Next-to-leading order electroweak corrections to $p\,p \to \mu^+ \mu^- e^+ e^-$

Benedikt Biedermann

Universität Würzburg

In collaboration with
Ansgar Denner, Stefan Dittmaier, Lars Hofer, Barbara Jäger

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Vector boson pair production

Particle physics at the LHC:

- Higgs boson at the LHC discovered in 2012
- So far not many hints for physics beyond the standard model

$\longrightarrow$ New insights in physics require more precision from both experiement and theory

Why is vector boson pair production interesting?

- Precision test of the electro-weak sector of the standard model
- Search for new physics with anomalous gauge couplings
- Higgs search in the mode

$$pp \to H \to VV \to 4f$$

p p $\rightarrow$ Z Z $\rightarrow$ 4 charged leptons

Very important irreducible background in Higgs physics

- in particular the processes

$$pp \rightarrow e^+e^-e^+e^-$$
$$pp \rightarrow \mu^+\mu^-e^+e^-$$
$$pp \rightarrow \mu^+\mu^-\mu^+\mu^-$$

Very clean signal:

- no jets, no missing transverse energy
- Leading order (LO) process is pure electro-weak $O(\alpha^4)$
  NLO EW and QCD corrections can be computed separately
  $\longrightarrow$ Mixing only at higher orders

Need for p p → Z Z beyond leading order

Leading order:

Rough estimate, may exhibit residual scale dependencies
Additional kinematic channels at higher orders

QCD corrections:

NLO QCD first contribution at α_s: need for **NNLO QCD** to reduce residual dependence on renormalisation scale

Electroweak corrections (NLO EW):

naïve expectation: $\alpha_s^2 \approx \alpha$ ↔ NLO EW == NNLO QCD
In reality more complicated because

- In high energy regime (TeV scale) enhancement of Sudakov logarithms can give rise to corrections of several 10%
  [M. Ciafaloni, P. Ciafaloni, Comelli; Beccaria, Renard, Verzegnassi; Beenakker, Werthenbach; Denner, Pozzorini; Melles; Fadin, Lipatov, Martin; Hori, Kawamura, Kodaira; Jantzen, Kühn, Penin, Smirnov; Chiu, Fuhrer, Golf, Kelley, Manohar, . . .]
- EW corrections near resonances can be large due to kinematic effects

p p → Z Z beyond leading order

NLO QCD: $O(\alpha^4 \alpha_s)$

Stable Z with leptonic decays in narrow width approximation

[Ohnemus, Owens 91; Mele, Nason, Ridolfi 91; Ohnemus 94; Dixon, Kunszt, Signer 98; Campbell, Ellis 99]

NNLO QCD: $O(\alpha^4 \alpha_s^2)$

Loop induced gluon fusion channel well known

[Glover, van der Bij 89; Dicus, Kao, Repko 87; Matsuura, van der Bij 91; Zecher, Matsuura, van der Bij 94; Binoth, Kauer, Mertsch 08; Campbell, Ellis, Williams 11;]

Full NNLO QCD inclusive calculation for on-shell Z-bosons

[Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs 14]

NLO EW: $O(\alpha^5)$

Known for on-shell Z-bosons

[Bierweiler, Kasprzik, Kühn 13; Baglio, Ninh, Weber 13]

Here: Full NLO EW corrections with leptonic decays and all vector bosons off-shell. Focus on the process $pp \to \mu^+\mu^- e^+e^-$

General setup

G_μ-scheme for electromagnetic coupling:

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right), \quad G_\mu = 1.16637 \times 10^{-5} \mathrm{GeV}^{-2}$$

Absorbs running of α to EW scale and some universal corrections

Complex-mass scheme for Z-boson resonances

[Denner, Dittmaier, Roth, Wackeroth, Wieders ’99, ’05]

Complex pole: $\mu_Z^2 = M_Z^2 - \mathrm{i} M_Z \Gamma_Z, \quad \mu_W^2 = M_W^2 - \mathrm{i} M_W \Gamma_W$

Complex EW mixing angle: $\cos\theta_W = \mu_W / \mu_Z$

Massless light fermions: $u, d, c, s, b; \quad e, \mu, \tau;$

t’ Hooft-Feynman gauge

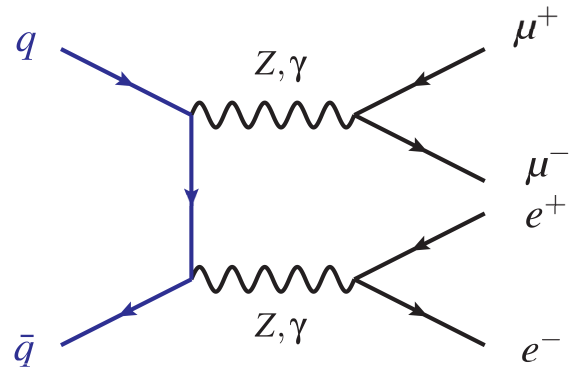
No flavour mixing: CKM matrix is the unit matrix

DIS-scheme for factorisation of initial-state singularities

Leading order contribution

Quark induced contributions:

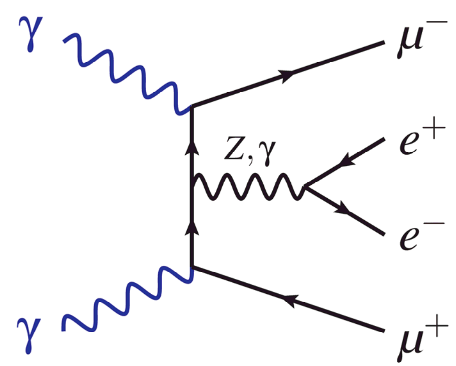
$q\,\bar{q} \rightarrow \mu^+\mu^-e^+e^-$



Two possibly resonant Z-propagators

Photon induced contributions:

$\gamma\,\gamma \rightarrow \mu^+\mu^-e^+e^-$



One possibly resonant Z-propagator

channel	σ_i [fb] (13 TeV)	$\sigma_i/\sigma_{\mathrm{LO}}$
$q\bar{q}(n_f = 4)$	11.1505(5)	96.8 %
$b\bar{b}$	0.3453(1)	3.0 %
$\gamma\gamma$	0.0158(1)	0.2 %
σ_{LO}	11.5117(5)	100 %

(Numerical setup explained later)

$p\,p \to \mu^+\mu^- e^+ e^-$ at NLO

$$d\sigma^{\rm NLO} = d\sigma^{\rm LO} + \delta d\sigma^{\rm NLO}_{\rm QCD} + \delta d\sigma^{\rm NLO}_{\rm EW}$$

$$\sim \alpha^4 \qquad \sim \alpha^4 \alpha_s \qquad \sim \alpha^5$$

$$\delta\sigma^{\rm NLO}_n = \int_n d\sigma^{\rm virt.}_n \oplus \int_{n+1} d\sigma^{\rm reell}_{n+1}$$

n=4=phase space multiplicity

virtual electro-weak corrections:

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

~~$\gamma\,\gamma \to \mu^+\mu^- e^+ e^-$~~

real electroweak corrections:

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

$q\,\gamma \to \mu^+\mu^- e^+ e^- + q$

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

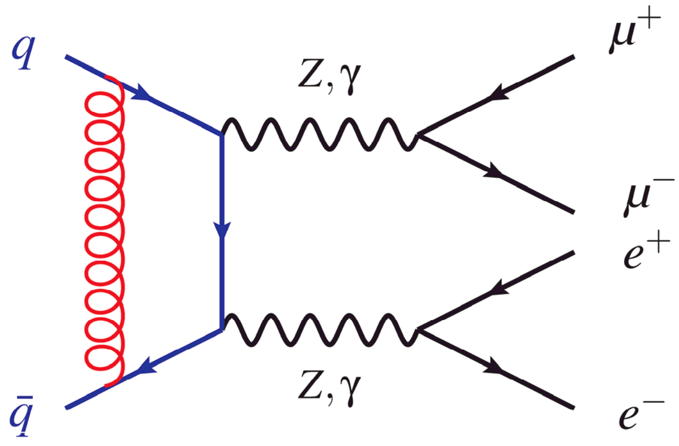
~~$\gamma\,\gamma \to \mu^+\mu^- e^+ e^- + \gamma$~~

NLO EW corrections to the photon-photon Born neglected!

Virtual QCD corrections

All possible gluon insertions between incoming quarks

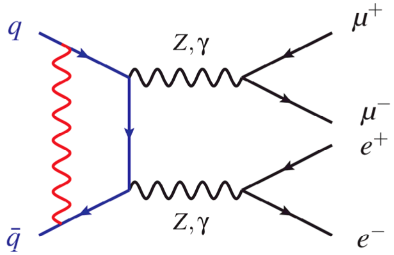
For example…

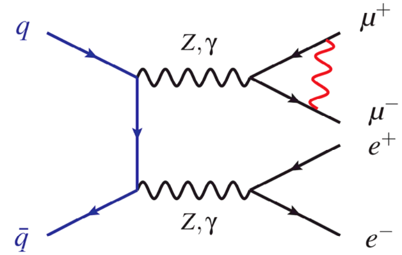


Virtual EW corrections

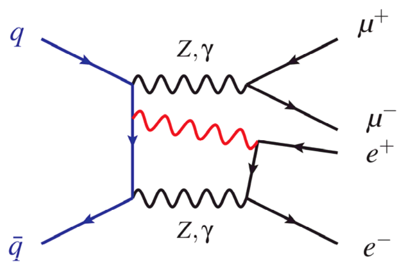
ALL one-loop diagrams of $O(\alpha^5)$ included!

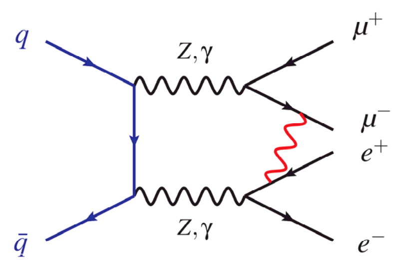
Factorisable contributions: (production and decay independent)

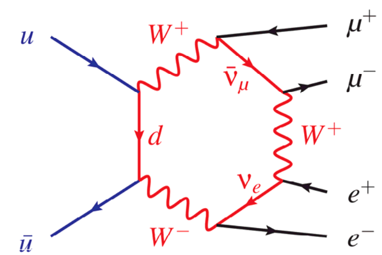


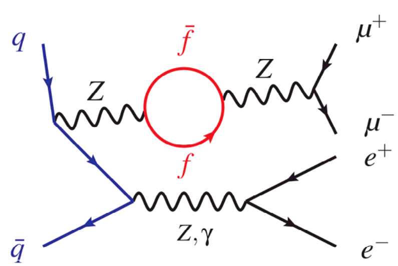


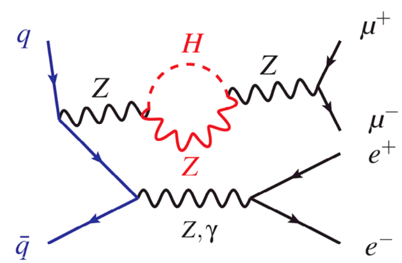
Non-factorisable contributions: (production and decay not independent)









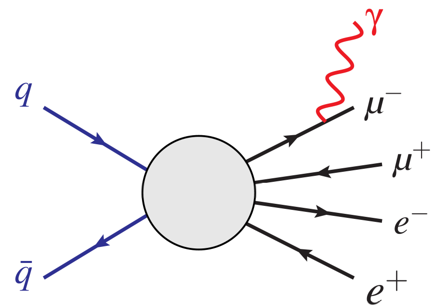


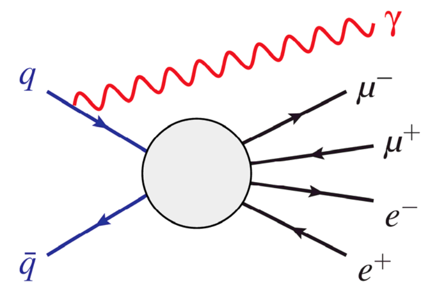
- Closed fermion loops with all standard model flavours included
- Higgs and top quark dependent
- Vector boson selfinteractions

Real corrections

Photon radiation in quark-induced channels:

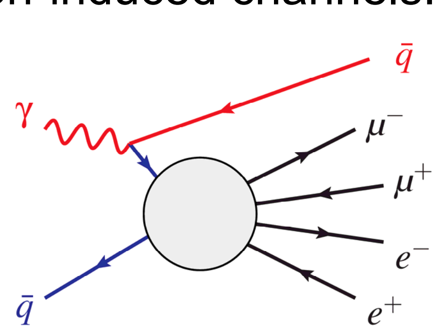
$$q\,\bar{q} \to \mu^+\mu^-e^+e^- + \gamma$$

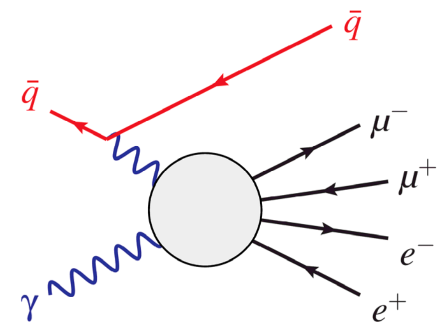




Quark radiation in photon-induced channels:

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





Motivation: photon-induced channels are sizeable in the process $pp \to W^+W^- \to \mu^+\nu_\mu e^-\bar{\nu}_e$

[Billoni et al. 2013]

Use dipole subtraction formalism

[Catani, Seymour 96; Dittmaier 99; Dittmaier Kabelschacht, Kasprzik 08]

Numerical implementation

RECOLA as matrixelement generator used [Actis, Denner, Hofer, Scharf, Uccirati 12]

RECOLA = **RE**cursive **C**alculation of **O**ne-**L**oop **A**mplitudes

- one-loop matrix elements
- Born matrix elements
- colour-, colour-helicity-correlated matrix elements (for QCD radiation)
- spin-correlated matrix elements (for QED radiation)

See Sandro Ucciratis talk on RECOLA for used techniques and functionality

COLLIER [Denner, Dittmaier, Hofer]

library linked to RECOLA for the evaluation of the occuring tensor integrals

See Lars' talk on the COLLIER library

Phase space integration

Integrator based on inhouse multi channel Monte Carlo

Numerical setup

Center of mass energy:

$$\sqrt{s} = 13 \text{ TeV}$$

Phasespace cuts (inspired by ATLAS):

$$p_T(\ell^\pm) > 15\,\text{GeV}, \qquad |\eta(\ell^\pm)| < 2.5, \qquad \Delta R(\ell_i, \ell_j) = 0.2.$$

Photon recombination:

Additional photon from real radiation in collinear regions recombined with closest charged lepton to form pseudoleptons according to a Cambridge/Aachen type jet algorithm with $R = 0.2$ (collinear safe setup). Discard photons with $|\eta_\gamma| < 5$ from recombination (lost in the beampipe)

Quark Radiation:

Radiated quark treated entirely inclusively (no jet veto applied)

Renormalisation and factorisation scale:

$$\mu_r = \mu_f = M_Z^{\text{pole}}$$

PDF set (includes a photon density):

NNPDF23_nlo_as_0118_qed [Ball et al. 2013]

Checks

Internal checks:
cancellation of IR poles between virt. corrections and integrated dipoles
Excellent agreement when switching between dimensional or mass regularisation

Independent cross-checks:
All matrix elements from RECOLA cross checked against private implementation from Stefan Dittmaier or the private program Pole from Meier/Mück/Hofer
Checks against independent integrators from Jäger/Dittmaier and Meier/Mück/Hofer both for total cross sections and differential distributions

Total cross section

Born:

channel	σ_i [fb]	$\sigma_i/\sigma_{\mathrm{LO}}$
$q\bar{q}(n_f = 4)$	11.1505(5)	96.8 %
$b\bar{b}$	0.3453(1)	3.0 %
$\gamma\gamma$	0.0158(1)	0.2 %
σ_{LO}	11.5117(5)	100 %

NLO EW dominated by $q\bar{q}$-channel

Photon-induced contributions strongly suppressed

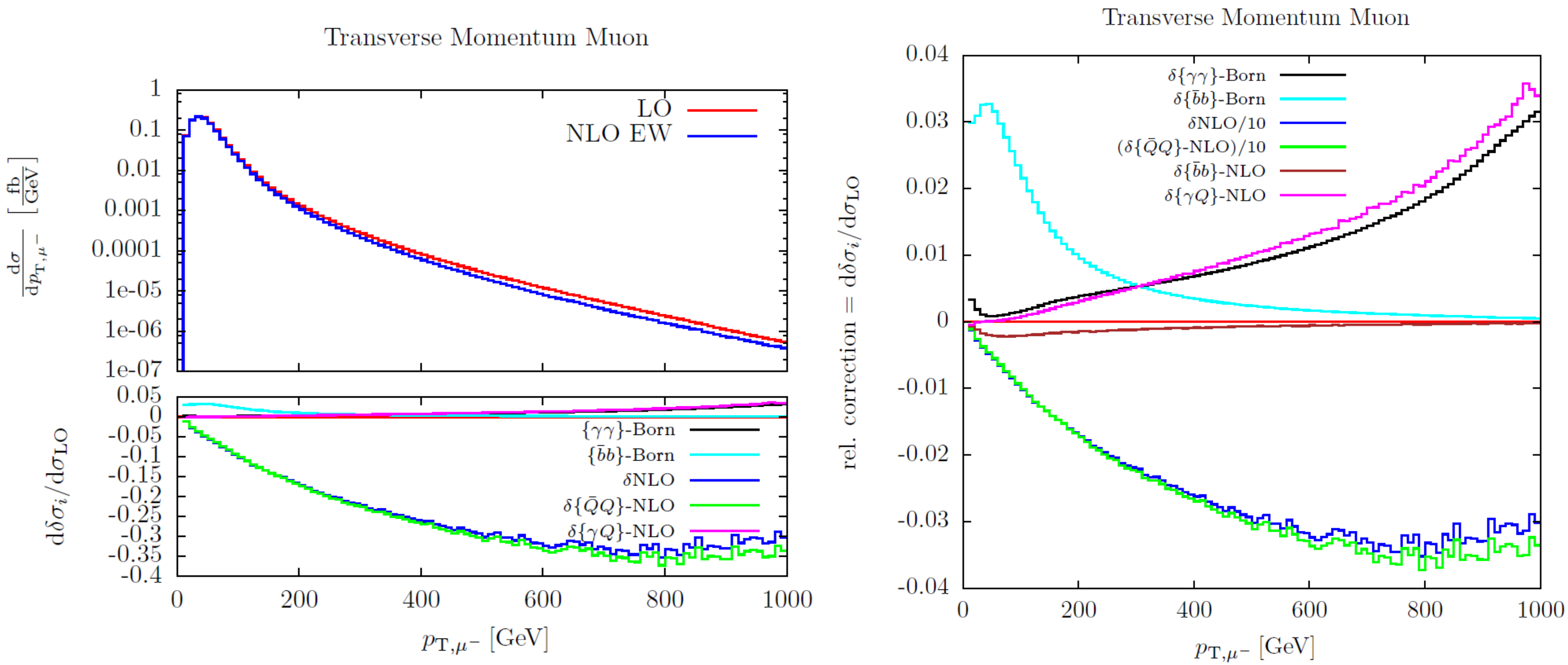
NLO EW:

channel (i)	$\delta\sigma_i$ [fb]	$\delta\sigma_i/\delta\sigma_{\mathrm{NLO}}$	$\delta\sigma_i/\sigma_{\mathrm{LO}}$
$q\bar{q}(n_f = 4)$	-0.589(1)	97 %	-5.1 %
$b\bar{b}$	-0.0203(2)	3 %	-0.2 %
$\{q/\bar{q}, \gamma\}(n_f = 4)$	0.00194(1)	0.3 %	+0.02 %
$\{b/\bar{b}, \gamma\}$	0.000072(4)	–	–
$\delta\sigma_{\mathrm{NLO}}$	-0.607(1)	100 %	-5.2 %

NLO QCD: (fixed scale, for rough comparison with NLO EW only)

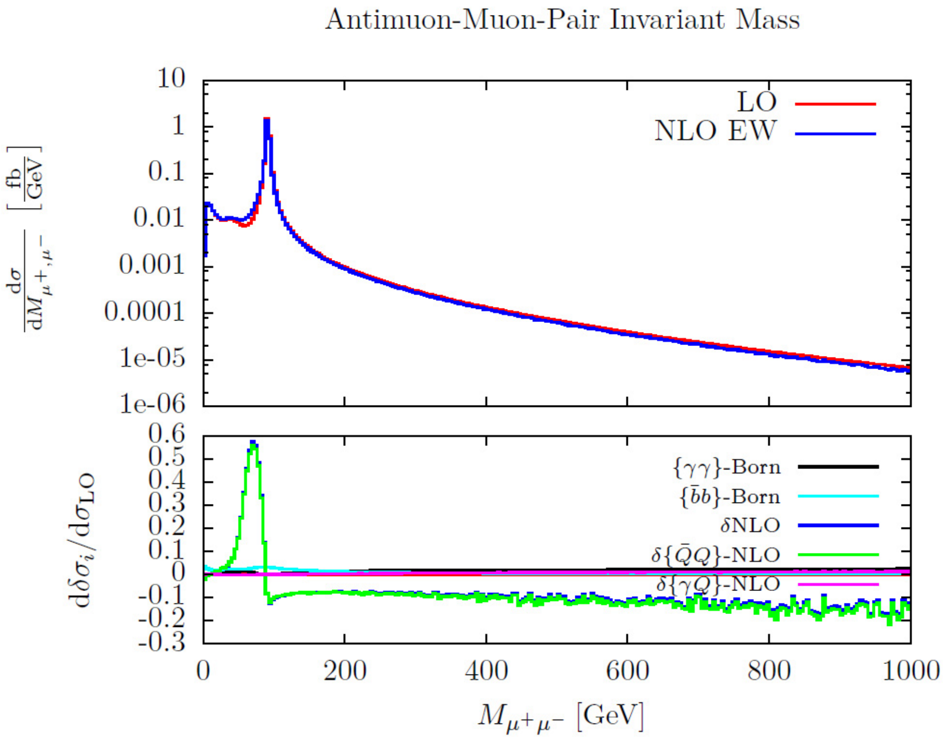
channel (i)	$\delta\sigma_i$ [fb]	$\delta\sigma_i/\sigma_{\mathrm{LO}}$	$\delta\sigma_i/\sigma_{\mathrm{LO}}$
$q\bar{q}(n_f = 5)$	3.4393(8)	25 %	+30 %
$\{q/\bar{q}, g\}(n_f = 5)$	0.8620(5)	75 %	+7 %
$\delta\sigma_{\mathrm{NLO}}$	4.301(1)	100%	+37 %

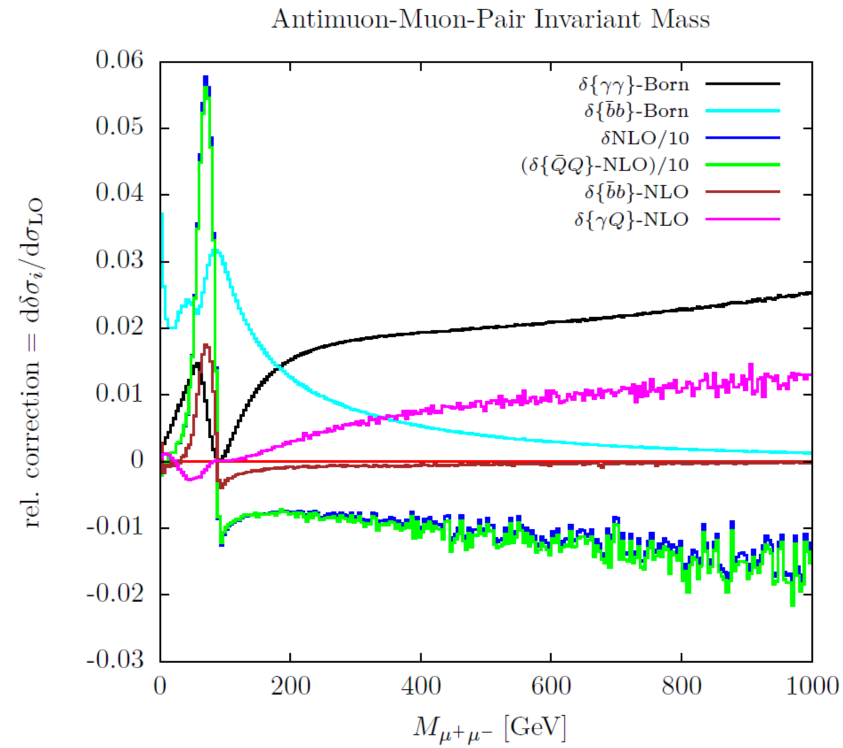
Differential distributions



- Photon-photon Born for high pT 2-3% (800-1000GeV)
- bb Born only sizeble in low pT region (<200 GeV)
- qq-channels dominate high pt, -30% correction (Sudakov regime)
- Photon induced contributions, follow the pattern of pho-pho-Born, below 3%

Differential distributions





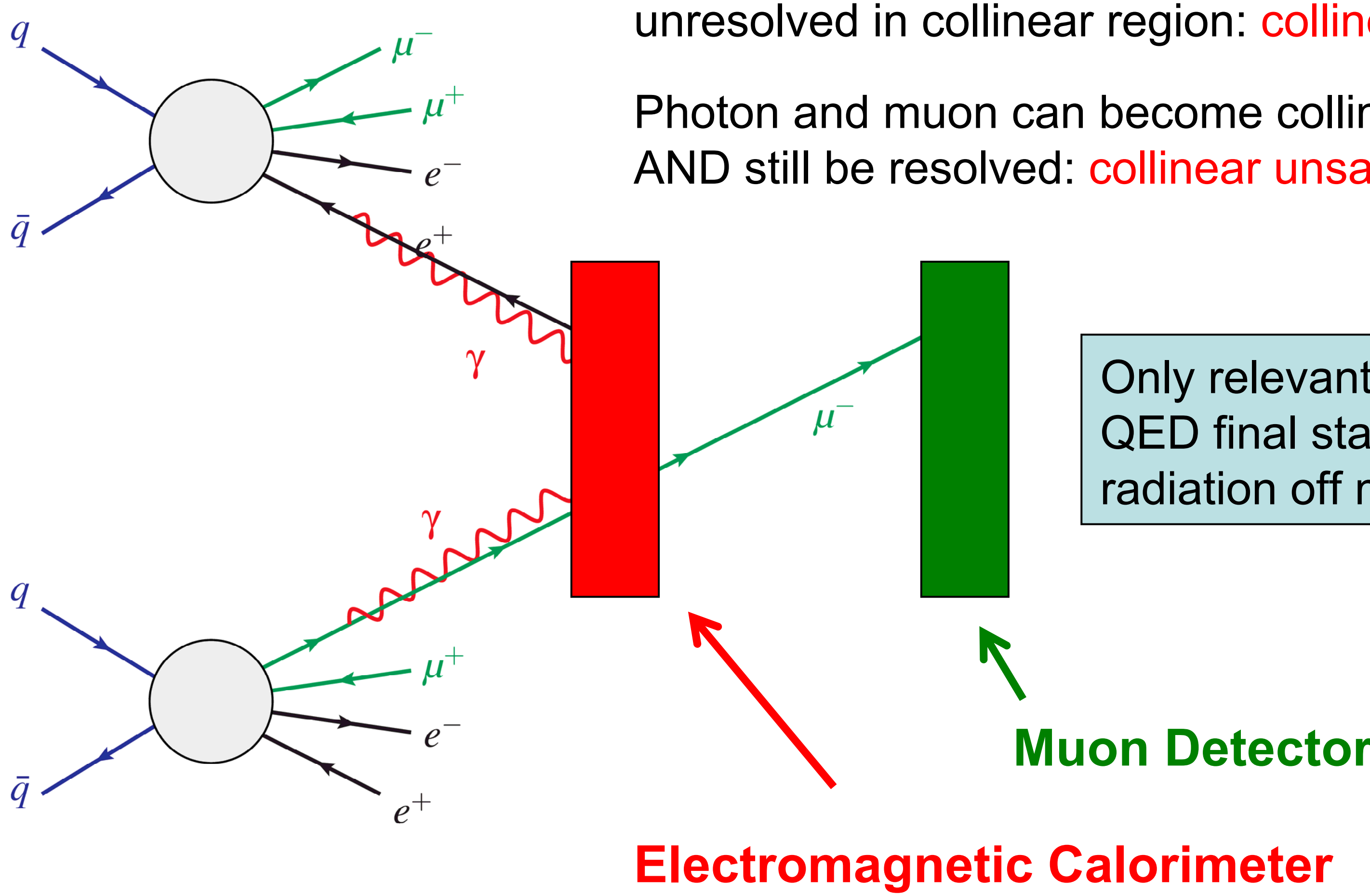
- Photon-photon Born for large invariant mass 2-3% (800-1000GeV)
- bb-Born only sizeable in low pT region (<200 GeV)
- qq-channels: large positive corrections below resonance, -20% correction for large invariant mass (Sudakov regime)
- Photon induced contributions, follow above the resonance the pattern of pho-pho-Born, below 1%

Collinear (un-)safe observables

@LHC: Muon detector and electromagnetic calorimeter spatially well separeted

Photon and electron in SINGLE detector unresolved in collinear region: collinear safe

Photon and muon can become collinear AND still be resolved: collinear unsafe



Only relevant for QED final state radiation off muons.

Computing collinear unsafe observables

[Dittmaier, Kabelschacht, Kasprzik ‘08]

Use physical muon mass as regulator:

Phasespace integrals in the subtraction formalism depend on $\log(M_\mu)$ which do NOT cancel entirely against the logarithms from the virtual corrections. $M_\mu = 105.6583715\ \mathrm{MeV}$

Exclude muons from recombination:

affects the phase space cuts and hence the total cross section and distributions

Different binning of dipole contribution:

Determine from reduced n-point dipole kinematics effective (n+1)-point kinematics for **cutting and binning**

$$\tilde{p}_\ell(z) = z \cdot p_\ell \qquad \tilde{p}_\gamma(z) = (1-z) \cdot p_\ell$$

coll. safe lepton momentum

coll. fraction between lepton and photon

$$\delta\sigma_{\mathrm{Dipoles}} = \int \mathrm{d}\Phi_n \mathrm{d}z\, f(p_1, \dots, p_\ell, \dots, p_n)\Theta_{n+1}\big(p_1, \dots, \tilde{p}_\ell(z), \dots, p_n, \tilde{p}_\gamma(z)\big)$$

matrix elements and dipoles evaluated with original n-point kinematics

Collinear safe vs. unsafe setup

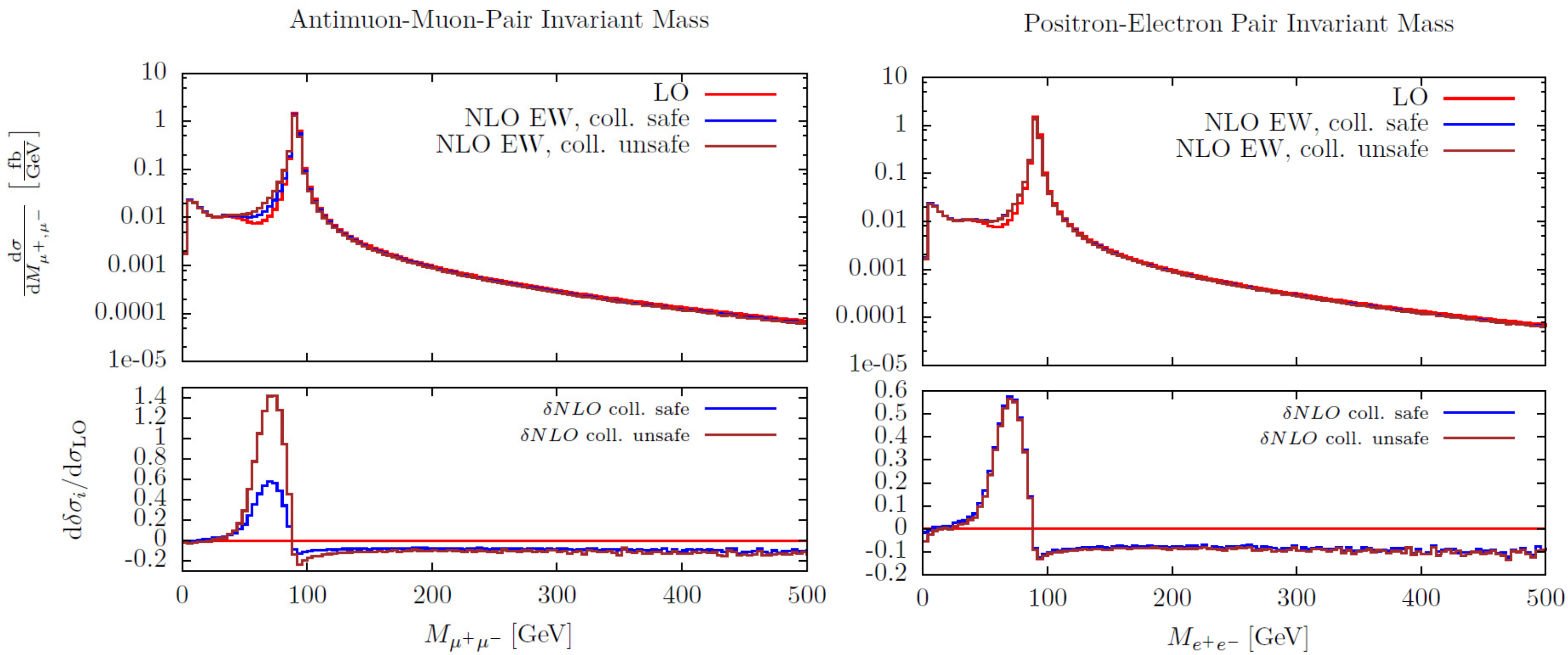
Total cross sections:

$$\sigma_{\mathrm{LO}} = 11.5117(5)\ \mathrm{fb}$$

	$\delta\sigma_i$ [fb]	$\delta\sigma_i/\sigma_{\mathrm{LO}}$
$\delta\sigma_{\mathrm{NLO,coll.safe}}$	-0.607(1)	-5.2 %
$\delta\sigma_{\mathrm{NLO,coll.unsafe}}$	-0.696(1)	-6.0 %
$\gamma\gamma$-Born	0.0158(1)	0.2 %
$\{q/\bar{q},\gamma\}$ NLO	0.00201(1)	+0.02 %

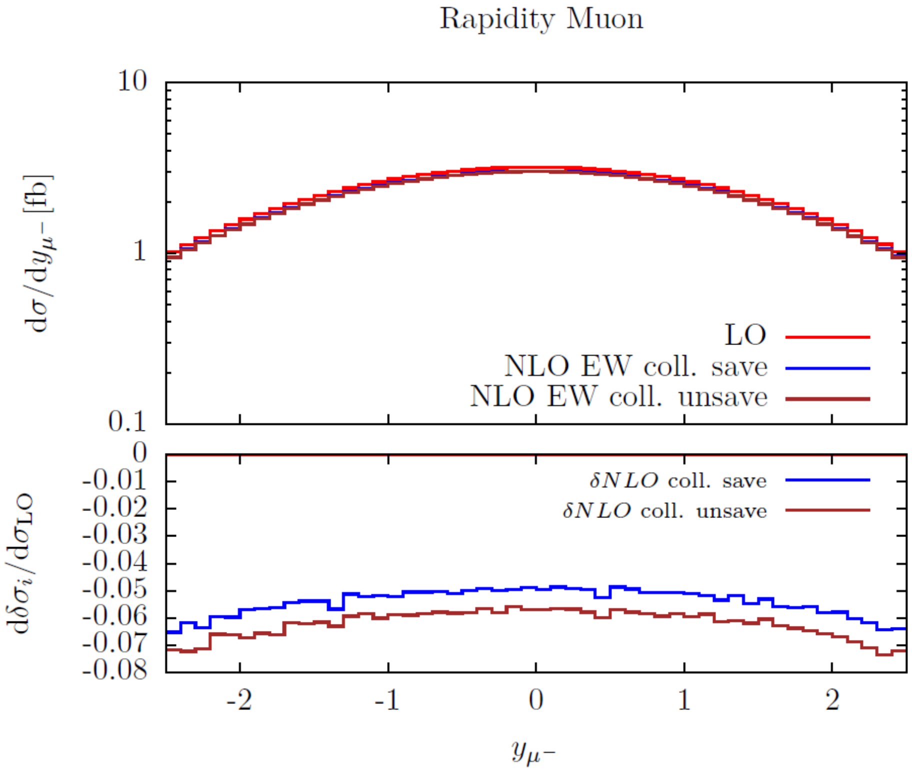
- Effects from collinear unsafe setup shift the result in the order of 1%.
- For the total cross section the effect is more than one order of magnitude larger than the photon induced NLO contributions.

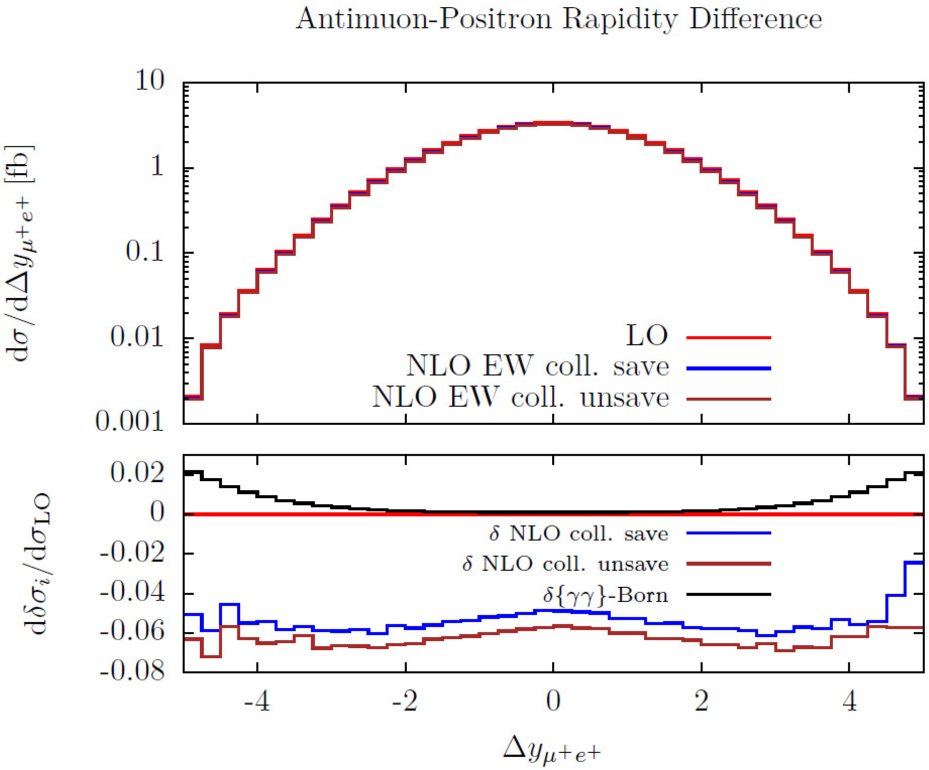
Effects on invariant mass distributions



- More than 100% positive corrections below the Z-resonance for $M_{\mu^+\mu^-}$ negative percent corrections above the resonance, differences at the Z-resonance enhanced by $\log(M_\mu/M_Z)$
- For $M_{e^+e^-}$ only a change of the normalisation

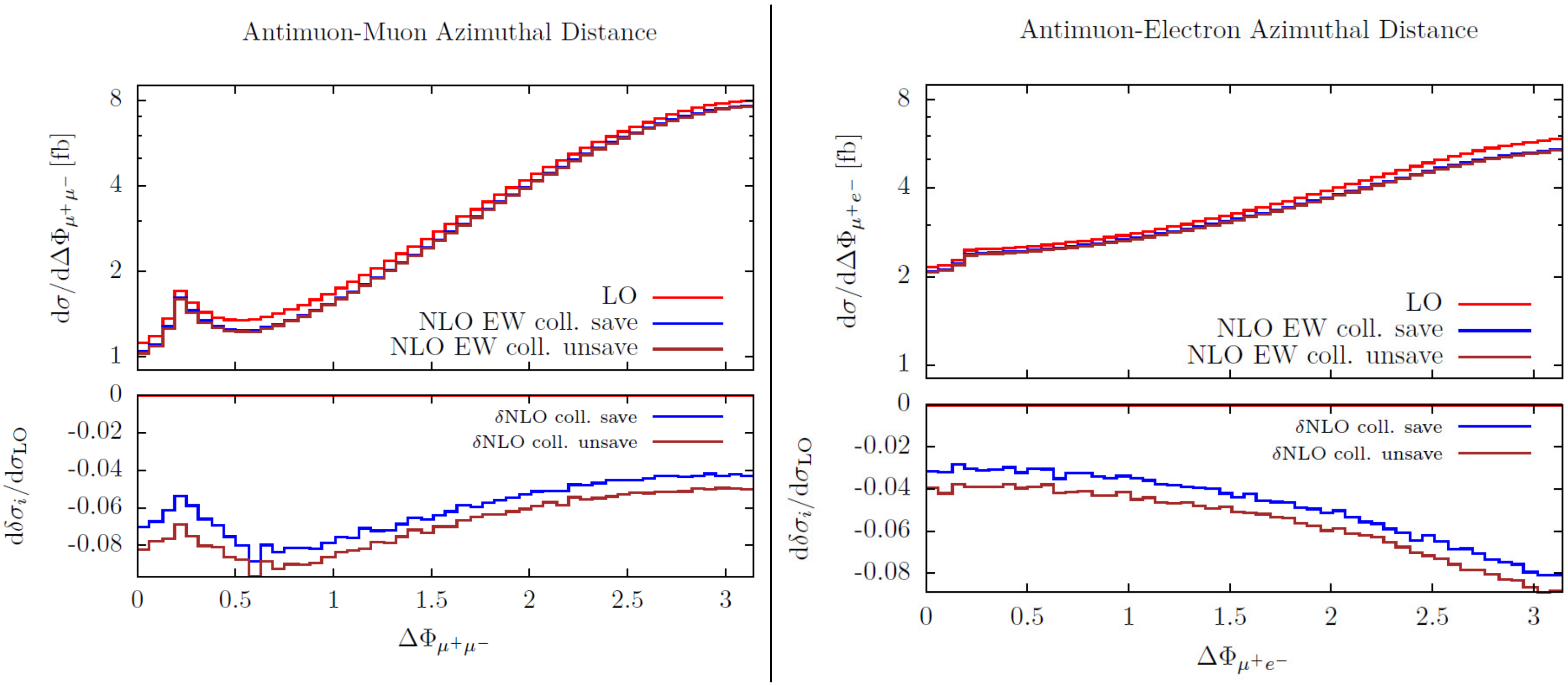
Rapidities





Photon-photon Born: forward-backward dominated due to leptons in t-channel
Qqbar: moderate rapidities dominate

Azimuthal correlations



Maximum at phi_ll = pi: in LO ZZ-diagrams Zs in CMS mainly with small scattering angles
Produced -> decay products in transverse plane mainly back-to-back
Peak at phi_ll=0: Z orthogonal to beampipe boosted -> decay products in same direction
Peak at phi_ll=0 is cut by R_ll > 0.2, with a little radiative tail
Electron-Muon involves different Zs: “flat” angular distribution
Moderate corrections, no significant distorsion of the distributions

Summary, conclusion and outlook

Full NLO EW corrections of $p\, p \to \mu^+\mu^- e^+e^-$ calculated.

ZZ production at NLO receives large EW corrections in the Sudakov regime of around -30%, and below the resonances of 50%-100%.

Contribution of photoninduced NLO corrections is below the permille level for the total cross section. In the Sudakov regime the correction amounts up to +3%.

b-quarks at NLO are at permille level for the total cross section, and affect distributions at most in the low pt region.

Collinear unsafe EW observables like the invariant $\mu^+\mu^-$-mass or the muon transverse momentum give raise to percent corrections with respect to the collinear safe setup and need to be considered in precision physics.