VBF (Zjj/Wjj) and VBS measurements

From the current status
to future prospective

Corinne Goy, LAPP CNRS/IN2P3
On behalf on the ATLAS and CMS collaborations

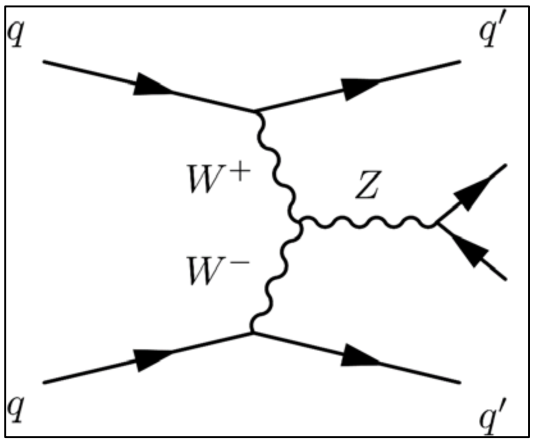
Ultimate precision at hadron colliders, Paris

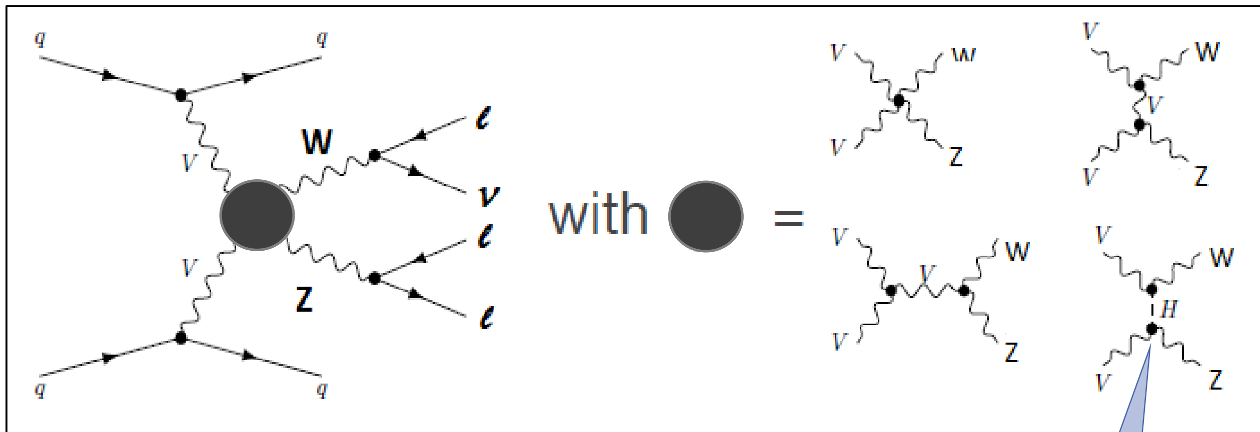
VBF

VBS

Zjj | Wjj

WZjj | ssWW, ZZ, Zg, Wg





Vector Boson Fusion (VBF): Vjj

Gauge structure (**a**TGC)

$\sigma \sim 10^{-1}$ pb

Vector boson scattering (VBS) : VVjj

Gauge structure (**a**TGC, **a**QCG) + EWSB mech ism

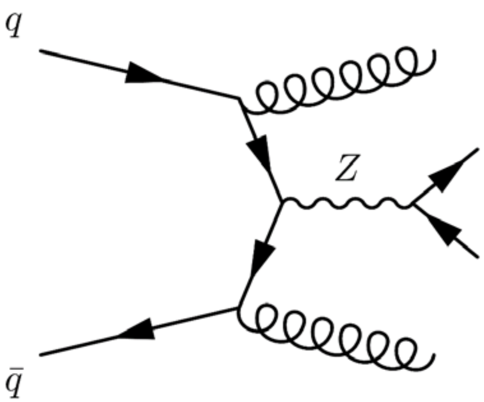
$\sigma \sim 10^{-3}$ pb

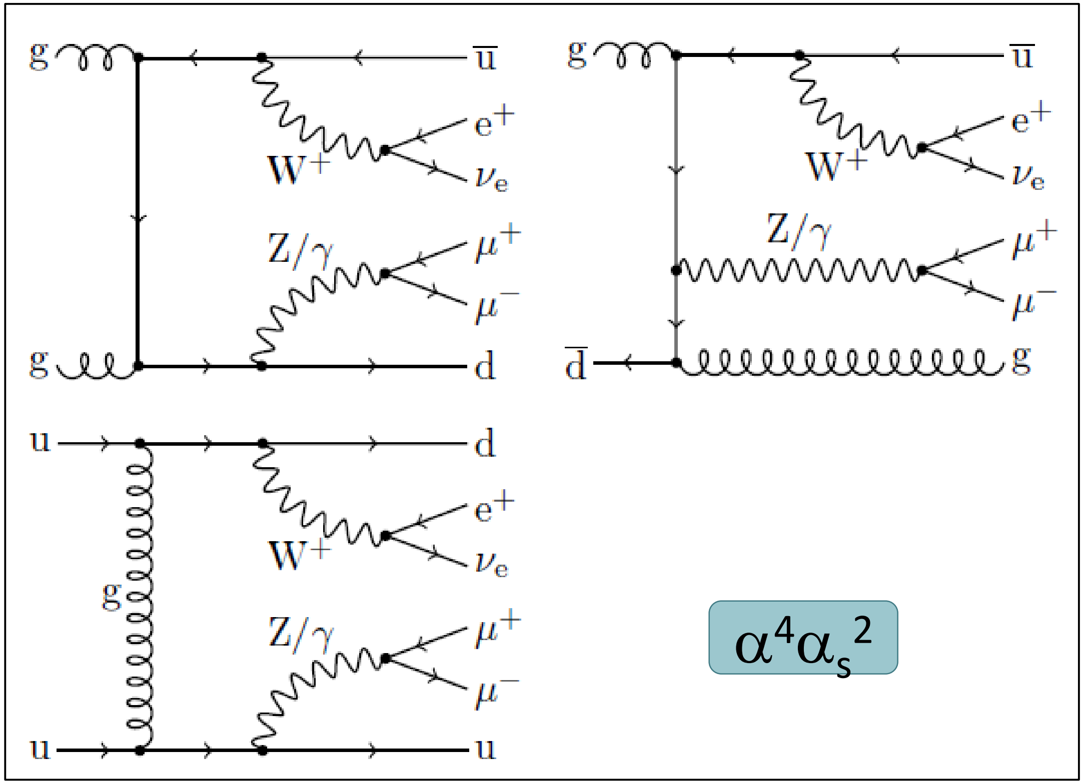
Exact ? cancellati on of LL scattering

α^4

α^6

Main background : QCD production



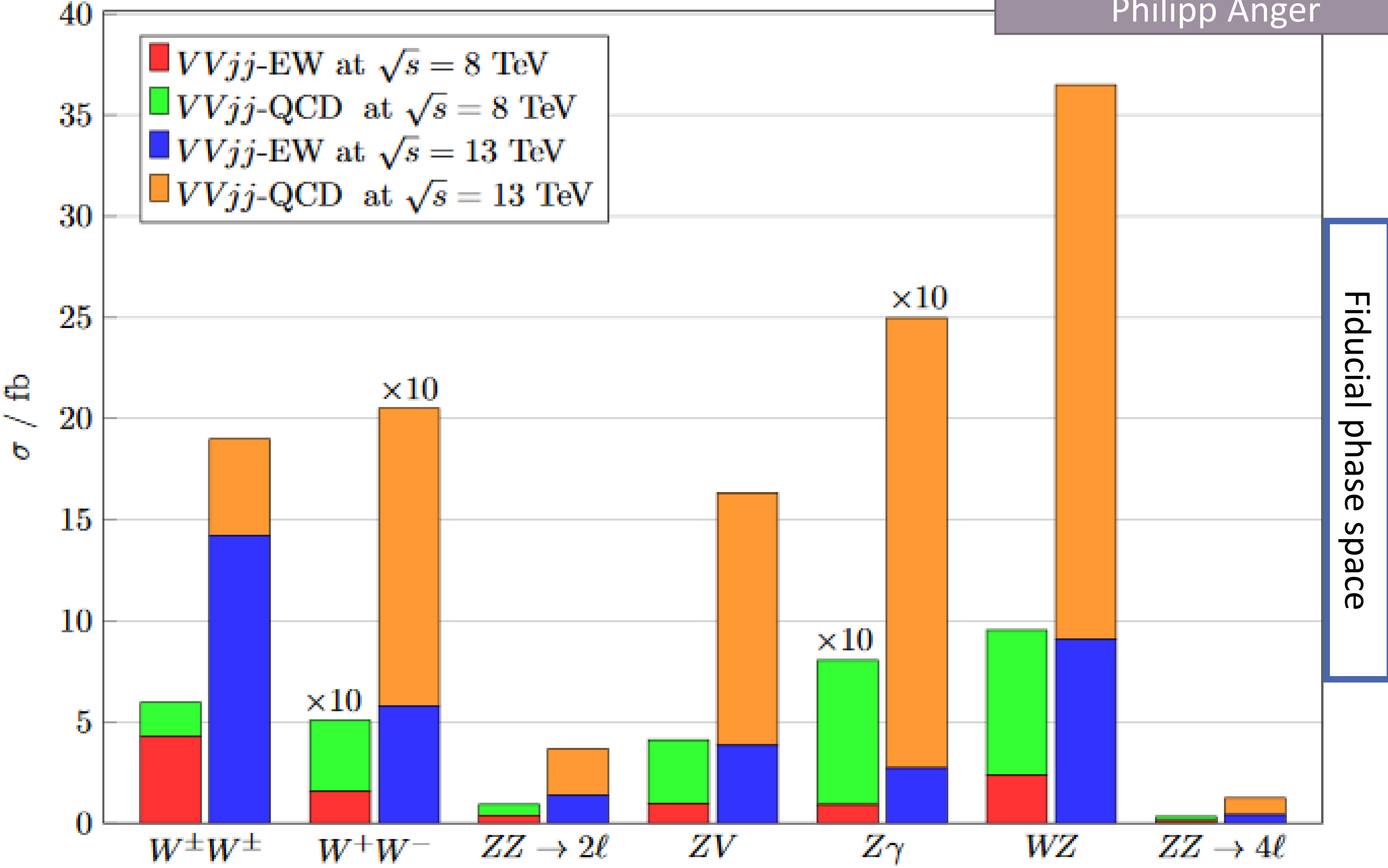


$\alpha^2 \alpha_s{}^2$

$\alpha^4 \alpha_s{}^2$

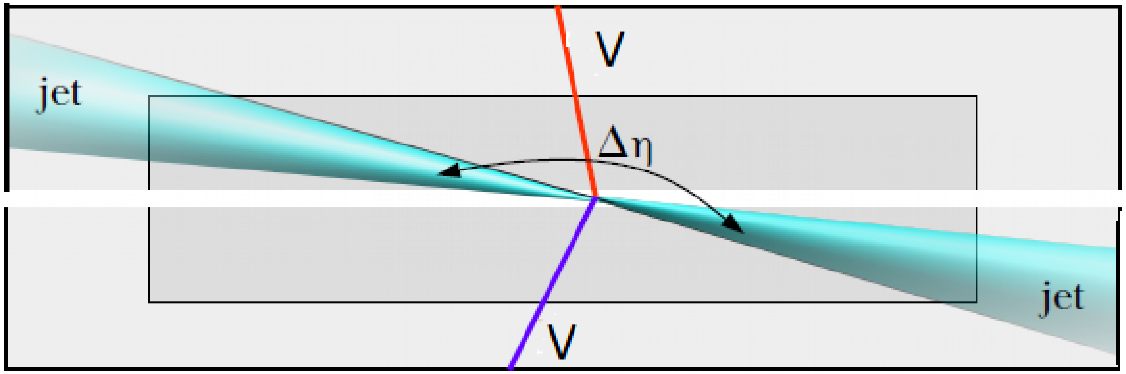
EW / QCD ratio (Sherpa 1.1)

CERN-THESIS-2015-105
Philipp Anger

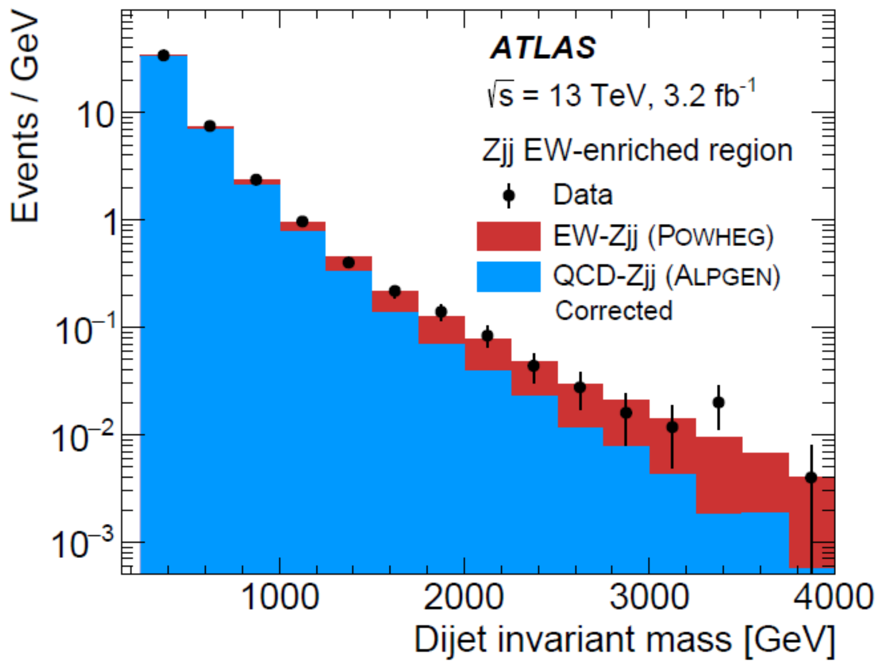


Clean experimental signature

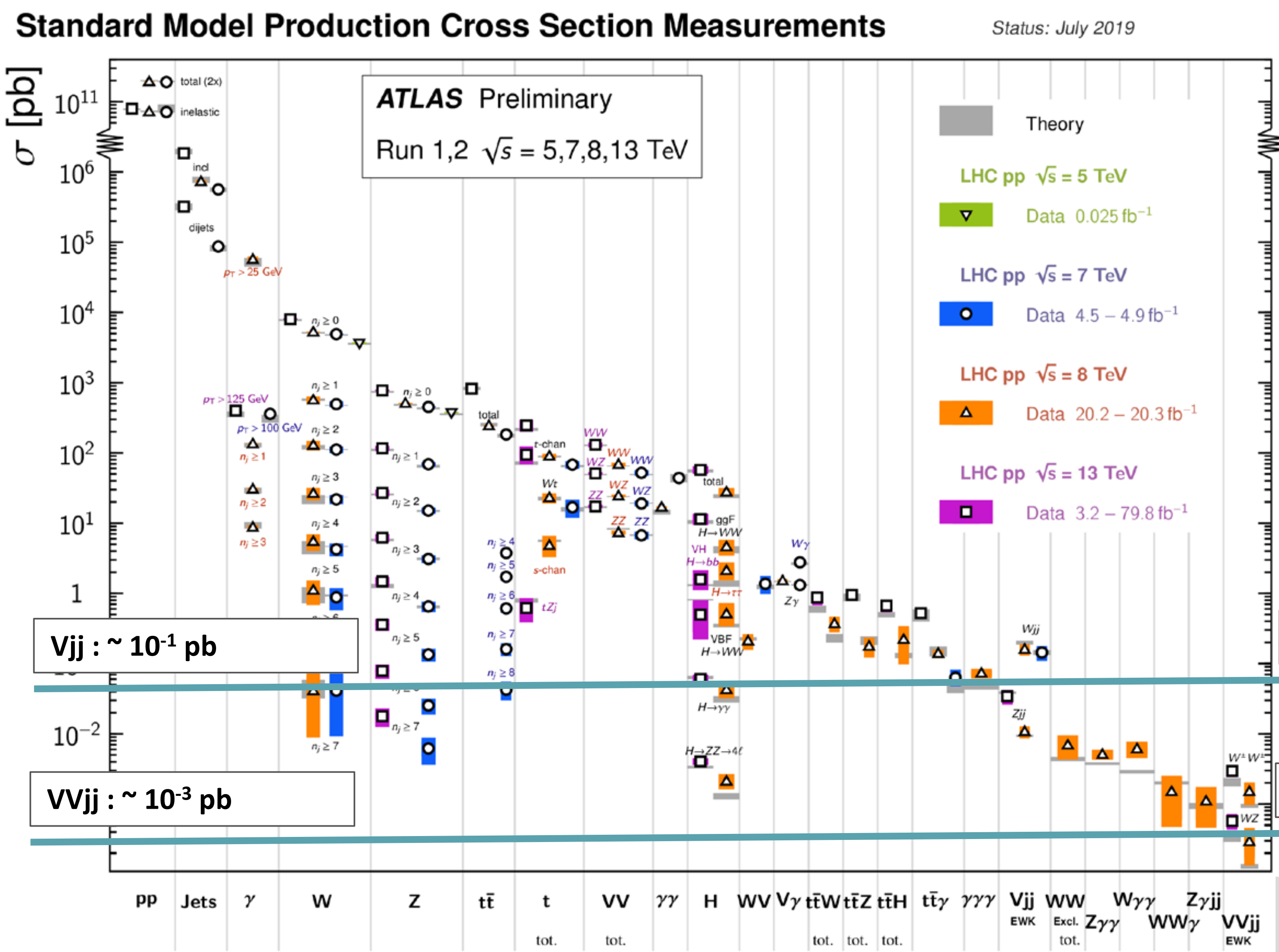
- 2 fwd jets
- 1 or 2 central bosons



Multivariate analysis, BDT, NN



EW production is enhanced at large Mjj



Vjj : ~ 10^{-1} pb

VVjj : ~ 10^{-3} pb

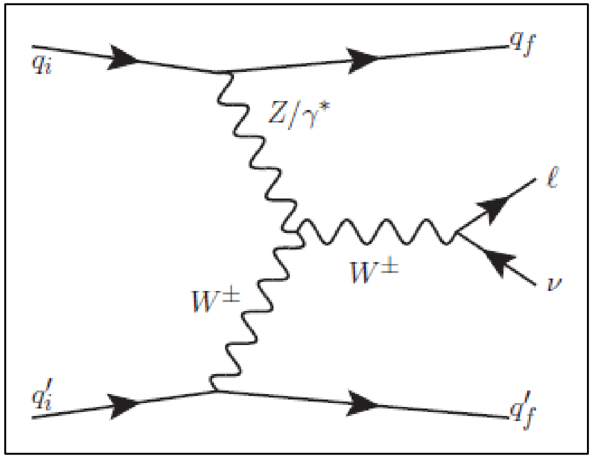
End of run2: 140 fb^{-1}

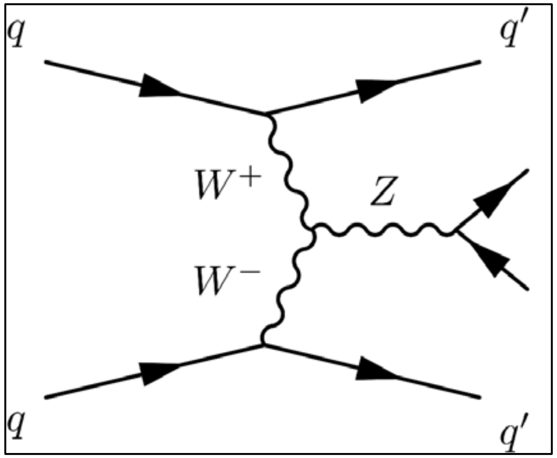
14000 events/exp

140 events/exp

Leptonic decays : e & μ
Z → ll : 3.3658(23) %
W→ lν : 10.86(9) %

VBF



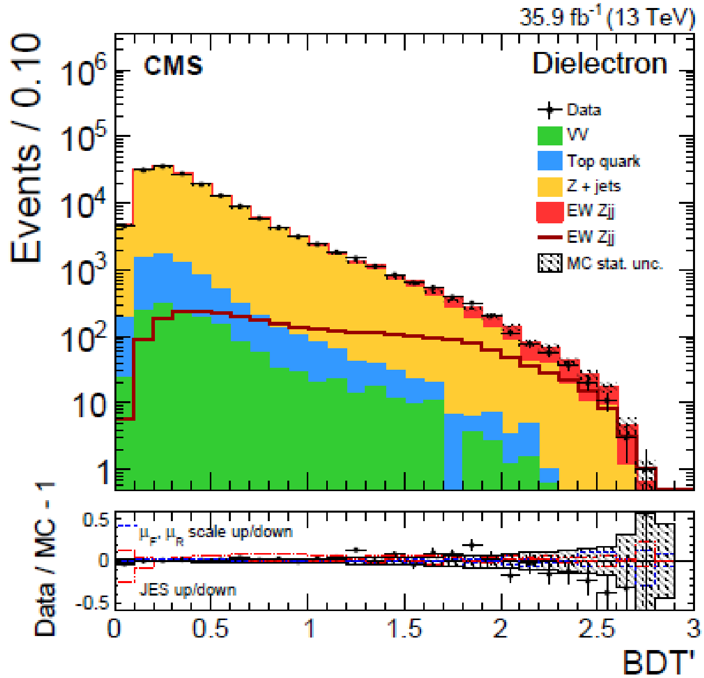


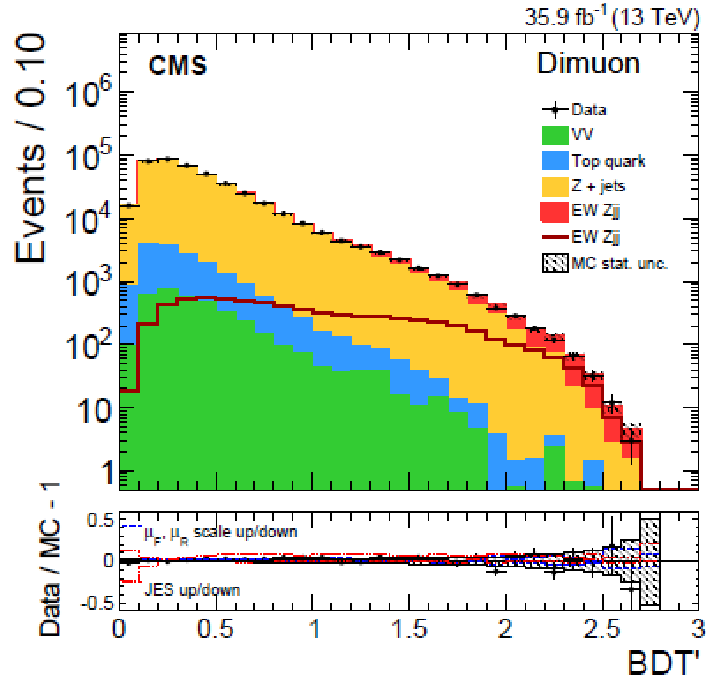
Compilation of current publications

	√ s	Luminosity /fb	Channel	arXiv[hep-ex]
ATLAS	7 TeV	4.7	Wjj	
	8 TeV	20.2	Zjj	1401.7610
			Wjj	1703.04362
	13 TeV	3.2	Zjj	1709.10264
CMS	7 TeV			
	8 TeV	19.3	Wjj	1607.06975
	13 TeV	**35.9**	**Zjj**	**1712.09814**

Zjj

35.9/fb





Statistics :

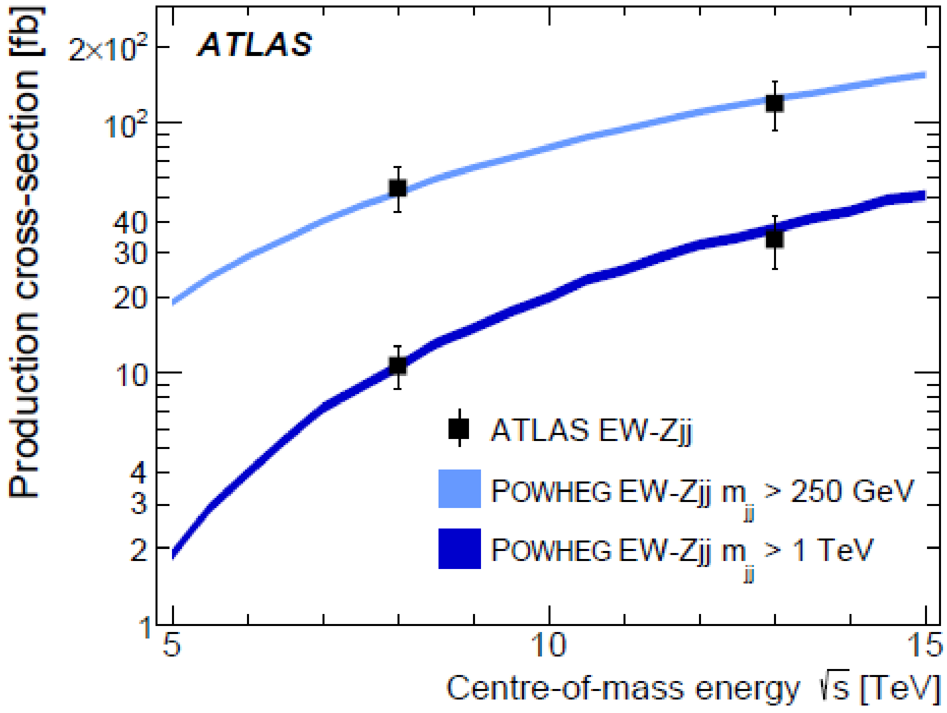
- 4%

Systematics exp:

- Jet Energy Scale : 3%

Systematics :

- QCD scale
  - 4% (QCD)
  - 6% (EW)
- Intf EW-QCD : 2 – 3%
- Parton Shower : 4 %



VBF – aTGC (wwz)

Effective field theory description

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

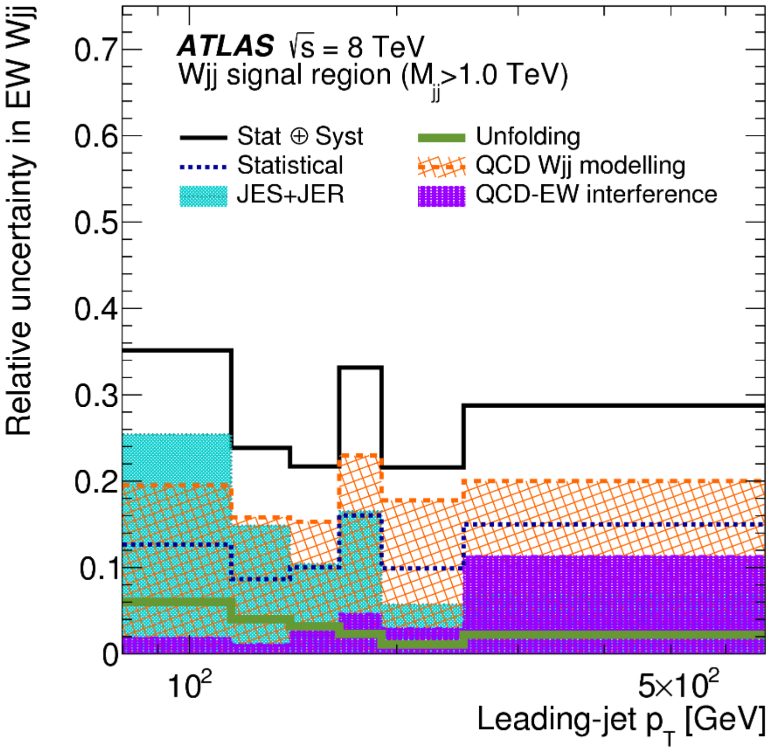
3 CP conserving parameters : cWWW,cW,cB

2 C or P violating parameters

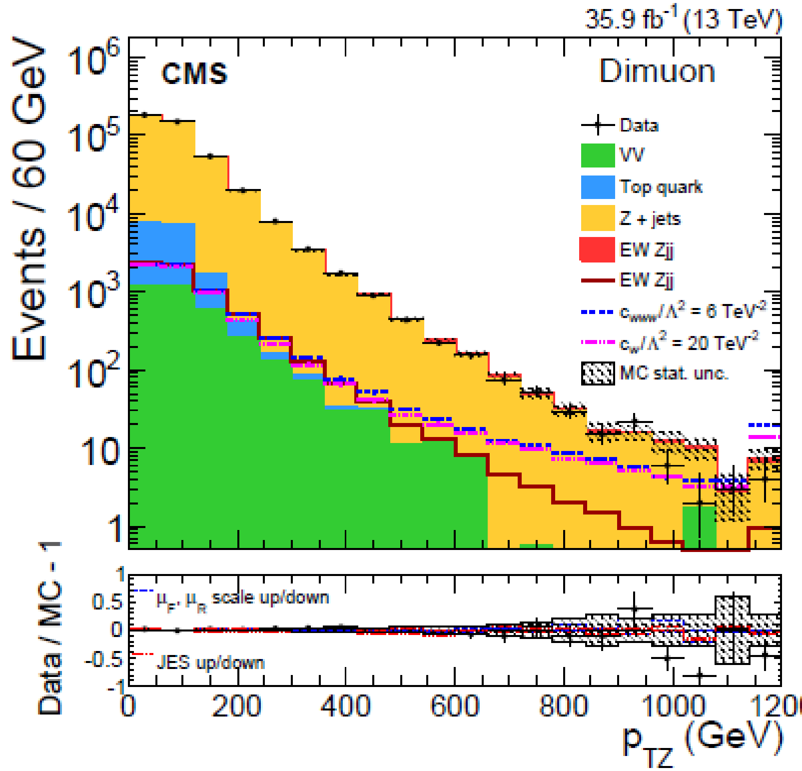
Distributions used for aTGC

- Wjj : jet-linked variables
  - p_T leading jet
  - p_T^{jj}
  - $\Delta\varphi(j1,j2)$
- Zjj : p_T^{Z}
  - well measured
  - In principle well modelled

Illustration of the main systematic in the last bins

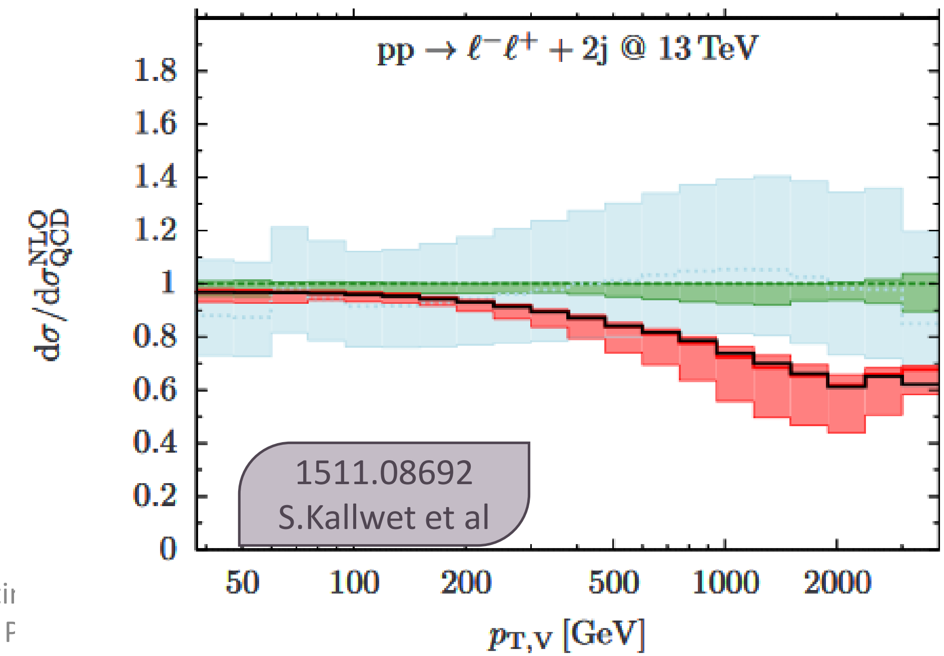


PtZ (Zjj)



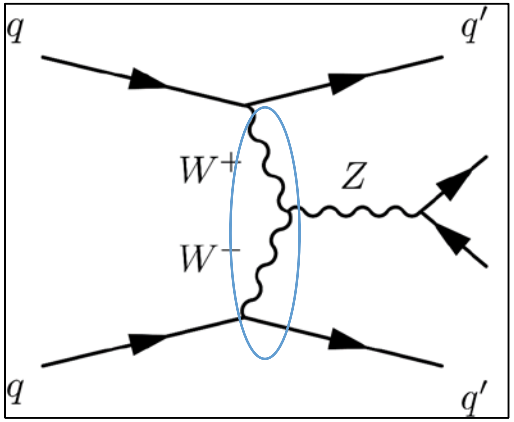
Better sensitivity with muons final states: end point 1.2 TeV (900 GeV with electrons)

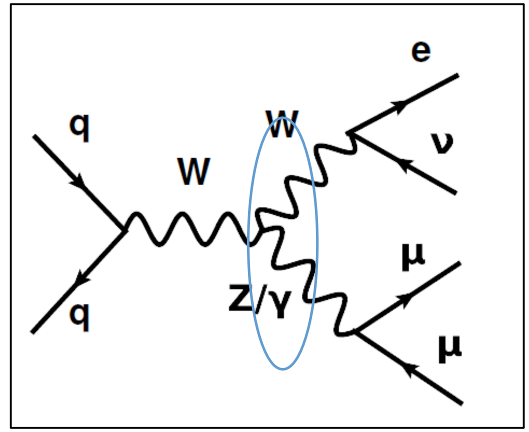
NLO-EW corrections sizeable at 1 TeV , but decrease the expected cross-sections (conservative effect)



aTGC via Inclusive Production

Off Shell : potentially large q2





On Shell : smaller q2

CMS : Zjj

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

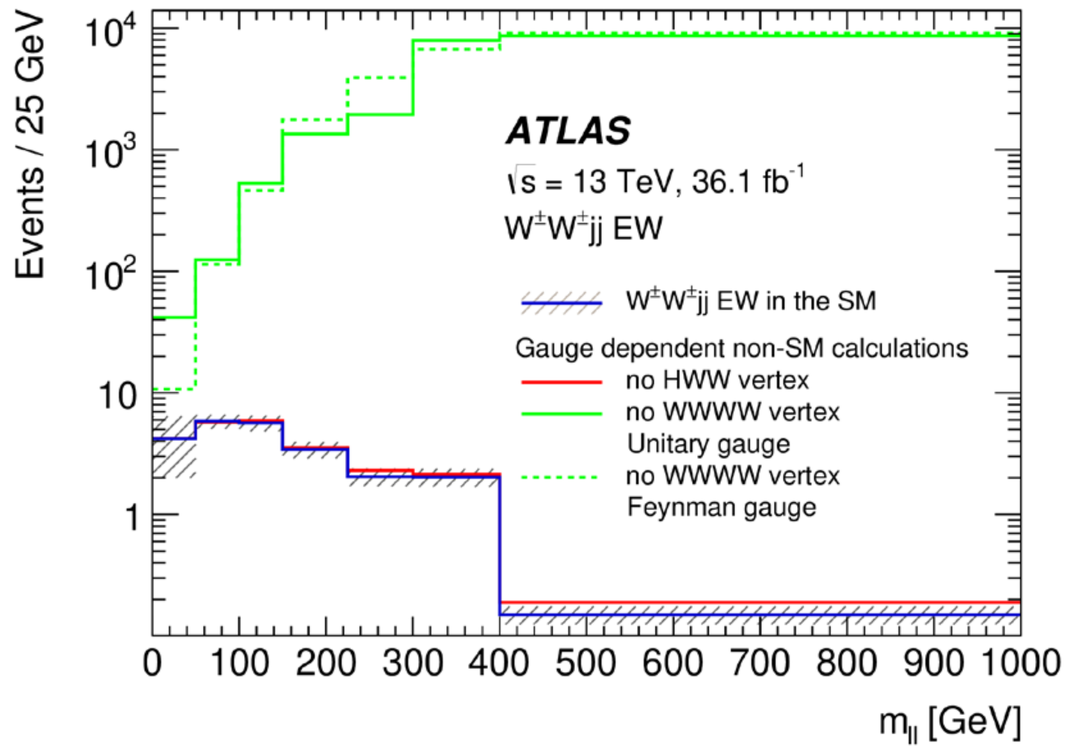
Coupling constant	Expected 95% CL interval (TeV^{-2})	Observed 95% CL interval (TeV^{-2})
c_{WWW}/Λ^2	$[-3.7, 3.6]$	$[-2.6, 2.6]$
c_W/Λ^2	$[-12.6, 14.7]$	$[-8.4, 10.1]$

Parameter	95% CI (expected) [TeV^{-2}]	95% CI (observed) [TeV^{-2}]
c_W/Λ^2	$[-2.3, 3.4]$	$[-2.2, 2.7]$
c_{WWW}/Λ^2	$[-33.2, 28.6]$	$[-13.8, 41.2]$
c_b/Λ^2	$[-360, 300]$	$[-230, 390]$

Complementary sensitivity

CMS : WZ inc fully lep

ssWWjj



arXiv;1906.03203
Atlas Collaboration

VBS

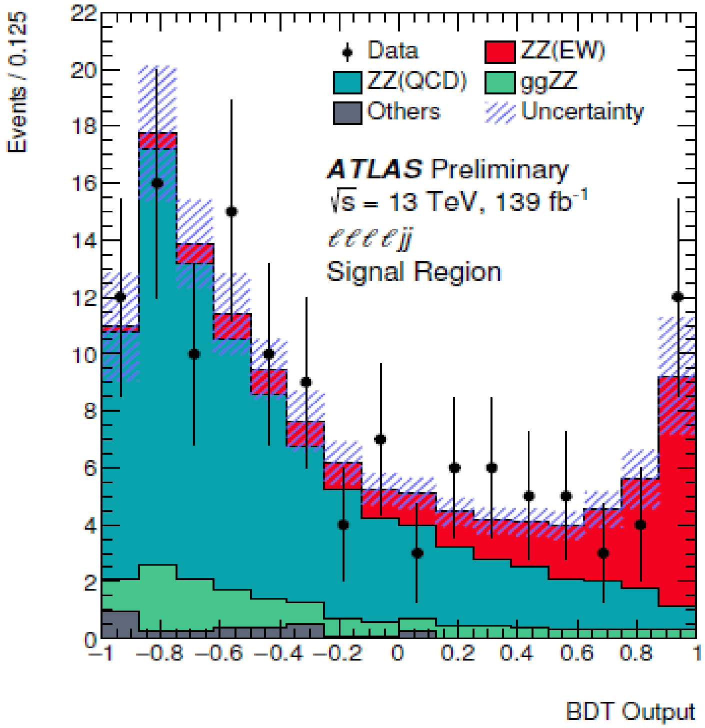
Pure QGC not accessible

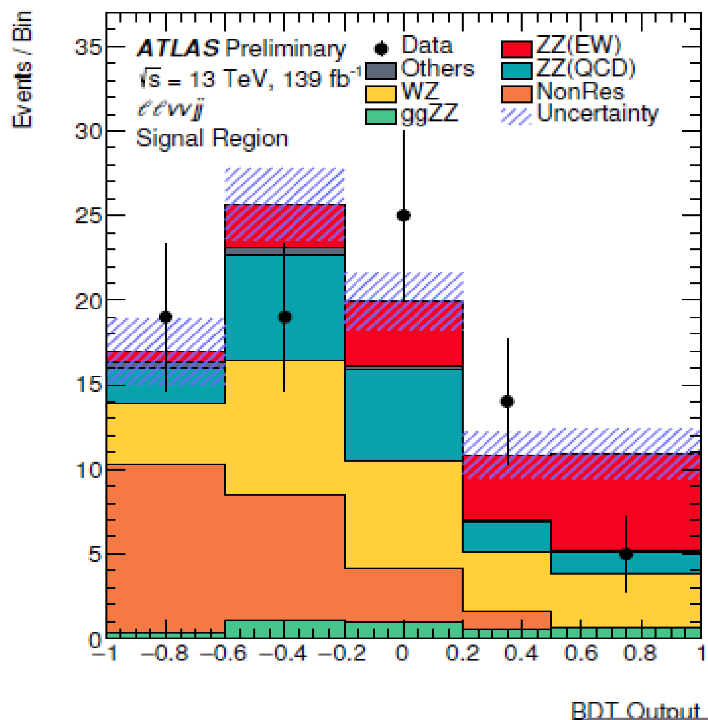
Sensitivity of the VVjj search in pp collisions

Never observed before LHC ($\sigma \sim 10^{-3}$ fb)

Ex	CoM	WWjj	ssWWjj	WZjj	ZZjj	Zγjj	Wγjj
CMS	7 TeV	~1 (5.05/fb)					
CMS	8 TeV		2.0 (19.7/fb)				2.7 (19.7/b)
ATLAS	8 TeV	2.7 (20.3/fb)	3.6 (20.3/fb)				
CMS	13 TeV		**5.5** (35.9/fb)	2.2 (35.9/fb)	2.7 (35.9/fb)	**4.7** (19.7/fb+ 35.9/fb)	
ATLAS	13 TeV		**6.5** (36.1/fb)	**5.3** (36.1/fb)	**5.5** (139/fb)	4.1 (36.1/fb)	

ATLAS : ZZjj in 4l and 2l 2ν (139/fb)





VBS analysis : Generalized usage of BDT

ATLAS-CONF-2019-033

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

VBS - aQGC

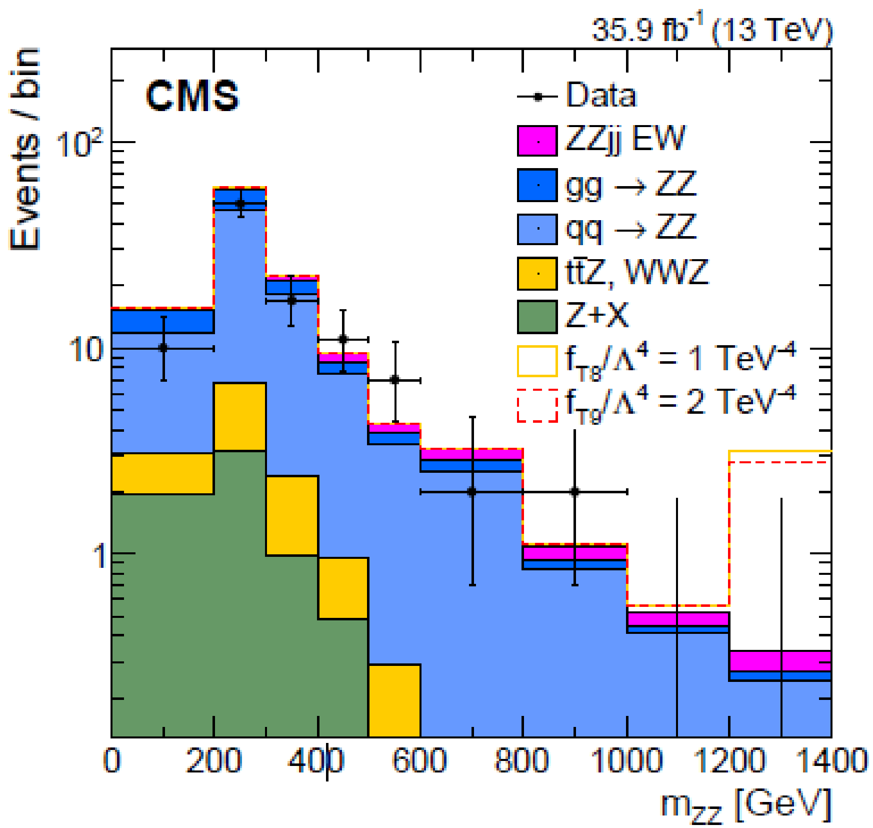
Described by dimension 8 operators

18 parameters

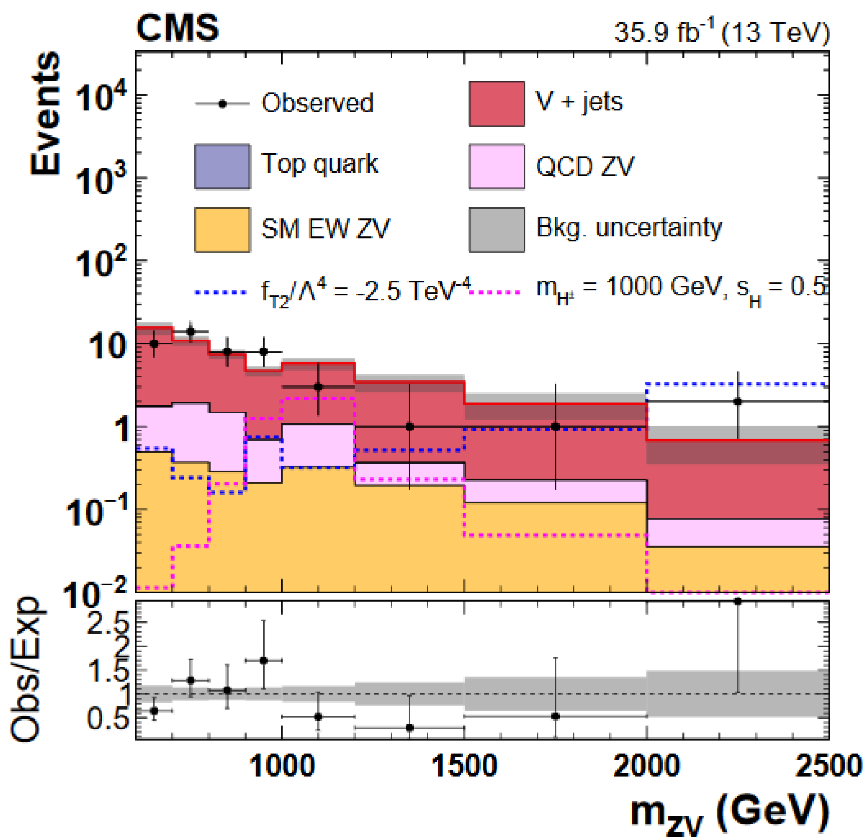
- All H fields (S)
- Mixing V & H fields (M)
- All V fields (T)

M_{VV}

2 events in the last bin

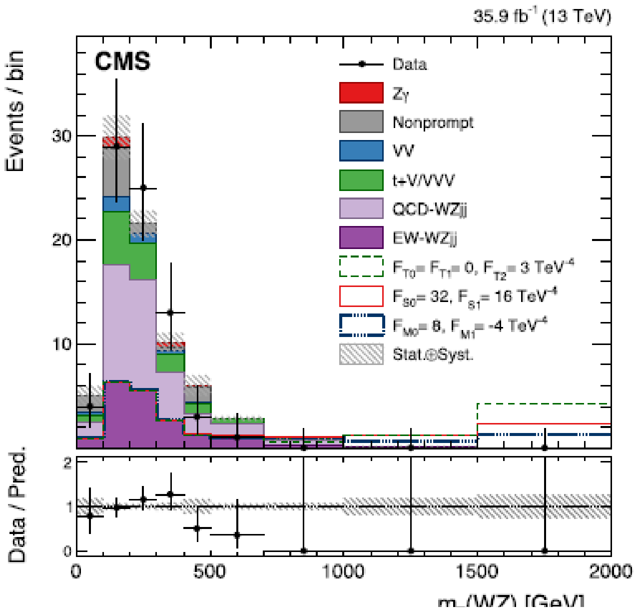


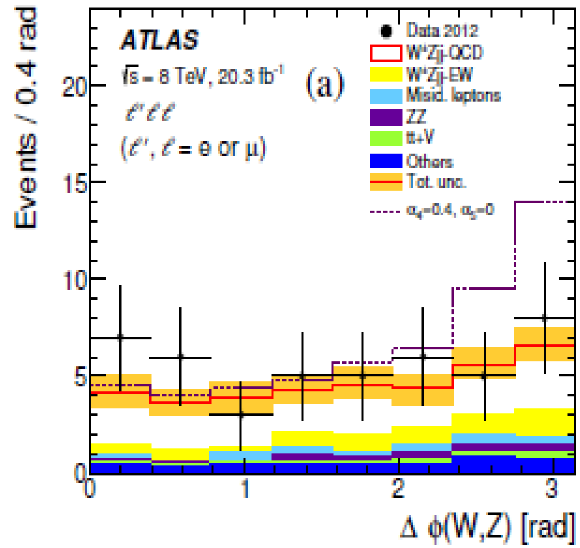
Semi-leptonic ZV



Other variables

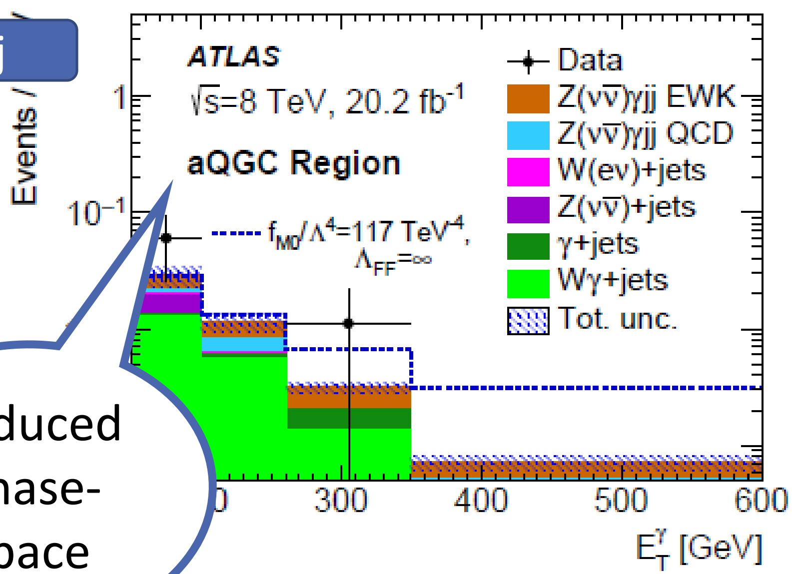
WZjj



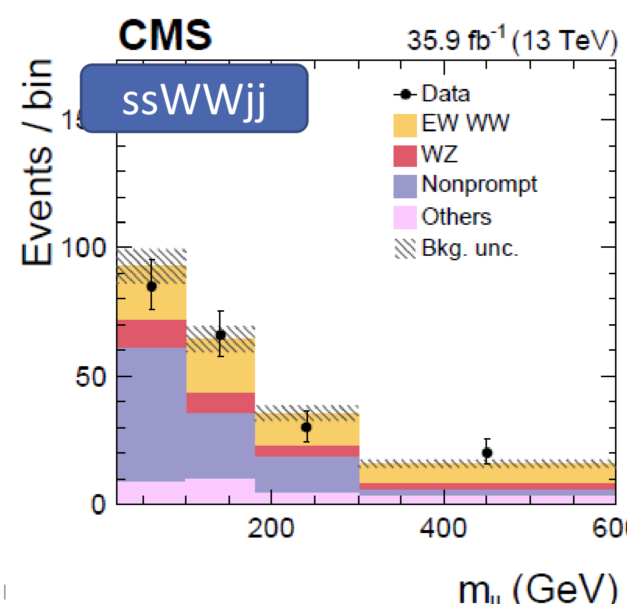


+ $\Sigma|P_T(l)|$

Zγjj



Reduced phase-space



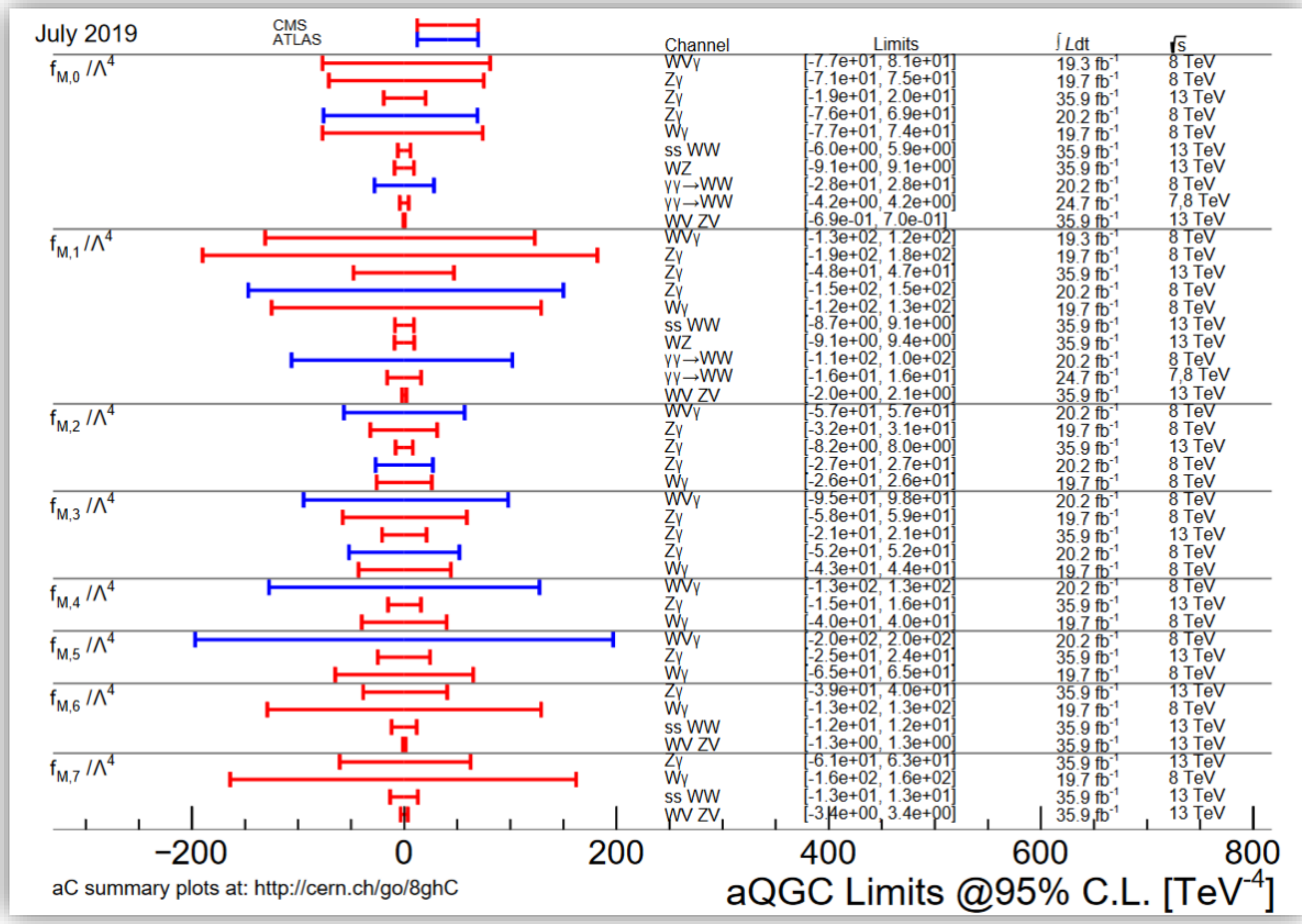
ssWWjj

+ $M_T(WW)$

M parameters

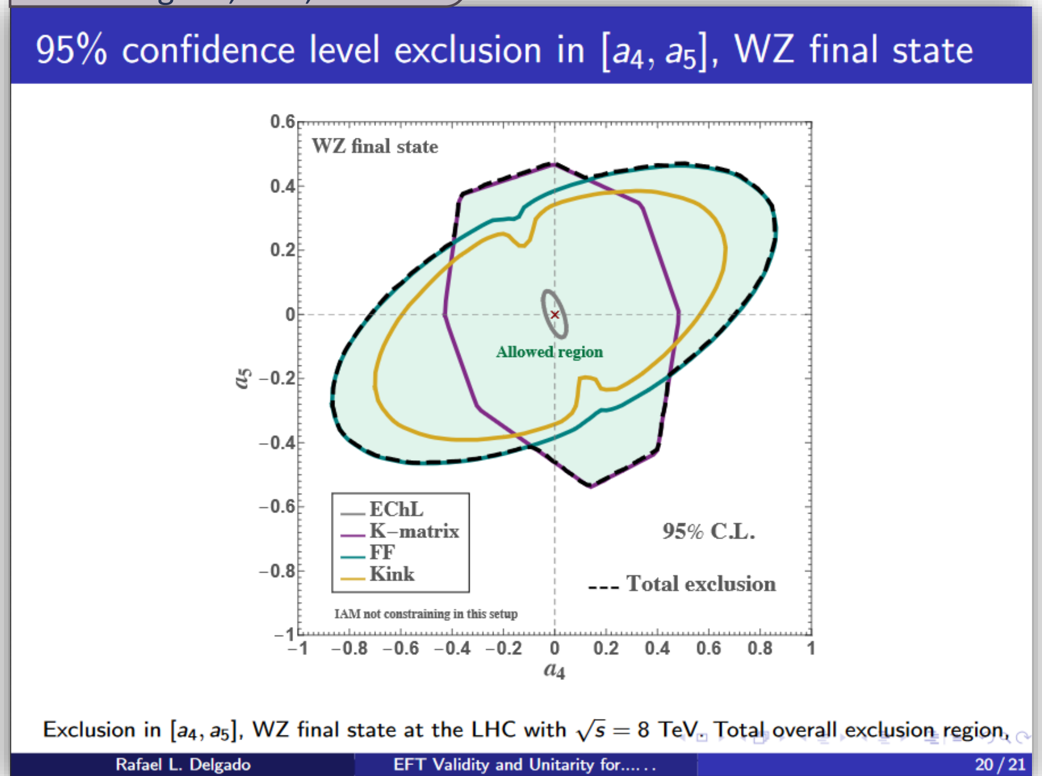
O(1),O(10)

- 13 TeV sets better limits
- Semi-leptonic decays sets better limits
- ! Positivity of parameters not exploited
- Unitarity methods different (if any)



Unitarity

R Delgado, MBI, 2019



f_i/Λ^4, from observation of $pp \to W^{\pm}W^{\pm}jjX$

ATLAS, 8 TeV[8] VBFNLO (T-matrix)		CMS, 8 TeV[7] Éboli
		[−38,40]
[−960,960]	⟵⟶	[−118,120]
		[−33,32]

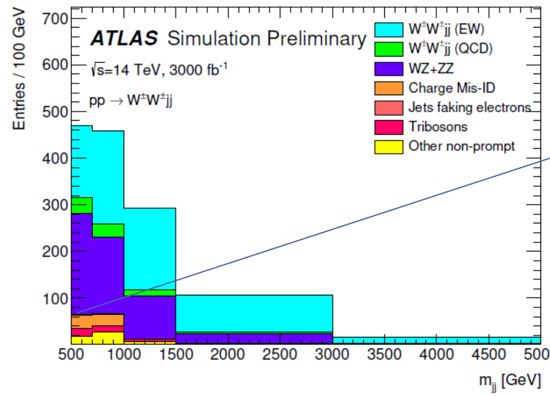
Eur. Phys. J. C (2018) 78:759 Genessis Perez, Marco Sekulla, Dieter Zeppenfeld

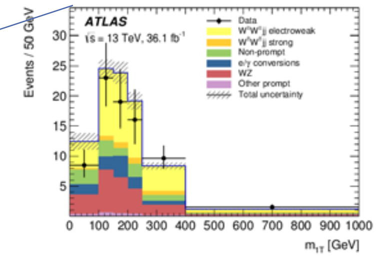
or clipping (scale)

A unique prescription to handle unitarity would be useful !

HL-LHC : From first observations to measurements

ssWW





VBS – The future

$\sqrt{s}$ = 14 TeV, 3000. fb^{-1}

CERN-LPCC-2018-03
Standard Model Physics at the HL-LHC and HE-LCH
2 volumes

Evolution of the experimental conditions

- Luminosity

Peak: 5- 7.5 10^{34} $cm^{-2}s^{-1}$
<PU> = 200

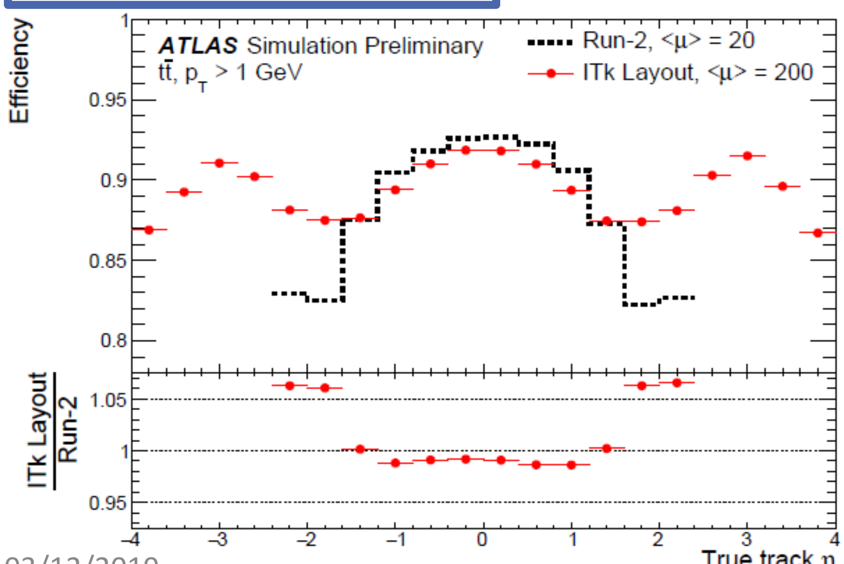
- Aging – radiation damages

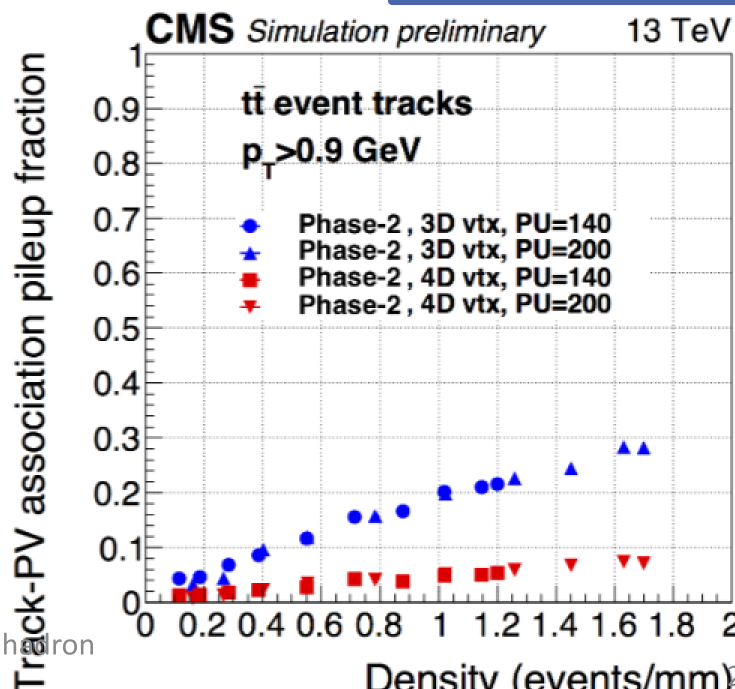
To cope with
Data rates
Detector occupation
And to maintain:
Trigger performance
Pile-Up jet rejection
Object performance

⇒ Upgrade of detectors
Hardness
Granularity

Timing detector

Tracking up to |η | < 4

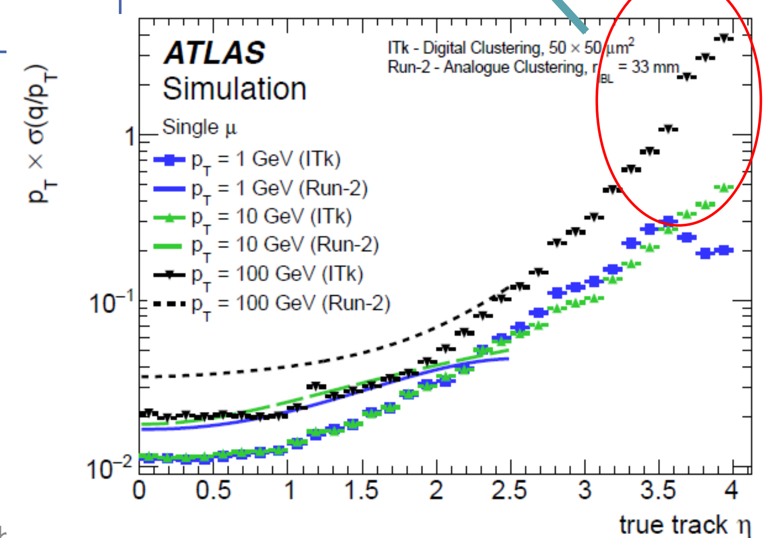




Consequences for object reconstruction

	|η|	
	CMS	ATLAS
Track reconstruction:		4.
Electrons:	3.	4.
Muons:	2.8	2.7 (4. with muon tagger)
PU rejection :	Excellent in the tracker acceptance	
	3. – 4.	3.8

Poor resolution for muons: Affects variables like MT



Gain in acceptance (example) :

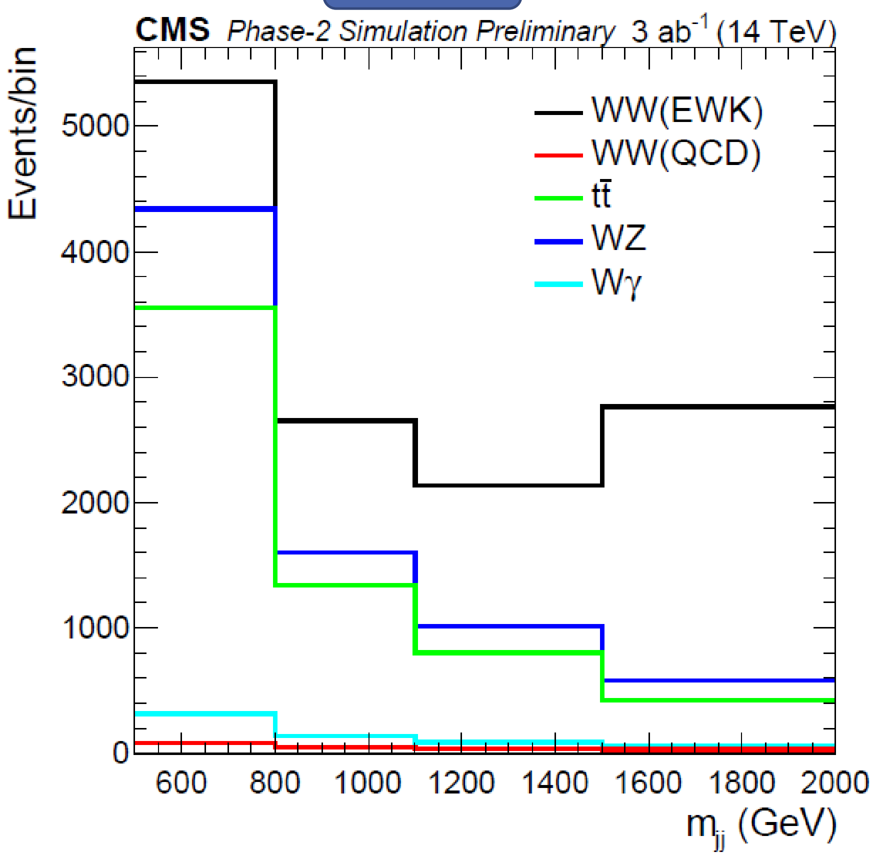
ATLAS: WZjj $\rightarrow 3\ell\nu$ +18% (+25%)

CMS : ZZjj $\rightarrow 4\ell$ +13%

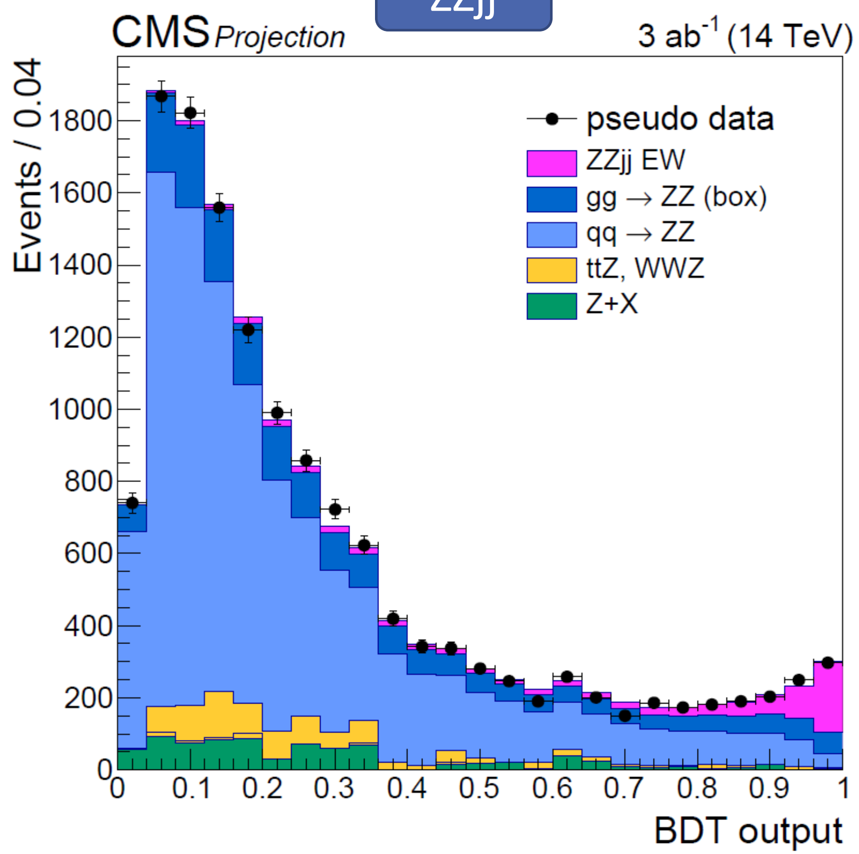
Cross-sections:

- ZZjj : 8.5 to 10.3%
- $W^{\pm}W^{\pm}jj$: 4.5 to 6%
- WZjj : 3 to 6%

ssWWjj



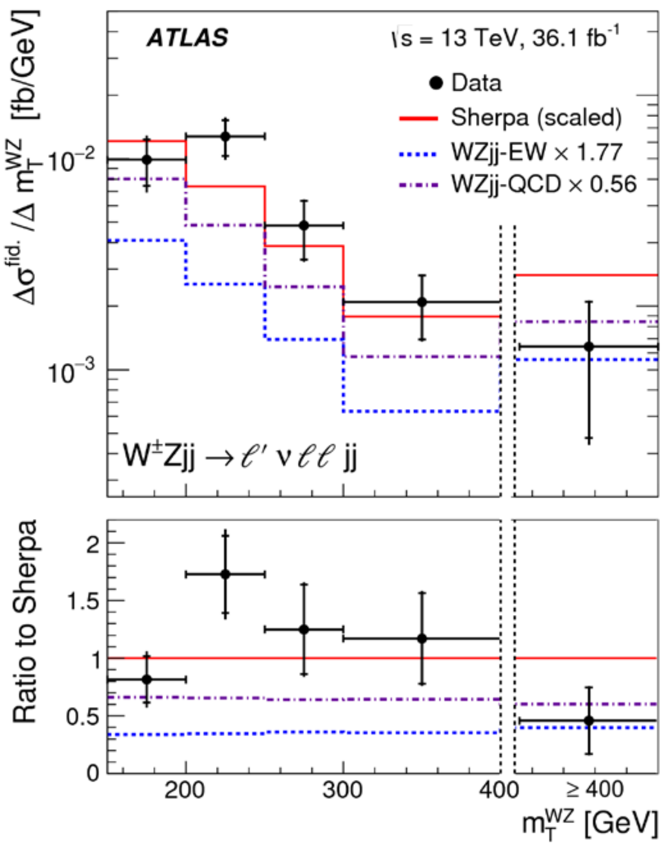
ZZjj



CERN-LPCC-2018-03

VBS – Systematics

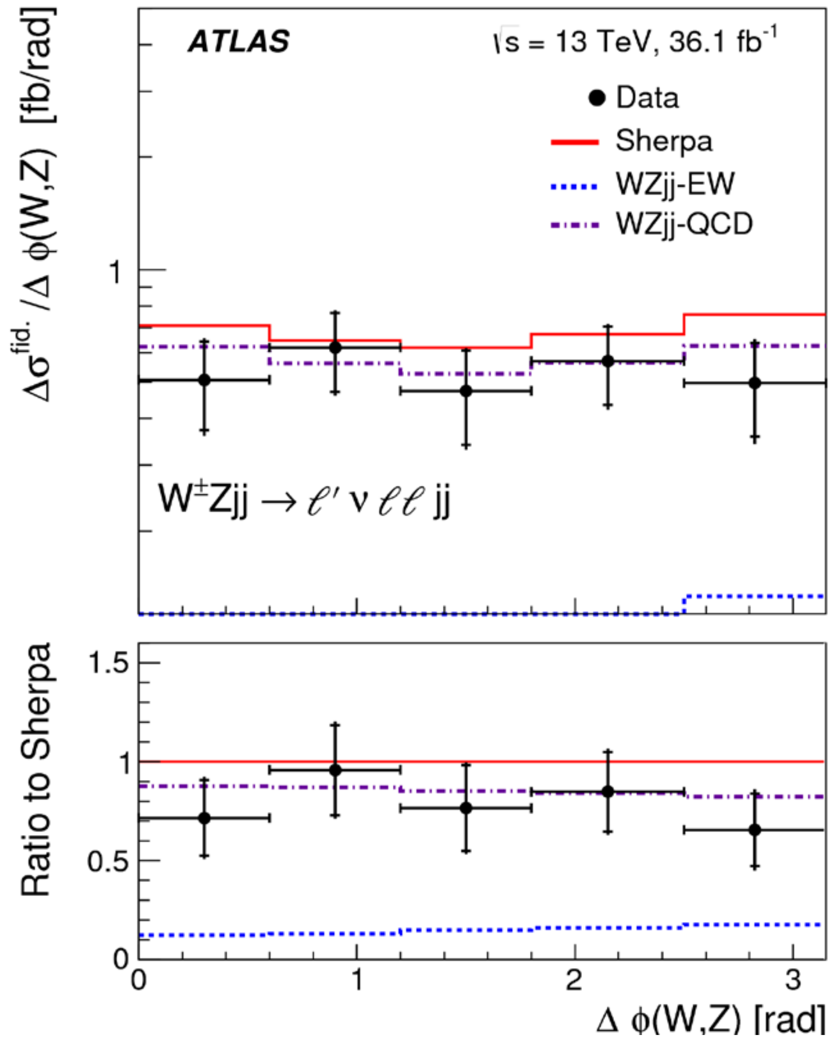
Systematic on M_TWZ
(potential variable for aQGC)



m_T^{WZ} [GeV]	150 – 200	200 – 250	250 – 300	300 – 400	≥ 400
$\Delta\sigma^{\text{fid.}}_{W^\pm Zjj}$ [fb]	0.49	0.64	0.24	0.21	0.06
Relative Uncertainties [%]					
Statistics	24.7	19.3	31.0	33.6	63.1
All systematics	16.9	11.8	10.6	9.9	18.4
Luminosity	2.8	2.3	2.4	2.5	3.0
Total	29.9	22.6	32.7	35.0	65.7
Uncorrelated syst.	4.2	0.7	1.0	1.4	5.6
Unfolding	5.2	9.1	6.0	2.0	8.6
Electrons	1.5	1.4	2.0	2.3	3.0
Muons	1.8	1.9	2.2	2.3	3.5
Jets	8.0	5.5	6.0	6.5	3.4
Red. Background	6.1	0.5	0.5	1.9	5.5
Irred. Background	10.6	3.0	4.3	4.6	11.9
Pileup	1.4	0.8	0.9	0.8	1.4

Δφ(W,Z)

$\Delta\phi(W,Z)$ [rad]	0.0 – 0.6	0.6 – 1.2	1.2 – 1.8	1.8 – 2.5	2.5 - 3.15
$\Delta\sigma^{\text{fid.}}_{W^\pm Zjj}$ [fb]	0.30	0.37	0.28	0.40	0.32
Relative Uncertainties [%]					
Statistics	26.6	23.8	28.3	23.7	27.9
All systematics	11.7	9.5	10.9	10.0	13.9
Luminosity	2.5	2.4	2.6	2.6	2.8
Total	29.1	25.6	30.3	25.7	31.2
Uncorrelated syst.	1.9	1.2	1.5	1.3	2.0
Unfolding	0.2	0.2	0.1	0.1	0.1
Electrons	1.6	1.4	1.5	1.5	1.6
Muons	2.1	2.0	1.9	1.8	1.9
Jets	7.4	6.5	6.0	5.2	7.1
Red. Background	4.3	2.9	2.7	2.2	4.5
Irred. Background	6.1	4.7	7.3	7.0	9.9
Pileup	2.0	0.9	0.9	0.5	0.5



Dominant systematics

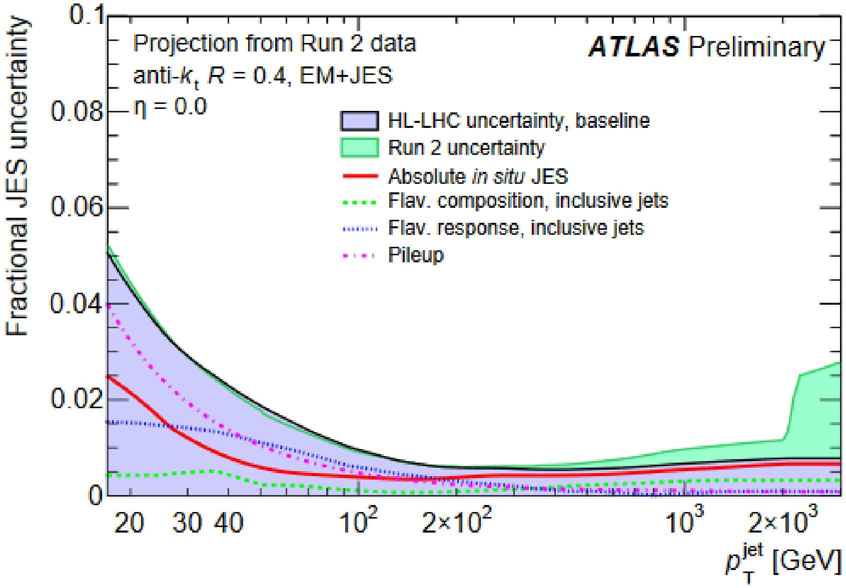
- **Th. Modelling**
  - QCD background / μR,μF (20 -30% , LO generator)
    - Controlled by CR region
    - Extrapolation under the signal region
  - Interference EW/QCD
  - EW signal
    - NLO-QCD / NLO-EW larger in the tails
- **Unfolding**
  - Depending of the distribution: ~ 5-10%
- **Pile Up**
  - Run2: <μ> = 35 to 200 but mitigating by extended tracker
  - Especially channels with a photon (wrong vertex association)
- **Jet Energy Scale**

	WZjj	ssWWjj	ZZjj
Statistic : 3000/fb			
	< 2%	1%	~4%
Current th. systematics			
EWjj	4.8%	3.1%	1-10%
QCDjj	5.2%	2.9%	10% + 10% (ggZZ)
Intf	1.9%	1.0%	
WZ		3.3%	

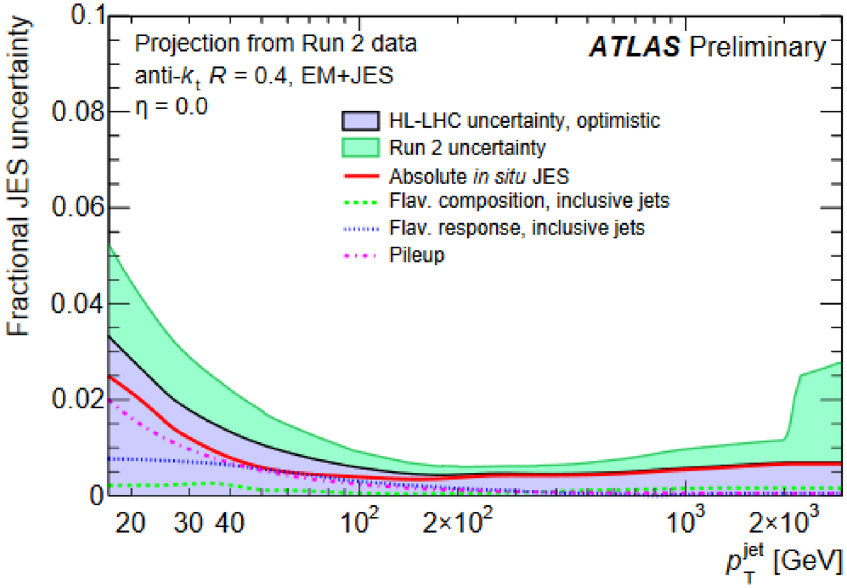
Mainly LO order event generators

Jet Energy Scale prospects

Baseline



Optimistic



ATL-PHYS-PUB-2019-005

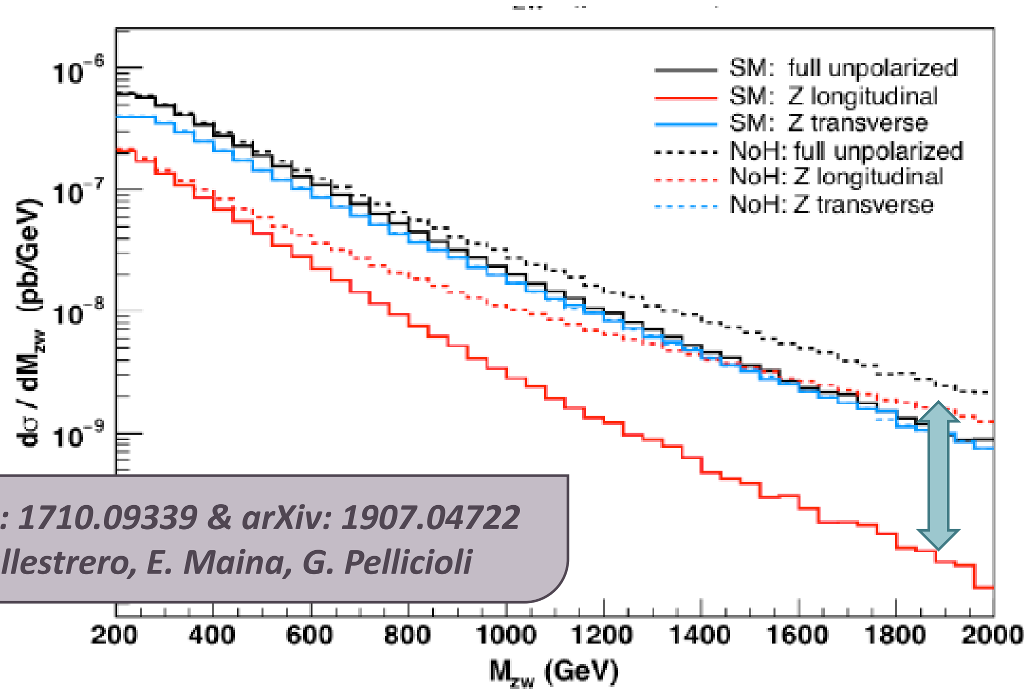
Guidance

- In the choice of variables / diff. distributions

  - Likely to be less affected by Higher Orders corrections QCD & EW

  - In conjunction with experimental systematics:
    - Unfolding
    - PU sensitivity
    - JES sensitivity

- Treatment of systematics linked to usage of MVA ?



VBS - polarized states

VxVx $\rightarrow$VxVx   Potentially 81 combinations of cross-sections

X = L,R,0

T = L+R , L/0 longitudinal

cosθ*: one of the most sensitive variable to the polarization of individual boson

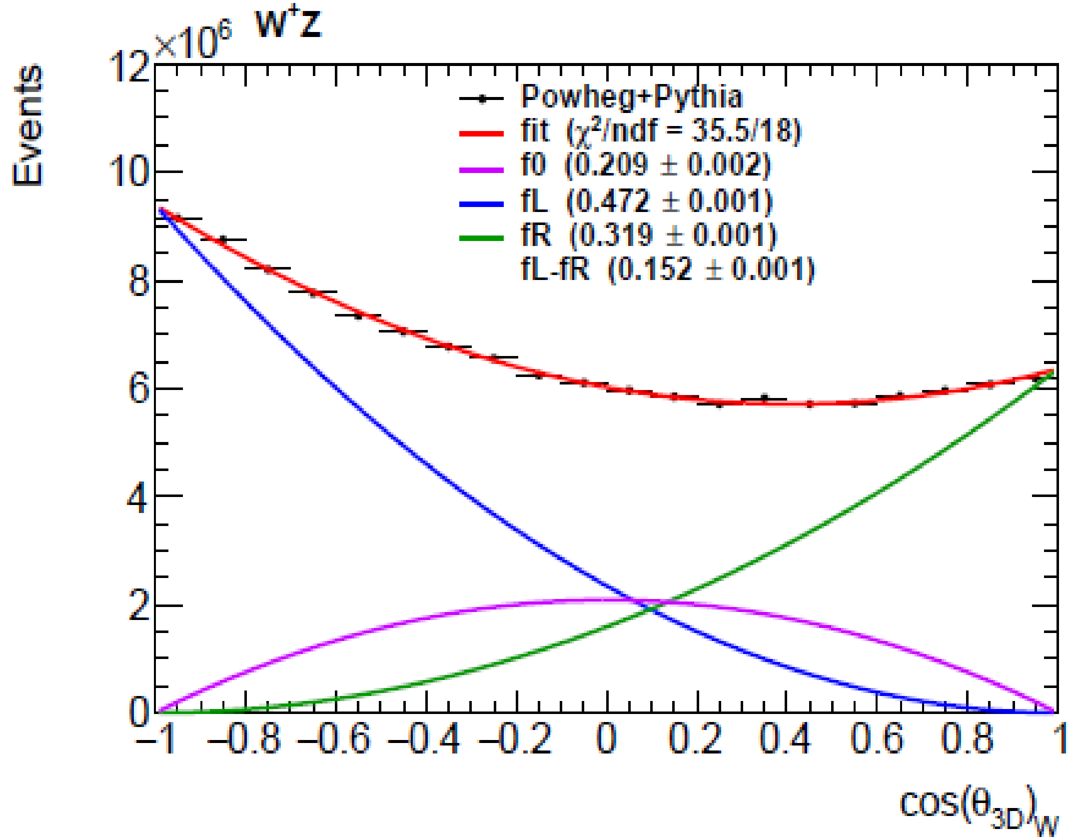
W :

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

No cut on the individual leptons , boson rest frame

Coordinate Systems :

- Collins-Soper,
- Helicity,
- Mod-Helicity

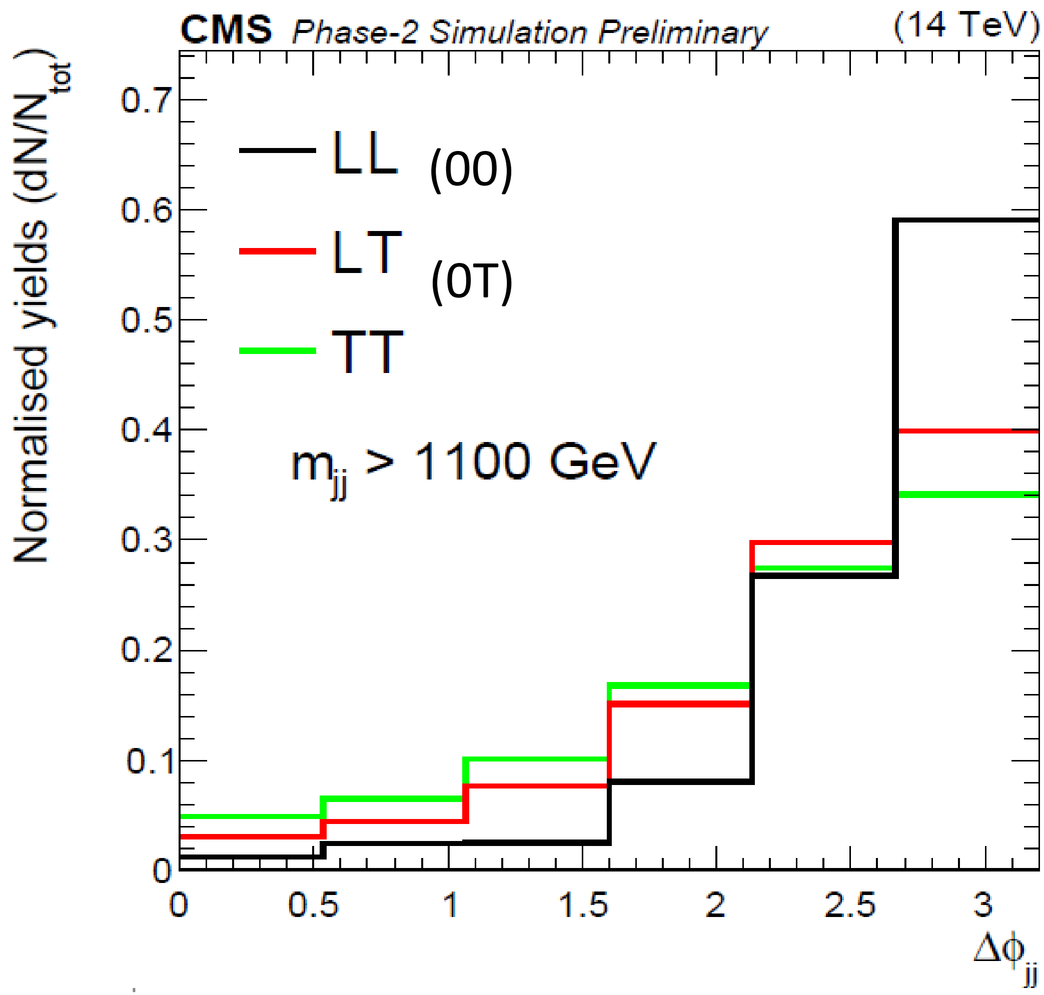


Full phase space

VBS : event variables

Sensitive to the polarization of the final state boson.

ssWWjj



Example : $\Delta\varphi_{jj}$

CERN-LPCC-2018-03
Standard Model Physics at the HL-LHC and HE-LCH

VBS : several variables mentioned in literature

Linked to the jet system

- $\Delta\varphi jj$
- $\Delta\eta jj$
- $\Delta Rjj = \sqrt{\Delta\eta jj + \Delta\varphi jj}$
- Mjj

Linked to the final state bosons

- **$\cos\theta^*$**
- η_V
- $p^T{}_V$
- $p^T{}_{lep}$
- $\Sigma p^T{}_l$

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

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

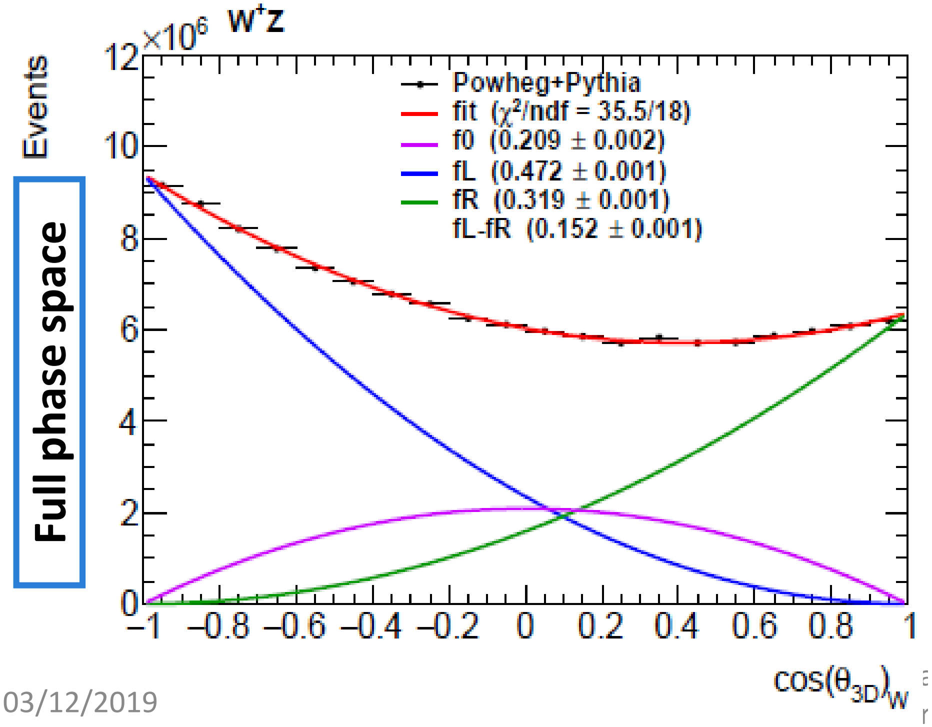
- CERN-LPCC-2018-03 Standard Model Physics at the HL-LHC and HE-LCH
- CERN-THESIS-2015-039, C. Bittrich
- *arXiv: 1710.09339 & arXiv: 1907.04722 A. Ballestrero, E. Maina, G. Pellicioli*

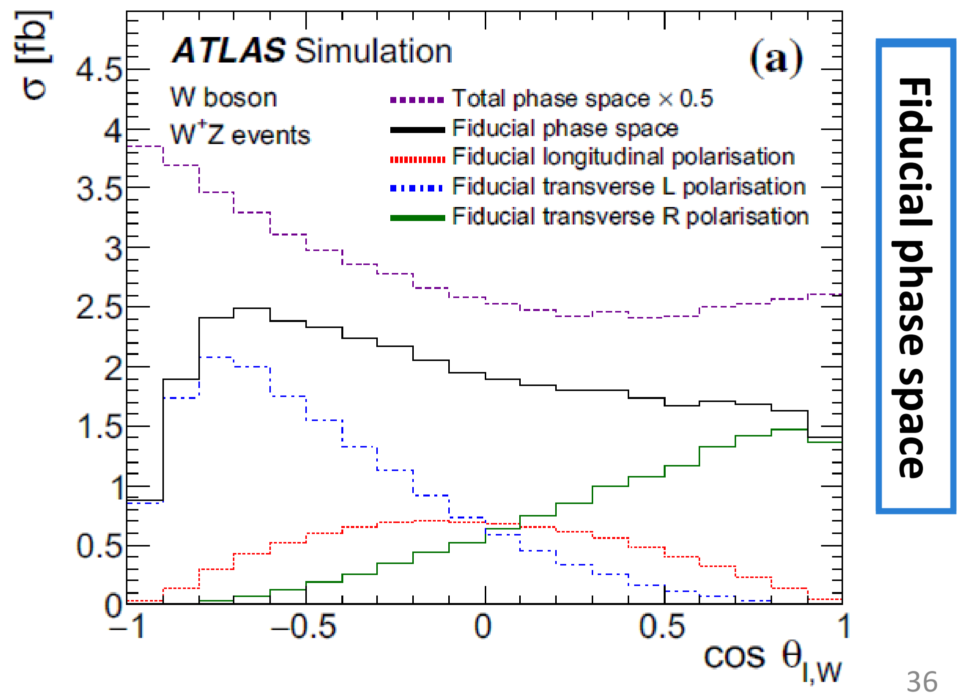
Templates : Reweighting method

CMS Collaboration, Phys. Rev. Lett. 107 (2011) 021802, [1104.3829].
ATLAS Collaboration,, Eur. Phys. J. C72 (2012) 2001, [1203.2165].

Longitudinal, Left and **Right** fractions are determined with an analytic fit in bins of pT(V) and Y_V, in total phase-space

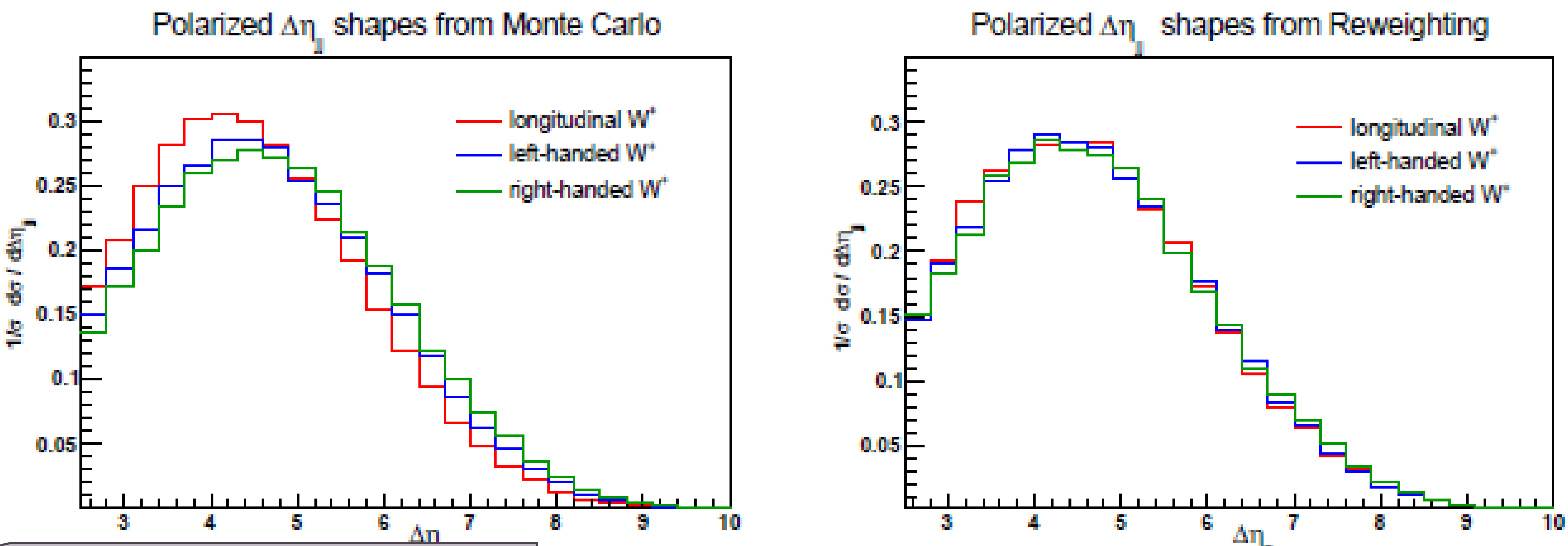
→Weights per event to create pure helicity state templates propagated to the reconstruction level in the fiducial phase space





- Fine binning & closure test
- Some effects like interference, off-shell incorporated
- Build in consistency

Drawback : cannot reweight any other variables

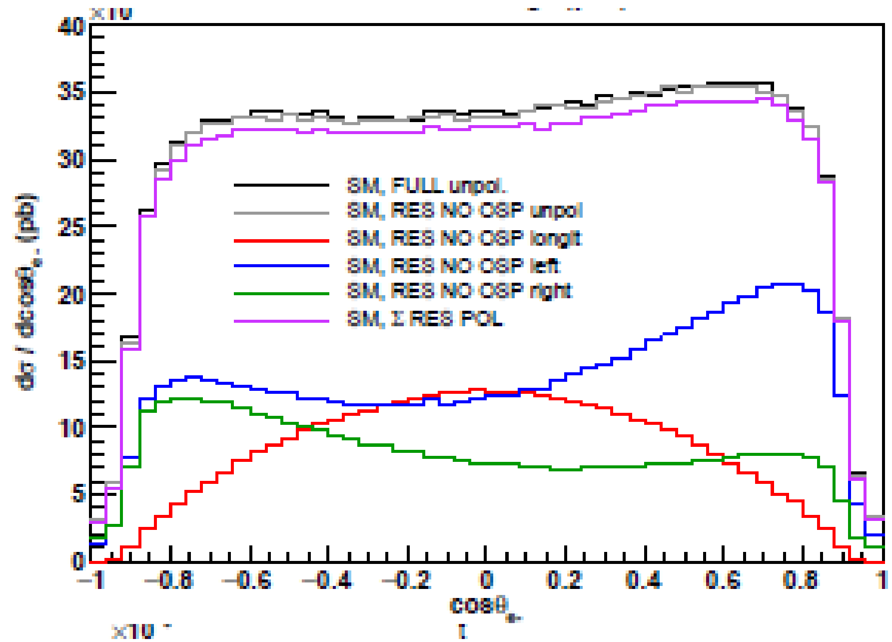


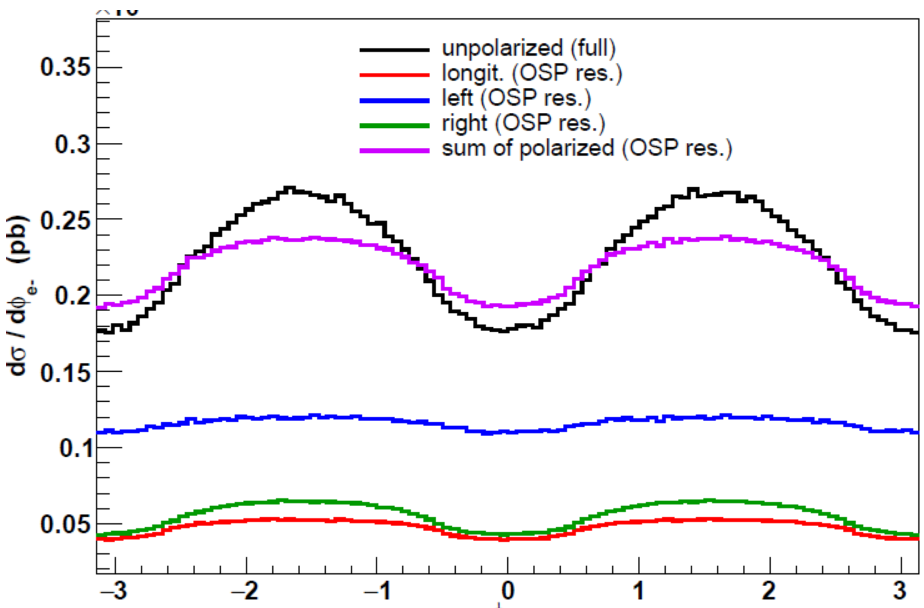
Discrepancy is lost or largely attenuated

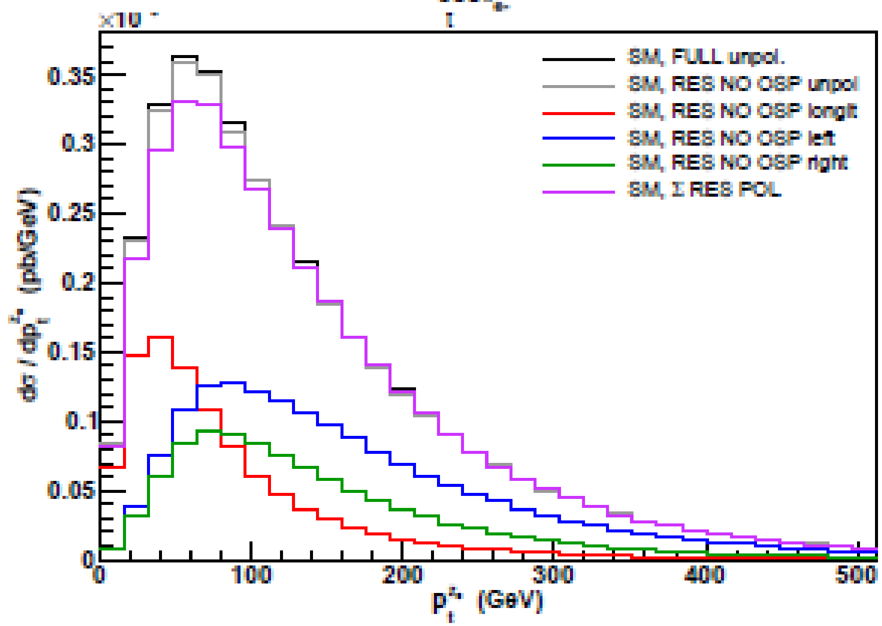
arXiv: 1710.09339 & arXiv: 1907.04722
A. Ballestrero, E. Maina, G. Pellicioli

Templates : generation of separate distributions L, R, 0

- **Phantom / Madgraph**
  - LO generation
  - INTF in presence of lepton cut
    3 states do not sum up to full
    Few % discrepancy







arXiv: 1710.09339 & arXiv: 1907.04722
A. Ballestrero, E. Maina, G. Pellicioli

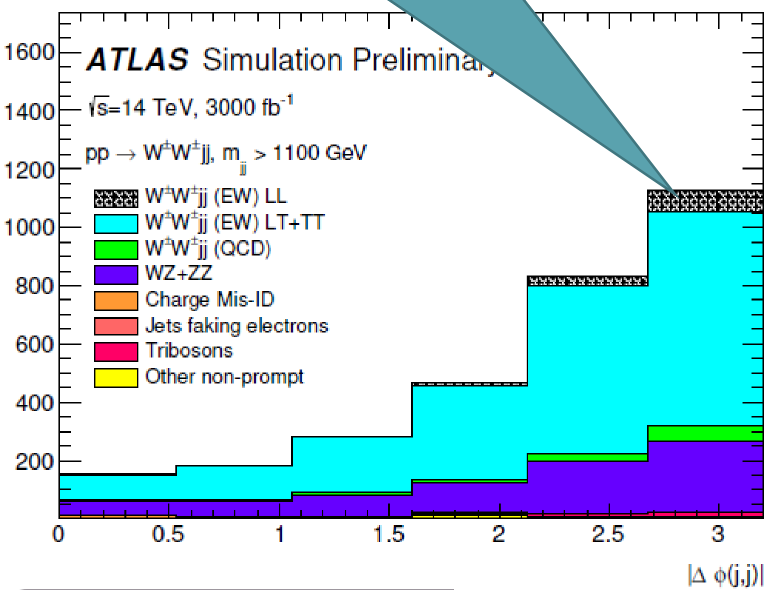
ssWWjj: $W^{\pm}W^{\pm} \rightarrow l^{\pm}l^{\pm}\nu\nu$

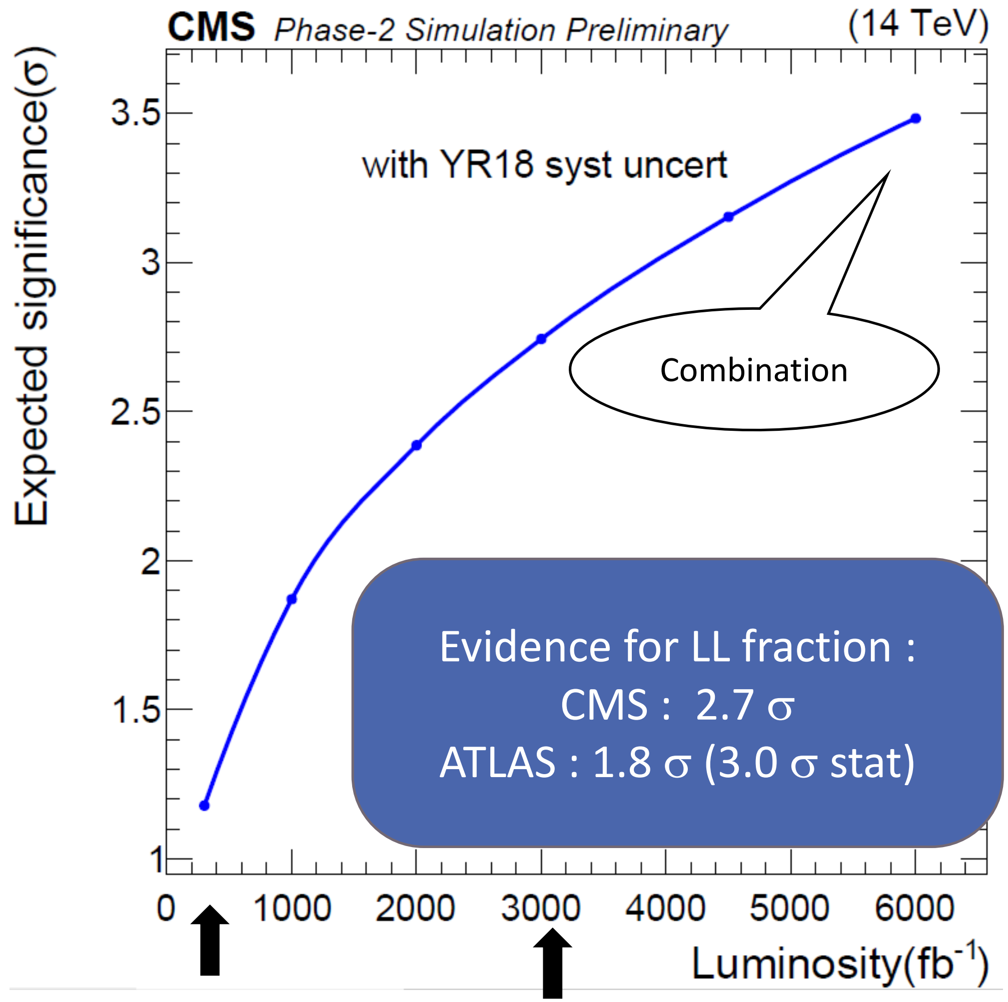
most promising channel

Helicity distributions obtained with MadGraph+DECAY

00 fraction : 6 – 7 %

00 contribution fitted
0T + TT fixed



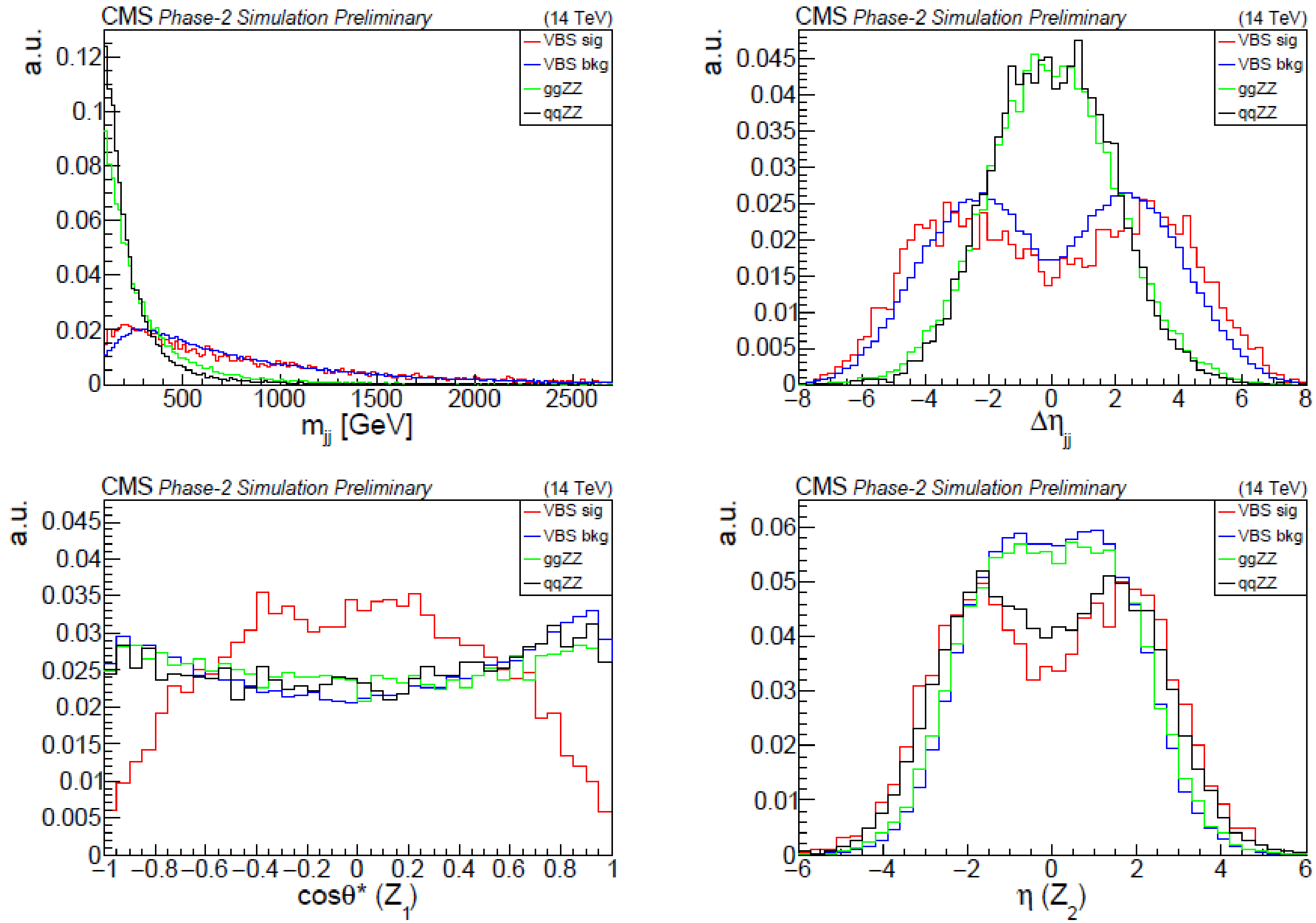


Evidence for LL fraction :
CMS : 2.7 σ
ATLAS : 1.8 σ (3.0 σ stat)

CERN-LPCC-2018-03

ZZjj: ZZ → 4l

$Z_T Z_T$, $Z_0 Z_T$ components considered as an additional background in a BDT with added variables



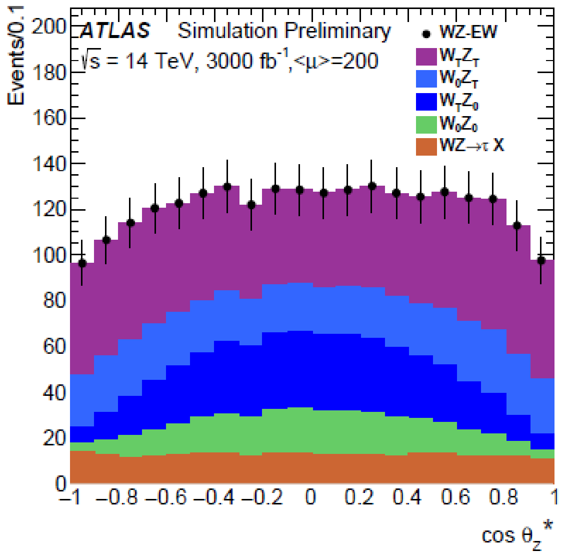
CERN-LPCC-2018-03

e (μ) acceptance

η coverage	significance
$\|\eta\| < 2.5(2.4)$	1.22σ
$\|\eta\| < 3.0(2.8)$	1.38σ
$\|\eta\| < 4.0(2.8)$	1.43σ

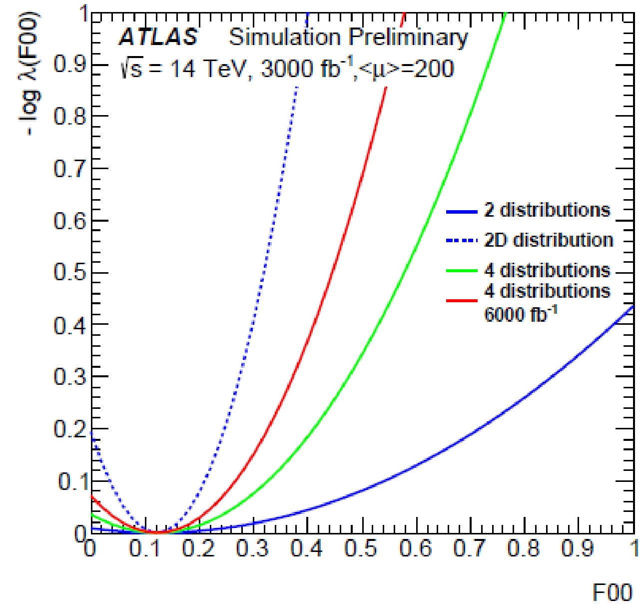
Fit of all contributions : more problematic

ATL-PHYS-PUB-2018-023

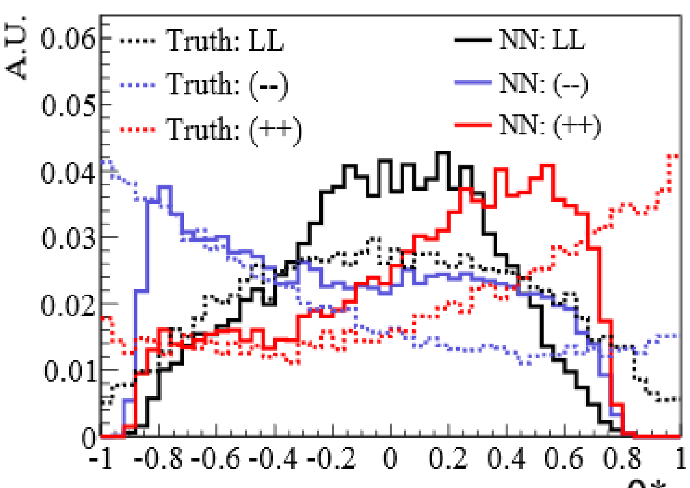


WZjj

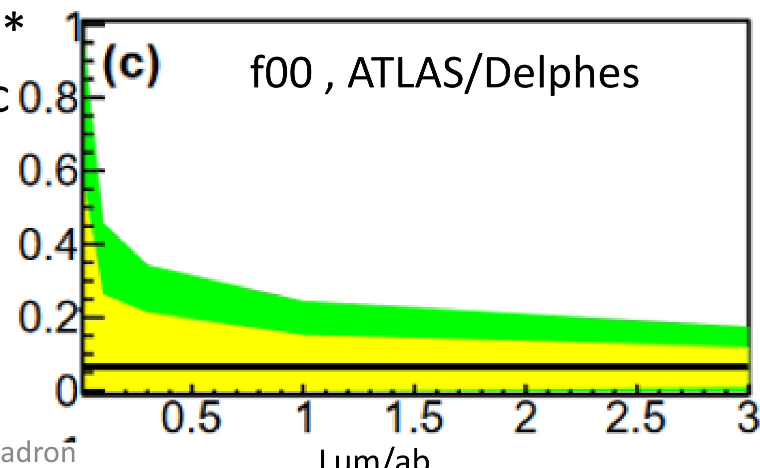
4 contributions :
TT , T0 & 0T , 00
(+ τ bkg only)



ssWWjj

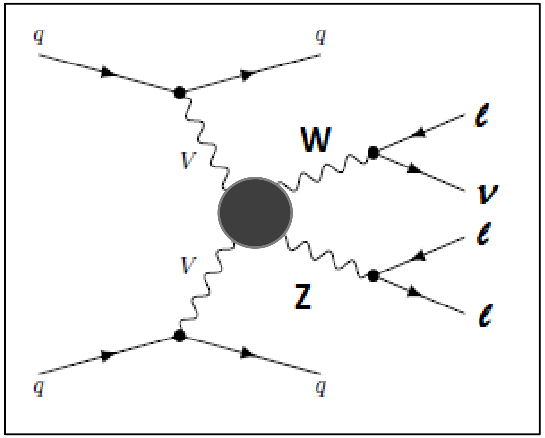


- Regression NN to approximate cosθ* from 14 kinematic variables .
- 3 components : TT, 00,0T
- 2D



arXiv:1510.01691 J Searcy et al

Observations



- Studies on VV $\rightarrow V_{L/0}V_{L/0}$
- Polarisation of initial state
  - Does jet-linked variable access instead initial state polarisation ?
  - Access to Initial state polarization in MC ?
- Exploiting semi-leptonic decays
  - tagging jet-linked variables
  - $|\cos\theta^*|$
- Polarisation
  - End of run3 (300/fb) : promising 1σ in ssWW
  - Multi-variate analysis not fully exploited

Meng Lu et al
1812.07591 /1908.05196

27 TEV : would be promising

Cross-section

X 4

process	$\sqrt{S} = 14$ TeV	$\sqrt{S} = 27$ TeV
W^+W^+jj	2.33 fb	8.65 fb
W^+W^+jj ($\lvert\Delta y_{jj}\rvert > 2.4$)	2.49 fb	9.11 fb
W^+Zjj	0.82 fb	3.16 fb
$ZZjj$	0.11 fb	0.44 fb

Fiducial phase space

aQGC :

Limits improved by a factor 5 -10

	14 TeV		27 TeV	
	$WZjj$	$W^\pm W^\pm jj$	$WZjj$	$W^\pm W^\pm jj$
f_{S_0}/Λ^4	[-8,8]	[-6,6]	[-1.5,1.5]	[-1.5,1.5]
f_{S_1}/Λ^4	[-18,18]	[-16,16]	[-3,3]	[-2.5,2.5]
f_{T_0}/Λ^4	[-0.76,0.76]	[-0.6,0.6]	[-0.04,0.04]	[-0.027,0.027]
f_{T_1}/Λ^4	[-0.50,0.50]	[-0.4,0.4]	[-0.03,0.03]	[-0.016,0.016]
f_{M_0}/Λ^4	[-3.8,3.8]	[-4.0,4.0]	[-0.5,0.5]	[-0.28,0.28]
f_{M_1}/Λ^4	[-5.0,5.0]	[-12,12]	[-0.8,0.8]	[-0.90,0.90]

Polarisation

NB 1 param fit

	significance		VBS $Z_L Z_L$ fraction uncertainty (%)	
	w/ syst. uncert.	w/o syst. uncert.	w/ syst. uncert.	w/o syst. uncert.)
HL-LHC	1.4σ	1.4σ	75%	75%
HE-LHC	5.2σ	5.7σ	20%	19%

CERN-LPCC-2018-03

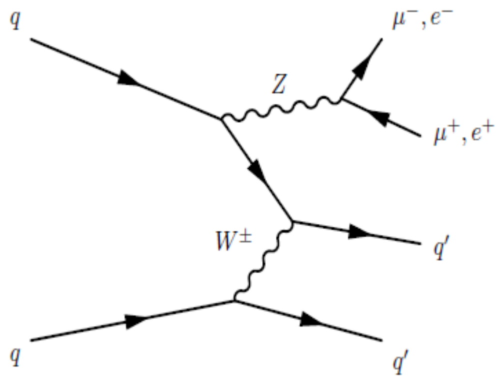
Conclusion

- VBF Z & W
  - Will be well measured at the end of Run3
  - aTGC limits complementary to those with inclusive VV
- VBS will enter an interesting phase with HL-LHC
  - Tot cross-section : few %
  - Polarization V_0V_0 : 1-3 σ/ exp
  - Polarisation not useful for aTGC
    - Lep heritage: only for CP violating parameter
    - for aQGC ?
- Benefice of combination CMS/ATLAS
  - Experimental syst (JES) not correlated
- But th. modelling is a concern

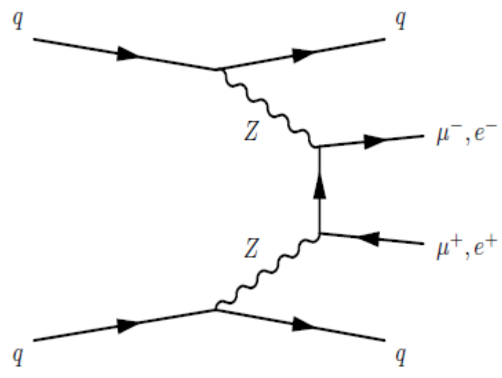
BACKUP

Other EW diagrams partly included in the signal

Resonant, irreducible



Non resonant



aTGC

Change of paradigm from LEP & Run I description

Phenomenological lagrangian

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

Effective field theory description

Low energy theory

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

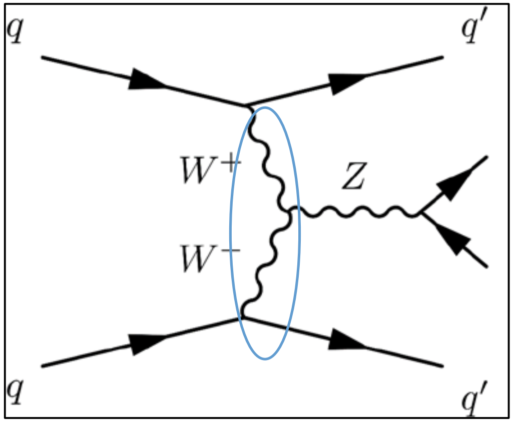
aTGC

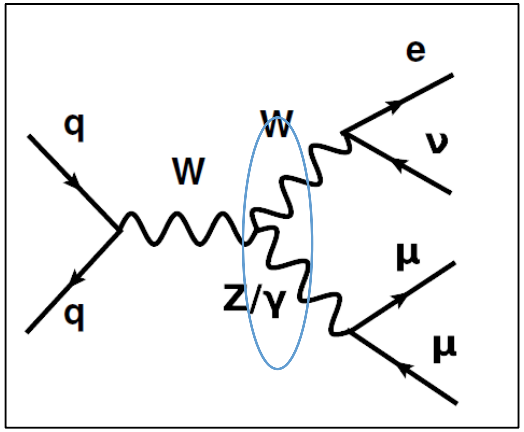
nTGC
aQGC

H Milder @ MBI
R Aggleton @ MBI

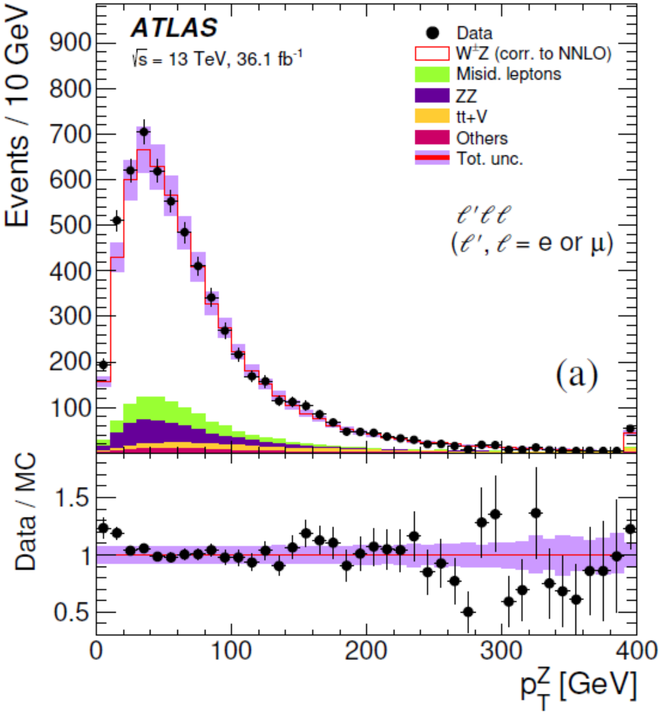
aTGC via Inclusive Production

Off Shell : potentially large q2



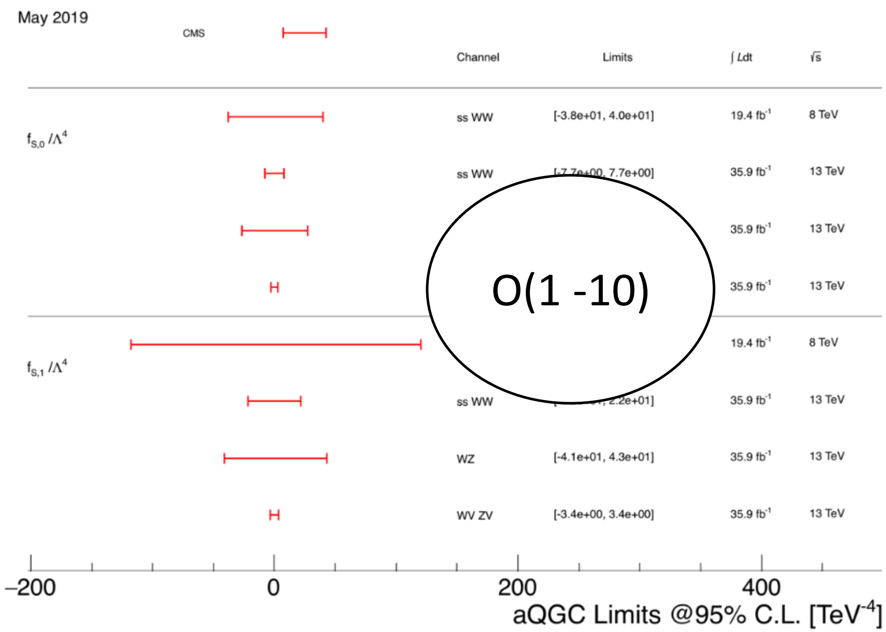


On Shell : smaller q2



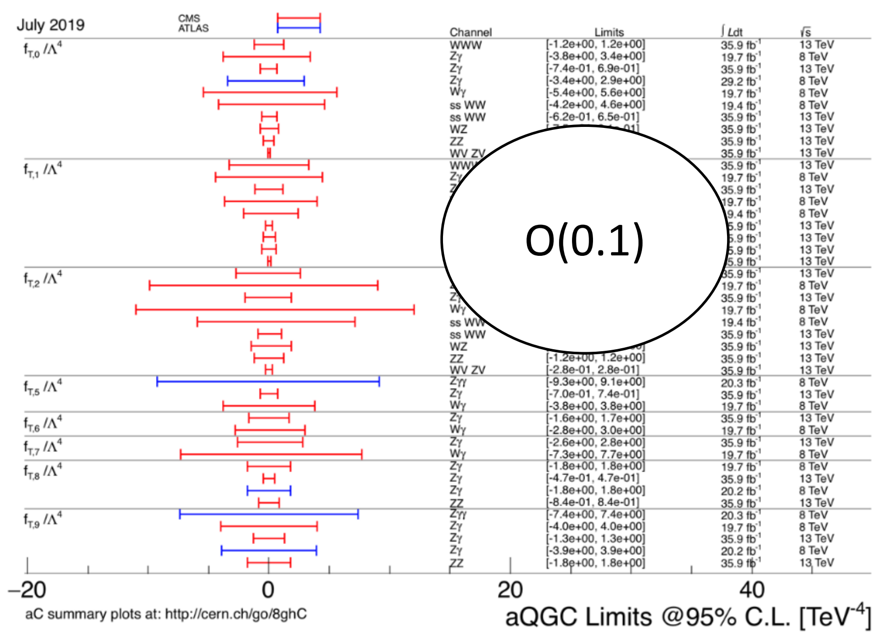
End point : ~ ½ TeV

RED is CMS ; BLUE is ATLAS



S parameters

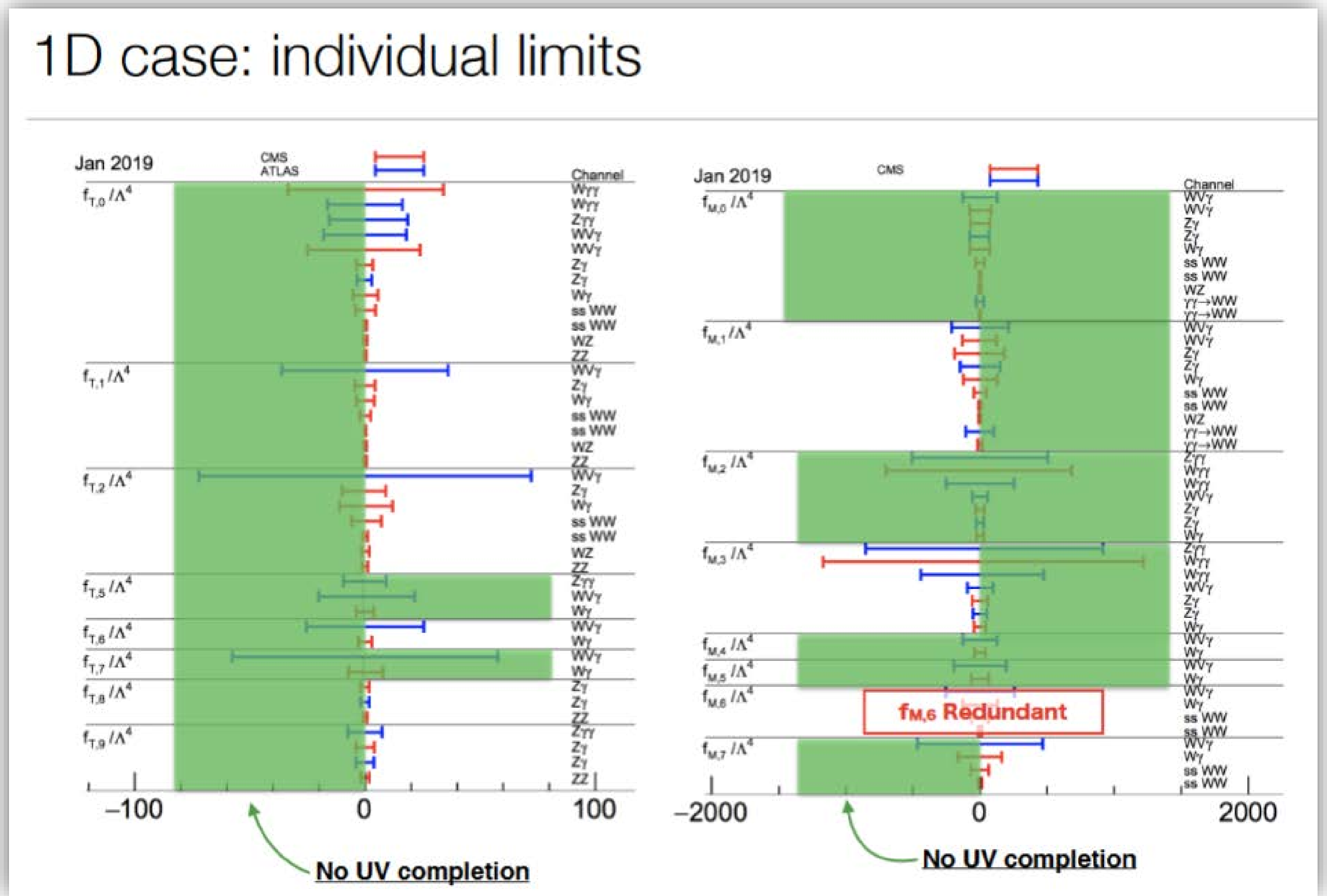
T parameters



Positivity

C. Zhang, MBI, 2019

Not used yet !



Evolution of the experimental conditions

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

To cope with

Data rates

Detector occupation

And to maintain:

Trigger performance

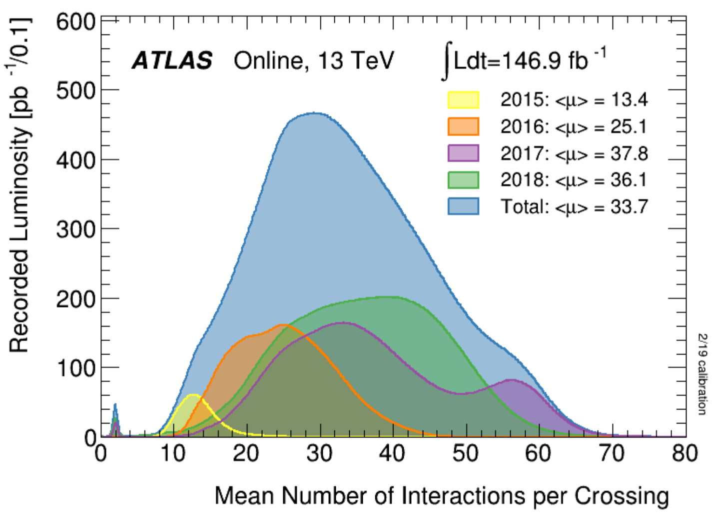
Pile-Up jet rejection

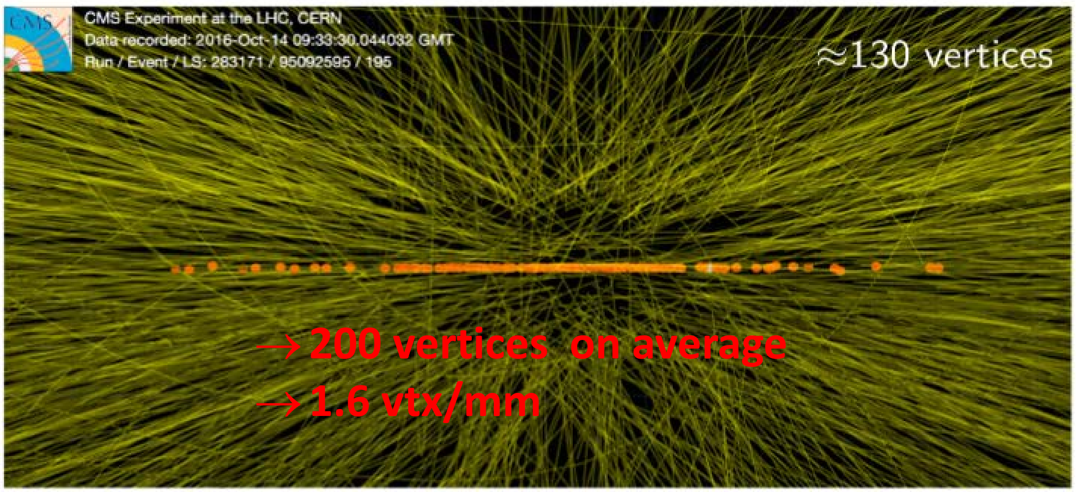
Object performance

⇒ Upgrade of detectors

Hardness

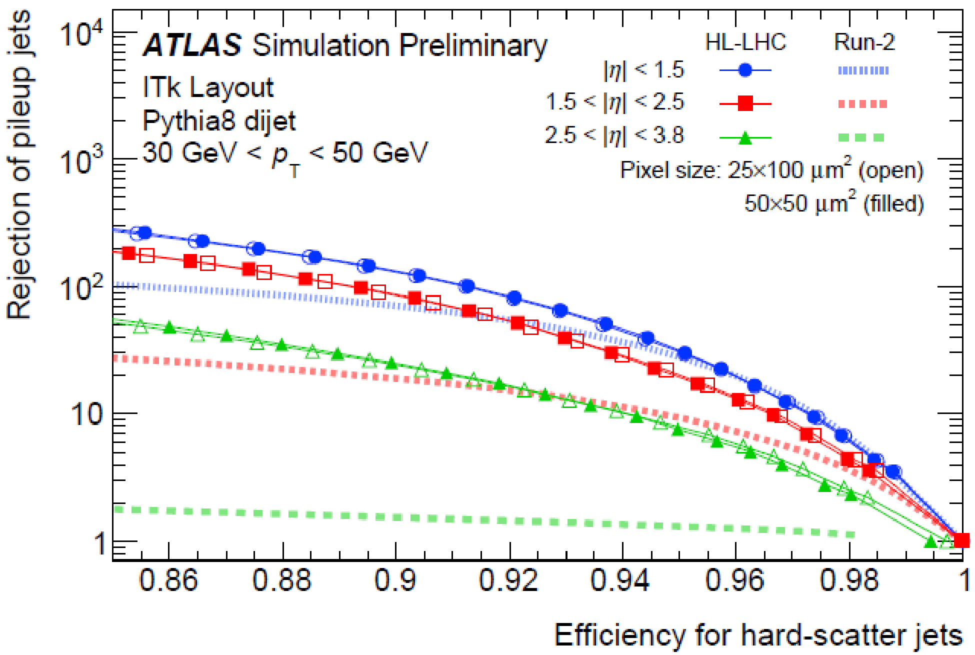
Granularity



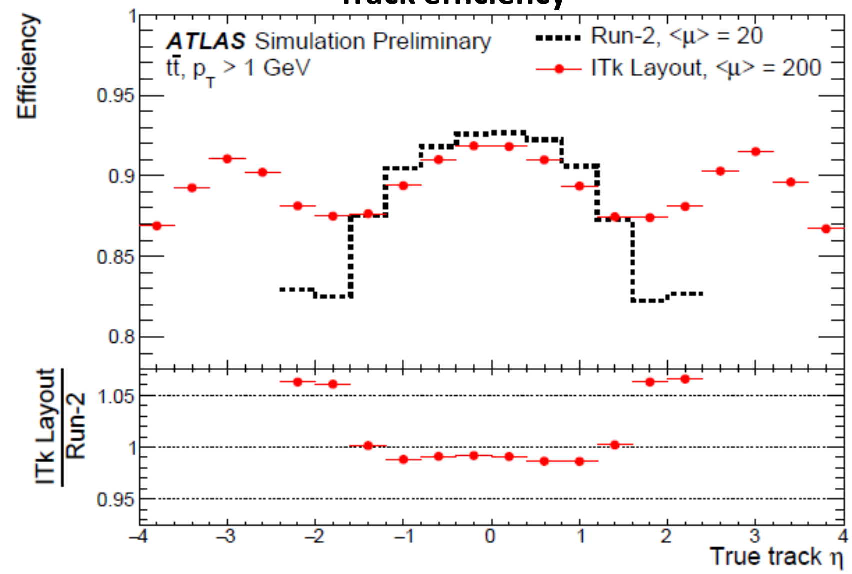


Tracking up to |η | < 4

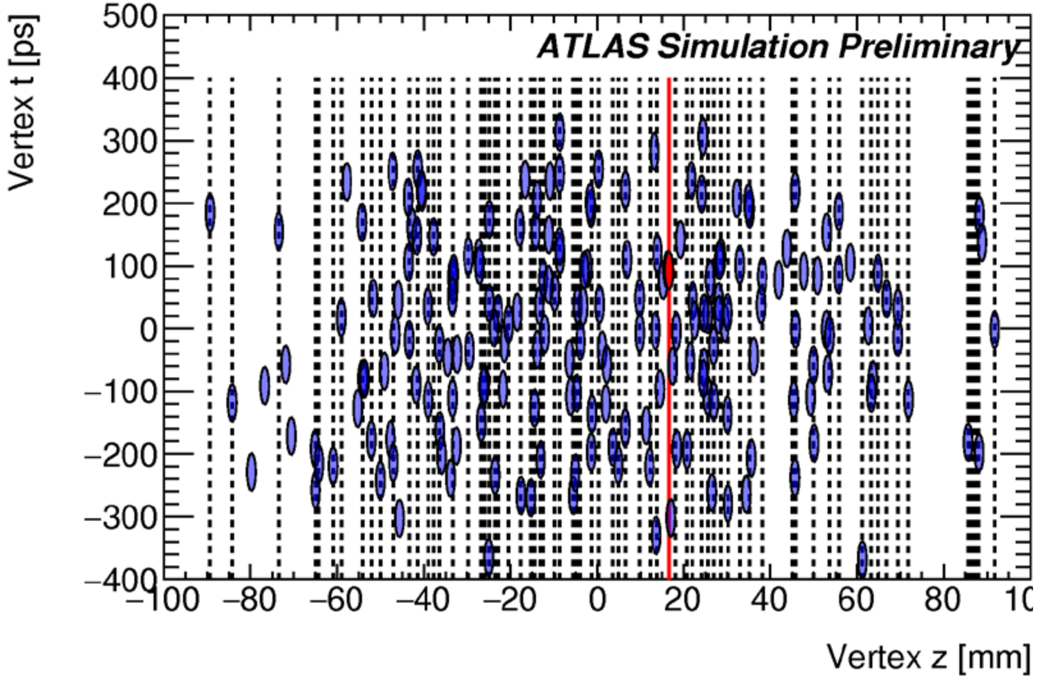
Pile Up rejection



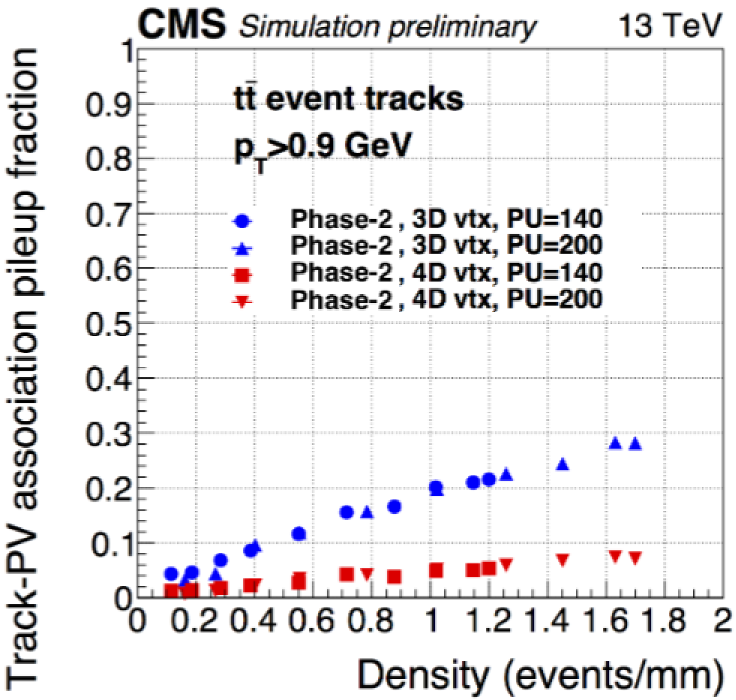
Track efficiency



Timing detector : a new dimension



ATLAS : 2.4 < |η | < 4.



CMS : 0 < |η | < 3.

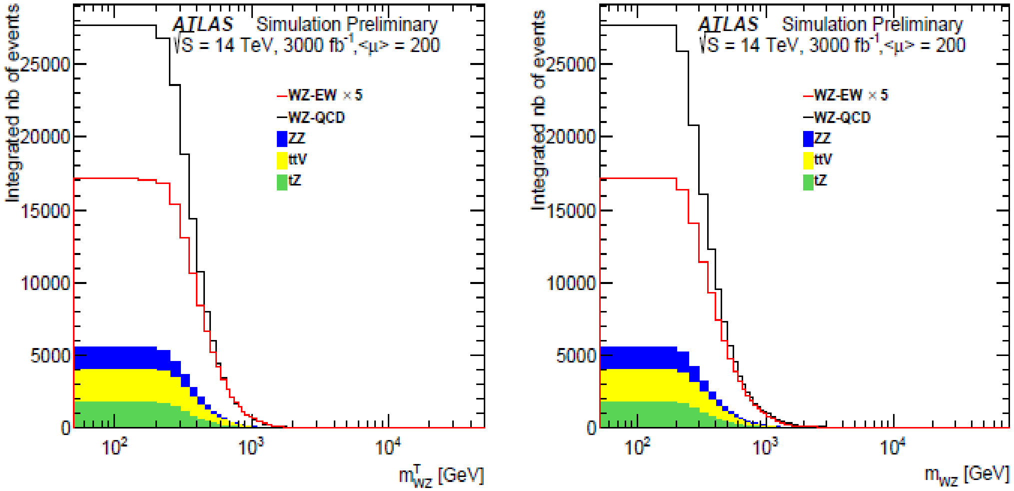
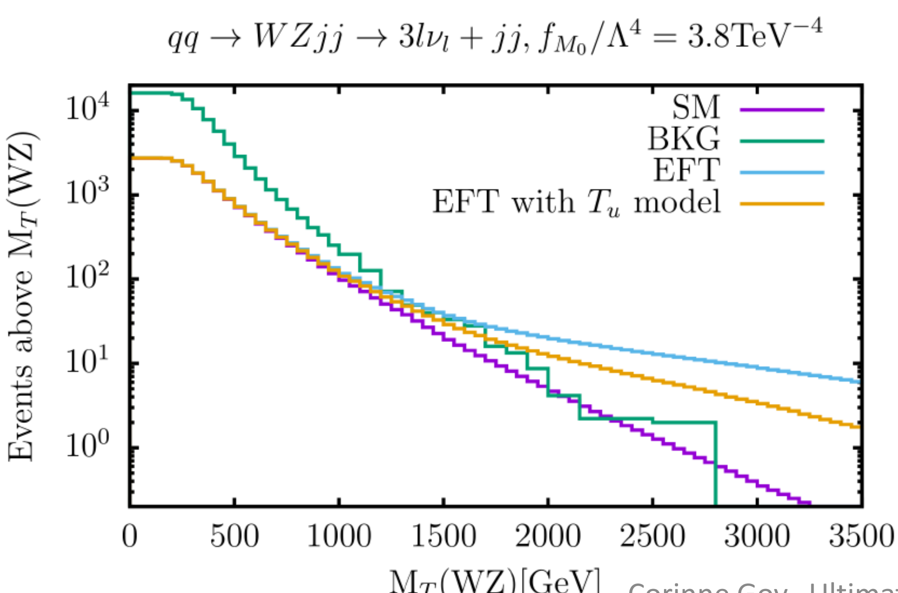
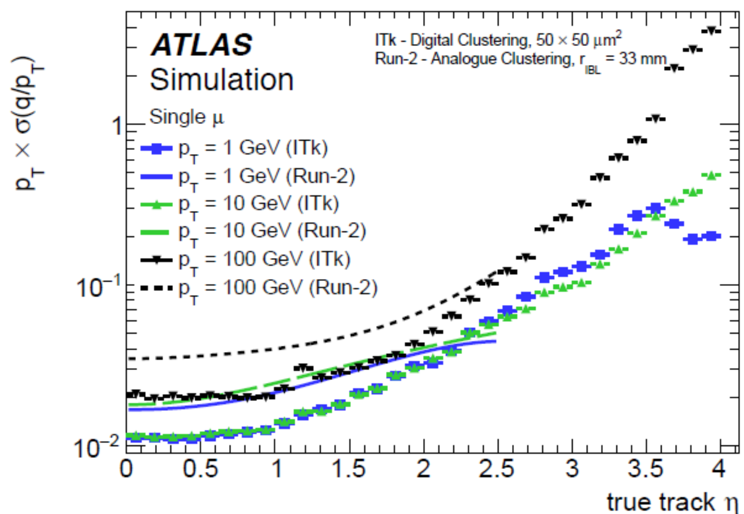


Figure 27: Left: Integrated number of events above m^T_{WZ} cut vs m^T_{WZ} cut. Right: Integrated number of events above m_{WZ} cut vs m_{WZ} cut.

Rapport jaune ,
Figure de Zeppenfeld

Experimental effects
Resolution tracks ….





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 simulati
  - The effect of the high pileup at the HL-LHC is incorporated by overlaying pileup jets onto the hard-scatter events with 2% efficiency

ATLAS

- Fast simulation using DELPHES
- Extrapolation from Run2 results
  - Scale of cross-sections
  - Scale of acceptance for leptons
  - Object performance using DELPHES

CMS

ssWWjj: $W^{\pm}W^{\pm} \rightarrow \ell^{\pm}\ell^{\pm}\nu\nu$

- **CMS** : full simulation

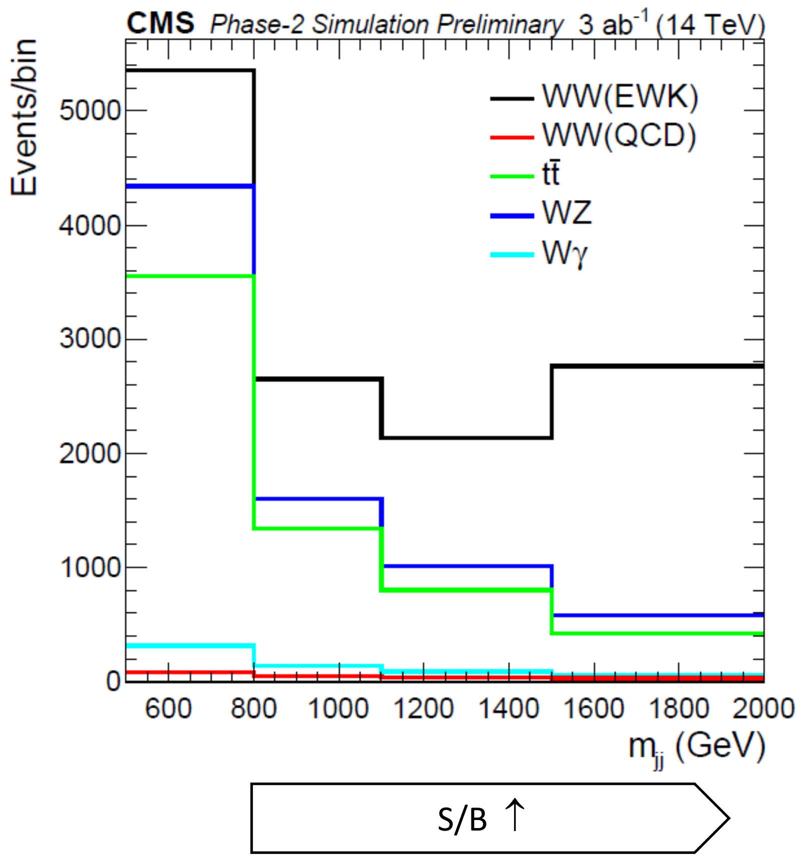
(except for jets at large eta)

and a cut-based selection

- **ATLAS** : parametric simulation

and a cut-based selection

- Main background is not QCD



WZjj: WZ→3ℓν

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 2σ.)
- 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
Zγ	–	296

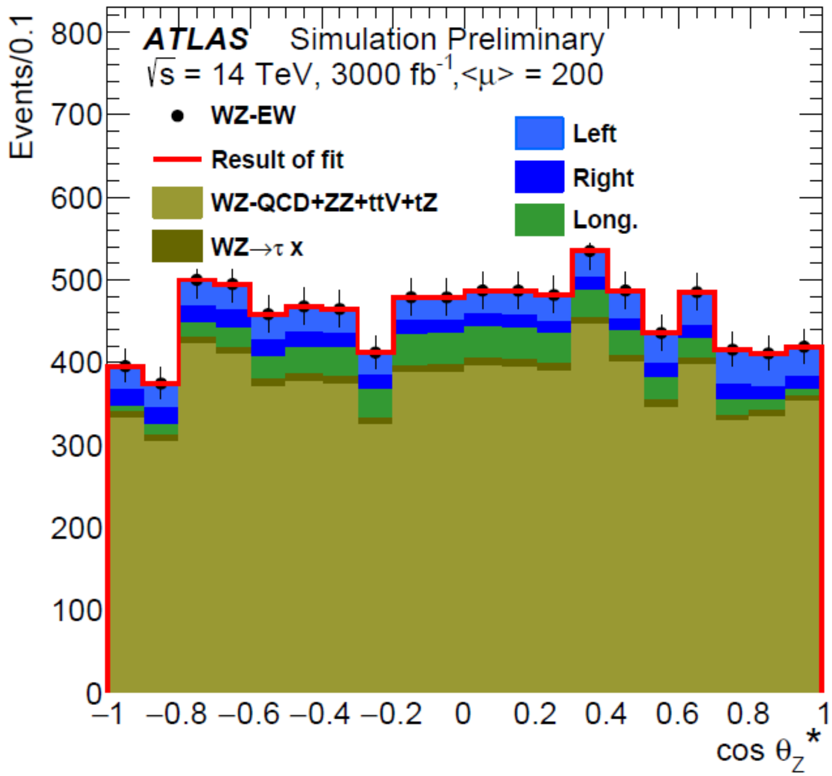
CMS

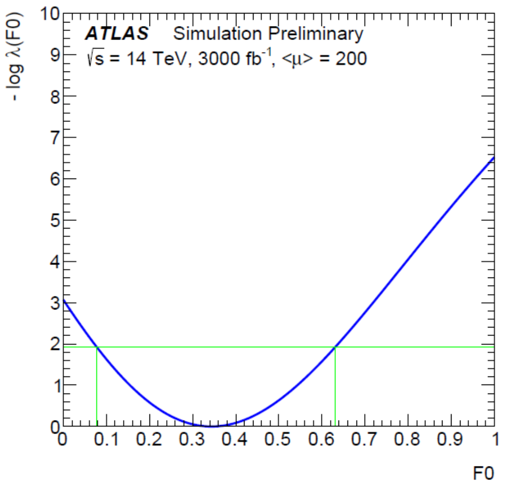
- Extrapolation from the Run 2 (2.2 σ)
- Tight selection

- S/B = 0.41

- WZ-QCD main background, but not as dominant

WZ→3ℓν : polarization of the individual boson W or Z



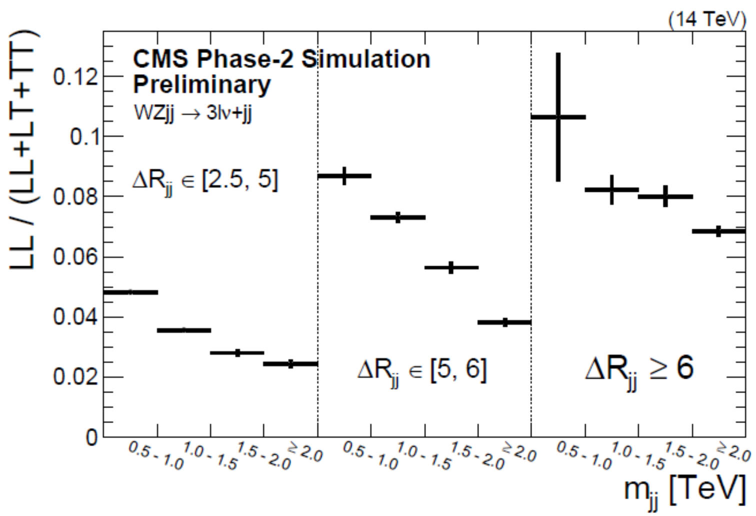


3 parameters : Nsig, F0, FL-FR
Using 3 templates and bkg normalisation
Syst on background normalization : 20 - 2.5 %

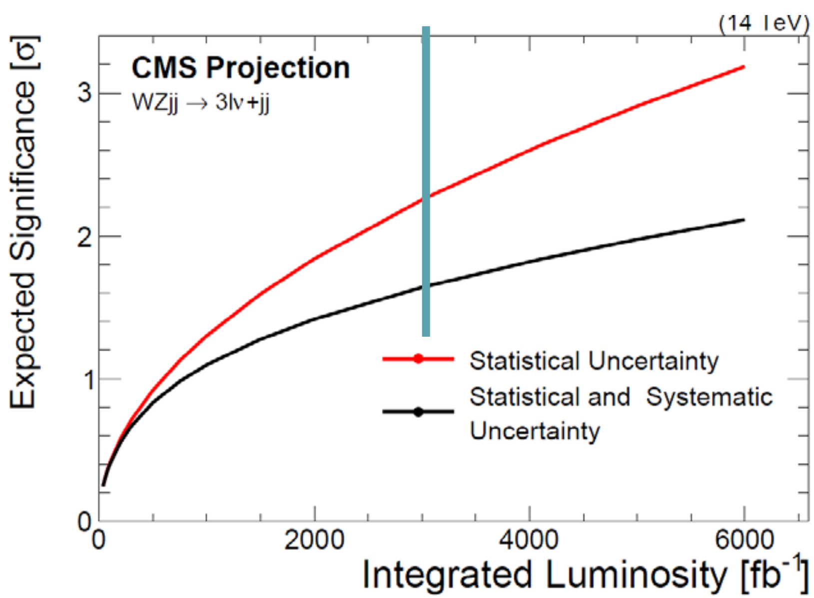
Simultaneous fit of 4 independent channels not exploited : eeμ, μμe, …

WZ→3ℓν : LL fraction

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



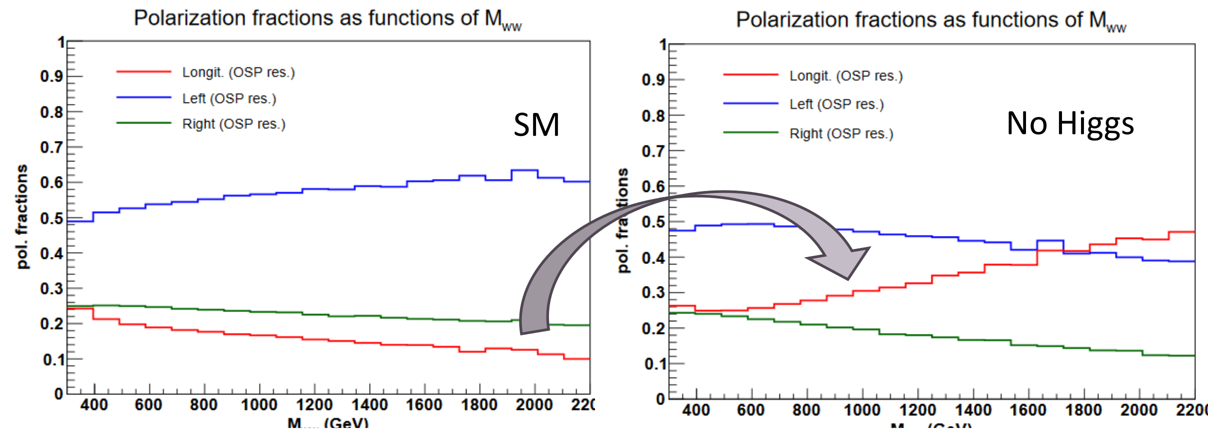
L : longitudinal/0
T : transverse (Left + Right)



LL contribution extracted alone
TT & LT considered as a fixed additional background in the Mjj vs Rjj plane

No HIGGS ! Extreme case

WWjj



(b) P

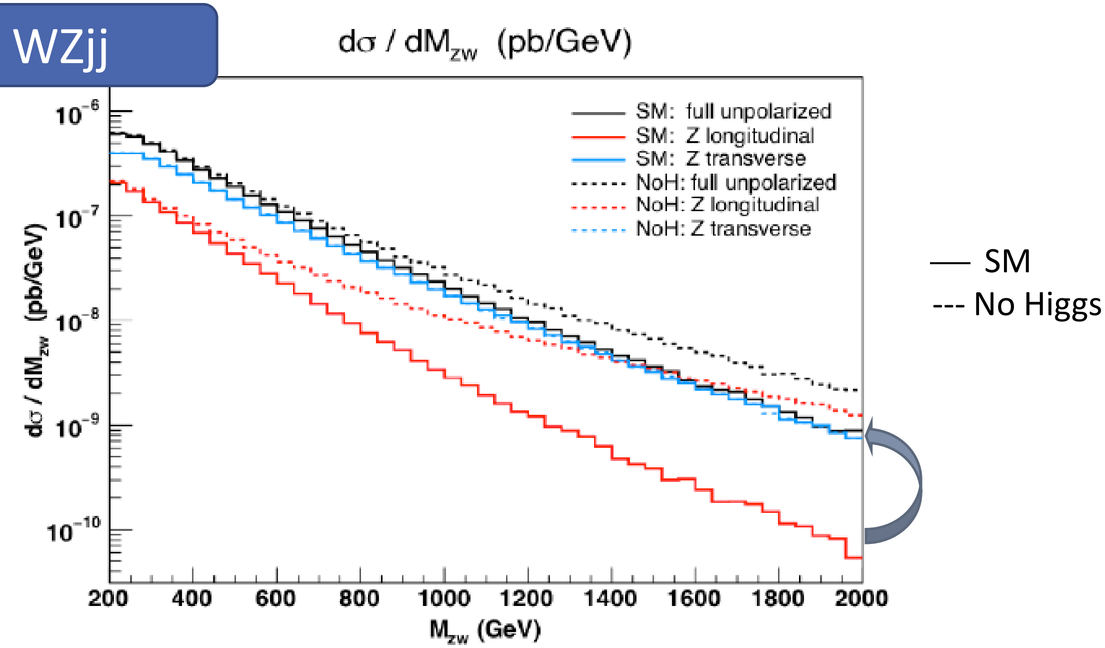
Polarizations fraction

Sensitivity to EWSB

Effect enhanced in considering only the longitudinal production

$V_L V_L \rightarrow V_L V_L$

WZjj



arXiv: 1710.09339 & arXiv: 1907.04722
A. Ballestrero, E. Maina, G. Pellicioli

Alternative method on the same line

$$\frac{d\sigma}{\sigma d\cos\theta d\phi} = \frac{3}{16\pi}\Big[(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin(2\theta)\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos(2\phi) + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin(2\phi) + A_6\sin(2\theta)\sin\phi + A_7\sin\theta\sin\phi\Big],$$

Ai coefficients can be calculated as expectation values of trigonometric functions :

- $A0 = 4 - \langle 10\cos 2\theta \rangle$ & $A4 = \langle 4\cos\theta \rangle$

And the polarization fractions expressed as :

$$f_L^{W^\pm} = \frac{1}{4}(2 - A_0^{W^\pm} \mp A_4^{W^\pm}),\ f_R^{W^\pm} = \frac{1}{4}(2 - A_0^{W^\pm} \pm A_4^{W^\pm}),\ f_0^{W^\pm} = \frac{1}{2}A_0^{W^\pm},$$
$$f_L^Z = \frac{1}{4}(2 - A_0^Z + \frac{1}{c}A_4^Z),\ f_R^Z = \frac{1}{4}(2 - A_0^Z - \frac{1}{c}A_4^Z),\ f_0^Z = \frac{1}{2}A_0^Z.$$

Computation in fiducial phase-space;

No template, borned functions

arXiv: 1810.1103
J Baglio & D.N Le

Semi-leptonic – 27 TeV

M(WWjj)
+ W-jet variables,lepton
+ Mjj

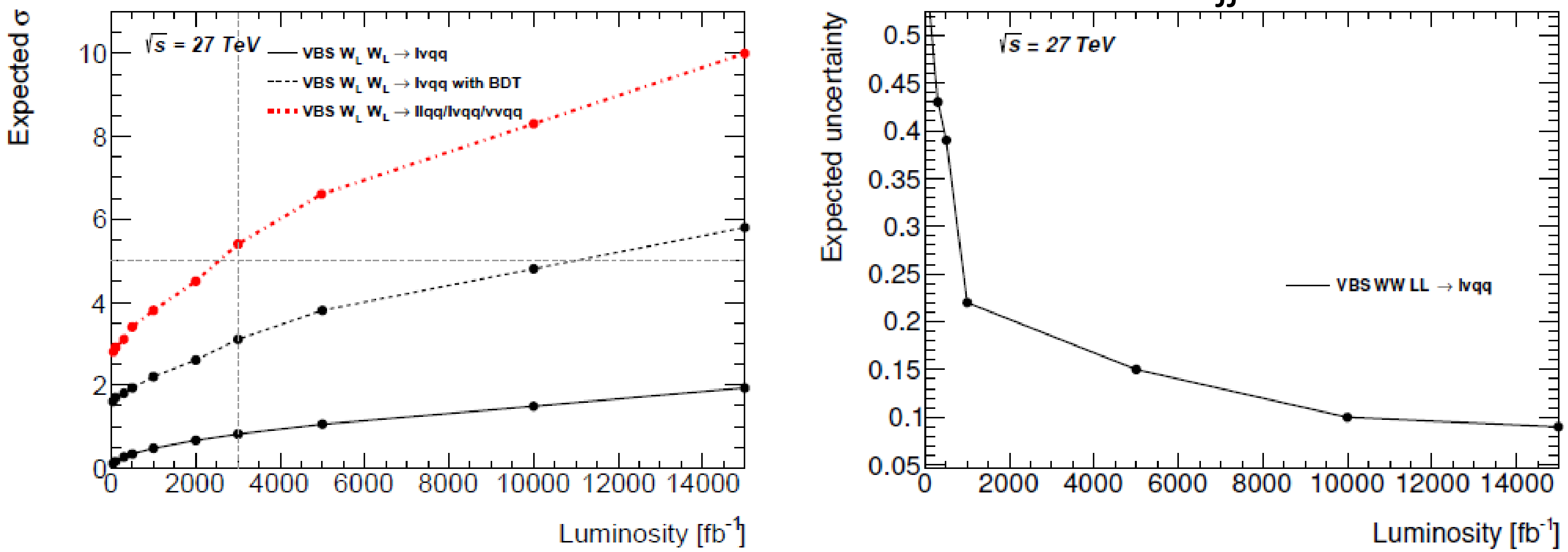


Figure 9: Observed significance as a function of integrated luminosity (left) and expected cross-section uncertainty (right) for the VBS $W_L W_L$ signal, assuming a 10% $W_L W_L$ fraction predicted by the MadGraph generator, in the $\ell\nu qq$ channel at $\sqrt{s} = 27$ TeV. The solid and dashed lines on the left shows the expected significance obtained by fitting to the total invariant mass of the VBS system and the BDT output, respectively. The dot-dashed line shows the expected significance from the combination of all the three semi-leptonic channels assumed to have sensitivity similar to the $\ell\nu qq$ channel.