Full 1-loop EW corrections to $e^+e^- \to$ 3 jets at linear colliders with flavour identification and event orientation

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Outline

- Motivations for
  - ILC: $e^+e^- \to 3$ jets
    - $e^+e^- \to \gamma/Z \to q\bar{q}g$
  - LHC: $pp \to Z/\gamma \to \ell^+\ell^- +$ jet (in short $Z+$ jet)
    - $q\bar{q} \to \ell^+\ell^- g$ + $qg \to \ell^+\ell^- q$ + $\bar{q}g \to \ell^+\ell^- \bar{q}$
- Existing literature
- The complete EW one-loop calculation
  - calculation details
  - implementation in a Monte Carlo event generator
- Results
  - unflavored sample
  - b-tagged sample
  - polarised initial state
- Conclusions

Motivations

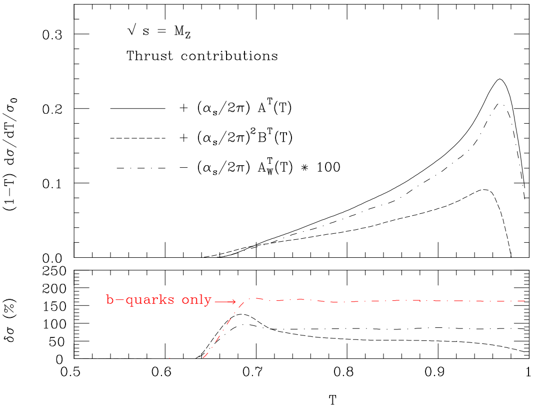
- at e^+e^- colliders ($e^+e^- \to \gamma^*/Z \to 3$ jets)
  - $e^+e^- \to 3$ jets was the "golden" process for QCD measurements and tests at LEP
  - precise measurement of α_s ($\mathcal{O}(1\%)$ at LEP/SLC, $\mathcal{O}(0.1\%)$ at GigaZ)
  - $\mathcal{O}(\alpha)$ EW RC roughly expected as large as NNLO QCD and, at high energies (Sudakov double-logs), as NLO QCD
  - EW effects can induce asymmetries in 3 jets observables
- 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 double-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 test the SM and disentangle it from BSM physics

Literature for $e^+e^- \to 3$ jets and Z+jet

- Restricting to EW corrections
  - ⋆ E. Maina, S. Moretti, D.A. 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) at M_Z
  - ⋆ E. Maina, S. Moretti, D.A. Ross, PLB 593 (2004), Erratum PLB 614 (2005)
    - weak corrections to $pp \to Z, \gamma+$ jet at high $p_T^{\gamma/Z}$. on-shell γ, Z
  - ⋆ Kuhn, Kulesza, Pozzorini, Schulze, 1. PLB 609 (2005) and 2. NPB 727 (2005) 368
    - 1. logarithmic weak corrections to $pp \to Z+$ jet (high $p_\perp^Z$) at one and two loop order with LL and NLL accuracy (Sudakov expansion)
    - 2. Exact one-loop corrections to $pp \to Z+$ jet
  - ⋆ Denner, Dittmaier, Gehrmann, Kurz, `arXiv:0906.0372 [hep-ph]`
    - 1-loop EW corrections to $e^+e^- \to 3$ jets
- QCD corrections to $e^+e^- \to 3$ jets are known up to NNLO order (work by Gehrmann-De Ridder, Gehrmann, Glover, Heinrich)

Weak factorizable RC at $\sqrt{s} = M_Z$

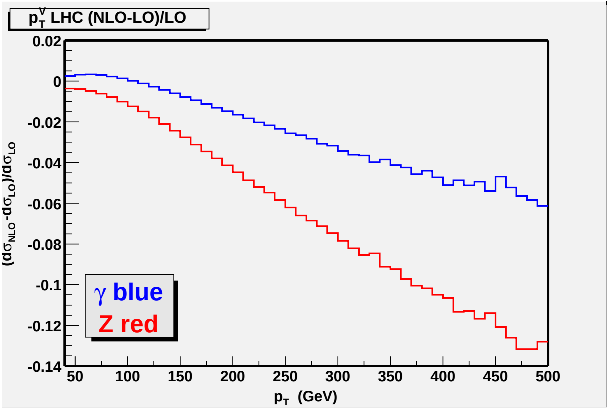
Maina et al., PLB



- weak corrections have a $\mathcal{O}(1\%)$ effect, which could be not negligible for α_s determination at GigaZ at the 0.1% level
- larger effect for the $b\bar{b}$ sub-sample (due to top in the loops)

Weak RC to γ/Z+jet

Maina et al., JHEP



- γ and Z are on-shell here
- large corrections ($\mathcal{O}(10\%)$) in the high boson $p_\perp$ tail, where SM is a background to new physics signatures

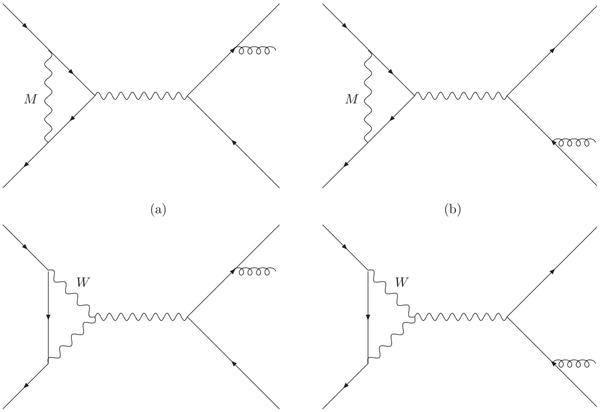
Complete 1-loop EW RC to $e^+e^- \to 3$ jets

- 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 are 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 (in principle) straighfordwardly obtained
- the precise control of SM effects is mandatory for precision tests of SM and new physics searches

Prototype diagrams

The 1-loop diagrams to be evaluated are:

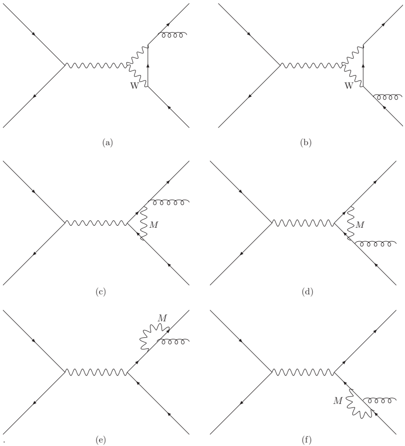
- e^+e^- vertices

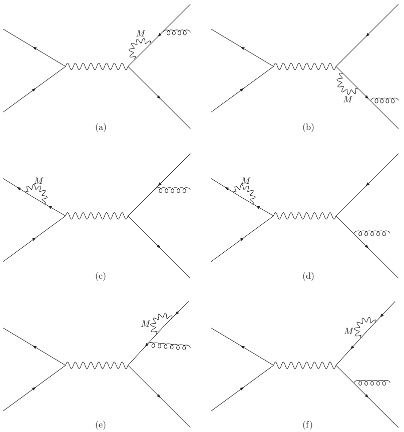


(a) (b) (c) (d)

Prototype diagrams

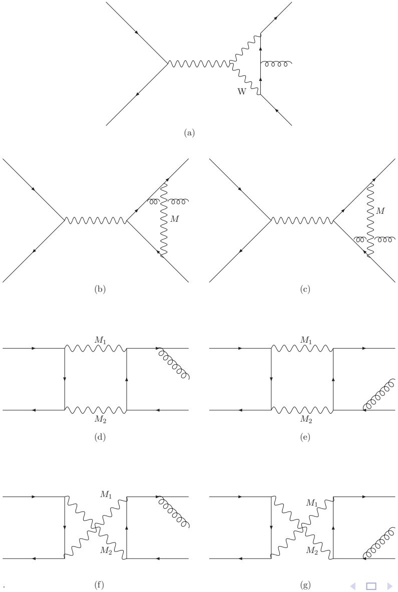
- $q\bar{q}$ and gluon vertices and fermion self-energies





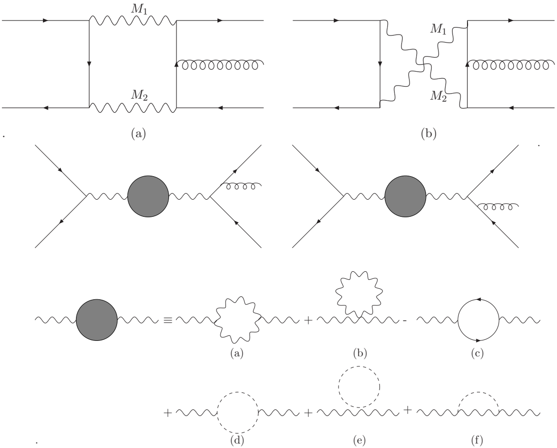
Prototype diagrams

- box diagrams (factorizable and not factorizable)



Prototype diagrams

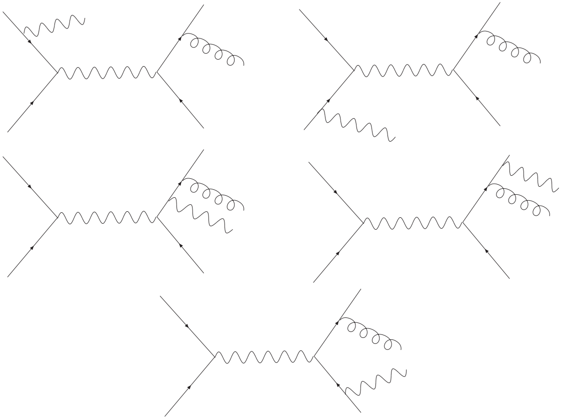
- pentagons and gauge-bosons self-energies



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 independent 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
  - ⋆ IR/collinear divergent scalar integrals calculated also in dimensional regularisation and cross-checked with mass regularisation up to high numerical accuracy

Real corrections



- 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 boson width

- 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 has to be retained in the virtual corrections (complex masses) (e.g., in order to ensure the cancellation of IR singularities between virtual and real corrections)
- in **`LoopTools`** only scalar functions up to 3-points are available with finite width
- we implemented a 4-point scalar function with complex masses, according to 't Hooft-Veltman (Nucl. Phys. **B** 153,1979) and to Denner-Beenakker (Nucl. Phys. **B** 338,1990) for IR configurations
- all the calculation can then be performed with complex Z (and W) mass

Cross section calculation

As usual, the cross section is split into two parts

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

$$\sigma_{2\to3} = \int d\Phi_3 \left(|\mathcal{M}_0|^2 + 2\Re[\mathcal{M}_0^* \mathcal{M}_\alpha^{virt}(\lambda)] \right)$$

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

$$\sigma_{2\to4} = \int_{\lambda<\omega} d\Phi_4 |\mathcal{M}_\alpha^{real}|^2 =$$

$$\int_{\lambda<\omega<k_0} d\Phi_4 |\mathcal{M}_\alpha^{real}|^2 + \int_{k_0<\omega} d\Phi_4 |\mathcal{M}_\alpha^{real}|^2 = \delta_s(\lambda, k_0)\sigma_0 + \sigma_{2\to4}^{hard}(k_0)$$

- $\sigma_{2\to3} + \sigma_{2\to4} \equiv \sigma^{SV}(k_0) + \sigma^{hard}(k_0)$ 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 QED effects

- Large collinear logs $\ln(s/m_e^2)$ associated with ISR
- for reliable predictions they need to be resummed, in order to take into account leading-log higher order QED corrections (α^n, $n \geq 2$)
- we use the SF formalism avoiding double counting

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

$$d\sigma_{\rm LL}^{\infty} = \int dx_1\, dx_2\, D(x_1,s)D(x_2,s)d\sigma_0(x_1x_2s)$$

$$d\sigma_{\rm LL}^{\alpha} = \int dx_1\, dx_2\, [D(x_1,s)D(x_2,s)]_{\alpha}d\sigma_0(x_1x_2s)$$

$$d\sigma_{{\rm exact}\ \mathcal{O}(\alpha)+h.o.} = d\sigma_{\rm LL}^{\infty} - d\sigma_{\rm LL}^{\alpha} + d\sigma_{\rm exact}^{\alpha}$$

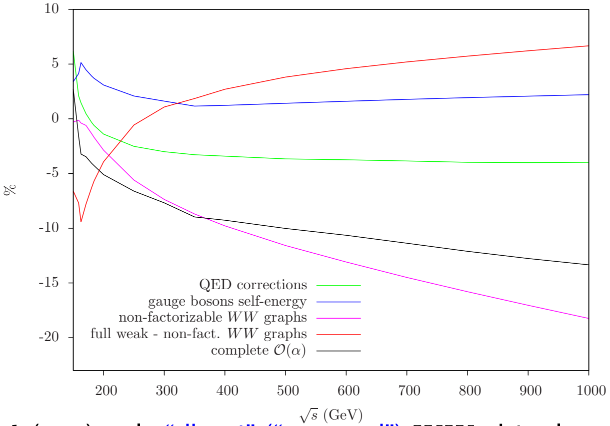
Results

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

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

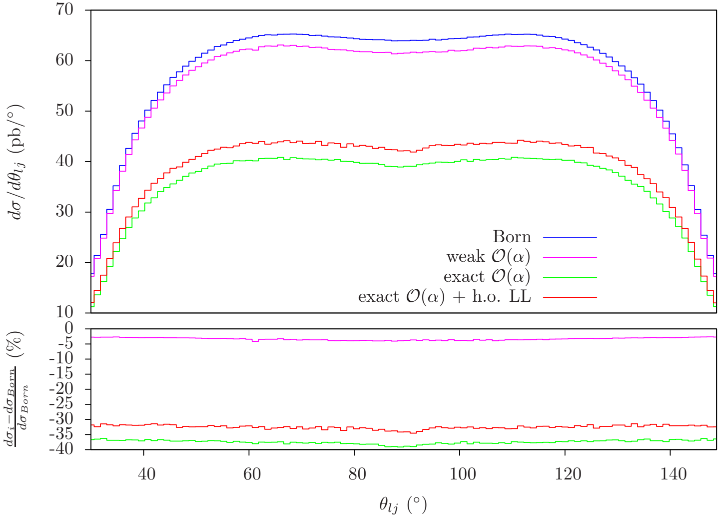
  - ⋆ photon (in $2 \to 4$) recombined according to the same algorithm
  - ⋆ at least 3 “hadronic” jets requested
  - ⋆ $y_{min} = 0.001, \quad 30^\circ < \theta_{\rm jets} < 150^\circ, \quad M_{3\ \rm jets} > 0.75\sqrt{s}$
  - ⋆ $\alpha_s = 0.118, \quad \alpha_{em} = 1/127.7, \quad M_Z = 91.18$ GeV, $\quad M_W = 80.4$ GeV
- for the inclusive case, summed over final state quarks ($q\bar{q} = u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}, b\bar{b}$) and over initial- and final-state helicities
- the final state $b\bar{b}$ has been treated retaining the full m_{top} dependence

Energy scan

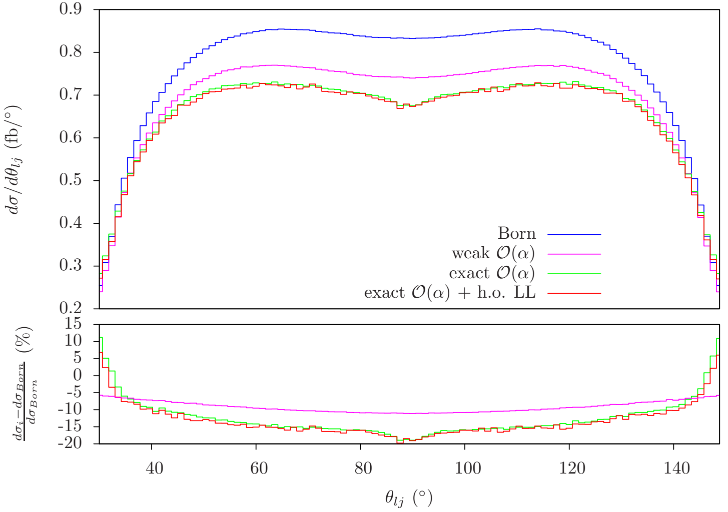


- for d, s, b (u, c) only "direct" ("crossed") WW virtual non-fact. diagrams survive (the ones giving negative correction)
- large negative corrections induced by lack of cancellation of WW direct and crossed diagrams, as it happens at LL level for ZZ diagrams

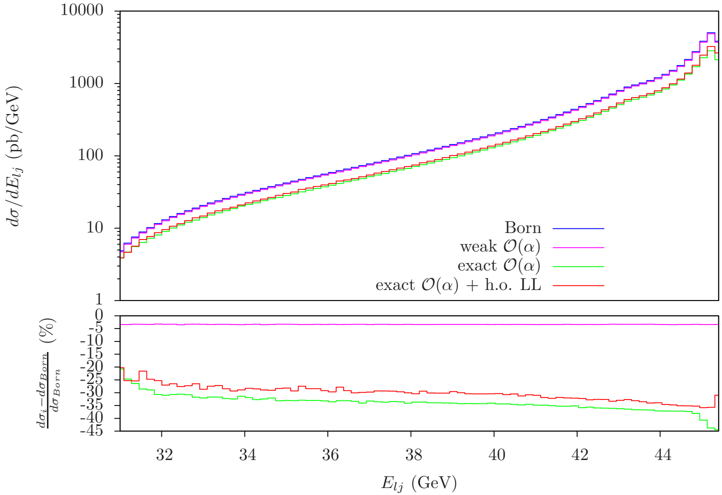
Leading jet angle at Z peak



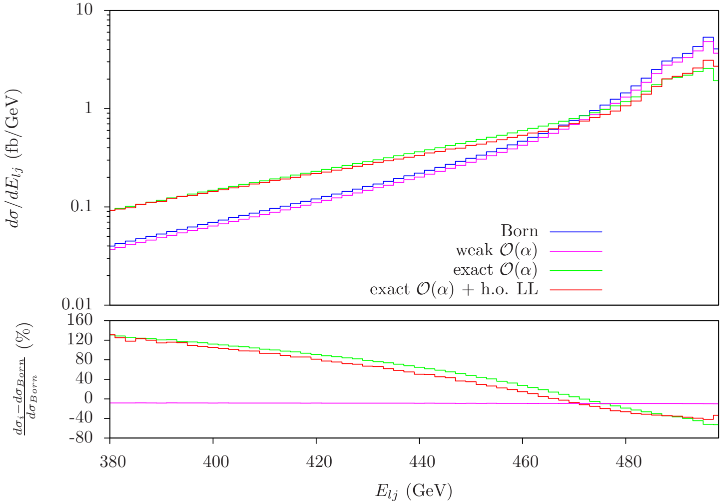
Leading jet angle at $\sqrt{s} = 1$ TeV



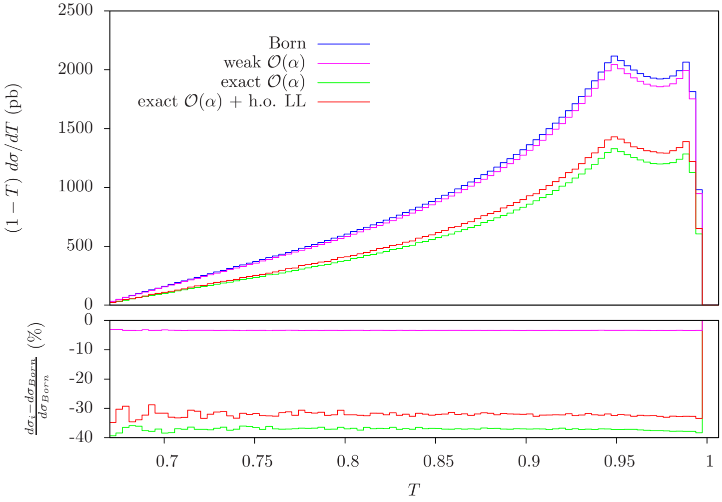
Leading jet energy at Z peak



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

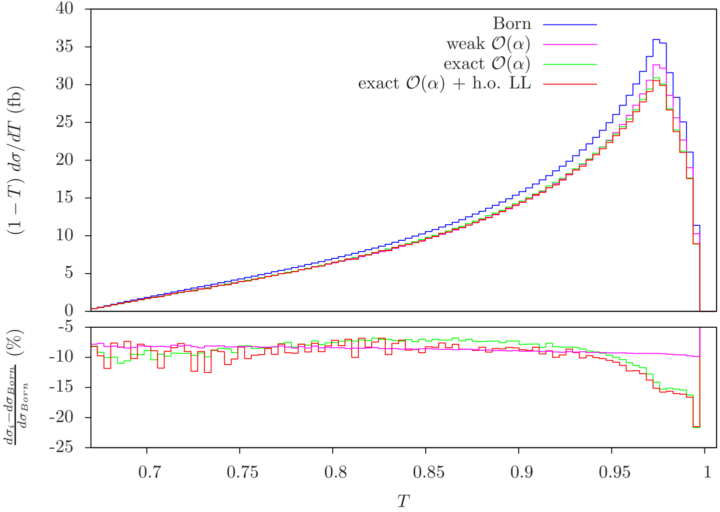


Thrust at Z peak

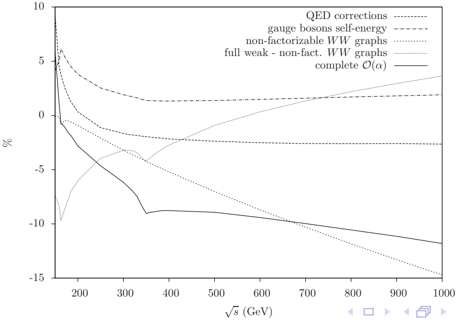


$$T = \max \frac{\sum_i |\vec{p}_i \cdot \vec{n}_T|}{\sum_i |\vec{p}_i|}$$

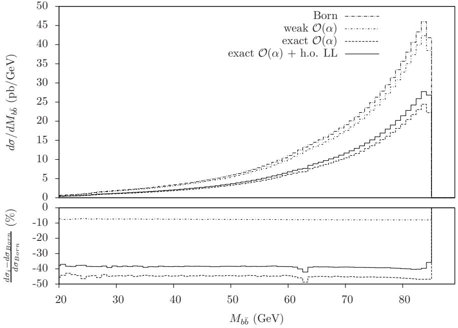
Thrust at $\sqrt{s} = 1$ TeV

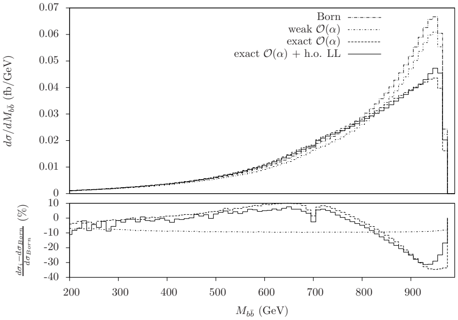


- thanks to b-flavour tagging techniques, quark and gluons can be distinguished, e.g. allowing for:
  1. verifying flavour independence of α_S
  2. studying the properties of the gluon
  3. measuring the b mass
- all of them can be studied in $e^+e^- \to b\bar{b}g$
  (for the sake of simplicity we assume 100% b-tag efficiency)
- Energy scan for $b\bar{b}$ sample

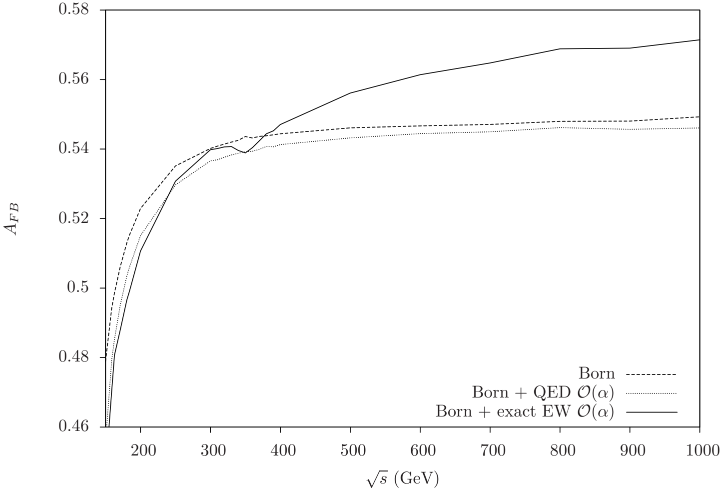


$b\bar{b}$ invariant mass at the Z peak and 1 TeV





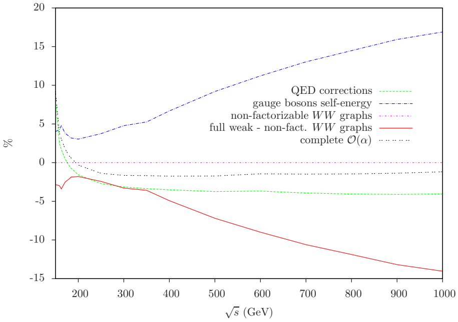
Forward-Backward asymmetry

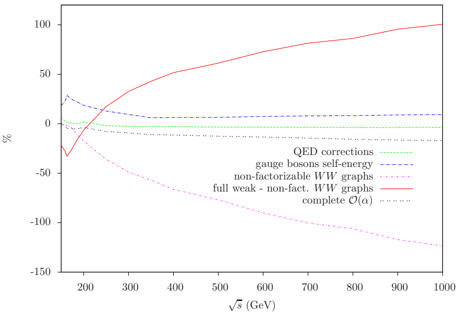


$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Polarised beams

- Polarisation is a search-ground for anomalous contribution to asymmetries
- EW corrections affect in a different way left- and right-polarised beams
- e.g. EW corrections for e^-_R and e^-_L (assuming 100% polarisation)



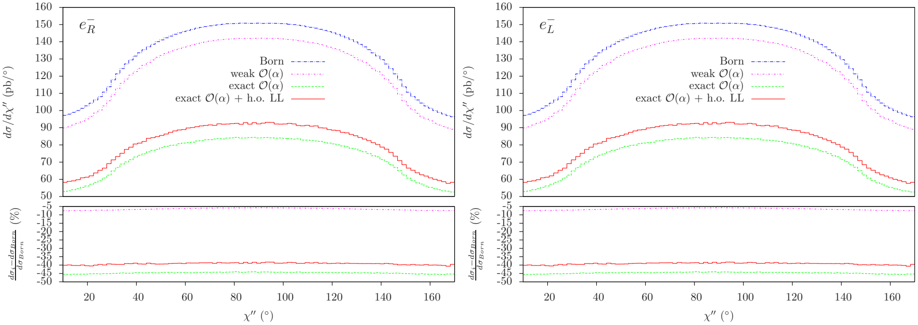


EW corrections on azimuthal angle

- Energy-ordered jets: $E_1 > E_2 > E_3$

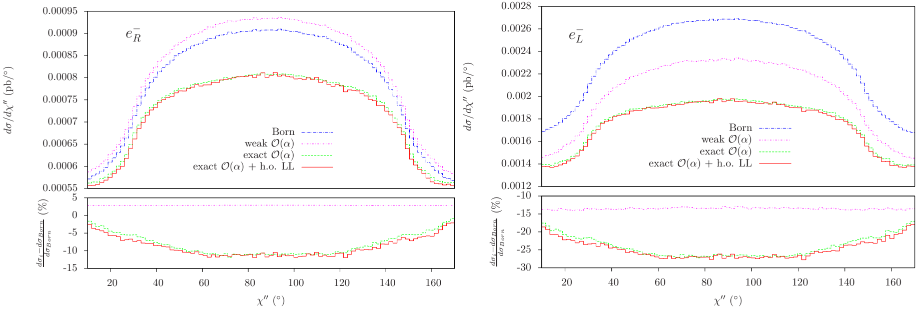
$$\cos\chi'' = \frac{\vec{1}\times\vec{3}}{|\vec{1}\times\vec{3}|}\cdot\frac{\vec{1}\times\vec{e^-}}{|\vec{1}\times\vec{e^-}|}$$

- at peak (70% polarization)



EW corrections on azimuthal angle

- at 1 TeV (100% polarization)



Conclusions

- ⋆ 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 effects of EW RC are important for future precision studies at ILC (e.g. α_s determination), test of SM and BSM searches
- ⋆ the phenomenology of EW RC is even richer in presence of polarised beams, unlike QCD RC
- ⋆ work in progress:
  - crossing the process to study EW RC to $Z+$jet at hadron colliders

Preliminary: $p_\perp^{jet}$ at LHC in Z+jet