QED ISR/FSR with YFS Resummation

Alan Price

With Frank Krauss and
Marek Schoenherr

MCnet

UNIVERSITÄT
SIEGEN

Center for
Particle Physics
Siegen

Overview

1. Motivation
2. Theory
3. Some Results
4. Outlook and Conclusion

Overview

Center for Particle Physics Siegen

1. Motivation
2. Theory
3. Some Results
4. Outlook and Conclusion

Sherpa has traditionally been more focused on Hadron-Hadron collisions and the improvements needed for e+e- have been mostly implemented by one Phd/Post-Doc (me)

Motivation

Center for Particle Physics Siegen

Observable	Where from	Current (LEP)	FCC (stat.)	FCC (syst.)	Now/FCC
M_Z [MeV]	Z linesh. [32]	$91187.5 \pm 2.1\{0.3\}$	0.005	0.1	3
Γ_Z [MeV]	Z linesh. [32]	$2495.2 \pm 2.1\{0.2\}$	0.008	0.1	2
$R_l^Z = \Gamma_h/\Gamma_l$	$\sigma(M_Z)$ [33]	$20.767 \pm 0.025\{0.012\}$	$6 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	12
$\sigma^0_{\rm had}$[nb]	$\sigma^0_{\rm had}$ [32]	$41.541 \pm 0.037\{0.025\}$	$0.1 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	6
N_ν	$\sigma(M_Z)$ [32]	$2.984 \pm 0.008\{0.006\}$	$5 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	6
N_ν	$Z\gamma$ [34]	$2.69 \pm 0.15\{0.06\}$	$0.8 \cdot 10^{-3}$	$< 10^{-3}$	60
$\sin^2\theta_W^{eff} \times 10^5$	$A_{FB}^{lept.}$ [33]	$23099 \pm 53\{28\}$	0.3	0.5	55
$\sin^2\theta_W^{eff} \times 10^5$	$\langle\mathcal{P}_\tau\rangle, A_{\rm FB}^{pol,\tau}$[32]	$23159 \pm 41\{12\}$	0.6	< 0.6	20
M_W [MeV]	ADLO [35]	$80376 \pm 33\{6\}$	0.5	0.3	12
$A_{FB,\mu}^{M_Z \pm 3.5\rm GeV}$	$\frac{d\sigma}{d\cos\theta}$ [32]	$\pm 0.020\{0.001\}$	$1.0 \cdot 10^{-5}$	$0.3 \cdot 10^{-5}$	100

QED corrections needed for FCC-ee, adapted from (Jadach et al, Eur. Phys. J. C79(2019))

- Emission of soft/collinear photons lead to large logs ~ log(s/m^2)
- LEP era calculations will not be sufficient for future e+e- machines

How to Treat ISR?

Center for Particle Physics Siegen

Collinear Resummation

- Calculate ISR using electron PDF (*Jadach et.al, Z.Phys.C 49 (1991) 577-584,* Europhys. Lett.17(1992) 123–128)
- Recently calculated up to NLL, improvement beyond this very difficult (Bertone et.al 1911.12040)
- New calculations also include photon pdf for photon initiated processes
- Needs to be matched to a Parton Shower for no inclusive observables
- Standard treatment of ISR in e+e- MC tools such as Whizard and Sherpa v1.x/2.x

Soft Resummation

- Soft photons can be resummed to all orders (Yennie, Frautshci, Suura, Annals Phys. 13 (1961) 379-452)
- Fully differential treatment of the multi-photon phasespace
- **Can be systematically improved order-by-order**
- Collinear logs are included in a truncated expression

Inclusive Calculations

- Inclusive calculation for e+e-> ɣ*/Z up to $\mathcal{O}(\alpha^6 L^6)$ (J. Blümlein, A. De Freitas,K. Schönwald et al, Nucl. Phys. B955 (2020),Phys. Lett. B 816 (2021))

How to Treat ISR?

Center for Particle Physics Siegen

Collinear Resummation

- Calculate ISR using electron PDF (*Jadach et.al, Z.Phys.C 49 (1991) 577-584,* Europhys. Lett.17(1992) 123–128*)*
- Recently calculated up to NLL, improvement beyond this very difficult (Bertone et.al 1911.12040, S.Frixione talk tomorrow)
- New calculations also include photon pdf for photon initiated processes
- Needs to be matched to a Parton Shower for no inclusive observables
- Standard treatment of ISR in e+e- MC tools such as Whizard and Sherpa v1.x/2.x

Soft Resummation

- Soft photons can be resummed to all orders (Yennie, Frautshci, Suura, Annals Phys. 13 (1961) 379-452)
- Fully differential treatment of the multi-photon phasespace
- **Can be systematically improved order-by-order**
- Collinear logs are included in a truncated expression

Inclusive Calculations

- Inclusive calculation for e+e-> ɣ*/Z (K. Schönwald talk on Monday, Nucl. Phys. B955 (2020))

Resummation à la YFS

Yennie, Frautschi, and Suura showed that in the soft limit the total cross section for a given process with n_V virtual and n_R real soft photons can be expressed as,

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

YFS Resummation

Center for Particle Physics Siegen

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

$$\tilde{\beta}_i = \sum_{n_v} \beta_i^{n_v}$$

$$\tilde{\beta}_0^0 = M_0^0 M_0^{0*}$$

$$\tilde{\beta}_0^1 = M_0^1 M_0^{0*} + M_0^{1*} M_0^0$$

$$\tilde{\beta}_1^1 = \frac{1}{2(2\pi)^3} M_0^{\frac{1}{2}} M_0^{\frac{1}{2}*} - \tilde{S}(k)\, M_0^0 M_0^{0*} = \frac{1}{2(2\pi)^3} M_0^{\frac{1}{2}} M_0^{\frac{1}{2}*} - \tilde{S}(k)\, \tilde{\beta}_0^0$$

- β are the IR finite ME
- Currently they are hard coded into Sherpa but can be taken from external tools e.g Recola, COMIX

YFS Resummation

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

- The explicit form factor is known explicitly
- Treatment of the full phasespace was detailed in Comput.Phys.Commun. 56 (1990) 351-384

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

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

Status in Sherpa

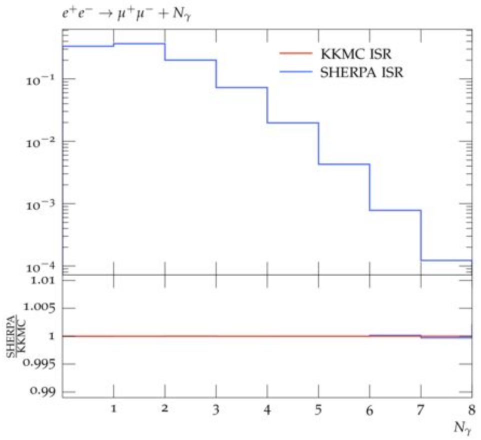
Center for Particle Physics Siegen

- For initial state radiation (ISR), the YFS algorithm can be applied to any e+e- process
  - ISR includes corrections up to $\alpha^3 L^3$, inclusion of FO calculations trivial
  - Full treatment of the Photon Phasespace, which allows for explicit photon creation
- Recently final state radiation has been added
  - It was implemented for decays in PHOTONS++ (JHEP 2008(12):018)
  - New treatment added to account for FSR in the total XS
  - Well validated for e+e- -> ffbar and testing is ongoing for WW/ZZ/ZH
- Initial-Final Interference
  - Currently not included
  - For e+e- -> ffbar can be included by “hand” but difficult to automate

$e^+e^- \to f\bar{f}$

Center for Particle Physics Siegen

- State of the art is KKMC (Comput.Phys.Commun. 130 (2000) 260-325)
- KKMC includes initial, final, and initial-final interference
- Sherpa does not include Initial-final interference

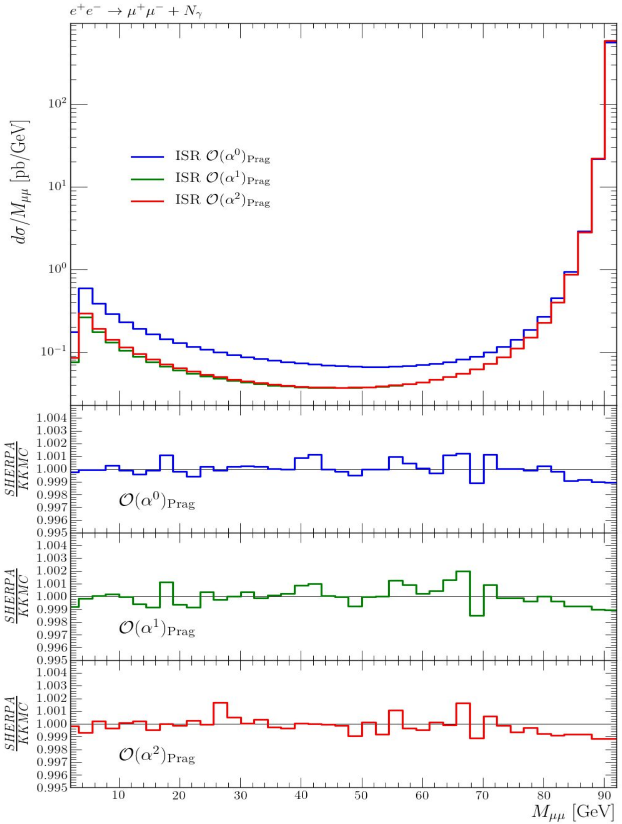


	Born [pb]	FSR [pb]	ISR [pb]	ISR+FSR [pb]
KKMC	1822.60	1863.03 +-0.33	1249.53+-0.37	1281.611 +-0.001
SHERPA	1822.60	1863.62 +-0.32	1249.49+-0.44	1282.28 +-0.4

There is excellent agreement between KKMC and Sherpa. Above is Xs for muon production at 91 GeV

- For final state leptons QED emission can be resummed in the YFS framework
- For final state quarks it is better to use Parton Shower with QED splittings (also in Sherpa)

$e^+e^- \to f\bar{f}$

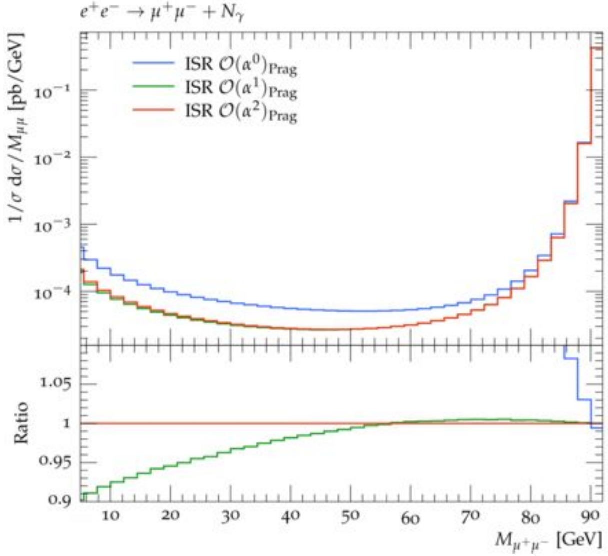


$$\mathcal{O}(\alpha^0)_{\rm Prag} = \text{Resummation only}$$

$$\mathcal{O}(\alpha^1)_{\rm Prag} = \alpha,\ \alpha L$$

$$\mathcal{O}(\alpha^2)_{\rm Prag} = \alpha,\ \alpha L,\ \alpha^2 L^2$$

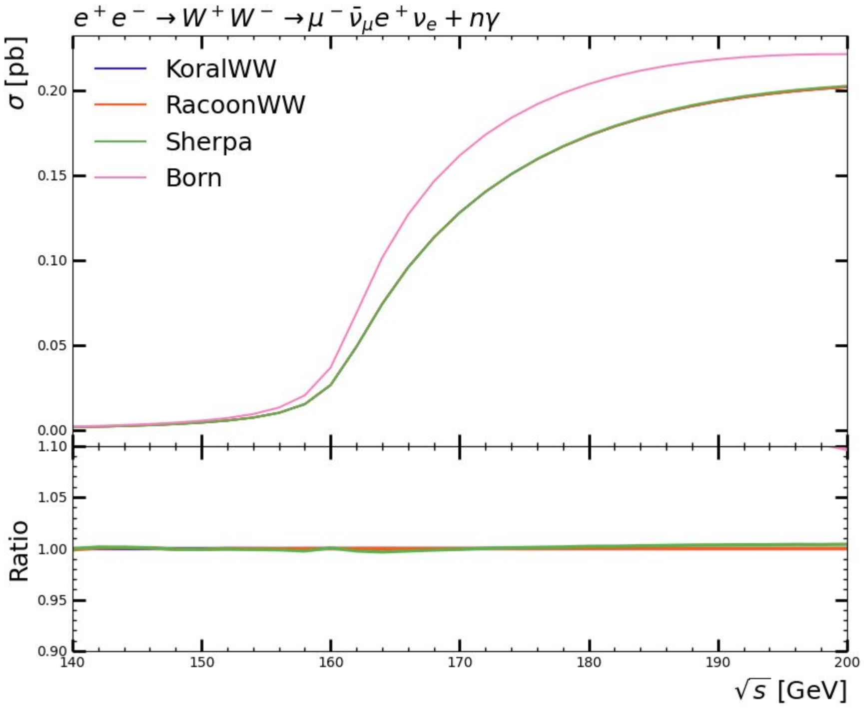
$$\mathcal{O}(\alpha^3)_{\rm Prag} = \alpha,\ \alpha L,\ \alpha^2 L^2,\ \alpha^2 L, \alpha^3 L^3$$



$e^+e^- \to W^+W^-$

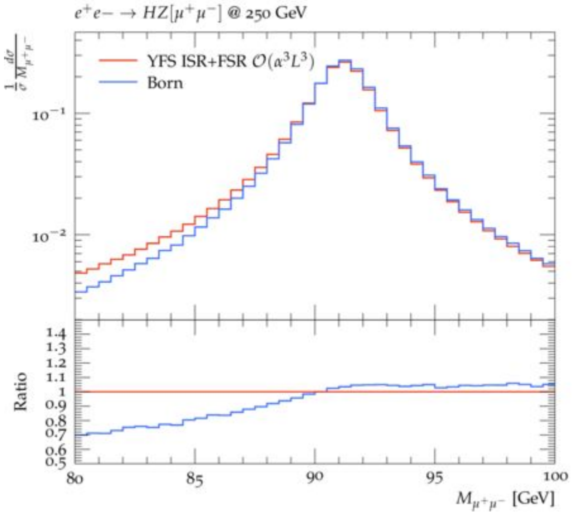
Center for Particle Physics Siegen

- Dedicated codes during LEP era:
  - YFSWW/KoralW (Comput.Phys.Commun. 140 (2001) 475-512)
    - ISR Corrections via YFS
    - Complete O(α) corrections included
    - Option of FSR via Photos
    - Coulomb corrections also implemented
  - RacoonWW (*Nucl.Phys.B* 587 (2000) 67-117)
    - ISR corrections via electron PDF
    - Complete O(α) corrections included
    - Coulomb corrections also implemented
- Sherpa
  - ISR Corrections via YFS
  - FSR corrections via YFS or PS, being tested, with option to combine PS and YFS for semi-leptonic decays
  - Coulomb Corrections included
  - Soft Photons for W also resummed
  - Complete O(α) with EW loops form Recola (under test)



$e^+e^- \to ZH$

- ISR has only been modelled via electron PDFs before
- Sherpa can now use YFS for ISR+FSR



250 GeV	**Born**	**ISR+FSR**
SHERPA [fb]	**7.05**	**5.98**

Above is example Xs for Z-> mu mu and H -> tau, tau at 250 GeV

- For final state leptons QED emission can be resummed in the YFS framework
- For final state quarks it is better to use Parton Shower with QED splittings (also in Sherpa)
- Ongoing study to investigate effect of FSR on Higgs mass from Z-recoil.

Outlook

Center for Particle Physics Siegen

- Sherpa has traditionally been more focused on Hadron-Hadron collisions and the improvements needed for e+e- have been mostly implemented by one Phd/Post-Doc (me)
- IFI still needs to be implemented
  - Method is known but difficult to automate. Work ongoing with ME generators
- More loops will be needed
  - Full 1-loop EW corrections can be included via Recola
  - Framework exists to include 2-loops as and when they become available
- For Linear colliders
  - Interface to LCIO (eConf C0303241 (2003) TUKT001) has been written and is undergoing testing
  - Interface to CIRCE (Comput.Phys.Commun. 101 (1997) 269-288) (for beam spectra) is under development
  - Planned to be added to Sherpa 3.X release

Conclusion

- ISR corrections have been implemented in a process independent manner and validated against existing calculations.
- Inclusion of FSR via YFS resummation is possible for some processes, work is ongoing to automate this and include IFI
- These features will be released in Sherpa 3.X but dedicated samples can be provided
- Can be used for BSM physics via UFO interface