Preparing SHERPA for e^+e^-

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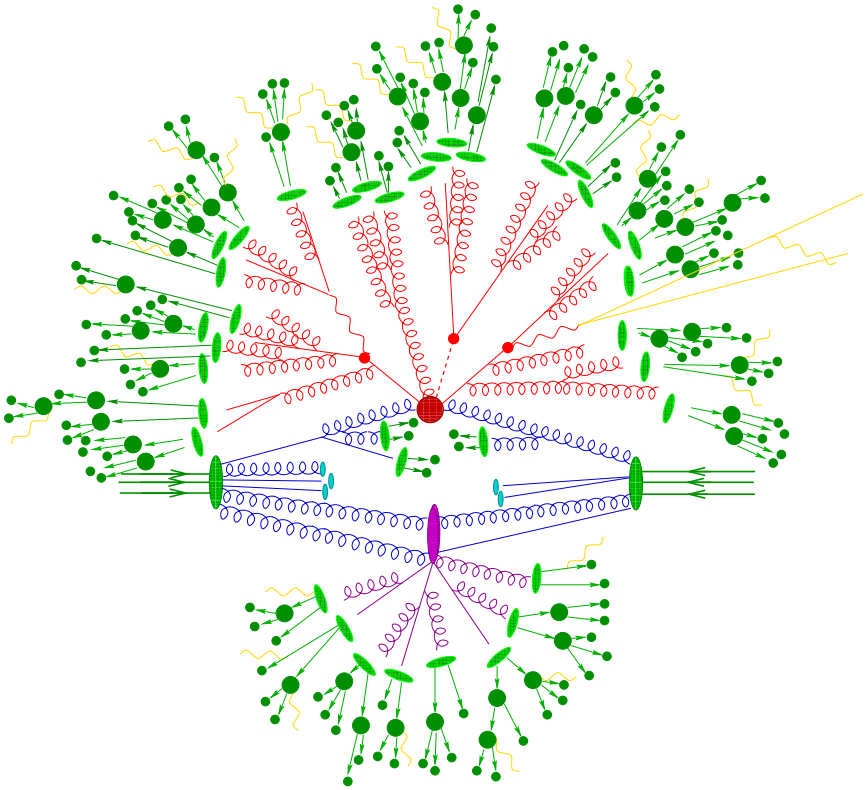
Introduction

1. Sherpa Event Generator
2. QED Corrections
3. NLO Calculations in Sherpa
4. BSM Calculations in Sherpa

Sherpa Event Generator

- Hard Interaction
  - LO, NLO QCD/EW
- Radiative Corrections
  - Catani-Seymour based PS, Dire, YFS QED Resummation
- Multiple Interactions
  - Sjöstrand-Zijl mode
- Hadronization
  - Cluster hadronization model
- Hadron Decays
  - Phase space or EFTs,YFS QED corrections



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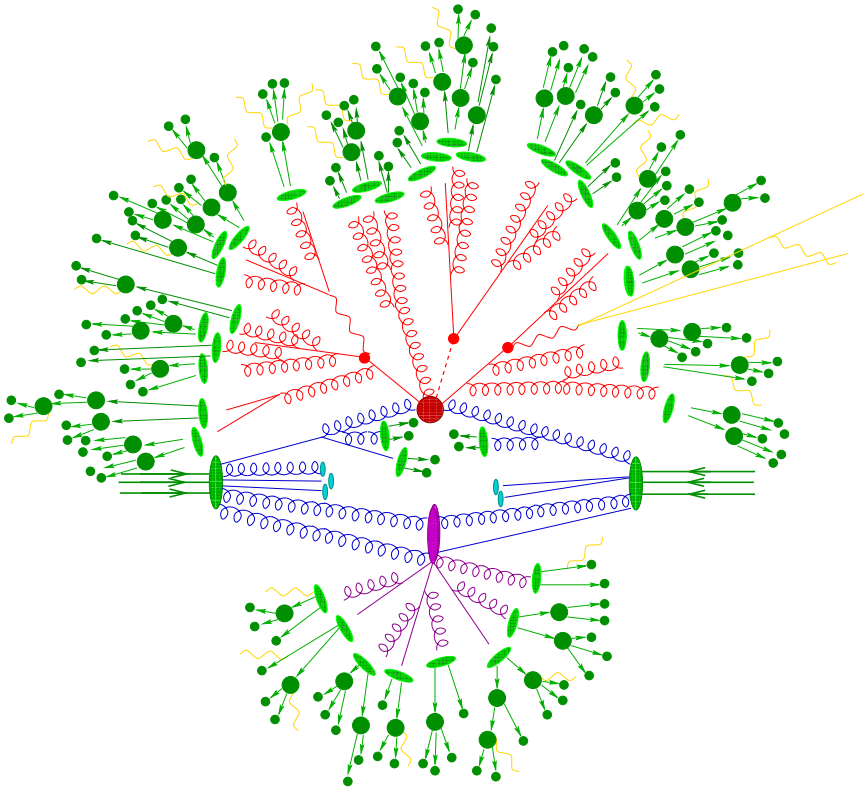
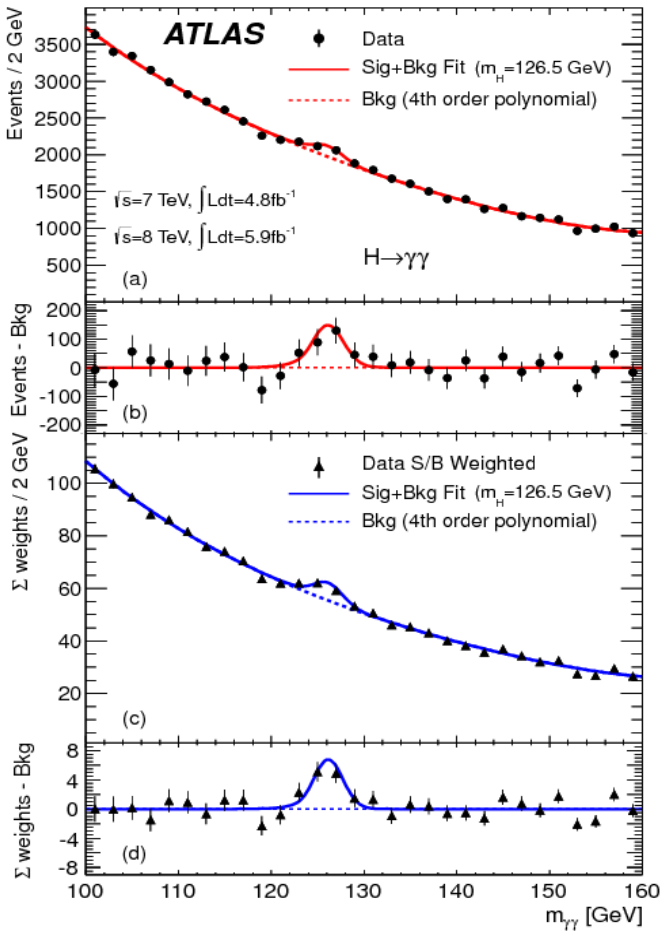


Motivation



- For precision physics a lepton-lepton collider is desirable
- The discovery of Higgs Boson tells us at what energy to run
- High precision understanding of the Higgs Boson requires below 1% uncertainties in the couplings
- $e^+e^- \to ZH$ optimal at 240GeV. Uncertainties mainly due to loops
- @ two-loop intrinsic uncertainty $\mathcal{O}(1\%)$, compared to expected experimental error $\mathcal{O}(0.4\%)$ (FCC-ee)

Motivation

We must not forget that an e^+e^- will precisely measure EW observables

Observable	Where from	Present (LEP)	FCC stat.	FCC syst	$\frac{\text{Now}}{\text{FCC}}$	Challenge
M_Z [MeV]	Z linesh.	$91187.5 \pm 2.1\{0.3\}$	0.005	0.1	3	QED Corrections
Γ_Z [MeV]	Z linesh.	$2495.2 \pm 2.1\{0.2\}$	0.008	0.1	2	QED Corrections
$R_l^Z = \Gamma_h/\Gamma_l$	$\sigma(M_Z)$	$20.767 \pm 0.025\{0.012\}$	$6 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	12	QED Corrections
N_ν	$\sigma(M_Z)$	$2.984 \pm 0.008\{0.006\}$	$5 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	6	Bhabha scattering (QED)
M_W [MeV]	ADLO	$80376 \pm 33\{6\}$	0.5	0.3	12	QED Corrections
$A_{FB,\mu}^{M_Z \pm 3.5\text{GeV}}$	$\frac{d\sigma}{d\cos\theta}$	$\pm 0.020\{0.001\}$	$1.0 \cdot 10^{-5}$	$0.3 \cdot 10^{-5}$	100	

Table: Adapted from Arxiv:1903.09895

QED Corrections at The Z Pole

Consider $e^+e^- \to X + n\gamma$

QED corrections (ISR) can be parametrised as,

$$\gamma_{n,m} = \left(\frac{\alpha}{\pi}\right)^n \left(2\ln\left(\frac{m_Z^2}{m_e^2}\right)\right)^m \qquad 0 \leq m \leq n$$

- For future lepton collider $\gamma \leq 10^{-5} \to$ need to include corrections up to $\mathcal{O}\left(\alpha^3, L_e^3\right), \quad L_e = \ln\left(\frac{s}{m_e}\right)$
- Soft and Collinear photons need to be resummed

YFS Exponentiation

- Lets first consider virtual photon corrections in the soft limit

$$\mathcal{M}_0^0 = M_0^0$$
$$\mathcal{M}_0^1 = \alpha B M_0^0 + M_0^1$$
$$\mathcal{M}_0^1 = \frac{(\alpha B)^2}{2} M_0^0 + \alpha B M_0^1 + M_0^2$$
$$\dots$$
$$\mathcal{M}_0^{nv} = \sum_{r=0}^{nv} M_0^{nv} \frac{(\alpha B)^r}{r\,!}$$

where B is the virtual infrared factor.

$$B = 2\alpha \Re \int \frac{d^4 k}{k^2} \frac{i}{(2\pi)^2} \left(\frac{2p_1 - k}{2kp_1 - k^2} - \frac{2p_2 - k}{2kp_2 - k^2} \right)^2$$

YFS Exponentiation

Summing to infinity yields,

$$\sum_{n_V=0}^{\infty} \mathcal{M}_0^{n_V} = e^{\alpha B} \sum_{n_V=0}^{\infty} M_0^{n_V}$$

This can be generalised to n_R real photons such that,

$$\sum_{n_V=0}^{\infty} \left| \mathcal{M}_{n_R}^{n_V+\frac{1}{2}n_R} \right|^2 = e^{2\alpha B} \sum_{n_V=0}^{\infty} \left| M_{n_R}^{n_V+\frac{1}{2}n_R} \right|^2$$

YFS: Real Emissions

For a single photon emission we have,

$$\frac{1}{2\left(2\pi\right)^3}\sum_{n_V=0}^{\infty}\left|M_1^{n_V+\frac{1}{2}}\right|^2=\tilde{S}\left(k\right)\left|M_0^{n_V+\frac{1}{2}}\right|^2+\sum_{n_V=0}^{\infty}\tilde{\beta}_1^{n_V+1}\left(k\right)$$

- Factorisation of real emissions occurs at the amplitude squared level
- Eikonal term $\tilde{S}\left(k\right)=-\frac{\alpha}{4\pi^2}\left(\frac{p_1}{p_1 k}-\frac{p_2}{p_2 k}\right)^2$
- $\tilde{\beta}_{n_R}^{n_V+n_R}$ complete IR finite squared matrix element for born process plus n_V virtual and n_R photons

For n_R photons summed over all virtual contributions,

$$\left(\frac{1}{2(2\pi)^3}\right)^{n_R} \left| \sum_{n_V=0}^{\infty} M_{n_R}^{n_V+\frac{1}{2}n_R} \right|^2$$

$$= \tilde{\beta}_0 \prod_{i=1}^{n_R} \left[\tilde{S}(k_i)\right] + \sum_{i=1}^{n_R} \left[\frac{\tilde{\beta}_1(k_i)}{\tilde{S}(k_i)}\right] \prod_{j=1}^{n_R} \left[\tilde{S}(k_j)\right]$$

$$+ \sum_{\substack{i,j=1 \\ i\neq j}}^{n_R} \left[\frac{\tilde{\beta}_2(k_i,k_j)}{\tilde{S}(k_i)\tilde{S}(k_j)}\right] \prod_{l=1}^{n_R} \left[\tilde{S}(k_l)\right] + \dots$$

$$+ \sum_{i=1}^{n_R} \left[\tilde{\beta}_{n_R-1}(k_1,\dots,k_{i-1},k_{i+1},\dots,k_{n_R})\,\tilde{S}(k_i)\right] + \tilde{\beta}_{n_R}(k_1,\dots,k_{n_R})$$

Master Equation

This gives us our cross section

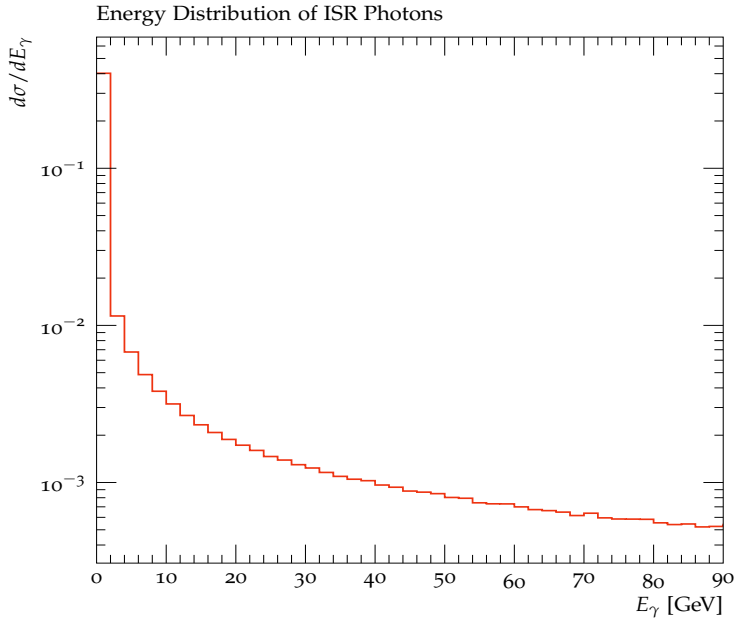
$$\sigma = \sum_{n=0}^{\infty} \frac{1}{n!} \int d\Phi_q \; e^{2\alpha B + 2\alpha \tilde{B}} \prod_{j=1}^{n} \tilde{S}\left(k_j\right) \theta(\Omega; k_j) \left[\tilde{\beta}_0 \left(p_1, p_2; q_1, \cdots, q_{n'}\right) \right.$$
$$+ \sum_{j=1}^{n} \frac{\tilde{\beta}_1 \left(p_1, p_2; q_1, \cdots, q_{n'}; , k_j\right)}{S(k_j)}$$
$$\left. + \sum_{\substack{j,l=1 \\ j \neq l}}^{n} \frac{\tilde{\beta}_2 \left(p_1, p_2; q_1, \cdots, q_{n'}; k_j, k_l\right)}{S(k_j) S(k_l)} + \cdots \right]$$

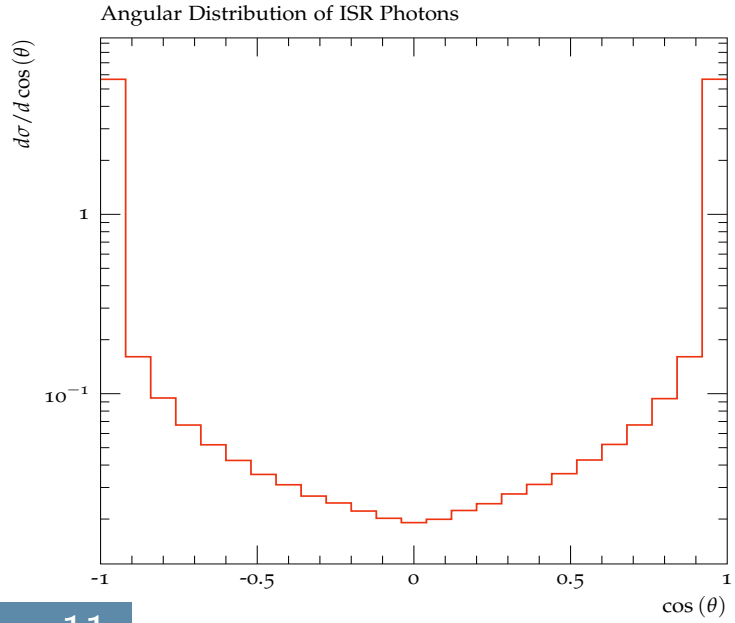
The exponentiation of real emissions gives a factor

$$\tilde{B} = -\frac{1}{8\pi^2} \int \frac{d^3 k}{k^0} \Theta(\Omega, k) \left(\frac{p_1}{p_1 k} - \frac{p_2}{p_2 k} \right)^2$$

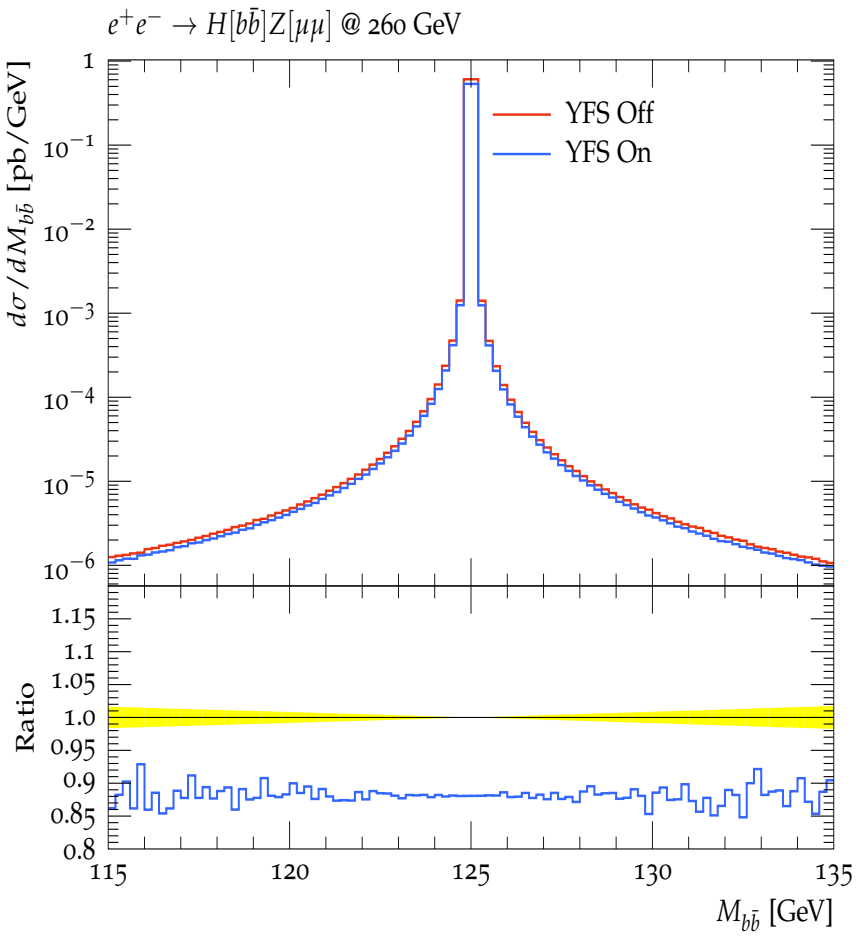
The Power of YFS

- $\tilde{\beta}$ are infrared finite and are calculated perturbatively *order by order*
  - Non trivial for other methods e.g Structure function
- Photons are explicitly created
  - Allows us to calculate properties of soft photons e.g Energy, Angular distribution
  - Allows for decays e.g $\gamma \to e^+e^-$





Higgs-Strahlung



- At the Higgs pole ISR contributes a $\approx 10\%$ effect

Some Results

Two processes $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to HZ \to \mu\mu bb$

	Z-Pole 92.1GeV	ZH-Pole 250 GeV
Born	2010.01 pb	4.682 fb
$\mathcal{O}(\alpha L)$	1616.34 pb	3.864 fb
$\mathcal{O}(\alpha^2 L^2)$	1619.11 pb	3.868 fb
$\mathcal{O}(\alpha^3 L^3)$	1619.72 pb	3.869 fb

Theoretical (conservative) uncertainty $\approx 0.03\%$

Current Status

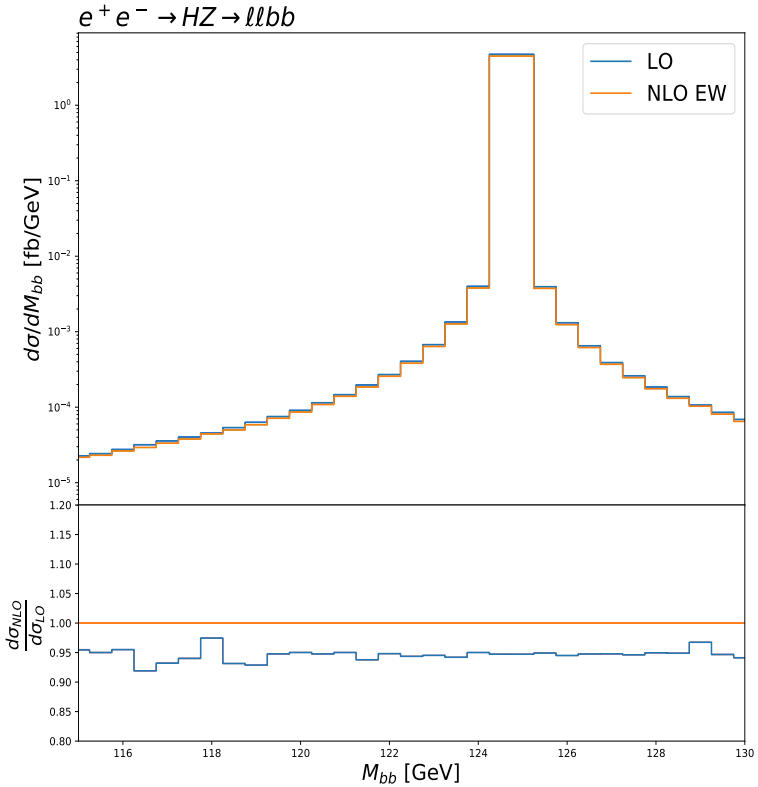
- It interface with other Sherpa modules e.g ME Generator, PS, Hadronization, UFO...
- Fully automated for arbitrary processes
- However some higher order corrections have been hard coded for $e^+e^- \to f\bar{f}$
- YFS has been fully implemented for FSR up to NNLO QCD and $\mathrm{NLO}_{\mathrm{EW}}$
- No ISR/FSR interference (yet)

NLO Calculations in Sherpa

Fully automated in Sherpa for $\mathrm{NLO_{QCD}}$ and $\mathrm{NLO_{EW}}$

- Based on Catani-Seymour dipole subtraction
- Sherpa $\rightarrow$ Born and real emission ME, infrared subtraction, phase space generation, process coordination
- Dedicated tools $\rightarrow$ Virtual corrections
  - OpenLoops — Buccioni et.al
  - Recola — Denner et.al
  - GoSam — Cullen et.al
  - MadLoop — Hirschi et.al

Higgs-Strahlung at $\mathrm{NLO_{EW}}$



- Calculations preformed in the G_μ scheme. Masses are treated in the complex mass scheme
- $\mathrm{NLO_{EW}}$ contributes a $\approx$ 5% effect at the Higgs pole
- Virtual loops taken from OpenLoops

BSM Calculations in Sherpa

[Höche,Kuttimalai,Schumann,Siegert,] arXiv:1412.6478

- Model information from Feynrules [Christensen,Duhr] arXiv:0806.4194,[Alloul et al.] arXiv:1310.1921 via UFO [Degrande at al.] arXiv:1108.2040
- Fully automated calculations: /prefix/bin/Sherpa-generate-model <path-to-ufo-model>

Model	number of processes tested	max. rel. deviation Comix $\leftrightarrow$ MadGraph5
Standard Model	60	$2.3 \cdot 10^{-10}$
Higgs Effective Field Theory	13	$4.3 \cdot 10^{-13}$
MSSM	401	$1.0 \cdot 10^{-10}$
Minimal Universal Extra Dimensions	51	$2.8 \cdot 10^{-12}$
Anomalous Quartic Gauge Couplings	16	$5.9 \cdot 10^{-12}$

Conclusion and Outlook

- Sherpa is dedicated to becoming a state of the art event generator for lepton-lepton colliders
- Soft and Collinear photons are resummed in Sherpa via YFS

  This will be soon matched to fixed order calculations i.e $\mathrm{NLO_{EW}}$
- Sherpa is fully automated for $\mathrm{NLO_{EW}}$ and $\mathrm{NLO_{QCD}}$ calculations
- BSM simulations are also fully automate via UFO models
- Beam-Strahlung is also being implemented
- Underlying events such as $\gamma\gamma$ will be modelled in the future

Questions?

The SHERPA 2.2 event generator framework

User Inputs

Initial Beams

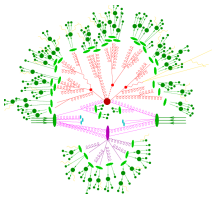
- collider setup
- PDFs (built-in, LHAPDF)
- beam spectra

Parameters/Models

- FeynRules/UFO
- couplings
- masses
- variations
- shower settings
- non-perturbative parameters

Physics Process

- parton level
- perturbative order (QCD/EW)
- selectors
- matching/merging
- partonic decays



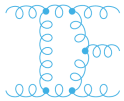
Matrix Elements

Matrix Element Generators

- AMEGIC
- COMIX
- CS subtraction

1-loop Amplitudes

- OpenLoops
- Recola
- GoSam
- BLHA



Parton Showers

CS-Shower (default)

- dipole shower
- fully massive
- QED splittings

DIRE

- hybrid dipole-parton shower algorithm
- fully massive

Matching and Merging

Automated MC@NLO style matching

Multijet-merging algorithms

- based on truncated showers
- tree-level and one-loop matrix elements: MEPS@LO and MEPS@NLO
- approximate electroweak corrections

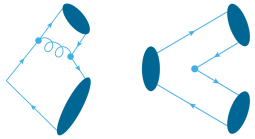
NNLO QCD with parton showers

- selected processes only

Soft Physics

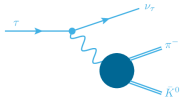
Hadronisation

- AHADIC: a cluster fragmentation model
- interface to Pythia string fragmentation



Hadron Decays

- decay tables for hadronic resonances
- dedicated form-factor models, e.g. τ, B, Λ
- spin correlations
- YFS QED corrections
- partonic channels



Underlying Event

- multiple parton interactions
- beam-remnant colours
- intrinsic transverse momentum

Interfaces/Outputs

Output Formats

- HepMC
- LHEF
- Root Ntuple

Interfaces

- RIVET analyses
- C++/Python ME access
- MCgrid
- integration into ATLAS/CMS

Code/Docu

- HepForge
- GitLab
- online documentation

sherpa.hepforge.org

gitlab.com/sherpa-team/sherpa