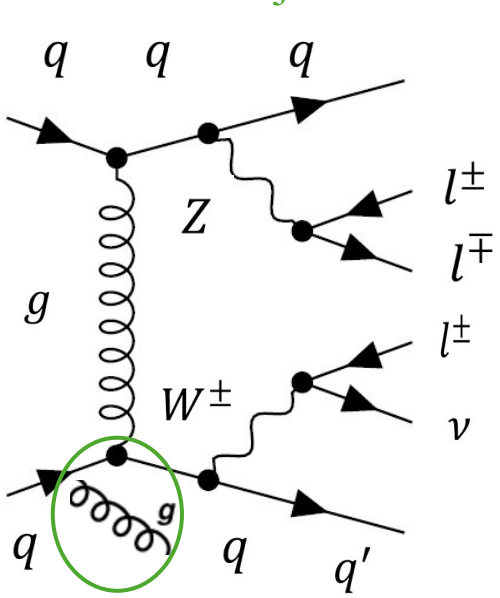
Generated Samples

✓ **Generator**: MG5_aMC@NLO + Pythia8

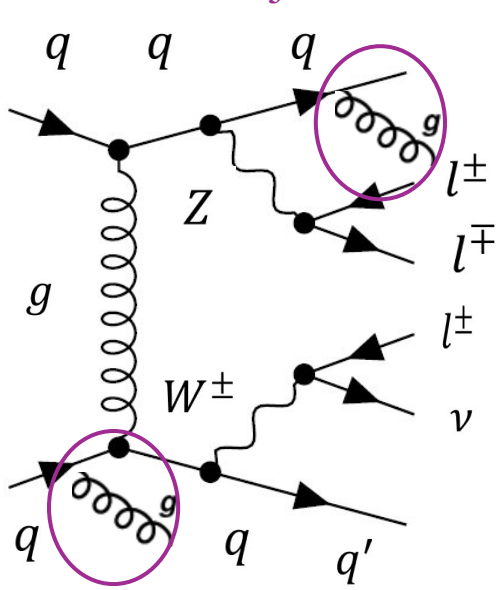
LO generation (13TeV)



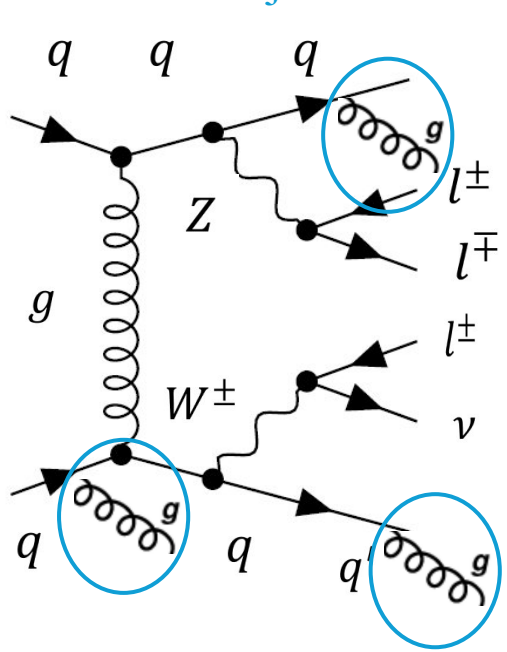
LO + 1j



LO + 2j

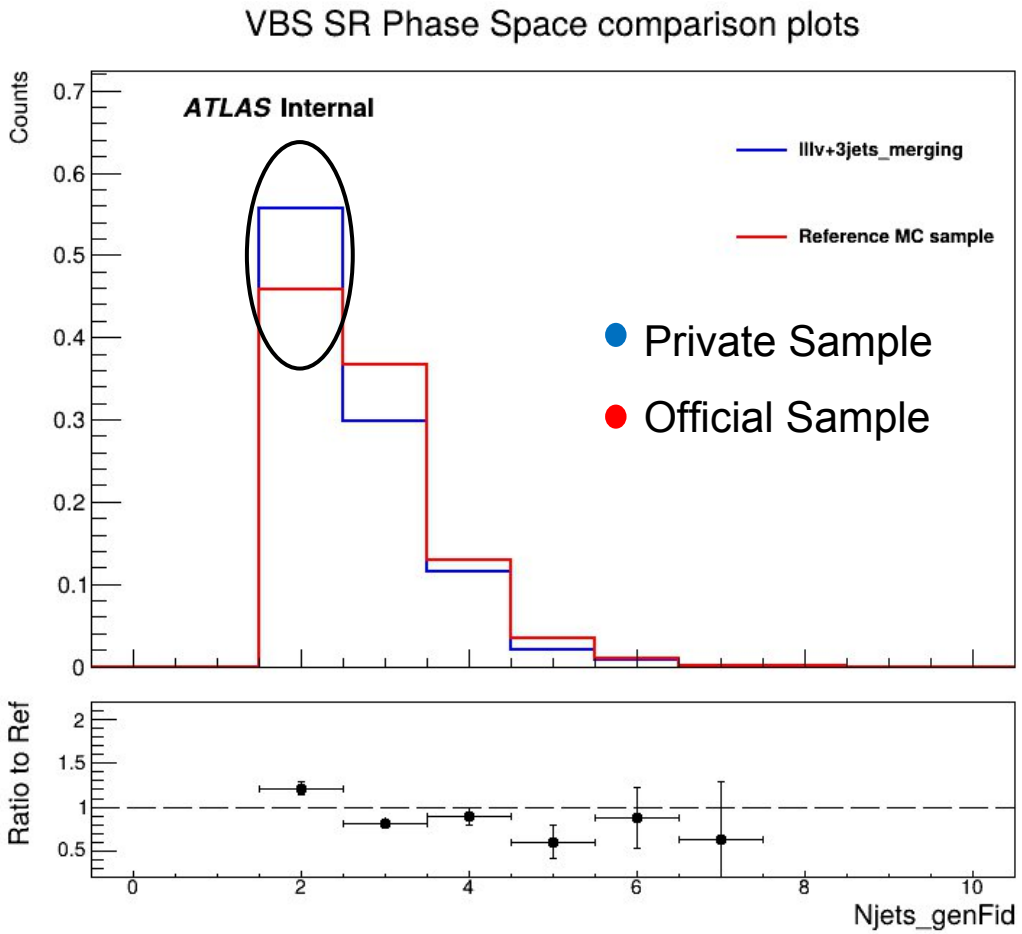


LO + 3j



Comparison against the **Reference Sample:** $pp \rightarrow WZ \rightarrow lll\nu + 0, 1, 2j@NLO, \sqrt{s} = 13\ TeV$

LO generation



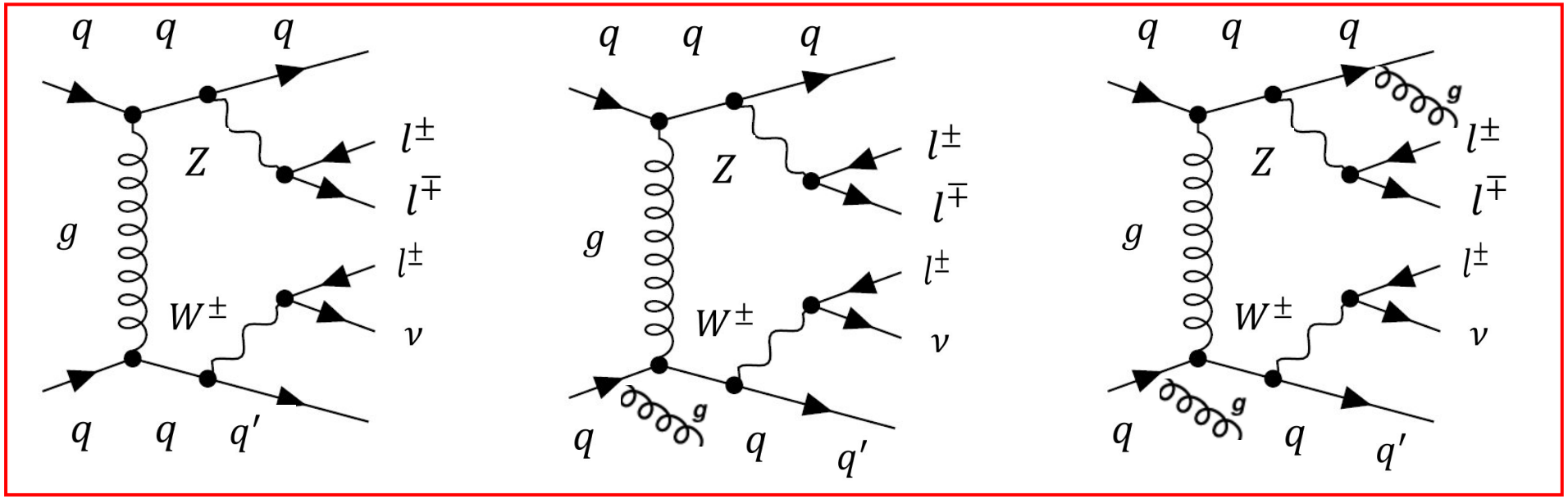
- The bin $N_{jets} = 2$ is higher than in the Reference Sample
- Does not serve the purpose of the initial idea
- Decided to go for a NLO production with up to 2 jets!

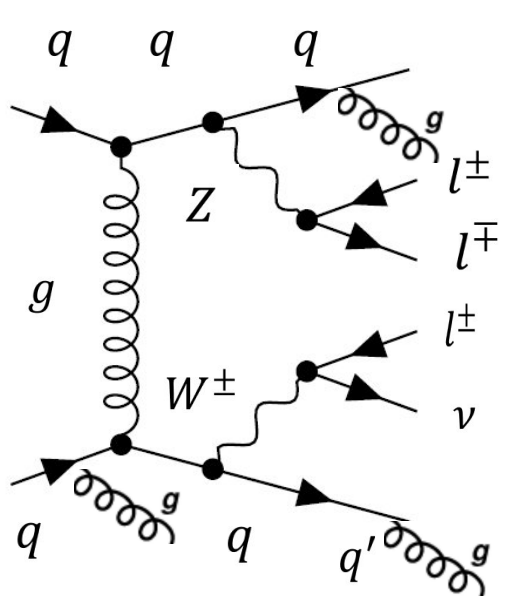
Generated Samples

- ✓ **Generator**: MG5_aMC@NLO + Pythia8

NLO generation (13.6 TeV)

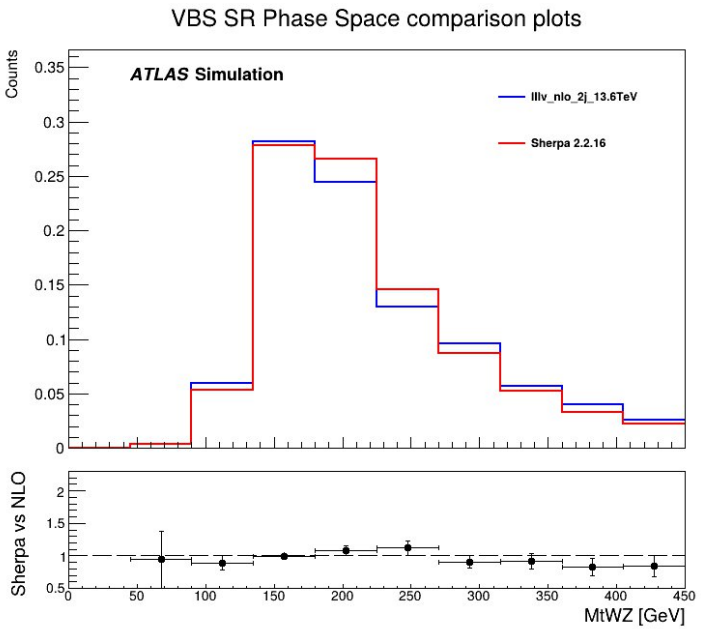
Different order/accuracy than the official

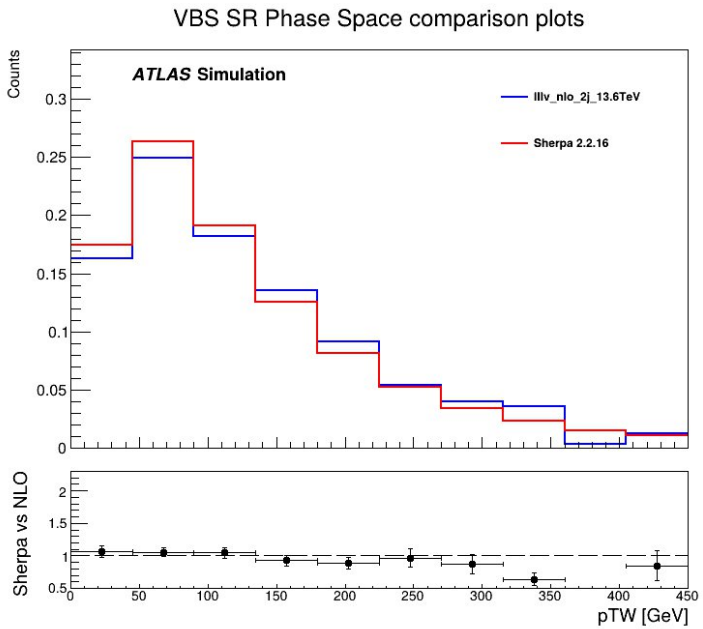


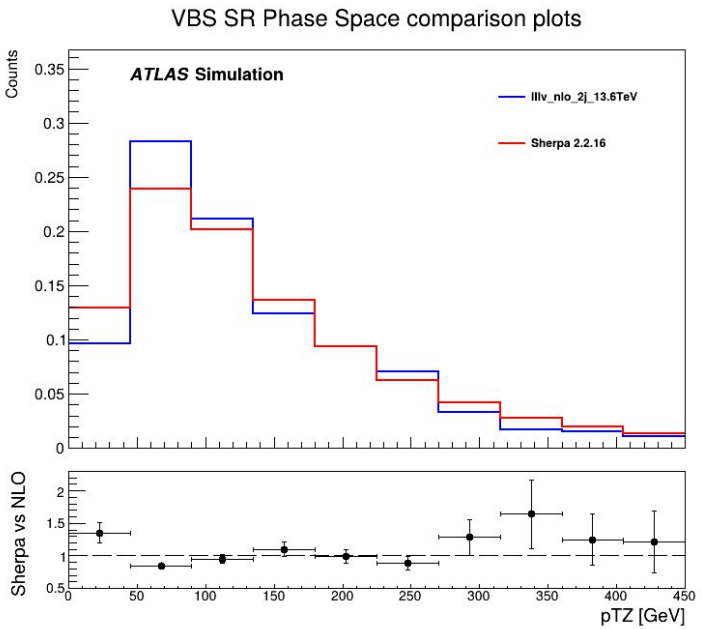


Comparison against the official **Sherpa 2.2.16 Sample:** $pp \rightarrow WZ \rightarrow lll\nu + 0, 1j@NLO + 2,3j@LO, \sqrt{s} = 13.6\ TeV$

NLO generation



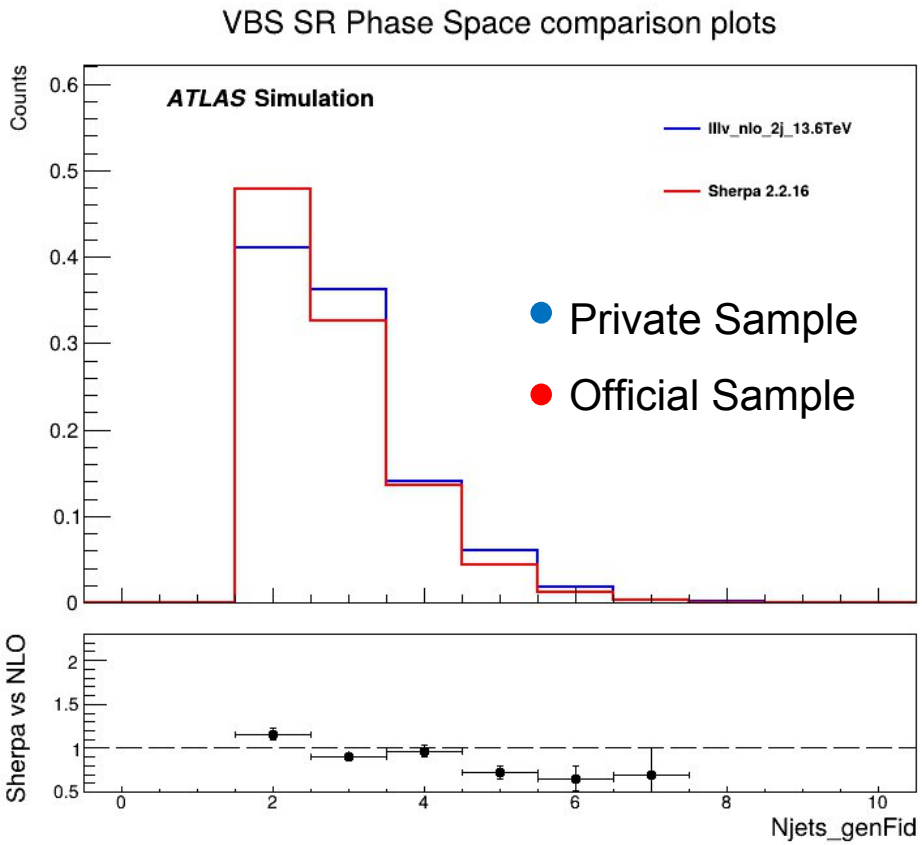




- Private Sample
- Official Sample

There seems to be agreement between the predictions of the two samples!

NLO generation



- ✓ In general, agreement between the predictions
- ✓ The $N_{jets} = 2$ bin seems to be going to the right direction
- ✓ Not yet fully reliable comparison because of a known bug in MG5

Qualification Project

Qualification Project

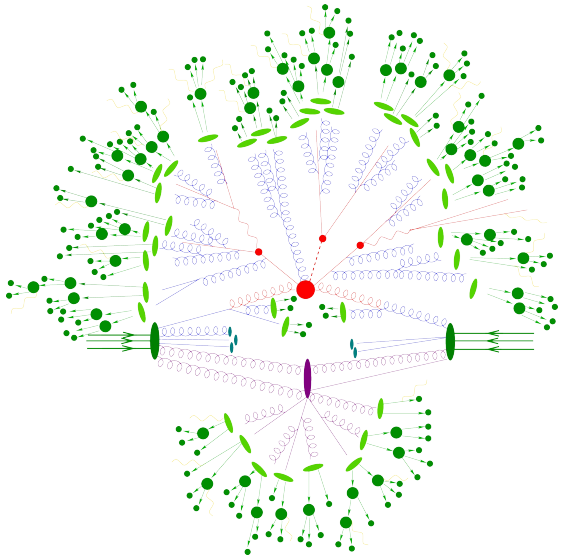
Qualification Project: 1st year ATLAS PhD students project in order to qualify and become ATLAS authors

Duration: 1 year

My Qualification Project

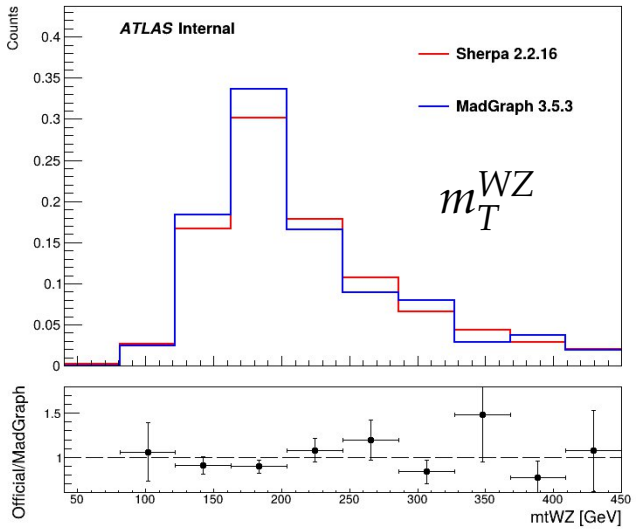
Use the MG5_aMC@NLO Monte Carlo generator to improve QCD initiated $VV + 2jets$ simulations for several diboson channels:

- $WZ \rightarrow lll\nu$
- $ZZ \rightarrow llll$
- $ZZ \rightarrow ll\nu\nu$
- $ssWW \rightarrow l\nu l\nu$
- $osWW \rightarrow l\nu l\nu$

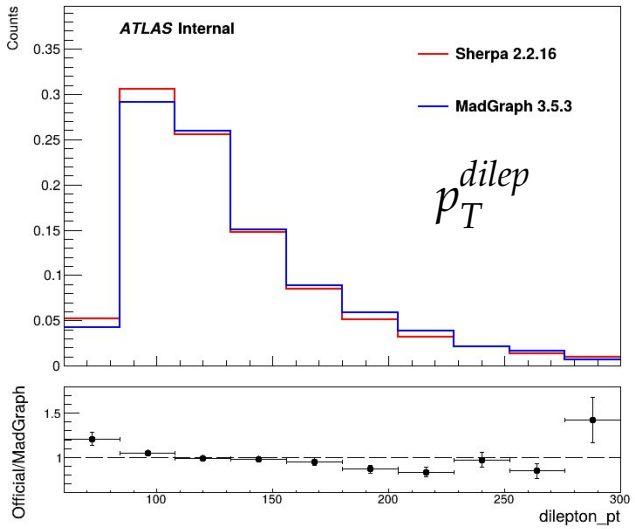


Validation Plots

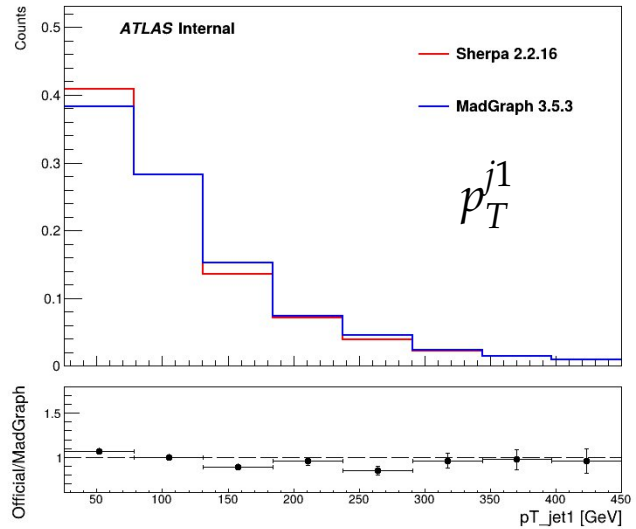
WZ→lllν comparison plots



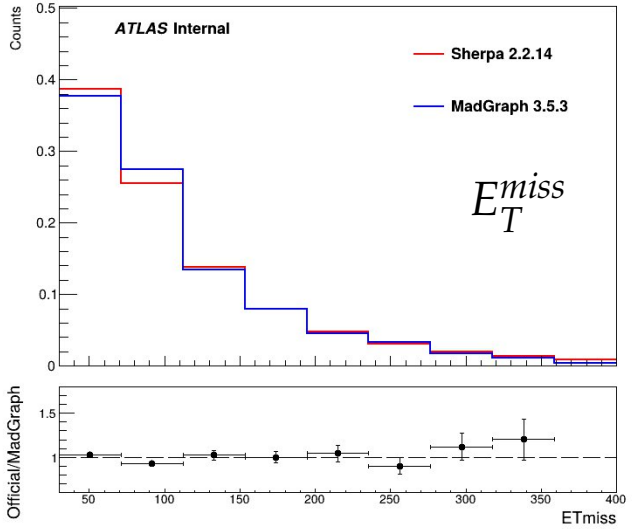
ZZ→llνν comparison plots



ZZ→llll comparison plots



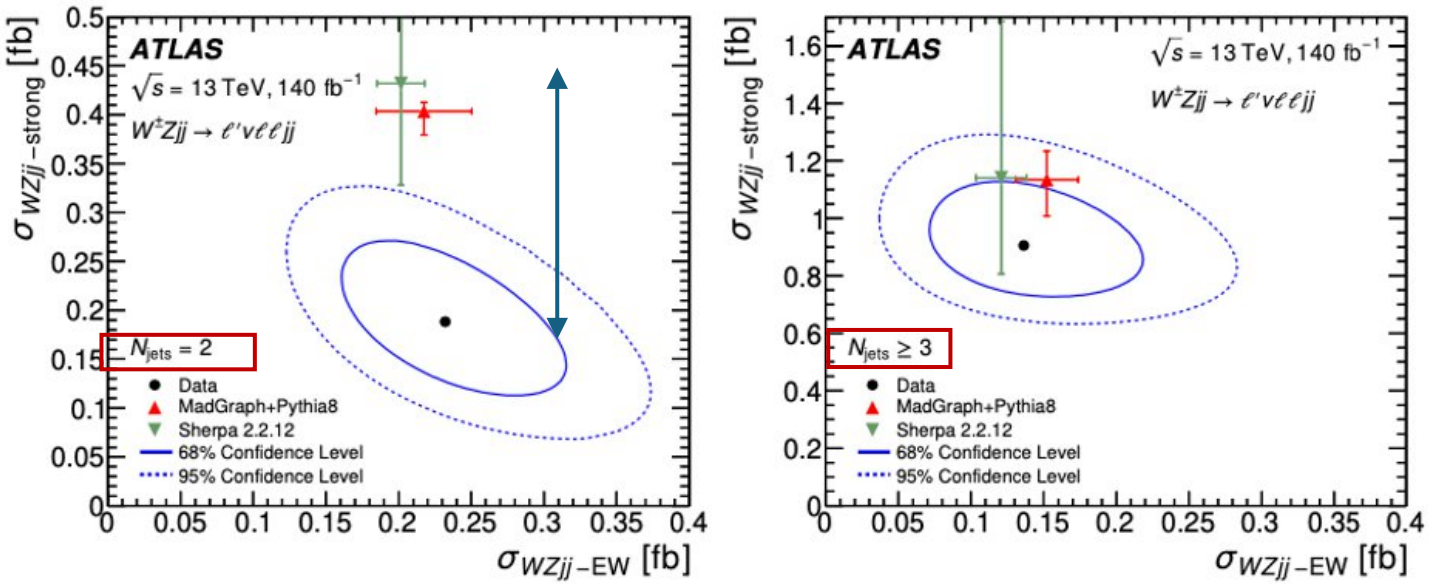
ssWW→lνlν comparison plots



- Private Sample
- Official Sample

Prospectives and next steps

- VBS (WZ) first observed by the ATLAS LAPP group at 2018
- EW-QCD simulataneous measurement in different subregions



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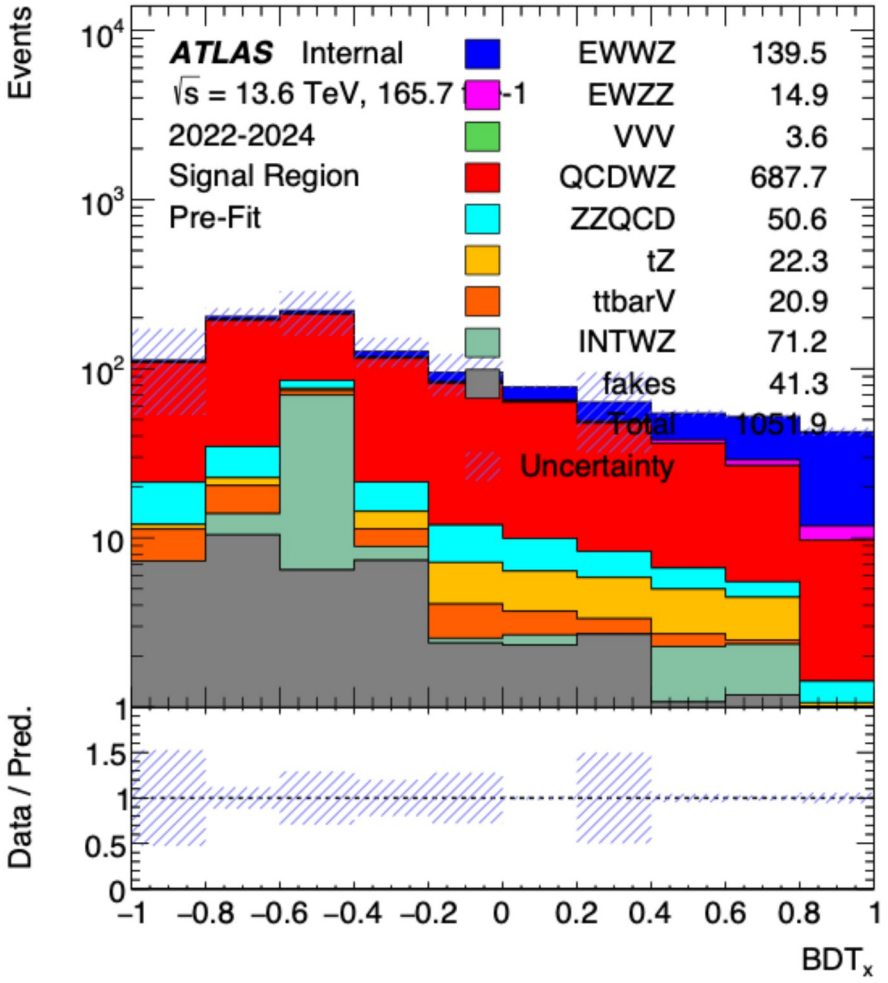
- ❑ Repeat this measurement t 13.6 TeV
- ❑ Perform full differetial cross section measurements
- ❑ Use different variables
  - Sensitive to BSM effects (m_T^{WZ})
  - Helpful for precise modeling predictions (N_{jets},m_{jj})

Preliminary Results

Just started working with 2022-2024 data but still in a preliminary stage!



Process	Expected Events
WZ–EW	139.5
ZZ–EW	14.9
VVV	3.6
WZ–QCD	687.7
ZZ–QCD	50.6
tZ	22.3
$t\bar{t}V$	20.9
WZ–INT	71.2
Fakes	41.3
All MC	1051.9

- Measure simultaneously
- Constrain in dedicated CRs
- Measured using data

  - Run2: 108 events (observed)
  - Full Run3: 340 events

Doctoral School Training

Successfully registered training hours:

- Physics in the XXIst Centrury (13 March – 22 May 2025, 20 hours)
- Français Langue Etrangère (20 January – 18 April 2025, 45 hours)
- Constuire son Projet Professionnel (26 March – 27 March 2025, 12h)
- Journée de rentrée des doctorants (14 November 2024, 4h)

Summer Schools:

- Gray Scott Computing School (L.A.P.P., Annecy, 23 June – 4 July 2025)

Talks and conferences:

- Physique ATLAS France (Conference, Annecy, 26 May – 28 May 2025)
- Congrès Général de la Société Française de Physique (Talk: Studying the VBS process, Troyes, 30 June – 4 July)
- WZ leptonic weekly meeting (Frequently presenting progress)
- PMG Weak Boson meeting (Frequently presenting progress for my QP)
- Shifts in the ATLAS Control Room

Backup Slides

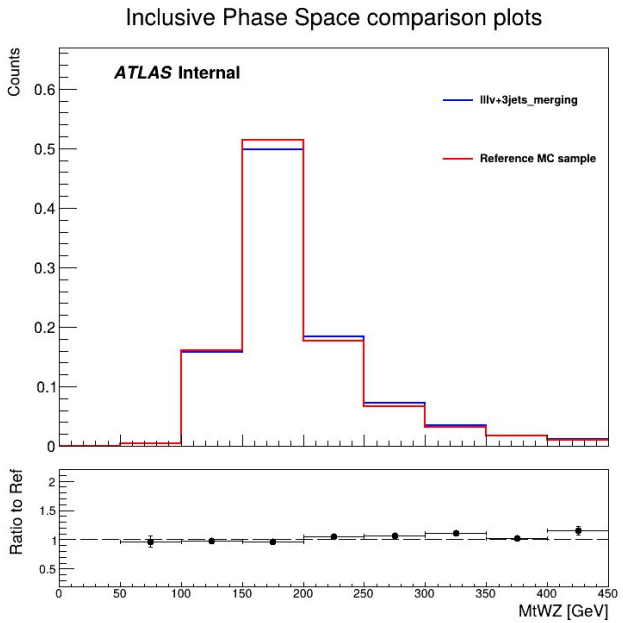
Phase Spaces

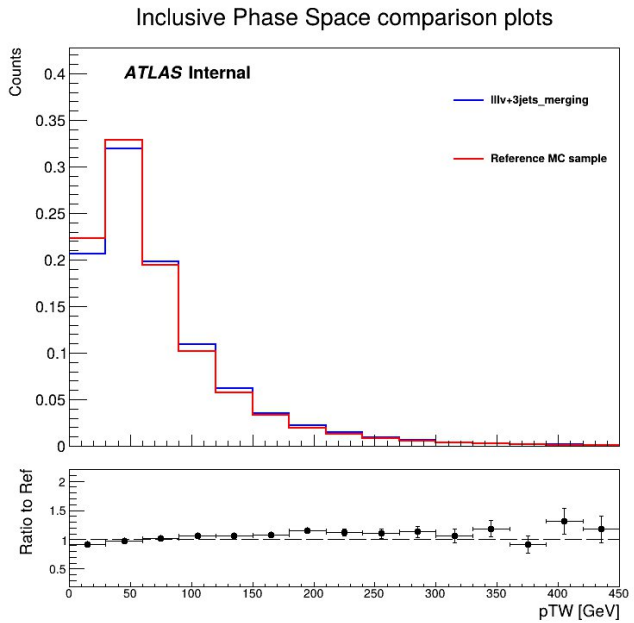
Fiducial Inclusive

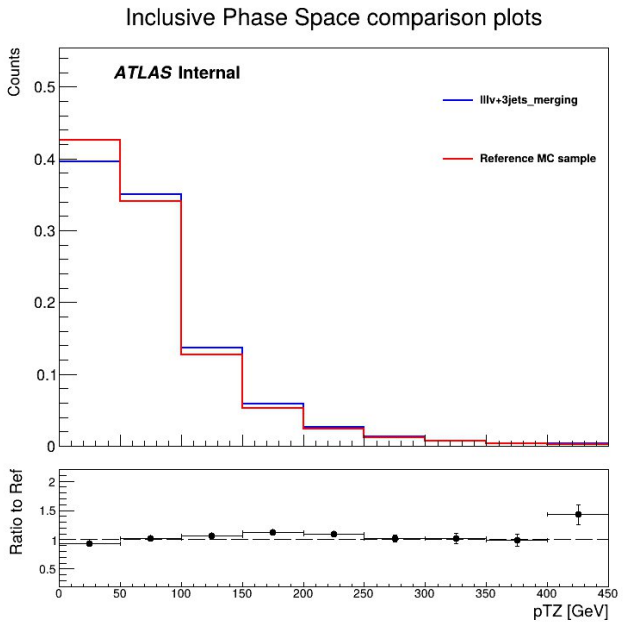
Variable	Fiducial $WZjj$–EW
Lepton $\lvert\eta\rvert$	< 2.5
p_{T} of ℓ_Z, p_{T} of ℓ_W [GeV]	$> 15, > 20$
m_Z range [GeV]	$\lvert m_Z - m_Z^{\mathrm{PDG}}\rvert < 10$
m_{T}^W [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	$> 0.2, > 0.3$
p_{T} two leading jets [GeV]	> 40
$\lvert\eta_j\rvert$ two leading jets	< 4.5
Jet multiplicity	≥ 2
$\eta_{j1} \cdot \eta_{j1}$	< 0
m_{jj} [GeV]	> 500
$\Delta R(j, \ell)$	> 0.3
$N_{b-\mathrm{quark}}$	$= 0$

Fiducial WZjj – EW Signal Region

WZ Inclusive Phase Space







Good agreement between the predictions of the two samples
in the WZ Inclusive Phase Space!

R_{23} values

$$R_{23} = \frac{\sigma_{N_{jets}=2}}{\sigma_{N_{jets}>2}}$$

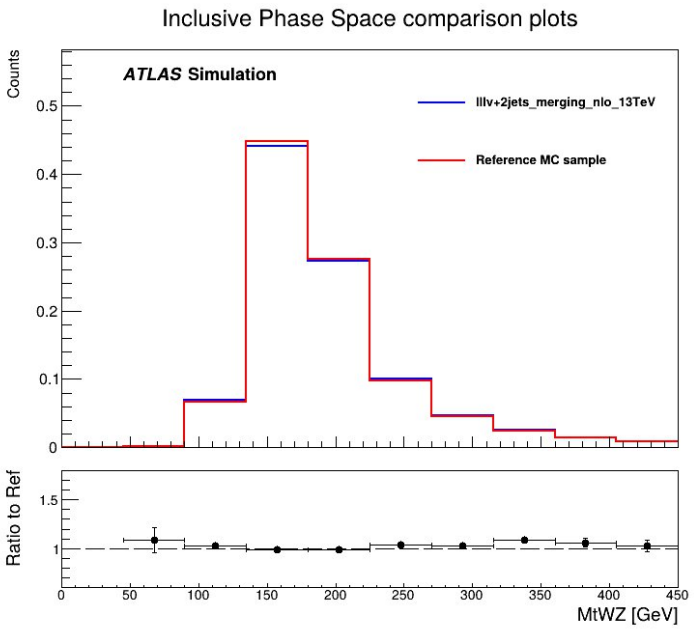
Sample	R_{23}
Data	0.209
Reference	0.388
Private	0.611

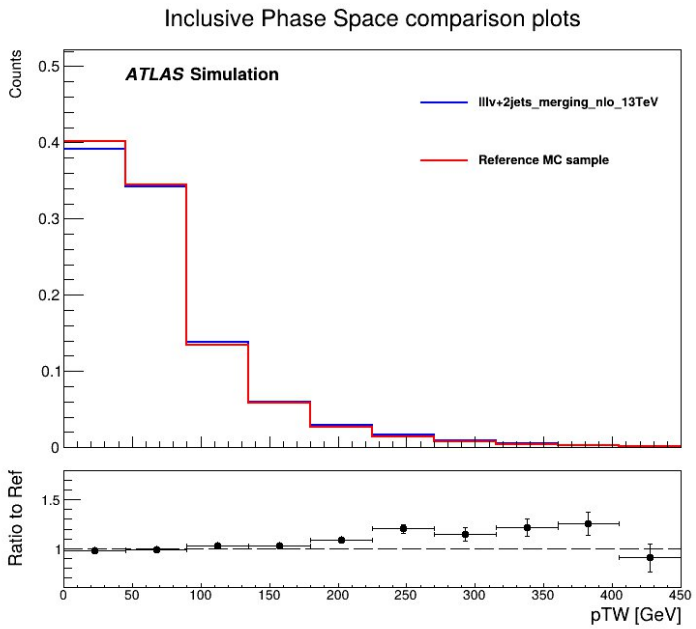
The LO sample predictions seem to be really off!

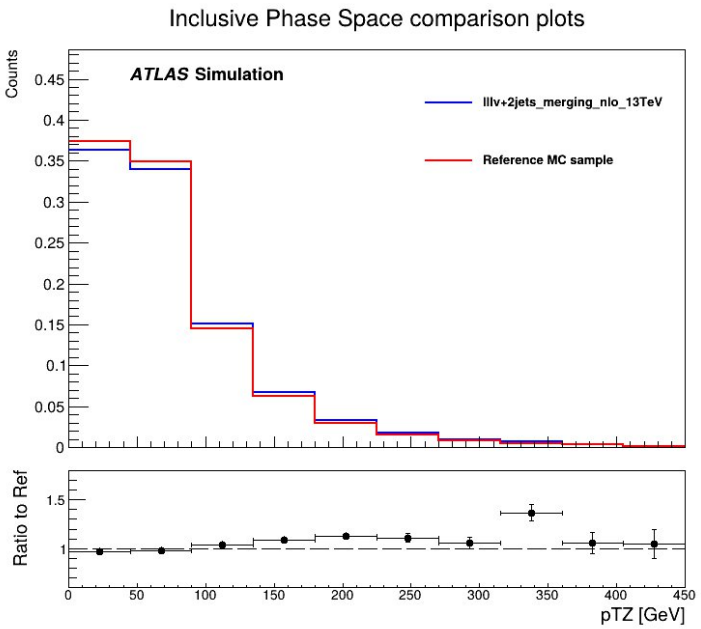
Therefore the idea of LO generation was abandoned, and we will proceed with the NLO generation!

Private Sample vs Reference Sample at 13TeV

WZ Inclusive Phase Space







Good agreement between the predictions of the two samples
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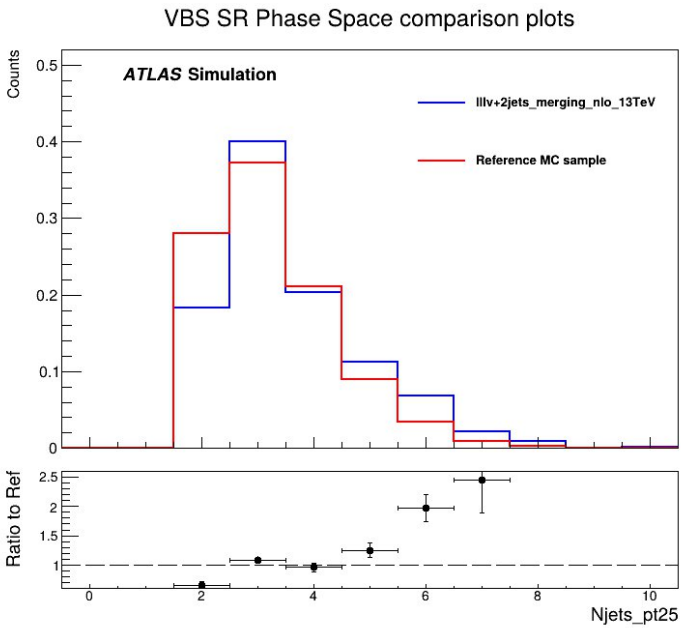
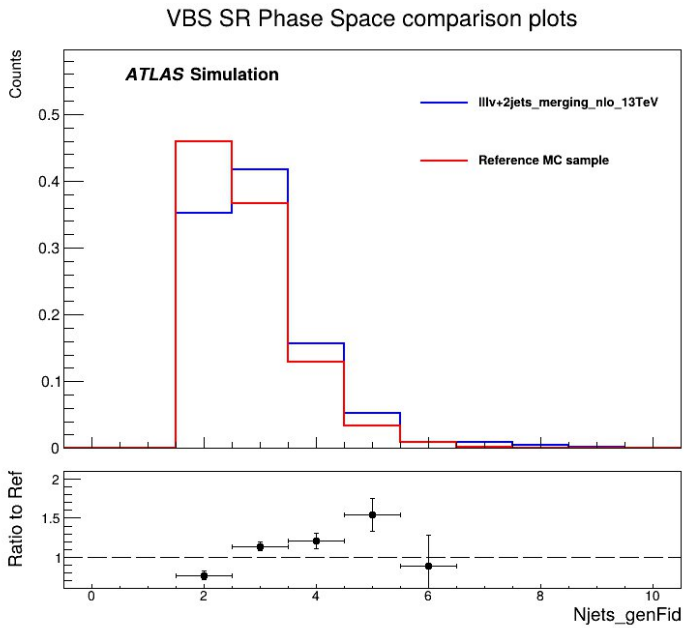
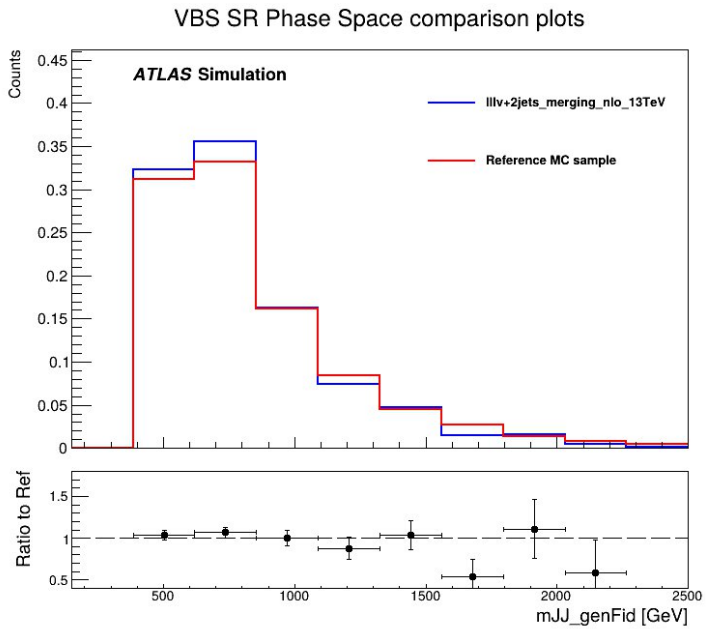
WZ VBS Signal Region

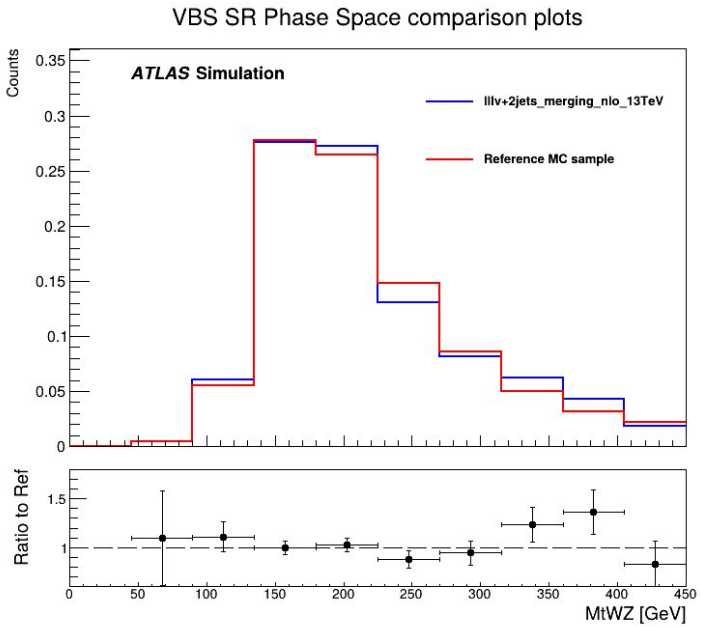


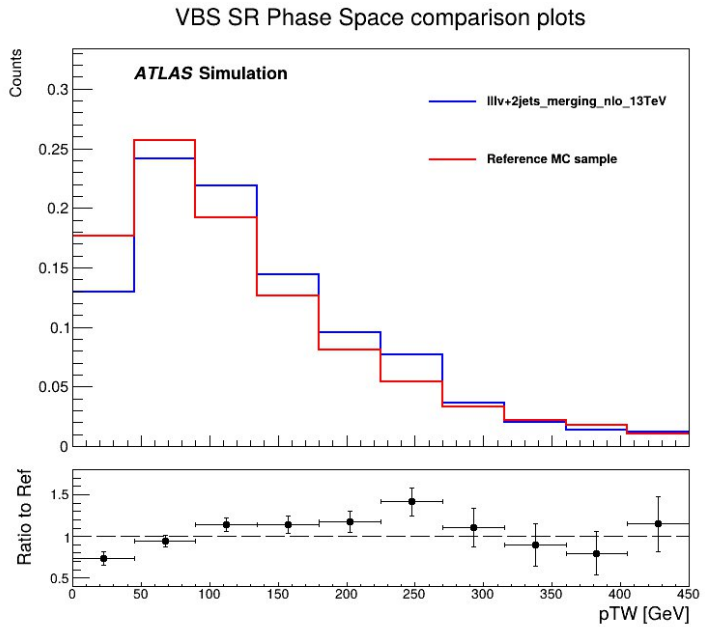


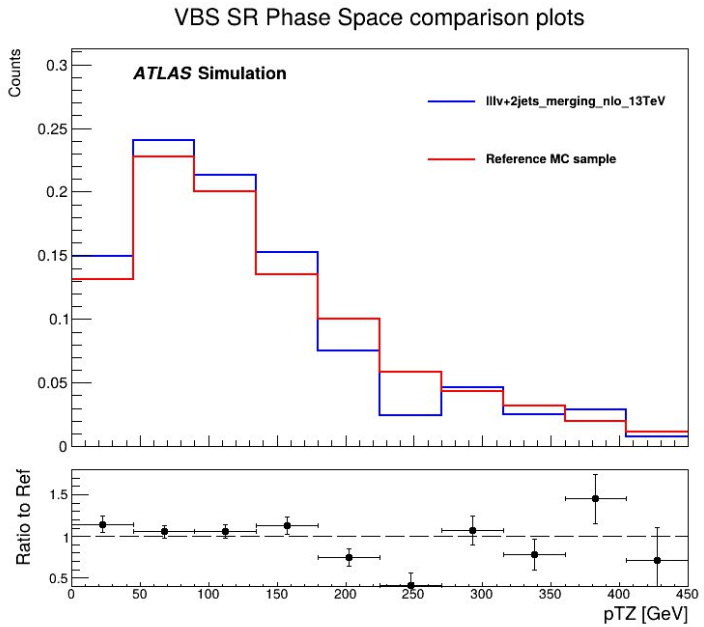


- ✓ Behavior in the $N_{jets} = 2$ seems to be in the right direction
- ✓ This comparison should not be fully trusted due to a know FxFx bug in MadGraph
- ✓ Jet multiplicity differences might originate from the bug

WZ VBS Signal Region



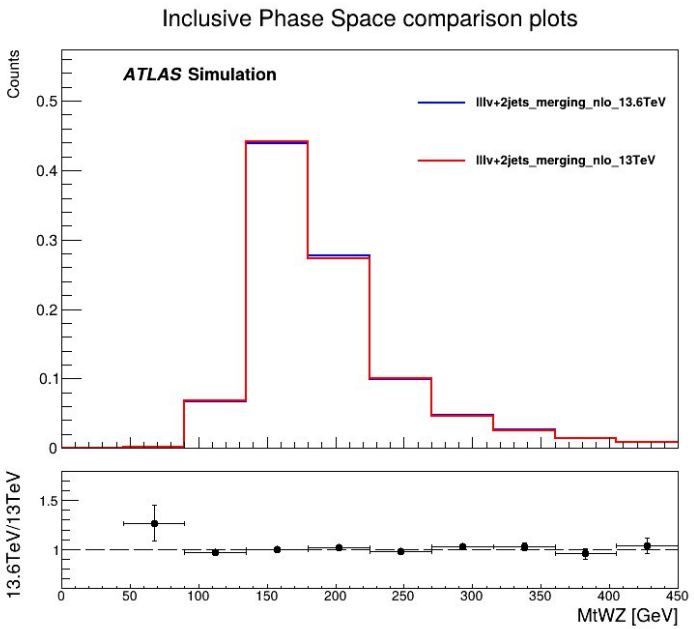


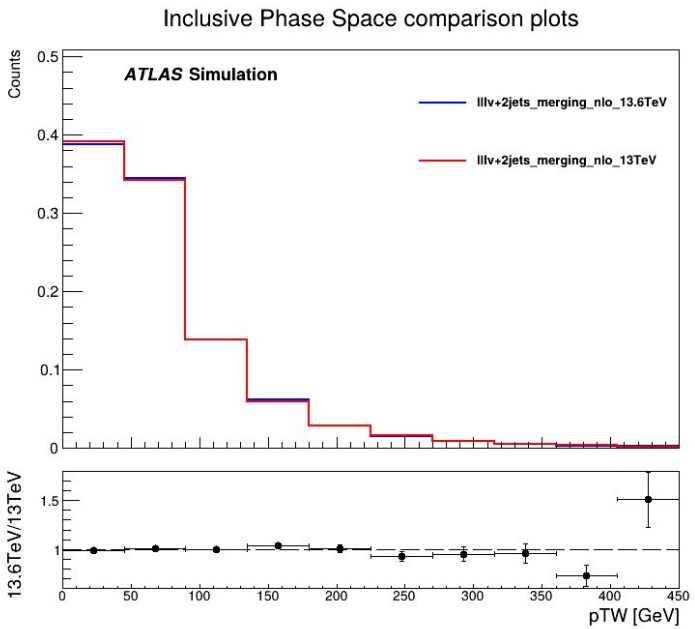


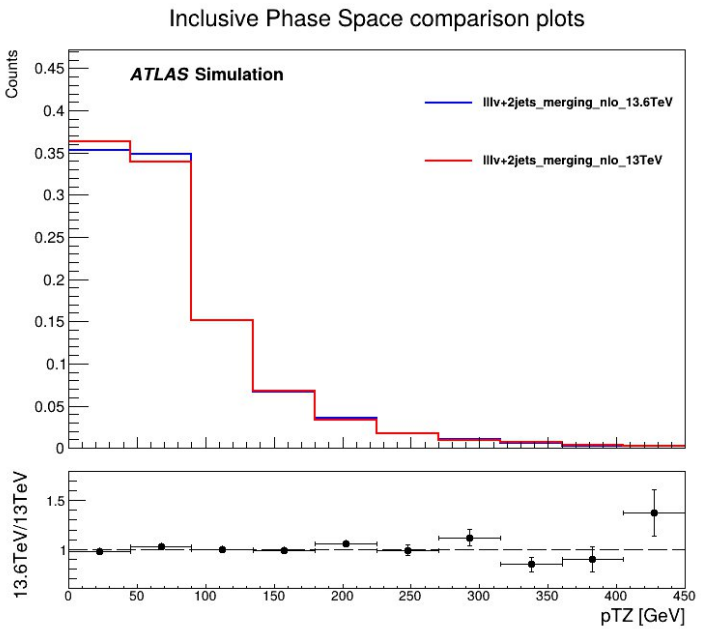
Although there is a clear lack of statistics, there seems to be agreement between the predictions of the two samples in the WZ VBS SR!

Private Sample at 13.6 TeV vs 13 TeV

WZ Inclusive Phase Space

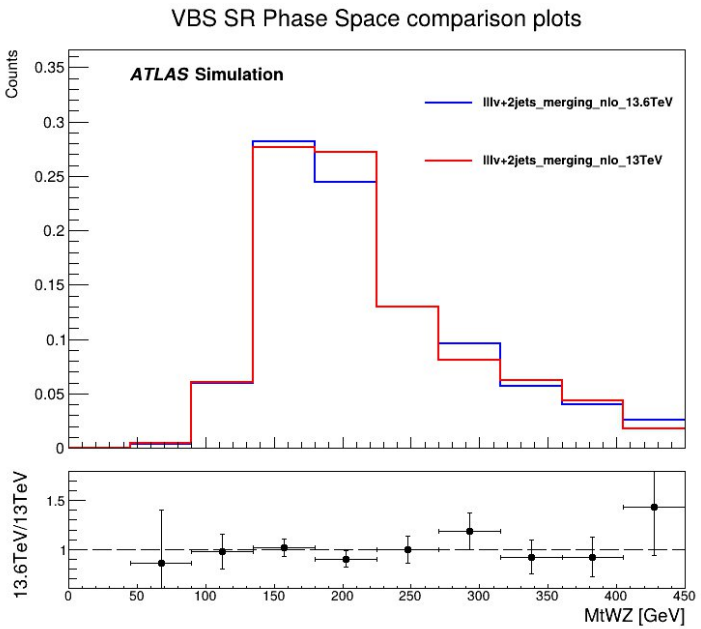


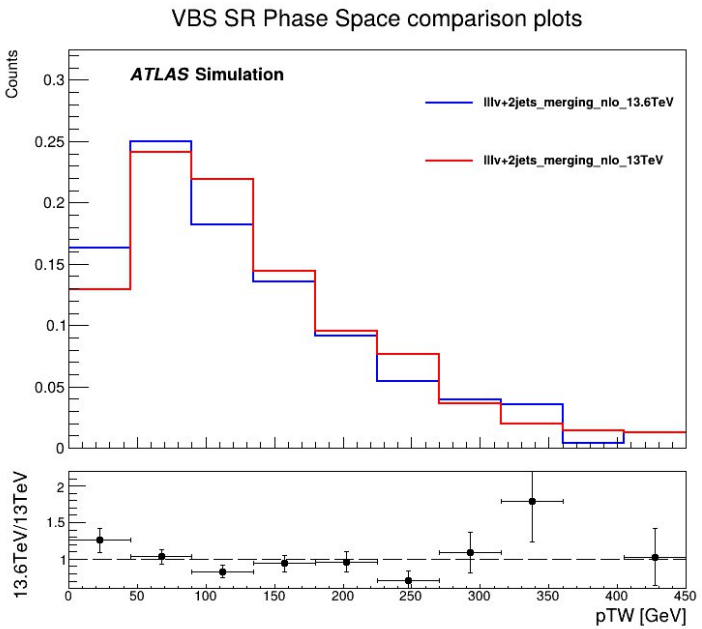


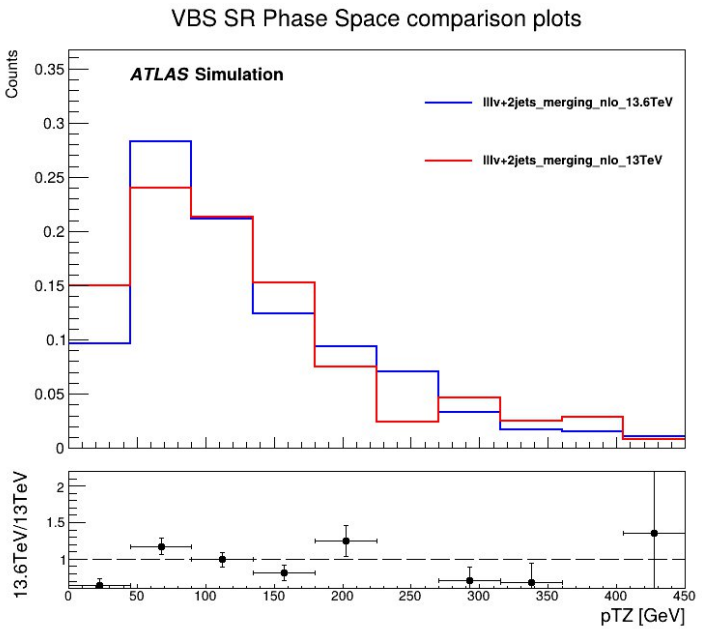


Good agreement between the predictions of the two samples
in the WZ Inclusive Phase Space!

WZ VBS Signal Region







Although there is a clear lack of statistics, the change in energy seems to have a negligible effect on the distirbutions

Generated Samples

✓ **Idea**: Replicate the NLO effect by generating the LO process and adding jets to the matrix element

Tools for generation

- **Matrix Element**: MG5_aMC@NLO
- **Parton Shower:** Pythia8
- **Matching/Merging Algorithm:** CKKW-L

Samples generated

- $pp \rightarrow WZ \rightarrow lll\nu + 0j, \sqrt{s} = 13\ TeV$
- $pp \rightarrow WZ \rightarrow lll\nu + 0, 1j, \sqrt{s} = 13\ TeV$
- $pp \rightarrow WZ \rightarrow lll\nu + 0, 1, 2j, \sqrt{s} = 13\ TeV$
- $pp \rightarrow WZ \rightarrow lll\nu + 0, 1, 2, 3j, \sqrt{s} = 13\ TeV$

Comparison against the **Reference Sample:** $pp \rightarrow WZ \rightarrow lll\nu + 0, 1, 2j@NLO, \sqrt{s} = 13\ TeV$

Generated Samples

Tools for generation

- **Matrix Element**: MG5_aMC@NLO
- **Parton Shower:** Pythia8
- **Matching/Merging Algorithm:** FxFx

Samples generated

- $pp \rightarrow WZ \rightarrow lll\nu + 0, 1, 2j, \sqrt{s} = 13\ TeV$
- $pp \rightarrow WZ \rightarrow lll\nu + 0, 1, 2j, \sqrt{s} = 13.6\ TeV$

- Comparison against the **Reference Sample:** $pp \rightarrow WZ \rightarrow lll\nu + 0, 1, 2j@NLO, \sqrt{s} = 13\ TeV$
- Comparison against the **Sherpa 2.2.16 Sample:** $pp \rightarrow WZ \rightarrow lll\nu + 0, 1@NLO + 2,3j@LO, \sqrt{s} = 13.6\ TeV$

Gridpack and Event Generation

Generation Steps

- **Gridpack generation**
  - Matrix element calcutations
  - Feynman digrams
- **Events generation**
  - Actual MC events

```
if not is_gen_from_gridpack():
    process = """
    set group_subprocesses True
    set nlo_mixed_expansion False
    import model loop_sm-no_b_mass
    define p = g u c b d s u~ c~ d~ s~ b~
    define j = g u c b d s u~ c~ d~ s~ b~
    define l = e+ mu+ ta+ e- mu- ta-

    define vl = ve vm vt ve~ vm~ vt~
    define wpm = w+ w-
    generate p p > wpm z / h [QCD] @ 0
    add process p p > wpm z j / h [QCD] @ 1
    add process p p > wpm z j j / h [QCD] @ 2
    output -f
    """

    process_dir = new_process(process)
else:
    process_dir = MADGRAPH_GRIDPACK_LOCATION


#Fetch default LO run_card.dat and set parameters
settings = {'parton_shower':'PYTHIA8',
            'req_acc':0.001,
            'lhe_version': '3.0',
            'sde_strategy' : 2,
            'ickkw': 3,
            'ptj': 10,
            'jetradius': 1.0,
            'maxjetflavor': 5,
            'mll': 4.,
            'mll_sf': 4.,
            'ptl': 1.,
            'nevents': int(nevents)
}
modify_run_card(process_dir=process_dir,runArgs=runArgs,settings=settings)
```