Top quark couplings studies in electron-positron colliders at high energies

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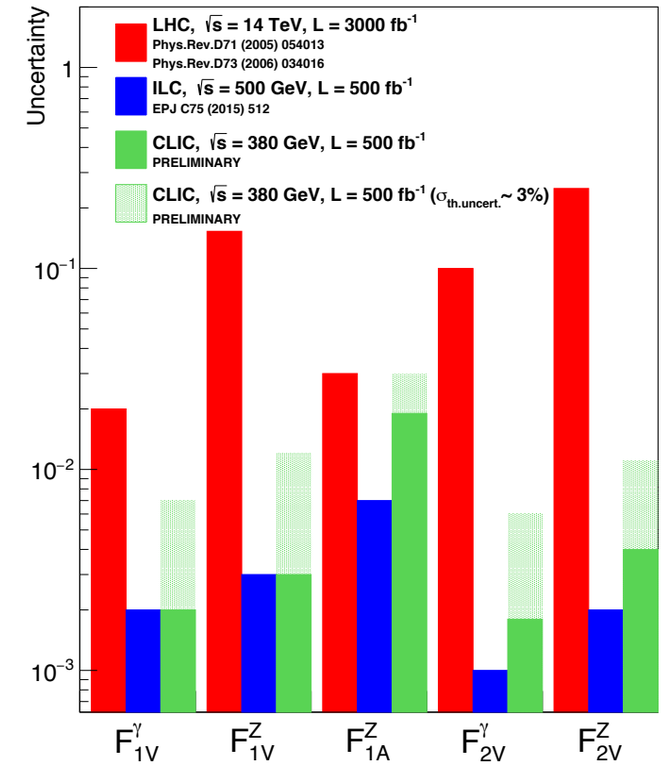
G. Durieux (DESY), C. Zhang (BNL)

Top quark couplings

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



Form-factors

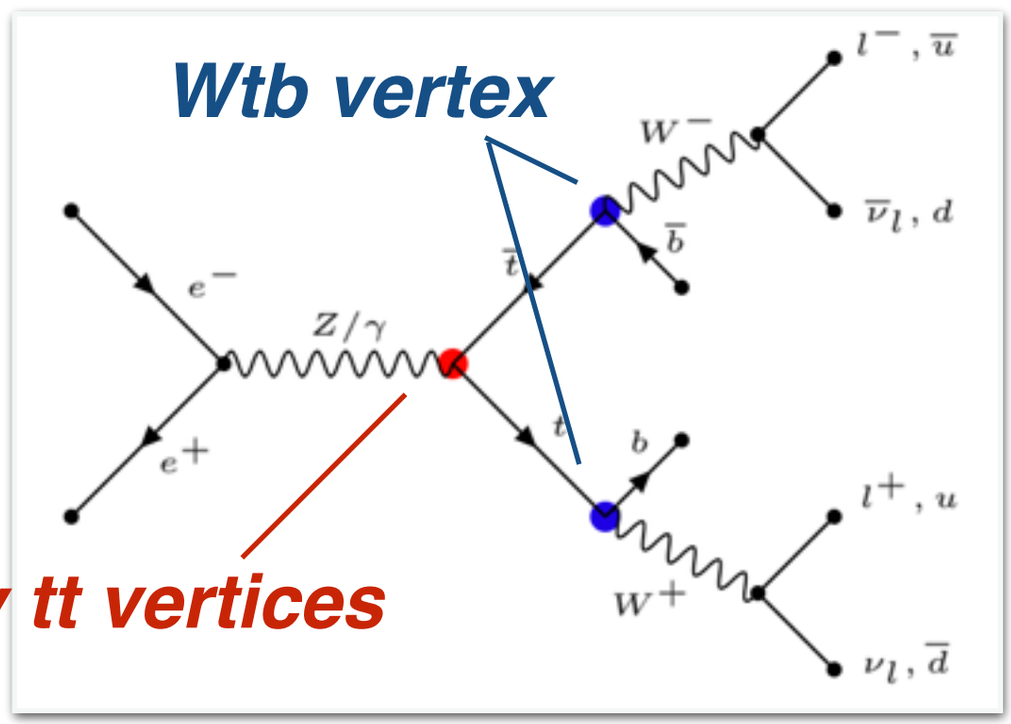
$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$

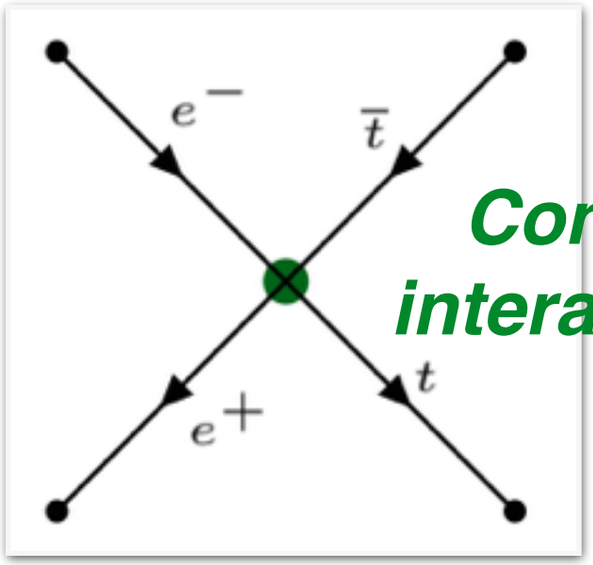
CP Conserving **CPV**

CPV paper under preparation

Effective Field Theory

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



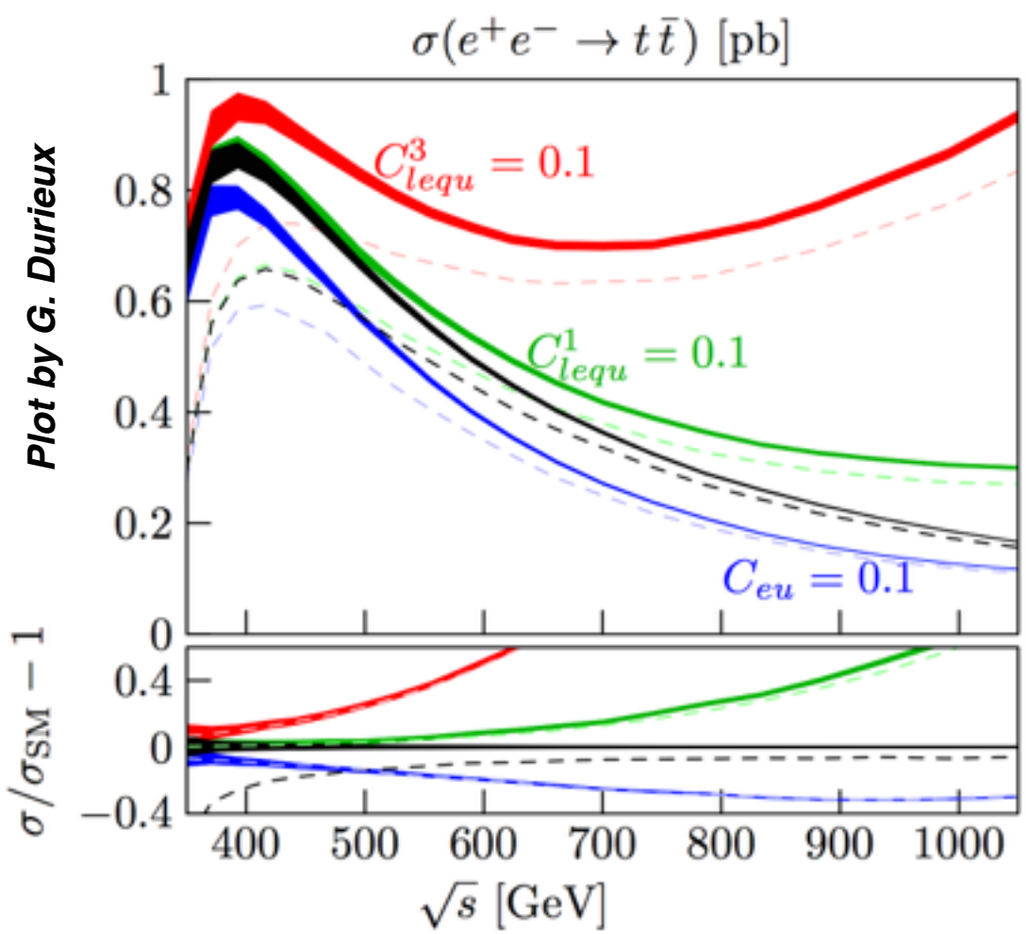


Cross-section sensitivity

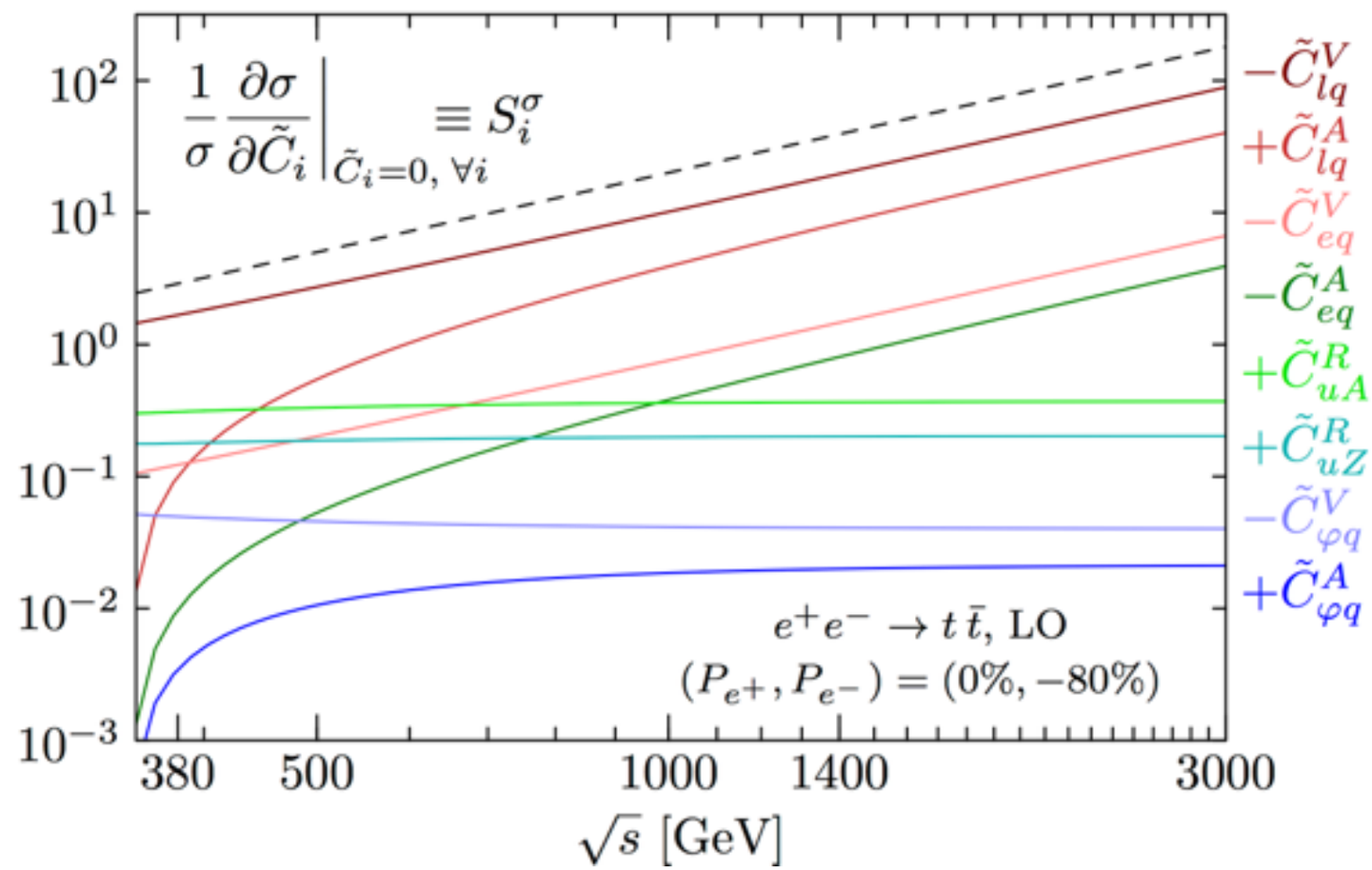
Durieux, Perelló, Vos, Zhang, to be published

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

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



Plot by G. Durieux



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

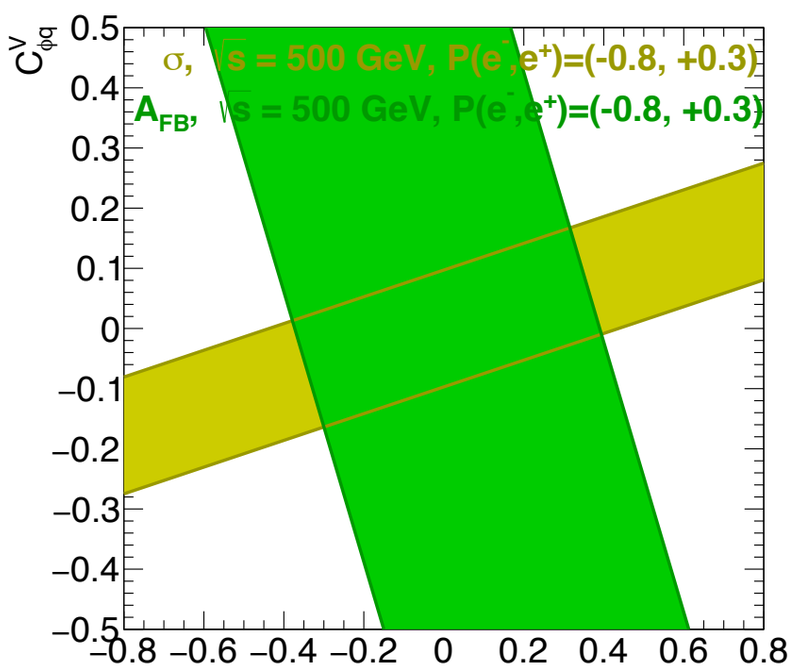
Observables

Final goal: finding several observables which provide good complementarities in a **global top couplings fit**.

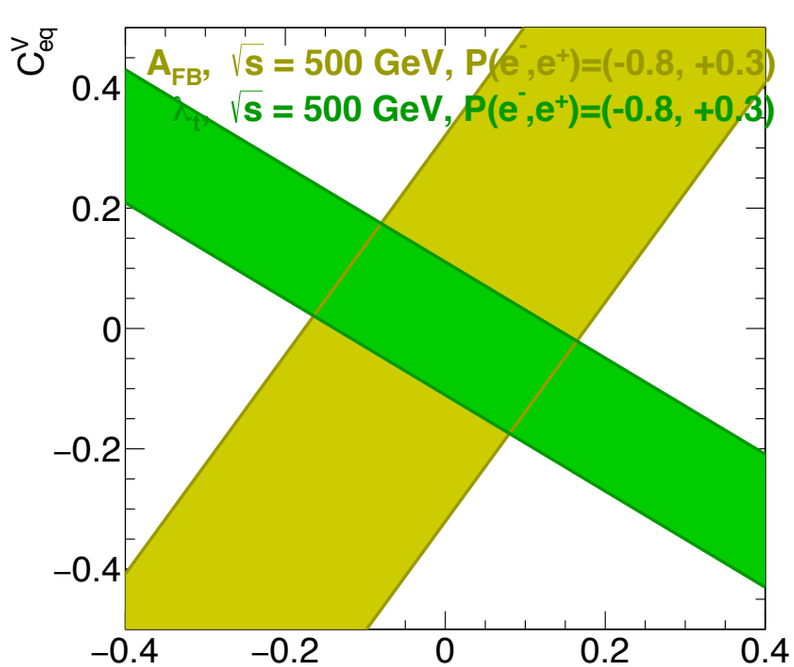
σ, Afb (see R.Ström's talk - *Towards Top Forward-Backwards Asymmetry at 1.4 TeV*)

Final state polarisation from top decay in different axes (sensitive to CPV physics)-> **We need good angular resolution**

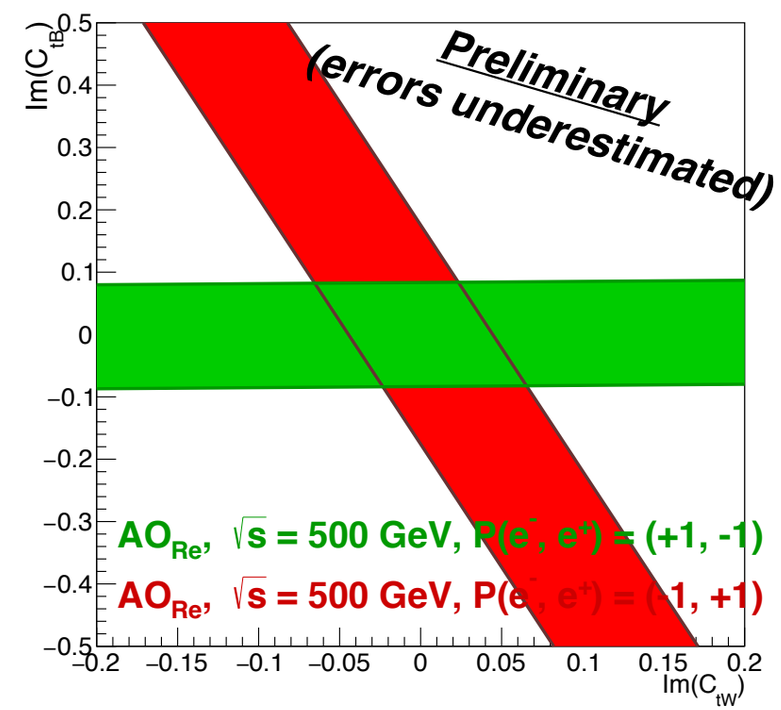
spin-correlation observables -> **Need to tagg a complete ttbar event**



cross-section vs Afb



Afb vs top polarization



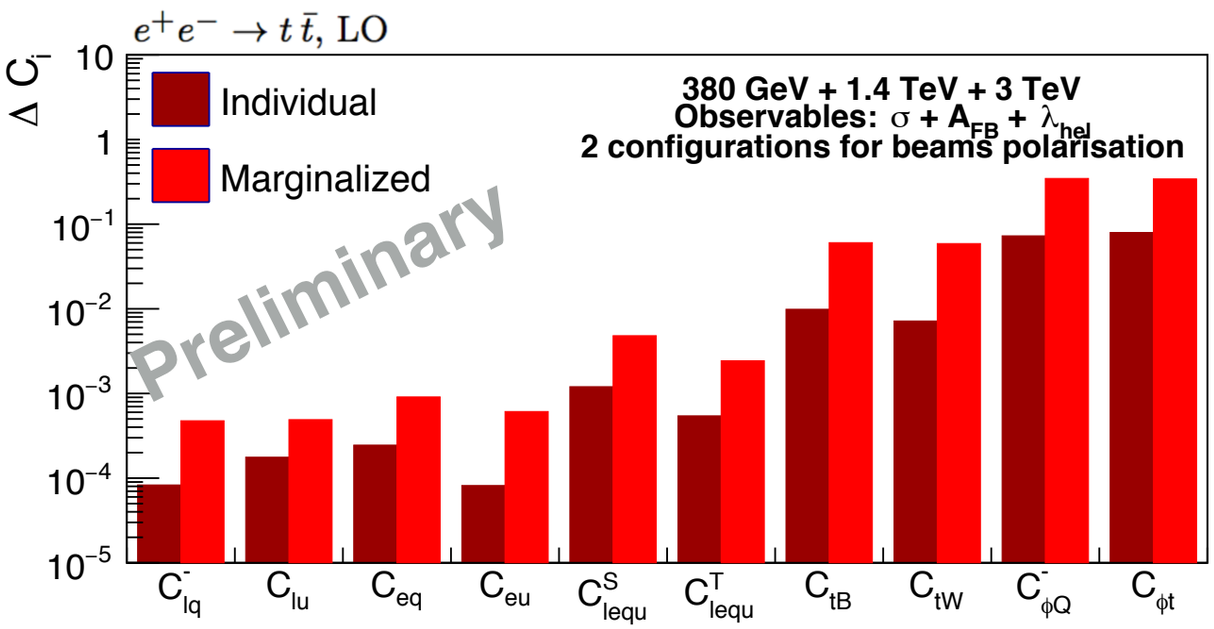
CPV observables *(W. Bernreuther, et al. - arXiv:hep-ph/9602273)*

Global Fit: CLIC program

Global fit in the CLIC energy program: **380 GeV + 1.4 TeV + 3 TeV**

Analysis by I. Garcia

CURRENT TOPIC



(NOW in progress)

- **Impact at <u>NLO</u>**. Global fit for $e^-e^+ \to W^+bW^-\bar{b}$ at NLO soon available.
- Study below ttbar production threshold.
- Deeper study of final state polarisations in top decay.

1.4 TeV

Type	ProdID	Events planned	Events produced	σ [fb]
ee -> yyuyyc	6595	50000	50400	29.7
ee -> yycyyu	6598	50000	52200	29.7
ee -> dduyyu	6601	50000	76600	30.0
ee -> ssussu	6604	10000	11600	0.018
ee -> ssubbu	6610	10000	11400	0.096
ee -> bbubbu	6607	10000	12800	0.013
ee -> ddcyyc	6613	10000	14400	1.82
ee -> sscssc	6616	10000	11800	1.52
ee -> sscbbc	6619	40000	58400	23.5
ee -> bbcbbc	6622	10000	12000	0.013

Signal sample (6-fermion **fully-hadronic** production compatible with ttbar) at 1.4 TeV assuming P(e-) = -80%

Signal Reconstruction:

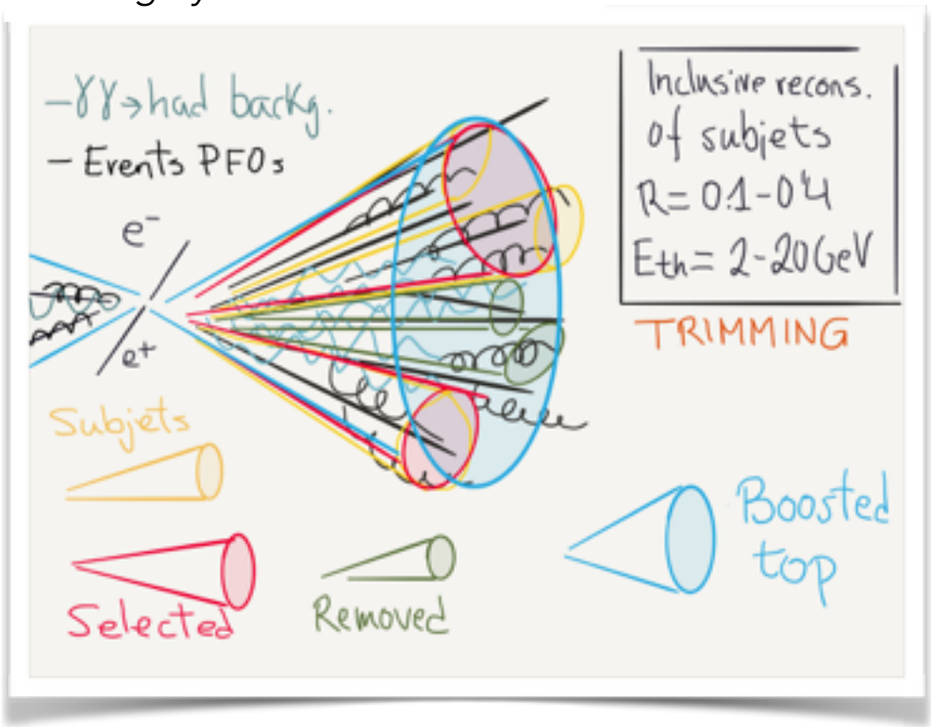
- ttbar selection at truth level
  - 2 b quark.
  - **|M(bjj) - M(topMC)| < 15 GeV** for both tops.

At the moment we focus on boosted ttbar events.

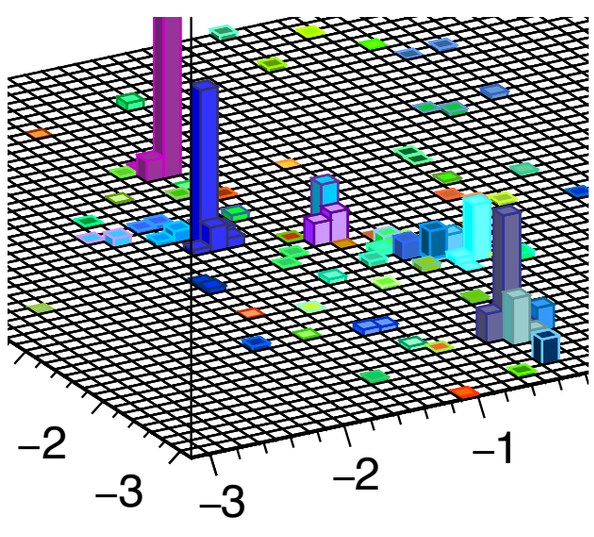
$$\sqrt{s'} > 1350\ GeV$$

Top reconstruction at high energies

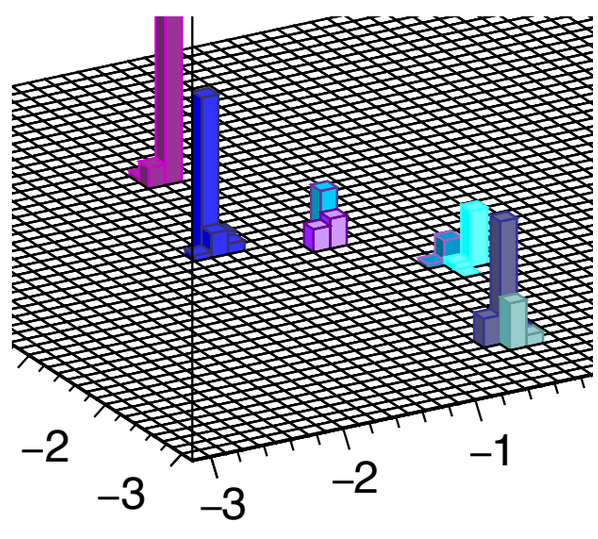
Drawing by I. Garcia



BEFORE TRIMMING



AFTER TRIMMING



1) Trimming technique

<u>Remove background</u>. *Inclusive reconstruction of subjets with high activity removing the soft stuff.*

⬇

<u>Subjets reconstruction</u>

- ee_genkt_algorithm
- $R_{subjets} = 0.4$
- $E_{threshold} = 5$ GeV

⬇

<u>Clustering the subjets into a big boosted jet.</u>

- VLC algorithm.

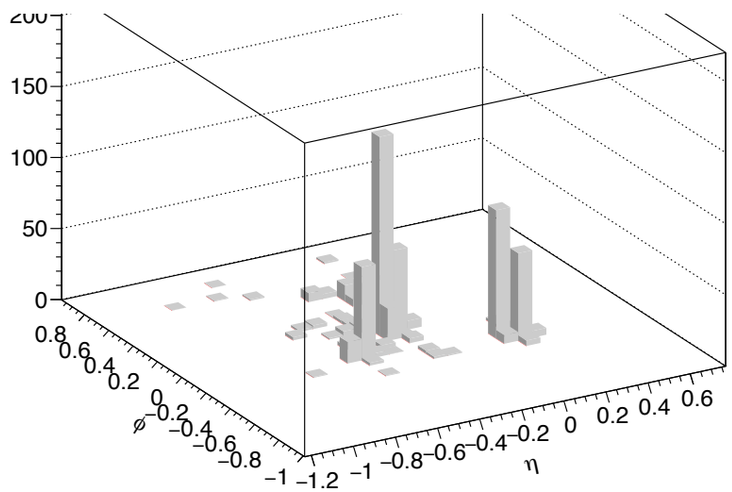
Top reconstruction at high energies

2) TopTagger

Following the method from Kaplan et al.: ***DOI: 10.1103/PhysRevLett.101.142001***

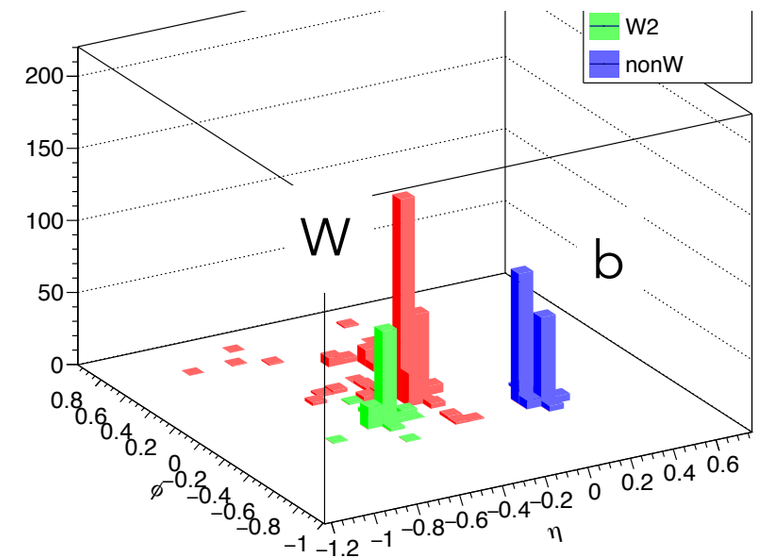
Parsing through jet cluster

- zoom in on one of the tops from a fully-hadronic ttbar event -



Top Tagging

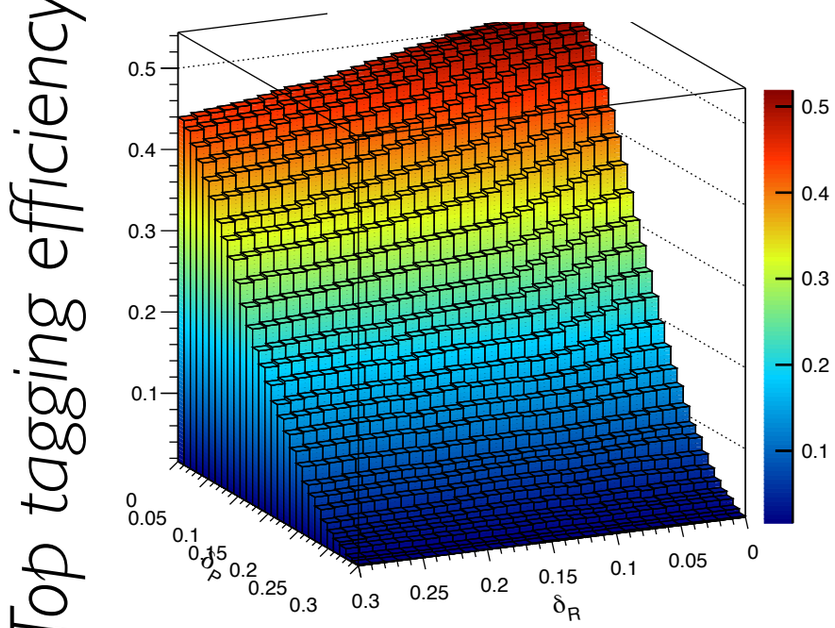
The three subjets after top tagging are shaded separately



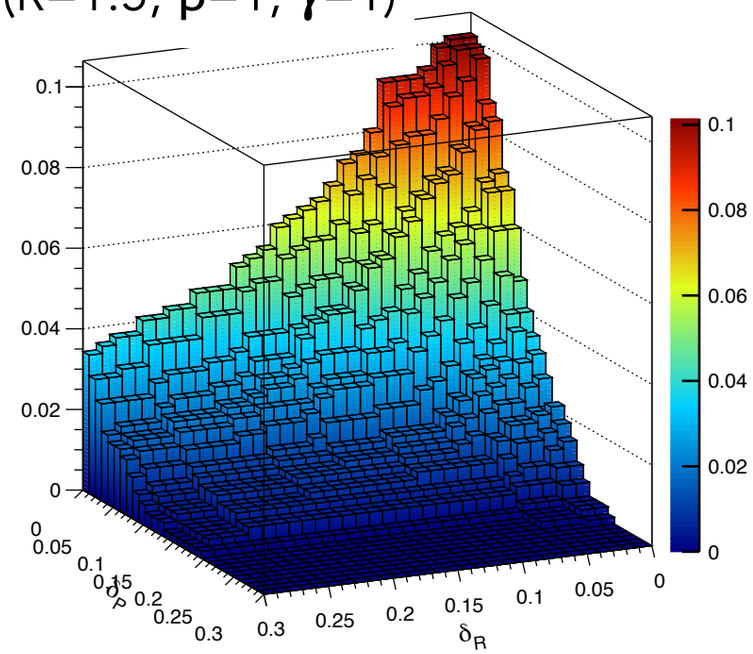
Purpose: make sure the resulting subjets are consistent with top mass, and that 2 are consistent with W mass.

TopTagger Parameters

VLC jet clustering algorithm (R=1.5, β=1, γ=1)



ttbar signal example:
$e^+e^- \rightarrow$ dduyyu (y=d, s, b)



background example:
$e^+e^- \rightarrow qq$

- *δr is the minimum distance between declustered subjets.*
- *δp is the minimum fraction of momentum of the declustered subjets respect to the full jet.*

δr = δp = 0.05

Chosen values for the optimisation (could vary depending on the analysis and the background rejection)

The following kinematic cuts are applied:

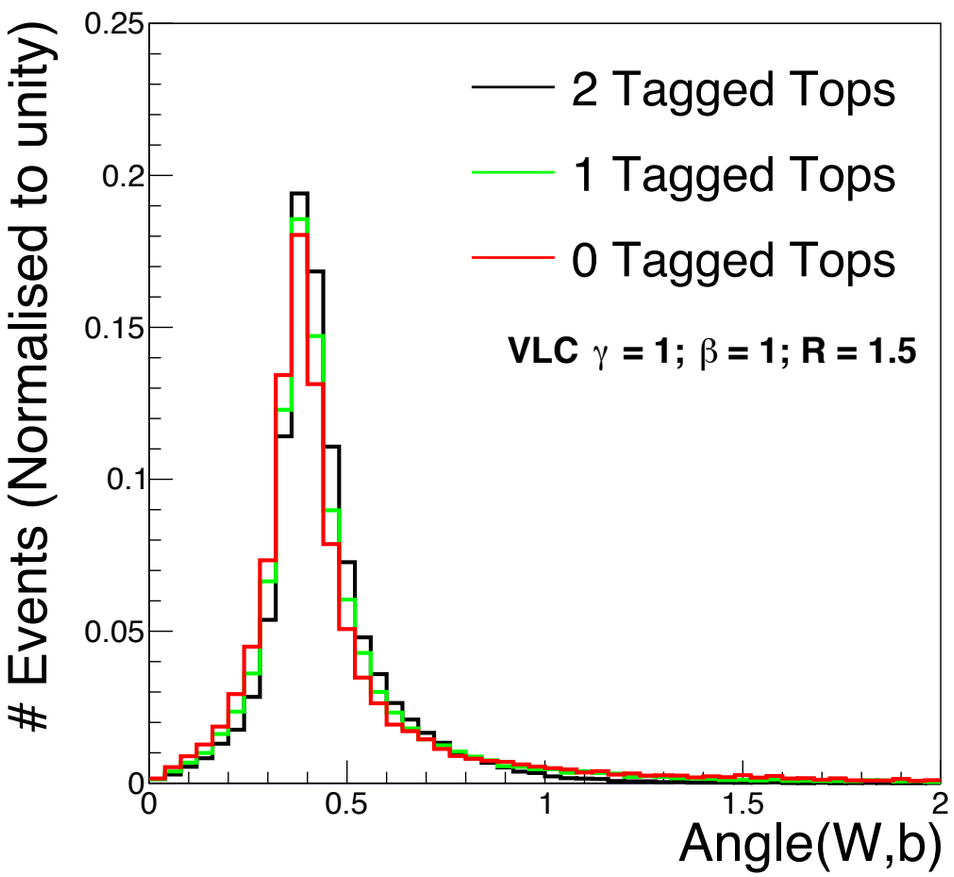
- Total invariant mass of 3-4 subjet system close to m_t:
  - 145 GeV ≤ m_t ≤ 205 GeV
- Two subjects which reconstruct the W mass within:
  - 65 GeV ≤ m_W ≤ 95 GeV

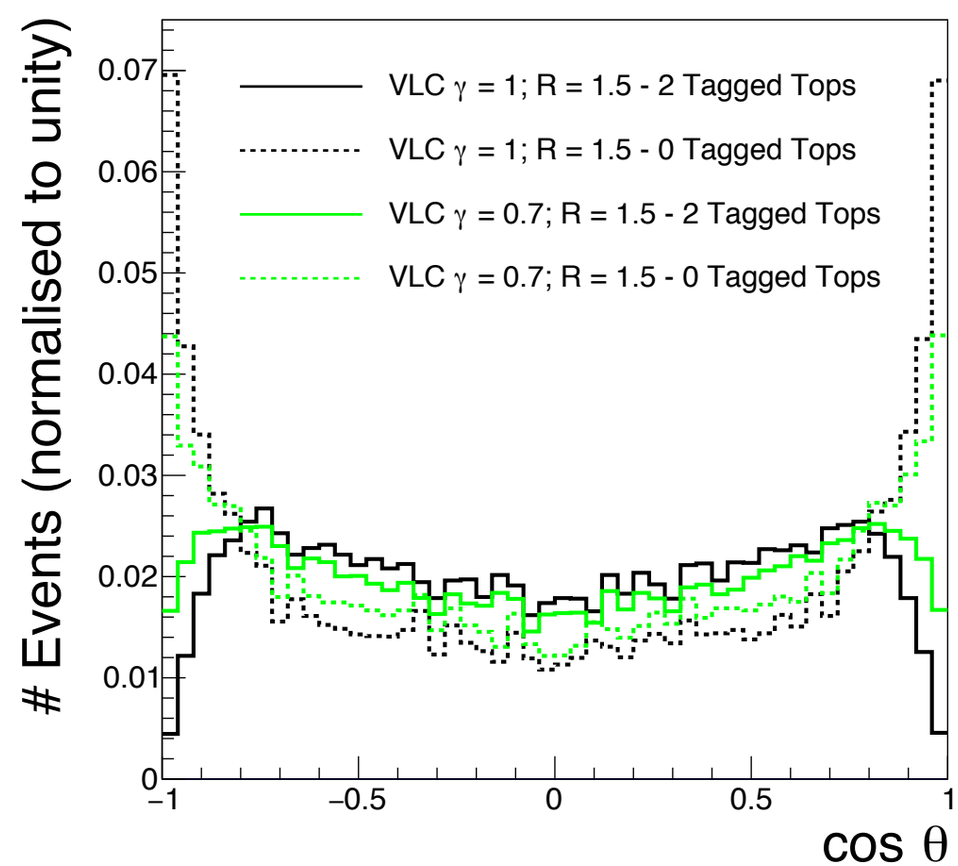
Top Tagging Efficiency

	Efficiency [%]
VLC R=1.5 β=1 γ=1	50,2
VLC R=1.5 β=1 γ=0.7	52,0
VLC R=1.7 β=1 γ=0.7	51,0

Where are we losing events?

Distributions at generation level…

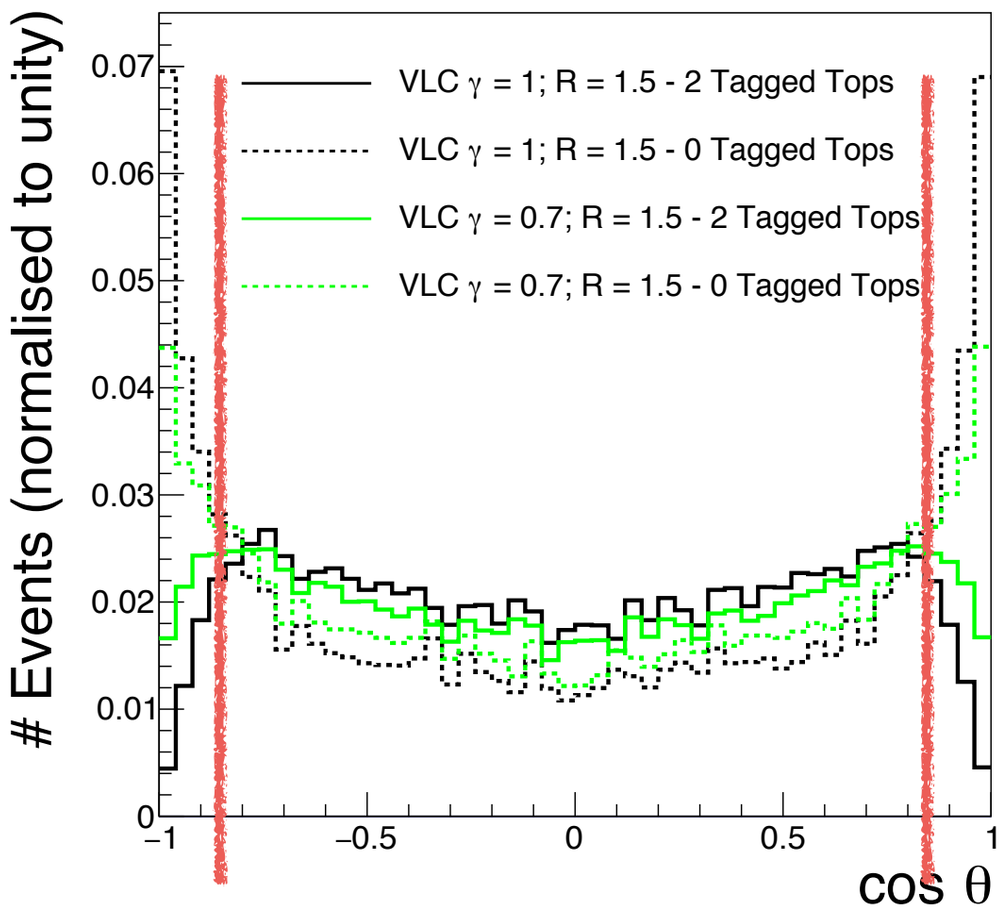




Top Tagging Efficiency

Forward cut on the top/antitop at generation level
$\pi/6 < \theta < 5\pi/6$

	Efficiency in the central region [%]	Efficiency in the forward region [%]
VLC R=1.5 β=1 γ=1	53,9	33,1
VLC R=1.5 β=1 γ=0.7	53,5	45,3
VLC R=1.7 β=1 γ=0.7	52,0	46,8



Further optimization in progress…

- Exploring the capability of VLC algorithm in the forward region.
- *(See R. Ström's presentation for a background analysis).*
- Any idea is welcome!

Summary

- Running at high energies gives important information in a top couplings global fit. Particularly we can put more precise bounds in contact interaction parameters.

- The reconstruction and identification of energetic top quarks are challenging steps (single top, low energy regime and forward tops are avoided at the moment).

- A “work in progress” gives us a tagging efficiency around 50%.

Backup

Top Tagging Algorithm

1) PFO objects are clustered into jets of size R (large jet) - any algorithm
   - Iteratively merge 4-vector pairs with closest $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ until $\Delta R < R$

2) Iteratively decluster each resulting jet (reversing each step in the jet clustering) to search for subjets
   - Split into two parts, reject softest if ..... $\frac{p_T^{\text{subjet}}}{p_T^{\text{jet}}} < \delta_p$
   - Declustering <u>continues on the harder</u> object until:

Both subjets are harder than	$p_T^{\text{jet}} \cdot \delta_p$	✔	Both subjets are too close	$\lvert\Delta\eta\rvert + \lvert\Delta\phi\rvert < \delta_r$	✗
Both subjets are softer than	$p_T^{\text{jet}} \cdot \delta_p$	✗	Only one calorimeter cell left		✗

3) If an original jet declusters into two subjets - step 2 is repeated on those subjets
   - Results in 1 (original jet), 2, 3, or 4 (additional soft gluon emission) subjets

4) Additional kinematic cuts

Selection efficiency

VLC R=1.5 β=1 γ=1

Cuts at generation level…

Boosted cut	Forward cut	tt Selection
$\sqrt{s'} > 1350$ GeV	$\pi/6 < \theta < 5\pi/6$	• 2 b quark. • **|M(bjj) - M(topMC)| < 15 GeV** for both tops.
26.1%	70.4%	65.8%
	(18.4%)	(12.1%)

Top Mass Reconstruction

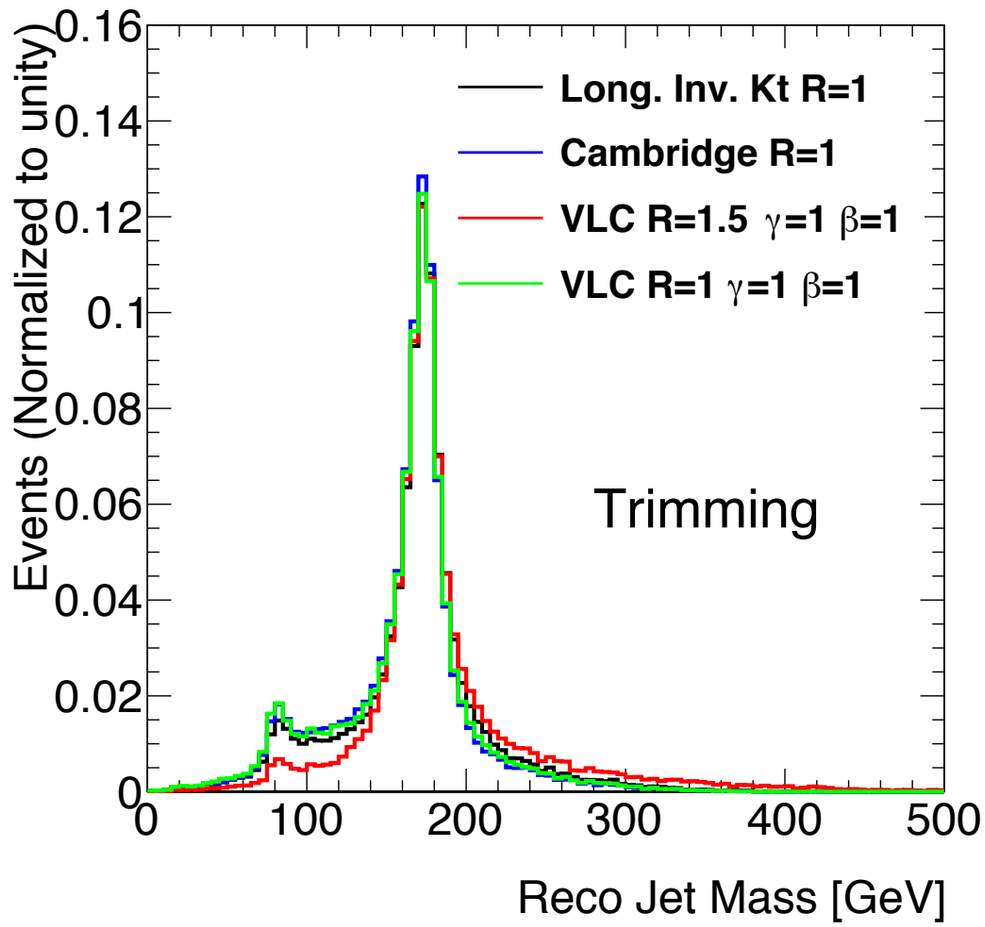


TABLE 3: Signal: > 1350 GeV + ttbar Selection + forward cut (pi/6 < theta < 5pi/6) - Selected PFOs

		Tagging Events Eff.	Tagging Jets Eff.	Mass From Jet Reco			Mass From Tagging			Energy			
				Mean (GeV)	Sigma (GeV)	RMS90	Mean (GeV)	Sigma (GeV)	RMS90	Mean (GeV)	Sigma (GeV)	RMS90	RMS90 (%)
2	VLC R=1.5 beta=1 gamma=1	54,5	32,7	173,5	9	40,5	173,6	8,4	44,5	6,1	22,7	46,1	6,6
4	long. inv. kt R=1	56,8	34,4	173,7	9	34,6	173,9	9,7	34,4	5,9	24,6	48,7	7
6	Cambridge R=1 (2 most energetic jets)	55,8	33,6	173,1	8,2	32,6	170,9	7,5	77,2	-	-	-	-
8	VLC R=1 beta=1 gamma=1	57,4	34,8	173,1	8,4	33,5	173,3	8,1	32,4	5,5	24,6	51,5	7,4

Valencia jet algorithm

A new clustering jet reconstruction algorithm that combines the good features of lepton collider algorithms, in particular the **Durham-like distance criterion;**

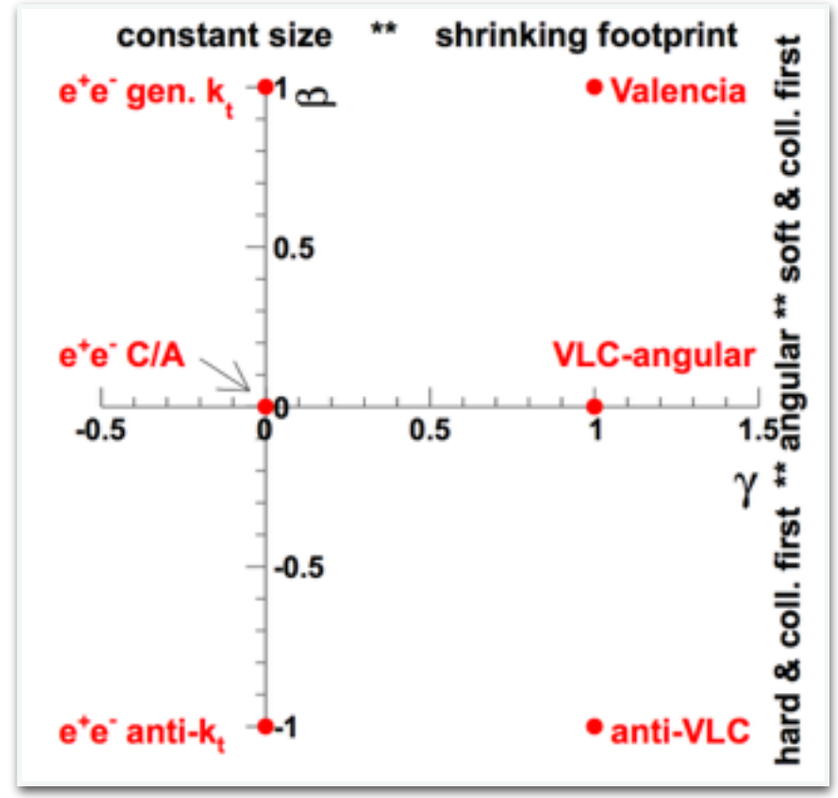
$$d_{ij} = min(E_i^{2\beta}, E_j^{2\beta})(1 - \cos\theta_{ij})/R^2$$

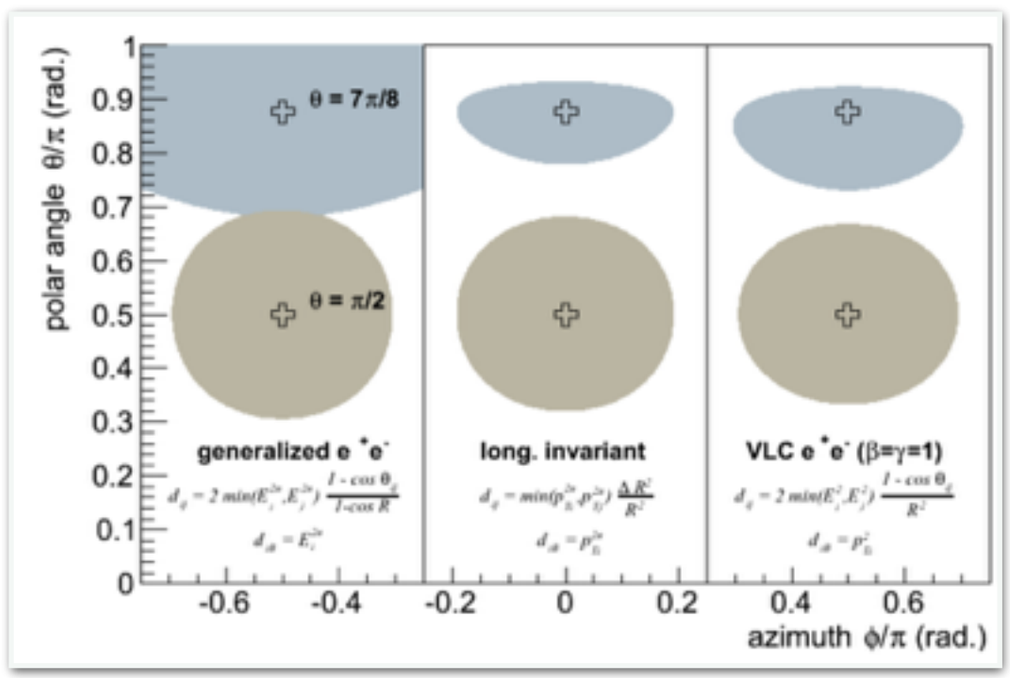
with the **robustness against background of** the longitudinally invariant **k_t algorithm**

$$d_{iB} = E^{2\beta} \sin^{2\gamma} \theta_{iB}$$

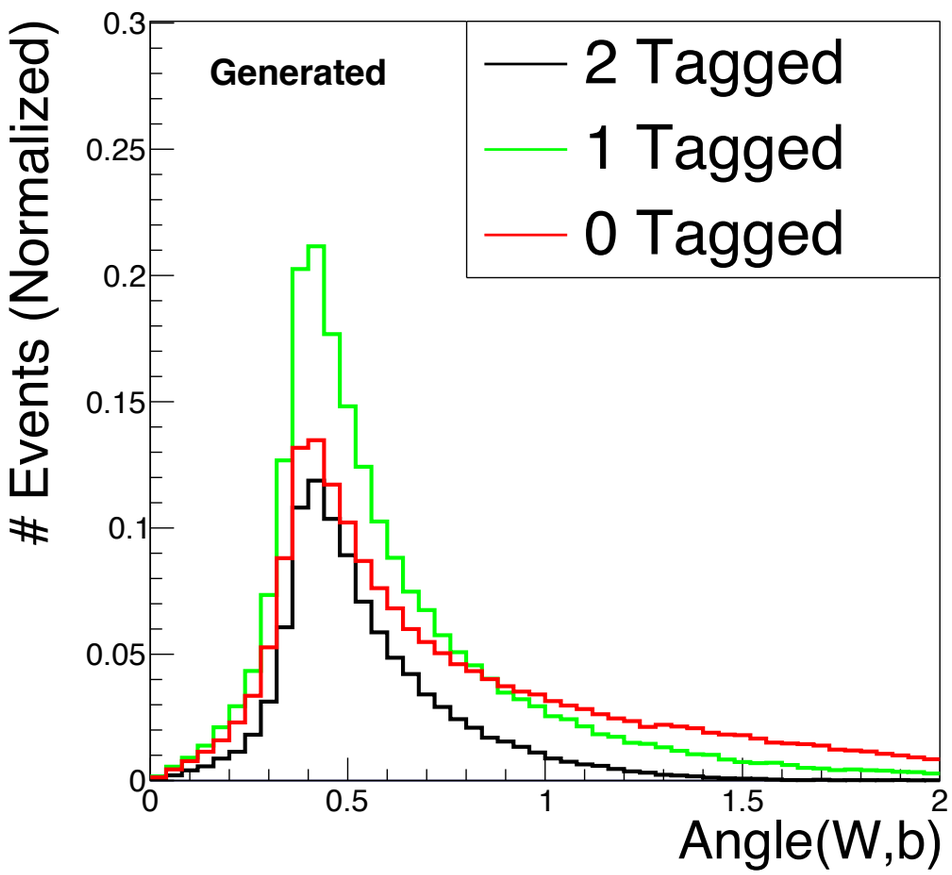
The γ parameter governs the evolution of the jet area with polar angle and β allows to ***change the clustering order.***

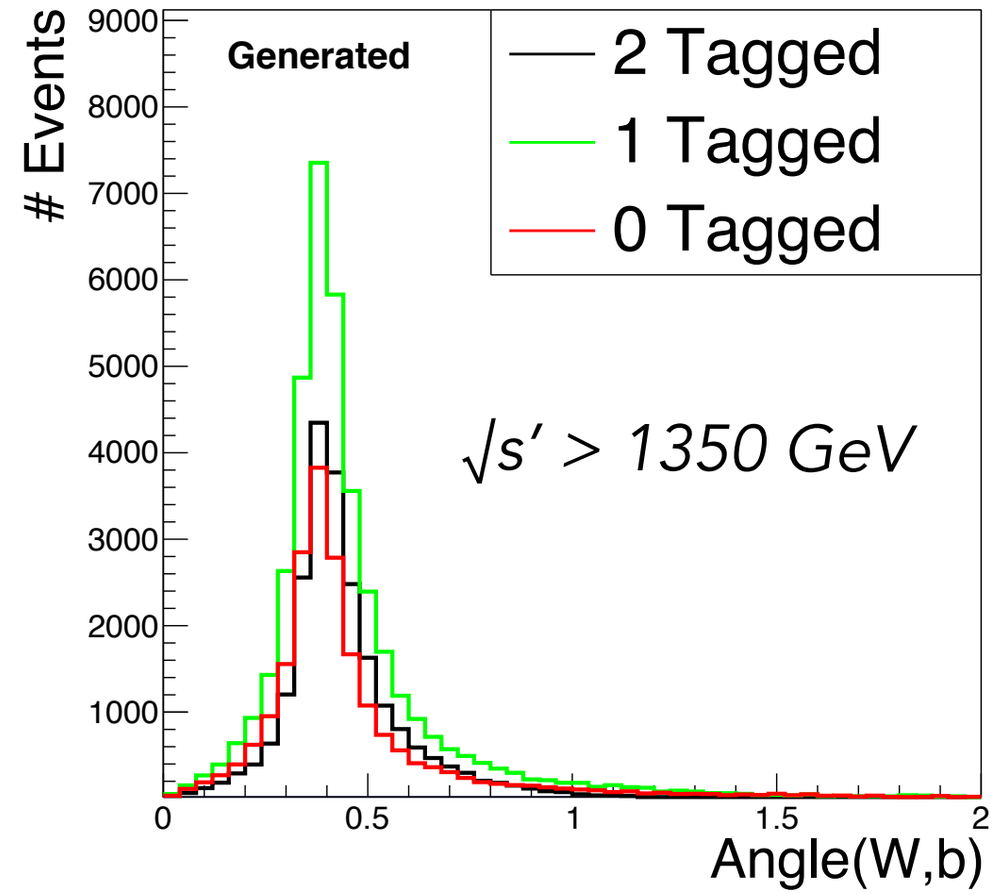
*In the default settings the two exponents β and γ are equal. For **β=γ=1** the expression simplifies to $d_{iB} = E^2 \sin^2 \theta_{iB} = p^2_{ti}$

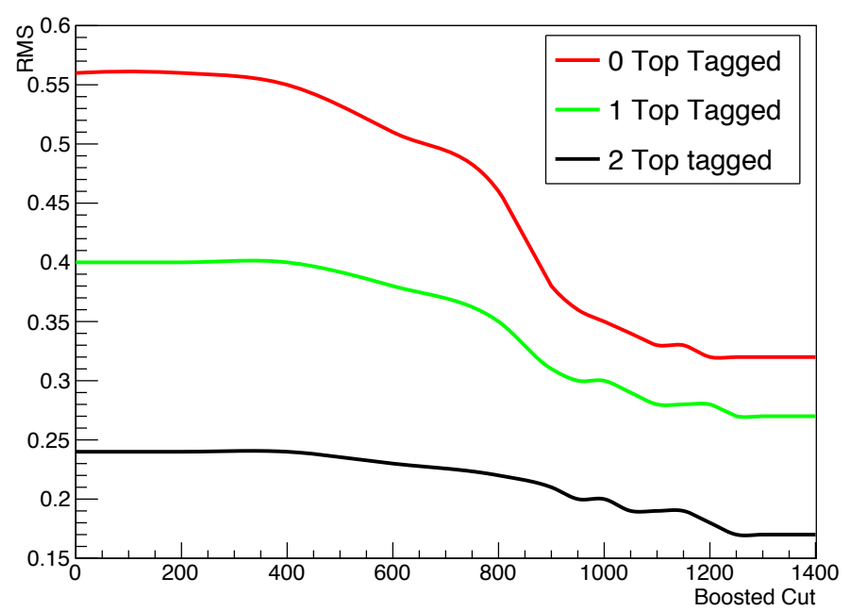




Angle between W and b







An EFT analysis

Gauthier Durieux in TopLC 2016 (KEK):

- Go global!
  - NP can generate several operators at a high scale
  - RG running down to low scales can mix them with others
  - Operators are re-express as combinations of others to form a basis

(Renormalisation Group)

- Face interferences!

$$\sigma_{e^+e^-\to t\bar{t}}^{\sqrt{s}=500\ \mathrm{GeV}}\ [\mathrm{fb}] = +568 + \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 \begin{pmatrix} C_{lq}^A \\ C_{eq}^A \\ C_{\phi q}^A \\ C_{lq}^V \\ C_{eq}^V \\ C_{\phi q}^V \\ C_{uZ}^R \\ C_{uA}^R \\ C_{uZ}^I \\ C_{uA}^I \end{pmatrix}^T \begin{pmatrix} +221 \\ -194 \\ +7.01 \\ -1110 \\ -737 \\ -8.24 \\ +33.8 \\ +209 \\ \cdot \\ \cdot \end{pmatrix} + \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 \begin{pmatrix} C_{lq}^A \\ C_{eq}^A \\ C_{\phi q}^A \\ C_{lq}^V \\ C_{eq}^V \\ C_{\phi q}^V \\ C_{uZ}^R \\ C_{uA}^R \\ C_{uZ}^I \\ C_{uA}^I \end{pmatrix}^T \begin{pmatrix} +367 & \cdot & +13.2 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & +367 & -11.5 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & +0.209 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & +868 & \cdot & +31.1 & -128 & -197 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & +868 & -27.3 & +112 & -197 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & +0.493 & -4.05 & -0.432 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & +9.36 & +2 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & +25.2 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & +2.51 & +0.536 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & +6.75 \end{pmatrix} \begin{pmatrix} C_{lq}^A \\ C_{eq}^A \\ C_{\phi q}^A \\ C_{lq}^V \\ C_{eq}^V \\ C_{\phi q}^V \\ C_{uZ}^R \\ C_{uA}^R \\ C_{uZ}^I \\ C_{uA}^I \end{pmatrix}$$

$$+ \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 \left\{ +1600 \left|C_{lequ}^S\right|^2 + 13900 \left|C_{lequ}^T\right|^2 \right\}$$

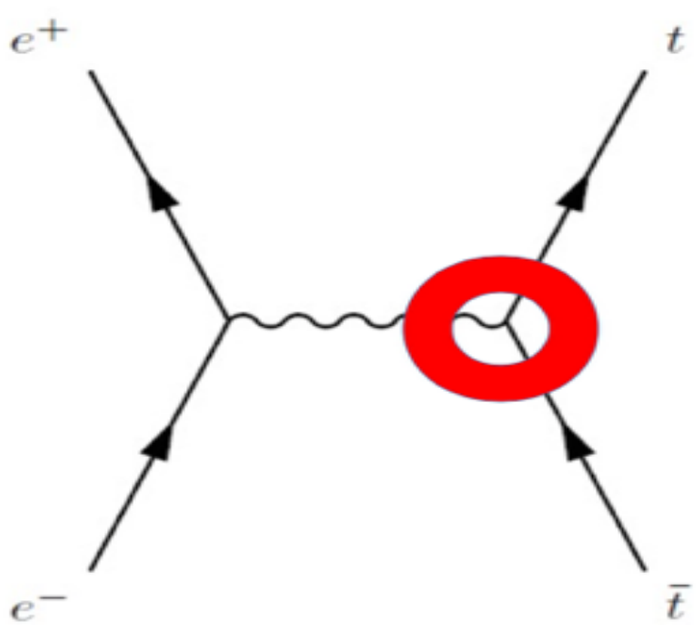
- Combine observables!
- Offer yourself N^{n}LO!

EFT: 2-fermion (vertex) operators

Alternative to form-factors: Integrate out explicit mediators and **describe BSM effect through effective D6 operators.**

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

Operators acting on EW vertices (“2-fermion” operators).



ttZ/ttγ vertices

$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}\gamma^\mu q)$$

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{q}\gamma^\mu \tau^I q)$$

$$O_{tB} = y_t g_Y\left(\bar{q}\sigma^{\mu\nu}t\right)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tW} = y_t g_w\left(\bar{q}\sigma^{\mu\nu}\tau^I t\right)\tilde{\varphi}W^I_{\mu\nu}$$

tWb vertices

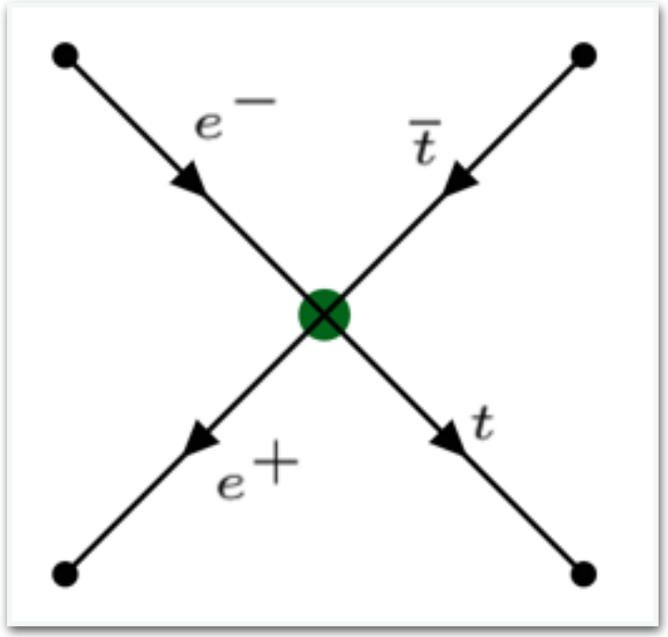
$$O_{bW} = y_b g_w\left(\bar{q}\sigma^{\mu\nu}\tau^I b\right)\varphi W^I_{\mu\nu}$$

$$O_{\varphi\varphi} = i\frac{1}{2}y_t y_b\left(\tilde{\varphi}^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu b)$$

$O_{\varphi Q}^{(3)}$ O_{tW}

EFT: 4-fermion (contact interaction) operators

Other group of D6 effective operators collect the e-e+tt contact interaction (**"4-fermion" operators**) :



($\bar{L}$L)($\bar{L}$L)	$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma_\mu l)\,(\bar{q}\gamma^\mu q)$
	$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma_\mu \tau^I l)\,(\bar{q}\gamma^\mu \tau^I q)$
($\bar{R}$R)($\bar{R}$R)	$\mathcal{O}_{eu}$	$(\bar{e}\gamma_\mu e)\,(\bar{u}\gamma^\mu u)$
($\bar{R}$R)($\bar{L}$L)	$\mathcal{O}_{eq}$	$(\bar{e}\gamma_\mu e)\,(\bar{q}\gamma^\mu q)$
($\bar{L}$L)($\bar{R}$R)	$\mathcal{O}_{lu}$	$(\bar{l}\gamma_\mu l)\,(\bar{u}\gamma^\mu u)$
($\bar{L}$R)($\bar{R}$L) & ($\bar{R}$L)($\bar{L}$R)	$\mathcal{O}_{lequ}^{(1)}$	$(\bar{l}e)\,\epsilon\,(\bar{q}u)$
	$\mathcal{O}_{lequ}^{(3)}$	$(\bar{l}\sigma_{\mu\nu}e)\,\epsilon\,(\bar{q}\sigma^{\mu\nu}u)$

Conversion to V/A - V basis:

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

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

multi-TeV operation

MC simulation for effective operators parameterisation: **MG5_aMC@NLO with an EW Effective Theory model** (*courtesy of C. Zhang, G. Durieux, et al.*).

$e^-e^+ \to t\bar{t}$ **LO production at…**

	Full - Simulation		Temporary scaling		
	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)
Cross-section (pb)	0,792	0,930	0,256	0,113	0,025
Lumi (fb-1)	500	500	1000	1500	3000

Parameterisation of different observables through effective operators…

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\mathrm{TeV})^2}\sigma_i^{(1)} + \sum_{i\leq j} \frac{C_i C_j}{(\Lambda/1\mathrm{TeV})^4}\sigma_{ij}^{(2)}$$