Vector boson scattering in the ATLAS detector

Journées de Rencontre Jeunes Chercheurs – 25/10/23

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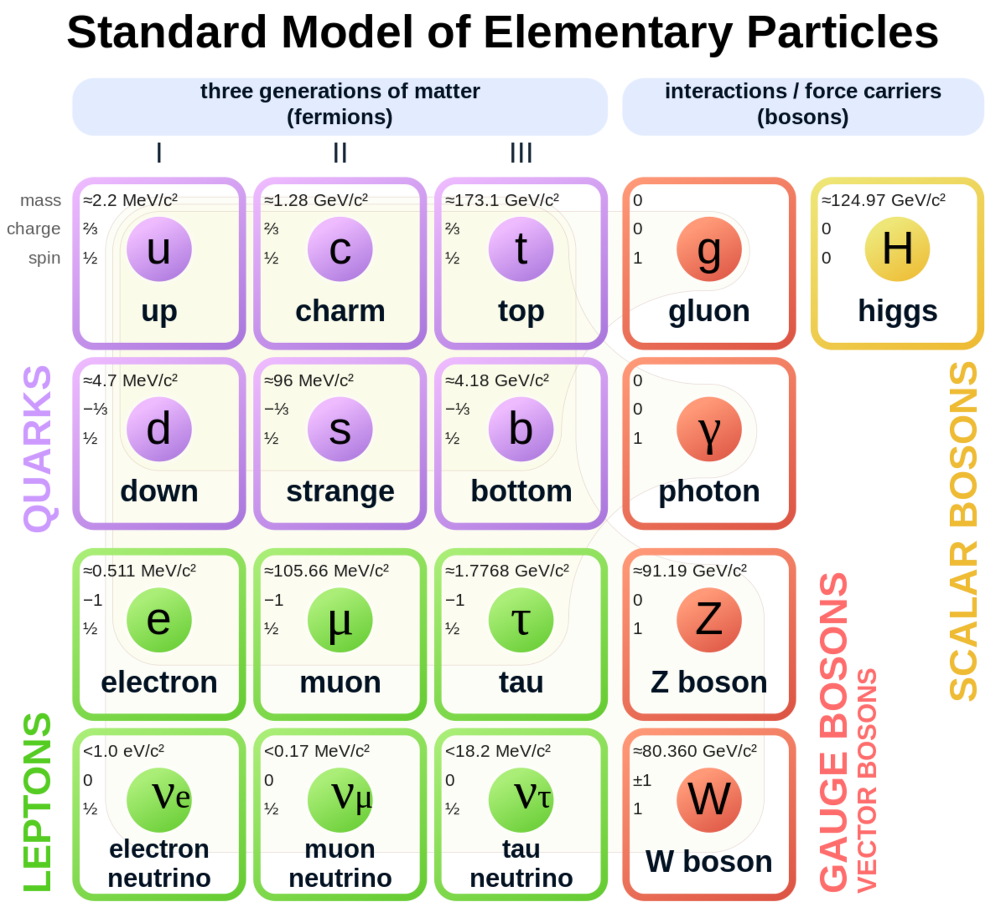
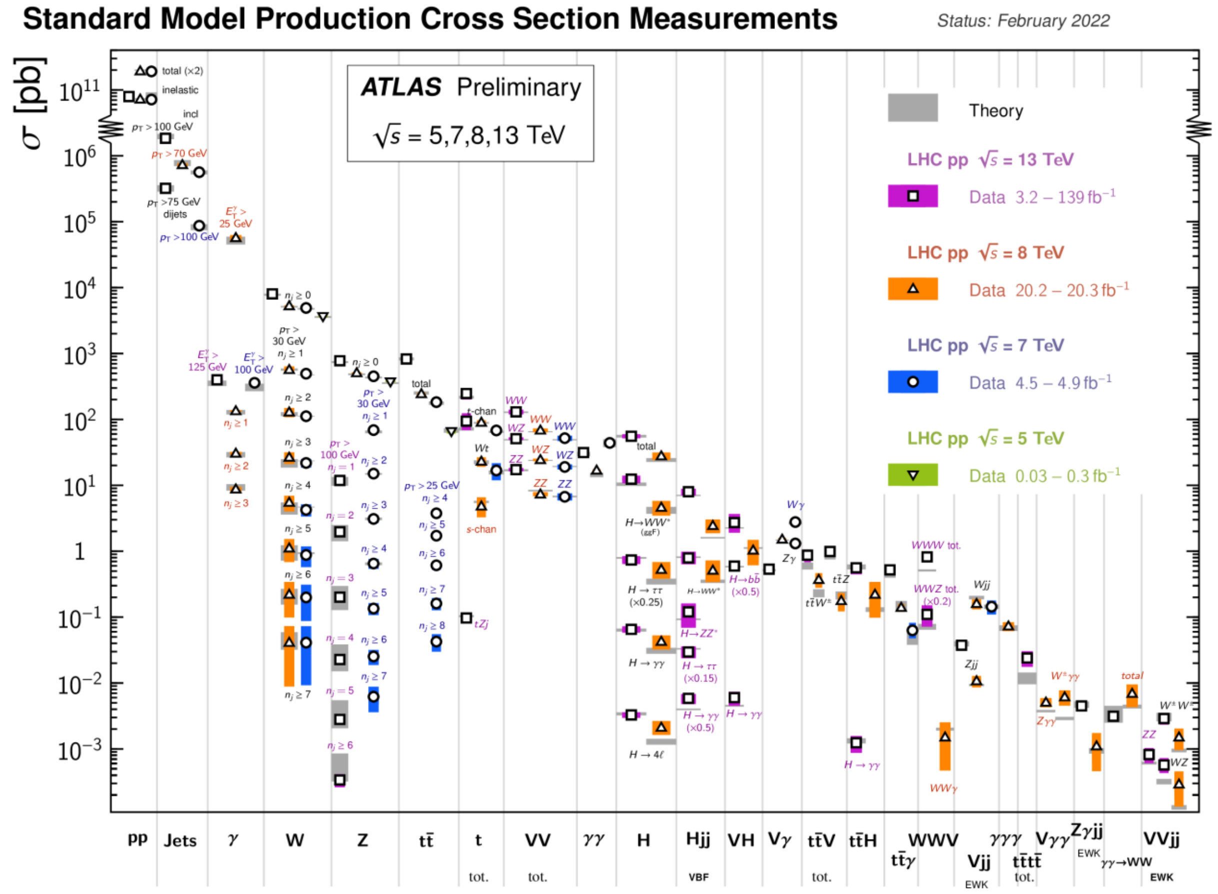
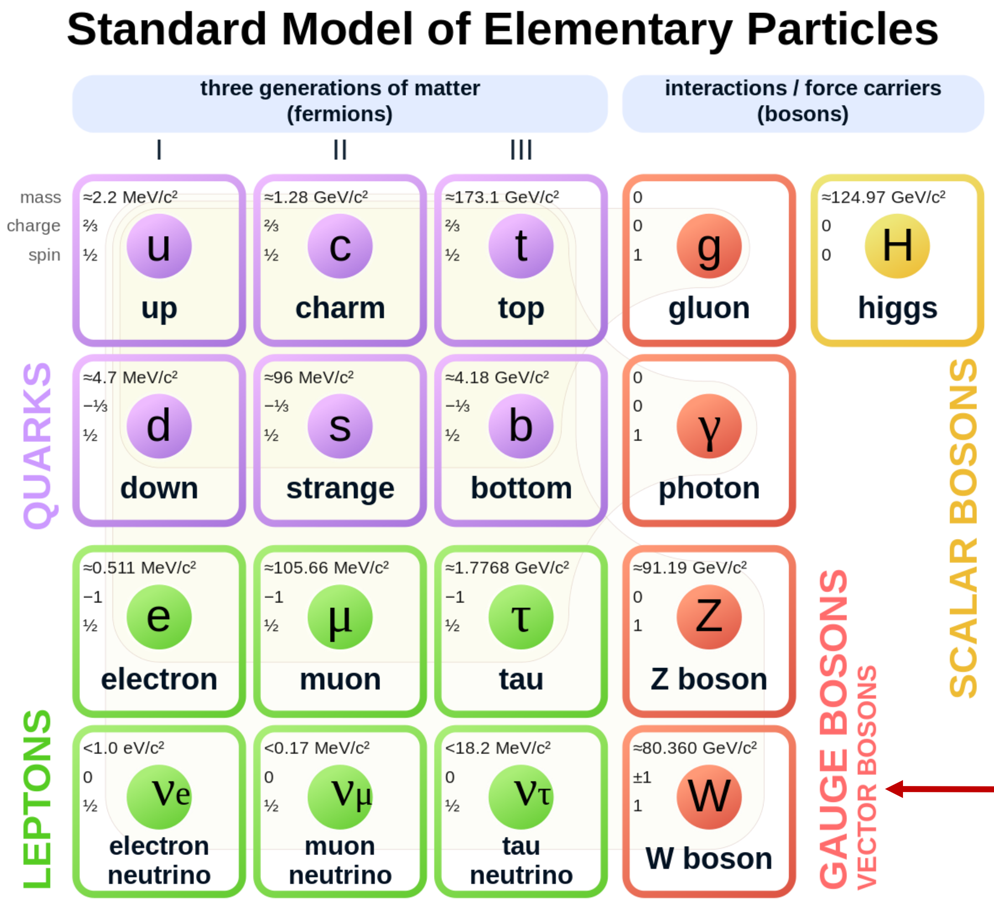
The standard model…

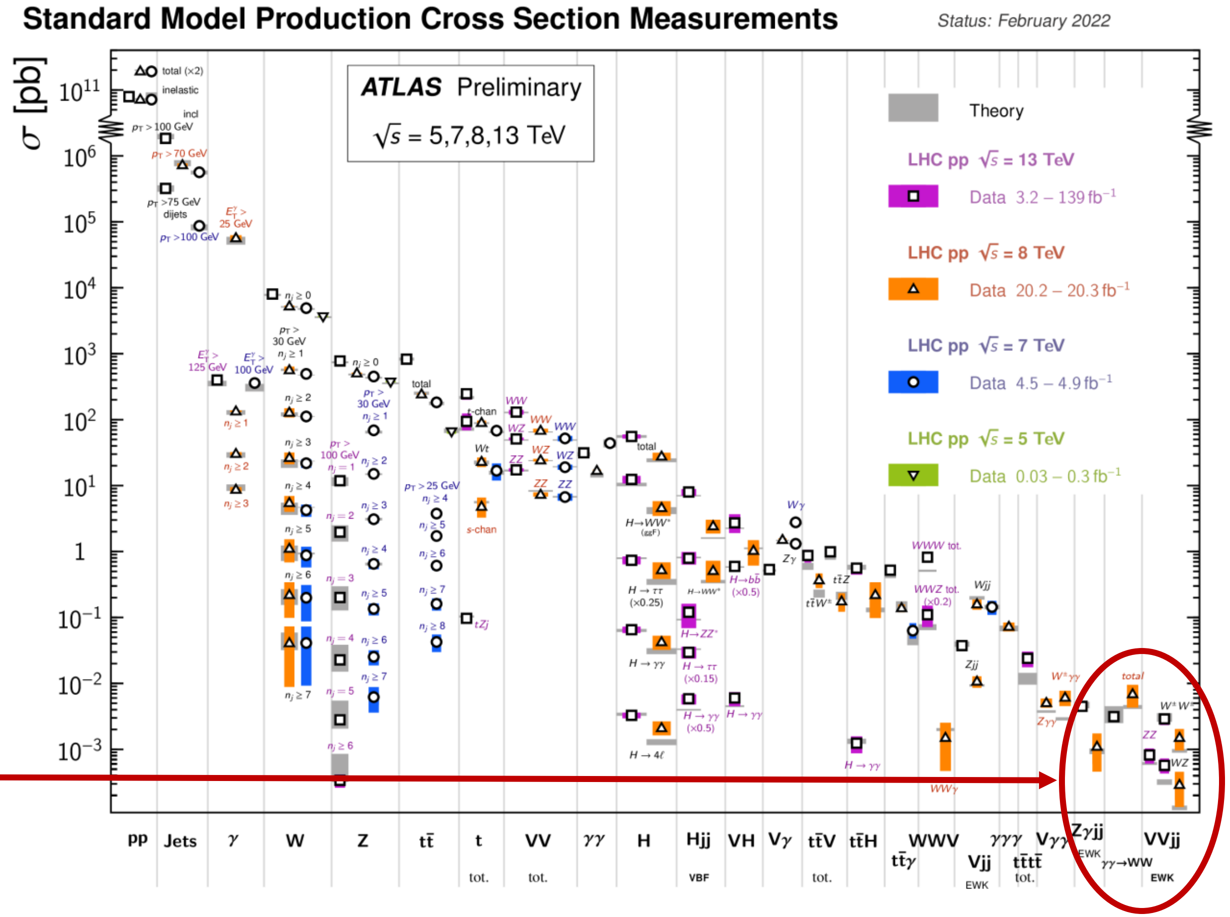




- The theory describing elementary particles and their interactions
- Well tested experimentally

The standard model...





- The theory describing elementary particles and their interactions
- Well tested experimentally

Some very rare processes

Vector boson scattering (VBS)

- Electroweak production of vector bosons associated with jets: scattering («collision») of vector bosons

$$V_1 V_2 jj \rightarrow V_3 V_4 jj$$

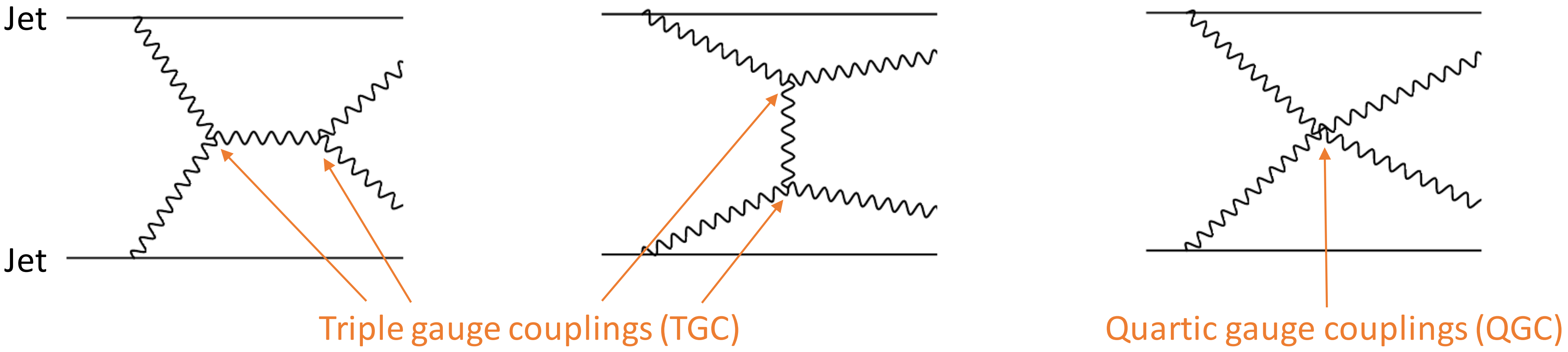
- V_i are electroweak gauge bosons (Z, $W^{\pm}$, photon)

- Reminder: quarks hadronize and form jets (*j*) in detectors

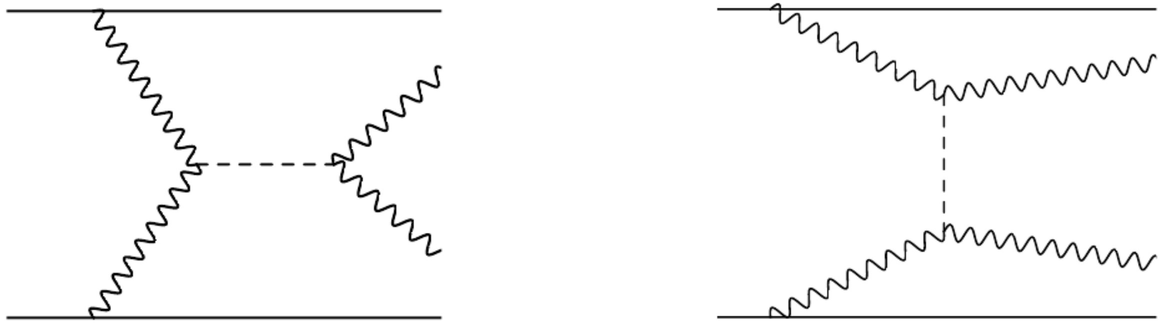
- High energy needed for such process: need to collide gauge bosons

VBS is very rich

Lots of different gauge couplings can be involved



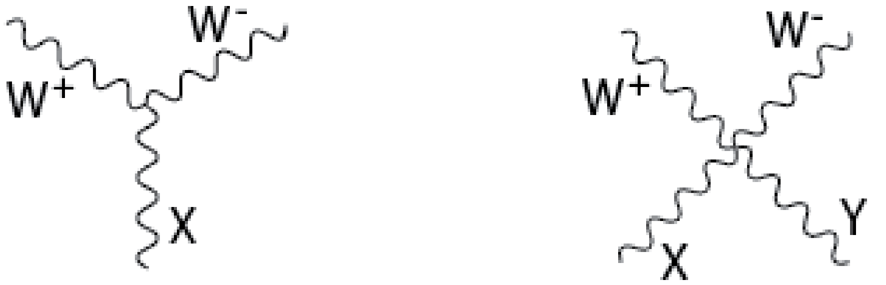
Even couplings with the Higgs boson



These graphs are necessary to allow VBS in the SM !

Study of gauge couplings

- Not all couplings are allowed in the Standard Model (SM)



TGC QGC

- Of course charge should be conserved at the vertex
- Furthermore there is no neutral couplings
- Search for deviation from SM in gauge couplings !

VBS and gauge couplings

- VBS (and triboson) processes are the only ones that are sensitive to quartic gauge couplings

- Unique way of probing physics beyond the SM (BSM) affecting these couplings
  - New QGC (e.g. neutral ones)
  - Alteration of couplings existing in the SM

  } Anomalous quartic gauge couplings (aQGC)

- Can be studied in the Effective Field Theory (EFT) framework

We haven't seen BSM physics for now

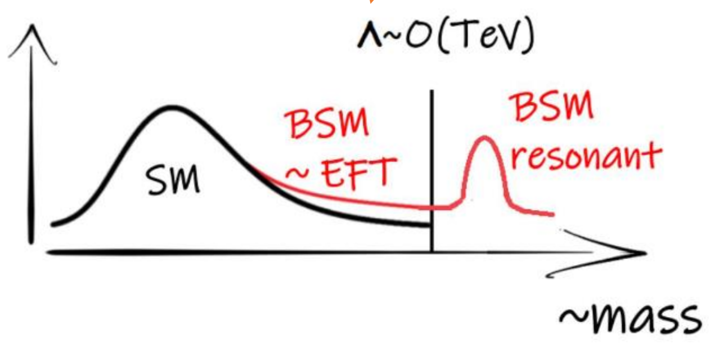
- It does not exist ? No, we know that SM is incomplete
- It is too weakly coupled ?
- It is hidden in SM backgrounds ?

Need to increase statistics and improve theory predictions

- It is present at too high energy for the current accelerators ? New accelerators EFT studies !

EFT approach

Energy scale (not directly accessible)



- Model-independent way of looking at BSM effects
- Expand the SM Lagrangian (mass dimension 4) to higher dimensions
- Effective Lagrangian $\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$

Dimension-n Lagrangians

- At a given dimension-n: $\mathcal{L}_n = \sum_i C_i^n Q_i^n$

Wilson coefficients — Dimension-n operators

- In the SM there is no high dimension term, Wilson coefficients are 0
- Operators are uniquely associated to Wilson coefficients and form a complete basis
- Odd-dimension operators violate lepton or baryon number conservation and are usually ignored

Dimension-n operators and aQGC

- Wilson coefficients associated to dimension-6 operators are constrained since dimension-6 can be probed with lots of analysis (different final states)
- Dimension-8 is not well known and can induce aQGC: VBS opportunity !
- Link with experiment ? Need observables from EFT
- For instance dimension-8 gives some amplitude (hence cross-section prediction):

$$\mathcal{A}^2 = |\mathcal{A}_{SM}|^2 + 2\sum_i \frac{C_i}{\Lambda^4} Re(\mathcal{A}_i^* \mathcal{A}_{SM}) + 2\sum_i \frac{C_i^2}{\Lambda^8}|\mathcal{A}_i|^2 + 2\sum_{i\neq j} \frac{C_i C_j}{\Lambda^8} Re(\mathcal{A}_i^* \mathcal{A}_j)$$

Pure SM — EFT-SM interference (linear) — Pure EFT (quadratic) — Interference between EFT operators

Eboli model

- Complete classification of dimension-8 operators respecting symmetries

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad , \quad \mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad , \quad \mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \quad , \quad \mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} + \mathrm{h.c.}$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu} D^\nu\Phi\right] \quad .$$

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right] \quad , \quad \mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right] \quad , \quad \mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \quad , \quad \mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \quad , \quad \mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \ .$$

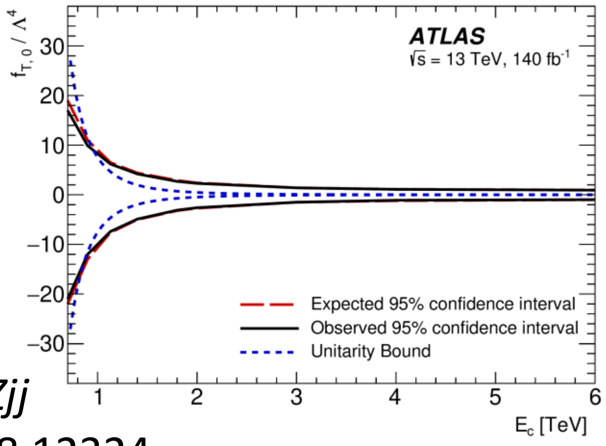
- Different vertices impacted

	SM				Not SM				
Operators	WWWW	WWZZ	WW$\gamma\gamma$	WWγZ	ZZZZ	ZZZγ	ZZ$\gamma\gamma$	Z$\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
FS0, FS1	✓	✓			✓				
FM0, FM1, FM7	✓	✓	✓	✓	✓	✓	✓		
FM2, FM3, FM4, FM5		✓	✓	✓	✓	✓	✓		
FT0, FT1, FT2	✓	✓	✓	✓	✓	✓	✓	✓	✓
FT5, FT6, FT7		✓	✓	✓	✓	✓	✓	✓	✓
FT8, FT9					✓	✓	✓	✓	✓

Unitarity violation

Main problem for VBS aQGC studies

- aQGC violates unitarity (interaction amplitudes give a probability higher than one) at high energy
- Can be prevented by reducing theory phase space: introduction of a cut-off scale (*clipping*) beyond which the Wilson coefficient is set to zero
- Different clipping points can be chosen
- Measured limits should beat limits given by unitarity...



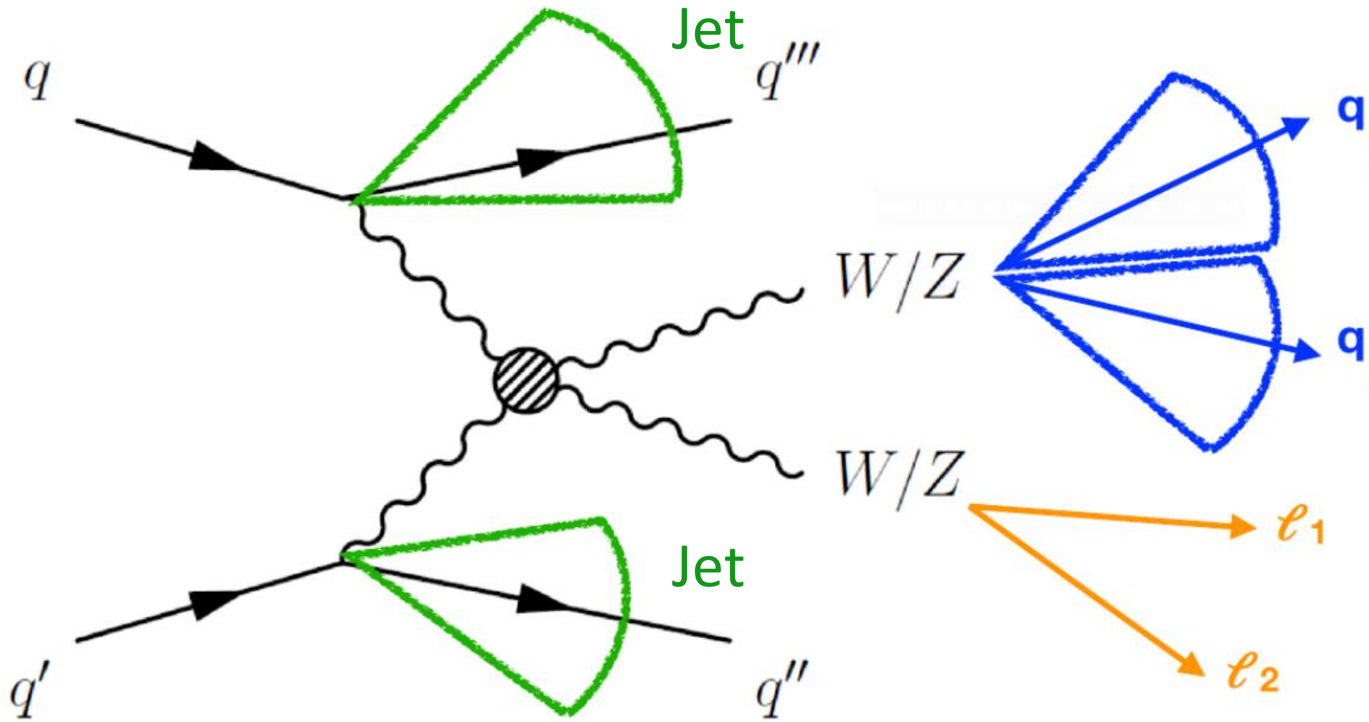
ALTLAS *ZZjj*
arXiv:2308.12324

Experimental search for VBS

- Lots of LHC analyses (ATLAS+CMS)
- Different and complementary analysis channels
  - *WWjj*
  - *WZjj*
  - $(ZZ \rightarrow 4l)jj$
  - $(ZZ \rightarrow 2l2\nu)jj$
  - *γγjj*
  - Inclusive *VVjj*
  - ...
- First evidence during run 1 (*WWjj*) confirmed during run 2

Semileptonic final states

- Inclusive *VVjj* (*V=W,Z*) production
- Semileptonic final state: one gauge boson decays hadronically (quarks pair) and the other one decays leptonically (leptons pair)



Sub-channels defined by number of charged leptons

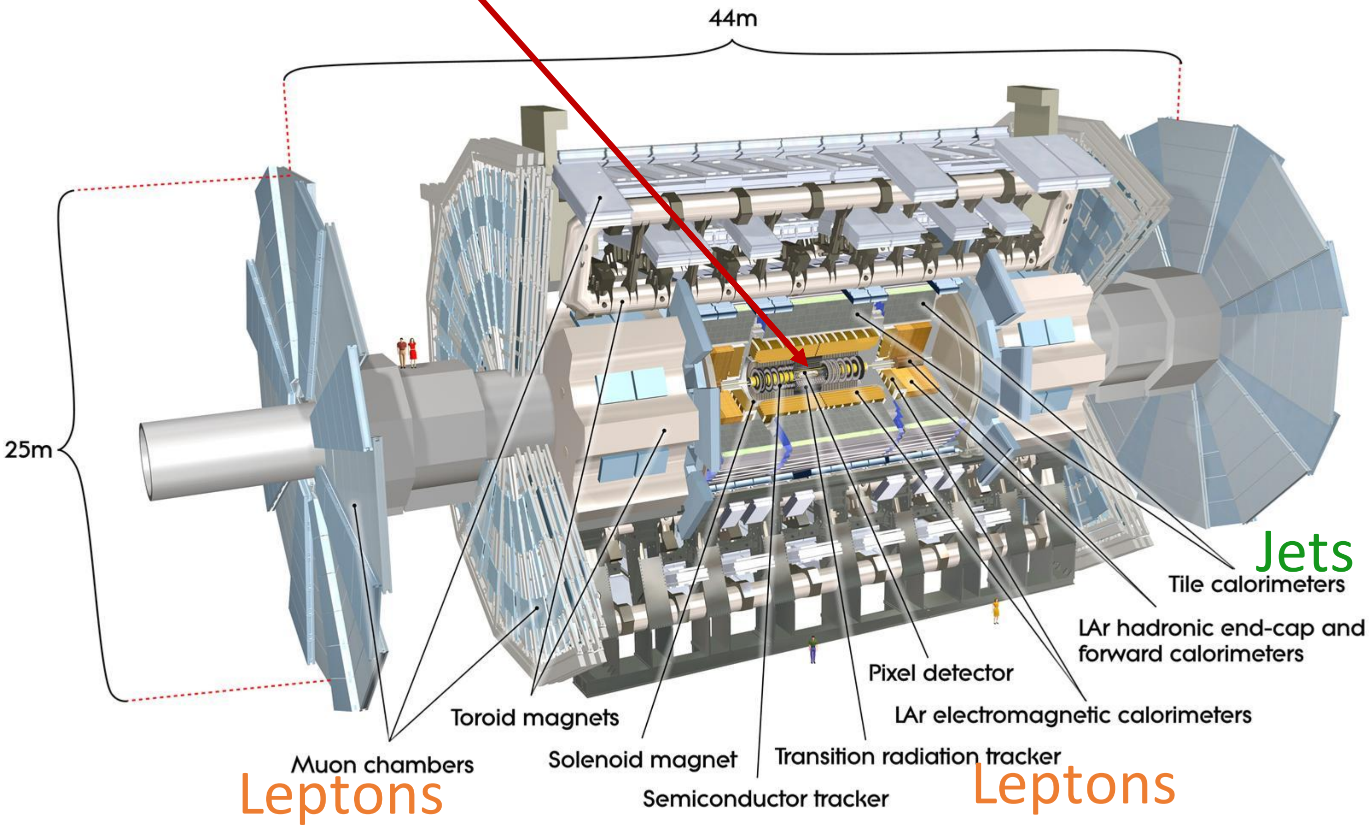
«0 lepton» $V\to q\bar{q}',\ Z\to \nu\bar{\nu}.$

«1 lepton» $V\to q\bar{q}',\ W\to l\nu.$

«2 leptons» $V\to q\bar{q}',\ Z\to l^+l^-.$

The ATLAS experiment

Protons collisions



Jets

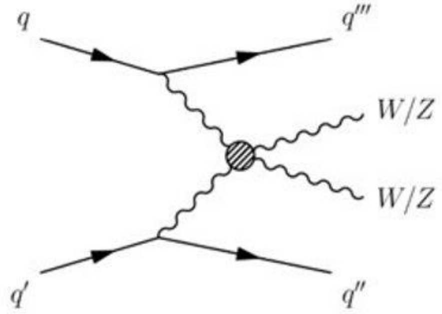
Leptons

Leptons

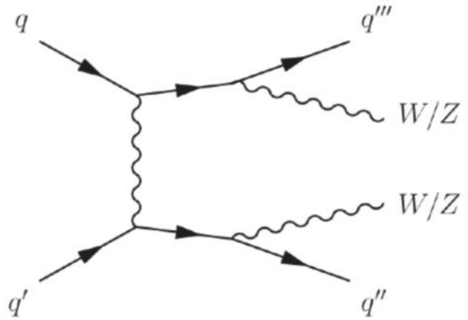
We look at the collision/decays products

What we want to measure

- VBS with *W*/*Z* decaying into quarks and leptons



- Can't be separated from other electroweak (non-VBS) productions

e.g. 

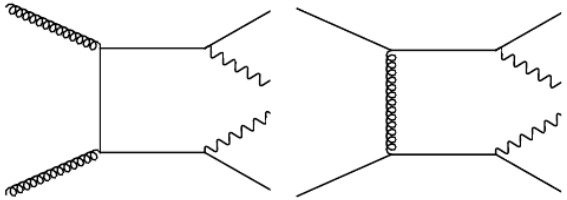
(not affected by aQGC)

- Need to be separated from non-electroweak production and other backgrounds

Multivariate techniques (RNN)

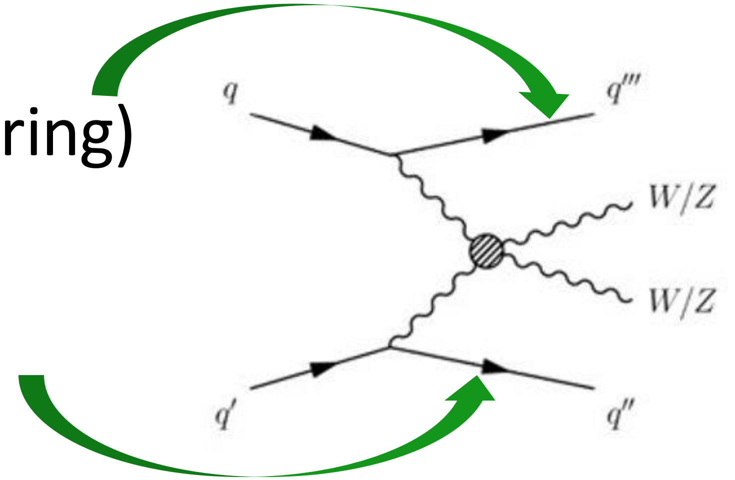
Backgrounds

- QCD production



- Diboson (no scattering) + jets
- *Z* + jets (in particular in 0 and 2 leptons channels)
- *W* + jets (in particular in 0 and 1 lepton channels)
- Top production (in particular in 1 lepton channel)

Analysis description

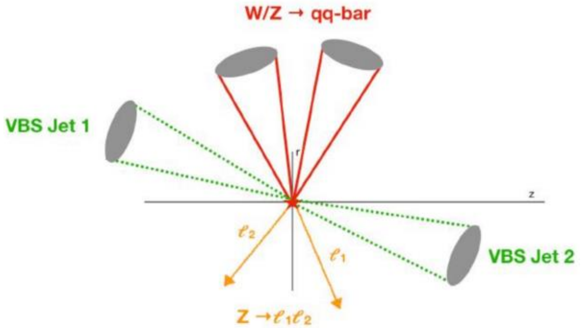


- Two VBS tagging jets (jets accompanying the scattering)
  - High energy
  - Opposite hemispheres

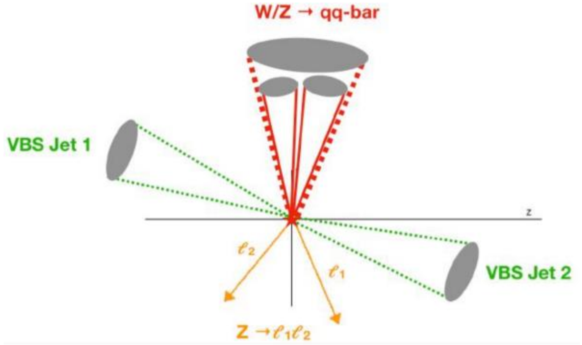
- Leptonically decaying boson
  - 0-lepton channel: only neutrinos (not directly detected so high missing transverse energy required)
  - 1-lepton channel: one charged lepton (e, μ) and one neutrino (missing transverse energy), b-veto
  - 2-leptons channel: two charged leptons with invariant mass window corresponding to e or μ

Analysis description

- Hadonically decaying boson
  - Resolved regime: the two quarks lead to two small jets (high energy required, no overlap with tagging jets)



  - Merged regime: in case of high boost, the two quarks lead to one large jet (high energy required)



- Summary of selections: 3 (merged) or 4 (resolved) jets with highest energies + 0 or 1 or 2 charged leptons

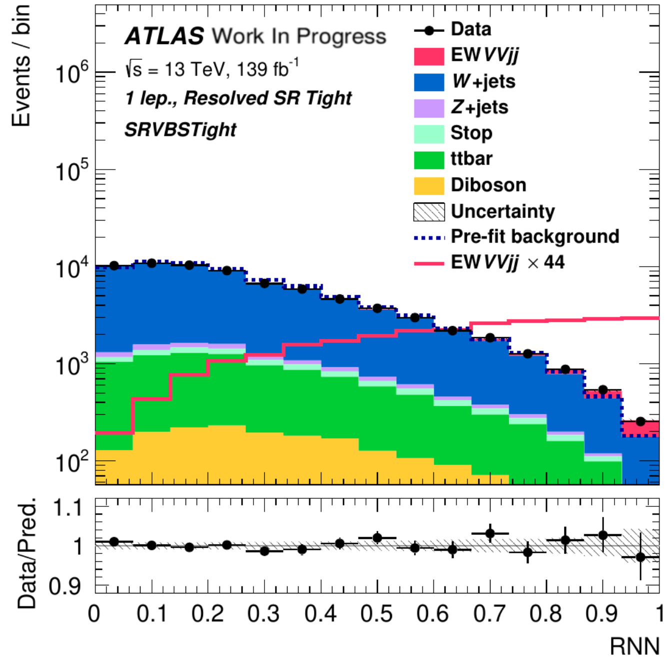
Measurements

- Signal regions (based on hadronically decaying boson)
  - Resolved (for each channel)
  - Merged with High Purity (for each channel) 9 SRs
  - Merged with Low Purity (for each channel)
- Control regions
  - *V*+jets (for each channel: *V*=*W* in 1 lepton, *V*=*Z* in 2 leptons)
    - Resolved
    - Merged 9 CRs
  - Top (only 1 lepton channel: *b*-jet instead of *b*-veto)

- We fit (standard fit: all channels and regions) the signal strength parameter μ ($\sigma_{VBS}^{observed}/\sigma_{VBS}^{SM\ predicted}$) as Parameter of Interest and consider systematics as Nuisance Parameters

Analysis status

- Unblinding and statistical analysis done
- Semileptonic VBS observed with a significance higher than 5σ
- μ compatible with 1 (SM value)
- Fiducial cross section measurement in progress
- aQGC interpretation
- Publication during the next months



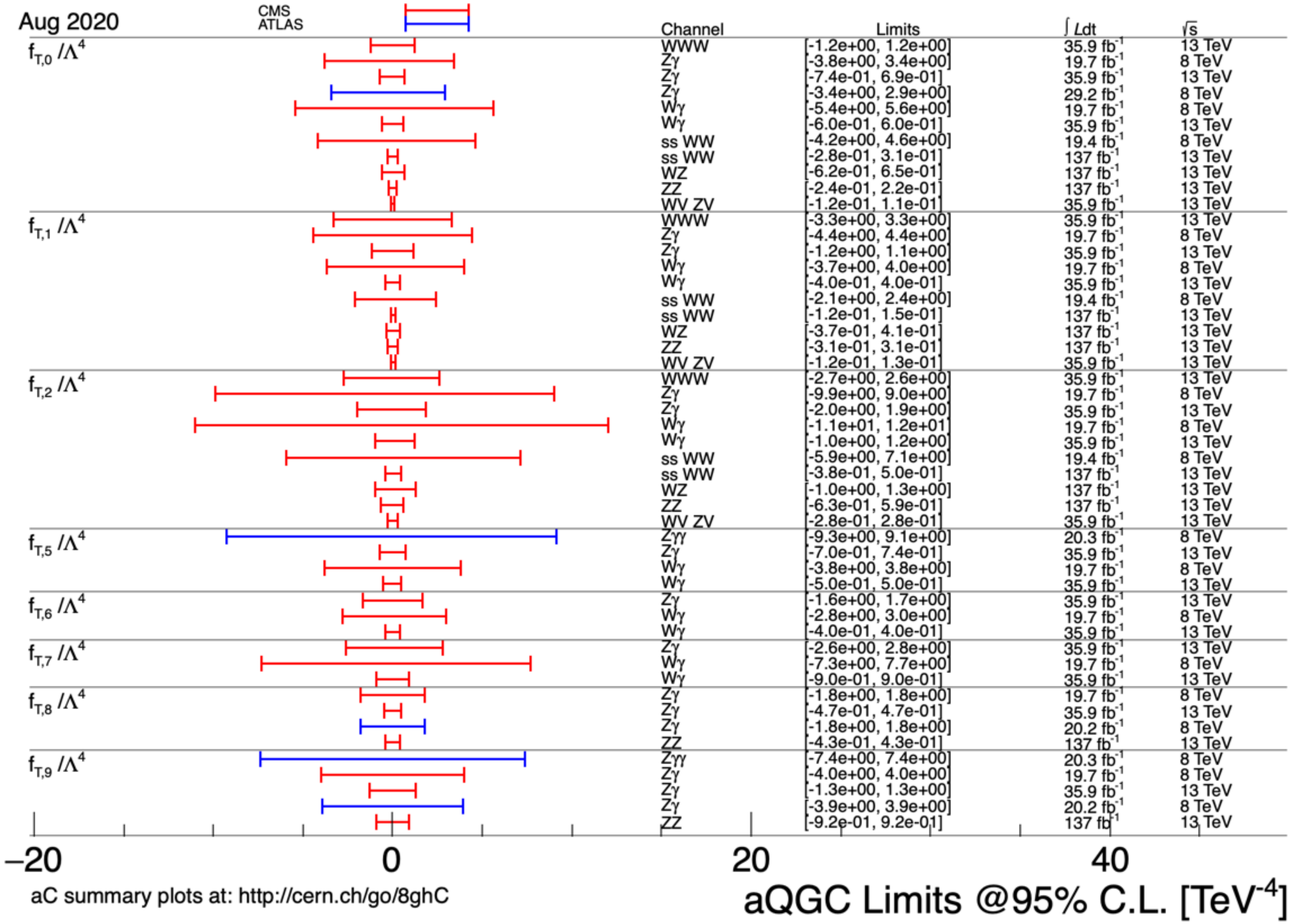
aQGC searches

- Inclusive analysis: all operators of the Eboli model can be constrained
- Dedicated EFT samples added to the data and Monte-Carlo (SM background and VBS signal)
- Unitarization procedure with clipping points at 1.5, 2, 3, 5 TeV + no clipping
- Fitting one operator and one clipping point at one time (SM VBS is now a background)

Operator	Expected [TeV^{-4}]	Observed [TeV^{-4}]
$FS1/\Lambda^4$	[-6.79, 6.81]	[-8.08, 8.12]
$FM0/\Lambda^4$	[-1.07, 1.07]	[-1.11, 1.19]
$FT0/\Lambda^4$	[-0.17, 0.15]	[-0.12, 0.18]
$FT1/\Lambda^4$	[-0.16, 0.17]	[-0.15, 0.14]

Some obtained limits (non unitarized)

LHC results



Aug 2020
CMS
ATLAS
Channel
Limits
∫ Ldt
√s
f_T,0 /Λ^4
WWW [-1.2e+00, 1.2e+00] 35.9 fb^-1 13 TeV
Zγ [-3.8e+00, 3.4e+00] 19.7 fb^-1 8 TeV
Zγ [-7.4e-01, 6.9e-01] 35.9 fb^-1 13 TeV
Zγ [-3.4e+00, 2.9e+00] 29.2 fb^-1 8 TeV
Wγ [-5.4e+00, 5.6e+00] 19.7 fb^-1 8 TeV
Wγ [-6.0e-01, 6.0e-01] 35.9 fb^-1 13 TeV
ss WW [-4.2e+00, 4.6e+00] 19.4 fb^-1 8 TeV
ss WW [-2.8e-01, 3.1e-01] 137 fb^-1 13 TeV
WZ [-6.2e-01, 6.5e-01] 137 fb^-1 13 TeV
ZZ [-2.4e-01, 2.2e-01] 137 fb^-1 13 TeV
WV ZV [-1.2e-01, 1.1e-01] 35.9 fb^-1 13 TeV
f_T,1 /Λ^4
WWW [-3.3e+00, 3.3e+00] 35.9 fb^-1 13 TeV
Zγ [-4.4e+00, 4.4e+00] 19.7 fb^-1 8 TeV
Zγ [-1.2e+00, 1.1e+00] 35.9 fb^-1 13 TeV
Wγ [-3.7e+00, 4.0e+00] 19.7 fb^-1 8 TeV
Wγ [-4.0e-01, 4.0e-01] 35.9 fb^-1 13 TeV
ss WW [-2.1e+00, 2.4e+00] 19.4 fb^-1 8 TeV
ss WW [-1.2e-01, 1.5e-01] 137 fb^-1 13 TeV
WZ [-3.7e-01, 4.1e-01] 137 fb^-1 13 TeV
ZZ [-3.1e-01, 3.1e-01] 137 fb^-1 13 TeV
WV ZV [-1.2e-01, 1.3e-01] 35.9 fb^-1 13 TeV
f_T,2 /Λ^4
WWW [-2.7e+00, 2.6e+00] 35.9 fb^-1 13 TeV
Zγ [-9.9e+00, 9.0e+00] 19.7 fb^-1 8 TeV
Zγ [-2.0e+00, 1.9e+00] 35.9 fb^-1 13 TeV
Wγ [-1.1e+01, 1.2e+01] 19.7 fb^-1 8 TeV
Wγ [-1.0e+00, 1.2e+00] 35.9 fb^-1 13 TeV
ss WW [-5.9e+00, 7.1e+00] 19.4 fb^-1 8 TeV
ss WW [-3.8e-01, 5.0e-01] 137 fb^-1 13 TeV
WZ [-1.0e+00, 1.3e+00] 137 fb^-1 13 TeV
ZZ [-6.3e-01, 5.9e-01] 137 fb^-1 13 TeV
WV ZV [-2.8e-01, 2.8e-01] 35.9 fb^-1 13 TeV
f_T,5 /Λ^4
Zγγ [-9.3e+00, 9.1e+00] 20.3 fb^-1 8 TeV
Zγ [-7.0e-01, 7.4e-01] 35.9 fb^-1 13 TeV
Wγ [-3.8e+00, 3.8e+00] 19.7 fb^-1 8 TeV
Wγ [-5.0e-01, 5.0e-01] 35.9 fb^-1 13 TeV
f_T,6 /Λ^4
Zγ [-1.6e+00, 1.7e+00] 35.9 fb^-1 13 TeV
Wγ [-2.8e+00, 3.0e+00] 19.7 fb^-1 8 TeV
Wγ [-4.0e-01, 4.0e-01] 35.9 fb^-1 13 TeV
f_T,7 /Λ^4
Zγ [-2.6e+00, 2.8e+00] 35.9 fb^-1 13 TeV
Wγ [-7.3e+00, 7.7e+00] 19.7 fb^-1 8 TeV
Wγ [-9.0e-01, 9.0e-01] 35.9 fb^-1 13 TeV
f_T,8 /Λ^4
Zγ [-1.8e+00, 1.8e+00] 19.7 fb^-1 8 TeV
Zγ [-4.7e-01, 4.7e-01] 35.9 fb^-1 13 TeV
Zγ [-1.8e+00, 1.8e+00] 20.2 fb^-1 8 TeV
ZZ [-4.3e-01, 4.3e-01] 137 fb^-1 13 TeV
f_T,9 /Λ^4
Zγγ [-7.4e+00, 7.4e+00] 20.3 fb^-1 8 TeV
Zγ [-4.0e+00, 4.0e+00] 19.7 fb^-1 8 TeV
Zγ [-1.3e+00, 1.3e+00] 35.9 fb^-1 13 TeV
Zγ [-3.9e+00, 3.9e+00] 20.2 fb^-1 8 TeV
ZZ [-9.2e-01, 9.2e-01] 137 fb^-1 13 TeV
–20
0
20
40
aC summary plots at: http://cern.ch/go/8ghC
aQGC Limits @95% C.L. [TeV^-4]

Planned combination

- LHC run 2 analyses are going to be finalized (run 3 already started in 2022)
- Lots of different and complementary ATLAS VBS analyses
  - Access to aQGC
  - Opportunity to constrain dimension-8 operators (most studies previously focused on dimension-6 before)
  - VBS is a nice candidate for a combination !
- Different vertices, hence operators, involved
- Lots of combinations already done in ATLAS
- Started the effort (selecting analyses and understanding their methodologies and differences)

Future of the combination

- Involved analyses (full run 2)
  - Semileptonic *VV*
  - *WW*
  - *ZZ* (4*l* and 2*l*2*v*)
  - *WZ*
  - *Wy*
  - *Zy*
  - *WWW*
  - *Wyy*

VBS (Semileptonic *VV*, *WW*, *ZZ*, *WZ*, *Wy*, *Zy*)

Triboson production (*WWW*, *Wyy*)

- Need to harmonize things
- Very promising, but challenges are expected...

Conclusion

- VBS processes probe the most fundamental structure of electroweak interactions
- They are very rare and provide high sensitivity to BSM physics affecting gauge and Higgs couplings
- This can be studied in the framework of EFT through anomalous gauge couplings
- EFT constrains BSM physics in a model independent way
- Despite challenges, VBS analyses are very promising candidates for an EFT combination
- The semileptonic final states analysis which will be part of the combination allows to study a lots of couplings

THANK YOU !