Complete electroweak corrections to $e^+e^- \to 3$ jets

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Outline

- ⋆ Motivations for ILC & LHC
- ⋆ Existing literature
- ⋆ The complete EW one-loop calculation
  - calculation details
  - results (technical checks & physics)
- ⋆ Conclusions

Motivations

- ⋆ at e^+e^- colliders ($e^+e^- \to \gamma^*/Z \to 3$ jets)
  - $e^+e^- \to 3$ jets was the "golden" process for QCD measurements and tests at LEP
  - precise measurement of α_s ($\mathcal{O}(1\%)$ at LEP/SLC, $\mathcal{O}(0.1\%)$ at GigaZ)
  - EW effects can induce asymmetries in 3 jets observables
  - $\mathcal{O}(\alpha)$ EW RC roughly expected as large as NNLO QCD at high energies (Sudakov double-logs)
- ⋆ at hadron colliders ($pp \to \gamma^*/Z \to \ell^+\ell^- +$ jet)
  - measurement of PDFs via $p_\perp^{\gamma/Z}$ spectrum, in particular the gluon PDF
  - large effects of EW Sudakov logs in $Z+$jet observables, e.g. at high $p_\perp^Z$ where BSM physics can show up
  - detector calibration for jets measurements
- SM effects must be well under control to match the experimental accuracy and to disentangle SM from BSM physics

Literature

Restricting to EW corrections

- ⋆ Maina, Moretti, Ross, JHEP 0304:056 (2003)
  - factorizable weak corrections to $e^+e^- \to 3$ jets (no real & virtual QED, no RC connecting initial and final state), effects studied at $\sqrt{s} = M_Z$
- ⋆ Maina, Moretti, Ross, PLB 593 (2004), Erratum PLB 614 (2005)
  - purely weak corrections to $pp \to Z$ or $\gamma +$ jet at high $p_T^{\gamma/Z}$. γ and Z on-shell
- ⋆ Kuhn, Kulesza, Pozzorini, Schulze, PLB 609 (2005)
  - logarithmic weak corrections to $pp \to Z +$ jet (high $p_\perp^Z$) at one and two loop order with LL and NLL accuracy
- ⋆ Kuhn, Kulesza, Pozzorini, Schulze, NPB 727 (2005) 368
  - Exact one loop corrections to $pp \to Z +$ jet

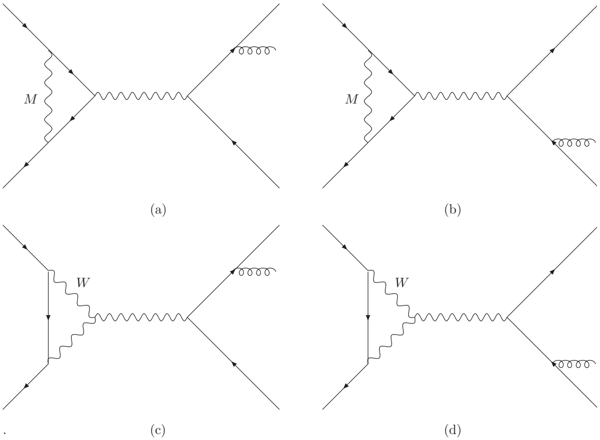
Complete 1-loop EW RC to $e^+e^- \to 3$ jets

- we calculated the full 1-loop EW corrections to $e^+e^- \to 3$ jets
  - QED can give a sizeable effect if realistic event selection criteria are considered
  - non-factorizable RC can be not negligible far from M_Z
  - non-factorizable RC can have a not trivial impact on asymmetries
- by crossing symmetry, EW RC to $pp \to \ell^+\ell^- +$ jet are straighfordwardly obtained
- the precise control of SM effects is mandatory for precision physics and new physics searches

Diagrams

The 1-loop diagrams to be evaluated are:

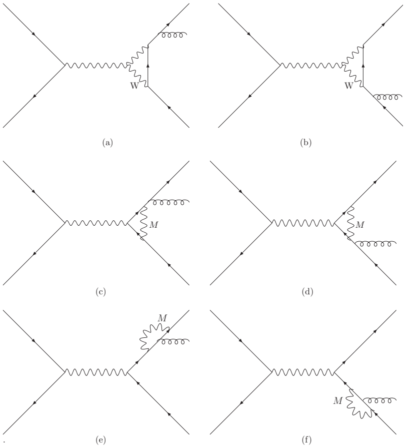
- e^+e^- vertices

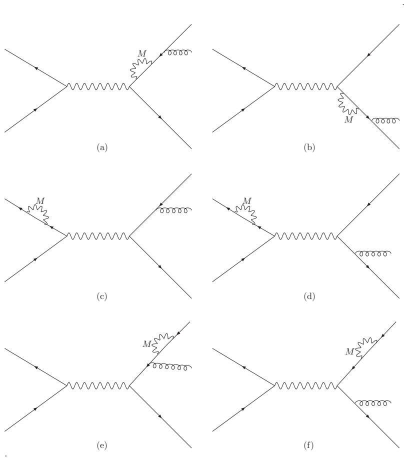


(a) (b) (c) (d)

Diagrams

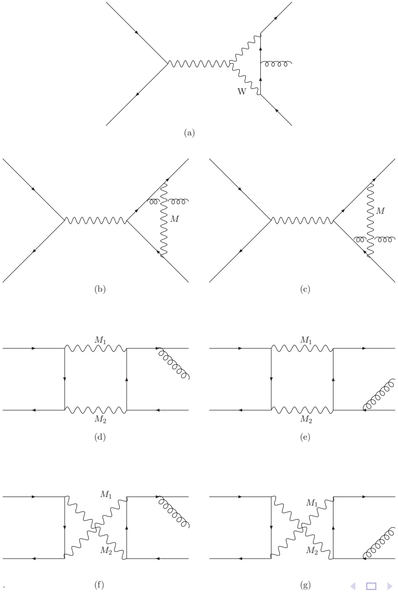
- $q\bar{q}$ and gluon vertices and fermion self-energies





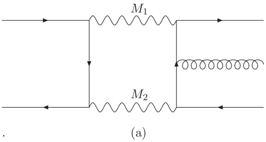
Diagrams

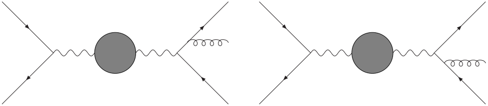
- box diagrams (factorizable and not factorizable)

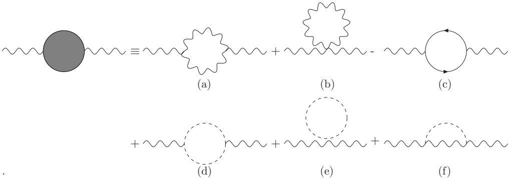


Diagrams

- pentagons and gauge-bosons self-energies







Calculation details

- the calculation has been performed in the limit $m^2_{ext}/s \to 0$
- collinear singularities cured with a small fermion & quark mass
- infrared divergencies regularized with a finite photon mass λ
- virtual corrections
  - ⋆ amplitudes evaluated with helicity techniques and manipulated with **FORM**
  - ⋆ two independend calculations
  - ⋆ up to 4-point functions: reduction of tensor integrals with Passarino-Veltman reduction
  - ⋆ 5-point functions, reduction according to PV or to Denner-Dittmaier (as coded in a our own library or in **LoopTools**)
  - ⋆ good agreement among different implementations
- the squared amplitude for the real emission process $e^+e^- \to q\bar{q}g\gamma$ has been calculated
  - ⋆ with **ALPHA** (Moretti & Caravaglios)
  - ⋆ with **MADGRAPH** (Maltoni, Stelzer et al.)

Gauge invariance and Γ_Z

- In the real part of the calculation we have the Z propagator with fixed width switched on, in order to avoid the Z pole in the phase space integration
- The same propagator should be retained in the virtual corrections (complex mass scheme) in order to ensure the cancellation of IR singularities between virtual and real corrections
- Actually the five point function routines in `LoopTools` don't implement yet complex masses
- But: non factorizable corrections are very small around the Z pole
- We switch off the non-fact corrections in a window of few widths around the pole and keep the propagator with Z width in the factorizable ones
- the mismatch in the IR cancellation between virtual and real part away from the Z pole is numerically small, checked to be beyond the numerical uncertainty

Cross section calculation

As usual, the cross section is split into two parts

- $e^+e^- \longrightarrow q\bar{q}g$

$$\sigma_{2\to 3} = \int d\Phi_3 \left(\, |\mathcal{M}_0|^2 + 2\Re[\mathcal{M}_0^* \mathcal{M}_\alpha^{virt}(\lambda)] \, \right)$$

- $e^+e^- \longrightarrow q\bar{q}g\gamma$

$$\sigma_{2\to 4} = \int_{\lambda<\omega} d\Phi_4 |\mathcal{M}_\alpha^{real}|^2 =$$

$$\int_{\lambda<\omega<k_0} d\Phi_4 |\mathcal{M}_\alpha^{real}|^2 + \int_{k_0<\omega} d\Phi_4 |\mathcal{M}_\alpha^{real}|^2 = \delta_s(\lambda, k_0)\sigma_0 + \sigma_{2\to 4}^{hard}(k_0)$$

- $\sigma_{2\to 3} + \sigma_{2\to 4} \equiv \sigma^{SV}(k_0) + \sigma^{hard}(k_0)$ has to be independent from the unphysical parameters λ and k_0
- the integral over $2 \to 3$ and $2 \to 4$ phase space is performed with a Monte Carlo generator

Initial state higher order effects

- Large collinear logs $\ln(s/m_e^2)$ associated with ISR
- for reliable predictions they need to be resummed
- we use the SF formalism avoiding double counting

G. Montagna, O. Nicrosini and F.P., Phys. Lett. **B385** (1996) 348

$$
\begin{aligned}
d\sigma &= d\sigma_{\mathrm{LL}} - d\sigma^{\alpha}_{\mathrm{LL}} + d\sigma^{\alpha}_{\mathrm{exact}} \\
d\sigma_{\mathrm{LL}} &= \int dx_1\, dx_2\, D(x_1, s)D(x_2, s)d\sigma_0(x_1 x_2 s) \\
d\sigma^{\alpha}_{\mathrm{LL}} &= \int dx_1\, dx_2\, [D(x_1, s)D(x_2, s)]_{\alpha} d\sigma_0(x_1 x_2 s)
\end{aligned}
$$

Results

- numerical results for $\sqrt{s} = M_Z$, 350 GeV and 1 TeV
- cuts & parameters:
  - ⋆ momenta clustered into jets according to the Durham algorithm, i.e. if $y_{ij} < y_{min}$, where

$$y_{ij} = 2\frac{\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{s}$$

  - ⋆ photon (in $2 \to 4$) recombined according to the same algorithm
  - ⋆ at least 3 “hadronic” jets requested
  - ⋆ $y_{min} = 0.001, \quad 30^\circ < \theta_{\rm jets} < 150^\circ, \quad M_{3\ \rm jets} > 0.75\sqrt{s}$
  - ⋆ $\alpha_s = 0.118, \quad \alpha_{em} = 1/128, \quad M_Z = 91.18$ GeV, $\quad M_W = 80.4$ GeV
- summed over final state quarks ($q\bar{q} = u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}, b\bar{b}$)
- the final state $b\bar{b}$ has been treated retaining the full m_t dependence

Technical checks

Only $\alpha_{\rm EM}$ contributions included

- independence of $\sigma_V + \sigma_S$ from the photon mass (λ)

λ^2 (GeV^2)	$5 \cdot 10^{-10}$	$5 \cdot 10^{-14}$
$\sigma_V + \sigma_S$ (pb)	-0.002492(5)	-0.002490(7)

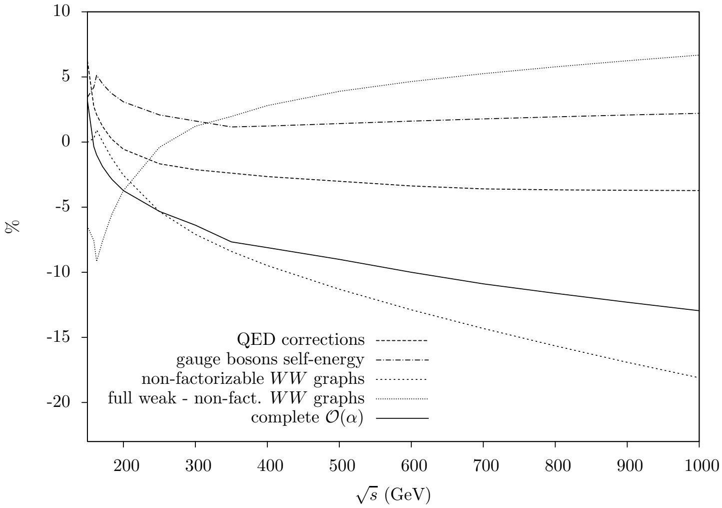
$\sqrt{s} = 300$ GeV, $k_0 = 0.15$ GeV,

- independence of $\sigma_{\rm real}$ from the soft-hard separator (k_0)

$2k_0/\sqrt{s}$	10^{-3}	10^{-5}
$\sigma_{\rm real}$ (pb)	1.8632(5)	1.8622(7)

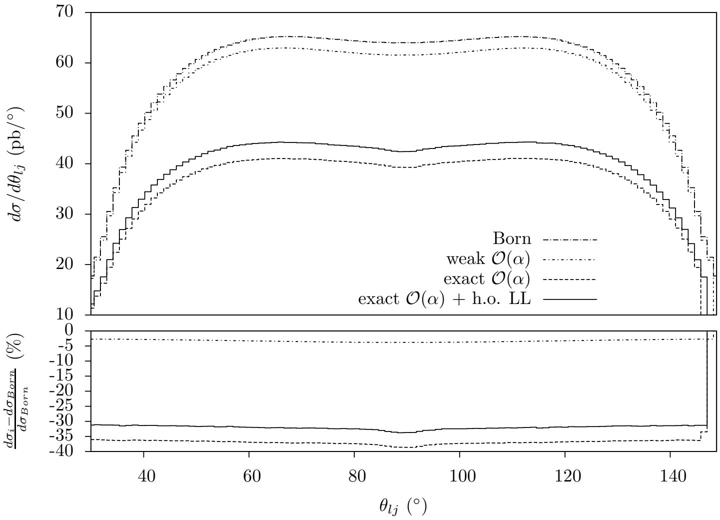
$\lambda^2 = 5 \cdot 10^{-10}$ GeV^2, $\sqrt{s} = 300$ GeV

Energy scan

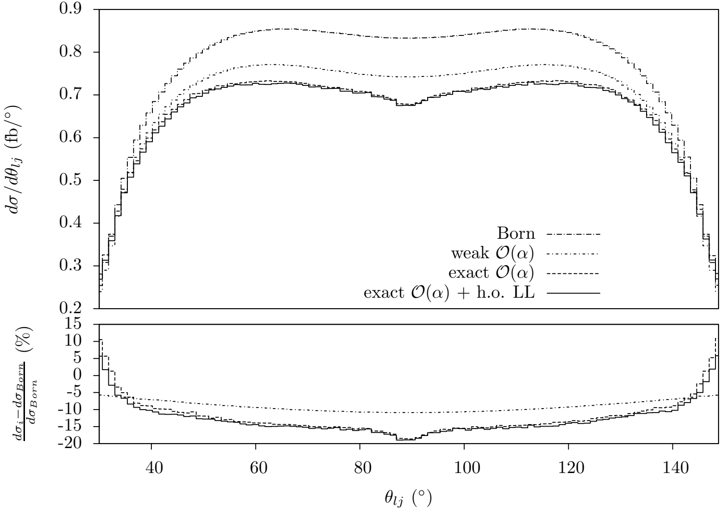


10
5
0
-5
-10
-15
-20
%
QED corrections
gauge bosons self-energy
non-factorizable WW graphs
full weak - non-fact. WW graphs
complete $\mathcal{O}(\alpha)$
200
300
400
500
600
700
800
900
1000
$\sqrt{s}$ (GeV)

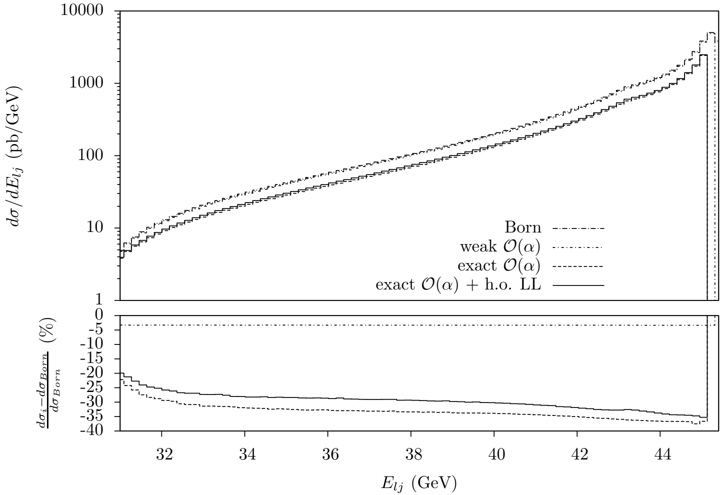
Leading jet angle at Z peak



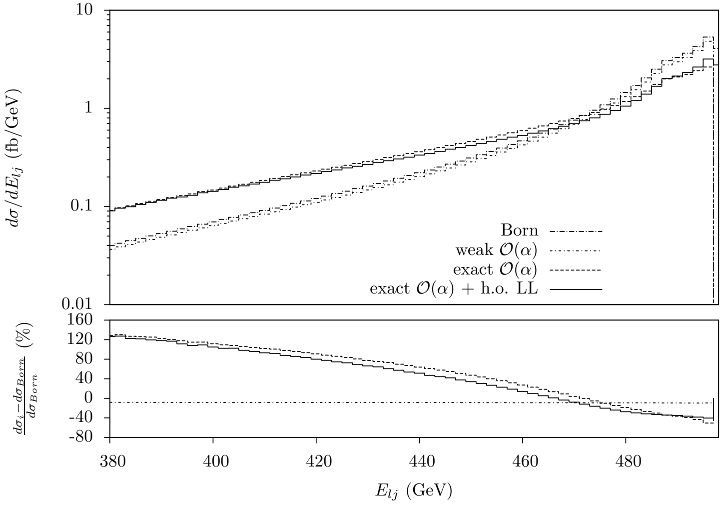
Leading jet angle at $\sqrt{s} = 1$ TeV



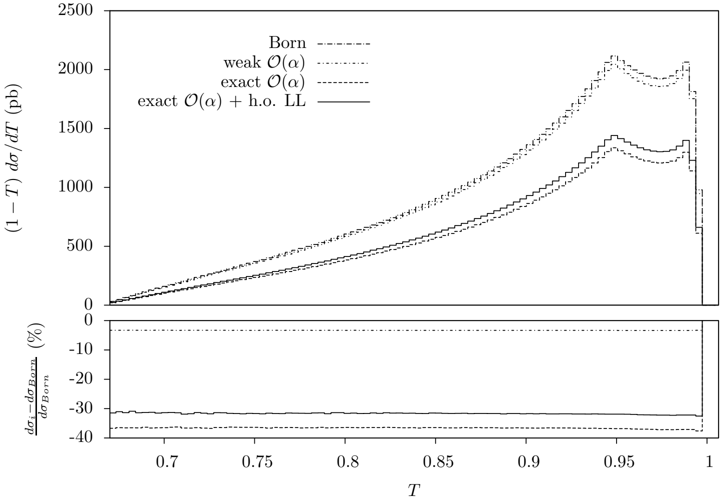
Leading jet energy at Z peak



Leading jet energy at $\sqrt{s} = 1$ TeV

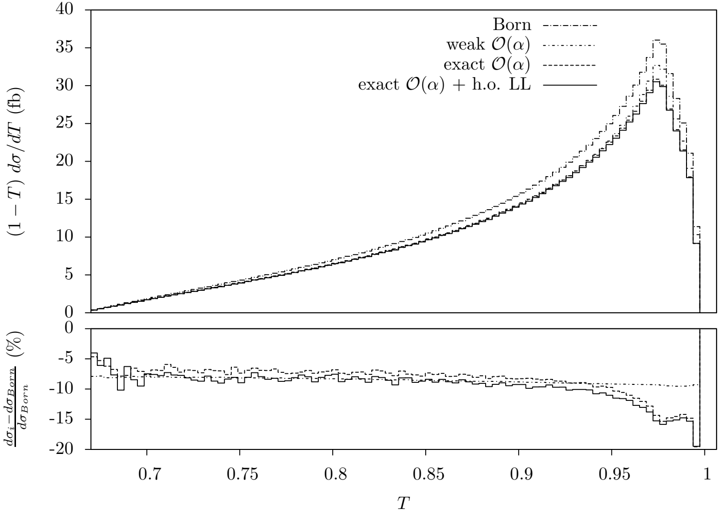


Thrust at Z peak

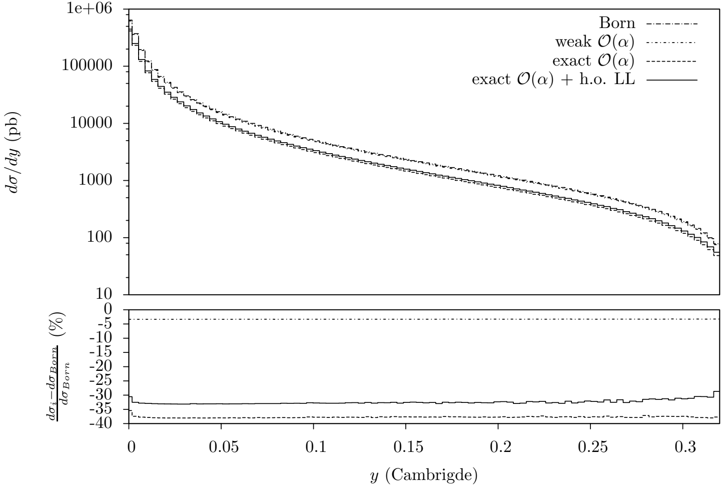


$$T = \max \frac{\sum_i |\vec{p}_i \cdot \vec{n}_T|}{\sum_i |\vec{p}_i|}$$

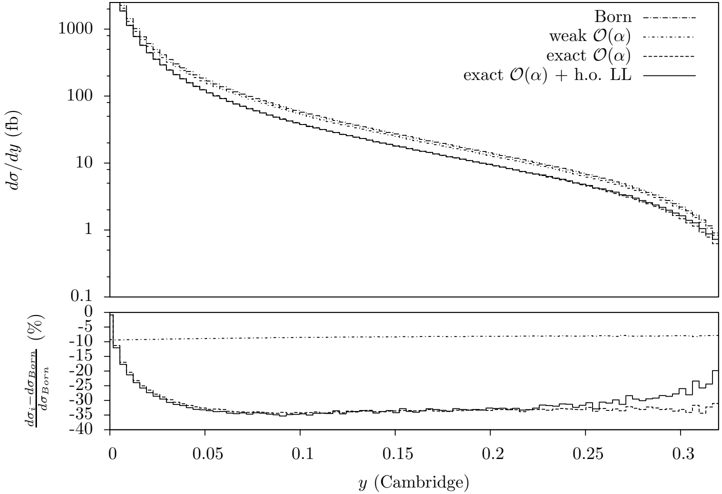
Thrust at $\sqrt{s} = 1$ TeV



y at Z peak


Born
weak $\mathcal{O}(\alpha)$
exact $\mathcal{O}(\alpha)$
exact $\mathcal{O}(\alpha)$ + h.o. LL
1e+06
100000
10000
1000
100
10
$d\sigma/dy$ (pb)
0
-5
-10
-15
-20
-25
-30
-35
-40
$\frac{d\sigma_i - d\sigma_{Born}}{d\sigma_{Born}}$ (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
y (Cambrigde)

y at $\sqrt{s} = 1$ TeV



Summary

- ⋆ the complete one-loop EW corrections to $e^+e^- \to 3$ jets have been calculated
  - each contribution calculated independently twice
  - good agreement between different implementations
  - the calculation is implemented in a Monte Carlo event generator
- ⋆ the effects of EW RC are important for future precision studies at ILC (e.g. α_s determination) and BSM searches
- ⋆ EW RC are expected to be even more relevant in presence of polarized beams, unlike QCD RC
- ⋆ work in progress:
  - study of the effects in presence of polarized beams
  - crossing the process to study EW RC to Z+jet at hadron colliders