Overview of Precision Predictions for VV Production

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Brookhaven National Laboratory

Introduction

- The LHC is exploring the electroweak scale.
- Although Higgs discovered, important to test the structure of electroweak theory at the highest energies possible.
  - May expect additional new physics associated with electroweak physics.
  - Test non-Abelian structure of electroweak boson interactions.
- Di-boson processes important for both of these.
  - Sensitive to trilinear gauge coupling.
  - Many final states consist of leptons plus missing energy, a typical new physics signal.
- Additionally, many di-boson processes are important backgrounds to Higgs signals.
  - Both distributions and rates.
- Need precision calculations.

QCD NLO Results

- Known for a long time. Numbers quoted for $8 - 14$ TeV LHC and from Campbell, Ellis, Williams JHEP 1107 (2011) 018
  - $Z\gamma$- LO increased by $\sim 18 - 24\%$
    Ohnemus PRD47 (1993) 940; Baur, Han, Ohnemus PRD57 (1998) 2823; Hollik, Meier PLB590 (2004) 69
    Dixon, Kunszt, Signer NPB531 (1998)
  - $W\gamma$- LO increased by $\sim 28 - 32\%$
    Ohnemus, PRD47 (1993) 940; de Florian, Signer EPJC16 (2000) 105; Dixon, Kunszt, Signer NPB531 (1998)
  - ZZ- LO increased by $\sim 57 - 62\%$
    Ohnemus, Owen PRD43 (1991) 3626; Mele, Nason, Ridolfi NPB357 (1991) 409; Dixon, Kunszt, Signer NPB531 (1998)
  - WW- LO increased by $\sim 67 - 71\%$
    Ohnemus PRD44 (1991) 1403; Frixione NPB410 (1993) 280, Ohnemus PRD50 (1994) 1931
    Dixon, Kunszt, Signer NPB531 (1998)
  - WZ- LO increased by $\sim 77 - 88\%$
    Ohnemus PRD44 (1991) 3477; Frixione, Nason, Ridolfi NPB383 (1992) 3; Dixon, Kunszt, Signer NPB531 (1998)
  - $\gamma\gamma$- LO increased by (with symmetric cuts) $\sim 22 - 30\%$
    Aurenche, Douiri, Baier, Fontannaz, Schiff, Z.Phys. C29(1985) 459; Campbell, Ellis, Williams JHEP 1107 (2011) 018

Overview of NLO results

8 TeV	ZZ	WZ	WW	$Z(\to \ell\ell)\gamma$	$W(\to \ell\nu)\gamma$	$\gamma\gamma$
σ_{LO} (pb)	5.06	12.94	35.56	9.23	45.39	43.01
σ_{NLO} (pb)	$7.92^{+4.7\%}_{-3.0\%}$	$22.88^{+7.5\%}_{-5.7\%}$	$57.25^{+4.1\%}_{-2.8\%}$	$11.48^{+3.5\%}_{-5.1\%}$	$59.7^{+6\%}_{-9\%}$	$55.8^{+4\%}_{-6\%}$
14 TeV	ZZ	WZ	WW	$Z(\to \ell\ell)\gamma$	$W(\to \ell\nu)\gamma$	$\gamma\gamma$
σ_{LO} (pb)	10.92	27.55	74.48	17.97	85.8	88.76
σ_{NLO} (pb)	$17.72^{+3.5\%}_{-2.5\%}$	$51.82^{+5.5\%}_{-4.3\%}$	$124.31^{+2.8\%}_{-2.0\%}$	$21.20^{+3.7\%}_{-6.6\%}$	$110.2^{+6\%}_{-12\%}$	$108.1^{+3\%}_{-5\%}$

Campbell, Ellis, Williams JHEP 1107 (2011) 018

- Although formally NNLO, *gg* boxes can contribute as much as 5% and are included above.
- Much recent progress in extending beyond NLO.

Large Logs

- Can extend fixed order calculations near edges of phase space.
  - Edges of phase space typically associated with soft gluons.
  - Amplitudes exhibit additional factorization properties that simplify calculations.
  - Can improve perturbative calculation by calculating pieces of higher orders in a simplified regime.
- However, near edges of phase space, large logs of widely separated scales appear.
- Will cancel in a fixed order calculation, but can be important experimentally.
  - Distributions sensitive to these logs.
  - Vetoing jets with $p_T \ll \sqrt{\hat{s}}$
- Logs occur at every order in perturbation series, spoiling convergence.
- Need to be resummed.

Threshold Resummation

- QCD factorization allows us to factorize the collinear and hard physics:

$$\frac{d\sigma}{dMd\cos\theta} = \int_\tau^1 \frac{dz}{z} C(z, M, \cos\theta, \mu_f) \mathcal{L}\left(\frac{\tau}{z}, \mu_f\right),$$

  - Hard scattering kernel C
  - Parton luminosity $\mathcal{L}$
  - $z = M^2/\hat{s}$, $\tau = M^2/s$.
- Near partonic threshold have a new scale, the energy of soft emissions $\sqrt{\hat{s}}(1-z)$.

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  - Hard scattering kernel C
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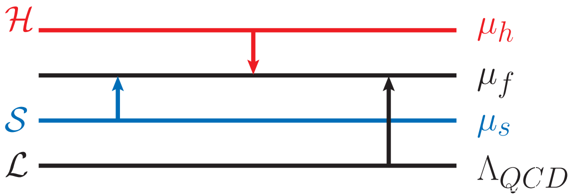
  - $z = M^2/\hat{s}$, $\tau = M^2/s$.
- Near partonic threshold have a new scale, the energy of soft emissions $\sqrt{\hat{s}}(1-z)$.
- Have additional factorization between soft and hard scales near threshold:
$$C(z, M, \cos\theta, \mu_f) = \mathcal{H}(M, \cos\theta, \mu_f) \mathcal{S}(\sqrt{\hat{s}}(1-z), \cos\theta, \mu_f) + \mathcal{O}(1-z)$$
- Two portions:
  - Hard function $\mathcal{H}$: depends on scale of hard process M
  - Soft function $\mathcal{S}$: depends on energy of soft emitted gluons $\sqrt{\hat{s}}(1-z)$
- Separation of scales suggests EFT approach $\Rightarrow$ Soft Collinear Effective Theory (SCET)

Bauer, Fleming, Luke, PRD63, 014006 (2000)
Bauer, Fleming, Pirjol, Stewart, PRD63, 114020 (2001)
Bauer, Pirjol, Stewart, PRD65, 054022 (2002)
Beneke, Chapovsky, Diehl, Feldmann, NPB643, 431 (2002)

SCET

- Near threshold:
$$\frac{d\sigma}{dM d\cos\theta} = \int_\tau^1 \frac{dz}{z} \mathcal{H}(M, \cos\theta, \mu_f) \mathcal{S}(\sqrt{\hat{s}}(1-z), \cos\theta, \mu_f) \mathcal{L}\left(\frac{\tau}{z}, \mu_f\right),$$
- The appropriate EFT is Soft Collinear Effective Theory (SCET)
  Bauer, Fleming, Luke, PRD63, 014006 (2000)
  Bauer, Fleming, Pirjol, Stewart, PRD63, 114020 (2001)
  Bauer, Pirjol, Stewart, PRD65, 054022 (2002)
  Beneke, Chapovsky, Diehl, Feldmann, NPB643, 431 (2002)
    - EFT consisting of soft and collinear degrees of freedom.
    - Hard virtual modes “integrated out."
- Each component evaluated at their relevant scales:
    - Hard function is a Wilson coefficient evaluated at a hard scale μ_h
    - Soft function evaluated at a soft scale μ_s

RG Running



- Run components to common scale μ_f via renormalization group equations.
- By choosing $\mu_s \sim \sqrt{\hat{s}}(1-z)$, this running exponentiates and resums large logs.
- Know hard function RGE:

$$\frac{d}{d\ln\mu}\mathcal{H}(M_{WW},\cos\theta,\mu) = 2\left[\Gamma_{\rm Cusp}(\alpha_s)\ln\frac{M_{WW}^2}{\mu^2} + \gamma^V(\alpha_s)\right]\mathcal{H}(M_{WW},\cos\theta,\mu)$$

- In limit $x \to 1$, PDF evolution is known:

$$\frac{d}{d\ln\mu}f_{q/N}(x,\mu) = \int_z^1 P_{q\leftarrow q}(z)\, f_{q/N}(x/z,\mu)$$

- Total cross section scale-invariant $\Rightarrow$ solve for soft function running in terms of PDFs and hard function.

Matching

- Resummed result depends on factorization that is only valid at threshold.
- Fixed order calculation valid away from threshold, without large logs.
- Need to combine these two results to obtain result valid for all z:

$$d\sigma^{matched} = d\sigma^{Thresh} + d\sigma^{F.O.} - d\sigma^{Leading}$$

- Have introduced the leading singularity term:

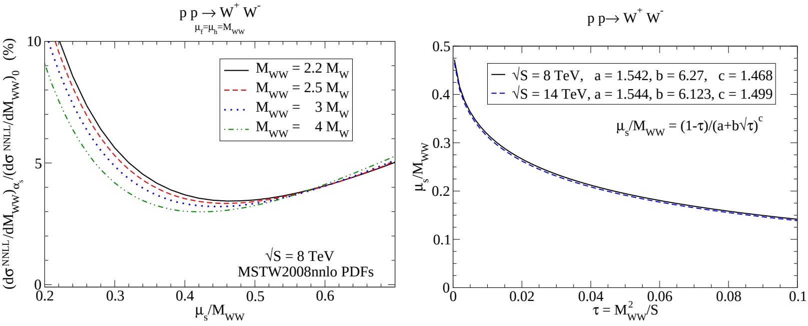
$$d\sigma^{Leading} = d\sigma^{Thresh}|_{\mu_s=\mu_h=\mu_f}$$

- The leading singularity is subtracted to prevent double counting between the fixed order and resummed results.
- Threshold resummation includes leading threshold logs of higher order corrections.
- For matching onto NLO, Di-Boson soft functions same as Drell-Yan, known to NNLO Becher, Neubert, Xu, JHEP 0807, 030 (2008).

Threshold Resummation

- The $NNLL$ matched onto NLO fixed order has been calculated for WW, WZ, and ZZ.
- WW and ZZ superseeded by NNLO calculations, but distributions still most up-to-date.
- Still useful to compare to fixed order calculations.
  - WW increases NLO by $\sim 1-3\%$ Dawson, Lewis, Zeng PRD88 (2013) 054028
  - WZ increases NLO by $\sim 3-4\%$ Wang, Li, Liu, Shao, PRD 90 (2014) 034008
  - ZZ increases NLO by $\sim 2-3\%$ Wang, Li, Liu, Shao, PRD 90 (2014) 034008
- Theoretical uncertainty similar to NLO calculation.

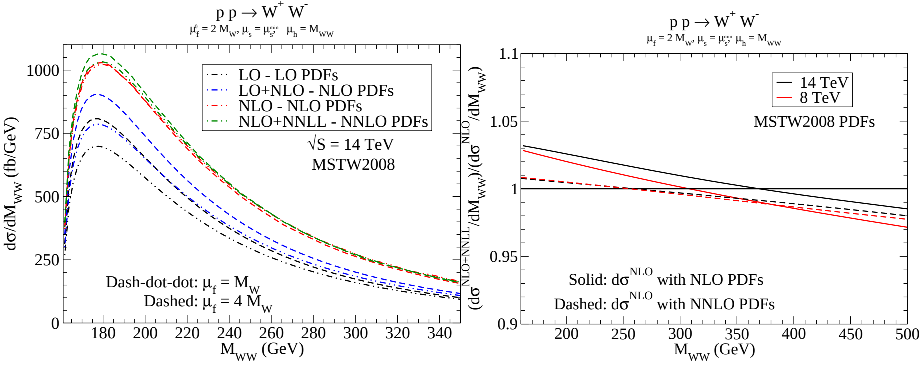
Scale Choice



Dawson, Lewis, Zeng PRD88 (2013) 054028

- Soft scale:
  - The soft scale is chosen by minimizing the one-loop contribution and $\mu_s \propto (1-\tau)$ as $\tau = M_{WW}^2/S \to 1$ Becher, Neubert, Xu, JHEP 0807, 030 (2008).
  - Little difference between 8 and 14 TeV.
- Hard scale:
  - Hard scale set to scale of hard scattering process: $\mu_h = M_{WW}$.

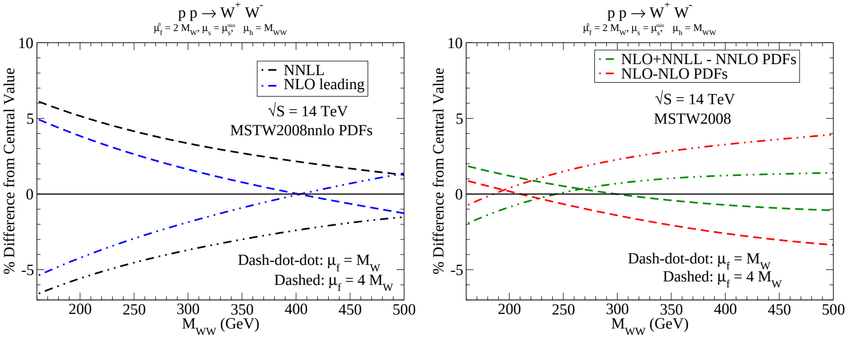
WW Threshold Resummation Distributions



Dawson, Lewis, Zeng PRD88 (2013) 054028

- Slight increase at peak of distribution.
- Mostly due to changing pdfs.

Factorization Scale Dependence

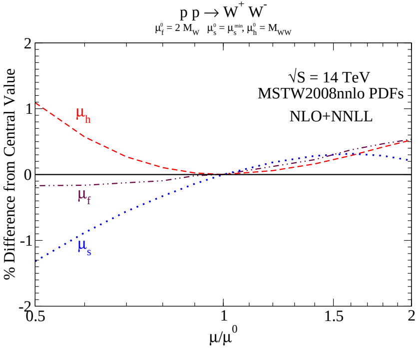


Dawson, Lewis, Zeng PRD88 (2013) 054028

$$d\sigma^{matched} = d\sigma^{Thresh} + d\sigma^{F.O.} - d\sigma^{Leading}$$

- For $M_{WW} \lesssim 400$ GeV, cancellation between NNLL resummed and leading singularity.
- For $M_{WW} \gtrsim 190$ GeV, cancellation between NNLL resummed and NLO contributions.

Full Scale Dependence



Dawson, Lewis, Zeng PRD88 (2013) 054028

$$d\sigma^{matched} = d\sigma^{Thresh} + d\sigma^{F.O.} - d\sigma^{Leading}$$

- In matched contribution, factorization scale dependence cancels among the three pieces.
- Factorization scale dependence greater than hard and soft scale dependencies.
- NLO scale dependence: $124.3^{+2.2\%}_{-1.7\%}$ pb
- Factorization scale dependence decreases significantly.

WZ and ZZ cross sections

σ (pb)	$\sqrt{S}=7$ TeV	$\sqrt{S}=8$ TeV	$\sqrt{S}=13$ TeV	$\sqrt{S}=14$ TeV
$\sigma^{\rm NLO}$	$17.28^{+0.65}_{-0.52}$	$21.37^{+0.76}_{-0.61}$	$44.16^{+1.20}_{-0.94}$	$49.09^{+1.27}_{-0.10}$
$\sigma^{\rm NNLL+NLO}$	$17.88^{+0.43}_{-0.22}$	$22.10^{+0.53}_{-0.27}$	$45.69^{+1.07}_{-0.58}$	$50.77^{+1.20}_{-0.65}$
$\sigma^{\rm NNLL+NLO}_{\pi^2}$	$19.40^{+0.30}_{-0.24}$	$23.96^{+0.37}_{-0.30}$	$49.35^{+0.83}_{-0.68}$	$54.81^{+0.94}_{-0.77}$

TABLE I: Total cross sections for $pp \to W^{\pm}Z$ with MSTW2008 PDFs.

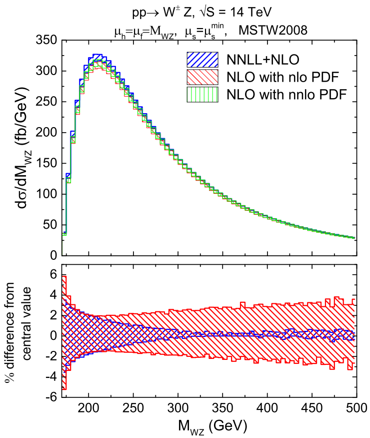
σ (pb)	$\sqrt{S}=7$ TeV	$\sqrt{S}=8$ TeV	$\sqrt{S}=13$ TeV	$\sqrt{S}=14$ TeV
$\sigma^{\rm NLO}$	$5.86^{+0.10}_{-0.07}$	$7.16^{+0.10}_{-0.07}$	$14.26^{+0.08}_{-0.02}$	$15.77^{+0.07}_{-0.01}$
σ^{gg}	$0.28^{+0.08}_{-0.06}$	$0.38^{+0.1}_{-0.09}$	$1.06^{+0.24}_{-0.20}$	$1.22^{+0.27}_{-0.21}$
$\sigma^{\rm NNLL+NLO}$	$5.98^{+0.08}_{-0.07}$	$7.33^{+0.10}_{-0.10}$	$14.66^{+0.27}_{-0.24}$	$16.21^{+0.31}_{-0.27}$
$\sigma^{\rm NNLL+NLO}_{\pi^2}$	$6.25^{+0.04}_{-0.08}$	$7.65^{+0.11}_{-0.11}$	$15.31^{+0.23}_{-0.25}$	$16.94^{+0.27}_{-0.30}$
$\sigma^{\rm NNLL+NLO}_{\rm tot}$	$6.53^{+0.09}_{-0.10}$	$8.03^{+0.15}_{-0.14}$	$16.37^{+0.33}_{-0.32}$	$18.16^{+0.38}_{-0.37}$

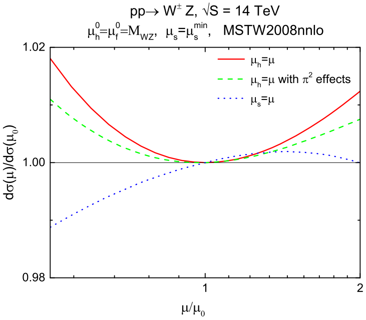
TABLE II: Total cross sections for $pp \to ZZ$ with MSTW2008 PDFs.

Wang, Li, Liu, Shao, PRD 90 (2014) 034008

- Have large π^2 terms in fixed order calculations arising from negative arguments in squared logs.
- Possible to resum these π^2.
  Parisi, PLB90 (1980) 295
  Sterman NPB281 (1987) 310
  Magnea and Sterman PRD42 (1990) 4222
  Eynck, Laenen, Magnea JHCEP 0306 (2003) 057
  Ahrens, Becher, Neubert, Yang PRD79 (2009) 033013
- Numbers previously quoted without π^2 resummations. With π^2:
  - ZZ increases NLO by $\sim 12-15\%$
  - WZ increases NLO by $\sim 11-12\%$

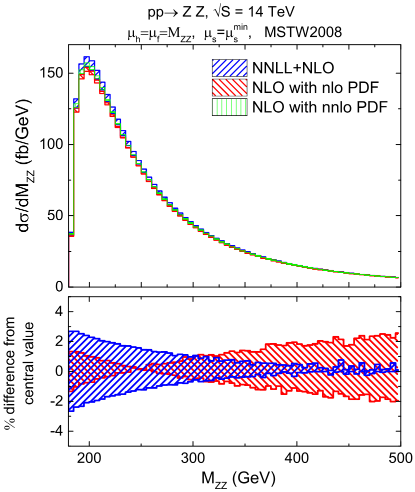
WZ Threshold Resummation Distributions

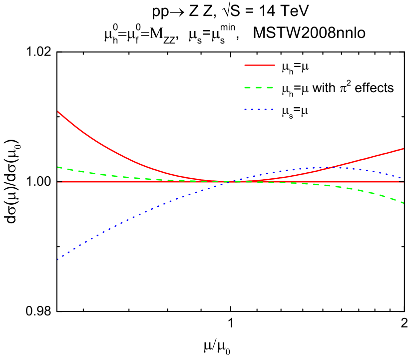




Wang, Li, Liu, Shao, PRD 90 (2014) 034008

ZZ Threshold Resummation Distributions





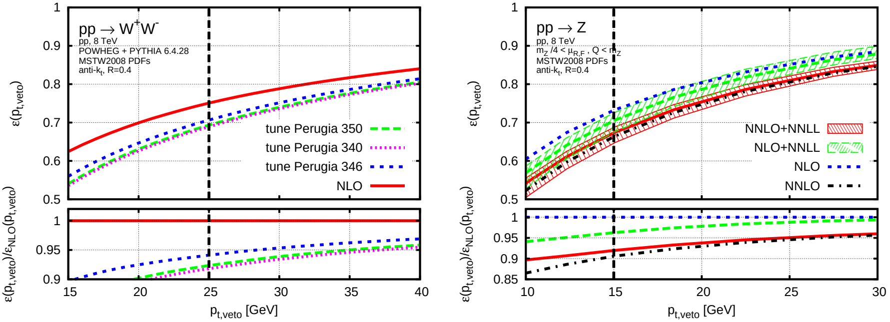
Wang, Li, Liu, Shao, PRD 90 (2014) 034008

Importance of jet veto

- Long-standing discrepancy in WW productions cross sections (comparing to NLO).
  - ATLAS: 7 TeV: $51.9 \pm 2.0\ (\text{stat.}) \pm 3.9\ (\text{syst.}) \pm 2.0\ (\text{lumi})$ pb
    ATLAS PRD87 (2013) 112001
  - CMS: 7 TeV: $52.4 \pm 2.0\ (\text{stat.}) \pm 4.5\ (\text{syst.}) \pm 1.2\ (\text{lumi})$ pb
    CMS EPJC73 (2013) 2610
  - SM from MCFM at NLO: 47 ± 2 pb
    Campbell, Ellis, Williams, JHEP07 (2011) 018

  - ATLAS: 7 TeV: $71.4 \pm 1.2\ (\text{stat.})^{+5.0}_{-4.4}\ (\text{syst.})^{+2.2}_{-2.1}\ (\text{lumi})$ pb
    ATLAS-CONF-2014-033
  - CMS: 8 TeV: $69.9 \pm 2.8\ (\text{stat.}) \pm 5.6\ (\text{syst.}) \pm 3.1\ (\text{lumi})$ pb
    CMS PLB721 (2013) 190
  - SM from MCFM at NLO: $57.3^{+2.4}_{-1.6}$ pb
    Campbell, Ellis, Williams, JHEP07 (2011) 018
- With one or more jets, dominant background is $t\bar{t}$.
- Control background by measuring zero-jet bin and extrapolate to exclusive cross section.
- How well does the extrapolation work?

WW Jet Veto From Rescaling *Z* Jet Veto

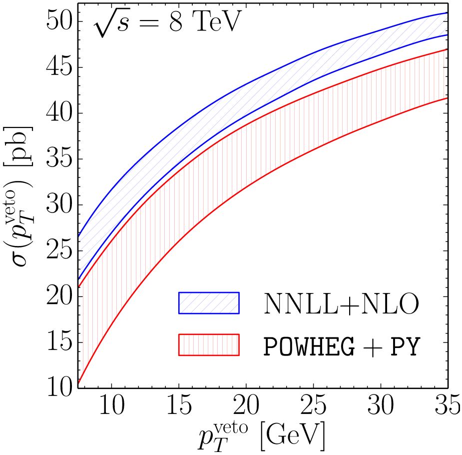


Monni, Zanderighi arXiv:1410.4745

- Rescale DY jet veto: $\frac{p^{DY}_{t,veto}}{M_Z} = \frac{p^{WW}_{t,veto}}{2M_W}$
- $p^{WW}_{t,veto} = 25$ GeV corresponds to $p^{DY}_{t,veto} \sim 15GeV$
- tune Perugia 350 overestimates effect of jet veto matched onto NLO.

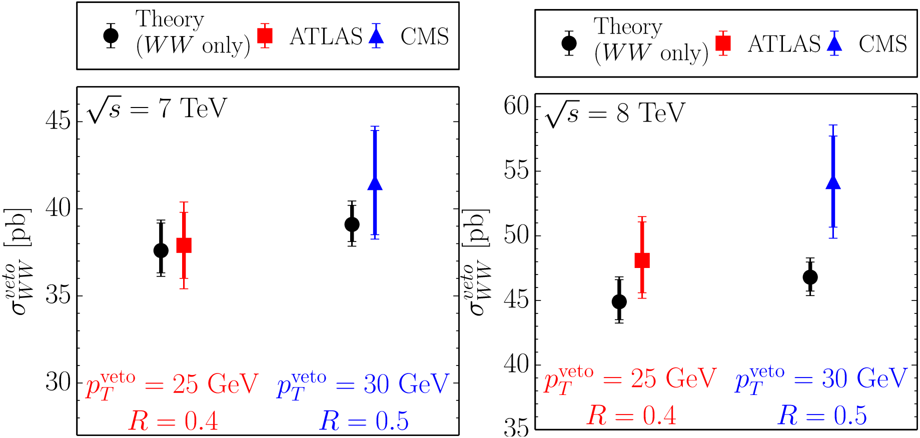
WW Jet Veto

- Full calculation with WW also calculated.



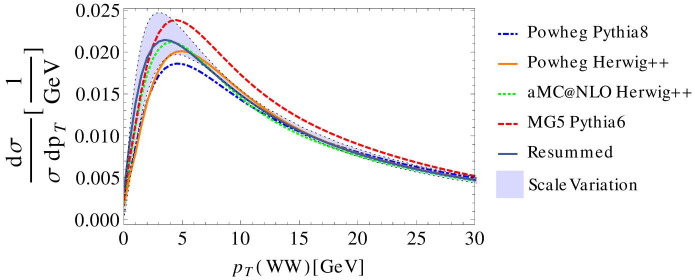
Jaiswal, Okui PRD90 (2014) 073009

WW Jet Veto



Jaiswal, Okui PRD90 (2014) 073009

p_T Resummation



Meade, Ramani, Zeng, arXiv:1407.4481

Can change acceptance after cuts.

Resummation also calculated in Grazzini JHEP 0601 (2006) 095

Overview of NNLO results

- Much progress on VV production at NNLO recently.
- Total rates now known for:
  - ZZ: Increases NLO rate by $11 - 17\%$ with residual uncertainty of $\sim 3\%$

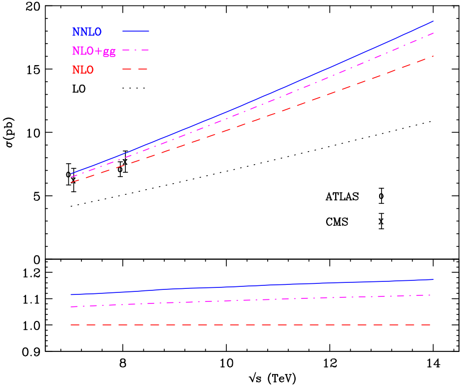
    Cascioli *et al* PLB735 (2014) 311
  - WW: Increases NLO rate by $9 - 12\%$ with residual 3% uncertainty

    Gehrmann *et al* arXiv:1408.5243
  - $Z\gamma$: Increases NLO rate $4 - 15\%$, depending on cuts

    Grazzini, Kallweit, Rathlev, Torre, PLB731 (2014) 204
  - $\gamma\gamma$: Increases NLO Rate by $\sim 65\%$, due to asymmetric photon cuts

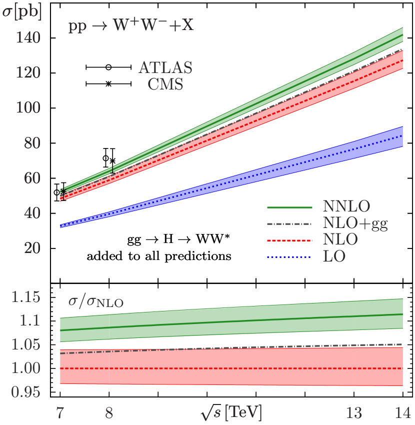
    Catani, Cieri, de Florian, Ferrera, Grazzini, PRL 108 (2012) 072001
- Differential distributions known for $\gamma\gamma$.
- Progress in extending to off-shell production Caola, Henn, Melnikov, Smirnov, arXiv:1404.5590; Caola, Henn, Melnikov, Smirnov, Smirnov, arXiv:1408.6409; Henn, Melnikov, Smirnov JHEP 1405 (2014) 090; Anastasiou, Cancino, Chavez, Duhr, Lazopoulos, Mistlberger, Mueller arXiv:1408.4546

ZZ and WW at NNLO



Cascioli, *et al* PLB735 (2014) 311

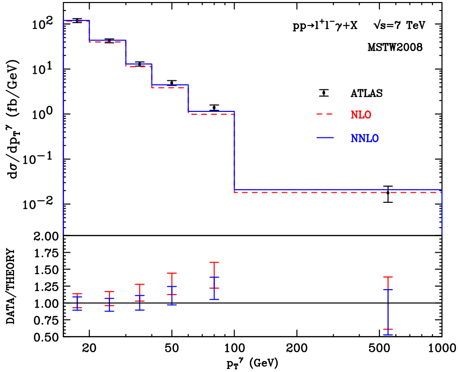
Increase NLO result by 11% to 17%.
Residual uncertainty of $\sim 3\%$



Gehrmann *et al* arXiv:1408.5243

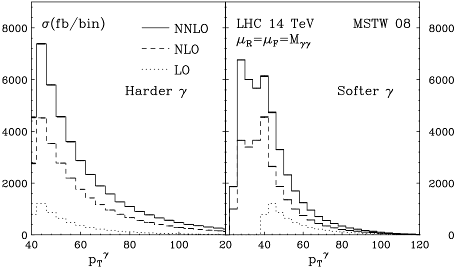
Increase over NLO 9% to 12% with 3% uncertainty.

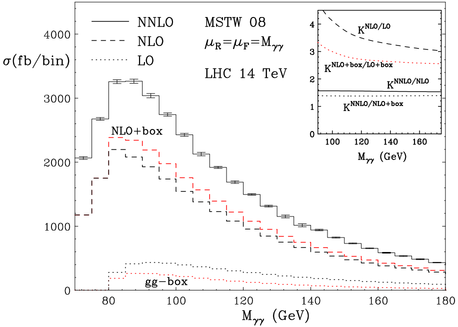
$Z\gamma$ at NNLO



Grazzini, Kallweit, Rathlev, Torre, PLB731 (2014) 204

$\gamma\gamma$ at NNLO





Catani, Cieri, de Florian, Ferrera, Grazzini, PRL 108 (2012) 072001

At NLO and NNLO, second photon allowed to be softer and populates low p_T region.

Electroweak Corrections

- Typically much smaller than QCD corrections, due to reduced coupling constant.
  - For typical LHC cuts, $W\gamma$ and $Z\gamma$ decrease by $\sim -5\%$ Accomando, Denner, Meier, EPJC47 (2006) 125
  - ZZ decrease by $\sim -4\%$ Bierweiler, Kasprzik, Kühn, JHEP 1312 (2013) 071
  - WZ decreases by $\sim -1.5\%$ Bierweiler, Kasprzik, Kühn, JHEP 1312 (2013) 071
  - WW decreases by $\sim -0.5\%$ Bierweiler, Kasprzik, Kühn, JHEP 1312 (2013) 071
  - $\gamma\gamma$ increase by $\sim 0.5\%$ Bierweiler, Kasprzik, Kühn, JHEP 1312 (2013) 071
  - $W\gamma$ and $Z\gamma$ decrease by $\sim -5\%$ Accomando, Denner, Meier, EPJC47 (2006) 125
- The results above depend greatly on momentum flows.
- Electroweak corrections can be sensitive to large Sudakov logs: $\ln \frac{p_T^V}{M_V}$
- Although overall change is small, can become substational in tails of distributions.

Effects of Cuts on Cross Sections

no cuts	W^-W^+ σ_{LO} (pb)	W^-W^+ δ_{EW}(%)	ZZ σ_{LO} (pb)	ZZ δ_{EW}(%)	W^+Z σ_{LO} (pb)	W^+Z δ_{EW}(%)	W^-Z σ_{LO} (pb)	W^-Z δ_{EW}(%)
LHC8	35.51	−0.4	5.064	−4.1	8.273	−1.4	4.643	−1.3
LHC14	75.02	−0.4	11.02	−4.2	17.11	−1.4	10.65	−1.3
Tevatron	7.916	−0.2	0.9466	−4.7	1.123	−1.1	1.123	−1.1

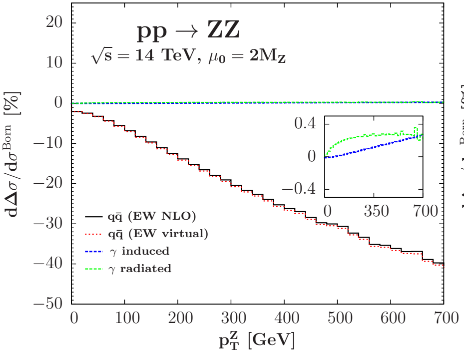
Table 2. Total leading-order cross sections and relative EW corrections for the LHC and the Tevatron evaluated without any phase-space cuts.

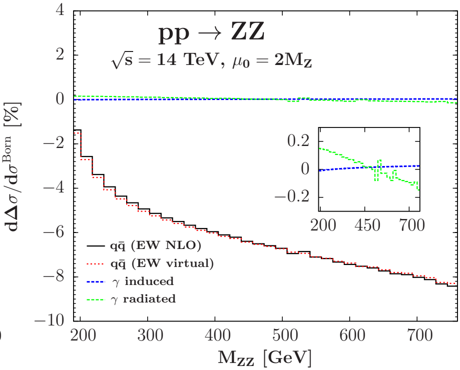
$pp \to V_1V_2(+\gamma) + X$ at $\sqrt{s} = 14$ TeV								
default cuts	ZZ		W^+Z		W^-Z		$\gamma\gamma$	
p_T^{cut} (GeV)	σ_{LO} (pb)	δ_{EW}(%)	σ_{LO} (pb)	δ_{EW}(%)	σ_{LO} (pb)	δ_{EW}(%)	σ_{LO} (pb)	δ_{EW}(%)
50	3.660	−6.3	4.498	−1.9	3.228	−1.7	2.979	0.6
100	1.087	−10.4	1.296	−3.7	0.849	−3.3	0.432	−1.6
250	7.495×10^{-2}	−23.0	90.56×10^{-2}	−12.9	4.583×10^{-2}	−12.3	2.451×10^{-2}	−7.0
500	49.89×10^{-4}	−38.9	63.64×10^{-4}	−24.9	24.79×10^{-4}	−24.4	16.95×10^{-4}	−13.0
750	72.16×10^{-5}	−50.6	92.43×10^{-5}	−33.3	31.25×10^{-5}	−33.0	25.66×10^{-5}	−17.3
1000	14.60×10^{-5}	−60.1	18.35×10^{-5}	−39.8	57.32×10^{-6}	−39.6	54.91×10^{-6}	−20.6
1250	35.28×10^{-6}	−68.4	42.92×10^{-6}	−45.1	12.86×10^{-6}	−45.1	14.15×10^{-6}	−23.5
1500	94.73×10^{-7}	−75.7	10.99×10^{-6}	−49.6	32.48×10^{-7}	−49.6	40.71×10^{-7}	−25.9

Table 3. Integrated leading-order cross sections and relative EW corrections at LHC14 for different cuts on the minimal boson transverse momenta.

Bierweiler, Kasprzik, Kühn, JHEP 1312 (2013) 071

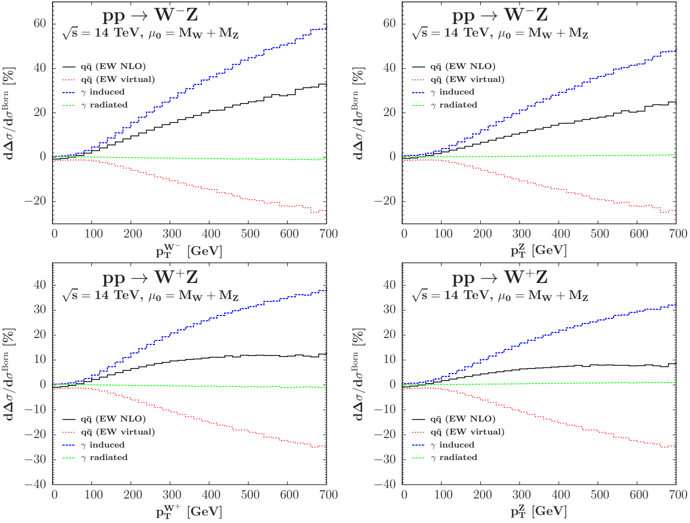
ZZ Distributions





Baglio, Duc Ninh, Weber, PRD88 (2013) 113005

WZ Distributions



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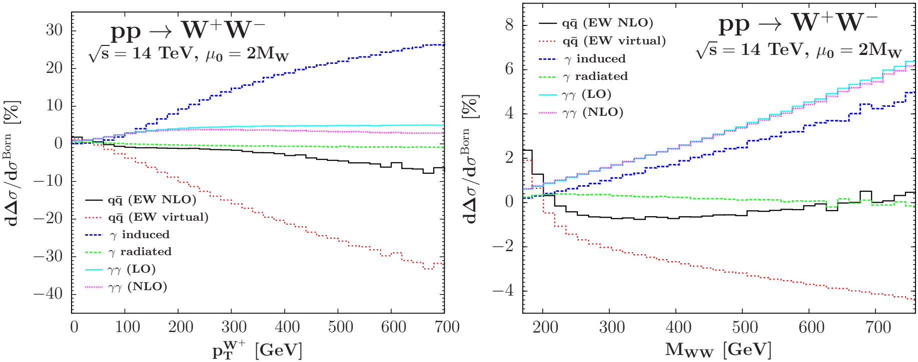
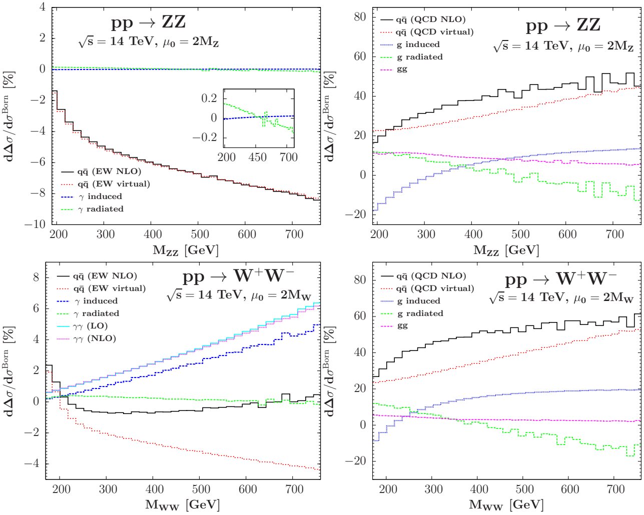
WW



Baglio, Duc Ninh, Weber, PRD88 (2013) 113005

- Unlike ZZ, in WZ and WW, the W has couplings to the photon.

Comparison of QCD and EW corrections



Baglio, Duc Ninh, Weber, PRD88 (2013) 113005

Including Gauge Boson Decays

- $W\gamma$ and $Z\gamma$ Accomando, Denner, Meier, EPJC47 (2006) 125:

	$\sigma_{\mathrm{pp}}^{(0)}$(fb)	$\sigma_{\mathrm{pp}}^{(1),\mathrm{tot}}$(fb)		$1/\sqrt{2L\sigma_{\mathrm{pp}}^{(0)}}$ (%)
$\nu_l\bar{\nu}_l\gamma$	212.26(7)	−9.65(3)	−4.5%	0.5%
$l\bar{l}\gamma$	38.99(9)	−2.61(7)	−6.7%	1.1%
$\nu_l\bar{l}\gamma$	124.57(8)	−2.36(5)	−1.9%	0.6%

Table 1: Total lowest-order cross section (second column) as well as the electroweak $\mathcal{O}(\alpha)$ corrections in absolute size (third column) and in per cent of the lowest-order cross section (fourth column) for the three considered final states. The last column shows the statistical error for an integrated luminosity of $L = 2 \times 100/\mathrm{fb}$.

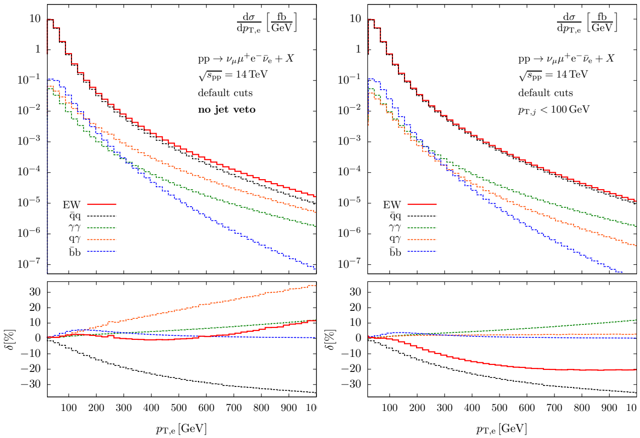
- WW with decays Billoni, Dittmaier, Jäger, Speckner, JHEP 1312 (2013) 043

	$\sigma_{\bar{q}q}^{\mathrm{LO}}$ [fb]	$\delta_{\bar{q}q}$ [%]	$\delta_{q\gamma}$ [%]	$\delta_{\gamma\gamma}$ [%]	$\delta_{\bar{\mathrm{b}}\mathrm{b}}$ [%]
LHC14	412.5(1)	−2.70(2)	0.566(5)	0.7215(4)	1.685(1)
LHC8	236.83(5)	−2.76(1)	0.470(3)	0.8473(3)	0.8943(3)
ATLAS cuts	163.84(4)	−2.96(1)	−0.264(5)	1.0221(5)	0.9519(4)

Table 1: Cross-section contributions to $\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e}$ at the LHC running at 14 TeV (first line) and 8 TeV (second line), respectively, with the default settings of Sec. 3.1. The third line shows the corresponding results for a collider energy of 8 TeV with the ATLAS setup defined in Sec. 3.1. The numbers in brackets represent the numerical error on the last given digit.

  - Jet veto of $p_T = 100$ GeV
  - ATLAS cuts have jet veto of $p_T = 25$ GeV

WW including decays



Billoni, Dittmaier, Jäger, Speckner, JHEP 1312 (2013) 043

Conclusions

- NLO QCD results known for a long time.
- Recently, much progress on fixed order NNLO corrections and resummation of large logs.
- Overall electroweak corrections on the order of a few percent.
- At high momentum fractions, Sudakov logs become important and electroweak corrections important.
- For both electroweak and QCD corrections, experimental cuts are important to overall size of corrections.
- For electroweak corrections, cuts important for relative size of different components of correction.
- Can effect cancellation of those components.

Extra Slides

WW Jet Veto From Rescaling Z Jet Veto

decay mode	$\sigma^{\text{exp.}}_{\text{fid.}}$ [fb]	$\sigma^{\text{th.}}_{\text{fid.}}$ [fb]
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}(\text{stat.})^{+25.1}_{-22.2}(\text{syst.})^{+11.4}_{-10.7}(\text{lumi.})$	$357.9^{+14.4}_{-14.4}$
e^+e^-	$68.5^{+4.2}_{-4.1}(\text{stat.})^{+7.7}_{-6.6}(\text{syst.})^{+2.1}_{-2.0}(\text{lumi.})$	$69.0^{+2.7}_{-2.7}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}(\text{stat.})^{+7.0}_{-6.0}(\text{syst.})^{+2.3}_{-2.1}(\text{lumi.})$	$75.1^{+3.0}_{-3.0}$

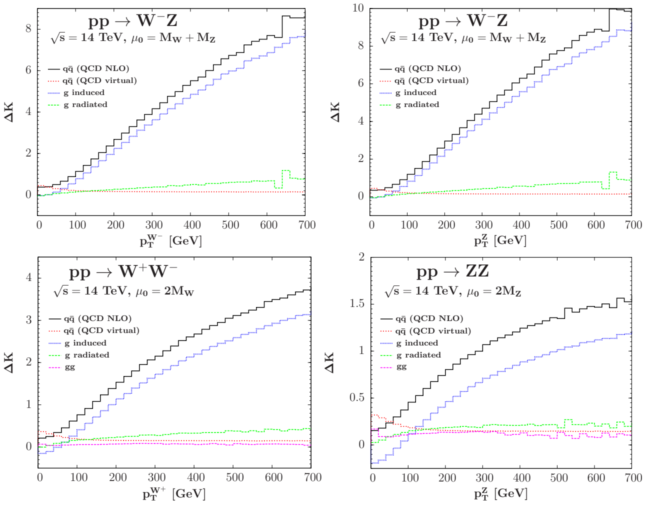
Table 4 Comparison between the measured fiducial cross section and the theory prediction with estimated NNLL+NNLO effects. Theory uncertainties have been symmetrized and combined in quadrature.

Monni, Zanderighi arXiv:1410.4745

- Rescale NLO cross sections:

$$\sigma^{\text{th.}}_{fid.} = \sum_{channel} \sigma^{(c),NLO}_{fid.} \times \frac{\varepsilon^{(c),NNLL+NNLO}(p^{(c)}_{t,veto})}{\varepsilon^{(c),NLO}(p^{(c)}_{t,veto})} \times \frac{\sigma^{(c),NNLO}_{incl.}}{\sigma^{(c),NLO}_{incl.}}$$

Giant K-factors



Baglio, Duc Ninh, Weber, PRD88 (2013) 113005