

# Di-boson final states @LHC

## $W, Z, \gamma$

### Review → Overview

Lots taken from the MBI – Multi-boson Interactions – workshop in Thessaloniki, Aug 2019

# Keynote address

- Dibosons production at LHC is not the core of the IRN-Terascale as by construction they are a key feature of the Standard model,
- On the other hand :
  - Gauge structure is the least tested part of the SM
  - Indirect searches gain in interest with increased luminosity
  - Background for many searches

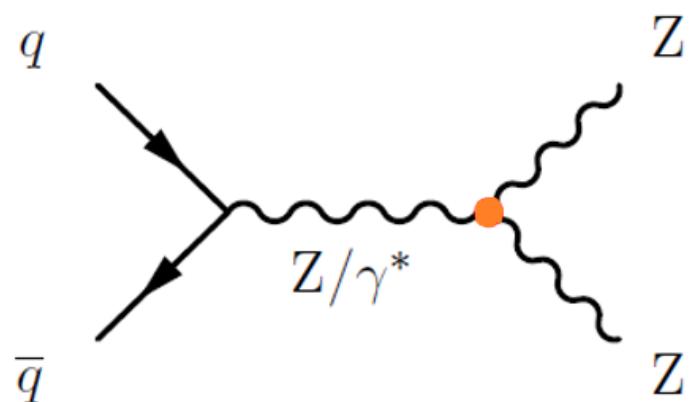
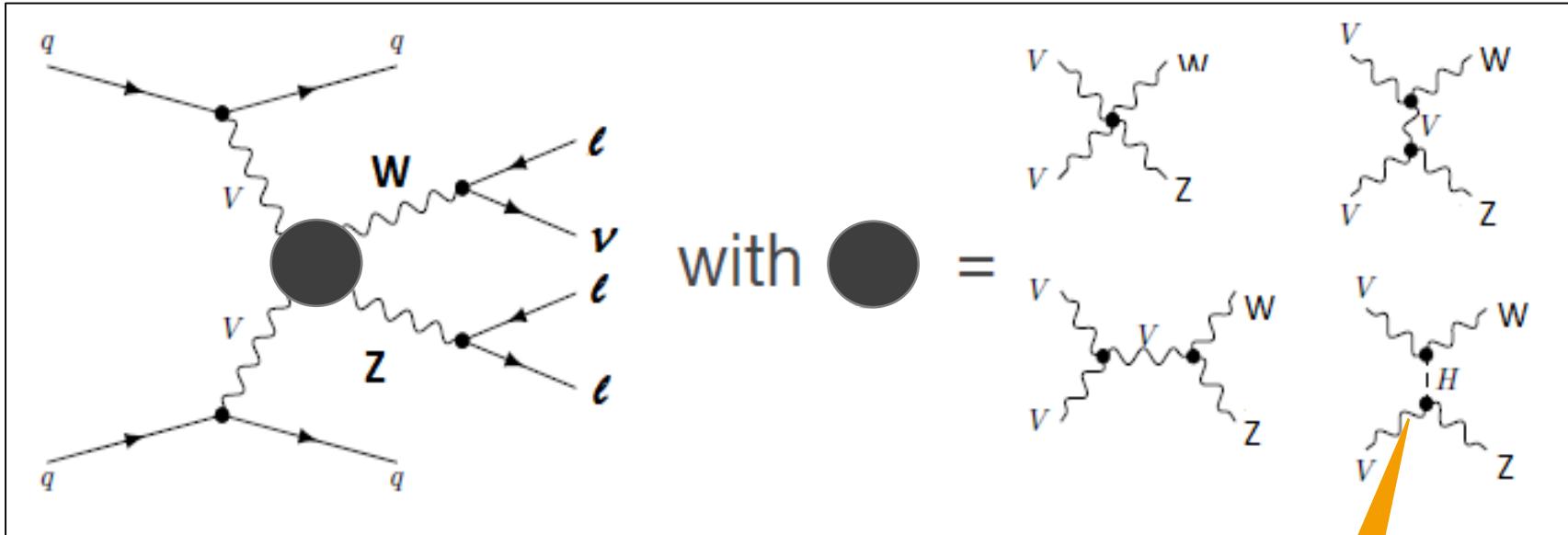
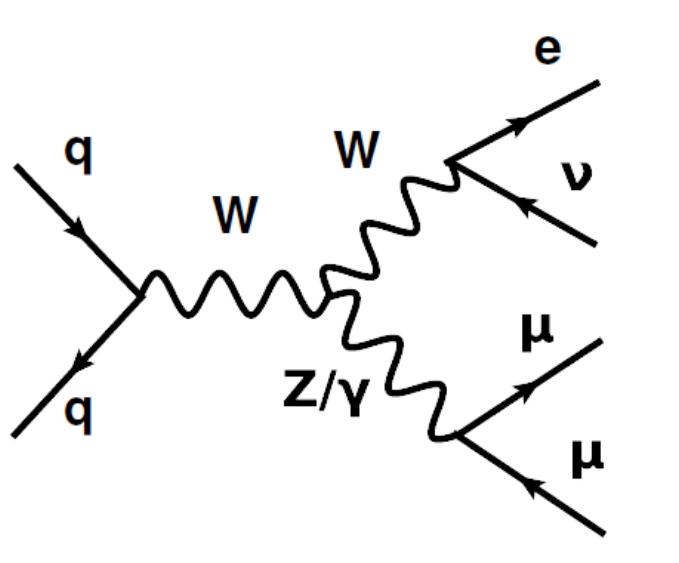
This presentation is meant to see whether subjects of interest can be identified within the IRN community

Inclusive production :  $VV$

Gauge structure (aTGC)

$\sigma \sim 50 \text{ pb}$

## 2 main classes



Vector boson scattering (VBS) :  $VVjj$

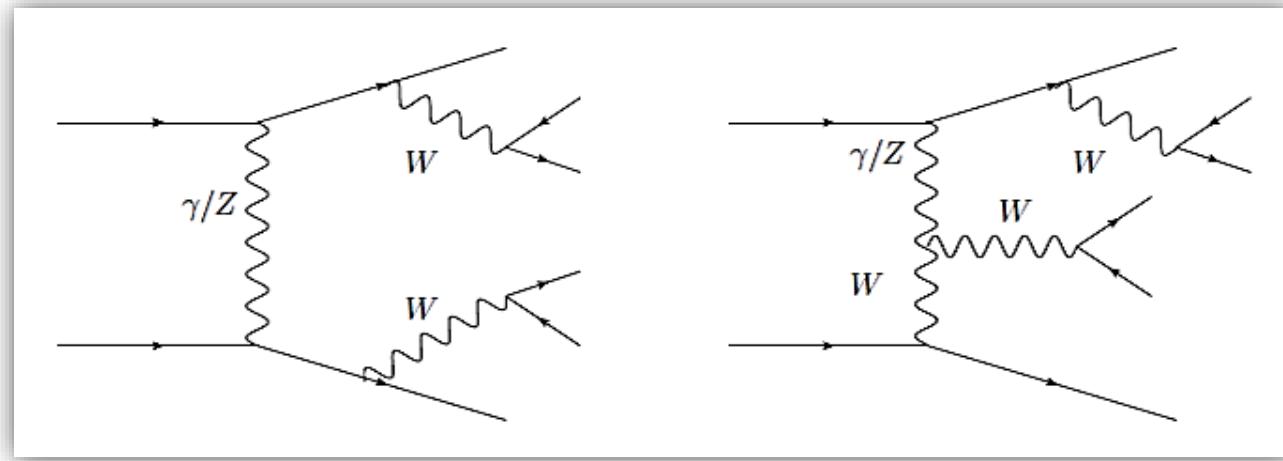
Gauge structure (aTGC, aQCG) + EWSB mechanism

$\sigma \sim 10^{-3} \text{ pb}$

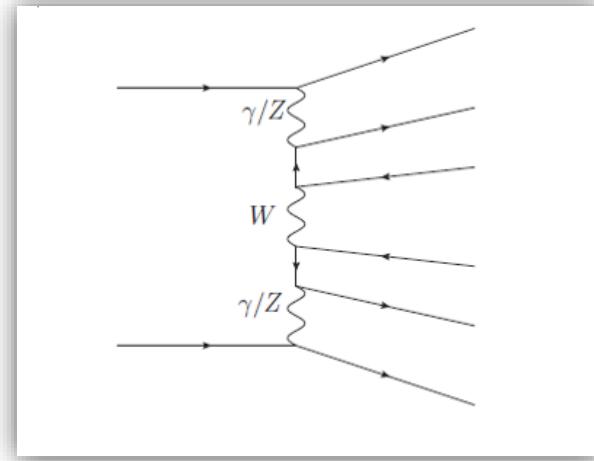
Exact ?  
cancellation  
of LL  
scattering

# Other EW diagrams - usually contained in the signal

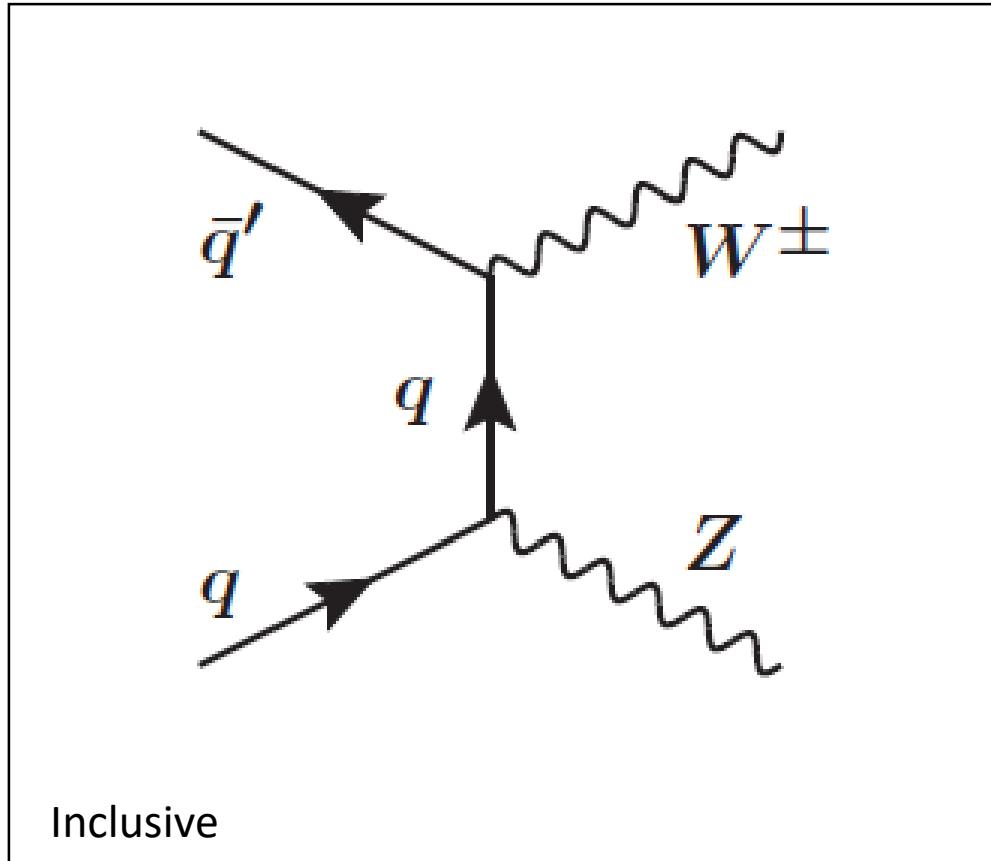
Other resonant diagrams (irreducible background)



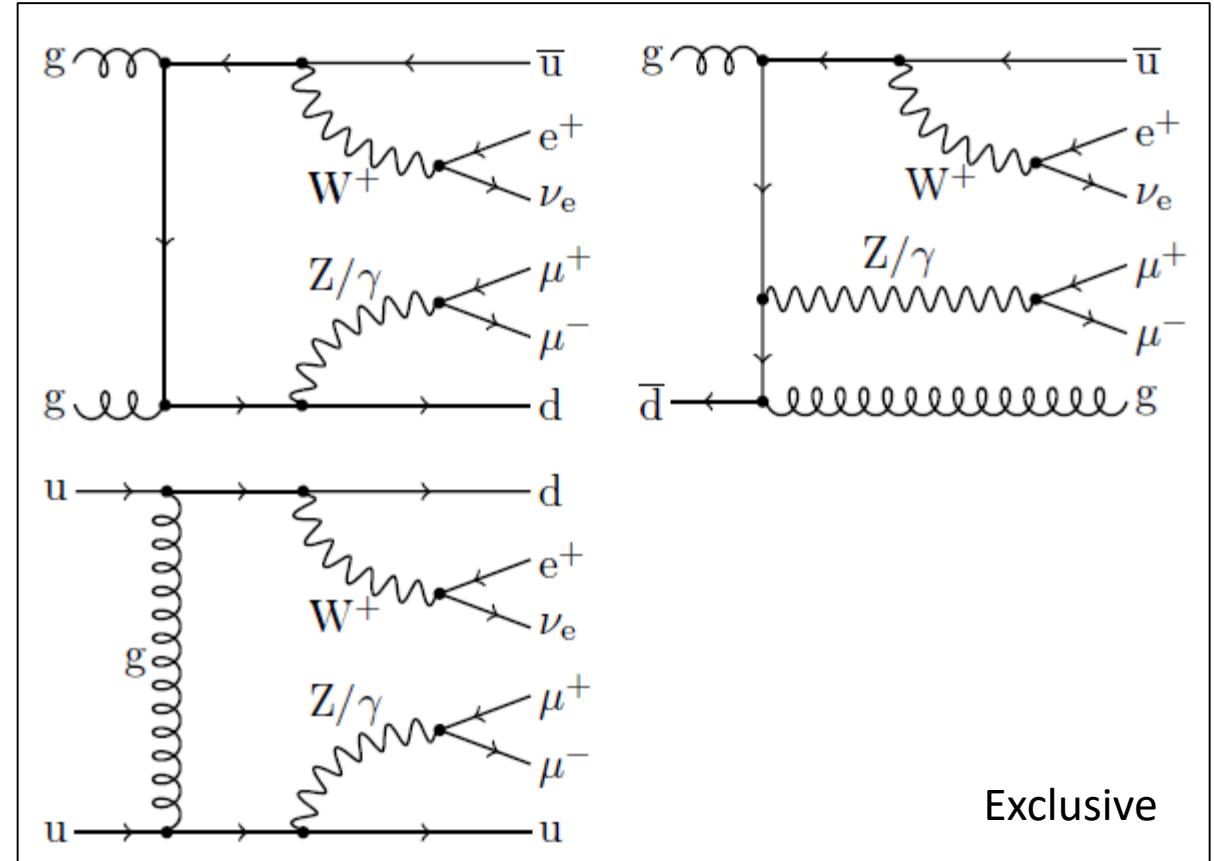
Non resonant diagrams



# QCD production – main background in general

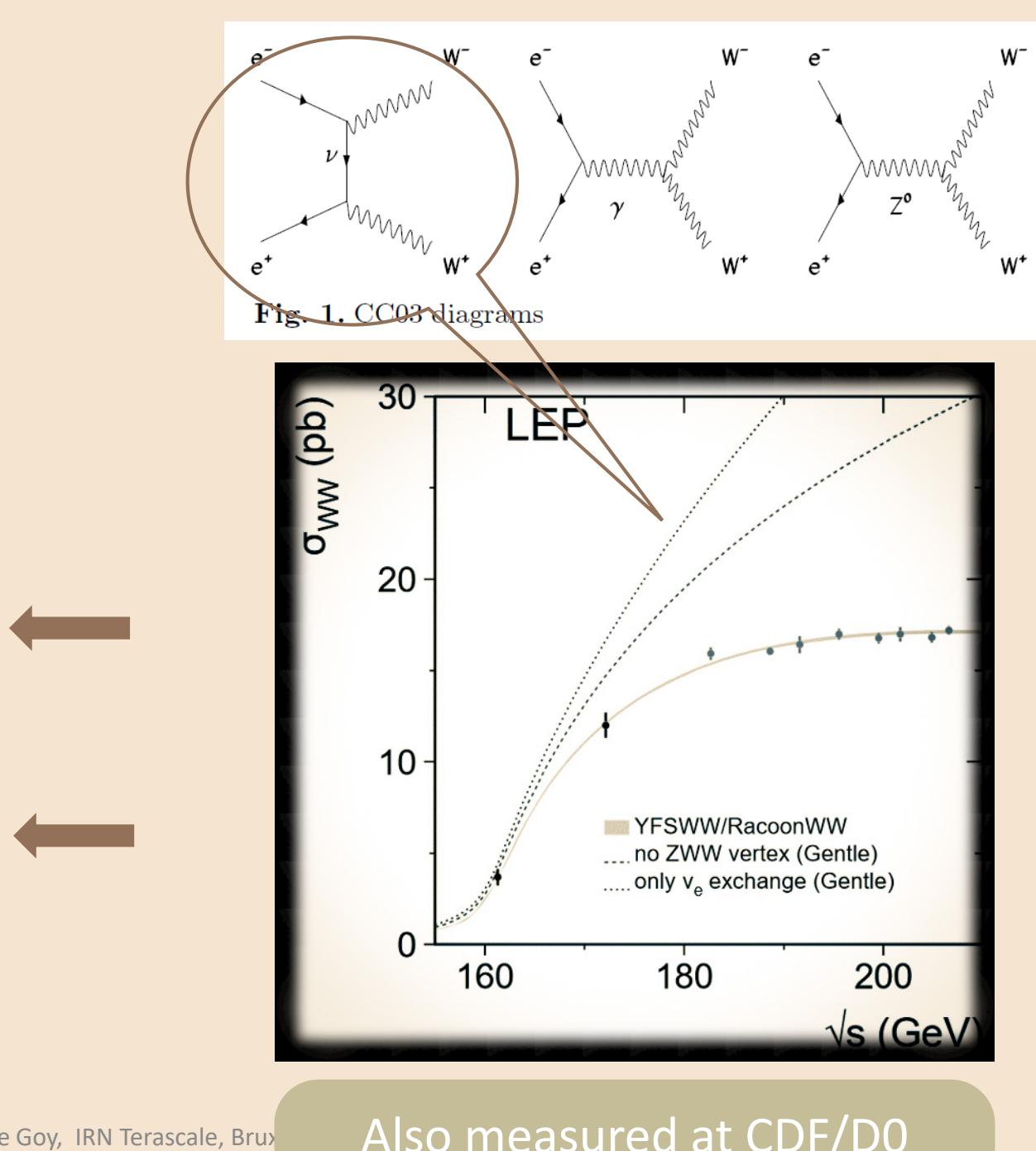
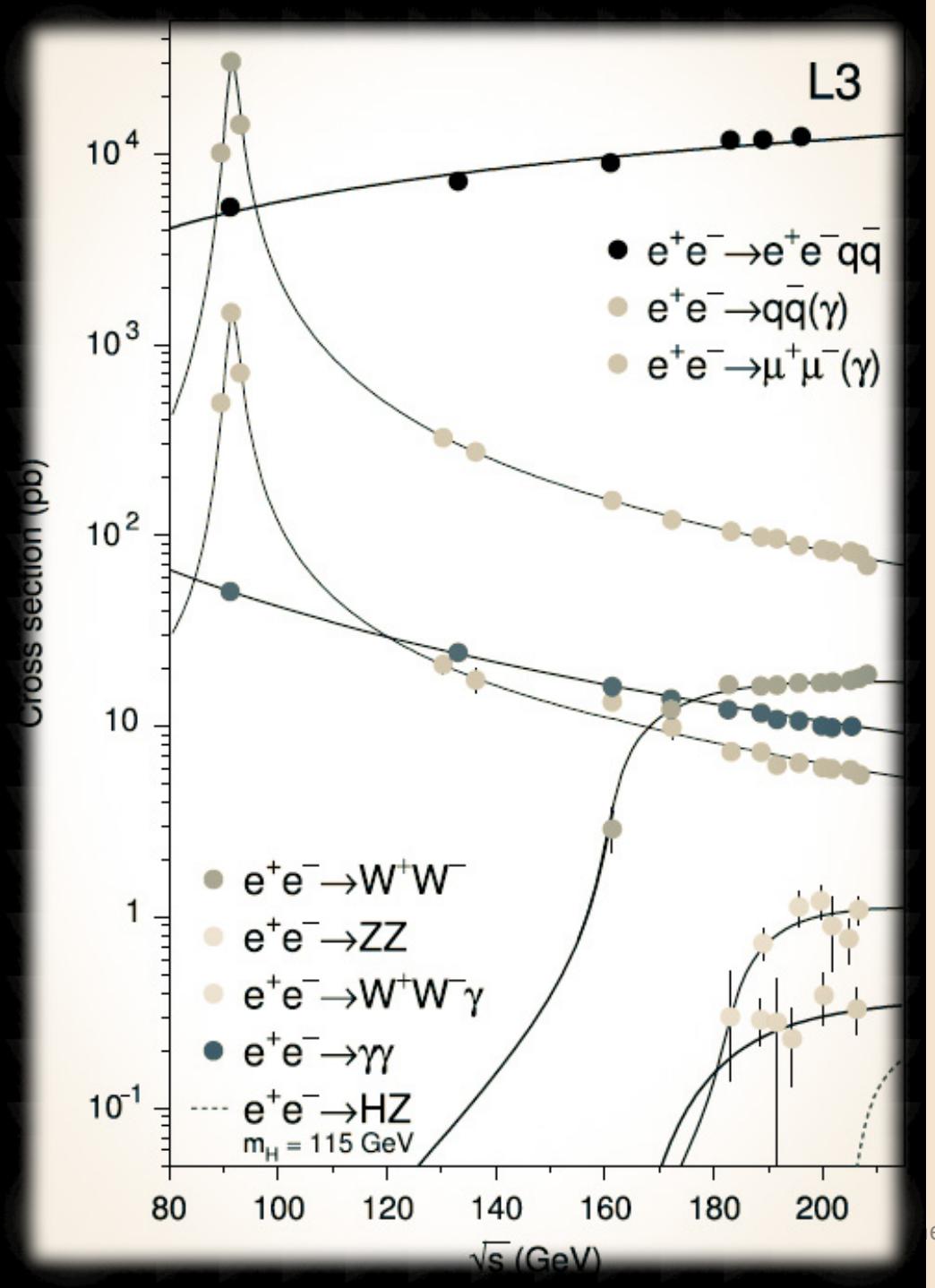


Inclusive



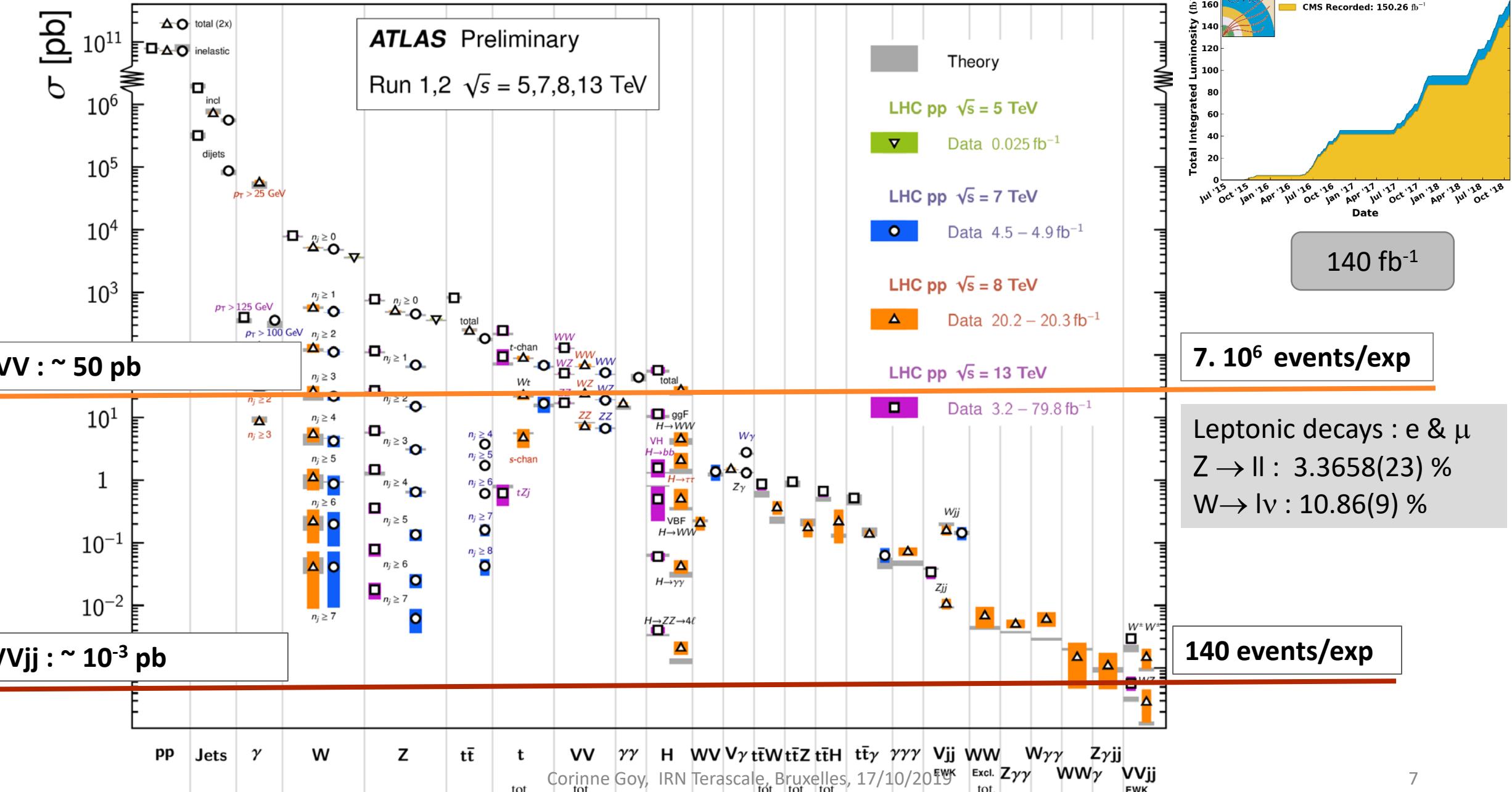
Exclusive

Example of WZ final state



# Standard Model Production Cross Section Measurements

Status: July 2019



# Inclusive production

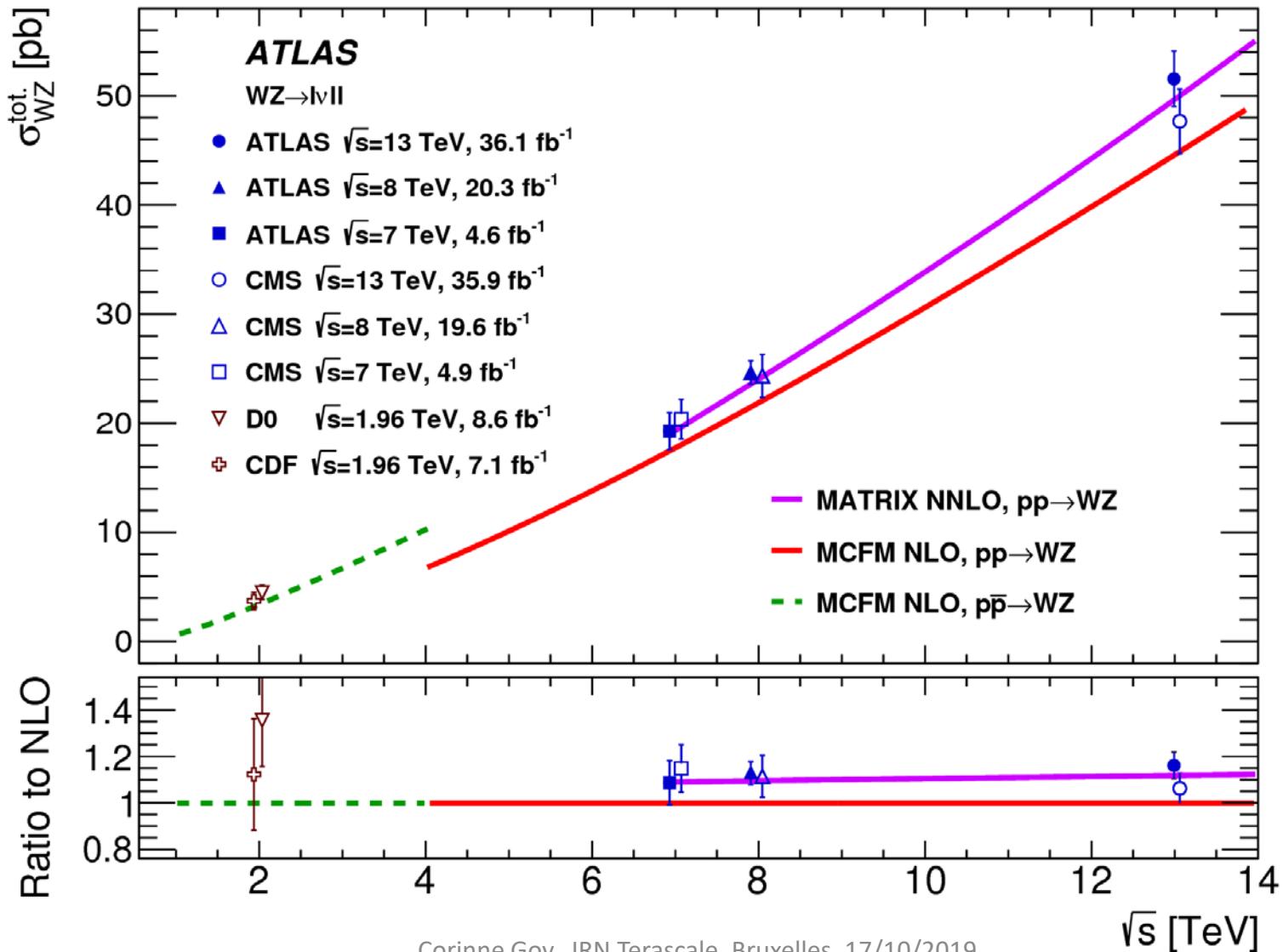
Need for theoretical precision

Differential distributions

Polarization measurements (WZ)

aTGC

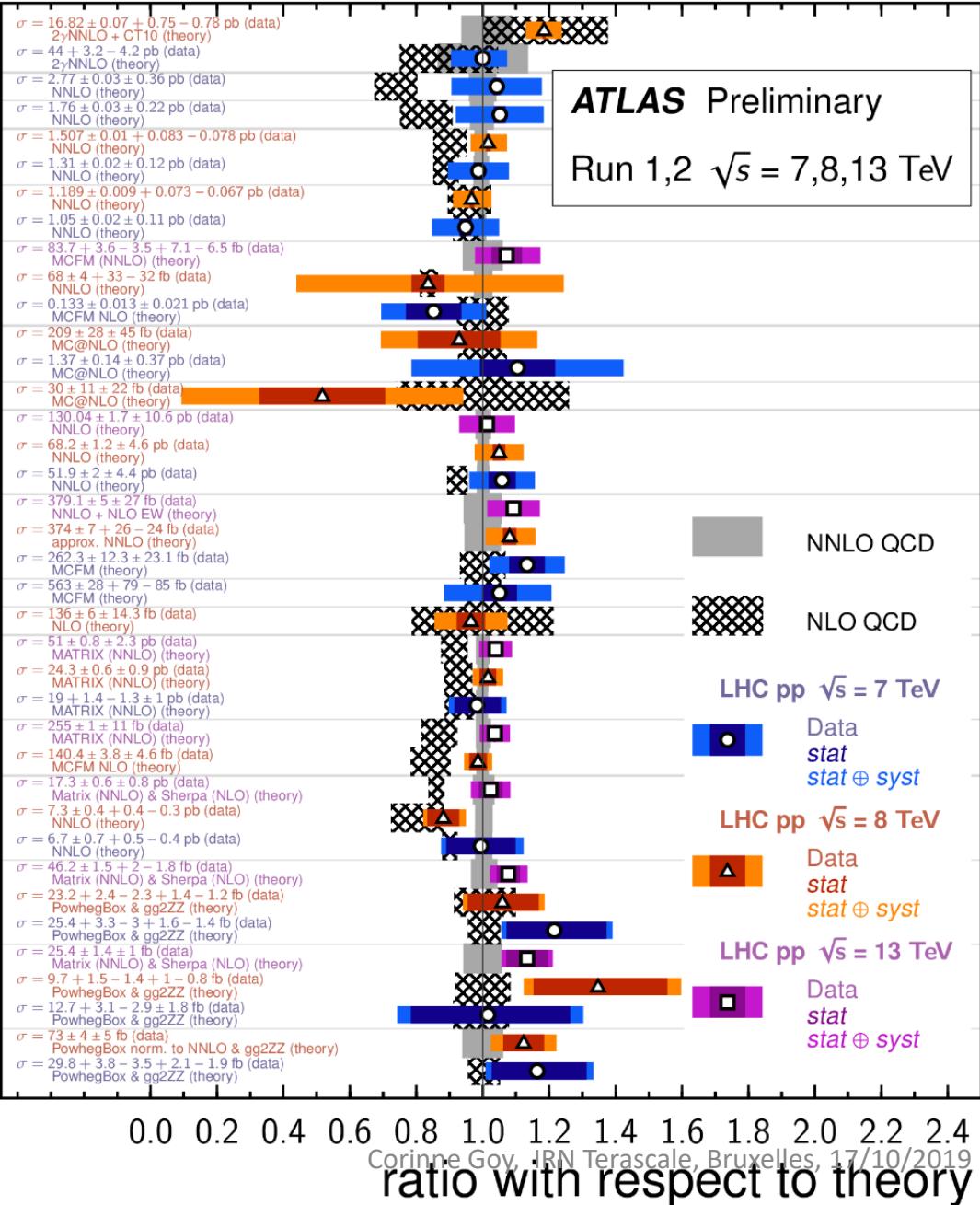
# The need for NNL0 precision



# Diboson Cross Section Measurements

Status: July 2019

- $\gamma\gamma$
- $W\gamma \rightarrow \ell\nu\gamma$ 
  - $[n_{jet} = 0]$
- $Z\gamma \rightarrow \ell\ell\gamma$ 
  - $[n_{jet} = 0]$
- $- Z\gamma \rightarrow \nu\nu\gamma$
- $WW \rightarrow \ell\nu jj$ 
  - $WW \rightarrow \ell\nu J$
- $WW$ 
  - $WW \rightarrow e\mu, [n_{jet} = 0]$
  - $WW \rightarrow e\mu, [n_{jet} \geq 0]$
  - $WW \rightarrow e\mu, [n_{jet} = 1]$
- $WZ$ 
  - $WZ \rightarrow \ell\nu\ell\ell$
- $ZZ$ 
  - $ZZ \rightarrow 4\ell$
  - $ZZ \rightarrow \ell\ell\nu\nu$
  - $ZZ^* \rightarrow 4\ell$



ATLAS Preliminary

Run 1,2  $\sqrt{s} = 7,8,13$  TeV

ratio with respect to theory

Observation :  
in many channels ,  
error on NLO does  
not cover NNLO

## Perturbative expansion

$$d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}}$$

NLO QCD      NLO EW

$$+ \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_S \alpha_{\text{EW}} d\sigma_{\text{NNLO QCDxEW}} + \dots$$

NNLO QCD      NNLO EW      NNLO QCD-EW

+ effects on the shape of distributions

Numerically  $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow \boxed{\text{NLO EW} \sim \text{NNLO QCD}}$

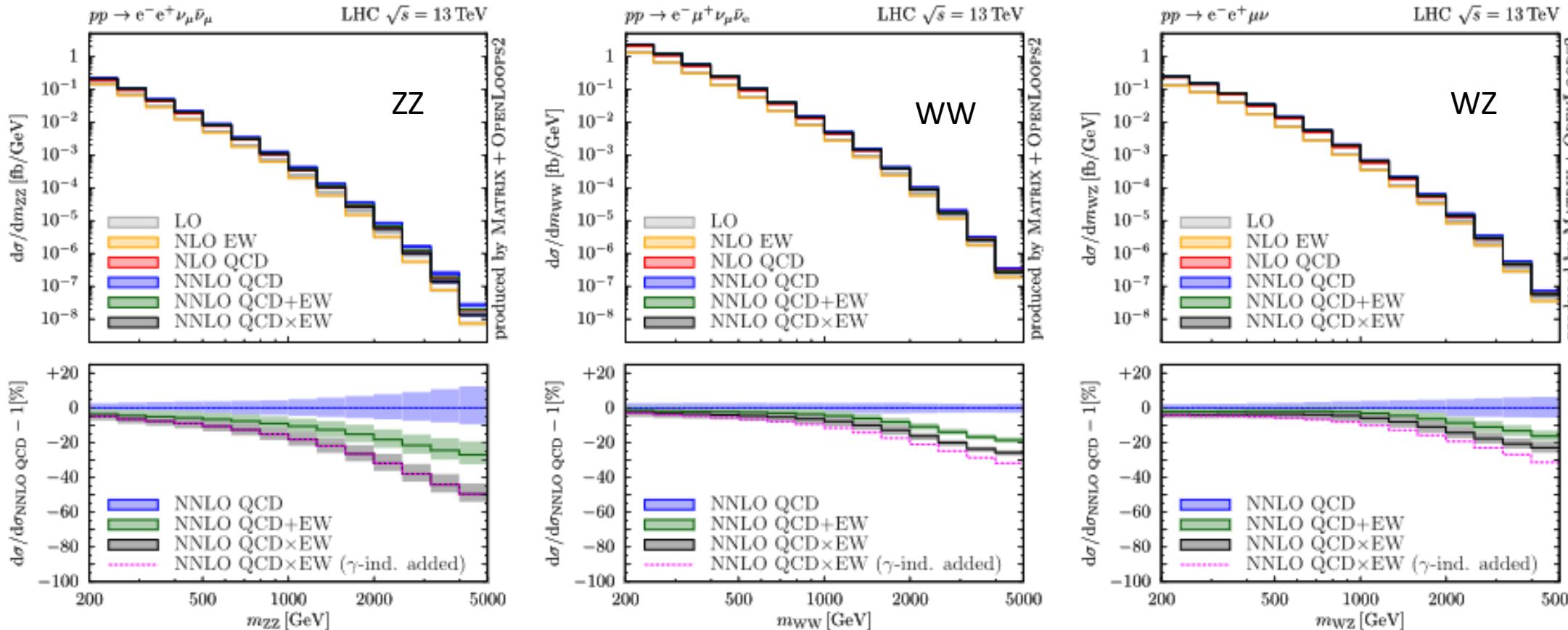
### NLO EW

- 4I-DF-ZZ                          Biedermann, Denner, Dittmaier, Hofer, Jäger; '16, '16
- 2I-DF-WW                          Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder; '16
- 2I-SF-ZZ & 2I-SF-ZZWW & 2I-DF-WW                  Kallweit, JML, Pozzorini, Schönherr; '17
- 3I-DF-WZ & 3I-DF-WZ                  Biedermann, Denner, Hofer, '17

# ZZ/WW/WZ: NNLO + NLO EW combination

**EW corrections are sizeable particularly at high energy - region of interest for aTGC**

from Kallweit's Moriond talk 2019



Preliminary!

[Grazzini, SK, Lindert, Pozzorini, Wiesemann, (in preparation)]

- Issue with add/mult. combination : difference not covered by their own scale uncertainties → large syst.
- ( Can be mitigated by jet veto )

# Precision frontier

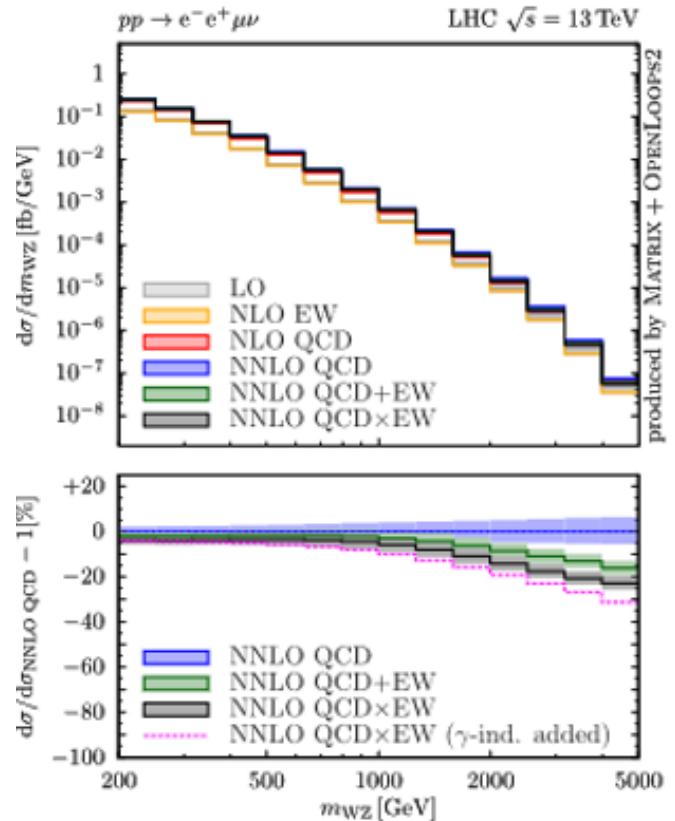
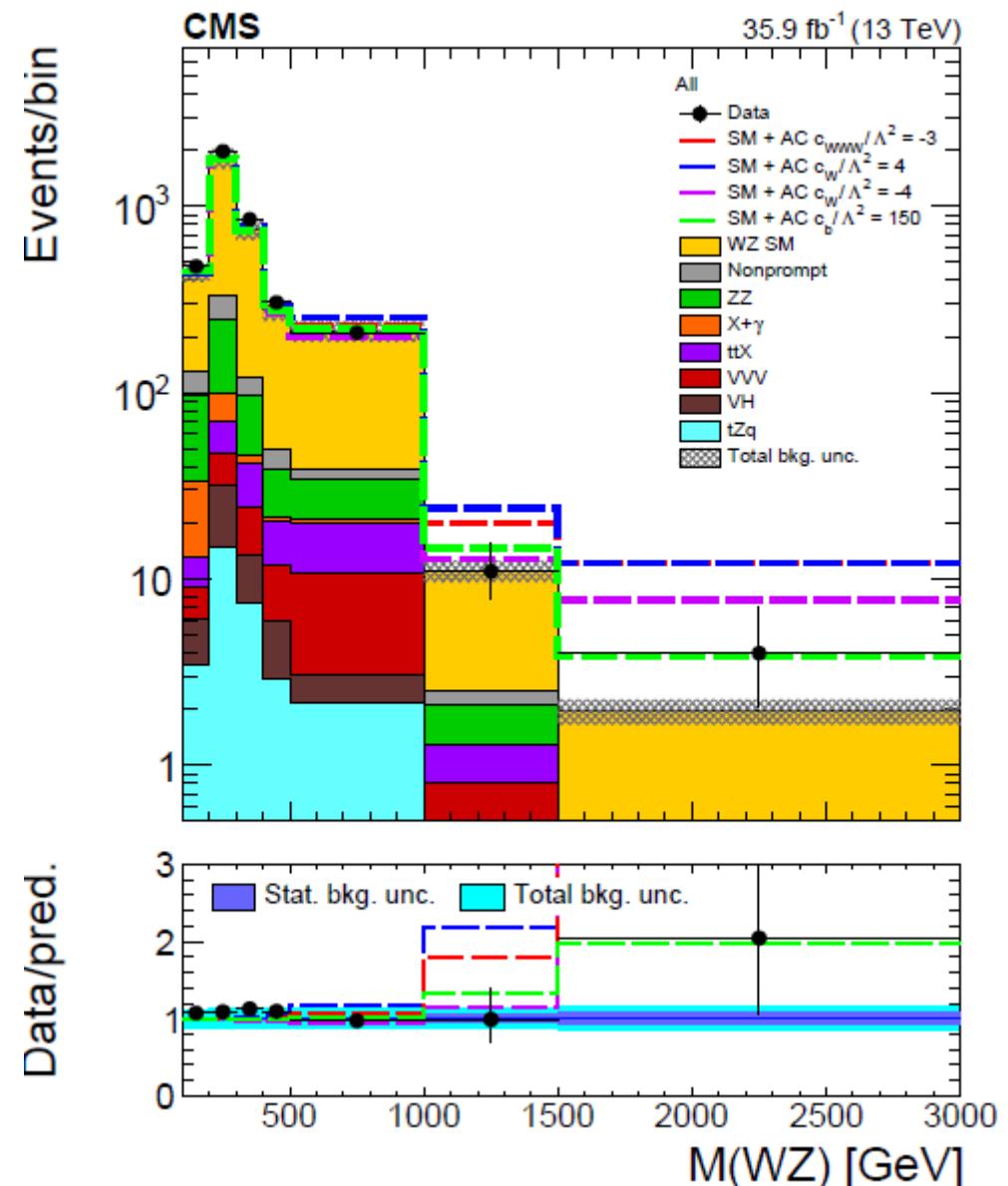
- Few results with full statistics available yet
  - $\sigma_{\text{Fid}}$  : 5 - 8%
- Differential distributions
  - Larger stat. with full Run2 +Run3 analysis : Tails ...
  - Increased sensitivity to MC descriptions
- Polarization

	Channel	Energy TeV	Luminosity /fb	arXiv:
ATLAS	Z $\gamma$ (l $\bar{l}\gamma$ )	13	139	ATLAS-CONF-2019-034
	ZZ (2l2v)	13	36.1	1905.07163
	W+W-	13	36.1	1905.04242
	WZ(3lv)	13	36.1	1902.05759
	Z $\gamma$ (vv $\gamma$ )	13	36.1	1810.04995
	ZZ (4l)	13	36.1	1709.07703
	WV(lvjj)	8	20.1	1706.01702
CMS	WZ	13	35.9	1901.03428
	ZZ	13	<b>137.0</b>	SMP-19-001
	WV	8	19.4	1703.06095
	Z $\gamma$ (vv $\gamma$ )	8	19.4	1602.07152
	W+W-	8	19.4	1507.03268

# WZ

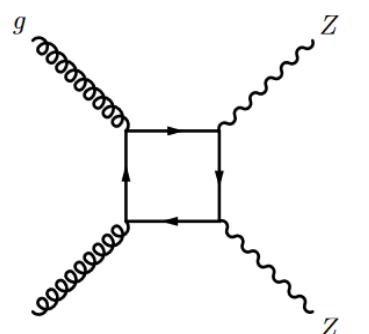
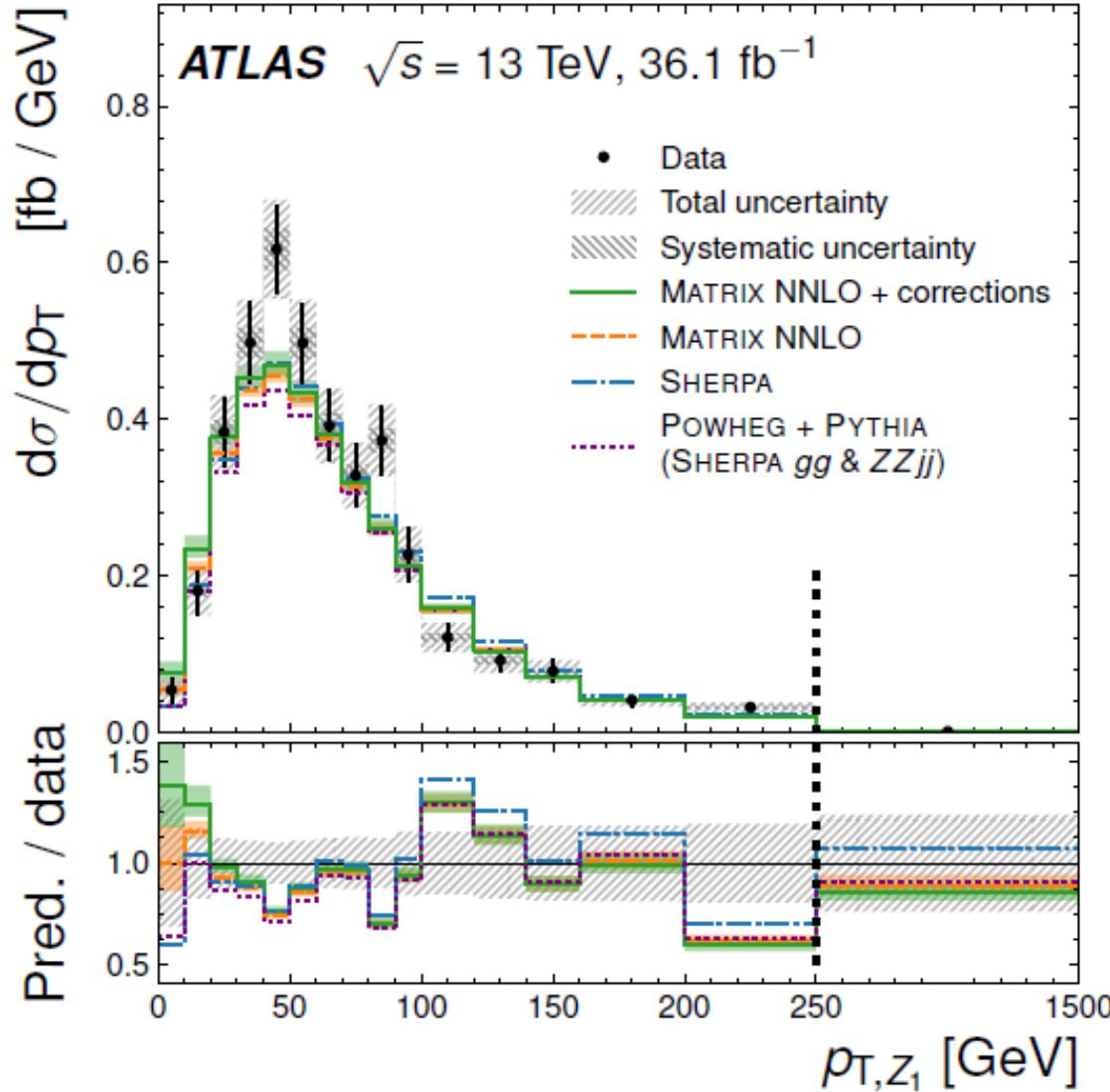
Exemple :  
 ~ 20 events > 1 TeV  
 End of run3 : 7%

**Combination**  
**ATLAS/CMS valuable**

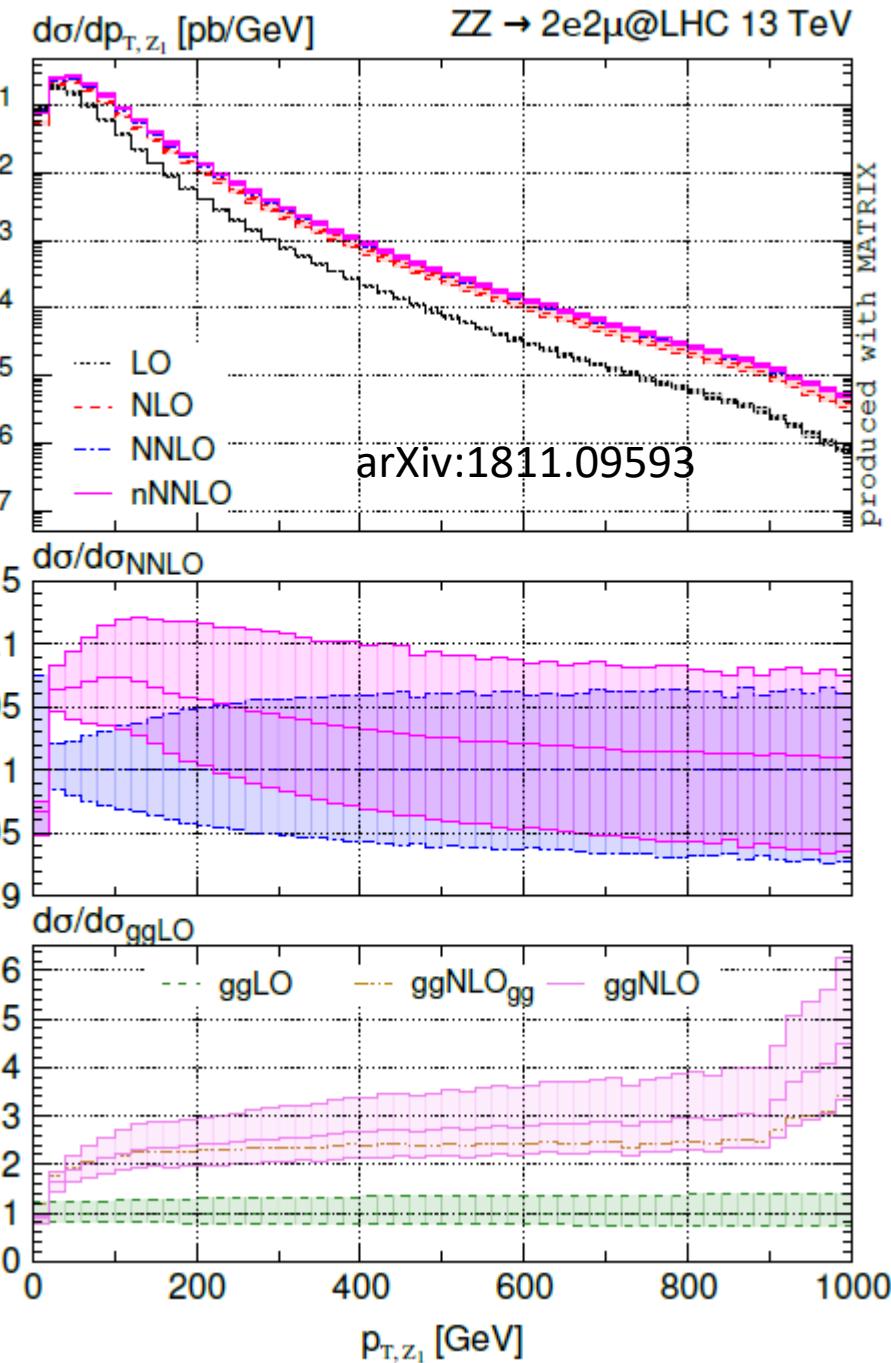


Soon sensitive

# ZZ (4l)



Not only the tails



# Polarisation: in WZ (inclusive) only

Eur. Phys. J. C (2019) 79:535  
<https://doi.org/10.1140/epjc/s10052-019-7027-6>

Regular Article - Experimental Physics

**Measurement of  $W^\pm Z$  production cross sections and gauge boson polarisation in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector**

ATLAS Collaboration\*

CERN, 1211 Geneva 23, Switzerland

$\mathcal{L} = 36.1 \text{ fb}^{-1}$   
 $\sqrt{s} = 13 \text{ TeV}$

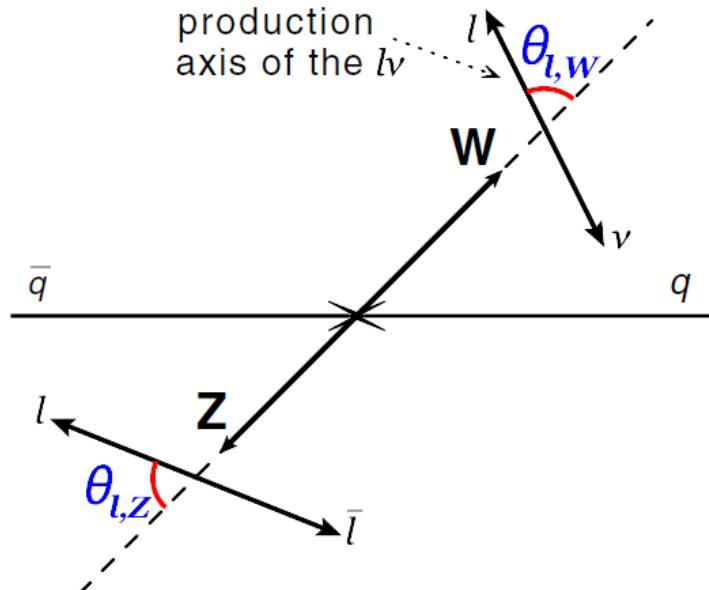
THE EUROPEAN  
PHYSICAL JOURNAL C



	Fiducial PS
Lepton $ \eta $	2.5
$pT$ of $Z$ lepton	15 GeV
$m_Z$	$ m_Z - m_{\text{PDG}}  < 10 \text{ GeV}$
$pT$ of $W$ lepton	20 GeV
$mT(W)$	30
$\Delta R(Z)$	$> 0.2$
$\Delta R(Z, W)$	$> 0.3$

Born lepton

# Method



$\theta$  is defined as the angle between the lepton direction in the V restframe and the V direction in the WZ restframe  
**(modified helicity coordinate system)**

*Other coordinate systems :*

- *Collins-Soper*
- *Helicity*

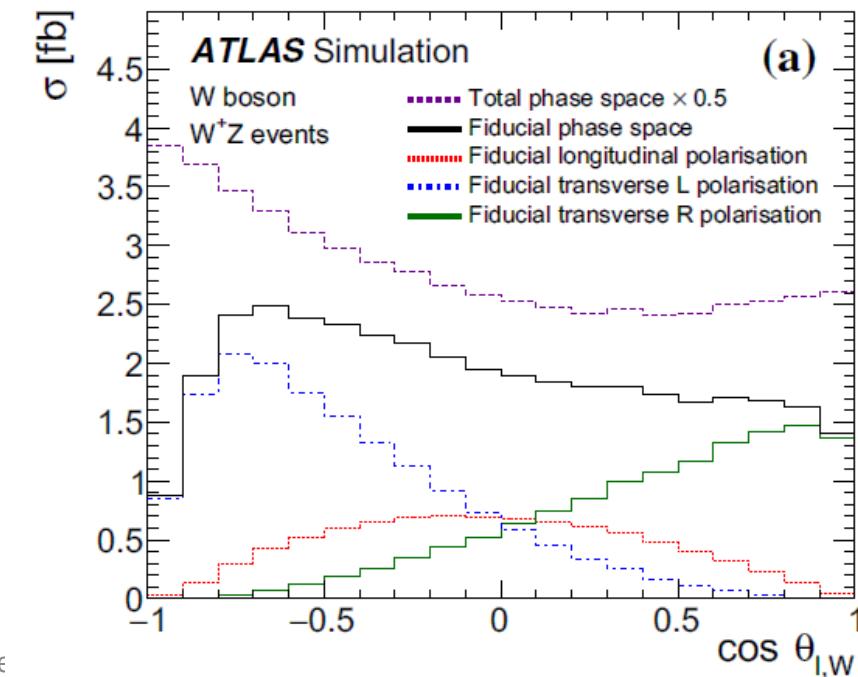
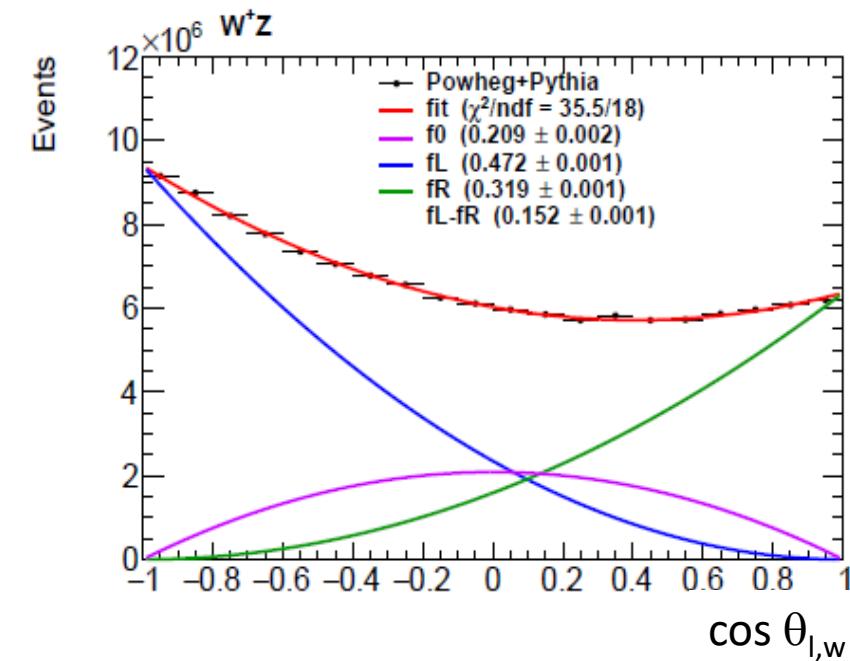
*Attached to each boson*  
*W uncertainty does not “leak” into WZ*  
*ATLAS & CMS combination*

$$\frac{1}{\sigma_{W^\pm Z}} \frac{d\sigma_{W^\pm Z}}{d \cos \theta_{\ell,W}} = \frac{3}{8} f_L (1 \mp \cos \theta_{\ell,W})^2 + \frac{3}{8} f_R (1 \pm \cos \theta_{\ell,W})^2 + \frac{3}{4} f_0 \sin^2 \theta_{\ell,W}$$

$$\frac{1}{\sigma_{W^\pm Z}} \frac{d\sigma_{W^\pm Z}}{d \cos \theta_{\ell,Z}} = \frac{3}{8} f_L (1 + 2A \cos \theta_{\ell,Z} + \cos^2 \theta_{\ell,Z}) + \frac{3}{8} f_R (1 + \cos^2 \theta_{\ell,Z} - 2A \cos \theta_{\ell,Z}) + \frac{3}{4} f_0 \sin^2 \theta_{\ell,Z}$$

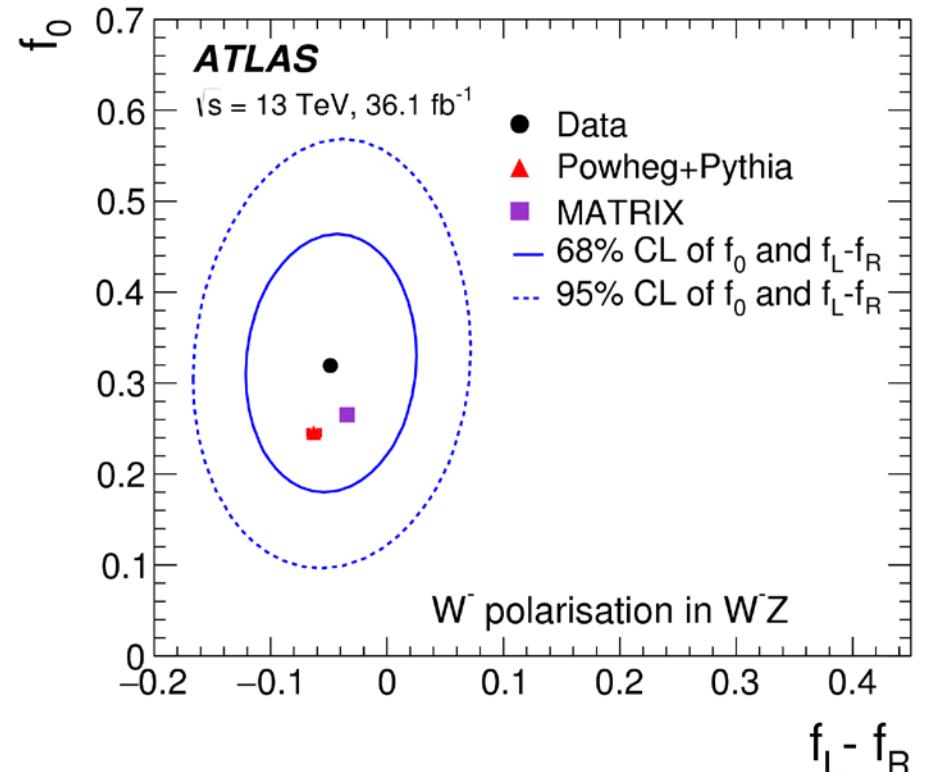
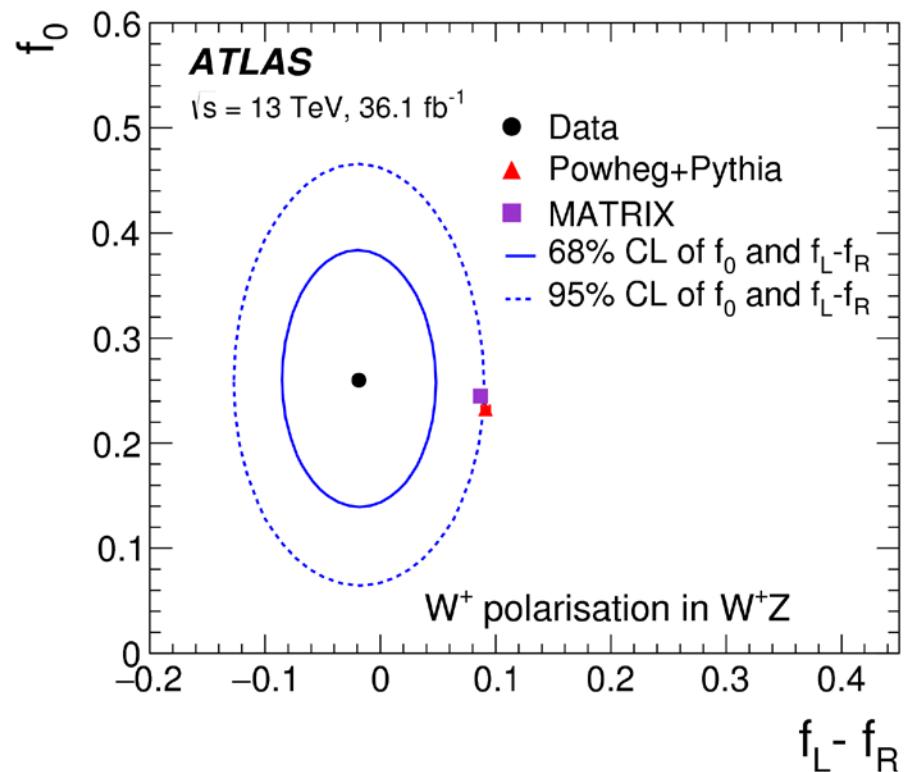
- Powheg-Pythia MC sample
- **Longitudinal, Left** and **Right** fractions are determined with an analytic fit in bins of  $pT(V)$  and  $Y_V$ , separately in  $ZW^+, ZW^-$  in total phase-space  
→ Weights per event to create pure helicity state templates at the reconstruction level

- Reweighting method previously used in e.g *PRL 107, 021802 (2011) CMS Collaboration, Eur. Phys. J. C(2012) ATLAS Collaboration*
- Are all dependencies taken into account with  $pT(V)$  and  $Y_V$  ?
- Cannot reweight other sensitive variables



W	$f_0$	Longitudinal (= F0)				Left – Right						
		Data	POWHEG+PYTHIA	MATRIX		$f_L - f_R$	Data	POWHEG+PYTHIA	MATRIX			
$W^+$ in $W^+Z$	0.26	0.08	0.233	0.004	0.2448	0.0010	-0.02	0.04	0.091	0.004	0.0868	0.0014
$W^-$ in $W^-Z$	0.32	0.09	0.245	0.005	0.2651	0.0015	-0.05	0.05	-0.063	0.006	-0.034	0.004
$W^\pm$ in $W^\pm Z$	0.26	0.06	0.2376	0.0031	0.2506	0.0006	-0.024	0.033	0.0289	0.0022	0.0375	0.0011

- Stat error dominant
- F0 is measured different from 0 at more than 3 sigma and in agreement with predictions
- FL-FR at 2  $\sigma$  from predictions for  $W^+$



Z

## Longitudinal (= F0)

 $f_0$ 

Data

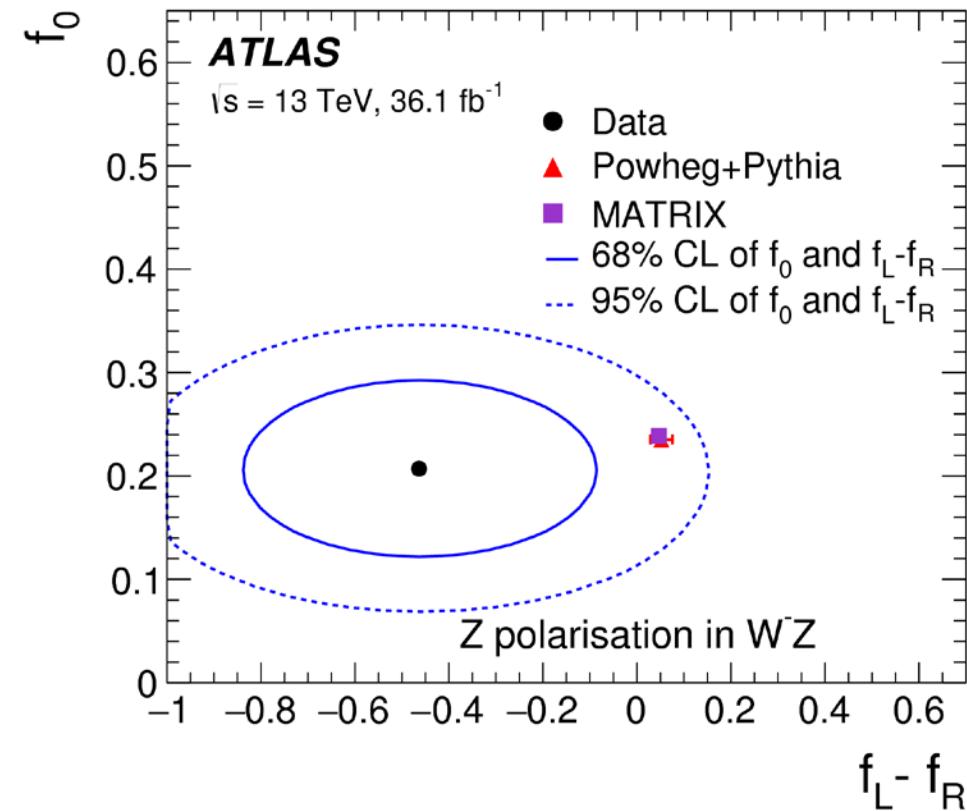
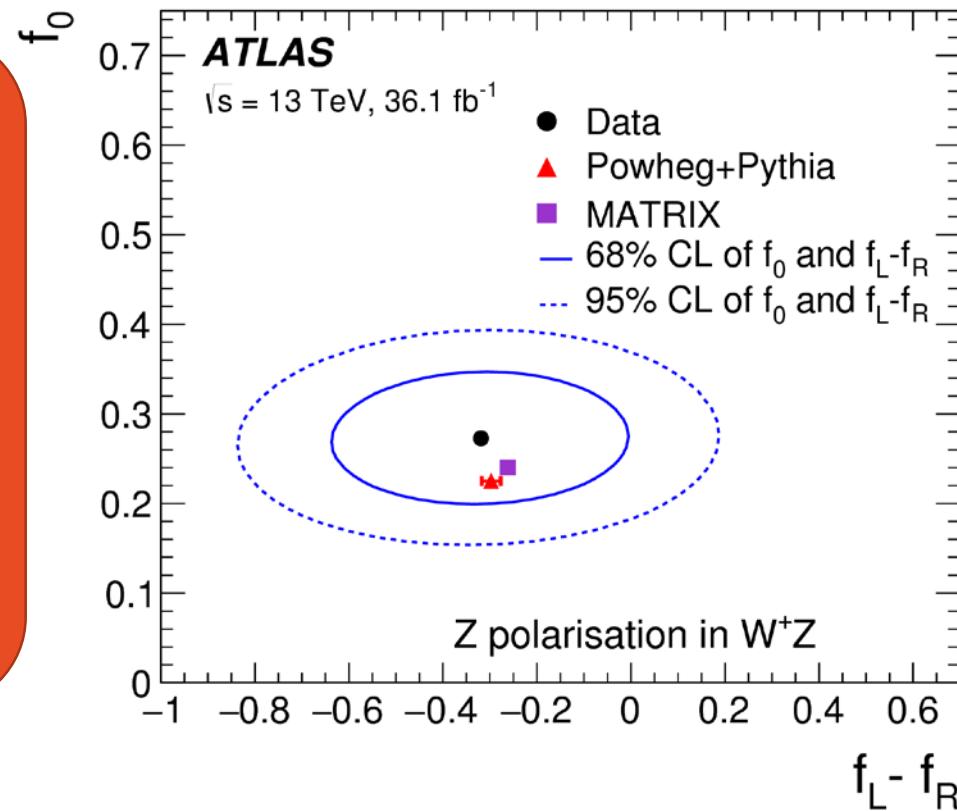
	POWHEG+PYTHIA			MATRIX	
Z in $W^+Z$	0.27	0.05	0.225	0.004	0.2401
Z in $W^-Z$	0.21	0.06	0.235	0.005	0.2389
Z in $W^\pm Z$	0.24	0.04	0.2294	0.0033	0.2398
					0.0014

 $f_L - f_R$ 

Data

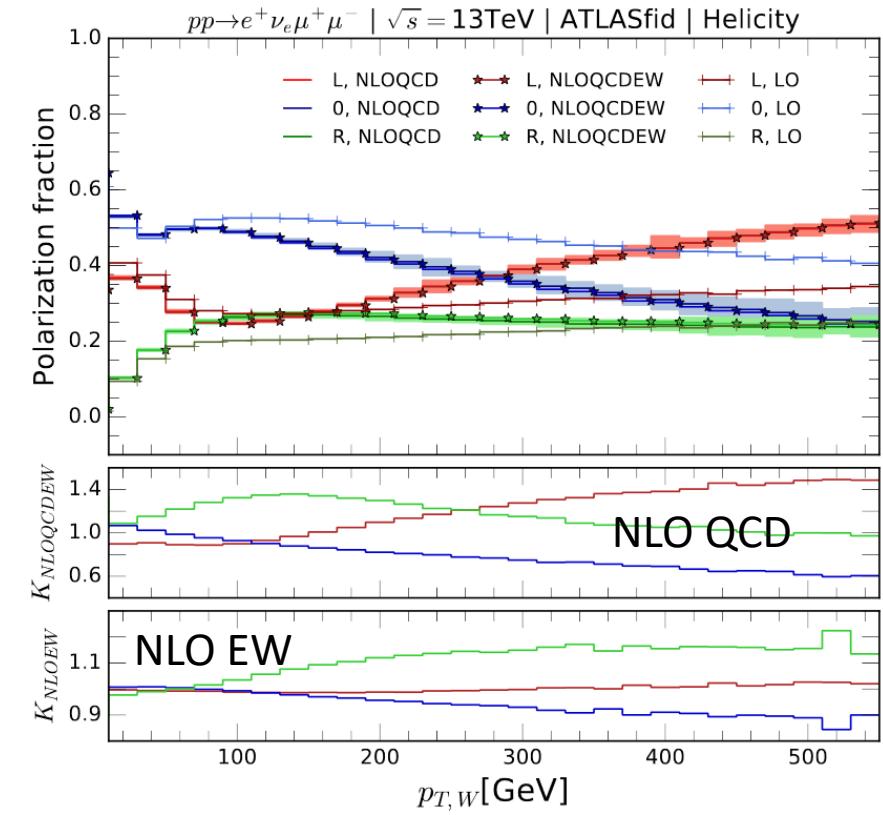
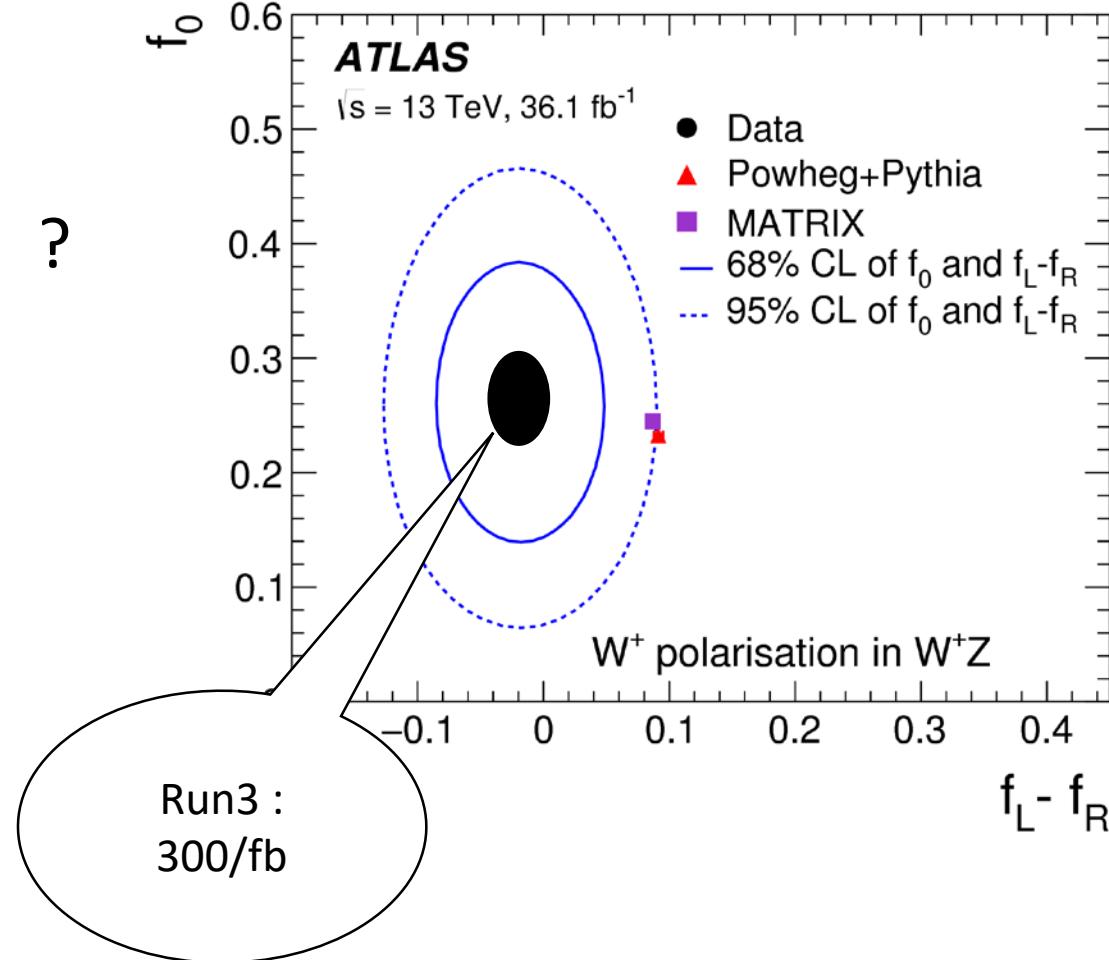
	POWHEG+PYTHIA			MATRIX	
Z in $W^+Z$	-0.32	0.21	-0.297	0.021	-0.262
Z in $W^-Z$	-0.46	0.25	0.052	0.023	0.0468
Z in $W^\pm Z$	-0.39	0.16	-0.156	0.016	-0.135
					0.006

- Stat error dominant
- F0 is measured different from 0 at more than 3 sigma and in agreement with predictions
- Better agreement in  $W^+Z$



# But what can we learn from measuring F0 in WZ inclusive ?

- $mV \neq 0$  ?
- $F_0$  vs  $|p_T|$    
  $M_{WZ}$  ?
- aTGG ?



JHEP 04 (2019) 065 / arXiv:1810.11034  
J. Baglio & D.N. Le

# First measurements @ LEP2

$$e^+ e^- \rightarrow WW \rightarrow l\nu qq'$$

$$\mathcal{L} = 520 \text{ pb}^{-1}$$

$$\sqrt{s} = 189 \text{ to } 209 \text{ GeV}$$

DELPHI:

- Using SDM
- One parameter fit
- CP violating aTGC

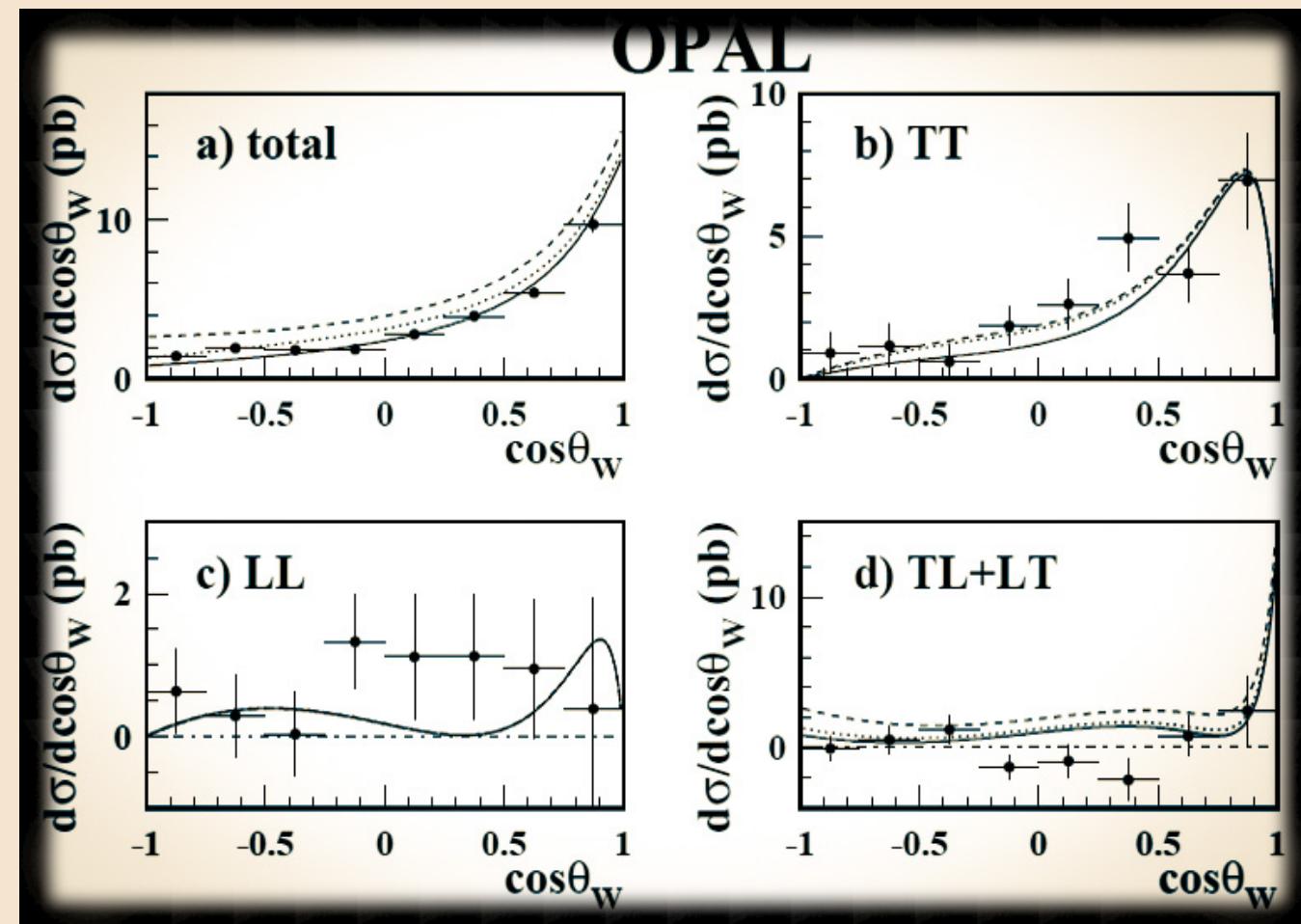
$$g_4^Z = -0.39^{+0.19}_{-0.20},$$

$$\tilde{\kappa}_Z = -0.09^{+0.08}_{-0.05},$$

$$\tilde{\lambda}_Z = -0.08 \pm 0.07.$$

"For the CP conserving TGC's, the values obtained in this (SDM) analysis are less precise than those measured in the DELPHI analysis using optimal observables "

T = Left + Right  
L = Longitudinal



"It is evident that the CP-violating couplings are better constrained by the SDM elements than by the  $W$  boson production angular distribution, whereas for the CP-conserving couplings the converse is true."

# aTGC

Change of paradigm from LEP & Run I  
description

Effective field theory description

Low energy theory

## Phenomenological lagrangian

$$\begin{aligned}\frac{\mathcal{L}_{WWV}}{g_{WWV}} = & ig_1^V \left( W_{\mu\nu}^\dagger W^{\mu\nu} V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu} \right) + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} \\ & + \frac{i\lambda_V}{m_W^2} W_{\rho\mu}^\dagger W_\nu^\mu V^{\nu\rho} - g_4^V W_\mu^\dagger W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\ & + g_5^V \epsilon^{\mu\nu\rho\sigma} (W_\mu^\dagger \overleftrightarrow{\partial}_\rho W_\nu) V_\sigma + i\tilde{\kappa}_V W_\mu^\dagger W_\nu \tilde{V}^{\mu\nu} \\ & + \frac{i\tilde{\lambda}_V}{m_W^2} W_{\rho\mu}^\dagger W_\nu^\mu \tilde{V}^{\nu\rho}\end{aligned}$$

$$\mathcal{L}^{\text{eff.}} = \mathcal{L}^{\text{SM}} + \sum_i \frac{c_6^i}{\Lambda^2} \mathcal{O}_6^i + \sum_i \frac{c_8^i}{\Lambda^4} \mathcal{O}_8^i + \dots$$



H Milder @ MBI

R Aggleton @ MBI

# EFT : optimal in terms of description of TGC

From 14 to 5 parameters

C and P conserving parameters

$$c_{WWW}/\Lambda^2 = \frac{2\lambda_\gamma}{3g^2m_W^2} = \frac{2\lambda_Z}{3g^2m_W^2},$$

$$c_W/\Lambda^2 = 2\frac{\Delta g_1^Z}{m_Z^2},$$

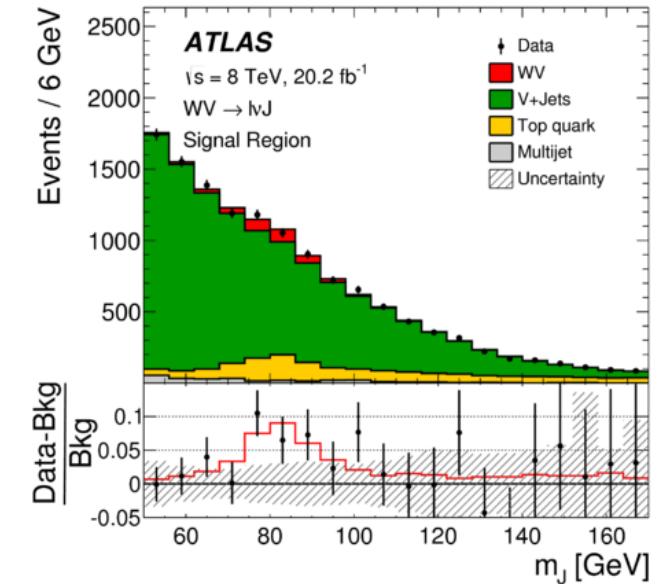
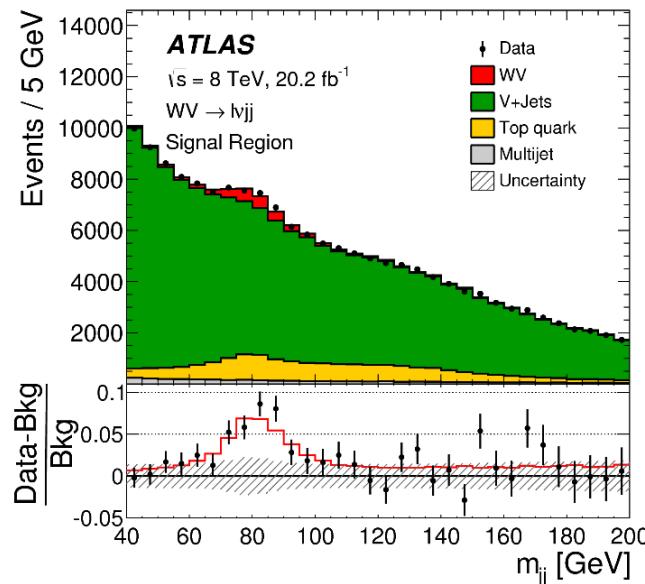
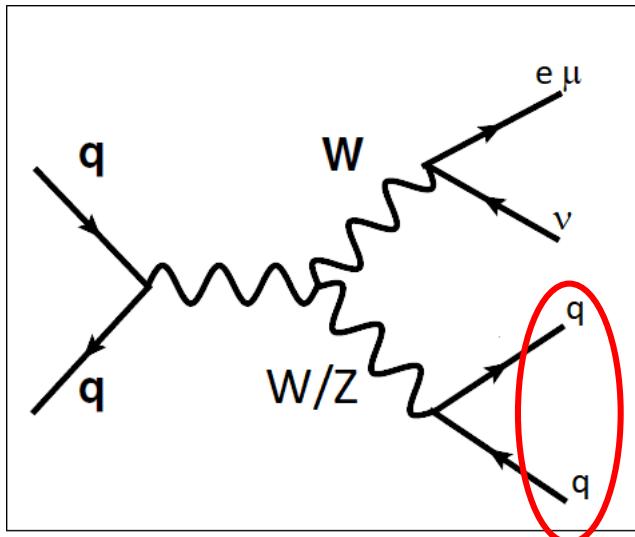
$$c_B/\Lambda^2 = 2 \left[ \frac{\Delta \kappa_\gamma}{m_W^2} - \frac{\Delta g_1^Z}{m_Z^2} \right] = 2 \frac{\Delta \kappa_\gamma - \Delta \kappa_Z}{m_Z^2}.$$

C or P violating parameters

$$\frac{c_{\tilde{W}}}{\Lambda^2} = \frac{2}{m_W^2} \tilde{\kappa}_\gamma = -$$

$$\frac{c_{\tilde{W}WW}}{\Lambda^2} = \frac{2}{3g^2m_W^2} \tilde{\lambda}_\gamma$$

# Better sensitivity using VV semi-leptonic decays



Parameter	$\text{WV} \rightarrow \ell\nu jj$		$\text{WV} \rightarrow \ell\nu J$	
	Observed [ $\text{TeV}^{-2}$ ]	Expected [ $\text{TeV}^{-2}$ ]	Observed [ $\text{TeV}^{-2}$ ]	Expected [ $\text{TeV}^{-2}$ ]
$c_{WWW}/\Lambda^2$	[ -5.3, 5.3]	[ -6.4, 6.3]	[ -3.1, 3.1]	[ -3.6, 3.6]
$c_B/\Lambda^2$	[ -36, 43]	[ -45, 51]	[ -19, 20]	[ -22, 23]
$c_W/\Lambda^2$	[ -6.4, 11]	[ -8.7, 13]	[ -5.1, 5.8]	[ -6.0, 6.7]

ATLAS: 20.2/fb  
 1D limit

# From 8 to 13 TeV : factor ~2 improvement

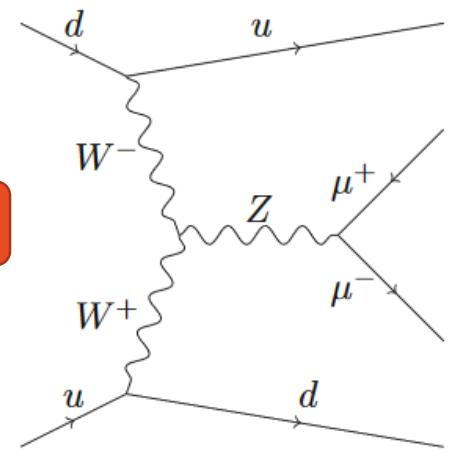
Parametrization	aTGC	Expected limit	Observed limit	Observed best-fit	CMS 8 TeV observed limit
EFT <b>CMS, 35.6/fb</b>	$c_{WWW}/\Lambda^2$ (TeV $^{-2}$ )	[-1.44, 1.47]	[-1.58, 1.59]	-0.26	[-2.7, 2.7]
	$c_W/\Lambda^2$ (TeV $^{-2}$ )	[-2.45, 2.08]	[-2.00, 2.65]	1.21	[-2.0, 5.7]
	$c_B/\Lambda^2$ (TeV $^{-2}$ )	[-8.38, 8.06]	[-8.78, 8.54]	1.07	[-14, 17]
1D limit LEP	$\lambda_Z$	[-0.0060, 0.0061]	[-0.0065, 0.0066]	-0.0010	[-0.011, 0.011]
	$\Delta g_1^Z$	[-0.0070, 0.0061]	[-0.0061, 0.0074]	0.0027	[-0.019, 0.024 ]
	$\Delta \kappa_Z$	[-0.0074, 0.0078]	[-0.0079, 0.0081]	-0.0010	[-0.018, 0.013 ]

(But no study on validity of EFT/unitarity or quadratic terms)

## ATLAS W+W- fully leptonic, 13 TeV, 36/fb

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

Less sensitive



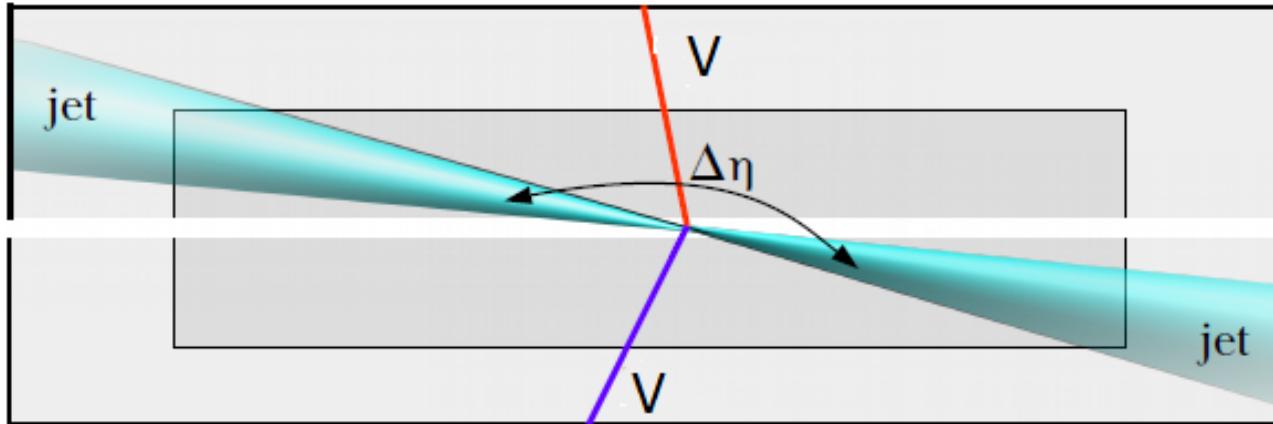
# Exclusive production - VBS

# Status of the VVjj search in pp collisions

Contrary to VV inclusive, never seen before LHC ( $\sigma \sim 10^{-3}$  fb)

Observed significance to date :							
Ex	CoM	WWjj	ssWWjj	WZjj	ZZjj	Z $\gamma$ jj	W $\gamma$ jj
CMS	8 TeV		2.0 (19.7/fb)				2.7 (19.7/b)
ATLAS	8 TeV		3.6 (20.3/fb)				
CMS	13 TeV		5.5 (35.9/fb)	2.2 (35.9/fb)	2.7 (35.9/fb)	<b>4.7</b> <b>(19.7/fb+35.9/fb)</b>	
ATLAS	13 TeV		6.5 (36.1/fb)	5.3 (36.1/fb)	<b>5.5</b> <b>(139/fb)</b>	<b>4.1</b> <b>(36.1/fb)</b>	

# Clean experimental signature



- 2 fwd jets
- 2 central bosons

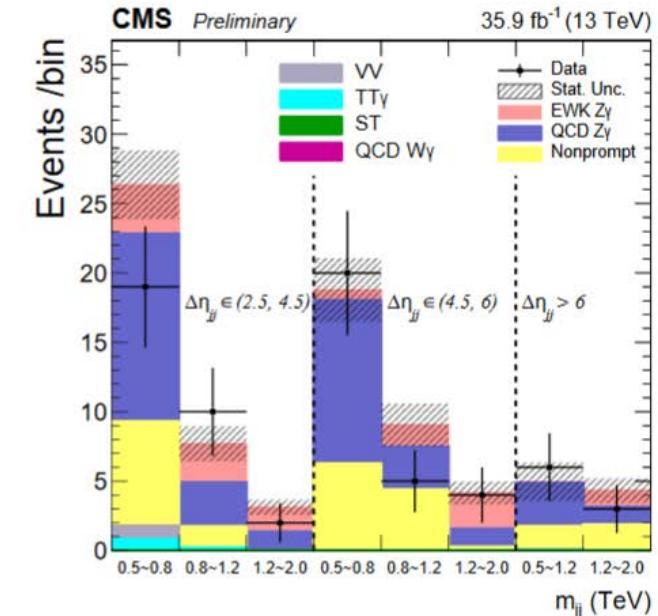
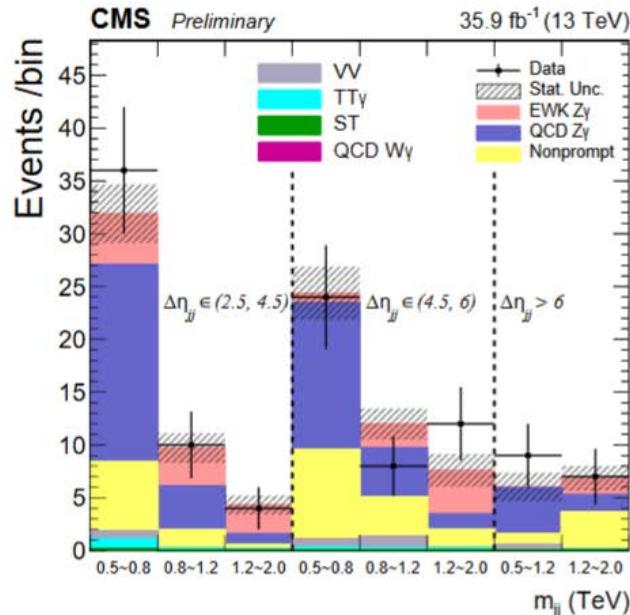
- Except for ssWW, large QCD background
- **Mitigated by first used of multivariate discriminants in SM analysis**
- Main systematic error:
  - Jet related syst (energy scale )
  - Background modelling VVjj-QCD
  - Interference (**usually included in the signal** )

# Z $\gamma$

CMS: SMP-18-007

ee/mm

Unrolled 2D distribution:  $m_{jj}$  vs  $\Delta\eta_{jj}$   
(MG5\_MC@NLO)



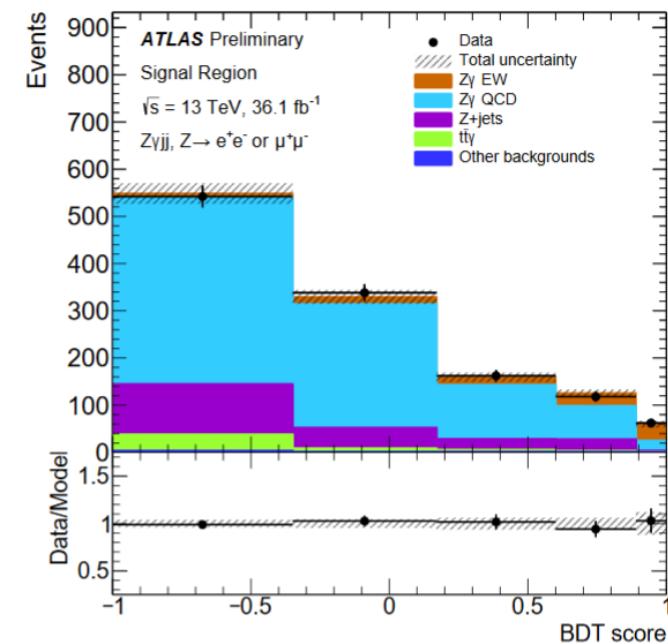
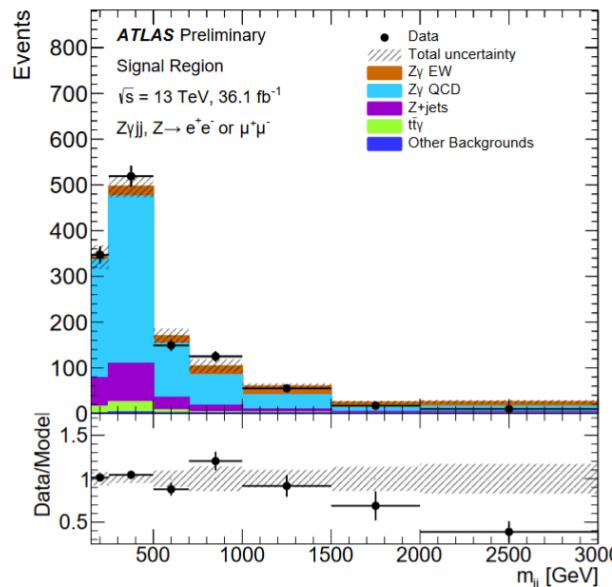
ATLAS : ATLAS-CONF-2019-039

BDT

poor description of the jets  
decreases the overall significance

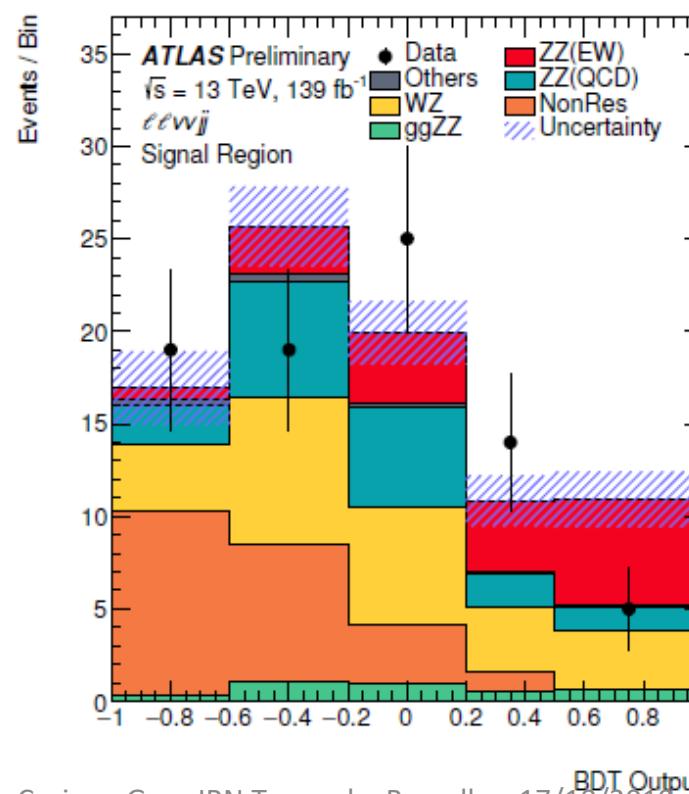
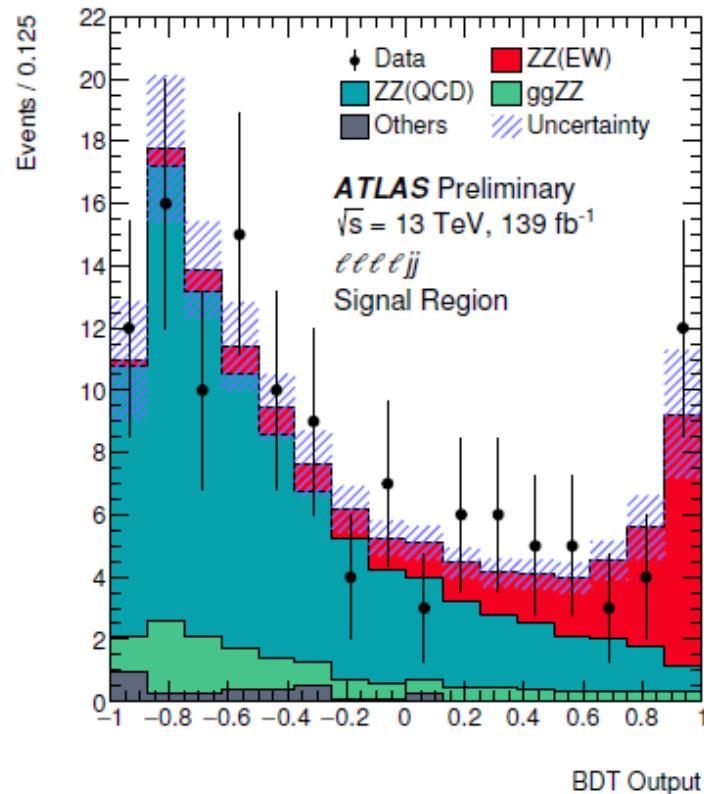
MC signal : MG5\_MC@NLO

MC QCD : Sherpa 2.2.2



# ATLAS : ZZjj in 4l and 2l 2v

	Measured fiducial $\sigma$ [fb]	Predicted fiducial $\sigma$ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell vv jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

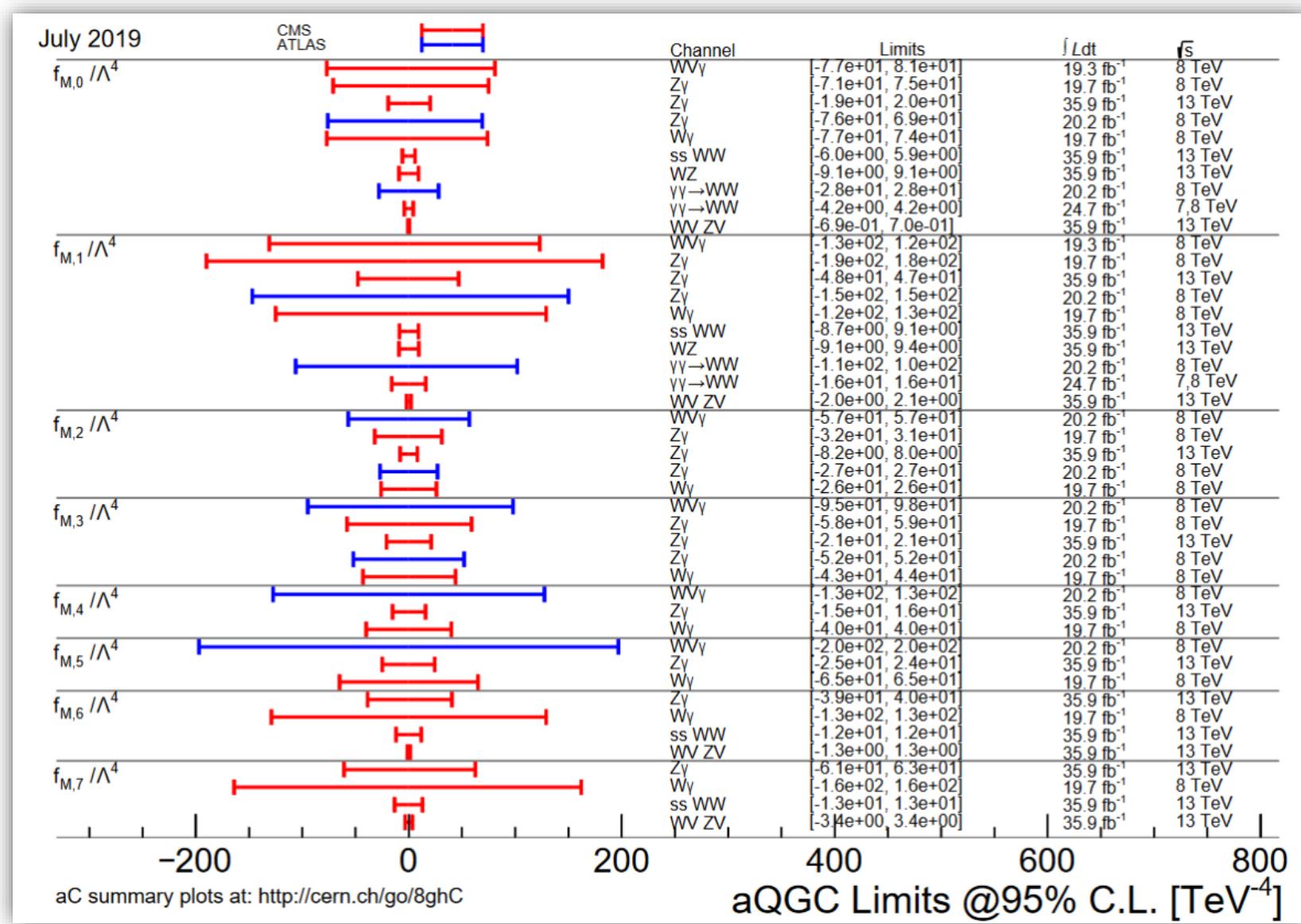


ATLAS-CONF-2019-033

# aQGC

Example : 8 parameters corresponding to operators mixing V & H fields

- Dim 8 operators
- 18 parameters
- 1D limits
  - Dim 6 supposed to be 0 (constrained)
  - Positivity not exploited
- Ultimately, combined fit with Higgs & Top

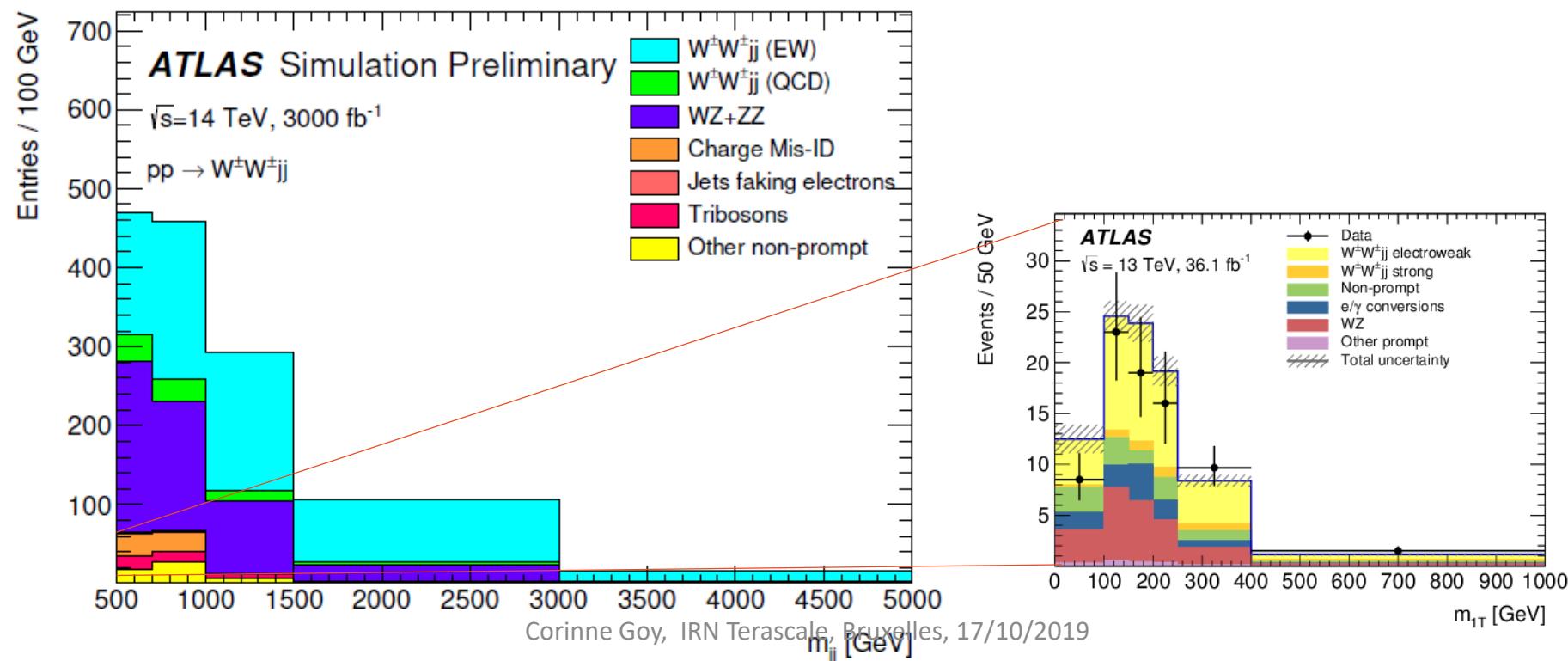


**HL - LHC**

# Prospects at HL-LHC : $\sqrt{s} = 14 \text{ TeV}, 3000. \text{ fb}^{-1}$

- Stress given on VVjj
- From first observations to measurements :
  - ZZjj : 8.5 to 10.3%
  - $W^\pm W^\pm jj$  : 4.5 to 6%
  - WZjj : 3 to 6%

CERN Yellow Report CERN-LPCC-2018-03



# General comments

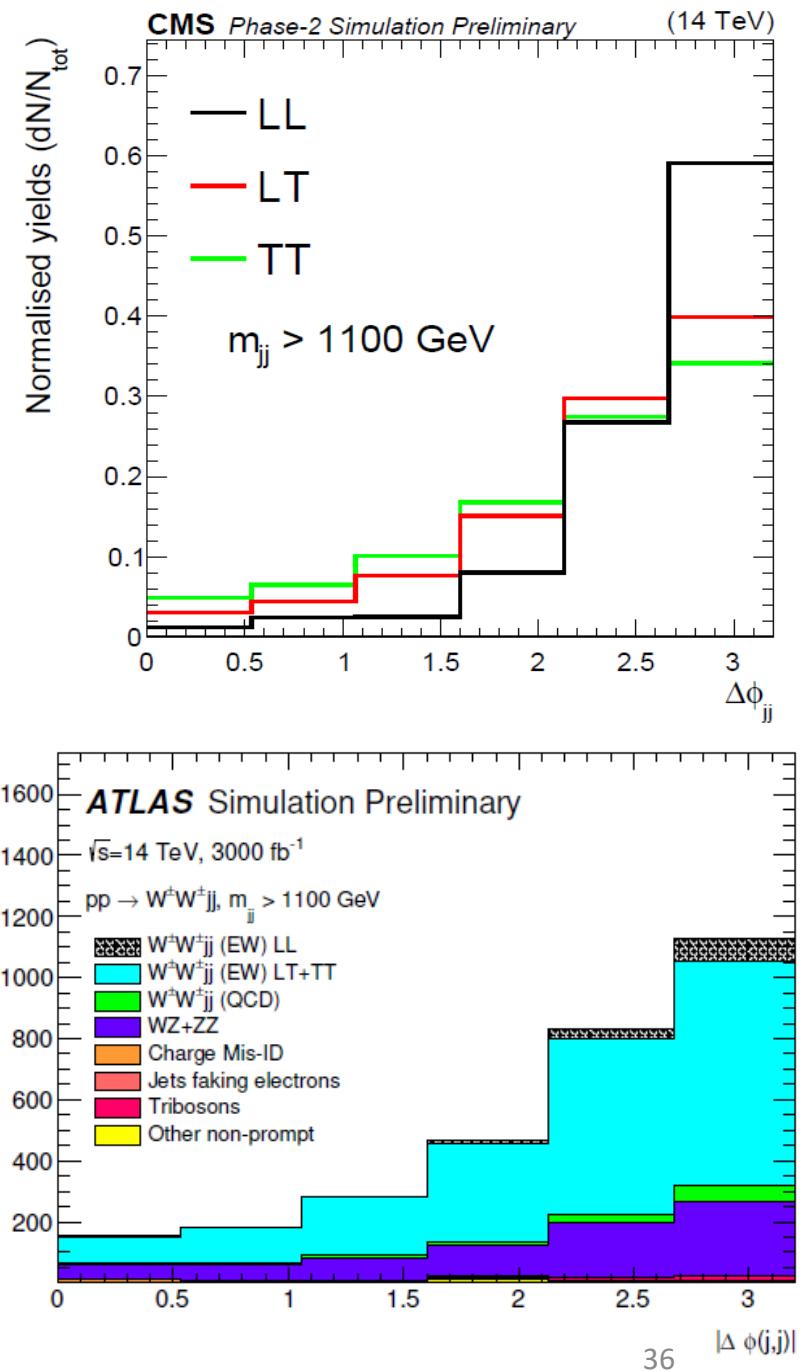
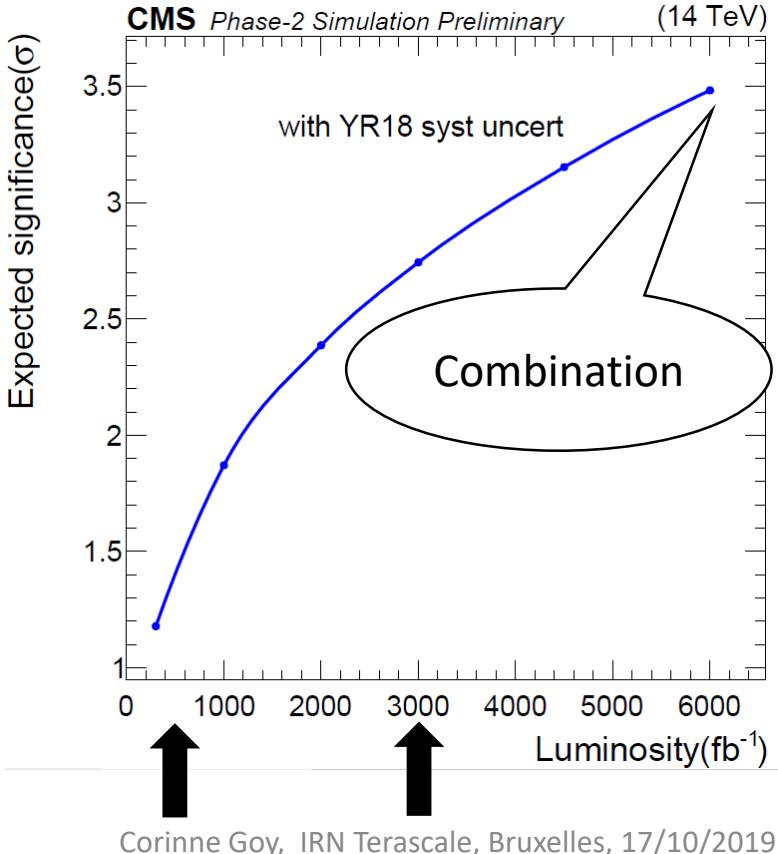
- Emphasis given on observing  $V_L V_L$  final states
  - $VV \rightarrow V_L V_L$
- MADGRAPH + decay
- H1 :  $V_T V_T$  &  $V_T V_L$  final states treated as known additional background
- H2 : Extraction of 3 or 4 components independently :
  - more difficult
- Multivariate methods not yet fully exploited in particular to distinguish 3 or 4 components → Improvement to be expected
  - $\cos\theta^*$
  - $\Delta\Phi_{jj}$
  - $pT(l), pT(V) \dots$

# ssWWjj: $W^\pm W^\pm \rightarrow \ell^\pm \ell^\pm \nu \nu$ most promising

Helicity distributions obtained with MadGraph+DECAY

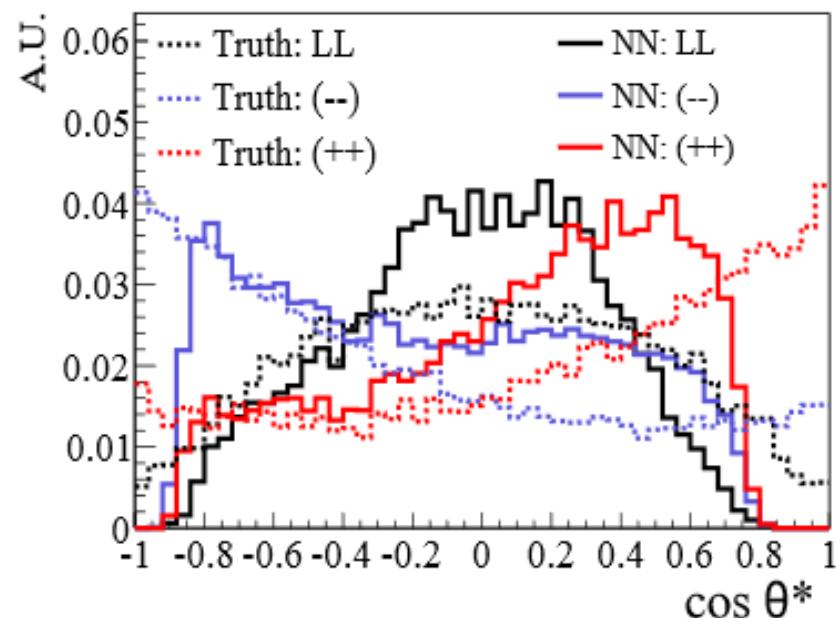
LL fraction : 6 – 7 %

Evidence for LL fraction :  
CMS :  $2.7\sigma$   
ATLAS :  $1.8\sigma$  ( $3.0\sigma$  stat)

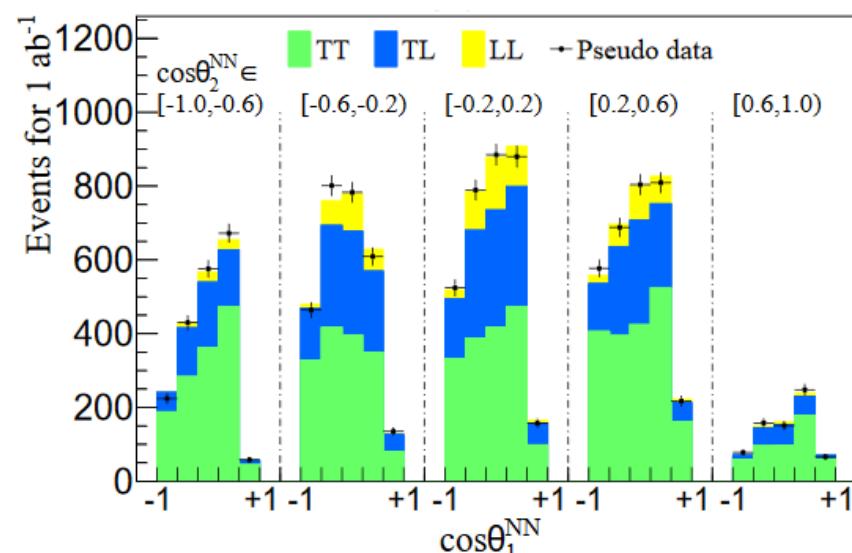


# Simultaneous fit of 3 components

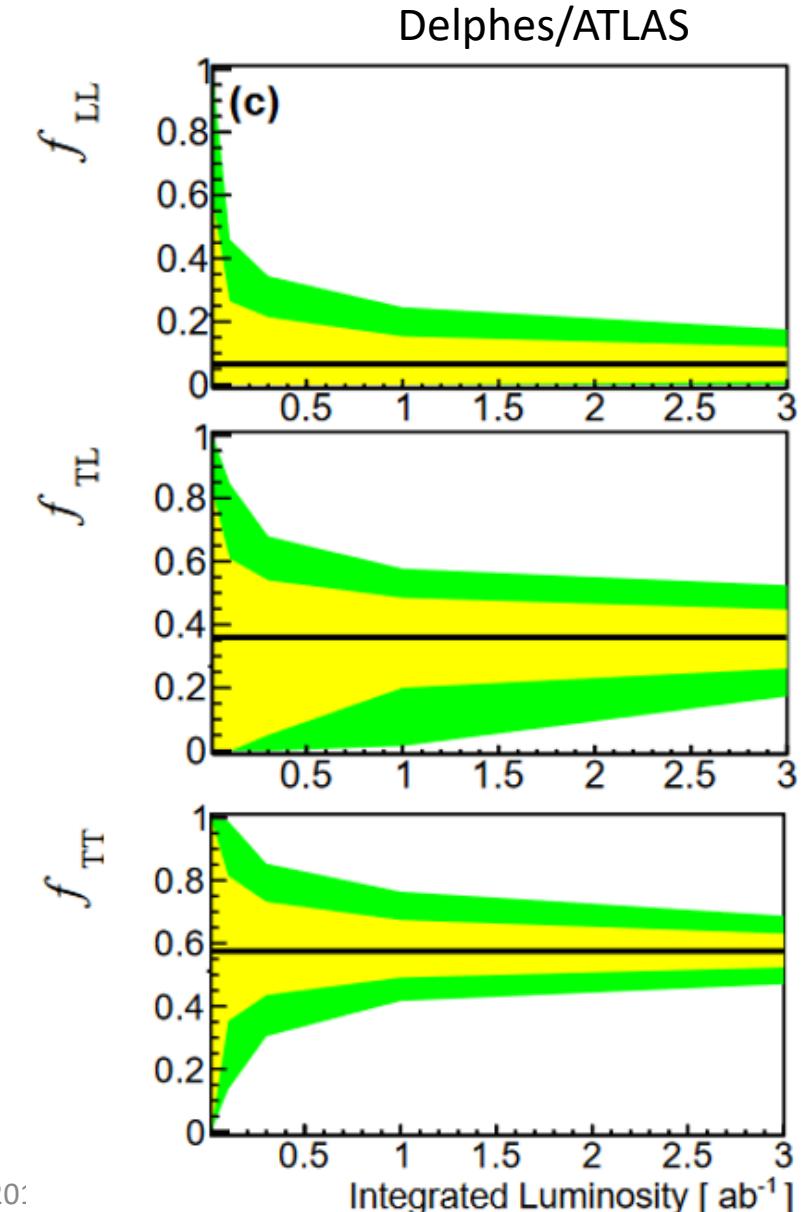
Regression NN to approximate  $\cos\theta^*$  from 14 kinematic variables



Unrolled 2D distribution :



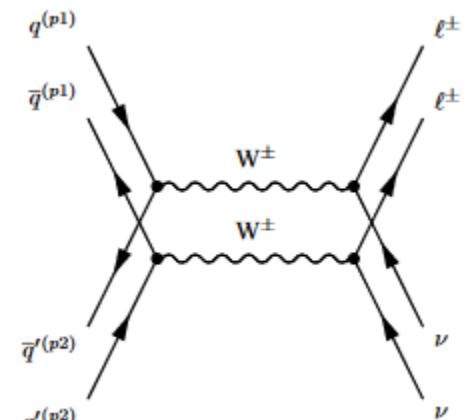
0/20:



# Outlook

- VV as resonances
  - Double parton interaction observed
- 

- Differential distributions:
  - Probe of tails ... (35/fb to 300/fb at the end of run3 )
  - Polarization
- VBS :
  - all channels soon observed
  - first differential at the end of Run3
    - Some already provided as VVjj-EW+VVjj-QCD
    - Hint of  $V_L V_L$  final state expected at the end of Run3 (300/fb) in ssWWjj channel
- aTGC/aQGC

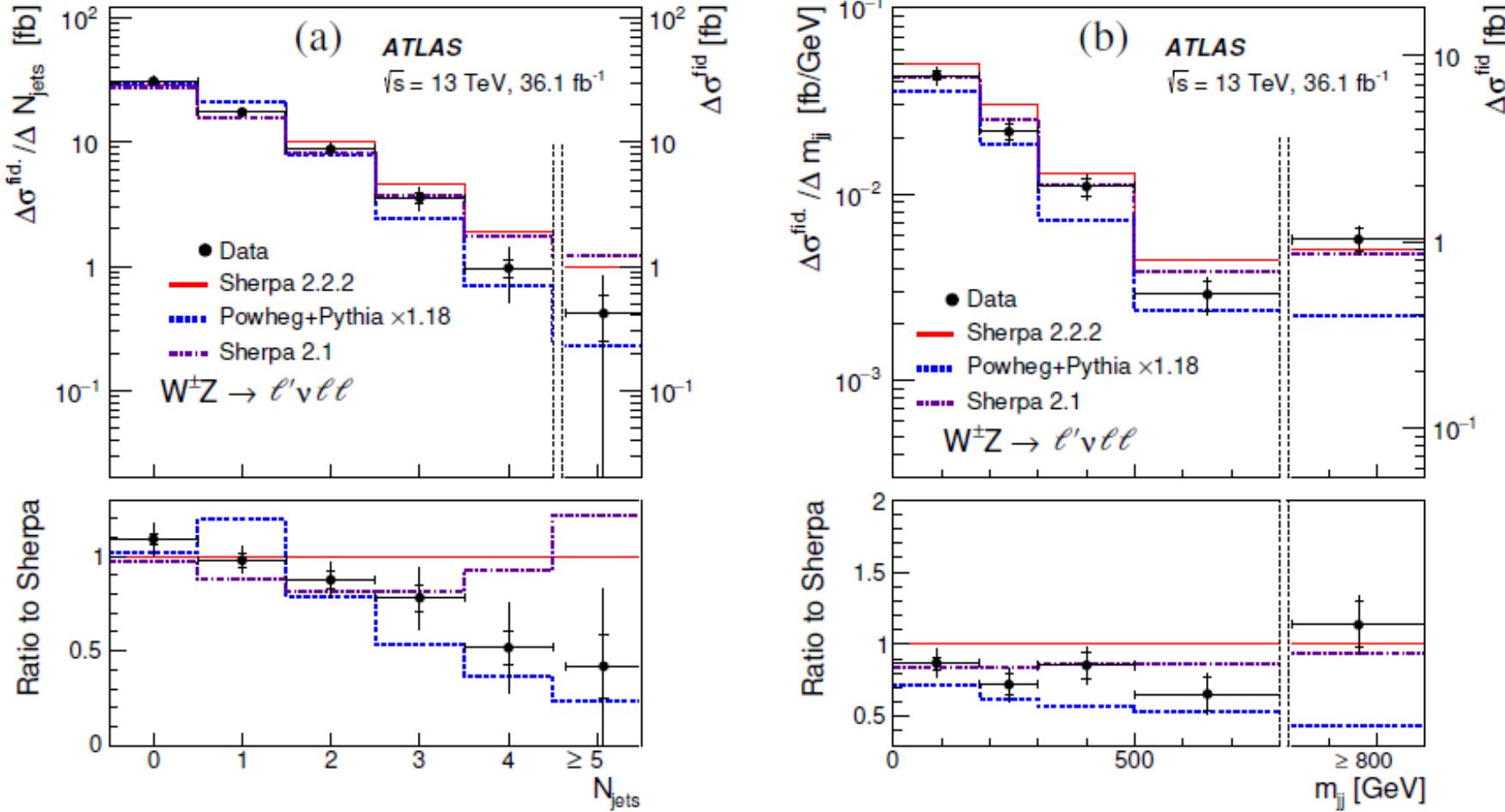


CMS –PAS- SMP-18-015



# Backup

# QCD/Jet description

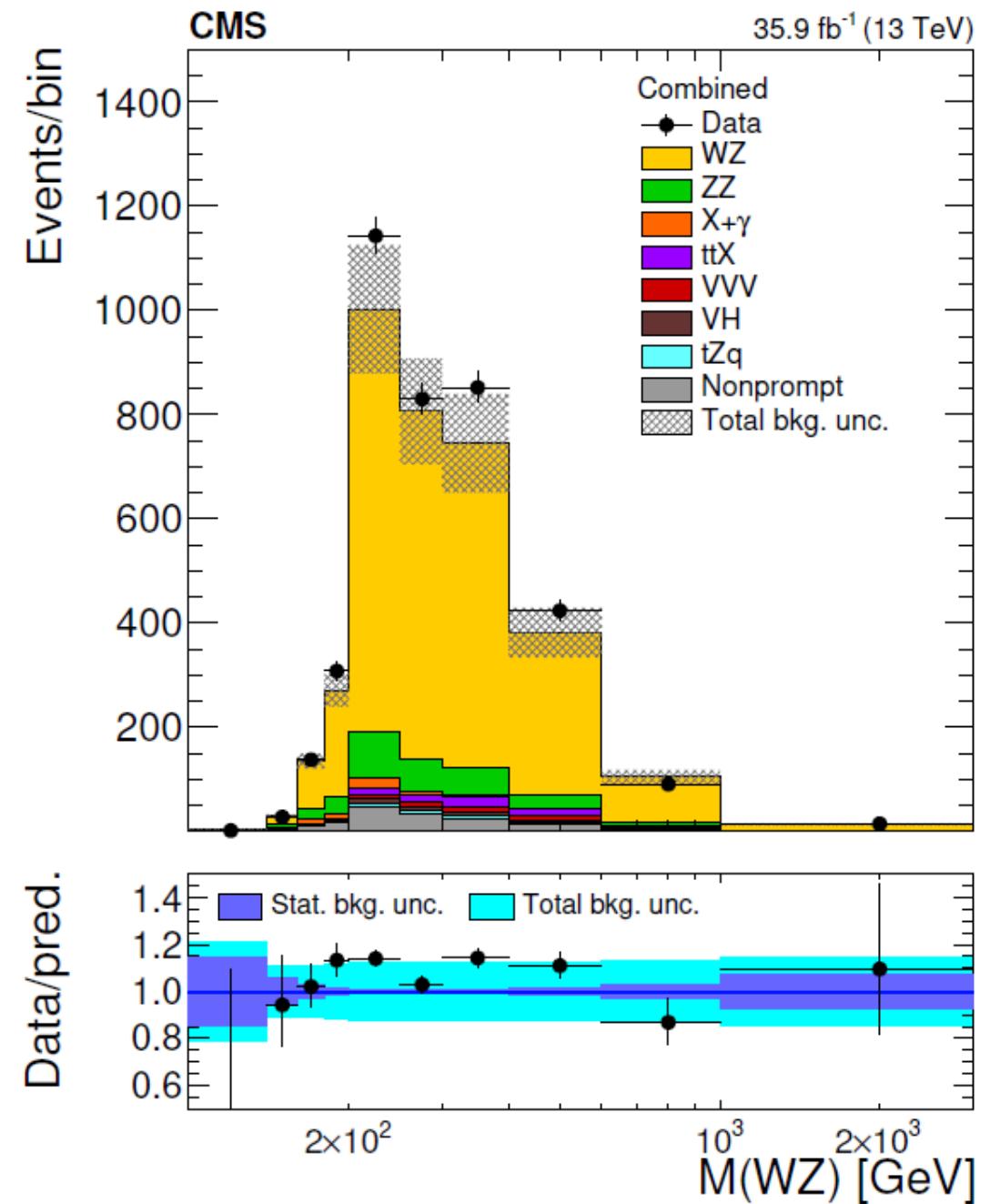


# WZ inclusive (ATLAS)

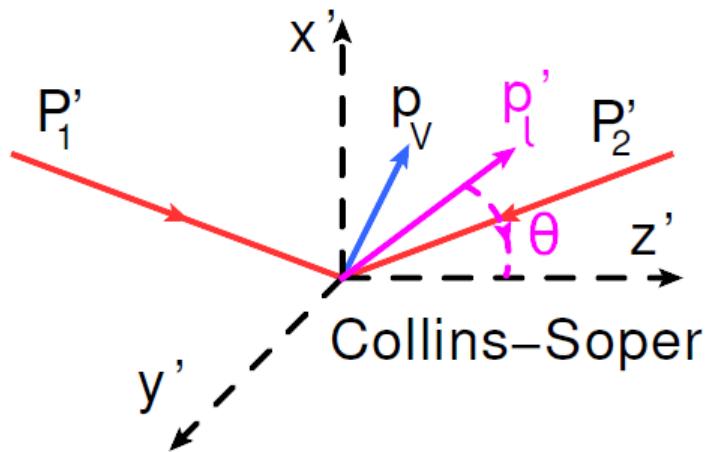
Channel	<i>eee</i>		$\mu ee$		$e\mu\mu$		$\mu\mu\mu$		All
Data	1279		1281		1671		1929		6160
Total expected	1221	7	1281	6	1653	8	1830	7	5986
<i>WZ</i>	922	5	1077	6	1256	6	1523	7	4778
Misid. leptons	138	5	34	2	193	5	71	2	436
<i>ZZ</i>	86	1	89	1	117	1	135	1	426
<i>t</i> $\bar{t}$ +V	50.0	0.7	54.0	0.7	56.1	0.7	63.8	0.8	225
<i>tZ</i>	23.1	0.4	24.8	0.4	28.8	0.4	33.5	0.5	110
<i>VVV</i>	2.5	0.1	2.8	0.1	3.2	0.1	3.6	0.1	12.0
									0.2

Number of events per channels (Data and Expectations)

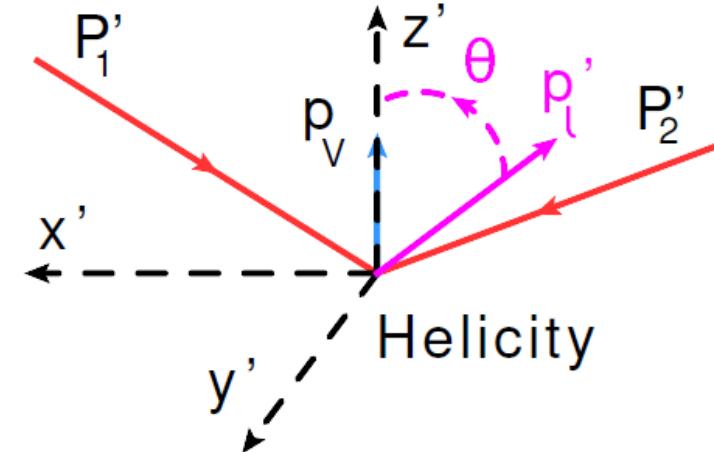
# WZ inclusive (CMS)



# Coordinate systems



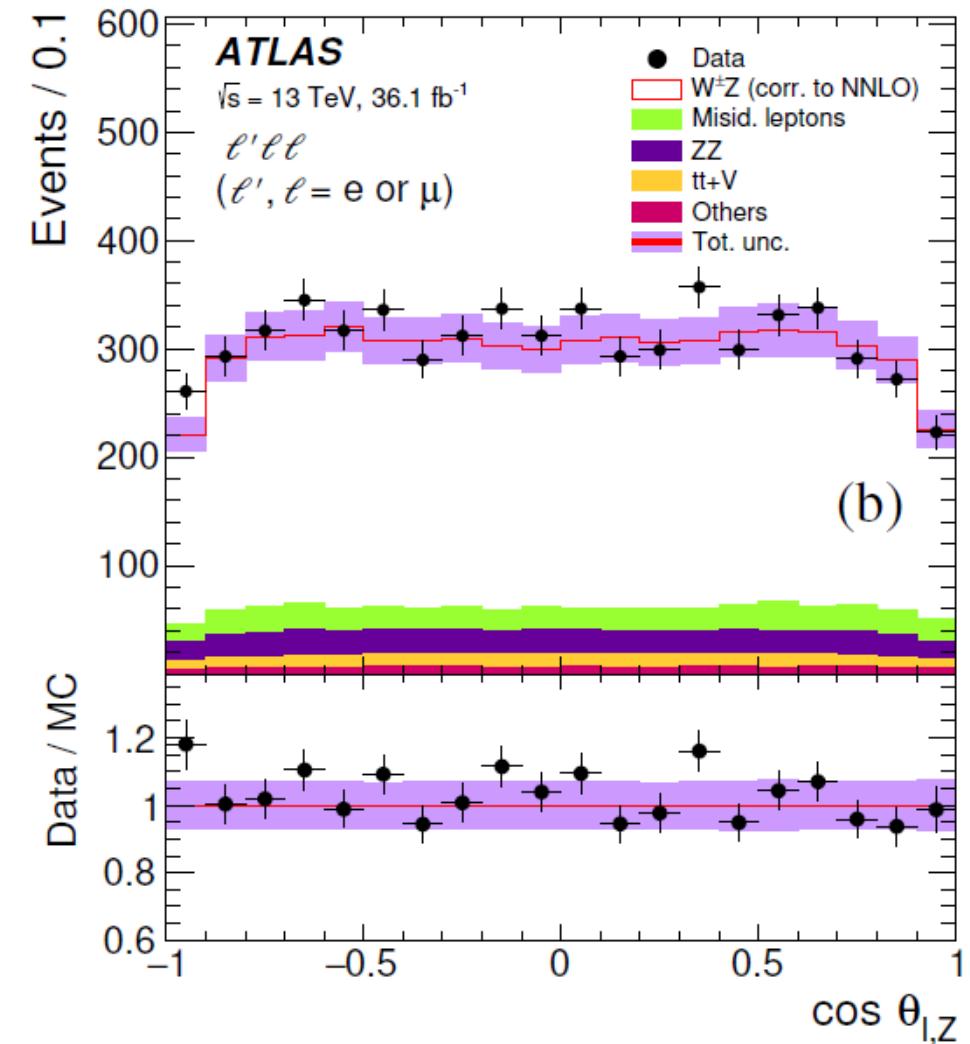
- $p'_1, p'_2$  directions of the beam in the boson c-o-m
- $Z'$  is the bisector of  $p'_1, - p'_2$
- $Z'$  points toward  $V$  in the lab



Z is the direction of V  
(Z,W) in the lab

# Example of $\cos\theta^*$ distributions in WZ events

	$W^\pm$ in $W^\pm Z$		$Z$ in $W^\pm Z$	
	$f_0$	$f_L - f_R$	$f_0$	$f_L - f_R$
$e$ energy scale and id. efficiency	0.0024	0.0004	0.005	0.0021
$\mu$ momentum scale and id. efficiency	0.0013	0.0027	0.0018	0.008
$E_T^{\text{miss}}$ and jets	0.0024	0.0010	0.0017	0.005
Pile-up	0.005	< 0.0009	0.0014	0.005
Misid. lepton background	0.031	< 0.001	0.007	0.019
ZZ background	0.009	0.0004	0.0007	0.0012
Other backgrounds	0.0012	0.0005	0.0018	0.005
QCD scale	0.0008	0.0013	0.0004	0.008
PDF	0.0011	0.0009	0.00004	< 0.00001
Modelling	0.004	0.007	0.0015	0.0028
Total systematic uncertainty	0.033	0.008	0.009	0.024
Luminosity	0.0015	< 0.0001	< 0.0001	0.0008
Statistics	0.06	0.032	0.04	0.15
Total	0.06	0.033	0.04	0.16



# Systematics

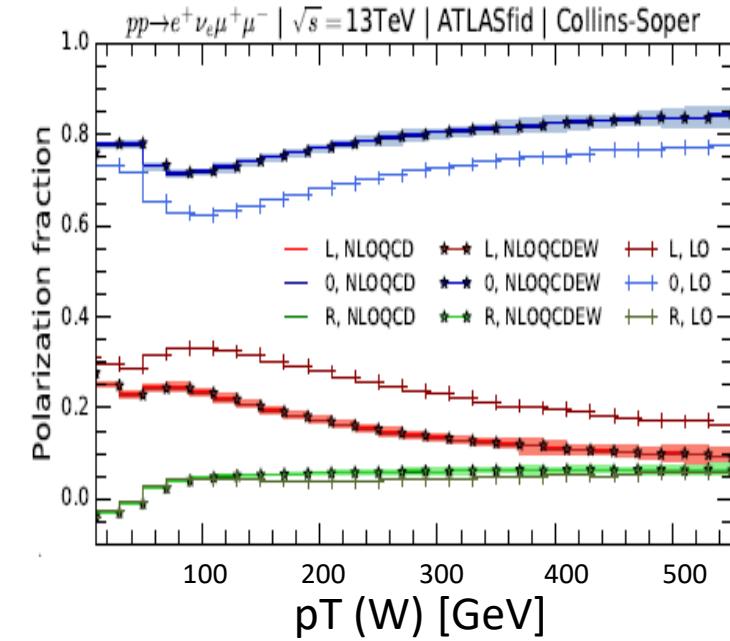
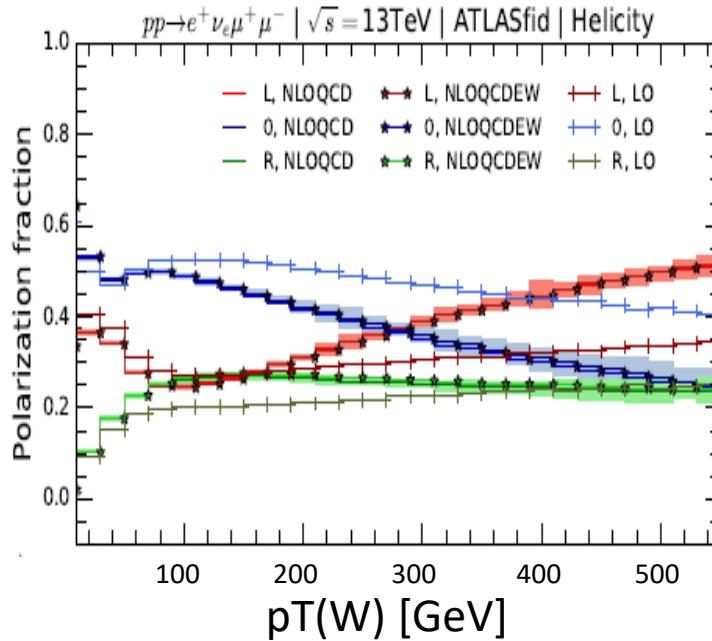
- Largely statistically dominated
- MC@NLO/Powheg +Pythia for helicity template syst.
- Pythia/Herwig for parton shower syst.

	$W^\pm$ in $W^\pm Z$		$Z$ in $W^\pm Z$	
	$f_0$	$f_L - f_R$	$f_0$	$f_L - f_R$
$e$ energy scale and id. efficiency	0.0024	0.0004	0.005	0.0021
$\mu$ momentum scale and id. efficiency	0.0013	0.0027	0.0018	0.008
$E_T^{\text{miss}}$ and jets	0.0024	0.0010	0.0017	0.005
Pile-up	0.005	0.00009	0.0014	0.005
Misid. lepton background	0.031	< 0.001	0.007	0.019
ZZ background	0.009	0.0004	0.0007	0.0012
Other backgrounds	0.0012	0.0005	0.0018	0.005
QCD scale	0.0008	0.0013	0.0004	0.008
PDF	0.0011	0.0009	0.00004	< 0.00001
Modelling	0.004	0.007	0.0015	0.0028
Total systematic uncertainty	0.033	0.008	0.009	0.024
Luminosity	0.0015	< 0.0001	< 0.0001	0.0008
Statistics	0.06	0.032	0.04	0.15
Total	0.06	0.033	0.04	0.16

# Remark 1 – coordinate systems

JHEP 04 (2019) 065 / arXiv:1810.11034  
J. Baglio & D.N. Le

- “Modified “ helicity
  - Direction of W/Z in the WZ restframe
  - “W uncertainty” leaks into Z
- Helicity
  - Direction of W/Z in the lab
  - F0, FL & FR represent the physical polarization fractions
- Collins-Soper



At the end, not the same value for the fractions.  
Should they agree in some limits ?  
Precision of the measurement ?  
Is one better ?

## Remark 2 : Reconstruction of $p_z(\nu)$

- To determine the W center of mass, one needs to reconstruct the longitudinal momentum of the neutrino.
- Method used:
  - Using the W mass constraint -> twofold ambiguity
    - If 2 physical solutions choose the smallest
    - If not, choose the real part of the solution
- Other methods to be tested (arXiv:1907.04722)

# Remark 3: Alternative variables

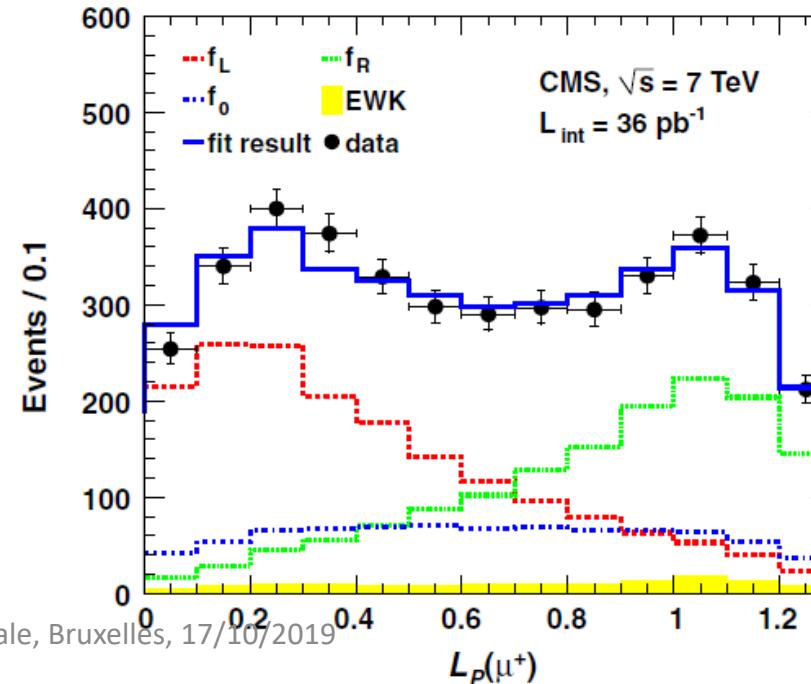
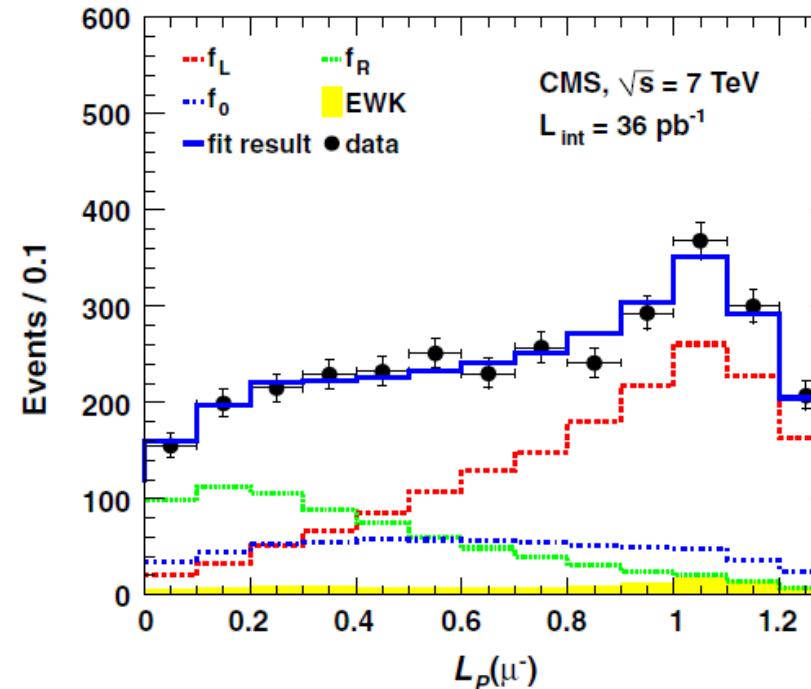
$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}.$$

$$\cos\theta^* = 2 \left( L_P - \frac{1}{2} \right)$$

$$P_T(W) \rightarrow \infty$$

PRL 107, 021802 (2011)

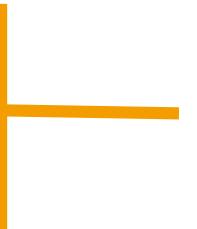
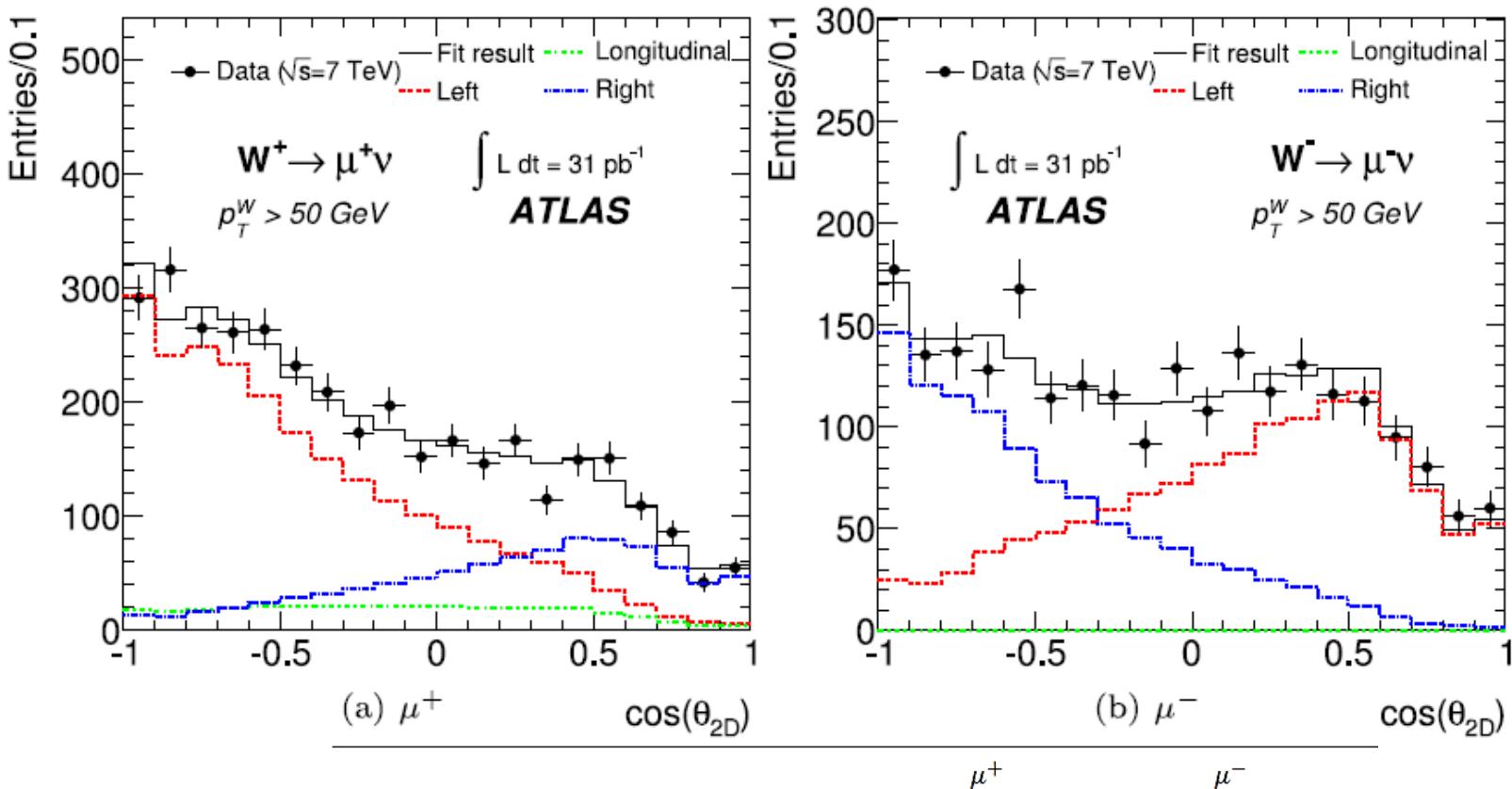
CMS collaboration



# Remark 3: Other variables

$$\cos \theta_{2D} = \frac{\vec{p}_T^{\ell*} \cdot \vec{p}_T^W}{|\vec{p}_T^{\ell*}| |\vec{p}_T^W|}$$

Large correction needed to obtain the “true” fraction



$35 < p_T^W < 50 \text{ GeV}$			
	$f_0 \text{ (%)}$	$20.9 \pm 0.8$	$20.9 \pm 0.8$
$\cos \theta_{3D}$ generator-level	$f_L - f_R \text{ (%)}$	$27.9 \pm 0.7$	$26.5 \pm 0.8$
$\cos \theta_{2D}$ fully simulated	$f_0 \text{ (%)}$	$30.1 \pm 2.4$	$19.5 \pm 2.2$
	$f_L - f_R \text{ (%)}$	$31.8 \pm 1.4$	$26.5 \pm 1.2$
$p_T^W \geq 50 \text{ GeV}$			
	$f_0 \text{ (%)}$	$22.7 \pm 1.0$	$22.7 \pm 1.0$
$\cos \theta_{3D}$ generator-level	$f_L - f_R \text{ (%)}$	$26.9 \pm 0.8$	$25.8 \pm 0.9$
$\cos \theta_{2D}$ fully simulated	$f_0 \text{ (%)}$	$25.1 \pm 1.9$	$20.7 \pm 2.2$
	$f_L - f_R \text{ (%)}$	$29.7 \pm 1.1$	$26.2 \pm 1.2$

# NLOQCD & EW corrections

$$f_L^{W^\pm} = -\frac{1}{2} \mp \langle \cos \theta_3 \rangle + \frac{5}{2} \langle \cos^2 \theta_3 \rangle, \quad f_R^{W^\pm} = -\frac{1}{2} \pm \langle \cos \theta_3 \rangle + \frac{5}{2} \langle \cos^2 \theta_3 \rangle,$$

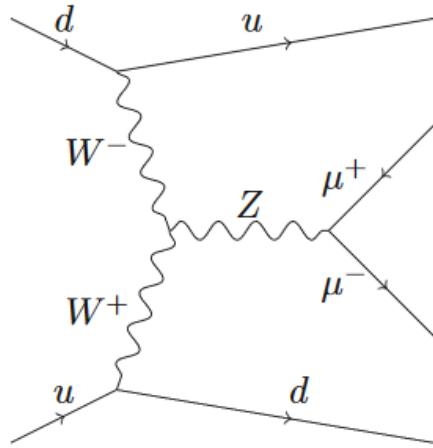
$$f_0^{W^\pm} = 2 - 5 \langle \cos^2 \theta_3 \rangle,$$

In Atlas Fiducial Phase Space

Method	$f_L^{W^-}$	$f_0^{W^-}$	$f_R^{W^-}$	$f_L^Z$	$f_0^Z$	$f_R^Z$
HE LO	$0.216(1)^{+0.1}_{-0.05}$	$0.555(1)^{+1}_{-1}$	$0.229(2)^{+1}_{-1}$	$0.324(1)^{+0.4}_{-0.3}$	$0.494(0.4)^{+1}_{-1}$	$0.181(1)^{+0.3}_{-0.4}$
HE NLOEW	0.218	0.554	0.228	0.298	0.496	0.206
HE NLOQCD	$0.286(2)^{+7}_{-6}$	$0.515(1)^{+4}_{-5}$	$0.199(1)^{+2}_{-2}$	$0.334(1)^{+2}_{-2}$	$0.475(0.5)^{+2}_{-2}$	$0.191(1)^{+1}_{-1}$
HE NLOQCDEW	0.289	0.513	0.198	0.321	0.475	0.204

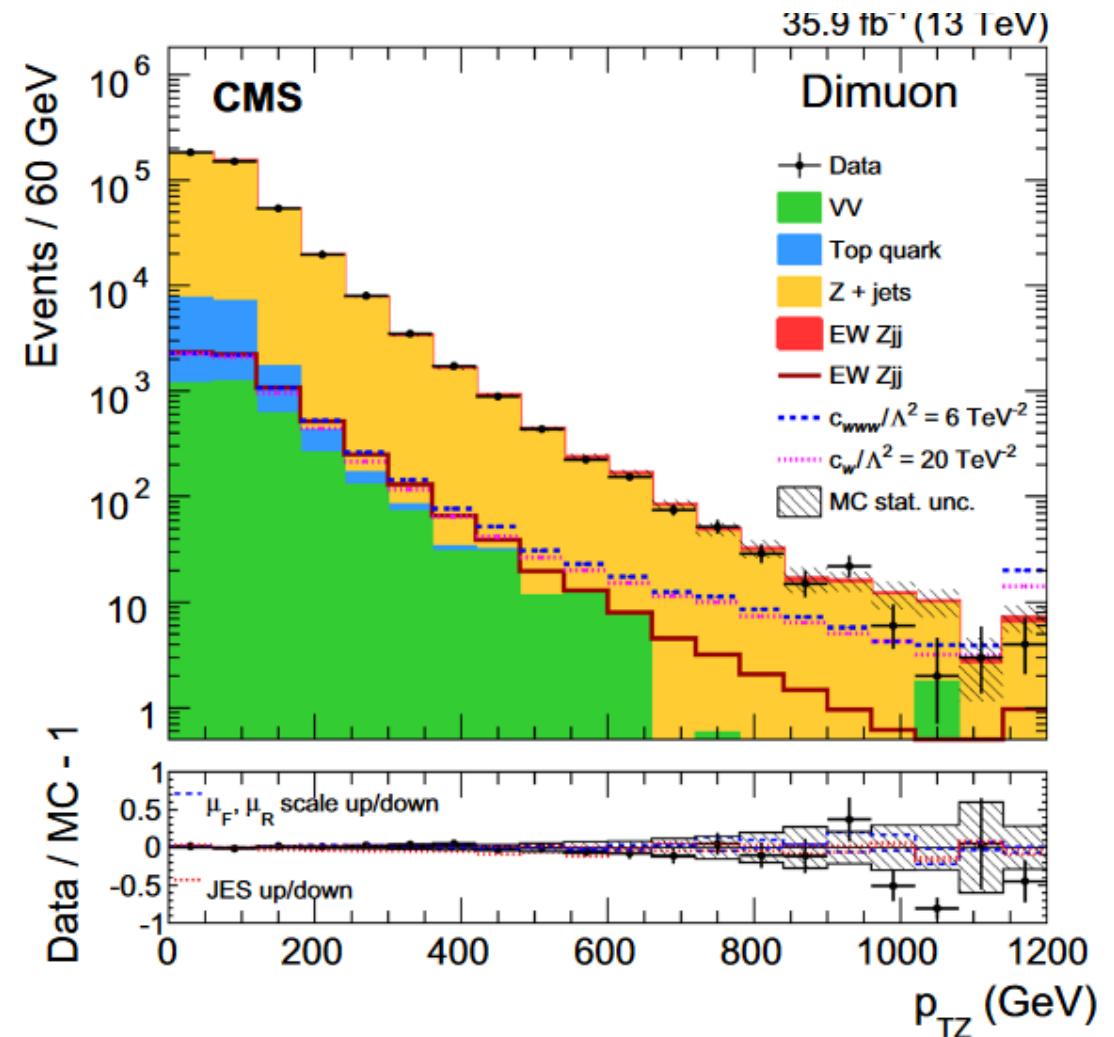
Method	$f_L^{W^+}$	$f_0^{W^+}$	$f_R^{W^+}$	$f_L^Z$	$f_0^Z$	$f_R^Z$
HE LO	$0.355(2)^{+2}_{-2}$	$0.513(1)^{+2}_{-3}$	$0.132(2)^{+1}_{-1}$	$0.222(1)^{+0.4}_{-1}$	$0.518(1)^{+1}_{-1}$	$0.261(1)^{+2}_{-1}$
HE NLOEW	0.352	0.514	0.134	0.216	0.519	0.264
HE NLOQCD	$0.320(2)^{+2}_{-2}$	$0.508(1)^{+2}_{-2}$	$0.172(2)^{+4}_{-3}$	$0.257(1)^{+3}_{-3}$	$0.493(1)^{+2}_{-3}$	$0.251(1)^{+1}_{-0.5}$
HE NLOQCDEW	0.317	0.509	0.174	0.255	0.493	0.252

NB : VBF sets also limits on aTGC but less sensitive

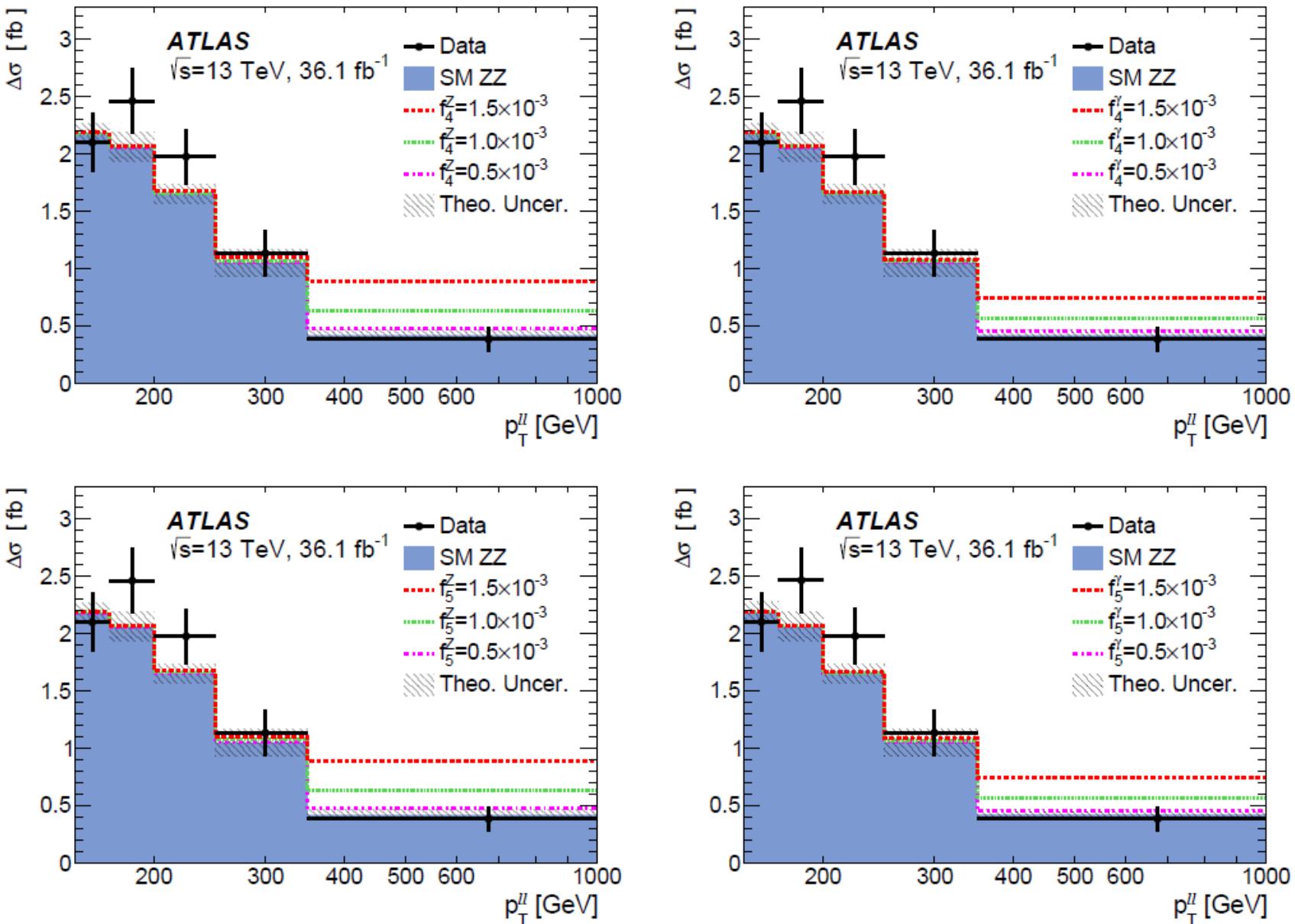


**Table 2** One-dimensional limits on the ATGC EFT parameters at 95% CL

Coupling constant	Expected 95% CL interval ( $\text{TeV}^{-2}$ )	Observed 95% CL interval ( $\text{TeV}^{-2}$ )
$c_{WWW}/\Lambda^2$	[-3.7, 3.6]	[-2.6, 2.6]
$c_w/\Lambda^2$	[-12.6, 14.7]	[-8.4, 10.1]



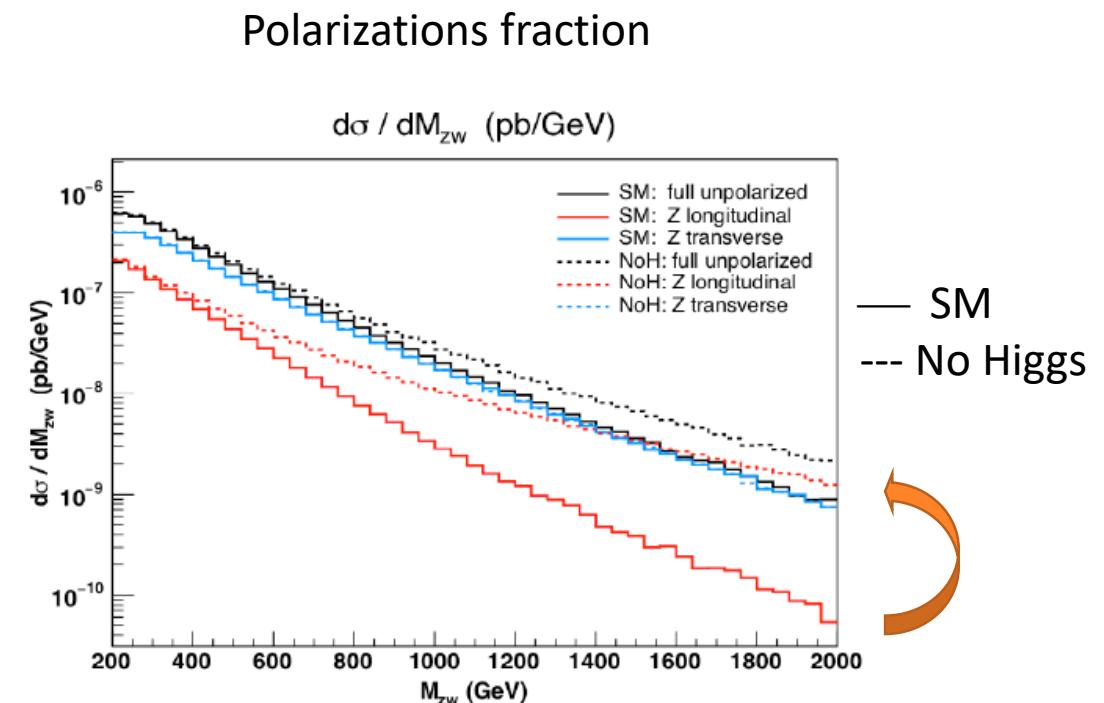
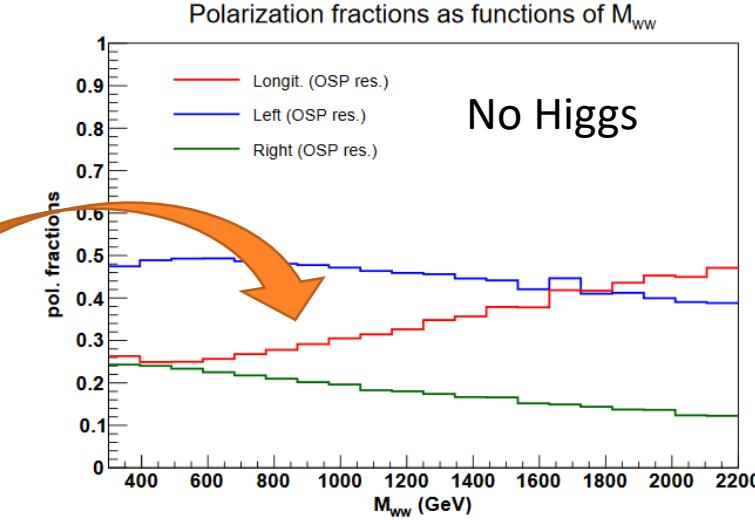
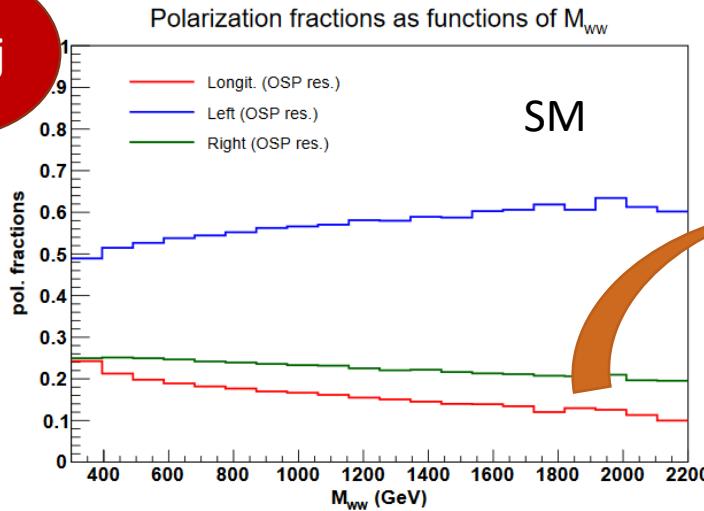
# Neutral TGC



No HIGGS !  
Extreme case

Effect enhanced in  
considering only the  
longitudinal production

$$V_L V_L \rightarrow V_L V_L$$



arXiv: 1710.09339 & arXiv: 1907.04722

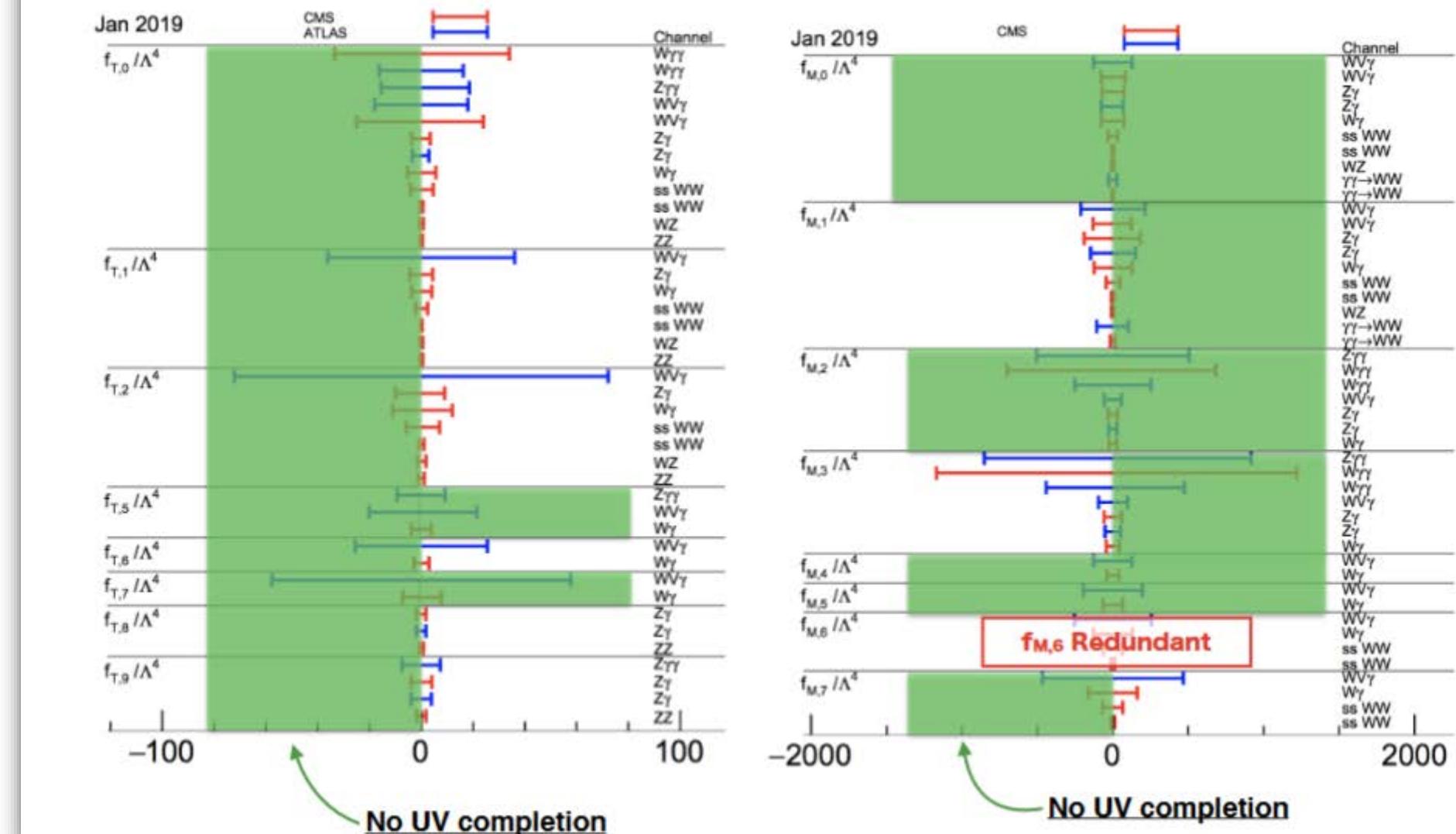
A. Ballestrero, E. Maina, G. Pellicioli

Corinne Goy, IRN Terascale, Bruxelles, 17/10/2019

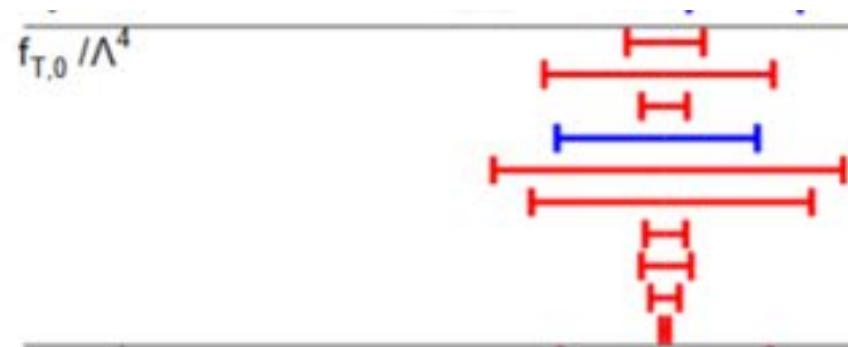
# 1D case: individual limits

Positivity bounds :

C Zhang @MBI



# Comparison with limits from 3-bosons final states



Channel	Limits	$\sqrt{s}$	$\text{fb}^{-1}$
WWW	$-1.2e+00, 1.2e+00$	35.9	13 TeV
Zy	$-3.8e+00, 3.4e+00$	19.7	8 TeV
Zy	$-7.4e-01, 6.9e-01$	35.9	13 TeV
Zy	$-3.4e+00, 2.9e+00$	29.2	8 TeV
W <sub>y</sub>	$-5.4e+00, 5.6e+00$	19.7	8 TeV
ss WW	$-4.2e+00, 4.6e+00$	19.4	8 TeV
ss WW	$-6.2e-01, 6.5e-01$	35.9	13 TeV
WZ	$-7.5e-01, 8.1e-01$	35.9	13 TeV
ZZ	$-4.6e-01, 4.4e-01$	35.9	13 TeV
WV ZV	$-1.2e-01, 1.1e-01$	35.9	13 TeV

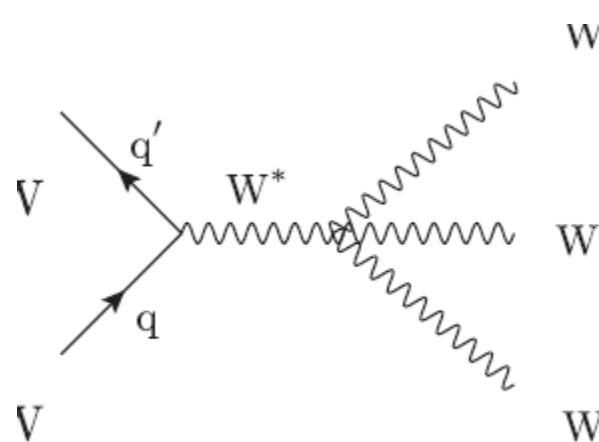


TABLE VIII. Limits on three anomalous quartic couplings at 95% CL.

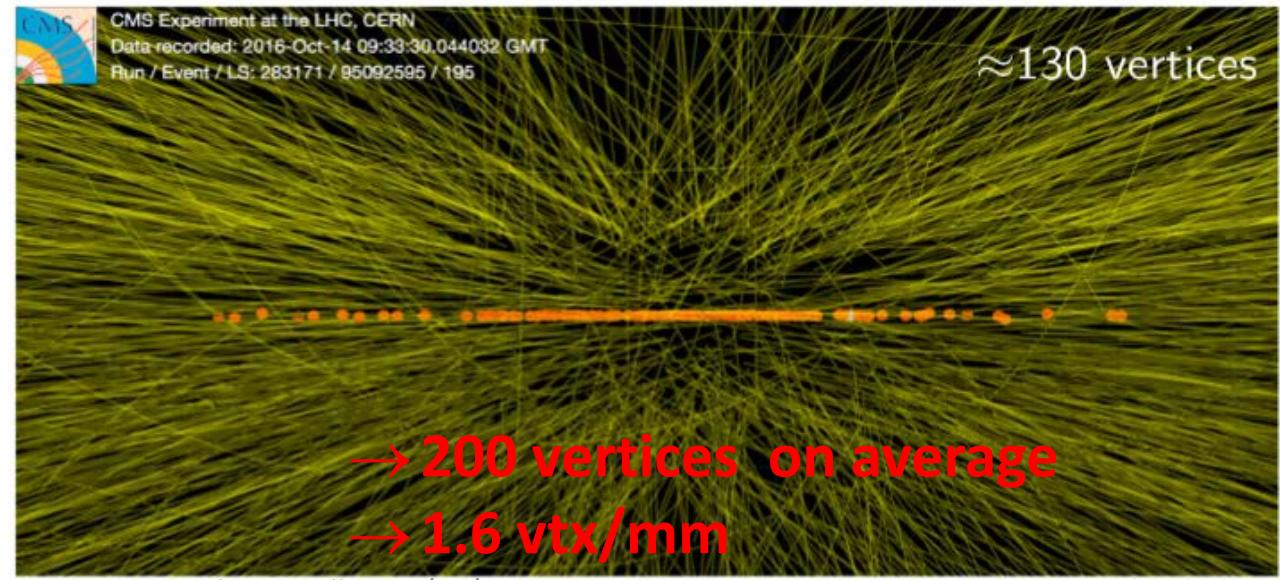
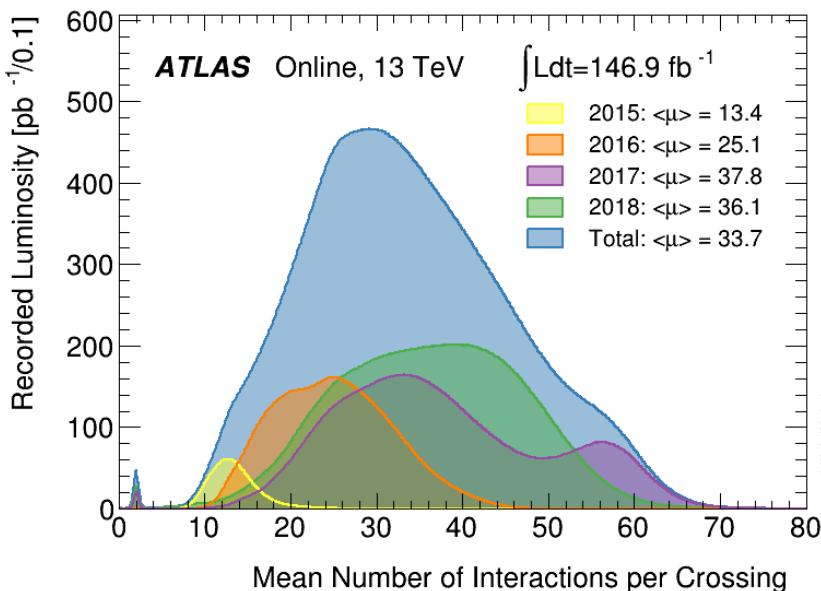
Anomalous coupling	Allowed range ( $\text{TeV}^{-4}$ )	
	Expected	Observed
$f_{T,0}/\Lambda^4$	$[-1.3, 1.3]$	$[-1.2, 1.2]$
$f_{T,1}/\Lambda^4$	$[-3.7, 3.7]$	$[-3.3, 3.3]$
$f_{T,2}/\Lambda^4$	$[-3.0, 2.9]$	$[-2.7, 2.6]$

# Evolution of the experimental conditions

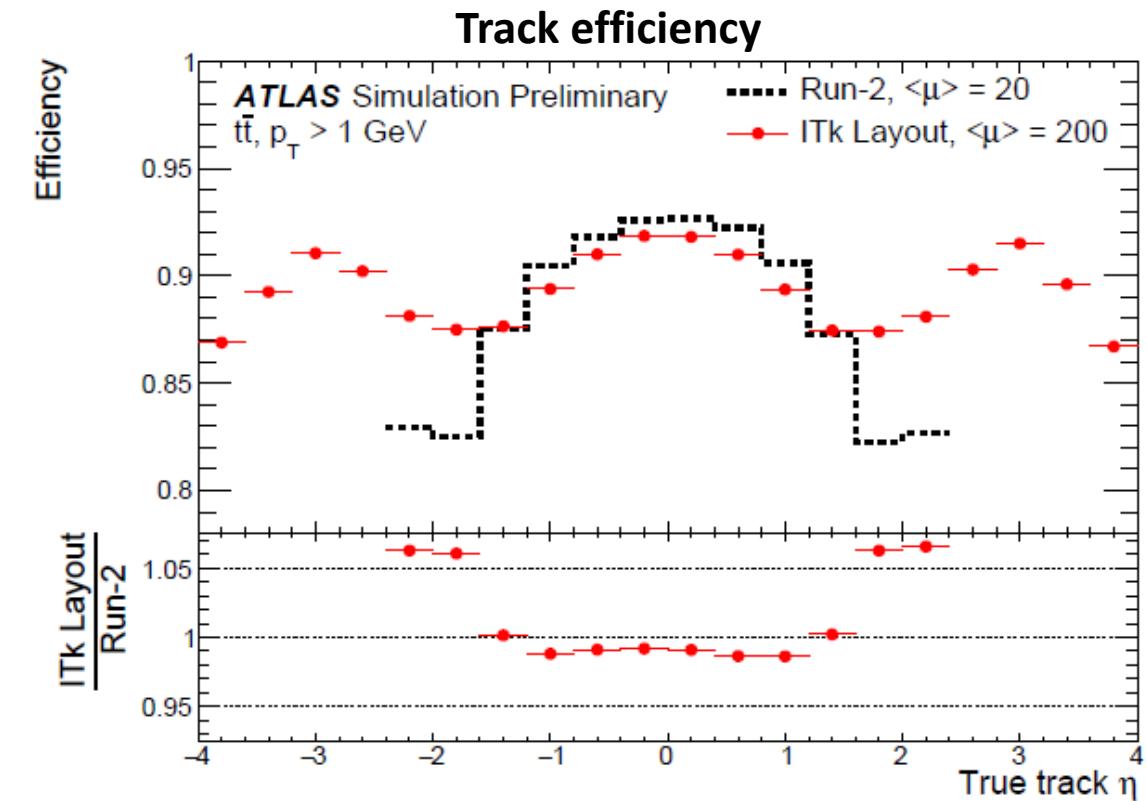
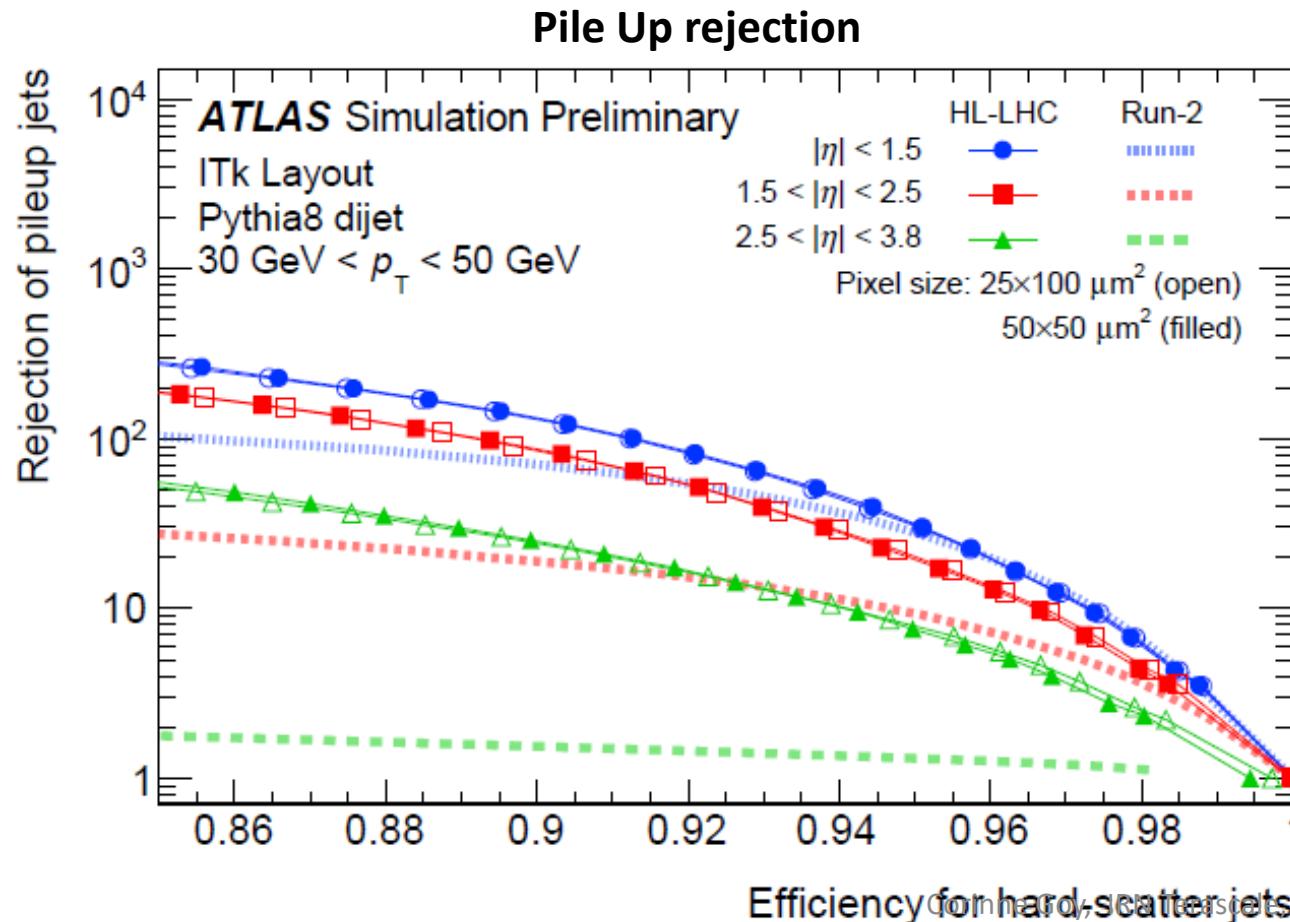
- Luminosity  
Peak:  $5\text{--}7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Aging – radiation damages

To cope with  
Data rates  
Detector occupation  
And to maintain:  
Trigger performance  
Pile-Up jet rejection  
Object performance

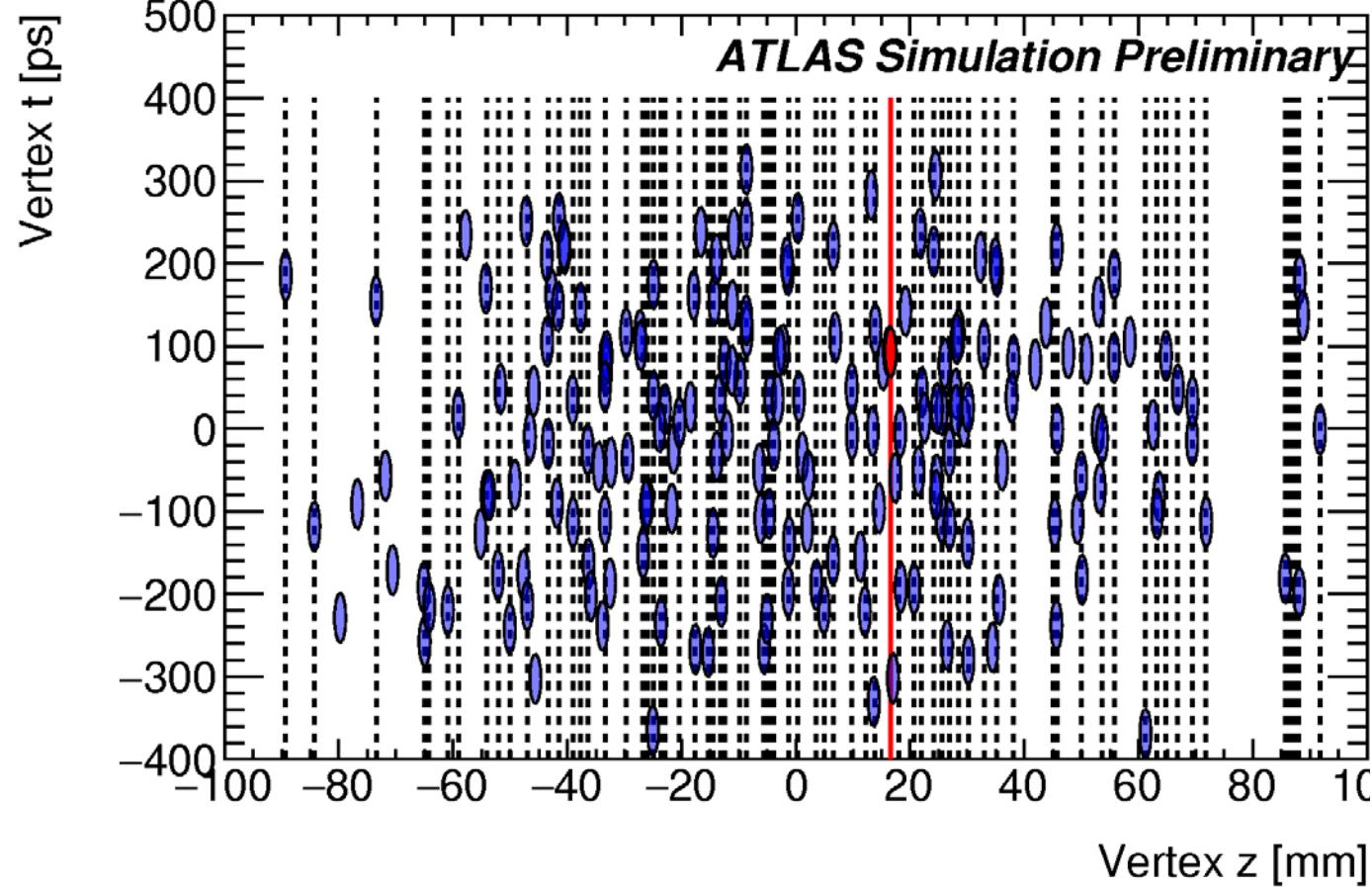
⇒ Upgrade of detectors  
Hardness  
Granularity



# Tracking up to $|\eta| < 4$

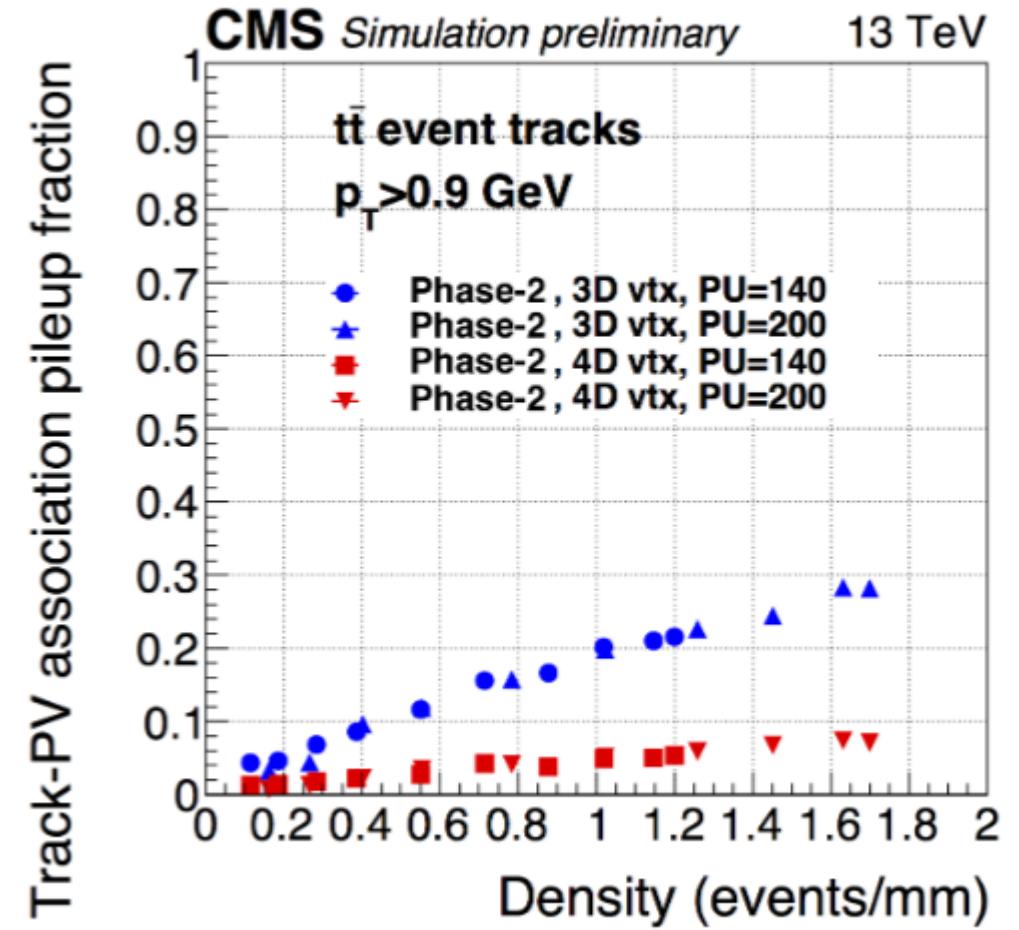


# Timing detector : a new dimension



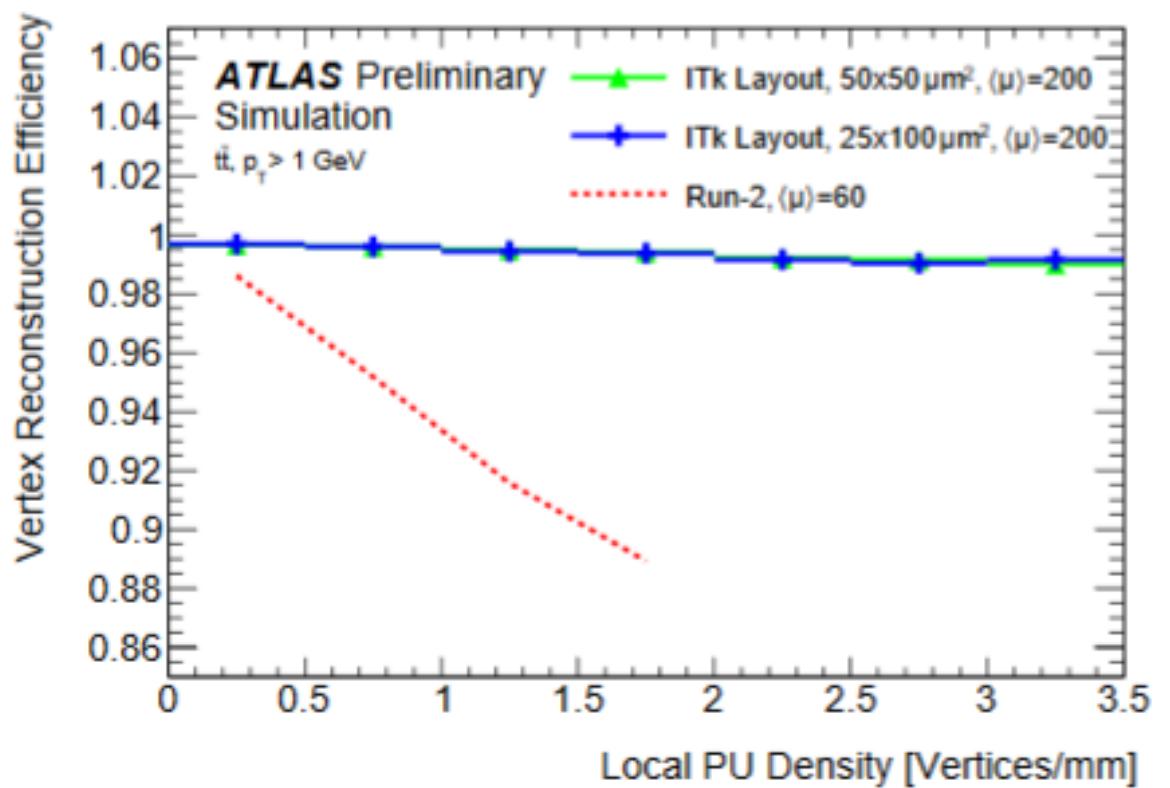
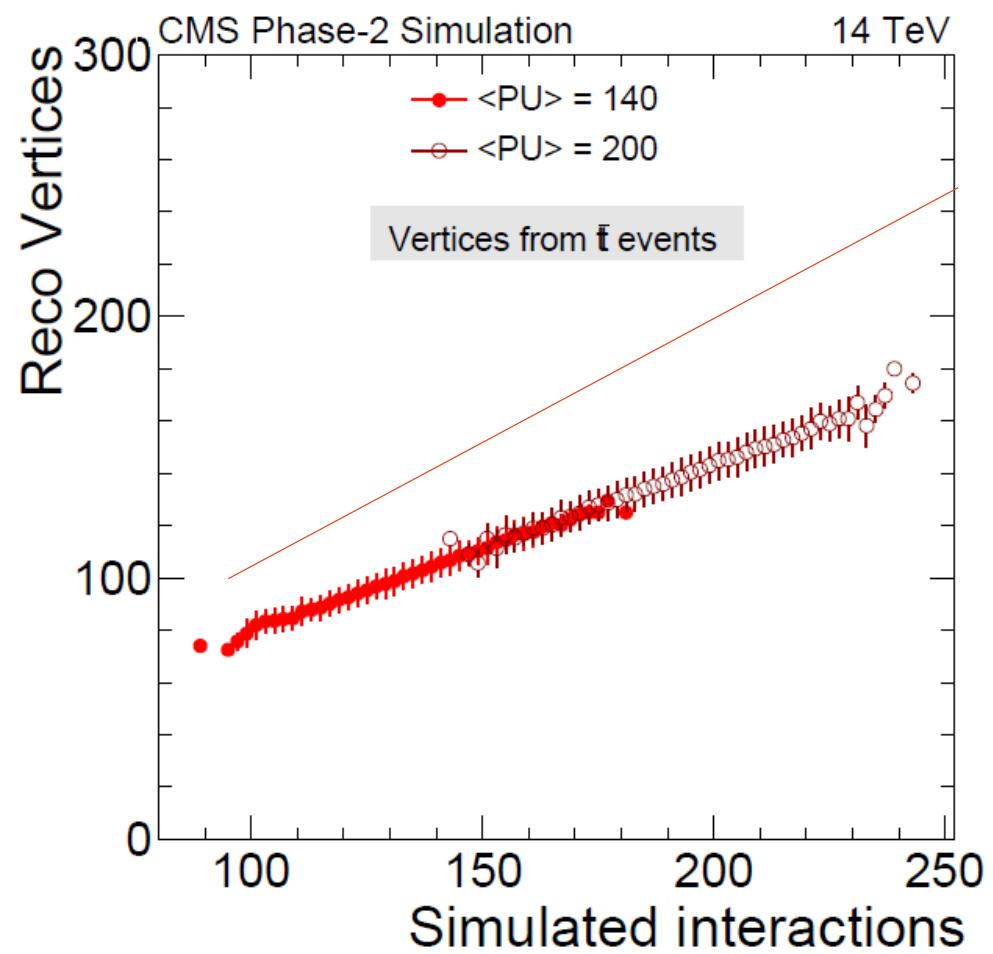
ATLAS :  $2.4 < |\eta| < 4$ .

Corinne Goy, IRN Terascale, Bruxelles, 17/10/2019



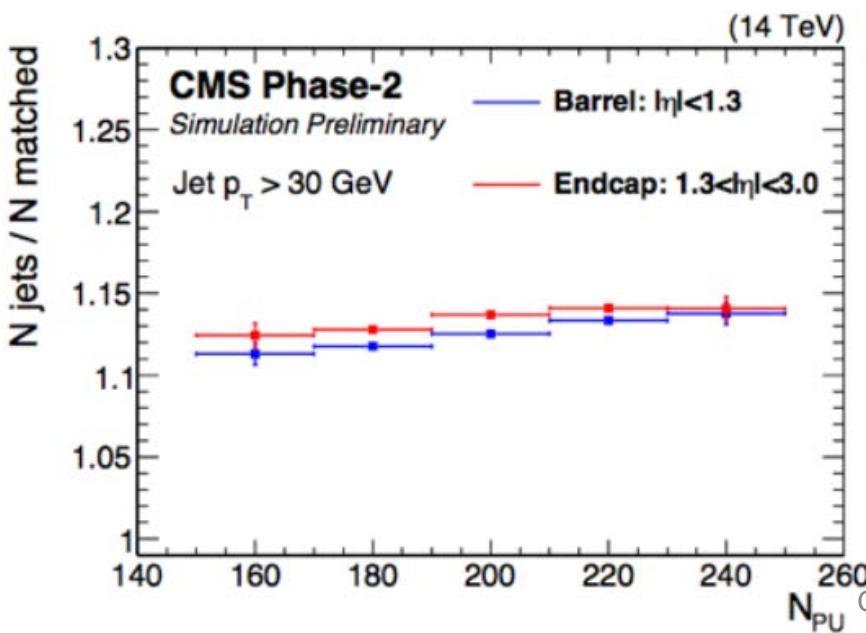
CMS :  $0 < |\eta| < 3$ .

59

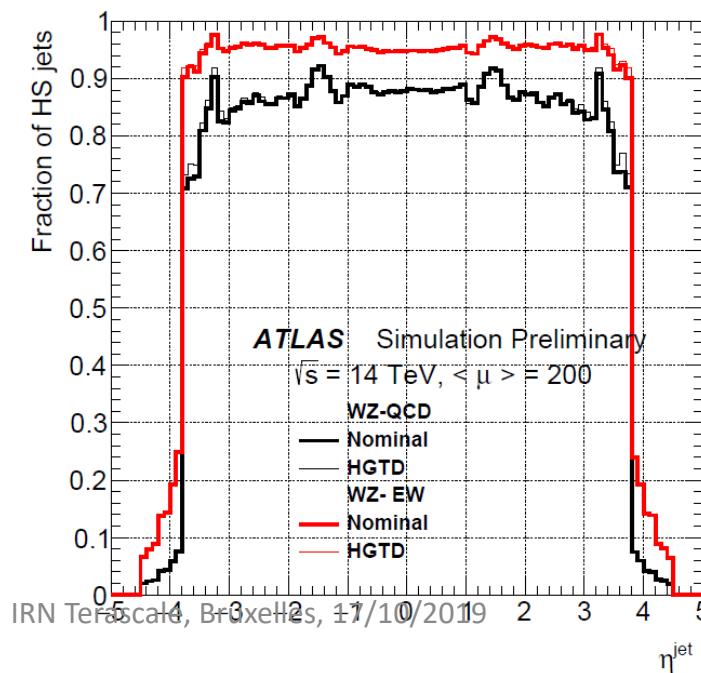


# Consequences for object reconstruction

$ \eta $	CMS	ATLAS
Track reconstruction		4.
Electrons	3.	4.
Muon	2.8	2.7 ( 4. with muon tagger)
PU rejection	Excellent in the tracker acceptance	
	3. – 4.	3.8



Corinne Goy, IRN Terascle, Bruxelles, 11/10/2019



Exemple:

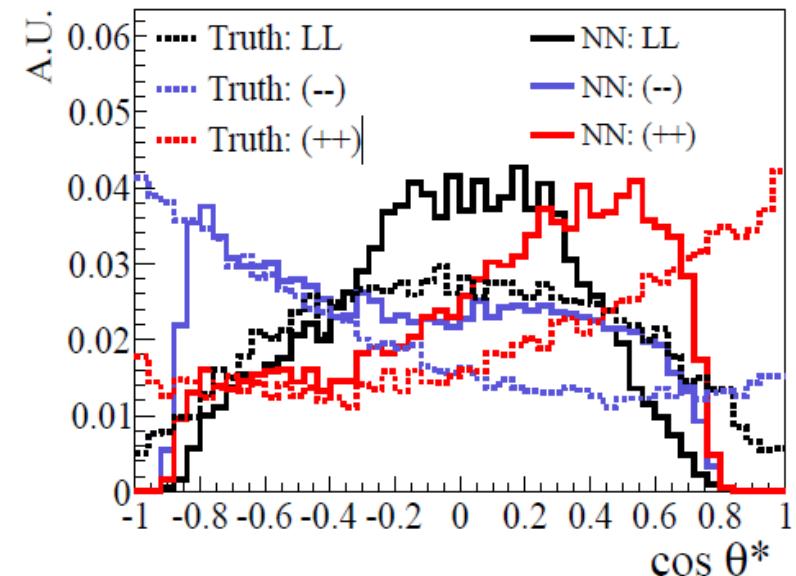
ATLAS:  $WZjj \rightarrow 3\ell\nu$  +18% (+25%)  
CMS :  $ZZjj \rightarrow 4\ell$  +13%

# Prospective - 4 methods

- Full simulation of signal and background
  - Rare
- Parametric simulation of detector effects
  - Experimental effects taken into account by parametrizations based on detector performance studies with the full simulation
  - The effect of the high pileup at the HL-LHC is incorporated by overlaying pileup jets onto the hard-scatter events with 2% efficiency
- Fast simulation using DELPHES
- Extrapolation from Run2 results
  - Scale of cross-sections
  - Scale of acceptance for leptons
  - Object performance using DELPHES

- **ssWWjj**

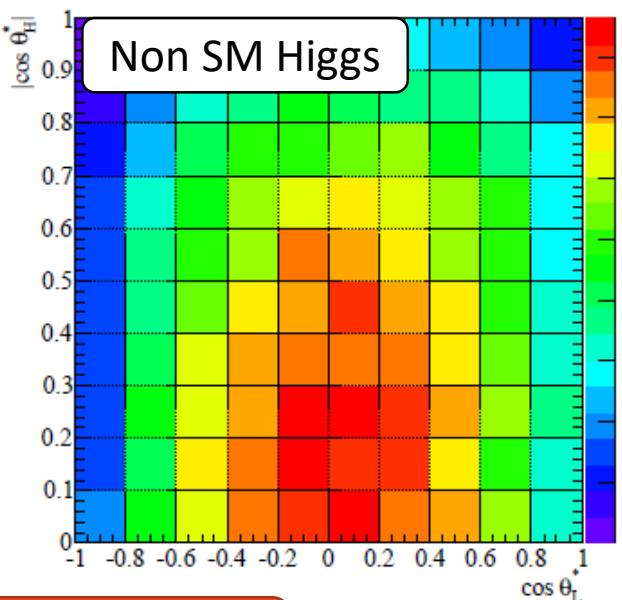
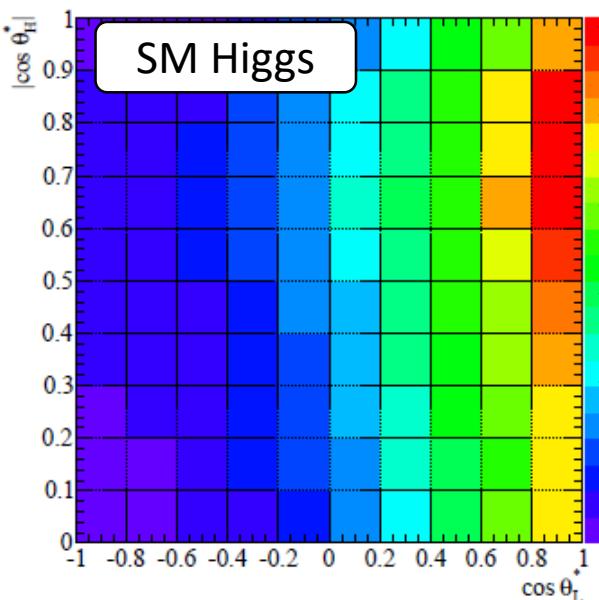
- Regression NN to approximate  $\cos\theta^*$  from 14 kinematic variables



arXiv:0911.3656 Tao Han et al

- **Using semileptonic decays ?**

- with  $|\cos\theta^*_H|$



# WWjj

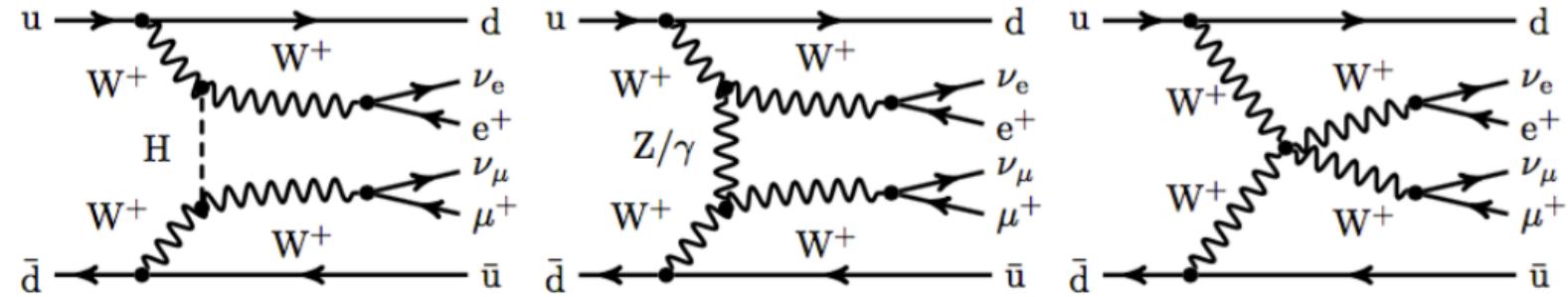


Figure 1: Representative Feynman diagrams for  $W^\pm W^\pm$  electroweak production in proton-proton collisions: (left) t-channel Higgs boson exchange, (middle) t-channel  $Z/\gamma$  exchange with triple gauge couplings, (right) quartic gauge coupling.

Exemple of  
discriminant  
variables

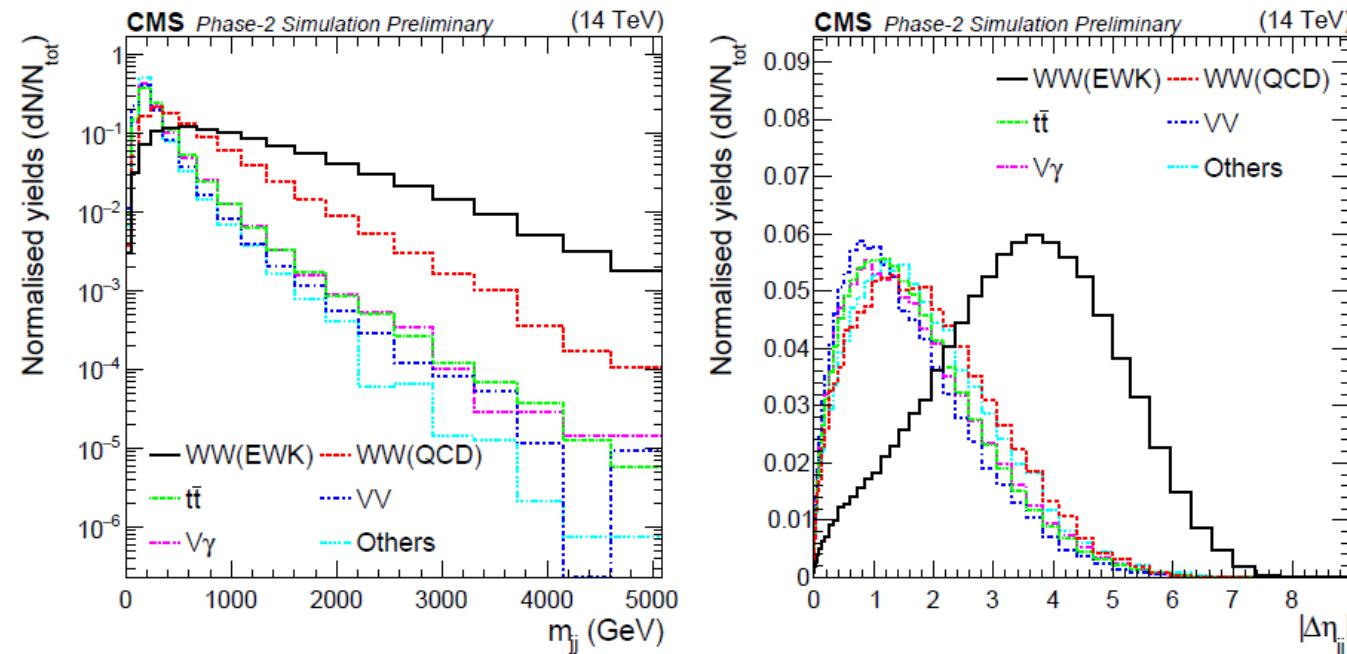


Figure 2: Shape comparisons for signal and background processes. Left: Invariant mass of the two leading jets. Right: The difference in pseudorapidity between them.

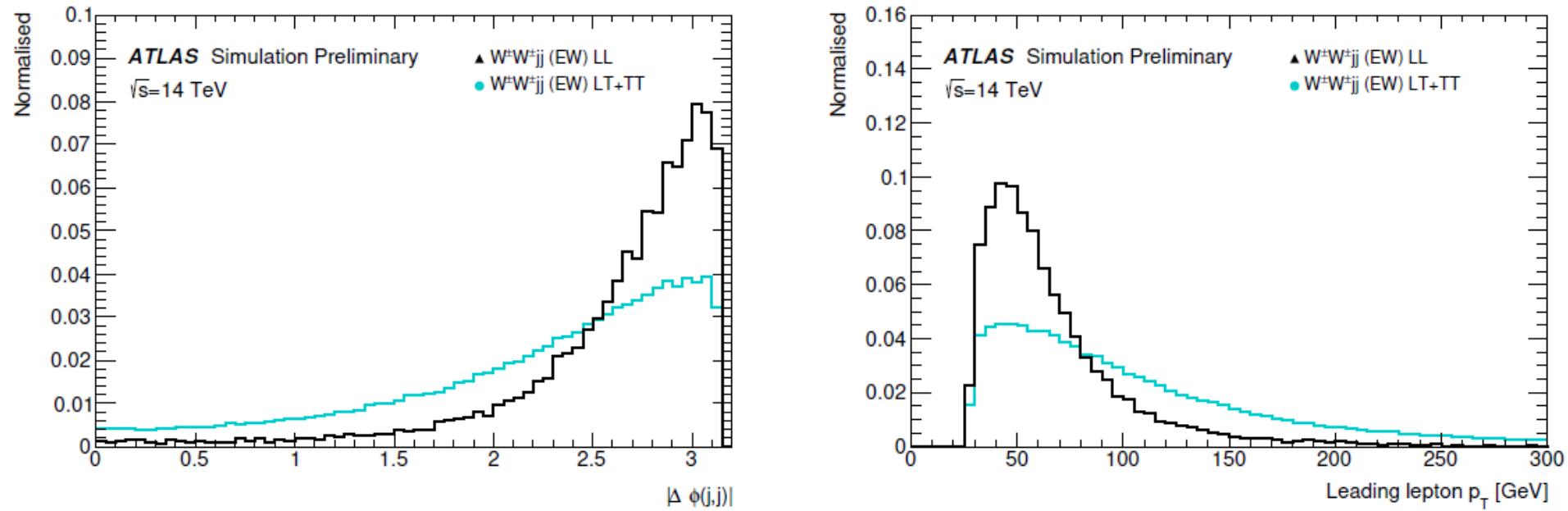


Figure 7: Shape comparisons for the dijet azimuthal separation  $|\Delta\phi(j,j)|$  (left) and leading lepton  $p_T$  (right) distributions, for the purely longitudinal (LL) and combined mixed and transverse (LT+TT)  $W^\pm W^\pm jj$  events.

# WZjj: WZ $\rightarrow$ 3 $\ell\nu$

ATLAS

- Parametric simulation
- Conservative bkg approach, loose event selection
- S/B = 0.11
- WZjj-QCD : **Phys. Lett B 793 (2019)** has shown that could be over estimated by 40% in certain regions of the PS , (but within  $2\sigma$ .)
- WZjj-EW : Signal suffers from the color flow feature in Sherpa (Sherpa/MadGraph = 87%)

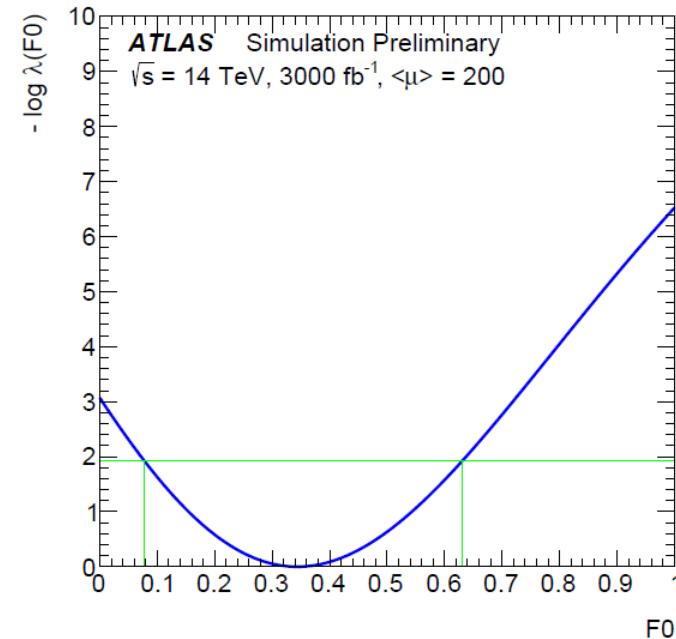
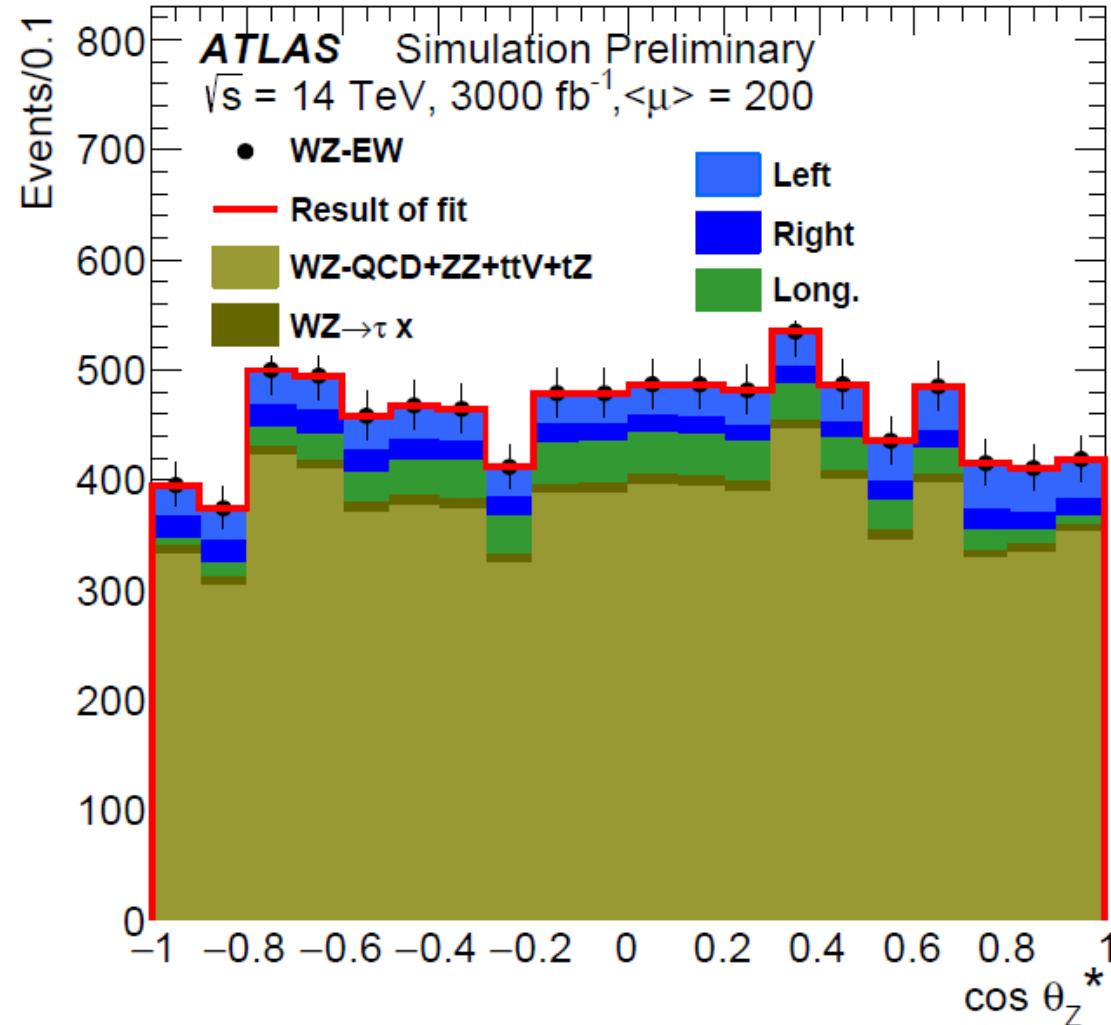
Nb of events for 3000 fb $^{-1}$

Process	ATLAS	CMS
$WZjj - EW$	3889	2757
$WZ - QCD$	29754	3486
$t\bar{t}V$	3145	–
$tZ$	2221	–
$tV/VVV$	–	1374
Non prompt	–	1192
$ZZ$	1970	–
$VV$	–	398
$Z\gamma$	–	296

CMS

- Extrapolation from the Run 2
- Tight selection
- S/B = 0.41
- WZ-QCD main background, but not as dominant

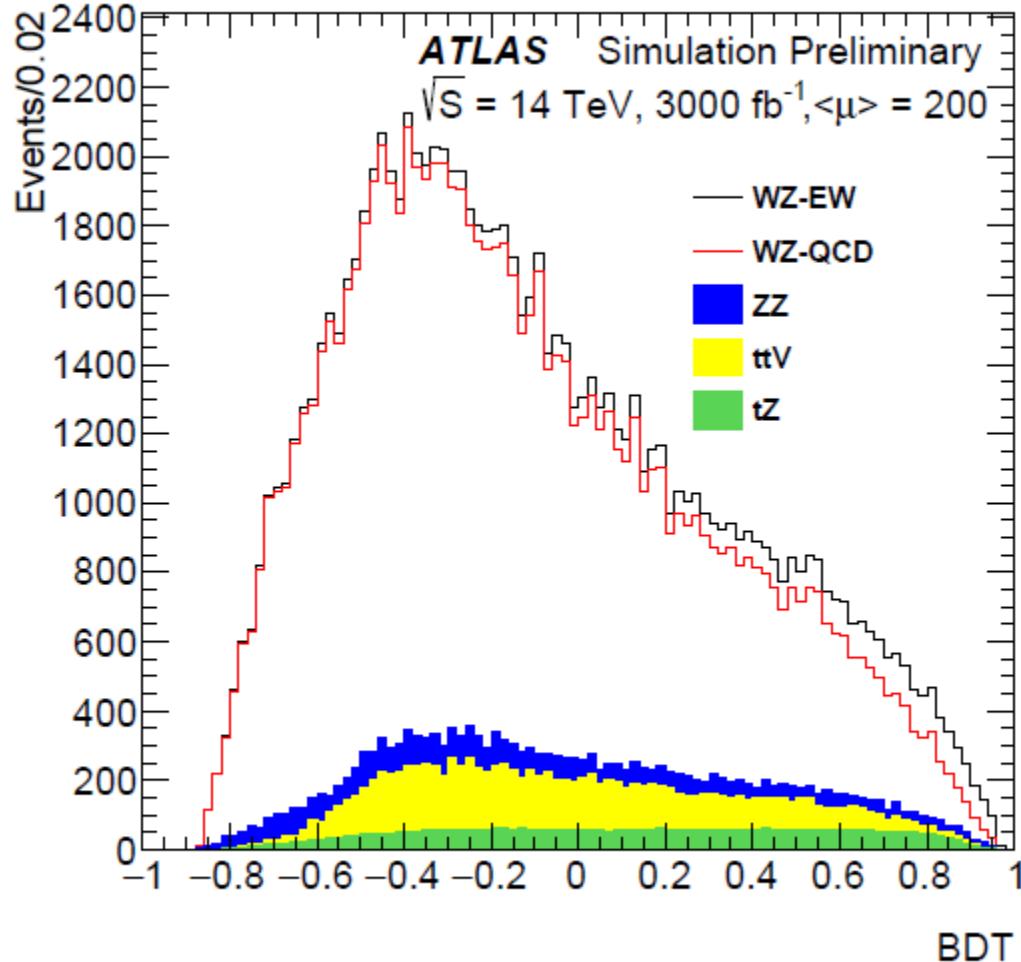
# WZ $\rightarrow$ 3 $\ell\nu$ : polarization of the individual boson W or Z



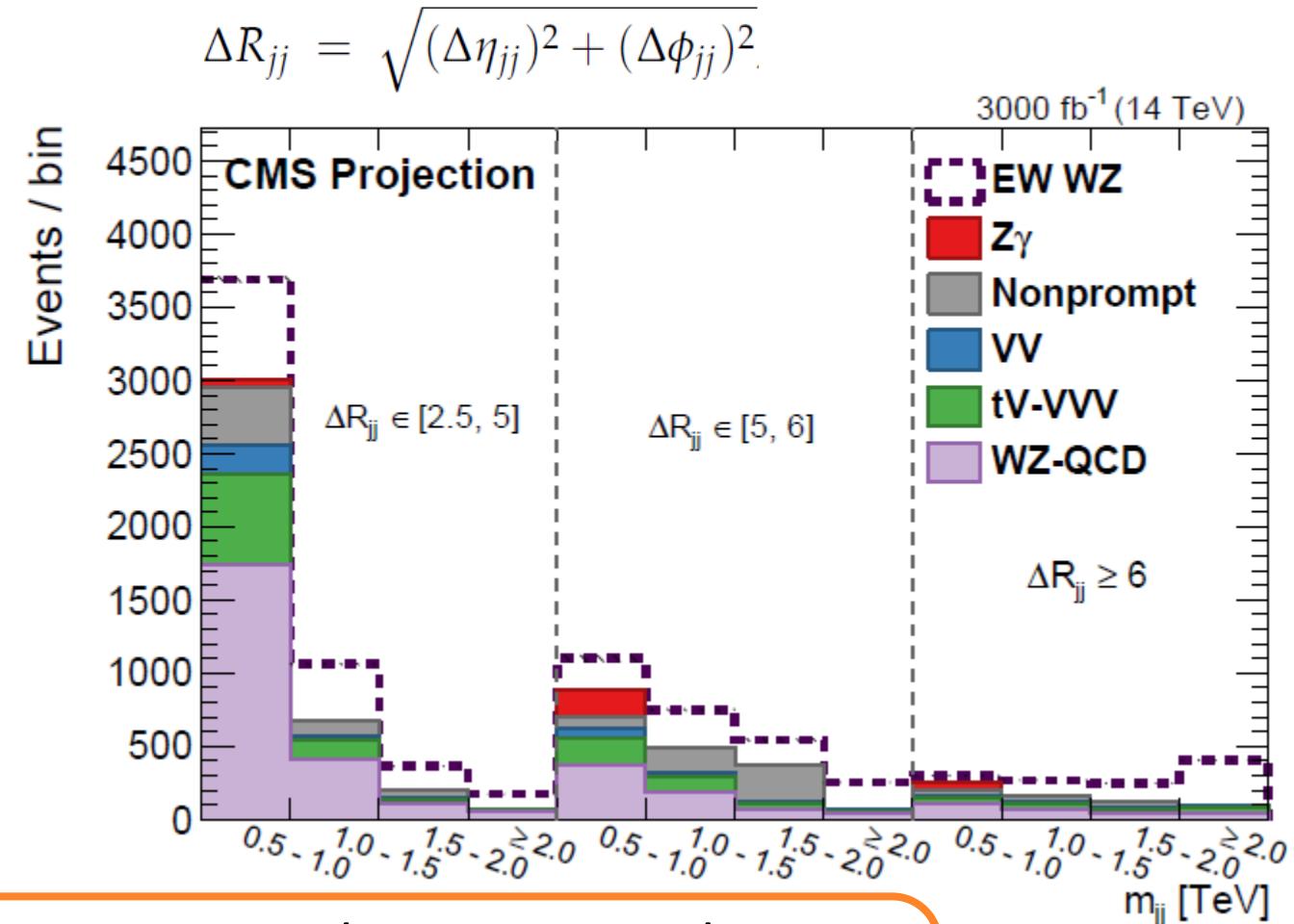
3 parameters : Nsig, F0, FL-FR  
Using 3 templates and bkg normalisation  
Syst on background normalization : 20 - 2.5 %

Simultaneous fit of 4 independent channels not exploited : ee $\mu$ ,  $\mu\mu e$ , ...

$\sigma_{WZjj}$  measured to a precision of  $\sim 3\%$



- Main systematic:
- Jet energy scale
  - WZjj-QCD modelling

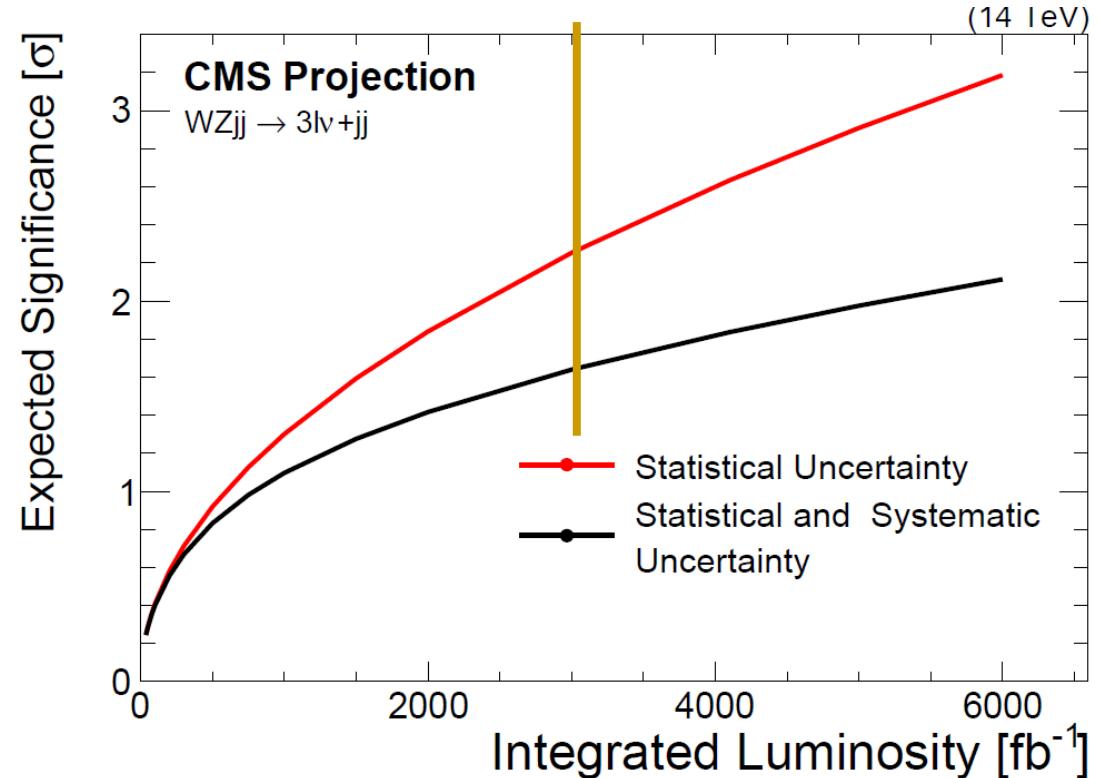
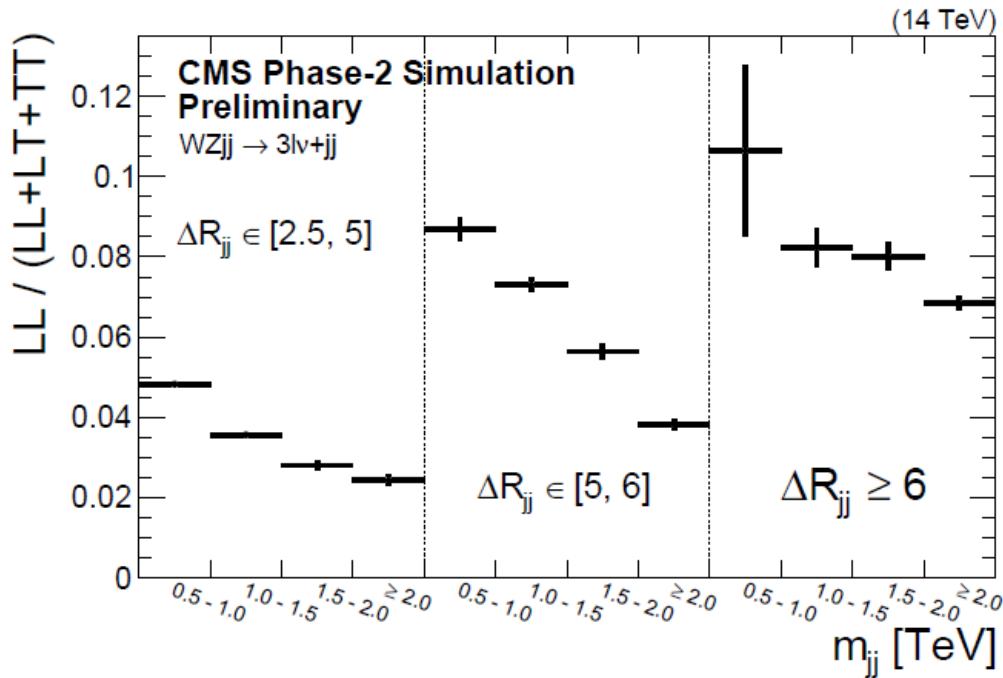


Fit in 2 dimensions and independent flavor channels

# $WZ \rightarrow 3\ell\nu$ : LL fraction

L : longitudinal/0  
T : transverse (Left + Right)

Helicity fractions obtained  
with MadGraph+DECAY  
LL fraction : 5%



LL contribution extracted alone  
TT & LT considered as a fixed additional  
background in the  $M_{jj}$  vs  $R_{jj}$  plane

# WZjj

Exercise as no background is considered.

Extraction of 00,T0,0T and TT :  
4 parameters fit

2D fit more efficient

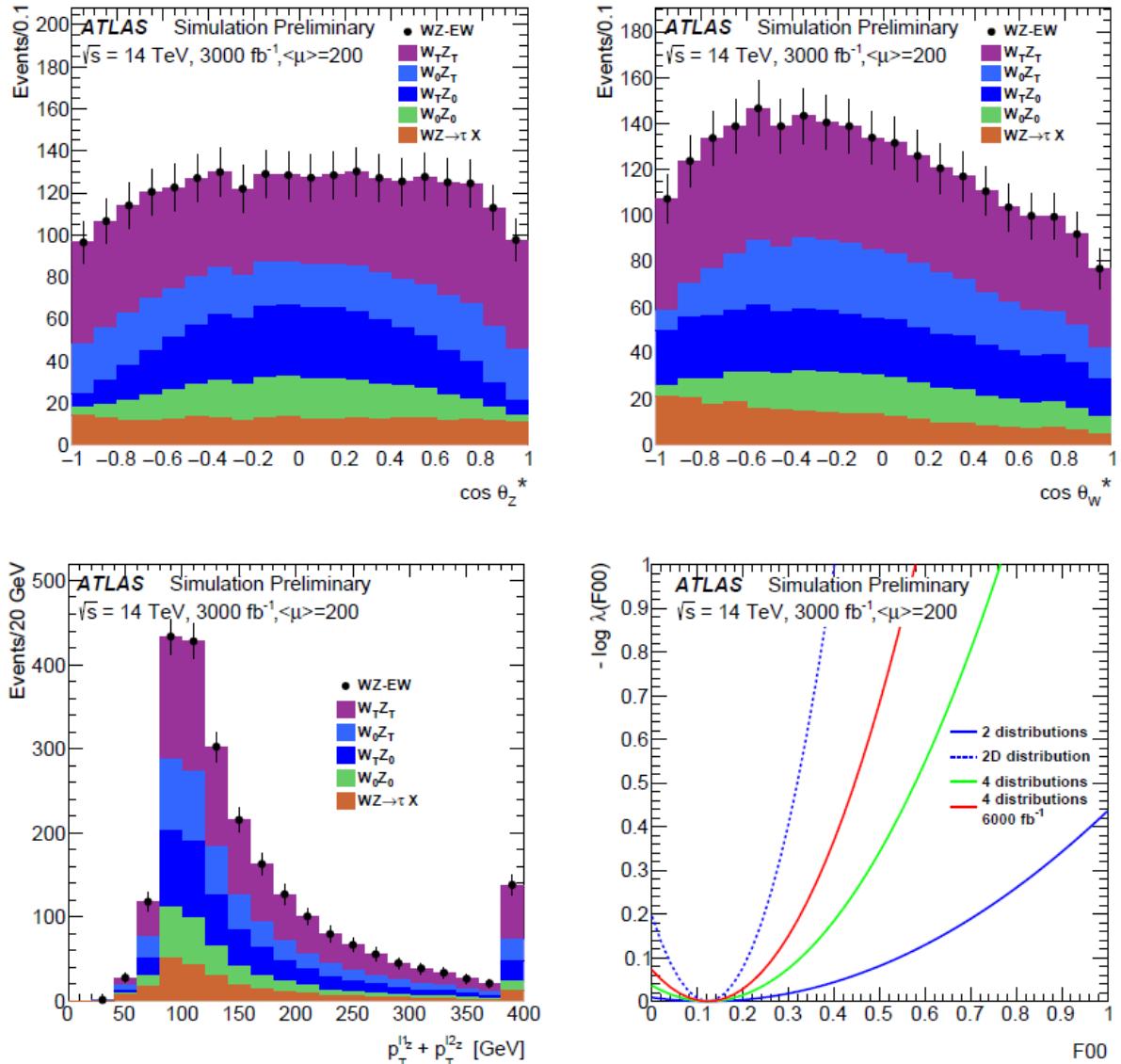
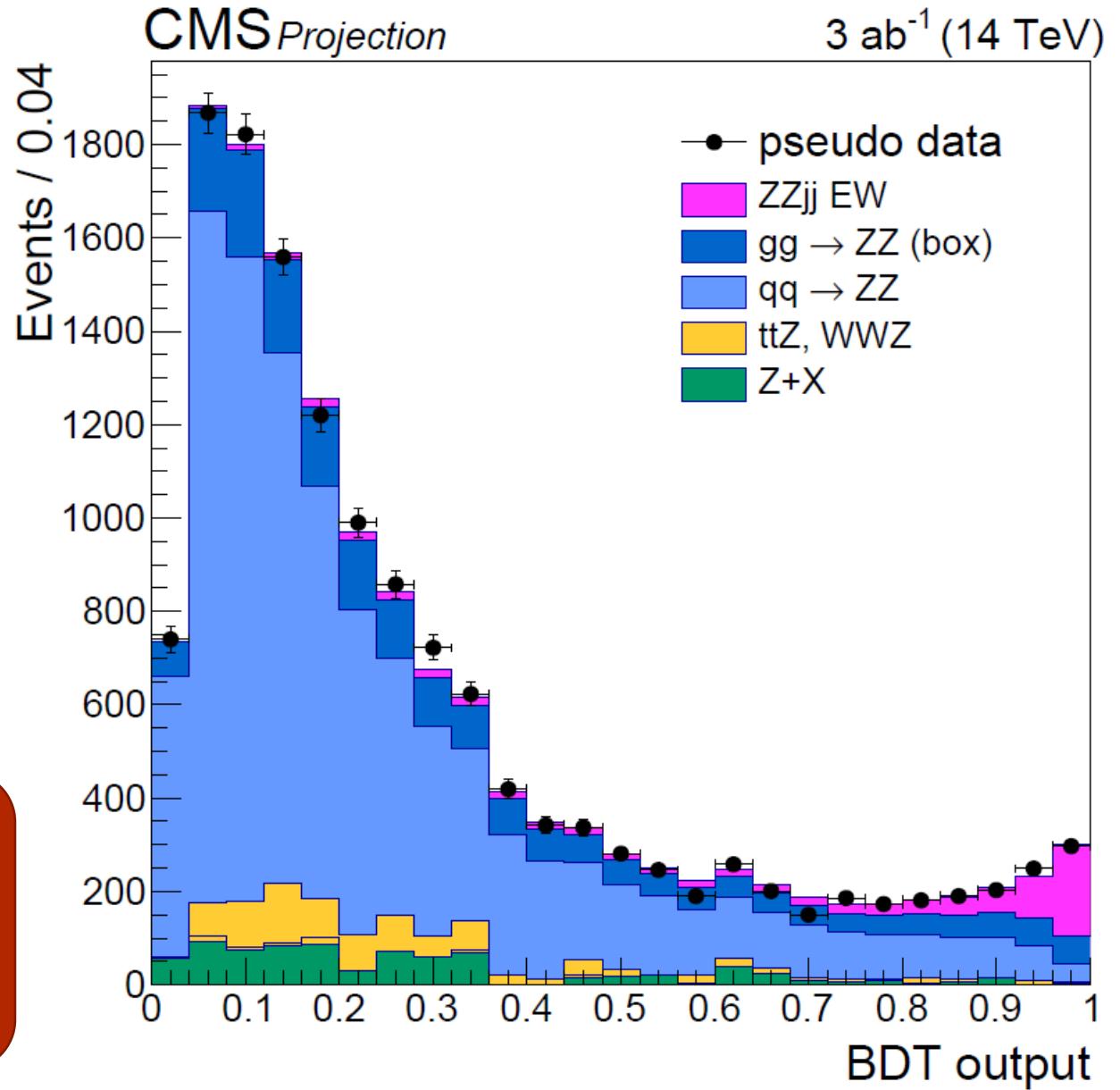


Figure 22: Results of the template fit for 3 distributions from the 4 used. Top Left:  $\cos \theta_Z^*$ , Top Right:  $\cos \theta_W^*$  and Bottom Left:  $p_T^{1z} + p_T^{2z}$ . Bottom Right: Negative log-likelihood profile vs  $F00$  for different fits.

# ZZjj: ZZ → 4ℓ

- Extrapolation method
- Fully reconstructed
  - Precise center-of-mass
  - Polarization of fermions
- Signal extracted via a BDT

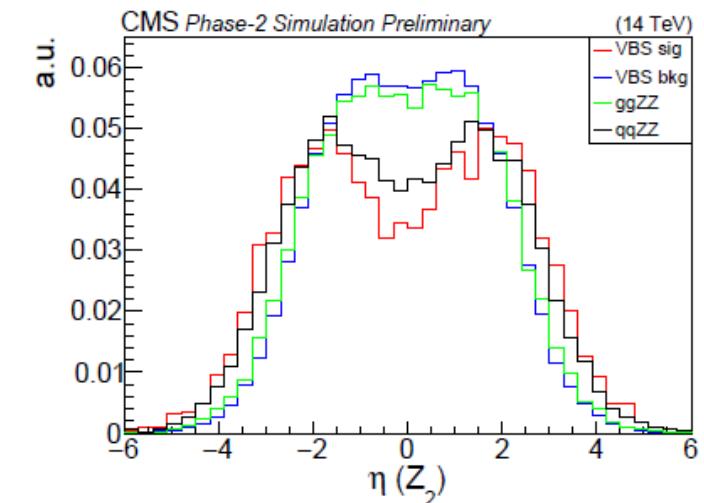
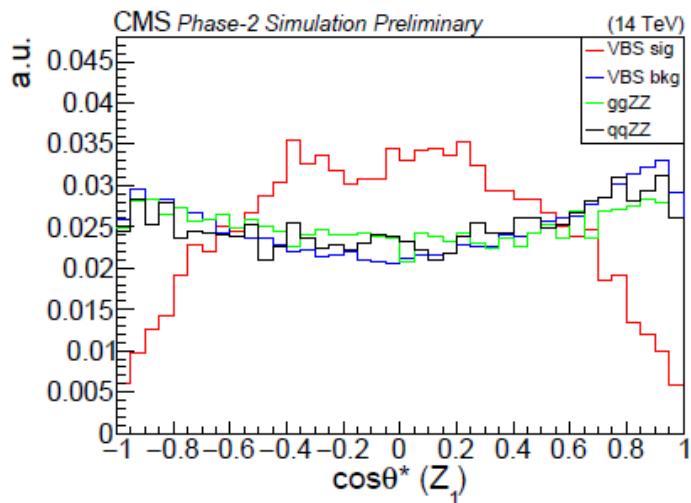
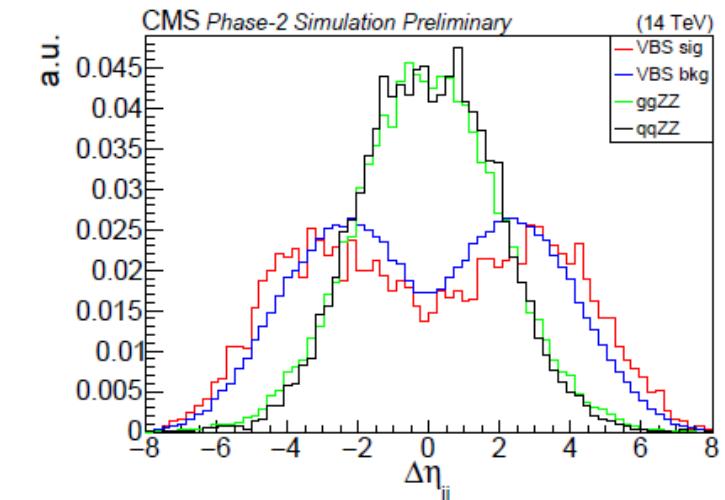
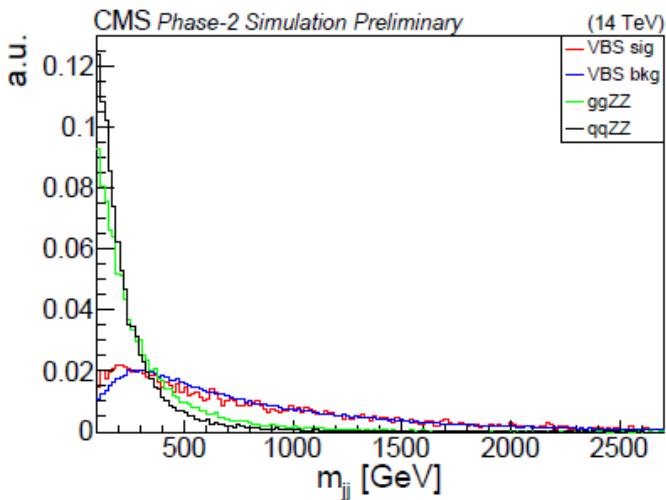
$\sigma_{ZZjj}$  expected to be measured to a precision of 8.5% - 10% depending on assumptions



# Polarization: LL fraction

Helicity fractions obtained  
with MadGraph+DECAY

Signal  $Z_L Z_L$  extracted with a  
BDT  
 $Z_T Z_T$ ,  $Z_L Z_T$  components  
considered as an additional  
background  
New variables  $\Rightarrow$



Lepton acceptance:  
 $e (\mu)$

$\eta$ coverage	significance	VBS $Z_L Z_L$ fraction uncertainty (%)
$ \eta  < 2.5(2.4)$	$1.22\sigma$	88
$ \eta  < 3.0(2.8)$	$1.38\sigma$	78
$ \eta  < 4.0(2.8)$	$1.43\sigma$	75