YFS Resummation in Sherpa

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Based on 2103.xxxx

With Frank Krauss and Marek Schoenherr

Overview

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

Motivation

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Observable	Where from	Current (LEP)	FCC (stat.)	FCC (syst.)	$\frac{\text{Now}}{\text{FCC}}$
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
σ^0_{had}[nb]	σ^0_{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
$\sin^2\theta_W^{eff} \times 10^5$	$\langle \mathcal{P}_\tau \rangle, A_{\text{FB}}^{pol,\tau}$[32]	$23159 \pm 41\{12\}$	0.6	< 0.6	20
M_W [MeV]	ADLO [35]	$80376 \pm 33\{6\}$	0.5	0.3	12
$A_{FB,\mu}^{M_Z \pm 3.5\text{GeV}}$	$\frac{d\sigma}{d\cos\theta}$ [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?

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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-> γ^*/Z (K. Schönwald talk on Monday, Nucl. Phys. B955 (2020))

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Collinear Resummation

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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

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

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

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

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

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

YFS Resummation

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

- 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

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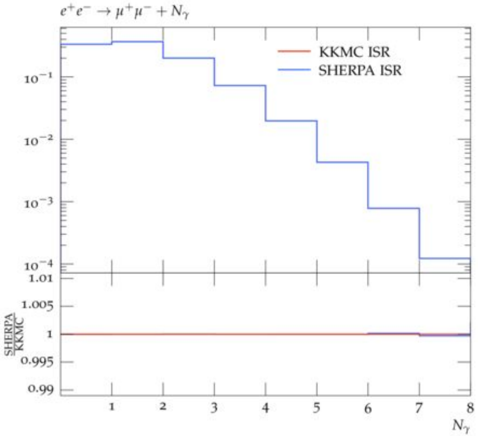
- For initial state radiation (ISR), the YFS algorithim can be applied to any e+e- process
  - ISR includes corrections up to $\alpha^3 L^3$
  - Full treatment of the Photon Phasespace, which allows for explicit photon creation
- Recently final state radiation has been added
  - It was implemented for 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 (So far looks good!)
- Initial-Final Interference
  - Currently not included
  - For e+e- -> ffbar can be included by “hand” but difficult to automate

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

- 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

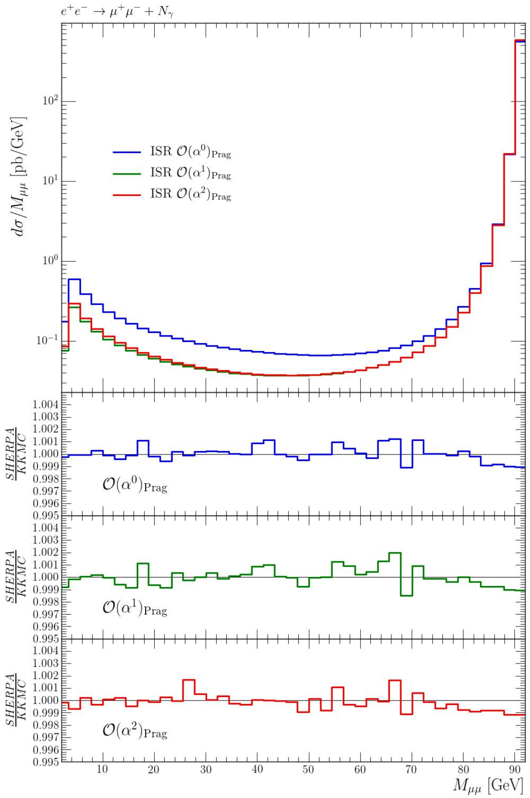


	Born [pb]	FSR [pb]	ISR [pb]	ISR+FSR [pb]
KKMC	1822.60	1863.03 +-0.33	1249.53+-0.37	1281.611 +-0.001
SHERPA	1822.60	1863.62 +-0.32	1249.49+-0.44	1282.28 +-0.4

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)

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

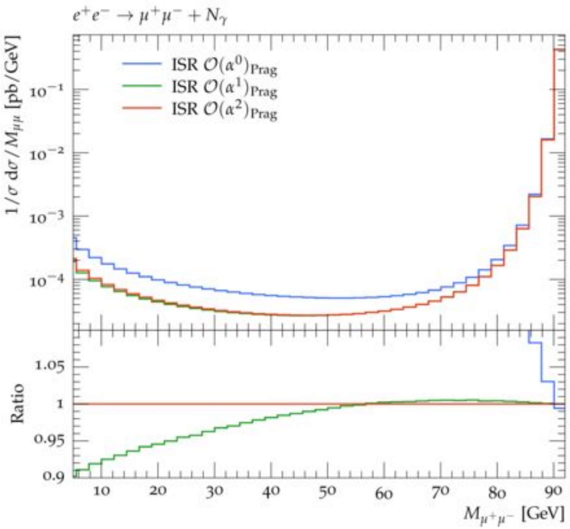


$$\mathcal{O}(\alpha^0)_{\text{Prag}} = \text{Resummation only}$$

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

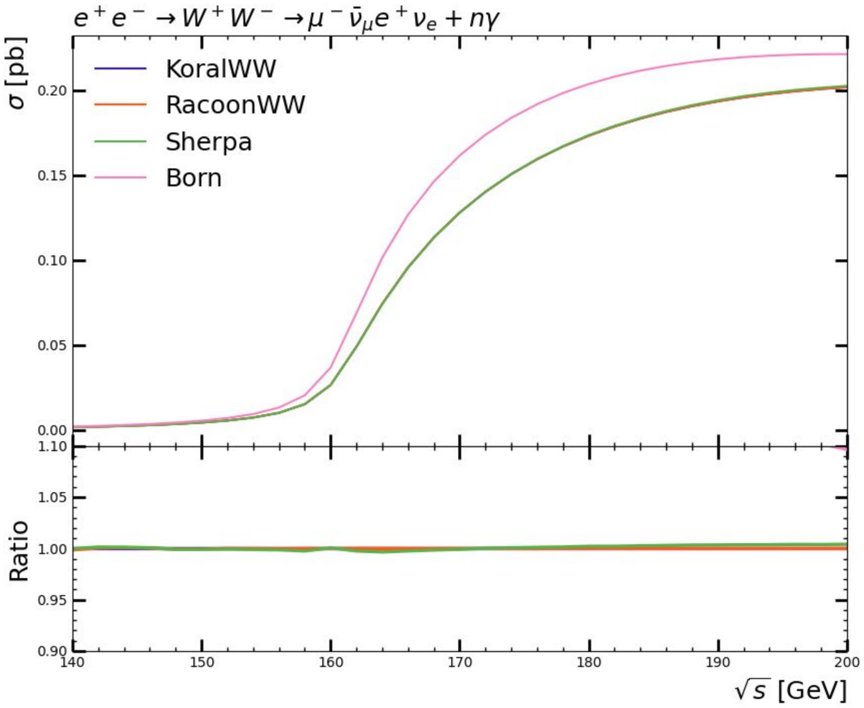
$$\mathcal{O}(\alpha^2)_{\text{Prag}} = \alpha,\ \alpha L,\ \alpha^2 L^2$$

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



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

- 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
  - ➢ Complete O(α) with EW loops form OPENLOOPS (under test)



$e^+e^- \to ZH$ (Preliminary)

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- ISR has only been modelled via electron PDFs before
- Sherpa can now use YFS for ISR+FSR (First MC to the best of my knowledge)

	Born [fb]	**FSR [fb]**	**ISR [fb]**	**ISR+FSR [fb]**
SHERPA	0.498	0.513	0.414	0.433

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.
- Full one-loop EW corrections are available from OPENLOOPS

Outlook

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- 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 OpenLoops
  - 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

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- 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