Science and Technology Facilities Council

ATLAS EXPERIMENT

Vector Boson Scattering to Unravel EWSB and Probe BSM Physics

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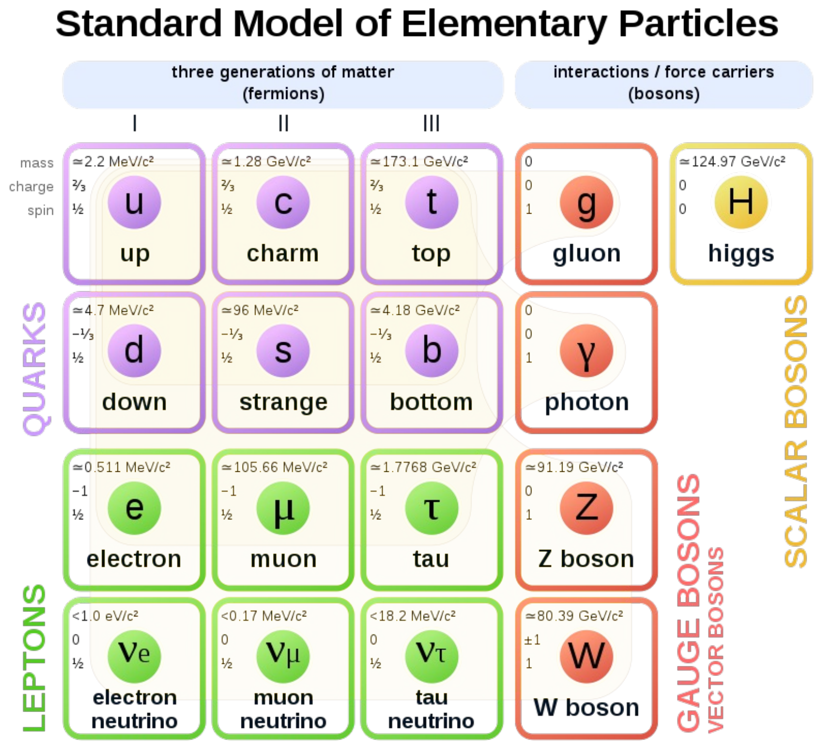
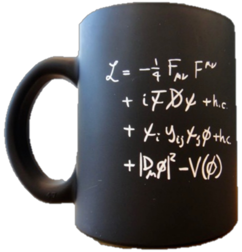
STFC Ernest Rutherford Fellow

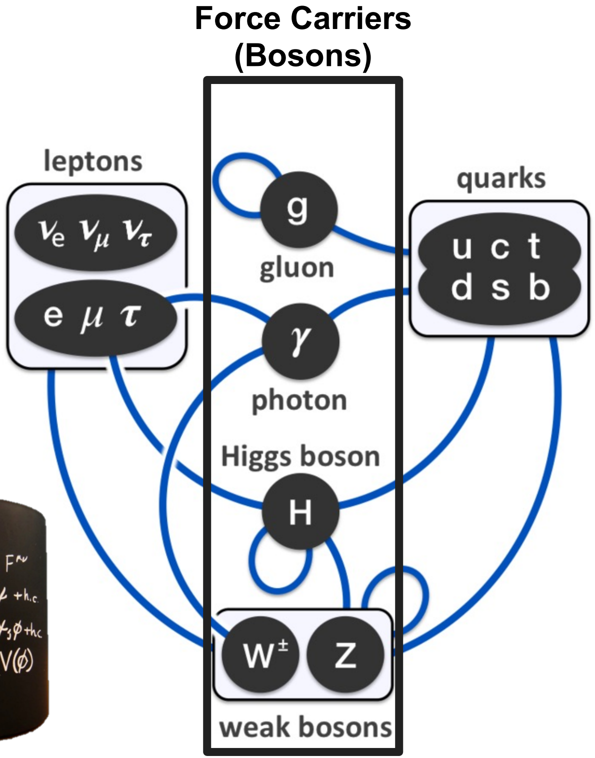
Elementary Particle Physics Seminar
University of Warwick
March 9, 2023

WARWICK
THE UNIVERSITY OF WARWICK

The Standard Model of Particle Physics





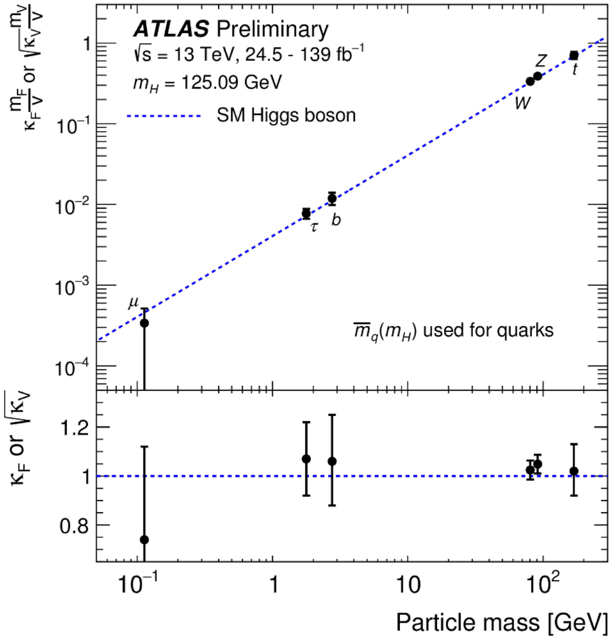


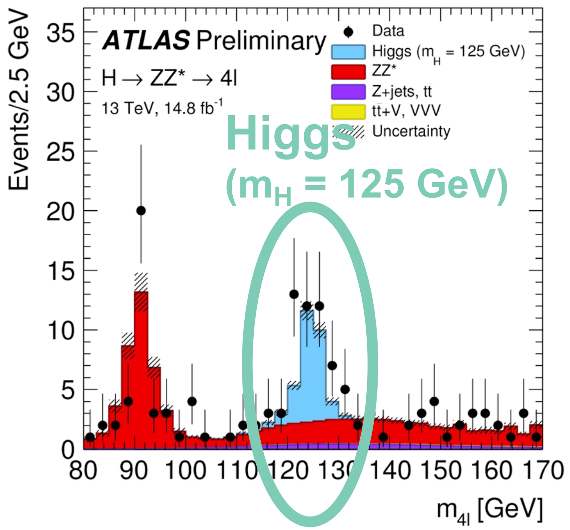
The Higgs boson

Higgs mechanism

- ➢ Implements (Spontaneous) Electroweak Symmetry Breaking (EWSB) in SM
- ➢ Cornerstone of SM: gives mass to fundamental particles

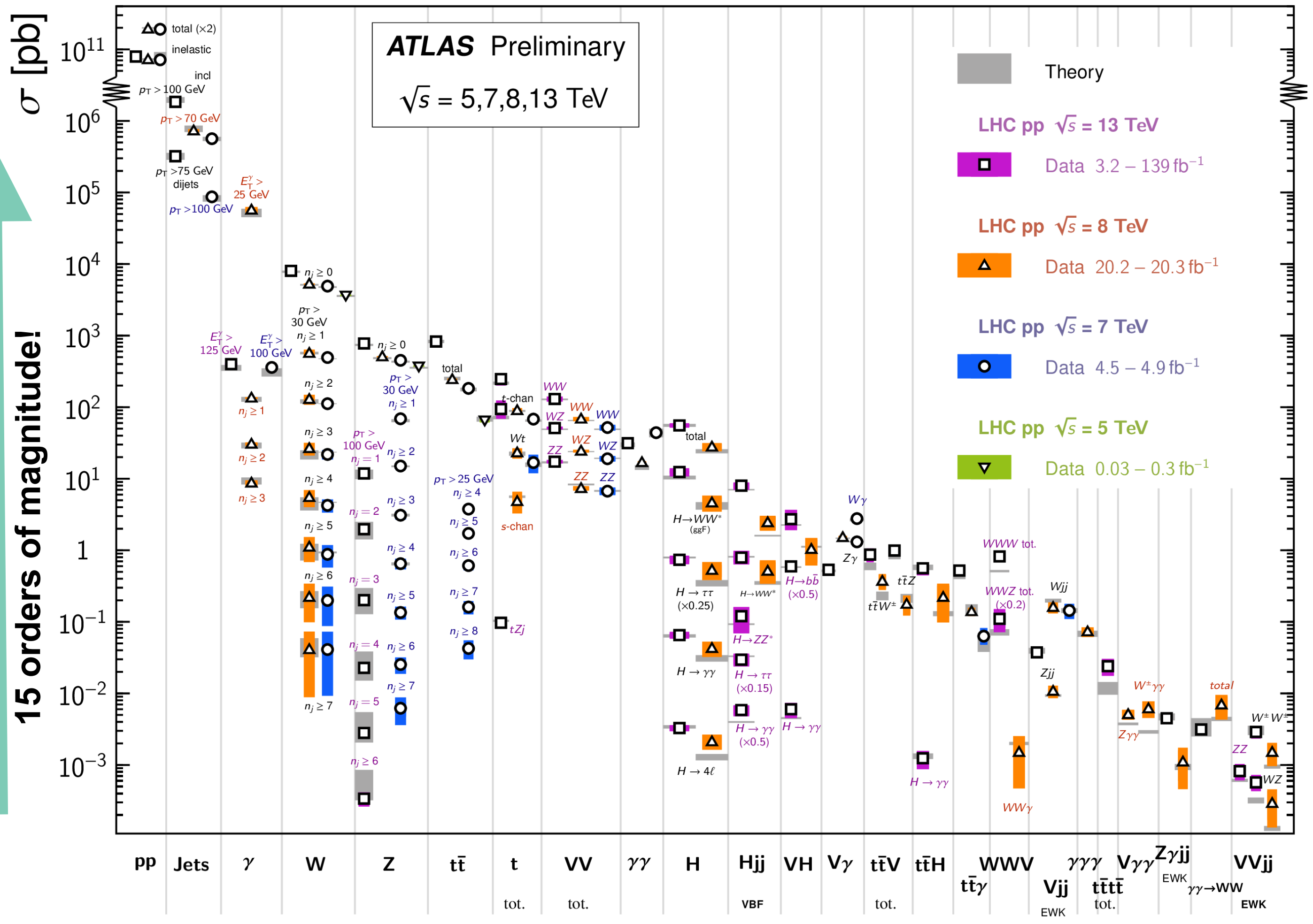
Higgs: last fundamental particle discovered (2012), after almost 50 years!





Standard Model Production Cross Section Measurements

Status: February 2022



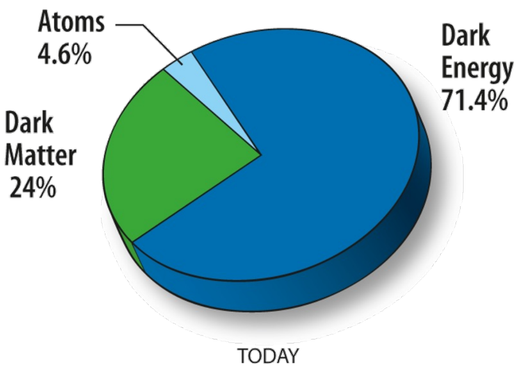
Production rate

15 orders of magnitude!

The Standard Model of Particle Physics

Yet, the Standard Model **doesn't explain many observed phenomena**

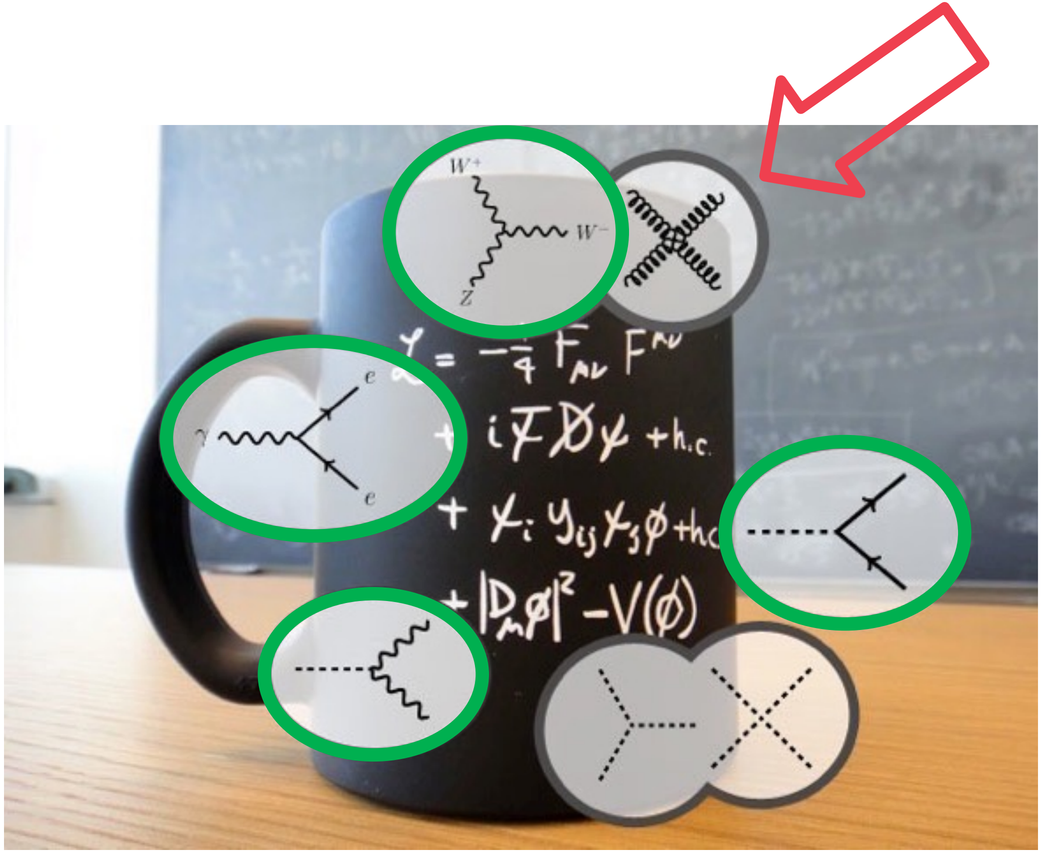
- **Gravity** is absent from the SM
- **Dark Matter and Dark Energy**
- **Massive neutrinos**
- The **matter-antimatter asymmetry**



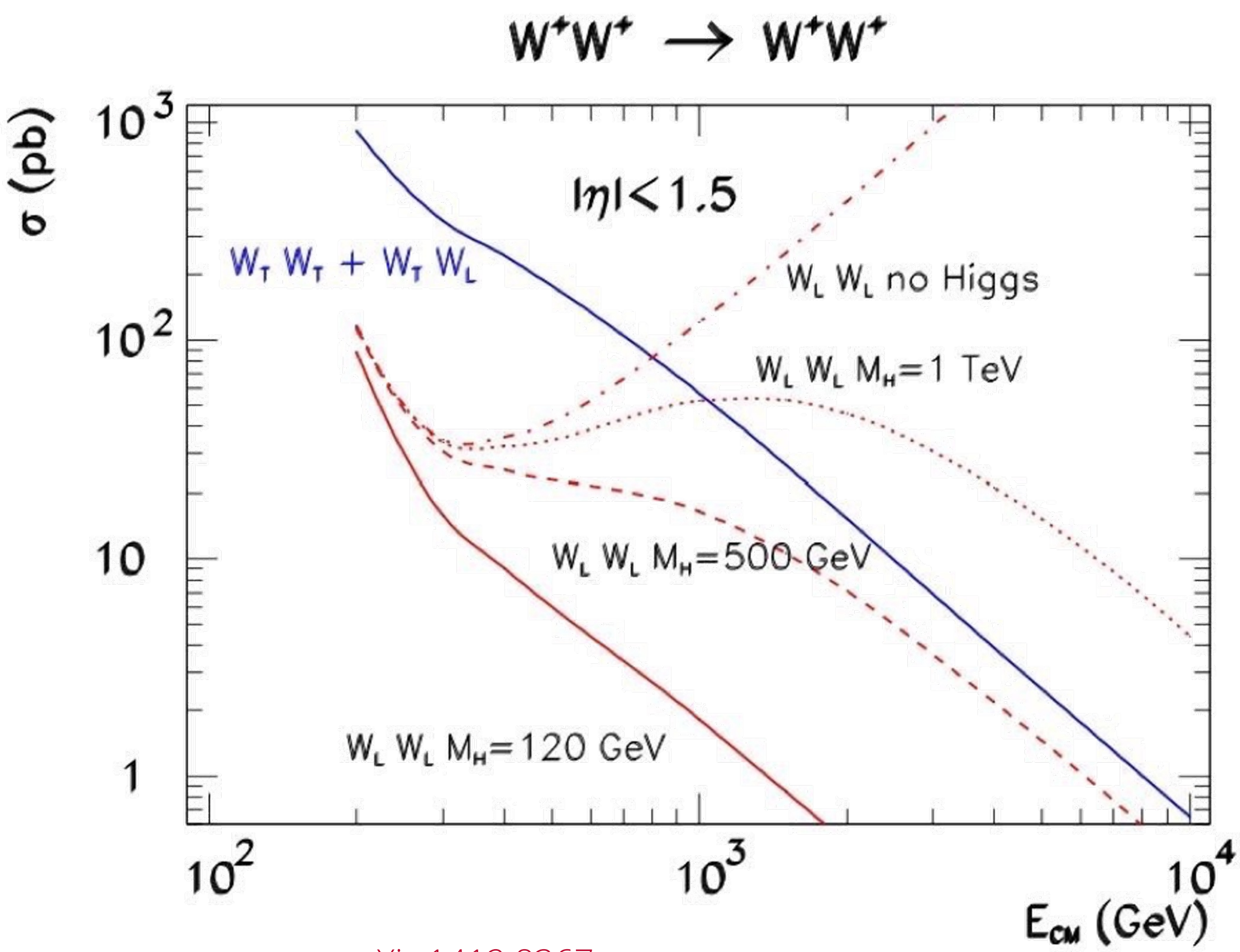
Large experimental programme to unravel the mysteries of our Universe at the Large Hardon Collider (LHC) at CERN.

Important to look at the LHC data, probing the rarest SM processes to look for deviations from theory, which could be hints of new physics.

Probing the SM of Particle Physics



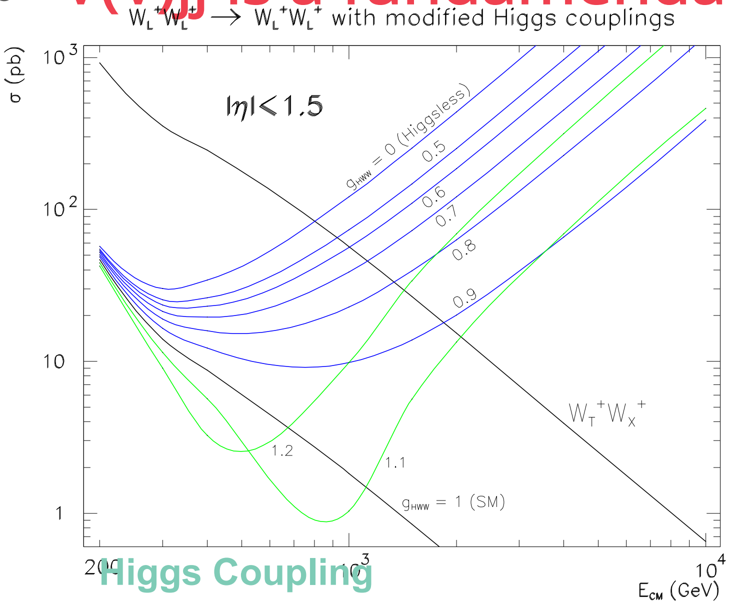
- γ/Z → ll, W → lν well understood
- H → γγ, WW, ZZ, ττ observed
- WW V (V=W, Z, γ) precisely measured at LEP and LHC
- *Higgs self-coupling not <u>yet</u> measurable*
- Probing WW VV limited by experimental data

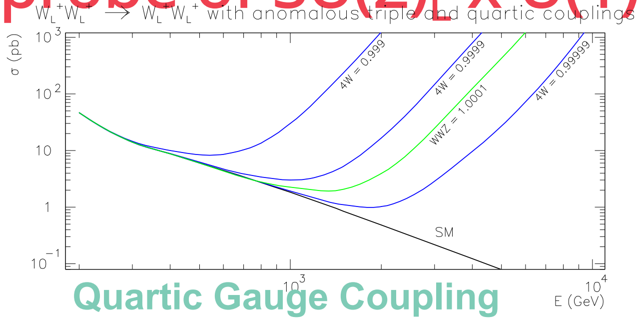


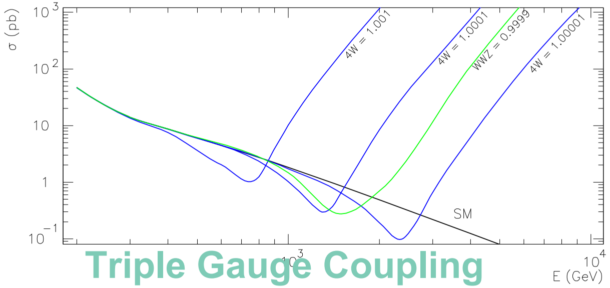
arXiv:1412.8367

Probing Electroweak Symmetry Breaking

- VBS at high energy subject to **delicate cancellation between terms**
  - $\sigma(W_L W_L \rightarrow W_L W_L)$ grows with energy w/o Higgs boson
  - Very sensitive to shifts in the trilinear or quartic gauge coupling
- V(V)jj is a fundamendal probe of $SU(2)_L \times U(1)_Y$

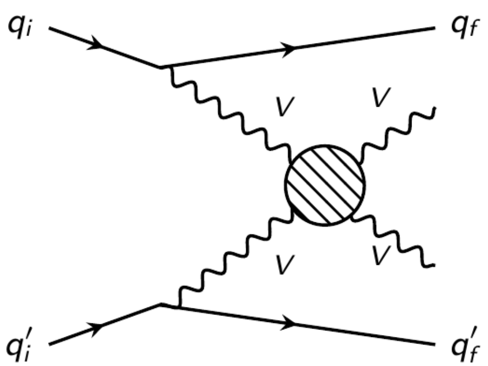






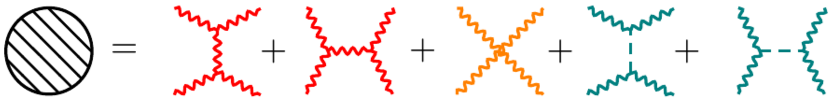
arXiv:1412.8367

Vector Boson Scattering (VBS)



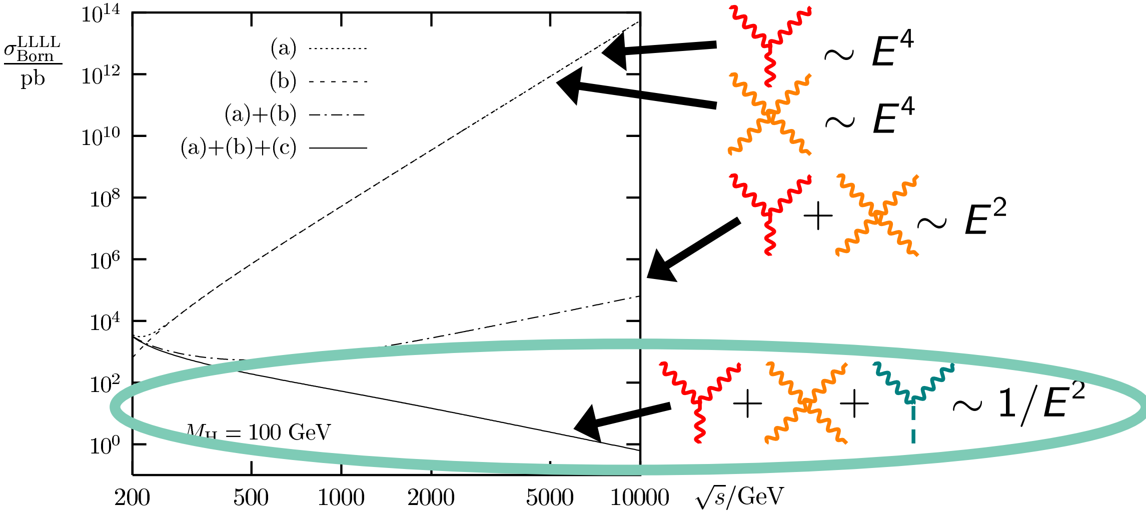
Complementary probe to direct Higgs measurements

Gauge structure of SM EWSB



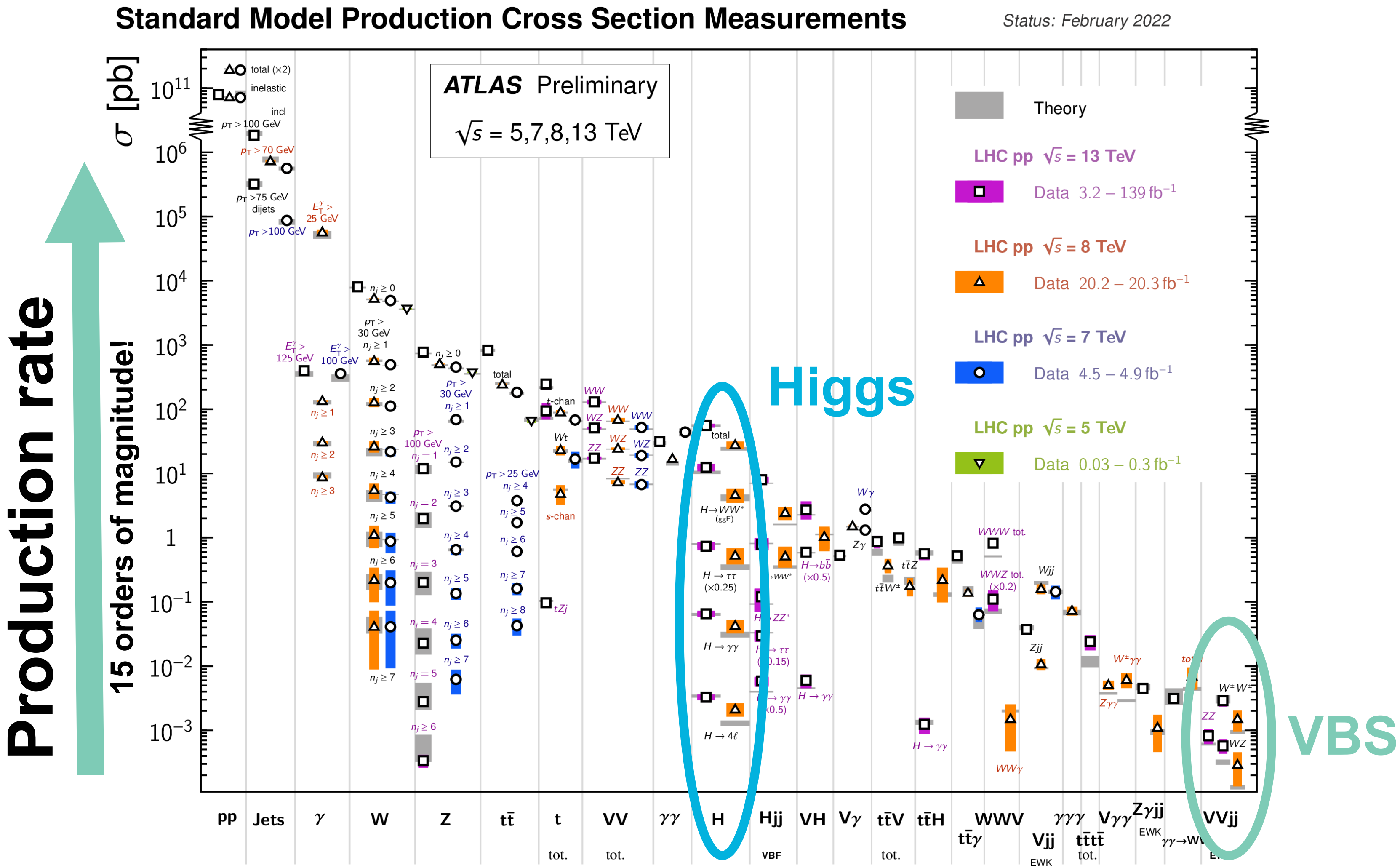
Triple Gauge Couplings Quartic Gauge Couplings **Higgs exchange**

Denner, Hahn, Nucl.Phys.B525:27-50,1998



A light Higgs boson **prevents cross-section of VBS processes from becoming unphysical (diverging)**

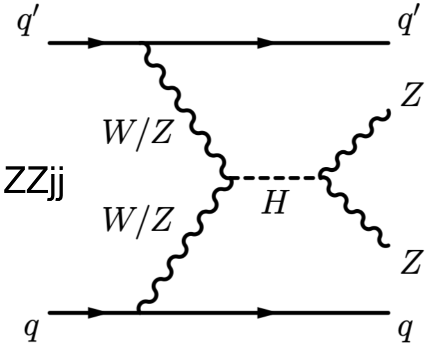
VBS measurements test the consistency of the SM and is sensitive to New Physics


Standard Model Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
√s = 5,7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 5 TeV
Data 0.03 – 0.3 fb⁻¹
Production rate
15 orders of magnitude!
Higgs
VBS
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
Hjj
VH
Vγ
tt̄V
tt̄H
tt̄γ
WWV
Vjj
γγγ
tt̄tt̄
Vγγ
Zγjj
VVjj

Probing VBS (and VBF) :: Motivation

- Important tests of Electroweak and Strong interaction
- They directly **probe EW boson self-interactions**
- They are a portal to
  - **Understanding EWSB**
  - **Probing BSM physics**

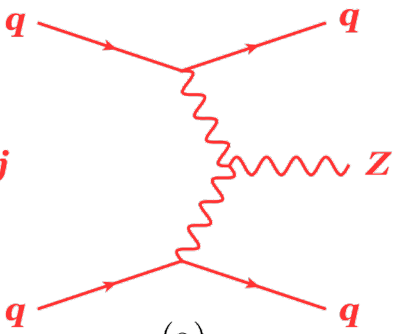
EW ZZjj



Measurements:

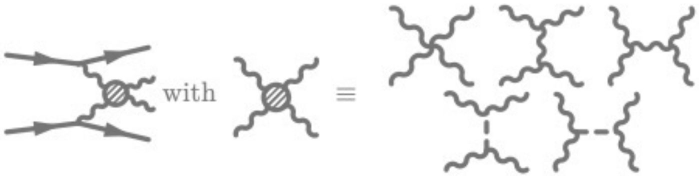
- Fiducial and differential cross-sections
- Looking for anomalous couplings (EFT)
- **Probing EW boson polarisation**

EW Zjj



(a)

Signal definition



VBS

EW Signal

VVjj

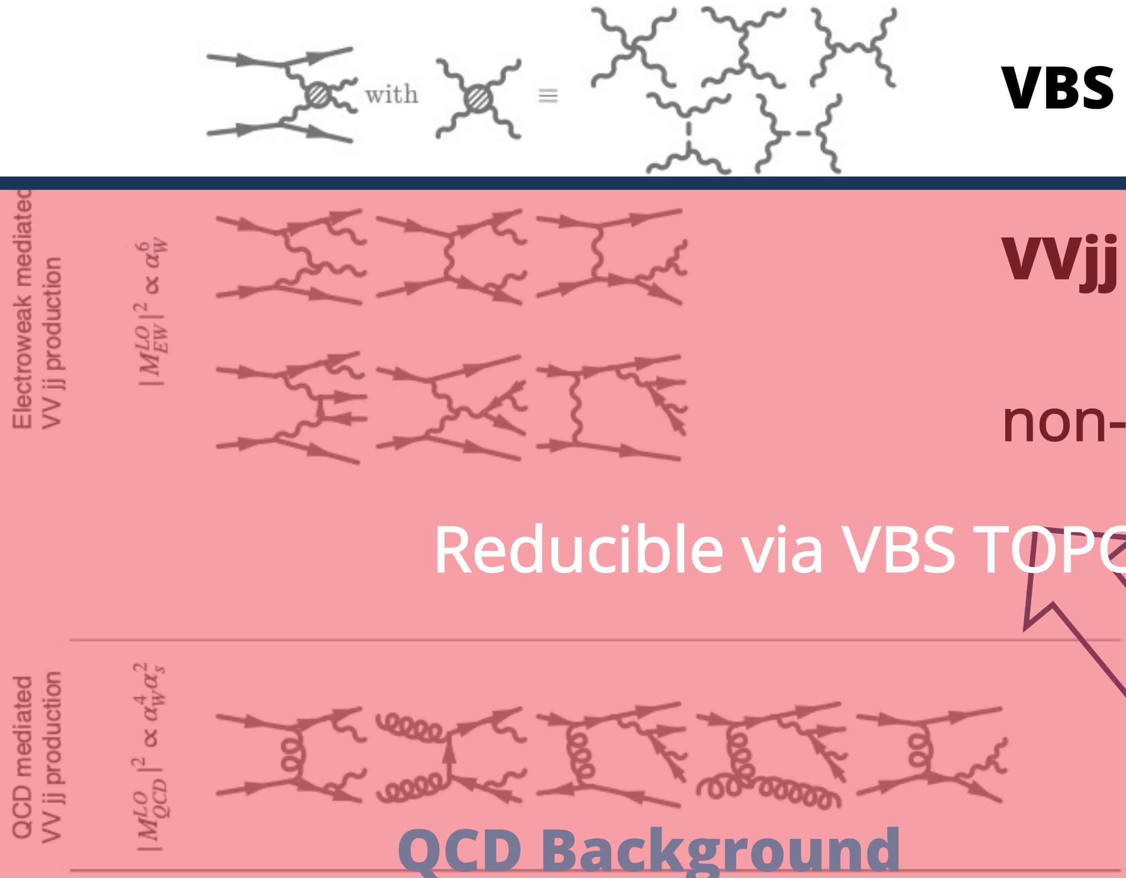
non-resonant

interference
between EW and QCD
mediated production

Interference

QCD Background

Signal definition



VBS

EW Signal

VVjj

non-resonant

Reducible via VBS TOPOLOGY

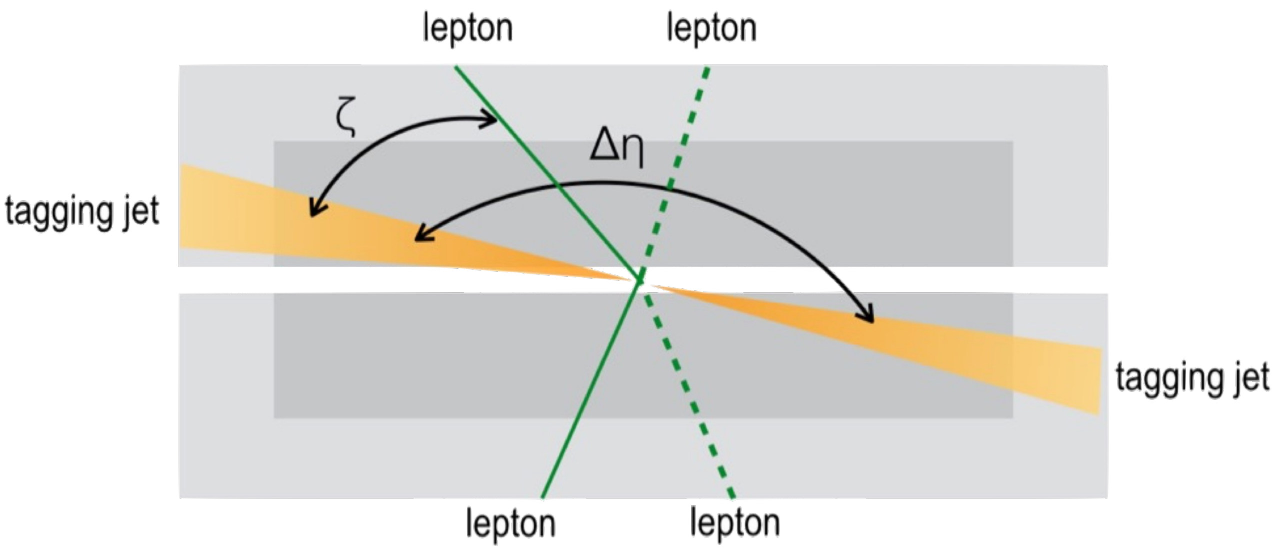
interference
between EW and QCD
mediated production

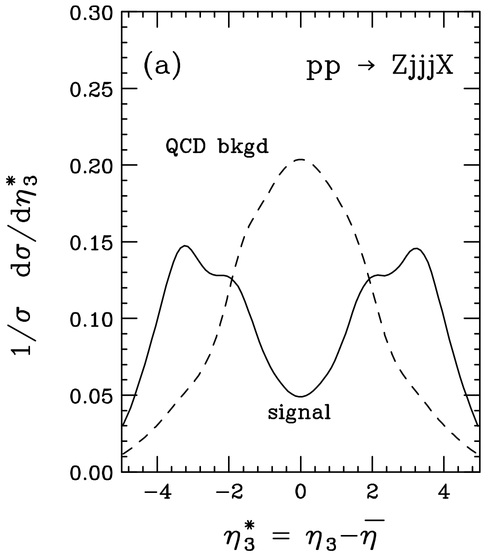
Interference

QCD Background

VBS Topology

arXiv:hep-ph/9605444 ; 1996





- Two hadronic jets in the forward/backward regions with high energy (tagging jets)
- Hadronic activity suppressed between two jets (rapidity gap) due to absence of colour flow between interacting partons
- Two bosons produced ~back-to-back

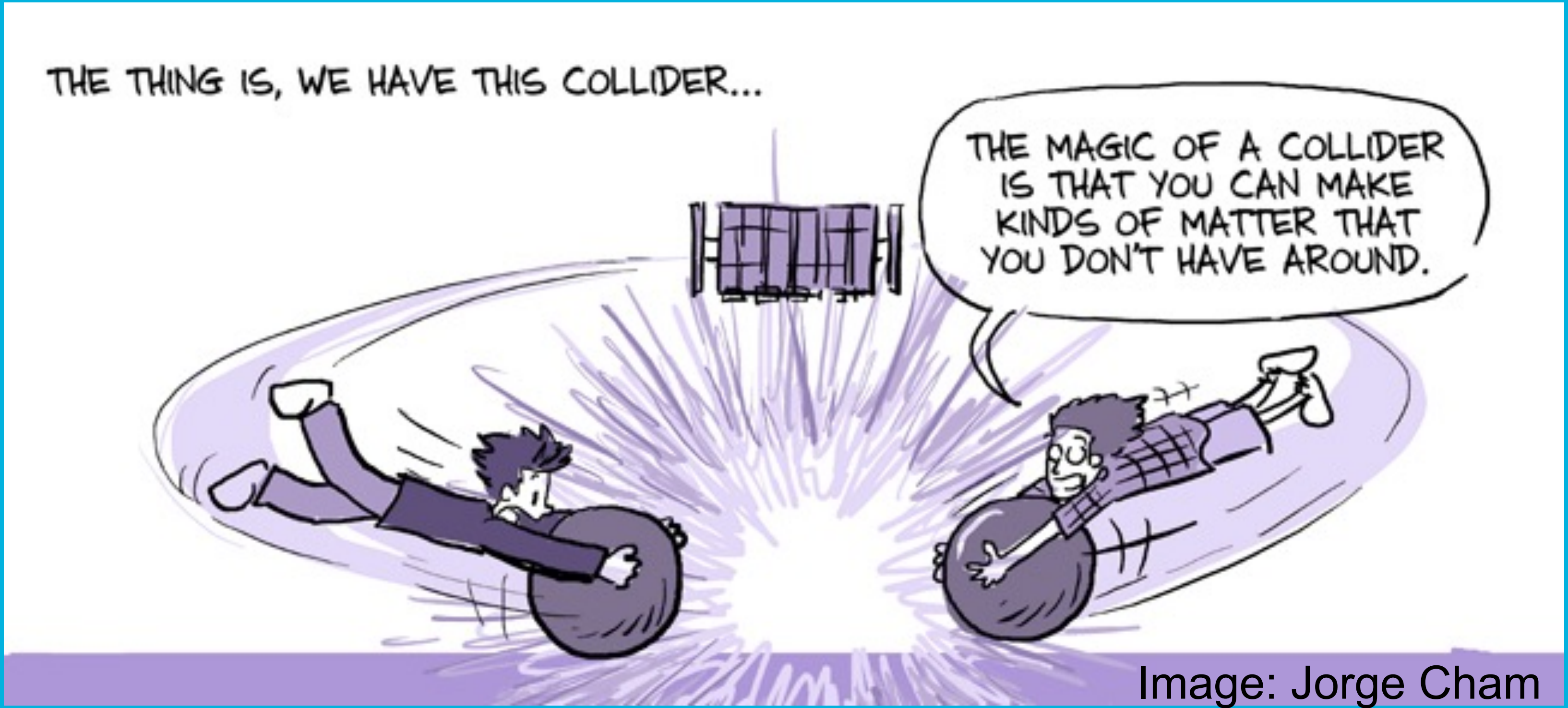
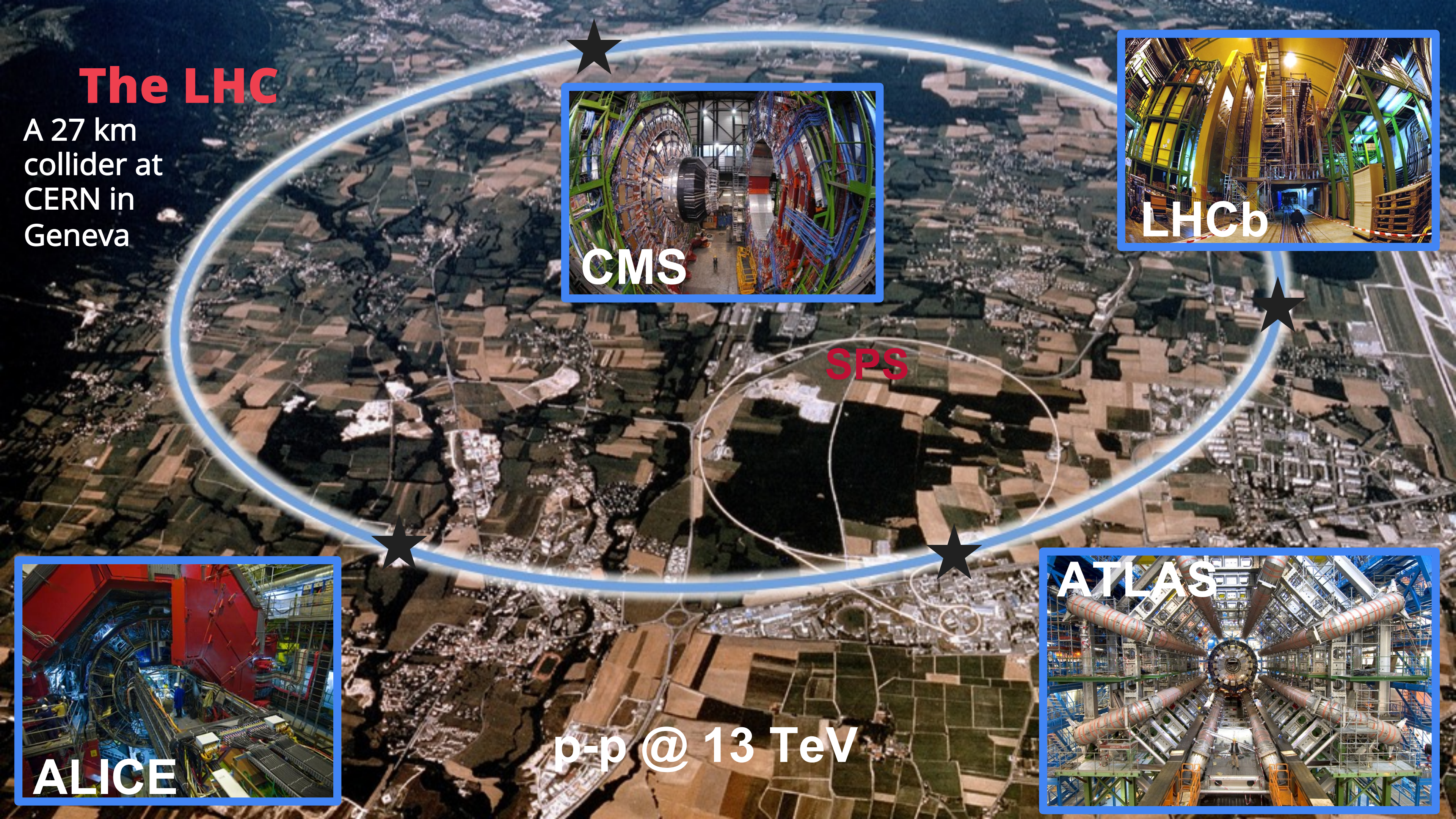


Image: Jorge Cham


The LHC
A 27 km collider at CERN in Geneva
CMS
LHCb
SPS
ATLAS
ALICE
p-p @ 13 TeV

Probing the rarest SM Processes

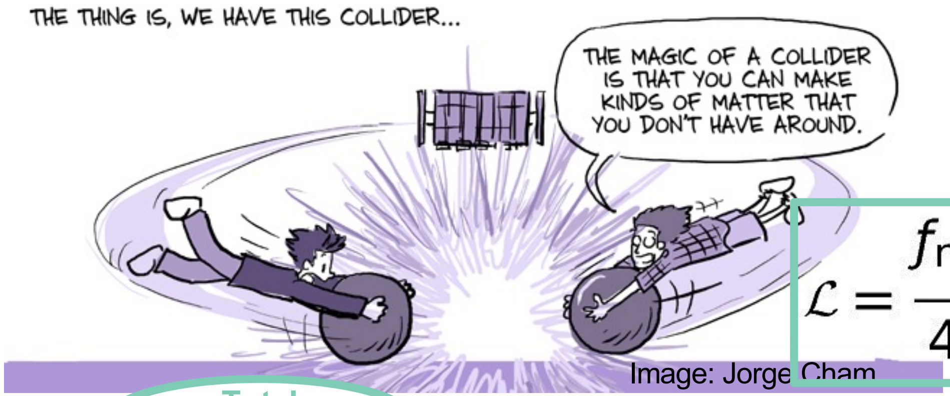
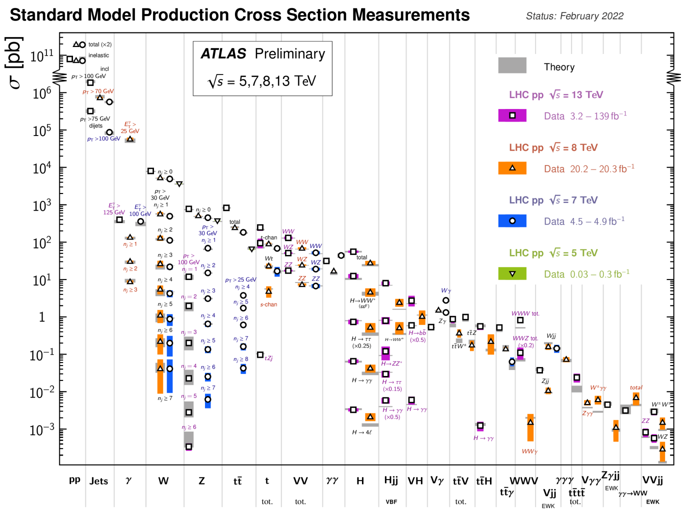


Image: Jorge Cham

$$\mathcal{L} = \frac{f_{\mathrm{rev}} n_{\mathrm{b}} N_{\mathrm{p}}^2}{4\pi\sigma_x\sigma_y}$$



Total Luminosity

$$N_{\mathrm{obs}} = \int \mathcal{L}dt \cdot \varepsilon \cdot \sigma$$

Detector Efficiency

Cross-section (Given by theory)

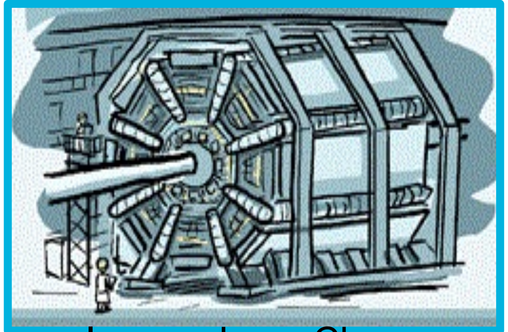
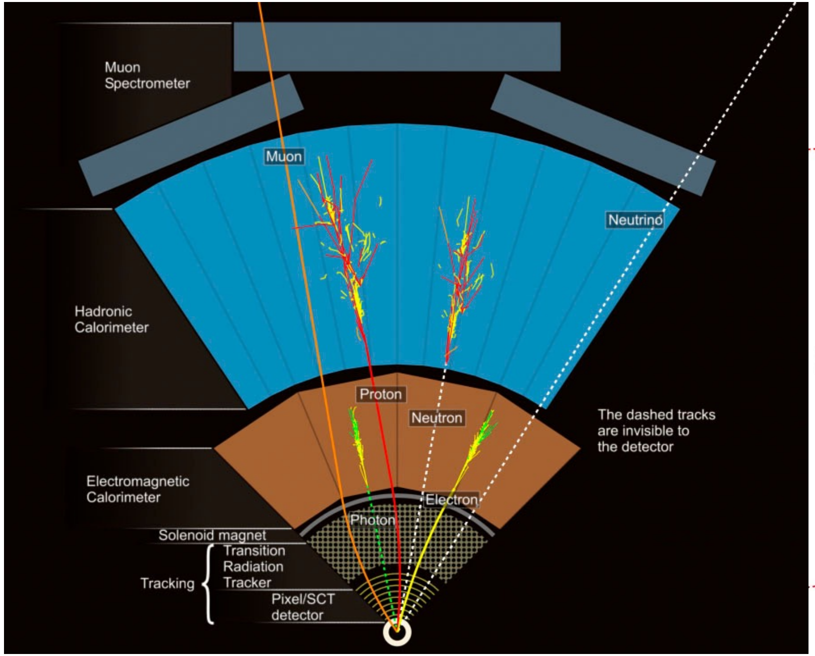
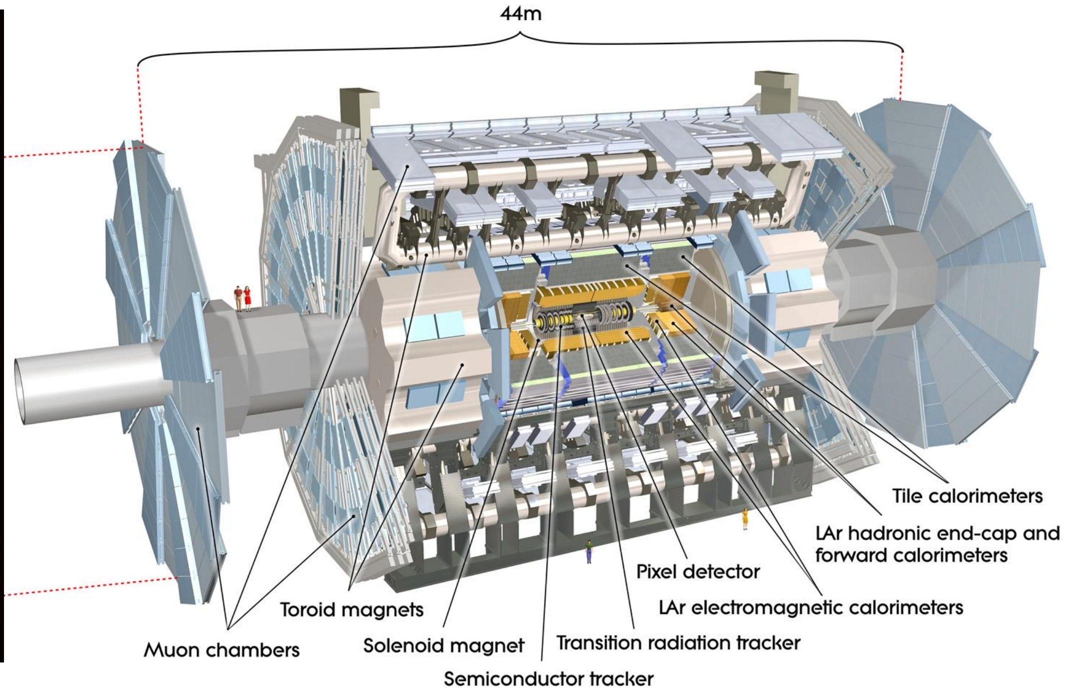


Image: Jorge Cham

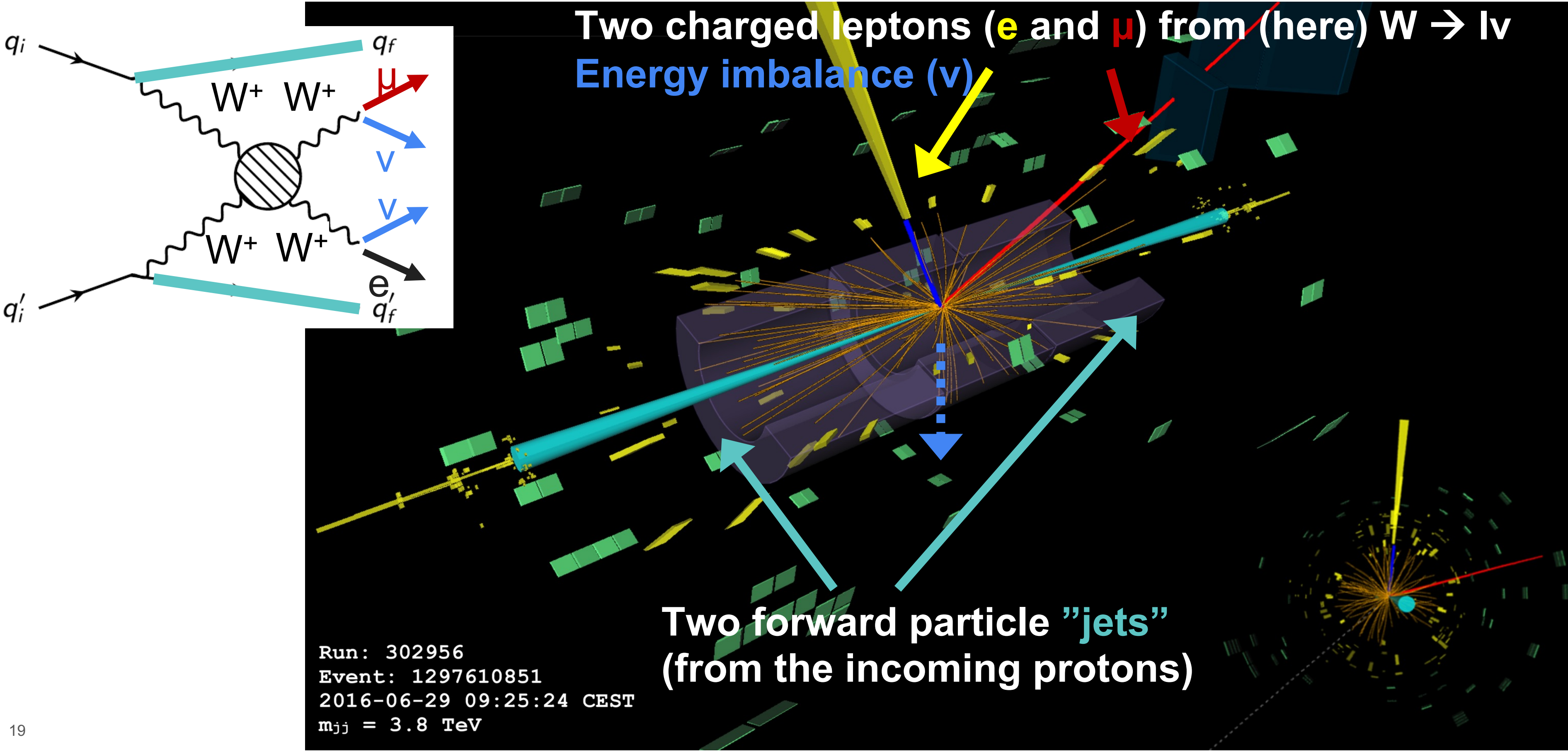
The ATLAS Detetor



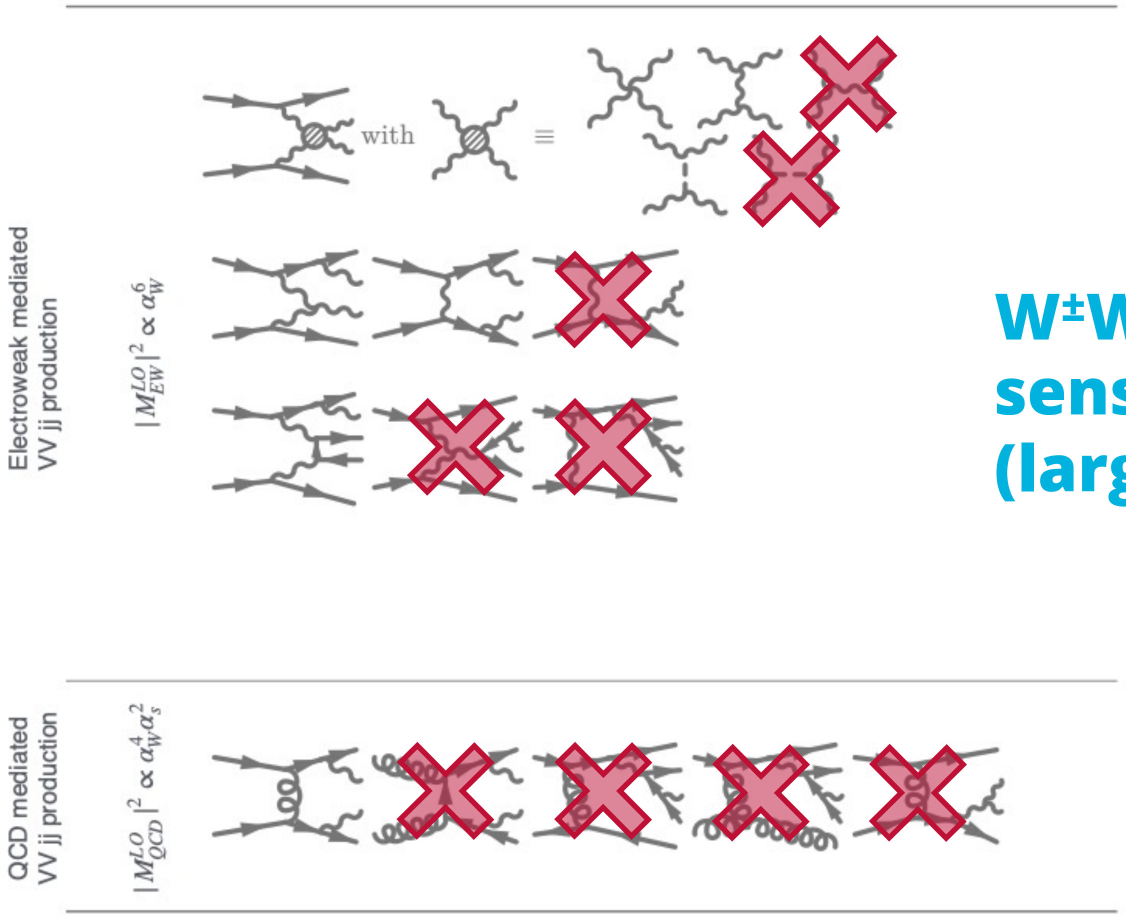
Transverse view



How does VBS look like in ATLAS ?

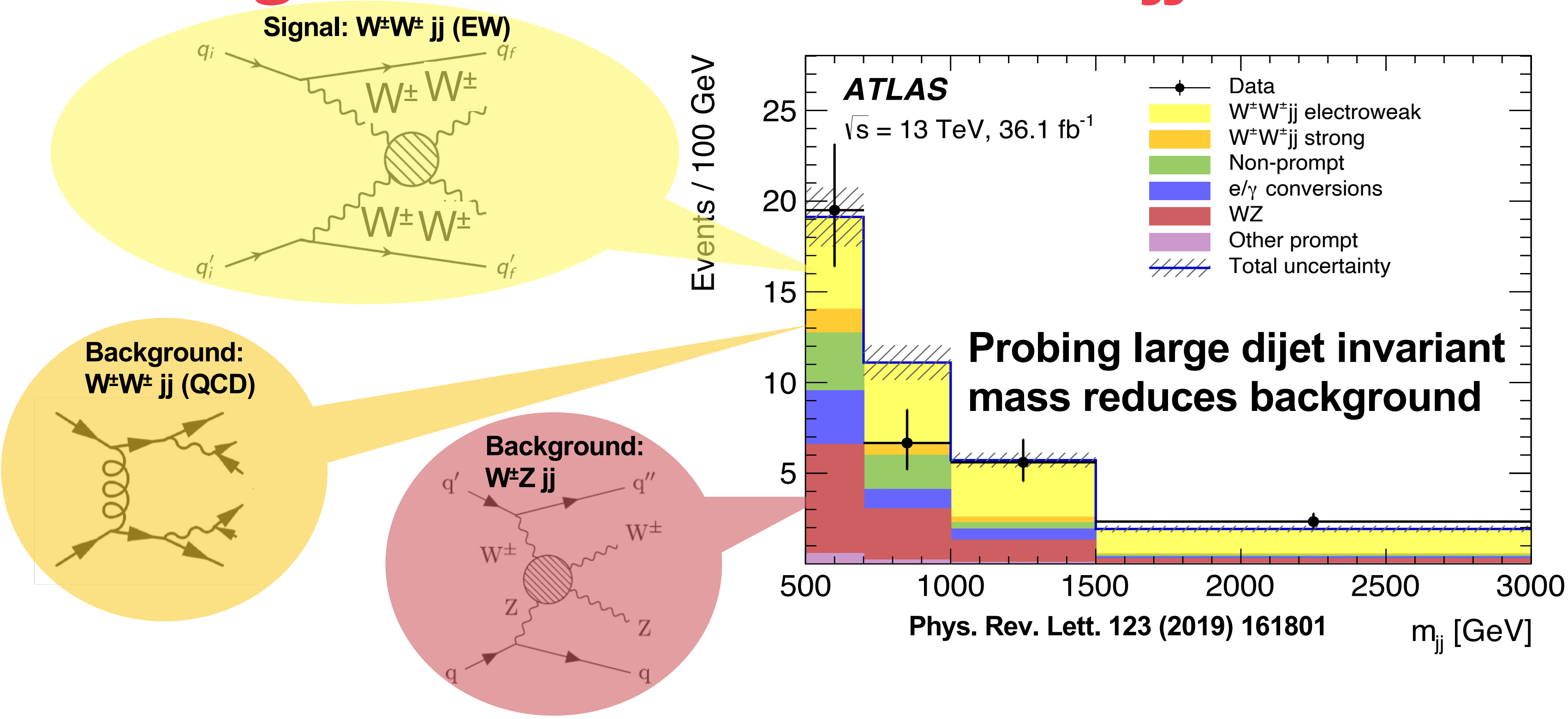


Probing Electroweak (EW) W±W±jj



W±W± jj is most sensitive VBS process (largest σ_{EW}/σ_{QCD} ratio)

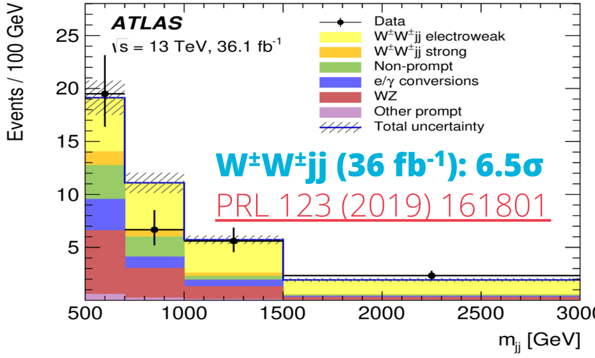
Probing Electroweak (EW) W±W±jj



Observation by ATLAS in 2018 using 36.1 fb^{-1} (~60 EW W±W±jj events, S/B ≈ 1)

Overview of Run-2 ATLAS VBS/VBF Analyses

Leptonic

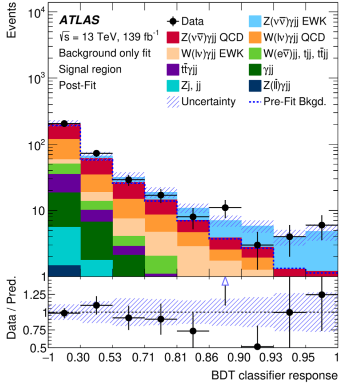


$W^{\pm}W^{\pm}jj$ (36 fb^{-1}): 6.5σ

PRL 123 (2019) 161801

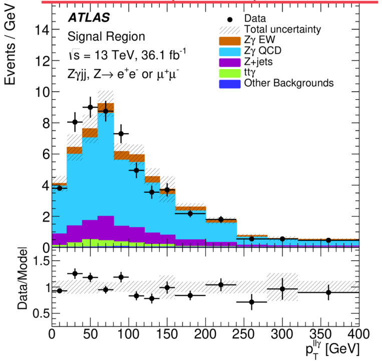
$Z(\nu\nu)\gamma jj$ (139 fb^{-1}): 6.3σ (*)

JHEP



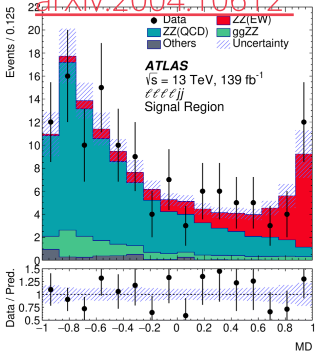
$Z(ll)\gamma jj$ (36 fb^{-1}): 4.1σ

PLB 803 (2020) 135341



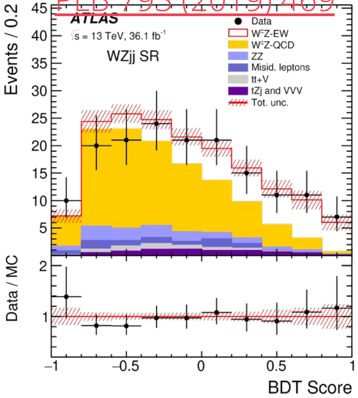
ZZjj (139 fb^{-1}): 5.5σ

arXiv:2004.10612



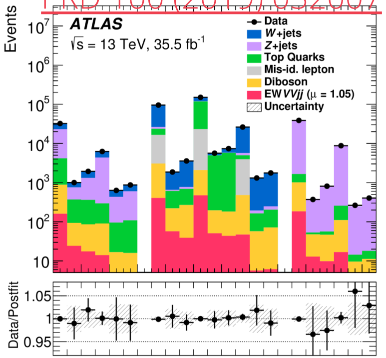
WZjj (36 fb^{-1}): 5.3σ

PLB 793 (2019) 469



VVjj (36 fb^{-1}): 2.7σ

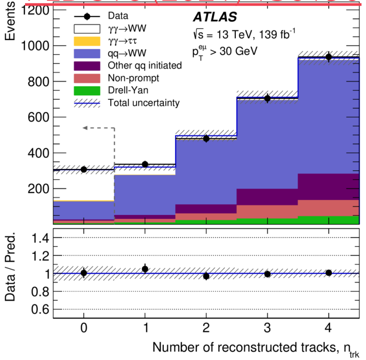
PRD 100 (2019) 032007



Semi-leptonic

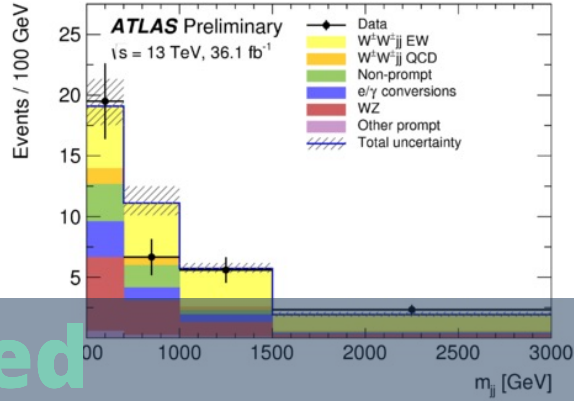
γγ → WW (139 fb^{-1}): 8.4σ

PLB 816 (2021) 136190



Observation of EW W±W±jj

	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	combined
WZ	1.7 ± 0.6	1.2 ± 0.4	13 ± 4	8.1 ± 2.5	5.0 ± 1.6	3.3 ± 1.1	32 ± 9
Non-prompt	4.1 ± 2.4	2.3 ± 1.8	9 ± 6	6 ± 4	0.57 ± 0.16	0.67 ± 0.26	23 ± 12
e/γ conversions	1.74 ± 0.31	1.8 ± 0.4	6.1 ± 2.4	3.7 ± 1.0	-	-	13.4 ± 3.5
Other prompt	0.17 ± 0.06	0.14 ± 0.05	0.90 ± 0.24	0.60 ± 0.25	0.36 ± 0.12	0.19 ± 0.07	2.4 ± 0.5
$W^\pm W^\pm$jj strong	0.38 ± 0.13	0.16 ± 0.06	3.0 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.26	7.3 ± 2.5
Expected background	8.1 ± 2.4	5.6 ± 1.9	32 ± 7	20 ± 5	7.7 ± 1.7	4.9 ± 1.1	78 ± 15
$W^\pm W^\pm$jj electroweak	3.80 ± 0.30	1.49 ± 0.13	16.5 ± 1.2	6.5 ± 0.5	9.1 ± 0.7	3.50 ± 0.29	40.9 ± 2.9
Data	10	4	44	28	25	11	122

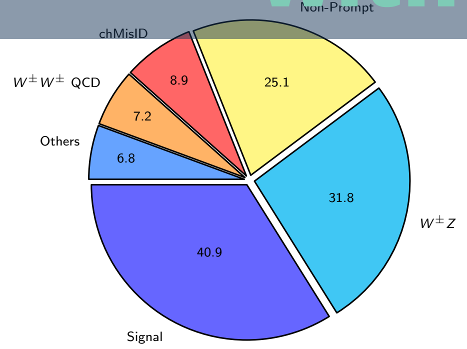


$$\sigma^{\mathrm{fid}} = 2.91^{+0.51}_{-0.47}\,(\mathrm{stat.}) \pm 0.27\,(\mathrm{sys.})\ \mathrm{fb}$$

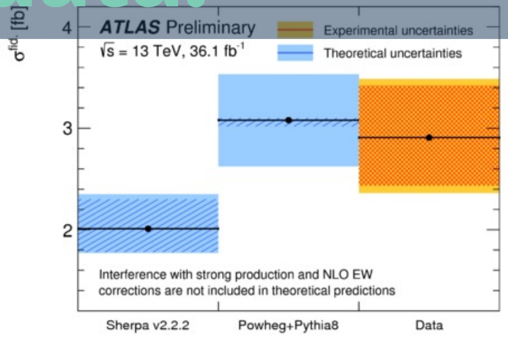
Result being updated with 2015-2018 (Run-2) data!

Phys. Rev. Lett. 123 (2019) 161801

Background composition in signal region:



Source	Impact [%]
Experimental	
Electrons	0.6
Muons	1.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	3.2
b-tagging	2.1
Pileup	1.6
Background, statistical	3.2
Background, misid. leptons	3.3
Background, charge misrec.	0.3
Background, other	1.8
Theory modeling	
$W^\pm W^\pm jj$ electroweak-strong interference	1.0
$W^\pm W^\pm jj$ electroweak, EW corrections	1.4
$W^\pm W^\pm jj$ electroweak, shower, scale, PDF & α_s	2.8
$W^\pm W^\pm jj$ strong	2.9
WZ	3.3
Luminosity	2.4



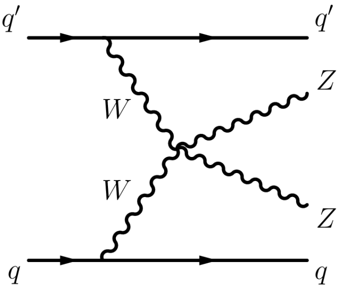
Inclusive ZZjj Production

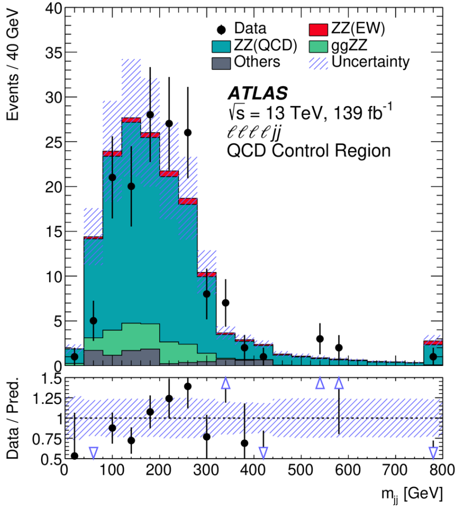
- Extracting inclusive cross-section in two SRs
- SR: EW selection + Z-mass (ll) window

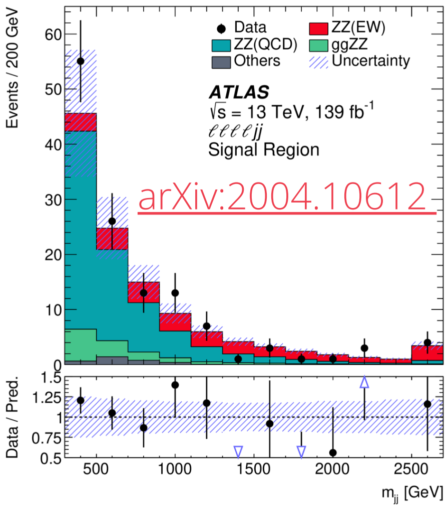
  + 2 jets with $y_{j1} \cdot y_{j2} < 0$, $m_{jj} > 400/300$ GeV, $|\Delta y_{jj}| > 2$
- **Large bkg. from WZ and non-resonant ll in llννjj**

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
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	1.2 ± 0.9
Total	114 ± 26	78.4 ± 6.2
Data	127	82

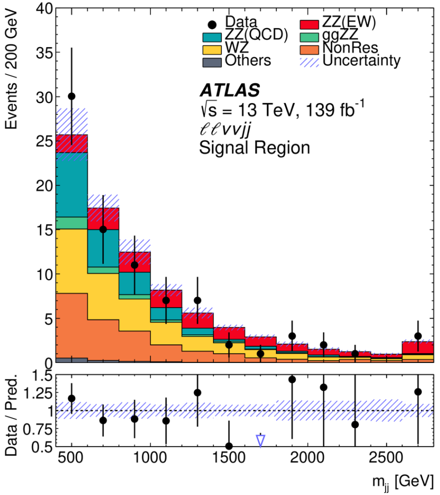
	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	1.27 ± 0.12(stat) ± 0.02(theo) ± 0.07(exp) ± 0.01(bkg) ± 0.03(lumi)	1.14 ± 0.04(stat) ± 0.20(theo)
$\ell\ell\nu\nu jj$	1.22 ± 0.30(stat) ± 0.04(theo) ± 0.06(exp) ± 0.16(bkg) ± 0.03(lumi)	1.07 ± 0.01(stat) ± 0.12(theo)







arXiv:2004.10612

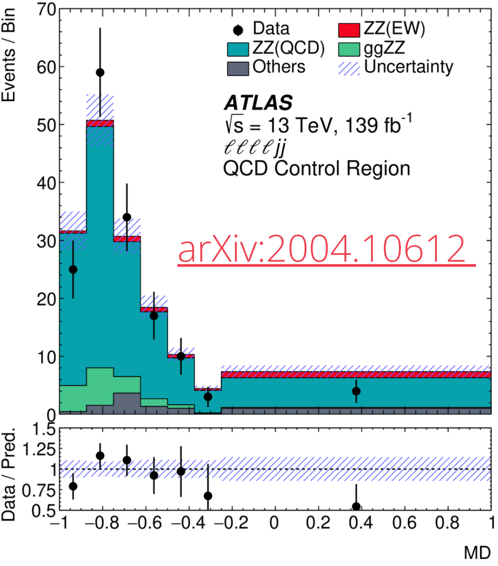


Electroweak ZZjj Production

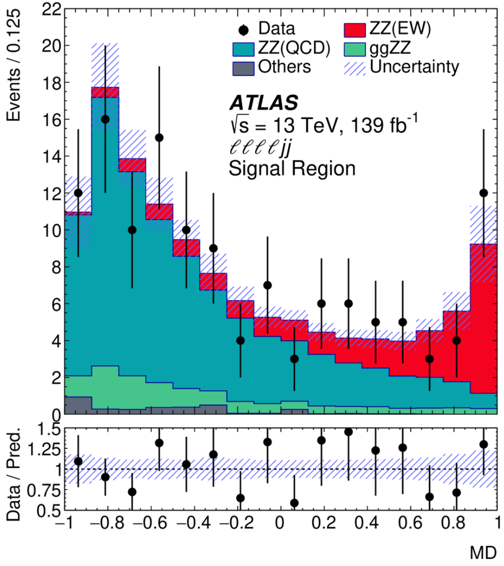
- **Using BDT to separate EW and QCD ZZjj**
- Also fitting QCD CR to constrain background
- **EW ZZjj cross-section : 0.82 ± 0.21 fb**
  (one of the smallest measured by ATLAS)

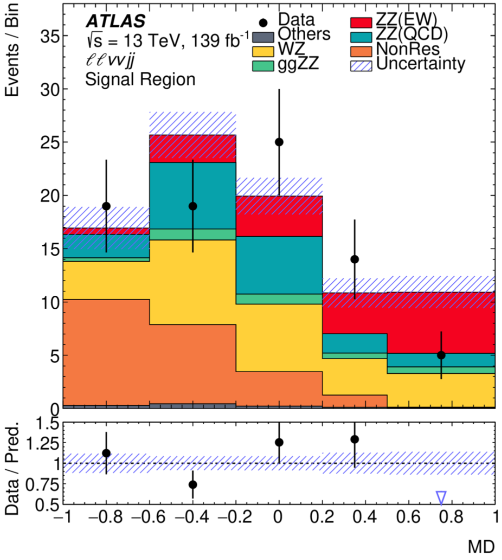
Observation of EW ZZjj (LO MG5+Pythia8)

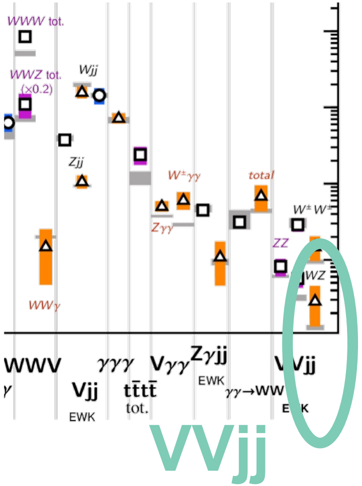
	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	$5.5\ (3.9)\ \sigma$
$\ell\ell\nu\nu jj$	$1.2\ (1.8)\ \sigma$
Combined	$5.5\ (4.3)\ \sigma$



arXiv:2004.10612



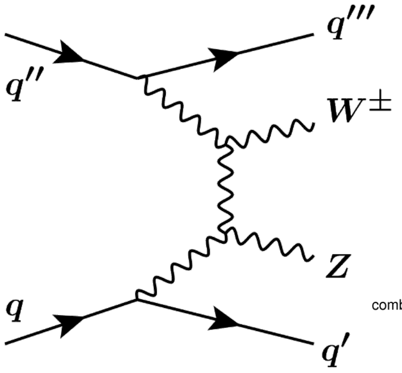


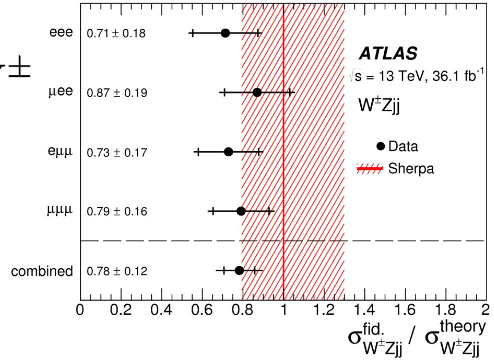


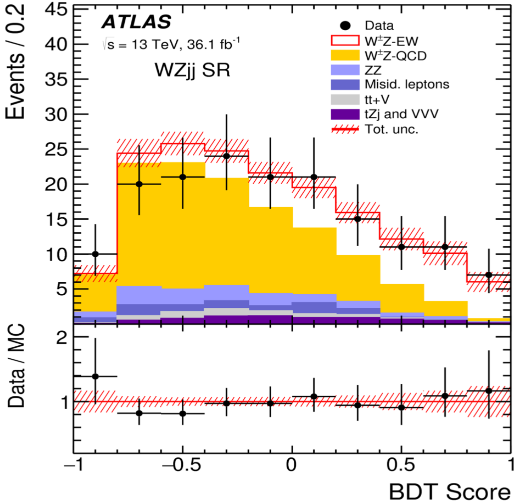
EW WZjj Production

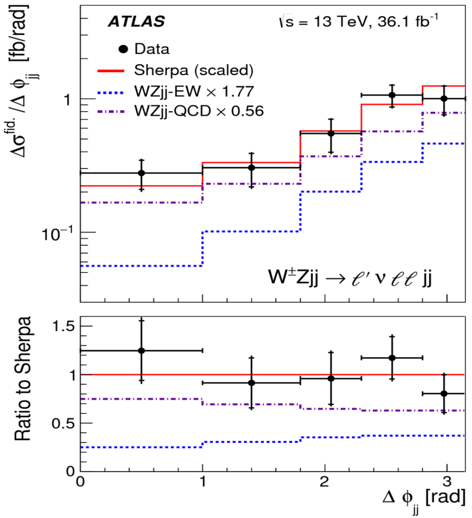
WZjj (36 fb^{-1}): 5.3σ

PLB 793 (2019) 469









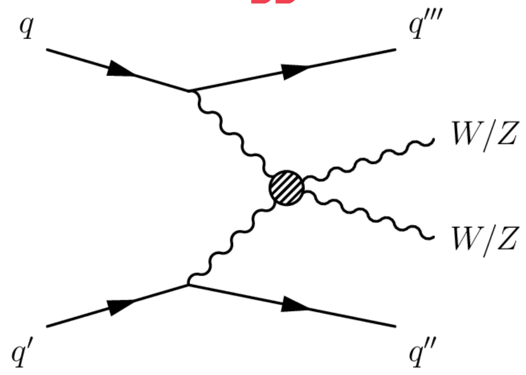
Source	Uncertainty [%]
$WZjj$−EW theory modelling	4.8
$WZjj$−QCD theory modelling	5.2
$WZjj$−EW and $WZjj$−QCD interference	1.9
Jets	6.6
Pile-up	2.2
Electrons	1.4
Muons	0.4
b-tagging	0.1
MC statistics	1.9
Misid. lepton background	0.9
Other backgrounds	0.8
Luminosity	2.1
Total Systematics	10.7

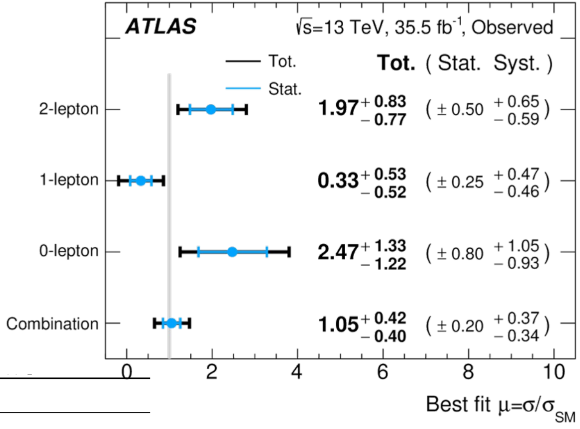
	SR	$WZjj$−QCD CR	b-CR	ZZ-CR
Data	161	213	141	52
Total predicted	167 ± 11	204 ± 12	146 ± 11	51.3 ± 7.0
$WZjj$−EW (signal)	44 ± 11	8.52 ± 0.41	1.38 ± 0.10	0.211 ± 0.004
$WZjj$−QCD	91 ± 10	144 ± 14	13.9 ± 3.8	0.94 ± 0.14
Misid. leptons	7.8 ± 3.2	14.0 ± 5.7	23.5 ± 9.6	0.41 ± 0.18
$ZZjj$−QCD	11.1 ± 2.8	18.3 ± 1.1	2.35 ± 0.06	40.8 ± 7.2
tZj	6.2 ± 1.1	6.3 ± 1.1	34.0 ± 5.3	0.17 ± 0.04
$t\bar{t}+V$	4.7 ± 1.0	11.14 ± 0.37	71 ± 15	3.47 ± 0.54
$ZZjj$−EW	1.80 ± 0.45	0.44 ± 0.10	0.10 ± 0.03	4.2 ± 1.2
VVV	0.59 ± 0.15	0.93 ± 0.23	0.13 ± 0.03	1.06 ± 0.30

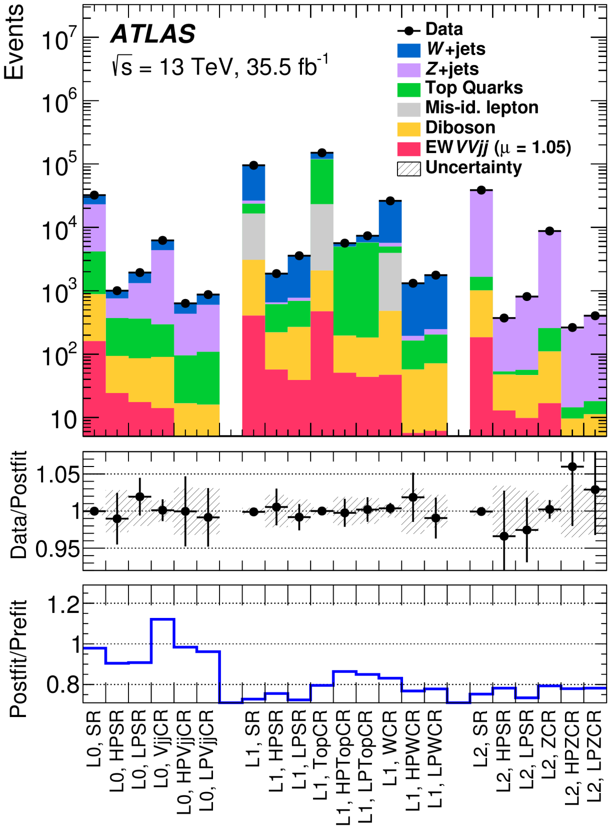
EW VVjj Production

VVjj (36 fb^{-1}): 2.7σ

PRD 100 (2019) 032007







Object selection		
Leptons		$p_T > 7$ GeV, $\lvert\eta\rvert < 2.5$
Small-R jets		$p_T > 20$ GeV if $\lvert\eta\rvert < 2.5$, and $p_T > 30$ GeV if $2.5 < \lvert\eta\rvert < 4.5$
Large-R jets		$p_T > 200$ GeV, $\lvert\eta\rvert < 2.0$
Event selection		
Leptonic V selection	0-lepton	Zero leptons, $p_T^{\nu\nu} > 200$ GeV
	1-lepton	One lepton with $p_T > 27$ GeV, $p_T^{\nu} > 80$ GeV
	2-lepton	Two leptons, with leading (subleading) lepton $p_T > 28$ (20) GeV $83 < m_{\ell\ell} < 99$ GeV
Hadronic V selection	Merged	One large-R jet, $\min(\lvert m_J - m_W\rvert, \lvert m_J - m_Z\rvert)$ $64 < m_J < 106$ GeV
	Resolved	Two small-R jets, $\min(\lvert m_{jj} - m_W\rvert, \lvert m_{jj} - m_Z\rvert)$ $p_T^{j_1} > 40$ GeV, $p_T^{j_2} > 20$ GeV $64 < m_{jj} < 106$ GeV
Tagging-jets		Two small-R non-b jets, $\eta_{\mathrm{tag},j_1} \cdot \eta_{\mathrm{tag},j_2} < 0$, highest m_{jj}^{tag} $m_{jj}^{\mathrm{tag}} > 400$ GeV, $p_T^{\mathrm{tag},j_{1,2}} > 30$ GeV
Number of b-jets	0-lepton	–
	1-lepton	0
	2-lepton	–

$$\mu^{\mathrm{obs}}_{\mathrm{EW}\,VVjj} = 1.05^{+0.42}_{-0.40} = 1.05 \pm 0.20(\mathrm{stat.})^{+0.37}_{-0.34}(\mathrm{syst.}).$$

EW VVjj Production

Fiducial phase space		Predicted $\sigma^{\text{fid,SM}}_{\text{EW}\,VVjj}$ [fb]	Measured $\sigma^{\text{fid,obs}}_{\text{EW}\,VVjj}$ [fb]
Merged	0-lepton	4.1 ± 0.3 (theo.)	10.1 ± 3.3 (stat.) $^{+4.2}_{-3.8}$ (syst.)
	1-lepton	6.1 ± 0.5 (theo.)	2.0 ± 1.5 (stat.) $^{+2.9}_{-2.8}$ (syst.)
	2-lepton	1.2 ± 0.1 (theo.)	2.4 ± 0.6 (stat.) $^{+0.8}_{-0.7}$ (syst.)
Resolved	0-lepton	9.2 ± 0.6 (theo.)	22.8 ± 7.4 (stat.) $^{+9.4}_{-8.5}$ (syst.)
	1-lepton	16.4 ± 1.0 (theo.)	5.5 ± 4.1 (stat.) $^{+7.7}_{-7.5}$ (syst.)
	2-lepton	6.0 ± 0.4 (theo.)	11.8 ± 3.0 (stat.) $^{+3.8}_{-3.5}$ (syst.)
Inclusive	0-lepton	13.3 ± 0.8 (theo.)	32.9 ± 10.7 (stat.) $^{+13.5}_{-12.3}$ (syst.)
	1-lepton	22.5 ± 1.5 (theo.)	7.5 ± 5.6 (stat.) $^{+10.5}_{-10.2}$ (syst.)
	2-lepton	7.2 ± 0.4 (theo.)	14.2 ± 3.6 (stat.) $^{+4.6}_{-4.2}$ (syst.)

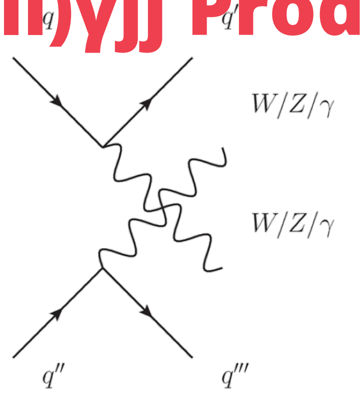
Fiducial phase space	Predicted $\sigma^{\text{fid,SM}}_{\text{EW}\,VVjj}$ [fb]	Measured $\sigma^{\text{fid,obs}}_{\text{EW}\,VVjj}$ [fb]
Merged	11.4 ± 0.7 (theo.)	12.7 ± 3.8 (stat.) $^{+4.8}_{-4.2}$ (syst.)
Resolved	31.6 ± 1.8 (theo.)	26.5 ± 8.2 (stat.) $^{+17.4}_{-17.1}$ (syst.)
Inclusive	43.0 ± 2.4 (theo.)	45.1 ± 8.6 (stat.) $^{+15.9}_{-14.6}$ (syst.)

Uncertainty source	σ_μ
Total uncertainty	0.41
Statistical	0.20
Systematic	0.35
Theoretical and modeling uncertainties	
Floating normalizations	0.09
$Z+$jets	0.13
$W+$jets	0.09
$t\bar{t}$	0.06
Diboson	0.09
Multijet	0.04
Signal	0.07
MC statistics	0.17
Experimental uncertainties	
Large-R jets	0.08
Small-R jets	0.06
Leptons	0.02
$E_{\text{T}}^{\text{miss}}$	0.04
b-tagging	0.07
Pileup	0.04
Luminosity	0.03

EW Z(ll)γjj Production

Zγjj (36 fb^{-1}): 4.1σ

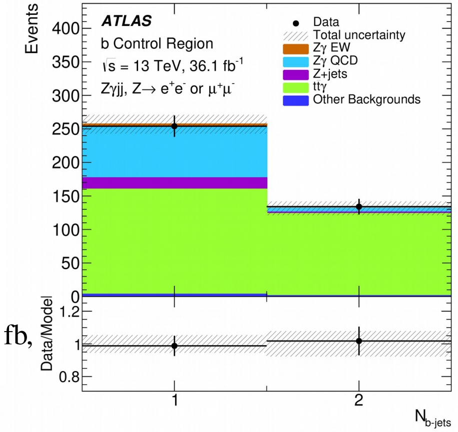
Phys. Lett. B 803 (2020) 135341

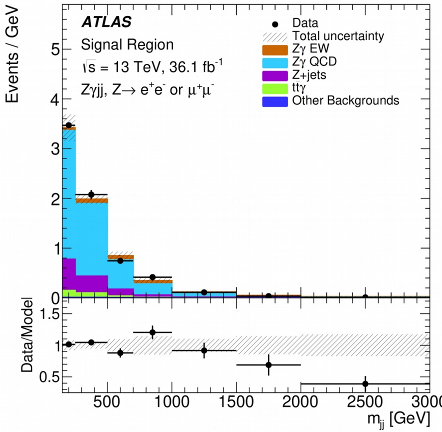


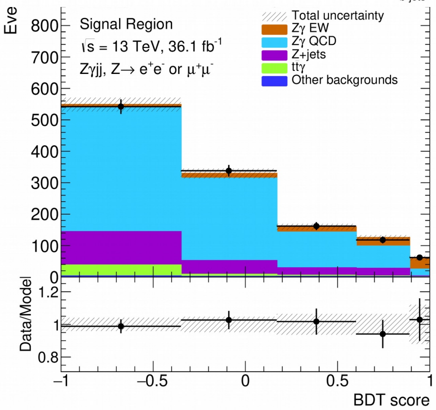
Source	Uncertainty [%]
Statistical	$^{+19}_{-18}$
$Z\gamma jj$–EW theory modelling	$^{+10}_{-6}$
$Z\gamma jj$–QCD theory modelling	±6
$t\bar{t}+\gamma$ theory modelling	±2
$Z\gamma jj$–EW and $Z\gamma jj$–QCD interference	$^{+3}_{-2}$
Jets	±8
Pile-up	±5
Electrons	±1
Muons	$^{+3}_{-2}$
Photons	±1
Electrons/photons energy scale	±1
b-tagging	±2
MC statistical uncertainties	±8
Other backgrounds normalisation (including Z+jets)	$^{+9}_{-8}$
Luminosity	±2
Total uncertainty	±26

	SR		b-CR	
Data	1222		388	
Total expected	1222	±35	389	±19
$Z\gamma jj$–EW (signal)	104	±26	5	± 1
$Z\gamma jj$–QCD	864	±60	82	± 9
Z+jets	200	±40	19	± 4
$t\bar{t}+\gamma$	48	±10	280	±21
Other backgrounds	7	± 1	4	± 1

$$\sigma^{\text{fid.}}_{Z\gamma jj-\text{EW}} = 7.8 \pm 1.5\,(\text{stat.}) \pm 1.0\,(\text{syst.})\,^{+1.0}_{-0.8}\,(\text{mod.})\ \text{fb}, \\ = 7.8 \pm 2.0\ \text{fb}$$







BDT used to separate EW Zγjj from backgrounds.

EW Z(νν)γjj Production

Z(νν)γjj (139 fb^{-1}): 3.2σ

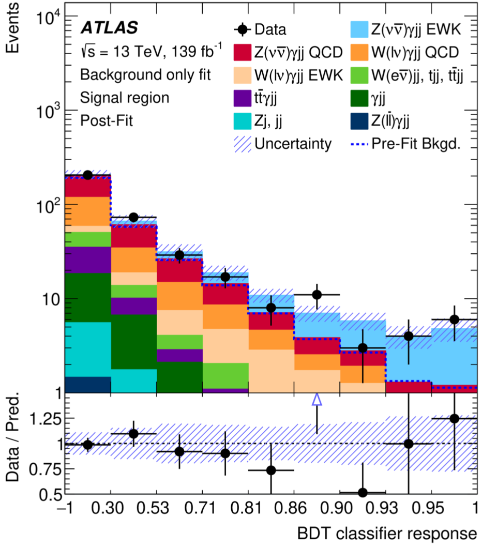
Accepted by JHEP

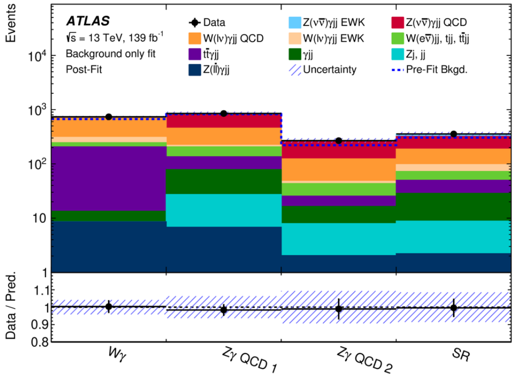
Selections	Cut value
E_T^{miss}	> 120 GeV
E_T^{γ}	> 150 GeV
Number of isolated photons	$N_\gamma = 1$
Photon isolation	$E_T^{cone40} < 0.022 p_T + 2.45$ GeV, $p_T^{cone20}/p_T < 0.05$
Number of jets	$N_{jets} \geq 2$ with $p_T > 50$ GeV
Overlap removal	$\Delta R(\gamma, jet) > 0.3$
Lepton veto	$N_e = 0$, $N_\mu = 0$
$\lvert\Delta\phi(\gamma, \vec{p}_T^{miss})\rvert$	> 0.4
$\lvert\Delta\phi(j_1, \vec{p}_T^{miss})\rvert$	> 0.3
$\lvert\Delta\phi(j_2, \vec{p}_T^{miss})\rvert$	> 0.3
m_{jj}	> 300 GeV
γ-centrality	< 0.6

Analysis targeting aQGC searches

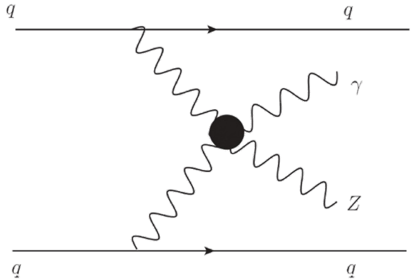
	$W\gamma$ CR	$Z\gamma$ QCD CR 1	$Z\gamma$ QCD CR 2	Signal region
$Z(\nu\bar{\nu})\gamma jj$ EWK	0.108 ± 0.028	11.0 ± 4.3	4.0 ± 2.2	37 ± 14
$Z(\nu\bar{\nu})\gamma jj$ QCD	1.04 ± 0.46	394 ± 84	143 ± 32	133 ± 39
$W(\ell\nu)\gamma jj$ QCD	425 ± 63	237 ± 71	76 ± 24	91 ± 30
$W(\ell\nu)\gamma jj$ EWK	63 ± 12	14.3 ± 2.7	4.5 ± 1.2	24.6 ± 4.9
$W(e\nu)jj, tjj, t\bar{t}jj$	39.8 ± 2.5	70.1 ± 4.1	17.9 ± 1.3	22.5 ± 1.5
$t\bar{t}\gamma jj$	193 ± 57	57 ± 20	9.1 ± 3.4	21.3 ± 7.6
γjj	4.8 ± 7.4	52 ± 36	8 ± 11	20 ± 17
Zj, jj	0.06 ± 0.66	20 ± 14	5.9 ± 6.9	6.6 ± 7.8
$Z(\ell\bar{\ell})\gamma jj$	8.6 ± 2.5	6.8 ± 2.0	2.04 ± 0.95	2.2 ± 1.3
Total	735 ± 30	863 ± 54	271 ± 25	357 ± 30
Data	737	849	268	356

Fiducial $\sigma_{Z\gamma \text{EWK}} = 0.77^{+0.34}_{-0.30}$ fb.





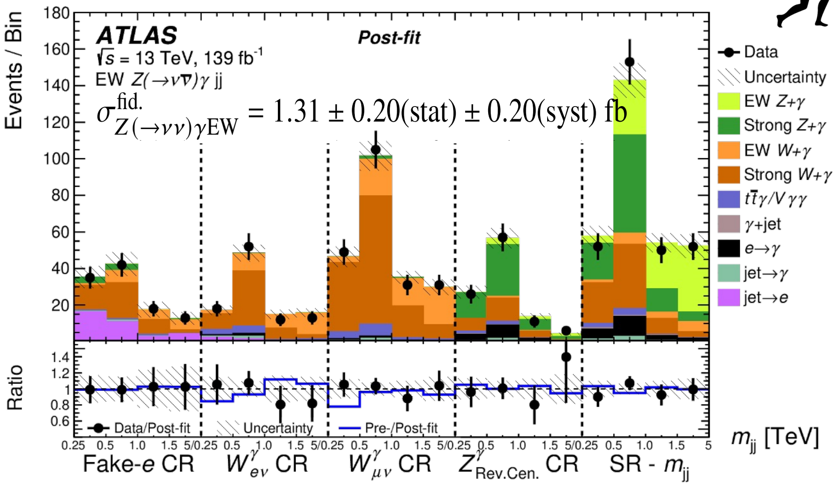
Source of uncertainty	$\Delta\sigma/\sigma$ [%]
Experimental	
Jets	$-3.2/+3.4$
Electrons and photons	$-0.3/+1.7$
Muons	$-0.4/+0.5$
E_T^{miss}	$-1.8/+2.2$
Pile-up modelling	$-1.7/+3.2$
Trigger efficiency	$-0.9/+2.1$
Luminosity	$-1.2/+2.6$
Theory	
$Z(\nu\bar{\nu})\gamma jj$ EWK/QCD interference	$-0.6/+2.6$
$Z(\nu\bar{\nu})\gamma jj$ EWK process	$-6\ /+12$
$Z(\nu\bar{\nu})\gamma jj$ QCD process	$-15\ /+16$
Other processes	$-5.3/+7.7$
Other sources	
Data-driven backgrounds	$-0.9/+1.2$
Pile-up background	$-1.2/+2.6$
$Z(\nu\bar{\nu})\gamma jj$ QCD m_{jj} modelling	$-4.4/+4.4$



EW Z(νν)γjj Production

Z(νν)γjj (139 fb^{-1}): 5.2σ
Accepted by JHEP

Observable	Requirements
N_{jet} with $p_{\text{T}} > 25$ GeV	≥ 2
$\lvert\eta(j_{1,2})\rvert$	< 4.5
$p_{\text{T}}(j_1)$ [GeV]	> 60
$p_{\text{T}}(j_2)$ [GeV]	> 50
$\Delta R(j, \ell)$	> 0.4
$\lvert\Delta\eta_{\text{jj}}\rvert$	> 3.0
C_3	< 0.7
m_{jj} [TeV]	> 0.5
truth-$E_{\text{T}}^{\text{miss}}$ [GeV]	> 150
$\Delta\phi(\text{truth-}\vec{E}_{\text{T}}^{\text{miss}}, j_i)$	> 1.0
$p_{\text{T}}(\gamma)$ [GeV]	$> 15, < 110$
$\lvert\eta(\gamma)\rvert$	< 2.37
$E_{\text{T}}^{\text{cone20}}/E_{\text{T}}^{\gamma}$	< 0.07
$\Delta R(\gamma, \text{jet-or-}\ell)$	> 0.4
C_γ	> 0.4
$\Delta\phi(\text{truth-}\vec{E}_{\text{T}}^{\text{miss}}, \gamma)$	> 1.8
N_ℓ with $p_{\text{T}} > 4$ GeV and $\lvert\eta\rvert < 2.47$	0



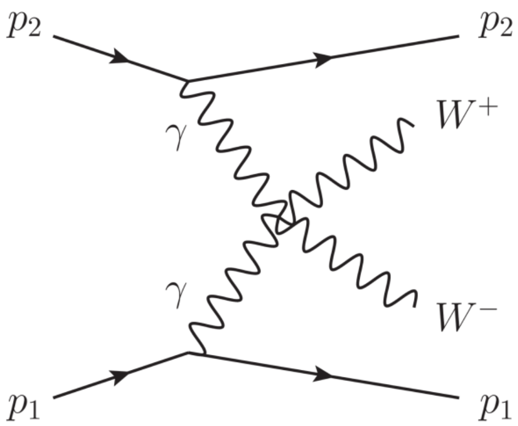
Process	SR - m_{jj} [TeV] 0.25-0.5	0.5-1.0	1.0-1.5	≥ 1.5
Strong $Z\gamma$ + jets	20 ± 6	54 ± 12	13 ± 5	5 ± 2
EW $Z\gamma$ + jets	4 ± 1	30 ± 7	25 ± 5	36 ± 7
Strong $W\gamma$ + jets	22 ± 6	35 ± 10	9 ± 3	3 ± 1
EW $W\gamma$ + jets	2 ± 1	6 ± 1	4 ± 1	5 ± 1
jet→ γ	1 ± 1	2 ± 2	1 ± 1	0.4 ± 0.3
jet→ e	–	–	–	–
$e \rightarrow \gamma$	6 ± 1	11 ± 1	2.6 ± 0.4	1.4 ± 0.3
γ + jet	0.7 ± 0.5	0.4 ± 0.3	0.1 ± 0.1	0.1 ± 0.1
$t\bar{t}\gamma/V\gamma\gamma$	2 ± 1	4 ± 1	0.4 ± 0.2	0.1 ± 0.1
Fitted Yields	58 ± 6	143 ± 12	54 ± 5	52 ± 6
Data	52	153	50	52
Data/Fit	0.90 ± 0.15	1.07 ± 0.11	0.93 ± 0.16	0.99 ± 0.18

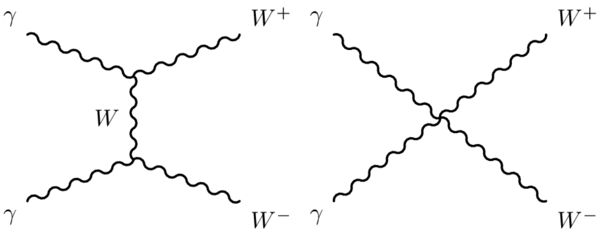
Combination of SM analysis with observation from search for invisible Higgs decays in E_T^{miss} γjj

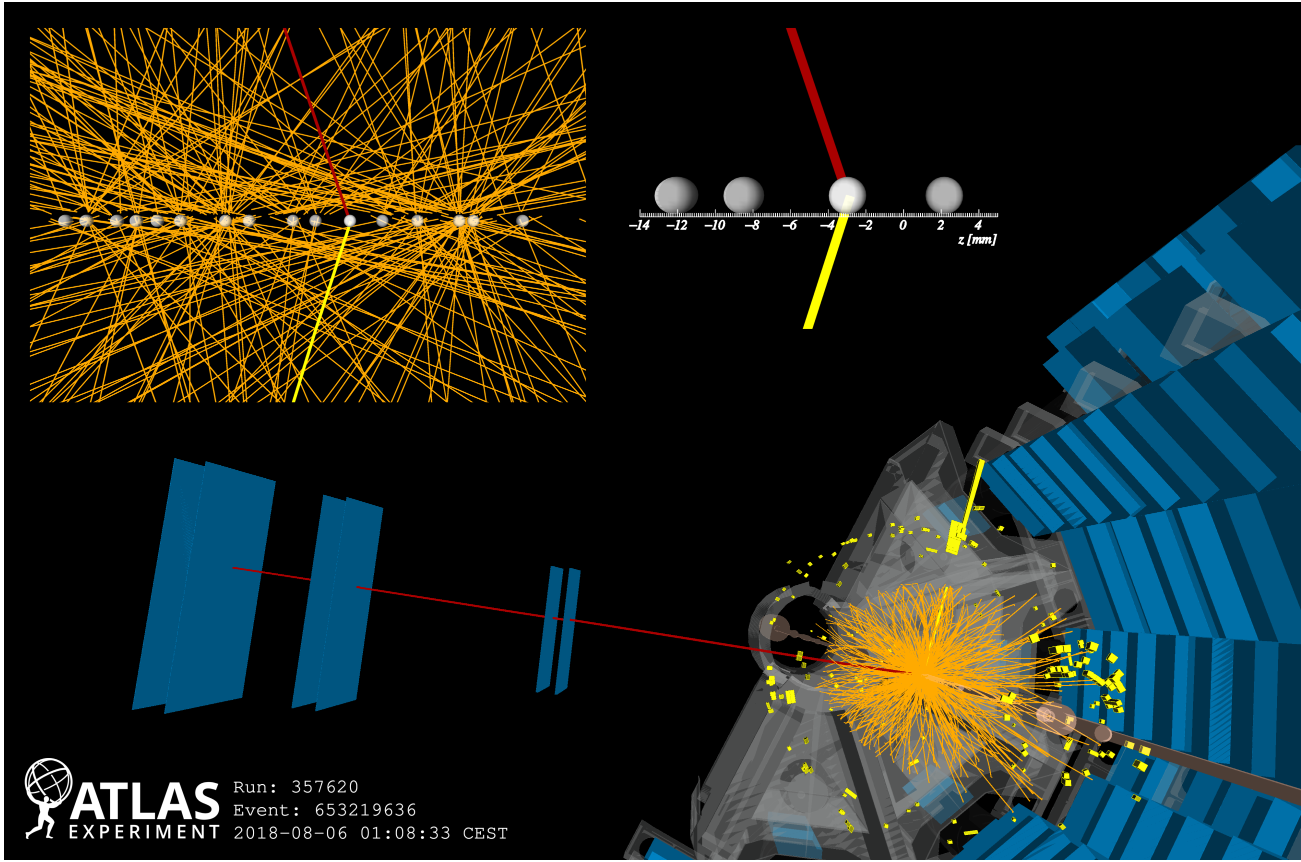
POI	Value: SM analysis	Inv. Higgs ana.	Combination
$\mu_{Z\gamma\text{EWK}}$	0.78 ± 0.33	1.03 ± 0.25	0.96 ± 0.18
$\mu_{Z\gamma\text{QCD}}$	1.21 ± 0.37	1.02 ± 0.41	1.17 ± 0.27
$\mu_{W\gamma}$	1.02 ± 0.22	1.01 ± 0.20	1.01 ± 0.13

Combination: 6.3σ
Accepted by JHEP

Photon-induced WW :: γγ → WW

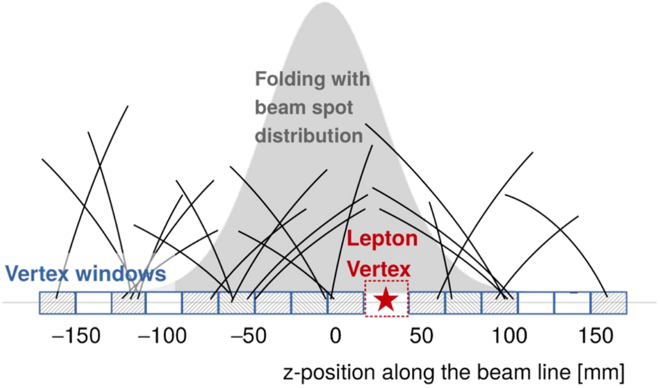






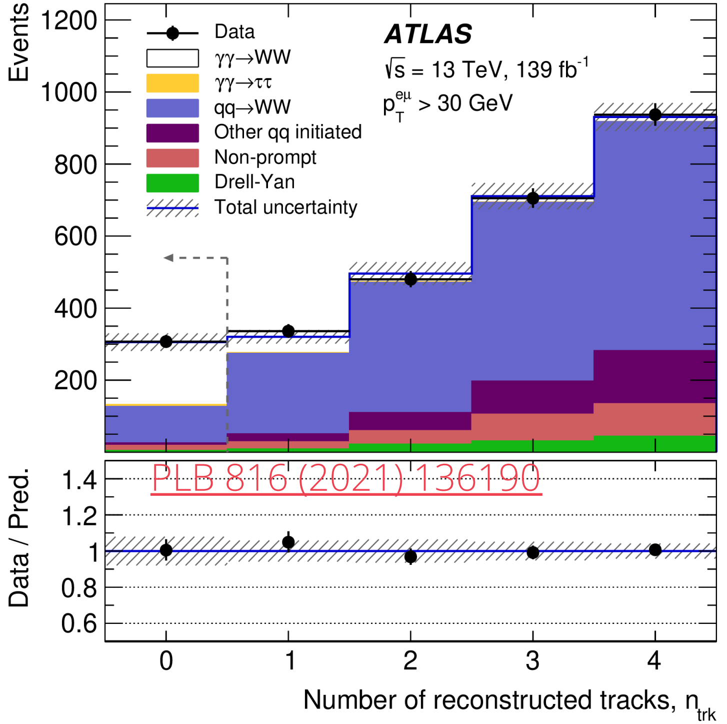
Photon-induced WW :: γγ → WW

σ(γγ→WW) = 3.13 ± 0.31(stat) ± 0.28(sys) fb
Observation: 8.4 σ



	Signal region		Control regions	
n_{trk}	$n_{trk}=0$		$1 \le n_{trk} \le 4$	
$p_T^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \to WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \to \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell–Yan	4.5 ± 0.9	280 ± 40	106 ± 19	4700 ± 400
$qq \to WW$ (incl. gg and VBS)	101 ± 17	55 ± 10	1700 ± 270	970 ± 150
Non-prompt	14 ± 14	36 ± 35	220 ± 220	500 ± 400
Other backgrounds	7.1 ± 1.7	1.9 ± 0.4	311 ± 76	81 ± 15
Total	305 ± 18	459 ± 19	2460 ± 60	6320 ± 130
Data	307	449	2458	6332

$$W^+W^- \to e^\pm \nu \mu^\mp \nu$$



PLB 816 (2021) 136190

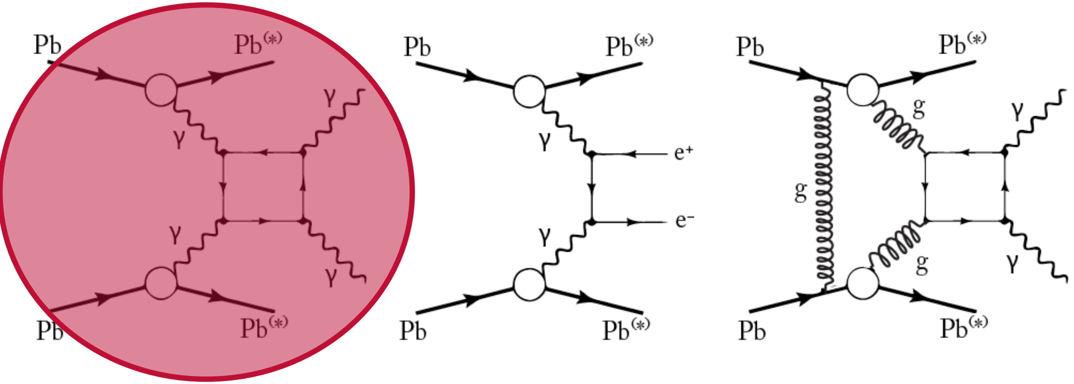
$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\text{ fb}$$

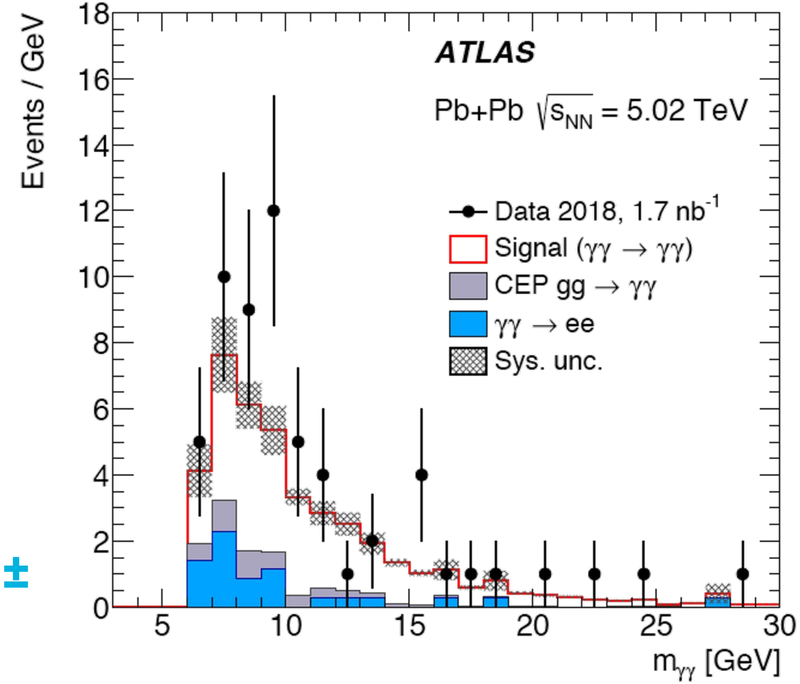
Photon-induced WW :: γγ → WW

$\sigma(\gamma\gamma \rightarrow WW)$ = 3.13 ± 0.31(stat) ± 0.28(sys) fb
Observation: 8.4 σ

Source of uncertainty	Impact [% of the fitted cross section]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons, systematic	1.5
Misidentified leptons, statistical	5.9
Other background, statistical	3.2
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other background modelling	1.7
Luminosity	1.7
Total	8.9

Photon-Photon Scattering in Pb+Pb Collisions





Signal: two back-to-back photons
Background: mis-reconstructed electrons and gg → γγ via QCD

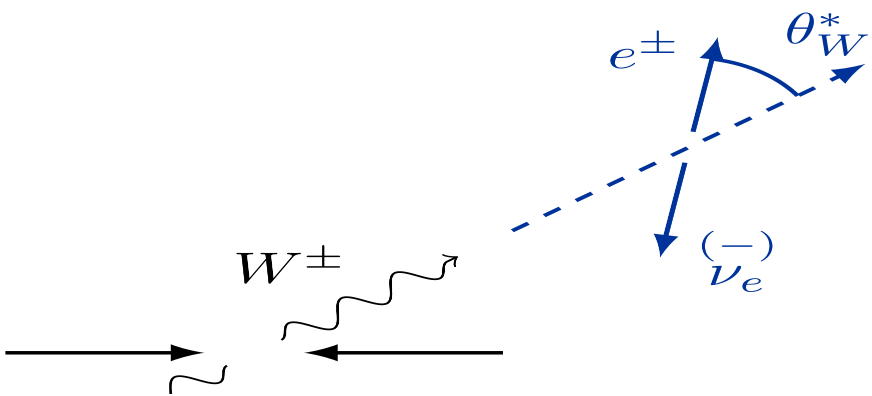
59 events w/ expected background of 12 ± 3
8.2σ observation of light-by-light scattering

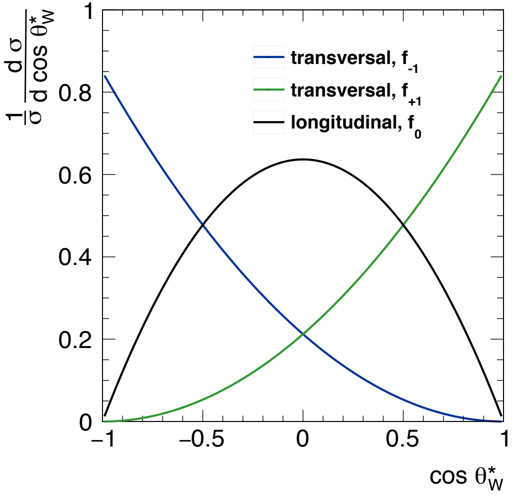
PRL 123 (2019) 052001

Opportunities in VBS Topologies

Polarised VBS Production

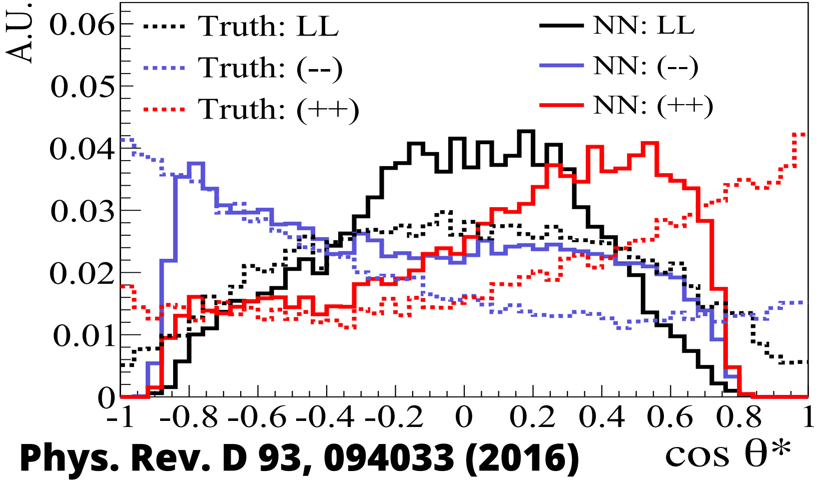
- Longitudinal VBS : key aspect of EWSB but SMALL (5-10% of $W^\pm W^\pm jj$ fraction)
- Probe of unitarization mechanism and new physics!
- Challenging to observe, esp. for $W^\pm_L W^\pm_L jj$ → will require HL-LHC (more later)
- Looking into **improving event selection and using** machine learning **to reconstruct kinematic properties of the W boson, as well as using** hadronic W decays



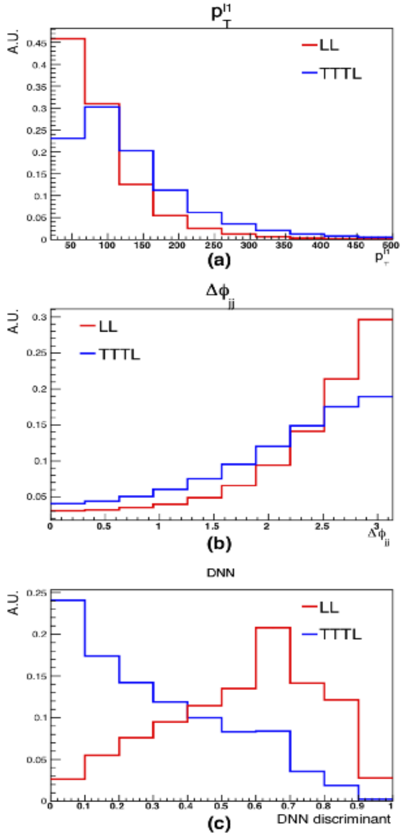


Polarised W±W±jj Production

Using ML to improve sensitivity

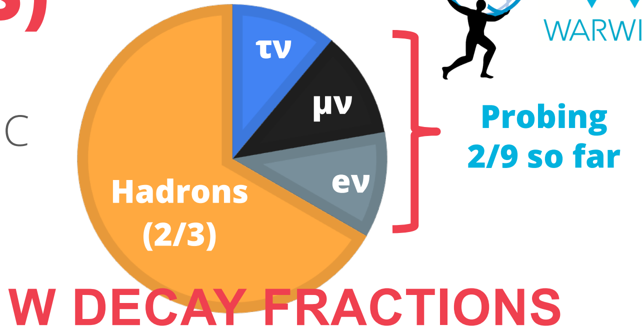


Phys. Rev. D 93, 094033 (2016)



Phys. Rev. D 99, 033004 (2019)

Probing all-hadronic $W^{\pm}W^{\pm}jj$ (VBS)

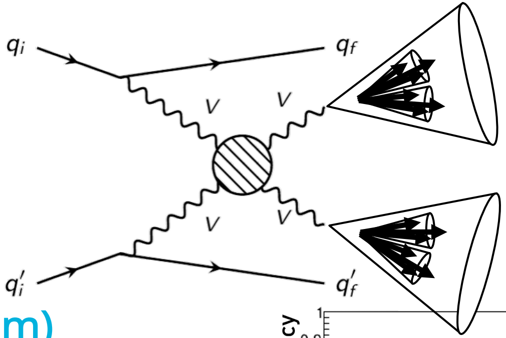


Excellent channel to probe longitudinal polarisation at the LHC

- Leveraging high branching fraction of W→qq
- Acces to both W decay products (to access polarisation)
- Tagging two forward jets (VBS) and two V-jets

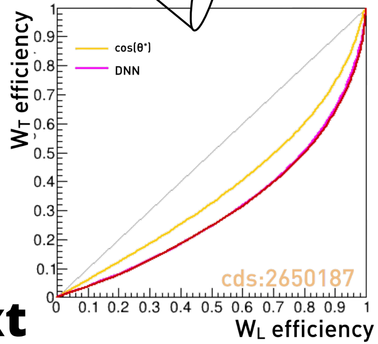
Challenges:

- Charge reconstruction
- Background suppression
- Discriminate $W^{\pm}W^{\pm}jj$ VBS from QCD
- Discriminate longitudinal (W_L) from transverse (W_T) (use difference in decay products w.r.t. W momentum)



Tools:

- Jet substructure techniques (grooming, n-subjettiness)
- Machine learning: DNN, GNN



Techniques developed useful in other LHC analysis context

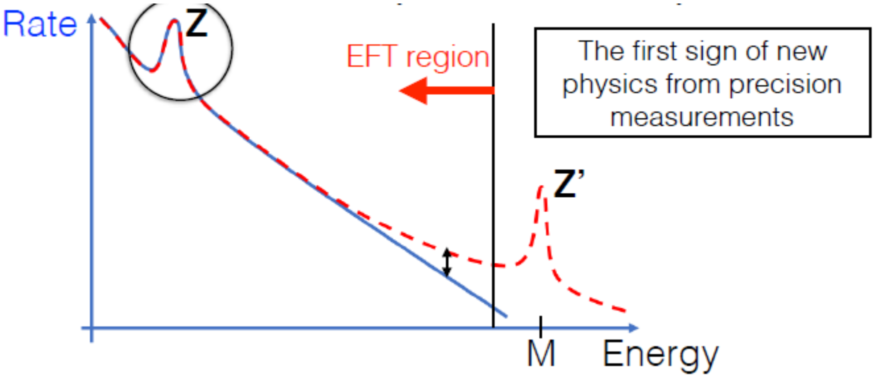
Looking for BSM Physics in VBS Topologies

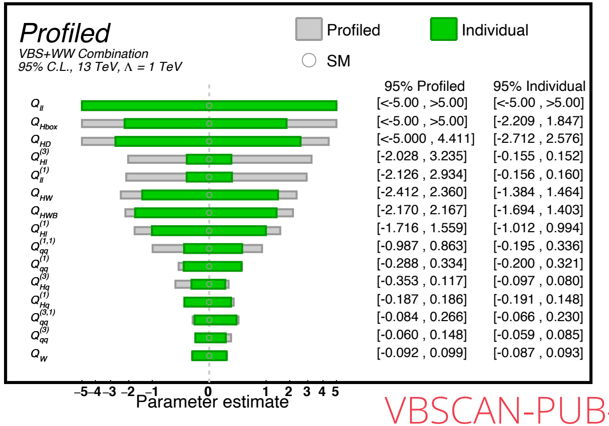
Effective Field Theory

- Deviations from the SM are studied in the context of SMEFT
  - Model-independent way to look at new interactions of SM particles
- High sensitivity of VBS to operators generating anomalous triple (TGC) and quartic (QGC) gauge couplings

$$\sigma \propto |\mathcal{M}_{\mathrm{SMEF}} = |\mathcal{M}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{M}_i^{(6)}\mathcal{M}_{\mathrm{SM}}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4}\left|\mathcal{M}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)}c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{M}_i^{(6)}\mathcal{M}_j^{(6)*}\right) + O\left(\Lambda^{-4}\right)$$

SM **Interference SM-EFT (linear)** **Pure EFT (quadradic)** **Interference between EFT (cross-term)**





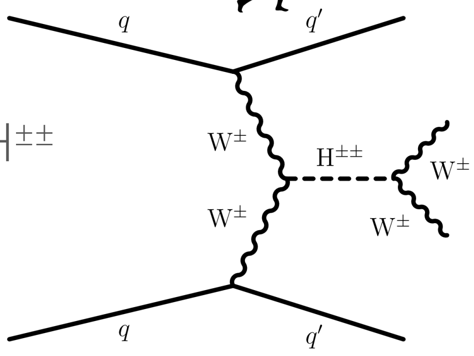
VBSCAN-PUB-05-21

Georgi-Machacek model

Nucl.Phys.B 262 (1985) 463-477

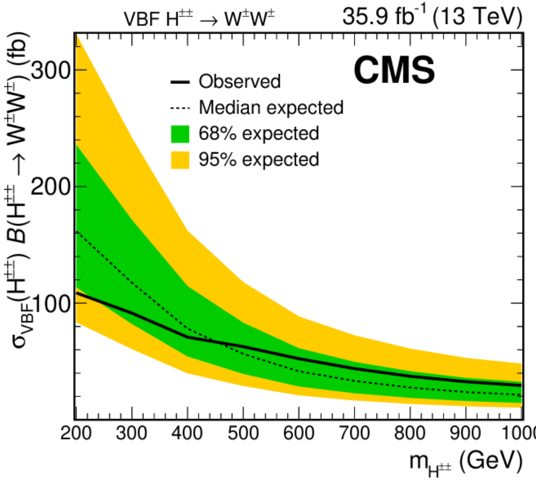
Higgs triplet extension: one real and one complex triplet

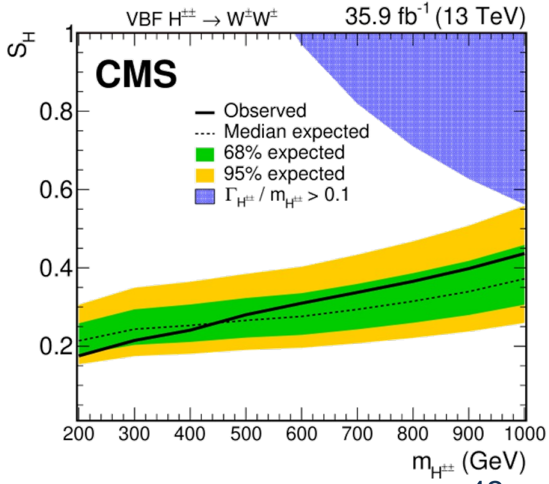
- Tree-level $H^{\pm}$ WZ coupling and doubly charged Higgs: $H^{\pm\pm}$
- Fermiophobic quintuplet under custodial symmetry with H, $H^{\pm}$, and $H^{\pm\pm}$ physical states



$$\sin\theta_H =: s_H = \frac{2\sqrt{2}v_\Xi}{v_{\rm SM}}$$

$$\Phi = \begin{pmatrix} \phi_2^* & \phi_1 \\ -\phi_1^* & \phi_2 \end{pmatrix}, \qquad \Xi = \begin{pmatrix} \chi_3^* & \xi_1 & \chi_1 \\ -\chi_2^* & \xi_2 & \chi_2 \\ \chi_1^* & -\xi_1^* & \chi_3 \end{pmatrix}.$$

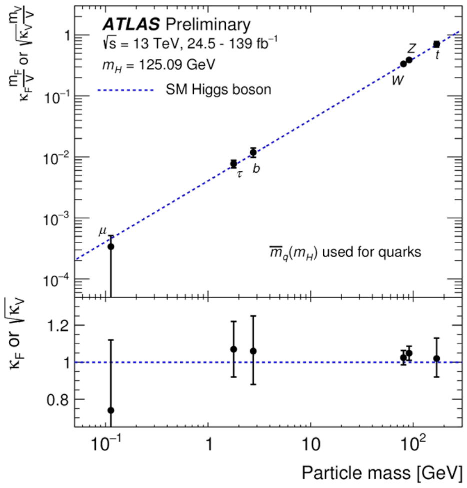


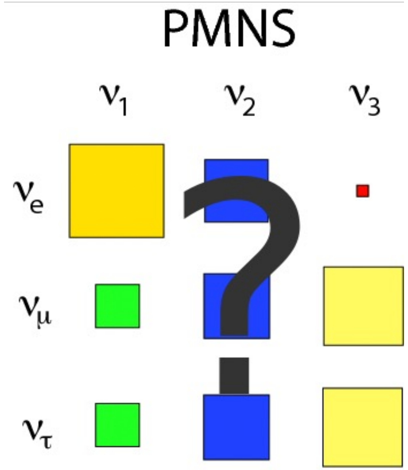


Origin of mass in the SM

Masses of **charged fermions**: Yukawa-like interactions with Higgs field

- Observed at the LHC
- On-going efforts for precision, CP tests…



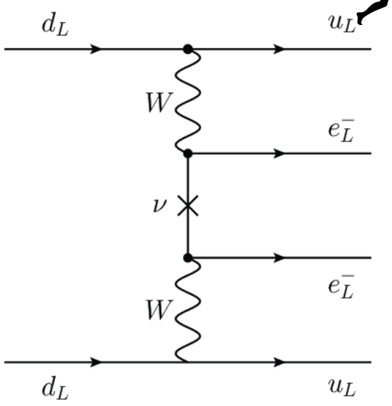


But mechanism behind **mass of neutrinos** (neutral fermions) *remains unclear*

- No right-handed ν in SM – no Higgs coupling
- From neutrino oscillation measurements: $m_\nu > 0$
- Much larger mixing compared to quarks

Neutrino-less double β decay (0νββ)

Phys. Rev. D 25, 2951 (1982) JHEP 1106 (2011) 091

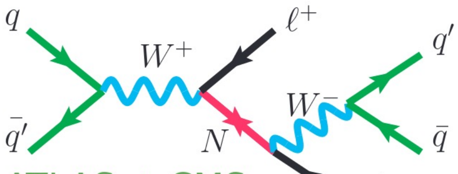


0νββ implies effective Majorana mass terms mχχ

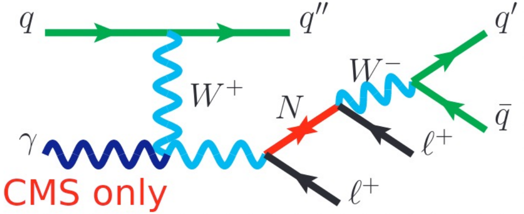
- Direct probe of new mass generation mechanism
- ΔL = 2 : source of matter-antimatter asymmetry

LHC focus has so-far been on s-channel production of heavy ν (100 GeV – 1 TeV)

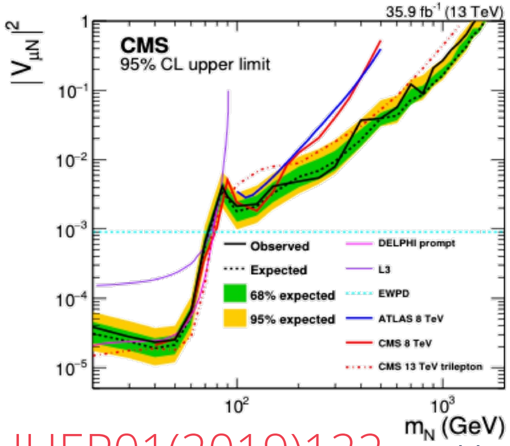
- Final state corresponding to t-channel not covered
- 2 jets, 2 SS e/μ/τ, <u>no Etmiss</u> → similar to $W^{\pm}W^{\pm}jj$



ATLAS + CMS



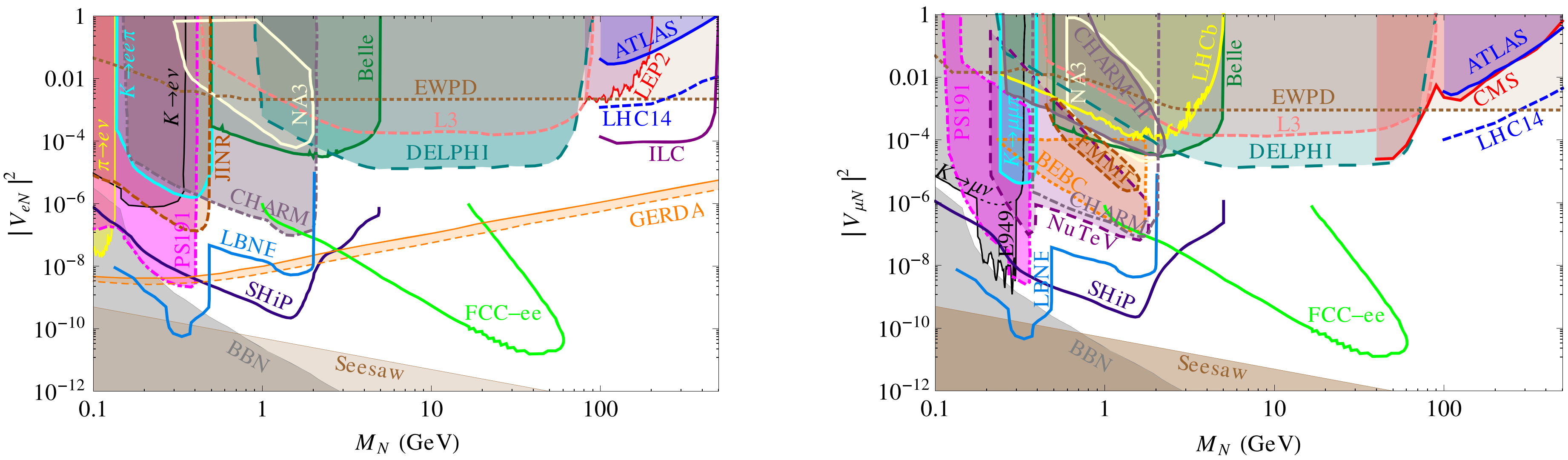
CMS only



Phys. Lett. B 798 (2019) 134942 JHEP 01 (2019) 016 JHEP01(2019)122

Neutrino-less double β decay (0νββ)

- GERDA = 0νββ experiment → electrons only
- EWPD = Z invisible width measurement at LEP
- **0νββ-like at LHC contributes for M_N > 1 TeV**

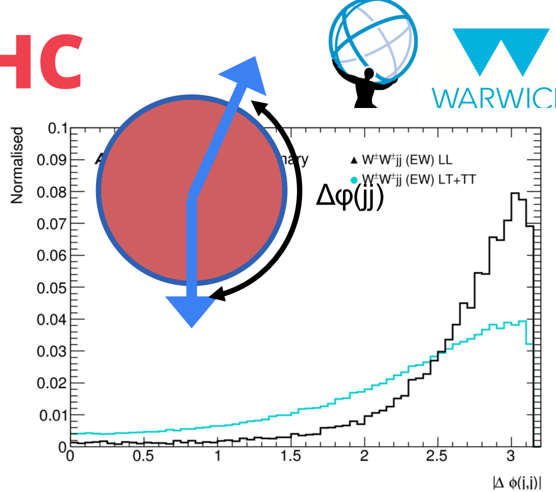


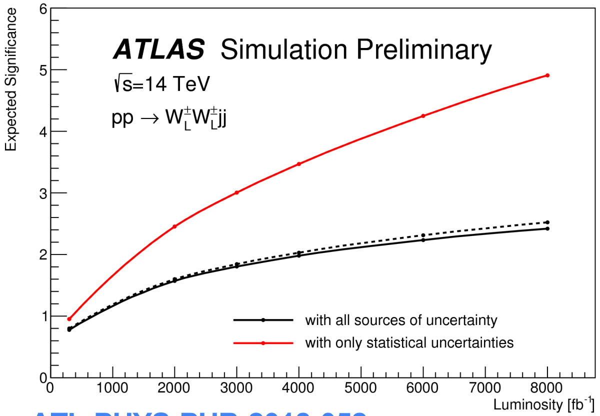
New J. Phys. 17 (2015) 075019 (LHC Run-1 only)

Prospects for VBS at HL-LHC

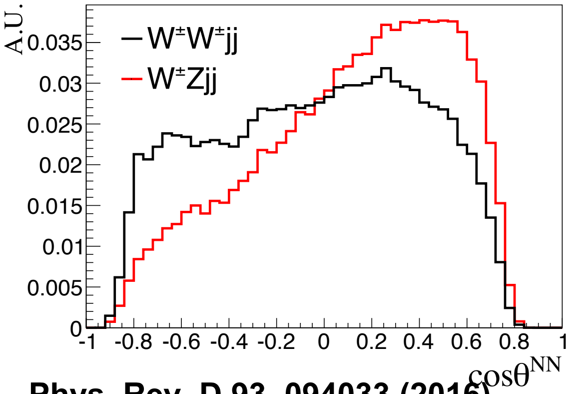
W±W±jj EW Production at the HL-LHC

- 5-10% of $W^\pm_L W^\pm_L jj$ fraction
- Probe of unitarization mechanism and new physics!
- Need ATLAS+CMS to measure (w/o new techniques)
- Using ML & hadronic decays

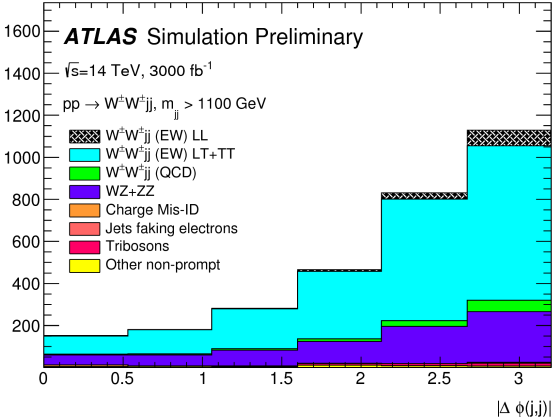




ATL-PHYS-PUB-2018-052



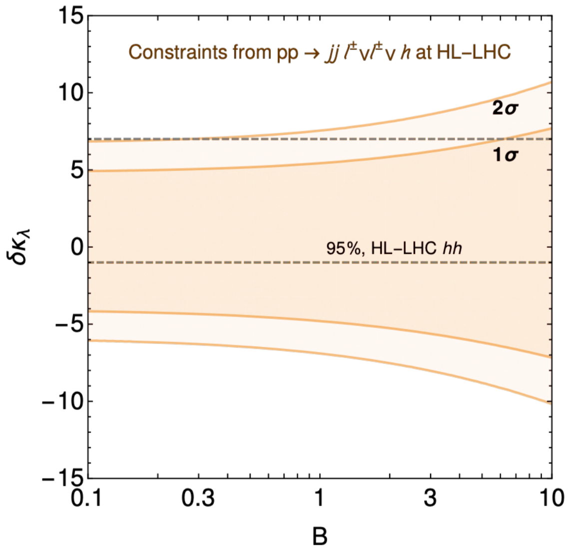
Phys. Rev. D 93, 094033 (2016)
(Simulation)



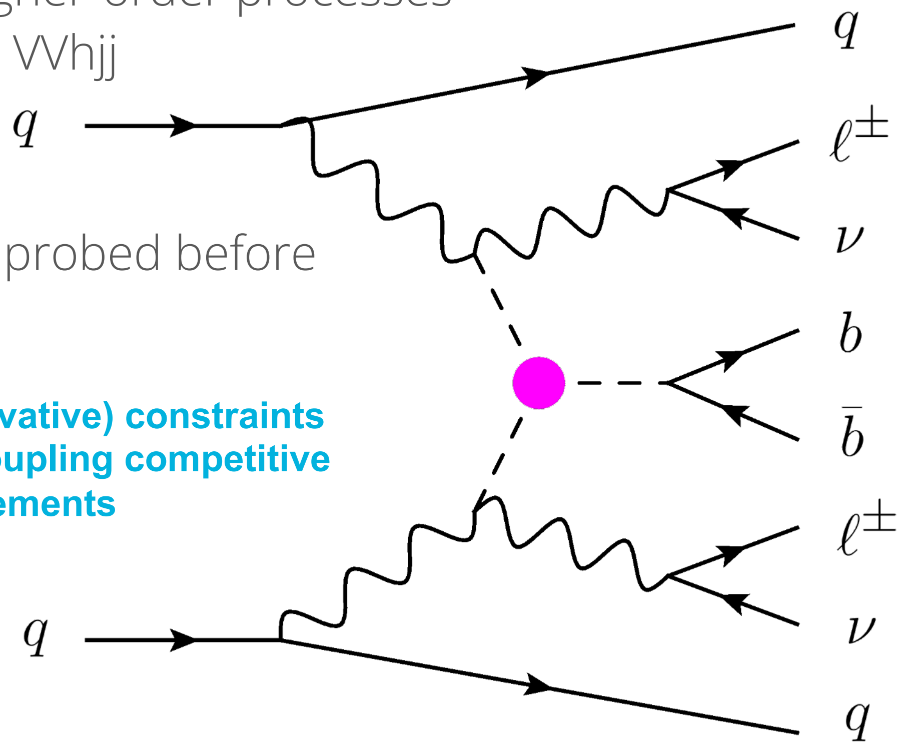
+ Prospects studies @ FCC-hh and muon collider (opposite-sign WWjj)

Probing the Higgs self-coupling

- VBS topology can be used to look at higher-order processes
- Higgs self-coupling accessible via pp → VVhjj
  - H → bb mode most promising
- Lepton channel viable @ HL-LHC
  - Semi-leptonic / hadronic might be probed before



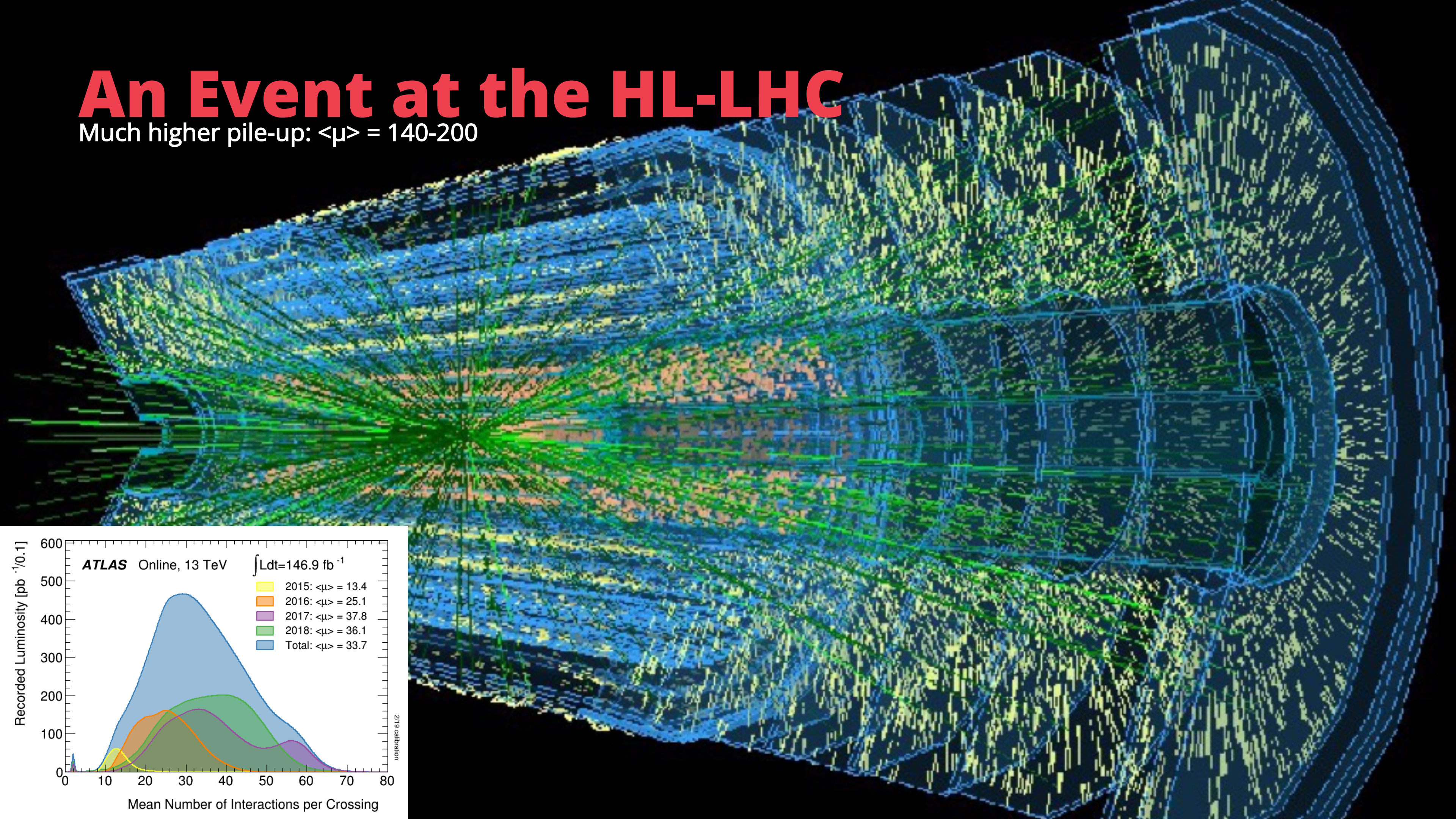
HL-LHC (conservative) constraints on Higgs self-coupling competitive with hh measurements



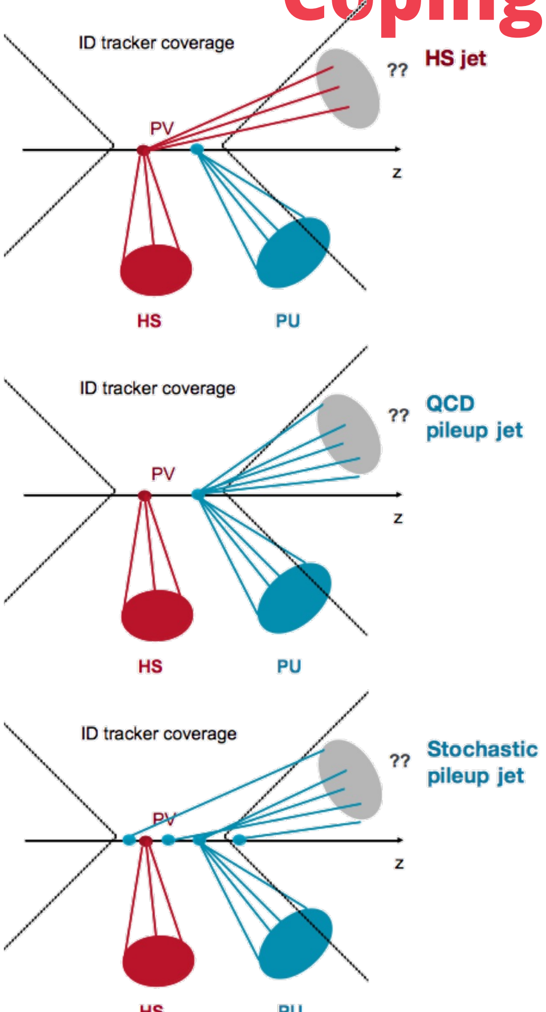
Phys. Rev. Lett. 123, 181801

An Event at the HL-LHC

Much higher pile-up: <μ> = 140-200



Coping with challenging conditions



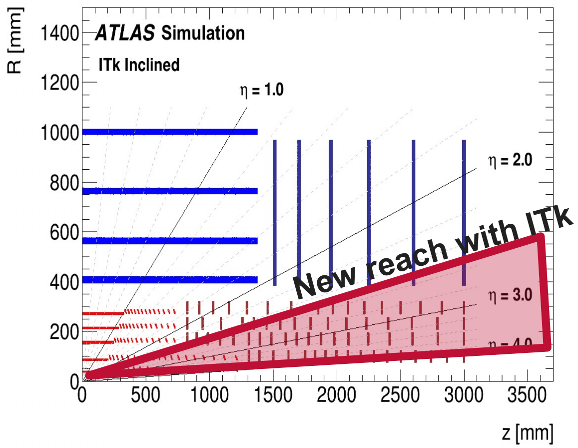
Multiple interactions (pile-up, PU) are a challenge

- $W^{\pm}W^{\pm}jj$: **forward jets** from the **hard-scatter** primary vertex
- **Pile-up** causes forward "pile-up" jets (QCD and stochastic)
  - Increases background contribution

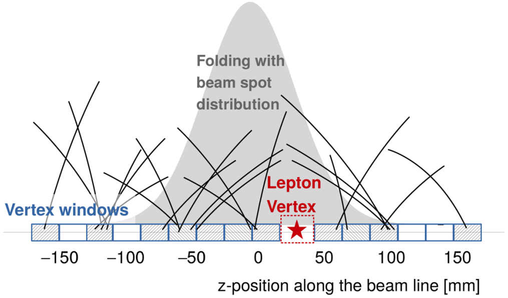
Lack of particle tracking coverage in the forward region makes it more **difficult to identify/suppress jets**

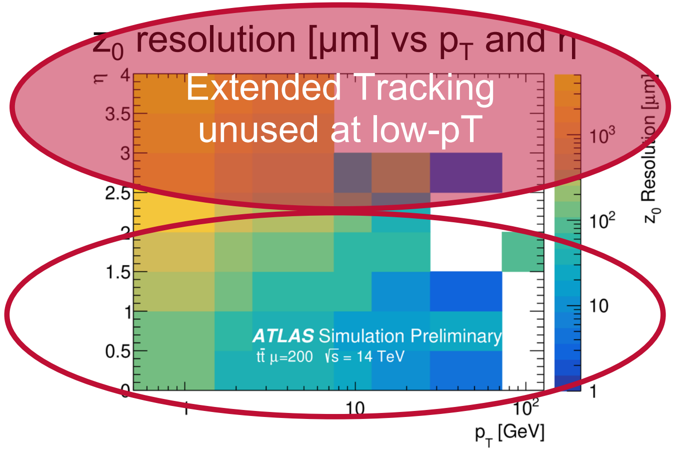
At the High-Luminosity LHC: **5x more pile-up**

- ATLAS Inner Tracker (ITk) upgrade with **extended tracking coverage**

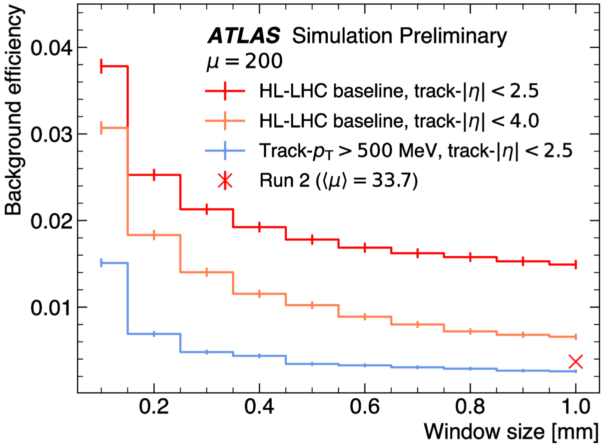


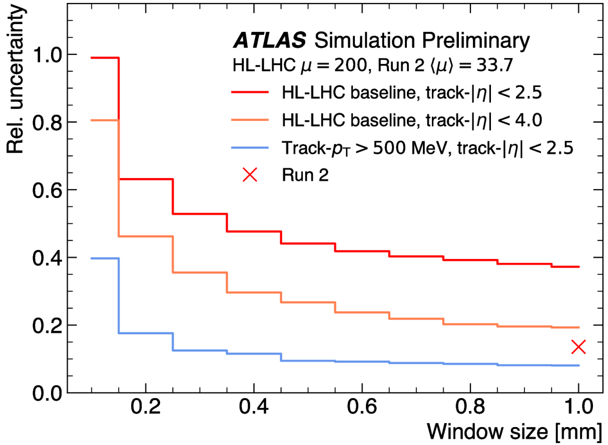
Photon-induced WW :: γγ → WW @ HL-LHC

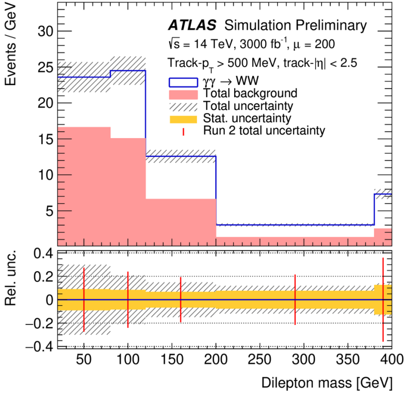


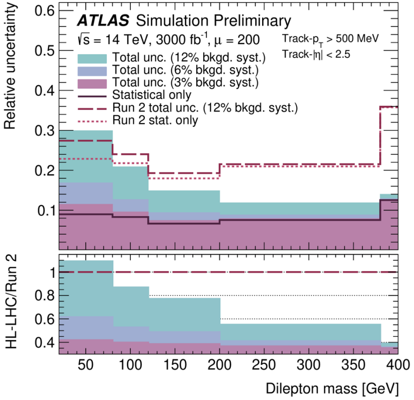


Low-pT tracking



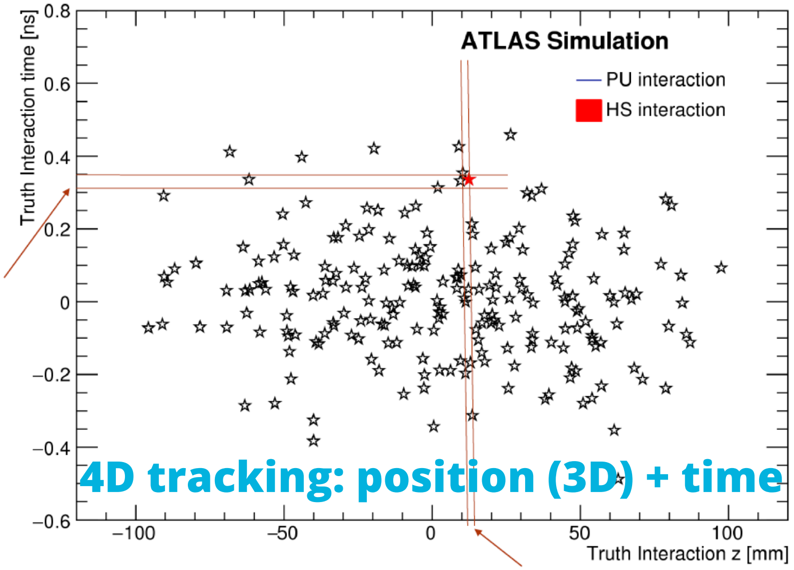






nominal systematic on the background of 12%

Improved tracking to handle high pile-up



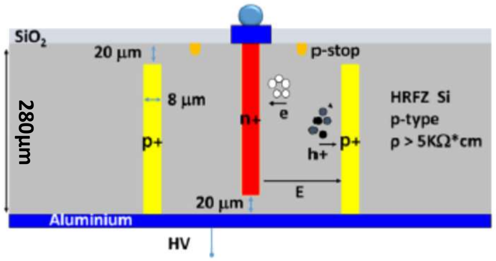
- Timing detectors promising to improve tracking under high pile-up conditions
  - Using **time-wise association of tracks to primary interaction vertex**
  - Low-Gain Avalanche Detectors (LGADs) have a **time resolution down to 30 ps**
- ATLAS & CMS will have LGAD **timing layers,** but **not near the collision point** (not radiation hard enough)
  - **Must go further: sensor R&D for 4D tracking in the whole tracker (e.g. 3D silicon designs)**

- **ATLAS will be upgraded early/mid 2030's:** replacement of two innermost layers
  - Opportunity **to develop new technologies** for fast silicon sensors (4D tracking)
- Also useful for future colliders (esp. FCC-hh, but also CEPC or FCC-ee)

3D sensor timing

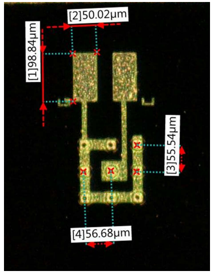
- Promising timing behaviour of 3D sensors
  - Better radiation hardness than LGADs

CNM double sided n-on-p, 50 x 50 µm



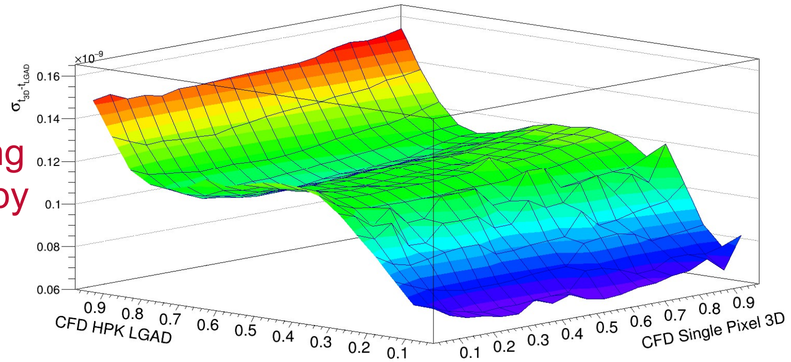
Tested Devices

- Process: 2-sided
- Substrate: high Z, p-type FZ Silicon, 4" wafers
- Thickness: ~ 280 um
- Run: CNM 5936-11
- Pixel Geometry: 50 x 50 um, 1E, single cell
- Capacitance: ~80 – 100 pF per cell



$$(\sigma_{\mathrm{Dut}})_{CFD_{ij}} = \sqrt{(\sigma^2_{\mathrm{Tot}})_{CFD_{ij}} - (\sigma^2_{\mathrm{Ref}})_{CFD_i}}$$

3D timing behind by > 60 ps



2D optimization plot – 0.5% binning

Time Resolution: $\sigma^2_{tot} = \underbrace{\sigma^2_{timewalk}}_{\sigma^2_{Dist.} + \sigma^2_{Landau}} + \underbrace{\sigma^2_{jitter}}_{\left(\frac{t_{rise}}{S/N}\right)^2} + \underbrace{\sigma^2_{conversion}}_{\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2} + \underbrace{\sigma^2_{Clock}}_{\text{Fixed Term} \sim 5\text{-}7\ psec}$

V. Gkougkousis, 17th "Trento" Workshop, March 2-4, 2022

The Start of a Long Journey

These sets of results using Run-2 data are ony the beginning…

As we learned to understand the backgrounds and signal, we can proceed with further probes:

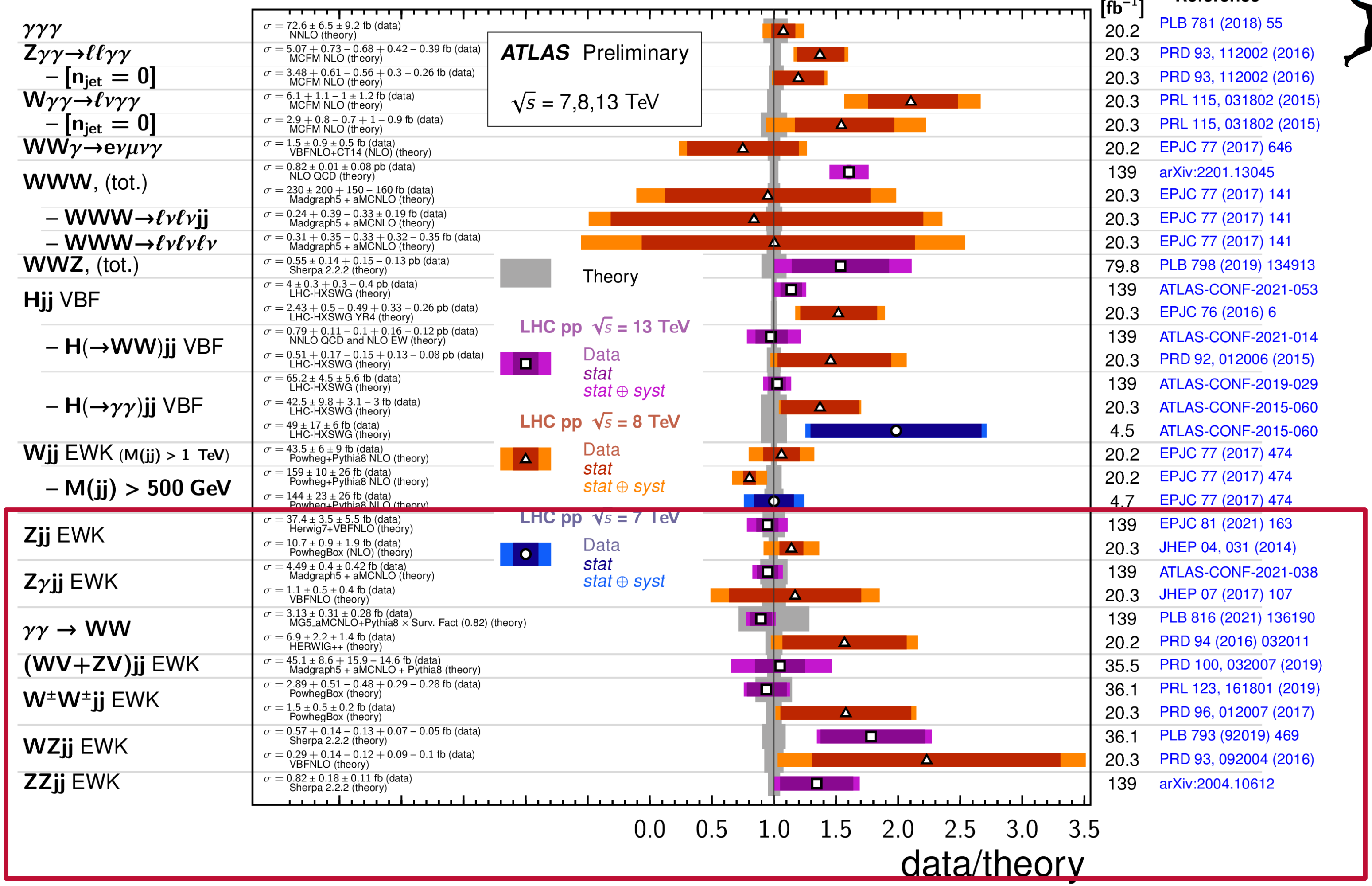
- Differential distributions
- Probing polarisation

But we will need the HL-LHC for high precision measurements and observation of polarisation

- Improved analysis techniques (ML, hadronic decays)
- Timing for HL-LHC

Stay tuned on this exciting field!

VBF, VBS, and Triboson Cross Section Measurements



ADDITIONAL MATERIAL

ZZjj Production :: Event Selection

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Muons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.7$	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Jets	$p_{\mathrm{T}} > 30$ (40) GeV for $\lvert\eta\rvert < 2.4$ ($2.4 < \lvert\eta\rvert < 4.5$)	$p_{\mathrm{T}} > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_{\mathrm{T}} > 20, 20, 10$ GeV for the leading, sub-leading and third leptons Two OSSF lepton pairs with smallest $\lvert m_{\ell^+\ell^-} - m_Z\rvert + \lvert m_{\ell'^+\ell'^-} - m_Z\rvert$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $60 < m_{\ell^+\ell^-} < 120$ GeV	$p_{\mathrm{T}} > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$

VVjj Production :: Event Selection

Table 1: Summary of the event selection in the 0-, 1- and 2-lepton channels.

Selection	0-lepton	1-lepton	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ triggers	Single-electron triggers Single-muon or $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers	Single-lepton triggers
Leptons	0 ‘loose’ leptons with $p_{\mathrm{T}} > 7$ GeV	1 ‘tight’ lepton with $p_{\mathrm{T}} > 27$ GeV 0 ‘loose’ leptons with $p_{\mathrm{T}} > 7$ GeV	2 ‘loose’ leptons with $p_{\mathrm{T}} > 20$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 28$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV	> 80 GeV	–
$m_{\ell\ell}$	–	–	$83 < m_{ee} < 99$ GeV $(-0.0117 \times p_{\mathrm{T}}^{\mu\mu} + 85.63\ \mathrm{GeV}) < m_{\mu\mu} < (0.0185 \times p_{\mathrm{T}}^{\mu\mu} + 94\ \mathrm{GeV})$
Small-R jets	$p_{\mathrm{T}} > 20$ GeV if $\lvert\eta\rvert < 2.5$, and $p_{\mathrm{T}} > 30$ GeV if $2.5 < \lvert\eta\rvert < 4.5$		
Large-R jets	$p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2$		
$V_{\mathrm{had}} \rightarrow J$ $V_{\mathrm{had}} \rightarrow jj$	V boson tagging, $\min(\lvert m_J - m_W\rvert, \lvert m_J - m_Z\rvert)$ $64 < m_{jj} < 106$ GeV, jj pair with $\min(\lvert m_{jj} - m_W\rvert, \lvert m_{jj} - m_Z\rvert)$, leading jet with $p_{\mathrm{T}} > 40$ GeV		
Tagging-jets	$j \notin V_{\mathrm{had}}$, not b-tagged, $\Delta R(J, j) > 1.4$ $\eta_{\mathrm{tag},j_1} \cdot \eta_{\mathrm{tag},j_2} < 0$, $m_{jj}^{\mathrm{tag}} > 400$ GeV, $p_{\mathrm{T}} > 30$ GeV		
Num. of b-jets	–	0	–
Multijet removal	$p_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$ $\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{small-}R\text{ jet})] > \pi/6$ $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, V_{\mathrm{had}}) > \pi/9$	–	–

VVjj Production :: Event Selection

Table 4: Fiducial phase-space definitions used for the measurement of electroweak $VVjj$ production.

Object selection		
Leptons		$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Small-R jets		$p_{\mathrm{T}} > 20$ GeV if $\lvert\eta\rvert < 2.5$, and $p_{\mathrm{T}} > 30$ GeV if $2.5 < \lvert\eta\rvert < 4.5$
Large-R jets		$p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2.0$
Event selection		
Leptonic V selection	0-lepton	Zero leptons, $p_{\mathrm{T}}^{\nu\nu} > 200$ GeV
	1-lepton	One lepton with $p_{\mathrm{T}} > 27$ GeV, $p_{\mathrm{T}}^{\nu} > 80$ GeV
	2-lepton	Two leptons, with leading (subleading) lepton $p_{\mathrm{T}} > 28$ (20) GeV $83 < m_{\ell\ell} < 99$ GeV
Hadronic V selection	Merged	One large-R jet, min($\lvert m_J - m_W\rvert, \lvert m_J - m_Z\rvert$) $64 < m_J < 106$ GeV
	Resolved	Two small-R jets, min($\lvert m_{jj} - m_W\rvert, \lvert m_{jj} - m_Z\rvert$) $p_{\mathrm{T}}^{j_1}$ >40 GeV, $p_{\mathrm{T}}^{j_2}$ >20 GeV $64 < m_{jj} < 106$ GeV
Tagging-jets		Two small-R non-b jets, $\eta_{\mathrm{tag},j_1} \cdot \eta_{\mathrm{tag},j_2} < 0$, highest m_{jj}^{tag} $m_{jj}^{\mathrm{tag}} > 400$ GeV, $p_{\mathrm{T}}^{\mathrm{tag},j_{1,2}} > 30$ GeV
Number of b-jets	0-lepton	–
	1-lepton	0
	2-lepton	–

VVjj Production :: Event Selection

Table 5: The distributions used in the global likelihood fit for the signal regions and control regions for all the categories in each channel. "One bin" implies that a single bin without any shape information is used in the corresponding fit region.

Regions		Discriminants		
		Merged high-purity	Merged low-purity	Resolved
0-lepton	SR	BDT	BDT	BDT
	VjjCR	m_{jj}^{tag}	m_{jj}^{tag}	m_{jj}^{tag}
1-lepton	SR	BDT	BDT	BDT
	WCR	m_{jj}^{tag}	m_{jj}^{tag}	m_{jj}^{tag}
	TopCR	One bin	One bin	One bin
2-lepton	SR	BDT	BDT	BDT
	ZCR	m_{jj}^{tag}	m_{jj}^{tag}	m_{jj}^{tag}

$$\sigma^{\text{fid.}}_{Z\gamma jj} = 71 \pm 2\,(\text{stat.})\ ^{+9}_{-7}\,(\text{syst.})\ ^{+21}_{-17}\,(\text{mod.})\ \text{fb}$$

$$\sigma^{\text{fid., MadGraph+Sherpa}}_{Z\gamma jj} = 88.4 \pm 2.4\,(\text{stat.}) \pm 2.3\,(\text{PDF} + \alpha_S)^{+29.4}_{-19.1}\,(\text{scale})\ \text{fb.}$$

$$\sigma^{\text{fid.}}_{Z\gamma jj\text{–EW}} = 7.8 \pm 1.5\,(\text{stat.}) \pm 1.0\,(\text{syst.})\ ^{+1.0}_{-0.8}\,(\text{mod.})\ \text{fb}$$

$$\sigma^{\text{fid., MadGraph}}_{Z\gamma jj\text{–EW}} = 7.75 \pm 0.03\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.40\,(\text{scale})\ \text{fb}$$

$$\sigma^{\text{fid., Sherpa}}_{Z\gamma jj\text{–EW}} = 8.94 \pm 0.08\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.50\,(\text{scale})\ \text{fb}$$

Probing VBF and VBS :: What we measure

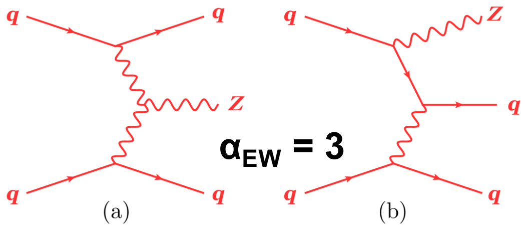
Cannot directly measure VBF/VBS

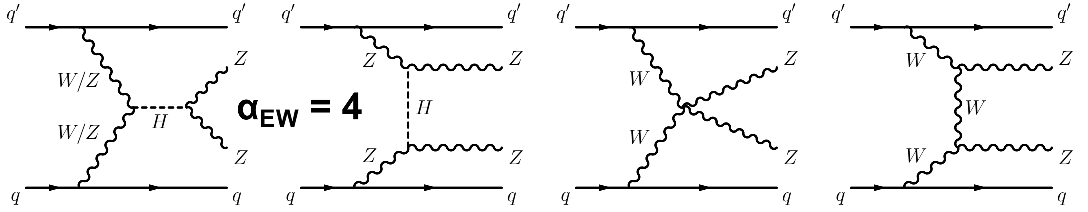
- **Significant interference with other diagrams with same order in**
- **Extracting** VBF/VBS component is **not gauge invariant**
- We can only **measure electroweak production** of VVjj (VBS) or Vjj (VBF)
- Moreover, QCD/strong production is much larger than EW (excl. $W^{\pm}W^{\pm}jj$)

Vector Boson Fusion (Vjj)

Vector Boson Scattering (VVjj)

EW





QCD