Top Physics at CLIC

CLIC Workshop 2016

Ignacio García
IFIC-Valencia

On behalf of the CLICdp collaboration

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CLICdp: Physics and Analysis

IFIC INSTITUT DE FÍSICA CORPUSCULAR
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
VNIVERSITAT DE VALÈNCIA

OUTLINE

1. **Motivation**

    Properties of the top quark and sensitivity to BSM physics

2. **Current Status: Top quark today (LHC measurements)**

    Top mass

    Top EW couplings

    Yukawa coupling

3. **Top quark at Future Linear Colliders**

    Top mass from a threshold scan

    Top EW couplings precision

    Yukawa coupling (ttH)

    FCNC top decays ($t \rightarrow cH$)

4. **Summary**

Motivation

A physics program of the top quark is mainly divided in two blocks

Properties of the top quark

Mass: important parameter of the SM (vacuum stability)

Width: top decays before hadronisation

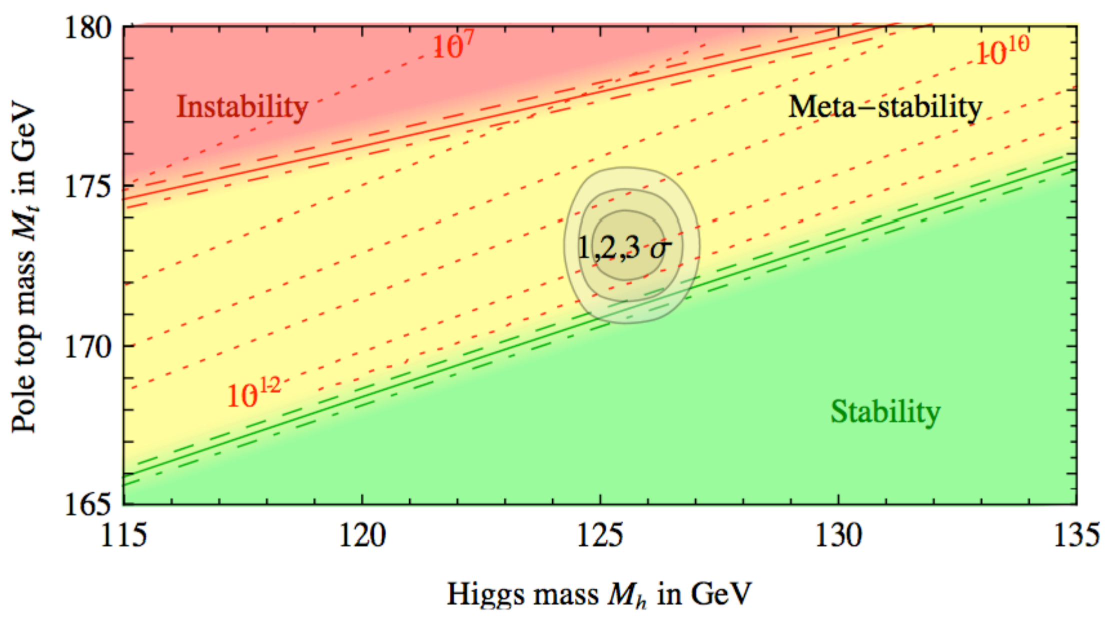
Yukawa coupling: strongly coupled to Higgs field

Sensitivity to BSM physics

Electroweak couplings: looking for deviations from the SM values

Is the top quark a **composite object?**
Is it just an **ordinary quark?**

M.Peskin LCWS15 - Canada



CLIC (and future e^+e^- colliders generally) **gives the opportunity to study the top quark with unprecedented precision**

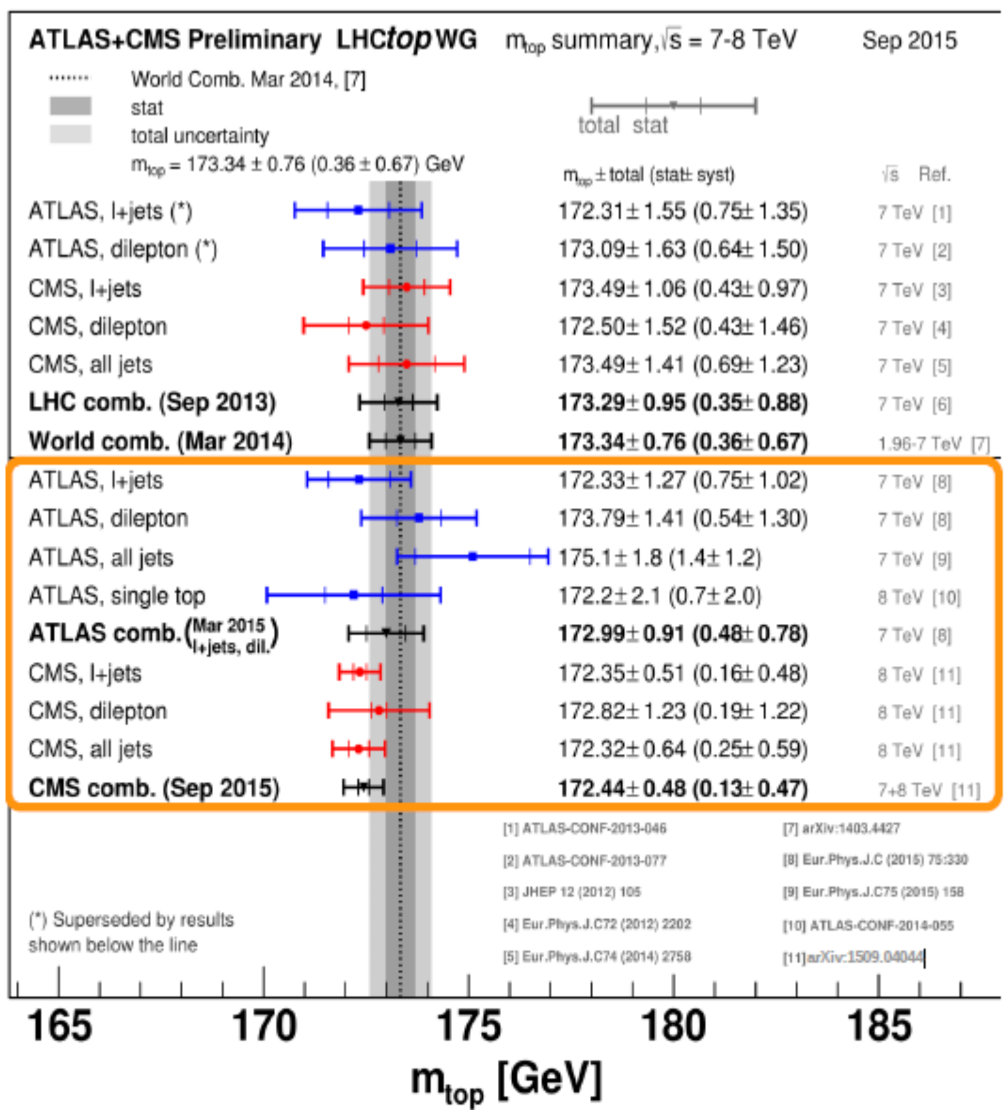
Top quark studies should have an important weight in the LC programs

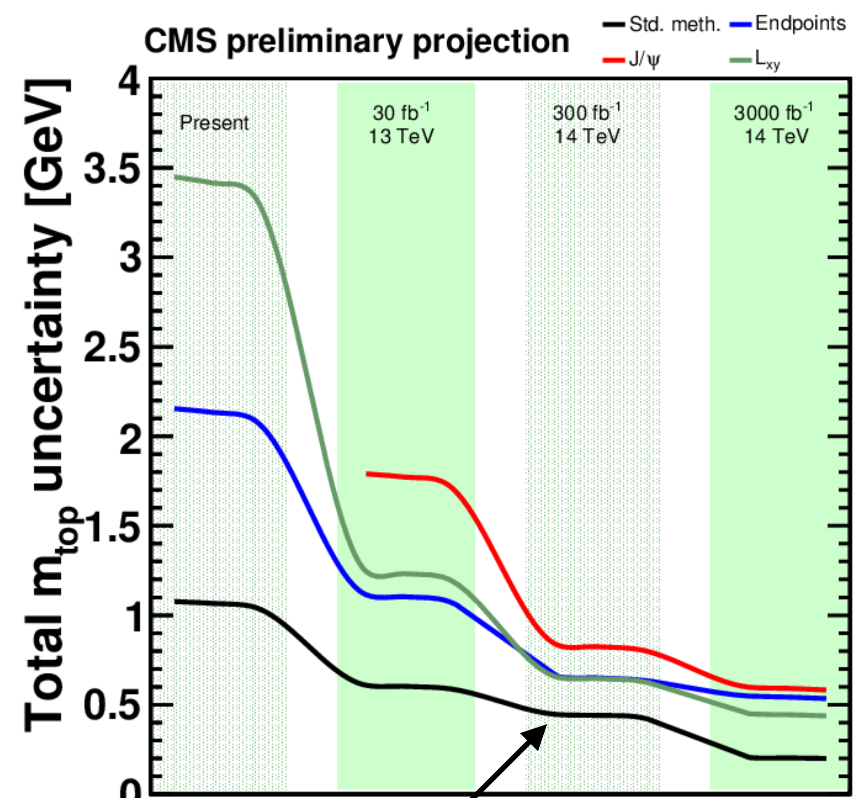
Current status: Top Mass

Hadron colliders (LHC and Tevatron) achieved a precision in the measurement of the top mass of **~ 0.76 GeV in March 2014** arXiv:1403.4427

Combination of consistent set of measurements from 4 experiments (ATLAS, CMS, CDF and D0)

New results from CMS even more precise
~ 0.5 GeV September 2015





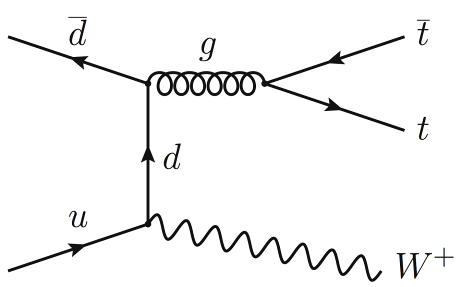
LHC already **exceeding prospects**, and the projection goes even beyond:

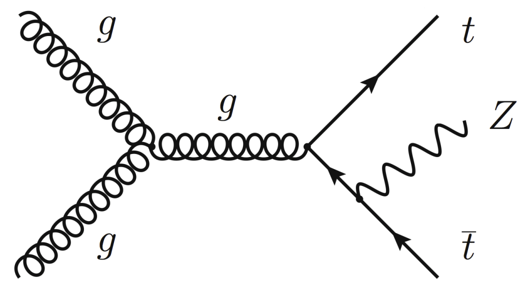
CMS: 200 MeV after 3000 fb^{-1} (conventional method, *CMS-FTR-13-017-PAS)* based on "*assumptions [that] are optimistic but not unrealistic*"

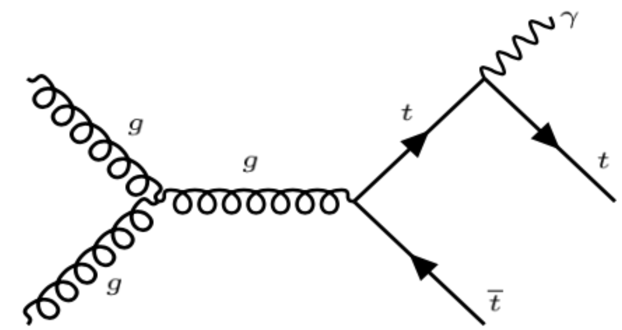
I.Garcia (Ignacio.Garcia@ific.uv.es)

Current status: Top EW couplings

First observations of *ttV* (V=W,Z,γ) production at the LHC

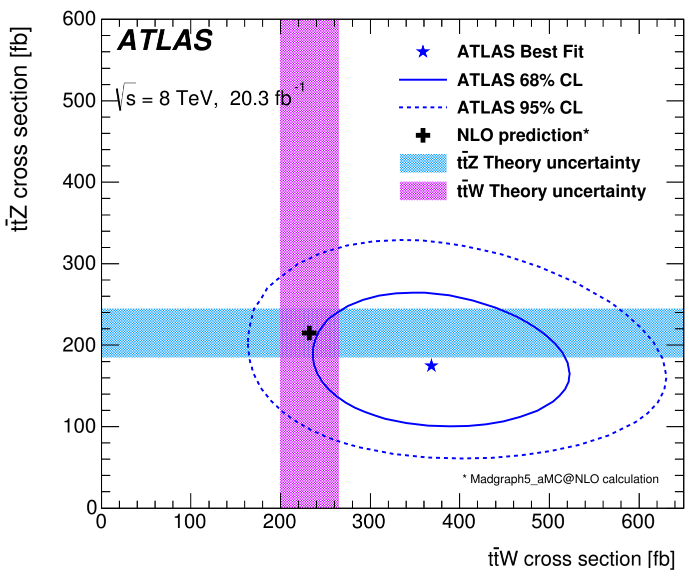




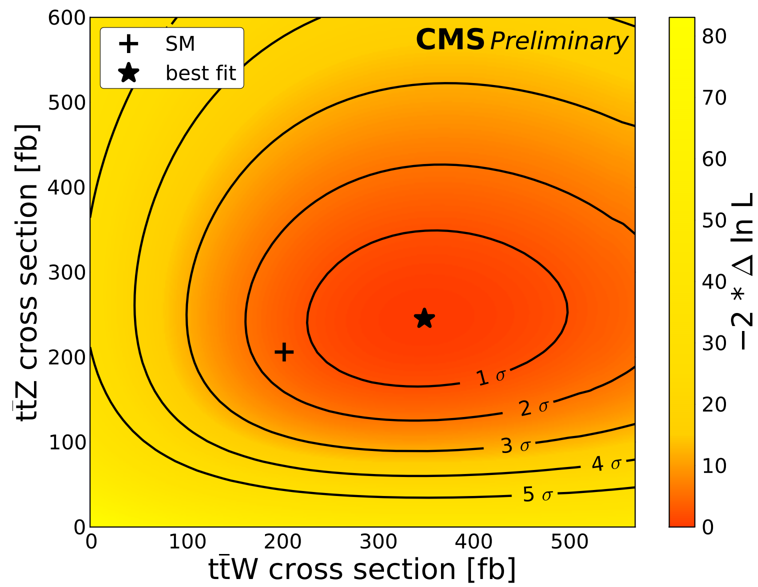


Access to the *top-Z* and *top-γ* vertices at the LHC

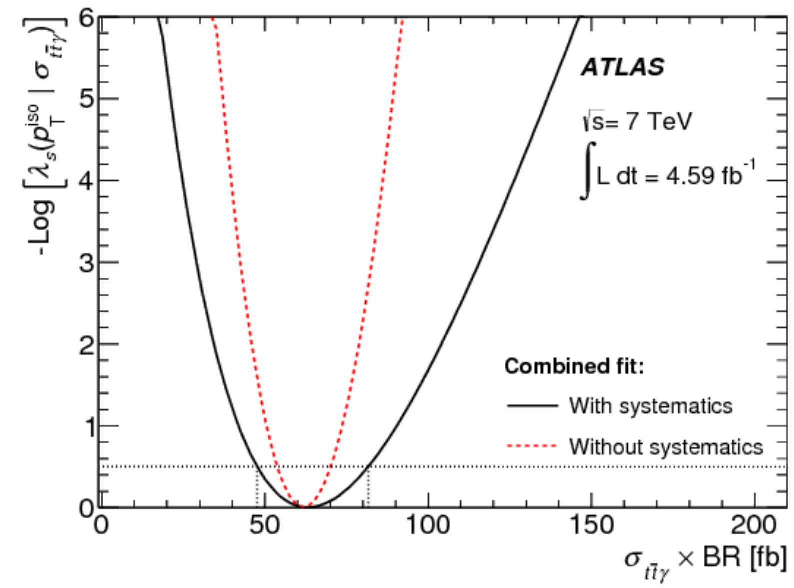
σ(*ttW*), σ(*ttZ*) and **(*ttγ*)** expected to be altered in new Physics models



ATLAS, arXiv:1509.05276



CMS, arXiv:1510.01131



ATLAS, arXiv:1502.00586

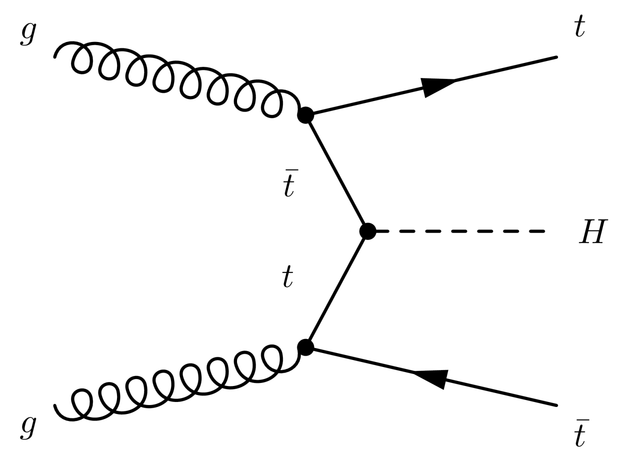
ATLAS/CMS have improved their analyses considerably

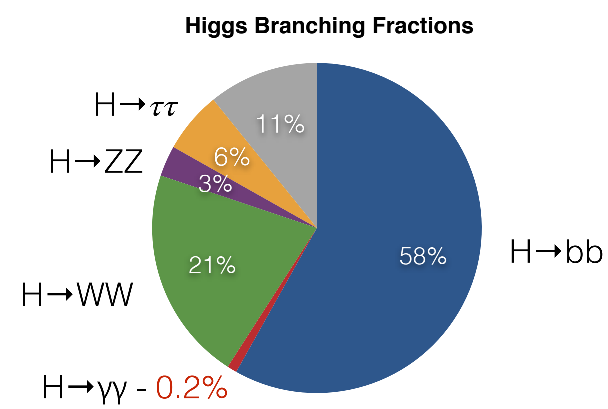
5σ observation for all top + EW associated production channel

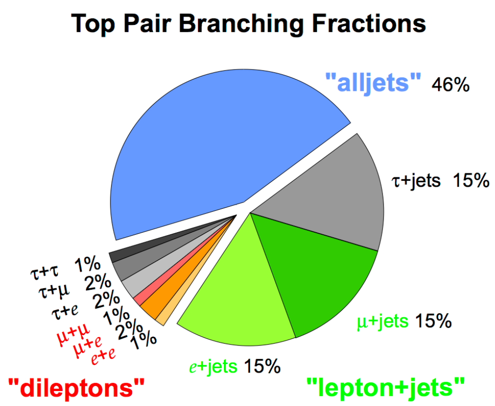
Still soft limits in the top quark form factors

	ttW	ttZ	ttγ
ATLAS	5.0 σ ArXiv:1509.05276	4.2 σ ArXiv:1509.05276	5.3 σ (7 TeV) ArXiv:1502.00586
CMS	4.8 σ ArXiv:1510.01131	6.4 σ ArXiv:1510.01131	CMS-PAS-TOP-13-011

Current status: Yukawa Coupling

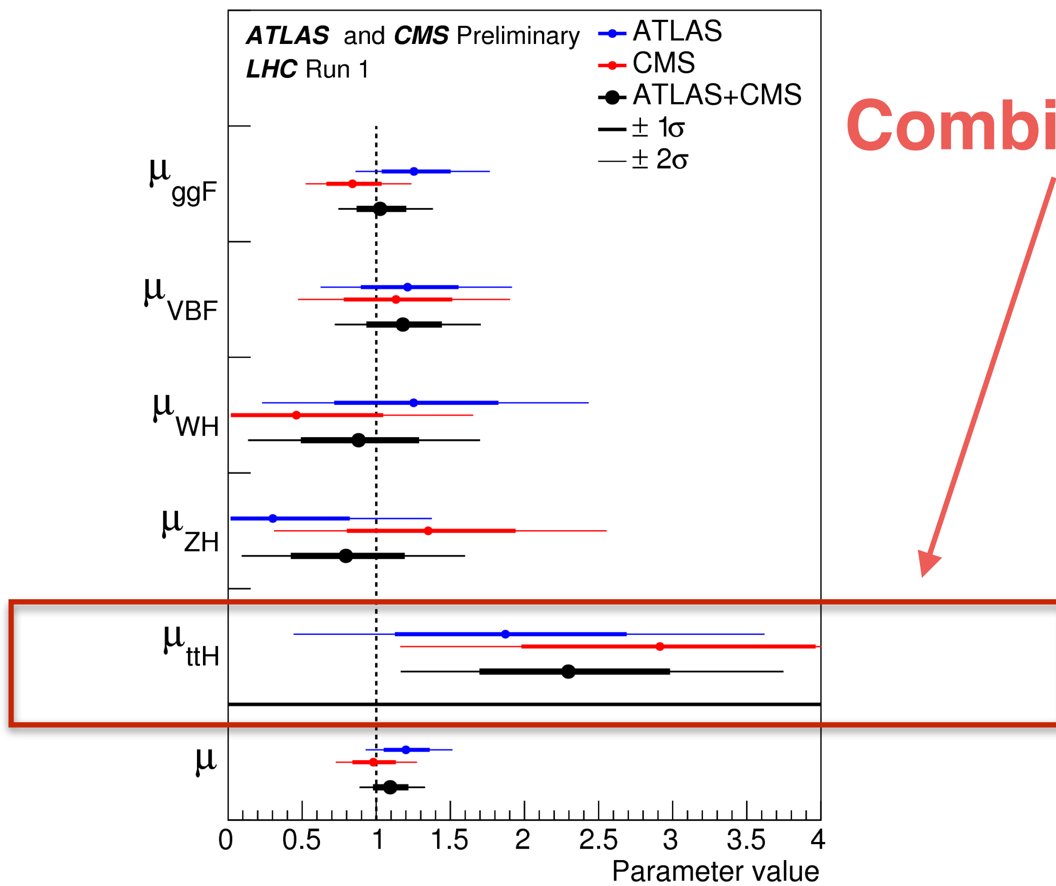






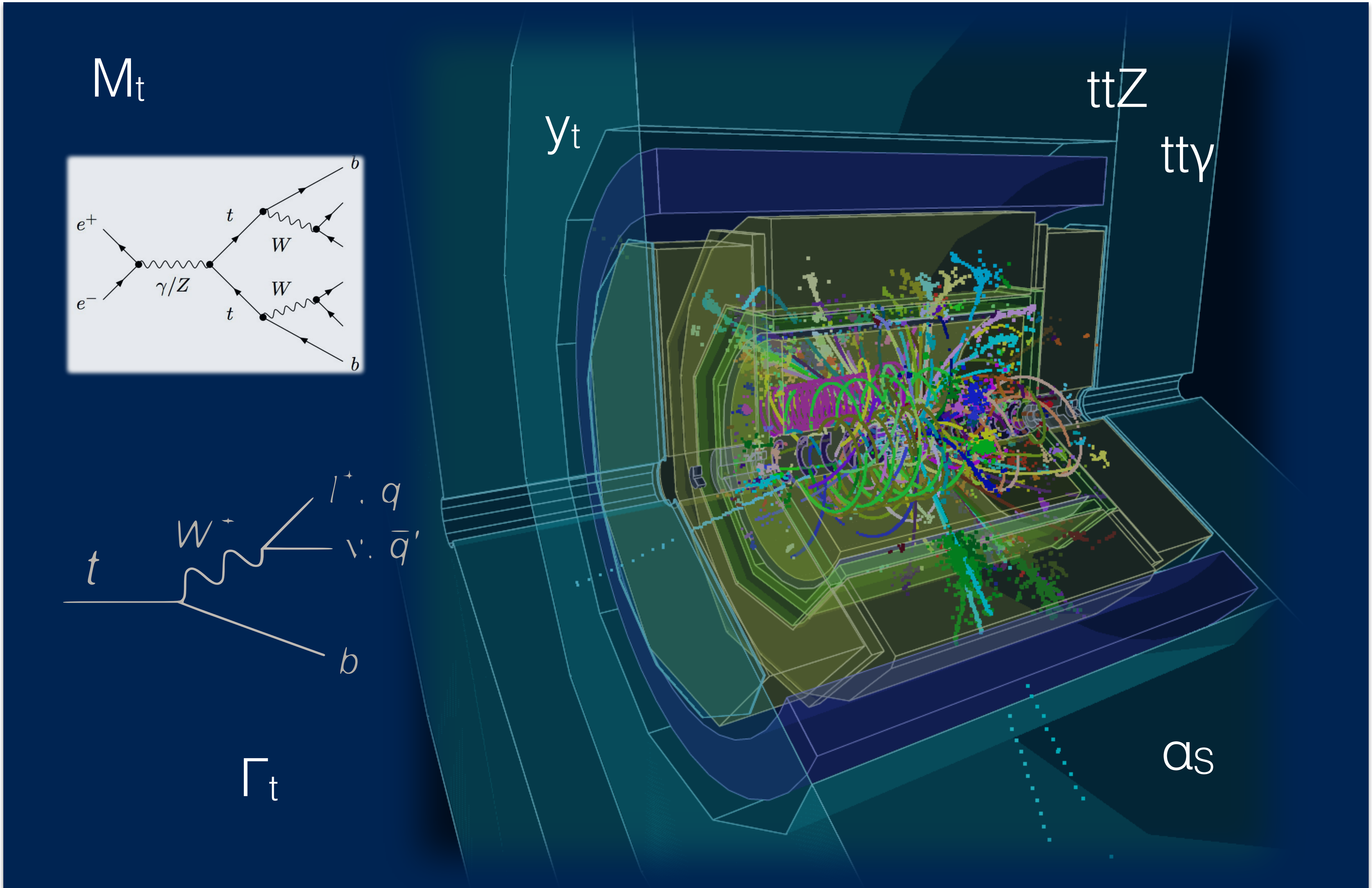
ttH searches have been **performed** at the LHC in all main Higgs decay modes at 7 and 8 TeV:

- Best fit signal strength **($\mu = \sigma/\sigma_{SM}$)**
  - $\mu_{ttH} = 1.9^{+0.8}_{-0.7}$ - *ATLAS*
  - $\mu_{ttH} = 2.9^{+1.0}_{-0.9}$ - *CMS*
  - $\mu_{ttH} = 2.3^{+0.7}_{-0.6}$ - *Combined*
    - significance - 4.4σ obs (2.0σ exp)
- Combined upper limits on σ/σ_{SM}
  - 3.2 obs (1.4 exp) - ATLAS
  - 4.5 obs (1.7 exp) - CMS



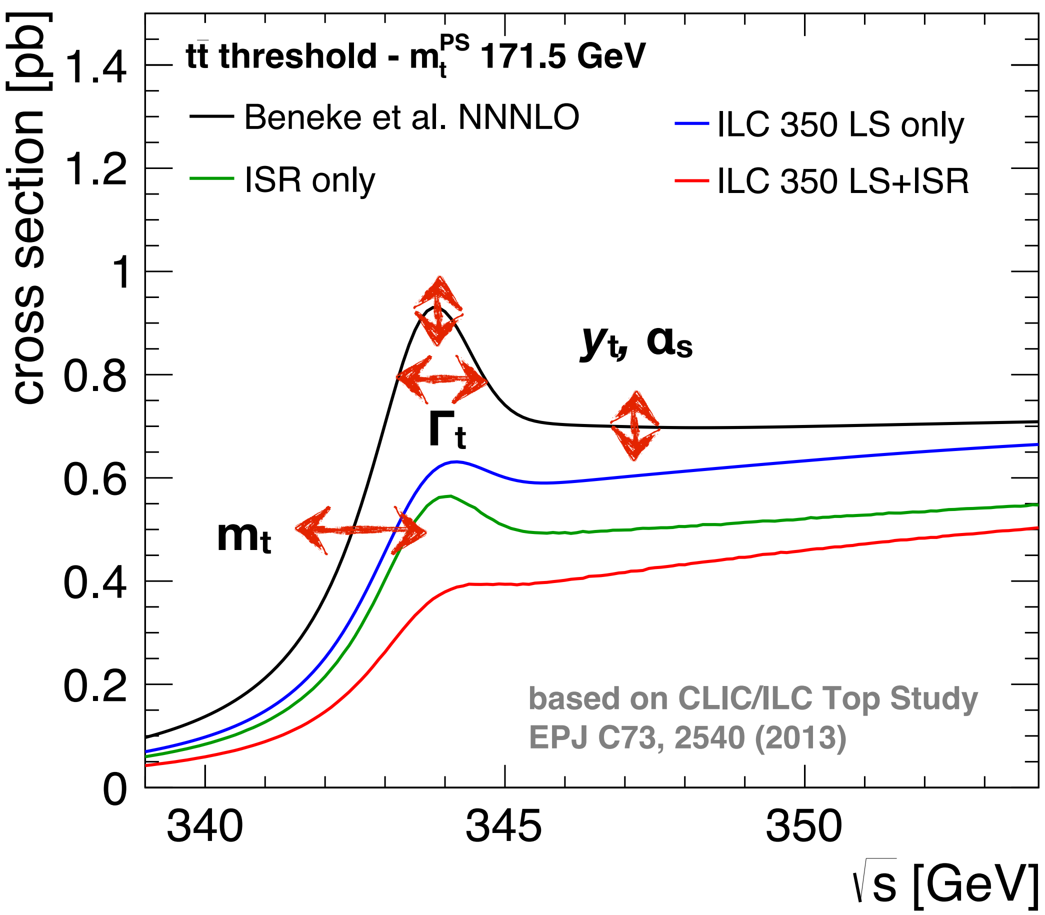
Combined μ_{ttH}

Top quark at Future Linear Colliders



Top pair threshold: Motivation

A scan of the ttbar threshold in e^+e^- collisions is the best method for a precise measurement of the top quark mass and other top properties

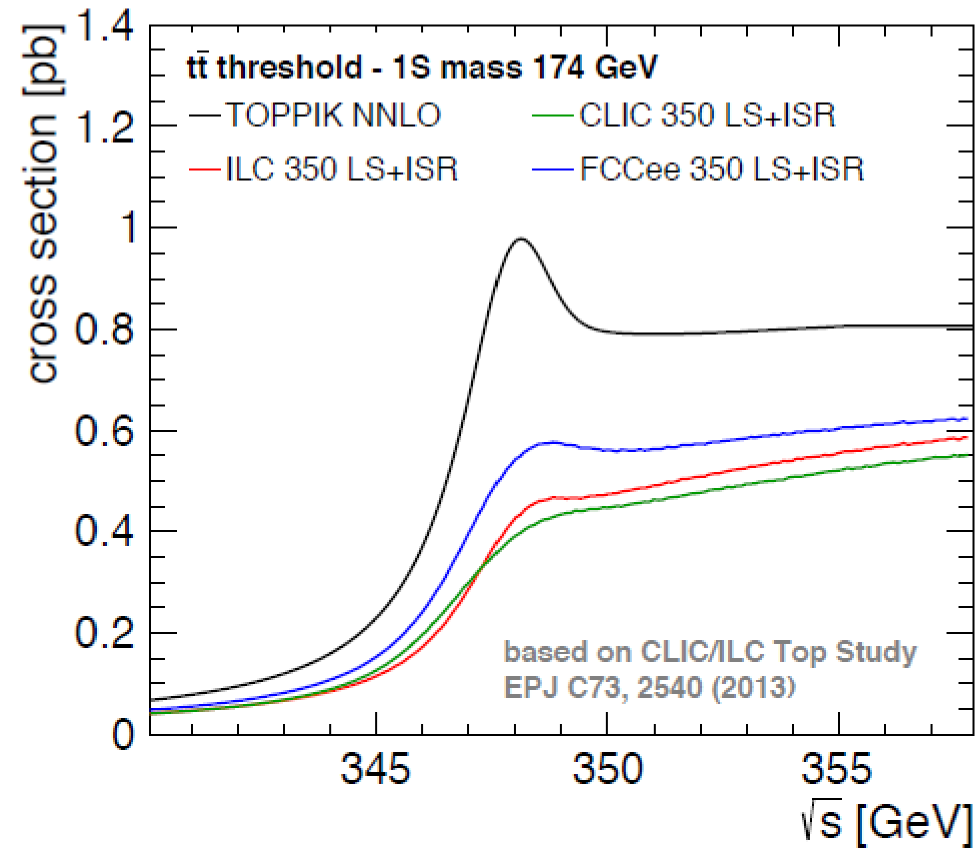


The *tt* **cross-section** around the **threshold** is affected by several properties of the top quark and by QCD

- **Top mass (m_t), width (Γ_t), Yukawa coupling (y_t)**
- Strong coupling constant (α_S) *Kuhn, Acta Phys.Polon. B12 (1981) 347*

Minor differences due to beam energy spectra of **ILC, CLIC and FCC-ee**

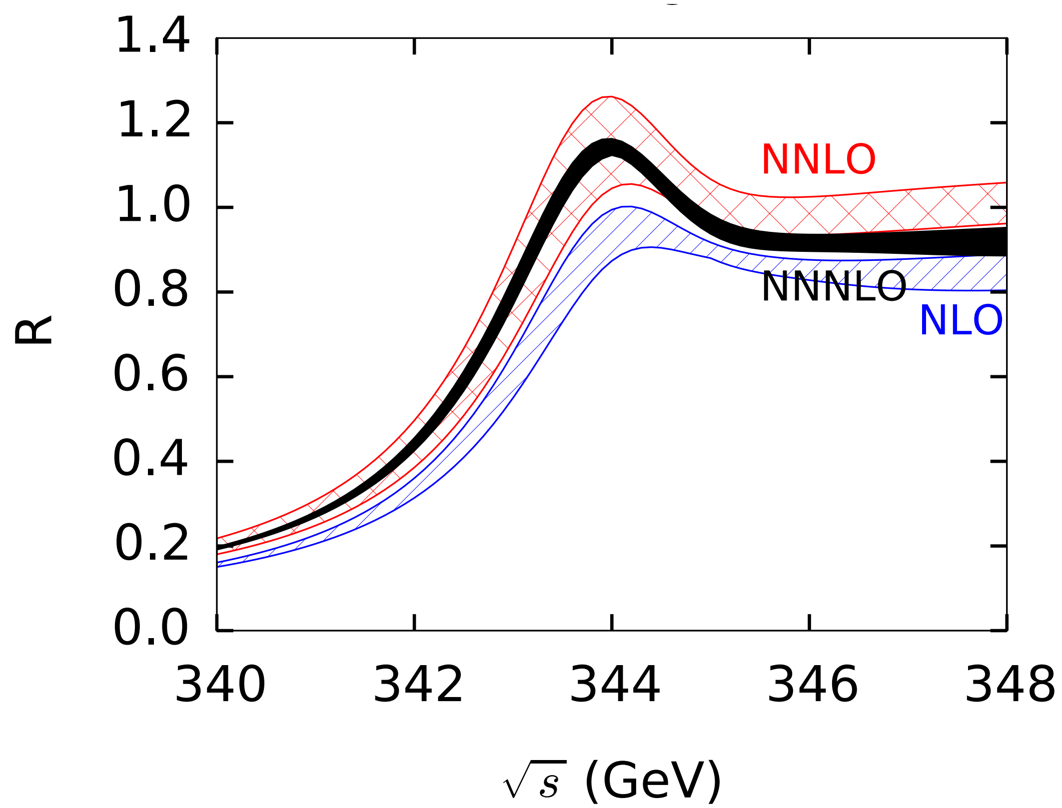
ILC and CLIC studies show that this **threshold shape** will be measured with **impressive accuracy**

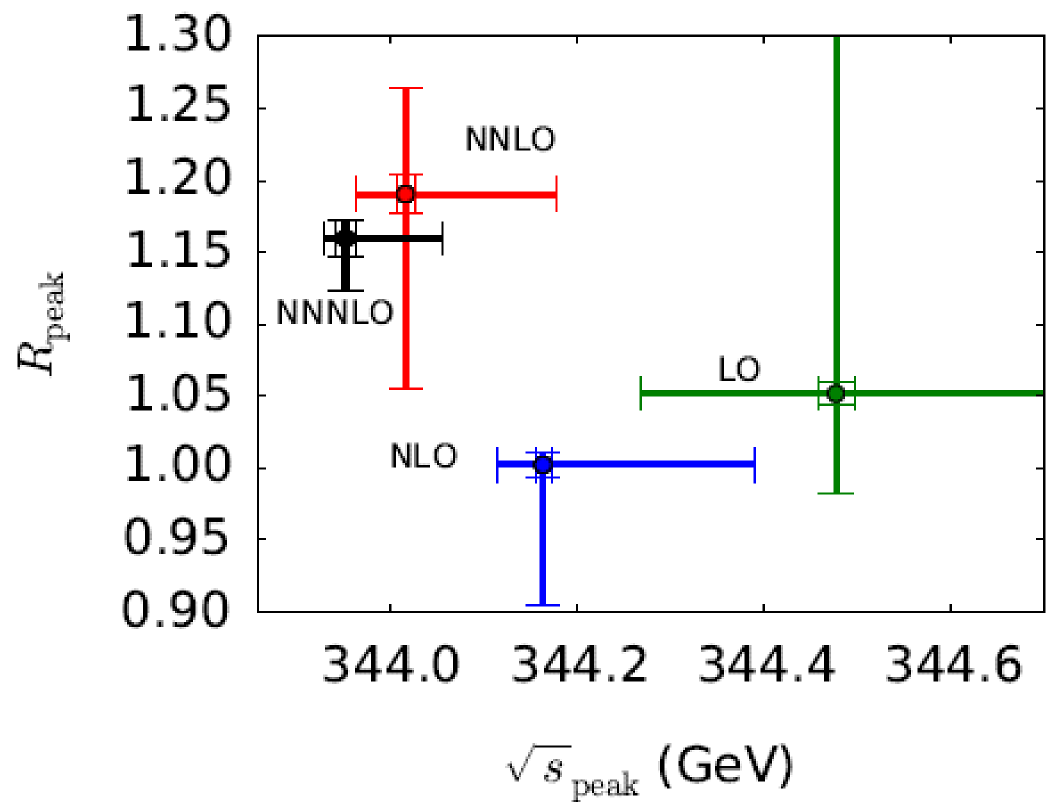


Top pair threshold: Theory status

NNNLO QCD description of tt production at threshold: A decade of work to get the 3rd order!

Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser, 1506.06864 [hep-ph]

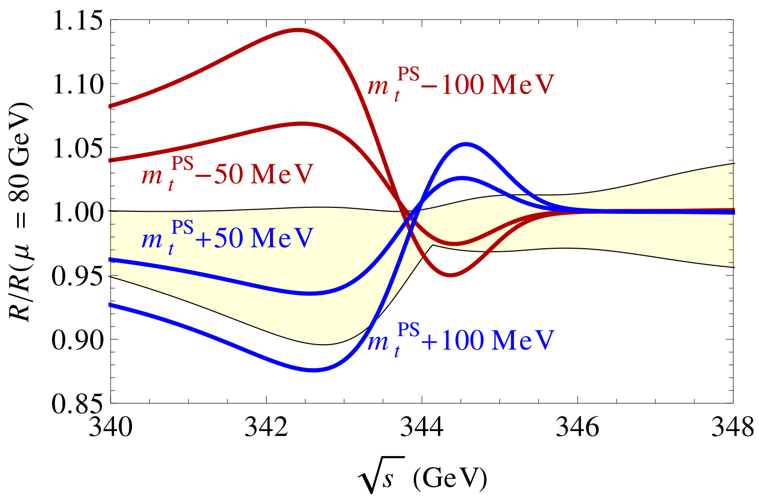




Position shift for PS mass:

- 310 MeV (LO to NLO)
- 150 MeV (to NNLO)
- **64 MeV (to NNNLO)**

Improvement of factor 3 in uncertainty in peak height



- suggests uncertainties on the 50 MeV level

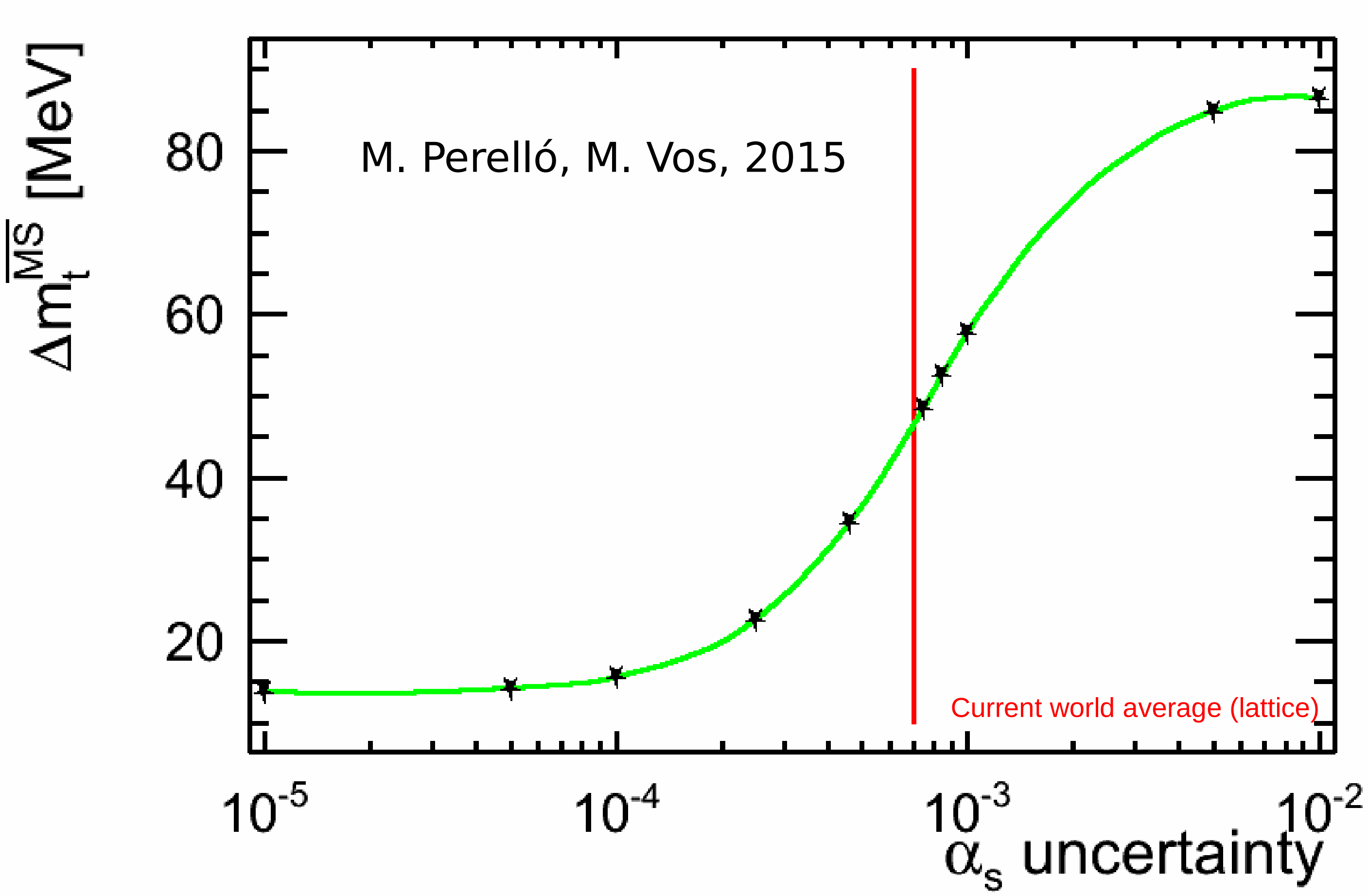
Top pair threshold: Theory status

Conversion of pole / 1S / PS mass to $\overline{\text{MS}}$ mass at NNNNLO QCD

Theory uncertainty in 4-loop calculation **< 10 MeV**
P. Marquard et al., arXiv:1502.01030, PRL114 (2015)

+ uncertainty induced by α_S uncertainty
~40 MeV

value of world $\alpha_s(M_z)$: = 0.1177 ± 0.0013



See M.Perelló talk at Top Workshop 2015 Valencia

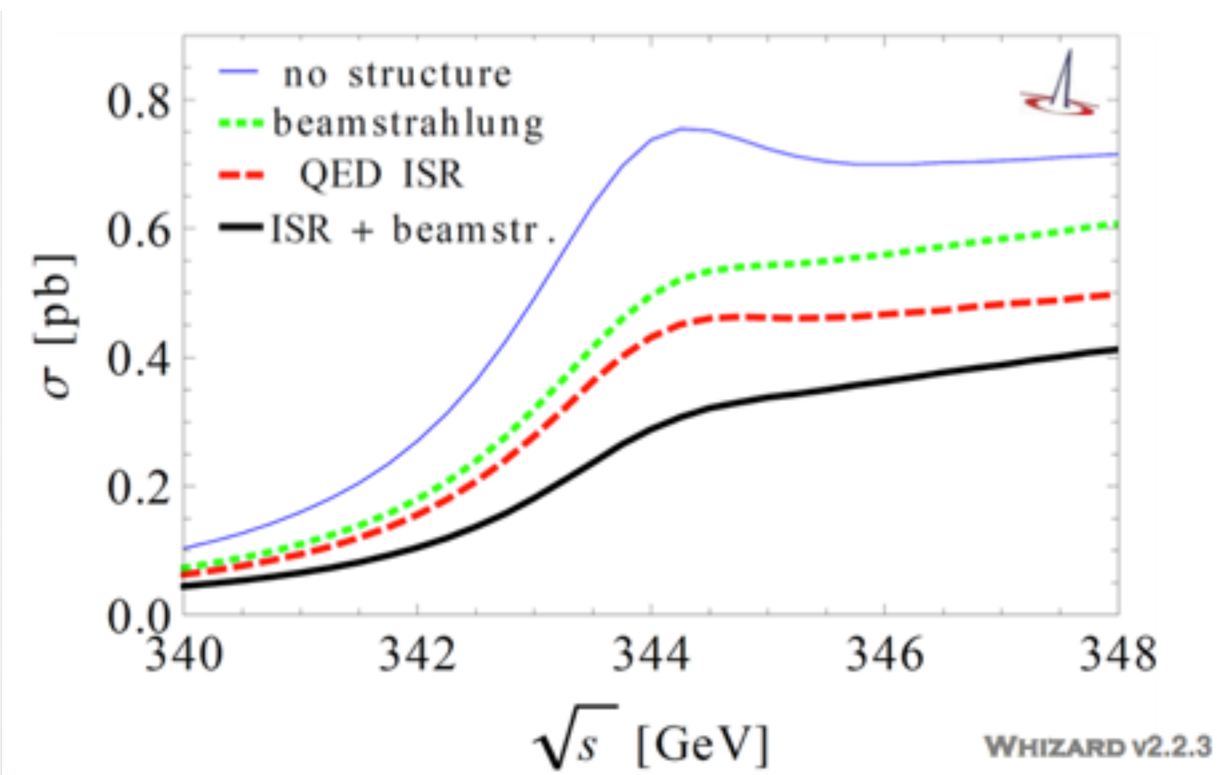
If the α_S uncertainty improves very considerably, a 12 MeV precision on the top quark $\overline{\text{MS}}$ mass is achieved

Top pair threshold: MC status

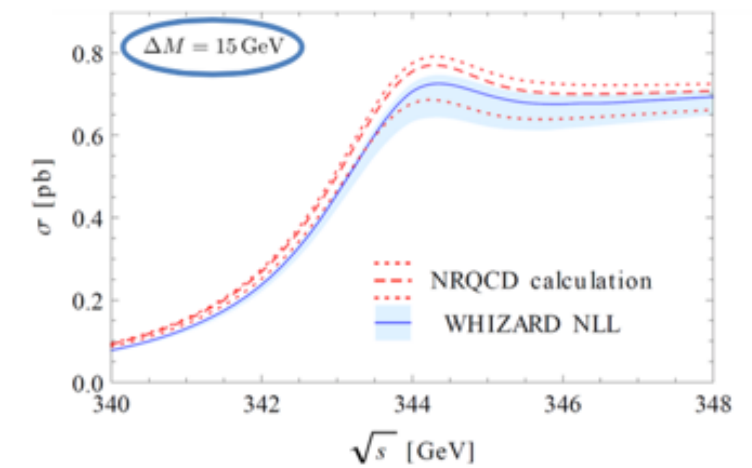
Now available: **NLO simulation of the ttbar threshold** in **WHIZARD** since version 2.2.3

More exclusive observables accesible beyond total cross section: Asymmetries, momentum distribution

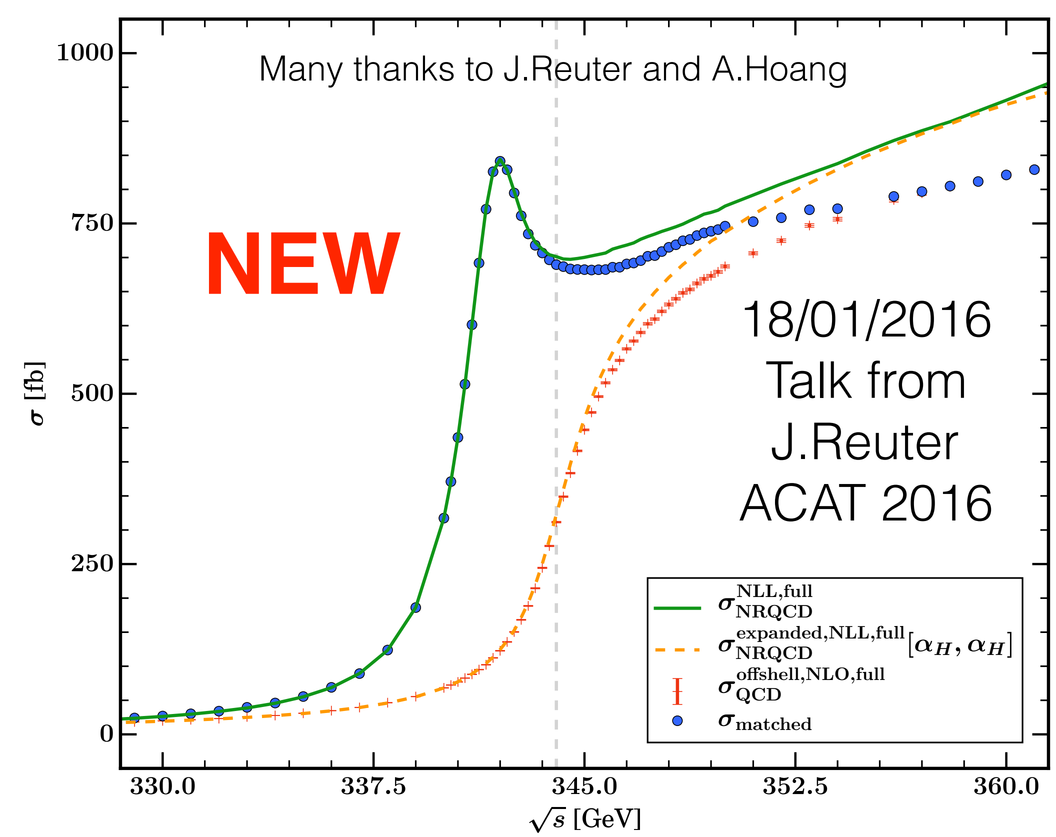
Incorporation of ISR and luminosity spectrum



Successful sanity check with theory calculations

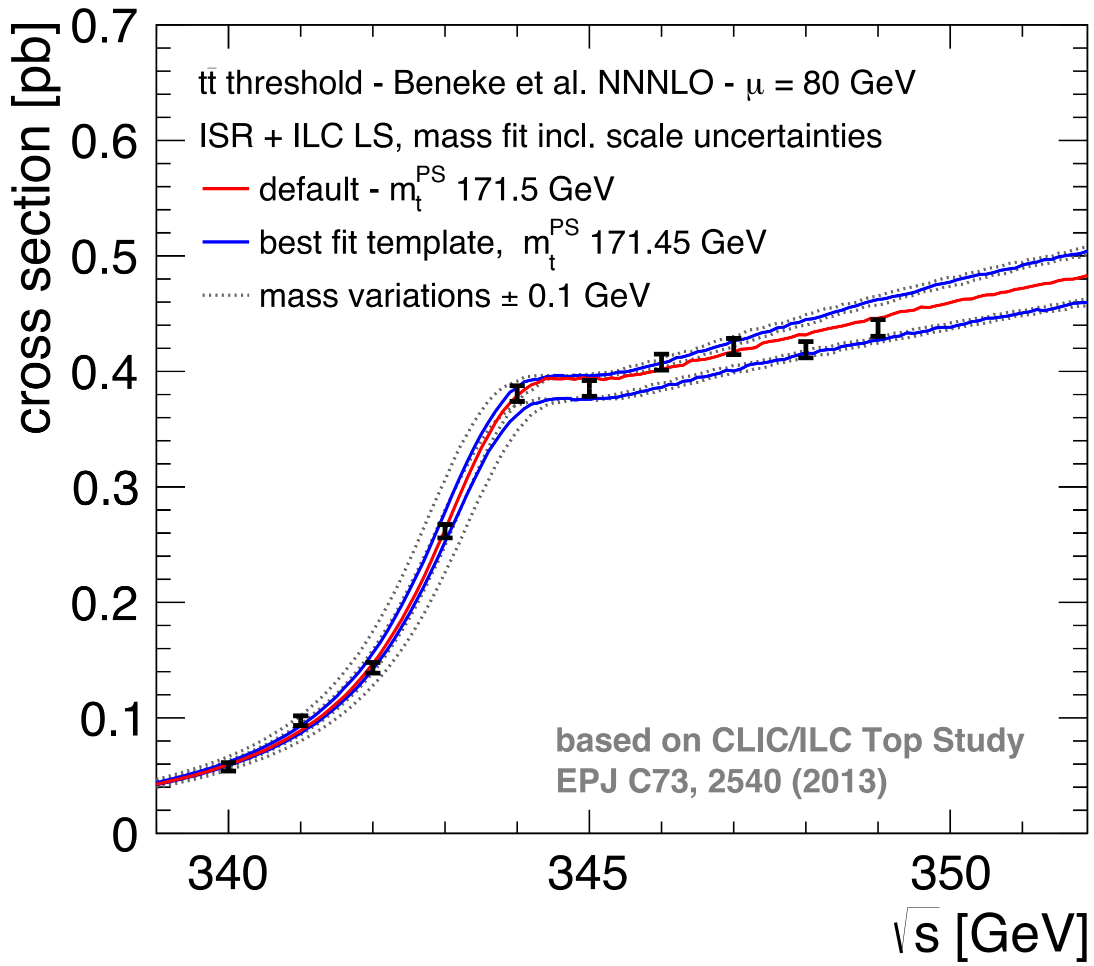


Good progress towards matched calculation, uncertainty bands to follow soon



I.Garcia (Ignacio.Garcia@ific.uv.es)

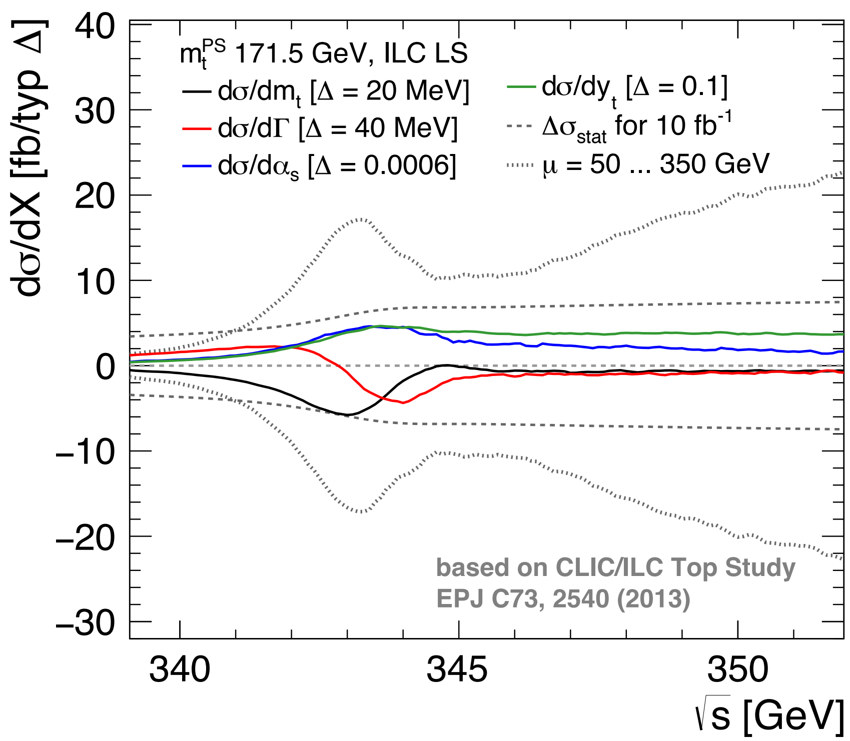
Top pair threshold: Top mass measurement



Threshold scan: **10 x 10 fb^{-1}**, points spaced by 1 GeV **from 340 to 349 GeV**

Based on CLIC/ILC top threshold study EPJ C73, 2540 (2013)

- CLIC_ILD detector model
- Efficiency and backgrounds from full simulations
- ILC TDR luminosity spectrum



For the first time: **Incorporation of NNNLO scale uncertainties** in the experimental evaluation

It translates into:

32 MeV fit uncertainty (including 19 MeV stat)

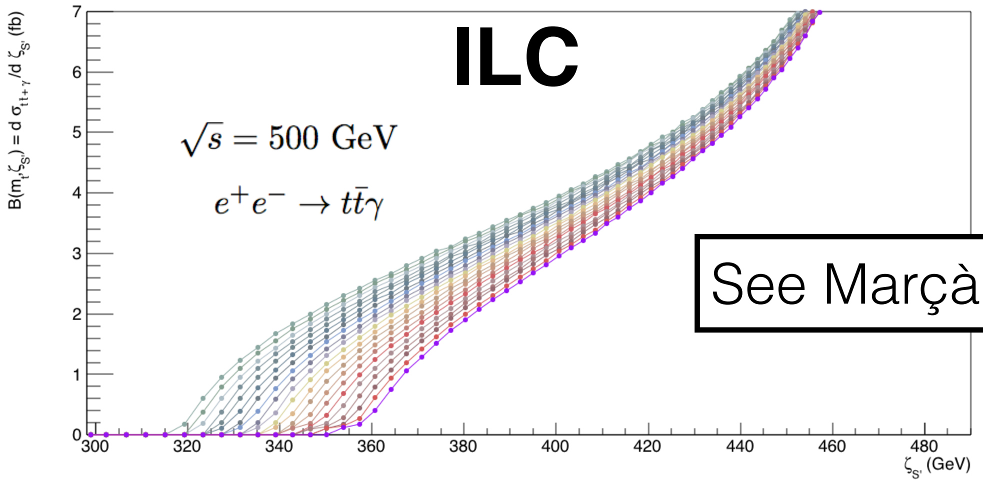
Top mass measurements: Alternative techniques

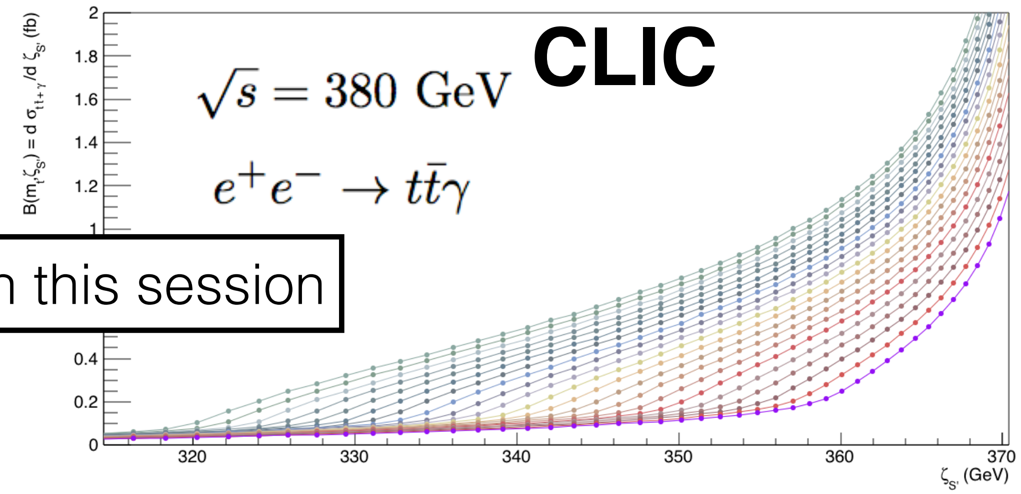
LC scenarios start above threshold (ILC@500GeV, CLIC@380GeV), hence the first measurement top quark mass will be made there

Extraction of the top quark mass from the differential ttγ and ttg cross-section versus s'

Precision seems competitive for √s ~ 400 GeV *Boronat, Fuster, Gomis, in preparation*

(cf. m(b) at m(Z) at LEP, EPJC73 (2013) 2438, ATLAS-CONF-2014-053)



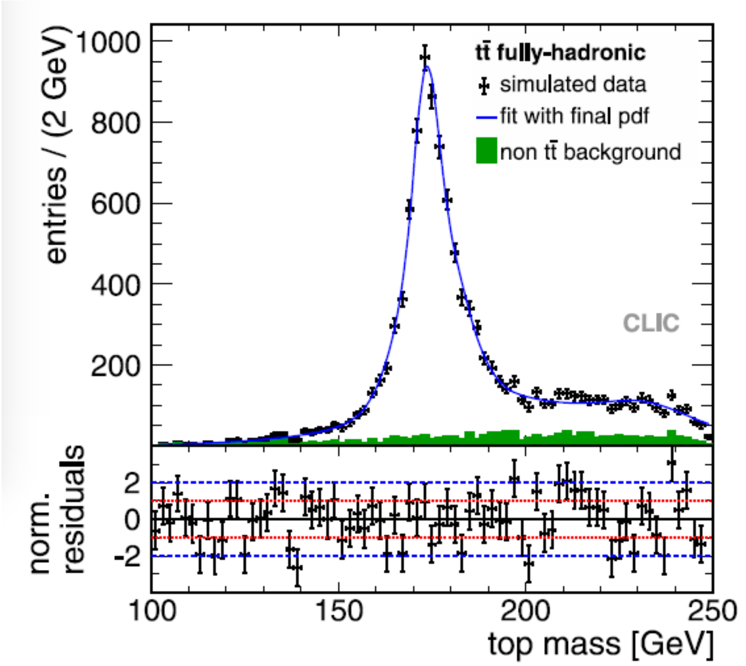


See Marçà's talk in this session

Conventional measurement on top decay products

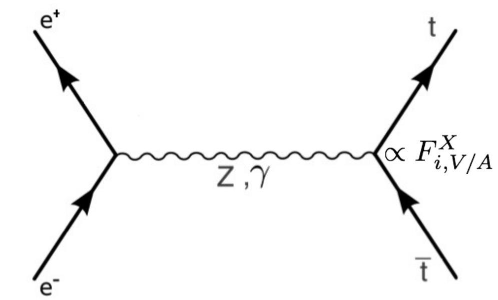
80 MeV stat. precision at 500 GeV
→ input to clarify MC mass interpretation

Seidel, Simon, Tesar, Poss, EPJ C73 (2013)



Top quark couplings

In e+e- colliders the **ttbar production is via γ/Z**



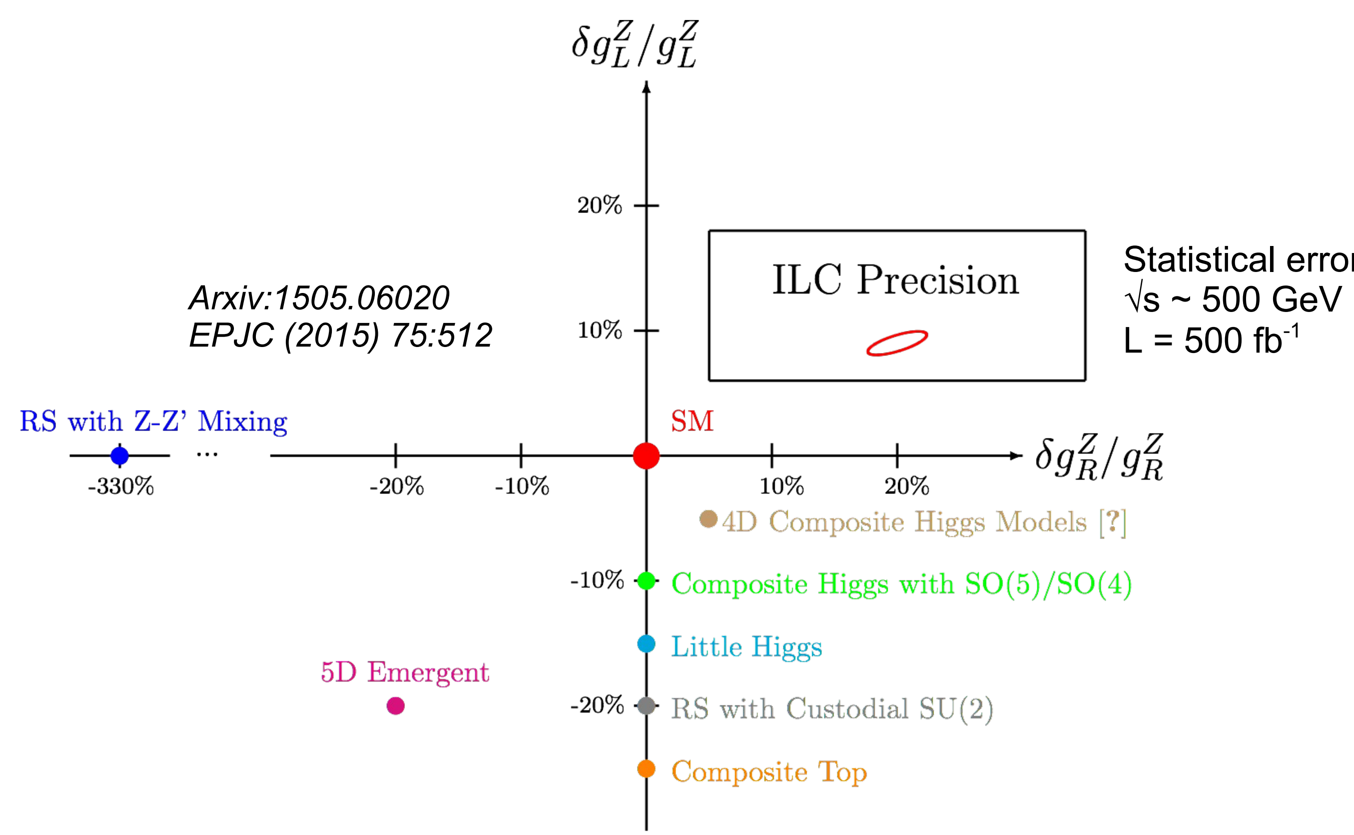
A way to describe the ttZ and ttγ vertices: arXiv:hep-ph/0601112

$$\Gamma^{ttX}_{\mu}(k^2,q,\overline{q}) = -ie\left\{\gamma_\mu\left(F^X_{1V}(k^2)+\gamma_5 F^X_{1A}(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\overline{q})^\mu\left(iF^X_{2V}(k^2)+\gamma_5 F^X_{2A}(k^2)\right)\right\}$$

Vector · Axial · Tensorial · CPV

New physics will modify the electro-weak ttX vertex described in the SM

Precision expected for top quark couplings will allow to distinguish between models



Top quark couplings: Sensitivity vs √s

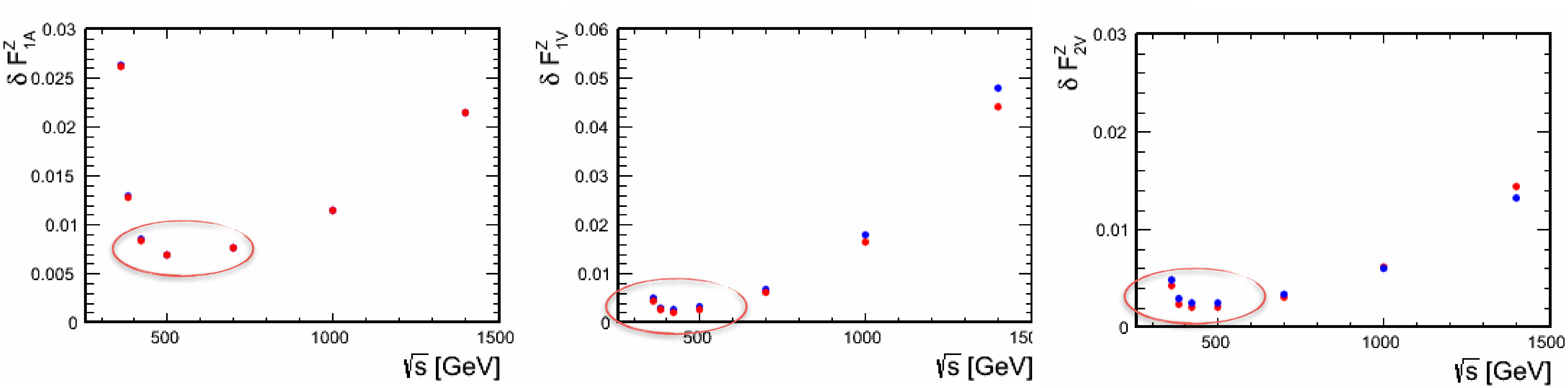
Detailed study at ILC@500GeV

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

Simple evaluation of statistical uncertainty at different scenarios (CLIC@380GeV, ILC@1TeV, CLIC@1.4TeV..)

stat. dominated uncertainty:
$\delta\sigma/\sigma \sim 1/\sqrt{N}$ $\quad \delta A_{FB} = (1 - A^2_{FB}) \times \delta\sigma/\sigma$
Integrated luminosity: 2 x 250/fb

Nominal beam polarization (e^- 80%, e^+ 30%)
Electron polarization only



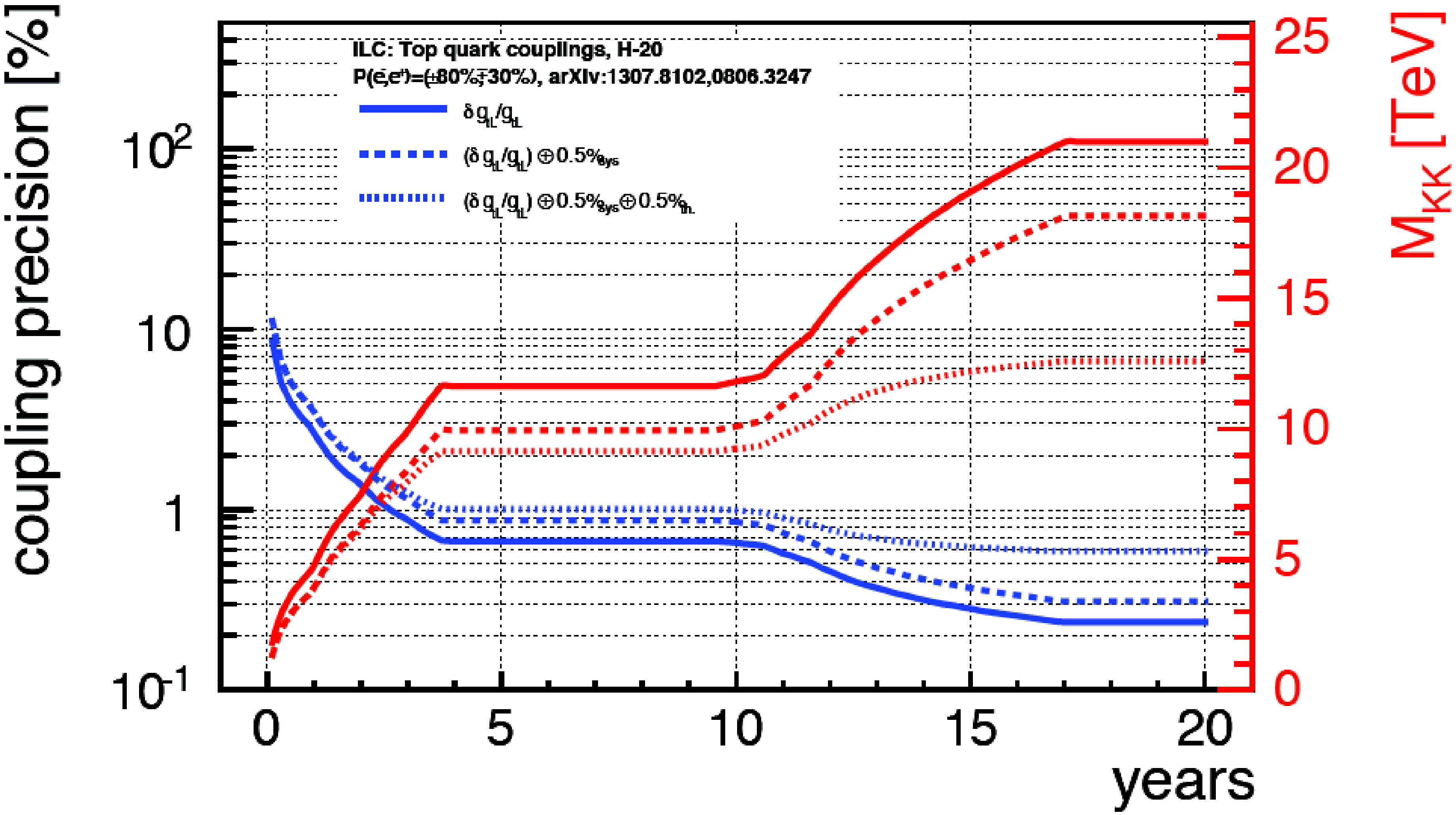
"Sweet spot" around 400-600 GeV

Top quark couplings: Sensitive vs √s

Complete 20-year ILC program ->

H20: 500/fb @ 500 GeV, 200/fb @ 350 GeV, 500/fb @ 250 GeV, 3500/fb @ 500 GeV, 1500/fb @ 250 GeV

Based on phenomenology described in Pomerol et al. arXiv:0806.3247



Can probe scales of ~25 TeV in typical scenarios

Top quark couplings: Full MC studies

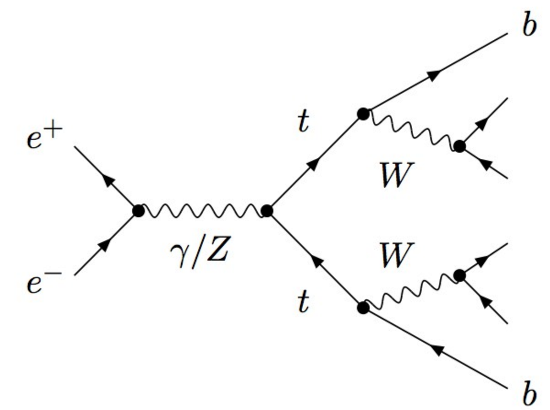
Measure 2 observables for 2 beam polarisations: total cross section and forward-backward asymmetry

Reconstruction of $e^+e^- \to tt \to l\nu bqqb$ final states

$F_{1A}^{\gamma,\mathrm{SM}} = 0$ 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}

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

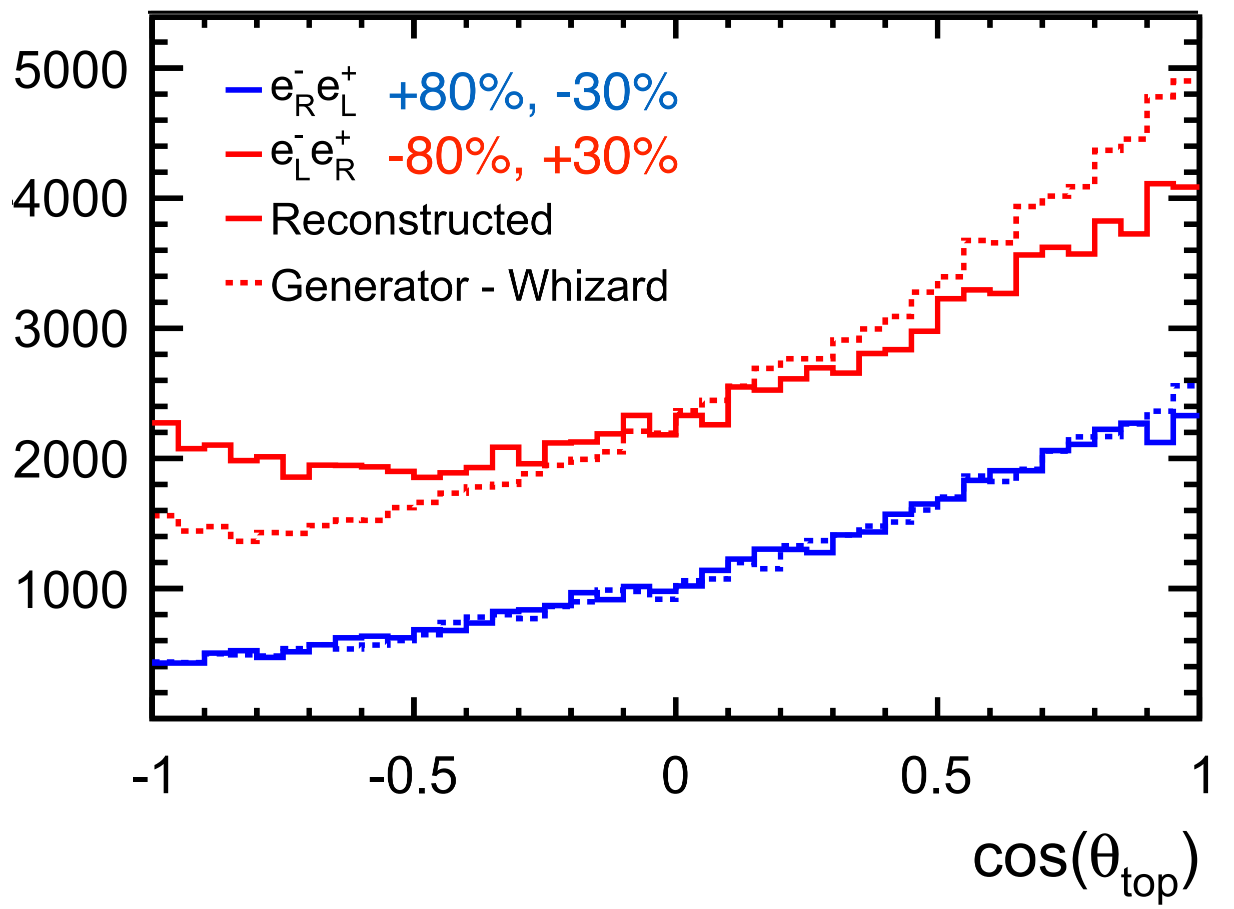
Eur. Phys. J. C (2015) 75:512
DOI 10.1140/epjc/s10052-015-3746-5

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

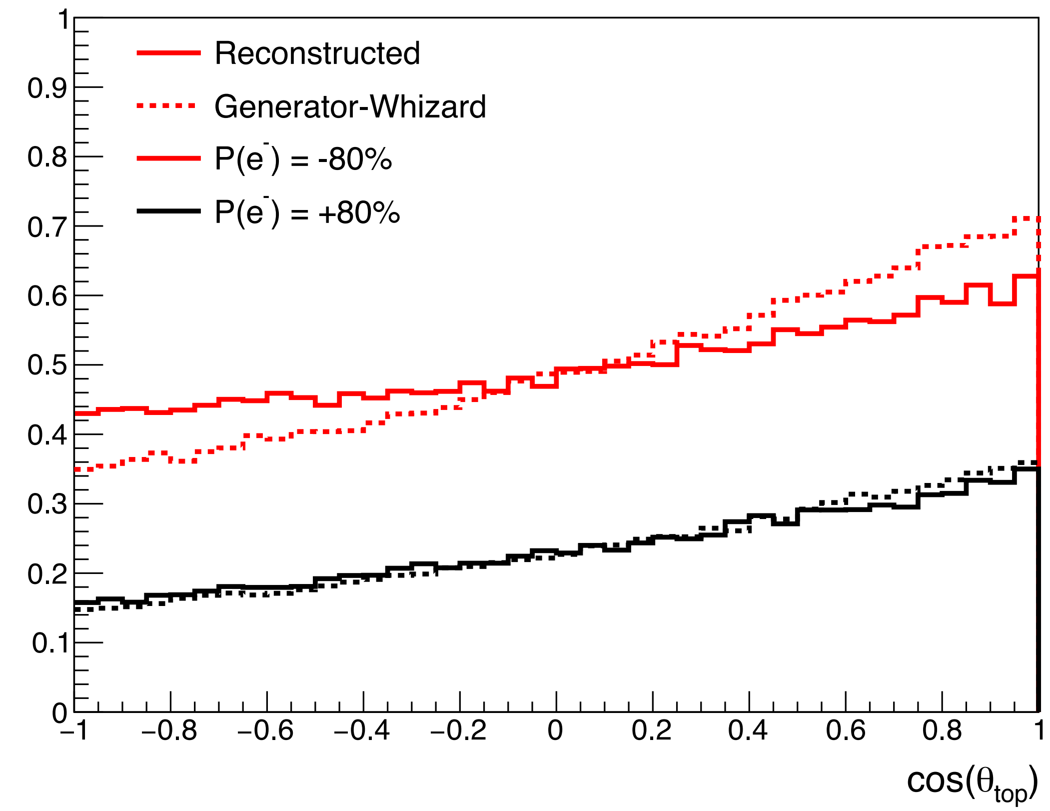
Polarisation
$e^-_L e^+_0$: -80%, 0%
$e^-_R e^+_0$: +80%, 0%

Top quark couplings: Observables

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



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

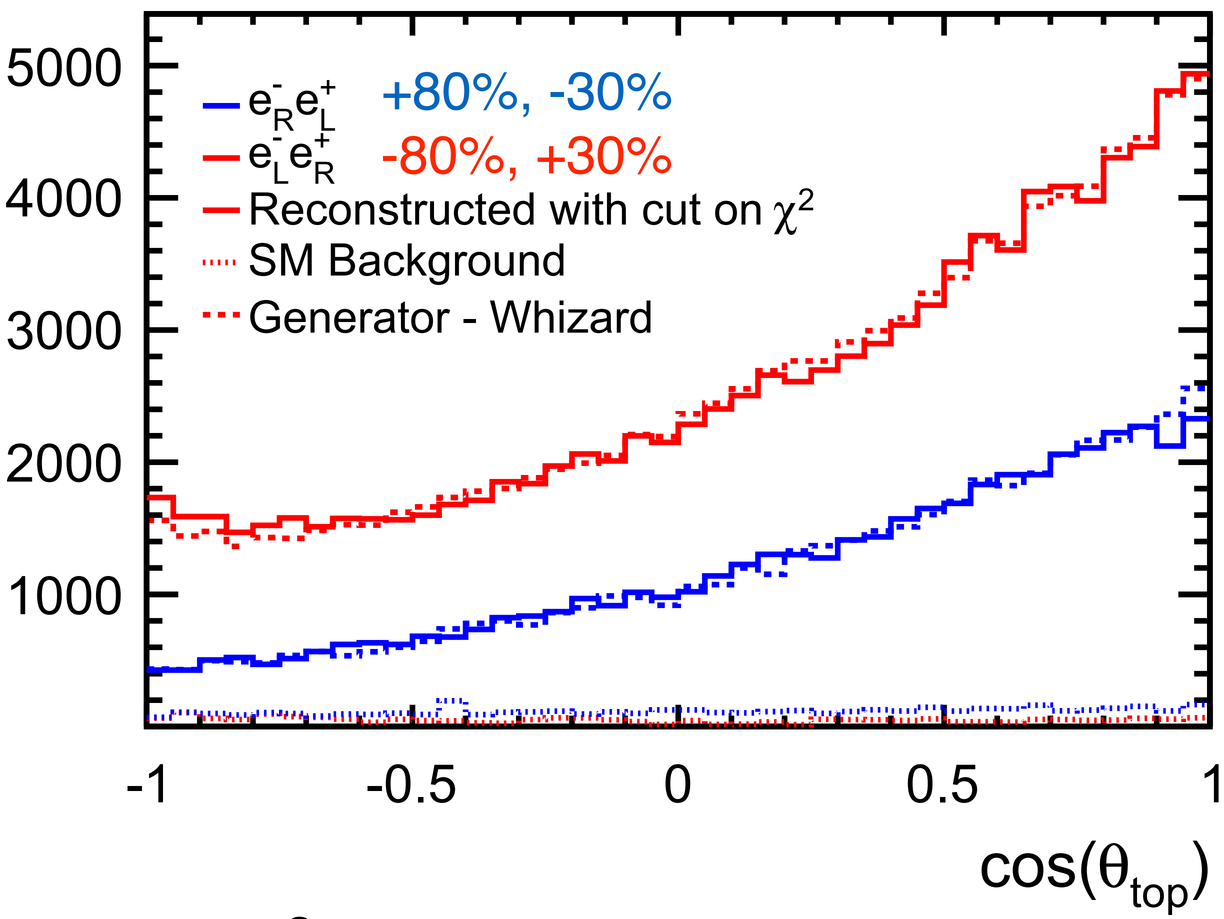


Migrations due to ambiguity in b-W pairing

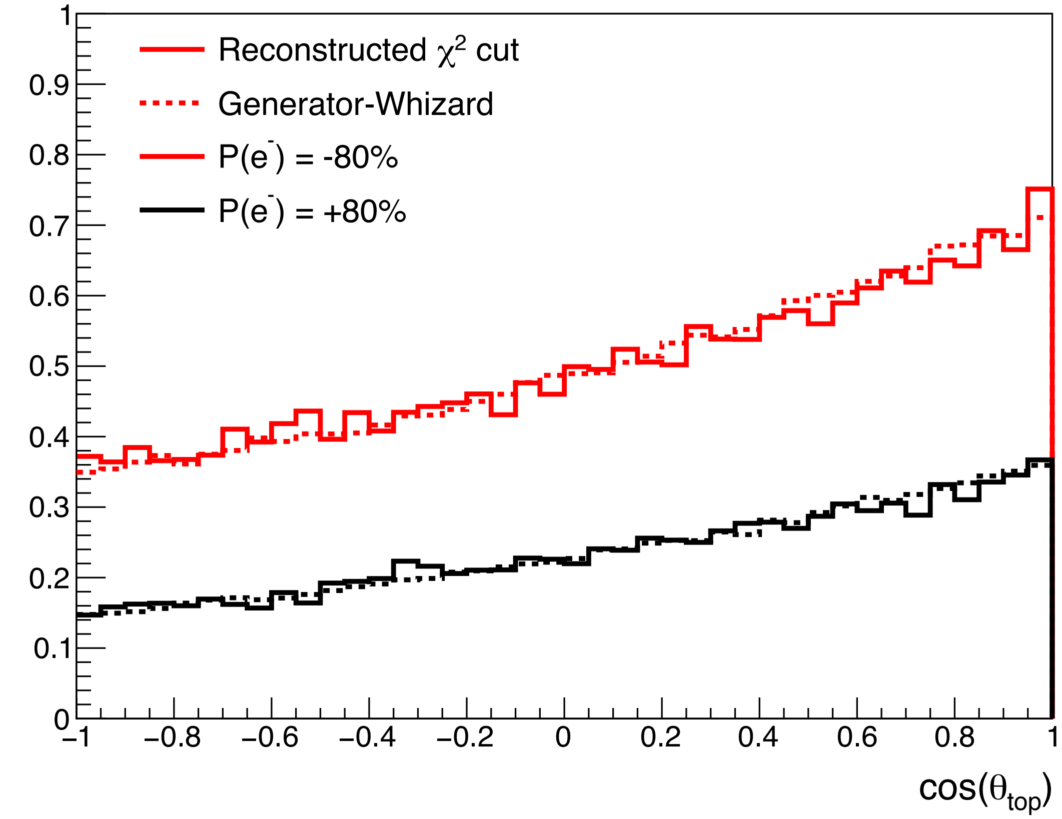
Remedy to address ambiguities: Select cleanly reconstructed events by **χ^2 analysis**

Top quark couplings: Observables

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



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



$\chi^2 < 15$

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

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

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

Curing migrations have a penalty in efficiency

Top quark couplings: Results

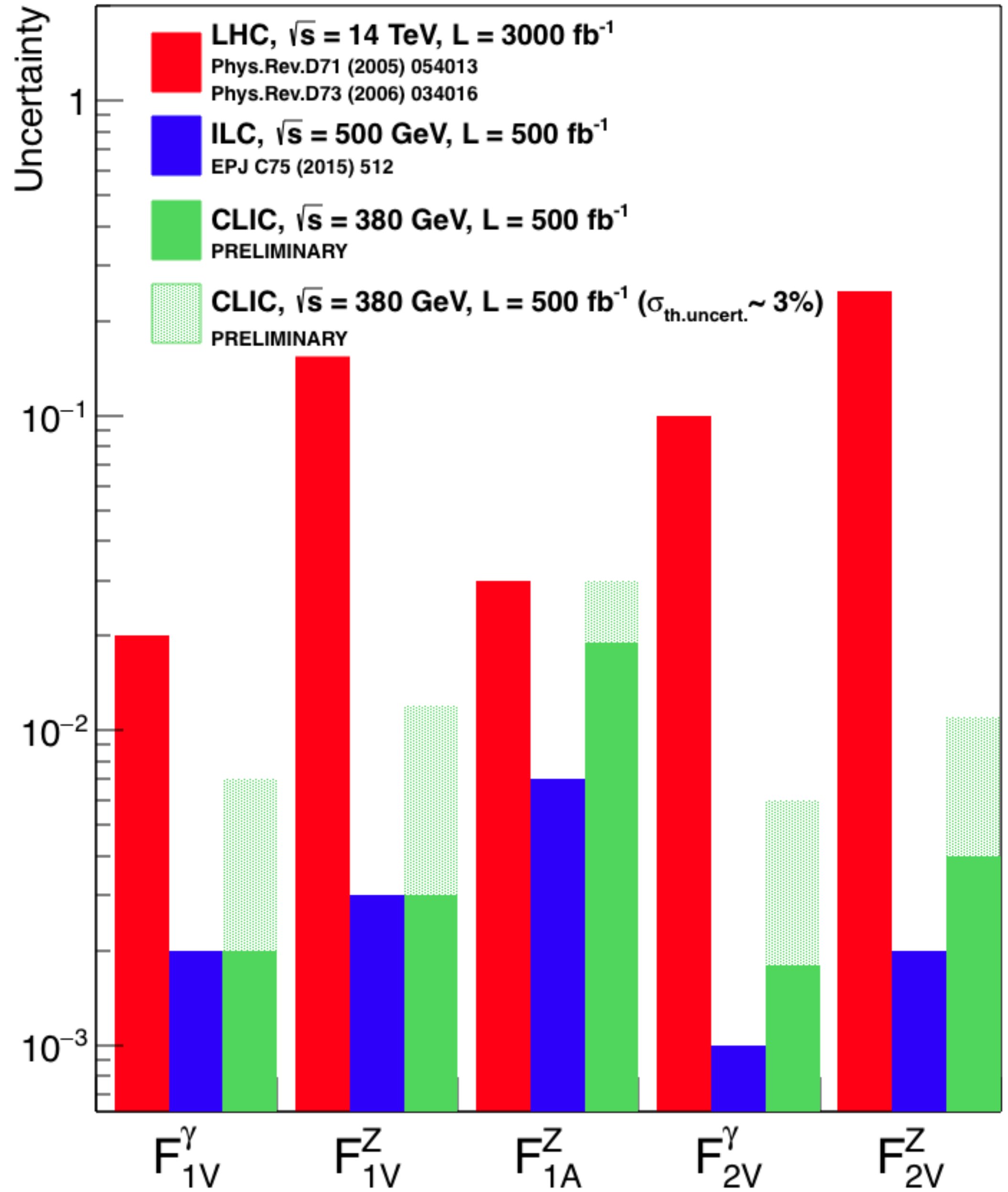
ILC@500GeV L=500fb^{-1}

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

$$\Gamma^{t\bar{t}X}_{\mu}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu (F^X_{1V}(k^2) + \gamma_5 F^X_{1A}(k^2)) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu (iF^X_{2V}(k^2) + \gamma_5 F^X_{2A}(k^2))\right\},$$



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

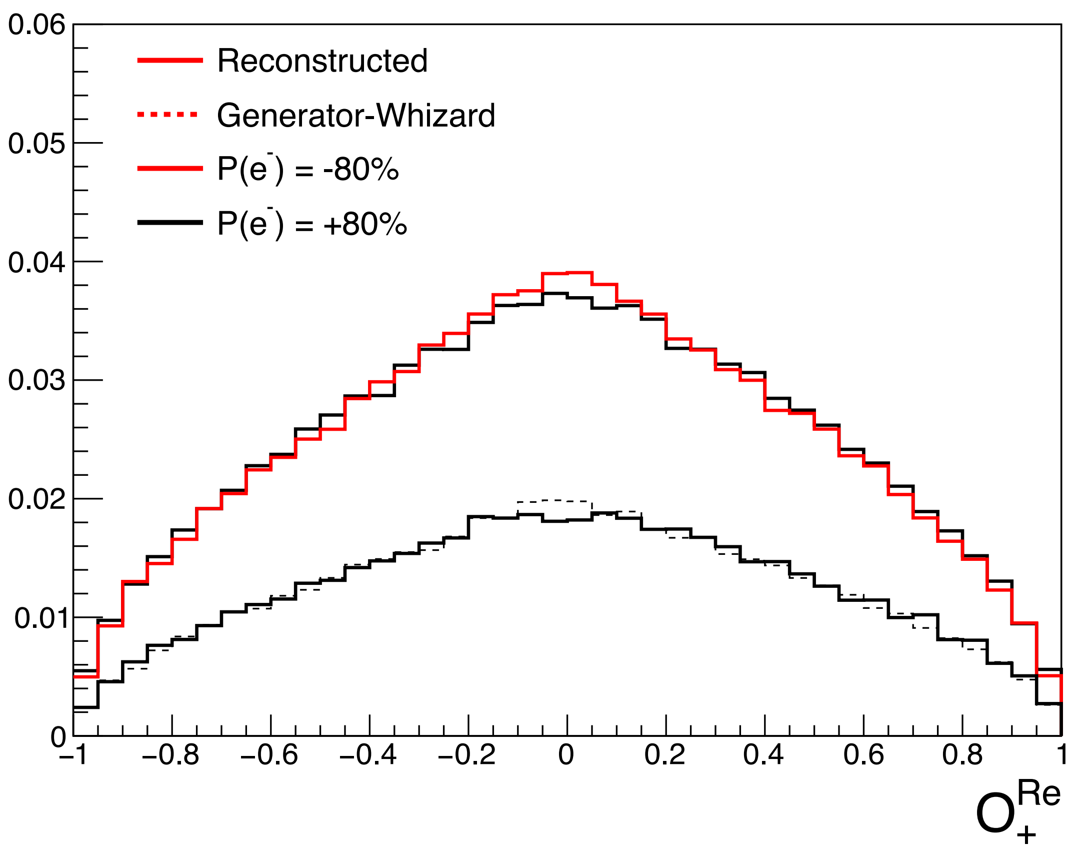
Top quark couplings: CPV sector

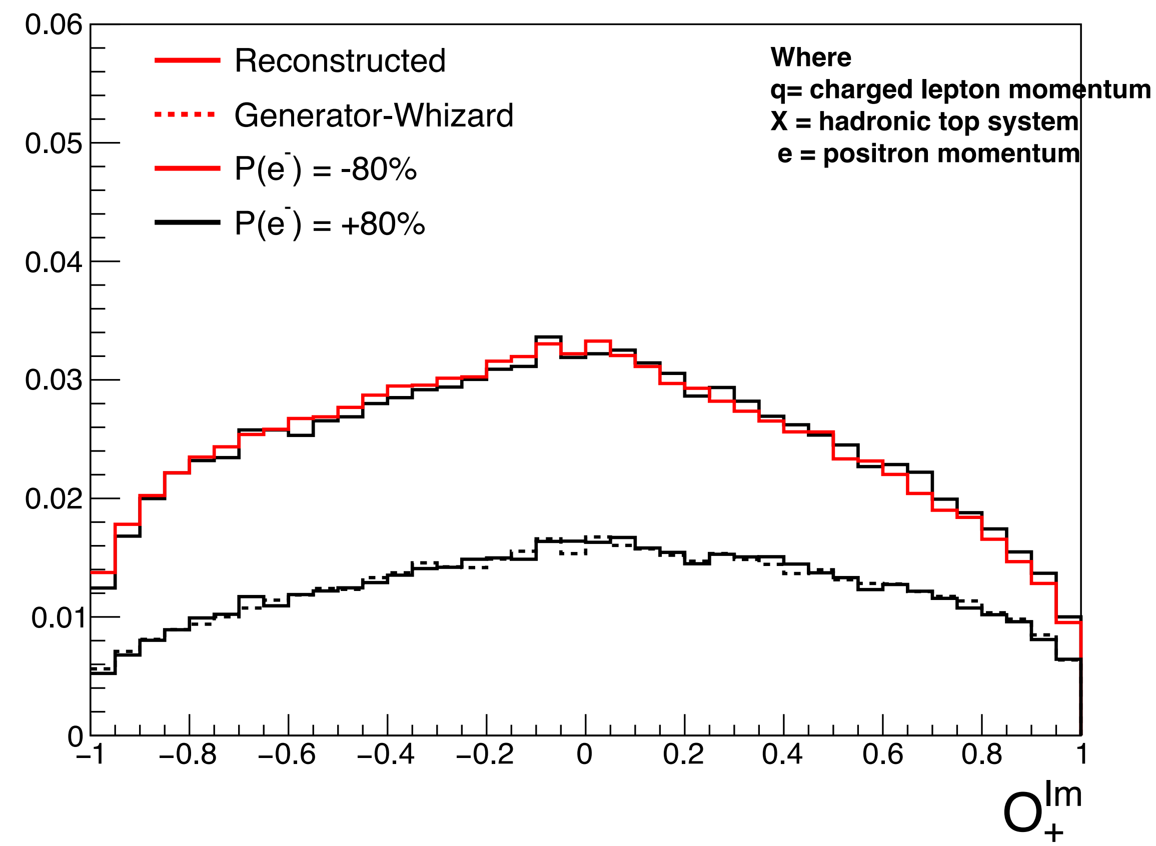
The “baseline” study is limited to CP-conserving form factors, but e^+e^- is known to do well also for **CP-violationg F_{2A}** at least since TESLA times

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

Reconstructing **optimal CP observables** from W. Bernreuther et. al. arXiv:hep-ph/9602273
In the lepton + jets final state:

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





Top quark couplings: CPV Preliminary results

These observables have simple relations to the four F_{2A} form factors

$$A^{Re}_{\gamma,Z} = \langle O^{Re}_{+} \rangle - \langle O^{Re}_{-} \rangle = c_\gamma[PRe(F^\gamma_{2A}) + KZRe(F^Z_{2A})]$$

$$A^{Im}_{\gamma,Z} = \langle O^{Im}_{+} \rangle - \langle O^{Im}_{-} \rangle = d_\gamma[Im(F^\gamma_{2A}) + PKZIm(F^Z_{2A})]$$

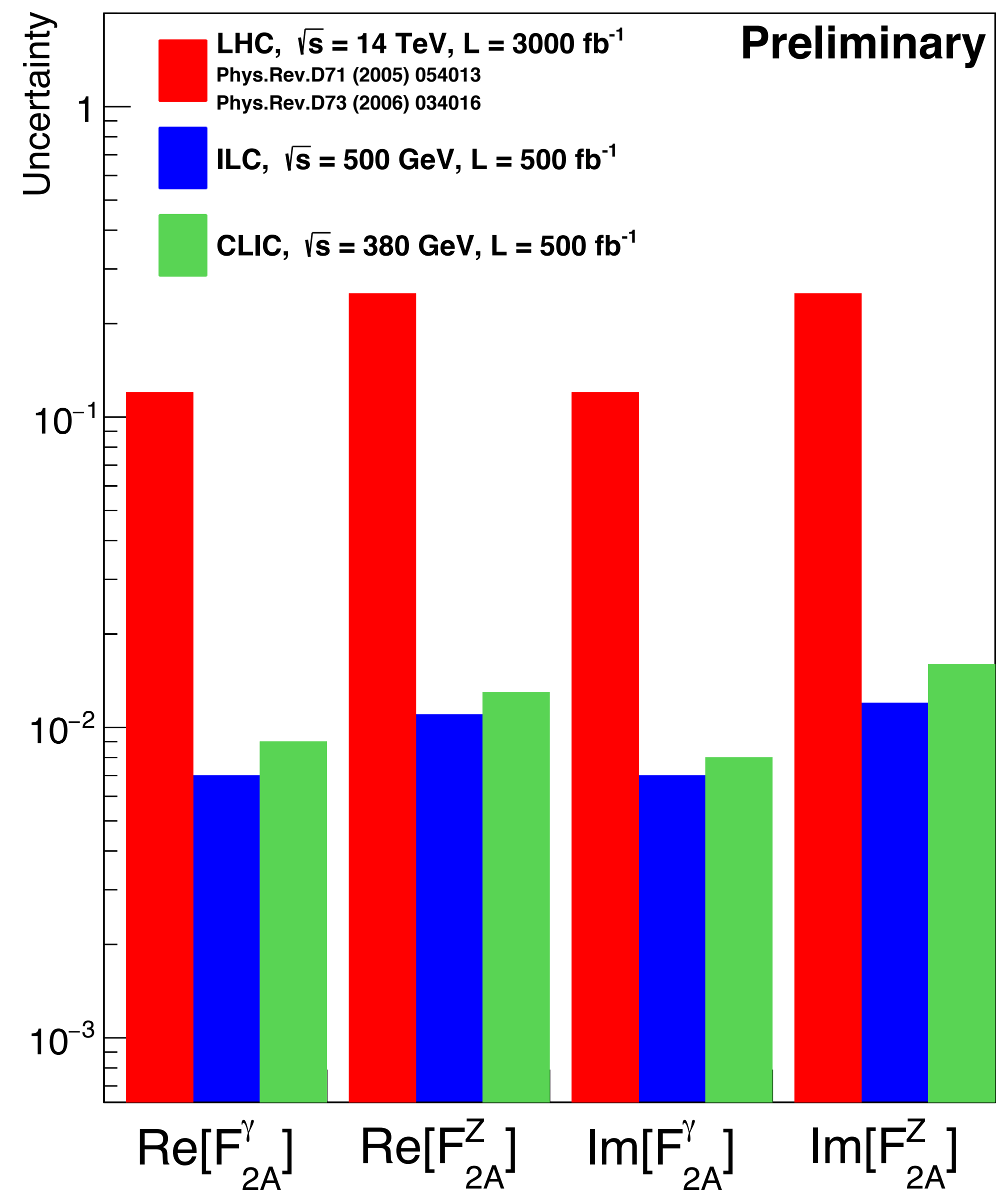
One can easily isolate F_{2A} from previous lineal relations

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

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

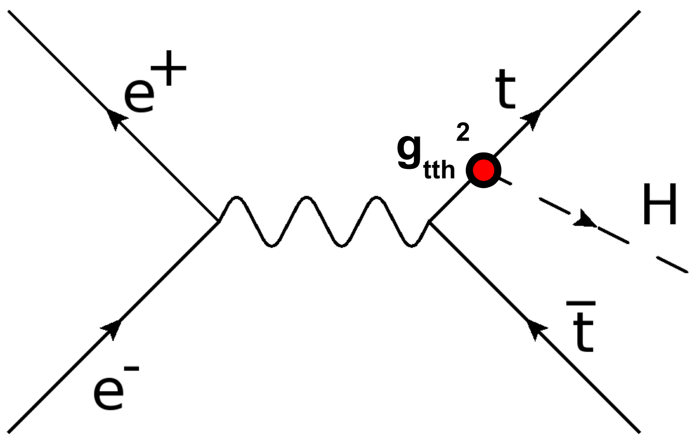
Quantity	$Re[F^\gamma_{2A}]$	$Re[F^Z_{2A}]$	$Im[F^\gamma_{2A}]$	$Im[F^Z_{2A}]$
SM value at tree level	0	0	0	0
LHC	0.12	0.25	0.12	0.25
TESLA TDR	0.007	0.008	0.008	0.010
ILC@500 GeV	0.007	0.011	0.007	0.012
CLIC@380 GeV	0.009	0.013	0.008	0.016

Confirm sensitivity of TESLA TDR study



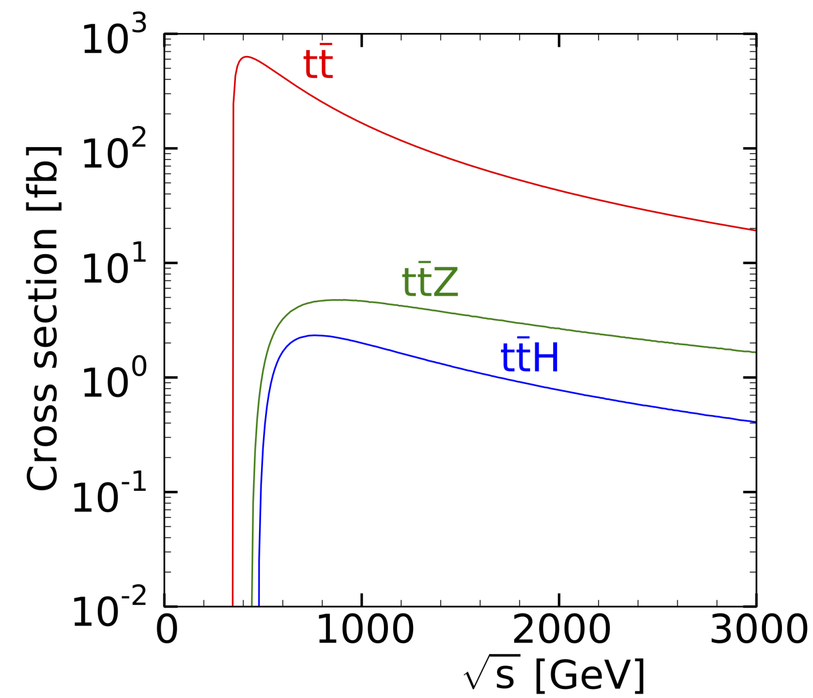
Top Yukawa coupling: ttH at LC

The top Yukawa coupling g_{tth} can be directly measured via ttH channel



$$\frac{\Delta g_{ttH}}{g_{ttH}} = c \cdot \frac{\Delta \sigma}{\sigma}$$

No Higgsstrahlung: c = 0.50
ILC 1 TeV: c = 0.52
CLIC 1.4 TeV: c = 0.53



Broad **maximum around 800GeV**

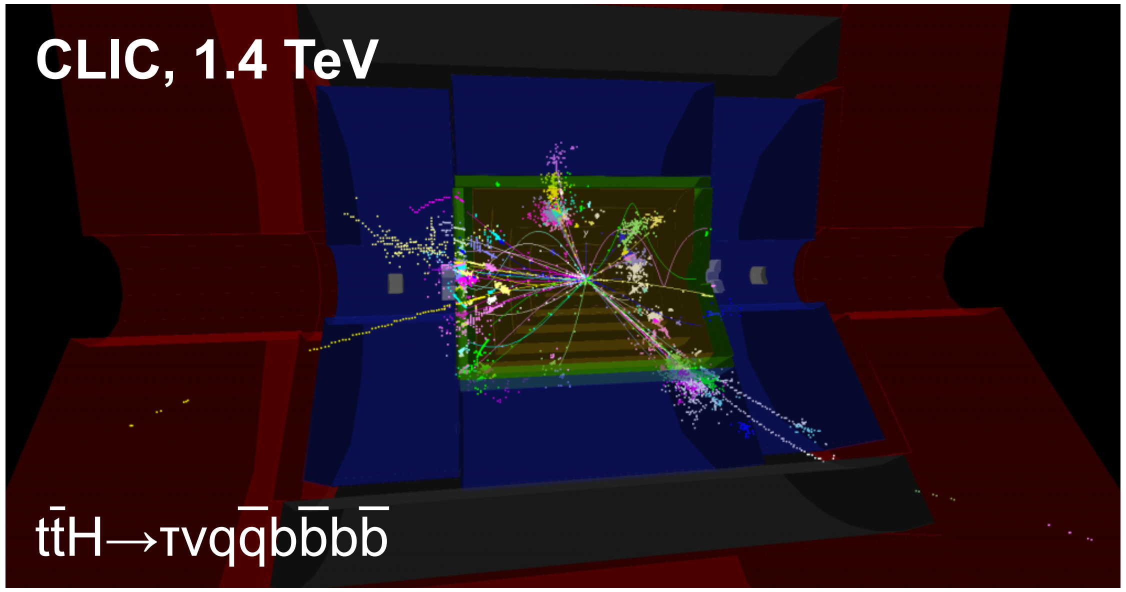
Recent / ongoing benchmark studies based on full detector simulations

500 GeV, ILC (ILD):
Yuji Sudo
1 TeV, ILC (ILD & SiD):
Tony Price, Ph.R.,
Jan Strube, Tomohiko Tanabe
1.4 TeV, CLIC (CLIC_SiD):
Sophie Redford, Ph.R., Marcelo Vogel

Investigated final states:
"*8 jets*": $t(\rightarrow q\bar{q}b)\bar{t}(\rightarrow q\bar{q}\bar{b})H(\rightarrow b\bar{b})$
"*6 jets*": $t(\rightarrow q\bar{q}b)\bar{t}(\rightarrow l\nu\bar{b})H(\rightarrow b\bar{b})$
["*4 jets*": $t(\rightarrow l\nu b)\bar{t}(\rightarrow l\nu\bar{b})H(\rightarrow b\bar{b})$]

Talk by Ph.Roloff at Top Workshop 2015 - Valencia

Top Yukawa coupling: ttH studies



Crucial tests of various detector performance and reconstruction aspects:

- Jet reconstruction in complex final states
- Flavour tagging
- Charged lepton identification
- Missing energy reconstruction
- Background rejection: tt, other ttH, ttZ, ttg(g→bb)

About 4% precision on the top Yukawa coupling achievable with 1ab^{-1} at 1TeV at the ILC or 1.5 ab^{-1} at 1.4TeV at CLIC

Collider	LHC		ILC	ILC	CLIC
CM Energy [TeV]	14	14	0.5	1.0	1.4
Luminosity [fb^{-1}]	300	3000	1000	1000	1500
Top Yukawa coupling κ_t	$(14-15)\%$	$(7-10)\%$	10%	4%	4%

from arXiv:1311.2028

Investigation of other observables in ttH events possible, like differential distributions to explore the CP properties.

FCNC top decays: t → cH

F. Zarnecki: **Measurement of FCNC top decays at ILC/CLIC studied at parton level.**

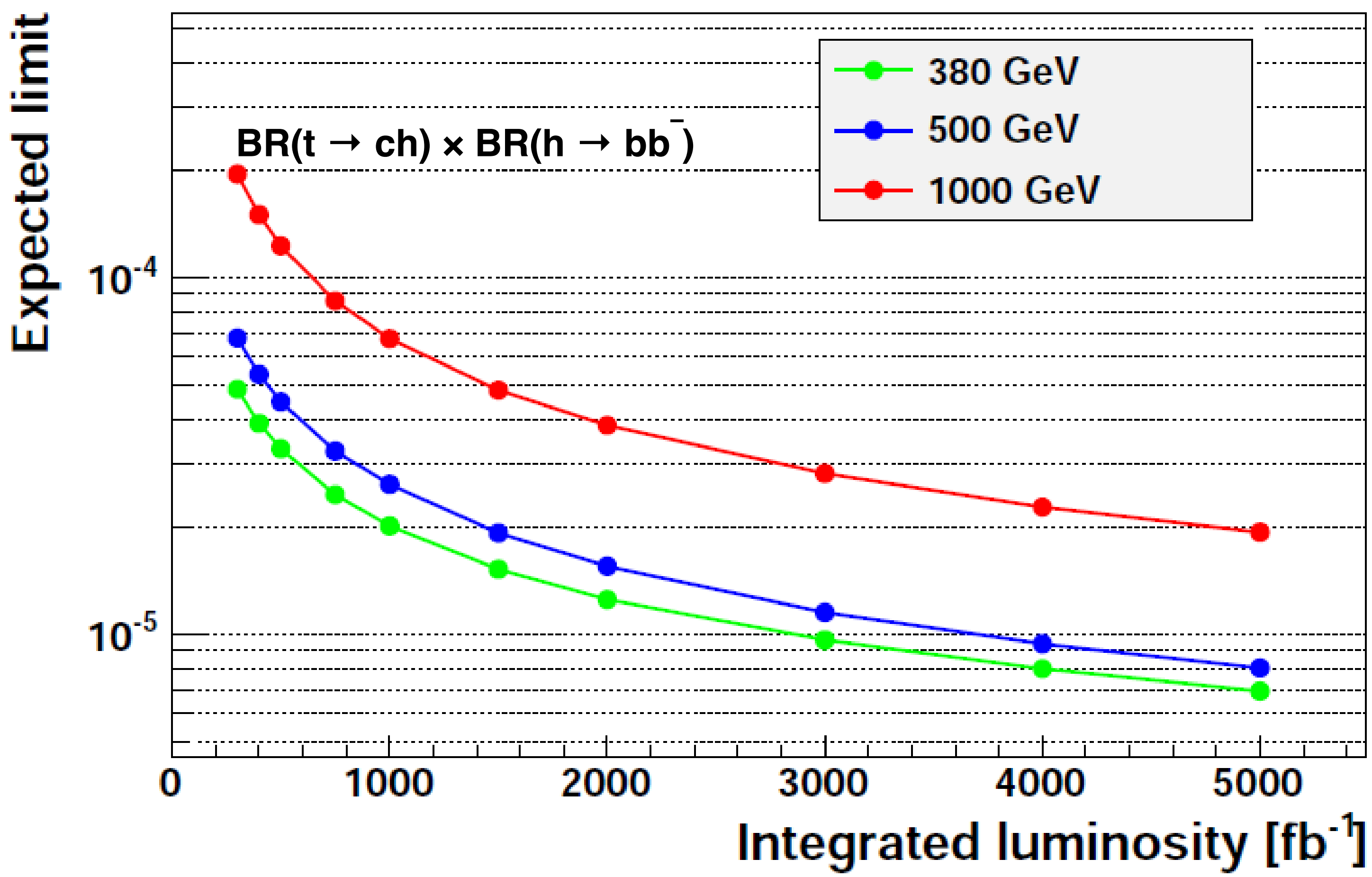
Top workshop Valencia July 15

https://indico.cern.ch/event/381148/session/5/contribution/4/attachments/759420/1674930/toplc2015.pdf

Decay t→c h is most interesting:

- well constrained kinematics
- test of Higgs boson couplings
- seems to be most difficult for LHC

Two Higgs Doublet Model (2HDM) as a test scenario



Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b}) \sim 10^{-5}$ depending on the energy, luminosity and detector parameters in a H-20 LC full program.

FCNC top decays: Status of further studies

Full detector simulation and reconstruction samples of $t \rightarrow cH$ generated

- Validation of parton-level results
- Waiting for the analysis to produce first results

Last version of WIZHARD includes more FCNC couplings: $t \rightarrow cH(cZ, c\gamma)$

- top-photon, top-gluon and top-Z
- $t \rightarrow c\gamma$ and $e^+e^- \rightarrow tc$ events generated and waiting to be analysed

I.Garcia (Ignacio.Garcia@ific.uv.es)

Summary

Top at Hadron Colliders

- Top **mass** measured with a precision of **500 MeV**
- **5σ** significance observed for all top **ttV (V=W,Z,γ)** production channels
- Yukawa coupling signal strength $\mu_{ttH} = 2.3^{+0.7}_{-0.6}$ ATLAS and CMS combination

Top at Future Linear Colliders

- tt threshold scan: **~ 50 MeV** precision in top mass including the different uncertainty sources. Alternative methods in continuum can reach O(100 MeV) precision
- ILC and CLIC can characterise **precisely** CP conserving and also CP violating ttγ and ttZ vertices, **an order of magnitude better than LHC**
- About **4%** precision on the top Yukawa coupling achievable with 1ab^{-1} at 1TeV at the ILC or 1.5 ab^{-1} at 1.4TeV at CLIC
- Expected limits on t → ch, **~**$\mathbf{10^{-5}}$ in a parton level study and new full simulation samples waiting to be analysed

THANK YOU VERY MUCH FOR YOUR ATTENTION

I.Garcia (Ignacio.Garcia@ific.uv.es)