CLICdp-Draft-2018-003
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Top-Quark Physics at the CLIC Electron-Positron Linear Collider

CLICdp Collaboration*[1)]

[author list is being prepared]

This is not a CLICdp official talk

IFIC collaboration

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Contents

Contents

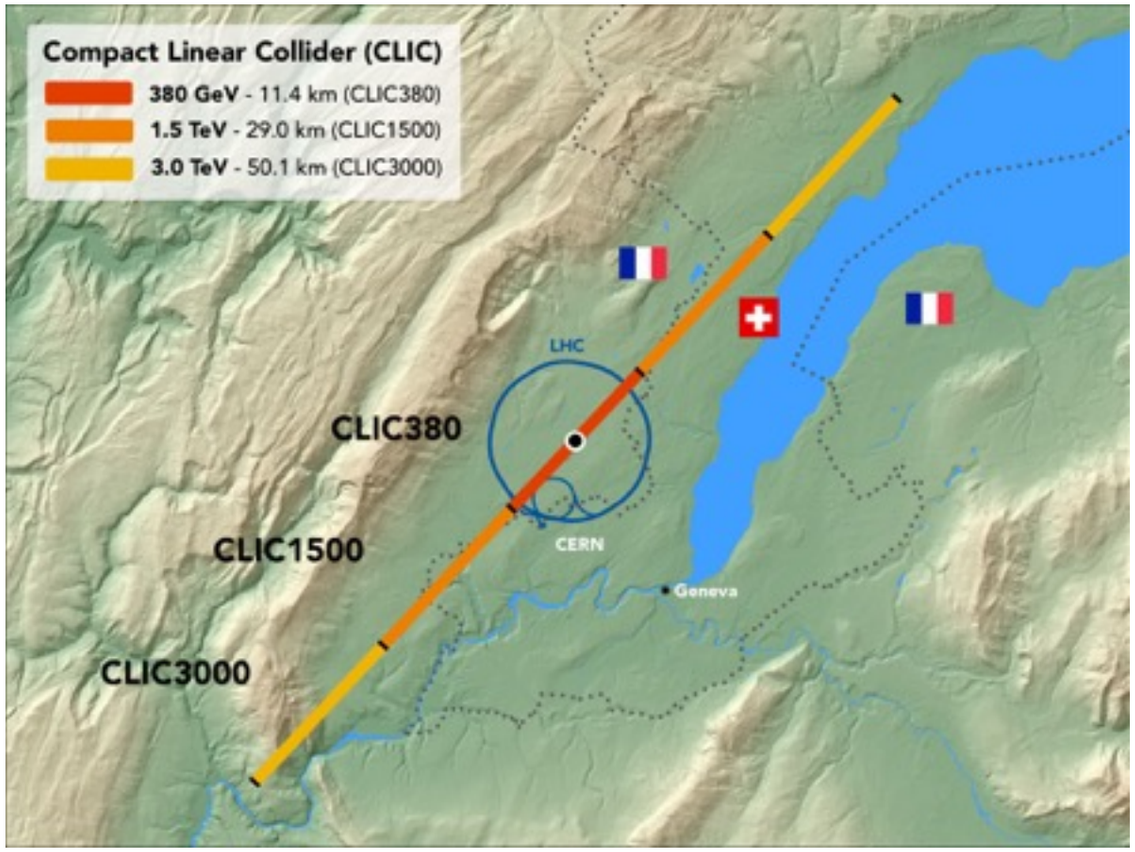
Few details

More or less

I'll go deeper in IFIC's contributions

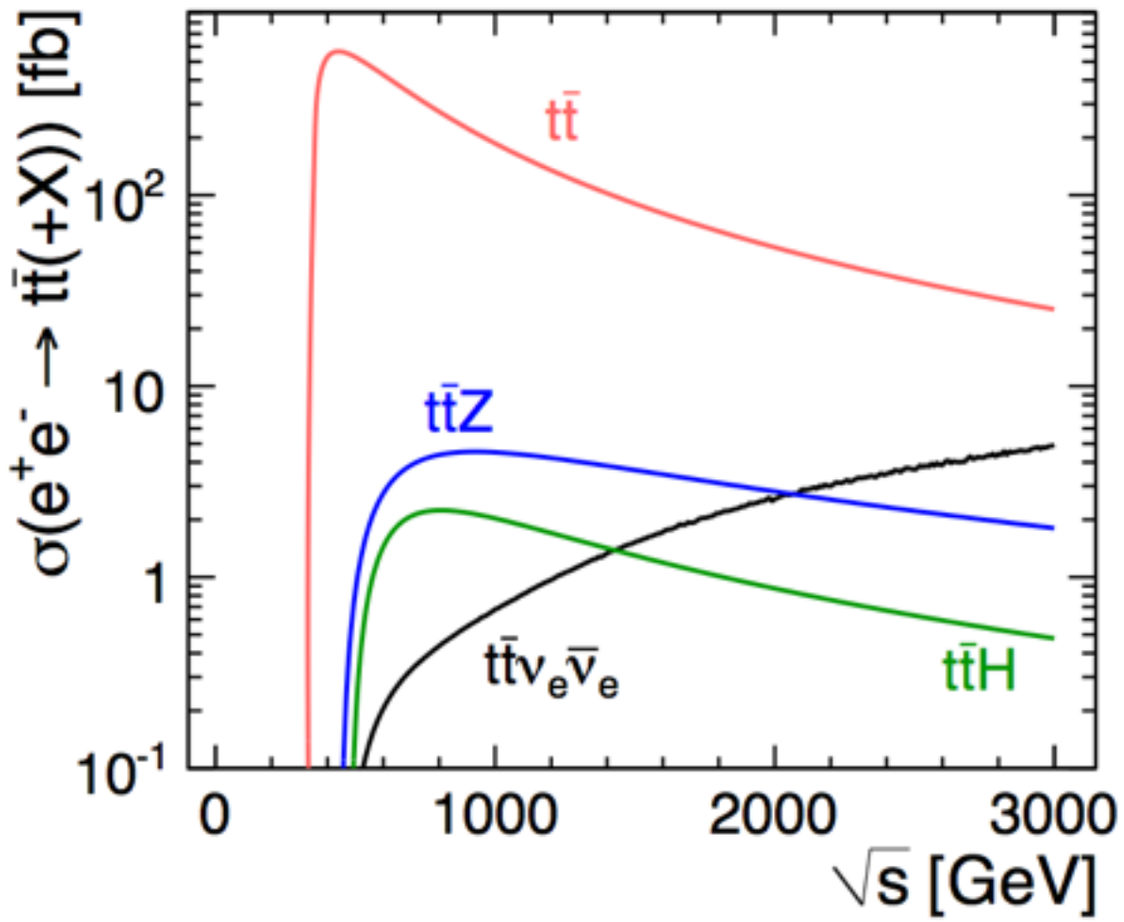
Top-quark physics at the Compact Linear Collider (CLIC)

http://clicdp.web.cern.ch/



	380 GeV	1.5 TeV	3 TeV
Lumi (fb-1)	500	1500	3000

Polarised electron beam P(e-) = ± 0.8



Why top quark?

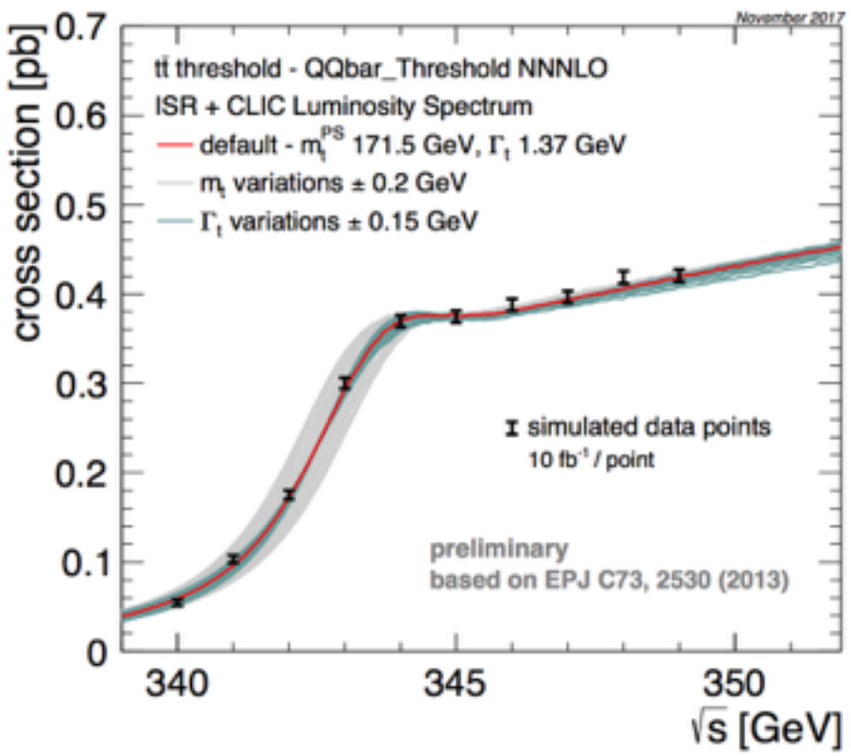
- Heaviest SM particle ~ 173 GeV (window to new physics)
- Never studied in an electron-positron collider -> precision needed

Top-quark mass measurements

- As an unstable, coloured particle, the definition of the top-quark mass is not straight-forward.

- Depending on the context different definitions are used:
  - "pole mass": mass of the propagator (numerically close to the mass parameter of the generator).
  - $\overline{\text{MS}}$ mass: usually used in precision calculations.
  - threshold region: 1S and PS masses (both provide stable calculations in that region)

Threshold scan at 350 GeV



- Statistical uncertainty:

optimised: bunch charge reduced to 70% of the nominal charge (reduction of the instantaneous luminosity)

	Δm_t^{PS} default spectrum	Δm_t^{PS} optimised spectrum
equal $\mathscr{L}_{int}$	23 MeV	19 MeV
equal running time	17 MeV	19 MeV

- Systematic uncertainties:

	Δm_t^{PS} default spectrum	Δm_t^{PS} optimised spectrum
QCD scale uncertainties	±42 MeV	±40 MeV
parametric α_s	– 30 MeV	– 27 MeV

Top-quark mass measurements

- As an unstable, coloured particle, the definition of the top-quark mass is not straight-forward.

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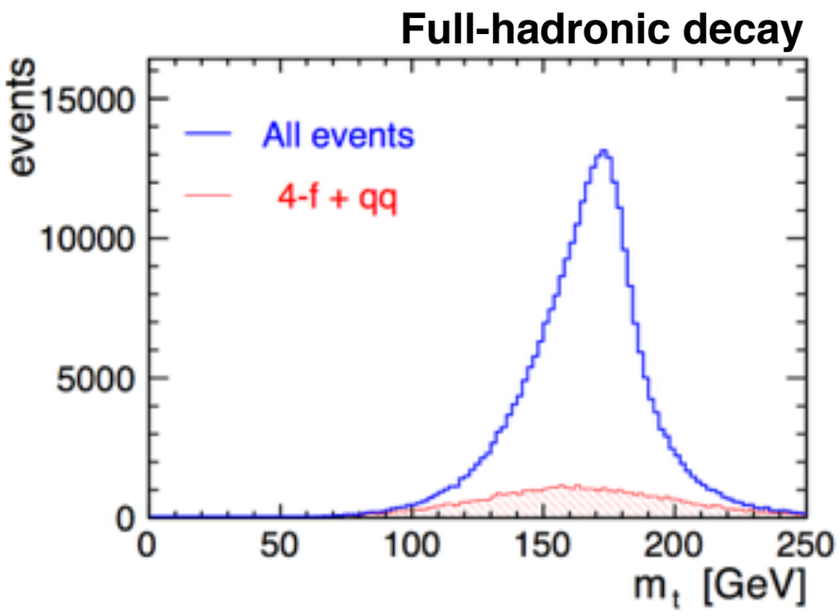
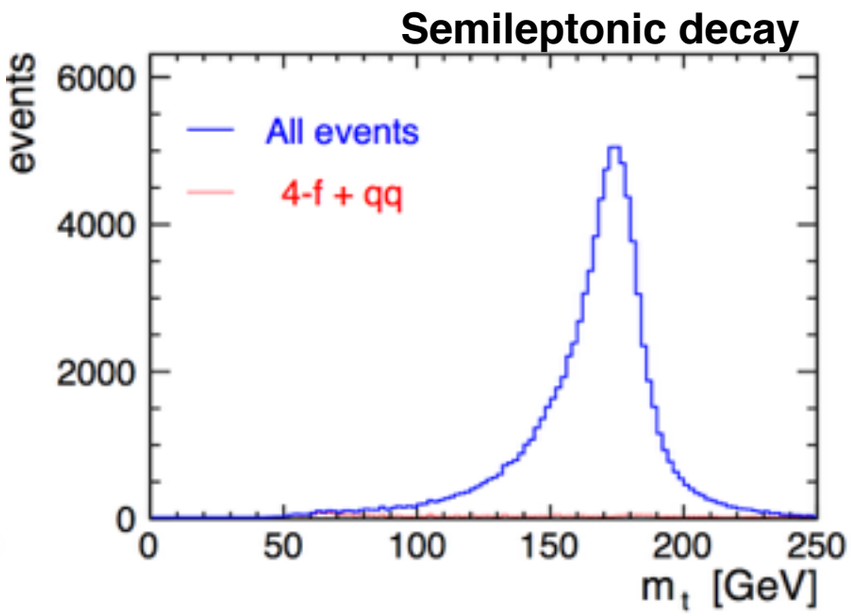
  - $\overline{\text{MS}}$ mass: usually used in precision calculations.
  - threshold region: 1S and PS masses (both provide stable calculations in that region)

Direct reconstruction in the continuum (6 jets from the full-hadronic decay or 4 jets + 1 lepton from the semileptonic decay)





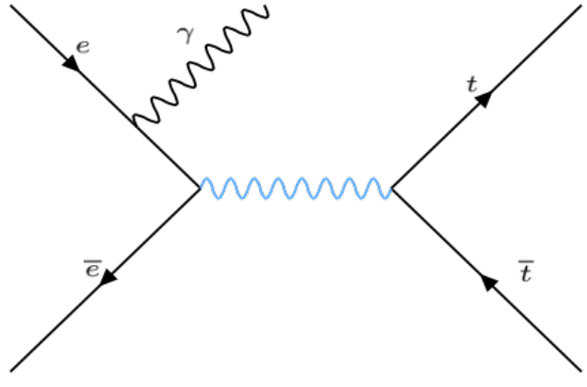
Requirement: clean samples of top-quark pair candidate events.

- VLC algorithm to cluster hadronic tops.
- b-tagging.
- BDT used for removing background (~80% efficiency achieve).

Combined statistical top quark mass precision **~40 MeV**

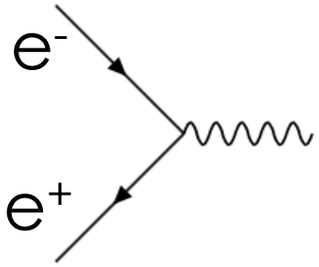
Top-quark mass from radiative events

- The idea is to measure the top-quark mass (m_t) measuring the differential cross section of the process $e^+e^- \to t\,\bar{t}\,\gamma_{\rm ISR}$.



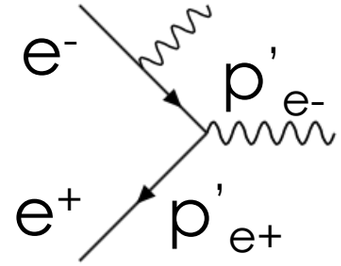
- The $t\,\bar{t}$ production cross section is sensitive to the center of mass energy and m_t:

$$\sigma(e^+e^- \to t\bar{t}) = f(s, m_t)$$



$$s = (p_{e^-} + p_{e^+})^2$$

$$\sigma(e^+e^- \to t\bar{t}\gamma) = f(s', m_t)$$



$$s' = (p'_{e^-} + p'_{e^+})^2$$

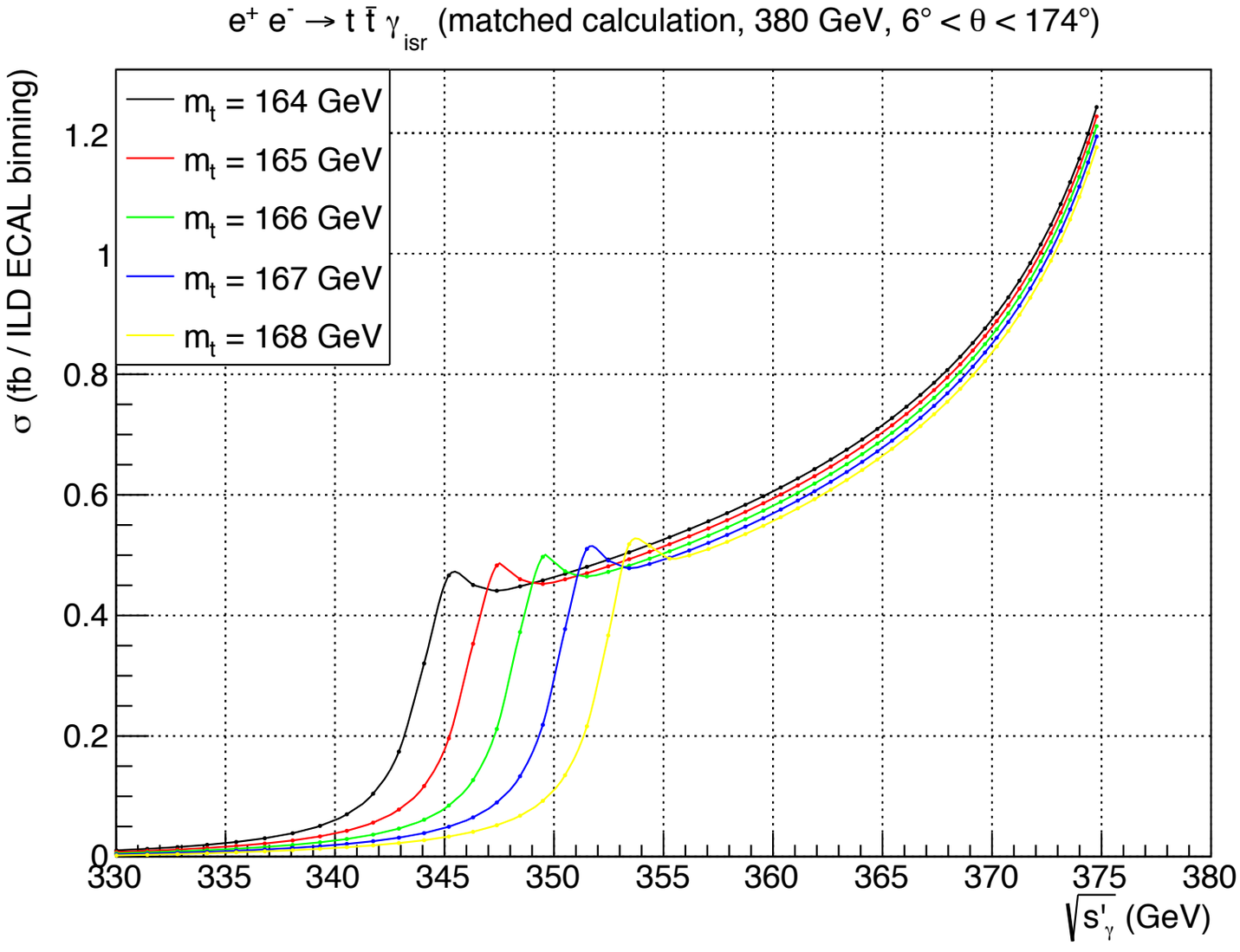
- The emitted $\gamma_{\rm ISR}$ reduces the available phase space for the $t\,\bar{t}$ production.
- Therefore the $t\,\bar{t}\,\gamma_{\rm ISR}$ production cross section is sensitive to the emitted ISR photon energy.

Top-quark mass from radiative events

- m_t can be measured by counting the $t\bar{t}$ events produced for a certain s' (i.e ISR energy photon):

$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

- Our observable is the differential cross section of the $t\bar{t}$ production as a function of $\sqrt{s'}$.



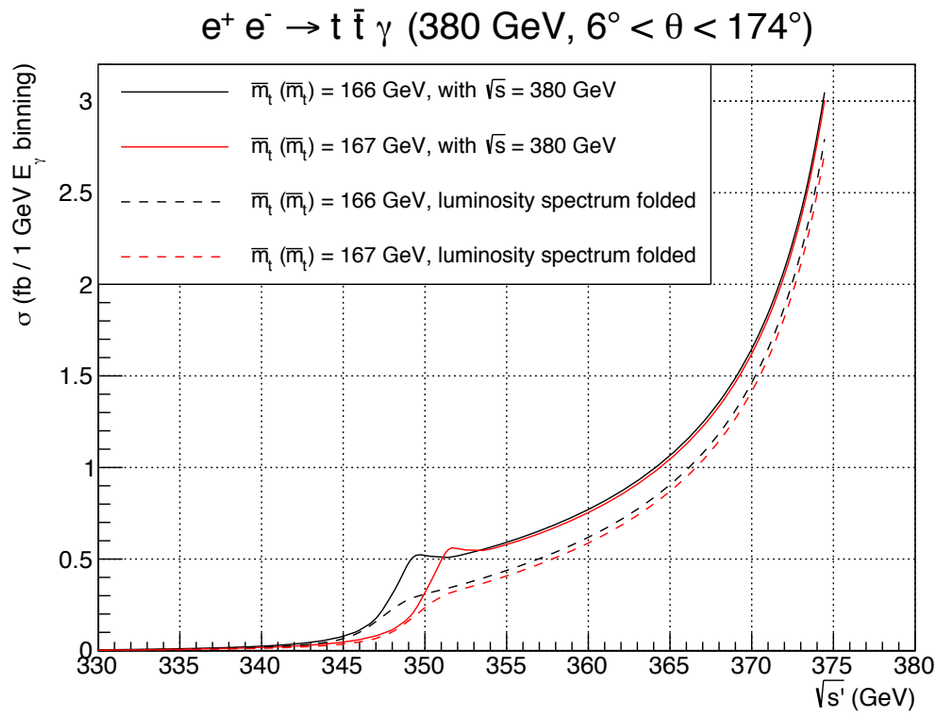
- The observable is more sensitive to m_t near the top production threshold, and the dependence diminishes as $\sqrt{s'}$ grows.

Sensitivity to the top-quark mass

- The theory model convolutes the ISR calculation with the threshold - continuum matched calculation by A. H. Hoang et al.

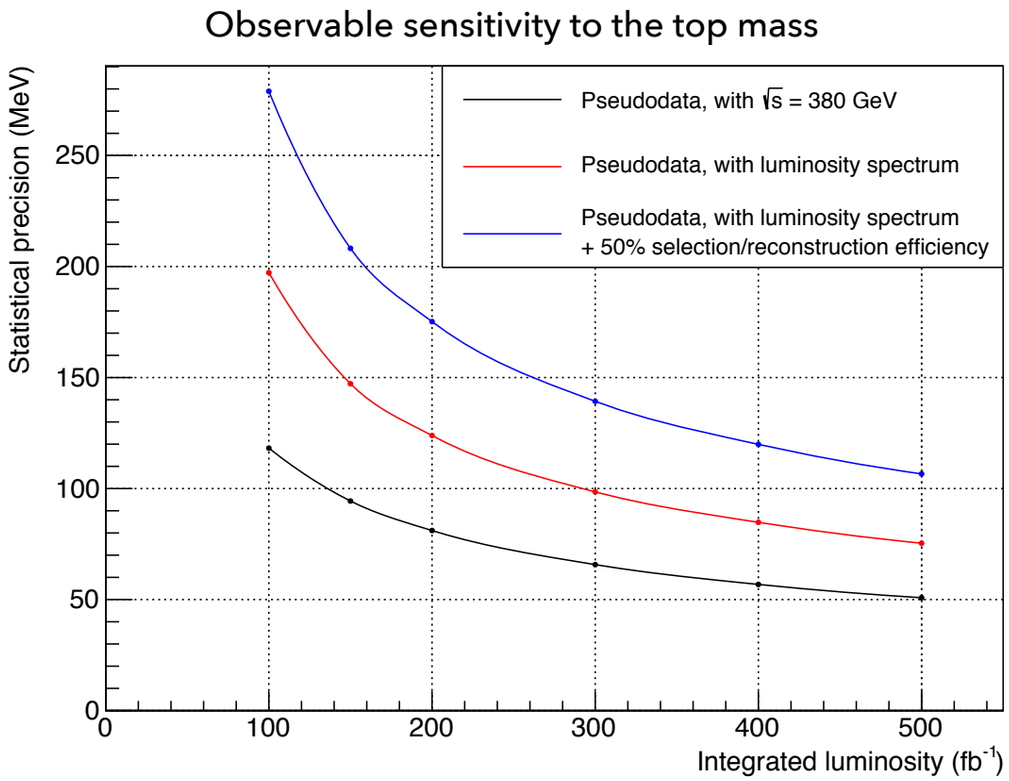
$$\sigma_{t\bar{t}\gamma_{ISR}}(m_t, s') = \sigma_{ISR}(E_\gamma) * \sigma_{t\bar{t}}(m_t, s')$$

- The input mass can be chosen to be any short-distance mass scheme, in this case we chose the $\overline{\text{MS}}$ scheme. For the calculation itself the 1S and MSR masses are used.



- For a detector coverage of $6° < \theta < 174°$, **50 MeV are within reach for 500 fb^{-1} at 380 GeV.**

- **Taking into account CLIC's luminosity spectrum, the precision goes down to 75 MeV.**

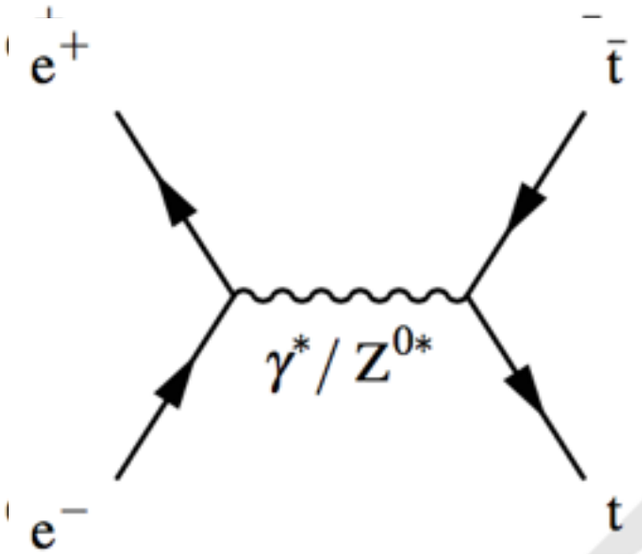


Top-quark pair production

Reconstruction at 380 GeV

- **Resolved analysis** - Production near threshold, use b-tagging, search for W, or 3 jets with a combined invariant mass near m_t

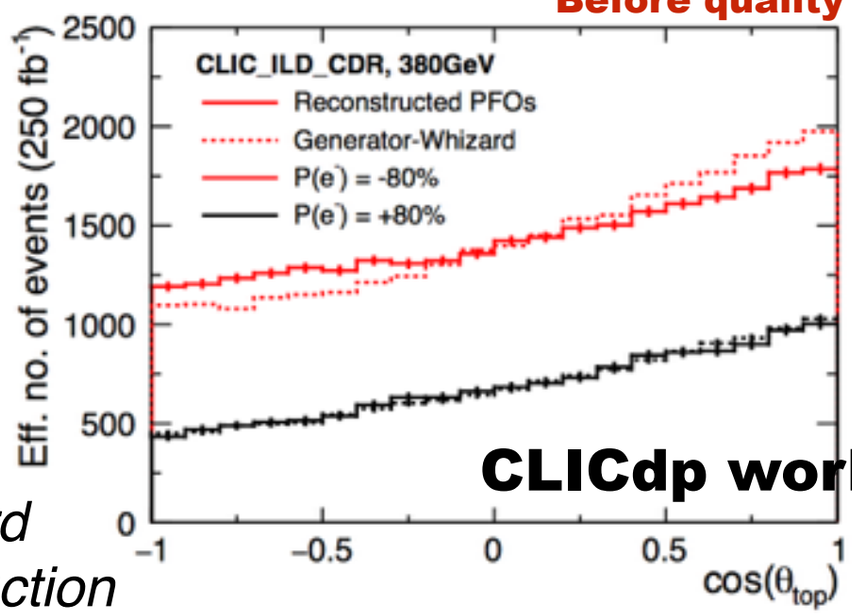
- **Semileptonic decay**: reconstruction of 4 jets (2 from the hadronic W + 2 b-quarks) + 1 lepton. Top quark candidates are formed by merging each of the two required b-tagged jets with the two non b-tagged jets from the hadronic W boson. The ambiguity in this reconstruction is solved by selecting the combination which minimises the kinematic variable d^2.



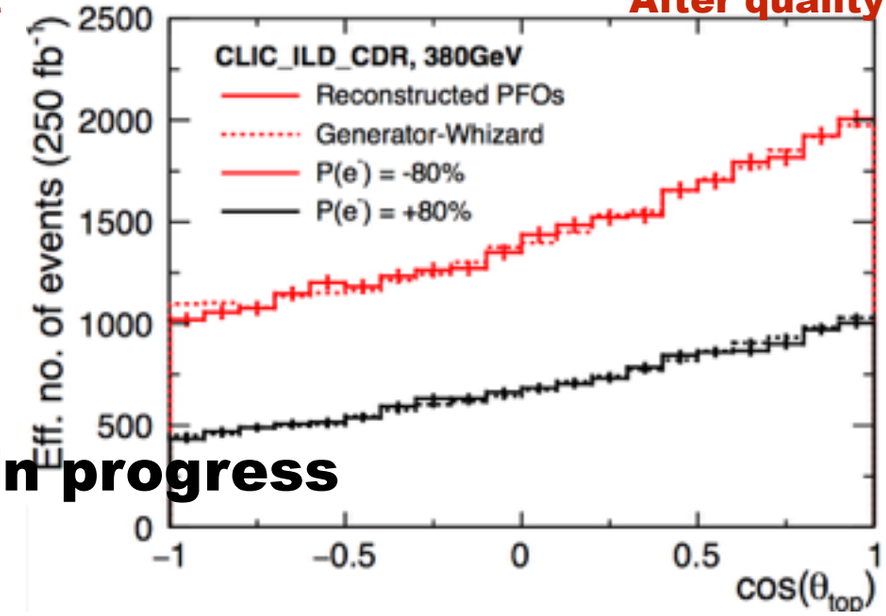
Need of a quality cut (mainly for reducing migrations - wrong W-b pairing)

$$d^2 = \left(\frac{m_t - 174\,\text{GeV}}{\sigma_{m_t}}\right)^2 + \left(\frac{E_t - 190\,\text{GeV}}{\sigma_{E_t}}\right)^2 + \left(\frac{E_b^* - 68\,\text{GeV}}{\sigma_{E_b^*}}\right)^2 + \left(\frac{\cos\theta_{bW} - \langle\cos\theta_{bW}\rangle}{\sigma_{\cos\theta_{bW}}}\right)^2$$

Before quality cut



After quality cut

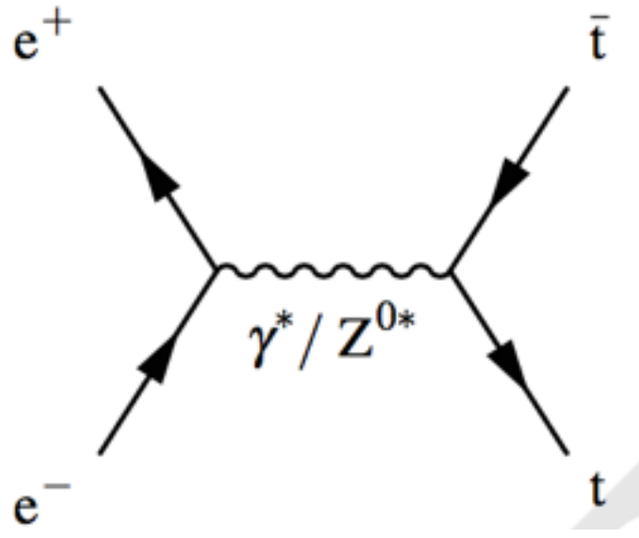


CLICdp work in progress

Forward-backward asymmetry reconstruction

Top-quark pair production

Reconstruction at 380 GeV



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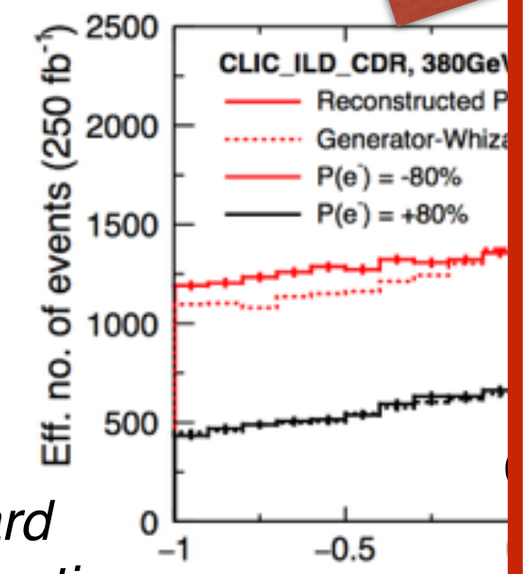
Need of a quality cut (mainly for reducing migrations - wrong W-b pairing)

$$d^2 = \left(\frac{m_t - 174\,\mathrm{G}}{\sigma_{m_t}}\right) \left(\frac{\cos\theta_{bW} - \langle\cos\theta_{bW}\rangle}{\sigma_{\cos\theta_{bW}}}\right)^2$$

CLICdp work in progress

$\sqrt{s}$	380 GeV	
$P(e^-)$	-80%	+80%
$\sigma_{t\bar{t}}$ [fb]	161.0	76.0
stat. unc. [fb]	0.9	0.8
A_{FB}	0.171	0.222
stat. unc.	0.002	0.004



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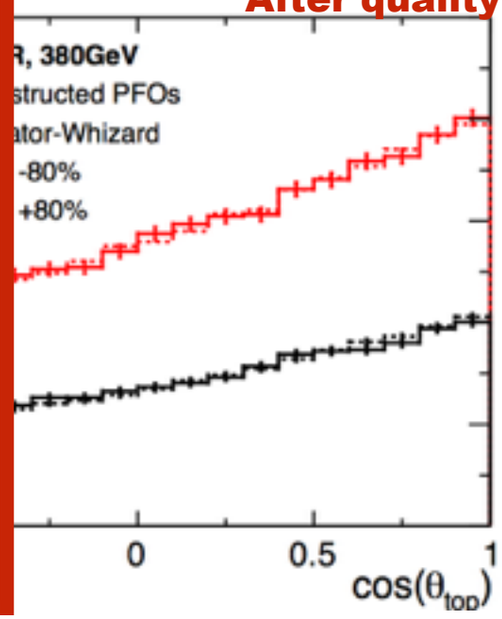
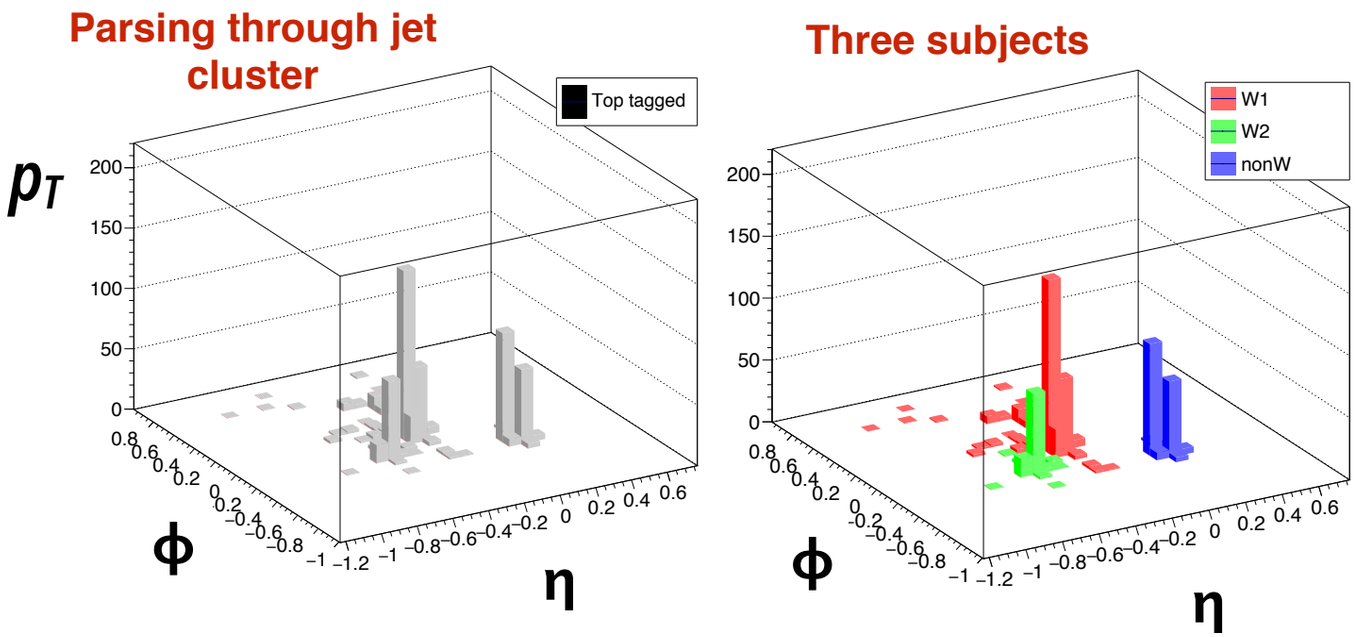


Forward-backward asymmetry reconstruction

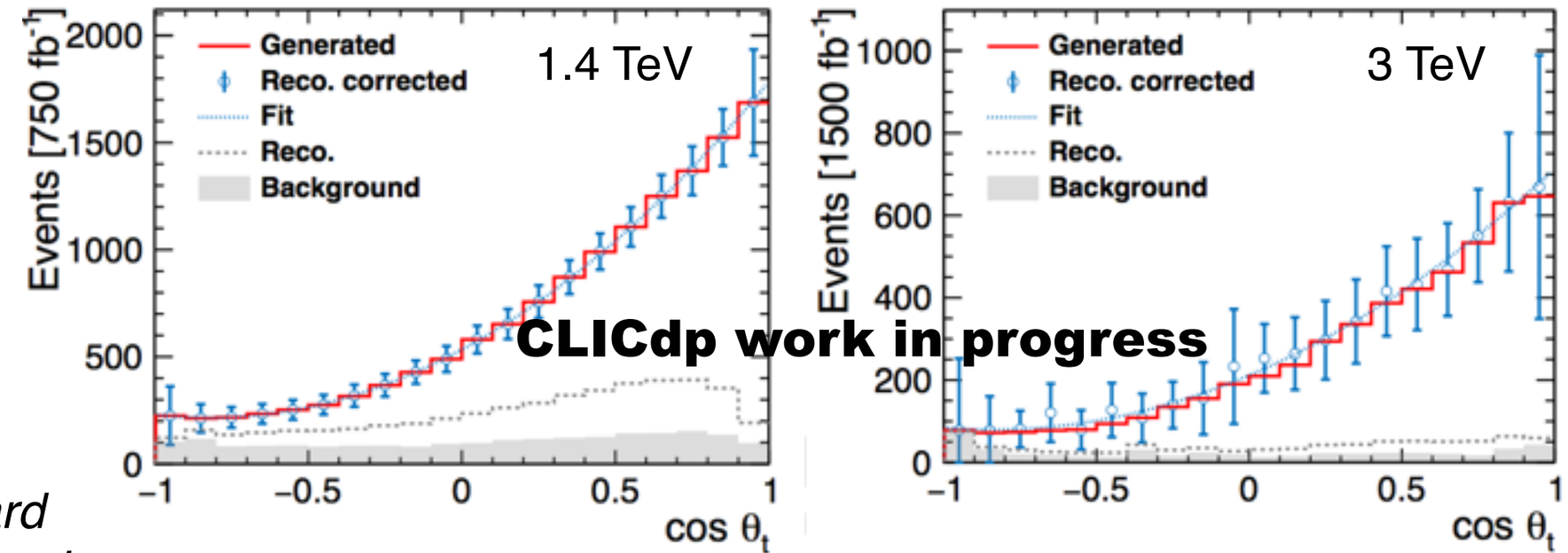
Top-quark pair production

Reconstruction at boosted topologies



Standard identification techniques may not work. Idea: tag tops by identifying sub-structure.

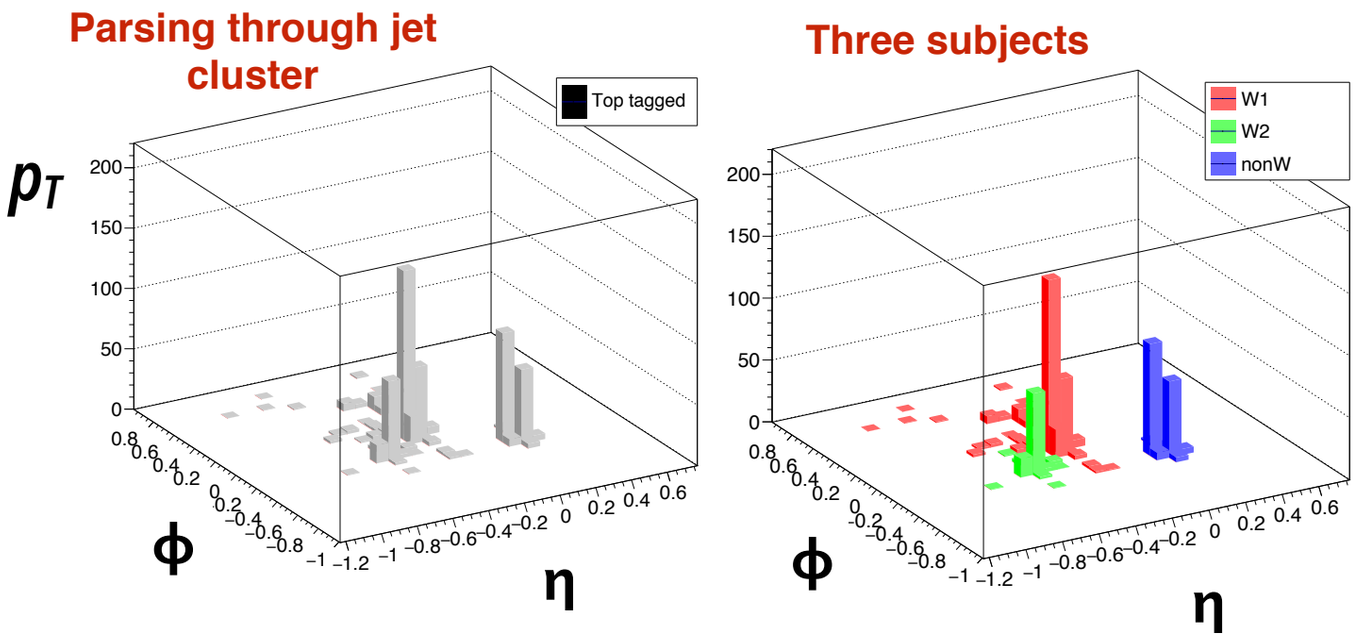
- Jet clustering (incl. trimming)
  - 2 exclusive large-R jets
- Jet tagging:
  - Parsing sub-structure
- Flavour-tagging (sub-jet, fat-jet)



Forward-backward asymmetry reconstruction

Top-quark pair production

Reconstruction at boosted topologies



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CLICdp work in progress

$\sqrt{s}$	1.4 TeV		3 TeV	
P(e^-)	-80%	+80%	-80%	+80%
$\sigma_{t\bar{t}}$ (stat.) [fb]	18.45 ± 0.43	9.86 ± 0.26	3.66 ± 0.52	1.93 ± 0.10
A_{FB} (stat.)	0.561 ± 0.018	0.619 ± 0.019	0.575 ± 0.099	0.643 ± 0.035

Associated tt production processes

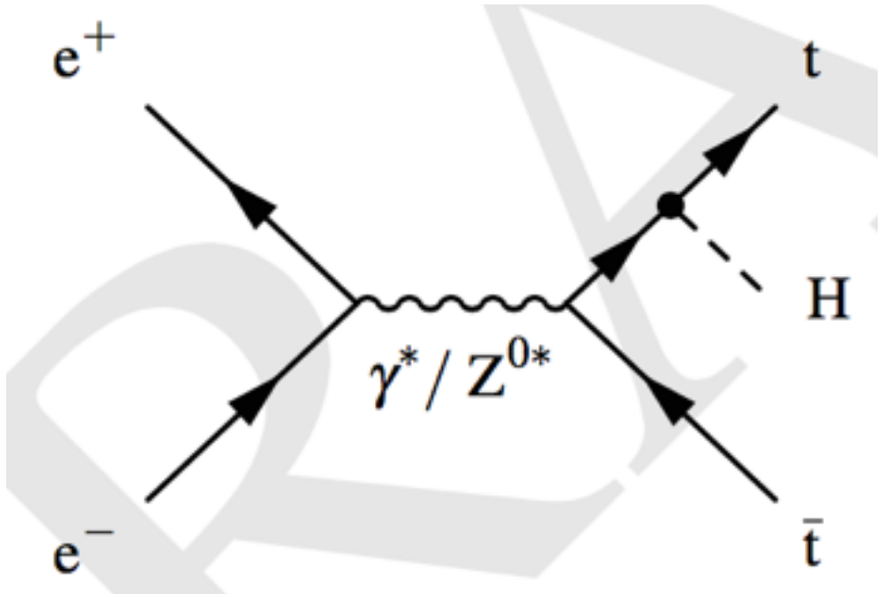
ttH production at 1.4 TeV

Using fully-hadronic and semileptonic tt decay and H->bb.

- Yukawa coupling.

$$\frac{\Delta y_t}{y_t} = 0.503 \frac{\Delta\sigma}{\sigma}.$$

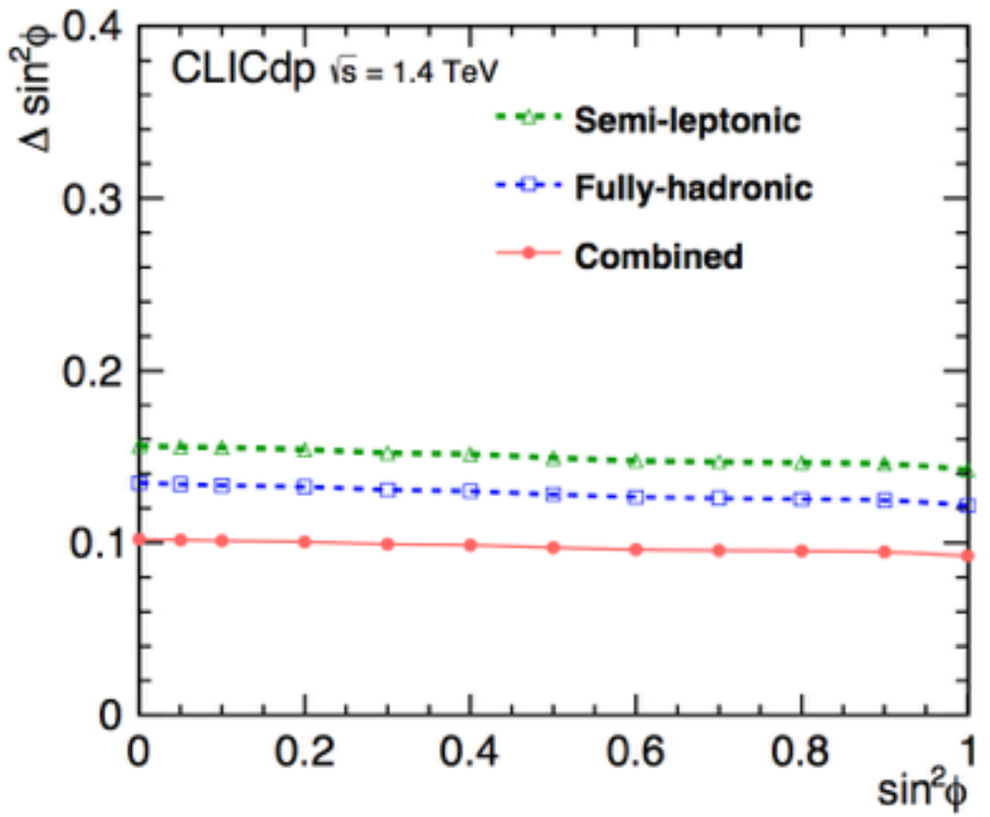
Precision achieved through the cross-section uncertainty.



- CP mixing study

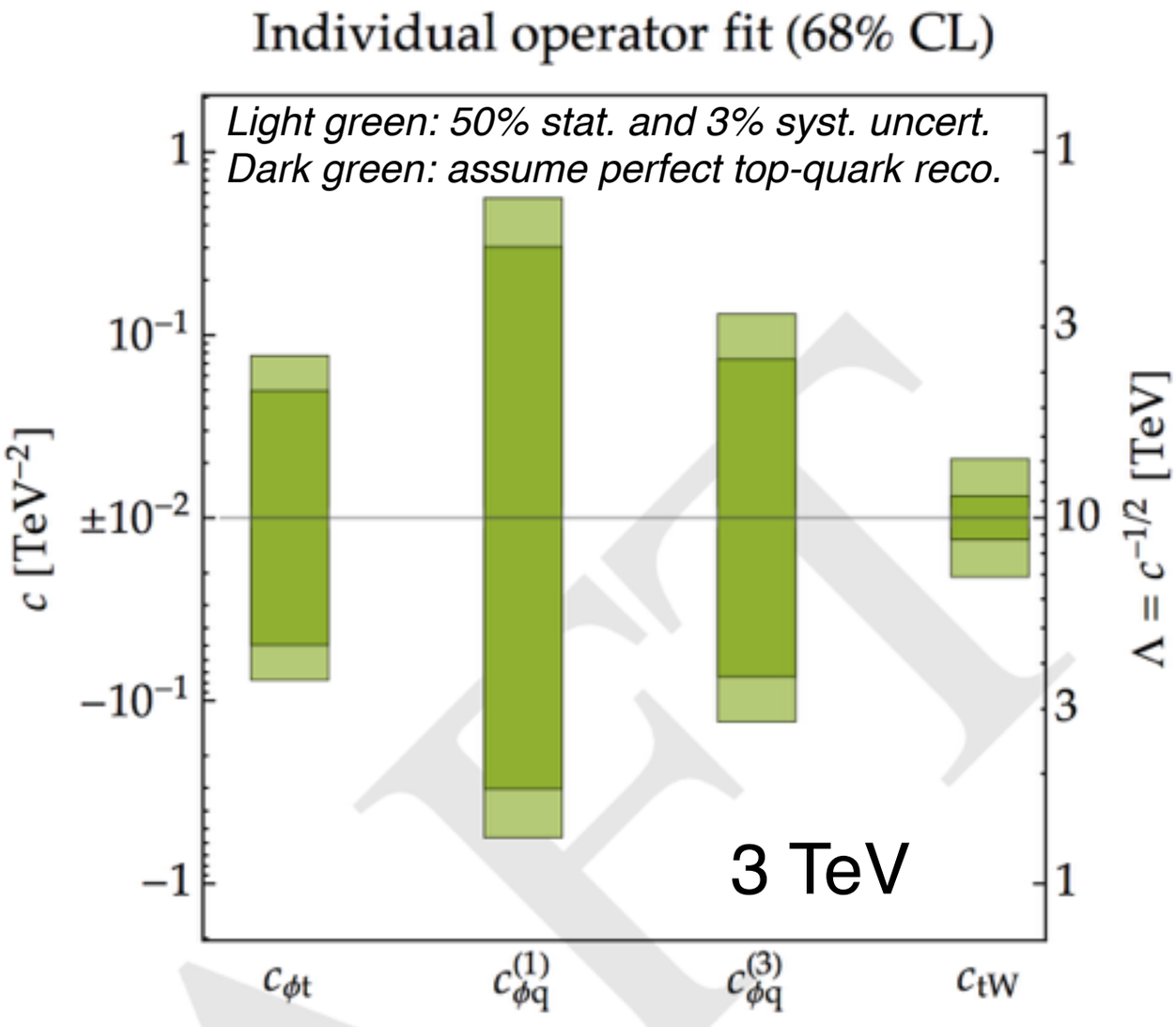
$$-ig_{\mathrm{ttH}}(\cos\phi + i\sin\phi\gamma_5)$$

In the SM $\sin^2\phi = 0$ *while* $\sin^2\phi = 1$ *corresponds to a pure CP-odd coupling*



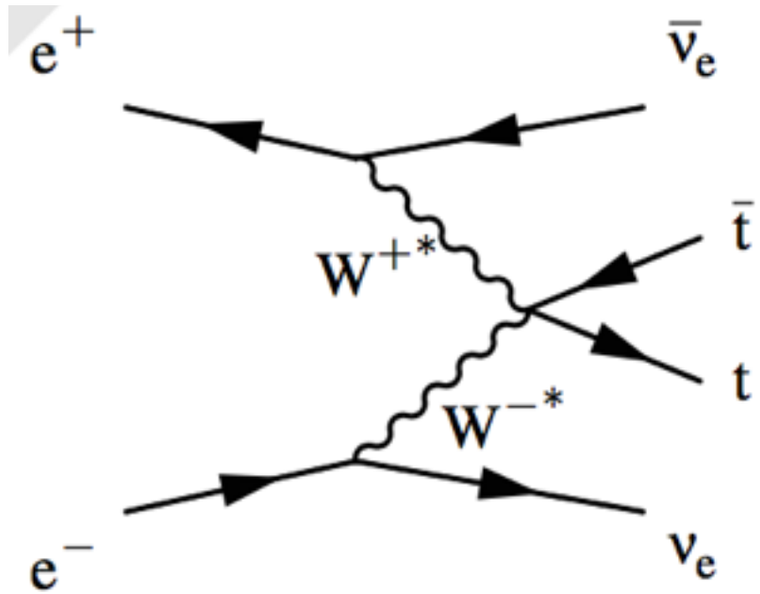
Associated tt production processes

Vector boson fusion production



"Higgs current" type operators

Direct WWtt production on-shell



Study through an effective field theory (EFT)

Observables used:

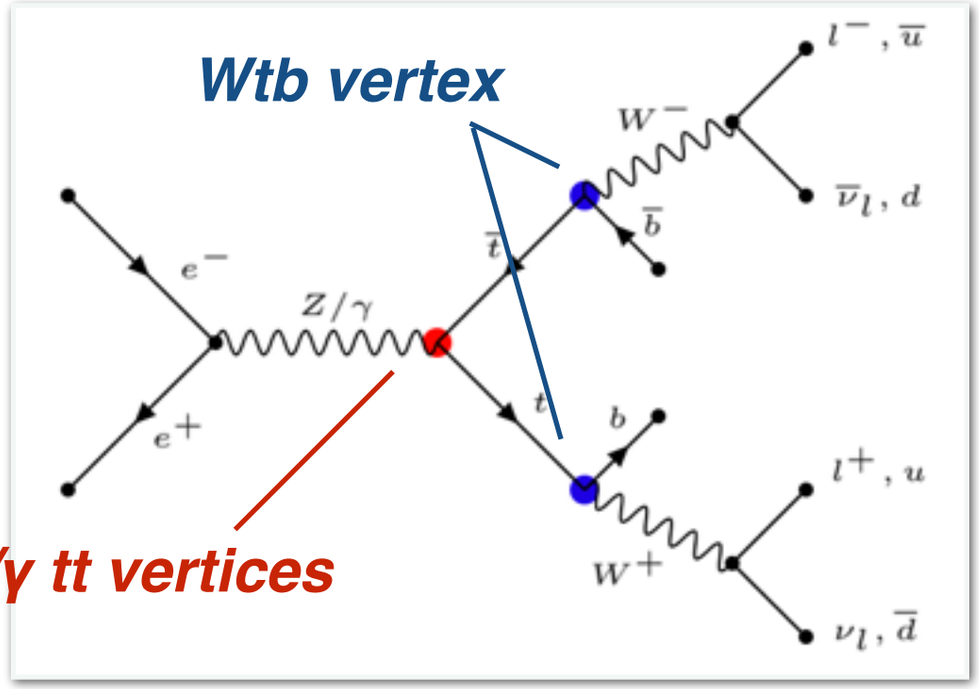
- tt invariant mass
- tt scatteting angle in the centre-of-mass frame

Phenomenological interpretations: towards a global fit

Global fit through an EFT approach using dim-6 operators:

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

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

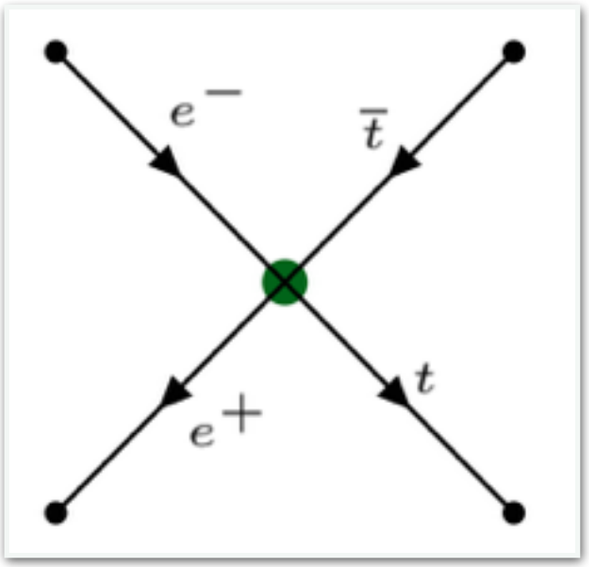


Contact interactions

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

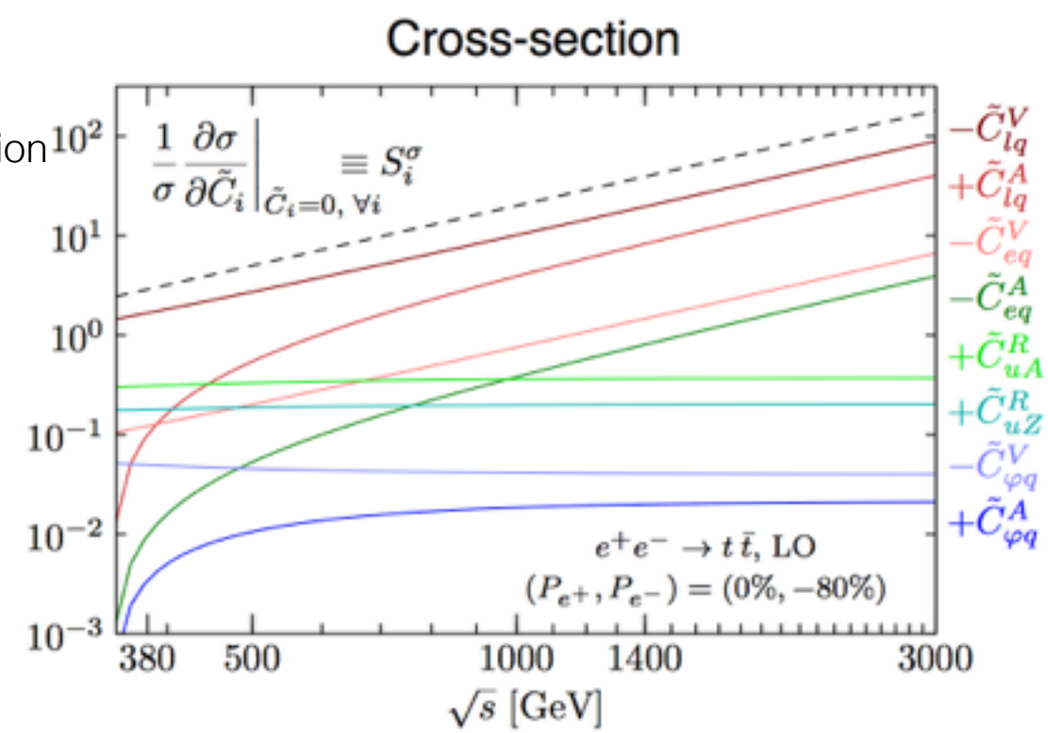
$$O^T_{lequ} \equiv \bar{q}\sigma^{\mu\nu}u\ \epsilon\ \bar{l}\sigma_{\mu\nu}e$$

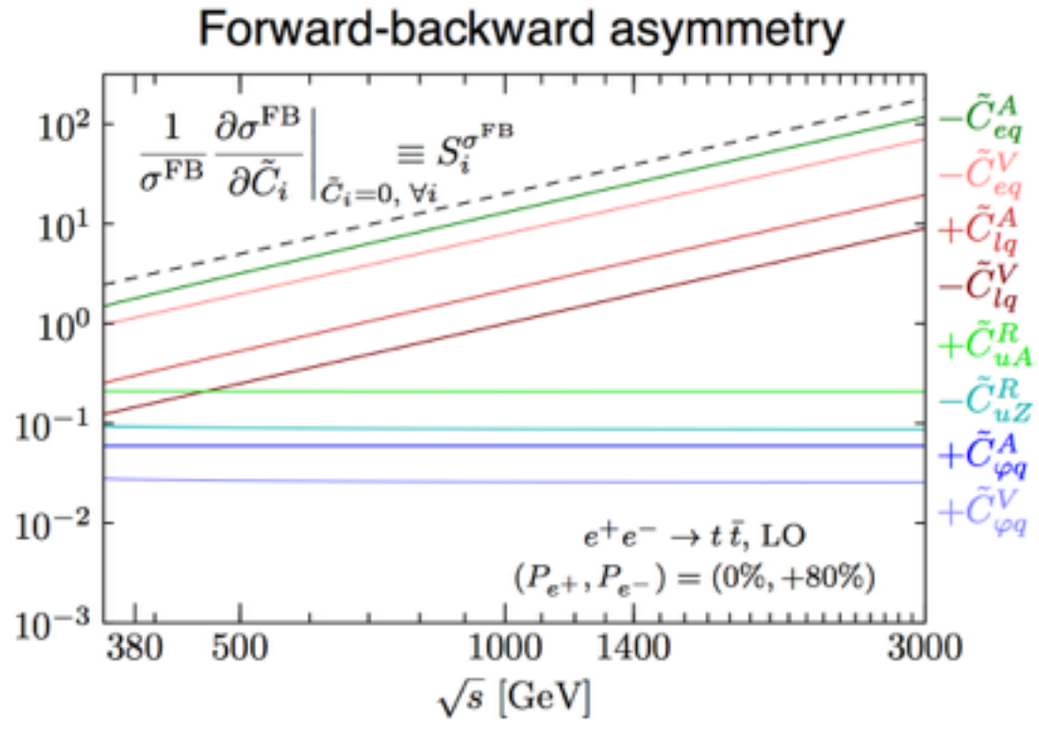
$$O^S_{lequ} \equiv \bar{q}u\ \epsilon\ \bar{l}e$$
$$O_{ledq} \equiv \bar{d}q \quad \bar{l}e$$



Global fit using common observables

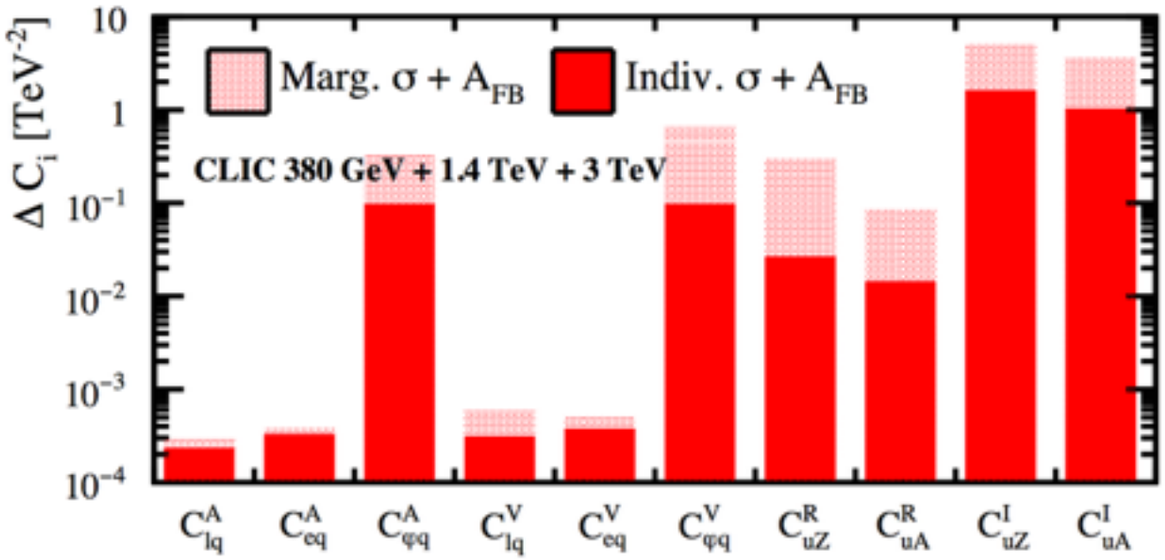
Sensitivity: Relative change in cross-section due to non-zero operator coefficient Δσ(C)/σ/ΔC





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

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

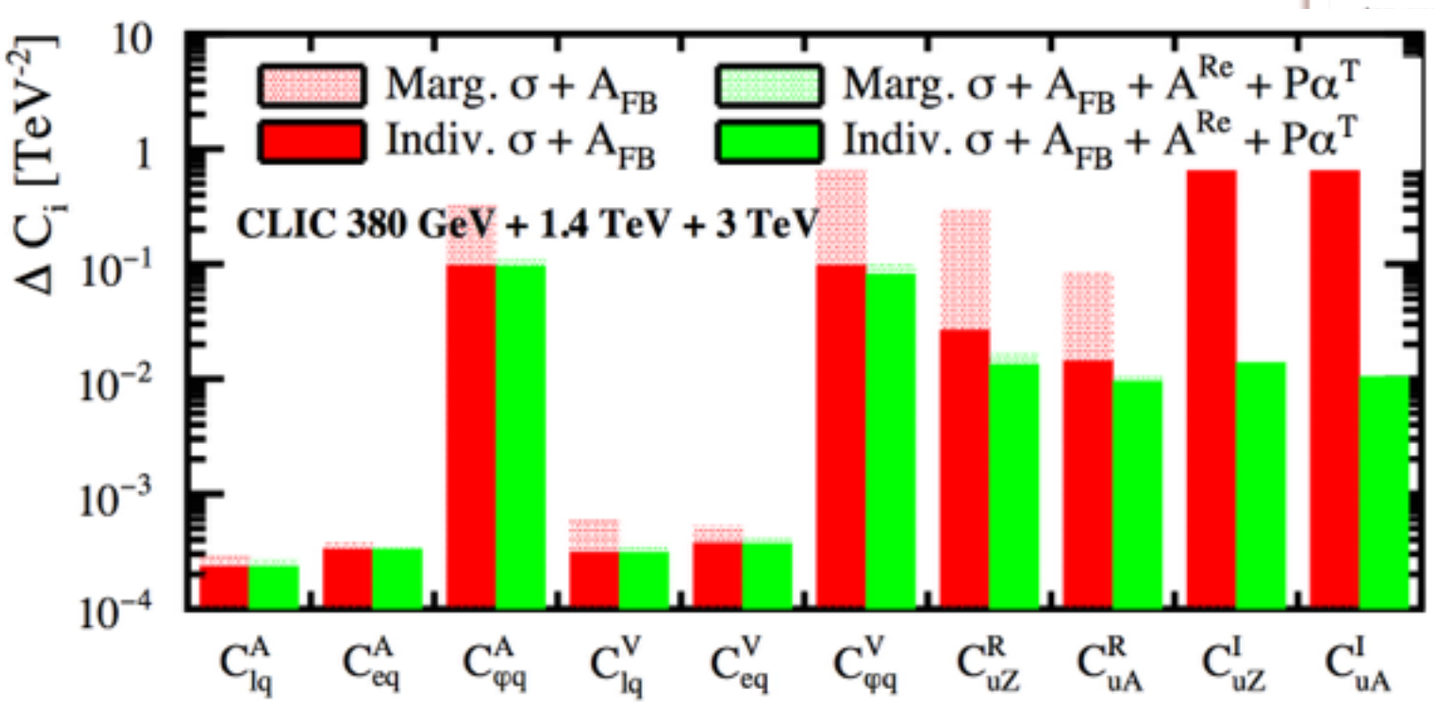


Theory fits (pseudo-experiment): assume an overall reconstruction efficiency of 20%

Global limit: a factor 1.3 to 8 worse (needs improvement)

Global fit using common observables

Intermediate step: add top quark polarizations at different axes (arXiv: 1005.5382) and CPV optimal observables (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
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f the top quark exceeds the prospects of the HL-LHC by over an order of magnitude.

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

Ratio between marginalized and individual limits improved by a factor 4 (still needs improvement)

Statistically optimal observables

G. Durieux @TopLC 2017:

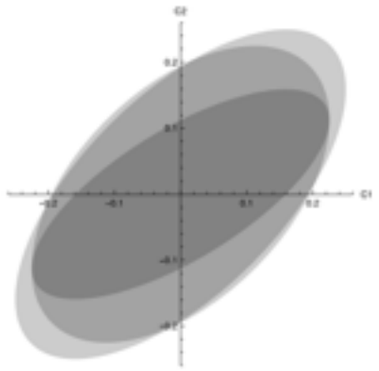
https://indico.cern.ch/event/595651/contributions/2573918/

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

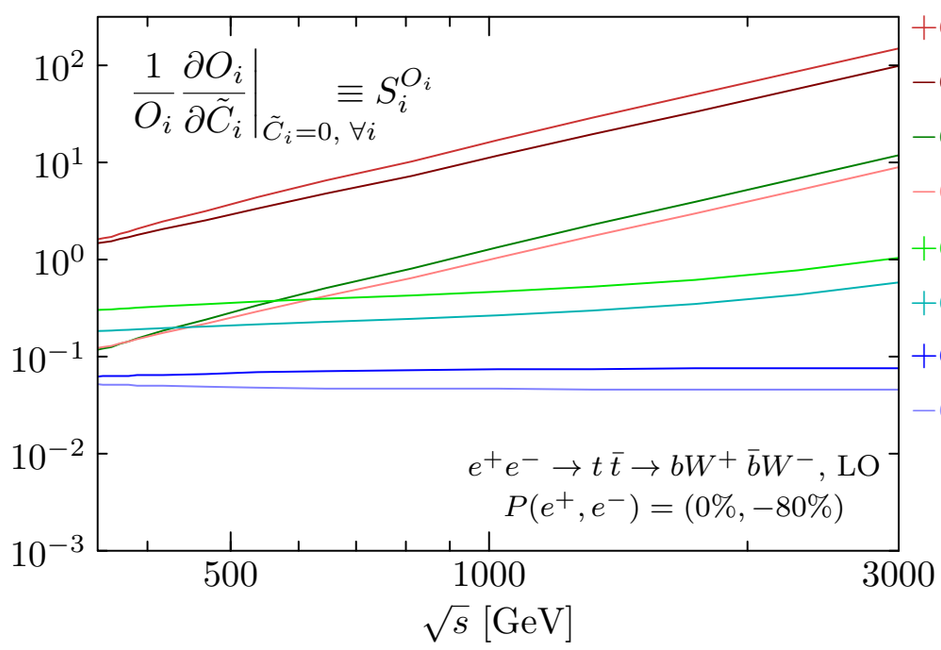


e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

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

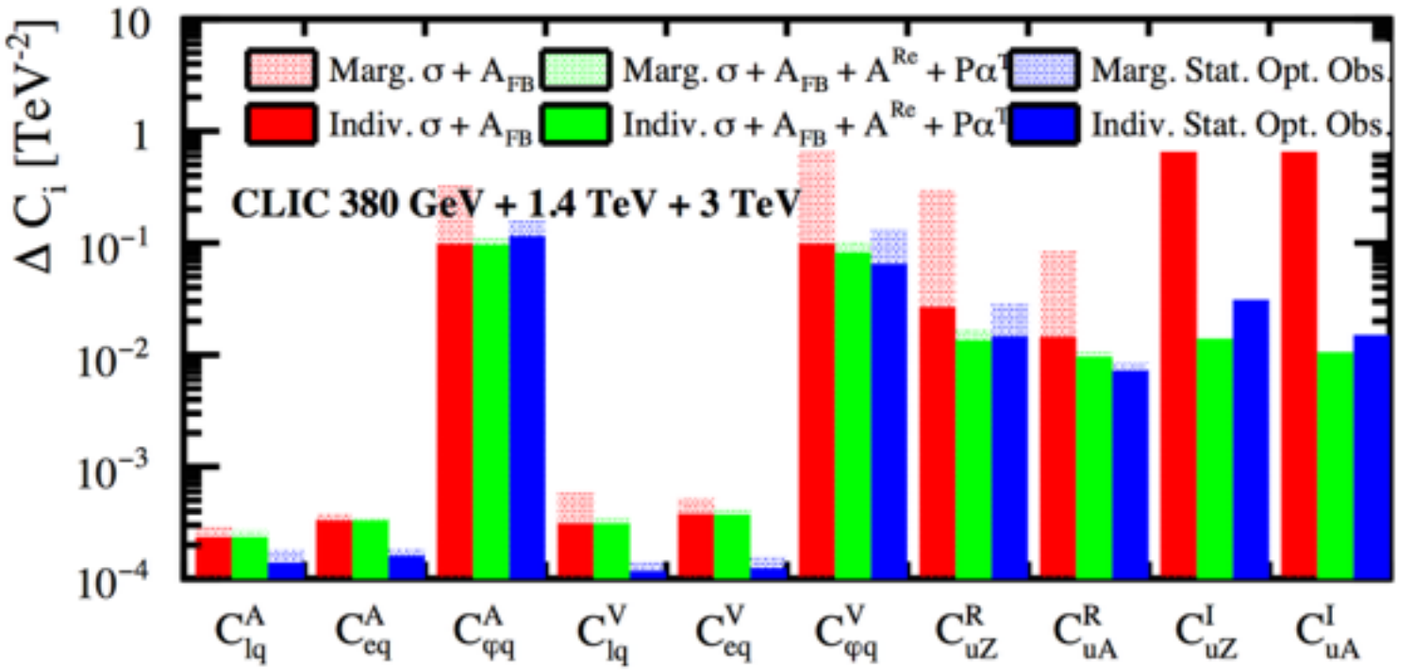
$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

Previous applications in
[Grzadkowski, Hioki '00] [Jano



Even better individual limits for four-fermion operators

Global limits within a factor 1.3 to 2



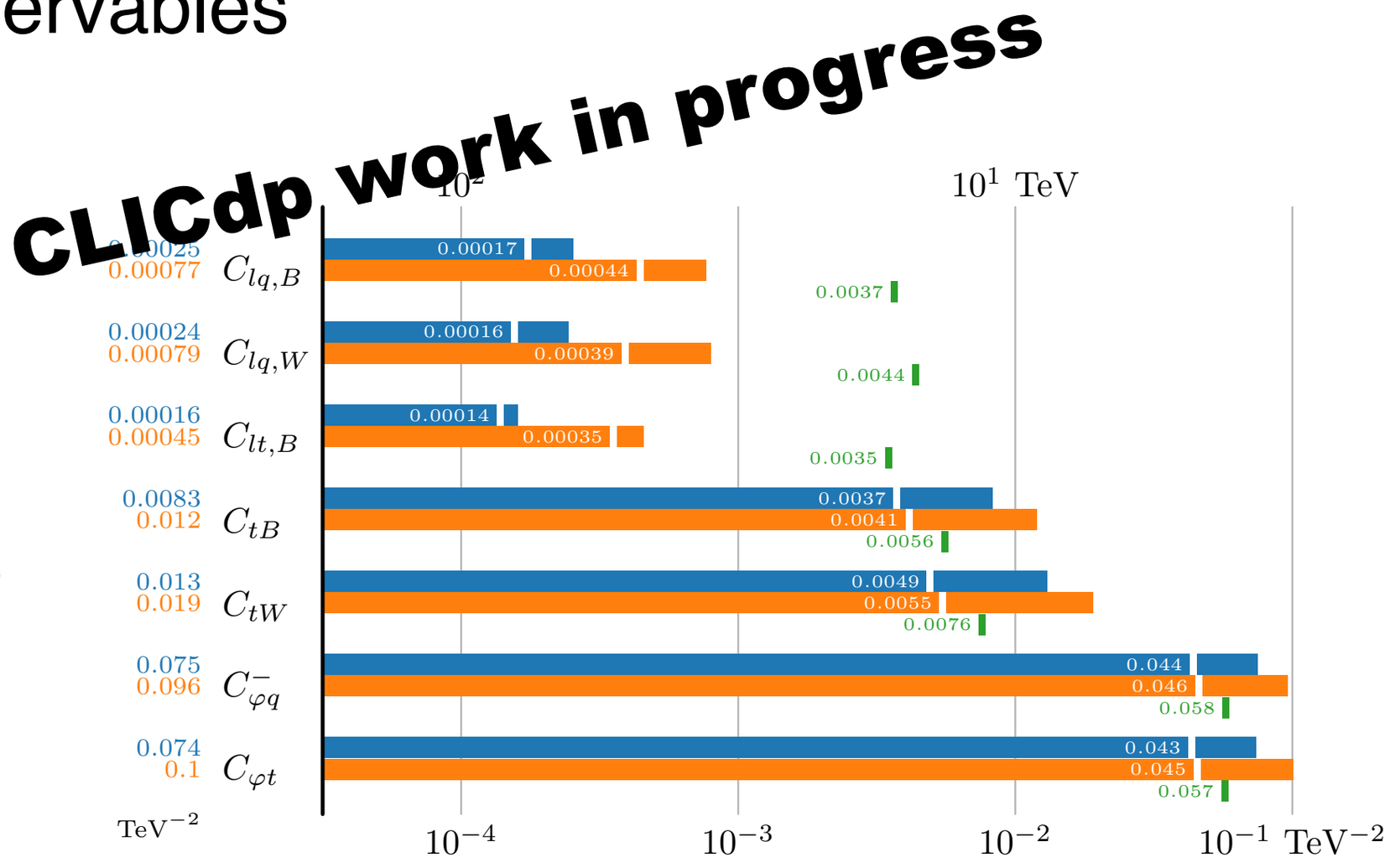
Full-simulation results

Using real reconstruction efficiencies for the stat. opt. observables

P(e⁻)	−80%	+80%
380	8%	11%
1400	9%	10%
3000	5%	6%

Final fit using a top-philic operator basis
(CPV operators not included)

Convert the results into limits for your favorite model!!



Summary

- Paper on top-quark physics at CLIC collider will be published in a short time scale.

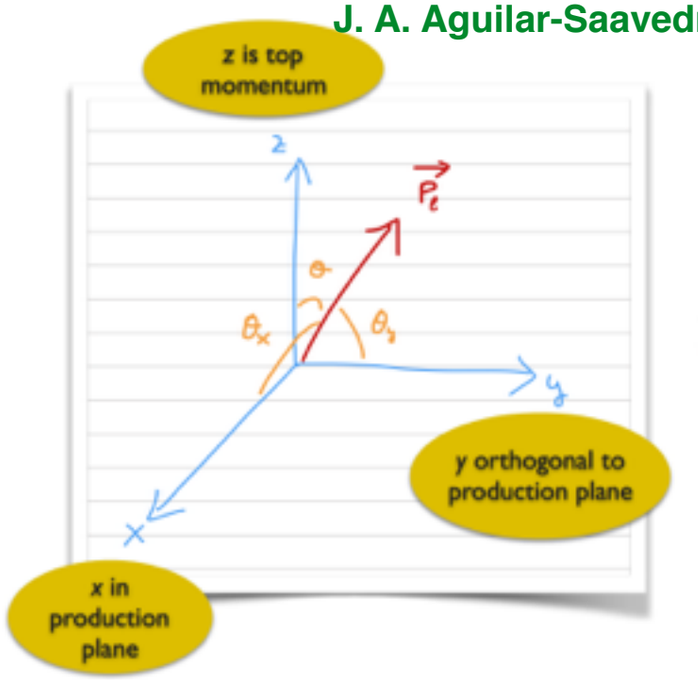
- IFIC has a great contribution on it.

Thanks!

Backup

Top quark polarization at different axes

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



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

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

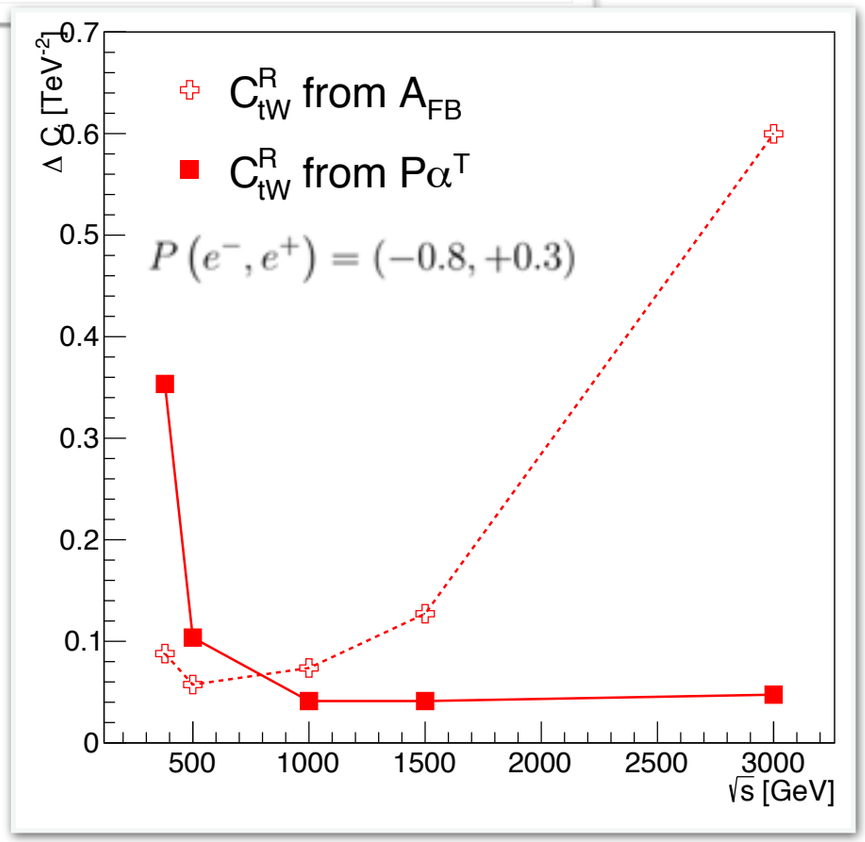
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_y} = \frac{1}{2}(1+\alpha P_2 \cos\theta_y)$$

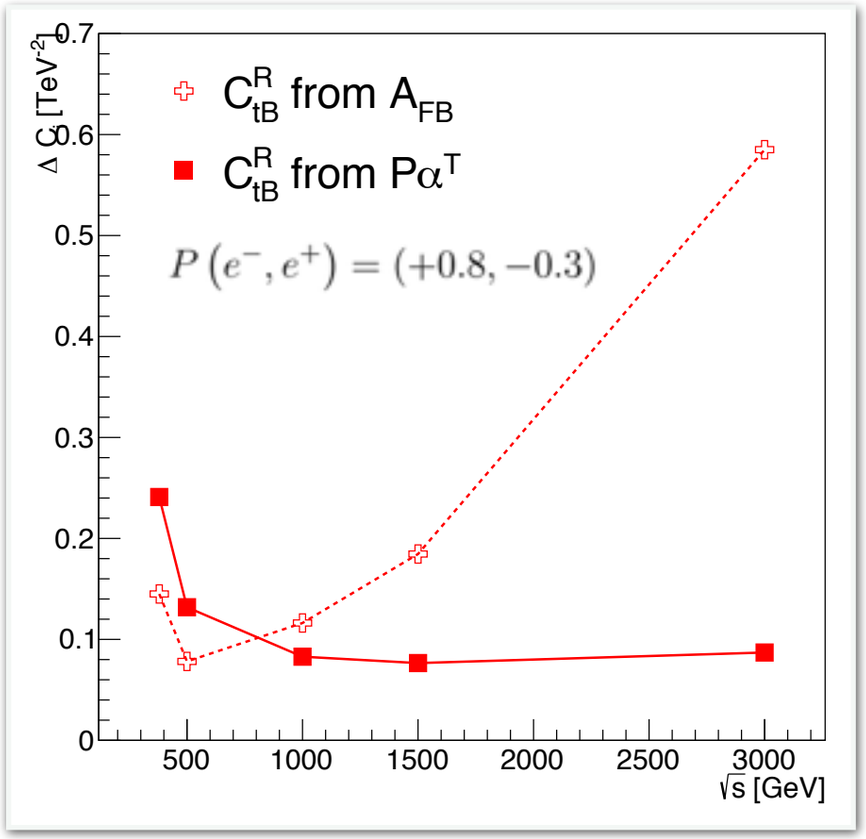
Studied process

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

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



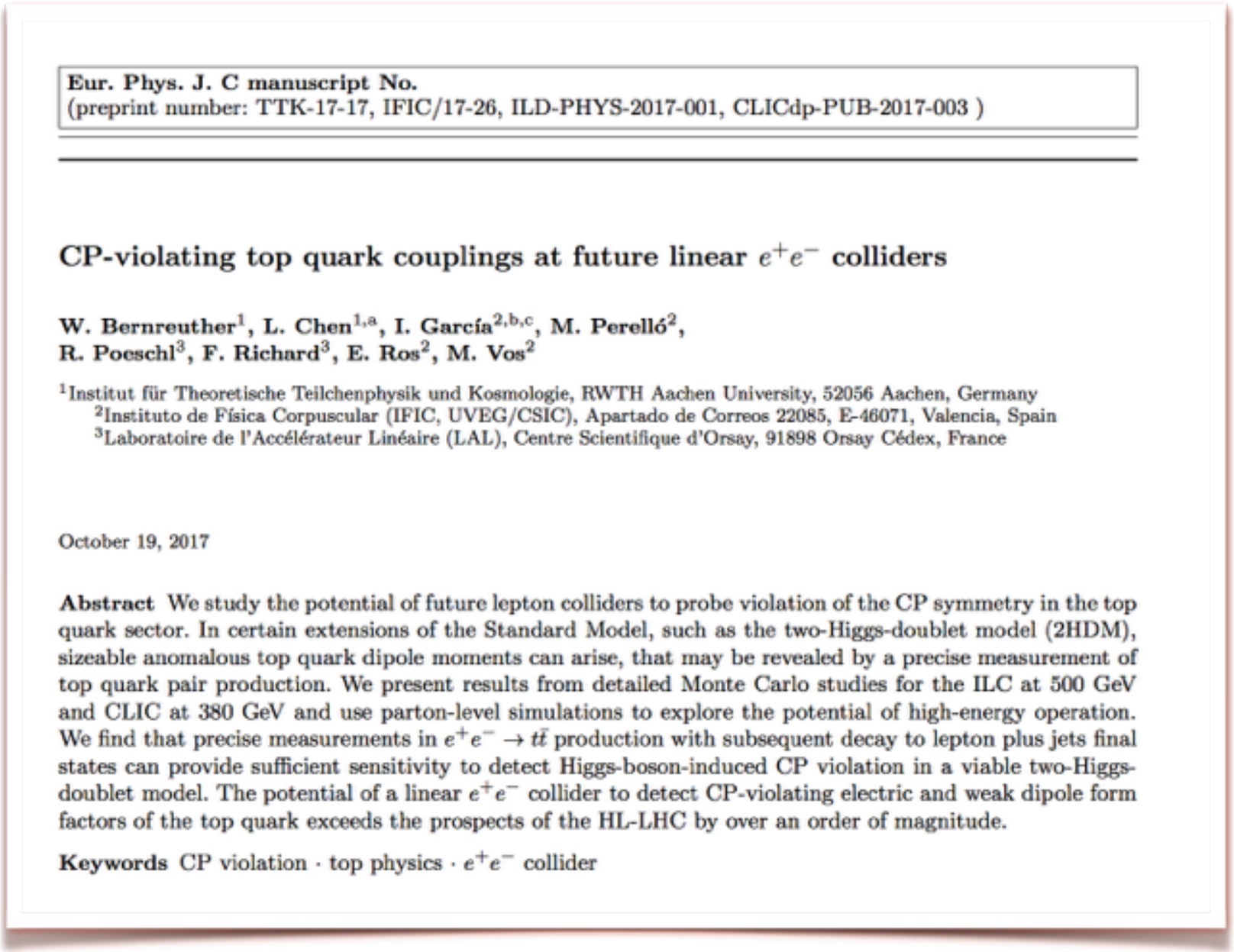


Optimal CP-odd observables

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



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

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

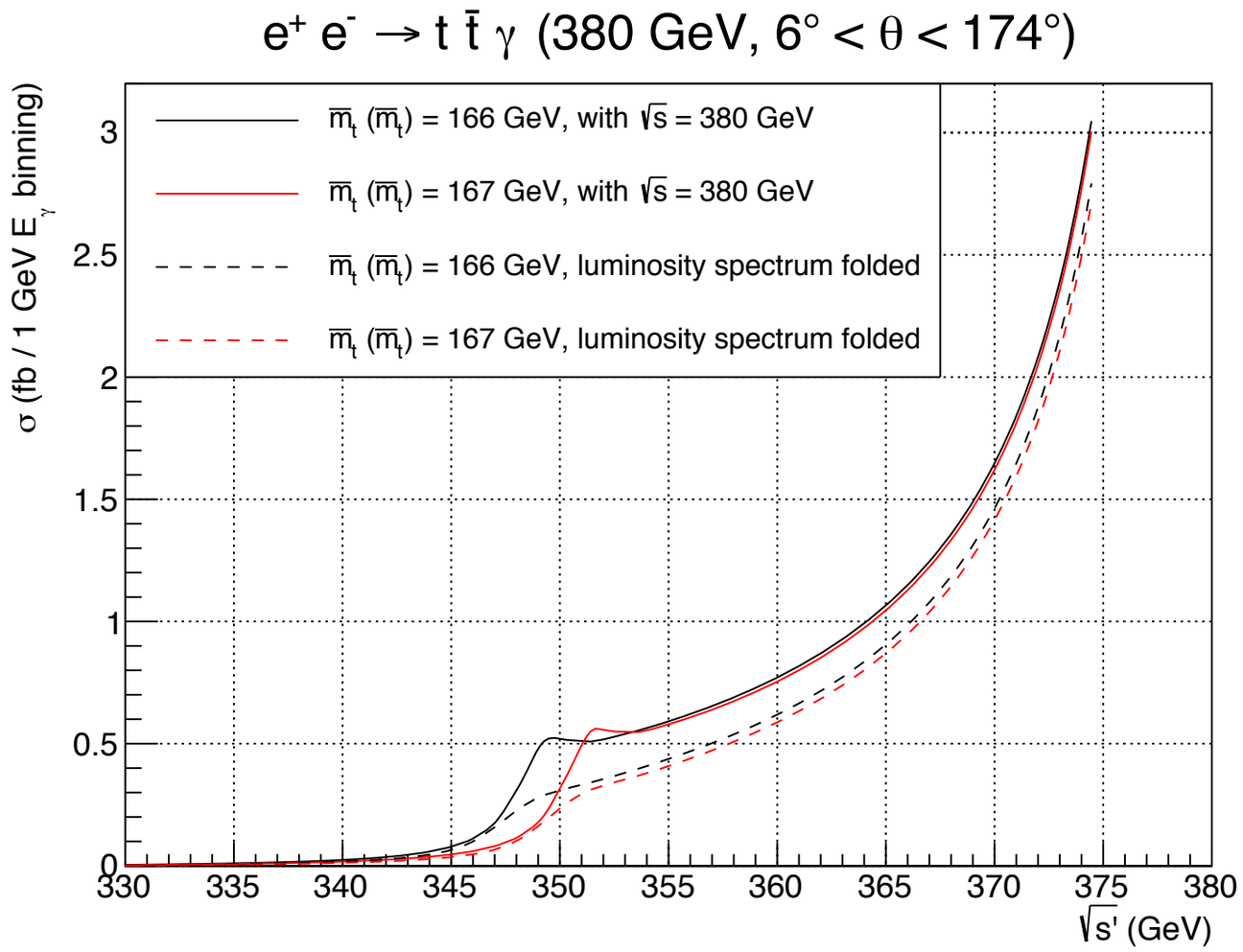
Theoretical model: matched calculation

- A factorization theorem valid at $O(\alpha_{QED})$ and to all orders in α_s (beyond perturbation theory) has been stablished by A. H. Hoang and V. Mateu in which the observable can be calculated analytically:

$$\sigma_{t\bar{t}\gamma_{ISR}}(m_t, s') = \sigma_{ISR}(E_\gamma) * \sigma_{t\bar{t}}(m_t, s')$$

- The model convolutes the ISR calculation with the threshold - continuum matched calculation by A. H. Hoang et al.

- The model outputs the differential cross section of the $e^+e^- \to t\bar{t}\gamma_{\mathrm{ISR}}$ as a function of the photon energy and polar angle respect to the head-on collision, for a given top mass.



- For more information and details on the matched calculation:

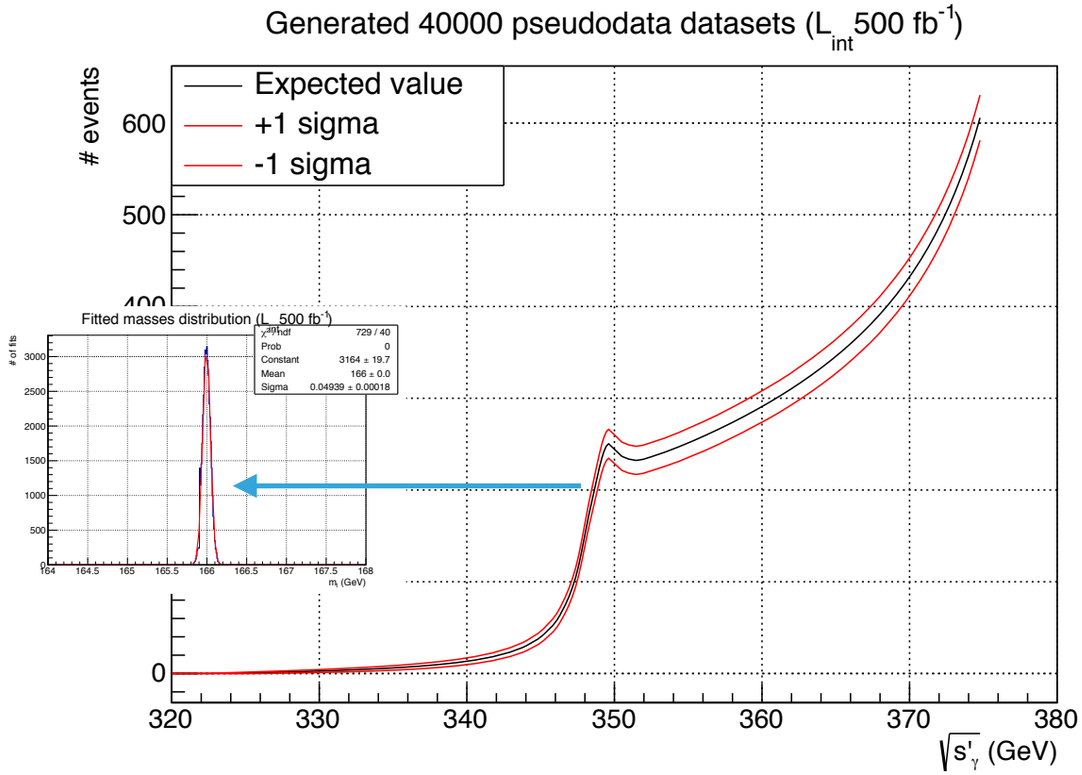
ANGELIKA WIDL LCWS17 TALK

- The input mass can be chosen to be any short-distance mass scheme, in this case we chose the $\overline{\mathrm{MS}}$ scheme. For the calculation itself the 1S and MSR masses are used.

Sensitivity to the top-quark mass

- In order to evaluate the sensitivity of the observable to the top mass we generate pseudo data of certain luminosities.

- We assume that the real number of events in that bin will follow a Poisson distribution with a mean equal to the multiplication of the cross section expected for each of the bins by the integrated luminosity.



- By generating thousands of datasets and fitting them to the theoretical model. We estimate the precision as the sigma of the mass spread.

- For a detector coverage of 6º < θ < 174º, 50 MeV are within reach for 500 fb^{-1} at 380 GeV.

- Taking into account CLIC's luminosity spectrum, the precision goes down to 75 MeV.