Multi-boson final states at ATLAS

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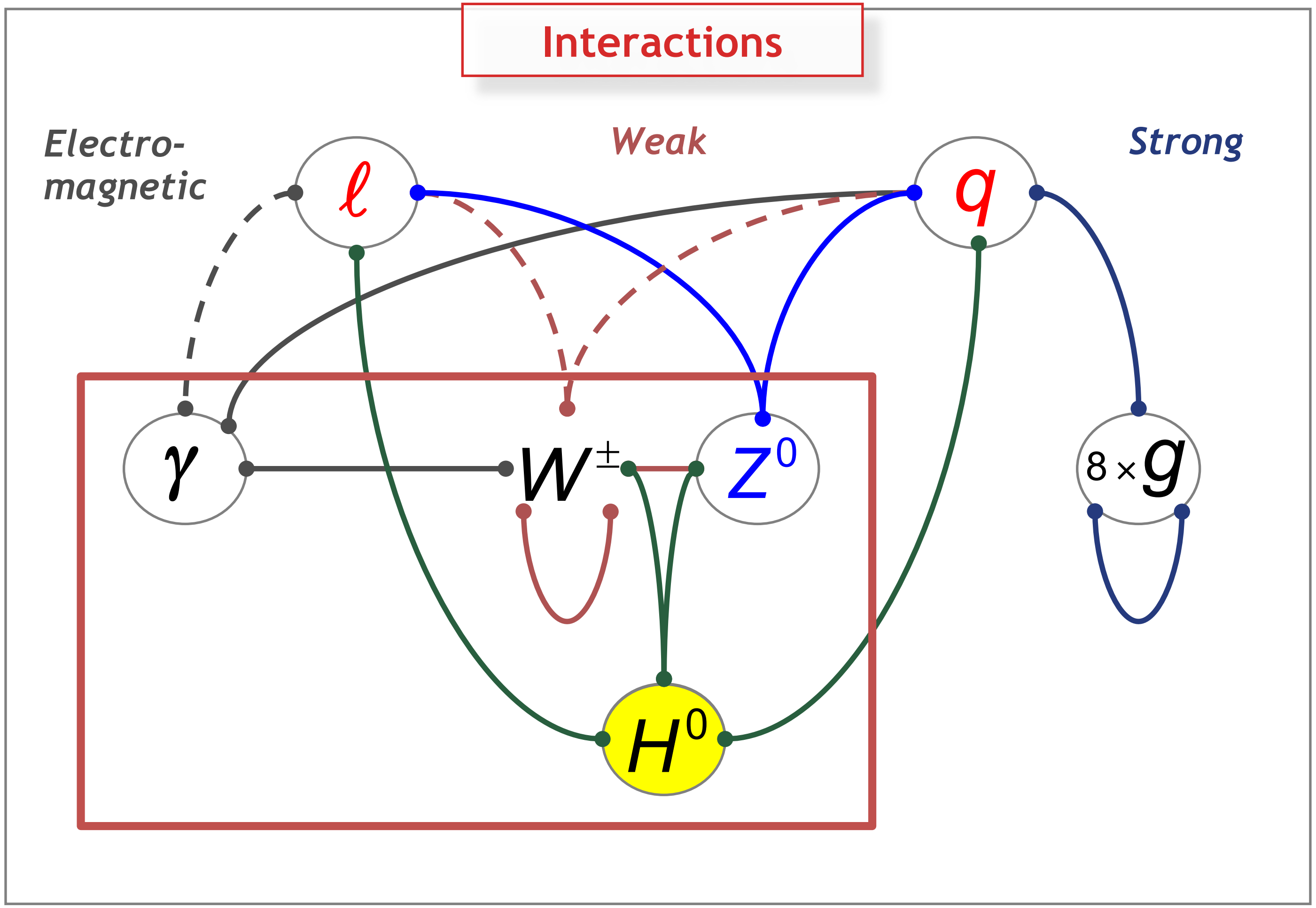
The Standard Model

The Standard Model consists of 24 elementary matter particles and 3 forces



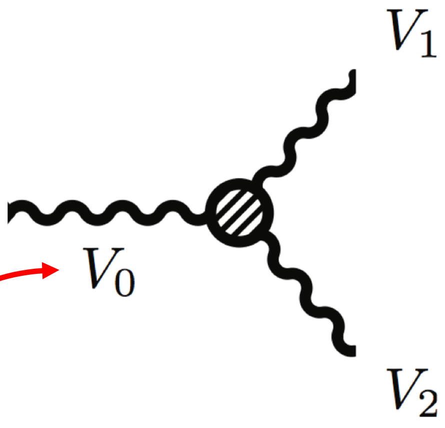
Motivation

- Standard Model EW Lagrangian:

$$\mathcal{L}_{EW} = \mathcal{L}_{boson} + \mathcal{L}_{fermion} + \mathcal{L}_{higgs} + \mathcal{L}_{yukawa}$$

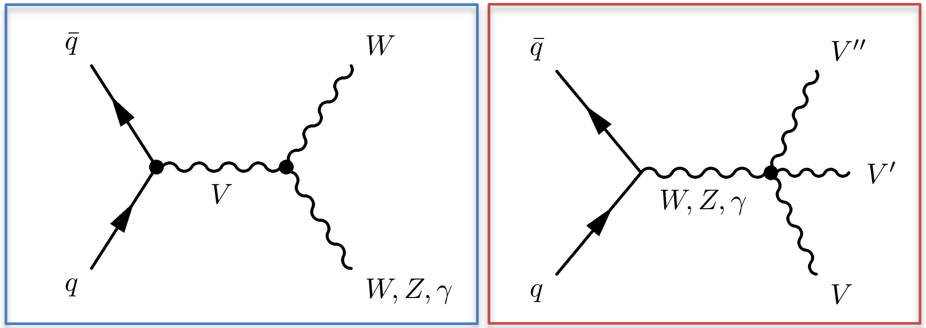
$$\overbrace{-\frac{1}{4}W^{i}_{\mu\nu}W^{i\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}}$$

$$\overbrace{\partial_\mu X^i_\nu - \partial_\nu X^i_\mu - \boxed{g f^{ijk} X^j_\mu X^k_\nu}}$$

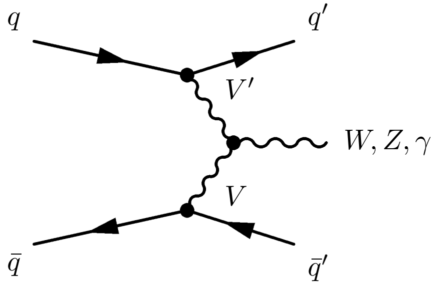


Motivation

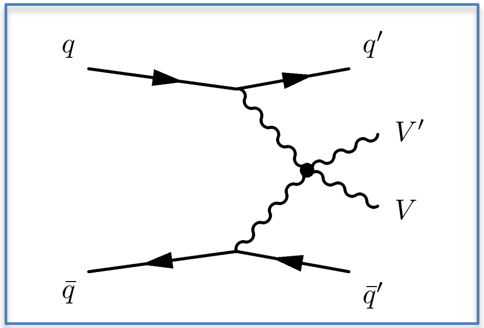
- Probing the non-abelian electroweak interaction with multi-boson final states:



di and tri-boson production



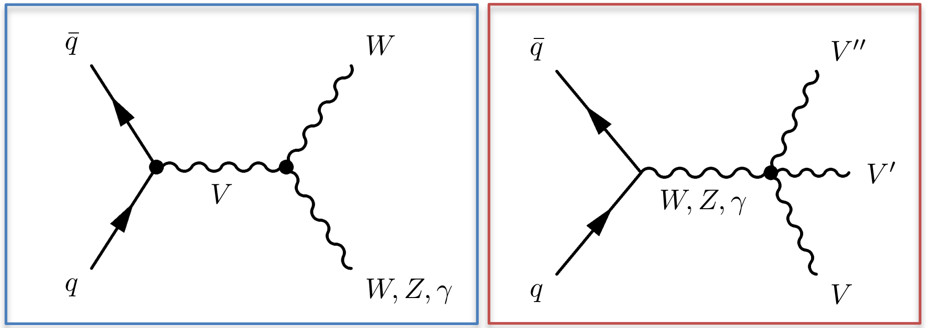
Vector boson fusion (VBS)



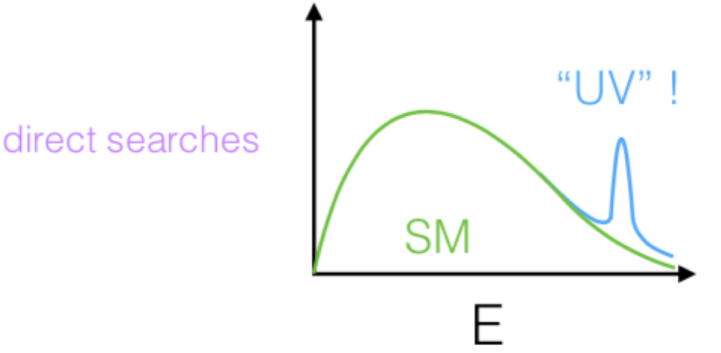
Vector boson fusion (VBS)

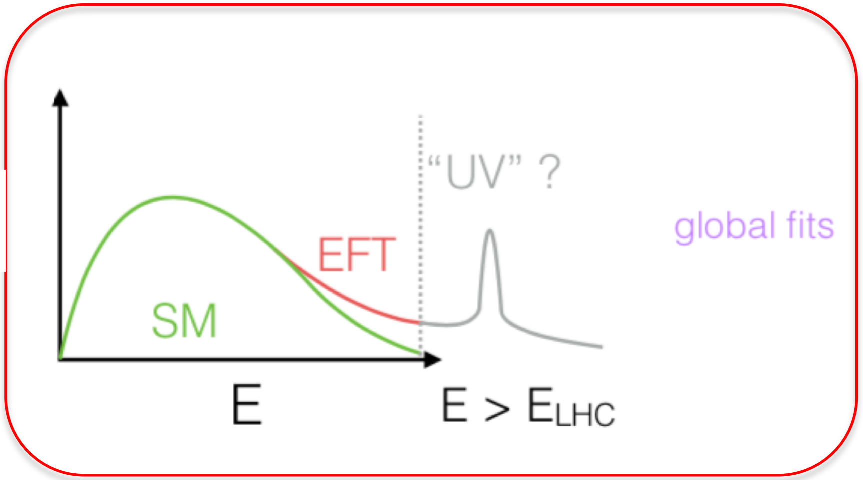
Motivation

- Probing the non-abelian electroweak interaction with multi-boson final states:



di and tri-boson production





Ken Mimasu, Be.HEP summer solstice meeting 2018

Anomalous

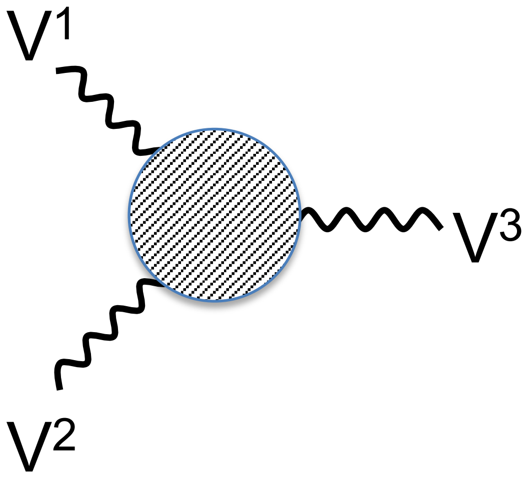
Triple Gauge Boson Couplings

- Extend SM to describe **new physics** with anomalous couplings or effective Lagrangian approach.

Charged aTGC

WWZ

WWγ



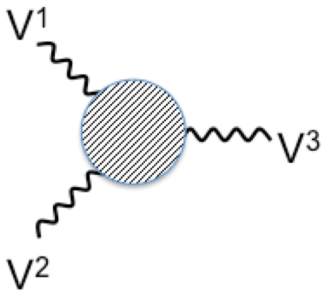
Neutral aTGC

ZZZ

ZZγ

Anomalous
Triple Gauge Boson Couplings

- Anomalous Lagrangian parameters (simplified).



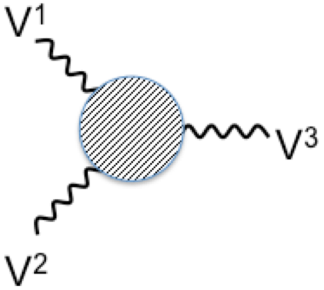
NB:
V = Z, γ. In the SM case anomalous coupling = 0.

Charged aTGC: Δg1=g1-1, Δκ=κ-1, λ

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\left[g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu V^{\nu\rho}\right]$$

Neutral aTGC: f4, f5

$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2}\left[f_4^V(\delta_\mu V^{\mu\beta})Z_\alpha(\delta^\alpha Z_\beta) + f_5^V(\delta^\sigma V_{\sigma\mu})Z^{\mu\beta}Z_\beta\right]$$



Anomalous
Triple Gauge Boson Couplings

Charged aTGC:

$\Delta g1$, $\Delta\kappa$: $\hat{s}^{1/2}$

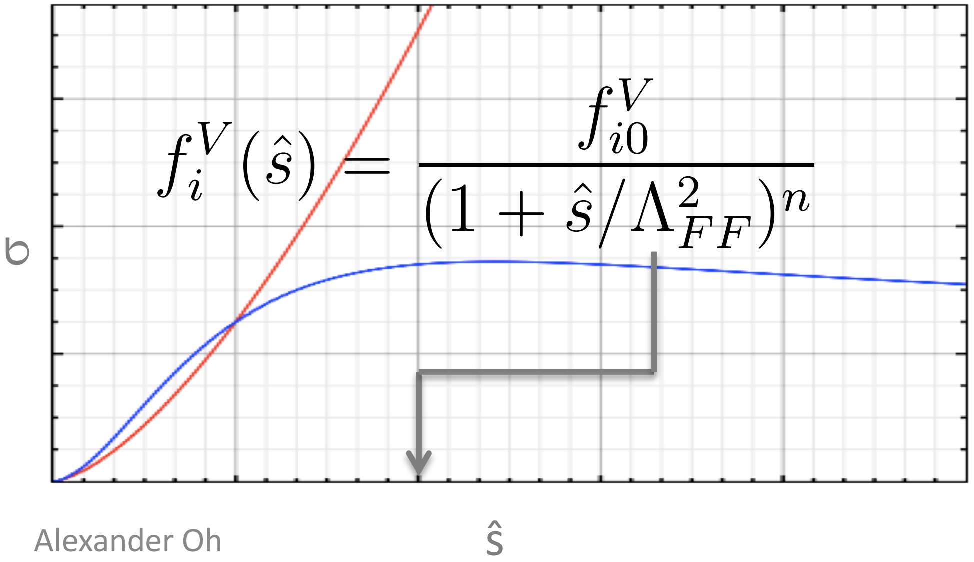
λ : $\hat{s}$

Neutral aTGC:

f4, f5 : $\hat{s}^{3/2}$

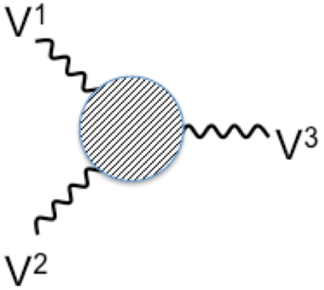
- Di-boson cross section with aTGC has a strong energy dependence and will grow severely with the parton centre of mass energy.
- Need to introduce **form factor** to guard unitarity.
- Typical ansatz is a dipole form factor with some power *n* :

http://arxiv.org/abs/1205.4231



$$f_i^V(\hat{s}) = \frac{f_{i0}^V}{(1+\hat{s}/\Lambda_{FF}^2)^n}$$

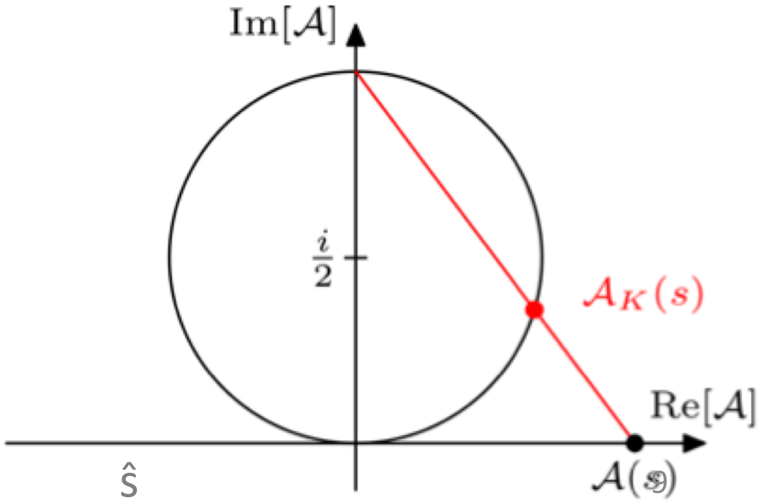
Needs fine-tuning.
Additional free parameters
n and Λ_{ff}.

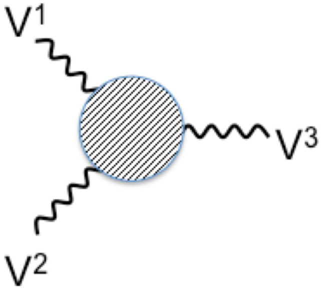


Anomalous
Triple Gauge Boson Couplings

- Alternative is to use “k-matrix” unitarisation. http://arxiv.org/abs/0806.4145
- Projecting the real scattering amplitude A(s) on the Argand circle→ saturation of amplitude.
- No free parameters -> less model dependent.
- Retains the property of probing the entire kinematic phase space without being unphysical.

So far only abailable for 2->2 processes





Effective Field Theory

- Alternative to anomalous gauge couplings: EFT approach.

dimensionless Wilson coefficients

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \cdots$$

NP energy scale

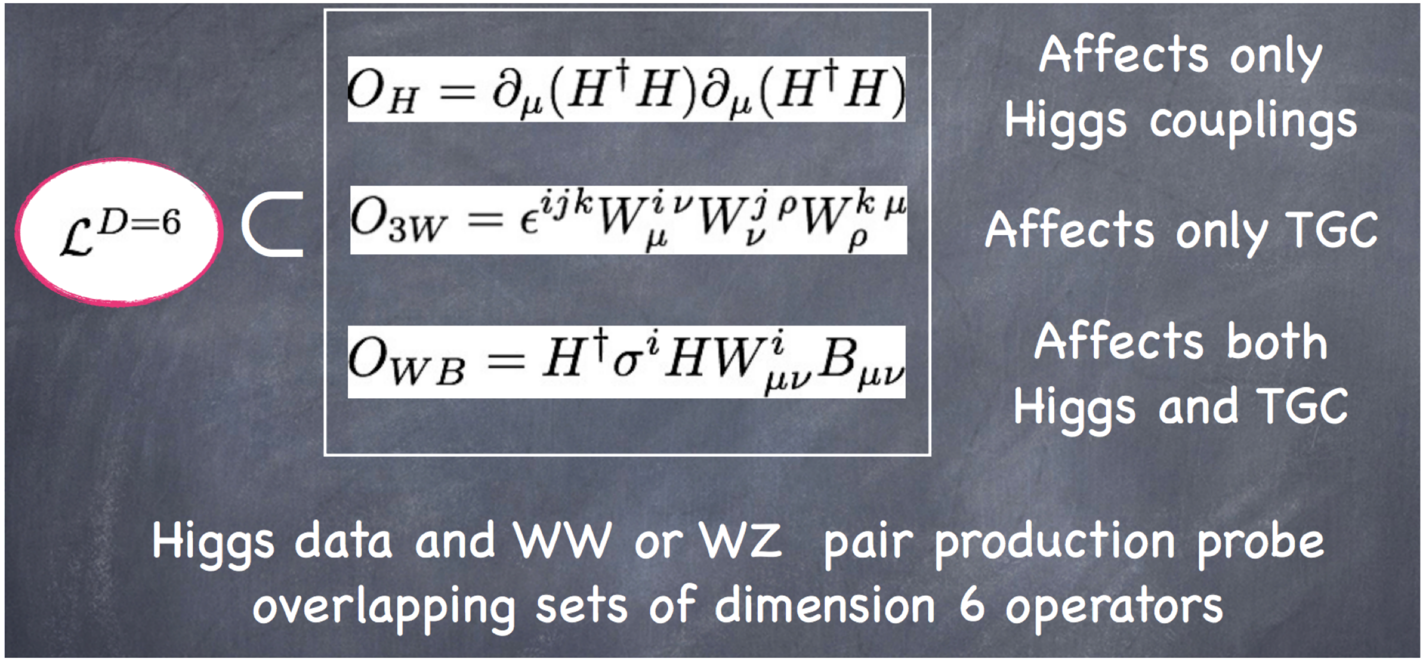
operator dim 6

- EFT constructed with SM fields
- **Dim 4**: Standard Model
- **Dim 5**: Violates lepton number conservation
- **Dim 6**: lowest order EFT operator
- By construction valid until new physics scale becomes important
  -> no unitarity concerns?

Theory – Higgs – TGC

interplay

- Different basis are equivalent if complete.
  - Hagiwara (SM), Higgs basis, SILH basis, Warsaw basis….
- Operators DIM6 affect both Higgs and boson couplings



$\mathcal{L}^{D=6} \subset$

$O_H = \partial_\mu(H^\dagger H)\partial_\mu(H^\dagger H)$ Affects only Higgs couplings

$O_{3W} = \epsilon^{ijk} W^{i\,\nu}_{\mu} W^{j\,\rho}_{\nu} W^{k\,\mu}_{\rho}$ Affects only TGC

$O_{WB} = H^\dagger \sigma^i H W^i_{\mu\nu} B_{\mu\nu}$ Affects both Higgs and TGC

Higgs data and WW or WZ pair production probe overlapping sets of dimension 6 operators

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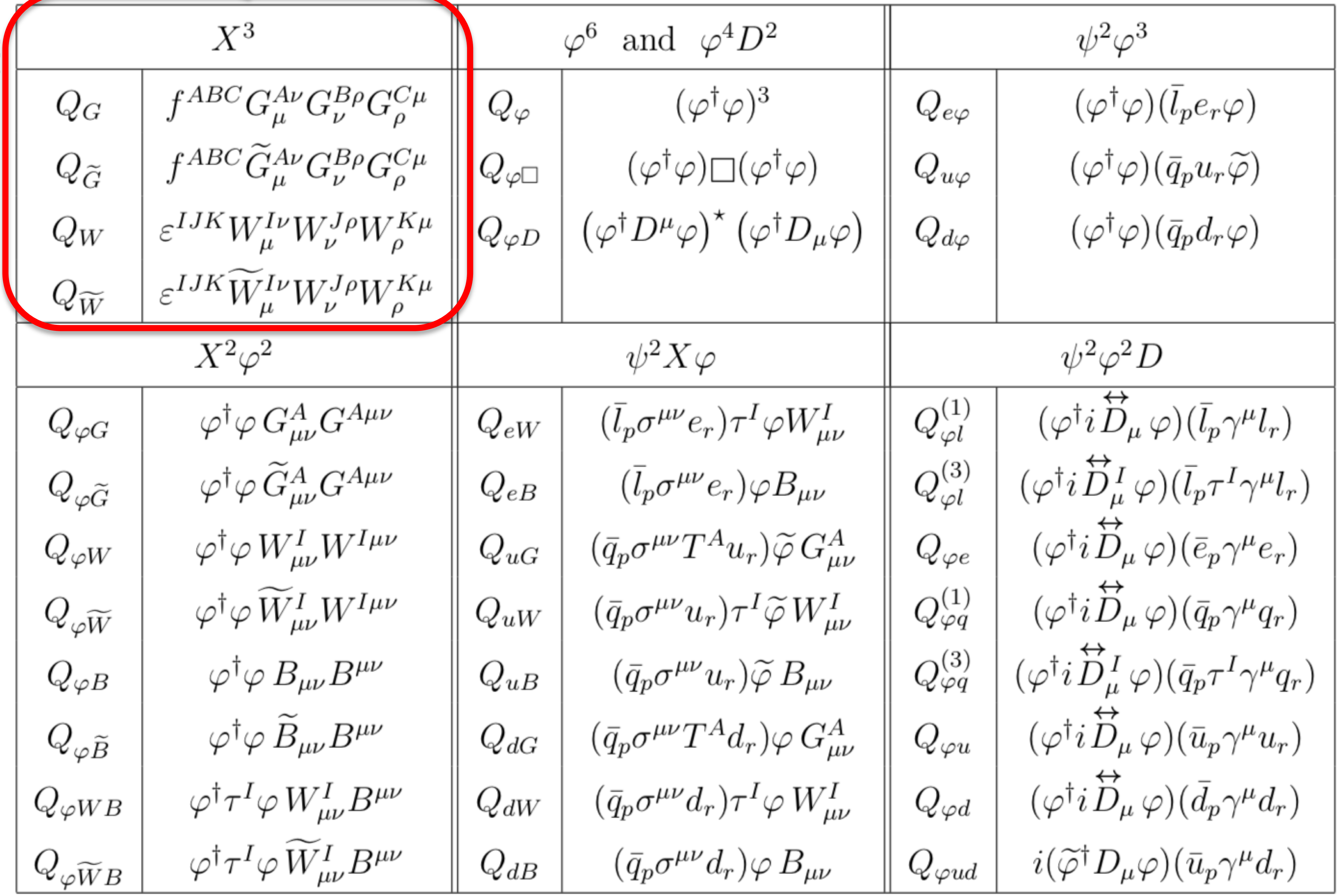
Example: Warsaw basis

tri-boson interactions

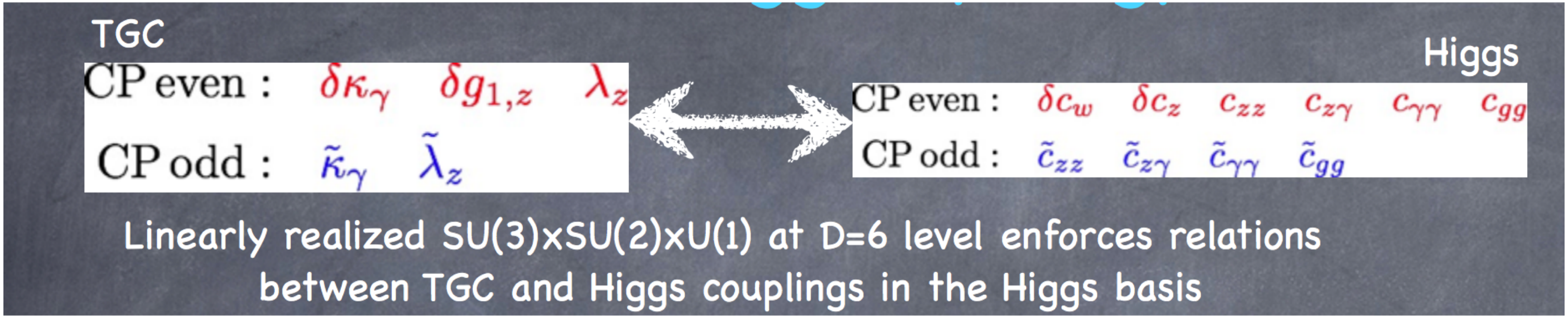


X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$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

arXiv:1008.4884

Theory – Higgs – TGC
interplay

- Translation between TGC limits and Higgs couplings possible.
- In Higgs basis 2 TGCs couplings, can be expressed by Higgs couplings to gauge bosons.
- TGCs have to be **simultaneously constrained** in multi-dimensional fit and **correlation matrix** should be given. <u>Important for combination of Higgs and TGC results.</u>



TGC

CP even : $\delta\kappa_\gamma$ $\delta g_{1,z}$ λ_z

CP odd : $\tilde{\kappa}_\gamma$ $\tilde{\lambda}_z$

Higgs

CP even : δc_w δc_z c_{zz} $c_{z\gamma}$ $c_{\gamma\gamma}$ c_{gg}

CP odd : $\tilde{c}_{zz}$ $\tilde{c}_{z\gamma}$ $\tilde{c}_{\gamma\gamma}$ $\tilde{c}_{gg}$

Linearly realized SU(3)xSU(2)xU(1) at D=6 level enforces relations between TGC and Higgs couplings in the Higgs basis

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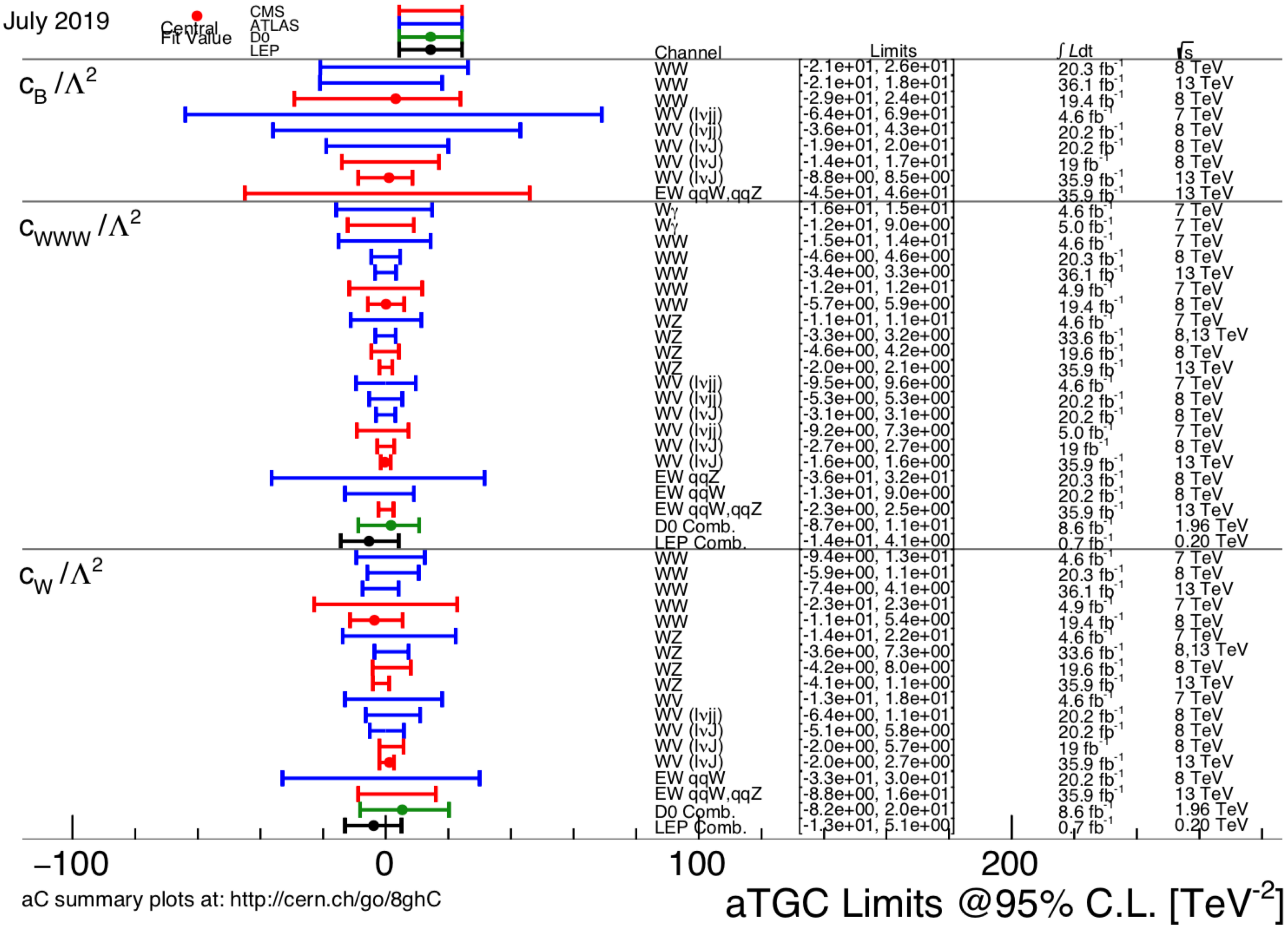
Summary plot of current one dimensional limits on EFT dim 6 parameters:



Channel	Limits	$\int Ldt$	$\sqrt{s}$
c_B/Λ^2			
WW	[-2.1e+01, 2.6e+01]	20.3 fb^{-1}	8 TeV
WW	[-2.1e+01, 1.8e+01]	36.1 fb^{-1}	13 TeV
WW	[-2.9e+01, 2.4e+01]	19.4 fb^{-1}	8 TeV
WV (lvjj)	[-6.4e+01, 6.9e+01]	4.6 fb^{-1}	7 TeV
WV (lvjj)	[-3.6e+01, 4.3e+01]	20.2 fb^{-1}	8 TeV
WV (lvJ)	[-1.9e+01, 2.0e+01]	20.2 fb^{-1}	8 TeV
WV (lvJ)	[-1.4e+01, 1.7e+01]	19 fb^{-1}	8 TeV
WV (lvJ)	[-8.8e+00, 8.5e+00]	35.9 fb^{-1}	13 TeV
EW qqW,qqZ	[-4.5e+01, 4.6e+01]	35.9 fb^{-1}	13 TeV
c_{WWW}/Λ^2			
Wγ	[-1.6e+01, 1.5e+01]	4.6 fb^{-1}	7 TeV
Wγ	[-1.2e+01, 9.0e+00]	5.0 fb^{-1}	7 TeV
WW	[-1.5e+01, 1.4e+01]	4.6 fb^{-1}	7 TeV
WW	[-4.6e+00, 4.6e+00]	20.3 fb^{-1}	8 TeV
WW	[-3.4e+00, 3.3e+00]	36.1 fb^{-1}	13 TeV
WW	[-1.2e+01, 1.2e+01]	4.9 fb^{-1}	7 TeV
WW	[-5.7e+00, 5.9e+00]	19.4 fb^{-1}	8 TeV
WZ	[-1.1e+01, 1.1e+01]	4.6 fb^{-1}	7 TeV
WZ	[-3.3e+00, 3.2e+00]	33.6 fb^{-1}	8,13 TeV
WZ	[-4.6e+00, 4.2e+00]	19.6 fb^{-1}	8 TeV
WZ	[-2.0e+00, 2.1e+00]	35.9 fb^{-1}	13 TeV
WV (lvjj)	[-9.5e+00, 9.6e+00]	4.6 fb^{-1}	7 TeV
WV (lvjj)	[-5.3e+00, 5.3e+00]	20.2 fb^{-1}	8 TeV
WV (lvJ)	[-3.1e+00, 3.1e+00]	20.2 fb^{-1}	8 TeV
WV (lvjj)	[-9.2e+00, 7.3e+00]	5.0 fb^{-1}	7 TeV
WV (lvJ)	[-2.7e+00, 2.7e+00]	19 fb^{-1}	8 TeV
WV (lvJ)	[-1.6e+00, 1.6e+00]	35.9 fb^{-1}	13 TeV
EW qqZ	[-3.6e+01, 3.2e+01]	20.3 fb^{-1}	8 TeV
EW qqW	[-1.3e+01, 9.0e+00]	20.2 fb^{-1}	8 TeV
EW qqW,qqZ	[-2.3e+00, 2.5e+00]	35.9 fb^{-1}	13 TeV
D0 Comb.	[-8.7e+00, 1.1e+01]	8.6 fb^{-1}	1.96 TeV
LEP Comb.	[-1.4e+01, 4.1e+00]	0.7 fb^{-1}	0.20 TeV
c_W/Λ^2			
WW	[-9.4e+00, 1.3e+01]	4.6 fb^{-1}	7 TeV
WW	[-5.9e+00, 1.1e+01]	20.3 fb^{-1}	8 TeV
WW	[-7.4e+00, 4.1e+00]	36.1 fb^{-1}	13 TeV
WW	[-2.3e+01, 2.3e+01]	4.9 fb^{-1}	7 TeV
WW	[-1.1e+01, 5.4e+00]	19.4 fb^{-1}	8 TeV
WZ	[-1.4e+01, 2.2e+01]	4.6 fb^{-1}	7 TeV
WZ	[-3.6e+00, 7.3e+00]	33.6 fb^{-1}	8,13 TeV
WZ	[-4.2e+00, 8.0e+00]	19.6 fb^{-1}	8 TeV
WZ	[-4.1e+00, 1.1e+00]	35.9 fb^{-1}	13 TeV
WV	[-1.3e+01, 1.8e+01]	4.6 fb^{-1}	7 TeV
WV (lvjj)	[-6.4e+00, 1.1e+01]	20.2 fb^{-1}	8 TeV
WV (lvJ)	[-5.1e+00, 5.8e+00]	20.2 fb^{-1}	8 TeV
WV (lvJ)	[-2.0e+00, 5.7e+00]	19 fb^{-1}	8 TeV
WV (lvJ)	[-2.0e+00, 2.7e+00]	35.9 fb^{-1}	13 TeV
EW qqW	[-3.3e+01, 3.0e+01]	20.2 fb^{-1}	8 TeV
EW qqW,qqZ	[-8.8e+00, 1.6e+01]	35.9 fb^{-1}	13 TeV
D0 Comb.	[-8.2e+00, 2.0e+01]	8.6 fb^{-1}	1.96 TeV
LEP Comb.	[-1.3e+01, 5.1e+00]	0.7 fb^{-1}	0.20 TeV

aC summary plots at: http://cern.ch/go/8ghC

Q

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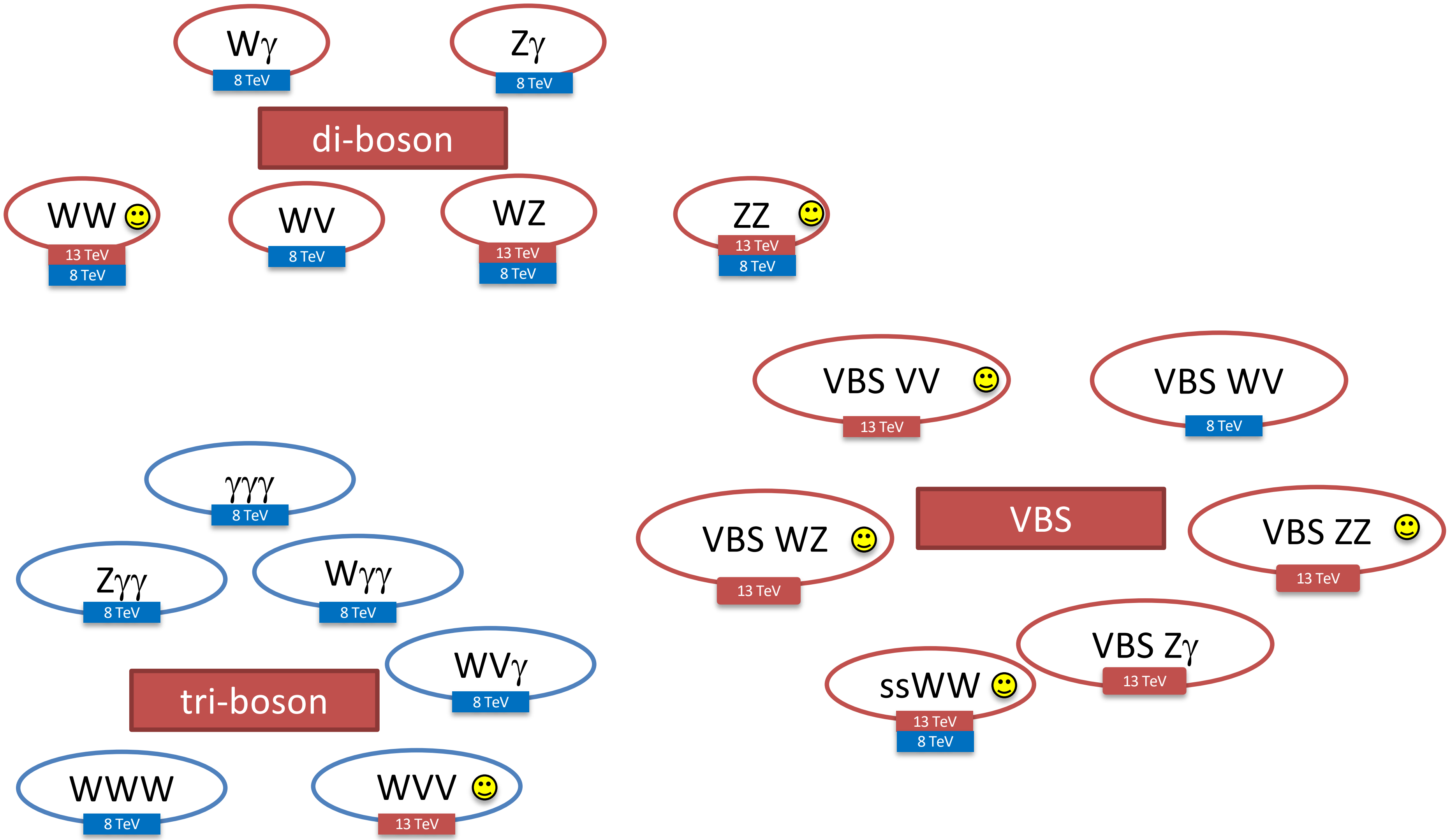
Experimental status: multi boson production



di-boson

Wγ 8 TeV

Zγ 8 TeV

WW ☺ 13 TeV 8 TeV

WV 8 TeV

WZ 13 TeV 8 TeV

ZZ ☺ 13 TeV 8 TeV

tri-boson

γγγ 8 TeV

Zγγ 8 TeV

Wγγ 8 TeV

WVγ 8 TeV

WWW 8 TeV

WVV ☺ 13 TeV

VBS

VBS VV ☺ 13 TeV

VBS WV 8 TeV

VBS WZ ☺ 13 TeV

VBS ZZ ☺ 13 TeV

VBS Zγ 13 TeV

ssWW ☺ 13 TeV 8 TeV

☺: 2019 result

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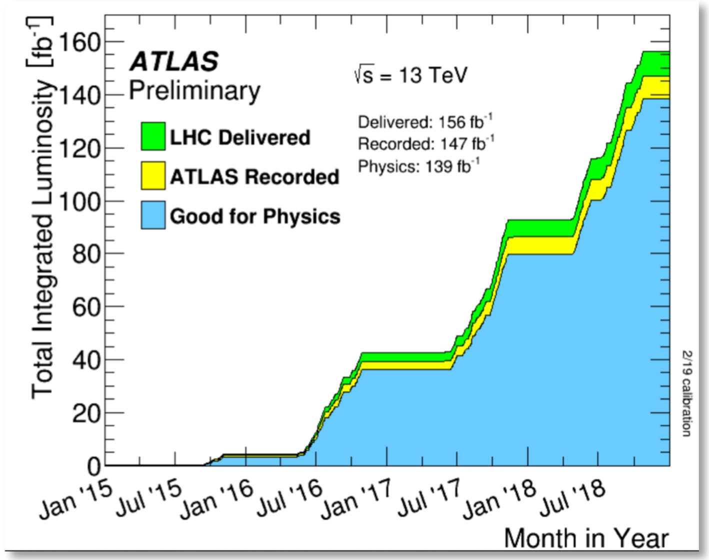
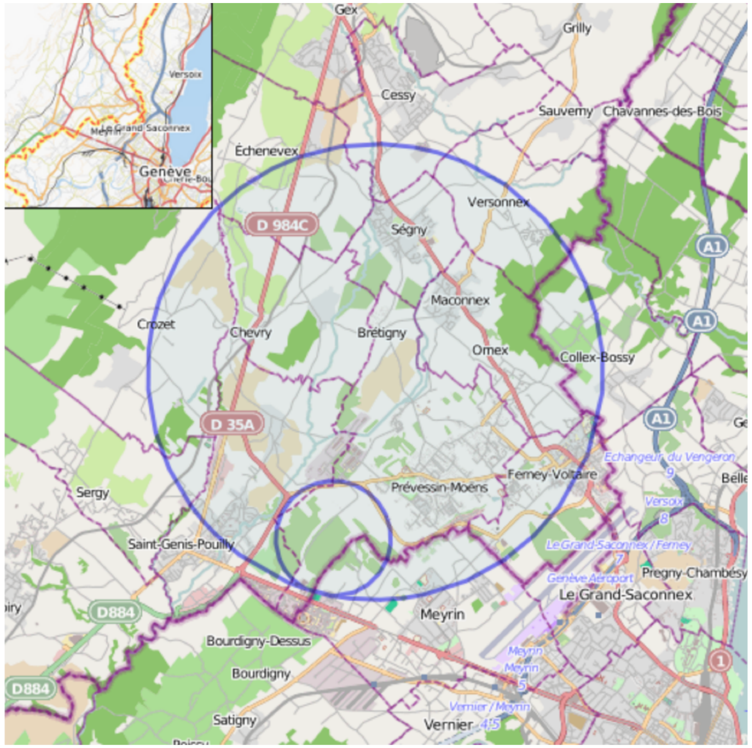
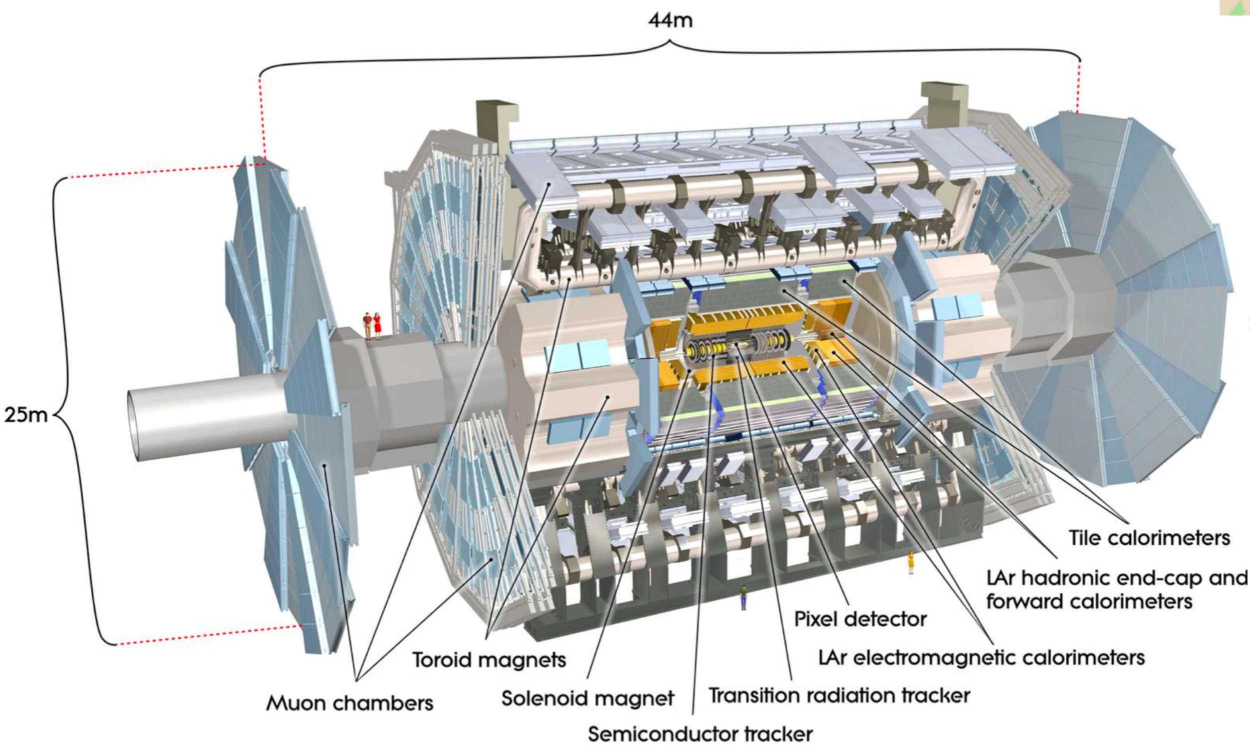
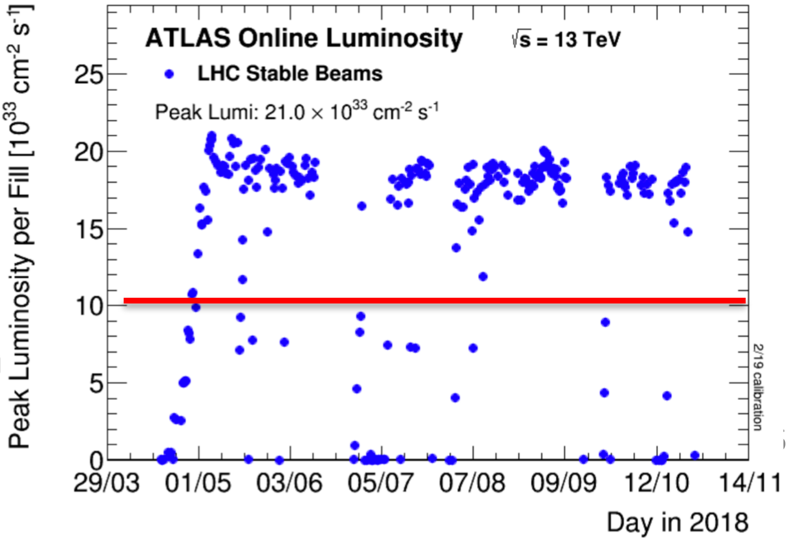


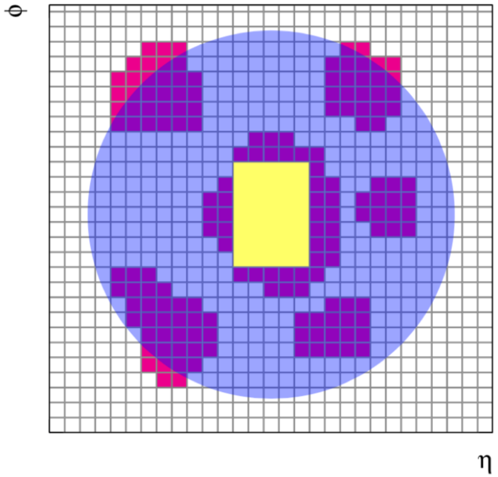


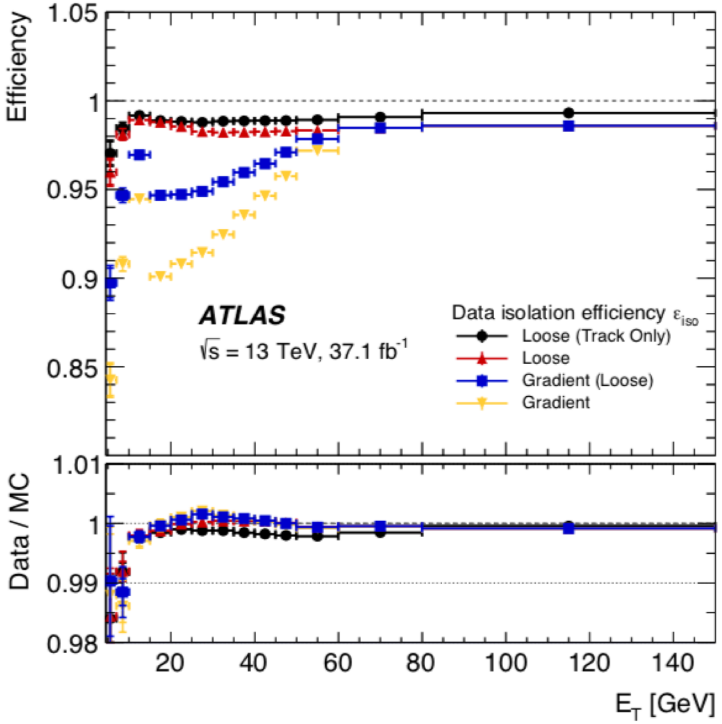


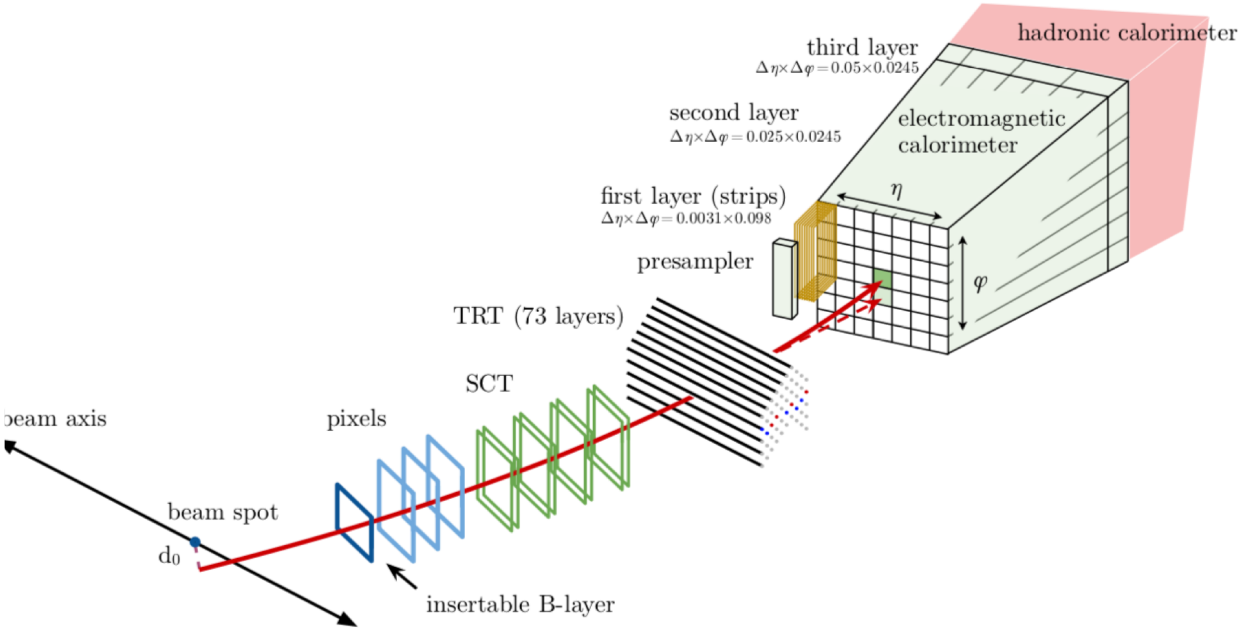


Common experimental techniques

- **Leptonic signatures (non-VBS)**
  - Leptons from vector boson decays isolated, use electron and muon channels.
  - Isolation requirements:
    - Track and calorimeter based isolation cone ΔR=0.2. Working point: ε>98%

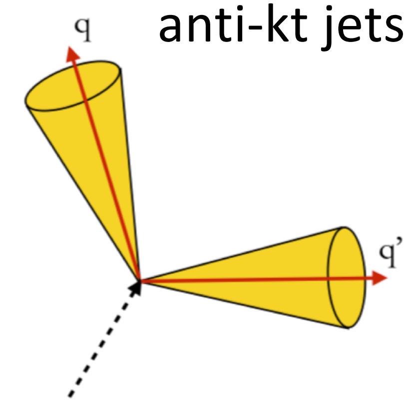






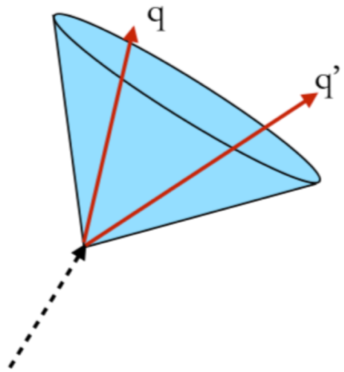
Common experimental techniques

- **hadronic signatures**
  - W/Z reconstruction with two resolved anti-kt jets R=0.4



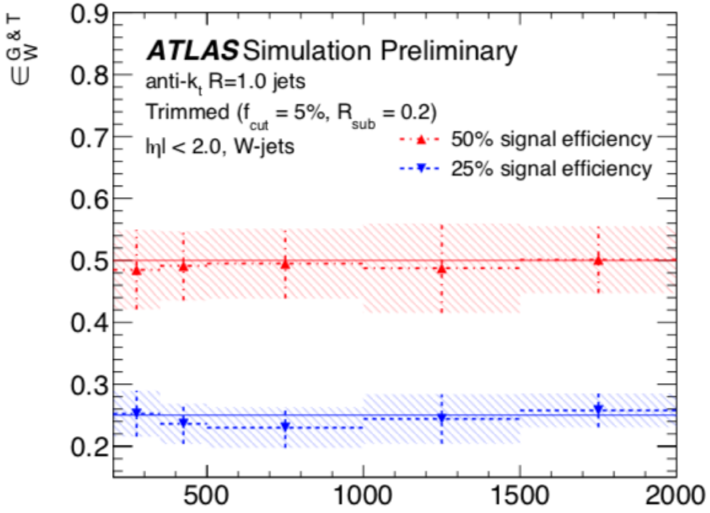
W/Z
$p_T \lesssim 200$ **GeV**

2 resolved
small-radius jets
(R = 0.4)

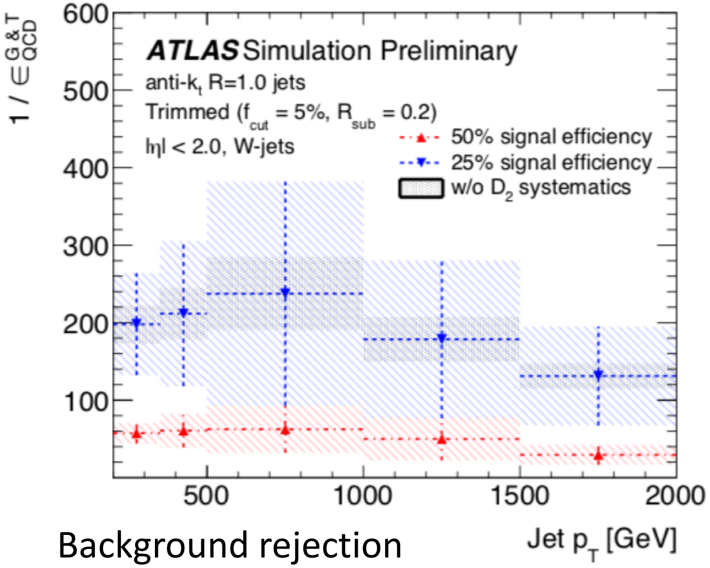


W/Z
$p_T \gtrsim 200$ **GeV**

All decay products fall within 1
large-radius jet
(R = 0.8 for CMS, 1 for ATLAS)



Signal efficiency



Background rejection

- **Large R-jets** with R=1.0 for boosted W/Z.
- Exploit jet-substructure to improve mass resolution and reject QCD jets (more later).

Sketches from Robin Aggleton, MBI2019

Common experimental techniques

- Background estimation
  - **Data driven techniques**
    - Normalization of leading contributions with dedicated control regions, e.g. V+jet, ttbar, WZ.
    - Lepton miss-id with “fake factor” determination.
    - Charge misidentification with control samples.
  - **MC samples** for most sub-leading backgrounds (e.g. EWK processes).

Experimental status: multi boson production

di-boson

- Wγ: 8 TeV
- Zγ: 8 TeV
- WW ☺: 13 TeV, 8 TeV
- WV: 8 TeV
- WZ: 13 TeV, 8 TeV
- ZZ ☺: 13 TeV, 8 TeV

tri-boson

- γγγ: 8 TeV
- Wγγ: 8 TeV
- Zγγ: 8 TeV
- WVγ: 8 TeV
- WWW: 8 TeV
- WVV ☺: 13 TeV

VBS

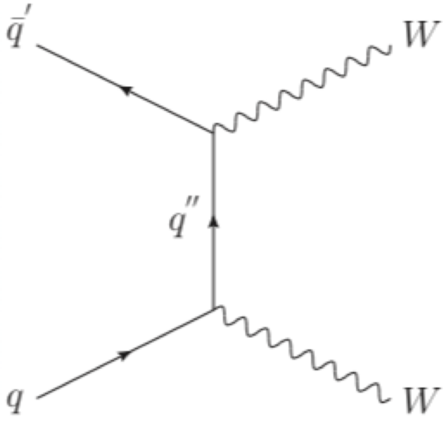
- VBS VV ☺: 13 TeV
- VBS WV: 8 TeV
- VBS WZ ☺: 13 TeV
- VBS ZZ ☺: 13 TeV
- VBS Zγ: 13 TeV
- ssWW ☺: 13 TeV, 8 TeV

☺: 2019 result

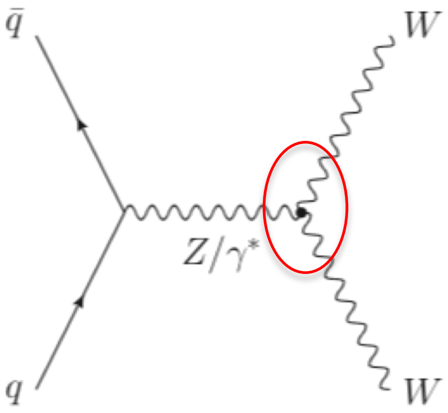
arXiv:1905.04242

WW

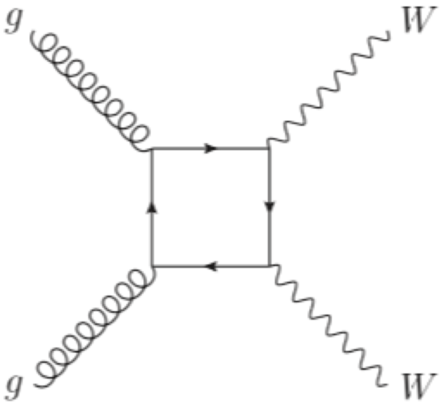
sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = fully leptonic



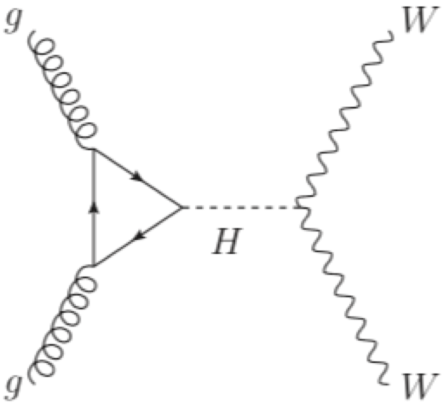
qq t-channel



qq s-channel



qq q-loop



qq H->WW

- **WW** production diagrams at tree level include triple gauge boson vertex in the s-channel.
- Analysis of fully leptonic final state with **one electron and one muon**, oppositely charged. **Clean signature**, no DY contamination.
- Focus on **fiducial cross sections** and differential distributions to compare to calculation and extract aTGC.

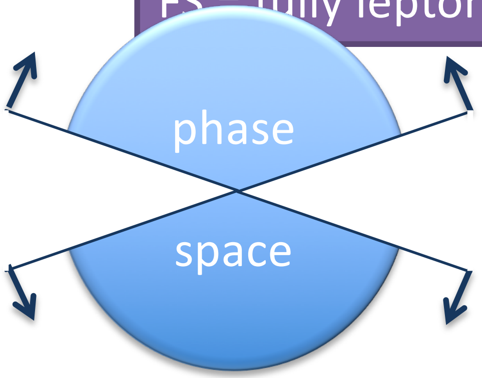
WW

arXiv:1905.04242

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = fully leptonic

Fiducial Cross sections

- **Minimize theory uncertainties due to phase-space extrapolations.**
  - Define a “fiducial volume” mimicking the detector acceptance.
  - Definition in terms of final state truth particles after showering
    - Charged lepton and photon kinematics.
    - Neutrino transverse energy
    - Vector boson mass calculated from leptons.
  - Leptons are “redressed” with brem photons in ΔR=0.1.
  - Allows theorists to test their favorite model.



$$\sigma_{Fiducial} = \frac{N_{Obs} - N_{Bkg}}{C \times L}$$

$$C = \frac{N_{MC}^{Reco}}{N_{MC\,Truth}^{Pass\,Fiducial}}$$

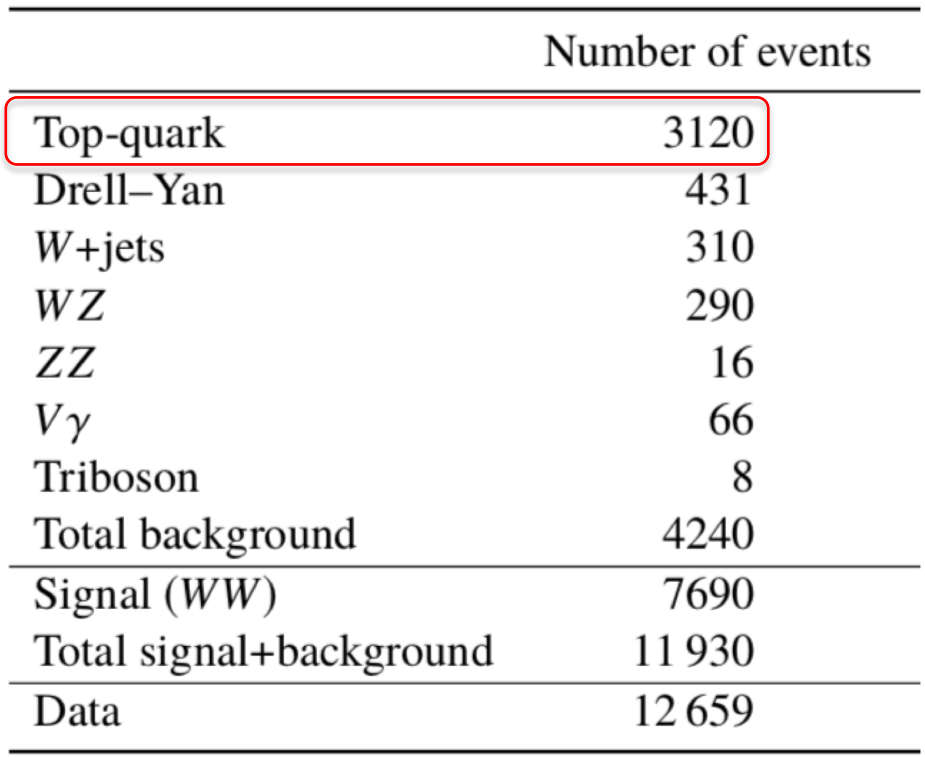
Fiducial selection requirements		
p_{T}^{ℓ}	>	27 GeV
$\lvert\eta^{\ell}\rvert$	<	2.5
$m_{e\mu}$	>	55 GeV
$p_{\mathrm{T}}^{e\mu}$	>	30 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	>	20 GeV
No jets with p_{T}	>	35 GeV, $\lvert\eta\rvert < 4.5$

arXiv:1905.04242

WW

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = fully leptonic

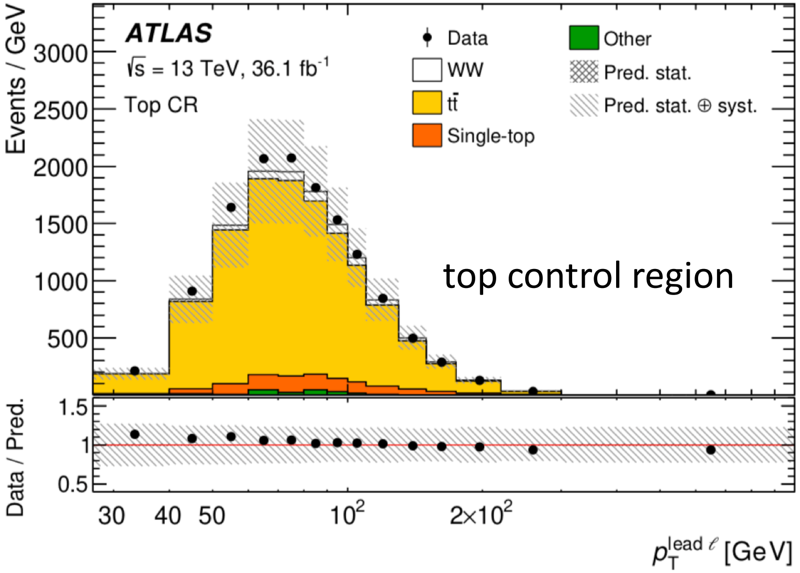
- Background sources:



	Number of events
Top-quark	3120
Drell–Yan	431
W+jets	310
WZ	290
ZZ	16
$V\gamma$	66
Triboson	8
Total background	4240
Signal (WW)	7690
Total signal+background	11 930
Data	12 659

Top-quark background dominant, reduced by (b-)jet veto.

Use control region to determine normalisation. background has 12% uncertainty (b-tagging, modelling).



top control region

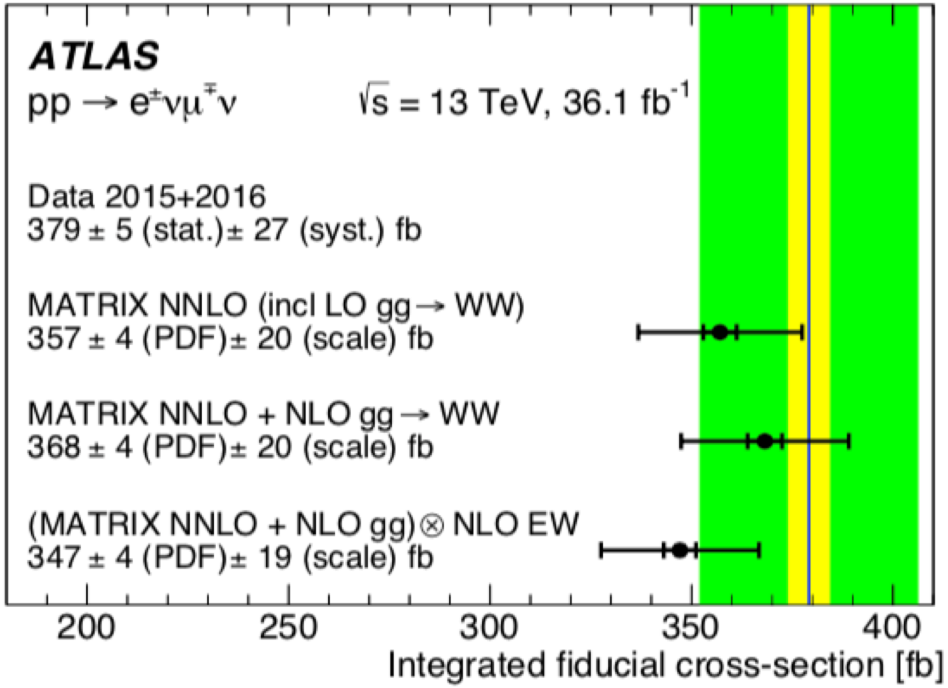
arXiv:1905.04242

WW

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = fully leptonic

- **Fiducial cross section:**

$$\sigma_{\text{fid}} = (379.1 \pm 5.0\ (\text{stat}) \pm 25.4\ (\text{syst}) \pm 8.0\ (\text{lumi}))\ \text{fb}$$



Good agreement with NNLO (qq) and NLO (gg) calculations.

Precision of 7.1% !!!

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

aTGC in EFT formalism provided.

Extracted from leading lepton distribution.

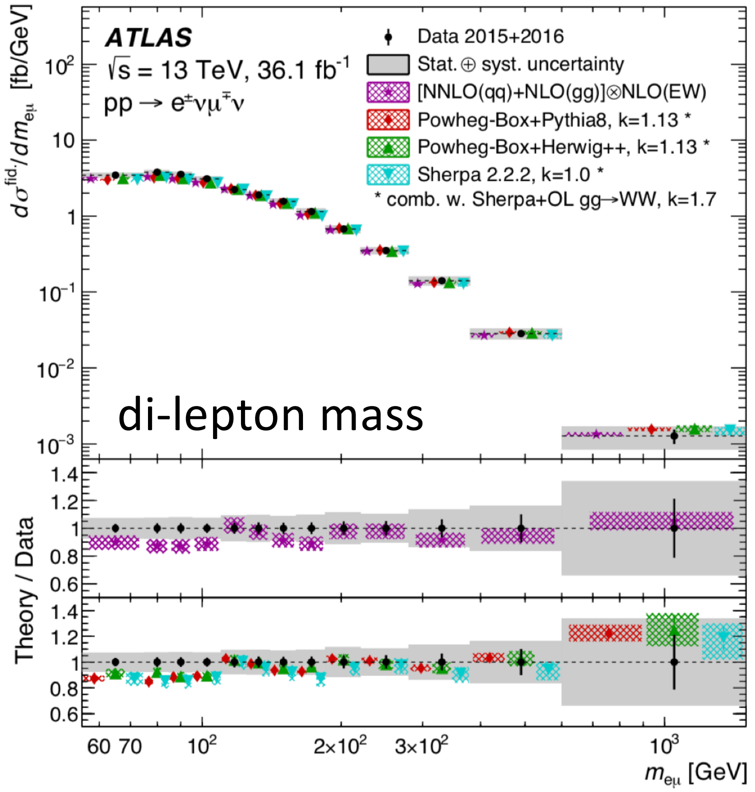
arXiv:1905.04242

WW

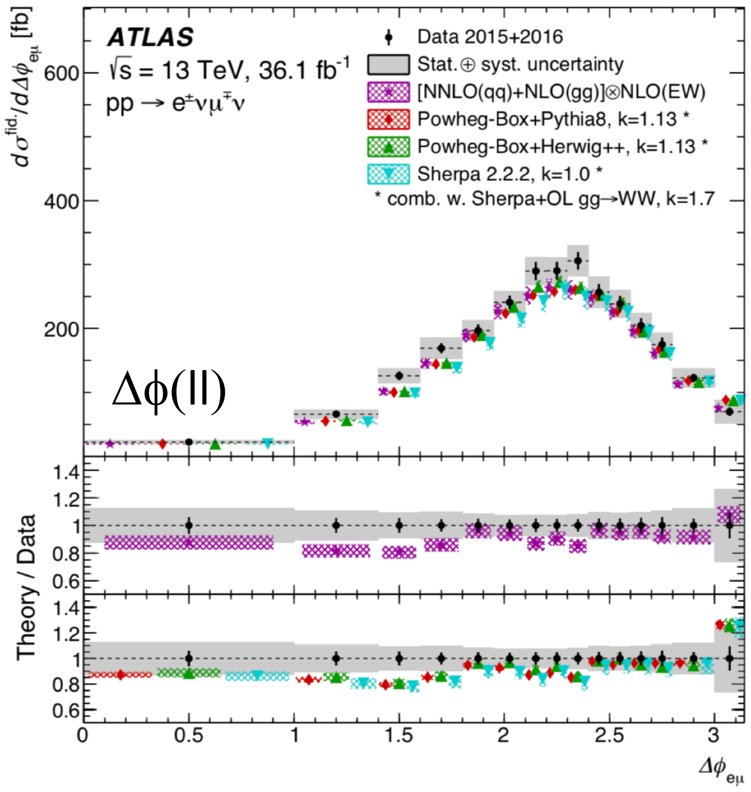
sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = fully leptonic

- **Differential distributions in comparison with calculations**

(4 angular, 2 mass/momentum)



di-lepton mass



$\Delta\phi$(ll)

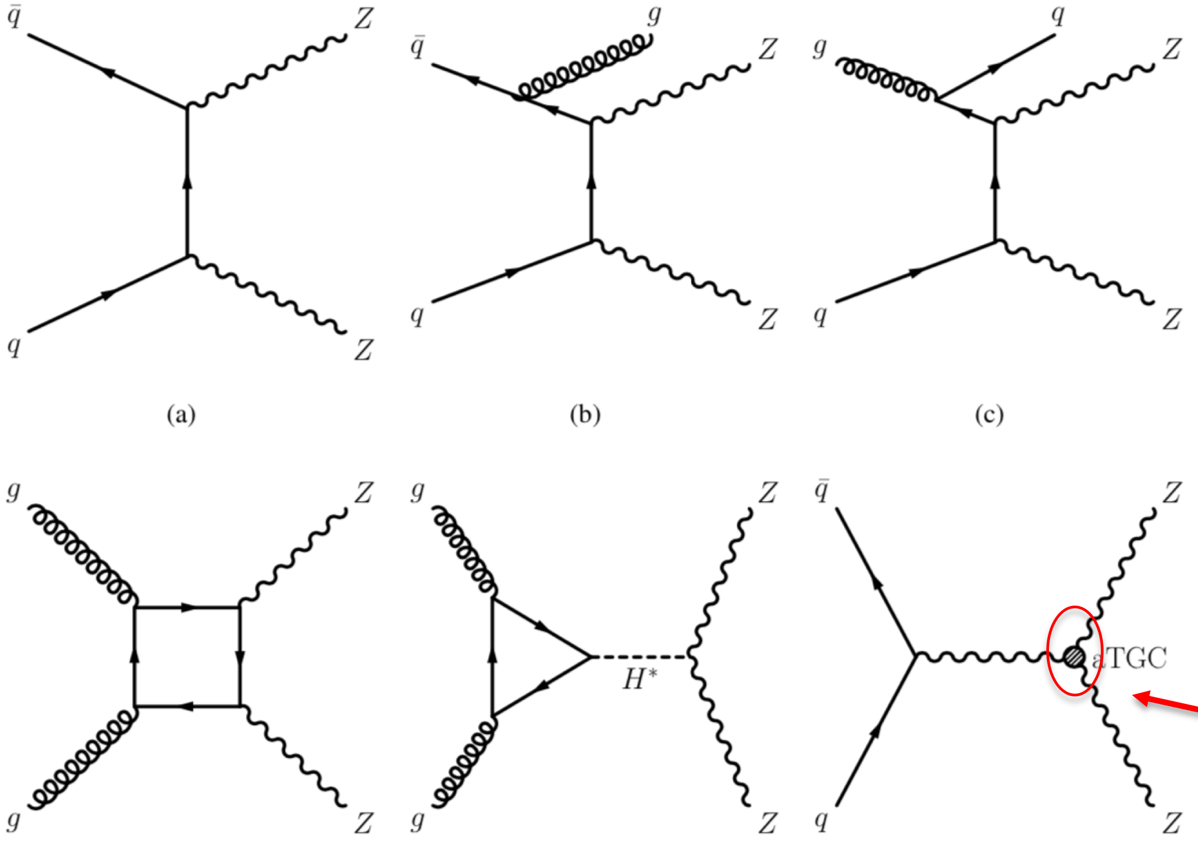
Underprediction in low m_{ll} range and at $\Delta\phi$ ~ 1.5

arXiv:1905.04242

ZZ -> llvv

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = ll $\nu\nu$

- **Production diagrams:**



(a) (b) (c)

(d) (e) (f)

- **Channel llvv**
  - Larger branching fraction compared to ll ll (arXiv:1709.07703).
  - Improved sensitivity to aTGC, but less precise integrated cross section.

neutral TGC not allowed in the SM at tree level.

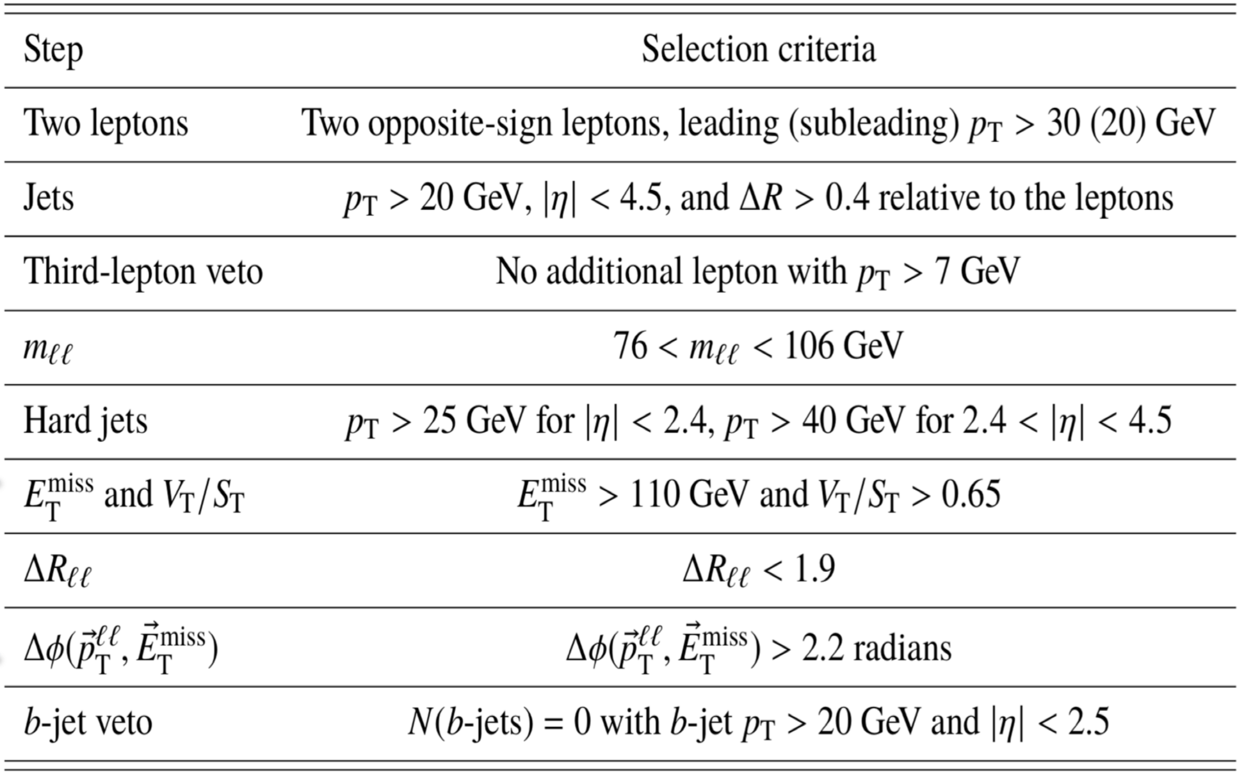
arXiv:1905.04242

ZZ -> llvv

$\sqrt{s}$ = 13 TeV
L = 36.1 fb^{-1}
FS = ll $\nu\nu$

Selection:

- Less clean then 4l channel, suppress backgrounds with stringer cuts:
- WZ background
- Select high mass events with Z decays back-to-back.
- top background



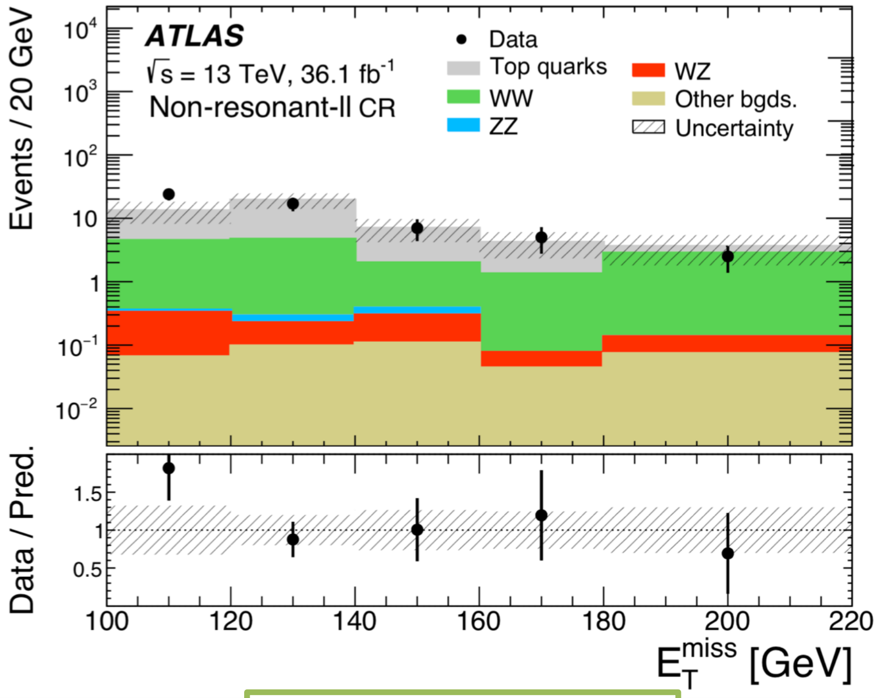
Step	Selection criteria
Two leptons	Two opposite-sign leptons, leading (subleading) $p_T > 30$ (20) GeV
Jets	$p_T > 20$ GeV, $\lvert\eta\rvert < 4.5$, and $\Delta R > 0.4$ relative to the leptons
Third-lepton veto	No additional lepton with $p_T > 7$ GeV
$m_{\ell\ell}$	$76 < m_{\ell\ell} < 106$ GeV
Hard jets	$p_T > 25$ GeV for $\lvert\eta\rvert < 2.4$, $p_T > 40$ GeV for $2.4 < \lvert\eta\rvert < 4.5$
E_T^{miss} and V_T/S_T	$E_T^{miss} > 110$ GeV and $V_T/S_T > 0.65$
$\Delta R_{\ell\ell}$	$\Delta R_{\ell\ell} < 1.9$
$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{miss})$	$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{miss}) > 2.2$ radians
b-jet veto	$N(b\text{-jets}) = 0$ with b-jet $p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$

arXiv:1905.04242

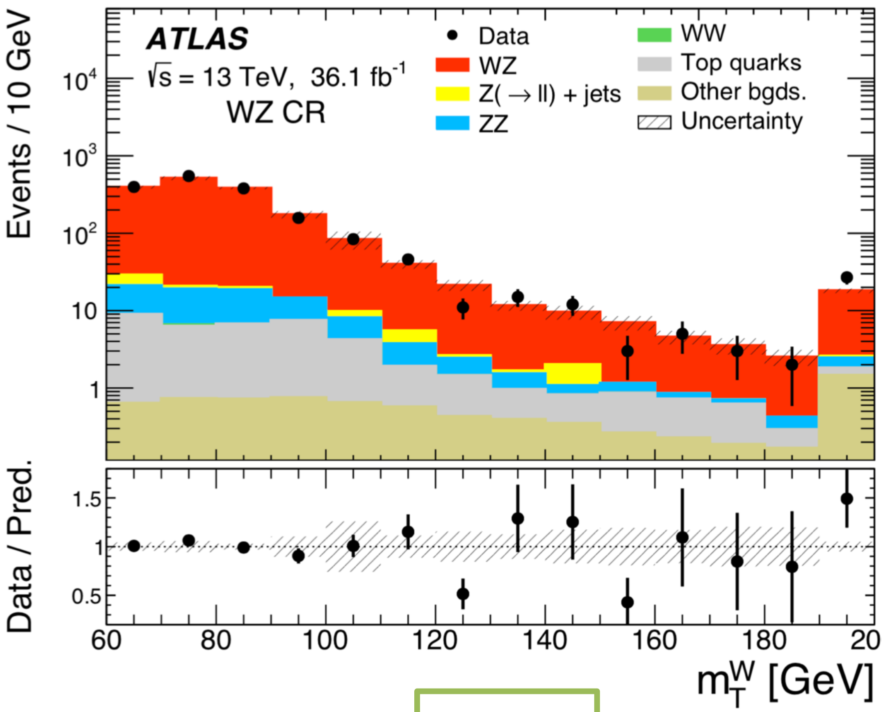
ZZ -> llvv

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = ll νν

- After selection signal to background about **S/N=1.7**
- Dominant background sources:
  - **WZ : 72%**
  - non-resonant ll production : 21%
  - Estimated with **control regions** from data.



non-resonant ll CR

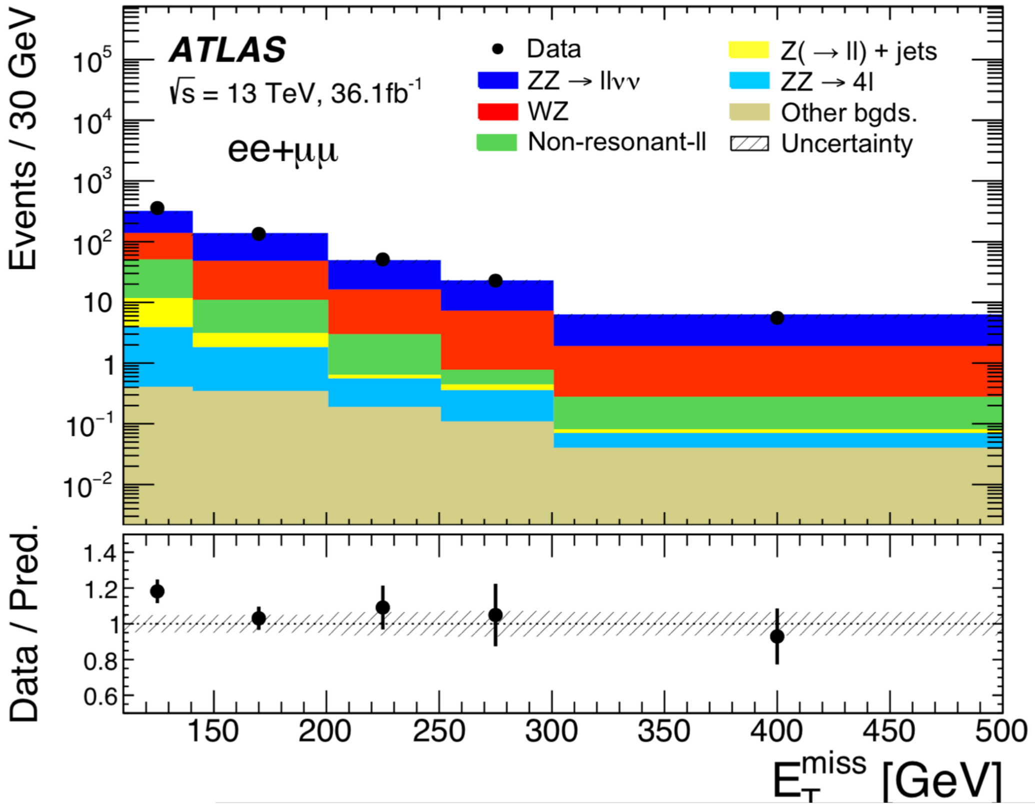


WZ CR

arXiv:1905.04242

ZZ -> llvv

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = ll $\nu\nu$



- Cross section:
  Binned ML fit to MET in ee and μμ channel.
- Integrated total and fiducial cross section results:
  - **Still statistically limited.**

		Measured	Predicted
$\sigma^{\text{fid}}_{ZZ\to\ell\ell\nu\nu}$ [fb]	ee	12.2 ± 1.0 (stat) ± 0.5 (syst) ± 0.3 (lumi)	11.2 ± 0.6
	$\mu\mu$	13.3 ± 1.0 (stat) ± 0.5 (syst) ± 0.3 (lumi)	11.2 ± 0.6
	$ee + \mu\mu$	25.4 ± 1.4 (stat) ± 0.9 (syst) ± 0.5 (lumi)	22.4 ± 1.3
σ^{tot}_{ZZ} [pb]	Total	17.8 ± 1.0 (stat) ± 0.7 (syst) ± 0.4 (lumi)	15.7 ± 0.7

for comparison $ZZ \to llll$ 17.3 ± 0.9 [±0.6 (stat.) ±0.5 (syst.) ±0.6 (lumi.)] pb

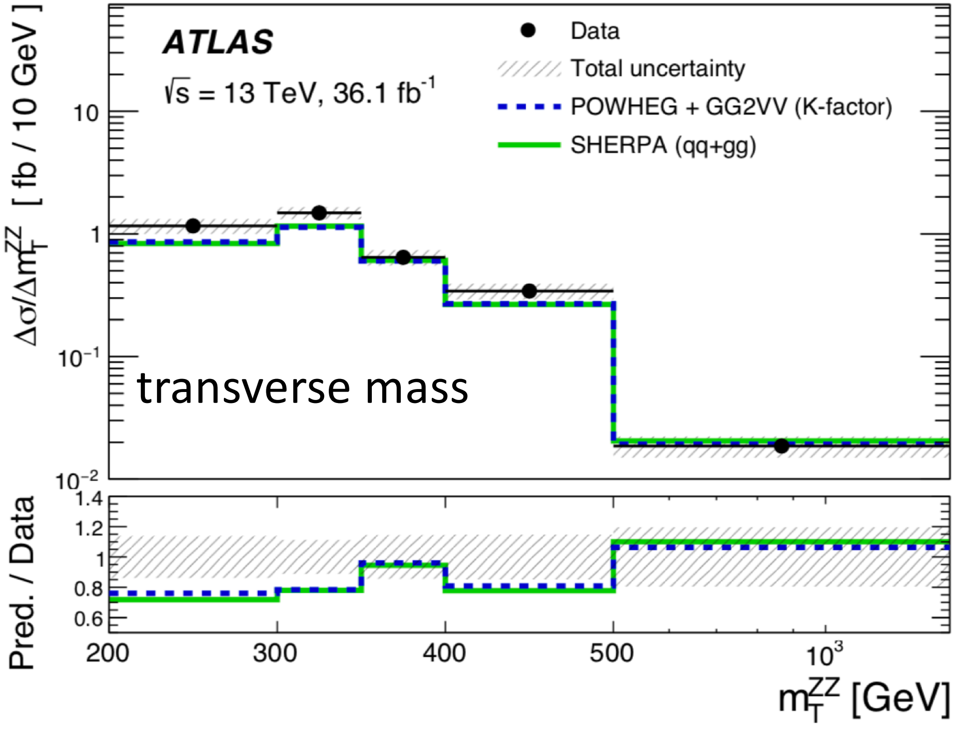
arXiv:1709.07703

arXiv:1905.04242

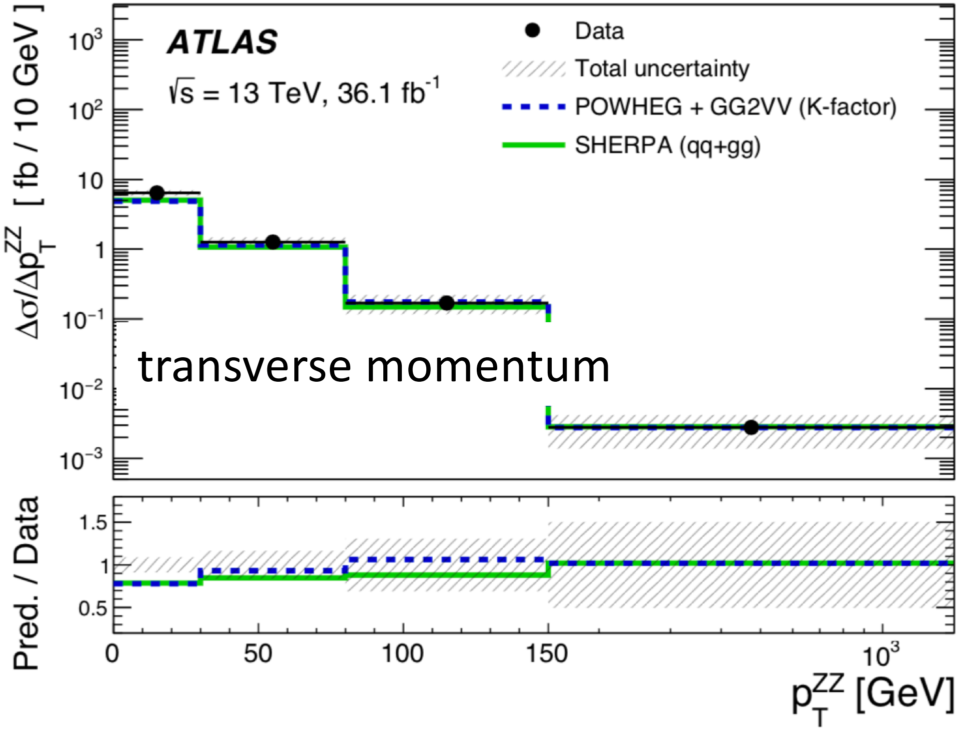
ZZ -> llνν

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = ll νν

- Unfolded differential cross sections:



transverse mass



transverse momentum

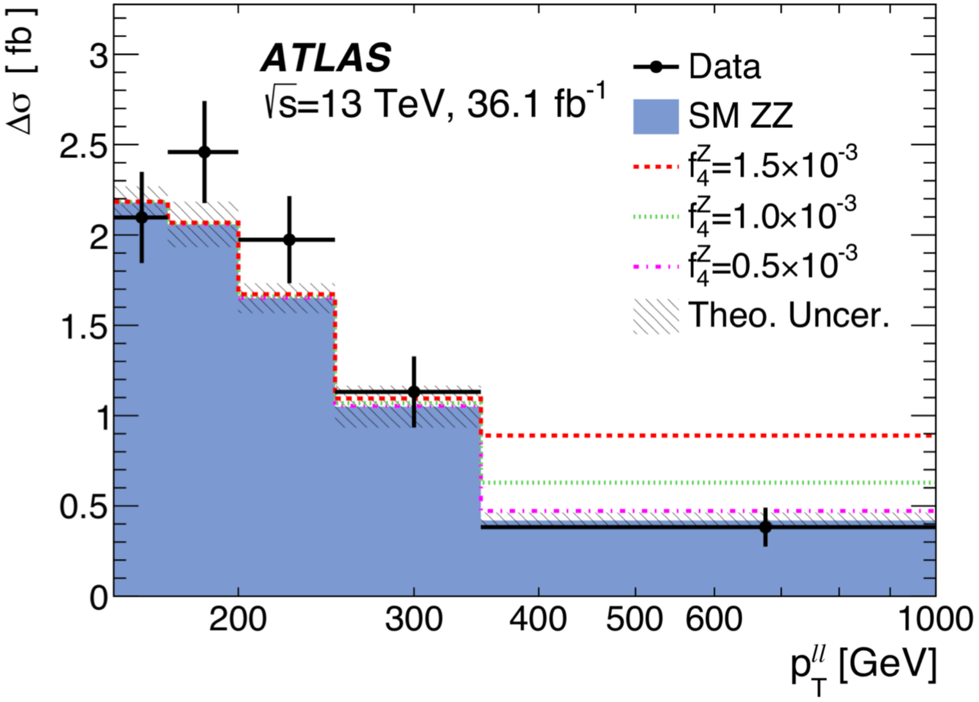
Only transverse observables possible.
Good agreement with NNLO calculations.

MANCHESTER
1824

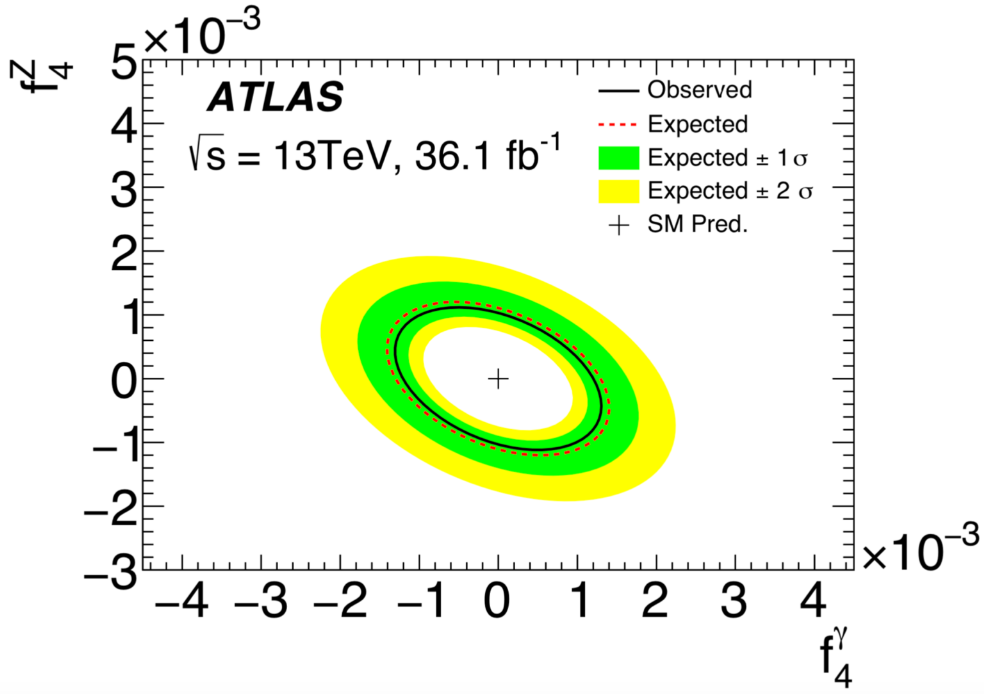
arXiv:1905.04242

ZZ -> llvv

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = ll νν



- Search for TGC:
  Fit unfolded p_T(ll) distribution.
- Sensitivity dominated by last bin.

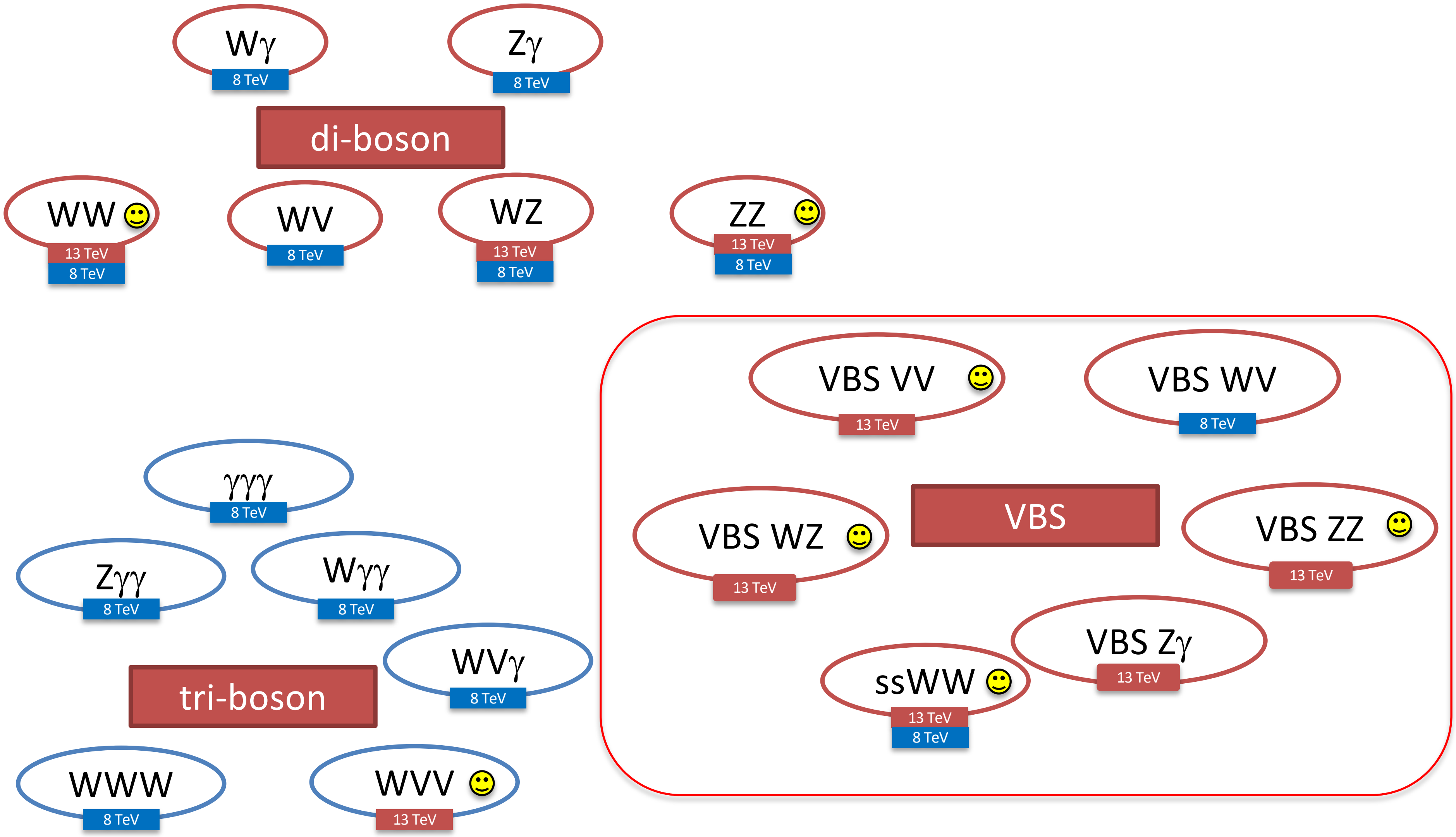


- Competitive limits on neutral aTGC parameter f^4_γ f^5_γ f^4_Z f^5_Z

Experimental status: multi boson production

Q

M



di-boson

Wγ 8 TeV

Zγ 8 TeV

WW ☺ 13 TeV 8 TeV

WV 8 TeV

WZ 13 TeV 8 TeV

ZZ ☺ 13 TeV 8 TeV

tri-boson

γγγ 8 TeV

Zγγ 8 TeV

Wγγ 8 TeV

WVγ 8 TeV

WWW 8 TeV

WVV ☺ 13 TeV

VBS

VBS VV ☺ 13 TeV

VBS WV 8 TeV

VBS WZ ☺ 13 TeV

VBS ZZ ☺ 13 TeV

VBS Zγ 13 TeV

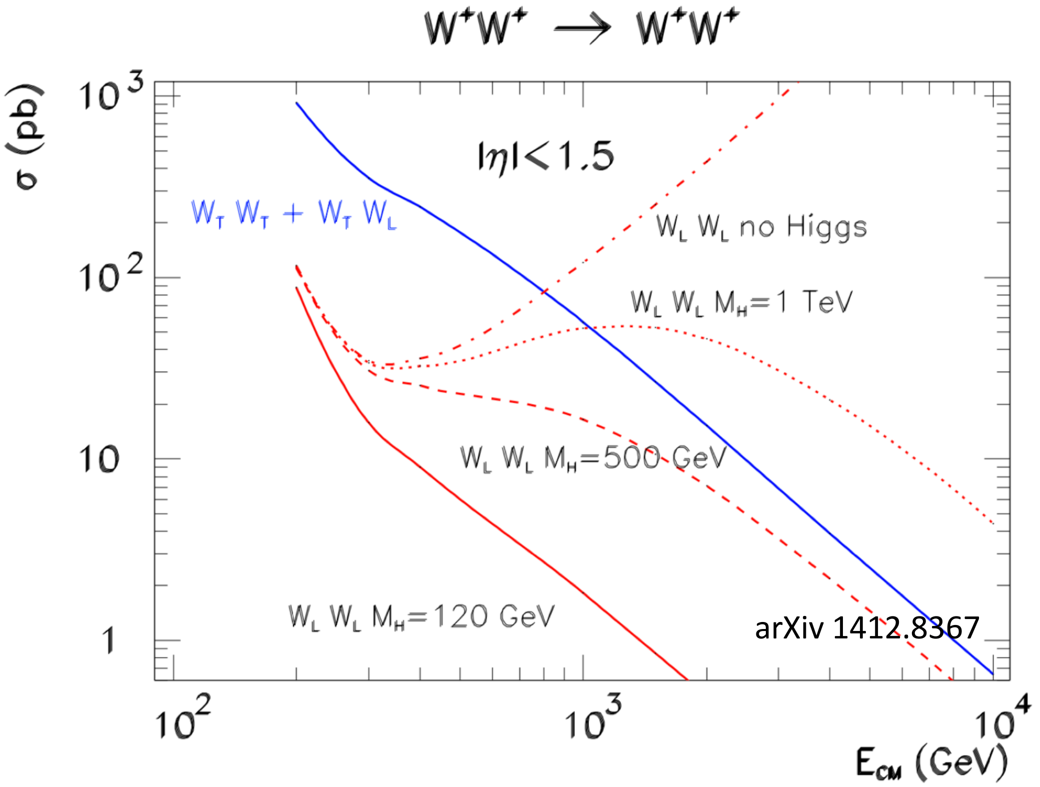
ssWW ☺ 13 TeV 8 TeV

☺: 2019 result

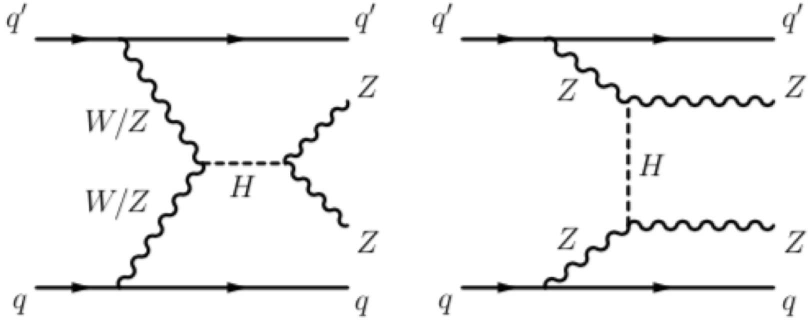
VBS processes

- Higgs needed for renormalizable EWK theory.

- VBS sensitive to diagrams containing Higgs as propagator, leading to cancellation with vector boson diagrams.



arXiv 1412.8367

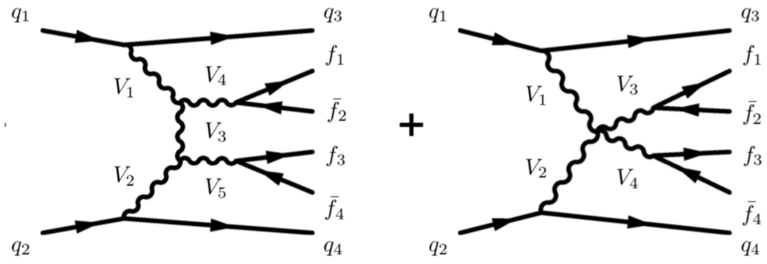


arXiv:1906.03203

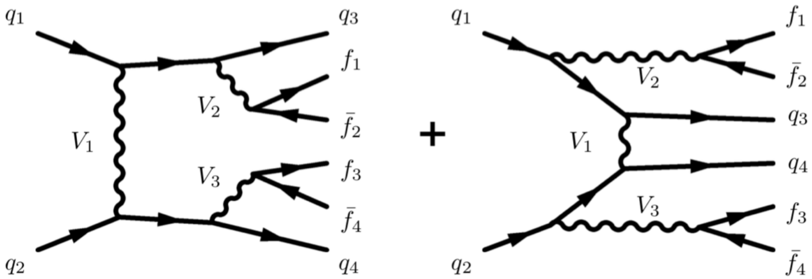
VBS ssWW

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = +l+l qq

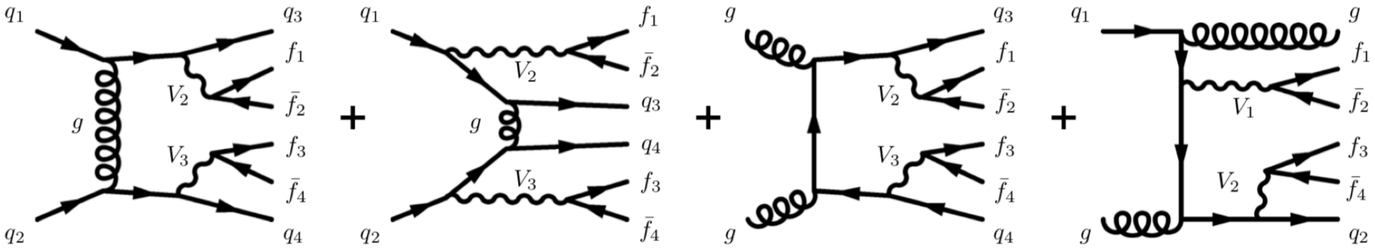
- **Same sign VBS WW cleanest channel for EWK VBS di-boson production.**
  - Absence of many SM backgrounds compared to opposite sign (s-channel).
  - Absence of gg and qg initial state QCD production.
  - **Highest EWK scattering fraction of all VBS processes.**



O(6) in EWK, TGC & QGC

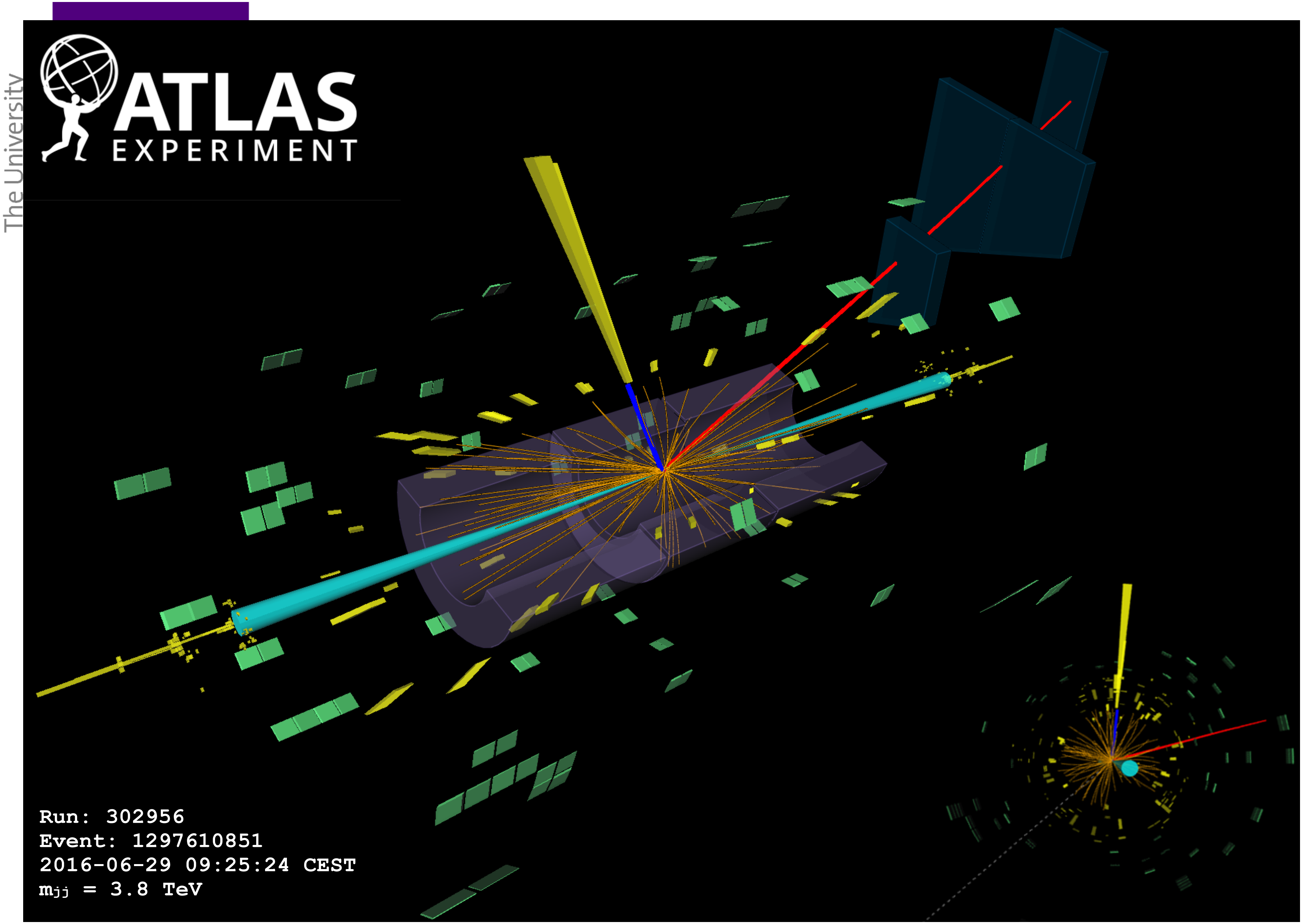


EWK w/o scattering



QCD production

Interference between EWK and QCD production assigned as sys uncertainty



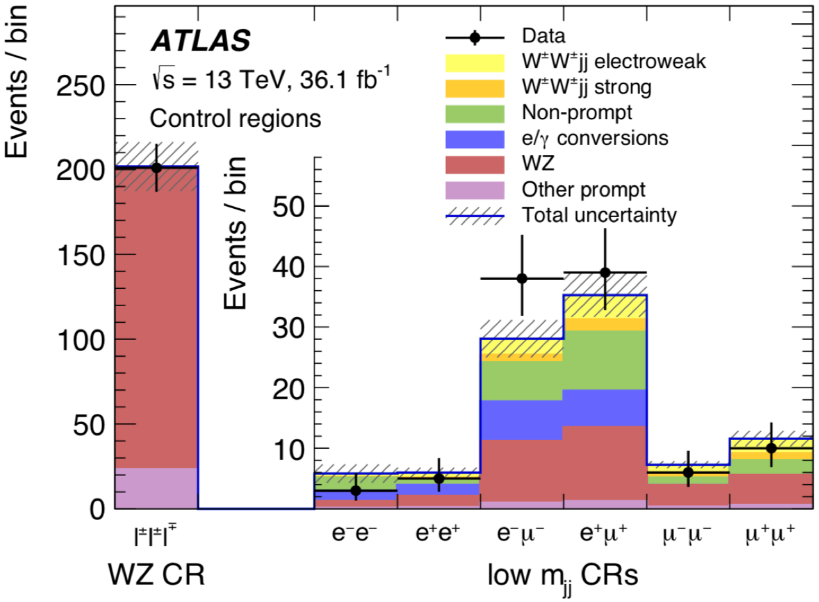
An electroweak $W^{\pm}W^{\pm}jj$ candidate event. The jets have $p_{\mathrm{T}}=118$ GeV and $p_{\mathrm{T}}=104$ GeV, with $m_{jj}=3.8$ TeV and $\Delta y_{jj}=7.1$.

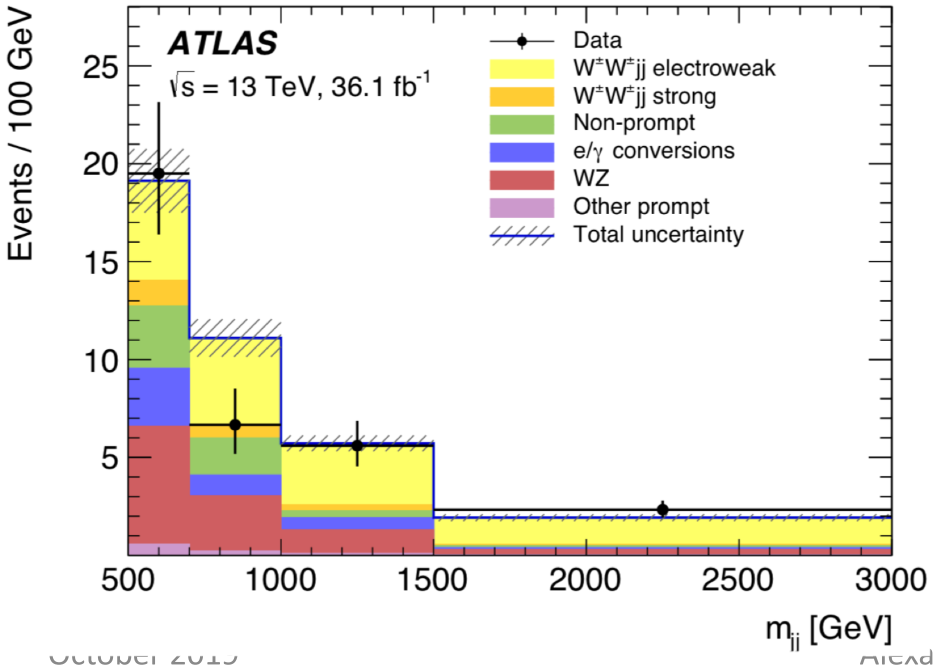
arXiv:1906.03203

VBS ssWW

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = +l+l qq

- Fit different **flavour/charge combinations** separately: different background compositions.
- Constrain **WZjj** from data.





- **Fiducial region:**
  2 same sign leptons and
  2 jets with
  $p_{t,j}$>65(35)GeV
  $|\Delta Y_{jj}| > 2$
  m_{jj} > 500GeV

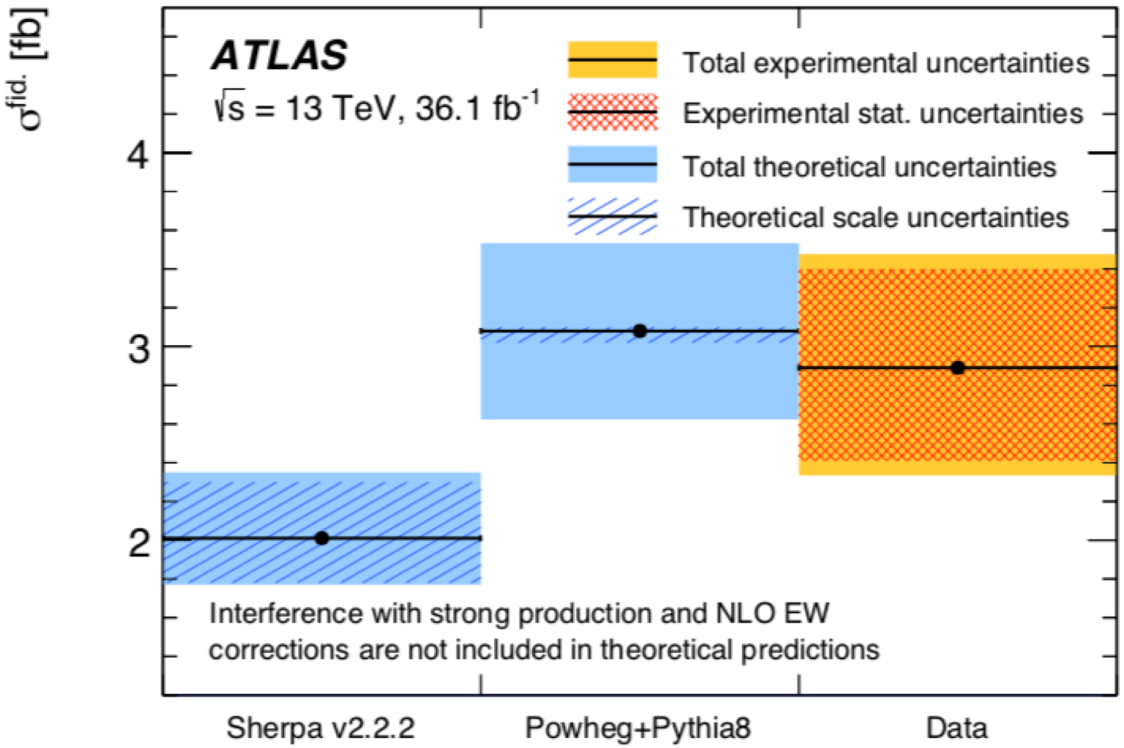
arXiv:1906.03203

VBS ssWW

sqrt(s) = 13 TeV
L = 36.1 fb^{-1}
FS = +l+l qq

- **Results**: Fiducial cross section

$$\sigma^{\text{fid.}} = 2.89^{+0.51}_{-0.48}\ (\text{stat.})^{+0.24}_{-0.22}\ (\text{exp. syst.})^{+0.14}_{-0.16}\ (\text{mod. syst.})^{+0.08}_{-0.06}\ (\text{lumi.})\ \text{fb}$$



Sherpa: $2.01^{+0.33}_{-0.23}$ fb

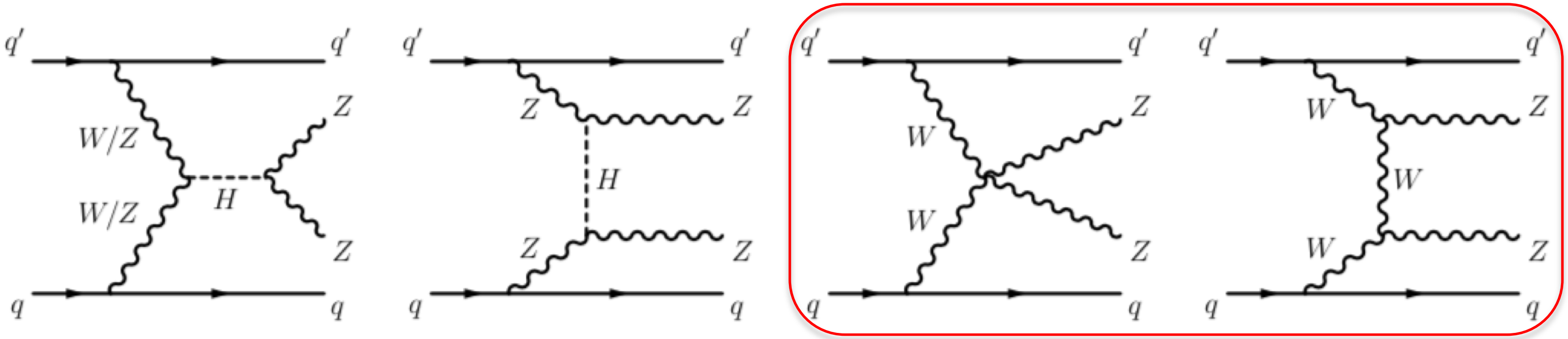
Powheg+Pythia8: $3.08^{+0.45}_{-0.46}$ fb

ATLAS-CONF-2019-033

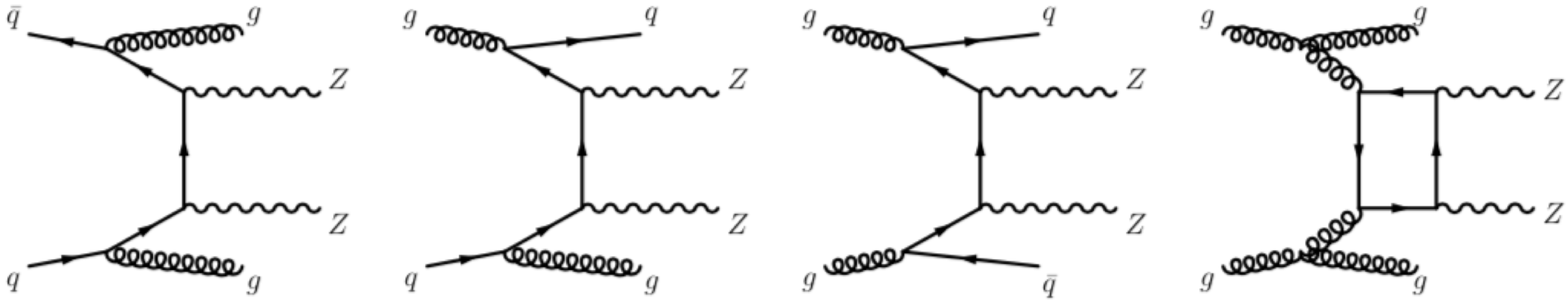
VBS ZZ

sqrt(s) = 13 TeV
L = 139 fb^{-1}
FS = qq ll ll(νν)

- **Full run-2 data-set**
- Final states: **jj ll ll , jj ll νν**
- VBS process with **lowest cross section O(0.1) fb** in fully leptonic final state.
- Observation of EWK process with **EWK VBS enhanced fiducial cross section**



EWK VBS



QCD

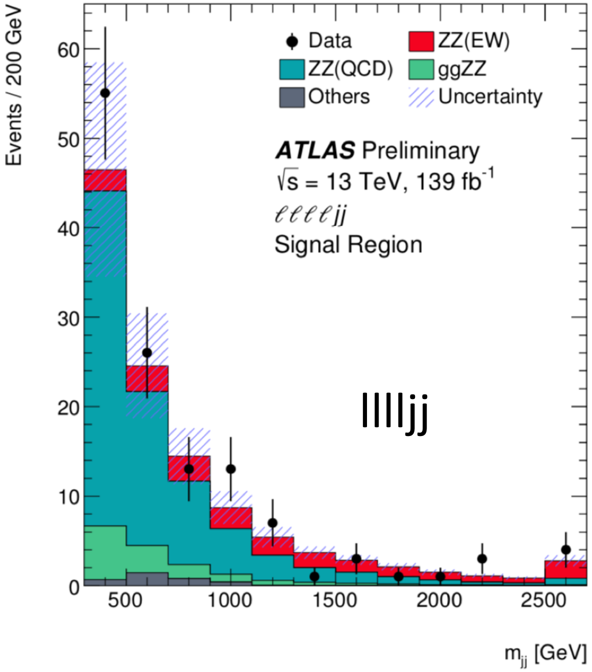
ATLAS-CONF-2019-033

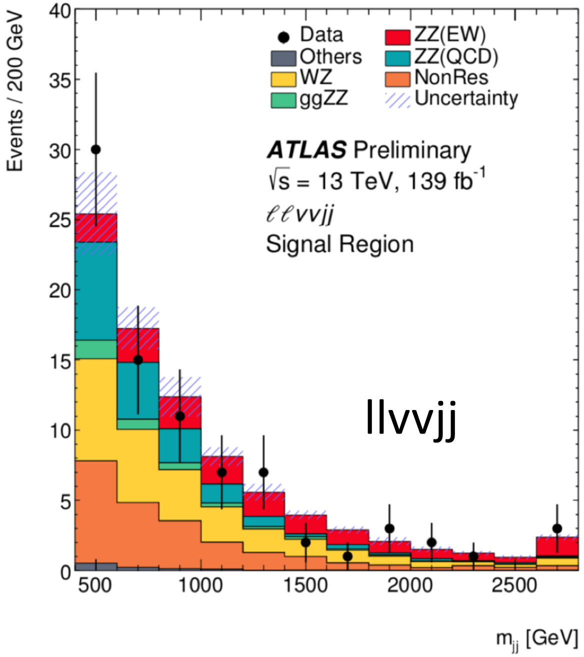
VBS ZZ

sqrt(s) = 13 TeV
L = 139 fb^{-1}
FS = qq ll ll(νν)

- Fiducial region (jj ll ll):
  2 opposite sign same flavour lepton pairs compatible with Z
  $p_{t,j}$> 40(30)GeV
  |ΔYjj| > 2
  m_{jj} > 300GeV
- Fiducial region (jj ll νν):
  2 opposite sign same flavour lepton pairs compatible with Z
  $p_{t,j}$ > 60(40)GeV
  |ΔYjj| > 2
  m_{jj} > 400GeV

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.30 ± 0.65
QCD $ZZjj$	77 ± 25	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.15 ± 0.89
Total	114 ± 26	78.4 ± 6.2
Data	127	82



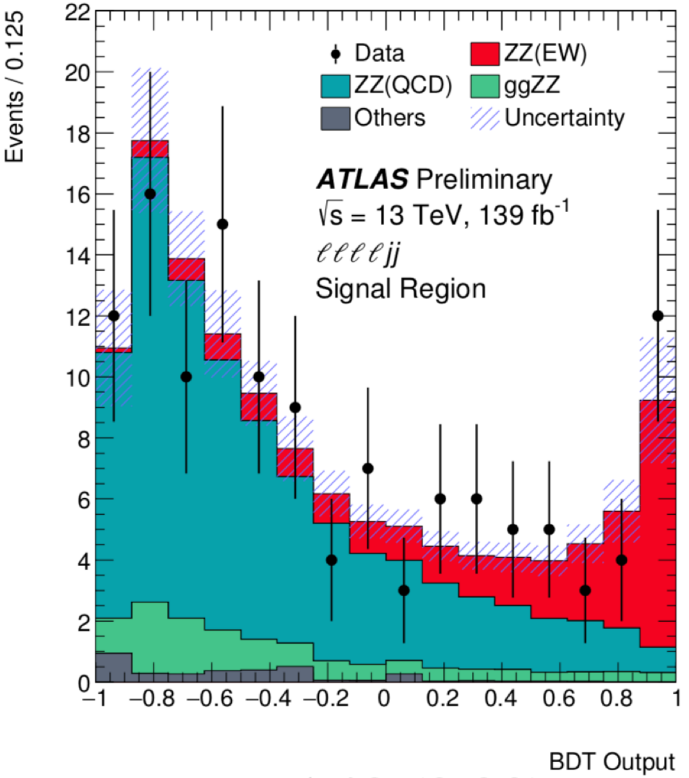


ATLAS-CONF-2019-033

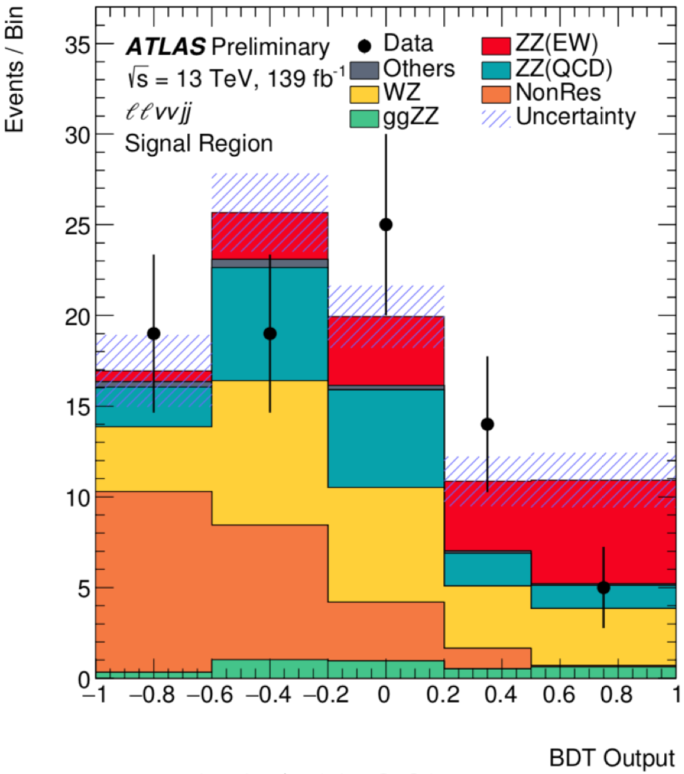
VBS ZZ

sqrt(s) = 13 TeV
L = 139 fb^{-1}
FS = qq ll ll(vv)

- **EWK signal extracted with BDT.**
- BDT discriminant fit simultaneously on both channels.
- QCD CR included
- EWK ZZjj production observed with background only hypothesis rejected at **5.52σ** with 4.30σ expected.
- **First observation!**



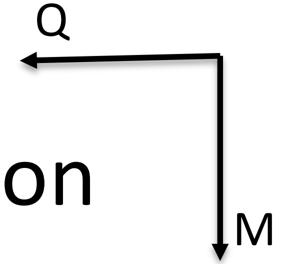
5.48 (3.90) σ



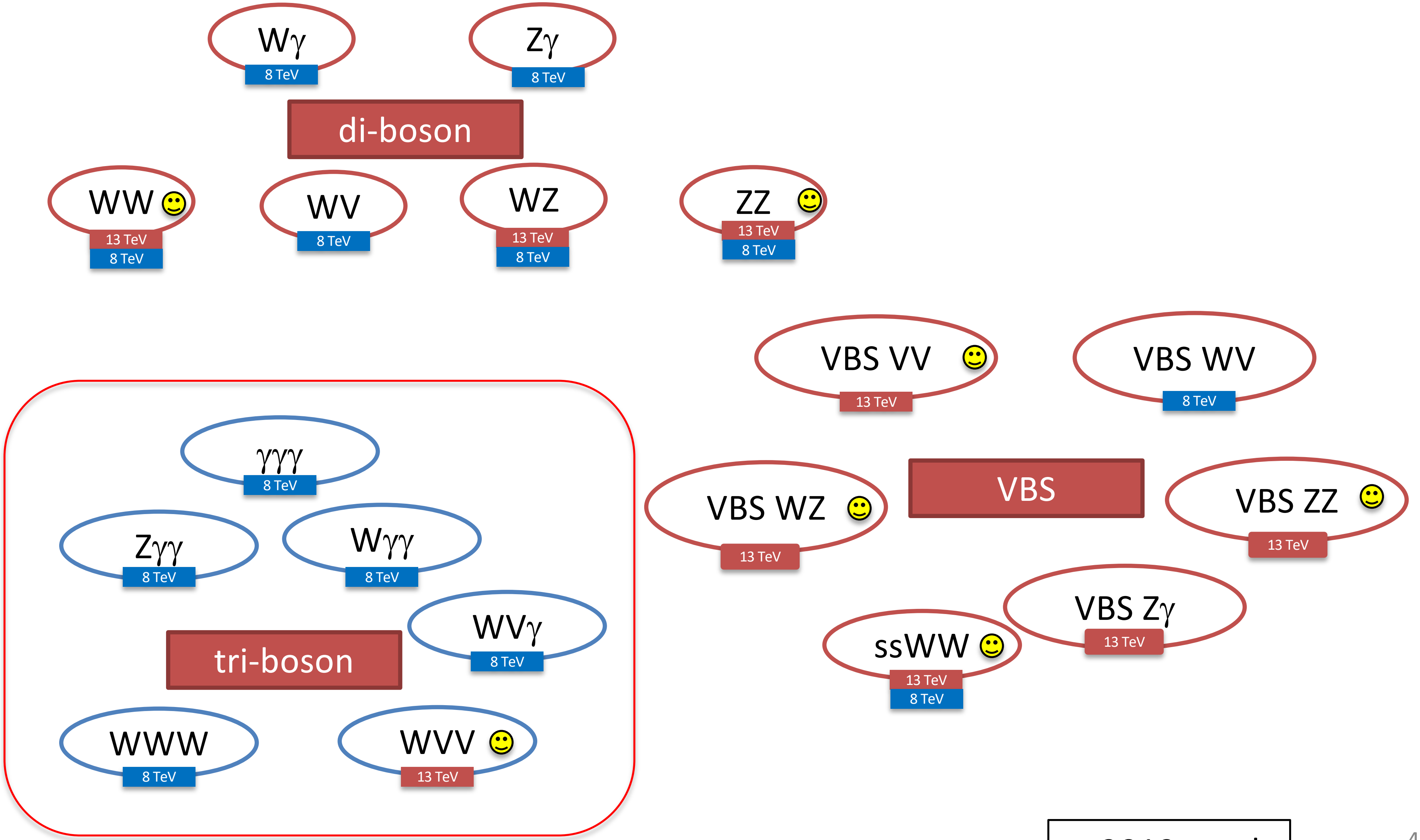
1.15 (1.80) σ

Fiducial cross section :
Exp. 0.61±0.03 fb

$$\sigma^{\text{fid.}}_{ZZjj-\text{EW}} = 0.82 \pm 0.21 \text{ fb}$$



Experimental status: multi boson production



Wγ 8 TeV
Zγ 8 TeV

di-boson

WW ☺ 13 TeV 8 TeV
WV 8 TeV
WZ 13 TeV 8 TeV
ZZ ☺ 13 TeV 8 TeV

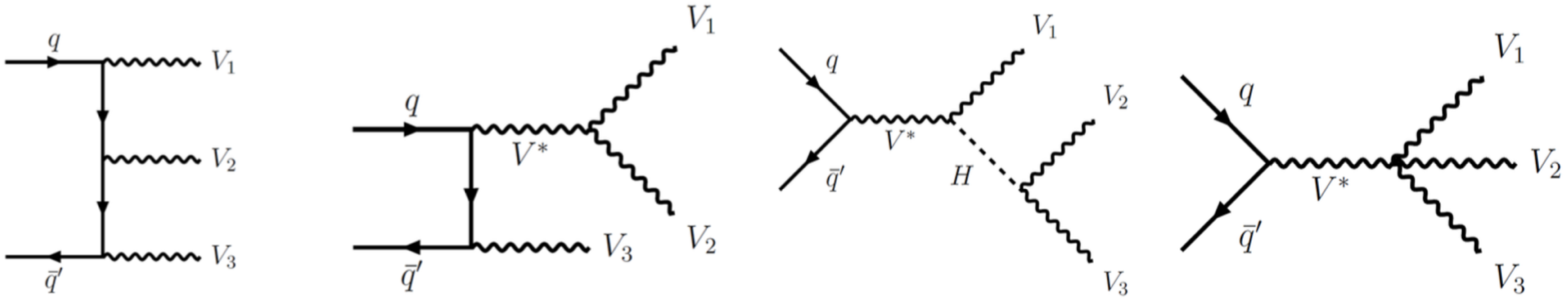
VBS VV ☺ 13 TeV
VBS WV 8 TeV
VBS WZ ☺ 13 TeV
VBS
VBS ZZ ☺ 13 TeV
VBS Zγ 13 TeV
ssWW ☺ 13 TeV 8 TeV

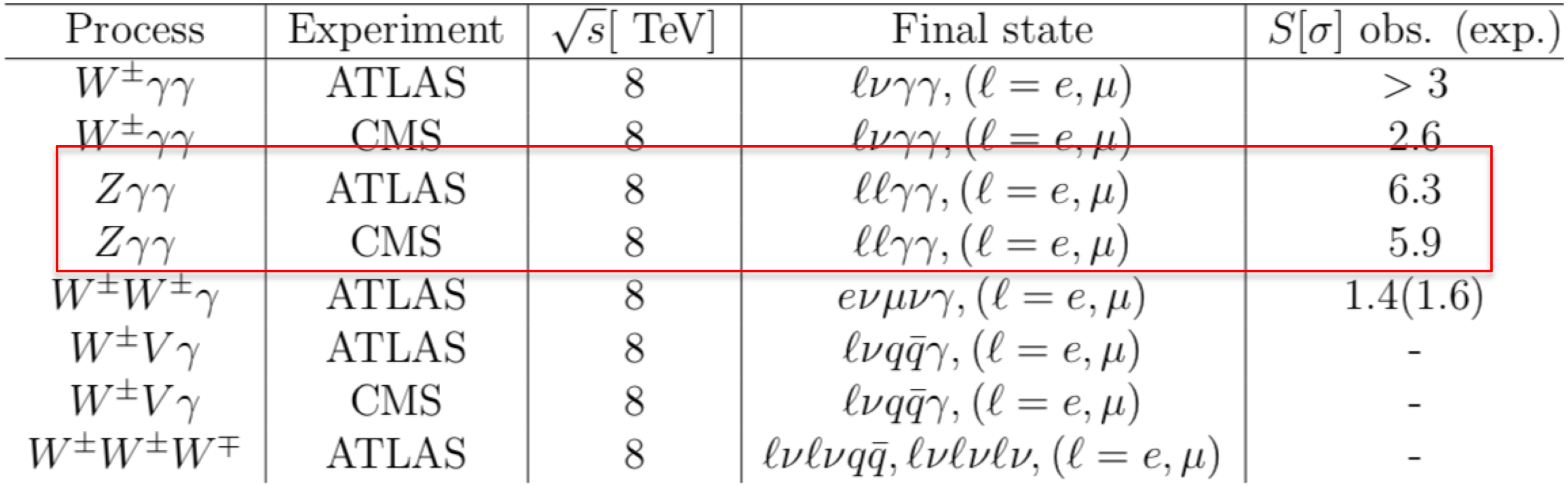
γγγ 8 TeV
Zγγ 8 TeV
Wγγ 8 TeV
WVγ 8 TeV
tri-boson
WWW 8 TeV
WVV ☺ 13 TeV

☺: 2019 result

Triboson processes

- **Rare process, production cross sections O(1 pb).**
- 3 massive vector boson observable at the LHC.
- **Statistically limited, so far observations for few processes only.**
- As for VBS: connecting Higgs sector to EW.





Process	Experiment	$\sqrt{s}$[TeV]	Final state	$S[\sigma]$ obs. (exp.)
$W^{\pm}\gamma\gamma$	ATLAS	8	$\ell\nu\gamma\gamma, (\ell = e, \mu)$	> 3
$W^{\pm}\gamma\gamma$	CMS	8	$\ell\nu\gamma\gamma, (\ell = e, \mu)$	2.6
$Z\gamma\gamma$	ATLAS	8	$\ell\ell\gamma\gamma, (\ell = e, \mu)$	6.3
$Z\gamma\gamma$	CMS	8	$\ell\ell\gamma\gamma, (\ell = e, \mu)$	5.9
$W^{\pm}W^{\pm}\gamma$	ATLAS	8	$e\nu\mu\nu\gamma, (\ell = e, \mu)$	1.4(1.6)
$W^{\pm}V\gamma$	ATLAS	8	$\ell\nu q\bar{q}\gamma, (\ell = e, \mu)$	-
$W^{\pm}V\gamma$	CMS	8	$\ell\nu q\bar{q}\gamma, (\ell = e, \mu)$	-
$W^{\pm}W^{\pm}W^{\mp}$	ATLAS	8	$\ell\nu\ell\nu q\bar{q}, \ell\nu\ell\nu\ell\nu, (\ell = e, \mu)$	-

arXiv:1903.10415

WVV

sqrt(s) = 13 TeV
L = 79.8 fb^{-1}
FS = fully + semi leptonic

- **Combined search for WWW, WWZ and WZZ production**
  - ZZZ smaller cross section, no sensitivity.
- **Consider 2,3 and 4 lepton final states (l=e,μ):**
- **WWW**:
  - semileptonic (**lvlvqq**, same sign l) and leptonic (**lvlvlv**)
  - Cut based, relatively clean signal.
- **WVZ:**
  - semileptonic (**lvqqll, qqllll**) and fully leptonic (**lvlvll**)
  - MVA discriminants.
- **Combine channels with profile likelihood fit including CR for background estimation.**

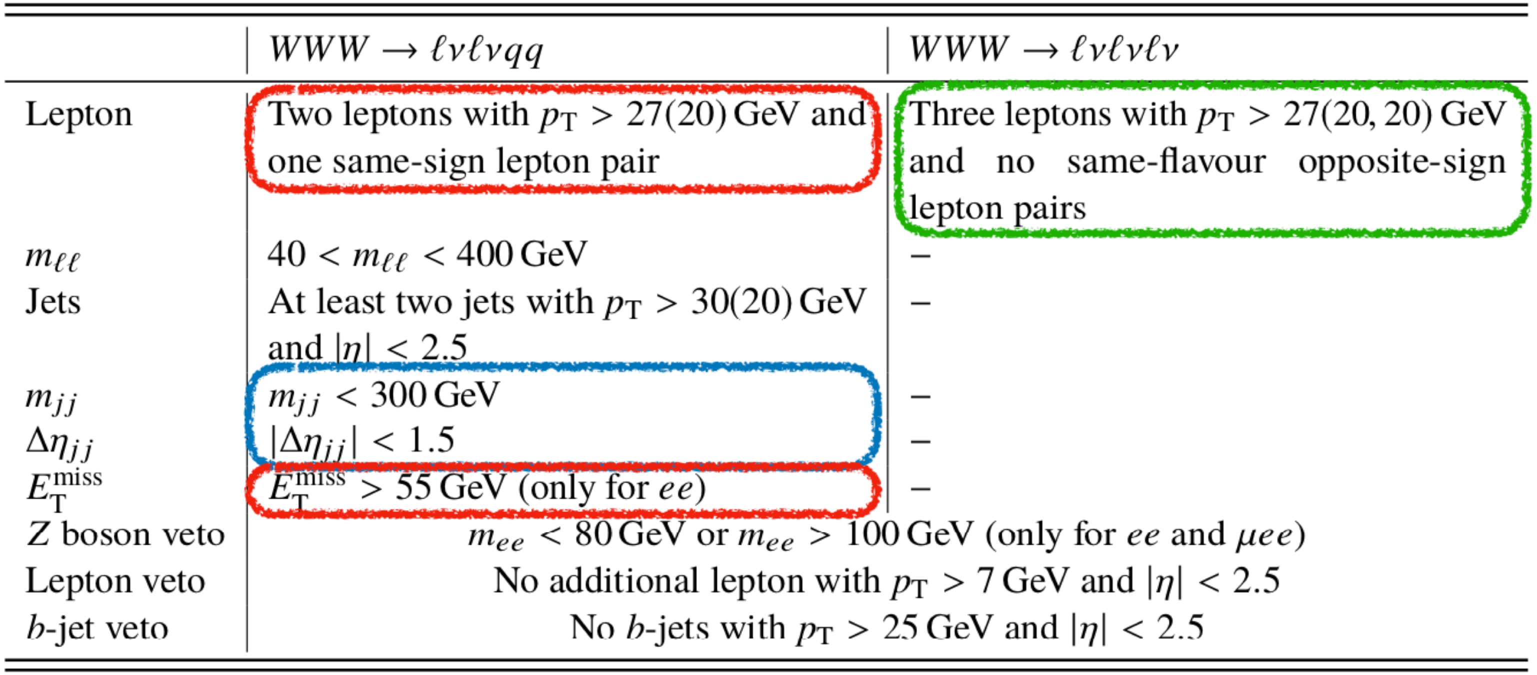
arXiv:1903.10415

WWW

lvlvlv, lvlvqq

sqrt(s) = 13 TeV
L = 79.8 fb^{-1}
FS = fully + semi leptonic

- Dominant background from di-boson production
- Event selection
  - lvlvqq: 2l, same sign, MET, 2 jets
  - lvlvlv: 3 leptons, MET



	$WWW \to \ell\nu\ell\nu qq$	$WWW \to \ell\nu\ell\nu\ell\nu$
Lepton	Two leptons with $p_{\mathrm{T}} > 27(20)$ GeV and one same-sign lepton pair	Three leptons with $p_{\mathrm{T}} > 27(20, 20)$ GeV and no same-flavour opposite-sign lepton pairs
$m_{\ell\ell}$	$40 < m_{\ell\ell} < 400$ GeV	–
Jets	At least two jets with $p_{\mathrm{T}} > 30(20)$ GeV and $\|\eta\| < 2.5$	–
m_{jj}	$m_{jj} < 300$ GeV	–
$\Delta\eta_{jj}$	$\|\Delta\eta_{jj}\| < 1.5$	–
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV (only for ee)	–
Z boson veto	$m_{ee} < 80$ GeV or $m_{ee} > 100$ GeV (only for ee and μee)	
Lepton veto	No additional lepton with $p_{\mathrm{T}} > 7$ GeV and $\|\eta\| < 2.5$	
b-jet veto	No b-jets with $p_{\mathrm{T}} > 25$ GeV and $\|\eta\| < 2.5$	

Suppress *Z* decays

Suppress W±W±

Suppress most 3ℓ backgrounds

from Andrea Sciandra, MBI2019

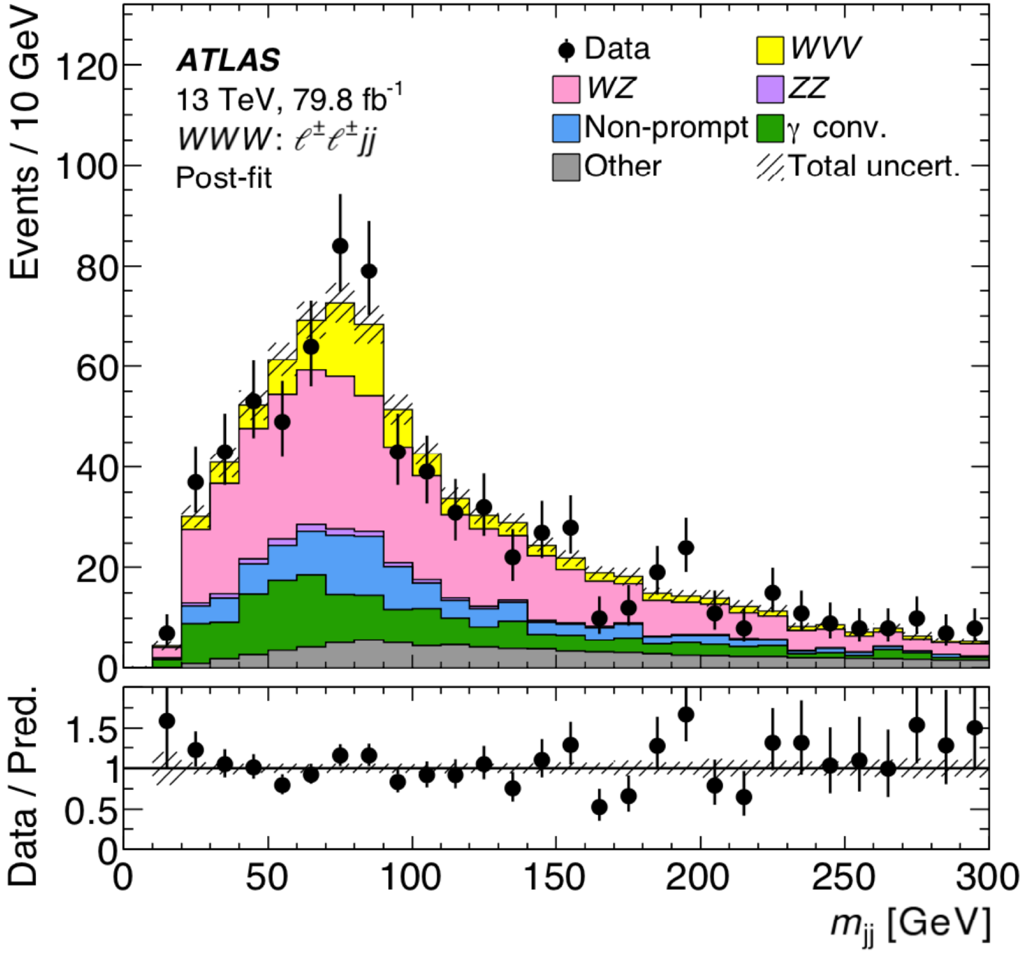
arXiv:1903.10415

WWW

lvlvlv, lvlvqq

sqrt(s) = 13 TeV
L = 79.8 fb^{-1}
FS = fully + semi leptonic

- **Dominant backgrounds:**
  - **WZ**
  - Vγ with γ faking electron
  - Non-prompt from mostly top and W+jets



from Andrea Sciandra, MBI2019

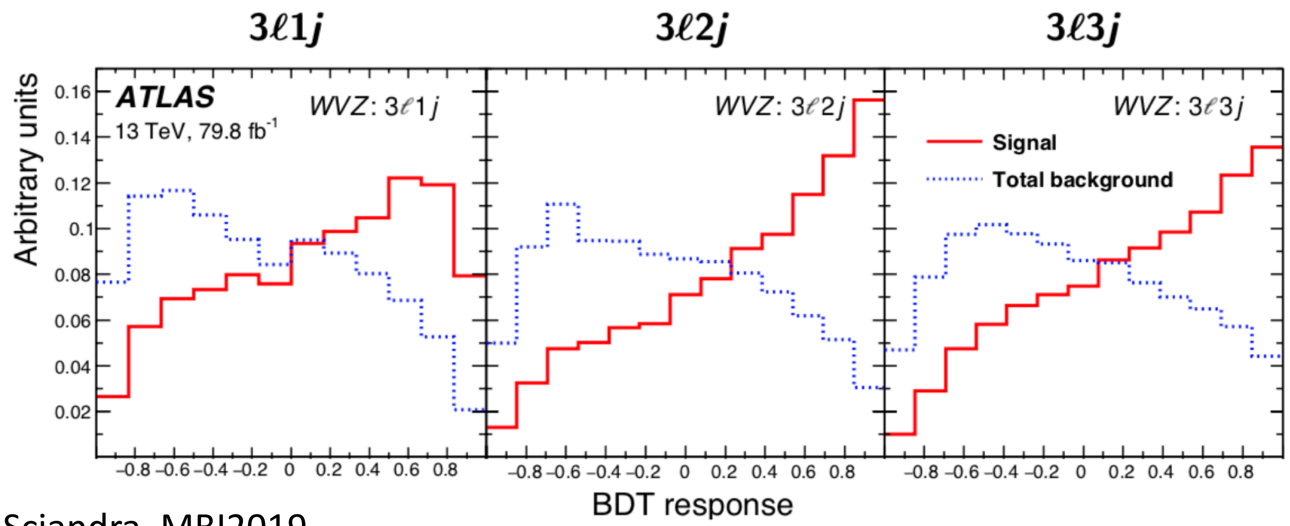
arXiv:1903.10415

WVZ

lvqqll, lvlvll, qqllll

sqrt(s) = 13 TeV
L = 79.8 fb^{-1}
FS = fully + semi leptonic

- **Event selection:**
  - 1 leptonic Z candidate
  - WVZ lvqqll
    - One jet
    - Scalar sum of lepton and jet pt (Ht) > 200 GeV (supresses Z+jets)
    - Split regions by jet multiplicity (3l,1j), (3l2j), (3l3j)
  - WWZ lvll and WZZ qqllll
    - stringent requirements on non-Z leptons (suppresses Z+jets)
    - Split into same flavour and different flavour leptons for non-Z leptons
- **MVA to discriminate against dominating di-boson backgrounds.**
  - invariant mass of event
  - di-jet invariant mass
  - hadronic W candidate mass



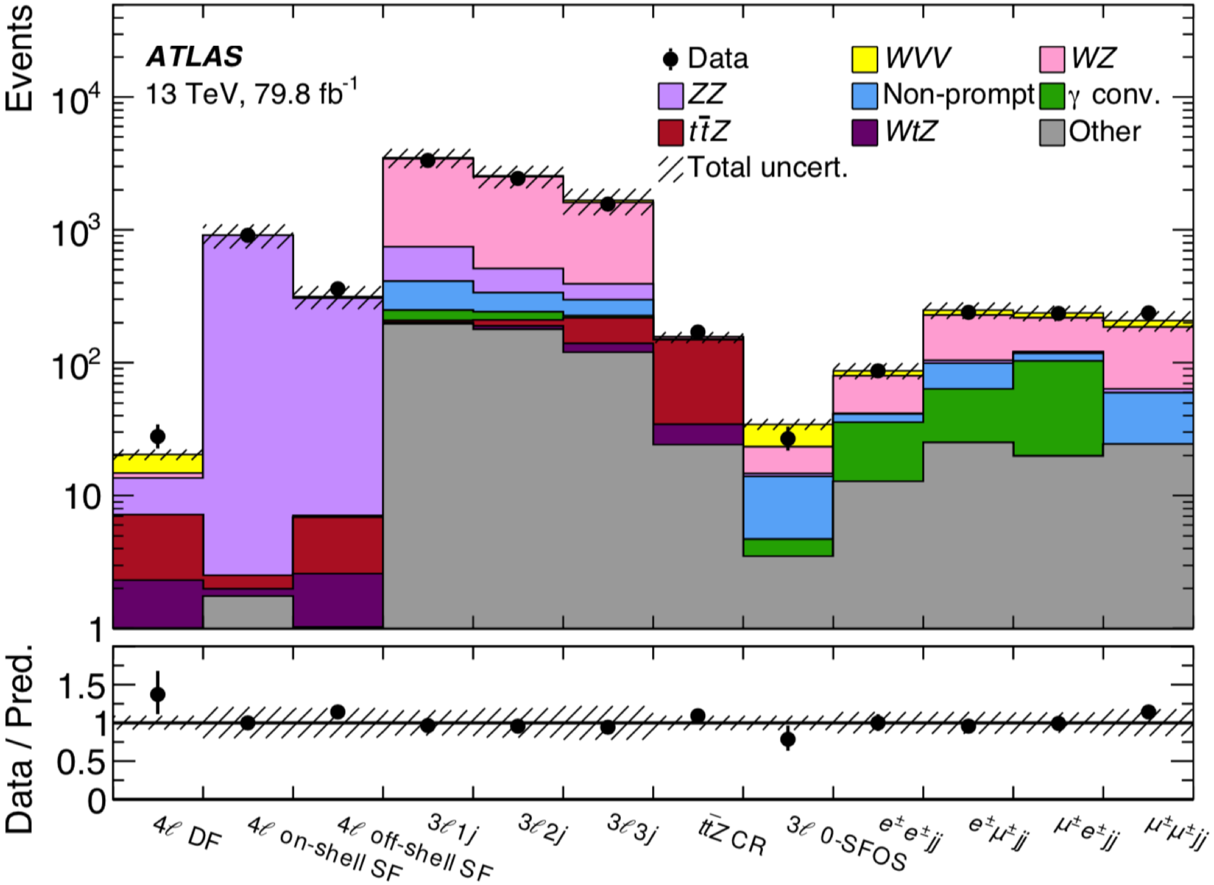
from Andrea Sciandra, MBI2019

arXiv:1903.10415

WWW+WVZ

sqrt(s) = 13 TeV
L = 79.8 fb^{-1}
FS = fully + semi leptonic

- **Signal extraction:**
  - Fit simultaneously all regions
  - Includes CR for **ttZ**
  - total 186 bins
- Correlated:
  - experimental systematics
  - irreducible background



from Andrea Sciandra, MBI2019

arXiv:1903.10415

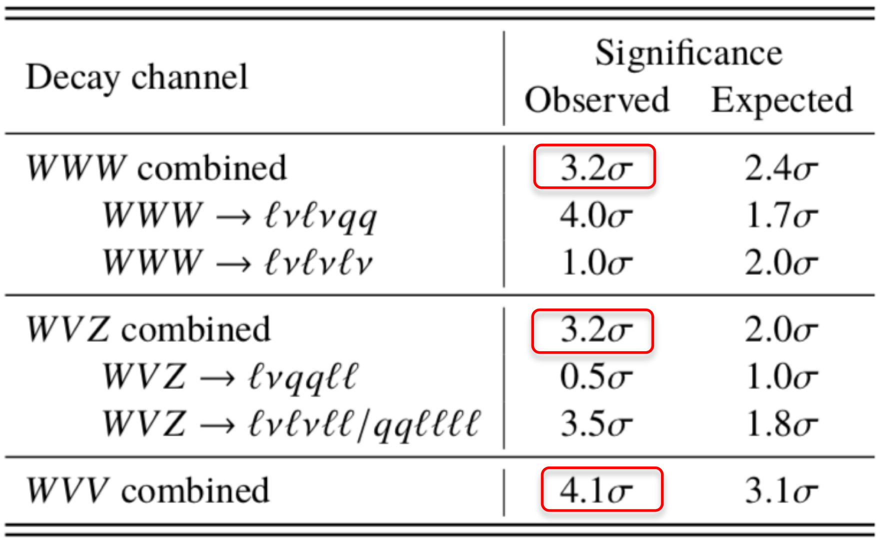
WWW+WVZ

sqrt(s) = 13 TeV
L = 79.8 fb^{-1}
FS = fully + semi leptonic

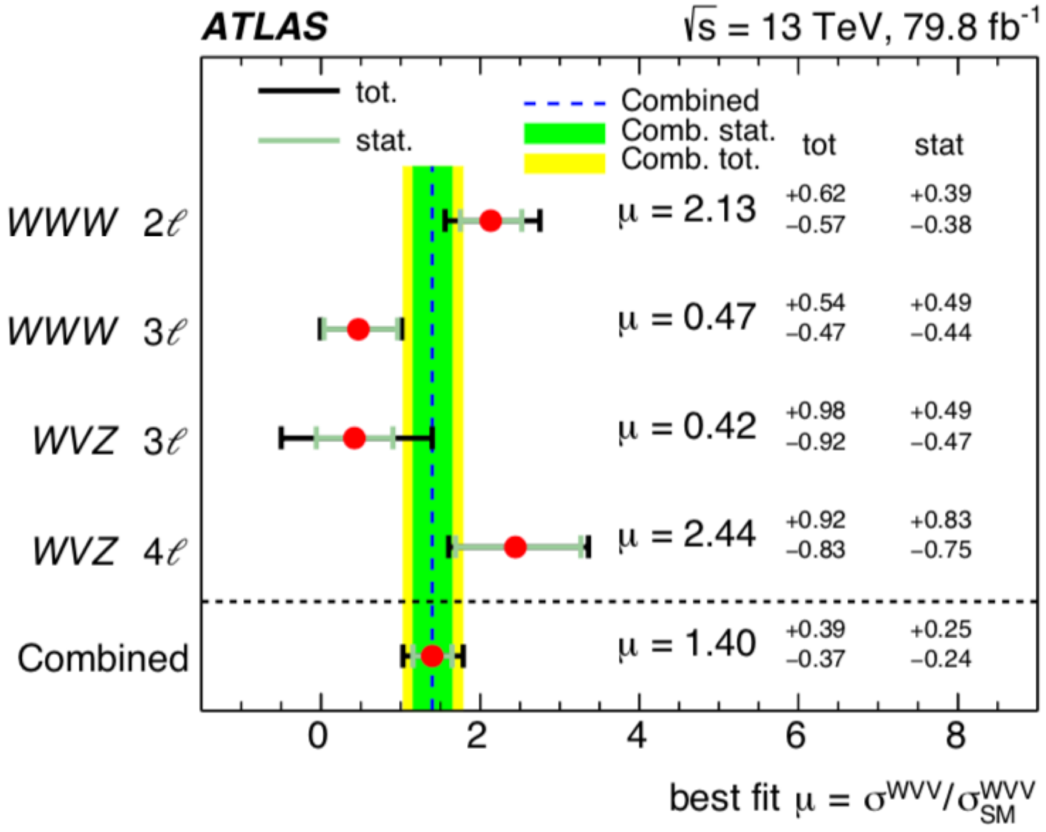
- **Fit result:**

>3σ evidence for WWW and WVZ (2.4σ expected)

>4σ evidence for combined WVV (3.1σ expected)

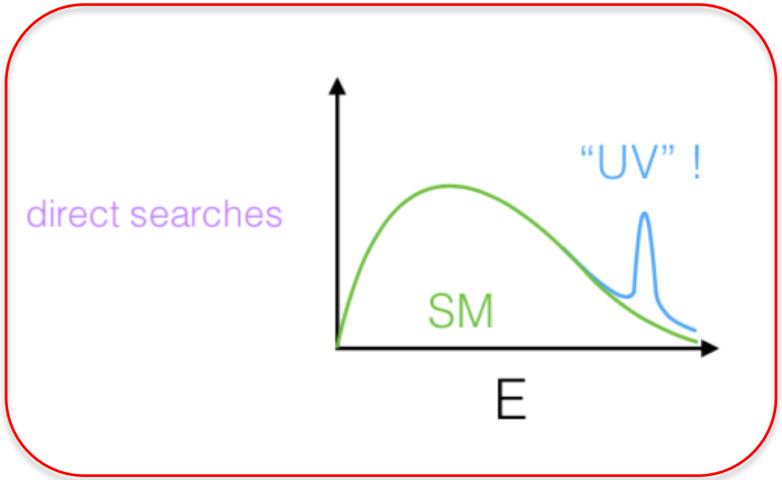


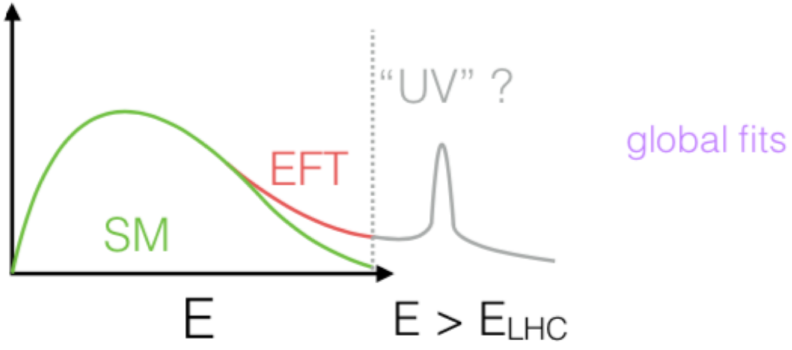
Decay channel	Significance	
	Observed	Expected
WWW combined	3.2σ	2.4σ
$WWW \rightarrow \ell\nu\ell\nu qq$	4.0σ	1.7σ
$WWW \rightarrow \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	3.2σ	2.0σ
$WVZ \rightarrow \ell\nu qq\ell\ell$	0.5σ	1.0σ
$WVZ \rightarrow \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
WVV combined	4.1σ	3.1σ



Search for Di-boson resonances

- Direct probe of **new physics** by looking at narrow resonance in the di-boson invariant mass spectrum.
- **Complementary strategy to EFT limits.**





Theoretical Framework

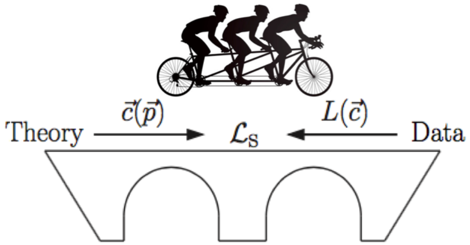
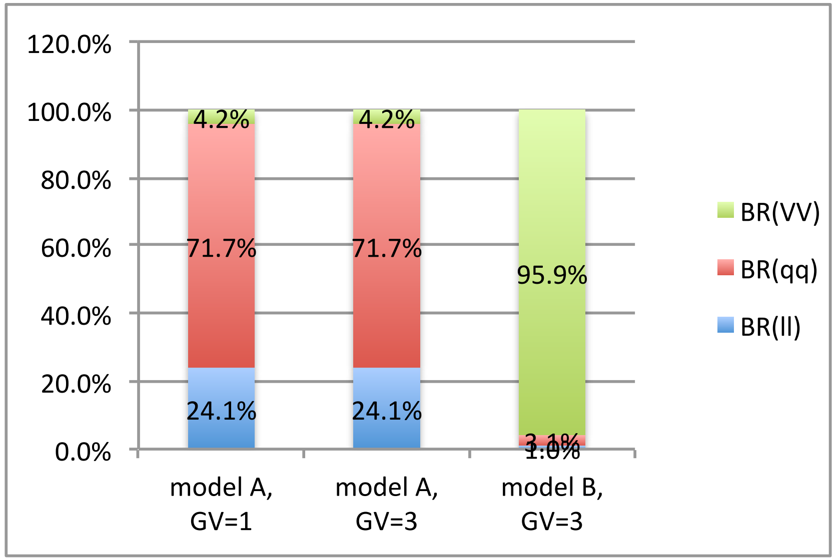
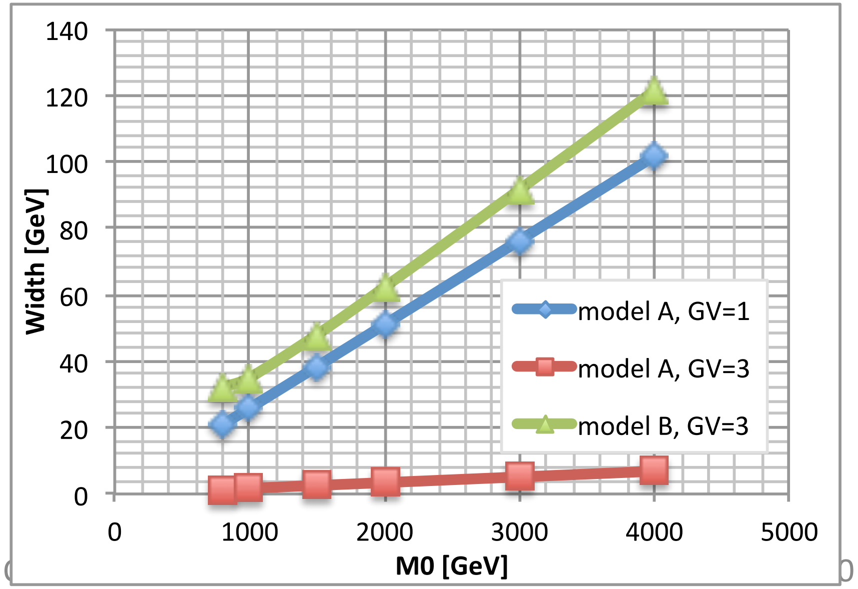


Figure 1.1: Pictorial view of the Bridge Method.

- [Heavy Vector Triplet](#)
  arXiv:1402.4431v2
  - Effective Lagrangian with additional fields $V^{+,0,-}$.
  - Can tune mass, couplings to fermions and bosons.
  - Two benchmark scenarios
    - **A**: weakly coupled extended gauge symmetry
    - **B**: strongly coupled minimal composite higgs model



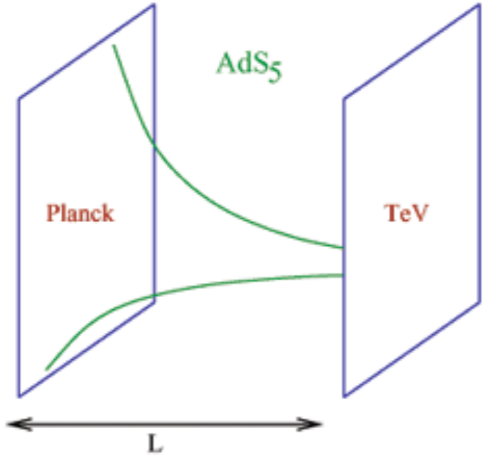


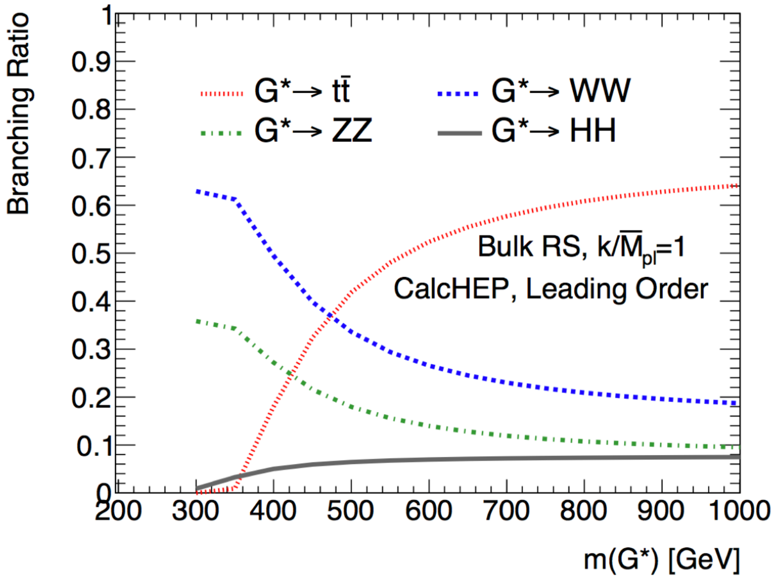
Theoretical Framework

- **“bulk” RS graviton with warped extra dimension**

  Phys.Rev.D76:036006,2007

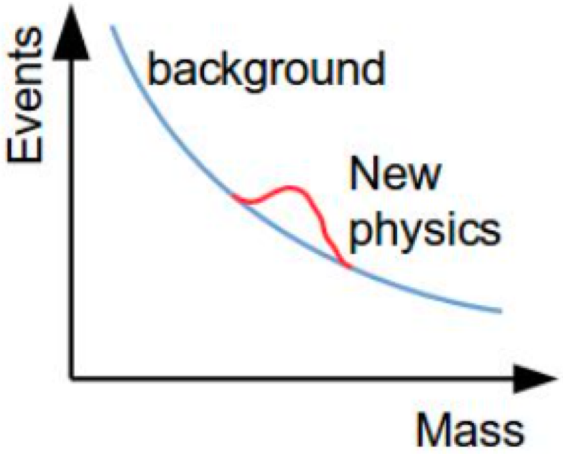
  – Extension of KK graviton in RS1 framework with SM particles extending into the “bulk”.
  – Couplings to light fermions suppressed.
  – gg fusion dominant production channel.
  – High BR of G* VV.



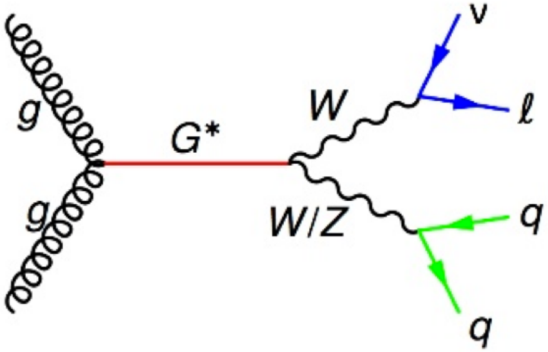


Techniques

- Search for **narrow** resonances
  - Look for peak in invariant mass spectrum over a smooth background.
  - Experimental mass resolution typically few percent for hadronic decays.
  - Use test statistics for hypothesis testing and derive limits on production cross section times branching ratio.

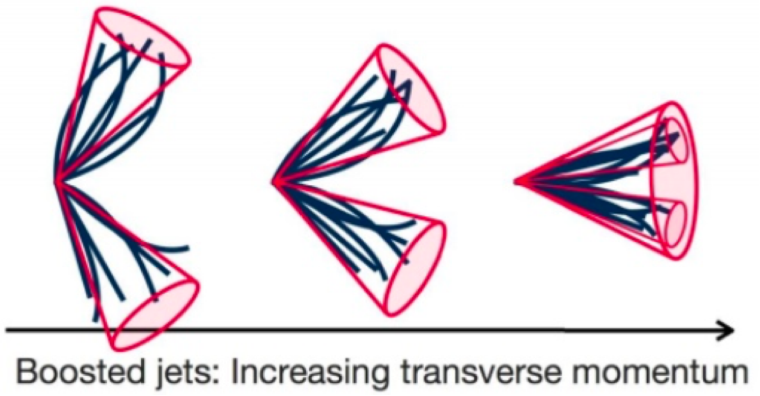


- **Final states**
  - semi-leptonic and hadronic.
    - High BR and acceptable mass resolution.
  - Fully leptonic
    - High mass resolution.

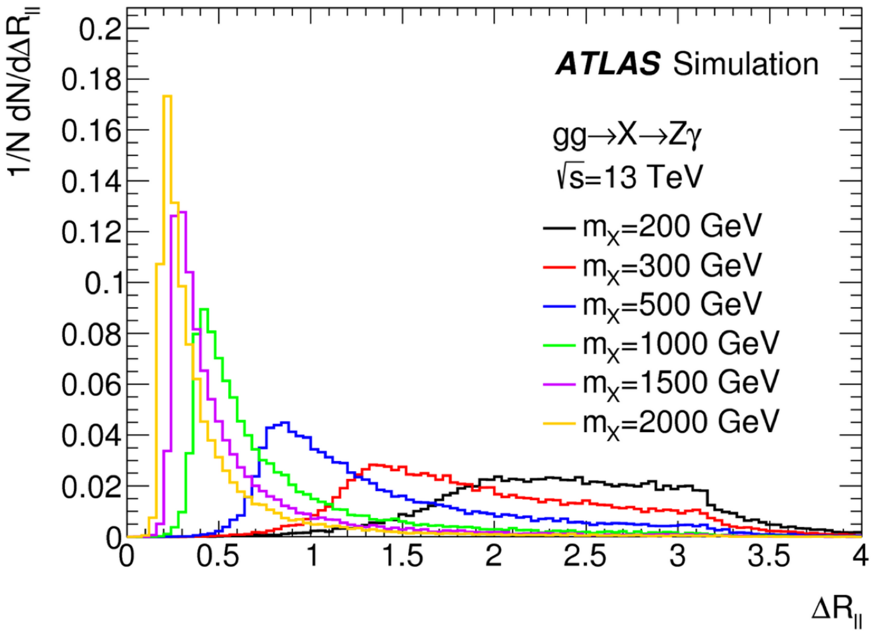


Techniques

- Boosted hadronically decaying bosons.
  - Large R jets



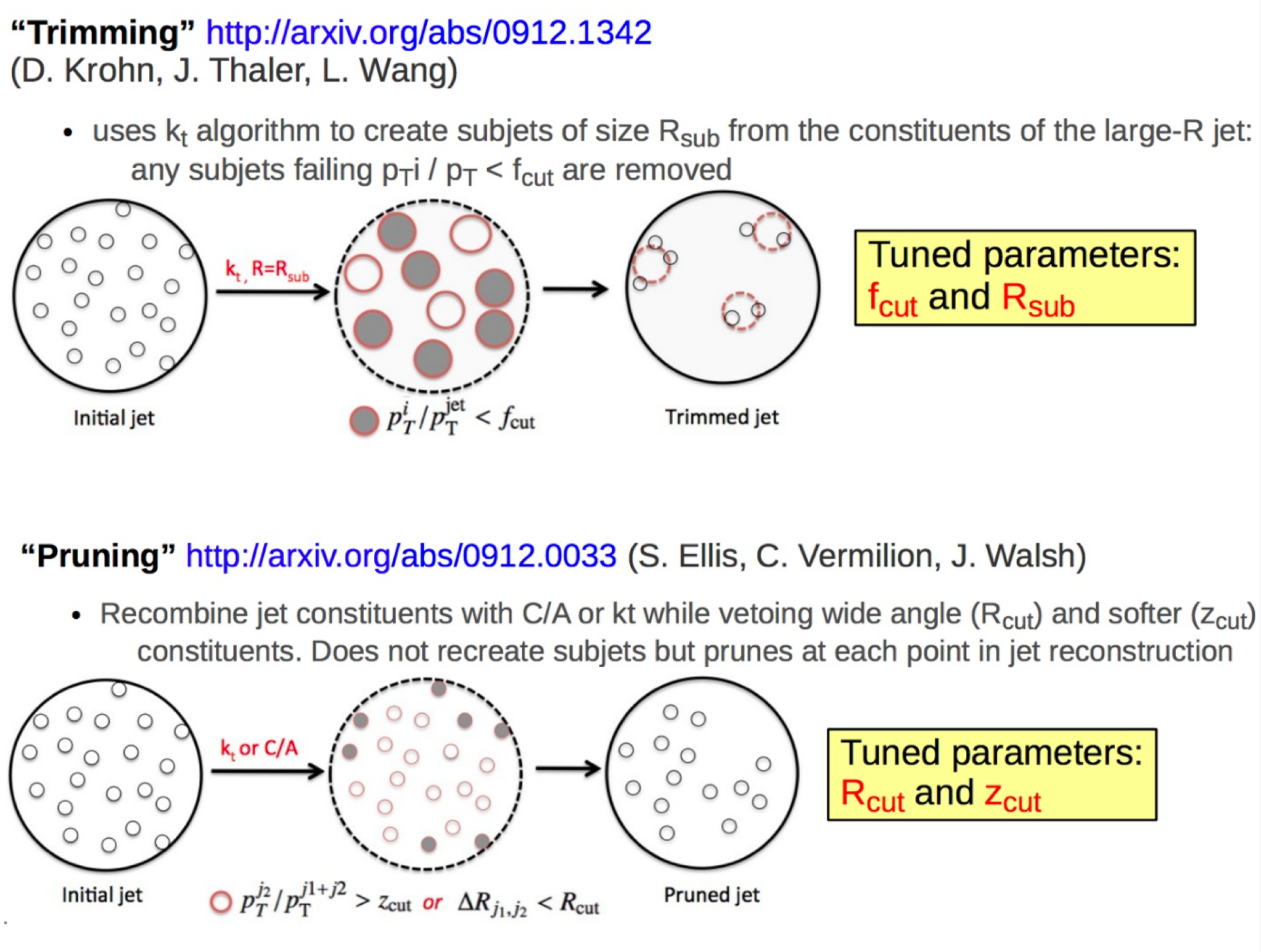
- Boosted leptonically decaying bosons.
  - Isolation cone variations.
  - Di-lepton isolation.



Techniques

Large R jet grooming:

Improve mass resolution by suppressing soft contributions from pile-up underlying event.



"Trimming" http://arxiv.org/abs/0912.1342
(D. Krohn, J. Thaler, L. Wang)

- uses k_t algorithm to create subjets of size R_{sub} from the constituents of the large-R jet: any subjets failing $p_Ti / p_T < f_{cut}$ are removed

Tuned parameters:
f_{cut} and R_{sub}

"Pruning" http://arxiv.org/abs/0912.0033 (S. Ellis, C. Vermilion, J. Walsh)

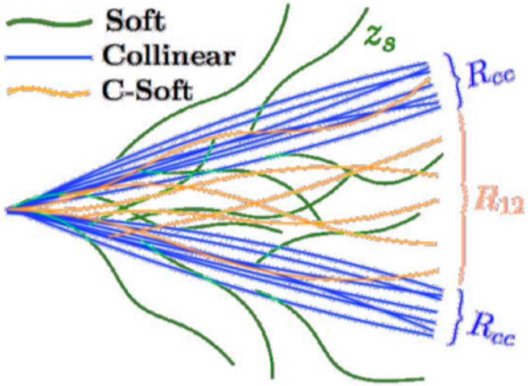
- Recombine jet constituents with C/A or kt while vetoing wide angle (R_{cut}) and softer (z_{cut}) constituents. Does not recreate subjets but prunes at each point in jet reconstruction

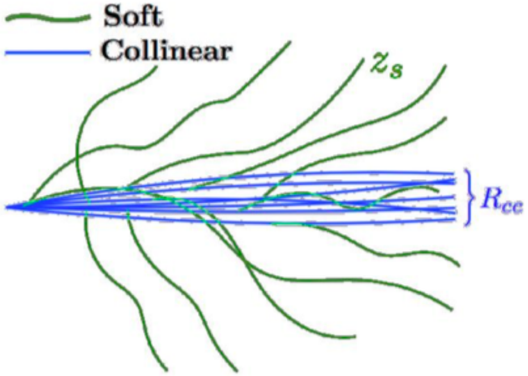
Tuned parameters:
R_{cut} and z_{cut}

Emily Thompson,BOOST2012

Techniques

- **W/Z boson tagging** for merged events
  - Require mass
    - Consistent with Z or W within ±15 GeV).
    - [H->qqbb] pT dependent window, masss computed from calo and tracking information.
  - “D2” substructure variable consistent with 2 prong decay.
- **Higgs boson tagging**
  - Use anti-kT R=0.2 track jets and b-tagging.

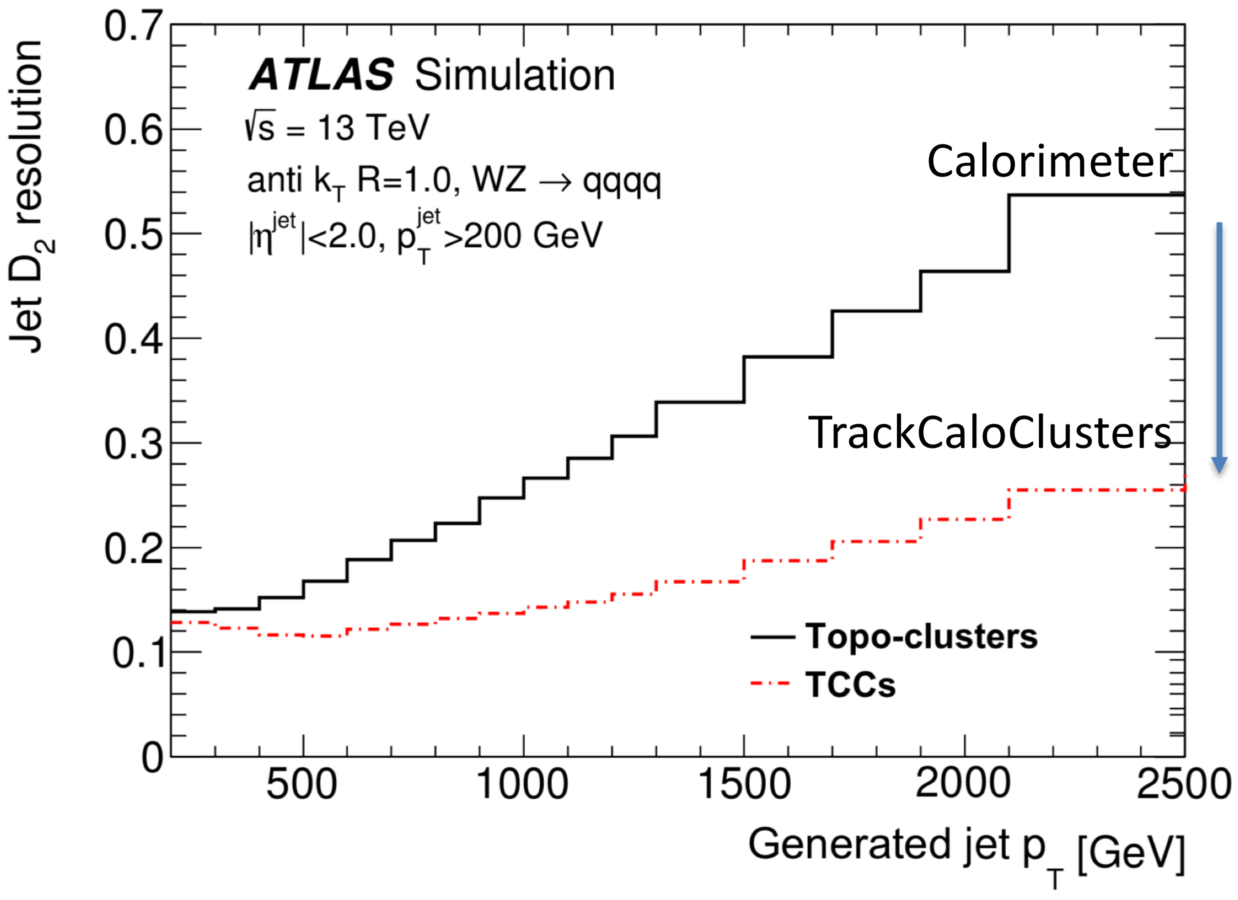


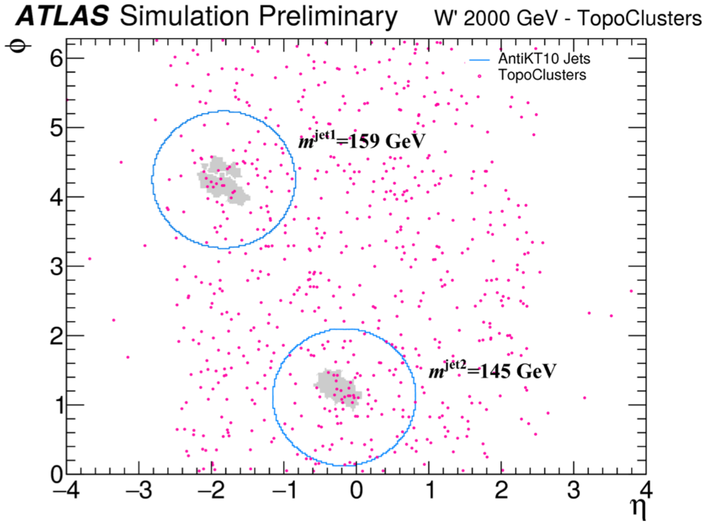


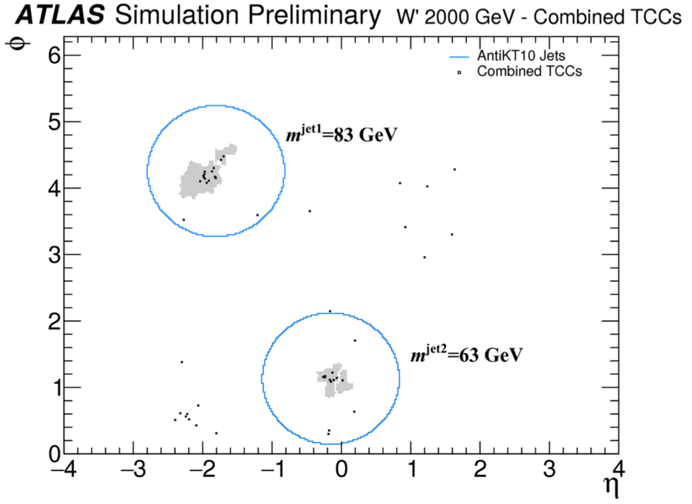
ATL-PHYS-PUB-2017-015

Techniques

- Improve jet resolution by combining tracker and calorimeter information, will be used for full run-2 analysis.

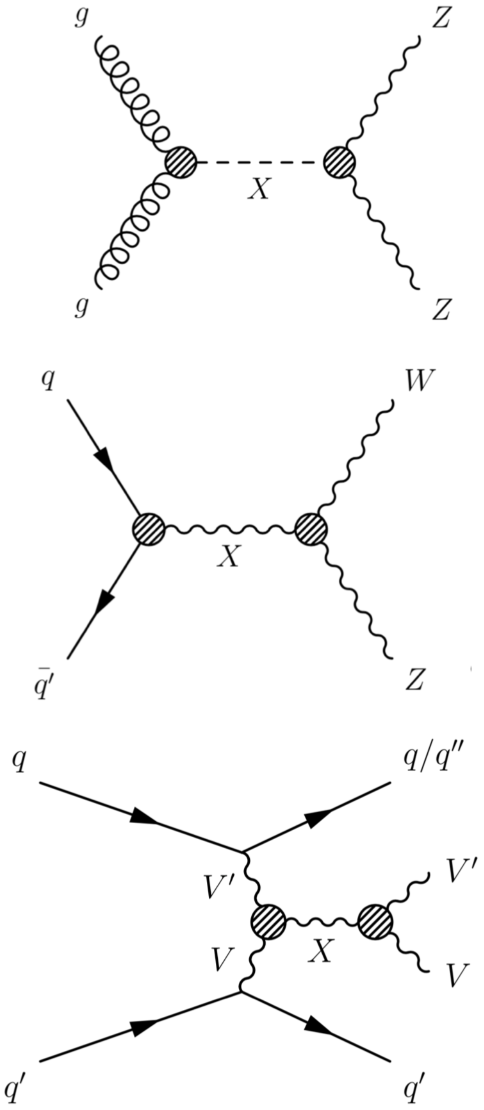






Narrow di-boson resonances

- **Production and decay of heavy resonances:**
  - Drell-Yan production and decay
  - Vector Boson Fusion
  - gluon—gluon fusion
- **Experimental signatures**
  - Semi-leptonic final state
    - vvqq, lvqq, llqq
  - Topologies:
    - Boosted: V->J large-R jet
    - Resolved: V->jj small-R jets
  - **fully hadronic JJ**



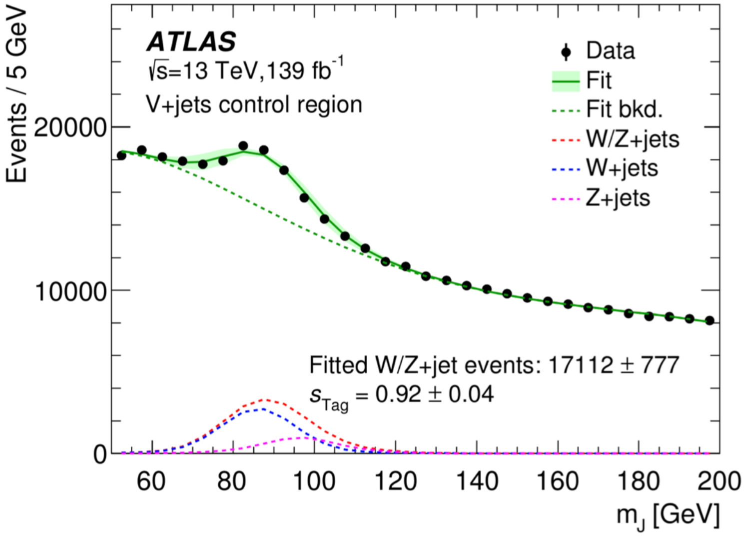
The University of Manchester

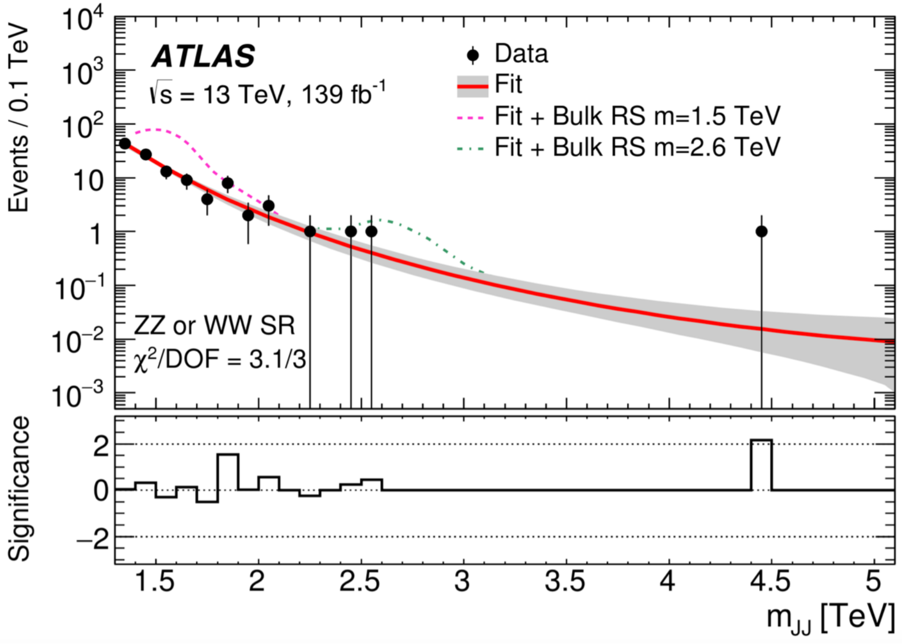
arXiv:1906.08589

VV->JJ resonances

sqrt(s) = 13 TeV
L = 139 fb^{-1}
FS = JJ

- **Fully hadronic final state.**
  - Look for two large R jets, consistent with hadronically decaying W or Z.
  - Sensitive to resonances above about 1.4 TeV





- Bump hunt in invariant mass spectrum.

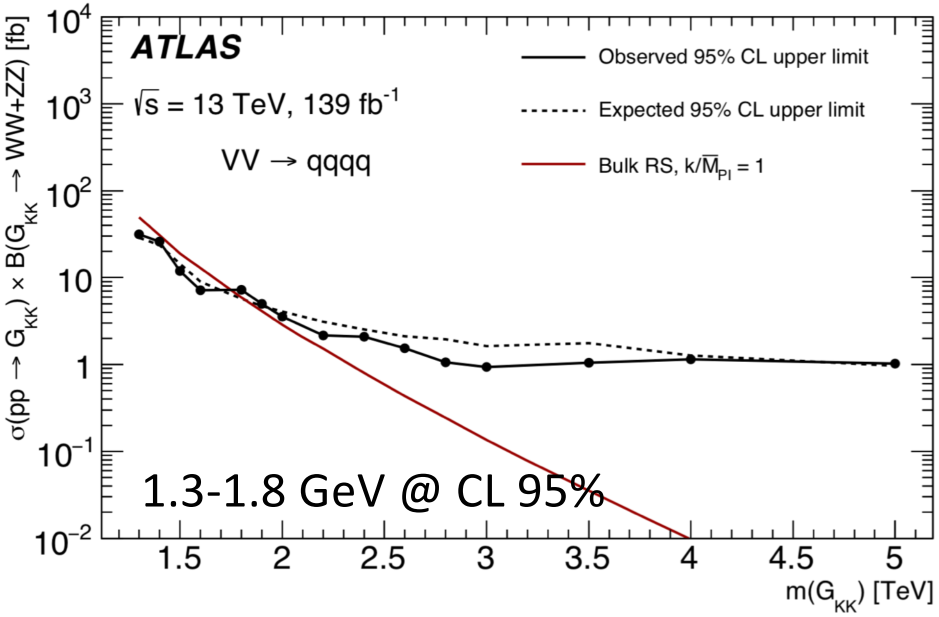
arXiv:1906.08589

VV->JJ resonances

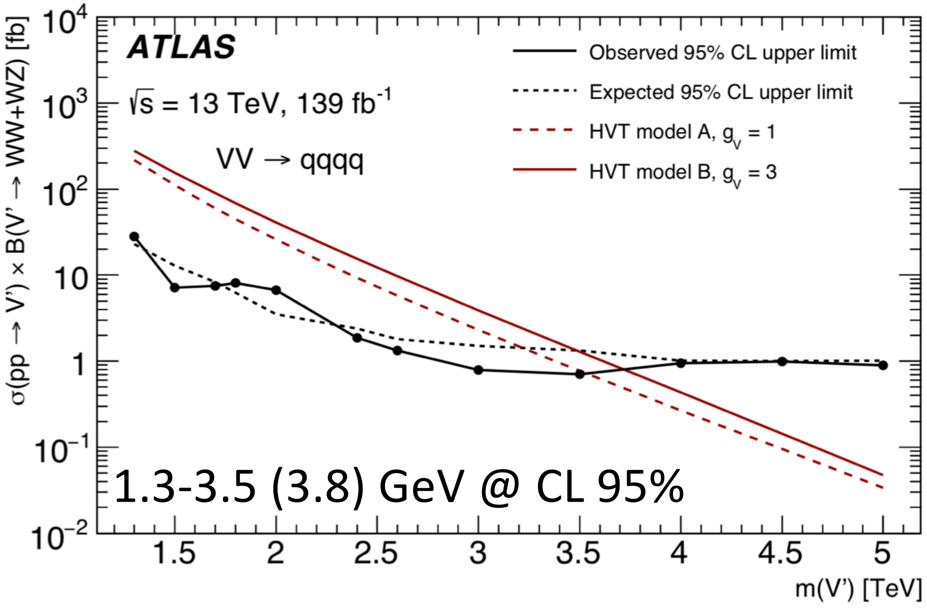
sqrt(s) = 13 TeV
L = 139 fb^{-1}
FS = JJ

- **No excess observed**
- **Limits** on HVT (spin-1) Graviton models (spin-2)
- Competitive limits compared to combination of 36fb^{-1} analysis on (all channels). arXiv:1808.02380

Model	Signal Region	Excluded mass range [TeV]
HVT model A, $g_V = 1$	WW	1.3–2.9
	WZ	1.3–3.4
	$WW + WZ$	1.3–3.5
HVT model B, $g_V = 3$	WW	1.3–3.1
	WZ	1.3–3.6
	$WW + WZ$	1.3–3.8
Bulk RS, $k/\overline{M}_{\rm Pl} = 1$	WW	1.3–1.6
	ZZ	none
	$WW + ZZ$	1.3–1.8



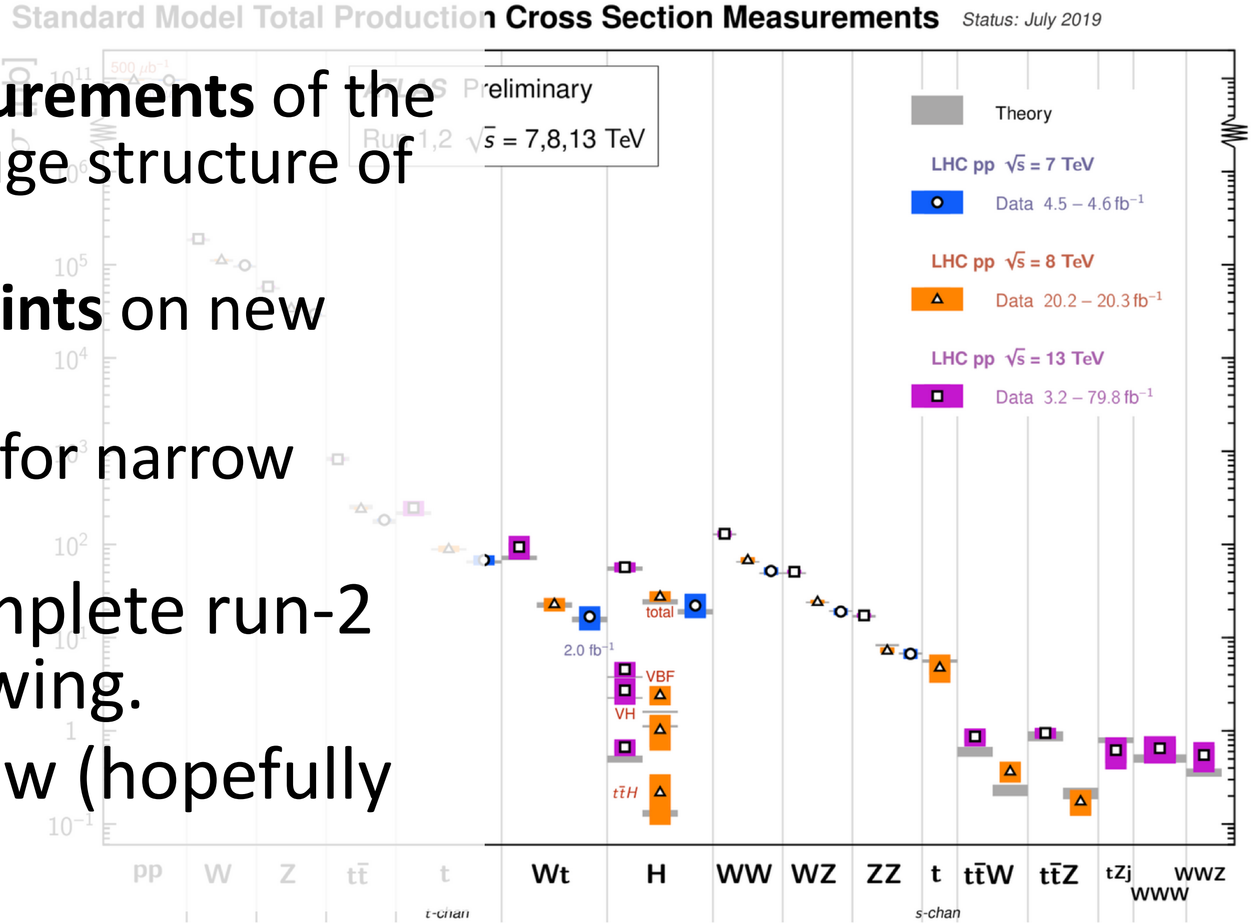
1.3-1.8 GeV @ CL 95%

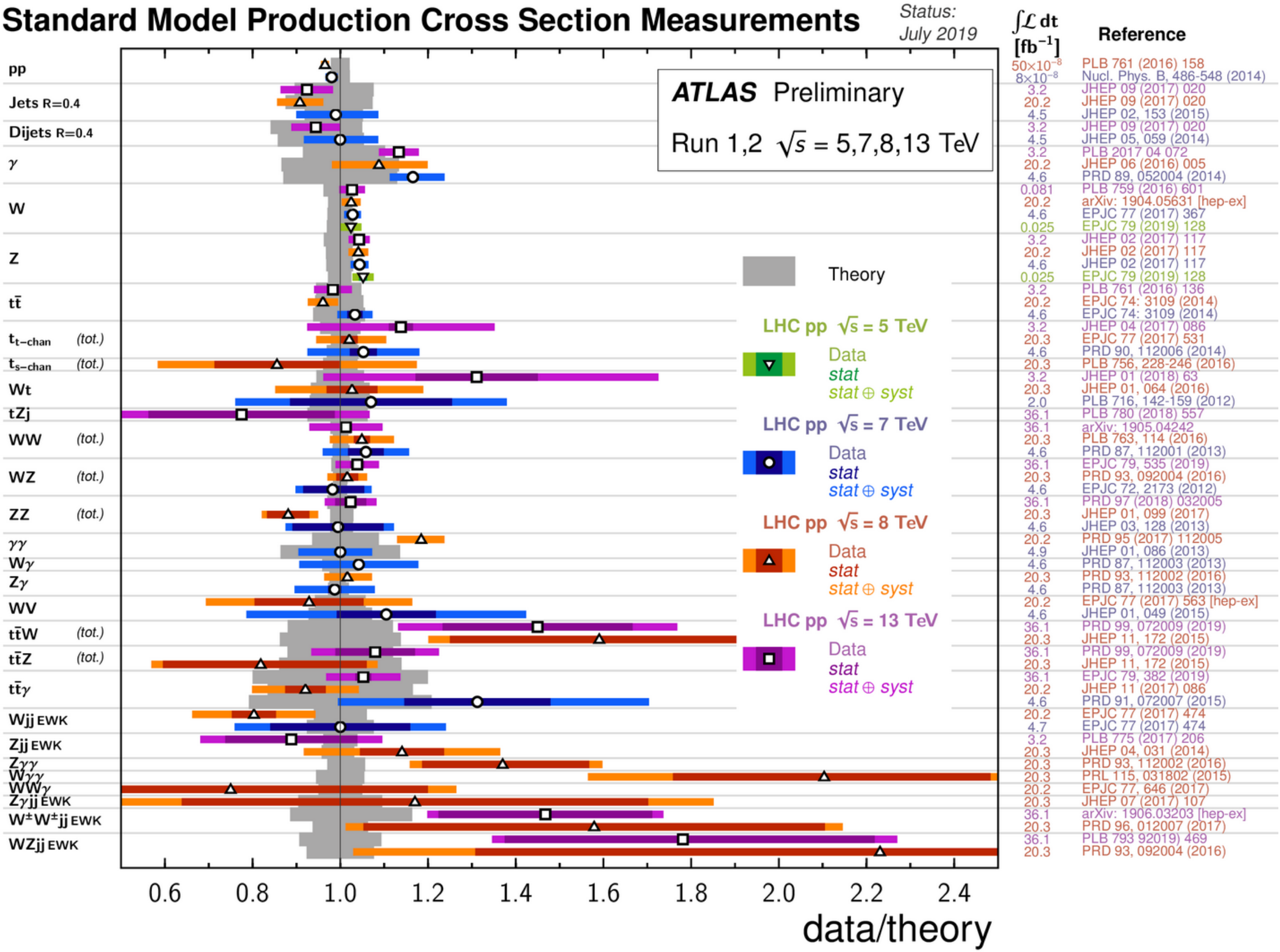


1.3-3.5 (3.8) GeV @ CL 95%

Wrap-up

- **Multi-boson final states**
  versatile tool for
  - **precision measurements** of the non-abelian gauge structure of the SM
  - **indirect constraints** on new physics (EFT)
  - **direct searches** for narrow resonances
- Analysis with complete run-2 statistics in full swing.
- Stay tuned for new (hopefully exiting) results!




Standard Model Production Cross Section Measurements
Status: July 2019
ATLAS Preliminary
Run 1,2 $\sqrt{s}$ = 5,7,8,13 TeV
$\int\mathcal{L}\,dt$ [fb^{-1}]
Reference
pp
Jets R=0.4
Dijets R=0.4
γ
W
Z
$t\bar{t}$
$t_{t\text{-chan}}$ (tot.)
$t_{s\text{-chan}}$ (tot.)
Wt
tZj
WW (tot.)
WZ (tot.)
ZZ (tot.)
$\gamma\gamma$
Wγ
Zγ
WV
$t\bar{t}$W (tot.)
$t\bar{t}$Z (tot.)
$t\bar{t}\gamma$
Wjj EWK
Zjj EWK
Z$\gamma\gamma$
W$\gamma\gamma$
WWγ
Zγjj EWK
W$^\pm$W$^\pm$jj EWK
WZjj EWK
Theory
LHC pp $\sqrt{s}$ = 5 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 7 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 8 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 13 TeV
Data
stat
stat ⊕ syst
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
data/theory
50×10^{-8} PLB 761 (2016) 158
8×10^{-8} Nucl. Phys. B, 486-548 (2014)
3.2 JHEP 09 (2017) 020
20.2 JHEP 09 (2017) 020
4.5 JHEP 02, 153 (2015)
3.2 JHEP 09 (2017) 020
4.5 JHEP 05, 059 (2014)
3.2 PLB 2017 04 072
20.2 JHEP 06 (2016) 005
4.6 PRD 89, 052004 (2014)
0.081 PLB 759 (2016) 601
20.2 arXiv: 1904.05631 [hep-ex]
4.6 EPJC 77 (2017) 367
0.025 EPJC 79 (2019) 128
3.2 JHEP 02 (2017) 117
20.2 JHEP 02 (2017) 117
4.6 JHEP 02 (2017) 117
0.025 EPJC 79 (2019) 128
3.2 PLB 761 (2016) 136
20.2 EPJC 74: 3109 (2014)
4.6 EPJC 74: 3109 (2014)
3.2 JHEP 04 (2017) 086
20.3 EPJC 77 (2017) 531
4.6 PRD 90, 112006 (2014)
20.3 PLB 756, 228-246 (2016)
3.2 JHEP 01 (2018) 63
20.3 JHEP 01, 064 (2016)
2.0 PLB 716, 142-159 (2012)
36.1 PLB 780 (2018) 557
36.1 arXiv: 1905.04242
20.3 PLB 763, 114 (2016)
4.6 PRD 87, 112001 (2013)
36.1 EPJC 79, 535 (2019)
20.3 PRD 93, 092004 (2016)
4.6 EPJC 72, 2173 (2012)
36.1 PRD 97 (2018) 032005
20.3 JHEP 01, 099 (2017)
4.6 JHEP 03, 128 (2013)
20.2 PRD 95 (2017) 112005
4.9 JHEP 01, 086 (2013)
4.6 PRD 87, 112003 (2013)
20.3 PRD 93, 112002 (2016)
4.6 PRD 87, 112003 (2013)
20.2 EPJC 77 (2017) 563 [hep-ex]
4.6 JHEP 01, 049 (2015)
36.1 PRD 99, 072009 (2019)
20.3 JHEP 11, 172 (2015)
36.1 PRD 99, 072009 (2019)
20.3 JHEP 11, 172 (2015)
36.1 EPJC 79, 382 (2019)
20.2 JHEP 11 (2017) 086
4.6 PRD 91, 072007 (2015)
20.2 EPJC 77 (2017) 474
4.7 EPJC 77 (2017) 474
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