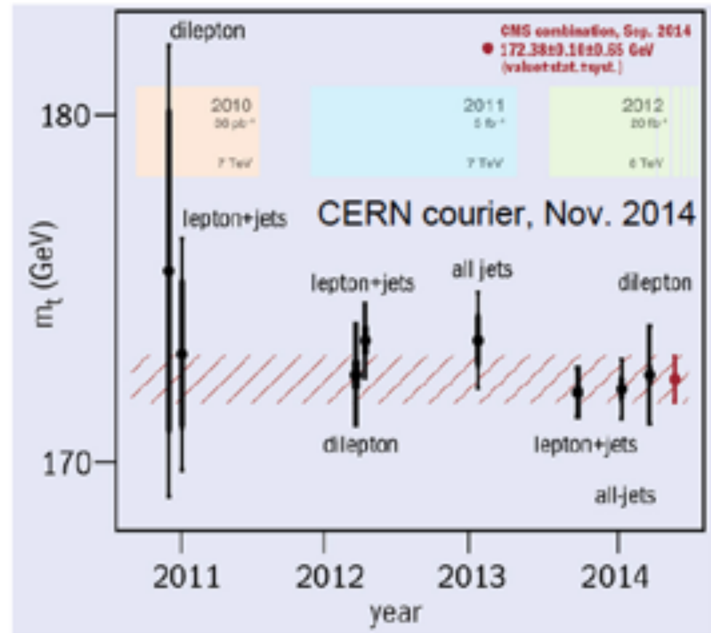
Top Physics @FCCee

Patrizia Azzi - INFN Padova & CERN

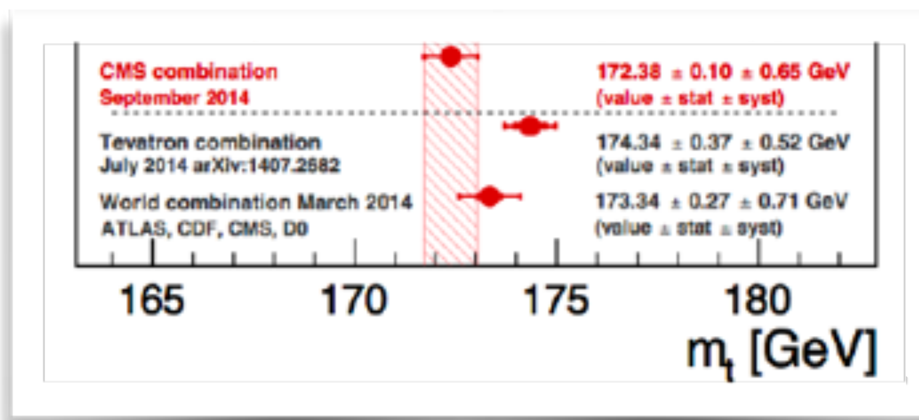
how is top physics doing now?

- Top just turned 20!
- LHC experiments are performing precision top physics:
    - a true top factory
    - very pure samples
    - impressive results
    - trampoline for BSM
- top measurements now a « standard candle » for calibration: jet energy scale, b tagging and boosted object tagging efficiencies!
- LHC-Run2 challenge: getting ready to profit of the higher CM energy without suffering of the harsher running conditions



$$m_t = 172.38 \pm 0.10\,(\text{stat.}) \pm 0.65\,(\text{syst.})\,\text{GeV}$$

±0.38%

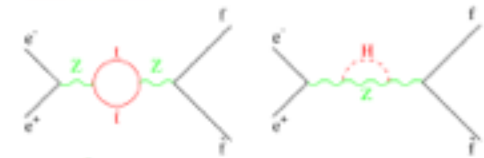


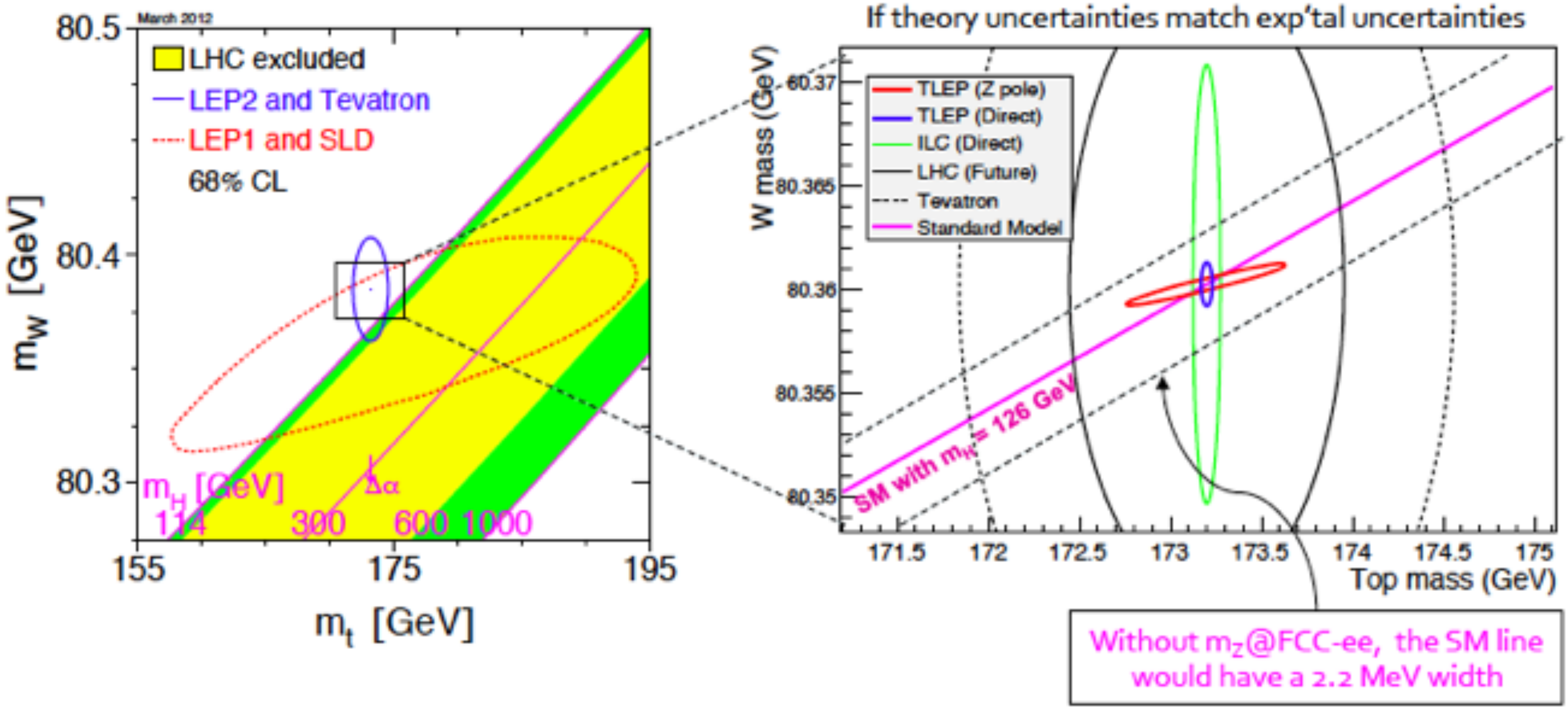
Top Physics at FCC-ee

- The strength of the FCC-ee program is to be able to span several centre of mass energies at high luminosity
- Where/when does top physics come in the program?
  - dedicated run at threshold @350GeV « Mega-Top » because of the ~1M top pair produced
  - higher energy runs for top coupling measurement (ttZ, ttγ,ttH?)
  - studies with production of single top quarks profiting of the run at 240GeV dedicated to Higgs precision measurement
  - periodic returns at the Z-peak in « FCC-ee top » conditions for calibration

but why? (1)

- Sensitivity to heavy new physics (with EW couplings)
  - E.g., LEP was able to predict m_{top} and m_H
    - Now that m_{top} and m_H are known, the standard model has nowhere to go

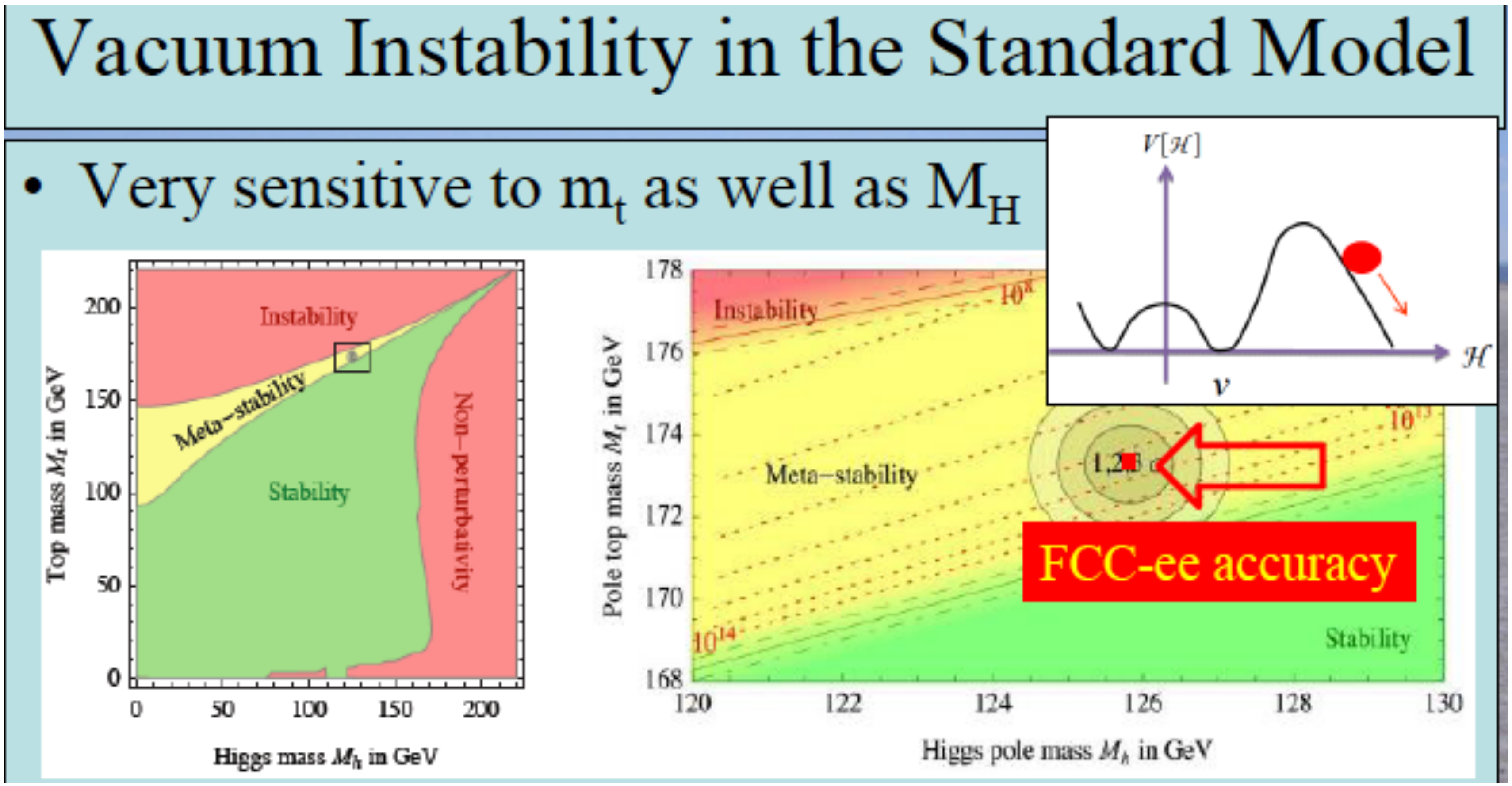




- Presence of new physics with EW couplings would drastically change this picture

but why? (2)

- top mass is a fundamental parameter of the Standard Model. It could tell us the fate of the Universe

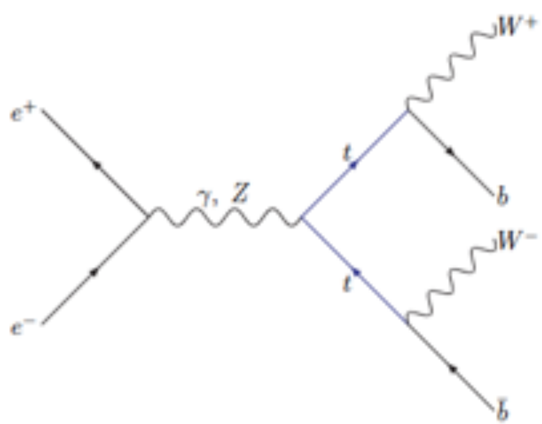


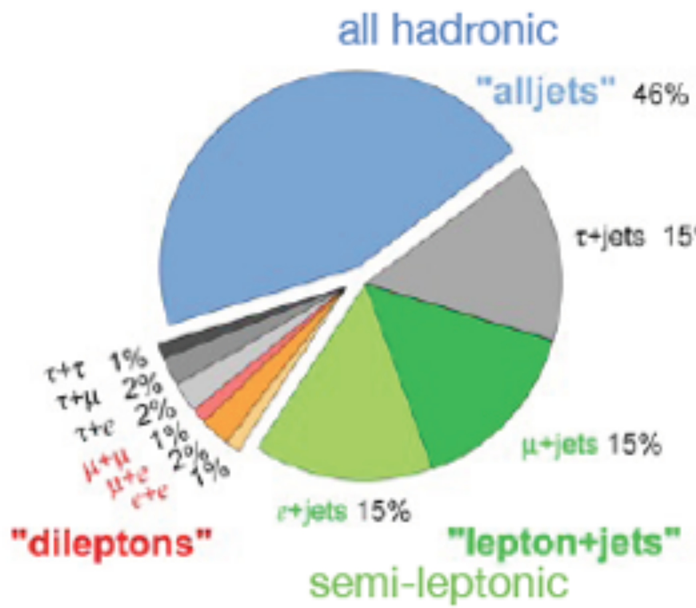
but why? (3)

- top precision measurements are a portal to new physics effects at high scales, the large statistics at FCC-ee will allow to probe:
  - **rare decays**
  - **(anomalous) couplings**
  - **indirect effects** from loop contributions
- at FCC-ee (by construction) and at other planned lepton collider (because of the current experimental limits) the window for direct production of heavier new physics objects is tiny.
- *standing on the shoulders of LHC-Run2 results for possible direct discovery of new particles in the TeV range!*

Production & decay

- top physics analysis is driven by production and decays modes
  - at lepton collider running closer to the threshold, pair production dominates

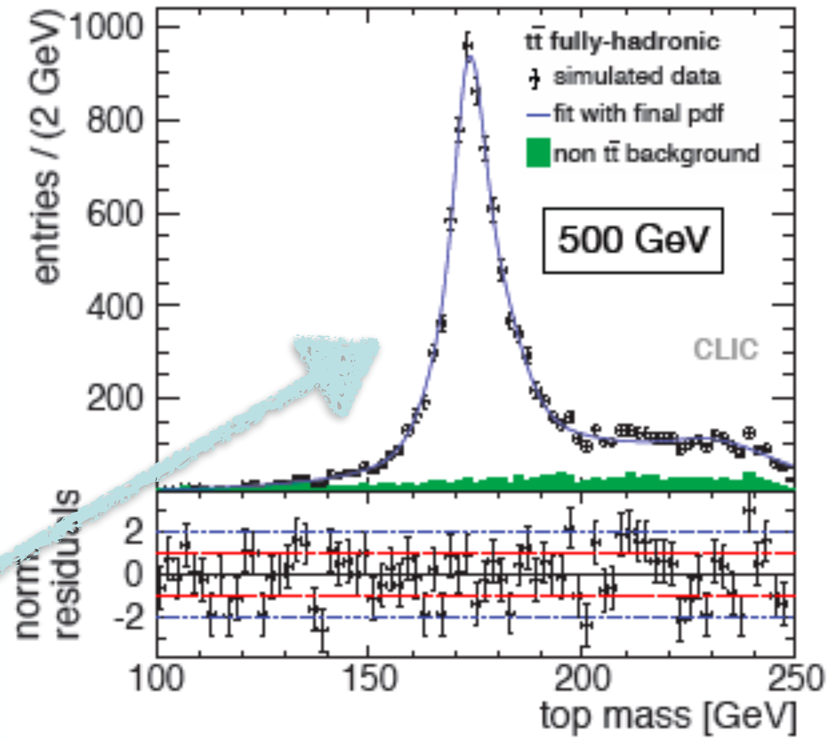




  - ~100% BR in Wb
  - final states classified on the basis of the W decay
  - at lower center of mass energies can profit of (anomalous) production of single top

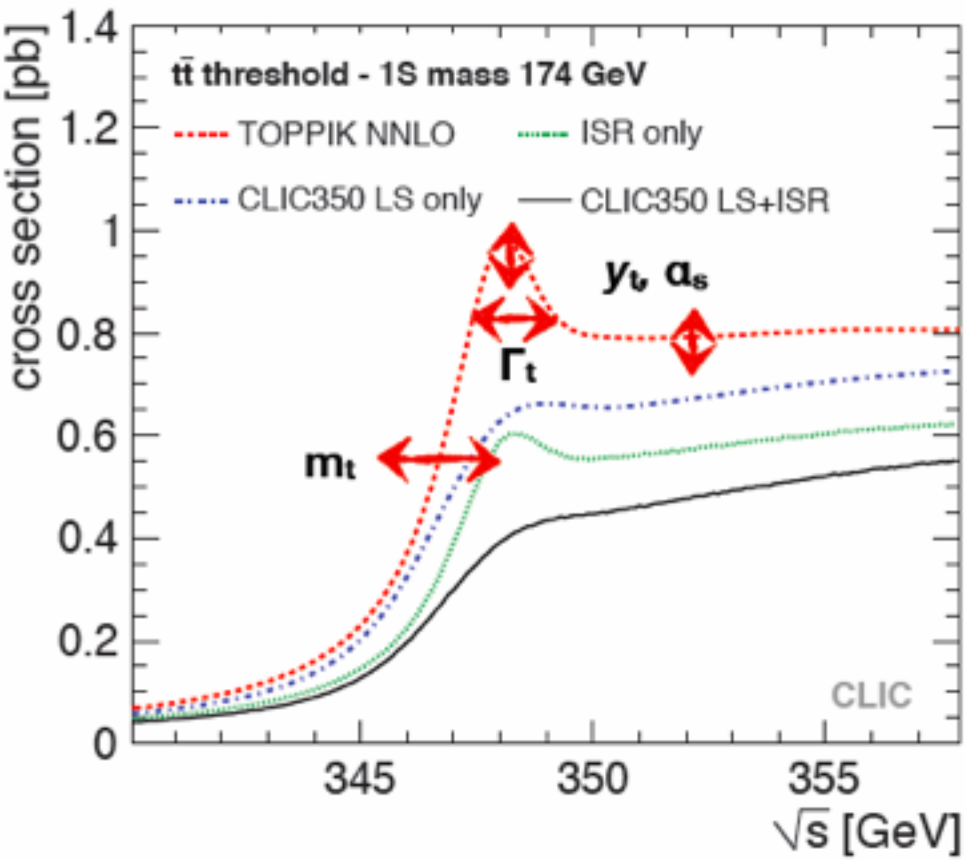
Reconstructing the top mass

- The methods that can be employed for the mass reconstruction are characterized by different experimental and theoretical issues and uncertainties:
- **« Reconstructed » mass: from a fit of the decay products in the various channels.** Most precise way (for now) at hadron colliders has the problem of being correlated with the real « pole » mass in a way that brings in significant theoretical uncertainties.
    - extrapolation shows no benefit in higher lumi for LHC: ~600MeV reach for LHC
    - at lepton collider could obtain precision of ~80MeV (CLIC study)
    - other methods considered for HL-LHC for instance could avoid this issue and bring down uncertainty to 500MeV (or better these methods would profit of increased statistics)
    - can be used above threshold as well
    - well defined experimentally



Mass fit - Result:
stat. uncertainty on m_t: 80 MeV (FH + SL) [100 fb^{-1}]
stat. uncertainty on Γ_t: 220 MeV (FH + SL)
exp. systematics of similar order

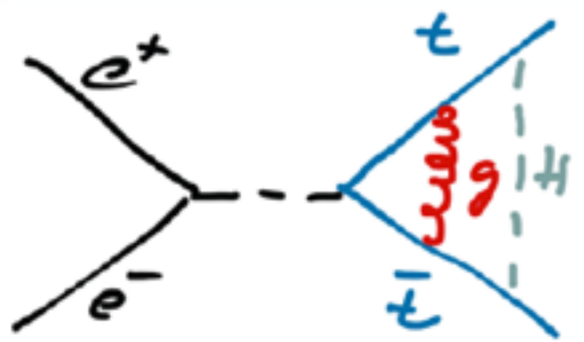
Threshold scan: not only mass



- Effects of some parameters are correlated; dependence on Yukawa coupling rather weak - precise external α_s helps

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

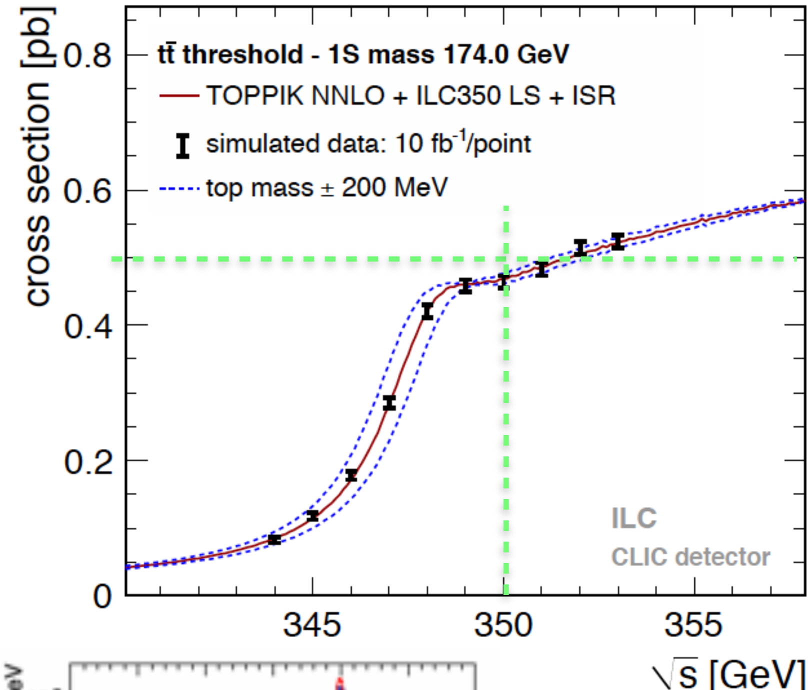
- Top mass, width, Yukawa coupling
- Strong coupling constant

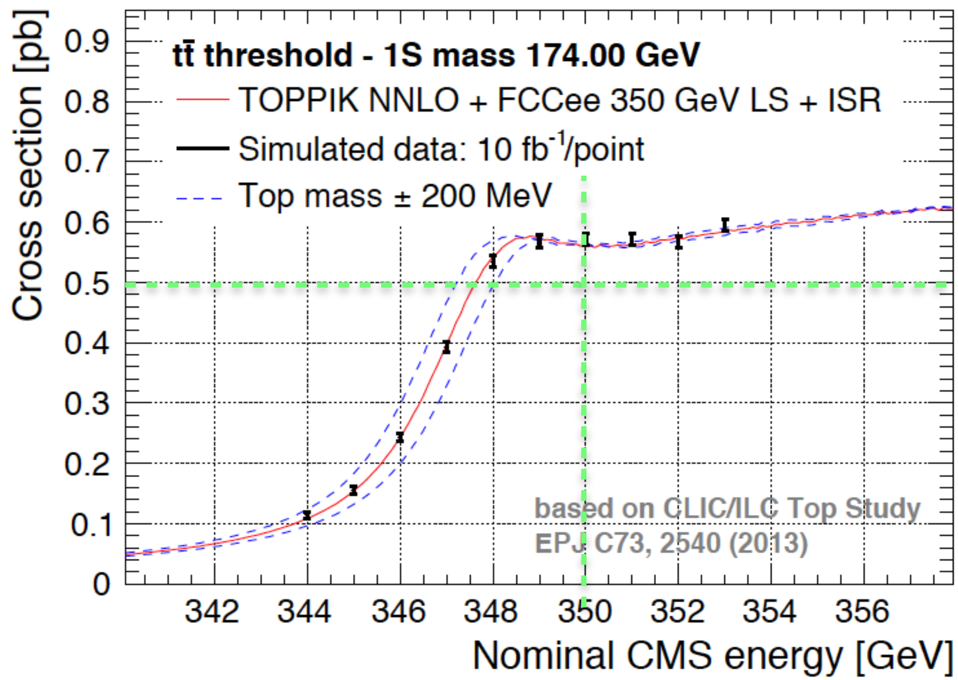


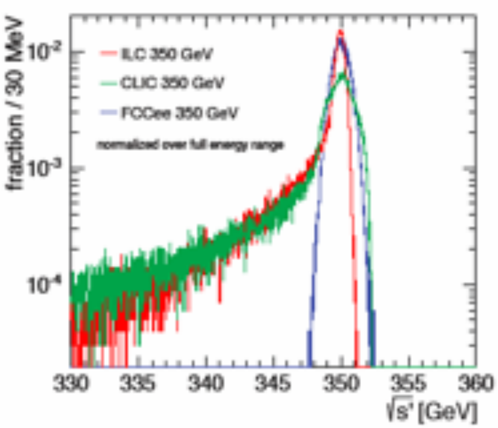
Here: Extract mass and α_s

Threshold scan

- Comparing ILC and FCCee - assuming identical detector performance







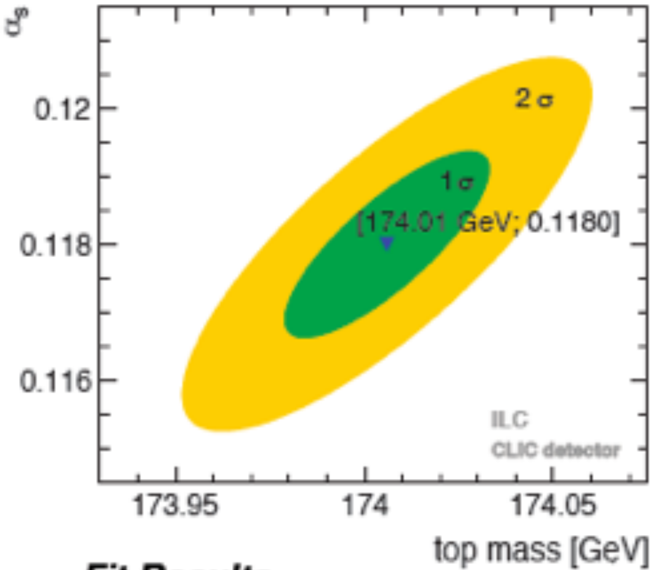
- The absence of beamstrahlung at FCC-ee (typical instead of linear collider configuration) has two effects:
    - enhances the steepness of the threshold profile
    - enhances the absolute value of the production cross section
- for 100fb-1same conditions: 18MeV@ILC —> 16MeV@FCCee
- which extrapolates to ~5MeV with 1ab-1

F. Simon @Top2014

Systematics

- Statistics is not the issue at FCC-ee.
- Two main systematics can affect the threshold measurement:
  - Beam energy measurement: need to know beam energy to a fraction of MeV.
    - can use the precision Z and W mass measurement (and energy/momentum conservation)
      - With fully constrained Z(γ) events , ZZ and WW events
      - Can reach combined statistical precision on E_{beam} of ~1MeV
  - α_s : can profit of the measurement of Z and W BR_{had} (if available from previous runs) with a $\sigma_{\alpha s}$~0.0002 or can do a simultaneous fit (2D method)

1D fit with external input



- Additional possibilities:
  - With high precision external α_s the Top Yukawa coupling can be measured with ~ 7% (stat) precision
  - The top width can also be included in the fit - uncertainties (stat) ~ 30 MeV

arXiv:1310.0563

Fit Results

[MeV]	Δm	theory 1%/3%	Δα	theory 1%/3%
ILC - 2D Fit	27	5/9	0.0008	0.0009/0.0022
CLIC - 2D Fit	34	5/8	0.0009	0.0008/0.0022

[MeV]	Δm	theory 1%/3%	α_s
ILC - 1D Fit	**18**	18/55	21
CLIC - 1D Fit	22	18/56	20

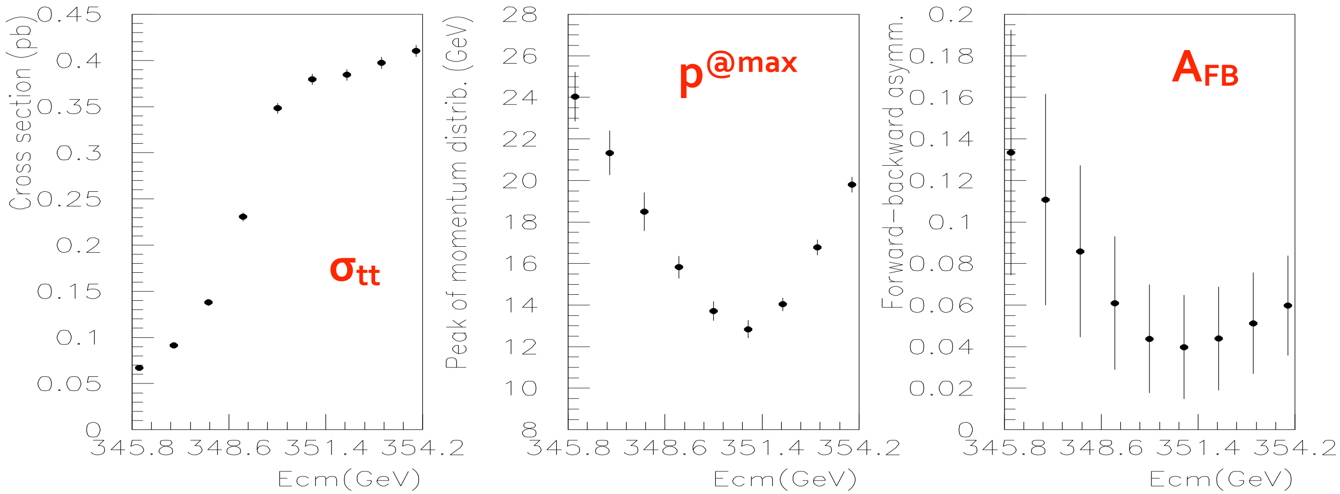
EPJ C73, 2540 (2013)

Perspectives for Top Physics at (I)LC
TOP2014, Cannes, October 2014

Contribute from $\Delta\alpha_s$ of ~30MeV per 0.0007
So if $\Delta\alpha_s$~0.0002 this can be divided by 3.

other methods & ideas

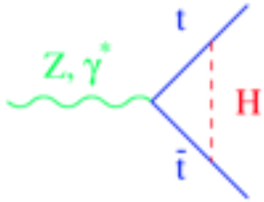
- other methods proposed in ILC studies: **use properties of decay kinematics in threshold scan** (from M. Martinez and R. Miquel, Eur. Phys. J. C27, 49 (2003), hep-ph/0207315)
- simultaneous fit of observables (σ_{tt}, A_{fb} and <p@max>) sensitive to m_{top}, Γ_{top} and λ_{top}
  - Results simply scaled to the FCCee case (no beamstrahlung bkg and higher luminosity)

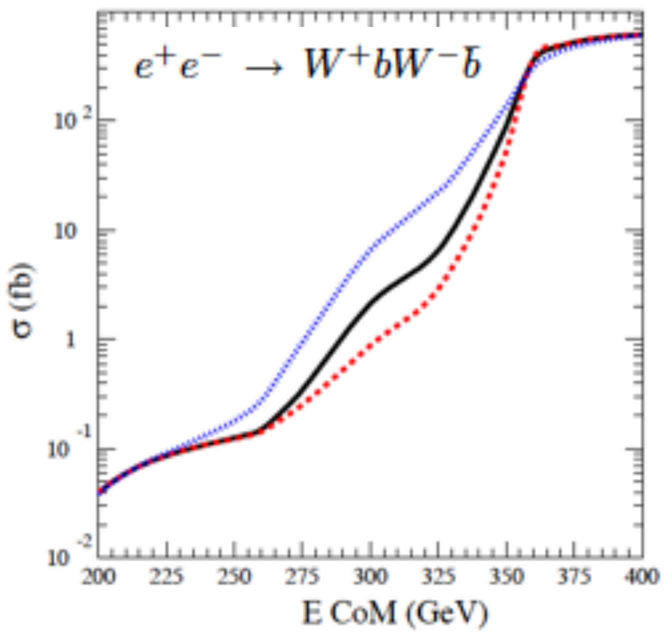


	Lumi / 5 years	# top pairs	Δm_{top}	$\Delta\Gamma_{top}$	$\Delta\lambda_{top}/\lambda_{top}$
TLEP	4x800 fb^{-1}	~ 1,000,000	10 MeV	12 MeV	13%
ILC	350 fb^{-1}	100,000	30 MeV	35 MeV	40%

EWK couplings of the top quark

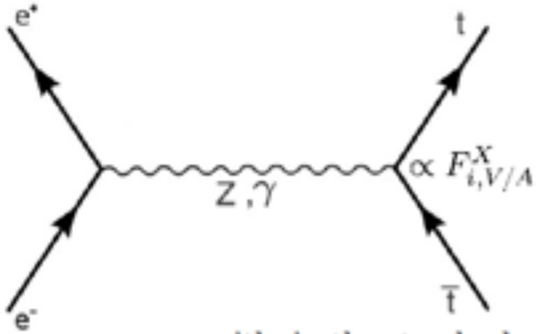
- λ_{top}: indirect measurement via threshold scan of 13% @FCCee
  - [to be compared with 10% @HL-LHC, and will need the full upgrade high energy ILC to get <10%]
  - reaching the sub-% will be a job for FCChh!
- g_{tWb} can be measured:
  - in top decays in pair production
  - single top production: threshold scan from m_{top} top $2m_{top}$.
    - Expect 2% on g_{tWb} with $\Gamma(t)$~100MeV @ILC $\sqrt{s}$=340 GeV (Snowmass 2005 Top Report)
    - can extrapolate to ~per mil for FCCee $\Gamma(t)$~12MeV: *to be done!*





$g_{Wtb} = g_{SM}$ (black solid)
$g_{Wtb} = 2g_{SM}$ (blue dashed),
$g_{Wtb} = g_{SM}/2$ (red dotted)

EWK couplings of the top quark



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

X=Z,γ A=axial V=vector

with, in the standard model, vanishing F_2s and

$$F^\gamma_{1V} = -\frac{2}{3}\,,\ F^Z_{1V} = \frac{1}{4\sin\theta_W\cos\theta_W}\left(1 - \frac{8}{3}\sin^2\theta_W\right)\,,$$
$$F^\gamma_{1A} = 0\,,\ F^Z_{1A} = \frac{1}{4\sin\theta_W\cos\theta_W}\,.$$

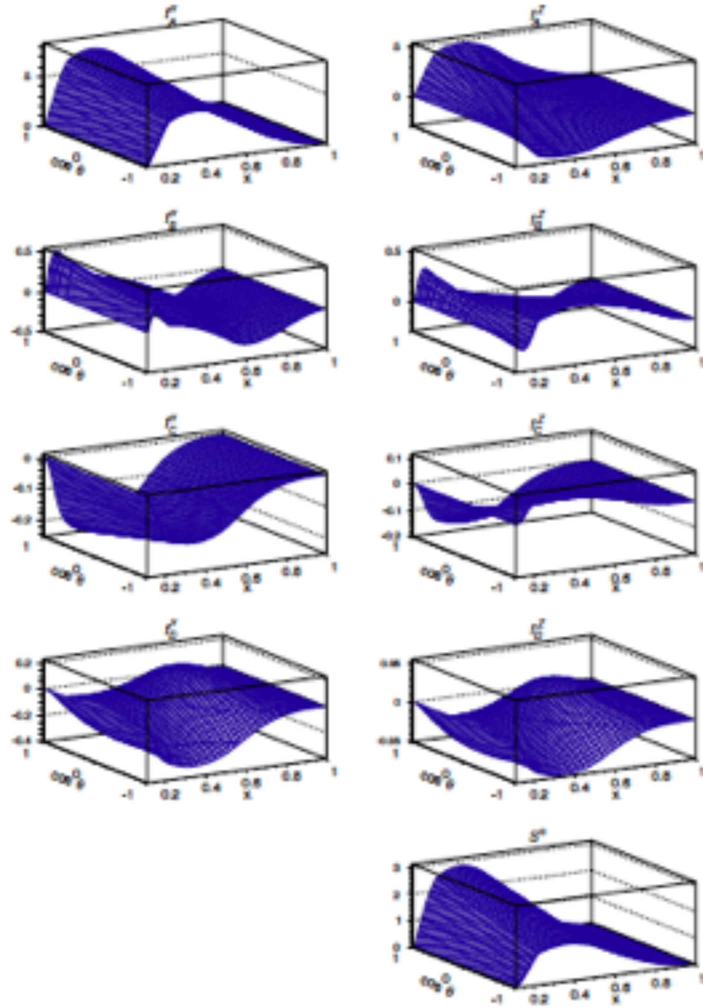
The sensitivities are expressed therein in terms of $\tilde{F}_1$, $\tilde{F}_2$ defined as

$$\tilde{F}^X_{1V} = -(F^X_{1V} + F^X_{2V})\,,\ \tilde{F}^X_{2V} = F^X_{2V}\,,\ \tilde{F}^X_{1A} = -F^X_{1A}\,,\ \tilde{F}^X_{2A} = -iF^X_{2A}\,.$$

- In order to disentangle and access the separate components from the ttZ and ttγ couplings and possible anomalous contributions the polarization information of the top decay products can be exploited.

Exploiting the final state

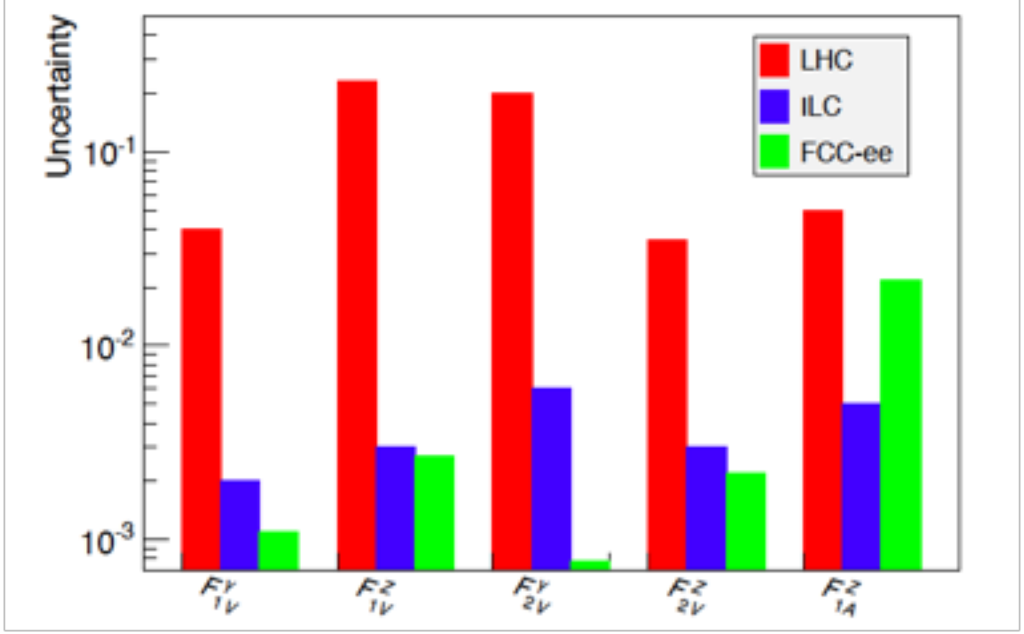
- It is known that the top polarization information is maximally transferred to its final state particles via the weak decay
  - the lack of beam polarization is compensated by the final state polarization and by a larger statistics
- In particular some optimal observable can be defined. In the case of tt->l+jets: the lepton polar angle and its reduced energy.
- main systematic comes from predicted event rate
- More final state variables can be considered: this is first look a more complete study is in progress



P. Janot. arXiv:1503.01325v2

Analysis results

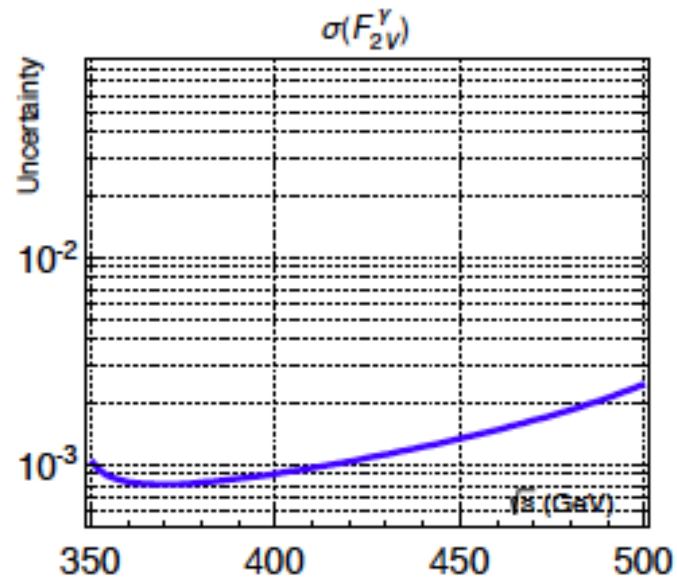
Statistical uncertainties for CP-conserving top quark form factors



LHC: Snowmass study 2005 $\sqrt{s}$=14TeV,300pb^{-1}

ILC: $\sqrt{s}$=500GeV, 500fb^{-1}polarized beams

FCC-ee = $\sqrt{s}$=365 GeV, 2.4 ab^{-1}



$\sqrt{s}$(GeV)

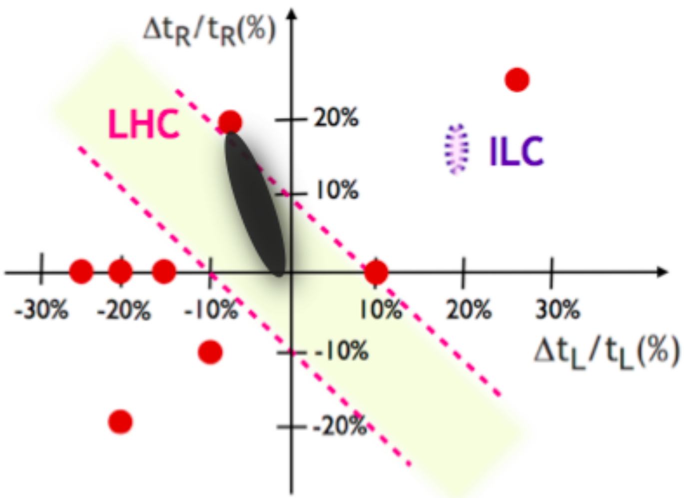
- can reach a precision at the per-mil level
- ttZ and ttγ can be disentangled without the need of polarization in the initial state
- no need for high energy runs, far above the threshold ($\sqrt{s}$=365 optimal)

P. Janot. arXiv:1503.01325v2

Sensitivity to BSM models

Various BSM models predict large deviations in the top EW couplings.
Ex. Zt_Lt_L, Zt_Rt_R ● = different BSM scenarios (left) 4DCHM (right)

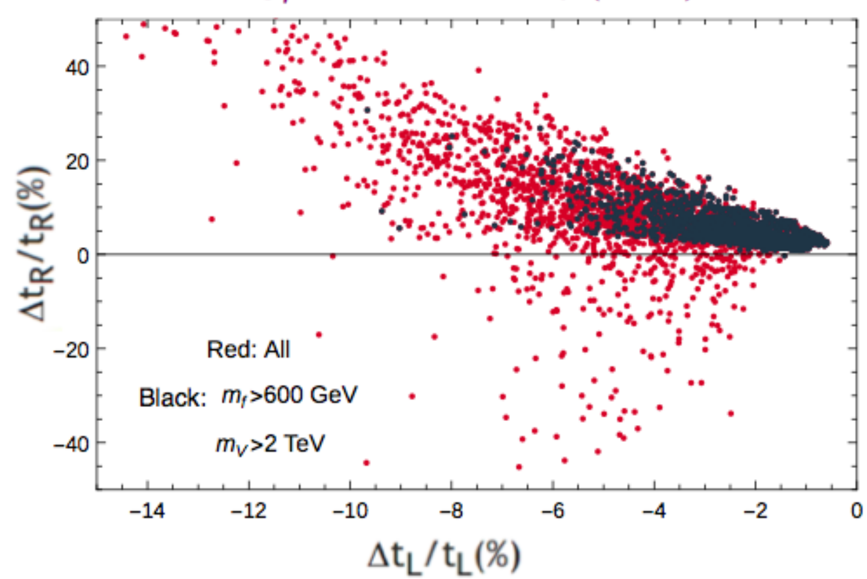
Richard 1403.2893; Grojean, LCWS14 talk



sensitivities: LHC ~ 10%
HL-LHC ~ 4%
ILC(500) < 1% with polarized beams
(ILC-TDR 1306.6352)

Barducci, DC, Moretti, Pruna, in preparation

$1.5 < g_\rho < 3,\ 0.75 < f(\text{TeV}) < 1.5$

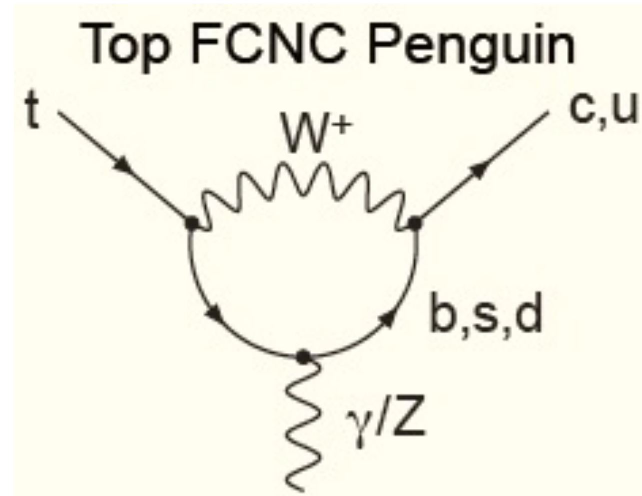


scan over 4DCHM fermion parameters
max deviation on the left/right couplings -10/+20%

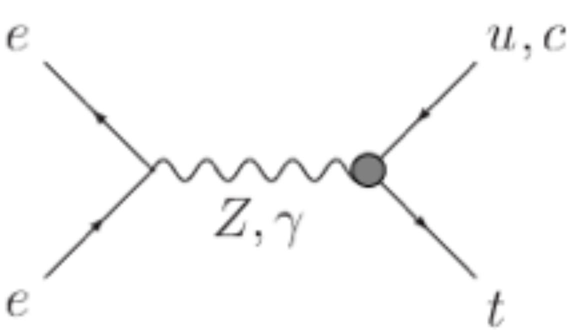
Barducci, De Curtis, Moretti, Pruna & 1311.3305

FCNC single top production

- FCNC in the SM are forbidden at tree level and only allowed via higher order corrections: strongly suppressed.
- Can be strongly enhanced in BSM models
- Can be studied at different center of mass energies in the single top production
- Process implemented in FeynRules and Madgraph5
- Preliminary results from studies in the l+jets and all-hadronic channel

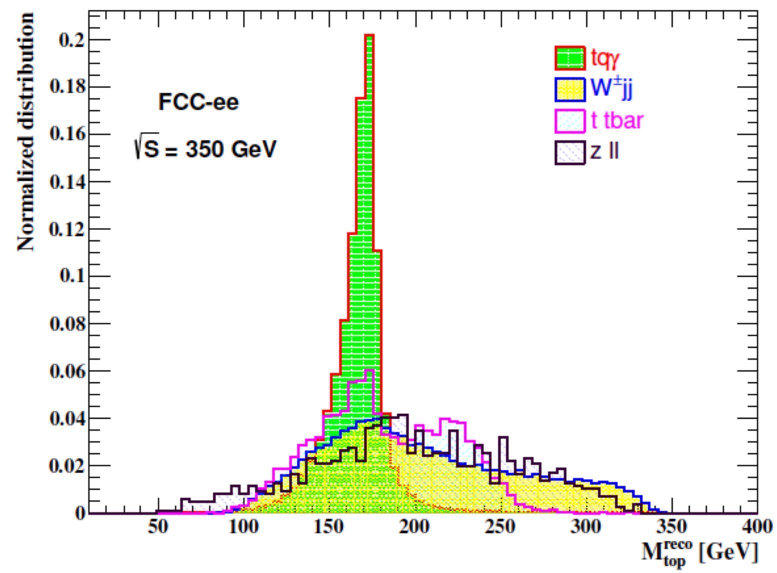


Process	SM
$t \to Zu$	7×10^{-17}
$t \to Zc$	1×10^{-14}
$t \to gu$	4×10^{-14}
$t \to gc$	5×10^{-12}
$t \to \gamma u$	4×10^{-16}
$t \to \gamma c$	5×10^{-14}
$t \to hu$	2×10^{-17}
$t \to hc$	3×10^{-15}



FCNC: l+jets

- Signal final state: e+e- —> lνb+jet
- Backgrounds from: W^+W^- >lνjj, tt,Z+ll
- Detector simulation ILD inspired using Delphes
- Basic selection:
  - p_T(lep)≥10GeV and |η|≤2.5, Emiss≥10GeV
  - p_T(jet)≥10GeV and |η|≤2.5
  - N(lep)=1, N(jet)=2, Dr≥0.4 between obj
  - N(btag)≥1
  - top mass reconstructed using leading b-tag jet
  - discriminant variables fed to an MVA: M(t), DR(W,b), η(b), p_T(t),E(lep), η(lep), E(jet)
- Signal eff ~90%, bkg eff~1%



√s(GeV)	240(l+jets) 10ab-1	350(l+jets) 3ab-1
Br(t->qγ)	2×10^{-5}	9.86×10^{-6}
Br(t->qZ)($\sigma_{\mu\nu}$)	2.44×10^{-5}	1.41×10^{-5}
Br(t->qZ)(γ_μ)	5.02×10^{-5}	5.27×10^{-5}

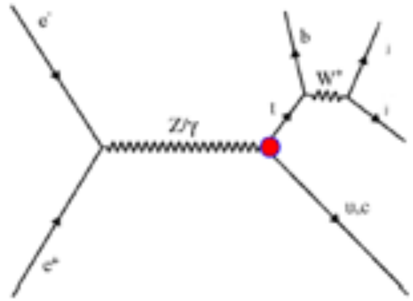
H. Khanpour, S. Khatibi, M. Khatiri, M. Mohammadi Najafabadi

FCNC: all hadronic

S. Biswas, F. Margaroli, B. Mele

Signal

$e^+e^- \rightarrow tj + h.c. \rightarrow bWj \rightarrow bjjj$



The basic cuts applied on the jets are $p_T^{j,b} > 20$ GeV, $|\eta^{j,b}| < 2.5$, and $\Delta R(jj, bb, bj) > 0.4$

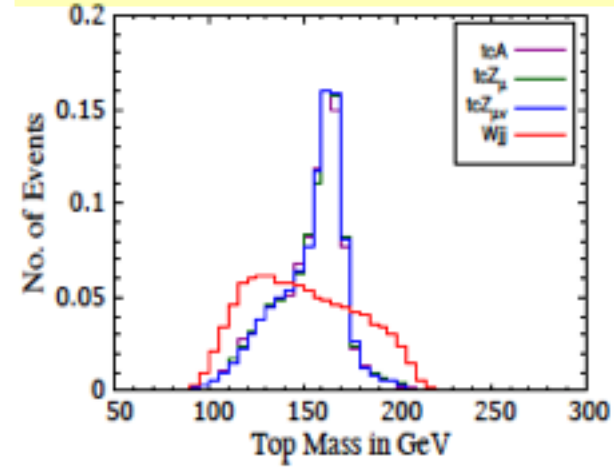
Background

Dominant background is $e^+e^- \rightarrow Wjj \rightarrow jjjj$

Other 4-jets background (*e.g.* $q\bar{q}b\bar{b}$) checked to be small.

	$\epsilon_b = 60\%$	$\epsilon_b = 80\%$
tcA	$903.05\lvert\lambda_{qt}\rvert^2$	$1073.96\lvert\lambda_{qt}\rvert^2$
tcZ, γ_μ	$378.93\lvert\mathcal{X}_{qt}\rvert^2$	$446.41\lvert\mathcal{X}_{qt}\rvert^2$
$tcZ, \sigma_{\mu\nu}$	$596.11\lvert\kappa_{qt}\rvert^2$	$710.16\lvert\kappa_{qt}\rvert^2$
Wjj	47.72	686.77

Table: Cross section normalisation factors (in fb) for 4-jets final state after basic cuts, b-tagging and $W \rightarrow jj$

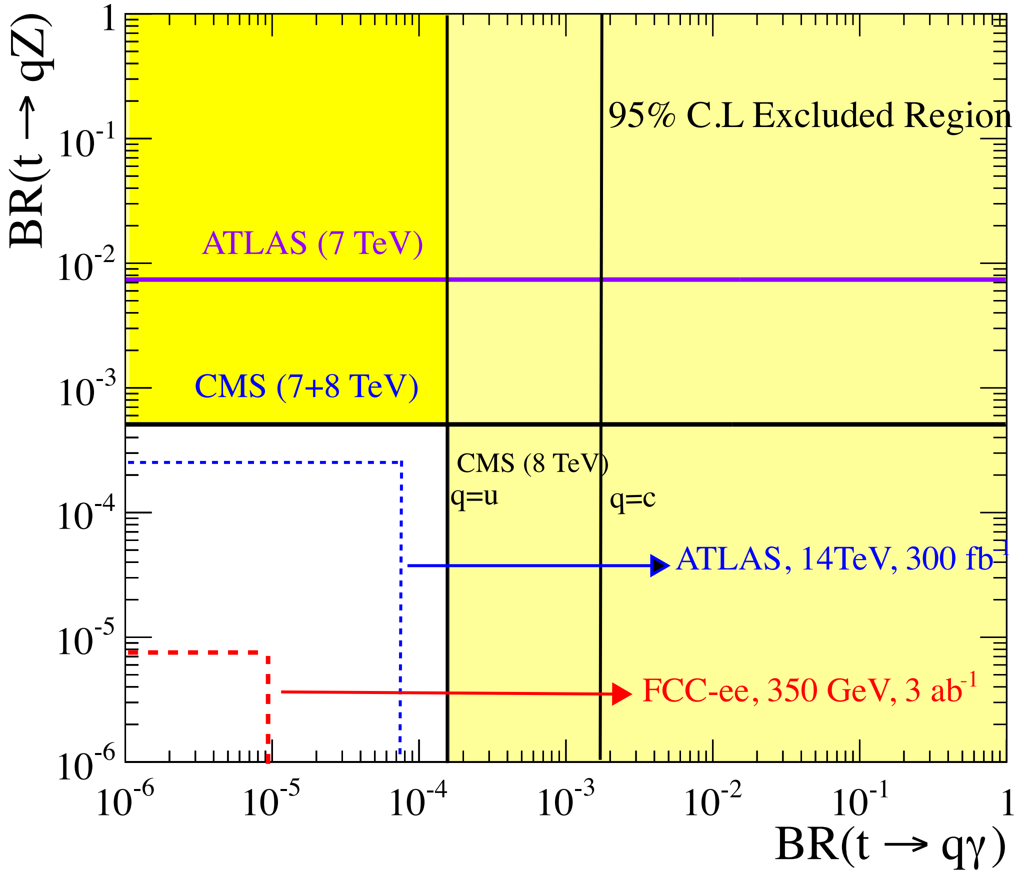


√s(GeV)	eff(b)=80%, rej=100	eff(b)=60%, rej=1000
Br(t->qγ)	1.06×10^{-4}	3.17×10^{-5}
Br(t->qZ) ($\sigma_{\mu\nu}$)	1.37×10^{-4}	8.22×10^{-5}
Br(t->qZ)(γ_μ)	2.79×10^{-4}	4.12×10^{-5}

BR limits @95% for 10ab -1 at √s=240 in the all-had channel

- Selection of 4 jet events to explicitly reconstruct and cut on m(t) and m(W).
- signal eff ~47%, bkg ~5%
- very preliminary look…but charm tagging will play a role

Summary for FCNC



l+jets only: not combined with 240 GeV result.

Conclusions

- the top physics program at FCCee is extremely rich due to:
  - the very high luminosity that can be collected
  - the possibility of runs at different(optimal) $\sqrt{s}$
- the measurement of the main parameters of the SM (mass, width, EWK couplings) with unprecedented precision is a priority
- the opportunities offered for indirect effect of new physics in rare/ forbidden/FCNC processes are extremely interesting
- we have learned from these preliminary results that FCCee is able to achieve extremely good precision on fundamental Top related measurements and:
  - very large $\sqrt{s}$ energy running does not seem necessary
  - beam polarization does not seem necessary
- very important to perform detailed studies to assess the nominal center of mass energy, statistics and running conditions for the complete Top Physics program.

Backup

Rare decays: the gold mine!

expectations from theory

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

current limits

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	7×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.5 fb^{-1}, 8 TeV	[130]
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	2.1 fb^{-1}, 7 TeV	[137]
$t \to gu$	3.1×10^{-5}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV	[131]
$t \to gc$	1.6×10^{-4}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV	[131]
$t \to \gamma u$	6.4×10^{-3}	ZEUS $e^{\pm}p \to (t \text{ or } \bar{t}) + X$	474 pb^{-1}, 300 GeV	[134]
$t \to \gamma q$	3.2×10^{-2}	CDF $t\bar{t} \to Wb + \gamma q$	110 pb^{-1}, 1.8 TeV	[132]
$t \to hq$	8.3×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV	[135]
$t \to hq$	2.7×10^{-2}	CMS* $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	5 fb^{-1}, 7 TeV	[136]
$t \to$ invis.	9×10^{-2}	CDF $t\bar{t} \to Wb$	1.9 fb^{-1}, 1.96 TeV	[133]

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	[140]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	[140]
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 250 GeV	Extrap.
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV	[141]
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV	[141]
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV	[140]
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV	[140]
$t \to \gamma q$	6×10^{-5}	ILC single top	500 fb^{-1}, 250 GeV	Extrap.
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV	[141]
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV	[141]
$t \to gu$	4×10^{-6}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gu$	1×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	1×10^{-5}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	4×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1}, 14 TeV	Extrap.

extrapolations

t->Zq, γq, Zc

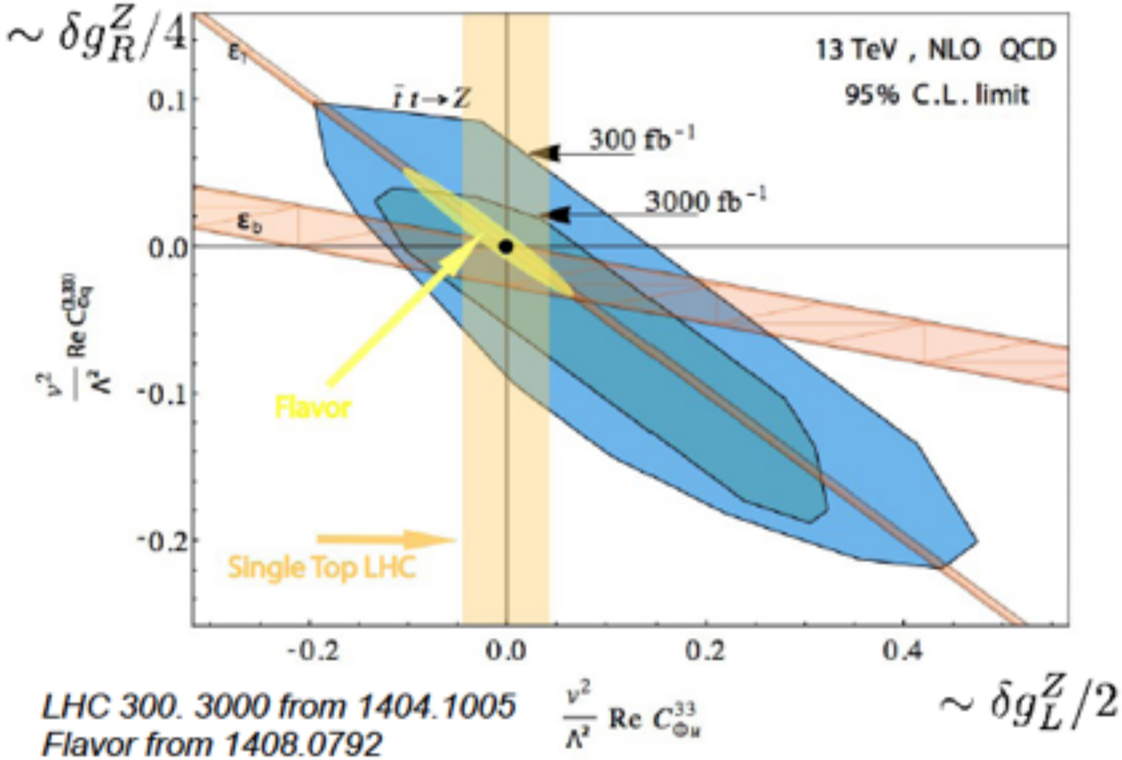
so many possibilities for the large integrated lumi and clean environment of FCCee

Results of full simulation study at $\sqrt{s}$ = 500 GeV and L=500 fb^{-1}

ArXiv: 1307.8102

Precision cross section ~ 0.5%, Precision A_{FB} ~ 2%, Precision λ_t ~ 3-4%

Accuracy on SM Z couplings compared with other experiments



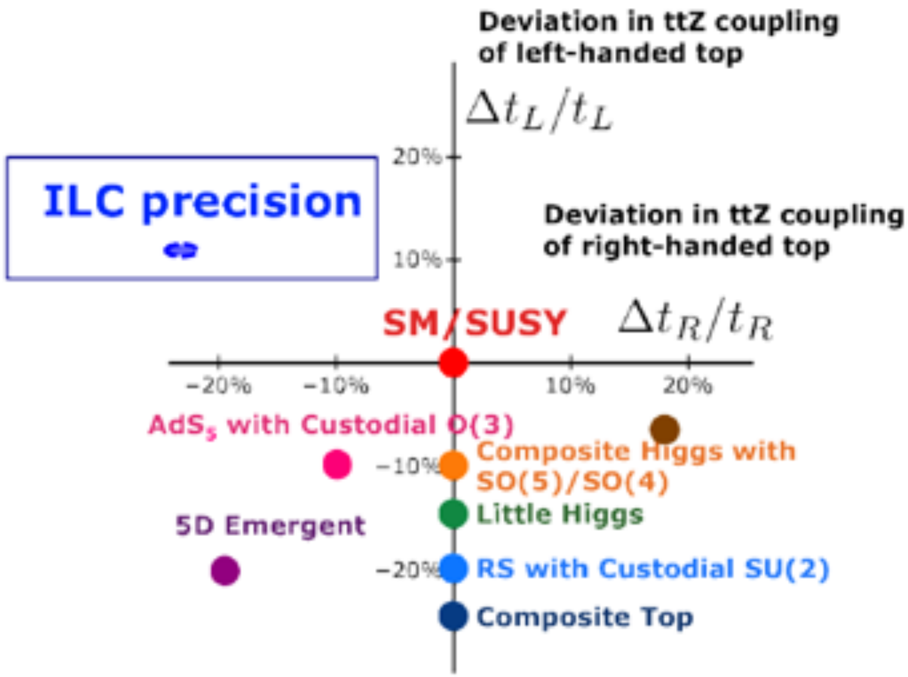
LHC 300. 3000 from 1404.1005
Flavor from 1408.0792
LHC Single top added by F. Richard

- ILC with polarised beams outperforms all present and future experiments (Stringent limits only from LEP)
- Before ILC single top at LHC and B factories can deliver complementary information
- In particular g_R can only be constrained by ILC!
- Maintaining this high level still requires substantial experimental and theoretical work

ILC promises to be high precision machine for electroweak top couplings

Sensitivity to BSM models

Top is primary candidate to be a messenger new physics in many BSM models
Incorporating compositeness and/or extra dimensions



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

EWK couplings of the top quark

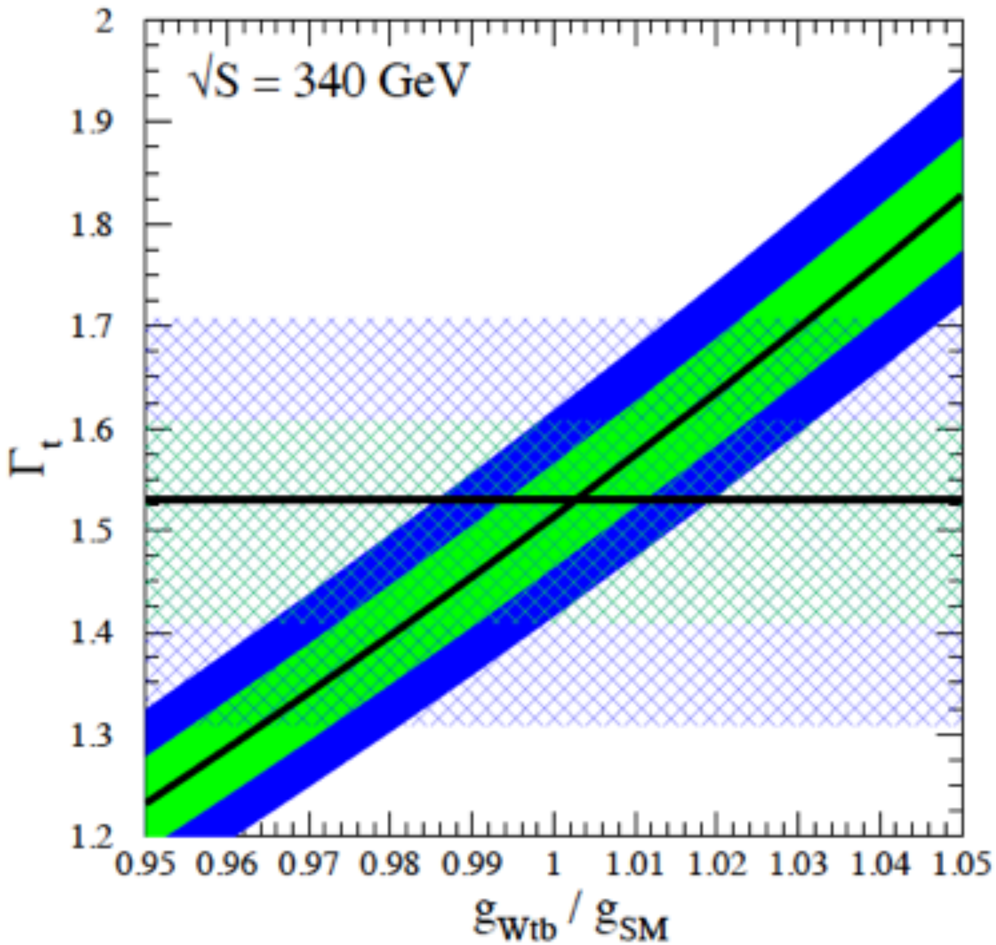


Figure 2: Curve corresponding to the SM rate and its 1σ and 2σ deviations in the plane of g_{Wtb} and Γ_t. Also overlaid is an expected measurement of Γ_t from the on-shell threshold scan with an uncertainty of 100 MeV.