Precision Calculations and Tools for e^+e^- Colliders

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Computing Tasks for e^+e^- Colliders: Physics

Despite large data sets and lots of experience from LHC, lepton-collider calculation/simulation methods are extrapolations of LEP (SLC) simulations

…but aiming at much higher statistics and ready for much higher energy

(QED radiation can be more relevant than QCD)

Per-mil precision on many observables, many things calculable in principle

Automated universal MC packages cover most of these tasks:
`Whizard`, `Sherpa`, `MadGraph5_aMCNLO`, …

⇒ New specific calculations, methods, algorithms to handle the LC computing challenges – reported at LCWS, and required in the future

e^+e^- Collider – Tools for Theory, Achievements and Challenges

1. Beam properties
2. Beam-induced background
3. Initial-state radiation
4. Hard processes: cross sections and exclusive events
5. SM and SMEFT, and BSM models
6. Resonances and QCD radiation
7. Jets, hadrons and leptons
8. Event samples

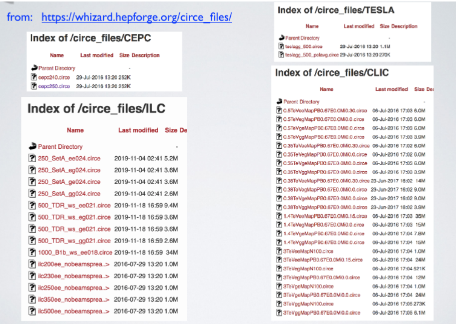
Beam Properties

Incoming electrons: energy distribution, soft photons = beamstrahlung

Beam simulation: `GuineaPig` depends on beam parameters [D. Schulte]

⇒ input to physics MC

⇒ reproduce beam simulation with high statistics = `CIRCE` [T. Ohl]



from: https://whizard.hepforge.org/circe_files/

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Beam Properties

Polarization

Beam polarization can be included in calculations and simulations by MC (initial-state density matrix)

$\Rightarrow$ should be matched to correct beam spectrum

Beam-induced background

$\gamma\gamma \to$ hadrons: significant low-E (non-perturbative) rates

$\gamma\gamma$ high-E tail: same simulation methods as for e^+e^-

Modeled/simulated using code by Barklow/Peskin, also: `PYTHIA`

$\Rightarrow$ improved description should use early ILC data

Luminosity

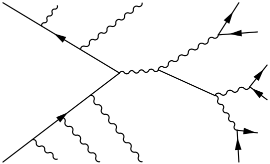
Lumi measurement: Bhabha scattering

Current status: $\rightsquigarrow$ talk M. Skrzypek

Lumi at ILC 500 GeV

Type of correction / Error	Update 2019	ILC 500 GeV forecast
(a) Photonic $[\mathcal{O}(L_e\alpha^2)]$ $\mathcal{O}(L_e^2\alpha^3)$	0.03%	10^{-5}
(b) Photonic $[\mathcal{O}(L_e^3\alpha^3)]$ $\mathcal{O}(L_e^4\alpha^4)$	0.021%	0.1×10^{-4}
(c) Vacuum polariz.	0.024%	1.2×10^{-4}
(d) Light pairs	0.013%	0.6×10^{-4}
(e) Z and s-channel γ exchange	0.04%	1.2×10^{-4}
(f) Up-down interference	0.004%	0.04×10^{-4}
(f) Technical Precision	(0.027)%	0.1×10^{-4}
Total	0.061%	2.0×10^{-4}

Initial-State Radiation



LC: only photons, various effects to be accurately computed:

1. Energy loss (spectrum), convoluted with beamstrahlung
2. Radiative return to Z resonance
3. Exclusive small-angle and soft photons in detector
4. Matching to hard photons (EW interactions) and virtual corrections
5. Interference with final-state photons

Initial-State Radiation (QED)

Eff. e $(+\gamma)$-PDF [Skrzypek, Jadach 1991]

$=$ PDF used in `WHIZARD` $+$ pT $\Rightarrow$ LC event samples

NLL e/γ-PDF: Bertone, Cacciari, Frixione, Stagnitto 2019

$\rightsquigarrow$ talk S. Frixione

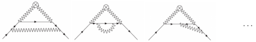
YFS resummation: `KKMCee`, `Sherpa`

Arbuzov, Jadach, Was, Ward, Yost 1999–2020; Price 2021

$\rightsquigarrow$ talk S. Jadach

$\rightsquigarrow$ talk A. Price

QED higher orders: Ablinger, Blümlein, De Freitas, Raab, Schönwald 2020–21

$\rightsquigarrow$ talk K. Schönwald 

QED Factorization: Laenen, Damst, Vernazza, Waalewijn, Zoppi 2021

$\rightsquigarrow$ talk L. Zoppi

Photons as DM signal: Kalinowski, Kotlarski, Sopicki, Zarnecki 2020

$\rightsquigarrow$ talk W. Kotlarski

Hard Processes: cross sections to events

Current LC Samples: Automated LO (SM/BSM) / PHS / unweighting

SM loop integrals from separate modules/programs:

`OpenLoops`, `GoSam`, `Recola`, `aMCNLO` (MG5), ...

NLO/MC framework

- provides automated subtraction method (CS, FKS)
- provides automated phase-space integration
- implements jet definitions, cuts, etc.

Issues with this procedure

- CPU intensive, parallel evaluation important
- many details: event definition, subtraction/recombination, scale setting, ... ⇒ validation?

Direct methods for NLO evaluation (e.g. Capatti, Hirschi, Pelloni, Ruijl 2020)?

Hard Processes: NLO QCD (partonic)

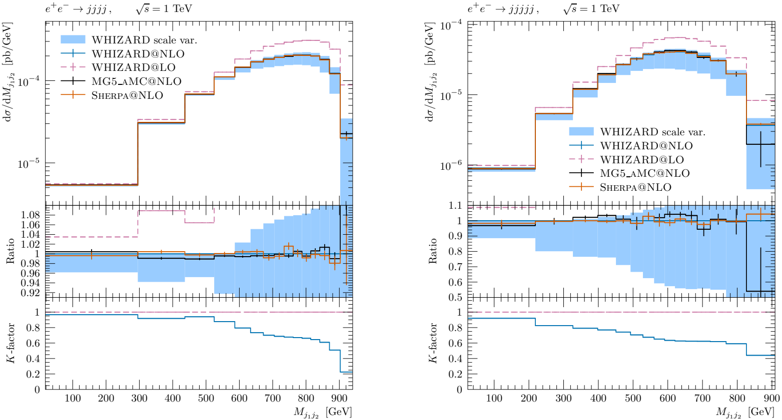
Pure-QCD multi-jet cross sections

$$e^+e^- \to 2j,\ 3j,\ 4j,\ 5j,\ 6j,\ \ldots$$

- As signal: QCD corrections to $e^+e^- \to f\bar{f}$
- As background: multi-boson processes with hadronic final states
- Jet properties studied at LHC with real data
- At LC: clean initial state, less systematic uncertainties, but high requirements on exclusive final-state description (and no data)
- Current LC event samples: LO exclusive + shower
- NLO-QCD is available with all major automated MC codes
- Higher orders, analytic methods (resummation), ...
  $\rightsquigarrow$ talk D. Reichelt

MC/QCD Multi-jet: observables at NLO (partonic)

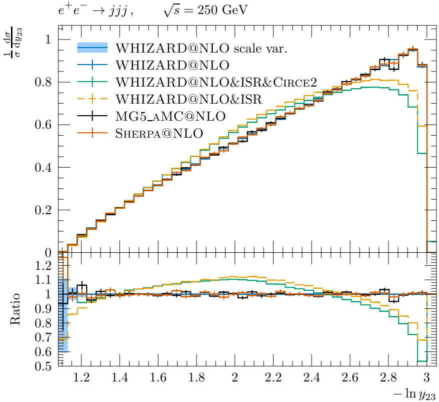
Technical comparison and systematic uncertainties (scale), example:



[by P. Bredt, J. Reuter, V. Rothe, P. Stienemeier]

MC/QCD Multi-jet: observables at NLO (partonic)

Towards LC simulation: Beamstrahlung, ISR and QCD-NLO, example:



[by P. Bredt, J. Reuter, V. Rothe, P. Stienemeier; y_{23} = Durham jet resolution scale]

Hard Processes: beyond NLO

SM processes at 2-loop EW/QCD accuracy – and beyond

Top threshold

Current status of top high-precision calculations: ⇝ talk A. Hoang

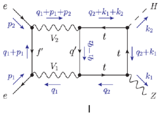
(Exclusive events require matching on-shell results with off-shell simulation)

Heavy quark asymmetries ⇝ talk L. Chen

Higgs/EW physics

Higgs production at 2 loops: ⇝ talk Q. Song

overview: ⇝ talk Kanemura



Hard Processes: BSM

No direct discovery

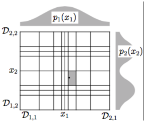
- At the LC: SMEFT framework consistent because $E_{\text{hard}} \approx \sqrt{s}$
- SMEFT / HEFT / ... Lagrangians encoded in `UFO` format
- MC simulations possible with all major codes (also some NLO)
- Reweighting events for EFT parameter scans

Direct discovery

- Perturbative models: also `UFO` (need separate simulation)
- Non-perturbative models: require dedicated code / plugins

$\rightsquigarrow$ many talks in BSM sessions

Hard Processes: Efficiency



MC production for large event samples:

- Matrix-element evaluation dominates computing time (NLO: expect substantial increase!)
- Efficiency is lost by unweighting events; multi-channel adaptive phase space is essential for precision
- Parallel evaluation has become possible, smooth scaling up to $O(100)$ cores (no trivial parallelization because of adaptation)

Adaptive mapping of multi-channel phase space = *Machine Learning*

Nevertheless: imperfect mapping, unweighting efficiency = O(percent)

⇒ *Deep Learning* = new class of multi-parameter mappings, room for improvement? Gain in efficiency vs. computing cost? [GAN, Norm.Flows]

Chen, Klimek, Perelstein [2018–21]; Butter, Plehn, . . . [2019–21]; Bishara, Montull [2019]; Bothmann, Janen, Knobbe, Schmale, Schumann [2020–21]; . . .

Parton Shower + hadrons: QCD

Exclusive events

- QCD part of hard matrix element
- higher-order QCD radiation = parton shower

$\Rightarrow$ matching/merging algorithm for combining: LO/LL $\Rightarrow$ NLO/NLL

$\Rightarrow$ hadronization modelled

Lots of experience, and sophisticated tools get input from LHC analyses:

LC simulations: LO + `PYTHIA6` = validated against LEP data

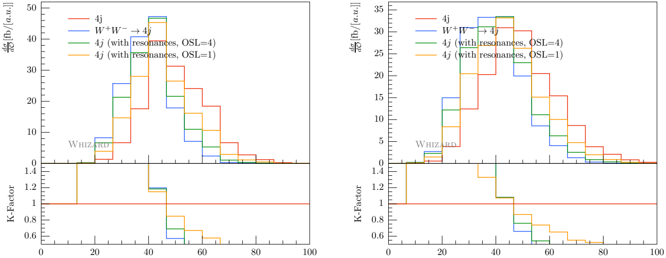
$\Rightarrow$ can make use of better understanding from LHC
$\Rightarrow$ involve improved e^+e^- shower frameworks, e.g., impl. in `Pythia8`
. . . but tuning will likely involve actual LC data

Parton Shower: Resonances

LC phenomenology: heavy electroweak (BSM?) resonances
= weak production + weak decay

QCD jet production = background, subdominant

⇒ Interplay between resonant and non-resonant production



[by B. Chokoufe: n_{charged} (left) n_γ (right)]

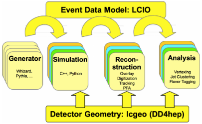
⇒ matrix-element based LO/LL resonance matching

Event Samples

Current agreement for common ILC samples (250 GeV)

- CIRCE spectra $\otimes$ e-PDF ISR $\otimes$ LO-partonic MC (`Whizard`) $\otimes\, \gamma/p_T$ recoil $\otimes$ `PYTHIA6` parton shower/hadrons
  $\Rightarrow$ `LCIO` event records

$\rightsquigarrow$ talks F. Gaede, H. Ono



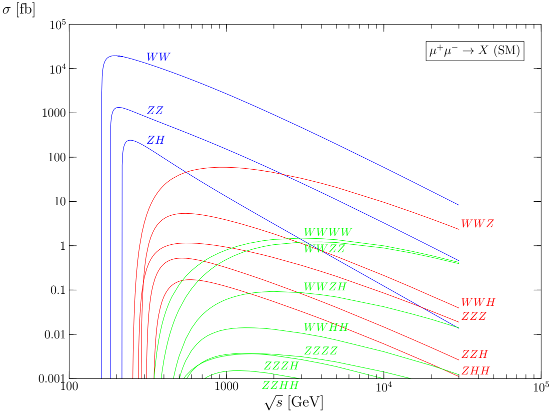
SMEFT studies etc.:

$\Rightarrow$ rescan complete event samples for recalculation of matrix element (explore parameter space by reweighting individual events)

BSM studies:

$\Rightarrow$ simulation runs with any BSM model possible in same framework

(Multi-)TeV Challenges: electroweak jets and showers



⇒ finite-order EW + QCD, EW splitting, Sudakov resummation, . . .

⇒ EW ISR shower: Han, Ma, Xie [2020]

Conclusions: Precision and Tools

Current status

- Precision of event samples (existing and under construction) is sufficient for physics studies, sensitivity analyses and benchmarks.
- Priority for complete physics coverage and user convenience

For the next > 10 years

- Producing more accurate event samples is technically feasible, but will likely become a major common effort
  - $\Rightarrow$ MC development & maintenance relies on support and communication between theory & experiment (WG3)
- Eventually, requirements on residual uncertainties have to be evaluated and compared to achievable precision in calculations
- All QCD effects will be re-validated against real data