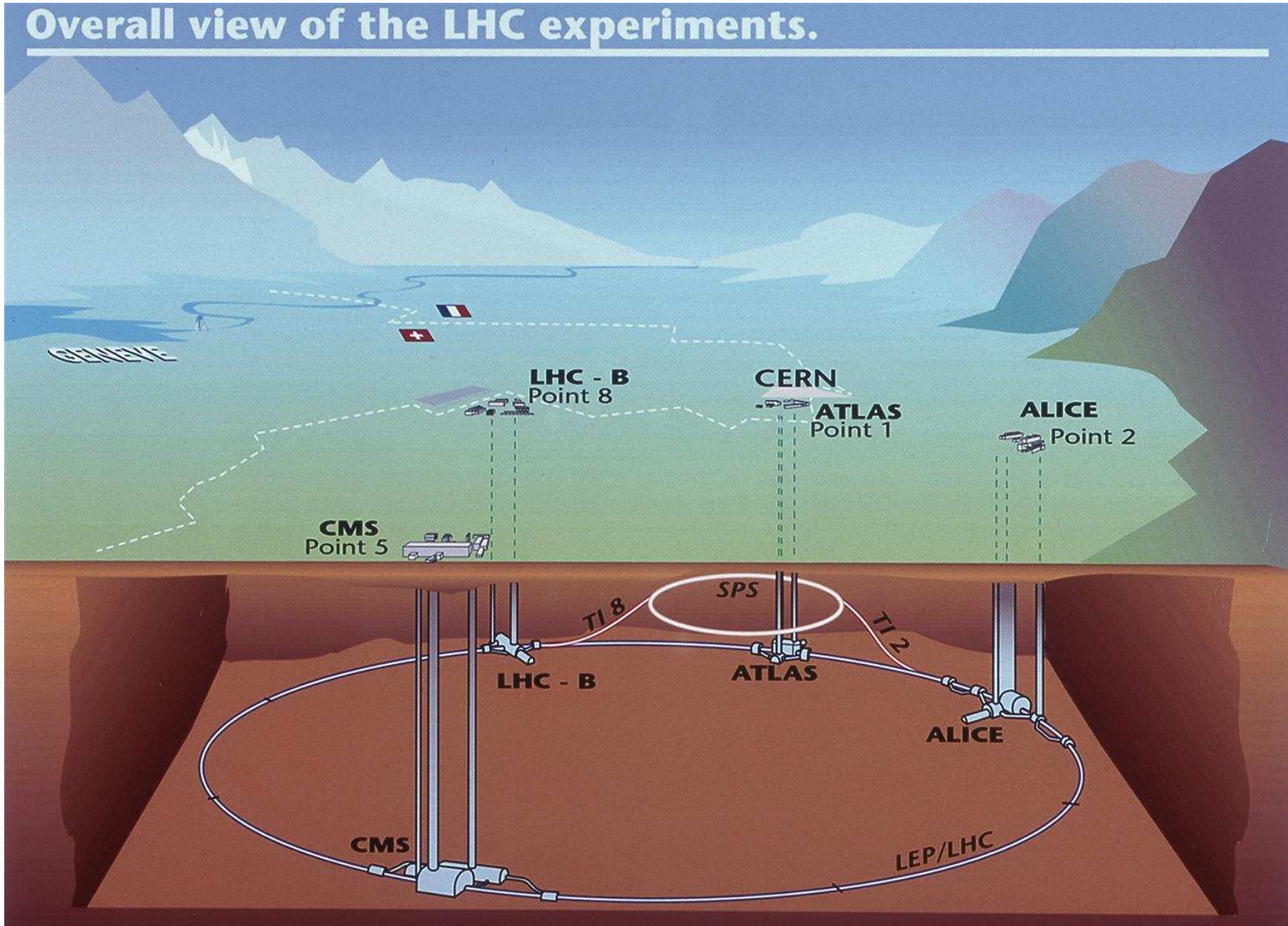


Universität Karlsruhe, Kolloquium über Teilchenphysik  
January 18, 2008

# **Sudakov Logarithms and Four-Fermion Scattering at the LHC**

**Bernd Jantzen**

*Paul Scherrer Institut (PSI), CH-Villigen*



# Overview

## I Drell–Yan processes at the LHC

- precision physics with Drell–Yan processes
- physics motivations
- status of loop calculations & tools for neutral-current processes
- Les Houches 2005/2007 & TeV4LHC

## II Electroweak Sudakov logarithms

- large logarithms in electroweak corrections
- one- & two-loop effects
- existing Sudakov results at two loops

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- factorization into QED contributions, form factor & reduced amplitude
- SU(2) form factor: calculation & results
- electroweak results

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- partonic cross sections
- hadronic distributions

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# I Drell–Yan processes at the LHC

## Precision collider physics

Precision measurements and electroweak (EW) + QCD corrections for observables at LEP, SLC and Tevatron enabled us to

- probe Standard Model (SM) of EW & strong interactions as a quantum field theory,
- test SM consistency by comparing direct with indirect measurements of model parameters ( $m_t, M_W, \sin^2 \theta_{\text{eff}}, \dots$ ),
- constrain SM Higgs boson mass,
- search for small deviations from SM predictions  $\Rightarrow$  indirect signals of new physics
- exclude or constrain new physics models.

$\Rightarrow$  Continue precision physics at LHC (and ILC):

- possibly discover Higgs and/or new physics particles
- measure new particles' masses, couplings, spin
- test consistency, search for deviations, constrain model parameters, ...

## Theoretical input needed for precision physics

- precise **predictions** for **signal** and **background** processes (SM and beyond)
- include all relevant **higher-order corrections**
- partonic and hadronic processes → **PDF's**, **fragmentation**
- estimate of **theoretical uncertainties**
- total **cross sections** and kinematic **distributions** with experimental/realistic cuts
- implementation in **event generators**

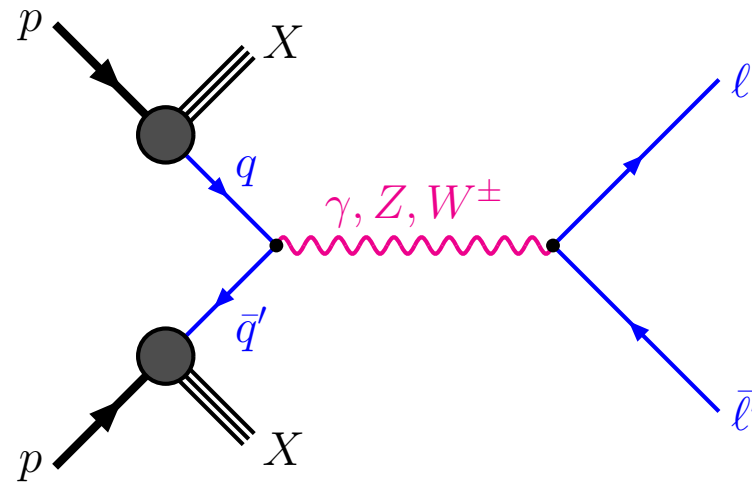
## Drell–Yan (DY) processes

↪ production of a **lepton–antilepton pair** with high invariant mass  $M_{\ell\ell}$  (or high  $p_T^\ell$ 's)

in a **hadron–hadron collision**:  $H_1 H_2 \rightarrow \ell \bar{\ell}' + X$  ( $H_{1,2} = p, \bar{p}$ )

Drell, Yan '70, '71

LHC ( $H_1 = H_2 = p$ ):



## Partonic reaction

- **neutral-current DY**:  $q \bar{q} \rightarrow \gamma/Z \rightarrow \ell^+ \ell^-$
- **charged-current DY**:  $q \bar{q}' \rightarrow W^\pm \rightarrow \ell^\pm \nu/\bar{\nu}$

## Factorization

$$\sigma_{\text{tot}} = \sum_{i,j} \int_0^1 dx_1 dx_2 f_i^{H_1}(x_1, \mu^2) f_j^{H_2}(x_2, \mu^2) \int d\sigma(q_i(x_1 p_1) + \bar{q}_j(x_2 p_2) \rightarrow \ell + \bar{\ell}', \mu^2)$$

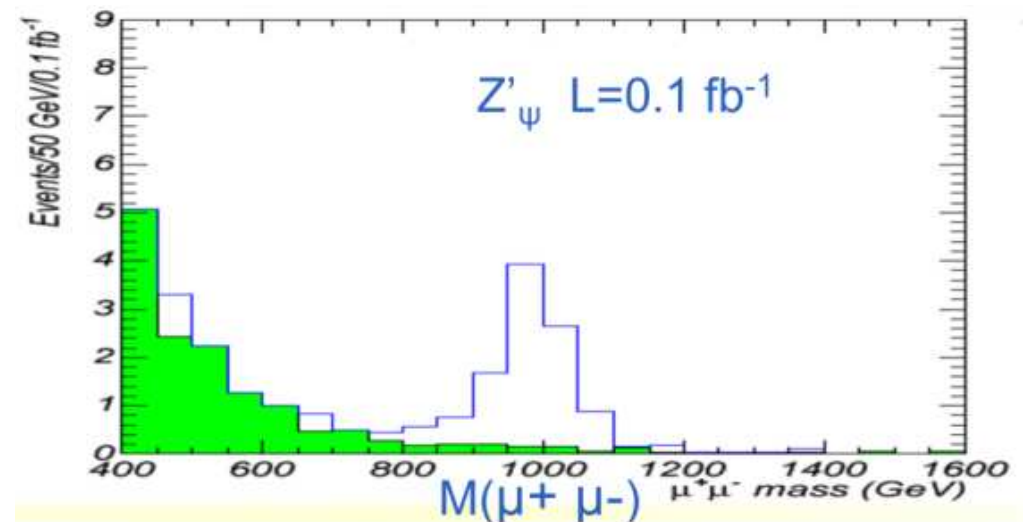


## Physics motivations

Why consider Drell–Yan at LHC?

- **easy detection**: high- $p_T$  lepton pair or lepton + missing  $p_T$   
(typically  $p_T > 20$  GeV in central detector region)
- **large cross sections**:  $\sigma(pp \rightarrow e^-e^+, \mu^-\mu^+) \sim 1.8$  nb,  $\sigma(pp \rightarrow e\nu_e, \mu\nu_\mu) \sim 17$  nb  
 $\hookrightarrow \mathcal{O}(10^8, 10^9)$  events for  $\mathcal{L} = 100$  fb $^{-1}$
- **detector calibration** and **luminosity monitoring** ( $\sim$  Bhabha at LEP)
- validating and constraining **PDF's**
- precision measurement of  $M_{W,Z}$  and  $\Gamma_{W,Z}$  at the  $W, Z$  peak
- background to **new physics searches** at high  $M_{\ell\ell} \implies$

$\hookrightarrow$  **need precise theoretical prediction for high-energy tail**





## Status of loop calculations & tools for neutral-current processes

### QCD

- total cross sections up to  $\mathcal{O}(\alpha_s^2)$  and resummation (RESBOS)  
Altarelli et al. '84; Hamberg et al. '91; van Neerven et al. '92; Giele et al. '93; Balazs et al. '97
- fully differential distributions up to  $\mathcal{O}(\alpha_s^2)$  (MCFM, FEWZ)  
Campbell et al. '02; Anastasiou et al. '04; Dixon et al. '03; Melnikov et al. '06
- merged/matched with parton shower (HERWIG, MC@NLO, ALPGEN, SHERPA, ...)  
Frixione et al. '02; Mangano et al. '03; Kraus et al. '05

### Electroweak

- complete EW  $\mathcal{O}(\alpha)$  corrections (ZGRAD2, HORACE, SANC)  
Baur et al. '02; Carloni Calame et al. '07; Bardin et al. '07
- multi-photon radiation (HORACE, ZINHAC)  
Carloni Calame et al. '05, '07; Płaczek et al.

⇒ Need combined tools for QCD & EW!

Strong enhancement by EW Sudakov logs at high energies

⇒ might need dominant EW 2-loop corrections

## Les Houches 2005 Workshop “Physics at TeV Colliders” & Tevatron-for-LHC (TeV4LHC) Electroweak Working Groups

hep-ph/0604120

arXiv:0705.3251 [hep-ph]

Tuned comparison of available Monte Carlo (MC) programs for **charged-current DY**:

- **common setup** for comparison:  
cuts ( $p_T^\ell > 20$  GeV,  $|\eta_\ell| < 2.5$ ), input parameter scheme, which distributions, ...
- estimate **remaining theoretical uncertainties**  
(missing higher-order corrections, PDF uncertainties, ...)
- identify **necessary improvements** to match experimental precision

## Les Houches 2007

Ongoing comparisons for **neutral-current DY**

## Mini-Workshop “Physics with LHC early data”

in Glasgow, November 26–30, 2007

<http://ppewww.physics.gla.ac.uk/~samir/MiniWorkshop>

- continue comparison for neutral-current DY (QCD & EW)
- implement **2-loop EW Sudakov logs** in MC programs

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### Large logarithms in electroweak corrections

EW corrections at high energies  $\sqrt{s} \sim \text{TeV} \gg M_{W,Z}$

- dominated by **Sudakov logarithms**  $\alpha^n \ln^j(s/M_W^2)$ ,  $j = 2n$ ,
- subleading logs ( $0 \leq j < 2n$ ) also important (cancellations!)

### Origin of large logs

- **mass singularities**: emission of soft/collinear gauge bosons from external particles
- remnants from **UV singularities**:  $\ln(s/\mu^2)$

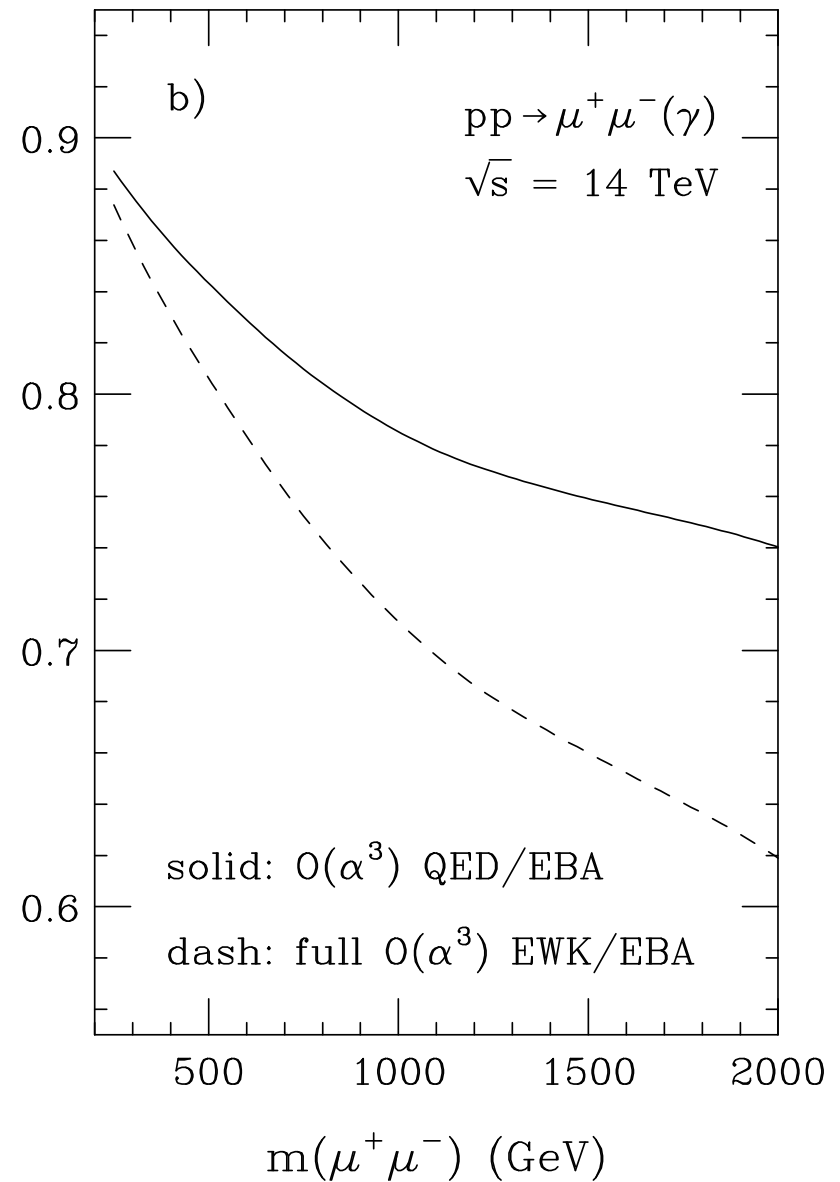
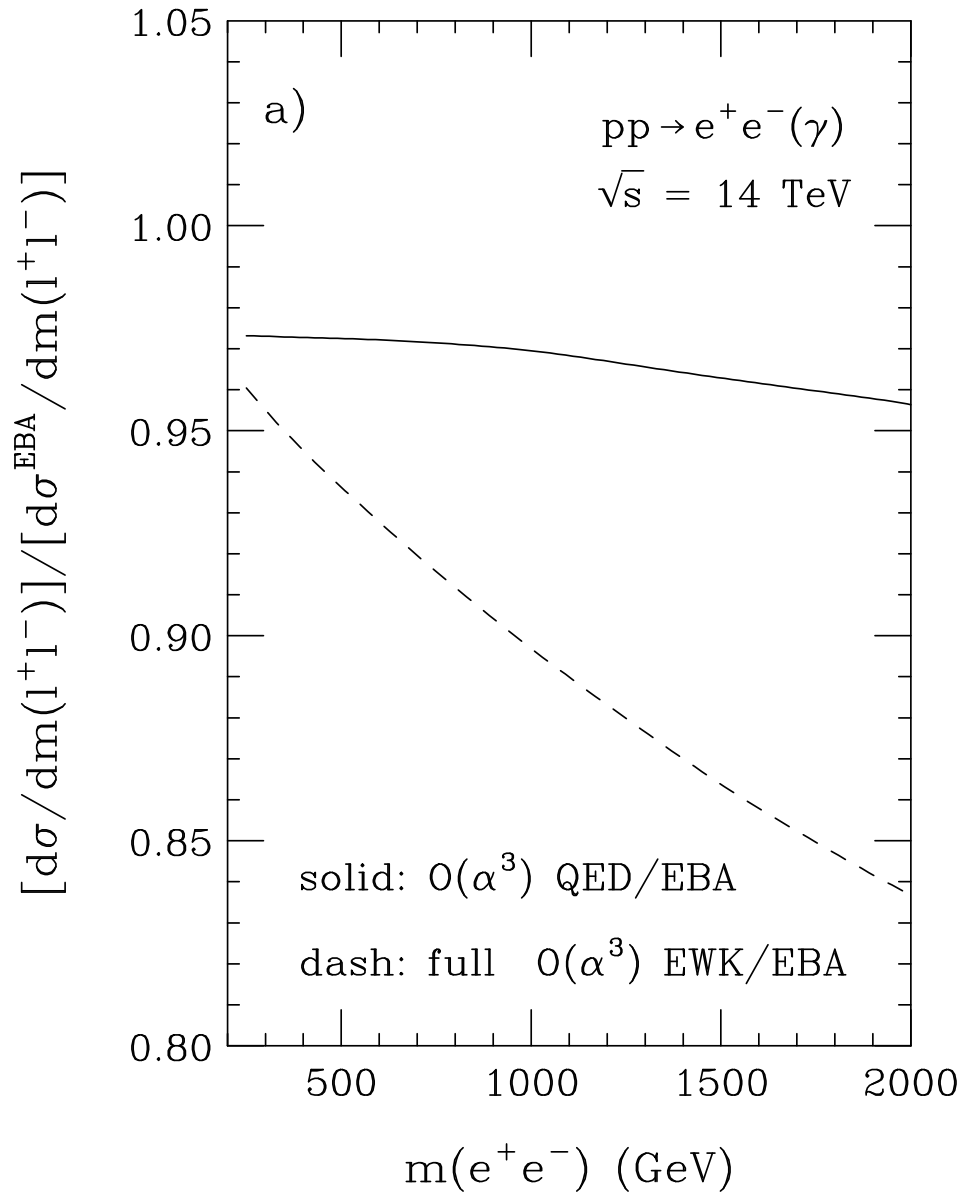
**Massless gauge bosons**: **real emission** of soft/collinear photons/gluons **cannot be detected**  $\Rightarrow$  mass singularities cancel (**KLN theorem**)

**Massive gauge bosons**: **real emission** of  $W$ 's,  $Z$ 's **can be detected separately**

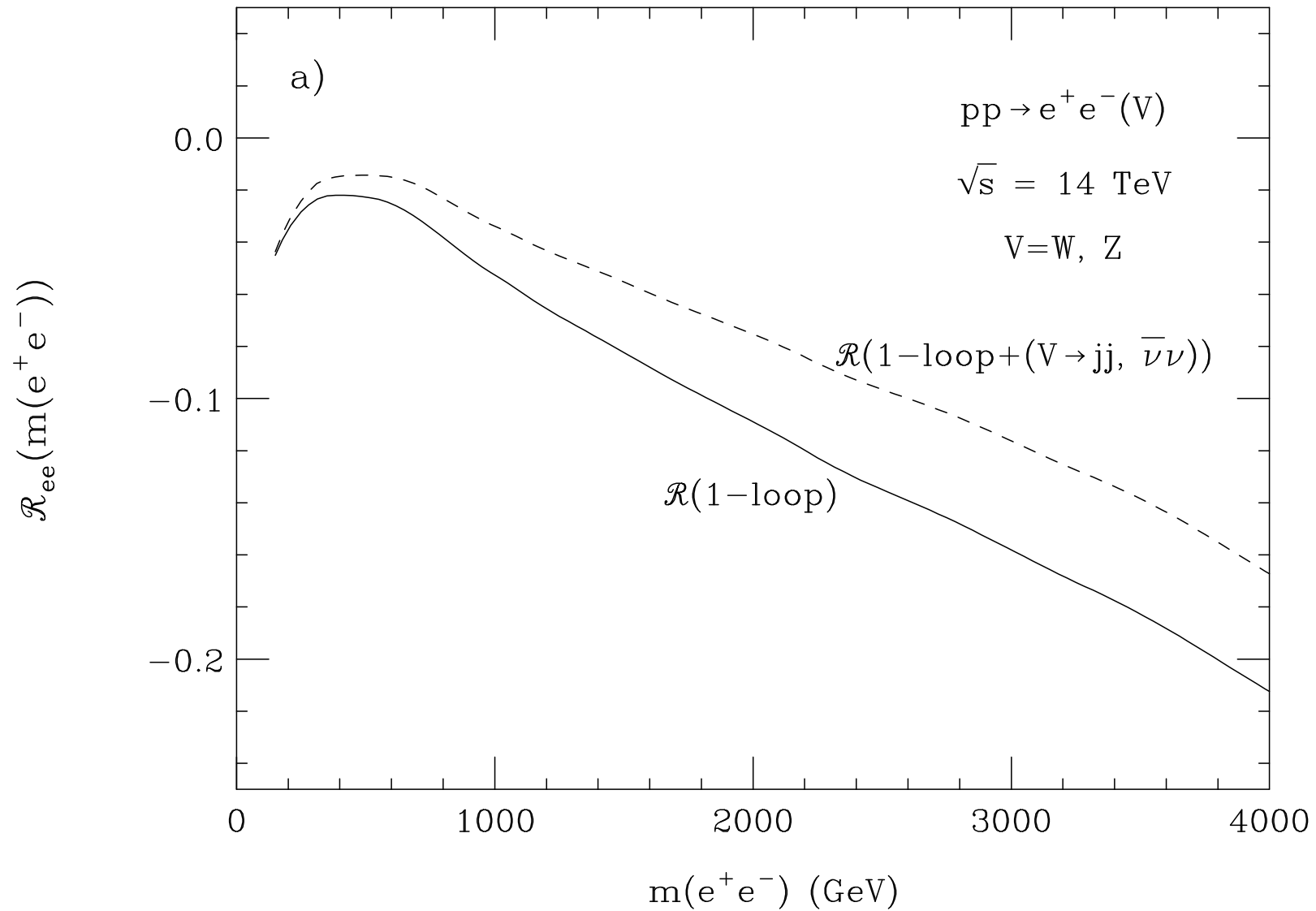
$\hookrightarrow$  large logs remain present in **exclusive observables**,

$\hookrightarrow$  even in inclusive observables (**Block–Nordsieck violations**)

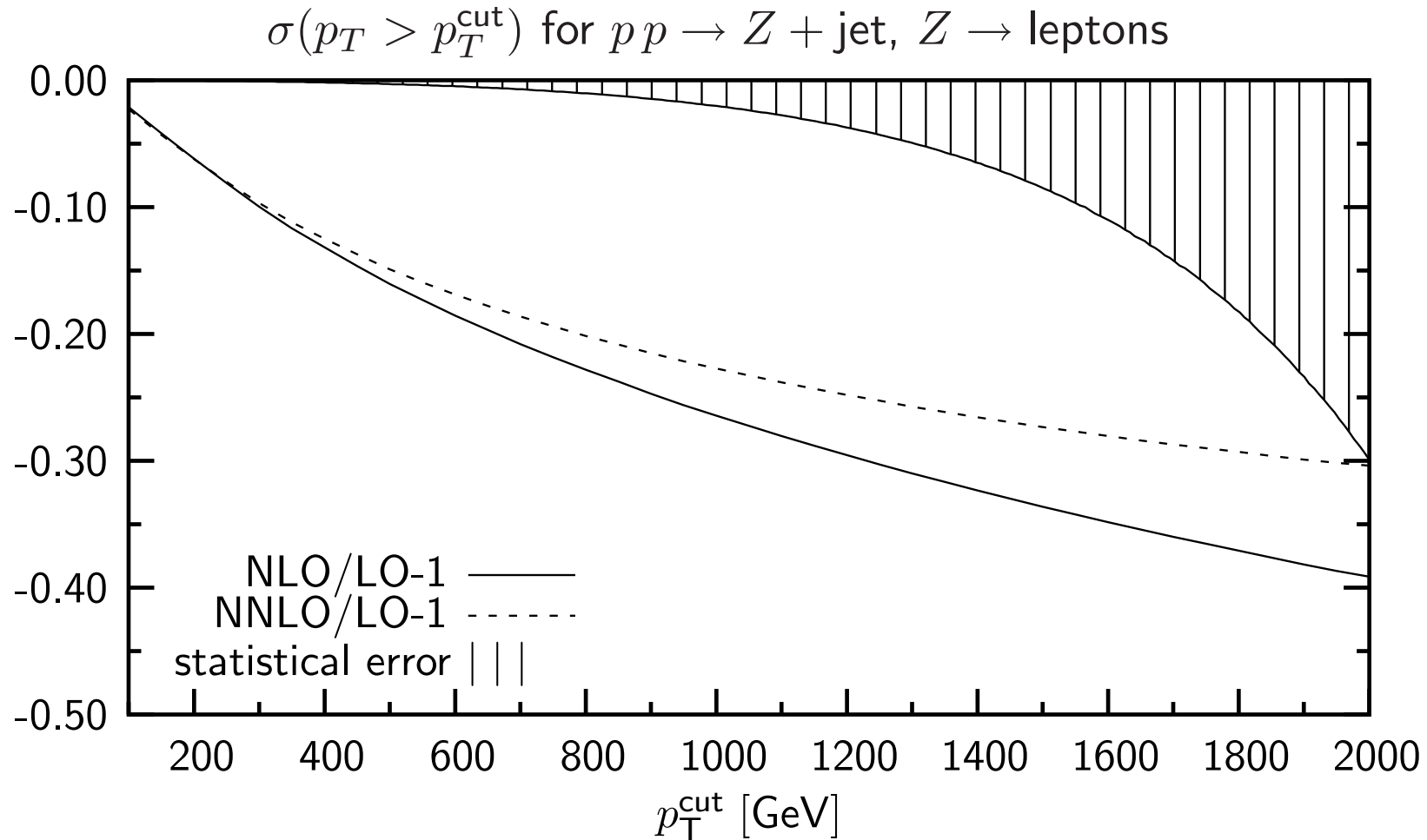
## One-loop effects of EW Sudakov logarithms



## Real $W, Z$ emission: only partial cancellation



## Two-loop effects of EW Sudakov logarithms



Kühn et al., Nucl. Phys. B727 (2005) 368

**Size of corrections** at  $p_T^{\text{cut}} \sim 1 \text{ TeV}$  vs. statistical error  $\sigma_{\text{stat}} \simeq 2\%$  ( $\mathcal{L} = 300 \text{ fb}^{-1}$ ):

- 1-loop:  $-26\% \simeq -13 \sigma_{\text{stat}}$
- dominant 2-loop terms:  $+4\% \simeq +2 \sigma_{\text{stat}}$



## Existing Sudakov results at two loops

Universal structure of mass singularities  $\Rightarrow$  use **evolution equations**

valid for unbroken  $SU(2) \times U(1)$  ( $M_\gamma = M_Z = M_W$ ) and for pure QED:

$$\alpha^2 \left[ \underbrace{C_{LL} \ln^4 \left( \frac{s}{M_W^2} \right)}_{\substack{\text{Fadin, Lipatov,} \\ \text{Martin, Melles '99}}} + \underbrace{C_{NLL} \ln^3 \left( \frac{s}{M_W^2} \right)}_{\text{Melles '00, '01}} + \underbrace{C_{NNLL} \ln^2 \left( \frac{s}{M_W^2} \right)}_{\substack{\text{K\"uhn, Moch, Penin,} \\ \text{Smirnov '99-'01}}} + \underbrace{C_{N^3LL} \ln \left( \frac{s}{M_W^2} \right)}_{\substack{\text{B.J., K\"uhn, Penin,} \\ \text{Smirnov '03-'05}}} \right]$$

arbitrary processes
massless  $f \bar{f} \rightarrow f' \bar{f}'$  processes

**Recently:**  $e^- e^+ \rightarrow W^+ W^-$  [K\"uhn, Metzler, Penin '07], SCET approach [Chiu, Golf, Kelley, Manohar '07]

**Explicit 2-loop calculations** based on EW Lagrangian:

$$\alpha^2 \left[ \underbrace{C_{LL} \ln^4 \left( \frac{s}{M_W^2} \right)}_{\substack{\text{Melles '00;} \\ \text{Hori, Kawamura, Kodaira '00;} \\ \text{Beenakker, Werthenbach '00, '01}}} + \underbrace{C_{NLL}^{\text{ang}} \ln \left( \frac{t}{s} \right) \ln^3 \left( \frac{s}{M_W^2} \right)}_{\text{Denner, Melles, Pozzorini '03}} + \underbrace{C_{NLL} \ln^3 \left( \frac{s}{M_W^2} \right)}_{\substack{\text{Pozzorini '04;} \\ \text{Denner, B.J., Pozzorini '06}}} \right]$$

arbitrary processes
 $n$ -fermion processes

$\Rightarrow$  agree with evolution equations

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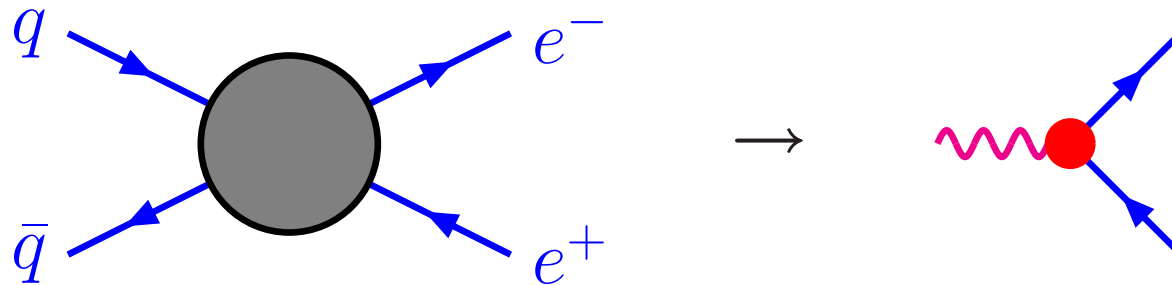
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J.H. Kühn, A.A. Penin, *hep-ph/9906545*

J.H. Kühn, A.A. Penin, V.A. Smirnov, *Eur. Phys. J. C* 17 (2000) 97

J.H. Kühn, S. Moch, A.A. Penin, V.A. Smirnov, *Nucl. Phys. B* 616 (2001) 286

B. Feucht (Jantzen), J.H. Kühn, S. Moch, *Phys. Lett. B* 561 (2003) 111

B. Feucht (Jantzen), J.H. Kühn, A.A. Penin, V.A. Smirnov, *Phys. Rev. Lett.* 93 (2004) 101802

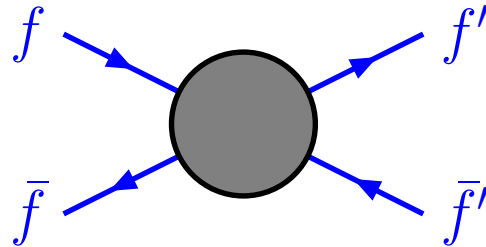
B. Jantzen, J.H. Kühn, A.A. Penin, V.A. Smirnov, *Phys. Rev. D* 72 (2005) 051301(R)

B. Jantzen, J.H. Kühn, A.A. Penin, V.A. Smirnov, *Nucl. Phys. B* 731 (2005) 188

B. Jantzen, V.A. Smirnov, *Eur. Phys. J. C* 47 (2006) 671

**Four-fermion scattering:**  $f\bar{f} \rightarrow f'\bar{f}'$ , important class of processes ( $\rightarrow$  Drell–Yan)

**Factorization of QED contributions:**



$$A = U_{\text{QED}} \cdot A_{\text{EW}}$$

- **QED factor**  $U_{\text{QED}}$   $\rightarrow$  IR singularities from virtual massless photons (regularized dimensionally or by small photon mass, compensated by real corrections)
- amplitude  $A_{\text{EW}}$   $\rightarrow$  remaining **electroweak contributions**, IR-safe
- calculate  $A_{\text{EW}}$  by evaluating  $A/U_{\text{QED}}$  with  $M_\gamma = M_W$   
 $\hookrightarrow$  works at NNLL accuracy  $\checkmark$

Problem at N<sup>3</sup>LL (2-loop linear log):

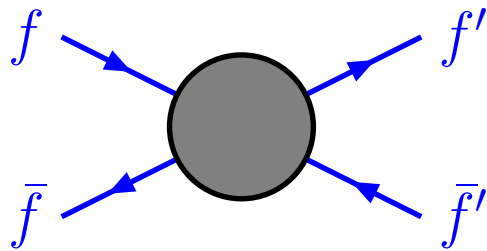
mixing of gauge groups  $SU(2) \times U(1)$  through Higgs mechanism

$\Rightarrow$  use **simplified model without mixing**:

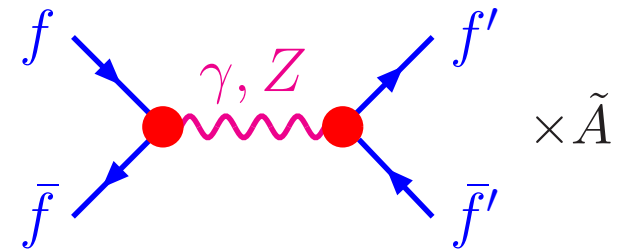
B.J., Kühn, Penin, Smirnov '04, '05

- factorization of QED contributions works at **N<sup>3</sup>LL accuracy**
- single mass parameter:  $M = M_W = M_{Z=W^3} = M_{\gamma=B}$
- include **mass difference** ( $M_Z - M_W$ ) by expansion around  $M_Z \approx M_W$
- remaining error  $\sim \mathcal{O}(\sin^2 \theta_W) \sim 20\%$  in coefficient of linear 2-loop log

## Factorization into form factor and reduced amplitude:



$$A_{\text{EW}} = \frac{ig^2}{s} F^2 \tilde{A}$$



Form factor  $F$  of vector current:

$$= F \cdot \bar{u}(p_2) \gamma^\mu u(p_1) + \mathcal{O}(\text{fermion masses})$$

High-energy behaviour  $s \sim |t| \sim |u| \gg M_{W,Z}^2$

references: see Kühn et al. '01

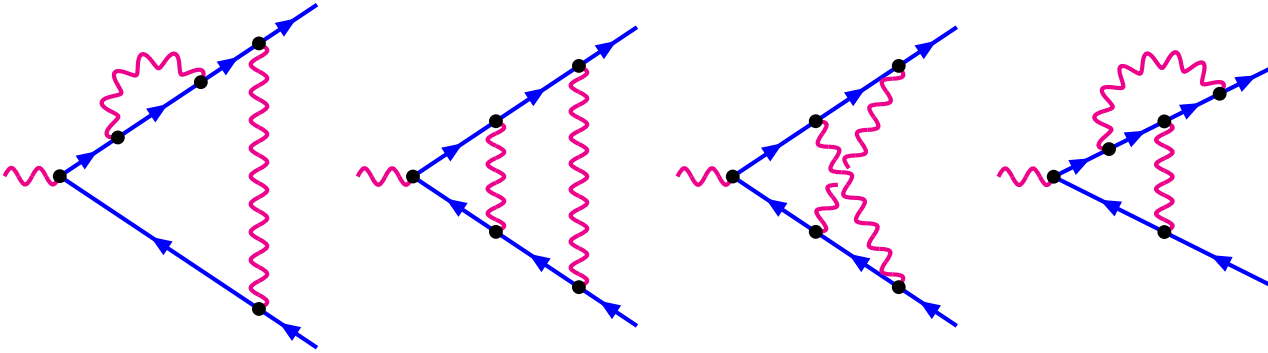
- all double logs  $\alpha^n \ln^{2n} \rightsquigarrow$  form factors  $F^2$
- **reduced amplitude**  $\tilde{A} \rightarrow$  only single logs  $\alpha^n \ln^n$
- $\tilde{A}$  obtained from 1-loop and massless 2-loop calculations via an **evolution equation**:

$$\frac{\partial \tilde{A}}{\partial \ln s} = \chi(\alpha(s)) \tilde{A}, \quad \chi = \text{matrix of soft anomalous dimensions}$$

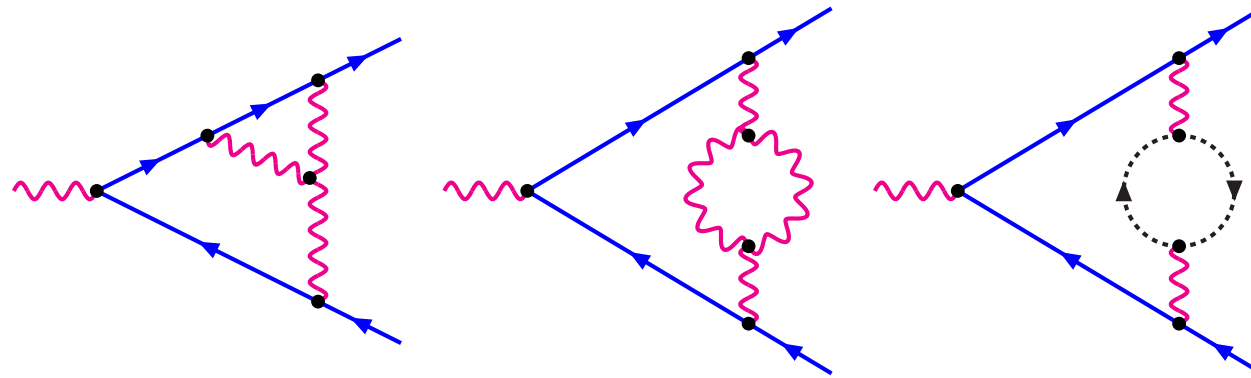
$\Rightarrow$  For full logarithmic ( $N^3\text{LL}$ ) 2-loop amplitude: need **form factor**  $F$

## SU(2) form factor in two loops: vertex diagrams

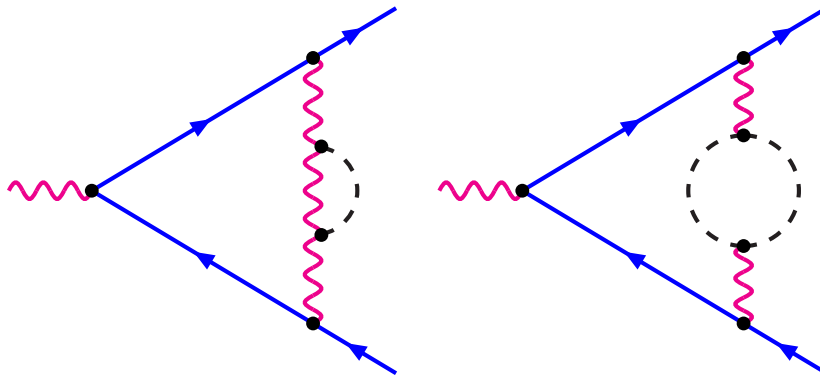
Abelian:  
 $\hookrightarrow U(1)$



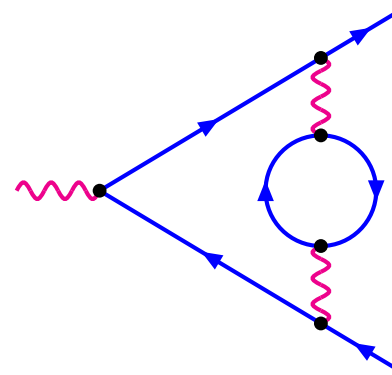
non-Abelian:



Higgs:



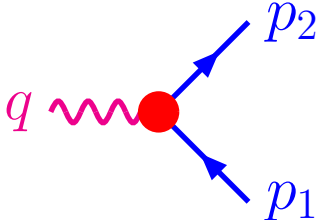
fermion:



+ 1-loop  $\times$  1-loop corrections + renormalization

## High-energy behaviour of the form factor

↪ Sudakov limit:



$$= F(Q^2) \cdot \bar{u}(p_2) \gamma^\mu u(p_1)$$

- momentum transfer  $-q^2 \equiv Q^2 \gg M^2 \equiv M_{W,Z}^2$   
 $\left[ \text{Euclidean } Q^2 > 0, \text{ real } F \xrightarrow[\text{continuation}]{\text{analytic}} \text{Minkowskian } Q^2 = -s - i0 < 0 \right]$
- neglect fermion masses  $\Rightarrow$  external on-shell fermions:  $p_1^2 = p_2^2 = 0$
- **logarithmic approximation**: neglect terms suppressed by a factor of  $M^2/Q^2$   
 ↪ works well for 2-loop  $n_f$  contribution where the exact result in  $M^2/Q^2$  is known  
B.F., Kühn, Moch '03  
 $\Rightarrow$  contains powers of the large log  $\ln(Q^2/M^2)$   
 $\Rightarrow$  leading order of asymptotic expansion in  $M^2/Q^2$
- only 2-loop logs  $\ln^{4,3,2,1}$ , non-logarithmic constant more difficult
- choose  $M_{\text{Higgs}} = M_W \Rightarrow$  calculation easier, affects only N<sup>3</sup>LL, small error
- methods: **expansion by regions** & **Mellin–Barnes representations** B.J., Smirnov '06



## SU(2) form factor in two loops: result

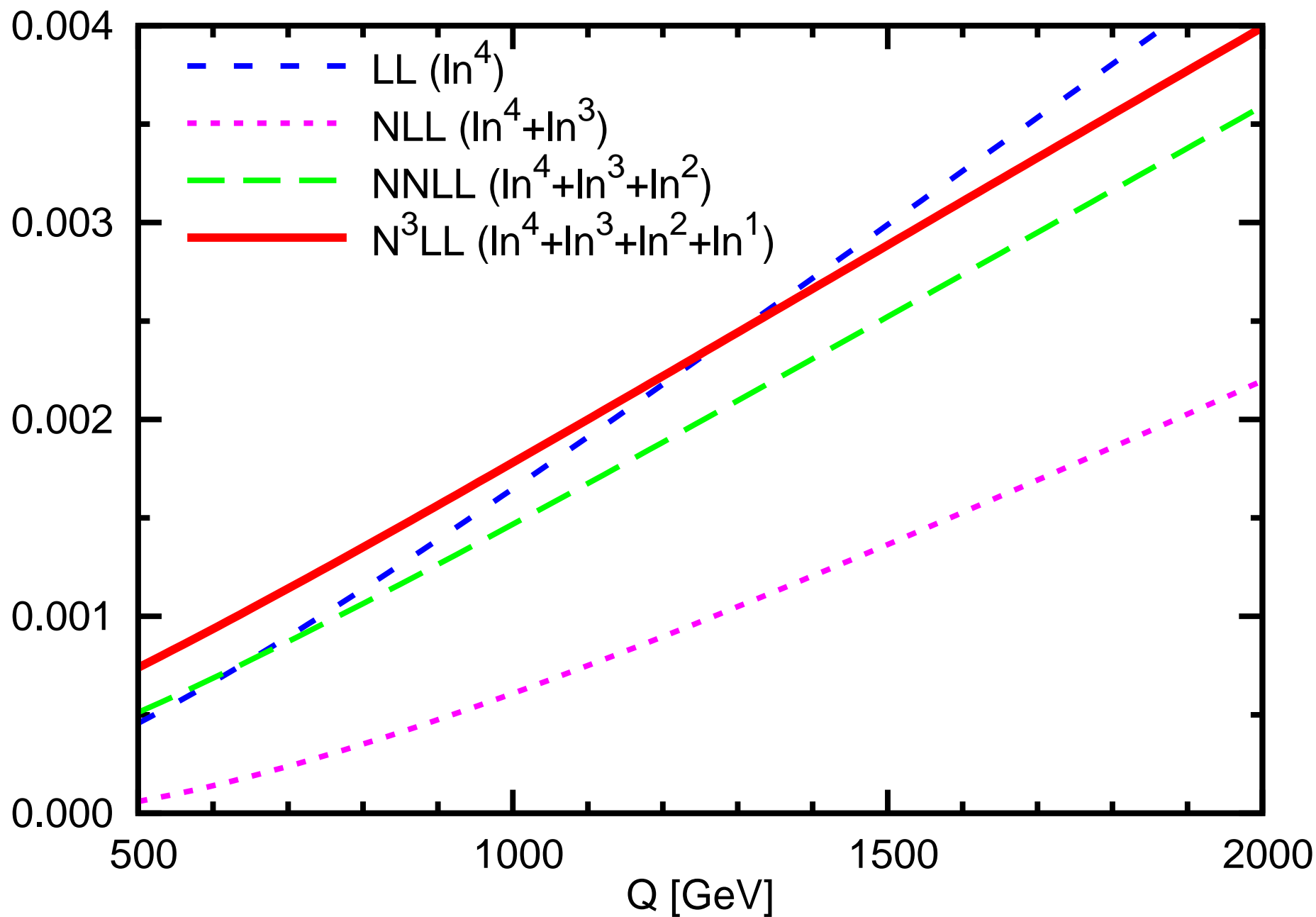
$$\left(\frac{\alpha}{4\pi}\right)^2 \left[ \begin{aligned} & \frac{9}{32} \ln^4\left(\frac{Q^2}{M^2}\right) - \frac{43}{48} \ln^3\left(\frac{Q^2}{M^2}\right) + \left(\frac{7}{8}\pi^2 - \frac{235}{48}\right) \ln^2\left(\frac{Q^2}{M^2}\right) \text{ confirmed } \checkmark \\ & + \left(\frac{13}{2}\sqrt{3} \text{Cl}_2\left(\frac{\pi}{3}\right) + \frac{15}{4}\sqrt{3}\pi - \frac{61}{2}\zeta_3 - \frac{11}{24}\pi^2 + \frac{65}{4}\right) \ln\left(\frac{Q^2}{M^2}\right) \text{ new!} \end{aligned} \right]$$

B.J., Kühn, Moch '03; B.J., Kühn, Penin, Smirnov '04, '05; B.J., Smirnov '06  
 $\ln^{4,3,2}$ : Kühn, Moch, Penin, Smirnov '01

Sizes of logarithmic contributions (at  $Q = 1$  TeV in per mil):

Abelian:	$+ 0.3 \ln^4$	$- 1.7 \ln^3$	$+ 8.2 \ln^2$	$- 11 \ln$	$+ 15$
	$+1.6$	$-2.0$	$+1.9$	$-0.5$	$+0.1$
fermionic:	$- 1.0 \ln^3$	$+ 9.5 \ln^2$	$- 26 \ln$	$+ 42$	
	$-1.2$	$+2.2$	$-1.2$	$+0.4$	
non-Abelian + Higgs:	$+ 1.8 \ln^3$	$- 14 \ln^2$	$+ 43 \ln$	$- \dots$	
	$+2.1$	$-3.2$	$+2.0$		
<b>total:</b>	$+ 0.3 \ln^4$	$- 0.9 \ln^3$	$+ 3.7 \ln^2$	$+ 6.9 \ln$	
	$+1.6$	$-1.0$	$+0.9$	$+0.3$	

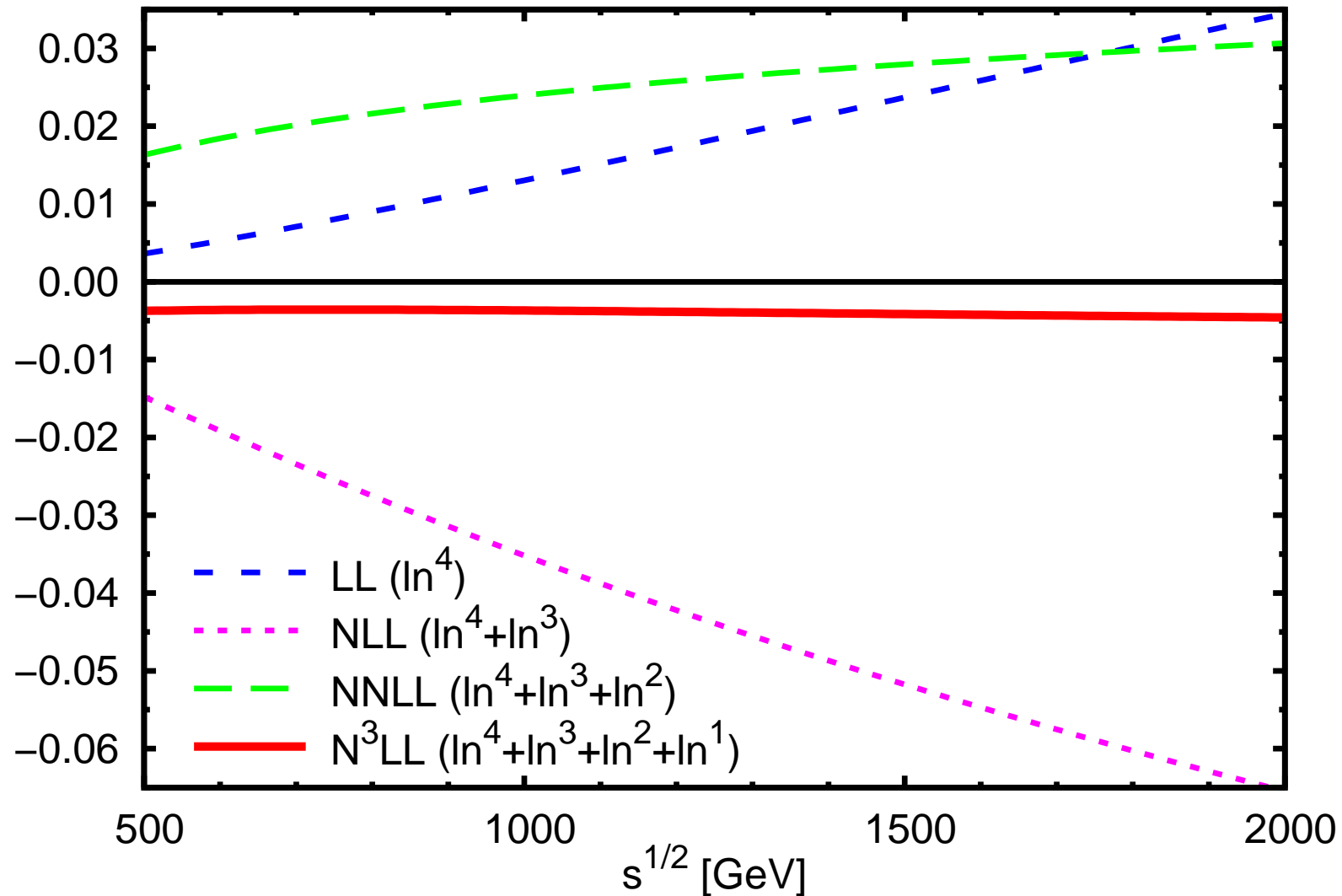
## SU(2) form factor in two loops: result (2)



## Electroweak results: example $\sigma(q \bar{q} \rightarrow e^- e^+)$ ( $q = d, s$ )

numerical 2-loop result:

$$\left(\frac{\alpha_{\text{ew}}}{4\pi}\right)^2 \left[ +2.79 \ln^4\left(\frac{s}{M_W^2}\right) - 51.98 \ln^3\left(\frac{s}{M_W^2}\right) + 321.34 \ln^2\left(\frac{s}{M_W^2}\right) - 757.35 \ln\left(\frac{s}{M_W^2}\right) \right]$$



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# IV Implementation of Sudakov corrections for LHC

## Running couplings & input parameter schemes

**Mathematica file** with all contributions up to 2 loops

A. Penin

**Rewriting Mathematica code** with all features needed for implementation:

B.J.

- couplings and mixing angles from Born amplitude are renormalized at scale  $s$   
 $\hookrightarrow$  implement **2-loop running**  $s \rightarrow M_W^2$ :  
 EW (incl. Yukawa) & optionally QCD contributions
- **fully differential cross section** (unpolarized or polarized)

Jones '81; Arason et al. '91

**Fortran code** implementing Mathematica results:

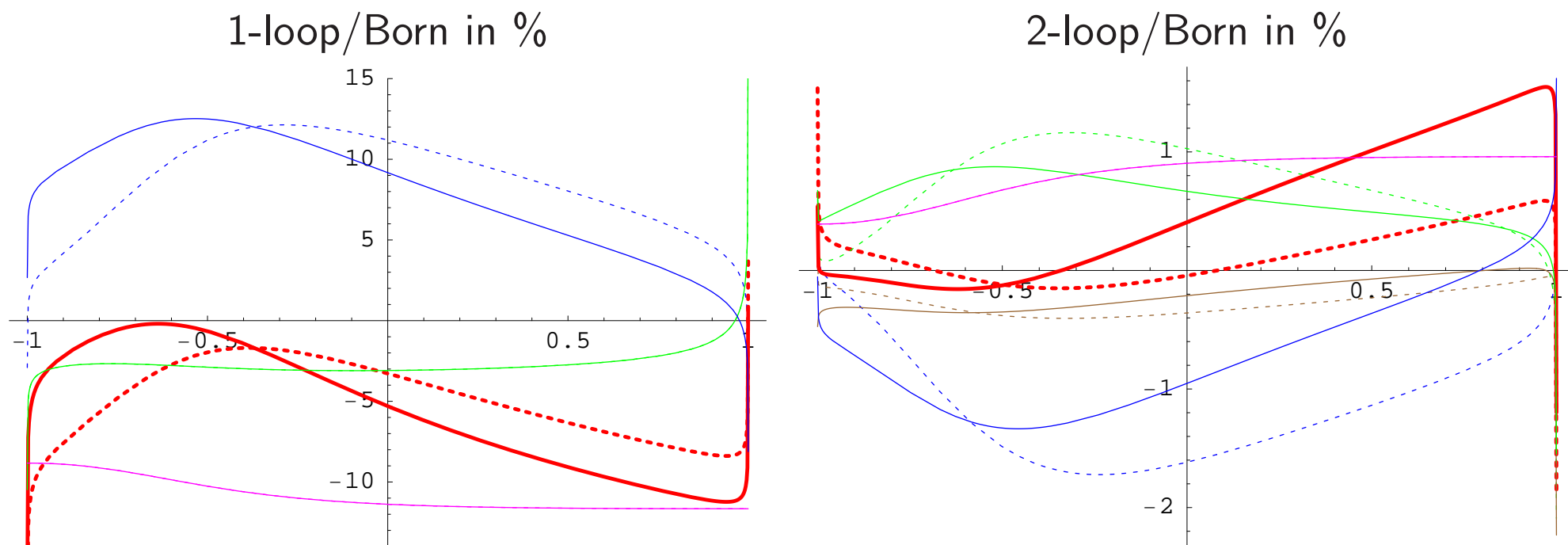
S. Pozzorini

- optional **conversion from  $\overline{MS}$  to  $G_\mu$  scheme**  $\Rightarrow$  closer to setup of MC programs
- provides ratios **1-loop/Born** & **2-loop/Born**
- **switches & variables** allow flexible settings

**Implementation** in MC programs **ZGRAD2** & **HORACE**

D. Wackerath, C.M. Carloni Calame

## Partonic cross sections: angular dependence for $u\bar{u} \rightarrow e^-e^+$

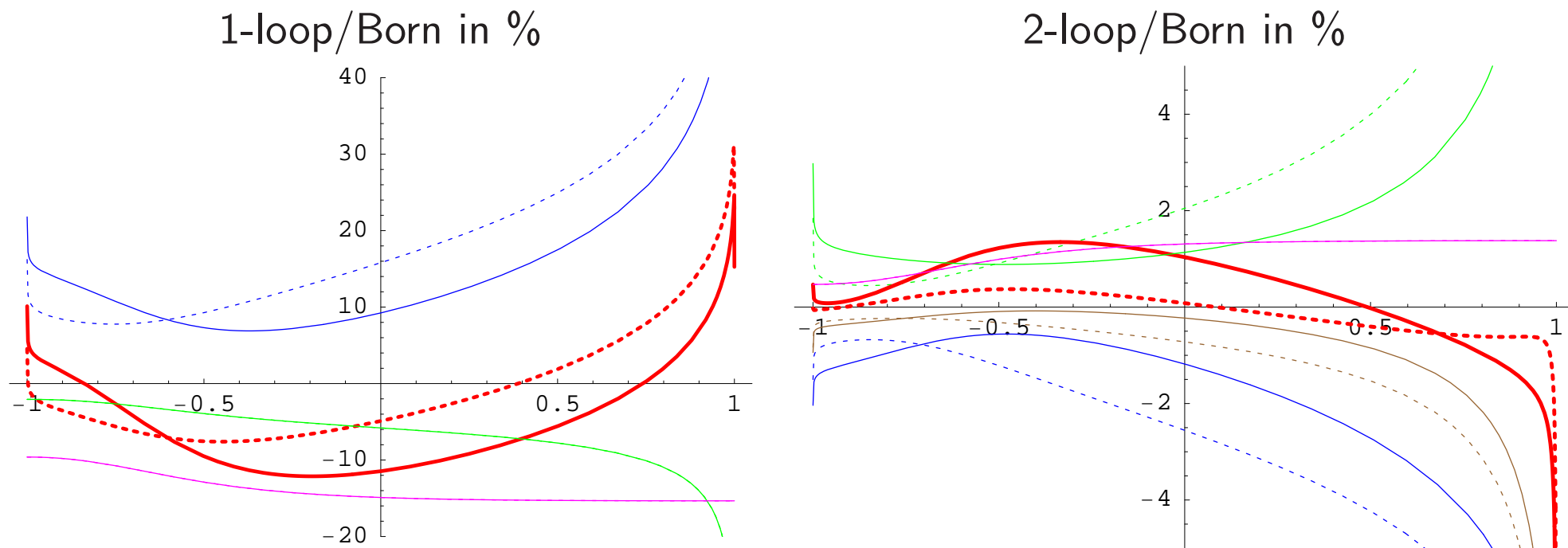


as a function of  $\cos\theta$  for  $s = 1 \text{ TeV}^2$

colors: **full result**; individual logs LL, NLL-log, NNLL, N<sup>3</sup>LL

solid/dashed: with/without running of Born couplings

## Partonic cross sections: angular dependence for $d\bar{d} \rightarrow e^-e^+$



as a function of  $\cos\theta$  for  $s = 1 \text{ TeV}^2$

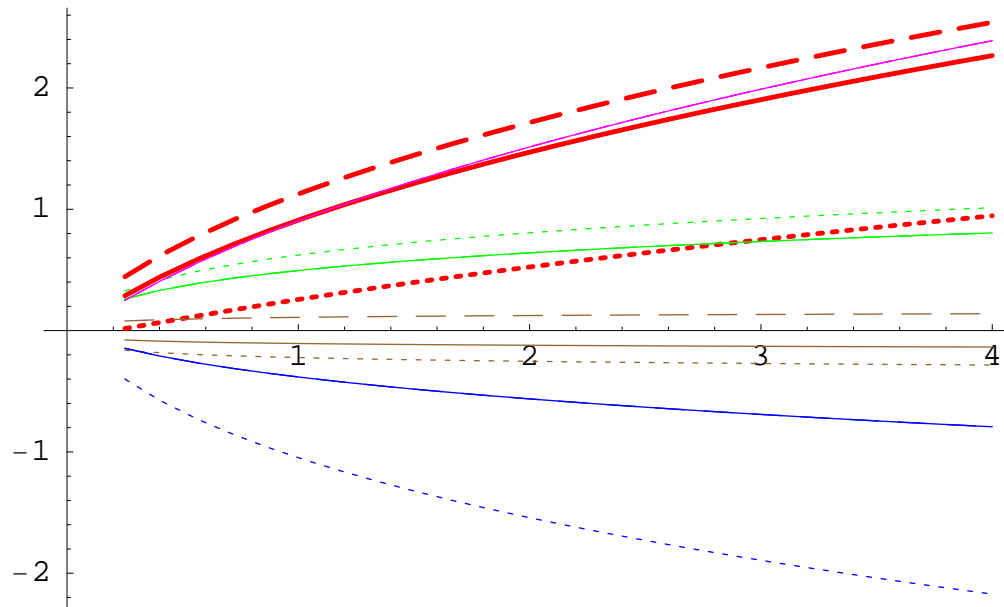
colors: **full result**; individual logs LL, NLL-log, NNLL, N<sup>3</sup>LL

solid/dashed: with/without running of Born couplings

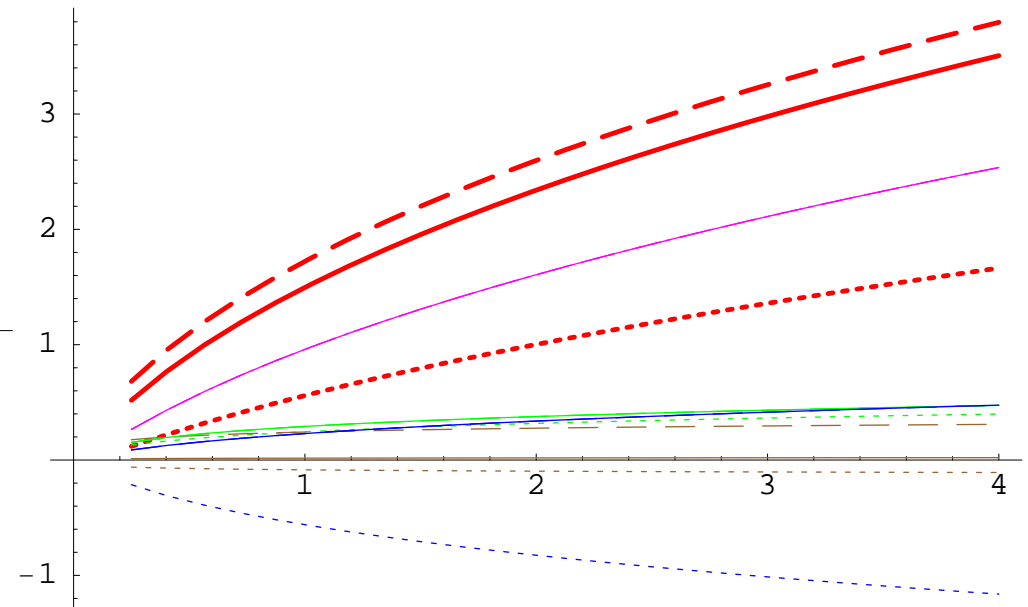


## Partonic cross sections: $u \bar{u} \rightarrow e^- e^+$

$\sigma_{\text{tot}}$  (2-loop/Born in %)



$15^\circ < \theta < 30^\circ$  (2-loop/Born in %)



as a function of  $s$  [ $\text{TeV}^2$ ]

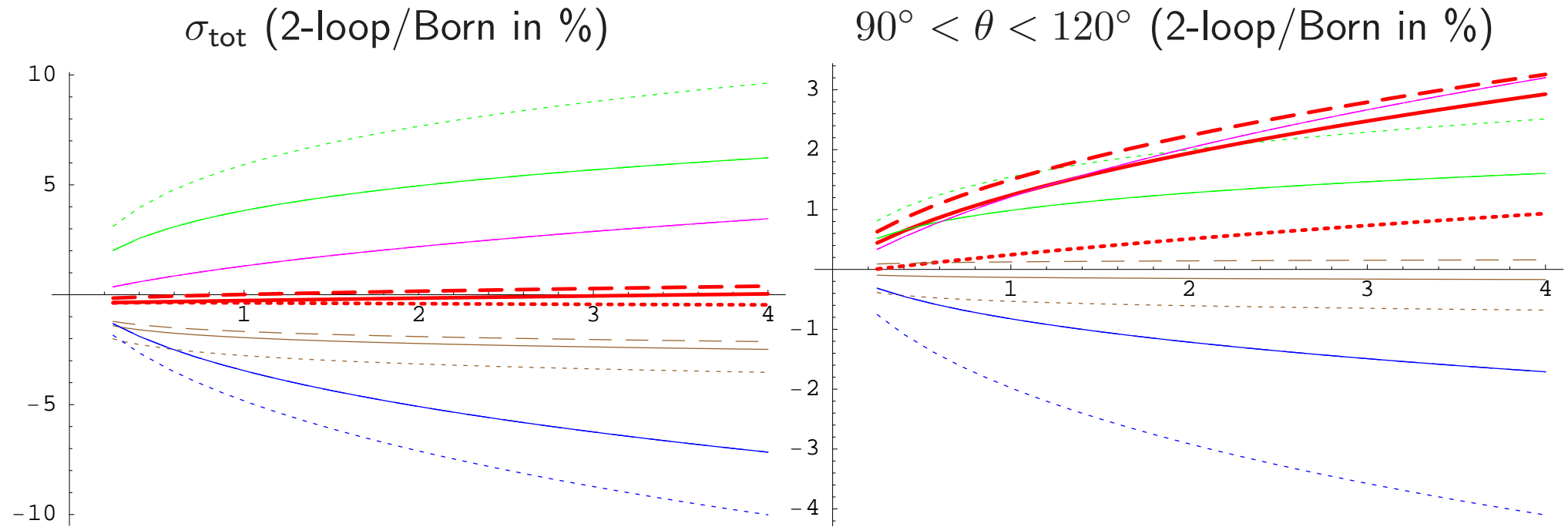
**colors:** **full result**; individual logs **LL**, **NLL-log**, **NNLL**, **N<sup>3</sup>LL**

**solid:** with EW contributions to the running

**long-dashed:** with EW+QCD contributions to the running

**short-dashed:** without running of Born couplings

## Partonic cross sections: $d\bar{d} \rightarrow e^-e^+$



as a function of  $s$  [TeV<sup>2</sup>]

**colors:** **full result**; individual logs **LL**, **NLL-log**, **NNLL**, **N<sup>3</sup>LL**

**solid:** with EW contributions to the running

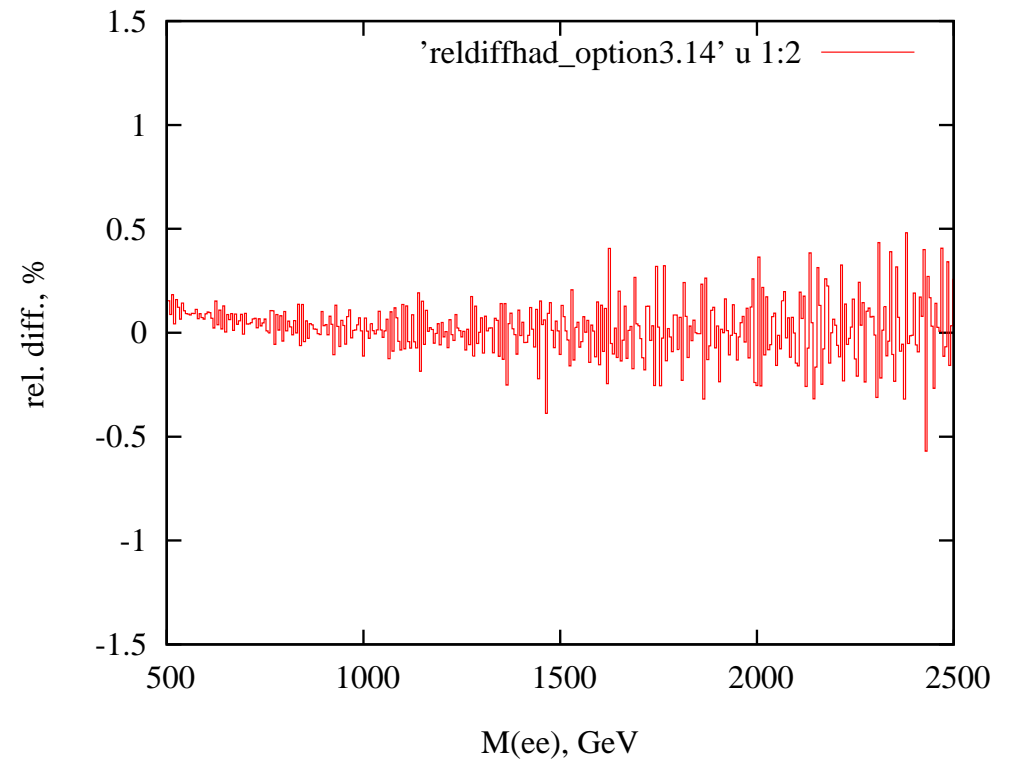
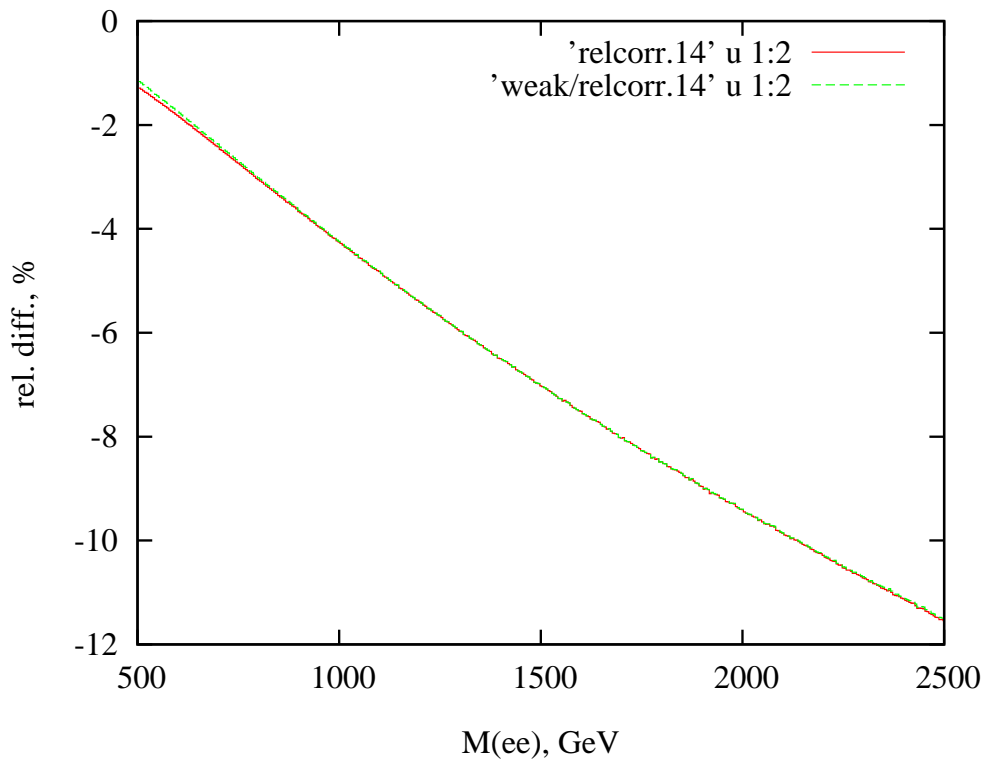
**long-dashed:** with EW+QCD contributions to the running

**short-dashed:** without running of Born couplings

## Hadronic distributions: 1-loop comparison of Sudakov corrections with ZGRAD2

1-loop/Born in % (Sudakov, ZGRAD2)

(Sudakov/ZGRAD2 - 1) in %

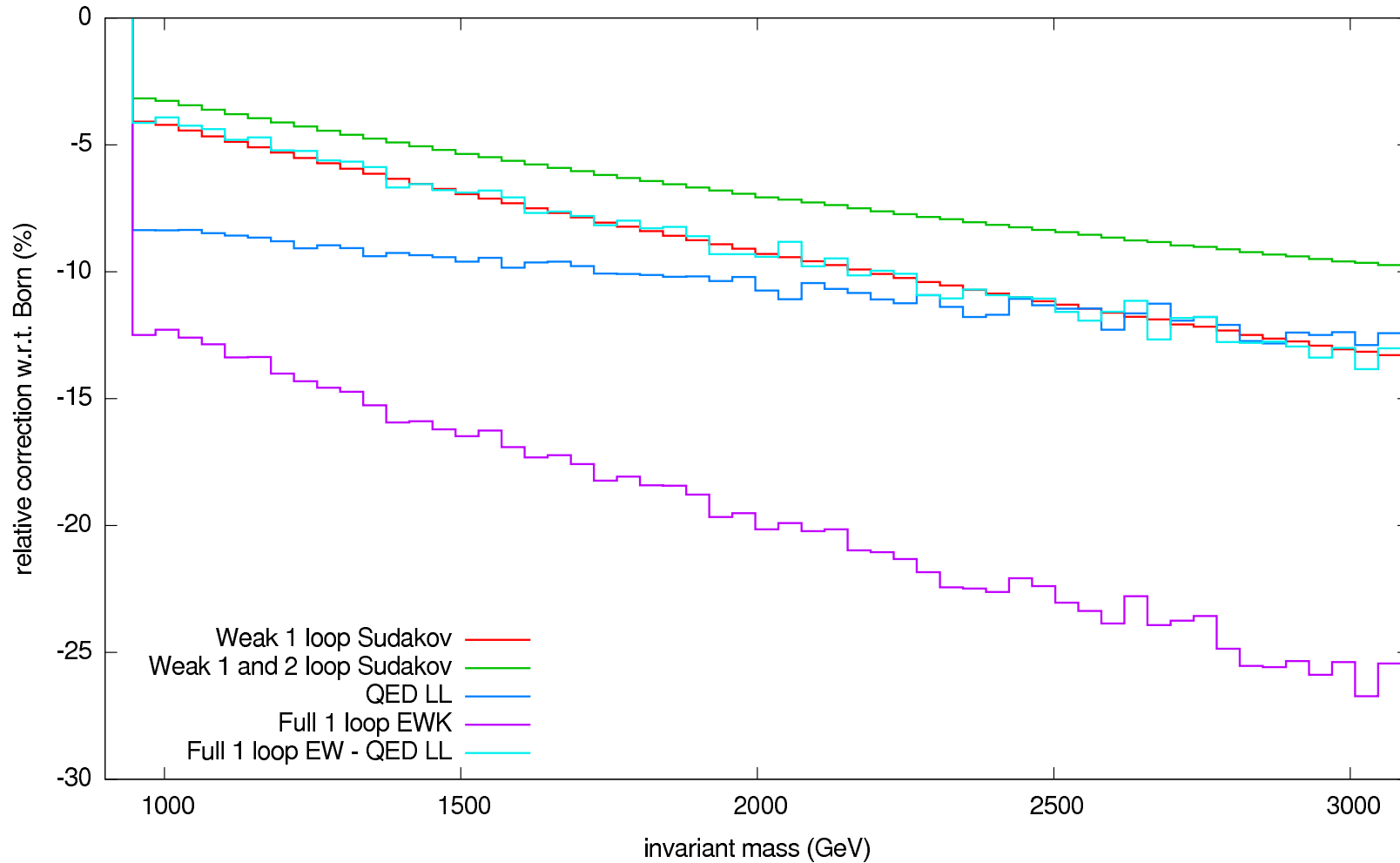


$$pp \rightarrow e^- e^+$$

D. Wackerath

↪ Same setup for separation of 1-loop QED contribution from EW corrections

## Hadronic distributions: 1- & 2-loop Sudakov corrections with HORACE



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

C.M. Carloni Calame

⇒ good 1-loop agreement after subtraction of QED leading logs

⇒ 2-loop Sudakov corrections of several %

# Overview

## I Drell–Yan processes at the LHC

- precision physics with Drell–Yan processes
- physics motivations
- status of loop calculations & tools for neutral-current processes
- Les Houches 2005/2007 & TeV4LHC

## II Electroweak Sudakov logarithms

- large logarithms in electroweak corrections
- one- & two-loop effects
- existing Sudakov results at two loops

## III Four-fermion scattering: two-loop calculation

- factorization into QED contributions, form factor & reduced amplitude
- SU(2) form factor: calculation & results
- electroweak results

## IV Implementation of Sudakov corrections for LHC

- running couplings & input parameter schemes
- partonic cross sections
- hadronic distributions

## V Summary

# V Summary

## Drell–Yan processes

- important for **precision physics at LHC**
- implement best available **theoretical predictions** into MC program(s)

## Electroweak Sudakov logarithms

- **large impact at high energies**, also 2-loop corrections important

## Four-fermion scattering

- **2-loop calculation** of amplitude and form factor presented
- **large logarithmic contributions**, but also large **cancellations**

## Implementation of Sudakov corrections for LHC

- **Mathematica & Fortran code** → coupling & scheme conversions
- first results for **distributions** of hadronic cross sections
- good **agreement at 1 loop**, preliminary **2-loop distributions**

Include results in **Les Houches 2007 Proceedings?** **Deadline!**

In any case  $\rightsquigarrow$  separate publication following Glasgow workshop