NLO Event Generation for Chargino Production at the ILC

based on hep-ph/0607127, hep-ph/0610401

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RWTH Aachen

3rd Vienna Central European Seminar
on Particle Physics and Quantum Field Theory, 2006

1. Introduction and Motivation
   - Standard model and supersymmetric extension
   - Charginos and Neutralinos in the MSSM
   - Experimental accuracy and NLO results
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Supersymmetric extension of Standard Model

Supersymmetry (SUSY):
fundamental symmetry between bosons and fermions

Motivation for SUSY:

- natural extension to the SM
- radiative corrections to Higgs mass under control (finetuning in SM)
- inclusion of gravity possible
- add-ons: Dark Matter candidates, gauge+ mass unification at high scales,...
- more "aesthetic": only Poincaré extension, natural in many string theory models

Supersymmetry: minimal extension (MSSM)

MSSM: Only 1 supersymmetry
$\Rightarrow$ each SM particle obtains "superpartner" with spin 1/2 (bosons)/ spin 0 (fermions), otherwise same quantum numbers

- examples

$$e \leftrightarrow \tilde{e},\; u \leftrightarrow \tilde{u},\; W^i \leftrightarrow \widetilde{W}^i, \ldots$$

- 2 Higgs Doublets required $H_u = \binom{H_u^+}{H_u^0}$, $H_d = \binom{H_d^0}{H_d^-}$
  $\Rightarrow$ extended Higgs sector wrt the SM
- **BUT:**Superpartners not observed $\Rightarrow$ SUSY has to be broken
- introduces new (SUSY-breaking) parameters (MSSM: 105)
- # can be reduced by additional assumptions
- many breaking scenarios: (m)SUGRA, gauge mediation, ...

Chargino and Neutralino sector: Reconstruction of SUSY parameters

- Charginos $\tilde{\chi}_i^{\pm}$ and Neutralinos $\tilde{\chi}_i^0$:
  superpositions of gauge and Higgs boson superpartners
- Chargino/ Neutralino sector:
  SUSY parameters at electroweak scale

  $$\tan\beta,\ \mu\ \text{(Higgs sector)},\ M_1,\ M_2\text{(soft breaking terms)}$$

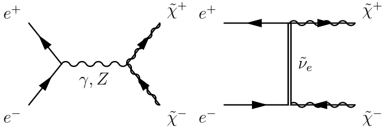
  can be reconstructed from

  $$\text{masses of } \tilde{\chi}_1^{\pm},\ \tilde{\chi}_2^{\pm},\ \tilde{\chi}_1^0,\ 2\ \sigma \text{ in the } \tilde{\chi}^{\pm} \text{ sector}$$

  (Choi ea 98, 00, 01)
- low-scale parameters + evolution to high scales (RGEs):
  $\Rightarrow$ hint at SUSY breaking mechanism (Blair ea, 02)
- requires high precision in ew-scale parameter determination

Chargino production at the ILC

- **ILC**: future e^+e^- collider, $\sqrt{s} = 500\,\mathrm{GeV}\,(1\,\mathrm{TeV})$
  "clean" environment, low backgrounds
  $\Rightarrow$ precision-machine, errors $\mathcal{O}(‰)$
- Charginos: (typically) light in the MSSM
  $\Rightarrow$ easily accessible at colliders (ILC/ LHC) $\Leftarrow$
- LO production at the ILC:



- decays: typically long decay chains

$$\text{e.g. } e^+ e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \tilde{\tau}_1^+ \tilde{\tau}_1^- \nu_\tau \bar{\nu_\tau} (\to \tau^+ \tau^- \nu_\tau \bar{\nu_\tau} \tilde{\chi}_1^0 \tilde{\chi}_1^0)$$

Experimental accuracy and theoretical next-to-leading-order (NLO) corrections

- experimental errors: obtained from simulation studies (LHC/ ILC study, Weiglein ea, 04)
- generate "experimental data" with known SUSY input parameters
- errors: combination of statistical and systematic errors

combined **LHC + ILC:** ‰

- **Theory**:
  Full NLO SUSY corrections for $\sigma(ee \to \widetilde{\chi}\widetilde{\chi})$ at ILC: in the % regime (Fritzsche ea 04, Öller ea 04, 05)

$\Rightarrow$ include complete NLO contributions in analyses $\Leftarrow$

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From σ_{tot} to Monte Carlo event generators

MC event generators: Generate event samples
(same form as experimental outcome)

- experiments: see final decay products
- need to compare with simulated event samples
- also: important irreducible background effects

(e.g. Hagiwara ea, 05)

$\Rightarrow$ include NLO results in Monte Carlo Generators $\Leftarrow$

- MC Generator WHIZARD (W. Kilian, LC-TOOL-2001-039):
- so far: LO Monte Carlo Event Generator for $2 \to n$ particle processes
- includes various physical models (SM, MSSM, non-commutative geometry, little Higgs models), initial state radiation, parton shower models,...

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NLO cross section contributions

σ_{tot} contributions and dependencies:

- σ_{born}
- virtual $\mathcal{O}(\alpha)$ corrections: $\sigma_{\text{virt}}(\lambda)$
- emission of soft/ hard collinear/ hard non-collinear photons:

  $\sigma_{\text{soft}}(\Delta E_\gamma, \lambda) + \sigma_{\text{hc}}(\Delta E_\gamma,\, \Delta\theta_\gamma) + \sigma_{2\to 3}(\Delta E_\gamma, \Delta\theta_\gamma)$
- higher order initial state radiation: $\sigma_{\text{ISR}} - \sigma_{\text{ISR}}^{\mathcal{O}(\alpha)}(Q)$

  λ: photon mass , ΔE_γ: soft cut , $\Delta\theta_\gamma$: collinear angle

Including FormCalc $\mathcal{O}(\alpha)$ results in WHIZARD (1)

- inclusion in WHIZARD : split photon phase space for real photon into soft/ hard-collinear/ hard non-collinear region:

$$\sigma_{\text{Born}+\gamma} = \sigma_{\text{soft}} + \sigma_{\text{hard, coll}} + \sigma_{\text{hard,noncoll}}$$

- soft photons ($E_\gamma \leq \Delta E_\gamma$): use soft photon approximation, add to virtual contribution ($\Rightarrow$ cancellation of IR divergencies): $\Rightarrow$ integrate over effective matrix element in Γ_2:

$$\sigma_{\text{Born}} + \sigma_{\text{virt}}(\lambda) + \sigma_{\text{soft}}(\Delta E_\gamma, \lambda) = \int d\Gamma_2 \, |\mathcal{M}_{\text{eff}}|^2(\Delta E_\gamma)$$

$$|\mathcal{M}_{\text{eff}}|^2(\Delta E_\gamma) = (1 + f_s(\Delta E_\gamma, \lambda)) \, |\mathcal{M}_{\text{born}}|^2 + 2 \, Re(\mathcal{M}_{\text{born}} \, \mathcal{M}^*_{\text{virt}}(\lambda))$$

ΔE_γ: soft photon cut, λ: photon mass

- in practice: create library from FormCalc code, link this to WHIZARD

Including FormCalc $\mathcal{O}(\alpha)$ results in WHIZARD (2)

- hard collinear photons: $E_\gamma > \Delta E_\gamma,\ \theta_\gamma \leq \Delta\theta_\gamma$
  use hard collinear approximation (Dittmaier ea, 1993):

$$\sigma_{\text{hard, coll}} = \int_{\text{hard, coll}} d\Gamma_3 |\mathcal{M}_{2\to 3}|^2$$
$$\longrightarrow \int d\Gamma_2 \int_0^{x_0} dx_i\, f_\pm(x_i)\, |\mathcal{M}^{(\pm)}_{\text{Born}}|^2(x_i, s),$$

  x_i: energy fraction of incoming fermion after photon radiation
  integrate in Γ_2
- hard, non-collinear photons: calculated exactly using $\mathcal{M}_{(2\to 3)}$
  generated by separate WHIZARD run using Γ_3

Fixed order method: Result and Drawback

- corresponds to analytic results (Fritzsche ea/ Öller ea)

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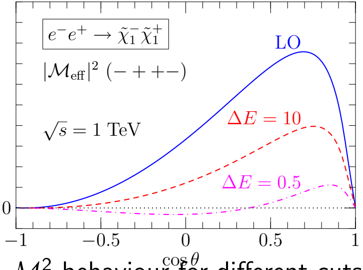
- Drawback: $|\mathcal{M}_{\text{eff}}|^2 < 0$ for small values of $\frac{\Delta E_\gamma}{\sqrt{s}}$
- well-known problem at LEP
- ad hoc solution: set $|\mathcal{M}_{\text{eff}}|^2 = 0$ for these cases
- too low energy cuts: $\mathcal{O}(\alpha)$ not sufficient, leads to "wrong" σ_{tot}



$\mathcal{M}^2$ behaviour for different cuts

θ: angle between e^- and $\tilde{\chi}^-$

remark: **event generator specific problem** ($\sigma_{\text{tot}} \geq 0$)

Resumming leading logs to all orders

solution to fixed order drawback:
$\Rightarrow$ resumm respective contributions to all orders $\Leftarrow$

- in practice: subtract $\mathcal{O}(\alpha)$ soft + virtual collinear contributions in $\mathcal{M}_{\text{eff}}$:

$$
\begin{aligned}
|\widetilde{\mathcal{M}}_{\text{eff}}|^2 &= (1 + f_s(\Delta E_\gamma))\,|\mathcal{M}_{\text{born}}|^2 + 2\,Re(\mathcal{M}_{\text{born}}\,\mathcal{M}^*_{\text{virt}}) \\
&- 2\,f_s^{ISR,\mathcal{O}(\alpha)}(\Delta E_\gamma)\,|\mathcal{M}_{\text{born}}|^2
\end{aligned}
$$

- add the resummed contribution by folding with ISR structure function:

$$
\int d\Gamma \int_0^1 dx_1 \int_0^1 dx_2\, f^{\text{ISR}}(x_1)\, f^{\text{ISR}}(x_2)\, |\widetilde{\mathcal{M}}_{\text{eff}}|^2(s, x_i)
$$

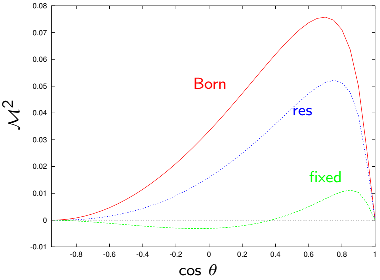
- $f^{\text{ISR}}(x)$: Initial state radiation (Jadach, Skrzypek, Z.Phys. 1991), describes collinear (real + virtual) photons in leading log accuracy
- $f_s^{\text{ISR},\mathcal{O}(\alpha)}$: soft integrated $\mathcal{O}(\alpha)$ contribution

Resumming: What do we get ??

- $\mathcal{O}(\alpha)$: equivalent to fixed order method

$\Rightarrow$ got rid of $|\mathcal{M}|^2 < 0$ effects !!

no negative weights



(-++-),

$\Delta E_\gamma = 0.5$ GeV

- higher orders:
  higher order ISR for $|\mathcal{M}_{\text{born}}|^2$ as well as Re $(\mathcal{M}_{\text{born}}\,\mathcal{M}^*_{\text{virt}})$!!!

  $\Rightarrow$ new higher order effects $\Leftarrow$

  additional possibility: also fold hard noncollinear process with ISR

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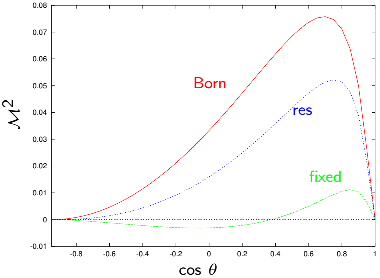

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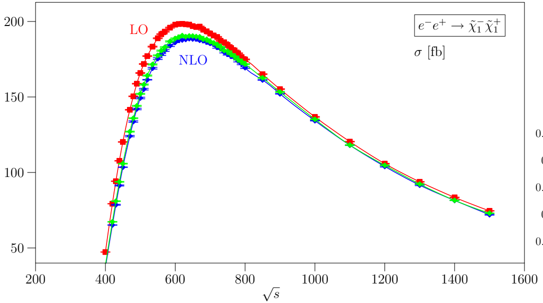
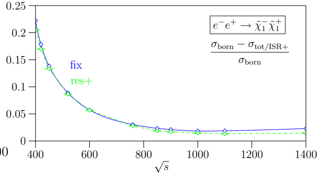
Results: cross sections



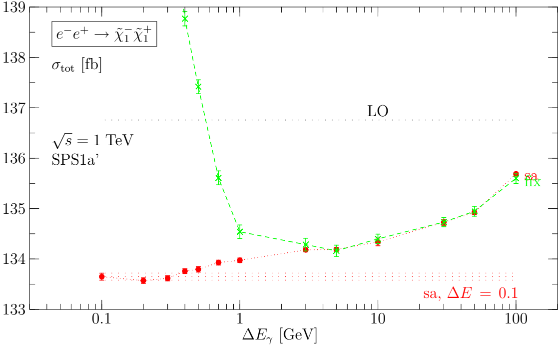
$\sigma(\sqrt{s})$



relative corrections

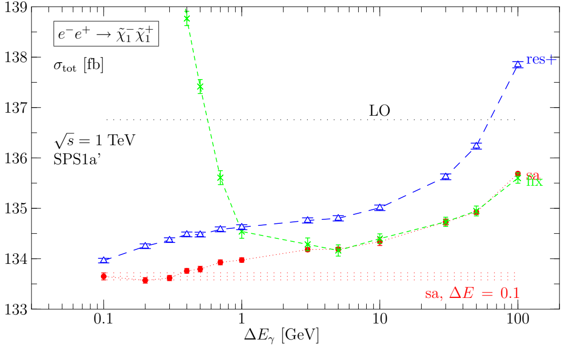
agrees with results in the literature (Fritzsche ea, Öller ea)

A closer look: ΔE_γ dependence of σ_{tot}



- semianalytic (FormCalc): tests soft approximation, shifts : 2 - 5 ‰ ($\Delta E_\gamma \leq 10\,\mathrm{GeV}$)
- fixed order result (WHIZARD): same as 'sa' for $\Delta E_\gamma \geq 3\,\mathrm{GeV}$, smaller values: $|\mathcal{M}_{\text{eff}}|^2 \leq 0$ effects

ΔE_γ dependence: resummation



$\sigma_{\text{tot}}(\Delta E_\gamma)$:

resummation includes higher order effects

5‰ difference to 'sa'

for $\Delta E_\gamma \leq 10\,\text{GeV}$

In summary:

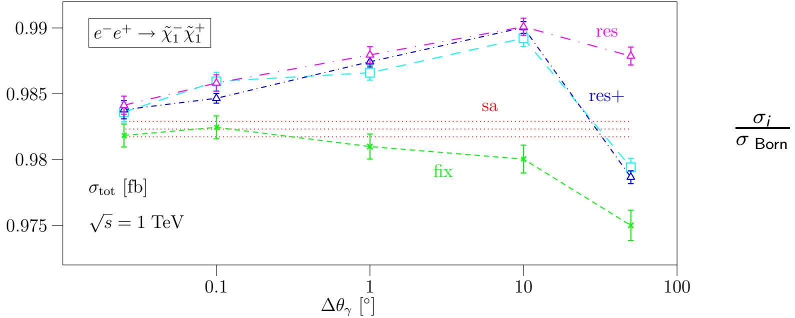
shift in ΔE_γ leads to ‰ effects, match ILC accuracy

$\Rightarrow$ careful choice of ΔE_γ, method important

"best" choice: fully resummed version with low energy cut

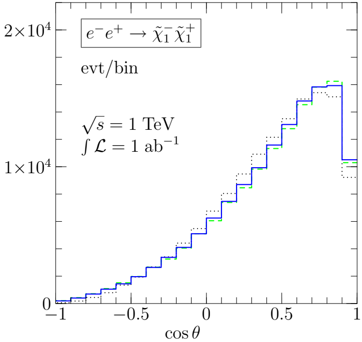
cut dependencies: $\Delta\theta_\gamma$

tests: collinear photon approximation

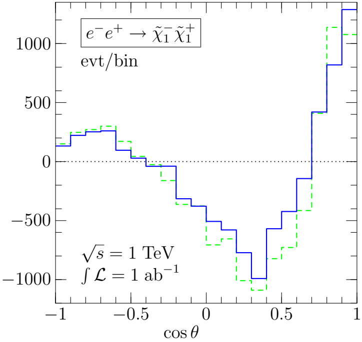


$\sigma_{\rm tot}$ again larger for resummation method
for higher angles: second order ISR effects between 0.05^o and 0.1^o $(\mathcal{O}(‰))$

simulation results: angular distributions



N_{tot}

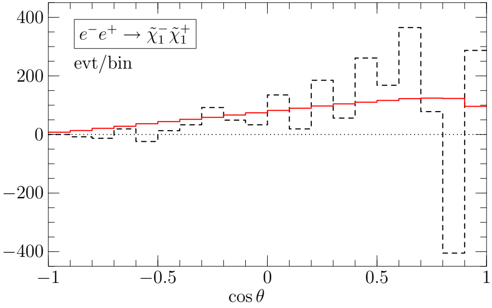


$N_i - N_{\text{Born}}$

Born, fixed order, resummation

!! more than 1 σ deviation !! $\sqrt{n_{\max}} \approx \mathcal{O}(10^2)$; nbins = 20

Angular distributions: higher orders



$N_{\mathrm{res},+} - N_{\mathrm{ex}}$
red: 1 standard dev from Born result

also higher order contributions statistically significant

Summary and Outlook

- Chargino/ neutralino sector of MSSM: high precision in SUSY paramater analysis at EW scale (‰ at ILC)
- same size/ larger NLO corrections

$\Rightarrow$ include NLO results in Monte Carlo Event generators

- resummation method for photons allows lower soft cuts/ inclusion of higher order contributions
- NLO as well as higher order contributions significant !!
- next steps: include NLO corrections to $\tilde{\chi}$ decays, non-factorizing contributions (start with photonic corrections in the double-pole approximation)
- general interface to FormCalc generated matrix elements: extendable to other processes...

Summary and Outlook

THANKS TO

Wolfgang Hollik, Thomas Fritzsche, Thomas Hahn at MPI in Munich for their advice/ code/ help

☺Thanks for listening ☺

Superpotential and breaking parts

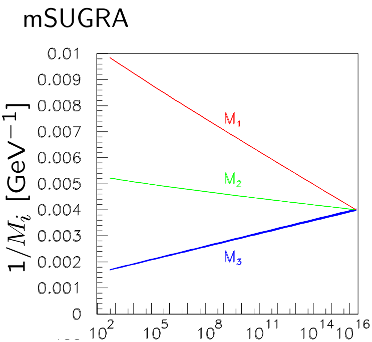
- Superpotential in MSSM

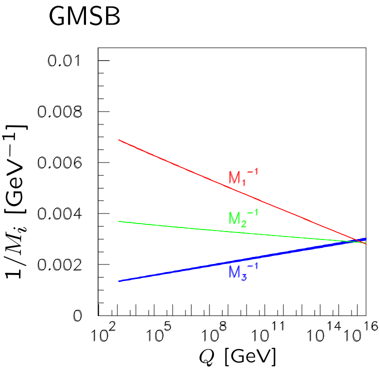
$$W = \bar{u} y_u Q H_u - \bar{d} y_d Q H_d - \bar{e} y_e L H_d + \mu H_u H_d$$

- soft SUSY breaking terms, gauge sector

$$\frac{1}{2}(M_1 \widetilde{B}\widetilde{B} + M_2 \widetilde{W}^a \widetilde{W}^a + M_3 \tilde{g}\tilde{g}) + h.c.$$

Mass unification in mSUGRA and GMSB



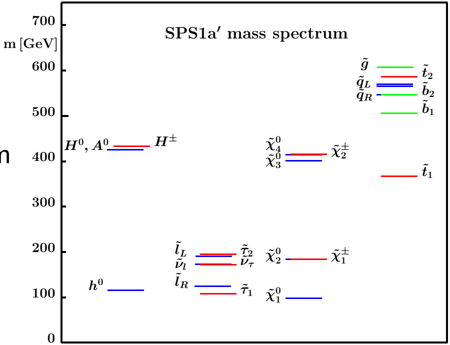


Blair ea, 02

Point SPS1a'

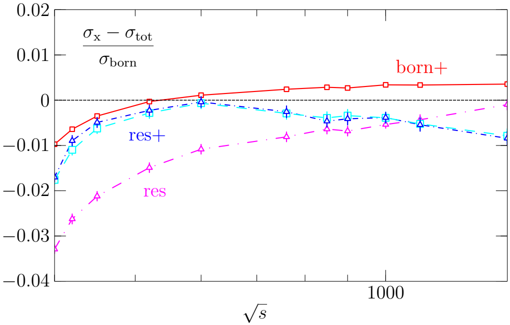
- mSUGRA scenario
- according to Snowmass Points (Allanach ea, 02), in agreement with cosmology data/ WMAP ($\tilde{\chi}_1^0$ as DM candidate)

spectrum $\Longrightarrow$



light sleptons
heavy squarks
some light $\tilde{\chi}$s
all masses < 1 TeV

$\sqrt{s}$ dependence of different higher order contributions

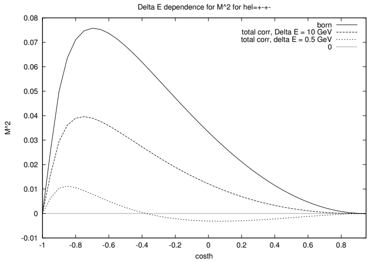


Born+: only Born folded w ISR, resummation , fully resummed result

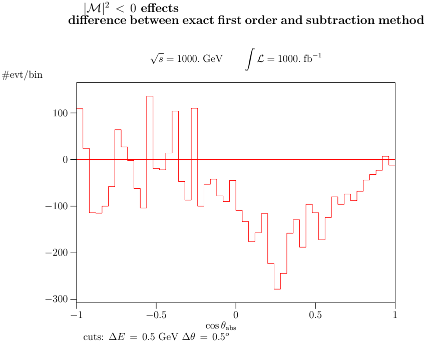
difference between Born+ and fully resummed result: multiple photon emission from interaction term

Angular distribution: Do we see $|\mathcal{M}|^2 < 0$ effects ?? ($\checkmark$)

Reminder:
$|\mathcal{M}_{eff}|^2$ behaviour
$(\Delta E_{low} = 0.5 \text{ GeV})$:



angular distribution:



η, f_s, hard collinear approximation, $ISR^{\mathcal{O}(\alpha)}$

- $\eta = \frac{2\alpha}{\pi}\left(\log\left(\frac{Q^2}{m_e^2}\right) - 1\right)$ (Q = scale of process)
- $$f_s = -\frac{\alpha}{2\pi} \sum_{i,j=e^\pm} \int_{|\mathbf{k}| \leq \mathbf{\Delta E}} \frac{d^3k}{2\omega_k} \frac{(\pm)\, p_i\, p_j\, Q_i\, Q_j}{p_i\, k\, p_j\, k},$$

  (Denner 1992)

  $\omega_k = \sqrt{\mathbf{k^2} + \lambda^2}$, p_i initial/ final state momenta, k: γ momentum
- hard collinear factor ($\pm$ helicity conserving/ flipping):

  $$f^+(x) = \frac{\alpha}{2\,\pi} \frac{1+x^2}{(1-x)} \left(\ln\left(\frac{s\,(\Delta\theta)^2}{4\,m^2}\right) - 1\right), f^-(x) = \frac{\alpha}{2\,\pi} x.$$

  (Dittmaier 1993)
- $$f_s^{ISR,\mathcal{O}(\alpha)} = \left[\int_{x_0}^{1} f_{ISR}(x)\, dx\right]_{\mathcal{O}(\alpha)} = \frac{\eta}{4}\left(2\ln(1-x_0) + x_0 + \frac{1}{2}x_0^2\right)$$

ISR in its full beauty (Skrzypek ea, 91)

$$\Gamma_{ee}^{LL}(x, Q^2) = \frac{\exp(-\frac{1}{2}\eta\gamma_E + \frac{3}{8}\eta)}{\Gamma(1+\frac{\eta}{2})} \frac{\eta}{2} (1-x)^{(\frac{\eta}{2}-1)}$$

$$- \frac{\eta}{4}(1+x) + \frac{\eta^2}{16}\left(-2(1-x)\log(1-x) - \frac{2\log x}{1-x} + \frac{3}{2}(1+x)\log x - \frac{x}{2}\right.$$

$$\left. - \frac{5}{2}\right) + \left(\frac{\eta}{2}\right)^3 \left[-\frac{1}{2}(1+x)\left(\frac{9}{32} - \frac{\pi^2}{12} + \frac{3}{4}\log(1-x) + \frac{1}{2}\log^2(1-x)\right.\right.$$

$$\left. - \frac{1}{4}\log x\log(1-x) + \frac{1}{16}\log^2 x - \frac{1}{4}\mathrm{Li}_2(1-x)\right)$$

$$+ \frac{1}{2}\frac{1+x^2}{1-x}\left(-\frac{3}{8}\log x + \frac{1}{12}\log^2 x - \frac{1}{2}\log x\log(1-x)\right)$$

$$\left. - \frac{1}{4}(1-x)\left(\log(10x) + \frac{1}{4}\right) + \frac{1}{32}(5-3x)\log x\right] \; ; \; \eta = \frac{2\,\alpha}{\pi}\left(\log\left(\frac{Q^2}{m_e^2}\right) - 1\right)$$