Global effective field theory for top physics at lepton colliders

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preliminary results
based on current work with Cen Zhang (Brookhaven),
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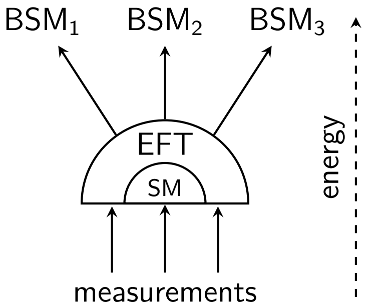
Introduction

The new physics effective field theory (aka SM EFT)

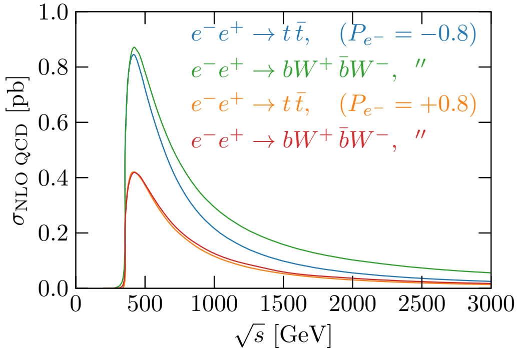
provides a systematic parametrization of the theory space
in direct vicinity of the SM

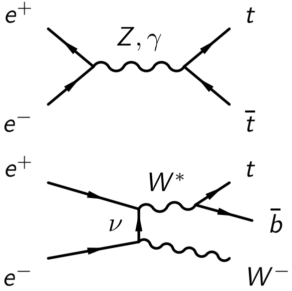
- in a low-energy limit
- through a proper QFT
- fully general when global



Aiming at a global EFT analysis of $e^+e^- \to t\,\bar{t} \to bW^+\,\bar{b}W^-$

- Including four-fermion operators, notably
- Examining the impact of – NLO QCD corrections
  – off-shell top effect
- Studying various observables
  + the impact of $\sqrt{s}$ and beam polarization





Up-sector EFT

[Grzadkowski et al '10]

Two-quark operators:

$$
\begin{array}{llllll}
\text{Scalar:} & O_{u\varphi} & \equiv & \bar{q}u\,\tilde{\varphi} & \varphi^\dagger\varphi, & & \\
\text{Vector:} & O^{1}_{\varphi q} & \equiv & \bar{q}\gamma^\mu q & \varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi & \equiv O^{+}_{\varphi q} + O^{V}_{\varphi q} - O^{A}_{\varphi q}, & \\
 & O^{3}_{\varphi q} & \equiv & \bar{q}\gamma^\mu\tau^I q & \varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi & \equiv O^{+}_{\varphi q} - O^{V}_{\varphi q} + O^{A}_{\varphi q} & \text{(CC also)} \\
 & O_{\varphi u} & \equiv & \bar{u}\gamma^\mu u & \varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi & \equiv O^{V}_{\varphi q} + O^{A}_{\varphi q} & \\
 & O_{\varphi ud} & \equiv & \bar{u}\gamma^\mu d & \tilde{\varphi}^\dagger i\overleftrightarrow{D}_\mu\,\varphi, & & \text{(CC only, } m_b \text{ int.)} \\
\text{Tensor:} & O_{uB} & \equiv & \bar{q}\sigma^{\mu\nu}u\,\tilde{\varphi} & B_{\mu\nu}, & \equiv O_{uA} - \tan\theta_W\, O_{uZ} & \\
 & O_{uW} & \equiv & \bar{q}\sigma^{\mu\nu}\tau^I u\,\tilde{\varphi} & W^I_{\mu\nu}, & \equiv O_{uA} + \text{cotan}\,\theta_W\, O_{uZ} & \text{(CC also)} \\
 & O_{dW} & \equiv & \bar{q}\sigma^{\mu\nu}\tau^I d\,\tilde{\varphi} & W^I_{\mu\nu}, & & \text{(CC only, } m_b \text{ int.)} \\
 & O_{uG} & \equiv & \bar{q}\sigma^{\mu\nu}T^A u\,\tilde{\varphi} & G^A_{\mu\nu}. & & \text{(NLO only)}
\end{array}
$$

Two-quark–two-lepton operators:

$$
\begin{array}{llllll}
\text{Scalar:} & O^{S}_{lequ} & \equiv & \bar{l}e\ \ \varepsilon\ \ \bar{q}u, & & \text{(CC also, } m_e \text{ int.)} \\
 & O_{ledq} & \equiv & \bar{l}e\ \ \ \bar{d}q, & & \text{(CC only, } m_e \text{ int.)} \\
\text{Vector:} & O^{1}_{lq} & \equiv & \bar{l}\gamma_\mu l\ \ \ \bar{q}\gamma^\mu q & \equiv O^{+}_{lq} + O^{V}_{lq} - O^{A}_{lq}, & \\
 & O^{3}_{lq} & \equiv & \bar{l}\gamma_\mu\tau^I l\ \ \ \bar{q}\gamma^\mu\tau^I q & \equiv O^{+}_{lq} - O^{V}_{lq} + O^{A}_{lq}, & \text{(CC also)} \\
 & O_{lu} & \equiv & \bar{l}\gamma_\mu l\ \ \ \bar{u}\gamma^\mu u & \equiv O^{V}_{lq} + O^{A}_{lq}, & \\
 & O_{eq} & \equiv & \bar{e}\gamma^\mu e\ \ \ \bar{q}\gamma_\mu q & \equiv O^{V}_{eq} - O^{A}_{eq}, & \\
 & O_{eu} & \equiv & \bar{e}\gamma_\mu e\ \ \ \bar{u}\gamma^\mu u & \equiv O^{V}_{eq} + O^{A}_{eq}, & \\
\text{Tensor:} & O^{T}_{lequ} & \equiv & \bar{l}\sigma_{\mu\nu}e\ \ \varepsilon\ \ \bar{q}\sigma^{\mu\nu}u. & & \text{(CC also, } m_e \text{ int.)}
\end{array}
$$

Anomalous vertices

$$t\bar{t}\gamma: \quad \gamma_\mu \overbrace{\left(F_{1V}^{\gamma} + \gamma_5 F_{1A}^{\gamma}\right)}^{\sim\not{0}} + \frac{\sigma_{\mu\nu} i q^\nu}{2m_t} \overbrace{\left(F_{2V}^{\gamma} + i\gamma_5 F_{2A}^{\gamma}\right)}^{\sim \mathrm{Re},\mathrm{Im}\{C_{uA}\}}$$

$$t\bar{t}Z: \quad \gamma_\mu \overbrace{\left(F_{1V}^{Z} + \gamma_5 F_{1A}^{Z}\right)}^{\sim C_{\varphi q}^{V}, C_{\varphi q}^{A}} + \frac{\sigma_{\mu\nu} i q^\nu}{2m_t} \overbrace{\left(F_{2V}^{Z} + i\gamma_5 F_{2A}^{Z}\right)}^{\sim \mathrm{Re},\mathrm{Im}\{C_{uZ}\}}$$

$$t\bar{b}W: \quad \gamma_\mu \overbrace{\left(F_{1V}^{W} + \gamma_5 F_{1A}^{W}\right)}^{\sim C_{\varphi ud}, C_{\varphi q}^{+} - \frac{1}{2}(C_{\varphi q}^{V} - C_{\varphi q}^{A})} + \frac{\sigma_{\mu\nu} i q^\nu}{2m_t} \overbrace{\left(F_{2V}^{W} + i\gamma_5 F_{2A}^{W}\right)}^{\sim s_W^2 C_{uA} + s_W c_W C_{uZ} \pm C_{dW}^{*}}$$

Insufficiencies:

- Miss four-fermion operators
- Conflict with gauge invariance
  Do not allow for radiative corrections to be computed
- Complex couplings where the tree-level EFT prescribes real ones
- Hide correlations induced by gauge invariance
  Preclude the combination of measurements in various sectors

Two ideas

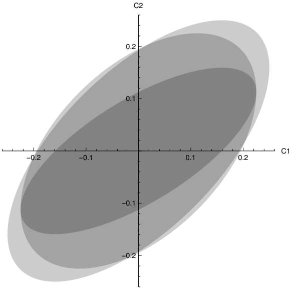
for global EFT analyses

Statistically optimal observables

[Atwood,Soni '92]
[Diehl,Nachtmann '94]

minimize the one-sigma ellipsoid in EFT parameter space.
(*joint efficient* set of estimators, saturating the Rao-Cramér-Fréchet bound: $V^{-1} = I$)

For small C_i, with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i\, \sigma_i(\Phi)$,
the statistically optimal set of observables is: $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.



e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

1. asymmetries: $O_i \sim \text{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1+\cos\phi}$

$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

Previous applications in $e^+e^- \to t\,\bar{t}$:
[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

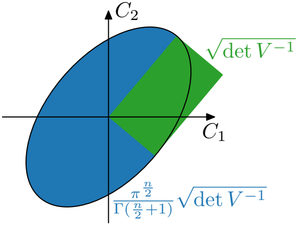
Global determinant parameter (GDP)

[GD, Grojean, Gu, Wang, '17]

In a n-dimensional Gaussian fit, with covariance matrix V,

$$\text{GDP} \equiv \sqrt[2n]{\det V^{-1}}$$

provides a geometric average of the constraints strengths.



Interestingly, GDP ratios are operator-basis independent!

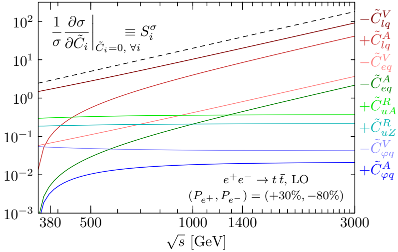
- as the volume scales linearly with coefficient normalization
- as the volume is invariant under rotations

$\Longrightarrow$ conveniently assess constraint strengthening.

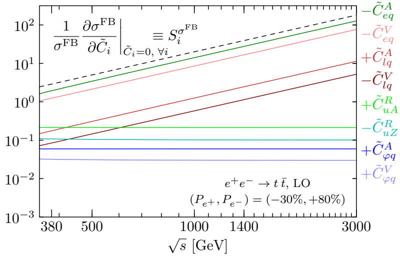
Operator sensitivities

σ and A^{FB} sensitivities

Total cross section (left pol.):



FB-integrated cross section (right pol.):



Few features:

- quadratic energy growth for four-fermion operators
- no growth for two-fermion operators (dipoles included)
- *p*-wave $\beta = \sqrt{1 - 4m_t^2/s}$ suppression of axial vectors at threshold
- enhanced sensitivity of axial vector operators in σ^{FB}
- sensitivity sign flip for $C_{\varphi q}^V$ and C_{uZ}^R when polarization is reversed
- etc.

Helicity amplitude decomposition in $bW^+\bar{b}W^-$

[Jacob, Wick '59]

Production amplitudes:

$$
\begin{aligned}
++ &: A_1 \sim \frac{2m_t}{\sqrt{s}} V + \sqrt{s}\,(D - \beta\tilde{D}) \\
-- &: A_2 \sim \frac{2m_t}{\sqrt{s}} V + \sqrt{s}\,(D + \beta\tilde{D}) \\
+- &: A_3 \sim (V + \beta A) + 2m_t D \\
-+ &: A_4 \sim (V - \beta A) + 2m_t D
\end{aligned}
$$

[Schmidt '95]

In terms of $\Omega = \{\theta_0, \theta_1, \phi_1, \theta_2, \phi_2\}$ helicity angles:

$$\frac{d\sigma}{d\Omega} \propto$$

$+3/4$		$(\lvert A_3\rvert^2 + \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 + \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 + \lvert b_3\rvert^2$	$(1+\cos^2\theta_0)$			
$+3/4$		$(\lvert A_3\rvert^2 - \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 + \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$(1+\cos^2\theta_0)$		$\cos\theta_2$	
$+3/4$		$(\lvert A_3\rvert^2 - \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 + \lvert b_3\rvert^2$	$(1+\cos^2\theta_0)$	$\cos\theta_1$		
$+3/4$		$(\lvert A_3\rvert^2 + \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$(1+\cos^2\theta_0)$	$\cos\theta_1$	$\cos\theta_2$	
$-3/2$		$(\lvert A_3\rvert^2 - \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 + \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 + \lvert b_3\rvert^2$	$\cos\theta_0$			
$-3/2$		$(\lvert A_3\rvert^2 + \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 + \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\cos\theta_0$		$\cos\theta_2$	
$-3/2$		$(\lvert A_3\rvert^2 + \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 + \lvert b_3\rvert^2$	$\cos\theta_0$	$\cos\theta_1$		
$-3/2$		$(\lvert A_3\rvert^2 - \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\cos\theta_0$	$\cos\theta_1$	$\cos\theta_2$	
$+3/2$		$(\lvert A_1\rvert^2 + \lvert A_2\rvert^2)$	$\lvert a_2\rvert^2 + \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 + \lvert b_3\rvert^2$	$\sin^2\theta_0$			
$-3/2$		$(\lvert A_1\rvert^2 - \lvert A_2\rvert^2)$	$\lvert a_2\rvert^2 + \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin^2\theta_0$		$\cos\theta_2$	
$+3/2$		$(\lvert A_1\rvert^2 - \lvert A_2\rvert^2)$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 + \lvert b_3\rvert^2$	$\sin^2\theta_0$	$\cos\theta_1$		
$-3/2$		$(\lvert A_1\rvert^2 + \lvert A_2\rvert^2)$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin^2\theta_0$	$\cos\theta_1$	$\cos\theta_2$	
$+3/2$	$\sqrt{2}$	$\mathrm{Re}\{A_1^* A_4\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_3\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$\sin\theta_1$	$(1+\cos\theta_2)$	$\cos\phi_1$
$+3/2$	$\sqrt{2}$	$\mathrm{Re}\{A_1^* A_4\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$\sin\theta_1$	$(1-\cos\theta_2)$	$\cos\phi_1$
$+3/2$	$\sqrt{2}$	$\mathrm{Re}\{A_2^* A_3\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2$	$\sin\theta_0(1-\cos\theta_0)$	$\sin\theta_1$	$(1+\cos\theta_2)$	$\cos\phi_1$
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$-3/2$	$\sqrt{2}$	$\mathrm{Re}\{A_2^* A_4\}$	$\lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$(1+\cos\theta_1)$	$\sin\theta_2$	$\cos\phi_2$
$-3/2$	$\sqrt{2}$	$\mathrm{Re}\{A_2^* A_4\}$	$\lvert a_2\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$(1-\cos\theta_1)$	$\sin\theta_2$	$\cos\phi_2$
$-3/2$	$\sqrt{2}$	$\mathrm{Re}\{A_1^* A_3\}$	$\lvert a_2\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin\theta_0(1-\cos\theta_0)$	$(1+\cos\theta_1)$	$\sin\theta_2$	$\cos\phi_2$
$-3/2$	$\sqrt{2}$	$\mathrm{Re}\{A_1^* A_3\}$	$\lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin\theta_0(1-\cos\theta_0)$	$(1-\cos\theta_1)$	$\sin\theta_2$	$\cos\phi_2$
-3		$\mathrm{Re}\{A_1^* A_2\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin^2\theta_0$	$\sin\theta_1$	$\sin\theta_2$	$\cos(\phi_1+\phi_2)$
$-3/2$		$\mathrm{Re}\{A_3^* A_4\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin^2\theta_0$	$\sin\theta_1$	$\sin\theta_2$	$\cos(\phi_1-\phi_2)$
$+3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_1^* A_4\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_3\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$\sin\theta_1$	$(1+\cos\theta_2)$	$\sin\phi_1$
$+3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_1^* A_4\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$\sin\theta_1$	$(1-\cos\theta_2)$	$\sin\phi_1$
$-3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_2^* A_3\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2$	$\sin\theta_0(1-\cos\theta_0)$	$\sin\theta_1$	$(1+\cos\theta_2)$	$\sin\phi_1$
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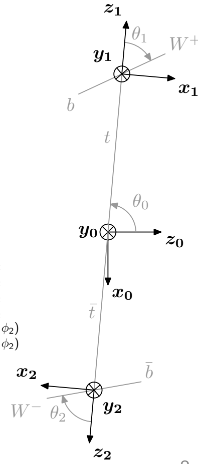
$+3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_2^* A_4\}$	$\lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$(1+\cos\theta_1)$	$\sin\theta_2$	$\sin\phi_2$
$+3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_2^* A_4\}$	$\lvert a_2\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$(1-\cos\theta_1)$	$\sin\theta_2$	$\sin\phi_2$
$-3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_1^* A_3\}$	$\lvert a_2\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin\theta_0(1-\cos\theta_0)$	$(1+\cos\theta_1)$	$\sin\theta_2$	$\sin\phi_2$



Helicity amplitude decomposition in $bW^+\bar{b}W^-$

[Jacob,Wick '59]

Production amplitudes: [Schmidt '95]

$$
\begin{aligned}
++ &: A_1 \sim \frac{2m_t}{\sqrt{s}} V + \sqrt{s}\,(D - \beta\tilde{D}) \\
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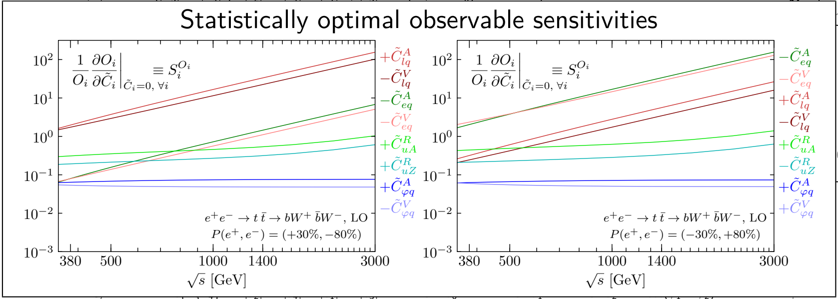
\end{aligned}
$$

In terms of $\Omega = \{\theta_0, \theta_1, \phi_1, \theta_2, \phi_2\}$ helicity angles:

$+3/4$	$(\lvert A_3\rvert^2 + \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 + \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 + \lvert b_3\rvert^2$	$(1+\cos^2\theta_0)$		
$+3/4$	$(\lvert A_3\rvert^2 - \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 + \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$(1+\cos^2\theta_0)$		$\cos\theta_2$
$+3/4$	$(\lvert A_3\rvert^2 - \lvert A_4\rvert^2)$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2 + \lvert b_3\rvert^2$	$(1+\cos^2\theta_0)$	$\cos\theta_1$	



$+3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_1^* A_4\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_3\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$\sin\theta_1$	$(1+\cos\theta_2)$	$\sin\phi_1$
$+3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_1^* A_4\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$\sin\theta_1$	$(1-\cos\theta_2)$	$\sin\phi_1$
$-3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_2^* A_3\}$	$\lvert a_2\rvert^2 - \lvert a_4\rvert^2$	$\lvert b_1\rvert^2$	$\sin\theta_0(1-\cos\theta_0)$	$\sin\theta_1$	$(1+\cos\theta_2)$	$\sin\phi_1$
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$+3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_2^* A_4\}$	$\lvert a_4\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$(1+\cos\theta_1)$	$\sin\theta_2$	$\sin\phi_2$
$+3/2$	$\sqrt{2}$	$\mathrm{Im}\{A_2^* A_4\}$	$\lvert a_2\rvert^2$	$\lvert b_1\rvert^2 - \lvert b_3\rvert^2$	$\sin\theta_0(1+\cos\theta_0)$	$(1-\cos\theta_1)$	$\sin\theta_2$	$\sin\phi_2$
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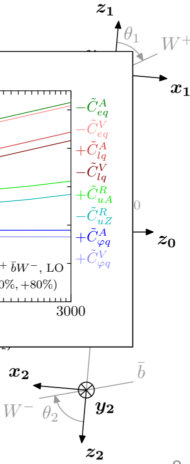


Benchmark analysis

resonant $e^+e^- \to t\,\bar{t} \to bW^+\,\bar{b}W^-$
$m_b/m_t \to 0$
analytically at LO
with perfect detector
and statistical uncertainties only

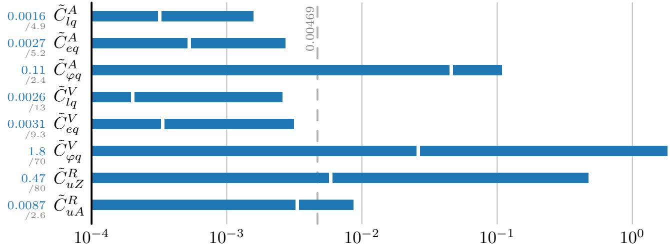
$500\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 500\,\mathrm{GeV}$
$1\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 1\,\mathrm{TeV}$

70% with $P(e^+, e^-) = (+0.3, -0.8)$
30% with $P(e^+, e^-) = (-0.3, +0.8)$

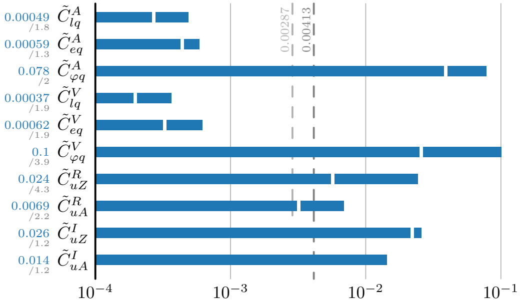
Global constraints

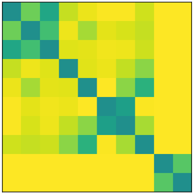
in TeV^{-2}

$\sigma + A^{\mathrm{FB}}$:



Statistically optimal observables:





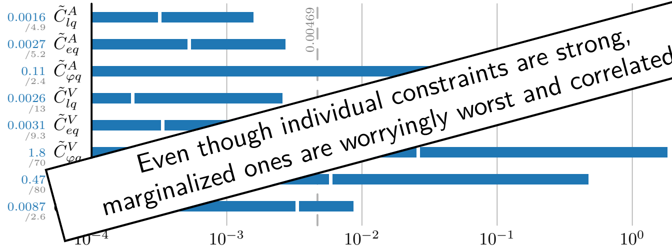
factor of 1.6 improvement of the 8-coefficient's GDP

with linear coefficient dependence only

Global constraints

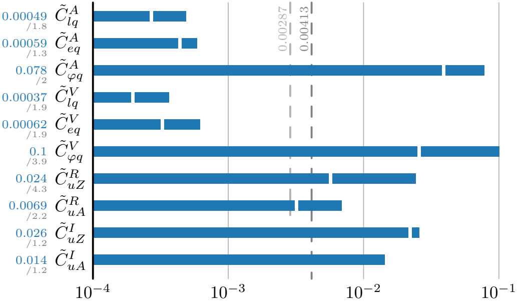
in TeV^{-2}

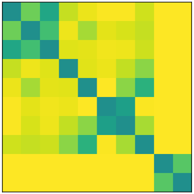
$\sigma + A^{\mathrm{FB}}$:



Even though individual constraints are strong, marginalized ones are worryingly worst and correlated.

Statistically optimal observables:



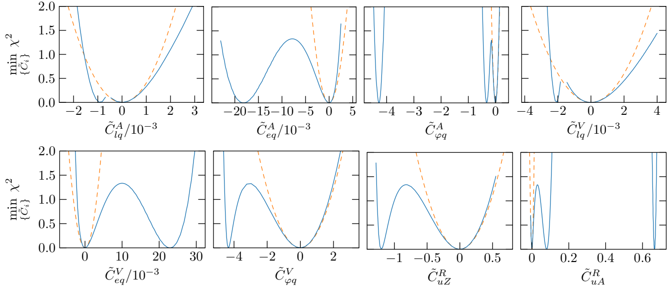


factor of 1.6 improvement of the 8-coefficient's GDP

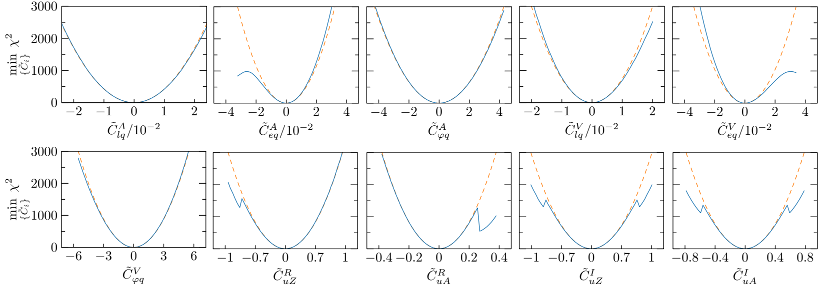
with linear coefficient dependence only

Adding quadratic coefficient dependences

$\sigma + A^{\mathsf{FB}}$:

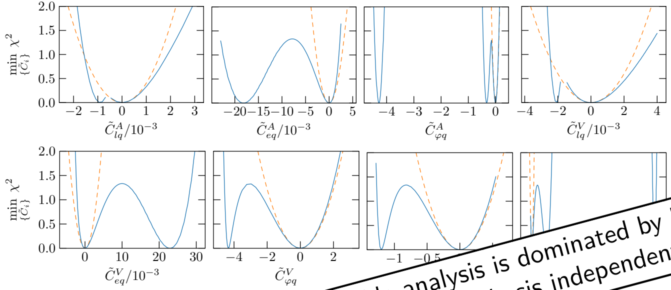


Statistically optimal observables:

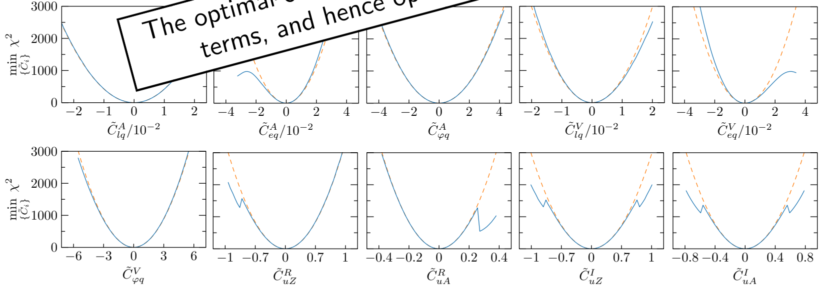


Adding quadratic coefficient dependences

$\sigma + A^{\mathrm{FB}}$:



Statistically optimal obser



The optimal-observable analysis is dominated by linear terms, and hence operator basis independent.

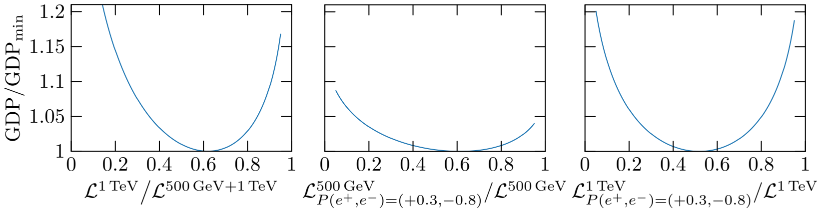
Run parameters optimization, GDP-based

Examples of run parameters optimization

Given $1.5\,\mathrm{ab}^{-1}$ to share between two energies and polarizations,
the optimal repartition is:

$\sqrt{s} = 500$ GeV	570 fb^{-1}	61% with $P(e^+, e^-) = (+0.3, -0.8)$
1 TeV	930 fb^{-1}	52%

$\longrightarrow$ GDP is 1.02 times better than the benchmark one
for the optimal observable analysis with all 11 coefficients.



Same performances require $5.6\,\mathrm{ab}^{-1}$ with only $\sqrt{s} = 380 + 500\,\mathrm{GeV}$:

$\sqrt{s} = 380$ GeV	1.7 ab^{-1}	59%	with $P(e^+, e^-) = (+0.3, -0.8)$
500 GeV	3.9 ab^{-1}	53%	

Summary

The EFT parametrizes systematically the theory space
in direct vicinity of the standard model.

A global analysis of future-lepton-collider constraints
on the top EFT is ongoing:

- including notably four-fermion operators,
- examining NLO QCD and off-shell top effects.

Statistically optimal observables greatly help

- constraining all directions in the effective-theory space,
- producing basis-independent limits.

Global determinant parameter ratios assess the strengthening
of global constraints, basis independently.

Backup

NLO in QCD for $e^+e^- \to bW^+\bar{b}W^-$

For various beam polarizations and center-of-mass energies:

Each cell: central value ±(uncertainty) with upper/lower variations; the number in parentheses is the small number printed under the value.

pol	$\sqrt{s}$ [GeV]	σ_{SM} [fb]	σ_i [fb] $\vert^{A}_{lq}$	$\vert^{A}_{eq}$	$\vert^{A}_{\phi q}$	$\vert^{V}_{lq}$	$\vert^{V}_{eq}$	$\vert^{V}_{\phi q}$	$\vert^{R}_{uZ}$	$\vert^{R}_{uA}$	$\vert^{I}_{uZ}$	$\vert^{I}_{uA}$	$\vert^{R}_{uG}$
00	300	2.92 ±0.3% $^{+1\%}_{-1\%}$ (1.15)	0.353 ±0.2% $^{+1\%}_{-1\%}$ (1.15)	−0.0856 ±0.4% $^{-2\%}_{+2\%}$ (1.27)	0.14 ±0.1% $^{+2\%}_{-1\%}$ (1.2)	−0.621 ±0.2% $^{-2\%}_{+3\%}$ (1.34)	−0.303 ±0.4% $^{-3\%}_{+4\%}$ (1.51)	−0.136 ±0.1% $^{-2\%}_{+2\%}$ (1.21)	0.349 ±0.3% $^{+2\%}_{-2\%}$ (1.21)	0.32 ±0.1% $^{+3\%}_{-2\%}$ (1.33)	−0.000225 ±90% $^{-7\%}_{+9\%}$ (—)	−0.000125 ±90% $^{-9\%}_{+10\%}$ (—)	0.000214 ±6% $^{+10\%}_{-9\%}$ (—)
00	380	825 ±0.5% $^{+2\%}_{-1\%}$ (1.18)	77.1 ±3% $^{+3\%}_{-2\%}$ (1.34)	−55.6 ±20% $^{-2\%}_{+3\%}$ (1.32)	53.1 ±0.1% $^{+2\%}_{-1\%}$ (1.2)	−993 ±2% $^{-1\%}_{+2\%}$ (1.19)	−635 ±1% $^{-1\%}_{+1\%}$ (1.16)	−62.9 ±0.6% $^{-1\%}_{+2\%}$ (1.19)	118 ±2% $^{+1\%}_{-1\%}$ (1.14)	323 ±2% $^{+2\%}_{-1\%}$ (1.19)	0.107 ±300% $^{+20\%}_{-20\%}$ (−1.36)	−0.434 ±80% $^{-10\%}_{+10\%}$ (—)	0.25 ±10% $^{+10\%}_{-9\%}$ (—)
00	500	669 ±0.5% $^{+0.4\%}_{-0.5\%}$ (0.952)	258 ±7% $^{+0.6\%}_{-0.7\%}$ (0.936)	−233 ±2% $^{-0.3\%}_{+0.4\%}$ (1.04)	49.2 ±1% $^{+0.08\%}_{-0.1\%}$ (0.99)	−1230 ±2% $^{-0.8\%}_{+0.7\%}$ (0.929)	−750 ±4% $^{-2\%}_{+1\%}$ (0.872)	−45.2 ±5% $^{-1\%}_{+0.9\%}$ (0.909)	102 ±5% $^{+0.3\%}_{-0.3\%}$ (0.97)	263 ±0.7% $^{+0.6\%}_{-0.8\%}$ (0.929)	−2.08 ±50% $^{-6\%}_{+8\%}$ (—)	1.78 ±80% $^{+10\%}_{-8\%}$ (—)	0.715 ±30% $^{+10\%}_{-9\%}$ (—)
00	1000	221 ±0.5% $^{+1\%}_{-1\%}$ (0.897)	756 ±9% $^{+2\%}_{-1\%}$ (1.21)	−475 ±20% $^{-0.2\%}_{+0.1\%}$ (0.983)	15.6 ±4% $^{+2\%}_{-2\%}$ (0.844)	−1070 ±20% $^{-3\%}_{+2\%}$ (0.784)	−940 ±6% $^{-0.6\%}_{+0.5\%}$ (0.95)	−15.5 ±3% $^{-1\%}_{+0.8\%}$ (0.914)	36.1 ±5% $^{+0.04\%}_{-0.05\%}$ (0.995)	87.3 ±3% $^{+1\%}_{-1\%}$ (0.899)	0.392 ±200% $^{+10\%}_{-10\%}$ (—)	−8.74 ±40% $^{-9\%}_{+10\%}$ (—)	0.907 ±5% $^{+10\%}_{-9\%}$ (—)
00	1400	132 ±3% $^{+0.6\%}_{-0.7\%}$ (0.936)	391 ±30% $^{+7\%}_{-9\%}$ (0.555)	−412 ±30% $^{-3\%}_{+2\%}$ (0.798)	8.29 ±3% $^{+2\%}_{-3\%}$ (0.803)	−1460 ±5% $^{-0.9\%}_{+0.7\%}$ (0.926)	−816 ±10% $^{-3\%}_{+2\%}$ (0.794)	−8 ±4% $^{-2\%}_{+1\%}$ (0.859)	21.6 ±8% $^{+0.2\%}_{-0.1\%}$ (1.03)	59.8 ±6% $^{+0.5\%}_{-0.4\%}$ (1.08)	1.8 ±80% $^{+8\%}_{-6\%}$ (—)	0.257 ±200% $^{+20\%}_{-20\%}$ (−0.906)	0.414 ±100% $^{+10\%}_{-10\%}$ (—)
00	3000	40.2 ±10% $^{+1\%}_{-1\%}$ (1.13)	1080 ±20% $^{+1\%}_{-0.8\%}$ (1.1)	−70.4 ±200% $^{-70\%}_{+60\%}$ (0.128)	1.28 ±10% $^{+8\%}_{-9\%}$ (0.533)	−1270 ±20% $^{-0.3\%}_{+0.2\%}$ (0.981)	−689 ±50% $^{-5\%}_{+4\%}$ (0.668)	−0.717 ±30% $^{-20\%}_{+10\%}$ (0.406)	10[illegible] ±30% $^{+3\%}_{-2\%}$ (1.38)	14.2 ±30% $^{+0.5\%}_{-0.4\%}$ (1.05)	1.85 ±100% $^{+7\%}_{-9\%}$ (0.441)	2.15 ±200% $^{+1\%}_{-1\%}$ (0.594)	−0.261 ±200% $^{-7\%}_{+8\%}$ (—)
+−	300	2.73 ±0.3% $^{+1\%}_{-1\%}$ (1.14)	0.351 ±0.2% $^{+1\%}_{-1\%}$ (1.14)	—	0.126 ±0.2% $^{+2\%}_{-1\%}$ (1.19)	−0.62 ±0.2% $^{-2\%}_{+3\%}$ (1.34)	—	−0.14 ±[illegible] $^{-2\%}_{+[illegible]2\%}$ (1.22)	0.376 ±[illegible].1% $^{[illegible]2\%}_{-2\%}$ (1.23)	0.241 ±0.2% $^{+2\%}_{-2\%}$ (1.28)	6.25e − 06 ±2000% $^{+70\%}_{-50\%}$ (−0.119)	2.7e − 06 ±2000% $^{+20\%}_{-30\%}$ (0.19)	0.000197 ±4% $^{+10\%}_{-9\%}$ (—)
+−	380	579 ±2% $^{+2\%}_{-1\%}$ (1.19)	73 ±1% $^{+3\%}_{-2\%}$ (1.35)	—	36.1 ±0.5% $^{+2\%}_{-1\%}$ (1.18)	−968 ±2% $^{-1\%}_{+1\%}$ (1.16)	—	[illegible]4.5 ±1% $^{-1[illegible]}_{+[illegible]}$ ([illegible]16)	165 ±0.4% $^{+2\%}_{-1\%}$ (1.18)	198 ±0.6% $^{+2\%}_{-1\%}$ (1.18)	0.44 ±70% $^{+10\%}_{-9\%}$ (—)	−0.324 ±100% $^{-10\%}_{+10\%}$ (—)	0.185 ±10% $^{+10\%}_{-9\%}$ (—)
+−	500	469 ±0.5% $^{+0.4\%}_{-0.4\%}$ (0.96)	287 ±5% $^{+0.4\%}_{-0.3\%}$ (1.03)	—	31.7 ±2% $^{+0.4\%}_{-0.5\%}$ (0.953)	−1270 ±2% $^{-0.3\%}_{+0.2\%}$ (0.972)	—	−[illegible]1.1 ±3% $^{-0.2\%}_{+0.2\%}$ (0.982)	130 ±1% $^{+0.8\%}_{-0.9\%}$ (0.918)	164 ±0.5% $^{+0.5\%}_{-0.6\%}$ (0.943)	1.35 ±50% $^{+10\%}_{-9\%}$ (—)	−0.442 ±200% $^{-6\%}_{+8\%}$ (—)	0.554 ±10% $^{+10\%}_{-8\%}$ (—)
+−	1000	160 ±1% $^{+0.9\%}_{-1\%}$ (0.902)	470 ±8% $^{+3\%}_{-4\%}$ (0.742)	—	11.8 ±4% $^{+0.6\%}_{-0.8\%}$ (0.931)	−1450 ±4% $^{-0.8\%}_{+0.7\%}$ (0.926)	—	−15.5 ±2% $^{-0.8\%}_{+0.7\%}$ (0.93)	44.9 ±3% $^{+0.8\%}_{-1\%}$ (0.916)	52.6 ±6% $^{+1\%}_{-1\%}$ (0.883)	−0.663 ±200% $^{-7\%}_{+9\%}$ (—)	5.09 ±40% $^{+10\%}_{-8\%}$ (—)	0.587 ±4% $^{+10\%}_{-9\%}$ (—)
+−	1400	84.9 ±10% $^{+2\%}_{-2\%}$ (0.817)	507 ±20% $^{+3\%}_{-4\%}$ (0.715)	—	7.57 ±6% $^{+0.7\%}_{-0.6\%}$ (1.07)	−1230 ±[illegible] $^{-3[illegible]}_{+3[illegible]}$ (0.772)	—	−7.76 ±6% $^{-2\%}_{+2\%}$ (0.835)	22.2 ±8% $^{+2\%}_{-3\%}$ (0.806)	29.5 ±9% $^{+0.9\%}_{-1\%}$ (0.905)	−1.22 ±300% $^{-8\%}_{+10\%}$ (—)	−2.38 ±90% $^{-10\%}_{+10\%}$ (—)	0.281 ±100% $^{+10\%}_{-10\%}$ (—)
+−	3000	23.8 ±7% $^{+2\%}_{-3\%}$ (0.787)	356 ±30% $^{+10\%}_{-10\%}$ (0.414)	—	0.574 ±30% $^{+20\%}_{-20\%}$ (0.338)	−14[illegible]0 ±[illegible]10% $^{-2\%}_{+1\%}$ (0.853)	—	−1.08 ±30% $^{-9\%}_{+7\%}$ (0.543)	6.28 ±30% $^{+2\%}_{-1\%}$ (1.25)	—	1.93 ±90% $^{+10\%}_{-10\%}$ (—)	8.36 ±30% $^{+7\%}_{-5\%}$ (—)	0.197 ±70% $^{+10\%}_{-10\%}$ (—)
−+	300	0.218 ±0.4% $^{-2\%}_{+0\%}$ (1.37)	—	−0.0855 ±0.1% $^{-2\%}_{+2\%}$ (1.27)	0.0147 ±0.1% $^{+3\%}_{-3\%}$ (1.42)	—	−0.302 ±0.2% $^{-3\%}_{+4\%}$ (1.51)	0.00343 ±0.1% $^{+4\%}_{-3\%}$ (1.59)	−0.0259 ±0.1% $^{-3\%}_{+4\%}$ (1.5)	0.0799 ±0.2% $^{+4\%}_{-3\%}$ (1.5)	3.38e − 06 ±300% $^{+6\%}_{-5\%}$ (—)	−7.78e − 06 ±200% $^{-0.1\%}_{+0.07\%}$ (1.3)	1.84e − 05 ±4% $^{+10\%}_{-9\%}$ (—)
−+	380	249 ±0.9% $^{-1\%}_{+0\%}$ (1.19)	—	−51.6 ±4% $^{-1\%}_{+2\%}$ (1.18)	16.2 ±0.6% $^{+2\%}_{-1\%}$ (1.18)	—	−649 ±0.2% $^{-1\%}_{+2\%}$ (1.18)	3.31 ±1% $^{+1\%}_{-1\%}$ (1.16)	−41.8 ±0.8% $^{-1\%}_{+1\%}$ (1.15)	124 ±0.4% $^{+2\%}_{-1\%}$ (1.19)	0.0946 ±200% $^{+10\%}_{-9\%}$ (—)	−0.0633 ±200% $^{-10\%}_{+20\%}$ (—)	0.000205 ±9000% $^{+200\%}_{-200\%}$ (−0.0614)
−+	500	203 ±1% $^{+0.5\%}_{+0\%}$ (0.948)	—	−213 ±1% $^{-0.5\%}_{+0.4\%}$ (0.958)	15.8 ±0.9% $^{+0.2\%}_{-0.3\%}$ (0.975)	—	−810 ±0.7% $^{-0.8\%}_{+0.6\%}$ (0.933)	0.767 ±4% $^{+2\%}_{-3\%}$ (0.783)	−34.2 ±5% $^{-0.9\%}_{+0.7\%}$ (0.923)	99.7 ±0.5% $^{+0.9\%}_{-1\%}$ (0.909)	0.316 ±40% $^{+10\%}_{-8\%}$ (—)	0.187 ±200% $^{+10\%}_{-8\%}$ (—)	0.255 ±20% $^{+10\%}_{-9\%}$ (—)
−+	1000	63.4 ±5% $^{+0.9\%}_{+0\%}$ (0.911)	—	−327 ±10% $^{-4\%}_{+4\%}$ (0.7)	4.88 ±3% $^{+2\%}_{-2\%}$ (0.828)	—	−810 ±5% $^{-2\%}_{+2\%}$ (0.82)	−0.24 ±10% $^{-1\%}_{+0.8\%}$ (0.907)	−10.4 ±6% $^{-2\%}_{+2\%}$ (0.812)	34.1 ±5% $^{+0.9\%}_{-1\%}$ (0.906)	−0.832 ±70% $^{-8\%}_{+10\%}$ (—)	0.255 ±300% $^{+3\%}_{-2\%}$ (1.26)	0.39 ±10% $^{+10\%}_{-8\%}$ (—)
−+	1400	33.8 ±6% $^{+0.8\%}_{+0\%}$ (0.917)	—	−493 ±10% $^{-0.4\%}_{+0.3\%}$ (0.93)	2.86 ±4% $^{+1\%}_{-1\%}$ (0.897)	—	−850 ±4% $^{-2\%}_{+2\%}$ (0.842)	−0.208 ±10% $^{-0.4\%}_{+0.5\%}$ (1.06)	−4.75 ±20% $^{-5\%}_{+4\%}$ (0.666)	10.2 ±0% $^{+0\%}_{+0\%}$ (0.504)	0.448 ±300% $^{+2\%}_{-2\%}$ (1.23)	0.475 ±400% $^{+20\%}_{-20\%}$ (−0.982)	0.258 ±30% $^{+10\%}_{-9\%}$ (—)
−+	3000	—	—	−424 ±60% $^{-0.7\%}_{+0.8\%}$ (1.09)	0.226 ±40% $^{+10\%}_{-20\%}$ (0.4)	—	—	0.146 ±0% $^{+0\%}_{+0\%}$ (—)	−1.5 ±70% $^{-6\%}_{+5\%}$ (0.651)	−497 ±0% $^{+0\%}_{+0\%}$ (—)	2.52 ±40% $^{+6\%}_{-5\%}$ (—)	2110 ±0% $^{+0\%}_{+0\%}$ (—)	−0.0453 ±200% $^{-0.04\%}_{+0.04\%}$ (1)

preliminary

(MG5_aMC@NLO, complex mass scheme, $m_b/m_t \to 0$,
EFT dependence of the total width not included)