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# 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
   - Decays $B \to f\bar{f}$
   - Processes $2f \to 2f$
   - Decays $F \to 3f$
4. Concluding remarks

# 1. SANC project and its roots

**People:**
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**S. Bondarenko – BTL, JINR; G. Passarino – Torino University.**
**In collaboration on MC issues with:**
**S. Jadach, Z. Was – INF Krakow and B.F.L. Ward – Knoxville University.**

**Goal:**
**creation of a software product for computation of pseudo- and realistic observables with one-loop precision for the processes of elementary particle interactions:**
$1 \to 2$, $1 \to 3$, $2 \to 2$, $1 \to 4$, $2 \to 3$...
**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)$\to f(p_1)\overline{f}(p_2)$

$H \to f\overline{f}$ decay – $\mathcal{A} \propto I\mathcal{F}_S$

1 structure (**I–basis**), **1 SFF**, **1 HA**

$Z \to f\overline{f}$ decay – $\mathcal{A} \propto i\gamma_\mu\gamma_6\mathcal{F}_{\mathbf{L}} + i\gamma_\mu\mathcal{F}_{\mathbf{Q}} + m_f\,(p_1-p_2)_\mu\,\mathcal{F}_{\mathbf{D}}$

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

$W \to u\overline{d}$ decay – $\mathcal{A} \propto i\gamma_\mu\gamma_6\mathcal{F}_{\mathbf{L}} + i\gamma_\mu\gamma_7\mathcal{F}_{\mathbf{R}} + m_u\,(p_1-p_2)_\mu\,\gamma_6\mathcal{F}_{\mathbf{LD}} + m_d\,(p_1-p_2)_\mu\,\gamma_7\mathcal{F}_{\mathbf{RD}}$

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:

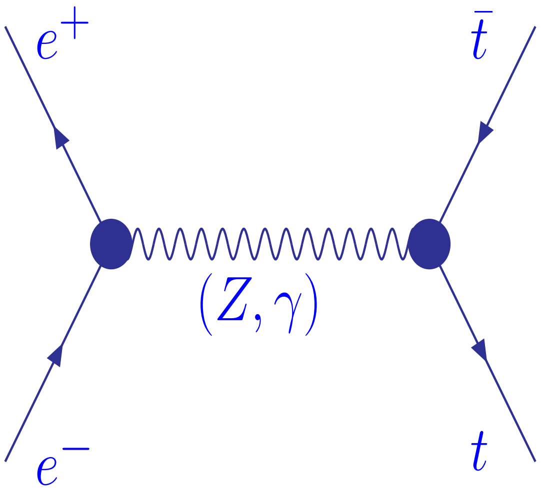
$$\mathbf{A}^{\mathbf{Z}}_{\mathbf{0}++} = \mathbf{A}^{\mathbf{Z}}_{\mathbf{0}--} = \frac{g m_f}{c_W}\left[a_f\mathcal{F}_{\mathbf{L}} + \delta_f\mathcal{F}_{\mathbf{Q}} + \frac{1}{2}a_f\beta_f^2 M_Z^2\mathcal{F}_{\mathbf{D}}\right]$$

$$\mathbf{A}^{\mathbf{Z}}_{++-} = \frac{g M_Z}{\sqrt{2}c_W}\left[a_f(1-\beta_f)\mathcal{F}_{\mathbf{L}} + \delta_f\mathcal{F}_{\mathbf{Q}}\right]$$

$$\mathbf{A}^{\mathbf{Z}}_{--+} = \frac{g M_Z}{\sqrt{2}c_W}\left[a_f(1+\beta_f)\mathcal{F}_{\mathbf{L}} + \delta_f\mathcal{F}_{\mathbf{Q}}\right]$$

$$\beta_f^2 = 1 - 4\frac{m_f^2}{M_Z^2}, \qquad \delta_f = v_f - a_f = -2Q_f s_W^2, \qquad a_f = I_f^{(3)}.$$

# Process $e^+e^- \to f\bar{f}$, amplitudes in $L, Q, D$ - basis




$$A \sim \left[i\gamma_\mu\left(1+\gamma_5\right)F^e_L\left(s\right)+i\gamma_\mu F^e_Q\left(s\right)\right]\otimes$$

$$\left[i\gamma_\mu\left(1+\gamma_5\right)F^f_L\left(s\right)+i\gamma_\mu F^f_Q\left(s\right)+m_t I D_\mu F^f_D\left(s\right)\right]$$

$$D_\mu = \left(p_t - p_{\bar{t}}\right)_\mu$$

**6 STRUCTURES**

# Process $e^+e^- \to f\bar{f}$, SCALAR FORM FACTORS (SFF)

The ultraviolet-finite results for six SFFs are:

$$
\begin{aligned}
F_{LL}(s,t,u) &= \mathcal{F}^{zee}_{L}(s) + \mathcal{F}^{zff}_{L}(s) + \mathcal{F}^{ct}_{LL}(s) + \mathcal{F}^{\mathrm{BOX}}_{LL}(s,t,u) \\
F_{QL}(s,t,u) &= \mathcal{F}^{zee}_{Q}(s) + \mathcal{F}^{zff}_{L}(s) + k\,\mathcal{F}^{\gamma ff}_{L}(s) + \mathcal{F}^{ct}_{QL}(s) + \mathcal{F}^{\mathrm{BOX}}_{QL}(s,t,u) \\
F_{LQ}(s,t,u) &= \mathcal{F}^{zee}_{L}(s) + \mathcal{F}^{zff}_{Q}(s) + k\,\mathcal{F}^{\gamma ee}_{L}(s) + \mathcal{F}^{ct}_{LQ}(s) + \mathcal{F}^{\mathrm{BOX}}_{LQ}(s,t,u) \\
F_{QQ}(s,t,u) &= \mathcal{F}^{zee}_{Q}(s) + \mathcal{F}^{zff}_{Q}(s) - \frac{k}{s^2_W}\left[\mathcal{F}^{\gamma ee}_{Q}(s) + \mathcal{F}^{\gamma ff}_{Q}(s)\right] + \mathcal{F}^{ct}_{QQ}(s) + \mathcal{F}^{\mathrm{BOX}}_{QQ}(s,t,u) \\
F_{LD}(s,t,u) &= \mathcal{F}^{zff}_{D}(s) + \mathcal{F}^{\mathrm{BOX}}_{LD}(s,t,u) \\
F_{QD}(s,t,u) &= \mathcal{F}^{zff}_{D}(s) + k\,\mathcal{F}^{\gamma ff}_{D}(s) + \mathcal{F}^{\mathrm{BOX}}_{QD}(s,t,u)
\end{aligned}
$$

$$k = c^2_W\left(M^2_Z/s - 1\right)$$

For the $IJ$ component of a box contribution we have:

$$\mathcal{F}^{\mathrm{BOX}}_{IJ}(s,t,u) = k^{AA}\mathcal{F}^{AA}_{IJ}(s,t,u) + k^{ZA}\mathcal{F}^{ZA}_{IJ}(s,t,u) + k^{ZZ}\mathcal{F}^{ZZ}_{IJ}(s,t,u) + k^{WW}\mathcal{F}^{WW}_{IJ}(s,t,u)$$

Moreover,

$$\mathcal{F}^{\gamma(z)ff}_{L,Q,D}(s) = \sum_{B=A,Z,H,W} \mathcal{F}^{\gamma(z)B}_{L,Q,D}(s)$$

except for $\mathcal{F}^{\gamma A}_{L}(s) = 0$ and $\mathcal{F}^{\gamma H}_{L}(s) = 0$.

## $e^+e^- \to f\bar{f}$ process in the HELICITY AMPLITUDES (HA)

**16 Helicity Amplitudes** for any $2f \to 2f$ process.
The unpolarized case, the electron mass is ignored $\longrightarrow$ **6 HAs**,
which depend on kinematical variables, coupling constants and **6 SFFs**:

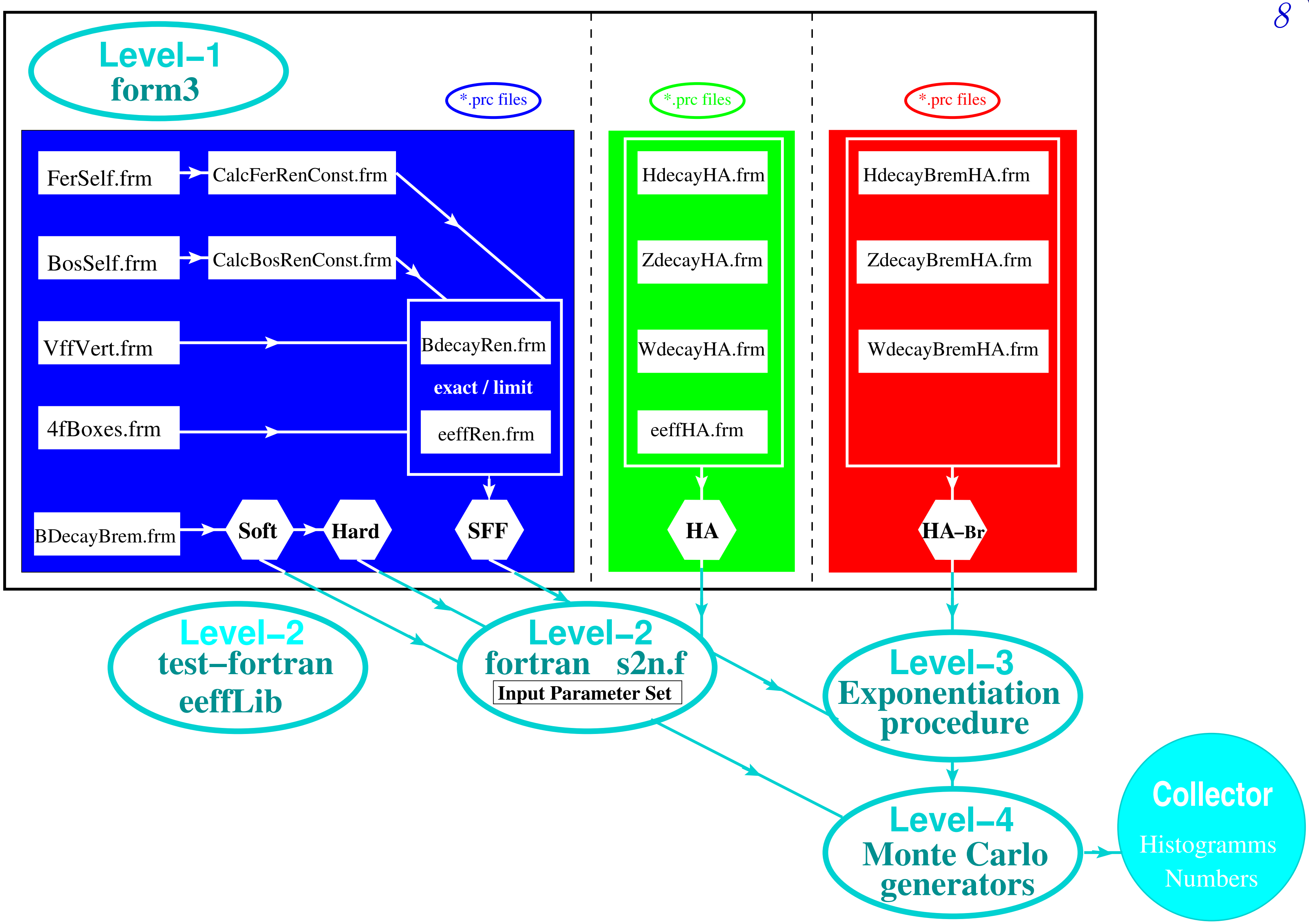
$$
\begin{aligned}
\mathcal{A}_{++++} &= 0, \qquad \mathcal{A}_{+++-} = 0, \qquad \mathcal{A}_{++-+} = 0, \qquad \mathcal{A}_{++--} = 0,\\
\mathcal{A}_{+-+-} &= s\,(1-\cos\vartheta)\Bigl(Q_eQ_fF_{GG} + \chi_Z\delta_e[\,(1+\beta_f)\,I^{(3)}_f F_{QL} + \delta_f F_{QQ}]\Bigr),\\
\mathcal{A}_{+--+} &= s\,(1+\cos\vartheta)\Bigl(Q_eQ_fF_{GG} + \chi_Z\delta_e[(1-\beta_f)I^{(3)}_f F_{QL} + \delta_f F_{QQ}]\Bigr),\\
\mathcal{A}_{+---} &= \mathcal{A}_{+-++} = 2\sqrt{s}m_f\sin\vartheta\Bigl(Q_eQ_fF_{GG} + \chi_Z\delta_e[I^{(3)}_f F_{QL} + \delta_f F_{QQ} + \frac{1}{2}s{\beta_f}^2 I^{(3)}_f F_{QD}]\Bigr),\\
\mathcal{A}_{-+++} &= \mathcal{A}_{-+--} = -2\sqrt{s}m_f\sin\vartheta\Bigl(Q_eQ_fF_{GG}\\
&\qquad +\chi_Z\Bigl[2I^{(3)}_e I^{(3)}_f F_{LL} + 2I^{(3)}_e\delta_f F_{LQ} + \delta_e I^{(3)}_f F_{QL} + \delta_e\delta_f F_{QQ} + \frac{1}{2}s{\beta_f}^2 I^{(3)}_f(2I^{(3)}_e F_{LD} + \delta_e F_{QD})\Bigr]\Bigr),\\
\mathcal{A}_{-++-} &= s\,(1+\cos\vartheta)\Bigl(Q_eQ_fF_{GG} + \chi_Z[\,(1+\beta_f)\,(2I^{(3)}_e I^{(3)}_f F_{LL} + \delta_e I^{(3)}_f F_{QL}) + \delta_f\,\bigl(2I^{(3)}_e F_{LQ} + \delta_e F_{QQ}\bigr)\,]\Bigr),\\
\mathcal{A}_{-+-+} &= s\,(1-\cos\vartheta)\Bigl(Q_eQ_fF_{GG} + \chi_Z[\,(1-\beta_f)\,I^{(3)}_f(2I^{(3)}_e F_{LL} + \delta_e F_{QL}) + \delta_f(2I^{(3)}_e F_{LQ} + \delta_e F_{QQ})]\Bigr),\\
\mathcal{A}_{--++} &= 0, \qquad \mathcal{A}_{--+-} = 0, \qquad \mathcal{A}_{---+} = 0, \qquad \mathcal{A}_{----} = 0.
\end{aligned}
$$

$$
\cos\vartheta \;=\; \left(t - m_f^2 + s/2\right)2/(s\beta_f)\,, \quad \beta_f^2 = 1 - 4m_f^2/s, \quad \delta_f = v_f - a_f.
$$

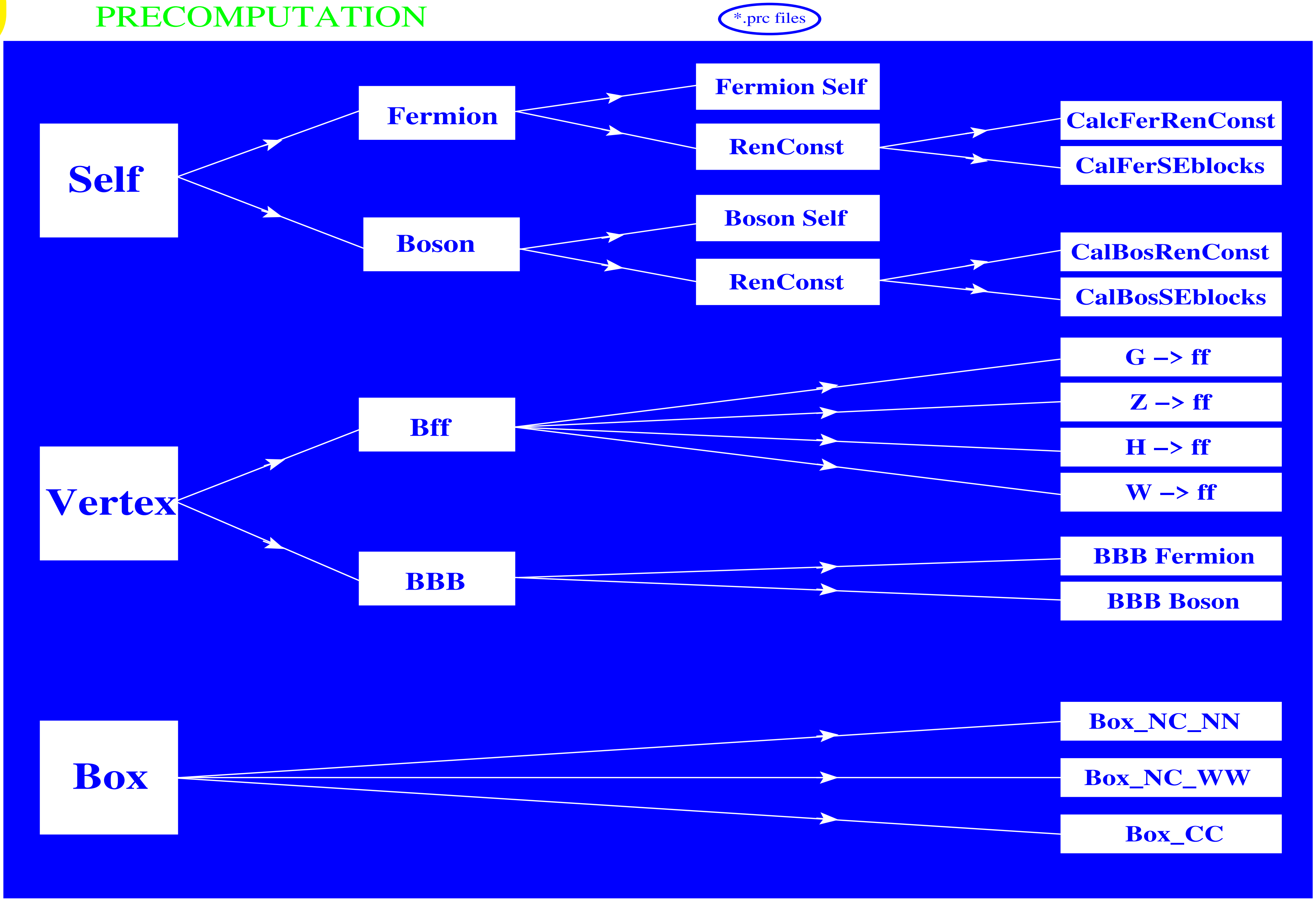
# 3. Present Status of the project

## 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, $H(Z,W) \to f_1 \bar{f}_2$ 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 $\Gamma^{(1)} = \Gamma^{\rm Born} + \Gamma^{\rm Virt} + \Gamma^{\rm Soft} + \Gamma^{\rm Hard}$;
  3. an infared 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.

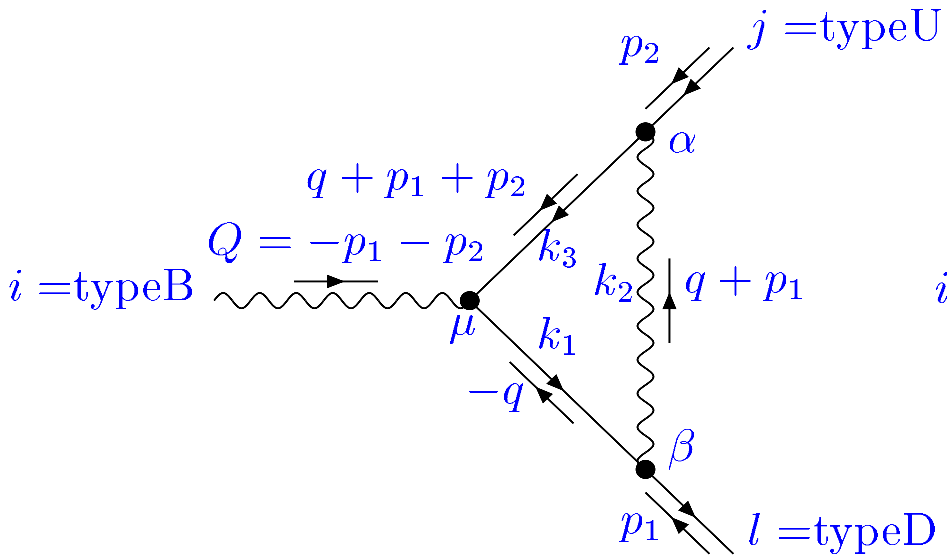

Level–1
form3
*.prc files
*.prc files
*.prc files
FerSelf.frm
CalcFerRenConst.frm
BosSelf.frm
CalcBosRenConst.frm
VffVert.frm
BdecayRen.frm
exact / limit
4fBoxes.frm
eeffRen.frm
BDecayBrem.frm
Soft
Hard
SFF
HdecayHA.frm
ZdecayHA.frm
WdecayHA.frm
eeffHA.frm
HA
HdecayBremHA.frm
ZdecayBremHA.frm
WdecayBremHA.frm
HA–Br
Level–2
test–fortran
eeffLib
Level–2
fortran s2n.f
Input Parameter Set
Level–3
Exponentiation
procedure
Level–4
Monte Carlo
generators
Collector
Histogramms
Numbers

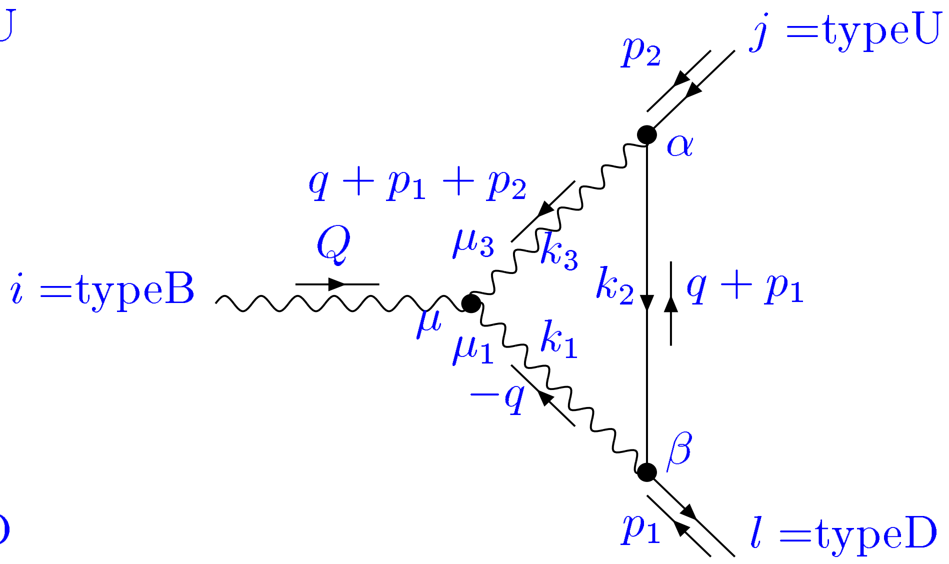
## PRECOMPUTATION



# An example of PRECOMPUTATION

**Chain:** $\boxed{\textbf{Vertex}} \rightarrow \boxed{\textbf{Bff}} \rightarrow \boxed{\textbf{Z}\rightarrow\textbf{ff}}$

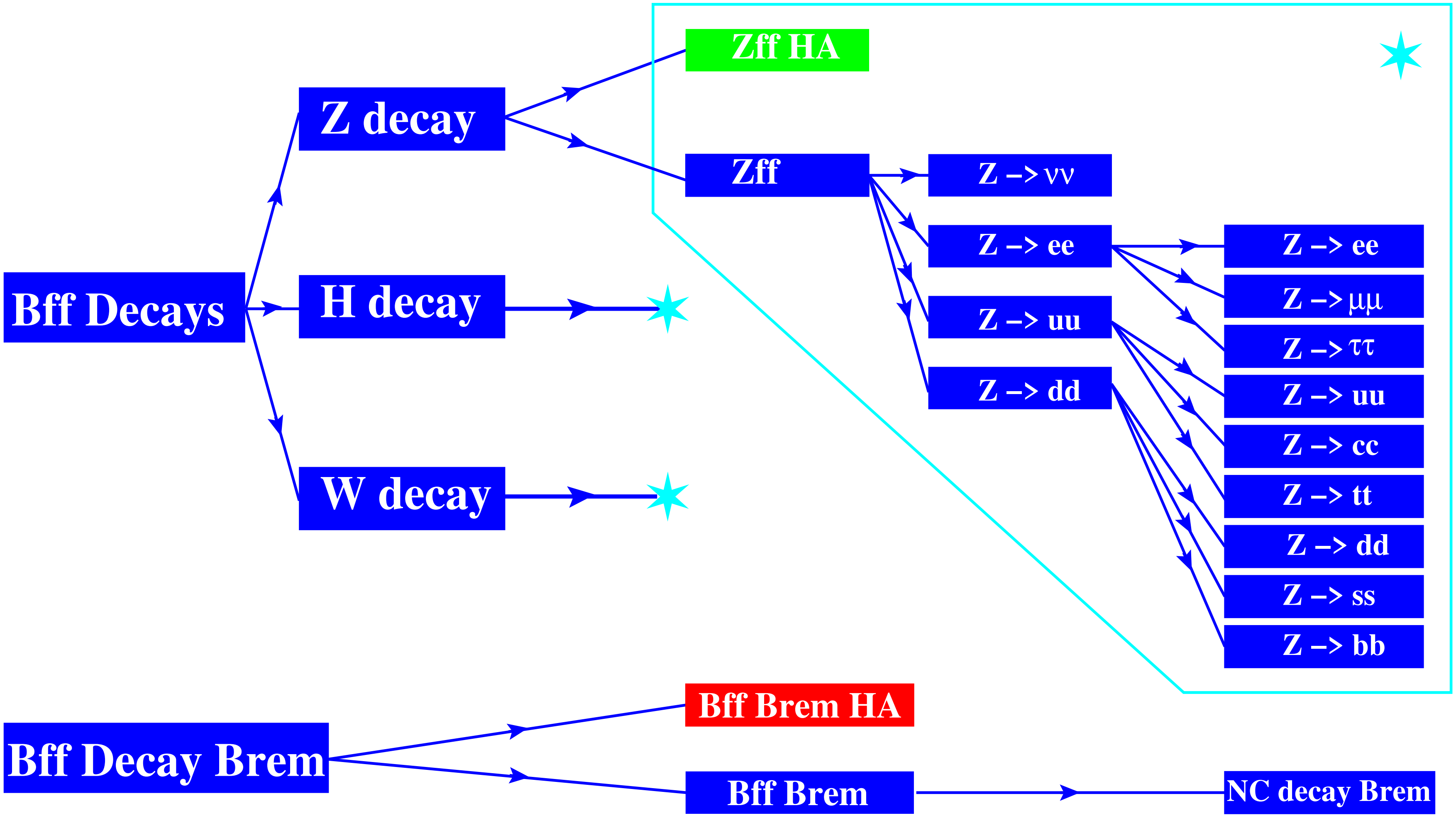


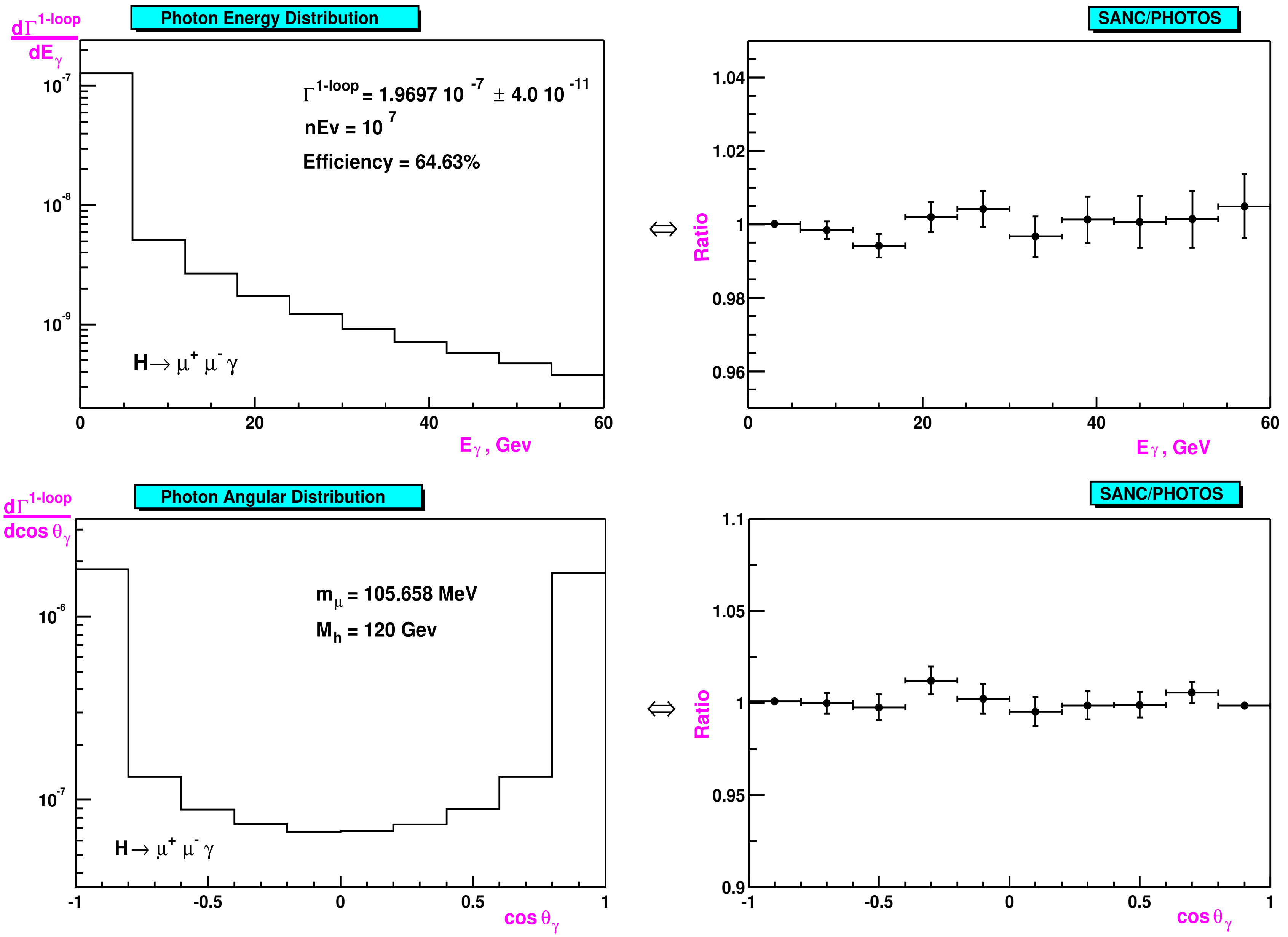




Vertices: FBF-topology, BFB-topology.

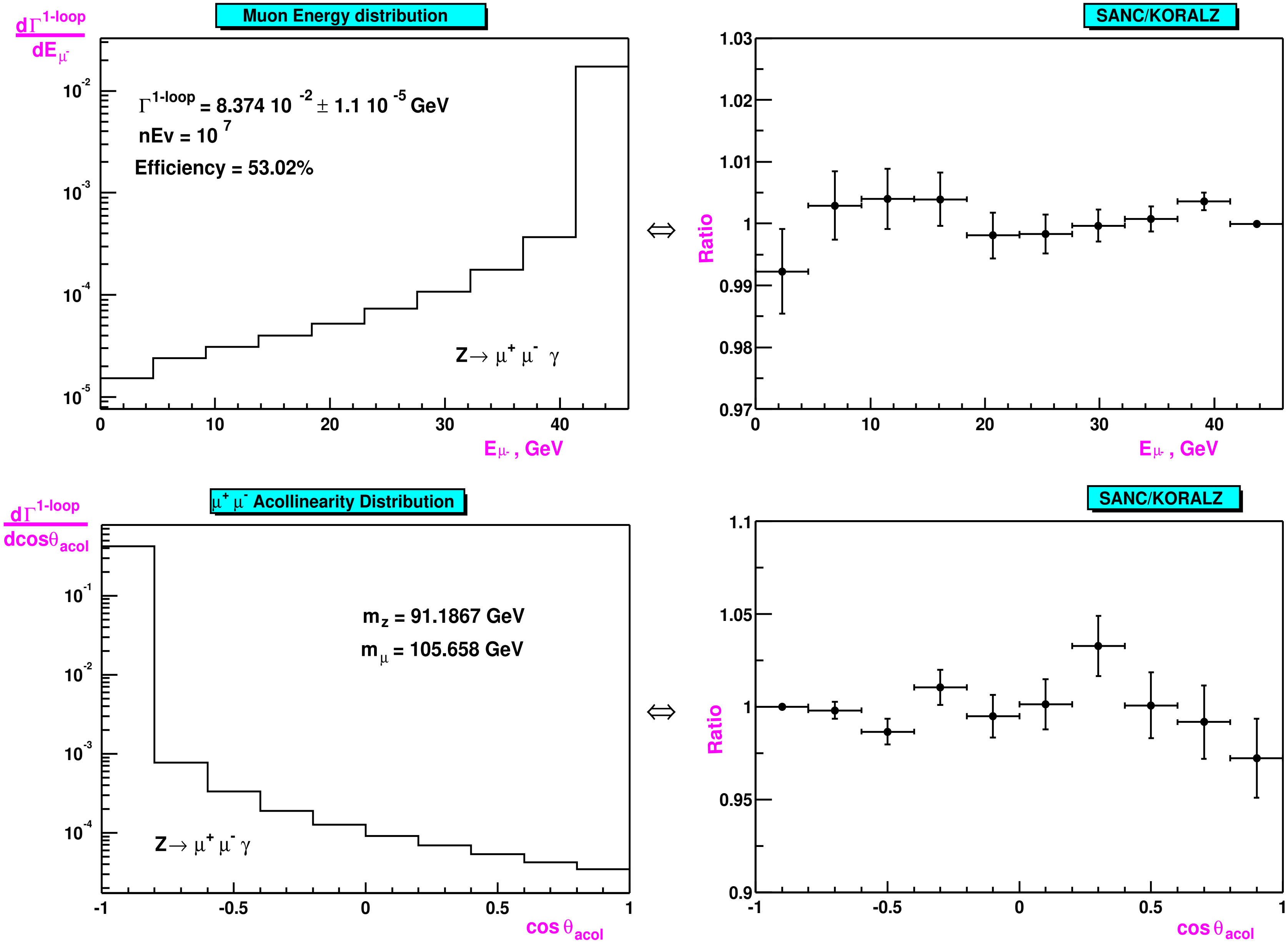
# PROGRAMS

*.prc files *.prc files *.prc files



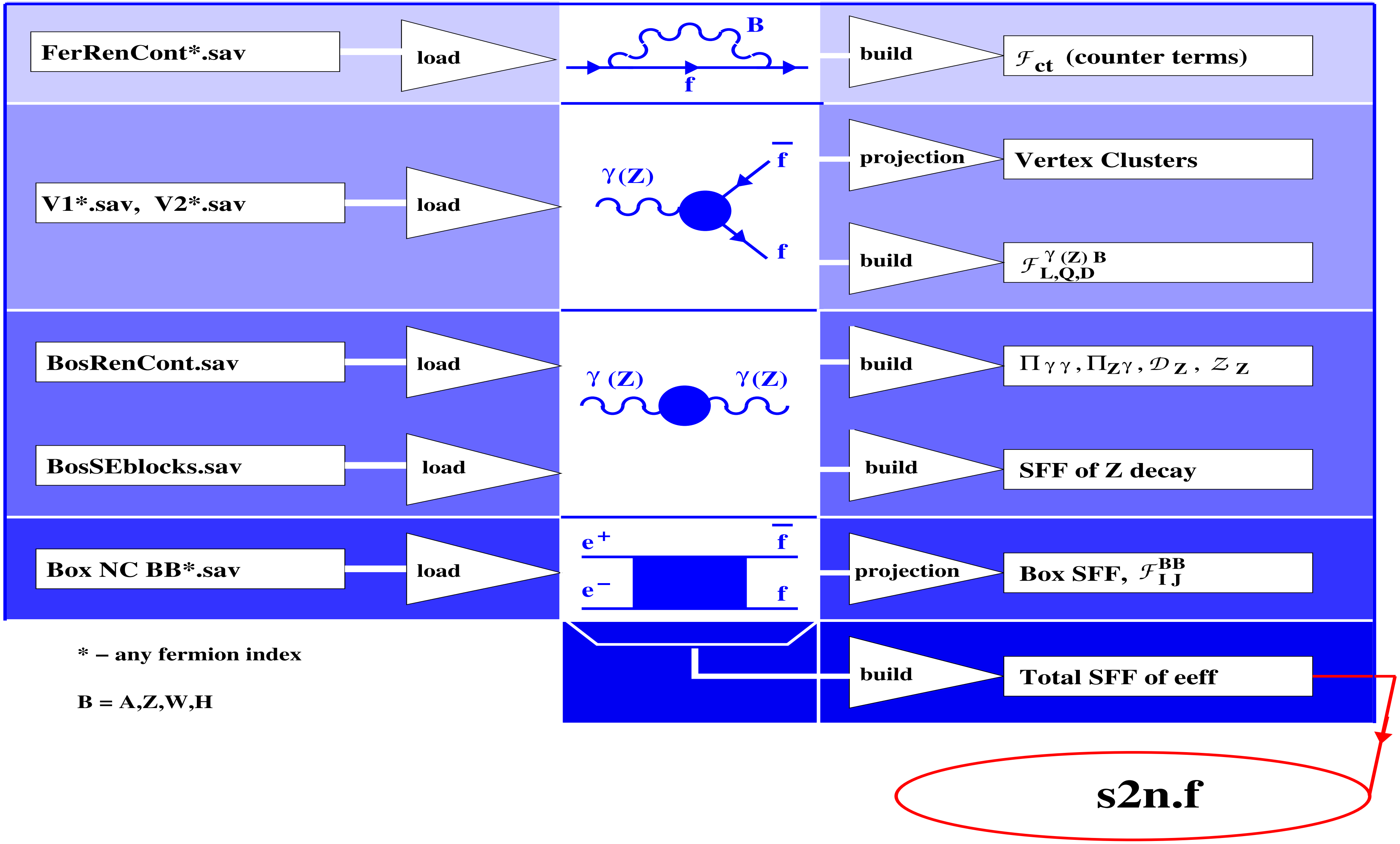


Photon Energy Distribution
dΓ^1-loop / dE_γ
Γ^1-loop = 1.9697 10^-7 ± 4.0 10^-11
nEv = 10^7
Efficiency = 64.63%
H→ μ+ μ- γ
10^-7
10^-8
10^-9
0
20
40
60
E_γ , Gev
SANC/PHOTOS
Ratio
1.04
1.02
1
0.98
0.96
E_γ , GeV
⇔
Photon Angular Distribution
dΓ^1-loop / dcos θ_γ
m_μ = 105.658 MeV
M_h = 120 Gev
H→ μ+ μ- γ
10^-6
10^-7
-1
-0.5
0
0.5
1
cos θ_γ
SANC/PHOTOS
Ratio
1.1
1.05
1
0.95
0.9
⇔



Muon Energy distribution
$\frac{d\Gamma^{1\text{-loop}}}{dE_{\mu^-}}$
$\Gamma^{1\text{-loop}} = 8.374\ 10^{-2} \pm 1.1\ 10^{-5}$ GeV
nEv = $10^{7}$
Efficiency = 53.02%
$Z \to \mu^+ \mu^- \gamma$
$E_{\mu^-}$ , GeV
⇔
SANC/KORALZ
Ratio
$E_{\mu^-}$ , GeV
$\mu^+ \mu^-$ Acollinearity Distribution
$\frac{d\Gamma^{1\text{-loop}}}{d\cos\theta_{acol}}$
$m_Z$ = 91.1867 GeV
$m_\mu$ = 105.658 GeV
$Z \to \mu^+ \mu^- \gamma$
$\cos\theta_{acol}$
⇔
SANC/KORALZ
Ratio
$\cos\theta_{acol}$

# Calculation flow in eeffRen.frm



# 3. Present status of the project, contd.

**COMPARISON $\longrightarrow$ AGREEMENT**

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

- `eeffLib–ZFITTER`

SFFs $\longrightarrow$ **8–9 digits**

Complete 1-loop differential cross section $d\sigma^{(1)}/d\cos\vartheta \longrightarrow$ **7–8 digits**

Total 1-loop cross section and $\sigma^{FB}$ for the light fermion masses $\longrightarrow$ **6–7 digits**

$e^+e^- \to t\bar{t}$

- `s2n.f–eeffLib`

Complete 1-loop differential cross-sections $d\sigma^{(1)}/d\cos\vartheta \longrightarrow$ **12–13 digits**

- `s2n.f–FeynArt`

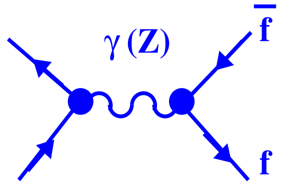
1-loop cross-section **without soft photons** $\longrightarrow$ **11 digits**

- `s2n.f–topfit`*

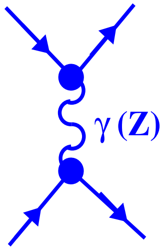
1-loop cross-section **with soft photons** $\longrightarrow$ **8 digits**

* Bielefeld–Zeuthen group (hep-ph/0202102, J. Fleisher et al. )

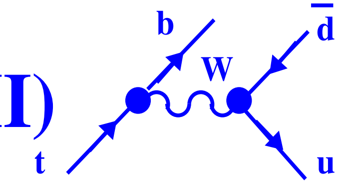
# DONE

I) 


$e\,e \dashrightarrow \nu\bar{\nu},\ l\,l,\ u\,\bar{u},\ d\,\bar{d},\ c\,\bar{c},\ s\,\bar{s},\ b\,\bar{b},\ t\,\bar{t}$ ( LEVEL 1–2 )

II) 


ANY NC t–channel ( LEVEL 1 )

III) 


ANY CC s–, t–channel ( LEVEL 1 )

**BASEMENT for more complicated processes is ready**

# Publications:

[1] D. Bardin, L. Kalinovskaya and G. Nanava, 'An electroweak library for the calculation of EWRC to $e^+e^- \to f\bar{f}$ within the `CalcPHEP` project', **hep-ph/0012080**, revised version, November 2001, CERN-TH/2001-308.

[2] D. Bardin, L. Kalinovskaya and F. Tkachov, 'New algebraic–numeric methods for loop integrals: Some 1-loop experience', **hep-ph/0012209**, QFTHEP-2000 (Tver) Proceedings, Moscow 2001.

[3] Dmitri Bardin, '12 years of precision calculations for LEP. What's next?', **hep-ph/0101295**, talk presented at Symposium in honor of Professor Alberto Sirlin's 70th Birthday, New York, October 27-28, 2000.

[4] D. Bardin, P. Christova, L. Kalinovskaya and G. Passarino, 'Atomic Parity Violation and Precision Physics', **hep-ph/0102233**, EPJ, **C22** (2001) 99.

[5] A. Andonov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya and G. Nanava, 'Project `CalcPHEP`: Calculus for Precision High Energy Physics', **hep-ph/0202004**, CAAP-2001 (Dubna) Proceedings, Dubna 2001.

[6] A. Andonov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya and G. Nanava, 'Further study of the $e^+e^- \to f\bar{f}$ process with the aid of the `CalcPHEP` system', **hep-ph/0202112**, February 2002, CERN-TH/2002-068.

[7] A. Andonov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya and G. Nanava, 'Update of one-loop corrections for $e^+e^- \to f\bar{f}$, first run of `CalcPHEP` system', **hep-ph/0202112**, July 2002, *to appear in Particles and Nuclei.*

[8] A. Andonov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, and G. Passarino, 'Present Status of the project `CalcPHEP`, version 0.03', to be published in ACAT–2002 Proceedings.

[9] L. Kalinovskaya, 'About implementation of $e^+e^- \to f\bar{f}$ processes into the framework of `CalcPHEP` system', to be published in ACAT–2002 Proceedings.

[10] P. Christova, 'QED Radiative Corrections within the `CalcPHEP` project', to be published in ACAT–2002 Proceedings.

[11] G. Nanava, 'A Monte Carlo simulation of decays within the `CalcPHEP` project', to be published in ACAT–2002 Proceedings.

[12] A. Andonov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, G. Passarino, 'Project `CalcPHEP`', to be published in ICHEP2002 Proceedings.

# 4. Concluding remarks

**ADDRESS** *http://brg.jinr.ru/*

**FIRST PHASE** $\longrightarrow$ **Versions**

- **v0.03, Summer'02** – realizes the full chain of calculations, returns numbers and distributions for decay widths at 1-loop level (demonstration of workability);
- **v0.10, nearest future** – one has very many almost finished 'preparations' for processes $2 \to 2$ and decays $1 \to 3$ (levels 1–2).

**SECOND PHASE** $\longrightarrow$ 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$\to$ 3** and **DECAYS 1$\to$ 4**