Vector Boson Scattering and the feasibility of measuring longitudinally polarized ZZ scattering at the FCC-hh

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Outline

1) Vector Boson Scattering (VBS)

2) Hard process cross sections

    a) Unpolarized

    b) Polarized

3) Typical Candidate Event Distributions

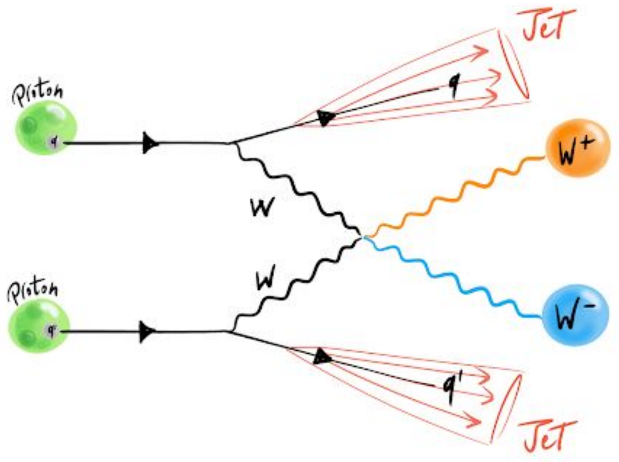
4) Optimization for Detector and Experiment Design at the FCC-hh

Vector Boson Scattering (VBS)

Definition: In proton-proton collisions, VBS occurs when a vector boson V ($W^{\pm}$, Z) is omitted off of an initial state valence quark from each proton, before scattering off of each other and decaying to fermions.

Key Features:

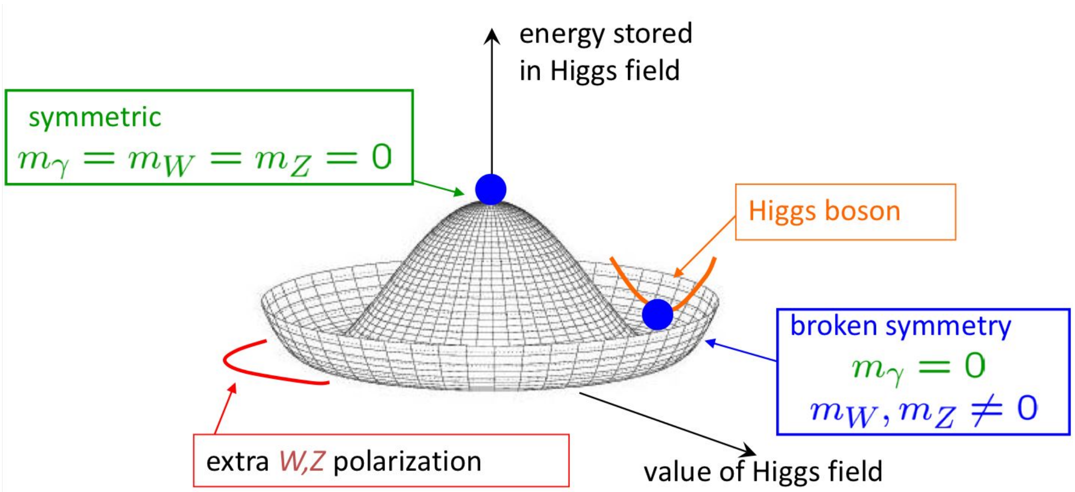
- Large Dijet Mass (m_{jj} > 500 GeV)
- Large Jet Rapidity Separation ($|\Delta\eta_{jj}| > 2.5$)



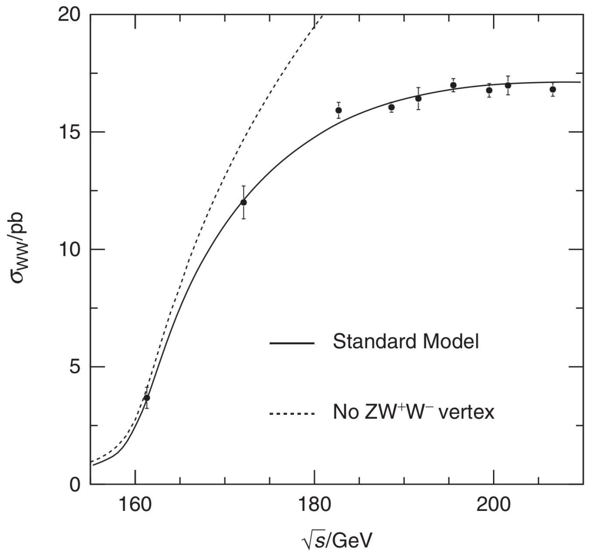
Cartoon of VBS event occurring in the WWos channel.

Vector Boson Scattering (VBS)

Without the presence of the BEH-Mechanism, we find there is unitarity violation in amplitudes involving the scattering of longitudinally polarized weak bosons. Measurements of longitudinal-VBS processes are essential to studying the BEH-Mechanism, and a prime place to determine precise Higgs couplings at high energies.



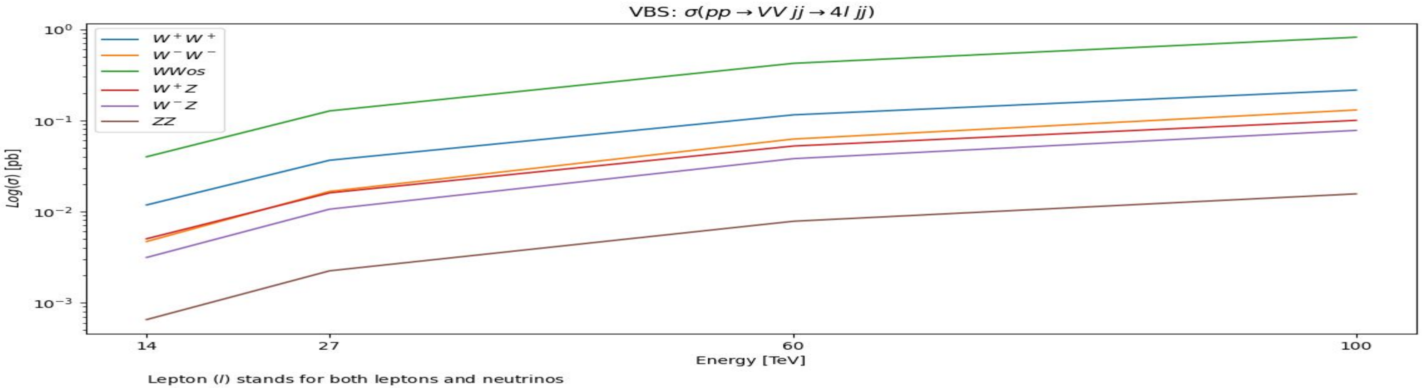
Annotated Schema of the Higgs Potential, Before and After EWSB
Mark Neubauer, https://msneubauer.github.io/projects/4_project/



$\sigma(e^+e^- \to W^+W^-)$ measurements at LEP
Mark Thomson, *Modern Particle Physics*

Unpolarized Cross Sections

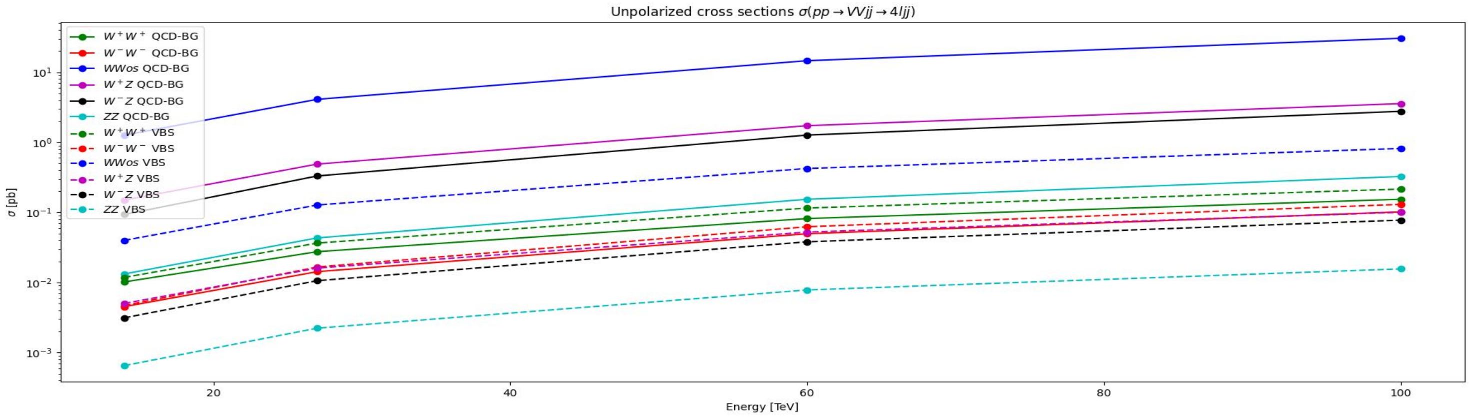
Before turning to the specific case of polarized VBS, cross sections for the hard processes pp → VV qq → 4l qq were calculated for a range of energies including √s = 14 TeV (HL-LHC), 27 TeV (HE-LHC) and √s = 100 TeV (FCC-hh) using MadGraph5_aMC@NLO.



	14 TeV	27 TeV	60 TeV	100 TeV	Gain $\frac{27TeV}{14TeV}$	Gain $\frac{100TeV}{14TeV}$
$\sigma(W^+W^+)$ [pb]	0.0118	0.0365	0.115	0.215	3.09	18.2
$\sigma(W^-W^-)[pb]$	0.00468	0.0166	0.0624	0.13	3.55	27.8
$\sigma(WWos)[pb]$	0.0399	0.127	0.423	0.818	3.2	20.5
$\sigma(W^+Z)[pb]$	0.00502	0.016	0.0523	0.1	3.19	20.0
$\sigma(W^-Z)[pb]$	0.00313	0.0106	0.038	0.0776	3.39	24.8
$\sigma(ZZ)[pb]$	0.000651	0.00223	0.00781	0.0156	3.42	24.0

Unpolarized Cross Sections

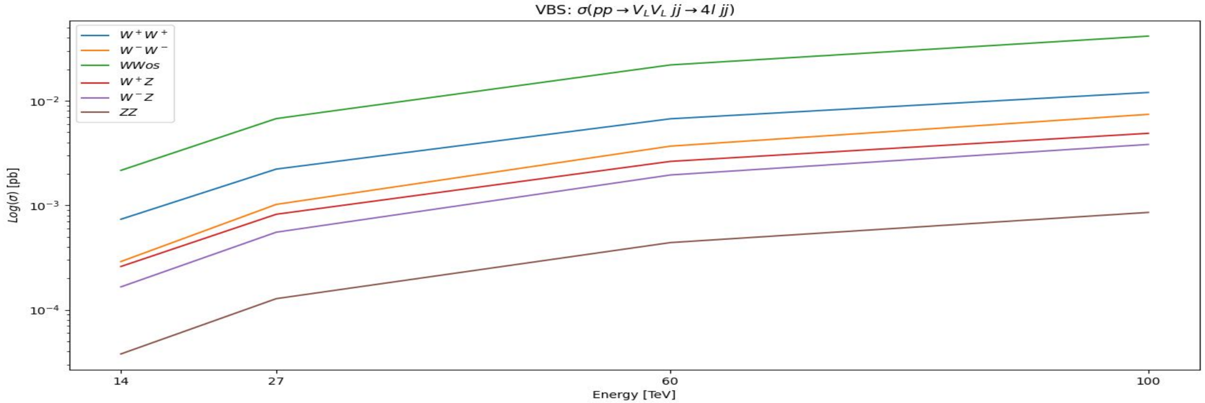
The associated background corresponds to QCD-induced processes; the signal-to-background ratio was determined for the same energy range.



	14 TeV	27 TeV	60 TeV	100 TeV
$(W^+W^+)_S/(W^+W^+)_B$	1.16	1.33	1.41	1.4
$(W^-W^-)_S/(W^-W^-)_B$	1.04	1.17	1.26	1.28
$(WWos)_S/(WWos)_B$	0.0315	0.031	0.029	0.0268
$(W^+Z)_S/(W^+Z)_B$	0.0334	0.0328	0.0303	0.0281
$(W^-Z)_S/(W^-Z)_B$	0.0335	0.032	0.03	0.028
$(ZZ)_S/(ZZ)_B$	0.0492	0.0515	0.0508	0.0479

Polarized Cross Sections

Longitudinally polarized VBS cross sections showed a consistent gain of ~3 (~20) across all channels for the expected HE-LHC (FCC-hh) center of mass energy.

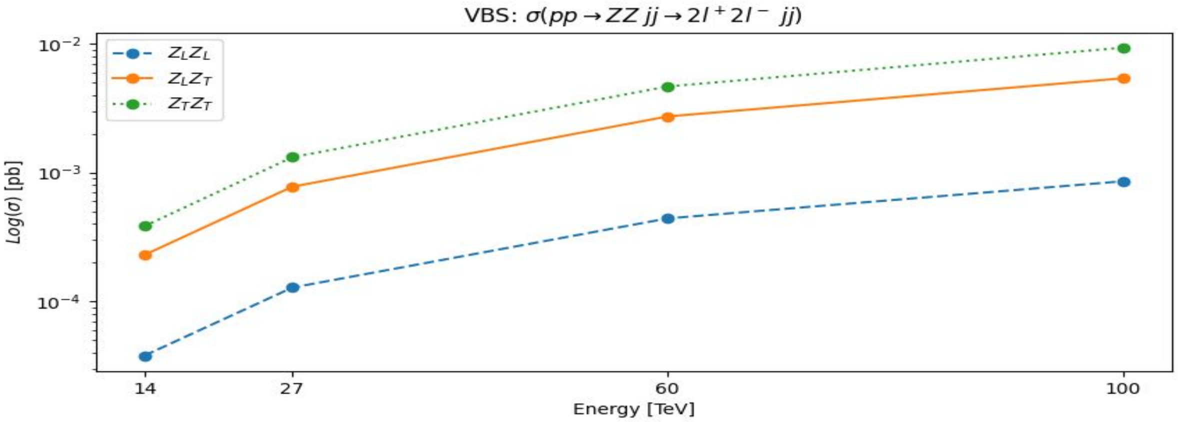


Lepton (*l*) stands for both leptons and neutrinos

	14 TeV	27 TeV	60 TeV	100 TeV	Gain $\frac{27TeV}{14TeV}$	Gain $\frac{100TeV}{14TeV}$
$\sigma(W^+W^+)$ [pb]	0.000736	0.00222	0.00672	0.012	3.01	16.3
$\sigma(W^-W^-)[pb]$	0.00029	0.00102	0.00368	0.00741	3.5	25.5
$\sigma(WWos)[pb]$	0.00216	0.00675	0.022	0.0415	3.12	19.2
$\sigma(W^+Z)[pb]$	0.00026	0.000821	0.00263	0.00488	3.16	18.8
$\sigma(W^-Z)[pb]$	0.000166	0.000553	0.00195	0.00382	3.32	22.9
$\sigma(ZZ)[pb]$	3.79e-05	0.000128	0.00044	0.000855	3.37	22.6

ZZ Scattering and Polarized Background

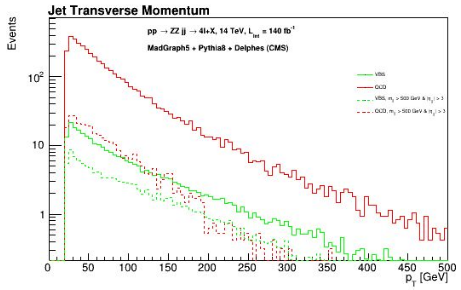
Though it has the smallest cross section, the ZZ channel is the only one where we have access to all final state particles, giving it the cleanest environment for event selection. Our signal (background) here corresponds to a $Z_L Z_L$ ($Z_L Z_T + Z_T Z_T$) intermediate state (both passing through EW vertices).

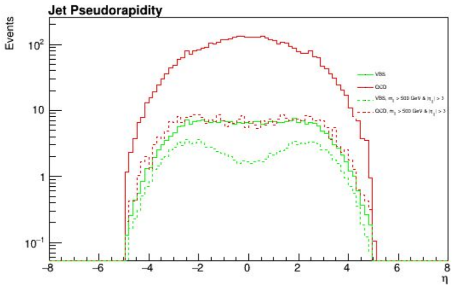


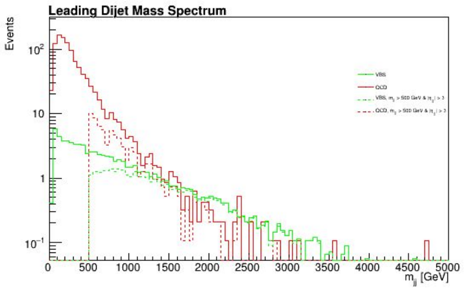
	14 TeV	27 TeV	60 TeV	100 TeV
$\sigma(Z_L Z_L)[pb]$	3.79e-05	0.000128	0.00044	0.000855
$\sigma(Z_L Z_T)[pb]$	0.000229	0.000775	0.00272	0.00538
$\sigma(Z_T Z_T)[pb]$	0.000383	0.00131	0.00465	0.00931
$LL/(LT+TT)$	0.0619	0.0612	0.0597	0.0582

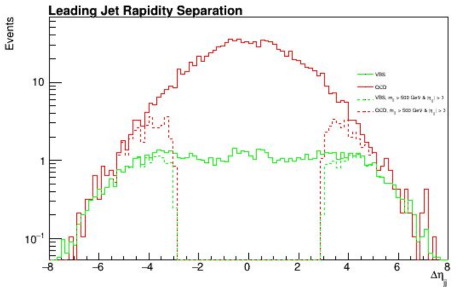
Typical Candidate Event Distributions

Distributions were plotted for jet p_T, η, m_{jj}, and $\Delta\eta_{jj}$ after having normalized the histograms using $N_{exp} = L_{Int} * \sigma * (N_{sel}/N_{Gen})$, both before and after applying VBS cuts.









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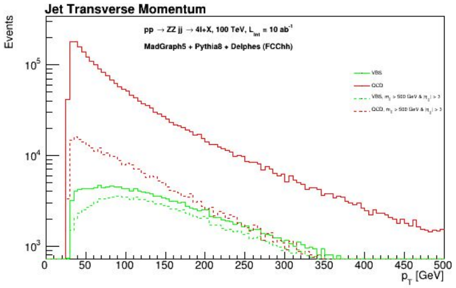
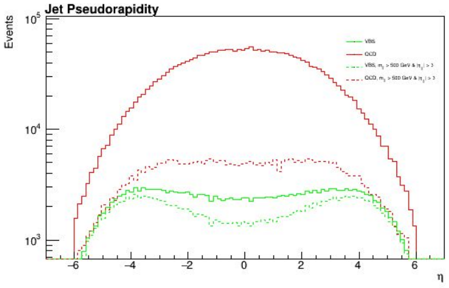
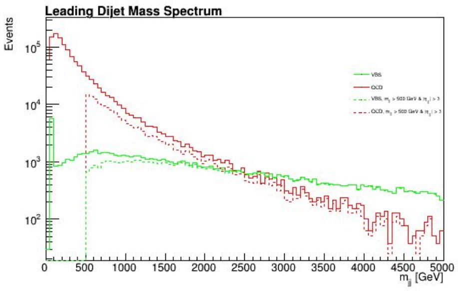
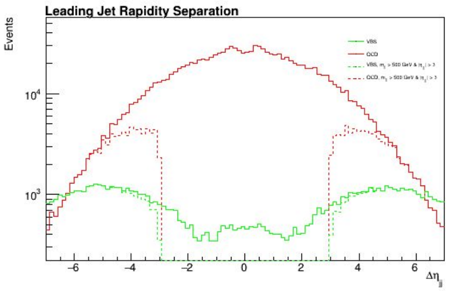
Typical Candidate Event Distributions

It’s clear that the standard VBS cuts were chosen to optimize the signal-to-background ratio at energies √s ~ 14 TeV, but are insufficient for √s ~ 100 TeV.





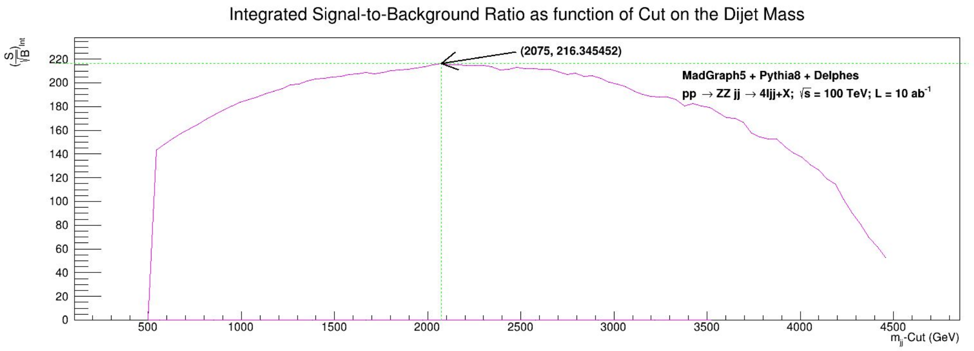




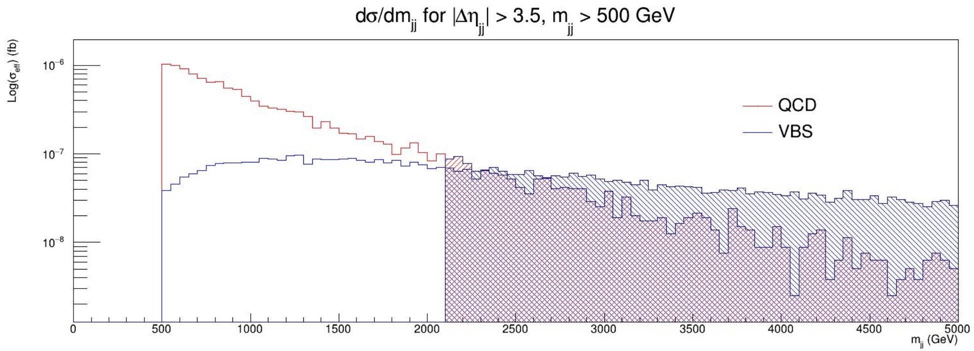
VBS Optimization for FCC-hh

The optimization for m_{jj}-cut was done by maximizing the following quantity:

$$\frac{S}{\sqrt{B}} = \frac{\int_{m_{jj}-cut}^{m_{jj}-max} \sigma_{VBS} dm_{jj}}{\sqrt{\int_{m_{jj}-cut}^{m_{jj}-max} \sigma_{QCD} dm_{jj}}}$$



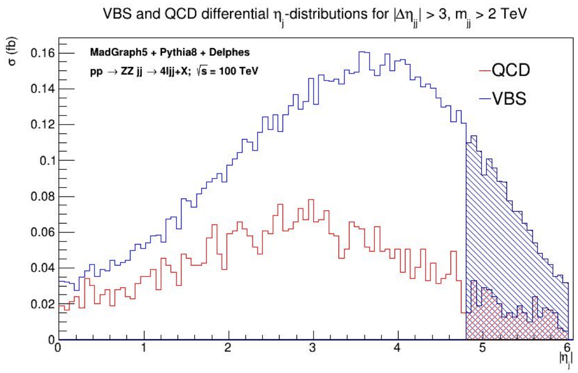
This yields an optimal cut of m_{jj} ~ 2 TeV. The same process gives us a cut on the jet rapidity separation $|\Delta\eta_{jj}|$ ~ 3.5.

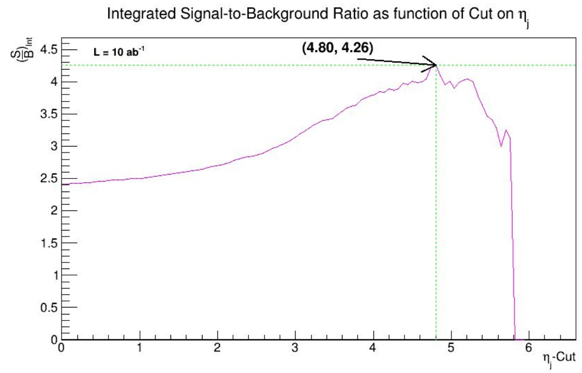


VBS Optimization for FCC-hh

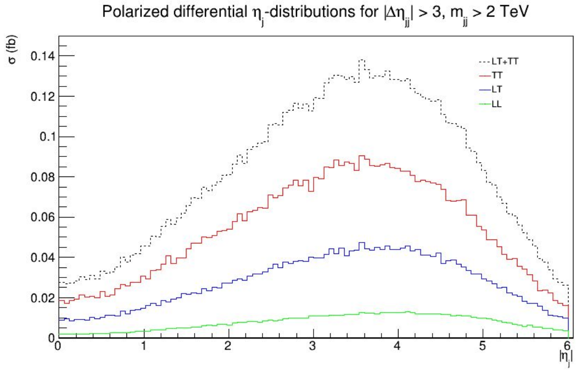
Optimal cut on individual jet pseudorapidity, $|\eta_j|$, for VBS separation and $Z_L Z_L$ separation.

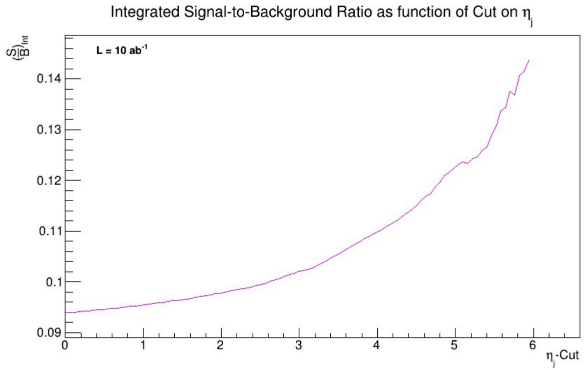
VBS vs. QCD:





$Z_L Z_L$ vs. $Z_{L(T)} Z_T$:

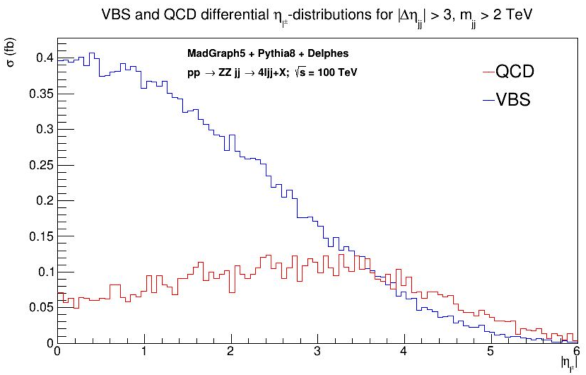


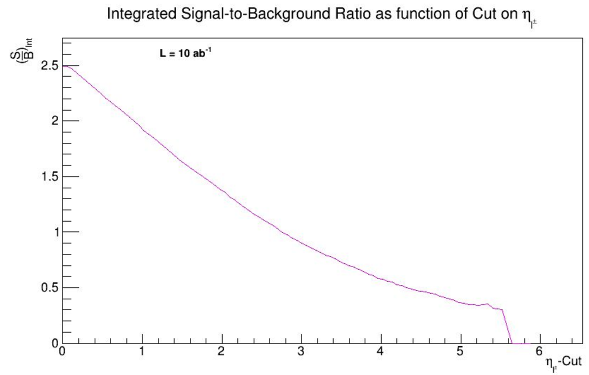


VBS Optimization for FCC-hh

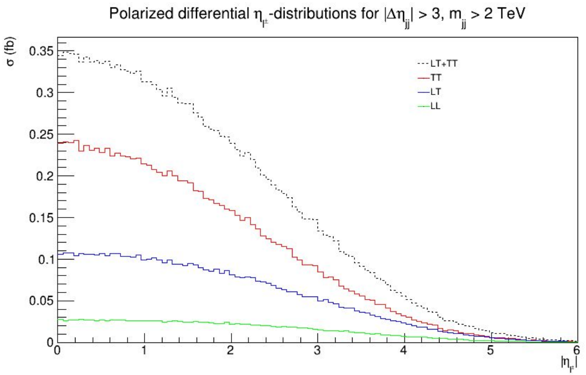
Optimal cut on individual lepton pseudorapidity, $|\eta_l|$, for VBS separation and $Z_L Z_L$ separation.

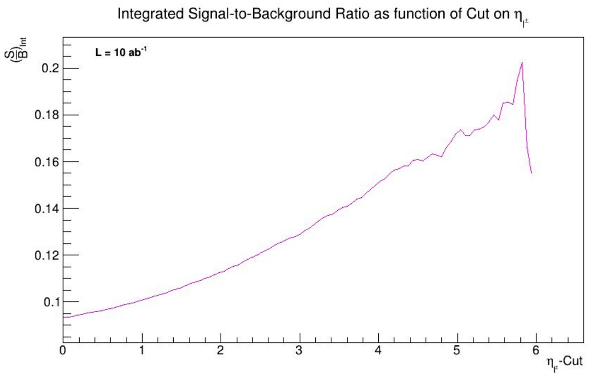
VBS vs. QCD:





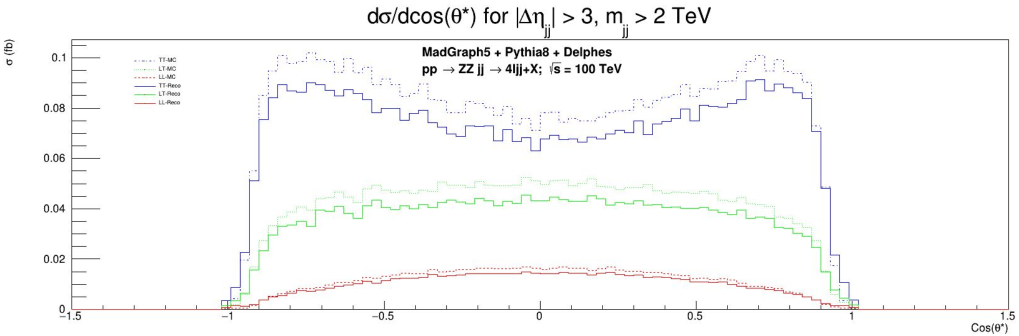
$Z_L Z_L$ vs. $Z_{L(T)} Z_T$:

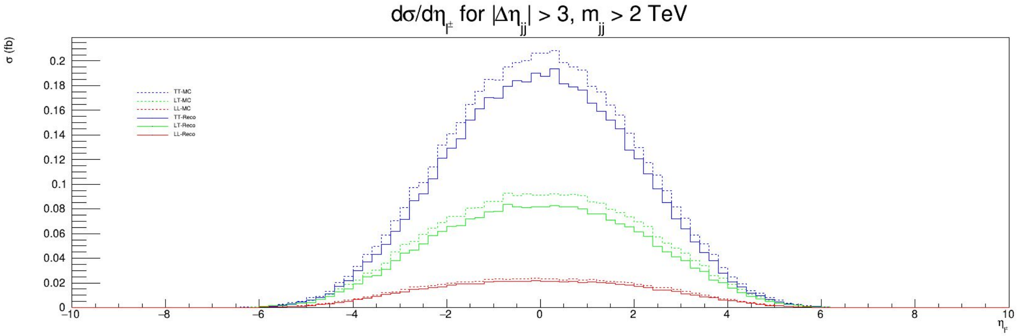




Final State Lepton Distributions

Leptons issued from polarized Zs have characteristic cos(θ*) and η distributions. Reconstruction efficiencies were confirmed to match those parameterized in Delphes.





<u>Tracking Efficiencies in Delphes:</u>

<u>Electrons:</u>

$\eta < 2.5$: 90-95%

$2.5 < \eta < 4$: 85-90%

$4 < \eta < 6$: 80-85%

<u>Muons:</u>

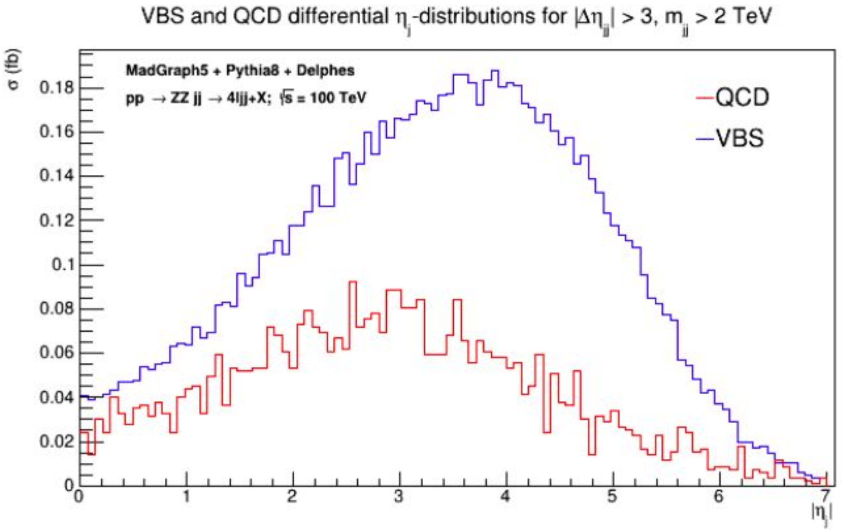
90-99%

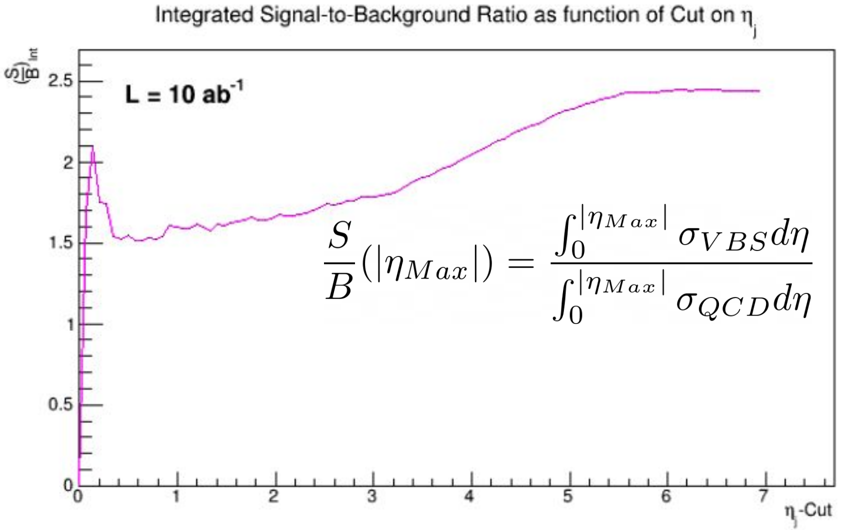
Low Efficiency Range: $0.5 < p_T < 1$

High Efficiency Range: $p_T > 1$

η-Sensitivity for Designing an FCC-hh Experiment

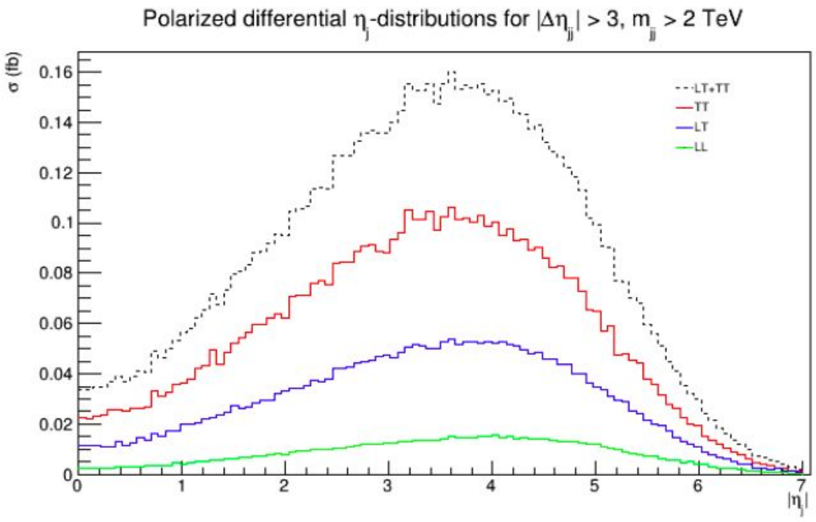
The sensitivity of a detector to η, $S/B(\eta_{Max})$, represents what is gained by having good tracking and reconstruction ability up to a certain value of η. We determined that an FCC-hh detector would ideally have efficient hadron tracking up to $|\eta| \sim 5$ in order to maximize its ability to separate VBS from QCD events, after which gains are minimal.

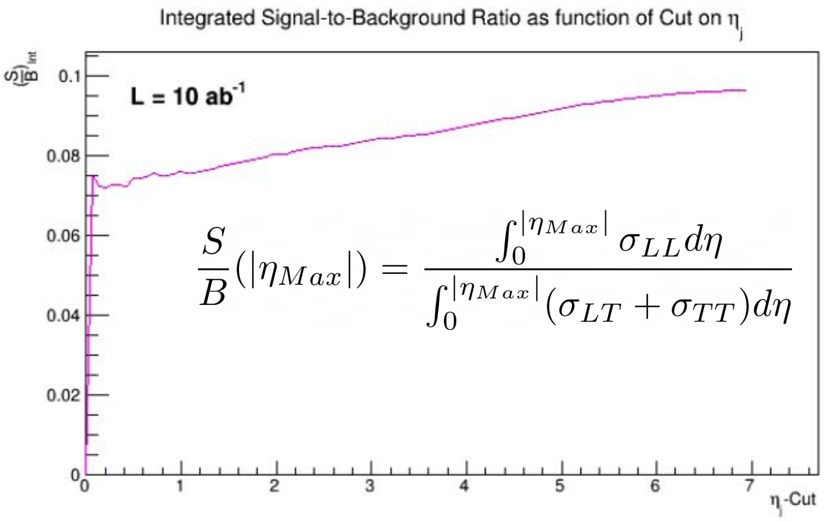




FCC-hh Sensitivity vs. Maximum η_j

The sensitivity to $|\eta_{Max}|$ in separating the longitudinal polarizations does not maximize within $|\eta_j| < 7$, but grows up to $|\eta_j| \sim 5$, then increases are very small.

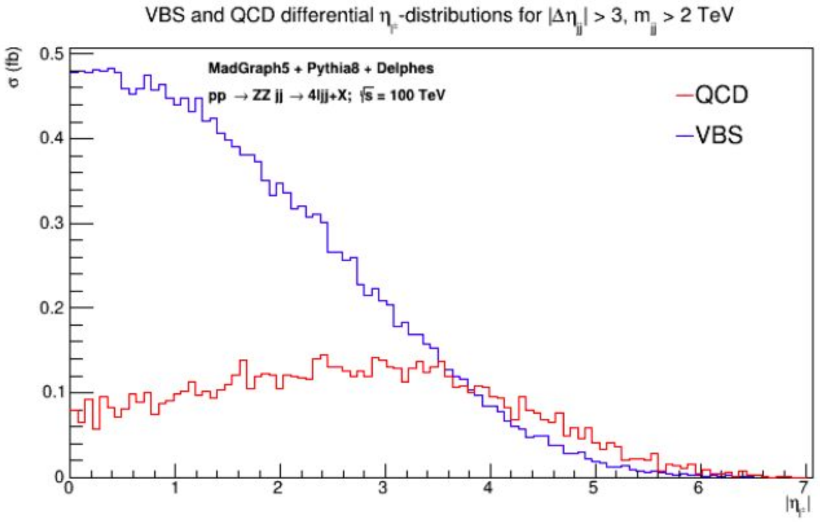


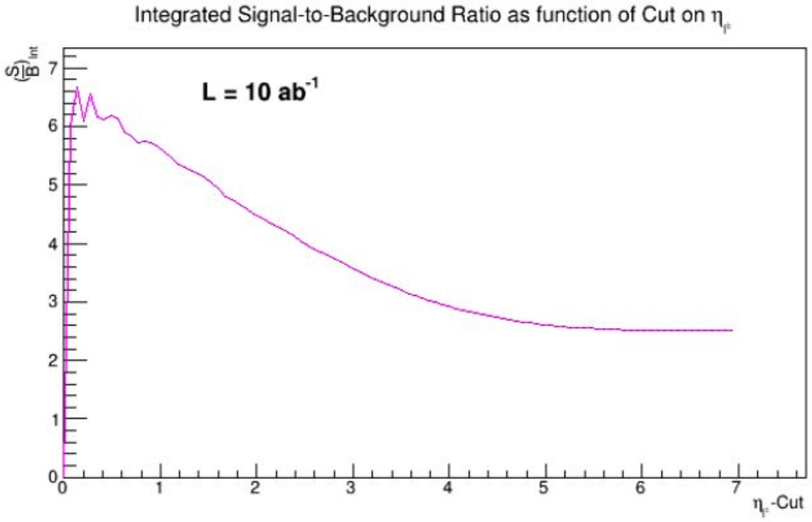


$$\frac{S}{B}(|\eta_{Max}|) = \frac{\int_0^{|\eta_{Max}|} \sigma_{LL} d\eta}{\int_0^{|\eta_{Max}|} (\sigma_{LT} + \sigma_{TT}) d\eta}$$

FCC-hh Sensitivity vs. Maximum η_l

Leptons issued from VBS processes are more likely to be found in the central region of the detector than those from QCD related processes, so there is no specific gain to be had for VBS separation by having lepton tracking in the high rapidity regions.





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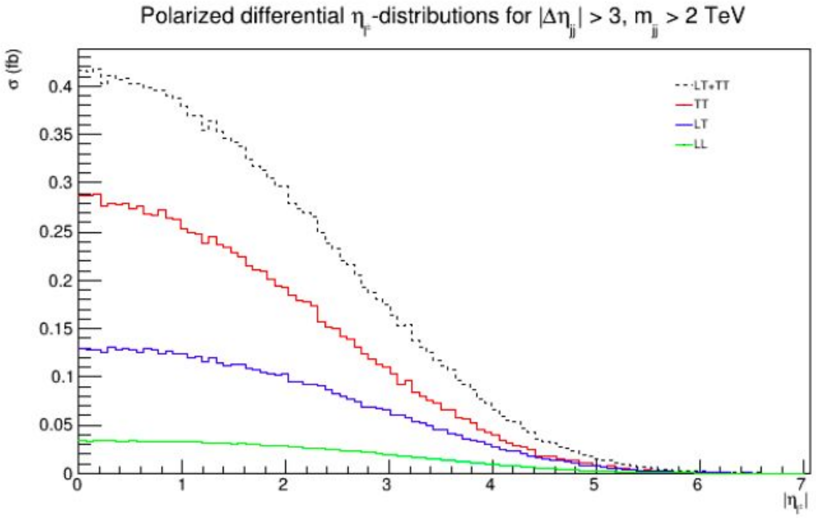
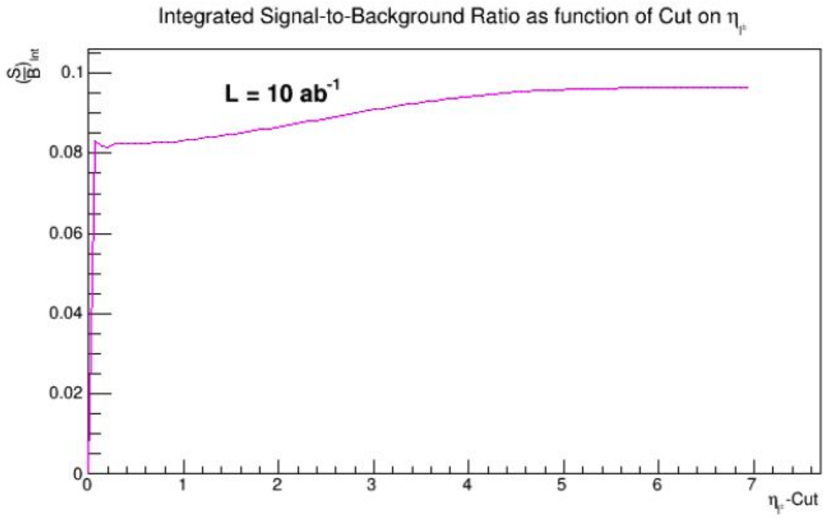
FCC-hh Sensitivity vs. Maximum η_l

There is a slight gain in separating the $Z_L Z_L$ states from the other polarization combinations if the detector has lepton tracking up to $|\eta|\sim4$, after which gains level out.





Conclusion

Vector Boson Scattering, particularly for longitudinally polarized states, is a crucial process in the Standard Model. Any deviation from the expected results would be a strong indicator of new physics in the electroweak and scalar sectors of the theory. The FCC-hh will allow for a strong separation in VBS events from their associated QCD backgrounds, as well as provide the energies and statistics needed to separate the longitudinal states in the ZZ channel.