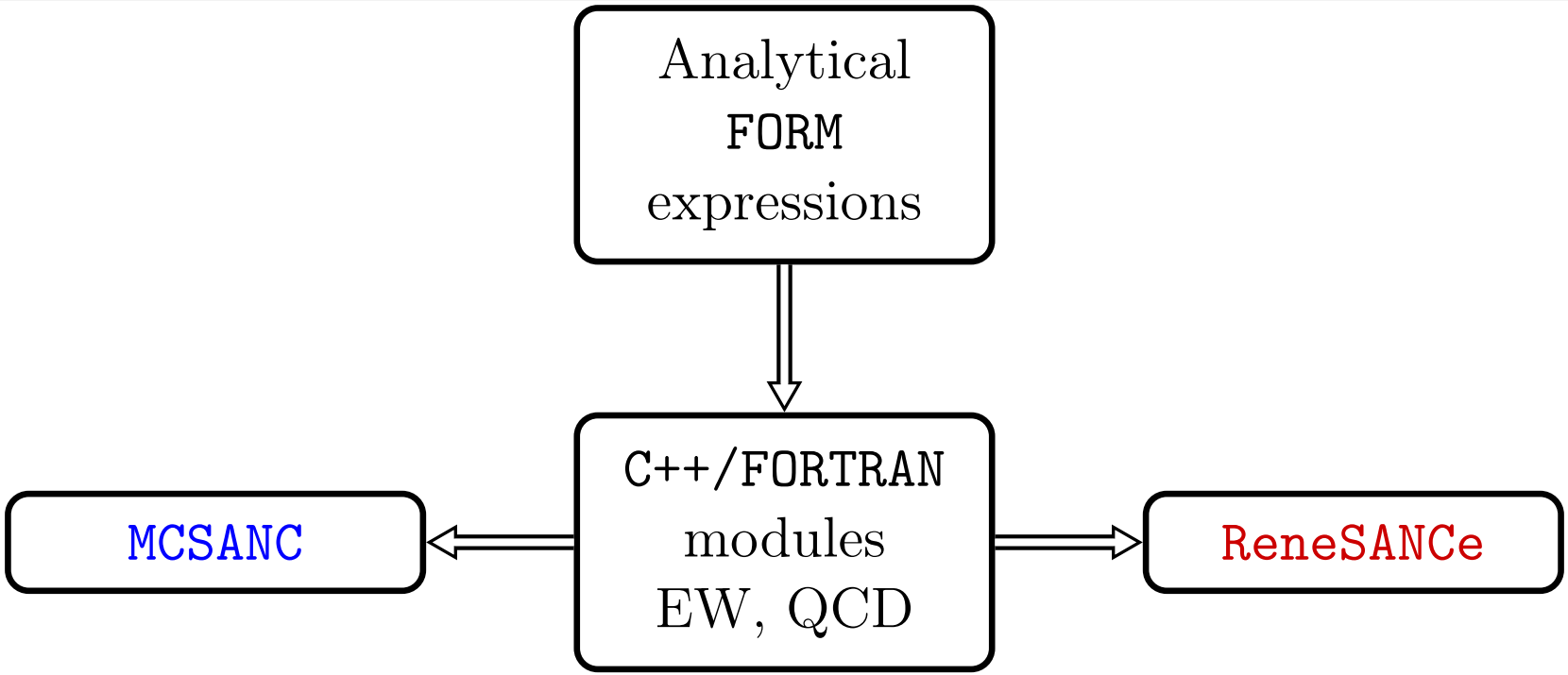
New developments in ReneSANCe

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on behalf of the SANC team

JINR, Dubna

The 2026 International Workshop on the High Energy Circular Electron Positron Collider, 26.10.2026, Shanghai

The SANC framework and products family



Publications:

SANC – Comput.Phys.Commun. 174 (2006), 481-517.
MCSANC (pp-mode) – Comput.Phys.Commun. 184 (2013),2343-2350; JETP Letters 103 (2016), 131-136.
SANCphot – Comput.Phys.Commun. 294 108929
ReneSANCe – Comput.Phys.Commun. 256 (2020), 107445.

SANC products are available at http://sanc.jinr.ru/download.php

SANC advantages:

- full one-loop electroweak corrections
- higher order corrections
- massive case
- accounting for polarization effects
- full phase space operation
- results of ReneSANCe event generator and SANC integrators are thoroughly cross checked

Initial state modes

Hadron-hadron

- $pp[p\bar{p}] \to Z, \gamma \to \ell^+\ell^-$
- $pp[p\bar{p}] \to W^- \to \ell^-\bar{\nu}_\ell$
- $pp[p\bar{p}] \to W^+ \to \ell^+\nu_\ell$

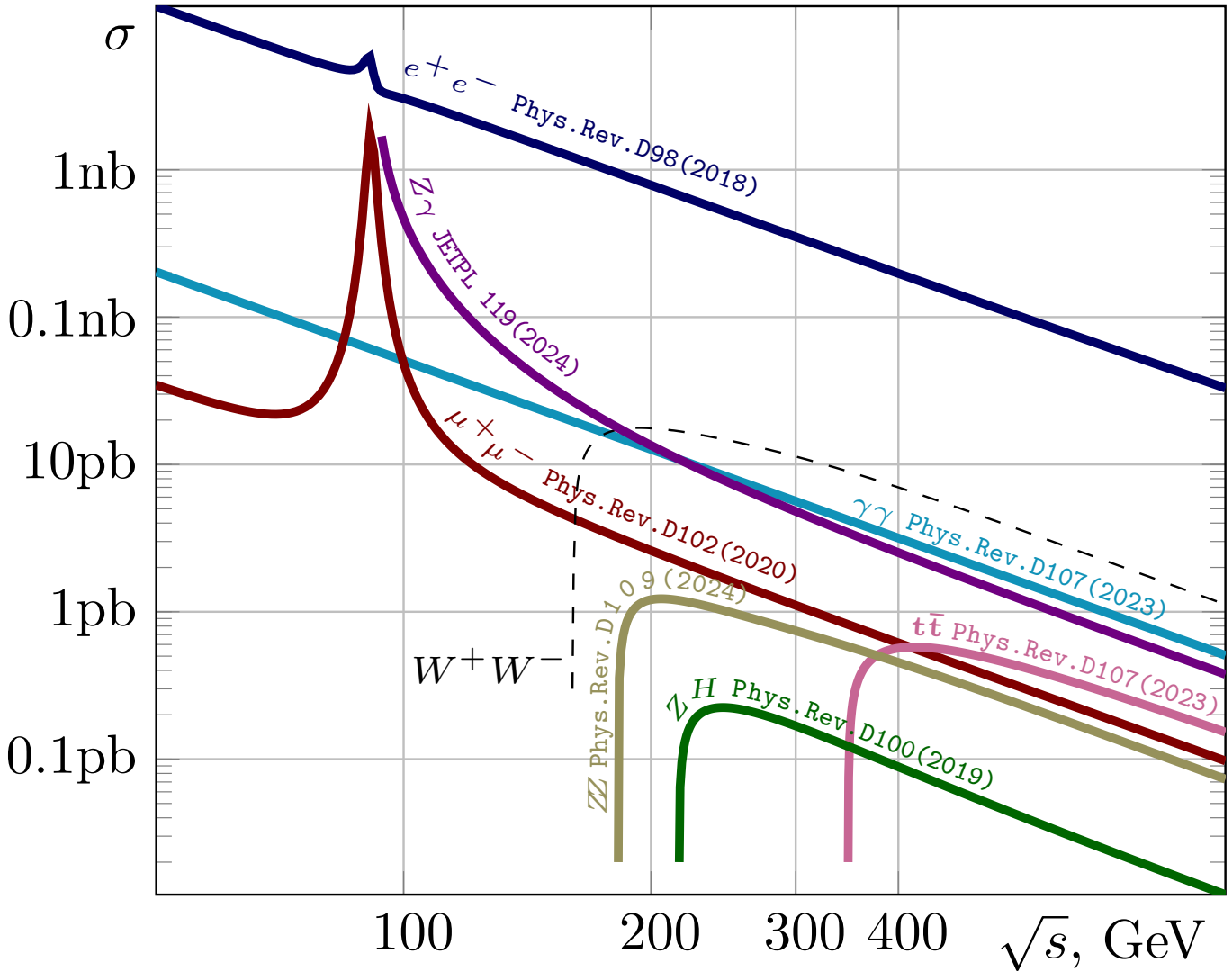
Photon-photon

See Renat Sadykov talk.

Lepton-lepton mode. Processes of interest

- Bhabha ($e^+e^- \to e^-e^+$), Phys. Rev. D 98, 013001.
- s-channel ($e^+e^- \to \mu^-\mu^+$, $e^+e^- \to \tau^-\tau^+$), Phys. Rev. D 102, 033004.
- Photon-pair ($e^+e^- \to \gamma\gamma$), Phys. Rev. D 107, 073003.
- ZH ($e^+e^- \to ZH$), Phys. Rev. D 100, 073002.
- Zγ ($e^+e^- \to Z\gamma$), JETP Letters 119, 2.
- ZZ ($e^+e^- \to ZZ$), Phys. Rev. D 109, 033012.
- s-channel ($e^+e^- \to t\bar{t}$), Phys. Rev. D 107, 113006.
- Muon-electron scattering ($\mu^+e^- \to \mu^+e^-$), Phys. Rev. D 105, 033009.
- Møller ($e^-e^- \to e^-e^-$, $\mu^+\mu^+ \to \mu^+\mu^+$), JETP Lett. 115, 9.

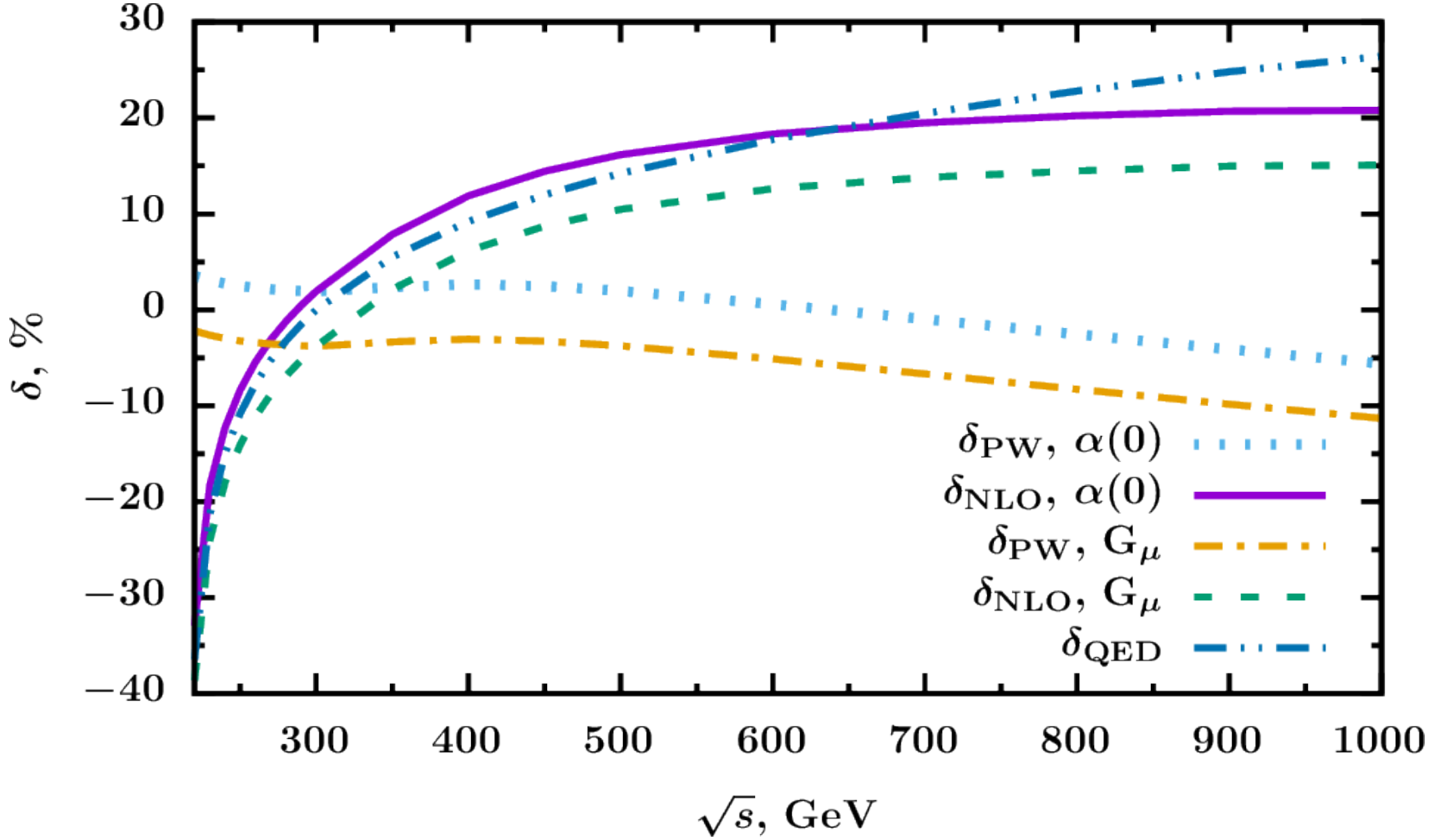
Basic processes of SM for e^+e^- annihilation



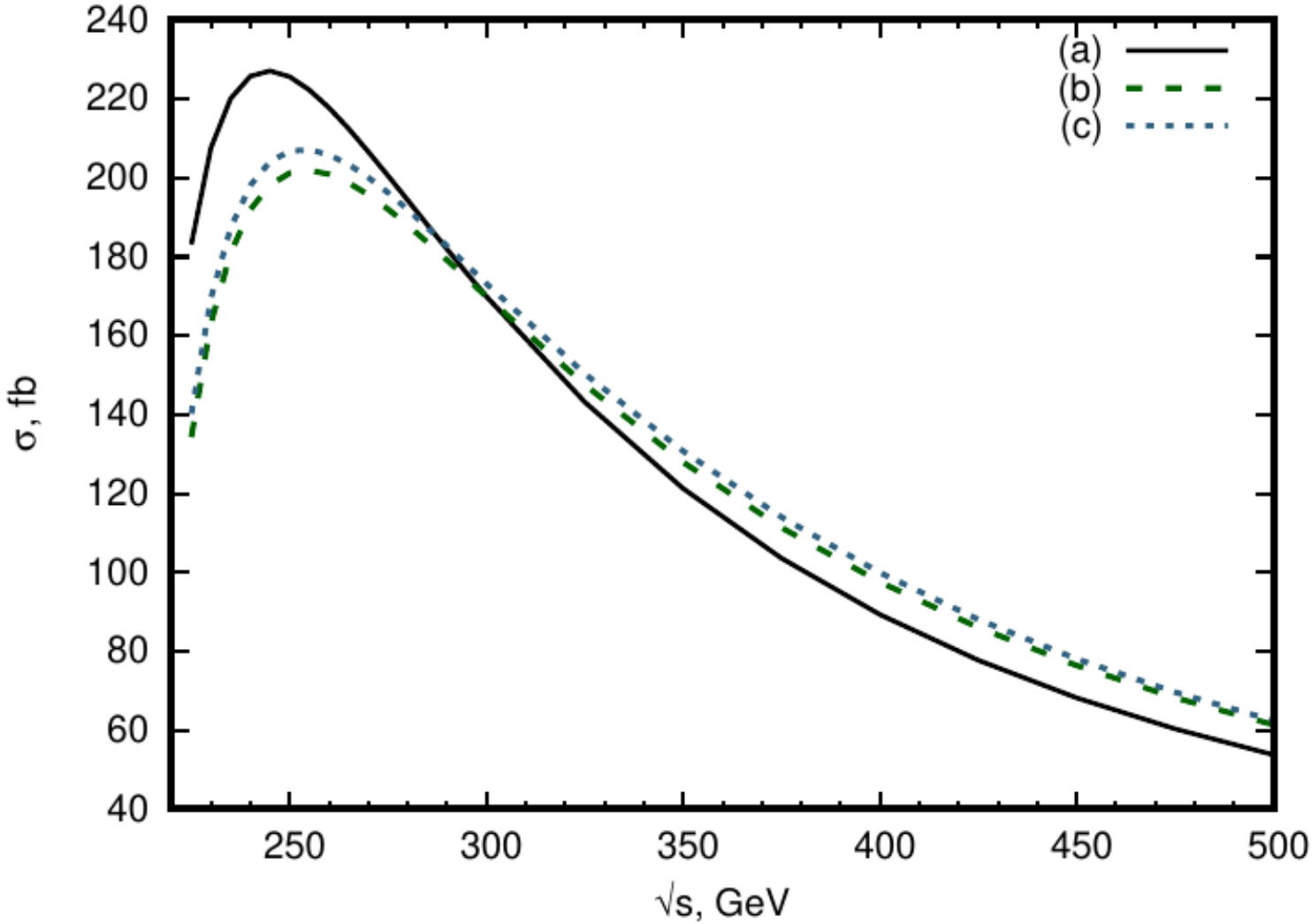
The cross sections are given for polar angles between $10^o < \theta < 170^o$ in the final state.

$e^+e^- \to ZH$, energy dependence

The relative corrections in parts as a function of the c.m.s. energy.



$e^+e^- \to ZH$ [Symmetry 13, 01256]

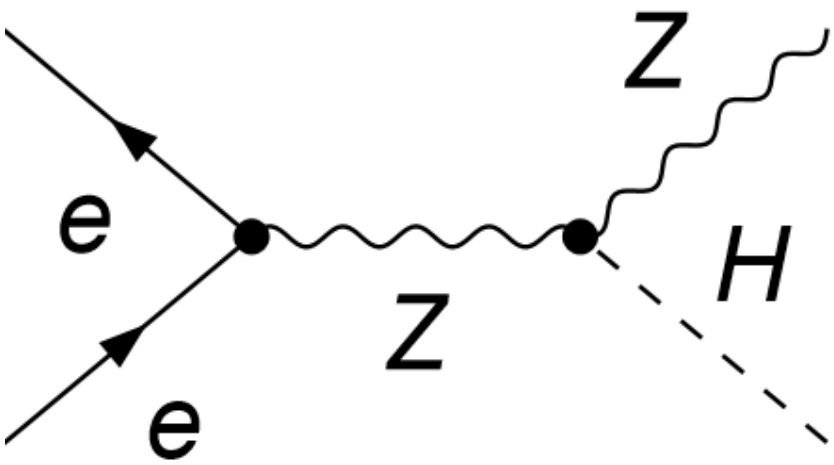


Cross-section: (a) Born, (b) $O(\alpha)$ QED, (c) with LL ressumation.

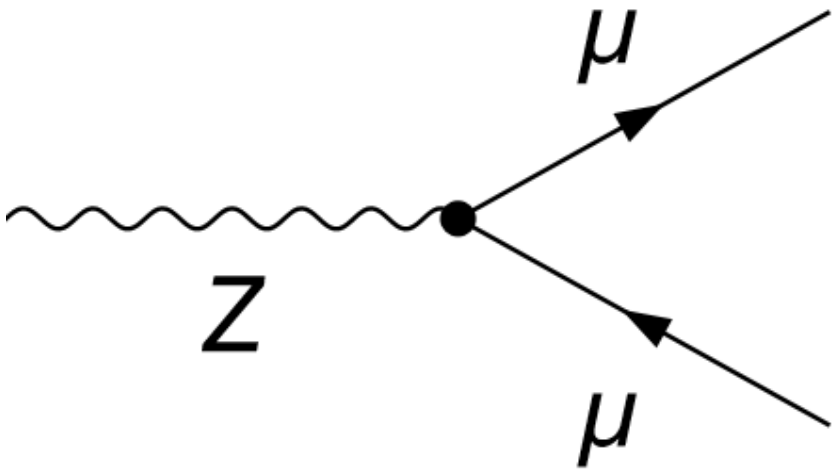
Decays. Motivation

- The dominant cross section at about 250 GeV for Higgs boson production at e^+e^- colliders is Higgstrahlung ($e^+e^- \to HZ$).
- Using only the observed Z boson, it is possible to measure the absolute Higgstrahlung cross section and, using the best-defined Z's with decay to $\mu^+\mu^-$, to measure the Higgs mass to 10 MeV (10^{-4} precision).
- Linear colliders can support longitudinal beam polarization both for electrons and positrons, an advantage in studying the chiral couplings of the SM. Unsurprisingly, the use of beam polarization turns out to give a significant advantage.

Z decay



$e^+e^- \to Z^*H$



$Z^* \to \mu^+\mu^-$

Amplitude representation

Helicity amplitudes approach

- any initial (not only longitudinal) polarization,
- polarization of final states,
- spin correlations, polarization transfer from the initial to the final state.

Identical structure for all orders:

$$\mathcal{H} = \sum Str_i \mathcal{F}_i(s,t,u)$$

Spin-tensor structures are constructed of Dirac spinors, γ-matrices and momenta (like $Str_1 = \bar{v}\left(\not{p}_3\gamma^\mu\gamma^\nu + \gamma^\mu p_4^\nu - \gamma^\nu p_3^\mu + (\not{p}_3 - \not{p}_4)\delta^{\mu\nu}\right)\bar{u}$). Form-factors $\mathcal{F}_i$ are scalar functions that depend only on the Mandelstam variables.

Dirac spinors as primary objects

The paradigm shift

Reconstruct the event directly in spinor space, treating Dirac spinors as the fundamental degrees of freedom rather than derived quantities from four-momenta.

Why spinor space?

- Eliminates unphysical gauge degrees of freedom.
- Simplifies helicity amplitude evaluations (`Fastor`, `Blaze`, `Eigen`).
- Momenta are uniquely defined.
- Avoids numerical loss of precision.

Event class implementation

```
// Dirac Spinor: 4-component
    complex vector
struct Spinor { std::complex<
    double> comp[4]; };

class Event {
    private:
    // Primary objects stored
        directly
    std::vector<Spinor>
        incoming_particles;
    std::vector<Spinor>
        outgoing_particles;

    public:
    // Momenta are calculated on-
        the-fly if needed
    FourMomentum get_momentum(
        size_t index) const {
        return
```

Change of spin axes

If we have particle with momentum p and polarization vector n, then spinors $u(p, \pm n)$ satisfy

$$u(p, \pm n)\bar{u}(p, \pm n) = (\not{p} + m)\frac{1}{2}(1 \pm \gamma_5 \not{n}),$$

If we have another spin vector s with $p \cdot s = 0$ and $s^2 = -1$ when projectors $\frac{1}{2}(1 \pm \gamma_5 \not{s})$ can be appied to $u(p, \pm n)$ to construct $u(p, \pm s)$

$$u(p, \pm s) = \frac{\mathcal{N}}{2}(1 \pm \gamma_5 \not{s})u(p, \pm n), \qquad \mathcal{N} = \sqrt{\frac{2}{1 - s \cdot n}},$$

$$u(p, \pm s)\bar{u}(p, \pm s) = (\not{p} + m)\frac{1}{2}(1 \pm \gamma_5 \not{s})$$

It it easy to see, that with $s = n$ we restore original spinors

Helicity spinor

Helicity state corresponds to spin vector

$$s^\mu = \frac{p^0}{m}\frac{p^\mu}{|\vec{p}|} - g^{\mu 0}\frac{m}{|\vec{p}|}, \qquad \not{s} = \frac{p^0}{m}\frac{\not{p}}{|\vec{p}|} - \gamma^0\frac{m}{|\vec{p}|}$$

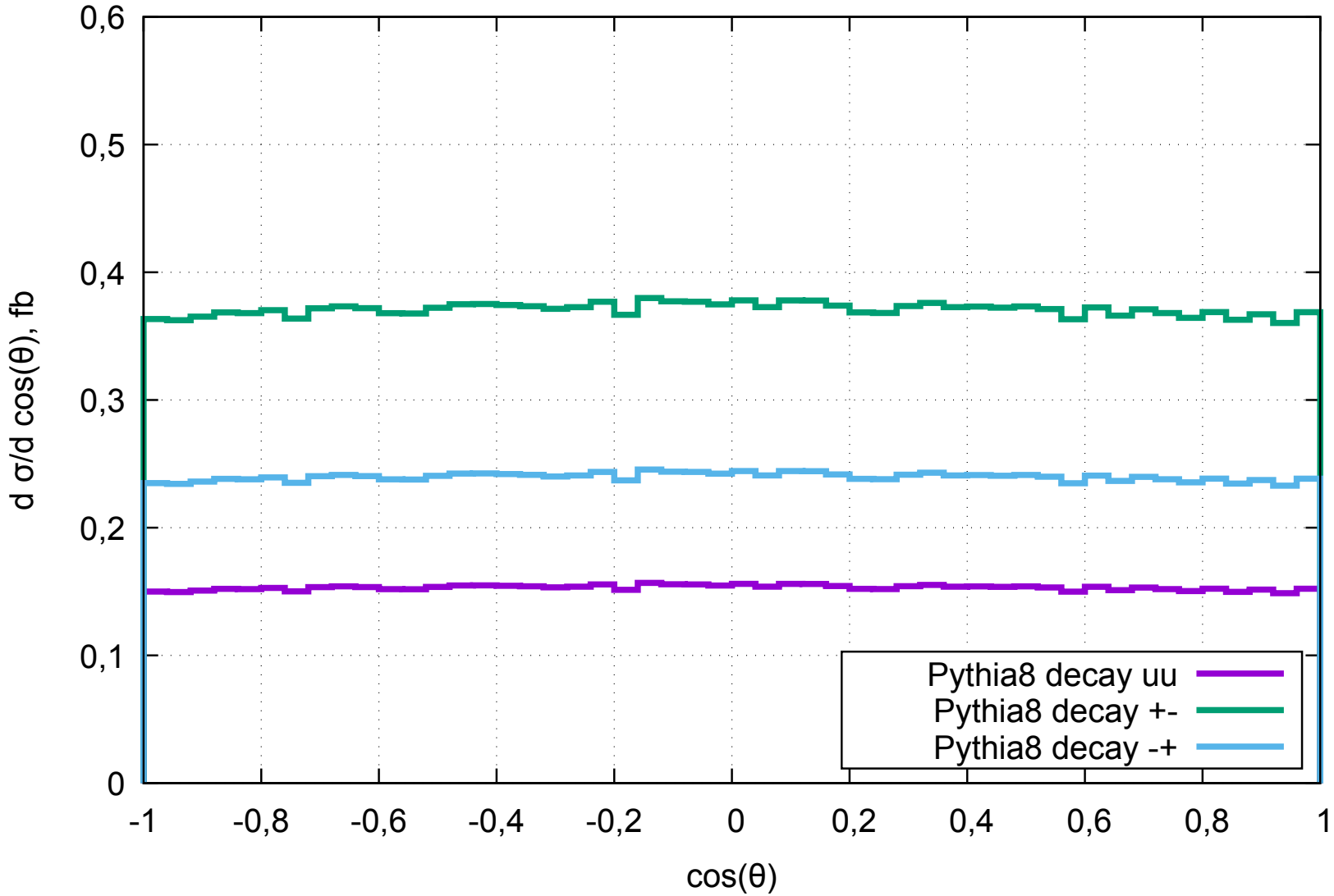
$$\begin{aligned}\frac{1}{2}\left[1 \pm \gamma^5 \not{s}\right] u(p, \pm n) &= \frac{1}{2}\left[1 \pm \gamma^5 \frac{p^0}{m}\frac{\not{p}}{|\vec{p}|} \mp \gamma^5\gamma^0\frac{m}{|\vec{p}|}\right] u(p, \pm n) \\ &= \frac{1}{2}\left[1 \pm \gamma^5 \frac{p^0}{|\vec{p}|} \pm \gamma^0\gamma^5\frac{m}{|\vec{p}|}\right] u(p, \pm n)\end{aligned}$$

$$\bar{u}(p,n)\gamma^\mu\gamma^5 u(p,n) = m n^\mu, \quad s\cdot n = -n^0\frac{m}{|\vec{p}|} = -\frac{\bar{u}(p,n)\gamma^0\gamma^5 u(p,n)}{|\vec{p}|}$$

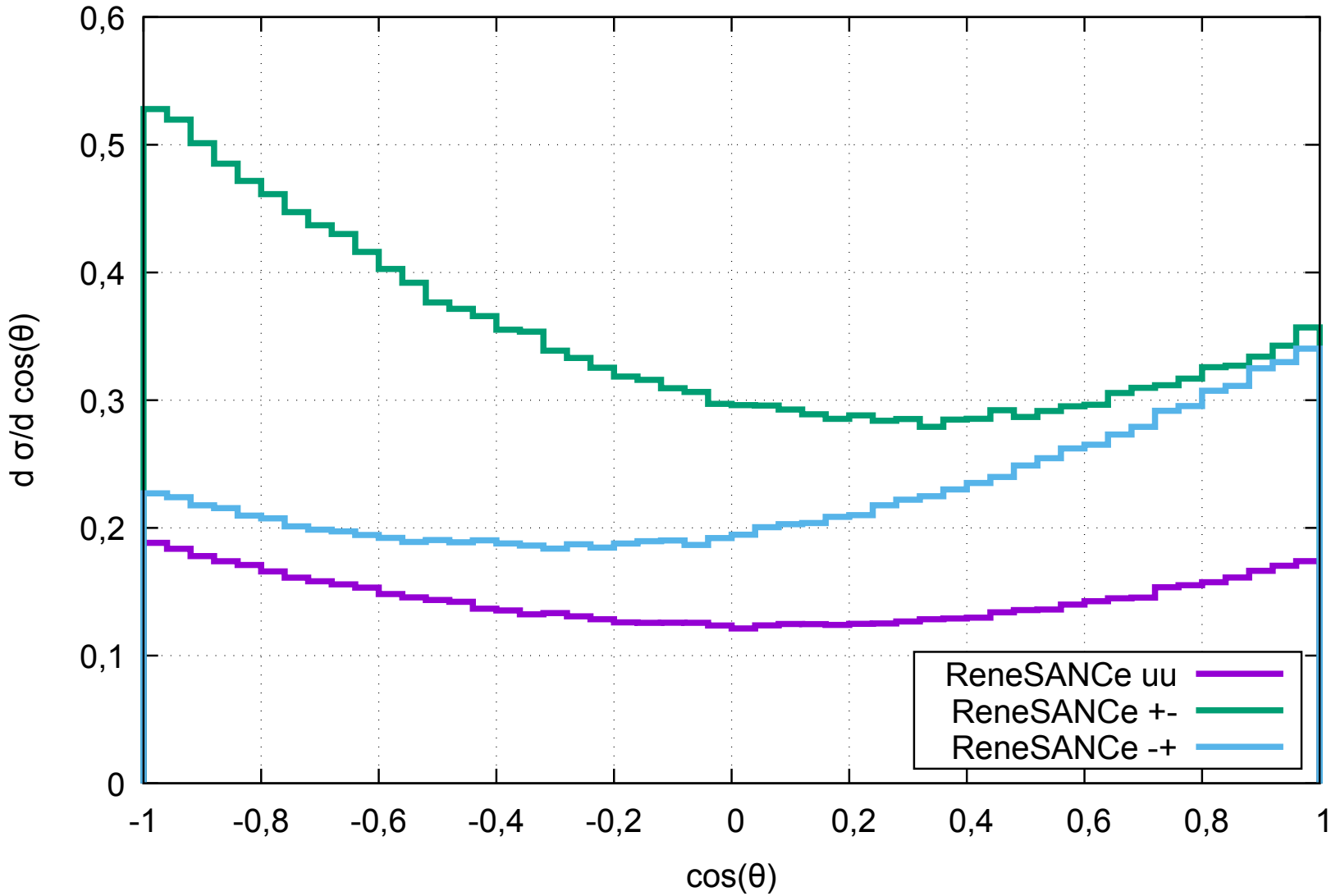
since $n \cdot p = 0$

$$\mathcal{N} = \sqrt{\frac{2|\vec{p}|}{|\vec{p}| + (p^0_+ - p^0_-)}}, \qquad p^0_\pm = \bar{u}(p,n)\gamma^0\gamma_\pm u(p,n)$$

$e^+e^- \to H\mu^+\mu^-$: with different polarizations of initial state. Z decay using Pythia. No spin correlations!



$e^+e^- \to H\mu^+\mu^-$: with different polarizations of initial state. Z decay using ReneSANCe



Decays. Summary

- Full spin correlations
- Factorized loop corrections (SPA)
- Accurate kinematics for hard Bremsstrahlung
- Speed optimization is still required
- No interference

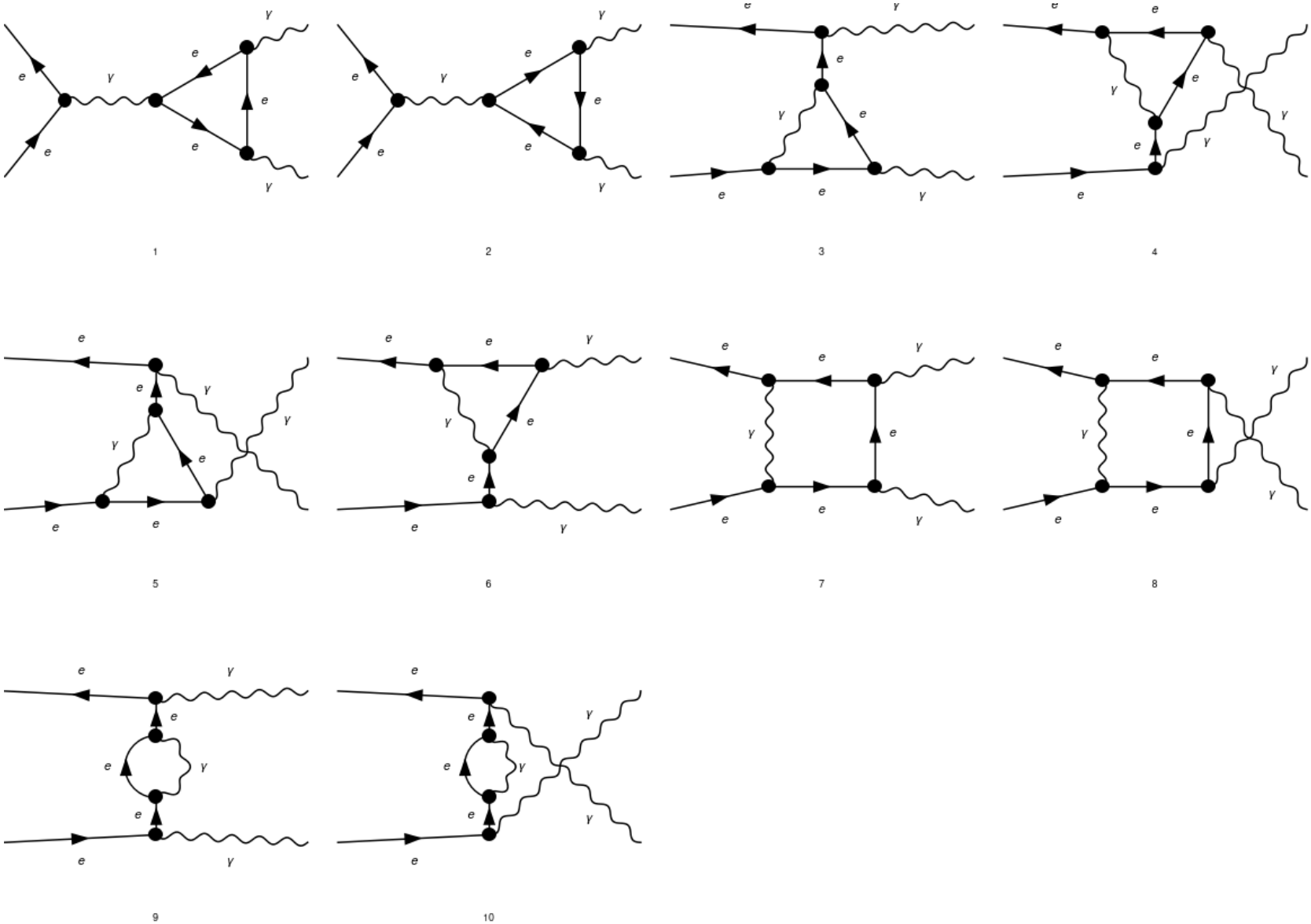
Luminosity in ReneSANCe

Processes for luminosity measurements:

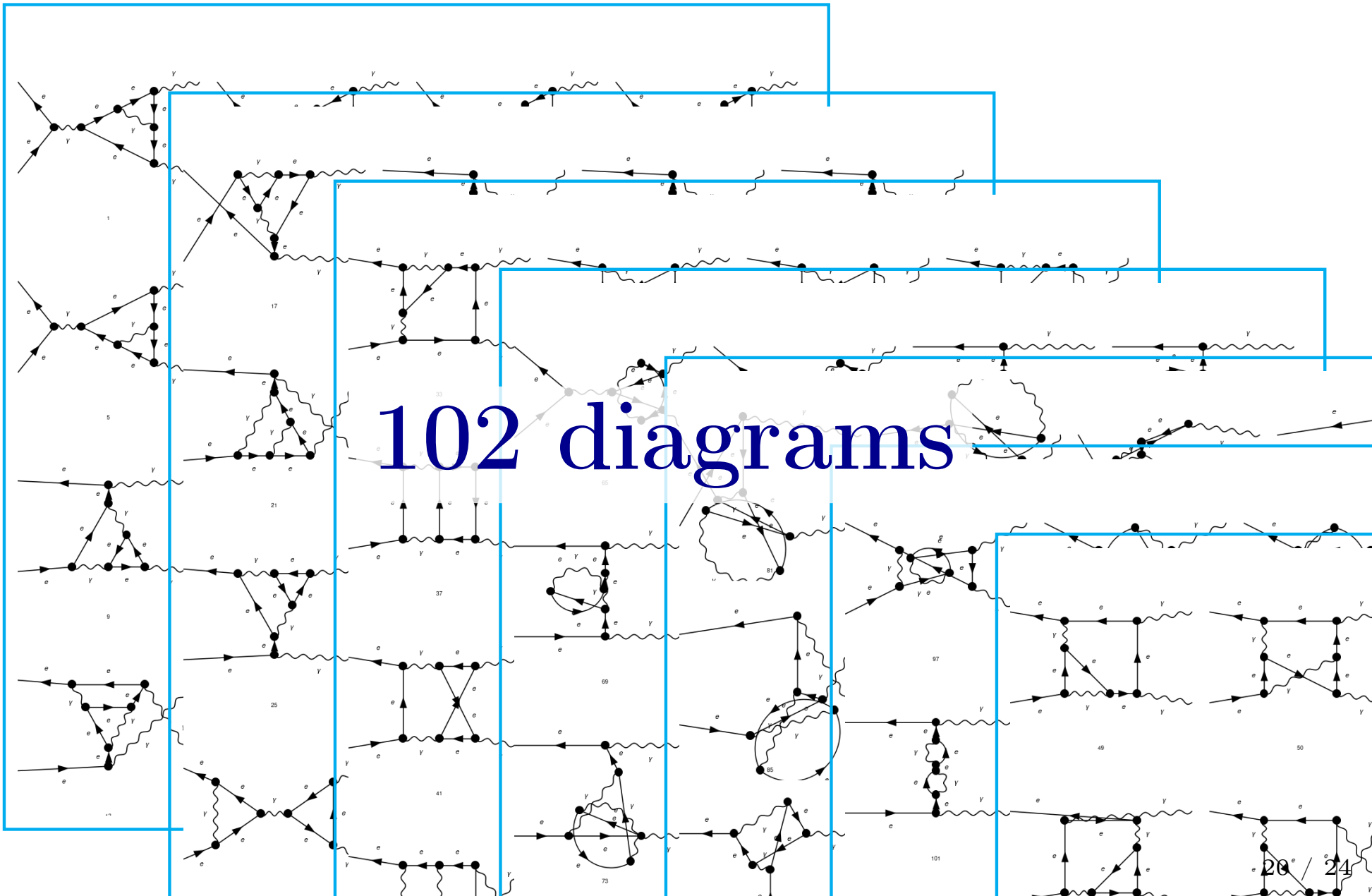
- $e^+e^- \to e^+e^-$ – SABS (Small Angle Bhabha Scattering)
- $e^+e^- \to e^+e^-$ – large angles Bhabha Scattering
- $e^+e^- \to \mu^+\mu^-$ – lepton pair production
- $e^+e^- \to \gamma\gamma$ – annihilation into photon pair

- **DONE**: complete 1-loop corrections for all processes
- **DONE**: leading 2-loop contributions. They include **EW** corrections at $O(G_\mu^2)$ and the mixed **EWxQCD** at $O(G_\mu \alpha_s)$
- **UNDER DEVELOPMENT**: NLL QED corrections using QED PDFs (see A. Arbuzov and U.Voznaya talks)
- **UNDER DEVELOPMENT**: complete 2-loop for $e^+e^- \to \gamma\gamma$

$e^+e^- \to \gamma\gamma$: One loop contribution



$e^+e^- \to \gamma\gamma$: Two loop contribution



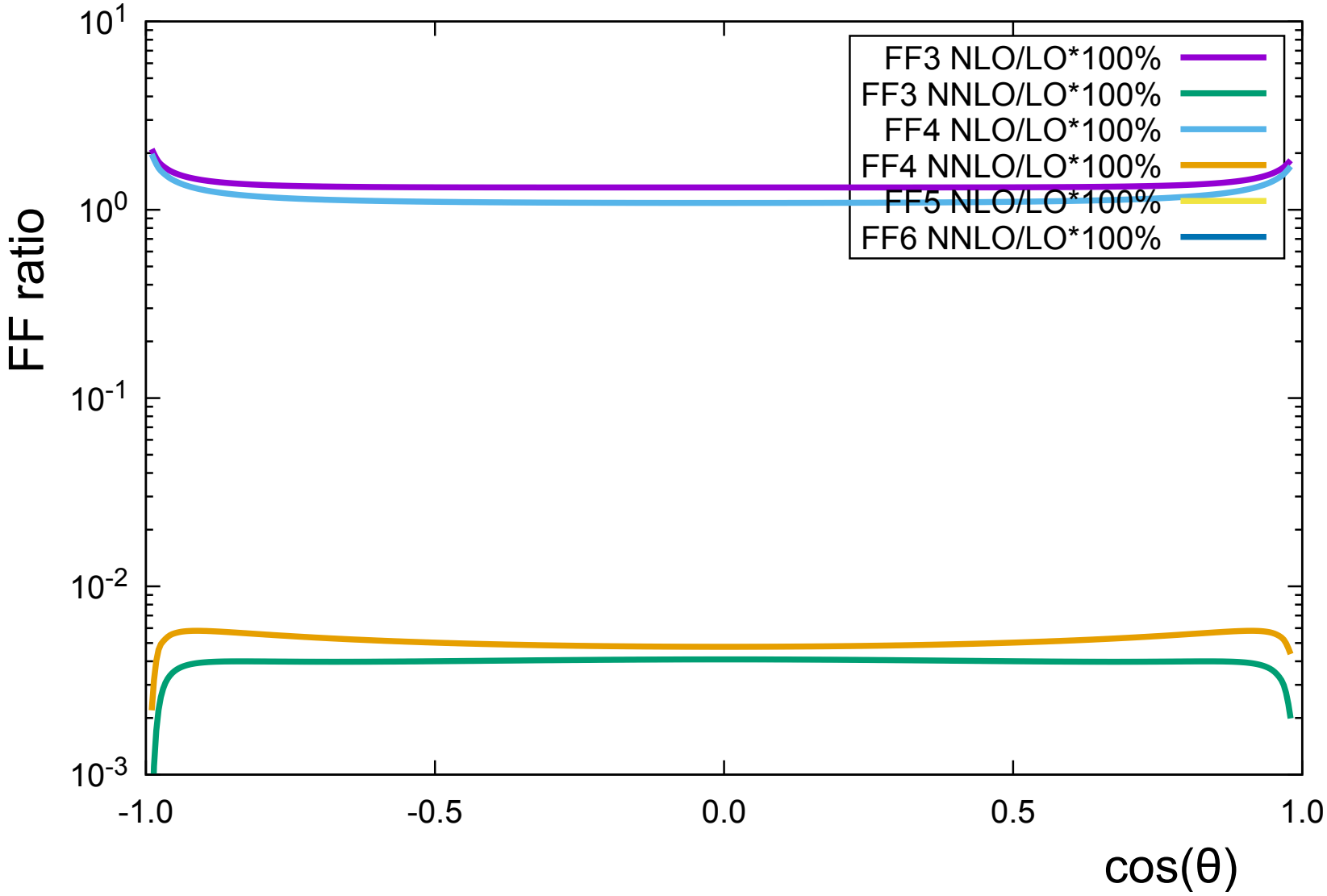
102 diagrams

$e^+e^- \to \gamma\gamma$: Two loop contribution

Analytical results of Roman Lee tbp, JHEP 08 (2025) 118

- Amplitude in the form $\mathcal{H} = \sum Str_i \mathcal{F}_i(s,t,u)$ – perfect for use in the generator with our new approach.
- Verified at 1-loop level.
- Only Li_2, Li_3, Li_4 appears.
- Form-factors are quite smooth.
- One loop corrections to $e^+e^- \to \gamma\gamma\gamma$ are still missing.

Form-factors behavior



Conclusions

- There is progress in `ReneSANCe` event generator development
- Decays of unstable particles implemented
- Library of radiative corrections in decays is under development
- First steps done to complete NNLO QED corrections
- Release of `ReneSANCe` is under preparation

Thank you for your attention!