ILCX2021 ILC Workshop on Potential Experiments

Summary for Session K “Modeling & precision theory & Electroweak physics”

Conveners:
Gudrun Heinrich (KIT)
Stefan Höche (FNAL)
Zhao Li (IHEP-CAS)
Jürgen Reuter (DESY)

Oct. 29, 2021

Talks in Session K

- Subleading Logarithmic QED Initial State Corrections to $e^+e^- \to \gamma^*/Z^*$
  Kay Schönwald

- High precision QED calculations
  Adrian Signer

- Status report on Whizard 3 for the ILC
  Pia Bredt

- Merging of ISR and EPA structure functions with matrix element calculations
  Krzysztof Mekala

- Electroweak precision observables at future electron-positron colliders
  Lisong Chen

1. Subleading Logarithmic QED Initial State Corrections to $e^+e^- \to \gamma^*/Z^*$

Kay Schönwald in collaboration with: J. Ablinger, J. Blu¨mlein, A. De Freitas

- At the next generation e^+e^- collider, the ISR effect is crucial for precision theoretical predictions w.r.t. experiment accuracy.
- The large log $L = \ln\left(s/m_e^2\right) \approx 10$ would be important.
- This could happen at various processes jet production via Z pole, $t\bar{t}$ production, ZH production etc.

1. Subleading Logarithmic QED Initial State Corrections to $e^+e^- \rightarrow \gamma^*/Z^*$

Kay Schönwald in collaboration with: J. Ablinger, J. Blu¨mlein, A. De Freitas

- 1988: First calculation to $O(\alpha^2)$ for the LEP analysis, through expansion of the phase space integrals (BBN).
  [Berends, Burgers, van Neerven (Nucl. Phys. B297 (1988))]
- 2012: New calculation up to $O(\alpha^2)$ using the method of massive operator matrix elements.
  [Blümlein, De Freitas, van Neerven (Nucl Phys. B855 (2012))]

$\Rightarrow$ Calculations do not agree at $O(\alpha^2 L^0)$!

- We revisited the original calculation, doing the expansion in m_e at the latest stage.
  [Blümlein, De Freitas, Raab, KS (Nucl. Phys. B956 (2020))]

$\Rightarrow$ our results agree with the ones obtained using massive OMEs

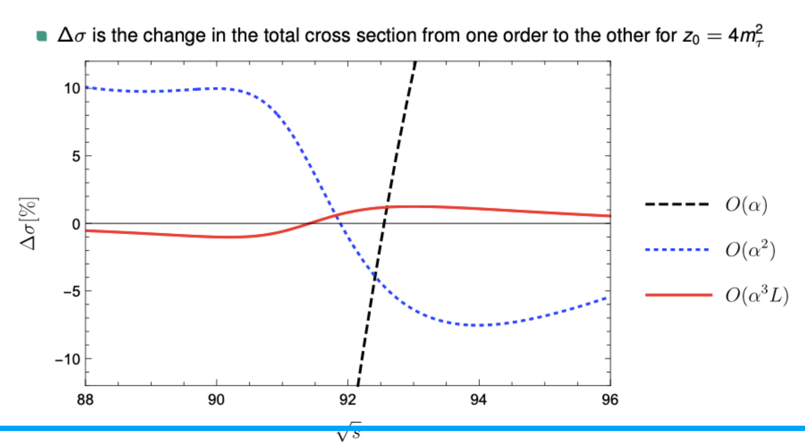
from Kay's talk slides

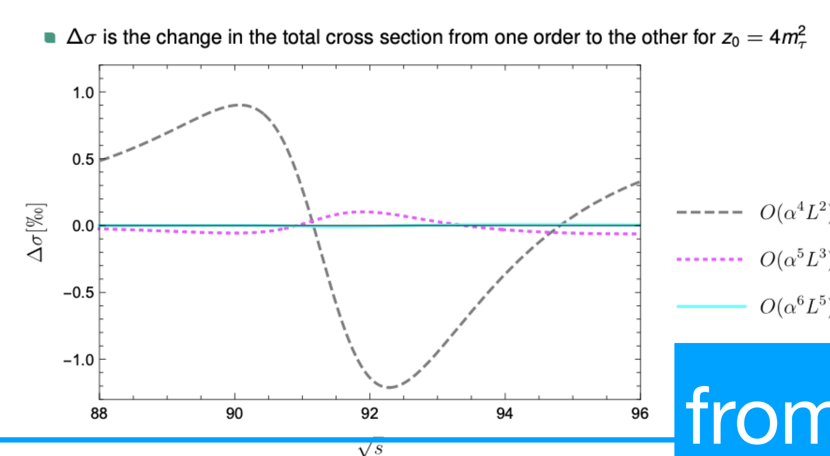
1. Subleading Logarithmic QED Initial State Corrections to $e^+e^- \to \gamma^*/Z^*$

Kay Schönwald in collaboration with: J. Ablinger, J. Blu¨mlein, A. De Freitas

- Using the method of massive operator matrix elements, they calculate the subleading QED initial state radiative corrections to the process $e^+e^- \to \gamma^*/Z^*$ for the first three logarithmic contributions from $O(\alpha^3 L^3)$, $O(\alpha^3 L^2)$, $O(\alpha^3 L)$ to $O(\alpha^5 L^5)$, $O(\alpha^5 L^4)$, $O(\alpha^5 L^3)$ and compare their effects to the leading contribution $O(\alpha^6 L^6)$ and one more subleading term $O(\alpha^6 L^5)$. The calculation is performed in the limit of large center of mass energies squared $s \gg m_e^2$.

$$\frac{\mathrm{d}\sigma_{ij}}{\mathrm{d}s'} = \frac{\sigma^{(0)}(s')}{s} \sum_{l,k} \Gamma_{li}\left(N, \frac{\mu^2}{m_e^2}\right) \cdot \tilde{\sigma}_{lk}\left(N, \frac{s'}{\mu^2}\right) \cdot \Gamma_{kj}\left(N, \frac{\mu^2}{m_e^2}\right) + O\left(\frac{m_e^2}{s}\right) = \frac{\sigma^{(0)}(s')}{s} H_{ij}\left(N, \frac{s}{m_e^2}\right)$$





from Kay's talk slides

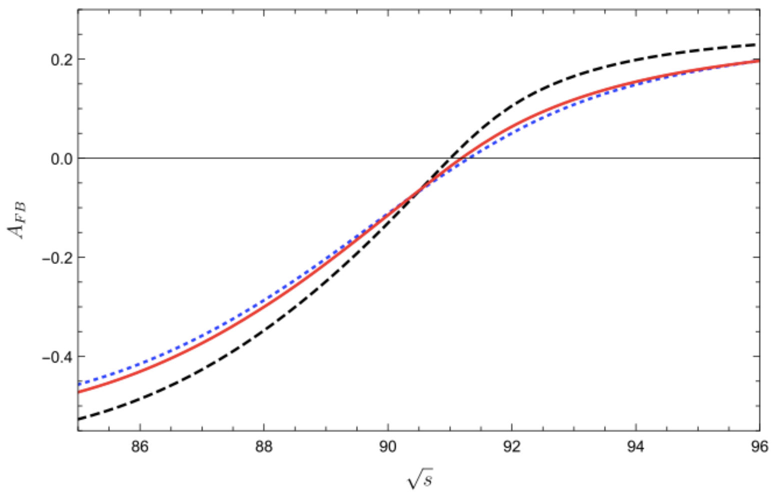
1. Subleading Logarithmic QED Initial State Corrections to $e^+e^- \to \gamma^*/Z^*$

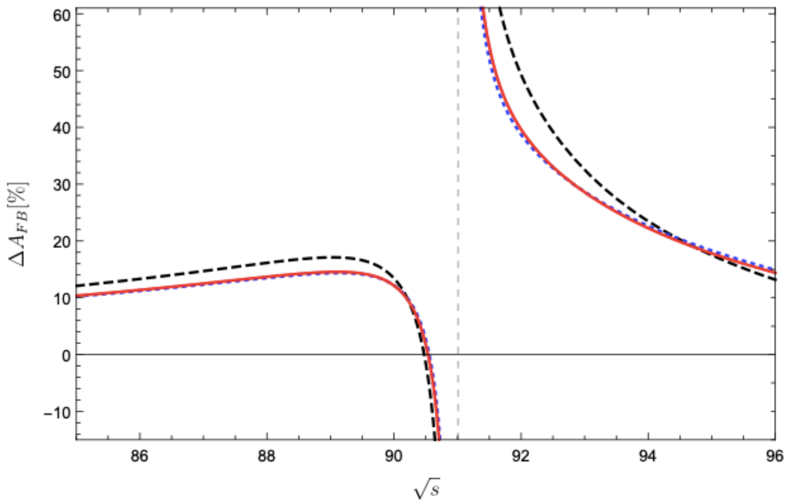
Kay Schönwald in collaboration with: J. Ablinger, J. Blu¨mlein, A. De Freitas

- They also applied their calculation on the Forward-Backward Asymmetry A_{FB}.

$$A_{FB}(s) = \frac{\sigma_F(s) - \sigma_B(s)}{\sigma_F(s) + \sigma_B(s)},$$

$$A_{FB}(s) = \frac{1}{\sigma_F(s) + \sigma_B(s)} \int_{z_0}^{1} \mathrm{d}z \frac{4z}{(1+z)^2} H_{FB}(z) \sigma_{FB}^{(0)}(zs)$$





- The corrections can become important at future e^+e^- machines running at high luminosities.
- The radiators can be used for various processes like $e^+e^- \to t\bar{t}$ and $e^+e^- \to ZH$.

from Kay's talk slides

2. High-precision QED calculations

Adrian Signer for the McMule Team

- NNLO QED corrections needed for

$$\begin{aligned} \ell p \to \ell p &\quad\longleftrightarrow\quad \text{P2 \& MUSE} \\ e\mu \to e\mu &\quad\longleftrightarrow\quad \text{MUonE} \\ e^-e^- \to e^-e^- &\quad\longleftrightarrow\quad \text{PRad} \\ e^+e^- \to e^+e^- &\quad\longleftrightarrow\quad \text{luminosity@}\ell\text{−colliders} \\ e^+e^- \to \gamma\gamma &\quad\longleftrightarrow\quad \text{PADME \& luminosity@}\ell\text{−colliders} \end{aligned}$$

- $\Rightarrow$ McMule, a framework for fully-differential higher-order QED
- also in McMule: Michel decay (NNLO), rare and radiative decay (NLO)
- planned: electroweak corrections, polarised leptons, $e^+e^- \to \ell^+\ell^-$

from Adrian's talk slides

2. High-precision QED calculations

Adrian Signer for the McMule Team

QED and QCD calculations have many common issues, but . . .

- QED matrix elements are easier due to Abelian structure [no big deal]
- The infrared structure of QED is much(!!) simpler [advantage 1]
- In QED we typically want to keep $m_\ell \neq 0$ since $\log(m_\ell)$ physical [problem 2]
- In QED we typically have to be exclusive w.r.t. hard collinear emission [problem 3]

consider (N. . .)NLO calculations in QED with massive fermions in McMule

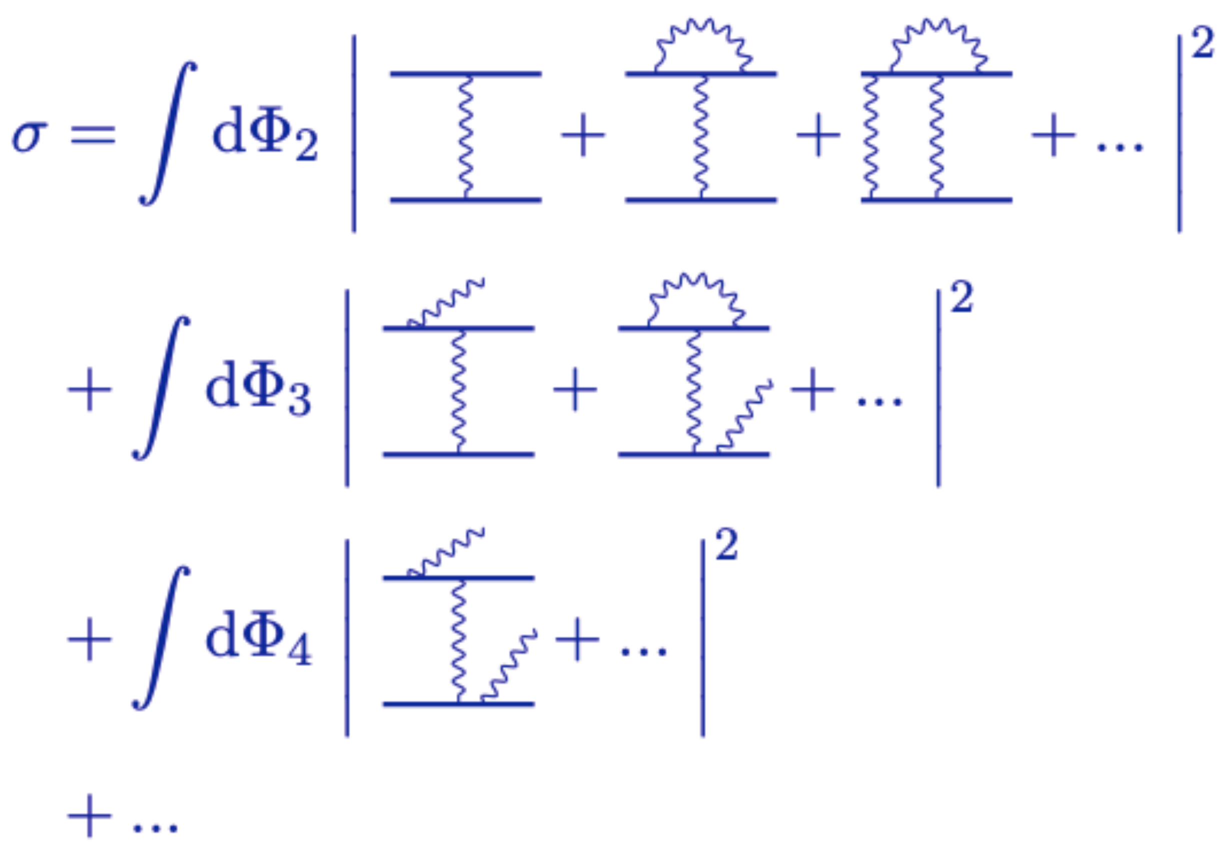
Monte Carlo for MUons and other LEptons https://mule-tools.gitlab.io

from Adrian's talk slides

2. High-precision QED calculations

Adrian Signer for the McMule Team

physical $(2 \to 2)$ cross section



challenges

1. fully differential phase-space integration

⇒ FKS$^\ell$

2. virtual amplitudes with massive particles

⇒ one-loop: OpenLoops

⇒ two-loop: massification

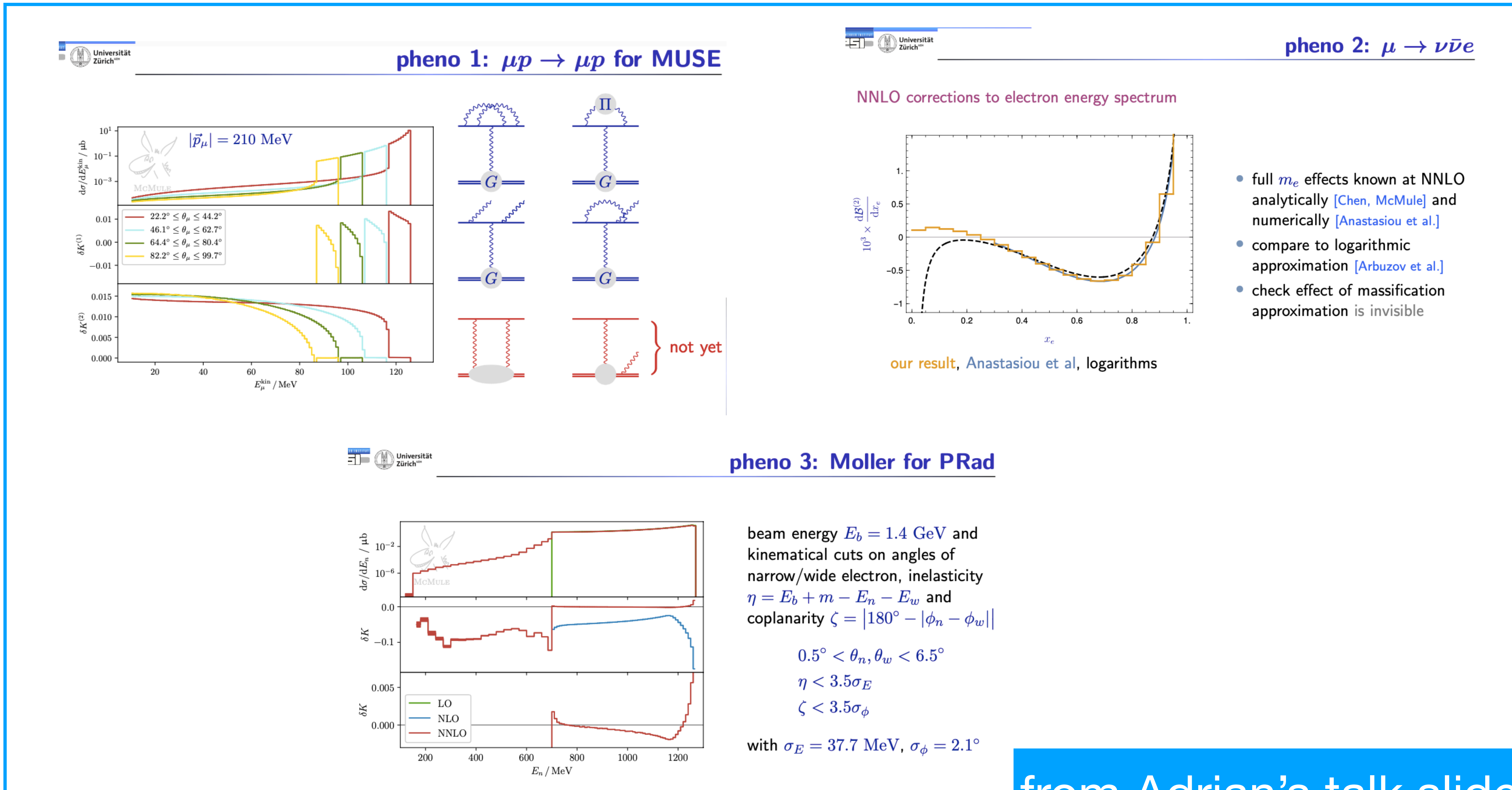
3. numerical instabilities due to pseudo-singularities

⇒ next-to-soft stabilisation

from Adrian's talk slides

2. High-precision QED calculations

Adrian Signer for the McMule Team



from Adrian's talk slides

3. Status report on WHIZARD 3 for the ILC

Pia Mareen Bredt

About WHIZARD

recent version: v3.0.1 (v3.0.2 to be released in November)
team: **Wolfgang Kilian, Thorsten Ohl, Jürgen Reuter**
Pia Bredt, Nils Kreher, Pascal Stienemeier, Tobias Striegl
webpage: https://whizard.hepforge.org/
support: https://launchpad.net/whizard
email contact: whizard@desy.de

WHIZARD is a **multi-purpose event generator** for multi-particle scattering cross sections and simulated event samples for **lepton and hadron collider** processes covering **SM** and **BSM** physics

Lepton collisions in WHIZARD

beam effect	in WHIZARD
beamstrahlung: *dense beams* ⇒ *strong EM fields* ⇒ *EM bunch-bunch interaction*	CIRCE1/CIRCE2: *fits to* GuineaPig *spectrum*
bremsstrahlung: *IS soft/collinear photon emission and small electron mass* ⇒ energy and p_T spectra shifted	ISR and EPA functions (cf. talk by K. Mekala): LL resummation in the strict collinear and/or soft limit event generation: *one photon per beam added.* p_T and recoil via isr_handler
beam polarization	inclusion for a user-defineable setup
other beam structure features	asymmetric beams, crossing angles, ...

- used for ILC TDR and the recent 250 GeV mass production full SM samples (2012 - 2021)

Status of BSM models

Internal hard-coded models:

Model type	Model name
Yukawa test model	Test
QED with e, μ, τ, γ	QED
QCD with d, u, s, c, b, t, g	QCD
Standard Model	SM, SM_CKM
SM with anomalous gauge couplings	SM_ac, SM_ac_CKM
SM with Hgg, $H\gamma\gamma$, $H\mu\mu$, He^+e^-	SM_Higgs, SM_Higgs_CKM
SM with bosonic dim-6 operators	SM_dim6
SM with charge 4/3 top	SM_top
SM with anomalous top couplings	SM_top_anom
SM with anomalous Higgs couplings	SM_rx/NoH_rx/SM_ul
SM extensions for VV scattering	SSC/AltH/SSC_2/SSC_AltT
SM with Z'	Zprime
Two-Higgs Doublet Model	THDM, THDM_CKM
MSSM	MSSM, MSSM_CKM
MSSM with gravitinos	MSSM_Grav
NMSSM	NMSSM, NMSSM_CKM
extended SUSY models	PSSSM
Littlest Higgs	Littlest
Littlest Higgs with ungauged $U(1)$	Littlest_Eta
Littlest Higgs with T parity	Littlest_Tpar
Simplest Little Higgs (anomaly-free)	Simplest
Simplest Little Higgs (universal)	Simplest_univ
SM with graviton	Xdim
UED	UED
"SQED" with gravitino	GravTest
Augmentable SM template	Template

External UFO models:

- WHIZARD 3.0: full UFO support ⇒ backwards-compatibility mode for FeynRules/SARAH interfaces
- numerous bug fixes and ameliorations
- Spin 0, 1/2, 1, 2 supported
- arbitrary Lorentz structures
- Dirac + Majorana statistics
- higher-level vertices (5-8 point)
- UFO support for SMEFTsim 3.0
- UFO customized propagators
- resonance histories with UFO
- BSM SLHA input

from Pia's talk slides

3. Status report on WHIZARD 3 for the ILC

Pia Mareen Bredt

Status of full SM NLO automation

- Automation of NLO fixed order corrections is based on the Frixione-Kunszt-Signer (FKS) subtraction [hep-ph/9512328]
  - NLO QCD automation completed ☑
  - NLO EW automation for LHC processes (nearly) completed ☑
    - pure EW corrections ☑
    - QCD-EW mixed corrections (in validation) ☑
  - next step: NLO EW for e^+e^- collisions ☐ (technical results for massive IS)
- One-loop provision by `OpenLoops` [1907.13071] as standard
- Matching to parton showers by POWHEG scheme (for e^+e^- processes in validation, for pp processes work in progress)
- Validation with several other Monte-Carlo event generators: `MG5_aMC@NLO`, `Sherpa`, `MUNICH`, `POWHEG-BOX`, ...

Mixed QCD-EW corrections

QCD-EW mixed corrections in `WHIZARD`s upcoming `v3.0.2`:

from Pia’s talk slides

3. Status report on WHIZARD 3 for the ILC

Pia Mareen Bredt

- We may expect Whizard be more powerful in the upcoming versions.

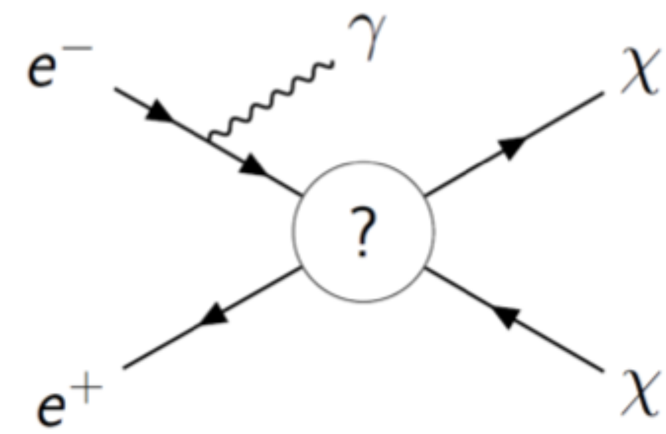
- NLO EW automation for e^+e^- (massless and massive)
- POWHEG matching for EW corrections
- Initial state photon shower
- YFS resummation with explicit photons
- Special treatment of WW threshold

from Pia’s talk slides

4. Merging of the ISR and EPA structure functions with matrix element calculations

Krzysztof Mękała

- This was motivated by the detection of DM at the future e^+e^- collider via mono-photon.



- Merging between ISR and ME photon to avoid double-counting using Whizard.

General idea: simulating very soft and collinear photons with the parametric approach and all detectable photons with the ME

Merging procedure:

$$\text{ME photons} - E \geqslant 1 \text{ GeV and } q_\pm \geqslant q_{merge}$$
$$\text{ISR photons} - E < 1 \text{ GeV or } q_\pm < q_{merge}$$

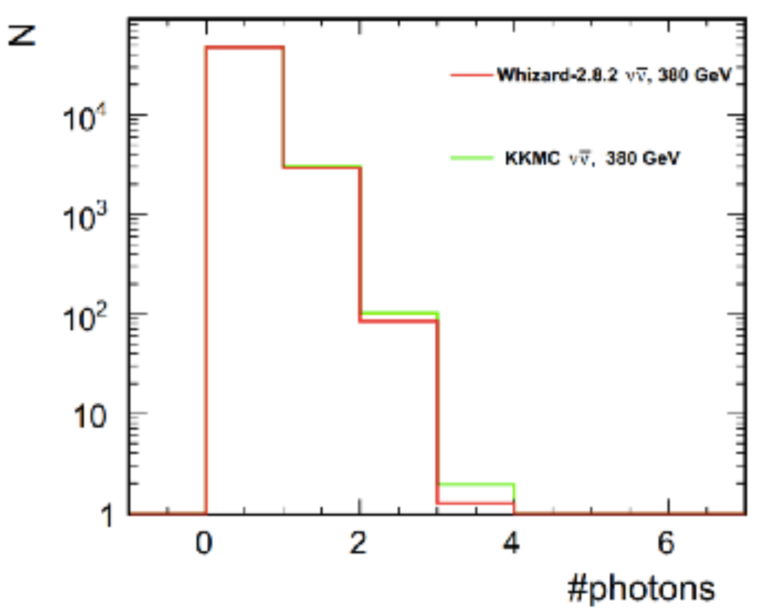
from Krzysztof's talk slides

4. Merging of the ISR and EPA structure functions with matrix element calculations

Krzysztof Mękała

CLIC380: results hardly depend on the merging scale and are comparable with those from another generator.

q_{merge} [GeV]	$\sigma(e^+e^- \to \nu\bar{\nu})$ [fb]
0.1	50,000
0.5	50,400
1	50,600
10	50,800
50	50,500



Example of physical analysis: *Sensitivity of future e^+e^- colliders to processes of dark matter production with light mediator exchange*, July 2021,
J. Kalinowski, W. Kotlarski, KM, P. Sopicki, A.F. Żarnecki, arXiv:2107.11194

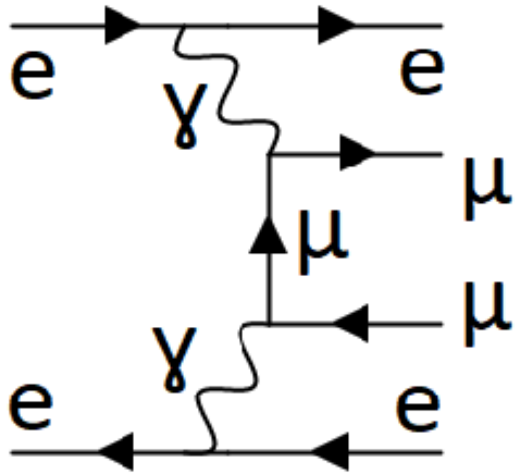
from Krzysztof's talk slides

4. Merging of the ISR and EPA structure functions with matrix element calculations

Krzysztof Mękała

Some important $e^+e^- \to$ hadrons processes can occur via exchange of very soft photons.
A part of the background channels can be described within the framework of the Equivalent Photon Approximation ($\gamma\gamma \to q\bar{q}$).
How to simulate such events?

For simplicity, let us consider the di-muon production process given by the following diagram:



from Krzysztof's talk slides

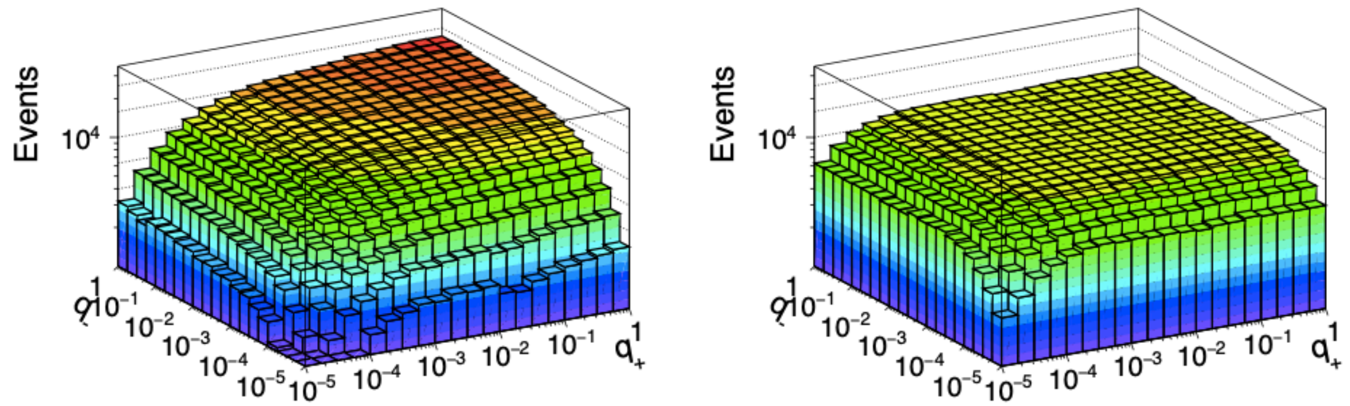
4. Merging of the ISR and EPA structure functions with matrix element calculations

Krzysztof Mękała

This process can be simulated using both the full matrix elements and the *Equivalent Photon Approximation*:

- "full" ME ($e^+e^- \to e^+e^-\mu^+\mu^-$)
- single EPA ($e^\pm\gamma \to e^\pm\mu^+\mu^-$)
- double EPA ($\gamma\gamma \to \mu^+\mu^-$)

$e^+e^- \to e^+e^-\mu^+\mu^-$, 250 GeV, pure QED



(a) Matrix elements (b) EPA

A closer look shows that there is still much to understand!

from Krzysztof's talk slides

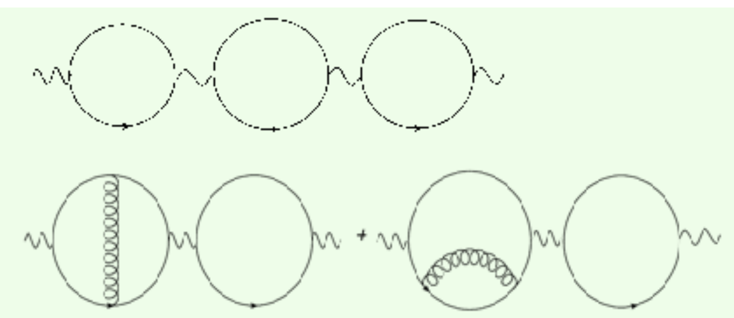
5. Electroweak Precision Observables at future colliders

Lisong Chen, in collaboration with Ayres Freitas.

- The theoretical uncertainties are mostly larger than expected experiment errors.

Experimental Uncertainties Given by Future Electron-Positron Colliders

	Global fits at LEP/SLD/LHC	Current intrinsic theo. error	CEPC	FCC-ee	ILC/GigaZ
M_W[MeV]	12	$4(\alpha^3, \alpha^2\alpha_s)$	1	$0.5 \sim 1$	2.5
Γ_Z[MeV]	2.3	$0.4(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.5	0.1	1.0
$\sin^2\theta_{\text{eff}}^f\ [10^{-5}]$	16	$4.5(\alpha^3, \alpha^2\alpha_s)$	2.3	0.6	1



Why Leading Fermionic Corrections?

- ❑ Enhancement by power of Top Mass.
- ❑ Enhancement by power of flavor numbers N_f

from Lisong's talk slides

5. Electroweak Precision Observables at future colliders

Lisong Chen, in collaboration with Ayres Freitas.

- The sizes of the corrections are smaller than expected.

	$\Delta\overline{M}_W$ (MeV)	$\Delta\sin^2\theta_{eff}$	$\Delta'\sin^2\theta_{eff}$	$\Delta\overline{\Gamma}_{tot}$ [MeV]	$\Delta'\overline{\Gamma}_{tot}$ [MeV]
$\mathcal{O}(\alpha^3)$	-0.389	1.34×10^{-5}	2.09×10^{-5}	0.331	0.255
$\mathcal{O}(\alpha^2\alpha_s)$	1.703	1.31×10^{-5}	-1.98×10^{-5}	-0.103	0.229
Sum	1.314	2.65×10^{-5}	0.11×10^{-5}	0.228	0.484

❖ Comparing between two schemes

	on-shell M_t		$\overline{\text{MS}}$ m_t	
	$\mathcal{O}(\alpha^2)$	$\mathcal{O}(\alpha^2\alpha_s)$	$\mathcal{O}(\alpha^2)$	$\mathcal{O}(\alpha^2\alpha_s)$
Δr $[10^{-4}]$	7.85	-1.09	7.56	-0.50
$\Delta\sin^2\theta^f_{eff}$ $[10^{-5}]$	30.98	1.31	31.18	0.75
$\Delta\overline{\Gamma}_\ell$ [MeV]	0.2412	-0.0157	0.2284	-0.0003
$\Delta\overline{\Gamma}_\nu$ [MeV]	0.4145	-0.0002	0.4152	0.0009
$\Delta\overline{\Gamma}_d$ [MeV]	0.6666	-0.0049	0.6780	-0.0018
$\Delta\overline{\Gamma}_u$ [MeV]	0.4964	-0.0203	0.4911	-0.0029
$\Delta\overline{\Gamma}_{tot}$ [MeV]	4.951	-0.103	4.947	-0.0093

from Lisong's talk slides

5. Electroweak Precision Observables at future colliders

Lisong Chen, in collaboration with Ayres Freitas.

- ❑ EWPOs, like Z-bosn mass, are defined gauge-invariant.
- ❑ Need a gauge invariant theoretical description up to any given accuracy to compare with the measured Z-resonance lineshape, where all EWPOs are extracted from (R.G. Stuart 91).
- ❑ Gives a model-independent profile of four-fermion interaction with gauge resonance.
- ❑ In future electron-positron colliders' era
  - Formally gauge invariant setup .
  - Extendability.

➔ Motivates this project! (GRIFFIN: Gauge-Resonance-In-Four-Fermion-INteraction)

from Lisong's talk slides

Summary of summary

- For many observables, e.g. vector boson masses, scattering cross sections, decay width, the uncertainties of theoretical predictions are still larger than the future ILC experiment accuracy.

- Higher order QED corrections, EW corrections, EW-QCD mixed corrections would be inevitable for the future physics analysis. These are still very challenging.

- The theoretical predictions to the higher order corrections at the future ILC may raise many new difficulties as confronting electron mass, soft/collinear photon, renormalization schemes etc. Serious investigations are needed.

- Toolkits, e.g. McMule, Whizard, GRIFFIN, are under development to cover many different problems.

Thank you!