# Preparing Sherpa for e+e-

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22nd MCnet Meeting
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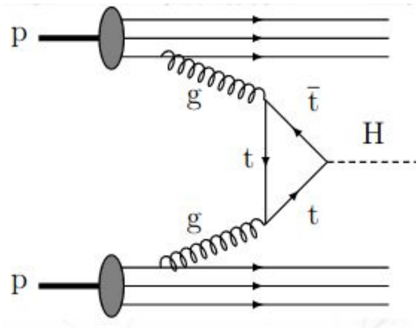
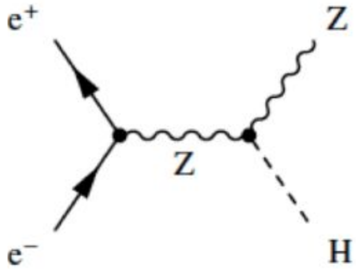
# Overview

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

# Motivation

| p-p Colliders | $e^+e^-$ Colliders |
|---|---|
| Protons are composite Particles | $e^+e^-$ are point like |
| • Initial state is not known | • Initial states are well defined |
| • This limits achievable precision | • Allows for High-Precision Measurements |
| High rates of QCD backgrounds | Clean experimental environment |
| • High level of radiation | • Low radiation levels |
| • Large cross section for colored-states | • Higher sensitivity for electroweak final states |
| Very high energies | Can be circular or linear |
| • Feasible up to $\mathcal{O}(100\text{TeV})$ | • Large luminosities at Circular |
| | • High energy at linear colliders |




“***An electron-positron Higgs factory is the highest-priority next collider***” - 2020 Update of the European Strategy for Particle Physics

# Motivation

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**A high precision e⁺e⁻ machine will require high precision calculations**

| 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 |
| $\Gamma_Z$ [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 |
| $\sigma^0_{\text{had}}$[nb] | $\sigma^0_{\text{had}}$ [32] | $41.541 \pm 0.037\{0.025\}$ | $0.1 \cdot 10^{-3}$ | $4 \cdot 10^{-3}$ | 6 |
| $N_\nu$ | $\sigma(M_Z)$ [32] | $2.984 \pm 0.008\{0.006\}$ | $5 \cdot 10^{-6}$ | $1 \cdot 10^{-3}$ | 6 |
| $N_\nu$ | $Z\gamma$ [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
- 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)
- 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 (Nucl. Phys. B955 (2020))

# How to Treat ISR?

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## Collinear Resummation

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## Inclusive Calculations

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

# Resummation à la YFS

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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,

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

# YFS Resummation

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

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

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

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

- $\beta$ 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

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

- 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

- 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

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

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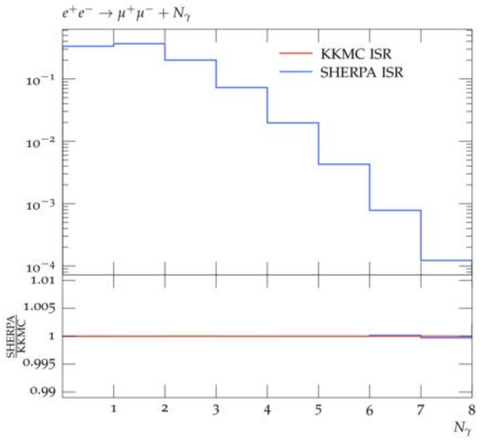
- State of the art is KKMC (Comput.Phys.Commun. 130 (2000) 260-325)
- KKMC includes initial, final, and initial-final interference
- Sherpa does not include Initial-final interference




| | 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)

# $e^+e^- \rightarrow f\bar{f}$

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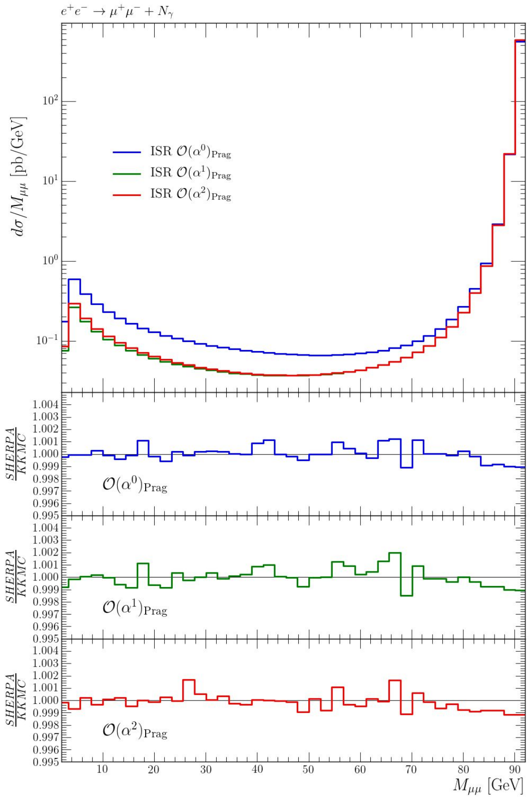
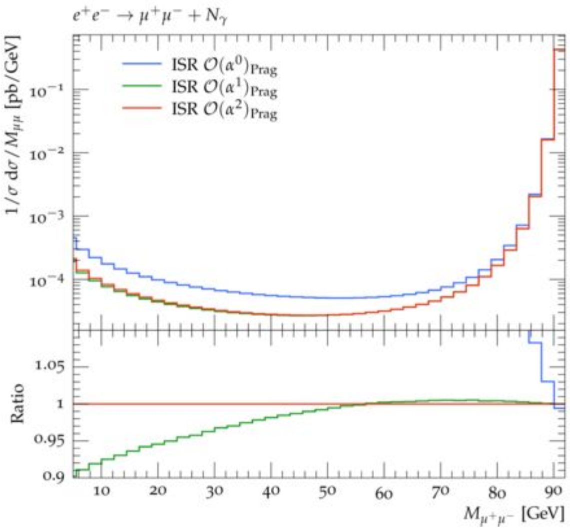



$$\mathcal{O}(\alpha^0)_{\rm Prag} = \text{Resummation only}$$

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

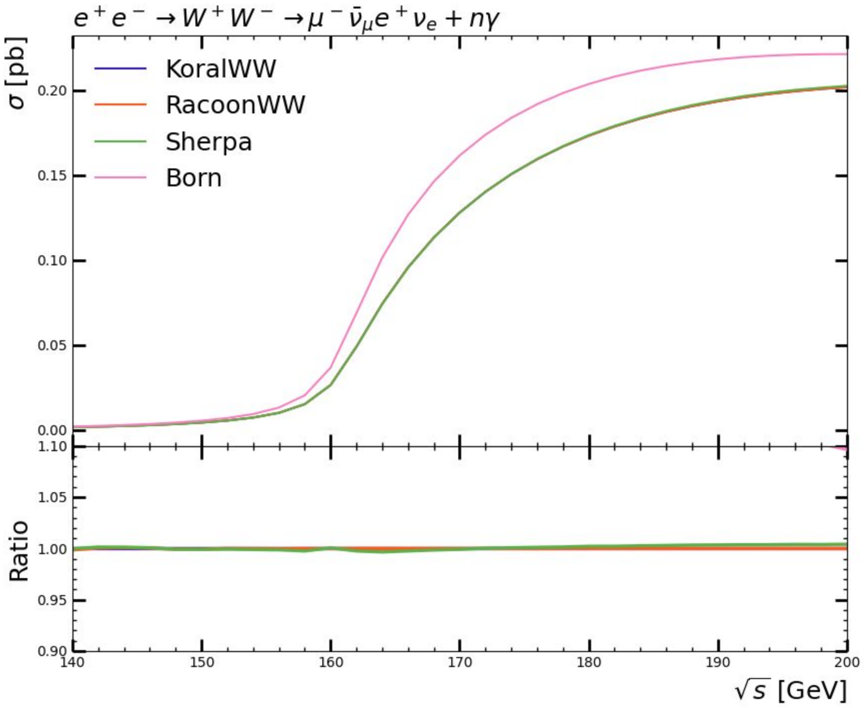
$$\mathcal{O}(\alpha^2)_{\rm Prag} = \alpha,\ \alpha L,\ \alpha^2 L^2$$

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



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

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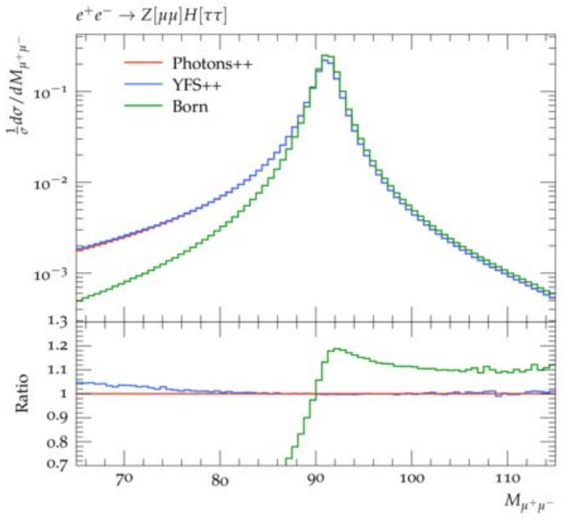
- ISR has only been modelled via electron PDFs before
- Sherpa can now use YFS for ISR+FSR (First MC to the best of my knowledge)




- 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



- 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

- 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