Top quark physics at Linear Colliders

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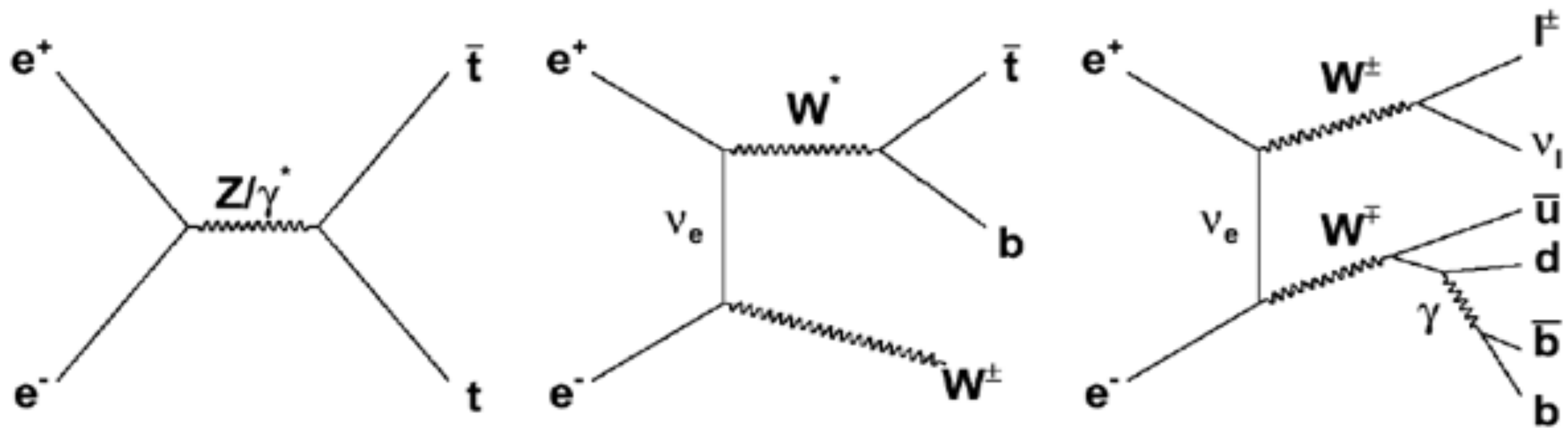
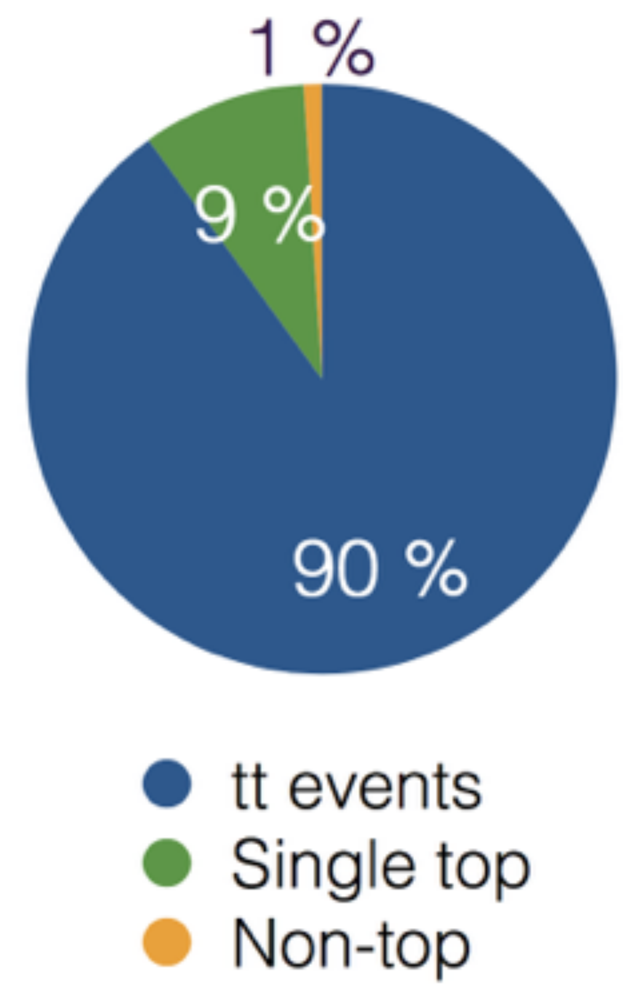
Outline

- **Single top production analysis**.
- **Valencia jet algorithm**.
- **Top quark mass** from the…
  - continuum (radiative processes).
  - tt production threshold.
- **Top quark couplings**.
  - CP conserving top couplings.
  - CPV top couplings.
  - Effective operators approach.

Single top analysis



3 processes give rise to the same WbWb final state



- A study at truth level shows that **the content of single top depends on the beam polarisation and in the center-of-mass energy.**
- In this study **a top is defined when the invariant mass of a Wb event satisfies**:

$$|m_{Wb} - m_t^{MC}| < 15 \text{ GeV}$$

- **Difficult to distinguish the source in a WbWb final state**: we advocate for the **analysis of inclusive WbWb production.**

Study of single top production at high energy electron positron colliders
J. Fuster, I. García, P. Gomis, M. Perelló, Eduardo Ros, Marcel Vos (Valencia U., IFIC)
Eur.Phys.J. C75 (2015) 223
(2015-05-22)
DOI: 10.1140/epjc/s10052-015-3453-2

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 $d_{iB} = E^2 \sin^2 \theta_{iB} = p^2_{ti}$

A robust jet reconstruction algorithm for high-energy lepton colliders
Marça Boronat, J. Fuster, Ignacio Garcia, E. Ros, Marcel Vos (Valencia U., IFIC)
Phys.Lett. B750 (2015) 95-99
(2015-08-27)
DOI: 10.1016/j.physletb.2015.08.055

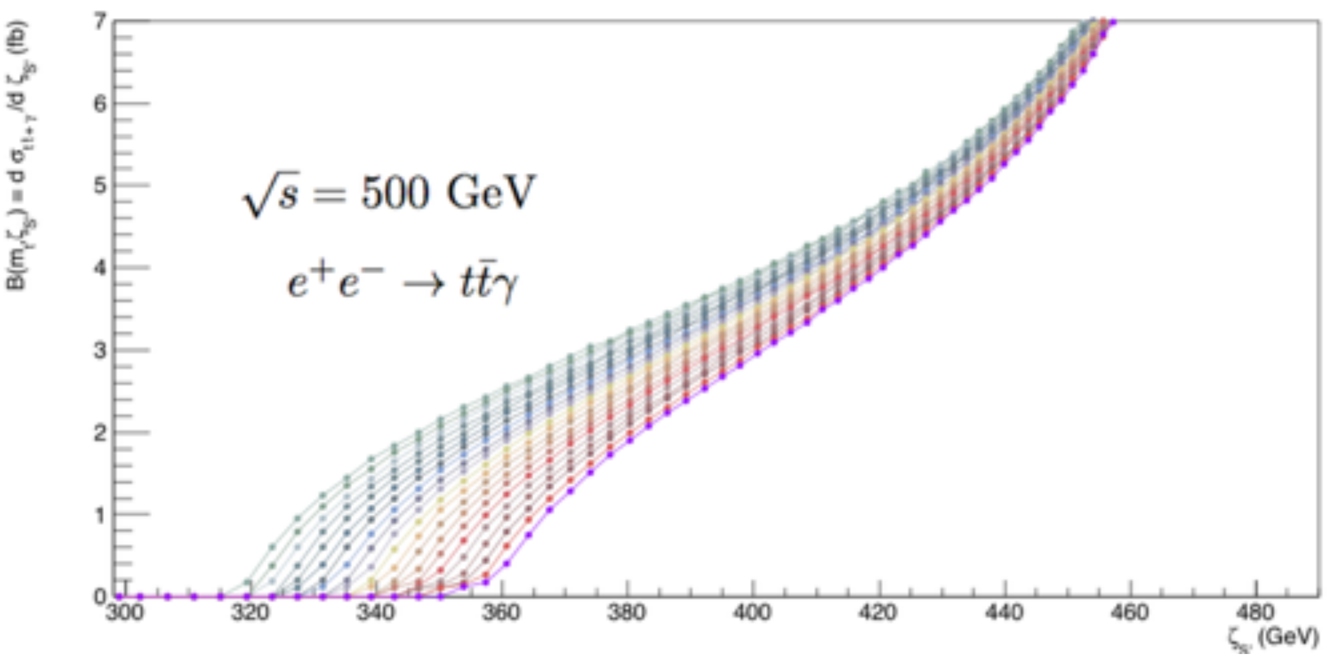
Top mass at continuum: motivation

Objective: **high precision measurement of the top quark mass in the continuum of an e-e+ collider.**

Observable: **cross-section** for the **radiative processes**: **ee —> tt + photon (ISR) / ee —> tt + gluon (FSR) in terms of the energy** taken by the **photon/gluon**.

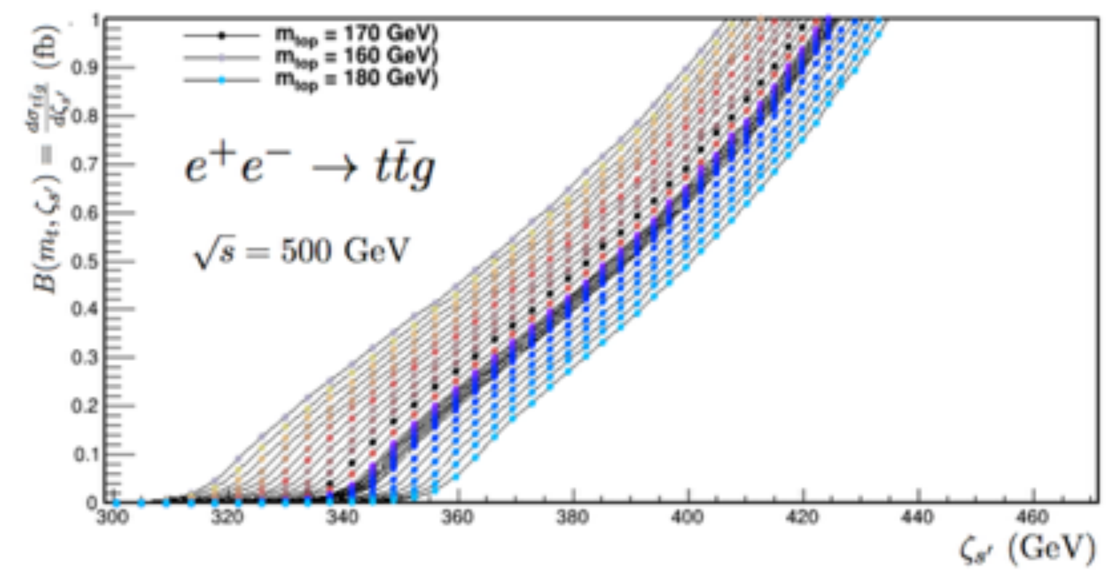
Conditions: **ILC + CLIC studies at different energy points. Preliminary study of detector simulation.**

Tools: **Pythia 8.1** for generating the theoretical cross-section curves (*see below*). **Extraction of the top mass** by the **template method**.



$$B(m_t,\zeta_{s'}) = \frac{d\sigma_{t\bar{t}\gamma}}{d\zeta_{s'}} \qquad \zeta_{s'} = \sqrt{s'} \qquad s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

$$\frac{1}{\sigma_0}\frac{d^2\sigma}{dx_1 dx_2} = C_F\frac{\alpha_s}{2\pi}\left[\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)} - \frac{4m_q^2}{s}\left(\frac{1}{1-x_1}+\frac{1}{1-x_2}\right) - \frac{2m_q^2}{s}\left(\frac{1}{(1-x_1)^2}+\frac{1}{(1-x_2)^2}\right) - \frac{4m_q^4}{s^2}\left(\frac{1}{1-x_1}+\frac{1}{1-x_2}\right)^2\right]$$



$$B(m_t,\zeta_{s'}) = \frac{d\sigma_{t\bar{t}g}}{d\zeta_{s'}} \qquad \zeta_{s'} = \sqrt{s'} \qquad s' = s\left(1 - \frac{2E_g}{\sqrt{s}}\right)$$

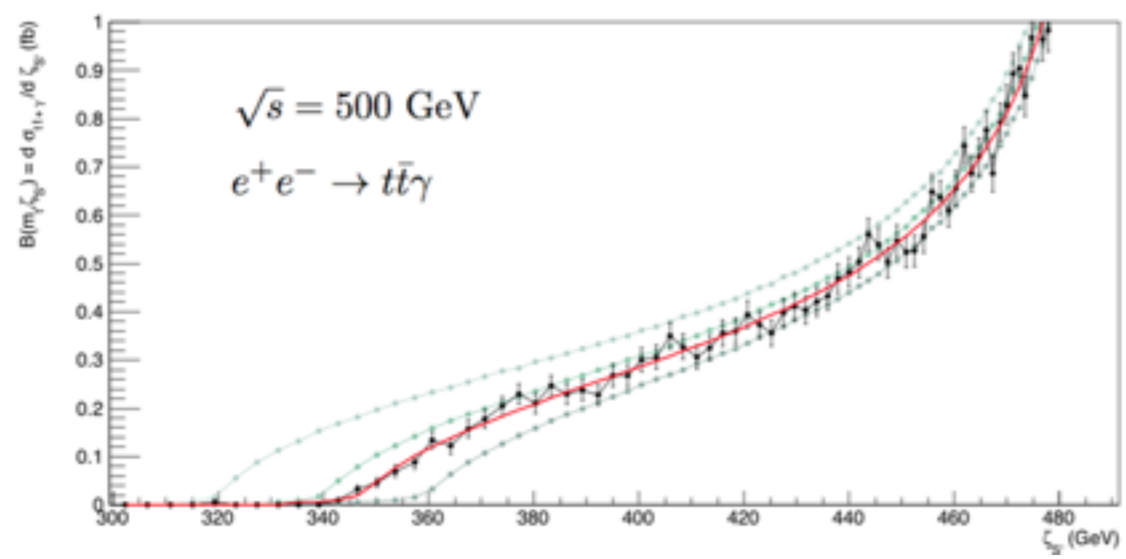
- These curves represent the cross section as a function of $\zeta_{s'}$ at **parton level** for several m_t.
- **For the ISR case, the curve is more sensitive to m_t near the top production threshold**.
- Detailed calculations at high theoretical accuracy (NLO, NNLO...) are needed to make the result meaningful

Top mass at continuum: results (i)

500 GeV	ISR (MeV)	FSR (MeV)	Both (MeV)
500 fb^{-1}	173.158 ± 0.155	173.153 ± 0.130	173.158 ± 0.105
1000 fb^{-1}	173.140 ± 0.103	173.127 ± 0.092	173.136 ± 0.069
2600 fb^{-1}	173.133 ± 0.061	173.114 ± 0.057	173.124 ± 0.042

Using the reference curves template fits are performed for several data sets (100-500) and different luminosity points.

Input mass m_t = 173.1 GeV



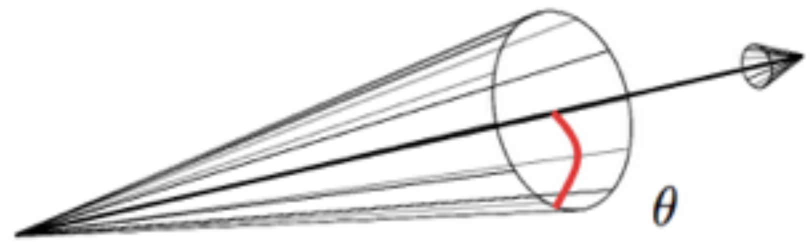
- This results are achieved from an ideal situation (**parton level study**) so **uncertainties are underestimated**.
- In the **next step** we include a more realistic approach at **particle level**. This is **only performed for the ISR case**.

A more realistic approach: particle level without detector simulation

- **To increase the realism of the study photons are identified using selection criteria.**
- **Polar angle of the photon needs to be greater than 7° due to detector coverage (ILC based).**
- **As high-energy ISR emission is usually collinear to the emitter, a good portion of the statistics are lost.**

	380 GeV	500 GeV	1000 GeV
ISR lost (%)	71	74	79

- **ISR photons are identified with respect to photons originated in the decay chain of particles by energy cuts ($E_\gamma > E_0$) and isolation angle cuts ($\theta > \theta_0$). An event selection, optimizing the cuts, is needed.**



Cut	CLIC	ILC 500	ILC 1000
E_0	3 GeV	10 GeV	30 GeV
θ_0	8°	8°	4°

Chosen cuts after the analysis

Top mass at continuum: results (ii)

Collider	Energy (GeV)	Luminosity (fb^{-1})	m_t (GeV)	Δm_t (MeV)
CLIC	380	500	173.141	100
ILC	500	500	173.327	294
ILC (LumUp)	500	4000	173.122	100
ILC	1000	1000	173.381	639
ILC (LumUp)	1000	3500	173.197	388

ISR results at particle level after the event selection. Same procedure in the fitting.

ILC energy points program from *J. Brau - PAC Meeting (Osay, Japan 13 April 2015)* and *Howard E. Haber - LCWS13 (Tokyo, Japan 15 November 2013).*

For a detailed review one can consult:

- https://indico.cern.ch/event/381148/session/1/contribution/11/attachments/759423/1041713/charla.pdf (**Top LC Valencia 2015 by P. Gomis**).
- https://indico.cern.ch/event/449801/session/9/contribution/146/attachments/1214873/1773599/TopContinuumMarca.pdf (**CLIC Workshop CERN 2016 by M. Boronat**).

Top mass at threshold: motivation

Objective: to extract the top quark mass in a **multi-parameter fit from the tt production threshold**.

Observable: **e+e- —>WbWb cross-section** at 10 energy points in a threshold scan (**344 - 353 GeV**).

ILC Conditions: **ISR + beamstrahlung** + polarized beams, P(e-, e+) = (-0.8, 0.3).

Tools: MC **simulations at parton level** (Whizard LO+NLL) + MINUIT (root package for **chi2 minimization**).

Multi-parameter fit:

1. **Top quark mass** at the **1S threshold scheme**:

$$\frac{m_t(m_t)}{GeV} = 163.643 \pm 0.007 + 0.069\,\delta_{\alpha_s} - 0.096\,\delta_{m_t}^{1S}$$

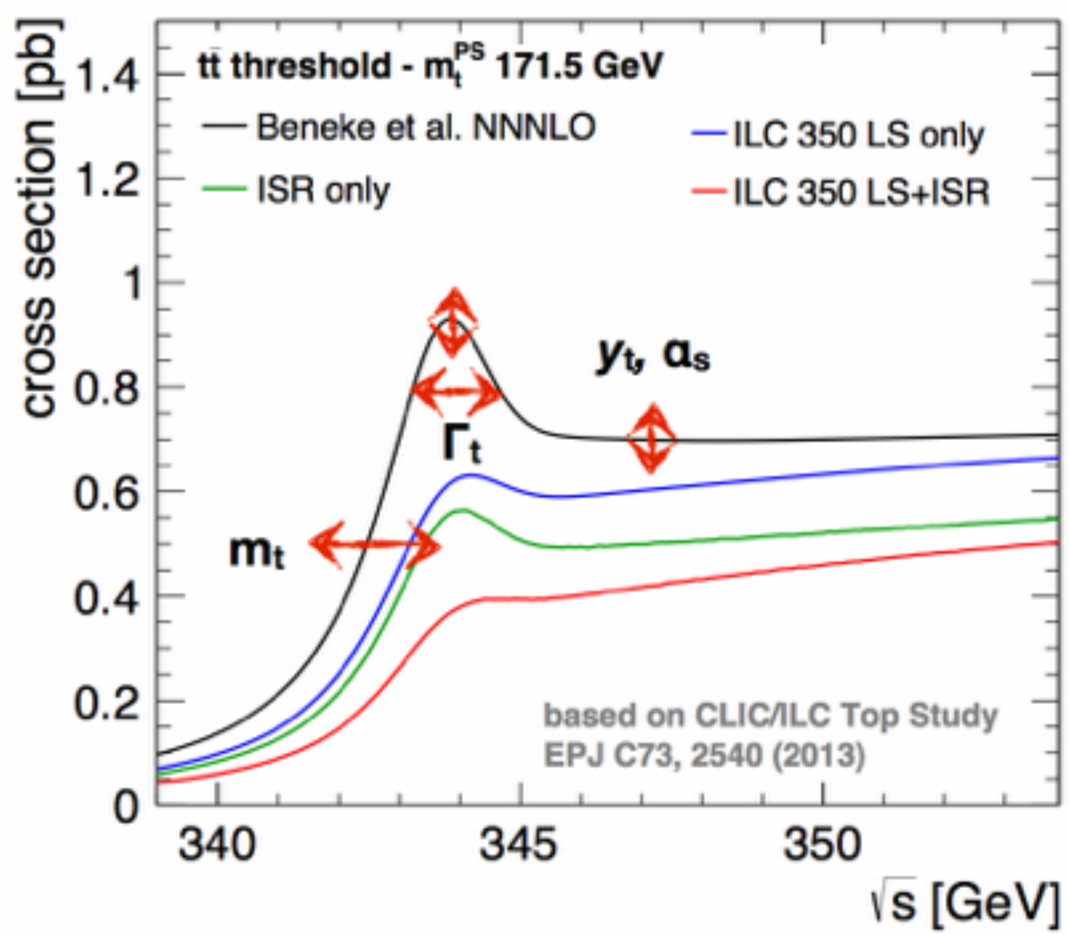
$$\delta_{\alpha_s} = [0.1185 - \alpha_s]/0.001$$

$$\delta_{m_t}^{1S} = [172.227\,GeV - m_t]/0.1$$

Conversion from 1S to MSbar mass scheme, *P. Marquard et al., arXiv:1502.01030, PRL114 (2015):*

2. **The CKM matrix element Vtb (replacing the top width)**.

3. **The strong coupling constant, alpha_s.**



Top mass at threshold: results of the multi-parameter fit

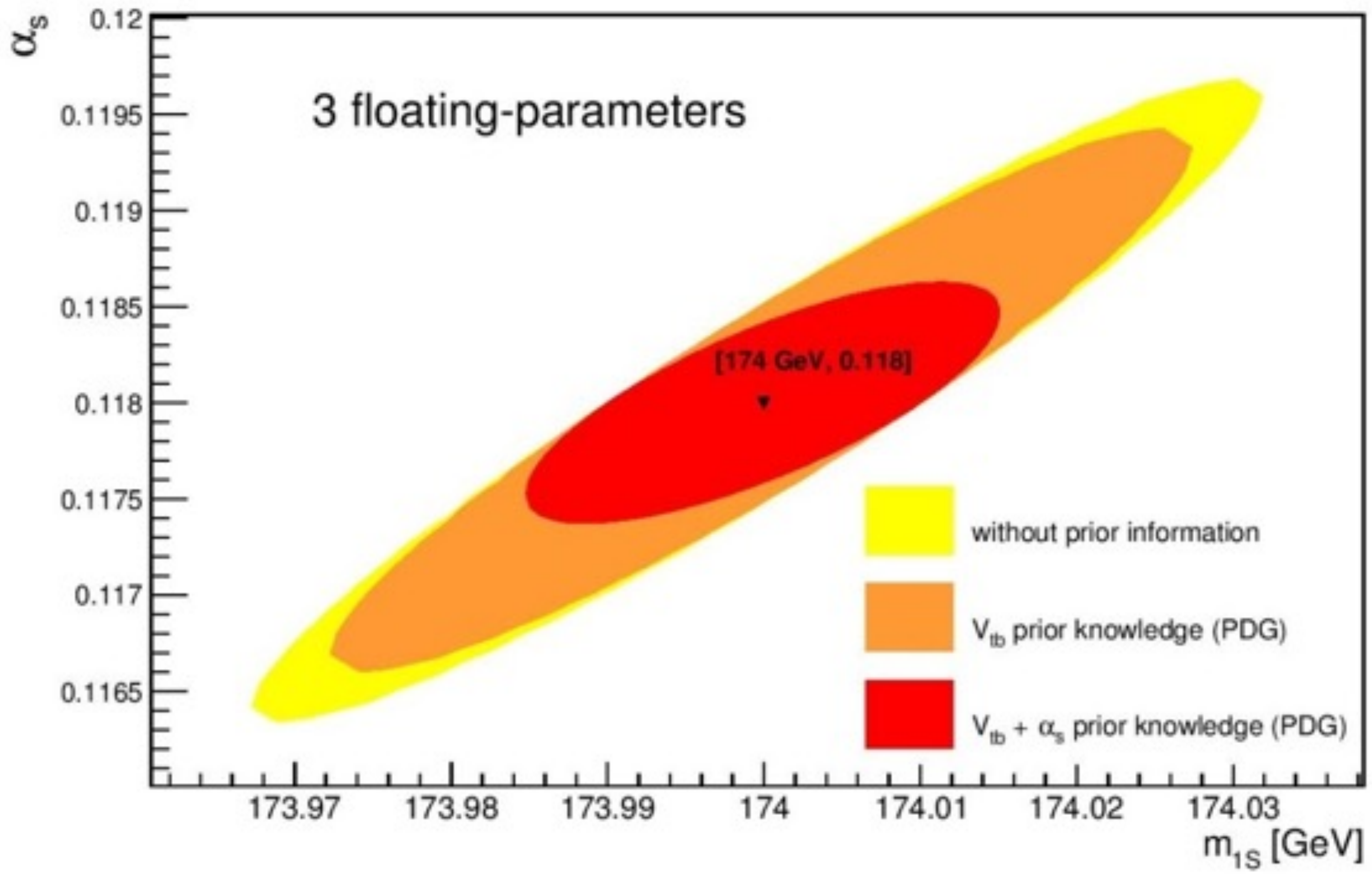
Fit	Δm_{1S} [MeV]	ΔV_{tb}	$\Delta \alpha_s$
Only m_{1S}*	10	-	-
m_{1S} vs V_{tb}	10	0,0095	-
m_{1S} vs α_s	15	-	0,0007
m_{1S} vs V_{tb} vs α_s	32	0,023	0,0017

Theoretical and systematic uncertainties are NOT included in the minimization.

- **Little impact of Vtb to the mass extraction**, **alpha_s hits harder**.
- **3 floating-parameters** strategy **aggravates** the uncertainties **estimation**.
- The negative impact of the multi-parameter fit must be canceled by **reducing the number of floating-parameters**.

Top mass at threshold: results with prior information

Adding **prior information** (from Vtb and alpha_s) **on the chi2 function**…

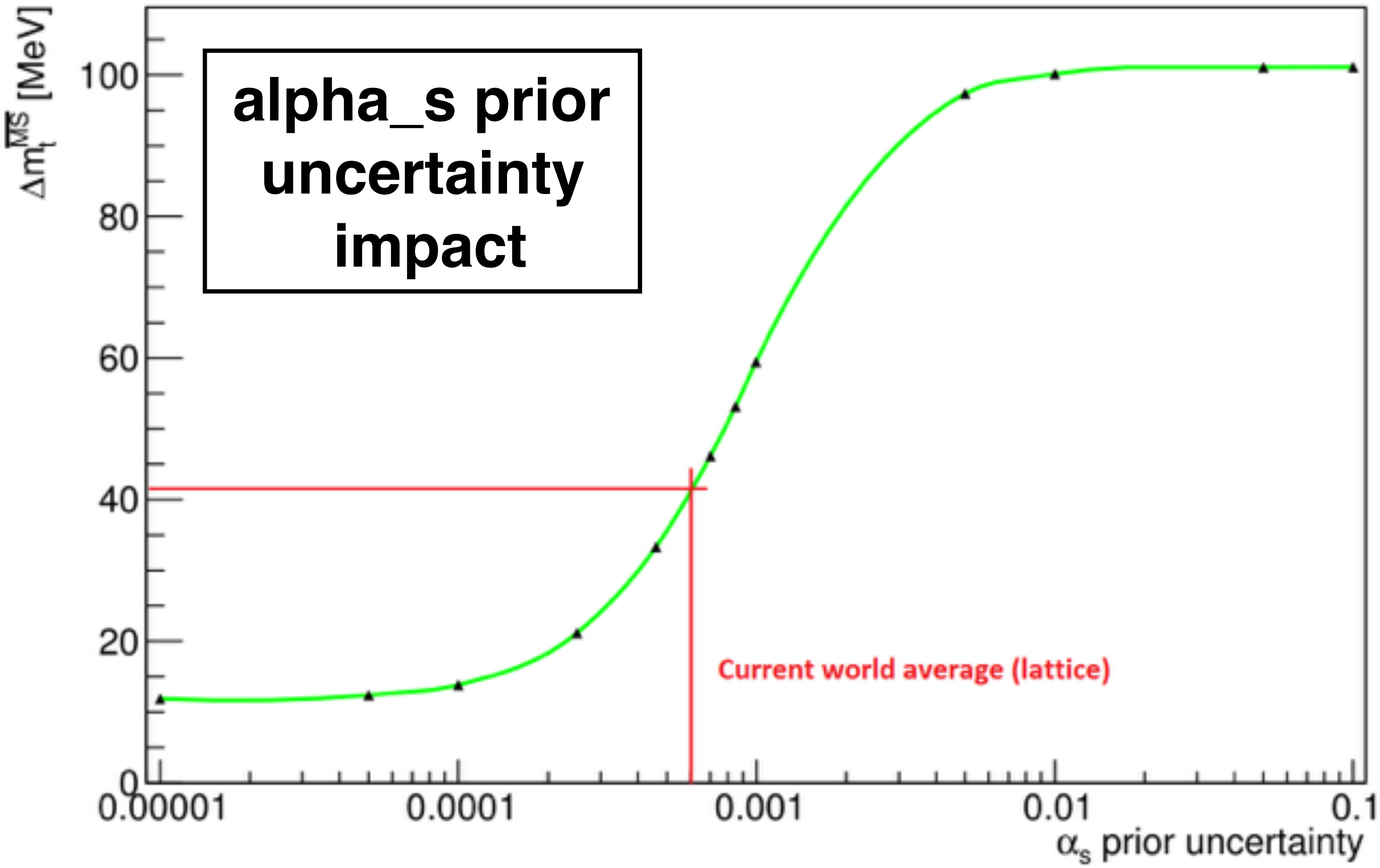


Achieved uncertainties:

- $\Delta m_{1S} = 14$ MeV
- $\Delta m^{\overline{MS}} = 41$ MeV
- $\Delta V_{tb} = 0{,}011$
- $\Delta \alpha_s = 0{,}00055$

- $\Delta V_{tb} = 0{,}032$ (PDG2014) $\Delta \alpha_s = 0{,}0006$ (world average).
- Vtb prior does not have an important impact in the $m_{1S} - \alpha_s$ interplay.
- α_s prior reduces considerably the uncertainties

Top mass at threshold: alpha_s impact



$$\Delta m^{\overline{MS}} = 41 \text{ MeV}$$
(3 floating-params.)
$$\rightarrow 12 \text{ MeV}$$
(2 floating-params.)

With **an uncertainty of approx. 0.0001 on alpha_s**, we find a **limit of 12 MeV on the top quark mass** (higher value considering systematics).

We have tested some ways to reduce alpha_s uncertainty at 500 GeV using WbWb + 1jet, but we haven't found competitive results. For a detailed review:

- https://indico.cern.ch/event/381148/session/1/contribution/10/attachments/759424/1041714/TopLC2015_Perello.pdf (**Top LC Workshop Valencia 2015 by M. Perelló**).
- http://agenda.linearcollider.org/event/6662/session/35/contribution/126/material/slides/0.pdf (**LCWS Canada 2015 by F. Simon**).

Top quark mass: review

Two ways for extracting the top quark mass:

- ***Continuum:***
    - An uncertainty of **approximately 300 MeV is reachable at ILC@500GeV**. This center-of-mass energy would be run before than the threshold providing **the best top quark mass measurement at that moment** (could be used as a constraint in threshold fits).
    - This **work is still in progress**, a complete **study at detector level** is being performed.
- ***Threshold:***
    - An uncertainty of **approximately 50 MeV is reachable at ILC**. **This value is limited by the alpha_s uncertainty**.
    - Several groups are studying the top mass extraction from threshold. **Our contribution has consisted on the study of a WbWb inclusive sample**, instead of the study of a ttbar sample, showing that **the results are competitive** (we avoid the single top mis-identification).

Top quark couplings

A way to describe the ttZ and ttgamma vertices *(arXiv:hep-ph/0601112)*:

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

Vector **Axial** **Tensorial** **CPV**

New physics will modify the electro-weak ttX vertex described in the SM by Vector and Axial couplings to the vector bosons, X=photon, Z.

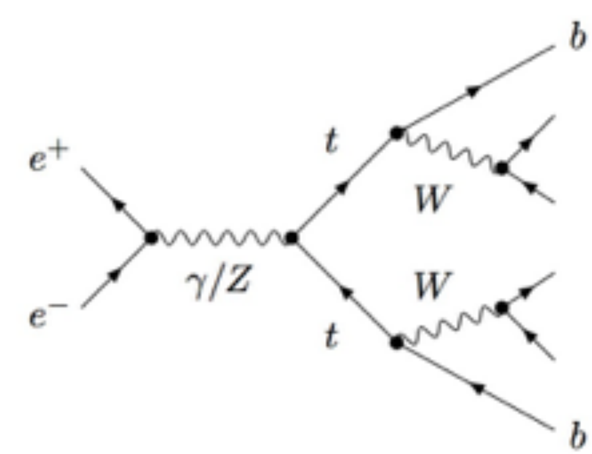
The Top quark is primary candidate to be a messenger in many BSM models.

STUDIES for CP conserving couplings: ***Measure 2 observables for 2 beam polarisations: total cross-section and forward-backward asymmetry.***

$F_{1A}^{\gamma,\mathrm{SM}} = 0$ always because of the gauge invariance

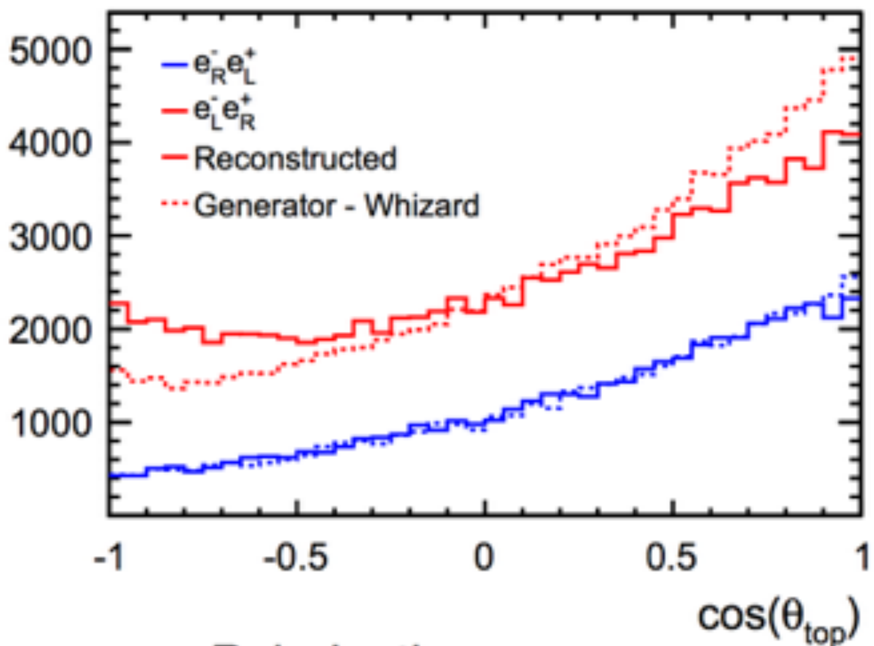
$$\begin{matrix}\sigma(+) & A_{FB}(+) \\ \sigma(-) & A_{FB}(-)\end{matrix} \qquad \left.\begin{matrix}(+ = e_R^-) \\ (- = e_L^-)\end{matrix}\right\} \Rightarrow \left\{\begin{matrix}F_{1V}^\gamma & * & F_{2V}^\gamma \\ F_{1V}^Z & F_{1A}^Z & F_{2V}^Z\end{matrix}\right\}$$

Measure **Extract**



ILC@500GeV L=500fb^{-1}

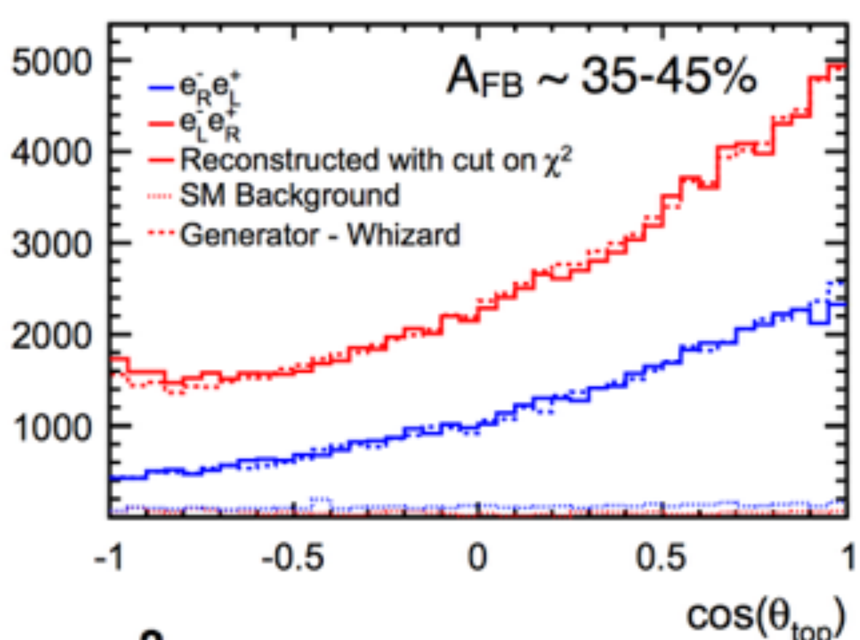
Eur. Phys. J. C (2015) 75:512
DOI 10.1140/epjc/s10052-015-3746-5



Migrations due to ambiguity in b-W pairing

Remedy to address ambiguities: Select cleanly reconstructed events by **χ^2 analysis**

Polarisation
$e^-_L e^+_R$: -80%, +30%
$e^-_R e^+_L$: +80%, -30%



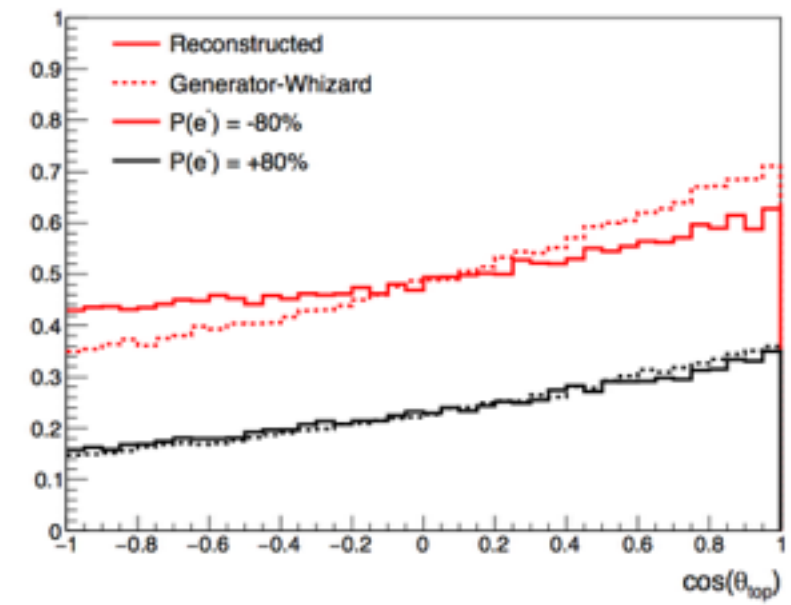
Migrations due to ambiguity in b-W pairing

Curing migrations have a penalty in efficiency

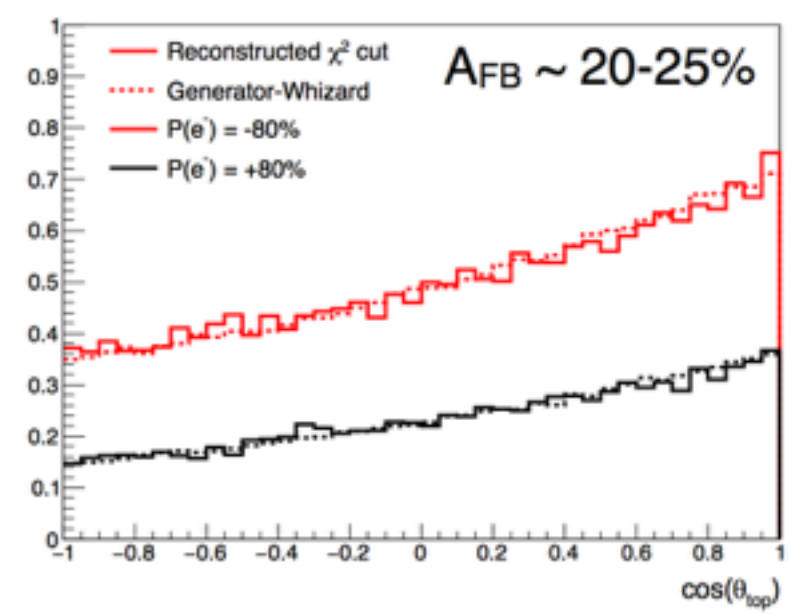
$\chi^2 < 15$

Reconstruction **efficiency** ~**30%** for eL and **50%** for eL

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



Polarisation
$e^-_L e^+_0$: -80%, 0%
$e^-_R e^+_0$: +80%, 0%



$\chi^2 < 1$ (very tight cut -> lower statistics)

Reconstruction efficiency ~**18%** for both polarisations

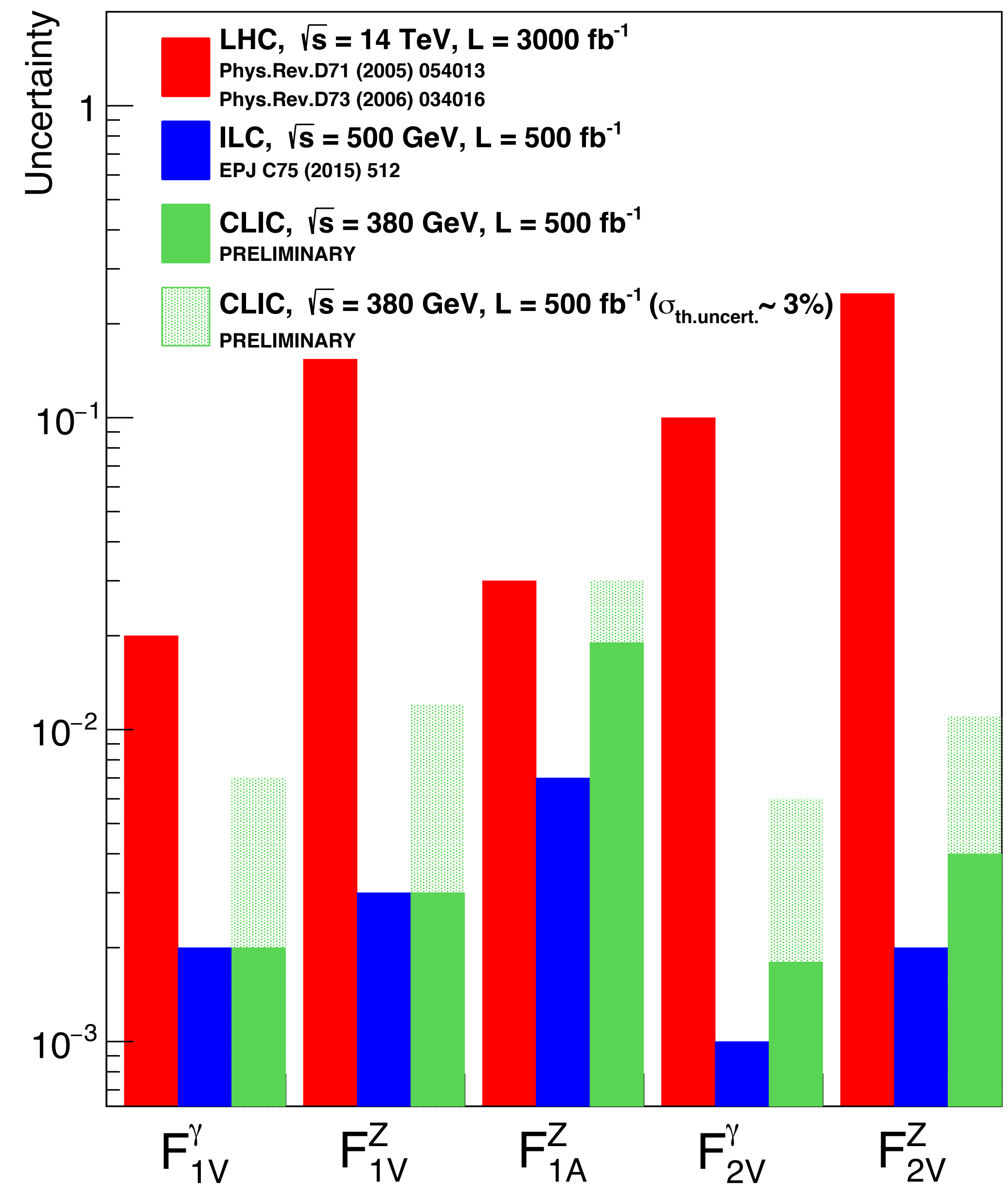
CP conserving couplings: results

ILC@500GeV L=500fb^{-1}

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

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

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



CLIC: **similar precision to ILC except** for the coupling F_{1A}^Z that suffers the large statistical error of **A_{FB} ~5%**

Conservative scenario for CLIC: NNNL calculations at threshold predict a **3% theory uncertainty**

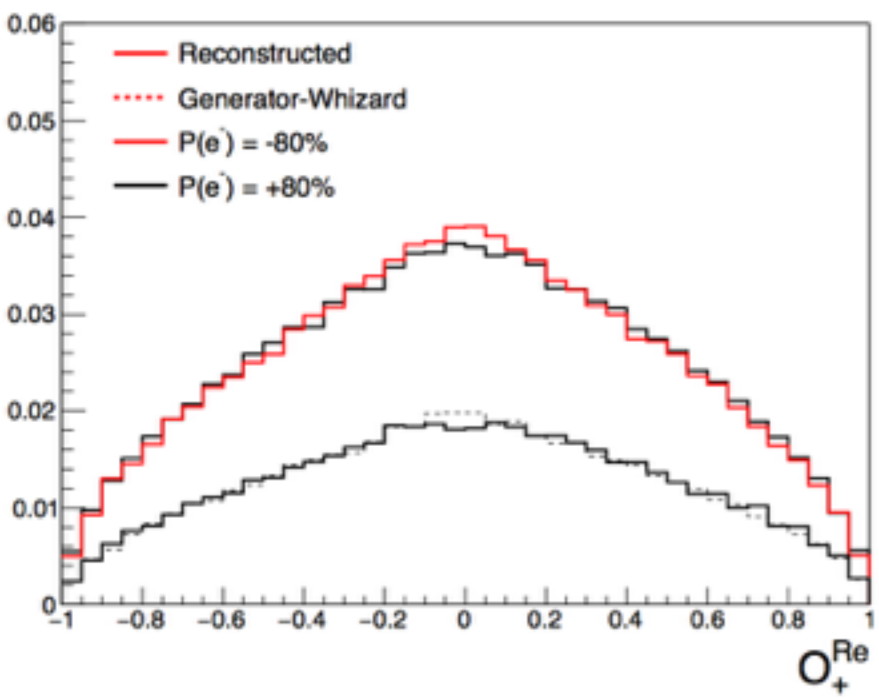
ILC and CLIC can characterise precisely ttγ and ttZ vertices, **an order of magnitude better than LHC** prospects from associated production

Valencia (IFIC) - Orsay (LAL) collaboration:

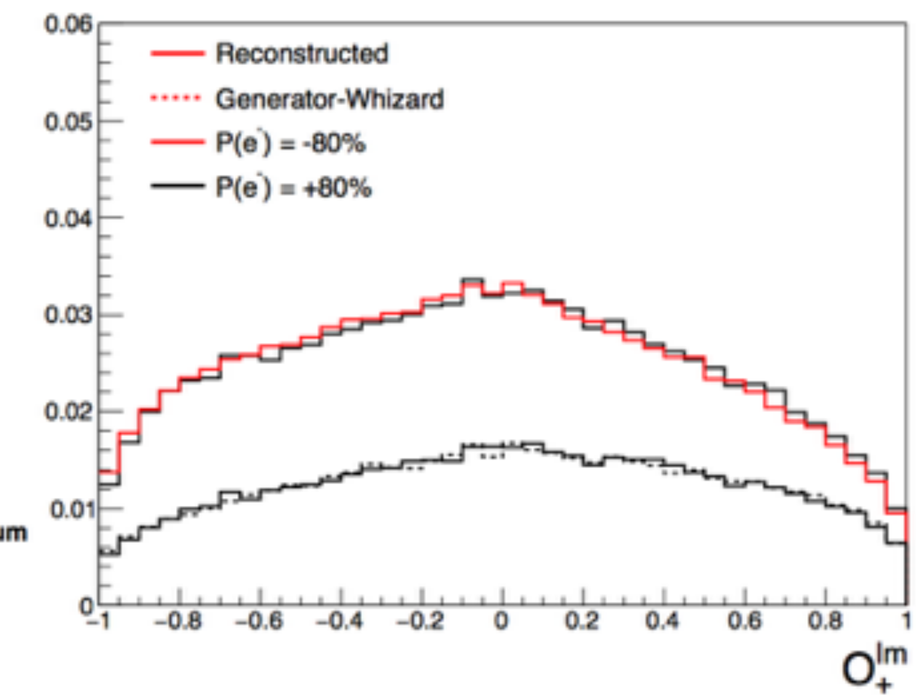
A precise characterisation of the top quark electro-weak vertices at the ILC
M.S. Amjad (Orsay, LAL & COMSATS, Islamabad) et al.
Eur.Phys.J. C75 (2015) 512
(2015-10-29)
DOI: 10.1140/epjc/s10052-015-3746-5

CPV couplings

Reconstructing **optimal CP violating observables** from *W. Bernreuther et. al. arXiv:hep-ph/9602273* **that measure differences in top polarization orthogonal to production plane and also differences in top quark flight direction**. In the lepton + jets final state we find:



Where
q= charged lepton momentum
X = hadronic top system
e = positron momentum



$$O_+^{Re} = (\hat{q}_+^* \times \hat{q}_{\bar{X}}) \cdot \hat{e}_+$$

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

This observables have s**imple relations to the four F2A form factors**:

$$A_{\gamma,Z}^{Re} = \langle O_+^{Re} \rangle - \langle O_-^{Re} \rangle = c_\gamma[PRe(F_{2A}^\gamma) + KZRe(F_{2A}^Z)]$$

$$A_{\gamma,Z}^{Im} = \langle O_+^{Im} \rangle - \langle O_-^{Im} \rangle = d_\gamma[Im(F_{2A}^\gamma) + PKZIm(F_{2A}^Z)]$$

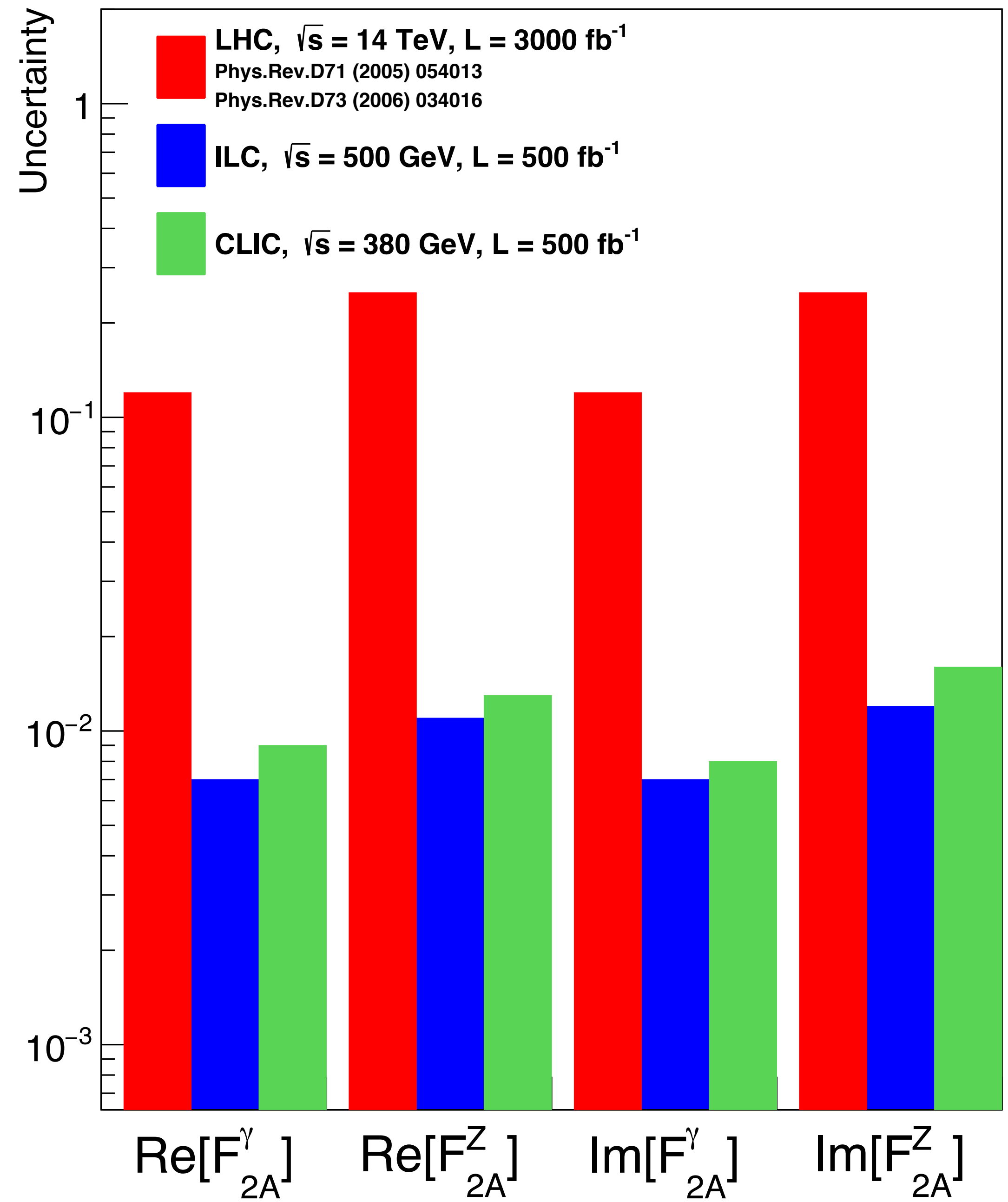
CPV couplings: results

Full simulations results exist for **ILC@500GeV** and **CLIC@380GeV**

MadGraph setup exists to introduce non-zero F_{2A} in full simulation but manpower is limited

Paper of LC potential in the CPV sector in preparation (IFIC-LAL collaboration)

Quantity	$Re[F_{2A}^{\gamma}]$	$Re[F_{2A}^{Z}]$	$Im[F_{2A}^{\gamma}]$	$Im[F_{2A}^{Z}]$
SM value at tree level	0	0	0	0
LHC	0.12	0.25	0.12	0.25
TESLA TDR	0.007	0.008	0.008	0.010
ILC@500 GeV	0.007	0.011	0.007	0.012
CLIC@380 GeV	0.009	0.013	0.008	0.016



Top quark effective operators

Alternative approach for the BSM searches…

- We can study models BSM through **effective operators theories which include new terms on the Lagrangian**:

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

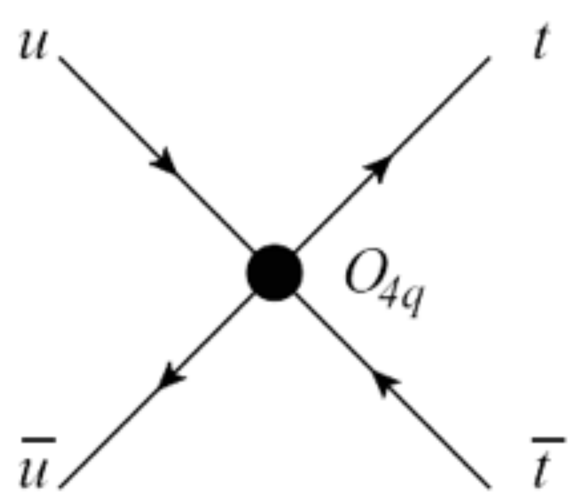
Dimension-six operators

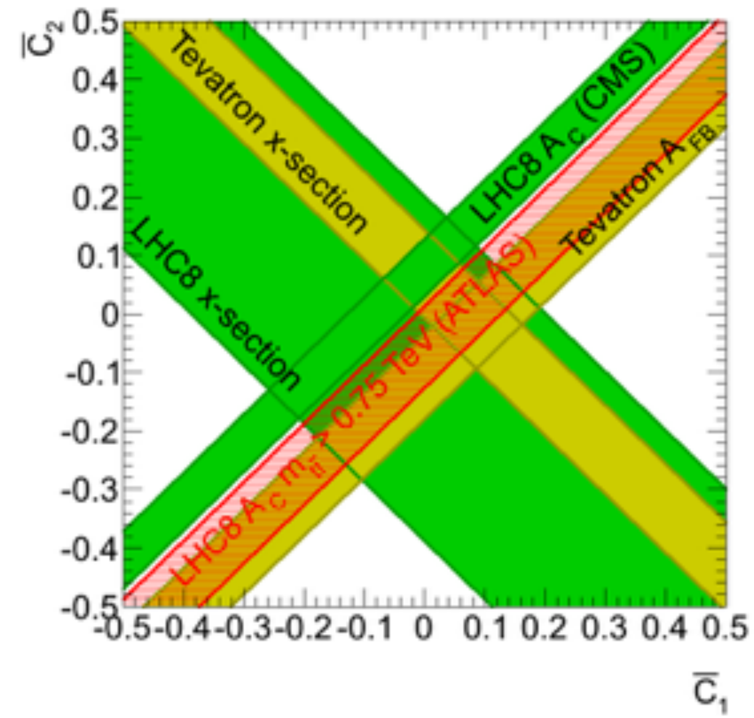
- The main goal is a **global fit of all observables involving top quark physics to all these possible extra BSM terms**. There is a TopFitter collaboration for this purpose:
  - *Constraining top quark effective theory in the LHC Run II era. TopFitter Collaboration. arXiv:1512.03360 [hep-ph], Dec 10, 2015.*

- **We have started with this idea by fitting the charge asymmetry measured at Tevatron and LHC to four-fermion dim-6 operators**. See:

Constraints on four-fermion interactions from the $t\bar{t}$ charge asymmetry at hadron colliders
Martin Perello Rosello, Marcel Vos
IFIC-15-94
e-Print: arXiv:1512.07542 [hep-ex]

The aim is to extend this study to ILC/ CLIC operators.





Summary and plan

- **Top quark mass from the continuum could provide an alternative and competitive result respect to the LHC current values which complements the threshold measurement *(Boronat and Gomis, work in progress)*.**

- **Top quark couplings studied at ILC (500 GeV) and CLIC (380 GeV) reduce the uncertainties by an order of magnitude respect to the LHC. New energy points must be considered for studying different potentials (*García and Perelló, work in progress*):**

  - ***500 GeV @CLIC (cross-check with ILC), 1.4 TeV and 3 TeV (CLIC).***

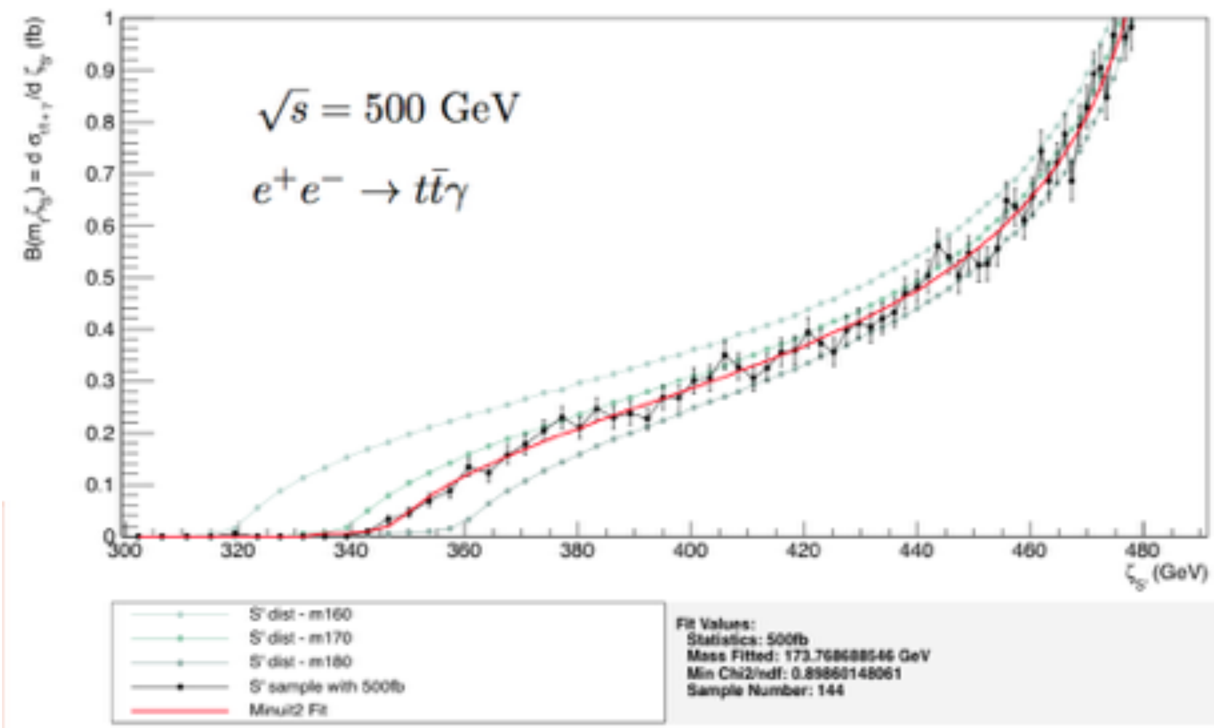
  - ***An alternative approach to be studied consists in including new effective operators in the Lagrangian.***

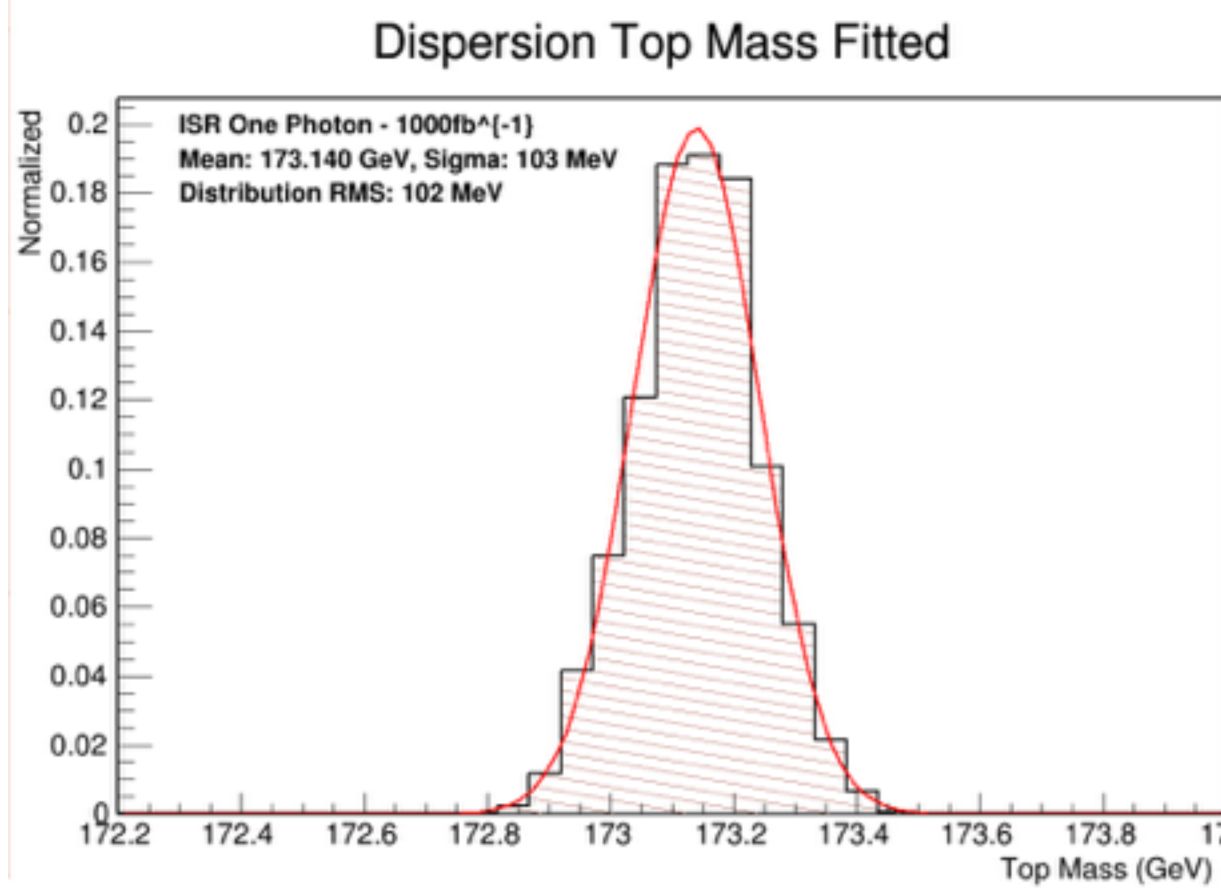
Thank you!

Backup

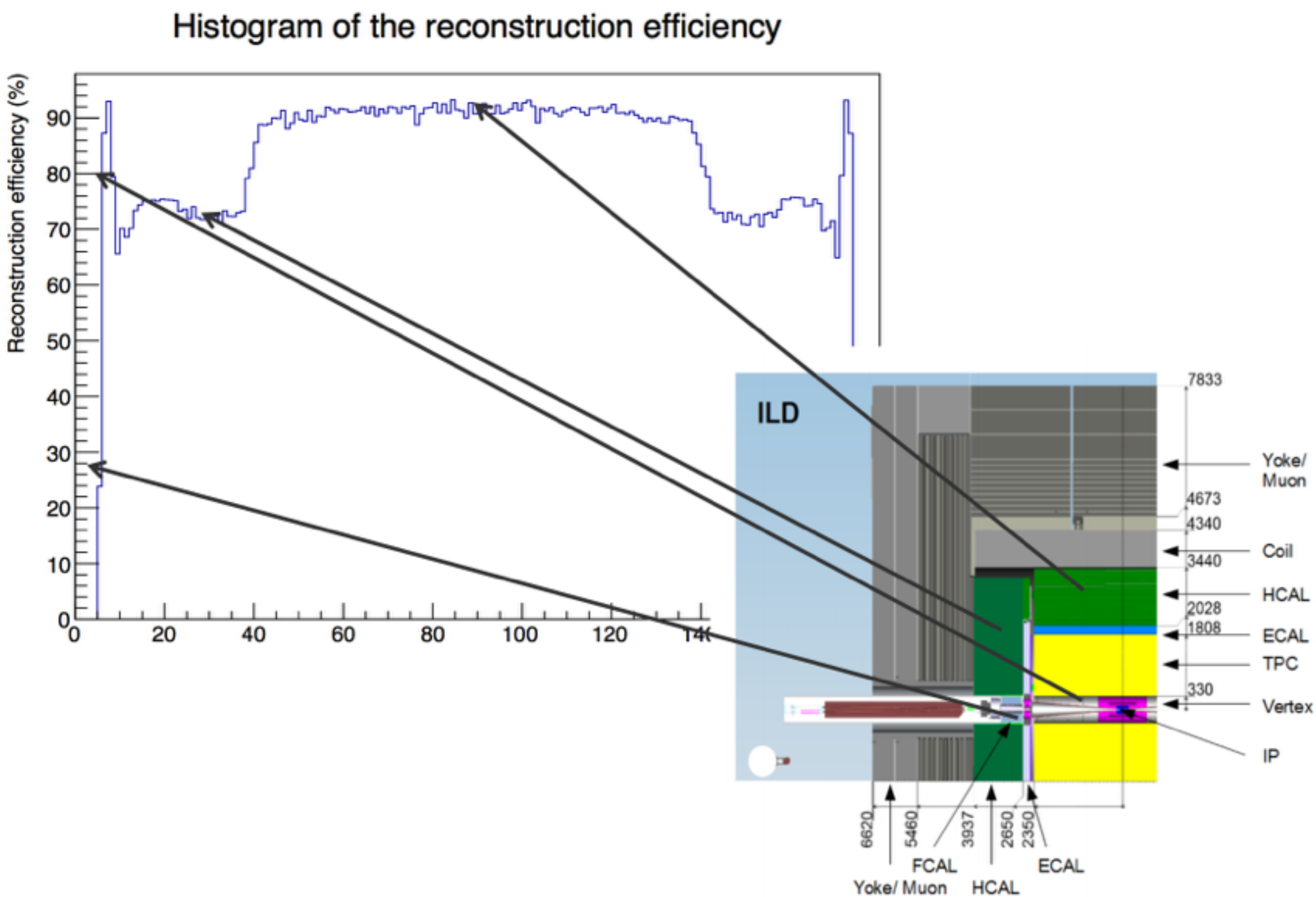
Top mass at continuum

Template method





Top mass at continuum: Angular efficiency



Top mass at continuum: Energy resolution