Going forward with theory

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11th FCC-ee workshop: Theory and Experiments

CERN, 11 January 2019

FCC hh ee he

National Science Centre Poland

cost European Cooperation in Science and Technology

STANDARD MODEL

1. $\alpha(M_Z^2)$ in precision physics (precision physics limitations)

Uncertainties of hadronic contributions to effective α are a problem for electroweak precision physics: besides top Yukawa y_t and Higgs self-coupling λ

α , G_μ, M_Z **most precise input parameters** $\Rightarrow$ **precision predictions**

50% non-perturbative

$\sin^2\Theta_f, v_f, a_f, M_W, \Gamma_Z, \Gamma_W, \cdots$

$\alpha(M_Z), G_\mu, M_Z$ **best effective input parameters for VB physics (Z,W) etc.**

$$\frac{\delta\alpha}{\alpha} \sim 3.6 \times 10^{-9}$$
$$\frac{\delta G_\mu}{G_\mu} \sim 8.6 \times 10^{-6}$$
$$\frac{\delta M_Z}{M_Z} \sim 2.4 \times 10^{-5}$$
$$\frac{\delta\alpha(M_Z)}{\alpha(M_Z)} \sim 0.9 \div 1.6 \times 10^{-4} \quad \text{(present : lost } 10^5 \text{ in precision!)}$$
$$\frac{\delta\alpha(M_Z)}{\alpha(M_Z)} \sim 5.3 \times 10^{-5} \quad \mathtt{(FCC-ee/ILC\ requirement)}$$

LEP/SLD: $\sin^2\Theta_{\rm eff} = (1 - v_l/a_l)/4 = 0.23148 \pm \boxed{0.00017}$

$\delta\Delta\alpha(M_Z) = 0.00020 \quad \Rightarrow \quad \delta\sin^2\Theta_{\rm eff} = \boxed{0.00007}$; $\delta M_W/M_W \sim 4.3 \times 10^{-5}$

affects most precision tests and new physics searches!!!

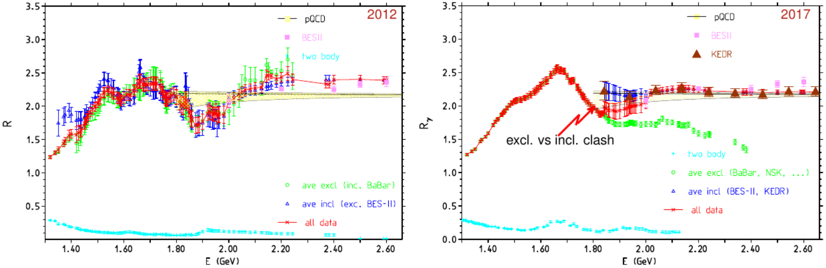
$$\frac{\delta M_W}{M_W} \sim 1.5 \times 10^{-4}, \quad \frac{\delta M_H}{M_H} \sim 1.3 \times 10^{-3}, \quad \frac{\delta M_t}{M_t} \sim 2.3 \times 10^{-3}$$

For pQCD contributions very crucial: precise QCD parameters $\alpha_s,\ m_c,\ m_b,\ m_t \Rightarrow$ **Lattice-QCD**

SM precision parameters determination: $\alpha(M_Z^2)$

❒ Still an issue in HVP

❒ region 1.2 to 2 GeV data; test-ground exclusive vs inclusive R measurements (more than 30 channels!) VEPP-2000 CMD-3, SND (NSK) scan, BaBar, BES III radiative return! still contributes 50% of uncertainty



● illustrating progress by BaBar and NSK exclusive channel data vs new inclusive data by KEDR. Why point at 1.84 GeV so high?

2. Reducing uncertainties via the Euclidean split trick: Adler function controlled pQCD

- experiment side: new more precise measurements of $R(s)$
- theory side: $\alpha_{\mathrm{em}}(M_Z^2)$ by the "Adler function controlled" approach

$$\alpha(M_Z^2) \quad = \quad \alpha^{\mathrm{data}}(-s_0) + \left[\alpha(-M_Z^2) - \alpha(-s_0)\right]^{\mathrm{pQCD}} + \left[\alpha(M_Z^2) - \alpha(-M_Z^2)\right]^{\mathrm{pQCD}}$$

data pQCD Adler pQCD HVP

- the space-like $-s_0$ is chosen such that pQCD is well under control for $-s < -s_0$; offset $\alpha^{\mathrm{data}}(-s_0)$ integrated $R(s)$ data
- the Adler function is i) the monitor to control the applicability of pQCD and ii) pQCD part $\left[\alpha(-M_Z^2) - \alpha(-s_0)\right]^{\mathrm{pQCD}}$ by integrated Adler function $D(Q^2)$
- small remainder $\left[\alpha(M_Z^2) - \alpha(-M_Z^2)\right]^{\mathrm{pQCD}}$ by calculation of VP function $\Pi'_\gamma(s)$

Conclusion: 3 approaches should be further explored for better error estimate

Note: theory-driven standard analyses ($R(s)$ integral) using pQCD above 1.8 GeV cannot be improved by improved cross-section measurements above 2 GeV !!!

precision in α:	present	direct	1.7×10^{-4}
		Adler	1.2×10^{-4}
	future	Adler QCD 0.2%	5.4×10^{-5}
		Adler QCD 0.1%	3.9×10^{-5}
	future	via $A_{\rm FB}^{\mu\mu}$ off Z	3×10^{-5}

- Adler function method is competitive with Patrick Janot's direct near Z pole determination via forward backward asymmetry in $e^+e^- \to \mu^+\mu^-$

$$A_{\rm FB}^{\mu\mu} = A_{\rm FB,0}^{\mu\mu} + \frac{3\,a^2}{4\,v^2}\frac{\mathcal{I}}{\mathcal{Z}+\mathcal{G}}$$

where

$\gamma - Z$ interference term	$\mathcal{I} \propto \alpha(s)\,G_\mu$
Z alone	$\mathcal{Z} \propto G_\mu^2$
γ only	$\mathcal{G} \propto \alpha^2(s)$
v vector Z coupling	also depends on $\alpha(s \sim M_Z^2)$ and $\sin^2\Theta_f(s \sim M_Z^2)$
a axial Z coupling	sensitive to ρ-parameter (strong M_t dependence)

❑ using v, a as measured at Z-peak

W-pair production

Success story at LEP2:

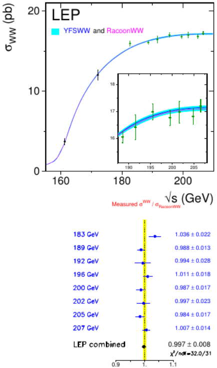
- σ_{WW}: 1%-level agreement with NLO theory

$\Rightarrow$ test of EW-sector of SM at quantum level

- measurement of branching rations (lepton universality)
- bounds on anomalous triple vector-boson couplings

$\Rightarrow$ test of non-abelian structure

- W-mass measurement from kinematic reconstruction ($+\ \sigma_{WW}$ at threshold)



SM W-physics, FCC-ee-W

Introduction

FCC-ee study: (1703.01626 [hep-ph])

- single point $\sqrt{s} = 161.4\,\text{GeV}$

  $$\Delta M_W \simeq 0.25\,\text{MeV}$$

  with $15\,\text{ab}^{-1}$ if

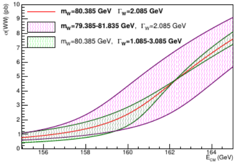
  $$\delta\sigma_{WW}^{\text{th.}} < 0.6\,\text{fb}(\approx 0.01\%)$$

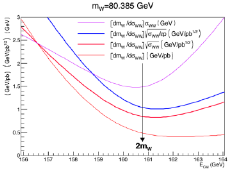
- simultaneous fit

  $\Delta M_W \simeq 0.41\,\text{MeV},\ \Delta\Gamma_W \simeq 1.10\,\text{MeV}$

  from two points

  $$\sqrt{s} = 157.5,\ 162.3\,\text{GeV}$$





CEPC study: (arXiv:1812.09855 [hep-ex])

- 3 points

  $$\sqrt{s} = 157.5,\ 161.5,\ 162.3\,\text{GeV}$$

- with 2.6ab^{-1}

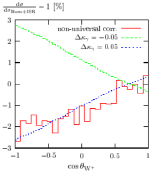
  $$\Delta M_W \simeq 1\,\text{MeV},\ \Delta\Gamma_W \simeq 2.8\,\text{MeV}$$

SM W-physics, FCC-ee-W

Beyond threshold: anomalous gauge couplings at $\sqrt{s} = 240\,\mathrm{GeV}$

- traditional TGC parameters g_1^Z, $\kappa_{Z/\gamma}$, $\lambda_{Z/\gamma}$ related to coefficients of $D = 6$ operators , $\mathcal{L}_{D=6} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$
- recent EFT calculations of $e^- e^+ \to W^- W^+$ and analysis of LEP2 data (Buchalla et al. 13; Wells/Zhang 15; Berthier et al. 16)
- some $\mathcal{O}_i$ affect both Higgs and EW measurements
  $\Rightarrow$ consistent EFT fit of FCC-ee data required
  (talks by Das Bakshi, You, de Blas)
- Effect of non-universal EW corrections similar to size of TGCs accessible at LEP2
  (Denner et al. 01)

$\Rightarrow$ NNLO EW for $e^- e^+ \to W^- W^+$ required for FCC-ee accuracy



NLO corrections near threshold

$$s - 4M_W^2 \sim M_W\Gamma_W \Rightarrow \beta \sim \sqrt{\Gamma_W/M_W} \sim \alpha^{1/2}$$

Schematic structure of NLO corrections to total cross section:

$$\Delta^{(1)}\sigma_{WW\to 4f}|_{s\approx 4M_W^2} \propto \beta\alpha\left[\frac{1}{\beta} + \ln\beta\ln\left(\frac{m_e}{M_W}\right) + \ln\left(\frac{m_e}{M_W}\right) + C^{(1)}\right] + \text{const} + \mathcal{O}(\beta)$$

Enhanced corrections in threshold limit

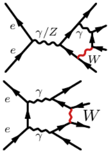
- mass logarithms $\ln\left(\frac{m_e}{M_W}\right)$: resum in ISR structure function
- Coulomb corrections $\sim \alpha/\beta \sim$ screened by finite W-width
  $\Rightarrow$ Coulomb corrections $\sim \alpha^n(M_W/\Gamma_W)^{n/2} \sim \alpha^{n/2}$
  enhanced but resummation not necessary
  (Method for all-order resummation known $\Rightarrow t\bar{t}$)
- soft $\ln\beta$ corrections $\sim \alpha\ln\alpha \sim 0.04$
  $\Rightarrow$ resummation not necessary

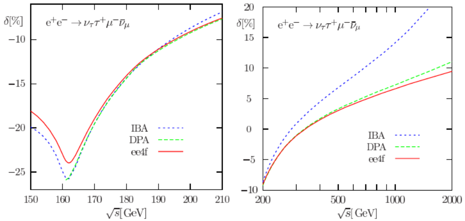
Full NLO calculation for $e^+e^- \to 4f$ (Denner, Dittmaier, Roth, Wieders 05)

- More than 1000 1-loop diagrams, 5, 6-point loop integrals

$\Rightarrow$ pioneering methods for six-point diagrams
now automated for LHC: `RECOLA`, `OpenLoops`, `MadLoops`

- complex mass scheme for W decay width
- fully differential calculation
- not easy to incorporate higher-order effects
- DPA not sufficient at threshold and for $\sqrt{s} > 500$ GeV





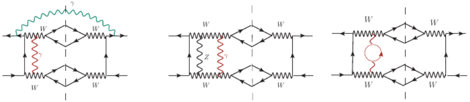
SM W-physics, FCC-ee-W

EFT expansion in $\alpha \sim \frac{\Gamma_W}{M_W} \sim \beta^2$ (Beneke/Falgari/CS/Signer/Zanderighi 07)

- systematically possible to include higher-order corrections
- limited to total cross section near threshold

Leading NNLO corrections

- 2nd Coulomb correction $\sim \alpha^2/\beta^2 \sim \alpha$ (Fadin et al. 95)
- Coulomb-enhanced corrections $\sim \alpha^2/\beta \sim \alpha^{3/2}$ (Actis et al. 08)



- Numerical effect: $\Delta\sigma_{WW} \sim 5‰$; $[\delta M_W] \lesssim 3\,\mathrm{MeV}$

	$\sigma(e^- e^+ \to \mu^- \bar{\nu}_\mu u \bar{d})$(fb)			
$\sqrt{s}$ [GeV]	$\mathrm{NLO}_{\mathrm{EFT}}$	$\mathrm{NLO}_{\mathrm{ee4f}}$ [DDRW]	$\Delta_{\mathrm{NNLO}}(\alpha^2/\beta^2)$	$\Delta_{\mathrm{NNLO}}(\alpha^2/\beta)$
161	117.5	118.77	0.44 (3.7‰)	0.15 (1.3‰)
170	397.8	404.5	0.25 (0.6‰)	1.6 (3.9‰)

Future improvements of theory predictions?

Implementation of state-of-the art calculations in public tools?

- NLO-EW $e^-e^+ \to 4f$ now possible with standard tools
  (RECOLA, OpenLoops, MadLoops + SHERPA, MadGraph, WHIZARD...)
  but not (yet) optimized for e^-e^+ (ISR, Beamstrahlung)
- Two-loop Coulomb-enhanced corrections for differential observables doable; (related: $t\bar{t}$ with Coulomb resummation in WHIZARD)
  (no guarantee of formal accuracy for general distributions)

Full NNLO in EFT for total cross section

- Soft $\log\beta$ terms can be adapted from QCD results
- NNLO $\log(m_e/M_W)$ terms doable (c.f. Bhabha scattering)
- two-loop hard non-logarithmic corrections
  (from amplitudes for $e^+e^- \to W^+W^-$ at threshold: border of current capabilities)
  resulting uncertainty from cross-section calculation
  $$\Delta\sigma^{(2}_{\text{hard}} = \left(\frac{\alpha}{2\pi}\right)^2 c^{(2)}\sigma^{(0)} \sim (1-2)‰ \text{ for estimate } c^{(2)} = (c^{(1)})^2$$

Full NNLO for $e^+e^- \to 4f$: completely new methods needed

SM W-physics, FCC-ee-W: hybrid approach

Conclusions and outlook

- KoralW+YFSWW3: LEP2 precision is 0.5%.
  Factor of $20 \div 50$ improvement is needed for FCCee
- Lesson from LEP2: be pragmatic, split into Double- and Single-Pole, pick only numerically dominant terms:
  - $\mathcal{O}(\alpha^1)$ for $e^- e^+ \to 4f$ must be implemented in MC with explicit split into Double Pole and Single Pole. Calculations exist
  - $\mathcal{O}(\alpha^2)_{DP}$ calculations for the Double-Pole production and decay parts are needed! Feasible?
  - $\mathcal{O}(\alpha^2)_{SP}$ and $\mathcal{O}(\alpha^3)$ seem to be negligible
- More detailed analysis at the threshold may be instrumental
  - EFT methods promising, but for now inclusive results only
  - Non-factorizable soft interferences can be exponentiated within YFS scheme. How much of the higher order corrs. would be reproduced this way?

The overall precision tag $\sim 2 \times 10^{-4}$ feasible (?)

YFSWW3$\oplus$KoralW with new exponentiation
look like a good starting point

PAUL SCHERRER INSTITUT

SM PRECISION PREDICTIONS FOR HIGGS PARTIAL WIDTHS

Michael Spira (PSI)

I Introduction

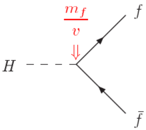
II Higgs Boson Decays

III Summary

SM Higgs

II *HIGGS BOSON DECAYS*

Standard Model



$BR(H \to b\bar{b}) \sim 58\%$
$BR(H \to \tau^+\tau^-) \sim 6\%$
$BR(H \to c\bar{c}) \sim 3\%$
$BR(H \to \mu^+\mu^-) \sim 0.02\%$

- $H \to b\bar{b}$ dominant

$$\Gamma(H \to f\bar{f}) = \frac{N_c G_F M_H}{4\sqrt{2}\pi}\, m_f^2\, (1 + \delta_{\mathrm{QCD}} + \delta_t + \delta_{mixed})\,(1 + \delta_{elw})$$

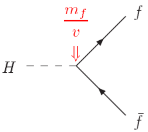
- elw. corr. δ_{elw}: moderate in interm. mass range

Fleischer, Jegerlehner
Bardin, . . .
Dabelstein, Hollik
Kniehl

$$\delta_{\mathrm{elw}} \approx \frac{3}{2}\frac{\alpha}{\pi} e_f^2 \left(\frac{3}{2} - \log\frac{M_H^2}{M_f^2}\right) + \frac{G_F}{8\pi^2\sqrt{2}}\left\{k_f M_t^2 + M_W^2\left[-5 + \frac{3}{s_W^2}\log c_W^2\right] - M_Z^2\frac{6v_f^2 - a_f^2}{2}\right\}$$

II *HIGGS BOSON DECAYS*

Standard Model



$$
\begin{aligned}
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Fleischer, Jegerlehner
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SM Higgs

Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$	$\sim 0.5\%$	NNNNLO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$	$\sim 0.5\%$	NLO
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	NNNLO approx. / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$	(N)NLO

- QCD: variation $\mu_R = [1/2, 2]\mu_0$
  elw: missing HO estimated from known structure at NLO
  different uncertainties added linearly for each channel

- parametric uncertainties:
  $m_t = 172.5 \pm 1$ GeV $\qquad \alpha_s(M_Z) = 0.118 \pm 0.0015$
  $m_b(m_b) = 4.18 \pm 0.03$ GeV $\qquad m_c(3\text{GeV}) = 0.986 \pm 0.025$ GeV
  different uncertainties added quadratically for each channel

- total uncertainties: parametric & theor. uncertainties added linearly

FCC-ee-H

One-loop electroweak radiative corrections to $e^+e^- \to e^+e^-, f\bar{f}, ZH$ for polarized $e+e-$ beams

Yahor Dydyshka[a], L. Kalinovskaya[a], L. Rumyantsev[a,b], R. Sadykov[a], V. Yermolchyk[a], A. Arbuzov[c], S. Bondarenko[c]

[a] *DLNP JINR, Dubna,* [c] *BLTP JINR, Dubna,*
[b] *IoP, Southern Federal University, Rostov-on-Don, Russia*

11th FCC-ee workshop: Theory and Experiments, 10.01.2019

Methods to determine m_c and m_b

- non-relativistic sum rules

  [Beneke,Maier,Piclum,Rauh'16; Penin,Zerf'14; . . .]

- $\Upsilon(1S)$ bounds state energy

  [Peset,Pineda,Segovia'18; Kiyo,Mishima,Sumino'16; . . .]

- lattice

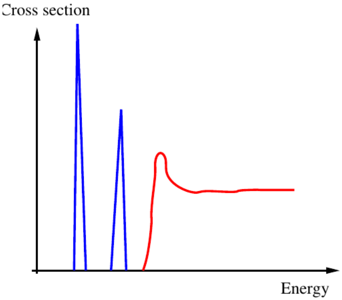
  [Fermilab Lattice+MILC+TUMQCD'18; HPQCD'18; . . .]

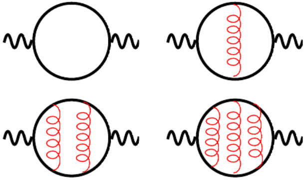
- . . .
- relativistic sum rules ("low-n SRs", "SVZ SRs")

  [Chetyrkin et al.; Dehnadi et al.'15; . . .]

SM FCC-ee-t

Relativistic sum rules





[Chetyrkin,Kühn,Sturm; Boughezal, Czakon, Schutzmeier;

Marquard; Schröder; Lee; ...]

$$\Pi_Q(q^2) \sim \sum \bar{C}_n \left(\frac{q^2}{4m_Q^2}\right)^n$$

$$R_Q = \frac{\sigma(e^+e^- \to Q\bar{Q} + \ldots)}{\sigma(e^+e^- \to \mu^+\mu^-)} = 12\pi \mathrm{Im}\left[\Pi_Q(q^2 = s + i\varepsilon)\right]$$

$$\mathcal{M}_n^{\mathrm{exp}} \equiv \int \frac{\mathrm{d}s}{s^{n+1}} R_Q(s) \qquad \mathcal{M}_n^{\mathrm{th}} = \frac{12\pi^2}{n!} \left(\frac{\mathrm{d}}{\mathrm{d}q^2}\right)^n \Pi_Q(q^2)\Big|_{q^2=0}$$

SM FCC-ee-t, e.g. m_c

m_c

$$\mathcal{M}_n^{\mathrm{th}} \stackrel{!}{=} \mathcal{M}_n^{\mathrm{exp}}$$

$$m_c(\mu) = \frac{1}{2}\left(\frac{\bar{C}_n}{\mathcal{M}_n^{\mathrm{exp}}}\right)^{1/(2n)}$$

latest development: $\bar{C}_4$ analytically to 4 loops [Marquard,Maier'17]

n	m_c(3 GeV)	exp	α_s	μ	np	total
1	993	7	4	2	1	8
2	982	4	7	5	1	10
3	982	3	8	6	1	10
4	1003	2	5	28	1	29

$\boxed{m_c(3\ \mathrm{GeV}) = 0.993(8)\ \mathrm{GeV}}$ $\boxed{m_c(m_c) = 1.279(8)\ \mathrm{GeV}}$

[Kühn,Steinhauser,Sturm'07; Chetyrkin,Kühn,Maier,Maierhöfer,Marquard,Steinhauser,Sturm'09'17]

[Uncertainties: $\delta\mathcal{M}_n^{\mathrm{exp}}$ | $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ | $\mu = (3 \pm 1)$ GeV]

[np: gluon condensate $\left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle$, NLO [Broadhurst et al.'94]]

Asymptotic behaviour

Karlsruhe Institute of Technology

$$m_t^{\mathrm{OS}} = m_t^{\overline{\mathrm{MS}}}(\mu_m)\left(1+\sum_{n\geq 1} c_n\,\alpha_s^n(\mu)\right)$$

IR renormalon predicts large-n behaviour:

$$c_n \underset{n\to\infty}{\longrightarrow} N\frac{\mu}{m(\mu_m)}\tilde{c}_n^{(\mathrm{as})}$$

$b = \beta_1/(2\beta_0)$

$$\tilde{c}_n^{(\mathrm{as})} = (2\beta_0)^n\frac{\Gamma(n+1+b)}{\Gamma(1+b)}\left(1+\frac{s_1}{n+b}+\frac{s_2}{(n+b)(n+b-1)}+\cdots\right).$$

- $s_1, s_2, b, \beta_0, \ldots$ known
- N unknown

[Beneke,Braun'94; Beneke'94; Beneke'95]

SM FCC-ee-t, top mass, beyond 4-loops, N-determined

$m^{\mathrm{OS}} - m^{\overline{\mathrm{MS}}}$

$$\boxed{\delta^{(5+)} m^{\mathrm{OS}} = 0.250^{+0.015}_{-0.038}\,(N) \pm 0.001\,(c_4) \pm 0.010\,(\alpha_s) \pm 0.071\ (\text{ambiguity})\ \mathrm{GeV}}$$

Check: Truncate series at minimal term:

$$\boxed{\delta^{(5+)} m^{\mathrm{OS}} = 0.272^{+0.016}_{-0.041}\,(N) \pm 0.001\,(c_4) \pm 0.011\,(\alpha_s) \pm 0.066\ (\text{ambiguity})\ \mathrm{GeV}}$$

m_c and m_b effects:

- $m_{u,d,s} \ll \Lambda_{\mathrm{QCD}} \ll m_{c,b}$
- typical loop momentum at $\mathcal{O}(\alpha_s^n)$: $m_t e^{-(n-1)}$ [Ball,Beneke,Braun'95]

$$\delta^{(5+)} m^{\mathrm{OS}} = 0.304^{+0.012}_{-0.063}\,(N) \pm 0.030\,(m_{b,c}) \pm 0.009\,(\alpha_s) \pm 0.108\ (\text{ambiguity})\ \mathrm{GeV}$$

$$\frac{m^{\mathrm{OS}}}{m^{\overline{\mathrm{MS}}}(m)} = 1.06213^{+0.00007}_{-0.00038}\,(N) \pm 0.00018\,(m_{b,c}) \pm 0.00086\,(\alpha_s) \pm 0.00066(\text{amb.})$$

[Beneke,Marquard,Nason,Steinhauser'16]

SM FCC-ee-t, Daniel Samitz, shower cuts dependence

MC Top Quark Mass Parameter

Why is there a non-trivial issue in the interpretation of $\mathbf{m_t^{MC}}$?

- picture of "top quark particle" does not apply (non-zero color charge)
- m_t is a scheme-dependent parameter of a perturbative computation
  $\rightarrow$ in which scheme do MC event generators calculate?
- relation of m_t^{MC} to any field theory mass definition can be affected by different contributions (let's consider pole mass just for convention)

$$m_t^{\mathrm{MC}} = m_t^{\text{pole}} + \Delta_m^{\text{pert}} + \Delta_m^{\text{non-pert}} + \Delta_m^{\mathrm{MC}}$$

pQCD contribution:

- perturbative corrections
- depends on MC parton shower setup

this talk

non-perturbative contribution:

- effects of hadronization model
- may depend on parton shower setup

Monte Carlo shift:

- contribution arising from systematic MC uncertainties
- e.g. color reconnection, b-jet modelling, finite width,...
- should be covered by "MC uncertainty" or better negligible

Conclusions/Outlook

- for angular ordered parton showers (Herwig) one can derive the **perturbative contributions** between generator mass and pole masse (Δ_m^{pert})

$$m^{\text{CB}}(Q_0) = m^{\text{pole}} - \frac{2}{3}\alpha_s(Q_0)Q_0 + \mathcal{O}(\alpha_s^2)$$

  this corresponds the **pole of the quark propagator** in presence of a shower cut

- current restrictions:
  - boosted top quarks
  - narrow width approximation
  - top production (2-jettiness)

  needed to remove restriction:
  - $\rightarrow$ parton shower algorithm for slow tops
  - $\rightarrow$ parton shower for unstable tops
  - $\rightarrow$ factorized predictions including top decay

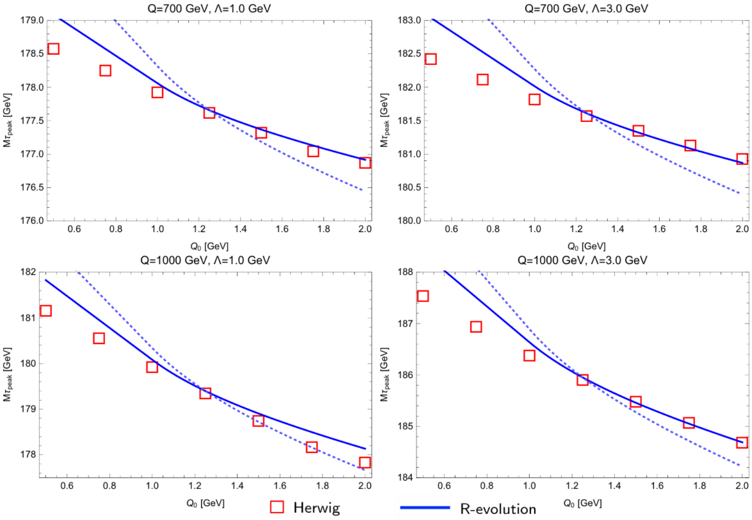
- for all three new conceptual developments are required (w.i.p.)

- study of non-perturbative contributions to the relation between generator mass and pole mass ($\Delta_m^{\text{non-pert}}$) can be carried out by dedicated MC simulations (w.i.p.)

- numerical calibration still important tool for consistency checks

SM FCC-ee-t, Daniel Samitz, shower cuts dependence

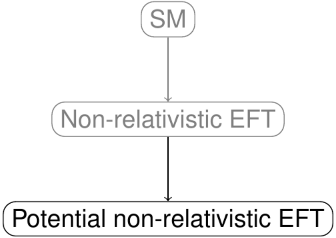
Comparison with Herwig



PNREFT at higher orders

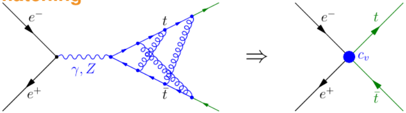
Scales: $m_t, m_W, m_Z, m_H \gg m_t v \gg m_t v^2 \gg \Lambda_{QCD}$

- hard modes: $k \sim m_t \to$ (local) effective vertices
- soft modes: $k \sim m_t v \to$ (non-local) potentials
- potential light particle modes $\to$ (non-local) potentials
- potential top quark modes: $k_0 \sim m_t v^2, \vec{k} \sim m_t v$
- ultrasoft modes: $k \sim m_t v^2$

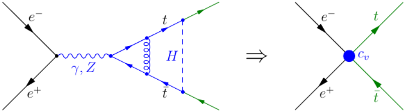


PNREFT at higher orders

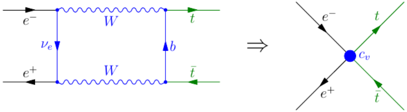
Hard matching



[Marquard, Piclum, Seidel, Steinhauser 2014]



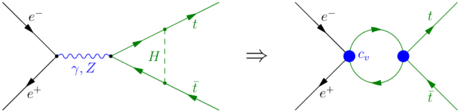
[Eiras, Steinhauser 2006]



[Grzadkowski, Kühn, Krawczyk, Stuart 1986]

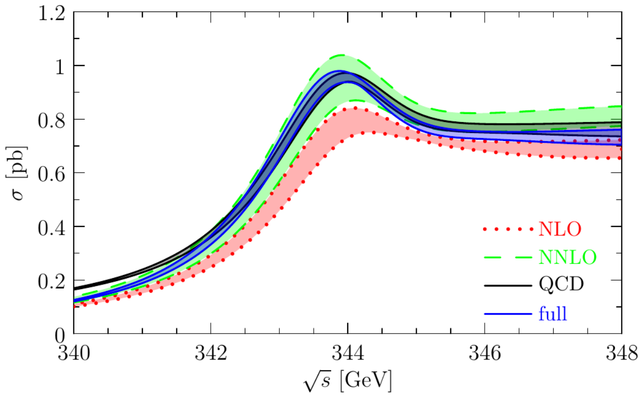
[Guth, Kühn 1991]

[Hoang, Reißer 2004 & 2006]



Top-pair production cross section

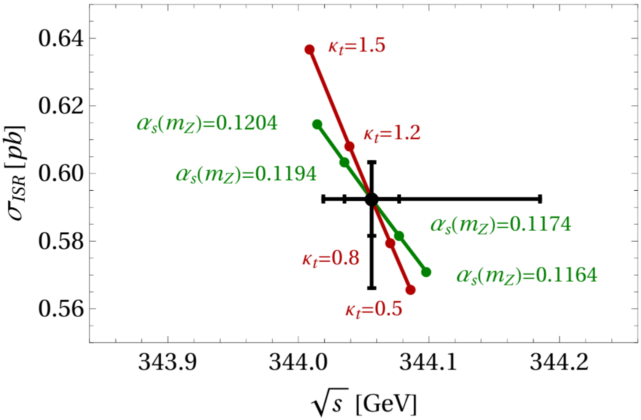
[Beneke, AM, Rauh, Ruiz-Femenía 2017]



$$m_t^{\rm PS}(20\,\text{GeV}) = 171.5\,\text{GeV}\,, \qquad \Gamma_t = 1.33\,\text{GeV}\,, \qquad m_H = 125\,\text{GeV}$$

$$\alpha_s(m_Z) = 0.1177\,, \qquad \alpha(m_Z) = 1/128.944\,, \qquad m_W, m_Z$$

Peak position



Conclusions

- Top pair threshold scan allows precise mass determination

$$\Delta m_t < 100\,\text{MeV}$$

- Theory-dominated error, $\sim 3\%$ QCD scale uncertainty
- Known corrections:
  - N^3LO QCD + Higgs
  - N^2LO electroweak + non-resonant
  - LL initial state radiation
- All corrections included in version 2 of `QQbar_threshold`
  `https://qqbarthreshold.hepforge.org/`

METHODS AND TOOLS

Progress in numerical approaches

Numerics for elliptic Feynman integrals

Stefan Weinzierl

Institut für Physik, Universität Mainz

in collaboration with L. Adams, Ch. Bogner, I. Hönemann, K. Tempest and A. Schweitzer

I:	**Review**:	**Numerics for multiple polylogarithms**
II:	**Example**:	**The two-loop electron self-energy**
III:	**Numerics**:	**Single-scale elliptic Feynman integrals**

Progress in numerical approaches

Annals of Mathematics, **141** (1995), 443-551

Pierre de Fermat

Modular elliptic curves and Fermat's Last Theorem

By Andrew John Wiles*

For Nada, Claire, Kate and Olivia

Andrew John Wiles

Cubum autem in duos cubos, aut quadratoquadratum in duos quadratoquadratos, et generaliter nullam in infinitum ultra quadratum potestatum in duos ejusdem nominis fas est dividere: cujes rei demonstrationem mirabilem sane detexi. Hanc marginis exiguitas non caperet.

Communications in
Number Theory and Physics
Volume 12, Number 2, 193–251, 2018

Feynman integrals and iterated integrals of modular forms

Luise Adams and Stefan Weinzierl

In this paper we show that certain Feynman integrals can be expressed as linear combinations of iterated integrals of modular forms to all orders in the dimensional regularisation parameter ε. We discuss explicitly the equal mass sunrise integral and the kite integral. For both cases we give the alphabet of letters occurring in the iterated integrals. For the sunrise integral we present a compact formula, expressing this integral to all orders in ε as iterated integrals of modular forms.

Progress in numerical approaches

Numerical evaluation of the dilogarithm

The dilogarithm:

$$\mathrm{Li}_2(x) = \int_0^x \frac{dt_1}{t_1} \int_0^{t_1} \frac{dt_2}{1-t_2} = \sum_{n=1}^{\infty} \frac{x^n}{n^2}$$

Map into region $|x| \leq 1$ and $-1 \leq \mathrm{Re}(x) \leq 1/2$, using

$$\mathrm{Li}_2(x) = -\mathrm{Li}_2\left(\frac{1}{x}\right) - \frac{\pi^2}{6} - \frac{1}{2}(\ln(-x))^2, \qquad \mathrm{Li}_2(x) = -\mathrm{Li}_2(1-x) + \frac{\pi^2}{6} - \ln(x)\ln(1-x).$$

Accelaration using Bernoulli numbers B_j:

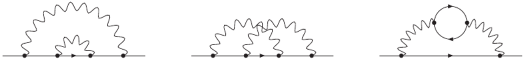
$$\mathrm{Li}_2(x) = \sum_{j=0}^{\infty} \frac{B_j}{(j+1)!} (-\ln(1-x))^{j+1},$$

't Hooft, Veltman, '79

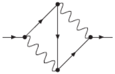
Progress in numerical approaches

Diagrams

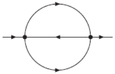
There are three Feynman diagrams contributing to the two-loop electron self-energy in QED with a single fermion:



All master integrals are (sub-) topologies of the kite graph:



One sub-topology is the sunrise graph with three equal non-zero masses:



Progress in numerical approaches

Iterated integrals

For ω_1, ..., ω_k differential 1-forms on a manifold M and $\gamma : [0,1] \to M$ a path, write for the pull-back of ω_j to the interval $[0,1]$

$$f_j(\lambda)\, d\lambda \quad = \quad \gamma^* \omega_j.$$

The iterated integral is defined by (Chen '77)

$$I_\gamma(\omega_1, \dots, \omega_k; \lambda) \quad = \quad \int\limits_0^{\lambda} d\lambda_1 f_1(\lambda_1) \int\limits_0^{\lambda_1} d\lambda_2 f_2(\lambda_2) \dots \int\limits_0^{\lambda_{k-1}} d\lambda_k f_k(\lambda_k).$$

Example 1: Multiple polylogarithms (Goncharov '98)

$$\omega_j \quad = \quad \frac{d\lambda}{\lambda - z_j}.$$

Example 2: Iterated integrals of modular forms (Brown '14): $f_j(\tau)$ a modular form,

$$\omega_j \quad = \quad 2\pi i \, f_j(\tau)\, d\tau.$$

Progress in numerical approaches

Iterated integrals of modular forms

Modular forms have a q-expansion. Using

$$2\pi i \, d\tau = \frac{dq}{q}$$

we may integrate term-by-term and obtain the q-expansion of the master integrals.

For example, for the ε^2-term of the sunrise integral one finds

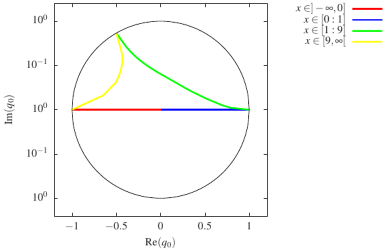
$$I_6^{(2)} = 3\,\mathrm{Cl}_2\left(\frac{2\pi}{3}\right) - 3\sqrt{3}\left[q - \frac{5}{4}q^2 + q^3 - \frac{11}{16}q^4 + \frac{24}{25}q^5 - \frac{5}{4}q^6 + \frac{50}{49}q^7 - \frac{53}{64}q^8 + q^9\right] + O\left(q^{10}\right)$$

We may truncate the q-series and evaluate the resulting polynomial numerically.

Convergence

We defined q_0 such that $q_0 = 0$ for $x = 0$.

For which values $x \in \mathbb{R}$ do we have $|q_0| < 1$?



We have $|q_0| < 1$ for $x \in \mathbb{R} \backslash \{1, 9, \infty\}$.

Bogner, Schweitzer, S.W., '17

Progress in numerical approaches: German Rodrigo

KEEP SPACE-TIME IN FOUR DIMENSIONS [SEE ALSO PITTAU'S TALK] | AVOID IR SUBTRACTIONS

LOCAL SUBTRACTION IN THE UV

UNSUBTRACTION IN THE IR

- **LTD:** open loops to trees
- **FDU:** mapping of V ▶R kinematics

- **Integrand cancellation** of singularities in d=4 space-time dimensions
- **V+R simultaneous:**
  - More efficient event generators
- LTD suitable for **amplitudes**, FDU aimed at **physical observ.**

G. Rodrigo, FCC-ee 2019

Progress in numerical approaches: "I hate counter-terms"

1. Four Dimensional Renormalization and the UV problem
2. *NNLO corrections in 4 dimensions*
   Ben Page, R.P., arXiv:1810.00234
3. Conclusions

“Vacuum” subtraction

1. $J(q^2) = \dfrac{1}{(q^2 - M^2)^2}$
2. $q^2 \stackrel{\text{GP}}{\to} \bar{q}^2 := q^2 - \mu^2$
3. $J(q^2) \stackrel{\text{GP}}{\to} \bar{J}(\bar{q}^2) := \dfrac{1}{(\bar{q}^2 - M^2)^2}$

$$\frac{1}{(\bar{q}^2 - M^2)^2} = \underbrace{\cancel{\left[\frac{1}{\bar{q}^4}\right]}}_{\Uparrow \atop \text{Vacuum}} + \left(\frac{M^2}{\bar{q}^2(\bar{q}^2 - M^2)^2} + \frac{M^2}{\bar{q}^4(\bar{q}^2 - M^2)}\right)$$

$$\boxed{\int [d^4 q] \frac{1}{(\bar{q}^2 - M^2)^2} := \lim_{\mu \to 0} \int d^4 q \left(\frac{M^2}{\bar{q}^2(\bar{q}^2 - M^2)^2} + \frac{M^2}{\bar{q}^4(\bar{q}^2 - M^2)}\right)}$$

Two core tenets of QFT

1. Gauge invariance

   - FDR integrals are invariant under the shift $q \to q + p \; \forall p$
   - Cancellations if $q^2 \stackrel{\mathrm{GP}}{\to} \bar{q}^2$ in the numerator

$$\int [d^4q] \frac{\bar{q}^2}{\bar{q}^2(\bar{q}^2 - M^2)^2} = \int [d^4q] \frac{1}{(\bar{q}^2 - M^2)^2}$$

$\Rightarrow$ One can prove graphical WI in QFT

2. Unitarity of $S = I + iT$

   - It requires $i(T - T^\dagger) = -T^\dagger T$

Our observable

$$\sigma_B \propto \int d\Phi_n \sum_{\text{spin}} |A_n^{(0)}|^2$$

$$\sigma_V \propto \int d\Phi_n \sum_{\text{spin}} \left\{ A_n^{(2)} (A_n^{(0)})^* + A_n^{(0)} (A_n^{(2)})^* \right\}$$

$$\sigma_R \propto \int d\Phi_{n+2} \sum_{\text{spin}} \left\{ A_{n+2}^{(0)} (A_{n+2}^{(0)})^* \right\}$$

$$\sigma^{NNLO} = \sigma_B + \sigma_V + \sigma_R$$

In particular

$\Gamma^{NNLO}(H \to b\bar{b})$ and $\sigma^{\text{NNLO}}_{\gamma^* \to jets}$

Best today

T. Gehrmann, J. M. Henn and N. A. Lo Presti, Phys. Rev. Lett. **116** (2016) no.6, 062001 [arXiv:1511.05409 [hep-ph]].

T. Gehrmann, J. M. Henn and N. A. Lo Presti, arXiv:1807.09812 [hep-ph].

D. Chicherin, T. Gehrmann, J. M. Henn, P. Wasser, Y. Zhang and S. Zoia, arXiv:1812.11160 [hep-ph].

C. G. Papadopoulos, D. Tommasini and C. Wever, JHEP **1604**, 078 (2016) [arXiv:1511.09404 [hep-ph]].

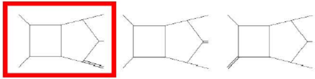


Figure 1. The three planar pentaboxes of the families P_1 (left), P_2 (middle) and P_3 (right) with one external massive leg.

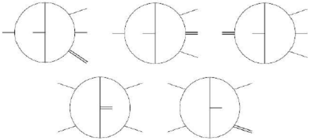


Figure 2. The five non-planar families with one external massive leg.

$$\begin{aligned} \mathbf{G} &= \varepsilon^{-2}\mathbf{b}_0^{(-2)} + \varepsilon^{-1}\left(\sum \mathcal{G}_a \mathbf{M}_a \mathbf{b}_0^{(-2)} + \mathbf{b}_0^{(-1)}\right) \\ &+ \varepsilon^{0}\left(\sum \mathcal{G}_{ab} \mathbf{M}_a \mathbf{M}_b \mathbf{b}_0^{(-2)} + \sum \mathcal{G}_a \mathbf{M}_a \mathbf{b}_0^{(-1)} + \mathbf{b}_0^{(0)}\right) \end{aligned}$$

OPP at two loops

- Write the "OPP-type" equation at two loops

$$\frac{N\left(l_1, l_2; \{p_i\}\right)}{D_1 D_2 \ldots D_n} = \sum_{m=1}^{\min(n,8)} \sum_{S_{m;n}} \frac{\Delta_{i_1 i_2 \ldots i_m}\left(l_1, l_2; \{p_i\}\right)}{D_{i_1} D_{i_2} \ldots D_{i_m}}$$

$$\sum \frac{\Delta_{i_1 i_2 \ldots i_m}\left(l_1, l_2; \{p_i\}\right)}{D_{i_1} D_{i_2} \ldots D_{i_m}} \rightarrow \text{spurious} \oplus \text{ISP} - \text{irreducible integrals}$$

ISP-irreducible integrals $\rightarrow$ use IBPI to Master Integrals

Libraries in the future: `QCD2LOOP`, `TwOLOop`

J. Gluza, K. Kajda and D. A. Kosower, Phys. Rev. D **83** (2011) 045012
C. G. Papadopoulos, R. H. P. Kleiss and I. Malamos, PoS Corfu **2012** (2013) 019.
H. Ita, arXiv:1510.05626 [hep-th].
P. Mastrolia, T. Peraro and A. Primo, arXiv:1605.03157 [hep-ph].
S. Badger, C. Brynnum-Hansen, H. B. Hartanto and T. Peraro, Phys. Rev. Lett. **120** (2018) no.9, 092001

Progress in analytical/numerical approaches

5BOX

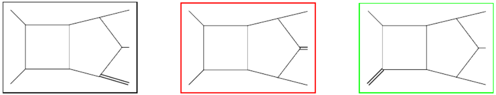


FIGURE: The three planar pentaboxes of the families P_1 (left), P_2 (middle) and P_3 (right) with one external massive leg.

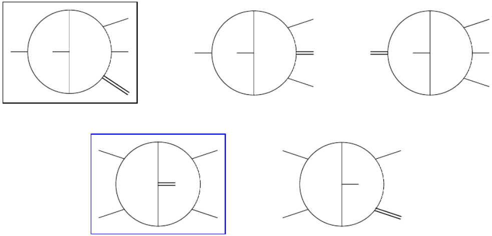


FIGURE: The five non-planar families with one external massive leg.

Massive box as 3-fold Mellin-Barnes integral I

And finally we reproduce the box integral, dependent on d and the internal variables $\{d, q_1, m_1^2, \cdots q_4, m_4^2\}$ or, equivalently, on a set of external variables, e.g. $\{d, \{p_i^2\}, \{m_i^2\}, s, t\}$:

$$
\begin{aligned}
J_4(d; \{p_i^2\}, s, t, \{m_i^2\}) \quad = \quad & \left(\frac{-1}{4\pi i}\right)^4 \frac{1}{\Gamma(\frac{d-3}{2})} \sum_{k_1,k_2,k_3,k_4=1}^{4} D_{k_1k_2k_3k_4} \left(\frac{1}{r_4}\frac{\partial r_4}{\partial m_{k_4}^2}\right) \\
& \left(\frac{1}{r_{k_3k_2k_1}}\frac{\partial r_{k_3k_2k_1}}{\partial m_{k_3}^2}\right) \left(\frac{1}{r_{k_2k_1}}\frac{\partial r_{k_2k_1}}{\partial m_{k_2}^2}\right) (m_{k_1}^2)^{d/2-1} \\
& \int_{-i\infty}^{+i\infty} dz_4 \int_{-i\infty}^{+i\infty} dz_3 \int_{-i\infty}^{+i\infty} dz_2 \left(\frac{m_{k_1}^2}{R_4}\right)^{z_4} \left(\frac{m_{k_1}^2}{R_{k_3k_2k_1}}\right)^{z_3} \left(\frac{m_{k_1}^2}{R_{k_2k_1}}\right)^{z_2} \\
& \Gamma(-z_4)\Gamma(z_4+1)\frac{\Gamma(z_4+\frac{d-3}{2})}{\Gamma(z_4+\frac{d-2}{2})}\Gamma(-z_3)\Gamma(z_3+1)\frac{\Gamma(z_3+z_4+\frac{d-2}{2})}{\Gamma(z_3+z_4+\frac{d-1}{2})} \\
& \Gamma(z_2+z_3+z_4+\frac{d-1}{2})\Gamma(-z_2-z_3-z_4-\frac{d+2}{2})\Gamma(-z_2)\Gamma(z_2+1).
\end{aligned}
\tag{31}
$$

The representation (31) can be treated by the Mathematica packages MB and MBnumerics of the MBsuite, replacing AMBRE by a derivative of MBnumerics: **MBOneLoop** [22].

Progress in analytical/numerical approaches: Ben Page

Numerical Unitarity @ Two Loops

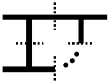
[Abreu, Ita, Jaquier, Febres Cordero, BP '17]

- Take an ansatz for loop-amplitude integrand, decomposing into master (M_Γ) and surface (S_Γ) integrands.

$$\bar{A}(\ell_l, \vec{x}) = \sum_{\text{Topologies}\,\Gamma} \; \sum_{i \in M_\Gamma \cup S_\Gamma} \frac{c_{\Gamma,i}(\vec{x})\, m_{\Gamma,i}(\ell_l)}{\prod_{\text{props}\,j} \rho_j}.$$

[Ita '15]

- Numerically fix $c_{\Gamma,i}(\vec{x})$ on finite field* from on-shell data.



$$= \sum_{\substack{\Gamma' \geq \Gamma, \\ i \in M_{\Gamma'} \cup S_{\Gamma'}}} \frac{c_{\Gamma',i}(\vec{x})\, m_{\Gamma',i}(\ell_l^\Gamma)}{\prod_{\text{props}\,j} \rho_j}.$$

[BDDK '94, '95]

- Insert master integrals, expand $\Rightarrow$ integrated amplitude.
- Amplitude naturally splits into rational functions of external kinematics $c_{\Gamma,i}(\vec{x})$ and special functions (master integrals).

*See also [Peraro '16]

Conclusions

- Alternative method for analytic computations: reconstruction from numerical samples over finite fields.
- We have analytically computed the leading-colour 5-gluon two-loop amplitudes.
- Natural next step - all 5-parton amplitudes at leading colour.
- Interesting structures revealed by computation.

Reduction of a gg→H at 3-loops non-planar topology

Algorithm	**Kira 1.1** (32 cores)	**Kira 1.2** (16 cores)
Generate system of equations	7.9 h	-
Reduce numerically	3.6 h	-
Generate and reduce numerically	-	3.4 h
Build triangular form (thread pools)	26 h	4.8 h
Backward substitution (heuristics)	18.8 d	4.1 d

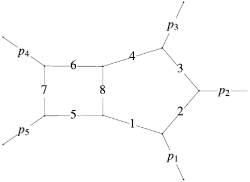
- Seed specification: {r: 10, s: 4, d: 1}
- Speedup comes from less calls to Fermat: 382.502.520 x 5 (Kira 1.1) v.s. 981 (Kira 1.2)

The Challenges of Higher-Order Computations

Increasing the number of legs, loops and scales can greatly increase the complexity of a calculation in two key ways:

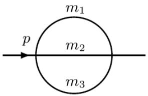
1) Expressions for the amplitudes (and/or IBP identities) can become large and computationally challenging to handle

   →Talk of Ben Page, Johann Usovitsch



2) The Feynman integrals encountered can become challenging to compute. They can have mathematical/algebraic structures beyond MPLs/GPLs (e.g. elliptic integrals)

   →Talk of Stefan Weinzierl



Proceeding purely analytically can become very challenging, **numerical methods** provide a complementary way to attack these problems

pySecDec

pySecDec: a program to numerically evaluate dimensionally regulated parameter integrals (written in python, FORM & c++)

Vermaseren 00; Kuipers, Ueda, Vermaseren 13; Ruijl, Ueda, Vermaseren 17

Code: https://github.com/mppmu/secdec/releases

Docs: https://secdec.readthedocs.io

Borowka, Heinrich, Jahn, SJ, Kerner, Schlenk, Zirke

Supports:

Contour deformation, Arbitrary loops/legs (within reason)

Soper 99; Binoth, Guillet, Heinrich, Pilon, Schubert 05; Nagy, Soper 06; Anastasiou, Beerli, Daleo 07; Beerli 08; Borowka, Carter, Heinrich 12; Borowka 14;

General parameter integrals (not just loop integrals)

Arbitrary number of regulators

Flexible numerators (contracted Lorentz vectors, inverse propagators)

Generates c++ Library (can be linked to your own program)

New: Quasi-Monte Carlo integration & CUDA GPU Support

1811.11720; Li, Wang, Yan, Zhao 15; Review: Dick, Kuo, Sloan 13;

$$\mathrm{SM} \underset{\textbf{SMEFT}}{\longleftrightarrow} \mathrm{BSM}$$

The dimension 6 SMEFT

- **The dimension 6 SMEFT:**

$$\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \xrightarrow[\text{suppressed by}]{\text{Effects}} \left(\frac{q}{\Lambda}\right)^{d-4} \quad q = v, E < \Lambda$$

Λ: Cut-off of the EFT

- **LO new physics effects "start" at dimension 6**
- **With current precision, and assuming Λ~TeV, sensitivity to $d>6$ is small**

$$\frac{M_Z^2}{(1\text{TeV})^2} \sim 0.8\% \qquad \frac{M_Z^4}{(1\text{TeV})^4} \sim 0.007\%$$

Truncate at $d=6$: 59 types of operators (2499 counting flavor)

W. Buchmüller, D. Wyler, Nucl. Phys. B268 (1986) 621
C. Arzt, M.B. Einhorn, J. Wudka, Nucl. Phys. B433 (1995) 41
B.Grzadkowski, M.Iskrynski, M.Misiak, J.Rosiek, JHEP 1010 (2010) 085

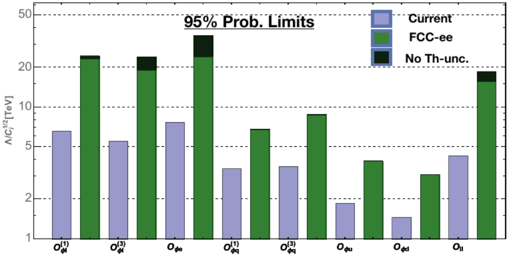
First complete basis, aka *Warsaw* basis

HEPfit, Jorge de Blas

The Global EW fit at FCC-ee

- **Global fit to electroweak precision measurements at FCC-ee**

Impact of theory uncertainties

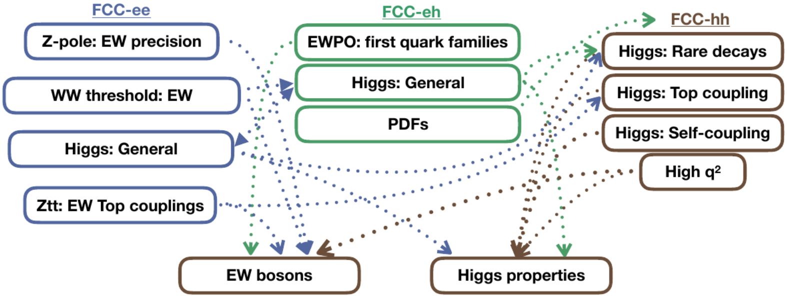


Theory uncertainties have a significant impact in the sensitivity to New Physics (not easy to see in this global fit)

	Current		FCCee		
	Exp.	SM	Exp.	SM (par.)	SM (th.)
δM_W [MeV]	± 15	± 8	± 1	$\pm 0.6/\pm 1$	± 1
$\delta \Gamma_Z$ [MeV]	± 2.3	± 0.73	± 0.1	± 0.1	± 0.2
$\delta \mathcal{A}_\ell$ [$\times 10^{-5}$]	± 210	± 93	± 2.1	$\pm 8/\pm 14$	± 11.8
δR_b^0 [$\times 10^{-5}$]	± 66	± 3	± 6	± 0.3	$\pm$ 5

HEPfit, Jorge de Blas

- **Current data (LEP/LHC) sensitive to NP in EW (Higgs) $\lesssim$1% (~10%)**
- **FCC can largely improve our knowledge of the EW/Higgs sectors. As with current data, no single machine can do all the work…**



- **Apart from a strong EW/Higgs program, FCC-ee is also fundamental to maximize the physics output of the FCC-eh/hh**

Tevong You (Cambridge)

Updated Global SMEFT Fit

- SILH basis

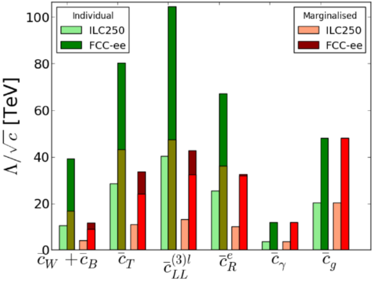
$$
\begin{aligned}
\mathcal{L}_{\text{SMEFT}}^{\text{SILH}} \supset\ & \frac{\bar{c}_W}{m_W^2}\frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu} + \frac{\bar{c}_B}{m_W^2}\frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\partial^\nu B_{\mu\nu} + \frac{\bar{c}_T}{v^2}\frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 \\
& + \frac{\bar{c}_{ll}}{v^2} 2(\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L) + \frac{\bar{c}_{He}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R) + \frac{\bar{c}_{Hu}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R) \\
& + \frac{\bar{c}_{Hd}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R) + \frac{\bar{c}'_{Hq}}{v^2}(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L) \\
& + \frac{\bar{c}_{Hq}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L) + \frac{\bar{c}_{HW}}{m_W^2} ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu} + \frac{\bar{c}_{HB}}{m_W^2} ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
& + \frac{\bar{c}_{3W}}{m_W^2} g^3\epsilon_{abc}W^{a\,\nu}_\mu W^b_{\nu\rho}W^{c\,\rho\mu} + \frac{\bar{c}_g}{m_W^2} g_s^2|H|^2 G^A_{\mu\nu}G^{A\mu\nu} + \frac{\bar{c}_\gamma}{m_W^2} g'^2|H|^2 B_{\mu\nu}B^{\mu\nu} \\
& + \frac{\bar{c}_H}{v^2}\frac{1}{2}(\partial^\mu|H|^2)^2 - \sum_{f=e,u,d}\frac{\bar{c}_f}{v^2} y_f|H|^2\bar{F}_L H^{(c)} f_R \\
& + \frac{\bar{c}_{3G}}{m_W^2} g_s^3 f_{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho - \frac{\bar{c}_{uG}}{m_W^2} 4g_s y_u H^\dagger\cdot\bar{Q}_L\gamma^{\mu\nu}T_a u_R G^A_{\mu\nu}\,. \qquad (6)
\end{aligned}
$$

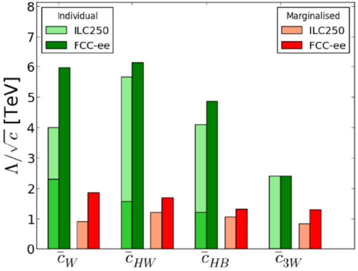
Future e+e- Constraints

J. Ellis and T.Y. [arXiv:1510:04561]

- Simplified FCC-ee projections based on four leptonic observables:

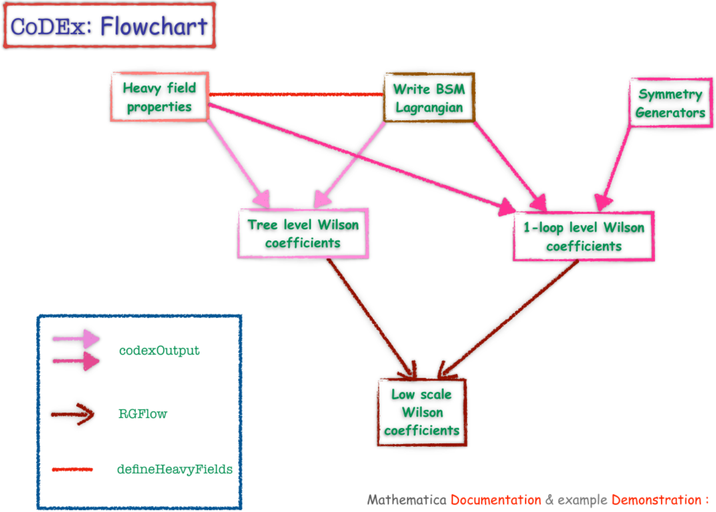
$$\sigma_{m_W} = 0.0005\ \mathrm{GeV} \quad , \quad \sigma_{\Gamma_Z} = 0.0001\ \mathrm{GeV} \quad , \quad \sigma_{R_l} = 0.001 \quad , \quad \sigma_{A_e} = 0.000015$$





- With and without theory uncertainties:

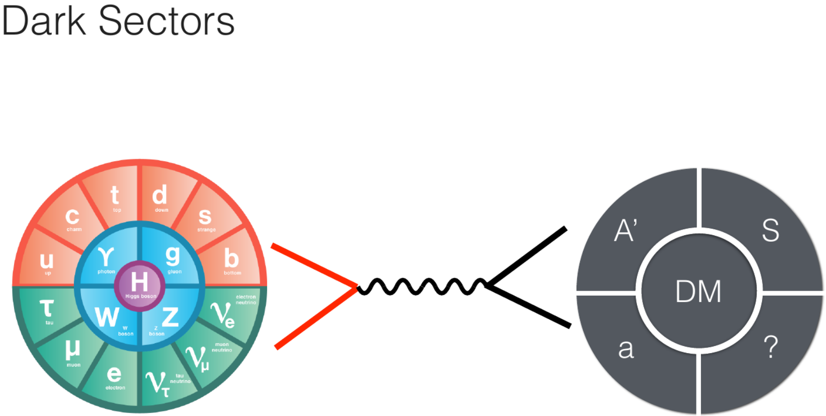
$$\sigma^{\mathrm{th}}_{\Gamma_Z} = 0.0001\ \mathrm{GeV} \quad , \quad \sigma^{\mathrm{th}}_{m_W} = 0.001\ \mathrm{GeV} \quad , \quad \sigma^{\mathrm{th}}_{A_e} = 0.000118$$



Mathematica Documentation & example Demonstration :
https://effexteam.github.io/CoDEx

BSM

- Dark Matter and Axion Like Particles - exposing dark sectors with future Z-factories by Wei Xue
- Axion-like particles at the FCC-ee by Speaker: Andrea Thamm



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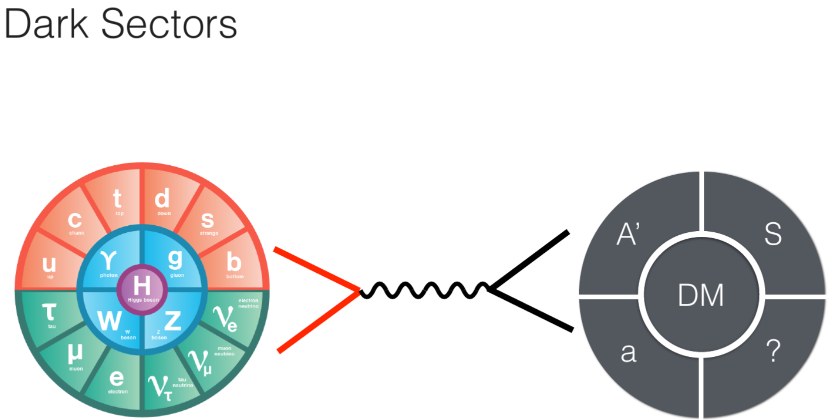


Higgs portal + fermionic DM

- S and higgs mixing

$$\mathcal{L} = -\lambda_1 \left(H^\dagger H\right) S - \lambda_2 \left(H^\dagger H\right) S^2 + \cdots$$

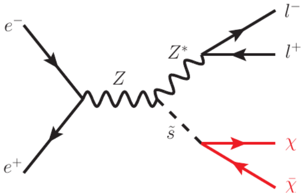
mixing angle α

$$\begin{pmatrix} \tilde{h} \\ \tilde{s} \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- linking to dark matter χ

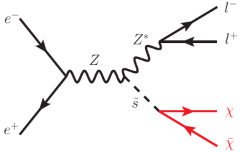
$$\mathcal{L} = -y_\chi S \bar{\chi}\chi$$

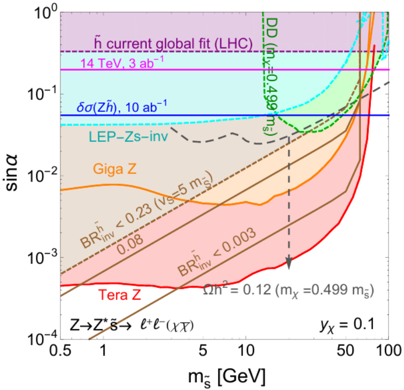
- exotic Z decays (MET+$\ell^+\ell^-$, 1 resonance)



BSM: DM, Higgs portal, vector portal, axion-like particles

Higgs portal + fermionic DM





- higgs invisible decay ($h \to ss$)
- indirect detection (p-wave) direct detection (> 10 GeV)

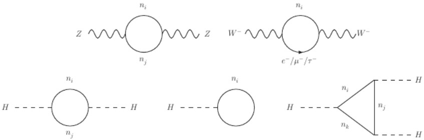
Richard Ruiz: Neutrinos

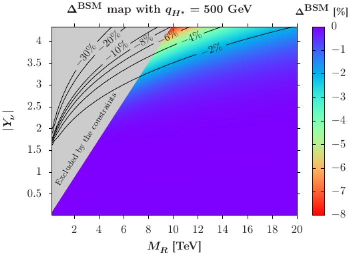
Lack of clear guidance from data and theory means we must take a broad, open approach to uncovering the origin of tiny ν masses.

1. Future e^+e^- machines explore new depths for light N
   - Searches for $\mathcal{B} \to N + X$, $Z \to N\nu$, $h \to NN$
   - Baseline luminosities at $\sqrt{s} = 240$ GeV sufficient to go beyond LHC
2. Upgrading to pp machines offers many opportunites:
   - N, $H^{\pm}$, $H^{\pm\pm}$, W_R, Z_{B-L}, $T^{\pm}T^0$ masses up to 10-15 TeV scale!
   - New analysis techniques $\Longrightarrow$ new territory for cLFV and LNV at LHC
3. LNV at colliders is well-motivated and feasibility clarified!
4. Colliders offer *incredibly complementary* to oscillation facilities:
   - Direct production of Seesaw particles
   - Test UV realizations of low-scale neutrino EFTs / NSIs

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

The triple Higgs coupling: A new observable for neutrino physics at future colliders





[J.B., C. Weiland, JHEP 1704 (2017) 038]

This can be probed at the CLIC!
Could we look into EW corrections at FCC-ee?

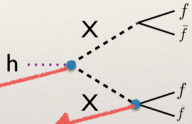
What could be done at FCC-ee with 1-loop $e^+e^- \to ZH$?

Exotic Higgs Decays (Theory)

Reviewed in Curtin et al,1312.4992

- First appearance: Hidden Valley models Strassler, Zurek, hep-ph/0604261, hep-ph/0605193.
  Also ubiquitous in realisations of Neutral Naturalness: Twin Higgs Chacko, Goh, Harnik, hep-ph/0506256 , Folded SUSY Burdman, Chacko, Goh, Harnik, hep-ph/0609152 , Fraternal Twin Higgs Craig, Katz, Strassler, Sundrum, 1501.05310 , Hyperbolic Higgs Cohen, Craig, Giudice, McCullough, 1803.03647 , Singlet Stops Cheng, Li, Salvioni, Verhaeren 1803.03651 .

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}M^2\phi^2 - A|H|^2\phi - \frac{1}{2}\kappa|H|^2\phi^2 - \frac{1}{3!}\mu\phi^3 - \frac{1}{4!}\lambda_\phi\phi^4 - \frac{1}{2}\lambda_H|H|^4$$



- H and ϕ mixing (depends on κ,A) gives physical states h,X. Phenomenology captured by m_X, $c\tau$ (X) $\equiv c\tau$, BR(h->XX).

- Constraints on h width allow BR(h->XX) ≲10 % and with tiny BSM couplings. X is long-lived and decays into SM particles with SM-like Higgs branching ratios.

- Signatures are encompassed in the larger group of Long-Lived Particles (LLPs): (see also talks by A. Thamm and W. Xue at this workshop)

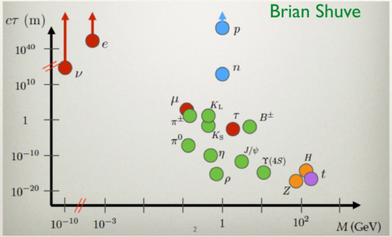
Remember: HL-LHC gives ~ 10^8 Higgs bosons, CEPC and FCC-ee (240) give 10^6.

For more on exotic Higgs physics, see talk by Sven Heinemeyer

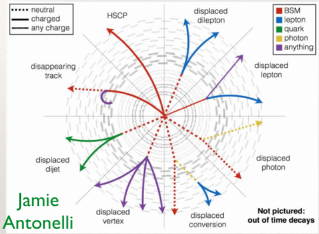
Long-Lived Particles (LLPs)

- LLPs: BSM states with macroscopic lifetimes (ns), theoretically well motivated.

Exist in the SM!



A lot of interesting signatures!



large cτ, small Γ

- Large mass hierarchies
- Compressed spectra
- Small couplings

EW Baryogenesis
Dark Matter
Hierarchy Problem
Neutrino Masses

BSM Models: RH neutrinos, dark QCD, stealth SUSY, Neutral Naturalness, Higgs Portal, Z′ Portal, Hidden Valleys, …

- LLP@LHC White Paper imminent! (on arXiv around Jan 15th).
- Next LLP@LHC Community workshop: 27th-29th May 2019 @CERN.

SMEFT basics

- BSM? → New Interactions of SM particles

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

- 59(3045) operators at dim-6: Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653
  Grzadkowski et al arXiv:1008.4884

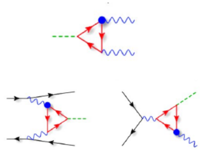
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

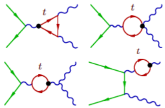
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Future Lepton Colliders

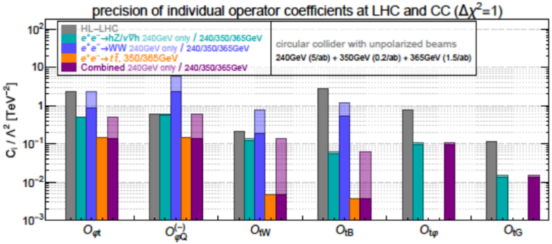
Future Circular Electron Positron Collider processes:



Higgs production and decay



WW production



Individual bounds

Predictions:

- Higgs: ZH, WW fusion, all decay channels.
- Diboson Angular distributions
- Precision EW observables
- Top pair projections from Durieux, Perello, Vos, Zhang arXiv: 1807.02121

Previous report: arXiv:1809.01830

Standard Model Theory for the FCC-ee: The Tera-Z

A. Blondel (Geneva U.), J. Gluza (Silesia U.), S. Jadach (Cracow, INP), P. Janot (CERN), T. Riemann (Silesia U. & DESY, Zeuthen), A. Akhundov (Valencia U. & Baku, Inst. Phys.), A. Arbuzov (Dubna, JINR), R. Boels (Hamburg U., Inst. Theor. Phys. II), S. Bondarenko (Dubna, JINR), S. Borowka (CERN) *et al.* Show all 38 authors

Sep 6, 2018 - 243 pages

Conference: C18-01-12
BU-HEPP-18-04, CERN-TH-2018-145, IFJ-PAN-IV-2018-09, KW 18-003, MITP/18-052, MPP-2018-143, SI-HEP-2018-21
e-Print: arXiv:1809.01830 [hep-ph] | PDF

Abstract (arXiv)
The future 100-km circular collider FCC at CERN is planned to operate in one of its modes as an electron-positron FCC-ee machine. We give an overview of the theoretical status compared to the experimental demands of one of four foreseen FCC-ee operating stages, which is Z-boson resonance energy physics, FCC-ee Tera-Z stage for short. The FCC-ee Tera-Z will deliver the highest integrated luminosities as well as very small systematic errors for a study the Standard Model (SM) with unprecedented precision. In fact, the FCC-ee Tera-Z will allow to study at least one more quantum field theoretical perturbative order compared to the LEP/SLC precision. The real problem is that the present precision of theoretical calculations of the various observables within the SM does not match that of the anticipated experimental measurements. The bottle-neck problems are specified. In particular, the issues of precise QED unfolding and of the correct calculation of SM pseudo-observables are critically reviewed. In an Executive Summary we specify which basic theoretical calculations are needed to meet the strong experimental expectations at the FCC-ee Tera-Z. Several methods, techniques and tools needed for higher order multi-loop calculations are presented. By inspection of the Z-boson partial and total decay widths analysis, arguments are given that at the beginning of operation of the FCC-ee Tera-Z, the theory predictions may be tuned to be precise enough not to limit the physics interpretation of the measurements. This statement is based on the anticipated progress in analytical and numerical calculations of multi-loop and multi-scale Feynman integrals and on the completion of two-loop electroweak radiative corrections to the SM pseudo-observables this year. However, the above statement is conditional as the theoretical issues demand a very dedicated and focused investment by the community.

Note: 243 pages, Report on the 1st Mini workshop: Precision EW and QCD calculations for the FCC studies;

"Open access" report till end March 2019, not only for speakers/participants, email soon