Precision event generation with SHERPA 3

Marek Schönherr

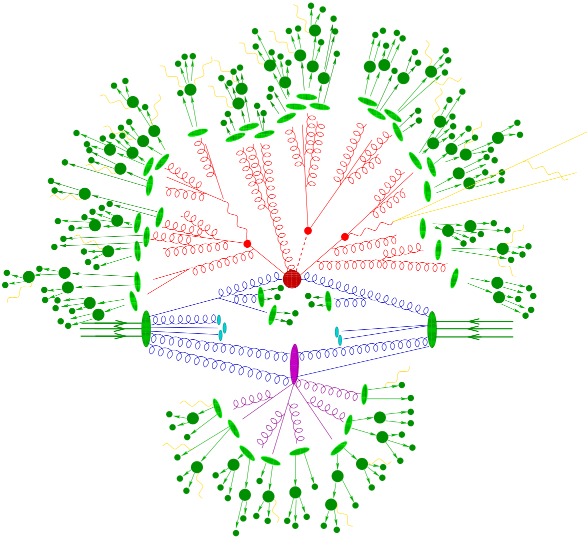
IPPP, Durham University

Outline

SHERPA 3

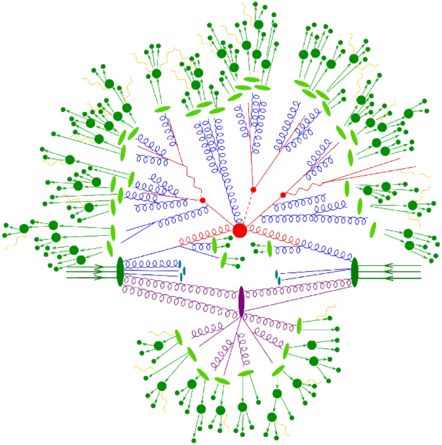
Physics improvements & new developments

SHERPA



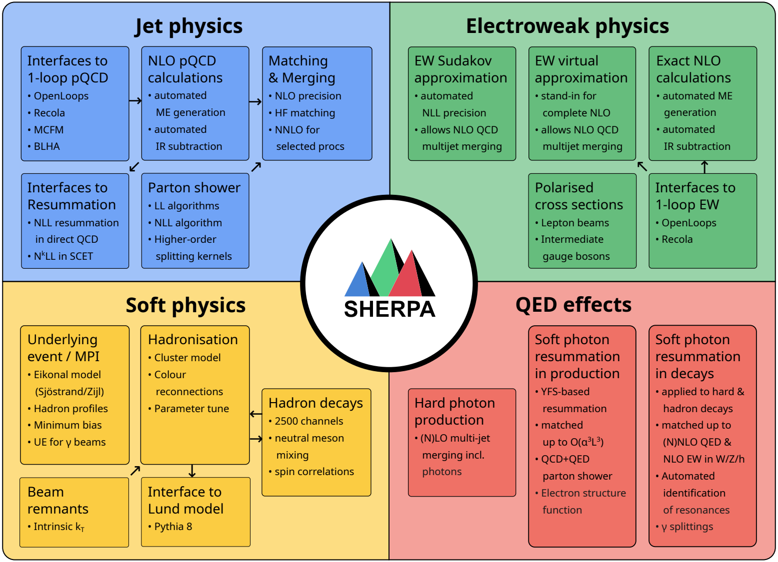
SHERPA 3 – overview

Bothmann et.al. '24



- Two tree-level built-in matrix element generators: COMIX, AMEGIC
- Higher order QCD effects: Matching via S-MC@NLO, multi-jet merging via CKKW-L algorithm
- Approximate NLO EW effects: EWvirt & EW Sudakov
- Two parton showers: CSS, DIRE
- A cluster fragmentation model
- A hadron- and tau-decay module
- Multiple interaction simulation á la PYTHIA
- Higher-order QED effects via YFS resummation
- Interfaces to
  - OpenLoops
  - Recola
  - GoSam
  - MCFM
  - BlackHat
  - MadLoop
  - RIVET 3 & 4
  - UFO
  - PYTHIA 8

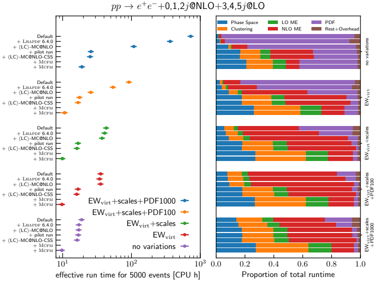
slide by F. Siegert


Jet physics
Interfaces to 1-loop pQCD
• OpenLoops
• Recola
• MCFM
• BLHA
NLO pQCD calculations
• automated ME generation
• automated IR subtraction
Matching & Merging
• NLO precision
• HF matching
• NNLO for selected procs
Interfaces to Resummation
• NLL resummation in direct QCD
• N^{k}LL in SCET
Parton shower
• LL algorithms
• NLL algorithm
• Higher-order splitting kernels
Electroweak physics
EW Sudakov approximation
• automated NLL precision
• allows NLO QCD multijet merging
EW virtual approximation
• stand-in for complete NLO
• allows NLO QCD multijet merging
Exact NLO calculations
• automated ME generation
• automated IR subtraction
Polarised cross sections
• Lepton beams
• Intermediate gauge bosons
Interfaces to 1-loop EW
• OpenLoops
• Recola
SHERPA
Soft physics
Underlying event / MPI
• Eikonal model (Sjöstrand/Zijl)
• Hadron profiles
• Minimum bias
• UE for γ beams
Hadronisation
• Cluster model
• Colour reconnections
• Parameter tune
Hadron decays
• 2500 channels
• neutral meson mixing
• spin correlations
Beam remnants
• Intrinsic k_T
Interface to Lund model
• Pythia 8
QED effects
Hard photon production
• (N)LO multi-jet merging incl. photons
Soft photon resummation in production
• YFS-based resummation
• matched up to $O(\alpha^3 L^3)$
• QCD+QED parton shower
• Electron structure function
Soft photon resummation in decays
• applied to hard & hadron decays
• matched up to (N)NLO QED & NLO EW in W/Z/h
• Automated identification of resonances
• γ splittings

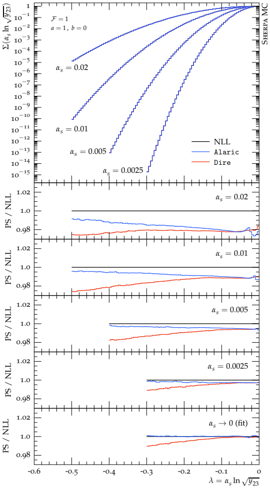
SHERPA 3 – code & performance

- ∼400k loc, mainly `C++`, `Python` interfaces exist
- fully open source, repository on GitLab
- input cards in `YAML` format
- release format:
  major → 3.**x**.0
  minor → 3.x.**y**
  (currently v.3.0.1 Nov '24)

Bothmann et.al. '22



SHERPA 3 – NLL accurate parton shower



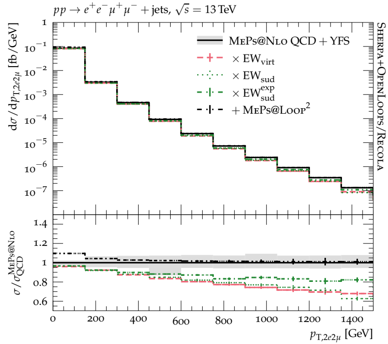
Herren, Höche, Krauss, Reichelt, MS '22
Assi, Höche '23
Höche, Krauss, Reichelt '24

ALARIC – NLL accurate shower

- CSSHOWER and DIRE not formally NLL accurate
- new ALARIC development based on split os soft and collinear dynamics
- extended to massive splittings and hadron colliders

SHERPA 3 – electroweak corrections

Kallweit et.al. '15; Bothmann, Napoletano '20; Bothmann et.al. '21

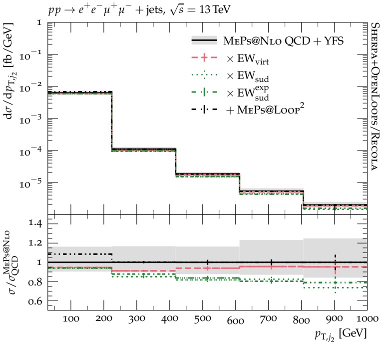


EW corrections at high energies

- NLO EW automated
  Schönherr '17
- EW_{virt} approximation uses IR regulated exact virtual corrs
  - expensive
    use for low multiplicities
- EW_{sud} approximation uses EW Sudakov logarithms
  - cheap
    use everywhere else

SHERPA 3 – electroweak corrections

Kallweit et.al. '15; Bothmann, Napoletano '20; Bothmann et.al. '21

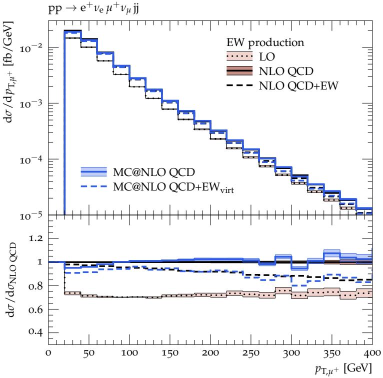


EW corrections at high energies

- NLO EW automated
  Schönherr '17
- EW$_{virt}$ approximation uses IR regulated exact virtual corrs
  - expensive
    use for low multiplicities
- EW$_{sud}$ approximation uses EW Sudakov logarithms
  - cheap
    use everywhere else

SHERPA 3 – VBF/VBS production

Buckley et.al. '21
Lindert, Pozzorini, MS '22
Denner, Pellen, MS, Schumann '24

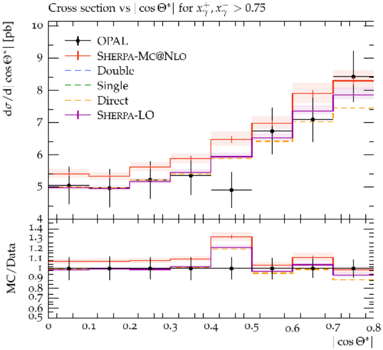


MC@NLO for VBF/VBS and seminleptonic di/tri-boson

- process with multiple disconnected colour singlets
- singlets evolve independently
- neglect s/t (or t/u) channel interference such that QCD correction has no QED divergences

SHERPA 3 – photon-induced processes

(Höche,) Meinzinger, Krauss '23,'24



Photons as incident particles

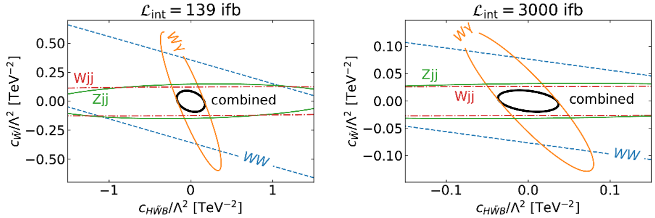
- photon sources through EPA, off e, p, A

Resolve photon substructure

- photon PDF
  $\gamma \to \gamma$, $\gamma \to q\bar{q}$
- vector meson dominance
  $\gamma \to \rho, \omega, \phi \to q\bar{q}$

SHERPA 3 – BSM processes

Höche et.al. '14; Biekötter, Krauss, Parisi, MS '20, '21



- `UFO` interface for BSM physics
- includes support for form factors, custom propators, spin correlations, automatic decay tables, multijet merging
- SHERPA as signal and background generator

Polarised cross sections

Polarised cross sections

Hoppe, MS, Siegert '23

Physical polarisation states are only defined for on-shell particles, and are frame dependent.
Both W/Z are short-lived and only occur as intermediate states, we have to make approximations

- neglect all non-resonant contributions
- consider only on-shell boson (some off-shell effects can be recovered) use either narrow width approximation (NWA) or pole approximation

Intrinsic accuracy: $\mathcal{O}(\Gamma/m)$

Narrow-width approximation
The intermediate particle is set directly on-shell

$$\left[\frac{1}{p^2-m^2+im\Gamma}\right]^2 \longrightarrow \frac{\pi}{m\Gamma}\,\delta\left(p^2-m^2\right)$$

Polarised cross sections

Hoppe, MS, Siegert '23

Physical polarisation states are only defined for on-shell particles, and are frame dependent.
Both W/Z are short-lived and only occur as intermediate states, we have to make approximations

- neglect all non-resonant contributions
- consider only on-shell boson (some off-shell effects can be recovered) use either narrow width approximation (NWA) or pole approximation

Intrinsic accuracy: $\mathcal{O}(\Gamma/m)$

Narrow-width approximation
The intermediate particle is set directly on-shell

$$\left[\frac{1}{p^2 - m^2 + im\Gamma}\right]^2 \longrightarrow \frac{\pi}{m\Gamma}\,\delta\left(p^2 - m^2\right)$$

Spin and spin density

Intermediate vector bosons

Decompose production and decay (neglect all non-factorisable contribs)

$$\mathcal{M} = \mathcal{M}_\mu^{\text{prod}} \left(\frac{i\left(-g^{\mu\nu} + \frac{p^\mu p^\nu}{m^2}\right)}{p^2 - m^2 + im\Gamma} \right) \mathcal{M}_\nu^{\text{decay}}$$

Again, using completeness relations,

$$\left(-g^{\mu\nu} + \frac{p^\mu p^\nu}{m^2}\right) = \sum_{\lambda=1}^{4} \varepsilon_\lambda^\mu(p)\, \varepsilon_\lambda^{*\nu}(p)$$

The unphysical fourth polarisation vanishes for $p^2 = m^2$. Define

$$\mathcal{M}_\lambda^{\text{prod}} = \mathcal{M}_\mu^{\text{prod}}\, \varepsilon_\lambda^\mu(p) \qquad\qquad \mathcal{M}_\lambda^{\text{decay}} = \varepsilon_\lambda^{*\nu}(p)\, \mathcal{M}_\nu^{\text{decay}}$$

Spin and spin density

Intermediate vector bosons

Decompose production and decay (neglect all non-factorisable contribs)

$$\mathcal{M} = \mathcal{M}_\mu^{\text{prod}} \left(\frac{i\left(-g^{\mu\nu} + \frac{p^\mu p^\nu}{m^2}\right)}{p^2 - m^2 + im\Gamma} \right) \mathcal{M}_\nu^{\text{decay}}$$

Again, using completeness relations,

$$\left(-g^{\mu\nu} + \frac{p^\mu p^\nu}{m^2}\right) = \sum_{\lambda=1}^{4} \varepsilon_\lambda^\mu(p)\, \varepsilon_\lambda^{*\nu}(p)$$

The unphysical fourth polarisation vanishes for $p^2 = m^2$. Define

$$\mathcal{M}_\lambda^{\text{prod}} = \mathcal{M}_\mu^{\text{prod}}\, \varepsilon_\lambda^\mu(p) \qquad\qquad \mathcal{M}_\lambda^{\text{decay}} = \varepsilon_\lambda^{*\nu}(p)\, \mathcal{M}_\nu^{\text{decay}}$$

Spin and spin density

Intermediate vector bosons

Decompose production and decay (neglect all non-factorisable contribs)

$$\mathcal{M} = \mathcal{M}_\mu^{\text{prod}} \left(\frac{i\left(-g^{\mu\nu} + \frac{p^\mu p^\nu}{m^2}\right)}{p^2 - m^2 + im\Gamma} \right) \mathcal{M}_\nu^{\text{decay}}$$

Intermediate pol. cannot be observed, can be different in $\mathcal{M}$ and $\mathcal{M}^*$

$$|\mathcal{M}|^2 \propto \sum_{\lambda,\lambda'} \left[\mathcal{M}_\lambda^{\text{prod}} \mathcal{M}_{\lambda'}^{\text{prod},*} \quad \sim\sim\sim \quad \mathcal{M}_\lambda^{\text{decay}} \mathcal{M}_{\lambda'}^{\text{decay},*} \right]$$

or, using spin density matrices,

$$|\mathcal{M}|^2 = \sum_{\lambda,\lambda'} \rho_{\lambda\lambda'}\, D^{\lambda\lambda'}$$

Properties of spin correlations

Intermediate spin/polarisation cannot be observed, can be different in $\mathcal{M}$ and $\mathcal{M}^*$.

$$|\mathcal{M}|^2 = \sum_{\lambda,\lambda'} \rho_{\lambda\lambda'}\, D^{\lambda\lambda'}$$

Production and decay spin densities, $\rho_{\lambda\lambda'}$ and $D^{\lambda\lambda'}$ are matrix valued, the intermediate particle does not have one specific spin state.

$$\rho_{\lambda\lambda'} = \begin{pmatrix} \rho_{LL} & \rho_{LR} & \rho_{L0} \\ \rho_{RL} & \rho_{RR} & \rho_{R0} \\ \rho_{0L} & \rho_{0R} & \rho_{00} \end{pmatrix}$$

Modern designations:

- $\rho_{\lambda\lambda}$ classical spin/polarisation correlations
- $\rho_{\lambda\lambda'}$ quantum spin/polarisation correlations
  interference of different intermediate spin/polarisation states

Properties of spin correlations

There are interference contributions between different spin states in $\mathcal{M}$ and $\mathcal{M}^*$. Their size depends on the process and the observable.

Often, but not always, the diagonal elements ($\lambda = \lambda'$) are dominant.

$$|\mathcal{M}|^2 \approx \sum_\lambda \rho_\lambda\, D^\lambda = |\mathcal{M}_L|^2 + |\mathcal{M}_R|^2 + |\mathcal{M}_0|^2$$

Useful approximation for LHC processes where intereferences, or quantum correlations, are smaller than the intrinsin Γ/m uncertainty.

In the spin-correlation algorithms used in SHERPA the interferences come at no extra cost and are always included.

Properties of spin correlations

There are interference contributions between different spin states in $\mathcal{M}$ and $\mathcal{M}^*$. Their size depends on the process and the observable.

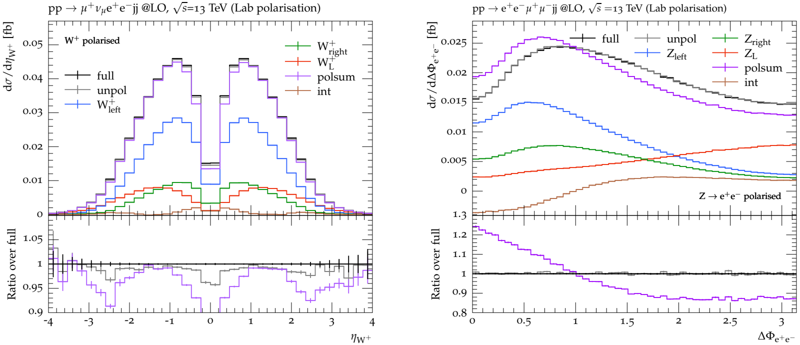
Often, but not always, the diagonal elements ($\lambda = \lambda'$) are dominant.

$$|\mathcal{M}|^2 \approx \sum_\lambda \rho_\lambda\, D^\lambda = |\mathcal{M}_L|^2 + |\mathcal{M}_R|^2 + |\mathcal{M}_0|^2$$

Useful approximation for LHC processes where intereferences, or quantum correlations, are smaller than the intrinsin Γ/m uncertainty.

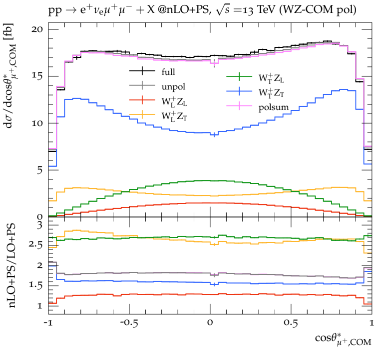
In the spin-correlation algorithms used in SHERPA the interferences come at no extra cost and are always included.

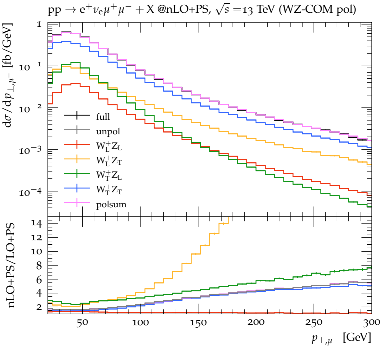
Polarised cross sections in VBS



- the complete unpolarised cross section (including interferences) reproduces the full off-shell well, usually better than $\mathcal{O}(\Gamma/m)$
- but interference contributions can be important as the incoherent pol. sum (excluding interferences) deviates more than $\mathcal{O}(\Gamma/m)$

Polarised cross sections in *WZ* beyond LO





- **nLO+PS**: polarisation correlations in virtual corrections currently approximated by Born polarisation correlations
  works well for NLO QCD, corrections often driven by real emissions

Precision event generation with SHERPA 3

EW precision resummation

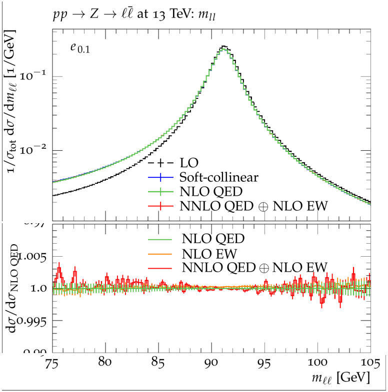
Yennie-Frautschi-Suura soft-photon resummation

Yennie, Frautschi, Suura '61

- method of choice for highest precision QED, e.g.
  - KKMC (YFS+NNLO) for $e^+e^- \to \mu^+\mu^-$ Jadach et.al '00
- has been implemented for generic QED FSR in SHERPA with up to YFS+NNLO QED+NLO EW for $Z \to \ell\ell$ MS, Krauss '08
  Krauss, Lindert, Linten, MS '18
- extended to include collinear $\gamma \to f\bar{f}$ splittings
  Flower, MS '22
- YFS QED ISR for e^+e^- colliders in SHERPA
  Krauss, Price, MS '22

EW precision resummation

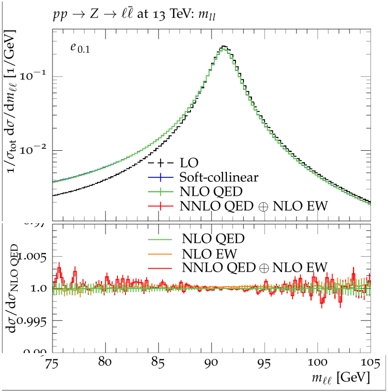
Krauss, Lindert, Linten, MS '18



- soft photon resummation matched to NNLO QED + NLO EW
- double-hard-photon emission corrections negligible
- permille accuracy in the description of the $Z \to \ell\ell$ kinematics

EW precision resummation

Krauss, Lindert, Linten, MS '18



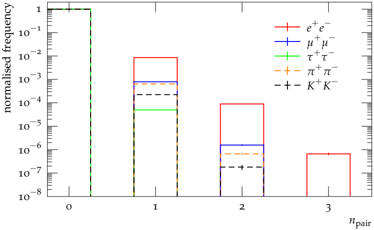
- soft photon resummation matched to NNLO QED + NLO EW
- double-hard-photon emission corrections negligible
- permille accuracy in the description of the $Z \to \ell\ell$ kinematics **?**

Resolving the photon cloud

Flower, MS '22

What happened to the photons after they were radiated?

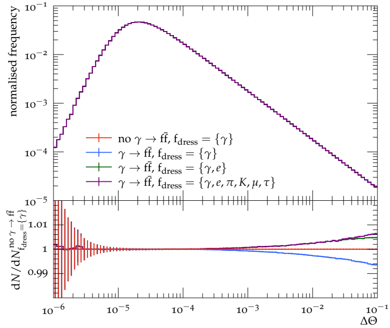
How does this impact the physical dressed lepton?



Photons split into other flavours (leptons, hadrons) and thereby remove themselves from a naïvely defined dressed lepton.

This exposes the measurement to logarithms of the lightest splitting product's mass, m_e.
A more inclusive dressed lepton definition will result in a stabler result.

Resolving the photon cloud

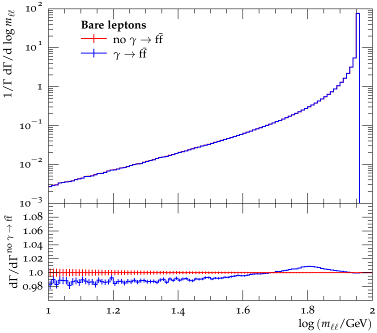


Flower, MS '22

On-shell $Z \to \ell\ell$ decays

- hard wide-angle photons have higher probability to split
- $\mathcal{O}(\alpha^2)$ effect, but impact much large than NNLO γ-radiation corrections as leading logarithms not already in resummation
- impact for small dressing cones moderate
- large dressing cones mandate expanded dress. prescription

Resolving the photon cloud



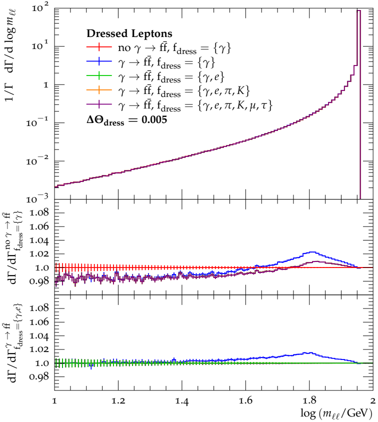
Flower, MS '22

On-shell $Z \to \ell\ell$ decays

- hard wide-angle photons have higher probability to split
- $\mathcal{O}(\alpha^2)$ effect, but impact much large than NNLO γ-radiation corrections as leading logarithms not already in resummation
- impact for small dressing cones moderate
- large dressing cones mandate expanded dress. prescription

Resolving the photon cloud

Flower, MS '22

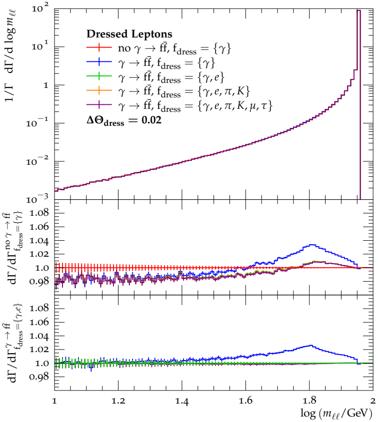


On-shell $Z \to \ell\ell$ decays

- hard wide-angle photons have higher probability to split
- $\mathcal{O}(\alpha^2)$ effect, but impact much large than NNLO γ-radiation corrections as leading logarithms not already in resummation
- impact for small dressing cones moderate
- large dressing cones mandate expanded dress. prescription

Resolving the photon cloud

Flower, MS '22

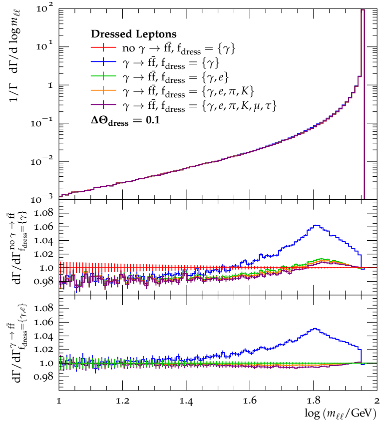


On-shell $Z \to \ell\ell$ decays

- hard wide-angle photons have higher probability to split
- $\mathcal{O}(\alpha^2)$ effect, but impact much large than NNLO γ-radiation corrections as leading logarithms not already in resummation
- impact for small dressing cones moderate
- large dressing cones mandate expanded dress. prescription

Resolving the photon cloud

Flower, MS '22

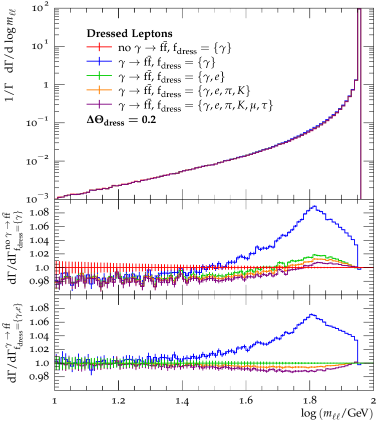


On-shell $Z \to \ell\ell$ decays

- hard wide-angle photons have higher probability to split
- $\mathcal{O}(\alpha^2)$ effect, but impact much large than NNLO γ-radiation corrections as leading logarithms not already in resummation
- impact for small dressing cones moderate
- large dressing cones mandate expanded dress. prescription

Resolving the photon cloud

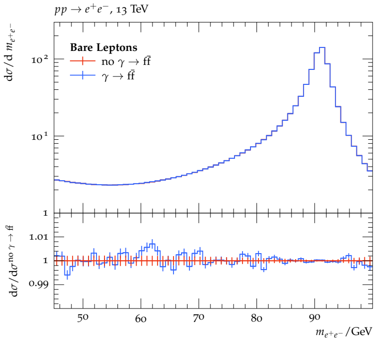
Flower, MS '22



On-shell $Z \to \ell\ell$ decays

- hard wide-angle photons have higher probability to split
- $\mathcal{O}(\alpha^2)$ effect, but impact much large than NNLO γ-radiation corrections as leading logarithms not already in resummation
- impact for small dressing cones moderate
- large dressing cones mandate expanded dress. prescription

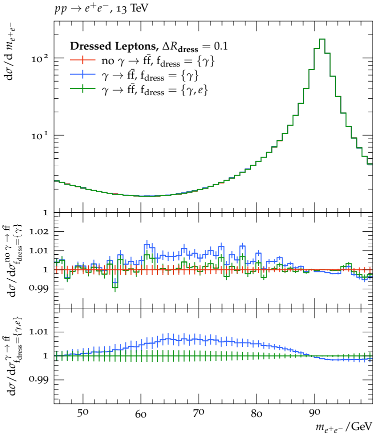
Resolving the photon cloud



Off-shell $pp \to e^+e^-$ decays

- hard wide-angle photons have higher probability to split
- $\mathcal{O}(\alpha^2)$ effect, but impact much large than NNLO γ-radiation corrections as leading logarithms not already in resummation
- can be compensated by more inclusive dressing procedure (ideally: flavoured EW jet)

Resolving the photon cloud



Off-shell $pp \to e^+e^-$ decays

- hard wide-angle photons have higher probability to split
- $\mathcal{O}(\alpha^2)$ effect, but impact much large than NNLO γ-radiation corrections as leading logarithms not already in resummation
- can be compensated by more inclusive dressing procedure (ideally: flavoured EW jet)

Initial state radiation at lepton colliders

Precision measurements at all proposed future lepton colliders rely on an accurate description of the partonic initial state.
There are (at least) three approaches to the problem:

- YFS soft-photon resummation
- structure functions
- PDFs

While soft-photon resummation is usually the method of choice for process near threshold (eg. $Z \to \ell\ell$ @ 92 GeV), the collinear resummation of structure functions and PDFs is more appropriate when there is a hierarchy between partonic and beam CM energy (eg. $Z \to \ell\ell$ @ 500 GeV).

Initial state soft-photon resummation

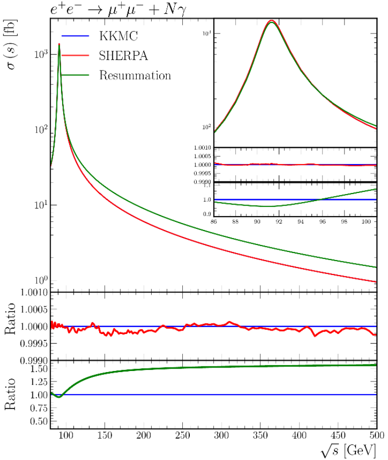
Soft-photon resummation:

- in the absence of QCD YFS soft-photon resummation efficiently resums QED ISR
- coherent ISR and FSR
- provides explicit photon momenta
- LEP: KKMC, YFSWW, YFSZZ, ...

Collinear structure function:

- photon radiation integr. out
- otherwise good agreement

Price, Krauss, MS '22



Initial state soft-photon resummation

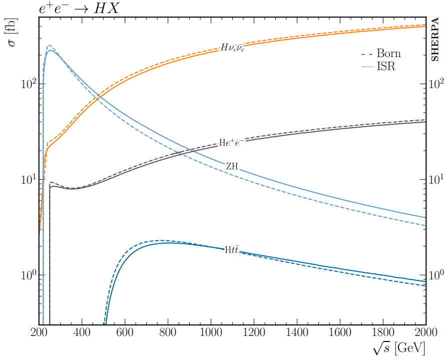
Price, Krauss, MS '22

Soft-photon resummation:

- in the absence of QCD YFS soft-photon resummation efficiently resums QED ISR
- coherent ISR and FSR
- provides explicit photon momenta
- LEP: KKMC, YFSWW, YFSZZ, ...

Collinear structure function:

- photon radiation integr. out
- otherwise good agreement



Initial state soft-photon resummation

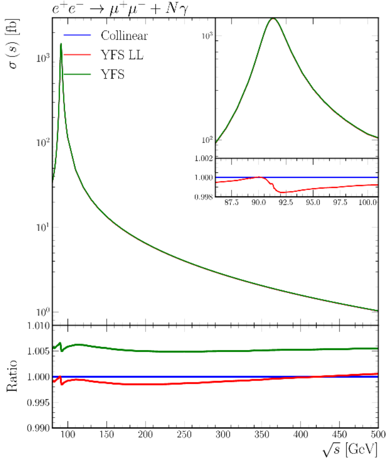
Price, Krauss, MS '22

Soft-photon resummation:

- in the absence of QCD YFS soft-photon resummation efficiently resums QED ISR
- coherent ISR and FSR
- provides explicit photon momenta
- LEP: KKMC, YFSWW, YFSZZ, ...

Collinear structure function:

- photon radiation integr. out
- otherwise good agreement

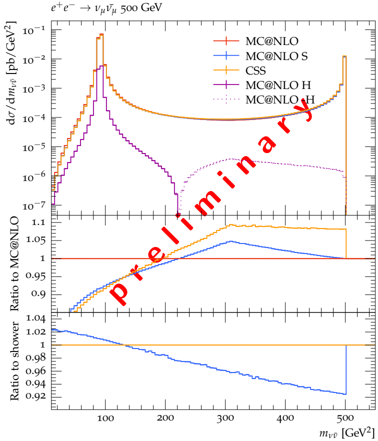


Collinear resummation of initial state radiation

Flower, MS to appear

Collinear resummation

- structure functions integrate out photon radiation
- exclusive photon kinematics and transverse recoil can be calculated using a QED parton shower (interesting challenges due to functional form of electron splitting function)
- can then be matched to NLO EW calculation ⇒ MC@NLO

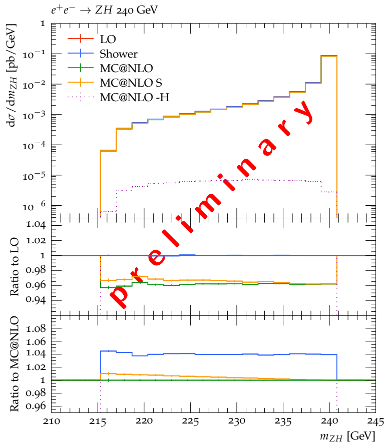


Collinear resummation of initial state radiation

Flower, MS to appear

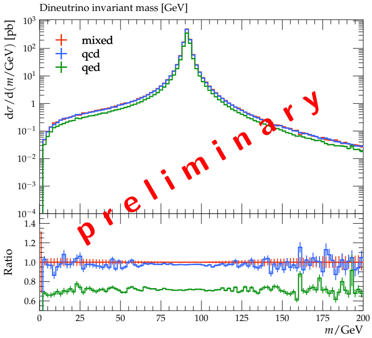
Collinear resummation

- structure functions integrate out photon radiation
- exclusive photon kinematics and transverse recoil can be calculated using a QED parton shower (interesting challenges due to functional form of electron splitting function)
- can then be matched to NLO EW calculation ⇒ MC@NLO



MC@NLO QCD+EW for hadron colliders

Roper, MS work in progress

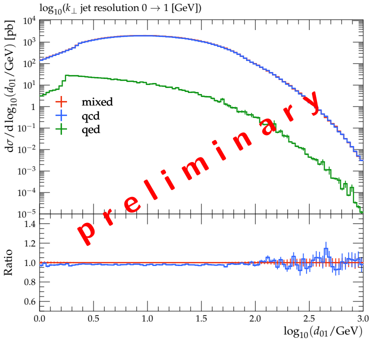


MC@NLO QCD+EW

- direct feedback to LHC precision physics
- interleaved MC@NLO QCD+EW for the LHC proton PDFs much better behave than electron structure function

MC@NLO QCD+EW for hadron colliders

Roper, MS work in progress



MC@NLO QCD+EW

- direct feedback to LHC precision physics
- interleaved MC@NLO QCD+EW for the LHC proton PDFs much better behave than electron structure function

Conclusions

- SHERPA 3 contains a large number of physics improvements wrt. SHERPA 2 series, in particular for precision calculations, eg.
  - NLL shower ALARIC
  - NLO EW automation
  - improved approx. EW correction in event generation
  - polarised cross sections
  - improved hadronisation and underlying event models
  - photon collision (incl. photon substructure)
  - YFS initial state resummation
  - ⋮
- well set-up for precision calculations for the LHC as well as all proposed lepton colliders

https://sherpa-team.gitlab.io

Thank you!

Backup

Spin and spin density

Fermions – Spin $\frac{1}{2}$

Separate production and decay (neglect all non-factorisable contribs)

$$\mathcal{M} = \mathcal{M}_\alpha^{\text{prod}} \left(\frac{i\,(\not{p} \pm m)^{\alpha\beta}}{p^2 - m^2 + im\Gamma} \right) \mathcal{M}_\beta^{\text{decay}}$$

Narrow-width approximation as before deals with denominator.

Completeness relation for numerator

$$(\not{p} \pm m)^{\alpha\beta} = \tfrac{1}{2} \sum_s \left[\left(1 \pm \sqrt{\frac{m^2}{p^2}} \right) u_s^\alpha(p) \bar{u}_s^\beta(p) + \left(1 \mp \sqrt{\frac{m^2}{p^2}} \right) v_s^\alpha(p) \bar{v}_s^\beta(p) \right]$$

thus with, for an on-shell fermion with $p^2 = m^2$,

$$\mathcal{M}_s^{\text{prod}} = \mathcal{M}_\alpha^{\text{prod}}\, u_s^\alpha(p) \qquad \mathcal{M}_s^{\text{decay}} = \bar{u}_s^\beta(p)\, \mathcal{M}_\beta^{\text{decay}}$$

Spin and spin density

Fermions – Spin $\frac{1}{2}$

Separate production and decay (neglect all non-factorisable contribs)

$$\mathcal{M} = \mathcal{M}_\alpha^{\text{prod}} \left(\frac{i\,(\not{p} \pm m)^{\alpha\beta}}{p^2 - m^2 + im\Gamma} \right) \mathcal{M}_\beta^{\text{decay}}$$

Narrow-width approximation as before deals with denominator.
Completeness relation for numerator

$$(\not{p} \pm m)^{\alpha\beta} = \tfrac{1}{2} \sum_s \left[\left(1 \pm \sqrt{\frac{m^2}{p^2}} \right) u_s^\alpha(p) \bar{u}_s^\beta(p) + \left(1 \mp \sqrt{\frac{m^2}{p^2}} \right) v_s^\alpha(p) \bar{v}_s^\beta(p) \right]$$

thus with, for an on-shell fermion with $p^2 = m^2$,

$$\mathcal{M}_s^{\text{prod}} = \mathcal{M}_\alpha^{\text{prod}}\, u_s^\alpha(p) \qquad\qquad \mathcal{M}_s^{\text{decay}} = \bar{u}_s^\beta(p)\, \mathcal{M}_\beta^{\text{decay}}$$

Spin and spin density

Fermions – Spin $\frac{1}{2}$

Separate production and decay (neglect all non-factorisable contribs)

$$\mathcal{M} = \mathcal{M}_\alpha^{\text{prod}} \left(\frac{i\,(\not{p} \pm m)^{\alpha\beta}}{p^2 - m^2 + im\Gamma} \right) \mathcal{M}_\beta^{\text{decay}}$$

Intermediate spin cannot be observed, can be different in $\mathcal{M}$ and $\mathcal{M}^*$

$$|\mathcal{M}|^2 \propto \sum_{s,s'} \left[\mathcal{M}_s^{\text{prod}} \mathcal{M}_{s'}^{\text{prod},*} \longrightarrow \mathcal{M}_s^{\text{decay}} \mathcal{M}_{s'}^{\text{decay},*} \right]$$

or, using spin density matrices,

$$|\mathcal{M}|^2 = \sum_{s,s'} \rho_{ss'}\, D^{ss'}$$

Spin and spin density

Fermions – Spin $\frac{1}{2}$

Separate production and decay (neglect all non-factorisable contribs)

$$\mathcal{M} = \mathcal{M}_\alpha^{\text{prod}} \left(\frac{i\,(\not{p} \pm m)^{\alpha\beta}}{p^2 - m^2 + im\Gamma} \right) \mathcal{M}_\beta^{\text{decay}}$$

Intermediate spin cannot be observed, can be different in $\mathcal{M}$ and $\mathcal{M}^*$

$$|\mathcal{M}|^2 \propto \sum_{s,s'} \left[\mathcal{M}_s^{\text{prod}} \mathcal{M}_{s'}^{\text{prod},*} \;\longrightarrow\; \mathcal{M}_s^{\text{decay}} \mathcal{M}_{s'}^{\text{decay},*} \right]$$

or, using spin density matrices,

$$|\mathcal{M}|^2 = \sum_{s,s'} \rho_{ss'}\, D^{ss'}$$

Spin and spin density

Fermions – Spin $\frac{1}{2}$

Separate production and decay (neglect all non-factorisable contribs)

$$\mathcal{M} = \mathcal{M}_\alpha^{\text{prod}} \left(\frac{i\,(\not{p} \pm m)^{\alpha\beta}}{p^2 - m^2 + im\Gamma} \right) \mathcal{M}_\beta^{\text{decay}}$$

Intermediate spin cannot be observed, can be different in $\mathcal{M}$ and $\mathcal{M}^*$

$$|\mathcal{M}|^2 \propto \sum_{s,s'} \left[\mathcal{M}_s^{\text{prod}} \mathcal{M}_{s'}^{\text{prod},*} \quad \longrightarrow \quad \mathcal{M}_s^{\text{decay}} \mathcal{M}_{s'}^{\text{decay},*} \right]$$

or, using spin density matrices,

$$|\mathcal{M}|^2 = \sum_{s,s'} \rho_{ss'}\, D^{ss'}$$

Properties of spin/polarisation definition

Spin/polarisation is frame and basis dependent

- spin and polarisation are dependent on Lorentz frame
  - need to specify frame
  - need to specify polarisation basis and prefactor conventions
  - need to specify Dirac matrix representation

Spin/polarisation in event record

- event record operates on $|\mathcal{M}|^2$ with definitive intermediate propagating states
  $\Rightarrow$ **no representation of quantum interference**
- inclusion of off-diagonal elements a posteriori not trivial as linked to quantum interference between different spin states
  $\rightarrow$ need to communicate spin-density matrix in agreed-upon basis

Properties of spin/polarisation definition

Spin/polarisation is frame and basis dependent

- spin and polarisation are dependent on Lorentz frame
  - need to specify frame
  - need to specify polarisation basis and prefactor conventions
  - need to specify Dirac matrix representation

Spin/polarisation in event record

- event record operates on $|\mathcal{M}|^2$ with definitive intermediate propagating states
  $\Rightarrow$ **no representation of quantum interference**
- inclusion of off-diagonal elements a posteriori not trivial as linked to quantum interference between different spin states
  $\rightarrow$ need to communicate spin-density matrix in agreed-upon basis