Generators and Theory developments for HET physics

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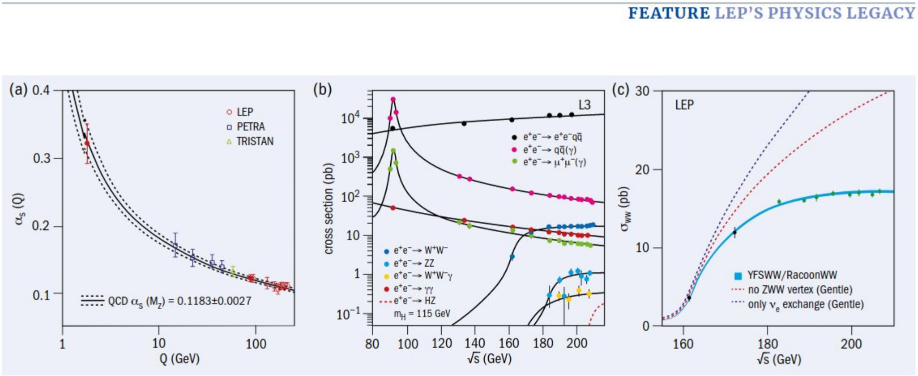
INFN, Sezione di Pavia

3rd ECFA workshop
on e^+e^- Higgs, Electroweak & Top factories

Campus des Cordeliers, Paris, October 9-11, 2024

Monte Carlo tools

✓ Monte Carlo event generators became essential tools for data-theory comparison since the LEP era



A. Siódmok, I ECFA workshop on H/W/T factories, 2022, DESY

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- ✓ Nowadays, all physics throughput from colliders (LHC, flavour factories) would be literally unthinkable without Monte Carlo generators
- ✓ Figuring out the physics potential (and foresee physics limitations) of a future machine impossible without Monte Carlo generators
- ✓ Monte Carlo generators provide the best solution to extract meaningful results (test the SM, unveil BSM) by comparing theory predictions to complex and precise data

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✓ Benchmarking and tuned comparisons essential to establish technical precision and estimate theoretical accuracy
talk by Alan Price

MC needs for a future e^+e^- collider

- Beamsstrahlung simulation (beam dynamics, luminosity spectra)

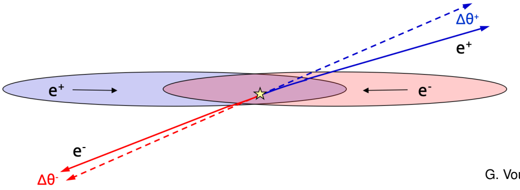
- quick reminder:
- extremely dense bunches of charged particles, (required for high luminosities at linear colliders with single bunch crossings)
  - produce strong electromagnetic fields
  - ∴ EM fields deflect charged particles in the opposing bunch
  - deflected beams emit beamstrahlung, in addition to the ISR from the hard scattering process
- ab-initio description of beamstrahlung and other beam transport effects outside of the scope of event generators for the hard "partonic" process
  - ∵ depends on bunch shapes and beam optics
  - ∵ completely independent of the hard partonic process
- physics event generators need energy distribution functions $D(x_1, x_2)$ and/or a corresponding stream of random numbers (x_1, x_2)

- $e^{\pm}$ energy spread from BS and average photon energy much smaller than beam energy spread $\Delta E_{e^{\pm}}/E_{\text{beam}} \approx 0.15\%$ after many bunch crossings:

FCC 2024	$\Delta_{BS} E_{e^{\pm}}$/Gev	$\langle E_{\gamma} \rangle_{BS}$/Gev	$0.15\% \cdot E_{e^{\pm}}$/Gev
Z	0.0012	0.0016	0.07
WW	0.0039	0.0059	0.12
ZH	0.0140	0.0189	0.18
Top	0.0329	0.0531	0.27

- only visible for the high energy designs

- nevertheless, already at LEP, on small-angle Bhabha scattering it induces a systematic bias on the acceptance



G. Voutsinas, E. Perez, M. Dam, P. Janot, arXiv:1908.01704

MC needs for a future e^+e^- collider

- QED RCs: soft and/or collinear resummation, YFS vs electron-PDFs, inclusive vs exclusive
- final state QCD showers, fragmentation and hadronisation
- fixed order RC in the full SM: NLO, NNLO
- on general grounds, the (impressive) $\mathcal{O}(0.1)\%$ theoretical accuracy of LEP results needs to be pushed down for future e^+e^- machines.
  This demands systematic improvements in the control of radiative corrections in the SM:
  - at NLO (nowadays fully automatic) and at NNLO
  - resummation techniques for leading higher-order corrections
  - consistent combination of the two, following and possibly extending the example at hadron colliders (MC@NLO, POWHEG, MiNNLO$_{\text{PS}}$, UN2LOPS, . . .)

QED resummation

- Instead of focussing on calculating order-by-order exact corrections in α for a given process, **ePDF**, **QED Parton Shower** and **Yennie-Fraustchi-Suura resummation** take a different point of view as starting point:

  they aim at calculating **approximate** and **"universal"** corrections **up to all orders**, by including (the important, leading) contributions arising from soft and/or collinear regions

- They rely on the general property of **factorization of soft/collinear divergencies** (enhancements) in QED, which leads to **exponentiation**

$\rightsquigarrow$ Sometimes, in some phase-space regions, for some observables, for certain experimental cuts, you better have an approximate but resummed result than a fixed-order one

$$\alpha < \alpha^2 L^2 \quad \text{somewhere, with } L = \log \frac{s}{m^2}$$

ePDF

- ePDF (or Structure Functions at LL) solve the DGLAP equations in QED
- Their logarithmic accuracy can be improved by using N^{n}LO splitting functions (e.g. $LL \to NLL$ [Frixione et al., 19, 21, 22])
- The formalism closely follows well established techniques in QCD
- Resum collinear logs, valid in the striclty collinear limit (inclusive over radiation)

$$d\sigma(L,\ell) = \mathcal{K}_{coll}(L;\ell) \otimes d\hat{\sigma}(\ell)$$

$$\longrightarrow \quad d\sigma_{kl} = \sum_{ij} \int dz_+ dz_- \, \Gamma_{i/k}(z_+,\mu^2,m^2)\, \Gamma_{j/l}(z_-,\mu^2,m^2)$$

$$\times\, d\hat{\sigma}_{ij}(z_+ p_k, z_- p_l, \mu^2; p_X, \{k_i\}_{i=0}^{n})$$

YFS resummation

- It's build upon the seminal paper YFS 61
- Naturally suited for exclusive radiation generation
- Resums infra-red logarithms
- After factorizing out all **soft** virtual and **soft** real corrections, the master formula is

$$\mathrm{d}\sigma = \sum_{n_\gamma=0}^{\infty} \frac{e^{Y(\Omega)}}{n_\gamma!}\,\mathrm{d}\Phi_Q \left[\prod_{i=1}^{n_\gamma} \mathrm{d}\Phi_i^\gamma\,\tilde{S}(k_i)\,\Theta(k_i,\Omega)\right]\left(\tilde{\beta}_0 + \sum_{j=1}^{n_\gamma}\frac{\tilde{\beta}_1(k_j)}{\tilde{S}(k_j)} + \sum_{\substack{j,k=1\\ j<k}}^{n_\gamma}\frac{\tilde{\beta}_2(k_j,k_k)}{\tilde{S}(k_j)\tilde{S}(k_k)} + \cdots\right)$$

  where
  - $e^{Y(\Omega)}$ resums all **soft** virtual and **soft** real emissions
  - $\tilde{S}(k_i)$ are eikonal factors
  - $\tilde{\beta}_n$ are IR-subtracted matrix elements remnants (with n photons)
- $\tilde{\beta}_n$ can be improved order-by-order to include exact NLO, NNLO, ...
- Comes with two "flavors": EEX (works at $|\mathcal{A}|^2$ level) and CEEX (works at the $\mathcal{A}$ level)
- It can be improved to better include collinear logs [Ward]

Many MCs for LEP (and LHC) by Jadach and colleagues based on it

QED Parton Shower

- It's an iterative MC solution of the (LL) DGLAP equations
- Kinematics of the emitted particles can be reconstructed $\rightarrow$ exclusive generation
- As ePDF, it naturally resums collinear logs. It can be tweaked to include correct infrared limit of emitted radiation.
- It can be matched to NLO to improve accuracy, avoiding double counting
- Can it be extended to work at NLL?

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✓ The availability of different QED resummation schemes gives the opportunity to check theoretical accuracy!

Two classes of Monte Carlo codes

- process taylored
  - BHLUMI, KKMC[ee],KORALW/Z, YFSWW, RACOONWW, RACOON4F
  - BABAYAGA
- general purpose
  - HERWIG, PYTHIA
  - MadGraph5_aMC@NLO, SHERPA, WHIZARD

KORALW, YFSWW

Jadach, Placzek, Skrzypek, Ward, Was

- Generators for $e^+e^- \to W^+W^- \to f_1 f_2 f_3 f_4$ at LEP
- Based on YFS resummation of QED corrections, include NLO EW corrections
- Include Coulomb effect at threshold
- Now combined in KandY
- Interfaced to TAUOLA for τ decays

KKMC[ee]

Jadach, Ward, Was, Yost, Siodmok

- Generator for $e^+e^- \to f\bar{f}$, with $f = \mu, \tau, q$
- It implements the CEEX YFS formalism for QED corrections
- It includes NLO EW corrections and collinear enhancement in resummation
- KKMCee is a port to `C++` of the original `Fortran` code

BabaYaga

- **BabaYaga@NLO** was developed to simulate Bhabha, $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \gamma\gamma$ at flavour factories, with a 0.1% theoretical accuracy in mind
- QED Radiative Corrections are included by means of an (in-house) QED Parton Shower
- The QED PS is matched to NLO exact matrix elements
- Fully exclusive event generation
- Although developed for low energies, it's being ported to high energies

  $\to$ e.g. $e^+e^- \to \gamma\gamma(+n\gamma)$ with NLO EW corrections, as luminosity process for FCCee

PLB 798 (2019) 134976

MadGraph5_aMC@NLO

[1,2] https://launchpad.net/mg5amcnlo

- MG5_aMC is an automatic event generator for any processes of the user's choice (in the SM and beyond)
- User input limited to run/model parameters, cuts, etc
- Unweighted events for PS matching can be generated at NLO QCD accuracy, possibly including multi-jet merging[3]
- NLO EW corrections can be computed as well[2], but only at fixed-order (no PS), either exactly or in the high-energy approximation[4] (Sudakov)[5a]
- In the Sudakov approximation, (the dominant part of) EW corrections can be included in NLO QCD-accurate events via reweighting[5b]
- Several other features are available
- All this works for arbitrary processes and colliders

1 Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Stelzer, Shao, Torrielli, MZ, 1405.0301
2 Frederix, Frixione, Hirschi, Pagani, Shao, MZ, 1804.10017
3 Frederix, Frixione, 1209.6215
4 Denner, Pozzorini, hep-ph/0010201, hep-ph/0104127
5a Pagani, MZ, 2110.03714; 5b +Vitos, 2309.00452

talk by M. Zaro at 2nd Workshop on HET factories, Paestum, 2023

Capabilities of MG5_aMC at e^+e^- colliders:

- NLO EW corrections can be included for (almost) all processes
- Through eMELA, ISR (possibly with beamstrahlung) in different ren/fact schemes can be employed
- The code automatically takes care to add to the short-distance xsection those terms necessary for consistency
  - Factorisation-scheme kernels included in the cross-section for Δ scheme and LL PDFs
  - Virtuals are corrected in order to account for different ren. scheme in model and PDFs ($\alpha(m_Z) \rightarrow$ MSbar)
- For details and how-to, see https://answers.launchpad.net/mg5amcnlo/+faq/3324

talk by M. Zaro at 2nd Workshop on HET factories, Paestum, 2023

More results:

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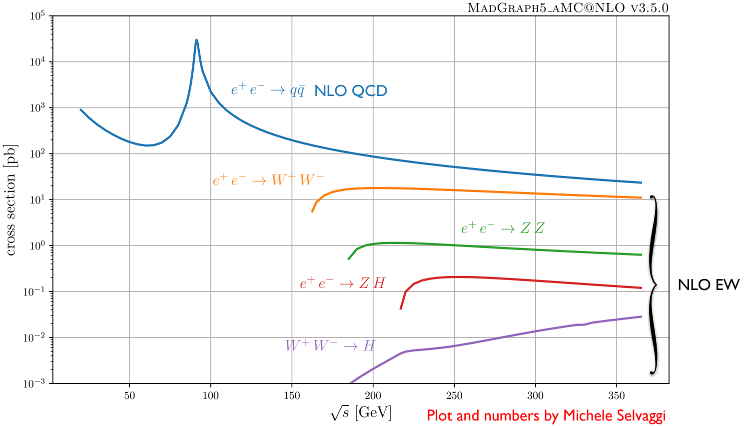
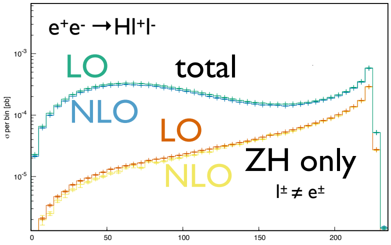


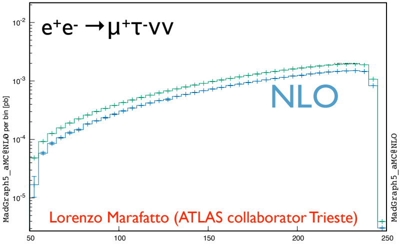
Plot and numbers by Michele Selvaggi

Marco Zaro, 12-10-2023 10

talk by M. Zaro at 2nd Workshop on HET factories, Paestum, 2023

Complex-mass scheme:
$e^+e^- \to Hl^+l^-$ and $e^+e^- \to \mu^+\tau^-\nu\nu$





- Qualitatively similar results to Denner, Dittmaier, Roth, Weber, hep-ph/0302198
- Results obtained in 15mins (on a cluster) @ 0.1%

Inclusive timing profile :

Overall slowest channel	0:06:15
Average channel running time	0:03:42
Aggregated total running time	8:05:57

- Very preliminary results
- Running time seems not to be an issue: for a 0.1%-accurate run:

Inclusive timing profile :

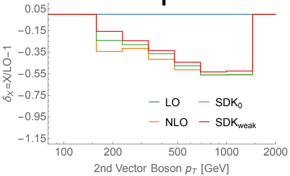
Overall slowest channel	0:20:06
Average channel running time	0:13:09
Aggregated total running time	1 day, 14:34:39

talk by M. Zaro at 2nd Workshop on HET factories, Paestum, 2023

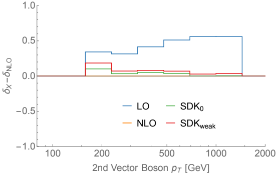
EW corrections at muon colliders

WIP in collaboration with Davide Pagani, Yang Ma

3Z production @ 3 TeV



Resummation is clearly necessary.

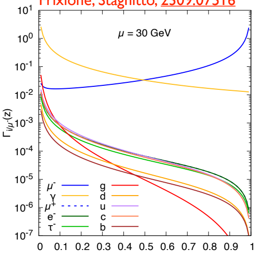


Finite flat corrections of just a few percents from non-Sudakov effects.

(Piece of) Slide from Davide Pagani

- μ PDF obtained by LL formula, with $m_e \rightarrow m_\mu$
- EW corrections both exact and in Sudakov approx
- Very recent: LL densities with QED+QCD evolution

Frixione, Stagnitto, 2309.07516



Marco Zaro, 12-10-2023

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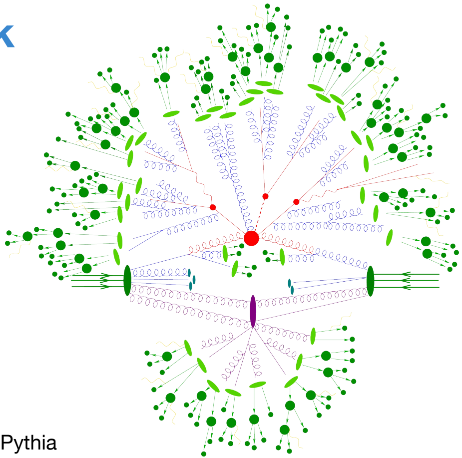
talk by M. Zaro at 2nd Workshop on HET factories, Paestum, 2023; Y. Ma, D. Pagani, M. Zaro, arXiv:2409.09129

talk by D. Reichelt

The SHERPA framework

- ME generators for hard process
  - Comix, Amegic
  - + interfaces to loop libraries (OpenLoops, Recola, MCFM)
- Parton Showers
  - CSShower, Dire
- Underlying Event/MPI model
- Hadronisation
  - Cluster Fragmentation, + interface to Pythia
- QED radiation via YFS resummation



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SHERPA 3 — multi-purpose event generation

- (Selected) Features:
  - Fixed Order
    - NLO QCD+**EW**,
    - **NNLO** QCD (selected processes)
  - Automated NLO (QCD) matching in S-MC@NLO
  - **UN2LOPS** matching to NNLO QCD
  - multi-jet merging in CKKW-L
  - Approximate **EW-corrections in matching & merging** (EWvirt/EWSud)
  - **Photoproduction @ NLO QCD + PS**

- YFS resummation of photon radiation
  - radiation from final state leptons
  - **initial state radiation** at e^+e^- colliders
  - extended by $\gamma \to f\bar{f}$ **splittings**
- Polarised
  - beams
  - **intermediate particles**
- MPI/MinBias and **fragmentation modelling, including color reconnection**

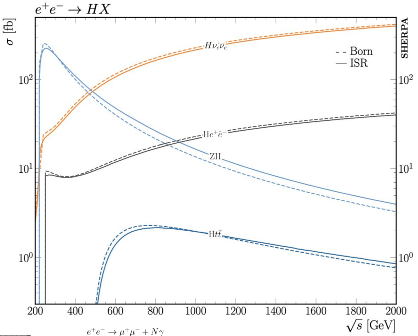
- External Interfaces:
  - HepMC 3
  - UFO 2 (including **form factors**)
  - RIVET 3/4
  - LHAPDF + several explicit pdf interfaces including various **photon pdfs**
  - OpenLoops/Recola/MCFM/MadLoops/BlackHat
  - **Pythia 8** (string fragmentation)

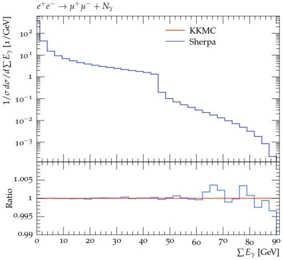
bold - added/significantly updated in Sherpa 3 development, some back-ported to Sherpa 2 4

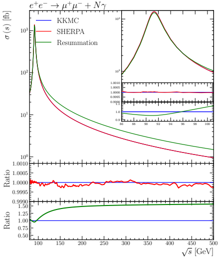
talk by D. Reichelt

QED initial state radiation

- Soft photon resummation in Sherpa via YFS module [Krauss, Schönherr '08]
- **New**: real photon emission from initial state [Krauss, Schönherr, Price '22]
- replace simple electron pdf with explicit multi-photon emissions
- validated agains KKMC [Jadach, War, Was '99]







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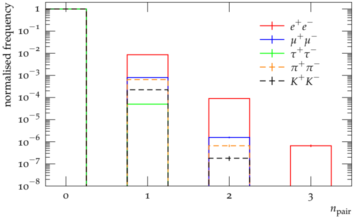
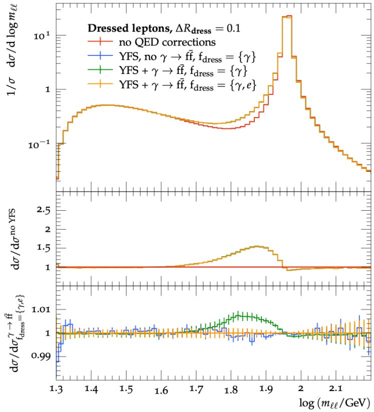
talk by D. Reichelt

QED radiation with $\gamma \to e^+e^-$

- Final state QED radiation, i.e. photon radiation from final state leptons [Krauss, Schönherr '08]
- **New**: supplemented with $\gamma \to e^+e^-$ splittings [Flower, Schönherr '22]
- Example: dilepton invariant mass in $pp \to e^+e^-$





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talk by D. Reichelt

Outlook: more accurate parton showers

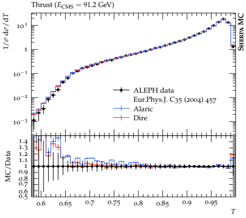
- **New:** Parton shower module ALARIC

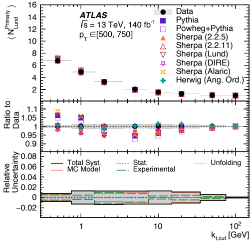
  [Herren, Höche, Krauss, DR, Schönherr,’22]

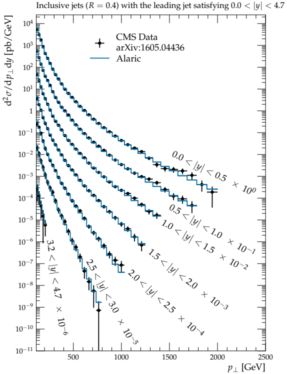
  - explore connection between angular ordering and dipole showers
  - address NLL deficiencies found in recoil schemes of current dipole showers
- Multi-jet merging available now

  [Höche, Krauss, DR ‘24]

  - + first LHC phenomenology
- full NLO matching still WIP
- Basis for development towards higher accuracy showers



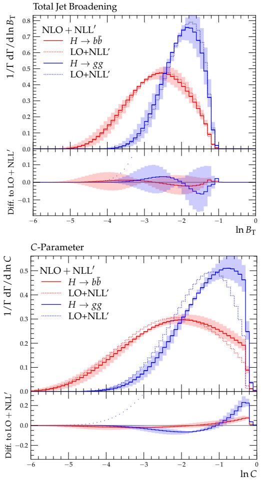




talk by D. Reichelt

Outlook: automated resummation

- accesible precise resummed calculations important
  - predictions for experiments
  - references for parton showers
- CAESAR formalism provides convenient framework event/jet shape-type observables [Banfi, Salam, Zanderighi '04]
- CAESAR implementation in Sherpa [Gerwick, Höche, Marzani, Schumann '15] [Baberuxki, Preuss, DR, Schumann '19]
  - several studies already for LEP/ LHC/RHIC/FCC-ee (future lepton collider)



Example: event shapes in $H \to gg$ and and $H \to q\bar{q}$ decays using EERad in conjunction with Sherpa+CAESAR

[Gehrmann-de Ridder, Preuss, DR, Schumann '24]

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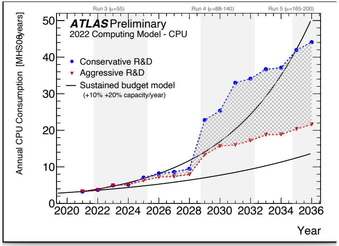
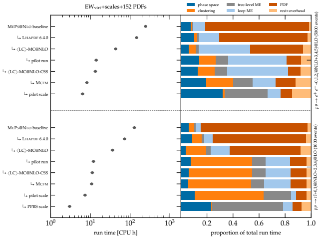
talk by D. Reichelt

Outlook: performance updates/HPC

[arXiv:2209.00843]
slide by E. Bothmann

- MC event generation uses significant+increasing resources
- (HL-)LHC measurements in danger of being limited by MC statistics
- Explore reduction of CPU footprint for heaviest use cases, e.g. ATLAS default setup $Z + 0{,}1{,}2j$@NLO + $3{,}4{,}5j$@LO
  1. LHAPDF improvement
  2. ⟨LC⟩-MC@NLO: reduce matching accuracy to leading colour, neglect spin correlations, i.e. S-MC@NLO → MC@NLO
     also useful to reduce negative event fractions [Danziger, Höche, Siegert 2110.15211]
  3. pilot run: minimal setup until PS point accepted, then rerun full setup
  4. ⟨LC⟩-MC@NLO-CSS: defer MC@NLO emission until after unweighting
  5. use analytical loop library where available
     here: OpenLoops → MCFM via interface [Campbell, Höche, Preuss 2107.04472]
  6. pilot scale definition in pilot run that requires no clustering
     small weight spread by correction to correct scale
- all new developments part of Sherpa 2.2.13 or later





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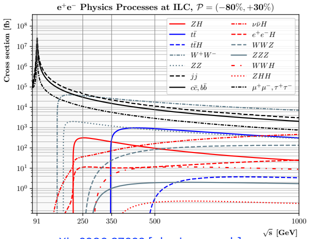
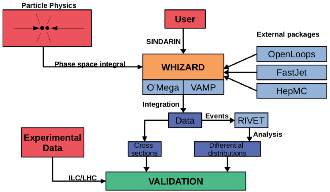
talk by D. Reichelt

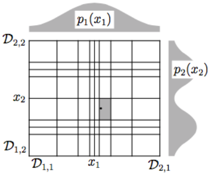


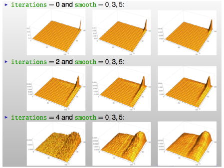
arXiv:2203.07622 [physics.acc-ph]



WHIZARD **Overview (I)**

- Complete MC event generator for all colliders: v3 released 27.4.2021
- Hard matrix elements @ LO internally (`O'Mega`)
- Hard matrix elements @ NLO externally (`OpenLoops`, `Recola`, `GoSam`, ...)
- Parton shower internal+external, hadronization external
- Dedicated interfaces to `Pythia6`, `Pythia8`, `Tauola`, ...
- Lepton collider beam simulations (Gaussian spread, parameterized fit, beam event files, 2d-histogram adapted, smoothened, photon collisions):





↪ Talk by Thorsten Ohl 06/2023: https://indico.cern.ch/event/1266492/

WHIZARD **Overview (II)**


```
model = NMSSM
process susyprod = e1, E1 => stau1, Stau1
process staudec = stau1 => neu1, e3

sqrts = 250 GeV
beams = e1, E1 => circe2 => isr
beams_pol_density = @(-1), @(+1)
beams_pol_fraction = 80%, 30%

n_events = 10000
sample_format = lhef, stdhep, hepmc
simulate (susyprod)
```

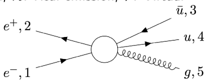
- Collider setup: arbitrarily polarized beams, crossing angle, asymmetric beams
- Event formats available: `LHA,LHE(v1-3),HepMC2,HepMC3(RootIO),LCIO,` EDM4HEP (w.i.p.)!
- Factorized processes (`unstable` feature, NWA, specific decay helicity, polarized resonance decays)
- Automated calculation of BRs of unstable particles, BRs can be set explicitly, e.g. to (N)NLO values
- BSM models through UFO interface (cf. later)
- Special treatment of top threshold physics (cf. later)
- Reweighting / recasting processes + multiple weights/observables
- **Focus here new developments: Completion NLO automation, NLO matching, high-performance, revalidations, new physics implementations: long-lived particles, initial-state QED treatment, EW PDFs etc.**

WHIZARD NLO Automation: Loops & Legs

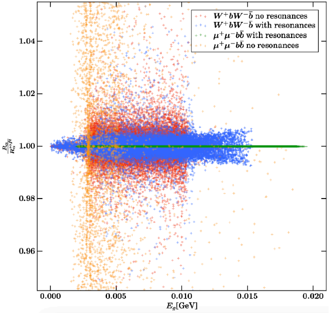
- NLO SM automation for lepton-/hadron colliders completed 2022 — Chokoufé; Weiss 2017; Rothe 2021; Stienemeier; Bredt 2022
- FKS subtraction, NLO matrix elements from OpenLoops/Recola/GoSam/...
- also: resonance-aware FKS subtraction — cf. Ježo/Nason, arXiv:1509.09071; Chokoufé, 2017
- Setup for automatic differential fixed-order results (histogrammed distributions)
- Photon isolation, photon recombination, light-, b-, c-jet selection; loop-induced processes

$$\sigma_{\text{NLO}} = \int d\Phi_n \mathcal{B} + \int d\Phi_{n+1} \underbrace{\left[\mathcal{R}(\Phi_{n+1}) - d\sigma_S(\Phi_{n+1})\right]}_{\text{finite by construction}} + \underbrace{\int d\Phi_n \mathcal{V} + \int d\Phi_n d\sigma_{S,\text{int}}}_{\text{finite by KLN}}$$

$\mathcal{B}$: Born, $\mathcal{R}$: Real emission, $\mathcal{V}$: Virtual



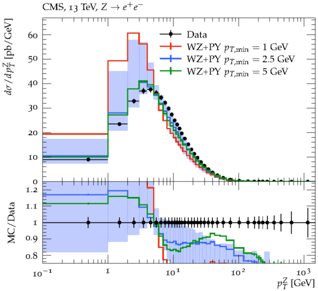
For NLO QCD possible singular regions: $(i, j) \in \{(3,5), (4,5)\}$

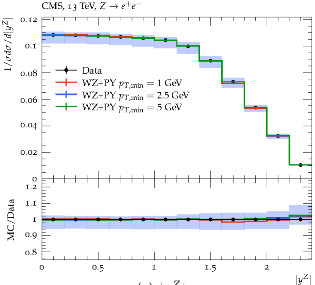


NLO POWHEG-type matching

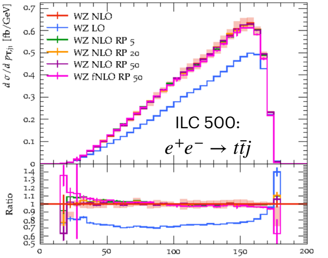
- Matching NLO real emission from hard ME and parton shower (PS)
- POWHEG method: hardest emission first [Frixione/Nason et al.]
- Process-independent NLO matching in WHIZARD

LHC 13 TeV: NC Drell-Yan $pp \to \ell^+\ell^-$ compared to CMS data





(c) $|y^Z|$

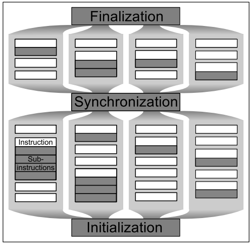


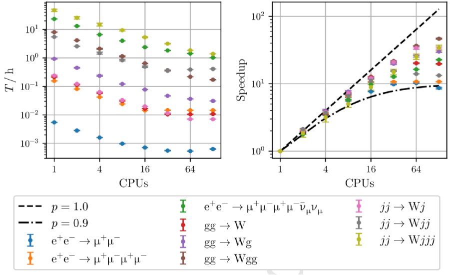
$$\mu_R = H_T/2 \quad \text{with} \quad H_T := \sum_i \sqrt{p_{T,i}^2 + m_i^2}$$

Available: all infrastructure for NLO QED/EW matching, needs to be completed/validated

Whizard in parallel

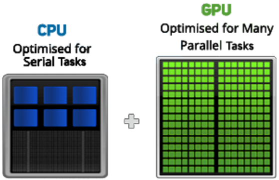
Braß/Kilian/JRR, arXiv:1811.09711





- Parallelization of integration: OMP multi-threading for different helicities
- MPI parallelization (using OpenMPI or MPICH)
- Distributes workers over multiple cores, grid adaption needs non-trivial communication
- Speedups of 20 to 50, saturation at O(100) tasks [can do also parallel event generation]
- Load balancer / non-blocking communication [v3.0.0]

Whizard on GPUs



- Joint project with former Phd student; now works for NEC supercomputers
- Main core serial (or MPI-parallel) on CPU,
- 1. step: matrix elements as libraries off-loaded to GPU
- (Semi-) automatized ME generator exists for amplitudes on GPU
- Moderate speed-ups can be seen for more complicated processes
- 2. step: phase-space generation (SIMD paradigm) on the GPU
- *W.i.p.:* phase-space adaption on the GPU (w/ minimal data transfer CPU $\longleftrightarrow$ GPU)

Preliminary:

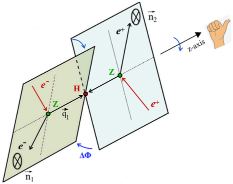
Process	$t^{CPU}[s]$	$t^{GPU}[s]$
$e^+e^- \to t\bar{t}$	0.98	4.28
$e^+e^- \to bW^+\bar{b}W^-$	28.8	23.1
$e^+e^- \to bW^+\bar{b}W^-H$	57.5	37.8
$e^+e^- \to b\bar{b}\bar{\nu}_e e^- \bar{\nu}_\mu \mu^+$	154	124
$e^+e^- \to 2j$	1.9	5.4
$e^+e^- \to 3j$	45	65
$e^+e^- \to 4j$	870	608
$e^+e^- \to 5j$	4106	978
$pp \to jj$	42	86
$pp \to W^+W^-W^+W^-$	670	192

Whizard MC Integrators:

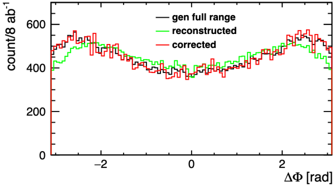
- VAMP: adaptive multi-channel Monte Carlo integrator
- VAMP2: fully MPI-parallelized version, using RNG stream generator
- [VGPU: VAMP implementation on GPU]
- [VXInt: new adaptive generator + integrator based on INNs]
  - (w.i.p first as a stand-alone tool)

News on the UFO / BSM in WHIZARD


```
model = SM  (ufo)
model = SM  (ufo ("<my UFO path>"))
```



- ☑ WHIZARD 2.8.3: Full UFO (1) support
- ☑ Fermion-number violating interactions (3.0.0)
- ☑ (N)LO matrix elements from UFO models (particularly SMEFTSim v3.x)
- ☑ Arbitrary Lorentz structures supported
- ☑ 5-, 6-, 7-, 8-, ... point vertices (optimization for code generation pending)
- ☑ Customized propators; Spin 0, 1/2, 1, 3/2, 2 ; BSM SLHA input (2.8.3,3.2.x)
- ☑ Lots of bug reports and constructive feedback from many different users



New paper on UFO 2.0: Darmé et al. arXiv: 2304.09883

I. Bozović-Jelizavčić, 2405.05820

BSM @ NLO (QCD) with UFO

- GoSam was the first OLP that kicked off NLO automation in Whizard in 2013
- Revived 2023 with NLO QCD for BSM models (e.g. SMEFT) for LHC J. Braun/P. Bredt/G. Heinrich/M. Höfer/JRR
- End of 2023: full validation of NLO QCD processes for LHC within SM: $pp \to t\bar{t}, pp \to t\bar{t}H, pp \to \gamma\gamma, pp \to \gamma j \ldots.$
- Full support for Whizard⊕GoSam for MPI (Message Passing Interface) parallelization
- GoSam UFO NLO interface allows support for almost any model
- W.i.p.: Note yet supported neither by the public Whizard nor GoSam versions
- Implementation and validation of resonance-aware subtraction for *pp* processes in Whizard
- 2024: First test runs for NLO QCD corrections for UFO BSM models

```
                                          GoSam
                                An Automated One-Loop
                               Matrix Element Generator
                              Version 2.1.0 Rev: 93fd8c5

                          (c) The GoSam Collaboration 2011-2021

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 This program is free software: you can redistribute it and/or modify
 it under the terms of the GNU General Public License either
 version 3, or (at your option) any later version.

 Scientific publications prepared using the present version of
 GoSam or any modified version of it or any code linking to GoSam
 or parts of it should make a clear reference to the publication:

    G. Cullen et al.,
    ``GoSam-2.0: a tool for automated one-loop calculations
                  within the Standard Model and Beyond'',
    Eur. Phys. J. C 74 (2014) 8,  3001
    [arXiv:1404.7096 [hep-ph]].
```

```
|==========================================================================
|                                WHIZARD 3.1.4.1
|==========================================================================
| Reading model file '/home/reuter/local/share/whizard/models/SM.mdl'
| Preloaded model: SM
| Process library 'default_lib': initialized
| Preloaded library: default_lib
| Reading model file '/home/reuter/local/share/whizard/models/SM_hadrons
| Reading commands from file 'gg_ttH_r.sin'
| Model: Generating model 'SM_with_ggh_UFO' from UFO sources
| Model: Searching for UFO sources in '/home/reuter/local/packages/whiza
UFO/Minimal_example'
| Model: Found UFO sources for model 'SM_with_ggh_UFO'
| Model: Model file 'SM_with_ggh_UFO.ufo.mdl' generated
| Reading model file 'SM_with_ggh_UFO.ufo.mdl'
| Switching to model 'SM_with_ggh_UFO' (generated from UFO source)
SM_with_ggh_UFO.MB =>  0.000000000000E+00
SM_with_ggh_UFO.MT =>  1.725000000000E+02
SM_with_ggh_UFO.WT =>  0.000000000000E+00
SM_with_ggh_UFO.MH =>  1.250000000000E+02
SM_with_ggh_UFO.WH =>  0.000000000000E+00
SM_with_ggh_UFO.Lambda =>  1.000000000000E+03
SM_with_ggh_UFO.CphiG =>  0.000000000000E+00
```

```
| ------------------------------------------------------------------------
| Process [scattering]: 'nlo_tt'
|   Library name  = 'default_lib'
|   Process index = 1
|   Process components:
|     1: 'nlo_tt_i1':   e+, e- => t, tbar [omega]
|     2: 'nlo_tt_i2':   e+, e- => t, tbar, gl [omega], [real]
|     3: 'nlo_tt_i3':   e+, e- => t, tbar [gosam], [virtual]
|     4: 'nlo_tt_i4':   e+, e- => t, tbar [inactive], [subtraction]
| ------------------------------------------------------------------------

   1       8192     8.813E+01   9.34E-03    0.01     0.01    45.0
   2       8192     8.812E+01   8.16E-03    0.01     0.01    76.9
|-----------------------------------------------------------------------------|
   2      16384     8.813E+01   6.15E-03    0.01     0.01    76.9    0.88   2
|=============================================================================|
| Integrate: sum of all components
|=============================================================================|
| It      Calls  Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]   Chi2 N[It] |
|=============================================================================|
   1          0     5.599E+02   1.30E-01    0.02     0.00    66.9
|-----------------------------------------------------------------------------|
| NLO Correction: [O(alpha_s+1)/O(alpha_s)]
|  (   2.75 +-   0.02 ) %
|=============================================================================|
| There were no errors and    2 warning(s).
| WHIZARD run finished.
|=============================================================================|
```

Content

- Benchmark Aims
- How to Benchmark
- Future Plans and Outlook

talk by A. Price

Motivation: Philosophy

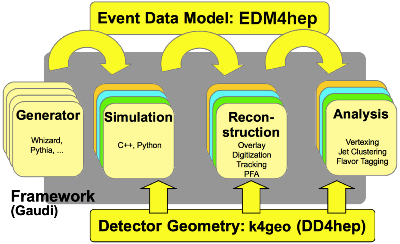
- Generators are generally trying to simulate the same physics
- Why not have one **master** input card that will work for all MC?
    - ➡ Authors are unlikely to change or decide on a common input!
- Have python module which will create generator specific runcards from one master input
- This will help improve reproducibility and hopefully reduce input errors
- Preserve the “LEP era” MC, who may not have active authors on the timeline of a Higgs Factory

talk by A. Price

Reproducibility

- Provide “**Add-on**” to Key4Hep framework
- Should be simple enough that:
  - New process can be easily added
  - MC authors can update interfaces if needed
- Keep some public event records
  - Juggle usefulness vs Storage
- More dedicated test for new generator releases

We already have a sophisticated software system!



See Juraj Smieško **Talk**

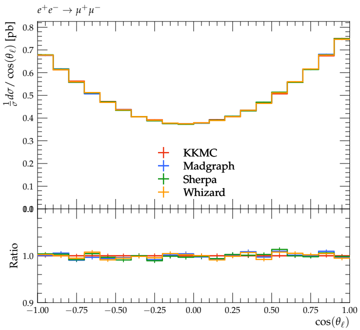
talk by A. Price

Current Processes

We have input cards for all relevant $2 \rightarrow 2$ processes

We seeing excellent agreement in most cases, one or two effects (<5%) that requires more detailed study

Differential distributions are also in good agreement



talk by A. Price

Summary → "Generators" section in the ECFA Report

- Editors: Carlo Carloni Calame, Juergen Reuter, Marco Zaro
- **Preliminary** outline:

(1) Hard processes: NLO QCD + NLO EW in the SM, NNLO
(2) Initial state radiation: LL/NLL ePDFs / YFS (coll. vs. soft resummation)
(3) Beam spectra: parameterized, simulated, Gaussian
(4) Parton showers and hadronization, incl. matching
(5) BSM simulations
(6) Dedicated processes with dedicated tools/implementations:
Bhabha, rad. Bhabha, $e^+e^- \to \gamma\gamma$, WW & $t\bar{t}$ thresholds
(7) Connection to software frameworks, event formats, and all that