ELEMENTARY PARTICLE PHYSICS
Current Topics in Particle Physics
Laurea Magistrale in Fisica,
curriculum Fisica Nucleare e Subnucleare
Lecture 7

Simonetta Gentile*

* Università Sapienza,Roma,Italia.

November 13, 2017

Preliminaries

Simonetta Gentile
terzo piano Dipartimento di Fisica *Gugliemo Marconi*
Tel. 0649914405
e-mail: simonetta.gentile@roma1.infn.it
pagina web:http://www.roma1.infn.it/people/gentile/simo.html

Bibliography

♠ Bibliography

- K.A. Olive et al. (Particle Data Group), *The Review of Particle Physics*, Chin. Phys. C, 38, 090001 (2014)(PDG) update 2015, http://pdg.lbl.gov/
- F. Halzen and A. Martin, *Quarks and Leptons: An introductory course in Modern Particle Physics* , Wiley and Sons, USA(1984).

♠ Other basic bibliography:

- A.Das and T.Ferbel, *Introduction to Nuclear Particle Physics* World Scientific,Singapore, 2$^{\text{nd}}$ Edition(2009)(DF).
- D. Griffiths, *Introduction to Elementary Particles* Wiley-VCH,Weinheim, 2^{nd} Edition(2008),(DG)
- B.Povh *et al.*, *Particles and Nuclei* Springer Verlag, DE, 2$^{\text{nd}}$ Edition(2004).(BP)
- D.H. Perkins,*Introduction to High Energy Physics* Cambridge University Press, UK, 2$^{\text{nd}}$ Edition(2000).
- Y.Kirsh & Y. Ne'eman, *The Particle Hunters*

♠ Particle Detectors bibliography:

- William R. Leo *Techniques for Nuclear and Particle Physics Experiments*, Springer Verlag (1994)(LEO)
- C. Grupen, B. Shawartz *Particle Detectors*, Cambridge University Press (2008)(CS)
- *The Particle Detector Brief Book*,(BB) http://physics.web.cern.ch/Physics/ParticleDetector/Briefbook/

Specific bibliography is given in each lecture

Lecture Contents - 1 part

1. Introduction. Lep Legacy
2. Proton Structure
3. Hard interactions of quarks and gluons: Introduction to LHC Physics
4. Collider phenomenolgy
5. The machine LHC
6. Inelastic cros section pp
7. W and Z Physics at LHC
8. Top Physics: Inclusive and Differential cross section $t\bar{t}$ W, $t\bar{t}$ Z
9. Top Physics: quark top mass, single top production
10. Dark matter

Specific Bibliography

♠ Bibliography of this Lecture

Contents

Interest to study electroweak physics

The Electroweak physics constitutes an wide interest in the framework of LHC.

- First we have to prove to **understand the the known physics** before claim any discovery. W Z cross sections measured with small uncertanties are benchmark for SM and are one of first validations,
- LHC is not a precision machine, but with the enormous statistics of W and Z collected can be considered as that. Data/MC comparison provide a powerful validation of QCD calculations,
- Understand the background is a main issue, W Z are among the most copious backgrounds,
- **Z and W** can be considered as a **candle** providing an excellent calibration signal for many purposes:
  - Electron energy scale,
  - Track momentum scale,
  - Lepton ID and trigger efficiencies,
  - E_T^{miss} resolution,
  - Luminosity (as Bhaba scattering at LEP),
  - .....

Z and W bosons :Experimental signatures

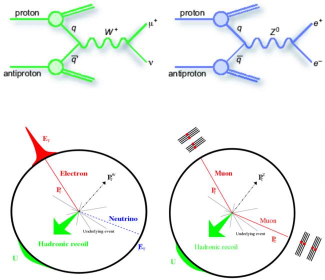


Figure :
On top are sketched diagrams: $W^+ \to \mu^+\nu$ (left) $Z \to e^+e^-$(left). On bottom $W^+ \to e^+\nu$ (left) $Z \to \mu^+\mu^-$(left).

- **Z pair of charged leptons**
  $Z \to \ell^+\ell^-$
  - Lepton requirements:
    - high $p_{\rm T}$ ($>$ 20 GeV)
    - isolated
    - opposite charge ($\ell^+\ell^-$)
  - $\sim 60 < m_{\ell^+\ell^-} <\sim 120$ GeV
- **W single charged lepton**
  $W^+ \to \ell^+\nu$
  - Lepton requirements:
    - high $p_{\rm T}$ ($>$ 20 GeV)
    - isolated
  - $E_T^{miss} > 20$ GeV from ν
  - Transverse mass: $M_W^T = \sqrt{2 \cdot p_{\rm T}^{\ell} \cdot p_{\rm T}^{\nu} \cdot (1 - \cos\Delta\phi^{\ell,\nu})} > 40GeV$

Z and W bosons: candidates

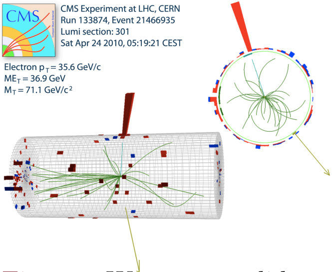


Figure : $W \to e\nu$ candidate

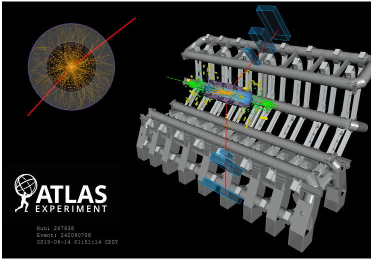
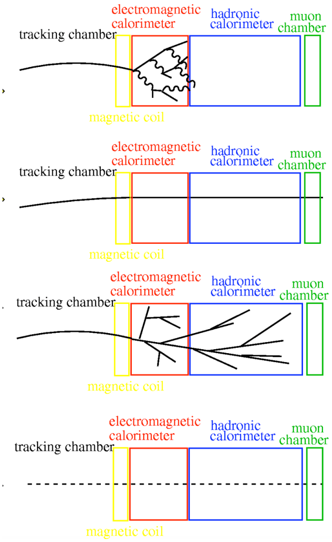


Figure : $Z \to \mu\mu$ candidate

On the right: Display of a $Z \to \mu\mu$ candidate event from proton-proton collisions recorded by ATLAS on 14 June 2015, at $\sqrt{s}$=13 TeV. The red lines shows the paths of two muons through the detector, with transverse momenta of 44.1 and 44.7 GeV. The green and yellow bars indicate energy deposits in the liquid argon and scintillating-tile calorimeters.Charged particle tracks reconstructed from hits in the inner tracking detector are shown as orange arcs, curving in the solenoidal magnetic field. The reconstructed dimuon invariant mass is 90.2 GeV.

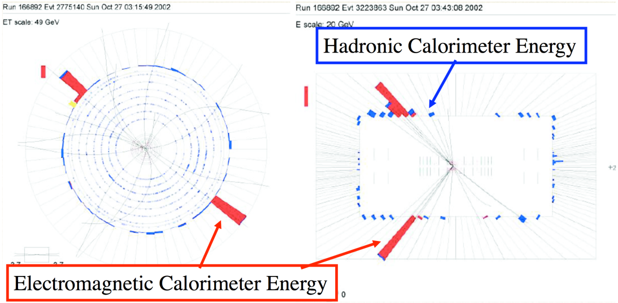
Lepton identification



- Electrons
  - compact electromagnetic cluster in calorimeter
  - Matched to track
- Muons
  - Track in the muon chambers
  - Matched to track
- Taus
  - Narrow jet
  - Matched to one or three tracks
- Neutrinos
  - Imbalance in transverse momentum
  - Inferred from total transverse energy

W/Z: electrons and jets

Jets can fake electrons. The fake rates has to be evaluated to estimate the backgrounds.



- jets can look like electrons, e.g.:
  - early showering charged pions
  - Semileptonic b-decays
- And there are lots of jets!!!
- Difficult to model in MC

Fake rate per jet:

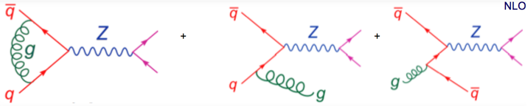
- CDF, tight cuts: 1/10000
- ATLAS, tight cuts: 1/80000
- Typical uncertainties 50%

Z boson production at LHC

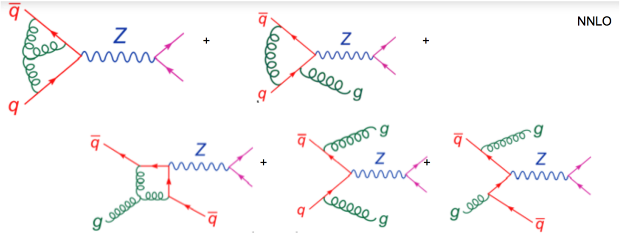
- Experimentally: Z bosons events (decaying into leptons) observed at large rate at LHC
  - At $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$:100 Z bosons per second
  - Leptons yield clean final state signature
  - Measured with high accuracy($\leq 1\%$)
- Theoretically well understood
  - Perturbative corrections up to NNLO
  - Process evaluated with percent level accuracy
- Precision physics
  - Electroweak masses and couplings
  - Parton distributions

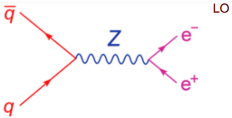
Predictions: Z-boson production at LHC

- New channels open up at NLO and NNLO
  - qg-induced processes at NLO



  - gg-induced processes at NNLO





Predictions: LO, NLO, NNLO

- Scale dependence
  - varied between $[M_Z/2; 2M_Z]$
- Scale variation is reduced at each order
  - LO:30%,NLO 6%,NNLO <1%
  - But:LO uncertainty band underestimates higher orders
- Origin of large NLO corrections
  - New partonic channel $qg \to Zq$
  - Large gluon luminosity leads to NLO corrections of 15-30% (depending on rapidity)

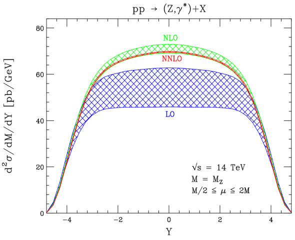


Figure : Rapidity in Z distribution

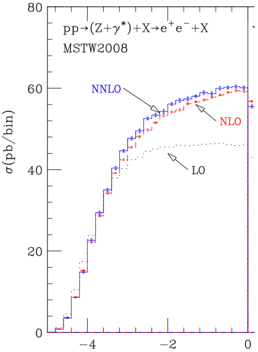
- Reliable estimate of theoretical uncertainty only at NNLO

Predictions

- Various predictions are available to Leading Order(LO), Next-to-Leading-Order(NLO),Next-to-Next-Leading-Order(NNLO). Corresponding to different precision,as example[1] the inclusive production of e^+e^- pairs from the decay of an on-shell Z boson.The cross sections:

$$\sigma_{LO} = .761 \pm 0.001 \text{ nb},$$
$$\sigma_{NLO} = 2.030 \pm 0.001 \text{ nb}$$
$$\sigma_{NNLO} = 2.089 \pm 0.003 \text{ nb}$$

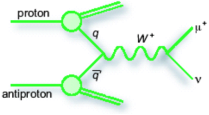
The total cross section is increased by about 3% in going from NLO to NNLO.



[1] S. Catani et al., Vector boson production at hadron colliders: a fully exclusive QCD calculation at NNLO, Phys. Rev. Lett. 103 (2009) 082001,arXiv:0903.2120[hep-ph]. and C. Anastasiou et al., High precision QCD at hadron colliders: Electroweak gauge boson rapidity distributions at NNLO, Phys.

Contents

Background subtraction in W selection



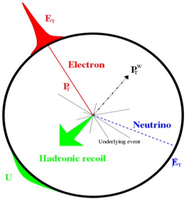


Figure :
On top diagram $W^+ \to \mu^+ \nu$
On bottom $W^+ \to e^+ \nu$ E_T^{miss} for W boson candidates with μ final states(right).

Measurement of Inclusive W and Z Boson Production Cross Sections in pp Collisions at $\sqrt{s}$*= 8TeV* S. Chatrchyan et al. (CMS Collaboration) Phys. Rev. Lett. 112, 191802,arXiv:1402.0923
https://arxiv.org/abs/1402.0923

W decay to charged leptons:

- high-p_T(> 20 GeV)
- isolated
- E_T^{miss} from ν
- Transverse mass: $M_W^T = \sqrt{2 \cdot p_T^\ell \cdot p_T^\nu (1 - \cos \Delta\phi^{\ell,\nu})}$

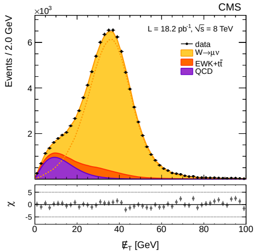


Figure : $\chi = N_{obs} - N_{exp}/\sqrt{N_{obs}}$

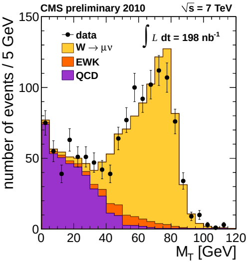
Background subtraction in W selection

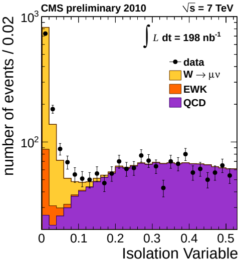
CMS Isolation variable

$$I^{\rm rel}_{\rm comb} = \left\{ \sum (p_{\rm T}(\text{tracks}) + E_T(\text{em}) + E_T(\text{had}) \right\} / p_{\rm T}(\mu)$$

$$\text{in cone} \quad \Delta = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$$

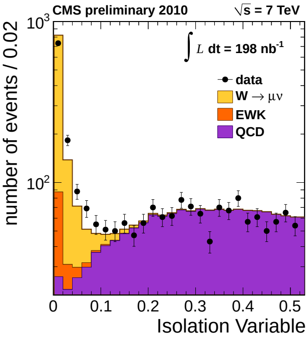
around the muon. With less statistics M_T[2]

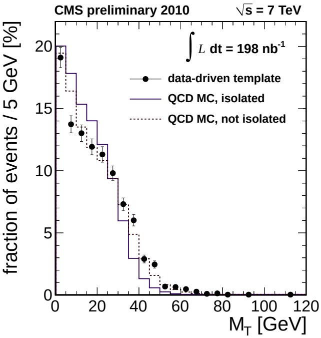




[2] Measurements of Inclusive W and Z Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV (CMS Collaboration) J. High Energy Phys. 01 (2011) 080 arXiv:1012.2466 http://arxiv.org/abs/1012.2466.

Background subtraction in W selection





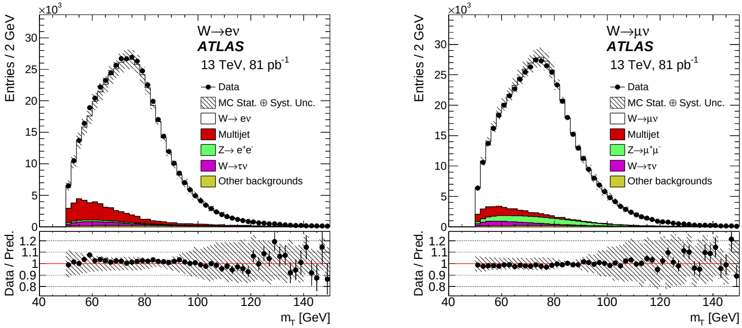
$p_T > 20$ GeV in $\eta < 2.1$ The muon is isolated if isolation variable $I^{rel}_{comb} < 0.15$.QCD backgrounds: mostly b-decays.

A high purity QCD template is obtained by using the same cuts as signal in the signal selection but the isolation cut, which is chosen $I^{rel}_{comb} > 20$. This shape is taken for fit M_T distribution

W selection

Brand new July 2016 ATLAS results [3]

Transverse mass distribution $W \to e\nu, W \to \mu\nu$.Logarithmic scale.



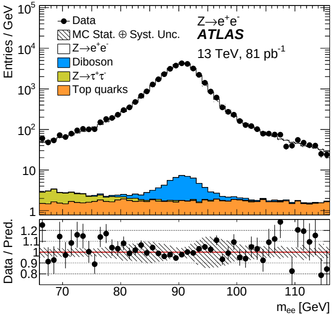
[3] Measurement of $W^{\pm}$ and Z-boson production cross sections in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector(ATLAS Collaboration),Phys. Lett. B 759 (2016) 601, arXiv:1603.09222. https://arxiv.org/abs/1603.09222

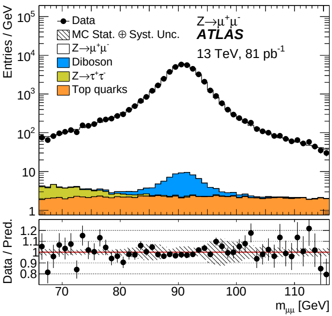
Z selection

• **Z** is important tool: **data-driven** methods for controlling **lepton efficiency, resolution, E^T_{miss}** (hadronic recoil).

Z decay to charged leptons:

- 2 ℓ same flavour
- opposite charge $\ell^+\ell^-$
- $66 < m_{\ell\ell} < 116$ GeV





Systematic Uncertaiities

$\delta C/C$ [%]	$Z \to e^+e^-$	$W^+ \to e^+\nu$	$W^- \to e^-\bar{\nu}$	$Z \to \mu^+\mu^-$	$W^+ \to \mu^+\nu$	$W^- \to \mu^-\bar{\nu}$
Lepton trigger	0.1	0.3	0.3	0.2	0.6	0.6
Lepton reconstruction, identification	0.9	0.5	0.6	0.9	0.4	0.4
Lepton isolation	0.3	0.1	0.1	0.5	0.3	0.3
Lepton scale and resolution	0.2	0.4	0.4	0.1	0.1	0.1
Charge identification	0.1	0.1	0.1	–	–	–
JES and JER	–	1.7	1.7	–	1.6	1.7
$E_{\mathrm{T}}^{\mathrm{miss}}$	–	0.1	0.1	–	0.1	0.1
Pile-up modelling	< 0.1	0.4	0.3	< 0.1	0.2	0.2
PDF	0.1	0.1	0.1	< 0.1	0.1	0.1
Total	1.0	1.9	1.9	1.1	1.8	1.8

Figure : Relative systematic uncertainties(%)

The systematic uncertanties are:

- Trigger: The lepton trigger efficiency is estimated in simulation, with a dedicated data-driven analysis performed to obtain the simulation-to-data trigger correction factors.
- Reconstruction, Identification, and Isolation:The lepton selection efficiencies as determined from simulation are corrected with simulation-to-data correction factor.

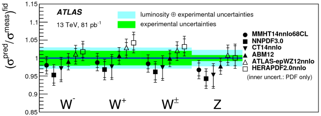
Systematic Uncertaiities

- Energy, Momentum Scale/Resolution:Uncertainties in the lepton calibrations can cause a change of acceptance because of migration of events across the p_{T} threshold and $m_{\ell\ell}$ boundaries.
- Electron charge misidentication may occur when electrons radiate early in the detector and the resulting photons subsequently convert and are reconstructed as high p_{T} tracks. A particle with reconstructed charge opposite to the parent electron may then accidentally be associated with the calorimeter cluster.
  The effect of electrons having their charge reconstructed wrongly is studied using a control sample of $Z \to ee$ events in which both electrons are reconstructed with the same charge.
  The probability of charge misidentification is negligible in the muon channel.

Systematic Uncertaiities

- Jet-Energy Scale/Resolution (JES and JER): The corresponding uncertainties are propagated to the calculation of the missing transverse momentum.
- E^T_{miss},Uncertainties in the soft component are included,
- Pile-up Incorrect modelling of pile-up effects can lead to acceptance changes and is accounted for with dedicated studies.
- PDF impact of PDF eigenvector variations is propagated to the correction factor

Z & W cross section



		stat	sys	lumi	
$\sigma^{tot}_{W^+}$	$= 11.83$	± 0.02	± 0.32	± 0.25	nb
$\sigma^{tot}_{W^-}$	$= 8.79$	± 0.02	± 0.24	± 0.18	nb
σ^{tot}_{Z}	$= 1.981$	± 0.007	± 0.038	± 0.042	nb

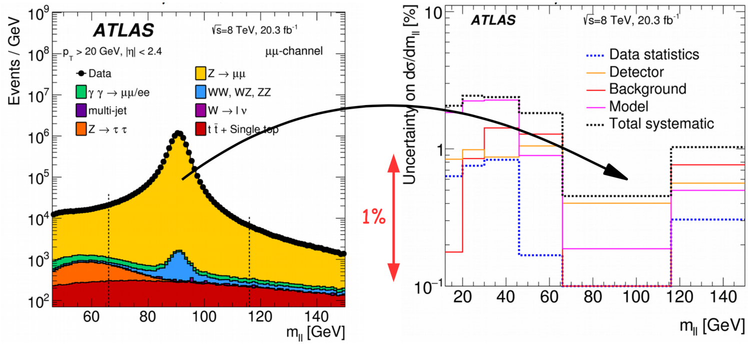
•The combined fiducial cross sections compared to the predictions using different PDF sets. Good agreement with the predictions and the experimental precision is comparable to the PDF uncertainties.

$\Longrightarrow$ need better for discrimination.

• Good agreement with with theoretical calculations based on NNLO QCD with NLO EW corrections.

•These measured cross sections have a global luminosity uncertainty of 2.1%, the remaining experimental uncertainties are W (3%)and Z-boson(1%) channels.

Z selection at $\sqrt{s}$= 8 TeV



- $\mathcal{O}$(10M) di-lepton pairs at Z peak → huge statistics.
- Most systematic sources are constrained by the data → syst ∼ stat. Total uncertainties at permille level.
- Test QCD and EW corrections at sub-percent level and constrain PDFs.

W/Z cross section at LHC

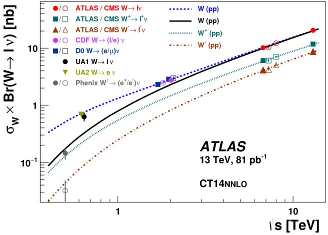


Figure : The measured values of $\sigma_W \times \mathrm{Br}(W \to \ell\nu)$ f or W^+, W^- and their sum, compared with NNLO QCD calculations.

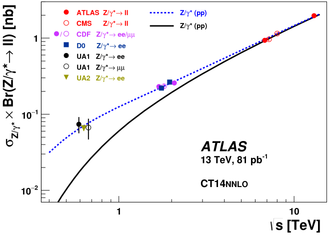
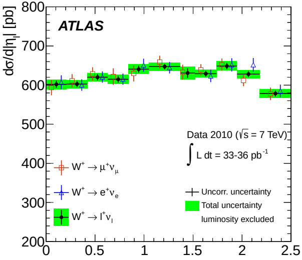
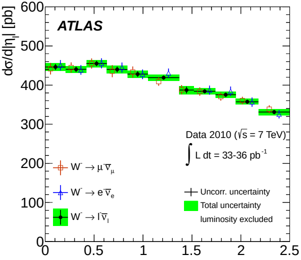


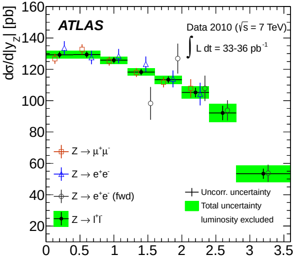
Figure : The measured values of f $\sigma_{Z/\gamma^*} \times \mathrm{Br}(Z/\gamma^{\to}\ell^+\ell^-)$ and their sum, compared with NNLO QCD calculations.

W/Z cross section in rapidity

The combined $\frac{d\sigma}{d|\eta_\ell|}$ for W^+ and W^- and $\frac{d\sigma}{d|y_Z|}$ for $Z \to \ell^+\ell^-$







- Z, W^+, W^- sensitive to different parton flavour configuration

$\Downarrow$

- impact on detailed understanding of PDF

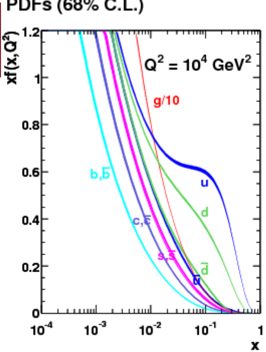
from Phys. Rev. D85 (2012) 072004,arXiv:1109.5141
http://arxiv.org/abs/1109.5141

W production asymmetry

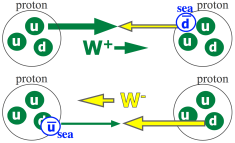
LHC is pp-collider p(uud)→ 2 valence up quark 1 valence d quark.

$$u\bar{d} \to W^+ \qquad d\bar{u} \to W^-$$

- LHC: a valence quark from proton and a sea quark from proton
- $W^{\pm}$ proton production asymmetry is governed by PDFs → constrain the PDFs with asymmetry measurements.
- Since valence quarks have high x and $N(u_v) > N(d_v)$ → more W^+ from $(u\bar{d})$ than W^- from $(d\bar{u})$.



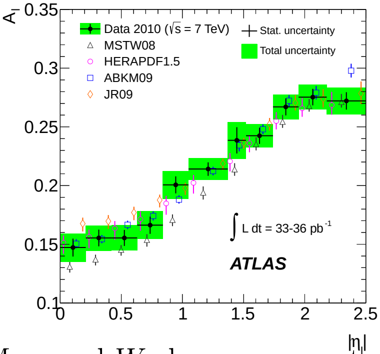
from: MSTW PDFs and impact of PDFs on cross sections at Tevatron and LHC - Watt, Graeme - arXiv:1201.1295



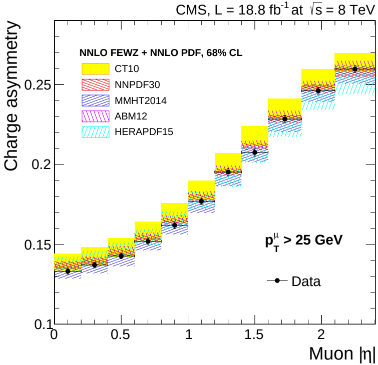
W charge asymmetry

$$\mathcal{A}_\ell = \frac{d\sigma/d\eta(W^+ \to e^+\nu) - d\sigma/d\eta(W^- \to e^-\bar{\nu})}{d\sigma/d\eta(W^+ \to e^+\nu) + d\sigma/d\eta(W^- \to e^-\bar{\nu})}$$

$W \to \ell\nu$



$W \to \mu\nu$

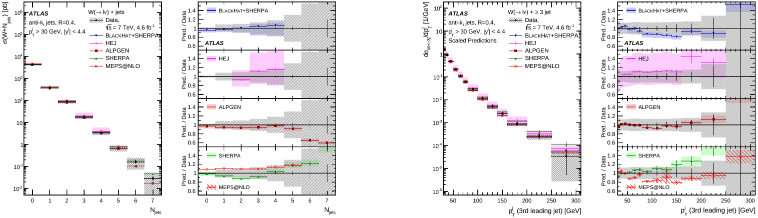


Measured W charge asymmetry as a function of lepton pseudorapidity $|\eta_\ell|$ compared with NNLO theoretical predictions.

- **sensitive to PDF choice**

Contents

W + jets: jet multilpicity

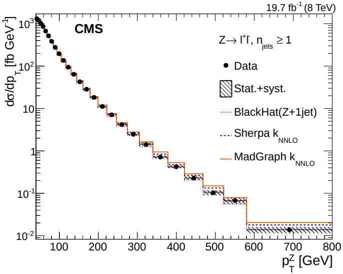


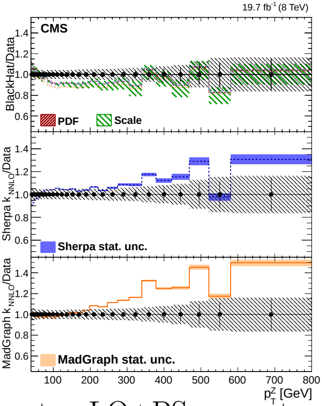
No theoretical prediction is able to provide an **accurate description** of the data on **multijets range**.The leading-order predictions ALPGEN + HERWIG for showering, SHERPA with its own parton showering model.ALPGEN and SHERPA use leading-order matrix element information for predictions of W + jets production.ALPGEN provides predictions with up to five additional partons from the matrix element in the final state, SHERPA includes up to four partons.[4]

[4] from: Measurements of the W production cross sections in association with jets with the ATLAS detector Eur. Phys. J. C (2015) 75:82 arXiv:1409.8639

Z + jets: differential

Differential cross sections of Z+ jets ($Z \to \ell^+\ell^-$) vs boson p_T at $\sqrt{s} = 8$ TeV (CMS).



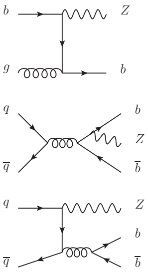


The estimations from the MC multiparton LO+PS generators MADGRAPH+PYTHIA6 and SHERPA compared to the data. The **p_T spectra for Z +jets**are **not well reproduced** by these MC models.[5]

[5] CMS Coll,J. High Energy Phys. 10 (2015) 128.arXiv:1505.06520 http://arxiv.org/abs/1505.06520

Z/W + heavy flavour

- W+c and Z+b most relevant to constrain PDFs,
- Z+b-jets production precision tests of perturbative QCD
- Z+1b-jet production → information on the b-quark content of the proton
- Z+2b-jets production, is a background in many searches



The production of a Z boson with b jets originates in *pp* collisions from gluon-gluon and $q - \bar{q}$ interactions mainly.

Z + heavy flavour

Z + bb jets production

$Z \to \ell^+\ell^-(\ell = \mu \; or \; e)$

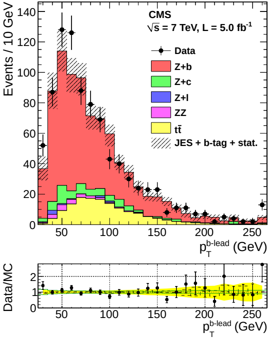
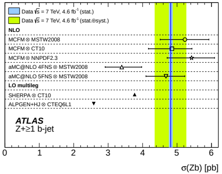


Figure : CMS,JHEP 06 (2014) 120,arXiv:1402.1521

Cross-sections for Z+ 1 bjets and Z + ≥ 2 bjets



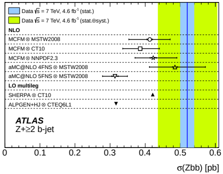
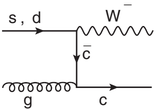
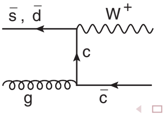


Figure : ATLAS JHEP10(2014)141,arXiv:1407.3643

W+ c

- The study of associated production of a W boson + quark c provides direct access to the strange-quark content of the proton at an energy scale of the order of the W-boson mass ($Q^2 \sim 1(00\ \text{GeV})^2 \rightarrow$) reduce the uncertainties in the strange quark and antiquark parton distribution functions (PDFs).
- W^-+c yield is expected to be slightly larger than the W^++c yield at the LHC because of the participation of down valence quarks in the initial state
- A key property of the $qg \rightarrow W + c$ reaction is the presence of a charm quark and a W boson with opposite-sign charges.
- It is background for signals involving bottom or top quarks and missing transverse energy in the final state.





W+ c

Associated production of a W boson with a charm-quark jet.

- The charge of the W boson and the charge of the c quark, which are always of opposite sign.
- W-boson decay into a well-identified charged lepton ($W^{\pm} \to \ell^{\pm}\nu$).
- The c quarks identified as the final-state mesons (D and $D*^{\pm}$)
- Allows ti unequivocally the signs of both the W boson and the charm-quark jet candidates (arXiv:1310.1138)

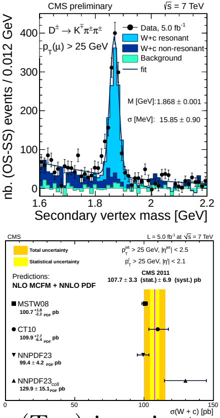
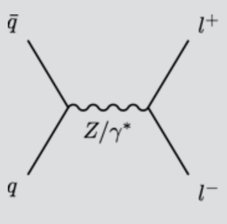


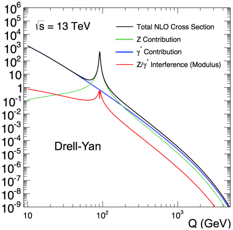
Figure : (Top) invariant mass distribution of three-prong secondary vertices, subtracted same sign, (bottom) $\sigma(W + c)$ with p_T^{ℓ} of ℓ associated W.

Contents

Drell-Yan production cross section $d\sigma/dM$

- **Drell-Yan (DY) lepton pairs are produced via γ/Z exchange in the s channel**.
- Theoretical calculations of the differential cross section $d\sigma/d|y|$, where $m_{\ell\ell}$ is the dilepton invariant mass and $|y|$ is the absolute value of the dilepton rapidity, are well established in SM up to the next-to-next-to-leading order (NNLO) in perturbative quantum chromodynamics (QCD) $\Longrightarrow$ Sensitive tool to check SM
- Drell-Yan cross section falls nine decades from 100 GeV $\rightarrow$ 1000 GeV
- Important background to many new physics channel





Drell-Yan production cross section $d\sigma/dM$

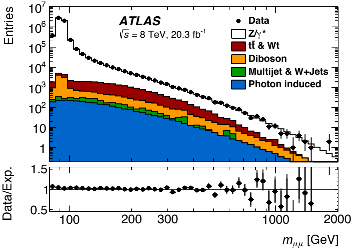


Figure : Invariant mass $m_{\mu\mu}$

- Precision 1% at low $m_{\ell\ell}$
- Data compatible with NNLO pQCD $\otimes$ NLO EW + Photon induced predictions
- **Measurements are sensitive to PDFs**

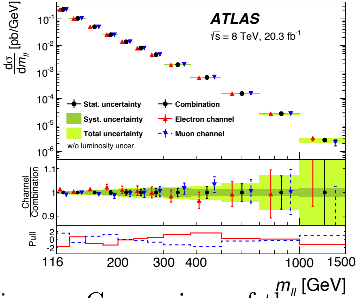
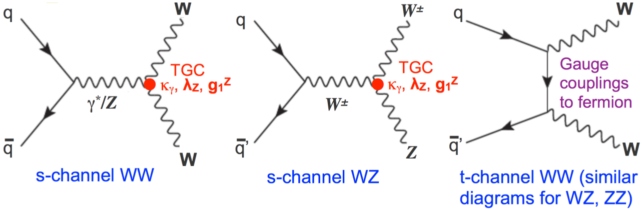


Figure : Comparison of the electron (red points), muon (blue points) and combined (black points) single-differential fiducial Born-level cross sections as a function of invariant mass $m_{\ell\ell}$. arXiv:1606.01736

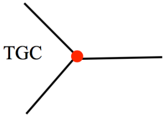
Contents

Diboson (Wγ, Zγ,WW,WZ,ZZ) production



- Critical test of the gauge structure of the SM
  - Allows to search for anomalous Triple Gauge Couplings (TGC)
- Mandatory preliminary study for Higgs searches:
  - Irriducibile background for Higgs search in WW and ZZ channels
- Probe for new physics
  - Resonances with diboson final state

Gauge Couplings

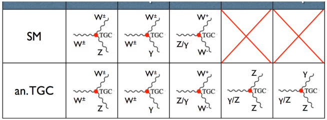


- Standard Model (SM) allow gauge bosons to interact with one another → Coupling between 3 gauge bosons Triple Gauge-Boson Coupling (TGC).
- SM only allows charged coupling ($WWZ, WW\gamma$), does not allow pure neutral coupling ($ZZZ, ZZ\gamma, Z\gamma\gamma, \gamma\gamma\gamma$)
- Physics beyond SM can introduce anomalous TGC which may allow neutral couplings, or increased the charged TGC coupling strength.
- Effective Lagrangians which characterized the charged and neutral TGC, introduced a few anomalous coupling parameters

Gauge Couplings

Charged TGC

- $\lambda_\gamma, \lambda_Z$
- $\Delta k_\gamma = k_\gamma - 1, \Delta k_Z = k_Z - 1, \Delta g_1^Z = g_1^Z - 1$
- SM at tree level $\lambda_\gamma = \lambda_Z = \Delta k_\gamma = \Delta k_Z = \Delta g_1^Z = 0$



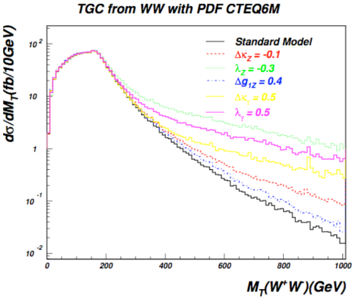
Neutral TGC

- $f_4^Z, g_5^Z, f_4^\gamma, g_5^\gamma,$
- SM at tree leve $f_4^Z = g_5^Z = f_4^\gamma = g_5^\gamma = 0$
- Each diboson production can probe one or more TGC
  - $WZ : WWZ$ vertex
  - $WW : WWZ, WW\gamma$ vertex
- Measures the anomalous coupling parameters

•The study of **TGC** can be done through the measurement of **diboson production**

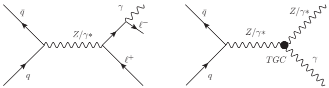
Diboson final states

- The presence of **anomalous TGC will enhance diboson production rate**, particularly at high transverse momentum of bosons

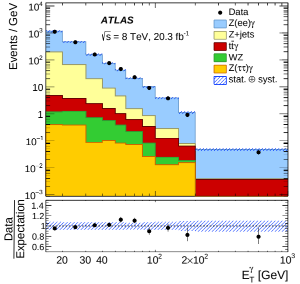


Diboson final states: $Z\gamma$

Examples of triple gauge-boson couplings involving Z

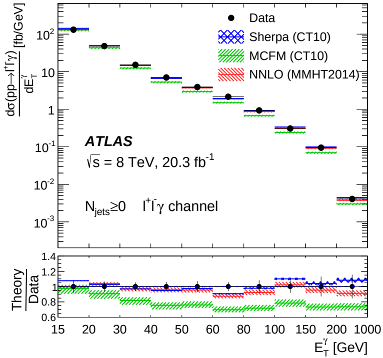


$Z \rightarrow ee\gamma$



https://arxiv.org/abs/1604.05232v1

$Z \rightarrow \ell\ell\gamma$ (inclusive: $N_jet \geq 0$)



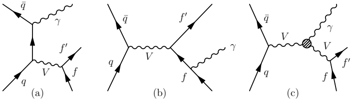
High order QCD (⇑) describe data well, NNLO effects clearly visible

Consistent with NNLO prediction ($\sim$ 2 % uncertainty)

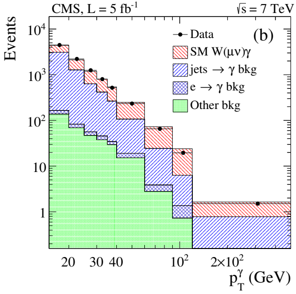
Backgrounds dominated by photon misidentification

Diboson final states: $W\gamma$

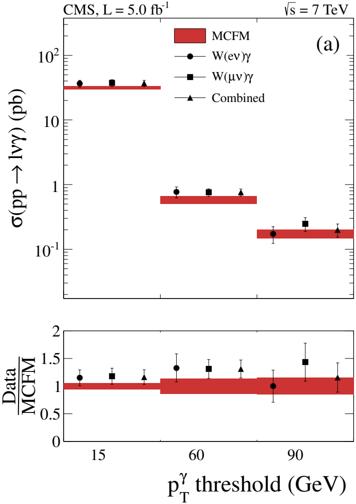
Examples of triple gauge-boson couplings involving W



$W \to \mu\nu\gamma$



$W \to \ell\nu\gamma$

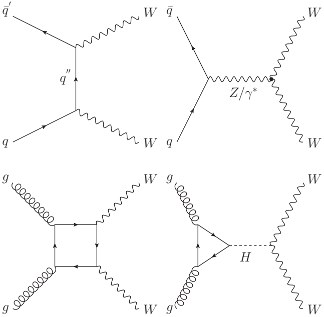


- consistent with predictions of SM.

http://arxiv.org/abs/1308.6832

Diboson final states: WW

Examples of triple gauge-boson couplings involving WW:



- Measured cross sections in $WW \to 2\ell\ 2\nu$ channel need **good calibration for missing $\mathbf{E^{T}_{miss}}$**

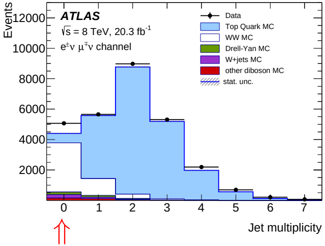
- Large irreducible background to searches for physics beyond the SM and to resonant $H \to W^+W^-$ production

- 0 jet - both leptonic Ws decays
  - 2 isolated leptons $p_T > 25(20) GeV + E^{miss}T$
  - ee, $\mu\mu$ and eμ channels
  - reject events with $\geq$ one jet to suppress top bkgd

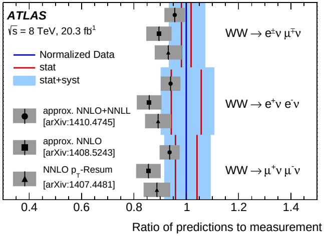
- 1 jet -
  - reject top with b-jet veto
  - largest bkgd from top

Diboson final states: WW

0-jet



0-jet



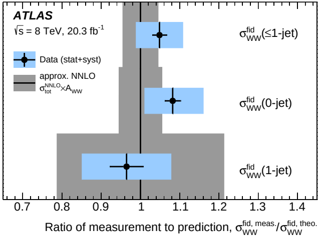
$t\bar{t}$ background calculated NLO

https://arxiv.org/abs/1603.01702

https://arxiv.org/abs/1608.03086

- *Fiducial* minimum phase space extrapolation
- σ^{WW}_{fid} in agreement with calculation in 1-2 σ(0-jet)
- QCD calculations describe data within uncertainties

0-1 jet



Diboson final states: WZ

Search for $WZ \to \ell\nu\ell'\ell'$, $\ell\ell' = e, \mu$

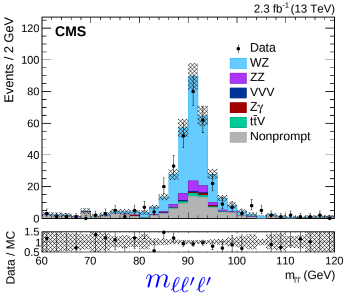
- lepton candidates $\ell\nu\ell'\ell'$
- $\ell'\ell'$ same flavor opposite sign as from Z
- $p_T^{\ell'} > 20$ GeV$p_T^{\ell'} > 10 GeV$
- select combination near m_Z
- $76 < m_{\ell'\ell'} < 106$ GeV
- no other lepton,no jets

Measured cross section in:
$70 < m_{\ell'\ell'} < 120$ GeV

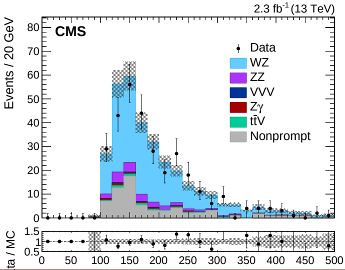
$$\sigma(pp \to WZ) = 39.9 \pm 3.2(stat)^{+2.9}_{3.1}(sys) \pm 0.4(theo) \pm 1.3(lumi)\text{pb}$$

consistent with SM prediction.http://arxiv.org/abs/1607.

$m_{\ell'\ell'}$



$m_{\ell\ell'\ell'}$

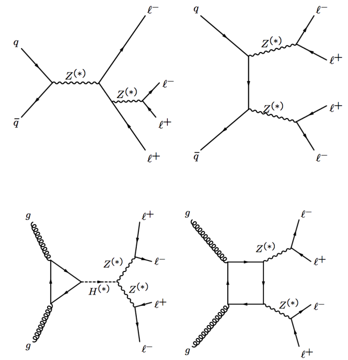


Diboson final states: ZZ

• ZZ production is dominated by quark-antiquark (qq) interactions, with an O(10%) contribution from loop-induced gluon-gluon (gg) interactions

• **ZZ** production is an important **background**in studies of the **Higgs boson**

Search for $WZ \to \ell^+\ell^-\ell'^+\ell'^-$, $\ell\ell' = e, \mu$



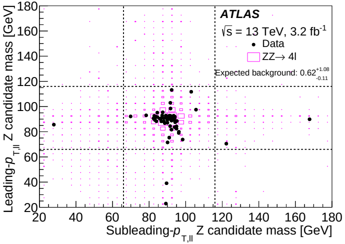
• LO diagram for $q\bar{q}$ initiated production 4ℓ. $s-$channel $q\bar{q} \to Z^* \to \ell^+\ell^-$with associated another ℓ pair (left)t-channel production $q\bar{q} \to Z^*Z^* \to \ell^+\ell^-$(right)

• The tree-level diagrams for gg initiated production 4ℓ.Higgs boson production through gluon-fusion $gg \to H^{(*)} \to ZZ^{(*)} \to 4\ell$ (left) $gg \to Z^{(*)}Z^{(*)} \to 4\ell$

Diboson final states: ZZ

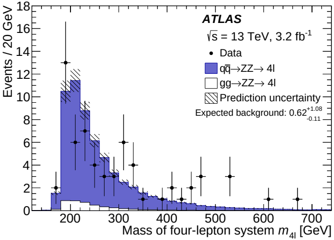
Search for $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$, $\ell\ell' = e, \mu$

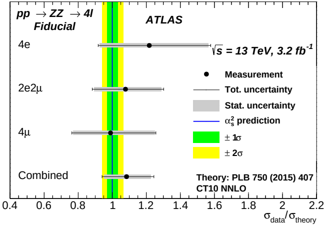
- $4\ \ell$ 2 on shell Z
- $66 < m_{\ell\ell} < 116$ GeV
- Small background $\sim 1\%$- largest contributions from ttZ and misidentified leptons.

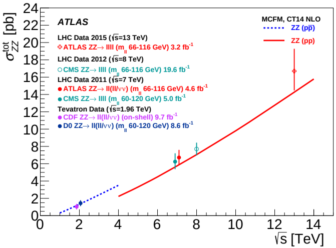


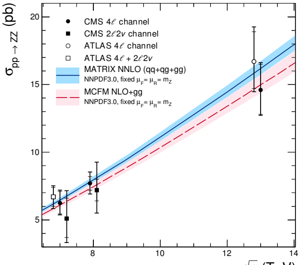
http://arxiv.org/abs/1512.05314

Diboson final states: ZZ









http://arxiv.org/abs/1512.05314, http://arxiv.org/abs/1607.08834

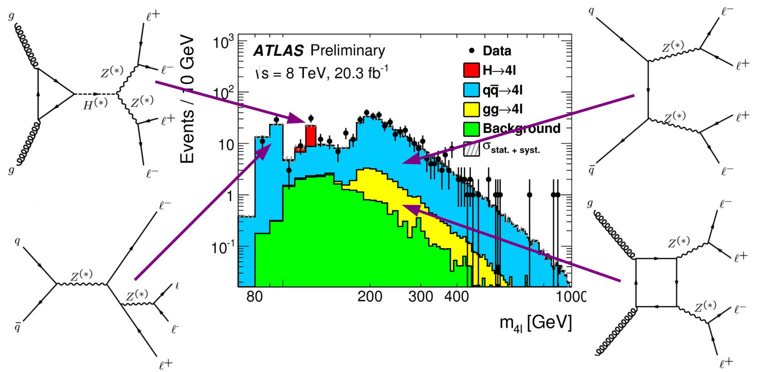
Diboson final states: ZZ

At $\sqrt{s} = 13$ TeV:

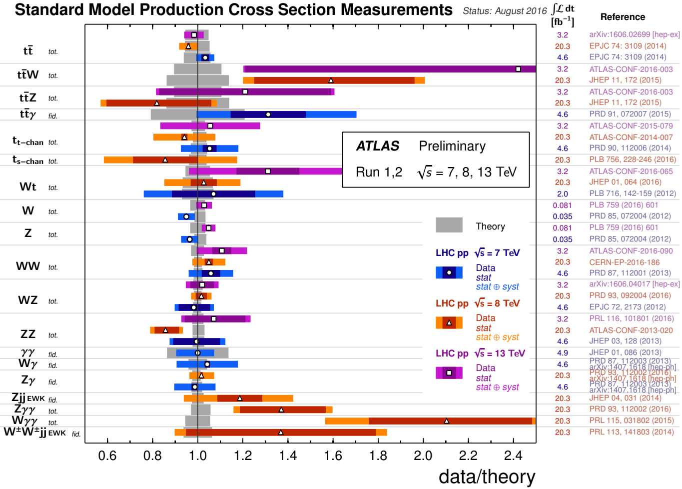
- Currently a statistically limited measurement.
- Systematics are dominated by uncertainties on scale factors used to correct lepton reconstruction and Identification efficiencies, and the difference between the MC generators used to model the signal processes.

$$\sigma(pp \to ZZ) \;=\; 16.7^{+2.2}_{-2.0}(stat)^{+0.9}_{0.7}(sys)^{+1.0}_{-0.7}(theo) \pm 1.3(lumi)\text{fb}$$
$$\mathcal{O}15.6 \pm 0.4\text{fb}$$

Diboson final states: ZZ



Summary of Boson production



Contents

Triple Gauge coupling (TGC)

All these results can be interpreted as anomalous of Anomalous Triple Coupling.
As example: CMS study of $Z\gamma \to \nu\bar{\nu}\gamma$

The branching fraction for a Z boson decay to a pair of neutrinos is six times higher than for a decay to a particular charged lepton pair.

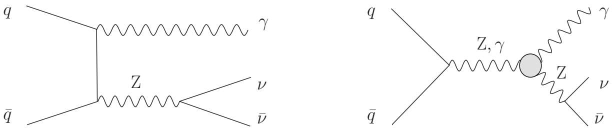
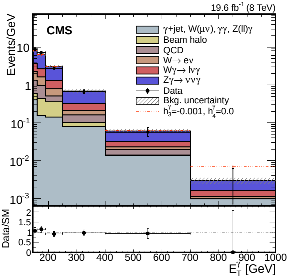
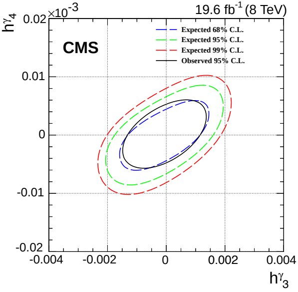


Figure : Zγ productionSM at tree level (left)via anomalous ZZγ or Z$\gamma\gamma$ trilinear gauge couplings (right)

Neutral linear coupling can be also expressed $h_i^v(i = 1, ...4).h_1$ and h_2 are CP-violating h_3, h_4 are CP conserving.At tree level in SM the individual values of these aTGCs are zero.The results are generally interpreted in terms of the CP-conservinga TGCs h_3^V and h_4^V.

Triple Gauge coupling (TGC)

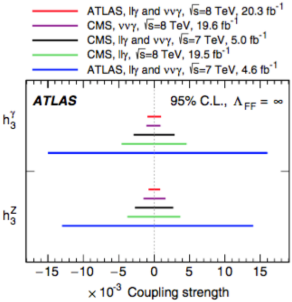


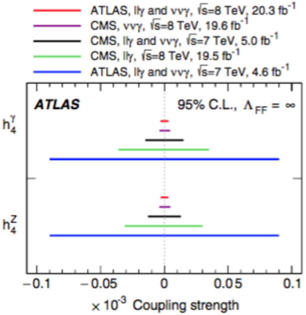


No evidence was found for **anomalous neutral trilinear gauge couplings** in $Z\gamma$ production.

http://arxiv.org/abs/1602.07152

Triple Gauge coupling (TGC)





Just for yuor info:

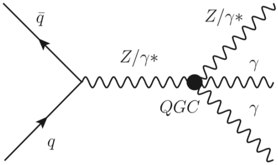
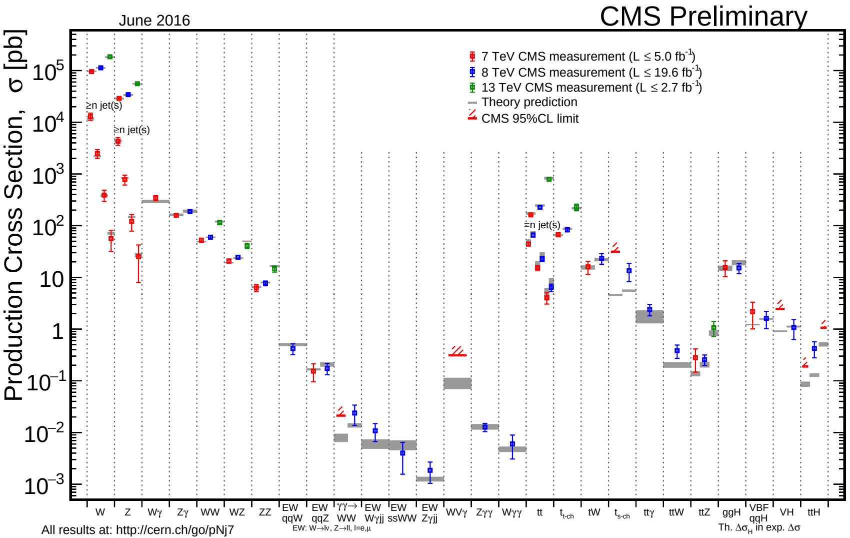
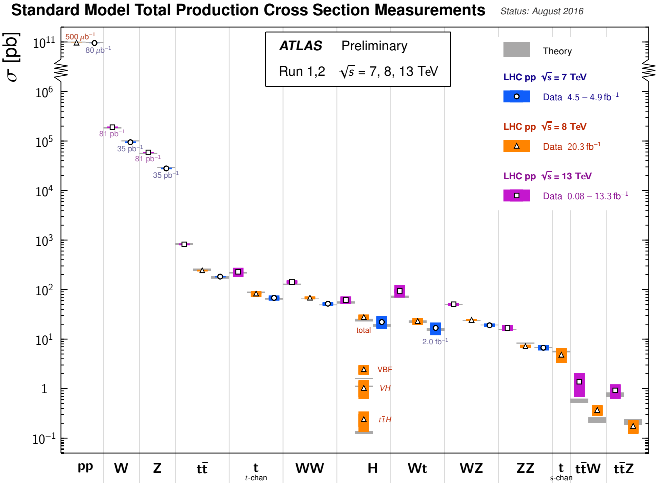


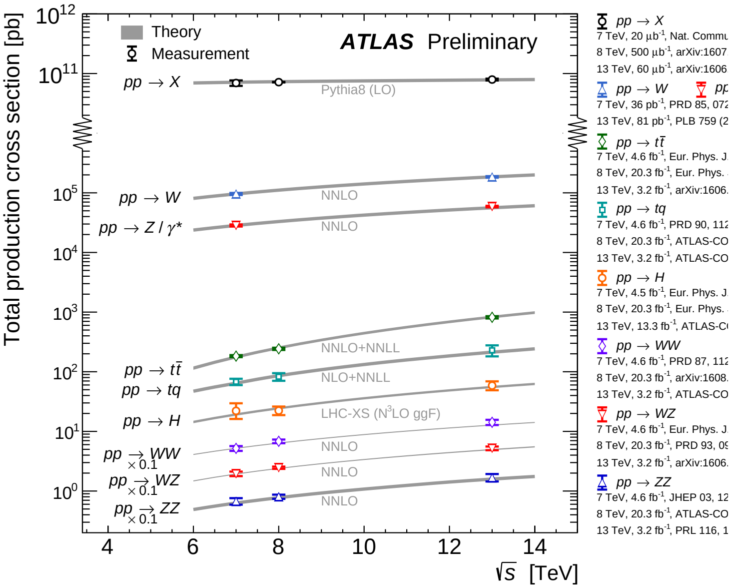
Figure : Quartic Coupling

Contents



CMS Preliminary
June 2016
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 2.7 fb-1)
Theory prediction
CMS 95%CL limit
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→WW
EW Wγjj
EW ssWW
EW Zγjj
WVγ
Zγγ
Wγγ
tt
t t-ch
tW
t s-ch
ttγ
ttW
ttZ
ggH
VBF qqH
VH
ttH
EW: W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7


Standard Model Total Production Cross Section Measurements
Status: August 2016
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 13.3 fb⁻¹
σ [pb]
500 μb⁻¹
80 μb⁻¹
81 pb⁻¹
35 pb⁻¹
81 pb⁻¹
35 pb⁻¹
total
2.0 fb⁻¹
VBF
VH
tt̄H
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
WZ
ZZ
t
s-chan
tt̄W
tt̄Z



Total production cross section [pb]
Theory
Measurement
ATLAS Preliminary
pp → X
Pythia8 (LO)
pp → W
NNLO
pp → Z / γ*
NNLO
pp → tt̄
NNLO+NNLL
pp → tq
NLO+NNLL
pp → H
LHC-XS (N3LO ggF)
pp → WW ×0.1
NNLO
pp → WZ ×0.1
NNLO
pp → ZZ ×0.1
NNLO
√s [TeV]
pp → X
7 TeV, 20 μb-1, Nat. Commu
8 TeV, 500 μb-1, arXiv:1607.
13 TeV, 60 μb-1, arXiv:1606.
pp → W
7 TeV, 36 pb-1, PRD 85, 072
13 TeV, 81 pb-1, PLB 759 (2
pp → tt̄
7 TeV, 4.6 fb-1, Eur. Phys. J.
8 TeV, 20.3 fb-1, Eur. Phys.
13 TeV, 3.2 fb-1, arXiv:1606.
pp → tq
7 TeV, 4.6 fb-1, PRD 90, 112
8 TeV, 20.3 fb-1, ATLAS-CO
13 TeV, 3.2 fb-1, ATLAS-CO
pp → H
7 TeV, 4.5 fb-1, Eur. Phys. J.
8 TeV, 20.3 fb-1, Eur. Phys.
13 TeV, 13.3 fb-1, ATLAS-C
pp → WW
7 TeV, 4.6 fb-1, PRD 87, 112
8 TeV, 20.3 fb-1, arXiv:1608.
13 TeV, 3.2 fb-1, ATLAS-CO
pp → WZ
7 TeV, 4.6 fb-1, Eur. Phys. J.
8 TeV, 20.3 fb-1, PRD 93, 09
13 TeV, 3.2 fb-1, arXiv:1606.
pp → ZZ
7 TeV, 4.6 fb-1, JHEP 03, 12
8 TeV, 20.3 fb-1, ATLAS-CO
13 TeV, 3.2 fb-1, PRL 116, 1