SANC project and QED DGLAP evolution

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OUTLINE

MOTIVATION

- The main problem of particle physics today is to define the energy domain of the SM applicability
- Very accurate experimental data should be confronted high-precision theoretical predictions
- Searches for new physics require SM predictions as well
- Absence of clear signals of SUSY etc. at LHC makes SM studies more and more actual.
- Tevatron has proved that a hadron collider can make precision measurements of EW processes. E.g. Tevatron reached the precision of M_W measurement better than LEP.
- For high-precision theoretical predictions we need to take into account many effects of different kind
- The predictions should be presented in a form suitable to be used in the data analysis

THE SANC PROJECT

SANC is a project to Support of Analytic and Numeric calculations for experiments at Colliders

SANC team:
D.Yu. Bardin, L.V. Kalinovskaya (leaders)
P.Ch. Christova, V.A. Kolesnikov, L.A. Rumyantsev, R.R. Sadykov, A.A. Sapronov, E.D. Uglov — DLNP, JINR, Dubna, Russia;
A.B. Arbuzov, S.G. Bondarenko — BLTP, JINR, Dubna, Russia;

G. Nanava — Scientific Computing Team Leader, Leibniz Universitat, Hannover, Germany;
Z. Was — IFJ, PAN, Krakow, Poland;
Lucia Di Ciaccio — ATLAS group of LAPP, Laboratoire d'Annecy-le-Vieux de physique des particules (LAPP), Annecy;
U. Klein, A. Glazov, J. Kretzschmar — CERN, DESY and University of Liverpool, England.

ROOTS OF SANC: ZFITTER

`ZFITTER` is a `Fortran` program for the calculation of fermion pair production and radiative corrections at high energy e^+e^- colliders. It is also suitable for other applications where electroweak radiative corrections appear.

Authors: D. Bardin et al.

`http://zfitter.com`,
`http://sanc.jinr.ru/users/zfitter`

T. Riemann (spokesperson since 2005)

ZFITTER code v.6.42 is described in *Comp.Phys.Comm.*'2006.

Review and status of the project: *Phys.Part.Nucl.*'2014.

ZFITTER is a semi-analytic code

The code is still supported and used

ROOTS OF SANC: HECTOR

A. Arbuzov, D. Y. Bardin, J. Blumlein, L. Kalinovskaya and T. Riemann,
"Hector 1.00: A Program for the calculation of QED, QCD and electroweak corrections to e p and lepton+- N deep inelastic neutral and charged current scattering,"
Comput. Phys. Commun. 94 (1996) 128

The proper treatment of QED corrections to DIS is important for fits of QED effects in PDFs

PHASES OF THE SANC PROJECT

First phase (2001-2005). The computer system SANC – v1.10 for semi-automatic calculations at the one-loop precision level (EW and QCD) has been created. The main results published in CPC '2006. The SANC system was made publicly available for external users at http://sanc.jinr.ru

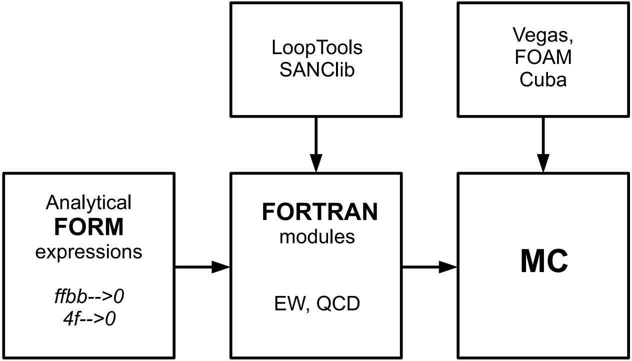
Second phase (2006–2009). The concept of SSFM (Standard SANC FORM/ FORTRAN Modules), aimed for usage in physical applications, was realized [CPC '2010]

Third phase (2010–present). Physical applications of SANC Monte Carlo Integrators and Generators based on the SSFM. Meantime, modules for several more processes were implemented into SANC framework: top quark decays, QCD corrections to Drell–Yan, 4-boson processes and single top quark production.

SANC FRAMEWORK

- The SANC system implements calculations of complete (real and virtual) NLO QCD and EW corrections for various processes at the partonic level. Virtual corrections are received as form factors at different Lorentz structures
- All calculations are performed within the on-mass-shell renormalization scheme in the R_ξ gauge which allows an explicit control of the gauge invariance
- Cross-sections of the processes at hadron level obtained by convolution the partonic level cross-sections with PDFs
- The list of processes implemented in the `MCSANC` integrator includes Drell-Yan processes (inclusive), associated Higgs and gauge boson production and single-top quark production in s- and t-channel [S.Bondarenko et al., CPC '2013].

SANC FRAMEWORK SCHEME



DRELL-YAN PROCESSES

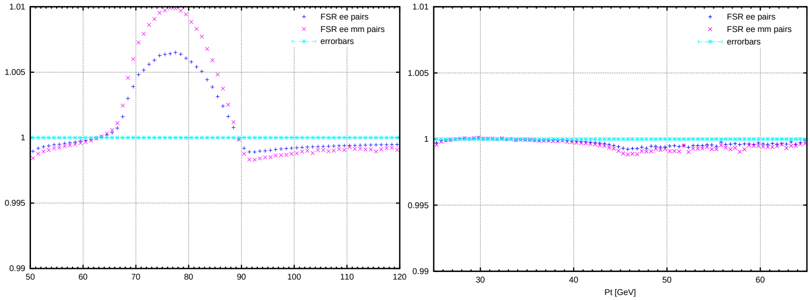
Drell-Yan (DY) processes at hadron colliders have clean signature and high statistics

They provide ultimately important tools for:

- EW tests, W mass and width measurement;
- PDF extraction;
- detector calibration;
- luminosity monitoring;
- background to many other processes;
- new physics searches

The precision tag (bin-by-bin) is about 1% or even better (?)

DRELL-YAN PROCESSES: LIGHT PAIR RC



Relative light pair corrections to invariant mass (left) and transverse momentum (right) distribution in $\mu^+\mu^-$ production.

Comparisons with pair emission, realized in PHOTOS, are in progress.

SIZE OF QED AND QCD EFFECTS

Typical size of QED (EW) corrections for sufficiently inclusive observables - a few percent: $\sim \alpha = 1/137$

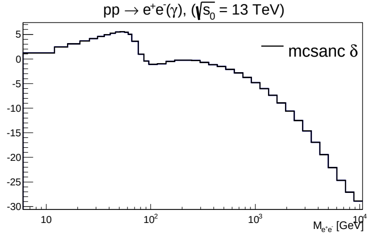
Typical size of QCD corrections is one order larger ~ 10 percent: $\alpha_s(M_Z) \approx 0.12$

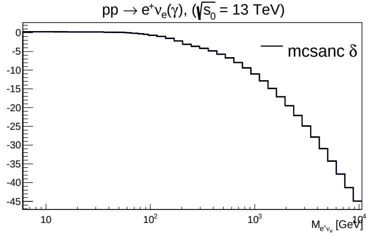
$pp \to +$	$Z^0(\mu^+\mu^-)$	$W^+(\mu^+\nu_\mu)$	$W^-(\mu^-\bar{\nu}_\mu)$
$\sigma_{\rm LO}$ (MCSANC), pb	3338(1)	10696(1)	7981(1)
$\sigma_{\rm LO}$ (MCFM), pb	3338(1)	10696(1)	7981(1)
$\sigma_{\rm NLO\ QCD}$ (MCSANC), pb	3388(2)	12263(4)	9045(4)
$\sigma_{\rm NLO\ QCD}$ (MCFM), pb	3382(1)	12260(1)	9041(5)
$\sigma_{\rm NLO\ EW}$ (MCSANC), pb	3345(1)	10564(1)	7861(1)
$\delta_{\rm QCD}$, %	1.49(3)	14.66(1)	13.35(3)
$\delta_{\rm EW}$, %	0.22(1)	-1.23(1)	-1.49(1)

[JETP Lett. ’2015]

N.B. Conditions for QCD effects are typically more “inclusive” than for QED ones (remind muons)

MCSANC v.1.20: missed corrections to DY





δ_{MISS} [%] contribution to $pp \to e^+e^-(\gamma)$ (left) and $pp \to e^+\nu_e(\gamma)$ (right) at $\sqrt{s} = 13$ TeV.

INTERPLAY OF QCD AND EW RC

Two methods of combination of HO EW and QCD corrections in the theoretical predictions were compared in [arXiv:1405.1067]

• **Factorized approach**, in which it is assumed that the HO EW corrections are the same for all orders of QCD and thus can be determined at LO QCD in terms of *K*-factors and then transferred to any higher order of QCD

$$\sigma_{NNLO_{QCD},NLO_{EW}} = K_{EW} \times \sigma_{NNLO_{QCD}}, \qquad K_{EW} = \frac{\sigma_{NLO_{EW}}}{\sigma_{LO}}$$

• **Additive approach** assumes that HO EW corrections (except QED FSR) are largely additive and the same term needs to be added to all orders of QCD

$$\begin{aligned} \sigma_{NNLO_{QCD},NLO_{EW}} &= \sigma_{NNLO_{QCD}} + \Delta\sigma_{NLO_{EW}}, \\ \Delta\sigma_{NLO_{EW}} &= \sigma_{NLO_{EW}} - \sigma_{LO}. \end{aligned}$$

This approach is implemented in FEWZ 3.1.b2.

For this comparison the electroweak corrections implemented in FEWZ were thoroughly cross checked with MCSANC code in electroweak G_μ scheme and found to be consistent over wide dilepton invariant mass range and gauge boson rapidity

QED STRUCTURE FUNCTIONS

In the Leading Logarithmic Approximation (LLA) the QED structure function method was developed in [E.A. Kuraev, V.S. Fadin, Yad.Fiz. ′1985]

Earlier it was applied to neutrino DIS in [J.F. Wheater, C. H. Llewellyn Smith, NPB ′1982]

The next-to-leading log approximation ($\sim$ *NLO*) for QED structure functions was first developed in [F.A.Berends, W.L.van Neerven, G.J.Burgers, NPB ′1988]

And then extended in [A.Arbuzov, K.Melnikov, PRD ′2002; JHEP ′2003]

Application to DIS [J. Blumlein, H. Kawamura, PLB ′2003]

PURE QED NLO FACTORIZATION

$$\mathrm{d}\sigma = \sum_{a,b,c,d} \int_{\bar{z}_1}^{1} \mathrm{d}z_1 \int_{\bar{z}_2}^{1} \mathrm{d}z_2 \mathcal{D}_{ae}^{\mathrm{str}}(z_1) \mathcal{D}_{be}^{\mathrm{str}}(z_2) \Big(\mathrm{d}\sigma_{ab\to cd}^{\mathrm{Born}}(z_1, z_2) + \mathrm{d}\bar{\sigma}^{(1)}(z_1, z_2)$$

$$+\mathcal{O}\left(\alpha^2 L^0\right)\Big) \int_{\bar{y}_1}^{1} \frac{\mathrm{d}y_1}{Y_1} \int_{\bar{y}_2}^{1} \frac{\mathrm{d}y_2}{Y_2} \mathcal{D}_{ec}^{\mathrm{frg}}\left(\frac{y_1}{Y_1}\right) \mathcal{D}_{ed}^{\mathrm{frg}}\left(\frac{y_2}{Y_2}\right)$$

$$\mathcal{D}_{ee}^{\mathrm{str},\mathrm{frg}}(z) = \delta(1-z) + \frac{\alpha}{2\pi} d_1(z, \mu_0, m_e) + \frac{\alpha}{2\pi} L P^{(0)}(z)$$

$$+\left(\frac{\alpha}{2\pi}\right)^2 \Big(\frac{1}{2} L^2 P^{(0)} \otimes P^{(0)}(z) + L P^{(0)} \otimes d_1(z, \mu_0, m_e)$$

$$+L P_{ee}^{(1;\gamma,pair)\mathrm{str},\mathrm{frg}}(z) \Big) + \mathcal{O}\left(\alpha^2 L^0, \alpha^3\right)$$

$$L \equiv \ln \frac{Q^2}{\mu_0^2} \qquad \mathrm{d}\bar{\sigma}^{(1)} = \mathrm{d}\sigma^{(1)}\Big|_{m_e=0,\ \overline{\mathrm{MS}}}, \qquad P^{(0)}(z) = \left[\frac{1+z^2}{1-z}\right]_+$$

$$d_1(z, \mu_0, m_e) = \left[\frac{1+z^2}{1-z}\left(\ln\frac{\mu_0^2}{m_e^2} - 2\ln(1-z) - 1\right)\right]_+$$

PURE QED EVOLUTION EQUATIONS

The LO evolution equation for non-singlet part of electron structure function:

$$\mathcal{D}_{ee}^{NS}(z,Q^2) = \delta(1-z) + \int\limits_{m^2}^{Q^2} \frac{\alpha(q^2)}{2\pi}\,\frac{\mathrm{d}q^2}{q^2} \int\limits_{z}^{1} \frac{\mathrm{d}x}{x}\, P_{ee}^{(0)}(x)\mathcal{D}_{ee}^{NS}(\frac{z}{x},q^2)$$

Very similar to QCD…

BUT! A few things a different:

• QED evolution equations can be solved perturbatively

• QED renormalization scale is typically chosen to be equal to electron mass

Because of pure resolved initial states at e^+e^- colliders we have huge ISR leading log corrections there. While for *pp* we do not feel the large logs.

INTERPLAY OF QCD AND QED EVOLUTION

Leading QCD and QED contributions to the quark density function are similar:

$$\frac{\alpha_s}{2\pi} C_F \left[\frac{1+x^2}{1-x}\right]_+ \ln\frac{Q^2}{\mu^2_{\text{QCD}}} \quad \text{versus} \quad \frac{\alpha}{2\pi} Q_q^2 \left[\frac{1+x^2}{1-x}\right]_+ \ln\frac{Q^2}{\mu^2_{\text{QED}}}$$

So neglecting QED contribution leads to an effective shift of the strong coupling constant:

$$\alpha_s^{\text{eff}} \approx \alpha_s + \alpha \frac{Q_q^2}{C_F}$$

N.B. The large logs in QCD and QED evolution are exactly the same by construction, while the choices of the factorization scale $\sqrt{Q^2}$ and the renormalization scale μ might be different depending on experimental conditions

QED-MODIFIED DGLAP EVOLUTION

QED-modified DGLAP evolution equations for PDFs of quarks $q_i(x,\mu_F^2)$, anti-quarks $\bar{q}_i(x,\mu_F^2)$, gluons $g(x,\mu_F^2)$, and photons $\gamma(x,\mu_F^2)$:

$$\frac{\partial q_i}{\partial \ln \mu^2} = \sum_{j=1}^{n_f} P_{q_i q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{q_i \bar{q}_j} \otimes \bar{q}_j + P_{q_i g} \otimes g + P_{q_i \gamma} \otimes \gamma,$$

$$\frac{\partial \bar{q}_i}{\partial \ln \mu^2} = \sum_{j=1}^{n_f} P_{\bar{q}_i q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{\bar{q}_i \bar{q}_j} \otimes \bar{q}_j + P_{\bar{q}_i g} \otimes g + P_{\bar{q}_i \gamma} \otimes \gamma,$$

$$\frac{\partial g}{\partial \ln \mu^2} = \sum_{j=1}^{n_f} P_{g q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{g \bar{q}_j} \otimes \bar{q}_j + P_{gg} \otimes g,$$

$$\frac{\partial \gamma}{\partial \ln \mu^2} = \sum_{j=1}^{n_f} P_{\gamma q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{\gamma \bar{q}_j} \otimes \bar{q}_j + P_{\gamma\gamma} \otimes \gamma.$$

See details in talk by Renat Sadykov

OUTLOOK

- For high-precision studies at hadron colliders QED and EW effects are important
- Interplay of EW and QCD RC to DY: implementation of $\mathcal{O}(\alpha\alpha_s)$ RC with matching to existing results
- Photon-induced sub-processes become important at the TeV-range of invariant masses and momentum transfer
- Collaboration between SANC and xFitter (and others) is fruitful and necessary
- QED evolution in PDFs should be done for:

  — consistent treatment of QCD observables
  — calculation of photon-induced sub-processes
  — resolution of QED initial state radiation
- NLO QED evolution ...