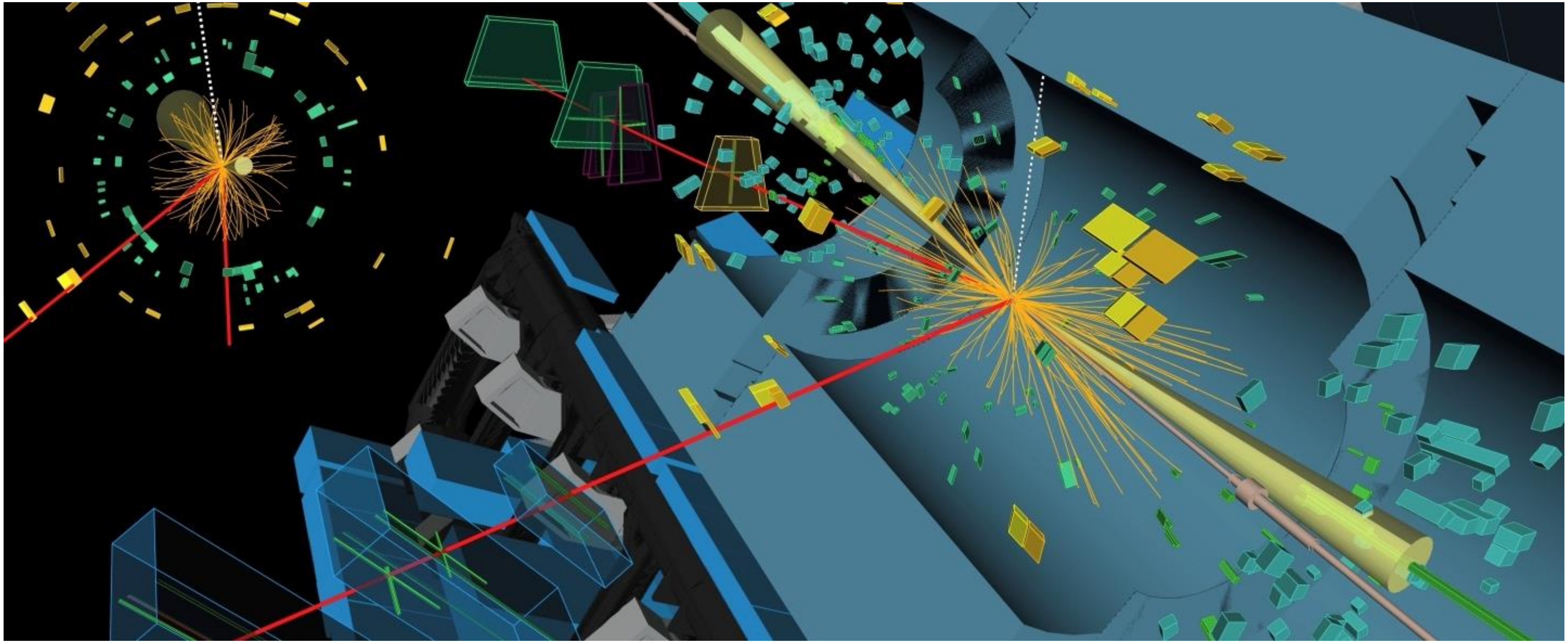


Testing Electroweak Symmetry Breaking through Same-Charge WW Scattering at the LHC and beyond

Queen Mary University of London Seminar, 20 May 2026

Chilufya Mwewa

DESY (Hamburg)

DESY.

ATLAS EXPERIMENT

Outline

- ❑ Overview of ElectroWeak Symmetry Breaking (EWSB)
- ❑ Testing EWSB via same-charge WW scattering at the LHC
- ❑ Longitudinally polarized same-charge WW scattering at the LHC, HL-LHC and future colliders
- ❑ Summary

Overview of ElectroWeak Symmetry Breaking

Discovery of the Higgs boson

- My first project in particle physics involved analyzing a small Higgs → $\gamma\gamma$ ATLAS dataset.
- Later that year, the Higgs boson was discovered.

- This was exciting news all over the world!
  - ❖ **The final missing piece in the SM had been found.**

The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

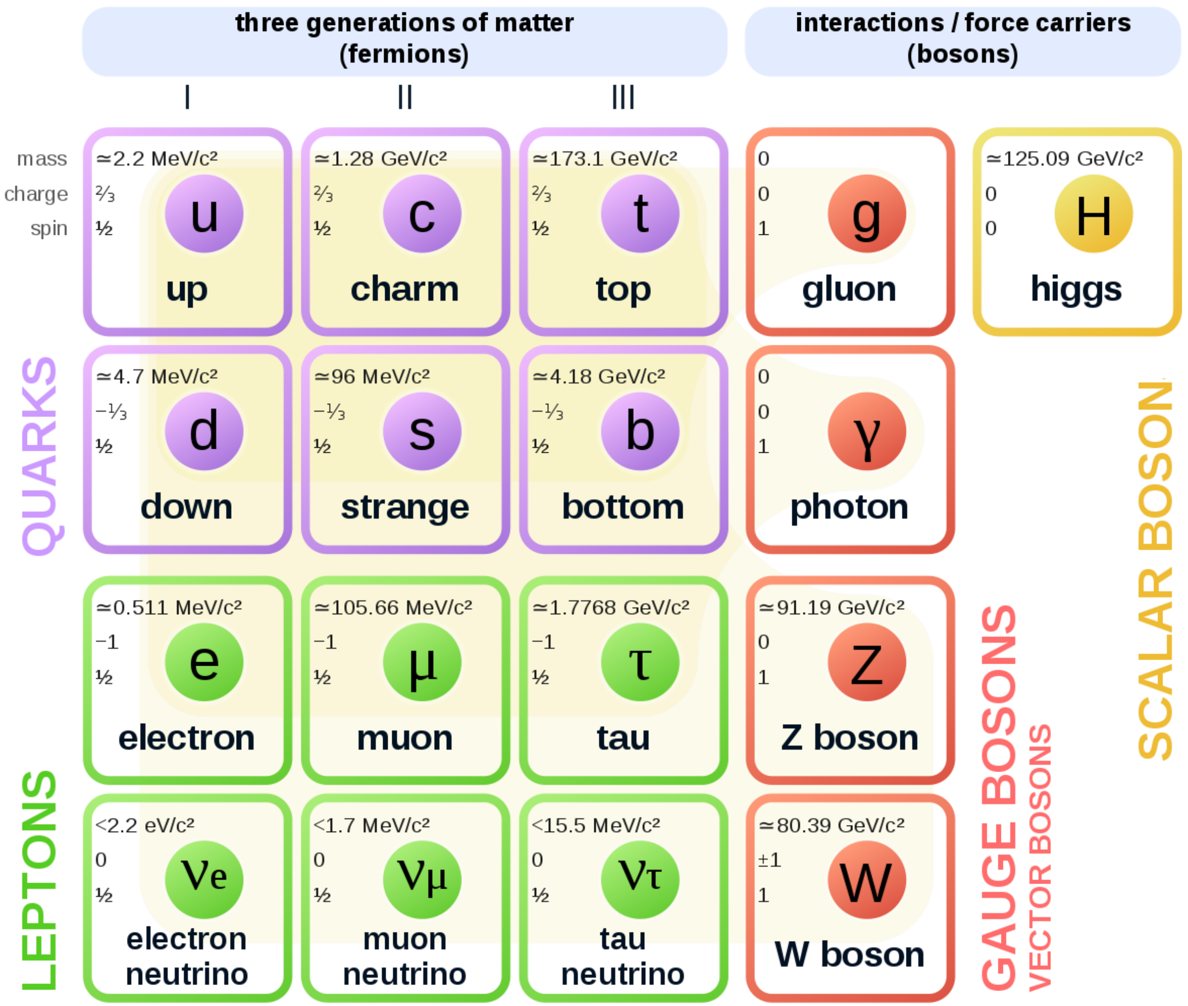
'God particle' likely discovered

Boson could be 'missing cornerstone of particle physics'

CBC News · Posted: Jul 04, 2012 4:21 AM EDT | Last Updated: July 4, 2012

home.cern.ch

The Higgs boson completes the Standard Model



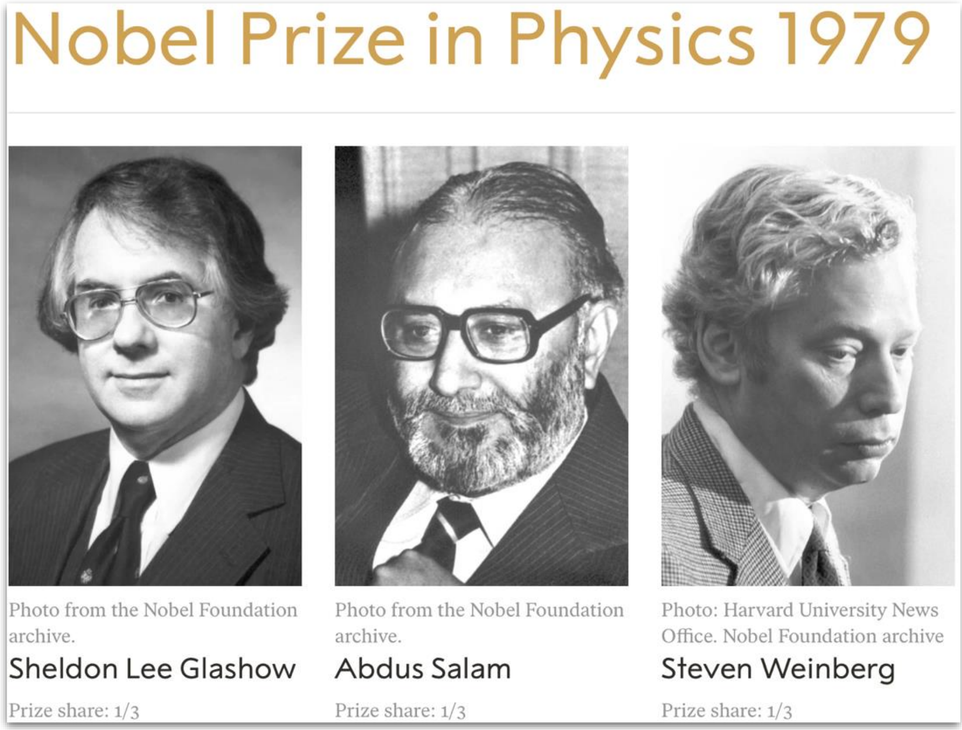
wikipedia

- Gluons mediate the strong force.
- Photons mediate the electromagnetic force.
- W and Z bosons mediate the weak force.
- The Higgs boson gives mass to all particles that interact with it.
- W and Z bosons are massive.
- Gluons and photons are massless.

❖ **W and Z bosons interact with the Higgs, whereas gluons and photons don't.**

Electroweak unification

- Glashow, Weinberg and Salam showed that electromagnetic and weak forces are unified at very high temperatures.



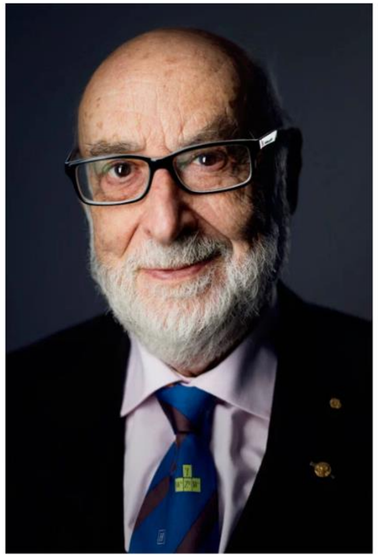
NobelPrize.org

- ❖ This introduced the electroweak theory which treats electromagnetic and weak forces together in a unified way.
- ❖ The $SU(2) \times U(1)$ gauge group in the SM was thus introduced. [full SM: $SU(3) \times SU(2) \times U(1)$]
- ❖ **The SM Lagrangian must be invariant under local symmetry transformations of this gauge group.**

But, mass terms are not allowed....

- Vector boson mass terms are not allowed.
  - ➢ Electroweak force carriers must have the same (zero) mass.
  - ➢ But, W and Z bosons are massive – Electroweak symmetry is broken.

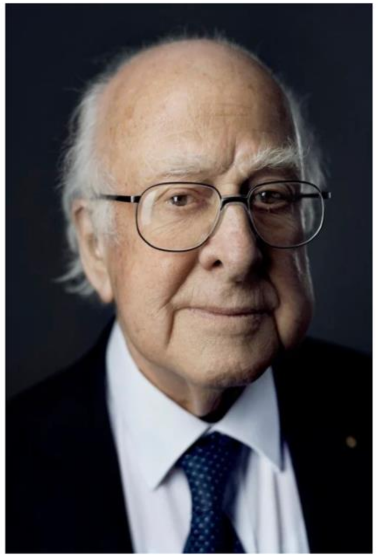
Nobel Prize in Physics 2013



© Nobel Prize Outreach. Photo: A. Mahmoud

François Englert

Prize share: 1/2



© Nobel Prize Outreach. Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

NobelPrize.org

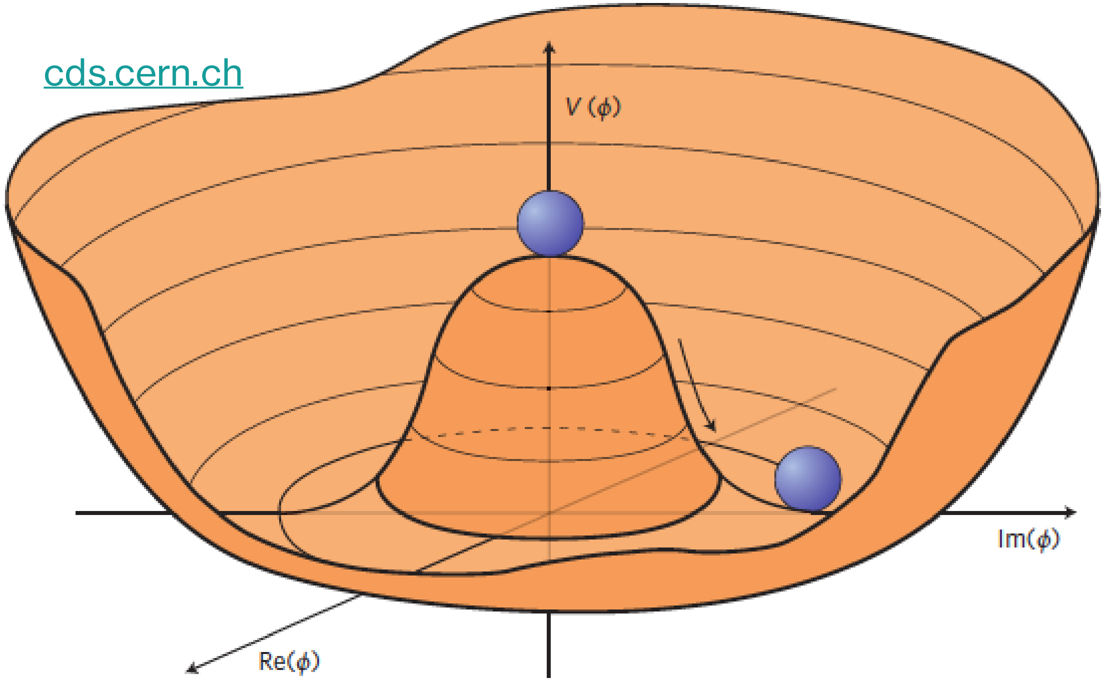
❖ **To keep the Lagrangian invariant despite the massive W and Z bosons, Glashow, Weinberg and Salam incorporated a spontaneous symmetry breaking mechanism – The Higgs mechanism.**

- ➢ Formulated by Brout, Englert and Higgs in 1964.

Electro-Weak Symmetry Breaking (EWSB)

SM Higgs potential: $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$

cds.cern.ch



- Maximum potential is at the top of the "hat" ($\phi = 0$) - an unstable point.
- ➢ Naturally, the field relaxes to the minimum potential.
- ➢ This results in a non-zero Vacuum Expectation Value.
- ➢ Consequently, W and Z bosons gain mass.
  - ➢ Electroweak symmetry is broken.

EWSB: Open questions

- The Higgs boson discovery in 2012 and subsequent measurements of its couplings have been a major milestone in re-affirming our understanding of EWSB.

- However, there are still some open questions.
  1. Is the Higgs potential what we think it is?
  2. Is the Higgs mechanism solely responsible for EWSB or are there other theories Beyond the SM (BSM) that contribute?

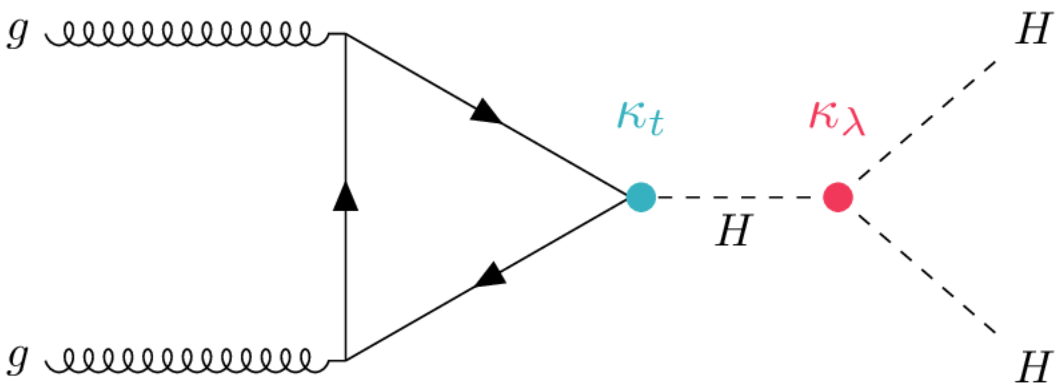
❖ **So, there's still some work left to probe and study EWSB.**

Probing EWSB

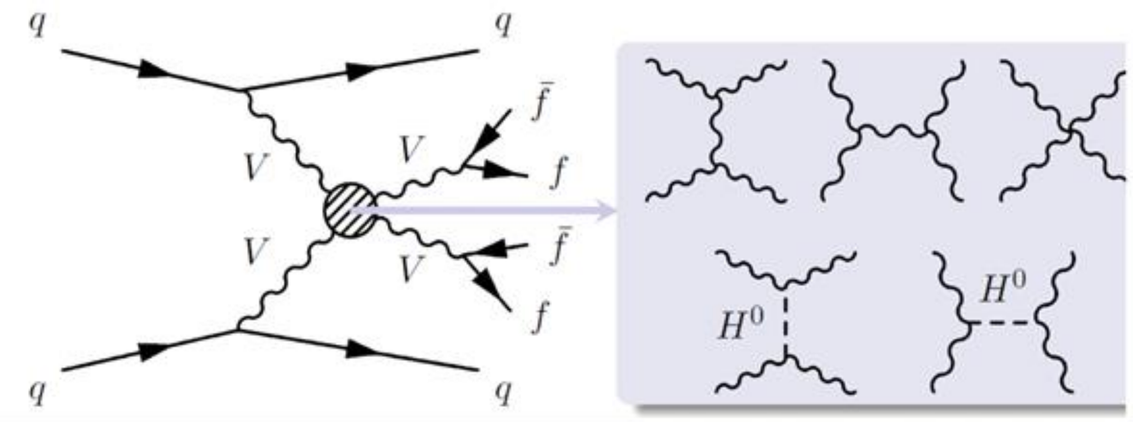
- To verify the shape of the Higgs potential, we can measure Higgs self-couplings (Di-Higgs production).
  - ➢ In some BSM models, the Higgs potential is modified, which leads to deviations in κ_λ.

❖ **We can measure electroweak Vector Boson Scattering (VBS) processes (next slides)**.

- ➢ This also provides an important probe for BSM physics contributions to EWSB

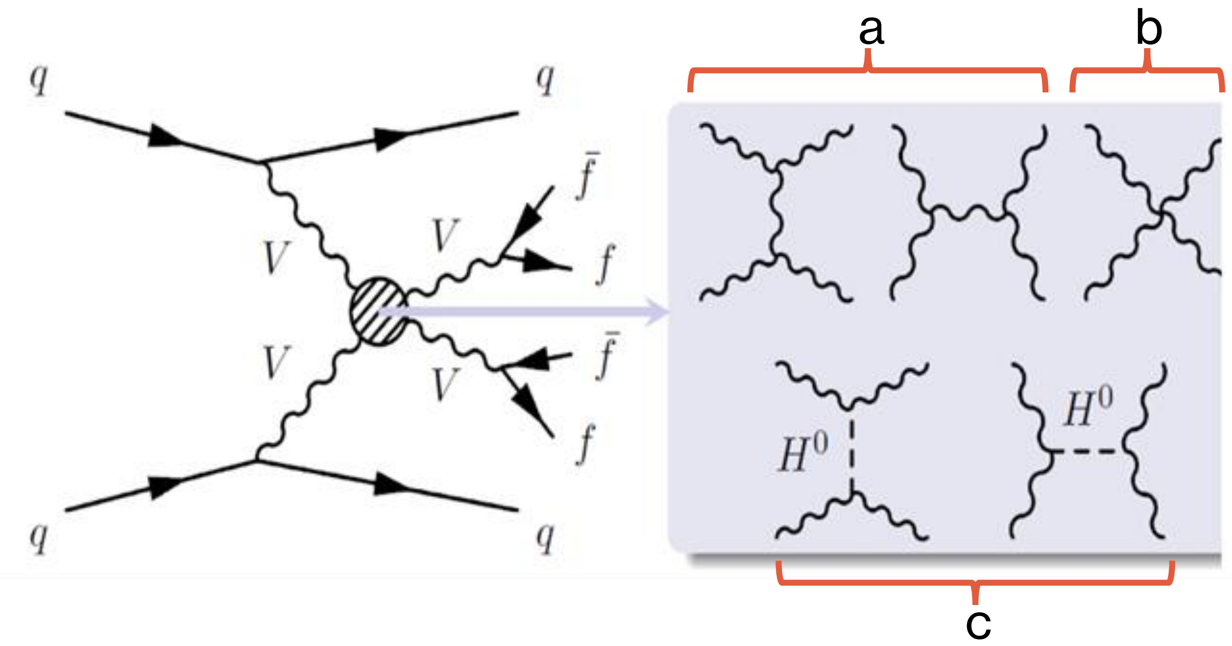


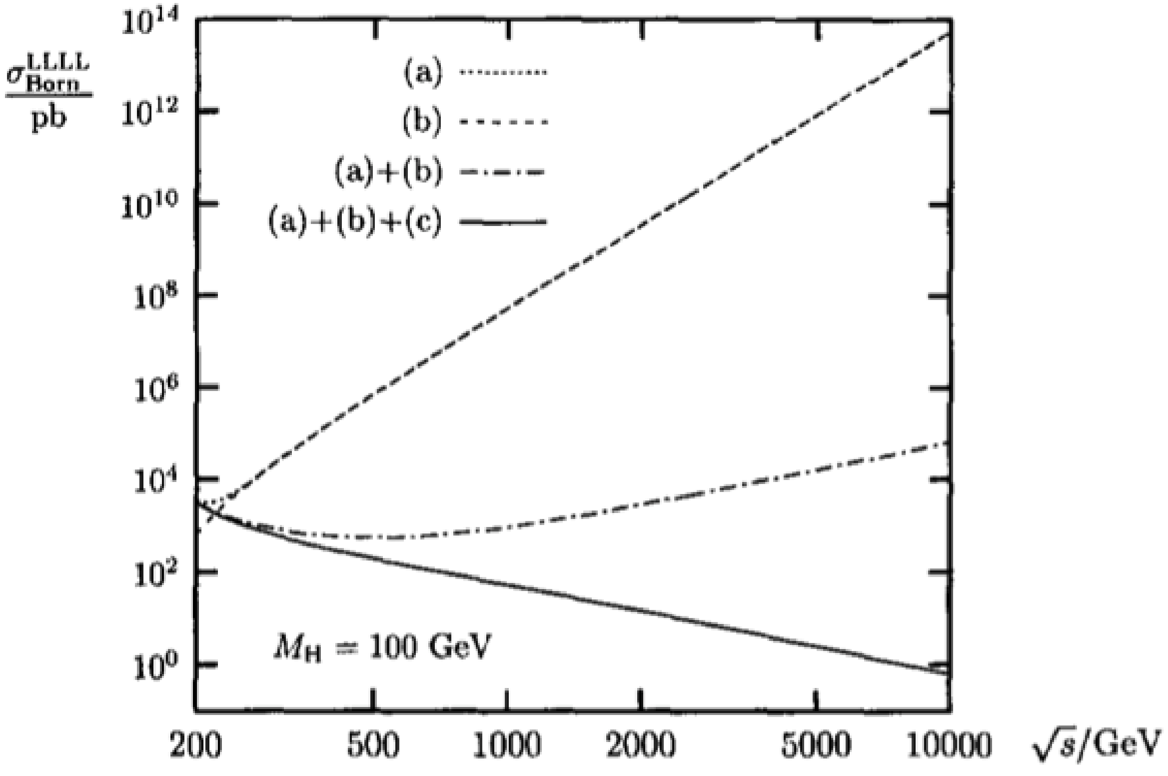
[ATLAS briefing: HH → $bb\gamma\gamma$]



* Any inconsistency with SM predictions would imply a revolution in our understanding of the universe.

Electroweak VBS



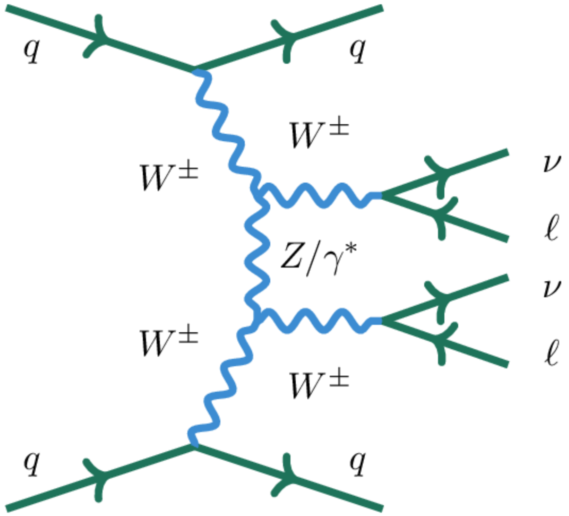


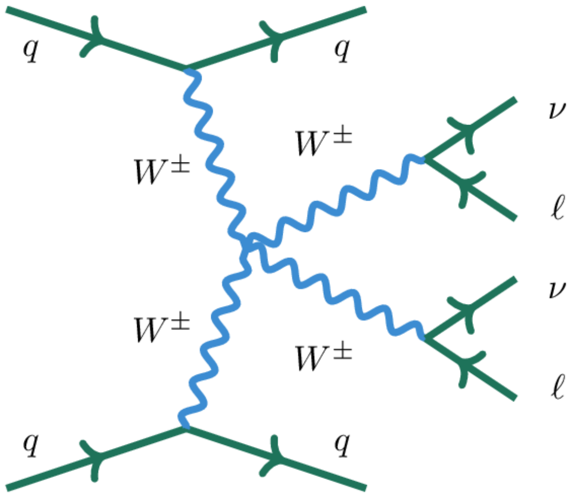
Nucl.Phys.B525:27-50

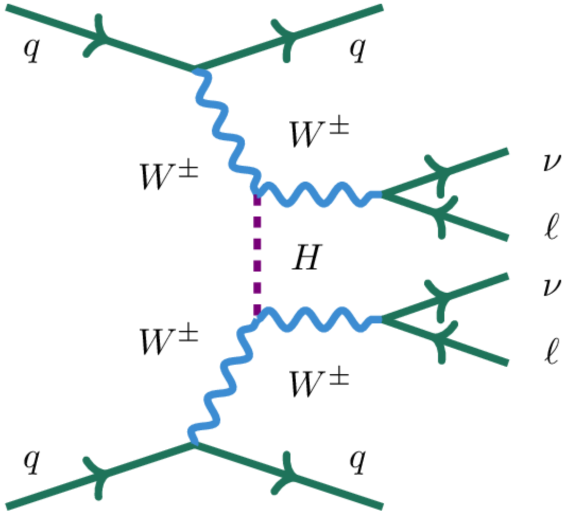
- VBS requires the presence of the SM Higgs boson for unitarity preservation at high energies.
- In the absence of Higgs diagrams, scattering amplitudes of **longitudinally polarised** vector bosons would increase as a function of centre of mass energies ($\sqrt{s}$), eventually violating unitarity.

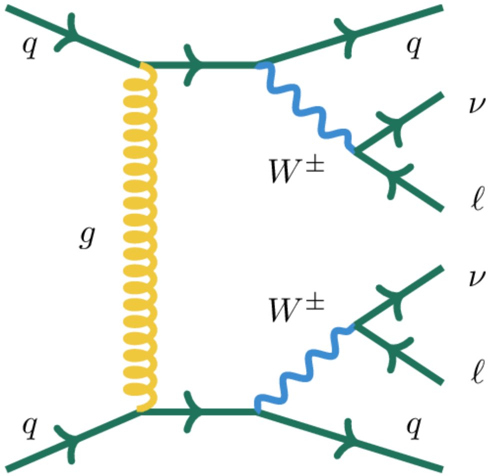
Same charge WW scattering at the LHC

Same-Charge WW ($W^{\pm}W^{\pm}jj$) scattering







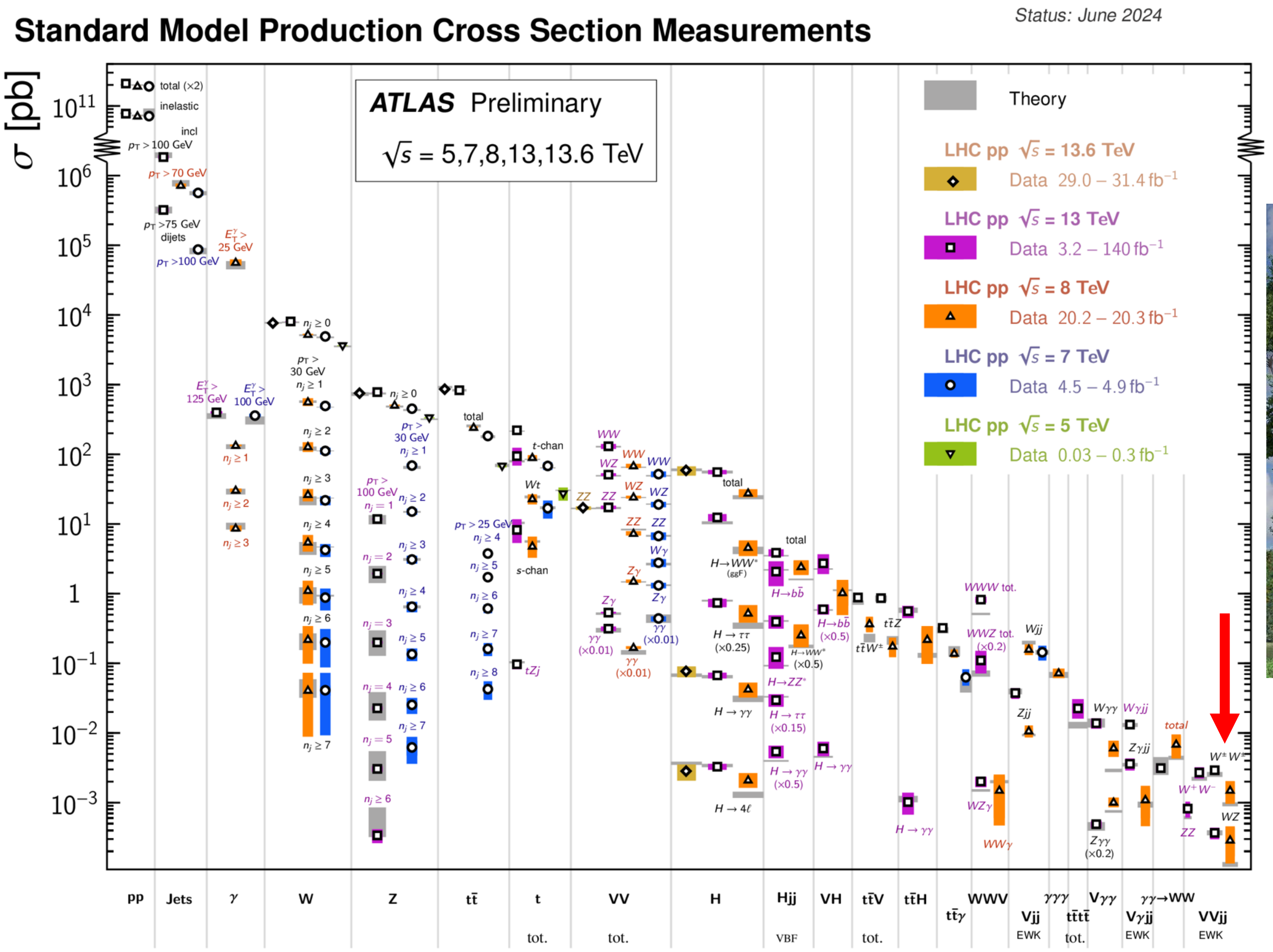


- QCD-induced VV production has the same final state as the VBS signal.

❖ **$W^{\pm}W^{\pm}jj$ has the largest Electroweak to QCD ratio among VBS processes.**

   ➢ QCD-induced background is largely suppressed.

$W^{\pm}W^{\pm}jj$ cross-section

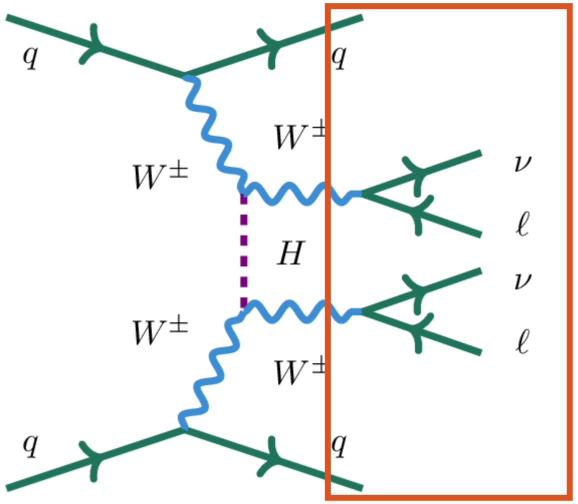


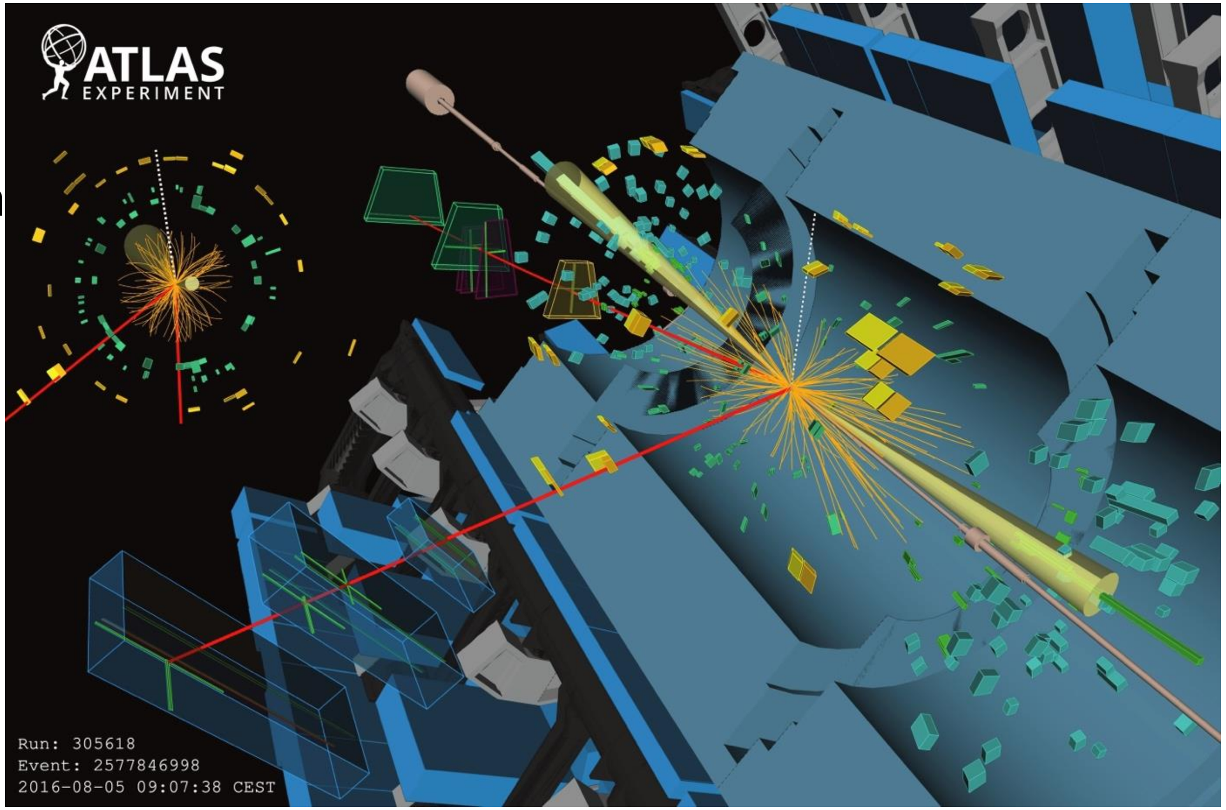
ATL-PHYS-PUB-2024-011

livescience.com

Selecting $W^{\pm}W^{\pm}jj$ events

- Two isolated same-sign leptons (electrons or muons) with high transverse momentum.
- Large missing transverse energy.
- VBS topology:
  - ➢ Two forward jets with high transverse momentum
  - ➢ Large di-jet invariant mass.
  - ➢ Large separation in rapidity.

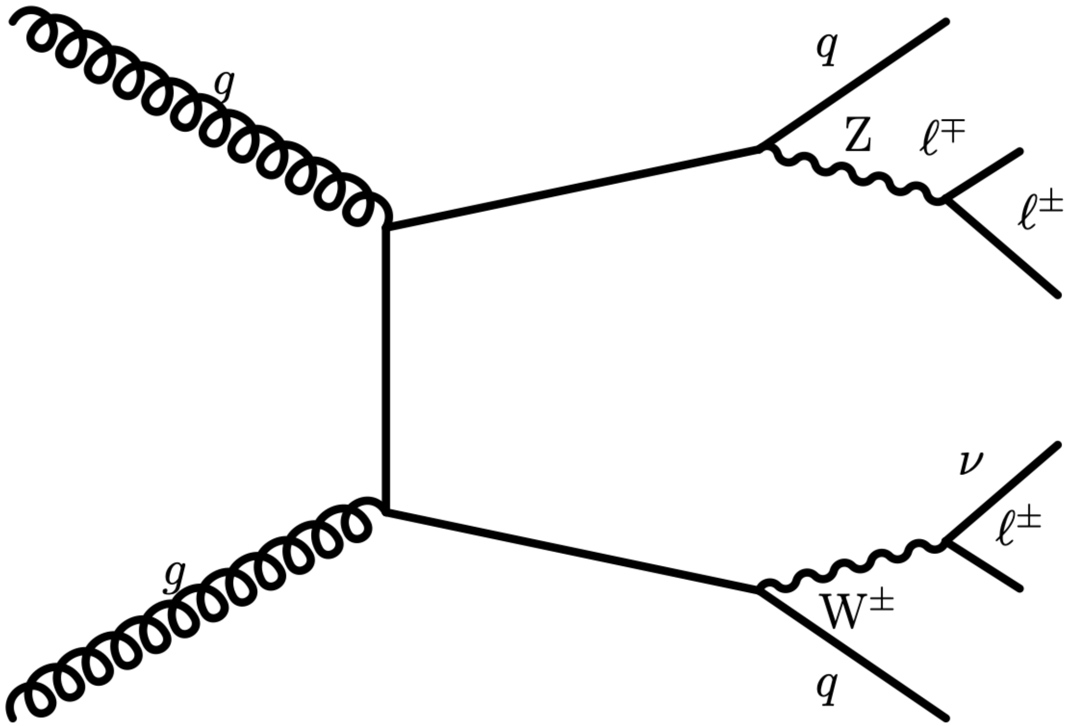




Background and signal estimation

❖ **The major background arises from QCD-induced WZ production.**

- It is modelled using Monte-Carlo (MC) simulations.
- A normalization factor is estimated by comparing data to MC in a dedicated control region.

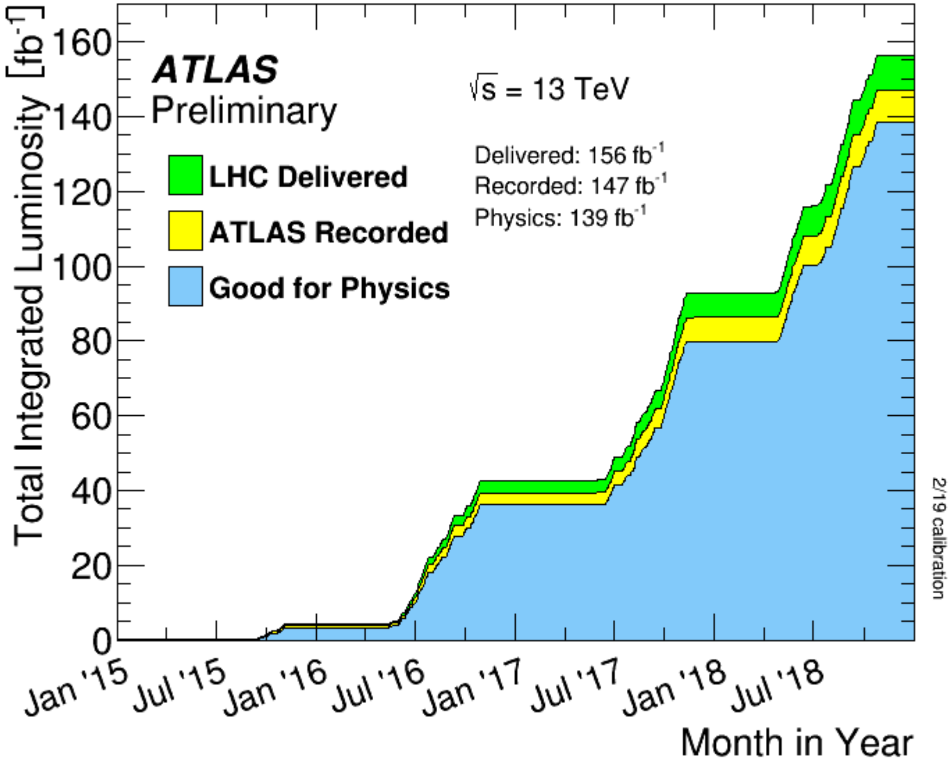


❖ **Other background processes are estimated either from MC simulations or using data-driven methods.**

❖ **The expected $W^{\pm}W^{\pm}jj$ signal is estimated from MC simulations.**

ATLAS data analysis

ATLAS online luminosity



- The LHC has completed two previous runs and is currently in Run 3.
  - ➢ Run 1 (2010 to 2012), Run 2 (2015 to 2018) and Run 3 (Since 2022)

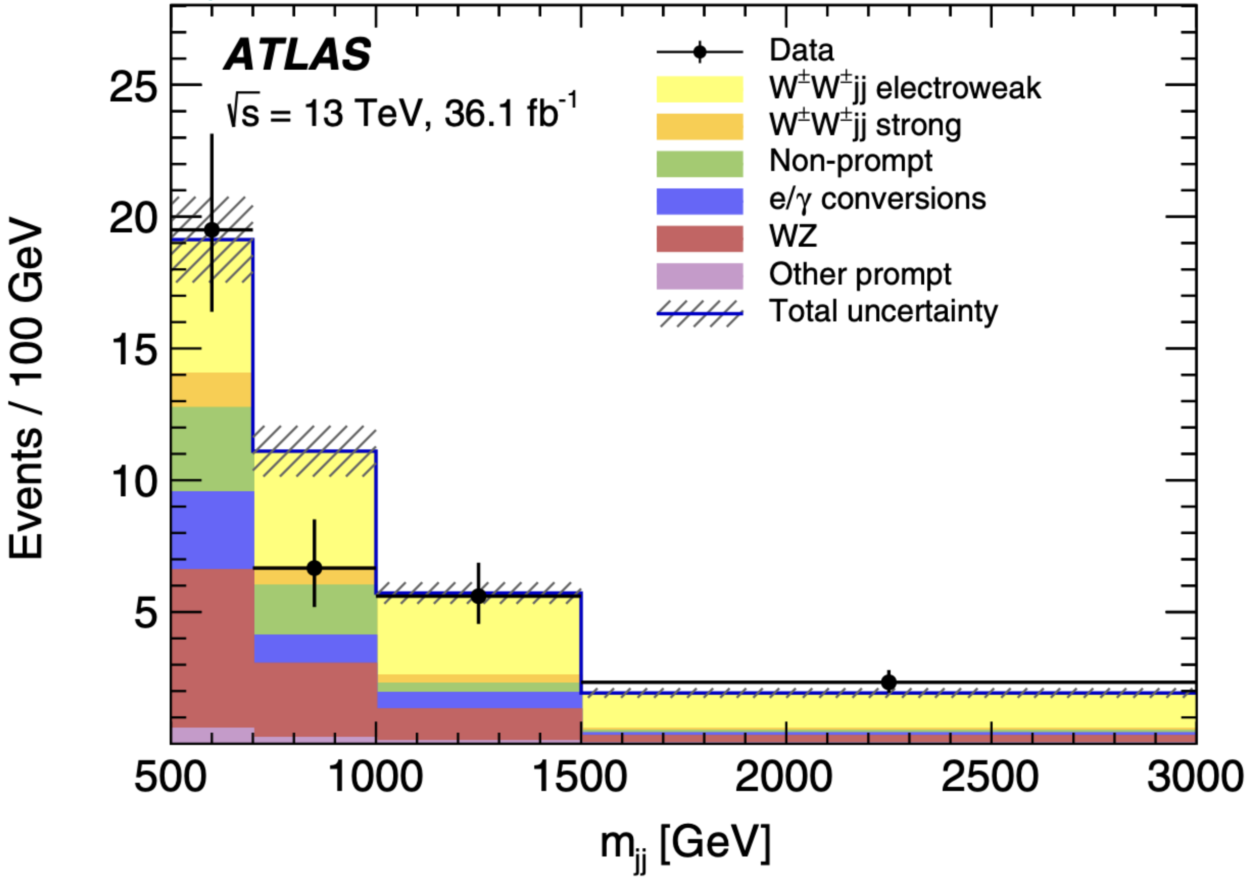
❖ **In Run 2, ATLAS recorded ~ 140 fb^{-1} of data.**

❖ **We perform a binned maximum likelihood fit of the data to the di-jet invariant mass (m_{jj}).**

- Fit ingredients: Expected signal and background events + systematic uncertainties.
- We extract the signal strength from the fit and can further determine the significance and cross-section.

First observation of $W^{\pm}W^{\pm}jj$ in ATLAS

Phys. Rev. Lett. **123**, 161801

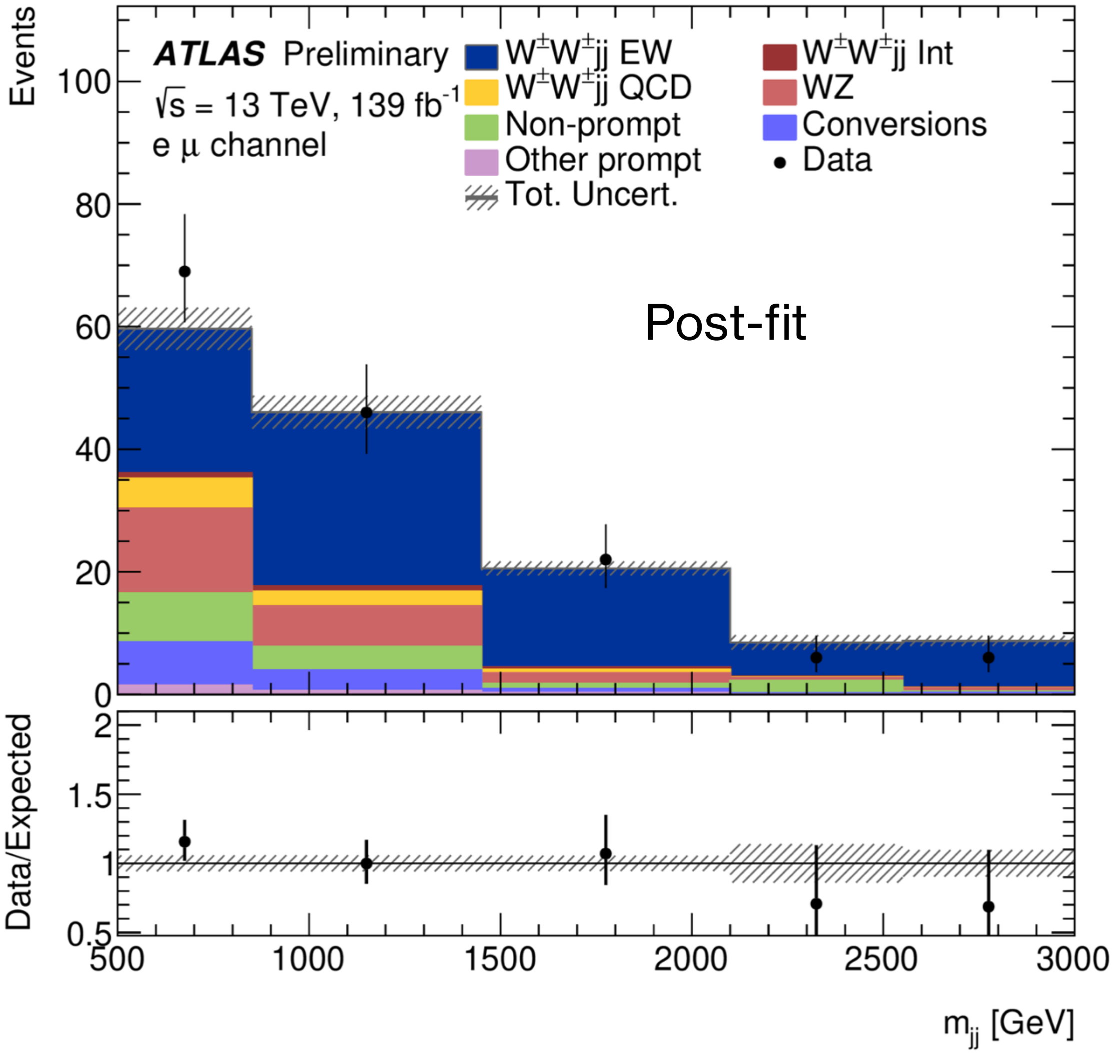


- With partial Run 2 data (36 fb^{-1}), we had the first observation of $W^{\pm}W^{\pm}jj$ in ATLAS.

$$\sigma_{obs} = 2.91^{+0.51}_{-0.47}(\text{stat}) \pm 0.23(\text{sys})\ \text{fb}$$

Precision $W^{\pm}W^{\pm}jj$ cross-section measurement

JHEP 04 (2024) 026



❖ With the full Run 2 dataset, we had a much more **precise measurement**.

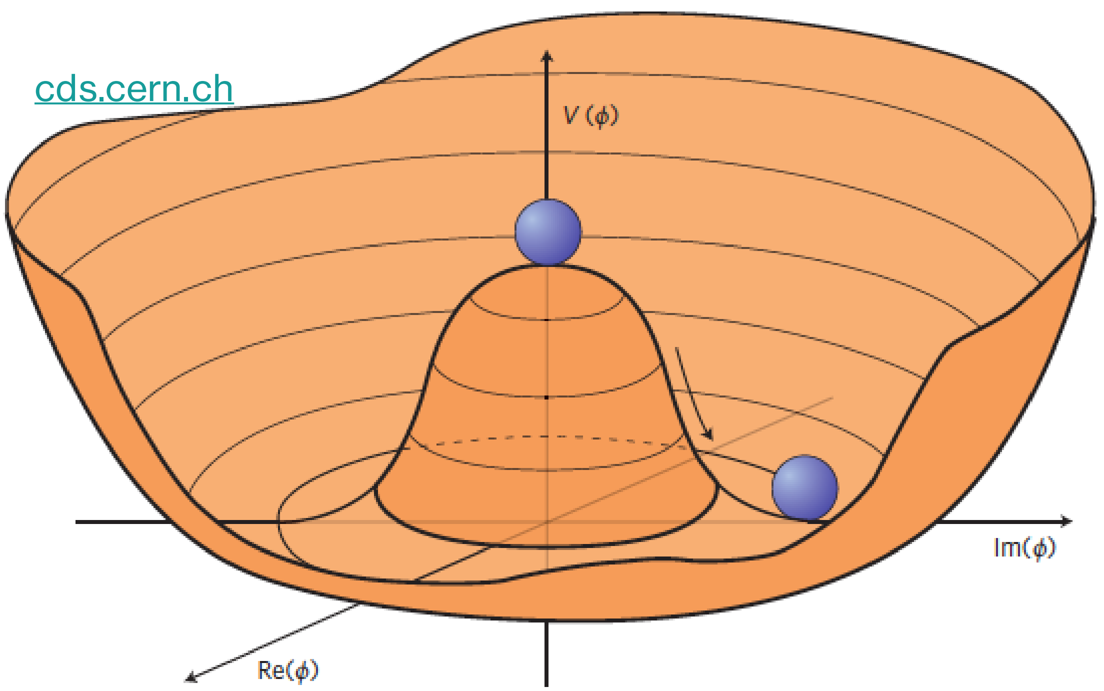
Description	$\sigma_{\text{fid}}^{\text{EW}}$, fb
Measured cross section	$2.88 \pm 0.22\,(\text{stat.}) \pm 0.19\,(\text{syst.})$
MG_AMC@NLO+HERWIG	$2.53 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$
MG_AMC@NLO+PYTHIA	$2.55 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$
SHERPA	$2.44 \pm 0.03\,(\text{PDF}) \pm^{0.40}_{0.27}\,(\text{scale})$

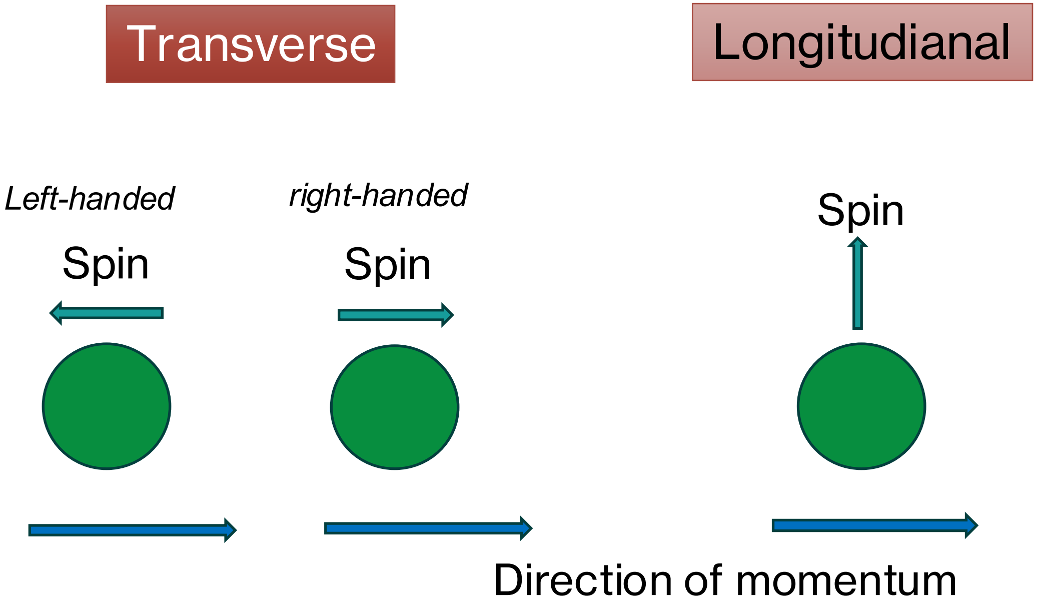
❖ **No deviation from the SM.**

Longitudinally polarized $W^{\pm}W^{\pm}jj$

An extra polarization state

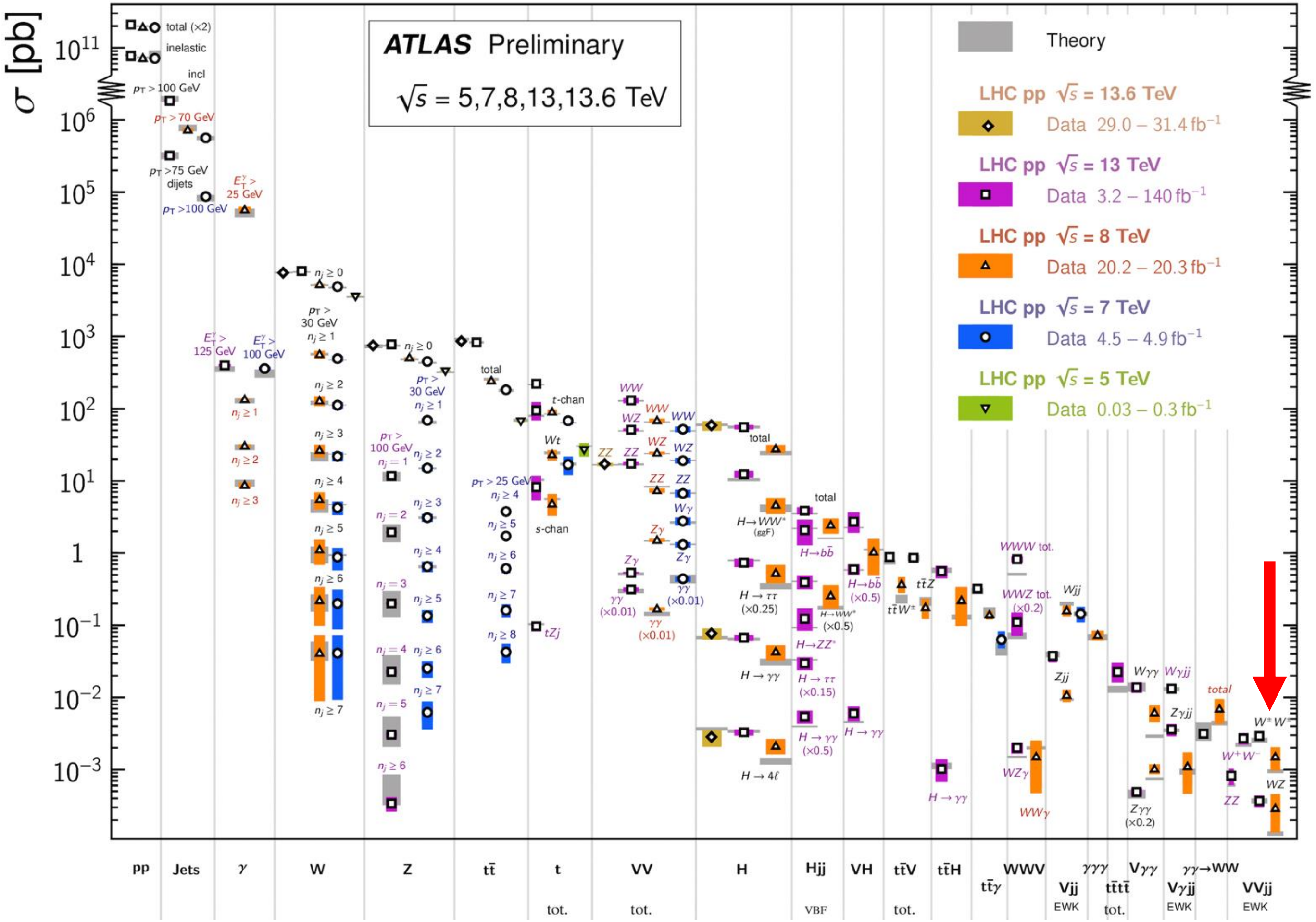
cds.cern.ch





- ❖ After EWSB, W and Z bosons gain mass and an extra polarization state – **the longitudinal polarization state**.
- ❖ Massles particles only have transverse polarization state.
- ❖ Longitudinal polarization states arise directly from EWSB and serve as evidence for it.
- ❖ Measuring their cross-sections and fractions is a crucial step in the test of EWSB.

Longitudinally polarized $W^{\pm}W^{\pm}jj$ cross-section

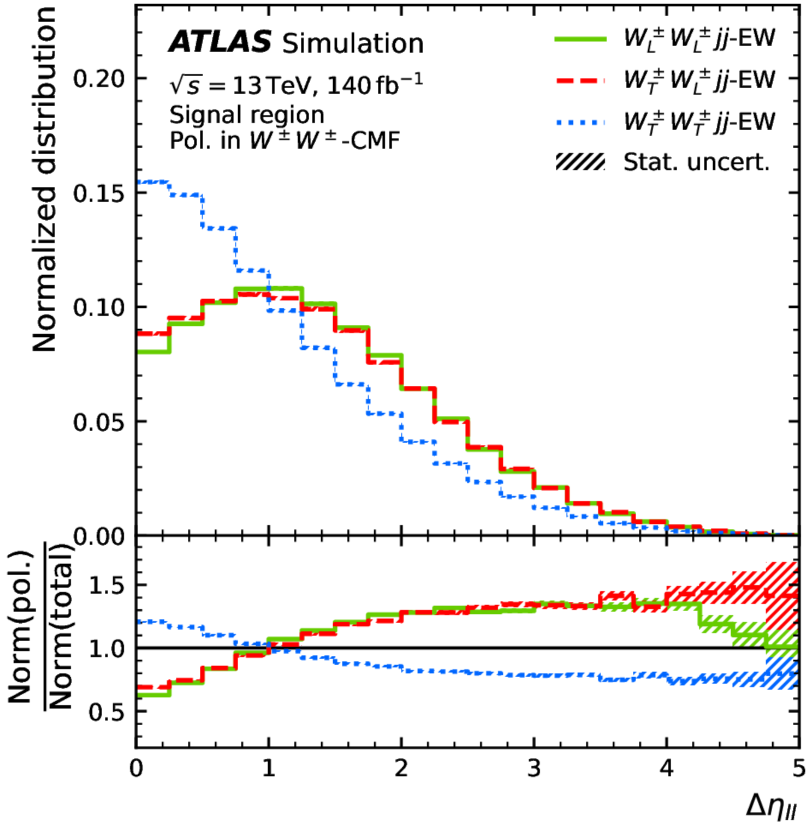


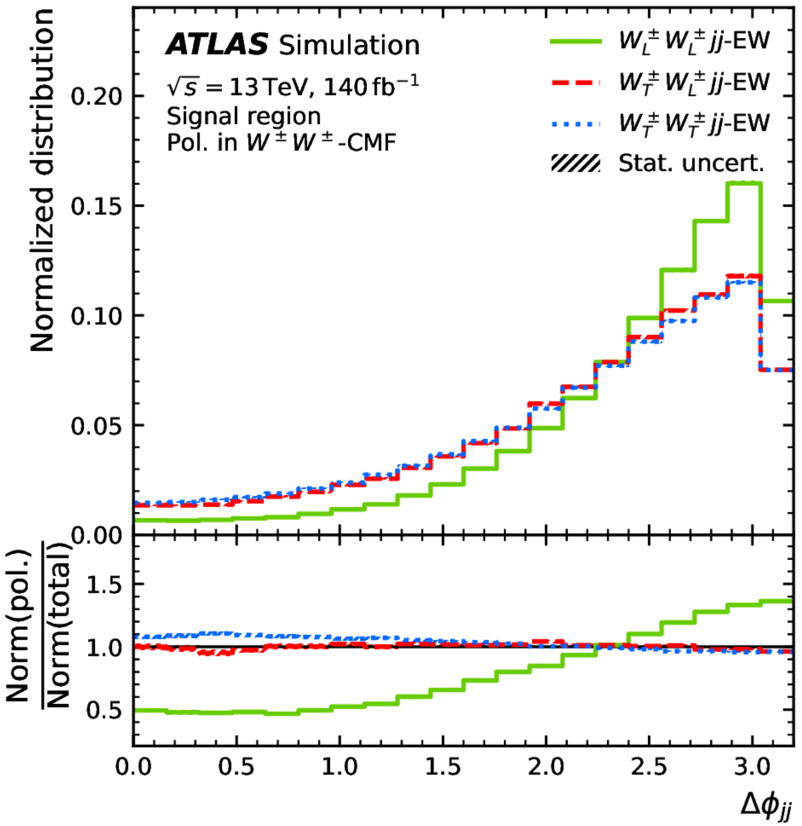
❖ **Access to longitudinally polarized $W^{\pm}W^{\pm}jj$ processes is extremely challenging at the LHC.**

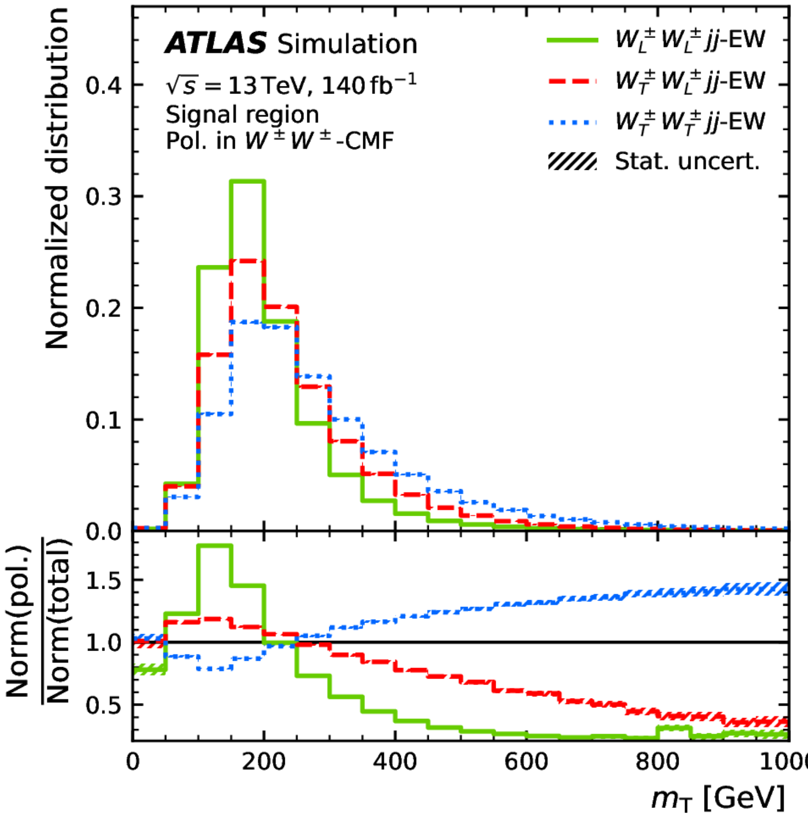
❖ **Cross-section is only ~10% of the total (inclusive) $W^{\pm}W^{\pm}jj$ cross-section.**

Event selection and background estimation

- Same event selection criteria and background estimation as the inclusive $W^{\pm}W^{\pm}jj$ analysis.
- A single kinematic distribution is not sufficient to optimally separate the different polarization states.
  - ➢ Each variable has a different separation power.







DNN classification

- Three dedicated Deep Neural Networks (DNNs) were trained using kinematic variables.

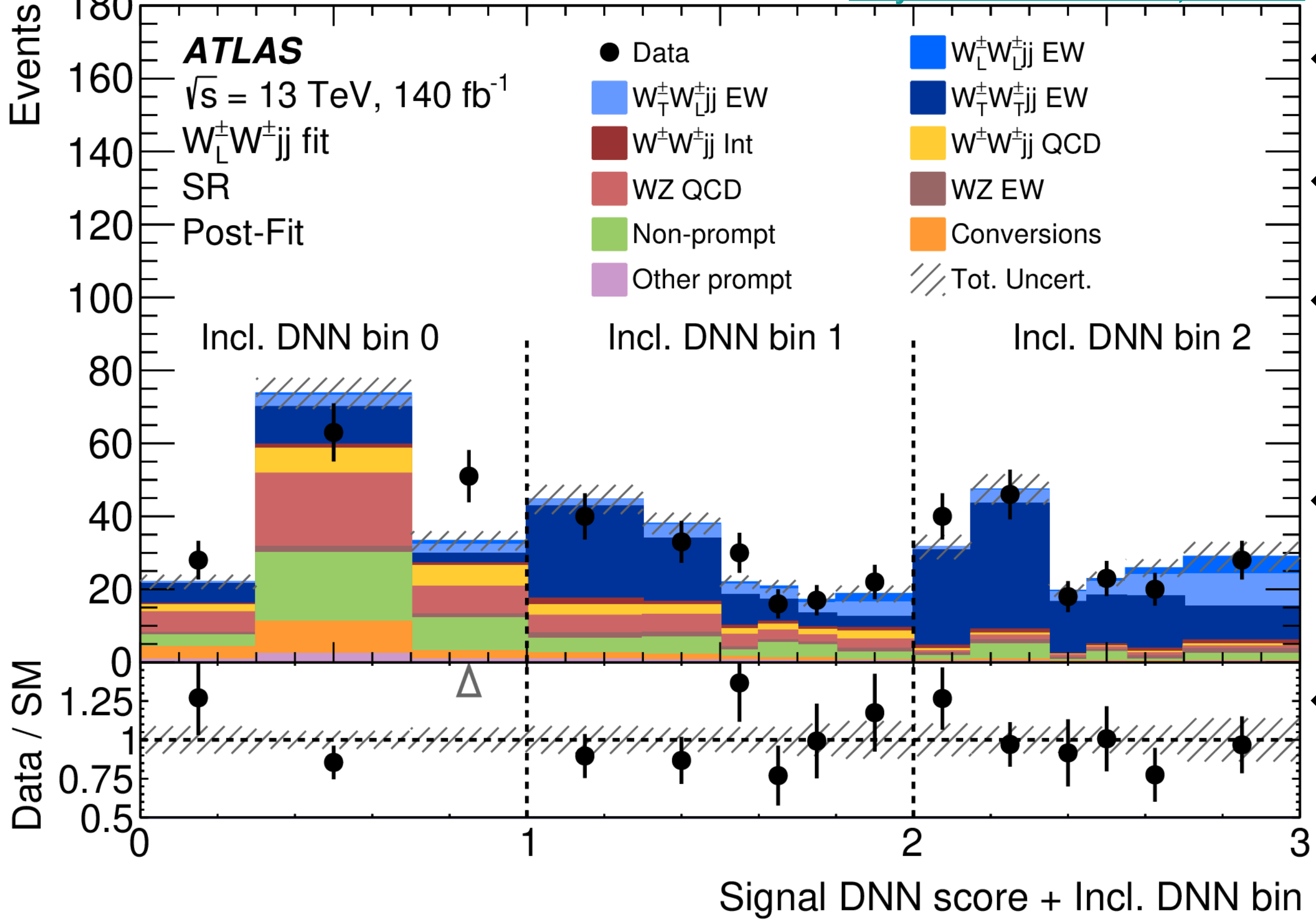
DNN	Purpose
Inclusive DNN	separate inclusive $W^{\pm}W^{\pm}jj$ from background events.
LX DNN	separate $W_L^{\pm}W^{\pm}jj$ from $W_T^{\pm}W_T^{\pm}jj$ events.
LL DNN	separate $W_L^{\pm}W_L^{\pm}jj$ from $W_T^{\pm}W^{\pm}jj$ events.

- A large set of various kinematic variables was used for training (only up to 20 were kept per DNN).

❖ **The LX and LL DNN outputs were fitted independently, each in three regions of the inclusive DNN.**

$W_L^{\pm}W^{\pm}jj$ Results

[Phys. Rev. Lett. **135**, 111802](Phys. Rev. Lett. 135, 111802)

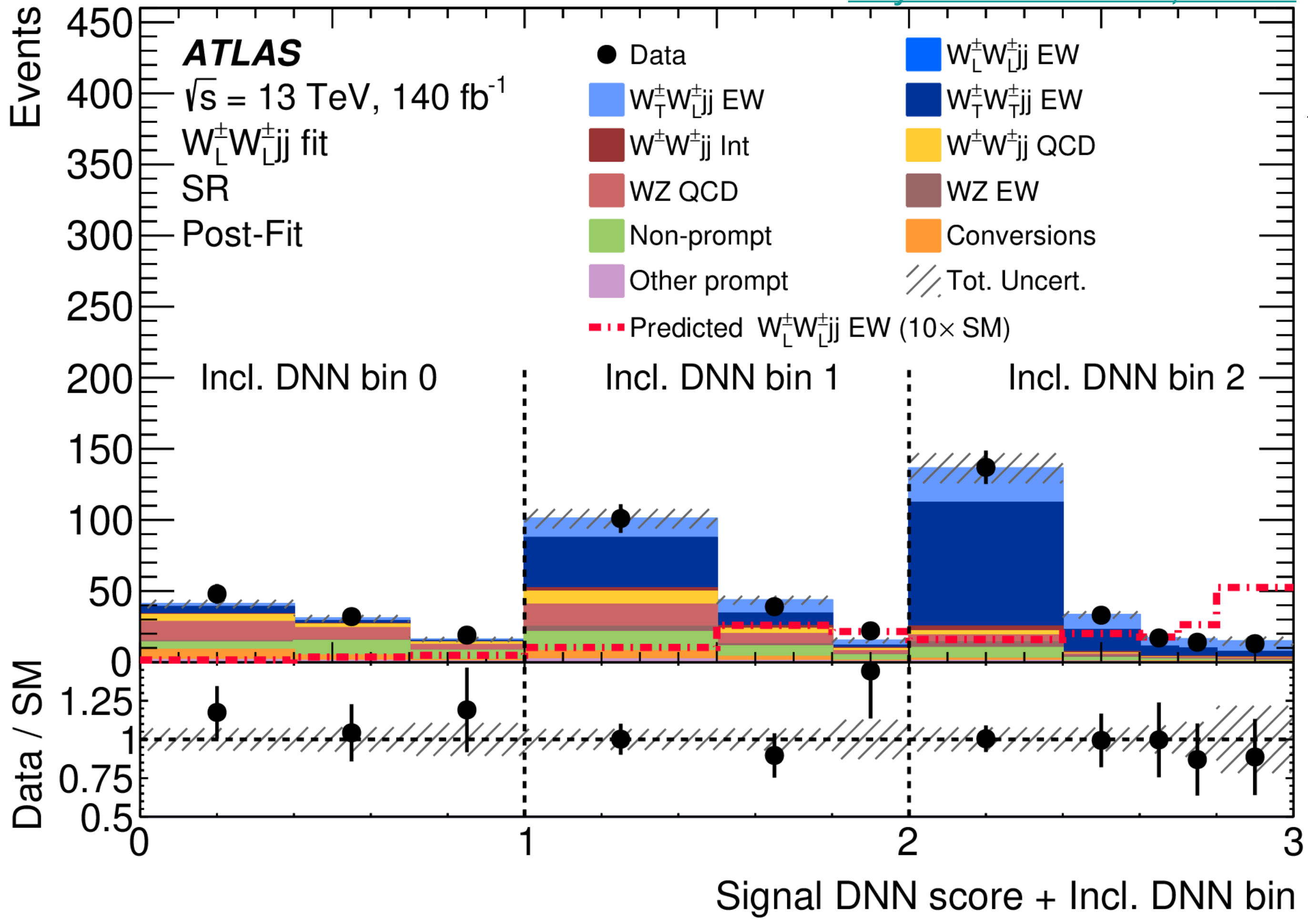


- ❖ LX DNN fit in three regions of the inclusive DNN.
- ❖ Obs. (Exp.) significance: $3.3\ \sigma\ (4.0\ \sigma)$.
- ❖ First evidence for a VBS process with at least one longitudinally polarized vector boson!
- ❖ Measured cross-section agrees with the SM prediction (modelled using Sherpa).
- ❖ Stat. uncertainties are dominant – Need more data.

Description	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)	Uncertainty breakdown (fb)
$W_L^{\pm}W^{\pm}jj$	1.24 ± 0.31	0.84 ± 0.37 (tot.)	± 0.35 (stat.) ± 0.05 (mod. syst.) ± 0.11 (exp. syst.)

$W_L^{\pm}W_L^{\pm}jj$ Results

[Phys. Rev. Lett. **135**, 111802]

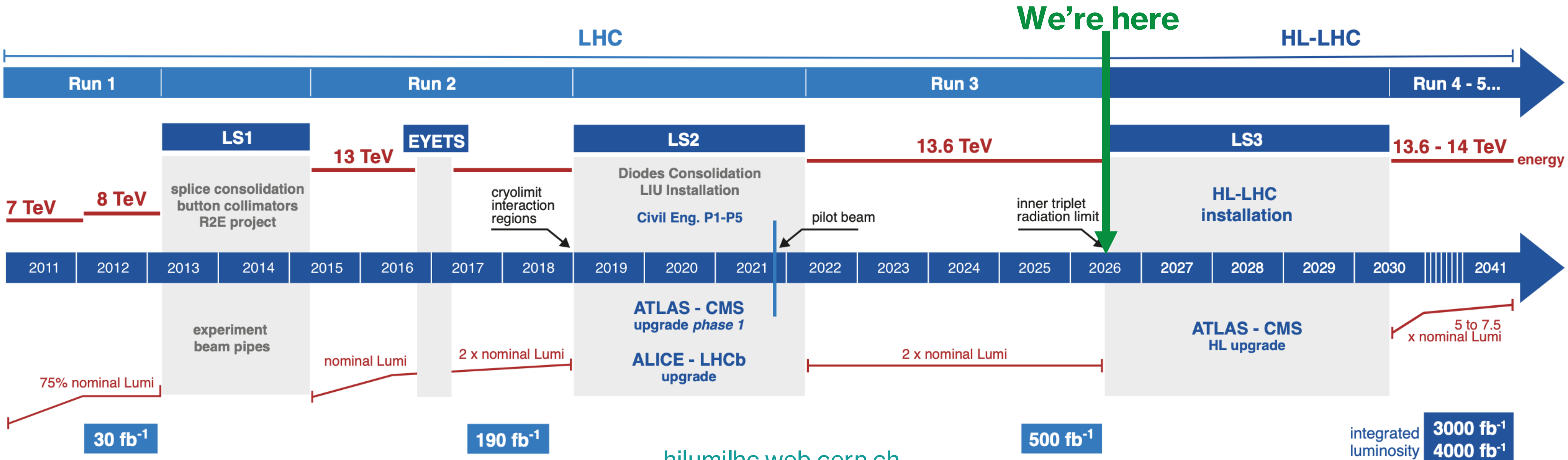


- ❖ LL DNN fit in three regions of the inclusive DNN.
- ❖ No significant excess of events observed.
- ❖ Obs. (Exp.) 95% CL upper limit on cross-section: 0.45 (0.70) fb.
- ❖ Most stringent limit to date.
- ❖ Stat. uncertainties are dominant here too – Need more data!

The High Luminosity LHC (HL-LHC)

- We have just completed Run 3 p-p data-taking and we have recorded > 300 fb^{-1} of data.
- Polarization studies will be repeated with full Run 3 data -> Possibly observe $W_L^{\pm}W^{\pm}jj$
- Between 29 June 2026 and mid-2030: Upgrades towards the HL-LHC

❖ **We anticipate at least 3000 fb^{-1} of data! Could we observe $W_L^{\pm}W_L^{\pm}jj$?**

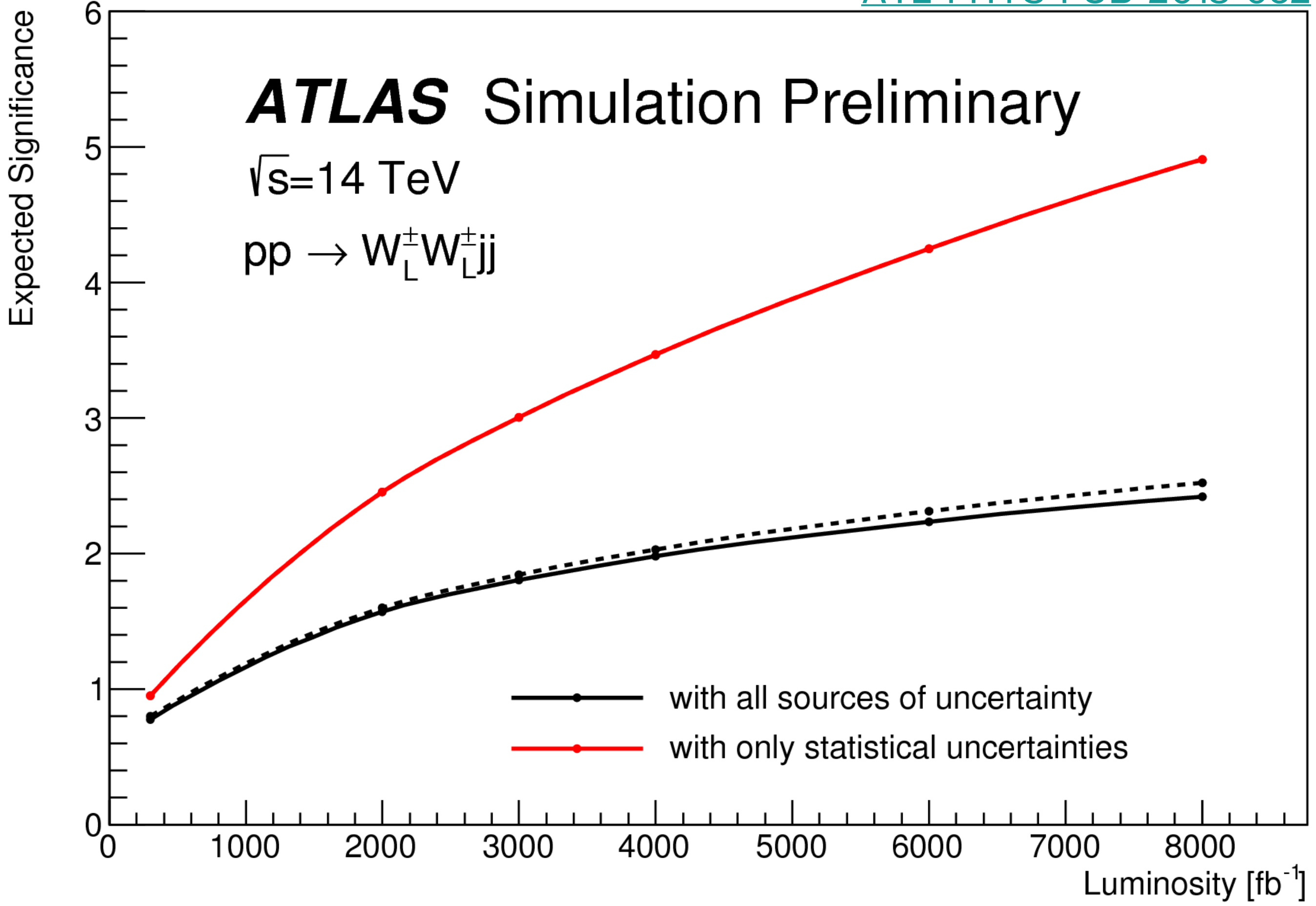


hilumilhc.web.cern.ch

$W_L^\pm W_L^\pm jj$ at the HL-LHC

- Projections of $W_L^\pm W_L^\pm jj$ at the HL-LHC have indicated that we can have evidence with 3000 fb^{-1} of data.

ATL-PHYS-PUB-2018-052

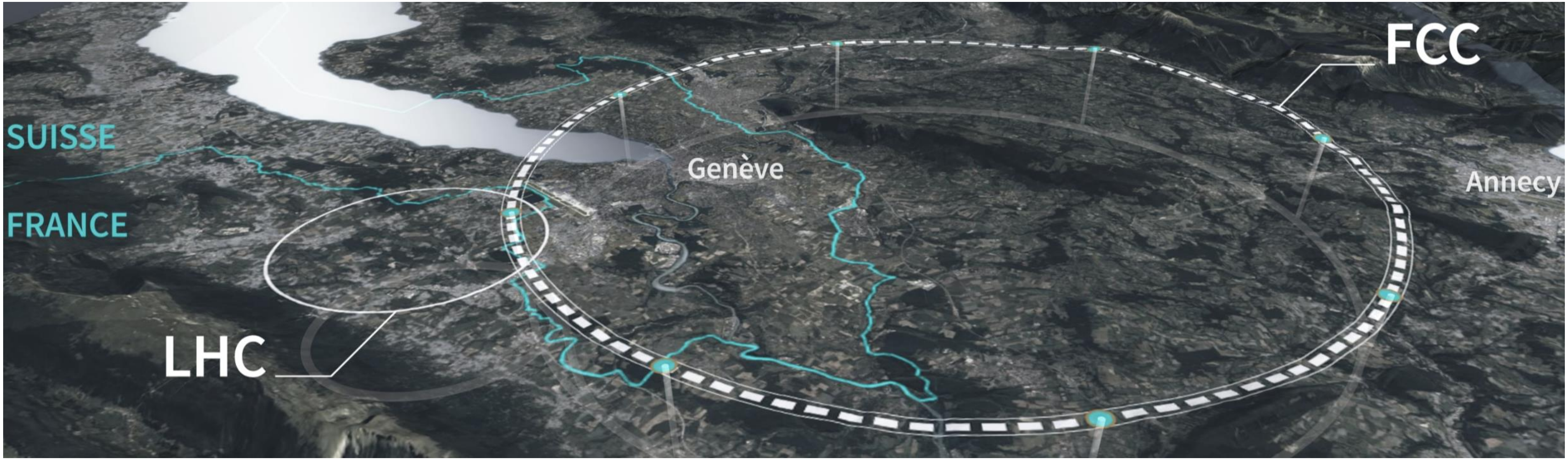


- Analysis techniques have also improved since this result, so we could expect more.
- A lot has been learned from the latest analyses.

❖ **This will be an interesting physics program for the HL-LHC.**

The Future Circular Collider (FCC)

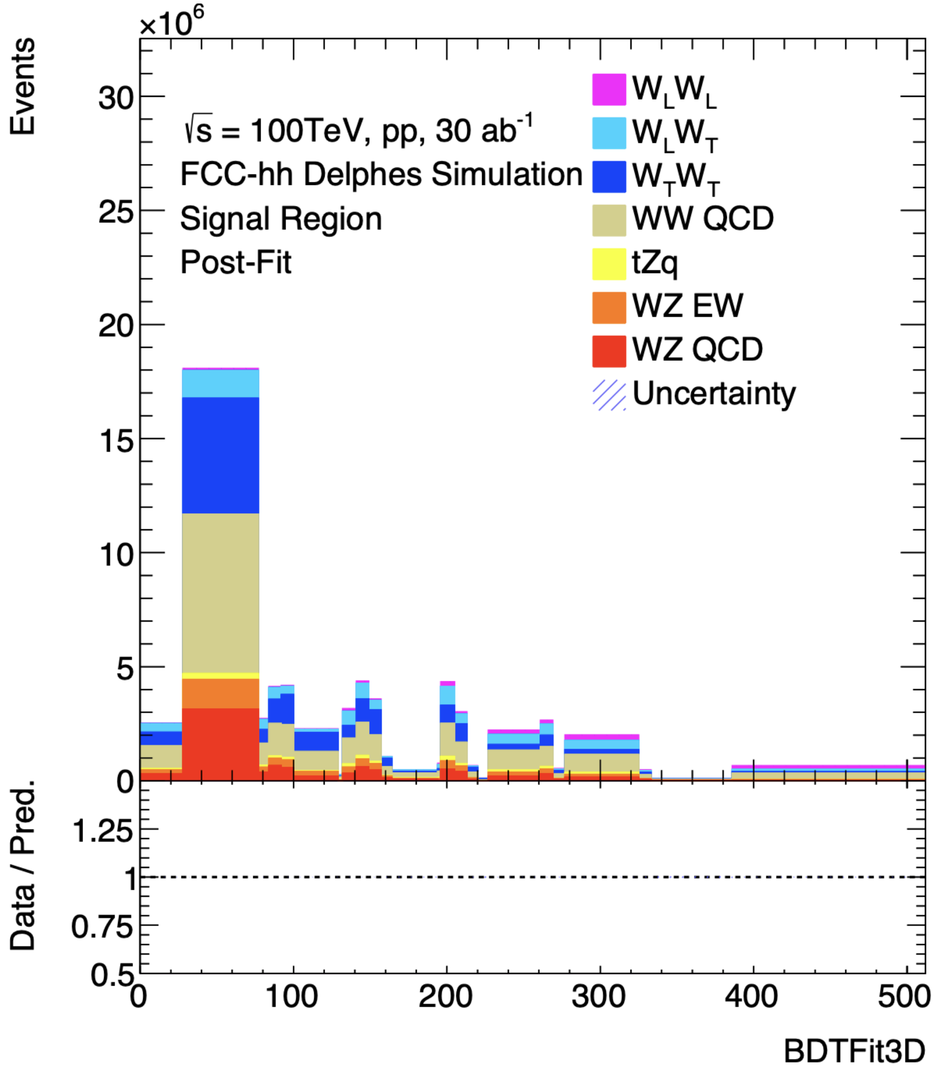
- The Future Circular Collider (FCC) is one of the next generation colliders proposed to take over the LHC.
- Proposed to start with an e^+e^- collider operating at 90-365 GeV.
- To be followed by a hadron collider (FCC-hh) proposed to operate at up to 100 TeV (84 TeV is the baseline).



home.cern.ch

$W_L^{\pm}W_L^{\pm}jj$ at a 100 TeV FCC-hh

Analysis details	
Sample simulation	Madgraph5+Pythia8 with Delphes for the detector response
Integrated luminosity	30 ab^{-1}
Backgrounds	$W^{\pm}W^{\pm}jj$ QCD……
Event selection	Same as LHC analyses, but with a larger/more conservative $m_{jj} > 2$ TeV
Systematics	Luminosity, PDF, QCD scale uncertainties



- Boosted Decision Trees (BDTs) trained on 15 variables were used to isolate the polarizations from backgrounds.

❖ **Result: We can measure the cross-section of $W_L^{\pm}W_L^{\pm}jj$ with a relative precision of 15% at the FCC-hh.**

Phys.Rev D 112, 093001

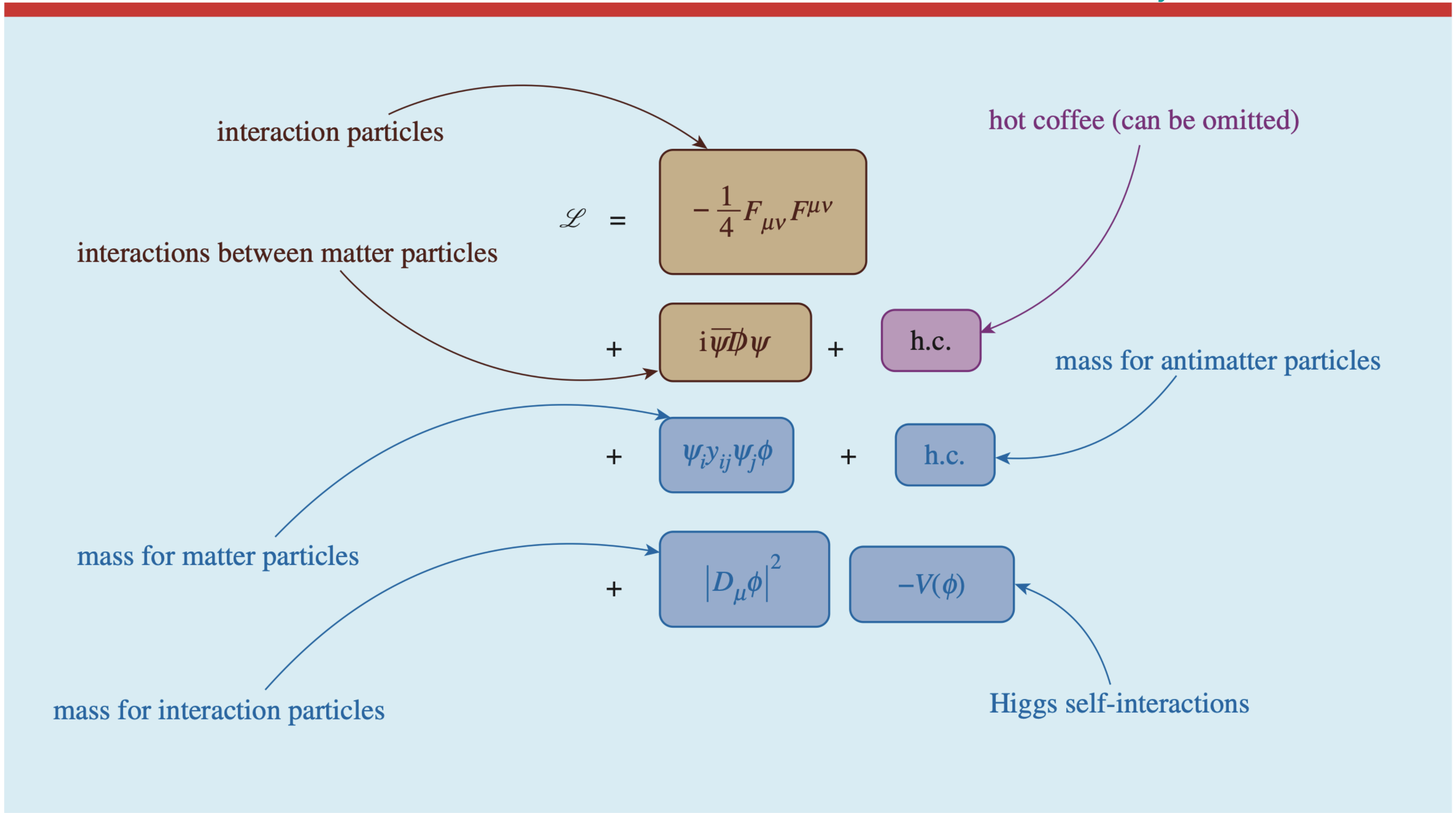
Summary

- Longitunally polarized same-charge WW VBS measurements play a crucial role in testing EWSB.
- So far, ATLAS has found evidence of at least one of the W bosons being longitudinally polarized.
- It is important that we measure the case where both W bosons are longitudinally polarized.
- This will be an exciting physics program for Run 3 data and at the HL-LHC.
- Projections at a 100 TeV FCC-hh indicate that we could have a cross-section measurement with a relative precision of 15%.

Additional material

Standard Model Lagrangian

Phys. Educ. **52** 034001



❖ A guage group is a mathematical way of expressing symmetry transformations that are allowed on fundamental particles without changing the undelying physics.

Higgs potential and Higgs pairs

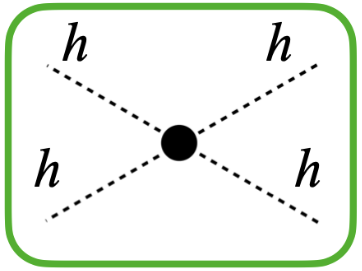
The Standard Model (SM) Higgs potential is given by

$$V(\phi) = -\mu\phi^2 + \lambda\phi^4$$

After electroweak symmetry breaking, we have $\phi = \begin{pmatrix} 0 \\ \nu + h \end{pmatrix}$

When inserting this into $V(\phi)$, we get the Higgs Lagrangian

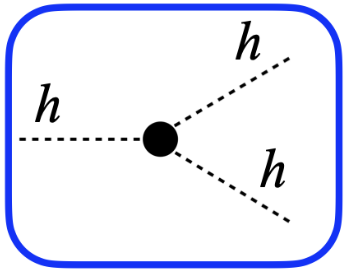
$$\mathscr{L}_{\text{Higgs}}(h) = \frac{1}{2}m_h^2h^2 + \boxed{\lambda v h^3} + \boxed{\frac{1}{4}\lambda h^4}$$



SM: $\lambda = \frac{m_h^2}{2v^2} \approx 0.13$

$$\boxed{\kappa_\lambda = \frac{\lambda_{\text{obs.}}}{\lambda_{\text{SM}}}}$$

SM: $\kappa_\lambda = 1$



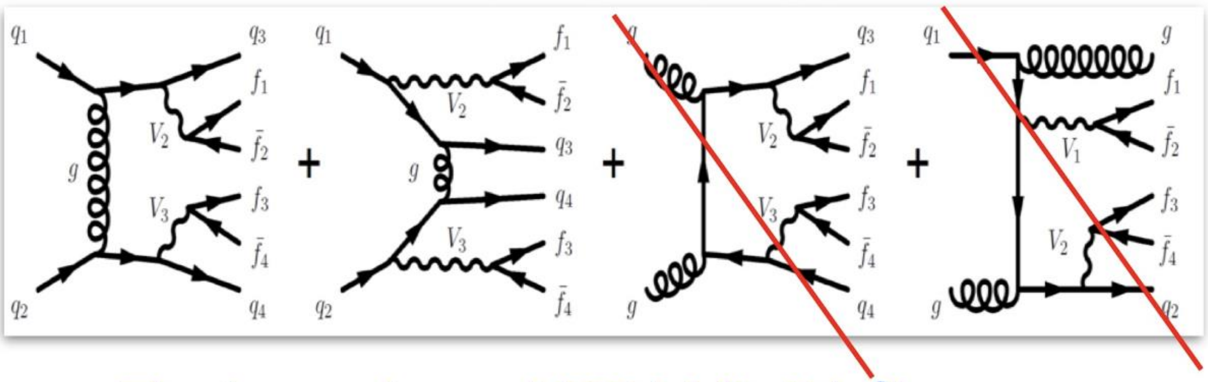
VBS EW and VBS QCD cross-section comparisons

P.Anger, PhD. Thesis 2014

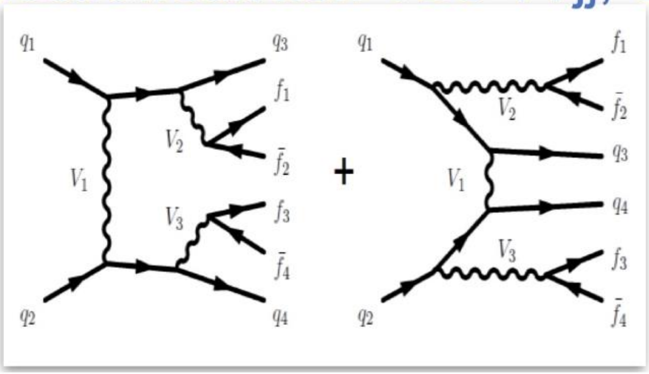
$VVjj$	final state	$\sigma(VVjj\text{–EW})$/fb	$\sigma(VVjj\text{–QCD})$/fb	EW/QCD
$W^{\pm}W^{\pm}$	$l^{\pm}l^{\pm}\nu\nu jj$	4.28 ± 0.01	1.69 ± 0.02	2.53
$W^{\pm}W^{\mp}$	$l^{\pm}l^{\mp}\nu\nu jj$	15.57 ± 0.08	35.24 ± 0.13	0.44
$W^{\pm}Z$	$l^{\pm}\nu l^{\pm}l^{\mp}jj$	2.36 ± 0.01	7.19 ± 0.01	0.33
ZZ	$l^{\pm}l^{\mp}l^{\pm}l^{\mp}jj$	0.12 ± 0.01	0.21 ± 0.01	0.57
ZZ	$l^{\pm}l^{\mp}\nu\nu jj$	0.39 ± 0.01	0.55 ± 0.01	0.71

Same-charge WW diagrams

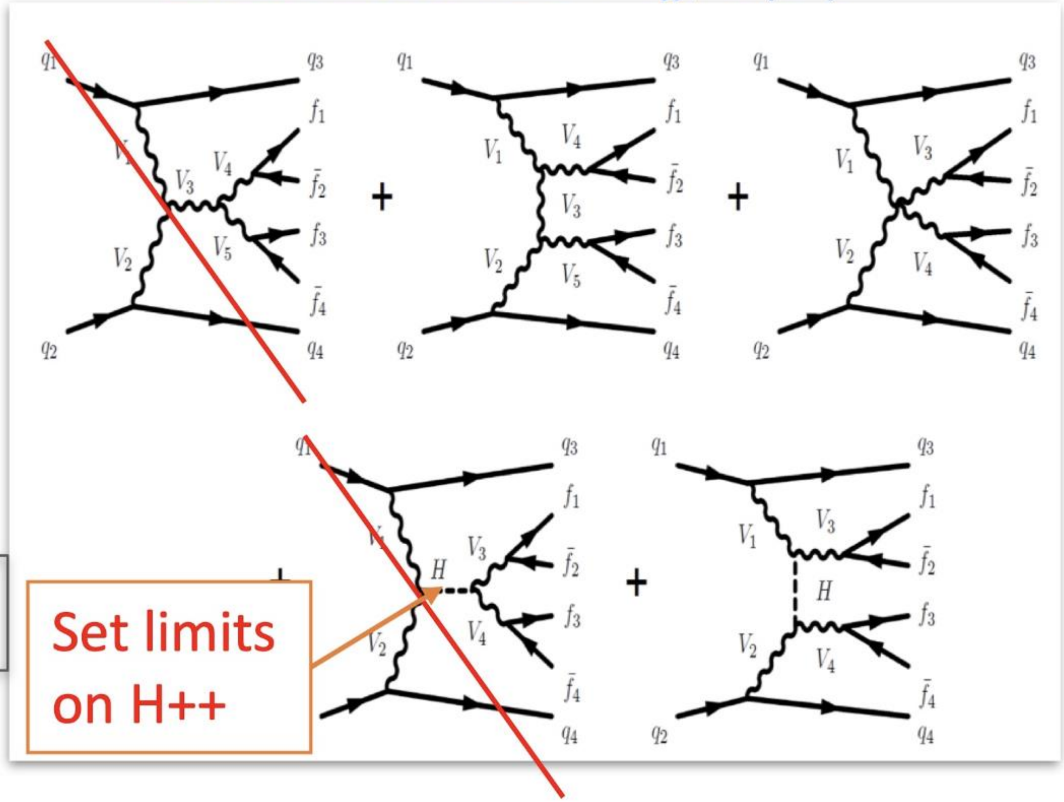
Strong VVjj, $O(\alpha^4\alpha_s^2)$



Electroweak non-VBS VVjj, $O(\alpha^6)$



Electroweak VBS VVjj, $O(\alpha^6)$



Not in SM $W^\pm W^\pm$

Set limits on H++

Same-charge WW event selection

Exactly two signal leptons with $p_{\mathrm{T}} > 27$ GeV and the same electrical charge with $\|\eta\| < 2.5$ for muons and with $\|\eta\| < 2.47$ excluding $1.37 \leq \|\eta\| \leq 1.52$ for electrons with $\|\eta\| < 1.37$ in the ee channel
$m_{\ell\ell'} \geq 20$ GeV
remove events with three or more preselected leptons
$\|m_{ee} - m_Z\| > 15$ GeV in the ee-channel
$E_{\mathrm{T}}^{\mathrm{miss}} \geq 30$ GeV
at least two jets leading and subleading jets satisfying $p_{\mathrm{T}} > 65$ GeV and $p_{\mathrm{T}} > 35$ GeV, respectively
$m_{\mathrm{jj}} \geq 500$ GeV
b-jet veto using the DL1r tagger with the 85% efficiency working point
$\|\Delta y_{jj}\| > 2$

Background and signal estimation

❖ WZ EW and WZ QCD background

- WZ QCD is the most dominant background
- Two same-charge leptons are picked up as signal
- WZ final states are modelled using Monte-Carlo (MC) simulations and are dominated by WZ QCD
- The normalization of the WZ QCD process is estimated from data in a dedicated WZ control region

❖ Charge flip and γ conversions background

- Main sources: $W^{\pm}W^{\mp}$ and $V\gamma$ processes
- One lepton's charge is measured incorrectly or an electron from a γ conversion is picked up as signal.
- This is the third-largest background source
- Charge flip is estimated using a data-driven method
- $V\gamma$ processes are estimated from MC simulations

❖ Non-prompt (fake) background

- Main sources: Semi-leptonic $t\bar{t}$, W+jets, single top processes
- Jets are misidentified as leptons or leptons from heavy flavour decays are picked up as signal.
- This is the second-largest background
- Estimated using a data-driven method

❖ Other prompt background

- Main sources: ZZ and VVV processes
- Two same-charge leptons are picked up as signal
- Smallest background contribution
- Estimated from MC simulation

❖ We also estimate the signal from MC simulations.

Fiducial cross-section definition

- Events with taus from W decays in the ME calculation are vetoed. They constitute around 15% of the SR cross section;
- Two prompt leptons (e or μ) with p_T> 27 GeV and $|\eta| < 2.5$ dressed with prompt photons within a $\Delta R < 0.1$.
- The two leptons must have same sign electric charge and have the invariant mass $m_{\ell\ell}$> 20 GeV;
- At least two jets from the AntiKt4TruthJets container with p_T>65 GeV for the leading and p_T>35 GeV for the sub-leading jet, and $|\eta|$<4.5, reconstructed with the anti-kt algorithm with radius parameter R = 0.4;
- Truth overlap removal. The AntiKt4TruthJets container is used to access truth jet information in DAOD_STDM3 samples. The jets in this container are clustered excluding neutrinos and muons, but including electrons, to match the detector level definitions of jets [53]. Therefore, an additional step of overlap removal between electrons and jets is needed. The adopted procedure is the following. If an electron and a jet overlap with $\Delta R(e, \text{jet}) < 0.4$, and the ratio $p_{T,e}/p_{T,jet} < 0.5$, then the electron is assumed to come from a hadron decay within the jet and is removed. If $p_{T,e}/p_{T,jet} > 0.5$, then most of the time the jet contains a single particle – electron, and is therefore removed. No overlap removal between muons and jets is applied;
- Z veto in the ee channel: ee events with the dielectron invariant mass in the range $|m_{ee} - m_Z| < 15$ GeV are removed;
- The truth-level MET as reconstructed from the visible final state objects passing the above selections must satisfy the condition $E_T^{miss} > 30$ GeV;
- The invariant mass of the two highest-p_T jets must be m_{jj} >500 GeV;
- The separation in rapidity between the two highest-p_T jets has to be $\Delta Y(j, j)$>2.0.

Maximum likelihood fit

- Binned maximum likelihood fits were performed separately for the LX and LL DNNs.

- Signal DNNs were fitted in three regions of the inclusive DNN – independently optimized to maximise the signal significance.

  - LX fit: (0, 0.3, 0.7, 1.0)
  - LL fit: (0, 0.2, 0.6, 1.0)

Normalization factors:

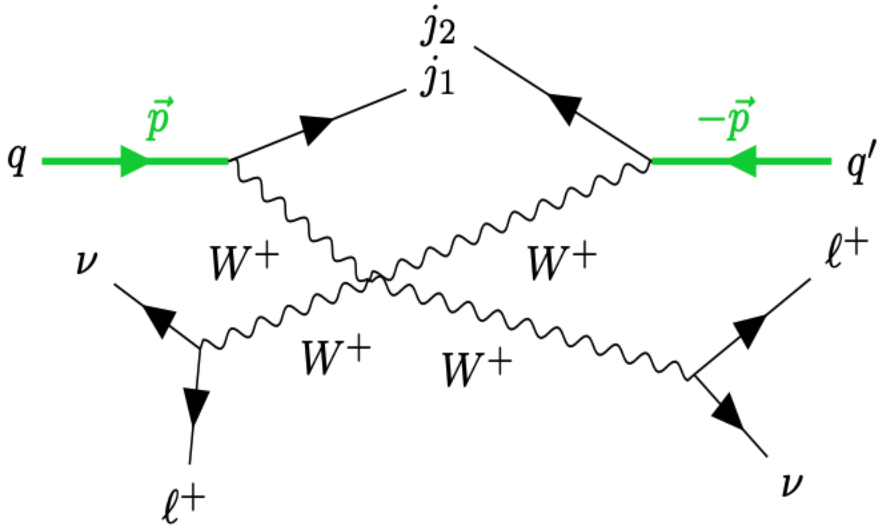
$\mu_{LX}, \mu_{TT}, \mu_{WZ}$

$\mu_{LL}, \mu_{TX}, \mu_{WZ}$

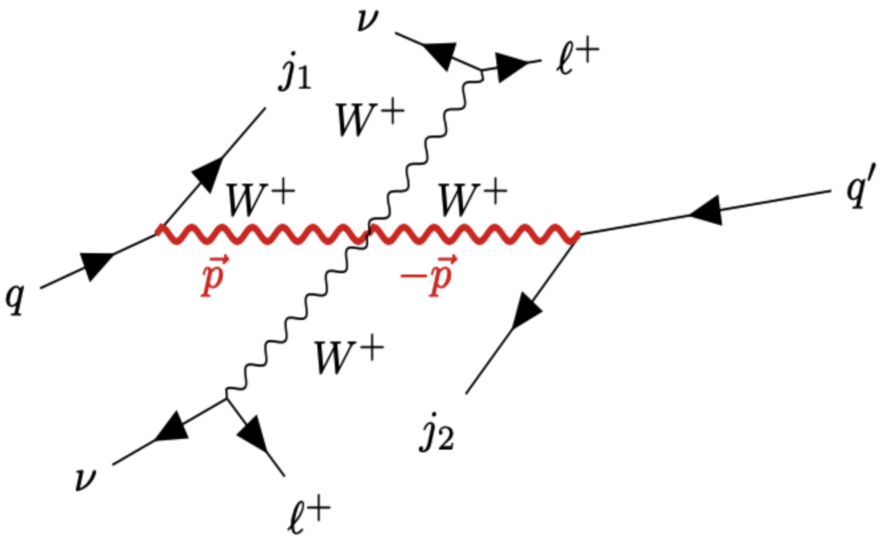
❖ Single bins of the low-m_{jj} and WZ control regions were also fitted simultaneously.

Reference frame choice

- Choosing a reference frame is important in polarizations studies.
  - ➢ Polarizations are not Lorentz invariant – the way the polarization is defined and measured depends on the reference frame.



- Two choices:
  - **Center-of-mass (COM) frame of the colliding partons**.
  - **Center-of-mass frame of the W bosons**.



- In ATLAS, we have used the W COM frame - gave better sensitivity.
  - Signal samples are modelled in this reference frame.

pjain.web.cern.ch

Electroweak VBS measurements

- VBS is studied in various processes; same-charge WW, opposite charge WW, WZ, ZZ, $V\gamma$
- Any deviation from the SM when we measure cross-sections would be indicative of new physics.

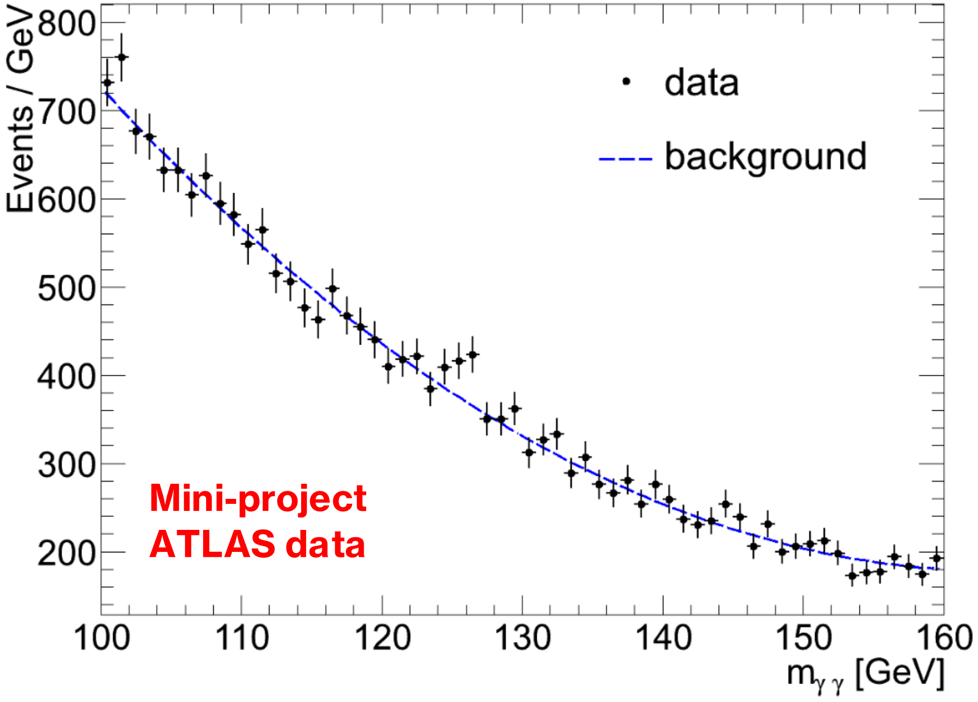
- So far, no deviation from the SM has been observed.

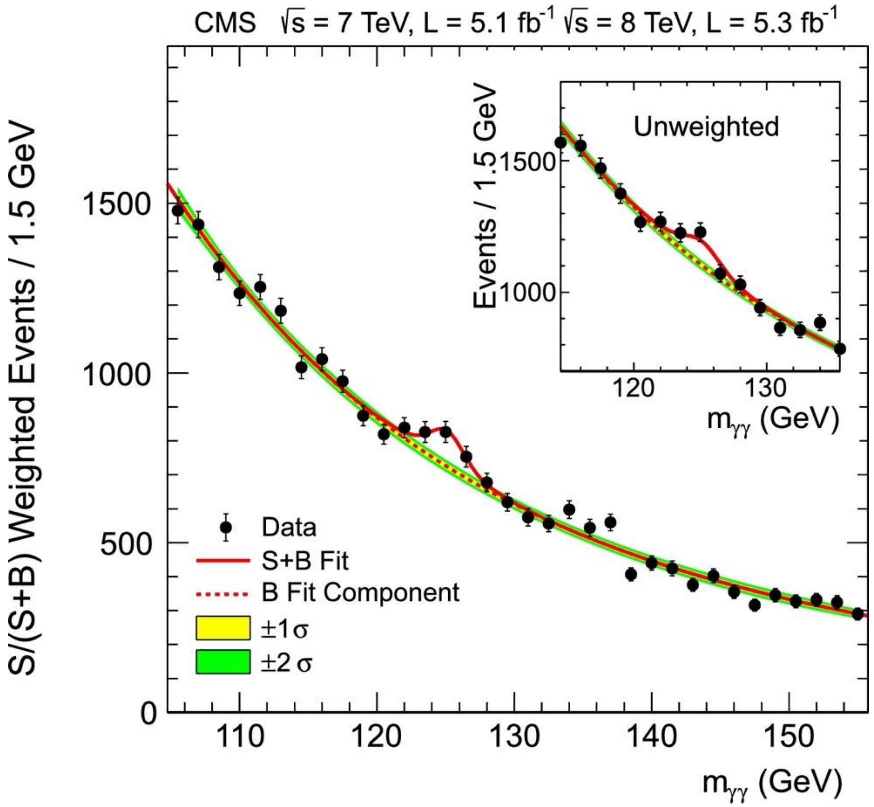
❖**Longitudinally polarized VBS has not yet been observed.**

- Next slides: same-charge WW scattering.

Discovery of the Higgs boson

- My first project in particle physics involved analyzing a small Higgs $\rightarrow \gamma\gamma$ ATLAS dataset.
- Later that year, the Higgs boson was discovered.





- This was exciting news all over the world!
  - ❖ **The final missing piece in the SM had been found.**

'God particle' likely discovered

Boson could be 'missing cornerstone of particle physics'

CBC News · Posted: Jul 04, 2012 4:21 AM EDT | Last Updated: July 4, 2012