Maxime Gouzevitch

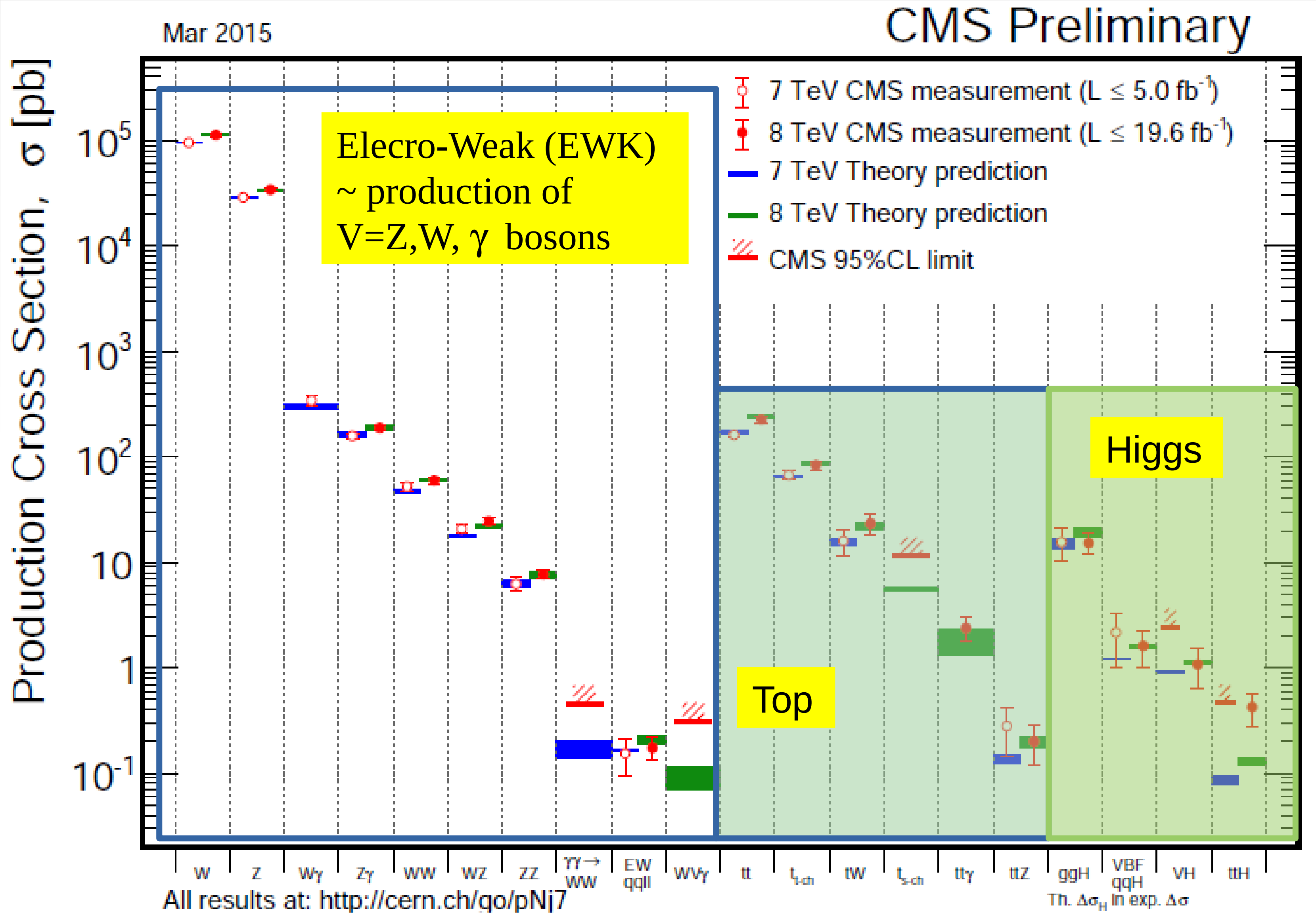
Electroweak physics measurements at the LHC

EPS HEP 2015

On behalf of the CMS and ATLAS collaborations

27/07/2015

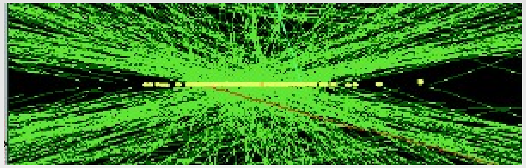
0) LCH physics landscape



EWK session: https://indico.cern.ch/event/356420/session/6/?slotId=7#20150723

0) Role of LHC in EWK landcape

- LHC is not a machine designed a priori for ElectroWeak (EWK) physics: large Pile-Up.

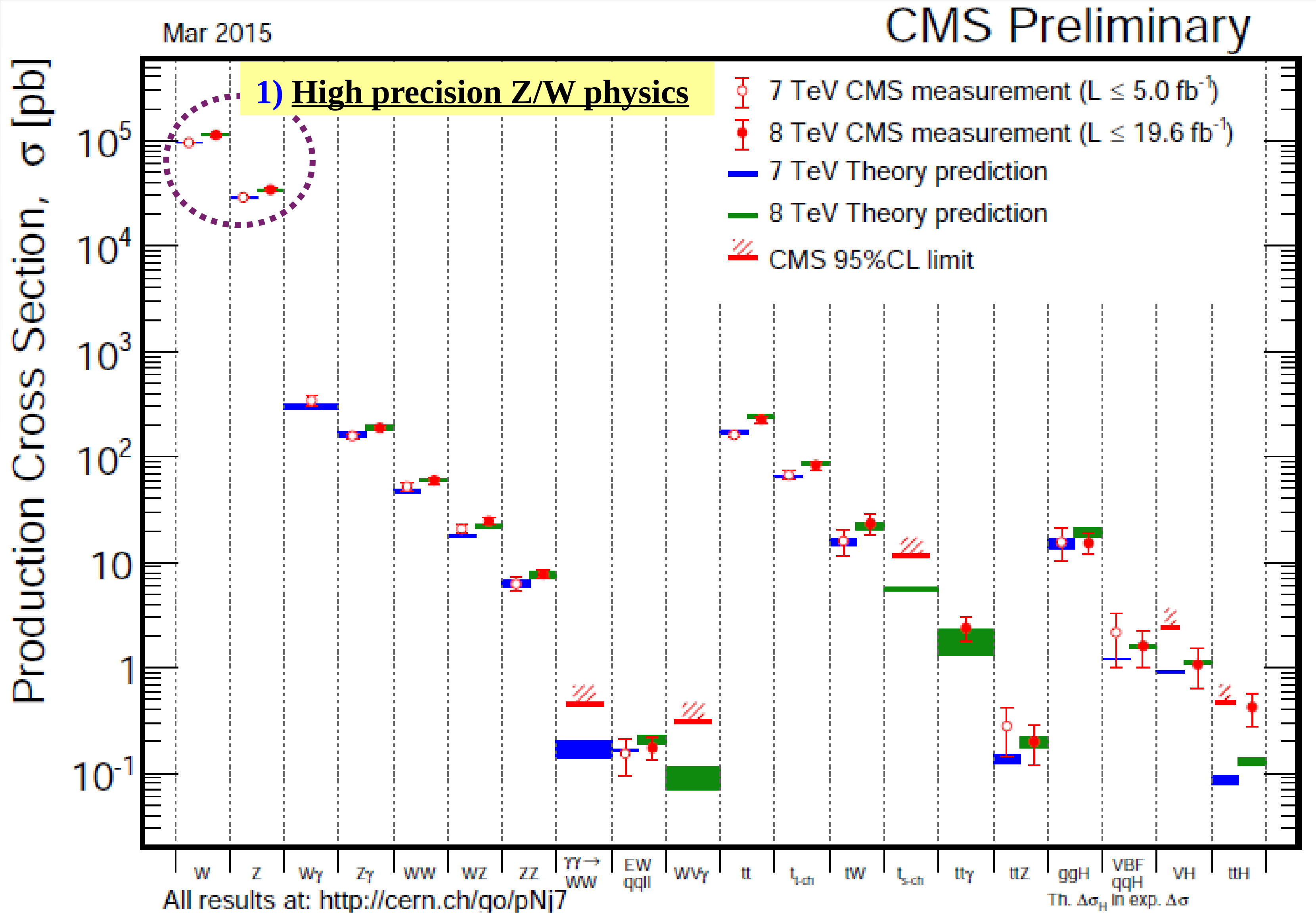


Event from special high pu run:
78 reconstructed vertices and 2 muons.

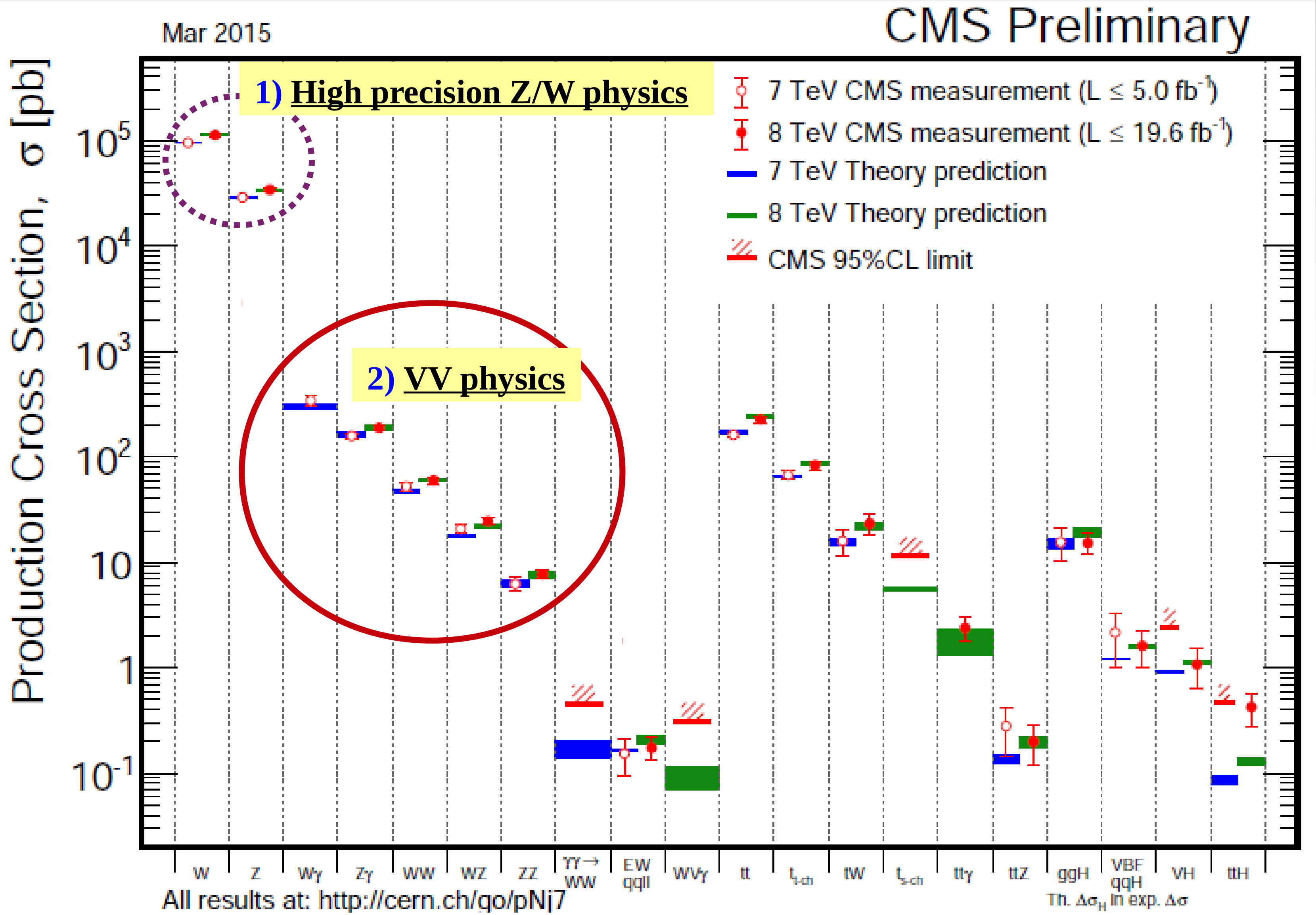
- But general purpose detectors were carefully designed to discover Higgs bosons with leptons/photon probes: e, μ, γ.
  - Efficient (> 80-90%)
  - Good separation of "isolated" leptons from EWK decays and in-jet leptons.
  - Trigger systems was optimized for probes with $p_T < M_W/2$.

- EWK physics is a very important "by-product" of the LHC design:
  - W is produced in s-channel in DY at Tevatron/LHC but not in ee collisions at LEP: large statistical sample to study W properties – mass/width.
  - VV production have to be well understood/measured: To support Higgs discovery. It is an (interfering) background for Higgs decays in VV final state.
  - High mass VV production and VV scattering are sensitive to the terms of SM/BSM Lagrangian well beyond LEP reach.

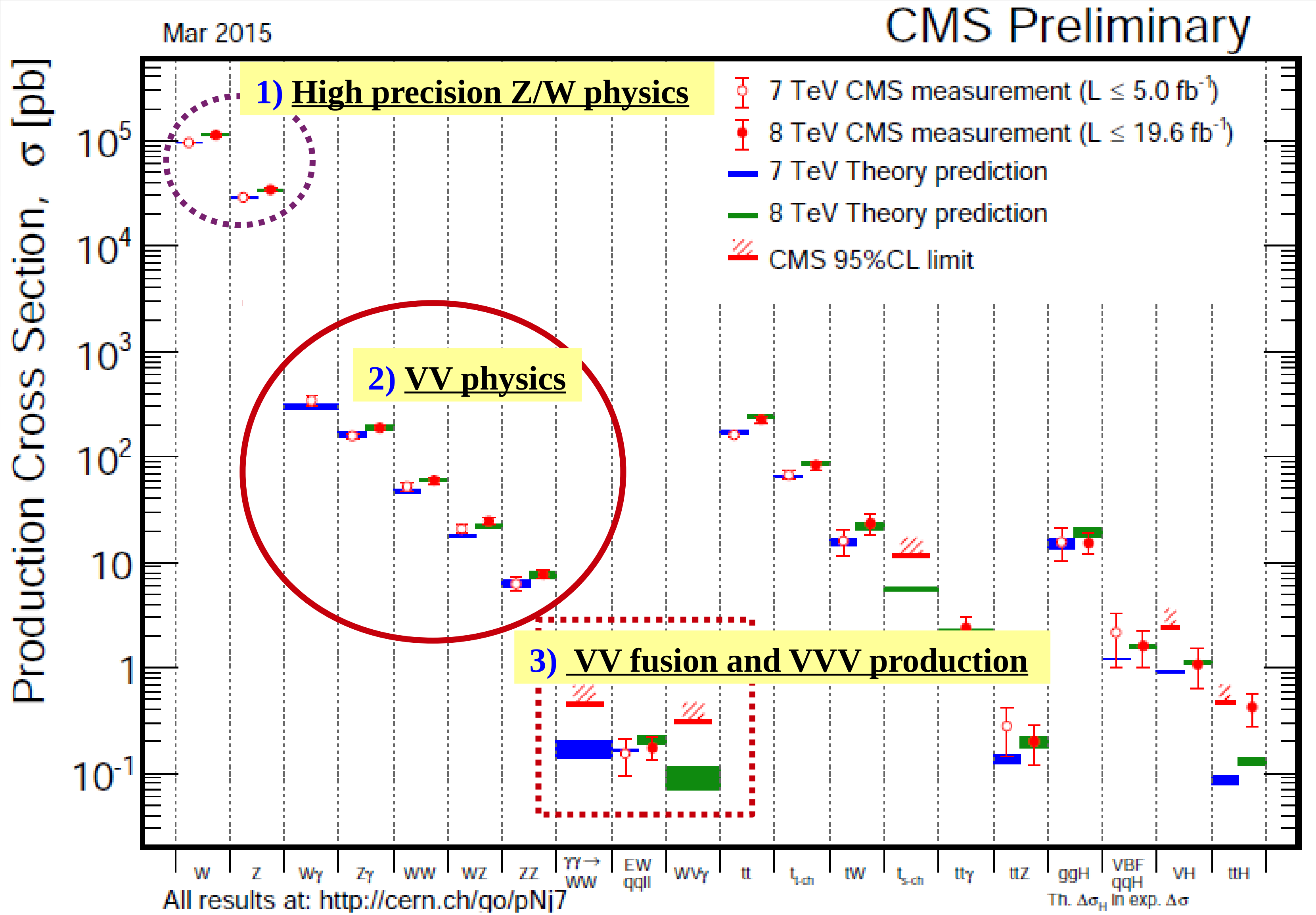
0) Table of content



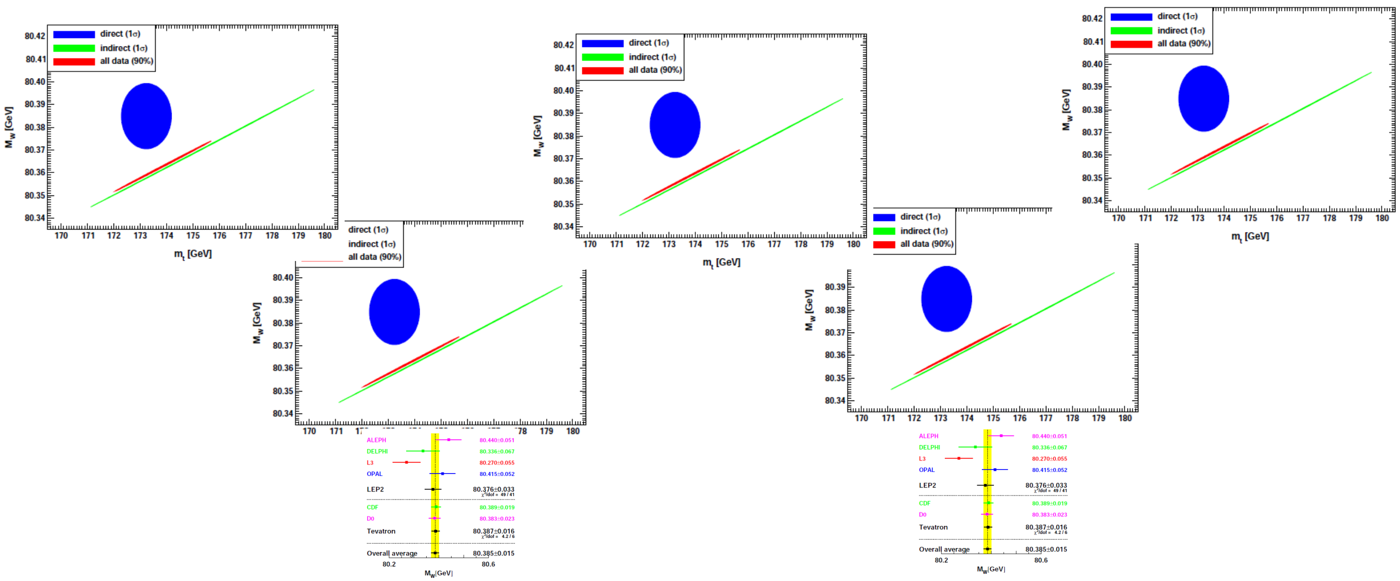
0) Table of content



0) Table of content

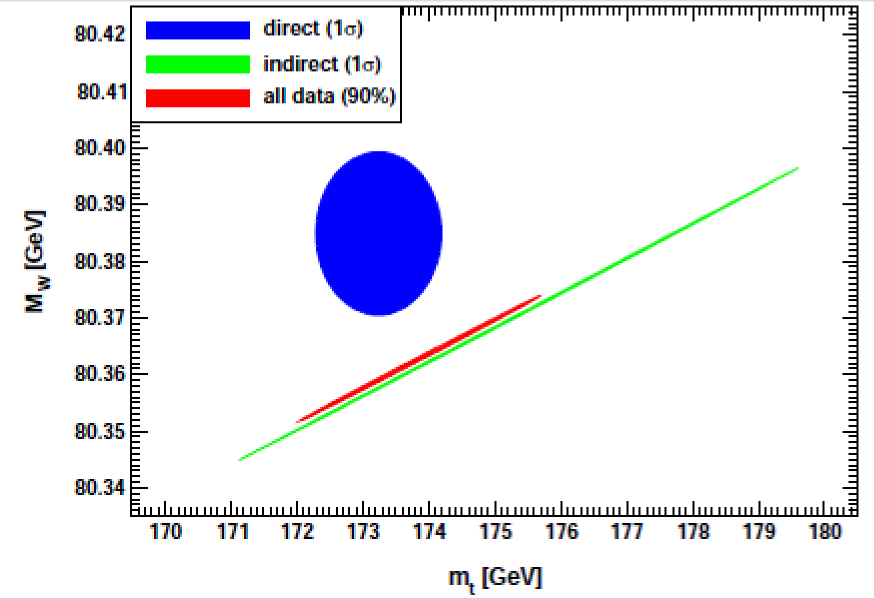


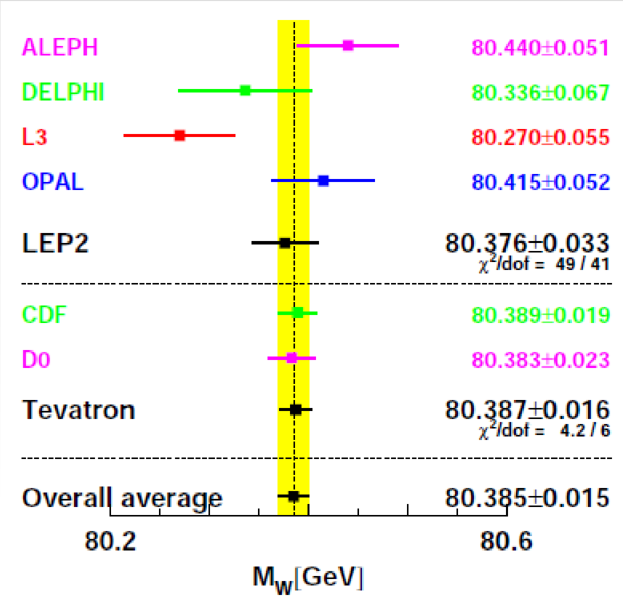
High precision W/Z physics



1.1) High precision W mass

PDG 2015 – CP C38 (2014) 090001





- M_W is the leading uncertainty in SM consistency tests.
- Previous measurements sets a natural goal of O(10 MeV) for the LHC.
  - LEP measurement limited by statistics (N_{WW} = O(40000) events).
  - Tevatron uses DY W → eν/μν events.
  - LHC follow the same trategy: statistics is 100 times larger than LEP one and not a limiting factor.

1.2) W mass challenge at the LHC

Current status:

Δ(QCD/QED) ~ Δ(calib) ~ Δ(stat)

Future (LHC/Tevatron):

Δ(QCD/QED) > Δ(calib) > Δ(stat)

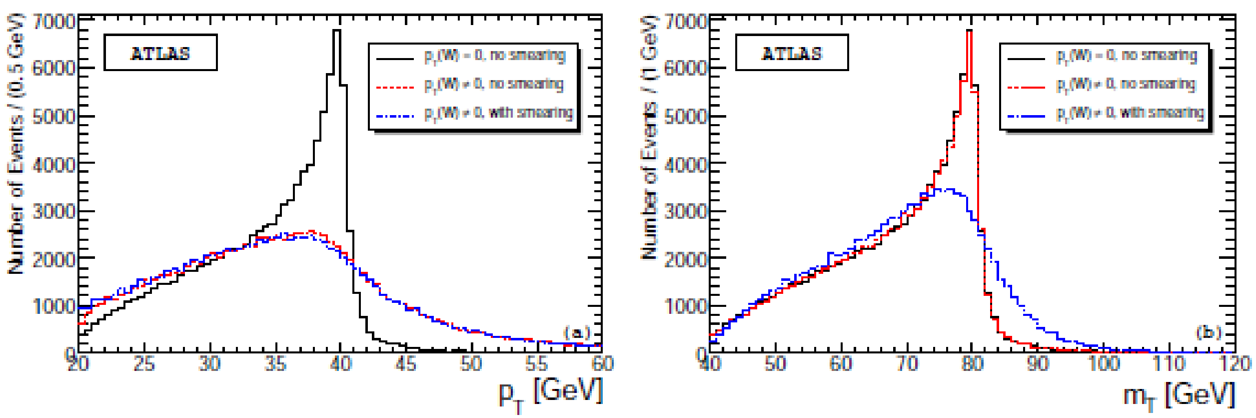
Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total	19

CDF – PRD D89 (2014) 072003

ATL-COM-PHYS-2009-102

$$\overrightarrow{p_T^{\nu}} = -\left(\overrightarrow{p_T^{l}} + \vec{u}\right)$$

$$M_T = \sqrt{p_T^{l} p_T^{\nu}(1 - \cos(\Delta\phi)}$$



- No QCD Initial State Radiation (ISR)
- With ISR
- With detector smearing

M_T: low dependence on QCD radiation, but large sensitivity to hadronic recoil

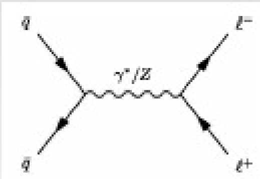
$P_{T,l}$: low sensitivity to experimental systematics, large dependence on QCD radiation.

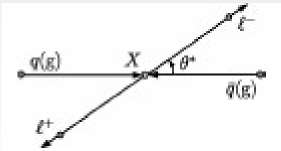
1.3) $\sin^2\theta_W$ extraction

For comparison : CDF PRD 89 (2014) 072005

ATLAS - arXiv:1503.03709

- Weinberg angle extracted from tensor structure of

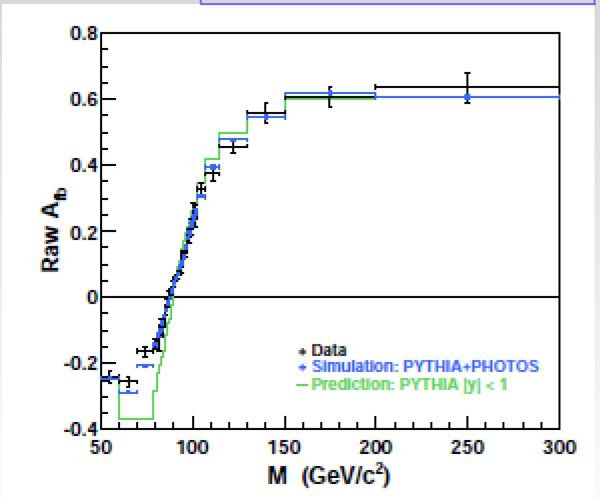


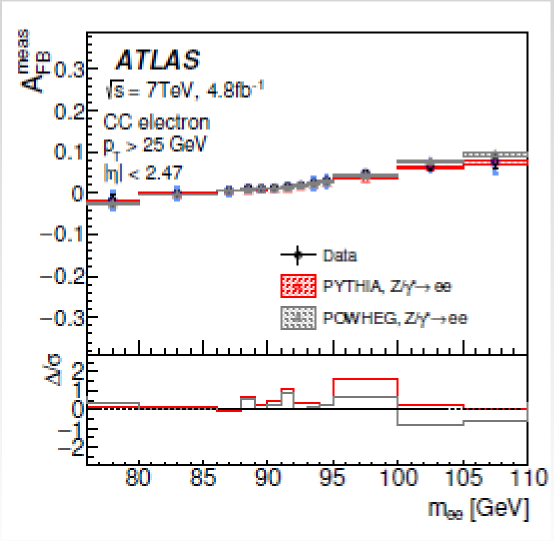


- Challenging!

Need to find q and qbar.

 - Easy ppbar and e^+e^-, hard in pp (dilution).



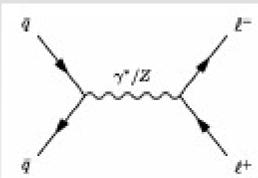


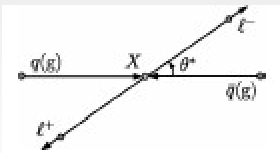
1.3) $\sin^2\theta_W$ extraction

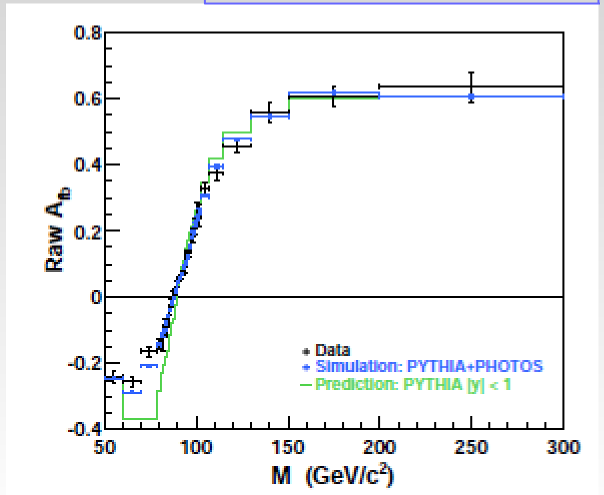
For comparison :
CDF PRD 89 (2014) 072005

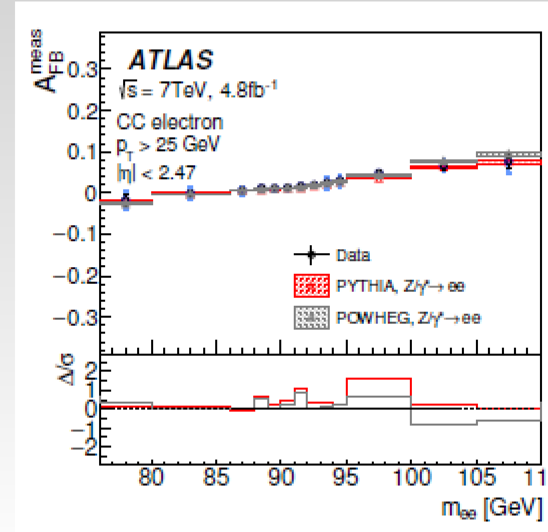
ATLAS - arXiv:1503.03709

- Weinberg angle extracted from tensor structure of



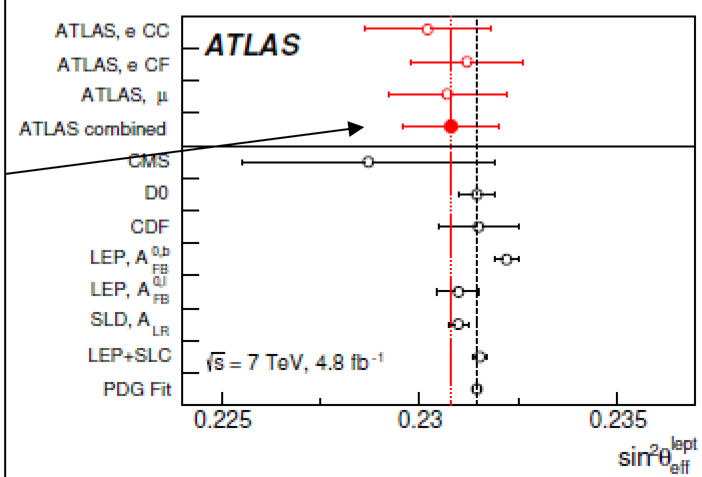






- Challenging!
Need to find q and qbar.
 - Easy ppbar and e+e-, hard in pp (dilution).

- 0.5% precision! Still room to improve to become world competitive.



- Related to W mass through:

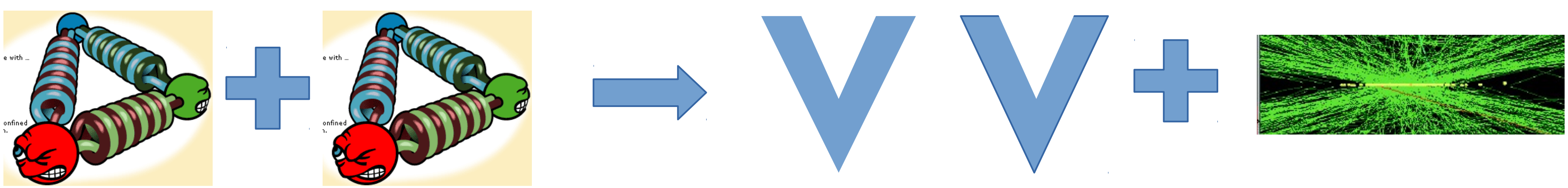
$$\cos\theta_W = \frac{m_W}{m_Z}$$

- Part of the same high precision analysis at LHC

- CMS AFB mesured but no cos yet → coming soon.

CMS-PAS-SMP-14-004

VV production



2.1) VV production in SM

- VV production is the bread and butter of EWK physics: all possible final states are measured ($\gamma\gamma$ production is not discussed in this talk)!
- Below a summary of what was performed till now.

7 TeV	W	Z
W	CMS : EPJC 73 (2013) 2610 ATLAS : PRD 87 (2013) 112001	
Z	CMS : SMP-12-006 ATLAS : EPJC 72 (2012) 2173	CMS : JHEP 01 (2013) 063 (4l) CMS : arXiv : 1503.05467 (2l2ν) ATLAS : JHEP 03 (2013) 128 (4l+2l2ν)
γ	CMS : PRD 89, 092005 (2014) ATLAS : PRD 87, 112003 (2013)	CMS : PRD 89 (2014) 092005 (llγ) CMS : JHEP 10 (2013) 164 (2$\nu\gamma$) ATLAS : PRD 87 (2013) 112003 (llγ)

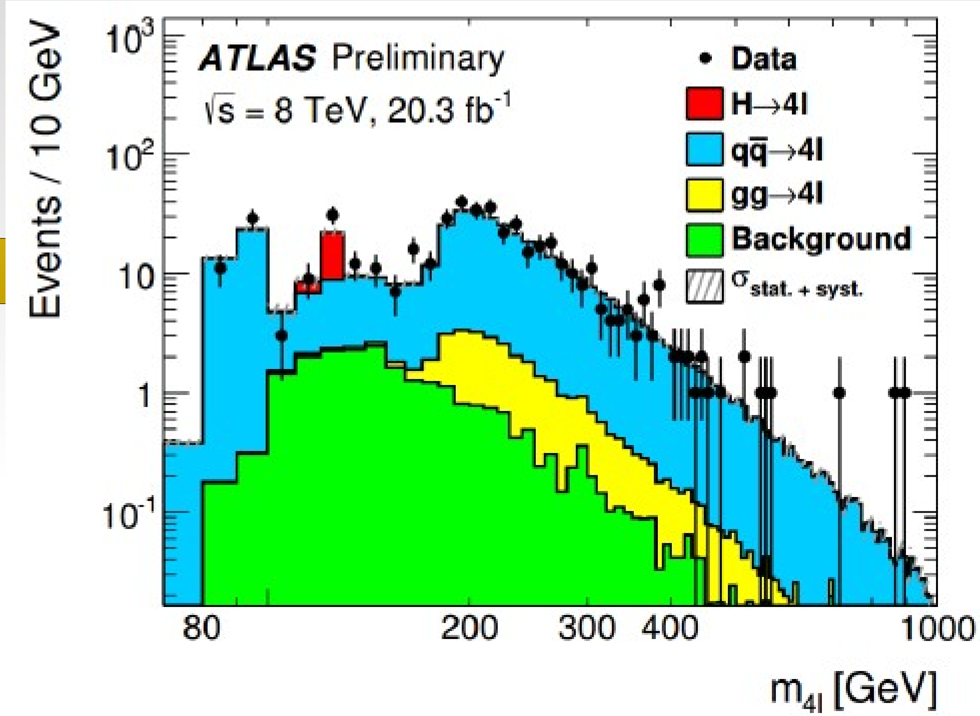
8 TeV	W	Z
W	CMS : arXiv:1507.03268 ATLAS : ATLAS-CONF-2014-033	
Z	CMS : SMP-12-006 ATLAS : ATLAS-CONF-2013-021	CMS : PLB 740 (2015) 250 (4l) CMS : arXiv:1503.05467 (2l2ν) ATLAS : ATLAS-CONF-2013-020 (4l+2l2ν)
γ		CMS : JHEP 04 (2015) 164 (llγ)

2.2) VV production: leptonic final states

- ZZ → 4l, WZ → 3lν :
  - Very clean final states.
  - S/B >> 1

ATLAS ZZ 8 TeV: ATLAS-CONF-2015-031

CMS ZZ 8 TeV: PLB 740 (2015) 250

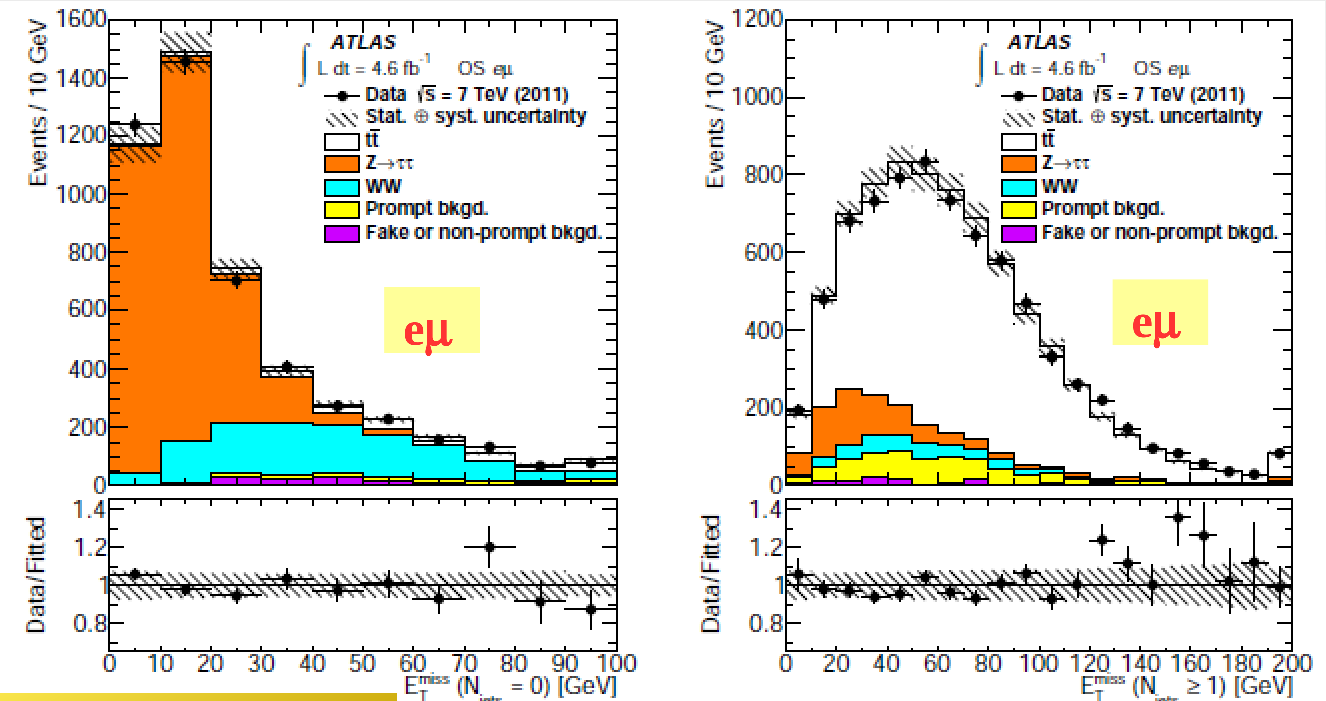


- WW → 2l2ν, ZZ → 2l2ν :
  - Larger BF.
  - S/B > 1: ttbar and Z→ττ are irreducible backgrounds.
  - V+jets an important background with fake $E_{T,miss}$. Using data to e

Next Page

2.3) Leptonic WW measurement

- WW cross section is measured together with major backgrounds – ttbar and Z $\rightarrow \tau\tau$
  - Using eμ final state to reduce DY.
  - Minor backgrounds: tW, WZ/ZZ fixed to SM prediction
  - Backgrounds from jets faking leptons extracted from data.



PRD 91 (2015) 052005

Well separated in $E_{T,miss}$ x N_{jets} space:

WW – lage $E_{T,miss}$
$N_{jets} \sim 0$

ttbar – lage $E_{T,miss}$
$N_{jets} > 0$

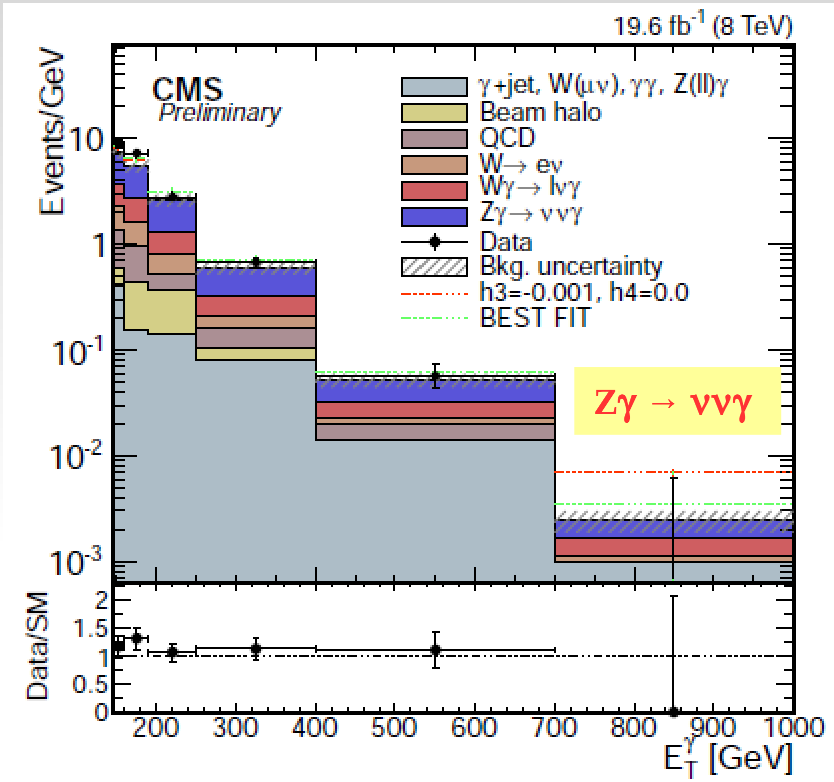
Z $\rightarrow \tau\tau$ – low $E_{T,miss}$

- Well measured cross sections at 7 TeV dominated by systematics (mainly in $E_{T,miss}$):
  – Typical uncertainty < 10%.

2.4) Photons and jet final states

- Zγ, Wγ :
  - V+jets an important background with jets faking photons (leading π^0).
  - S/B > 1: background systematics matters.

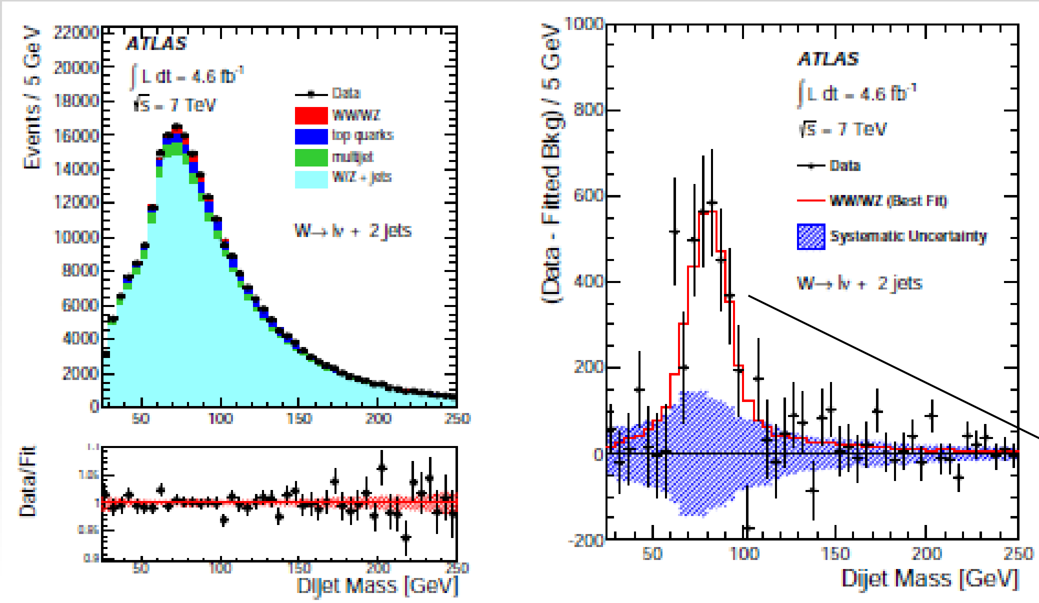
CMS-PAS-SMP-14-019



- WV → lνjj:
  - Rediscovery at LHC of quark final states in EWK physics.
  - Largest Branching Fraction – important at large M_{VV}. Interesting for aTGC.
  - S/B << 1 : large background systematics

Next Page

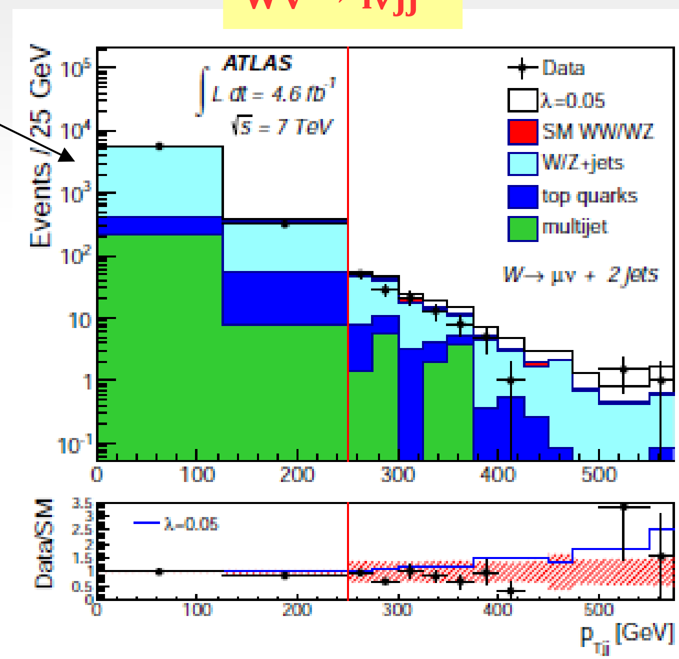
2.5) Hadronic decays of V: W/Z → jj ; Z → bb



CMS - EPJC 73 (2013) 2283

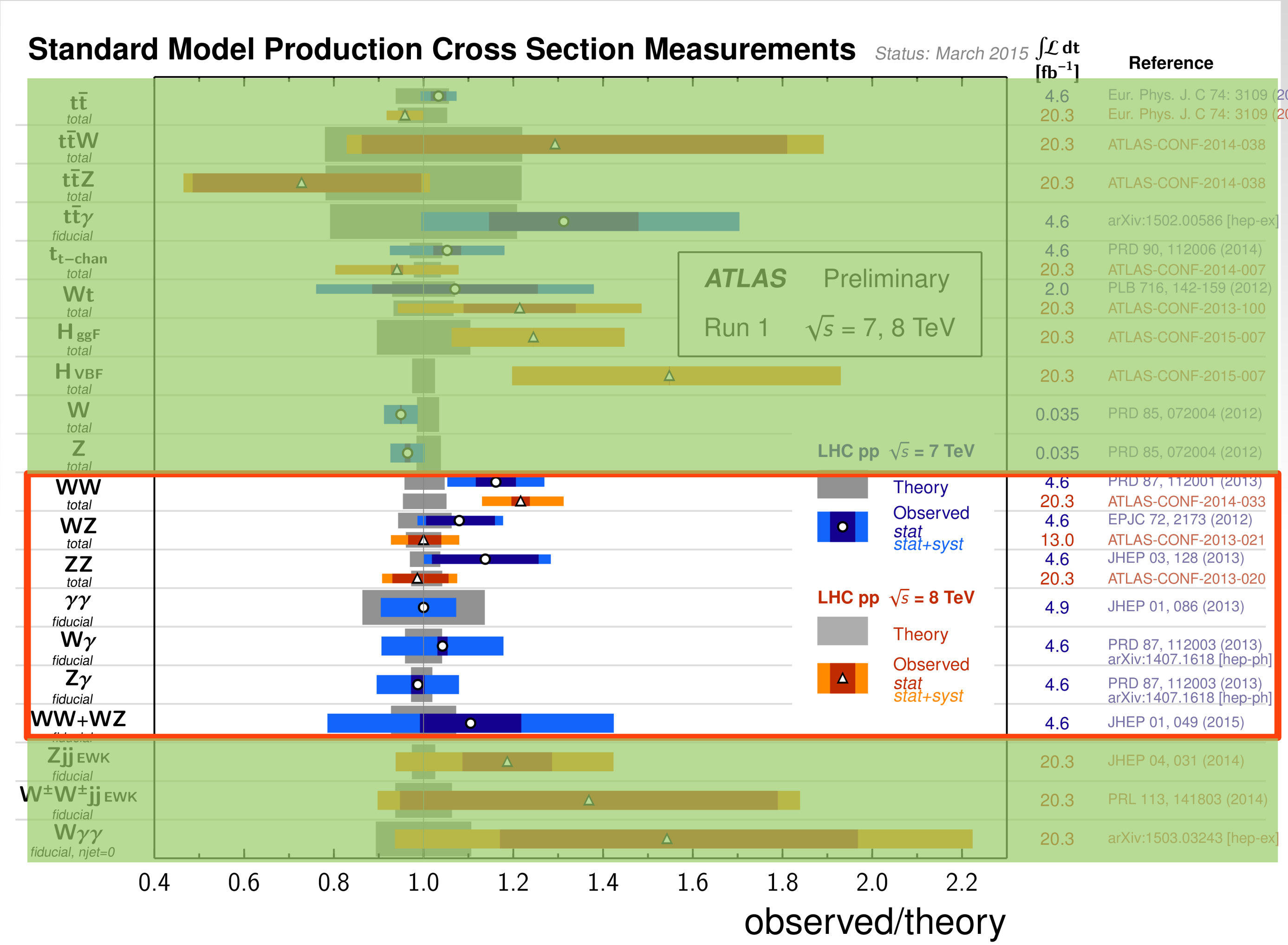
ATLAS - JHEP 01 (2015) 049

WV → lνjj



- Low S/B; Template fit within each $p_{T,jj}$ bin. The W → qq signal is clearly observed.
- Main systematic from W/Z+jets background templates.
- Requiring 2 b-tags it is also possible to observe Z → bb (EPJC 74 (2014) 2973)

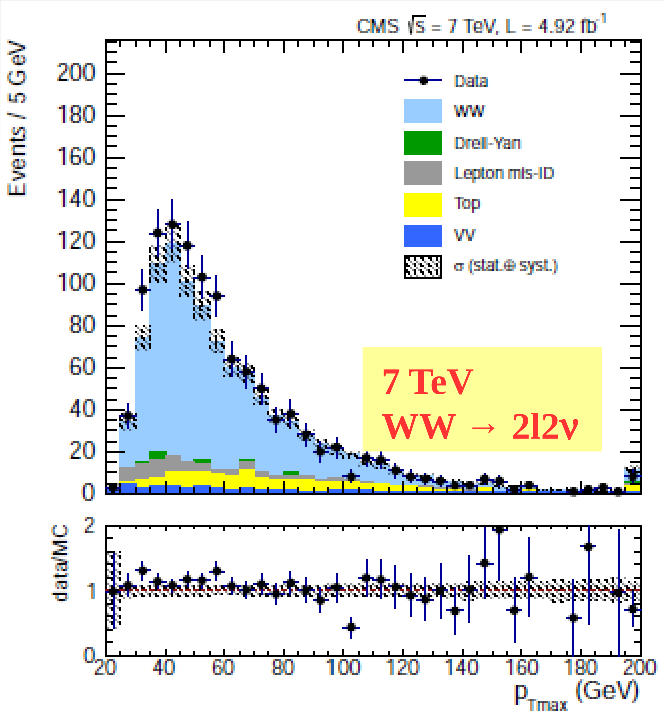
2.6) Physics interpretation: low $p_{T,V}$



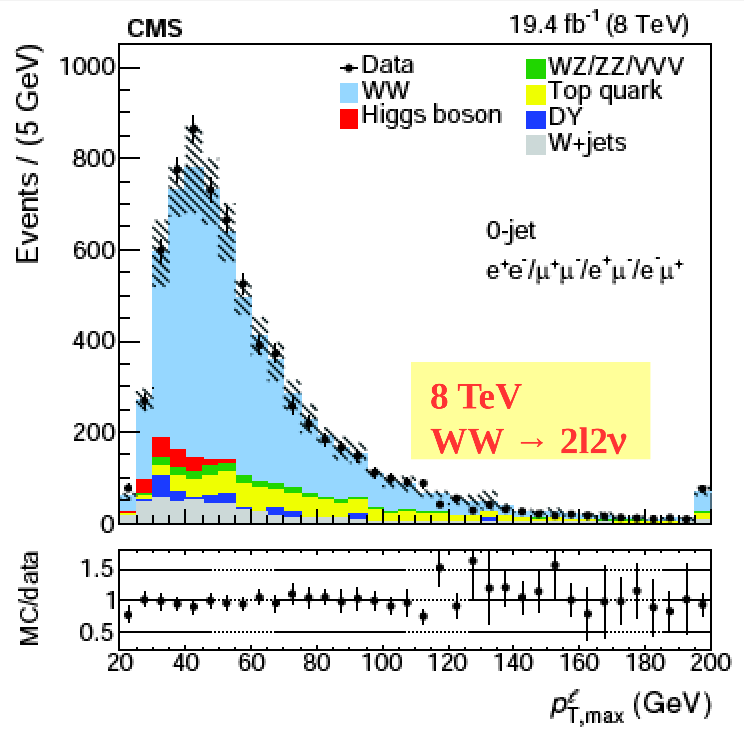
- Good agreement for fiducial measurements vs SM prediction at NLO for ATLAS.
- Interesting exception WW production that generated few BSM papers. What happens there?

2.7) Physics interpretation: low $p_{T,V}$

- Differential CMS measurement at 7 TeV: compared to NLO. Excess at 7 TeV was localized at low $p^{l}_{T,max}$ (or low M_{VV}).
- Since then large efforts done to understand this phenomenon:
  - NNLO + NNLL prdictions produced and included in experimental measurement.
  - Rare processes considered: Higgs production, $\gamma\gamma$ induced, diffraction etc...
- Under active work: very exciting laboratory or complex and rare QCD/EWK processes.



EPJC 73 (2013) 2610



arXiv:1507.03268

2.8) Physics interpretation: aTGC

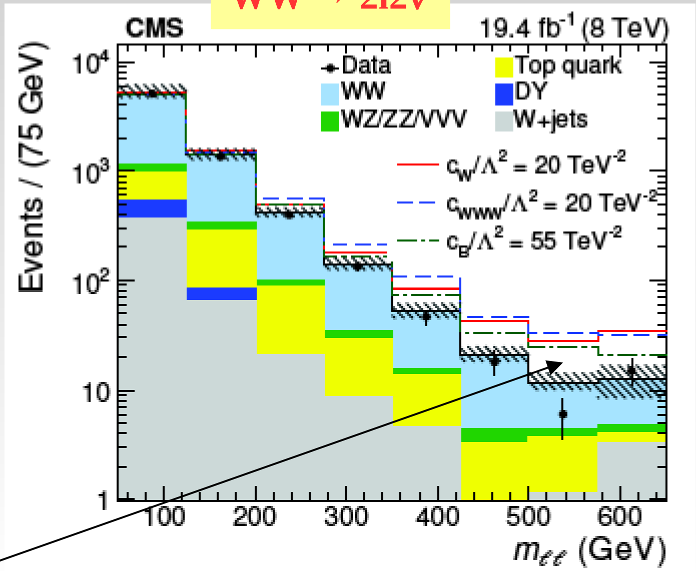
arXiv:1507.03268

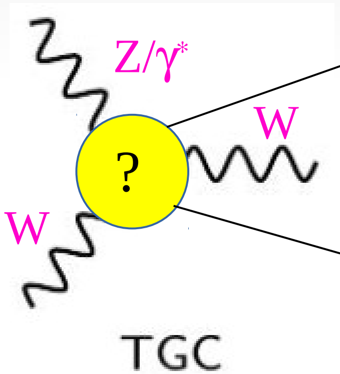
- The new physics in VV sector can be effectively parametrized by an operators expansion.

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \cancel{\frac{1}{\Lambda}\mathcal{L}^{D=5}} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \cancel{\frac{1}{\Lambda^3}\mathcal{L}^{D=7}} + \frac{1}{\Lambda^4}\mathcal{L}^{D=8} + \ldots$$

  – 1^{st} order of new physics compatible with precision tests: D6
  – Λ is the BSM scale (typically > 1 TeV)
  – Need to be careful with unitarity violations.

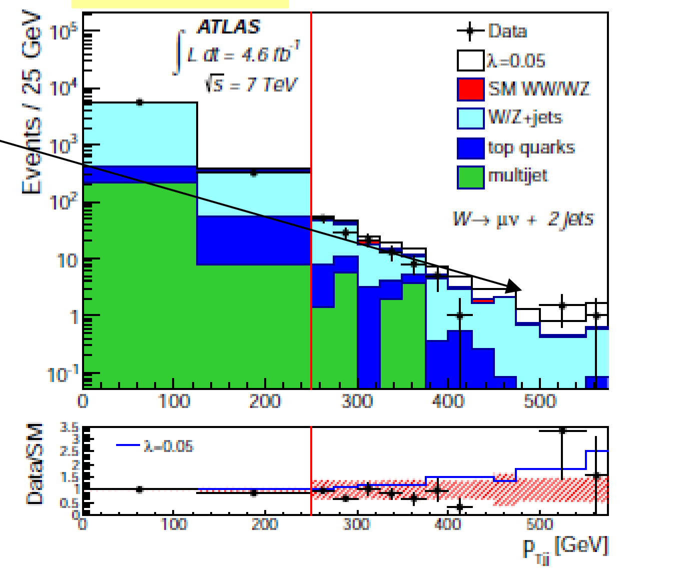
WW → 2l2ν





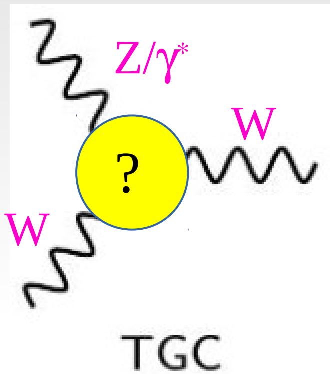
WV → lνjj

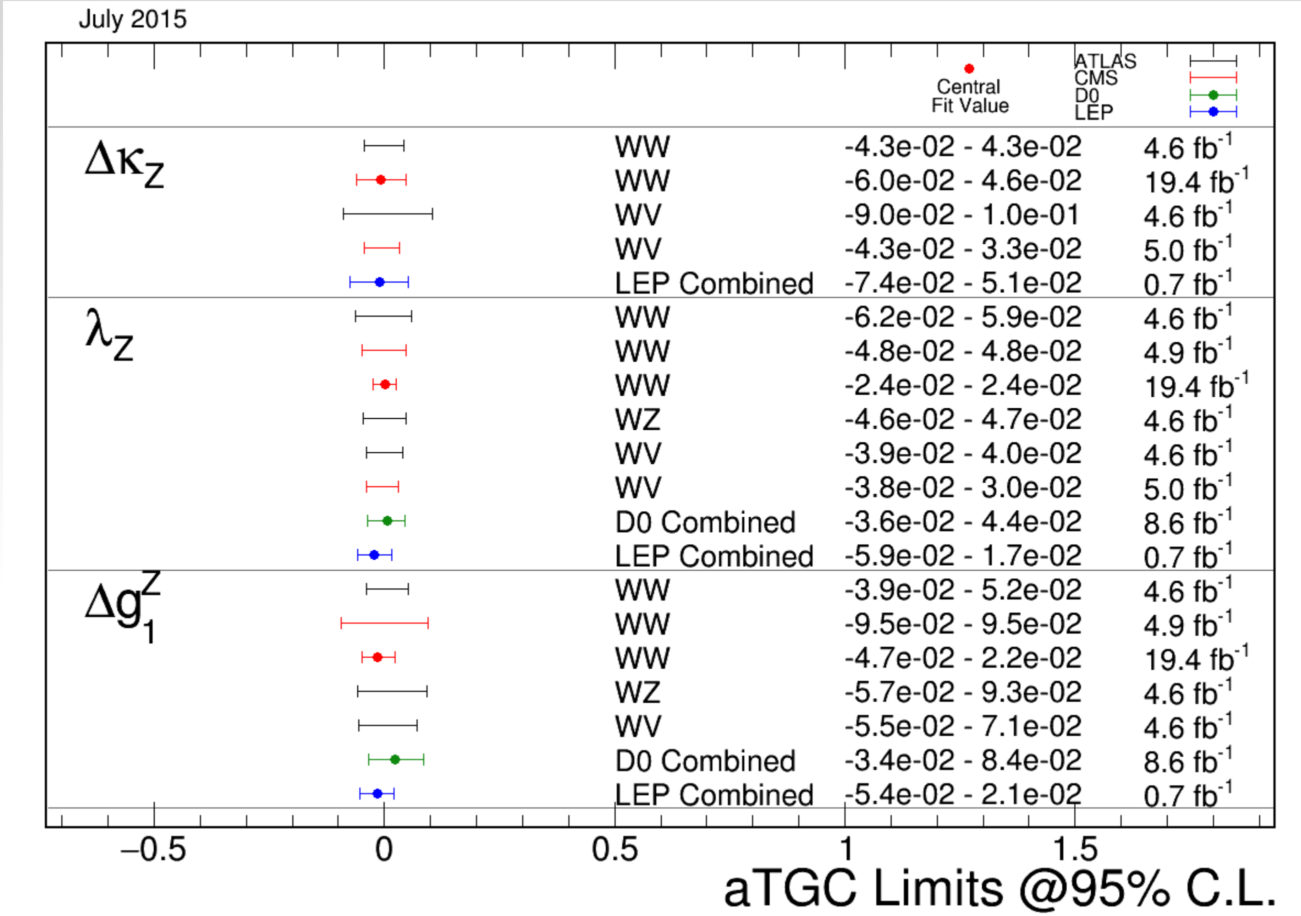
JHEP 01 (2015) 049



- Typically aTGC leads to large center-of-mass energy of VV system:
  – large M_{VV}
  – large $p_{T,V}$ if M_{VV} cannot be reconstructed.

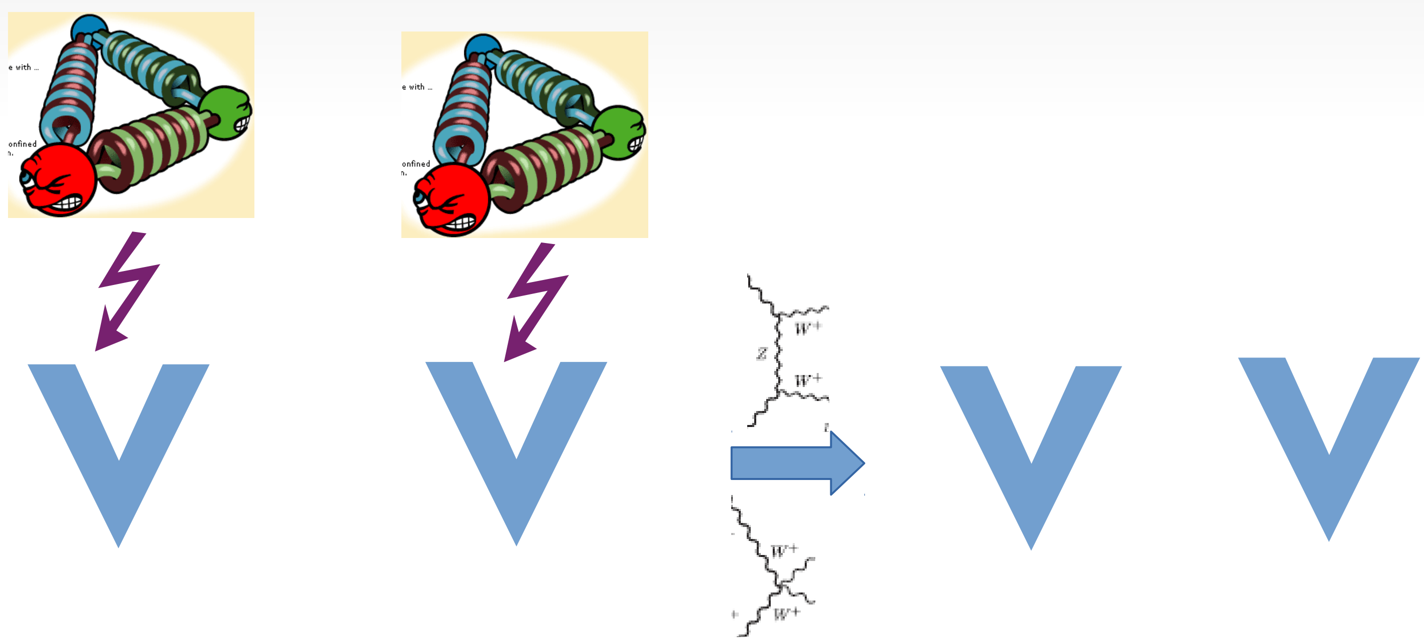
2.9) Physics interpretation: : aTGC and high $p_{T,V}$



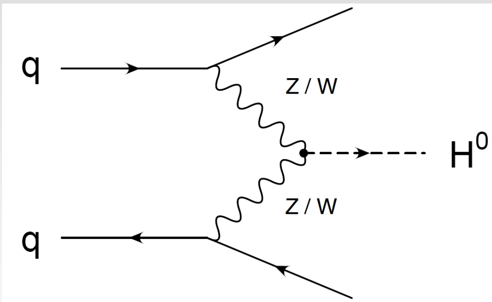


- « LEP » parametrisation: all parameters 0 for SM.
- For the charged aTGC: LHC on the leading edge of world sensitivity.
  - New physics with ~5% of SM coupling strength is excluded.
- The WV final state is slightly more sensitive than WW one.
- For more info and neutral aTGC see: **http://cern.ch/go/kMP8**

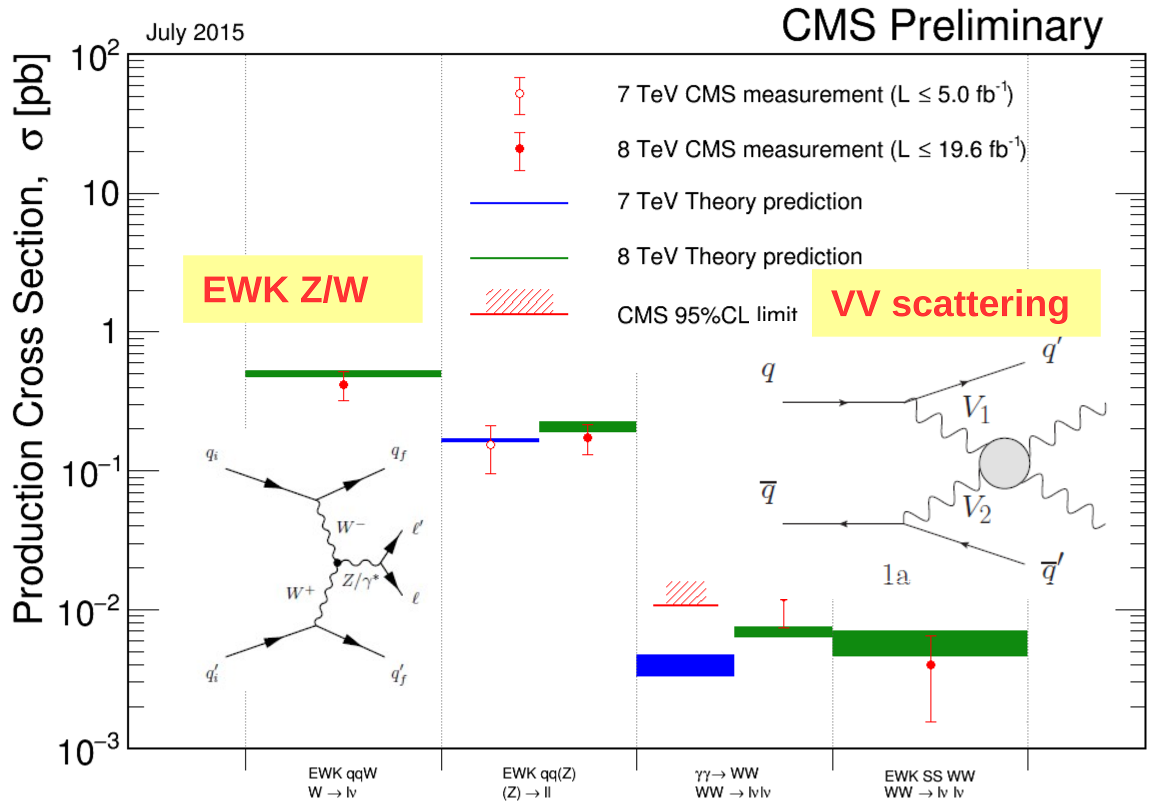
Electroweak production



3) LHC as a VV collider

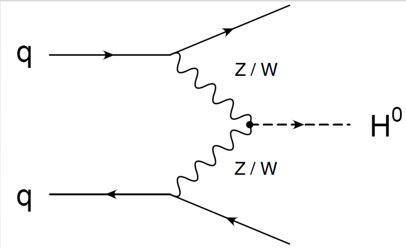


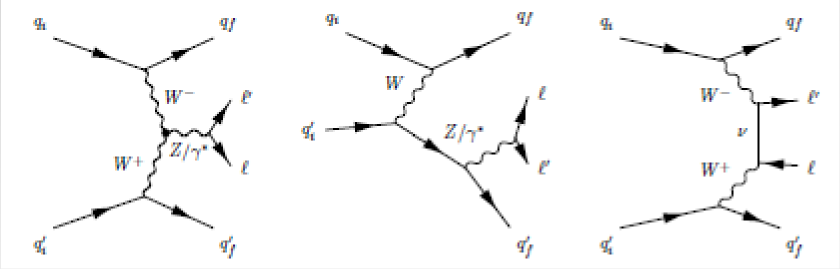
VBF Higgs

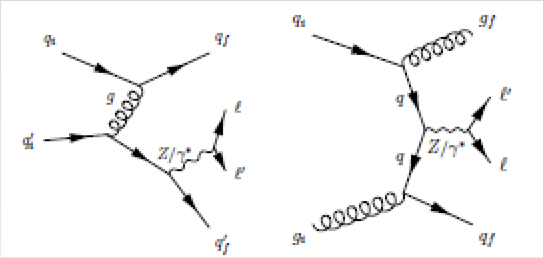


- The Vector-Boson fusion process (1) is well known channel to search for Higgs boson and measure the SM Lagrangian properties.
- In fact this is a general process in SM - “EWK scattering”: a way to turn the quark-gluon collider to a vector boson collider!
  - TGC like scattering (similar to VV):
    - VV → V similar to VBF H.
  - QGC like scattering (similar to VVV):
    - VV → VV scattering interesting to study unitarization in SM.

3.1) EWK production: comparison H and Z/W







(0)VBF H   1) VBF Z   2) Z Brem.   3) Multi-peripheral   4) Z Brem.   5) DY

- For Higgs the signal is quite clean mainly (0)
- For Z production: S=EWK (1-2-3); B=STRONG: (4) interfering; (5) not-interfering.
- σ(Z → ll) cross section in « EWK phase-space »: 200 fb.

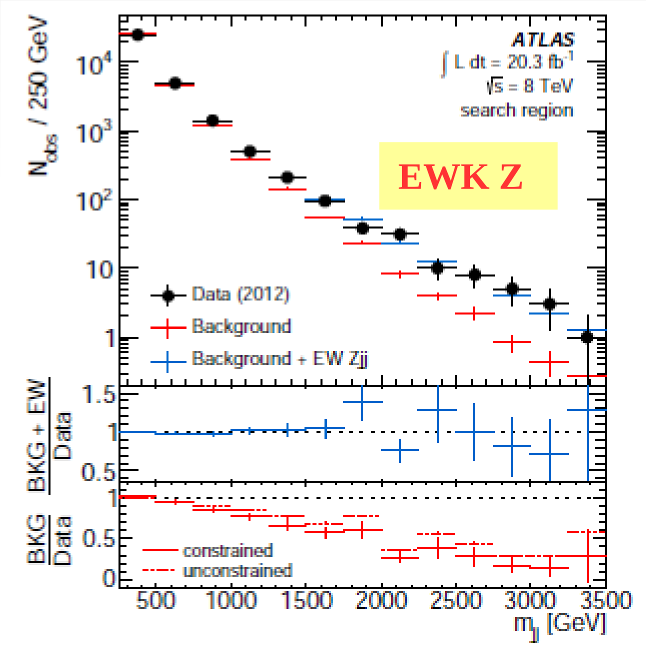
- Main properties:
  - At LO in QCD tagging jets are quarks, not gluons.
  - Large |Δη| between 2 tagging jets and large M_{jj}. Not case for strong production.
  - Low activity between jets and well balanced system Z vs JJ.

- In Run I VBF H is very challenging. Do we have a proof we understand this process?

But EWK Z and W can be discovered and properties of this process studied.

3.2) EWK Z/W production: technique

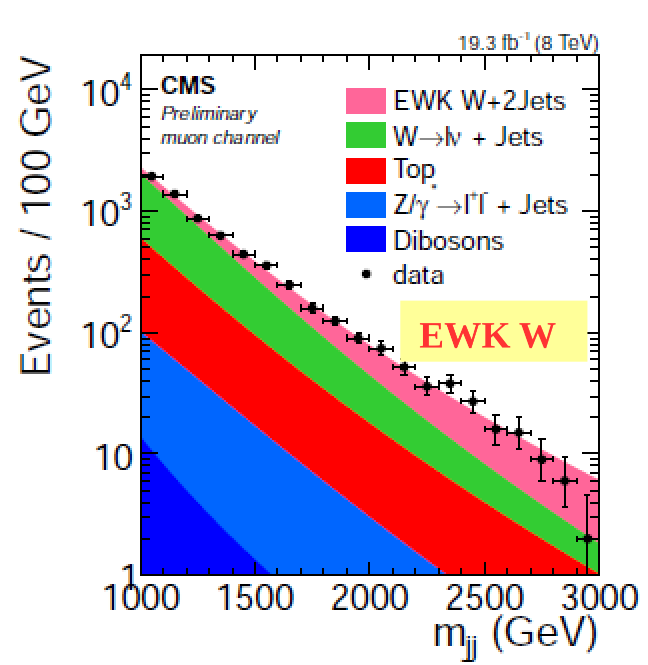
- S/B < 1: used cuts/Multi-Variate-Analysis (MVA) with many variables to improve it.
- M_{jj} spectrum give the best handle for S-B separation.
  - STRONG background is data driven: Large systematics.
  - Jet Energy Scale/Resolution:
    important especially since 1 jet is typically in forward region (no tracker coverage).



ATLAS 8 TeV: JHEP 04 (2014) 031

CMS Z 8 TeV: EPJC 75 (2015) 66
CMS Z 7 TeV: JHEP 10 (2013) 101

- Template fit.
- Shapes taken from side bands, typically region with large jets activity.
- For Run II: possibility to have pure EWK sample once enough stats.

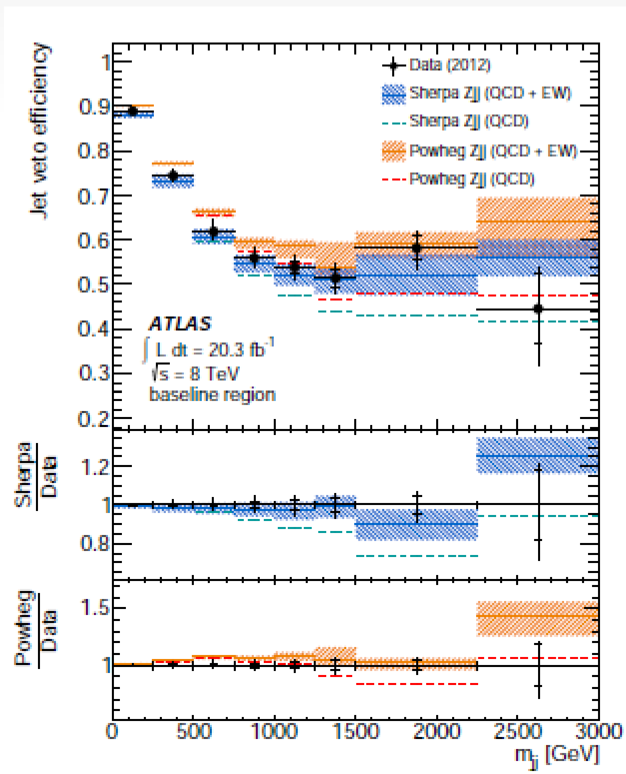


CMS-PAS-SMP-13-012 (NEW)

3.3) EWK Z/W production: results

- Clearly the process is discovered.
- Measurements compatibles with SM.
- Less sensitive to aTGC than VV production.
- Already dominated by the systematics.
- STRONG backgrounds better constraint → reduce systematics.

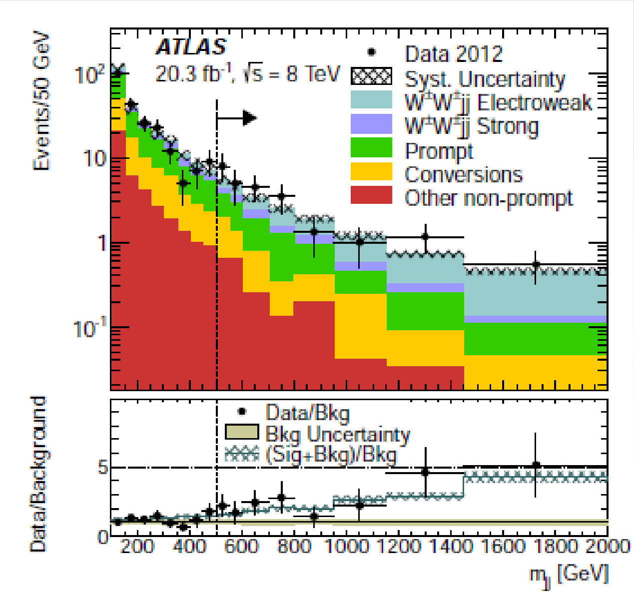
	Fiducial σ	Stat	Sys
CMS Z 7 TeV	154 fb	16 %	35 %
CMS Z 8 TeV	174 fb	9 %	23 %
ATLAS Z 8 TEV	57.7 fb	8 %	+18 - 19 %
CMS W 8 TeV	42 fb	10 %	22 %

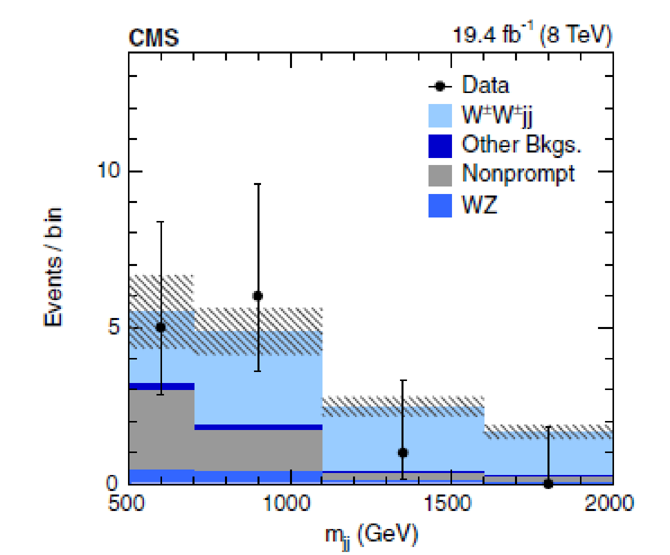


- The inter-jet activity is studied.
- Reasonably described within 20% by SHERPA/POWHEG.
- Important information for VBF H measurements.

3.4) EWK production: W±W±

First direct look on VV → VV vertex ever done!



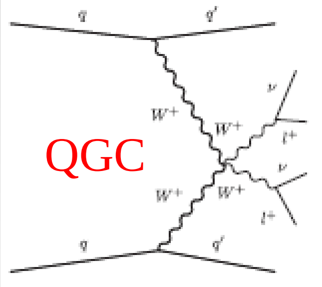


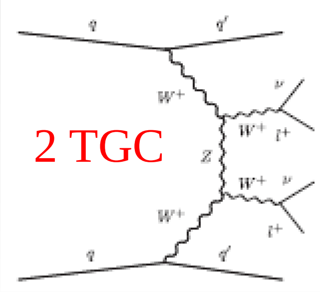
$$\sigma^{\rm fid} = 1.3 \pm 0.4({\rm stat}) \pm 0.2({\rm syst})\ {\rm fb}$$

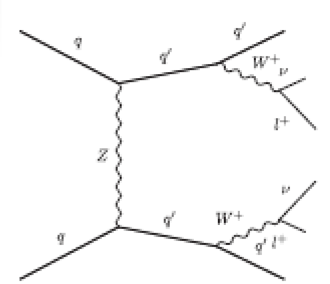
1.9σ (2.9σ)

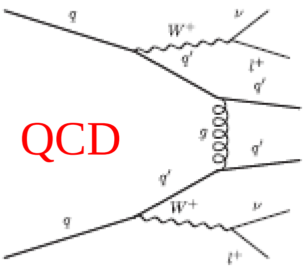
ATLAS: PRL 113 (2014) 141803

CMS: PRL 114 (2015) 051801





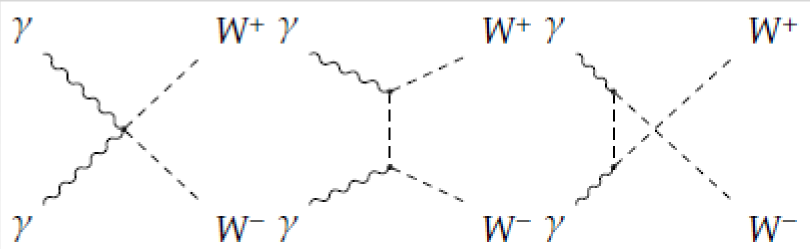




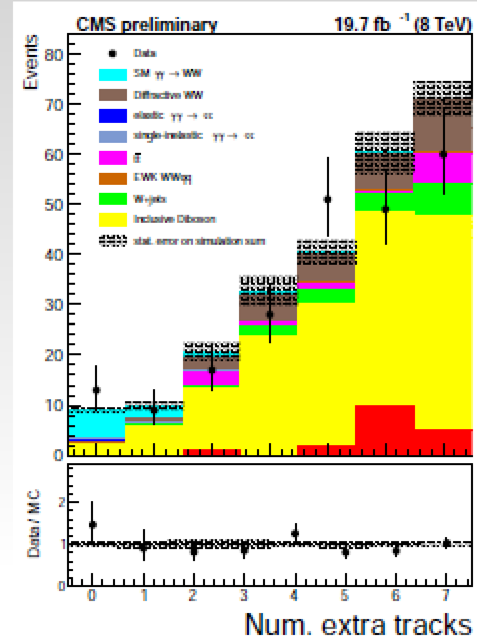
- The W±W±2j is the most sensitive final state to EWK VV production: low QCD background, no ttbar background.
- Production at the edge of the LHC sensitivity: stat. dominated. [remember σ(1 fb) = 20 events].
- BUT, we have an evidence of this process!!!

3.5) γγ → p*WWp* production

CMS 7 TeV: JHEP 07 (2013) 116
CMS 8 TeV: FSQ-13-008



- Sensitivity to EWK TGC/QGC
- Evidence: 3.6σ
- $\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 12.3^{+5.5}_{-4.4}\mathrm{fb}$

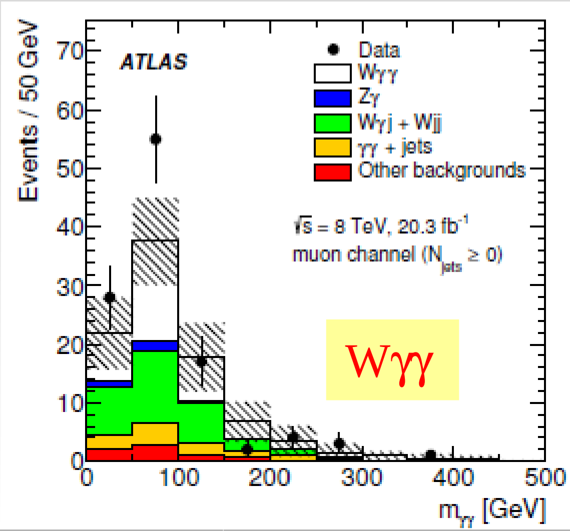


- Require **eμ** (reduce DY) + 0 tracks associated to **eμ** vertex.
- Low background: WW main one.
- Dissociated proton is hard to simulate and not so well understood: it can add tracks to the vertex and reduce signal. Data driven estimate.
- ATLAS performed a measurement of the exclusive **γγ** → **μμ/ee** production, that gives a handle on **γγ** → WW backgrounds.

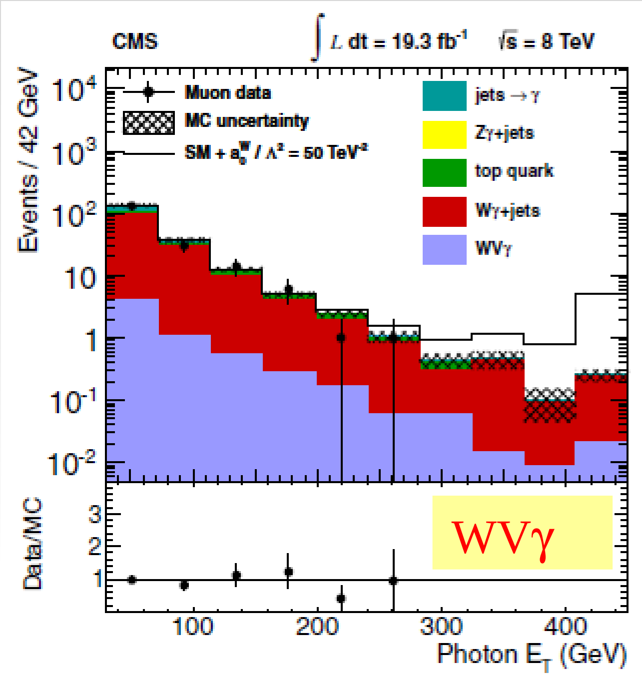
arXiv:1506.07098v1

3.6) VVV production

arXiv:1503.03243



PRD 90 (2014) 032008

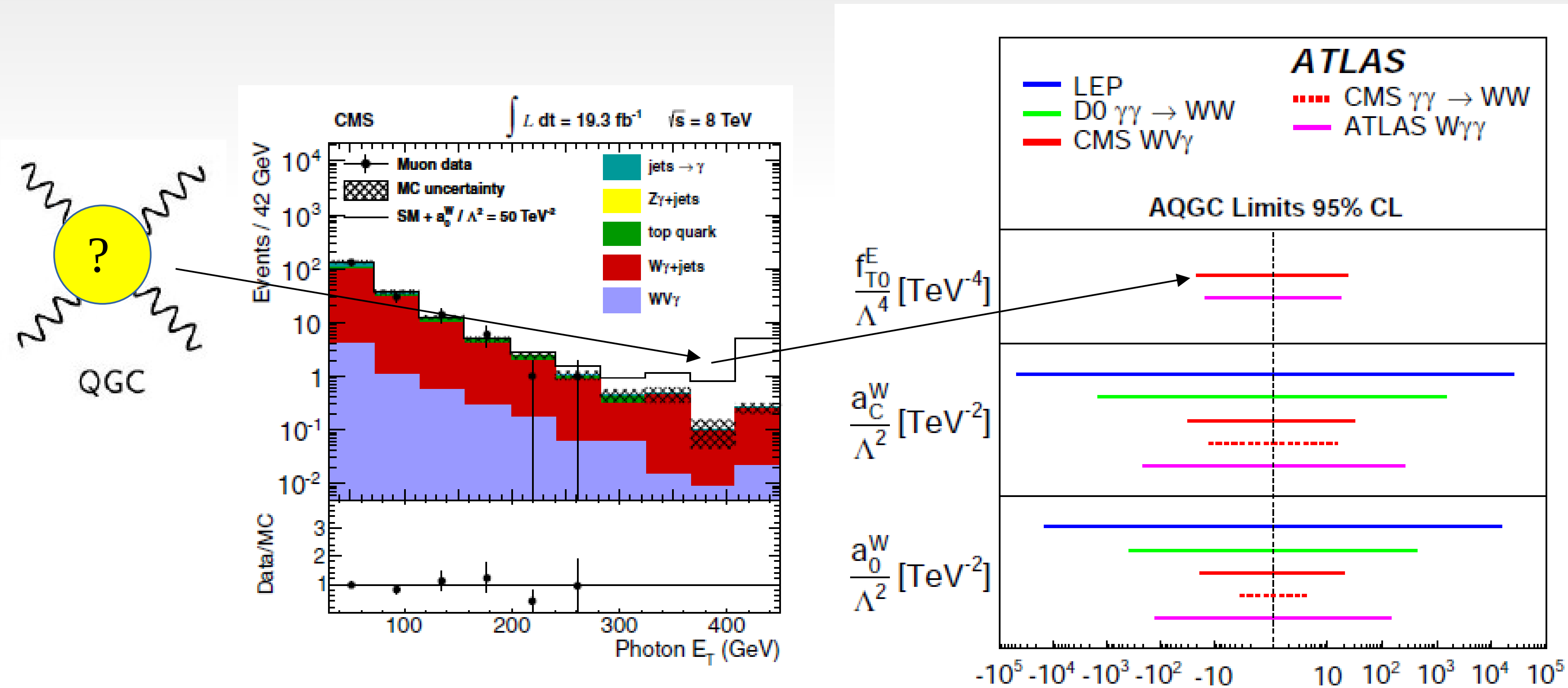


	Fiducial σ	Stat	Sys
ATLAS lνγγ	6.1 fb	16 %	20 %
MCFM	2.9		6 %

- VVV production is sensitive to the TGC and a bit to QGC: experimentally limited by statistics. Different ways to maximize it:
  - ATLAS: Wγγ and shows for a first time an evidence (> 3 σ).
  - CMS: maximize stats using hadronic V=W/Z

3.7) Constraining aQGC

- DIM6/DIM8 operators matters $\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\cancel{\mathcal{L}^{D=5}} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \frac{1}{\Lambda^3}\cancel{\mathcal{L}^{D=7}} + \frac{1}{\Lambda^4}\mathcal{L}^{D=8} + \dots$
- AQGC leads to large center-of-mass energy of VV or VVV system.
- Note the logarithmic scale in exclusion limits: we are really in a new territory to explore.



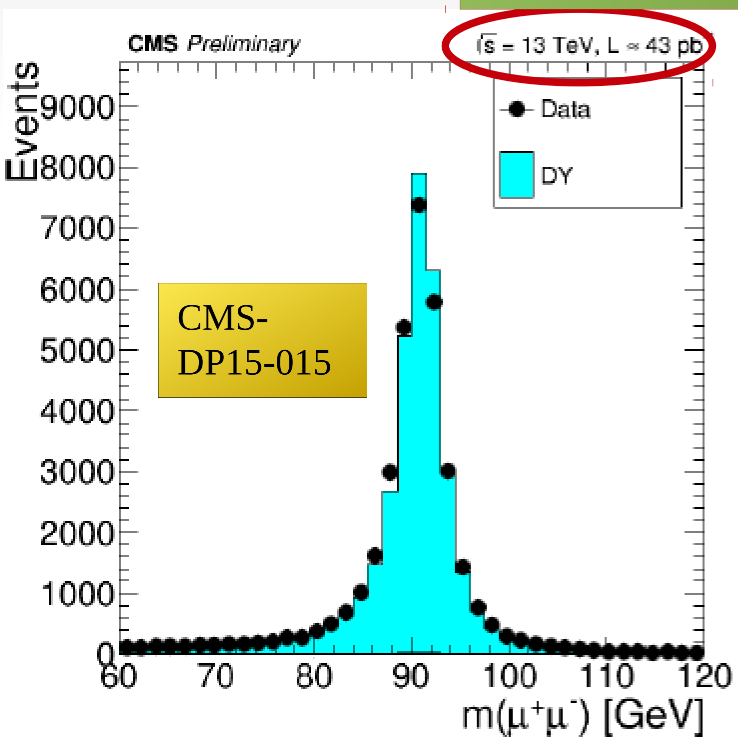
If you had to remember 1 thing after my talk

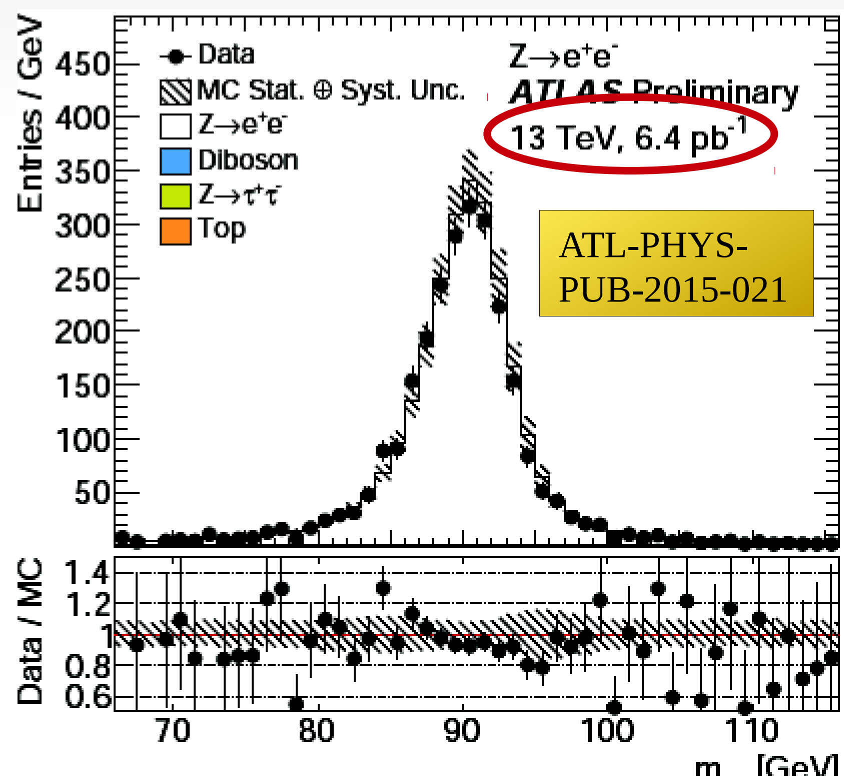
- Run I of the LHC have proven to be the leading machine for TeV scale EWK effects within SM and BSM.
- Especially the heroic feat was to demonstrate that LHC can be used as EWK boson collider. Just need Run II statistics to really use all the potential!
- Instead of a boring conclusion just have a look on those plots:

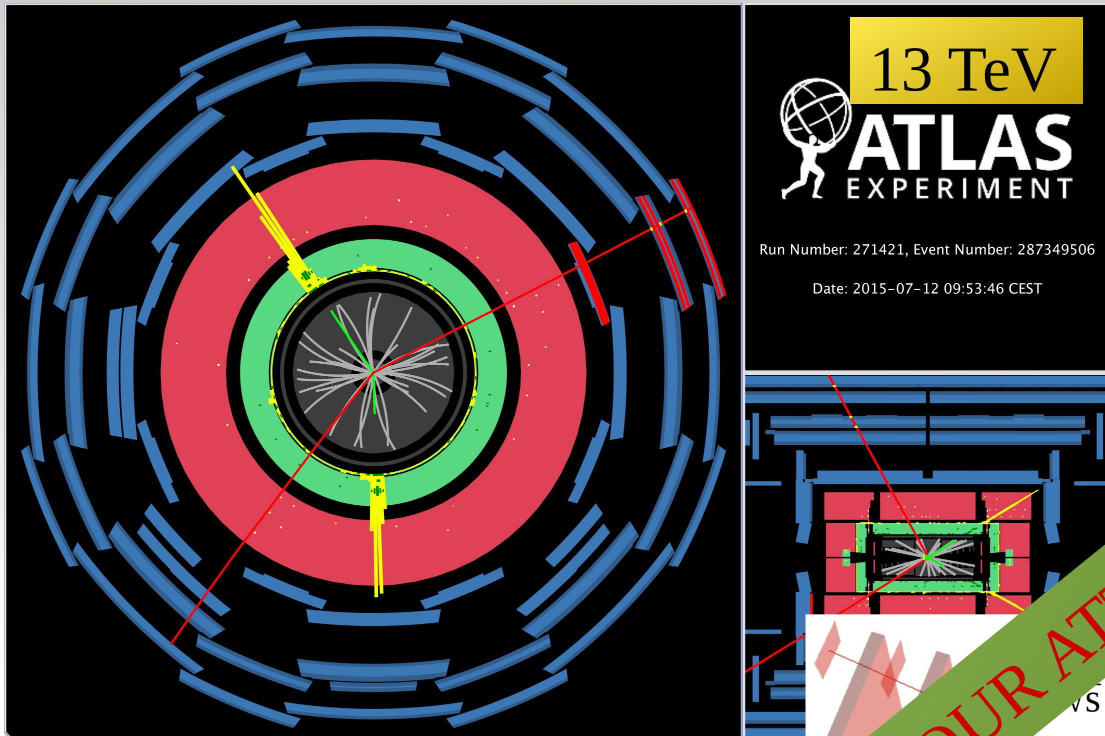
If you had to remember 1 thing after my talk

- Run I of the LHC have proven to be the leading machine for TeV scale EWK effects within SM and BSM.
- Especially the heroic feat was to demonstrate that LHC can be used as EWK boson collider. Just need Run II statistics to really use all the potential!
- Instead of a boring conclusion just have a look on those plots:

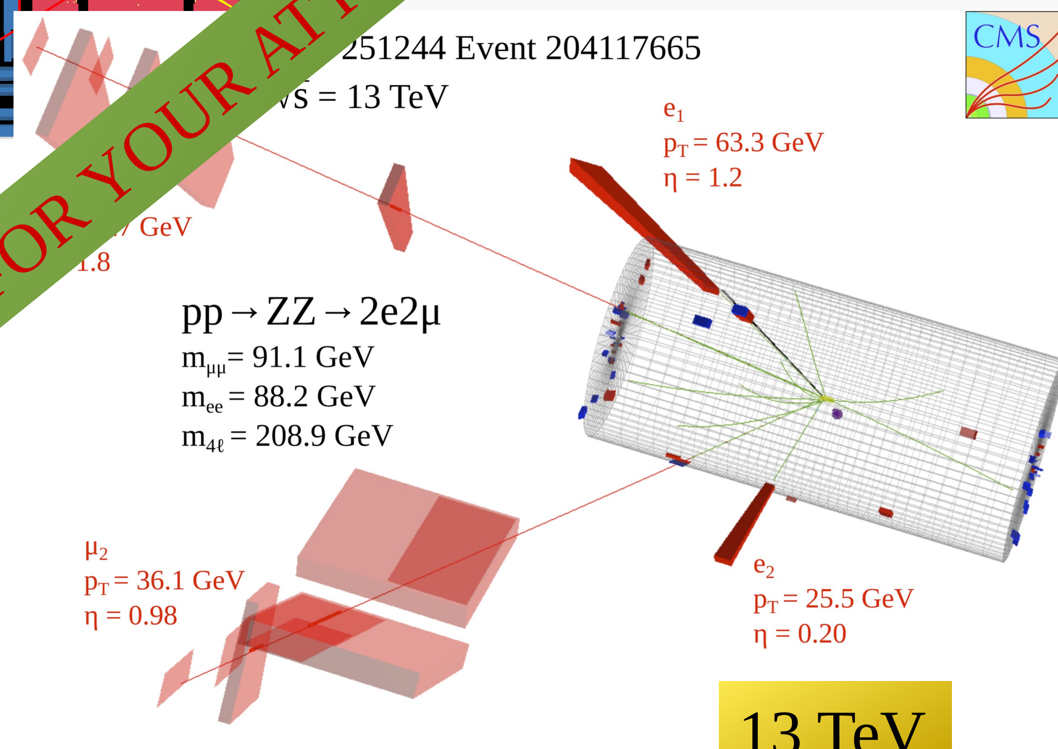
WE ARE INDEED RESTARTING







THANKS FOR YOUR ATTENTION



BACKUP

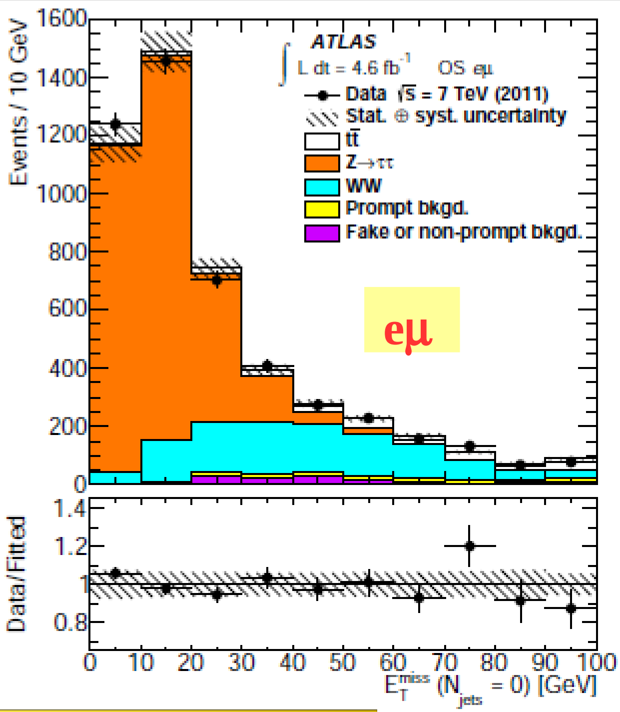
1.4) ATLAS WW, ttbar, Z → ττ

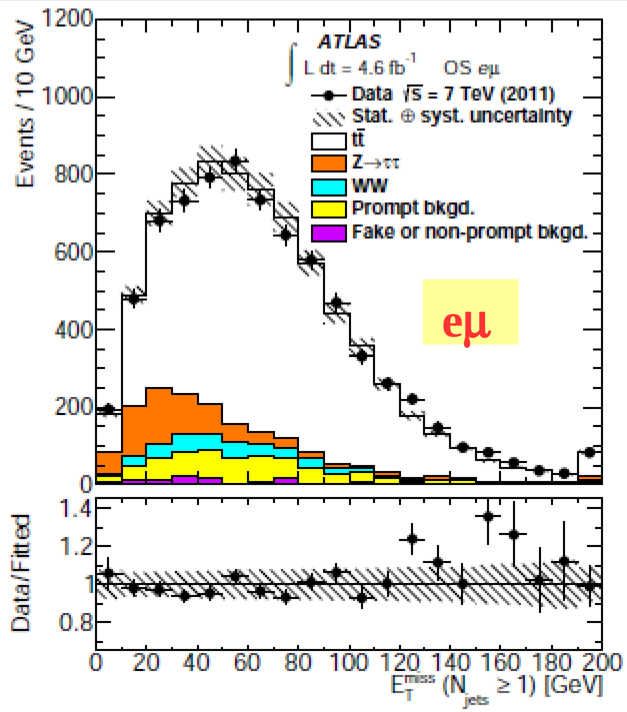
Source \ Process	$t\bar{t}$ $\mathcal{C}$	$t\bar{t}$ $\mathcal{A}\cdot\mathcal{C}$	$t\bar{t}$ Shape	WW $\mathcal{C}$	WW $\mathcal{A}\cdot\mathcal{C}$	WW Shape	$Z/\gamma^*\to\tau\tau$ $\mathcal{C}$	$Z/\gamma^*\to\tau\tau$ $\mathcal{A}\cdot\mathcal{C}$	$Z/\gamma^*\to\tau\tau$ Shape
ISR/FSR+Scale	±1.1	±0.4	+1.0(−1.5)	±1.0	±0.8	+4.7(−3.5)	±1.1	±0.4	+0.7(−1.0)
Generator	±0.7	±0.8	+0.2(−0.0)	±0.6	±0.5	+4.5(−0.4)			+0.0(−0.7)
PS Modeling	±0.9	±0.6	+0.0(−0.1)	±0.5	±1.0	+3.5(−0.0)			+0.0(−0.6)
$Z/\gamma^*\to\tau\tau$ PS Modeling			+0.0(−0.5)			+0.0(−0.6)	±1.8	±3.3	+0.5(−0.0)
PDF	±0.6	±1.7	±0.5	±0.1	±0.7	±1.6	±0.2	±1.3	±0.8
e reco., ID, isolation	±3.2		+0.0(−0.1)	±3.2		+0.3(−0.3)	±3.3		+0.0(−0.8)
μ reconstruction	±0.8		+0.0(−0.0)	±0.8		+0.0(−0.0)	±0.8		+0.0(−0.0)
$E_{\mathrm{T}}^{\mathrm{miss}}$–cellout	±0.0		+0.4(−0.2)	±0.0		+8.1(−9.9)	±0.0		+2.3(−0.2)
$E_{\mathrm{T}}^{\mathrm{miss}}$ pile-up	±0.0		+0.1(−0.1)	±0.0		+3.7(−4.5)	±0.0		+1.0(−1.7)
Jet energy scale	±0.8		+1.4(−1.4)	±0.6		+0.5(−4.8)	±0.5		+1.4(−3.1)
Jet energy resolution	±0.2		+0.3(−0.0)	±0.2		+0.0(−2.6)	±0.2		+0.0(−0.1)
Jet vertex fraction	±0.8		+0.1(−0.0)	±0.3		+0.0(−1.7)	±0.2		+0.0(−0.3)

Systematic Uncertainties (%)

	$t\bar{t}$	WW	$Z/\gamma^*\to\tau\tau$
Fake or non-prompt background	±0.8	±5.6	±0.7
Luminosity	±1.8	±1.8	±1.8
LHC beam energy	±1.8	±1.0	±0.8

1.4) Leptonic WW measurement



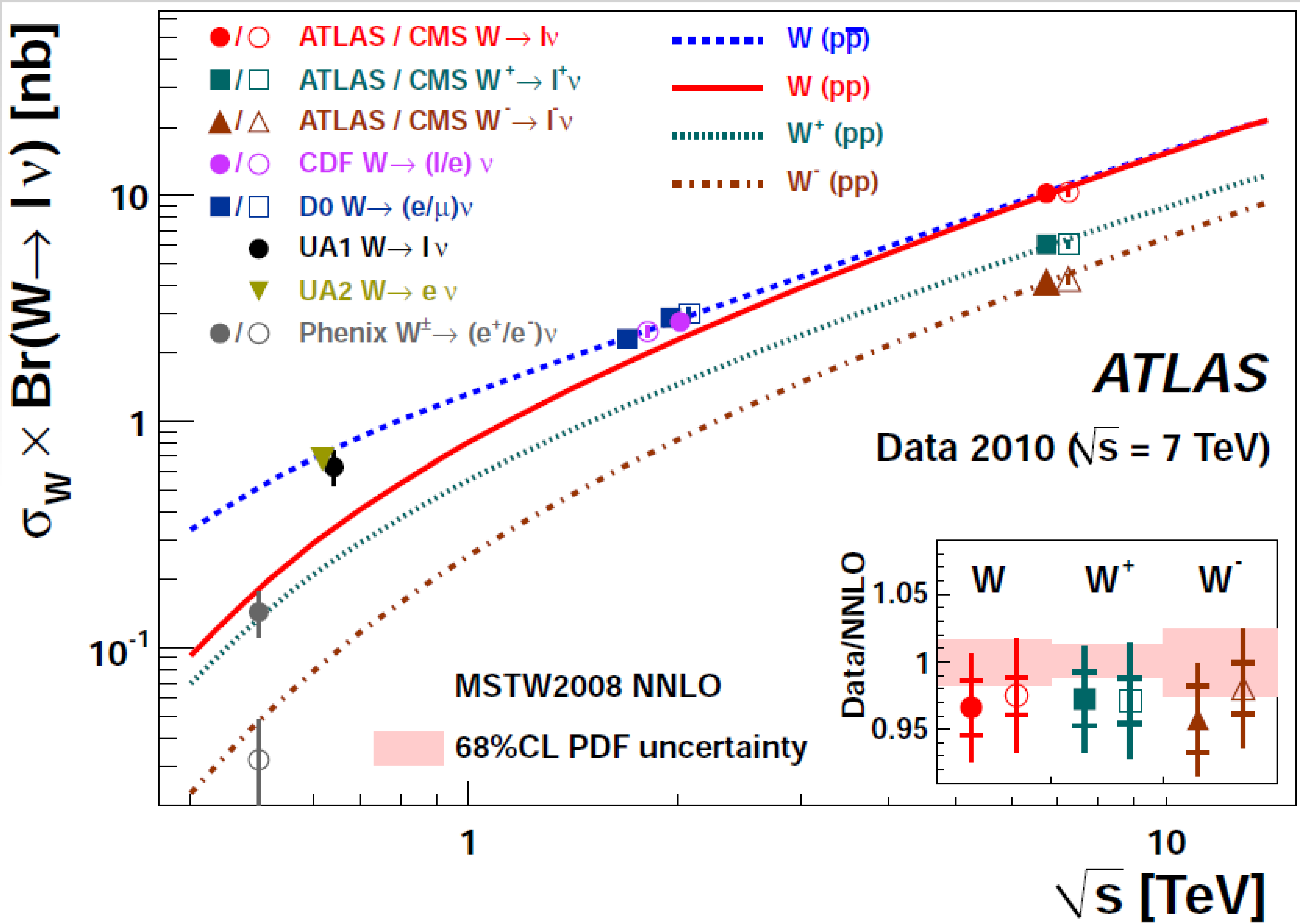


- Using eμ final state to reduce DY.
- Well separated in $E_{T,miss}$ x N_{jets} space.
- 3 major signals are measured.
- tW, WZ/ZZ fixed
- Background with leptons faked by jets is extracted from data.

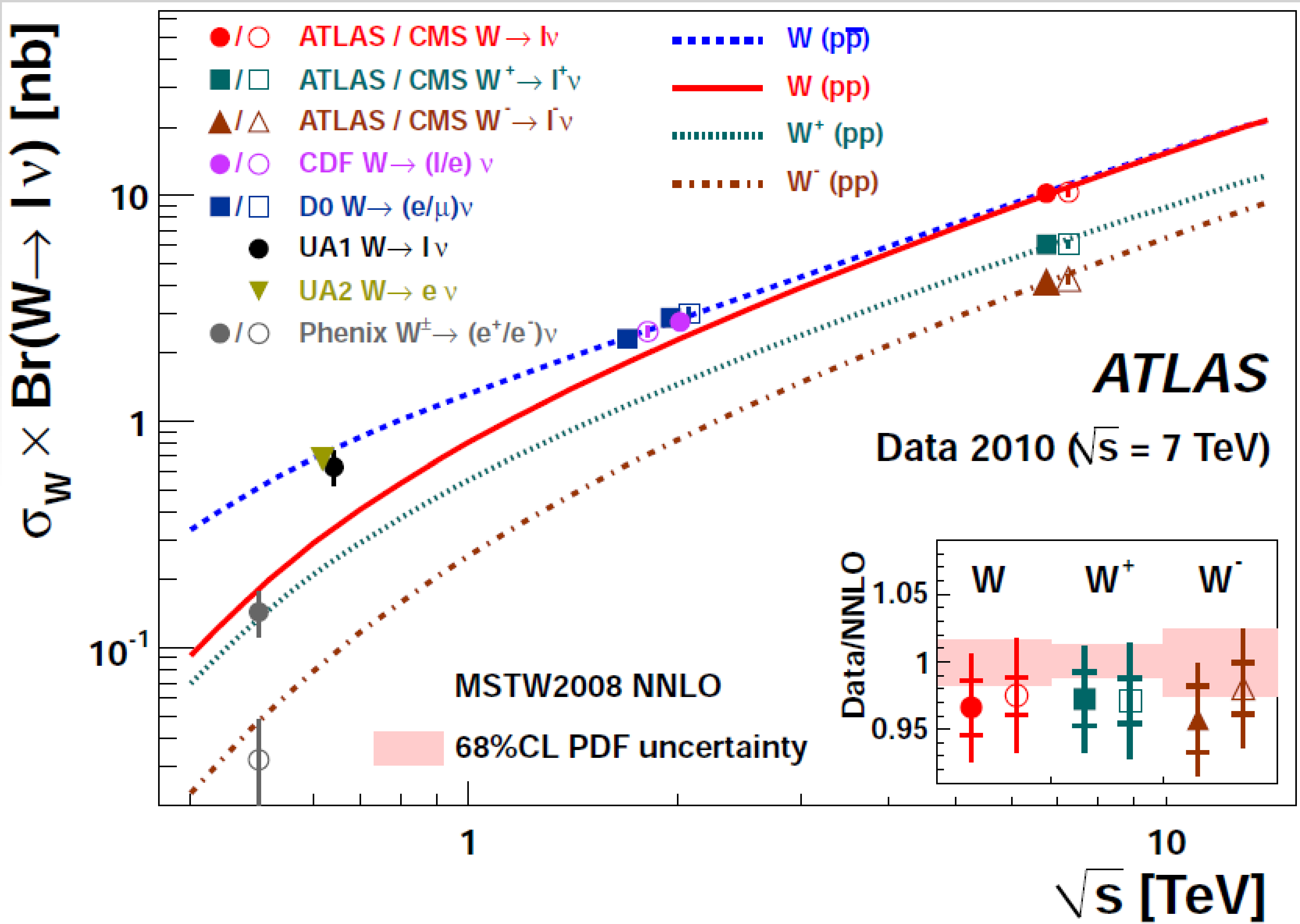
PRD 91 (2015) 052005

Process	$t\bar{t}$	WW	$Z/\gamma^* \to \tau\tau$
σ_X^{tot} [pb]	181.2	53.3	1174
Uncertainties (%)			
Statistical	1.5	5.0	2.1
Systematic	+5.4(−5.3)	+13.8(−14.9)	+6.1(−7.5)
Luminosity	1.8	1.8	1.8
LHC beam energy	1.8	1.0	0.8
Total	6.1	15.9	8.0

- Well measured cross sections at 7 TeV dominated by systematics (mainly in $E_{T,miss}$).
- WW cross section is measured the best in Njets = 0 bin since ttbar bakground limited.



ATLAS / CMS W→ lν
ATLAS / CMS W⁺→ l⁺ν
ATLAS / CMS W⁻→ l⁻ν
CDF W→ (l/e) ν
D0 W→ (e/μ)ν
UA1 W→ l ν
UA2 W→ e ν
Phenix W±→ (e⁺/e⁻)ν
W (pp̄)
W (pp)
W⁺ (pp)
W⁻ (pp)
ATLAS
Data 2010 (√s = 7 TeV)
MSTW2008 NNLO
68%CL PDF uncertainty
σ_W × Br(W→ l ν) [nb]
√s [TeV]
Data/NNLO
W
W⁺
W⁻


ATLAS / CMS W→ lν
ATLAS / CMS W+→ l+ν
ATLAS / CMS W-→ l-ν
CDF W→ (l/e) ν
D0 W→ (e/μ)ν
UA1 W→ l ν
UA2 W→ e ν
Phenix W±→ (e+/e-)ν
W (pp̄)
W (pp)
W+ (pp)
W- (pp)
ATLAS
Data 2010 (√s = 7 TeV)
MSTW2008 NNLO
68%CL PDF uncertainty
σW × Br(W→ l ν) [nb]
√s [TeV]
Data/NNLO
W
W+
W-

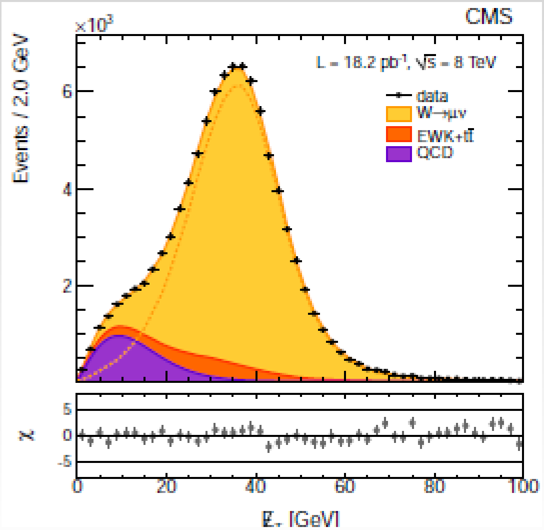
1.1) VV production in SM

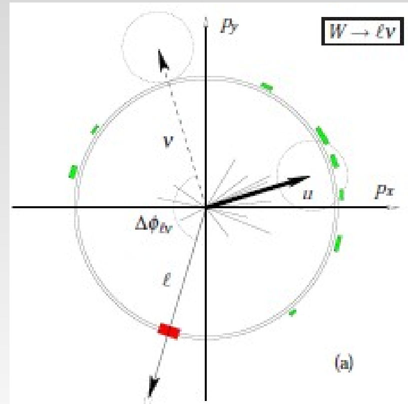
- VV production is the bread and butter of EWK physics: all combination o final states are measured.
- Below a summary of what was performed till now.

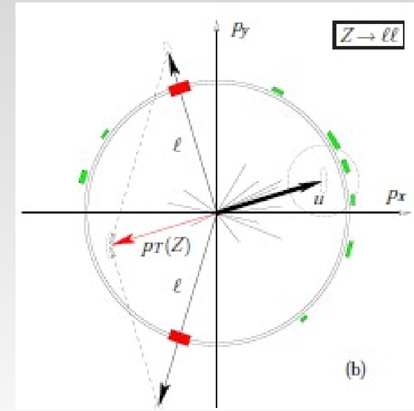
7 TeV	W	Z
W	CMS : EPJC 73 (2013) 2610 ATLAS : PRD 87 (2013) 112001	
Z	CMS : SMP-12-006 ATLAS : EPJC 72 (2012) 2173	CMS : JHEP 01 (2013) 063 (4l) CMS : arXiv : 1503.05467 (2l2ν) ATLAS : JHEP 03 (2013) 128 (4l+2l2ν)
γ	CMS : PRD 89, 092005 (2014) ATLAS : PRD 87, 112003 (2013)	CMS : PRD 89 (2014) 092005 (llγ) CMS : JHEP 10 (2013) 164 (2νγ) ATLAS : PRD 87 (2013) 112003 (llγ)

8 TeV	W	Z
	CMS : arXiv:1507.03268 ATLAS : ATLAS-CONF-2014-033	

1.3) M_T extraction: hadronic recoil

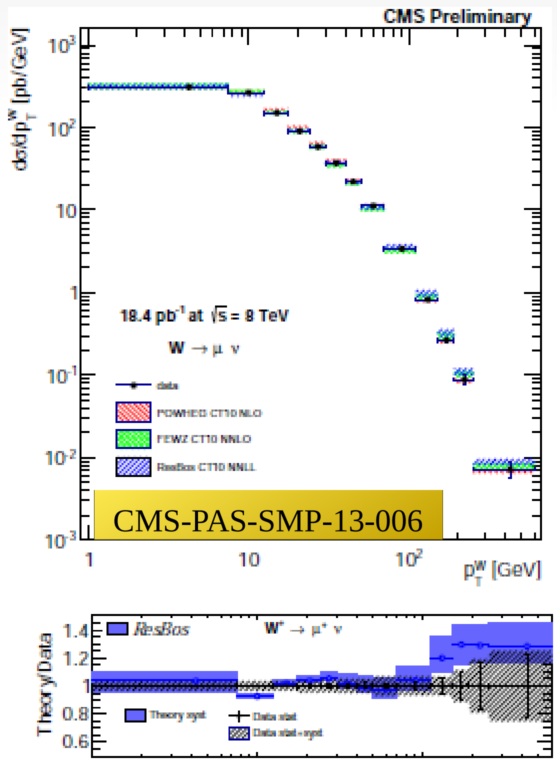


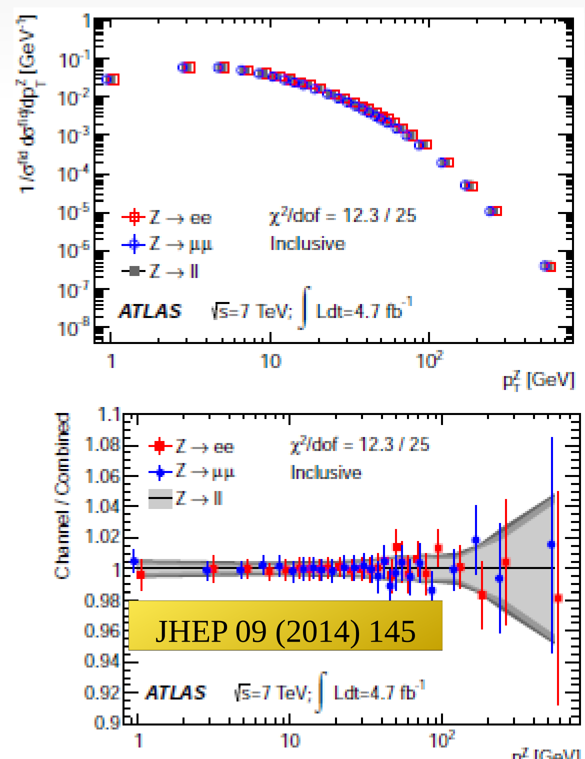




Is measured using hadronic recoil.

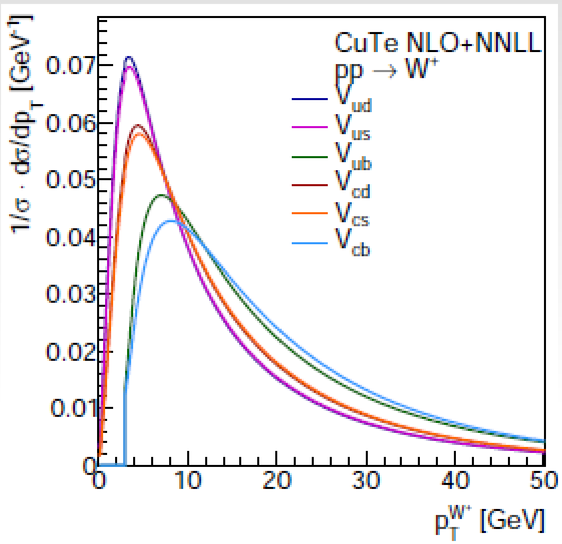
- $p_T(Z \to ll)$ used to calibrate MET: < 1% precision.
- $p_T(W)$ measurement used as cross check: ~5% precision. Improvements forseen.



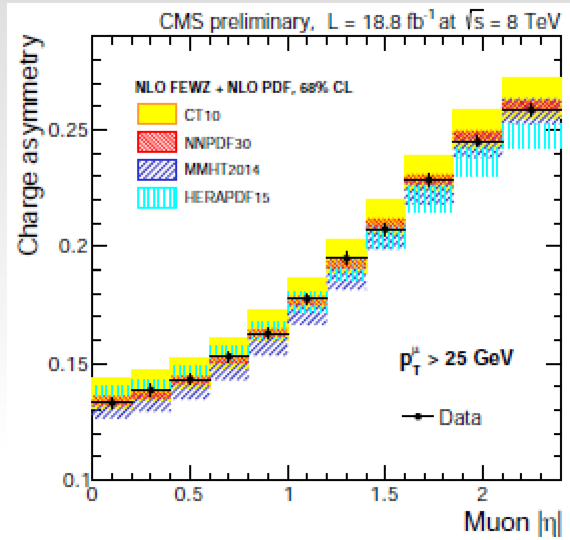


1.4) $p_{T,l}$ extraction: QCD/QED uncertainties

ATL-PHYS-PUB-2014-015

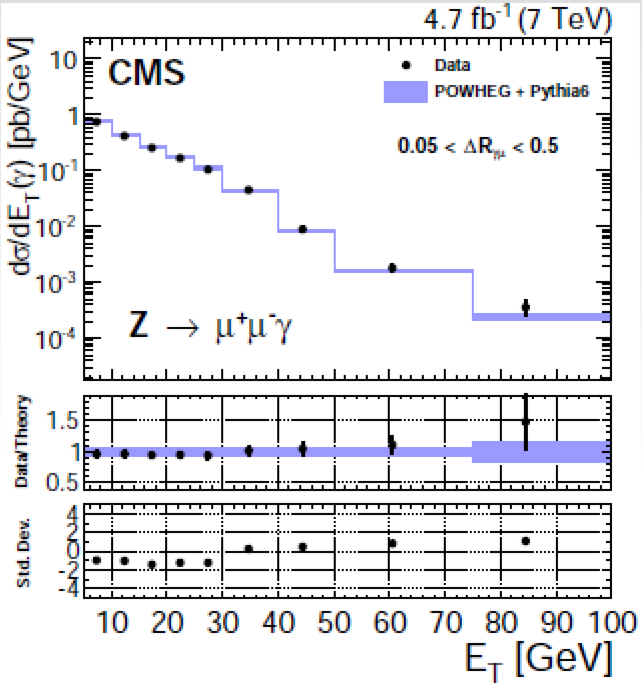


CMS-PAS-SMP-14-022



$$A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \mu^-\overline{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \mu^-\overline{\nu})}$$

PRD 91 (2015) 092012



- At LHC the detailed sea flavors are important, not well constrained by HERA.
- Need to constraint PDFs using W/Z production LHC data.

Example:

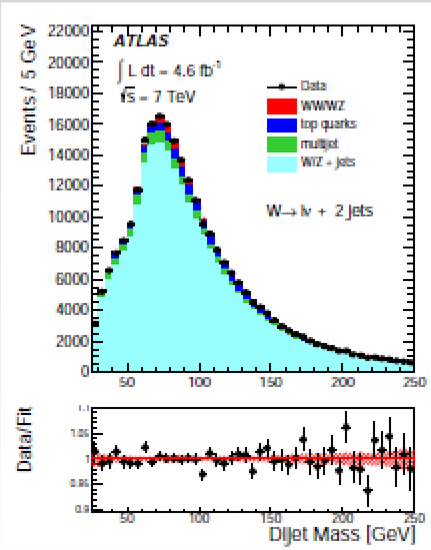
- W asymmetry :

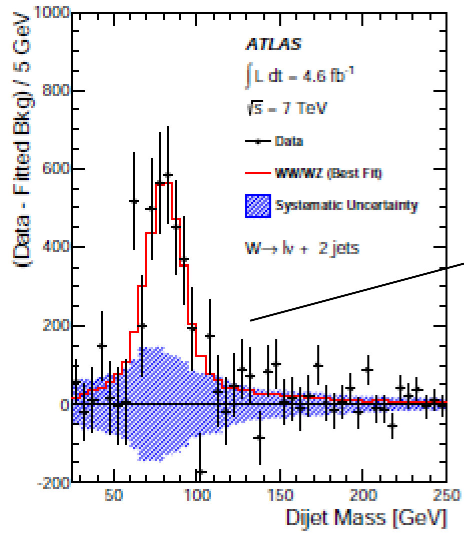
- sensitive to difference between u and d valence; strangeness.

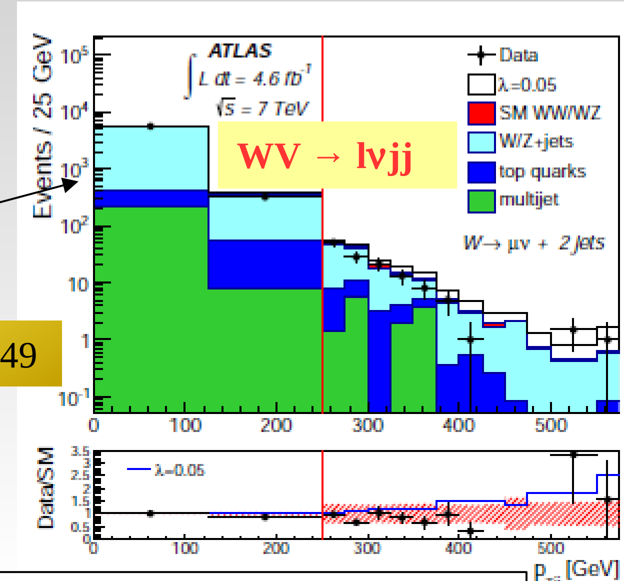
- < 1% precision

- Verify the QED effects using CMS $Z \to \mu\mu\gamma$ data.
- Data precision 5% well described by POWHEG+PYTHIA6

2.5) Hadronic decays of V: W/Z → jj ; Z → bb



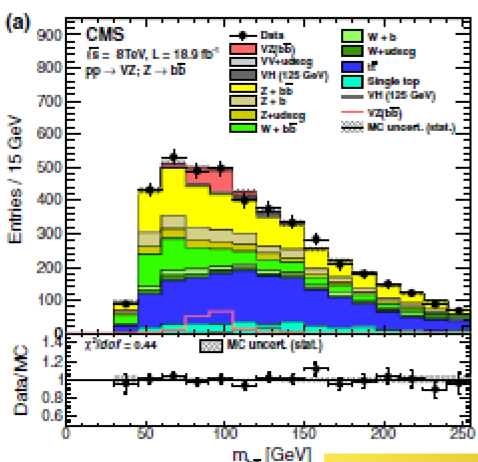




WV → lνjj

JHEP 01 (2015) 049

- Low S/B; Template fit within each $p_{T,jj}$ bin. The W → qq signal is clearly observed.
- Main systematic from W/Z+jets background templates.

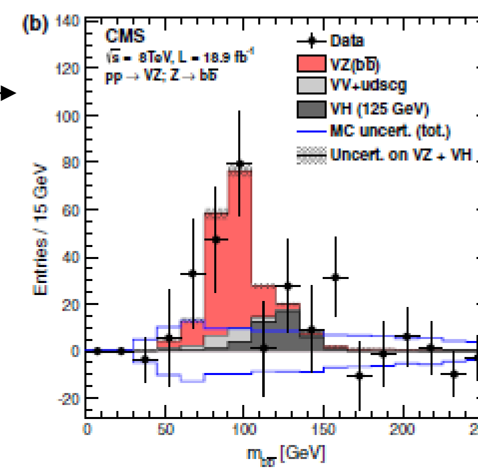


WZ → lνbb / ZZ → llbb

- Z → bb extracted using Mbb spectrum or using MVA

$$\mu_{WZ} = 1.37^{+0.42}_{-0.37}$$

$$\mu_{ZZ} = 0.85^{+0.34}_{-0.31}$$



EPJC 74 (2014) 2973

2.8) Physics interpretation: aTGC

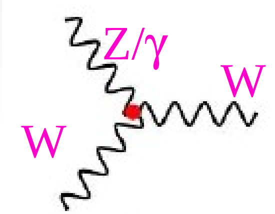
- The new physics in VV sector can be effectively parametrized by an operators expansion.

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots$$

- SM: D4 (or less) operators
- 1st order of new physic: D6 operators

« kappa formalism » from LEP – parametrize deviations multipliers wrt to the SM Lagrangian + higher dimension operators with derivatives

<u>Example</u>:



TGC

$$\frac{c_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^{\ \mu}],$$

$$\frac{c_W}{\Lambda^2}\mathcal{O}_W = \frac{c_W}{\Lambda^2}(D^\mu\Phi)^\dagger W_{\mu\nu}(D^\nu\Phi),$$

$$\frac{c_B}{\Lambda^2}\mathcal{O}_B = \frac{c_B}{\Lambda^2}(D^\mu\Phi)^\dagger B_{\mu\nu}(D^\nu\Phi).$$

3 Parameters

$$g_{WWV}\left[g_1^V V^\mu\left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2}V^{\mu\nu}W_\nu^{+\rho}W^-_{\rho\mu}\right]$$

6 Parameters,
3 removed by
gauge invariace relations:

$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2(\theta_W),$$
$$\lambda_Z = \lambda_\gamma,$$

<u>Relation</u> $g_1^Z \;=\; 1 + c_W\frac{m_Z^2}{2\Lambda^2}\cdots$