Vector Boson Scattering

as a portal to new physics

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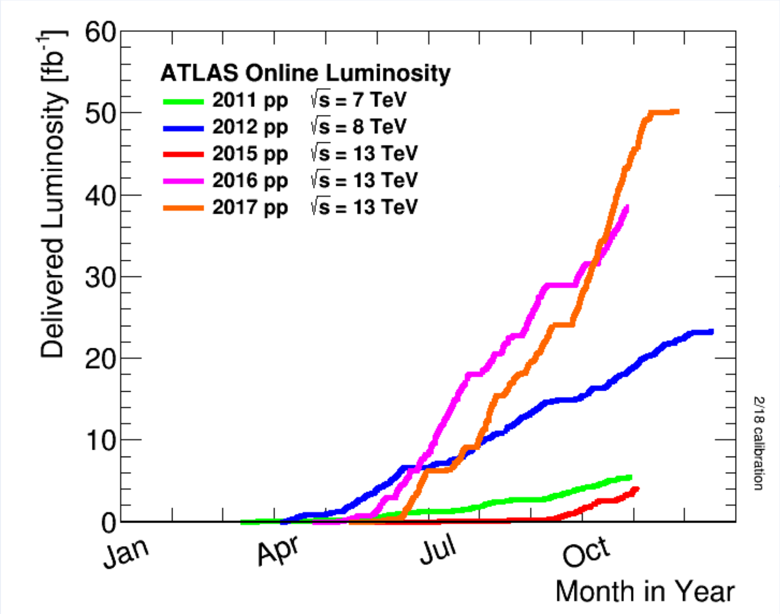
Introduction

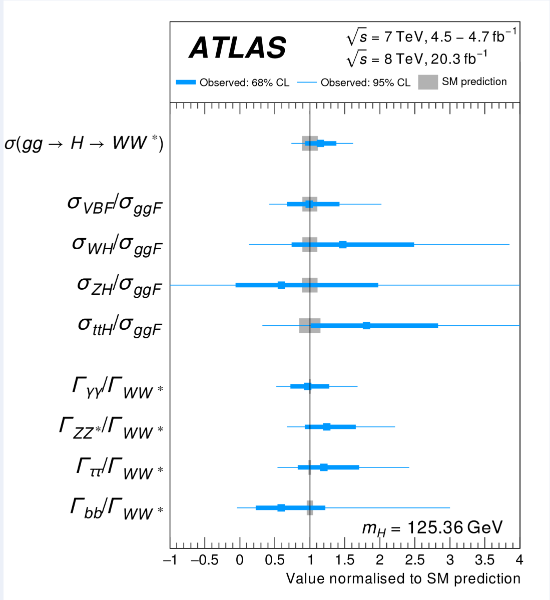
- Already many years of proton-proton collisions in LHC

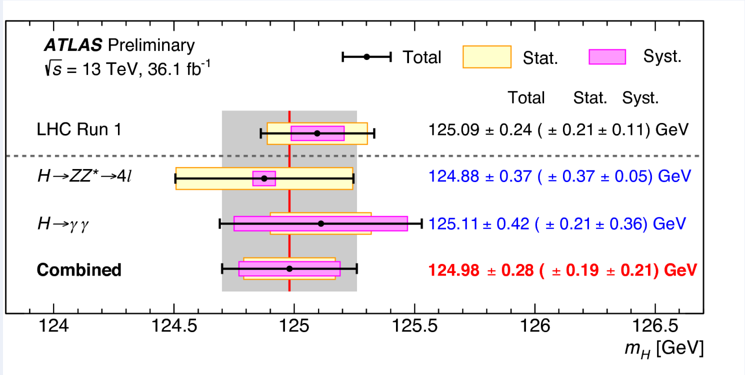


- Higgs discovery in 2012
- Deep study of the electroweak symmetry breaking

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

higgs decay ratios





higgs mass

- What else is out there?

Introduction

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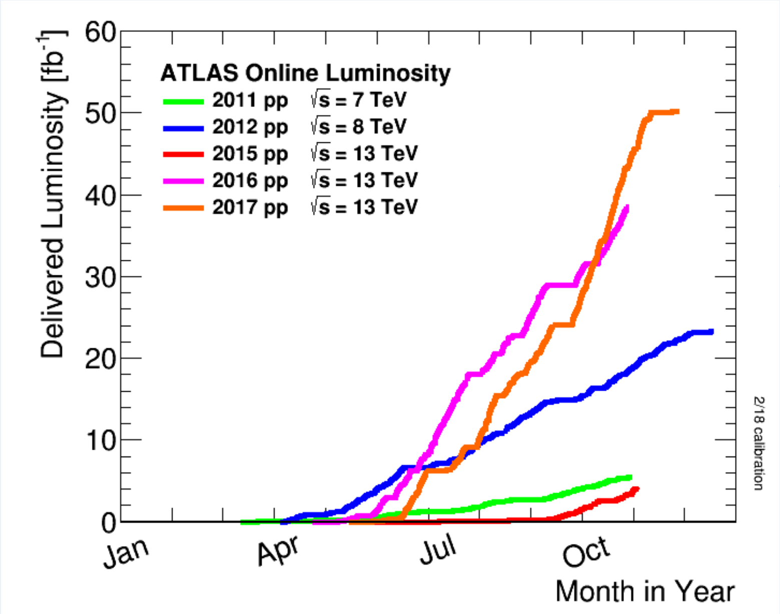
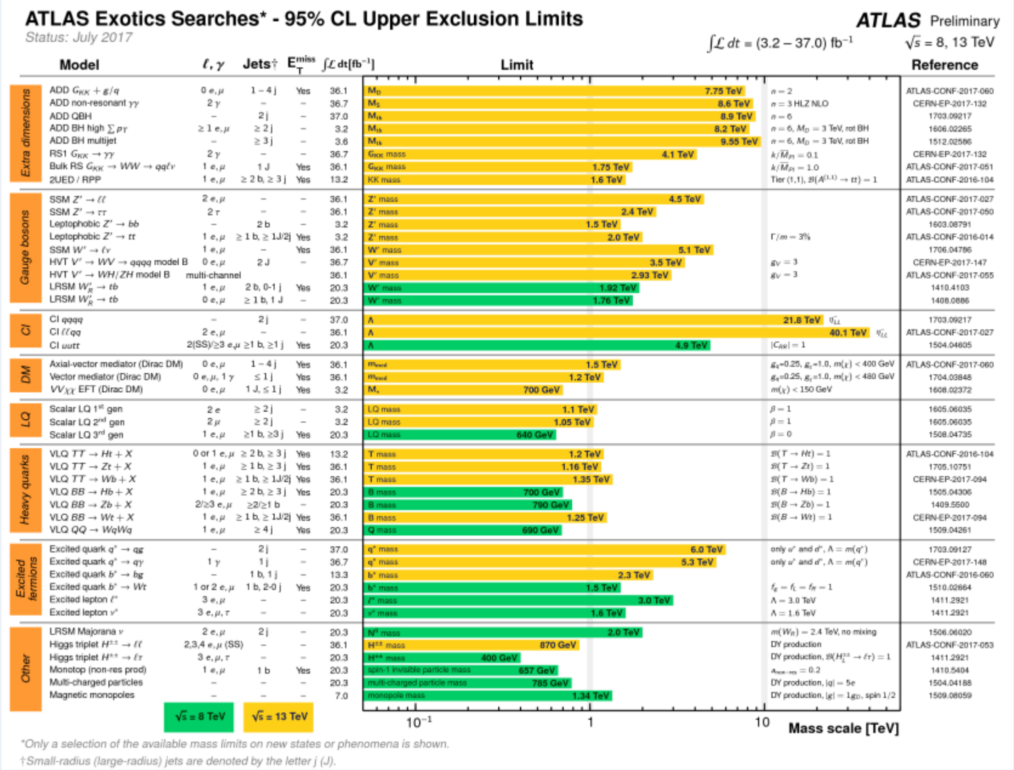
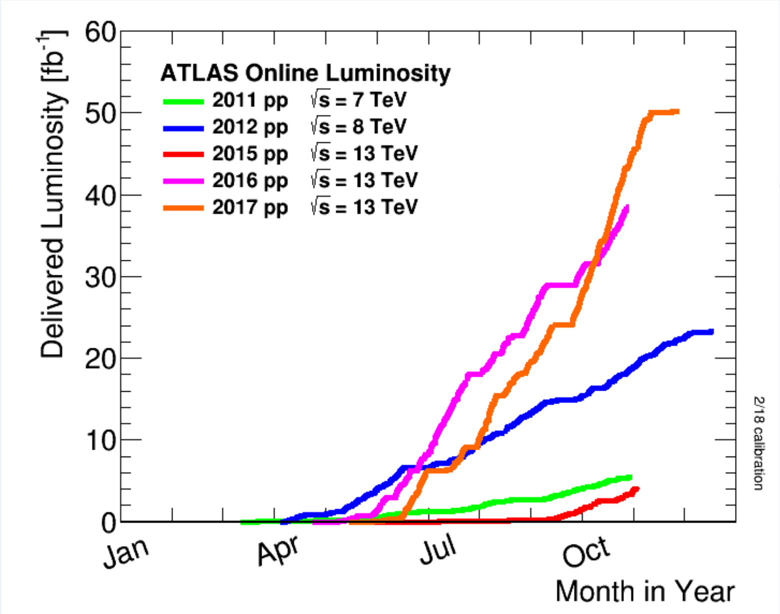




Introduction



- Already many years of proton-proton collisions in LHC

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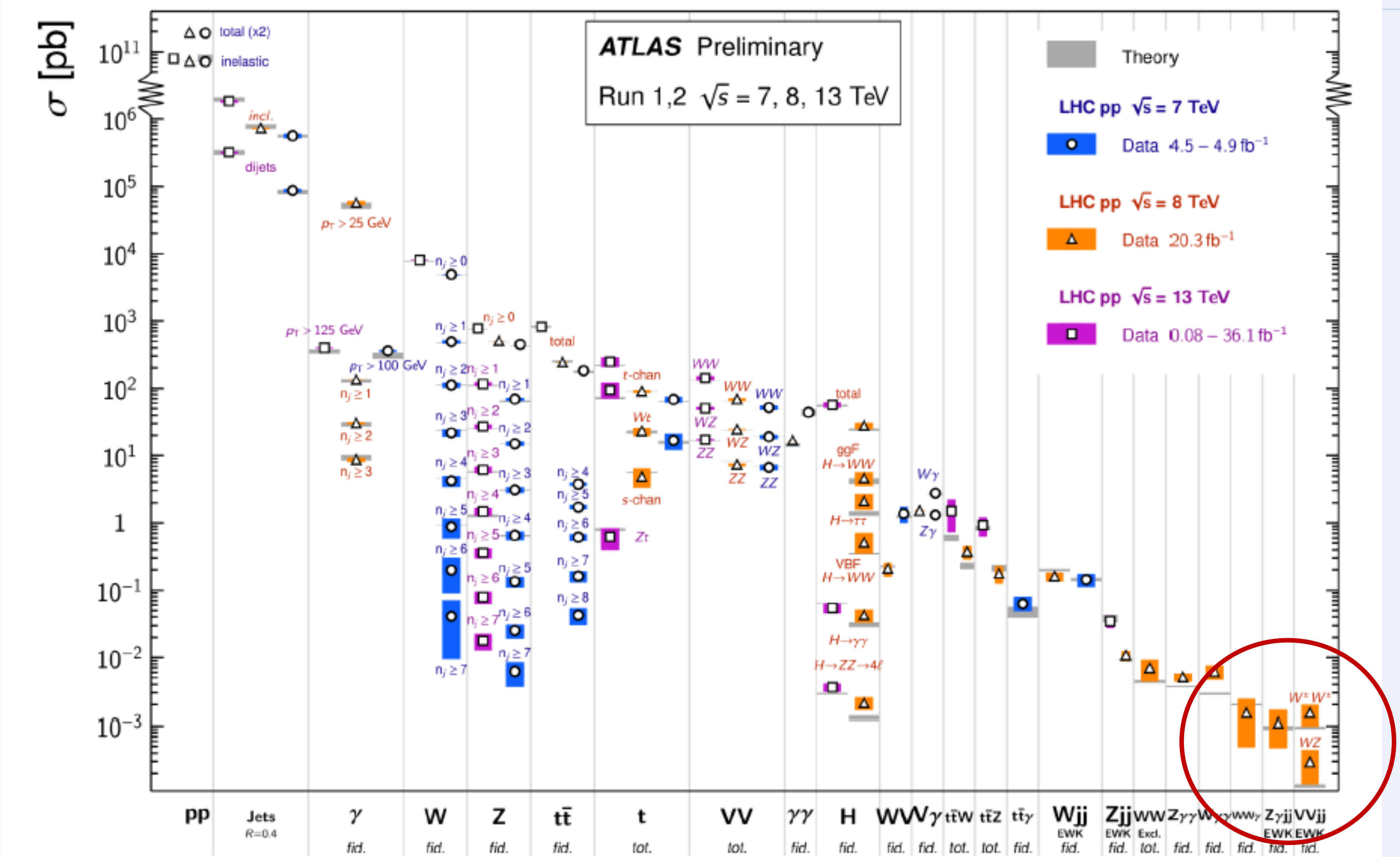
- Deep study of the electroweak symmetry breaking

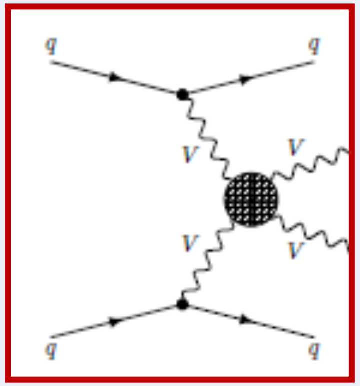
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Could it be… nothing?

- What else is out there?

Time for rare processes





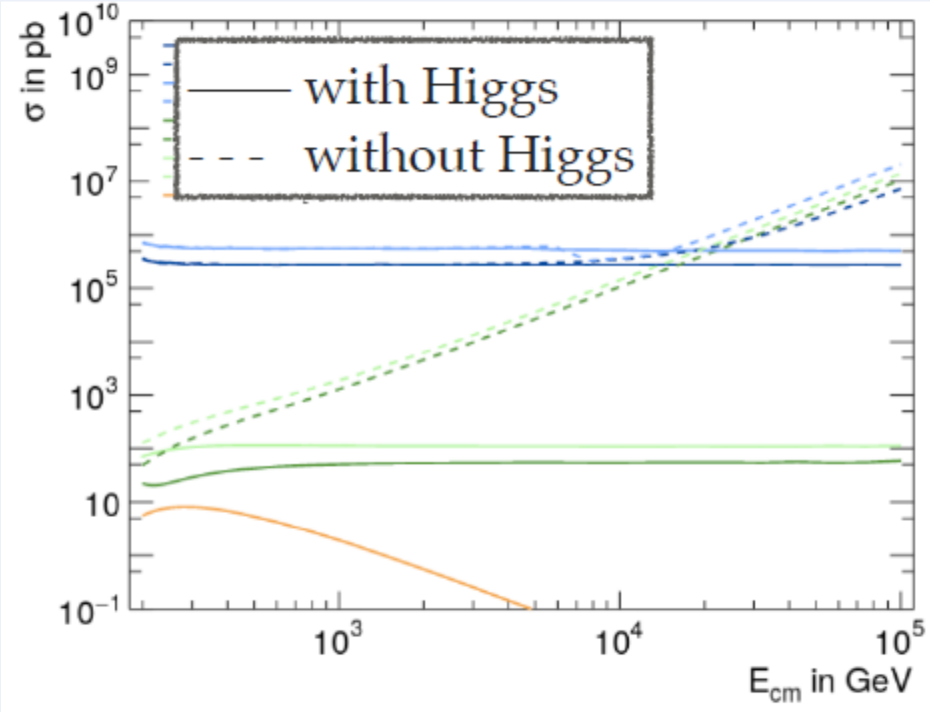
Vector Boson Scattering (VBS)

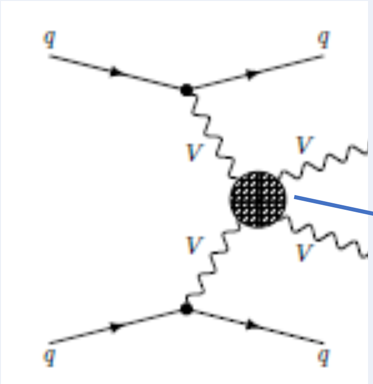
Vector Boson Scattering: EW symmetry breaking

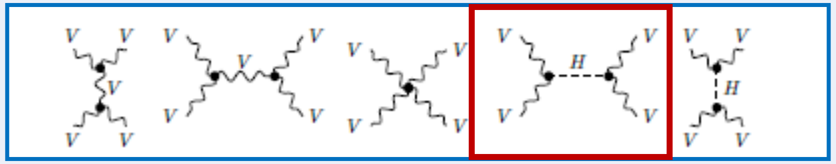
- The cross section computation includes interactions with the Higgs boson
- These interactions unitarize the scattering amplitude

➢Important test of the ***EW*** symmetry breaking

➢Complementary to direct Higgs studies





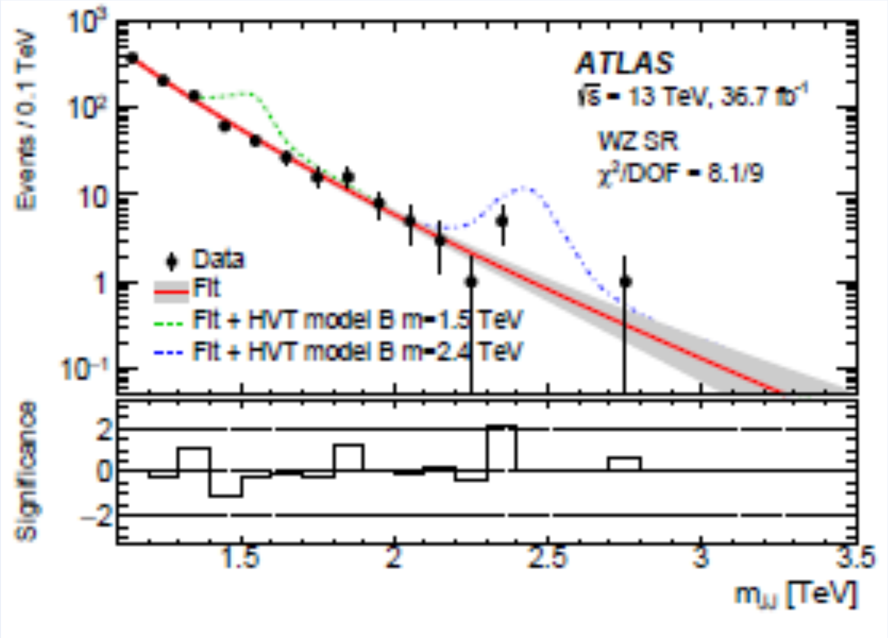


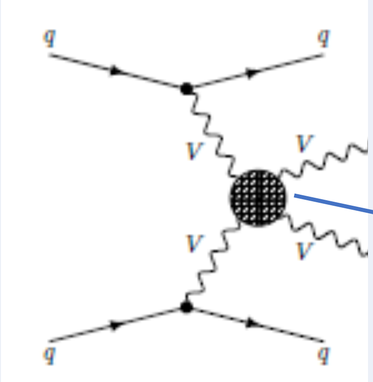
VBS: Quartic Gauge boson Couplings (QGC)

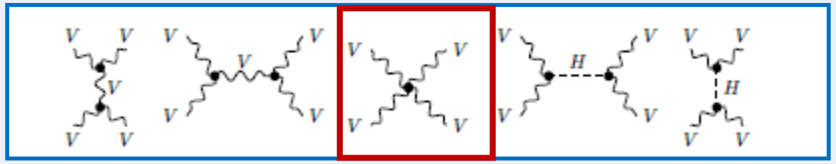
- VBS process can give us access to quartic gauge boson couplings

- Anomalous QGCs could lead to deviation in the VBS cross section

➢ and allow new physics to appear







VBS: Quartic Gauge boson Couplings (QGC)

- Anomalous QGC in a EFT framework:

$$\mathcal{L} = \boxed{\mathcal{L}^{\mathrm{SM}}} + \boxed{\sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i} + \boxed{\sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j.}$$

SM effective Lagrangian

Gauge boson interactions as described by the SM

Valid below an energy scale Λ

dim-6 : operators describing aTGCs and aQGCs

VBS processes not really competitive for their constraint

dim-8 : lowest order operators describing only aQGCs

Can be constrained by VBS

arXiv:1310.6708v1 [hep-ph] 24 Oct 2013

VBS: Quartic Gauge boson Couplings (QGC)

- Three different types of parameters:

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

$$
\boxed{
\begin{aligned}
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}
}
$$

only neutral couplings can be induced

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

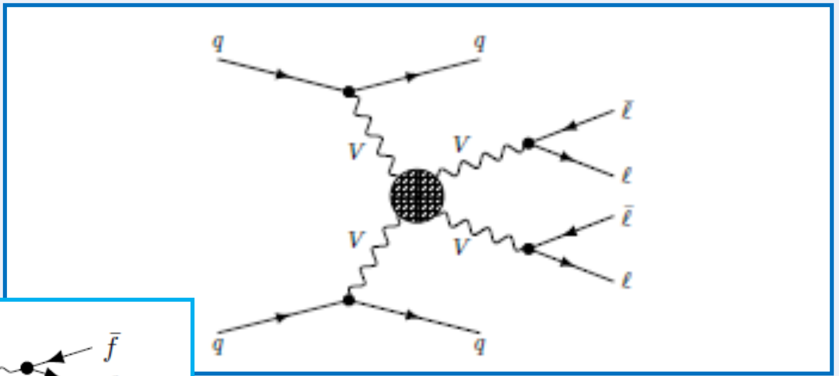
$$
\boxed{
\begin{aligned}
\mathcal{L}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{L}_{S,1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]
\end{aligned}
}
$$

pure Higgs field (f_S)
(cannot induce couplings with photons)

VVjj final state	ZZ	Zγ γγ	W+W- WZ	W±W±	Wγ
$f_{S,0}$, $f_{S,1}$	✔		✔	✔	
$f_{M,0}$, $f_{M,1}$, $f_{M,6}$, $f_{M,7}$	✔	✔	✔	✔	✔
$f_{M,2}$, $f_{M,3}$, $f_{M,4}$, $f_{M,5}$	✔	✔	✔		✔
$f_{T,0}$, $f_{T,1}$, $f_{T,2}$	✔	✔	✔	✔	✔
$f_{T,5}$, $f_{T,6}$, $f_{T,7}$	✔	✔	✔		✔
$f_{T,8}$, $f_{T,9}$	✔	✔			

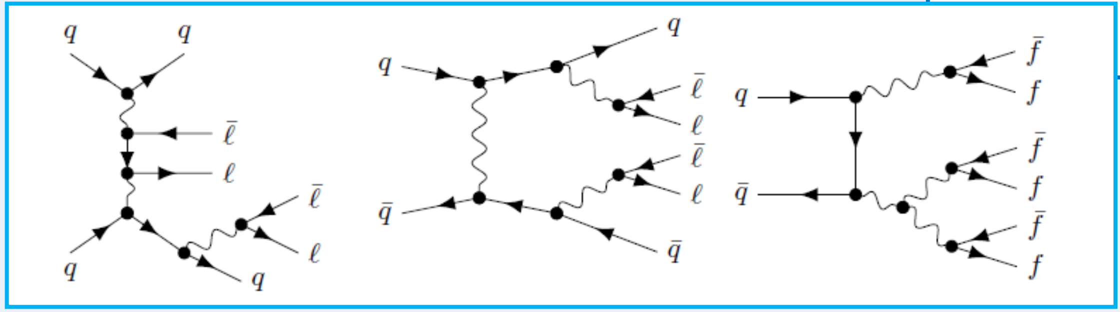
VBS: a challenging process

- Very low cross section ($\sim fb$) with a high background

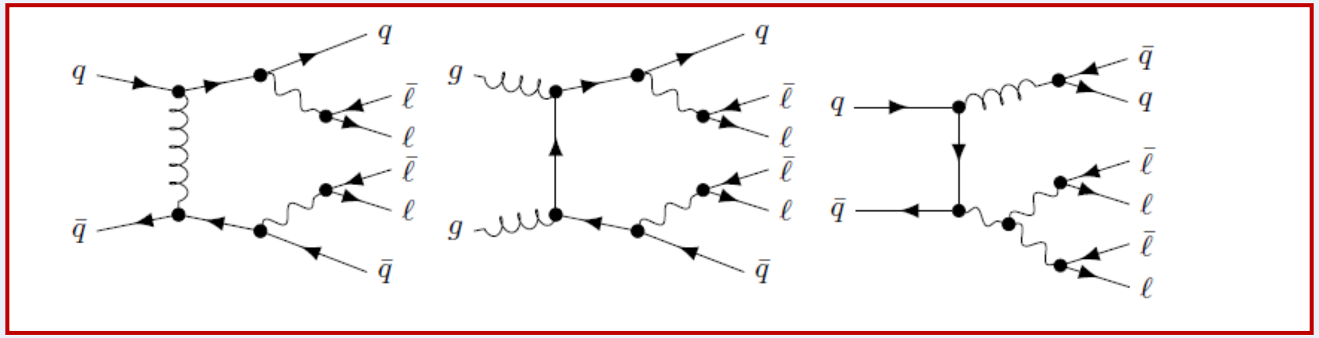


can be enhanced with an optimal choice of analysis phase space

- Electroweak diboson production (signal)

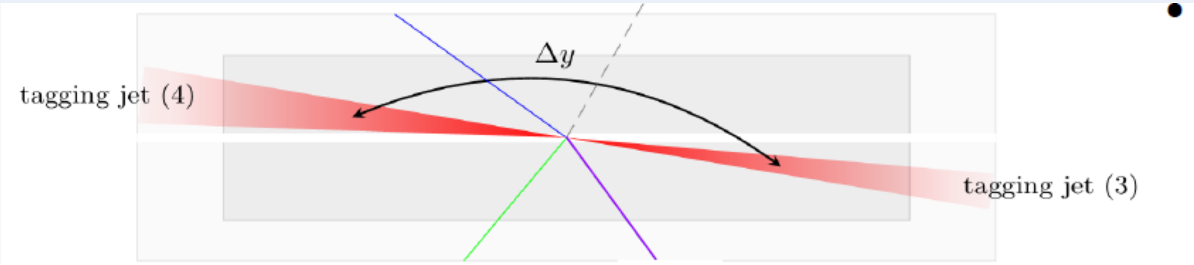


- QCD diboson production

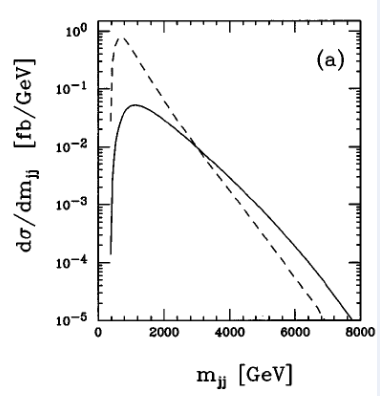


With a clear cinematic signature

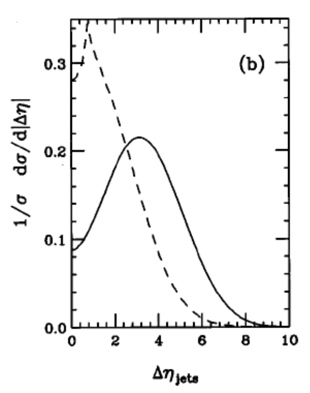
- Two forward jets and suppressed hadronic activity in between (absence of color flow between interacting partons)



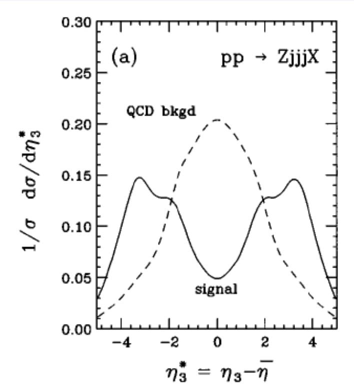
➢Cinematic discriminative variables (D. Zeppenfeld et al.)



dijet invariant mass



dijet Δη



centrality

arXiv:hep-ph/9605444

Diboson final states

- *https://twiki.cern.ch/twiki/bin/view/ CMSPublic/PhysicsResultsSMP*
- *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults*

8 TeV	ATLAS	CMS	
WWss	limits on QGCs	only dim-6	most optimal S/B
WZ	limits on QGCs	No ew	
ZZ	-	No ew	low reducible background
Zγ	limits on QGCs	limits on QGCs	
Wγ	-	limits on QGCs	largest cross section

13 TeV	ATLAS	CMS	
WWss	?	limits on QGCs	first EW production observation
ZZ	?	limits on QGCs	

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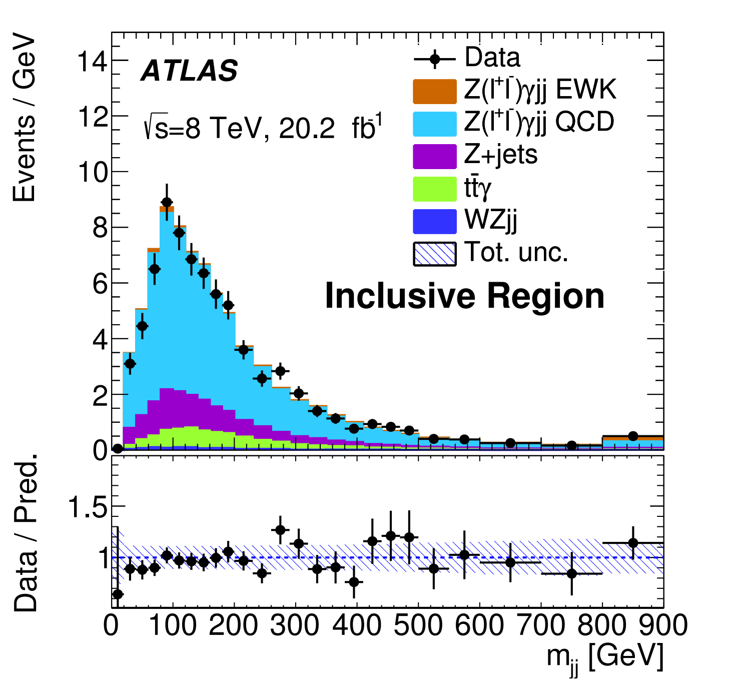
ATLAS Zγ Run 1 Analysis

- M_{jj} variable used to
  - ➢define a QCD control region
  - ➢create a VBS enriched phase space



2 leptons:
P_T^{γ}>25 GeV, $|\eta|$<2.47 (2.5 for μ)
m_{ll}>40 GeV, $m_{ll\gamma}$>182 GeV
2 jets: *P_T>30 GeV, $|\eta|$<4.5*

	Inclusive region		Control region		Search region	
	$Z(\ell^+\ell^-)\gamma + \geq 2$ jets		$150 < m_{jj} < 500$ GeV		$m_{jj} > 500$ GeV	
	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$
Data	781	949	362	421	58	72
Z+jets bkg.	134 ± 36	154 ± 42	57 ± 16	67 ± 18	8.5 ± 2.5	9.4 ± 2.7
Other bkg. ($t\bar{t}\gamma$, WZ)	88 ± 17	91 ± 18	47 ± 9	46 ± 9	5.8 ± 1.1	5.0 ± 1.0
$N_{Z\gamma\ \mathrm{QCD}}$ (SHERPA MC)	583 ± 41	671 ± 47	249 ± 24	290 ± 26	37 ± 5	41 ± 5
$N_{Z\gamma\ \mathrm{EWK}}$ (SHERPA MC)	25.4 ± 1.5	27.3 ± 1.7	8.6 ± 0.6	9.3 ± 0.6	11.2 ± 0.8	11.6 ± 0.7

initial S/B

Reducible background: extracted from data

Irreducible background: normalized in CR

Signal

ATLAS Zγ Run 1 Analysis

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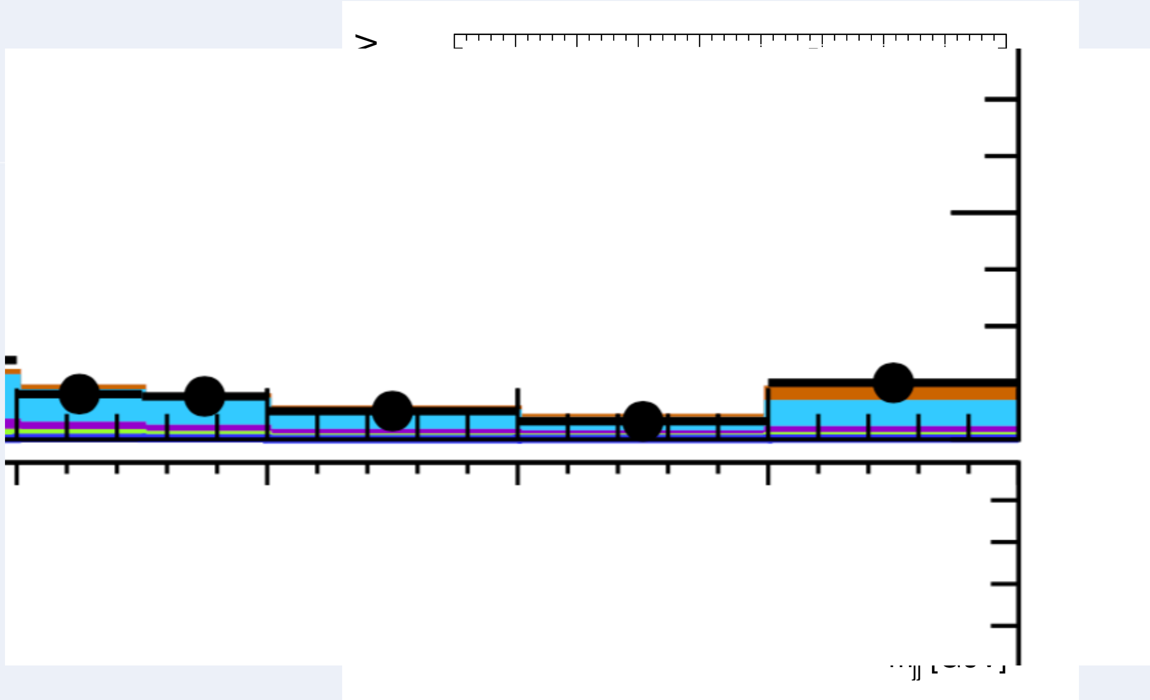
  - ➢ define a QCD control region
  - ➢ create a VBS enriched phase space



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initial S/B

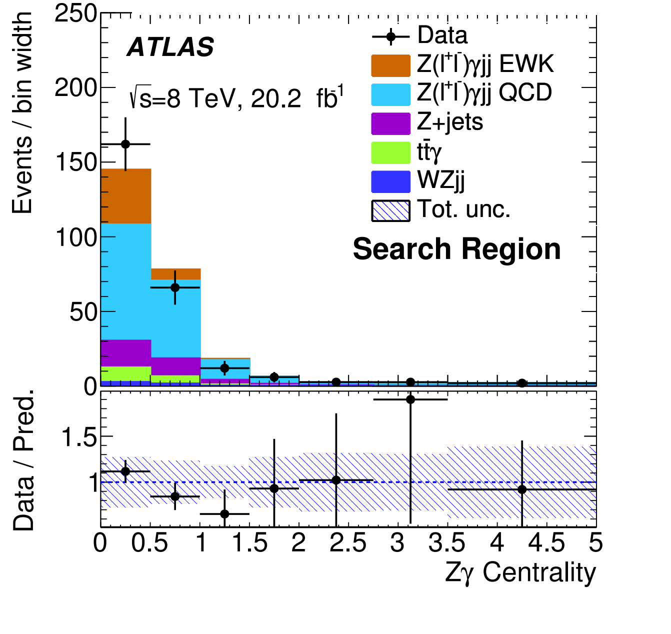
→ **Reducible background: extracted from data**

→ **Irreducible background: normalized in CR**

→ **Signal**

ATLAS Zγ Run 1 Analysis

$$\zeta_X = \left| \frac{y_X - (y_{j1} + y_{j2})/2}{(y_{j1} - y_{j2})} \right|$$



- Centrality variable used as « template »

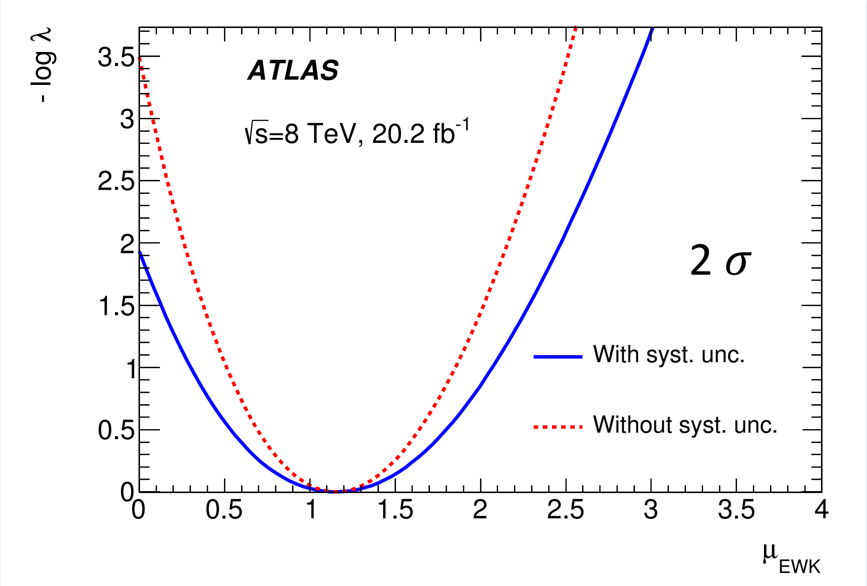
  ➢ Negative Log Likelihood ratio minimization

  ➢ parameter of interest: $\mu = \frac{\sigma^{meas.}}{\sigma^{MC}}$

$$-\ln(\lambda(\mu)) = -ln \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}$$

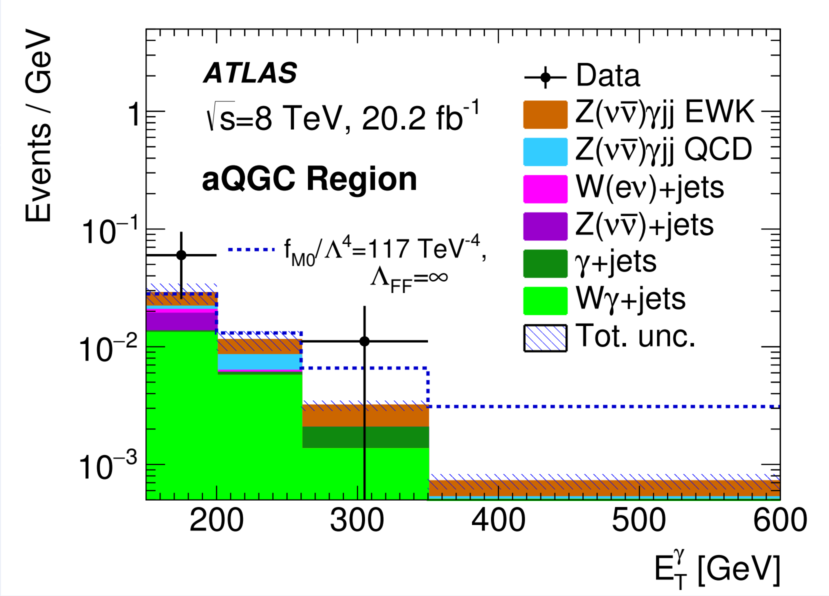
  ➢ θ: nuisance parameters (systematics)

$$\sigma^{\mathrm{EWK}}_{Z\gamma jj} = 1.1 \pm 0.5\ (\mathrm{stat}) \pm 0.4\ (\mathrm{syst})\ \mathrm{fb}$$



ATLAS Zγ Run 1 Analysis

- $E_T(\gamma)$ variable used to probe the QGC
  - ➢High energy tails would be modified if aQGC
  - ➢7 effective operators varied one by one



95% CL intervals	Measured [TeV^{-4}]
f_{T9}/Λ^4	$[-6.9, 6.9] \times 10^4$
f_{T8}/Λ^4	$[-3.4, 3.3] \times 10^4$
f_{T0}/Λ^4	$[-7.2, 6.1] \times 10^1$
f_{M0}/Λ^4	$[-1.0, 1.0] \times 10^3$
f_{M1}/Λ^4	$[-1.6, 1.7] \times 10^3$
f_{M2}/Λ^4	$[-1.1, 1.1] \times 10^4$
f_{M3}/Λ^4	$[-1.6, 1.6] \times 10^4$

Non-zero $f_{T,8-9}$ only accessible by Zγ and ZZ channels

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

JHEP07(2017)107

CMS WWss Run 2 Analysis

2 same sign leptons:
P_T^1>25 GeV, P_T^2>20 GeV, |η|<2.5 (2.4 for μ)
2 jets: *P_T>30 GeV, |η|<5.0, m_{jj}>500 GeV, |$\Delta\eta_{jj}$|>2.5*
Centrality: *$|\eta_l-(\eta_{j1}+\eta_{j2})/2|/|\Delta\eta_{jj}|<0.75$*

Data	201
Signal + total bkg.	205 ± 13
Signal	66.9 ± 2.4
Total bkg.	138 ± 13
Nonprompt	88 ± 13
WZ	25.1 ± 1.1
QCD WW	4.8 ± 0.4
Wγ	8.3 ± 1.6
Triboson	5.8 ± 0.8
Wrong sign	5.2 ± 1.1

Signal

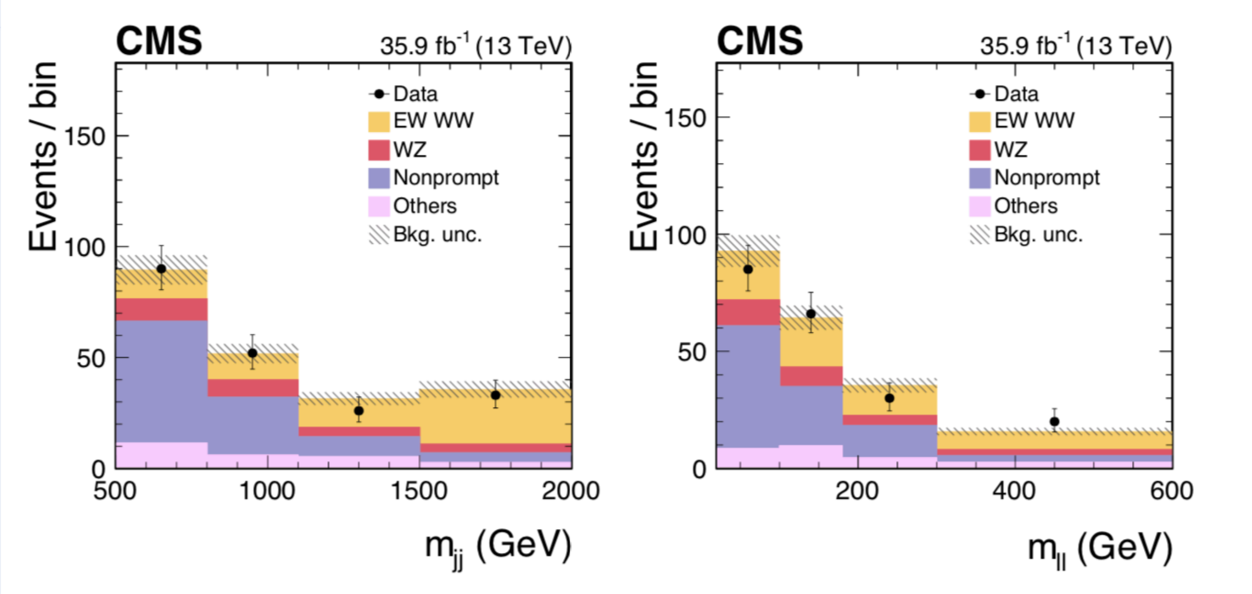
Reducible background: extracted from data

main background: normalized in CR

- First (and only) Run 2 VBS analysis to appear
  - 35.9 fb^{-1} with an optimal S/B
- Main background: WZ -> measured in dedicated CR asking for a 3rd lepton

CMS WWss Run 2 Analysis

- Cross section extraction:



➢ 2-dimentionnal fit

➢ 2 free parameters: μ_{WW}, μ_{WZ}

➢ 2regions: SR and WZ CR (only m_{jj})

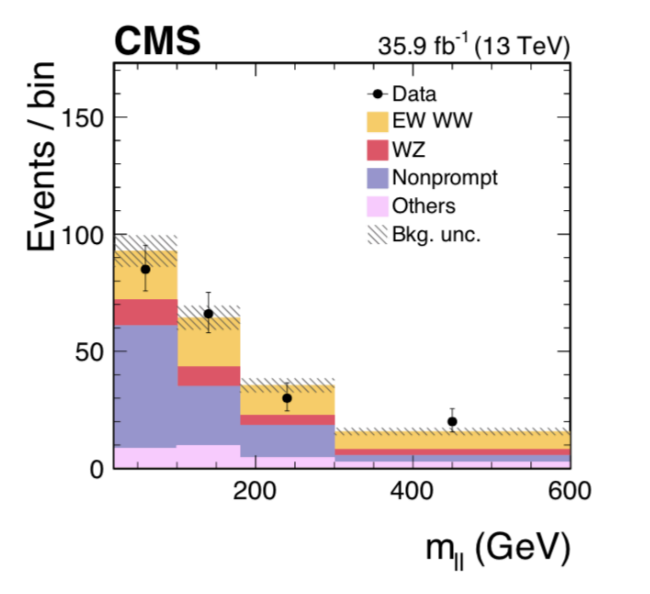
➢Results: $\sigma^{EWK}_{W^{\pm}W^{\pm}} = 3.83 \pm 0.66\,(stat) \pm 0.35\,(syst) fb$

➢ $\frac{{\sigma_{fid}}^{\mathrm{meas}}}{{\sigma_{fid}}^{\mathrm{SM}}} = 0.90 \pm 0.22$ with a statistical significance of: $\boxed{5.5\,\sigma}$

CMS WWss Run 2 Analysis

arXiv:1709.05822v2 [hep-ex] 11 Mar 2018

- m_{ll} sensible to aQGC
  - ➢ 9 effective operators varied one by one



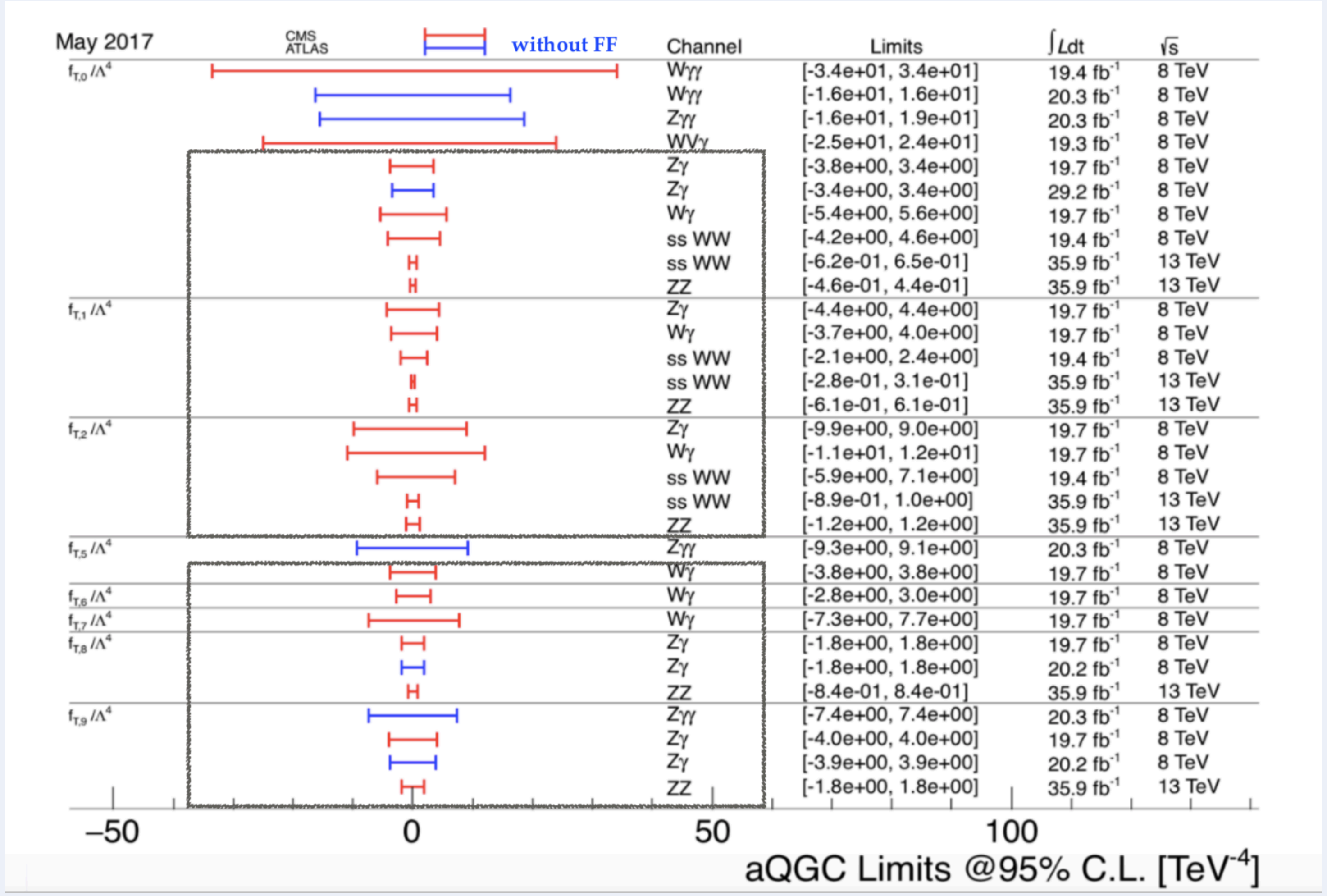
	Observed limits (TeV $^{-4}$)
f_{S0}/Λ^4	$[-7.7, 7.7]$
f_{S1}/Λ^4	$[-21.6, 21.8]$
f_{M0}/Λ^4	$[-6.0, 5.9]$
f_{M1}/Λ^4	$[-8.7, 9.1]$
f_{M6}/Λ^4	$[-11.9, 11.8]$
f_{M7}/Λ^4	$[-13.3, 12.9]$
f_{T0}/Λ^4	$[-0.62, 0.65]$
f_{T1}/Λ^4	$[-0.28, 0.31]$
f_{T2}/Λ^4	$[-0.89, 1.02]$

Not accessible with Zg analysis

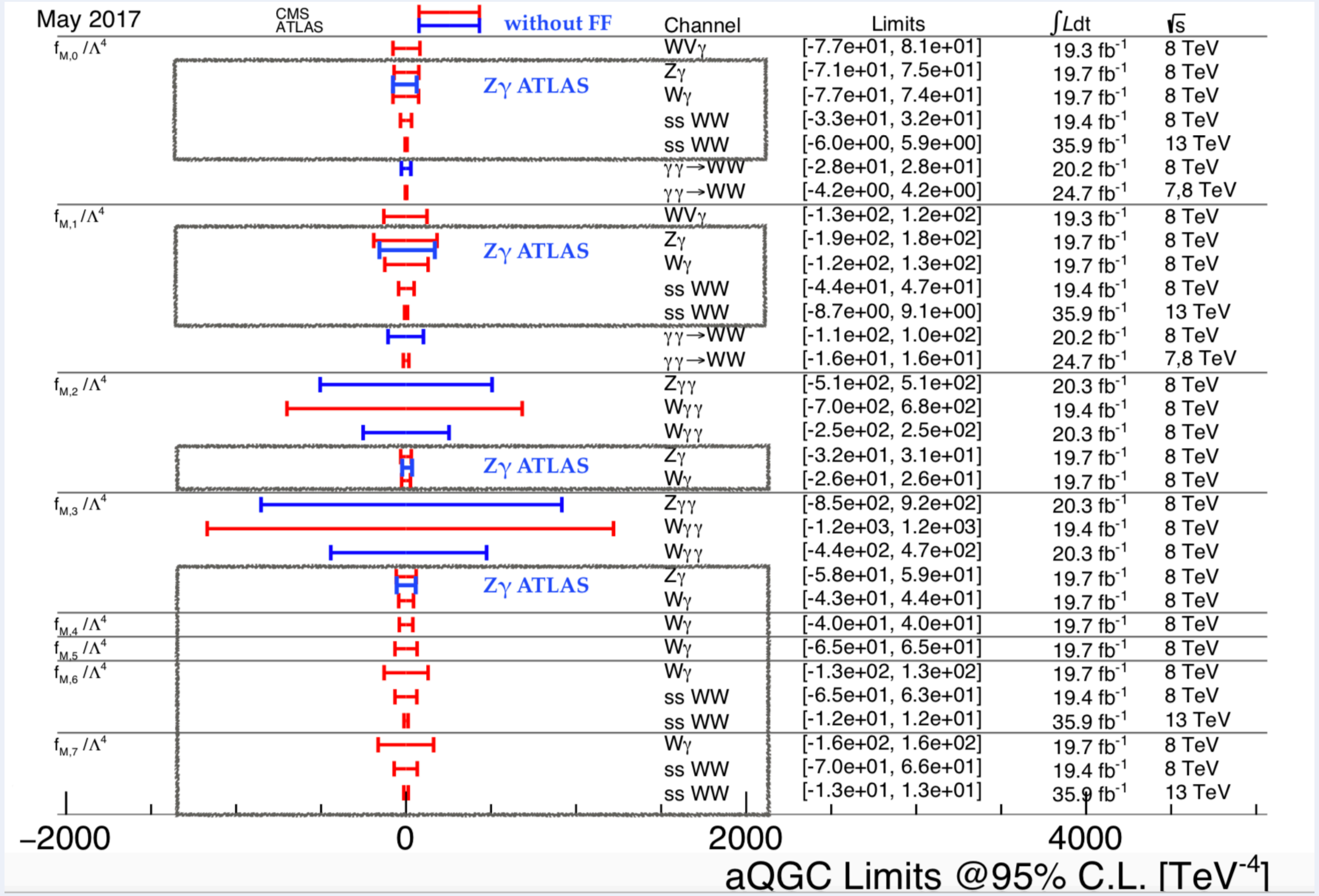
$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

We need the complementarity of several analysis!

Summary of results: f_T



Summary of results: f_M



Summary

- *VBS* is the “new”, interesting chapter of indirect new physics searches
  - First observation with same sign WW (CMS)
  - Already used in Run 1 to set limits to aQGC – machinery in place
- To come:
  - New results with much more statistics and new analysis technics
  - Close ATLAS-CMS collaboration in order to combine their results
  - Close collaboration with theorists for the interpretation of the results
- We’re looking forward to this