MC for LHC, EW tools, 14 July, 2003

Project SANC:

(Support of Analytic and Numeric calculations for experiments at Colliders)

Ideas and Realization

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OUTLINE

1. **Ideas**
2. **Basic notions**
3. **Realization:** *http://brg.jinr.ru*
   - **Decays** $B \to f\bar{f}$
   - **Decays** $H \to \gamma\gamma (Z\gamma, ZZ)$
   - **Processes** $2f \to 2f$ **(***talk by Lida Kalinovskaya***)**
4. **Conclusion: demonstration of version 0.20**

1. Ideas

- **main idea of the project is to create a tool similar to `CompHEP`, i.e.**
  - **many processes ME MC generator;**

  but:
  - **at one-loop precision level (QED, EW, QCD);**
  - **keeping all external particle masses finite;**
    - **whenever necessary (e.g. processes with top-quark);**
  - **assuming REI (Reactions of Experimental Interest) criterion, i.e.**
    - **initial particles (electrons, photons, partons) are massless;**
    - **actually fermions of first generation are massless whenever possible;**
- **present phase assumes to reach a description of any 5 particle processes:**
  - **$2 \to 3$ processes;**
  - **$1 \to 4$ decays;**
    - **we prefer to say $5 \to 0$**

Of course, there is GRACE LOOP version 2.xx !

Network system SANC: technical detasls

SANC SERVER

- acts as an application provider. It provides access to various applications written in several computer languages
- provides functionality to access database servers, builds SANC-specific database structure and manipulates SANC data
- supports list of its own functions, procedures and methods (Server Functions List – SFL) and exports this list to the other SANC Servers
- provides functionality (via SOAP – PRC) to access and execute the methods from its SFL
- implements Intermediate Access Ideology
- is a user control system
- is an encrypt – decrypt system
- is an internal CVS (Concurent Versions System)

SANC CLIENT is

- a multi-purpose development environment
- a text editor
- a Database browser
- a project management tool

USED TECHNOLOGIES : **JAVA, XML, SOAP**

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 *auxiliary* 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.

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

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

$H \rightarrow f\overline{f}$ – $\mathcal{A} \propto I\,\mathbf{SFF_S}$

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

$Z \rightarrow f\overline{f}$ – $\mathcal{A} \propto i\gamma_\mu\gamma_6\,\mathbf{SFF_L} + i\gamma_\mu\,\mathbf{SFF_Q} + m_f\,(p_1-p_2)_\mu\,\mathbf{SFF_D}$

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

$W \rightarrow u\bar{d}$ – $\mathcal{A} \propto i\gamma_\mu\gamma_6\,\mathbf{SFF_L} + i\gamma_\mu\gamma_7\,\mathbf{SFF_R} + m_u\,(p_1-p_2)_\mu\gamma_6\,\mathbf{SFF_{LD}} + m_d\,(p_1-p_2)_\mu\gamma_7\,\mathbf{SFF_{RD}}$

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:

$$
\begin{aligned}
\mathbf{HA^Z_{0++}} = \mathbf{HA^Z_{0--}} &= \frac{gm_f}{c_W}\Big[a_f\,\mathbf{SFF_L} + \delta_f\,\mathbf{SFF_Q} + \frac{1}{2}a_f\beta_f^2M_Z^2\,\mathbf{SFF_D}\Big] \\
\mathbf{HA^Z_{++-}} &= \frac{gM_Z}{\sqrt{2}c_W}\big[a_f(1-\beta_f)\,\mathbf{SFF_L} + \delta_f\,\mathbf{SFF_Q}\big] \\
\mathbf{HA^Z_{--+}} &= \frac{gM_Z}{\sqrt{2}c_W}\big[a_f(1+\beta_f)\,\mathbf{SFF_L} + \delta_f\,\mathbf{SFF_Q}\big]
\end{aligned}
$$

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

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

Example of decays H(Q)$\to V(p_1)V(p_2)$ $[V=\gamma, Z]$

$$H \to \gamma\gamma \;-\; \mathcal{A} \propto \left(\delta_{\mu\nu} - 2\frac{p_{1\nu}p_{2\mu}}{M_H^2}\right)\epsilon^1_\mu\epsilon^2_\nu\, \mathbf{SFF}_{\gamma\gamma}\,,$$

1 structure, **1 SFF**, **1 HA**

$$H \to Z\gamma \;-\; \mathcal{A} \propto \left[\left(1-\frac{M_Z^2}{M_H^2}\right)\delta_{\mu\nu} - 2\frac{p_{1\nu}p_{2\mu}}{M_H^2}\right]\epsilon^1_\mu\epsilon^2_\nu\, \mathbf{SFF}_{\mathbf{Z}\gamma}\,,$$

1 structure, **1 SFFs**, **1 HA**

$$H \to ZZ \;-\; \mathcal{A} \propto \left(\delta_{\mu\nu}\,\mathbf{SFF^d_{ZZ}} + \frac{p_{1\nu}p_{2\mu}}{M_H^2}\,\mathbf{SFF^p_{ZZ}}\right)\epsilon^1_\mu\epsilon^2_\nu\,,$$

2 structures, **2 SFFs**, **2 HAs**

Example of **2 HAs** for $H \to ZZ$ decay depending on **2 SFFs** (only non-zero **HAs** are shown):

$$\mathbf{HA^H_{++}} = \mathbf{HA^H_{--}} \;\propto\; -\,\mathbf{SFF_d}$$

$$\mathbf{HA^H_{00}} \;\propto\; \left[\left(-1+\frac{1}{2}\frac{M_H^2}{M_Z^2}\right)\mathbf{SFF^d_{ZZ}} + \left(-1+\frac{1}{4}\frac{M_H^2}{M_Z^2}\right)\mathbf{SFF^p_{ZZ}}\right]$$

From analytic results to numbers

$$d\Gamma(d\sigma) \sim \sum_{\lambda_i\lambda_j\lambda_k\lambda_l} \left| \mathbf{HA}(\mathbf{SFF}^{\mathbf{Born+1-loop}})_{\lambda_i\lambda_j\lambda_k\lambda_l} \right|^2$$

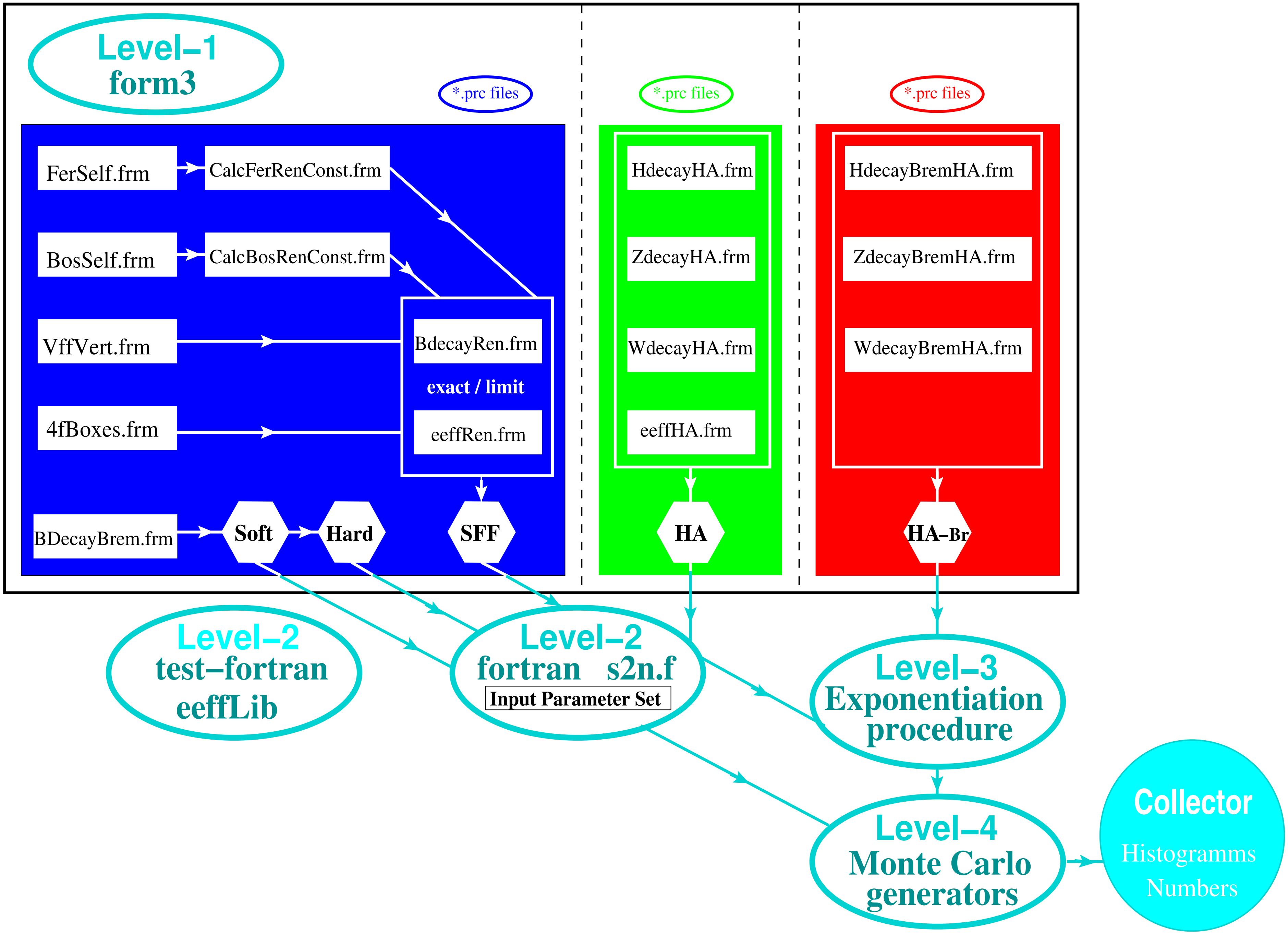
$$d\Gamma(d\sigma) \sim \sum_{\lambda_i\lambda_j\lambda_k\lambda_l} \left| \mathbf{HA}(\mathbf{SFF}^{\mathbf{Born+1-loop+2-loop}})_{\lambda_i\lambda_j\lambda_k\lambda_l} \right|^2$$

A. Ferroglia, G. Passarino, M. Passera, S. Uccirati, Nucl.Phys. B650 (2003) 162-228

+ **Soft bremsstrahlung**

+ **Hard bremsstrahlung either from an analytic calculations**

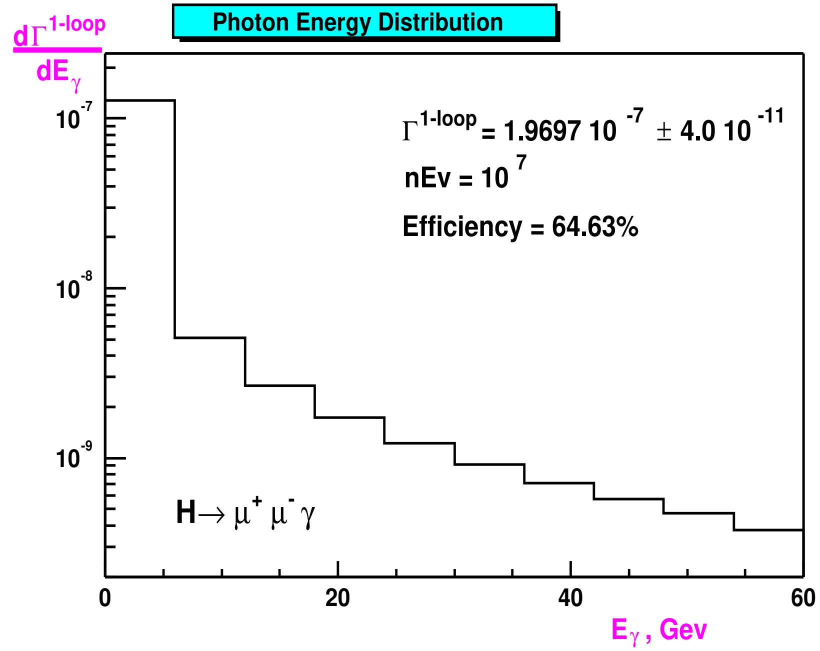
or from a (partner) MC, e.g. WINHAC


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

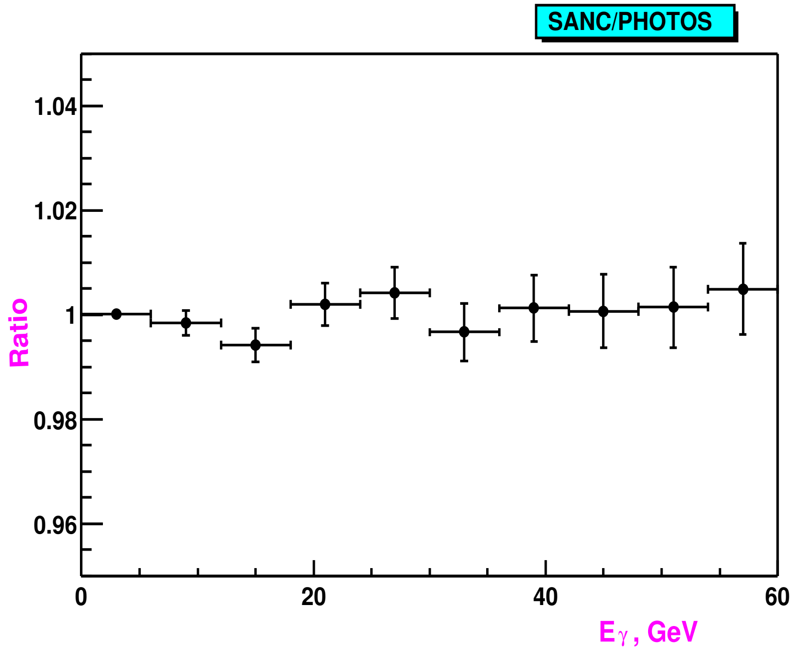
First application of SANC for decays

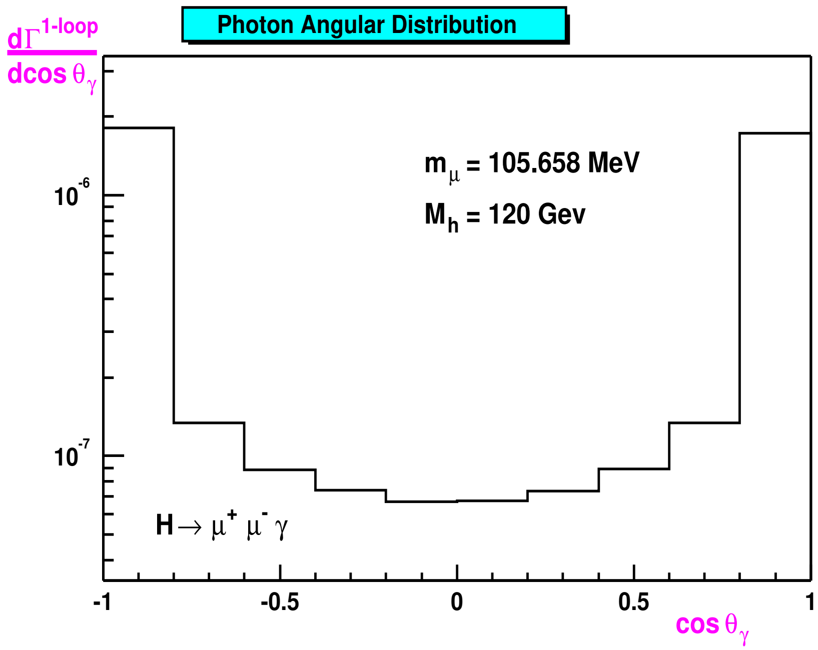
1. COMPARISON OF SANC WITH KORALZ AND PHOTOS.
   By A. Andonov (Dubna, JINR), S. Jadach (Cracow, INP), G. Nanava (Dubna, JINR), Z. Was (Cracow, INP and CERN). CERN-TH-2002-315, Dec 2002. Published in Acta Phys. Polon. B34 p.2665-2672, 2003.
   hep-ph/0212209

2. HOW TO USE SANC TO IMPROVE THE PHOTOS MONTE CARLO SIMULATION OF BREMSSTRAHLUNG IN LEPTONIC W BOSON DECAYS.
   By G. Nanava (Dubna, JINR), Z. Was (Cracow, INP and CERN). CERN-TH-2003-075, Mar 2003. Submitted to Acta Phys. Polon. hep-ph/0303260

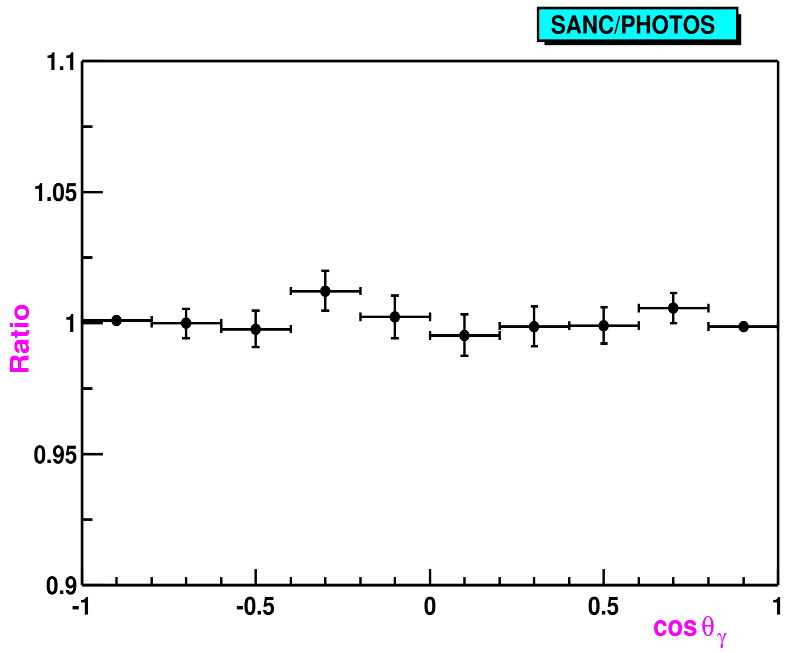

Photon Energy Distribution
dΓ^1-loop / dE_γ
10^-7
10^-8
10^-9
Γ^1-loop = 1.9697 10^-7 ± 4.0 10^-11
nEv = 10^7
Efficiency = 64.63%
H→ μ+ μ- γ
0
20
40
60
E_γ , Gev

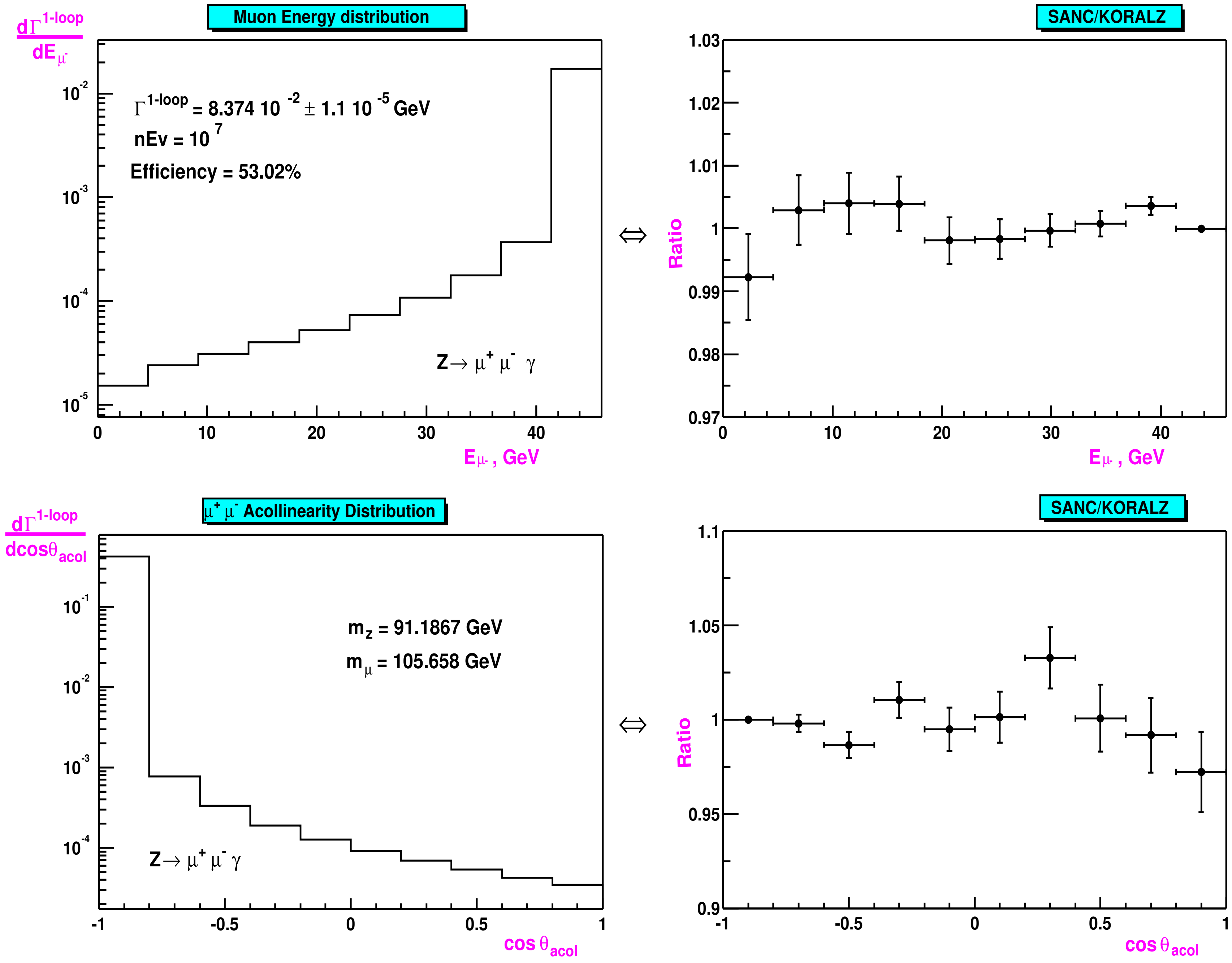
⇔


SANC/PHOTOS
Ratio
1.04
1.02
1
0.98
0.96
0
20
40
60
E_γ , GeV

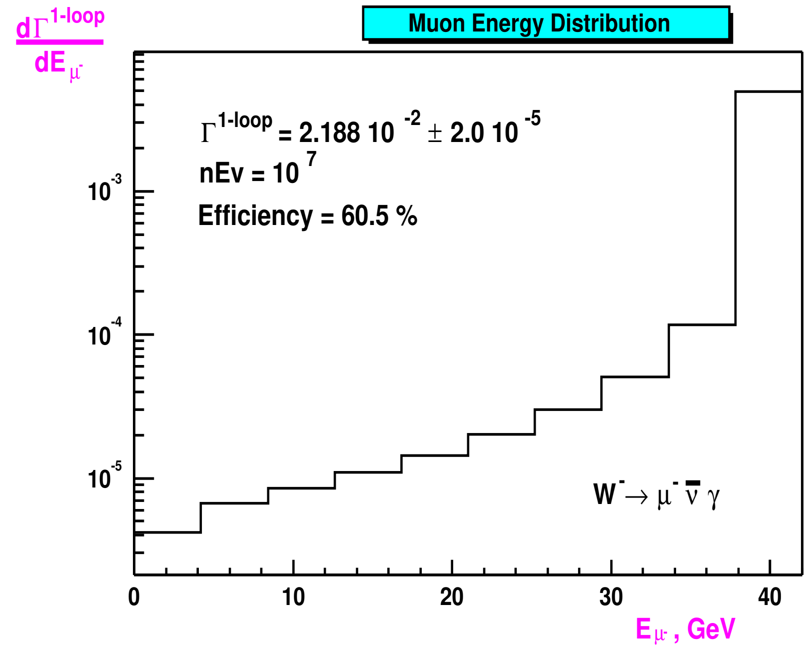

Photon Angular Distribution
dΓ^1-loop / dcos θ_γ
10^-6
10^-7
m_μ = 105.658 MeV
M_h = 120 Gev
H→ μ+ μ- γ
-1
-0.5
0
0.5
1
cos θ_γ

⇔

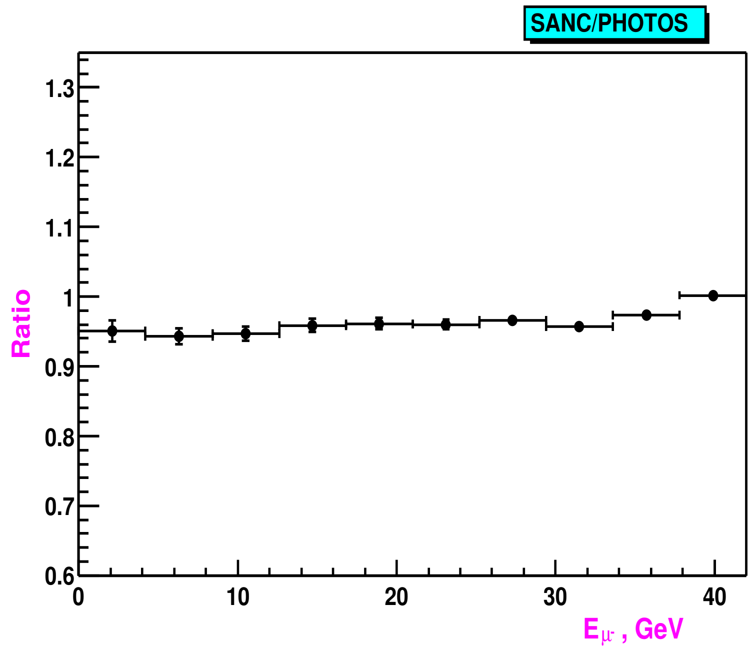

SANC/PHOTOS
Ratio
1.1
1.05
1
0.95
0.9
-1
-0.5
0
0.5
1
cos θ_γ

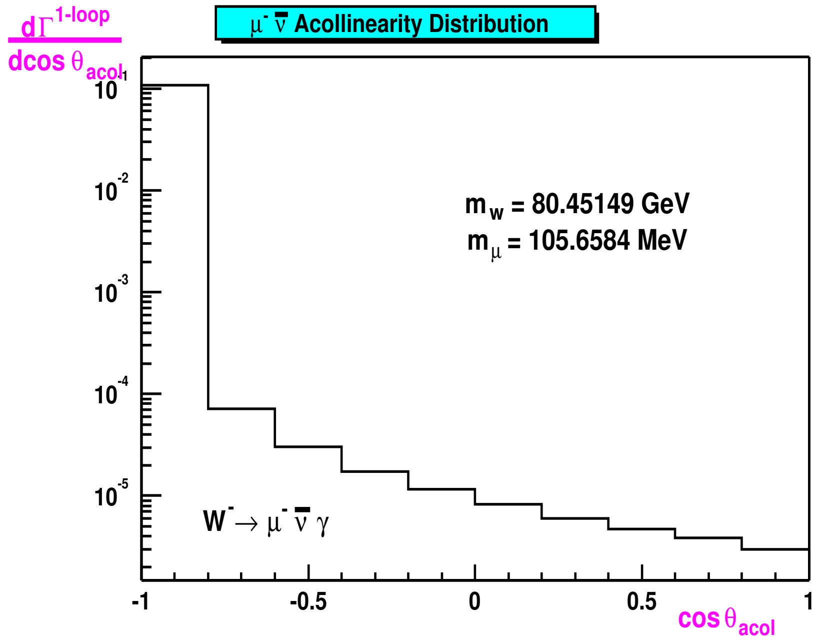


Muon Energy distribution
dΓ^1-loop / dE_μ-
Γ^1-loop = 8.374 10^-2 ± 1.1 10^-5 GeV
nEv = 10^7
Efficiency = 53.02%
Z→ μ+ μ- γ
E_μ- , GeV
⇔
SANC/KORALZ
Ratio
E_μ- , GeV
μ+ μ- Acollinearity Distribution
dΓ^1-loop / dcosθ_acol
m_Z = 91.1867 GeV
m_μ = 105.658 GeV
Z→ μ+ μ- γ
cos θ_acol
⇔
SANC/KORALZ
Ratio
cos θ_acol

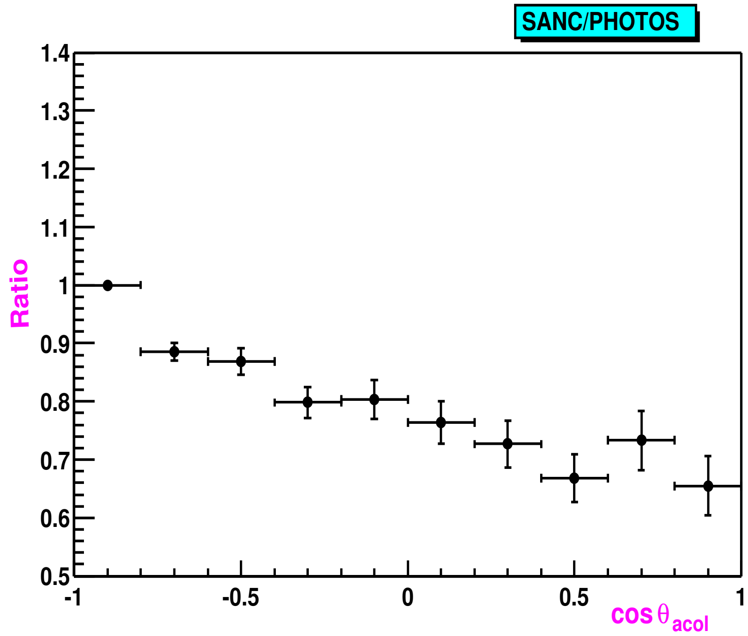

Muon Energy Distribution
dΓ^1-loop / dE_μ-
Γ^1-loop = 2.188 10^-2 ± 2.0 10^-5
nEv = 10^7
Efficiency = 60.5 %
W^- → μ^- ν̄ γ
10^-3
10^-4
10^-5
0
10
20
30
40
E_μ- , GeV

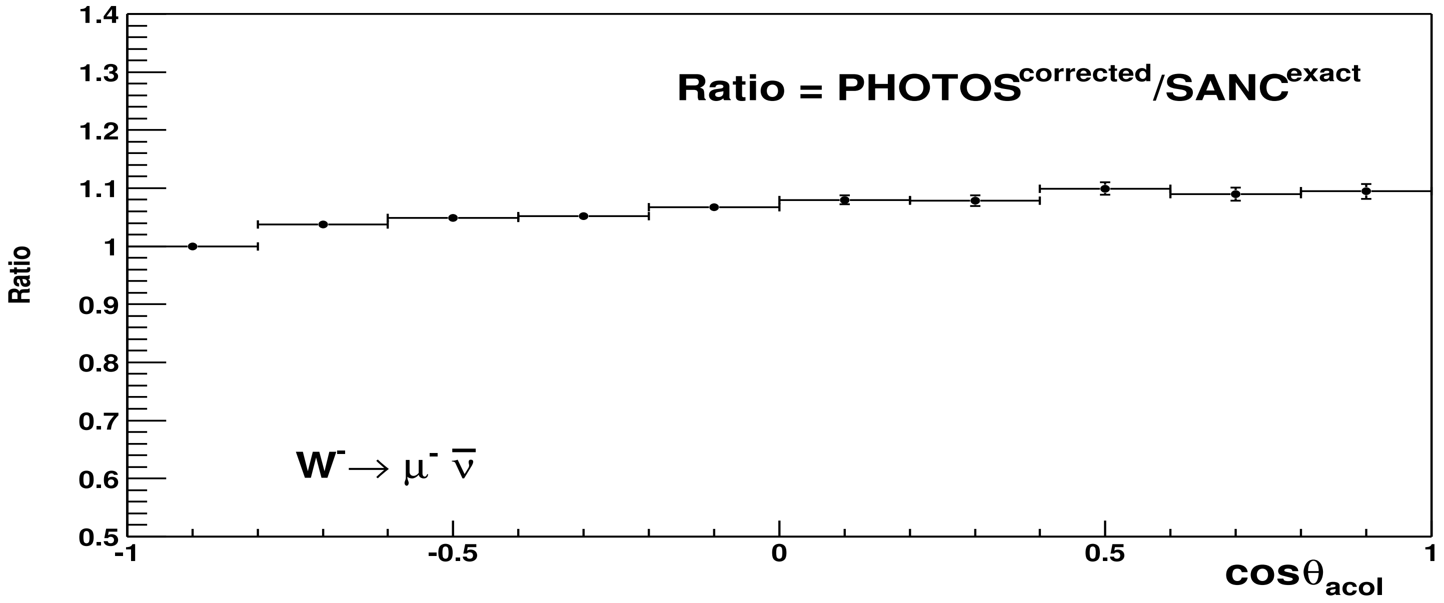
⟺

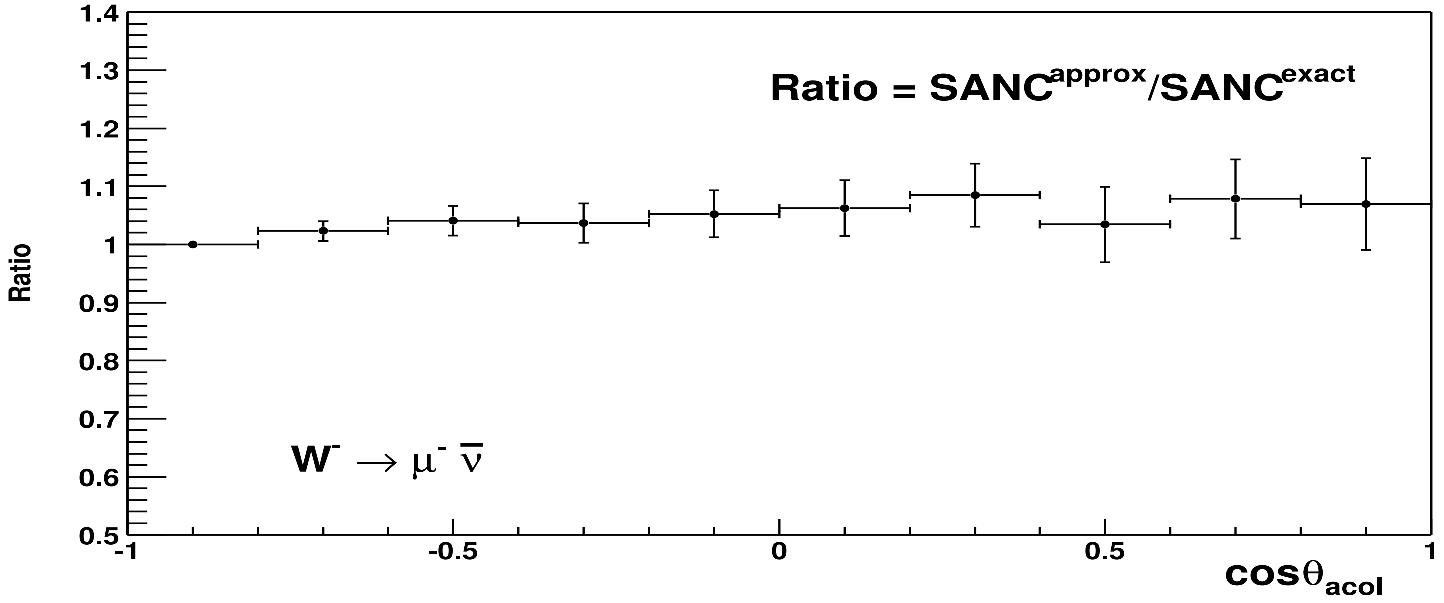

SANC/PHOTOS
Ratio
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0
10
20
30
40
E_μ- , GeV


μ^- ν̄ Acollinearity Distribution
dΓ^1-loop / dcos θ_acol
10^-1
10^-2
10^-3
10^-4
10^-5
m_W = 80.45149 GeV
m_μ = 105.6584 MeV
W^- → μ^- ν̄ γ
-1
-0.5
0
0.5
1
cos θ_acol

⟺


SANC/PHOTOS
Ratio
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
-1
-0.5
0
0.5
1
cos θ_acol


Ratio = PHOTOS^{corrected}/SANC^{exact}
$W^- \to \mu^- \bar{\nu}$
Ratio
$\cos\theta_{acol}$
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
-1
-0.5
0
0.5
1


Ratio = SANC^{approx}/SANC^{exact}
$W^- \to \mu^- \bar{\nu}$
Ratio
$\cos\theta_{acol}$
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
-1
-0.5
0
0.5
1

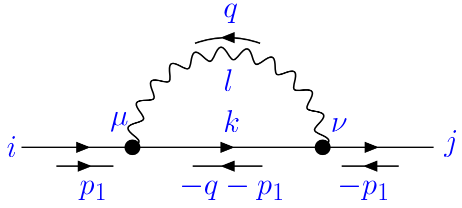
ANNEX

1. **Examples of precomputation chains**

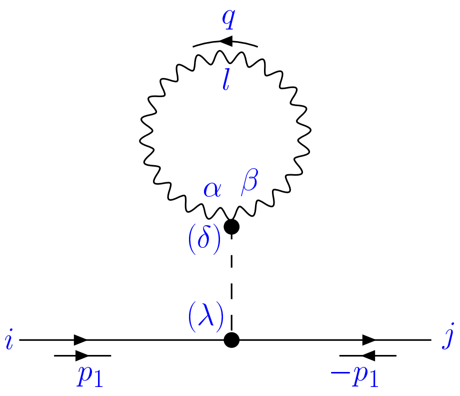
2. **Classification of processes in the SM**

3. **Examples of some $2 \to 2$ and $2 \to 3$ hard processes**

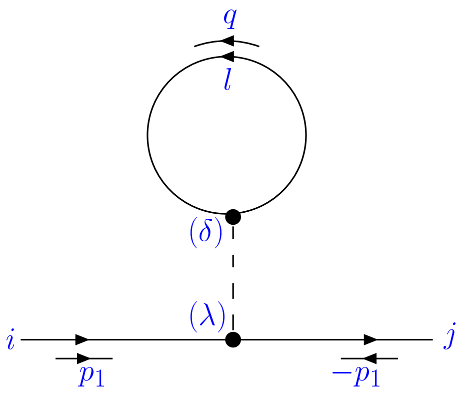
Chain: $\boxed{\text{Self}} \rightarrow \boxed{\text{Fermion}} \rightarrow \boxed{\text{Fermion Self}}$



Two point fermionic diagrams.

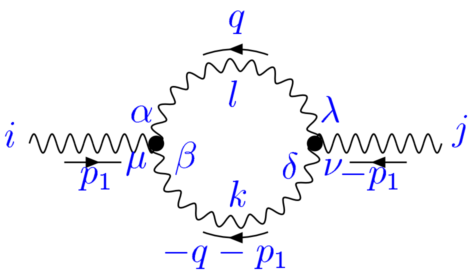


Tadpoles: bosonic part,

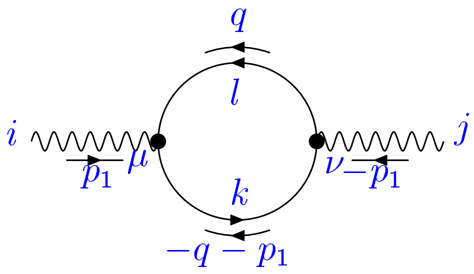


fermionic part

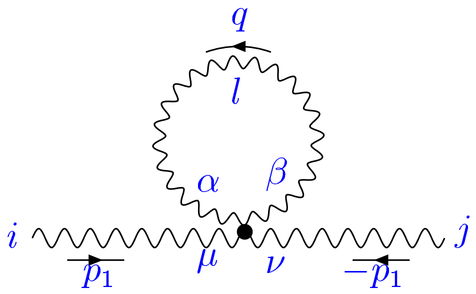
Chain: $\boxed{\text{Self}}$ → $\boxed{\text{Boson}}$ → $\boxed{\text{Boson Self}}$



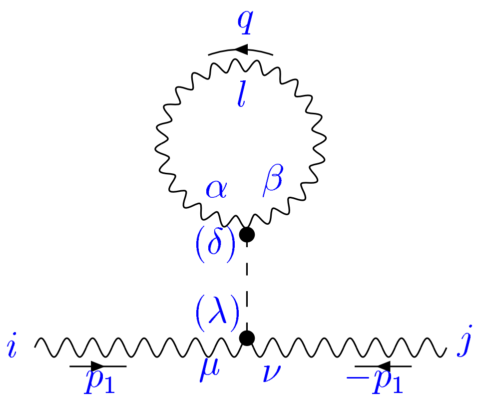
Two point bosonic diagrams,



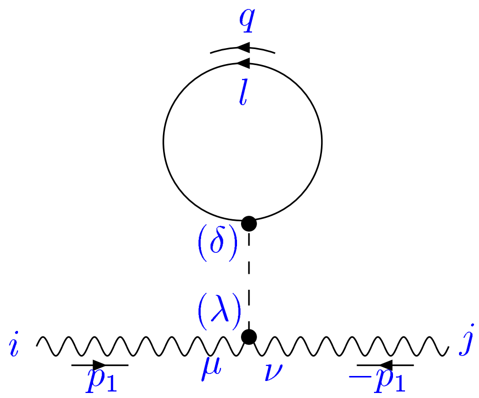
fermionic component



One point bosonic diagrams.

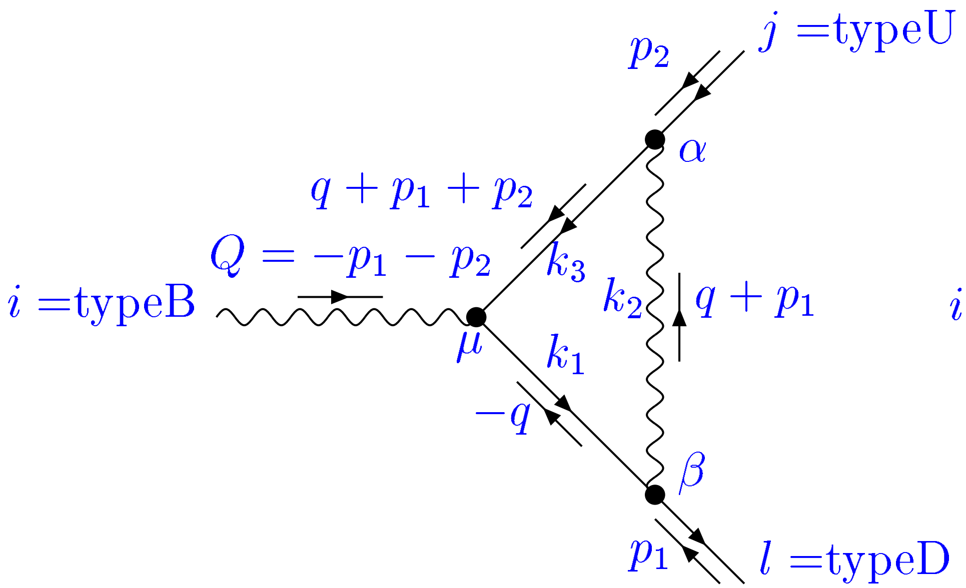


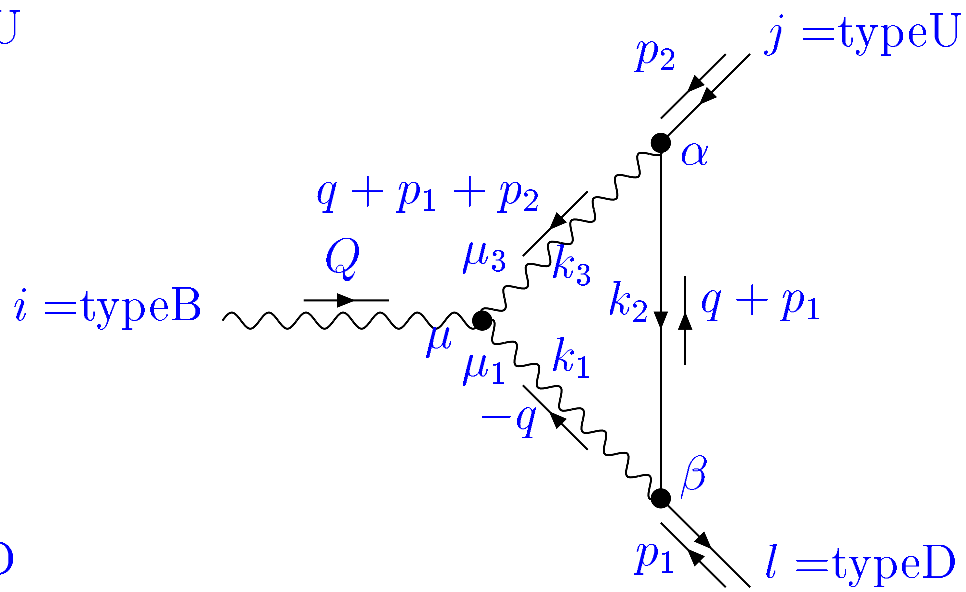
Tadpoles: bosonic part,



fermionic part

Chain: $\boxed{\text{Vertex}} \rightarrow \boxed{\text{Bff}} \rightarrow \boxed{\text{B}\rightarrow\text{ff}}$





Vertices: FBF-topology, BFB-topology.

Classification of processes in the SM

1. PROCESSES $3 \to 0$

- $\mathrm{Bf\bar{f}} \to 0$ decays
  - $\mathrm{H} \to \mathrm{f\bar{f}}$ $\longrightarrow$ 1 scalar form factor (SFF)
  - decay $\mathrm{Z} \to \mathrm{f\bar{f}}$ and transition $\gamma^* \to \mathrm{f\bar{f}}$ $\longrightarrow$ 3 (SFF)
  - decay $\mathrm{W} \to \mathrm{f\bar{f}'}$ and crossing-channel $\mathrm{t} \to \mathrm{W^+b}$ $\longrightarrow$ 4 (SFF)
- $3\mathrm{B} \to 0$ decays and fusions
  - decays $\mathrm{H} \to \gamma\gamma$, $\mathrm{H} \to \mathrm{Z}\gamma$, $\mathrm{H} \to \mathrm{ZZ}$, $\mathrm{W^+W^-}$ $\longrightarrow$ correspondingly 1,1,2,2 (SFF)
  - fusion $2 \to 1$

    dominant Higgs boson production channel at hadronic colliders $\mathrm{gg} \to \mathrm{H}$
  - virtual transitions $\mathrm{Z^*} \to \mathrm{W^+W^-}$ and $\gamma^* \to \mathrm{W^+W^-}$

    "building blocks" for more complicated processes

Decay rates are typical pseudo-observables.

2. PROCESSES $4 \to 0$

- Processes $4f \to 0$
  - Neutral Current (NC): $f\bar{f} \to (\gamma, Z, H) \to f'\bar{f}'$
    $\longrightarrow$ 4 SFF (for massless fermions) & $\longrightarrow$ 10 SFF (for massive fermions)
  - Charged Current (CC):
    - $f_1\bar{f}_2 \to (W) \to f_3\bar{f}_4$ $\longrightarrow$ 16 SFF (all fermions are massive)
    - $F \to 3f$ — μ, τ decays, $t \to bu\bar{d}$
    - partonic processes at hadron colliders, for instance:

$$q_i + \bar{q}_j \;\to\; \bar{b} + t \; (b + \bar{t})$$

- Processes $2B2f \to 0$
  - Compton effect: $\gamma e \to \gamma e$
  - radiative decays: $Z \to f\bar{f}\gamma$, $H \to f\bar{f}\gamma$
  - $e^+e^- \to W^+W^-$, ZZ, $Z\gamma, \gamma\gamma$
  - partonic processes at hadron colliders, for instance:

$$q_i + \bar{q}_j \;\to\; W(Z) + H$$

- **Processes 4B $\rightarrow$ 0**
  - **light-by-light scattering:** $\gamma\gamma \rightarrow \gamma\gamma$
  - **virtual transitions ZZ $\rightarrow$ ZZ (and many others)**

3. PROCESSES $5 \to 0$

- Processes $4fB \to 0$
  - radiative $f\bar{f}\gamma$ production in e^+e^- annihilation: $e^+e^- \to f\bar{f}\gamma$
  - or some partonic processes at LHC:

$$g + q_i \;\to\; q_j + \bar{b} + t\,,$$
$$q_i + q_i \;\to\; q_j + q_j + H$$

  - or Higgs decay into four leptons (muons):

$$H \;\to\; \mu^+ + \mu^- + \mu^+ + \mu^-$$

- Processes $3B2f \to 0$
  - one more well-known partonic process at LHC:

$$g + g \;\to\; t + \bar{t} + H$$

  - ...
- Processes $5B \to 0\ldots$

4. PROCESSES $6 \to 0\ldots$