Physics Tools for e^+e^- Colliders

Wolfgang Kilian

University of Siegen

ECFA PED/Higgs Kickoff Meeting, June 18, 2021

Physics Simulations for Future e^+e^- Collider

Major Topics

1. Hard processes: coherent QCD/EW multi-fermion production
2. Final state: precision QCD and exclusive events
3. Initial state: beam properties and QED radiation

Event generator interface to simulation $\Rightarrow$ talk by G.Ganis

Material, references and (much) more detail: summary talks and individual contributions at

3rd FCC P&E-WS: https://indico.cern.ch/event/838435

4th FCC P&E-WS: https://indico.cern.ch/event/932973

LCWS 2021: https://indico.cern.ch/event/995633

Hard Processes at e^+e^- Colliders

Tree approximation

automated perturbative helicity-amplitude calculation for multi-leg processes with interfering resonances

self-optimizing multi-channel phase-space parameterization

integrals + distributions + exclusive events

Z factory: 2–4f // W/H factory: 4–8f // Top-thr. . . TeV+: 8–12f // . . .

Whizard   https://launchpad.net/whizard
- DBD e^+e^- samples (v1), ILC/CLIC/CEPC/FCC studies (v2)

Sherpa   https://sherpa-team.gitlab.io

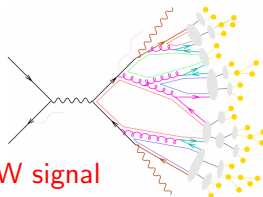MadGraph5   http://launchpad.net/mg5amcnlo

+ CalcHEP, CompHEP, AlpGen, HELAC/PHEGAS, . . .

QCD final-state effects

Legacy: LEP – LHC – Flavor Factories
High rates, high energy, multi-scale structure, jets as EW signal

1. PYTHIA6 shower and hadronization interfaced to MC
   $\Rightarrow$ validated within ILC/CLIC simulation framework

2. Pythia8   https://pythia.org
   Sherpa
   Herwig7   https://herwig.hepforge.org
   . . .

3. New developments in multi-jet physics

4. Next generation of shower/interface/hadronization/fragmentation models?
   $\Rightarrow$ validation and tuning with genuine e^+e^- data sets?

Hard Processes: generic QCD-NLO

Standard method: virtual corrections modular ("One-Loop Provider")

- ▶ aMC@NLO, OpenLoops, Recola, GoSam, . . .

Subtraction + parton definition + integration + event generation: MC

- ▶ Madgraph5_aMC@NLO, Sherpa, Whizard (v3.0)
- ▶ Requires vastly more computing resources
  ⇒ parallel: OpenMP, MPI, GPU

- ▶ Event samples depend on schemes and conventions
  ⇒ scales, jet definition, shower matching/merging

Hard Processes: generic EW-NLO

Currently: straightforward extension of methods developed for QCD:

Tree + OLP + subtraction + real-rad + integration + event-gen

- Madgraph5_aMC@NLO, Sherpa, (Whizard)
- ...
- Interplay with beam/initial-state description and QED radiation
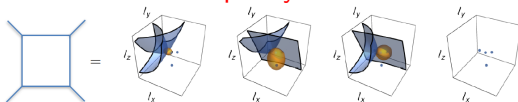
Hard Processes: generic higher-order EW/QCD

- Ongoing theory effort: multi-loop methods and results (LHC-driven)
  + massive propagators / resonances

- Two-loop $2 \rightarrow 3$ within reach
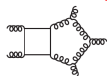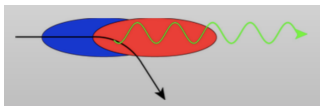
   [cf. talk C.Duhr, 3rd FCC P&E WS, 2020]

- Revival of 4D and purely numerical methods

  [cf. talk G.Rodrigo, 3rd FCC P&E WS, 2020; Capatti et al. 2020]
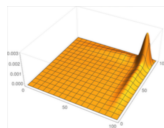
Beam Properties

Beamstrahlung

- Detailed simulation of machine and interaction region (GuineaPig)
  $\Rightarrow$ to be repeated for each parameter set
- Circular colliders: beamstrahlung $\Rightarrow$ beam-energy spread
- Fit to beam-simulation data
  - parameterized spectra (Circe1)
  - beam-event generator (Circe2)

  https://whizard.hepforge.org/circe.html

- Beamstrahlung interfaced with MCGenerator
  - Whizard: integrated in e^+e^- physics simulation framework
  - Sherpa, Madgraph5: to become available soon
  - Others: Circe2 available as plug-in module

Beam Properties

Polarization

- "Classical" method for simulation: merge distinct event samples with 100% ±left/right polarization

- "Quantum" method: polarization via initial-state density matrix, allows for arbitrary polarization fraction and spin rotation

  [polarization measurement essential for assessment of systematics]

  [part of beam-interaction simulation/monitoring?]

$\Rightarrow$ Polarized event samples available from any generator which uses helicity amplitudes internally (NLO: spin-correlated matrix elements)

Specific Processes

Soft Background

- $\gamma\gamma \to$ hadrons
  $\Rightarrow$ SLAC code based on Chen, Barklow, Peskin, PRD49 (1994)
    (integrated in ILC simulation environment)

Luminosity: $e^+e^- \to e^+e^-$ (or $\gamma\gamma$)

account for multiple photon radiation + QED/EW 1-loop

- LEP Legacy: BHLUMI/BHWIDE (KKMCee) for FCC-ee
    https://nz42.ifj.edu.pl/user/jadach/main
- BabaYaga (NLO + QED-Parton-shower + matching)
    https://www2.pv.infn.it/~hepcomplex/babayaga.html
- MCSANCee ($\to$ EW-1loop MC)
    http://sanc.jinr.ru
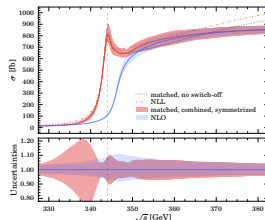- 2loop fixed order, numerical stability: P.Banerjee et al., 2106.07469

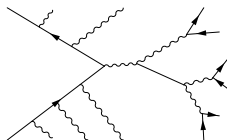# Specific Processes (Higher orders, QED radiation)

$e^+e^- \rightarrow W^+W^-$

- for LEP: RacoonWW; YFSWW, Jadach/Skrzypek 1906.09071
- EFT threshold expansion
  C.Schwinn, 11.FCC-ee Workshop

$e^+e^- \rightarrow t\bar{t}$ (and $t\bar{t}H$)

- tt on-shell multi-loop / threshold resummation
- off-shell NLO MC + threshold resummation: Whizard

  ⇒ talk A.Hoang, LCWS21

Initial-State Radiation

$$\frac{\alpha}{\pi} = \frac{1}{400} \ \bigg| \ \log \frac{\sqrt{s}}{0.1 \ \text{GeV}} = 8 \ \bigg| \ \log \frac{\sqrt{s}}{m_e} = 13$$

1. SF convolution/exact ME: RacoonWW, Whizard ($+$ heuristic pT)
2. ISR shower: Pythia, Sherpa, . . .
3. IR resummation / YFS semi-exclusive: YFSWW, KKMCee ($ee \rightarrow 2f$)
   $\Rightarrow$ Sherpa, in validation
4. NLL collinear resummation $+$ matching: 1909.03886, 1911.12040
   $\Rightarrow$ MG5_aMCNLO, in validation
5. Specific kinematics: radiative return, $\gamma + X$ final state

Conclusions and Outlook

1. Physics studies for future e^+e^- colliders:
    - Focus on sensitivity and detector performance
    - Pragmatic approach to theoretical predictions
    - Practical availability of event samples for studies

2. Preparation and machine/detector construction
    - Specify concrete demands on precision and exclusive description
      (resonances, radiation, jets, showers, hadrons)
    - Theory refinements incorporated in simulation
      (NLO EW; exclusive photons beyond LL/NLO)

3. Real data
    - Revision and re-tuning of QCD models for exclusive events
    - Monitoring of beam properties connected to simulation
    - Theory: systematics, detailed SM tests and new-physics searches

Outlook: Preparation Phase

- ▶ Matched resummed/exclusive QED radiation in universal MC
- ▶ 1-loop EW in simulated event samples
- ▶ Practical higher orders for Z resonance and luminosity monitors
- ▶ Path towards new level of precision in QCD radiation / hadrons
- ▶ . . .