EFT fit on top quark EW couplings

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Outline

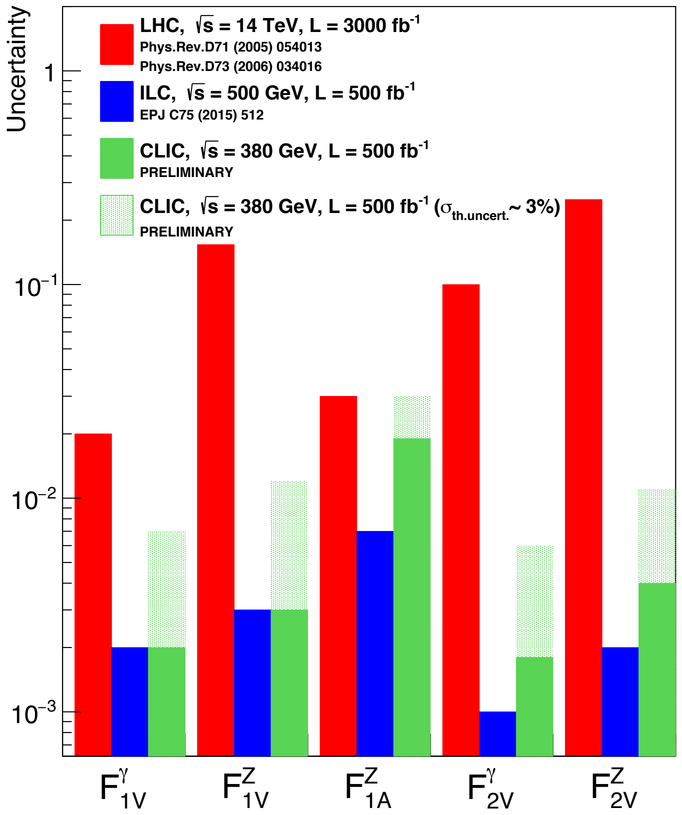
- Introduction to quark couplings and EFT
- Observables sensitivities:
  - A_{FB} + cross-section
  - Optimal CP-odd observables
  - Top quark polarization
  - Statistically optimal observables
- Full-simulation at CLIC380 and ILC500
- Full-simulation at high energies

Introduction to quark couplings and EFT

Top quark couplings

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

CLIC baseline document
arXiv:1608.07537



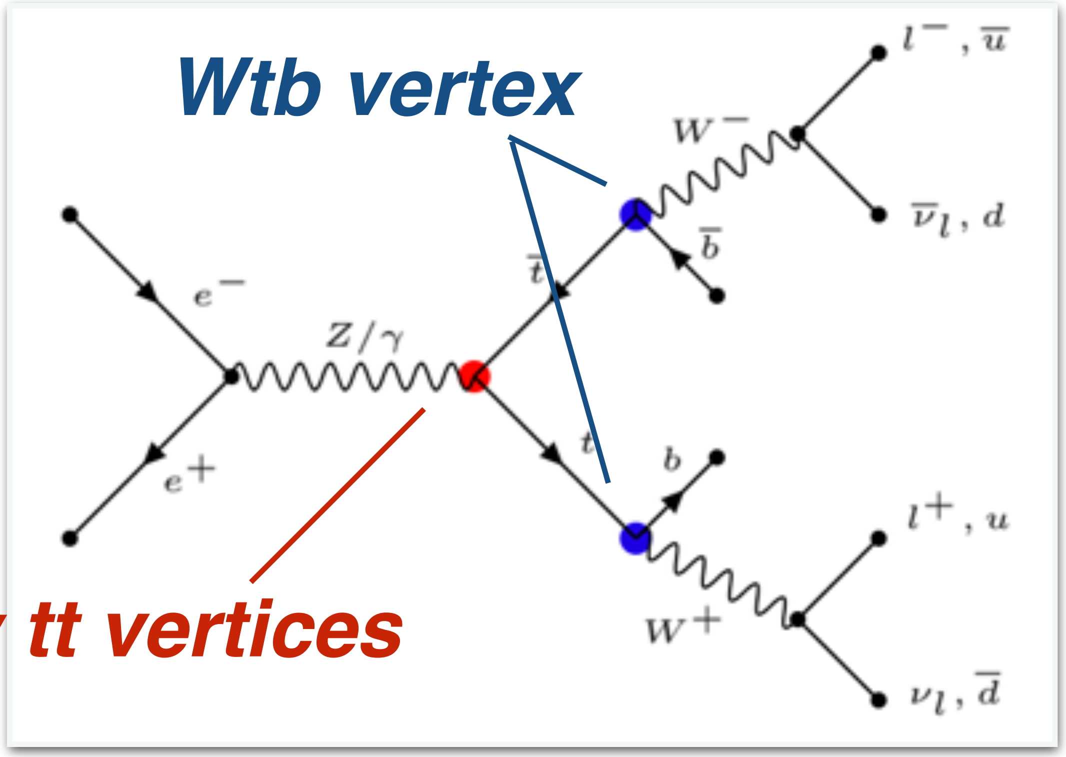
Form-factors

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

CP Conserving **CPV**

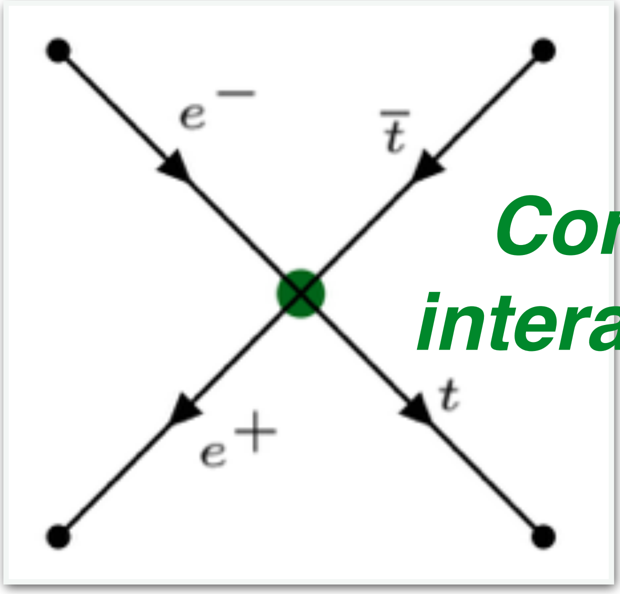
Effective Field Theory

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



Wtb vertex

Z/γ tt vertices

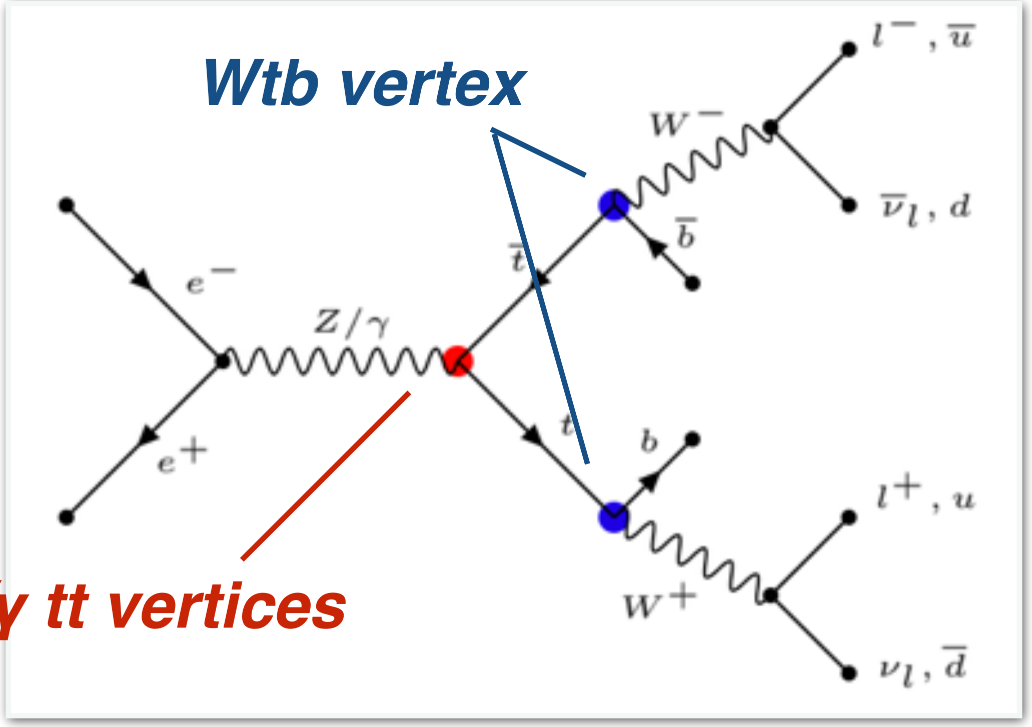


Contact interactions

Dim-6 operators

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

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



Wtb vertex

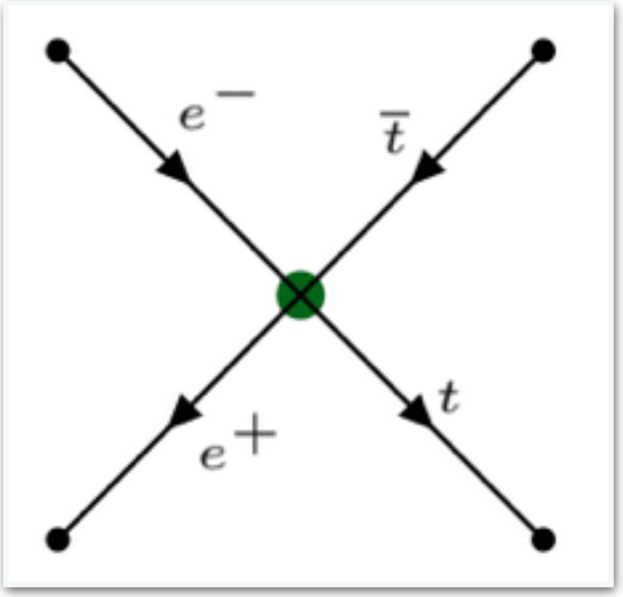
Z/γ tt vertices

Contact interactions

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

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

$$
\begin{aligned}
O^S_{lequ} &\equiv \bar{q}u\ \epsilon\ \bar{l}e \\
O_{ledq} &\equiv \bar{d}q\ \ \bar{l}e
\end{aligned}
$$



Change of basis

Transformation between effective operators and form-factors:

$$
\begin{aligned}
F^{Z}_{1,V} - F^{Z,SM}_{1,V} &= \frac{1}{2}\left(\underline{C^{(3)}_{\varphi Q} - C^{(1)}_{\varphi Q} - C_{\varphi t}}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}\underline{C^{V}_{\varphi q}}\frac{m_t^2}{\Lambda^2 s_W c_W} \\
F^{Z}_{1,A} - F^{Z,SM}_{1,A} &= \frac{1}{2}\left(\underline{-C^{(3)}_{\varphi Q} + C^{(1)}_{\varphi Q} - C_{\varphi t}}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}\underline{C^{A}_{\varphi q}}\frac{m_t^2}{\Lambda^2 s_W c_W} \\
F^{Z}_{2,V} &= \left(\underline{\mathrm{Re}\{C_{tW}\}c_W^2 - \mathrm{Re}\{C_{tB}\}s_W^2}\right)\frac{4m_t^2}{\Lambda^2 s_W c_W} = \mathrm{Re}\{\underline{C_{uZ}}\}\frac{4m_t^2}{\Lambda^2} \\
F^{\gamma}_{2,V} &= \left(\underline{\mathrm{Re}\{C_{tW}\} + \mathrm{Re}\{C_{tB}\}}\right)\frac{4m_t^2}{\Lambda^2} = \mathrm{Re}\{\underline{C_{uA}}\}\frac{4m_t^2}{\Lambda^2} \\
\left[F^{Z}_{2,A}, F^{\gamma}_{2,A}\right] &\propto \underline{\left[\mathrm{Im}\{C_{tW}\}, \mathrm{Im}\{C_{tB}\}\right]}
\end{aligned}
$$

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

10 operators in the current global fit:

- 4 CP-conserving ttX vertices
- 2 CP-violating ttX vertices
- 4 contact interactions

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

$$
\begin{aligned}
C^{V}_{lq} &\equiv C_{lu} + C^{(1)}_{lq} - C^{(3)}_{lq} \qquad & C^{V}_{eq} &\equiv C_{eu} + C_{eq} \\
C^{A}_{lq} &\equiv C_{lu} - C^{(1)}_{lq} + C^{(3)}_{lq} \qquad & C^{A}_{eq} &\equiv C_{eu} - C_{eq}
\end{aligned}
$$

Observables sensitivities

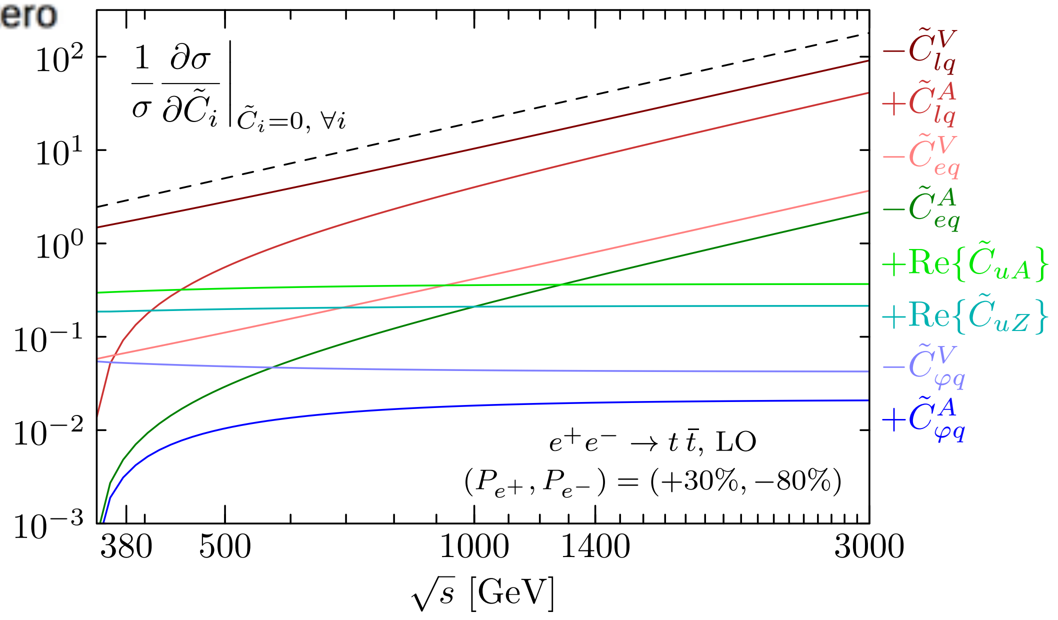
Observables sensitivity: A_{FB} + cross-section

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

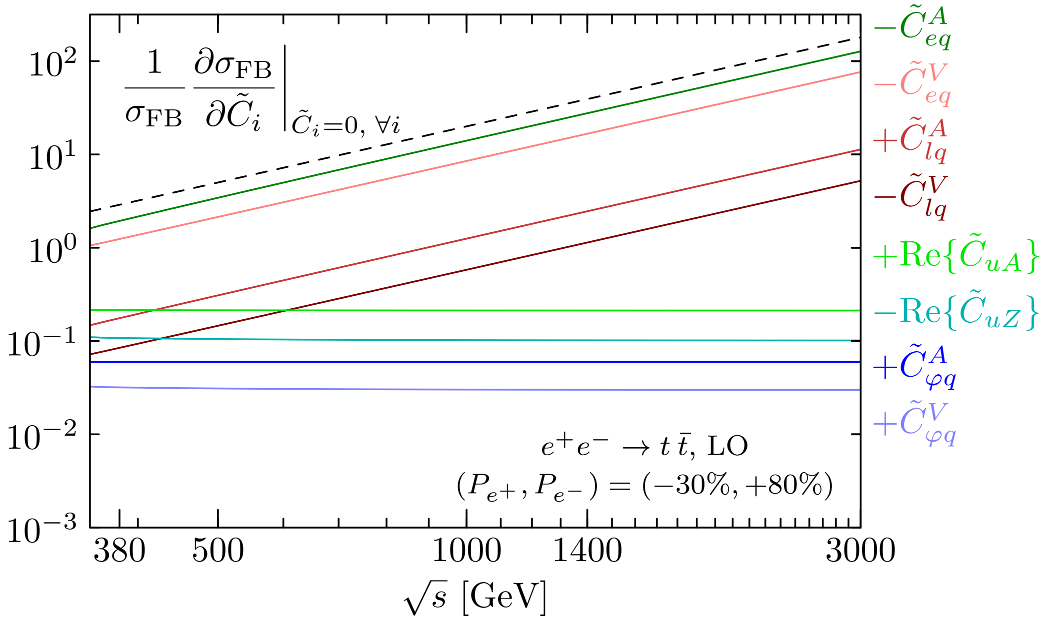
Durieux, Perelló, Vos, Zhang, to be published

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

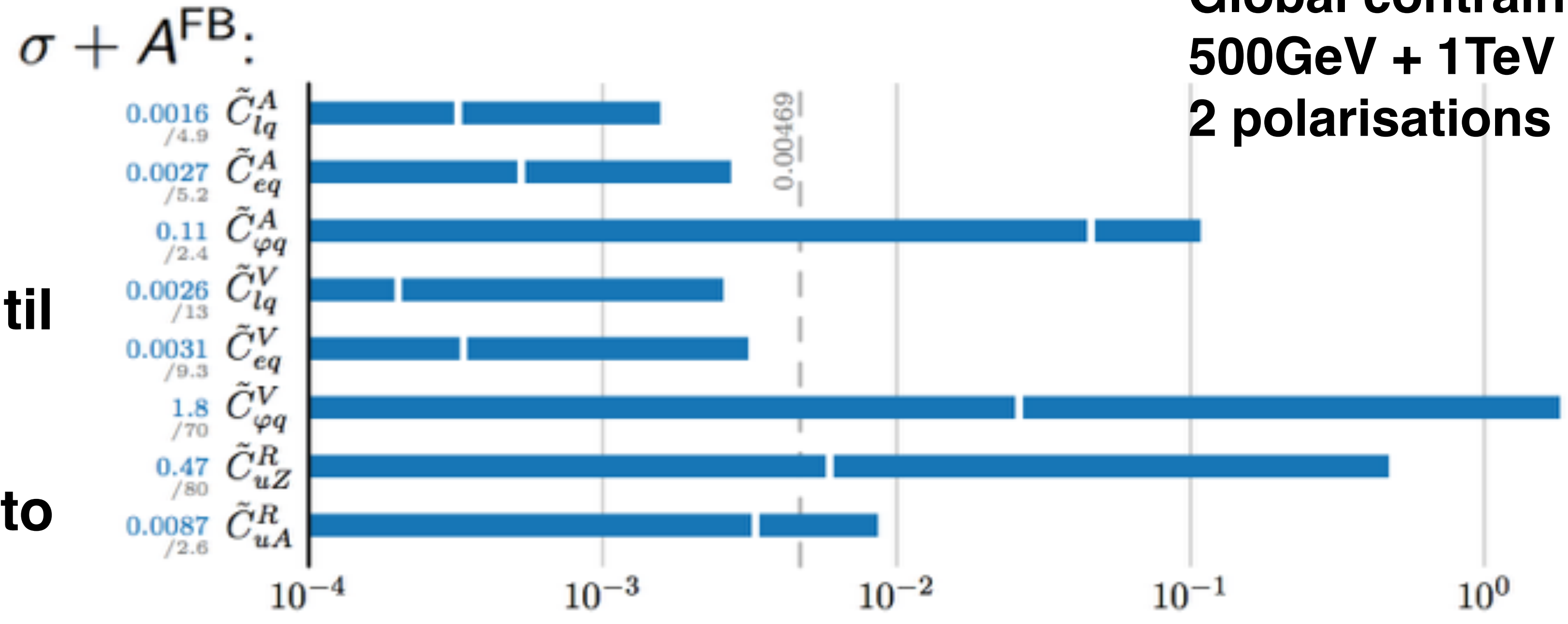
Cross-section



Forward-backward asymmetry



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



Global contraints 500GeV + 1TeV for 2 polarisations

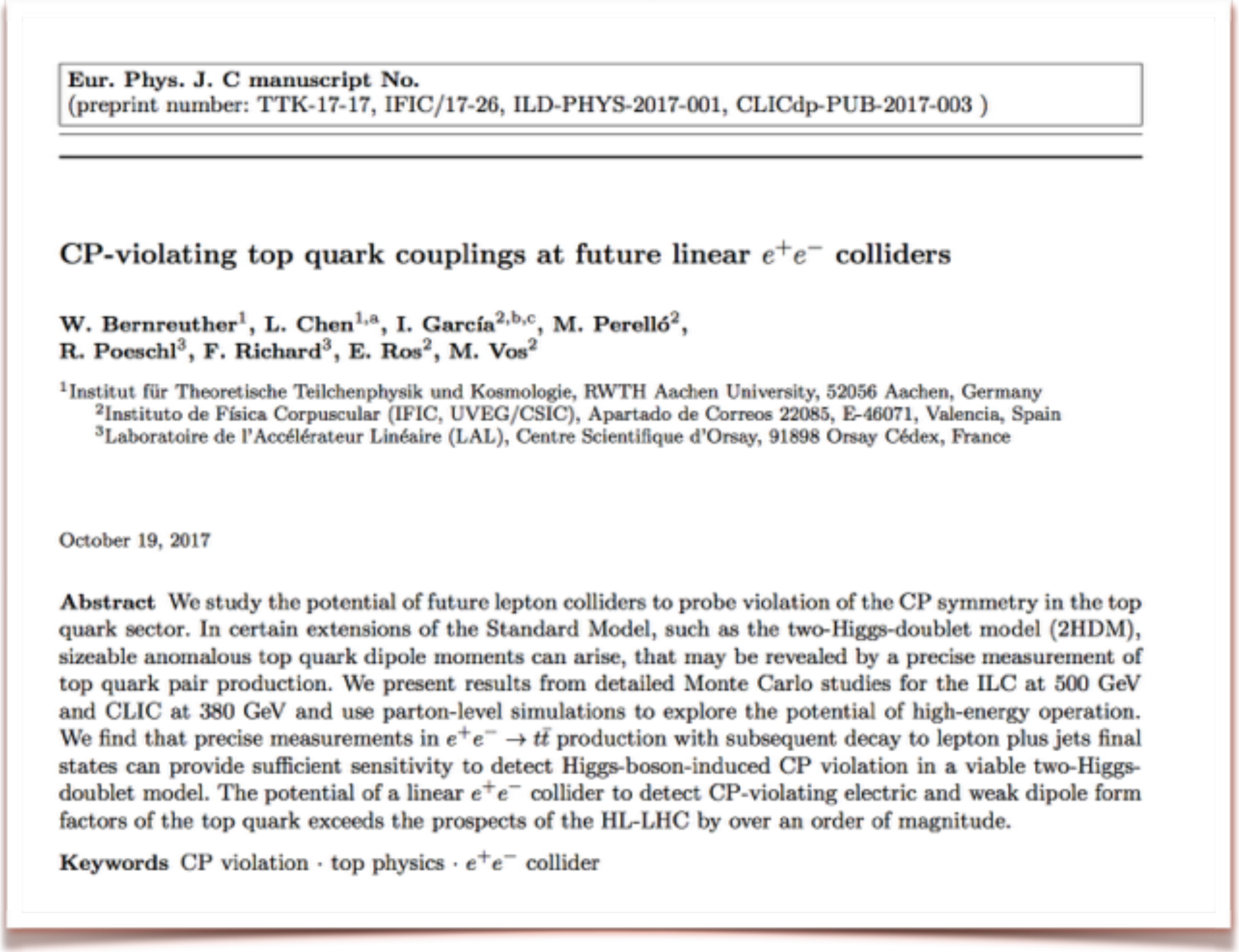
- **Very good individual limits (until de gap)**
- **Global limits (full bar) factor 3 to 80 worse**

Optimal CP-odd observables

The **CP-violating effects** in $e^+e^- \to t\bar{t}$ manifest themselves in specific **top-spin effects**, namely **CP-odd top spin-momentum correlations and $t\bar{t}$ spin correlations**.

- **CP-odd observables** are defined with the **four momenta available in tt semi-leptonic decay channel**
- The way to **extract** the **CP-violating form factor** is to construct **asymmetries sensitive to CP-violation effects**

arXiv:1710.06737



Eur. Phys. J. C manuscript No.
(preprint number: TTK-17-17, IFIC/17-26, ILD-PHYS-2017-001, CLICdp-PUB-2017-003)

CP-violating top quark couplings at future linear e^+e^- colliders

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October 19, 2017

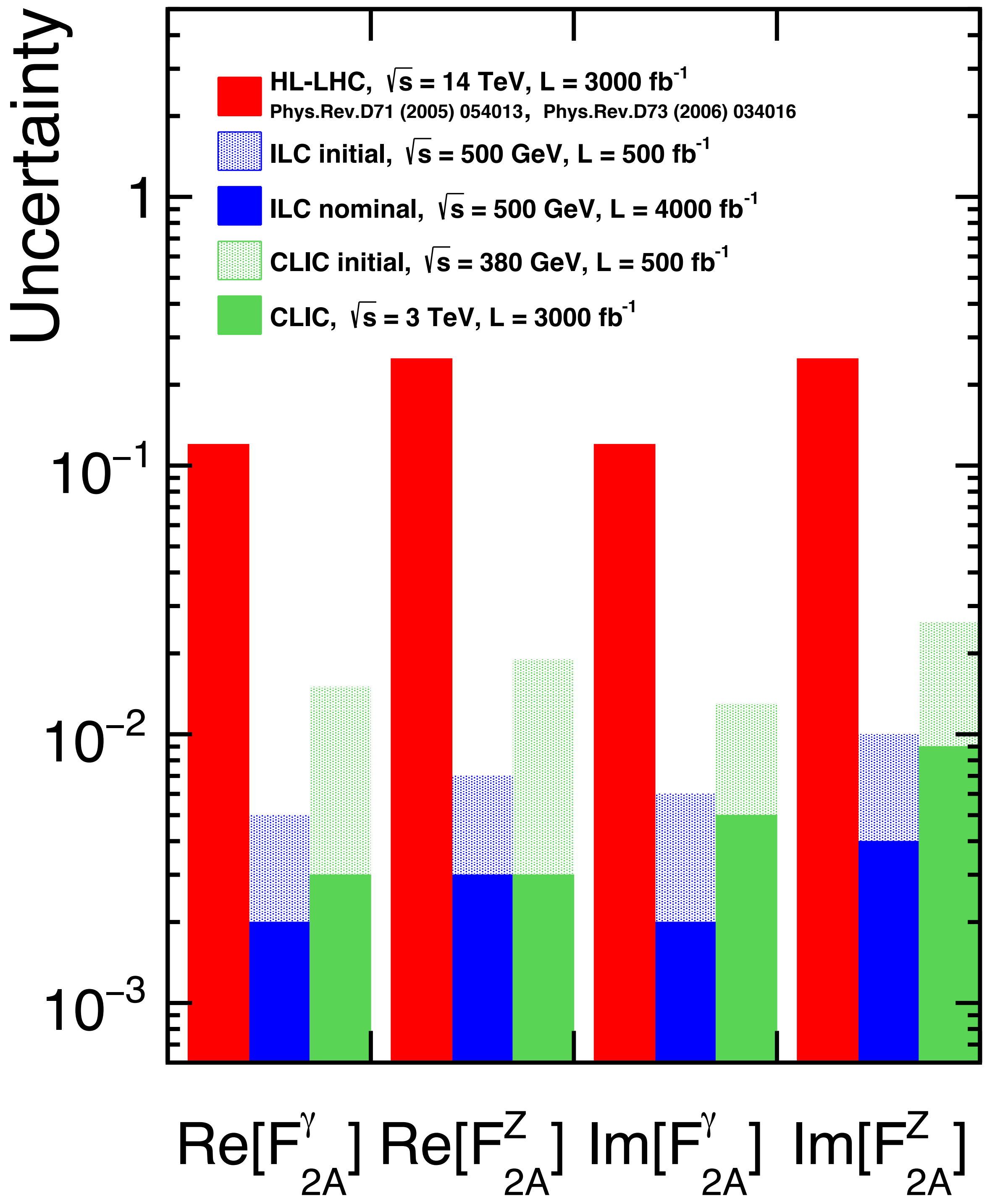
Abstract We study the potential of future lepton colliders to probe violation of the CP symmetry in the top quark sector. In certain extensions of the Standard Model, such as the two-Higgs-doublet model (2HDM), sizeable anomalous top quark dipole moments can arise, that may be revealed by a precise measurement of top quark pair production. We present results from detailed Monte Carlo studies for the ILC at 500 GeV and CLIC at 380 GeV and use parton-level simulations to explore the potential of high-energy operation. We find that precise measurements in $e^+e^- \to t\bar{t}$ production with subsequent decay to lepton plus jets final states can provide sufficient sensitivity to detect Higgs-boson-induced CP violation in a viable two-Higgs-doublet model. The potential of a linear e^+e^- collider to detect CP-violating electric and weak dipole form factors of the top quark exceeds the prospects of the HL-LHC by over an order of magnitude.

Keywords CP violation · top physics · e^+e^- collider

Prospects of CPV optimal observables

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

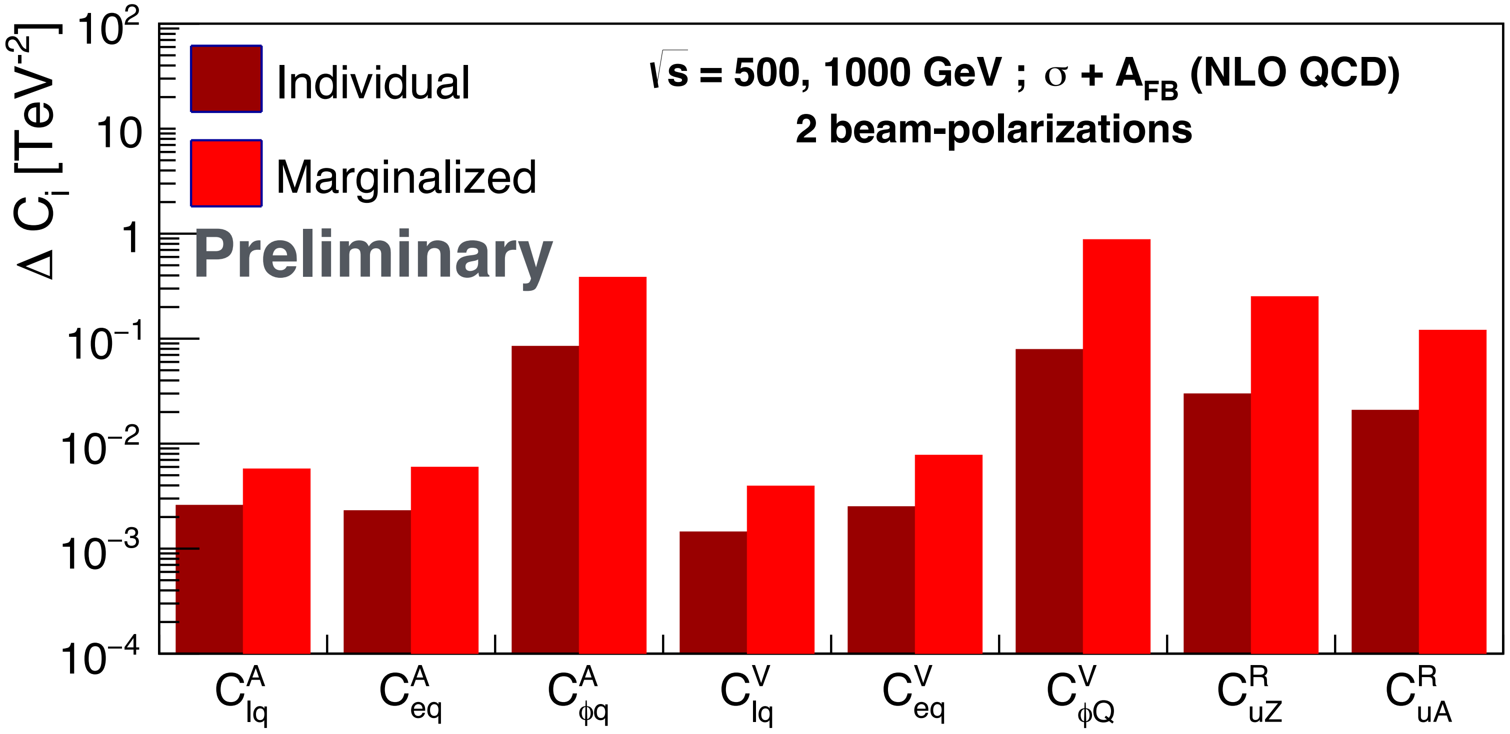
- Assuming that systematic uncertainties can be controlled to the required level, a luminosity upgrade of both machines **may bring a further improvement.**



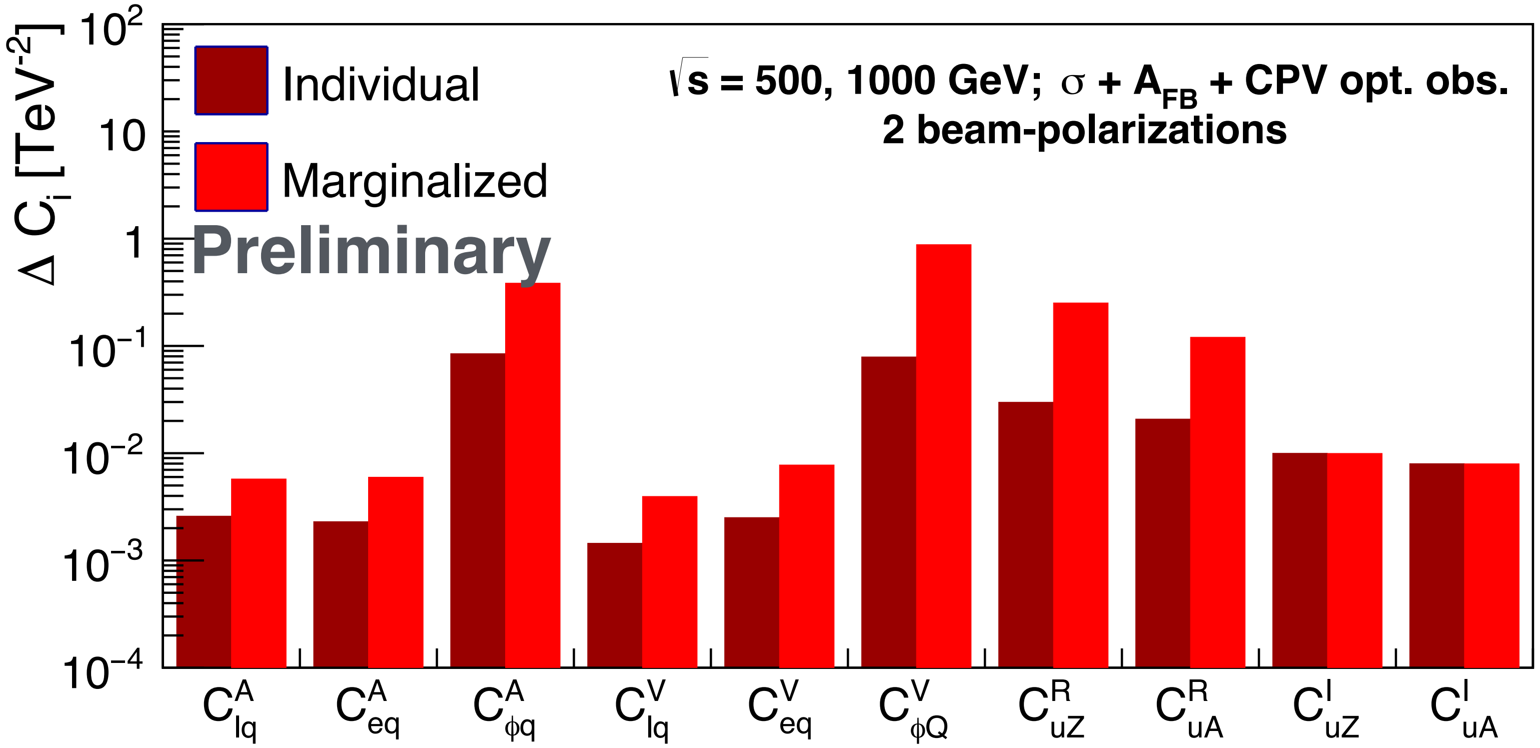
CPV observables in the global fit

Including CPV observables in the EFT global fit…

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

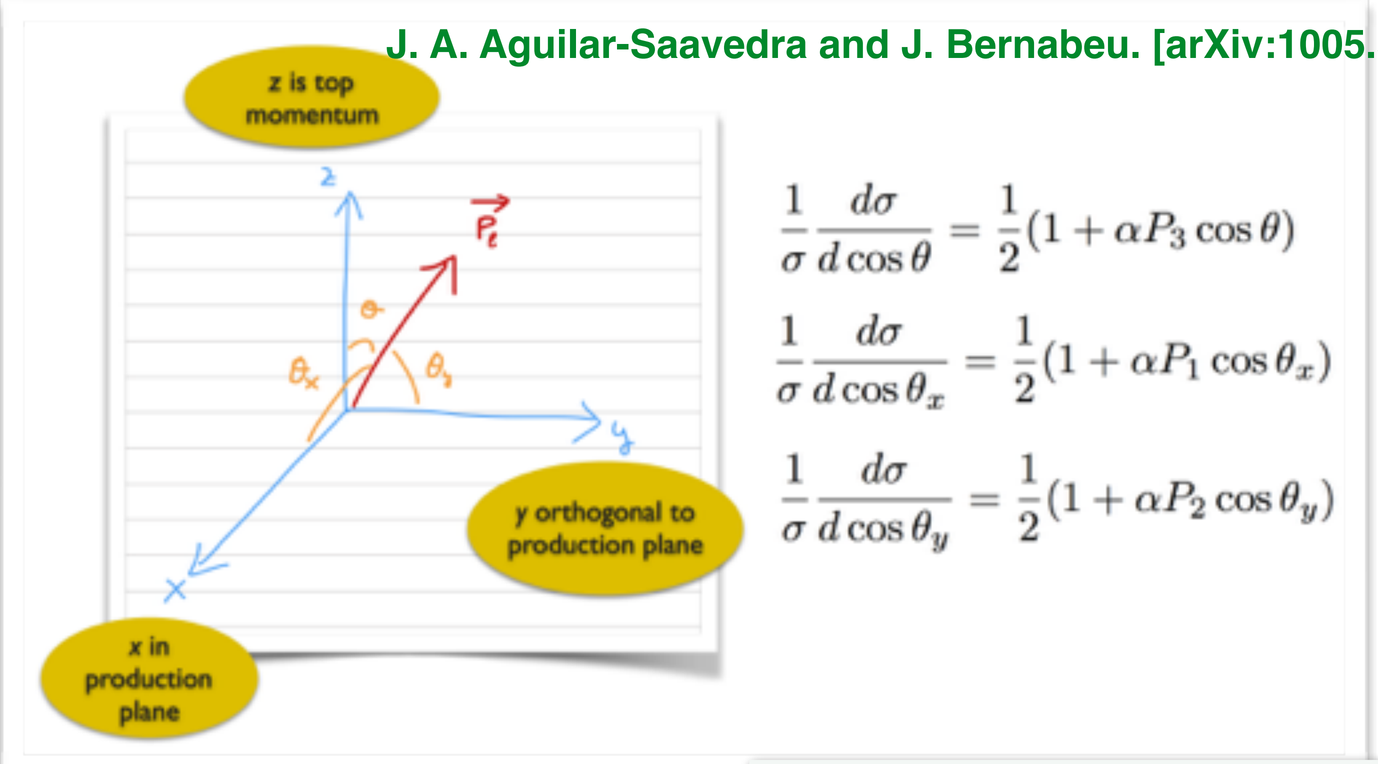


We still need to improve the marginalized fit



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

Top quark polarization at different axes



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

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

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

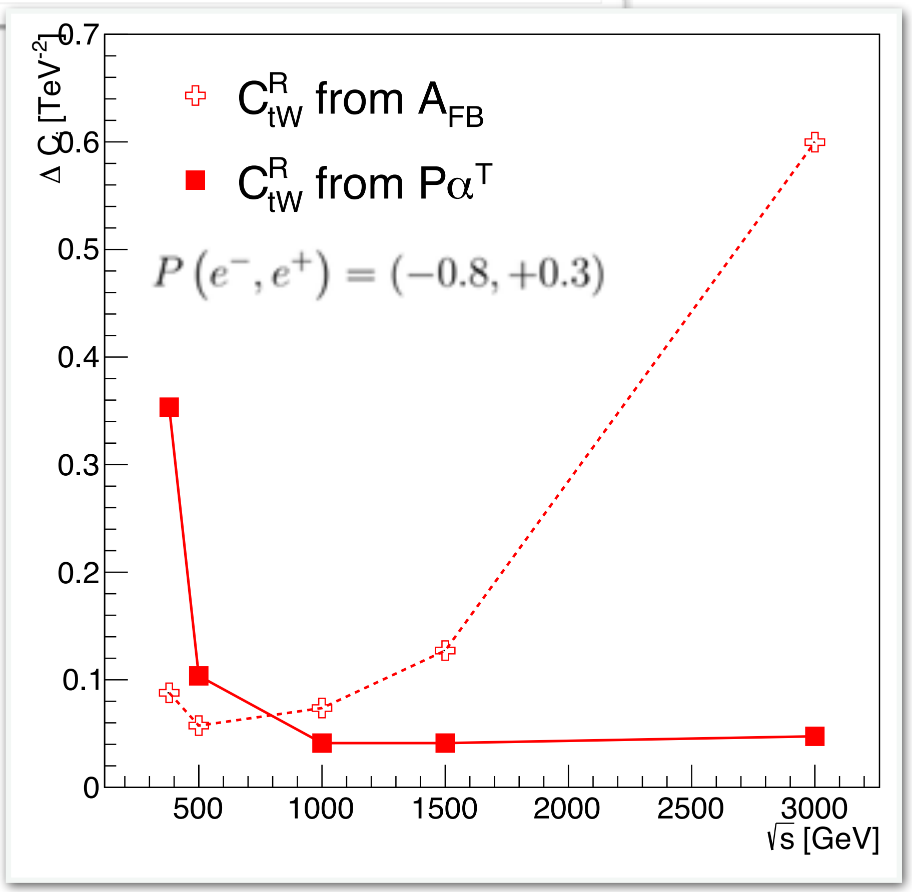
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_y} = \frac{1}{2}(1+\alpha P_2\cos\theta_y)$$

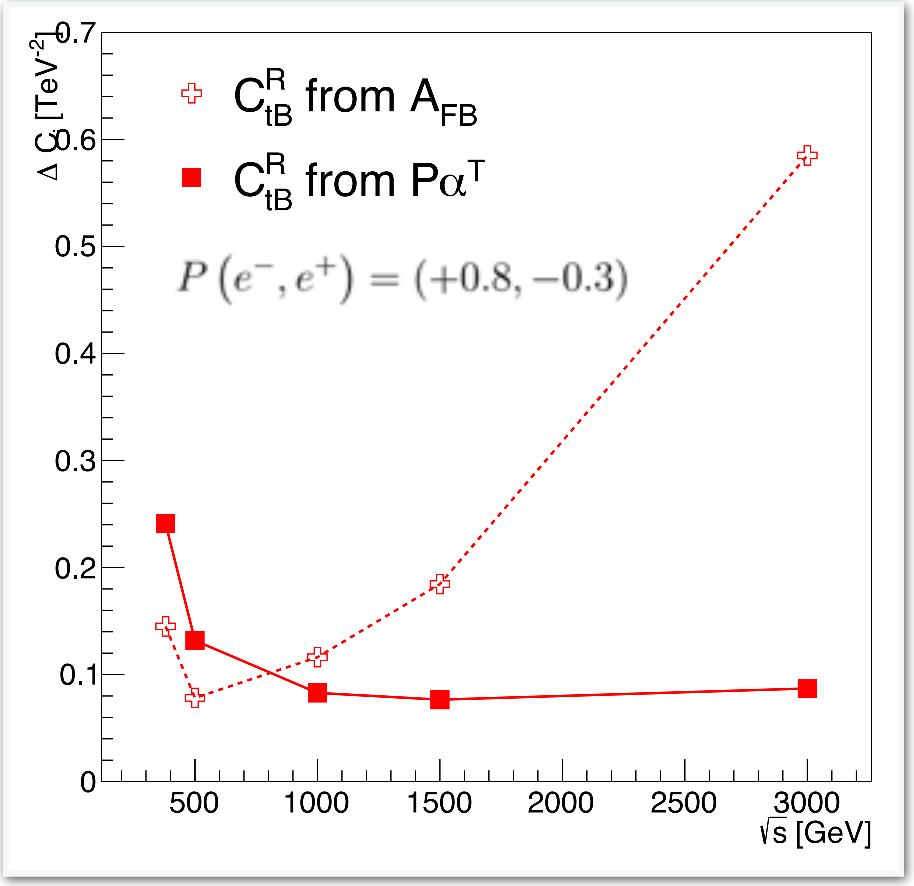
Studied process

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

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

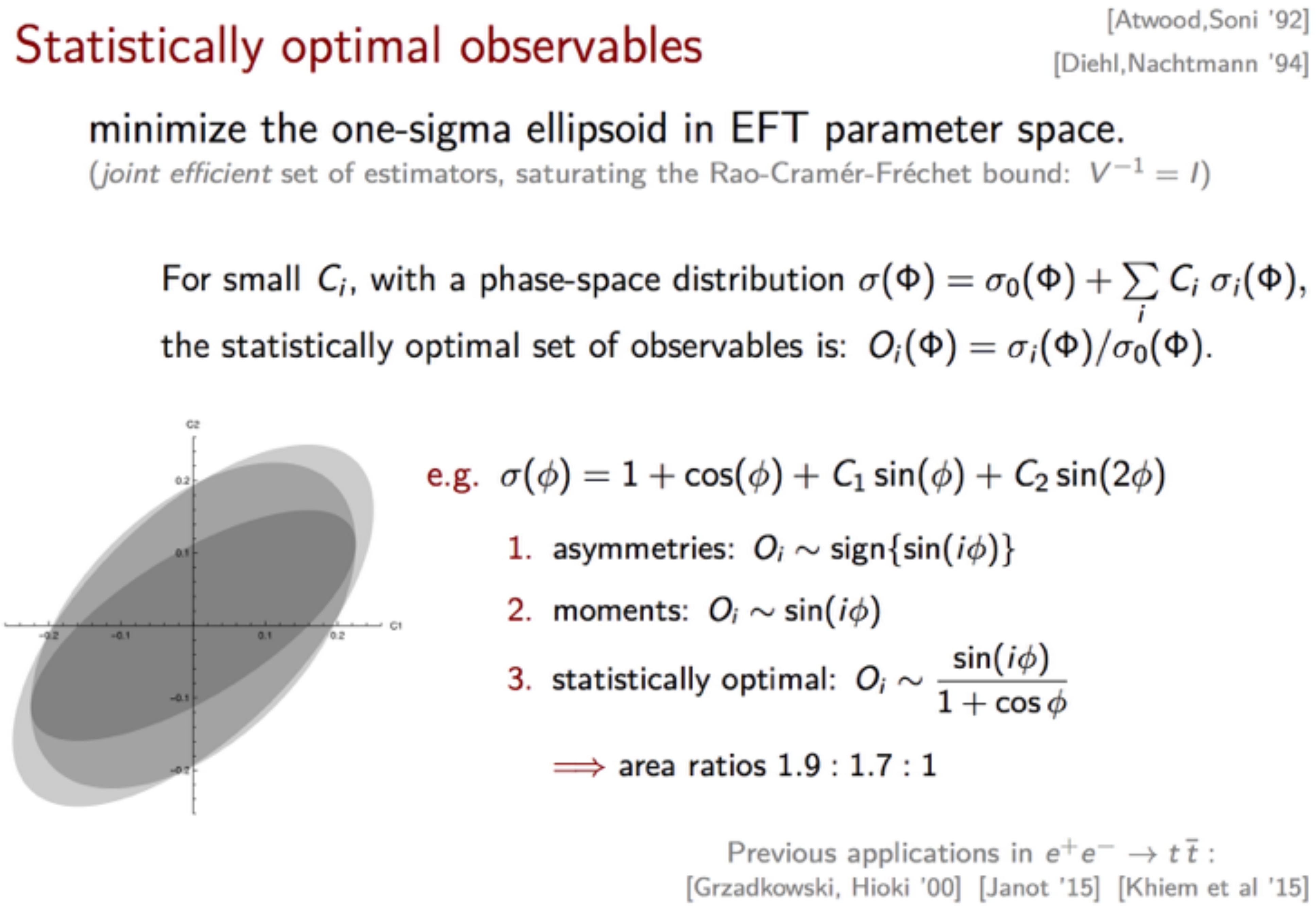




Statistically optimal observables

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

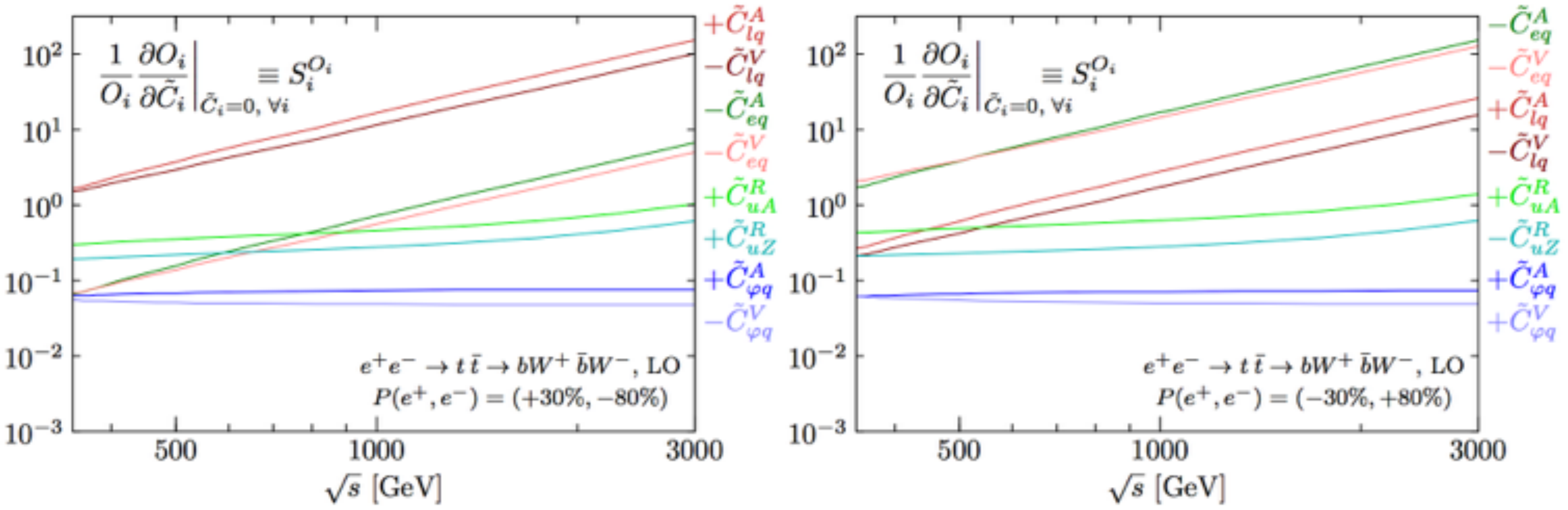
e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

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

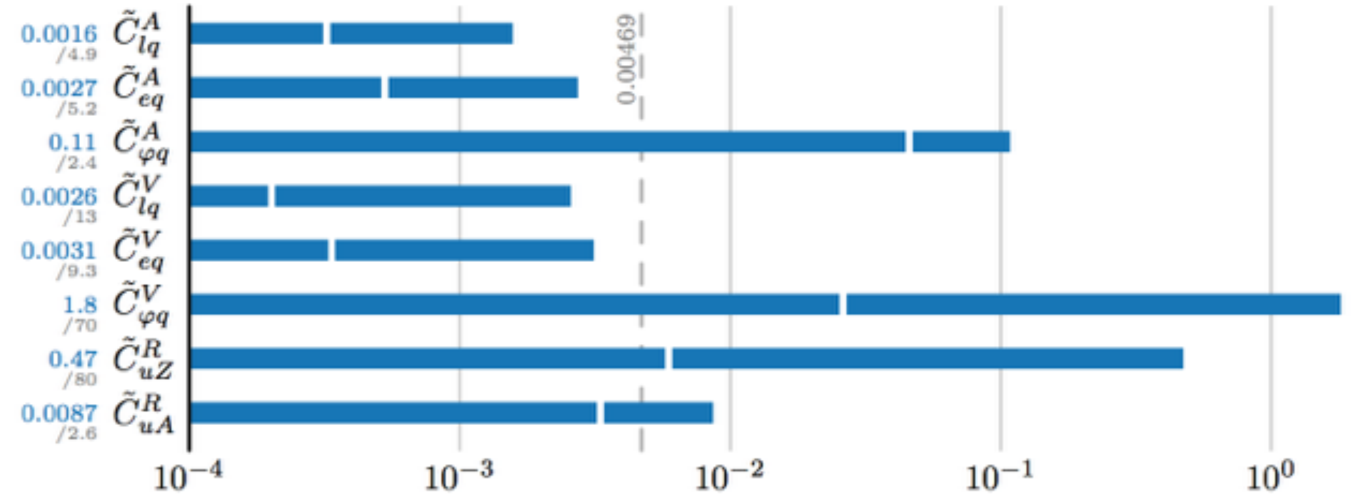
Previous applications in $e^+e^- \to t\,\bar{t}$:
[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

Statistically optimal observables sensitivities

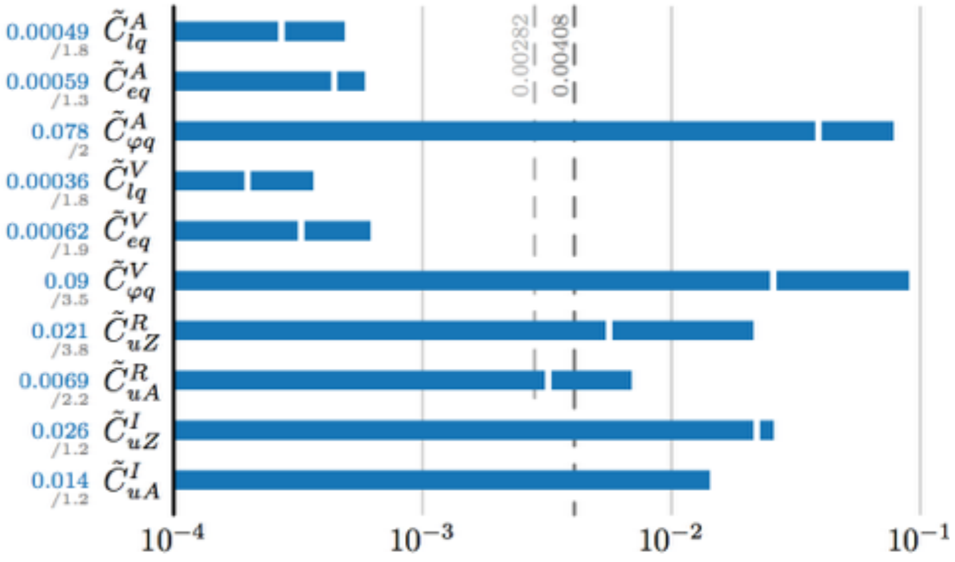


Comparison in the global limits (500GeV + 1TeV for 2 pols.):

$\sigma + A_{FB}$

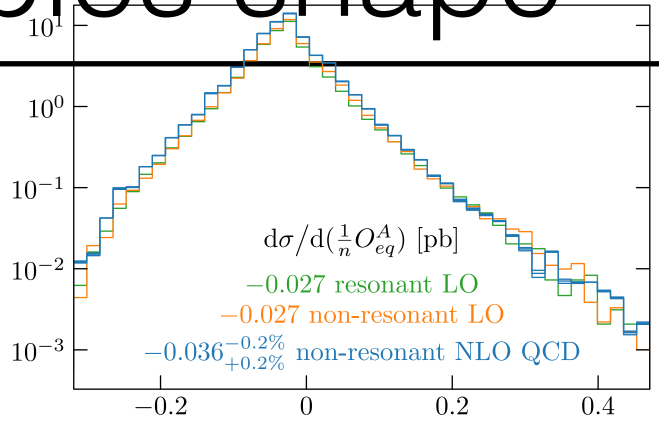


Statistically optimal observables:



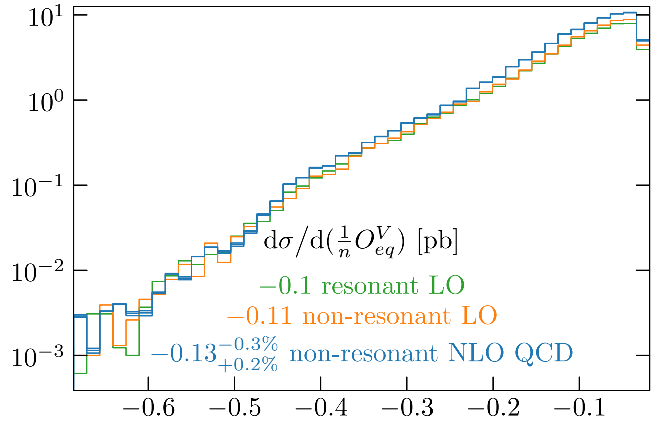
- **Even better individual limits**
- **Global limits within a factor 1.3 to 3.5**

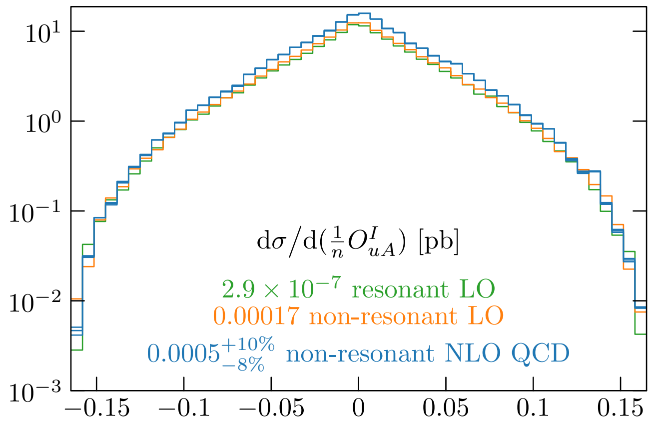
Statistically optimal observables shape

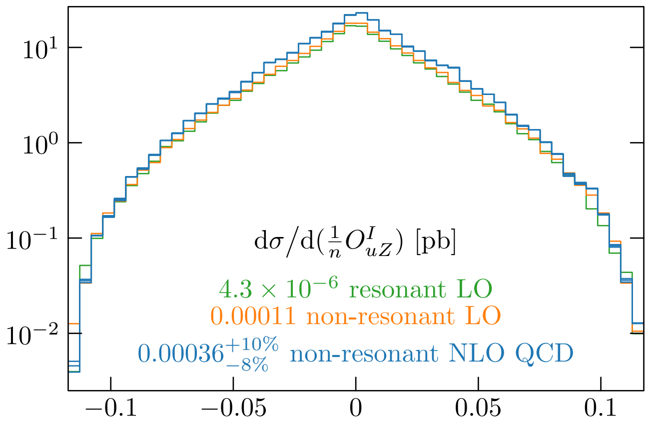


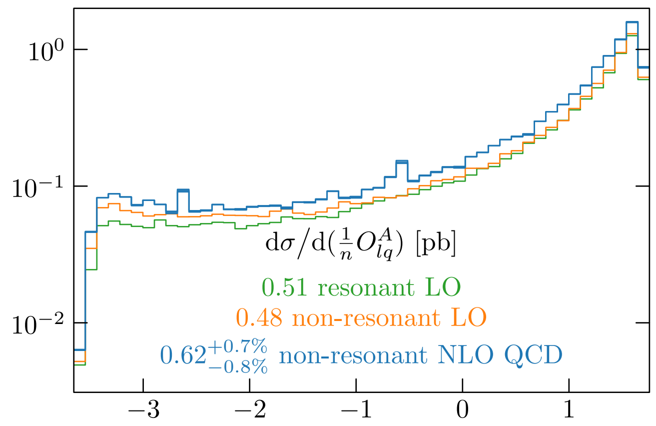
Example for 500 GeV (e-, e+) = (-0.8, 0.3)

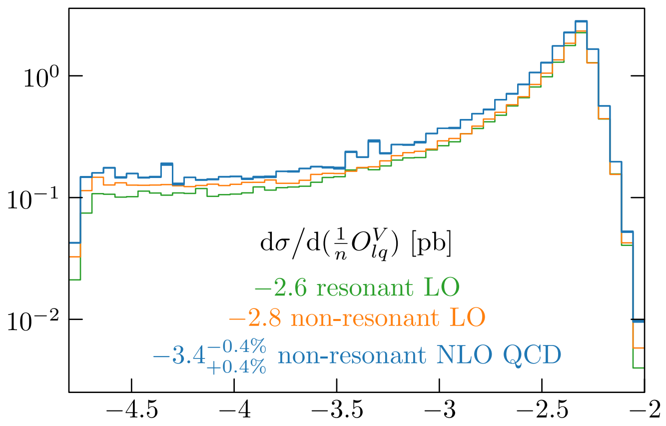
Theory uncertainties under study

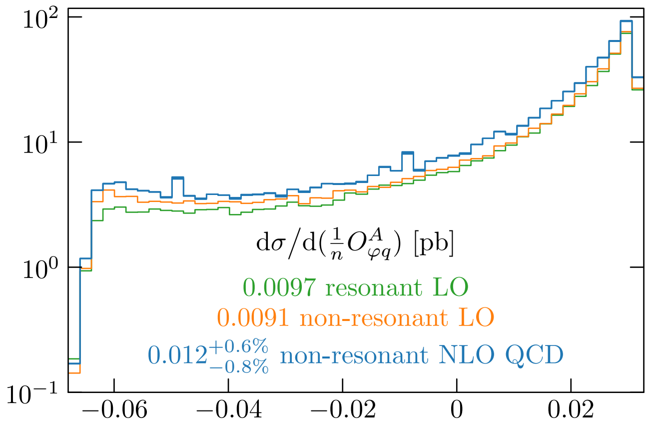


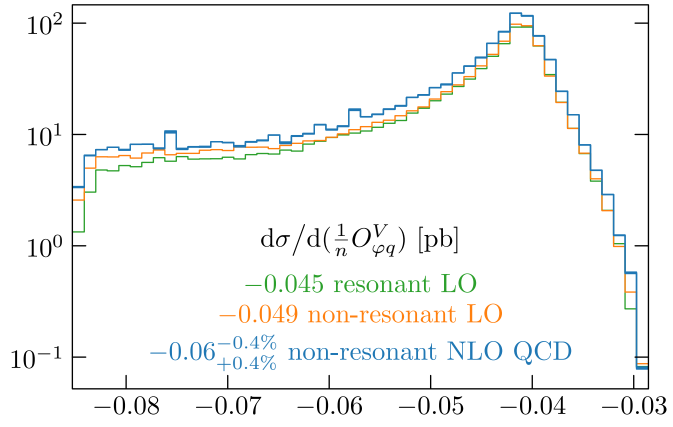


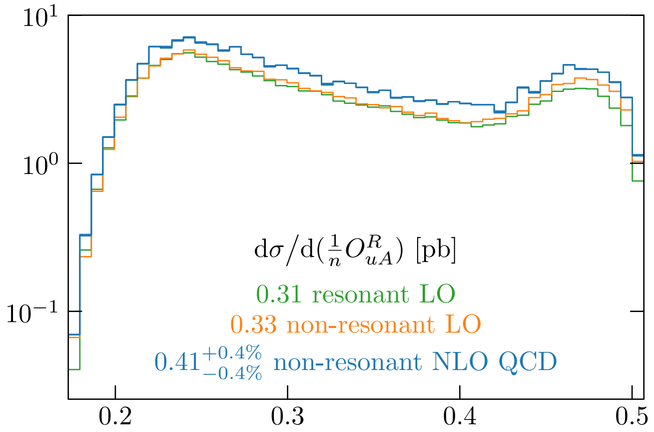


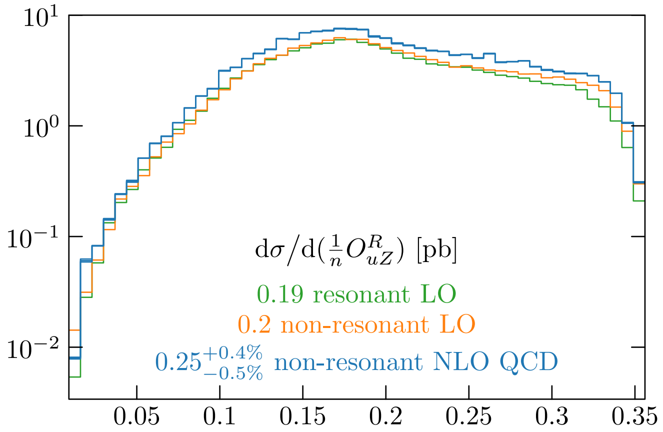












Full-simulation at CLIC380 and ILC500

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

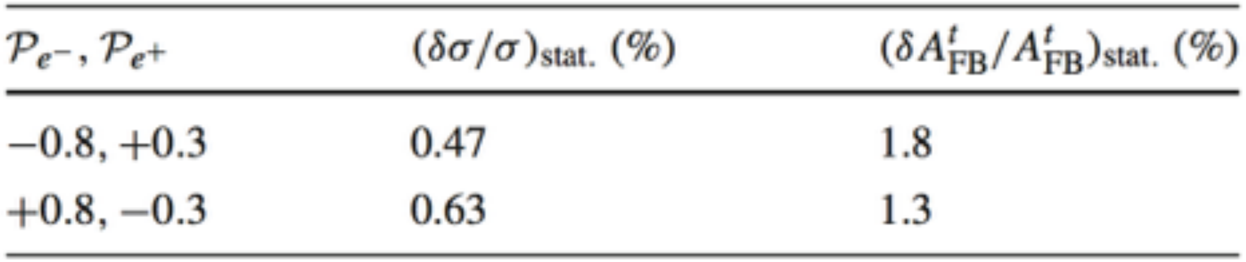
🟩 **CLIC**
🟦 **ILC**

	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

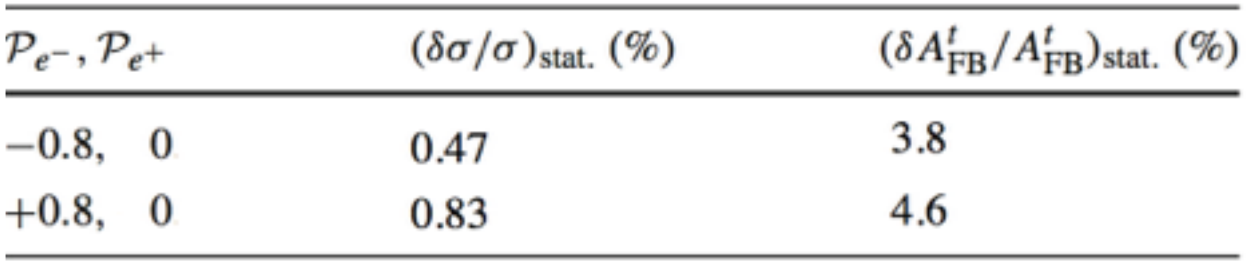
(https://cds.cern.ch/record/2239794?ln=en)

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)

*Absolute uncertainty

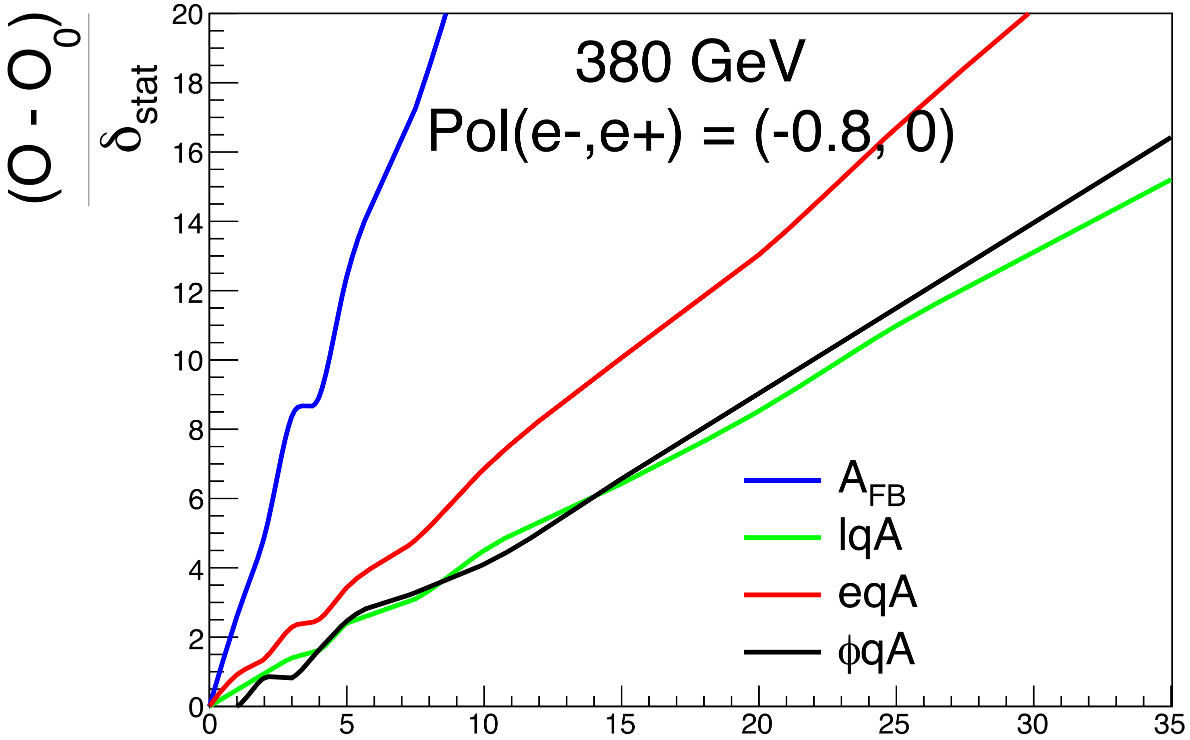
statistical uncertainty [%]	cross-section	lqA	eqA	pqA	lqV	eqV	pqV	ReuZ	ReuA	ImuZ*	ImuA*
380 (e-,e+) = (-0.8, 0)	0,8	3	5	3	0,1	0,5	0,1	0,2	0,1	1E-3	2E-3
380 (e-,e+) = (0.8, 0)	0,8	5	4	4	0,5	0,1	0,3	0,2	0,1	2E-3	2E-3
500 (e-,e+) = (-0.8, 0.3)	0,6	2	8	2	0,2	4	0,2	0,3	0,2	2E-3	4E-3
500 (e-,e+) = (0.8, -0.3)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

Reconstruction effects

Need of a quality cut (mainly for reducing migrations - wrong W-b pairing)

$$\chi^2 = \left(\frac{\gamma_t - \gamma_t^0}{\sigma_{\gamma_t}}\right)^2 + \left(\frac{E_b^* - E_b^{*0}}{\sigma_{E_b^*}}\right)^2 + \left(\frac{\cos\theta_{bW} - \cos\theta_{bW}^0}{\sigma_{\cos\theta_{bW}}}\right)^2$$

	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%**



Deviation from the expected value in terms of induced migrations

% migrations

- Similar behaviour we oberved in the Afb reconstruction.
- From arXiv:1505.06020: "It is expected that these ambiguities can be (partially) eliminated by an event-by-event determination of the charge of the b quark from the t decay."
- Study of this b-charge determination in $e^+e^- > b\bar{b}$: arXiv:1709.04289

Systematic uncertainties

Selection effects

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

Reconstruction effects

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

Residual uncertainty expected to be smaller than the effect

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

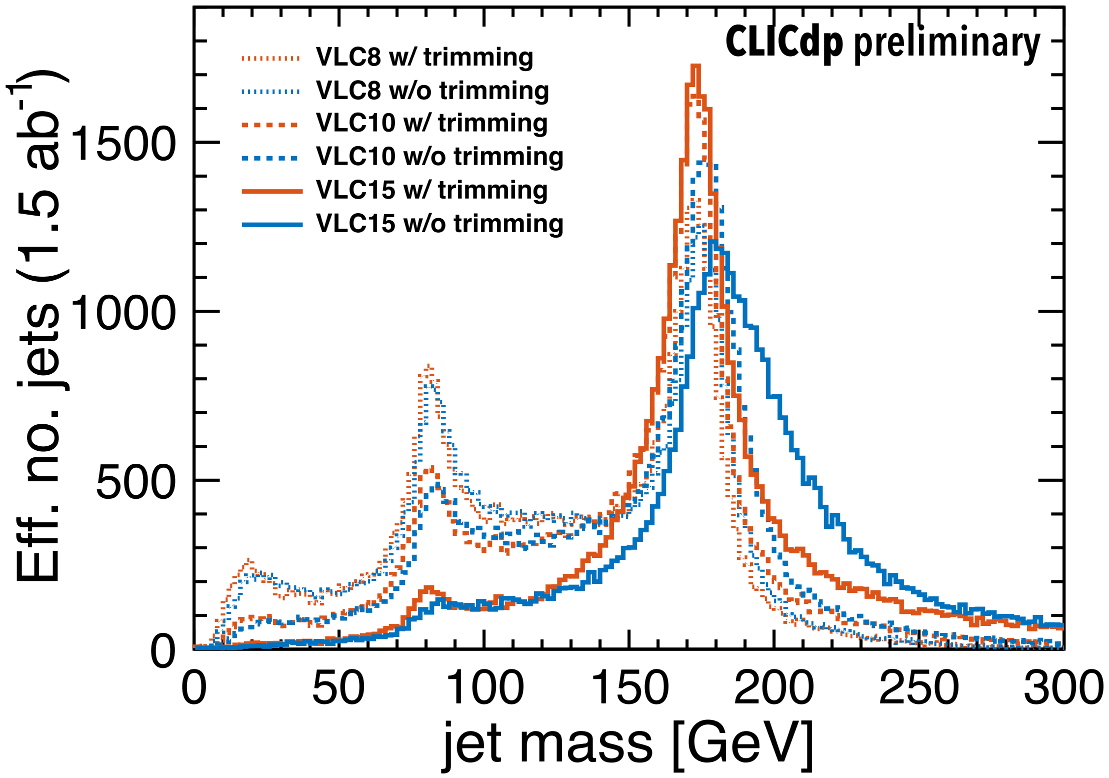
Uncertainty from parameters variation < 1%

Full-simulation at high energies

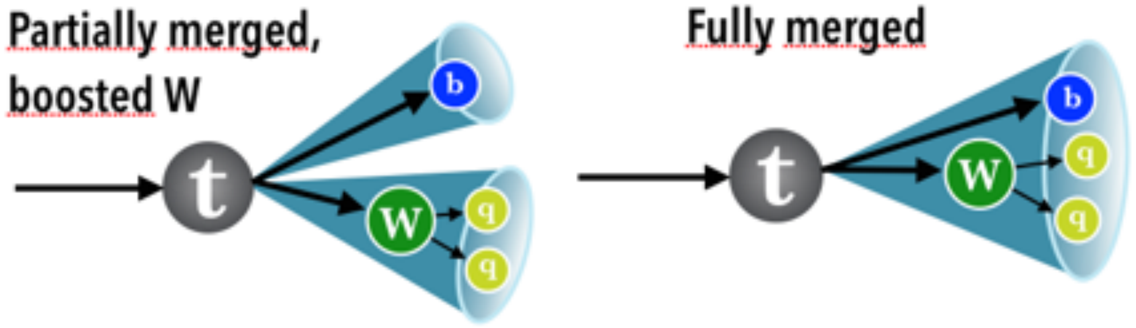
For a detailed explanation visit R. Ström's talk at CLICdp Collaboration Meeting: https://indico.cern.ch/event/633975/contributions/2689114/

Boosted top reconstruction techniques

- Collimated decay products - Identify and correctly assign the top decay products
- **Resolved analysis** - Production near threshold (lower effective centre-of-mass due to ISR, beamstrahlung), use b-tagging, search for W, or 3 jets with a combined invariant mass near m_t
- **Boosted analysis -** Standard identification techniques may not work: b-tagging not foreseen, tracks are very close to each other, W decay products not isolated from each other or b-jet,
  - Idea: tag tops by identifying prongy sub-structure



Optimization in jet clustering parameters by Rickard Ström
Fully-hadronic decay mode reconstruction

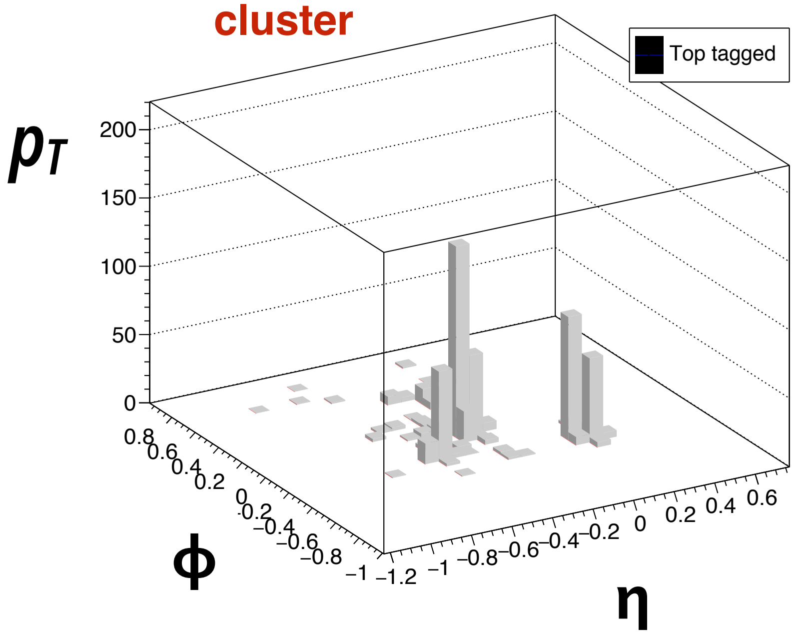


- Jet clustering (incl. trimming)
  - 2 exclusive large-R jets
- Jet tagging:
  - Parsing sub-structure (method 1)
  - Jet structure variables (method 2) - **not explained here, see Alasdair Winter's talk at CLIC WS 2017** (https://indico.cern.ch/event/577810/contributions/2485031/)
- Flavour-tagging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

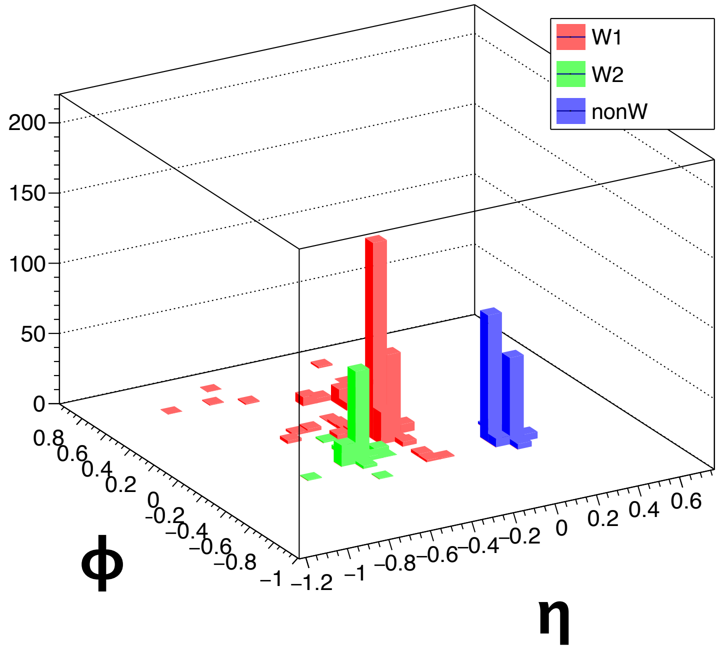
Parsing sub-structure (method 1)

Jet de-clustering (FastJet extension), **DOI: 10.1103/PhysRevLett.101.142001**

Parsing through jet cluster



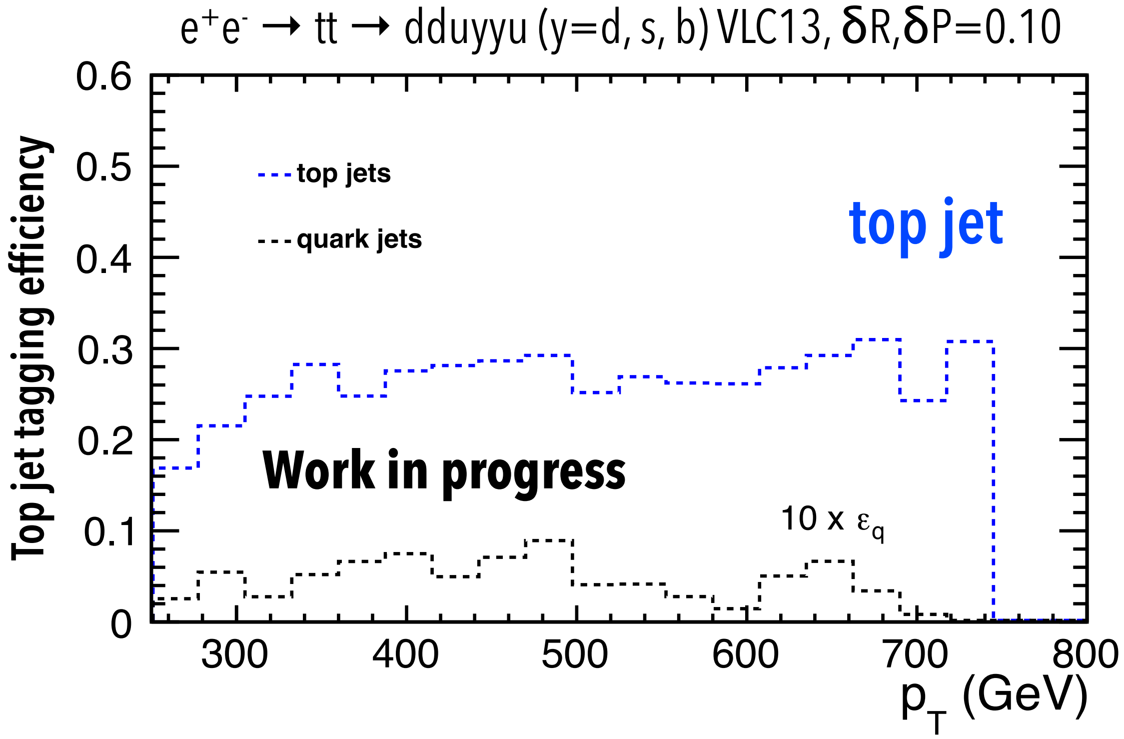
Three subjects identified



- 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)

JH Top Tagger - results

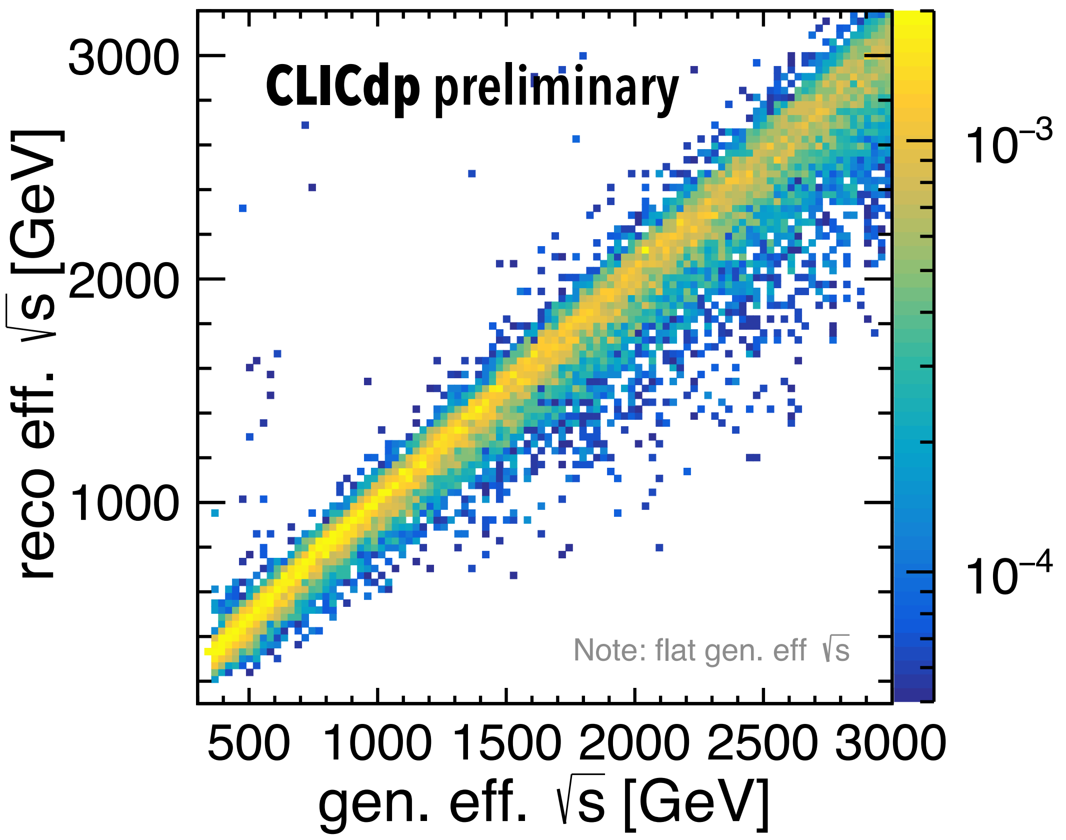
- Top quark mass recovered for sufficiently large-R jet (efficiency drop for R < 1.3)
- Good discrepancy towards background processes without top
- More efficient than simple mass cut (still being optimised)



Full-simulation at CLIC@1.4 and CLIC@3 TeV

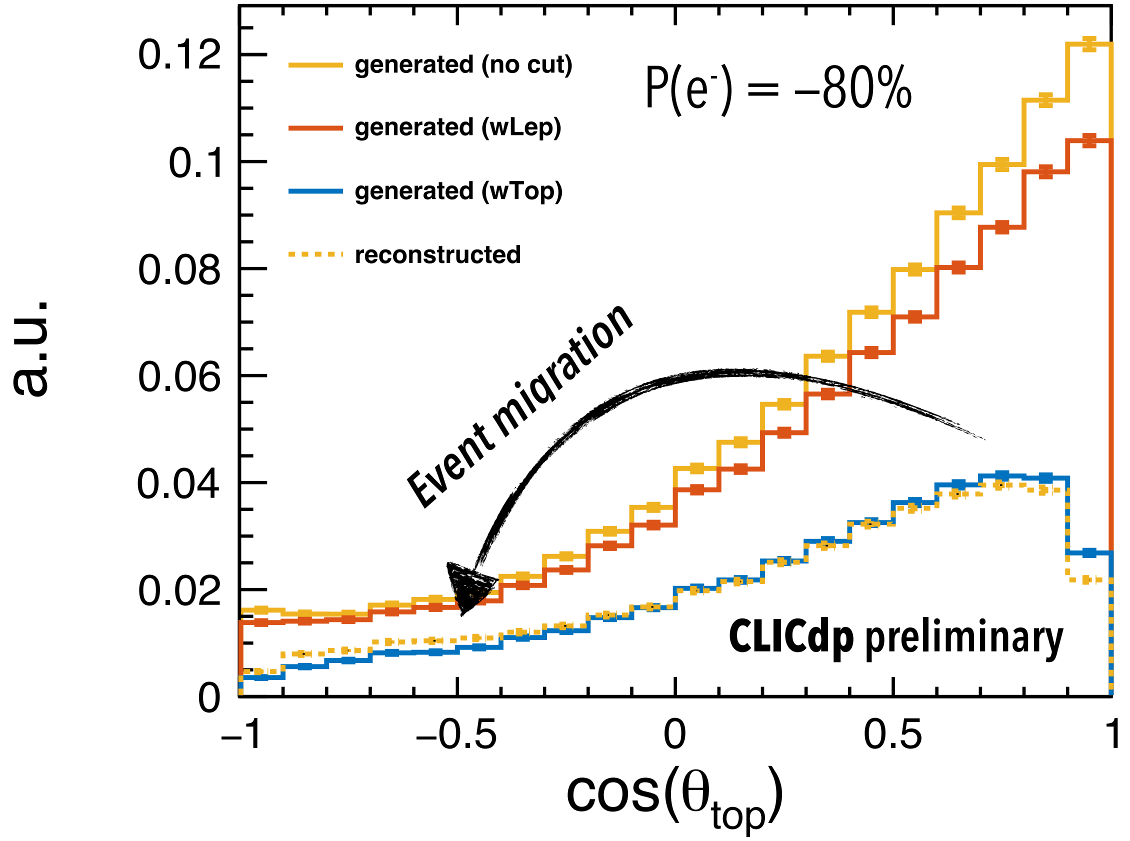
Event selection

- Technical cut (gen. level) in √s' (same cut can be done at reconstruction level)
- 1 isolated lepton, 1 top tagged jet ("JH Top Tagger")
- Flavour tagging (fat-jet / sub-jet) → BDT
- Exploiting kinematics of semi-leptonic side → BDT



Top quark A_{FB} results

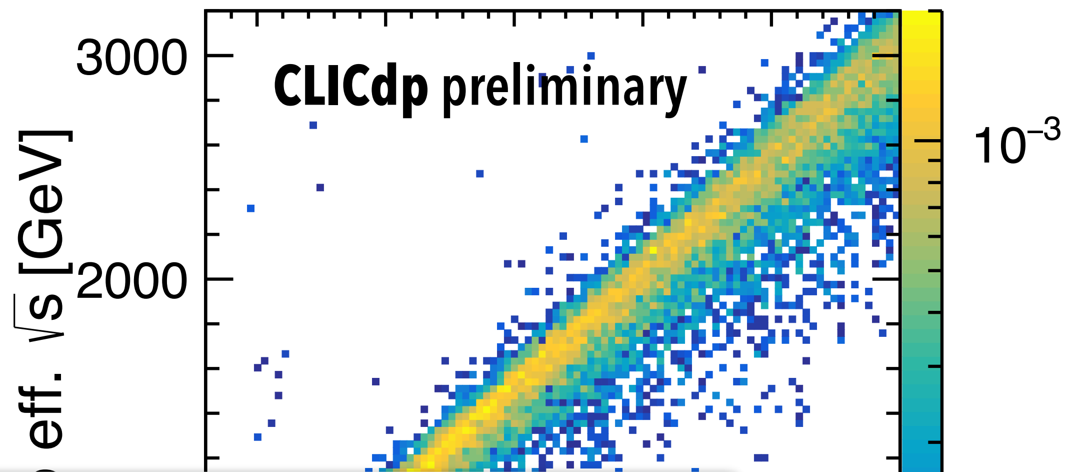
- Less migration is observed for $P(e^-) = +80\%$ Backgrounds substantially reduced
- Relative error on A_{FB}:
  - **$P(e^-) = -80\%$: ~2% (signal only)**
  - **$P(e^-) = +80\%$: ~3% (signal only)**
- Both methods yield a similar result

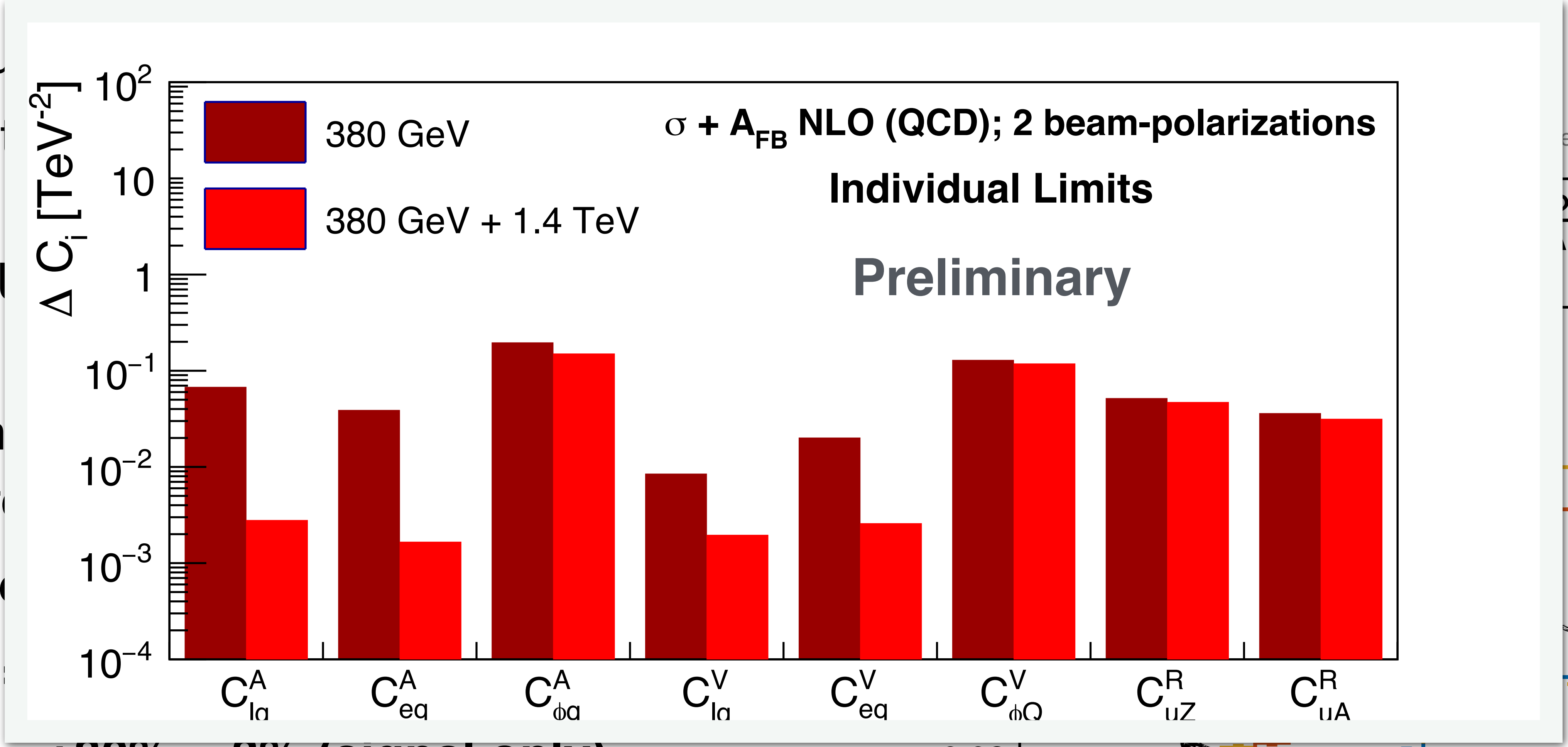


Full-simulation at CLIC@1.4 and CLIC@3 TeV

Event selection

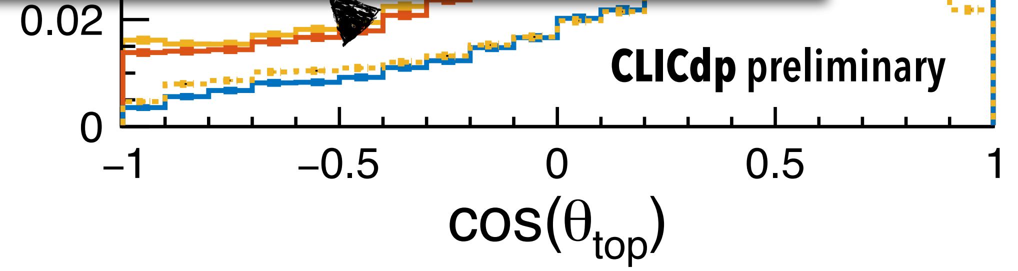
- Technical cut (gen. level) in √s' (same cut can be done at reconstruction level)
- 1 isolated lepton, 1 top tagged jet ("JH Top Tagger")
- Flavou
- Exploi





Top qu

- Less m
  Backgr
- Relativ
  - P(e$^-$)
  - P(e$^-$) = +80%: ~3% (signal only)
- Both methods yield a similar result



Conclusions

- Cross-section + A_{FB} are not enough for global EFT fit. Top polarization 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 A_{FB} @CLIC1400.

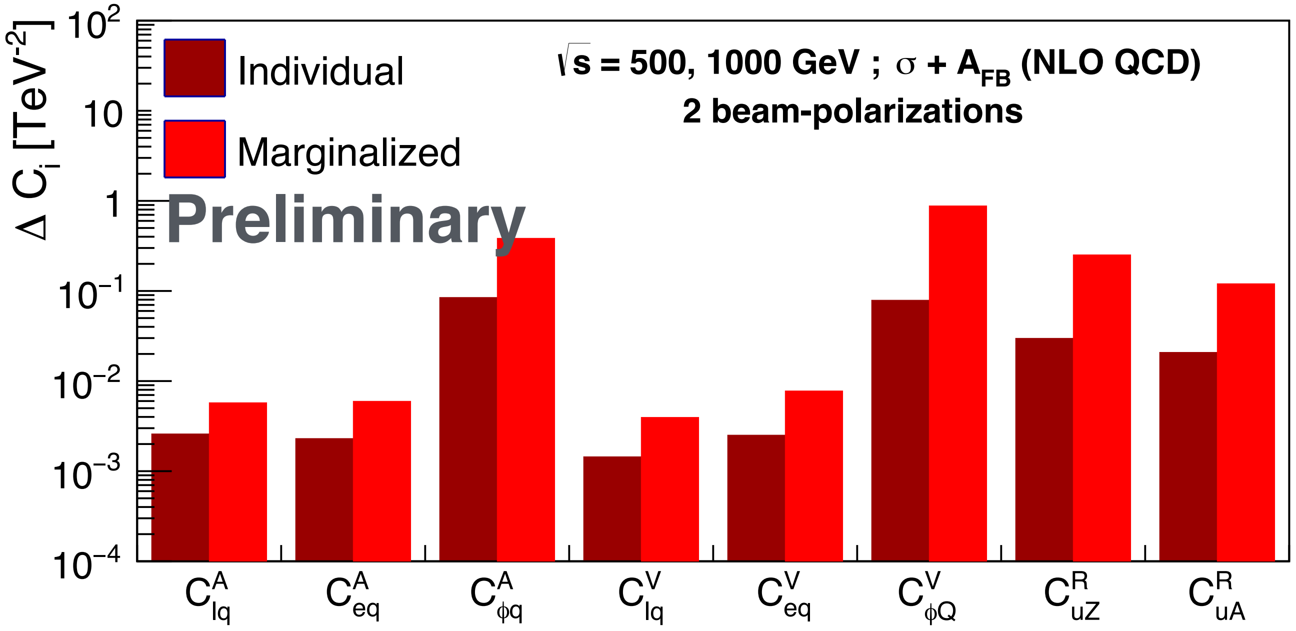
Back up

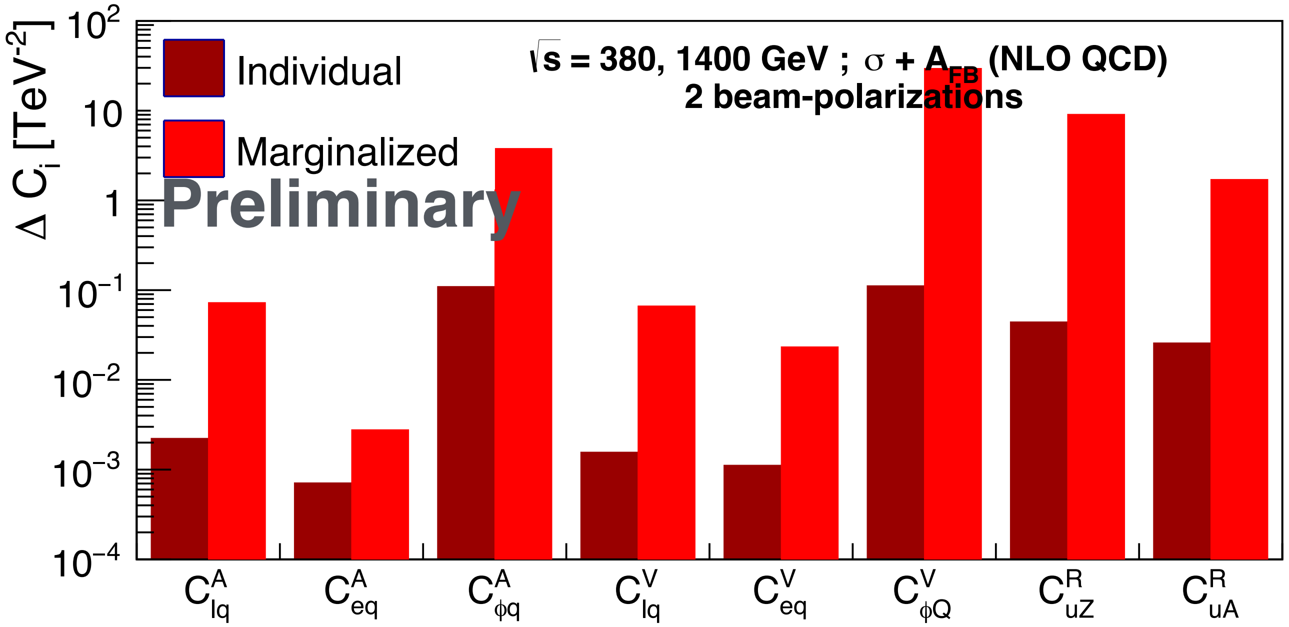
Global Fit: Afb + σ

Studied process $e^-e^+ \to W^+bW^-\bar{b}$ @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 $e^-e^+ \to t\bar{t}$ @LO and $e^-e^+ \to W^+bW^-\bar{b}$ @NLO (QCD)

Low uncertainties are achieved, but we can do it better

We should improve the marginalized fit

Some technical numbers at reconstruction

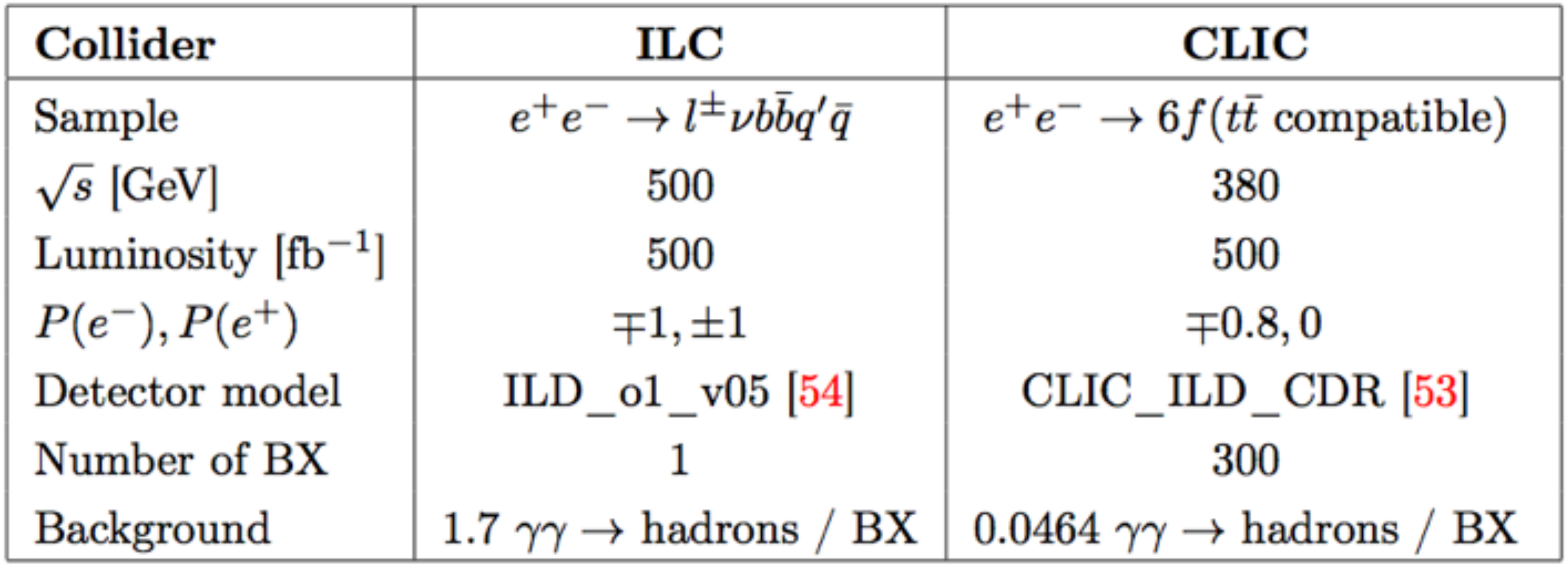
https://cds.cern.ch/record/2239794?ln=en

CLIC380 (Repository https://twiki.cern.ch/twiki/bin/view/CLIC/MonteCarloSamplesForTopPhysics)

- Jet clustering: VLC algorithm (R=1.6, β = 0.8, γ = 0.8).

ILC500

- Jet clustering: VLC algorithm (R=1.2, β = 0.8, γ = 0.8).



Collider	**ILC**	**CLIC**
Sample	$e^+e^- \to l^\pm \nu b\bar{b}q'\bar{q}$	$e^+e^- \to 6f$ ($t\bar{t}$ compatible)
$\sqrt{s}$ [GeV]	500	380
Luminosity [fb^{-1}]	500	500
$P(e^-), P(e^+)$	$\mp 1, \pm 1$	$\mp 0.8, 0$
Detector model	ILD_o1_v05 [54]	CLIC_ILD_CDR [53]
Number of BX	1	300
Background	1.7 $\gamma\gamma \to$ hadrons / BX	0.0464 $\gamma\gamma \to$ hadrons / BX

[53] L. Linssen, A. Miyamoto, M. Stanitzki and H. Weerts, Physics and Detectors at CLIC: CLIC Conceptual Design Report, 1202.5940.
[54] H. Abramowicz et al., The International Linear Collider Technical Design Report - Volume 4: Detectors, 1306.6329.

CPV: 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**.

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

$$\begin{aligned} t\ \bar{t} \quad &\to \quad \ell^+(\mathbf{q}_+) + \nu_\ell + b + \overline{X}_{\text{had}}(\mathbf{q}_{\bar{X}}) \\ t\ \bar{t} \quad &\to \quad X_{\text{had}}(\mathbf{q}_X) + \ell^-(\mathbf{q}_-) + \bar{\nu}_\ell + \bar{b} \end{aligned}$$

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

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

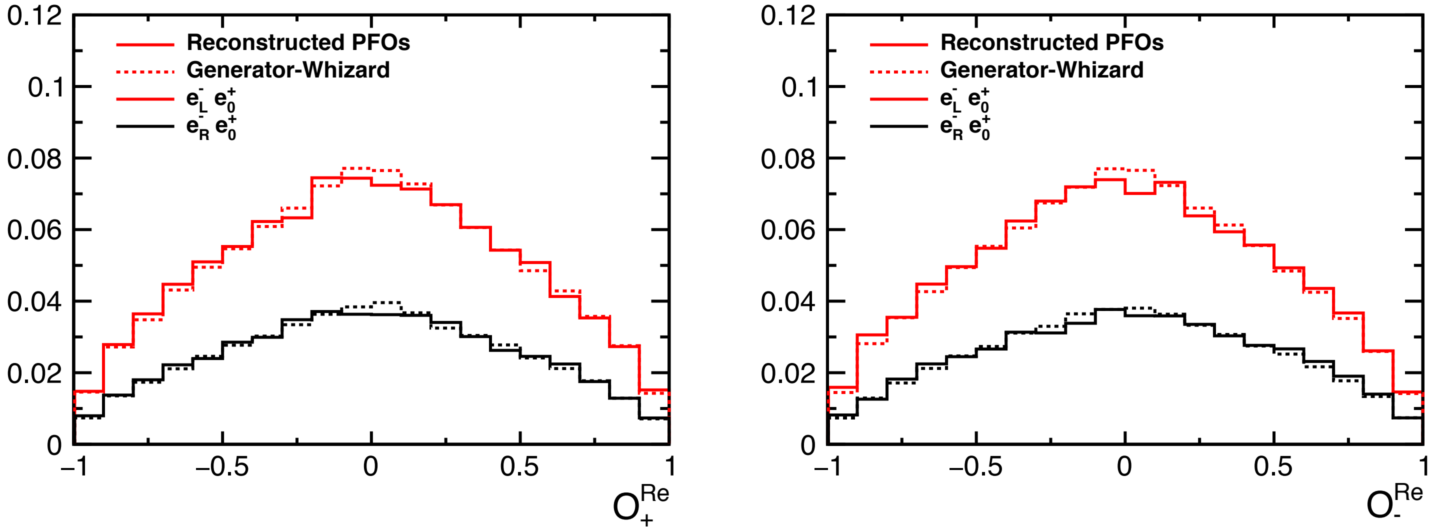
- The way to **extract** the **CP-violating form factor** is to construct **asymmetries sensitive to CP-violation effects**

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

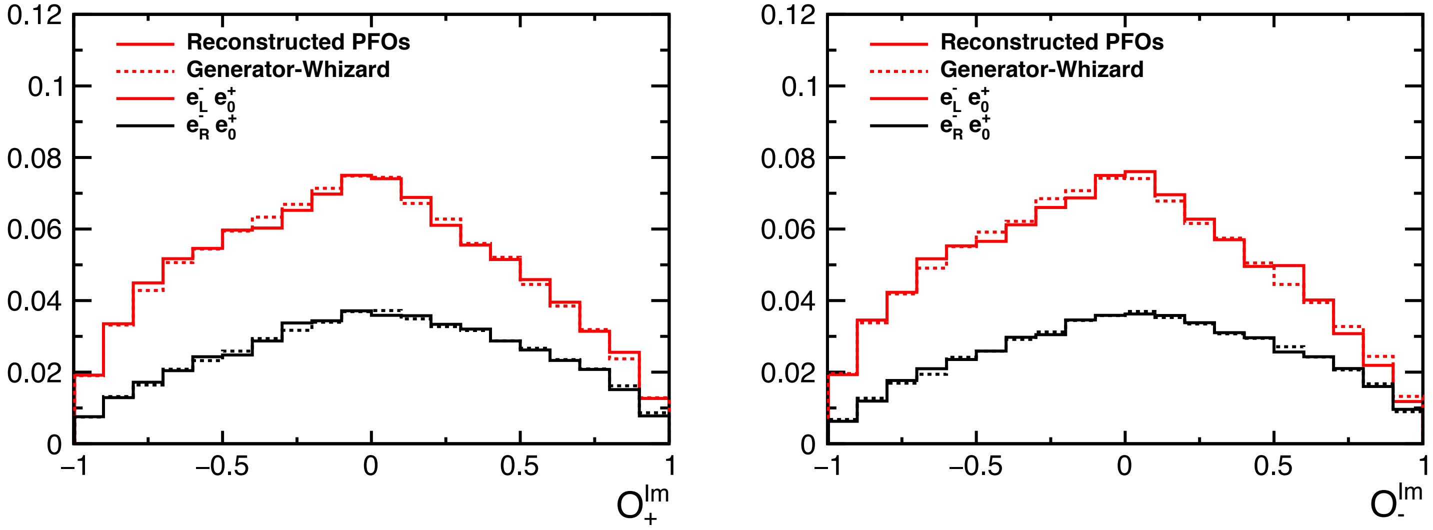
$$\mathcal{A}^{Im} = \langle \mathcal{O}_+^{Im} \rangle - \langle \mathcal{O}_-^{Im} \rangle = \boxed{\tilde{c}_\gamma(s)}\text{Im}F_{2A}^\gamma + \boxed{\tilde{c}_Z(s)}\text{Im}F_{2A}^Z$$

$$\boxed{\begin{array}{cc} \mathcal{A}_{\gamma,Z}^{Re\ \text{L}} & \mathcal{A}_{\gamma,Z}^{Re\ \text{L}} \\ \\ \mathcal{A}_{\gamma,Z}^{Im\ \text{R}} & \mathcal{A}_{\gamma,Z}^{Im\ \text{R}} \end{array}}$$

CPV: Full-simulation: CLIC@380GeV



(a) $\mathcal{O}^{Re}_+$ (b) $\mathcal{O}^{Re}_-$



(c) $\mathcal{O}^{Im}_+$ (d) $\mathcal{O}^{Im}_-$

polarization	e^-_L $(P_{e^-} = -0.8)$	e^-_R $(P_{e^-} = +0.8)$
$\mathcal{A}^{Re}$	-0.00006 ± 0.003	0.0072 ± 0.003
$\mathcal{A}^{Im}$	0.0004 ± 0.003	-0.0019 ± 0.003

- Distributions are **centered at zero**
- **Differences** between reconstructed and generated events are **very small**.
- Any **distortions** in the reconstructed distributions are **expected to cancel in the asymmetries** A_{Re} and A_{Im}
- **Asymmetries** are **compatible with zero** within the statistical error

CPV: Coefficients vs sqrt(s)

The sensitivity of A_{Re}/A_{Im} to F_{2A} increases strongly with the c.o.m. energy

$$P_{e^-} = -1\ ,\ P_{e^+} = +1$$

c.m. energy $\sqrt{s}$ [GeV]	$c_\gamma(s)$	$c_Z(s)$	$\tilde{c}_\gamma(s)$	$\tilde{c}_Z(s)$
380	0.245	0.173	0.232	0.164
500	0.607	0.418	0.512	0.352
1000	1.714	1.151	1.464	0.983
1400	2.514	1.681	2.528	1.691
3000	5.589	3.725	10.190	6.791

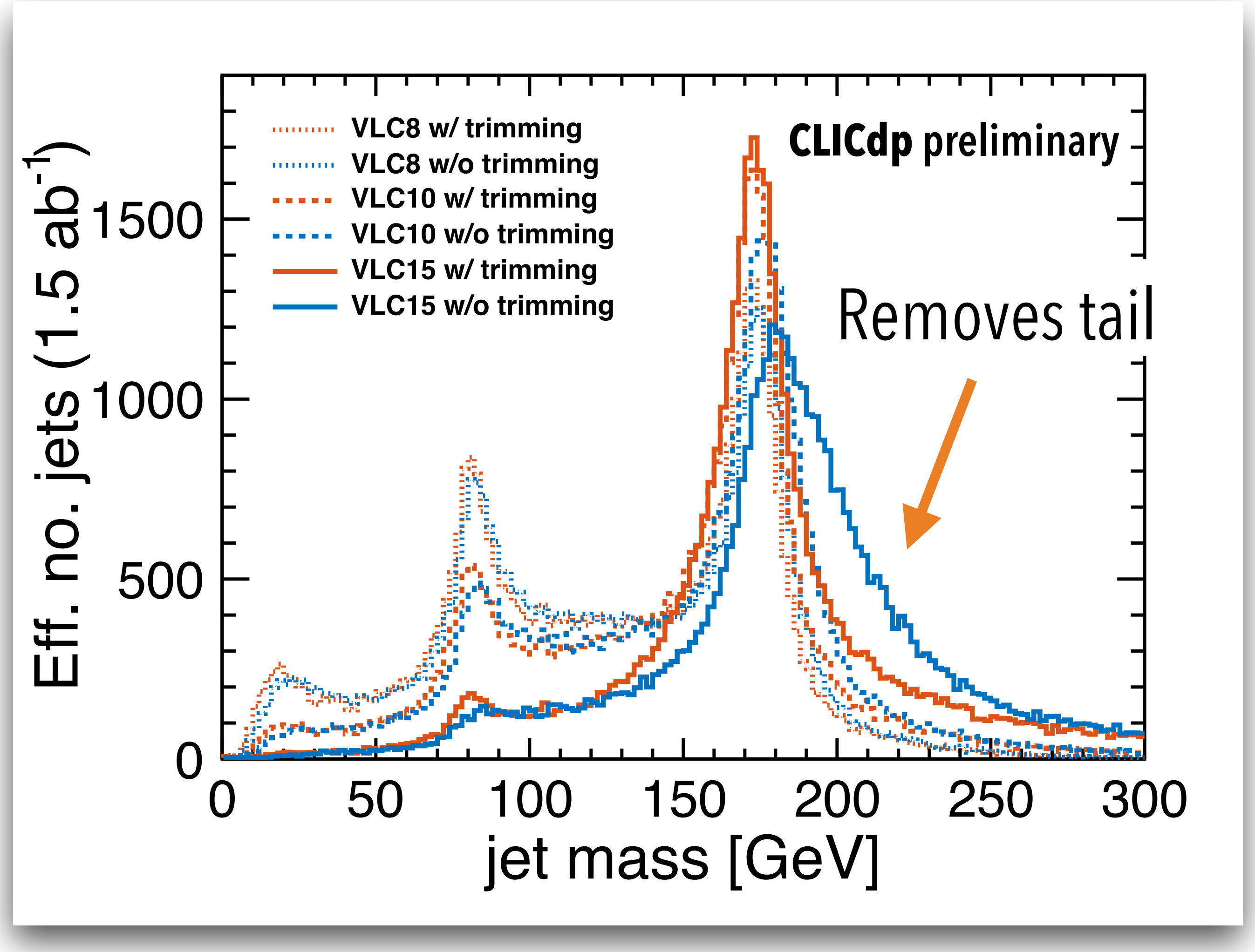
$$P_{e^-} = +1,\ P_{e^+} = -1$$

c.m. energy $\sqrt{s}$ [GeV]	$c_\gamma(s)$	$c_Z(s)$	$\tilde{c}_\gamma(s)$	$\tilde{c}_Z(s)$
380	-0.381	0.217	0.362	-0.206
500	-0.903	0.500	0.761	-0.422
1000	-2.437	1.316	2.081	-1.124
1400	-3.549	1.909	3.569	-1.920
3000	-7.845	4.205	14.302	-7.667

Thanks to Bernreuther

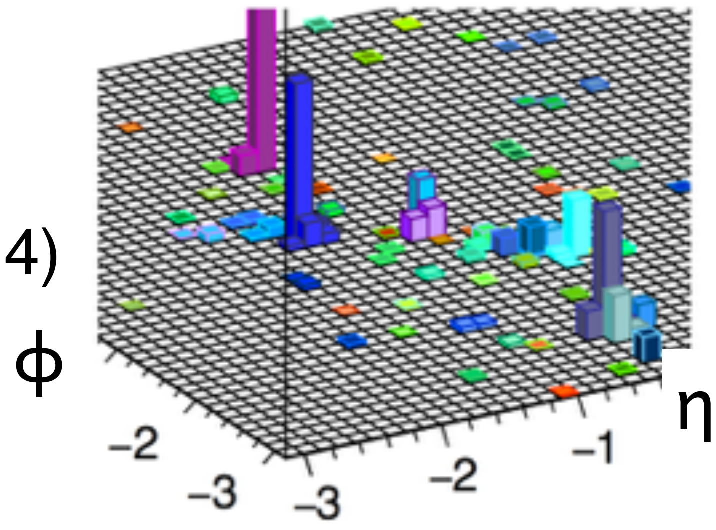
High energies: Jet trimming

- **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)

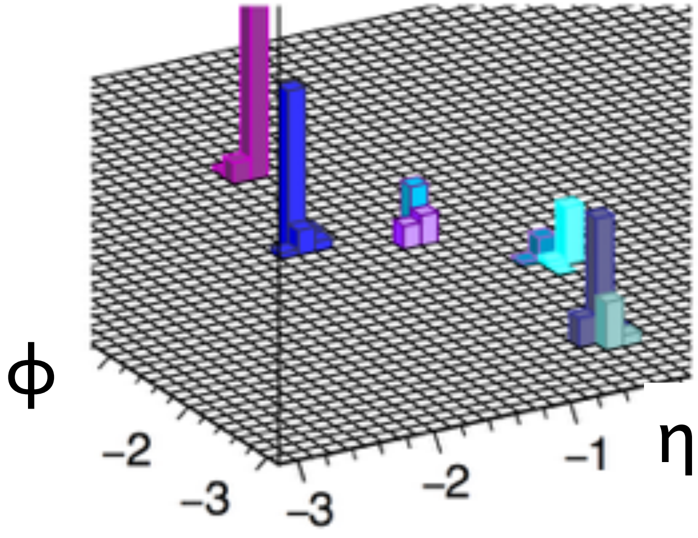


Removes tail

BEFORE TRIMMING



AFTER TRIMMING



High energies: Jet structure variables (method 2)

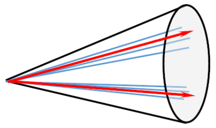
- Multiplicity - re-cluster fat jets into N “microjets” with kt algorithm R=0.05
- “N-subjettiness” - jet shape variable to measure consistency of jet to have N subjets [J.Thaler, K.Tilburg, arXiv:1011.2268]
- Angular distribution of subjets - re-cluster fat jet into 3 subjets and measure angular separation (identifies forced splitting)

$$\tau_N = \frac{1}{d_0}\sum_k p_{\mathrm{T}k} \times \Delta R_k^{\mathrm{min}} \quad \text{with} \quad d_0 \equiv \sum_k p_{\mathrm{T}k} \times R$$

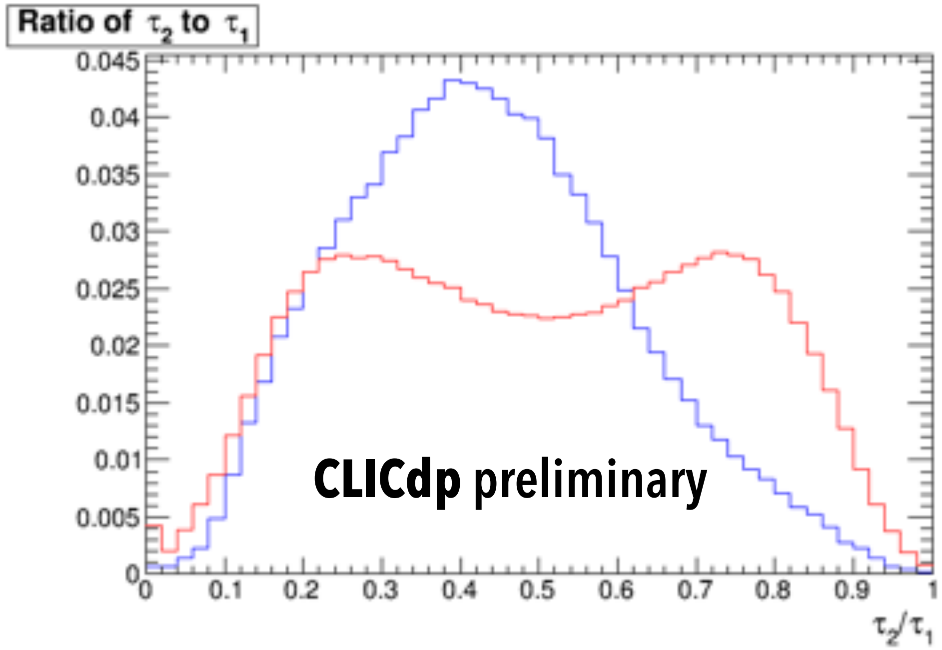
p_{T} of constituent k

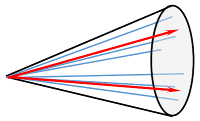
distance between constituent k & axis of closest subjet

large-R jet distance parameter

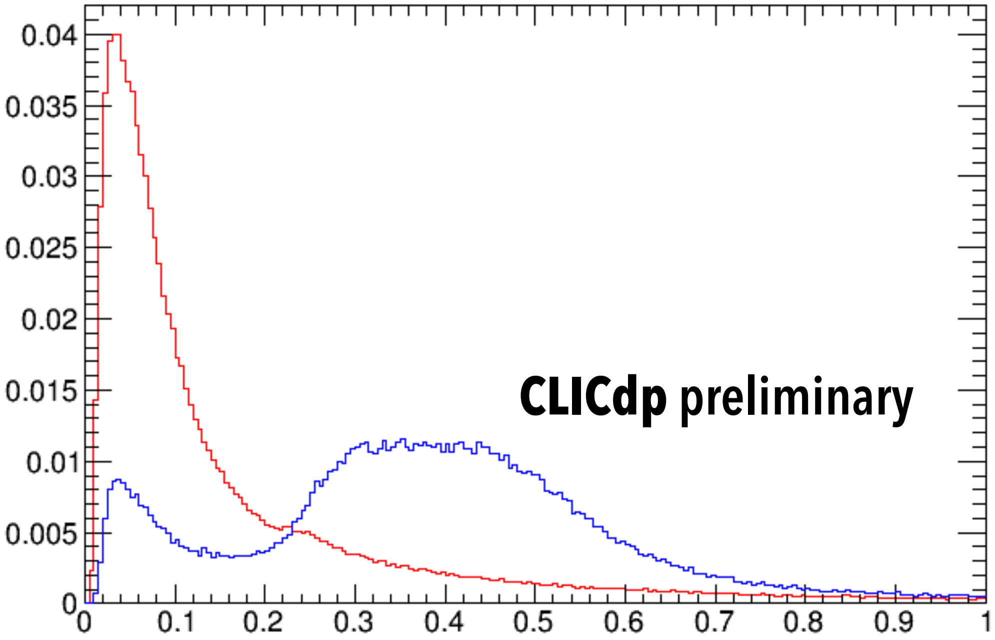


Low τ_2 (constituents close to subjet axes)





High τ_2 (consitutents spread out)



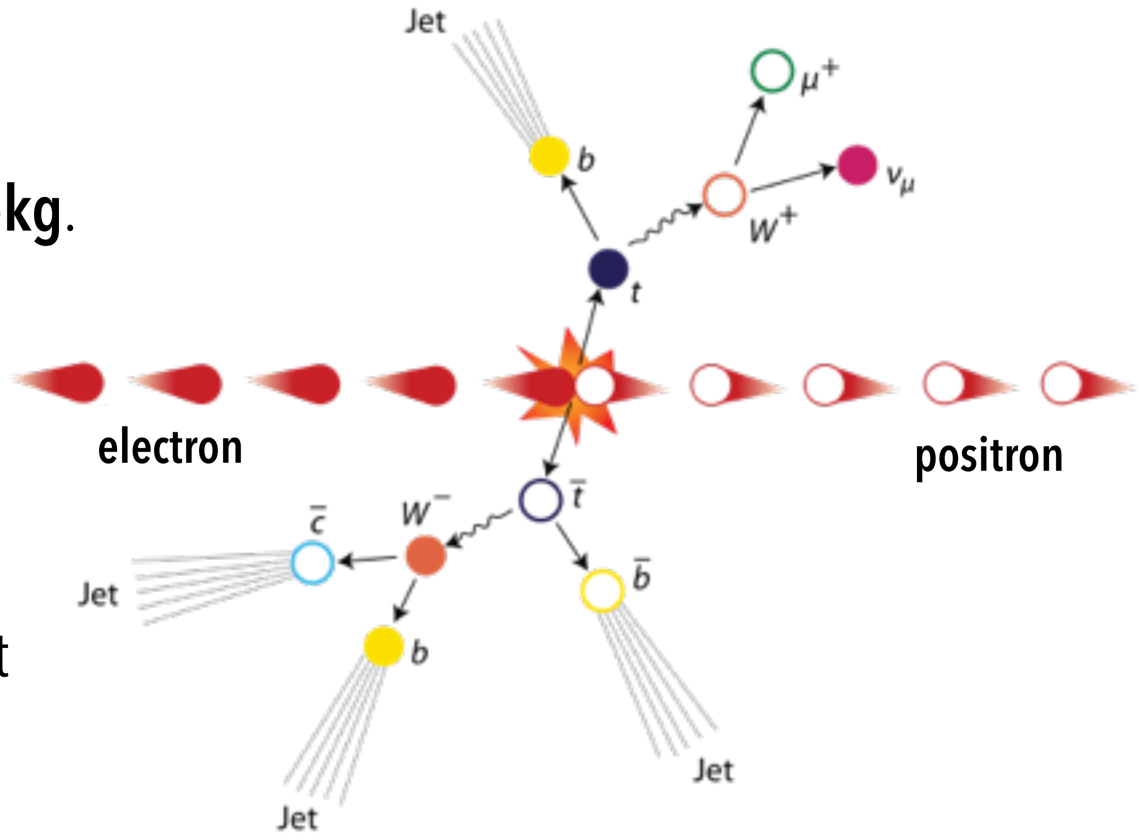
High energies: General analysis strategy tt → qqqqlv

- Analysis concept studied at a benchmark collision energy of 1.4 TeV using CLIC-ILD
- Signal definition: semi-leptonic ttbar (tt → qqqqlv)
- Use lepton charge to reconstruct the charge of the top/anti-top

Event generation, detector simulation and reconstruction

- The results based on detailed MC studies incl. relevant **SM bkg.** processes
- Event generation using **WHIZARD** 1.95
- Fragmentation and hadronisation using **PYTHIA** 6.4
- **GEANT4** based simulations of the CLIC_ILD detector concept
- **Pile-up** from gamma+gamma → hadrons included
- Full reconstruction of the simulated events.
- **Particle flow** reconstruction using PandoraPFA
- ⇒ Particle Flow Objects (PFO)

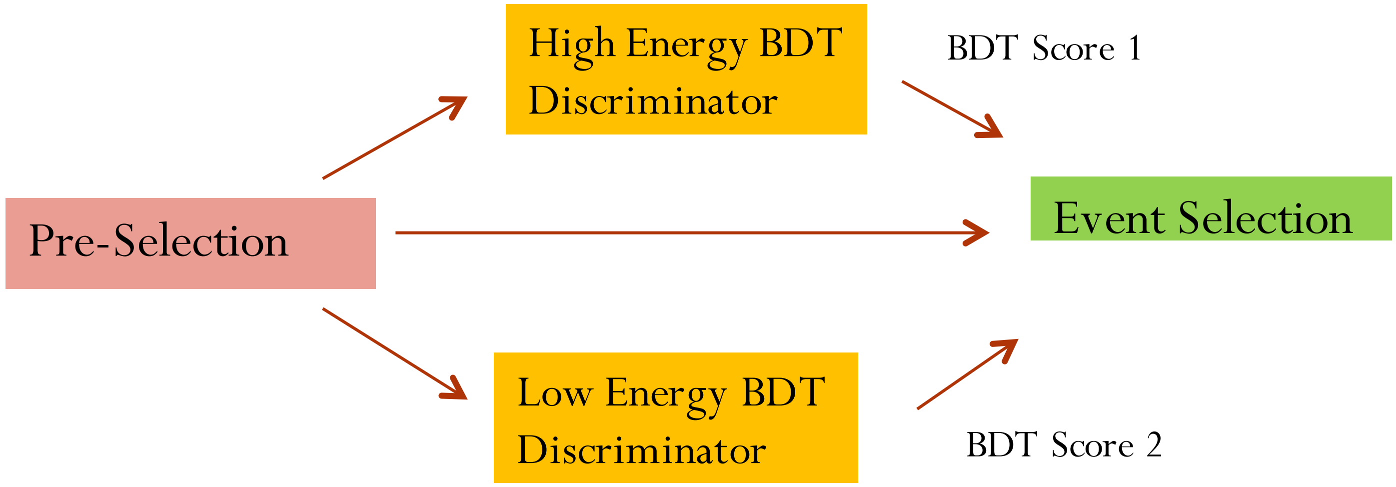
"leptonic side"



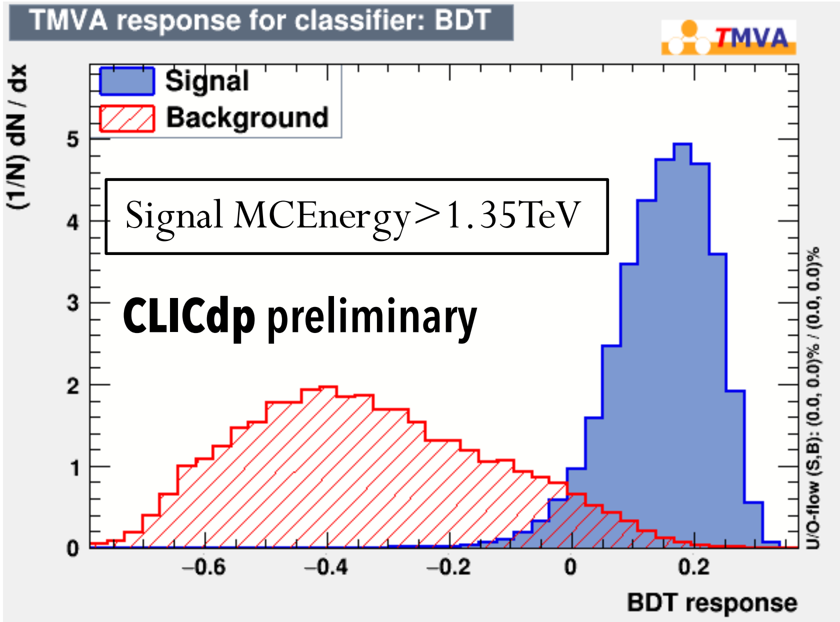
"hadronic side"

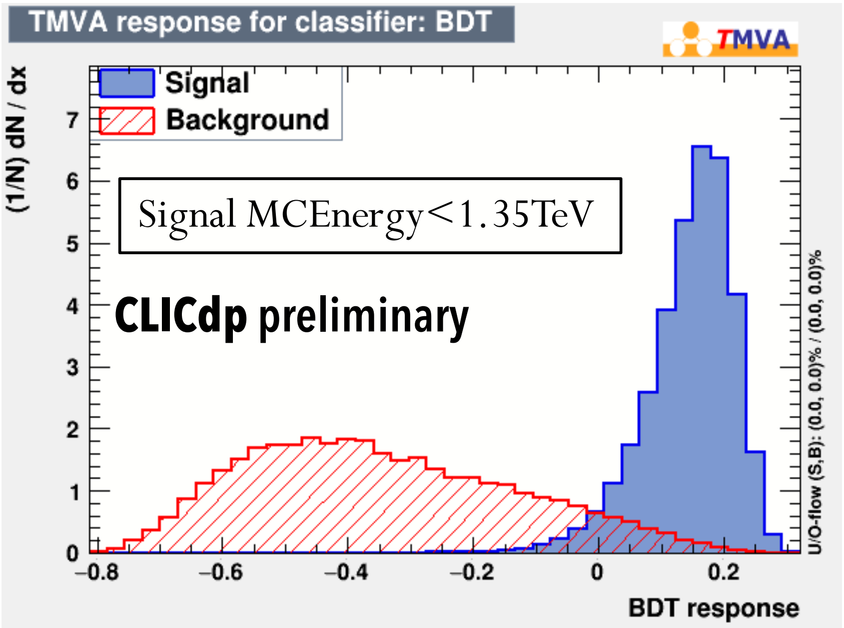
High energies: Event selection - Method 2

- Technical cut (gen. level): two regions (different BDTs)
- 1 isolated lepton (based on Pandora PID)
- Pre selection (hadronic = highest jet energy)
- Jet structure variables in BDT (top tagging)



- **Pre selection:**
  - Visible p_T>200 GeV
  - Hadronic top: E>100 GeV
  - Leptonic top p_T>20 GeV
  - $Y_{23}<7$, $Y_{34}<9$





$e^+e^- \rightarrow tt \rightarrow qqqlv$:

LE: 31% efficiency

HE: 42% efficiency

(purity ~60%)

√s’ reconstruction at CLIC@1.4 and 3 TeV

- Agreement between √s’-generated and √s’-reconstructed is good
- Since the √s’-generated is very peaked around the nominal energy plots are re-normalised into using a flat √s’-generated distribution.