
Project SANC (former CalcPHEP):
Support of Analytic and Numeric calculations for experiments at Colliders

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OUTLINE

1. SANC project and its roots
2. Basic notions
3. Present status of the project
4. Concluding remarks
1. SANC project and its roots

People:
D. Bardin, L. Kalinovskaya, P. Christova, A. Andonov, G. Nanava – LNP, JINR;
S. Bondarenko – BTL, JINR; G. Passarino – Torino University.
In collaboration on MC issues with:

Goal:
creation of a software product for computation of pseudo- and realistic observables
with one-loop precision for the processes of elementary particle interactions:
1 → 2, 1 → 3, 2 → 2, 1 → 4, 2 → 3...
Application: LHC, Linacs.

Roots:
Codes aimed at a theoretical support of HEP experiments;
ZFITTER and the others...
Book DB and G. Passarino:
The Standard Model in the Making, OUP 1999;
numerous book-supporting form2-codes...
2. Basic notions

• The Standard Model (SM) Lagrangian in the $R_\xi$ gauge:

$$\mathcal{L} = \mathcal{L}(\text{IPS of 25 parameters, fields, } \xi_A, \xi_z, \xi)$$

• **Fields:** fermions, vector bosons, example of Feynman Rules

  vector boson propagators:

  $$A : \quad \frac{1}{p^2} \left\{ \delta_{\mu\nu} + \left( \xi_A^2 - 1 \right) \frac{p_\mu p_\nu}{p^2} \right\}$$

  $$Z : \quad \frac{1}{p^2 + M_Z^2} \left\{ \delta_{\mu\nu} + \left( \xi_Z^2 - 1 \right) \frac{p_\mu p_\nu}{p^2 + \xi_Z^2 M_Z^2} \right\}$$

  $$W^\pm : \quad \frac{1}{p^2 + M_W^2} \left\{ \delta_{\mu\nu} + \left( \xi^2 - 1 \right) \frac{p_\mu p_\nu}{p^2 + \xi^2 M_W^2} \right\}$$

• **Unphysical fields:** $\phi^0, \phi^\pm, Y_A, Y_Z, X^\pm$, the physical $H$ field.

• **Passarino–Veltman (PV) functions and reduction:**
  Presently, SANC knows ALL up to third rank tensorial reduction of up to four-point PV functions: $A_0, B_0, C_0$ and $D_0$; and the so-called special PV functions: $a_0, b_0, c_0$ and $d_0$, which are due to particular form of photonic propagator in $R_\xi$ gauge (terms $\propto 1/p^4$).

• **A fortran library** for numerical calculation of these functions is created and thoroughly tested by means of comparison with the other codes.
2. Basic notions, contd.

Amplitude's basis, Scalar Form Factors (SFF), Helicity Amplitudes (HA)

Example of decays $B(Q) \to f(p_1) \bar{f}(p_2)$

$H \to f \bar{f}$ decay $\quad A \propto I \mathcal{F}_s$

1 structure (I–basis), 1 SFF, 1 HA

$Z \to f \bar{f}$ decay $\quad A \propto i \gamma_\mu \gamma_6 \mathcal{F}_L + i \gamma_\mu \mathcal{F}_Q + m_f (p_1 - p_2)_\mu \mathcal{F}_D$

3 structures (L,Q,D–basis), 3 SFFs, 3 HAs

$W \to u \bar{d}$ decay $\quad A \propto i \gamma_\mu \gamma_6 \mathcal{F}_L + i \gamma_\mu \gamma_7 \mathcal{F}_R + m_u (p_1 - p_2)_\mu \gamma_6 \mathcal{F}_{LD} + m_d (p_1 - p_2)_\mu \gamma_7 \mathcal{F}_{RD}$

4 structures (L,R,LD,RD–basis), 4 SFFs, 4 HAs

The 3 HAs depend on kinematical factors, coupling constants and 3 SFFs, example of Z decay:

\[
A^Z_{0++} = A^Z_{0--} = \frac{g m_f}{c_W} \left[ a_f \mathcal{F}_L + \delta_f \mathcal{F}_Q + \frac{1}{2} a_f \beta_f^2 M^2_Z \mathcal{F}_D \right]
\]

\[
A^Z_{++--} = \frac{g M_Z}{\sqrt{2} c_W} \left[ a_f (1 - \beta_f) \mathcal{F}_L + \delta_f \mathcal{F}_Q \right]
\]

\[
A^Z_{--++} = \frac{g M_Z}{\sqrt{2} c_W} \left[ a_f (1 + \beta_f) \mathcal{F}_L + \delta_f \mathcal{F}_Q \right]
\]

\[
\beta_f^2 = 1 - 4 \frac{m_f^2}{M_Z^2}, \quad \delta_f = v_f - a_f = -2 Q_f s^2_w, \quad a_f = I_f^{(3)}.
\]
3. Present Status of the project

Basic information about SANC

- **Four-level computer system** for automatic calculation of pseudo- and realistic observables (decay rates, event distributions) for experiments at future colliders.

*Flow chart* illustrates how it works for simplest POs, $H(Z,W) \rightarrow f_1 \bar{f}_2$ decay rates:

1. from $\mathcal{L}_{SM}$ to the Ultra Violet free helicity amplitudes (all in form3);
   - calculation of **Scalar Form Factors, SFF**;
   - of the **Soft** and **Hard** photons contributions to the decay rates;
   - of Helicity Amplitudes for basic process, **HA**;
   - of Helicity Amplitudes for an accompanying Bremsstrahlung process, **HA-Br**;

2. an **s2n.f** software generates the **fortran** codes for $\Gamma^{(1)} = \Gamma^{\text{Born}} + \Gamma^{\text{Virt}} + \Gamma^{\text{Soft}} + \Gamma^{\text{Hard}}$;

3. an infrared re-arrangement (or exponentiation) procedure (in the stage of development);

4. the latter are used in a Monte Carlo event generator to produce distributions (‘manually written’ **fortran** code for the time being).

- **Internet based**
- **Database based**, i.e. a storage of source codes written in several languages, which talk to each other being placed into a homogeneous environment written in **JAVA** (linker).

- **PRECOMPUTATION**: one-loop diagrams could be precomputed and stored (to save CPU);
- **Principle of intermediate access**, full chain ‘from the Lagrangian to realistic distribution’ may work out in real time; it has several intermediate ‘entries’, or just its final product is accessed.
**PRECOMPUTATION**

- **Self**
  - Fermion
  - Boson

- **Vertex**
  - Bff
  - BBB

- **Box**
  - Box_CC
  - Box_NC_WW
  - Box_NC_NN

- **Fermion Self**
- **Boson Self**
- **RenConst**
- **CalcFerRenConst**
- **CalFerSEblocks**
- **CalBosRenConst**
- **CalBosSEblocks**
- **G \rightarrow ff**
- **Z \rightarrow ff**
- **H \rightarrow ff**
- **W \rightarrow ff**
- **BBB Fermion**
- **BBB Boson**
- ***.prc files**
An example of PRECOMPUTATION

Chain: $\text{Vertex} \rightarrow \text{Bff} \rightarrow \text{Z} \rightarrow \text{ff}$

Vertices: FBF-topology, BFB-topology.
**Z decay**

- $Z \rightarrow dd$
- $Z \rightarrow ss$
- $Z \rightarrow uu$
- $Z \rightarrow cc$
- $Z \rightarrow ee$
- $Z \rightarrow \nu\nu$
- $Z \rightarrow \tau\tau$
- $Z \rightarrow \mu\mu$
- $Z \rightarrow tt$
- $Z \rightarrow bb$

**H decay**

- $H \rightarrow Z \rightarrow \nu\nu$
- $H \rightarrow Z \rightarrow ee$
- $H \rightarrow Z \rightarrow uu$
- $H \rightarrow Z \rightarrow dd$
- $H \rightarrow Z \rightarrow \tau\tau$
- $H \rightarrow Z \rightarrow \mu\mu$
- $H \rightarrow Z \rightarrow tt$
- $H \rightarrow Z \rightarrow bb$

**W decay**

- $W \rightarrow Z \rightarrow \nu\nu$
- $W \rightarrow Z \rightarrow ee$
- $W \rightarrow Z \rightarrow uu$
- $W \rightarrow Z \rightarrow dd$
- $W \rightarrow Z \rightarrow \tau\tau$
- $W \rightarrow Z \rightarrow \mu\mu$
- $W \rightarrow Z \rightarrow tt$
- $W \rightarrow Z \rightarrow bb$

**Bff Decays**

**Bff Decay Brem**

**Bff Brem HA**

**Bff Brem HA**

**Bff Brem**

**NC decay Brem**
3. Present status of the project, contd.

- **Versions:**
  - **v0.01, March 2001** – realizes a part of analytic calculations of Level-1 (SFFs) for the decays $H(Z,W) \rightarrow f_1 \bar{f}_2$ (demonstration of viability);
  - several versions **v0.02c/d** – towards realization of levels 1, 2, 4 for decays $H(Z,W) \rightarrow f_1 \bar{f}_2$;
  - **v0.03, Summer 2002** – realizes the full chain of calculations, returns numbers and distributions for the decay widths at one-loop level (demonstration of workability);
  - **v0.10, nearest future** – one has very many almost finished ‘preparations’ for processes $2 \rightarrow 2$ and decays $1 \rightarrow 3$ (levels 1-2).

- **Publications:**
Calculation flow in ee\text{ffRen.frm}

\begin{itemize}
  \item \text{FerRenCont*.sav} \rightarrow \text{load} \rightarrow \text{build} \rightarrow \mathcal{F}_{ct} \text{ (counter terms)}
  \item \text{V1*.sav, V2*.sav} \rightarrow \text{load} \rightarrow \text{build} \rightarrow \mathcal{F}^{\gamma(Z)}_{L,Q,D}
  \item \text{BosRenCont.sav} \rightarrow \text{load} \rightarrow \text{build} \rightarrow \Pi_{\gamma\gamma}, \Pi_{Z\gamma}, D_z, Z \gamma
  \item \text{BosSEblocks.sav} \rightarrow \text{load} \rightarrow \text{build} \rightarrow \text{SFF of Z decay}
  \item \text{Box NC BB*.sav} \rightarrow \text{load} \rightarrow \text{projection} \rightarrow \text{Box SFF, } \mathcal{F}^{BB}_{I,J} \rightarrow \text{build} \rightarrow \text{Total SFF of eeff}
\end{itemize}

* – any fermion index

B = A,Z,W,H

s2n.f

D.Bardin, JINR, Dubna, ICHEP2002, 26/07/02
3. Present status of the project, contd.

**COMPARISON → AGREEMENT**

\[ e^+e^- \rightarrow f\bar{f}, \text{ ALL CHANNELS} \]

- **e\text{effLib–ZFITTER}**
  - SFFs \( \rightarrow \) 8–9 digits
  - Complete 1-loop differential cross section \( d\sigma^{(1)}/d\cos\theta \) \( \rightarrow \) 7–8 digits
  - Total 1-loop cross section and \( \sigma^{FB} \) for the light fermion masses \( \rightarrow \) 6–7 digits

- **s2n.f e\text{effLib}**
  - Complete 1-loop differential cross-sections \( d\sigma^{(1)}/d\cos\theta \) \( \rightarrow \) 12–13 digits

- **s2n.f FeynArt**
  - 1-loop cross-section **without soft photons** \( \rightarrow \) 11 digits

- **s2n.f topfit**
  - 1-loop cross-section **with soft photons** \( \rightarrow \) 8 digits

* Bielefeld Zeuthen group (hep-ph/0202102, J. Fleisher et al.)
\[ \frac{d\Gamma^{1\text{-loop}}}{dE_\gamma} \]

\[ \Gamma^{1\text{-loop}} = 1.9697 \times 10^{-7} \pm 4.0 \times 10^{-11} \]

\( nE\nu = 10^7 \)

Efficiency = 64.63% 

\[ H \rightarrow \mu^+ \mu^- \gamma \]

\[ \text{Photon Angular Distribution} \]

\[ \frac{d\Gamma^{1\text{-loop}}}{d\cos \theta_\gamma} \]

\[ m_\mu = 105.658 \text{ MeV} \]

\[ M_h = 120 \text{ GeV} \]

\[ H \rightarrow \mu^+ \mu^- \gamma \]
Muon Energy distribution

$\frac{d\Gamma}{dE_\mu} = 8.374 \times 10^{-2} \pm 1.1 \times 10^{-5}$ GeV

$nE\nu = 10^7$

Efficiency = 53.02%

$Z \rightarrow \mu^+ \mu^- \gamma$

SANC/KORALZ

Acollinearity Distribution

$Z \rightarrow \mu^+ \mu^- \gamma$

$\Gamma_{\text{1-loop}} = 91.1867$ GeV

$m_\gamma = 105.658$ GeV

$\frac{d\Gamma}{d\cos\theta_{\text{acol}}}$

$\frac{\Gamma_{\text{1-loop}}}{\Gamma_{\text{1-loop}}}$
4. Concluding remarks

ADDRESS http://brg.jinr.ru/

FIRST PHASE $\rightarrow$ release of demonstration version 0.10 in 2002

SECOND PHASE $\rightarrow$ a complete software product, accessible via an Internet-based environment, and realizing the chain of calculations ‘from the Lagrangian to the realistic distributions’ at the one-loop level, including

PROCESSES $2 \rightarrow 3$ and DECAYS $1 \rightarrow 4$

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  \]
  
  \[
  Z : \quad \frac{1}{p^2 + M^2_Z} \left\{ \delta_{\mu\nu} + (\xi^2_Z - 1) \frac{p_\mu p_\nu}{p^2 + \xi^2_Z M^2_Z} \right\} 
  \]
  
  \[
  W^\pm : \quad \frac{1}{p^2 + M^2_W} \left\{ \delta_{\mu\nu} + (\xi^2 - 1) \frac{p_\mu p_\nu}{p^2 + \xi^2 M^2_W} \right\} 
  \]

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\]

\[
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  - Fermion Self
  - RenConst
- Boson
  - Boson Self
  - RenConst
  - CalcFerRenConst
  - CalFerSEblocks
- CalBosRenConst
- CalBosSEblocks
- G -> ff
- Z -> ff
- H -> ff
- W -> ff
- BBB Fermion
- BBB Boson

Vertex
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- Box_CC
An example of PRECOMPUTATION

Chain: $\text{Vertex} \rightarrow \text{Bff} \rightarrow \text{Z} \rightarrow \text{ff}$

Vertices: FBF-topology, BFB-topology.
Z decay

Z → vv
Z → ee
Z → uu
Z → dd

H decay

Z → ττ
Z → μμ
Z → uu
Z → cc
Z → tt
Z → dd
Z → ss
Z → bb

W decay

Bff Decays

Bff Brem HA

Bff Decay Brem

Bff Brem

NC decay Brem
3. Present status of the project, contd.

- **Versions:**
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- **Publications:**


Calculation flow in ee\textit{ffRen.frm}

- **FerRenCont*.sav**
  - load
  - build $\mathcal{F}_{ct}$ (counter terms)

- **V1*.sav, V2*.sav**
  - load
  - build $\mathcal{F}_{L,Q,D}$

- **BosRenCont.sav**
  - load
  - build $\Pi_{\gamma\gamma}, \Pi_{Z\gamma}, \mathcal{D}_{Z}, Z_{Z}$

- **BosSEblocks.sav**
  - load
  - build SFF of Z decay

- **Box NC BB*.sav**
  - load
  - projection Box SFF, $\mathcal{F}_{I,J}^{BB}$

- **e^+ f**
  - load
  - projection $\mathcal{F}_{I,J}$
  - build Total SFF of ee\textit{ff}

- **s2n.f**

* – any fermion index

B = A,Z,W,H
3. Present status of the project, contd.

COMPARISON $\rightarrow$ AGREEMENT

$e^+e^- \rightarrow f\bar{f}$, ALL CHANNELS

- **eefLib-ZFITTER**
  
  SFFs $\rightarrow$ 8–9 digits
  
  Complete 1-loop differential cross section $d\sigma^{(1)}/d\cos\theta \rightarrow$ 7–8 digits
  
  Total 1-loop cross section and $\sigma^{FB}$ for the light fermion masses $\rightarrow$ 6–7 digits

- **s2n.f eefLib**
  
  Complete 1-loop differential cross-sections $d\sigma^{(1)}/d\cos\theta \rightarrow$ 12–13 digits

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  1-loop cross-section **without soft photons** $\rightarrow$ 11 digits

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Photon Energy Distribution

\[ \Gamma^{\text{1-loop}} = 1.9697 \times 10^{-7} \pm 4.0 \times 10^{-11} \]

\[ n \text{EeV} = 10^7 \]

Efficiency = 64.63%

\[ H \rightarrow \mu^+ \mu^- \gamma \]

Photon Angular Distribution

\[ m_\mu = 105.658 \text{ MeV} \]

\[ M_h = 120 \text{ GeV} \]

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\[ \frac{d\Gamma^{1\text{-loop}}}{dE_{\mu}} \]

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SANC/KORALZ

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SANC/KORALZ

\[ m_Z = 91.1867 \text{ GeV} \]

\[ m_\mu = 105.658 \text{ GeV} \]

\[ Z \rightarrow \mu^+ \mu^- \gamma \]

\[ \frac{d\Gamma^{1\text{-loop}}}{d\cos \theta_{acol}} \]

\( \cos \theta_{acol} \)

\[ 0.97 \]

\[ 0.98 \]

\[ 0.99 \]

\[ 1 \]

\[ 1.01 \]

\[ 1.02 \]

\[ 1.03 \]

\[ 1.00 \]

\[ 0.99 \]

\[ 0.98 \]

\[ 0.97 \]

\[ 0.96 \]

\[ 0.95 \]

\[ 1 \]

\[ 1.05 \]

\[ 1.1 \]

\[ \frac{d\Gamma^{1\text{-loop}}}{d\cos \theta_{acol}} \]

\( \cos \theta_{acol} \)
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**PROCESSES 2$\rightarrow$ 3** and **DECAYS 1$\rightarrow$ 4**