Vector boson scattering in the ATLAS detector

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ATLAS EXPERIMENT

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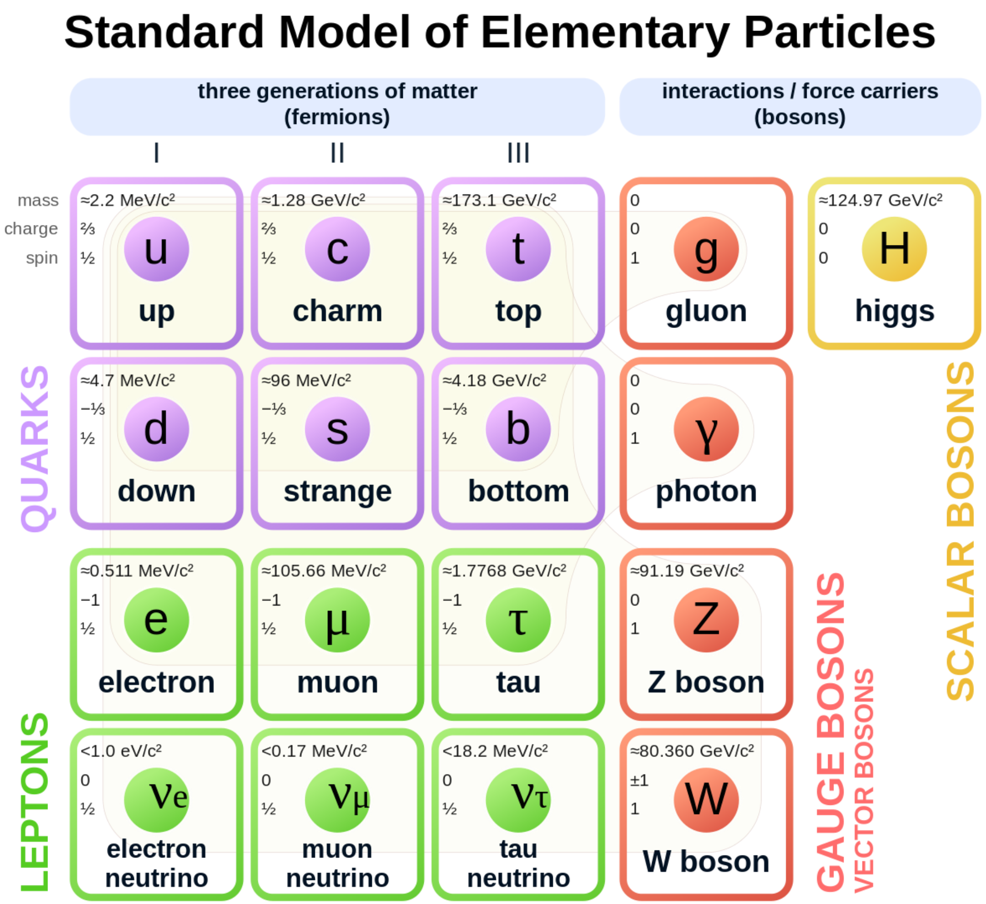
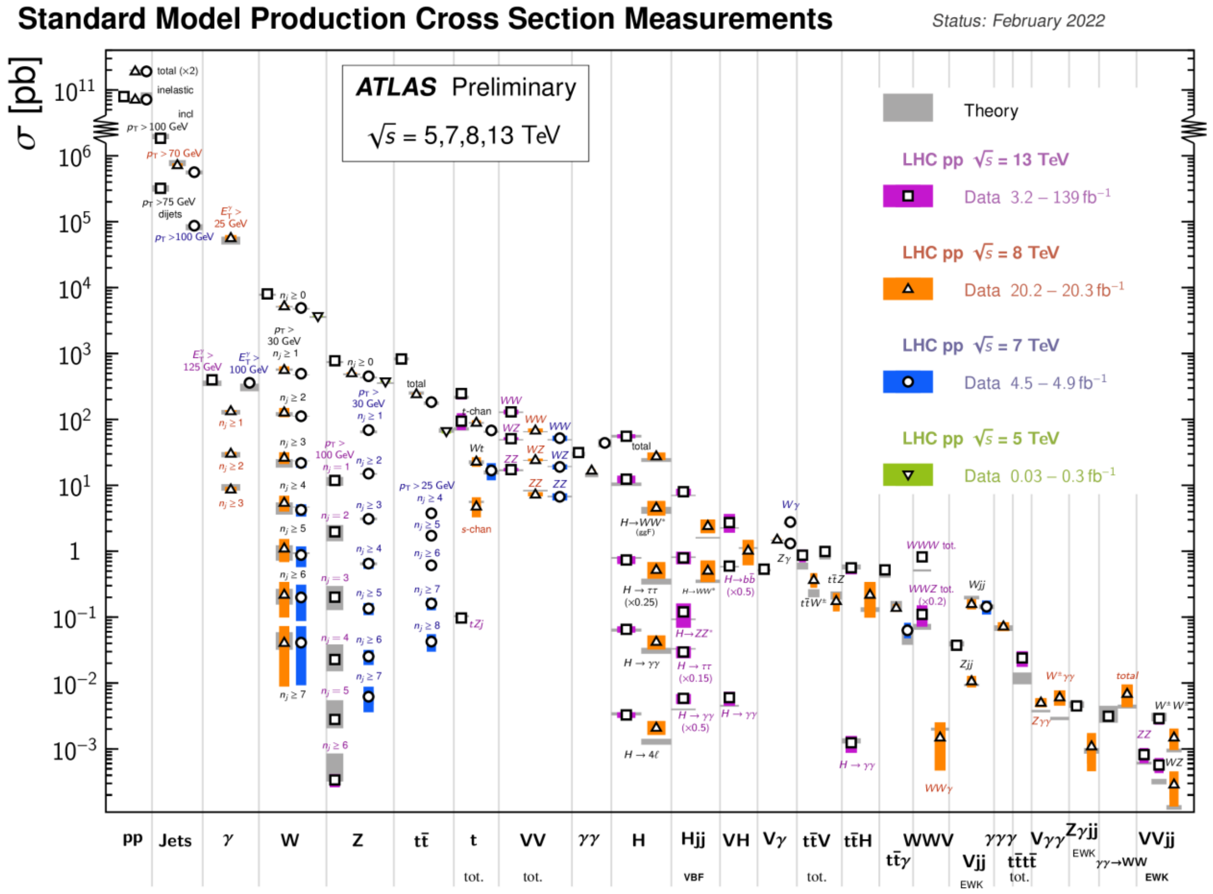
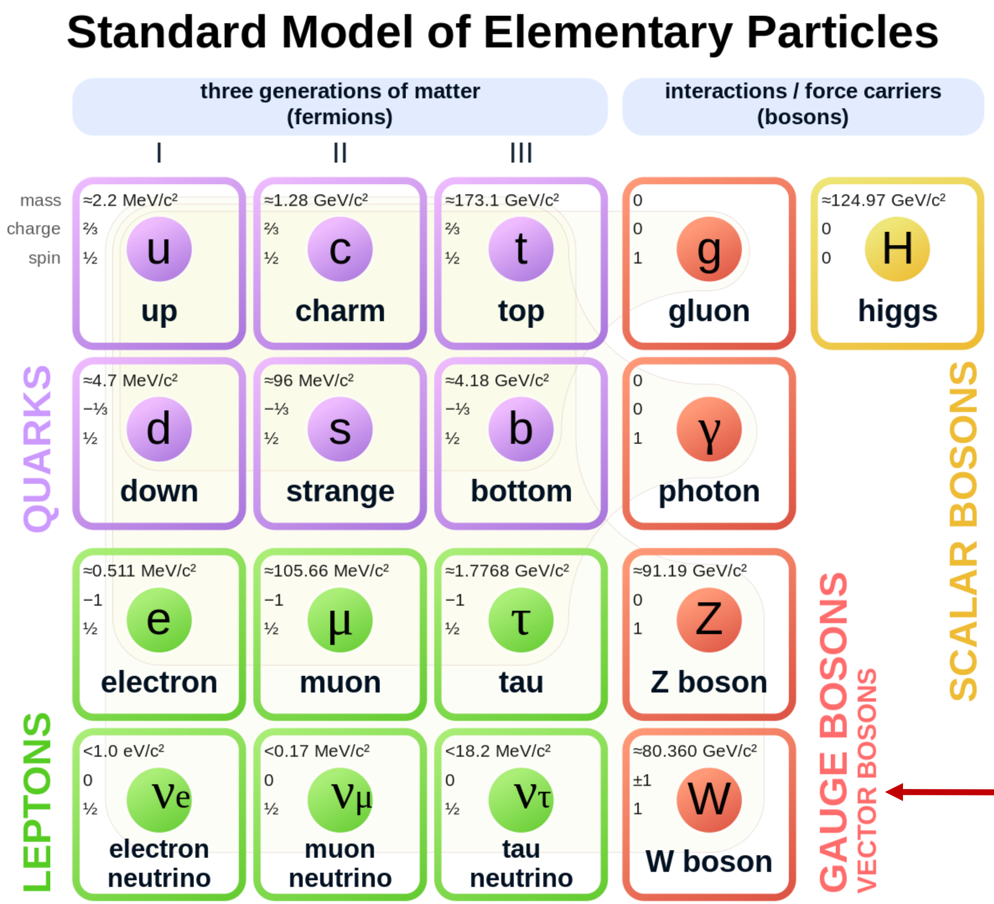
The standard model of particle physics

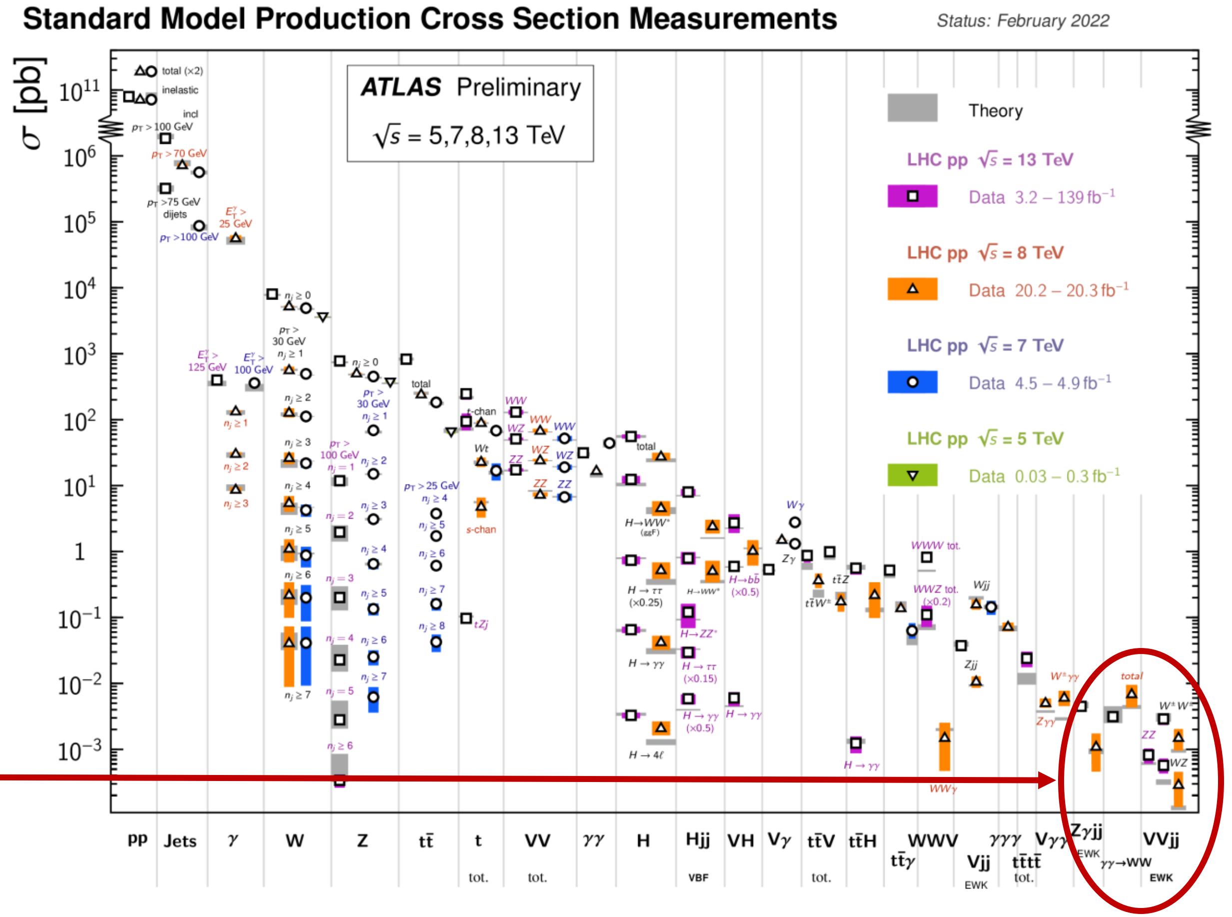




- **The** theory describing elementary particles and their interactions
- Well tested experimentally

The standard model of particle physics





Some very rare processes

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

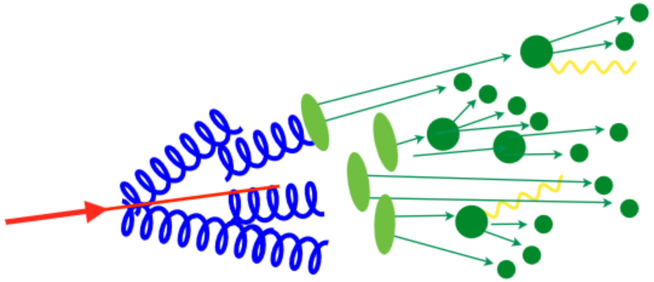
Vector boson scattering (VBS)

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

$$V_1V_2jj \rightarrow V_3V_4jj$$

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

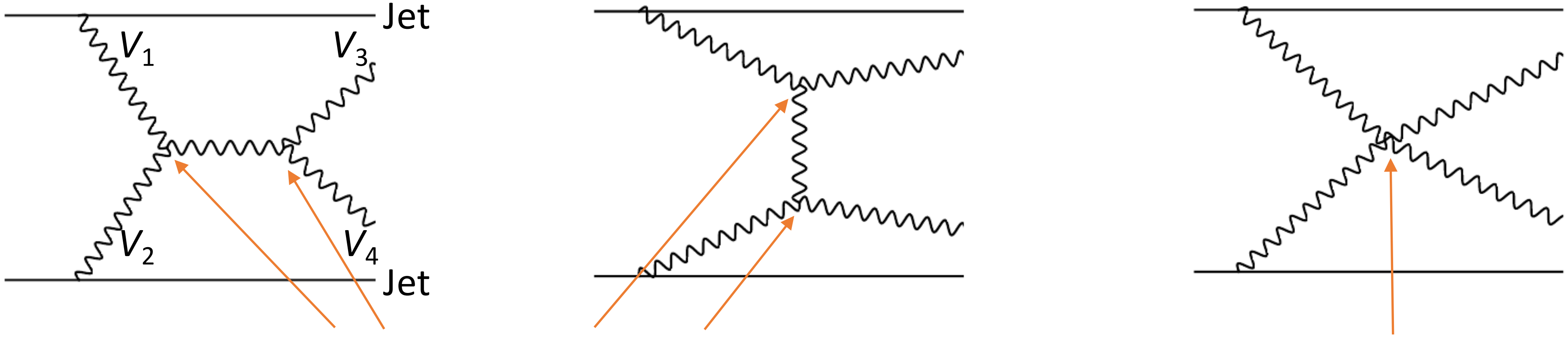
- Quarks hadronize and form jets (j) in detectors



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

VBS is very rich

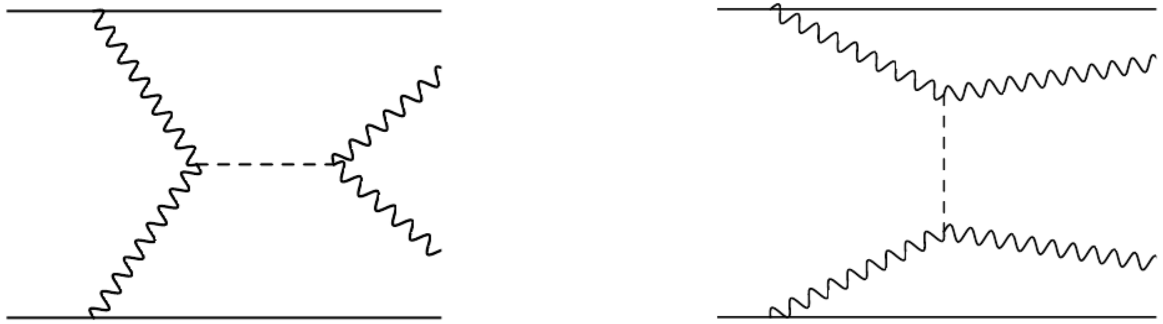
Lots of different gauge couplings can be involved



Triple gauge couplings (TGC)

Quartic gauge couplings (QGC)

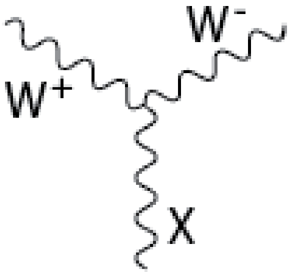
Even couplings with the Higgs boson



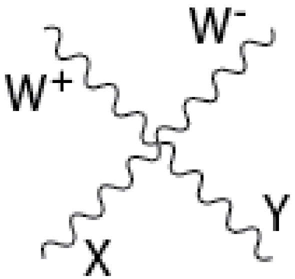
These graphs are necessary to allow VBS in the SM !

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 in the SM
- Search for deviation from SM in gauge couplings !

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

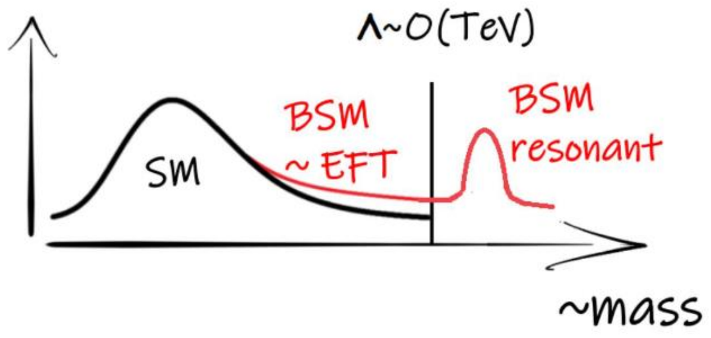
- It is present at too high energy for the current accelerators ?

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):

$$\mathcal{A}^2 = \underbrace{|\mathcal{A}_{SM}|^2}_{\text{Pure SM}} + \underbrace{2\sum_i \frac{C_i}{\Lambda^4} Re(\mathcal{A}_i^* \mathcal{A}_{SM})}_{\text{EFT-SM interference (linear)}} + \underbrace{2\sum_i \frac{C_i^2}{\Lambda^8} |\mathcal{A}_i|^2}_{\text{Pure EFT (quadratic)}} + \underbrace{2\sum_{i\neq j} \frac{C_i C_j}{\Lambda^8} Re(\mathcal{A}_i^* \mathcal{A}_j)}_{\text{Interference between EFT operators}}$$

Eboli model

- Complete classification of dimension-8 operators respecting symmetries

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

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

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

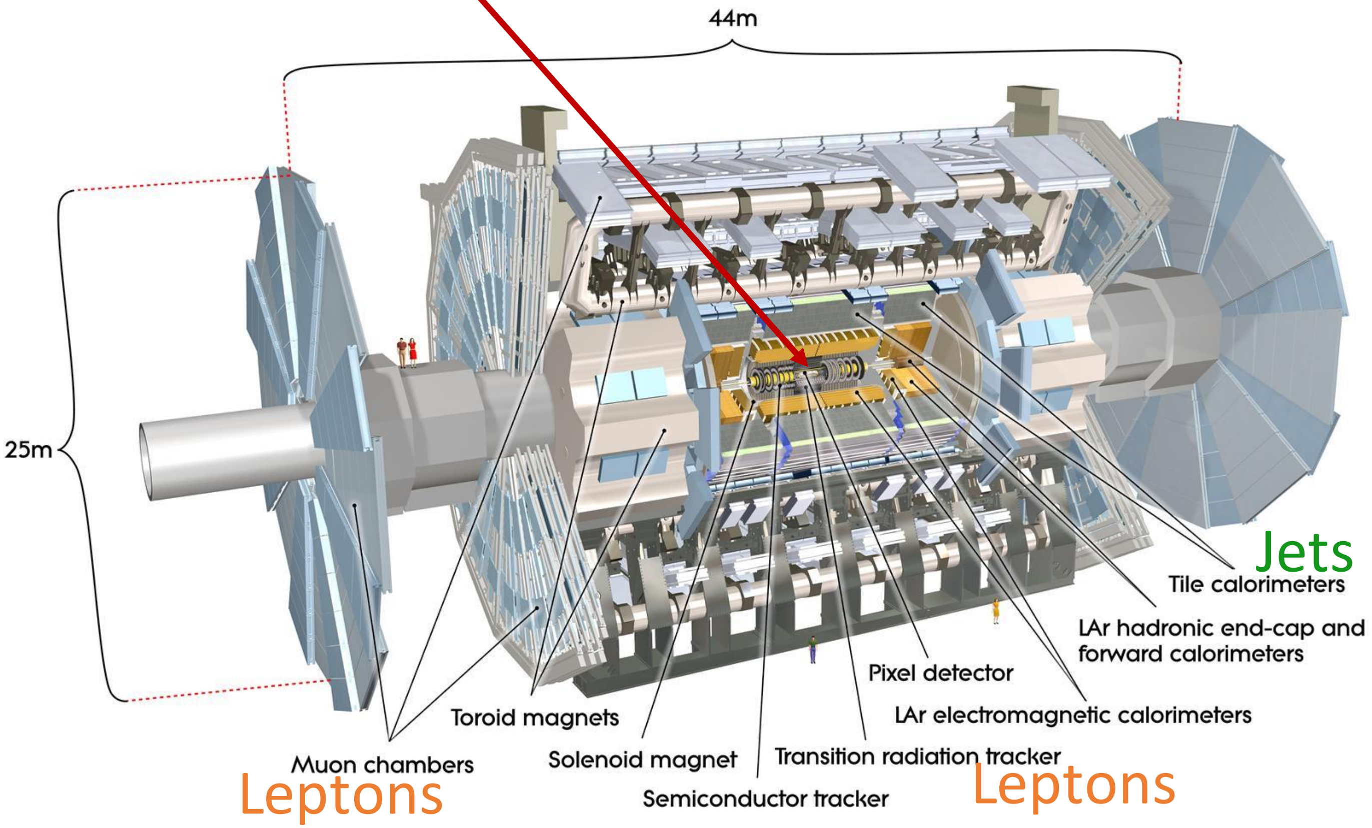
SM fields

- 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					✓	✓	✓	✓	✓

The ATLAS experiment

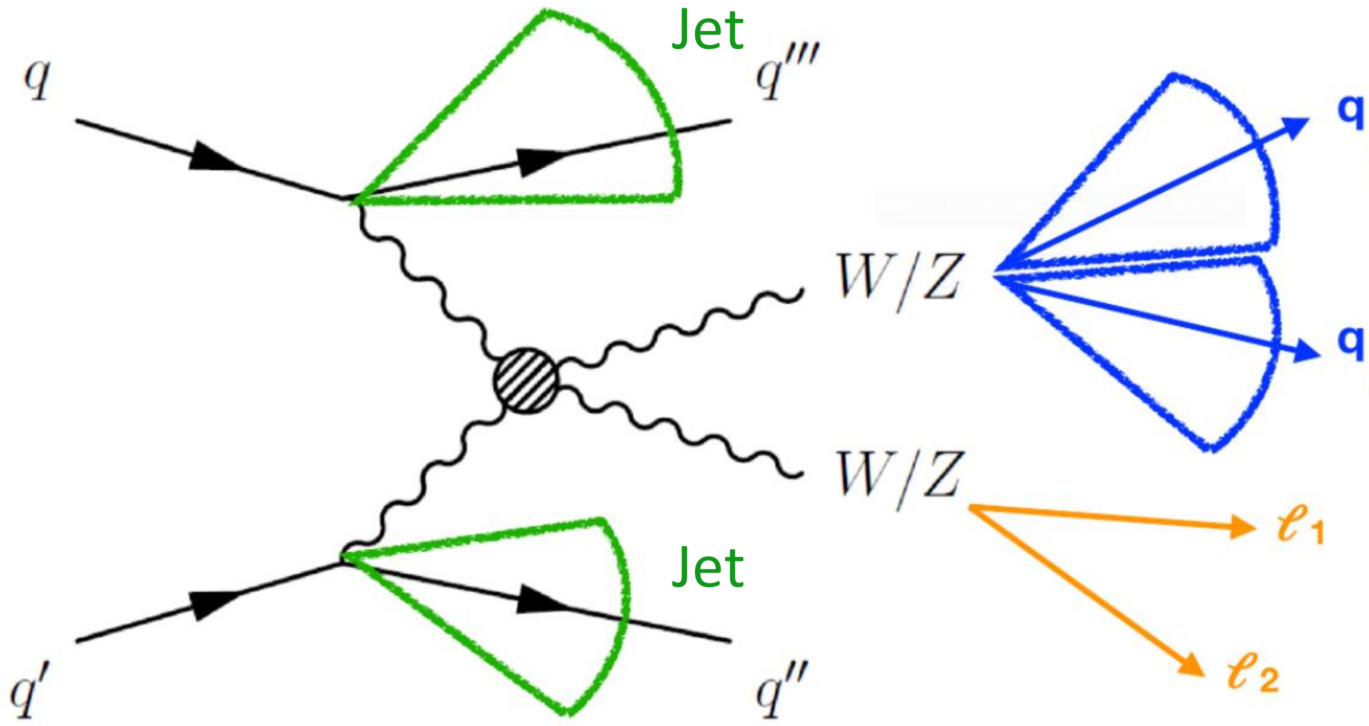
13 TeV protons collisions



We look at the collision and decays products

Semileptonic final states

- Inclusive *VVjj* (*V*=*W*,*Z*) production in LHC Run-2 data
- Semileptonic final states: one gauge boson decays hadronically (quarks pair) and the other one decays leptonically (leptons pair)



Jets

Sub-channels defined by number of charged leptons

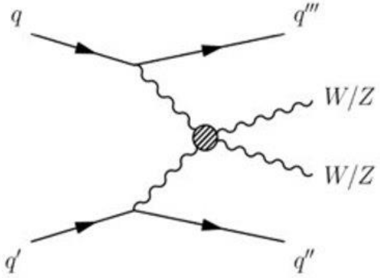
«0 lepton» $V\to q\bar{q}',\ Z\to \nu\bar{\nu}.$

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

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

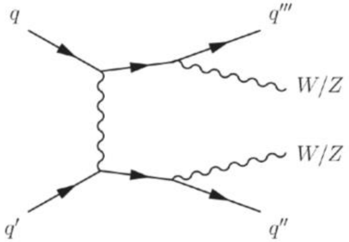
What we want to measure

- VBS with W/Z decaying into quarks and leptons



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

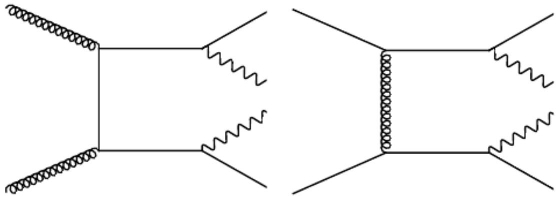
e.g.



(not affected by aQGC)

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

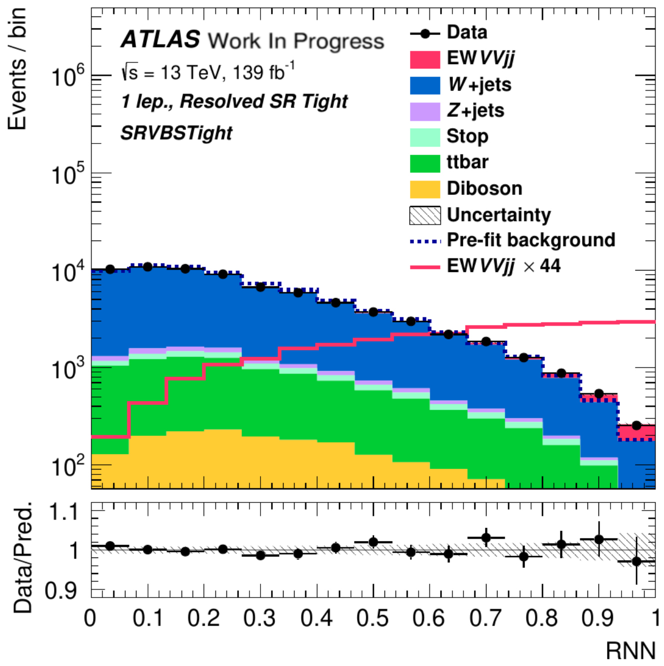
→ Multivariate techniques (RNN)



QCD diboson production (no scattering) + jets W + jets Z + jets Top production ...

Analysis results

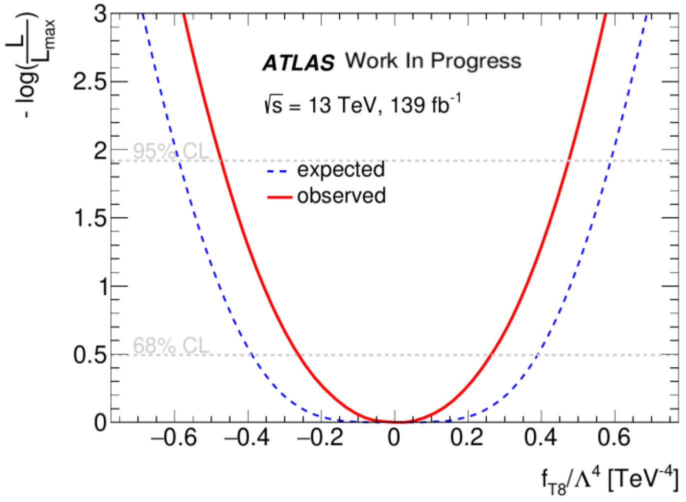
- Semileptonic VBS observed with a significance higher than 5σ
- Measurement compatible with SM signal expectation
- Observed fiducial cross section 33.0 ± 5.5 fb
- aQGC interpretation
- Publication during the next months



aQGC limits

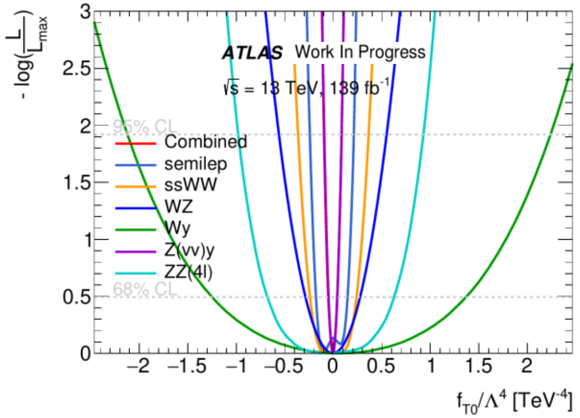
- Inclusive analysis: all operators of the Eboli model can be constrained
- Dedicated EFT samples added to the Monte-Carlo (SM background and VBS signal)
- SM VBS is now a background for aQGC
- Constraints (95% CI) on different operators are very competitive

Operator	Expected [TeV^{-4}]	Observed [TeV^{-4}]
$FS0/\Lambda^4$	[-3.22, 3.22]	[-3.72, 3.73]
$FS1/\Lambda^4$	[-6.84, 6.85]	[-7.62, 7.63]
$FM0/\Lambda^4$	[-1.12, 1.12]	[-1.20, 1.19]
$FM1/\Lambda^4$	[-3.24, 3.24]	[-3.77, 3.77]
$FM2/\Lambda^4$	[-1.66, 1.66]	[-1.76, 1.76]
$FT0/\Lambda^4$	[-0.20, 0.18]	[-0.24, 0.21]
$FT6/\Lambda^4$	[-0.76, 0.72]	[-0.71, 0.68]



QGC combination

- 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
  - VBS in a nice candidate for a combination !
- Started the effort with semileptonic, *WW*, *WZ*, *Wy*, *Zy* and *ZZ* analyses
- Complementary final states, hence operators, involved
- Expecting great results, improved 1D and 2D limits



- Challenges: harmonization and correlations between analyses...

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
- The semileptonic final states analysis allows to study a lot of couplings
- It is part of the ATLAS Full Run-2 aQGC combination: great results expected !

THANK YOU !