Global EFT fit for top couplings at future lepton colliders

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Based on
1807.02121 with G. Durieux, M. Perelló, M. Vos;
1804.09766 & 1809.03520 with G. Durieux, J. Gu, E. Vryonidou.

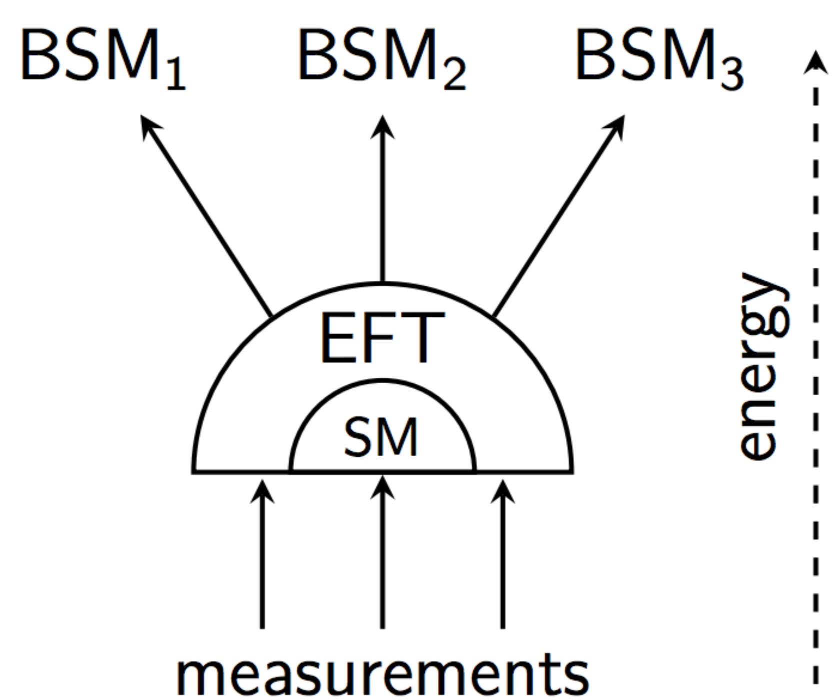
SMEFT

systematically parametrizes the theory space in direct vicinity of the SM

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i^{(6)} O_i^{(6)}}{\Lambda^2} + \sum_i \frac{f_i^{(8)} O_i^{(8)}}{\Lambda^4} + \cdots$$

- based on SM fields and symmetries
- in a low-energy limit
- systematic (and renormalizable) when global

(...) if one writes down the most general possible Lagrangian, including all terms consistent with assumed symmetry principles, (...) the result will simply be the most general possible S-matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry. [*Phenomenological Lagrangians*, Weinberg '79]



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- based on SM fields and symmetries
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- systematic (and renormalizable) when global

Identify SM deviations through precise measurements

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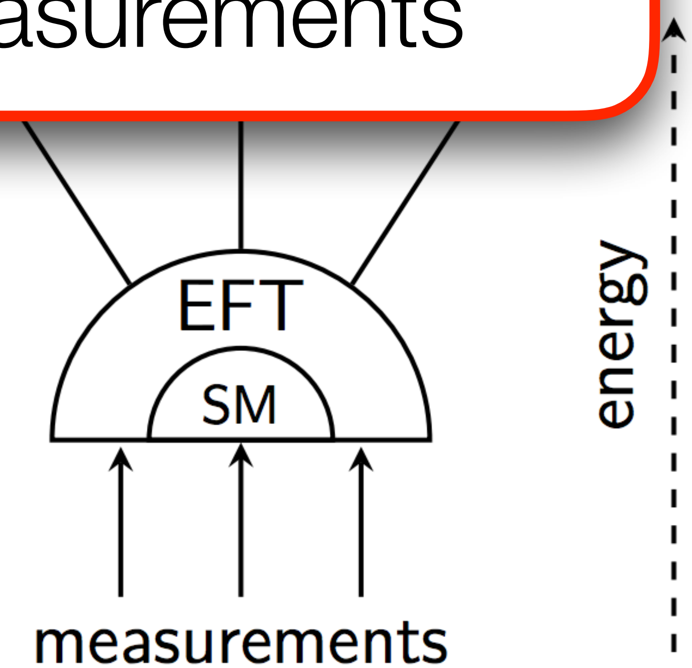
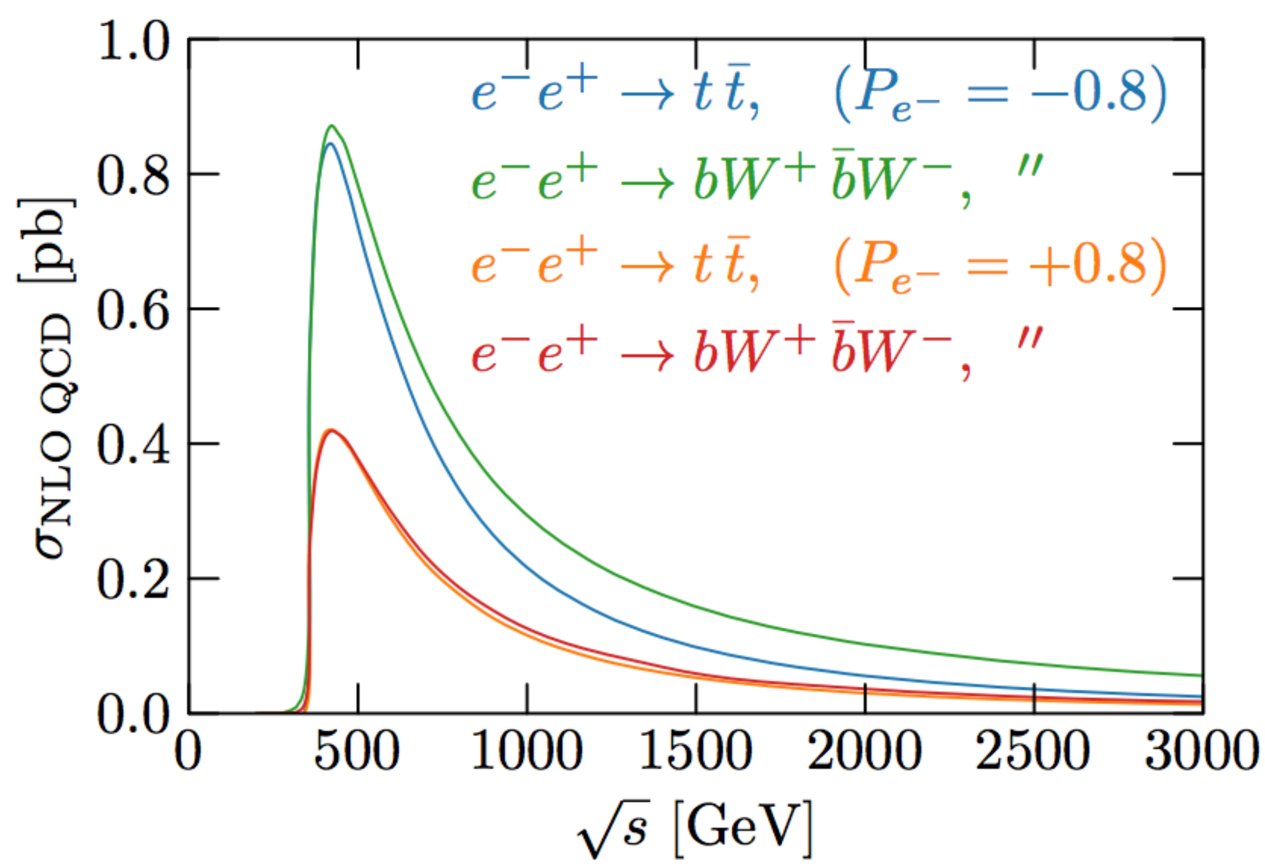
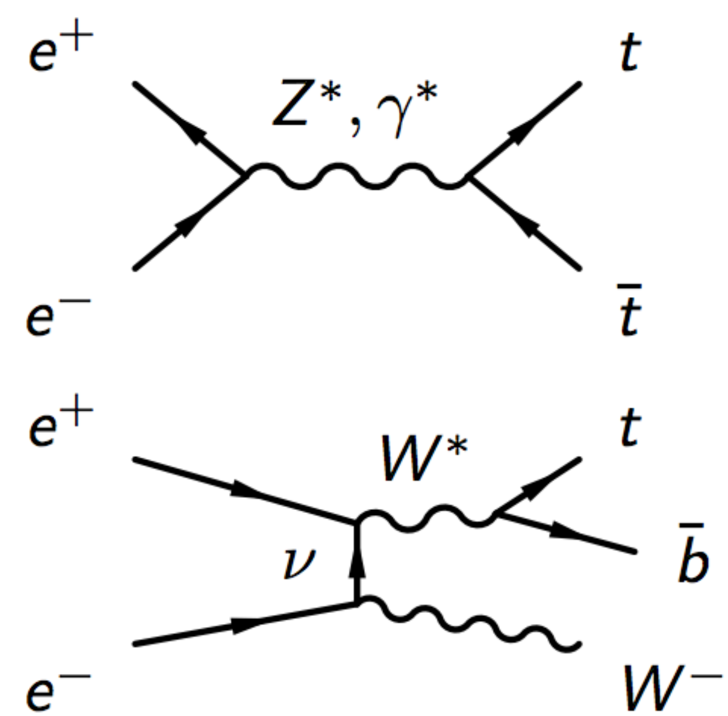


Top pair production





$+\ W^+W^- \to t\,\bar{t}$
catching up at multi-TeV
w/ unitarity breaking effects
[Grojean, Wulzer, You, Zhang]

- σ peaked at about **410 GeV (NLO+ISR)**
- enhanced for a left-handed beam
- fall-off as $1/s$
- single-top contribution increasingly important

Top EW couplings

$$\mathcal{L}_{\text{EFT}} = \sum_i \frac{C_i}{\Lambda^2} O_i$$

Two-quark operators:

Scalar:
$$O_{u\varphi} \equiv \bar{q} u \,\tilde{\varphi}\; \varphi^\dagger\varphi,$$

Vector:
$$\begin{aligned}
O^1_{\varphi q} &\equiv \bar{q}\gamma^\mu q \;\; \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi && \equiv O^+_{\varphi q} + O^V_{\varphi q} - O^A_{\varphi q}, \\
O^3_{\varphi q} &\equiv \bar{q}\gamma^\mu \tau^I q \;\; \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi && \equiv O^+_{\varphi q} - O^V_{\varphi q} + O^A_{\varphi q} && \text{(CC also)} \\
O_{\varphi u} &\equiv \bar{u}\gamma^\mu u \;\; \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi && \equiv O^V_{\varphi q} + O^A_{\varphi q} \\
O_{\varphi ud} &\equiv \bar{u}\gamma^\mu d \;\; \tilde{\varphi}^\dagger i\overleftrightarrow{D}_\mu \varphi, && && \text{(CC only, } m_b \text{ int.)}
\end{aligned}$$

Tensor:
$$\begin{aligned}
O_{uB} &\equiv \bar{q}\sigma^{\mu\nu} u \,\tilde{\varphi}\, g_Y B_{\mu\nu}, && \equiv O_{uA} - \tan\theta_W O_{uZ} \\
O_{uW} &\equiv \bar{q}\sigma^{\mu\nu}\tau^I u \,\tilde{\varphi}\, g_W W^I_{\mu\nu}, && \equiv O_{uA} + \text{cotan}\,\theta_W O_{uZ} && \text{(CC also)} \\
O_{dW} &\equiv \bar{q}\sigma^{\mu\nu}\tau^I d \,\tilde{\varphi}\, g_W W^I_{\mu\nu}, && && \text{(CC only, } m_b \text{ int.)} \\
O_{uG} &\equiv \bar{q}\sigma^{\mu\nu} T^A u \,\tilde{\varphi}\, g_s G^A_{\mu\nu}. && && \text{(NLO only)}
\end{aligned}$$

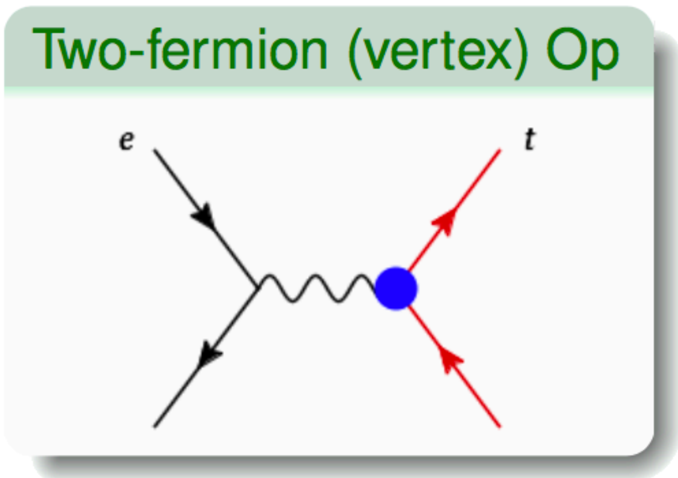
Two-quark–two-lepton operators:

Scalar:
$$\begin{aligned}
O^S_{lequ} &\equiv \bar{l} e \;\; \varepsilon \;\; \bar{q} u, && \text{(CC also, } m_e \text{ int.)} \\
O_{ledq} &\equiv \bar{l} e \;\; \bar{d} q, && \text{(CC only, } m_e \text{ int.)}
\end{aligned}$$

Vector:
$$\begin{aligned}
O^1_{lq} &\equiv \bar{l}\gamma_\mu l \;\; \bar{q}\gamma^\mu q && \equiv O^+_{lq} + O^V_{lq} - O^A_{lq}, \\
O^3_{lq} &\equiv \bar{l}\gamma_\mu \tau^I l \;\; \bar{q}\gamma^\mu \tau^I q && \equiv O^+_{lq} - O^V_{lq} + O^A_{lq}, && \text{(CC also)} \\
O_{lu} &\equiv \bar{l}\gamma_\mu l \;\; \bar{u}\gamma^\mu u && \equiv O^V_{lq} + O^A_{lq}, \\
O_{eq} &\equiv \bar{e}\gamma^\mu e \;\; \bar{q}\gamma_\mu q && \equiv O^V_{eq} - O^A_{eq}, \\
O_{eu} &\equiv \bar{e}\gamma_\mu e \;\; \bar{u}\gamma^\mu u && \equiv O^V_{eq} + O^A_{eq},
\end{aligned}$$

Tensor:
$$O^T_{lequ} \equiv \bar{l}\sigma_{\mu\nu} e \;\; \varepsilon \;\; \bar{q}\sigma^{\mu\nu} u. \qquad \text{(CC also, } m_e \text{ int.)}$$

Top EW couplings



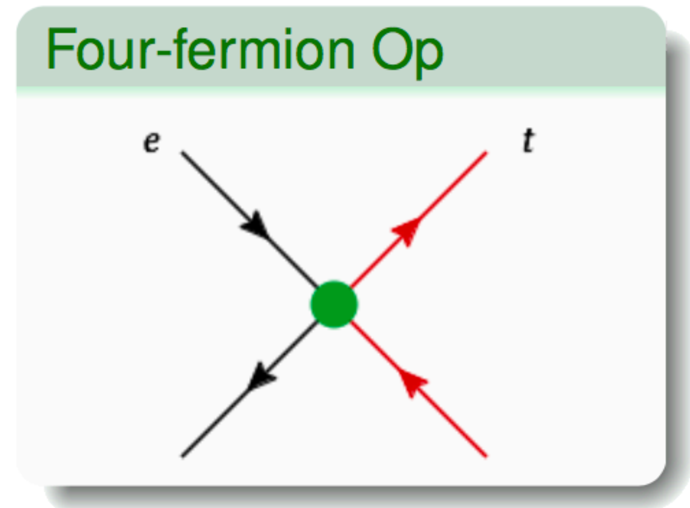
(Axial-)Vector like $O_{\varphi q}^{V}, O_{\varphi q}^{A}$

- Sensitivity independent of energy.

Dipole (CP-even) $\mathrm{Re}O_{uA}, \mathrm{Re}O_{uZ}$

- $\sim E$ in amplitude, but suppressed by interference at *tt* level (cross section and A^{FB})
- $\sim E^2$ sensitivity can be obtained with OO

Dipole (CP-odd) $\mathrm{Im}O_{uA}, \mathrm{Im}O_{uZ}$



Left-handed *ee* O_{lq}^{V}, O_{lq}^{A}

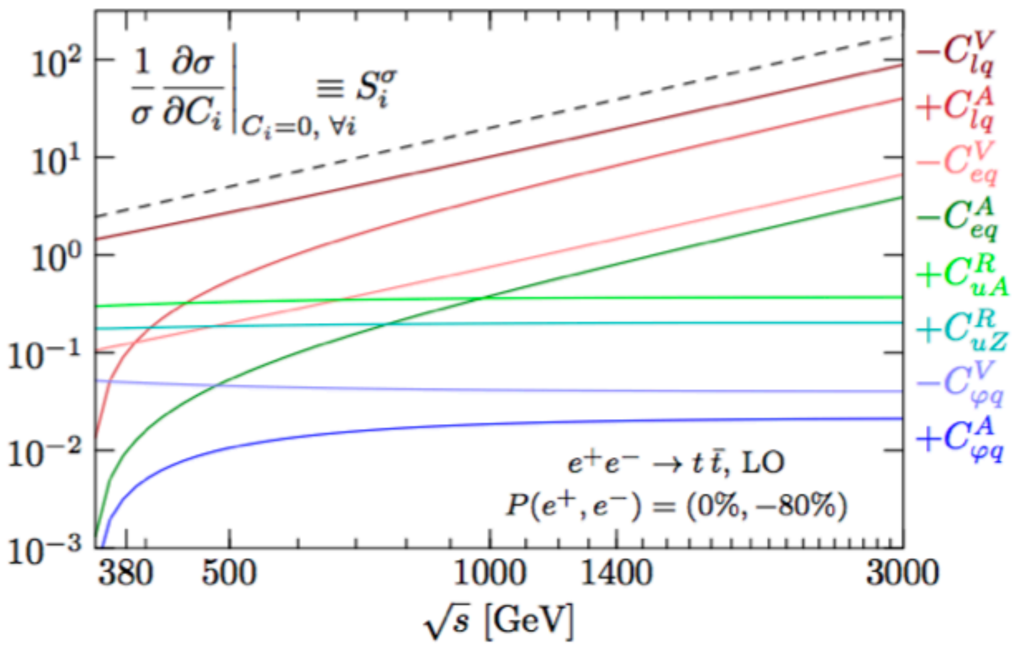
Right-handed *ee* O_{eq}^{V}, O_{eq}^{A}

- E^2 dependence in general observables.
- Similar to the V-A vertex operators. Need at least two different CoM energies to distinguish.

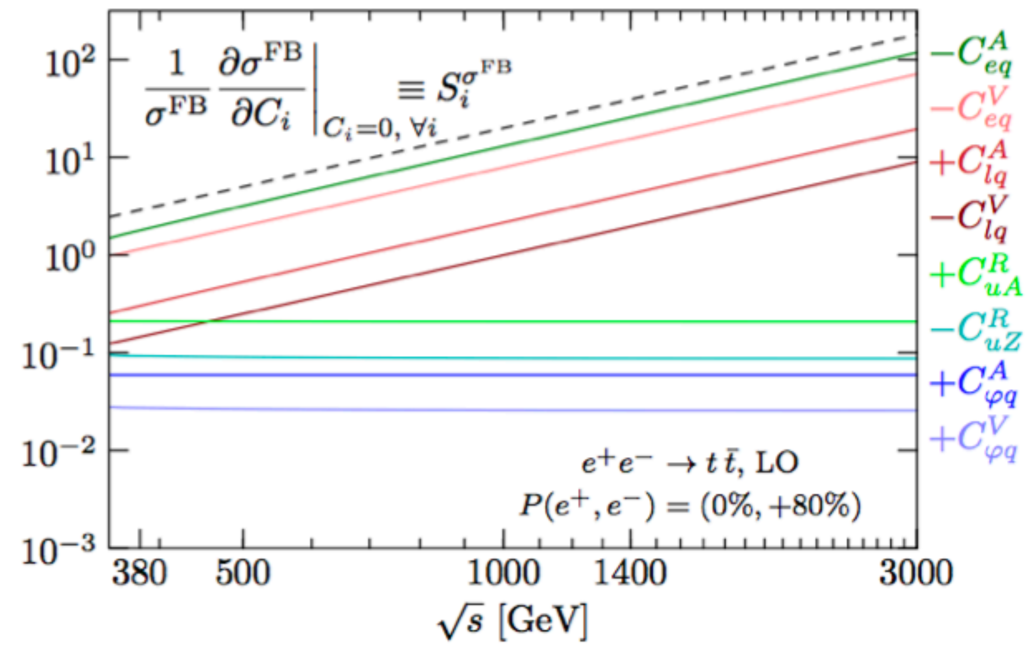
Sensitivity

ee>tt

Total cross section (left pol.):

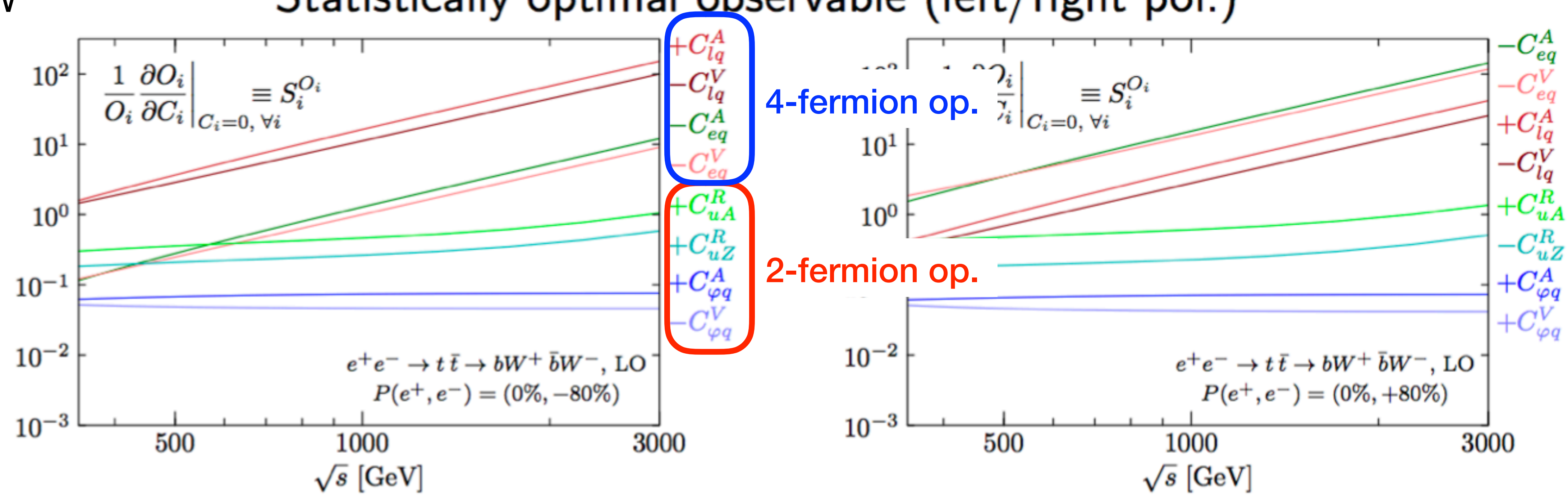


FB-integrated cross section (right pol.):



ee>bWbW

Statistically optimal observable (left/right pol.)

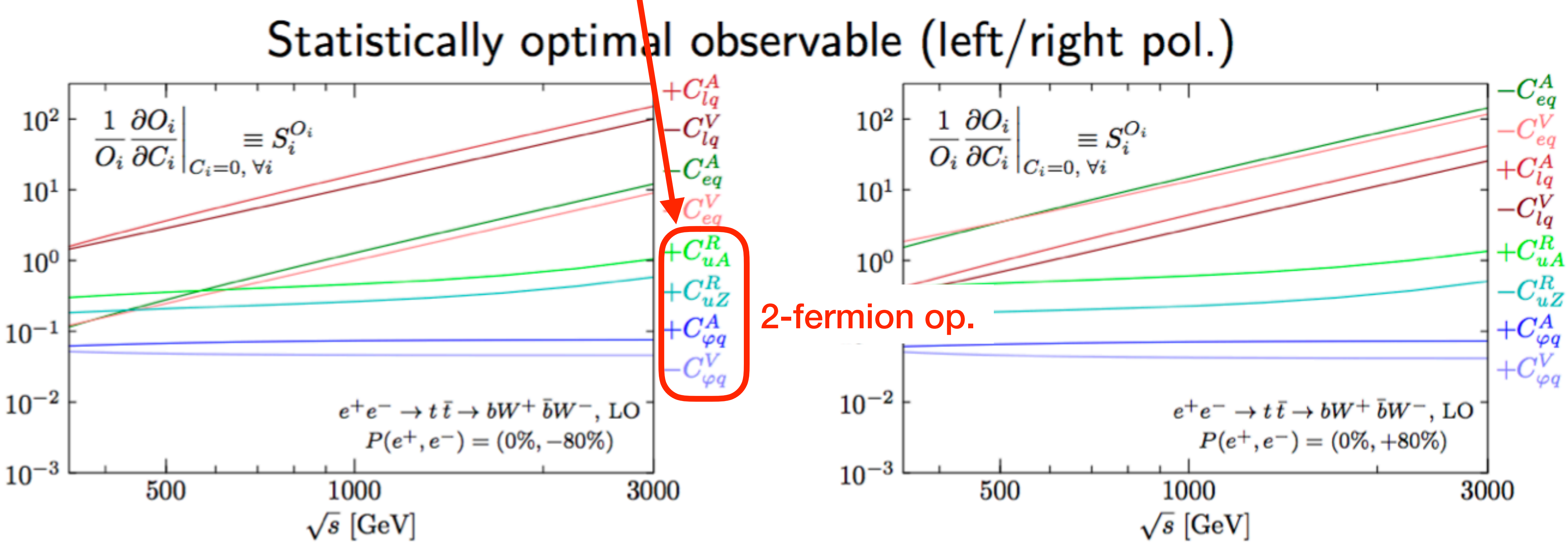


Sensitivity

Patrick Janot arXiv:1503.01325

$$\Gamma_\mu^{ttX} = -ie\left\{\gamma_\mu\left(F_{1V}^X + \gamma_5 F_{1A}^X\right) + \frac{\sigma_{\mu\nu}}{2m_t}(p_t + p_{\bar{t}})^\nu\left(iF_{2V}^X + \gamma_5 F_{2A}^X\right)\right\},$$

(without 4-fermion Ops.) "For four out of five couplings, optimum precision is actually reached for √ s = 365 GeV, and for the fifth one the precision is within 50% of optimum at this energy"



Individual limits

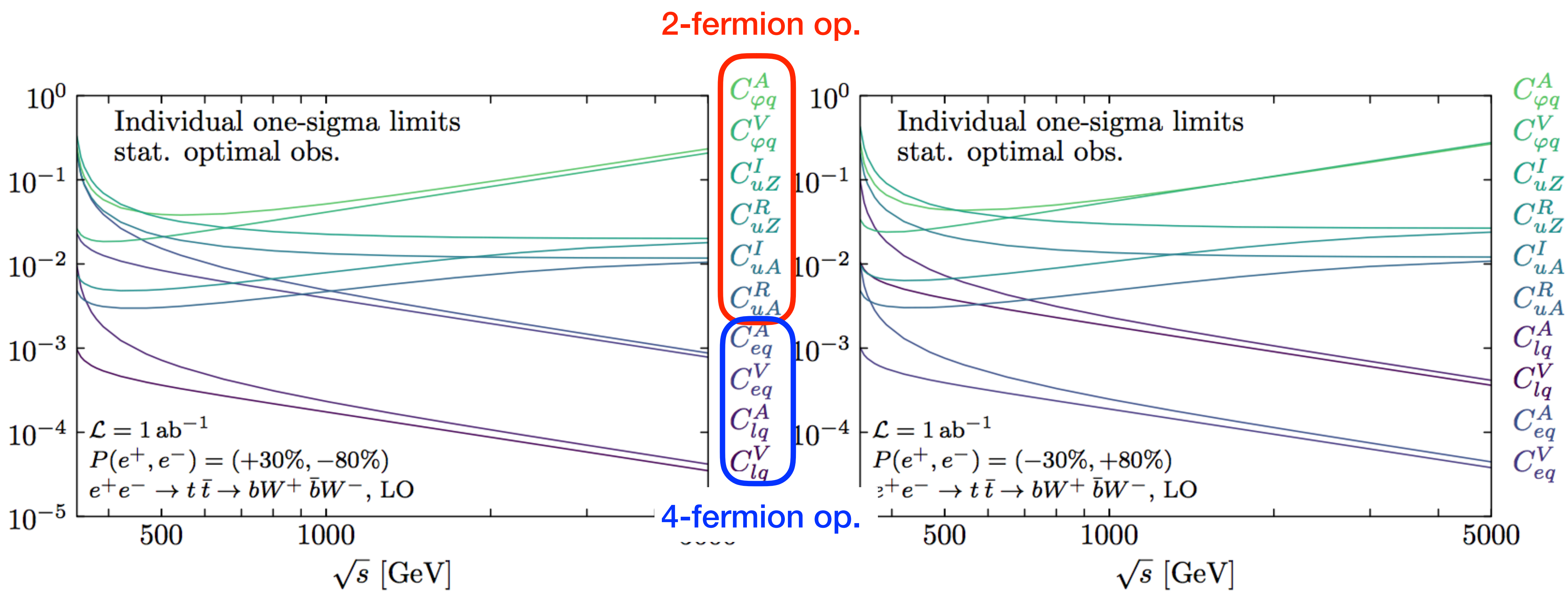


Figure 16. Individual statistical one-sigma constraints on the effective operator coefficients as functions of the centre-of-mass energy, for either mostly left-handed and mostly right-handed electron beam polarizations, and a fixed integrated luminosity of 1 ab^{-1}. Different integrated luminosities are trivially obtained through a $(\mathcal{L}\,[\mathrm{ab}^{-1}])^{-1/2}$ rescaling.

Complementarity

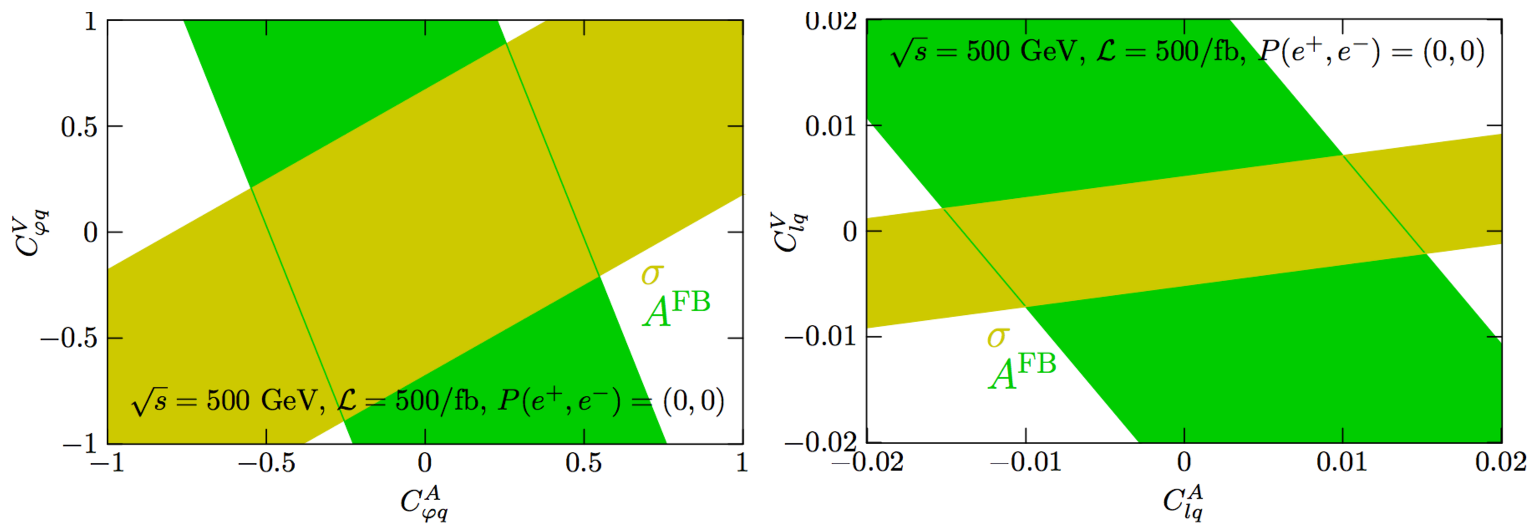


Figure 7. The 68% C.L. regions allowed by measurements of the cross section and forward-backward asymmetry in $e^+e^- \to t\,\bar{t}$ production. An integrated luminosity of 500 fb^{-1} at a centre-of-mass energy of 500 GeV is considered, with unpolarized beams. Central values are assumed to confirm the standard model.

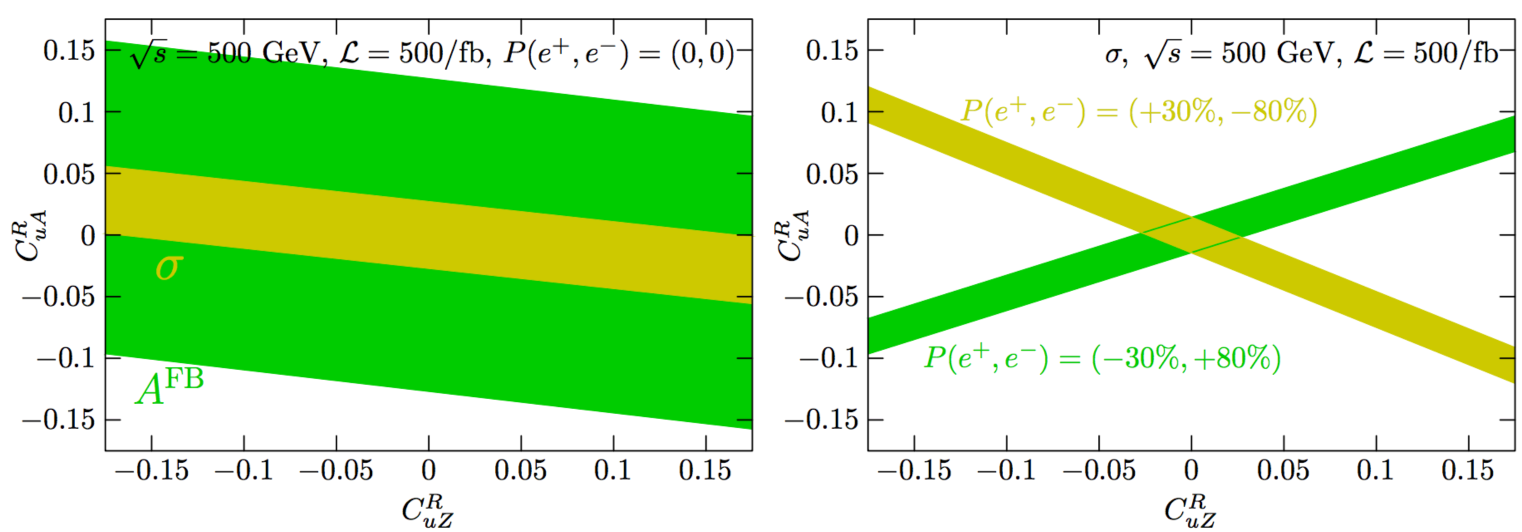


Figure 8. The 68% C.L. regions allowed by measurements of the cross section and forward-backward asymmetry in $e^+e^- \to t\,\bar{t}$ production with unpolarized beams (left) and that of the cross sections with two different configurations of the beam polarization (right). A total luminosity of 500 fb^{-1} collected at 500 GeV is split evenly among two beam polarization configurations. The central values of measurements are assumed to match standard model predictions.

Optimal observable

minimize the one-sigma ellipsoid in EFT parameter space

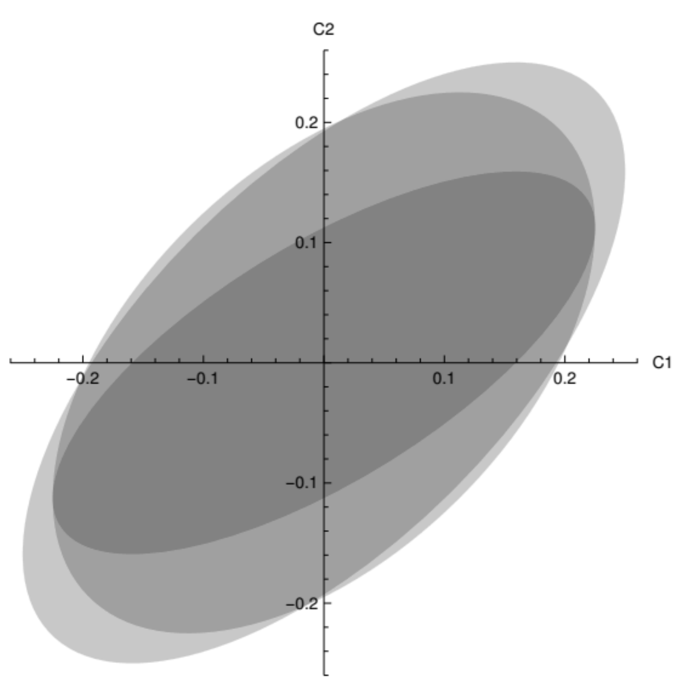
(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$,like MEM)

For small C_i, with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i\, \sigma_i(\Phi)$,

the stat. opt. obs. are the average values of $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.

The associated covariance at $C_i = 0,\ \forall i$ is

$$\mathrm{cov}(C_i, C_j)^{-1} = \epsilon\mathcal{L} \int \mathrm{d}\Phi\ \frac{\sigma_i(\Phi)\sigma_j(\Phi)}{\sigma_0(\Phi)}.$$



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

1. asymmetries: $O_i \sim \mathrm{sign}\{\sin(i\phi)\}$
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 $e^+e^- \to t\,\bar{t}$, on different distributions:
[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

Scenarios

- FCC-ee
  - 200 fb^{-1} at 350 GeV;
  - 1.5 ab^{-1} at 365 GeV;
  - no polarization.

Assume that threshold scan does not interfere with coupling measurements

- ILC
  - 500 fb^{-1} at 500 GeV;
  - 1.0 ab^{-1} at 1 TeV (i.e. no luminosity upgrade);
  - (-0.3,+0.8) and (+0.3,-0.8), equally shared.
- CLIC
  - 500 fb^{-1} at 380 GeV;
  - 1.5 ab^{-1} at 1.4 TeV;
  - 3.0 ab^{-1} at 3.0 TeV;
  - (0,+0.8) and (0,-0.8), equally shared.

Uncertainties

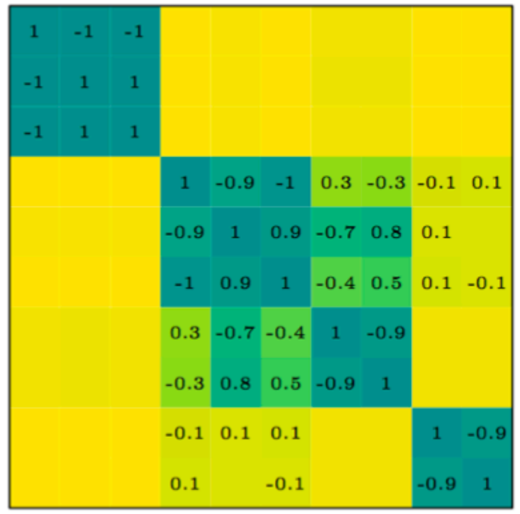
$\sqrt{s}$ [GeV]	350	365	380	500	1000	1400	3000
acceptance times efficiency [%]	-	-	64-67[8]	~ 50	-	37-39	33-37
equivalent $t\bar{t}$ event fraction [%]	10	10	10	10	6	6	5

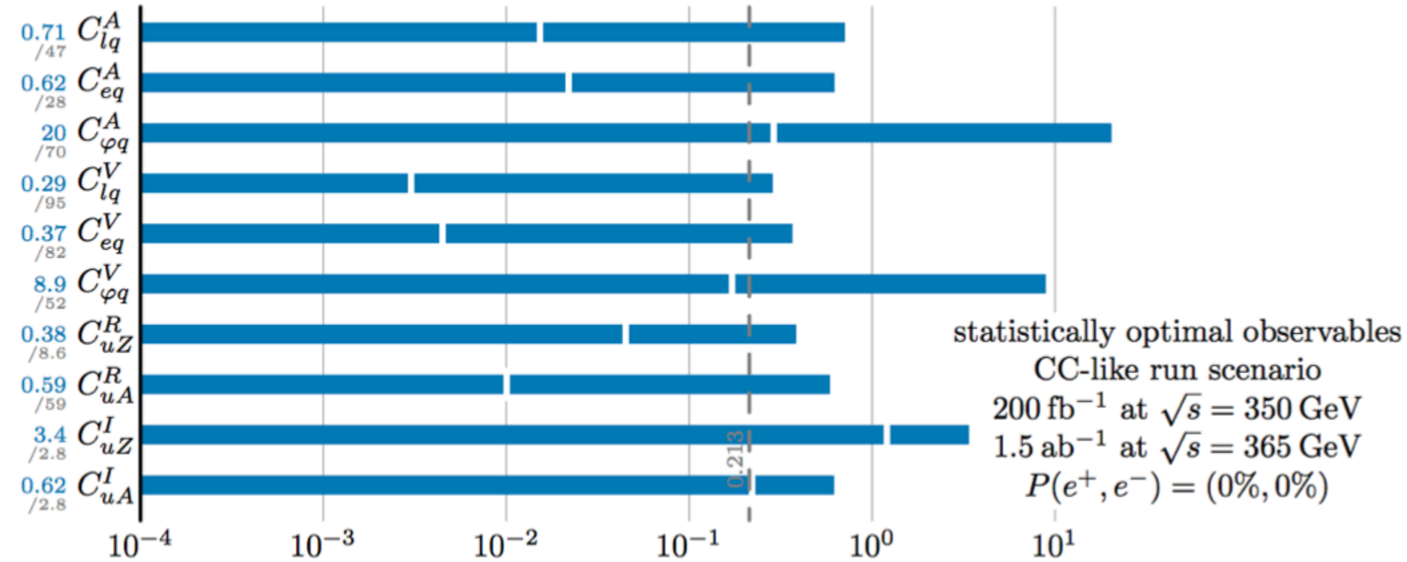
Table 5. Summary of the efficiencies obtained in Refs. [1, 21] (first row) and effective rate fractions available for analysis used in this study (second row). When multiplied by the $e^+e^- \to t\,\bar{t}$ cross section for the nominal centre-of-mass energy and the integrated luminosity, these yield the number of events available for analysis.

- Full-detector simulation performed by ILC and CLIC collaborations.
- Good reconstruction can be obtained with moderate quality cuts.
- Systematics expected to be controlled to the level of statistics.

FCC-ee

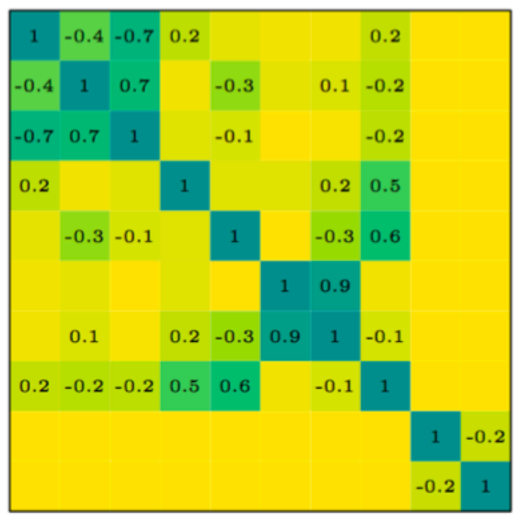
- 200 fb^{-1} at 350
- 1.5 ab^{-1} at 365
- No polarization

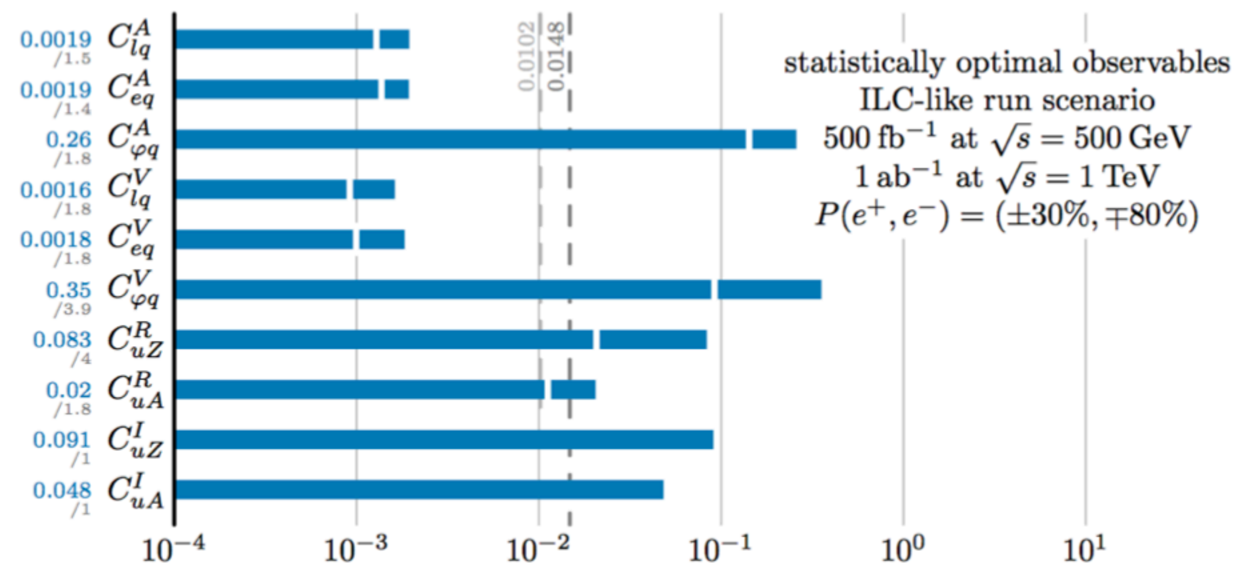




ILC

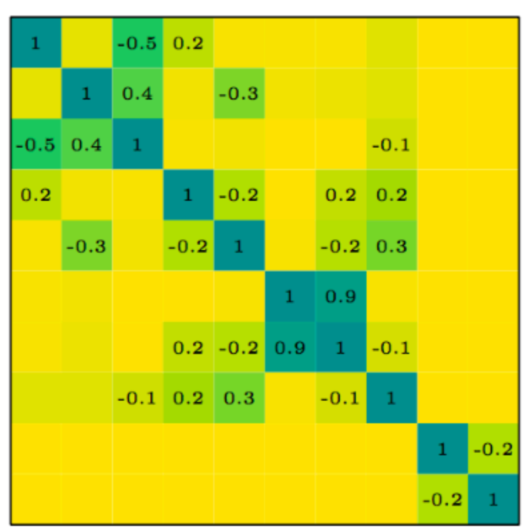
- 500 fb^{-1} at 500
- 1.0 ab^{-1} at 1000
- (-.3,+.8)&(+.3,-.8) equally shared

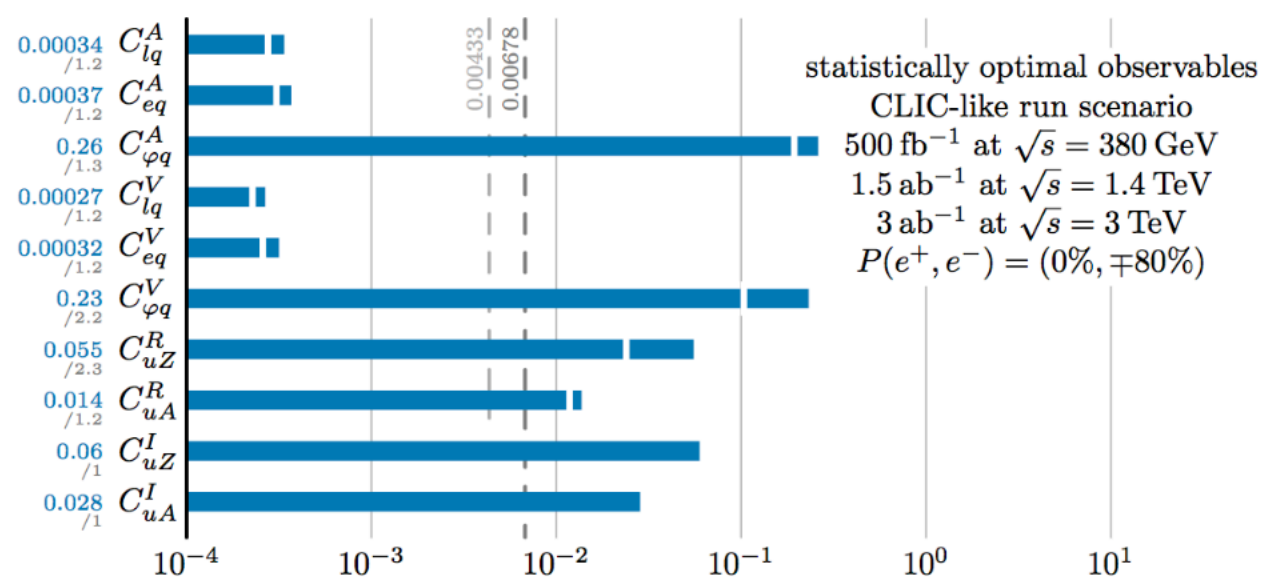




CLIC

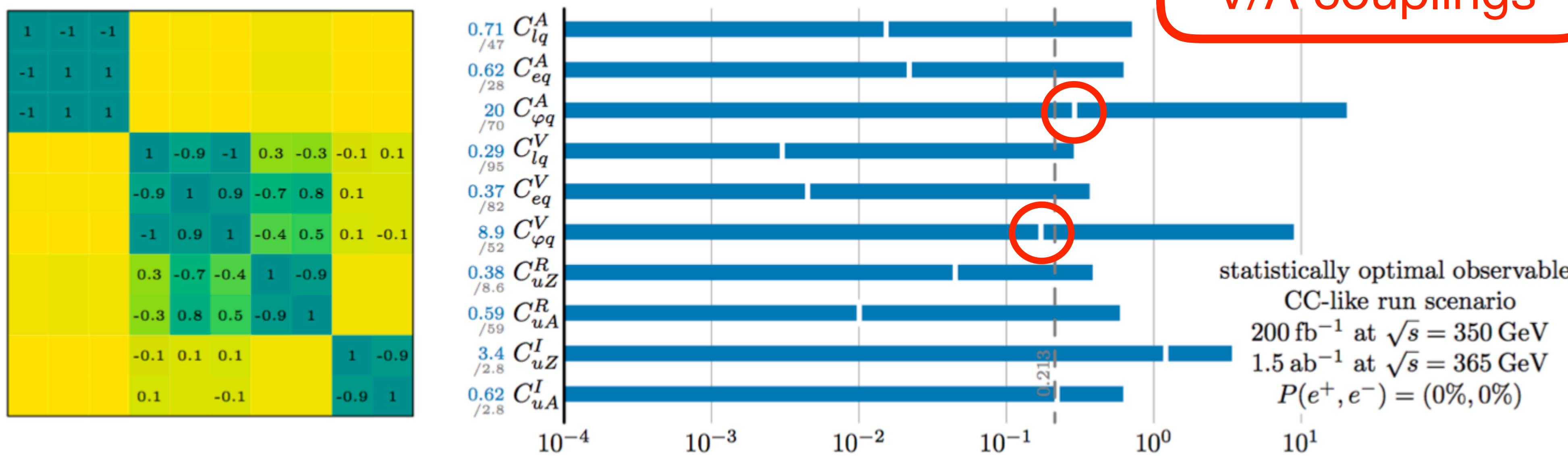
- 500 fb^{-1} at 380
- 1.5 ab^{-1} at 1400
- 3.0 ab^{-1} at 3000
- (0,+.8)&(0,-.8) equally shared





V/A couplings

FCC-ee
- 200 fb^{-1} at 350
- 1.5 ab^{-1} at 365
- No polarization



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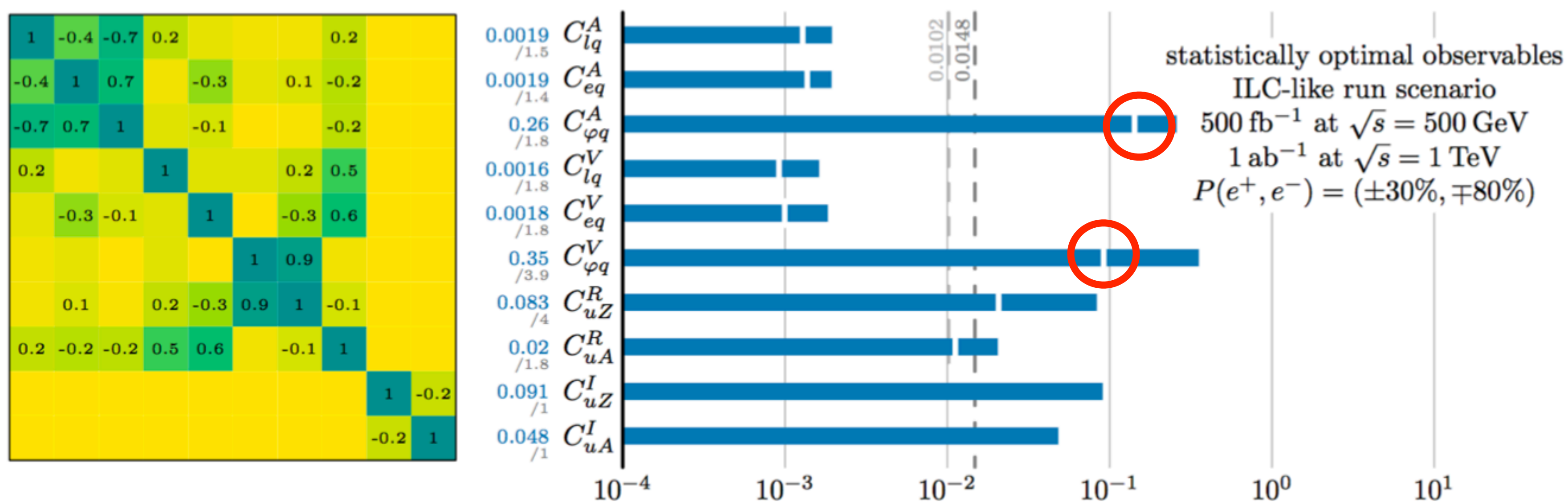

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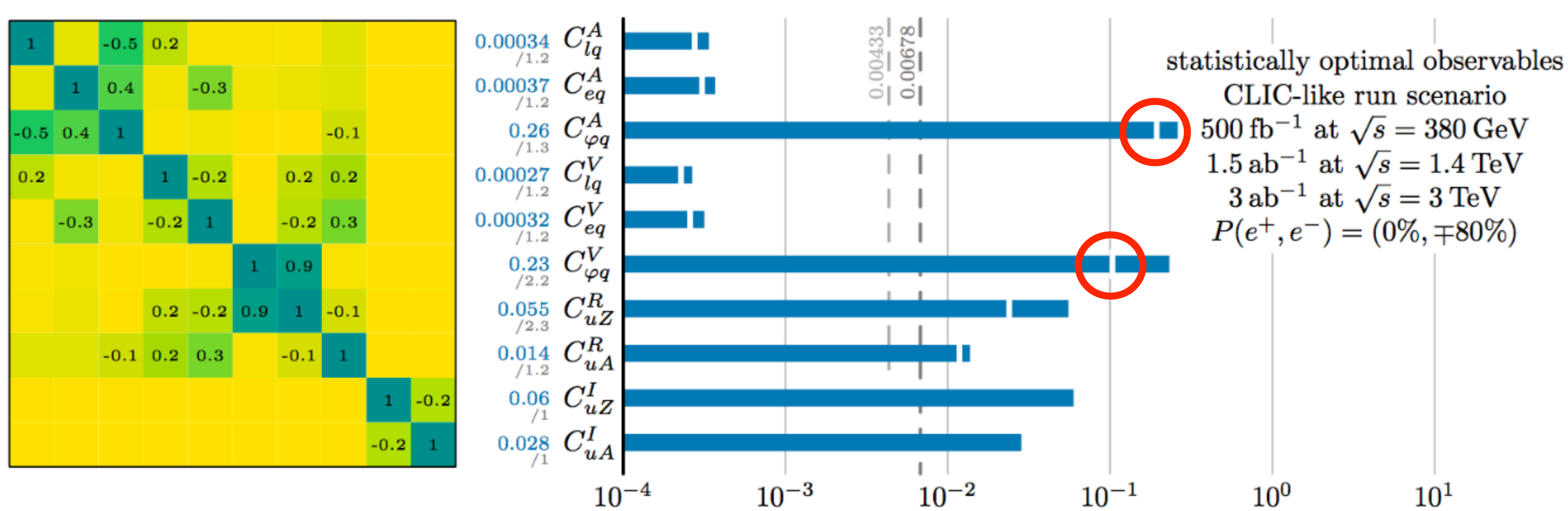

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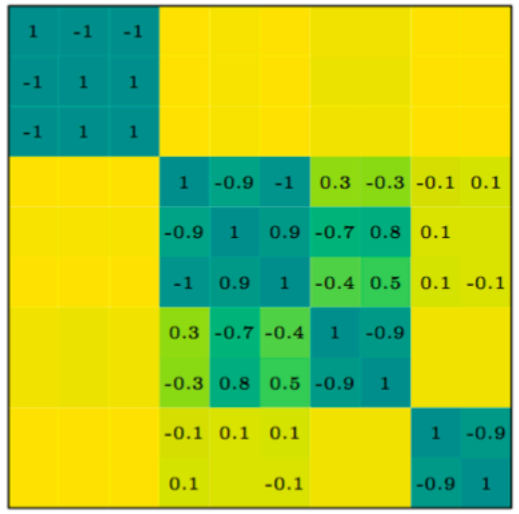

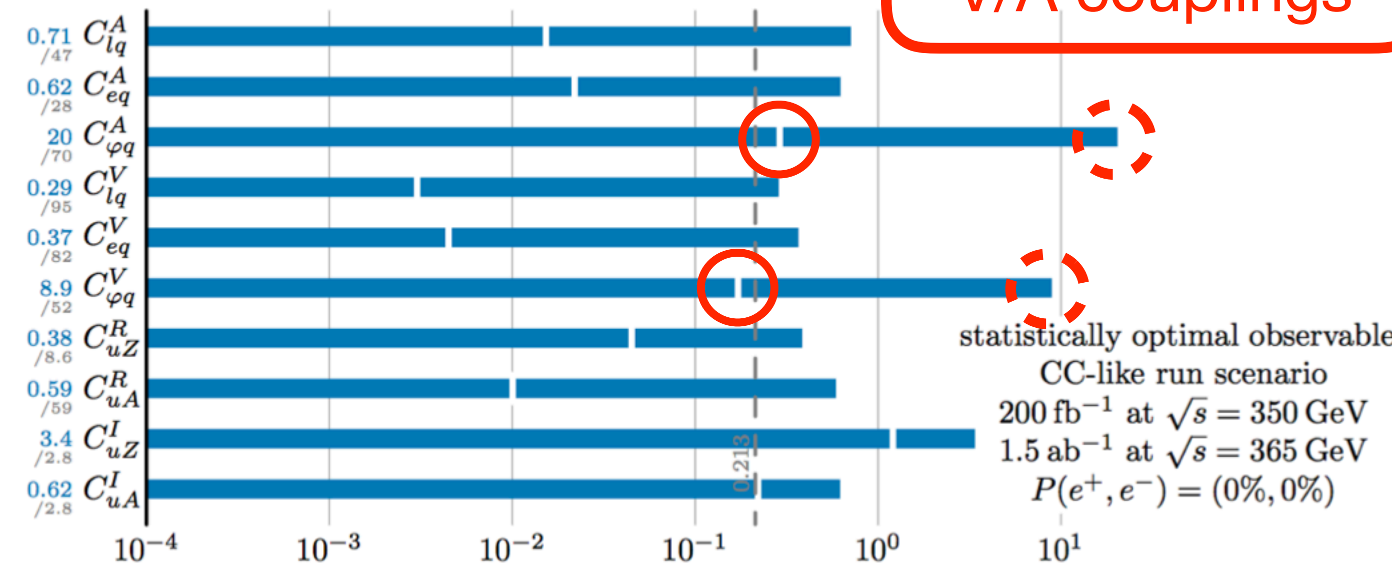

ILC
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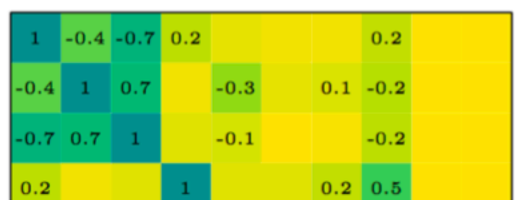
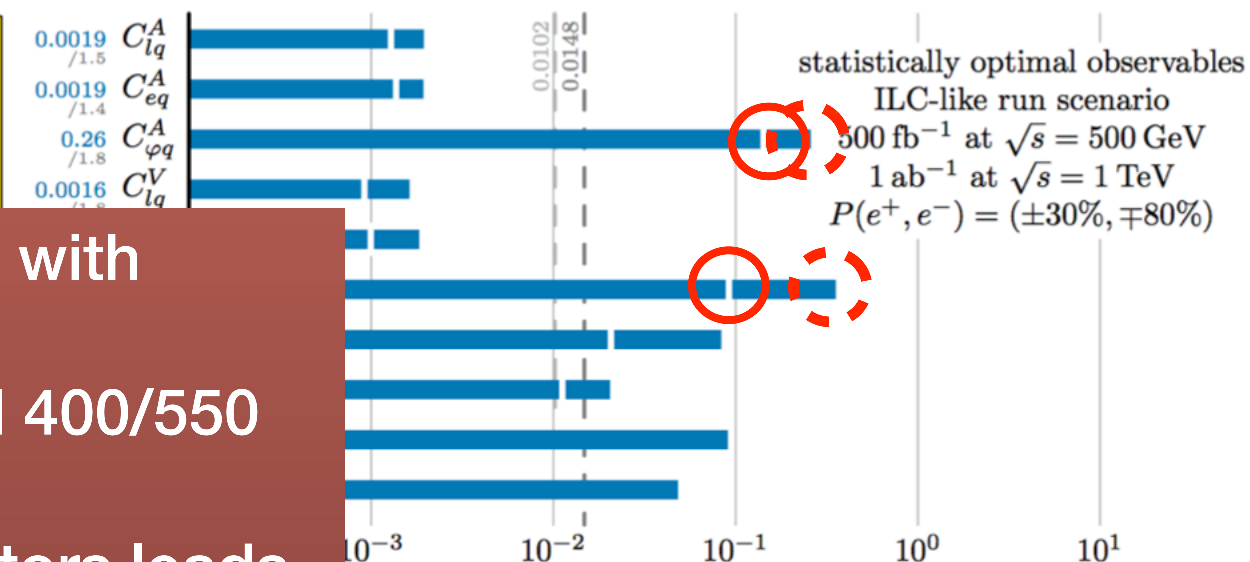
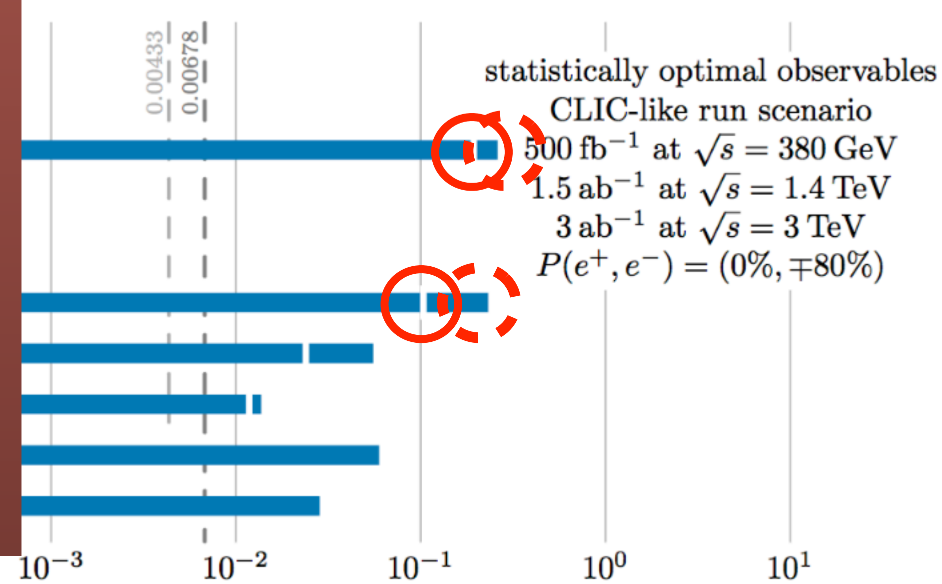


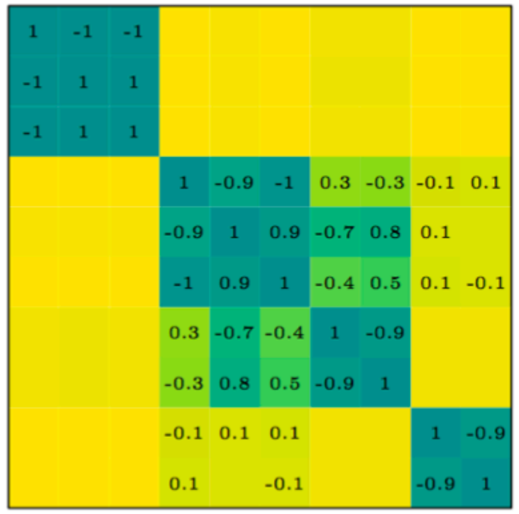


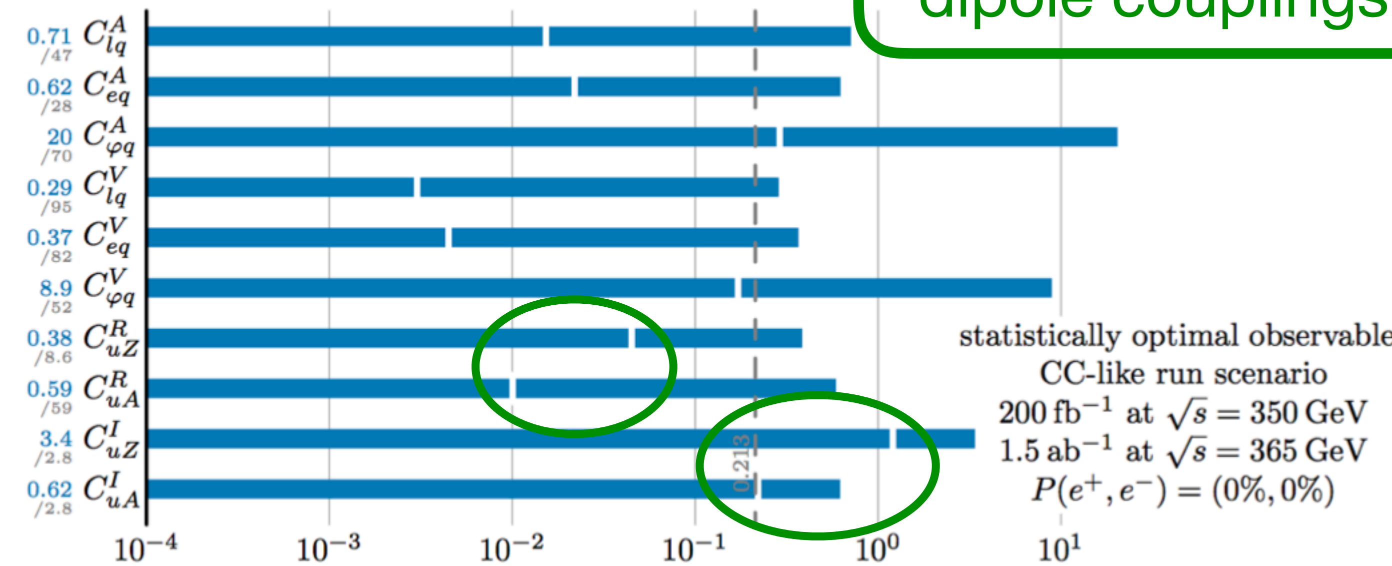


- Individual sensitivity does not grow with energy
- Most efficiently constrained around 400/550 GeV
- Correlation with four-fermion operators leads to much weaker global (marginalized) constraints
- Beam polarization or angular distributions are unable to disentangle
- Higher energy runs improves the marginalized constraints
- A factor of three at least better than HL-LHC

dipole couplings

FCC-ee
- 200 fb^{-1} at 350
- 1.5 ab^{-1} at 365
- No polarization





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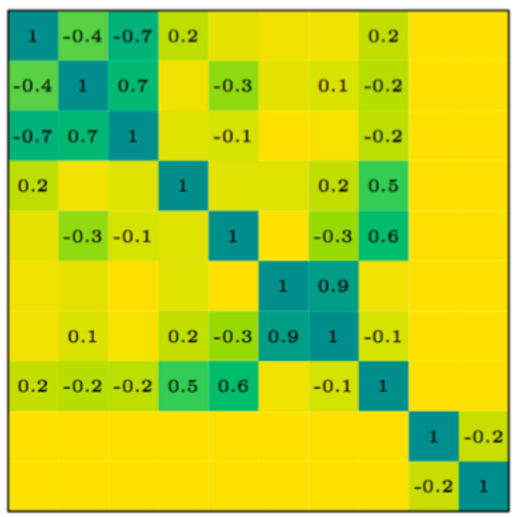
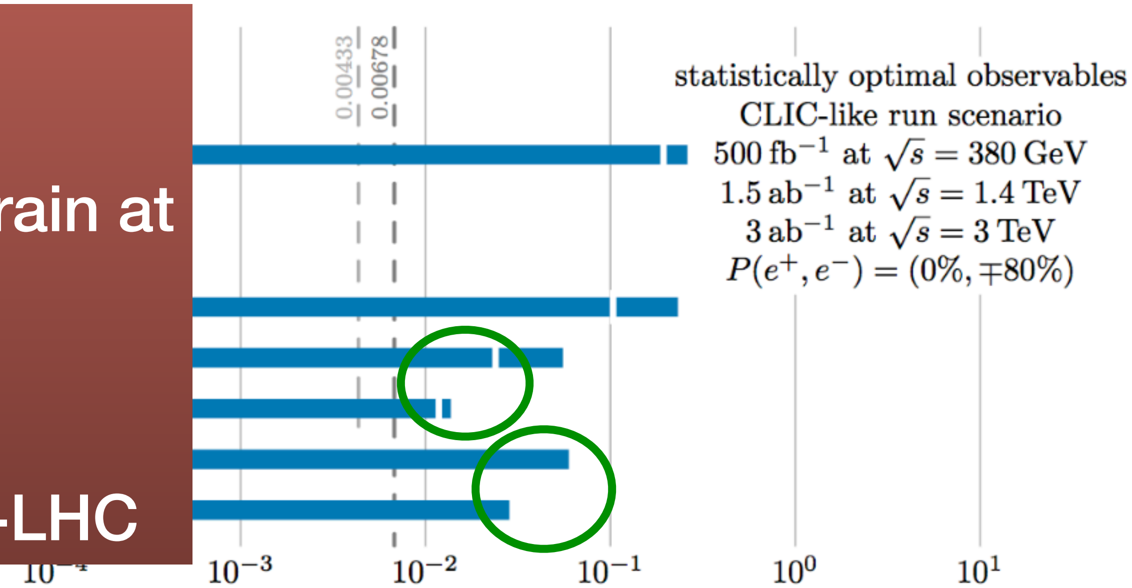
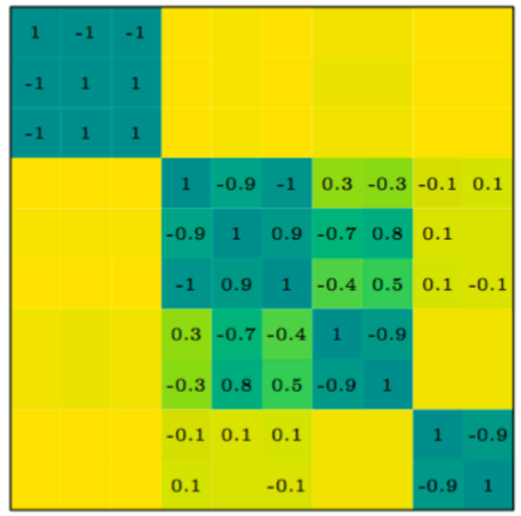


- CP-conserving part most efficiently constrained at lower energy
- CP-violating part slightly easier to constrain at large energy
- No correlation between CPV and other operators.
- Two orders of magnitude better than HL-LHC

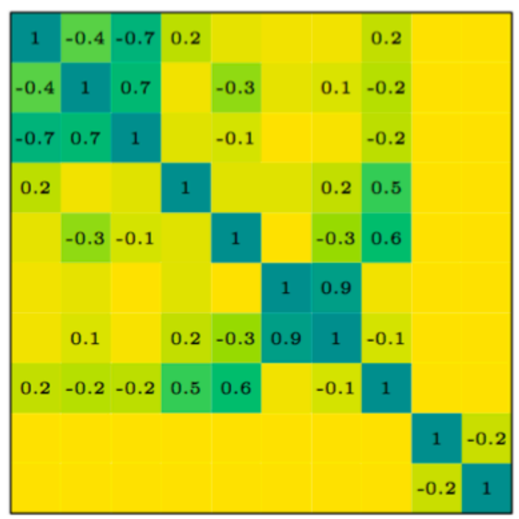


Four fermion

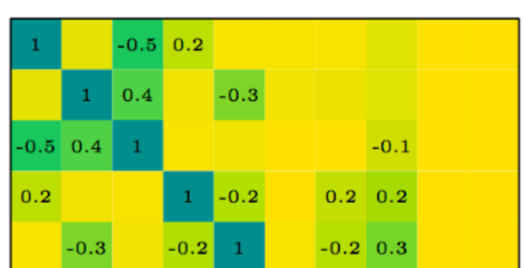
FCC-ee
- 200 fb^{-1} at 350
- 1.5 ab^{-1} at 365
- No polarization



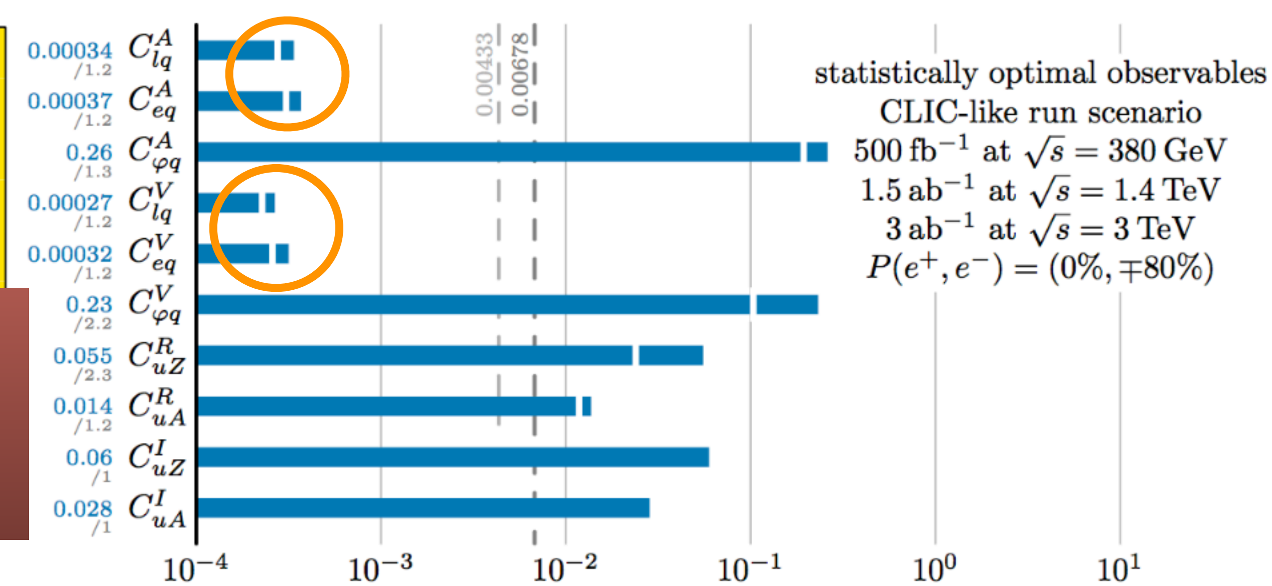
ILC
- 500 fb^{-1} at 500
- 1.0 ab^{-1} at 1000
- (-.3,+.8)&(+.3,-.8) equally shared



CLIC
- 500 fb^{-1} at 380
- 1.5 ab^{-1} at 1400



- Benefit greatly from large energy
- A factor of a few ~ 4 orders of magnitude better than HL-LHC



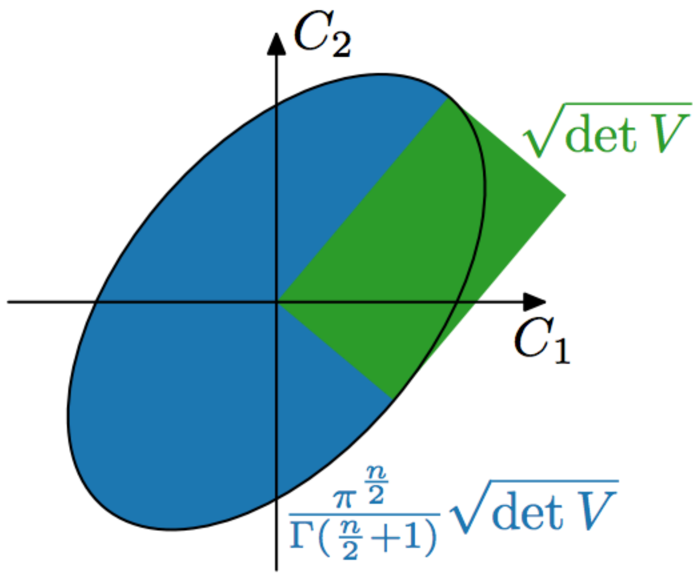
GDP Global Determinant Parameter

[Durieux, Grojean, Gu, Wang, ’17]

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

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

provides a geometric average
of the constraints strengths.



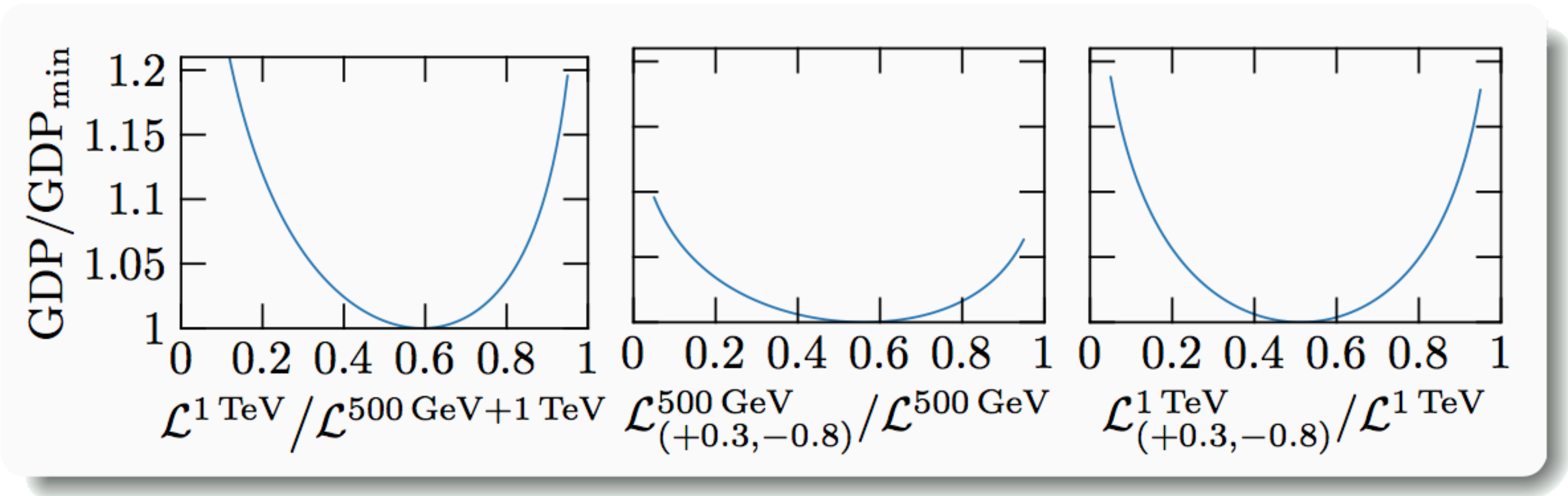
Interestingly, GDP ratios are operator-basis independent!

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

$\Longrightarrow$ conveniently assess constraint strengthening.

Optimization

How to split certain amount of luminosity onto different energies/polarizations, to optimize the GDP?



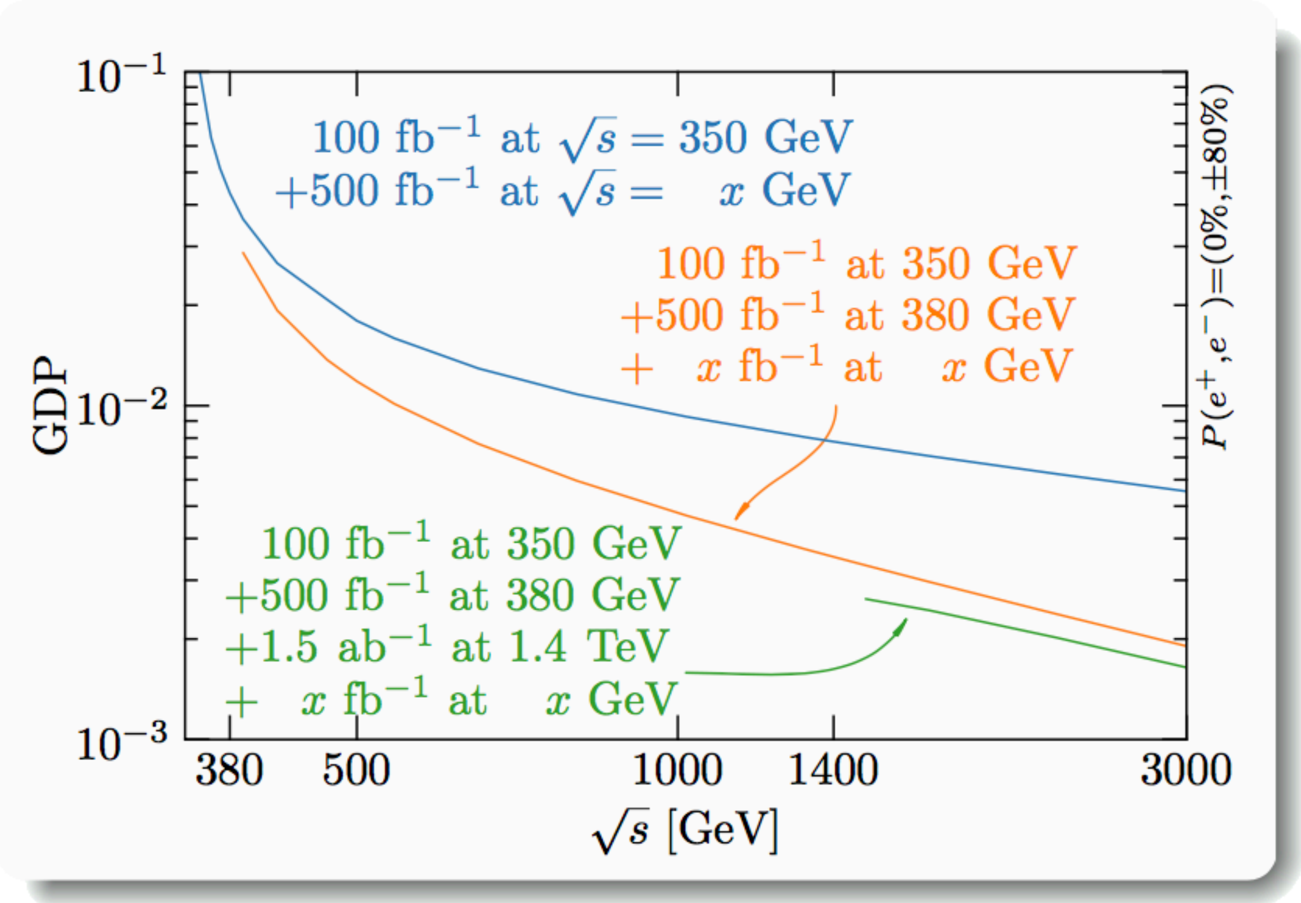
- ILC: the optimal repartition of 1.5 $\rm ab^{-1}$ in total is the following:

$\sqrt{s} = 500\,\rm GeV$	610 $\rm fb^{-1}$	57% with $P(e^+, e^-) = (+30\%, -80\%)$
1 TeV	890 $\rm fb^{-1}$	51% 〃

- It requires about 4.6 $\rm ab^{-1}$ shared between $\sqrt{s} = 380$ and $500\,\rm GeV$ runs to achieve the same performance:

$\sqrt{s} = 380\,\rm GeV$	1.5 $\rm ab^{-1}$	57% with $P(e^+, e^-) = (+30\%, -80\%)$
500 GeV	3.1 $\rm ab^{-1}$	51% 〃

Optimization

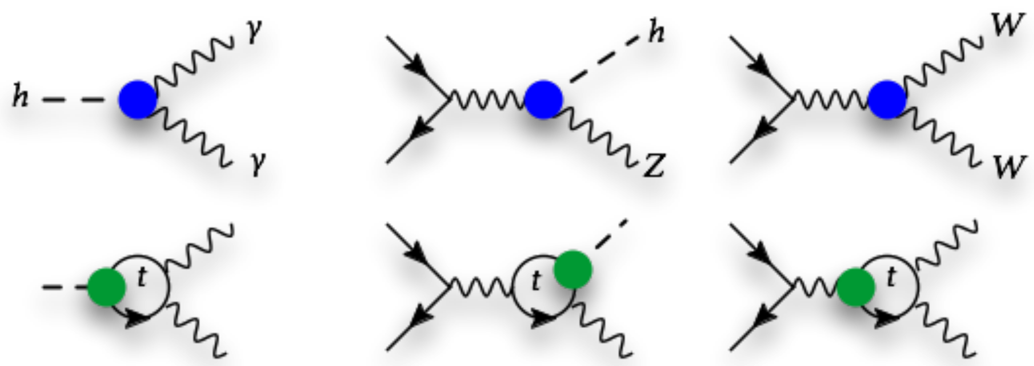


- Runs at two separate centre-of-mass energies are indispensable to distinguish two- and four-fermion operators.
- Average constraint strength improves significantly with the separation between available centre-of-mass energies.
- Four-fermion operators are the mostly affected.

Top loops

Top operators entering at one loop lead to complication in future precision Higgs measurements.

- We want to be able to disentangle
  - **H coupling tree level** and
  - **Top coupling loop level**?



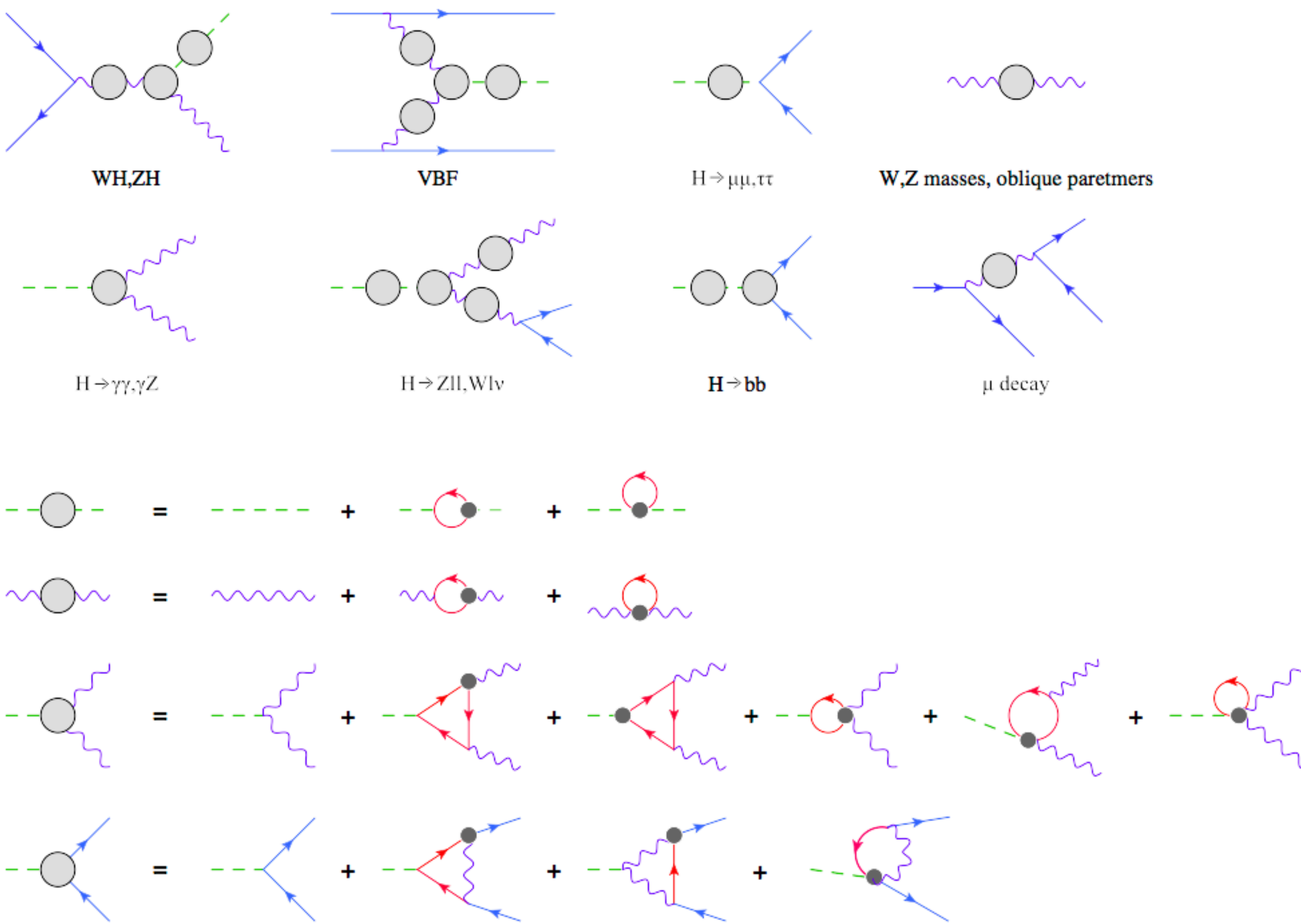
- At future CC even below ttbar threshold, it's possible to probe top EW couplings with good individual precision (better than HL-LHC).
- Strong correlation between top/H couplings -> top uncertainty will downgrade precision on H couplings.

Automatic EW NLO with MadGraph5_aMC@NLO

Top coupling at one loop:

[Vryonidou, CZ '18]

All dim-6 top loop contributions in Higgs



Global fit

[Durieux, Gu, Vryonidou, CZ '18]

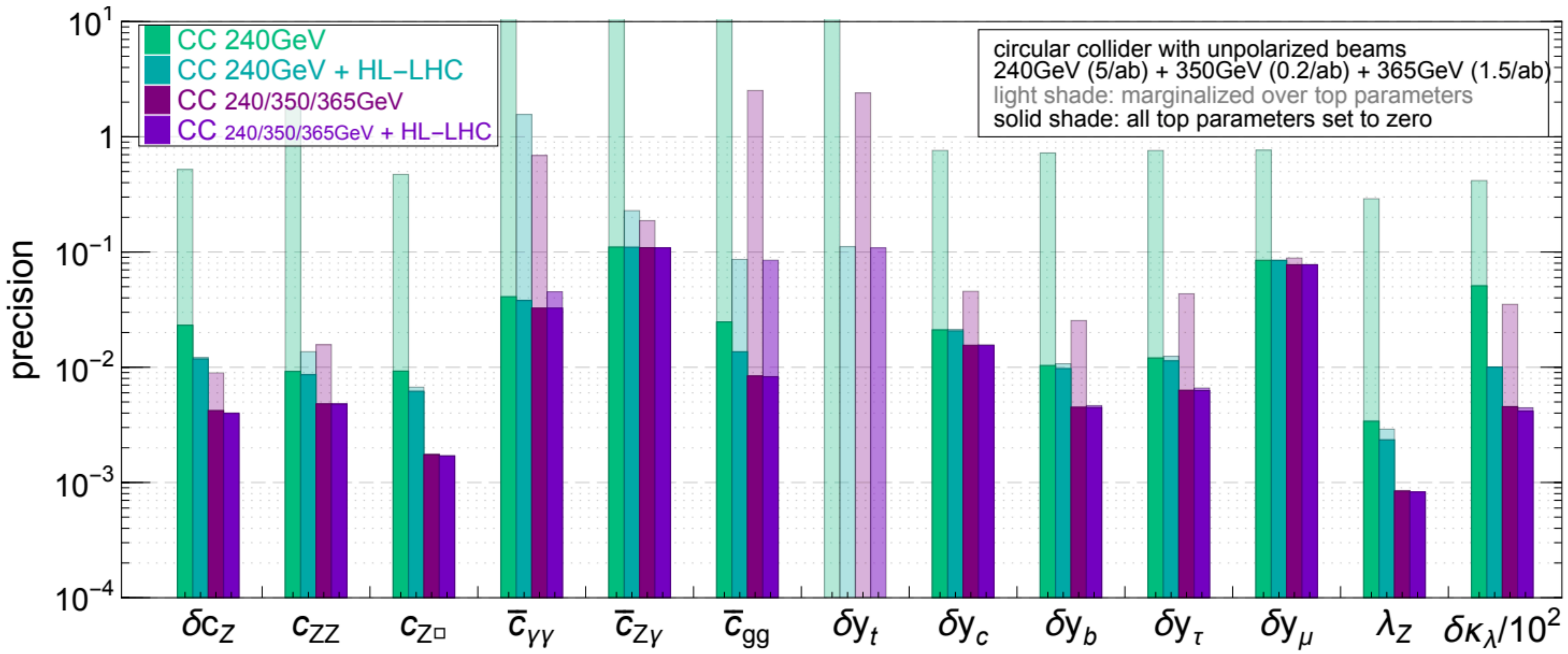
- **Below tt threshold:** CEPC 240 GeV 5 ab^{-1}
- **Above tt threshold:** FCC-ee 350 GeV 0.2 ab^{-1}, and 365 GeV 1.5 ab^{-1}

- **Higgs** ZH, WW fusion, all decay channels.
  Based on [Durieux, Grojean, Gu, Wang, '17]
- **Diboson** Angular distributions.
- **Precision tests** Assuming oblique new physics and a factor of 5 improvements.
- **Top** ttbar with statistical optimal observable.
  Based on [Durieux, Perello, Vos, CZ, '18]

Global fit at future ee collider: H/top interplay

- How does the top-coupling uncertainties downgrade the H precision at future CC?
- Global H + top loop fit

light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. $\to 0$



Uncertainties on the top have a big effect on the Higgs

- Higgsstr. run: insufficient
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$: large y_t contaminations in various coefficients
- Higgsstr. run $\oplus$ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$ $\oplus$ top@HL-LHC: top contam. in $\bar{c}_{gg}$ only

Summary

- Global EFT fit to assess the sensitivity to top-couplings.
  - Individually, 2-fermion Ops are best constrained at lower energy, while 4-fermion Ops are constrained at larger energy.
  - Globally, some correlations between the two types of Ops can be resolved only by using different energies.
  - GDP parameter can be used to measure the overall constraining strength and optimize the running parameters.
- Should keep in mind that
  - A combination of two different energies is useful.
  - We have assumed there is no interference between threshold scan and coupling measurement.
  - Apart from coupling strength, it is also important to maximize the number of top quarks, e.g. for studying rare top decays etc.
- There is also some interplay between Higgs and top measurements.

Thank you

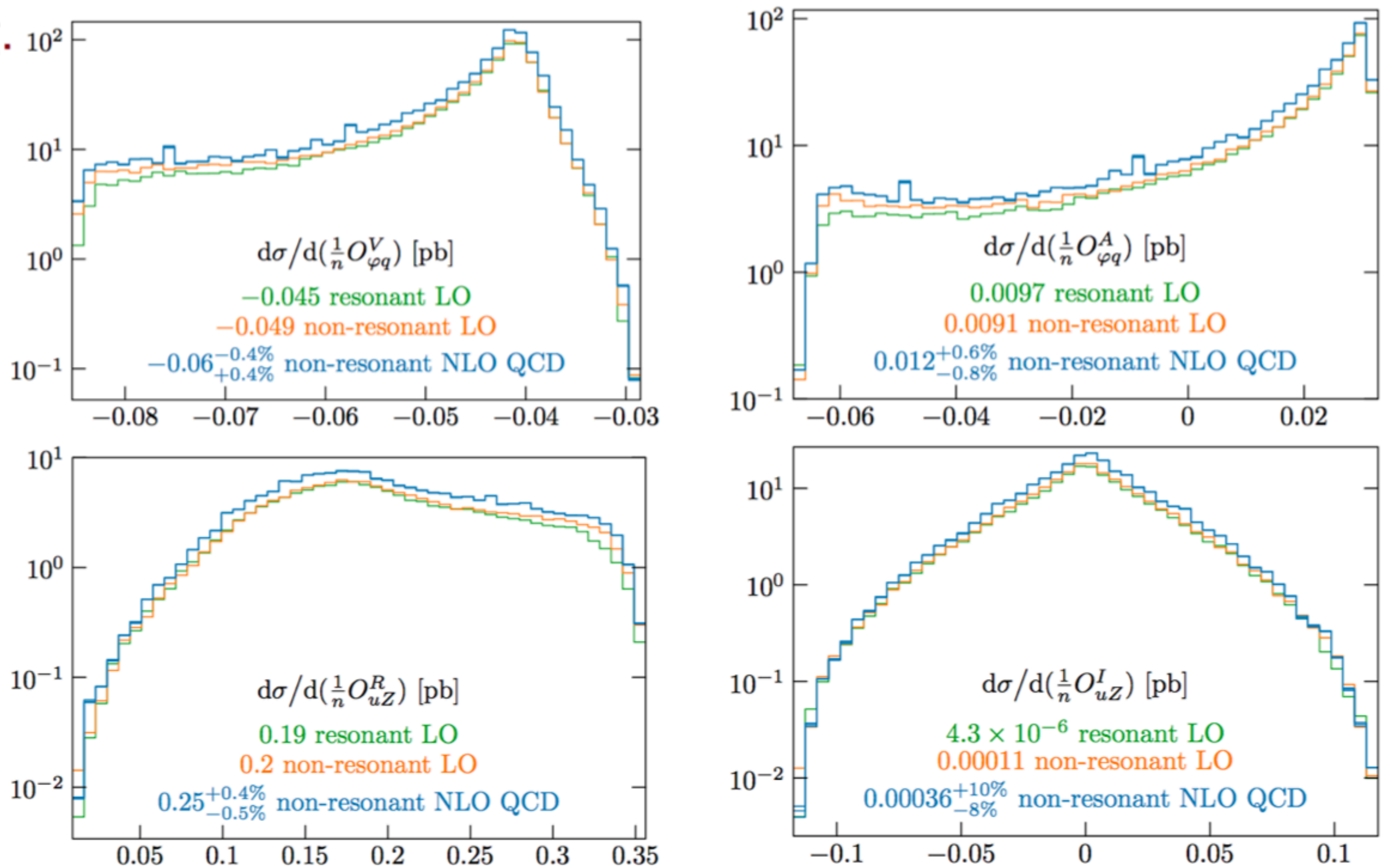
Backups

TH robustness

Non-resonant and NLO QCD effects can be studied

- mostly flat k factor (24% at $\sqrt{s} = 500$ GeV)
- couple-of-percent shape effects, excepted on axial operators ($O(10)\%$)

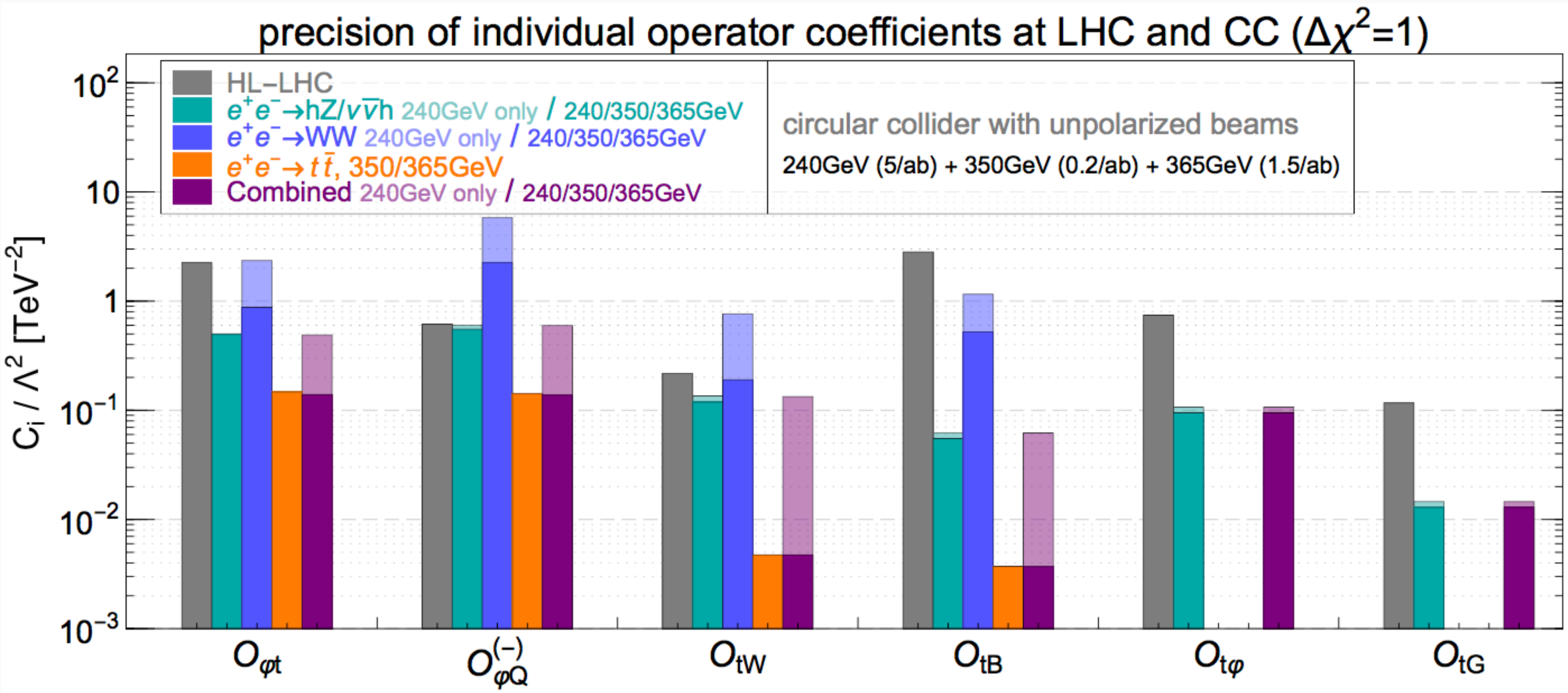
e.g.



$\sqrt{s} = 500$ GeV, $P(e^+, e^-) = (+30\%, -80\%)$,
quoted average values of distribution are $\bar{O}_i / \mathcal{L}$ in pb,
QCD scale variation from $m_t/2$ to $2m_t$

Individual limits

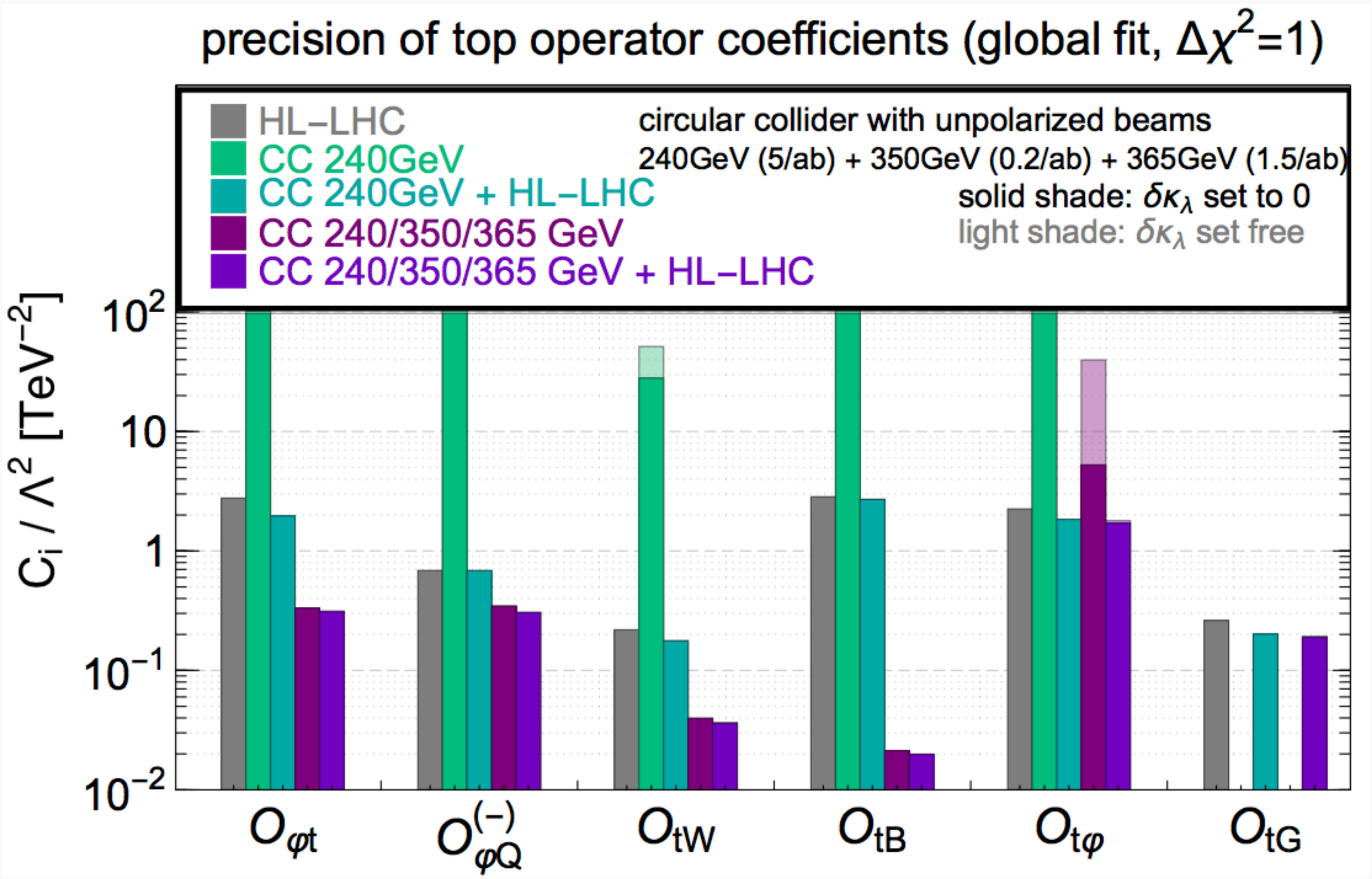
Individual one-sigma reach, one at a time



- Good sensitivity to top couplings below $t\bar{t}$ threshold.
- Loop suppression of top-quark operator contributions is compensated by the high precision of lepton collider.
- Still $ee \to tt$ above 350 GeV provides best sensitivity.
- Diboson sensitivity increases with energy.

Marginalized limits: Top

Global one-sigma precision reach on top-quark operators



- Indirect bounds are much worse. In particular, large degeneracies if only run at 240 GeV.
- Correlations between Top/Higgs, e.g. $C_{t\varphi}$, C_{tB} and $\bar{c}_{\gamma\gamma}$; $C_{t\varphi}$, C_{tG} and $\bar{c}_{gg}$.

Marginalized limits: Higgs

Consider $H \to \gamma\gamma$ on C_{tB} and $\bar{c}_{\gamma\gamma}$

- $H \to \gamma\gamma$ imposes a strong constraint, but also leaves a flat direction.
- Including loop corrections to all other measurements lift this flat direction, but not strong enough to eliminate the degeneracy.
- HL-LHC is too weak.
- $ee \to tt$ at 350/365 will fix C_{tB} which in turn improves $\bar{c}_{\gamma\gamma}$.