KKMCee for precision monte carlo: Tests and extensions

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Abstract

- Future high-luminosity e^+e^- colliders (FCC-ee) demand Monte Carlo generators of unprecedented precision.
- We report tests and practical extensions of `KKMCee` aimed at precision studies in $\tau^+\tau^-$ production and decay.
- Focus: (i) validation of factorization/frames in presence of ISR, (ii) helicity-like tagging and polarimetric vectors for NP reweighting, (iii) enriched `HepMC3` output for user workflows.

Motivation: precision workflows need robust interfaces

- **KKMCee**: high-precision $e^+e^- \to f\bar{f}$ with ISR, FSR and ISR–FSR interference; YFS exclusive exponentiation with exact $\mathcal{O}(\alpha^2)$ via reweighting (β_1, β_2).
- Practical analyses often need to apply **small NP modifications** on top of a **precision SM+QED baseline** without breaking the accuracy of radiation.
- Goal: provide **clean event records and attributes** that allow external applications to remain simple and correct.

KKMCee in one slide

- YFS exclusive exponentiation ⇒ explicit multi-photon generation, IR-safe event-by-event.
- ISR/FSR and their interference consistently implemented.
- Exact QED $\mathcal{O}(\alpha^2)$ ingredients included as corrections to the matrix element via weights.

New `HepMC3` attributes and why

- Added attributes in C++ `KKMCee` `HepMC3` output:
  - **Tau helicity-like flags** to enable sample splitting / fits (as in LEP g_V/g_A-type strategies).
  - **Polarimetric vectors in lab frame** (`polarimetricInLabFrame`) to support NP interaction insertions in production+decay on top of QED-corrected simulation.
- Current dev version:
  `https://holeczek.web.cern.ch/public/KrakowHEPSoft/KKMCee-dev/`

External application: factorization and frames

- We prepare an **external-to-KKMCee** application to modify **Born-level (partial) differential** interactions while retaining KKMCee precision radiation.
- **Advantage:** user code can stay independent of KKMCee internal frame conventions; user controls only their chosen reference frame and its relation to lab frame.
- Frame/orientation details must still be consistent for τ decays and polarimetry.

Demo site:`https://th.ifj.edu.pl/kkmc-demos/index.html`

`HepMC3` event record snapshot

```
E 1 3 12
U GEV MM
W 1.00000000000000000000e+00 9.51534617634131940633 32e-01 9.99388782711154055604 65e-01 1.00000000000000000000e+00
A 0 GenCrossSection 1.08086680e+03 1.40909673e+02 -1 -1 1.02797885e+03 1.16028763e+02 1.08020956e+03 1.28185640e+02 1.08086680e+03 1.28341035e+02
A 0 SpinWT 0.75436
A 0 SpinWThelApprox 0.74962
A 5 approximateHelicity 1
A 6 approximateHelicity -1
A 5 polarimetricInLabFrame 1.465124 2.109355 -0.374166 2.595374
A 6 polarimetricInLabFrame 0.347424 -0.417422 -0.136156 0.559895
P 1 0 11 0.00000000000000000e+00 0.00000000000000000e+00 5.28999997531946 60e+00 5.29000000000000000e+00 5.10999070475549 05e-04 4
P 2 0 -11 0.00000000000000000e+00 0.00000000000000000e+00 -5.28999997531946 60e+00 5.29000000000000000e+00 5.10999070475549 05e-04 4
V -1 0 [1,2]
P 3 -1 22 -6.43817509795252 49e-05 -2.66362622204594 04e-05 -3.30186068272019 31e-03 3.30259571676851 19e-03 -8.23180634978399 11e-11 1
P 4 -1 22 1.01632434566255 71e-05 1.59446474932883 65e-06 -2.89192628095577 30e-04 2.89375551801154 00e-04 -5.14487896861499 45e-12 1
P 5 -1 15 2.21717611054101 79e+00 4.32097927234447 89e+00 1.10664328387463 27e+00 5.28860074475557 70e+00 1.77704999999999 80e+00 2
P 6 -1 -15 -2.21712189203349 52e+00 -4.32095423054700 77e+00 -1.10305223056381 68e+00 5.28780728397585 25e+00 1.77705000000000 09e+00 2
P 7 5 16 7.52671003341674 80e-01 2.20004439353942 87e+00 1.16599702835083 01e+00 2.60120320320129 39e+00 0.00000000000000 00e+00 1
P 8 5 -211 1.25448298454284 67e+00 1.69436347484588 62e+00 -3.06231319904327 39e-01 2.13491272926330 57e+00 1.39569326432407 49e-01 1
P 9 5 111 2.10022270679473 88e-01 4.26571756601333 62e-01 2.46877565979957 58e-01 5.52485167980194 09e-01 1.34975962832666 50e-01 1
P 10 6 -16 2.43405383080244 06e-02 -9.18952152132987 98e-02 2.18953087925910 95e-01 2.38699898123741 15e-01 0.00000000000000 00e+00 1
P 11 6 211 1.25762280076742 17e-02 -3.68874341249465 94e-01 -1.78540706634521 48e-01 4.33108508586883 54e-01 1.39569893392779 59e-01 1
P 12 6 111 -2.25403857231140 14e+00 -3.86018443107604 98e+00 -1.14346456527709 96e+00 4.61599874496459 96e+00 1.34979532081221 27e-01 1
```

Detector granularity & why KKMC needs future work

1) Granularity sets precision regimes

- Acceptance is irregular (cell structure, dead zones, barrel vs forward, faulty parts).
- At $\sim 0.3\%$ one may still use simplified acceptance models, but below that granularity must be treated together with theory.

2) Granularity forces full phase space (multi-photon)

- Lepton + nearby photons can mimic faulty cells / background-like objects.
- LEP already needed explicit multi-photon configurations; FCC likely needs even more (order of 5 photons) to control detector-cell effects.

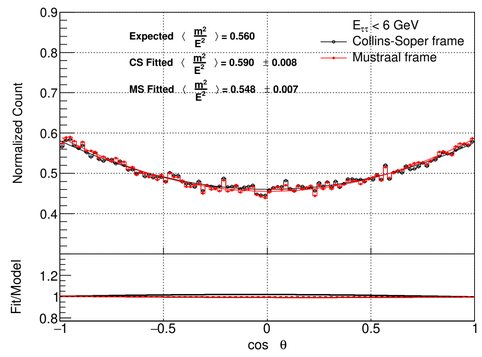
3) Future work pressure in KKMC-like projects

- Target precision $\sim 0.01\%$ demands consistent QED separation, higher orders, and much stronger validation/benchmarking.
- This is a long-term physics+software effort: algorithms, tests, and robust interfaces.

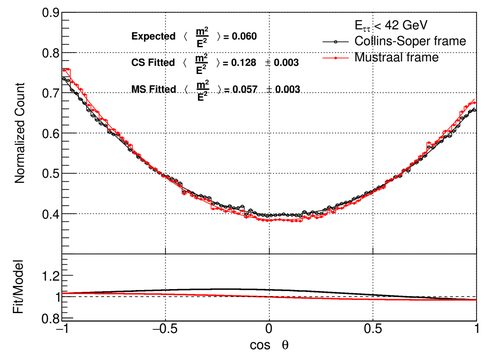
Validation I: factorization checks via scattering angle

- KKMC provides a precision baseline to test how a factorized "Born kinematic" picture behaves.
- In presence of ISR, the **Mustraal frame** matches better with theoretical expectations.

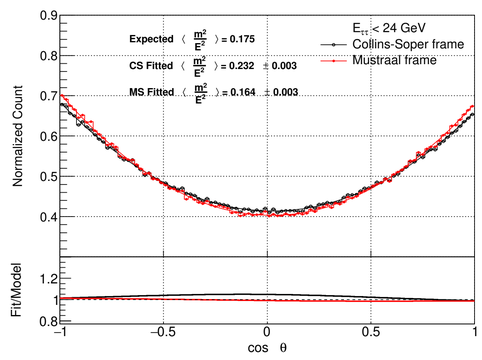
CM energy = 10.58 GeV



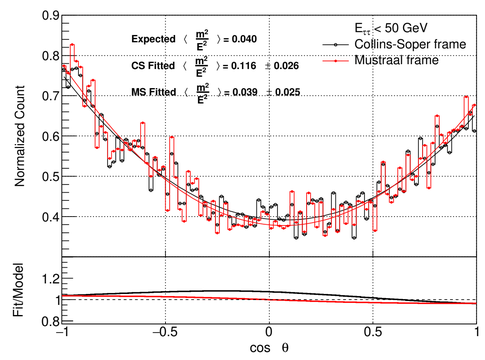
CM energy = 74.06 GeV



CM energy = 42.32 GeV

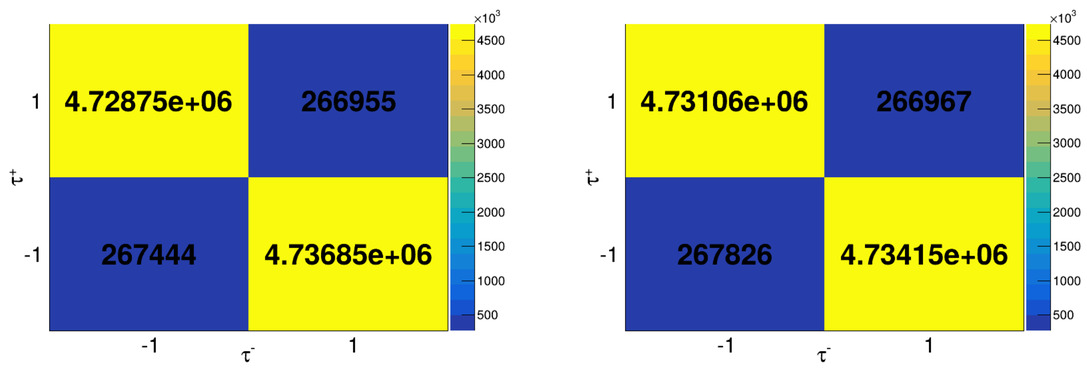


CM energy = 91.17 GeV



Validation II: helicity-like attribution (approximate, but useful)

- Exact τ helicities are not directly assignable event-by-event (quantum entanglement), but **helicity-like / chiral projections** are useful in analysis chains.
- We validate a practical approximation: project polarimetric vectors along τ momentum (chiral mode).



- Left: external code (lab-frame controlled); Right: KKMCee-internal.
- For 10.58 GeV, distributions are nearly identical ⇒ consistency of the approximation and interface.

Conclusions and outlook

- Separation into Born-like variables and photon-emission parts works sufficiently well for small-interaction modifications.
- Helicity-like tagging and lab-frame polarimetry enable flexible NP insertions while preserving a precision SM+QED baseline.
- Ongoing: extend systematic validation (rare corners, hard photons), document ambiguities, and provide user-facing examples.
- **Detector granularity is a theory issue at per-mille precision:** irregular acceptance (cells, cracks, dead zones, barrel/forward differences) couples to ISR/FSR radiation and distorts tails in a way that cannot be "fixed later" without model bias.
- **Unfolding becomes intrinsically model-dependent** once radiation+acceptance correlations matter; the safer strategy is **forward-folded predictions** (generate → detector/reco → apply the same cuts).

References

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[2] D. R. Yennie, S. C. Frautschi, H. Suura, *Annals Phys.* 13 (1961) 379.

[3] S. Jadach, B. F. L. Ward, Z. Was, KORALZ/KKMC series (LEP precision MC).

[4] Z. Was, *Acceptance and Higher Order EW and QED – FCC-ee Precision Monte Carlo and associated projects past and future*, talk/slides, MPI Garching, Jan 2026.