EFT fit on top quark EW couplings

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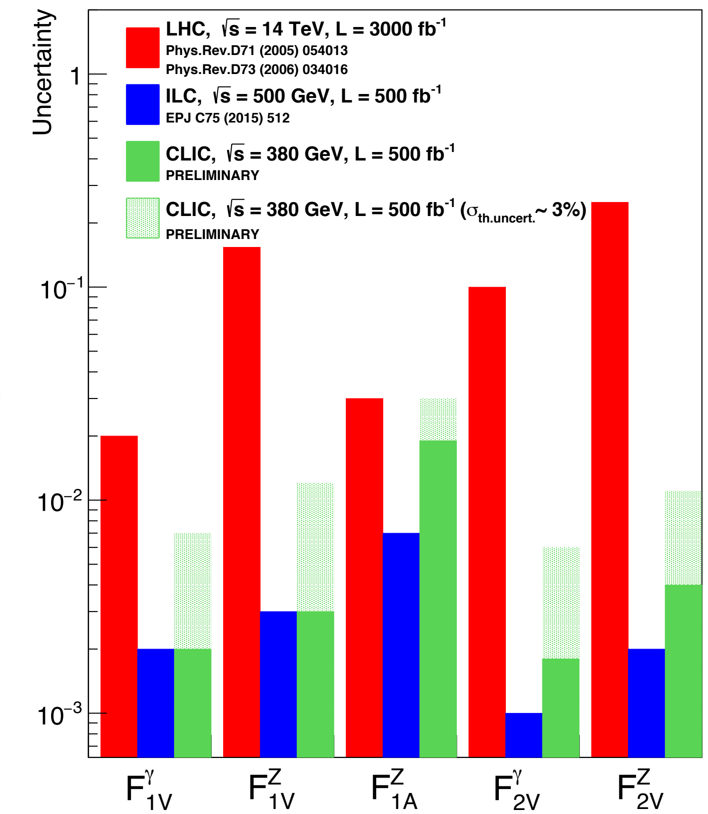
Outline

- Introduction to quark couplings and EFT
- Observables sensitivities:
    - Afb + cross-section
    - Optimal CP-odd observables
    - Top quark polarization
    - Statistically optimal observables
- Full-simulation at CLIC380 and ILC500
- Full-simulation at high energies

Introduction to quark couplings and EFT

Top quark couplings

Objective: to study the potential of a global fit in the top EW sector.



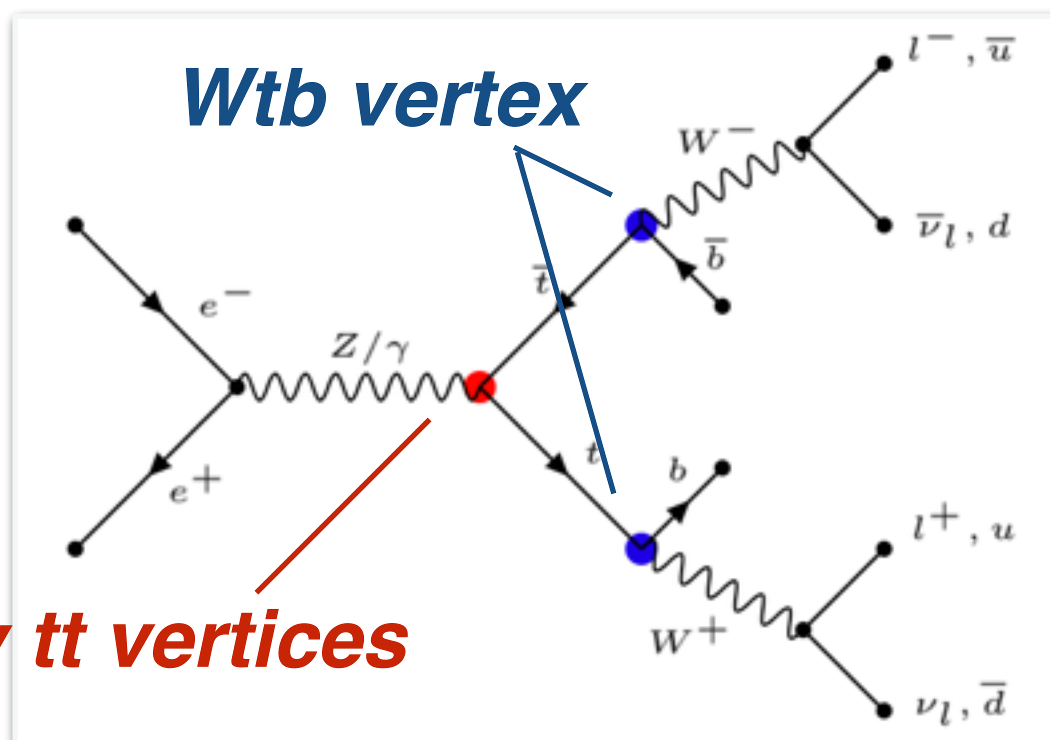
Form-factors

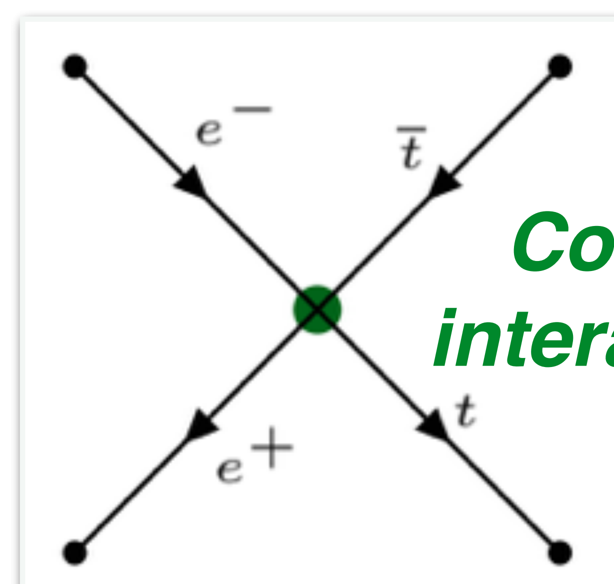
$$\Gamma_{\mu}^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$

CP Conserving **CPV**

Effective Field Theory

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

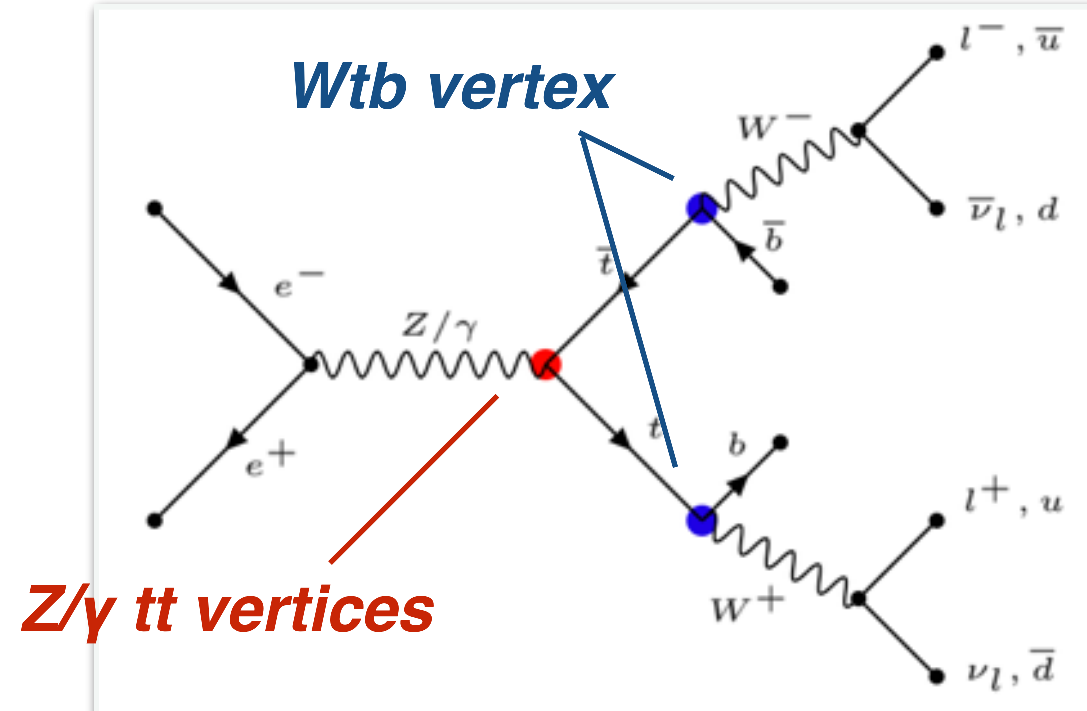




Dim-6 operators

$$O_{\varphi q}^{1} \equiv \frac{y_t^2}{2} \quad \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi$$
$$O_{\varphi q}^{3} \equiv \frac{y_t^2}{2} \quad \bar{q}\tau^I\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi$$
$$O_{\varphi u} \equiv \frac{y_t^2}{2} \quad \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi$$
$$O_{\varphi ud} \equiv \frac{y_t^2}{2} \quad \bar{u}\gamma^\mu d \quad \varphi^T\epsilon\, iD_\mu\varphi$$

$$O_{uG} \equiv y_t g_s \quad \bar{q}T^A\sigma^{\mu\nu}u \quad \epsilon\varphi^* G_{\mu\nu}^A$$
$$O_{uW} \equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu}u \quad \epsilon\varphi^* W_{\mu\nu}^I$$
$$O_{dW} \equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu}d \quad \epsilon\varphi^* W_{\mu\nu}^I$$
$$O_{uB} \equiv y_t g_Y \quad \bar{q}\sigma^{\mu\nu}u \quad \epsilon\varphi^* B_{\mu\nu}$$

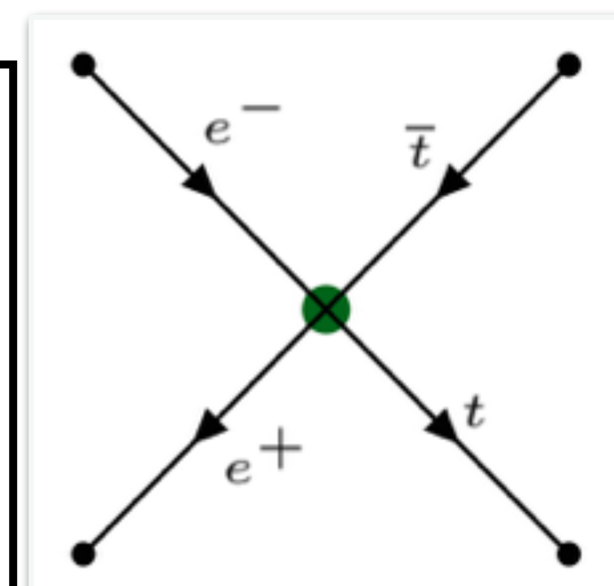


Contact interactions

$$O_{lq}^{1} \equiv \bar{q}\gamma_\mu q \quad \bar{l}\gamma^\mu l$$
$$O_{lq}^{3} \equiv \bar{q}\tau^I\gamma_\mu q \quad \bar{l}\tau^I\gamma^\mu l$$
$$O_{lu} \equiv \bar{u}\gamma_\mu u \quad \bar{l}\gamma^\mu l$$
$$O_{eq} \equiv \bar{q}\gamma_\mu q \quad \bar{e}\gamma^\mu e$$
$$O_{eu} \equiv \bar{u}\gamma_\mu u \quad \bar{e}\gamma^\mu e$$

$$O_{lequ}^{T} \equiv \bar{q}\sigma^{\mu\nu}u\ \epsilon\ \bar{l}\sigma_{\mu\nu}e$$

$$O_{lequ}^{S} \equiv \bar{q}u\ \epsilon\ \bar{l}e$$
$$O_{ledq} \equiv \bar{d}q \quad \bar{l}e$$



Change of basis

Transformation between effective operators and form-factors:

$$F_{1,V}^{Z} - F_{1,V}^{Z,SM} = \frac{1}{2}\left(C_{\varphi Q}^{(3)} - C_{\varphi Q}^{(1)} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}C_{\varphi q}^{V}\frac{m_t^2}{\Lambda^2 s_W c_W}$$

$$F_{1,A}^{Z} - F_{1,A}^{Z,SM} = \frac{1}{2}\left(-C_{\varphi Q}^{(3)} + C_{\varphi Q}^{(1)} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}C_{\varphi q}^{A}\frac{m_t^2}{\Lambda^2 s_W c_W}$$

$$F_{2,V}^{Z} = \left(\mathrm{Re}\{C_{tW}\}c_W^2 - \mathrm{Re}\{C_{tB}\}s_W^2\right)\frac{4m_t^2}{\Lambda^2 s_W c_W} = \mathrm{Re}\{C_{uZ}\}\frac{4m_t^2}{\Lambda^2}$$

$$F_{2,V}^{\gamma} = \left(\mathrm{Re}\{C_{tW}\} + \mathrm{Re}\{C_{tB}\}\right)\frac{4m_t^2}{\Lambda^2} = \mathrm{Re}\{C_{uA}\}\frac{4m_t^2}{\Lambda^2}$$

$$\left[F_{2,A}^{Z}, F_{2,A}^{\gamma}\right] \propto \left[\mathrm{Im}\{C_{tW}\}, \mathrm{Im}\{C_{tB}\}\right]$$

We can change to an alternative basis (**Vector/Axial - Vector**)

Conversion to V/A - V basis in contact interactions:

$$C_{lq}^{V} \equiv C_{lu} + C_{lq}^{(1)} - C_{lq}^{(3)} \qquad C_{eq}^{V} \equiv C_{eu} + C_{eq}$$

$$C_{lq}^{A} \equiv C_{lu} - C_{lq}^{(1)} + C_{lq}^{(3)} \qquad C_{eq}^{A} \equiv C_{eu} - C_{eq}$$

Observables sensitivities

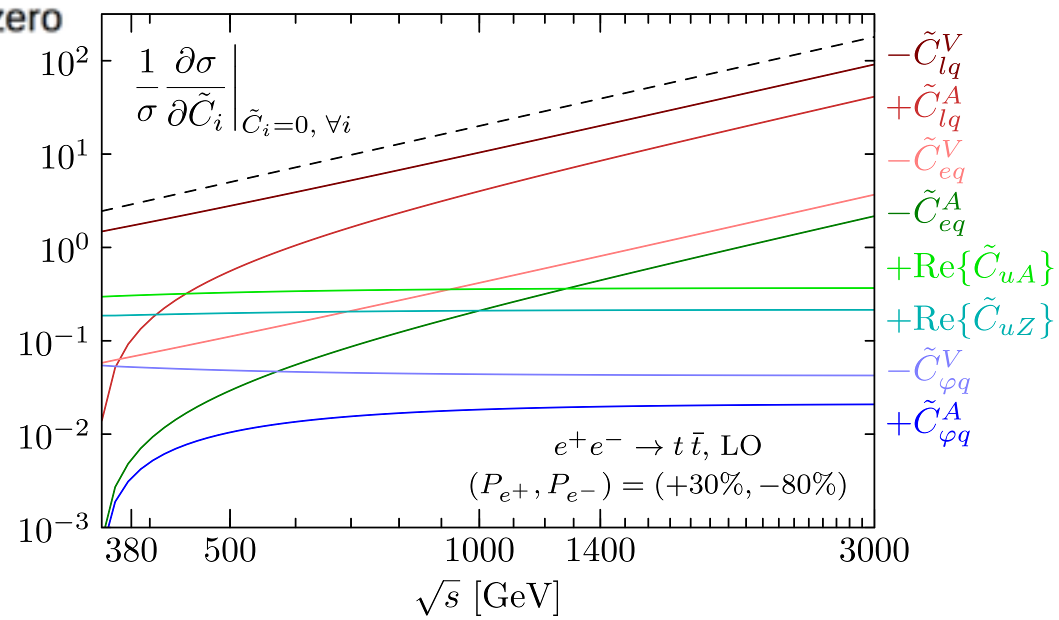
Observables sensitivity: Afb + cross-section

$e^+e^- \to t\,\bar{t}$, LO

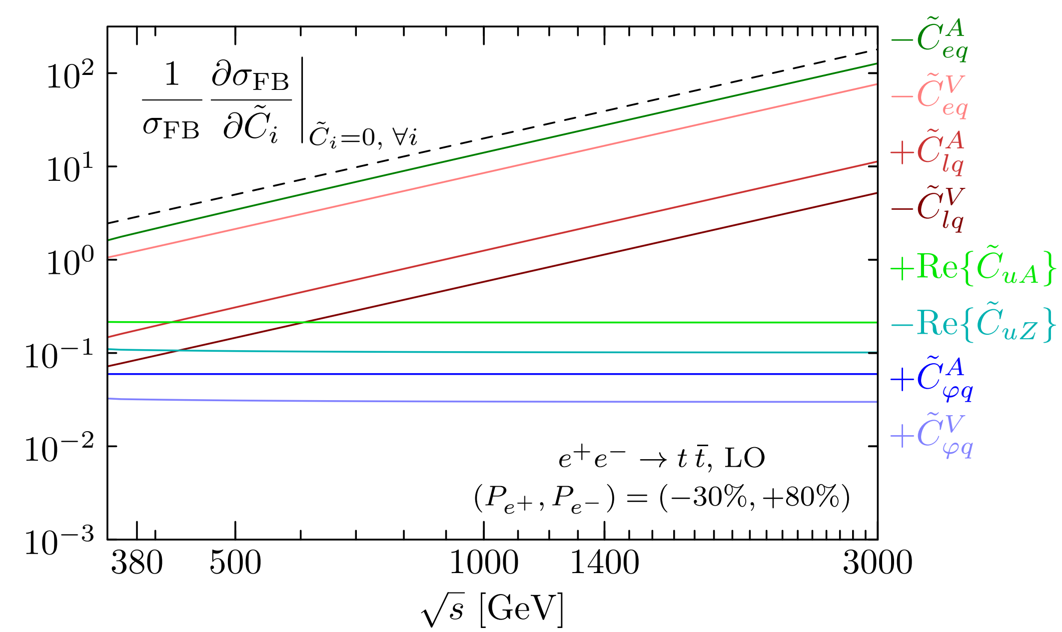
Durieux, Perelló, Vos, Zhang, to be published

Sensitivity:
Relative change in cross-section due to non-zero operator coefficient
Δσ (C) / σ / ΔC

Cross-section



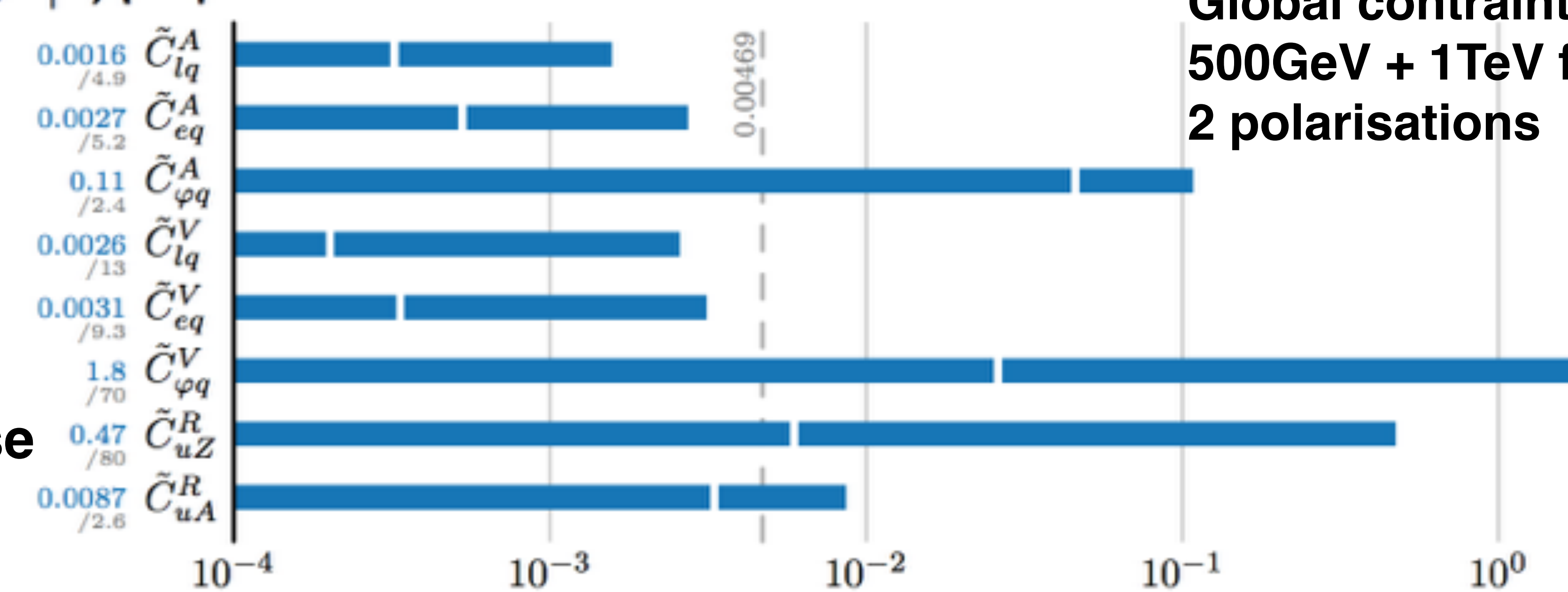
Forward-backward asymmetry



(multi-) TeV operation provides better sensitivity to contact-interaction operators.

- **Very good individual limits**
- **Global limits factor 3 to 80 worse**

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



Global contraints 500GeV + 1TeV for 2 polarisations

Optimal CP-odd observables

The **CP-violating effects** in e+e− → tt̄ manifest themselves in specific **top-spin effects**, namely **CP-odd top spin-momentum correlations and tt̄ spin correlations**.

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$$e^+(\mathbf{p}_+, P_{e^+}) + e^-(\mathbf{p}_-, P_{e^-}) \quad \rightarrow \quad t(\mathbf{k}_t) + \bar{t}(\mathbf{k}_{\bar{t}})$$

$$t\ \bar{t} \quad \rightarrow \quad \ell^+(\mathbf{q}_+) + \nu_\ell + b + \overline{X}_{\rm had}(\mathbf{q}_{\bar{X}})$$

$$t\ \bar{t} \quad \rightarrow \quad X_{\rm had}(\mathbf{q}_X) + \ell^-(\mathbf{q}_-) + \bar{\nu}_\ell + \bar{b}$$

- **CP-odd observables** are defined with the **four momenta available in tt semi-leptonic decay channel**

$$\mathcal{O}_+^{Re} = (\hat{\mathbf{q}}_{\bar{X}} \times \hat{\mathbf{q}}_+^*) \cdot \hat{\mathbf{p}}_+ \,,$$

$$\mathcal{O}_+^{Im} = -[1 + (\frac{\sqrt{s}}{2m_t} - 1)(\hat{\mathbf{q}}_{\bar{X}} \cdot \hat{\mathbf{p}}_+)^2]\hat{\mathbf{q}}_+^* \cdot \hat{\mathbf{q}}_{\bar{X}} + \frac{\sqrt{s}}{2m_t}\hat{\mathbf{q}}_{\bar{X}} \cdot \hat{\mathbf{p}}_+ \hat{\mathbf{q}}_+^* \cdot \hat{\mathbf{p}}_+$$

- The way to **extract** the **CP-violating form factor** is to construct **asymmetries sensitive to CP-violation effects**

$$\mathcal{A}^{Re} = \langle \mathcal{O}_+^{Re} \rangle - \langle \mathcal{O}_-^{Re} \rangle = c_\gamma(s) {\rm Re} F_{2A}^\gamma + c_Z(s) {\rm Re} F_{2A}^Z$$

$$\mathcal{A}^{Im} = \langle \mathcal{O}_+^{Im} \rangle - \langle \mathcal{O}_-^{Im} \rangle = \tilde{c}_\gamma(s) {\rm Im} F_{2A}^\gamma + \tilde{c}_Z(s) {\rm Im} F_{2A}^Z$$

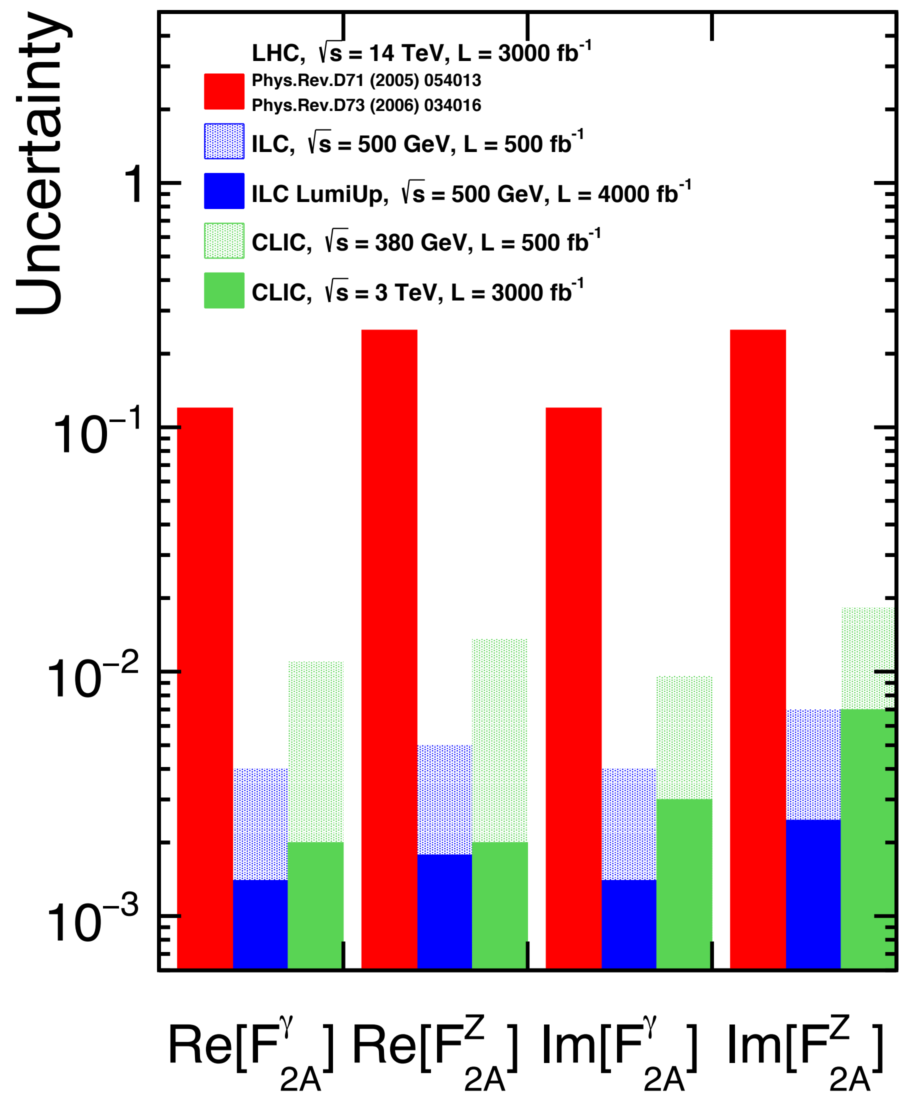
$\mathcal{A}^{Re}_{\gamma,Z}{}^{\rm L}$ $\mathcal{A}^{Re}_{\gamma,Z}{}^{\rm L}$

$\mathcal{A}^{Im}_{\gamma,Z}{}^{\rm R}$ $\mathcal{A}^{Im}_{\gamma,Z}{}^{\rm R}$

Prospects of CPV opt. obs.

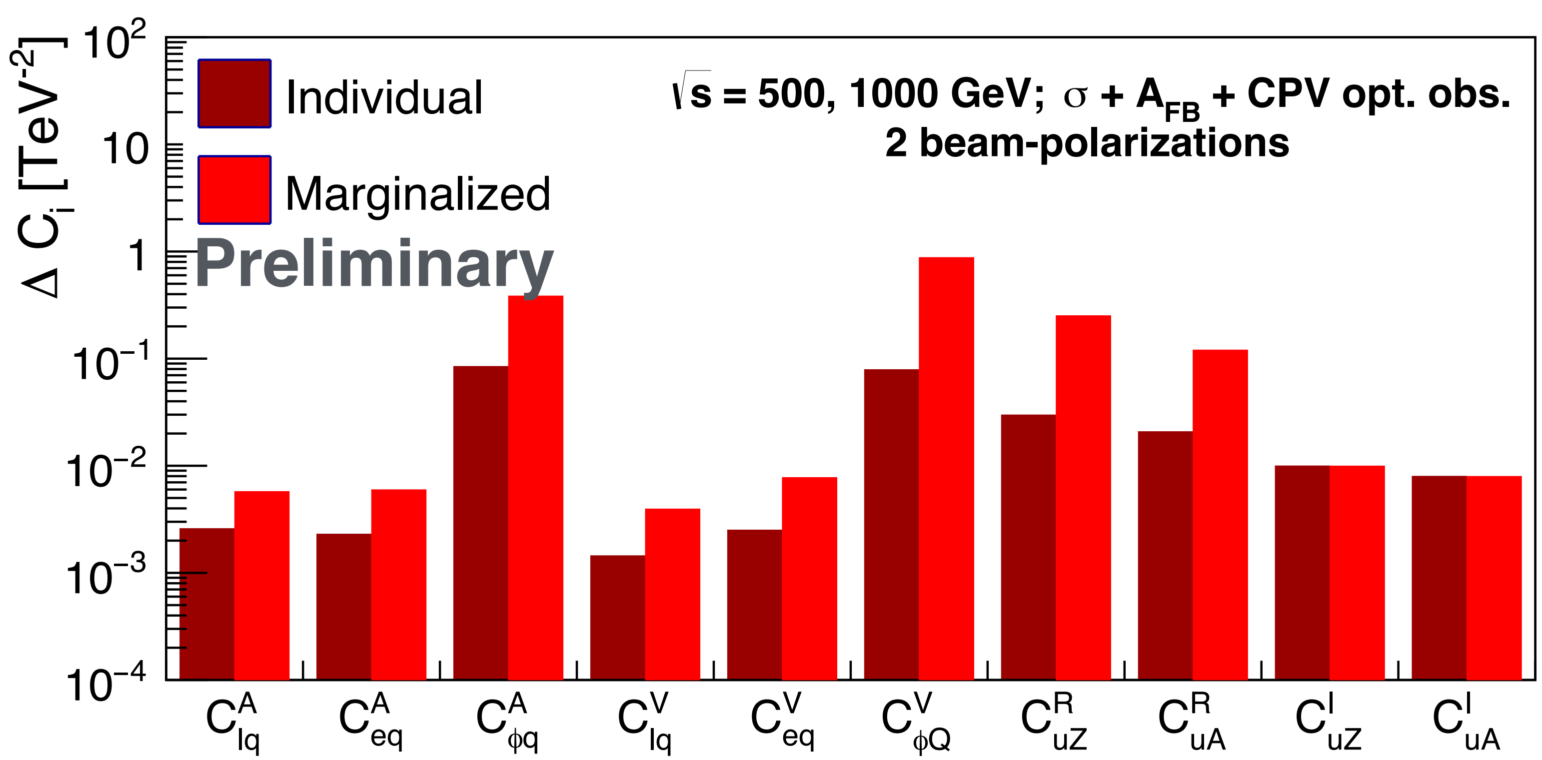
- **ILC500** and **CLIC380** have a very similar sensitivity to form factors, reaching **limits of $|F_{2A}^{\gamma}|<0.01$.**

- Assuming that systematic uncertainties can be controlled to the required level, a luminosity upgrade of both machines **may bring a further improvement.**



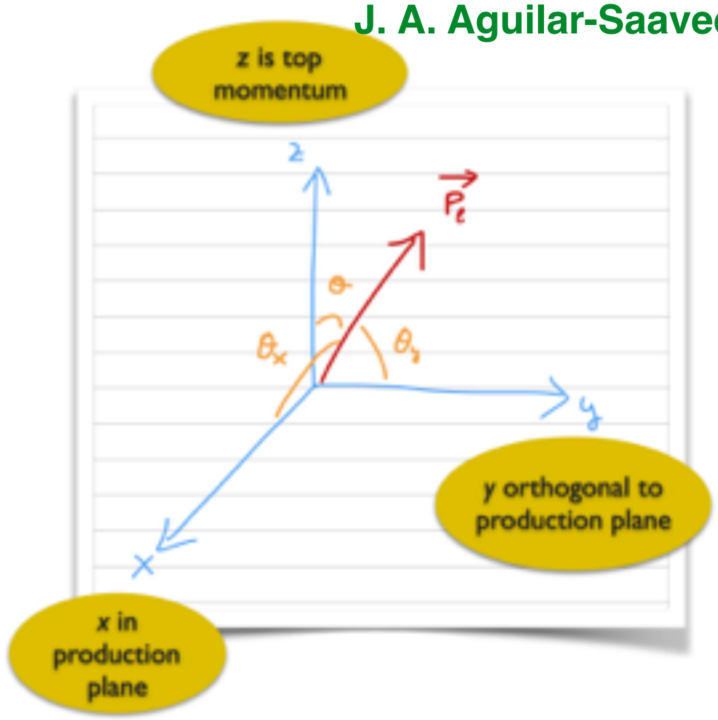
Including CPV observables in the EFT global fit…

$$[F_{2,A}^{Z}, F_{2,A}^{\gamma}] \propto [\mathrm{Im}\{C_{uA}\}, \mathrm{Im}\{C_{uZ}\}]$$



Top quark polarization at different axes

J. A. Aguilar-Saavedra and J. Bernabeu. [arXiv:1005.5382].



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{1}{2}(1+\alpha P_3 \cos\theta)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_x} = \frac{1}{2}(1+\alpha P_1 \cos\theta_x)$$

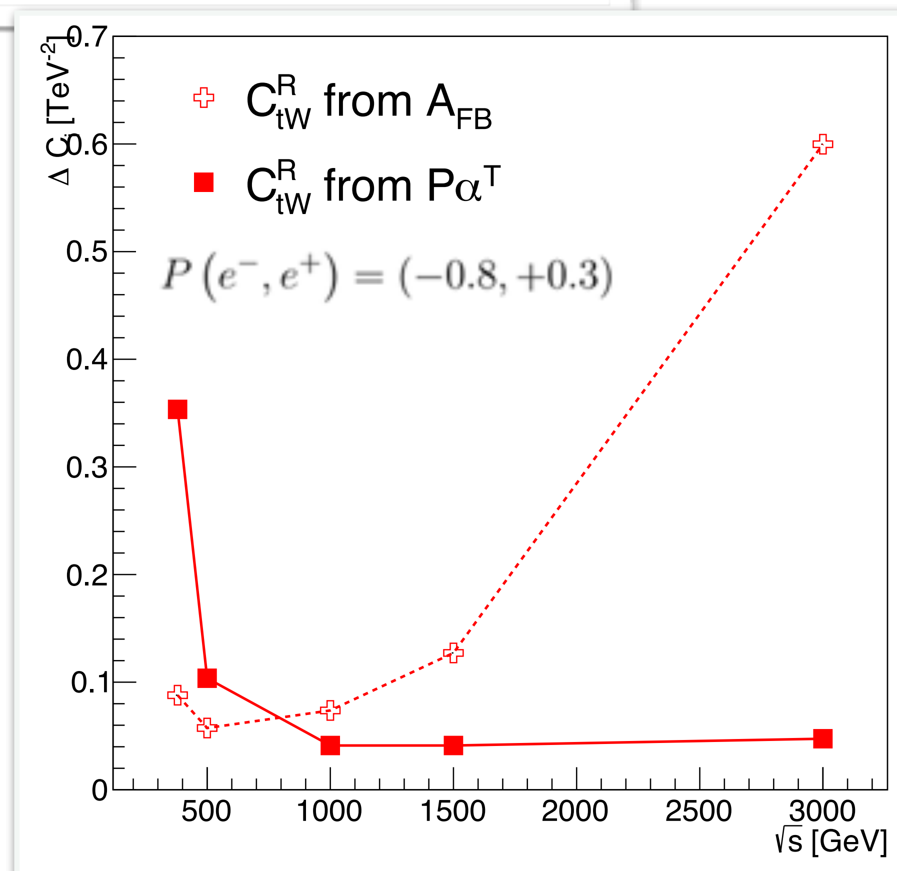
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_y} = \frac{1}{2}(1+\alpha P_2 \cos\theta_y)$$

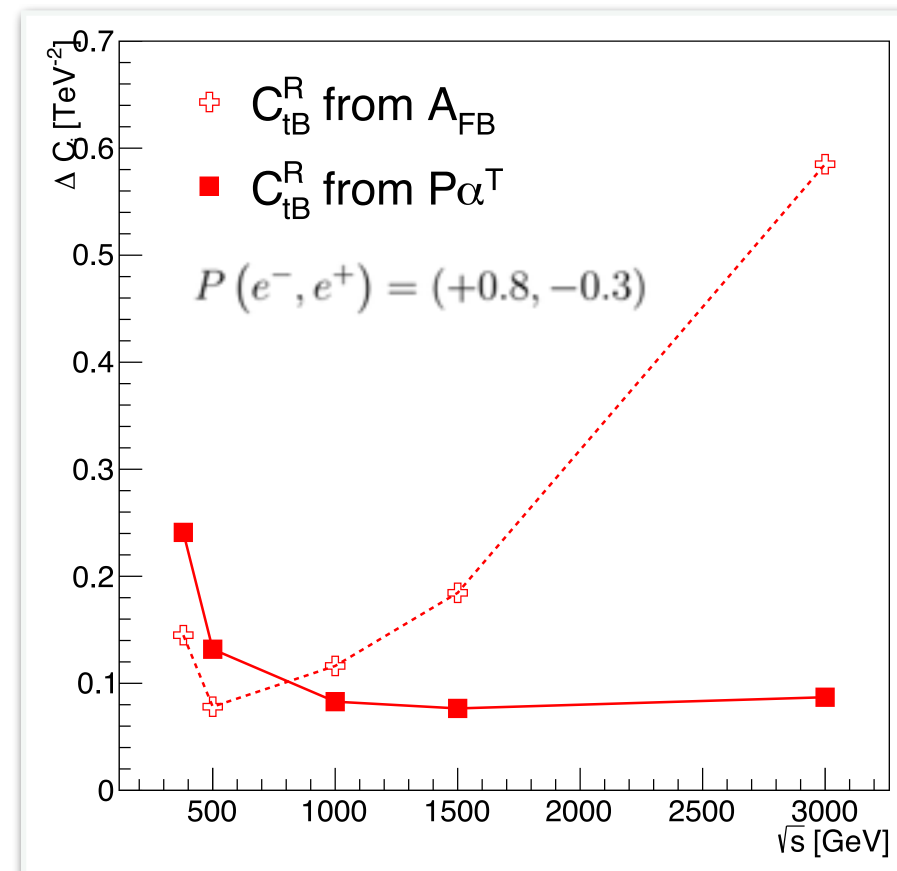
Studied process

$$e^-e^+ \to t\bar{t} \to W^+bW^-\bar{b} \to l\nu b\bar{b}q\bar{q}$$

Top polarization in the transverse axis *(perpendicular to the top flight direction in the production plane)* provides good sensitivity to the real part of dipoles operators (CtW and CtB).

Evolution of individual limits with center-of-mass energy





Statistically optimal observables

G. Durieux @TopLC 2017:

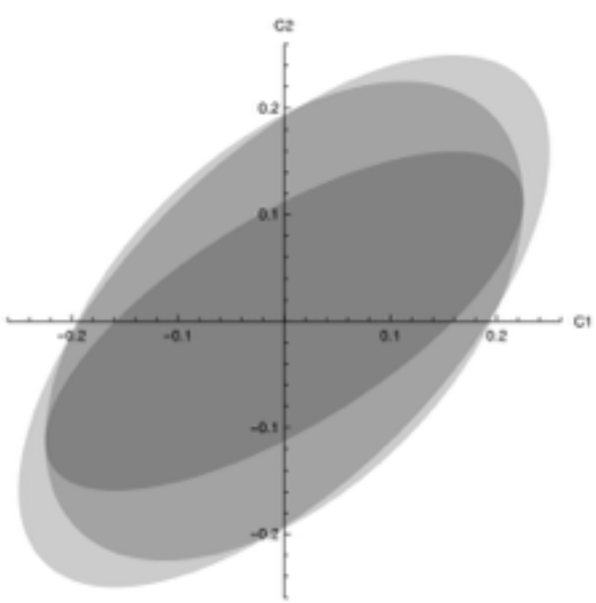
https://indico.cern.ch/event/595651/contributions/2573918/attachments/1473086/2280215/durieux-top-lc-2017.pdf

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: $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.



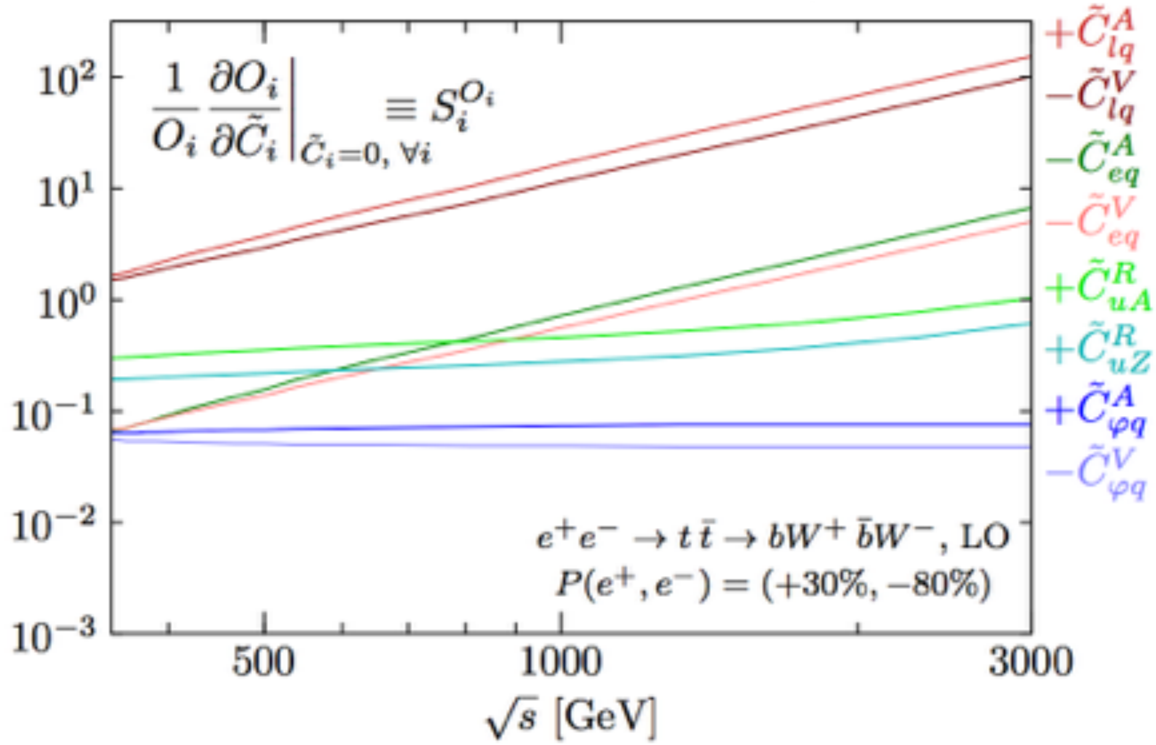
e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

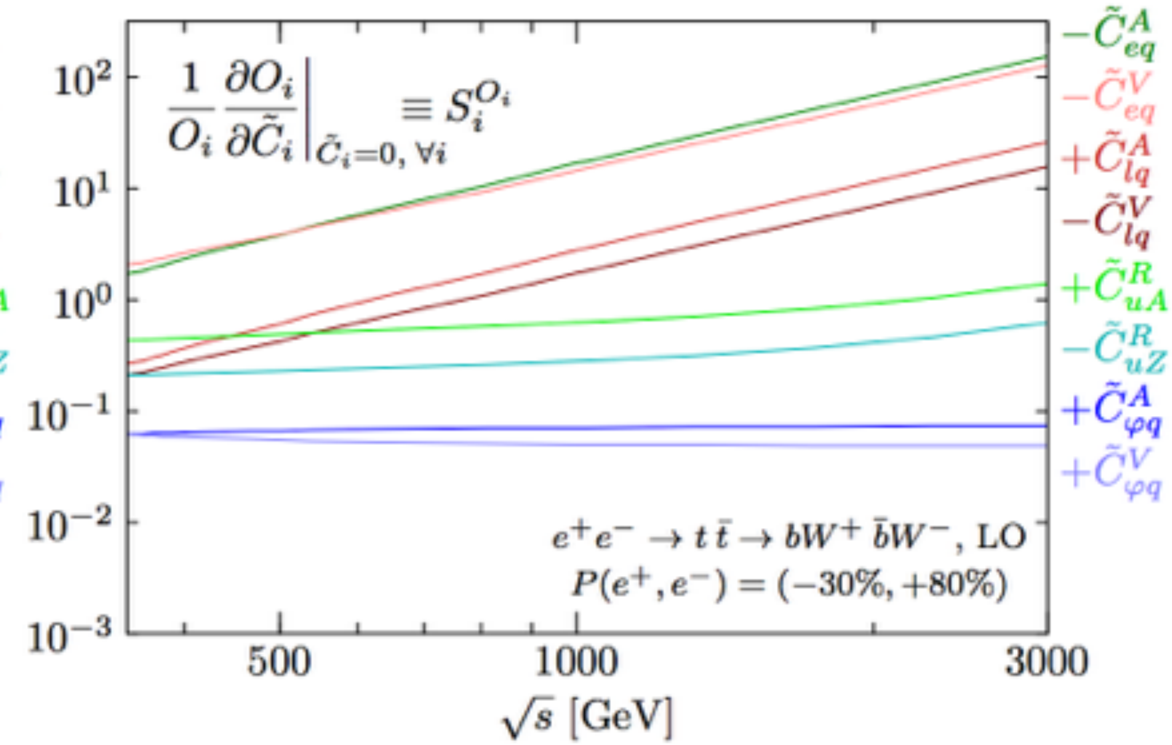
1. asymmetries: $O_i \sim \text{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1+\cos\phi}$

$\Longrightarrow$ 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]

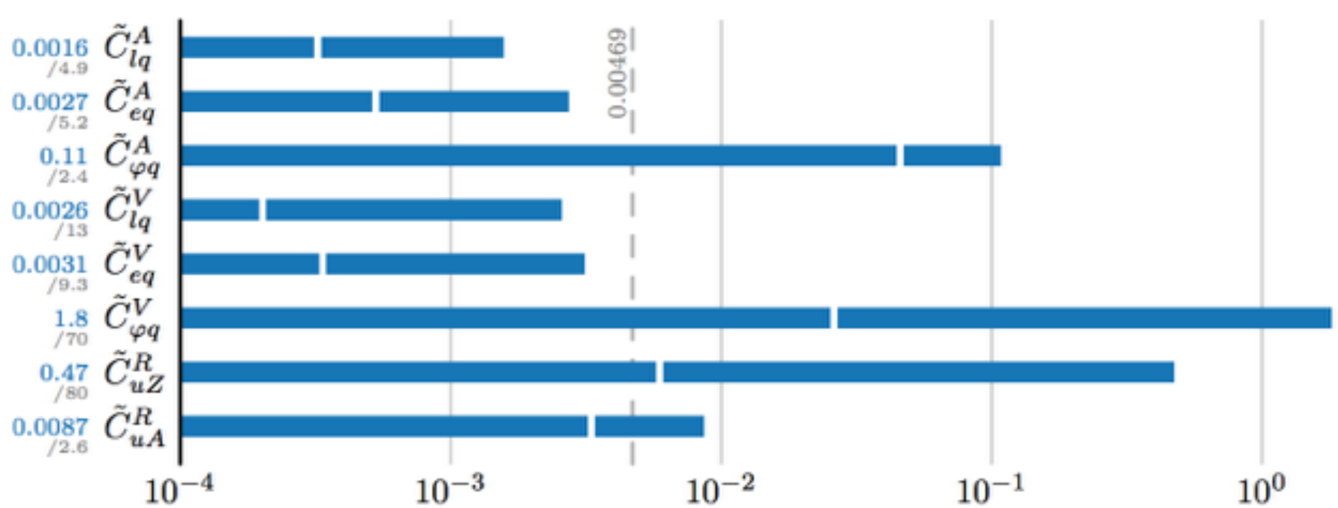
Statistically optimal observables sensitivities



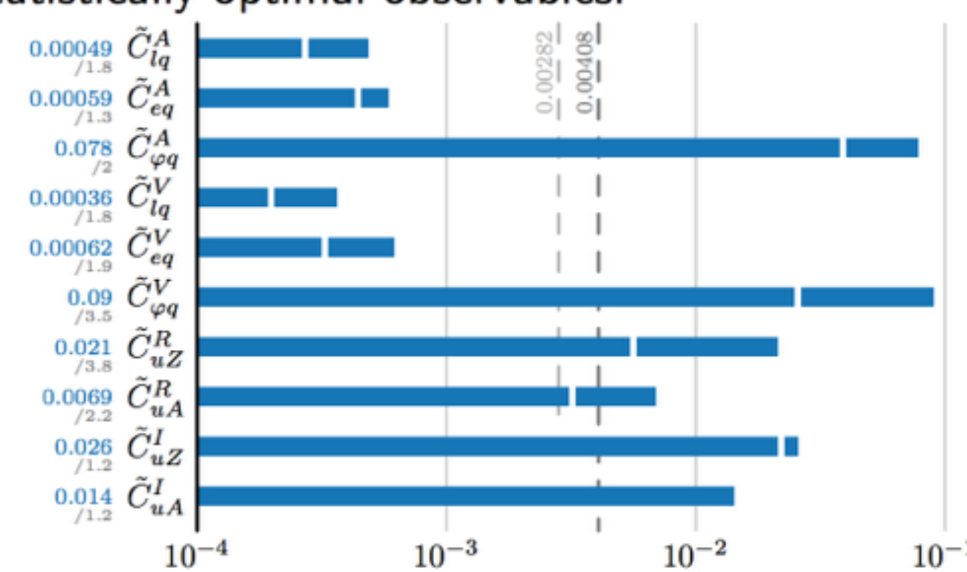


Comparison in the global limits (500GeV + 1TeV for 2 pols.):

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

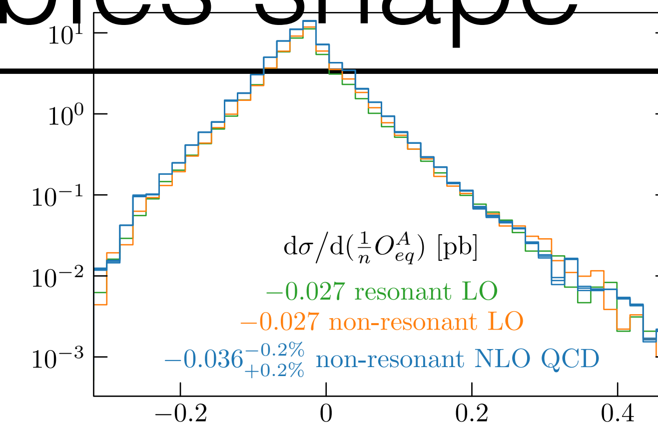


Statistically optimal observables:



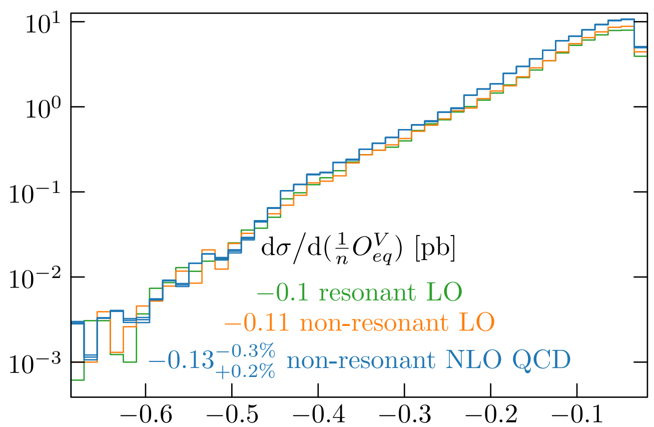
- **Even better individual limits**
- **Global limits within a factor 1.3 to 3.5**

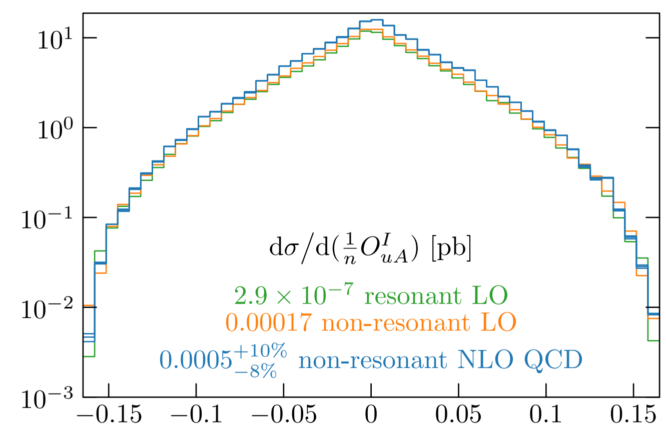
Statistically optimal observables shape

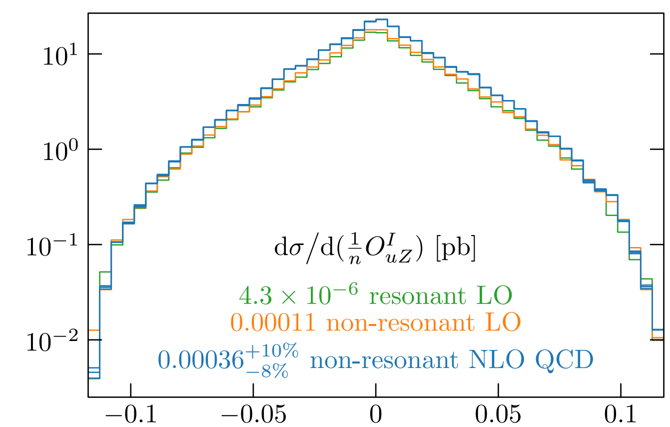


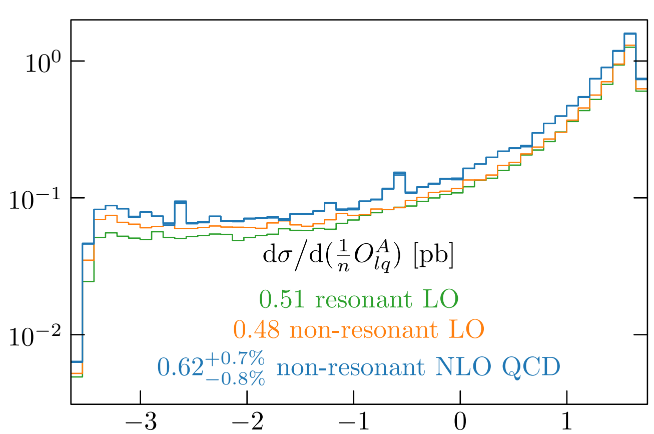
Example for 500 GeV (e-, e+) = (-0.8, 0.3)

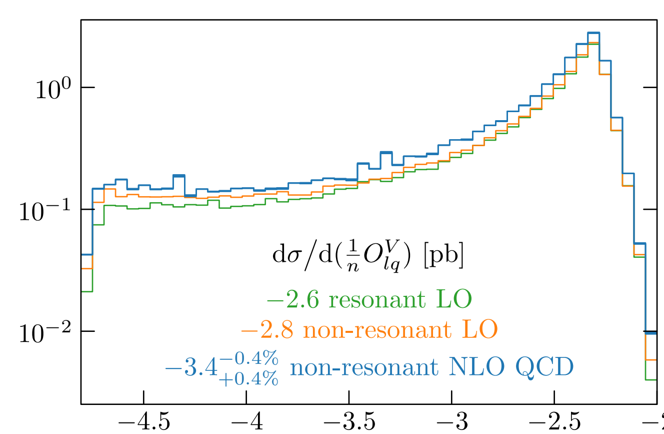
Theory uncertainties below 1% for the distributions means

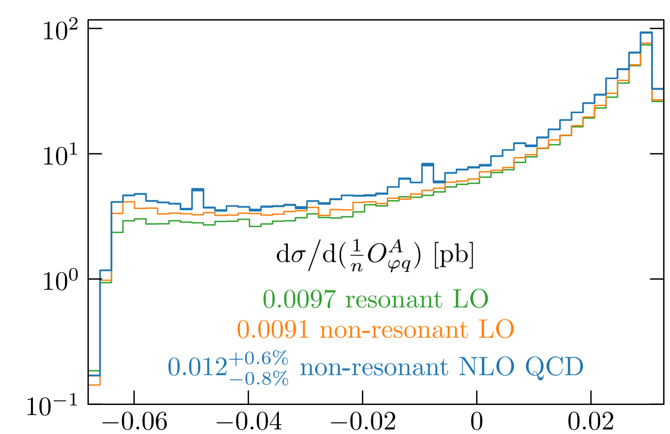


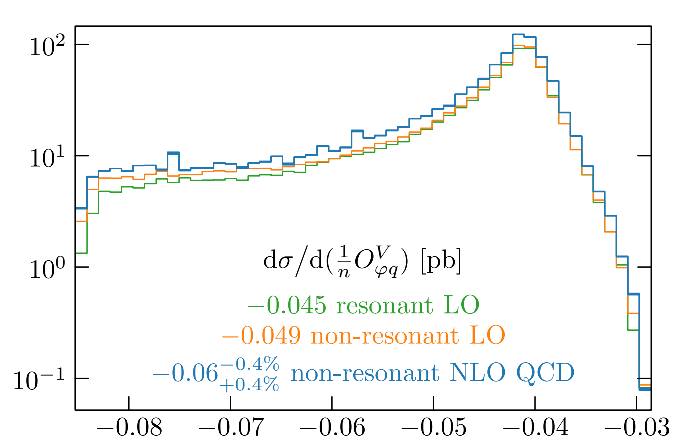


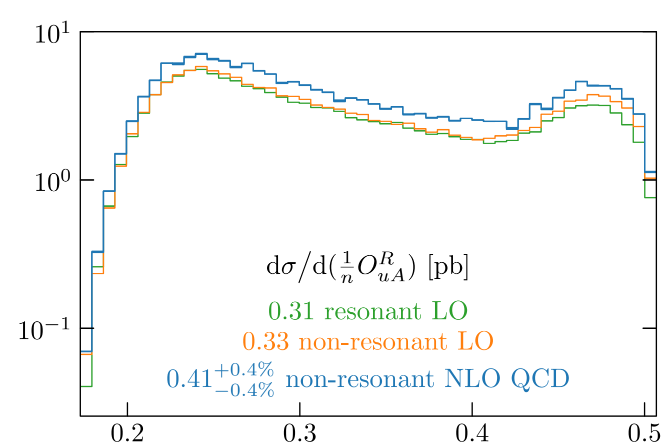


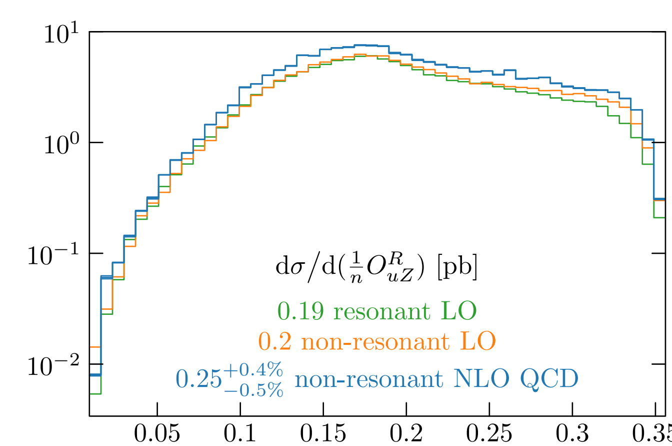












Full-simulation at CLIC380 and ILC500

Full-simulation

Studied process

$$e^-e^+ \to t\bar{t} \to W^+bW^-\bar{b} \to l\nu b\bar{b}q\bar{q}$$

$\sqrt{s}$ = {380, 500, 1000, 1400, 3000} GeV

- CLIC
- ILC

	380 GeV	500 GeV	1 TeV	1.4 TeV	3 TeV
Pol (e-, e+)	(-0.8, 0)	(-0.8, +0.3)	(-0.8, +0.2)	(-0.8, 0)	(-0.8, 0)
	(+0.8, 0)	(+0.8, -0.3)	(+0.8, -0.2)	(+0.8, 0)	(+0.8, 0)
σ[L,R] (fb)	792	930	256	113	25
σ[R,L] (fb)	418	480	142	66	15
Lumi (fb-1)	500	500	1000	1500	3000

Studies at CLIC380 and ILC500 included in I. Garcia thesis

ILC@500GeV L=500fb^{-1} [arXiv:1505.06020]

$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{\text{stat.}}$ (%)	$(\delta A^t_{\text{FB}}/A^t_{\text{FB}})_{\text{stat.}}$ (%)
−0.8, +0.3	0.47	1.8
+0.8, −0.3	0.63	1.3

CLIC@380GeV L=500fb^{-1}

$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{\text{stat.}}$ (%)	$(\delta A^t_{\text{FB}}/A^t_{\text{FB}})_{\text{stat.}}$ (%)
−0.8, 0	0.47	3.8
+0.8, 0	0.83	4.6

Full-simulation at CLIC@380 and ILC@500

Studied process

$$e^-e^+ \to t\bar{t} \to W^+bW^-\bar{b} \to l\nu b\bar{b}q\bar{q}$$

Same cuts used in previous studies which reduce background.

Signal selection:

- **Hadronic top in the range: 120 < mt < 230**
- **Hadronic W: 50 < mW < 110**
- **only 1 lepton per event**
- **2 b-tags (b-tag1 > 0.8 and b-tag2 > 0.5)**

Statistical uncertainties:

$O_i=(\Sigma\ \sigma_i/\sigma_0)$ (normalization)

$O_i=1/n(\Sigma\ \sigma_i/\sigma_0)$ (distribution mean)

statistical uncertainty [%]	cross-section	lqA	eqA	pqA	lqV	eqV	pqV	ReuZ	ReuA	ImuZ*	ImuA*
380 (e-,e+) = (-0.8, 0)	0,8	3	5	3	0,1	0,5	0,1	0,2	0,1	1E-3	2E-3
380 (e-,e+) = (0.8, 0)	0,8	5	4	4	0,5	0,1	0,3	0,2	0,1	2E-3	2E-3
500 (e-,e+) = (-0.8, 0.3)	0,6	2	8	2	0,2	4	0,2	0,3	0,2	2E-3	4E-3
500 (e-,e+) = (0.8, -0.3)	0,8	6	2	2	2	0,4	0,7	0,7	0,3	4E-3	7E-3

*Absolute uncertainty

Reconstruction effects

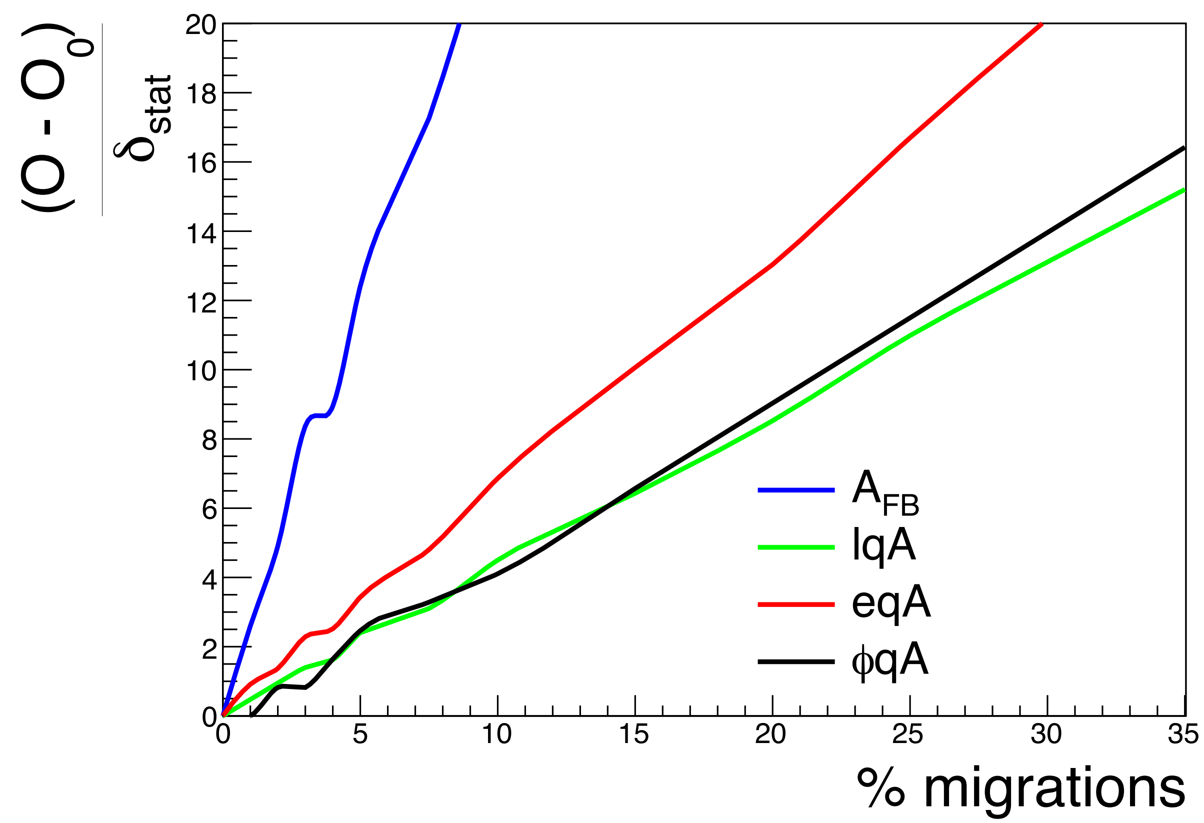
Starting reconstruction at CLIC@380 and ILC@500

Need of a quality cut (mainly for reducing migrations)

$$\chi^2 = \left(\frac{\gamma_t - \gamma_t^{MC}}{\sigma_{\gamma_t}}\right)^2 + \left(\frac{E_b^* - E_b^{*MC}}{\sigma_{E_b^*}}\right)^2 + \left(\frac{\cos\theta_{bW} - \cos\theta_{bW}^{MC}}{\sigma_{\cos\theta_{bW}}}\right)^2$$

	efficiency	quality cut chi2 < X	efficiency after quality cut
380L	37%	5	**18%**
380R	33,3%	40	**30,4%**
500L	34,4%	50	**29,4%**
500R	35%	50	**30,1%**

380 GeV (e-,e+) = (-0.8, 0)



Similar behaviour we oberved in the Afb study.

Systematic uncertainties

Selection effects

Normalization: Biases around 3σ
Shape: Selection biases around 1σ - 3σ

Residual uncertainty expected to be smaller than the effect

Reconstruction effects

Normalization: biases < 1σ
Shape: Reconstruction biases around 1σ - 2σ

Beam structure effects (using WHIZARD 2.6.0 for MC generation)

Beamstrahlung (switching on/off CIRCE2 package)

Normalization: 20σ
Shape: Biases < 1σ in all cases

Uncertainty to be estimated with Bhabha scattering study

ISR (Switching on/off ISR)

Normalization: 20σ
Shape: Biases around 1σ - 2σ

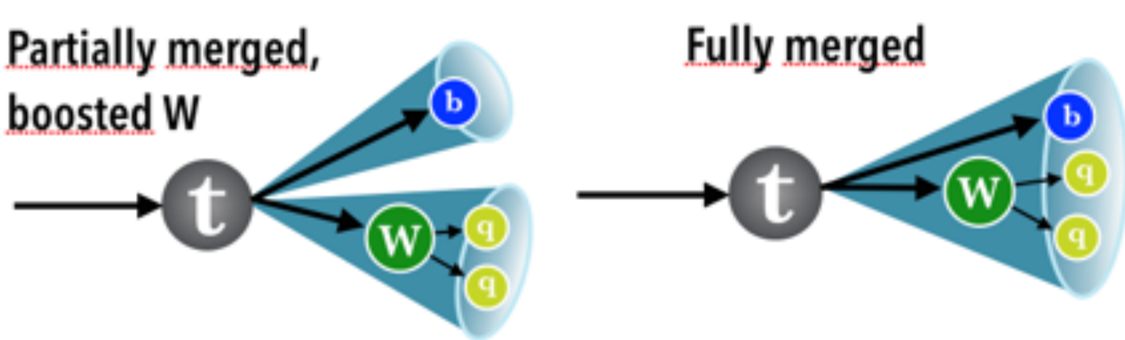
Uncertainty from parameters variation < 1%

Full-simulation at high energies

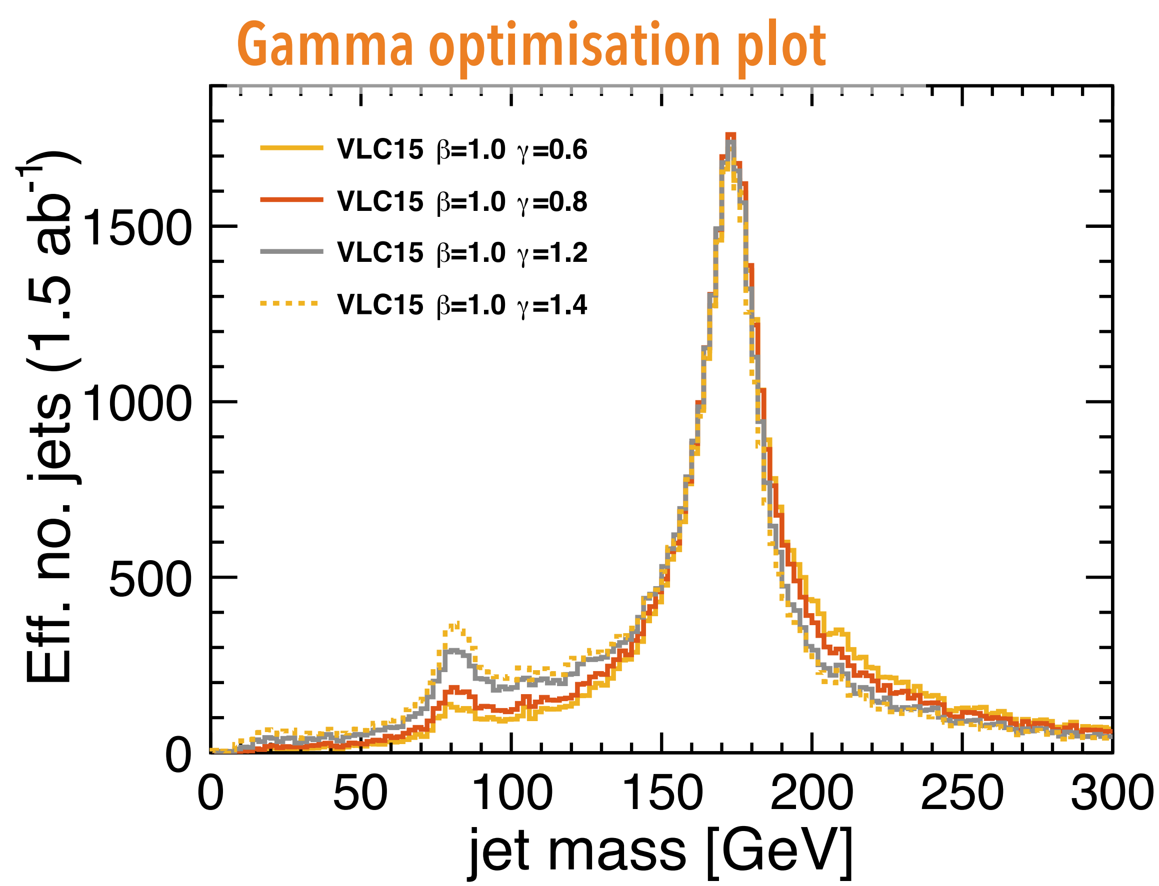
For a detailed explanation visit R. Ström's talk at CLICdp Collaboration Meeting: https://indico.cern.ch/event/633975/contributions/2689114/

Boosted top reconstruction techniques

- Jet clustering (incl. trimming)
  - 2 exclusive large-R jets
- Jet tagging:
  - Parsing sub-structure (method 1)
  - Jet structure variables (method 2)
    - not explained here, see Alasdair Winter's talk at CLIC WS 2017 (https://indico.cern.ch/event/577810/contributions/2485031/)
- B-tagging (sub-jet, fat-jet)

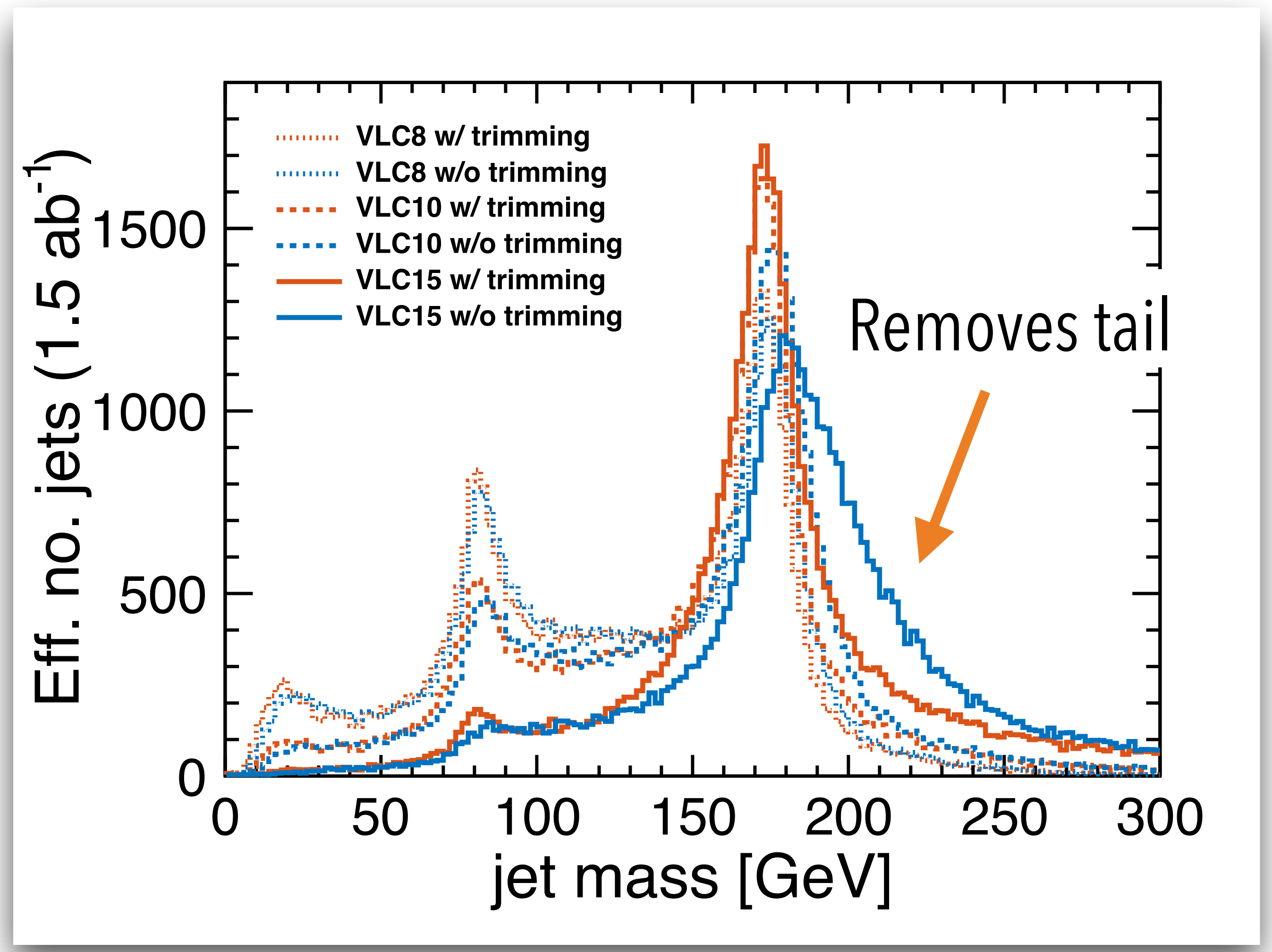


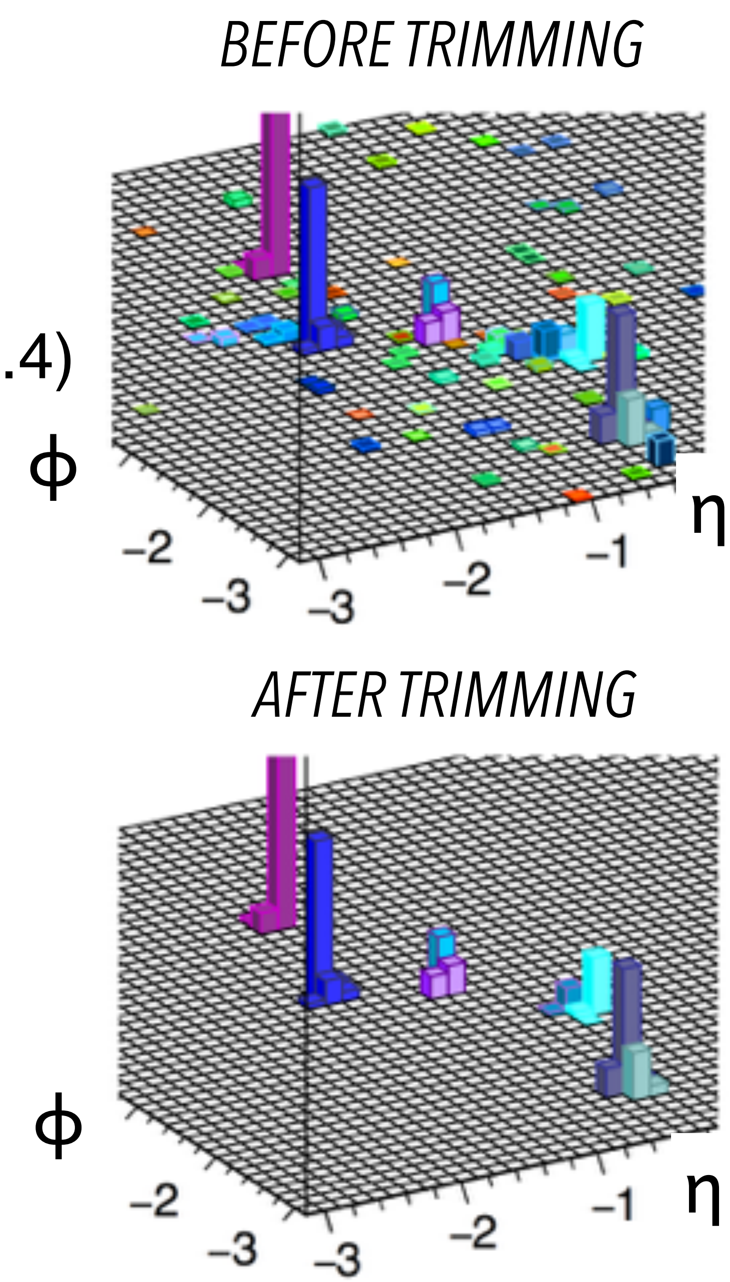
Solid optimization in jet clustering parameters by Rickard Ström



Jet trimming

- **Jet trimming** is a complementary way to reduce the impact from beamstrahlung
- **Pre-clustering into micro-jets**
  - Inclusive clustering with minimum p_T threshold
  - generalised kt algoritm (~ kt for e^+e^- + beam jets)
  - p_T threshold and micro-jet radius optimised (E_{th}=5 GeV, R=0.4)

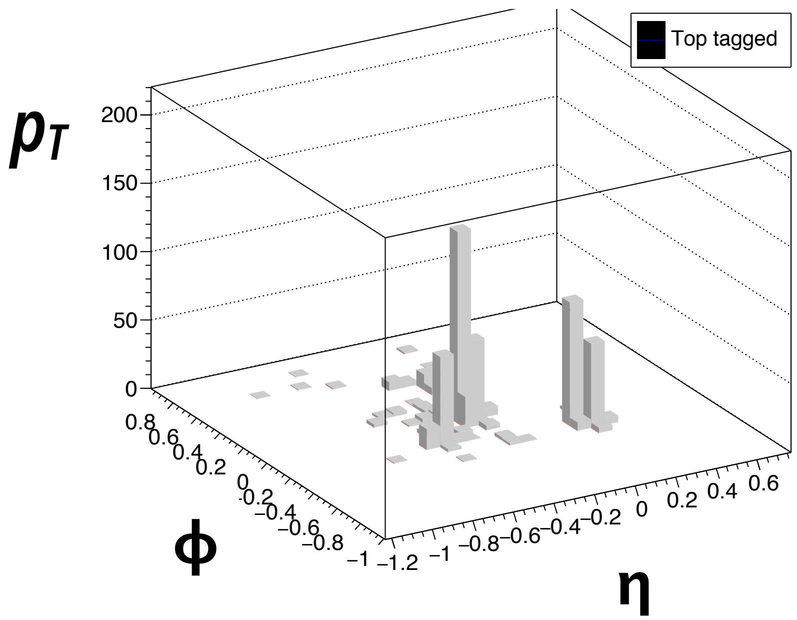




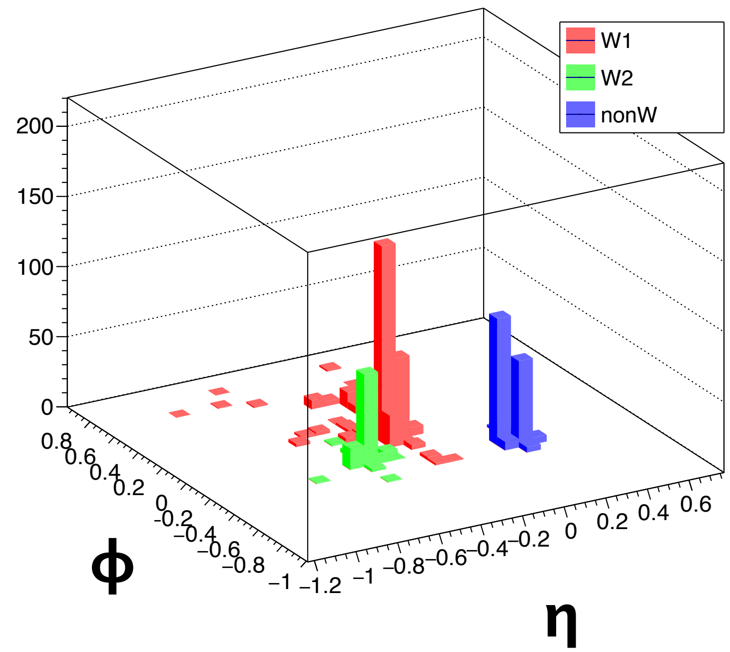
Parsing sub-structure (method 1)

Parsing through jet cluster

Zoom on a fully-hadronic tt event

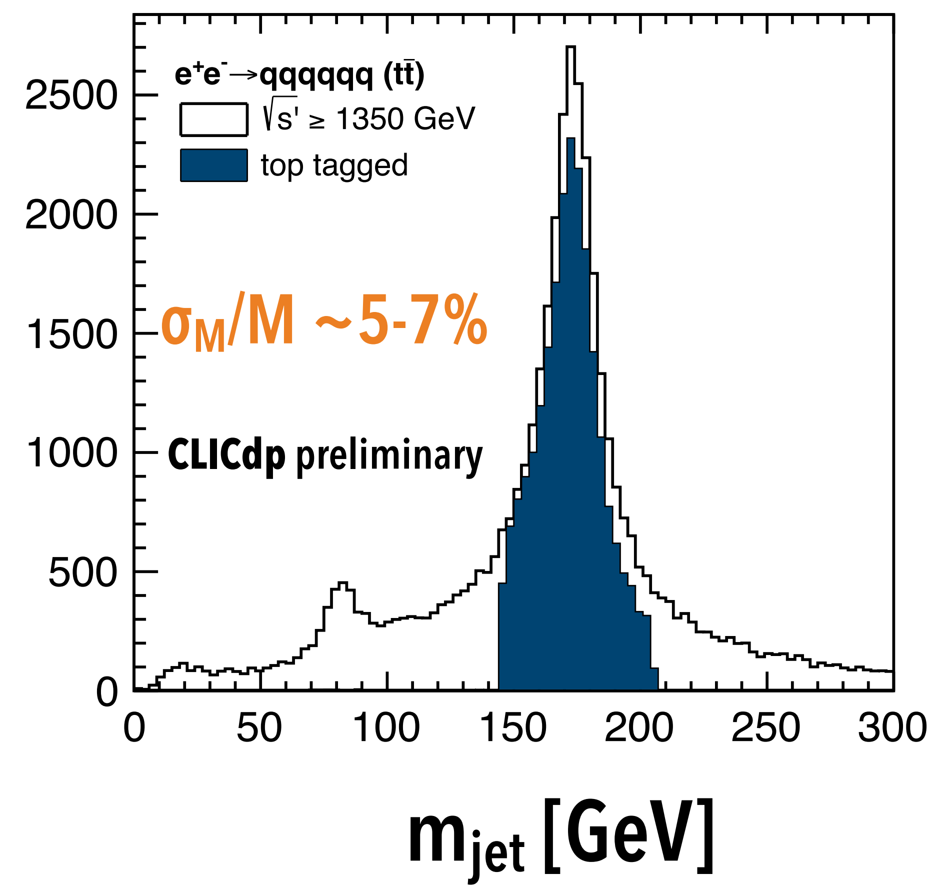


Three subjects identified



fully-hadronic $e^+e^- \rightarrow tt \rightarrow qqqqqq$

VLC15 (2 excl.), δR,δP=0.05

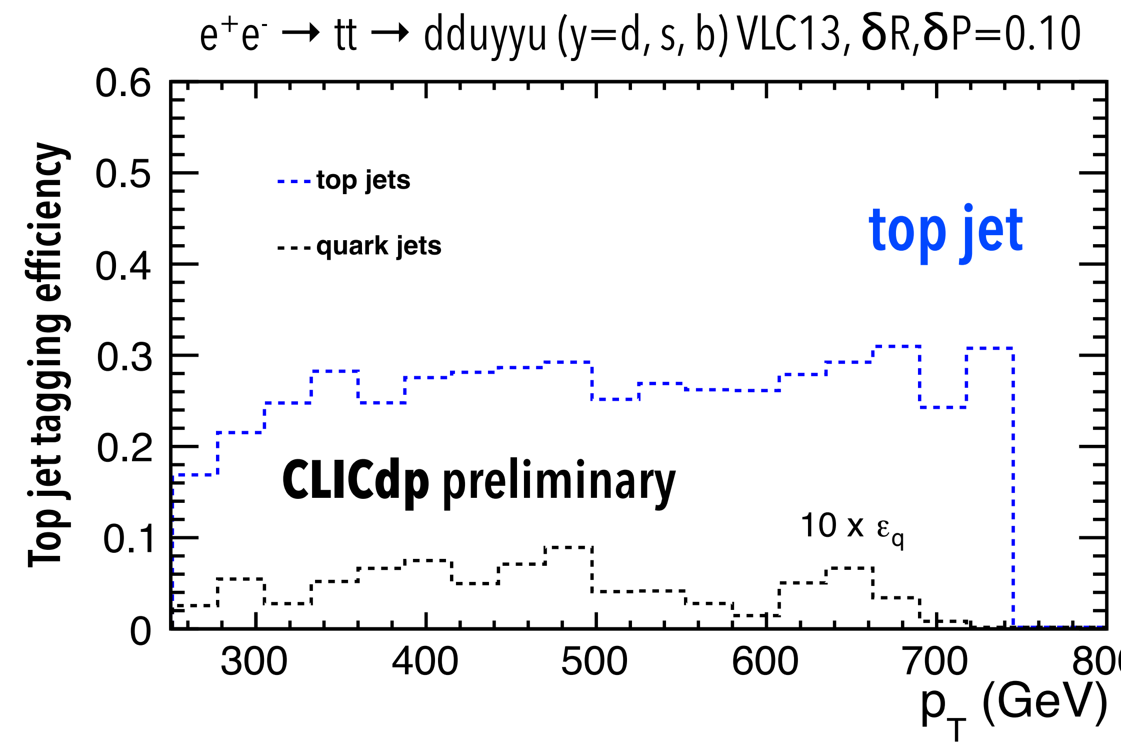


- Jet de-clustering (FastJet extension), **DOI: 10.1103/PhysRevLett.101.142001**
- VLC jet clustering algorithm (R=1.5, β=1, γ=1) + trimming
- "JH Top Tagger" + kinematic cuts ($m_t \in [145,205]$ GeV, $m_W \in [65,95]$ GeV)

Full-simulation at CLIC1400

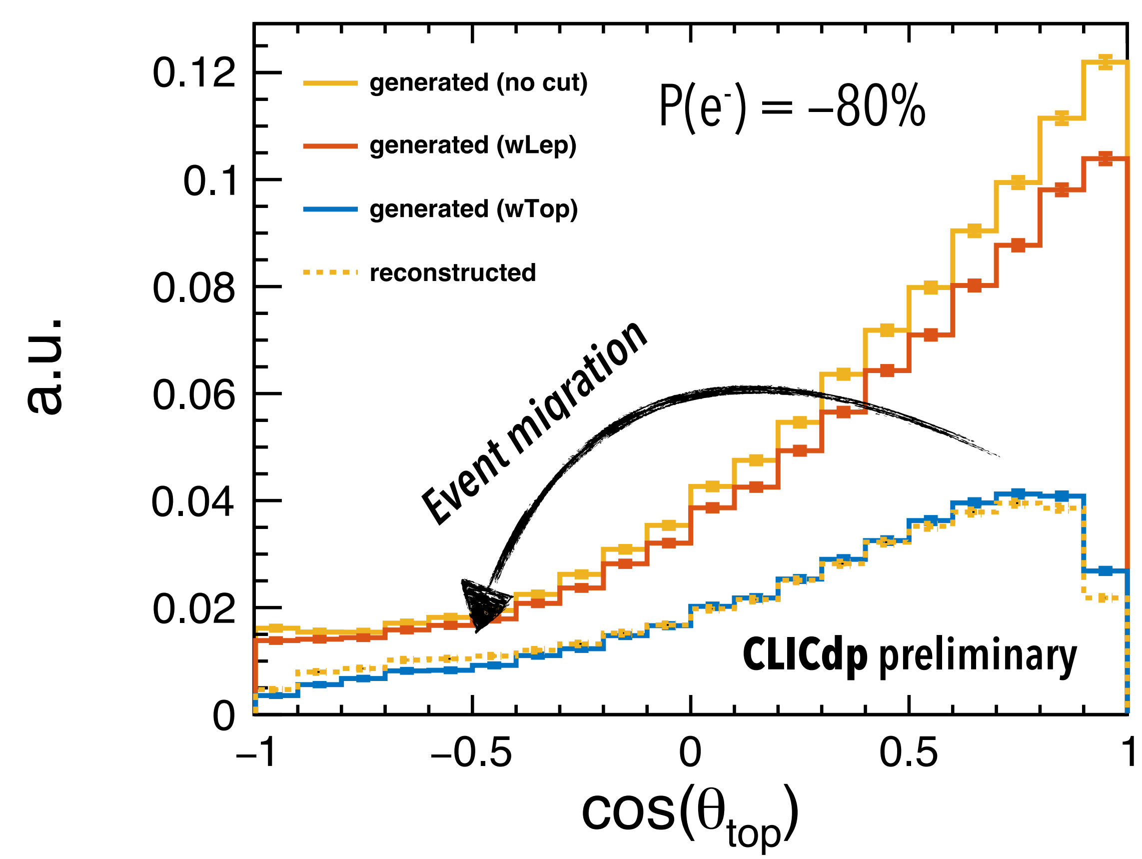
JH Top Tagger - results

- Top quark mass recovered for sufficiently large-R jet (efficiency drop for R < 1.3)
- Good discrepancy towards background processes without top
- More efficient than simple mass cut



Top quark A_{fb} results

- Less migration is observed for $P(e^-) = +80\%$ Backgrounds substantially reduced
- Relative error on A_{fb}:
  - **$P(e^-) = -80\%$: ~2% (signal only)**
  - **$P(e^-) = +80\%$: ~3% (signal only)**
- Both methods yield a similar result



Conclusions

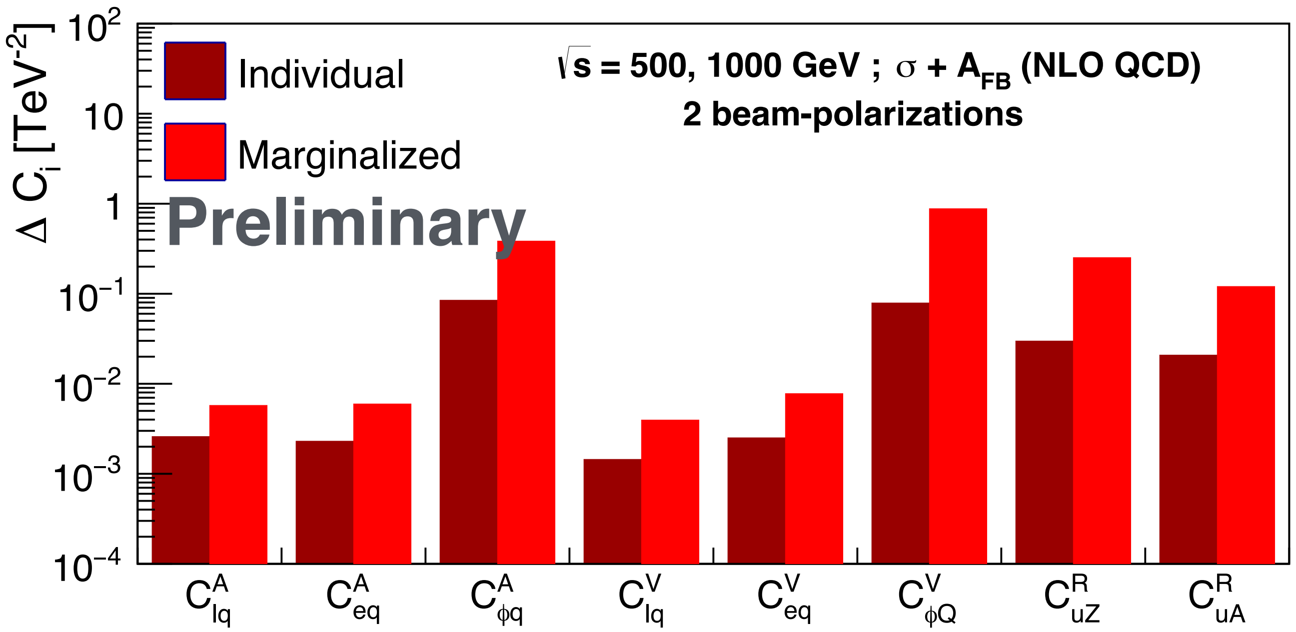
- Cross-section + Afb are not enough for global EFT fit. Top polarisation at different axes and CP-odd observables help in the operators disentangling.
- Optimal observables seem to be the proper solution and are found to be robust
- Reconstruction new techniques at high energies are making progress providing first results for Afb @CLIC1400.

Back up

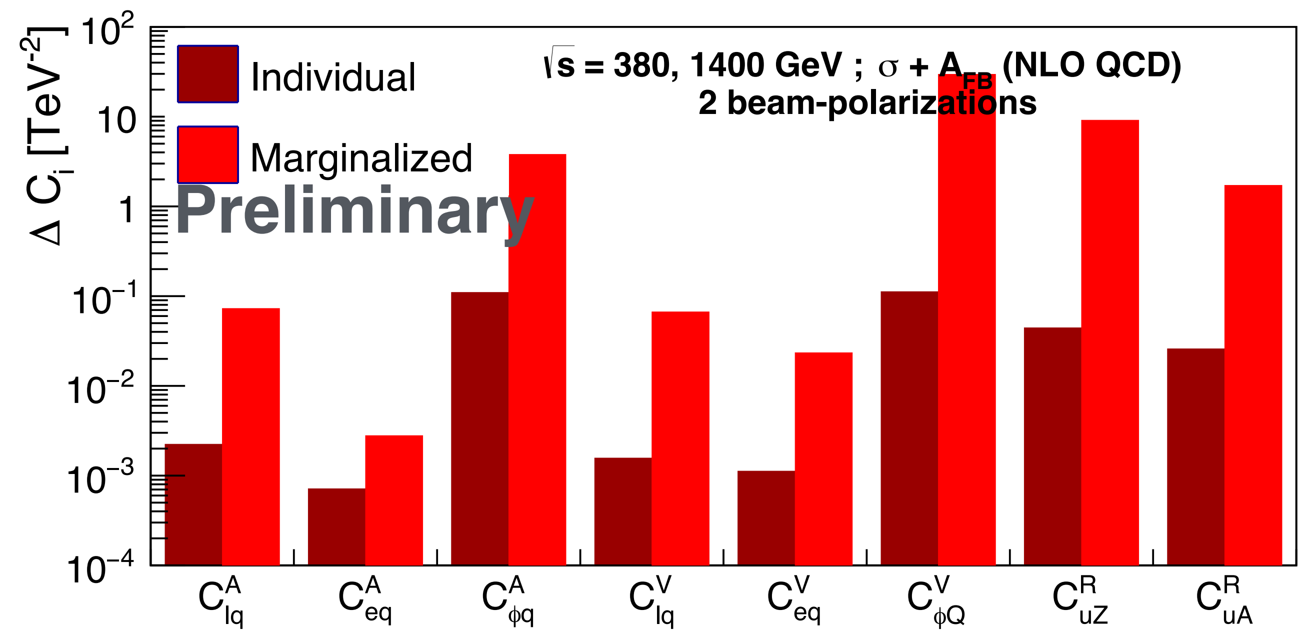
Global Fit: Afb + σ

Studied process $e^-e^+ \rightarrow W^+bW^-\bar{b}$ @NLO **[Motivation from arXiv:1411.2355]**

ILC: **500 GeV + 1 TeV**



CLIC: **380 GeV + 1.4 TeV + (3) TeV**



Individual: assuming variation in only 1 parameter each time.
Marginalized: assuming variation in all the parameters at the same time.

Similar behaviour at $e^-e^+ \rightarrow t\bar{t}$ @LO and $e^-e^+ \rightarrow W^+bW^-\bar{b}$ @NLO (QCD)

Low uncertainties are achieved, but we can do it better

We should improve the marginalized fit