Precision calculations for future e+e− colliders: targets and tools

Jun 7 – 17, 2022
CERN
US/Eastern timezone

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The main goal is to identify clear theoretical and computational targets for high-precision predictions of relevance to the programme of future e+e− colliders. The workshop will be divided into two parts, of one week each, as follows:

- **Week 1** (7th to 10th of June): select key physics questions and observables
- **Week 2** (13th to 17th of June): current status and advancements in multi-loop calculations required to match the precision goals

During **Week 1**, we will involve both theorists and experimentalists to identify key physics objectives and a set of important observables, to provide clear reference targets for the theory community.

During **Week 2**, we will dive deeper into the technical aspects of such calculations, with an overview of the status of current computational techniques (with a focus on multi-loop calculations), and discussions on the required future steps.

The workshop will have a limited number of invited talks occupying only a small fraction of the days, with ample time for discussions and collaborative work. We aim at promoting the development of an active community and foster new collaborations that will target these important questions.

Z/W physics

P. Janot

Theory and experiment at the Z pole

- Tasks for theory
  - Identify observables/parameters that contain sensitivity to new phenomena
    - Via loops in γ, Z, W propagators (flavour universal), e.g., S, T, U @LEP/SLC
    - Via boxes and vertices (flavour dependent), e.g., δ_b @ LEP/SLC
    - Via direct long distance propagator effects (universality violation): e.g., new Z'
    - Via mixing with known particles, e.g., Z'/Z mixing, ν/N mixing, …
  - Develop high-precision SM procedures to extract these parameters from measurements
    - Precise (maybe not universal?) QED/QCD Monte Carlo / radiator for ISR/FSR/IFI, …
  - Perform high-precision calculations of these observables/parameters in the SM
    - Precise multi-loop calculations with, e.g., m_Z, G_F, $\alpha_{QED}(0)$ as basic inputs
      - → Also requires high-precision theory to extract ancillary quantities from experimental measurements

        $\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$, m_{top} , m_b, m_H, etc. to reduce parametric uncertainties
  - Develop sophisticated MC event generators, for direct tests of the theoretical prediction
    - Also needed to remove detector acceptance and selection inefficiencies

Z/W physics

P. Janot

Summary: Theory inputs for Z lineshape observables

- Numbers are given here for FCC-ee (best prospects)

Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	91187500 ± 2100	4	100	10 ?	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	2495500 ± 2300 [*]	4	25	5 ?	Lineshape QED unfolding Relation to measured quantities
σ^0_{had} (pb)	41480.2 ± 32.5 [*]	0.04	4	0.8	Bhabha cross section to 0.01% $e^+e^- \rightarrow \gamma\gamma$ cross section to 0.002%
N_ν ($\times 10^3$) from σ_{had}	2996.3 ± 7.4	0.007	1	0.2	Lineshape QED unfolding $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{SM}$
R_ℓ ($\times 10^3$)	20766.6 ± 24.7	0.04	1	0.2 ?	Lepton angular distribution (QED ISR/FSR/IFI, EW corrections)
$\alpha_s(m_Z)$ ($\times 10^4$) from R_ℓ	1196 ± 30	0.1	1.5	0.4 ?	Higher order QCD corrections for Γ_{had}
R_b ($\times 10^6$)	216290 ± 660	0.3	?	< 60 ?	QCD (gluon radiation, gluon splitting, fragmentation, decays, ...)

- And also sophisticated and state of the art MC generators (signal and backgrounds)
  - Plus, maybe, redefined EW Precision Parameters (EWPP) and extraction procedures ?

[*] https://arxiv.org/abs/1912.02067

Z/W physics

P. Janot

Summary: Theory inputs for asymmetries

Observables	Present value (×10⁴)	TeraZ / GigaZ stat.	TeraZ / GigaZ current syst.	Theory input (not exhaustive)
A_e from P_τ (FCC-ee)	1514 ± 19	0.07	0.20	SM relation to measured quantities
A_e from A_{LR} (ILC)		0.15	0.80	
A_μ from A_{FB} (FCC-ee)	1456 ± 91	0.23	0.22	Accurate QED (ISR, IFI, FSR)
A_μ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_τ from P_τ (FCC-ee)	1449 ± 40	0.05	2.00	Prediction for non-τ backgrounds
A_τ from A_{FB} (FCC-ee)		0.23	1.30	
A_τ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_b from A_{FB} (FCC-ee)	8990 ± 130	0.24	2.10	QCD calculations
A_b from A_{FB}^{pol} (ILC)		0.90	5.00	
A_c from A_{FB} (FCC-ee)	65400 ± 210	2.00	1.50	
A_c from A_{FB}^{pol} (ILC)		2.00	3.70	

Projections from https://www.overleaf.com/read/xnfpvbdgfgpr

- And also sophisticated and state of the art MC generators (signal and backgrounds)
  - Plus, maybe, redefined EW Precision Parameters (EWPP) and extraction procedures ?

Z/W physics

A. Freitas

Z lineshape

- Deconvolution of initial-state QED radiation:

$$\sigma[e^+e^- \to f\bar{f}] = \mathcal{R}_{\rm ini}(s,s') \otimes \sigma_{\rm hard}(s')$$

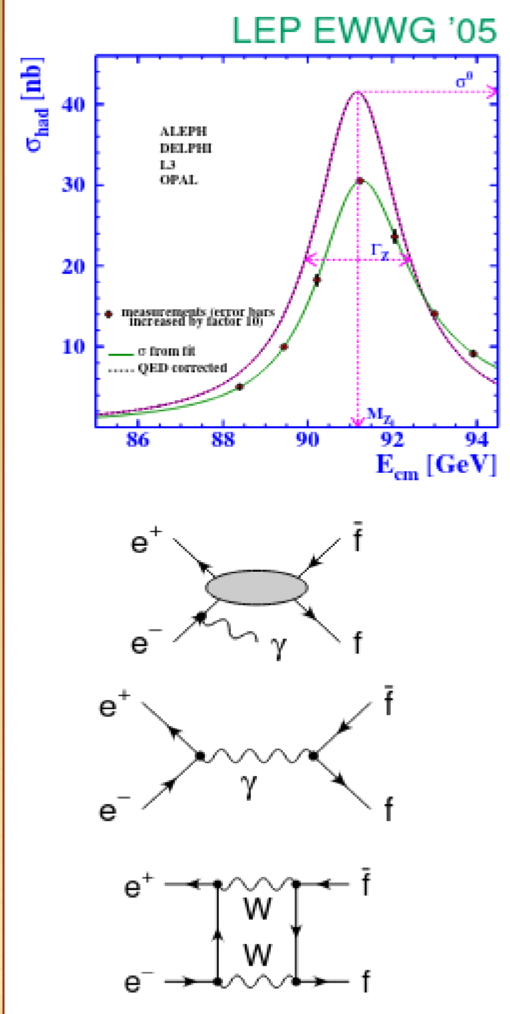
- Subtraction of γ-exchange, γ–Z interference, box contributions:

$$\sigma_{\rm hard} = \sigma_{\rm Z} + \underbrace{\sigma_\gamma + \sigma_{\gamma \rm Z} + \sigma_{\rm box}}$$

- Z-pole contribution:

$$\sigma_{\rm Z} = \frac{R}{(s-\overline{M}^2_{\rm Z})^2 + \overline{M}^2_{\rm Z}\overline{\Gamma}^2_{\rm Z}} + \sigma_{\rm non-res}$$

computed in SM



Z/W physics

A. Freitas

Pole expansion

Expand amplitude for $e^+e^- \to f\bar{f}$ about **complex pole** $s_0 \equiv \overline{M}_Z^2 + i\overline{M}_Z\overline{\Gamma}_Z$:

$$\mathcal{M}_{ij} = \frac{R_{ij}}{s - s_0} + S_{ij} + (s - s_0)S'_{ij} + \dots \qquad (i,j = V,A)$$

Current state of art: R @ NNLO + leading higher orders
S @ NLO
S' @ (N)LO

For future ee colliders: (at least) one order more!

$\rightarrow$ also matching to Monte-Carlo for QED/QCD ISR/FSR/IFI

Z/W physics

A. Freitas

Future theory and parametric uncertainties

Freitas, Heinemeyer, et al. '19

	CEPC	FCC-ee	perturb. error with 3-loop†	Param. error scen. 1*	Param. error scen. 2*
M_W [MeV]	0.5	0.4	1	2.1	0.6
Γ_Z [MeV]	0.025	0.025	0.15	0.15	0.1
R_b [10^{-5}]	4.3	6	5	< 1	< 1
$\sin^2\theta^\ell_{\text{eff}}$ [10^{-5}]	<1	0.5	1.5	2	1

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2\alpha_s)$, leading 4-loop
(N_f^n = at least n closed fermion loops)

Parametric inputs:

***Scenario 1:** $\delta m_t = 600$ MeV, $\delta\alpha_s = 0.0002$, $\delta M_Z = 0.5$ MeV,
$\delta(\Delta\alpha) = 5\times10^{-5}$

***Scenario 2:** $\delta m_t = 50$ MeV, $\delta\alpha_s = 0.0002$, $\delta M_Z = 0.5$ MeV,
$\delta(\Delta\alpha) = 3\times10^{-5}$

Z/W physics

- Measurement of WW threshold: [P. Azzurri]
  $\Delta\Gamma_W = 0.96$ MeV and $\Delta m_W = 0.41$ MeV
- Measurements in WW continuum: [P. Azzurri, G. Wilson]
  W mass with ~2 MeV, precise W decay BRs
  → good control of ISR and final-state jet dynamics
- Need NLL and NNLL QED PDFs for simulation of QED radiation [S. Frixione]

S. Kluth

Shopping list

	f.o.	resummation	soft corrections
$e^+e^- \rightarrow$ 3 jets	N3LO?	beyond N3LL?	y dependent
$e^+e^- \rightarrow$ 4 jets	NNLO?	MC N(N?)LL PS	possible? MC
$e^+e^- \rightarrow$ 5 jets	NNLO?	MC N(N?)LL PS	possible? MC
$e^+e^- \rightarrow$ hadrons		beyond NMMLA?	
$e^+e^- \rightarrow$ γ+n jets	NLO EW		
$e^+e^- \rightarrow Q\bar{Q}g$	NNLO	NNLL? N(N?)LL MC PS?	
Z/W EWPO	α_S^5, α^2, α^3, $\alpha\alpha_S^2$, $\alpha^2\alpha_S$		
τ had. decays	α_S^5? FOPT/CIPT^{RS}		OPE vs DV models

QCD

- Non-perturbative aspects important for strong coupling determination [P. Nason]
  → new ideas to test and reconcile MC and analytic methods
  → move to higher cm energies to reduce NP QCD
- Definition of new observables to reduce NP QCD [A. Banfi]

Top

M. Beneke

Summary

I $e^+e^- \to t\bar{t}X$ cross section near threshold now computed at NNLO in (PNR)QCD + top-Yukawa effects

- Sizeable 3rd order corrections and reduction of theoretical uncertainty to about $\pm 3\%$.

II Realistic predictions for $e^+e^- \to W^+W^-b\bar{b}$ near top-pair threshold

- NNLO available, including cuts invariant mass cuts.

III Parameter dependences $(m_t, \Gamma_t, y_t, \alpha_s)$ can be studied.

- (m_t, Γ_t) with unrivaled accuracy.
- y_t with 20% accuracy from threshold already challenging.

IV Further requirements:

- ISR / QED PDF's for $x \to 1$ with NLL evolution
- N4LO QCD would be reassuring, but appears prohibitive. ← needed for Δmt < 40 MeV

https://www.hepforge.org/downloads/qqbarthreshold/

Higgs

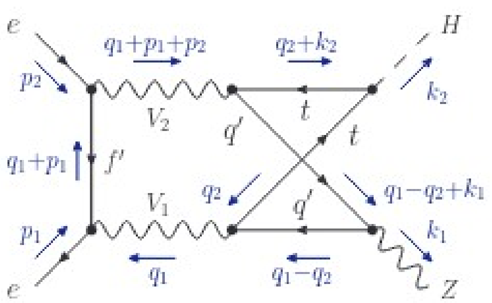
L. Yang

Towards two-loop EW corrections to ZH

A must to match the ~0.3% experimental accuracy

A rather challenging task: ~20000 diagrams, a lot of physical scales Li, Wang, Wu: 2012.12513

Evaluation of a class of double boxes with a top quark loop Song, Freitas: 2101.00308



Further development of computational techniques required!

→ Talks covering both analytic and numeric methods

e.g.: Canonical differential equations in both GPL sectors and elliptic sectors

Numeric solutions (pySecDec, DiffExp, AMFlow, ...)

Perhaps some kind of approximate result is good enough

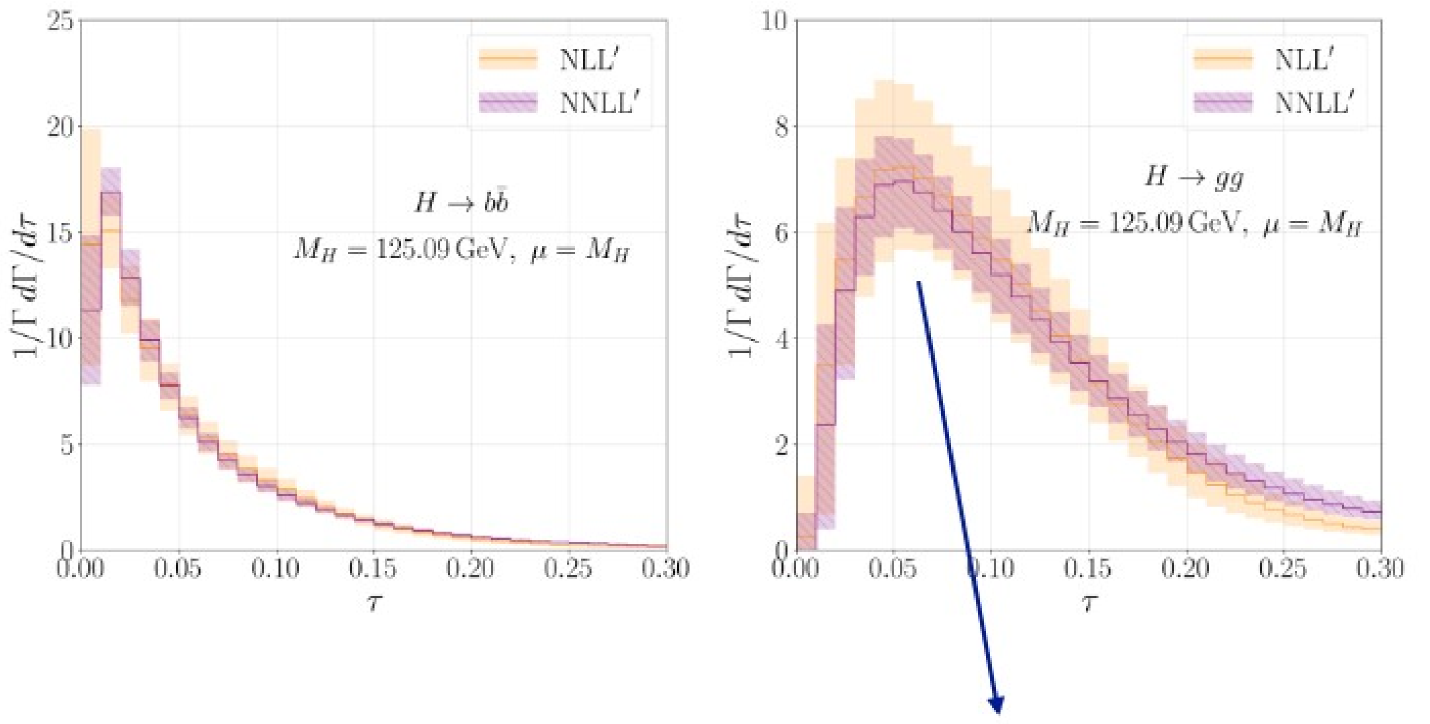
→ Vague thought: asymptotic expansion in the limit $m^2_{\text{everything}} \ll s, m_t^2$?

Higgs

L. Yang

Resummed predictions

Alioli et al.: 2009.13533



Large uncertainties in the gluon channel; N^3LL or N^3LL' needed?

Techniques for EW calc.

- **Challenge:** many parameters (masses, kin. scales)
- Common approach: reduction of large # of integrals to small # of *master integrals* (IBP red.)

  [T. Peraro, V. Sotnikov]

  – Huge expressions when many scales/masses

  – Partially overcome with finite-field methods (reconstruct analytical from numerical) and syzygies (find easily solvable relations)

  – Or fully numerically...?

- Solve MIs with differential equations
  – Special functions [A. v. Manteuffel, S. Weinzierl]
  – Numerical integration [L. Chen]
  – Series expansions [N. Rana, M. Hidding, X. Liu]

  (IBP red. needed but can be simplified in some cases)

Techniques for EW calc.

- Direct numerical integration
  - Sector decomposition [V. Magerya]
  - Mellin-Barns representations [J. Gluza]

  Slow convergence of multi-dim. Integrals, but can be improved with QMC integration, GPUs

- Local unitarity (loop-tree duality) [V. Hirschi]

  → integrate loop and real radiation together

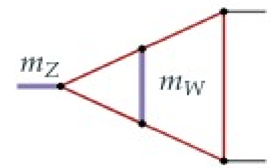
  → need to avoid/subtract spurious and physical singularities

  (related discussion by C. Anastasiou)

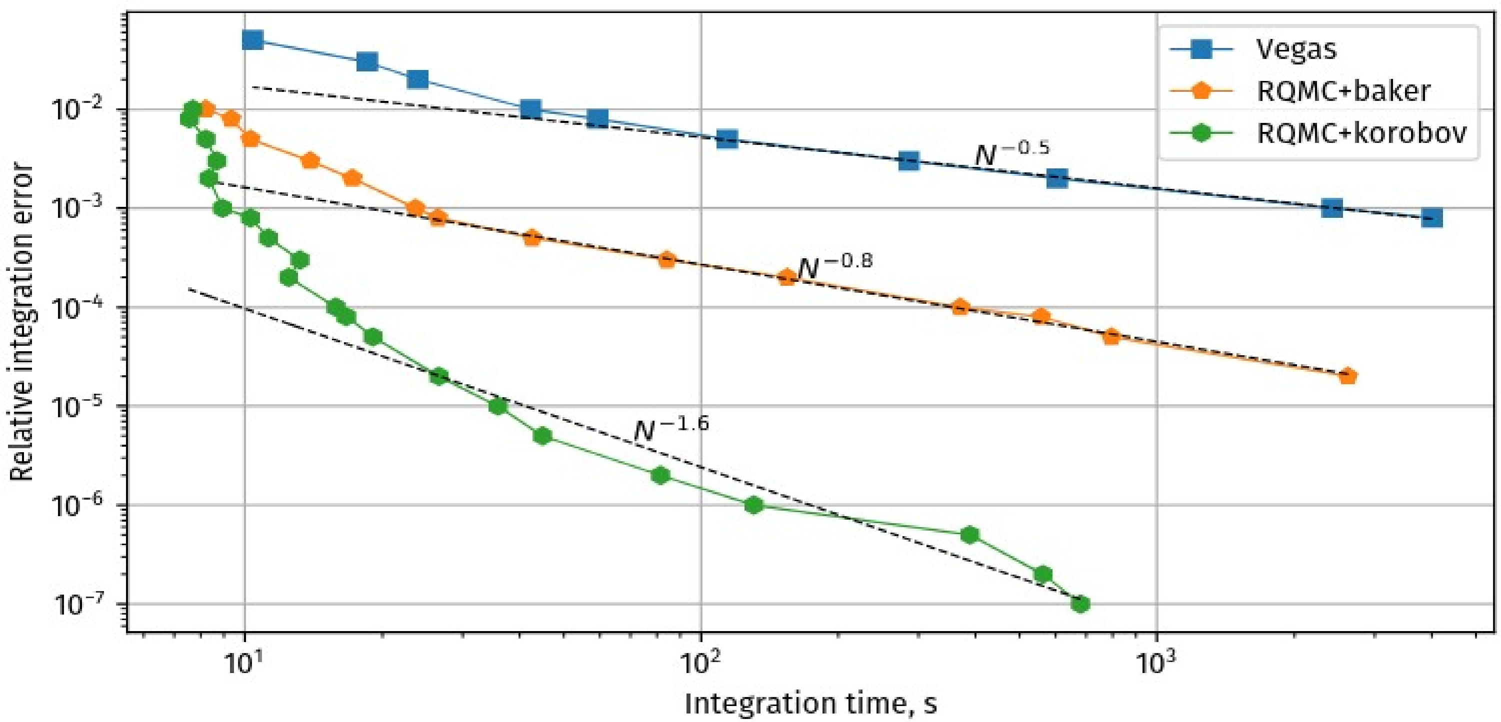
Techniques for EW calc.

Monte Carlo vs RQMC

Integration time scaling for Monte Carlo (VEGAS)
vs Randomized Quasi Monte Carlo (QMC).[1]



V. Magerya



[1] pySECDEC v1.5.3 on NVidia A100 GPU.