

# NLO and FSR NNLO radiative corrections for Drell–Yan processes at LHC

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- Introduction
- Notations and Born cross section
- EWK Boson Self Energies
- EWK/QCD Vertices, EWK Boxes. Asymptotic Approach
- Real photon/gluon and inverse gluon bremsstrahlung
- $M$ - and  $G/N$ - methods
- Rebuilding to fully differential cross section. Code READY
- Independence from unphysical parameters
- Comparison with existing results on hadronic level
- Numerical estimations at CMS setup
- Approaches to NNLO radiative corrections
- Conclusions

Despite the fact that the Standard Model (SM) keeps for oneself the status of consistent and experimentally confirmed theory, the search of New Physics (NP) manifestations is continued. The possible traces of NP can be

- the supersymmetry,
- extra spatial dimensions,
- extra neutral gauge bosons, etc.

One of powerful tool in the modern experiments at LHC from this point of view is the investigation of **Drell–Yan lepton-pair production**;

$$pp \rightarrow \gamma, Z \rightarrow l^+ l^- X \quad (1)$$

at **large invariant mass** of lepton-pair:  $M \geq 1$  TeV.

# Drell-Yan process (1970, BNL)

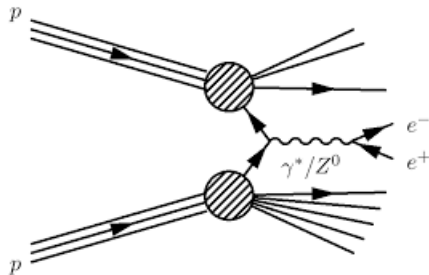


Рис. 1: Drell-Yan process with neutral current ( $\gamma/Z$ )

- $\sqrt{S}$  is total energy in c.m.s. of hadrons
- $M$  is dilepton  $l^+l^-$  invariant mass ( $l = e, \mu$ )
- $y$  is dilepton rapidity

QED RC:

- **V. Mosolov,**  
**N. Shumeiko,**  
Nucl.Phys. B  
**186,** 394 (1981);
- **A. Soroko,**  
**N. Shumeiko,**  
Yad.Fiz **52,** 514  
(1990).



*Рис. 2: Николай Максимович Шумейко (1942–2016) – белорусский физик и организатор науки.*

- EWK RC:  
**U. Baur, et al. (ZGRAD), Phys.Rev.D 65: 033007, (2002).**
- QCD NLO RC:  
**H. Baer, et al., Phys.Rev.D 40, 2844 (1989); Phys.Rev.D 42, 61 (1990).**
- QCD NNLO RC:  
**R. Hambert, W.L. van Neerven, T. Matsuura, Nucl.Phys.B 359, 343 (1991).**

# Modern codes for NLO and NNLO RC for DY process at hadronic colliders (in the ABC order)

- DYNNLO (S. Catani, L. Cieri, G. Ferrera et. al)
- FEWZ (R. Gavin, Y. Li, F. Petriello, S. Quackenbush)
- HORACE (C.Carloni Calame, G.Montagna, O.Nicrosini et. al)
- LPPG and READY (E. Dydyska and V. Zykunov, RDMS CMS)
- MC@NLO (S. Frixione, F. Stoeckli, P. Torrielli et. al)
- PHOTOS (N. Davidson, T. Przedzinski, Z. Was et al.)
- POWHEG (L. Barze, G. Montagna, P. Nason et. al)
- RADY (S. Dittmaier, A. Huss, C. Schwinn et. al)
- SANC (Dubna group: A.Andonov, A.Arbutov, D.Bardin et.al)
- WINHAC (W. Placzek, S. Jadach, M.W. Krasny et. al)
- WZGRAD (U. Baur, W. Hollik, D. Wackerroth et al.)

# Current experimental situation at CMS LHC

- The measured Drell–Yan cross sections and forward-backward asymmetries **are consistent with the SM predictions** at

$$\sqrt{S} = 8 \text{ TeV (19.7 fb}^{-1}\text{) for } M \leq 2 \text{ TeV,}$$

$$\sqrt{S} = 13 \text{ TeV (85 fb}^{-1}\text{) for } M \leq 3 \text{ TeV}$$

- differential  $\frac{d\sigma}{dM}$  cross sections,
  - double-differential  $\frac{d^2\sigma}{dMdy}$  cross sections,
  - **A<sub>FB</sub>** asymmetries.
- The latest published results can be found in  
CMS PAS-SMP-16-009, CMS PAS-SMP-17-001  
(PAS = Physics Analysis Summaries)
  - NNLO RC are taken into account by using of **FEWZ 3.1**
  - NNLO PDFs are **CT10 NNLO** and **NNPDF2.1**.



At the edges of kinematical region (extra large  $\sqrt{s}$ ,  $M$ ) the important task is make the correction procedure of background both accurate and fast. For the latter it is desirable to obtain the set of **compact** formulas for the EWK and QCD RC.

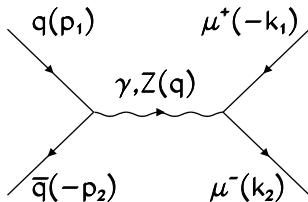
To get leading effect of **Weak RC** in the region of large invariant dilepton mass we used the Sudakov Logarithms (**SL**):

$$l_{i,x} = \ln \frac{m_i^2}{|x|} \quad (i = \mathbf{Z}, \mathbf{W}; \quad x = s, t, u), \quad (2)$$

**V. Sudakov, Sov. Phys. JETP 3, 65 (1956).**

Collinear Logarithms (**CL**) play leading role in **QED RC and QCD RC**

$$\ln \frac{m_f^2}{|x|} \quad (\mathbf{f} = \mathbf{e}, \mu, \mathbf{q}; \quad x = s, t, u). \quad (3)$$



**Рис. 3:** The lowest order graph giving contribution to the DY scattering at parton level

The standard set of Mandelstam invariants for the partonic elastic scattering:

$$\mathbf{s} = (\mathbf{p}_1 + \mathbf{p}_2)^2, \quad \mathbf{t} = (\mathbf{p}_1 - \mathbf{k}_1)^2, \quad \mathbf{u} = (\mathbf{k}_1 - \mathbf{p}_2)^2. \quad (4)$$

# Common convolution formula for Born and V-contribution

$$\sigma_V^H = \frac{1}{3} \int d^3\Gamma \sum_{q=u,d,s,c,b} \theta_K \theta_M \theta_D [f_q^A(x_1, Q^2) f_{\bar{q}}^B(x_2, Q^2) \sigma_V^{q\bar{q}}(\mathbf{t}) + f_{\bar{q}}^A(x_1, Q^2) f_q^B(x_2, Q^2) \sigma_V^{\bar{q}q}(\mathbf{t})], \quad \int d^3\Gamma[\dots] = \int_0^1 dx_1 \int_0^1 dx_2 \int_{-S}^0 dt[\dots],$$

where  $\mathbf{V} = \{\mathbf{0}, \text{BSE}, \text{LV}, \text{HV}, \mathbf{b}, \text{fin}\}$ ,  $\mathbf{b} = \{\gamma\gamma, \gamma\mathbf{Z}, \mathbf{ZZ}, \mathbf{WW}\}$ ,  
 $\theta_K = \theta(\mathbf{s} + \mathbf{t})$ ,  $\theta_M$ ,  $\theta_D$  are kinematical factors,  
 $\mathbf{M} = \sqrt{(\mathbf{k}_1 + \mathbf{k}_2)^2}$  is the invariant dilepton mass.

The propagator for  $\mathbf{j}$ -boson depends on its mass and width:

$$D^{\mathbf{j}s} = \frac{1}{s - m_j^2 + im_j\Gamma_j}. \quad (5)$$

# Born cross section and coupling constants

Born cross section looks like

$$\sigma_0^{q\bar{q}} = \frac{2\pi\alpha^2}{s^2} \sum_{i,j=\gamma,Z} \mathbf{D}^i \mathbf{D}^{j*} (\mathbf{b}_+^{ij} t^2 + \mathbf{b}_-^{ij} u^2), \quad (6)$$

where

$$\mathbf{b}_\pm^{n,k} = \lambda_{q_+}^{n,k} \lambda_{l_+}^{n,k} \pm \lambda_{q_-}^{n,k} \lambda_{l_-}^{n,k}, \quad (7)$$

$$\lambda_{f_+}^{ij} = \mathbf{v}_f^i \mathbf{v}_f^j + \mathbf{a}_f^i \mathbf{a}_f^j, \quad \lambda_{f_-}^{ij} = \mathbf{v}_f^i \mathbf{a}_f^j + \mathbf{a}_f^i \mathbf{v}_f^j, \quad (8)$$

$$\mathbf{v}_f^\gamma = -\mathbf{Q}_f, \quad \mathbf{a}_f^\gamma = \mathbf{0}, \quad \mathbf{v}_f^Z = \frac{l_f^3 - 2s_W^2 Q_f}{2s_W c_W}, \quad \mathbf{a}_f^Z = \frac{l_f^3}{2s_W c_W}. \quad (9)$$

The Feynman rules from paper M. Böhm, H. Spiesberger, W. Hollik, *Forsch.Phys.* 34 (1986) 687–751 were used.

# Main features of QCD RC and EWK RC calculation

- the t'Hooft–Feynman gauge,
- on-mass renormalization scheme ( $\alpha, \alpha_s, \mathbf{m}_W, \mathbf{m}_Z, \mathbf{m}_H$  and the **fermion masses** as independent parameters),
- ultrarelativistic limit.

QCD result can be obtained from QED case by substitution:

$$Q_q^2 \alpha \rightarrow \sum_{a=1}^{N^2-1} \mathbf{t}^a \mathbf{t}^a \alpha_s = \frac{N^2 - 1}{2N} \mathbf{1} \alpha_s \rightarrow \frac{4}{3} \alpha_s, \quad (10)$$

here  $2\mathbf{t}^a$  – Gell-Man matrices,  $\mathbf{N} = 3$ .

# EWK Boson Self Energies

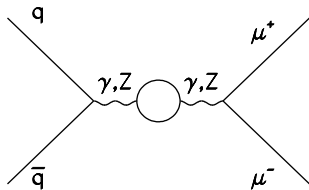


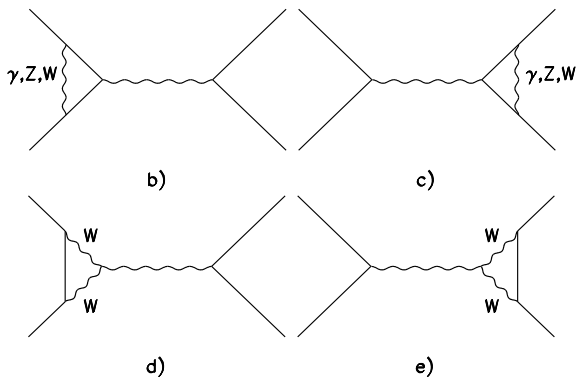
Рис. 4:  $\gamma\gamma$ -,  $\gamma Z$ - and  $ZZ$ -Self Energy diagrams

$$\sigma_{\text{BSE}}^{\text{q}\bar{\text{q}}} = -\frac{4\alpha^2\pi}{s^2} \left[ \sum_{i,j=\gamma,Z} \Pi^i \mathbf{D}^i \mathbf{D}^{j*} \sum_{\chi=+,-} \lambda_{\text{q}\chi}^{ij} \lambda_{\text{l}\chi}^{ij} (\mathbf{t}^2 + \chi \mathbf{u}^2) + \right. \\ \left. + \Pi^{\gamma Z} \mathbf{D}^Z \sum_{i=\gamma,Z} \mathbf{D}^{i*} \sum_{\chi=+,-} (\lambda_{\text{q}\chi}^{\gamma j} \lambda_{\text{l}\chi}^{Z,j} + \lambda_{\text{q}\chi}^{Z,j} \lambda_{\text{l}\chi}^{\gamma j}) (\mathbf{t}^2 + \chi \mathbf{u}^2) \right]$$

is connected with the renormalized  $\gamma$ -,  $Z$ - and  $\gamma Z$ -self energies as

$$\Pi^\gamma = \frac{\hat{\Sigma}^\gamma}{s}, \quad \Pi^Z = \frac{\hat{\Sigma}^Z}{s - m_Z^2}, \quad \Pi^{\gamma Z} = \frac{\hat{\Sigma}^{\gamma Z}}{s}.$$

# Light and Heavy Vertices (EWK RC)



**Рис. 5: Feynman graphs for Vertices diagrams. Unsigned helix lines mean  $\gamma$  or  $Z$ .**

# EW Form Factors

The results are presented as the **Form Factor** set to the Born vertices (as, for example, in **M. Böhm *et al.*, Fortschr. Phys. 34, 687 (1986)**), so we can easily use them to construct the cross section: all that we need is to replace the coupling constants in Born vertex to the corresponding form factors:

$$\mathbf{v}_f^j \rightarrow \delta \mathbf{F}_{V,A}^{jf}, \mathbf{a}_f^j \rightarrow \delta \mathbf{F}_A^{jf}. \quad (11)$$

Electroweak **form factors**  $\delta \mathbf{F}_{V,A}^{jf}$  in ultrarelativistic limit depend on the Sudakov logarithms by means of functions  $\Lambda_{2,3}(\mathbf{m}_i)$  as:

$$\Lambda_2(\mathbf{m}_i) = \frac{\pi^2}{3} - \frac{7}{2} - 3\mathbf{l}_{i,s} - \mathbf{l}_{i,s}^2, \quad \Lambda_3(\mathbf{m}_i) = \frac{5}{6} - \frac{1}{3}\mathbf{l}_{i,s}. \quad (12)$$

Then  $\text{Ver}=\{\text{HV}, \text{LV}\}$  contribution to cross section looks like

$$\sigma_{\text{Ver}}^{\text{q}\bar{\text{q}}} = \frac{4\pi\alpha^2}{s^2} \text{Re} \sum_{i,j=\gamma,Z} \mathbf{D}^i \mathbf{D}^{j*} \sum_{\chi=+,-} (\lambda_{\mathbf{q}\chi}^{\text{F}ij} \lambda_{\mathbf{l}\chi}^{ij} + \lambda_{\mathbf{q}\chi}^{ij} \lambda_{\mathbf{l}\chi}^{\text{F}ij}) (\mathbf{t}^2 + \chi \mathbf{u}^2).$$



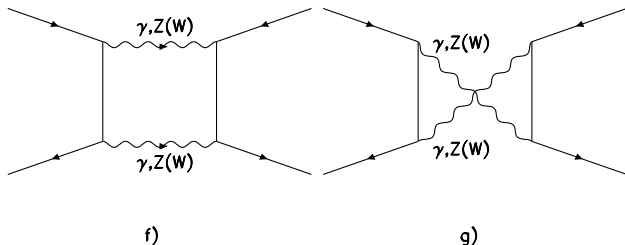


Рис. 6: Feynman graphs for Boxes

The calculation of two heavy boson contribution is more complicated procedure since it demands the integration of 4-point functions with complex masses in unlimited from above kinematical region of invariants (see pioneer paper: **G.'t Hooft and M. Veltman**, *Nucl. Phys. B* **153**, 365 (1979)).

# Asymptotic Approach. Equivalent Transformation

First of all we construct the box cross section for  $q\bar{q} \rightarrow l^+l^-$  using the standard Feynman rules:

$$d\sigma_{ZZ} = -\frac{4\alpha^3}{\pi s} d\Gamma_2 \operatorname{Re} \frac{i}{(2\pi)^2} \int d^4k \sum_{\mathbf{k}=\gamma, Z} \mathbf{D}^{\mathbf{k}s*} (\mathbf{D}^{ZZ} + \mathbf{C}^{ZZ}),$$

here  $\mathbf{D}^{ZZ}(\mathbf{C}^{ZZ})$  is contribution of direct (crossed) diagram.

To extract the part of cross section which predominates in region  $s, |\mathbf{t}|, |\mathbf{u}| \gg \mathbf{m}_Z^2$  we should make equivalent transformation based on the close connection of infrared divergency and SL terms:

$$\mathbf{D}^{ZZ} = (\mathbf{D}_{\mathbf{k}\rightarrow 0}^{ZZ} + \mathbf{D}_{\mathbf{k}\rightarrow \mathbf{q}}^{ZZ}) + (\mathbf{D}^{ZZ} - \mathbf{D}_{\mathbf{k}\rightarrow 0}^{ZZ} - \mathbf{D}_{\mathbf{k}\rightarrow \mathbf{q}}^{ZZ}) = \mathbf{D}_1^{ZZ} + \mathbf{D}_2^{ZZ}.$$

Integrating over  $k$  and retaining the terms which are proportional to the **second** ( $\sim l_{i,x}^2$ ), **first** ( $\sim l_{i,x}^1$ ) and **zero** ( $\sim l_{i,x}^0$ ) power of **Sudakov logarithms** we get the **asymptotic expressions**.

Using t'Hooft and Veltman'1979 method:

$$\frac{i}{(2\pi)^2} \int d^4k D_1^{ZZ} \approx -\frac{2}{s} (\mathbf{b}_+^{ZZ,k} \mathbf{t}^2 + \mathbf{b}_-^{ZZ,k} \mathbf{u}^2) \left( \frac{\pi^2}{3} + \frac{1}{2} l_{2,t}^2 \right).$$

Using Kahane'1964 method:

$$\frac{i}{(2\pi)^2} \int d^4k D_2^{ZZ} \approx \mathbf{b}_-^{ZZ,k} \mathbf{u} \ln \frac{s}{|\mathbf{t}|} + \left( \mathbf{b}_-^{ZZ,k} \frac{\mathbf{t}^2 + \mathbf{u}^2}{2s} + \mathbf{b}_+^{ZZ,k} \frac{\mathbf{t}^2}{s} \right) \ln^2 \frac{s}{|\mathbf{t}|}.$$

To obtain the  $WW$ -**box contribution** one should:

- 1 to do the trivial substitution  $\mathbf{Z} \rightarrow \mathbf{W}$ ,
- 2 to take into consideration the charge conservation law (some parton  $WW$ -box diagrams are forbidden).

The second feature of  $WW$ -boxes explains the **fact of domination of  $WW$ -box** in comparison with  $ZZ$  (and  $\gamma Z$ )-boxes.

The  $ZZ$ ,  $\gamma Z$ -contributions are proportional to difference

$$I_{Z,t}^2 - I_{Z,u}^2 = \ln \frac{u}{t} (I_{Z,t}^1 + I_{Z,u}^1), \quad (13)$$

whereas the  $WW$ -box does not contain the difference (13) and are proportional to  $I_{W,x}^2$ .

# Photon/gluon bremsstrahlung

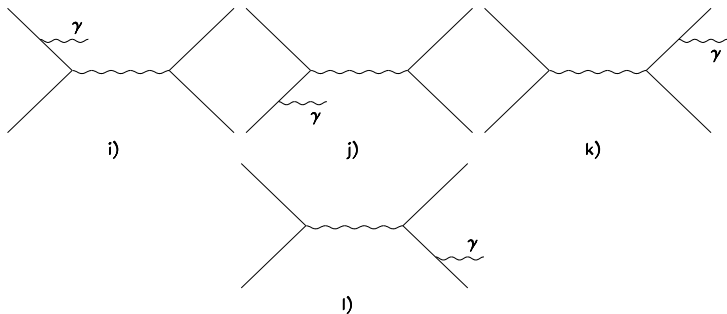


Рис. 7:  $\gamma$  bremsstrahlung diagrams. Unsigned helix lines –  $\gamma$  or  $Z$ .

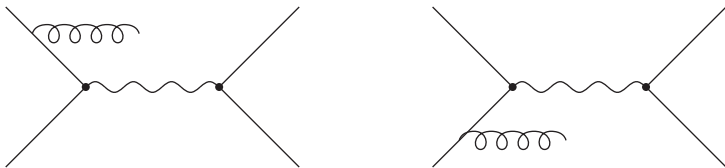


Рис. 8: Gluon bremsstrahlung diagrams.

# Inverse gluon bremsstrahlung

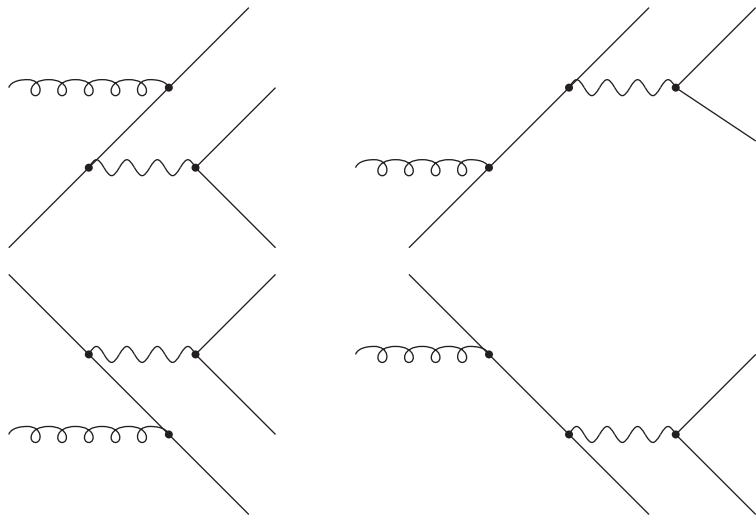


Рис. 9: Inverse gluon bremsstrahlung diagrams

# Phase space via 4 invariants ( $M$ -method)

Phase space looks like

$$I_{\Omega}^6[\mathbf{A}] = \int_0^1 dx_1 \int_0^1 dx_2 \frac{4s}{\pi^2} \int d\Phi \theta_M^R \theta_D^R \mathbf{A},$$

with phase space of 3-particle final state

$$\int d\Phi = \frac{\pi}{4s} \iiint_{\Omega} dt dv dz du_1 \frac{1}{\pi \sqrt{\mathbf{R}_{u_1}}}$$

with Gram determinant  $\mathbf{R}_{u_1}$ , radiative invariants based on 4-momenta of real photon/gluon,  $\mathbf{p}$ :

$$\mathbf{z}_1 = 2\mathbf{p}_1\mathbf{p}, \quad \mathbf{u}_1 = 2\mathbf{p}_2\mathbf{p}, \quad \mathbf{z} = 2\mathbf{k}_1\mathbf{p}, \quad \mathbf{v} = 2\mathbf{k}_2\mathbf{p}.$$

For numerical integration we used Monte Carlo routine based on the **VEGAS** algorithm: **G. Peter Lepage'1978**.

# Phase space in new $G/N$ -method

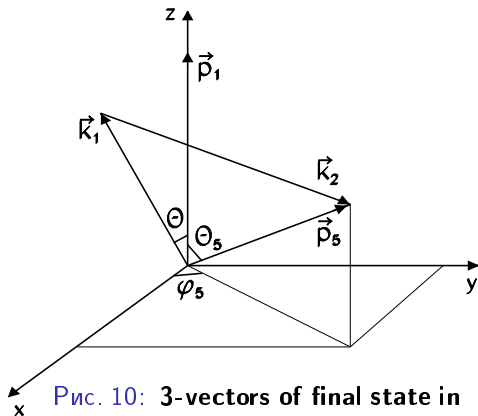


Рис. 10: 3-vectors of final state in c.m.s. of quarks

It is suitable to use

- c.m.s. of quarks,
- reverse vector

$$\vec{p}_5 = -\vec{p}$$

- with

$$\theta_p = \pi - \theta_5, \quad \varphi_p = \pi + \varphi_5.$$

$$\int \mathbf{d}\Phi \dots = \int_{\omega}^{\Omega} \mathbf{p}_0 d\mathbf{p}_0 \int_{-1}^1 \mathbf{d} \cos \theta \int_{-1}^1 \mathbf{d} \cos \theta_p \int_0^{2\pi} \mathbf{d}\varphi_p \frac{\pi |\vec{k}_1| \dots}{4k_{20} K_A(k_{10})}.$$



## Some details of $G/N$ -method

Factor in phase space is

$$K_A(\mathbf{x}) = 1 + \frac{\mathbf{x}(1 - \mathbf{p}_0 \mathbf{A} / \sqrt{\mathbf{x}^2 - m^2})}{\sqrt{\mathbf{x}^2 - 2\mathbf{p}_0 \mathbf{A} \sqrt{\mathbf{x}^2 - m^2} + \mathbf{p}_0^2}},$$

with  $\mathbf{A}$  – cosine between  $\vec{\mathbf{k}}_1$  and  $\vec{\mathbf{p}}_5$ :

$$\mathbf{A} = \sin \theta \sin \theta_5 \cos \varphi_5 + \cos \theta \cos \theta_5.$$

Lepton energy depends on sign of  $\mathbf{A}$ :

$$k_{10} = \frac{\mathbf{BC} \pm \sqrt{\mathbf{C}^2 + m^2(1 - \mathbf{B}^2)}}{1 - \mathbf{B}^2}, \quad (14)$$

where

$$\mathbf{B} = \frac{\sqrt{s} - \mathbf{p}_0}{\mathbf{A}\mathbf{p}_0}, \quad \mathbf{C} = \frac{(2\mathbf{p}_0 - \sqrt{s})\sqrt{s}}{2\mathbf{A}\mathbf{p}_0}. \quad (15)$$

## One usefull possibility of $G/N$ -method

Using  $G/N$ -metod we can combain soft and hard photon/gluon parts to avoid of  $\omega$ -dependance:

$$\text{soft} + \text{hard} = \int_{\lambda}^{\omega} \mathbf{dp}_0 \dots + \int_{\omega}^{\Omega} \mathbf{dp}_0 \dots = \int_{\lambda}^{\Omega} \mathbf{dp}_0 \dots .$$

# Treatment with Soft photon/gluon part

Fin-part (sum of Virtual and Soft photon/gluon part)

$$\sigma_{\text{fin,EWK}}^{\text{q}\bar{\text{q}}} = \frac{\alpha}{\pi} \delta_{\text{EWK}} \sigma_0^{\text{q}\bar{\text{q}}}, \quad \sigma_{\text{fin,QCD}}^{\text{q}\bar{\text{q}}} = \frac{4}{3} \frac{\alpha_s}{\pi} \delta_{\text{QCD}} \sigma_0^{\text{q}\bar{\text{q}}},$$

where

$$\begin{aligned} \delta_{\text{EWK}} = & 2 \ln \frac{2\omega}{\sqrt{s}} \left( Q_q^2 \left( \ln \frac{s}{m_q^2} - 1 \right) - 2Q_q Q_l \ln \frac{t}{u} + Q_l^2 \left( \ln \frac{s}{m^2} - 1 \right) \right) + \\ & + Q_l^2 \left( \frac{3}{2} \ln \frac{s}{m^2} - 2 + \frac{\pi^2}{3} \right) + Q_q^2 \left( \frac{3}{2} \ln \frac{s}{m_q^2} - 2 + \frac{\pi^2}{3} \right) \\ & - Q_q Q_l \left( \ln \frac{s^2}{tu} \ln \frac{t}{u} + \frac{\pi^2}{3} + \ln^2 \frac{t}{u} + 4\text{Li}_2 \frac{-t}{u} \right), \\ \delta_{\text{QCD}} = & 2 \ln \frac{2\omega}{\sqrt{s}} \left( \ln \frac{s}{m_q^2} - 1 \right) + \frac{3}{2} \ln \frac{s}{m_q^2} - 2 + \frac{\pi^2}{3}. \end{aligned}$$

# Rebuilding to fully differential cross section

Here we rebuild all of the cross sections to completely differential form

$$\sigma_{\mathbf{C}} \rightarrow \sigma_{\mathbf{C}}^{(3)} \equiv \frac{d^3\sigma_{\mathbf{C}}}{dM dy d\psi},$$

where

$\mathbf{y} \equiv |\mathbf{y}(\mathbf{l}^- \mathbf{l}^+)|$  – dilepton rapidity,

$\psi$  – cosine of angle between  $\vec{\mathbf{P}}_{\mathbf{A}}$  and  $\vec{\mathbf{k}}_1$ .

For non-radiative part the translation to differential form simply to do using the Jacobian  $\mathbf{J}_{\mathbf{N}}$ :

$$\mathbf{J}_{\mathbf{N}} = \frac{\mathbf{D}(\mathbf{x}_1, \mathbf{x}_2, \mathbf{t})}{\mathbf{D}(\mathbf{M}, \mathbf{y}, \psi)} = \frac{4\mathbf{M}^3 e^{2\mathbf{y}}}{\mathbf{S} [1 + \psi + (1 - \psi) e^{2\mathbf{y}}]^2}.$$

The radiative Jacobian can introduce in the following way

$$\mathbf{J}_{\mathbf{R}}^{(3)} = \frac{4\mathbf{M} e^{2\mathbf{y}}}{\mathbf{S}} \frac{(\mathbf{v} + \mathbf{M}^2)(z_1 + \mathbf{M}^2)(\mathbf{u}_1 + \mathbf{M}^2)}{[(1 + \psi)(z_1 + \mathbf{M}^2) + (1 - \psi) e^{2\mathbf{y}}(\mathbf{u}_1 + \mathbf{M}^2)]^2}.$$

# Leading Logs for **EWK** bremsstrahlung, **QCD** gluon bremsstrahlung, and Inverse Gluon Emission (**IGE**)

Common features of formulas:

- Collinear  $\mathbf{u}_1$ - and  $\mathbf{z}_1$ -peaks for ISR,  $\mathbf{p} = (1 - \eta)\mathbf{p}_{1,2}$ ,  $\gamma/g$  is collinear to  $\mathbf{q}, \bar{\mathbf{q}}$
- Collinear  $\mathbf{z}$ - and  $\mathbf{v}$ -peaks for FSR,  $\mathbf{p} = \frac{1-\eta}{\eta}\mathbf{k}_{1,2}$ ,  $\gamma/g$  is collinear to  $\mu^+, \mu^-$
- Proportional to the Born expressions:  $\mathbf{J}_N$  and  $\mathbf{t}_B^2 + \chi\mathbf{u}_B^2$
- PDFs grouped into combinations  $\mathbf{f}_q^A(\mathbf{x}_1^B)\mathbf{f}_q^B(\frac{\mathbf{x}_2^B}{\eta})$
- EWK/QCD and IGE splitting functions

$$\frac{1 + \eta^2}{\eta} \text{ and } \frac{(1 - \eta)^2 + \eta^2}{\eta}$$

are factorized at Collinear Logs

# Quark Mass Singularity in QED- and QCD-corrections

To solve Quark Mass Singularity (QS) problem in  $\overline{\text{MS}}$ -scheme, then **CL-terms** are adsorbing into PDFs depending on the factorization scale,  $M_{\text{sc}}$ . The part to be subtracted is

$$\sigma_{\text{QS}} = \frac{1}{3} \int \mathbf{d}^3\Gamma \int_0^{1-2\omega/M} \mathbf{d}\eta \sum_{\mathbf{q}=\text{u,d,s,c,b}} \left[ \left( \mathbf{f}_{\mathbf{q}}(\mathbf{x}_1, \mathbf{Q}^2) \Delta \bar{\mathbf{q}}(\mathbf{x}_2, \eta) + \Delta \mathbf{q}(\mathbf{x}_1, \eta) \mathbf{f}_{\bar{\mathbf{q}}}(\mathbf{x}_2, \mathbf{Q}^2) \right) \sigma_0^{\mathbf{q}\bar{\mathbf{q}}} + (\mathbf{q} \leftrightarrow \bar{\mathbf{q}}) \right] \theta_{\mathbf{K}} \theta_{\mathbf{M}} \theta_{\mathbf{D}},$$

$$\Delta \mathbf{q}(\mathbf{x}, \eta) = \mathbf{C}_{\text{RC}} \left[ \frac{1}{\eta} \mathbf{f}_{\mathbf{q}}\left(\frac{\mathbf{x}}{\eta}, \mathbf{M}_{\text{sc}}^2\right) \theta(\eta - \mathbf{x}) - \mathbf{f}_{\mathbf{q}}(\mathbf{x}, \mathbf{M}_{\text{sc}}^2) \right] \frac{1 + \eta^2}{1 - \eta} \times \\ \times \left( \ln \frac{\mathbf{M}_{\text{sc}}^2}{\mathbf{m}_{\mathbf{q}}^2 (1 - \eta)^2} - 1 \right), \quad \mathbf{C}_{\text{QED}} = \frac{\alpha}{2\pi} \mathbf{Q}_{\mathbf{q}}^2, \quad \mathbf{C}_{\text{QCD}} = \frac{4}{3} \frac{\alpha_s}{2\pi}.$$

For IGE the result of QS-term subtraction is trivial:

$$\sigma_{\text{IGE}} - \sigma_{\text{IGE,QS}} = \sigma_{\text{IGE}}(\mathbf{m}_{\mathbf{q}} \rightarrow \mathbf{M}_{\text{sc}}).$$

In the following the scale of radiative corrections and their effect on the observables of Drell–Yan processes will be discussed using FORTRAN program **READY**: (**R**adiative corr**E**ctions to **L**arge invariant mass **D**rell-**Y**an process).

We used the following set of prescriptions:

- the standard PDG set of SM input electroweak parameters:
- the light quark “effective” masses provide  $\Delta\alpha_{\text{had}}^{(5)}(m_Z^2) = 0.0276$ ,
- 5 active flavors of quarks in proton, their masses as regulators of the collinear singularity,
- CTEQ, MRST 2004QED, and MSTW8 sets of PDFs (with the choice  $\mathbf{Q} = \mathbf{M}_{\text{sc}} = \mathbf{M}$ ).

We impose the experimental restriction conditions

- on the detected lepton angle  $-\zeta^* \leq \zeta \leq \zeta^*$  and on the rapidity  $|\mathbf{y}(\mathbf{l})| \leq \mathbf{y}(\mathbf{l})^*$ ; for CMS detector the cut values of  $\zeta^*$  and  $\mathbf{y}(\mathbf{l})^*$  are determined as

$$\mathbf{y}(\mathbf{l})^* = -\ln \tan \frac{\theta^*}{2} = \mathbf{2.5} \text{ (or } = \mathbf{2.4}),$$

- the second standard CMS restriction  $\mathbf{p}_T(\mathbf{l}) \geq \mathbf{20 GeV}$ ,
- the “bare” setup for muons identification requirements (no smearing, no recombination of muon and photon).



Independence of EWK RC from  $\omega$  (GeV) and quark masses  
 at  $\mathbf{l} = \mu$ ,  $\sqrt{\mathbf{S}} = \mathbf{14}$  TeV,  $\mathbf{M} = \mathbf{2}$  TeV,  $\mathbf{y} = \mathbf{0}$ ,  $\psi = \mathbf{0}$

| $\omega$ | $m_q/m_u$ | $\delta_{\text{fin}}$ | $\delta^{\text{hard}}$ | $\delta_{\text{fin}} - \delta_{\text{QS}}^{\text{soft}}$ | $\delta^{\text{hard}} - \delta_{\text{QS}}^{\text{hard}}$ | $\delta_{\text{tot}}$ |
|----------|-----------|-----------------------|------------------------|--|---|-----------------------|
| 10       | 10.0      | -0.4555               | 0.3294                 | -0.3292  | 0.2250  | -0.1042               |
|          | 1.0       | -0.4846               | 0.3527                 | -0.3291  | 0.2250  | -0.1042               |
|          | 0.1       | -0.5136               | 0.3759                 | -0.3291  | 0.2250  | -0.1041               |
| 1        | 10.0      | -0.7117               | 0.5831                 | -0.4862  | 0.3799  | -0.1064               |
|          | 1.0       | -0.7581               | 0.6235                 | -0.4862  | 0.3799  | -0.1064               |
|          | 0.1       | -0.8045               | 0.6639                 | -0.4862  | 0.3799  | -0.1064               |
| 0.1      | 10.0      | -0.9679               | 0.8390                 | -0.6256  | 0.5190  | -0.1066               |
|          | 1.0       | -1.0316               | 0.8967                 | -0.6256  | 0.5190  | -0.1066               |
|          | 0.1       | -1.0953               | 0.9545                 | -0.6256  | 0.5190  | -0.1066               |
| 0.01     | 10.0      | -1.2241               | 1.0951                 | -0.7476  | 0.6410  | -0.1066               |
|          | 1.0       | -1.3052               | 1.1702                 | -0.7476  | 0.6410  | -0.1066               |
|          | 0.1       | -1.3862               | 1.2454                 | -0.7476  | 0.6410  | -0.1066               |
| 0.001    | 10.0      | -1.4803               | 1.3513                 | -0.8522  | 0.7456  | -0.1066               |
|          | 1.0       | -1.5787               | 1.4438                 | -0.8522  | 0.7456  | -0.1066               |
|          | 0.1       | -1.6771               | 1.5362                 | -0.8522  | 0.7456  | -0.1066               |

Independence of QCD RC from  $\omega$  (GeV) and quark masses  
 at  $\mathbf{l} = \mu$ ,  $\sqrt{\mathbf{S}} = \mathbf{14}$  TeV,  $\mathbf{M} = \mathbf{2}$  TeV,  $\mathbf{y} = \mathbf{0}$ ,  $\psi = \mathbf{0}$

| $\omega$ | $m_q/m_u$ | $\delta_{\text{fin}}$ | $\delta^{\text{hard}}$ | $\delta_{\text{fin}} - \delta_{\text{QS}}^{\text{soft}}$ | $\delta^{\text{hard}} - \delta_{\text{QS}}^{\text{hard}}$ | $\delta_{\text{tot}}$ |
|----------|-----------|-----------------------|------------------------|--|---|-----------------------|
| 10       | 10.0      | -5.6024               | 4.5893                 | 2.1076   | -1.7306   | 0.3770                |
|          | 1.0       | -7.3746               | 5.9937                 | 2.1122   | -1.7306   | 0.3815                |
|          | 0.1       | -9.1469               | 7.3980                 | 2.1167   | -1.7306   | 0.3861                |
| 1        | 10.0      | -9.0318               | 7.9905                 | 4.7309   | -4.3551   | 0.3758                |
|          | 1.0       | -11.8625              | 10.4443                | 4.7313   | -4.3551   | 0.3762                |
|          | 0.1       | -14.6932              | 12.8982                | 4.7318   | -4.3551   | 0.3767                |
| 0.1      | 10.0      | -12.4611              | 11.4170                | 8.4329   | -8.0567   | 0.3762                |
|          | 1.0       | -16.3503              | 14.9284                | 8.4329   | -8.0567   | 0.3762                |
|          | 0.1       | -20.2395              | 18.4399                | 8.4330   | -8.0567   | 0.3763                |
| 0.01     | 10.0      | -15.8905              | 14.8461                | 13.1958  | -12.8196  | 0.3763                |
|          | 1.0       | -20.8382              | 19.4159                | 13.1958  | -12.8196  | 0.3763                |
|          | 0.1       | -25.7858              | 23.9858                | 13.1959  | -12.8196  | 0.3763                |
| 0.001    | 10.0      | -19.3198              | 18.2754                | 19.0175  | -18.6412  | 0.3763                |
|          | 1.0       | -25.3260              | 23.9037                | 19.0175  | -18.6412  | 0.3763                |
|          | 0.1       | -31.3322              | 29.5321                | 19.0175  | -18.6412  | 0.3763                |

# Comparison at Hadronic Level

$$\frac{d\sigma}{dMdy} = \int_{-\zeta^*}^{\zeta^*} d\psi \sigma^{(3)} \theta_D; \quad \frac{d\sigma}{dM} = \int_{-\zeta^*}^{\zeta^*} d\psi \int_{-\ln \frac{\sqrt{s}}{M}}^{+\ln \frac{\sqrt{s}}{M}} dy \sigma^{(3)} \theta_D.$$

Comparing the relative EWK RC to  $d\sigma/dM$  with the results of

- **HORACE** (C. M. Carloni Calame, G. Montagna, O. Nicrosini, A. Vicini // JHEP. 2007. Vol. 10. P. 109, arXiv:0710.1722)
- **SANC** (A. Andonov *et al.* Comput. Phys. Commun. 2006. Vol. 174. P. 481 [hep-ph/0411186])
- **ZGRAD2** (U. Baur *et al.* Phys. Rev. D. 2002. Vol. 65, 033007, P. 1–19. [hep-ph/0108274])

published in Proc. of Les Houches 2007, Physics at TeV colliders, arXiv:0803.0678 [hep-ph] we have a good agreement at  $M \geq 0.5$  TeV.

# Comparison of $M$ -distribution

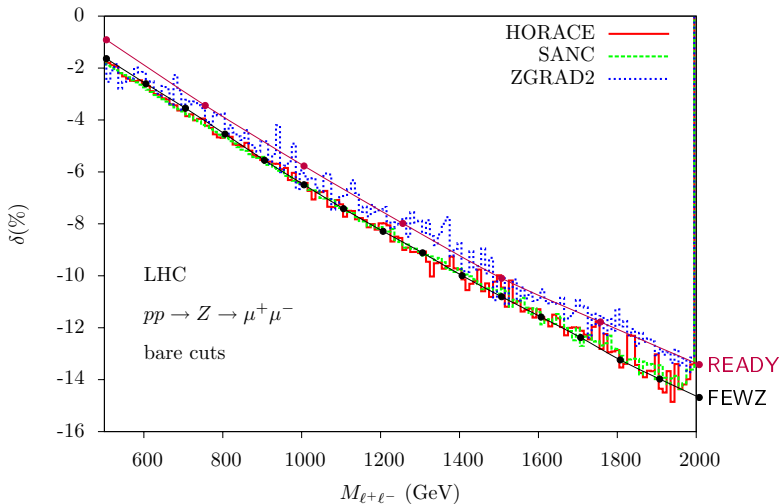


Рис. 11: Relative electroweak corrections  $\delta(\%)$  to  $d\sigma/dM$  vs  $M$ .  
READY accuracy is  $< 0.1\%$ , a time per dot is  $\sim 1200$  s.

# Comparison of forward-backward asymmetry

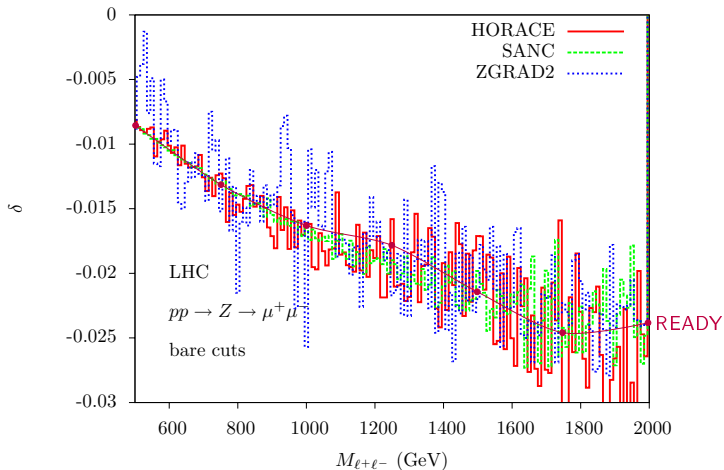


Рис. 12: The difference between the NLO and LO predictions for  $A_{FB}$  due to electroweak corrections.

# READY5.4 settings

Form of in54.dat input-file:

```
1      ! 1=PDG'08, 2=arXiv:1606.02330
2      ! 1=d $\sigma$ /dM/dy/d $\psi$ , 2=d $\sigma$ /dM, 4=AFB
1      ! 1=EWK, 2=QCD, 3=EWK+QCD
1      ! 1=muon, 2=electron
4      ! 1,2,3-CTEQ (MSbar,DIS,LO), 4-MRST4, 5-MSTW8, ...
10000      ! base number of iterations by VEGAS
13000.     ! LHC energy, GeV
0.986614  ! y limitation of CMS (y=2.5, cos(a)=0.986614)
20.0      ! pT limitation of CMS (20 GeV)
```

Contributions needed to calculate (in order of difficulty increasing):

- FSR radiation (EWK)
- ISR radiation (EWK and QCD)
- Their interference and interplay

Simplest (but principal) part of NNLO radiative correction is NNLO QED FSR contribution.

To get it we need to calculate

- **Q-part:**  
Quadratic NLOs, or square of one-loop NLO FSR corrections
- **T-part:**  
all Two-loop FSR diagrams with photon
- **O-part:**  
One-photon emission with NLO V-contributions (soft and hard)
- **D-part:**  
Double-photon emission (soft and hard)



# NNLO QED FSR with **soft real photons**

Summing up  $Q$ -,  $T$ -,  $O$ -,  $D$ -parts (and subtracting  $R$ -part) on partonic level we get:

$$\begin{aligned}\sigma_{\text{NNLO}} &= \sigma_Q + \sigma_T + \sigma_O + \sigma_D - \sigma_R = \\ &= \sigma_0 \left[ |\mathbf{F}^{(1)}(\mathbf{s})|^2 + 2\text{Re}\mathbf{F}^{(2)}(\mathbf{s}) + \delta_1^{\mathbf{S}} \cdot 2\text{Re}\mathbf{F}^{(1)}(\mathbf{s}) + \frac{1}{2}(\delta_1^{\mathbf{S}})^2 - \right. \\ &\quad \left. - \frac{1}{2} \left( \frac{\alpha}{\pi} \right)^2 \frac{2}{3} \pi^2 (\mathbf{L} - \mathbf{1})^2 \right].\end{aligned}$$

All important form factors  $\mathbf{F}^{(1)}(\mathbf{s})$ ,  $\mathbf{F}^{(2)}(\mathbf{s})$ , and  $\delta_1^{\mathbf{S}}$  expressed via three logarithms – **collinear**, **infrared**, and **soft** ones:

$$\mathbf{L} = \log \frac{\mathbf{s}}{\mathbf{m}^2}, \quad \mathbf{L}_\lambda = \log \frac{\lambda^2}{\mathbf{m}^2}, \quad \mathbf{L}_\omega = \log \frac{2\omega}{\sqrt{\mathbf{s}}},$$

where  $\lambda$  is **mass** of internal virtual photon,  $\omega$  is **maximal energy** of soft real photon.

# One-loop form factors via logs

$$\mathbf{F}^{(1)}(\mathbf{s}) = \frac{\alpha}{\pi} \left[ -\frac{1}{4}\mathbf{L}^2 + \frac{1}{2}\mathbf{L}_\lambda\mathbf{L} + \frac{3}{4}\mathbf{L} - \frac{1}{2}\mathbf{L}_\lambda - 1 + \frac{\pi^2}{3} + \right. \\ \left. + i\pi \left( \frac{1}{2}\mathbf{L} - \frac{1}{2}\mathbf{L}_\lambda - \frac{3}{4} \right) \right],$$

$$\delta_1^{\mathbf{S}} = \frac{\alpha}{\pi} \left[ \frac{1}{2}\mathbf{L}^2 - \mathbf{L}_\lambda\mathbf{L} + 2\mathbf{L}_\omega\mathbf{L} + \mathbf{L}_\lambda - 2\mathbf{L}_\omega - \frac{\pi^2}{3} \right],$$

where

$$\mathbf{L} = \log \frac{\mathbf{s}}{\mathbf{m}^2}, \quad \mathbf{L}_\lambda = \log \frac{\lambda^2}{\mathbf{m}^2}, \quad \mathbf{L}_\omega = \log \frac{2\omega}{\sqrt{\mathbf{s}}}.$$

## Two-loop form factor via logs

$$\begin{aligned} \text{Re}\mathbf{F}^{(2)}(\mathbf{s}) = & \left(\frac{\alpha}{\pi}\right)^2 \left[ \frac{1}{32}\mathbf{L}^4 - \frac{3}{16}\mathbf{L}^3 + \left(\frac{17}{32} - \frac{5}{4}\zeta_2\right)\mathbf{L}^2 \right. \\ & + \left(-\frac{21}{32} + 3\zeta_2 + \frac{3}{2}\zeta_3\right)\mathbf{L} + \frac{2}{5}\zeta_2^2 - \frac{9}{4}\zeta_3 - 3\zeta_2 \log 2 \\ & - \frac{1}{2}\zeta_2 + \frac{405}{216} + \mathbf{L}_\lambda^2 \left(\frac{1}{8}\mathbf{L}^2 - \frac{1}{4}\mathbf{L} + \frac{1}{8} - \frac{3}{4}\zeta_2\right) \\ & \left. + \mathbf{L}_\lambda \left(-\frac{1}{8}\mathbf{L}^3 + \frac{1}{2}\mathbf{L}^2 + \left(-\frac{7}{8} + \frac{5}{2}\zeta_2\right)\mathbf{L} + \frac{1}{2} - \frac{13}{4}\zeta_2\right) \right]. \end{aligned}$$

This is result of **F.A. Berends, W.L. Van Neerven, G.J.H. Burgers** (Nucl. Phys. B., 1988, Vol. 297, 429).

# Choice of maximal energy of soft real photon

Crucial importance is the choice of  $\omega$  to correspond to experimental situation of CMS LHC detector.

We used effective values at each kinematical point which reproduce exact (with hard photon taking into account) relative correction to cross section.

| $M, \text{ TeV}$ | $\delta_{\text{EWK}}$ | $\omega_{\text{eff}}/\sqrt{S}$ |
|------------------|-----------------------|--------------------------------|
| 0.5              | -0.0094               | 0.0032                         |
| 1.0              | -0.0582               | 0.0057                         |
| 1.5              | -0.1016               | 0.0077                         |
| 2.0              | -0.1350               | 0.0097                         |

# The $\lambda^2$ -independence of FSR NNLO result, $\mu$ -case

The relative corrections to the cross section  $d\sigma/dM$  at  $M = 2$  TeV,  $\mu$ -case, inducing different contributions to FSR NNLO correction

$$\text{NNLO} = Q + T + O + D - R$$

depending on  $\lambda^2$ , where  $\lambda^2 = 10^n$  GeV.

| $n$ | $Q$     | $T$     | $O$      | $D$     | $R$     | NNLO     |
|-----|---------|---------|----------|---------|---------|----------|
| -7  | 0.20371 | 0.18014 | -0.67833 | 0.29976 | 0.00620 | -0.00092 |
| -8  | 0.25185 | 0.22449 | -0.85315 | 0.38209 | 0.00620 | -0.00092 |
| -9  | 0.30522 | 0.27377 | -1.04826 | 0.47455 | 0.00620 | -0.00092 |
| -10 | 0.36375 | 0.32793 | -1.26345 | 0.57705 | 0.00620 | -0.00092 |
| -11 | 0.42740 | 0.38694 | -1.49859 | 0.68950 | 0.00620 | -0.00092 |
| -12 | 0.49620 | 0.45079 | -1.75374 | 0.81192 | 0.00620 | -0.00092 |

# The $\lambda^2$ -independance of FSR NNLO result, e-case

The relative corrections to the cross section  $d\sigma/dM$  at  $M = 2$  TeV, e-case, inducing different contributions to FSR NNLO correction depending on  $\lambda^2$ , where  $\lambda^2 = 10^n$  GeV.

| $n$ | $Q$     | $T$     | $O$      | $D$     | $R$     | NNLO     |
|-----|---------|---------|----------|---------|---------|----------|
| -7  | 0.27168 | 0.24818 | -0.87264 | 0.36633 | 0.01530 | -0.00175 |
| -8  | 0.35980 | 0.33250 | -1.19183 | 0.51308 | 0.01530 | -0.00175 |
| -9  | 0.46035 | 0.42897 | -1.56021 | 0.68444 | 0.01530 | -0.00175 |
| -10 | 0.57337 | 0.53764 | -1.97792 | 0.88046 | 0.01530 | -0.00175 |
| -11 | 0.69889 | 0.65851 | -2.44497 | 1.10116 | 0.01530 | -0.00175 |
| -12 | 0.83677 | 0.79156 | -2.96146 | 1.34636 | 0.01530 | -0.00175 |

We control the cancellation of collinear logs of highest orders – NNLO result contains only  $\mathbf{L}^2$ ,  $\mathbf{L}^1$ , and  $\mathbf{L}^0$ :

$$\sigma_{\text{NNLO}} = \left(\frac{\alpha}{\pi}\right)^2 \left[ \mathbf{c}_2 \mathbf{L}^2 + \mathbf{c}_1 \mathbf{L} + \mathbf{c}_0 \right] \sigma_0,$$

where

$$\mathbf{c}_2 = 2\mathbf{L}_\omega^2 + 3\mathbf{L}_\omega - 2\zeta_2 + \frac{9}{8},$$

$$\mathbf{c}_1 = -4\mathbf{L}_\omega^2 + \mathbf{L}_\omega(4\zeta_2 - 7) + \frac{11\zeta_2}{2} + 3\zeta_3 - \frac{45}{16},$$

$$\mathbf{c}_0 = 2\mathbf{L}_\omega^2 + 4\mathbf{L}_\omega(1 - \zeta_2) - \frac{6\zeta_2^2}{5} + \frac{3\zeta_2}{8} - 6\zeta_2 \ln 2 - \frac{9\zeta_3}{2} + \frac{19}{4}.$$

# Conclusions

- The NLO EWK+QCD and “soft” FSR NNLO RC to Drell–Yan process at **extra large  $M$**  in **fully differential form** have been studied.
- The results are **the compact expressions**, they expand in Sudakov and collinear logarithms.
- The new  $G/N$ -method of taking into account of radiative events without any approximations is demonstrated.
- At the parton/hadron level FORTRAN **code READY** gives a good coincidence for cross section and  $A_{\text{FB}}$  with other groups at  $M > 0.5$  TeV and **fast convergence**.
- We have first result on NNLO RC to Drell–Yan process. Our next steps are taking into account hard photons in FSR NNLO order, ISR QED and QCD modes, their interplay, etc.



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