Observation of electroweak diboson production in the WZjj and $W^{\pm}W^{\pm}jj$ channels with the ATLAS and CMS detectors

Iro Koletsou

Laboratoire de Physique des Particules d'Annecy

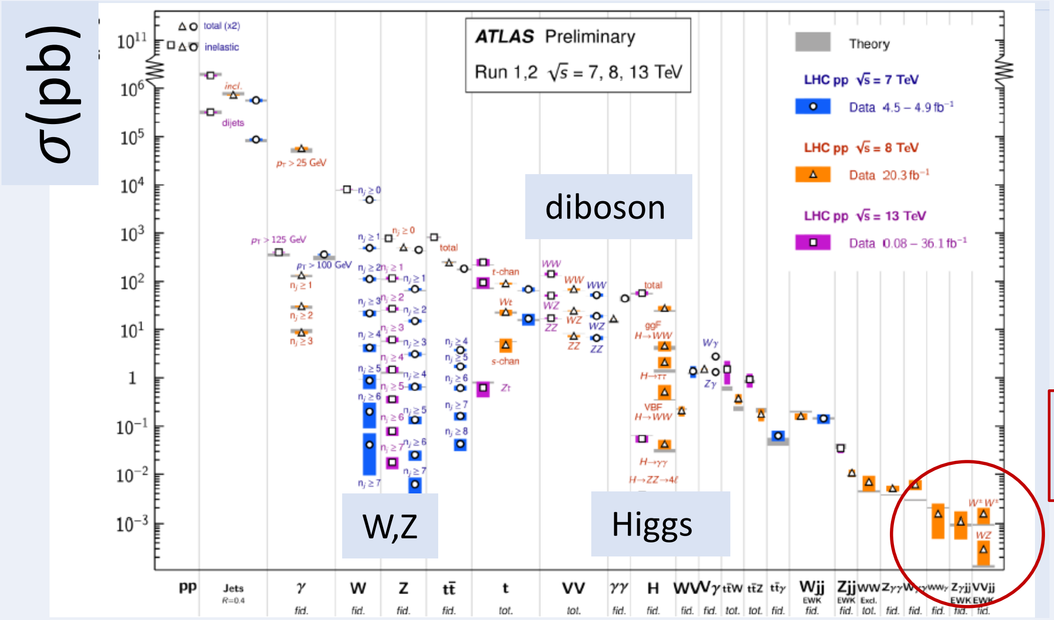
Université Savoie Mont Blanc

On behalf of the ATLAS and CMS collaborations

HEP 2019, NCRS Demokritos, Athens, Greece

Overview

- Introduction to the vector boson scattering:



- ✓ Motivations
- ✓ General aspects of the analysis
- ✓ Timeline

One of the lowest cross section processes studied with the LHC

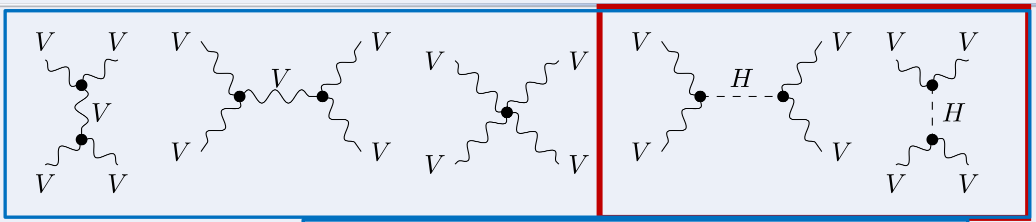
- Observation of the electroweak diboson production with the CMS and the ATLAS detectors

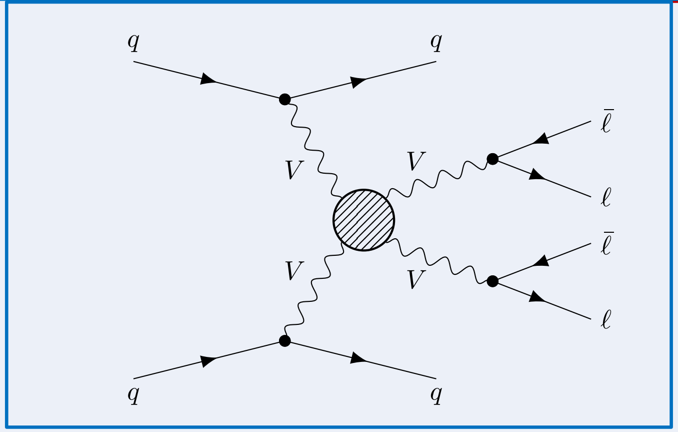
- Future plans

Vector Boson Scattering

α_{EW} order: 6
α_s order: 0

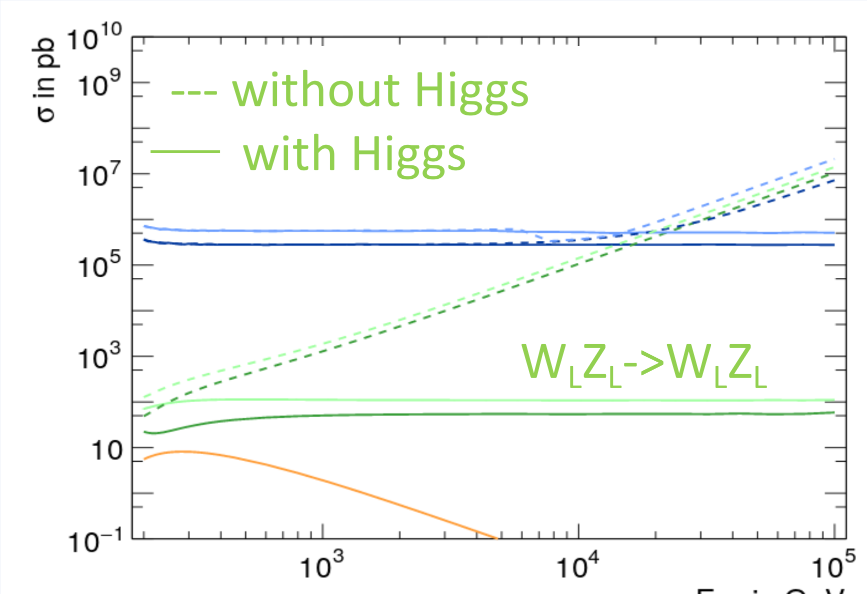
Diboson production via vector boson scattering





- Very precisely described process with the Standard Model
- Deviation from prediction could be a sign of new physics

EW sym. breaking sector: unitarity



C. Bittrich, CERN-THESIS-2015-039

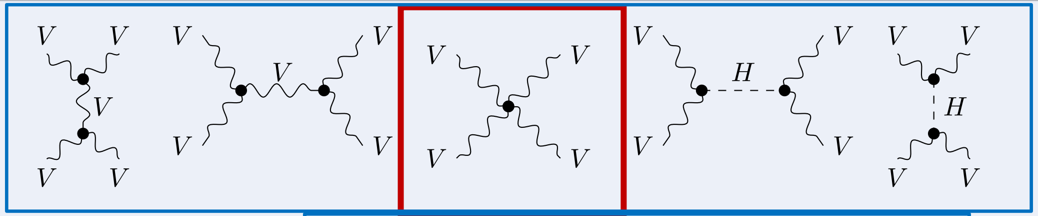
- Can be used to constraint non SM Higgs Models with enhanced couplings to vector bosons

- Could be used as an indirect probe of Higgs properties, through longitudinally-polarized boson scattering (need higher integrated luminosity)

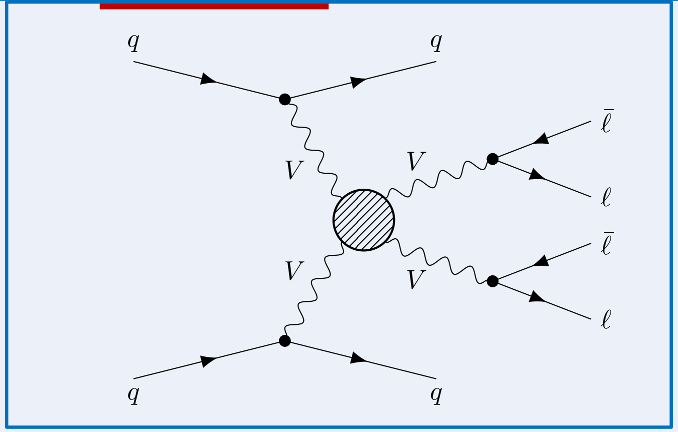
Vector Boson Scattering

α_{EW} order: 6
α_s order: 0

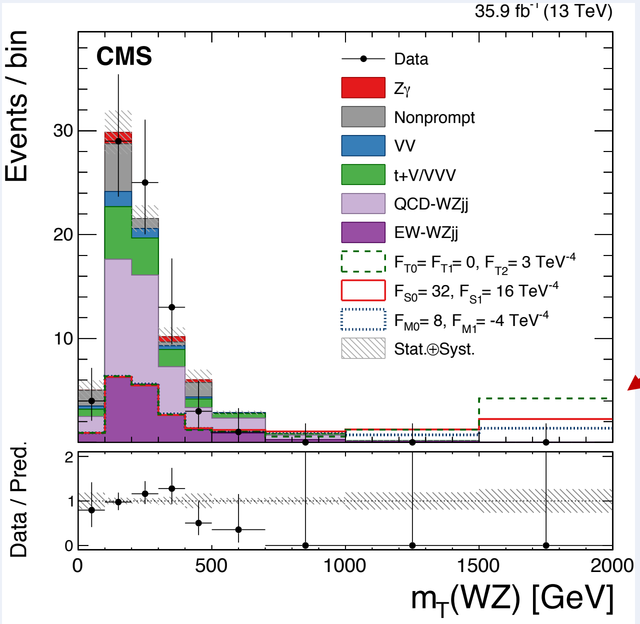
Diboson production via vector boson scattering



- Very precisely described process with the Standard Model
- Deviation from prediction could be a sign of new physics



access to Quartic Gauge Couplings



- Quartic gauge couplings could be modified by new physics (aQGC)
- Effect on high energy tails of kinematical distribution such as M_{jj}
- ATLAS and CMS choice for interpretation: Effective Field Theory

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} \mathscr{L}_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4} \mathscr{L}_i^{(8)}$$

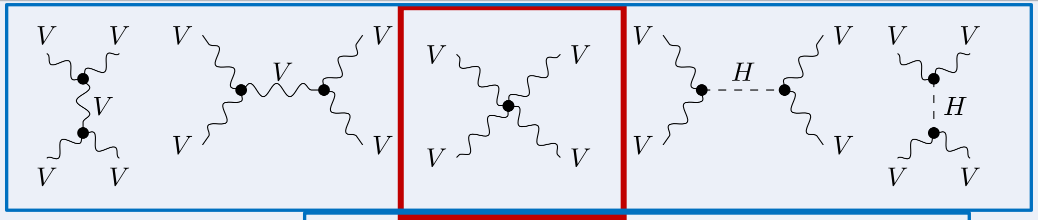
VBS very sensitive to dim.8 parameters

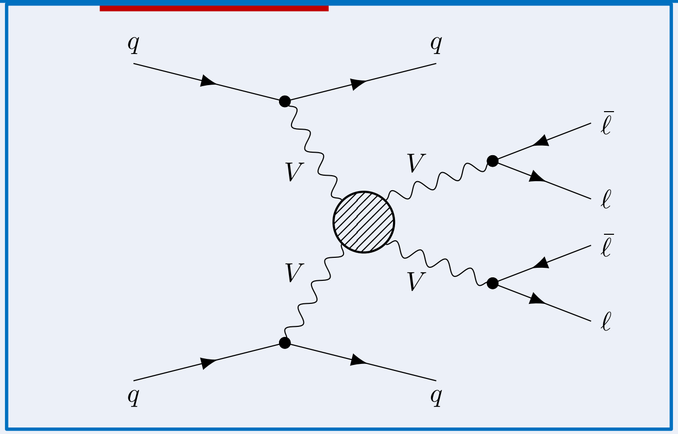
for more details: see talks from D. Sampsonidou and E. Kasimi

Vector Boson Scattering

α_{EW} order: 6
α_s order: 0

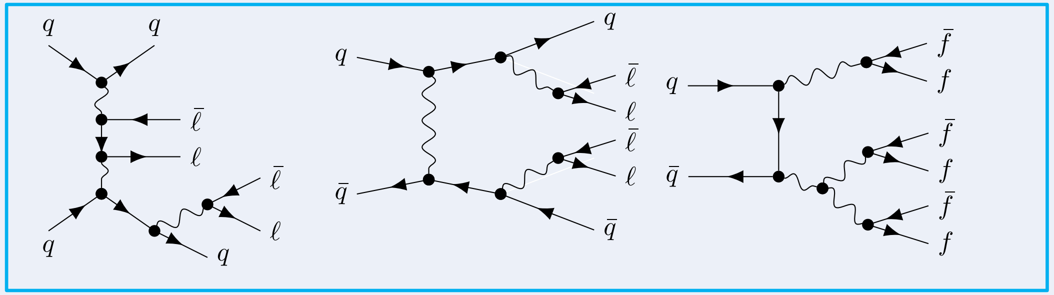
Diboson production via vector boson scattering





- Very precisely described process with the Standard Model
- Deviation from prediction could be a sign of new physics

EW diboson production



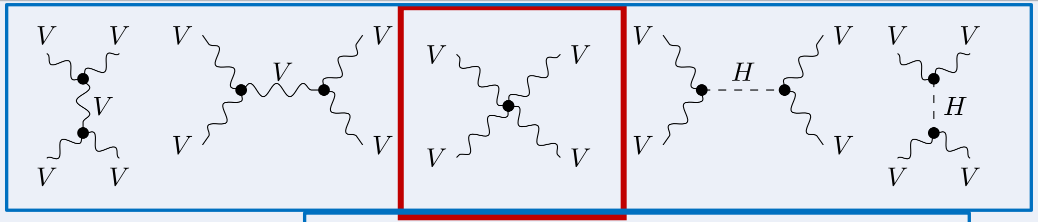
- can't be dissociated from VBS process
- observation and cross section measurements concern both groups of diagrams

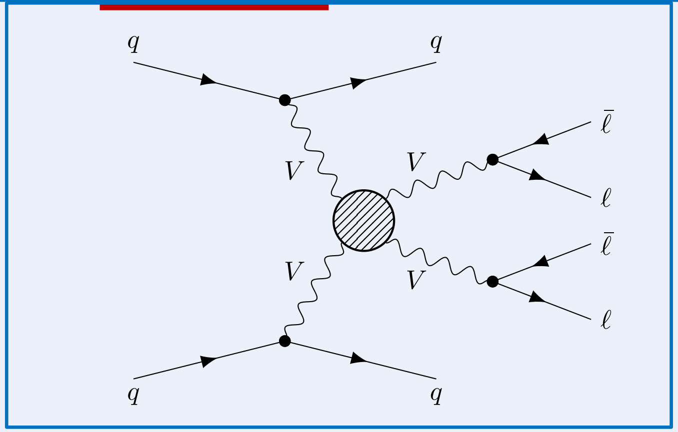
α_{EW} order: 6
α_s order: 0

Vector Boson Scattering

α_{EW} order: 6
α_s order: 0

Diboson production via vector boson scattering

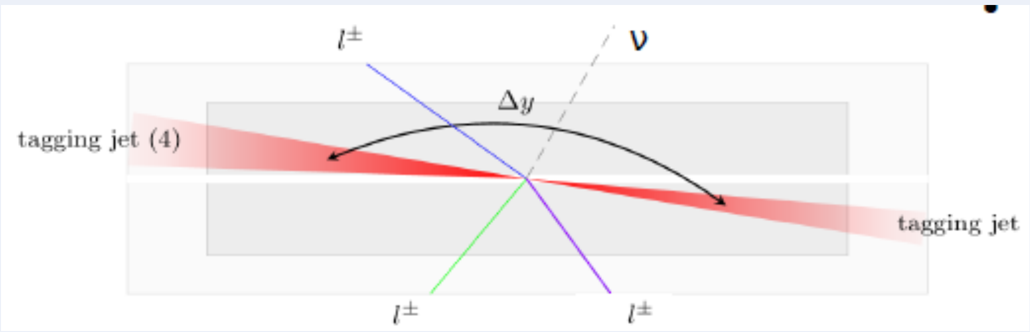




- Very precisely described process with the Standard Model
- Deviation from prediction could be a sign of new physics

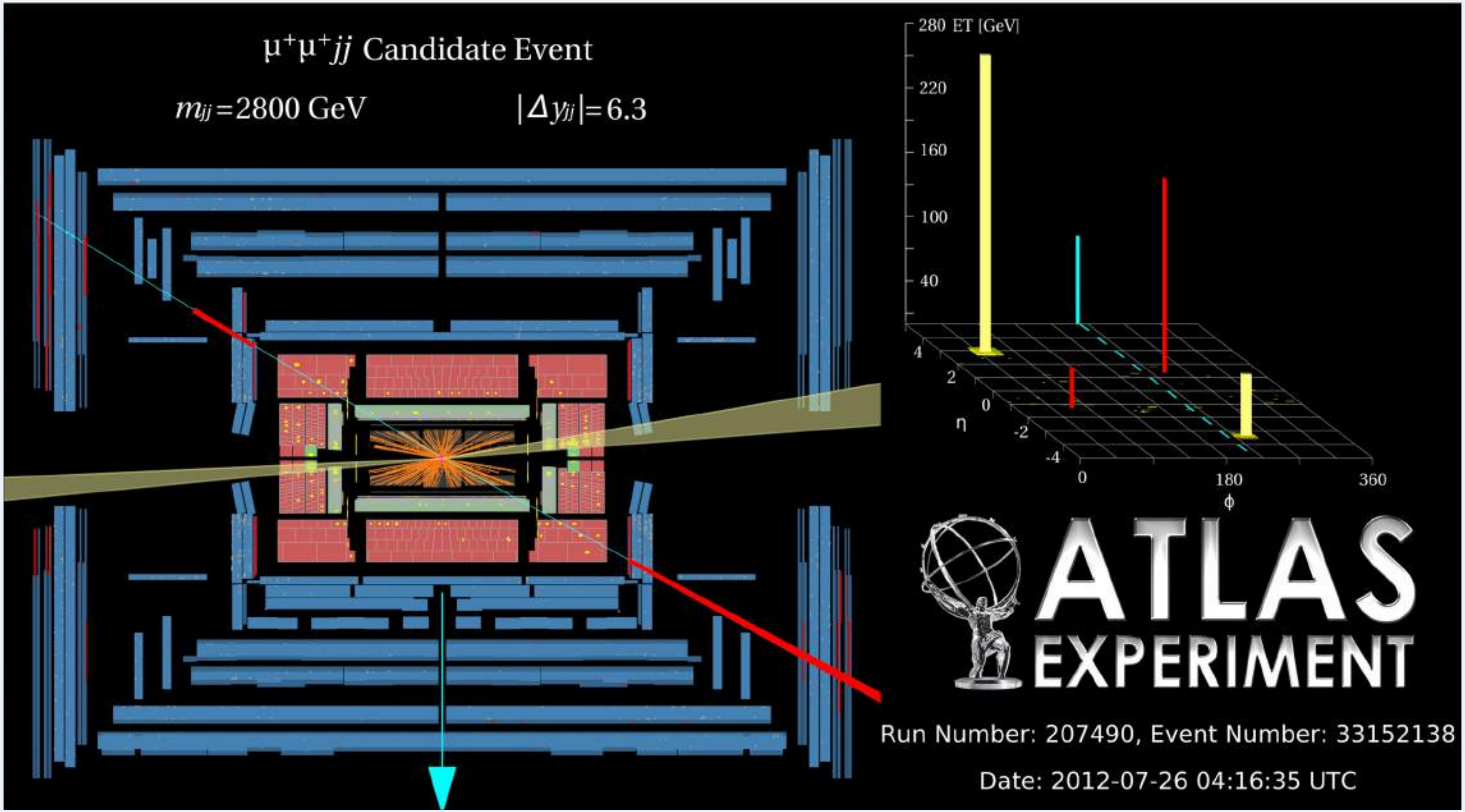
- Create an VBS enhanced phase space

Very characteristic kinematical profil:



- Two high P_T forward jets (high $\Delta\eta$, high m_{jj})
- Diboson products in the central region

A typical VBS event (W^+W^+jj)

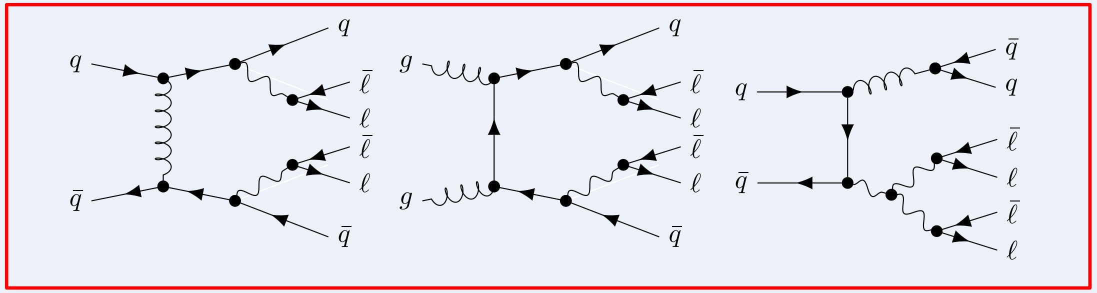


QCD diboson production

α_{EW} order: 4
α_s order: 2

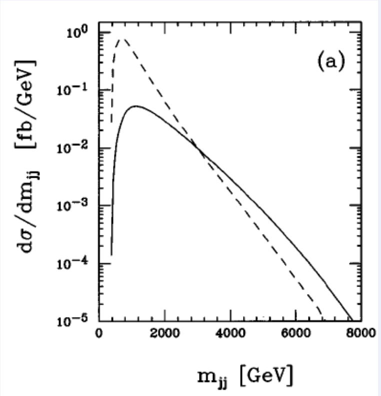
QCD diboson production in association with two jets

- Very high background for most channels

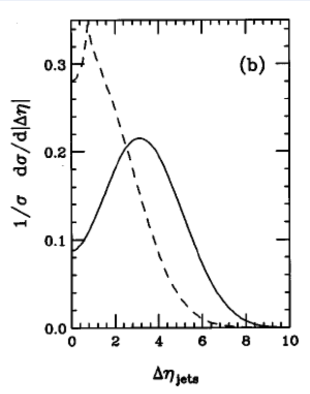


EW diboson production: very characteristic kinematic signature

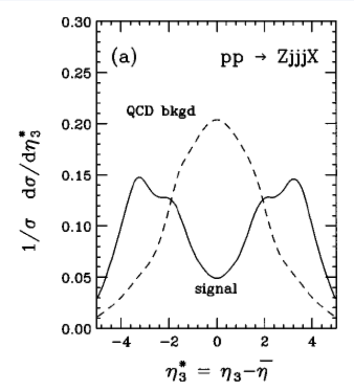
typically m_{jj}>500 GeV in VBS analyses



dijet invariant mass



dijet Δη



centrality

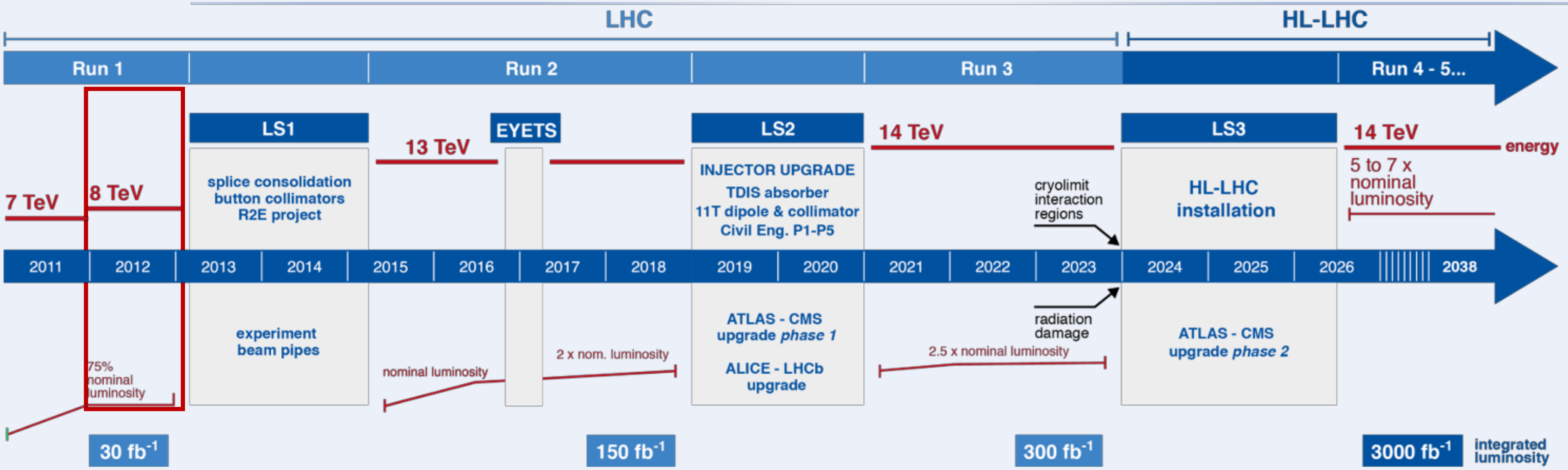
arXiv:hep-ph/9605444

8

Same final state as EW: $|MIN_C|^2 = |M_{QCD} + M_{EW}|^2 = |M_{QCD}|^2 + |M_{EW}|^2 + 2\times Re\left(M_{QCD}{}^{*}\times M_{EW}\right)$

Interference term: Taken into account as shape uncertainty in most analyses

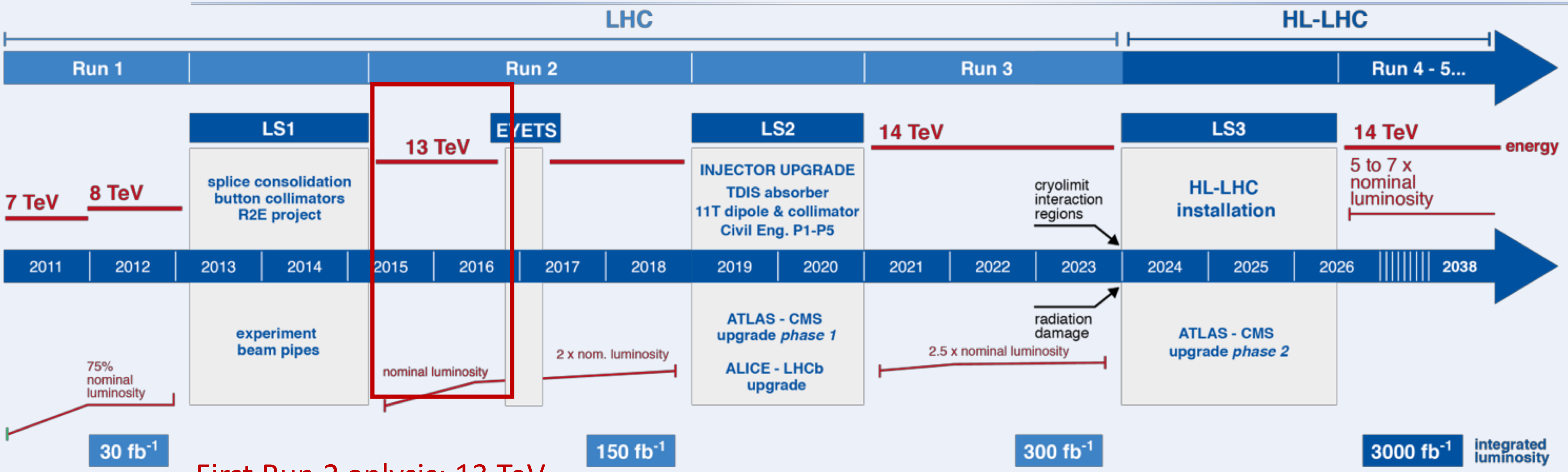
LHC / HL-LHC Plan



Run 1 anlysis: 8 TeV

8 TeV	ATLAS	CMS
WWss and Vγ	limits on aQGC	limits on aQGC
WZ	limits on aQGC	-
semi-leptonic WV+jj	limits on aQGC	-

LHC / HL-LHC Plan



First Run 2 anlysis: 13 TeV

13 TeV	ATLAS (36.1 fb^{-1})	CMS (35.9 fb^{-1})
WWss	observation	observation, limits on aQGC and charged Higgs
WZ	observation (limits on charged Higgs*)	limits on aQGC and charged Higgs
ZZ	-	limits on QGC

**Phys. Lett. B 787 (2018) 68 , from resonances searches*

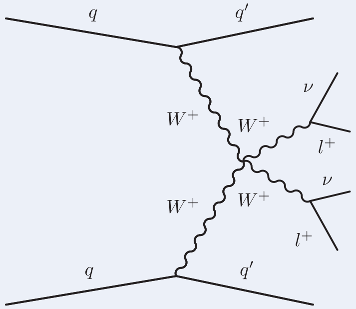
also see talk from K. Kordas

$W^{\pm}W^{\pm}jj$ channel

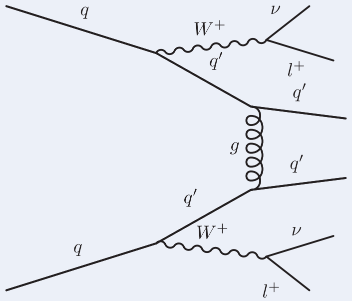
Best EW/QCD and S/B ratio channel

Selection:

- Exactly two same sign leptons
- At least two high P_T forward jets
- Missing energy



ssWW EW



ssWW QCD: very low

Suffering from **high fake background**

- **Non prompt leptons**
- Electron charge misID

- Important background from WZ QCD

First EW diboson production observation by CMS

Observation both by ATLAS and CMS:

ATLAS-CONF-2018-030
CMS: PRL 120 (2018) 081801

CMS analysis strategy and results

- Selection:

2 same sign leptons:
P_T^1>25 GeV, P_T^2>20 GeV, m_{ll}>20 GeV, $|m_{ee}-M_z|$>15 GeV
2 jets: P_T>30 GeV, $|\eta|<5.0$, **m_{jj}>500 GeV**, $|\Delta\eta_{jj}|>2.5$
Centrality: $|\eta_l-(\eta_{j1}+\eta_{j2})/2|/|\Delta\eta_{jj}|<0.75$
P_T^{miss} >40 GeV

- Signal modelling and background estimation:

Data	201
Signal + total background	205 ± 13
Signal	66.9 ± 2.4
Total background	138 ± 13
Nonprompt	88 ± 13
WZ	25.1 ± 1.1
QCD WW	4.8 ± 0.4
$W\gamma$	8.3 ± 1.6
Triboson	5.8 ± 0.8
Wrong sign	5.2 ± 1.1

Signal: MadGraph5 aMC@NLO2.3.3: LO EWK, LO QCD

Reducible background: extracted from data (Nonprompt)

normalized in dedicated CR (invert 3l veto) (WZ)

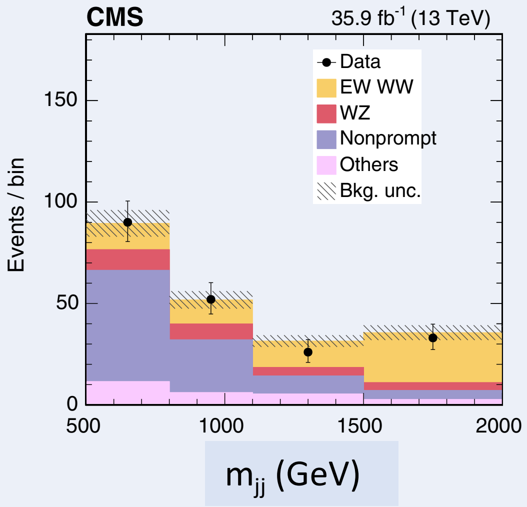
simulation corrected with data (Wrong sign)

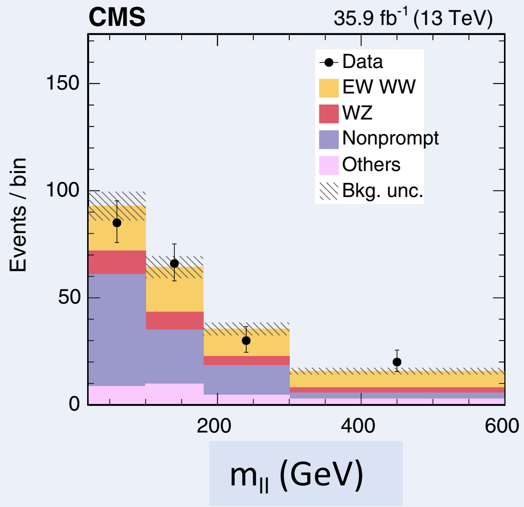
CMS analysis strategy and results

- Signal extraction:

with a 2D template fit using m_{ll} and m_{jj}

simultaneously with WZ CR





5.5 σ observation (5.7 expected)

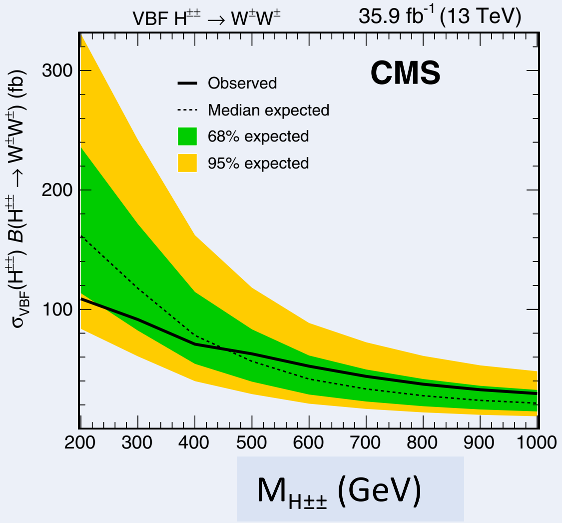
- Fiducial cross section measurement: (MadGraph: 4.25 ± 0.27 fb)

$$\sigma_{\text{fid}}(W^{\pm}W^{\pm}jj) = 3.83 \pm 0.66\,(\text{stat}) \pm 0.35\,(\text{syst})\ \text{fb}$$

- Limits on $\sigma_{\text{VBF}}(H^{\pm\pm})\mathcal{B}(H^{\pm\pm} \to W^{\pm}W^{\pm})$

in a Georgi-Machacek model of Higgs triplets

predicting doubly charged Higgs bosons



ATLAS analysis strategy and results

- Selection:

2 same sign leptons:
P_T>27 GeV, m_{ll}>20 GeV, $|m_{ee}-M_z|$>15 GeV
2 jets: P_T>65/35 GeV, $|\eta|$<4.5, m_{jj}>500 GeV, $|\Delta\eta_{jj}|$>2
Centrality: no cut
E_t^{miss} **>30 GeV**

- Signal modelling and background estimation:

	combined
WZ	32 ± 9
Non-prompt	23 ± 12
e/γ conversions	13.4 ± 3.5
Other prompt	2.4 ± 0.5
$W^{\pm}W^{\pm}$jj strong	7.3 ± 2.5
Expected background	78 ± 15
$W^{\pm}W^{\pm}$jj electroweak	40.9 ± 2.9
Data	122

normalized in dedicated CR (invert 3l veto)

Reducible background: extracted from data and further constrained in CR

Signal: Sherpa2.2.2, LO EWK, 2,3j@LO QCD
EW corrections applied as shape uncertainty

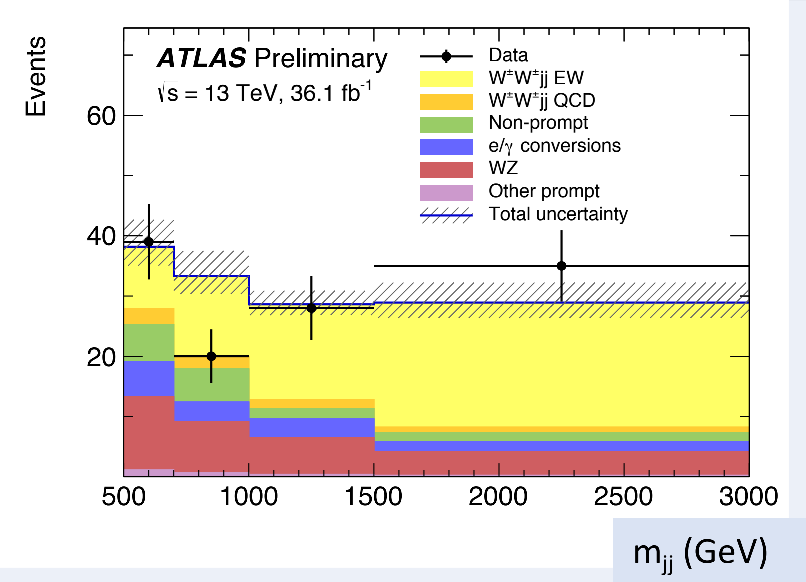
ATLAS analysis strategy and results

- Signal extraction:

with a 1D template fit using m_{jj} in 6 categories

simultaneously with WZ and non-prompt CR

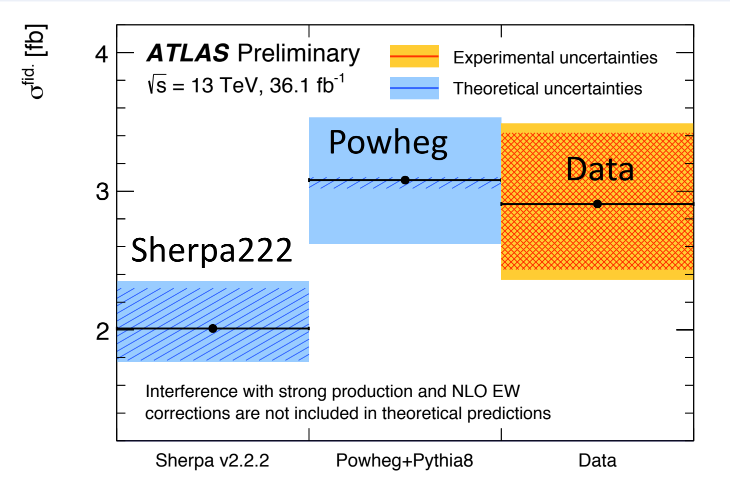
6.9 σ observation (4.25 expected)



- Fiducial cross section measurement:

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

- Comparison of Sherpa222 and Powheg+Pythia8 generators predicted cross section

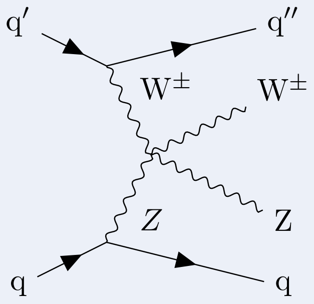


WZ jj channel

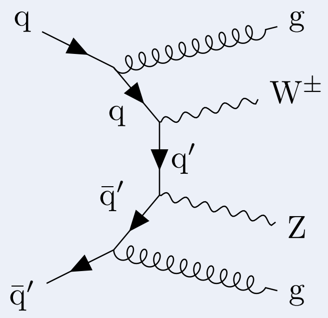
Low fake background

Selection:

- Exactly 3 leptons
- At least two high P_T forward jets



WZ EW



WZ QCD: $\frac{EW}{QCD} < 0.5$
in a typical VBS SR

Low EW/QCD ratio channel

- Need to discriminate the signal using MV technics

Observation by ATLAS
arXiv:1812.09740, submitter to Phys. Lett. B

aGCS limits by CMS
arXiv:1901.04060, submitter to Phys. Lett. B

CMS analysis strategy and results

- Selection:

3 leptons: *m_{3l}>100 GeV*
Z: *P_T^1>25 GeV, P_T^2>15 GeV, $|M_z - M_{z\text{-}PDG}|$<15 GeV*
W: *P_T>20*
2 jets: *P_T>50 GeV, $|\eta|$<4.7,* ***m_{jj}>500 GeV****, $|\Delta\eta_{jj}|$>2.5, no b-jet with >30 GeV*
Centrality: $|\eta_{3l}-(\eta_{j1}+\eta_{j2})/2| / |\Delta\eta_{jj}|$<2.5
P_T^{miss}>30 GeV

- Signal modelling and background estimation:

Process	Total yield
QCD WZ	34.1 ± 1.1
t+V/VVV	12.9 ± 0.5
Nonprompt	9.9 ± 2.3
VV	3.5 ± 0.2
$Z\gamma$	2.1 ± 0.8
Pred. background	62.4 ± 2.8
EW WZ signal	15.1 ± 1.6
Data	75

QCD WZ → QCD: MadGraph5 aMC@NLO2.4.2: LO with up to 3 partons at Born level

Nonprompt → **Reducible background: extracted from data**

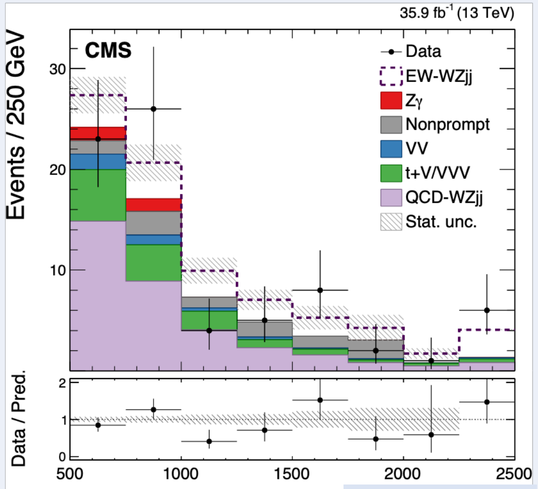
EW WZ signal → Signal: MadGraph5 aMC@NLO2.4.2, LO EWK, LO QCD

CMS analysis strategy and results

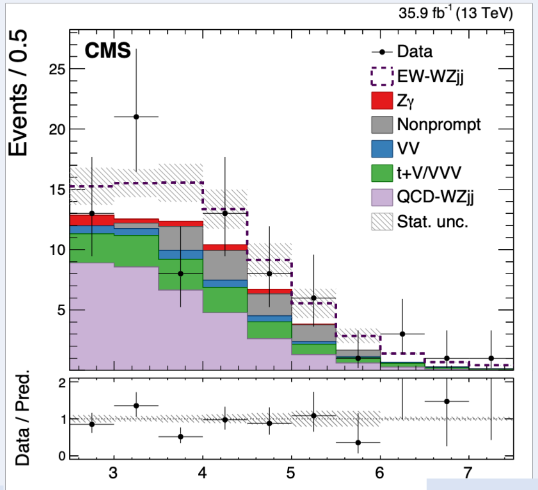
- Signal extraction:

with a 2D template fit using $|\Delta\eta_{jj}|$ and m_{jj} simultaneously with QCD CR

2.2 σ (2.5 expected)

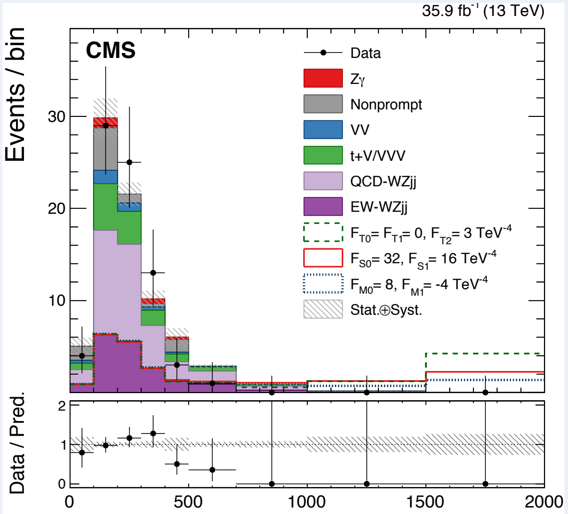


m_{jj} (GeV)



$|\Delta\eta_{jj}|$

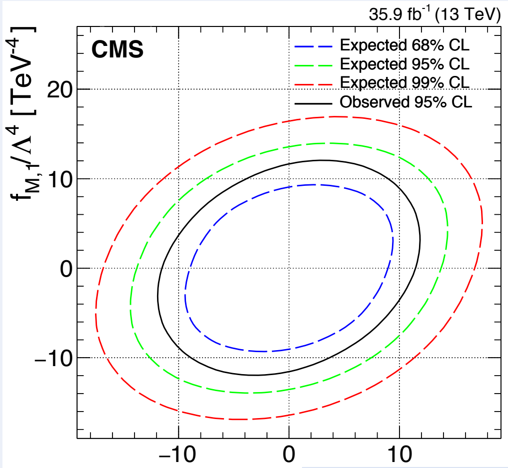
- Limits on aQGC using m_T^{WZ} distribution:



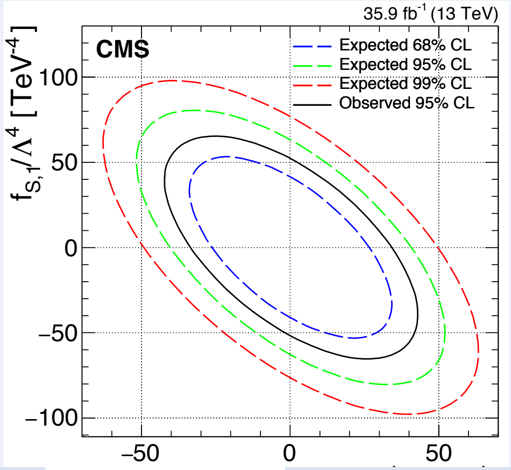
$m_T(WZ)$ [GeV]

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

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$



$f_{M,0}/\Lambda^4$ [TeV^{-4}]

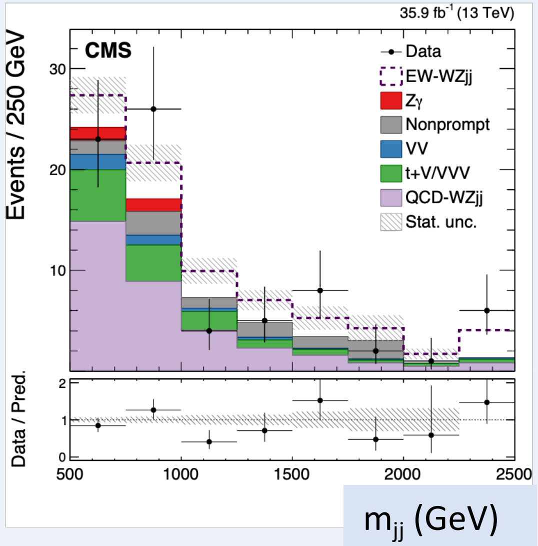


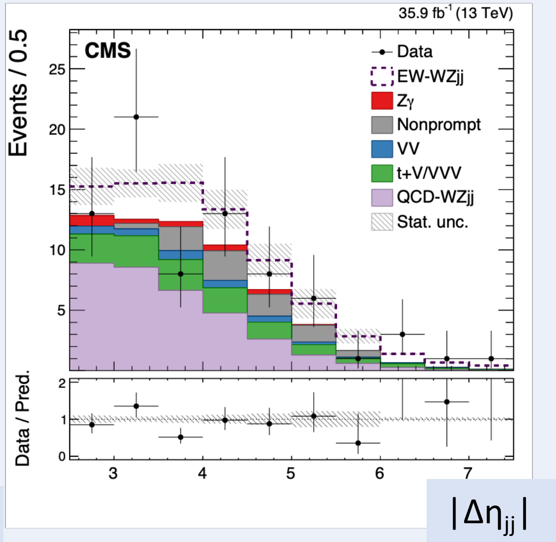
$f_{S,0}/\Lambda^4$ [TeV^{-4}]

CMS analysis strategy and results

- Signal extraction:

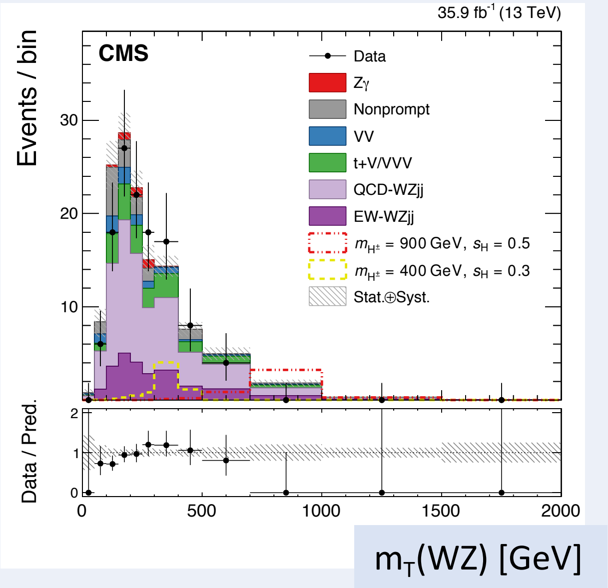
with a 2D template fit using $|\Delta\eta_{jj}|$ and m_{jj} simultaneously with QCD CR





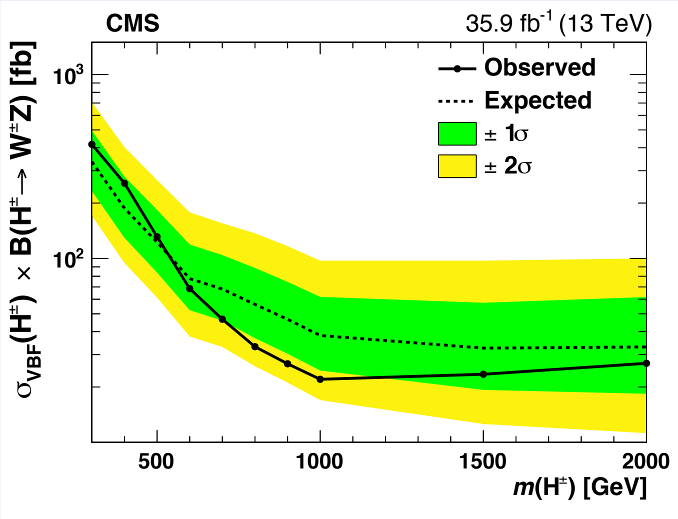
2.2 σ (2.5 expected)

- Limits on $\sigma(\mathrm{H}^{\pm})\,\mathcal{B}(H^{+} \to \mathrm{WZ})$



combined fit of EW+QCD in the SR and QCD in the QCD CR

In a Georgi-Machacek model where coupling with bosons are enhanced



ATLAS analysis strategy and results

- Selection:

3 leptons
Z: *$P_T^{1,2}$>15 GeV, $|M_z\text{-}M_{z\text{-}PDG}|$<10 GeV*
W: *P_T>20*
2 jets: *P_T>40 GeV, $|\eta|$<4.5,* ***m_{jj}>500 GeV****, $\eta_{j1}*\eta_{j2}$<0, no b-jet*
Centrality: no cut
m_T^W>30 GeV

- Signal modelling and background estimation:

	SR	
Data	161	
Total predicted	167	± 11
$WZjj$–EW (signal)	44	± 11
$WZjj$–QCD	91	± 10
Misid. leptons	7.8	± 3.2
$ZZjj$–QCD	11.1	± 2.8
tZj	6.2	± 1.1
$t\bar{t}+V$	4.7	± 1.0
$ZZjj$–EW	1.80	± 0.45
VVV	0.59	± 0.15

Signal: Sherpa2.2.2, LO EWK, 2,3j@LO

QCD: Sherpa2.2.2, up to 1j@ NLO + 2,3j@LO

Reducible background: extracted from data

Normalized in dedicated CR

ATLAS analysis strategy and results

- CR construction: release b-jet veto and loosen m_{jj} cut to 150 GeV

b control region (~45% purity)

Used to normalize the second irreducible background ($N_{b\text{-jets}}$)

QCD control region (~80% purity)

Used to normalize the main irreducible background (m_{jj})

b-CR ($t\bar{t}$ + V)
$N_{b\text{-jet}} > 0$

QCD-CR (WZjj-QCD)
$m_{JJ} < 500$ GeV
$N_{b\text{-jet}} = 0$

SR (WZjj-EW)
$m_{JJ} > 500$ GeV
$N_{b\text{-jet}} = 0$

Signal region:
MVA (BDT score) using kinematical variables

+ ZZ CR (70% purity) (m_{jj})

with the inversion of the 4th lepton veto

centrality ← ζ

$$R_{p_T}^{hard} = \frac{\left(\sum_{l,j} p\right)_T}{\sum_{l,j} p_T}$$

$\Delta y(\ell_W, Z)$	m_{jj}	η_W
ζ	$\Delta R(j1, Z)$	p_T^{j2}
$R_{p_T^{hard}}$	$\Delta\eta(j1, j2)$	p_T^{j1}
N_{jets}	p_T^W	m_T^{WZ}
$\Delta\phi(j1, j2)$	η_{j1}	p_T^Z

most important variables

ATLAS analysis strategy and results

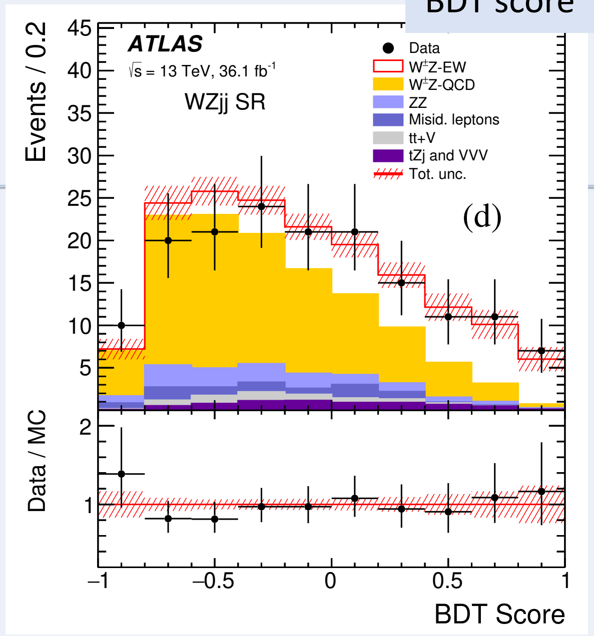
- Signal extraction:

with a 1D template fit using BDT score

simultaneously with QCD CR, b-CR and ZZ-CR

5.3 σ observation (3.2 expected)

BDT score



- Fiducial cross section measurement: ($\sigma^{\text{fid., Sherpa}}_{WZjj-\text{EW}} = 0.321 \pm 0.002\,(\text{stat.}) \pm 0.005\,(\text{PDF})^{+0.027}_{-0.023}\,(\text{scale})\ \text{fb}$)

$$\sigma^{\text{fid.}}_{WZjj-\text{EW}} = 0.57\ ^{+0.14}_{-0.13}\,(\text{stat.})\ ^{+0.05}_{-0.04}\,(\text{exp. syst.})\ ^{+0.05}_{-0.04}\,(\text{mod. syst.})\ ^{+0.01}_{-0.01}\,(\text{lumi.})\ \text{fb}$$

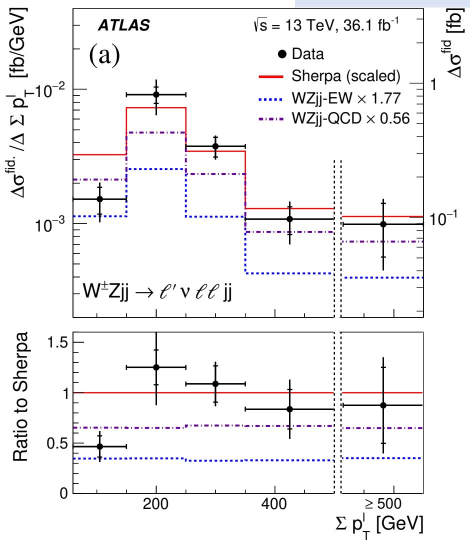
$$\sigma^{\text{fid.}}_{W^{\pm}Zjj} = 1.68 \pm 0.25\ \text{fb}$$

- Differential cross section measurement (QCD and EW)

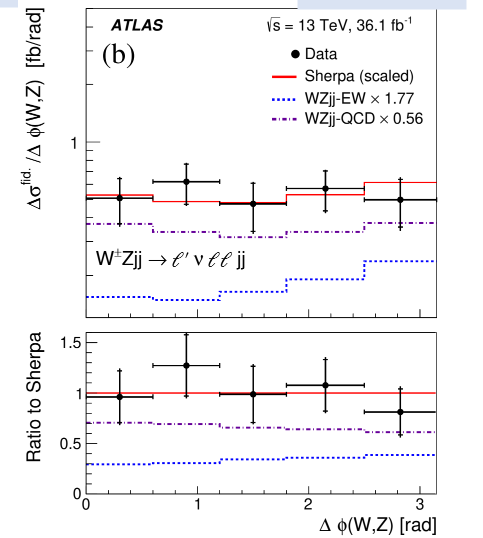
Sensible to aQGCs: m_T^{WZ}, $\sum p_T^l$, $\Delta\phi(W,Z)$

Jets modelling in MC : N_{jets}, M_{jj}, $\Delta\phi(j_1,j_2)$, $\Delta y(j_1,j_2)$, N_{jets}^{gap}

$\sum P_T^l$ (GeV)



$\Delta\Phi$(W,Z)



Main sources of systematic uncertainty

ATLAS WZjj analysis

Source	Uncertainty [%]
Jets	6.7
Pileup	2.2
Electrons	1.6
Muons	0.7
b-tagging	0.3
MC statistics	2.1
Misid. lepton background	1.0
Other backgrounds	0.1
Theory ($WZjj$-EW)	5.0
Theory ($WZjj$-QCD)	2.3
$WZjj$-EW and $WZjj$-QCD interference	1.9
Luminosity	2.1

Main unc: jet reconstruction and calibration

Interferences: *shape uncertainty, computed using MadGraph5_aMC@NLO 2.3 at LO*

QCD scale:
20-30% for QCD, 5% for signal (but flat)
PDF uncertainties: both ~1-2%
QCD and PDF considered shape uncertainties

QCD modelling uncertainty:

compare nominal Sherpa 2.2.2 to
MadGraph5_aMC@NLO 2.3 at LO

Signal modelling uncertainty:

compare nominal Sherpa 2.2.2 to
MadGraph5_aMC@NLO 2.3 at LO

Main sources of systematic uncertainty

ATLAS WZjj analysis

Source	Uncertainty [%]
Jets	6.7
Pileup	2.2
Electrons	1.6
Muons	0.7
b-tagging	0.3
MC statistics	2.1
Misid. lepton background	1.0
Other backgrounds	0.1
Theory ($WZjj$-EW)	5.0
Theory ($WZjj$-QCD)	2.3
$WZjj$-EW and $WZjj$-QCD interference	1.9
Luminosity	2.1

CMS: main uncertainty!

Main unc: jet reconstruction and calibration

CMS: second main uncertainty: non-prompt background

Interferences:* *shape uncertainty*, *computed using MadGraph5_aMC@NLO 2.3 at LO

CMS: similar effect

CMS: similar effect

QCD scale:
20-30% for QCD, 5% for signal (but flat)
PDF uncertainties: both ~1-2%
QCD and PDF considered shape uncertainties

CMS: similar effect

QCD modelling uncertainty:

compare nominal Sherpa 2.2.2 to
MadGraph5_aMC@NLO 2.3 at LO

Signal modelling uncertainty:

compare nominal Sherpa 2.2.2 to
MadGraph5_aMC@NLO 2.3 at LO

CMS: not taken into account, deviations within theory uncertainties

Theoretical uncertainties

ATL-PHYS-PUB-2019-004

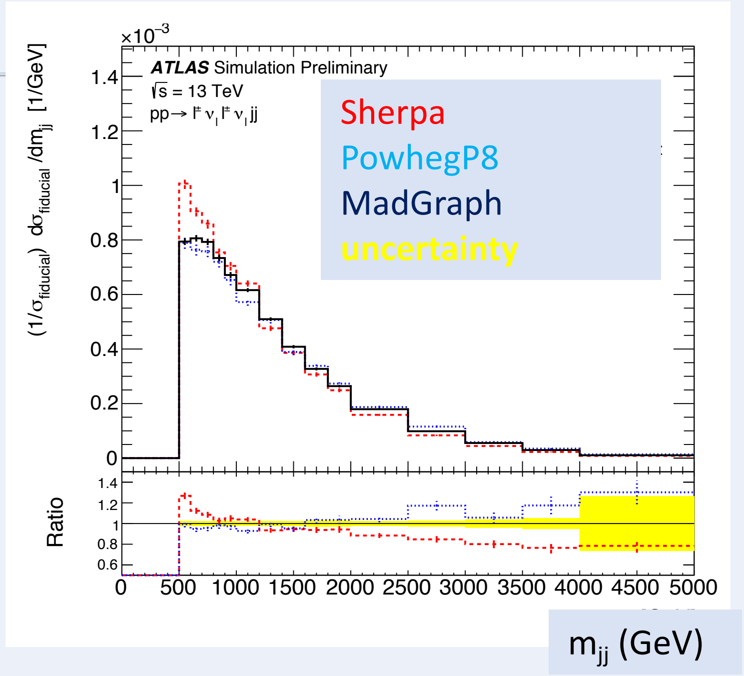
Important dependence on generator

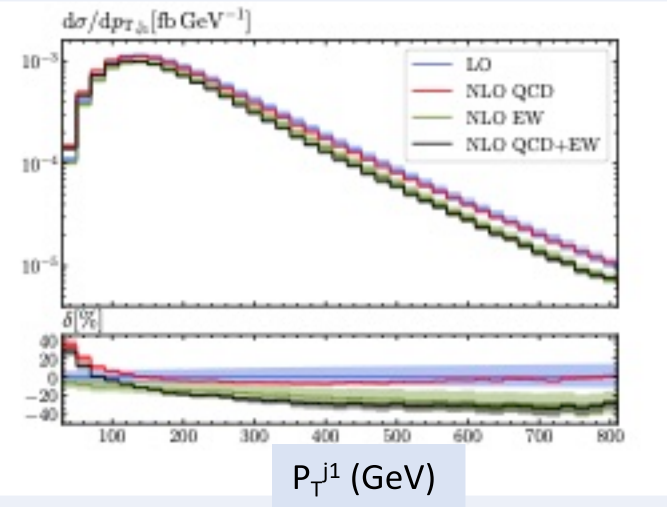
- High theoretical uncertainties on the measurement

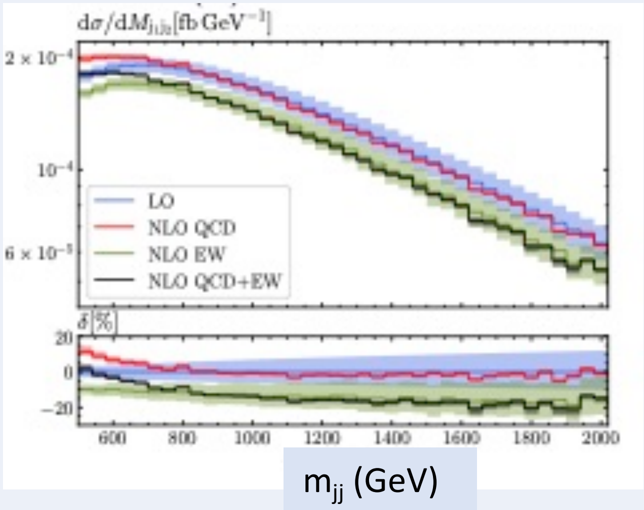
Important QCD and EW corrections

- Negative EW corrections (~ 15-20%)
- Shape effect (signal extraction)

Constantly improving precision from theory side

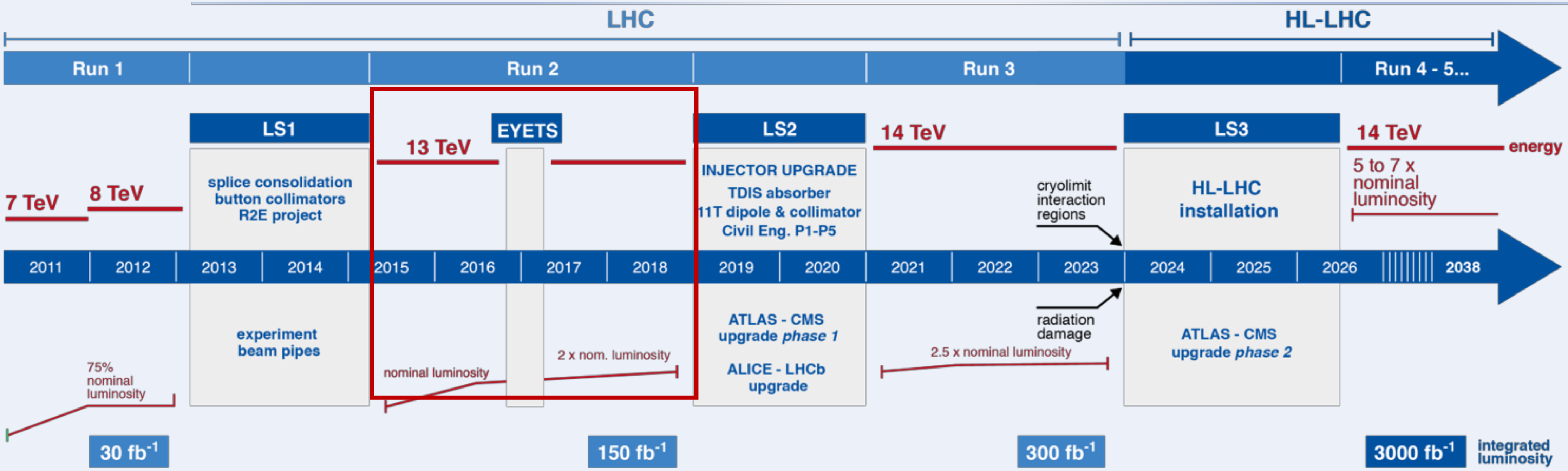






arXiv:1904.00882

LHC / HL-LHC Plan

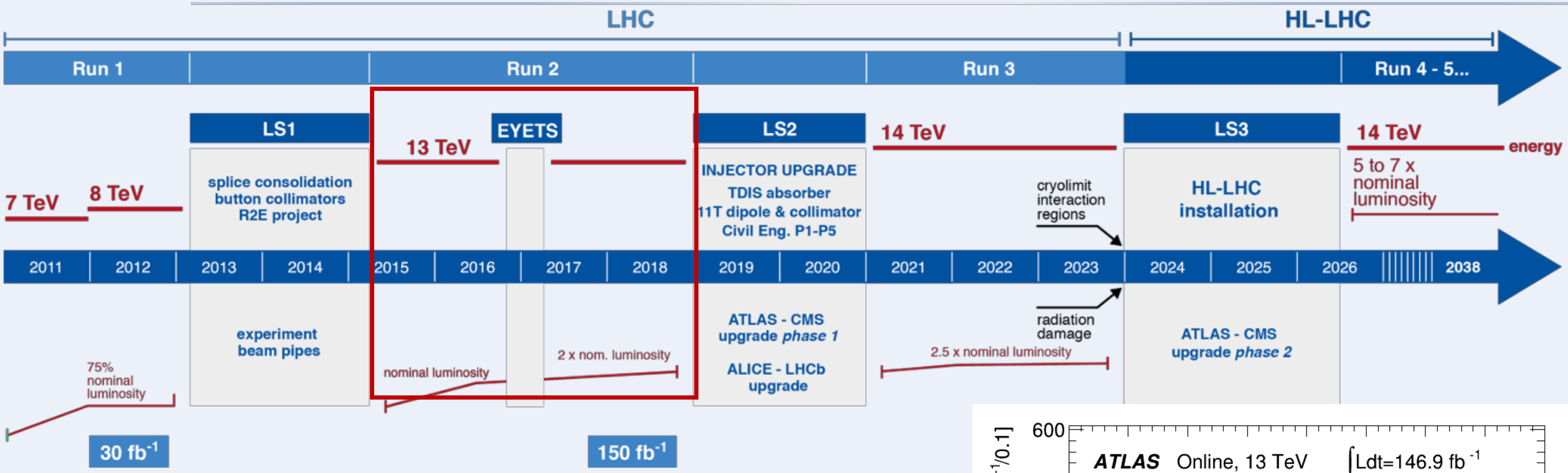


Full Run 2 anlysis: 13 TeV

Full Run 2 analysis will allow interpretation studies on various channel

- Combine results:
  - ✓ In different channels
  - ✓ Between ATLAS and CMS results
  - ✓ Go towards a large scale combination of Higgs / top / EW constraints

LHC / HL-LHC Plan

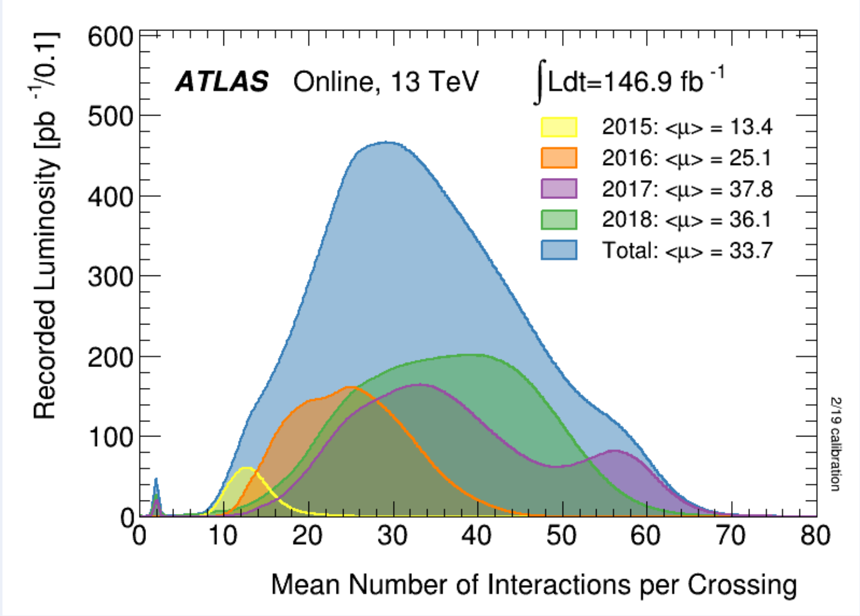


Full Run 2 anlysis: 13 TeV

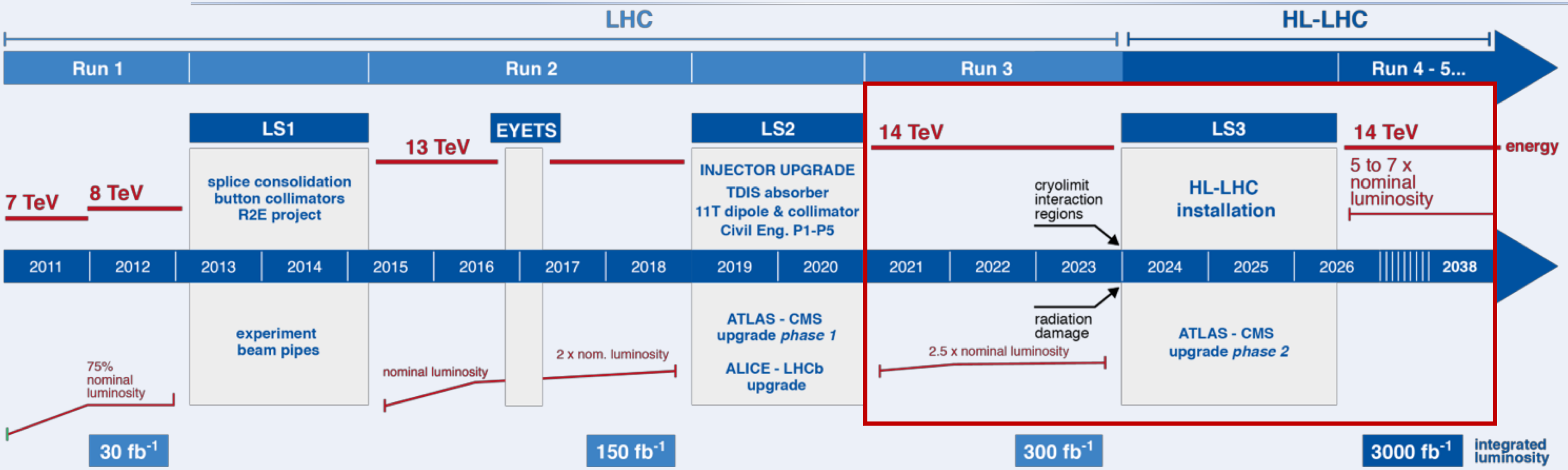
Experimental challenges due to high pile up:

✓ Pile-up rejection development (forward region)

✓ Quark/gluon separation (ongoing)



LHC / HL-LHC Plan



HL-LHC: 14 TeV

Up to 3000 fb^{-1} will allow us to reach very detailed VBS features, such as polarized states scattering (such as $V_L V_L$)

This could need the development of ML techniques

Conclusions

- Vector Boson scattering became accessible with Run 2 LHC data
- Electroweak diboson production was observed in the $W^{\pm}W^{\pm}jj$ and WZjj final states
- More channels to come (ZZjj, semileptonic channels)
    - will alllow to study different quartic boson couplings
    - could lead to combination studies
- Full Run 2 and, in the longer term, HL-LHC statistics will allow further interpretation studies
    - aQGCs
    - charged Higgs sector
    - polarized VBS
- **Close collaboration between the AUTH and the LAPP ATLAS groups**
- **To be continued for interpretation analysis**