Project SANC and applications to ATLAS

Andrej Arbuzov
BLTP, JINR, Dubna

(on behalf of the SANC team)

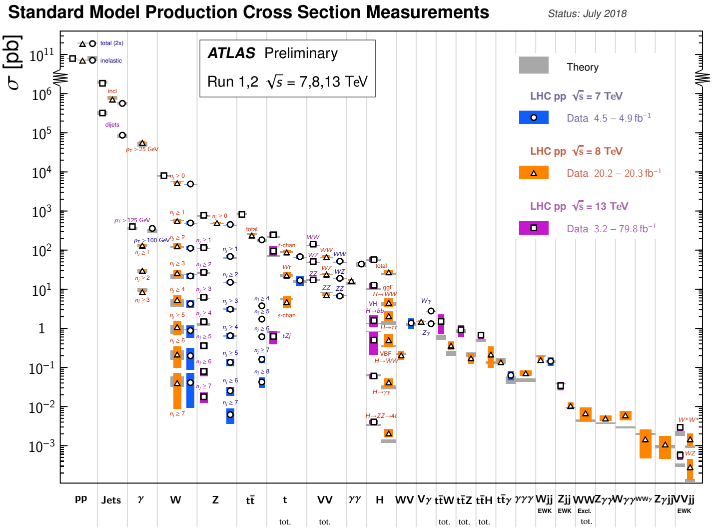
July 23rd, CALC-2018, Dubna

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

MOTIVATION (II)



SM cross sections measured by ATLAS (public results 2018)

The SANC project

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;

W. von Schlippe — Queen Mary Uni., London, UK;
G. Nanava — 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, UK.

+ students

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)

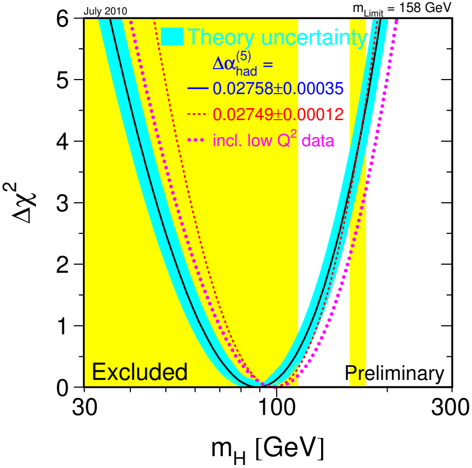
ZFITTER code v.6.42 is described in *Comp.Phys.Comm.*'2006.

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

ZFITTER is a semi-analytic code

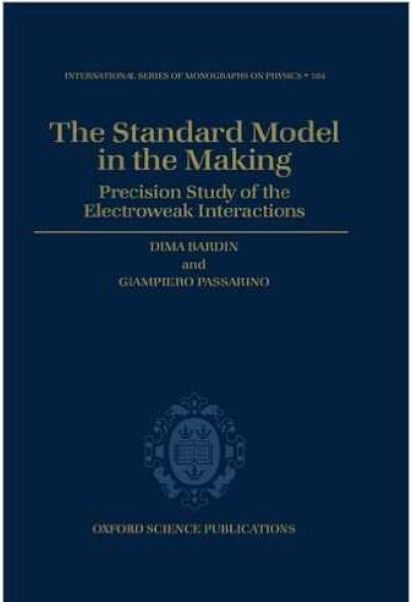
The code is still supported and used

ROOTS OF SANC: ZFITTER



LEP EW working group, report 2010.

ROOTS OF SANC: THE BOOK



Oxford, UK: 1999, 685pp.

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]

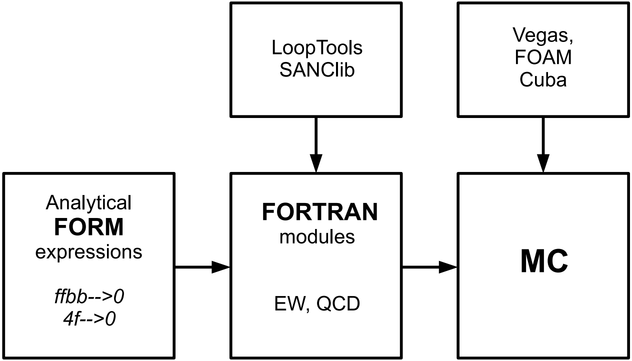
Third phase (2010–2018). Physical applications of SANC Monte Carlo Integrators and Generators based on the SSFM. Meantime, modules for several more processes were implemented into SANC framework: top quark decays, QCD corrections to Drell–Yan, 4-boson processes, and single top quark production.

Future plans. See talks by Renat Sadykov and Yahor Dydyshka

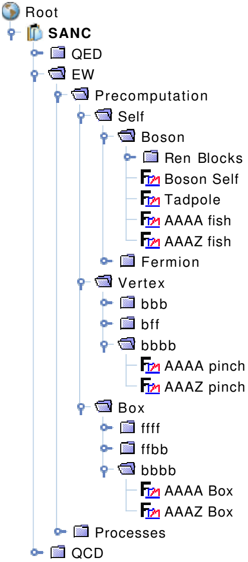
SANC FRAMEWORK

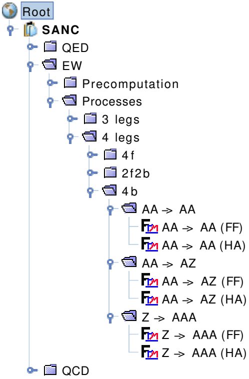
- The SANC system implements calculations of complete (real and virtual) NLO QCD and EW corrections for various processes at the partonic level. Virtual corrections are received as form factors at different Lorentz structures
- All calculations are performed within the on-mass-shell renormalization scheme 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 v.1.20` integrator includes Drell-Yan processes, associated Higgs and gauge boson production, single-top quark production in *s*- and *t*-channel [D.Bardin et al., CPC '2013; JETP Lett. 2016].

SANC FRAMEWORK SCHEME

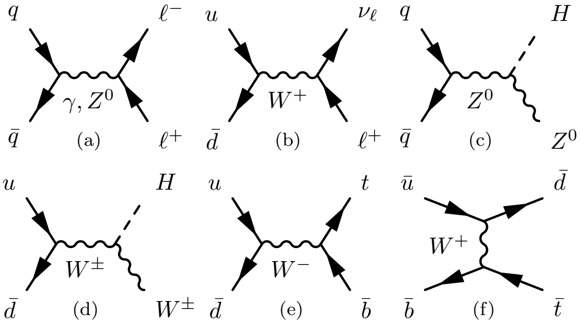


SANC process example: $Z\gamma\gamma\gamma \to 0$





MCSANC INTEGRATOR



Feynman graphs for tree level Drell-Yan process neutral (*a*) and charged (*b*) currents, Higgs and gauge boson production neutral (*c*) and charged (*d*) currents, and single top-quark production s-channel (*e*) and t-channel (*f*) implemented in the MCSANC integrator [CPC '2013].

Version 1.20 of MCSANC is described in [JETP Lett. '2016]

TUNED COMPARISONS (I)

Besides internal validation, SANC participated in many tuned comparisons with other codes

• Workshops: Les Houches, Tev4LHC, W-mass, etc. — comparisons between bunches of codes like `SANC, HORACE, ZGRAD2, WGRAD2, WINHAC, DK, FEWZ, ...`

• Tête-á-tête comparisons — to test particular effects, e.g. `SANC/PHOTOS` (FSR), `SANC/READY` (virtual EW), `SANC/DK` (photon induced) etc.

• Even at the lowest order, comparisons with `PYTHIA` and `HERWIG` help to define input parameters there

Tuned comparisons are time and effort consuming but useful

N.B. SANC modules with EW corrections were implemented in `WINHAC` [D.Bardin et al., Acta Phys. Pol. '2009]

TUNED COMPARISONS (II)

Recent analysis of tuned comparisons were published in [S. Alioli, A.A., D.Yu. Bardin at al., Precision Studies of Observables in $pp \to W \to l\nu_l$ and $pp \to \gamma, Z \to l^+l^-$ processes at the LHC, EPJC 77 (2017) 280]

The report was prepared within the LPCC Electroweak Precision Measurements at the LHC WG

http://lpcc.web.cern.ch/electroweak-precision-measurements-lhc-wg

Monte Carlo codes participated:
DYNNLO, DYNNLOPS, FEWZ, HORACE, PHOTOS, POWHEG, POWHEG_BMNNP, POWHEG_BMNNPV, POWHEG_BW, RADY, SANC, SHERPA NNLO+PS, WINHAC, WZGRAD

That was crucial to establish reliable estimates of theoretical uncertainties

SANC applications: Drell-Yan processes

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

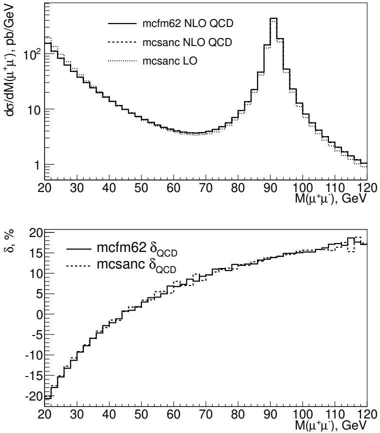
DRELL-YAN PROCESSES IN SANC

The SANC DY NLO electroweak corrections were thoroughly compared with other calculations earlier during theoretical workshops on the subject. The newer QCD results are validated using the MCFM program.

$pp \to$	$Z^0(\mu^+\mu^-)$	$W^+(\mu^+\nu_\mu)$	$W^-(\mu^-\bar{\nu}_\mu)$
$\sigma_{\rm LO}$ (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)

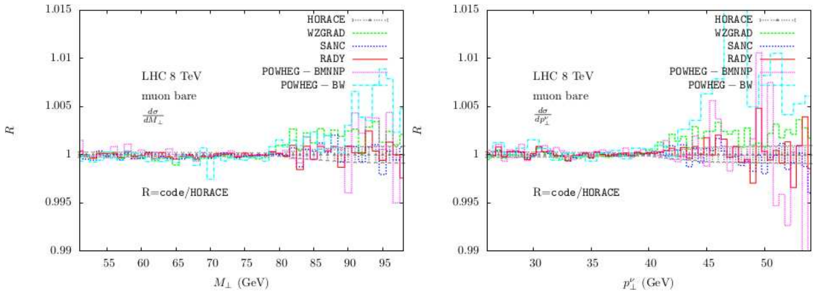
[A.A., D. Bardin, S. Bondarenko et al., JETP Lett. '2016]

DRELL-YAN PROCESSES: NLO QCD



Comparison of differential cross sections and correction factors δ(QCD) for neutral current Drell–Yan $pp \to \mu^+\mu^-$ process in dimuon invariant mass distribution.

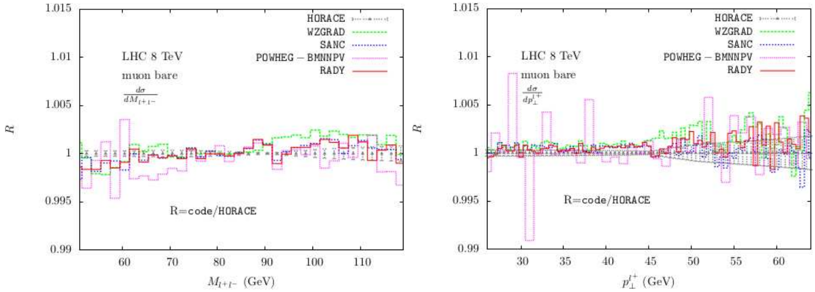
DRELL-YAN PROCESSES: NLO EW (CC)



Comparison of differential cross sections of charged current Drell–Yan $pp \to \mu^+\nu_\mu + X$ process at the 8 TeV LHC with ATLAS/CMS cuts in the bare setup, including NLO EW corrections. Distributions the transverse mass $M_\perp$ (left) and $p_\perp^\nu$ (right).

[S. Alioli, A.A., D.Yu. Bardin at al., EPJC '2017]

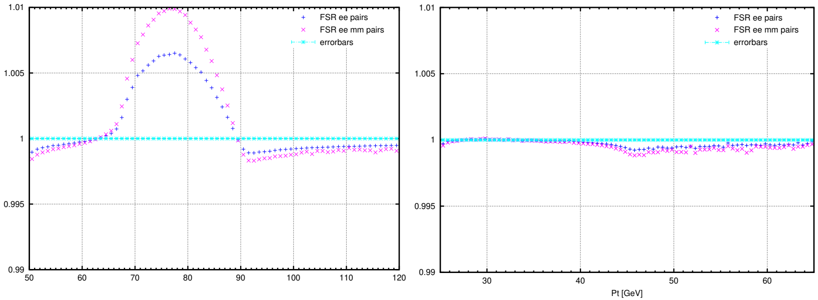
DRELL-YAN PROCESSES: NLO EW (NC)



Comparison of differential cross sections for neutral current Drell–Yan $pp \to \mu^+\mu^- + X$ process at the 8 TeV LHC with ATLAS/CMS cuts in the bare setup, including NLO EW corrections. Distributions the transverse mass $M_{l^+l^-}$ (left) and $p_\perp^{\mu^+}$ (right).

[S. Alioli, A.A., D.Yu. Bardin at al., EPJC '2017]

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: [S. Antropov, A.A., R. Sadykov, Z. Was, Acta Phys. Polon. B '2017]

MCSANC v.1.20

In the MCSANC−v1.20 version of the Monte-Carlo tool based on the SANC modules, the inverse photon — $(q\gamma)$ and $(\gamma\gamma)$ configurations in the initial pp state of beam — contributions to the Drell-Yan processes are added.

The MCSANC−v1.20 version was used to calculate the following corrections to the Drell-Yan processes at $\sqrt{s} = 13$ TeV:

• the missed (pure weak, ISR-FSR QED interference and ISR QED) one-loop contributions to the M_{inv} distribution;

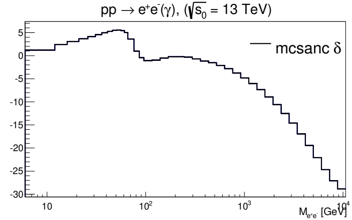
• the inverse photons contributions for fiducial cuts

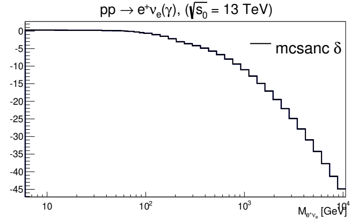
The predictions were calculated in the following fiducial volumes:

- neutral current: $p_T(\ell) > 30$ GeV and $|\eta(\mu)| < 2.4$ or $|\eta(e)| < 2.47$ for muon or electron channel, respectively;
- charged current: $M_T > 60$ GeV, $p_T(\mu) > 30$ GeV, $E_T(\nu_\mu) > 30$ GeV and $|\eta(\mu)| < 2.4$ for muon channel, and $M_T > 60$ GeV, $p_T(e) > 65$ GeV, $E_T(\nu_\mu) > 65$ GeV and $|\eta(\mu)| < 2.47$ for electrons

The obtained results were used by the ATLAS Standard Model WG

MCSANC V.1.20: MISSED CORRECTIONS TO DY





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

MCSANC V.1.20: PHOTON-INDUCED CORRECTIONS TO DY

Process	LO, pb	NLO(qγ), pb	δ, %
pp$\to e^+e^-$	606.63(1)	606.20(1)	-0.071(1)
pp$\to \mu^+\mu^-$	586.49(1)	586.07(1)	-0.073(1)
pp$\to e^+\nu_e$	8.291(1)	8.378(1)	1.06(1)
pp$\to \mu^+\nu_\mu$	5.476(1)	5.540(1)	1.17(1)
pp$\to e^-\nu_e$	3298.46(3)	3299.51(3)	0.032(1)
pp$\to \mu^-\nu_\mu$	2610.50(2)	2611.25(2)	0.029(1)

Process	LO, pb	NLO($\gamma\gamma$), pb	δ, %
pp$\to e^+e^-$	606.63(1)	607.38(1)	0.124(1)
pp$\to \mu^+\mu^-$	586.49(1)	587.22(1)	0.124(1)

Contributions of the (qγ) and ($\gamma\gamma$) configuration in the initial state of pp beams

LEADING TWO-LOOP ELECTROWEAK CORRECTIONS

In `MCSANC v.1.20` we follow the recipe introduced by J. Fleischer, O. Tarasov, and F. Jegerlehner in 1993 and implemented further in `ZFITTER`

The $\Delta\rho$ parameter as the ratio of the neutral current to charged current amplitudes at zero momentum transfer

$$\rho = \frac{G_{NC}(0)}{G_{CC}(0)} = \frac{1}{1-\Delta\rho}$$

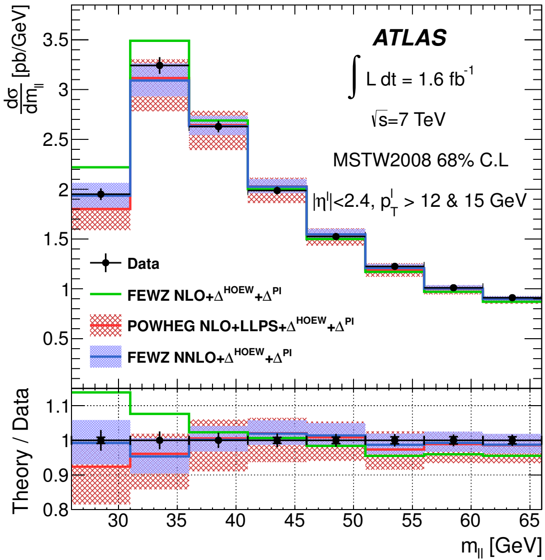
The leading in $G_\mu m_t^2$ NLO EW contribution is

$$\Delta\rho^{(1)} = 3x_t = \frac{3\sqrt{2}G_\mu m_t^2}{16\pi^2}$$

At the two-loop level

$$\Delta\rho = N_c\frac{\sqrt{2}G_\mu m_t^2}{16\pi^2}\left[1+\rho^{(2)}\left(M_H^2/m_t^2\right)\,x_t\right]\left[1-\frac{2\alpha_s(M_Z^2)}{9\pi}(\pi^2+3)\right]$$

CONFRONTING THE LHC DATA



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

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

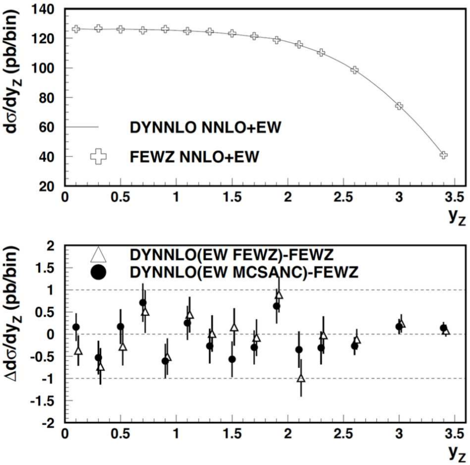
• **Additive approach** assumes that HO EW corrections (except QED FSR) are largely additive and the same term needs to be added to all orders of QCD

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

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

INTERPLAY OF QCD AND EW RC (II)



Top: high precision NC DY y_Z predictions using missed EW either from FEWZ or from MCSANC applied in additive way to the NNLO QCD DYNNLO prediction. Bottom: difference of the predictions.

Some other applications of SANC

QED BREMSSTRAHLUNG IN DECAYS OF ELECTROWEAK BOSONS

[A.A., R. Sadykov and Z. Was, Eur. Phys. J. C '2013]

Tuned comparisons of single and multiple photonic Final State Radiation (FSR). It is relevant for high-precision analysis of processes with Z and W boson production.

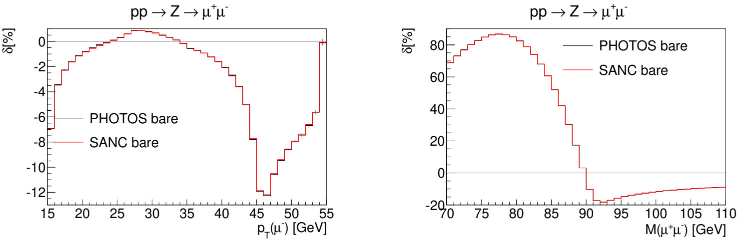


Figure: $\mathcal{O}(\alpha)$ corrections for basic kinematical distributions from PYTHIA+PHOTOS and SANC in $Z \to \mu\mu$ decay.

EW CORRECTIONS TO NEUTRINO DIS

[A.A., D. Bardin, L. Kalinovskaya, JHEP '2005]

(ISCH, ILLA), EW scheme	R^ν	δR^ν_{NC}	δR^ν_{CC}	$\Delta^\nu \sin^2\theta_W$
(0,1), G_F	0.31006	−0.00291	−0.02147	−0.01130
(1,1), G_F	0.31063	0.00071	−0.02327	−0.01044
(1,2), G_F	0.31067	0.00071	−0.02315	−0.01039
(1,2), $\alpha(0)$	0.31080	−0.05816	0.03743	−0.01020

Effect of RC on R^ν, R^-, and $\sin^2\theta_W$ values in different approximations.

$$R^\nu = \frac{\sigma^\nu_{NC}(\nu_\mu N \to \nu_\mu X)}{\sigma^\nu_{CC}(\nu_\mu N \to \mu^- X)},$$

$$\delta R^\nu_{NC} = \frac{\sigma^{\rm Corr.}_{\nu NC} - \sigma^{\rm Born}_{\nu NC}}{\sigma^{\rm Born}_{\nu NC}}, \qquad \delta R^\nu_{CC} = -\frac{\sigma^{\rm Corr.}_{\nu CC} - \sigma^{\rm Born}_{\nu CC}}{\sigma^{\rm Born}_{\nu CC}}.$$

Results of this study were used by the **NOMAD** Collaboration

RADIATIVE CORRECTIONS TO HIGH ENERGY LEPTON BREMSSTRAHLUNG ON HEAVY NUCLEI

[A.A., JHEP '2008] used by COMPASS experiment

$$l(p_1) \; + \; A(P) \; \to \; l(p_2) \; + \; \gamma(k) + A(P')$$

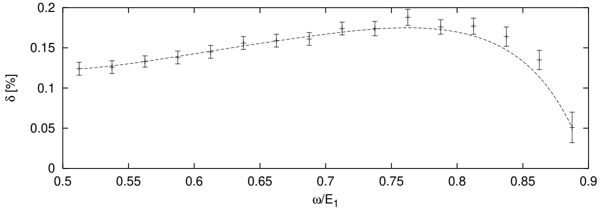


Figure: Relative contribution of one-loop corrections for realistic set-up *vs.* the photon energy fraction.

N.B. SANC modules were efficient with respect to numerical instability issues

CONTRIBUTION TO XFITTER

SANC team members V. Kolesnikov, R. Sadykov, and A. Sapronov participate in the development of the `xFitter` (DESY) project for QCD analysis of experimental data and extraction of Partonic Density Functions (PDFs), strong coupling constant, heavy quark masses etc.

With participation of the SANC group members It was substantially extended to include proton-(anti)proton collisions measured at the LHC experiments.

The current version of the xFitter framework provides a set of tools for QCD analysis of pp, $p\bar{p}$ and ep scattering data, determination of PDFs and extraction of fundamental QCD parameters, such as heavy quark masses and strong coupling constant, and provides a common testing ground for theoretical models and consistency checks of the experimental results.

QED-MODIFIED EVOLUTION IN XFITTER

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 $\gamma(x, \mu_F^2)$:

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

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

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

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

These evolution equations are implemented into the beta version of `QCDNUM` program and cross-checked with `partonevolution` program in FFNS, with MRST2004QED PDF set, and with `APFEL` program in VFNS [R.Sadykov, arXiv:1401.1133]. The `APPLGRID` interface to `SANC` Monte Carlo generator was created for fast evaluation of LO photon-induced cross sections.

Outlook

GENERAL ISSUES

- Matching specific higher order corrections with general tools like `PYTHIA` or `HERWIG` without double counting of effects
- How to estimate the theoretical uncertainty? We have a considerable scheme and scale dependence even for EW corrections.
- Interplay of EW and QCD RC to DY: implementation of $\mathcal{O}(\alpha\alpha_s)$ RC with matching to existing results
- NLO treatment of QED evolution in PDFs should be done for a consistent treatment of QED initial state radiation (ISR)
- New precision level challenge at future e^+e^- colliders

SANC ACHIEVEMENTS

- Many scientific results valuable for LHC physics and not only
- Theoretical support of experimental projects
- Training of young researchers. There were many defenses of PhD, master, and bachelor theses withing the SANC project
- Collaboration and exchange of knowledge with many other groups
- Friendly working inspiring atmosphere in the group

OUTLOOK

- Precision tests of the SM at LHC are of ultimate importance
- Many effects of various nature should be taken into account
- The SANC project contributes to studies of EW observables
- Common efforts of different group give us reliable theoretical predictions
- Creation of (optimal) interfaces between different codes is in progress
- LHC Run2, ILC and CLIC, provide new challenges for us
- The SANC project as a part of the JINR research program is closed in this year

SANC is over.
Long live SANC!