RADCOR2002, 9 September, 2002, Kloster Banz

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

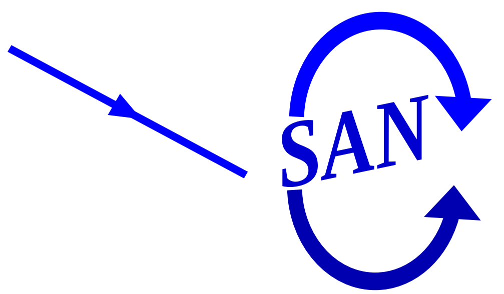
1. SANC project and its roots

People:
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:
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_ξ 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:** ϕ^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_ξ 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**

$W \to u\bar{d}$ 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:

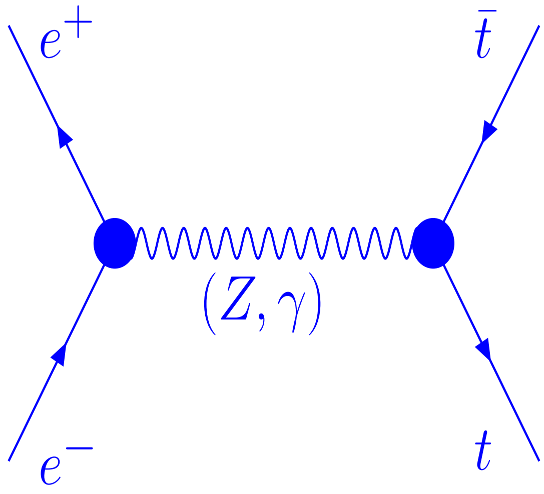
$$\mathbf{A}^{\mathbf{Z}}_{\mathbf{0}++} = \mathbf{A}^{\mathbf{Z}}_{\mathbf{0}--} = \frac{gm_f}{c_W}\Big[a_f\mathcal{F}_{\mathbf{L}} + \delta_f\mathcal{F}_{\mathbf{Q}} + \frac{1}{2}a_f\beta_f^2 M_Z^2\mathcal{F}_{\mathbf{D}}\Big]$$

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

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

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

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



$$A \sim \left[i\gamma_\mu\left(1+\gamma_5\right)F_L^e\left(s\right)+i\gamma_\mu F_Q^e\left(s\right)\right]\otimes$$

$$\left[i\gamma_\mu\left(1+\gamma_5\right)F_L^f\left(s\right)+i\gamma_\mu F_Q^f\left(s\right)+m_t I D_\mu F_D^f\left(s\right)\right]$$

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

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**:

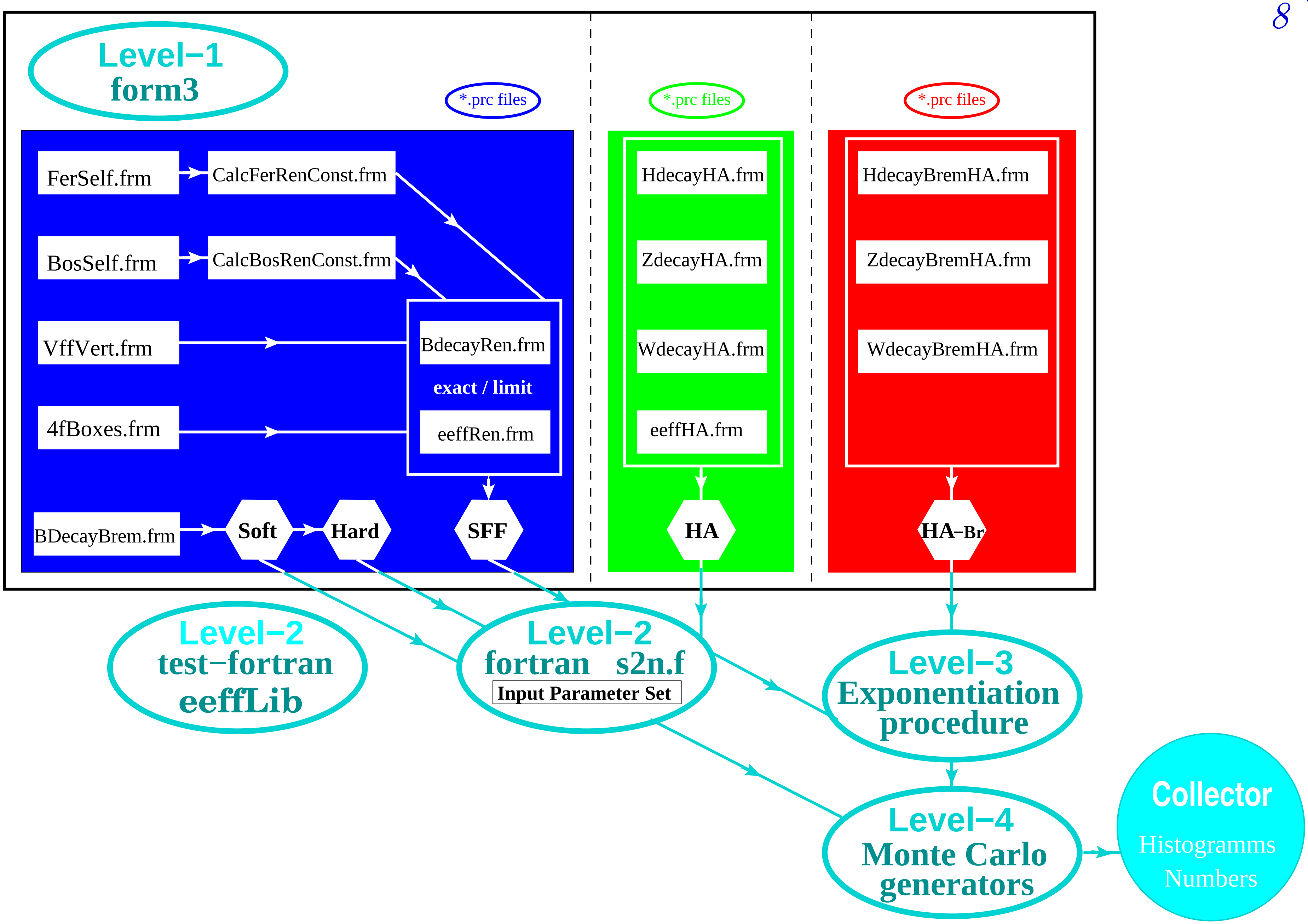
$$
\begin{aligned}
\mathcal{A}_{++++} &= 0, \qquad \mathcal{A}_{+++-} = 0, \qquad \mathcal{A}_{++-+} = 0, \qquad \mathcal{A}_{++--} = 0,\\
\mathcal{A}_{+-+-} &= s\,(1-\cos\vartheta)\left(Q_eQ_fF_{GG} + \chi_Z\delta_e[\,(1+\beta_f)\,I_f^{(3)}F_{QL} + \delta_fF_{QQ}]\right),\\
\mathcal{A}_{+--+} &= s\,(1+\cos\vartheta)\left(Q_eQ_fF_{GG} + \chi_Z\delta_e[(1-\beta_f)I_f^{(3)}F_{QL} + \delta_fF_{QQ}]\right),\\
\mathcal{A}_{+---} &= \mathcal{A}_{+-++} = 2\sqrt{s}m_f\sin\vartheta\Big(Q_eQ_fF_{GG} + \chi_Z\delta_e[I_f^{(3)}F_{QL} + \delta_fF_{QQ} + \frac{1}{2}s{\beta_f}^2I_f^{(3)}F_{QD}]\Big),\\
\mathcal{A}_{-+++} &= \mathcal{A}_{-+--} = -2\sqrt{s}m_f\sin\vartheta\Big(Q_eQ_fF_{GG}\\
&\qquad +\chi_Z\Big[2I_e^{(3)}I_f^{(3)}F_{LL} + 2I_e^{(3)}\delta_fF_{LQ} + \delta_eI_f^{(3)}F_{QL} + \delta_e\delta_fF_{QQ} + \frac{1}{2}s{\beta_f}^2I_f^{(3)}(2I_e^{(3)}F_{LD} + \delta_eF_{QD})\Big]\Big),\\
\mathcal{A}_{-++-} &= s\,(1+\cos\vartheta)\left(Q_eQ_fF_{GG} + \chi_Z[\,(1+\beta_f)\,(2I_e^{(3)}I_f^{(3)}F_{LL} + \delta_eI_f^{(3)}F_{QL}) + \delta_f\left(2I_e^{(3)}F_{LQ} + \delta_eF_{QQ}\right)]\right),\\
\mathcal{A}_{-+-+} &= s\,(1-\cos\vartheta)\left(Q_eQ_fF_{GG} + \chi_Z[\,(1-\beta_f)\,I_f^{(3)}(2I_e^{(3)}F_{LL} + \delta_eF_{QL}) + \delta_f(2I_e^{(3)}F_{LQ} + \delta_eF_{QQ})]\right),\\
\mathcal{A}_{--++} &= 0, \qquad \mathcal{A}_{--+-} = 0, \qquad \mathcal{A}_{---+} = 0, \qquad \mathcal{A}_{----} = 0.
\end{aligned}
$$

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

3. Present Status of the project

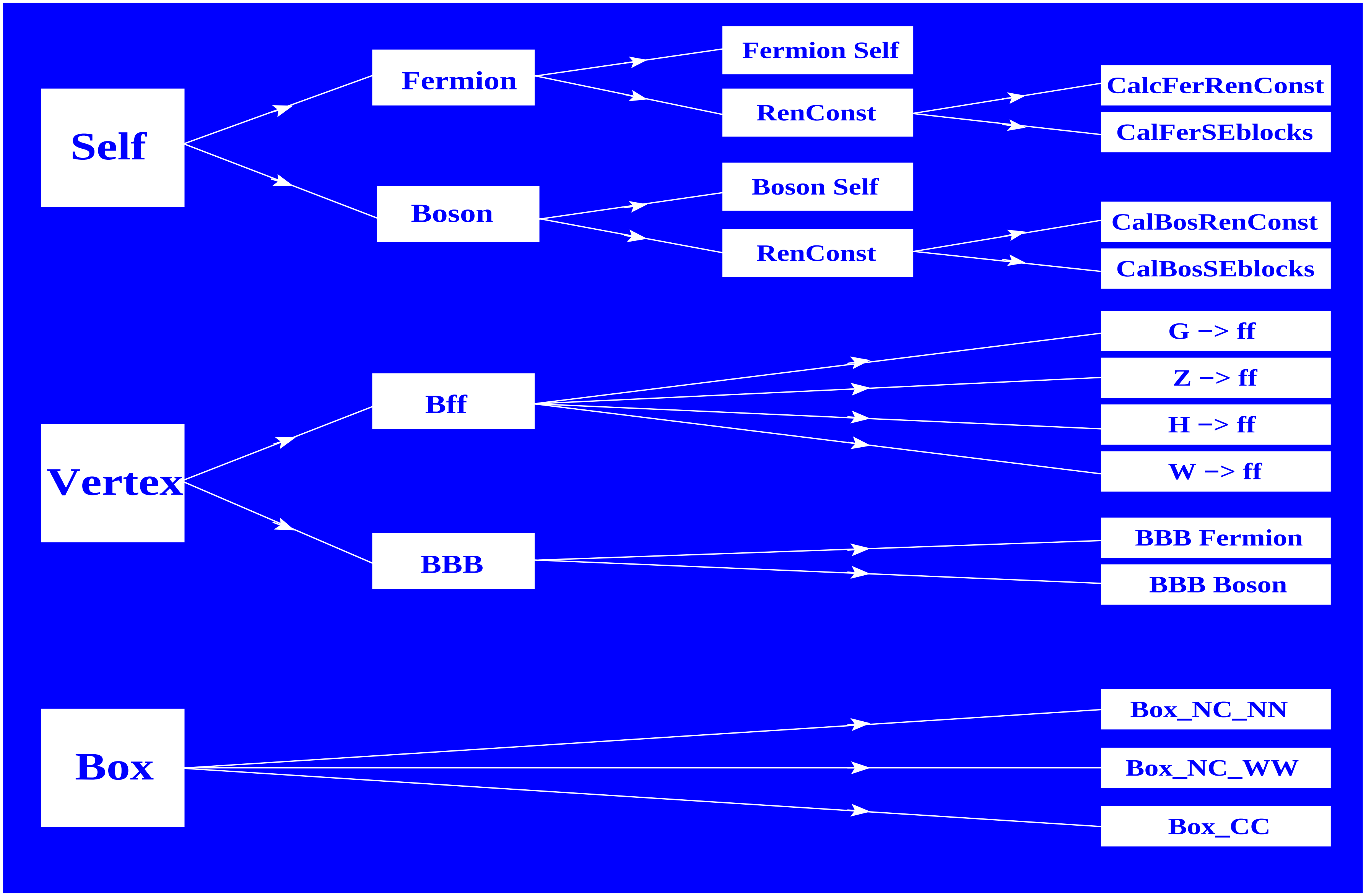
Basic information about SANC

- **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

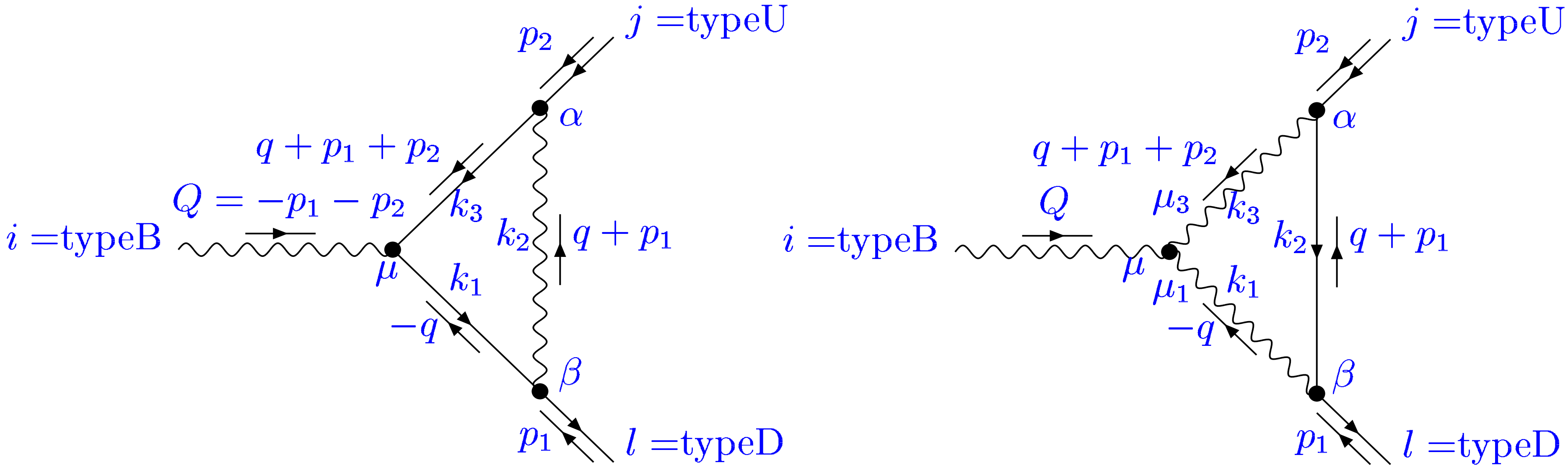
PRECOMPUTATION

*.prc files



An example of PRECOMPUTATION

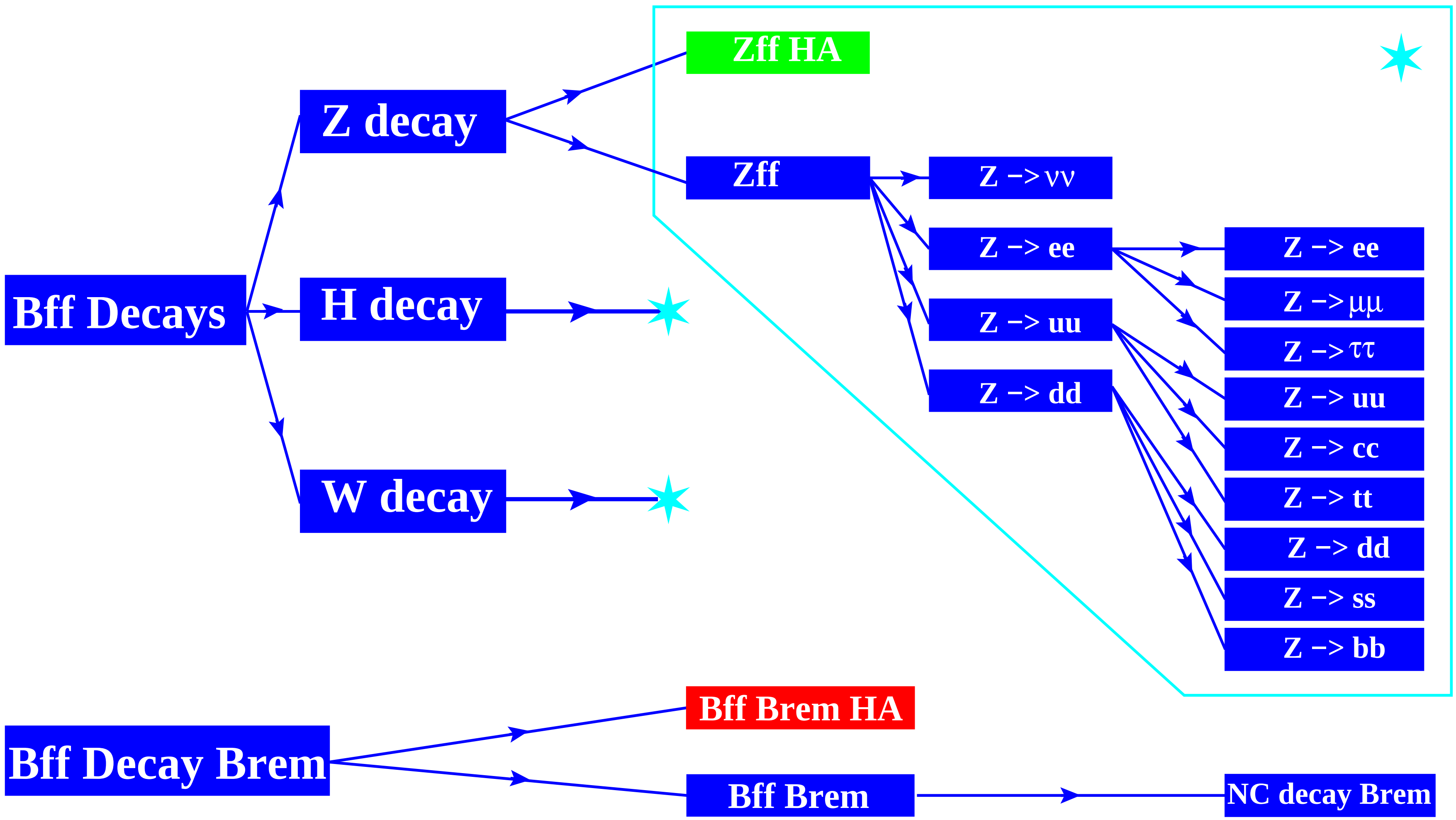
Chain: **Vertex** → **Bff** → **Z→ff**

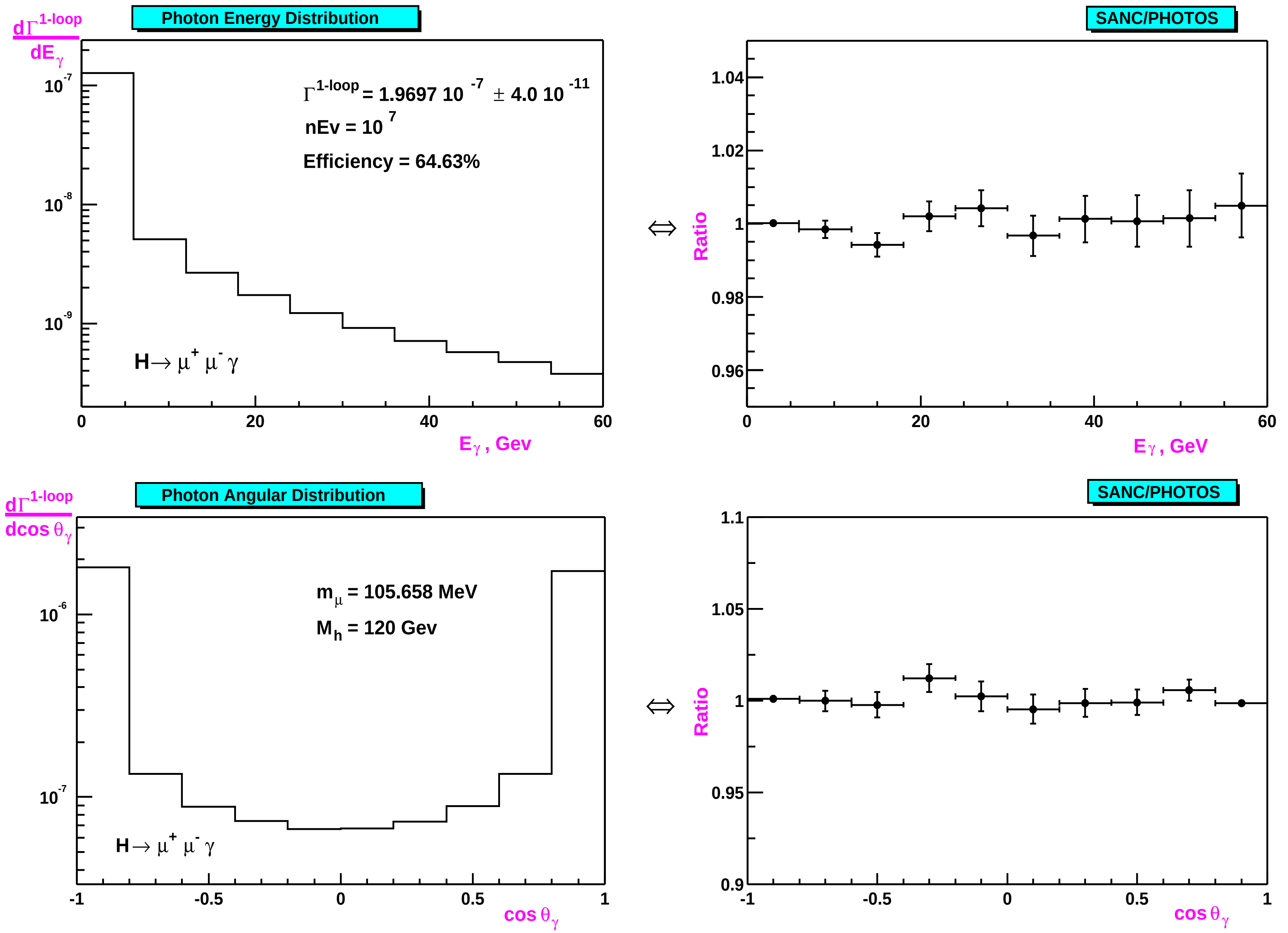


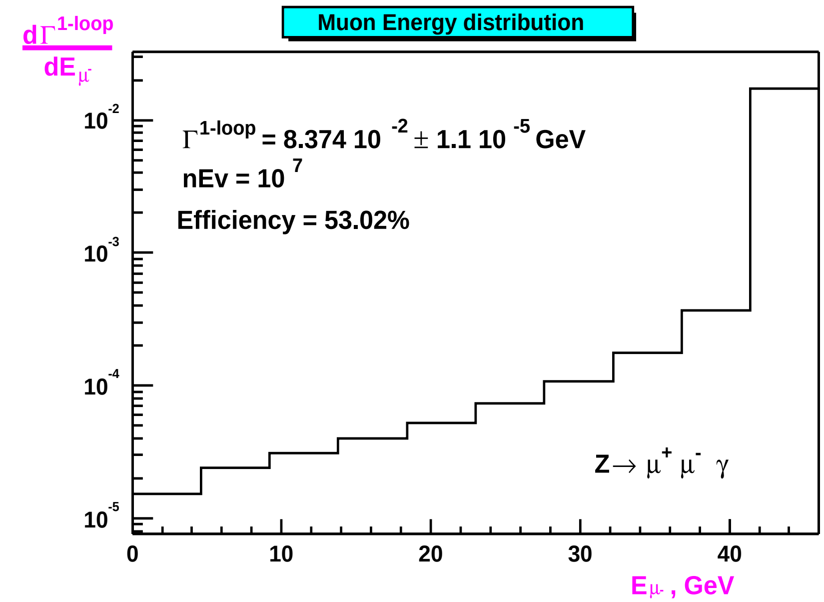
Vertices: FBF-topology, BFB-topology.

PROGRAMS

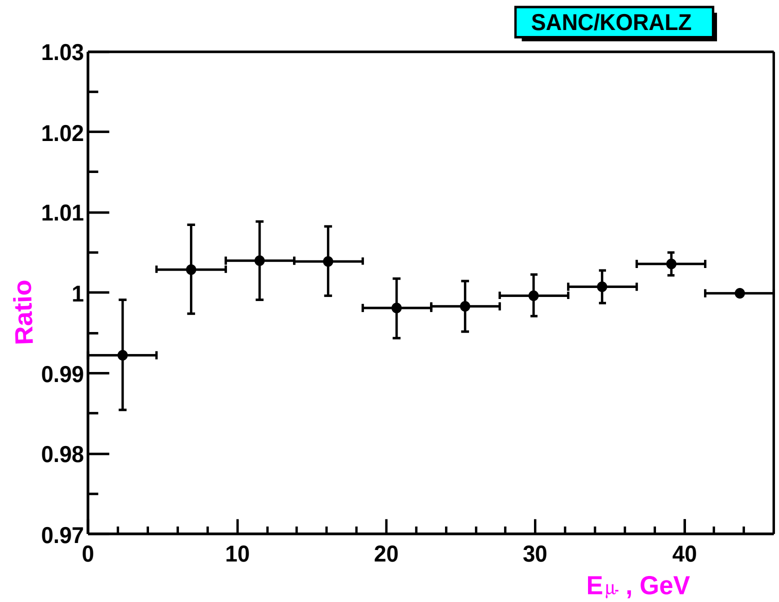
*.prc files *.prc files *.prc files

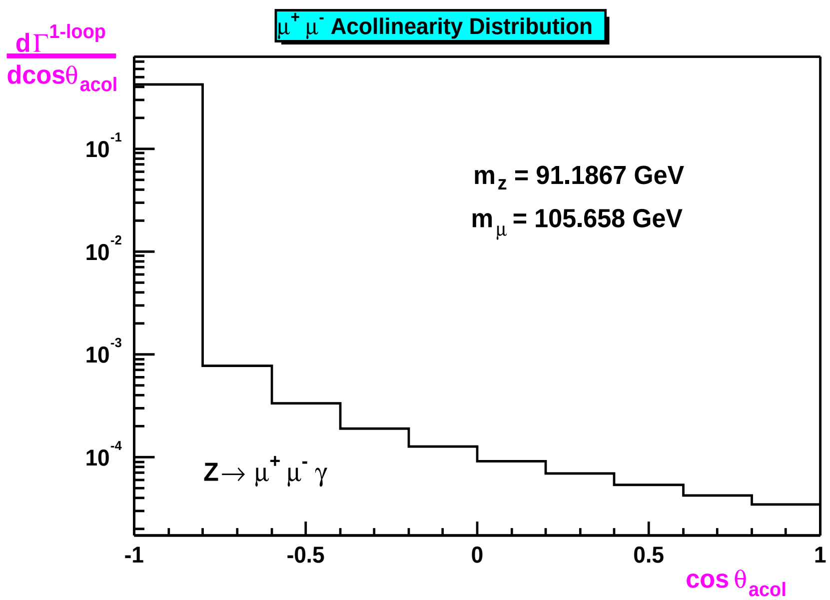



Photon Energy Distribution
dΓ^1-loop / dE_γ
Γ^1-loop = 1.9697 10^-7 ± 4.0 10^-11
nEv = 10^7
Efficiency = 64.63%
H→ μ+ μ- γ
E_γ , Gev
SANC/PHOTOS
Ratio
E_γ , GeV
Photon Angular Distribution
dΓ^1-loop / dcos θ_γ
m_μ = 105.658 MeV
M_h = 120 Gev
H→ μ+ μ- γ
cos θ_γ
SANC/PHOTOS
Ratio
cos θ_γ

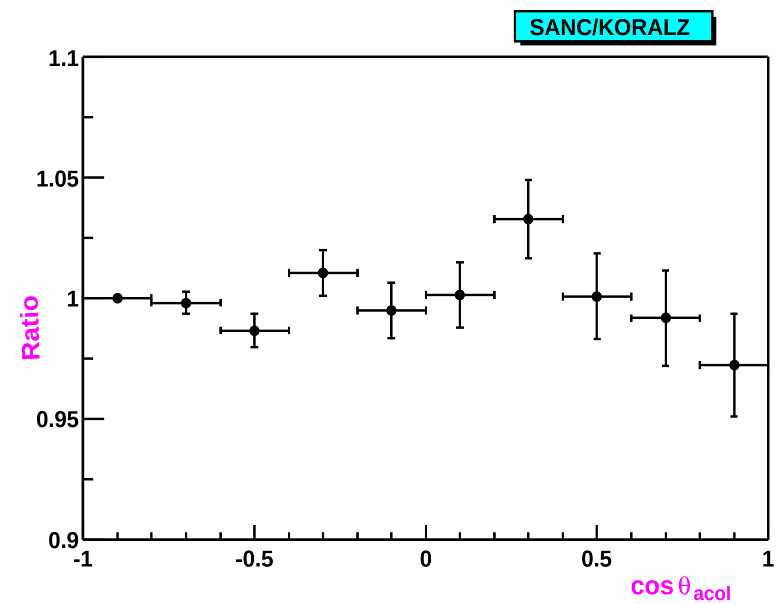

Muon Energy distribution
dΓ^1-loop / dE_μ-
Γ^1-loop = 8.374 10^-2 ± 1.1 10^-5 GeV
nEv = 10^7
Efficiency = 53.02%
Z→ μ+ μ- γ
Eμ- , GeV

⇔

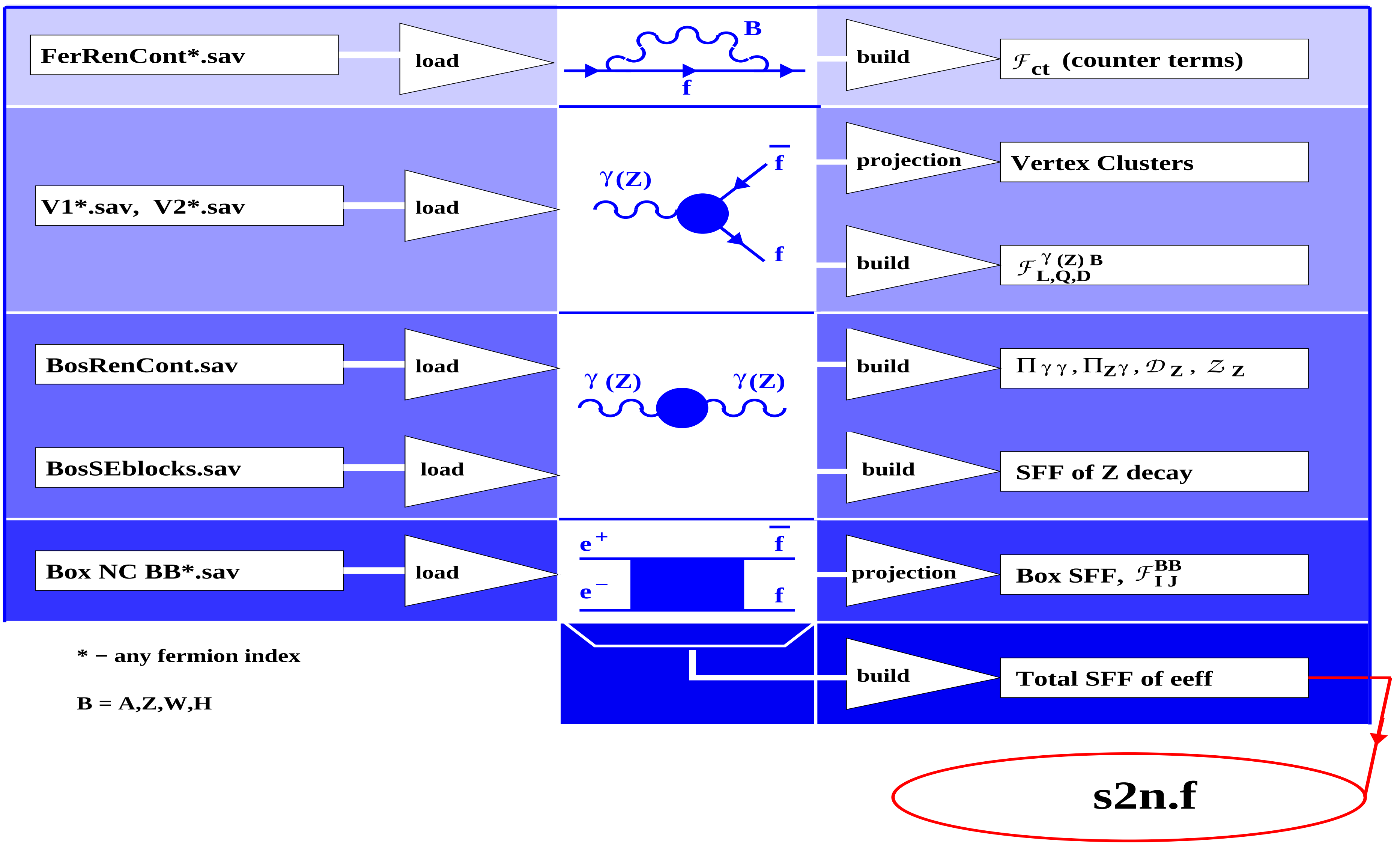

SANC/KORALZ
Ratio
Eμ- , GeV


μ+ μ- Acollinearity Distribution
dΓ^1-loop / dcosθ_acol
m_Z = 91.1867 GeV
m_μ = 105.658 GeV
Z→ μ+ μ- γ
cos θ_acol

⇔


SANC/KORALZ
Ratio
cos θ_acol

Calculation flow in eeffRen.frm



3. Present status of the project, contd.

COMPARISON ⟶ AGREEMENT

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

- `eeffLib–ZFITTER`

  SFFs ⟶ **8–9 digits**

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

  Total 1-loop cross section and σ^{FB} for the light fermion masses ⟶ **6–7 digits**

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

- `s2n.f–eeffLib`

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

- `s2n.f–FeynArt`

  1-loop cross-section **without soft photons** ⟶ **11 digits**

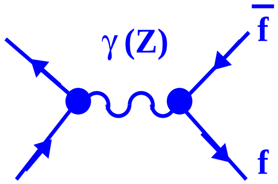
- `s2n.f–topfit`*

  1-loop cross-section **with soft photons** ⟶ **8 digits**

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

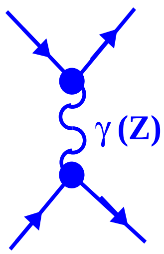
DONE

I)



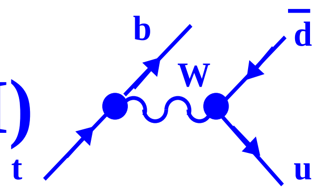
e e --> $\nu\bar{\nu}$, l l, $u\,\bar{u}$, $d\,\bar{d}$, $c\,\bar{c}$, $s\,\bar{s}$, $b\,\bar{b}$, $t\,\bar{t}$ (LEVEL 1−2)

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 ⟶ 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 ⟶ 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→ 3 and **DECAYS 1→ 4**