Vector Boson Scattering with the ATLAS Detector and EFT prospects

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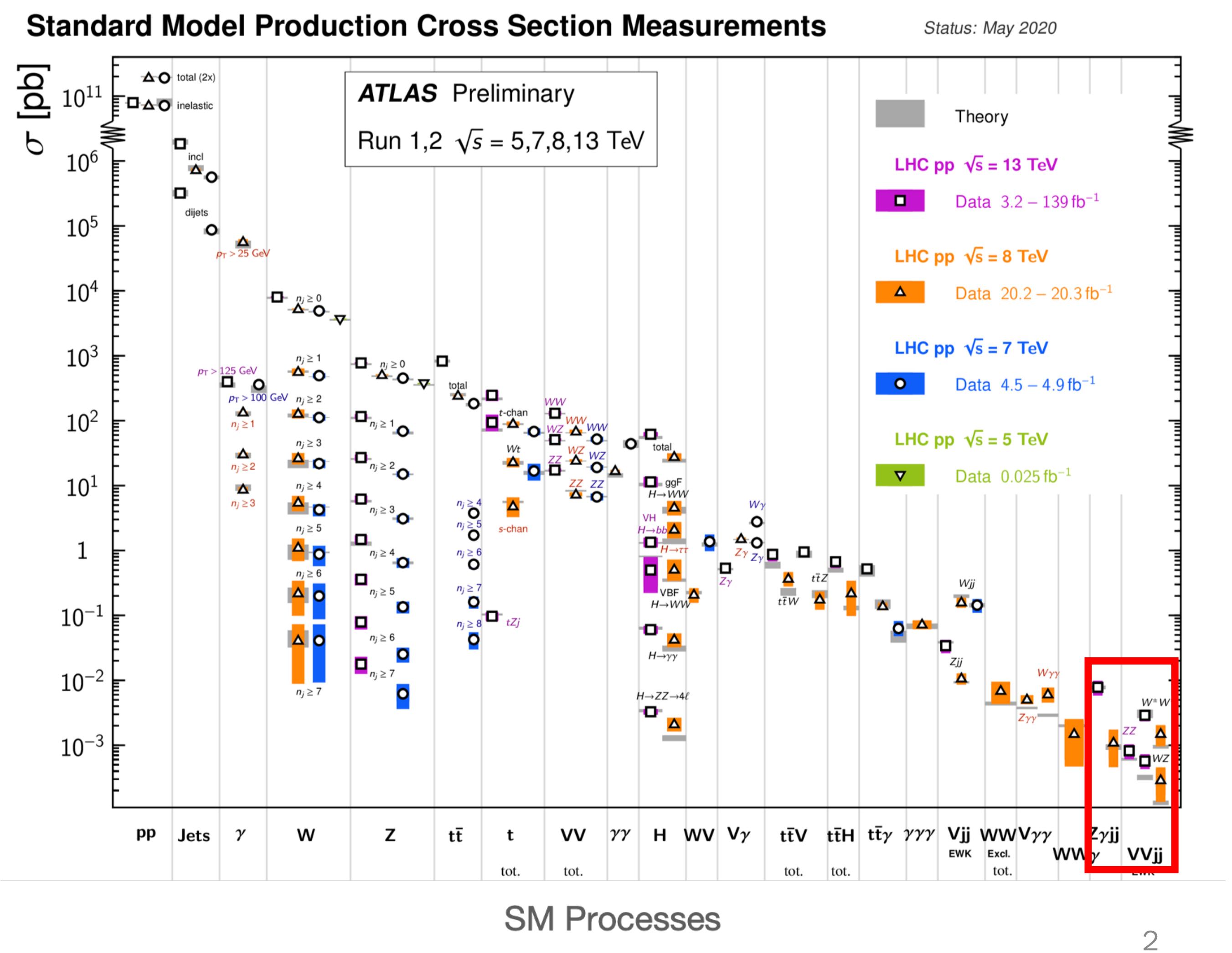
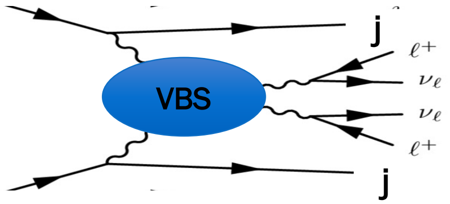
Outline

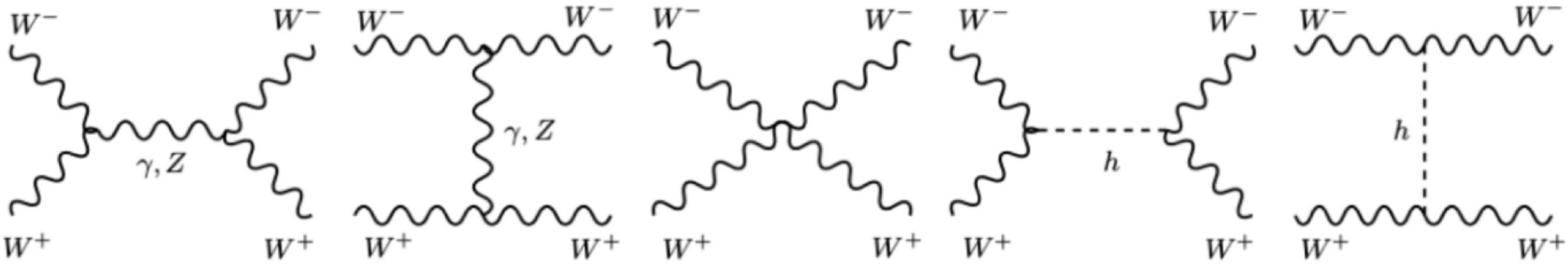
- Vector Boson Scattering
- Observation of the electroweak diboson production with the ATLAS detector
- EFT prospects



Vector Boson Scattering: Motivation

- Unitary process in the SM, very precisely predicted

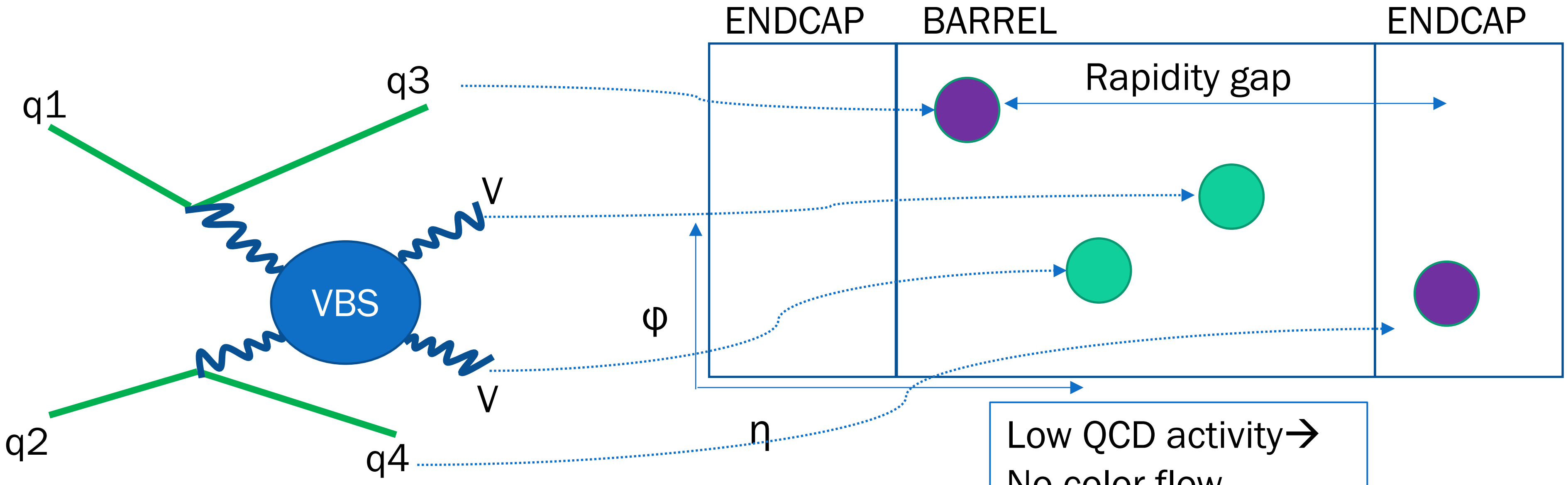




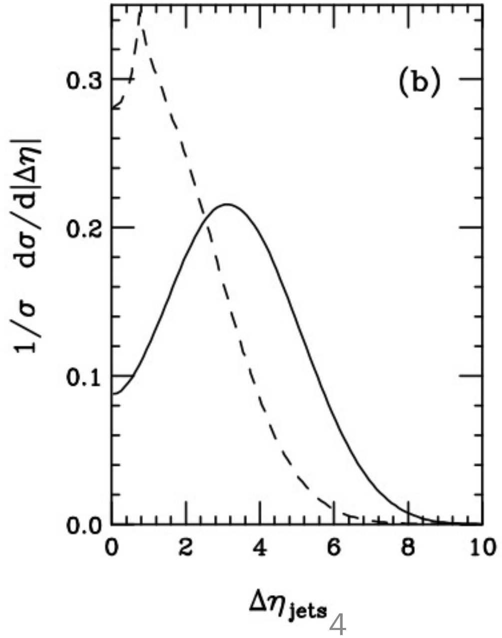
- Any deviations from the prediction signal new physics in a model-independent way and hints on the scale of NP
- Provides access to quartic gauge couplings that could be modified by New Physics

VBS signature at LHC

- Distinct event topology
  - Two energetic jets with large di-jet mass (m_{jj}) and high rapidity separation
  - Diboson system, centrally produced with respect to the two forward jets



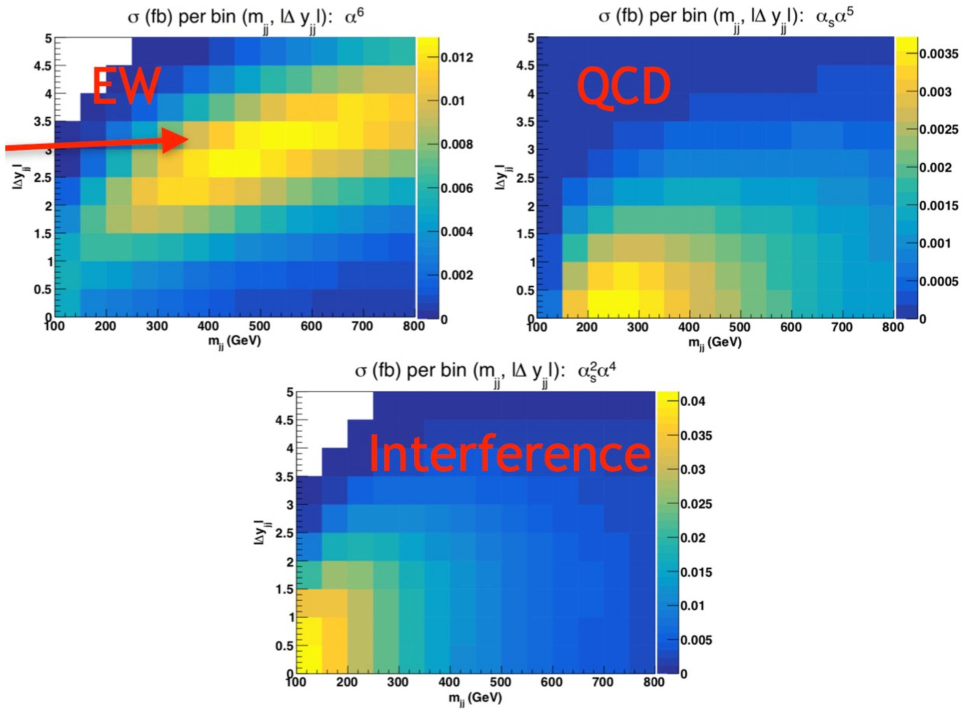
Low QCD activity→
No color flow
between tagging
jets



arXiv:hep-ph/9605444

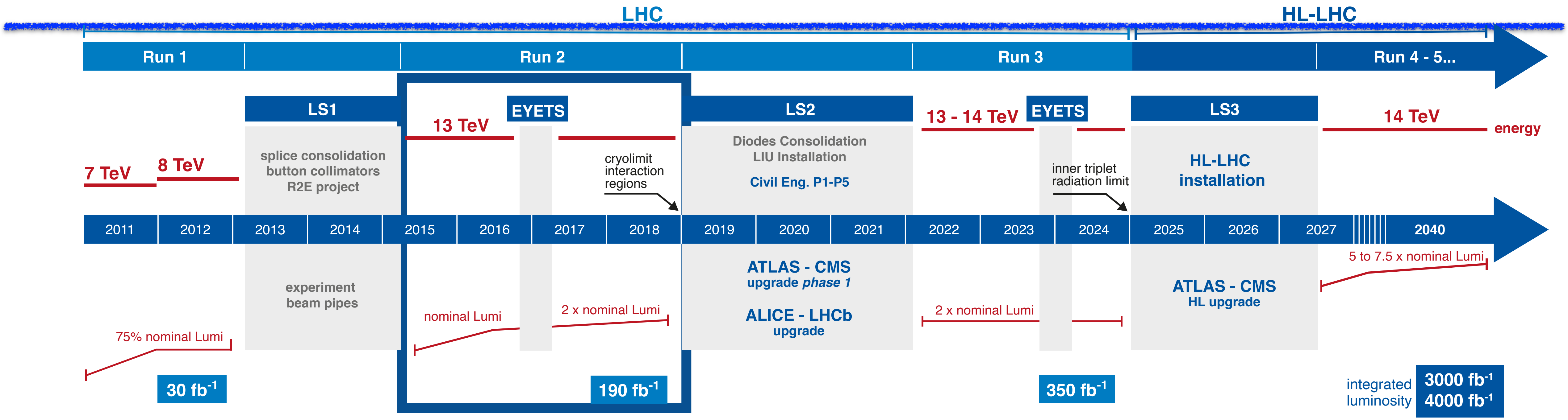
VBS signature

- Signal: EWK contribution—>six fermions final state at leading order O(α^6)
- Background:
  - Irreducible
    - QCD background: at LO ($\alpha^4 \alpha s^2$)
    - already at LO interference with signal: (αs^5)
  - Reducible:
    - misidentification of final state particles
  - significant systematic uncertainties from jet energy reconstruction and background modelling



Ballestrero, et al.; 1803.07943

LHC / HL-LHC Plan



Overview of ATLAS VBS measurements

Channel	Final state	Observed Significance	Recent measurement
ssWW	llνν jj	6.9σ	13 TeV
WZ	lllν jj	5.3σ	13 TeV
ZZ	llll jj /llννjj	5.52σ	13 TeV
Zγ	(ll/νν)γjj	4.1σ	13 TeV
WV	lljjjj	2.7σ	13 TeV

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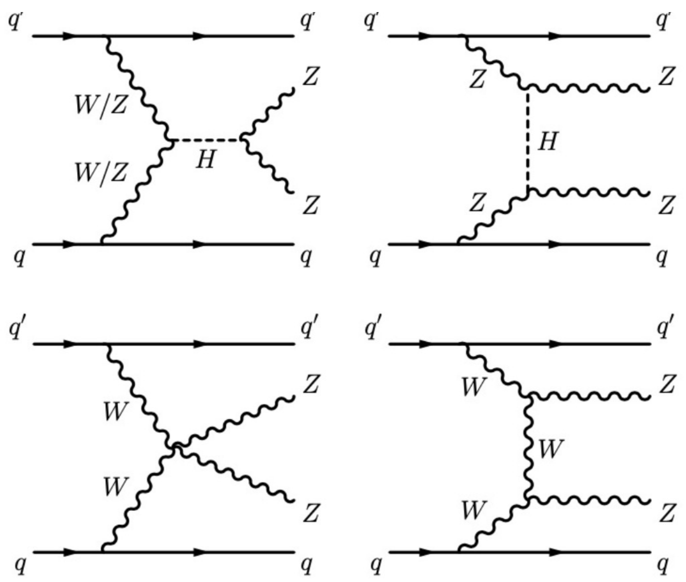
In this talk

Electroweak ZZjj production

- 2 signatures:
  - 4ljj:
    - Clean signature
    - Lower statistics compared to other diboson processes
  - 2l2v:
    - Higher branching ratio
    - Not as clean signature
    - Sensitive to BSM in the high pT regime
- Full Run2 dataset (139 fb-1) was used to probe ZZjj→4ljj and ZZjj→ 2l2vjj



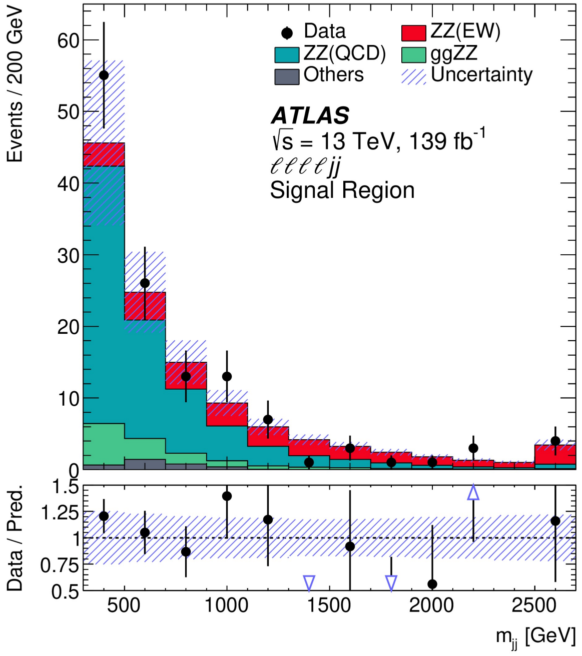
Electroweak ZZjj production

See more in G. Maznas' and A. Marantis' Talks

- Different background composition, data driven estimation for the main components

<u>ZZjj→4ljj</u>

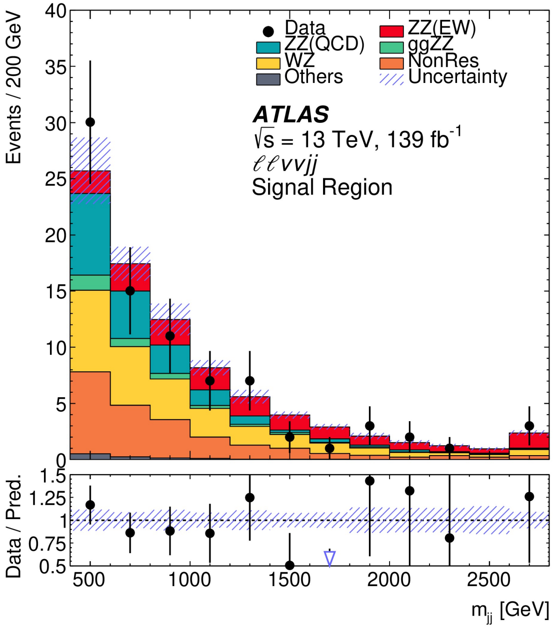
- QCD ZZjj control region with low mjj or Δy(jj) included in the fit



Dominant Bkg: ZZ-QCD

<u>ZZjj→2l2νjj</u>

- WZ estimated in 3-lepton control region
- Non-resonant (ttbar and WW) estimated in eμ control region



Dominant Bkg: WZ

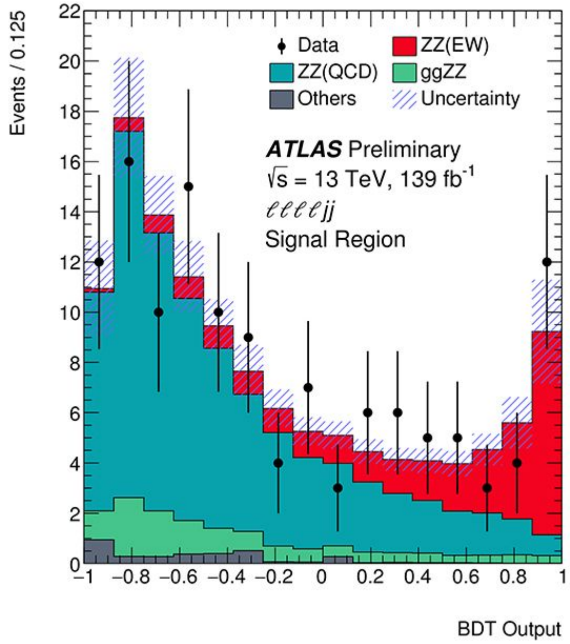
ZZjj-results

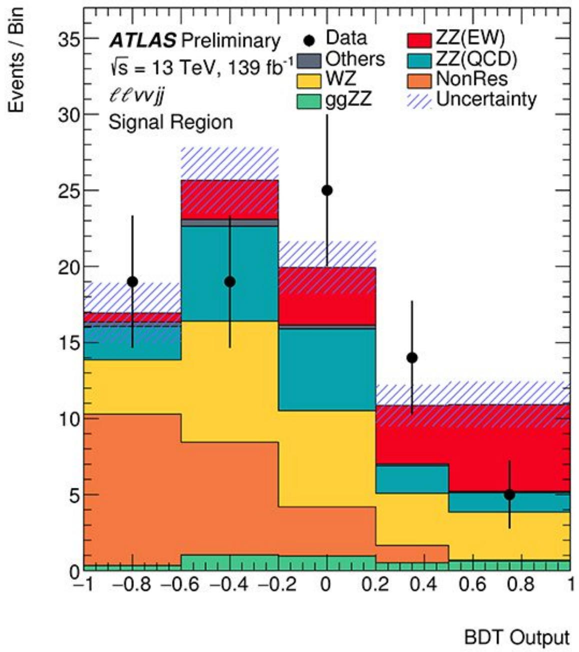
arXiv:2004.10612

- Extract inclusive cross-section EWK+QCD in the signal region

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

- Use multi-variate discriminant to extract EWK component





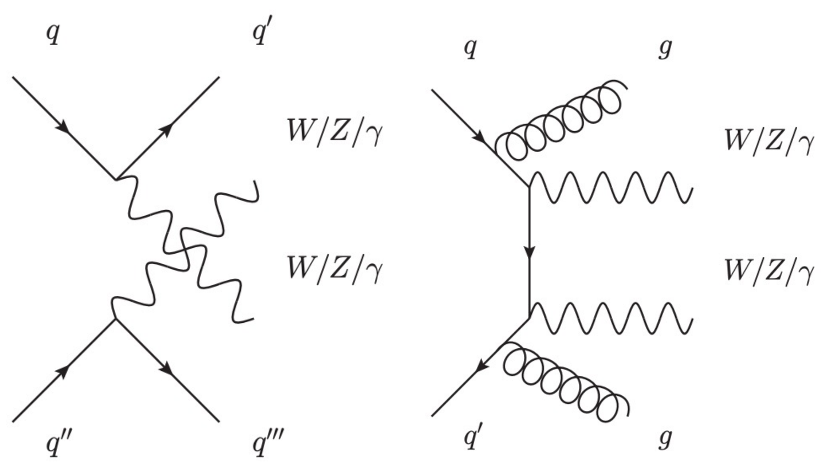
	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	$5.5\ (3.9)\ \sigma$
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	$1.2\ (1.8)\ \sigma$
Combined	1.35 ± 0.34	0.96 ± 0.22	$\boxed{5.5\ (4.3)\ \sigma}$

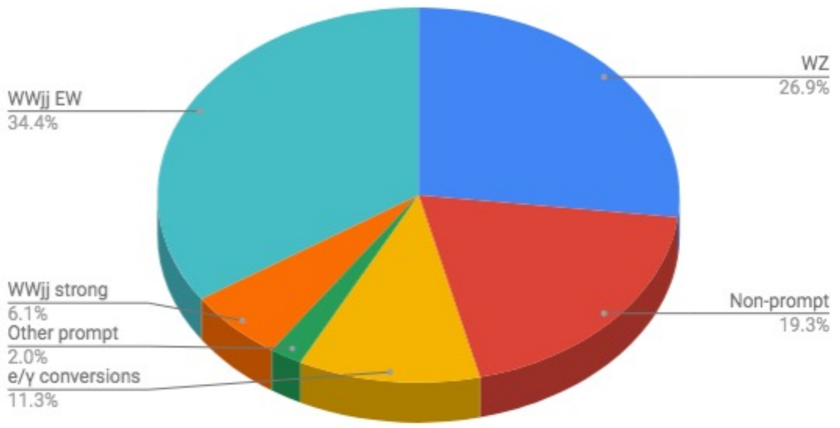
Observation!

Electroweak ssWW production

arXiv:1906.03203

- EW production of two same-sign charged leptons
- EW/QCD>13, best EW/QCD ratio channel!
- Low cross-section, low background
- Main BG→WZjj-QCD
  - The shape is taken from MC and the normalization is taken from the data
- Publication with 36fb^{-1} data





ssWW-Results

arXiv:1906.03203

Selection

2 ss leptons:

PT1>25 GeV,
PT2>20 GeV,
mll>20 GeV,
|mee-Mz|>15 GeV

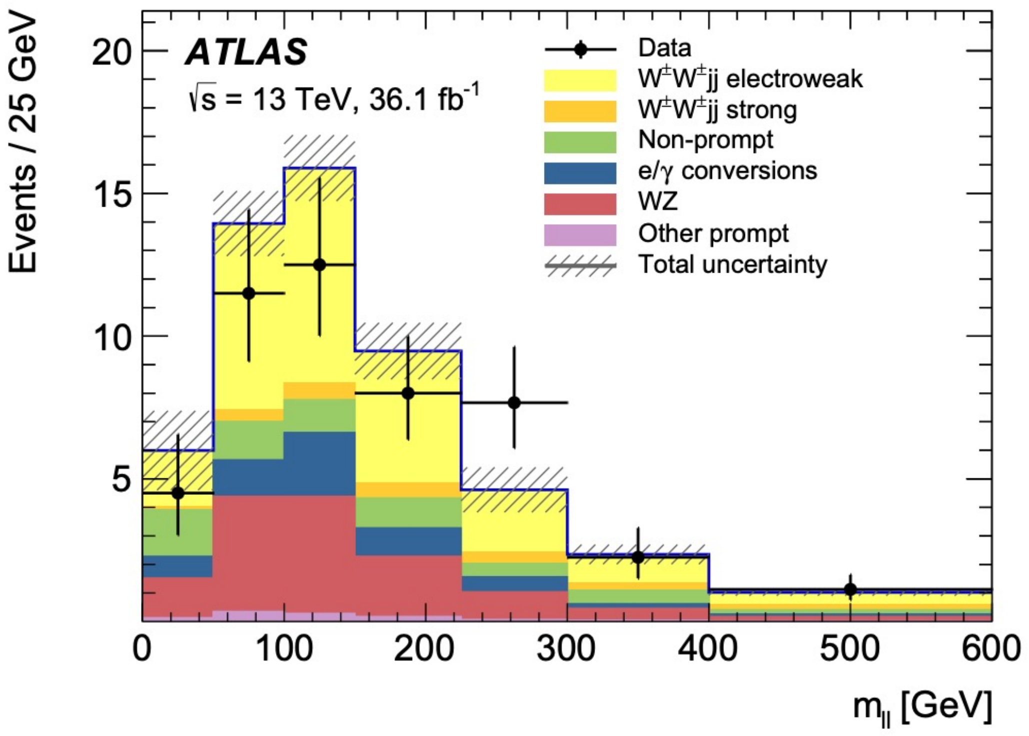
2 jets:

PT>30 GeV
|η|<5.0, mjj>500 GeV
|Δηjj|>2.5

P_T^{miss} >40 GeV

Signal Extraction

1D template fit using mjj simultaneously with WZ and non-prompt CR



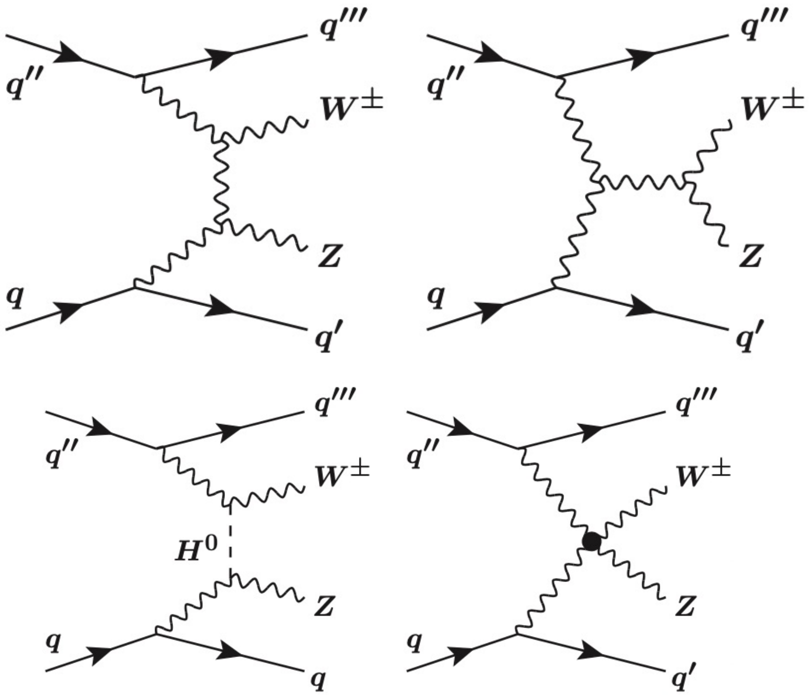
- ssWWjj-EW observed xsec: $2.91_{-0.47}^{+0.51}$ ±0.27(sys) fb with 6.9σ

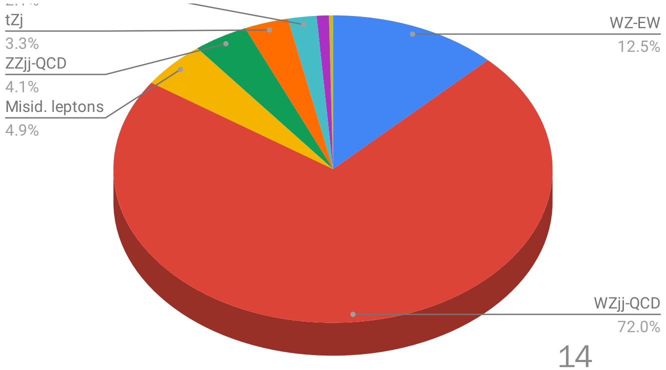
Observation!

Electroweak WZjj production

arXiv:1812.09740

- three leptons final state
- Less clean signature than W±W±, but cross section accessible with large dataset
- EW/QCD<0.5
- Backgrounds
  - QCD production of WZjj is the dominant background
  - non-prompt contributions estimated from data
- Publication with $36 fb^{-1}$ data





WZjj-Results

arXiv:1812.09740

Selection

3 leptons:

Z: $P_{Tl1,2}$>15 GeV, |Mz-Mz-PDG|<10GeV

W:$P_{T,l}$>20GeV

m_T^W>30 GeV

jets:

PT>40 GeV

|η|<4.5

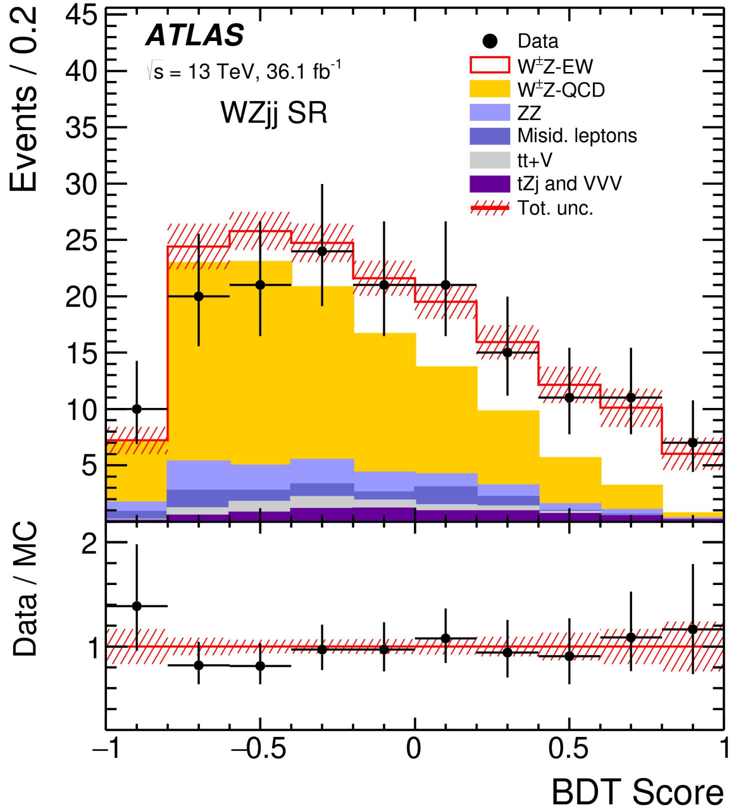
mjj>500 GeV

ηj1*ηj2<0

no b-jet

Signal Extraction

With a 1D template fit using BDT score of 15 varibles simultaneously with QCD CR, b-CR and ZZ-CR



WZjj-EW observed xsection:

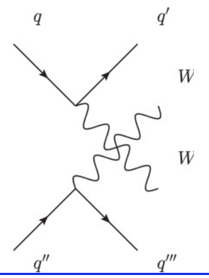
$0.57_{-0.14}^{+0.15}$ fb with 5.3σ

Observation!

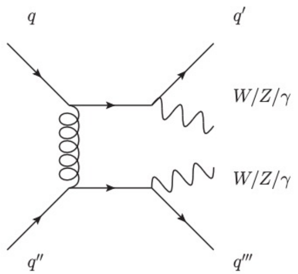
Electroweak Zγjj production

arXiv:1910.09503

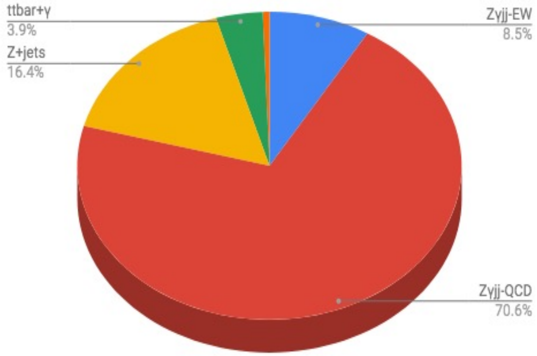
- EWK Zllγ has not been observed yet
- higher statistics due to photons
- Interesting channel to probe neutral quartic couplings
- EW/QCD~0.12
- Publication with 36fb^{-1} data
- Dominant Backgrounds:
  - QCD Zγ: Normalization estimated from data
  - Z+jet: 2D sideband method (photon ID, isolation)

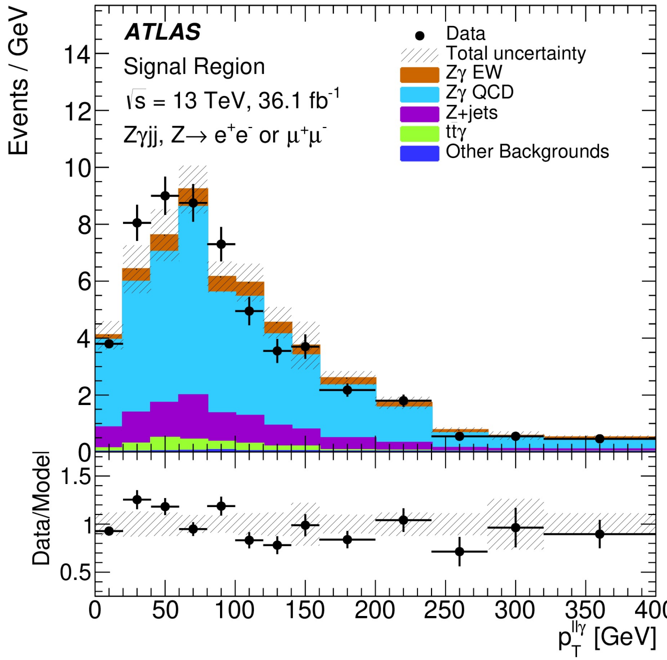


EWK signal



QCD Bkg





Zγjj - results

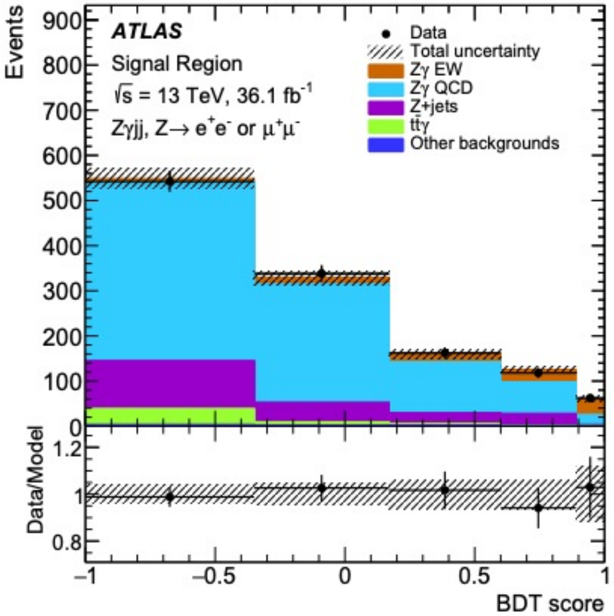
arXiv:1910.09503

<u>Selection</u>

- mll+mllγ cut to reduce FSR contributions
- b-jets are vetoed
- VBS selection: Δηjj>1, centrality (Zγ)<5, mjj> 150GeV

<u>Signal Extraction</u>

with a 1D template fit using BDT score in SR simultaneously with b-CR



- <u>Zγjj-EW observed xsec:</u>

$7.8_{-1.9}^{+2.0}$ fb with 4.1σ

Evidence

Effective Field Theories

See more in Prof. Dedes' Talk

- SM expansion to higher order terms

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{c_j}{\Lambda^4} O_j + O_k$$

- EFT: low energy parametrisation of an unknown model that will become apparent at “very high” energies
- First to look for: Dim-6 and Dim-8

Dim-6 EFT operators parametrization

arXiv:1709.06492v2

- Parametrization: SMEFT model using Warsaw basis
- Dim-6 operators in Warsaw basis, excluding four fermion
- Operators contributing across physics channels, this is a simplified picture
- Aim for a global fit across different channels

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

SM

Higgs

Higgs

Top

Dim-8 EFT operators parametrization

arXiv:1604.03555

- Parametrization: Eboli model for Dim-8 EFT operators
- Used by both CMS and ATLAS for aQGC interpretation for now.
- 18 independent operators

Longitudinal operators

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\begin{aligned}
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \\
\mathcal{L}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{L}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}$$

Mixed operators:Pure Higgs field

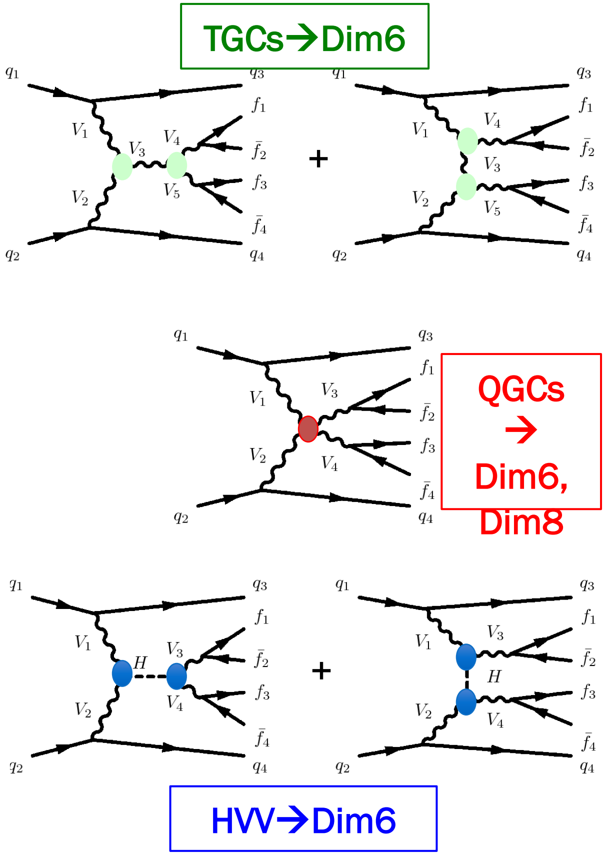
Transverse operators

$$\begin{aligned}
\mathcal{L}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right. \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right. \\
\mathcal{L}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right. \\
\mathcal{L}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{L}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}$$

	$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$	$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$	$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$
$WWWW$	X	X		X		
$WWZZ$	X	X	X	X	X	
$ZZZZ$	X	X	X	X	X	X
$WWZ\gamma$		X	X	X	X	
$WW\gamma\gamma$		X	X	X	X	
$ZZZ\gamma$		X	X	X	X	X
$ZZ\gamma\gamma$		X	X	X	X	X
$Z\gamma\gamma\gamma$				X	X	X
$\gamma\gamma\gamma\gamma$				X	X	X

Experimental Approach to EFTs

- Associate the operators to couplings between bosons and fermions
  - Quartic gauge couplings can be parametrized in terms of Dim-6 operators and Dim-8 operators
  - Triple gauge couplings can be parametrized in terms of Dim-6 operators
  - Higgs couplings can be parametrized in terms of Dim-6 operators



<u>EFT operators are built from:</u>

- the Higgs doublet field

$$\Phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+H) \end{pmatrix}$$

- the fermion fields ψ
- the covariant derivative

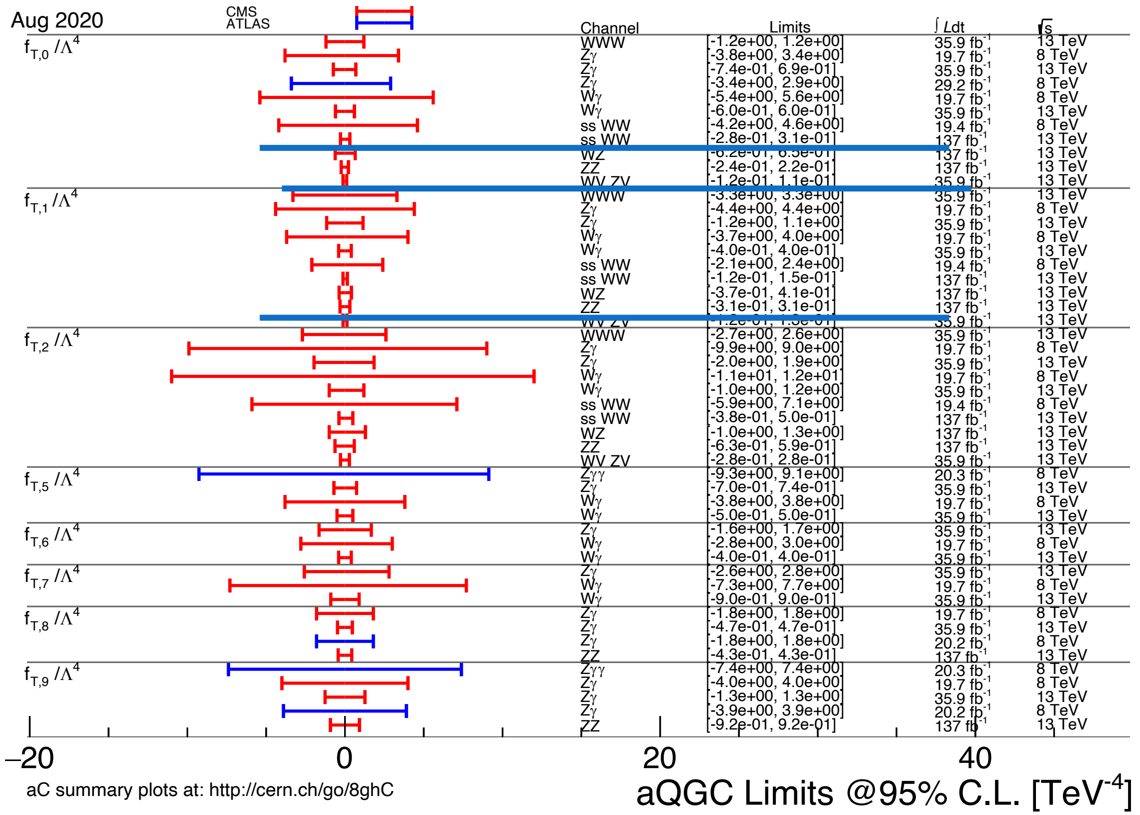
$$D_\mu = \partial_\mu + ig\frac{\sigma^j}{2}W^j{}_\mu$$

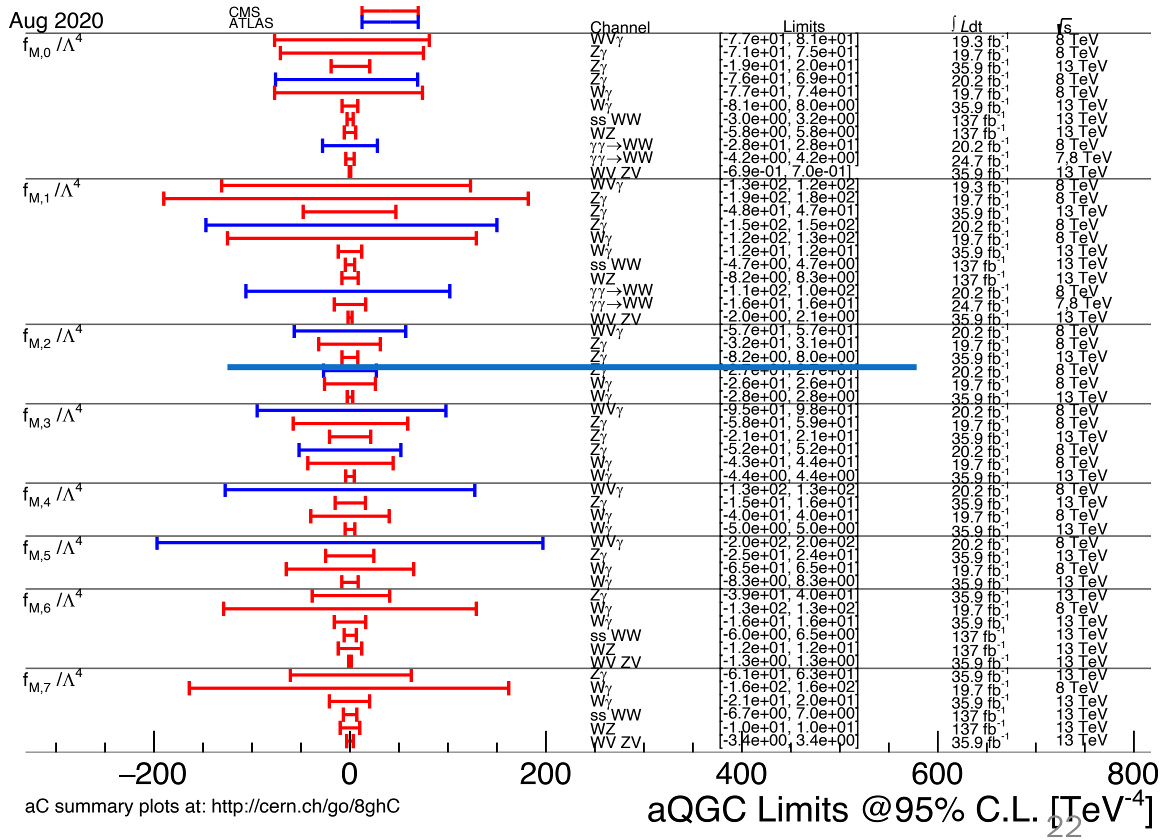
- the field strength tensors

$$\widehat{W}^{\mu\nu} = ig\frac{\sigma^j}{2}W^{j,\mu\nu} = ig\frac{\sigma^j}{2}\left(\partial^\mu W^{j,\nu} - \partial^\nu W^{j,\mu} - g\epsilon^{jkl}W^{k,\mu}W^{l,\nu}\right)$$

$$\widehat{B}^{\mu\nu} = ig'\frac{1}{2}B^{\mu\nu} = ig'\frac{1}{2}\left(\partial^\mu B^\nu - \partial^\nu B^\mu\right)$$

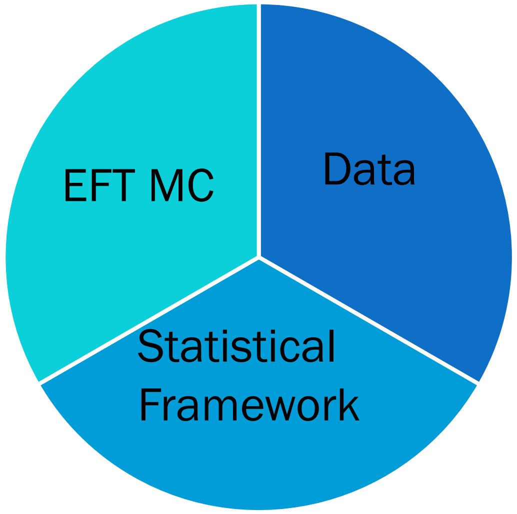
Current EFT limits





EFT re-interpretations and challenges

- EFT MC
  - best approach to interpolate various between EFT points
    - Reweighting (MC@NLO, MadGraph)
    - Possibility to generate single terms of the Lagrangian Linear only or linear + quadratic terms
  - Linear only or linear + quadratic terms
- Things to take into account
  - EFT contributions in the Background processes
  - How to deal with dim-8 operators in dim-6 case
  - How to deal with dim-6 operators in dim-8 case
  - Higher order corretions



Combination

- So far interpretations have been tailored for individual analyses whereas now the collaboration is moving towards a global approach using the acquired expertise
- Combining between the various channels→ more powerful constraints
- Growing number of EFT measurements in ATLAS with full Run-2 data
- Theory framework is largely in place – Still many challenges to meet

Combination-First attempt

- Combination within the VBS channels: WZjj and ssWW
- Relevant Operators: fS0, fS1, fT0, fT1, fT2, fM0, fM1
- Reinterpetation using public data at 36 fb-1, by fitting
  - mll distribution at reconstruction level for ssWW
  - unfolded mtWZ distribution for WZjj
  - Combination between reconstructed and unfolded distributions
- All systematics uncertainties taken into account
  - Correlation between the channels are considered
- Results to be public soon

Summary

- In Run2, observation for the EWK diboson production in the $W^{\pm}W^{\pm}jj$, $WZjj$ and $ZZjj$ final states and evidence for the $Z\gamma jj$
- VBS can serve as a probe for the effects of EFTs at accessible energies
- Using the full statistics of Run2 will allow to perform EFT interpretations
- Increased statistics of Full Run2 and in the long term, HL-LHC will provide a portal to further BSM interpretations in the VBS phase space