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NLO Electroweak Corrections in Di-Boson Production

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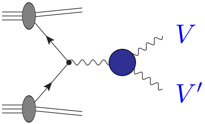
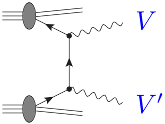
in collaboration with B. Biedermann, M. Billoni, S. Dittmaier, L. Hofer, B. Jäger, L. Salfelder

Multi-Boson Interactions, Madison, August 24–26, 2016





$V, V' = \gamma, \mathrm{Z}, \mathrm{W}^{\pm}$

Physics issues:

- precision test of electroweak sector of Standard Model
- search for anomalous triple-gauge-boson couplings
  sensitivity grows with energy of gauge bosons
  $\hookrightarrow$ EW corrections significant $\quad \propto \alpha \log^2(E/M_\mathrm{W})$
- important class of background processes
  - to Higgs production: $\mathrm{H} \to \mathrm{WW}^*/\mathrm{ZZ}^* \to 4f$
    $\hookrightarrow$ invariant masses below VV thresholds,
    proper description of off-shell VV production needed!
  - to new-physics searches at high invariant masses
    $\hookrightarrow$ EW corrections significant

Treatment of hard process $\mathrm{pp} \to VV' \to 4\,\mathrm{leptons}$ (massive VV'):

- On-shell VV' production
  - + ok for total cross section
  - – no treatment of physical final state
- Narrow-width approximation ($\Gamma \to 0$)
  production and decay of on-shell vector bosons
  - + includes decays of vector bosons and possibly spin correlations
  - – neglects terms of order Γ/M and irreducible background
  - + different final states treated on same footing
- (Double-)pole approximation (D)PA
  - + includes off shell effects of resonant bosons and phase space
  - – matrix elements include only resonant parts
    no interferences, no irreducible background
  - + PA only for virtual NLO corrections!
  - + different final states treated on same footing
- Full calculation
  - + includes off-shell effects, irreducible background, interferences
  - – complicated calculation, depends on final state

Known corrections to VV' production

State-of-the-art predictions:

$\mathrm{W}\gamma/\mathrm{Z}\gamma$ (full calculation with leptonic decays)

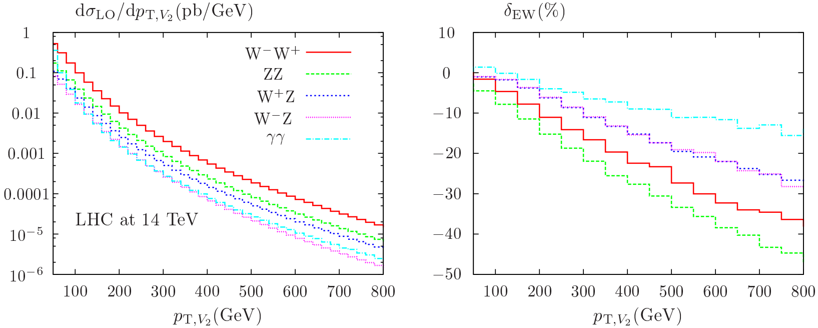
- NNLO QCD — Grazzini, Kallweit, Rathlev '14,'15
- NLO EW — Denner, Dittmaier, Hecht, Pasold '14, '15

$\mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ}$

- NNLO QCD — including leptonic decays
  - ZZ (distributions) — Cascioli et al. '14; Grazzini, Kallweit, Rathlev '15
  - WW (distributions) — Gehrmann et al. '14; Grazzini, et al. '16
  - WZ (inclusive rates) — Grazzini, et al. '16
  - $\mathrm{gg} \to VV \to 4$ leptons — Binoth et al. '05, '06
    + NLO corrections for on-shell V's — Caola et al. '15
- NLO EW — inclusion of decays non-trivial
  - stable W/Z bosons — Bierweiler, Kasprzik, Kühn, Uccirati '12, '13; Baglio, Le, Weber '13
  - approximative inclusion in HERWIG++ (via correction factor) — Gieseke, Kasprzik, Kühn '14
  - $\mathrm{pp} \to \mathrm{WW} \to 4$ leptons in DPA — Billoni, Dittmaier, Jäger, Speckner '13
  - full off-shell calculation — Biedermann et al. '16

stable/on-shell W/Z bosons

Bierweiler, Kasprzik, Kühn '13



EW corrections

- small for integrated cross section ($-1\% \ldots -5\%$)
- several 10% corrections in distributions from Sudakov logarithms $\propto \alpha \ln^2(E/M_W)$

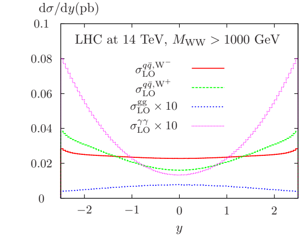
Photonic corrections

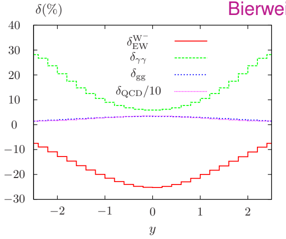
- radiative tails below thresholds and resonances
- enhanced by QED logarithms $\propto \alpha \ln(E/m_\ell)$
- on-shell calculation not applicable below VV' threshold!

Photonic contributions to WW production

stable/on-shell W bosons

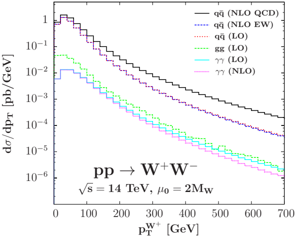
Bierweiler, Kasprzik, Kühn '12

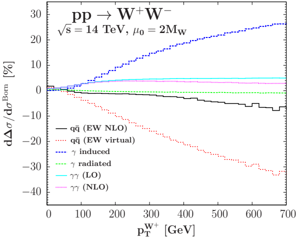




Note:
large contribution by $\gamma\gamma$ channel for high invariant WW masses!
large uncertainty of photon PDFs

Baglio, Le, Weber '13

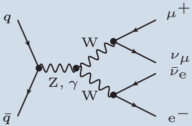


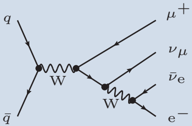


Note:
large impact of $q\gamma$ collisions
($q\gamma \to q\mathrm{W}$)
overwhelmed by QCD corrections
eliminated by jet veto

WW production

$q\bar{q} \to \mu^+ \nu_\mu \mathrm{e}^- \bar{\nu}_\mathrm{e}$

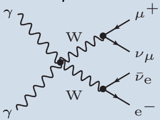




2 W resonances 1 W resonance

$\sigma \approx 270\,\mathrm{fb}$ @13 TeV

$\gamma\gamma \to \mu^+ \nu_\mu \mathrm{e}^- \bar{\nu}_\mathrm{e}$

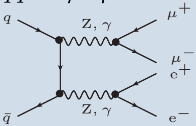


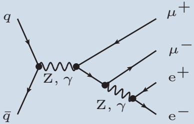
2 W resonances

1.0% contribution @13 TeV

ZZ production

$q\bar{q} \to \mu^+ \mu^- \mathrm{e}^+ \mathrm{e}^-$

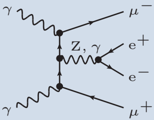




2 Z resonances 1 Z resonance

$\sigma \approx 11\,\mathrm{fb}$ @13 TeV

$\gamma\gamma \to \mu^+ \mu^- \mathrm{e}^+ \mathrm{e}^-$



1 Z resonance

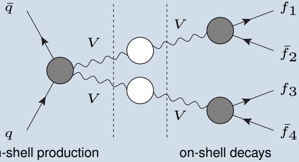
0.2% contribution @13 TeV

pure EW processes

return

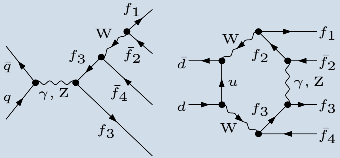
Double-pole approximation vs. full calculation

double-pole approximation



- expansion about resonance poles for virtual corrections only
  $\hookrightarrow$ factorizable & non-fact. corrs.
- $\sim 10^2$ diagrams ($2\to 2$ production)
- + numerically fast
- – valid only for $\sqrt{\hat{s}} > 2M_V + \mathcal{O}(\Gamma_V)$
- error estimate for $\sqrt{\hat{s}} \lesssim 0.5{-}1\,\mathrm{TeV}$:
  $\Delta \sim \frac{\alpha}{\pi}\frac{\Gamma_V}{M_V}\log(\dots) \sim 0.5{-}2\%$

full off-shell calculation



- off-shell calculation for $\bar{q}q \to 4f$ with complex-mass scheme
- $\sim 10^3$ off-shell diagrams/channel
- – CPU intensive
- + NLO accuracy everywhere
- global error estimate:
  $\Delta \sim \delta_{\mathrm{NNLO\,EW}} \sim \delta^2_{\mathrm{NLO\,EW}}$

approaches compared for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$ Denner, Dittmaier, Roth, Wieders ’05
and $\mathrm{pp} \to \mathrm{WW} \to 4f$ Biedermann et al. ’16

Details of the full $4f$ NLO calculation

Virtual corrections

- matrix elements numerically with RECOLA — Actis et al. '13, '16
  (Recursive computation of one-loop amplitudes)
  generator for arbitrary LO and NLO matrix elements in SM
- loop integrals evaluated with COLLIER — Denner, Dittmaier, Hofer '16
  (Complex one-loop library in extended regularizations)
  numerically stable and fast calculation of tensor one-loop integrals
- $\mathrm{W/Z}$ resonances in *complex-mass scheme* — Denner et al. '99, '05
  applicable and gauge-invariant everywhere in phase space
- G_μ scheme for electromagnetic coupling
  $\Rightarrow$ absorbs running of α from 0 to M_W
  and universal corrections related to ρ parameter
- photonic corrections with $\alpha(0)$

Assumptions

- massless light fermions $\mathrm{u, d\, c, s, b; e}, \mu, \tau$
- flavour mixing neglected

Real corrections and Monte Carlo integration

- IR singularities treated with dipole subtraction
  Catani, Seymour '96; Dittmaier '99; Dittmaier et al. '08
- collinear-unsafe ("bare") and -safe ("dressed") leptons supported
- multi-channel Monte Carlo integration

γ-induced contributions using NNPDF2.3QED Ball et al. '13

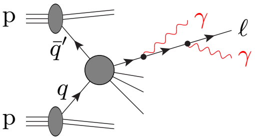
- $\gamma\gamma$ processes included at LO (small contributions)
- $q\gamma$ contributions taken into account (NLO)

Checks

- independent diagrammatic calculation as for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$
  Denner et al. '05
- additional checks with FEYNARTS/FORMCALC in the framework of POLE
  Accomando et al. '05

$\Rightarrow$ two independent calculations of all important ingredients

Collinear final-state radiation off leptons



Universal logarithmically enhanced corrections

$$\propto \alpha^n \ln^n(m_l^2/Q^2)$$

from final-state radiation

possible treatments:

- "bare leptons" (typical for muons, non-collinear-safe (NCS) case)
  photons are experimentally separated from leptons
  collinear singularities regularised by lepton (muon) mass
  $\Rightarrow$ logarithmically enhanced corrections $\Rightarrow$ large radiative tails
- "dressed leptons" (typical for electrons, collinear safe (CS))
  recombination of leptons with (collinear) photons
  $\Rightarrow$ mass-singular logarithms cancel, collinear-safe observables
  predictions depend on photon-recombination scheme
  $\Rightarrow$ smaller radiative tails
- dedicated photonic parton showers, e.g. PHOTOS
  Placzek, Jadach '03; Carloni Calame et al. '04; Golonka, Was '07

full FSR not universal, in general not separable from EW corrections
combination of PHOTOS with full EW corrections difficult in practice

Setups for WW production

Lepton–photon recombination for $\Delta R_{\gamma l} < 0.1$
Jet definition: $p_{\mathrm{T,j}} > 25\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 5$

Inclusive scenario

$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \quad |y_\ell| < 2.5$
$\Delta R_{\ell \mathrm{j}} > 0.4$ for $p_{\mathrm{T,j}} > 25\,\mathrm{GeV}$
$p_{\mathrm{T,j}} < 100\,\mathrm{GeV}$ (jet veto to avoid large QCD corrections)

ATLAS scenario (following 1210.2979 and 1410.7238)

$p_{\mathrm{T},\ell_1} > 25\,\mathrm{GeV}, \quad p_{\mathrm{T},\ell_2} > 20\,\mathrm{GeV}, \quad |y_\ell| < 2.5$
$\Delta R_{\mathrm{e}^-\mu^+} > 0.1, \quad M_{\mathrm{e}^-\mu^+} > 10\,\mathrm{GeV},$
$p_{\mathrm{T,miss}} > 25\,\mathrm{GeV}, \quad p_{\mathrm{T,j}} < 25\,\mathrm{GeV} \;\Rightarrow$ no jets

Higgs-search scenario (following 1412.2641)

ATLAS scenario with $p_{\mathrm{T,miss}} > 20\,\mathrm{GeV}$
plus $10\,\mathrm{GeV} < M_{\mathrm{e}^-\mu^+} < 55\,\mathrm{GeV}, \quad \Delta\phi_{\mathrm{e}^-\mu^+} < 1.8$

NLO EW cross section for W-pair production

13 TeV LHC	$\sigma^{\rm LO}_{\bar{q}q}$ [fb]	$\delta^{\rm NLO}_{\bar{q}q}$ [%]	$\delta^{q\neq{\rm b}}_{q\gamma}$ [%]	$\delta_{\gamma\gamma}$ [%]	$\delta_{\rm EW}$ [%]	$\delta_{{\rm b}\gamma}$ [%]
Inclusive	390.6	-3.41	0.49	0.73	-2.20	2.30
ATLAS	271.6	-3.71	-0.27	0.87	-3.11	0.23
Higgs bkgd	49.9	-2.54	-0.22	0.52	-2.25	0.18

- photon-induced contributions below one percent
- photon-bottom-induced contributions involve $\rm tW$ production

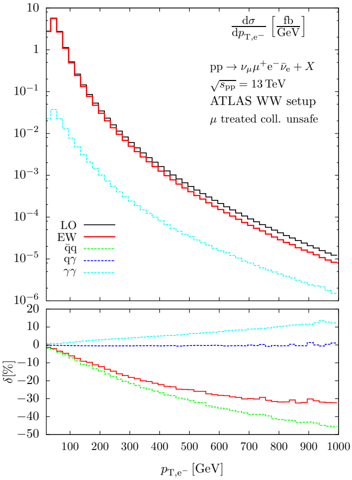
13 TeV LHC	$\sigma^{\rm LO}_{\bar{q}q}$ [fb]	$\delta^{\rm NLO,DPA}_{\bar{q}q,{\rm CUS}}$ [%]	$\delta^{\rm NLO}_{\bar{q}q,{\rm CUS}}$ [%]	$\delta^{\rm NLO}_{\bar{q}q,{\rm CS}}$ [%]
Inclusive	390.6	-3.43	-3.41	-2.91
ATLAS	271.6	-3.68	-3.71	-3.18
Higgs bkgd	49.9	-2.54	-2.54	-1.95

- accuray of DPA (only for virtual NLO) below one per mille
- difference between collinear-safe and unsafe scenario: 0.5%

relative corrections for $8\,\rm TeV$ similar

Transverse-momentum distribution (ATLAS setup)

Biedermann et al. '16



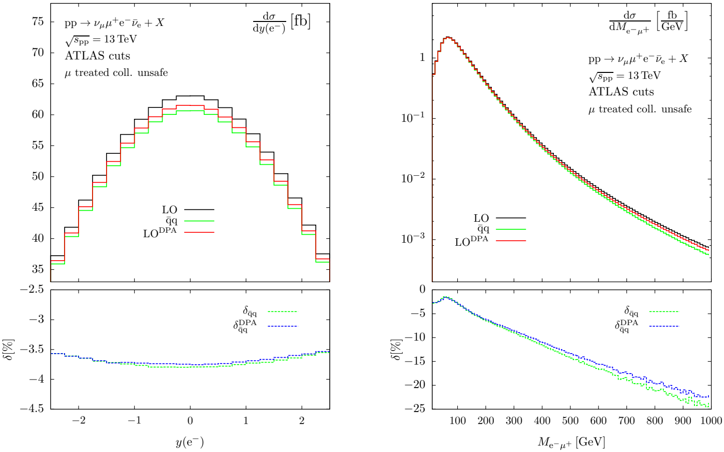
EW corrections

- $\bar{q}q$: -45% at $p_{T,e^-} = 1\,TeV$
- $\gamma\gamma$: $+12\%$ at $p_{T,e^-} = 1\,TeV$
  large uncertainty from PDFs
- $q\gamma$: negligible owing to jet veto

W-pair production: DPA versus full off-shell EWC

Rapidity and invariant-mass distributions

Biedermann et al. '16



- electron rapidity: agreement as for integrated cross section
- $M_{\mathrm{e}^-\mu^+}$ distribution: deviation 1–3% for $M_{\mathrm{e}^+\mu^-} > 500\,\mathrm{GeV}$
  importance of singly-resonant diagrams grows with invariant mass

Error estimate of full NLO calculation

(missing 2-loop EW corrections)

$$\Delta \sim (\delta_{\mathrm{EW}})^2$$

Error estimate of DPA

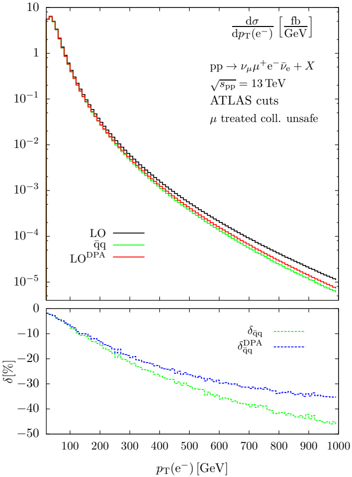
$$\Delta_{\mathrm{DPA}} \sim \max\left\{ \left(\delta_{\mathrm{EW}}^{\mathrm{DPA}}\right)^2, \underbrace{\frac{\alpha}{\pi}\frac{\Gamma_{\mathrm{W}}}{M_{\mathrm{W}}}\ln(\ldots)}_{\lesssim 0.5\%}, \left|\delta_{\mathrm{EW}}^{\mathrm{DPA}}\right| \times \frac{\left|\sigma_{\mathrm{LO}} - \sigma_{\mathrm{LO}}^{\mathrm{DPA}}\right|}{\sigma_{\mathrm{LO}}^{\mathrm{DPA}}} \right\}$$

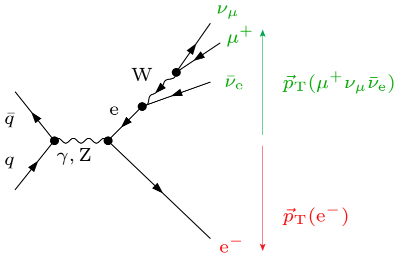
- missing 2-loop EW corrections
- missing off-shell contributions in regions where DPA applies
- change of NLO corrections due to failure of DPA

W-pair production: DPA versus full off-shell EWC

Transverse-momentum distribution of a single lepton

Biedermann et al. '16



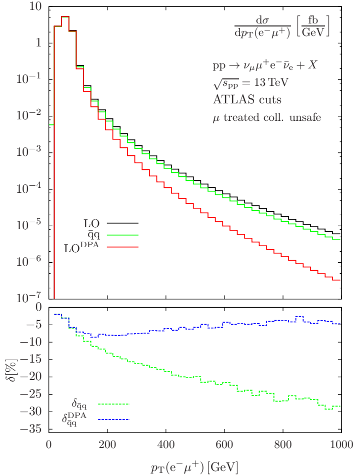


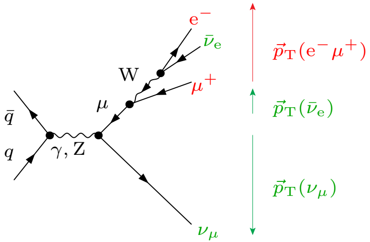
- impact of singly-resonant diagrams where e^- takes recoil from $(\mu^+\nu_\mu\bar{\nu}_e)$
- doubly-resonant diagrams do not favour high-p_T leptons
  decay products of resonances prefer lower p_T

difference of 5% (10%) at $500\,GeV$ $(1\,TeV)$
$\Rightarrow$ full off-shell calculation necessary

Transverse-momentum distribution of the charged lepton pair

Biedermann et al. '16





- doubly-resonant diagrams extremely suppressed!
- singly-resonant diagrams dominate where $(e^-\mu^+)$ recoil against $(\nu_\mu\bar{\nu}_e)$

DPA fails for $p_T \gtrsim 200\,GeV$, since off-shell production dominates!

Outline

Setups for ZZ production

Lepton–photon recombination for $\Delta R_{\gamma l} < 0.2$

Inclusive scenario (following ATLAS 1403.5657)

$p_{\mathrm{T},\ell} > 15\,\mathrm{GeV}, \quad |y_\ell| < 2.5, \quad \Delta R_{\ell\ell} > 0.2$

Higgs-search scenario (motivated by ATLAS/CMS 1408.5191 and 1312.5353)

$p_{\mathrm{T},\ell} > 6\,\mathrm{GeV}, \quad |y_\ell| < 2.5, \quad \Delta R_{\ell\ell} > 0.2$

$40\,\mathrm{GeV} < M_{\ell_1^+\ell_1^-} < 120\,\mathrm{GeV}, \quad 12\,\mathrm{GeV} < M_{\ell_2^+\ell_2^-} < 120\,\mathrm{GeV}$

$M_{4\ell} > 100\,\mathrm{GeV}$

Processes: $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-, \mu^+\mu^-\mu^+\mu^-$

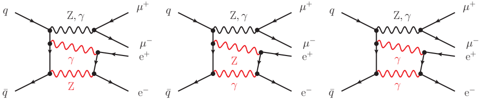
Lepton pairing for identical leptons

leading lepton pair $\ell_1^+\ell_1^-$: pair ij with $M_{\ell_i\ell_j}$ closest to M_Z

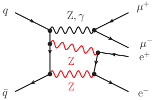
sub-leading lepton pair $\ell_2^+\ell_2^-$: pair of remaining two leptons

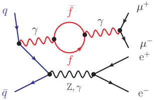
Gauge-invariant splitting into weak and photonic corrections for processes without charged currents at LO

- photonic corrections: diagrams with a photon in a loop coupling to external fermion lines



- weak corrections: remaining diagrams including all (gauge-invariant) fermion-loop diagrams





- NC interaction in SM equivalent to $\mathrm{U}(1)_\gamma \times \mathrm{U}(1)_\mathrm{Z}$ gauge theory
  $\Rightarrow$ renormalizable theory, gauge-invariant EW corrections
- photonic corrections separately gauge invariant since $\mathrm{U}(1)$ charges can be freely chosen

Processes: $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-$: $[2\mu 2\mathrm{e}]$
$\mathrm{pp} \to \mu^+\mu^-\mu^+\mu^-$: $[4\mu]$ effective symmetry factor 1/2

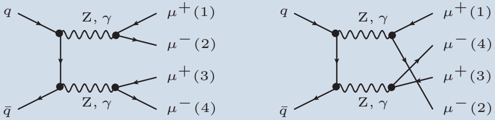
13 TeV LHC	$\sigma^{\mathrm{LO}}_{\bar{q}q}$ [fb]	$\delta^{\mathrm{weak}}_{\bar{q}q}(\%)$	$\delta^{\mathrm{phot}}_{\bar{q}q,\mathrm{CS}}(\%)$	$\delta^{\mathrm{phot}}_{\bar{q}q,\mathrm{CUS}}(\%)$	$\delta_{\gamma\gamma}(\%)$	$\delta_{q\gamma}(\%)$
incl. $[2\mu 2\mathrm{e}]$	11.50	-4.32	-0.93	-1.68	$+0.13$	$+0.02$
incl. $[4\mu]$	5.73	-4.32	-0.94	-2.43	$+0.11$	$+0.02$
Higgs $[2\mu 2\mathrm{e}]$	13.86	-3.59	-0.04	-0.28	$+0.23$	-0.09
Higgs $[4\mu]$	7.12	-3.42	-0.09	-0.66	$+0.30$	-0.14

- weak corrections moderate
- photonic corrections
  negligible Higgs-search scenario
  few percent for collinear-unsafe case (0.7% per muon)
- photon-induced contributions negligible
  ($\gamma\gamma$ singly resonant, $q\gamma$ not enhanced by t-channel W exchange)
- deviation from on-shell calculation $\mathcal{O}(1\%)$

Cross section and interference for ZZ production

13 TeV LHC	$\sigma^{\mathrm{LO}}_{\bar{q}q}$ [fb]	$\delta^{\mathrm{weak}}_{\bar{q}q}(\%)$	$\delta^{\mathrm{phot}}_{\bar{q}q,\mathrm{CS}}(\%)$	$\delta^{\mathrm{phot}}_{\bar{q}q,\mathrm{CUS}}(\%)$	$\delta_{\gamma\gamma}(\%)$	$\delta_{q\gamma}(\%)$
incl. [2μ2e]	11.50	-4.32	-0.93	-1.68	$+0.13$	$+0.02$
incl. [4μ]	5.73	-4.32	-0.94	-2.43	$+0.11$	$+0.02$
Higgs [2μ2e]	13.86	-3.59	-0.04	-0.28	$+0.23$	-0.09
Higgs [4μ]	7.12	-3.42	-0.09	-0.66	$+0.30$	-0.14

Interference effects for equal-flavour final states

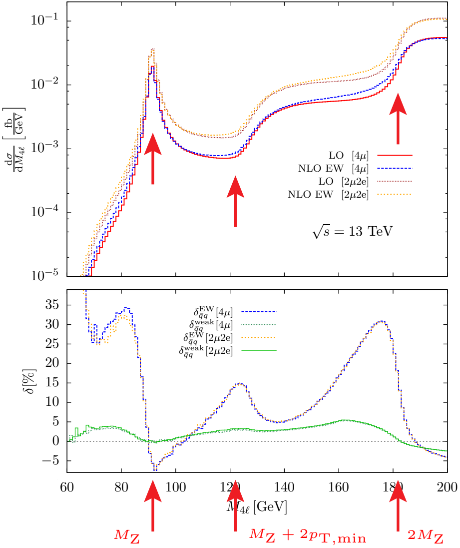


interference suppressed
by Γ_Z/M_Z
per resonance
$\Rightarrow$ LO effect

	$\dfrac{\sigma_{\mathrm{LO}}[2\mu 2e]}{2\sigma_{\mathrm{LO}}[4\mu]} \approx$		interference	suppression
inclusive:	1.003	$\Rightarrow$	-0.3%	$\sim (\Gamma_Z/M_Z)^2$
Higgs-specific:	0.973	$\Rightarrow$	2.5%	$\sim \Gamma_Z/M_Z$

Invariant 4-lepton-mass distribution (inclusive scenario)

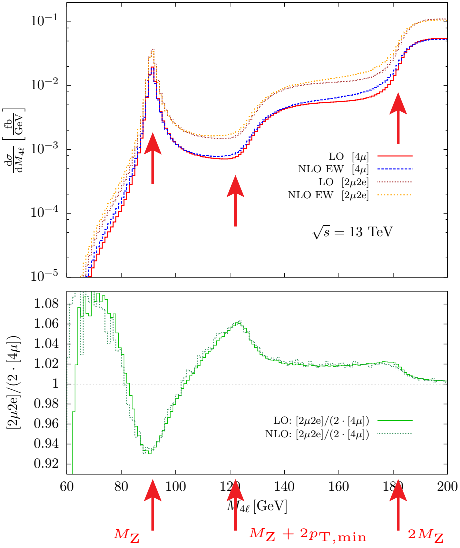
Biedermann et al.
preliminary



- regions:
  - $2M_Z \lesssim M_{4\ell}$ doubly-resonant contributions
  - $M_Z + 2p_{T,\min} \lesssim M_{4\ell} \lesssim 2M_Z$ singly-resonant contributions
  - $M_{4\ell} \lesssim M_Z + 2p_{T,\min}$ non-resonant contributions
  - $M_{4\ell} \sim M_Z$: Z-boson resonance ▸ diagrams
- radiative tails
  below thresholds and peaks
- weak corrections below $\sim 5\%$
  positive below ZZ threshold
  negative above ZZ threshold
  -20% for $M_{4\ell} = 1\,\text{TeV}$ ▸ plot
- photonic contribution $\lesssim 1\%$

Invariant 4-lepton-mass distribution (inclusive scenario)

Biedermann et al.
preliminary



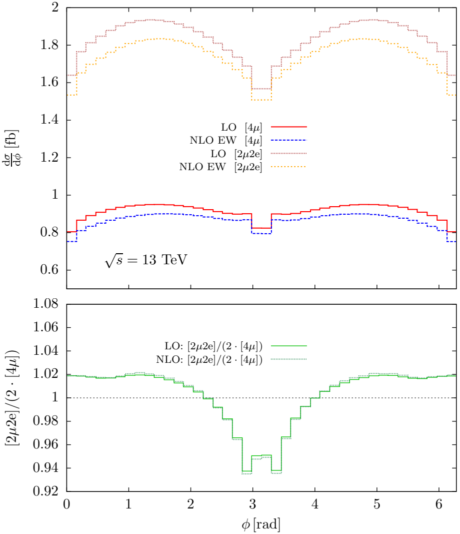
- distribution does not depend on lepton pairing
  $\Rightarrow$ $[2\mu2e]/(2\cdot[4\mu])$ gives interference
- interference mainly LO effect
- interference effect:
  - permille level in doubly-resonant region
    suppression $(\Gamma_Z/M_Z)^2$
  - 2% in singly-resonant region
    suppression (Γ_Z/M_Z)
  - 7% in non-resonant region
    no suppression

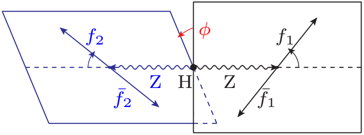
$\Rightarrow$ 4μ matrix elements needed

Distribution in angle between decay planes

Biedermann et al.
preliminary

(sensitive to Higgs coupling structure) (inclusive scenario)



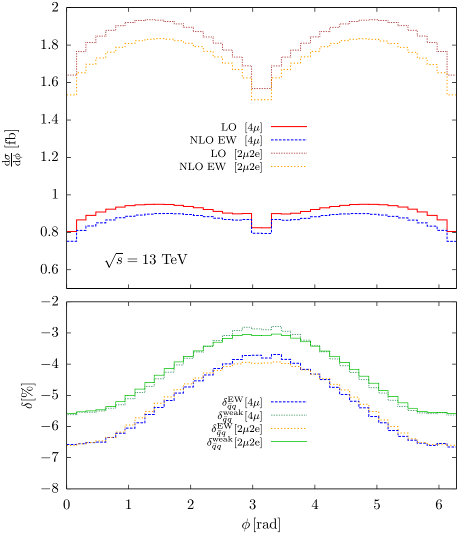


- distribution does not depend on interchange of lepton pairs
  $\Rightarrow [2\mu 2e]/(2 \cdot [4\mu])$ gives interference
- few percent interference effect:
  - small angle: destructive interference (like-sign muons parallel)
  - large angle: constructive interference
  - similar for Higgs-bkgd scen.

Distribution in angle between decay planes

Biedermann et al.
preliminary

(sensitive to Higgs coupling structure) (inclusive scenario)



distribution dominated by resonant ZZ production

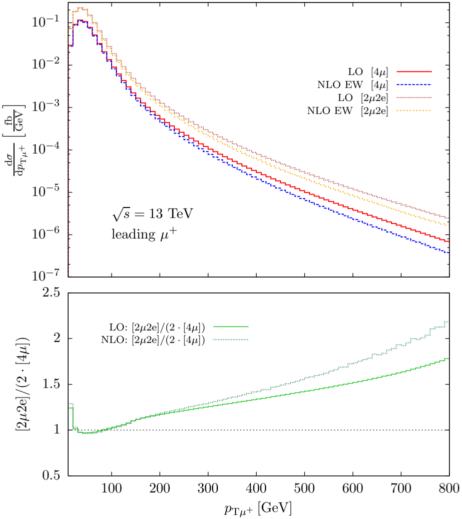
EW/weak corrections

- weak corrections distort distribution by 3% (2% for Higgs-background scenario)
- photonic corrections $\sim -1\%$ (ϕ insensitive to collinear photon emission off leptons)

Z-pair production: EW corrections/muon pair selection

Transverse-momentum distribution of the (leading) muon (inclusive scenario)

Biedermann et al.
preliminary

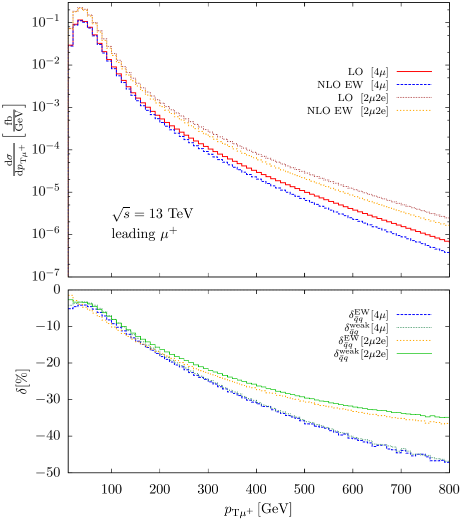


- sensitive to event selection
  leading muon from muon pair with $M_{\mu\mu}$ closer to M_Z
  ⇒ differences between
  4μ and $2e2\mu$
- $2e2\mu$: distribution at high p_T dominated by muons not resulting from a resonance (compare WW production)
- 4μ: distribution of leading muon dominated by doubly-resonant contributions
  suppressed for high p_T
  (sub-leading muon enhanced)

Transverse-momentum distribution of the (leading) muon

Biedermann et al. preliminary

(inclusive scenario)

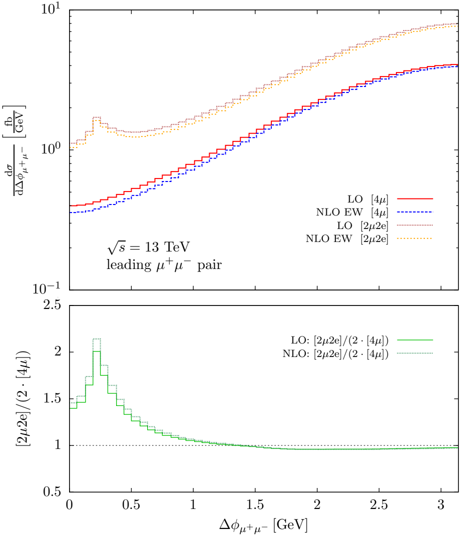


- EW/weak corrections larger for leading muon (4μ)
  (smaller for sub-leading muon)
  Sudakov logarithms larger for doubly-resonant contributions
- photonic corrections yield constant offset of
  $\sim -2\%$ for $2\mu2e$
  $\lesssim 1\%$ for 4μ

Azimuthal-angle difference between (leading) muons

Biedermann et al. preliminary

(inclusive scenario)

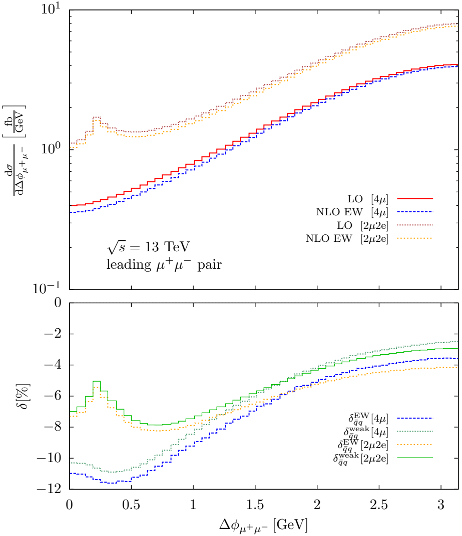


- distribution dominated by doubly-resonant contributions with $M_{4\ell} \gtrsim 2M_Z$
  $\Rightarrow$ leading muons dominantly back to back
  $\Rightarrow$ large $\Delta\phi_{\mu^+\mu^-}$
- region of small $\Delta\phi_{\mu^+\mu^-}$:
  - muon pair in $2e2\mu$ (as sub-leading muon pair) enhanced by photon pole truncated by cut on lepton-separation $\Delta R_{\ell\ell}$
  - leading muon pair suppressed (dominantly from on-shell Z boson)

Azimuthal-angle difference between (leading) muons

Biedermann et al.
preliminary

(inclusive scenario)



EW/weak corrections

- large $\Delta\phi_{\mu^+\mu^-}$: as for σ_{int}
- small $\Delta\phi_{\mu^+\mu^-}$: increased negative corrections owing to larger contributions from high-energetic muons
  - leading muon pair: large negative correction
  - $2\mu 2\text{e}$, sub-leading μ pair: contribution of $\text{Z}\gamma^*$ $\Rightarrow$ smaller correction

photonic corrections

- 1–2%
- larger where doubly-resonant diagrams dominate

Outline

Di-boson production at the LHC

Excursion

- sensitive to non-Abelian gauge-boson self-interactions
- important background
  - to new-physics searches
  - to precision Higgs analyses in $\mathrm{pp} \to \mathrm{H} \to \mathrm{WW/ZZ} \to 4f$

$\Rightarrow$ precise predictions with QCD and EW corrections required

NLO EW corrections to $\mathrm{pp} \to \mathrm{WW/ZZ} \to 4$ leptons (fully off shell) exist

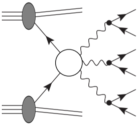
- EW corrections of several 10% in tails of distributions
- radiative tails near resonances and thresholds, enhanced for bare muons
- DPA fails for transverse momentum distributions
  where singly-resonant contributions become sizeable
- corrections negative above VV threshold but positive below
- per-cent level interference effects for $\mathrm{pp} \to \mu^+\mu^-\mu^+\mu^-$
  below VV threshold
- photon-induced contributions small for WW and negligible for ZZ

EW corrections for $\mathrm{pp} \to \mathrm{WZ} \to 4$ leptons in preparation

6 Backup

Triple vector-boson production

$2 \to 6$ process: $\mathrm{pp} \to VV'V'' \to 6\ell$



Existing calculations:

- NLO QCD corrections for on-shell vector bosons:
  - $\mathrm{pp} \to \mathrm{ZZZ}$ — Lazopoulos, Melnikov, Petriello ’07
  - $\mathrm{pp} \to VV'V''$ (massive) — Binoth, Ossola, Papadopoulos, Pittau ’08
- NLO QCD corrections including leptonic decays:
  - $\mathrm{pp} \to \mathrm{WWZ}$ — Hankele, Zeppenfeld ’07 (VBFNLO)
  - $\mathrm{pp} \to VV'V''$ — Campanario et al. ’08–’11 (VBFNLO)
- NLO EW corrections for on-shell vector bosons:
  - $\mathrm{pp} \to VV'V''$ (massive) — Nhung, Ninh, Weber ’13
- NLO EW corrections to production with leptonic decays in NWA:
  - $\mathrm{pp} \to \mathrm{WZZ}, \mathrm{WWW}$ — Shen Yong-Bai et al. ’15, ’16

Automated tools: RECOLA, OPENLOOPS, MADGRAPH5_AMC@NLO
$\Rightarrow$ calculation of EW corrections (in PA) within reach

$2 \to 6$ process: $\mathrm{pp} \to VV' + 2\mathrm{j} \to 4\ell + 2\mathrm{j}$ enormously complex!

EW production: $\mathcal{O}(\alpha^6)$ QCD-induced production: $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^4)$

Existing building blocks:

- full LO predictions: Ballestrero, Franzosi, Maina '10
- NLO QCD corrections to EW diagrams:
  Jäger, Oleari, Zeppenfeld (+ Bozzi) '06, '07, '09 (VBFNLO);
  Denner, Hosekova, Kallweit '12
- NLO QCD corrections to QCD diagrams:
  Melia, Melnikov, Röntsch, Zanderighi '10, '11; Greiner et al. '12;
  Campanario, Kerner, Ninh, Zeppenfeld '13, '14 (VBFNLO)
- NLO EW corrections for on-shell vector-boson scattering $VV \to VV$

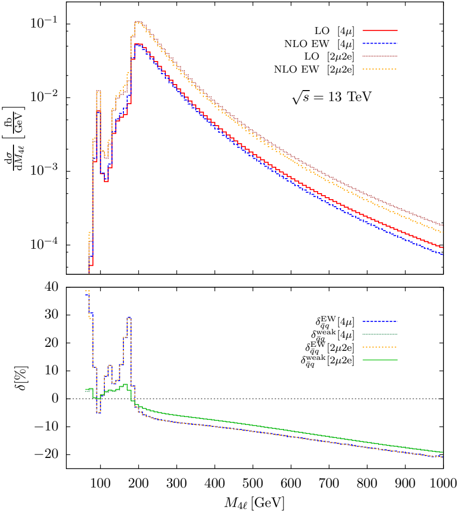
Automated tools: RECOLA, OPENLOOPS, MADGRAPH5_AMC@NLO

$\Rightarrow$ calculation of EW corrections (in DPA) within reach

return

Invariant 4-lepton-mass distribution (inclusive scenario)

Biedermann et al.
preliminary



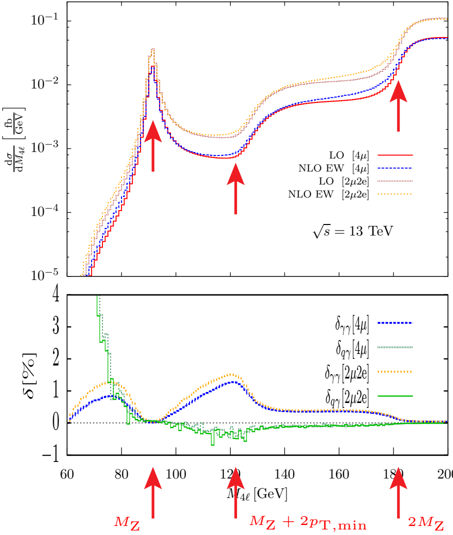
- regions:
  - $2M_Z \lesssim M_{4\ell}$
    doubly-resonant contributions
  - $M_Z + 2p_{T,min} \lesssim M_{4\ell} \lesssim 2M_Z$
    singly-resonant contributions
  - $M_{4\ell} \lesssim M_Z + 2p_{T,min}$
    non-resonant contributions
  - $M_{4\ell} \sim M_Z$:
    Z-boson resonance
- radiative tails
  below thresholds and peaks
- weak corrections
  -20% for $M_{4\ell} = 1\,\mathrm{TeV}$
  positive below ZZ threshold
  negative above ZZ threshold

return

Z-pair production: photonic contributions

Invariant 4-lepton-mass distribution (inclusive scenario)

Biedermann et al.
preliminary

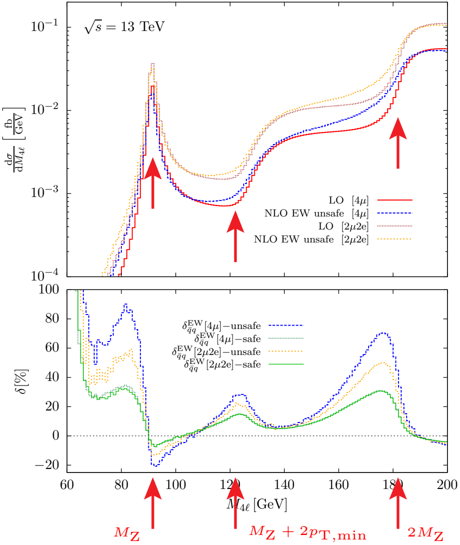


- regions:
  - $2M_Z \lesssim M_{4\ell}$
    doubly-resonant contributions
  - $M_Z + 2p_{T,\min} \lesssim M_{4\ell} \lesssim 2M_Z$
    singly-resonant contributions
  - $M_{4\ell} \lesssim M_Z + 2p_{T,\min}$
    non-resonant contributions
  - $M_{4\ell} \sim M_Z$:
    Z-boson resonance
- photon-induced contributions:
  - per-mille level in doubly-resonant region
  - $< 1\%$ in singly-resonant region
  - $\sim 1\%$ in non-resonant region
  - vanishing for $M_{4\ell} = M_Z$

Z-pair production: collinear safe vs. collinear unsafe

Invariant 4-lepton-mass distribution (inclusive scenario)

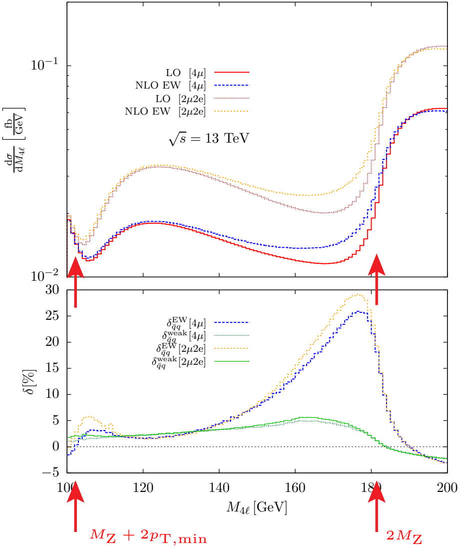
Biedermann et al.
preliminary



- regions:
  - $2M_Z \lesssim M_{4\ell}$
    doubly-resonant contributions
  - $M_Z + 2p_{T,min} \lesssim M_{4\ell} \lesssim 2M_Z$
    singly-resonant contributions
  - $M_{4\ell} \lesssim M_Z + 2p_{T,min}$
    non-resonant contributions
  - $M_{4\ell} \sim M_Z$:
    Z-boson resonance
- radiative tails
  below thresholds and peaks
  enhanced for each
  collinear-unsafe muon

Invariant 4-lepton-mass distribution (Higgs scenario)

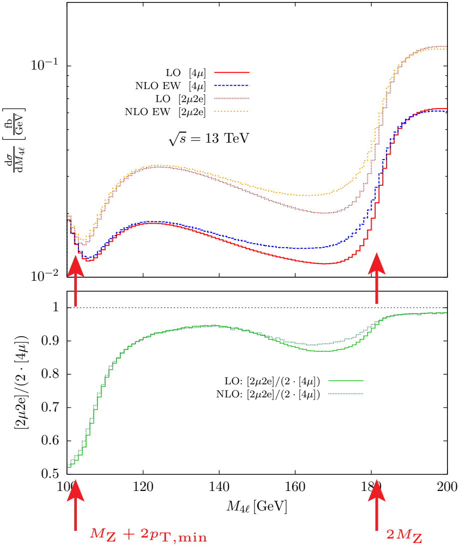
Biedermann et al.
preliminary



- regions:
  - $2M_Z \lesssim M_{4\ell}$
    doubly-resonant contributions
  - $M_Z + 2p_{T,min} \lesssim M_{4\ell} \lesssim 2M_Z$
    singly-resonant contributions
  - $M_{4\ell} \lesssim M_Z + 2p_{T,min}$
    non-resonant contributions
- radiative tails
  below thresholds and peaks
- weak corrections below $\sim 5\%$
  positive below ZZ threshold
  negative above ZZ threshold
  -20% for $M_{4\ell} = 1\,\mathrm{TeV}$
- photonic contributions $\lesssim 1\%$

Invariant 4-lepton-mass distribution (Higgs scenario)

Biedermann et al.
preliminary



- distribution does not depend on lepton pairing
  $\Rightarrow$ $[2\mu2e]/(2\cdot[4\mu])$ gives interference
- invariant-mass cuts depend on lepton pairing
- interference mainly LO effect
- interference effect:
  - 1% in doubly-resonant region
  - 10% in singly-resonant region

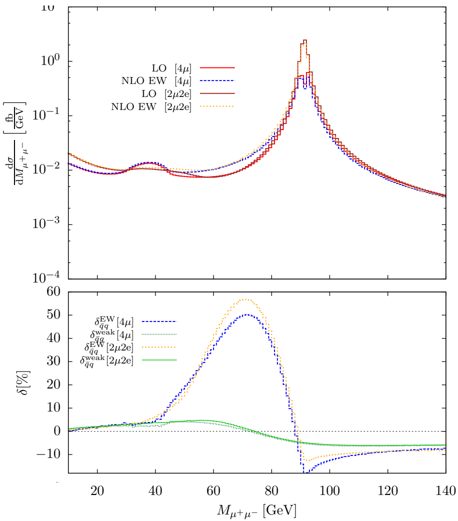
  $\Rightarrow$ 4μ matrix elements needed

Z-pair production: EW corrections

Invariant subleading di-lepton-mass distribution

Biedermann et al.
preliminary

(inclusive scenario)



Distribution

- for $[2\mu 2e]$ dominated by on-shell e^+e^- pair
- for subleading lepton pair: similar outside resonance suppressed near resonance

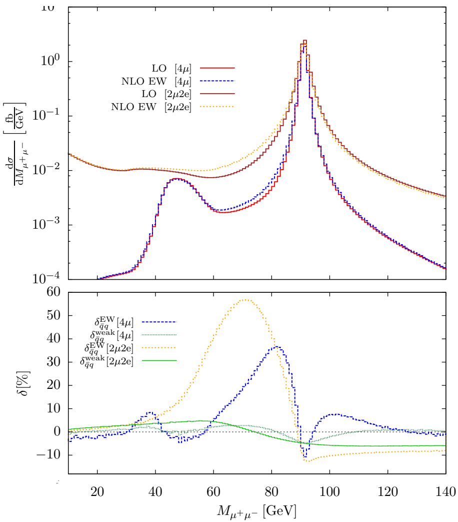
EW corrections

- radiative tails below resonance
- weak corrections change sign near resonance (interference between photon and Z changes sign)
- corrections for subleading pair similar to $\mu^+\mu^-$ pair in $[2\mu 2e]$

Invariant leading di-lepton-mass distribution

(inclusive scenario)

Biedermann et al.
preliminary



Distribution

- depends on lepton pairing
- for $[2\mu 2e]$ dominated by on-shell e^+e^- pair
- for leading muon pair suppressed outside resonance
- peak near $45\,\mathrm{GeV}$ due to Z resonance in $M_{4\ell}$

EW corrections

- radiative tails below resonance
- weak corrections change sign near resonance (interference between photon and Z changes sign)
- corrections for leading pair differ from $\mu^+\mu^-$ pair in $[2\mu 2e]$