An introduction to HEPfit and how to constraint EW couplings using it

GenT workshop on Precision probes of New Physics

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Ana Peñuelas (Instituto de Física Corpuscular, València)

Based on arXiv:1910.14012 and arXiv:1907.10619

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

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EXCELENCIA SEVERO OCHOA

Outline of the talk

- HEPfit
  - What is it?
  - Why is it a nice tool?
  - Projects using HEPfit
- An application: Global fit and future prospects on electroweak couplings of top and bottom quarks

What is HEPfit?

Usual “definition"

Flexible open-source C++ code to perform fits in the SM and as many models as possible featuring flavour, electroweak and Higgs observables

Open source, **NO** HEPfit collaboration

What is HEPfit?

How does a phenomenologist work? (simplification!)

1. Take your favourite mode
2. Choose one/some observables
3. Compare theory and experimental data
4. Write a paper

[From O. Eberhardt]

2HDM, Manohar-Wise

Higgs signal strengths, $\mathcal{R}_{D^{(*)}}$

LHC data

arXiv:19xx.xxxx

What is HEPfit?

How does a phenomenologist work? (closer to reality)

1. Take your favourite mode
2. **Choose one/some observables**
3. Compare theory and experimental data
4. Write a paper

Observables may depend on multiple parameters

2HDM: Yukawa couplings $y_f^{\varphi_i^0}$, mass of the scalars $M_{H,A,H^\pm}$, $\tilde{\alpha}, \varsigma_f \dots$

What is HEPfit?

How does a phenomenologist work? (closer to reality)

1. Take your favourite mode
2. Choose one/some observables
3. **Compare theory and experimental data**
4. Write a paper

Experimental observables can be correlated

Correlation between several signal strengths or between $\mathcal{R}_D$ and $\mathcal{R}_{D^*}$

What is HEPfit?

How does a phenomenologist work? (closer to reality)

1. Take your favourite mode
2. Choose one/some observables
3. **Compare theory and experimental data**
4. Write a paper

Theoretical uncertainties

PDFs,
form factors..

What is HEPfit?

How does a phenomenologist work? (closer to reality)

1. Take your favourite mode
2. Choose one/some observables
3. Compare theory and experimental data
4. **Write a paper**

Problems with referees

Why is HEPfit a nice tool?

To solve this issues...

1. Parameter scan: Generate random points, evaluate observables and take best points
   - Inefficient
   - You can miss features/solutions (global mode)
   - No statistical meaning
2. Random scans with χ^2 determination
   - Still one can miss the global mode
3. Fitter
   - Statistical framework which fits the model parameters to the experimentally measured observables by maximising the likelihood

Fitters

Frequentist vs. **Bayesian**

Determine the probability of data for given parameters $\rightarrow$ p-value

Bayes' theorem $P(\boldsymbol{x}|D) = \frac{P(D|\boldsymbol{x})P_0(\boldsymbol{x})}{\int P(D|\boldsymbol{x})P_0(\boldsymbol{x})d\boldsymbol{x}} \rightarrow$ posterior probability

(Frequentist vs. Bayesian)

Example-unfair coin
We flip an unfair coin that shows tails more than heads..

Frequentist

10 tries → probability heads 5/10. Observed 3/10
100 tries → probability heads 50/100. Observed 27/100
...
As tries increase, the *observed value* is closer to the *true value*. We do not incorporate our belief to the fairness of the coin.

Bayesian

10 tries → probability heads 5/10. Observed 3/10
100 tries → probability heads 30/100. Observed 27/100
...
As tries increase, we modify the *prior belief* that the coin is fair. The *posterior belief* is modified.

Fitters

Frequentist vs. **Bayesian**

Determine the probability of data for given parameters $\rightarrow$ p-value

Bayes' theorem $P(\boldsymbol{x}|D) = \frac{P(D|\boldsymbol{x})P_0(\boldsymbol{x})}{\int P(D|\boldsymbol{x})P_0(\boldsymbol{x})d\boldsymbol{x}} \rightarrow$ posterior probability

CKMfitter, GAMBIT, GAPP, GFitter, HiggsSignals, MasterCode, UTfit, HEPfit...

HEPfit

Model ⟶ Parameters

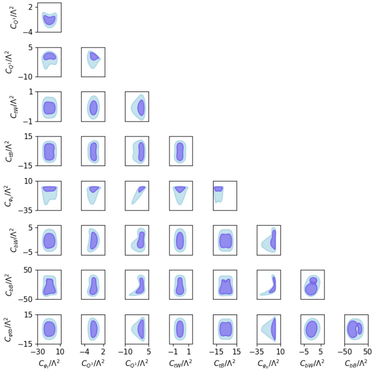
↓ Priors $P_0(\boldsymbol{x})$

Observables

Likelihood $P(D|\boldsymbol{x})$

[From O. Eberhardt]

- Posterior distribution of all the parameters and observables



HEPfit

Model ⟶ Parameters

↓ Priors $P_0(\boldsymbol{x})$

Observables

Likelihood $P(D|\boldsymbol{x})$

[From O. Eberhardt]

- Correlation between parameters

	$C_{\varphi t}$	$C^3_{\varphi Q}$	$C^1_{\varphi Q}$	C_{tW}	C_{tB}	$C_{\varphi b}$	C_{bW}	C_{bB}	$C_{\varphi tb}$
$C_{\varphi t}$	+1	-0.071	+0.087	-0.0068	-0.0056	+0.079	-0.0071	+0.041	+0.0031
$C^3_{\varphi Q}$	-0.071	+1	-0.056	+0.068	-0.017	+0.25	+0.14	+0.12	+0.00098
$C^1_{\varphi Q}$	+0.087	-0.056	+1	-0.0039	+0.012	+0.9	+0.34	+0.47	+0.014
C_{tW}	-0.0068	+0.068	-0.0039	+1	+0.023	+0.026	+0.0015	+0.018	+0.00045
C_{tB}	-0.0056	-0.017	+0.012	+0.023	+1	+0.004	+0.0033	+0.0051	+0.0014
$C_{\varphi b}$	+0.079	+0.25	+0.9	+0.026	+0.004	+1	+0.31	+0.6	+0.0094
C_{bW}	-0.0071	+0.14	+0.34	+0.0015	+0.0033	+0.31	+1	+0.26	+0.1
C_{bB}	+0.041	+0.12	+0.47	+0.018	+0.0051	+0.6	+0.26	+1	+0.014
$C_{\varphi tb}$	+0.0031	+0.00098	+0.014	+0.00045	+0.0014	+0.0094	+0.1	+0.014	+1

HEPfit

Model ⟶ Parameters

↓

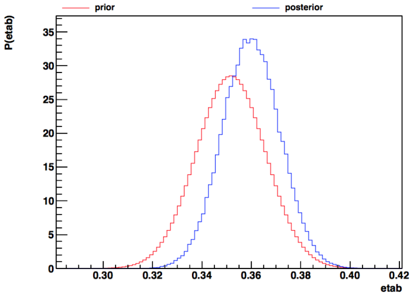
Priors $P_0(\boldsymbol{x})$

Observables

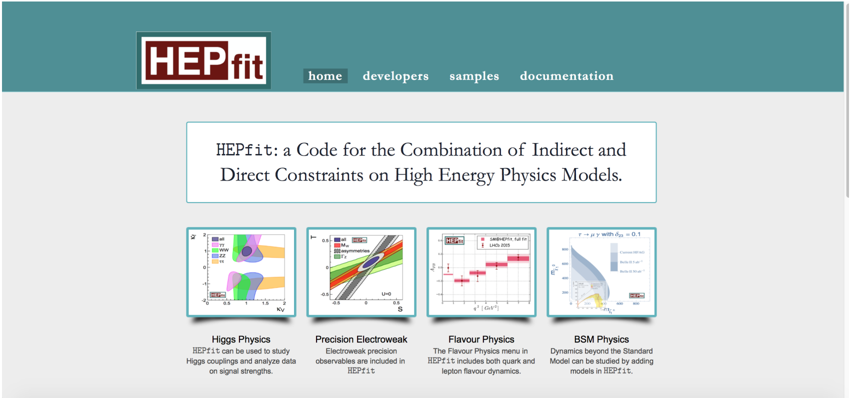
Likelihood $P(D|\boldsymbol{x})$

[From O. Eberhardt]

- Comparision of prior and posterior probability



HEPfit



http://hepfit.roma1.infn.it

HEPfit

CERN-TH-2019-178 CPHT-RR060.102019
DESY 19-184 FTUV/19-1031
IFIC/19-44 KEK-TH-2163
LPT-Orsay-19-36 PSI-PR-19-22
UCI-TR-2019-26

HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models

J. de Blas,[a,b] D. Chowdhury,[c,d] M. Ciuchini,[e] A. M. Coutinho,[f] O. Eberhardt,[g] M. Fedele,[h] E. Franco,[i] G. Grilli di Cortona,[j] V. Miralles,[g] S. Mishima,[k] A. Paul,[l,m] A. Peñuelas,[g] M. Pierini,[n] L. Reina,[o] L. Silvestrini,[i,p] M. Valli,[q] R. Watanabe[e] and N. Yokozaki[r]

[a] *Dipartimento di Fisica e Astronomia "Galileo Galilei", Università di Padova, Via Marzolo 8, I-35131 Padova, Italy*
[b] *INFN, Sezione di Padova, Via Marzolo 8, I-35131 Padova, Italy*
[c] *Centre de Physique Théorique, CNRS, École Polytechnique, IP Paris, 91128 Palaiseau, France*
[d] *Laboratoire de Physique Théorique (UMR8627), CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France*
[e] *INFN, Sezione di Roma Tre, Via della Vasca Navale 84, I-00146 Roma, Italy*
[f] *Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[g] *IFIC, Universitat de València - CSIC, Apt. Correus 22085, E-46071, València, Spain*
[h] *Dept. de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona, Martí Franquès 1, E-08028 Barcelona, Spain*
[i] *INFN, Sezione di Roma, Piazzale A. Moro 2, I-00185 Roma, Italy*
[j] *Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, PL–02–093 Warsaw, Poland*
[k] *Theory Center, IPNS, KEK, Tsukuba 305-0801, Japan*
[l] *DESY, Notkestraße 85, D-22607 Hamburg, Germany*
[m] *Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany*
[n] *CERN, Geneva, Switzerland*
[o] *Physics Department, Florida State University, Tallahassee, FL 32306-4350, USA*
[p] *Theoretical Physics Department, CERN, Geneva, Switzerland*
[q] *Department of Physics and Astronomy, University of California, Irvine, CA 92697 USA*
[r] *Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan*

E-mail: hepfit-support@roma1.infn.it

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Models and observables

Models implemented in HEPfit:

• Standard Model	18 parameters
• Two-Higgs doublets	7/66 parameters
• Georgi-Machacek model	8 parameters
• Standard Model Effective Field Theory	59 parameters
• Manohar-Wise models	14 parameters
• MSSM with complex couplings	108 parameters
• Left-Right symmetric model	13 parameters
• Other generic SM extensions	

Models and observables

Observables implemented in HEPfit:

- Electroweak precision observables
  - STU
  - W mass and width
  - ...
- Higgs physics
  - Strengths
  - Direct searches
- Flavour observables
  - $\Delta F = 2, \Delta F = 1$
  - $B \to \tau\nu$
  - $B \to D^{(*)}\ell\nu$
  - ...
- Theoretical constraints
- Electroweak observables
- Model-dependent observables

HEPfit at IFIC

Ongoing projects

"Global fits in the coloured scalar model" O. Eberhardt, V. Miralles, A. Pich

"Lepton Flavour Violation in hadron tau decays and $\ell - \tau$ conversion in nuclei" T. Husek, K. Monsálvez-Pozo, J. Portolés

"Global fits in the A2HDM" O. Eberhardt, A. Peñuelas, A. Pich

Published

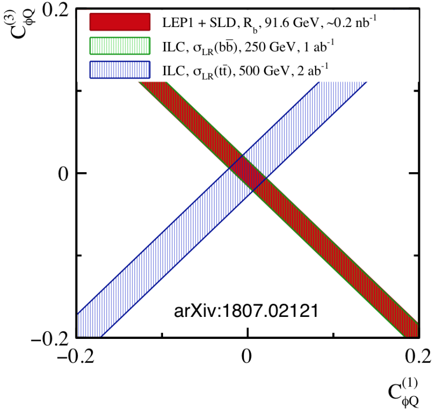
"The electro-weak couplings of the top and bottom quarks - global fit and future prospects" G. Durieux, A. Irles, V, Miralles, A. Peñuelas, R. Pöschl, M. Perelló, M. Vos

The electro-weak couplings of the top and bottom quarks - global fit and future prospects

- NP model predict deviations for the electroweak (EW) couplings of top and bottom quarks [G. Durieux, O. Matsedonskyi, 2019]
- Top quark EW sector poorly constrained
- LHC measurements provide the first constraints on top EW couplings
- Data from LHC, LEP and SLC + EFT $\rightarrow$ current constraints and prospects in future colliders

Theoretical framework

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$



Complementarity between $b\bar{b}$ (LEP) and $t\bar{t}$ (future e^+e^- collider)

$$\delta g_L^t = -\left(C^1_{\varphi Q} - C^3_{\varphi Q}\right) m_t^2/\Lambda^2$$
$$\delta g_L^b = -\left(C^1_{\varphi Q} + C^3_{\varphi Q}\right) m_t^2/\Lambda^2$$

Theoretical framework

$$\begin{aligned} O^1_{\varphi Q} &\equiv \frac{y_t^2}{2} & \bar{q}\gamma^\mu q & \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi, \\ O^3_{\varphi Q} &\equiv \frac{y_t^2}{2} & \bar{q}\tau^I\gamma^\mu q & \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi, \\ O_{\varphi u} &\equiv \frac{y_t^2}{2} & \bar{u}\gamma^\mu u & \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi, \\ O_{\varphi d} &\equiv \frac{y_t^2}{2} & \bar{d}\gamma^\mu d & \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi, \end{aligned}$$

→ left and right-handed couplings of the top and bottom quark to the Z

$$O_{\varphi ud} \equiv \frac{y_t^2}{2} \quad \bar{u}\gamma^\mu d \quad \varphi^T \epsilon i D_\mu \varphi,$$

→ charged current interaction

$$\begin{aligned} O_{uW} &\equiv y_t g_W & \bar{q}\tau^I\sigma^{\mu\nu} u & \quad \epsilon\varphi^* W^I_{\mu\nu}, \\ O_{dW} &\equiv y_t g_W & \bar{q}\tau^I\sigma^{\mu\nu} d & \quad \epsilon\varphi^* W^I_{\mu\nu}, \\ O_{uB} &\equiv y_t g_Y & \bar{q}\sigma^{\mu\nu} u & \quad \epsilon\varphi^* B_{\mu\nu}, \\ O_{dB} &\equiv y_t g_Y & \bar{q}\sigma^{\mu\nu} d & \quad \epsilon\varphi^* B_{\mu\nu}, \end{aligned}$$

→ EW dipole operators

$$O_{u\varphi} \equiv \bar{q}u \quad \epsilon\varphi^* \; \varphi^\dagger\varphi,$$

→ top yukawa

LHC and LEP data

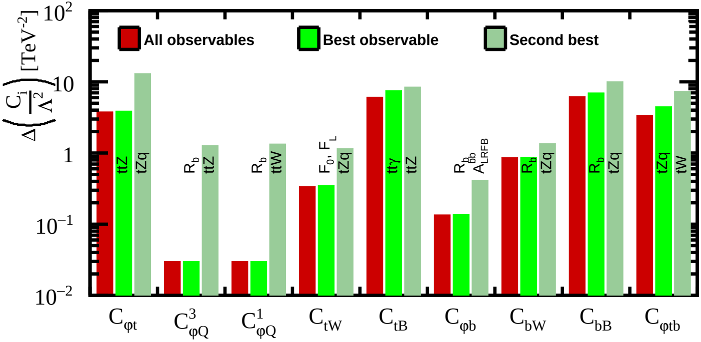
Process	Observable	$\sqrt{s}$	Experiment
$pp \to t\bar{t}H$	cross section	13 TeV	ATLAS 2016
$pp \to t\bar{t}Z/W$	cross section	13 TeV	ATLAS 2019
$pp \to t\bar{t}\gamma$	fid. x-sec.	13 TeV	ATLAS 2018
single-top (t-ch)	cross section	13 TeV	CMS 2018
single-top (Wt)	cross section	13 TeV	CMS 2018
single-top (tZq)	cross section	13 TeV	CMS 2018
$t \to W^+ b$	F_0, F_L	8 TeV	ATLAS 2016
$e^- e^+ \to b\bar{b}$	R_b , A^{bb}_{FBLR}	$\sim$ 91 GeV	LEP, SLC

Observables with tree-level dependence on the dim-6 operators

EWPO and flavour observables not included

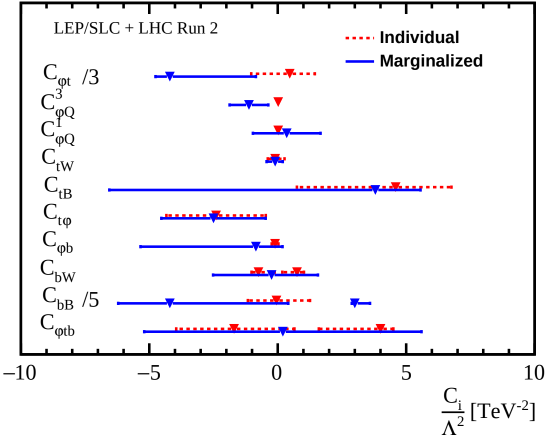
Results - LHC and LEP/SLC data

68% probability for each Wilson coefficient



- Good interplay between the parameters and choosen observables
- LHC: good observables for a LHC EW top fit

Results - LHC and LEP/SLC data



- Robust fit with all operators
- Global limits weaker for some operators (large observable hierarchy)

Results - Impact of Λ^{-4} terms

	Λ^{-2} and Λ^{-4} terms	Λ^{-2} term only
$C_{\varphi t}/\Lambda^2$	$(-16, -2.4)$	$(-2.1, +4.5)$
$C^3_{\varphi Q}/\Lambda^2$	$(-1.9, -0.4)$	$(-0.7, +0.5)$
$C^1_{\varphi Q}/\Lambda^2$	$(-1, +1.7)$	$(-0.6, +0.7)$
C_{tW}/Λ^2	$(-0.4, +0.2)$	$(-0.42, +0.24)$
C_{tB}/Λ^2	$(-6.8, +5.6)$	$(-9.6, +38.4)$
$C_{t\varphi}/\Lambda^2$	$(-4.6, -0.4)$	$(-4.42, 0)$
$C_{\varphi b}/\Lambda^2$	$(-5.4, +0.2)$	$(-0.6, +0.2)$
C_{bW}/Λ^2	$(-2.6, +2.1)$	—
C_{bB}/Λ^2	$(-31.2, +2.4)$, $(+14.4, +18)$	—
$C_{\varphi tb}/\Lambda^2$	$(-5.2, 5.6)$	—

- Λ^{-4} terms $\rightarrow$ two minima for C_{bB}
- C_{tB} : Λ^{-2} term suppressed in $t\bar{t}X$

Results - Impact of Λ^{-4} terms

	Λ^{-2} and Λ^{-4} terms	Λ^{-2} term only
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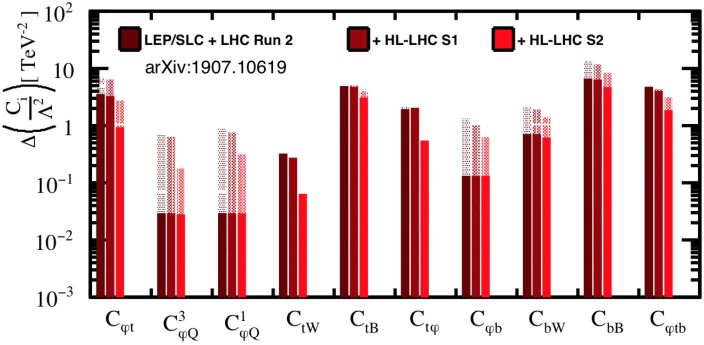
$C_{\varphi tb}/\Lambda^2$	$(-5.2, 5.6)$	—

- $C_{bW}, C_{bb}, C_{\varphi tb}$: interference with the SM (Λ^{-2}) vanish if $m_b = 0$ (no limits)
- Λ^{-4} terms $\rightarrow$ validity of EFT expansion carefully!
- Concrete BSM scenario: verify dim-8 operators are subdominant comparing to dim-6

Future prospects: HL-LHC

HL-LHC: 300 fb^{-1}, 14 TeV

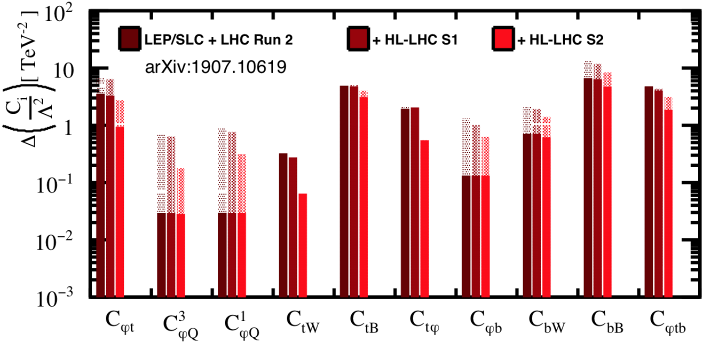
- **S1**: Stat. uncertainty scaled with luminosity
- **S2**: Stat. and syst. uncertainty scaled with (integrated luminosity)$^{1/2}$. Theory uncertainty reduced factor of 2



Solid: individual fit. Dotted: 10-parameter fit

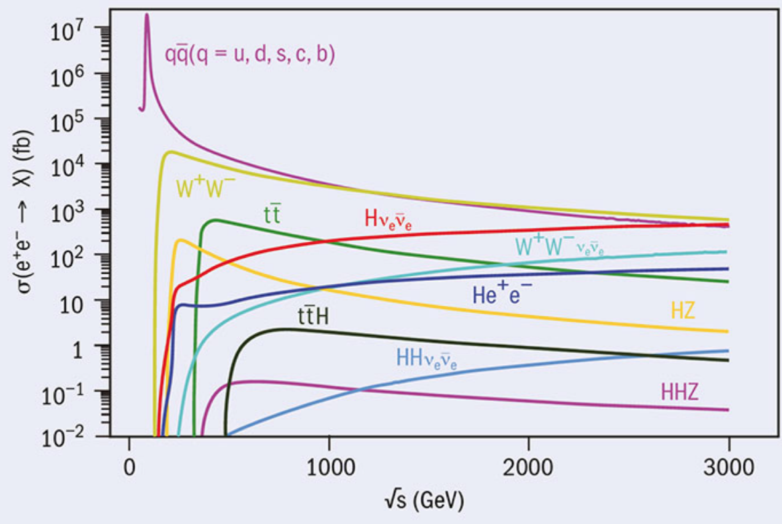
Future prospects: HL-LHC

- **S1** Wilson coefficients only improve marginally → conservative assumptions on systematic uncertainties
- **S2** almost all bounds improve
- C_{tb}: limited sensibility to LHC observables



Solid: individual fit. Dotted: 10-parameter fit

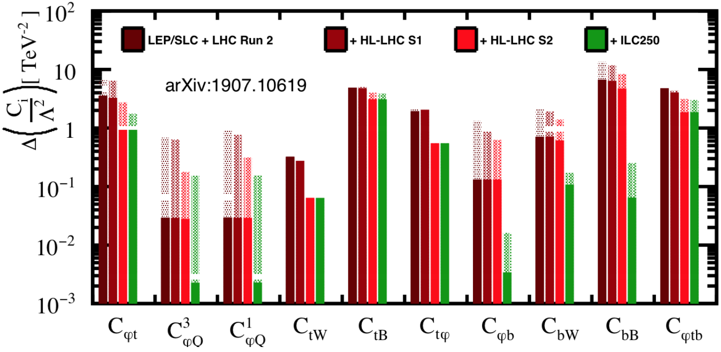
Future prospects: ILC



Future prospects: ILC 250

ILC250: $\sqrt{s} = 250$ GeV

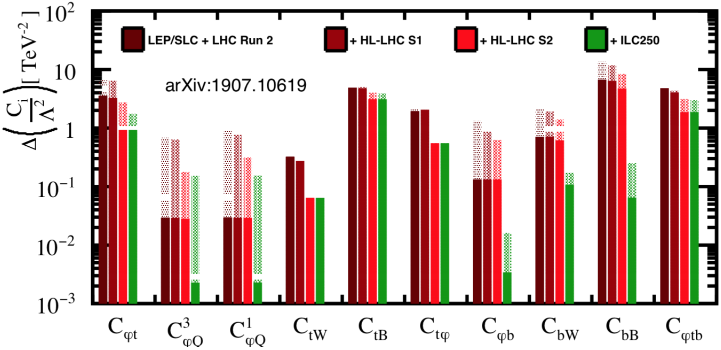
- Including **cross-section** and $\mathbf{A_{fb}}$ from $b\bar{b}$ production



Solid: individual fit. Dotted: 10-parameter fit

Future prospects: ILC 250

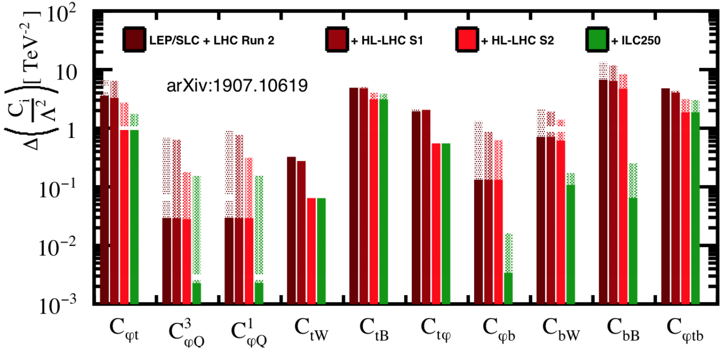
- *b*-quark operator bounds improve one order of magnitude
- Left-handed couplings barely improve compared to LEP



Solid: individual fit. Dotted: 10-parameter fit

Future prospects: ILC 250

- Right-handed and dipole operators improve significantly
- *t*-quark operators improve somewhat due to the correlation

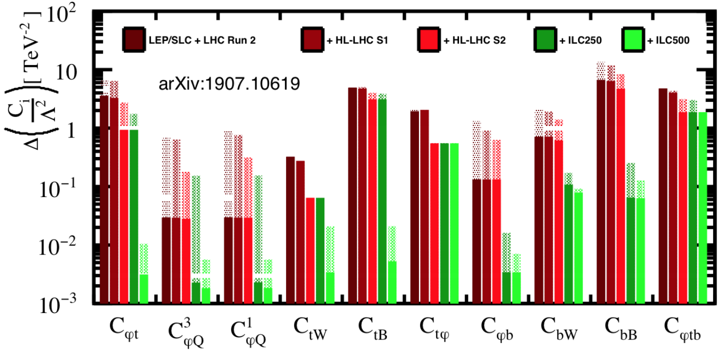


Solid: individual fit. Dotted: 10-parameter fit

Future prospects: ILC 500

ILC500: $\sqrt{s} = 500$ GeV

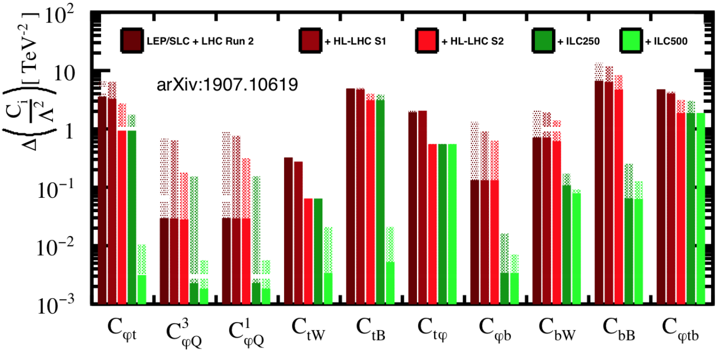
- Including **cross-section** and $\mathbf{A_{fb}}$ from $b\bar{b}$ production and **optimal** $t\bar{t}$ **observables**



Solid: individual fit. Dotted: 10-parameter fit

Future prospects: ILC 500

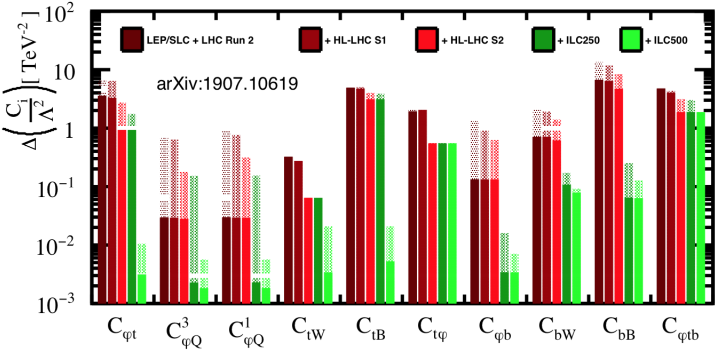
- b-sensibility similar to ILC250: $b\bar{b}$ production decreases with center of mass energy
- Additional $e^+e^- \to t\bar{t}$: access to $Z/\gamma t\bar{t}$ vertices



Solid: individual fit. Dotted: 10-parameter fit

Future prospects: ILC 500

- Bounds on top-quark operator reduced 1-2 orders of magnitude
- Bounds for the left-coupling reduced in the global fit



Solid: individual fit. Dotted: 10-parameter fit

Top Yukawa coupling

Why top-quark Yukawa is important?

- $\delta y_t \equiv -\frac{C_{t\varphi} v^2}{\Lambda^2}$
- Larger coupling in the SM
- NP model can shift it (2HDM, supersymmetric models, composite Higgs...)
- $t\bar{t}H$ production provides a direct constraint

Top Yukawa coupling

scenario	LHC Run 2 +LEP/SLC	HL-LHC S2 +LEP/SLC	ILC500
$\sqrt{s}$, $\int \mathcal{L}$	13 TeV, 36 fb^{-}1	14 TeV, 3 ab^{-}1	500 GeV, 4 ab^{-}1
68% probability interval for effective operator coefficient $C_{t\varphi}/\Lambda^2$ [TeV^{-2}]			
individual	$[-4.4, +0.0]$	$[-0.55, +0.55]$	$[-1.06, +1.06]$
marginalized	$[-4.6, -0.2]$	$[-0.55, +0.55]$	$[-1.07, +1.07]$
corresponding relative uncertainty on top-quark Yukawa coupling $\Delta y_t/y_t$ [%]			
individual	13.2	3.3	6.4
marginalized	13.2	3.3	6.4

- Top Yukawa in the global fit is robust but improvable
- Operators affecting $t\bar{t}H$ need to be controlled with other operators

Final remarks

- HEPfit is an useful to calculate different observables in different models
- An application to electro-weak couplings of the top and bottom quark has been shown
  - We obtain constraints from LHC + LEP+SLC data
  - We present prospects for HL-LHC and ILC

Thank you!

Bayesain framework

Bayes theorem (model parameters $\boldsymbol{x}$, data D):

$$P(\boldsymbol{x}|D) = \frac{P(D|\boldsymbol{x})P_0(\boldsymbol{x})}{\int P(D|\boldsymbol{x})P_0(\boldsymbol{x})d\boldsymbol{x}}$$

$P_0(\boldsymbol{x}) \rightarrow$ prior distribution of the parameters. Prior knowledge of the parameters (can come from experiments or theory)
$\int P(D|\boldsymbol{x})P_0(\boldsymbol{x})d\boldsymbol{x} \rightarrow$ normalization or evidence
$P(D|\boldsymbol{x}) \rightarrow$ likelihood
Marginalized distributions (1D)

$$P(x_i|D) = \int P(\boldsymbol{x}|D) \prod_{j\neq i} dx_j$$

Markov Chain Monte Carlo

- Posterior distribution difficult to calculate when there is a prolifeation in model parameters
- Using naive Monte Carlo sampling algorithm can lead to unacceptable exectuion
- MCMC in BAT
  1. Start at a random point in the parameter space $\boldsymbol{x}$
  2. Generate a proposal point $\boldsymbol{y}$ according to a symmetric probability distribution $g(\boldsymbol{x}, \boldsymbol{y})$
  3. Compare the value of the function f at proposal point $\boldsymbol{y}$ with the value at the current point $\boldsymbol{x}$. The proposal point is accepted if:
     - $f(\boldsymbol{y}) \geq f(\boldsymbol{x})$
     - otherwise, generate a random number r from a uniform distribution in the range [0, 1] and accept the proposal if $f(\boldsymbol{y})/f(\boldsymbol{x}) > r$ If neither conditions are satisfied the proposal is rejected.
  4. Continue from step 1

MPI implementation

Physics Problem	Hardware	Run Configuration	Time
Unitarity Triangle Fit	3 nodes, 120 CPUs	120 chains, 1.4M iterations	00:02:10
	1 nodes, 40 CPUs	40 chains, 600K iterations	00:00:21
$b \to s$ decays in SMEFT† [?]	6 nodes, 240 CPUs	240 chains, 12.5K iterations	02:05:00
	6 nodes, 240 CPUs	240 chains, 39K iterations	05:20:00
combination of Higgs signal strengths and EWPO[?]	1 node, 16 CPUs	16 chains, 5M iterations	00:14:15
	1 node, 16 CPUs	16 chains, 24M iterations	02:08:00
$D \to PP$ decays and CP asymmetry[?]	3 nodes, 240 CPUs	240 chains, 4M iterations	00:18:30
	1 node, 8 CPUs	8 chains, 200K iterations	00:00:10

Table: Some representative runs with HEPfit to show the advantages of the MPI implementation. Times are given in DD:HH:MM. The number of iterations refer to the sum total of pre-run and main-run iterations. The number of chains are equal to the number of CPUs by choice. †The $b \to s$ analysis is done with factorized priors, hence the number of iterations should be multiplied by the number of parameters ($\sim$50) to get a comparative estimate with the other cases. All runs performed in the BIRD or Maxwell clusters at DESY, Hamburg.

Including two-lepton and two-fermion operators

$$
\begin{aligned}
O_{lq}^{1} &\equiv \tfrac{1}{2}\ \bar{q}\gamma_\mu q \quad \bar{l}\gamma^\mu l,\\
O_{lq}^{3} &\equiv \tfrac{1}{2}\ \bar{q}\tau^I\gamma_\mu q \quad \bar{l}\tau^I\gamma^\mu l,\\
O_{lu} &\equiv \tfrac{1}{2}\ \bar{u}\gamma_\mu u \quad \bar{l}\gamma^\mu l,\\
O_{ld} &\equiv \tfrac{1}{2}\ \bar{d}\gamma_\mu d \quad \bar{l}\gamma^\mu l,\\
O_{eq} &\equiv \tfrac{1}{2}\ \bar{q}\gamma_\mu q \quad \bar{e}\gamma^\mu e,\\
O_{eu} &\equiv \tfrac{1}{2}\ \bar{u}\gamma_\mu u \quad \bar{e}\gamma^\mu e,\\
O_{ed} &\equiv \tfrac{1}{2}\ \bar{d}\gamma_\mu d \quad \bar{e}\gamma^\mu e
\end{aligned}
$$

Including two-lepton and two-fermion operators

	10-parameter fit ILC250 + ILC500	17-parameter fit + ILC1000
$C_{\varphi t}/\Lambda^2$	0.01	0.09
$C^3_{\varphi Q}/\Lambda^2$	0.005	0.04
$C^1_{\varphi Q}/\Lambda^2$	0.005	0.04
C_{tW}/Λ^2	0.02	0.014
C_{tB}/Λ^2	0.02	0.015
$C_{t\varphi}/\Lambda^2$	0.54	0.54
$C_{\varphi b}/\Lambda^2$	0.007	0.008
C_{bW}/Λ^2	0.09	0.17
C_{bB}/Λ^2	0.13	0.17
$C_{\varphi tb}/\Lambda^2$	1.9	1.9
C_{eu}/Λ^2	—	0.0006
C_{ed}/Λ^2	—	0.0005
C_{eq}/Λ^2	—	0.0004
C_{lu}/Λ^2	—	0.0006
C_{ld}/Λ^2	—	0.0009
C^-_{lq}/Λ^2	—	0.0006
C^+_{lq}/Λ^2	—	0.0005