Center for Particle Physics Siegen

UNIVERSITÄT SIEGEN

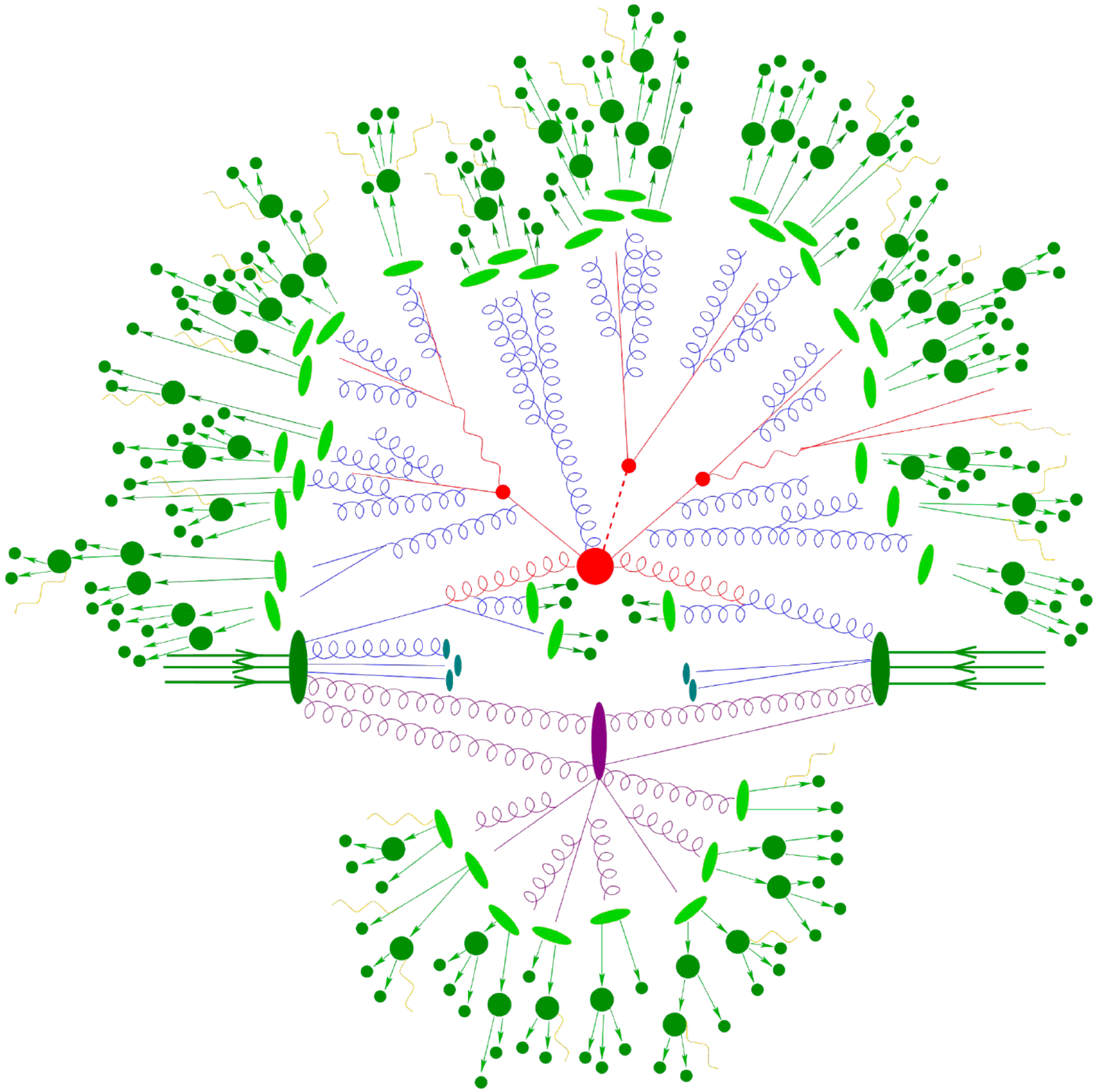
SHERPA Event Generator

Alan Price on behalf of the Sherpa Authors

STAR Sensing and Sensibility
Transcending Disciplines for a Responsible Future

SHERPA Framework

- **Automated Hard Interaction**
  - LO, NLO QCD/EW, NNLO QCD
  - Internal ME generators AMEGIC/COMIX
- **Radiative Corrections**
  - Catani-Seymour based PS
  - DIRE, YFS QED resummation
  - EW Sudakovs
- **Multiple interactions**
  - Sjöstrand-Zijl model
- **Hadronization**
  - Cluster hadronization model
- **Hadron Decays**
  - Phase space or EFTs,
  - YFS QED corrections



SciPost Phys. 7 (2019) 3, 034

SHERPA Framework

Sherpa has traditionally focused on LHC physics, but is becoming more broad in its application

Lepton-Lepton Colliders

YFS Resummation for Future Lepton-Lepton Colliders in SHERPA
SciPost Phys. 13 (2022) 2, 026, F.Krauss, A.P, M. Schönherr

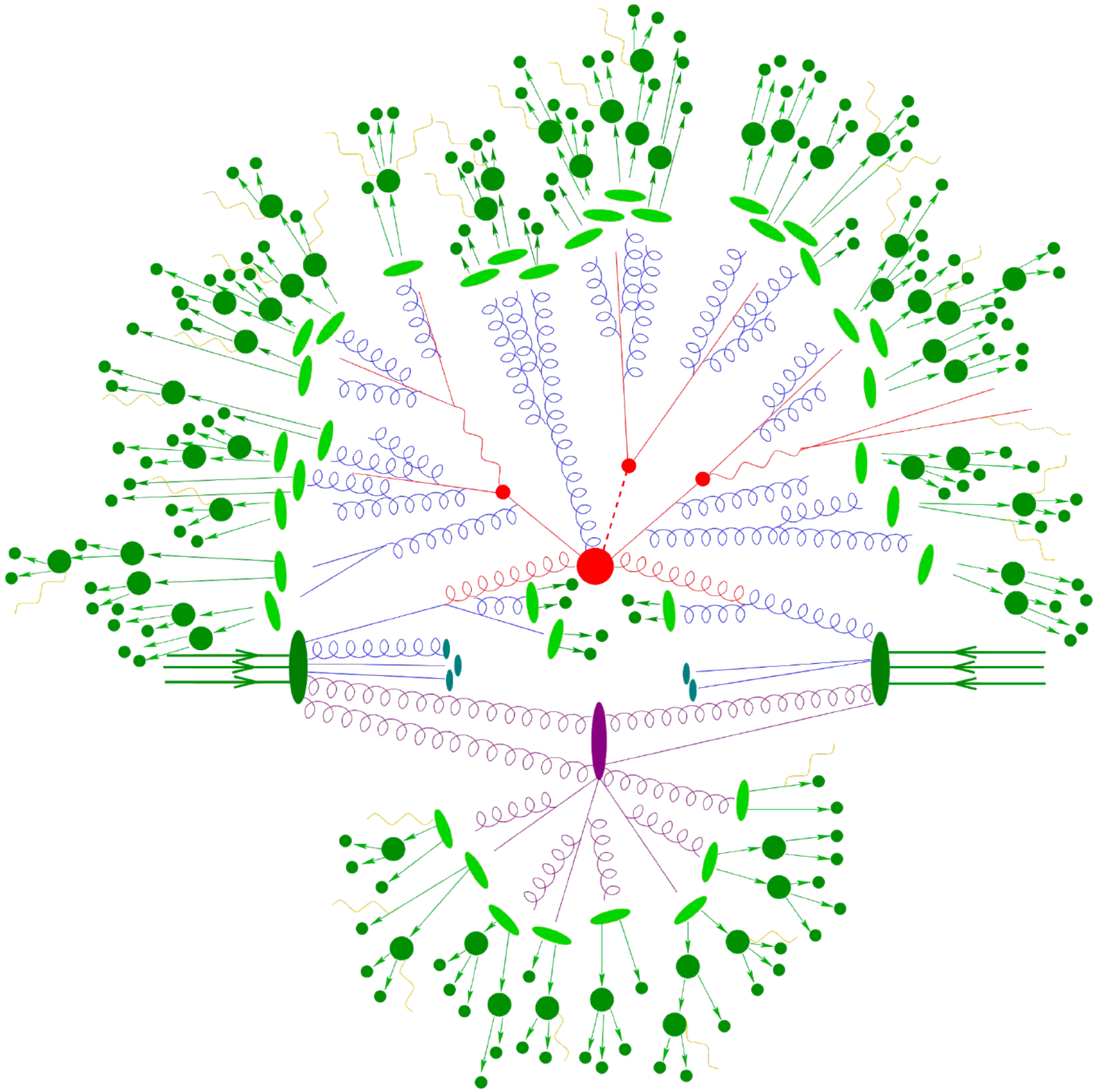
Measuring Hadronic Higgs Boson Branching Ratios at Future Lepton Colliders 2306.03682 M.Knobbe, F.Krauss, D.Reichlet, S. Schumann

Lepton-Hardron Colliders

(N)NLO+NLL’ accurate predictions for plain and groomed 1-jettiness in neutral current DIS
JHEP 09 (2023) 194 M.Knobbe, D.Reichelt, S.Schumann

Neutrino Experiments

Novel event generator for the automated simulation of neutrino scattering
Phys.Rev.D 105 (2022) 9, 096006 J.Isaacson, S.Höche, D.Gutierrez, N.Rocco



SciPost Phys. 7 (2019) 3, 034

What can Sherpa do for lepton collider experiments?

YFS Resummation

- Yennie-Frautschi-Suura allows us to resum **soft logs to infinite order**
- Provides a systematic method to include **perturbative corrections**
- The multi-photon phasespace is treated exactly => Explicit Photons
- The MC implementation developed and championed by the Krakow group

Comput.Phys.Commun. 130 (2000) 260-325

$$d\sigma = \sum_{n_\gamma=0}^{\infty} \frac{e^{Y(\Omega)}}{n_\gamma!} d\Phi_Q \left[\prod_{i=1}^{n_\gamma} d\Phi_i^\gamma\, S(k_i)\, \Theta(k_i, \Omega) \right] \left(\tilde{\beta}_0 + \sum_{j=1}^{n_\gamma} \frac{\tilde{\beta}_1(k_j)}{S(k_j)} + \sum_{\substack{j,k=1 \\ j<k}}^{n_\gamma} \frac{\tilde{\beta}_2(k_j, k_k)}{S(k_j)S(k_k)} + \cdots \right),$$

~Process Independent **Process Dependent**

YFS Resummation

$$Y(\Omega) = 2\alpha \sum_{i<j} \left(\mathscr{R}e\, B(p_i, p_j) + \tilde{B}(p_i, p_j, \Omega) \right)$$

$$S(k) = -\sum_{i,j} \frac{\alpha}{4\pi^2} Z_i Z_j \theta_i \theta_j \left(\frac{p_i}{p_i \cdot k} - \frac{p_j}{p_j \cdot k} \right)^2$$

$$B(p_i, p_j) = -\frac{i}{8\pi^3} Z_i Z_j \theta_i \theta_j \int \frac{d^4k}{k^2} \left(\frac{2p_i\theta_i - k}{k^2 - 2(k \cdot p_i)\theta_i} + \frac{2p_j\theta_j + k}{k^2 + 2(k \cdot p_j)\theta_j} \right)^2$$

$$\tilde{B}(p_i, p_j, \Omega) = \frac{1}{4\pi^2} Z_i Z_j \theta_i \theta_j \int d^4k\, \delta(k^2) \big(1 - \Theta(k, \Omega)\big) \left(\frac{p_i}{(p_i \cdot k)} - \frac{p_j}{(p_j \cdot k)} \right)^2$$

$$d\sigma = \sum_{n_\gamma=0}^{\infty} \frac{e^{Y(\Omega)}}{n_\gamma!} d\Phi_Q \left[\prod_{i=1}^{n_\gamma} d\Phi_i^\gamma S(k_i)\, \Theta(k_i, \Omega) \right] \left(\tilde{\beta}_0 + \sum_{j=1}^{n_\gamma} \frac{\tilde{\beta}_1(k_j)}{S(k_j)} + \sum_{\substack{j,k=1 \\ j<k}}^{n_\gamma} \frac{\tilde{\beta}_2(k_j, k_k)}{S(k_j)S(k_k)} + \cdots \right),$$

$$\tilde{\beta}_{n_\gamma} = \sum_{\bar{n}_\gamma=0}^{\infty} \tilde{\beta}_{n_\gamma}^{\bar{n}_\gamma + n_\gamma}$$

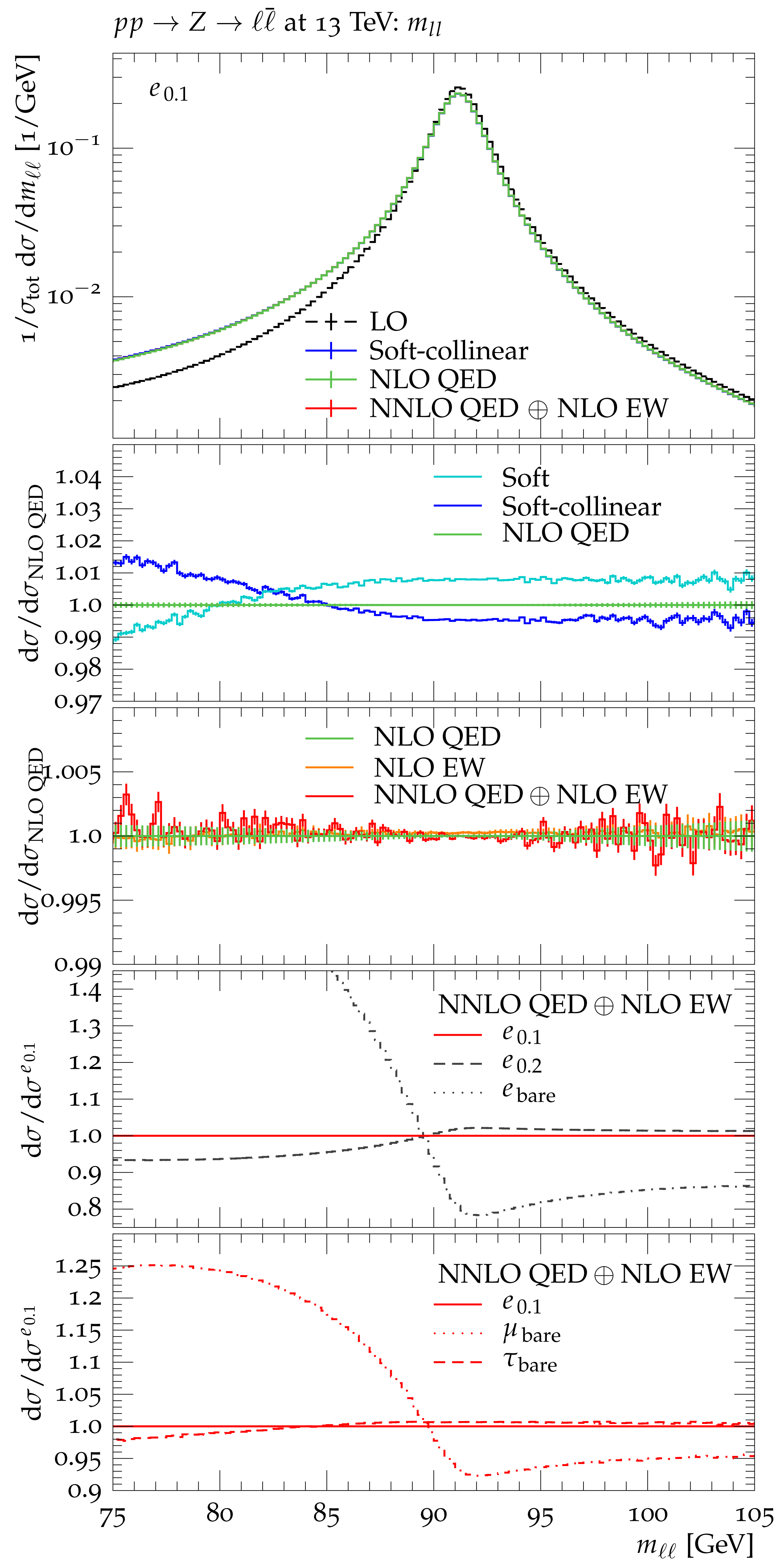
$\bar{n}_\gamma =$ # Virtual Photons

YFS for FSR

Original YFS was limited to FSR in Sherpa

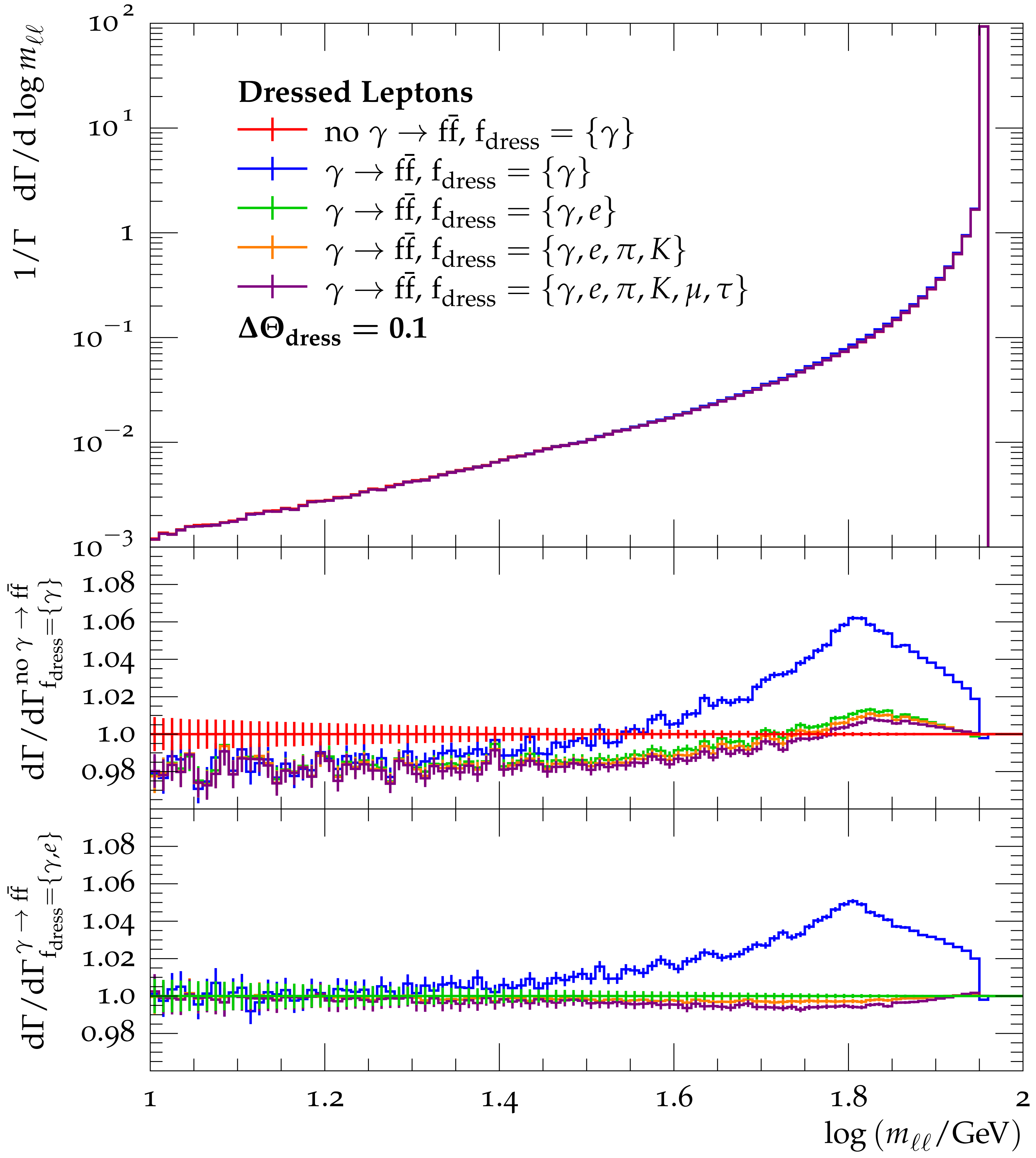
For boson decays, we have YFS corrections up to NNLO QED and NLO EW.

Eur.Phys.J.C 79 (2019) 2, 143 F.Krauss, A. Lindert, R. Linten, M. Schönherr



Photon Splitting

- Photon splitting is also included, which is NNLO correction to YFS
- Captures the logarithmic enhancement for collinear splittings
- Includes Photons splitting to both charged fermions and scalars
- Currently limited to FSR. ISR implementation underway



L.Flower and M.Schoenherr JHEP 03 (2023), 238

YFS for Leptonic Processes

$$d\sigma = \sum_{n_\gamma=0}^{\infty} \frac{e^{Y(\Omega)}}{n_\gamma!} d\Phi_Q \left[\prod_{i=1}^{n_\gamma} d\Phi_i^\gamma \, S(k_i) \, \Theta(k_i, \Omega) \right] \left(\tilde{\beta}_0 + \sum_{j=1}^{n_\gamma} \frac{\tilde{\beta}_1(k_j)}{S(k_j)} + \sum_{\substack{j,k=1 \\ j<k}}^{n_\gamma} \frac{\tilde{\beta}_2(k_j, k_k)}{S(k_j) S(k_k)} + \cdots \right),$$

Automated for $e^+e^- \to$ anything

How? $\tilde{\beta}_0^0$ essentially born Matrix element and Sherpa can automatically construct this

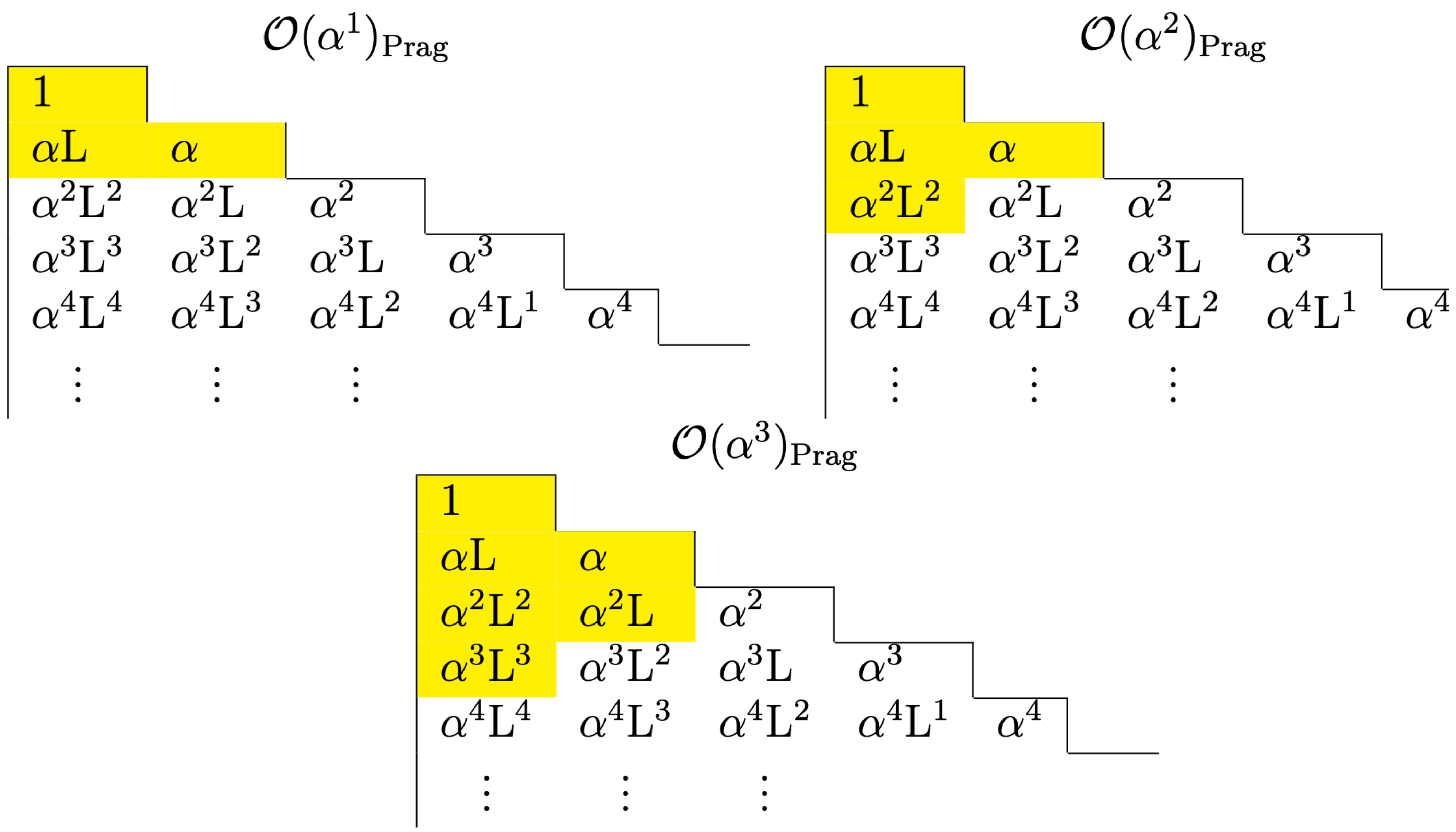
Higher Order Corrections

$$\tilde{\beta}_0 + \sum_{j=1}^{n_\gamma} \frac{\tilde{\beta}_1(k_j)}{S(k_j)} + \sum_{\substack{j,k=1 \\ j<k}}^{n_\gamma} \frac{\tilde{\beta}_2(k_j, k_k)}{S(k_j)S(k_k)} + \cdots$$

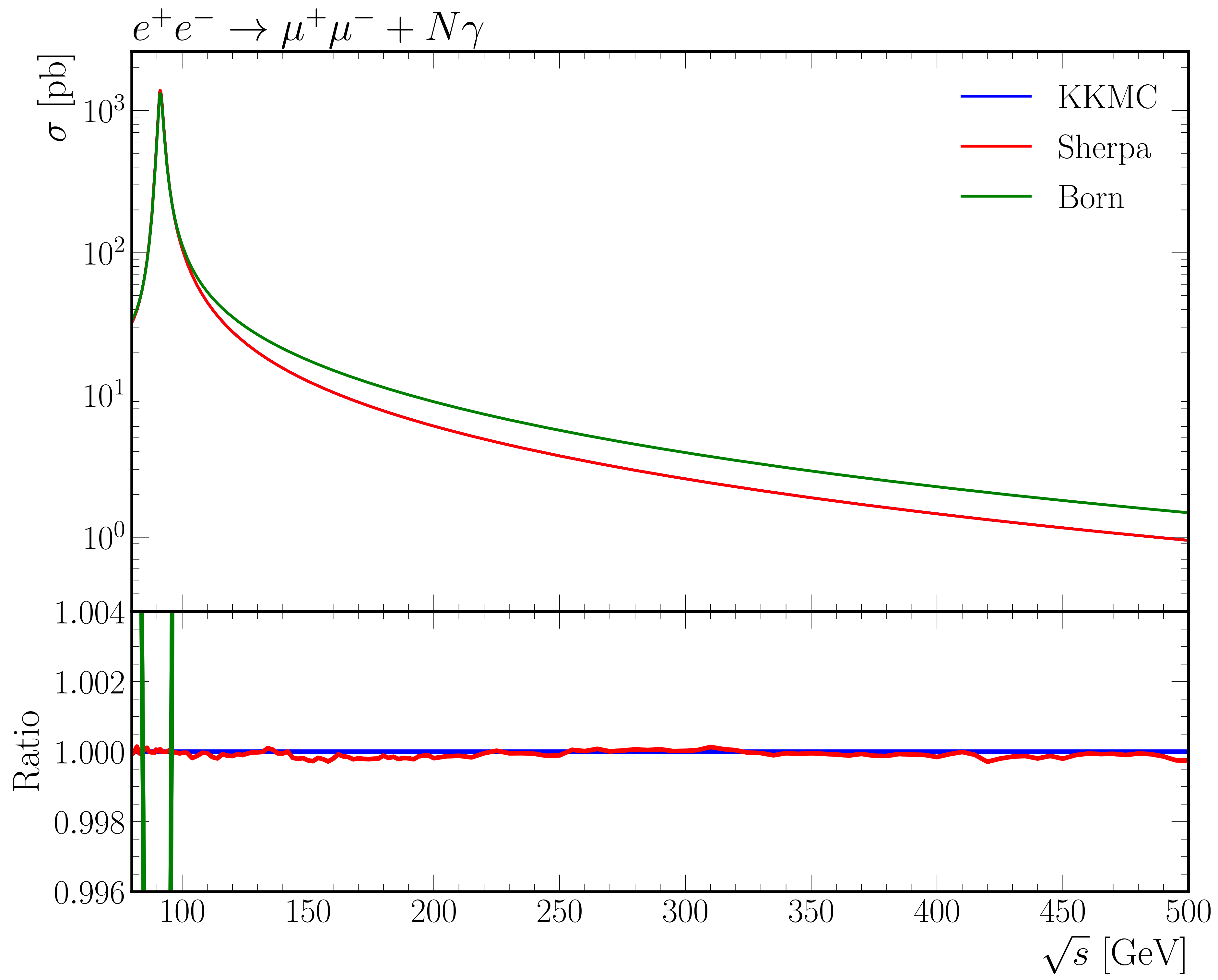
Originally implemented in EEX framework of KKMC

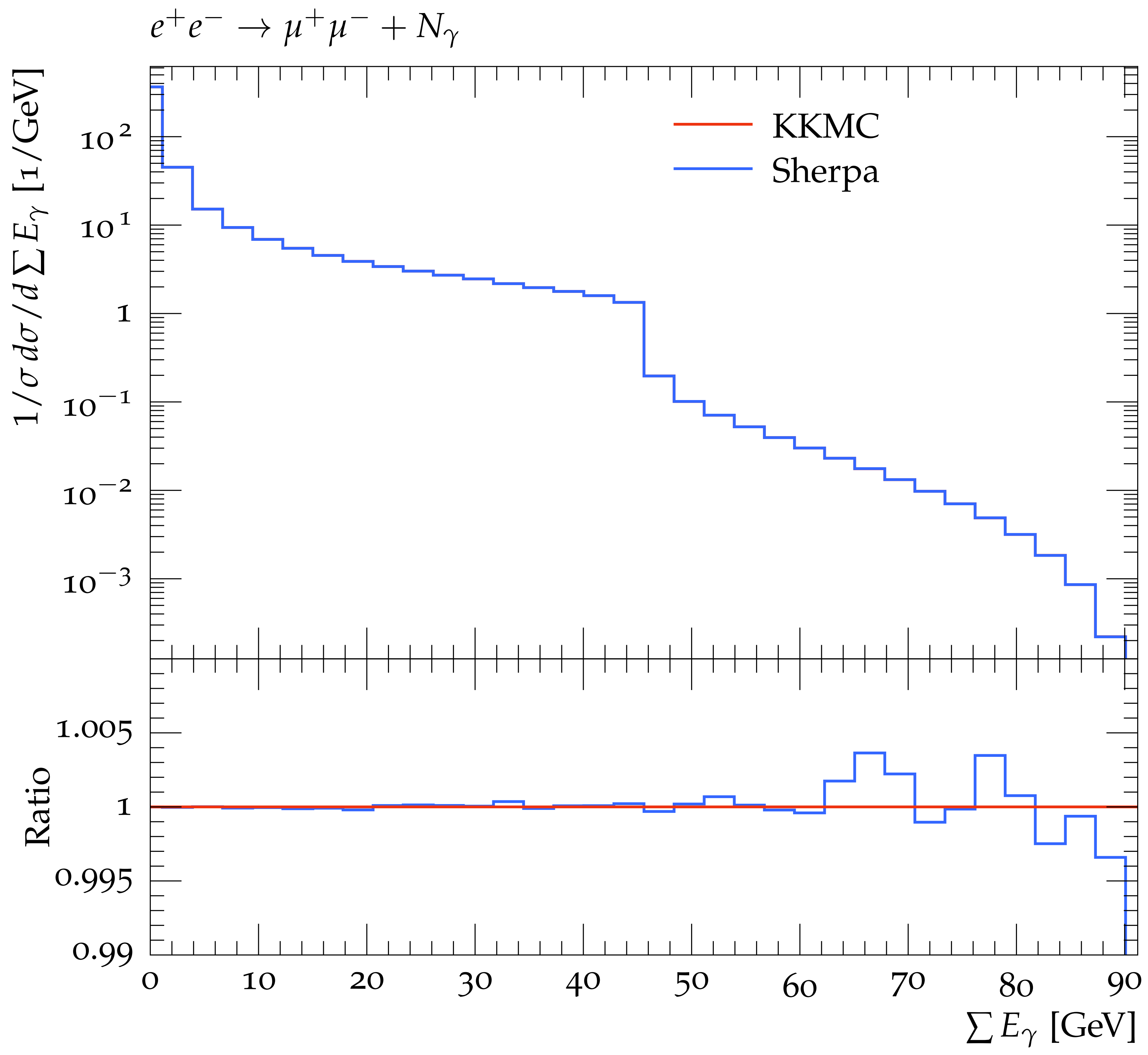
While easy to implement suffers from a lack of accuracy e.g No Initial-final interference

Solved in KKMC with CEEX corrections



YFS Validation





Sherpa has been intensely validated against **KKMC**
Can be extended to low energy and different calculations e.g **PHOKARA**

Automatic One-Loop Corrections

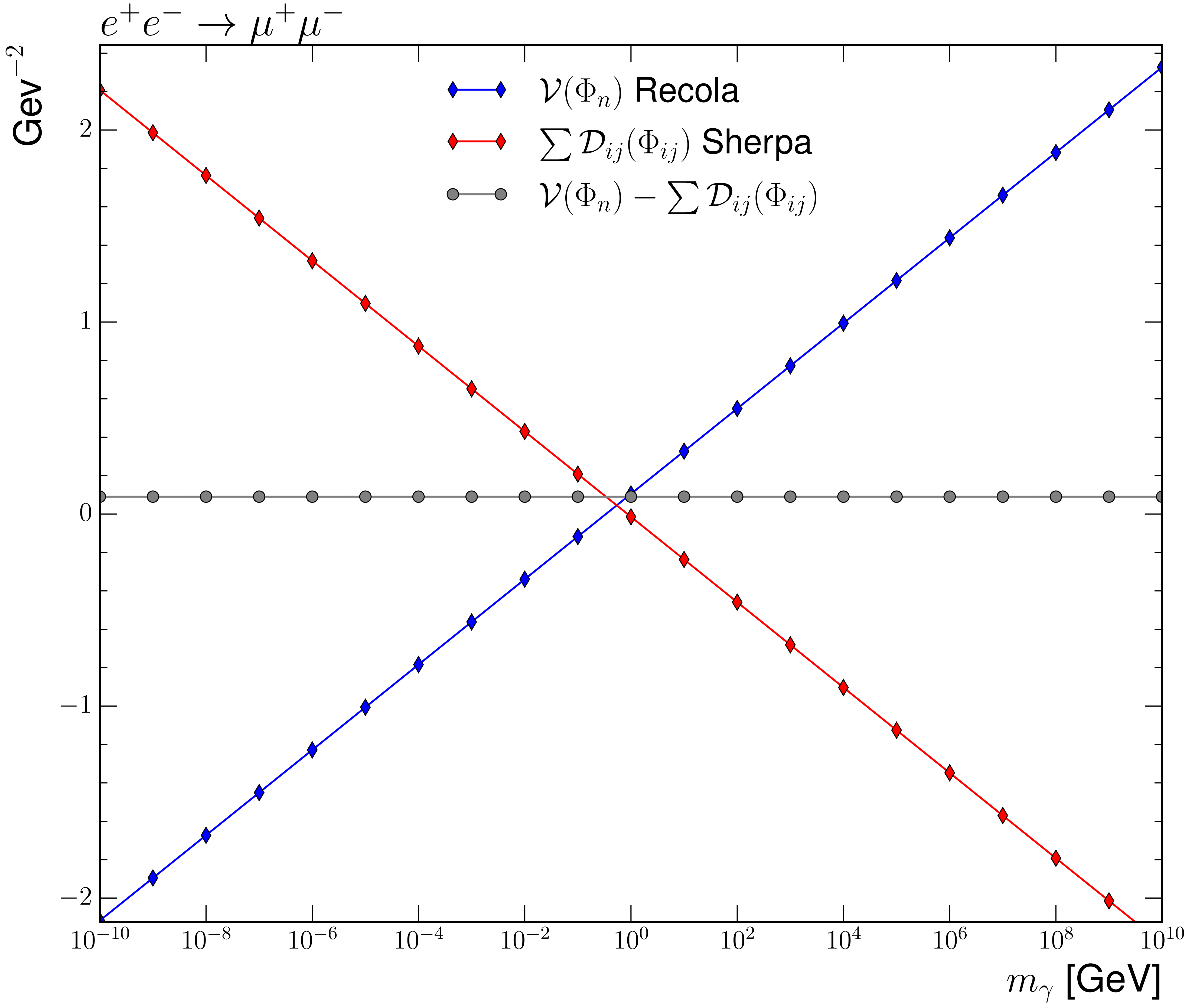
$$\tilde{\beta}_0^1\left(\Phi_n\right) = \mathscr{V}\left(\Phi_n\right) - \sum_{ij} \mathscr{D}_{ij}\left(\Phi_{ij}\right)$$

- Full One Loop EW contribution
  - Contains IR divergent terms
- Need a loop generator that can include all lepton masses!
  - Currently only Recola can provide this
- All or nothing. Cannot separate ISR/FSR

- Fully automated within YFS module
- Constructed from all dipoles
- Really should be limited to leptonic final states only
- Works for massive quarks but should not be combined with QCD resummation

One-Loop Corrections

$$\log(m_\gamma^2) \rightarrow \frac{\Gamma(1+\epsilon)}{\epsilon}(4\pi\mu^2)^\epsilon$$



$$\tilde{\beta}_0^1\left(\Phi_n\right) = \mathscr{V}\left(\Phi_n\right) - \sum_{ij} \mathscr{D}_{ij}\left(\Phi_{ij}\right)$$

Loops provided by Recola

Comput.Phys.Commun. 214 (2017) 140-173

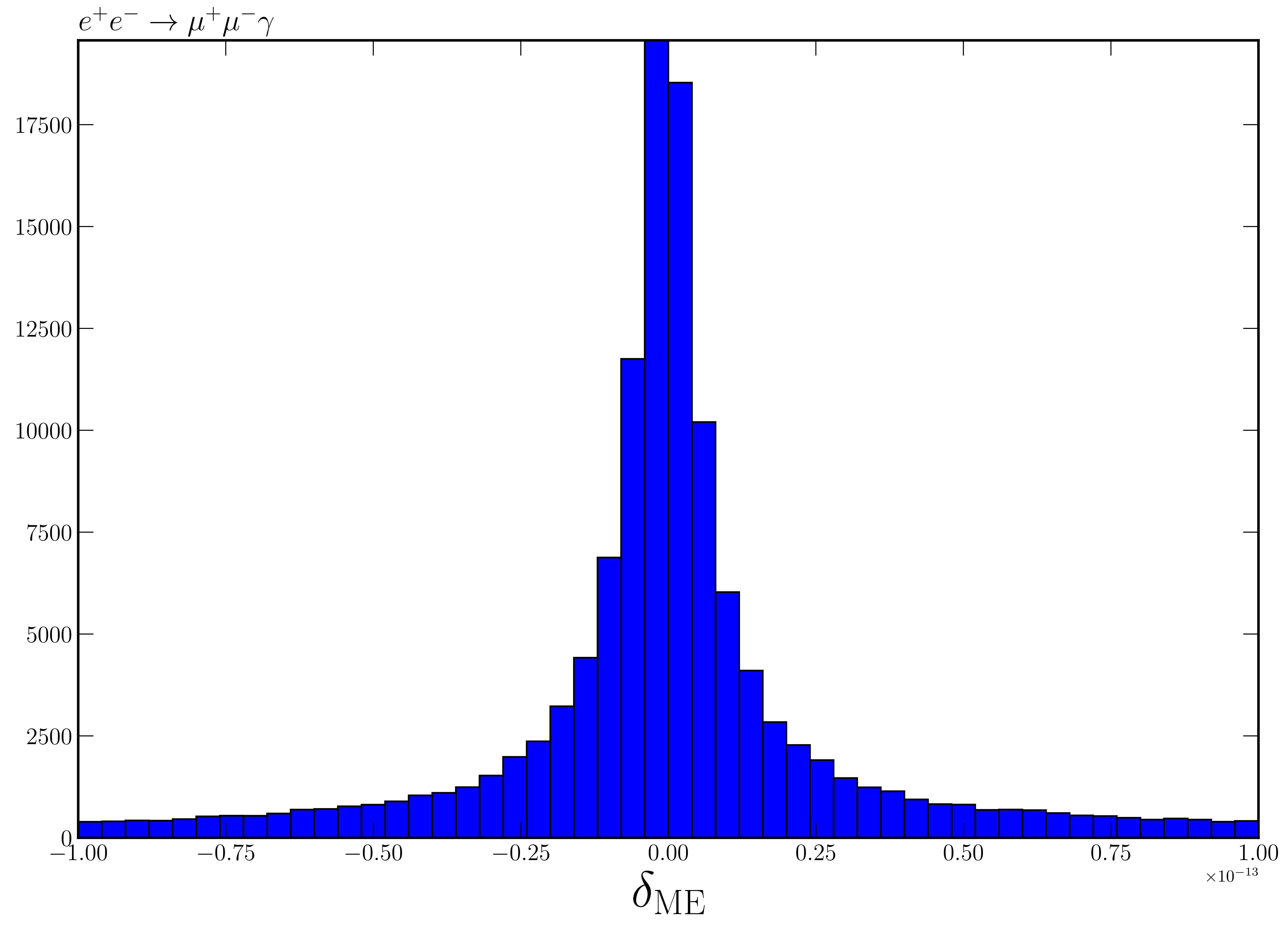
Real Corrections

$$\tilde{\beta}^1_1\left(\Phi_{n+1}\right) = \mathscr{R}\left(\Phi_{n+1}\right) - \tilde{\beta}^0_0\left(\Phi_n\right)\sum_{ij}\tilde{S}_{ij}(k)$$

- Real photon correction to born process
- In Principle, can be taken from AMEGIC or COMIX

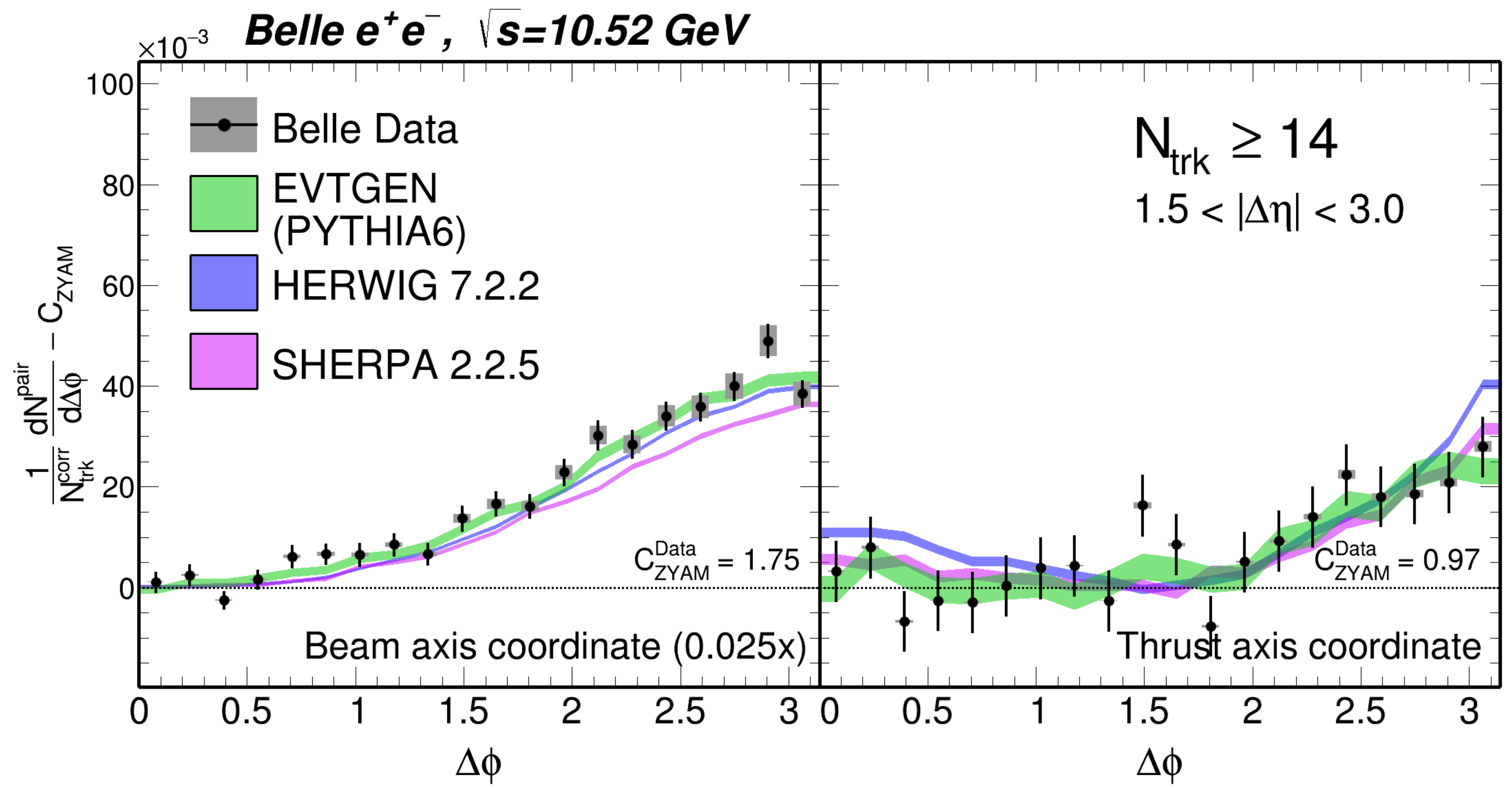
- Subtraction term calculate from the eikonals of all dipoles
- Automated within YFS

Real Corrections



Sherpa for $e^+e^- \to \pi^+\pi^-$

- In principle, not too difficult. One just has to add the amplitudes
- For B-factories we already have dedicated $e^+e^- \to B\bar{B}$ channels, can adapt to $e^+e^- \to \pi^+\pi^-$
- Some dedicated treatment needed for form-factor
- ISR and FSR can then be calculated using YFS



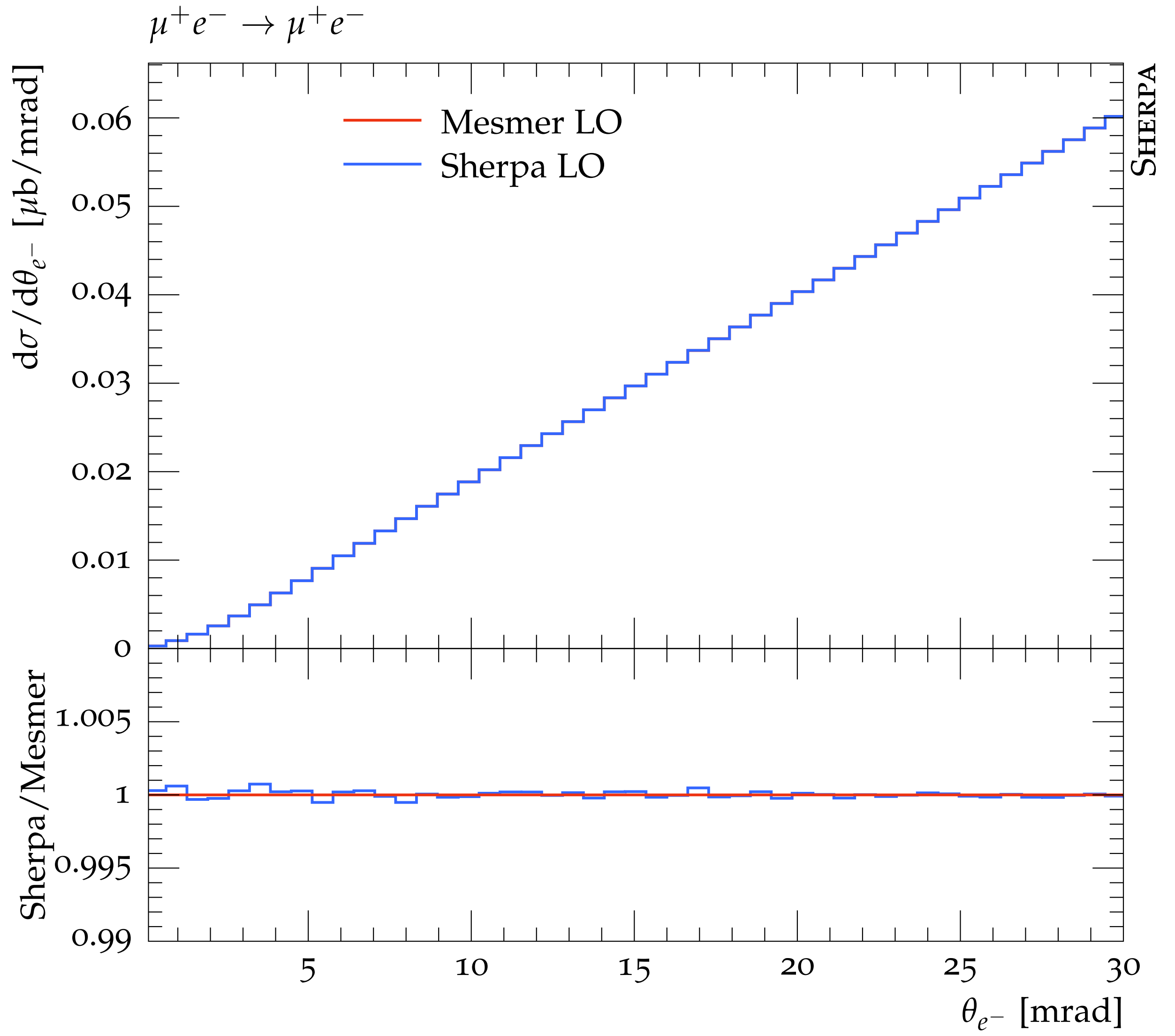
Phys.Rev.Lett. 128 (2022) 14, 142005

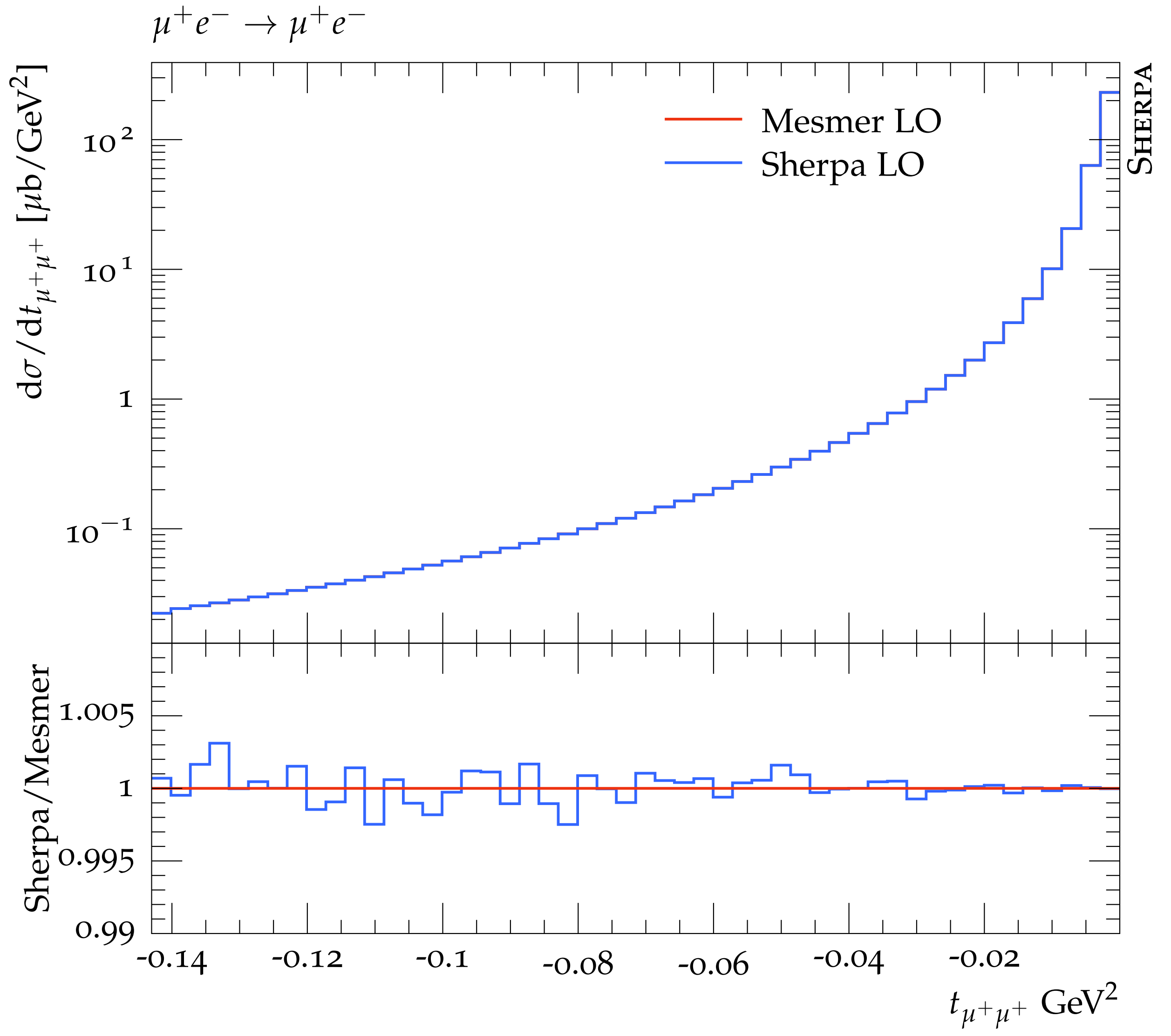
Sherpa for $\mu^+e^- \to \mu^+e^-$

- New fixed target mode allowing Sherpa to calculate $\mu^+e^- \to \mu^+e^-$ for MUonE
- Excellent agreement at LO with Mesmer. Predictions correspond to setup 1 in JHEP 11 (2020) 028
- Application of YFS to this process needs further study, still preliminary → Outcome of this workshop?
- YFS certainly feasible to achieve sub-permille precision

$\mu^+e^- \to \mu^+e^-$	LO	YFS_{Born}	YFS_{EEX}
SHERPA	245.034(3)	261.296(9)	256.315(8)
	LO	NLO	NNLO
Mesmer	245.038910(1)	255.8437(5)	256.092(1)

Table 1: Total cross-sections for $\mu^\pm e^- \to \mu^\pm e^-$in μb.





Conclusion

- Sherpa is well placed to provide additional predictions for cross checks and validation
  - E.g PHOKARA vs KKMC vs SHERPA
- Sherpa's powerful YFS will can help provide an additional estimate of QED uncertainty
- We are happy to accommodate requests for physics implementations
  - $e^+e^- \to \pi^+\pi^-$ process will be added
  - Vacuum polarisation can easily be realised

The SHERPA 2.2 event generator framework

User Inputs

Initial Beams

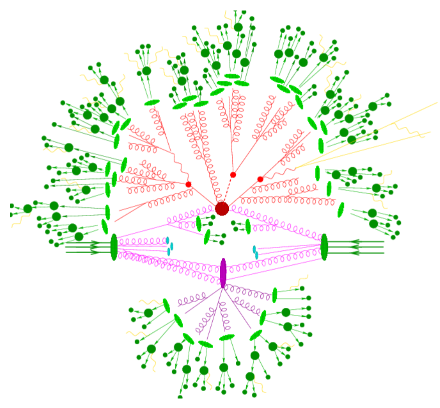
- collider setup
- PDFs (built-in, LHAPDF)
- beam spectra

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



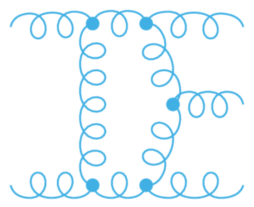
Matrix Elements

Matrix Element Generators

- AMEGIC
- COMIX
- CS subtraction

1-loop Amplitudes

- OpenLoops
- Recola
- GoSam
- BLHA



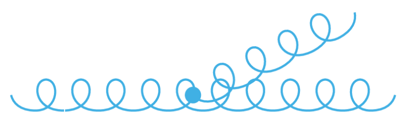
Parton Showers

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

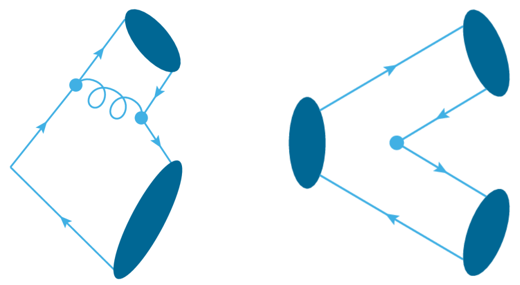
NNLO QCD with parton showers

- selected processes only

Soft Physics

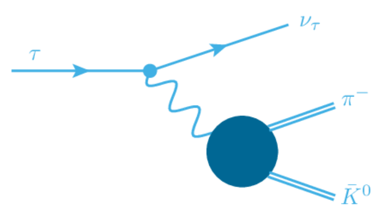
Hadronisation

- 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



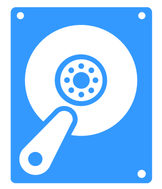
Underlying Event

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

Interfaces/Outputs

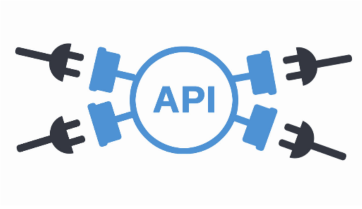
Output Formats

- 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