ICHEP2002, 26 July, 2002, Amsterdam

Project SANC (former CalcPHEP):

Support of Analitic and Numeric calculations for experiments at Colliders

D. Bardin

Laboratory of Nuclear Problems, Joint Institute for Nuclear Research

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:
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)→ $f(p_1)\overline{f}(p_2)$

$H \to f\overline{f}$ 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:

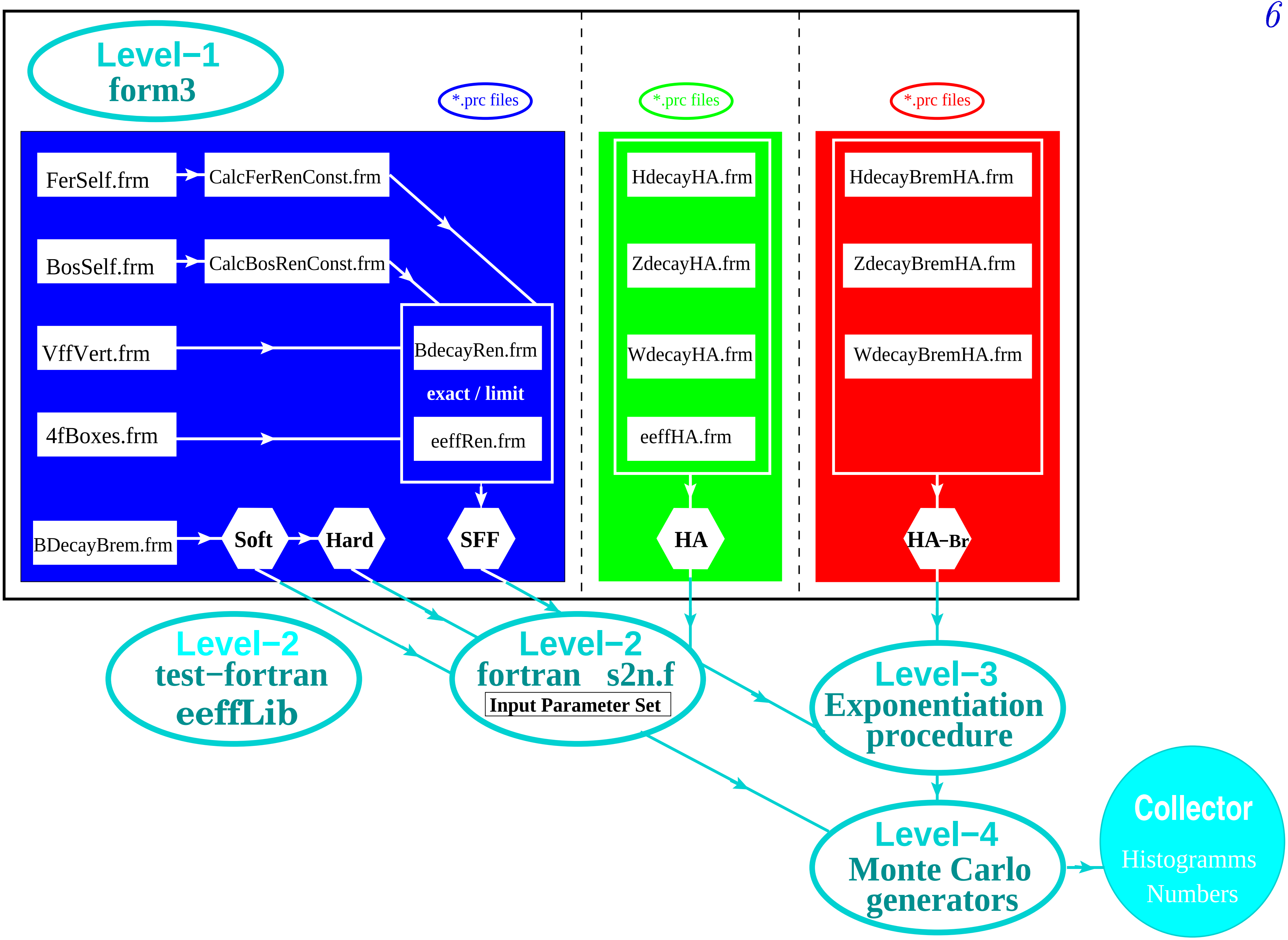
$$
\begin{aligned}
\mathbf{A}^{\mathbf{Z}}_{\mathbf{0}++} = \mathbf{A}^{\mathbf{Z}}_{\mathbf{0}--} &= \frac{gm_f}{c_W}\Big[a_f\mathcal{F}_{\mathbf{L}} + \delta_f\mathcal{F}_{\mathbf{Q}} + \frac{1}{2}a_f\beta_f^2 M_Z^2\mathcal{F}_{\mathbf{D}}\Big] \\
\mathbf{A}^{\mathbf{Z}}_{++-} &= \frac{gM_Z}{\sqrt{2}c_W}\big[a_f(1-\beta_f)\mathcal{F}_{\mathbf{L}} + \delta_f\mathcal{F}_{\mathbf{Q}}\big] \\
\mathbf{A}^{\mathbf{Z}}_{--+} &= \frac{gM_Z}{\sqrt{2}c_W}\big[a_f(1+\beta_f)\mathcal{F}_{\mathbf{L}} + \delta_f\mathcal{F}_{\mathbf{Q}}\big]
\end{aligned}
$$

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

3. Present Status of the project

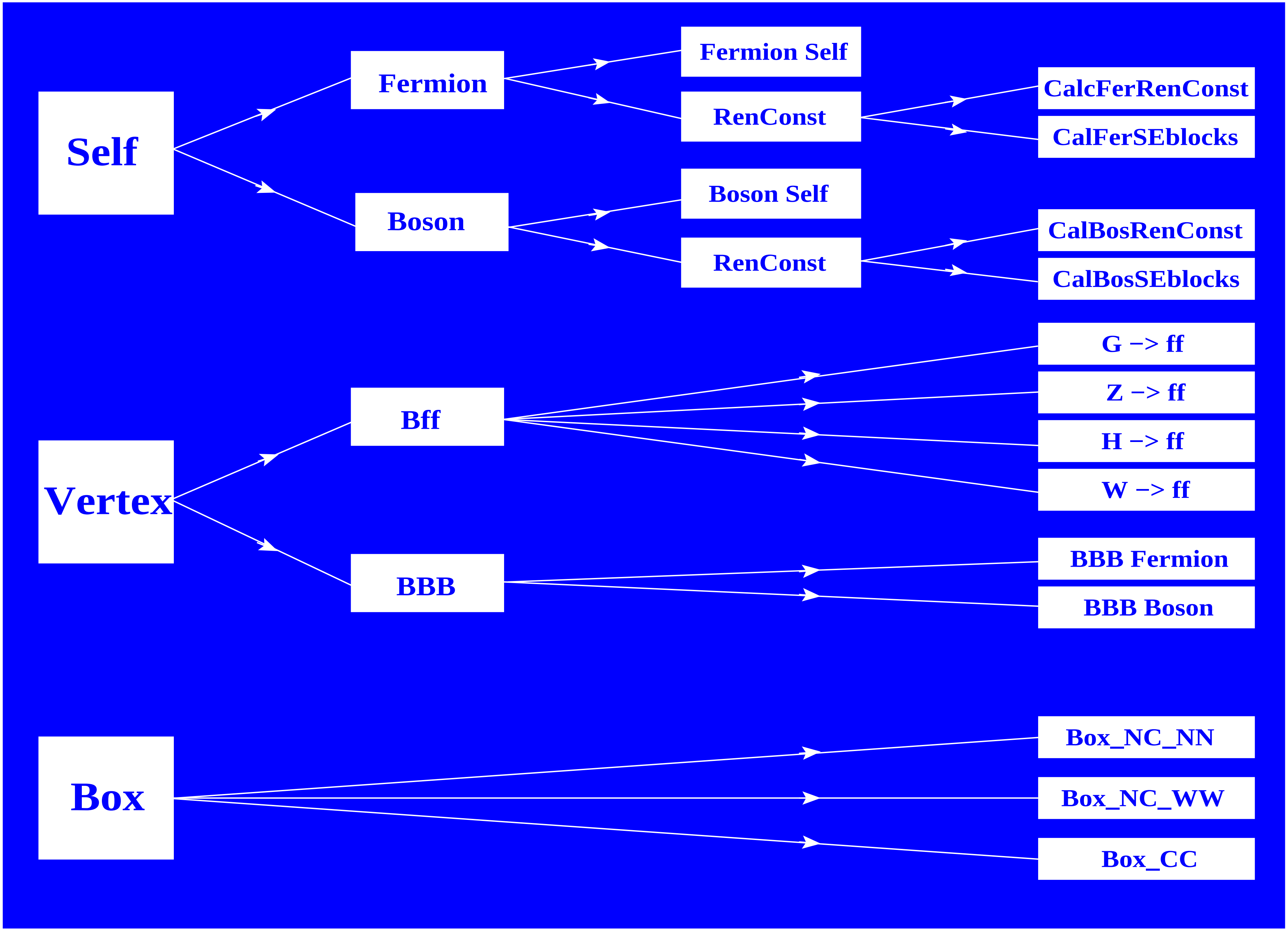
Basic information about SANC

- **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

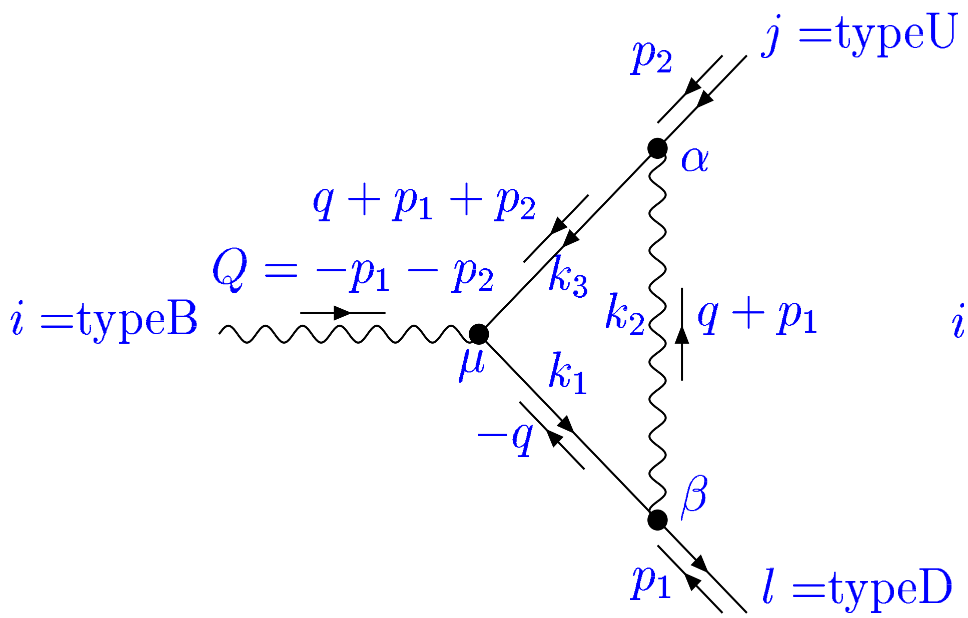
PRECOMPUTATION

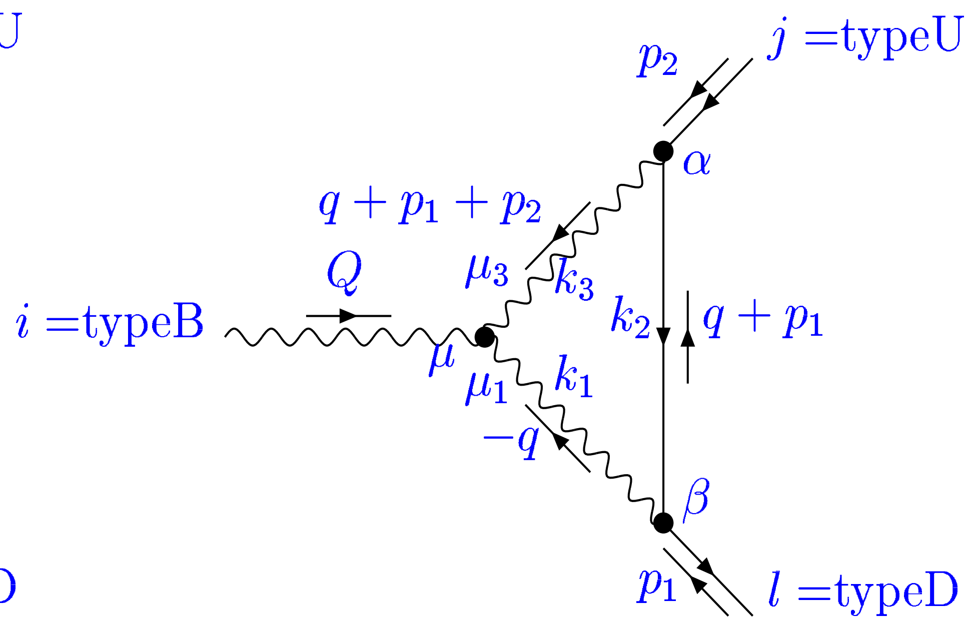
*.prc files



An example of PRECOMPUTATION

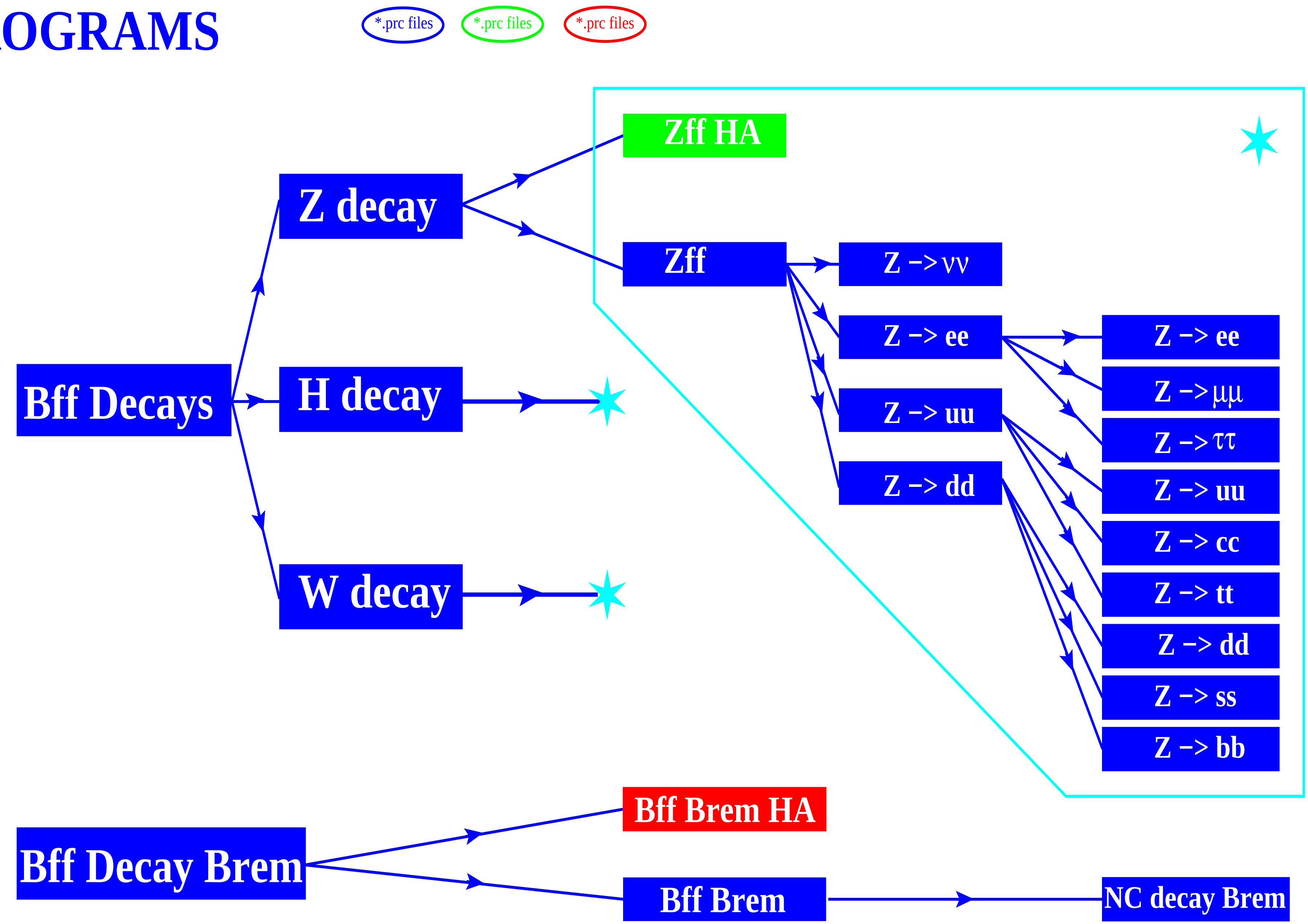
Chain: $\boxed{\textbf{Vertex}} \to \boxed{\textbf{Bff}} \to \boxed{\textbf{Z}\to\textbf{ff}}$





Vertices: FBF-topology, BFB-topology.

PROGRAMS


*.prc files
*.prc files
*.prc files
Zff HA
Z decay
Zff
Z -> νν
Z -> ee
Z -> uu
Z -> dd
Z -> ee
Z -> μμ
Z -> ττ
Z -> uu
Z -> cc
Z -> tt
Z -> dd
Z -> ss
Z -> bb
Bff Decays
H decay
W decay
Bff Decay Brem
Bff Brem HA
Bff Brem
NC decay Brem

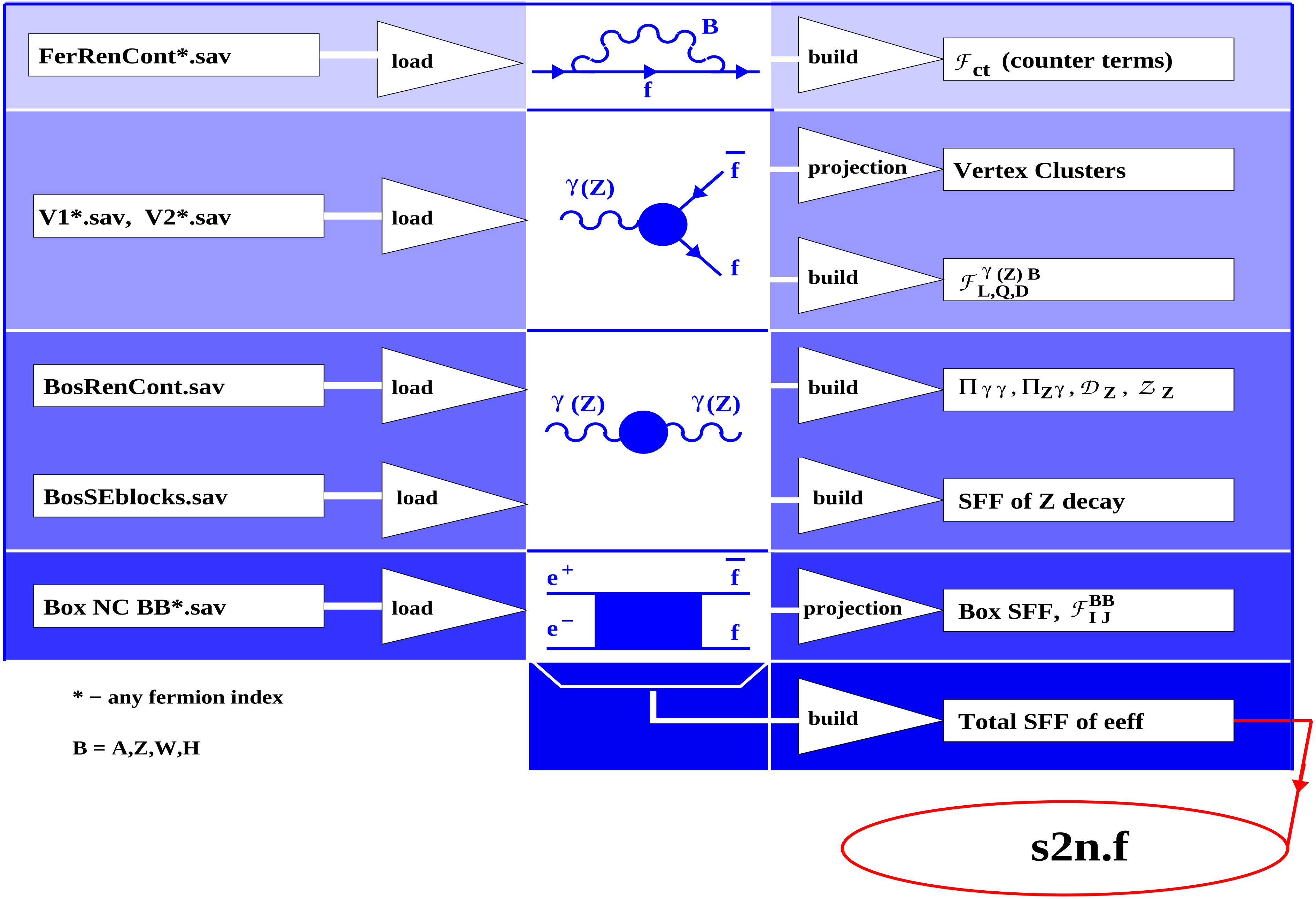
3. Present status of the project, contd.

- **Versions:**
  - **v0.01, March 2001** – realizes a part of analytic calculations of Level-1 (SFFs) for the decays $H(Z,W) \to f_1 \bar{f}_2$ (demostration of viability);
  - several versions **v0.02c/d** – towards realization of levels 1,2,4 for decays $H(Z,W) \to f_1 \bar{f}_2$;
  - **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 $2 \to 2$ and decays $1 \to 3$ (levels 1–2).

- **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.*

Calculation flow in eeffRen.frm



* − any fermion index

B = A,Z,W,H

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 σ^{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**

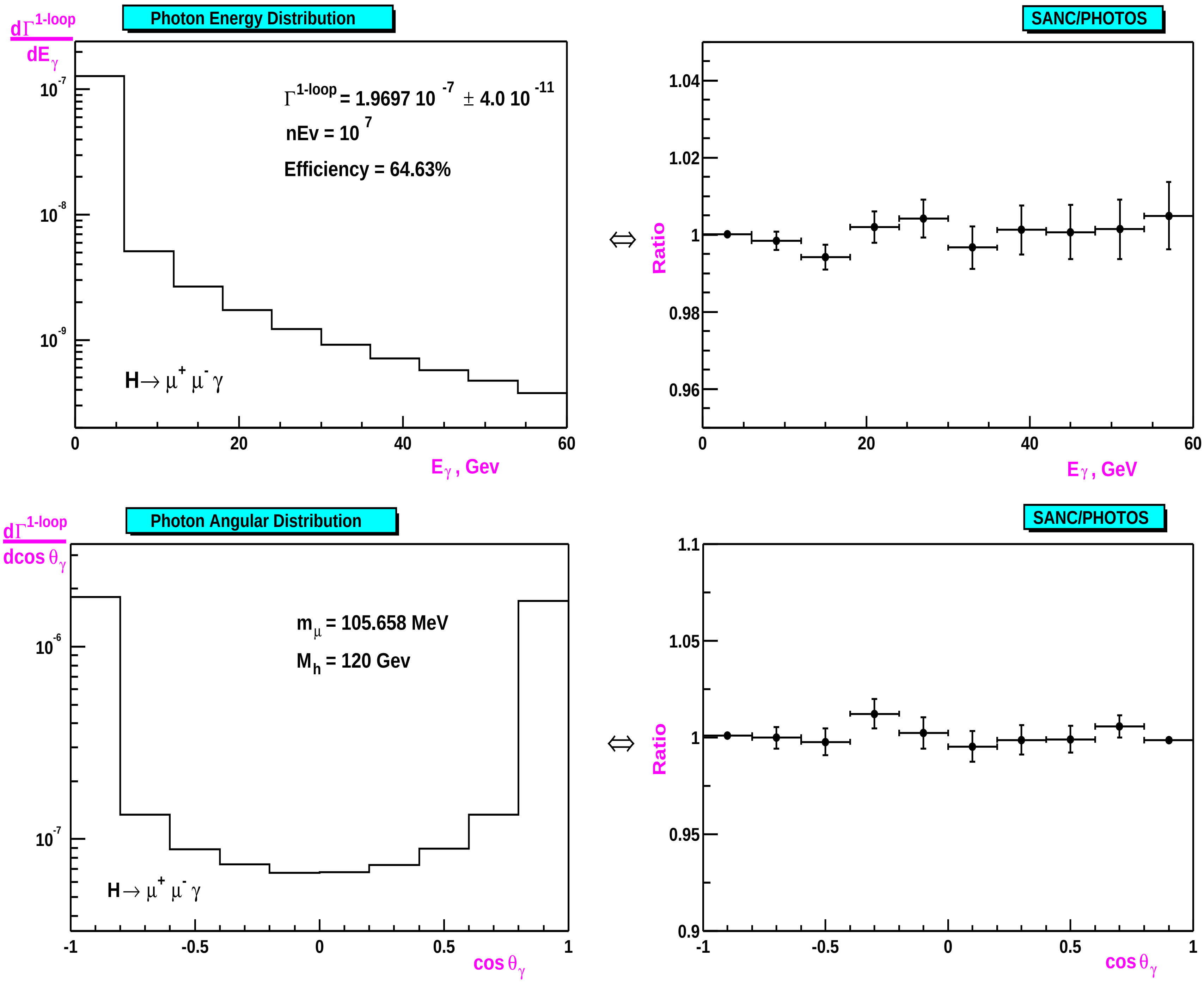
- `s2n.f–FeynArt`

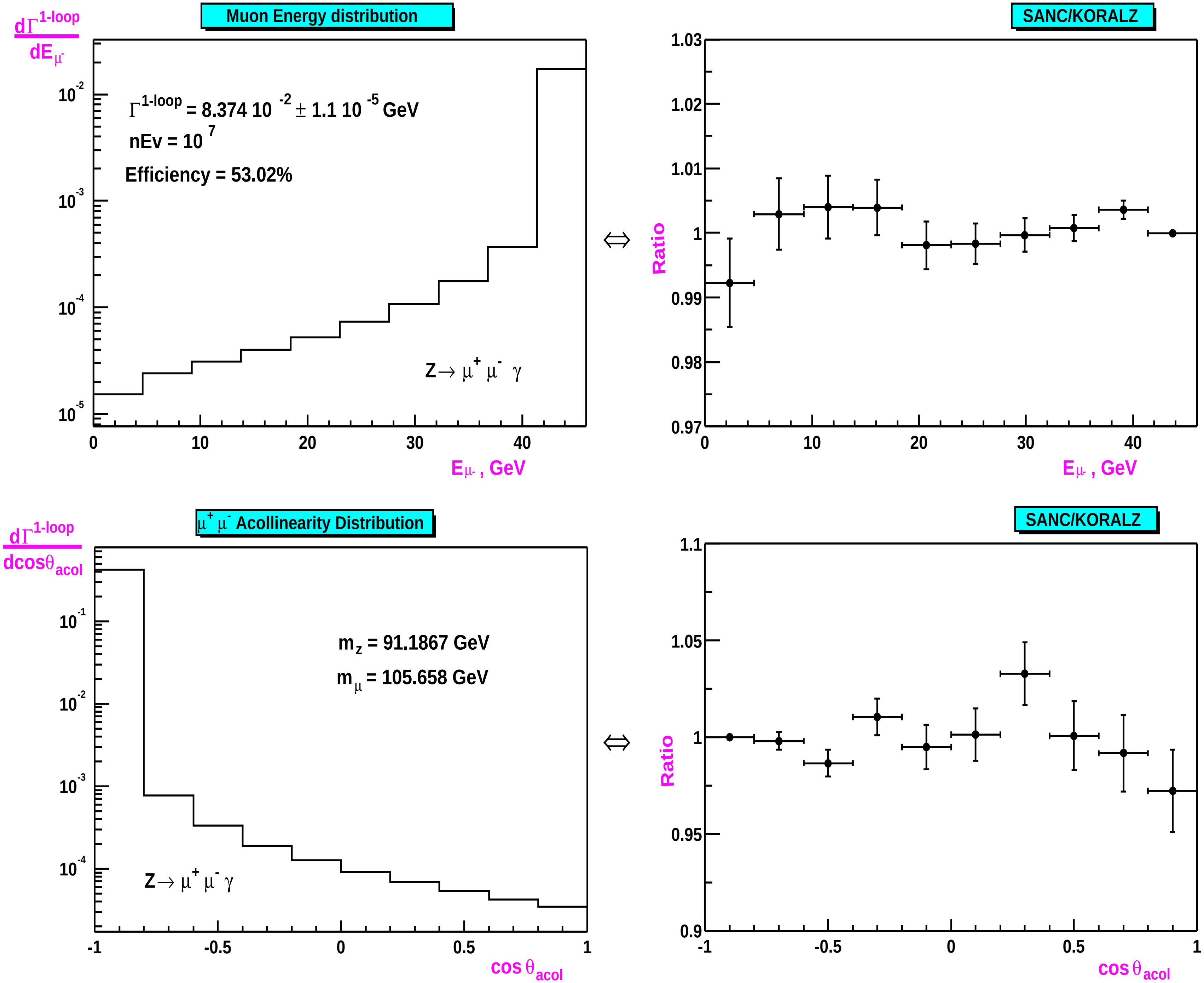
  1-loop cross-section **without soft photons** $\longrightarrow$ **11 digits**

- `s2n.f–topfit`*

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

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


Photon Energy Distribution
$\frac{d\Gamma^{1\text{-loop}}}{dE_\gamma}$
$\Gamma^{1\text{-loop}} = 1.9697\ 10^{-7} \pm 4.0\ 10^{-11}$
nEv = 10^{7}
Efficiency = 64.63%
$H \to \mu^+ \mu^- \gamma$
E_γ, Gev
SANC/PHOTOS
$\Leftrightarrow$
Ratio
E_γ, GeV
Photon Angular Distribution
$\frac{d\Gamma^{1\text{-loop}}}{d\cos\theta_\gamma}$
m_μ = 105.658 MeV
M_h = 120 Gev
$H \to \mu^+ \mu^- \gamma$
$\cos\theta_\gamma$
SANC/PHOTOS
$\Leftrightarrow$
Ratio
$\cos\theta_\gamma$


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_{μ^-}, GeV
SANC/KORALZ
Ratio
$\Leftrightarrow$
$\mu^+ \mu^-$ 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
$\Leftrightarrow$

4. Concluding remarks

SAN

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

FIRST PHASE $\longrightarrow$ release of *demonstration version 0.10* in 2002

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$\rightarrow$ 3 and **DECAYS 1$\rightarrow$ 4**

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Application: LHC, Linacs.

Roots:

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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.

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

Example of decays B(Q)→ $f(p_1)\overline{f}(p_2)$

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

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

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

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

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

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:

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

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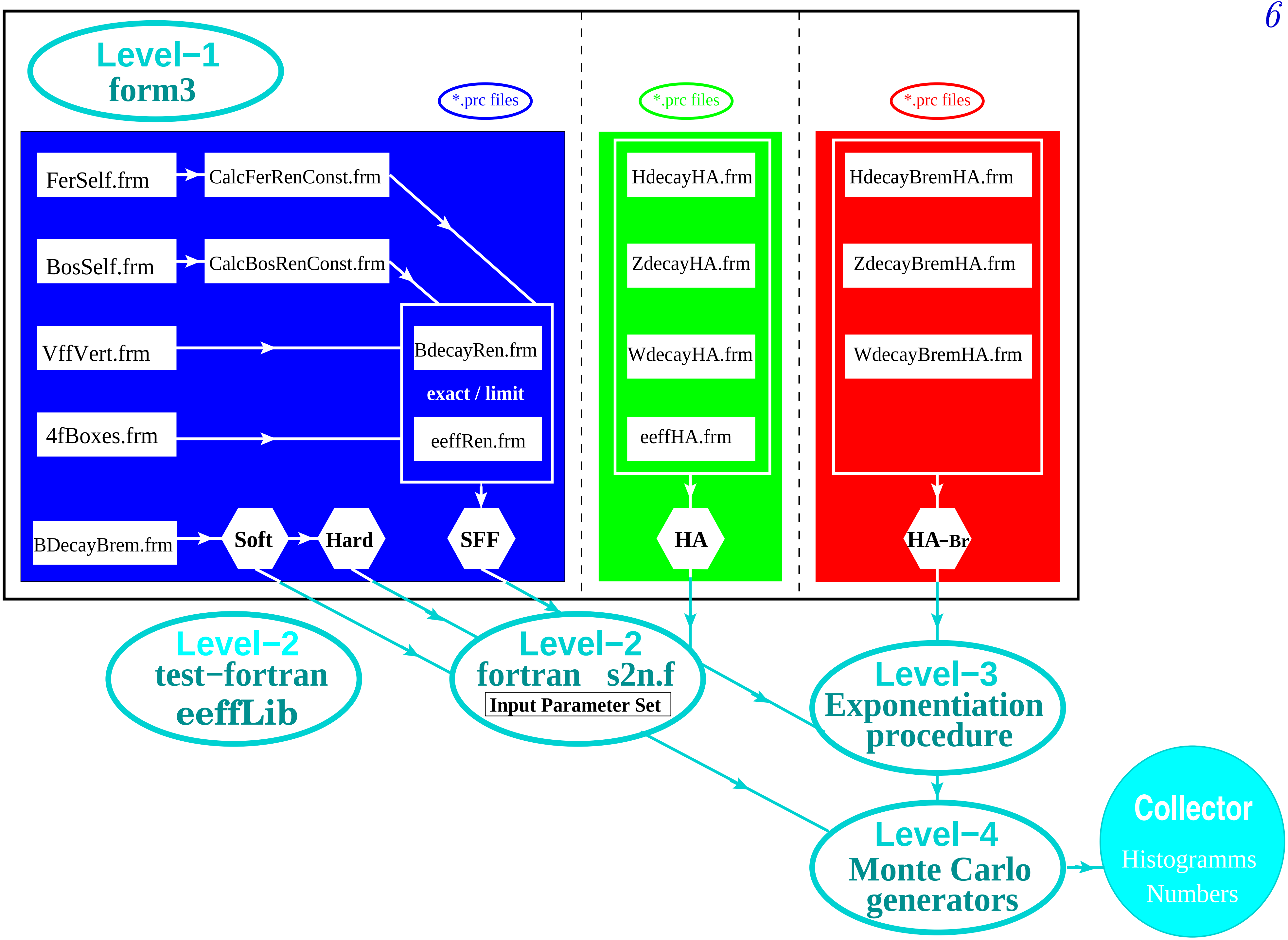
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VffVert.frm
BdecayRen.frm
exact / limit
4fBoxes.frm
eeffRen.frm
BDecayBrem.frm
Soft
Hard
SFF
HdecayHA.frm
ZdecayHA.frm
WdecayHA.frm
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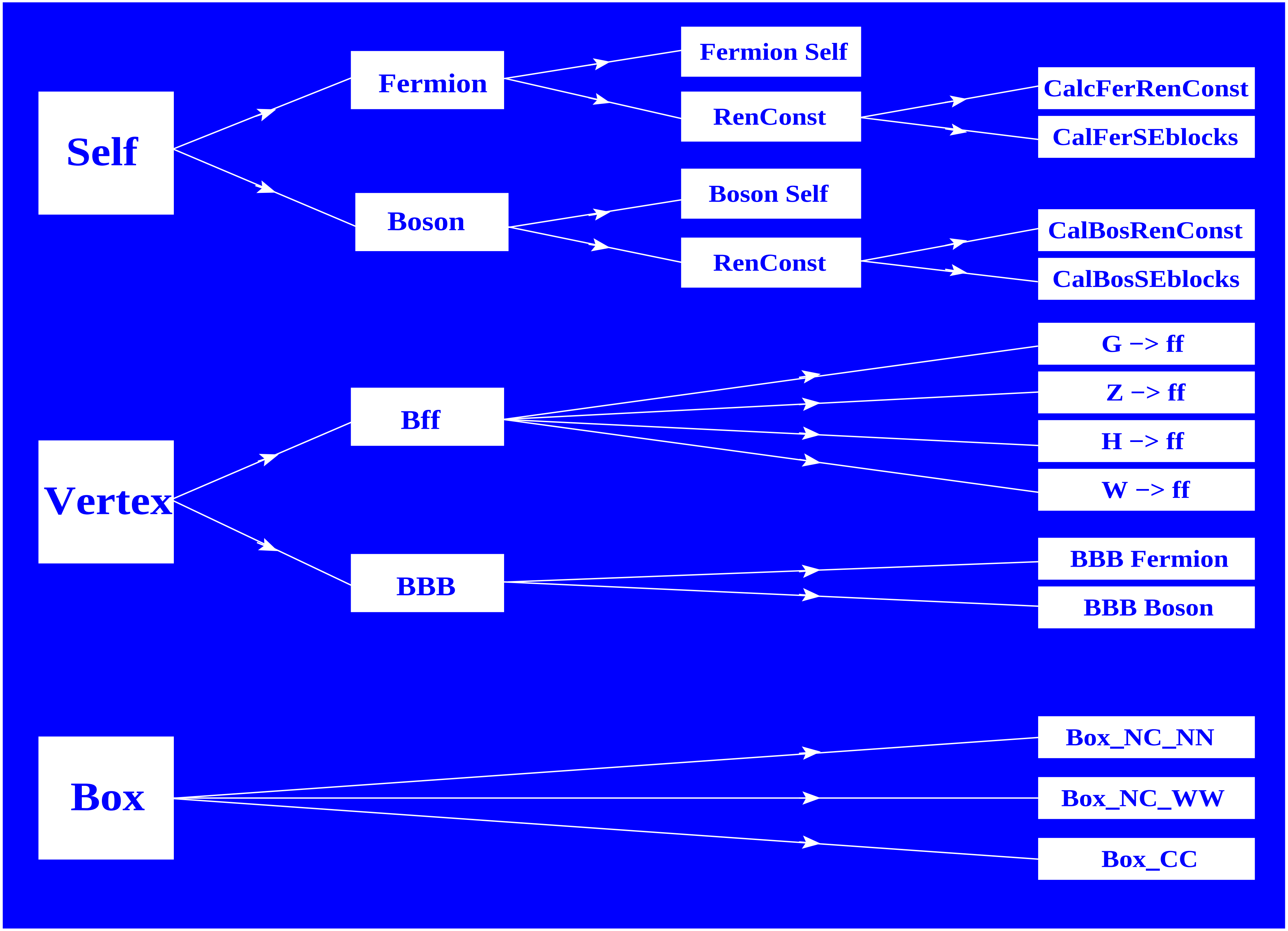
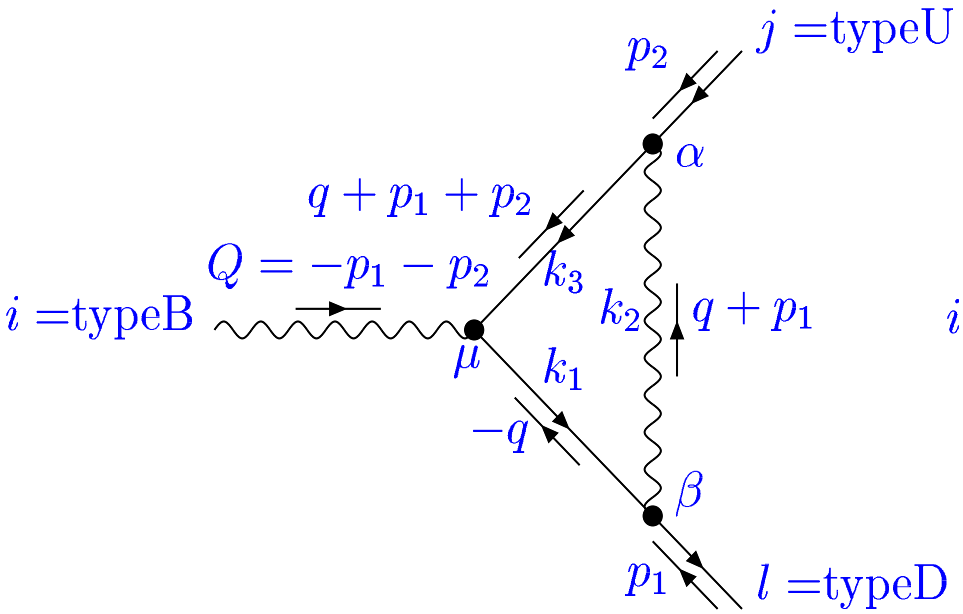
PRECOMPUTATION

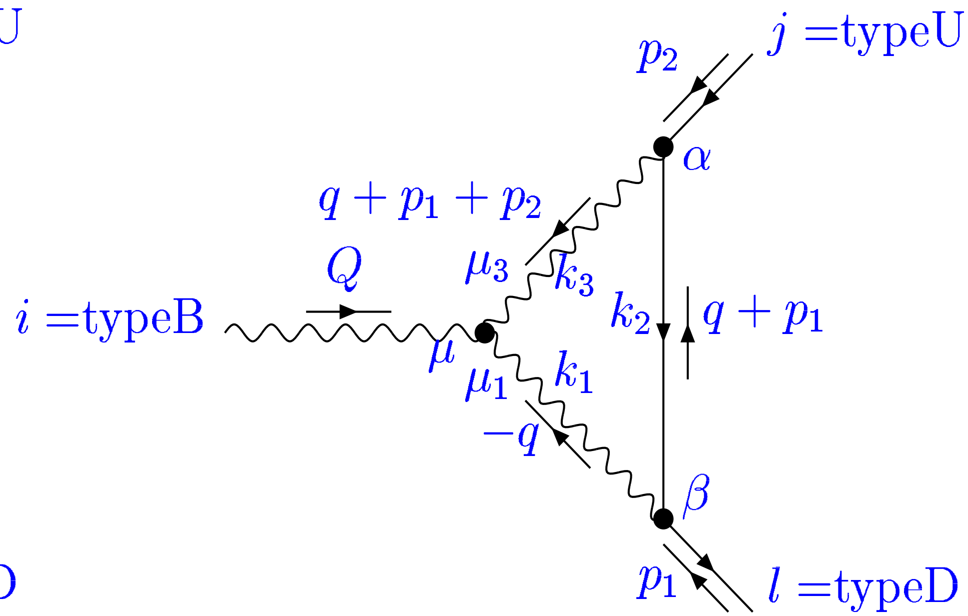
*.prc files



An example of PRECOMPUTATION

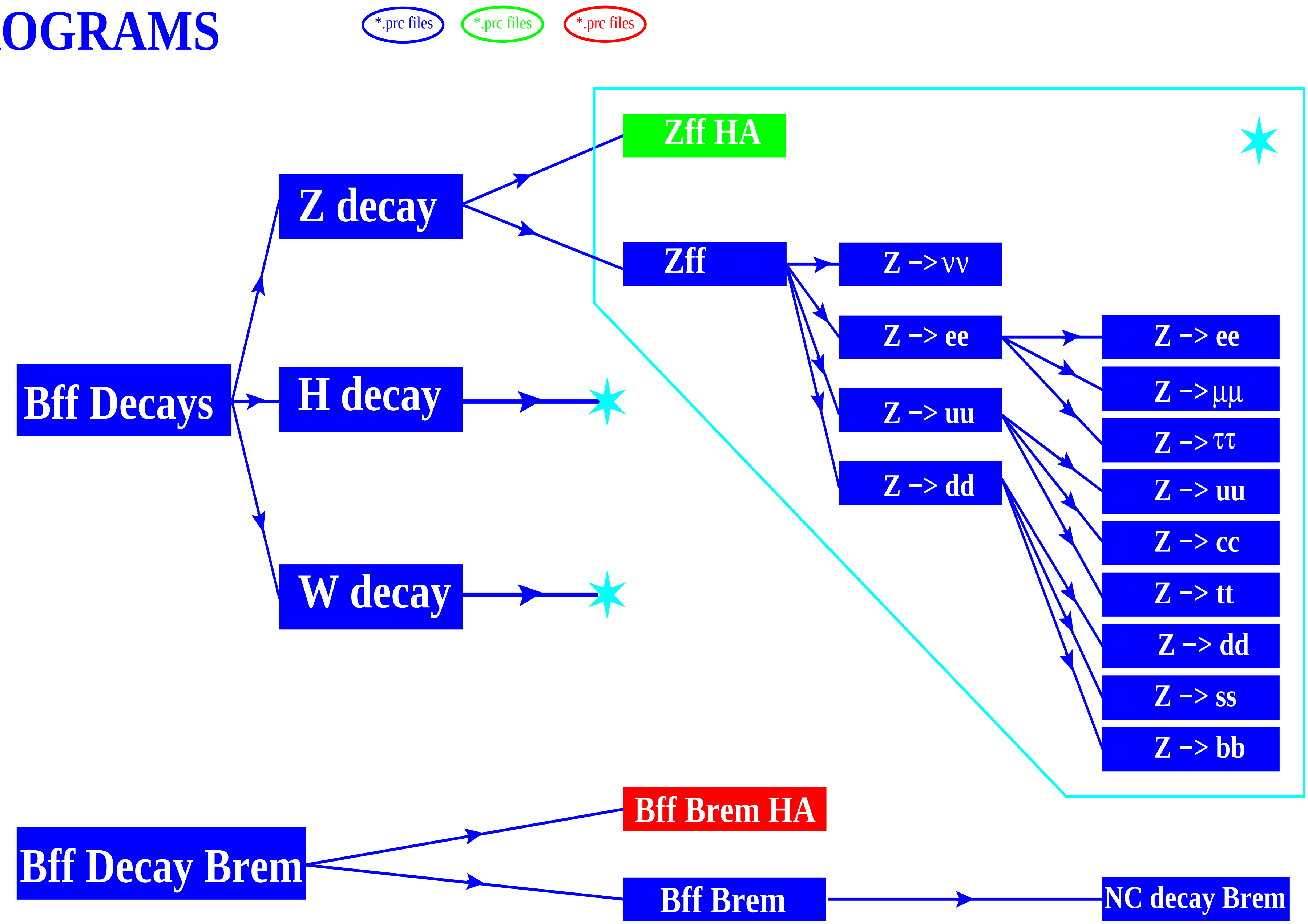
Chain: $\boxed{\textbf{Vertex}} \rightarrow \boxed{\textbf{Bff}} \rightarrow \boxed{\textbf{Z}\rightarrow\textbf{ff}}$





Vertices: FBF-topology, BFB-topology.

PROGRAMS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Bff Brem HA
Bff Decay Brem
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3. Present status of the project, contd.

- **Versions:**
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- **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.

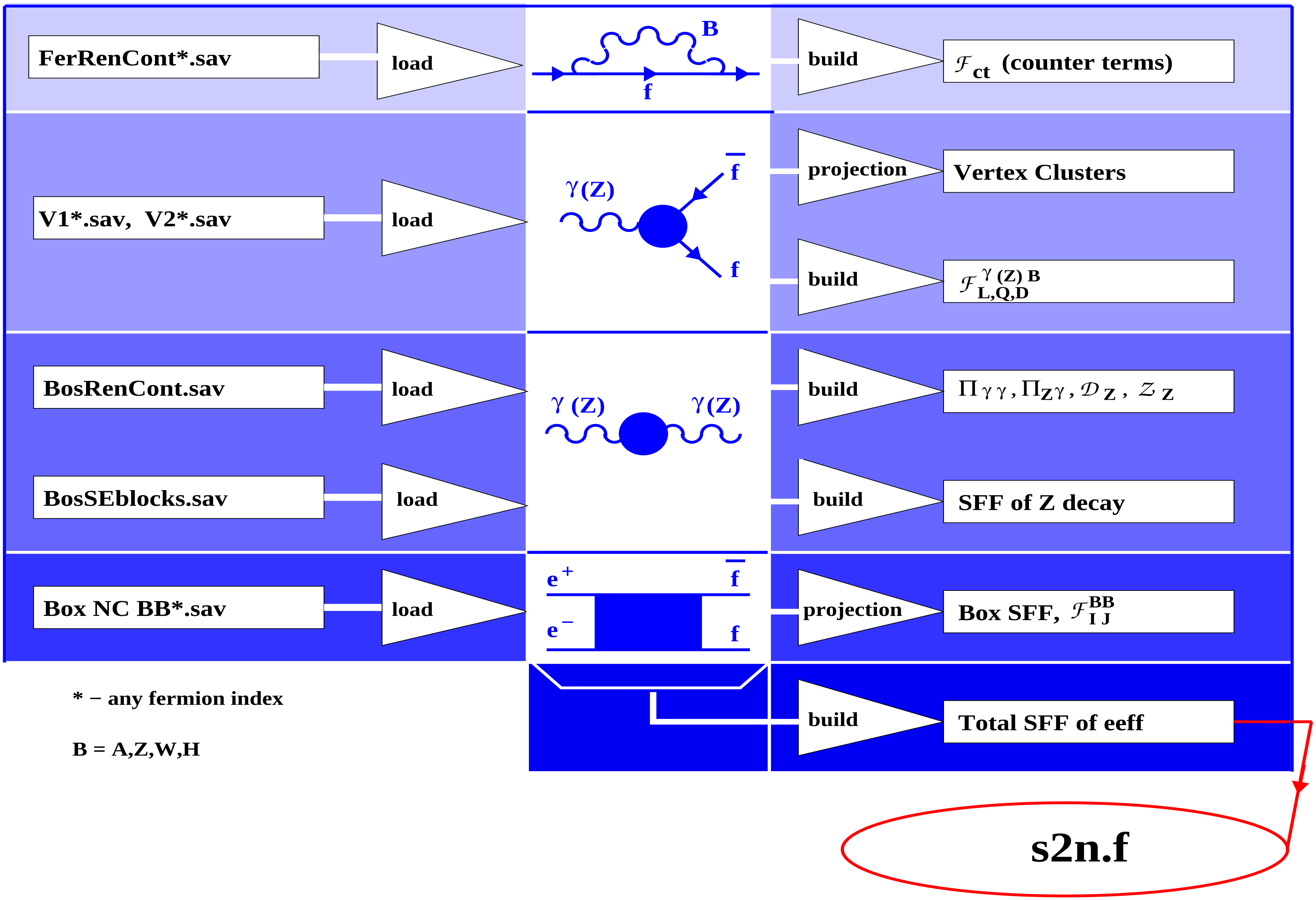
[4] D. Bardin, P. Christova, L. Kalinovskaya and G. Passarino, 'Atomic Parity Violation and Precision Physics', `hep-ph/0102233`, EPJ, **C22** (2001) 99.

[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.*

Calculation flow in eeffRen.frm



* − any fermion index

B = A,Z,W,H

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 σ^{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**

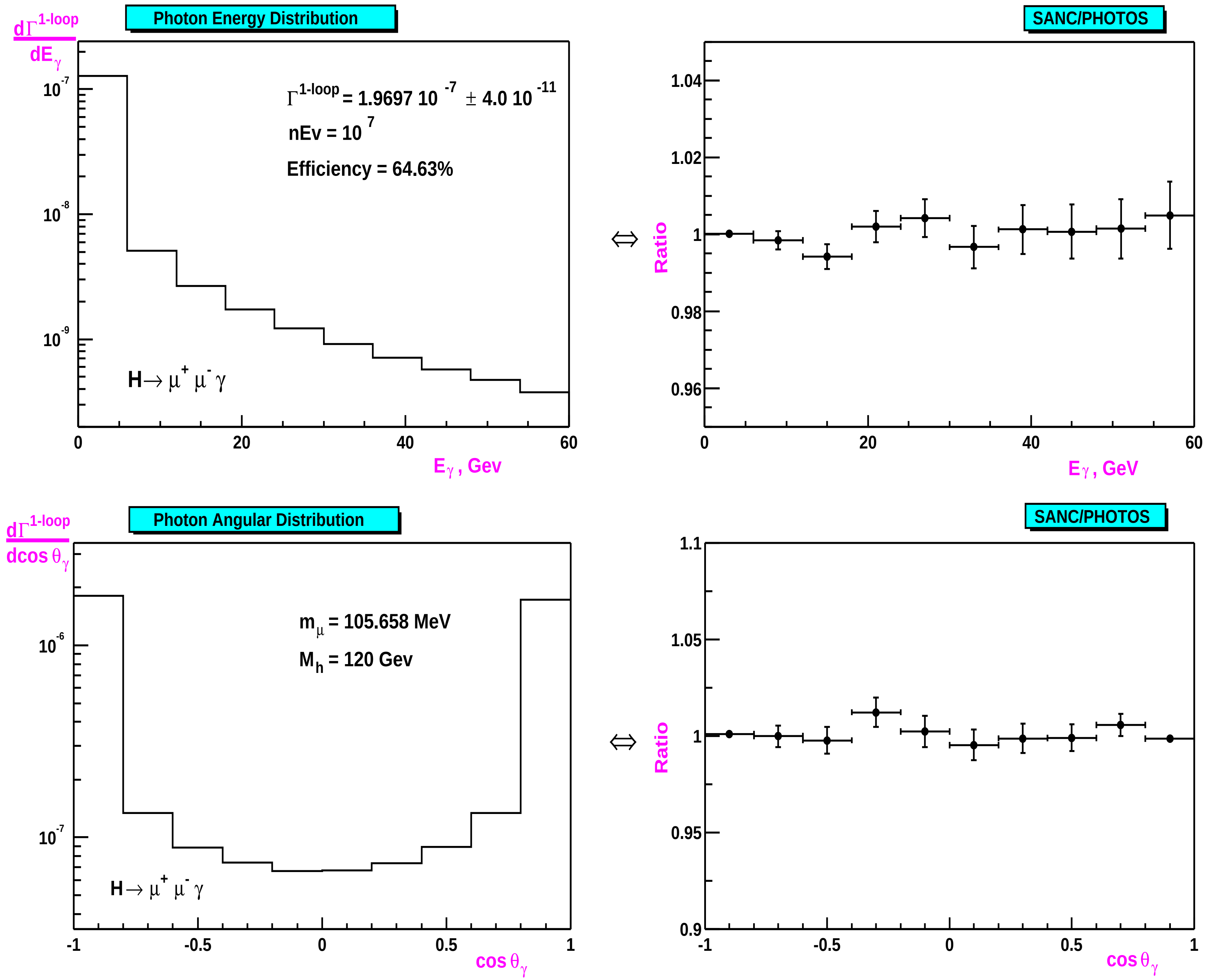
- `s2n.f–FeynArt`

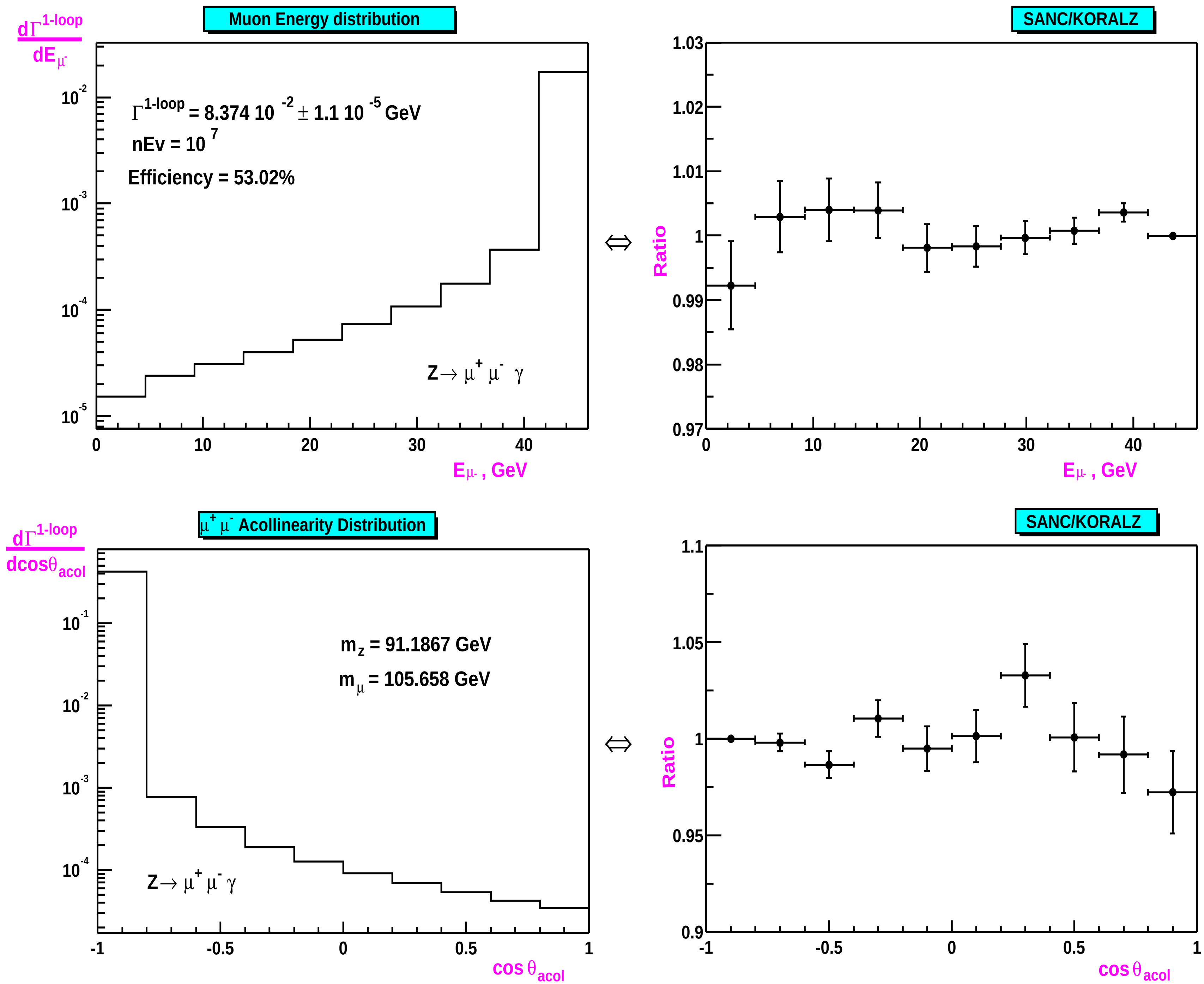
  1-loop cross-section **without soft photons** $\longrightarrow$ **11 digits**

- `s2n.f–topfit`*

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

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


Photon Energy Distribution
$\frac{d\Gamma^{1\text{-loop}}}{dE_\gamma}$
$\Gamma^{1\text{-loop}} = 1.9697\ 10^{-7} \pm 4.0\ 10^{-11}$
nEv = 10^{7}
Efficiency = 64.63%
$H \to \mu^+ \mu^- \gamma$
E_γ, Gev
SANC/PHOTOS
Ratio
E_γ, GeV
Photon Angular Distribution
$\frac{d\Gamma^{1\text{-loop}}}{d\cos\theta_\gamma}$
m_μ = 105.658 MeV
M_h = 120 Gev
$H \to \mu^+ \mu^- \gamma$
$\cos\theta_\gamma$
SANC/PHOTOS
Ratio
$\cos\theta_\gamma$



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
E_μ- , GeV
SANC/KORALZ
Ratio
E_μ- , 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

4. Concluding remarks

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

FIRST PHASE $\longrightarrow$ release of *demonstration version 0.10* in 2002

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**