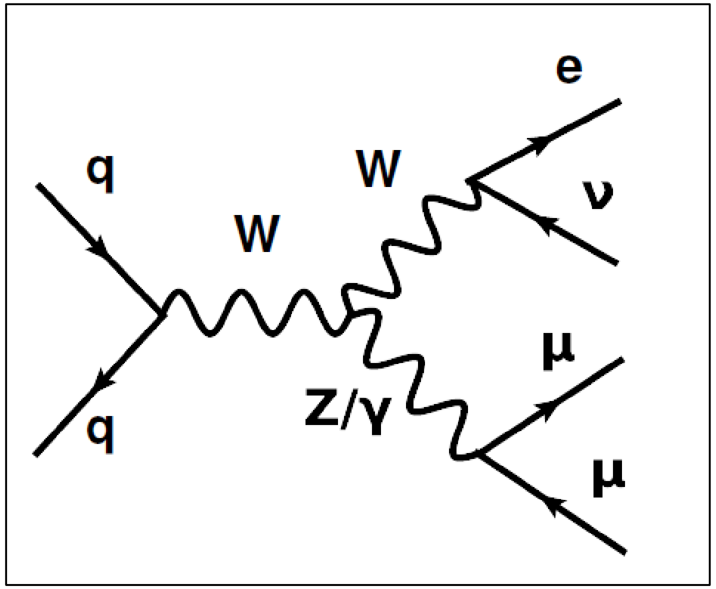
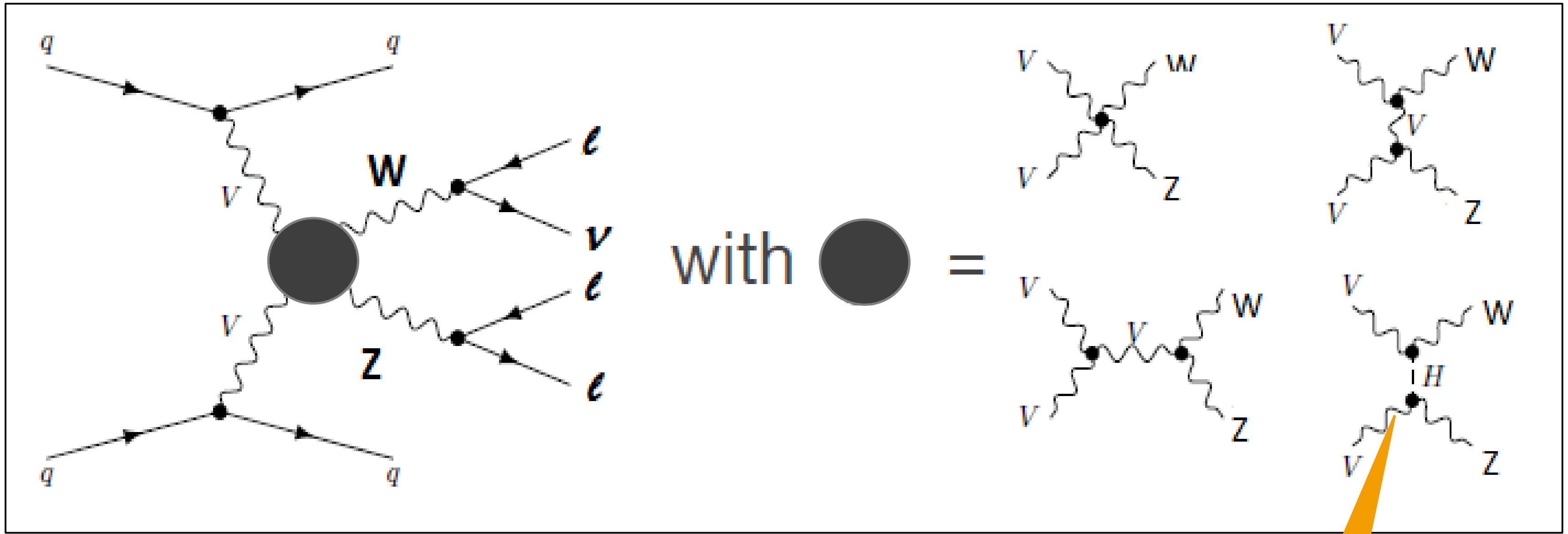
Measurements of gauge boson polarization in diboson production @LHC

Corinne Goy, LAPP, IN2P3/CNRS

Multi-boson interactions
Thessaloniki
26 – 28 August 2019

Polarization: potentially a handle to New Physics





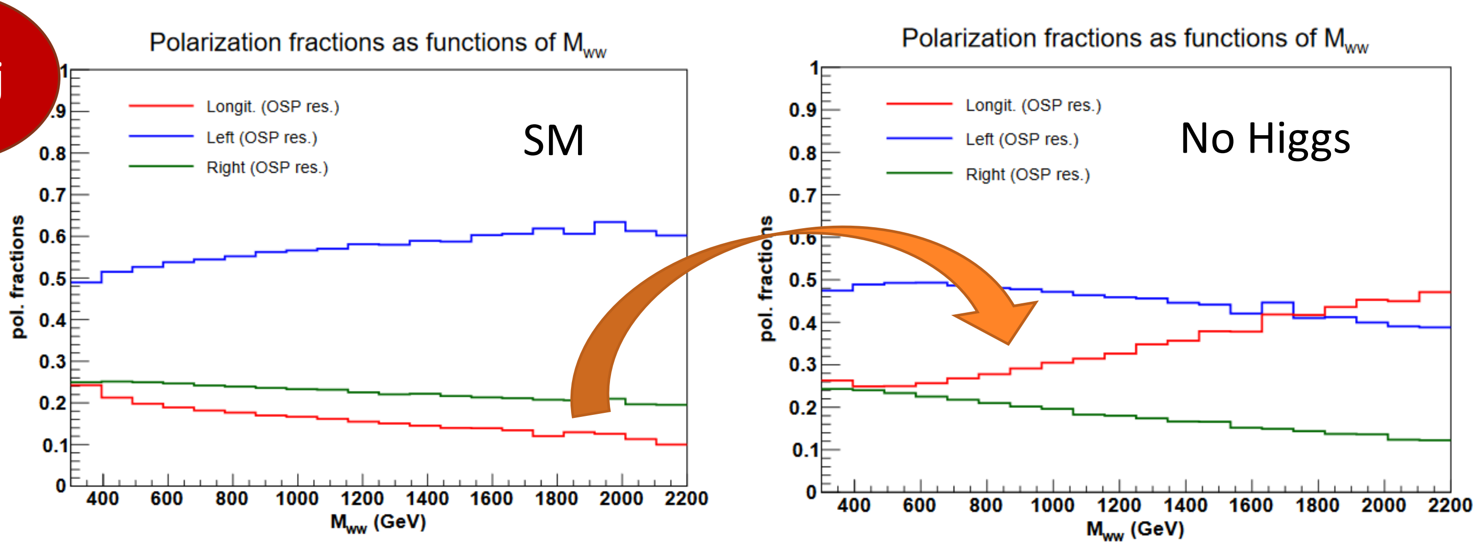
Inclusive production : VV	Vector boson scattering : VVjj
Gauge structure (aTGC)	Gauge structure (aTGC, aQCG) + EWSB mechanism
$\sigma \sim 50$ pb	$\sigma \sim 10^{-3}$ pb

+ other resonant diagrams (bkg)
+ non resonant diagram for gauge invariance

Exact ? cancellation of LL scattering

WWjj

No HIGGS !
Extreme case

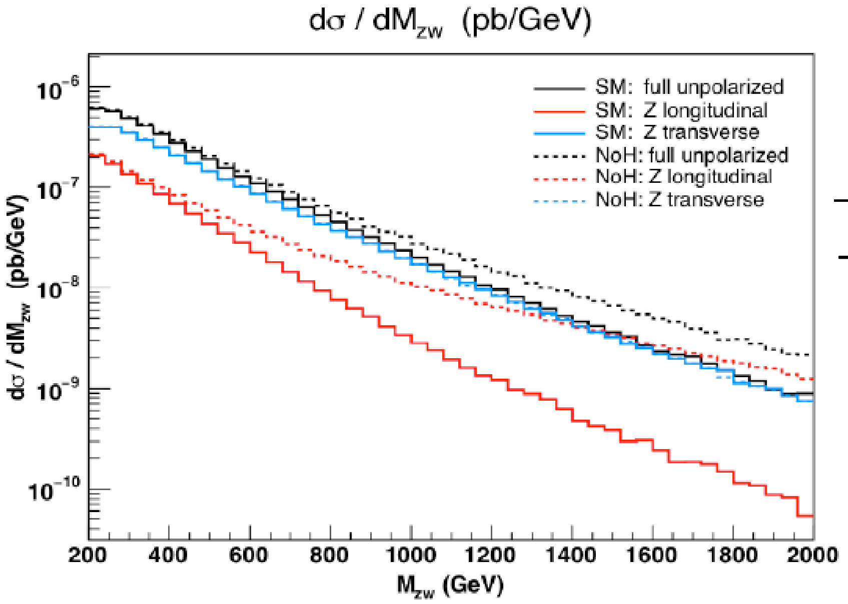


Polarizations fraction

Effect enhanced in considering only the longitudinal production

$V_L V_L \rightarrow V_L V_L$

WZjj



— SM
--- No Higgs

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

First measurements @ LEP2

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

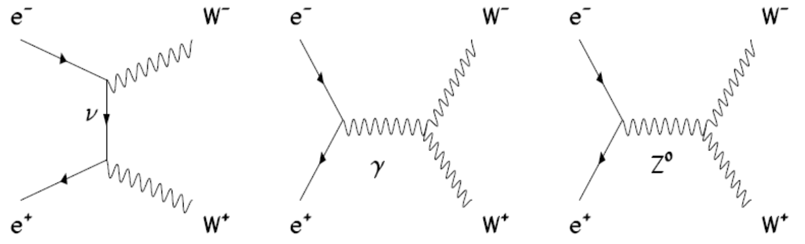
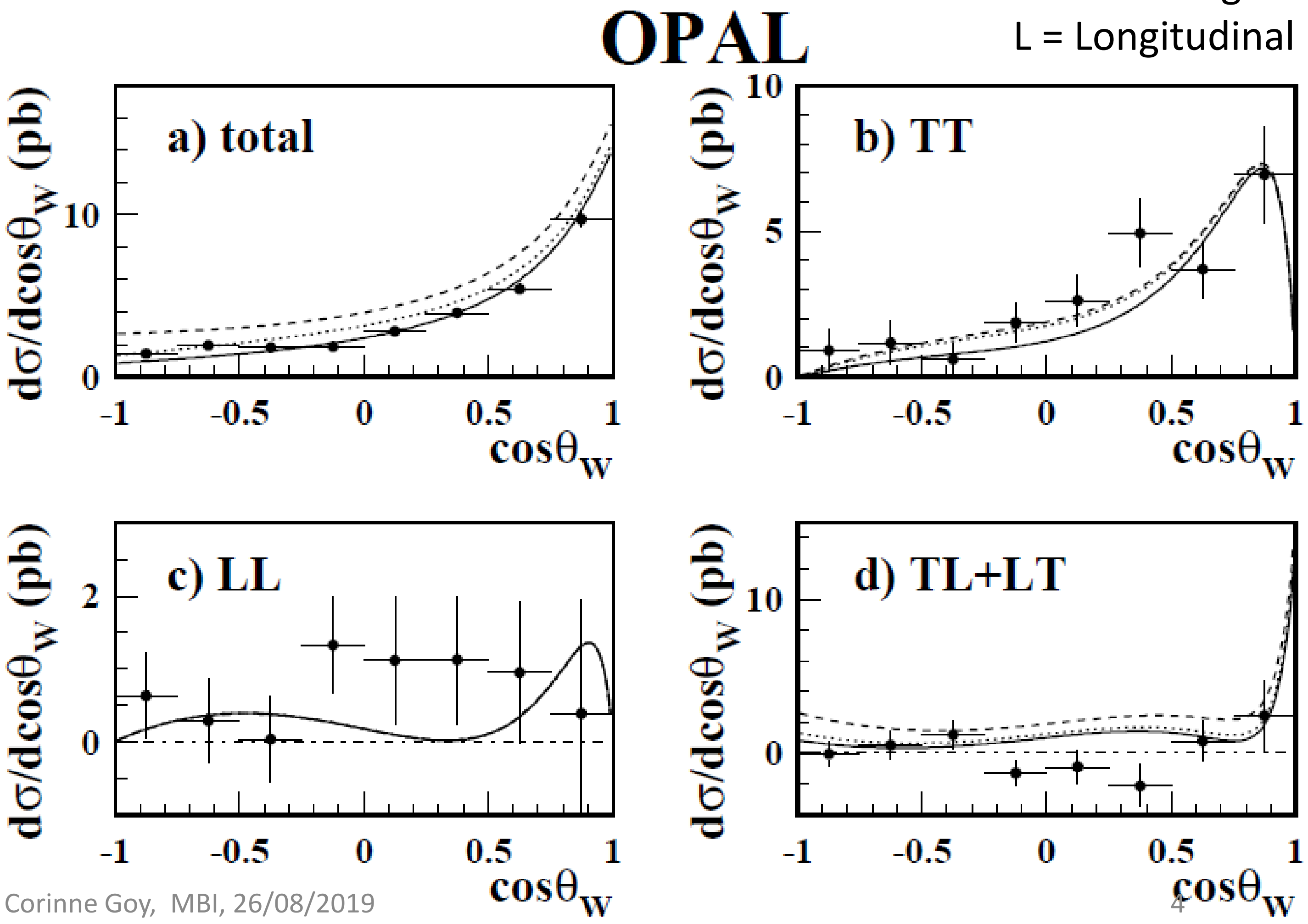


Fig. 1. CC03 diagrams

$\mathcal{L}$ = 520 pb^{-1}
√S = 189 to 209 GeV

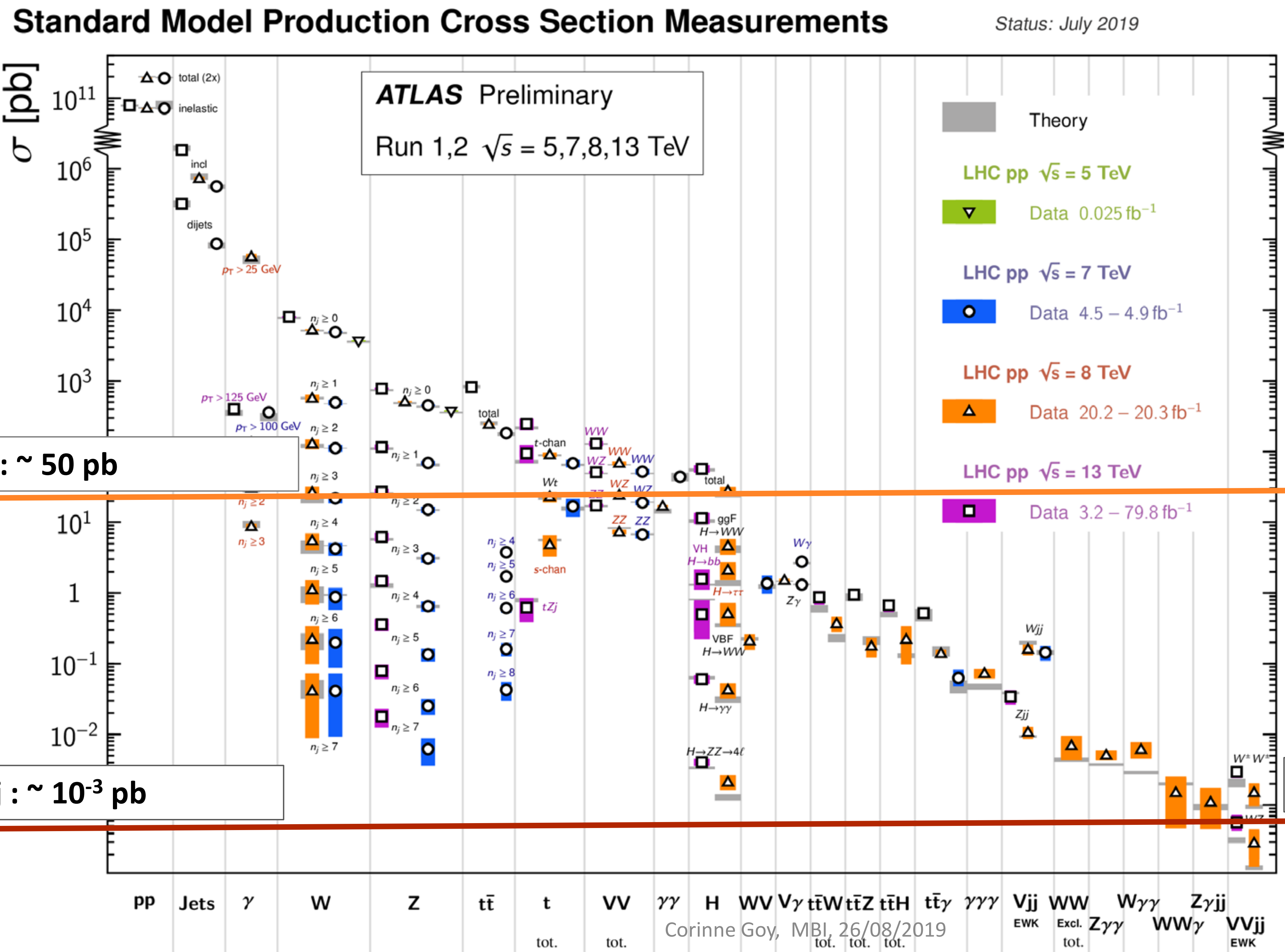
T = Left + Right
L = Longitudinal

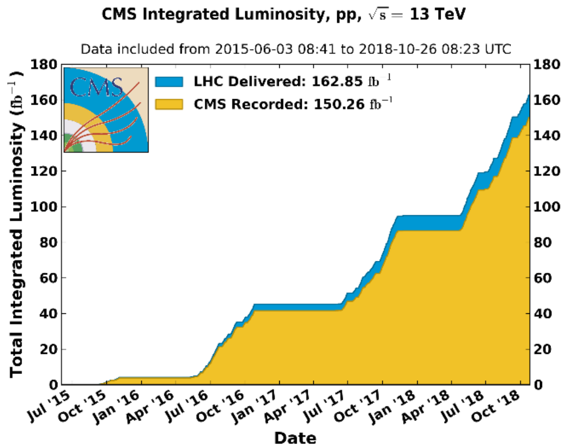


DELPHI:

- Using SDM
- One parameter fit
- CP violating aTGC

$$g_4^Z = -0.39^{+0.19}_{-0.20}\,,$$
$$\tilde{\kappa}_Z = -0.09^{+0.08}_{-0.05}\,,$$
$$\tilde{\lambda}_Z = -0.08 \pm 0.07\,.$$





VV : ~ 50 pb

VVjj : ~ 10^{-3} pb

140 fb^{-1}

7. 10^6 events/exp

Leptonic decays : e & μ
$Z \rightarrow ll$: 3.3658(23) %
$W \rightarrow l\nu$: 10.86(9) %

140 events/exp

• Existing measurements @ LHC

Eur. Phys. J. C (2019) 79:535
https://doi.org/10.1140/epjc/s10052-019-7027-6
THE EUROPEAN PHYSICAL JOURNAL C
Check for updates
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

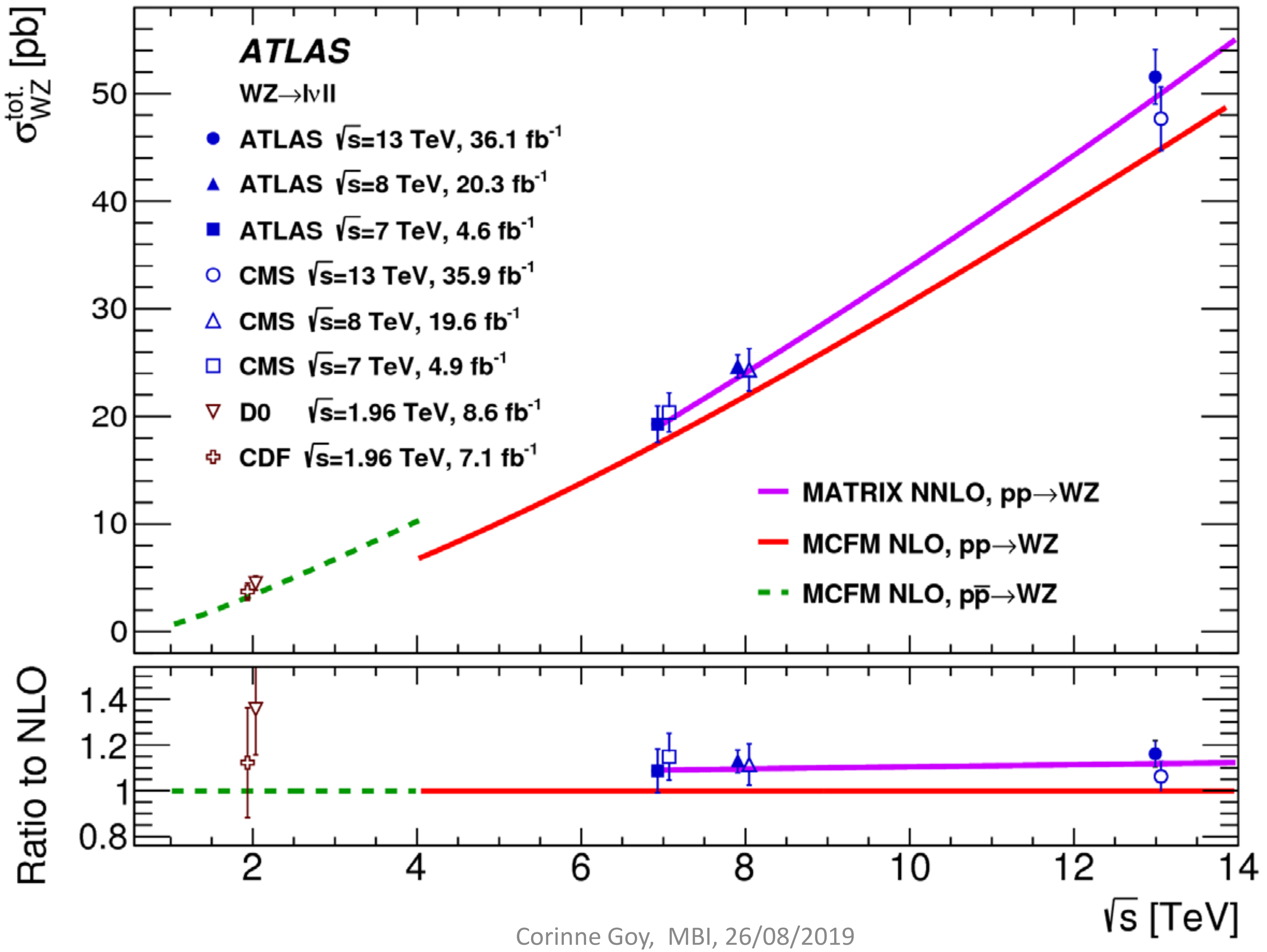
First presented at ICHEP 2018
Now published

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

• Prospective @ HL-LHC

- 3000 – 4000 fb^{-1} :
  - First opportunity to study the longitudinal scattering of weak bosons
- *CERN Yellow Report CERN-LPCC-2018-03*
  - *+ related ATLAS/CMS notes*

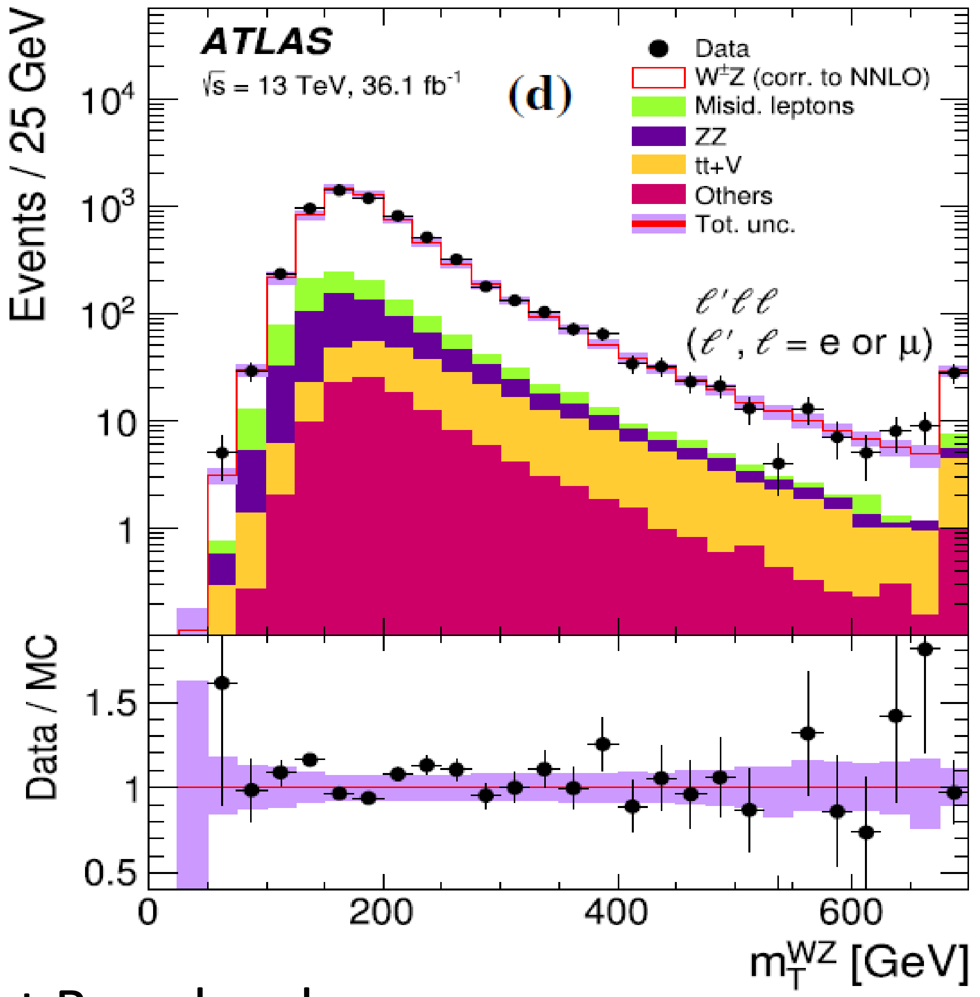
WZ : the need for NNL0 precision



Fiducial phase-space

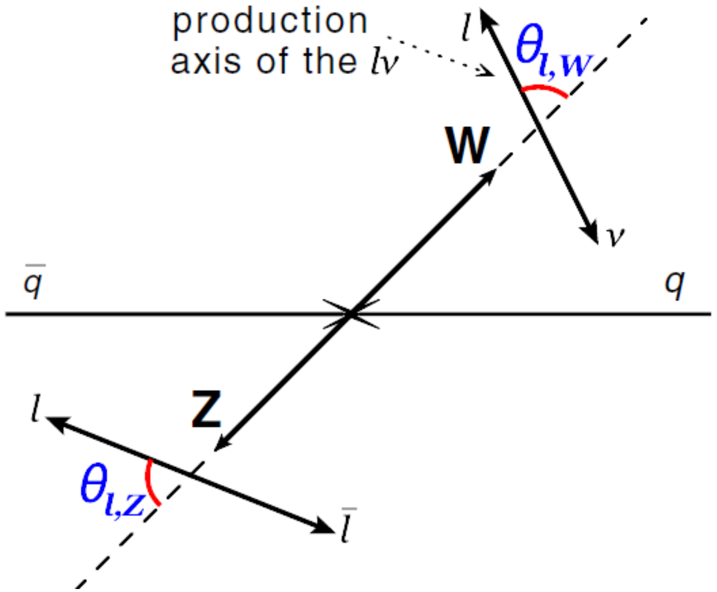
Reflects the main selection criteria

	Fiducial PS
Lepton $\|\eta\|$	2.5
pT of Z lepton	15 GeV
mZ	$\|mZ - mPDG\| < 10$ GeV
pT of W lepton	20 GeV
mT(W)	30
ΔR (lZ)	> 0.2
ΔR (lZ, lW)	> 0.3



Polarization results presented at Born level

Method

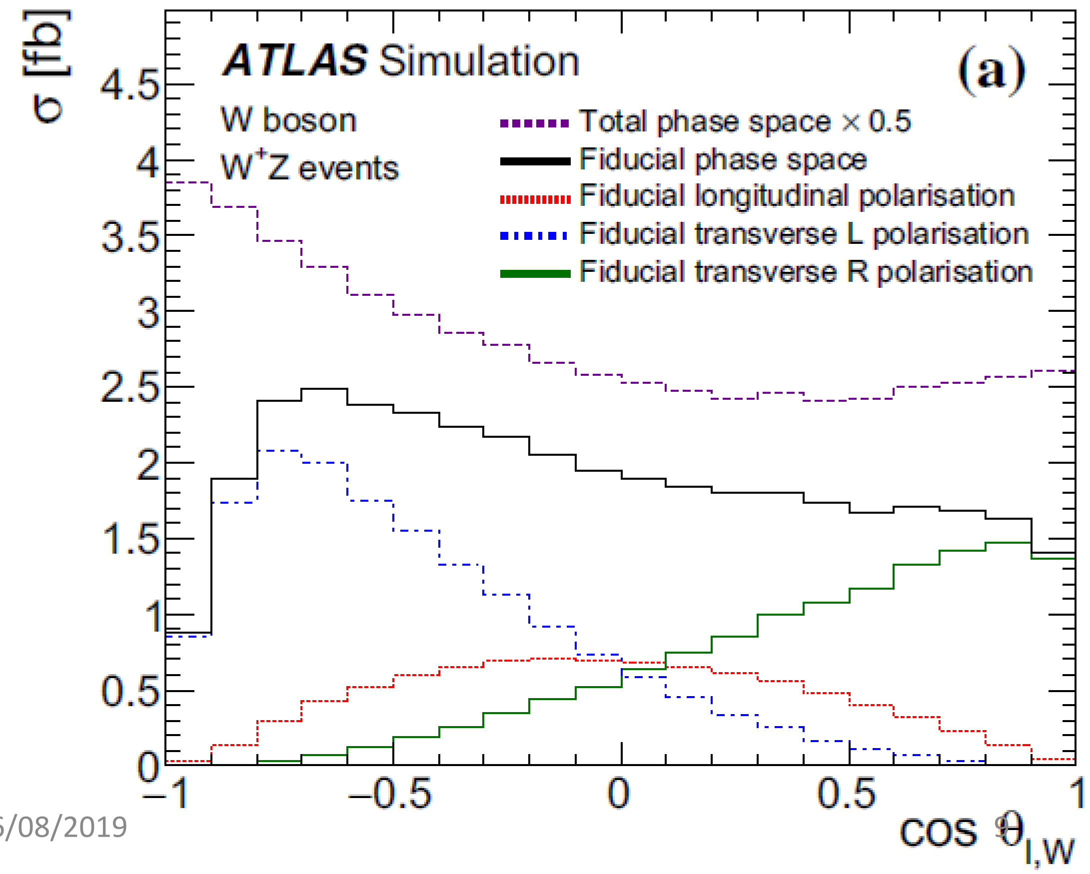


θ* is defined as the angle between the lepton direction in the V restframe and the V direction in the WZ restframe

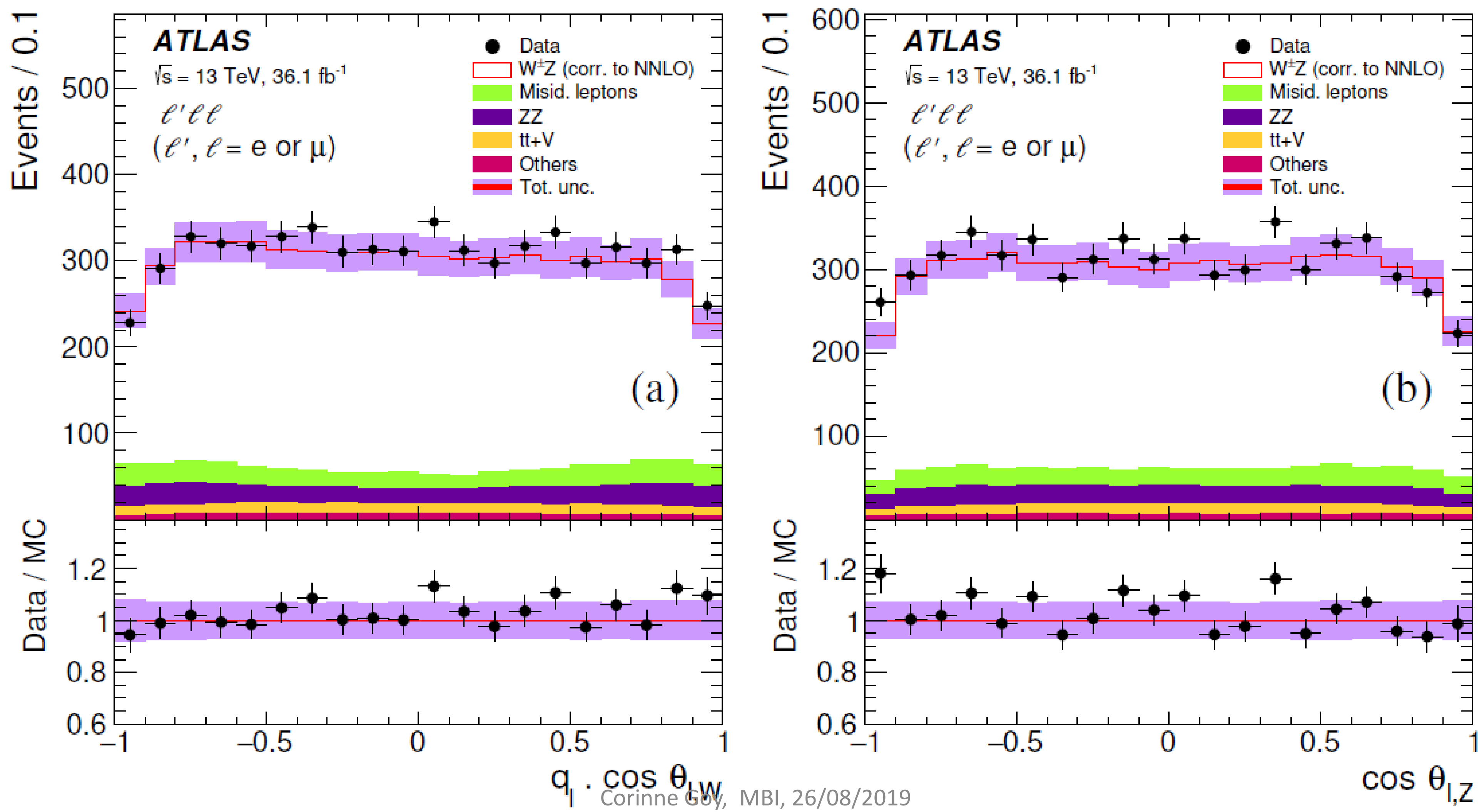
Reweighted method previously used in e.g
PRL 107, 021802 (2011) CMS Collaboration
Eur. Phys. J. C(2012) ATLAS Collaboration

- Powheg-Pythia MC sample
- **Longitudinal**, **Left** and **Right** fractions are determined with a fit in bins of pT(V) and Y_V, separately in ZW^+,ZW^-

→Weights to create pure helicity state templates at the reconstruction level



Example of cosθ* distributions in WZ events



Systematics

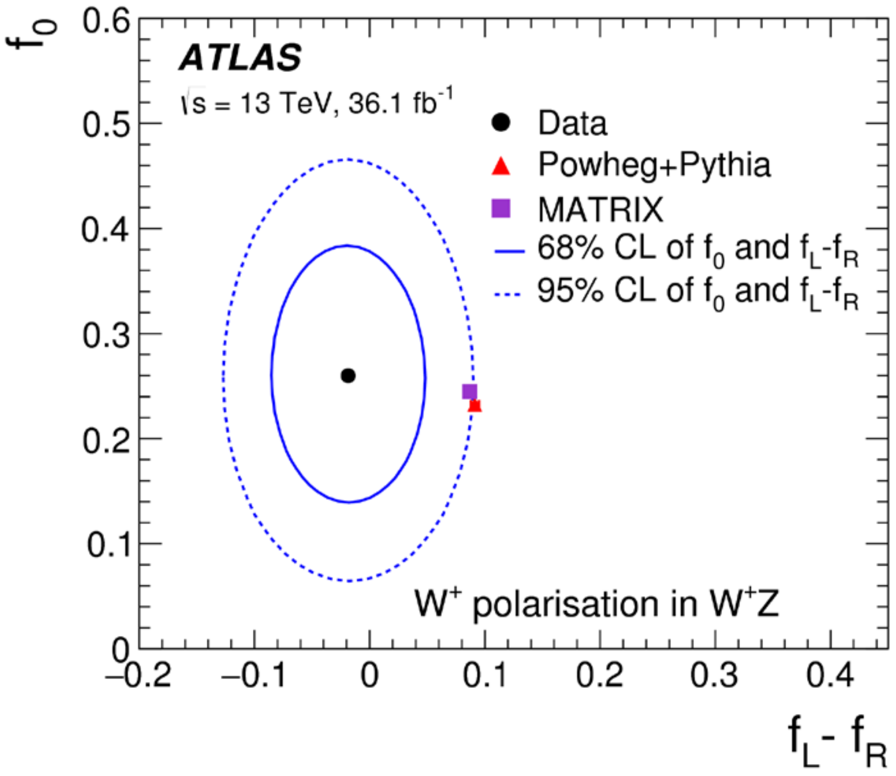
- Largely statistically dominated
- MC@NL0/Powheg +Pythia for helicity template syst.
- Pythia/Herwig for parton shower syst.

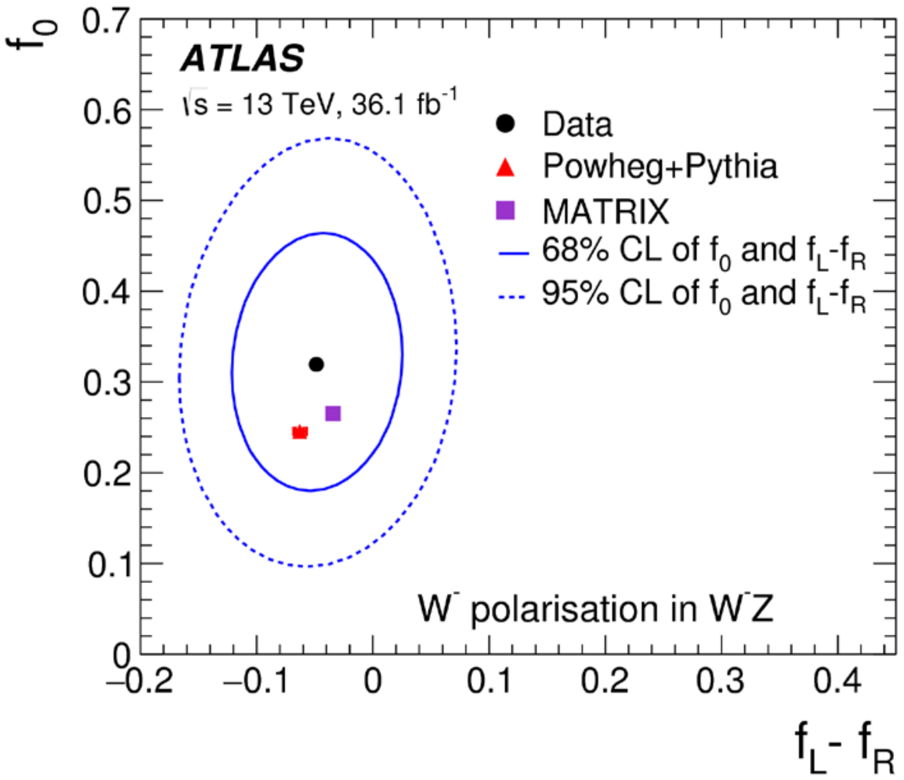
	$W^{\pm}$ in $W^{\pm}Z$		Z in $W^{\pm}Z$	
	f_0	$f_L - f_R$	f_0	$f_L - f_R$
e energy scale and id. efficiency	0.0024	0.0004	0.005	0.0021
μ momentum scale and id. efficiency	0.0013	0.0027	0.0018	0.008
E_T^{miss} and jets	0.0024	0.0010	0.0017	0.005
Pile-up	0.005	0.00009	0.0014	0.005
Misid. lepton background	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

W

	Longitudinal (= F0) f_0						Left – Right $f_L - f_R$					
	Data		POWHEG+PYTHIA		MATRIX		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

- F0 is measured different from 0 at more than 3 sigma and in agreement with predictions
- FL-FR at 2 σ from predictions in W^+

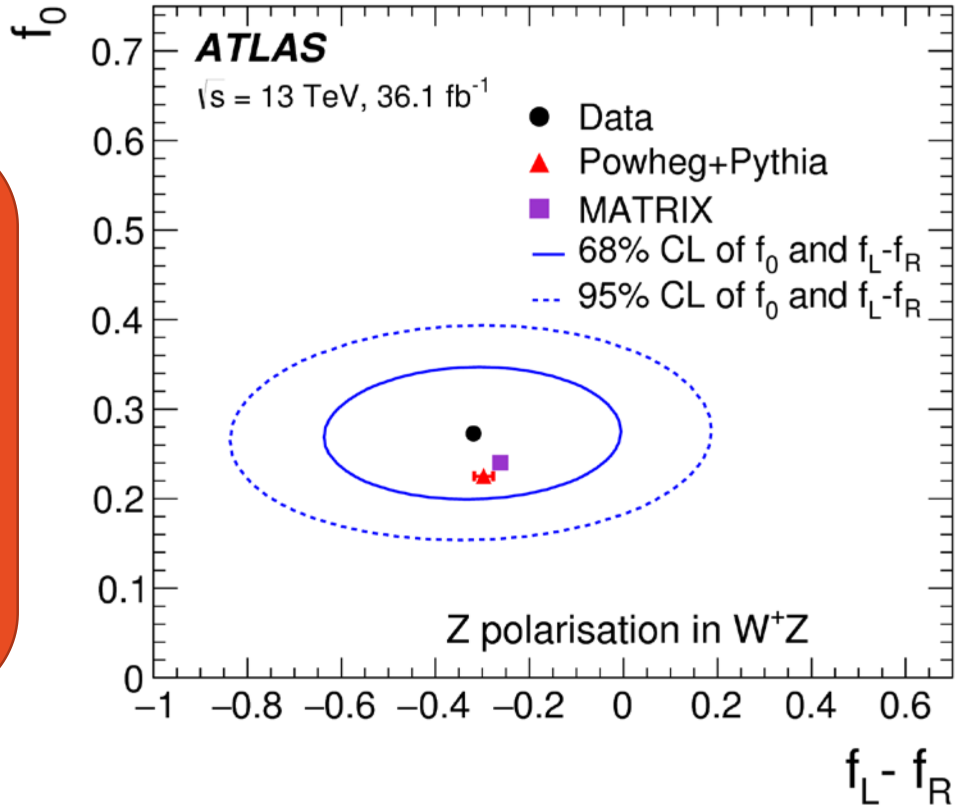


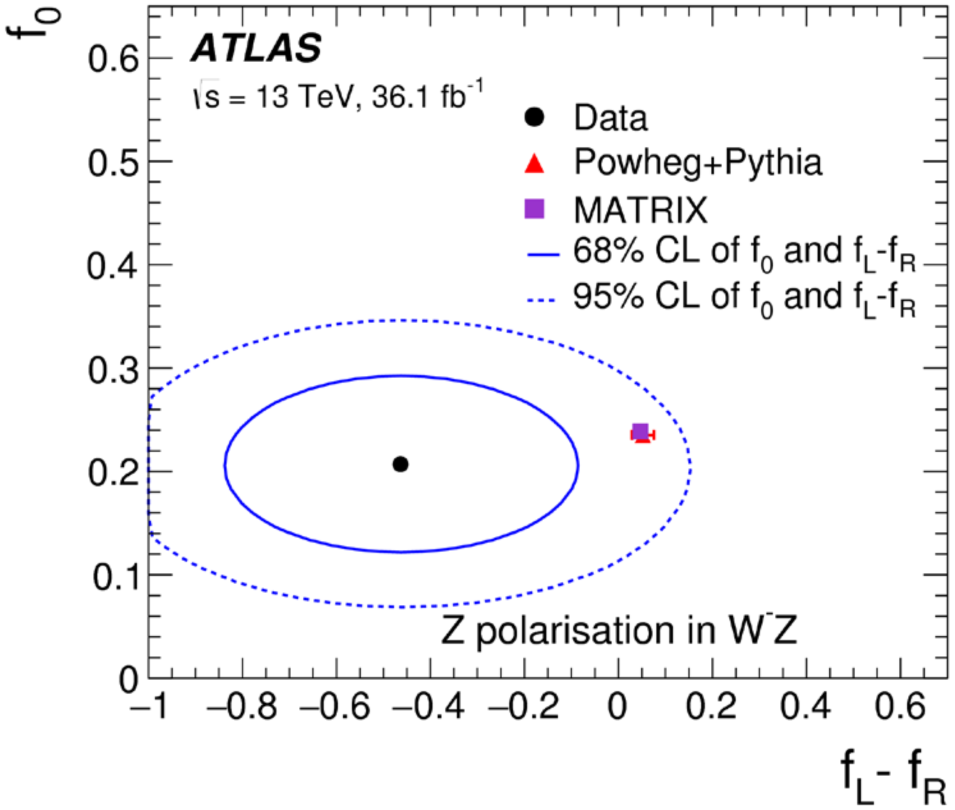


Z

	Longitudinal (= F0) f_0						Left – Right $f_L - f_R$					
	Data		POWHEG+PYTHIA		MATRIX		Data		POWHEG+PYTHIA		MATRIX	
Z in W^+Z	0.27	0.05	0.225	0.004	0.2401	0.0014	−0.32	0.21	−0.297	0.021	−0.262	0.009
Z in W^-Z	0.21	0.06	0.235	0.005	0.2389	0.0015	−0.46	0.25	0.052	0.023	0.0468	0.0034
Z in $W^\pm Z$	0.24	0.04	0.2294	0.0033	0.2398	0.0014	−0.39	0.16	−0.156	0.016	−0.135	0.006

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

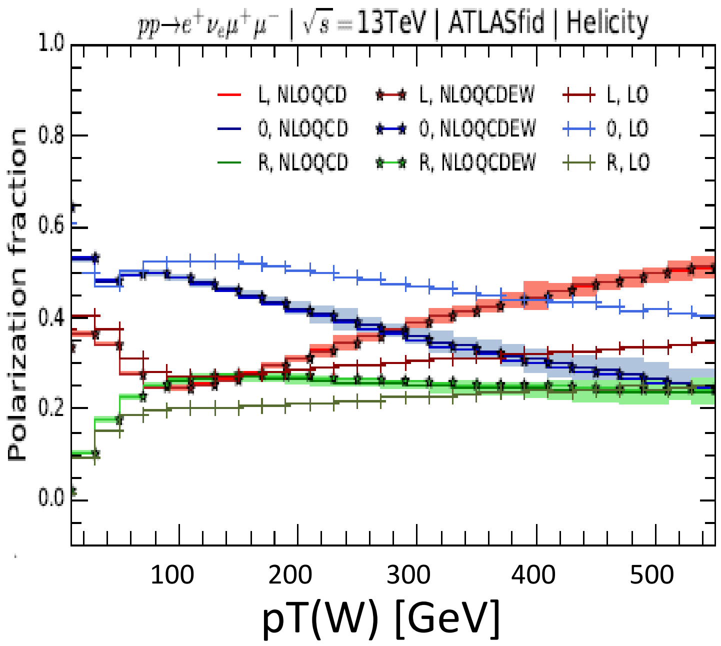


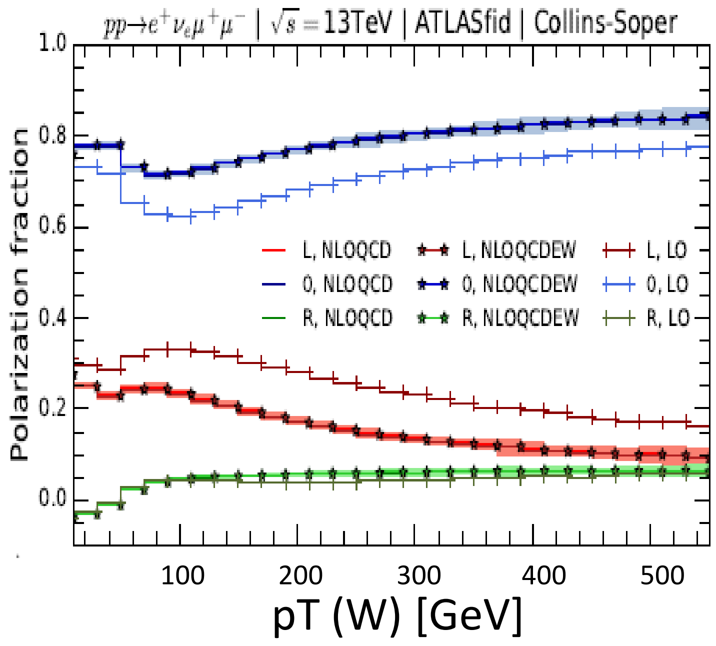


Remark 1 – coordinate systems

JHEP 04 (2019) 065 / arXiv:18101.11034
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)

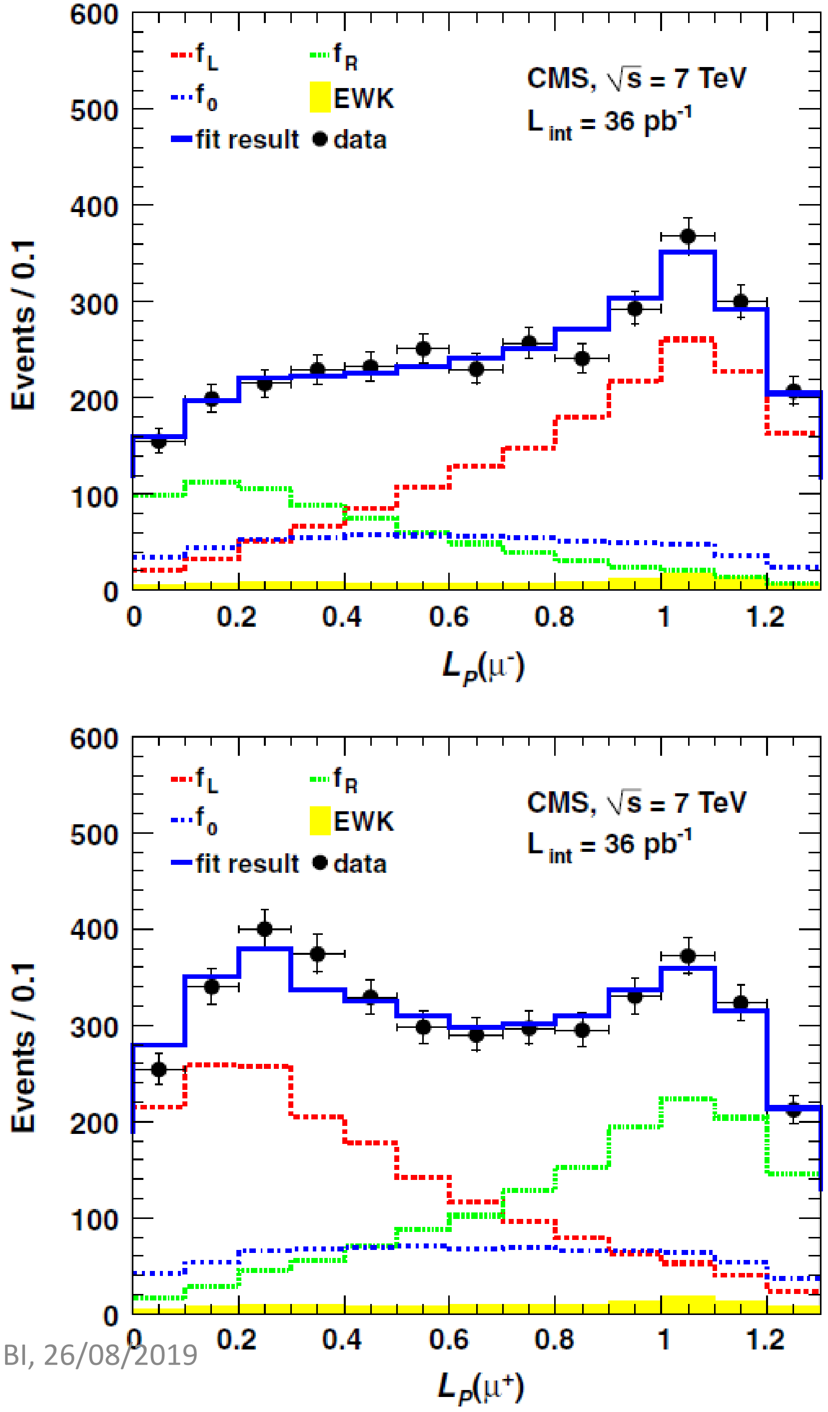
Remark 3: Alternative variables

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

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

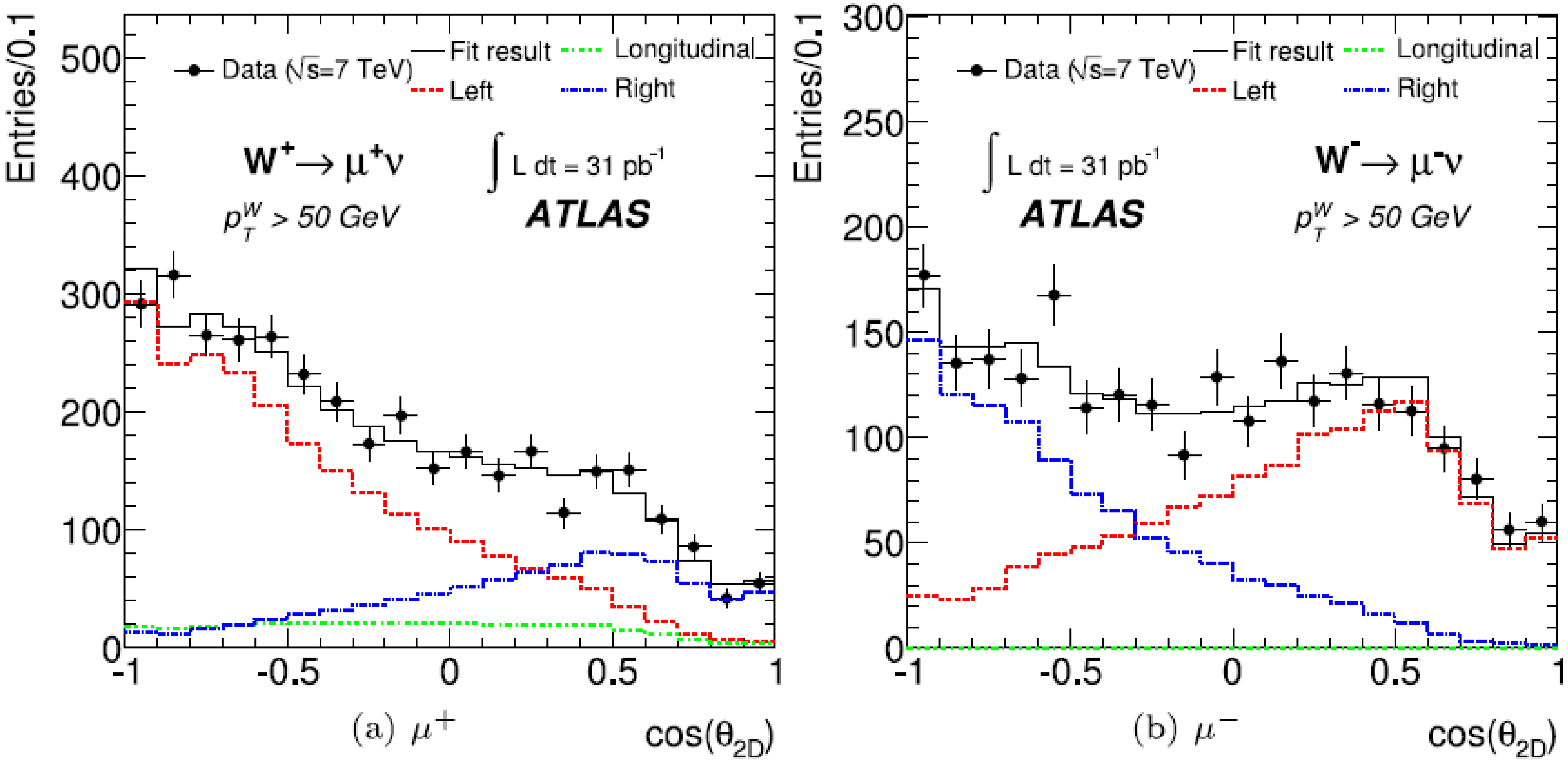
$P_T(W) \to \infty$

PRL 107, 021802 (2011)
CMS collaboration



Remark 3: Other variables

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



(a) μ^+ (b) μ^-

Large correction needed to obtain the "true" fraction

		μ^+	μ^-
		$35 < p_T^W < 50$ GeV	
$\cos\theta_{3D}$ generator-level	f_0 (%)	14.6 ± 0.8	20.9 ± 0.8
	$f_L - f_R$ (%)	27.9 ± 0.7	26.5 ± 0.8
$\cos\theta_{2D}$ fully simulated	f_0 (%)	30.1 ± 2.4	19.5 ± 2.2
	$f_L - f_R$ (%)	31.8 ± 1.4	26.5 ± 1.2
		$p_T^W \geq 50$ GeV	
$\cos\theta_{3D}$ generator-level	f_0 (%)	18.3 ± 1.0	22.7 ± 1.0
	$f_L - f_R$ (%)	26.9 ± 0.8	25.8 ± 0.9
$\cos\theta_{2D}$ fully simulated	f_0 (%)	25.1 ± 1.9	20.7 ± 2.2
	$f_L - f_R$ (%)	29.7 ± 1.1	26.2 ± 1.2

NLO QCD & EW corrections

Using Powheg template (ATLAS)

Method	$f_0^{W^+}$	$f_L^{W^+} - f_R^{W^+}$	f_0^Z	$f_L^Z - f_R^Z$
ATLAS data	0.26{8}	−0.02{4}	0.27{5}	−0.32{21}
ATLAS POWHEG+PYTHIA	0.233{4}	0.091{4}	0.225{4}	−0.297{21}
ATLAS MATRIX	0.2448{10}	0.0868{14}	0.2401{14}	−0.262{9}
NLOQCD	0.241	0.082	0.232	−0.307
NLOQCDEW	0.244	0.078	0.237	−0.244

Cf: Duc Ninh LE VBScan – Istanbul 2019

Method	$f_0^{W^-}$	$f_L^{W^-} - f_R^{W^-}$	f_0^Z	$f_L^Z - f_R^Z$
ATLAS data	0.32{9}	−0.05{5}	0.21{6}	−0.46{25}
ATLAS POWHEG+PYTHIA	0.245{5}	−0.063{6}	0.235{5}	0.052{23}
ATLAS MATRIX	0.2651{15}	−0.034{4}	0.2389{15}	0.0468{34}
NLOQCD	0.257	−0.049	0.232	0.079
NLOQCDEW	0.259	−0.045	0.236	0.050

- EW corrections are sizeable for Z due to radiative decays.
- Overall, tend to improve agreement with measurements

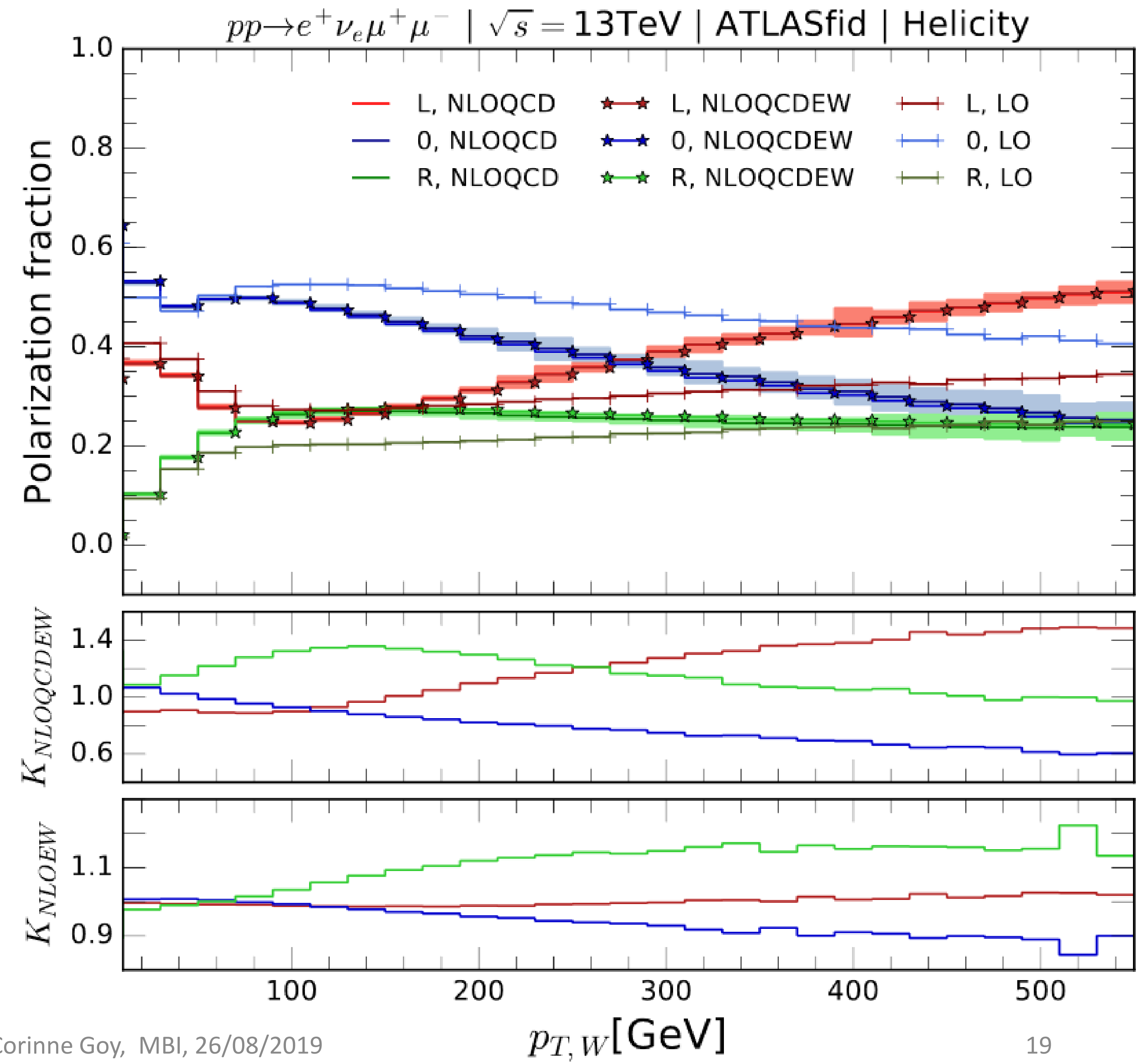
JHEP 04 (2019) 065 / arXiv:18101.11034
J. Baglio & D.N. Le

JHEP 10 (2017) 043
B. Biedermann, A. Denner & L. Hofer

f0 vs pT(V)

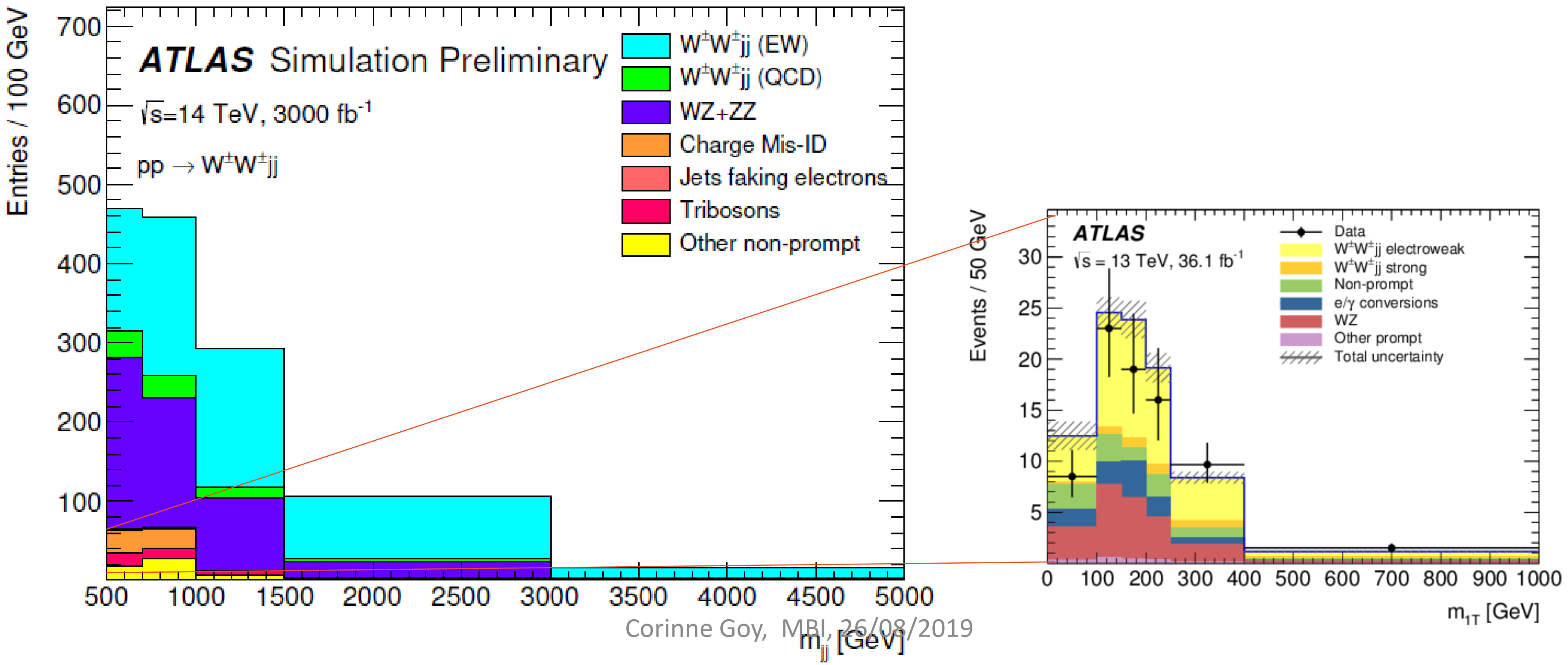
QCD corrections are large anyway

But electroweak correction gets greater at large pT(V) up to 10%



Prospects at HL-LHC : $\sqrt{s}$ = 14 TeV, 3000. 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%

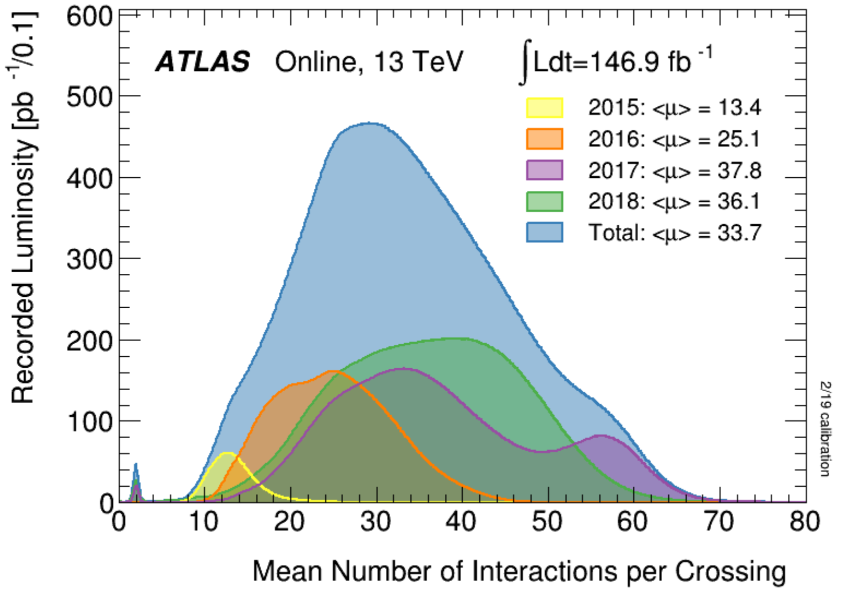


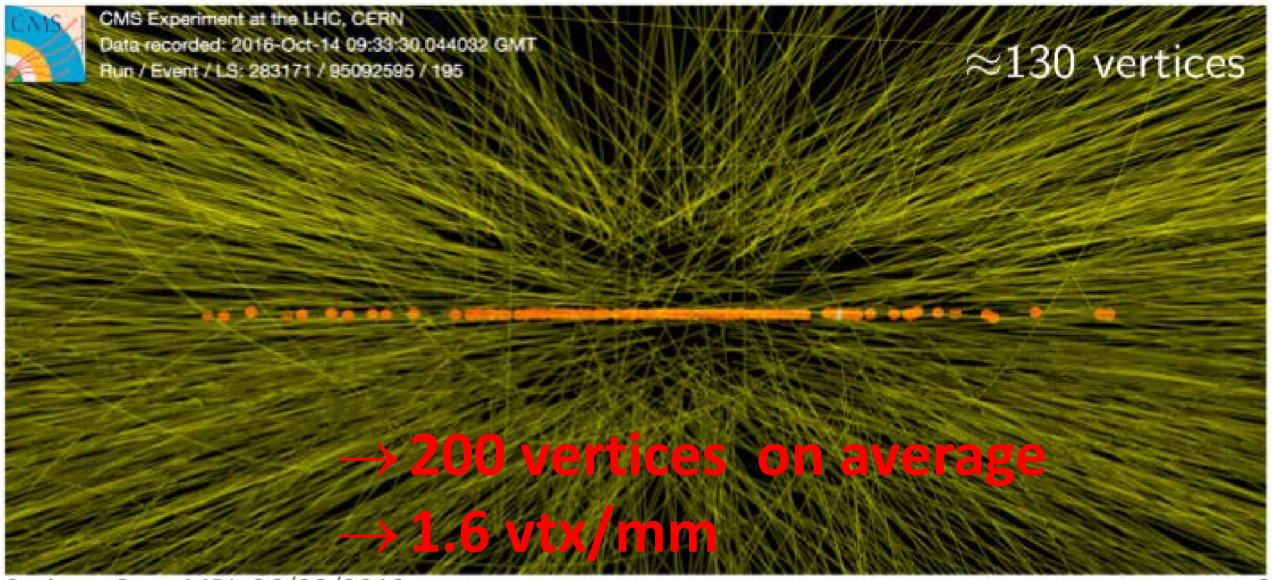
Evolution of the experimental conditions

- 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

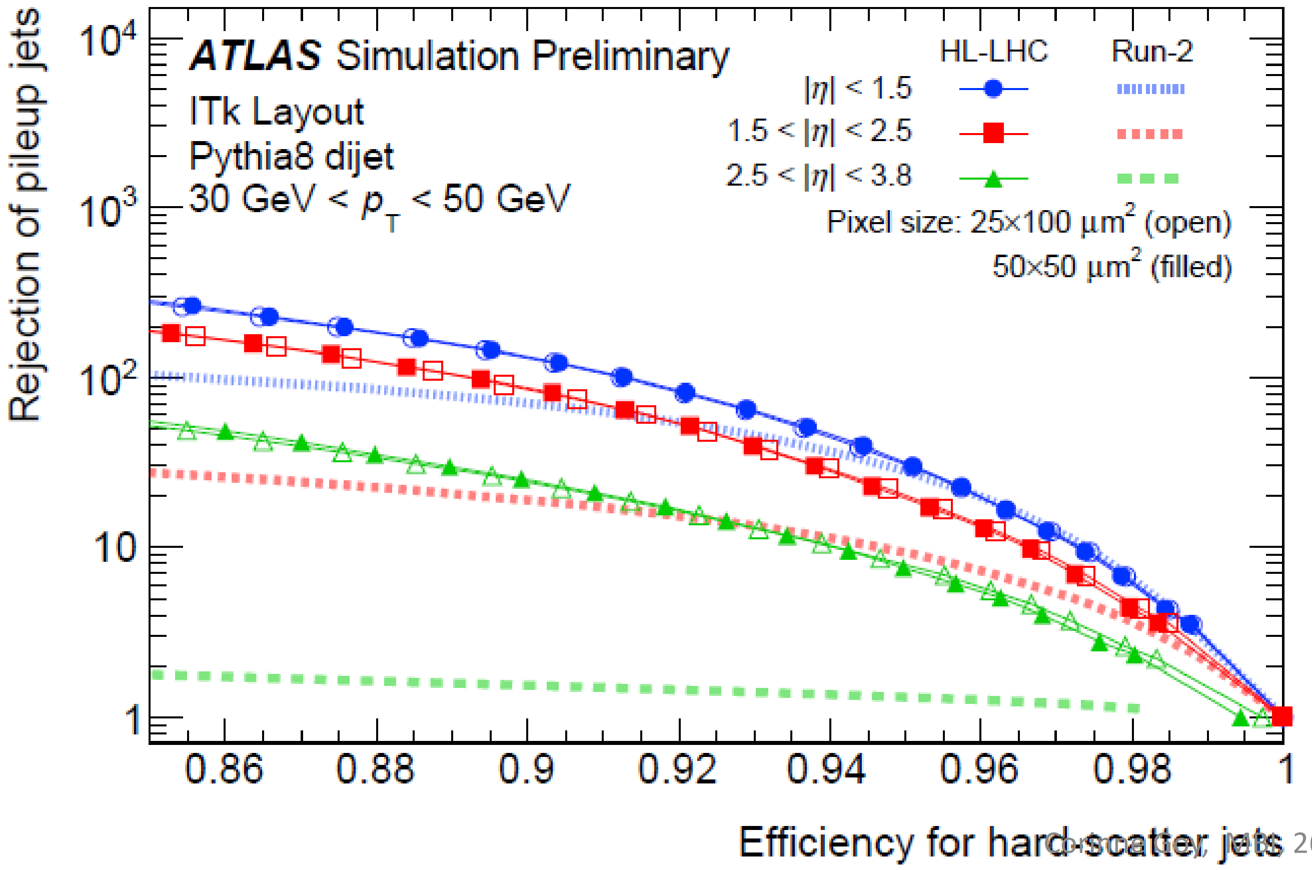
$\Rightarrow$ Upgrade of detectors
  Hardness
  Granularity



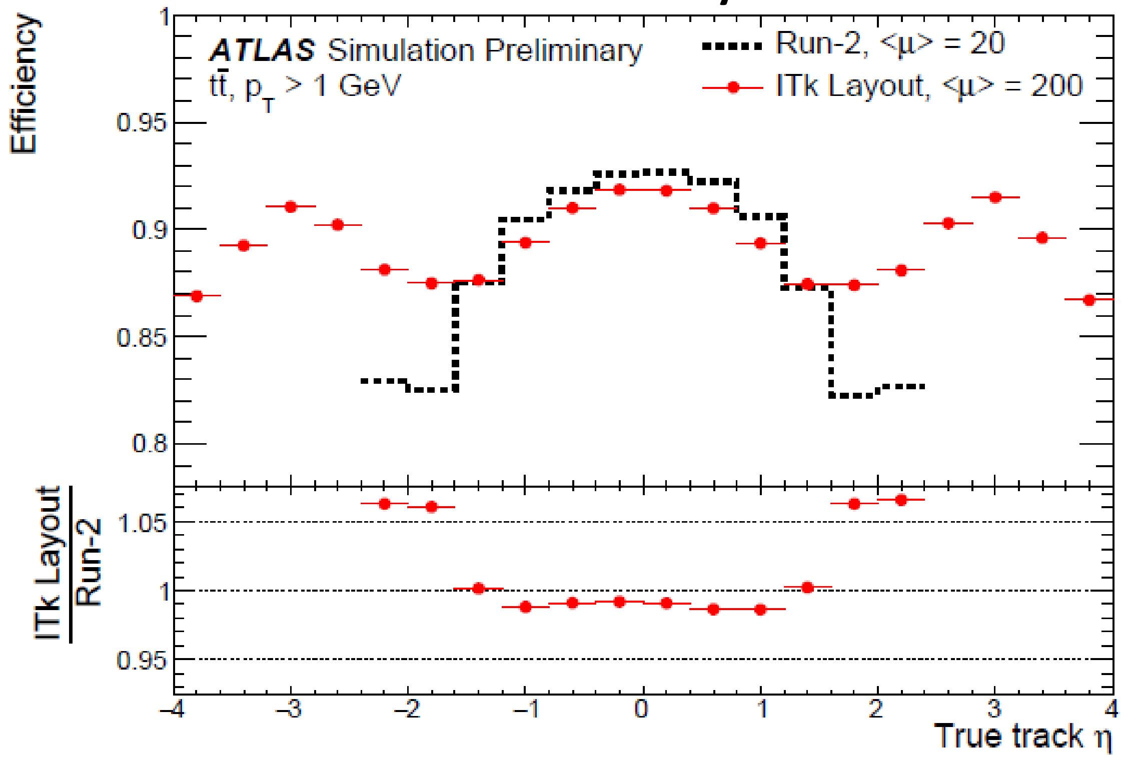


Tracking up to |η | < 4

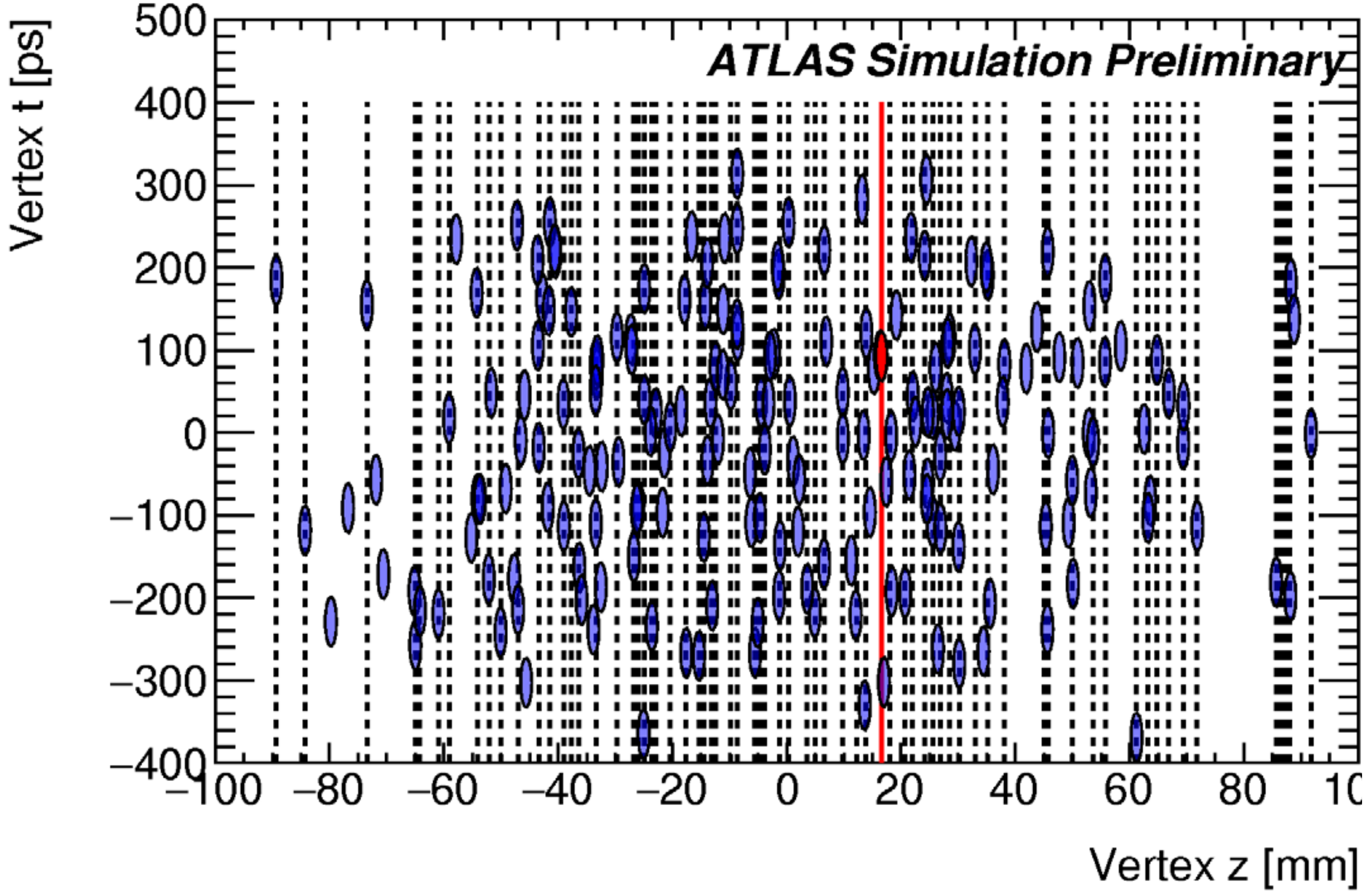
Pile Up rejection

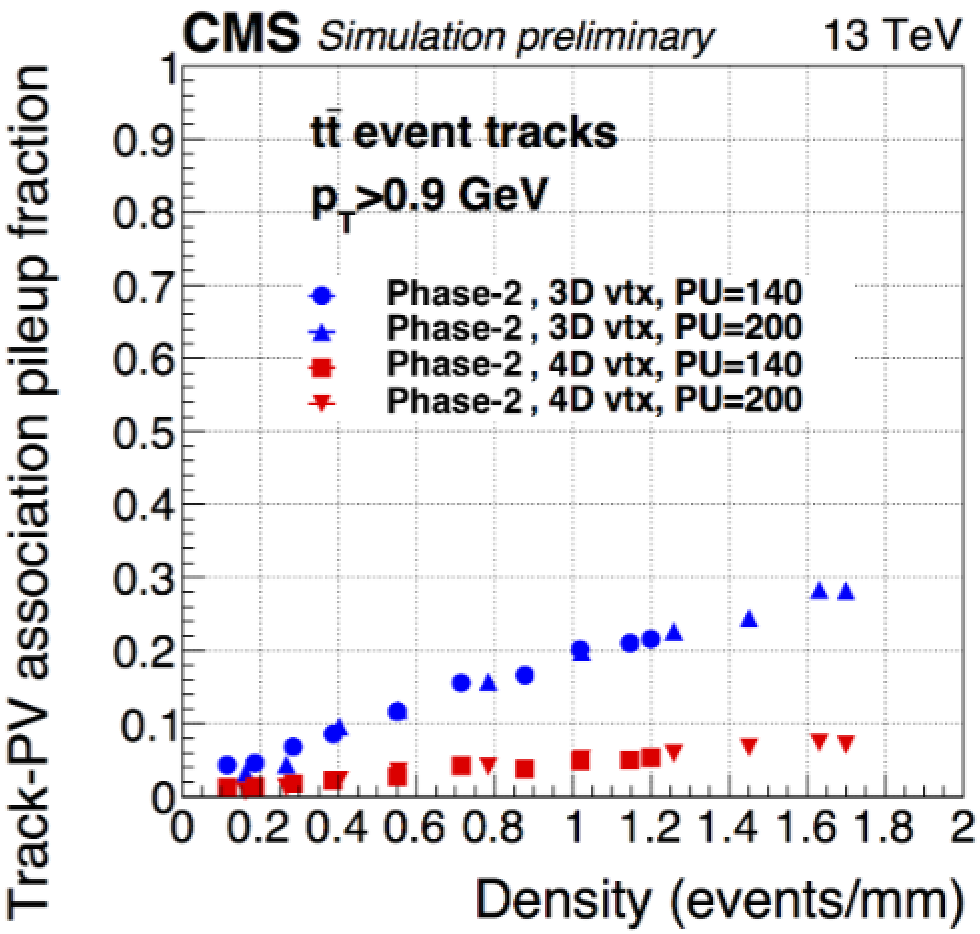


Track efficiency



Timing detector : a new dimension





ATLAS : 2.4 < | η | < 4.

CMS : 0 < | η | < 3.

Consequences for object reconstruction

$\|\eta\|$	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

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

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 $^{-1}$

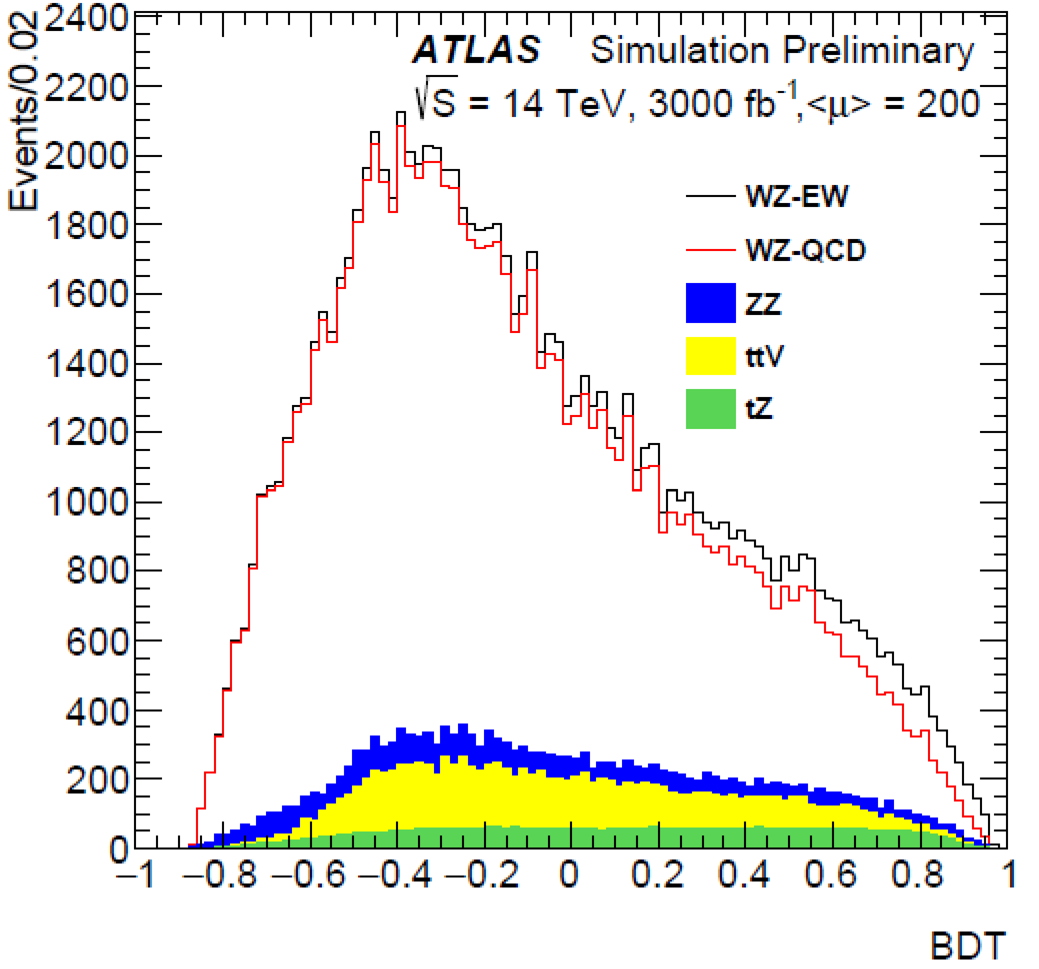
Process	ATLAS	CMS
$WZjj-EW$	3889	2757
$WZ-QCD$	29754	3486
$t\bar{t}V$	3145	–
tZ	2221	–
tV/VVV	–	1374
Non prompt	–	1192
ZZ	1970	–
VV	–	398
$Z\gamma$	–	296

CMS

- Extrapolation from the Run 2
- Tight selection

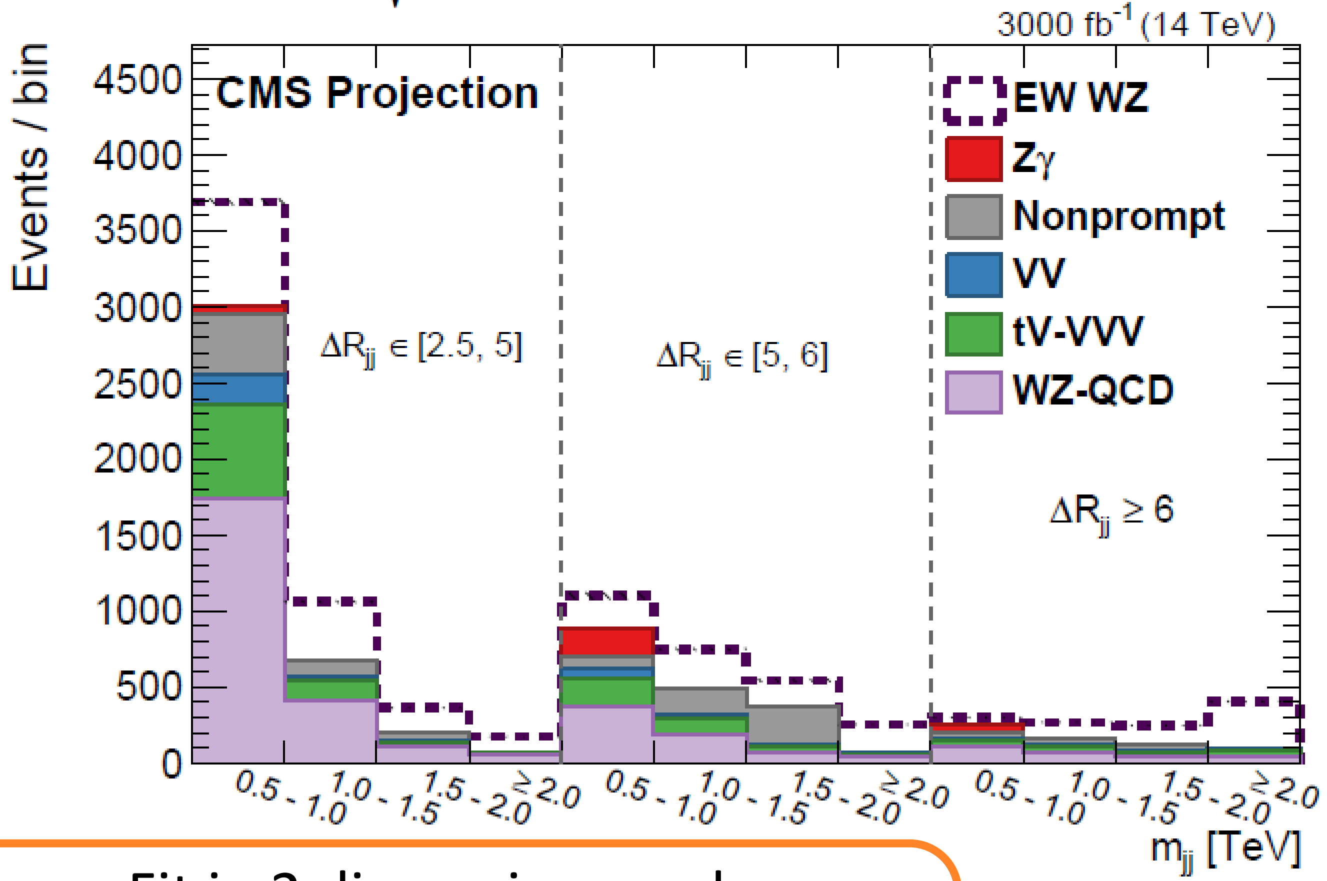
- S/B = 0.41

- WZ-QCD main background, but not as dominant



σ_{WZjj} measured to a precision of ~ 3%

$$\Delta R_{jj} = \sqrt{(\Delta\eta_{jj})^2 + (\Delta\phi_{jj})^2}$$

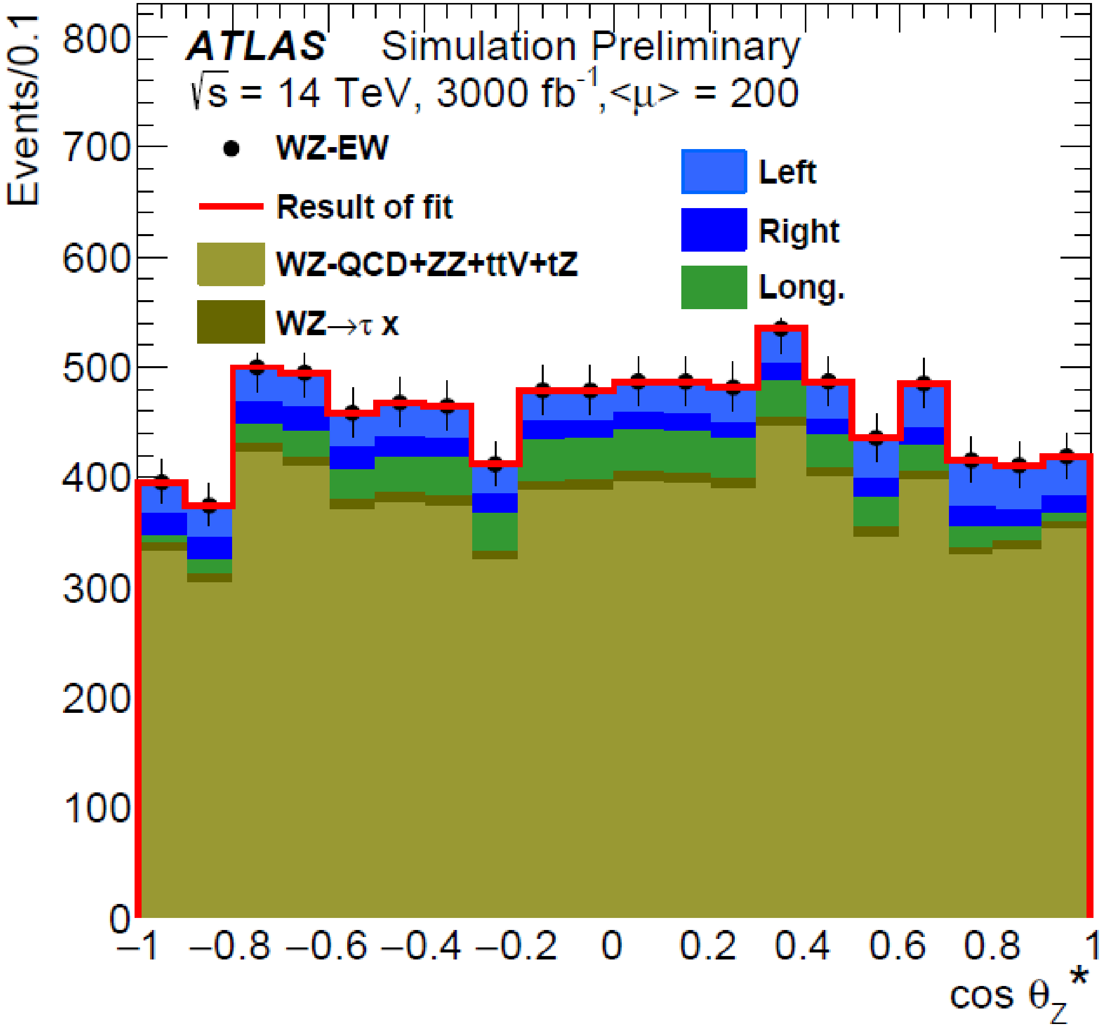


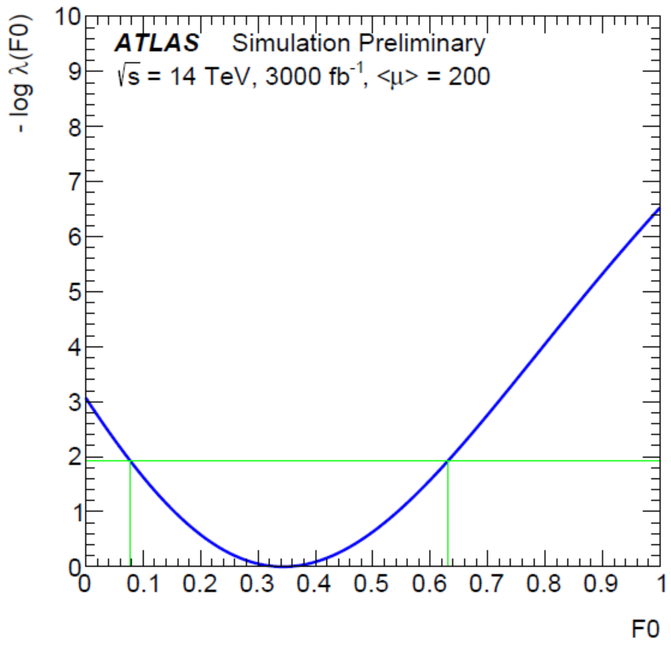
Main systematic:

- Jet energy scale
- WZjj-QCD modelling

Fit in 2 dimensions and independent flavor channels

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





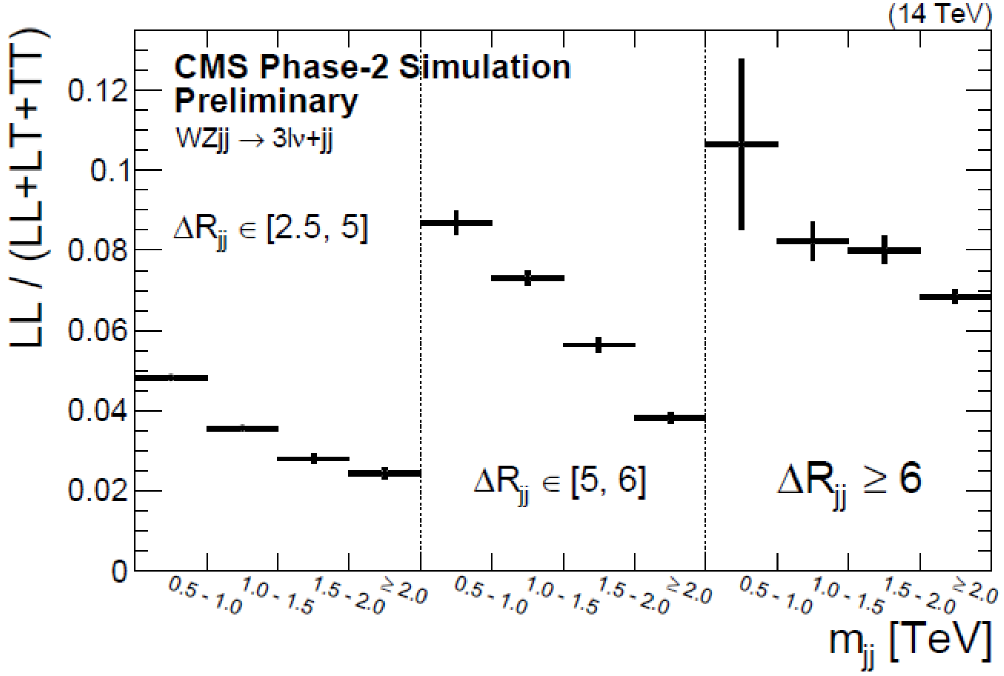
3 parameters : Nsig, F0, FL-FR
Using 3 templates and bkg normalisation
Syst on background normalization : 20 - 2.5 %

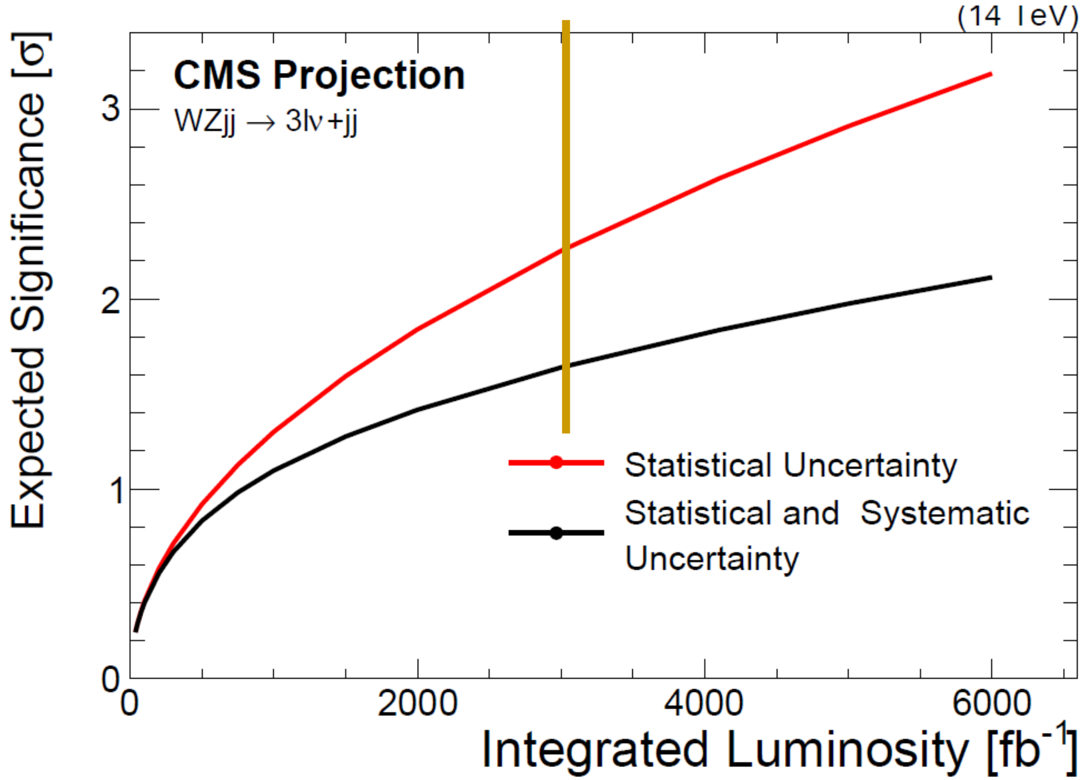
Simultaneous fit of 4 independent channels not exploited : eeμ, μμe, …

WZ→3ℓν : LL fraction

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

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



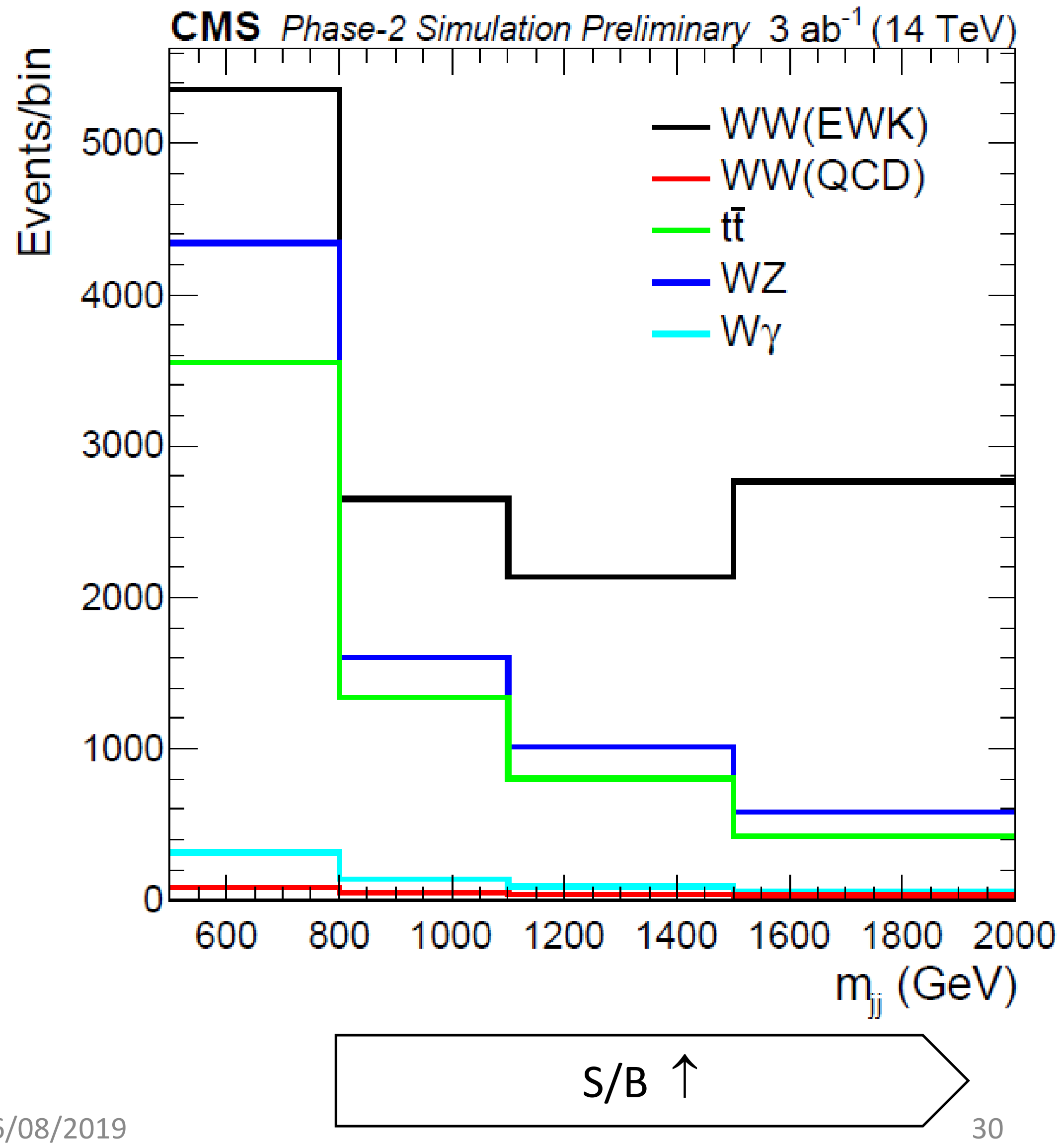


LL contribution extracted alone
TT & LT considered as a fixed additional background in the Mjj vs Rjj plane

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

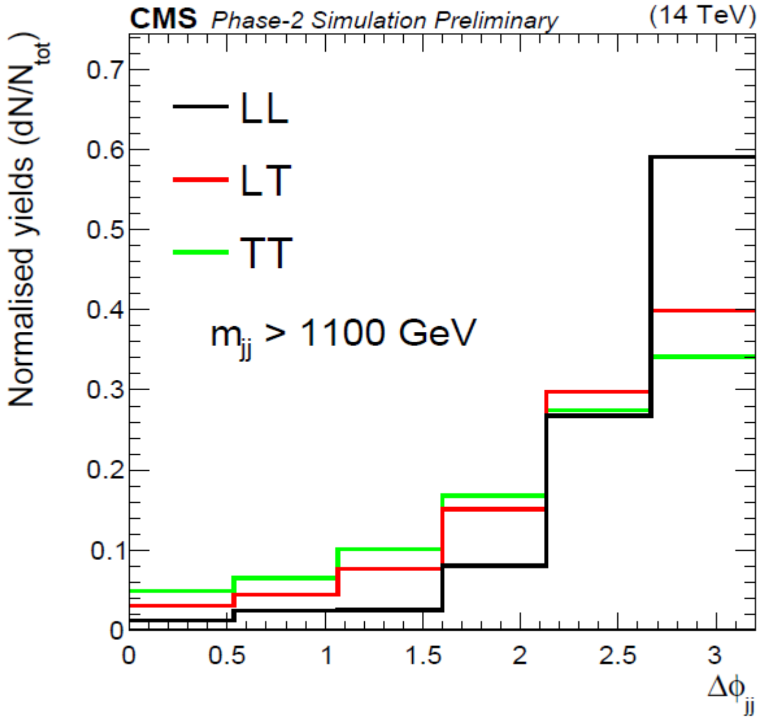


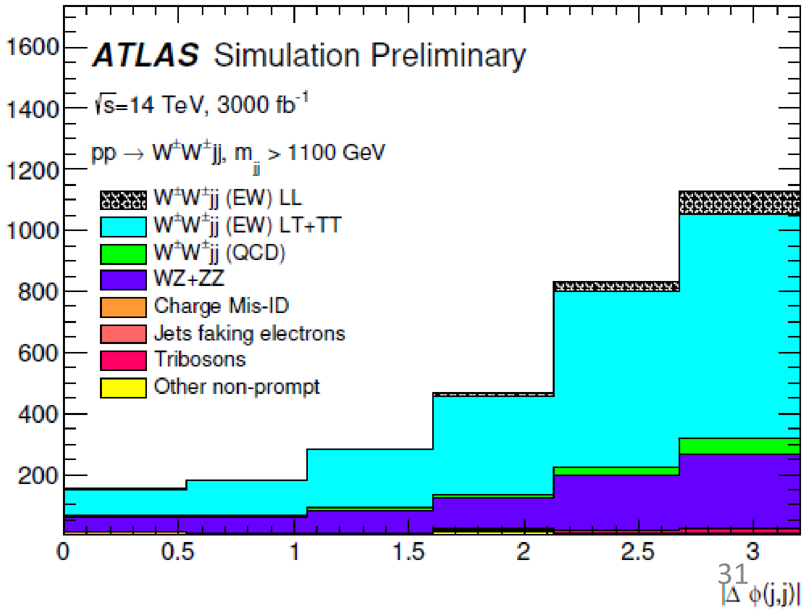
Polarization: LL fraction

Helicity fractions obtained with
MadGraph+DECAY
LL fraction : 6 – 7 %

- Total error on σ:
  CMS : 4.5%
  ATLAS : 6 %
- Binned likelihood in 3 or 4 flavor channels

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

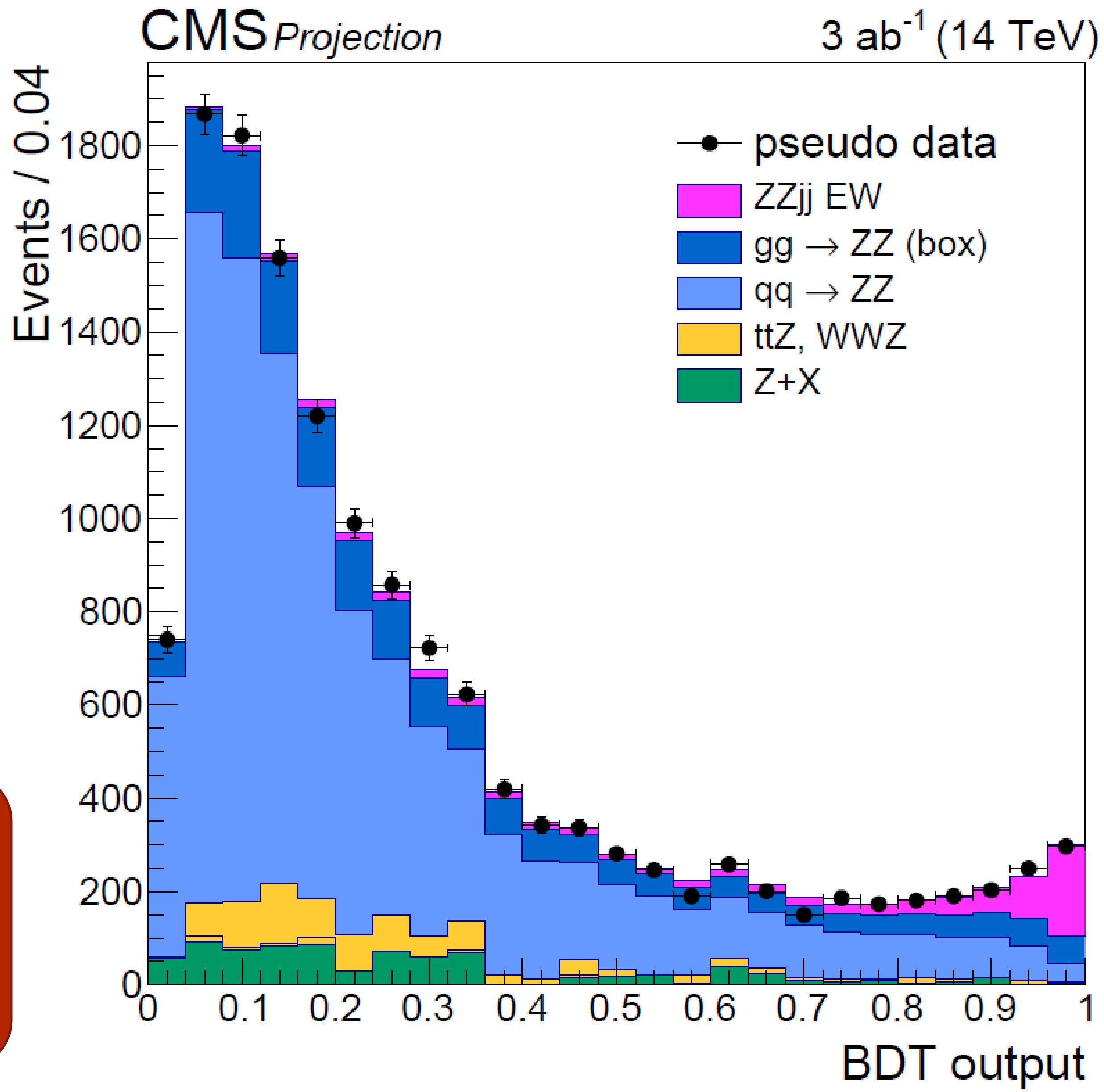




ZZjj: $ZZ \to 4\ell$

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

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



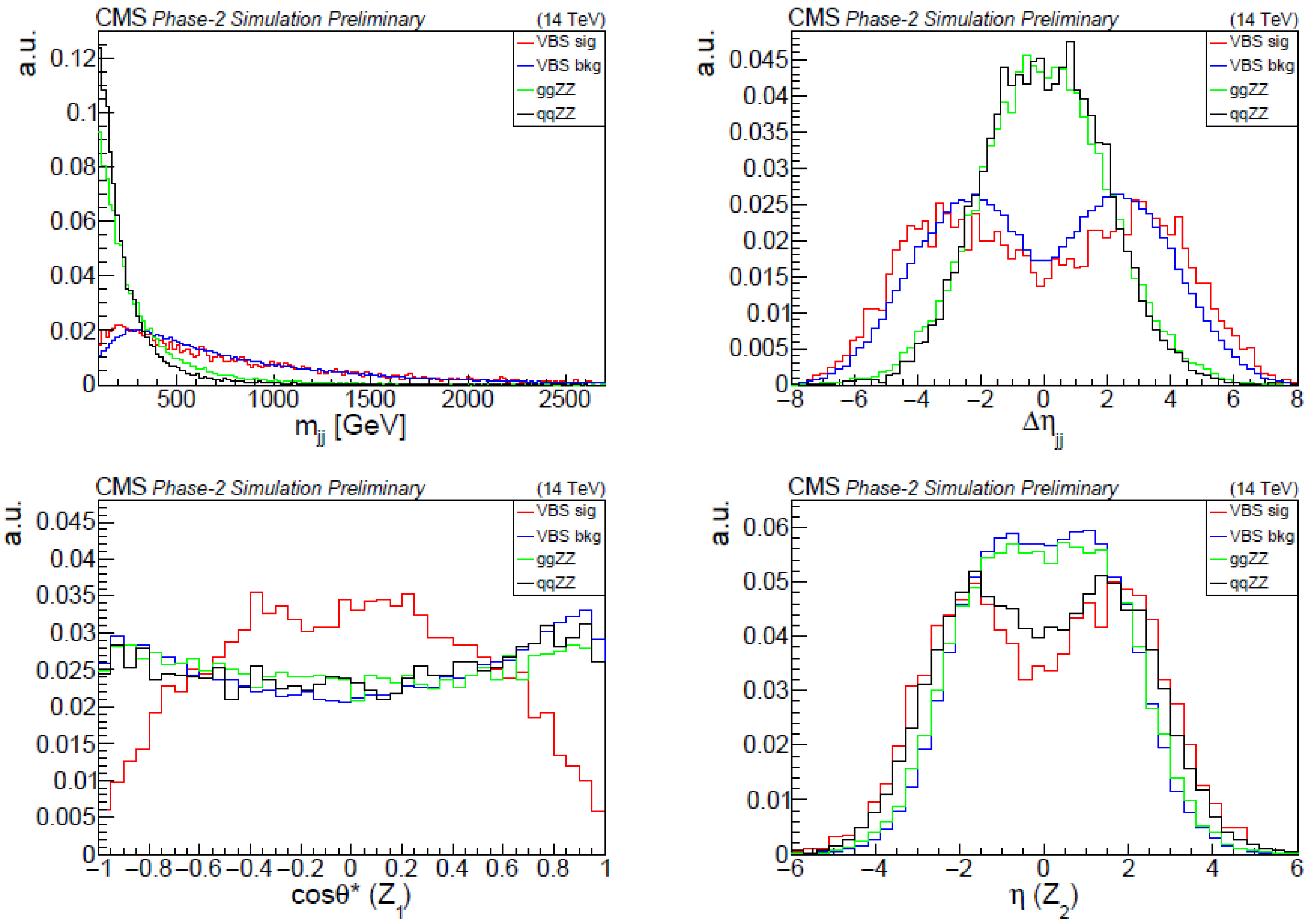
Polarization: LL fraction

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 ⇒

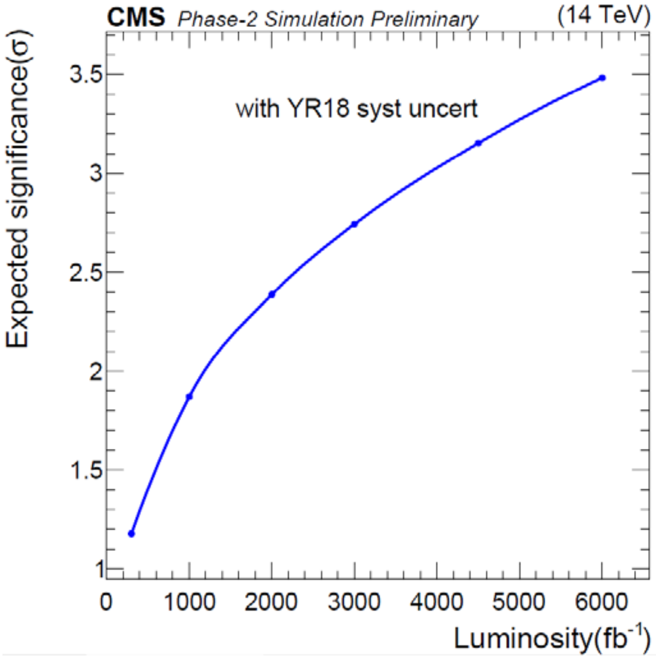


η coverage	significance	VBS $Z_L Z_L$ fraction uncertainty (%)
$\|\eta\| < 2.5(2.4)$	1.22σ	88
$\|\eta\| < 3.0(2.8)$	1.38σ	78
$\|\eta\| < 4.0(2.8)$	1.43σ	75

Lepton acceptance: e (μ)

a) Conclusion and outlook

- Obviously only at the beginning of the story
  - Individual polarization sensitivity in particular for inclusive production (ala WZ @ATLAS)
  - Other handle to aTGC ?
    - Quoting DELPHI paper : *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*
  - Potentially LL sensitivity at the end of run3 (300 fb^{-1}) : ~1σ for ssWWjj



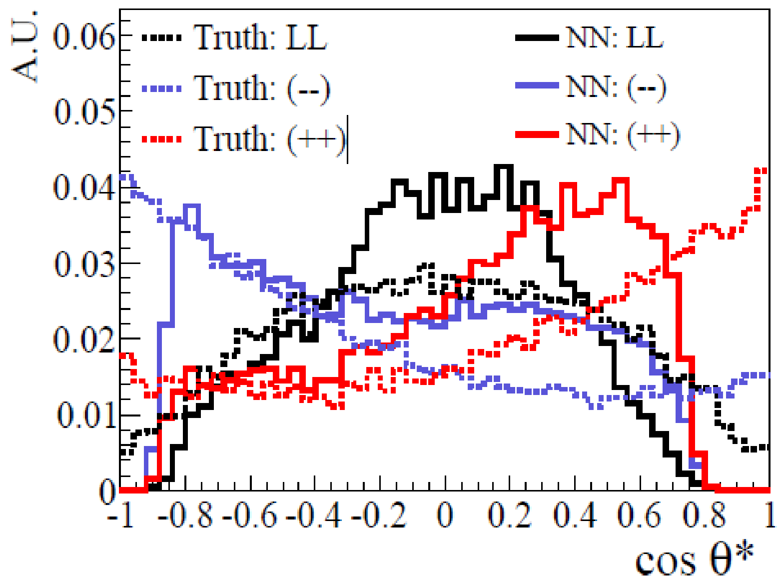
- MC pure helicity state distributions:
  - Reweighting method:
    - Some effects (interference, off-shell) incorporated in the templates
    - Are all dependence accounted for in pT(V) & Y_V ?
    - Reweighting other variables ?
  - Individual simulation (Madgraph, Phantom)
    - Easy access to all variables
    - The 3 states do not necessarily sum up to total (interference)

b) Conclusion and outlook : HL-LHC

- Good opportunity to study VBS and longitudinal scattering
  - Evidence for LL at 1.5 to 3 σ/ exp
- Stricto Sensu: $VV \rightarrow V_L V_L$
  - What about polarization of the initial state ?
- Multivariate methods not fully exploited yet in LL extraction
  - Several variables sensitive:
    - **$\cos\theta^*$**
    - **$\Delta\Phi_{jj}$**
    - pT(l), pT(V) …

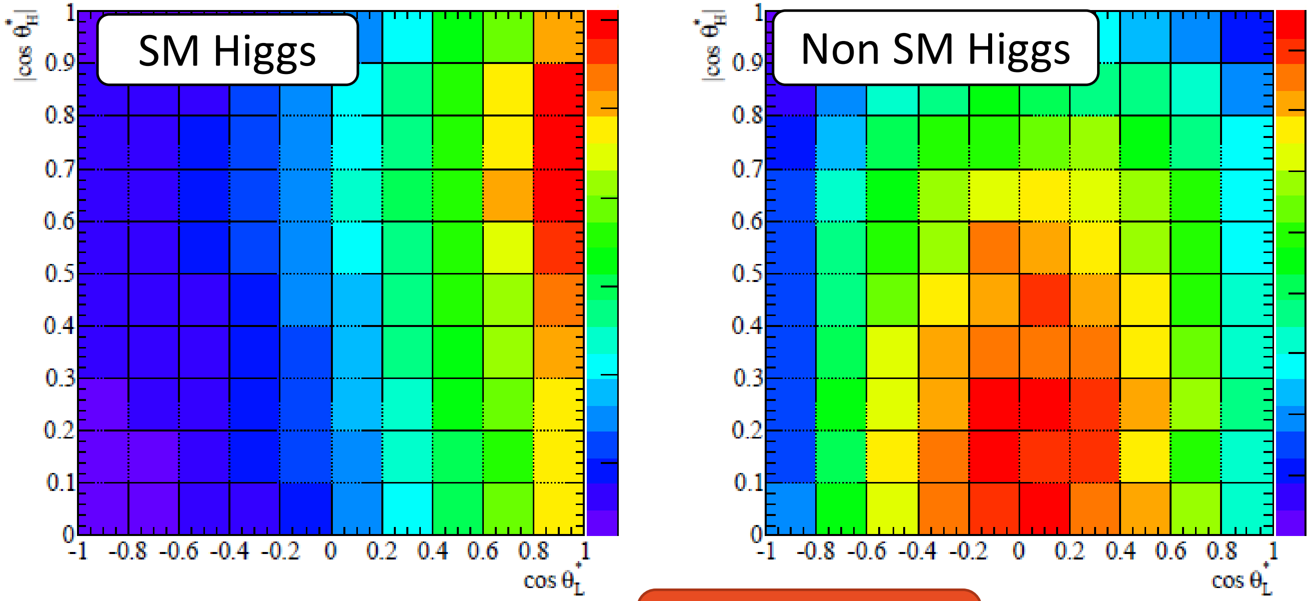
arXiv:1510.01691 J Searcy et al.

- **ssWWjj**
  - Regression NN to approximate cosθ* from 14 kinematic variables



arXiv:0911.3656 Tao Han et al

- **Using semileptonic decays ?**
  - with $|\cos\theta^*_H|$



Cori

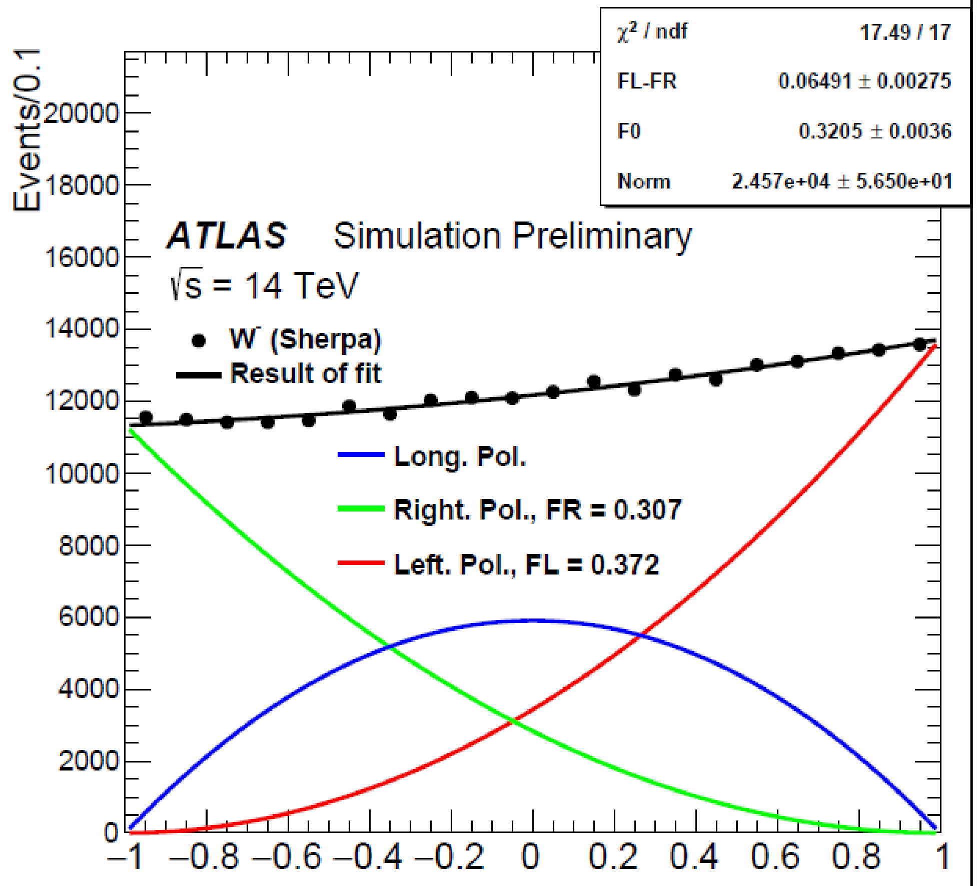
WWjj

BACKUP

Extracting the polarization of vector boson

- Several variables are sensitive.
- The most powerful:
  - Angular distribution of the decay products in the V restframe
- Hadronic decays
  - Z/W difficult
  - q/antiquark
- Leptonic decays : e & μ
  - $Z \rightarrow \ell\ell$: 3.3658(23) %
  - $W \rightarrow \ell\nu$: 10.86(9) %

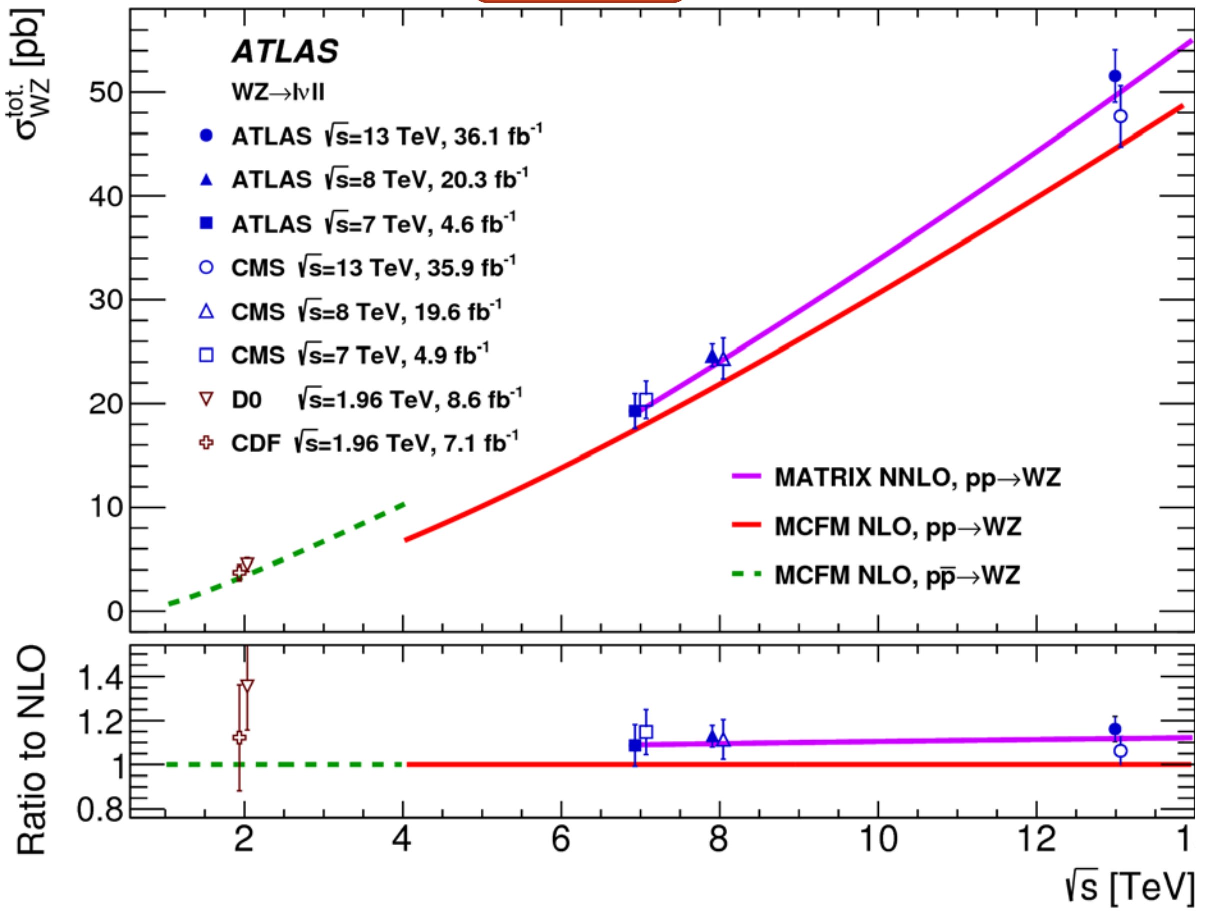
W⁻Zjj

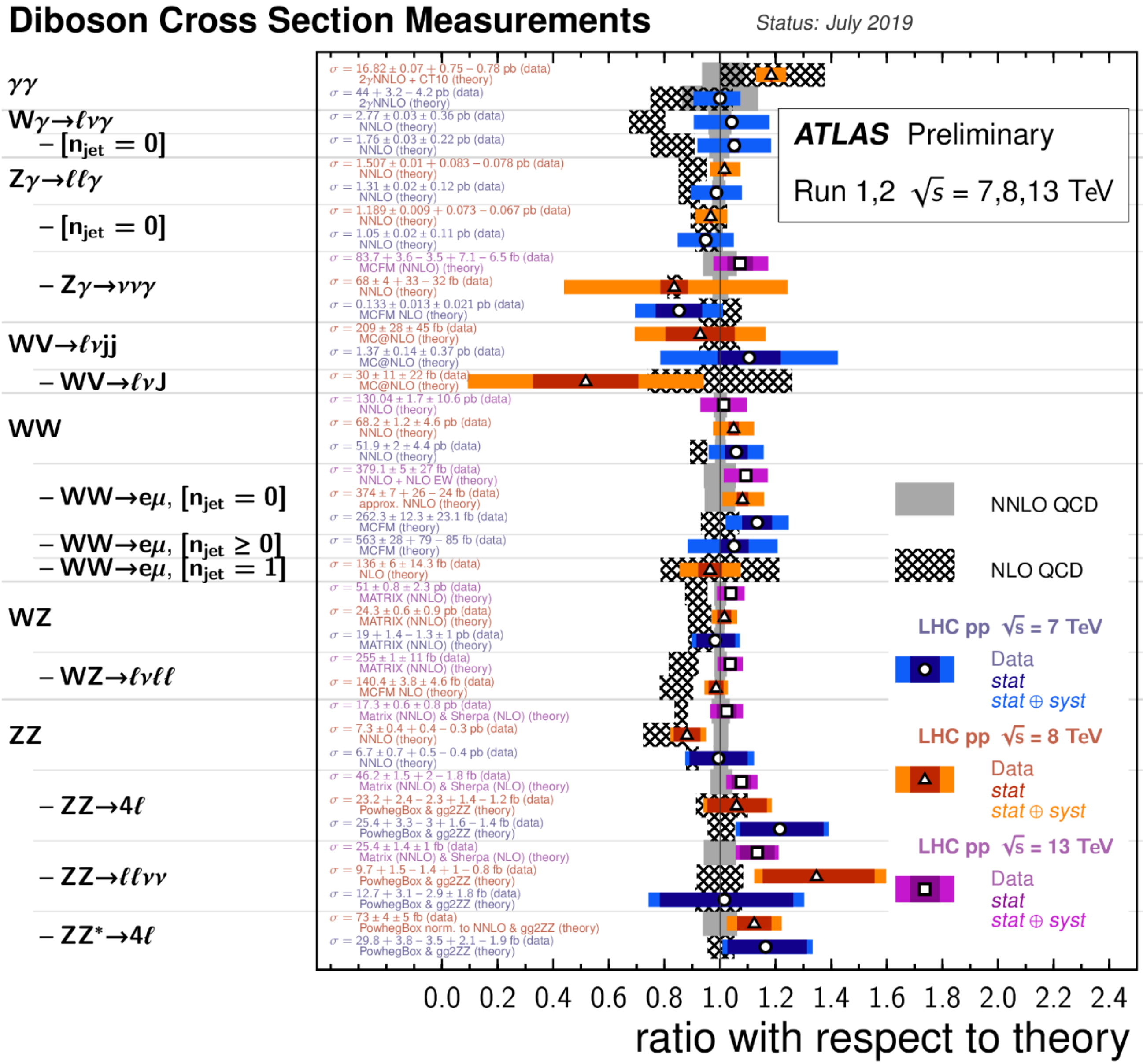


"cosθ*" : angle of the lepton direction in the V restframe with respect to the direction of the W in WZ c-o-m

WZ : the need for NNLO precision

WZ



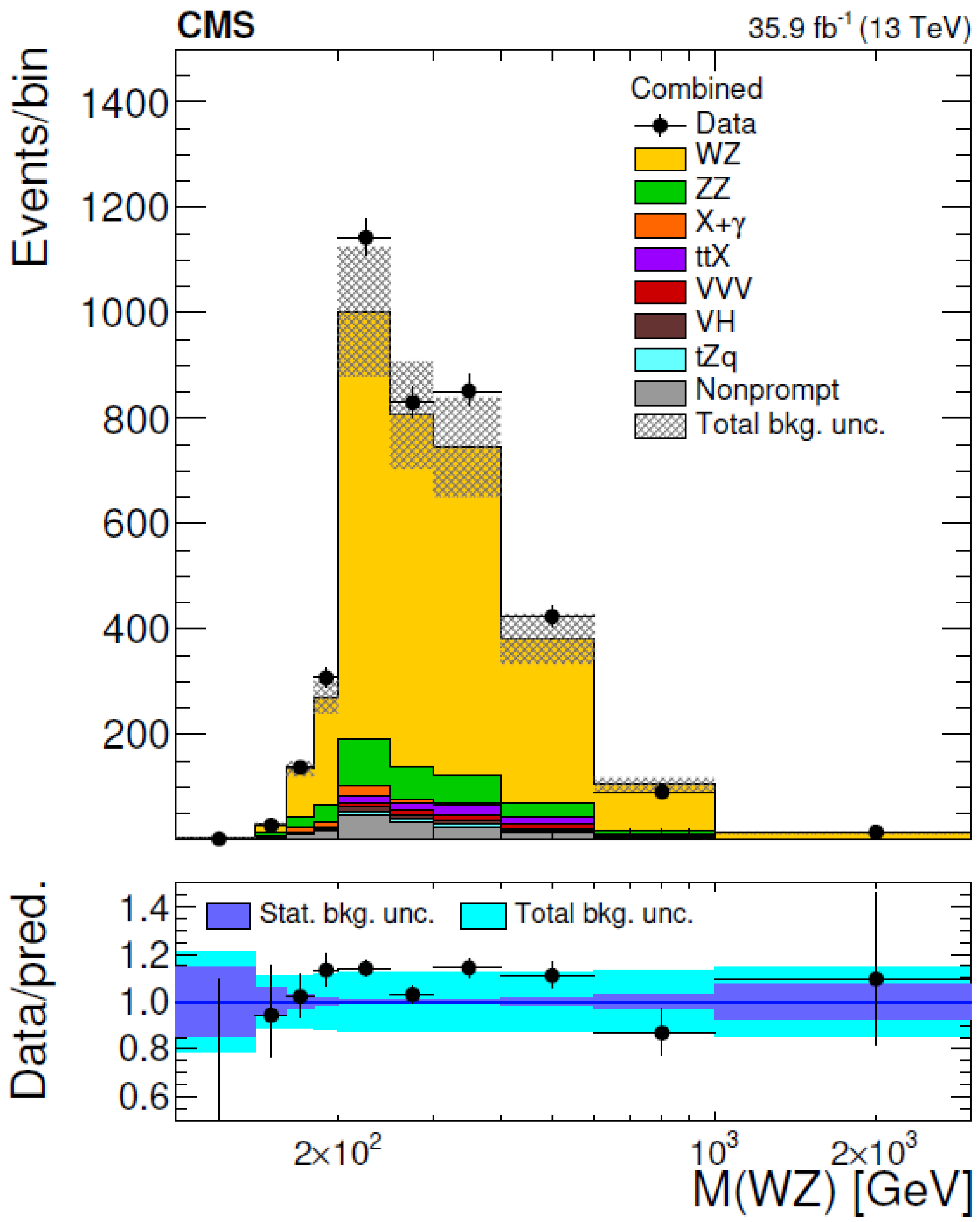


WZ inclusive (ATLAS)

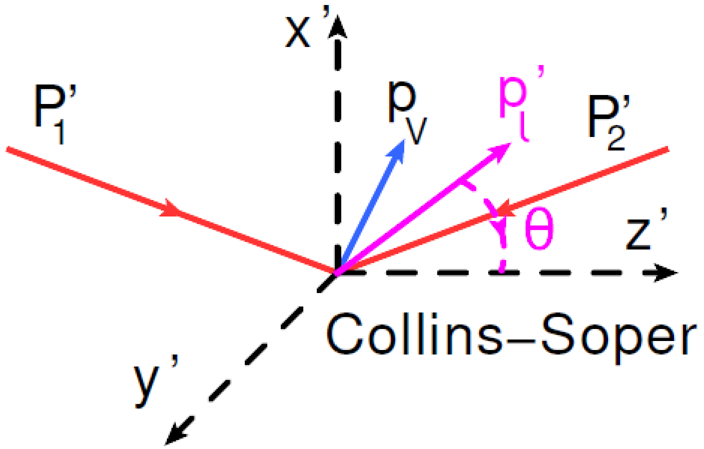
Channel	eee		μee		$e\mu\mu$		$\mu\mu\mu$		All	
Data	1279		1281		1671		1929		6160	
Total expected	1221	7	1281	6	1653	8	1830	7	5986	14
WZ	922	5	1077	6	1256	6	1523	7	4778	12
Misid. leptons	138	5	34	2	193	5	71	2	436	8
ZZ	86	1	89	1	117	1	135	1	426	3
$t\bar{t}$+V	50.0	0.7	54.0	0.7	56.1	0.7	63.8	0.8	225	1
tZ	23.1	0.4	24.8	0.4	28.8	0.4	33.5	0.5	110	1
VVV	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)

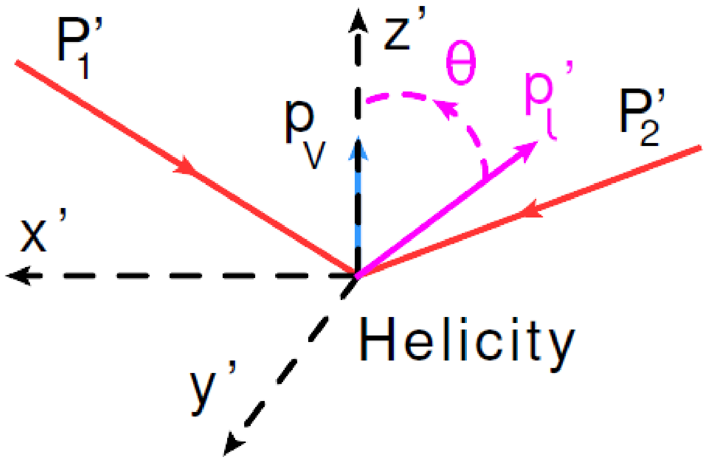
WZ inclusive (CMS)



Coordinate systems



- p1',p2' directions of the beam in the boson c-o-m
- Z' is the bisector of p1', - p2'
- Z' points toward V in the lab



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

NLOQCD & EW corrections

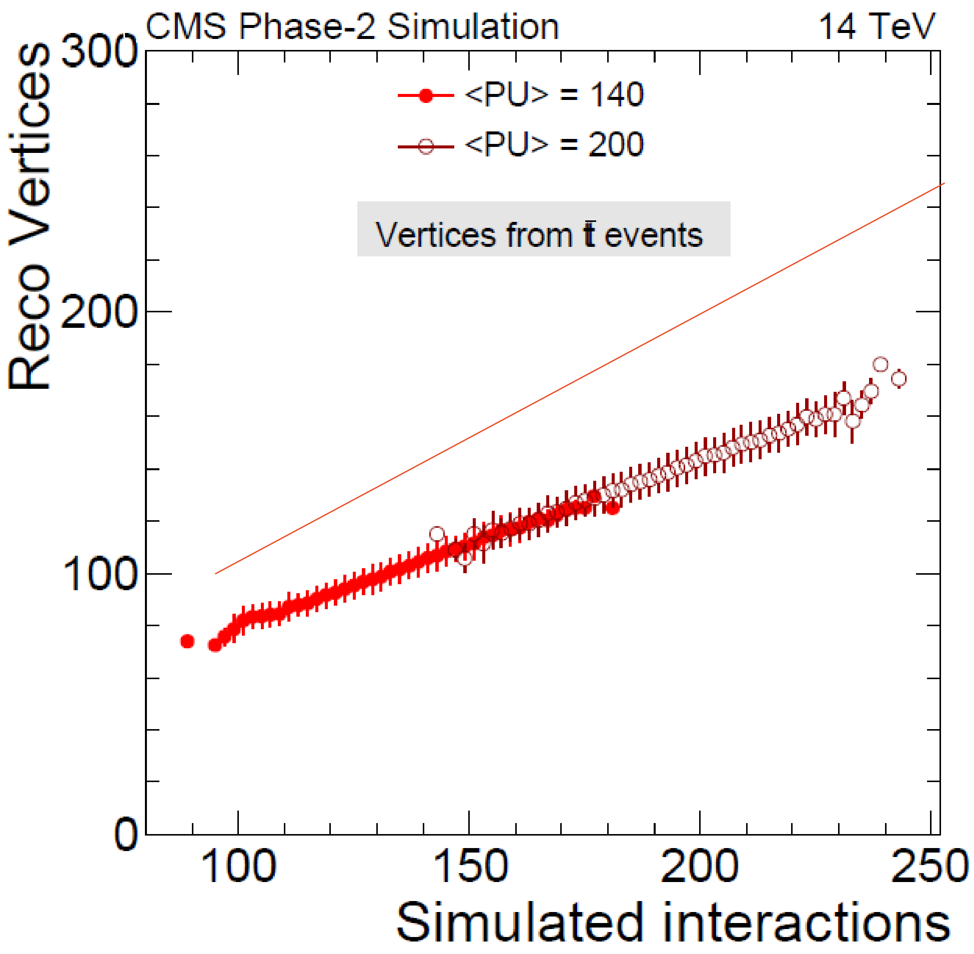
$$f_L^{W\pm} = -\frac{1}{2} \mp \langle\cos\theta_3\rangle + \frac{5}{2}\langle\cos^2\theta_3\rangle, \qquad f_R^{W\pm} = -\frac{1}{2} \pm \langle\cos\theta_3\rangle + \frac{5}{2}\langle\cos^2\theta_3\rangle,$$

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

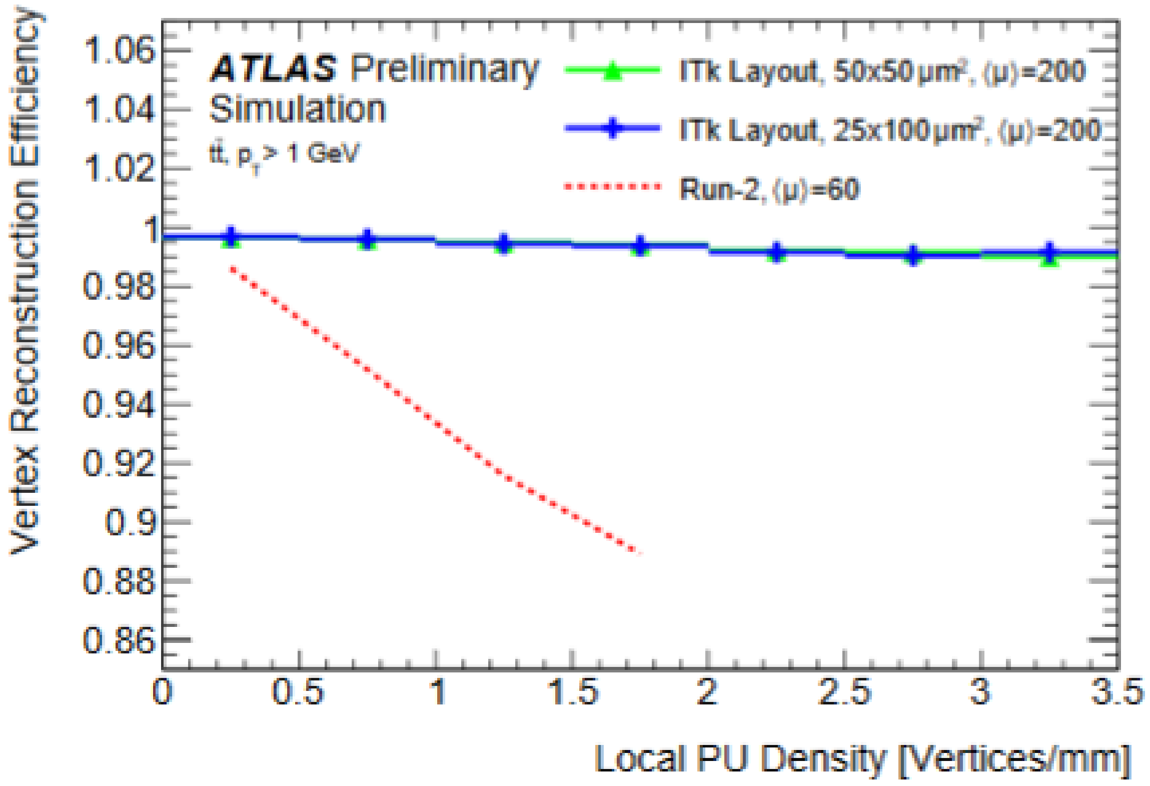
In Atlas Fiducial Phase Space

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



CMS Phase-2 Simulation
14 TeV
<PU> = 140
<PU> = 200
Vertices from tt̄ events
Reco Vertices
Simulated interactions
0
100
200
300
100
150
200
250



ATLAS Preliminary
Simulation
tt̄, p_T > 1 GeV
ITk Layout, 50x50µm², ⟨µ⟩=200
ITk Layout, 25x100µm², ⟨µ⟩=200
Run-2, ⟨µ⟩=60
Vertex Reconstruction Efficiency
Local PU Density [Vertices/mm]
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0.88
0.86
0
0.5
1
1.5
2
2.5
3
3.5

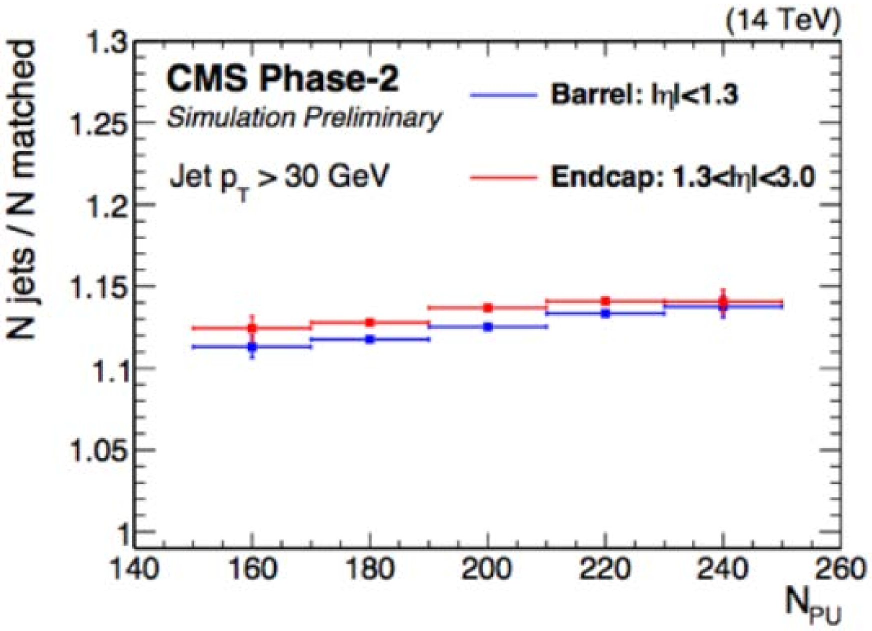
Consequences for object reconstruction

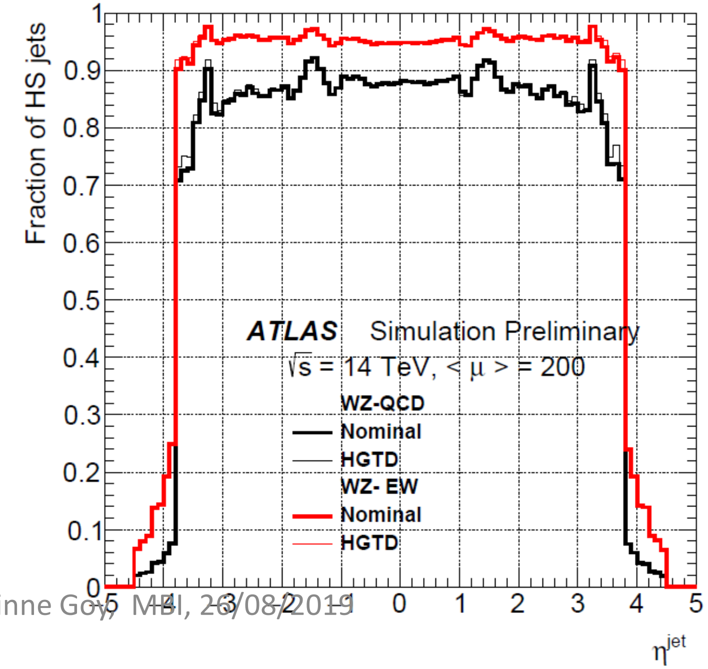
$\|\eta\|$	CMS	ATLAS
Track reconstruction	4.	
Electrons	3.	4.
Muon	2.8	2.7 (4. with muon tagger)
PU rejection	Excellent in the tracker acceptance	
	3. – 4.	3.8

Exemple:

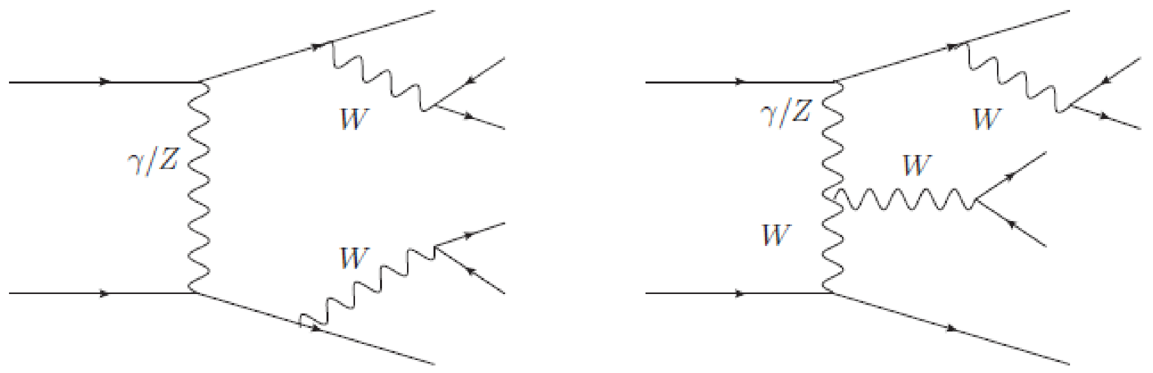
ATLAS: WZjj $\rightarrow 3\ell\nu$ +18% (+25%)

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

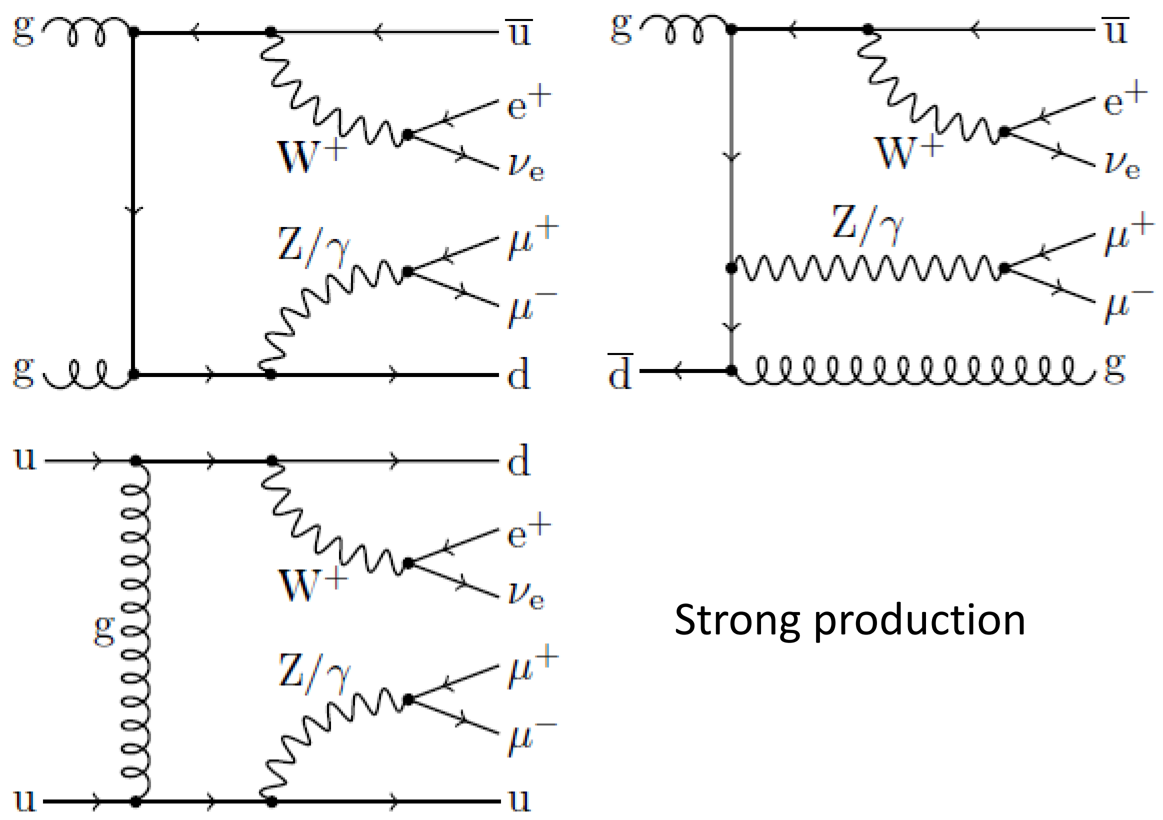




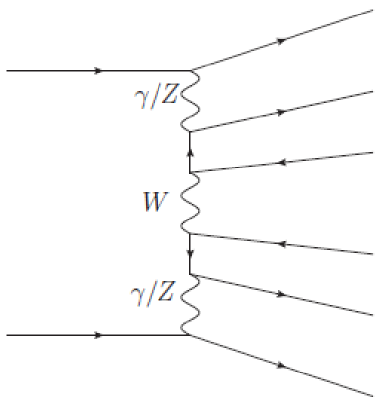
Example of diagrams



EW Resonant diagrams: irreducible background.

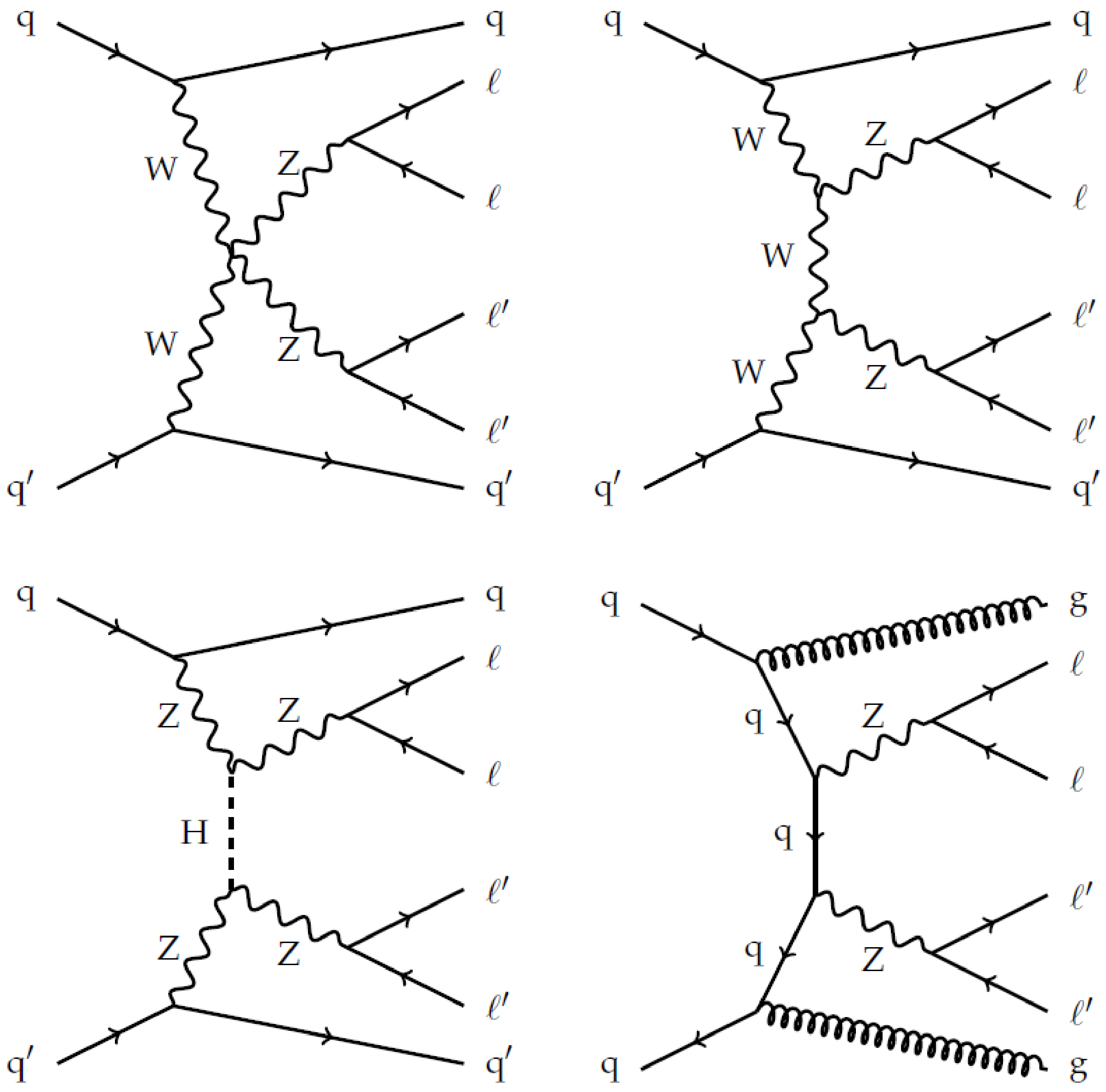


Strong production

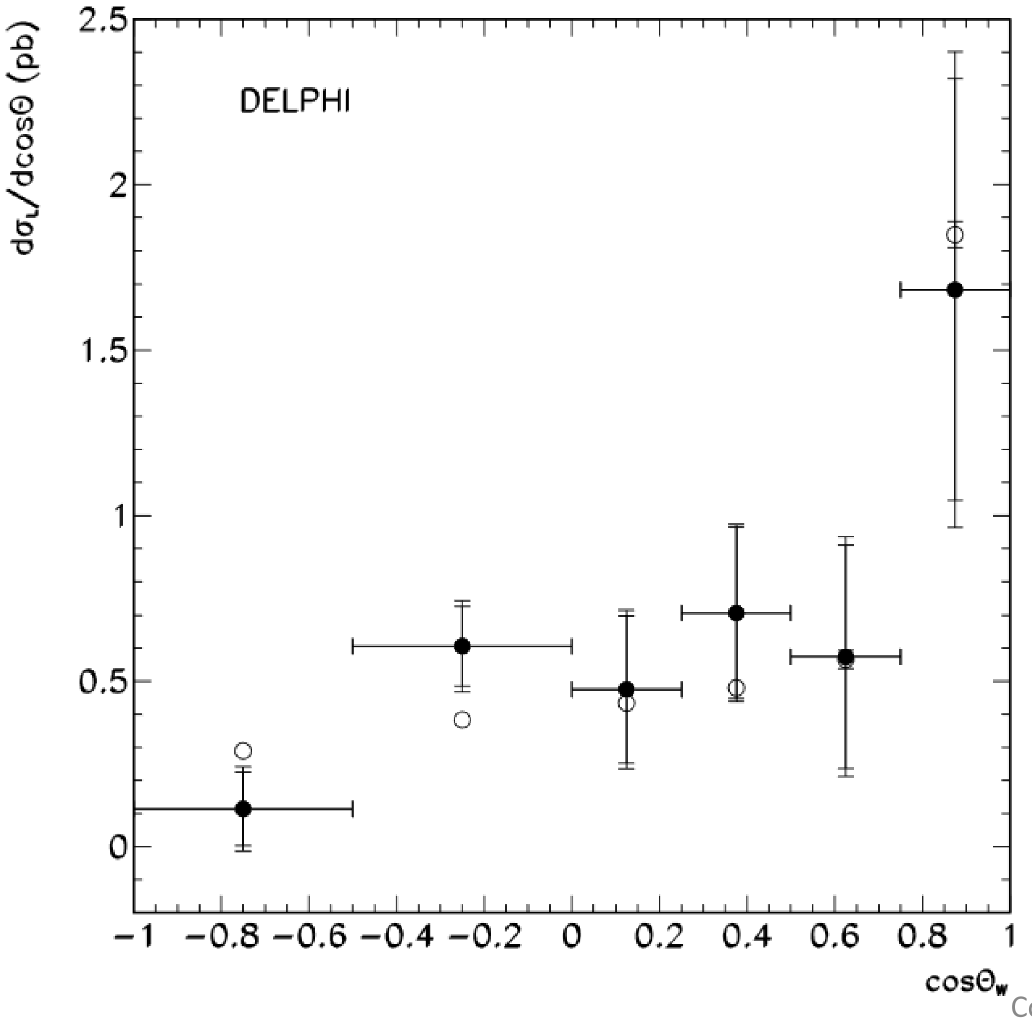


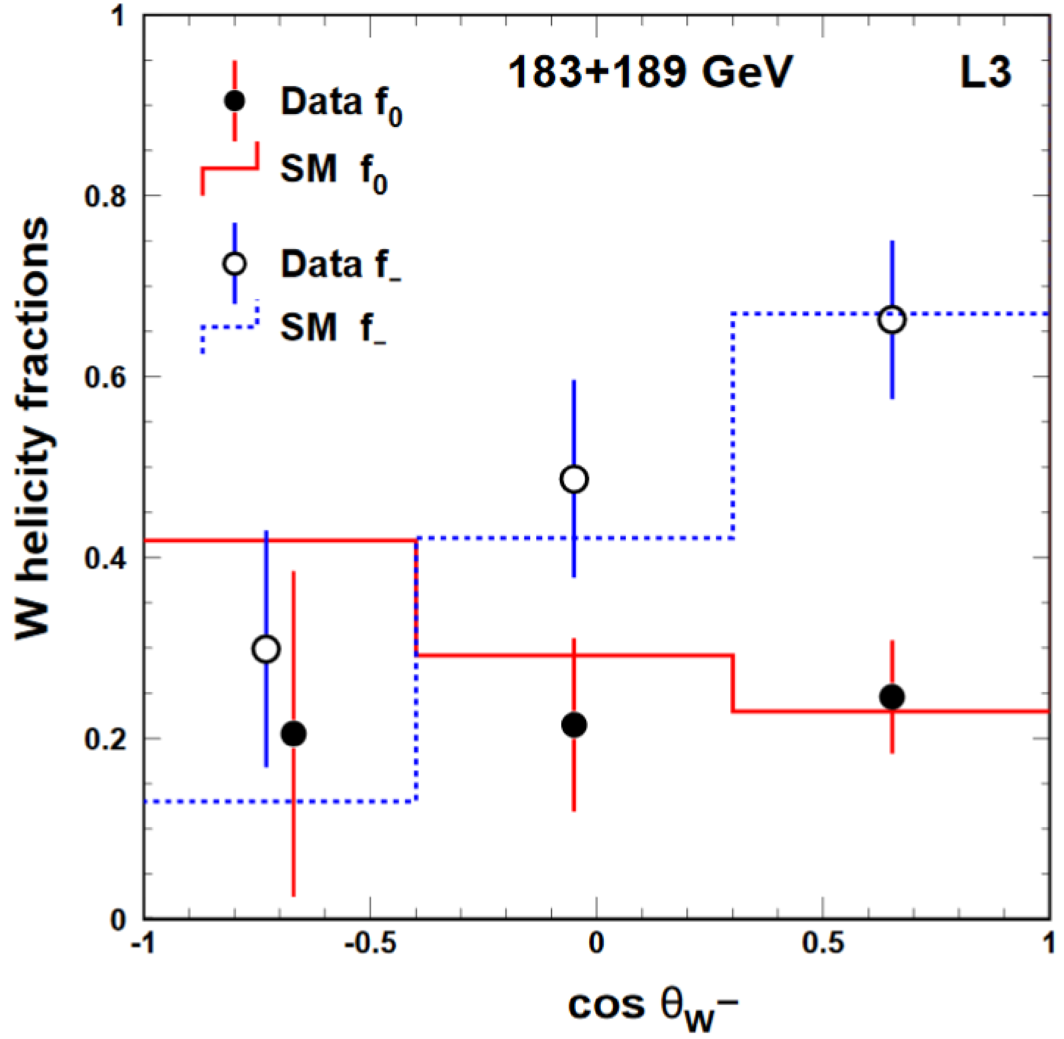
(c) Non resonant diagrams.

ZZjj diagrams



First measurements performed @LEP





WWjj

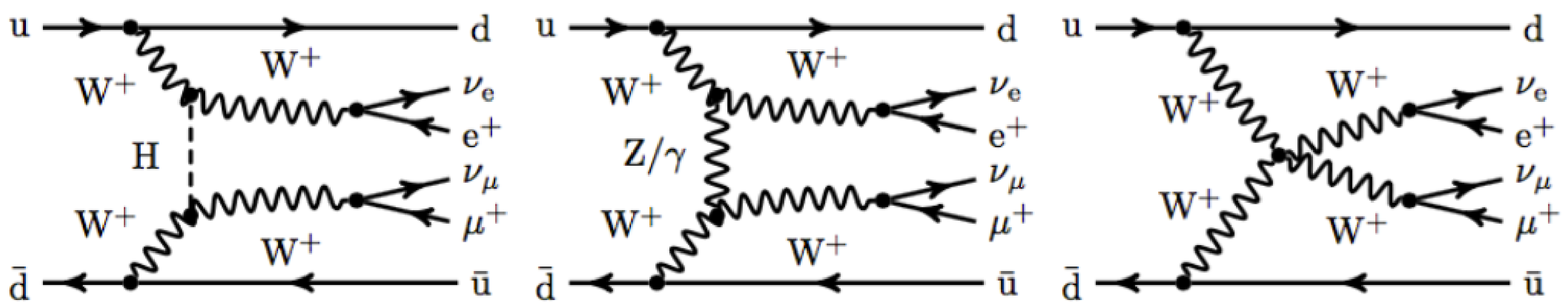


Figure 1: Representative Feynman diagrams for $W^{\pm}W^{\pm}$ electroweak production in proton-proton collisions: (left) t-channel Higgs boson exchange, (middle) t-channel Z/γ exchange with triple gauge couplings, (right) quartic gauge coupling.

Exemple of discriminant variables

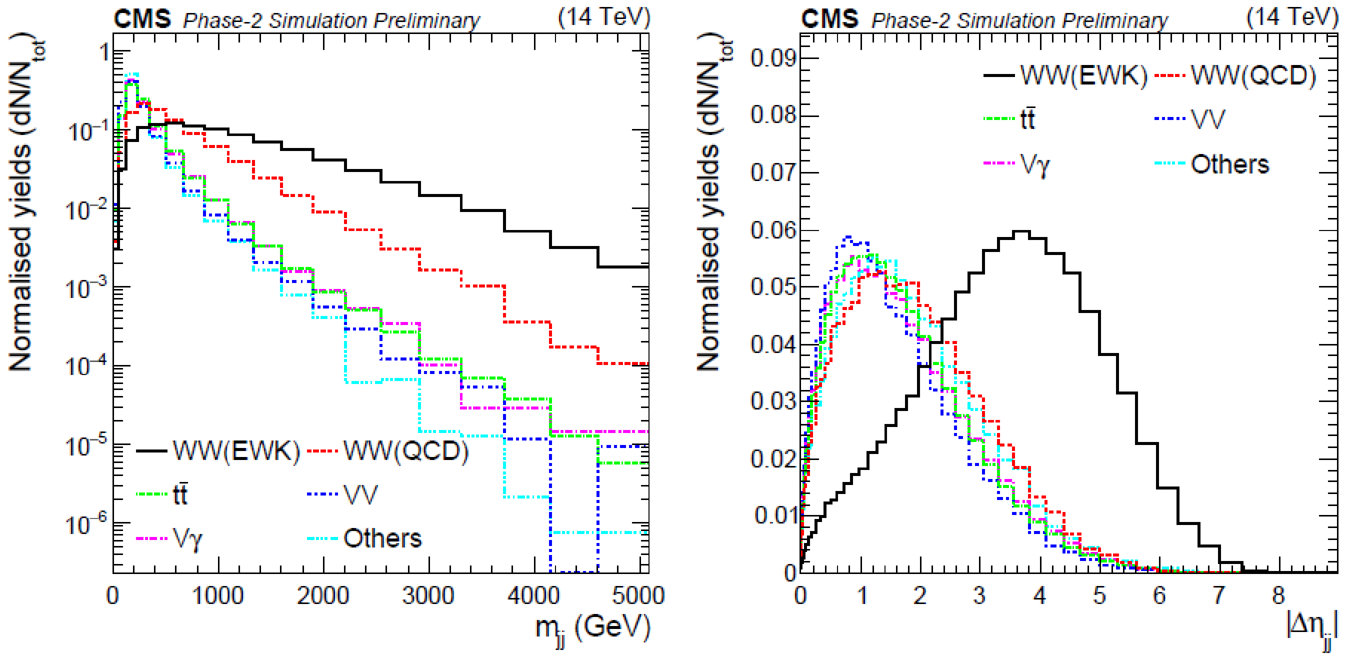


Figure 2: Shape comparisons for signal and background processes. Left: Invariant mass of the two leading jets. Right: The difference in pseudorapidity between them.

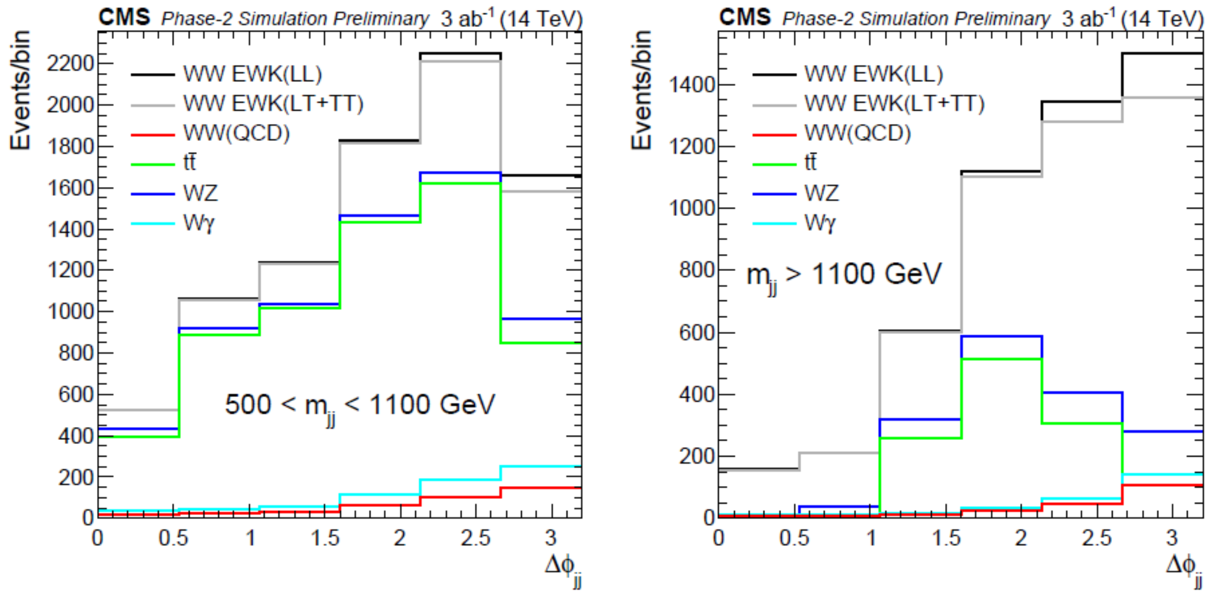


Figure 6: Distributions of the azimuthal angle difference between the two leading jets for dijet invariant mass in the range 500–1100 GeV (left) and above 1100 GeV (right). Stacked contributions from the signal and various backgrounds are shown.

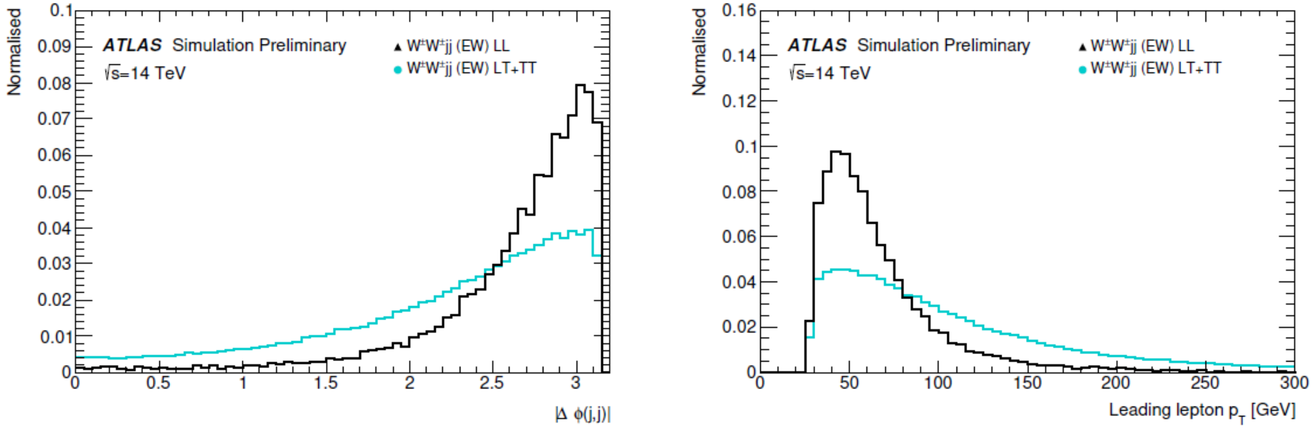
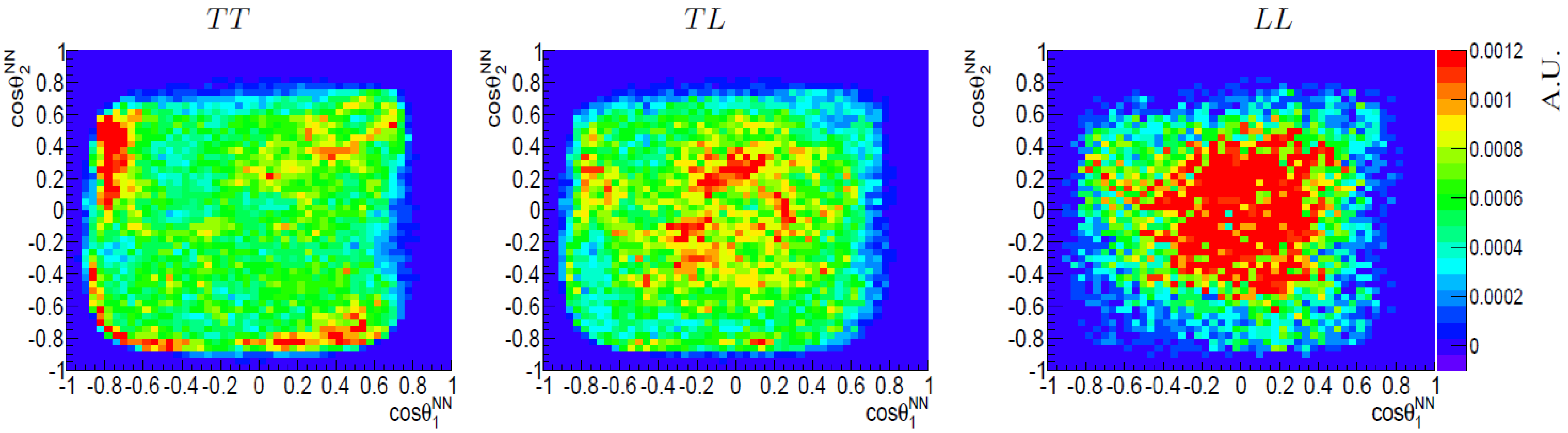
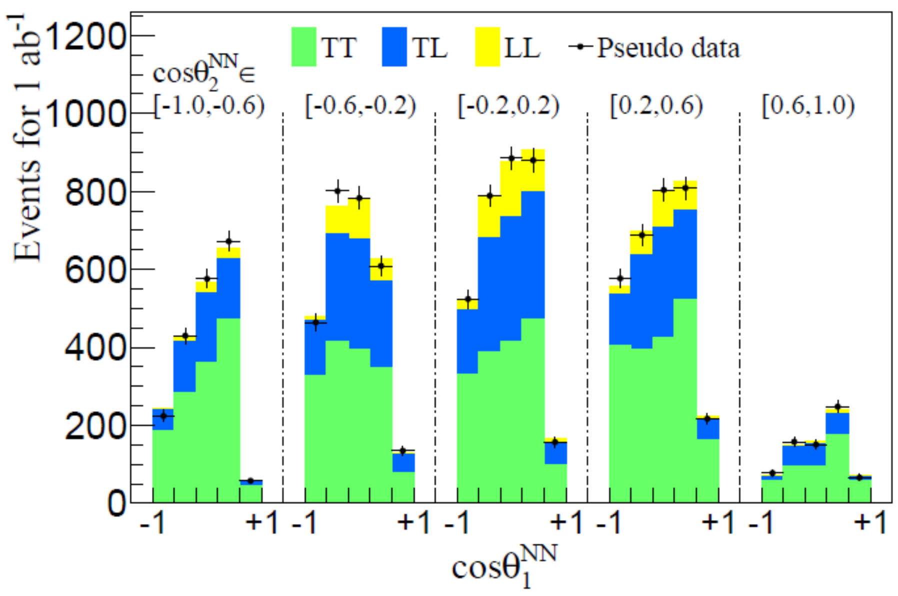
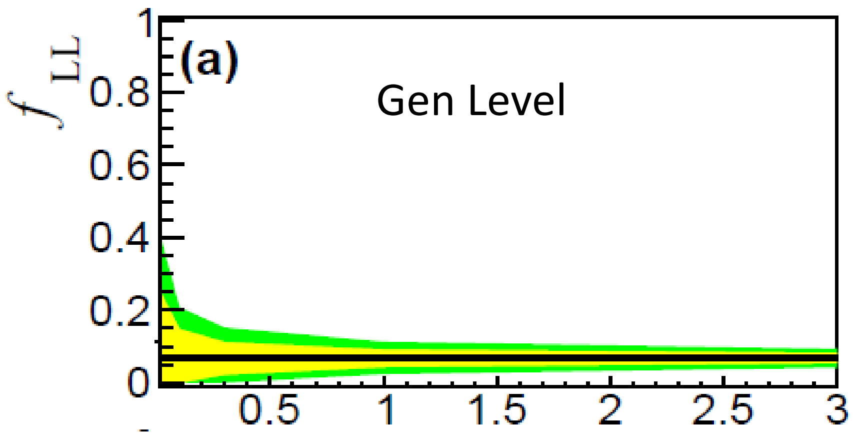
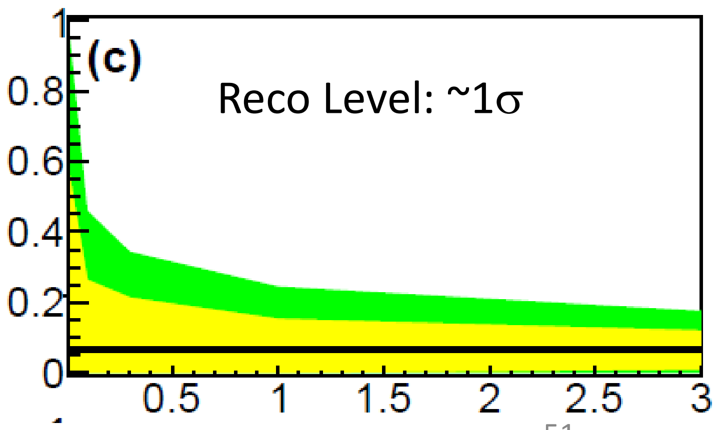


Figure 7: Shape comparisons for the dijet azimuthal separation $|\Delta\phi(j, j)|$ (left) and leading lepton p_T (right) distributions, for the purely longitudinal (LL) and combined mixed and transverse (LT+TT) $W^{\pm}W^{\pm}jj$ events.


TT
TL
LL
$\cos\theta_2^{NN}$
$\cos\theta_1^{NN}$
A.U.
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0


Events for 1 ab^{-1}
TT
TL
LL
Pseudo data
$\cos\theta_2^{NN} \in$
[-1.0,-0.6)
[-0.6,-0.2)
[-0.2,0.2)
[0.2,0.6)
[0.6,1.0)
$\cos\theta_1^{NN}$


f_{LL}
(a)
Gen Level


(c)
Reco Level: ~1σ

WZjj

Exercise as no background is considered.

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

2D fit more efficient

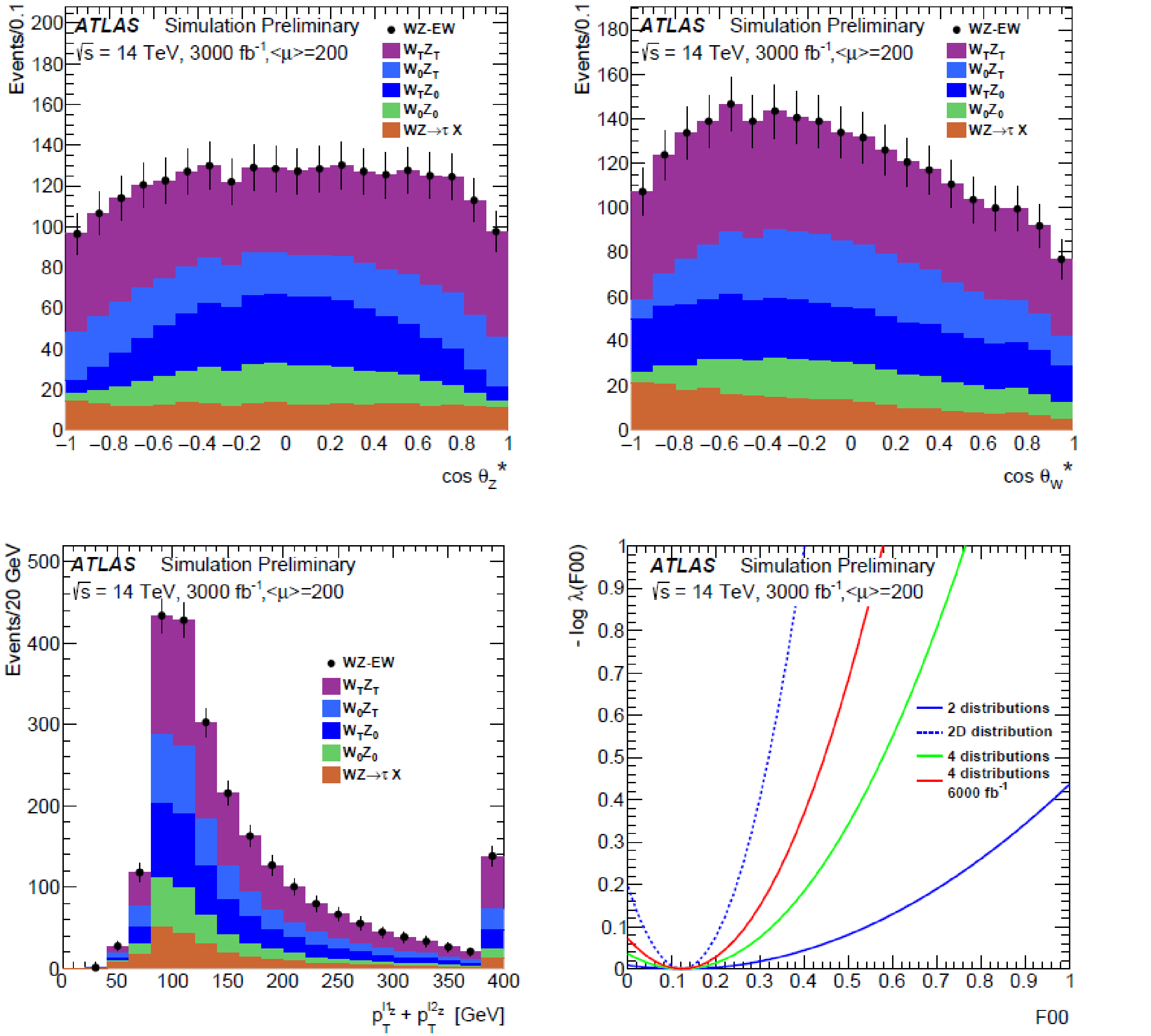
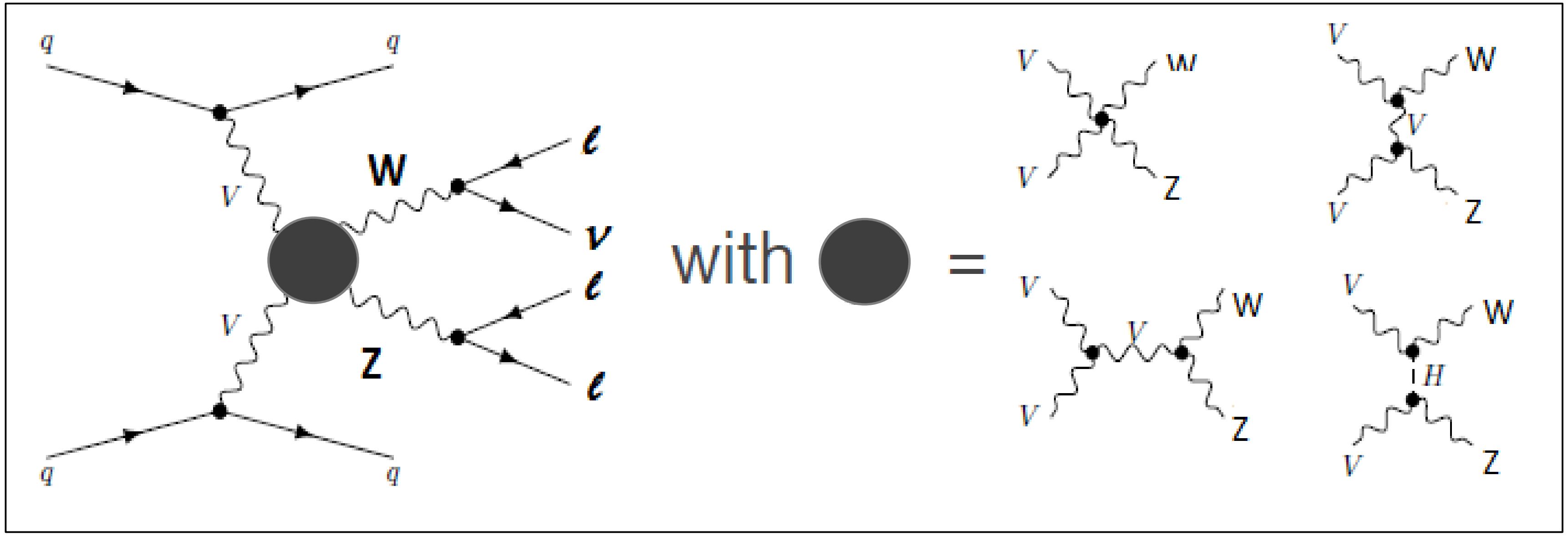


Figure 22: Results of the template fit for 3 distributions from the 4 used. Top Left: $\cos\theta^*_Z$,Top Right: $\cos\theta^*_W$ and Bottom Left: $p_T^{l1z} + p_T^{l2z}$. Bottom Right: Negative log-likelihood profile vs F00 for different fits.


q
q
V
W
ℓ
ν
V
ℓ
Z
ℓ
q
q
with
=
V
W
V
Z
V
W
V
V
Z
V
W
V
V
Z
V
W
H
V
Z