A theoretical status of weak gauge boson pair production at the LHC

LE Duc Ninh

Humboldt-Universität zu Berlin,
and ICISE, Quy Nhon

PIC, Quy Nhon, 13-17 Sep 2016

Bundesministerium
für Bildung
und Forschung

Outline

- Motivation
- fiducial and total Xsections, theory and data.
- NLO QCD, NNLO QCD, NLO EW results.
- Summary

Motivation (I)

The SM is NOT the complete theory. There must be new physics. Does it have new effects on $pp \to VV$? Yes, for sure!

The question: how strong are these effects (%, ‰, ...)? where, in which observables?

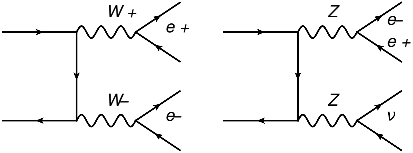
We dont know.

But one thing we do know: if we want to see small new-physics effects, we have to UNDERSTAND the SM effects very well. This means higher-order effects have to be understood.

Motivation (II)

- triple-gauge-boson couplings, studies of anomalous gauge couplings. $\rightarrow$ Ouraou's talk!
- backgrounds to new physics searches.
- constraints on PDFs (e.g. exclusive $\gamma\gamma \rightarrow W^+W^-$ by ATLAS arXiv:1607.03745 ?). Dont absorb new physics effects into PDFs!
- For calibration (MC tuning parameters ...), V and VV processes are important.

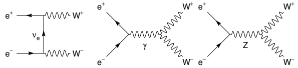
Definitions

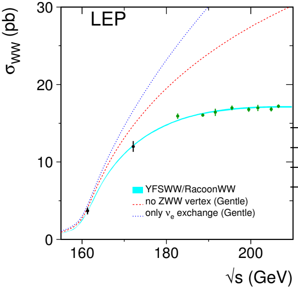


- W^+W^- ($Q = 0$): ee, $\mu\mu$, $e\mu$ $+E_{\text{miss}}$ with cuts to suppress Drell-Yan contribution to $ee/\mu\mu$.
- ZZ ($Q = 0$): $4e$, 4μ, $2e2\mu$ with cuts to enhance ZZ.
- $W^{\pm}Z$ ($Q = \pm 1$): eee, $\mu\mu\mu$, $ee\mu$, $\mu\mu e$ $+E_{\text{miss}}$ with cuts to enhance WZ.

WW at LEP2

Ref. LEP2 report 2013, arxiv:1302.3415.





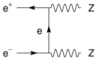
- data-taking time: 1995 - 2000
- combined data (ALEPH, DELPHI, L3, OPAL): 3 fb^{-1}
- CM energies: 130 GeV - 209 GeV

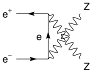
$\sqrt{s}$[GeV]	182.7	199.5	206.6
σ[pb]	15.92 ± 0.34	16.77 ± 0.29	17.20 ± 0.24
meas/theo	1.037 ± 0.022	0.987 ± 0.018	1.007 ± 0.015

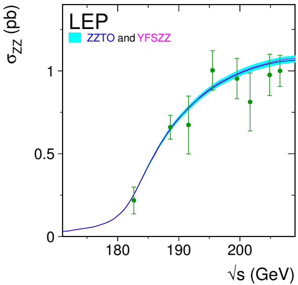
Remark: precision for total Xsection: $1 - 2\%$.

ZZ at LEP2

Ref. LEP2 report 2013, arXiv:1302.3415.



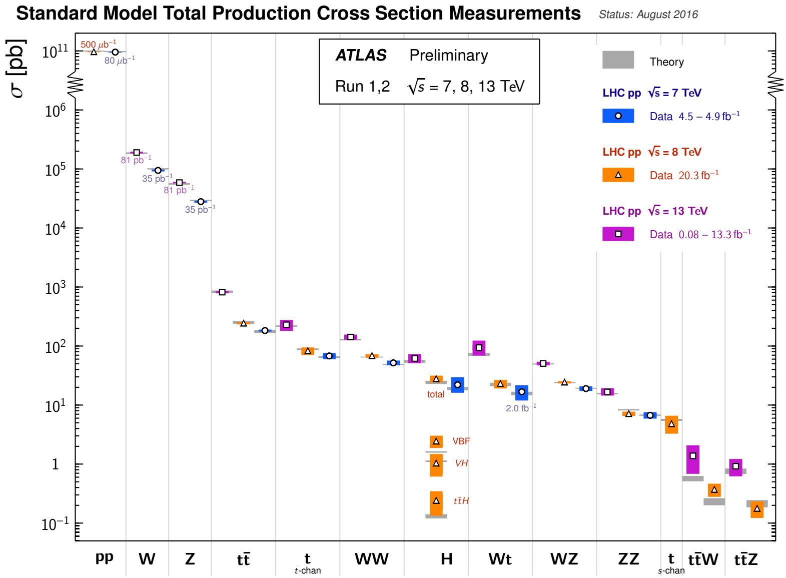




$\sqrt{s}$[GeV]	182.7	199.5	206.6
σ[pb]	0.22 ± 0.08	0.95 ± 0.12	1.00 ± 0.09
meas/theo	0.857 ± 0.320	0.97 ± 0.13	0.938 ± 0.091

Remark: precision for total Xsection: $10 - 40\%$.

LHC: t and V production



Experimental signatures

LEP2 ($3\,\text{fb}^{-1}$):

- WW: fully hadronic (45.6%), fully leptonic (10.5%), semileptonic (43.9%).
- ZZ: 4 quarks (48.87%), 4 charged leptons (1.02%), 2 quarks and 2 charged leptons (14.12%).

TEVATRON ($1.96\,\text{TeV}$, $8.6\,\text{fb}^{-1}$):

- WW, ZZ, WZ: fully leptonic.
- $WW + WZ$: $l\nu qq$ (arXiv:1112.0536, $L = 4.3\,\text{fb}^{-1}$).

LHC8 ($20.3\,\text{fb}^{-1}$), LHC13 ($3.2\,\text{fb}^{-1}$, June '16) :

- WW, ZZ, WZ: fully leptonic.
- $WW + WZ$: $l\nu qq$ (arXiv:1410.7238, $7\,\text{TeV}$, $4.6\,\text{fb}^{-1}$).
- more semileptonic in the near future? hadronic mass resolution is limited; BUT boosted jets!

fiducial and total XS

- fiducial XS is closer to the true data, more model-independent.
- total XS is simpler for theorists to calculate, OS approximation, $\rightsquigarrow$ better understanding of various effects.
- fiducial $\to$ total: extrapolation has to be fully specified.

Theorists need 3 things from exp. papers: fiducial XS, total XS, and extrapolation.
This is perfectly done in ATLAS arXiv:1606.04017 and CMS arXiv:1607.06943 (WZ):

$$\sigma_{WZ}^{tot} = \frac{\sigma_{WZ\to l'\nu ll}^{fid}}{B_W B_Z A_{WZ}} \tag{1}$$

where $B_W = 10.86\%$, $B_Z = 3.37\%$ are branching fractions, $A_{WZ}^{ATLAS} = 0.343$ obtained using POWHEG+PYTHIA (acceptance factor calculated at particle level as the ratio of the number of events in the fiducial phase space to the number of events in the total phase space).

CMS, ATLAS, and theory (WZ)

$WZ \to l'\nu ll$; $l, l' = e, \mu$; 13 TeV.
ATLAS fid: $p_T^{l_Z} > 15\,\text{GeV}$, $p_T^{l_W} > 20\,\text{GeV}$, $|\eta_l| < 2.5$,
$|m_{ll}^Z - m_Z| < 10\,\text{GeV}$, $m_T^W > 30\,\text{GeV}$, $\Delta R_{ll}^Z > 0.2$, $\Delta R_{l_W l_Z} > 0.3$.
CMS fid: $p_T^{l_{1,Z}} > 10\,\text{GeV}$, $p_T^{l_{2,Z}} > 20\,\text{GeV}$, $p_T^{l_W} > 20\,\text{GeV}$, $|\eta_l| < 2.5$,
$60 < m_{ll}^Z < 120\,\text{GeV}$.
ATLAS tot: $66 < m_{ll}^Z < 116\,\text{GeV}$.
CMS tot: $60 < m_{ll}^Z < 120\,\text{GeV}$.

- $\sigma_{ATLAS}^{fid} = 63.2 \pm 4.4\,\text{fb}$ ($NLO = 53.4 \pm 3.6$), $\sigma_{ATLAS}^{tot} = 50.6 \pm 3.6\,\text{pb}$.
- $\sigma_{CMS}^{fid} = 258 \pm 30\,\text{fb}$ ($NLO = 274 \pm 15$), $\sigma_{CMS}^{tot} = 39.9 \pm 4.7\,\text{pb}$.
- LO OS (tot): $25.517 \pm 1.3\,\text{pb}$
- NLO (QCD+EW) OS (tot): $46.86 \pm 2.5\,\text{pb}$ (where $3\%\sigma$ is PDF+α_s) [Baglio, LDN, Weber, arXiv:1307.4331].
- NNLO OS (tot): $51.11 \pm 1.1(\text{scale})\,\text{pb}$ [Grazzini, Kallweit, Rathlev, Wiesemann, arXiv:1604.08576]. Assuming 2% for PDF error $\rightsquigarrow \pm 2.1 pb$.

All agree within 2σ!
Ratios (W^+Z/W^-Z, 13/8 TeV) at total XS level are useful.

CMS, ATLAS, and theory (ZZ)

$ZZ \to l'l'll$; $l, l' = e, \mu$; 13 TeV.

- $\sigma^{fid}_{ATLAS} = 29.7^{+3.9}_{-3.6}(\text{stat.})^{+1.0}_{-0.8}(\text{syst.})^{+1.7}_{-1.3}(\text{lumi.})\,\text{fb}$ $(NNLO = 27.4^{+0.9}_{-0.8})$, $\sigma^{tot}_{ATLAS} = 16.7 \pm 2.6\,\text{pb}$.
- $\sigma^{fid}_{CMS} = 34.8^{+4.6}_{-4.2}(\text{stat})^{+1.2}_{-0.8}(\text{syst}) \pm 0.9(\text{lumi})\,\text{fb}$ $(NLO = 34.4 \pm 0.9\,\text{fb})$, $\sigma^{tot}_{CMS} = 14.6 \pm 2\,\text{pb}$.
- LO OS (tot): $9.887 \pm 0.6\,\text{pb}$
- NLO (QCD+EW) OS (tot): $14.6 \pm 1\,\text{pb}$ [Baglio, LDN, Weber, arXiv:1307.4331].
- NNLO OS (tot): $16.91 \pm 0.5\,\text{pb}$ [Cascioli et al., arXiv:1405.2219].

All agree within 1σ!

CMS, ATLAS, and theory (WW)

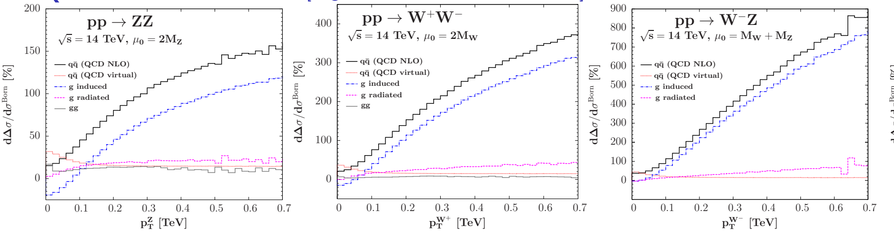
$W^+W^- \to l'^+\nu l^-\bar{\nu}$; $l, l' = e, \mu$; 13 TeV.
Problem: $t\bar{t}$ background is huge. $\rightsquigarrow$ jet veto in fiducial phase space (ATLAS: 0 jets, CMS: 0 or 1 jet).
New exp. results from ICHEP2016!

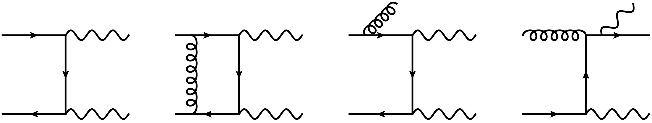
- $\sigma^{tot}_{ATLAS} = 142 \pm 5(\text{stat}) \pm 13(\text{syst}) \pm 3(\text{lumi})\,\text{pb}$.
- $\sigma^{tot}_{CMS} = 115.3 \pm 5.8(\text{stat.}) \pm 5.7(\text{exp.syst.}) \pm 6.4(\text{theo.syst.}) \pm 3.6(\text{lumi.})\,\text{pb}$.
- LO OS (tot): $67.16 \pm 4.5\,\text{pb}$
- NLO (QCD+EW) OS (tot): $109.8 \pm 6\,\text{pb}$ [Baglio, LDN, Weber, arXiv:1307.4331].
- NNLO OS (tot): $118.7 \pm 3.5(\mathit{scale})\,\text{pb}$ [Gehrmann et al., arXiv:1408.5243].

VV@LHC: a theoretical review

- LO: many automated tools (MadGraph, Sherpa, ...), all decay modes done!
- NLO: many automated tools (Gosam+Sherpa, MadGraph5, OpenLoop+Sherpa, Recola+In-house-Real, ...); hard-coded programs (MCFM, VBFNLO) [NLO QCD, fully/semi-leptonic, anomalous couplings].
  Recent results:
  - NLO EW corrections, on-shell level: [Kasprzik et al. '12 & '13; Baglio et al. '13]
  - NLO EW corrections, fully leptonic decays: [Biedermann et al. '16]
- NNLO (QCD): automated tools not yet, active field of research, recent results (all ZZ, WW, WZ, Grazzini et al., '14 - '16 at both OS and off-shell level) are calculated with MATRIX in combination with many other tools. [Huge efforts of many people: two-loop integrals, subtraction methods, ...]

NLO QCD corrections [Baglio, LDN, Weber, arXiv:1307.4331]





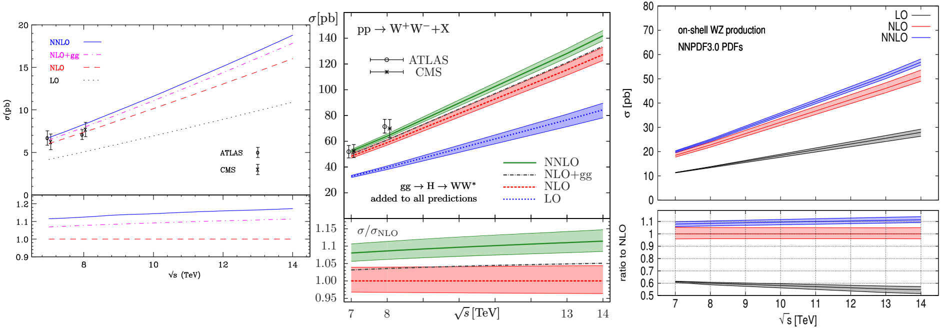
LO *QCD Virtual* *g radiated* *gq induced*

- The little hierarchy: p_T distributions at large energies (700GeV), qg dominant,

$$\frac{d\Delta\text{NLO}}{d\text{LO}} : 120\% \approx \delta_{ZZ} \approx \frac{\delta_{W+W-}}{3} \approx \frac{\delta_{W-Z}}{6}$$

- Total cross section: NLO QCD corrections are about 50%.
- QCD effects start at NLO $\rightsquigarrow$ NNLO QCD corrections are important (μ_R cancellation starts at NNLO).
- New effect at NNLO QCD: $gg \to q\bar{q} \to q\bar{q}VV$, events with two hard jets and two soft massive-gauge bosons.

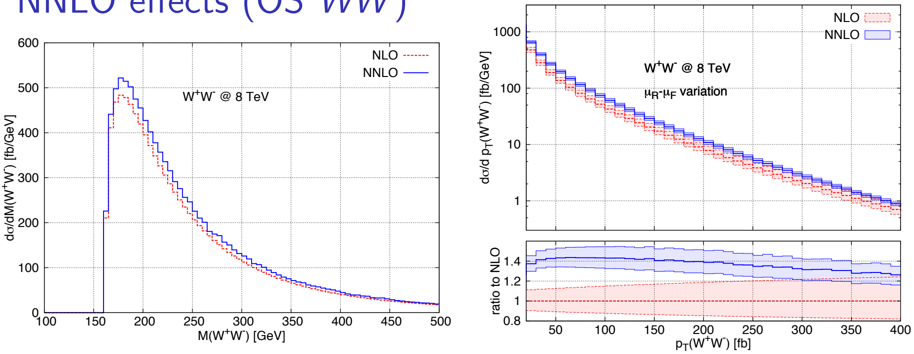
NNLO QCD: OS level



[Cascioli et al., arXiv:1405.2219; Gehrmann et al., arXiv:1408.5243; Grazzini et al., arXiv:1604.08576]

- *ZZ* (*WW*): loop-induced *gg* fusion ≈ 60% (35%) of NNLO correction (OS level, 7-14 TeV).

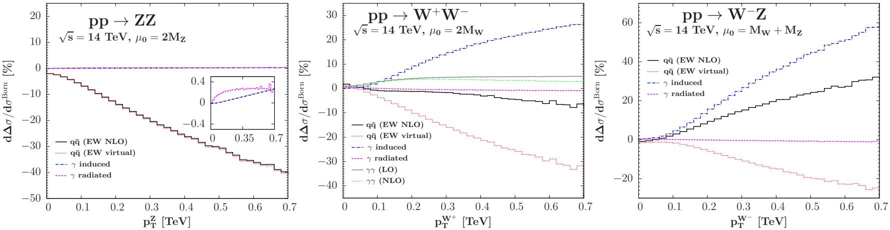
NNLO effects (OS WW)

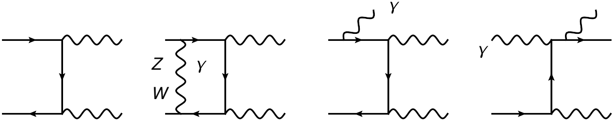


[Grazzini et al., arXiv:1507.02565]

- Large NNLO corrections when $W^{\pm}$ are soft (as expected)!

NLO EW corrections (OS level) [Baglio, LDN, Weber, arXiv:1307.4331]





LO *EW Virtual* *γ radiated* *qγ induced*

- The big hierarchy: p_T distributions at large energies (700GeV), $q\gamma$,

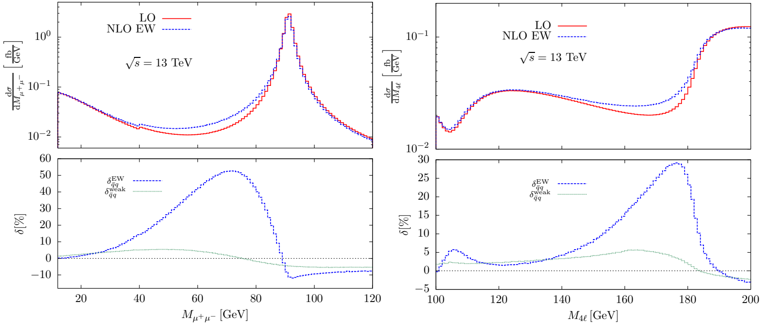
$$\frac{d\Delta \text{NLO}}{d\text{LO}} : 0.3\% \approx \delta_{ZZ} \approx \frac{\delta_{W+W-}}{90} \approx \frac{\delta_{W-Z}}{190}$$

- Virtual EW corrections: $-A_{VV}\alpha \log^2(p_T^2/M_V^2) \otimes \text{pdf}(q\bar{q})$, $V = W, Z$ [Sudakov double logs].
- $q\gamma$ induced corrections: $+B_{VV}\alpha \log^2(p_T^2/M_V^2) \otimes \text{pdf}(q\gamma)$, $B_{ZZ} \ll B_{WW} < B_{WZ}$.

$ZZ \to 2\mu 2e$: NLO EW effects [Biedermann et al., arXiv:1601.07787]

Basic cuts, $|M_{l_1 l_1} - M_Z| < |M_{l_2 l_2} - M_Z|$:

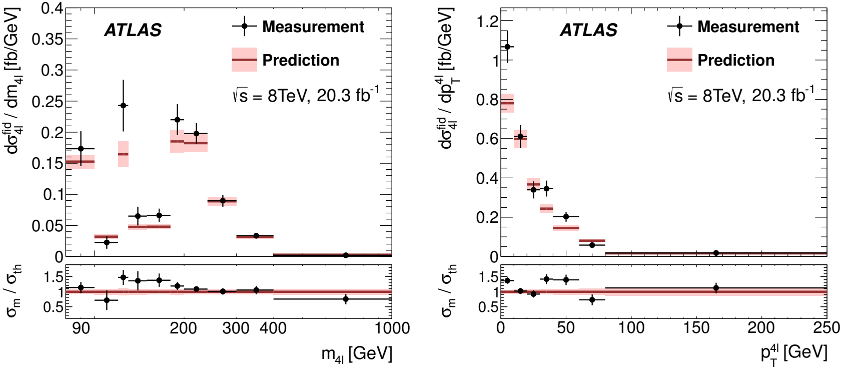
$$40 < M_{l_1^+ l_1^-} < 120\,\text{GeV},\; 12 < M_{l_2^+ l_2^-} < 120\,\text{GeV},\; M_{4l} > 100\,\text{GeV}.$$



- genuine WEAK corrections separately calculated (discard QED diagrams) $\to$ fetch this into MC to have QED resum. results.
- weak corrections change sign.
- large QED corrections before the resonances due to FSR.

4-lepton signature

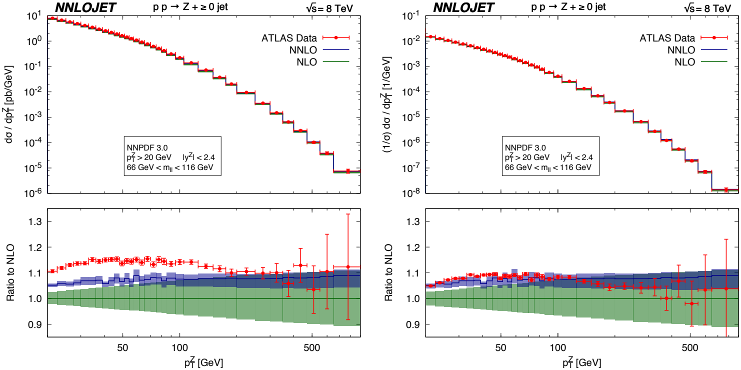
ATLAS: arXiv:1509.07844



- inclusive measurement, no theoretical background (476 signal events, 26 technical background events) $\rightsquigarrow$ model independent!
- resonances: Z, H, ZZ
- better agreement using normalized distributions?

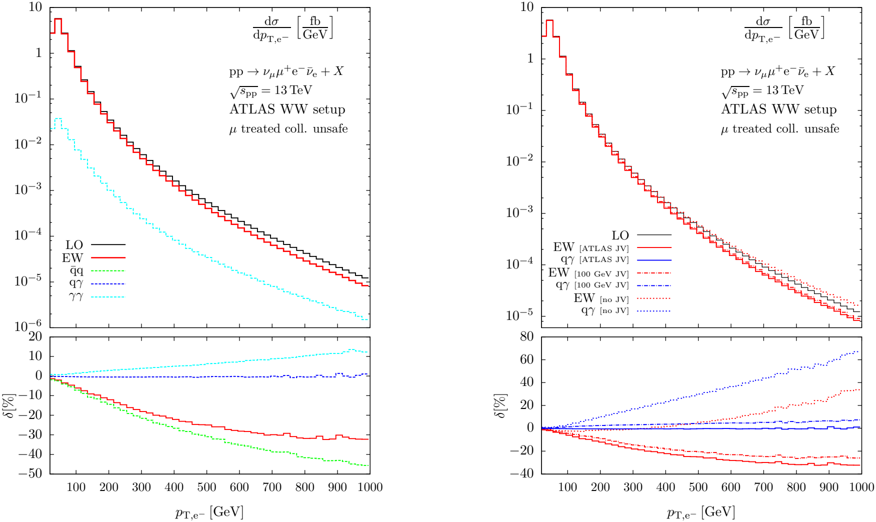
unnormalized vs. normalized

Gehrmann et al. arXiv:1605.04295



- normalized distributions are better for comparison with data.

$WW \to \mu e \nu\nu$: NLO EW effects [Biedermann et al., arXiv:1605.03419]



Basic ATLAS WW cuts, $p_{T,jet}^{veto} = 25\,\text{GeV}$.

Summary

- There has been a lot of theoretical progress in the understanding of diboson production at the LHC: NNLO QCD and NLO EW at OS and off-shell (leptonic) level.
- Comparisons with data: within 2σ at the fiducial and total XS.
- Next steps: precision physics at distribution level, and studies of polarization fractions?
- Question: at what level can we compare theoretical and experimental distributions, after or before (unfolding?) parton shower? In any case, matching and merging between fixed-order calculations and parton shower at NNLO level are mandatory $\rightsquigarrow$ to be done!

Thank You!