From ASP2010 to probing longitudinal VBS at a future hadron collider

Chilufya Mwewa

Brookhaven National Laboratory

3 December 2022

7th Biennial African School of Fundamental and Applied Physics

Contents

❖ Introduction

- ASP2010
- My career path
- Some opportunities at CERN and ATLAS
- My current work

❖ Longitudinal Vector Boson Scattering

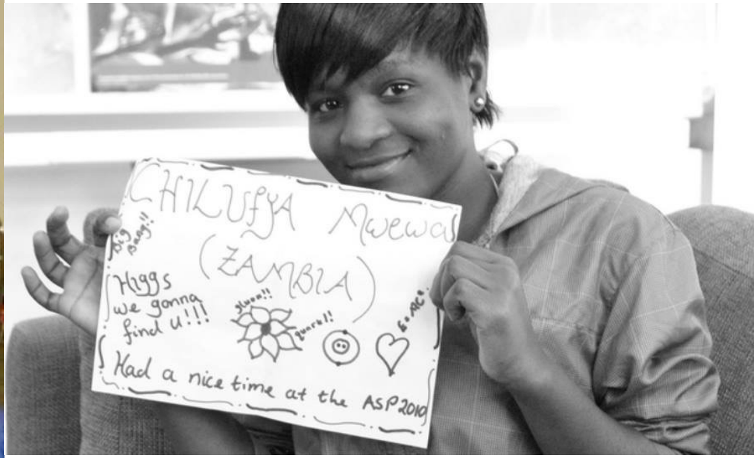
- Vector bosons and the Higgs boson
- Electroweak symmetry breaking
- Longitudinal Vector Boson Scattering (VBS)
- Longitudinal same-charge WW VBS results from the LHC

❖ Longitudinal same-charge WW VBS at a future hadron collider

- The future circular collider
- Selection of VBS events and background estimation
- Statistical analysis and results

Introduction

ASP 2010 – Stellenbosch, South Africa



- Final year undergrad - Learned about particle physics and CERN for the first time
- Met a lot of people – ASP is still my single biggest network to date

My career path

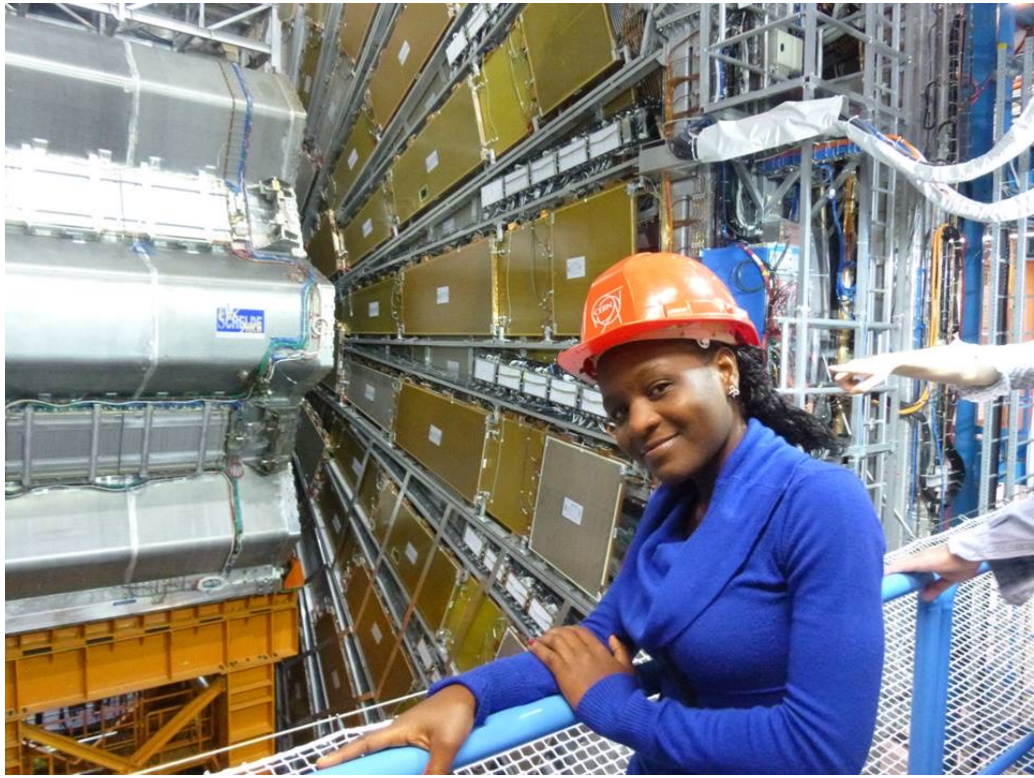
Bachelor's degree in Physics – University of Zambia (2011)

Postgraduate diploma – AIMS (2012)

- MSc. Experimental particle physics – University of Cape Town (2014)
- PhD Experimental particle physics – University of Cape Town (2020)
- Postdoc – University of Cape Town (July 2020 – October 2020)
- Postdoc at Brookhaven National Laboratory (November 2020 to date)

CERN summer student program

ATLAS cavern - 2013



- Every summer, CERN hosts students from all over the world and offers them an opportunity to work with CERN researchers on various aspects of experiments at CERN. (details here)
- Opportunity to learn about all of CERN's facilities; Lectures, tours…also an excellent Networking opportunity!
- You work on a dedicated project supervised by a CERN researcher. Opportunity to acquire new skills!
- **Applications are currently open until 30th January 2023**
- My experience was phenomenal! I would wish everyone to experience being a part of this progam

ATLAS PhD grant

- Prestigious grant awarded to a few PhD candidates working on any aspect of the ATLAS experiment – no restriction on nationality!
- Opportunity to spend at least one year based at CERN – I spent 1.5 years at CERN on this grant
- Opportunity for in-person collaboration with specialists on your team!
- [Details here]

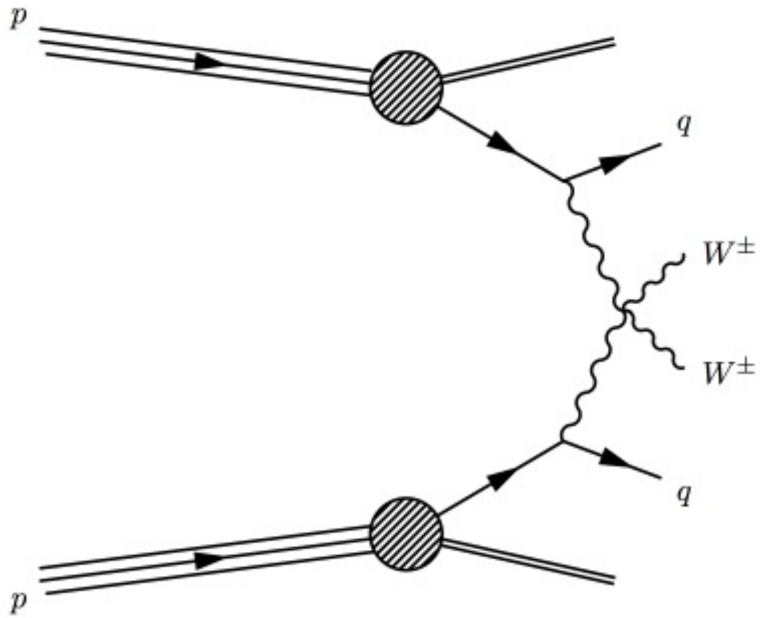
My current work

❖ **Detector operations**

- Software developer for the ATLAS Liquid Argon calorimeter
- Part of run coordination team for the Liquid Argon calorimeter – generally oversee all work related to operation of the Liquid Argon calorimeter
- Super-shifter – responsible for the training of shifters on the ATLAS control room's calorimeter desk

❖ **Physics analysis**

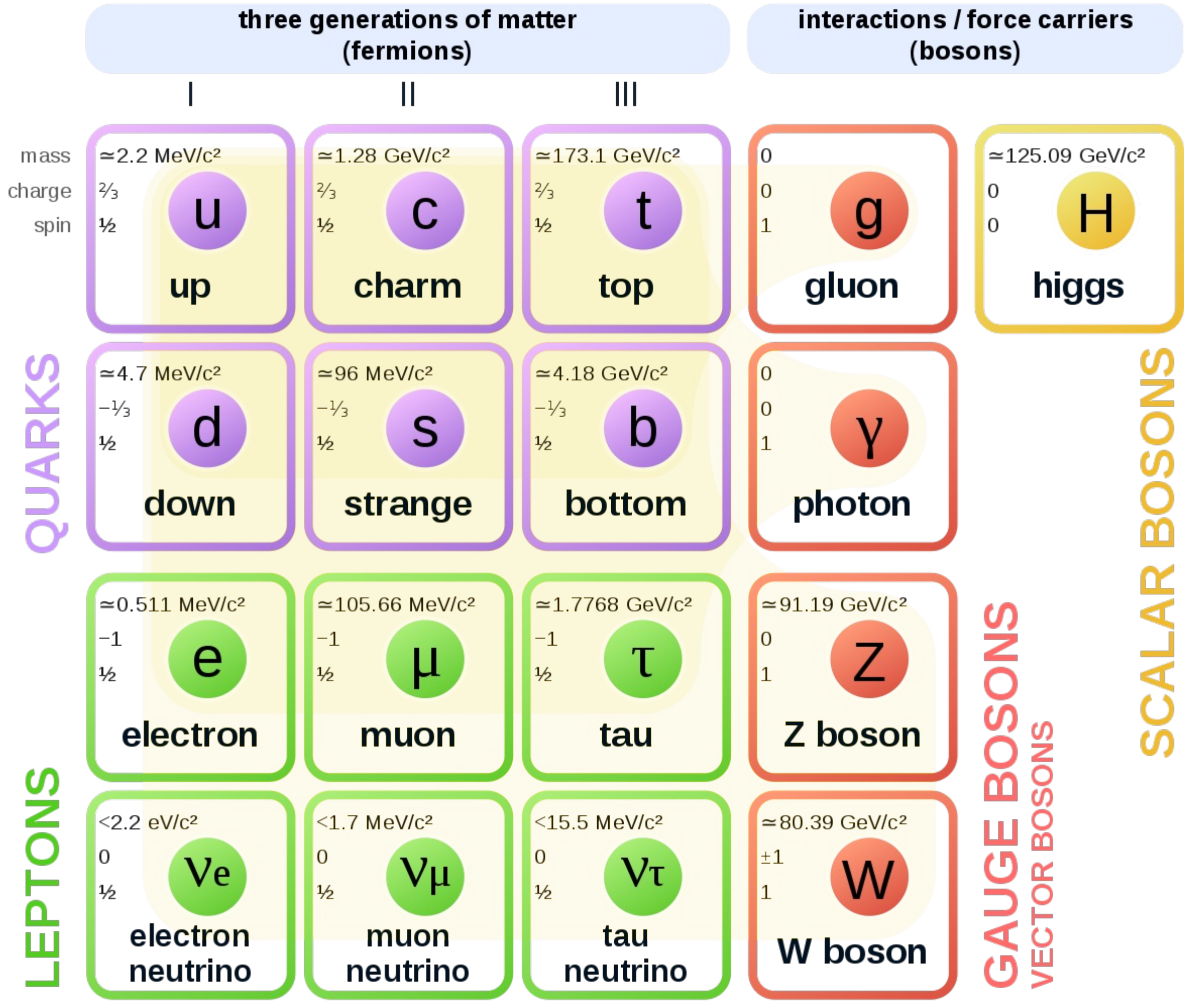
- Vector Boson Scattering (VBS) analyses in the same sign WW channel both at the LHC (real data) and at future hadron colliders (simulated data)
  - ➢ In this talk: Longitudinal VBS at future hadron colliders



Longitudinal Vector Boson Scattering

Vector bosons and the Higgs boson

The Standard Model of particle physics



Source: https://en.wikipedia.org/wiki/Standard_Model

- **Vector bosons**: spin 1 force-carrying particles

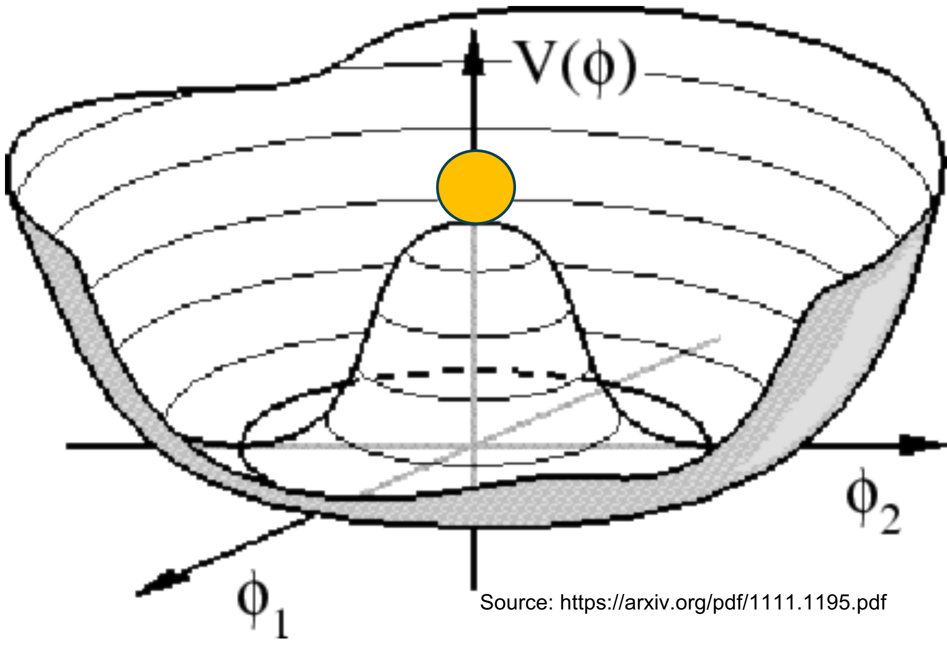
Gluon ⟶ strong force, photon ⟶ electromagnetic force, W and Z ⟶ weak force

- **Higgs boson:** spin 0 particle responsible for particle masses
- 1970's: Glashow, Weinberg and Salam showed that electromagnetic and weak forces could be described as a single electroweak interaction (electroweak unification)
- Current observation of electromagnetic and weak forces as separate entities is attributed to the Higgs mechanism; W and Z bosons acquire mass while the photon remains massless
  - ➢ Electroweak symmetry is broken

Electroweak symmetry breaking

- The Standard Model (SM) is based on gauge theories
  - ➢ certain symmetries must be obeyed
- To write the SM Lagrangian in such a way that it obeys the underlying symmetry, mass terms for vector bosons are not allowed
  - ➢ Electroweak force carriers must have the same (or symmetric) zero mass, but W and Z bosons are massive
- To keep the Lagrangian invariant despite the massive W and Z bosons, a spontaneous symmetry breaking mechanism is introduced
- Higgs mechanism: Higgs boson interacts with W and Z bosons, making them massive, hence breaking electroweak symmetry
  - ➢ This also gives W and Z bosons an extra polarization state (the **longitudinal polarization**)

Higgs potential



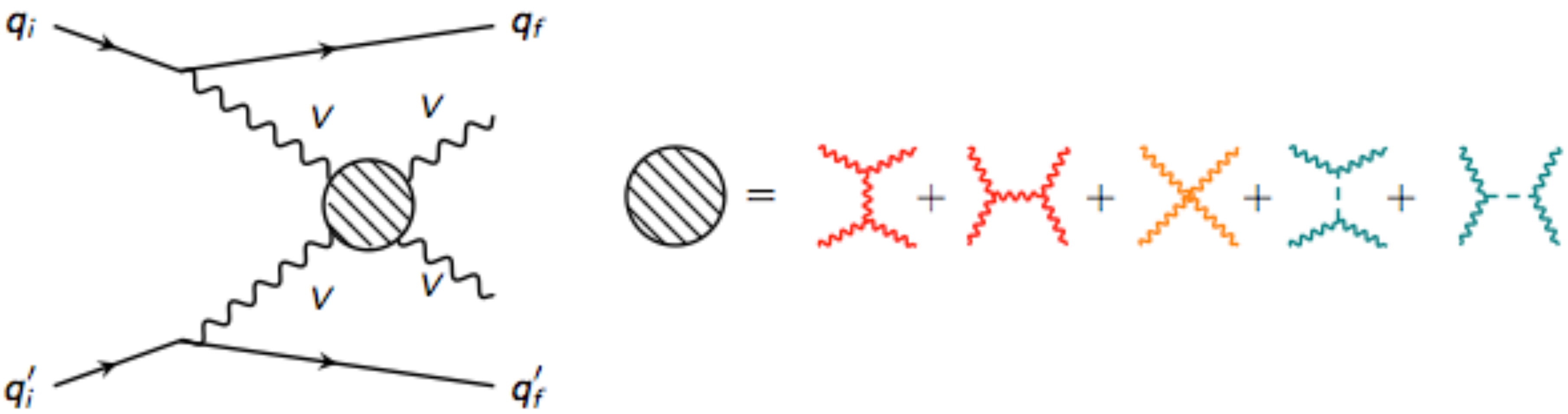
Source: https://arxiv.org/pdf/1111.1195.pdf

Spontaneous symmetry breaking happens when the Higgs rolls down to the circle of minimum potential

❖ **Ability to probe longitudinally polarized vector bosons is important in our understanding of the nature of electroweak symmetry breaking**

Vector boson scattering

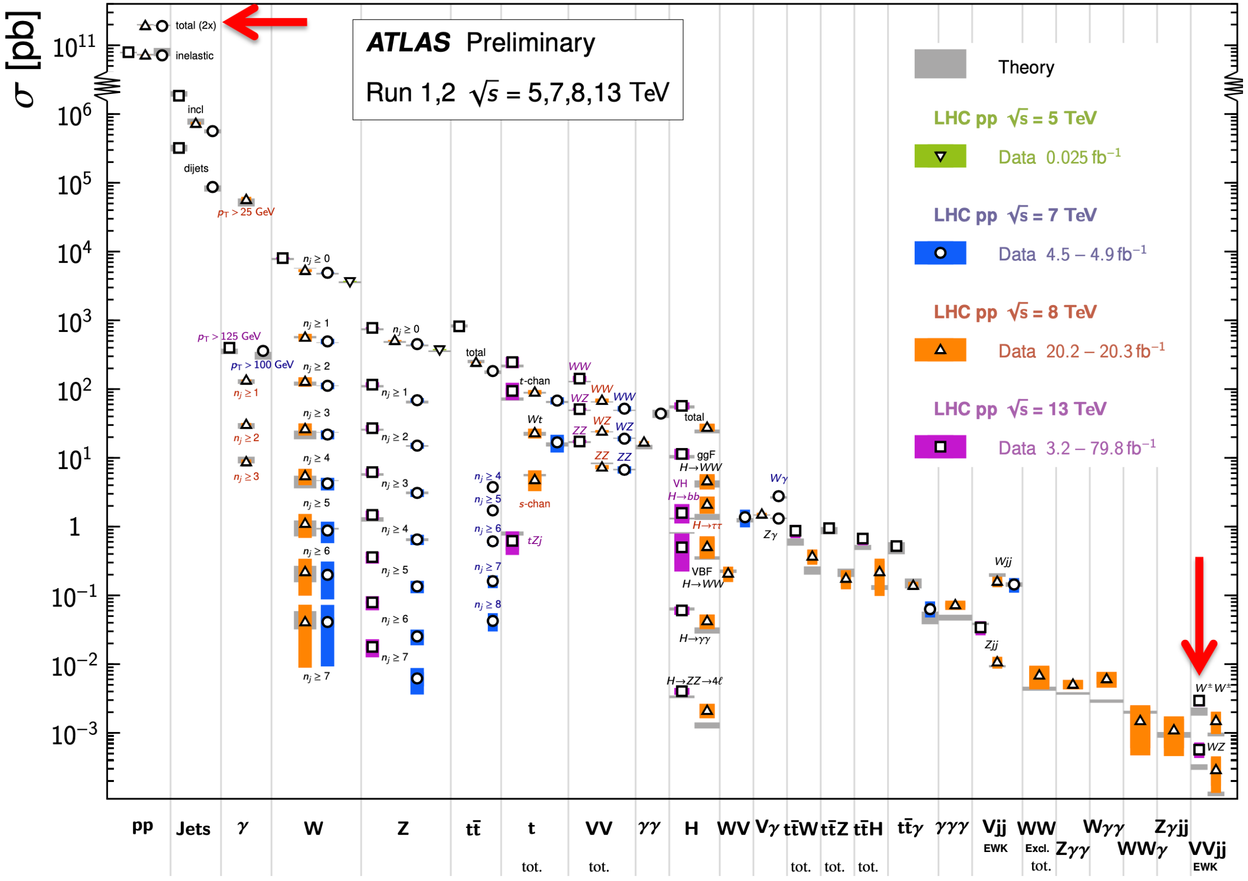
- We can probe longitudinally polarized vector bosons by studying Vector Boson Scattering (VBS) processes



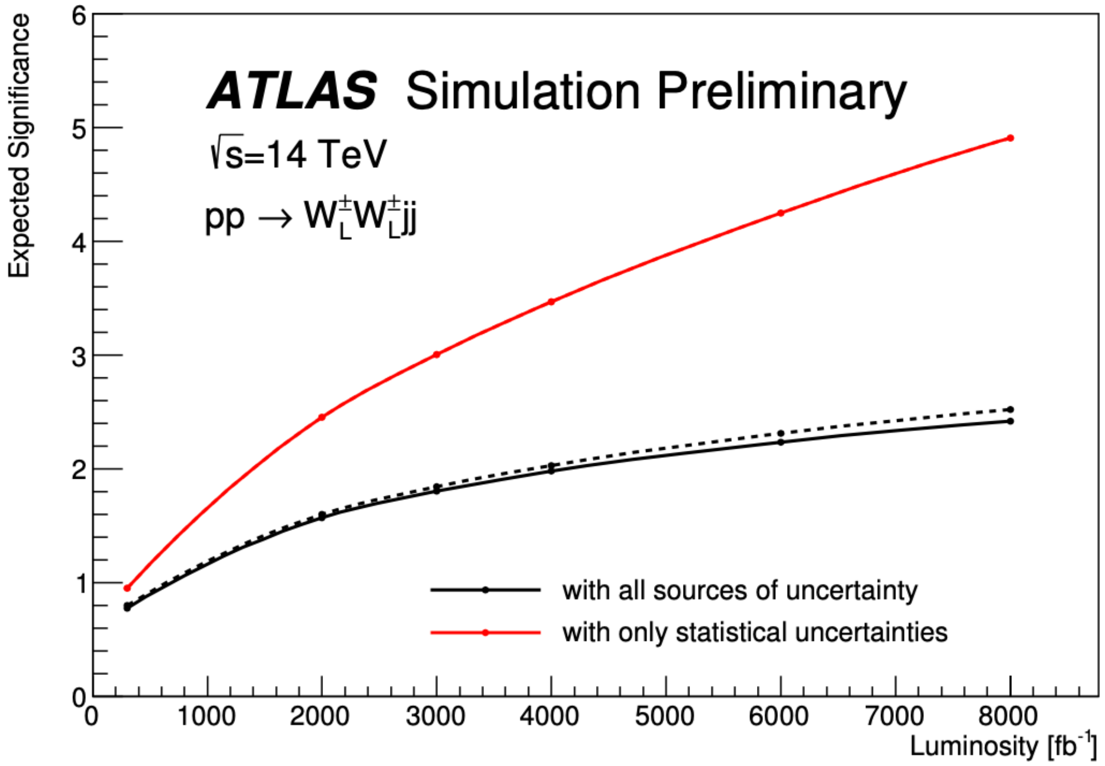
- VBS is particularly important for this because it requires the presence of the Higgs boson for unitarity to be preserved at high energies
  - ➢ Unitarity: Probabilities of all diagrams contributing to a particular VBS process should add up to one
  - ➢ In the absence of Higgs diagrams, probability keeps growing with energy leading to probabilities > 1
- Studied in various processes; same-charge WW, opposite charge WW, WZ, ZZ
- Next slides: Scattering of longitudinally polarized same-charge WW bosons

Results from the LHC

- Access to longitudinally polarized same-charge WW bosons is extremely challenging at the Large Hadron Collider (LHC) due to its small cross-section (about 7% of the total same-charge WW scattering cross-section)
- Projections at the high energy/high luminosity indicate that this process will be challenging to observe at the LHC



Source:https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-010/



Source: https://inspirehep.net/files/ead46ef053a4df9617669e65106e666d

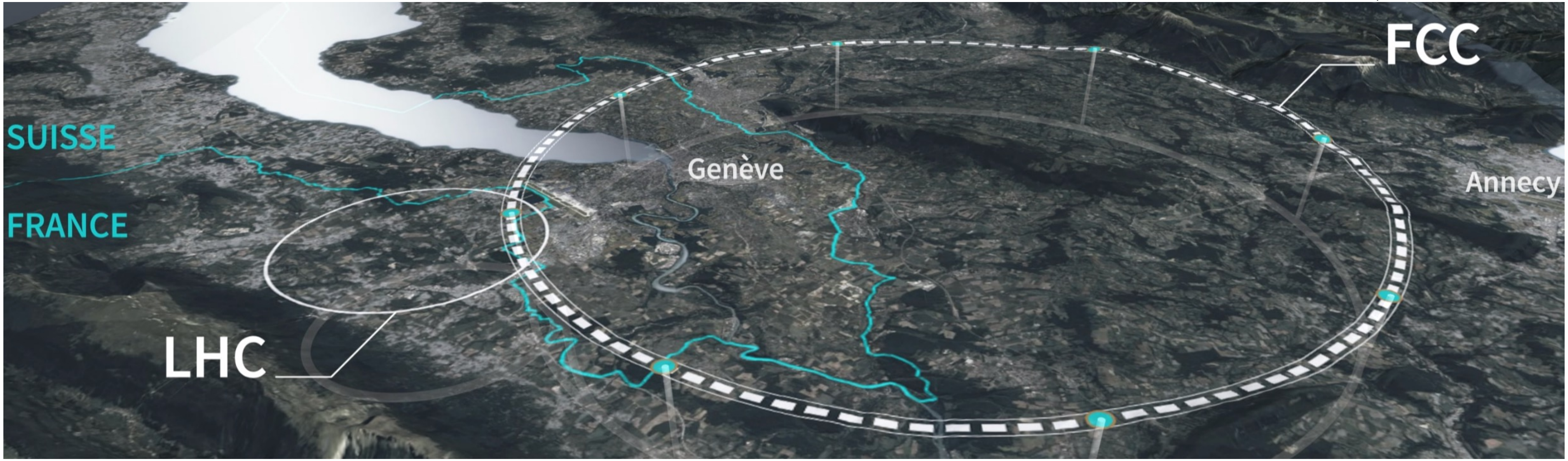
- Can we measure this process at a future hadron collider, and with what precision?

Longitudinal same-charge WW VBS at a future hadron collider

The future circular collider

- Next generation collider proposed to take over the Large Hadron Collider (LHC) era

Source:https://fcc.web.cern.ch/overview



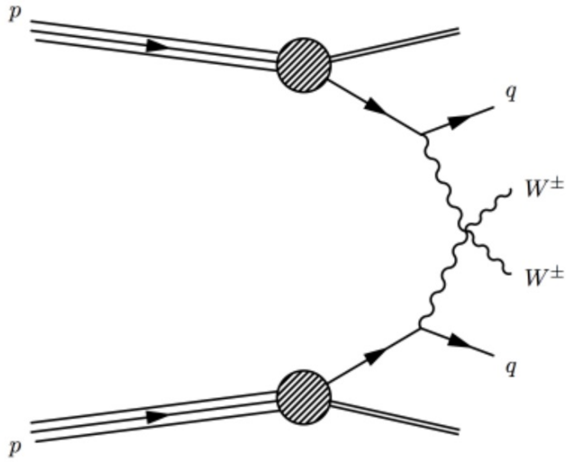
- Proposed to start with a lepton collider (FCC-ee) operating at energies between ~91 GeV and ~340 GeV
- To be followed by a hadron collider (FCC-hh) at 100 TeV
- Anticipated to reach an integrated luminosity of 5 times larger than the LHC
- Unique instrument to further explore SM and beyond the SM physics

❖ Following study was performed for Snowmass2021
- ➢ Snowmass is a strategy defining the future of high energy physics in the United states

Event selection and background estimation

- Study is based purely on simulation (using the madgraph event generator)
- Detector effects are simulated using a detector response simulation framework called Delphes

Electroweak VBS

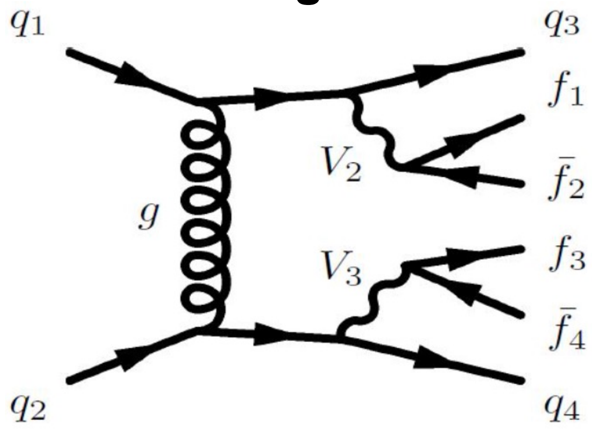


❖ **The W bosons decay to a lepton and a neutrino**

Event selection

- Two same-charge leptons with high transverse momentum
- Large missing transverse energy to account for neutrinos
- Two forward jets with large dijet invariant mass

Strong VBS



Backgrounds: any other processes that could mimic the signal

- Only **same sign WW QCD**, **WZ (QCD and EW)** and **tZq** backgrounds are considered
- All detector-specific backgrounds (charge-flip, fakes) are ignored

Statistical analysis and results

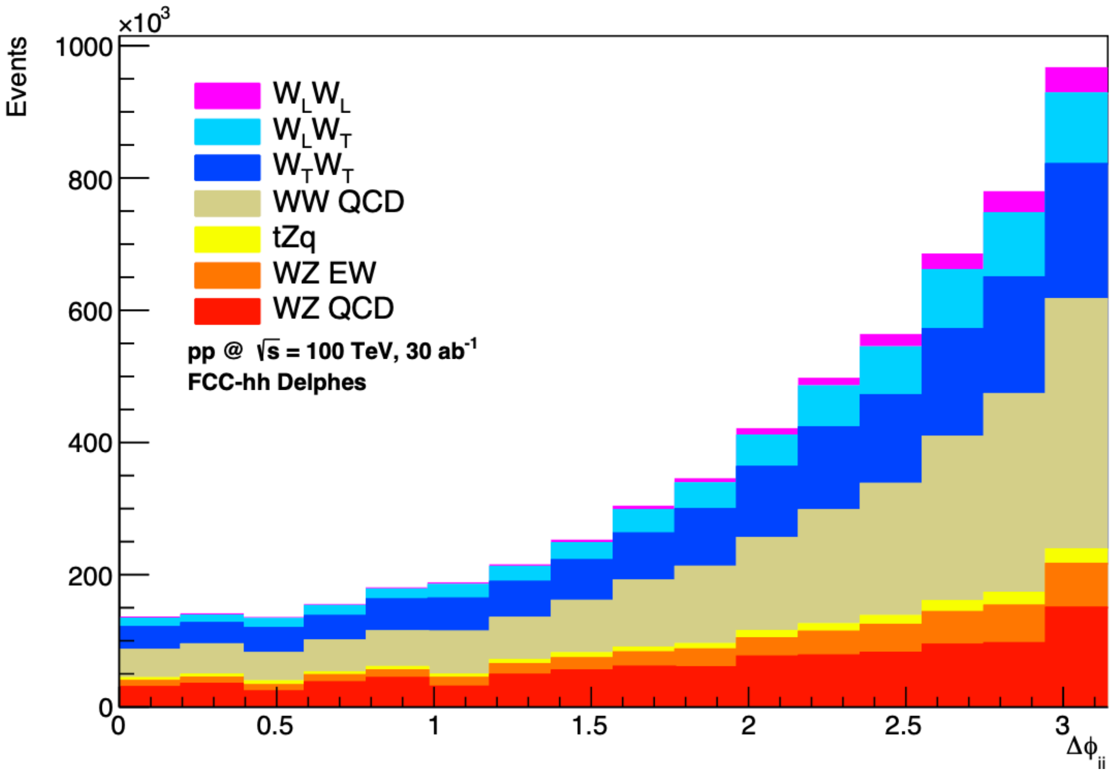
- Use a maximum likelihood fit to the $\Delta\phi_{jj}$ distribution
- Expected number of events per bin:

$$N_i^{exp}(\theta) = \mu \cdot N_i^{sig}(\theta) + N_i^{bkg}(\theta)$$

  - ➢ μ is the signal strength
  - ➢ θ are systematic uncertainties (only luminosity here)
- Probability of observing a particular number of data events per bin is given by a likelihood function
- An artificial dataset (Asimov data) is used

$$L(\mu|\theta) = \prod_i Poisson(N_i^{obs}|N_i^{exp})$$

- We're interested in the value of μ that maximizes the likelihood and its uncertainty
- **Result:** We can measure this process at a future 100 TeV hadron collider with 17% precision



Polarization	Signal Strength		
	$\sqrt{s} = 27$ TeV	$\sqrt{s} = 50$ TeV	$\sqrt{s} = 100$ TeV
μ_{LL}	1 ± 0.39	1 ± 0.22	1 ± 0.17

Link to paper