TOP PHYSICS @FCC-EE

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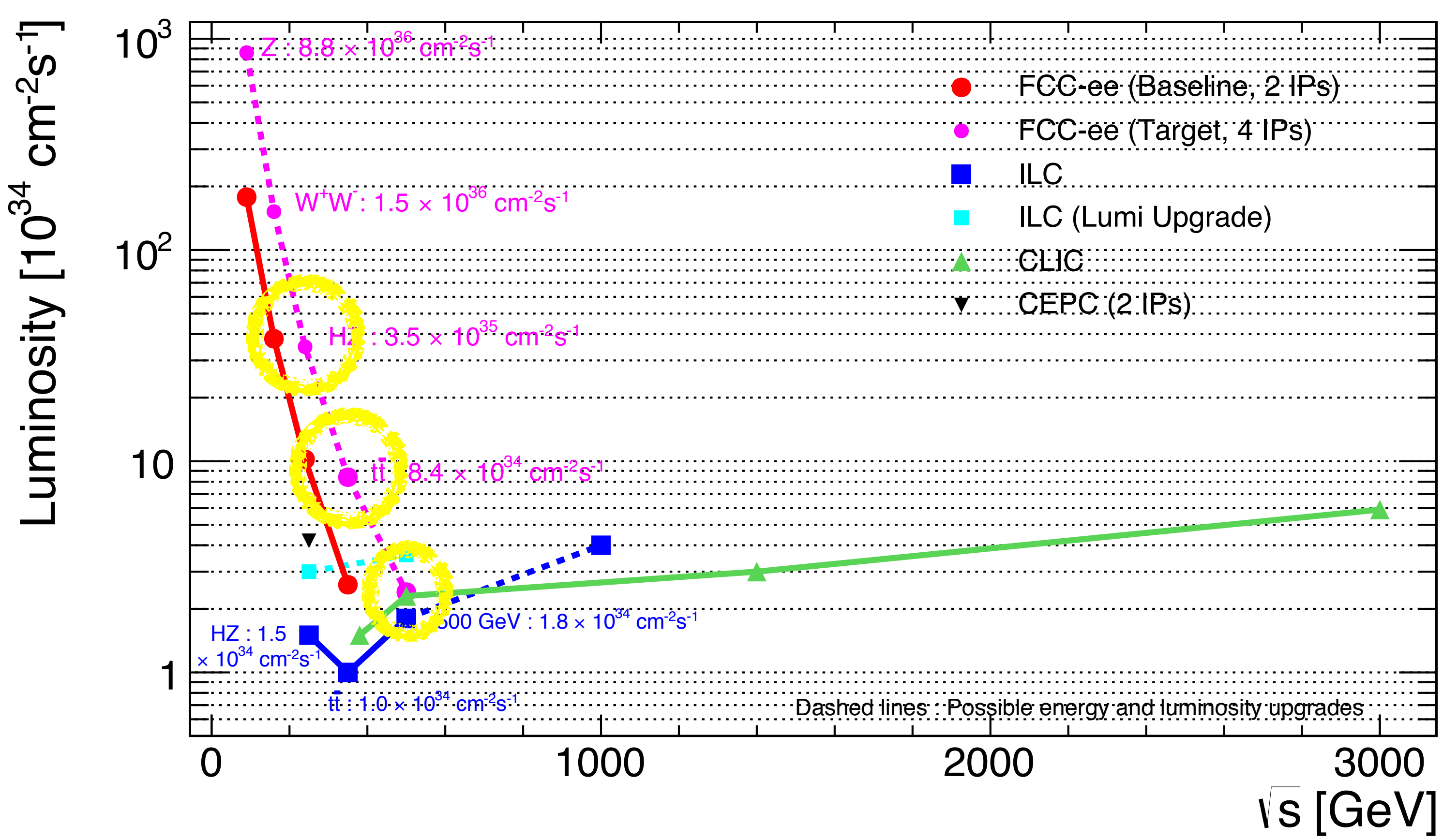
TOP PHYSICS AT FCC-EE

➤**The strength of the FCC-ee program is the ability to span several centre of mass energies at high luminosity**

➤**Top physics comes in the program in several places!**

- dedicated run at (and around) threshold @350GeV « Mega-Top » because of the ~1M top pair produced
- studies with production of single top quarks profiting of the run at 240GeV dedicated to Higgs precision measurement
- maybe higher energy runs for top coupling measurement (ttZ,ttγ,ttH)?



- periodic returns at the Z-peak in « FCC-ee top » conditions for calibration

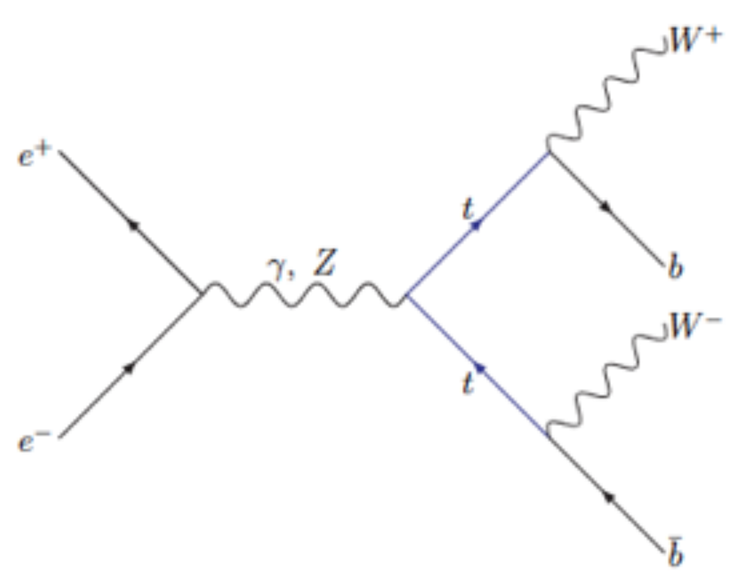
BUT WHY?

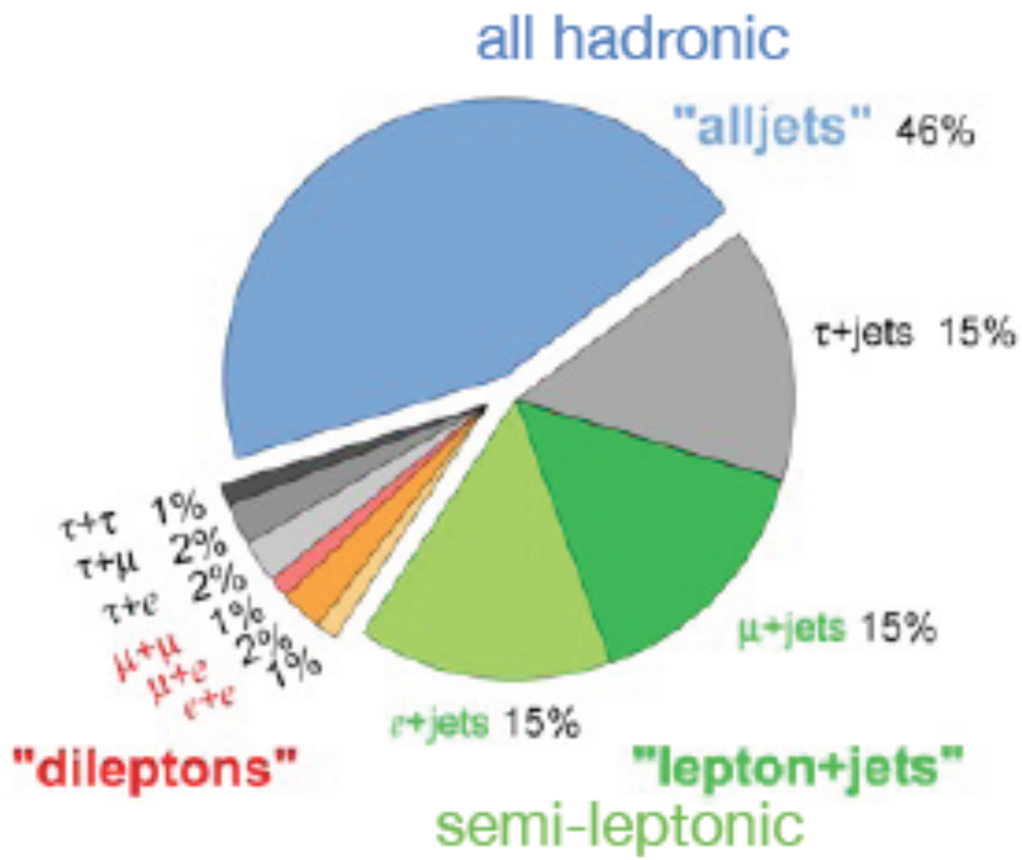
- **Beyond the SM needs for a precise knowledge of the top quark**
- **Top precision measurements are a portal to new physics effects at high scales, the large statistics at FCC-ee will allow to probe:**
  - **rare decays**
  - **(anomalous) couplings**
  - **indirect effects** from loop contributions
- **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**
  - next machine allowing direct searches for multi-TeV objects is the FCC-hh

PRODUCTION & DECAY

➤**top physics analysis is driven by production and decays modes**

- at lepton collider running close to threshold (or above), pair production dominates

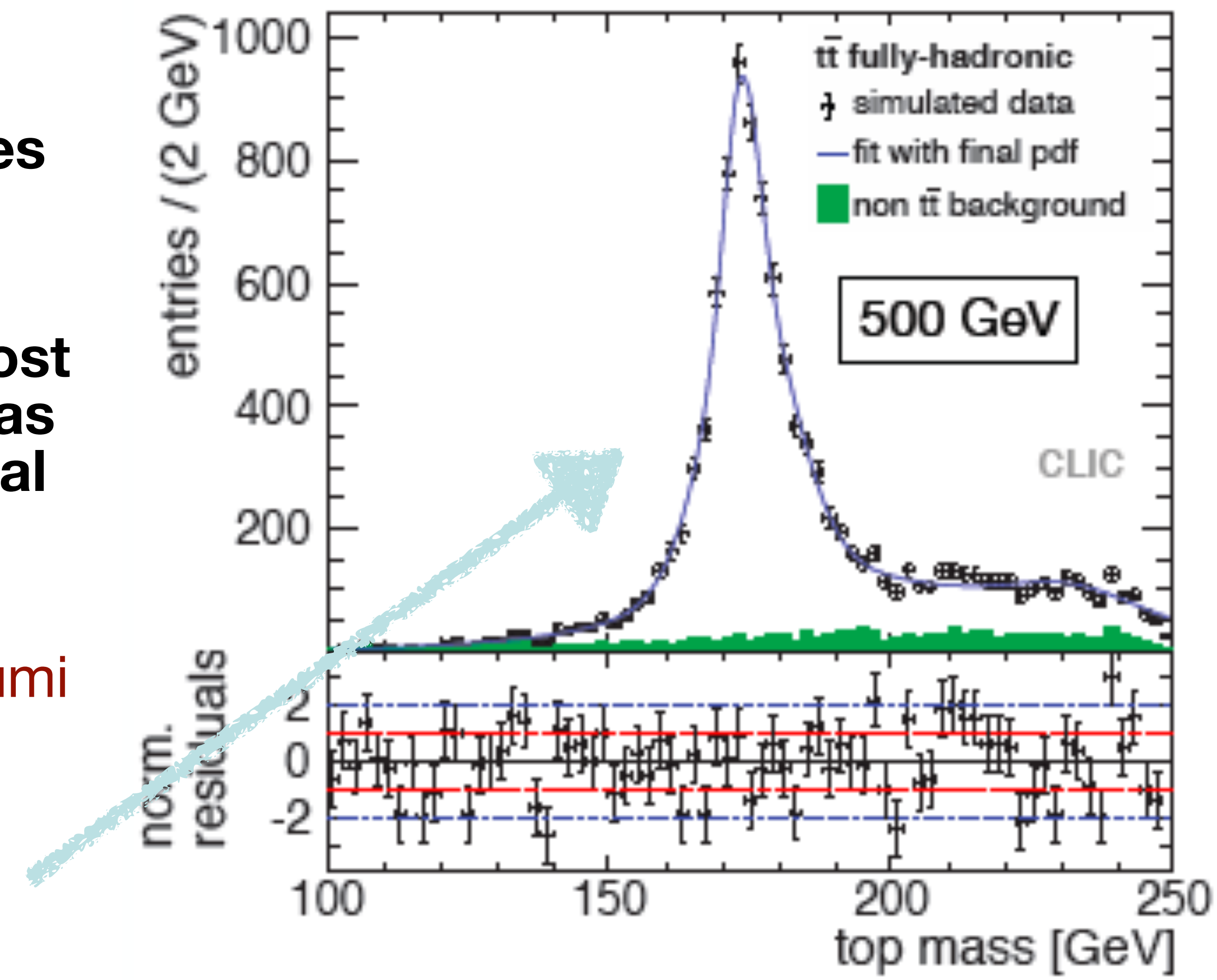




- ~100% BR in Wb
- final states classified on the basis of the W decay
- at lower center of mass energies can profit of (anomalous) production of single top (SM cross section is tiny)
  - more on this later

(CLASSIC) TOP MASS RECONSTRUCTION

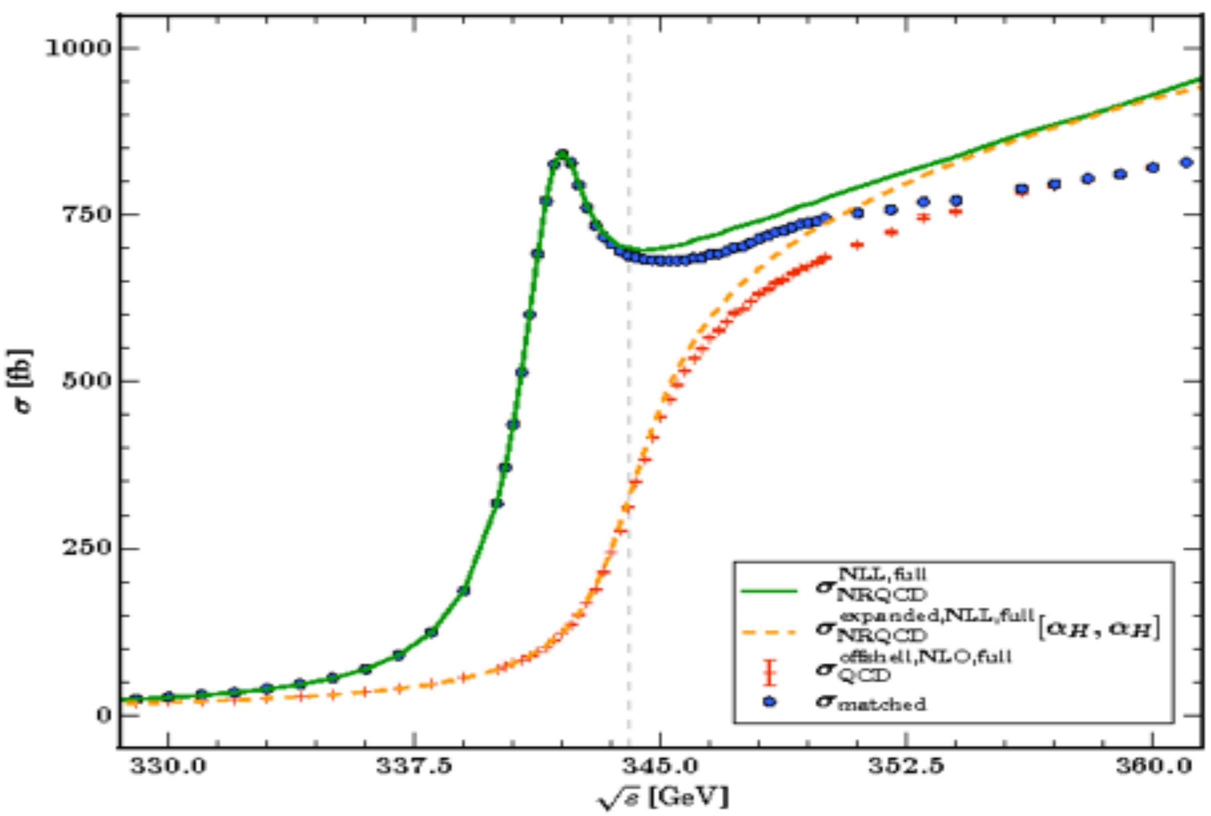
- **The methods that can be employed for the mass reconstruction are characterized by different experimental and theoretical issues and uncertainties:**
- **« Reconstructed » mass: from a fit of the decay products in the various channels. Most precise way (for now) at hadron colliders has the problem 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 some methods would profit of increased statistics) DP-2016-64
  - can be used above threshold
  - 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

MERIT OF MTOP THRESHOLD SCAN

arXiv:1604.08122



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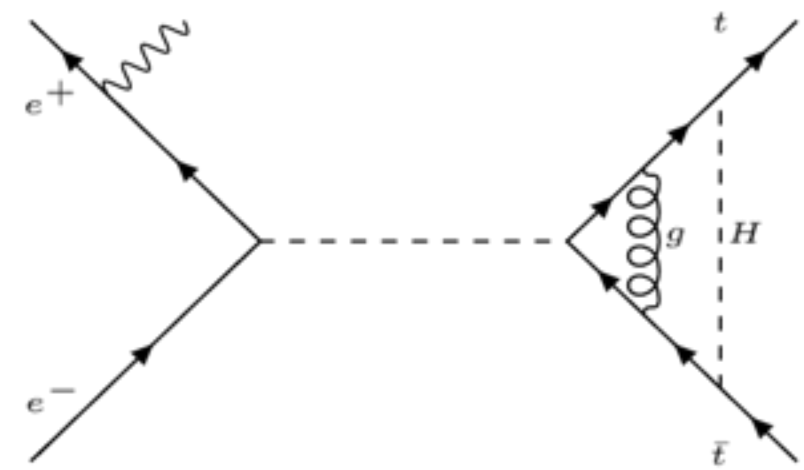


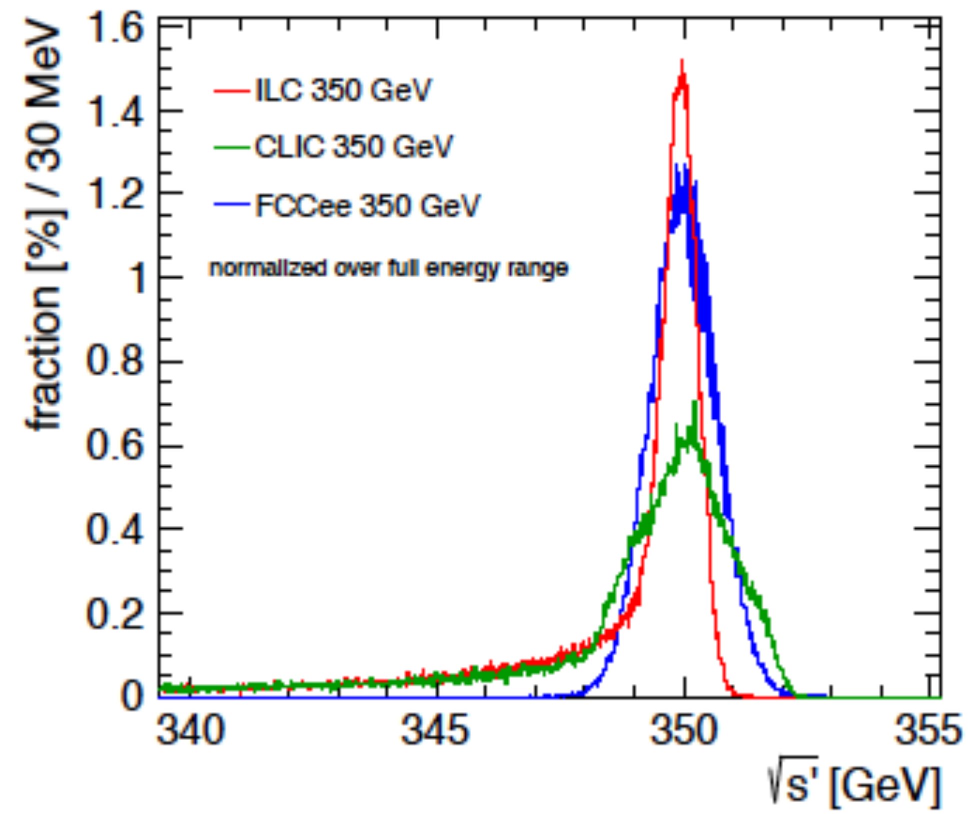
At lepton colliders, measurement of photons from ISR can be used to scan cross section vs centre-of-mass

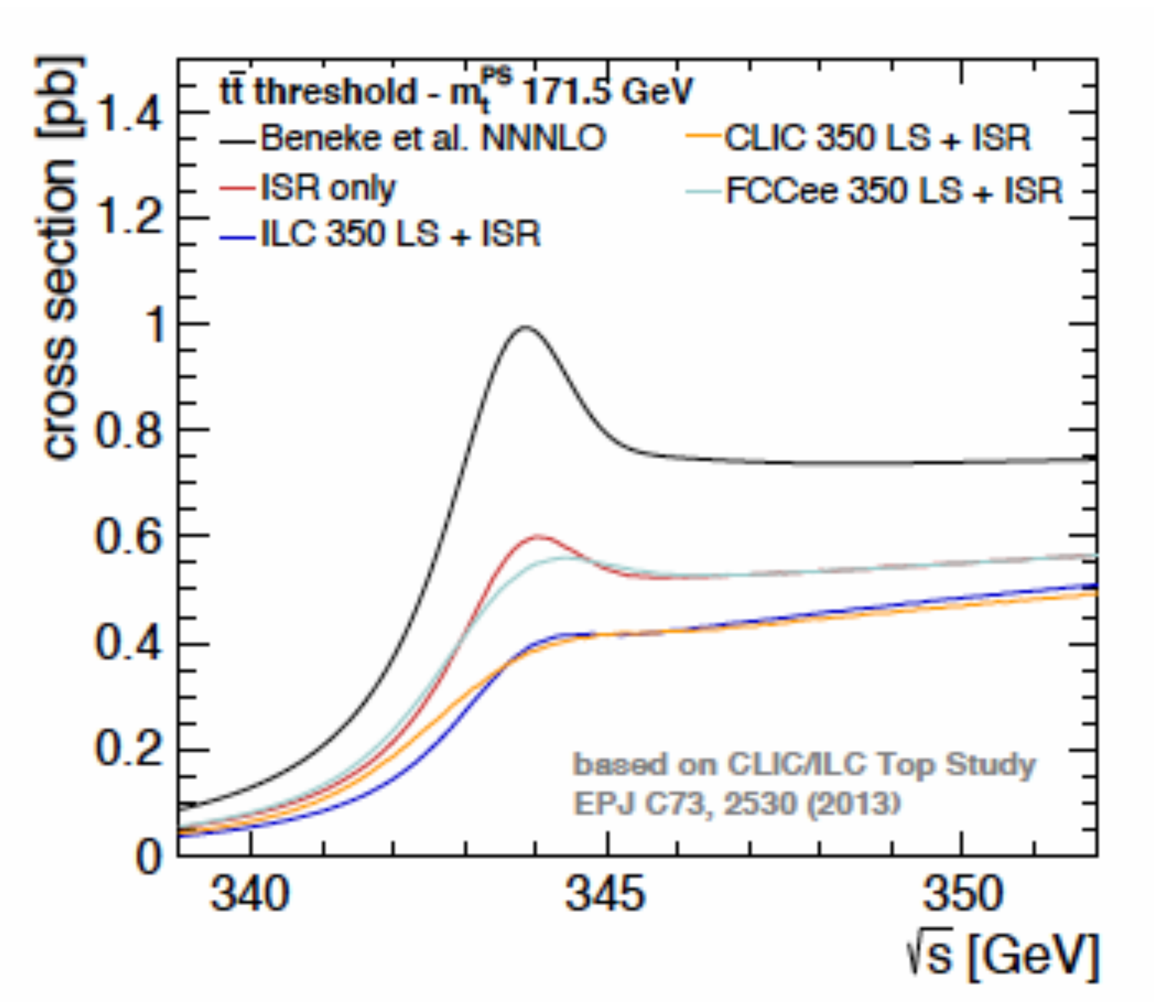
- Cross section shape depends strongly on top quark mass and width, α_s and Y_t
- FCC-ee will measure α_s with unprecedented precision at Z pole and WW threshold runs
  - (see 1512.05194v1 and P. Skands presentation)
- Top mass and width can then be extracted directly with an accurate top cross section threshold scan
  - Improved α_s drastically improves correlations m_t, Γ_t and Y_t

TOP MASS AND THRESHOLD SCAN

F. Simon arXiv: 1611:03399v1(2016)

- **The threshold shape is affected by ISR and luminosity profile**
    - Width of turn-on affected by width luminosity peak
    - Possibility to shift below threshold energy means reduction in effective cross section
- This work done using the ILC setup and software, adding the FCC beam shape.





- The FCC-ee has very steep luminosity profile, enhancing size of top sample and knowledge of centre-of-mass
- With 100 fb-1 and a ILD/CLIC-style detector FCC-ee can **measure top quark mass** with **16 MeV statistical accuracy**
    - which extrapolates to ~5MeV with 1ab^{-1}

UNCERTAINTIES

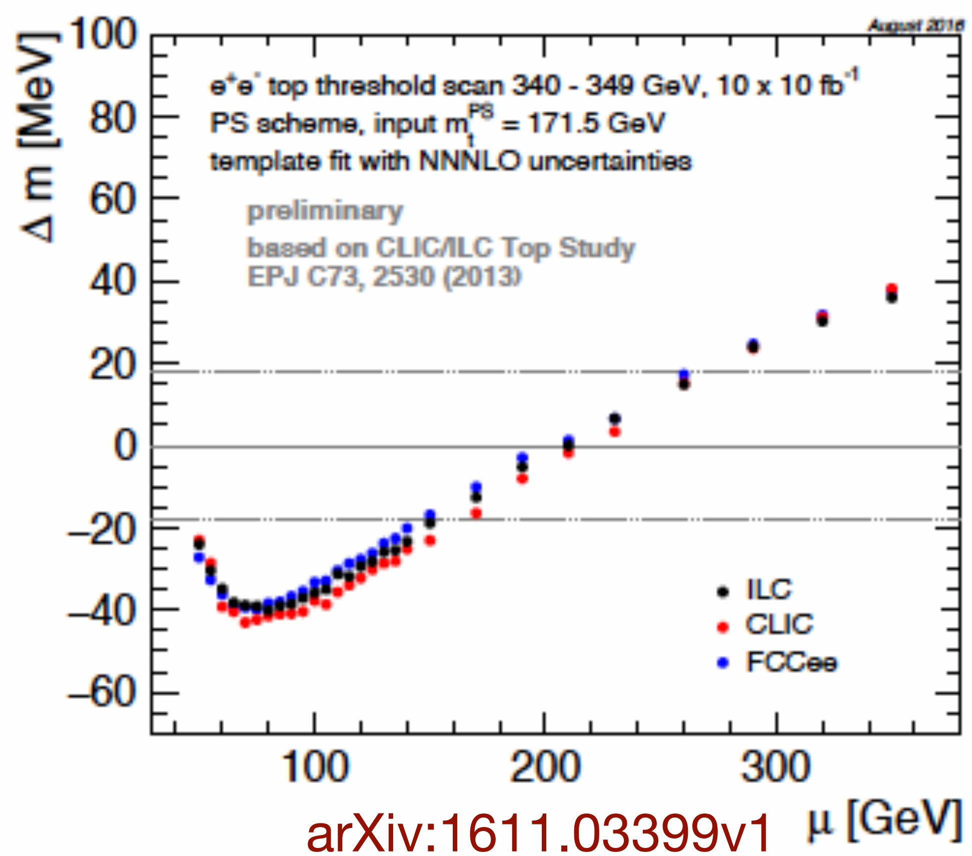
➢ **Statistics is not really the issue (thinking of the run plan of the exact point/stat to sample):**

- ➢ In general FCCee has a 20% improvement due to the beam shape characteristics (compared to ILC/CLIC)

➢ **Main systematics:**

- **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
- ➢ **Uncertainty due to α_S:**
  - ➢ If external input: Δm_{top} ~2.7MeVx10^{-4} with current $\Delta\alpha_s$ (from ILC studies). Can be divided by factor 3
  - ➢ Input measured (at FCC-ee) with precision of $\Delta\alpha_s < 0.0002$ using W/Z boson hadronic branching fraction.
- ➢ **Theory uncertainty:**
  - ➢ Better description for the process e+e- to bWbW calculated at NNLL allows for more detailed studies on systematics.
  - ➢ Recent studies on scale dependence show (no difference among colliders): ~40MeV

➢ **From this preliminary new studies it seems that there are still theory improvements needed to bring down the uncertainty m_{top}**

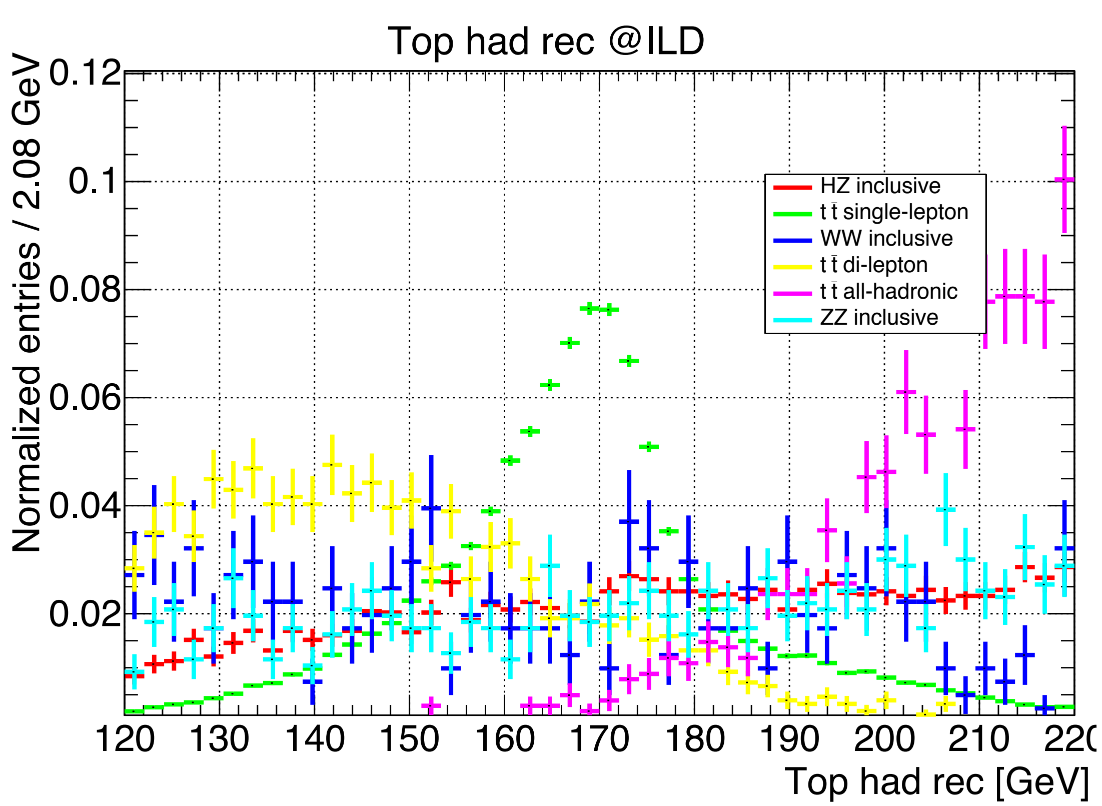


arXiv:1611.03399v1

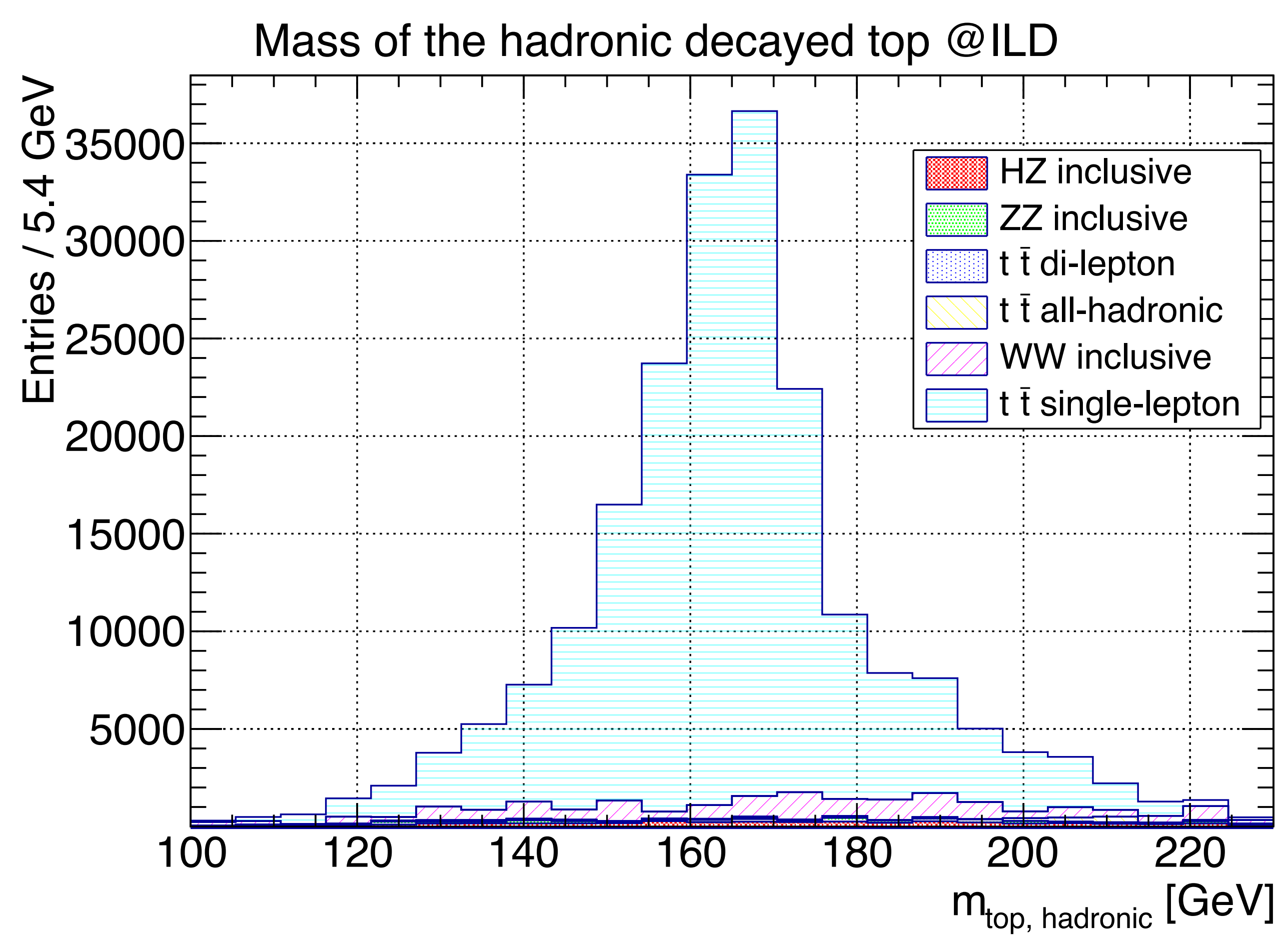
WORK IN PROGRESS: FCC-EE NATIVE ANALYSIS

N. Foppiani

- **work in progress to have the top mass (and more?) measurement at threshold using the native FCC software and reconstruction (PAPAS+HEPPY)**
- **Currently still using Madgraph for signal simulation to setup technical steps in the analysis, Pythia for backgrounds.**
  - now comparing performance with old ILC analysis. Already quite close.
- **Top analysis an excellent tool to help detector design studies especially for b-tag & c-tag**
- **Planning for complete result for Berlin FCCWeek (using Whizard for signal and syst estimates)**



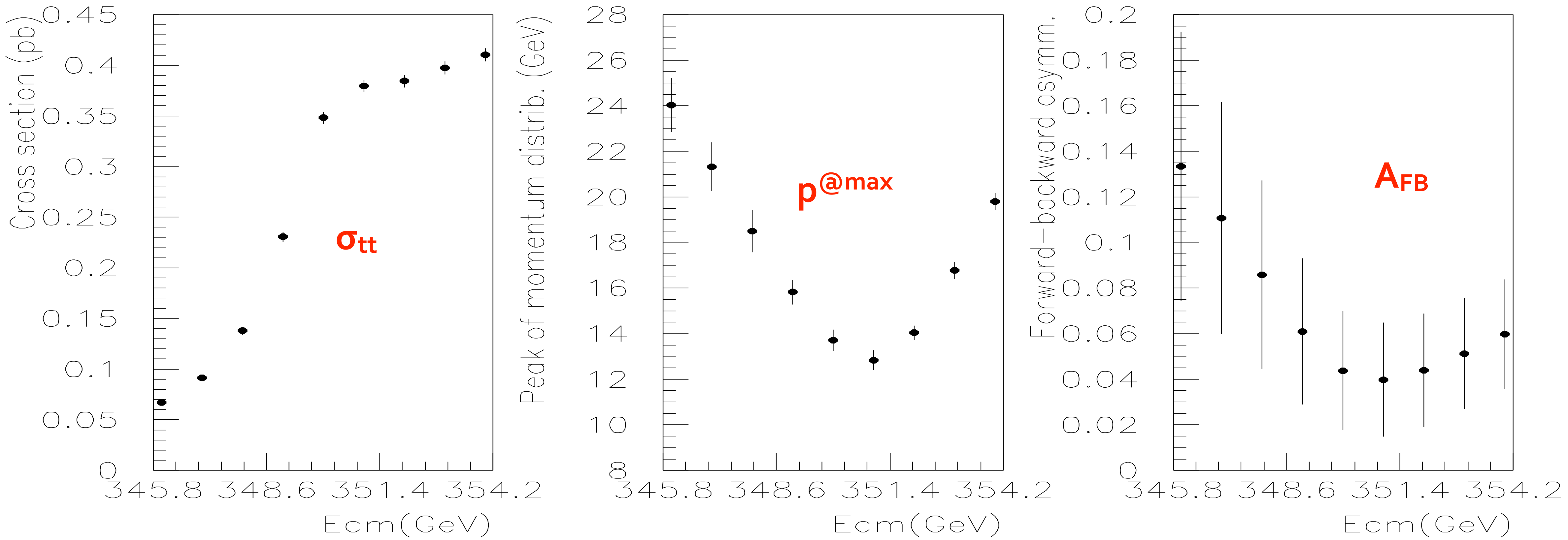
Reco 3jet hadronic top mass (shape only)



Reco 3jet hadronic top mass (after cuts)

OTHER(OLDER) METHODS & IDEAS

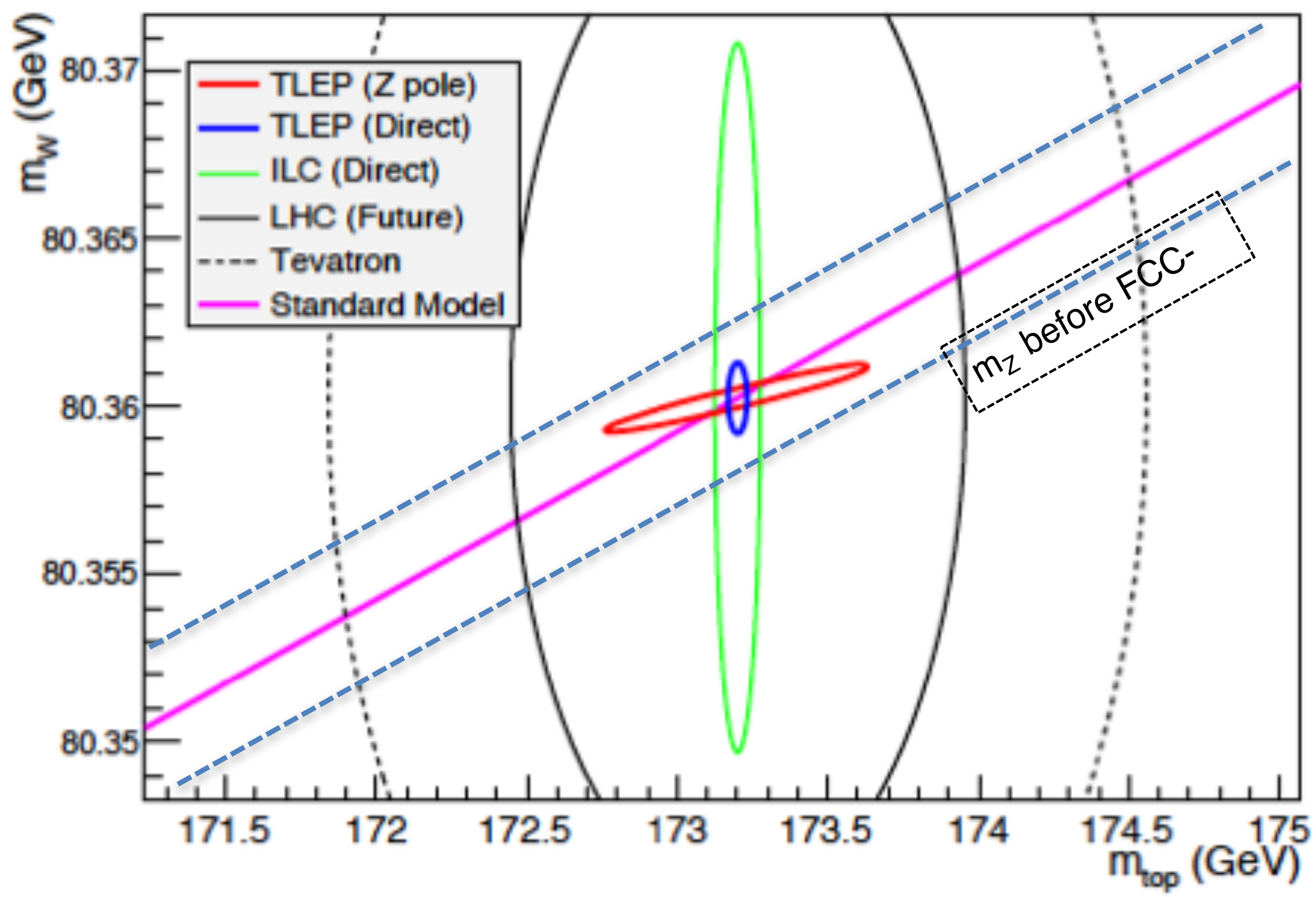
- **other methods proposed in ILC studies: use properties of decay kinematics in threshold scan (from M. Martinez and R. Miquel, Eur. Phys. J. C27, 49 (2003), hep-ph/0207315)**
- **simultaneous fit of observables (σ_{tt}, A_{fb} and <p@max>) sensitive to m_{top}, Γ_{top} and λ_{top}**



- Results simply scaled to the FCCee case (no beamstrahlung bkg and higher luminosity)
- Need to redo the exercise

	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%

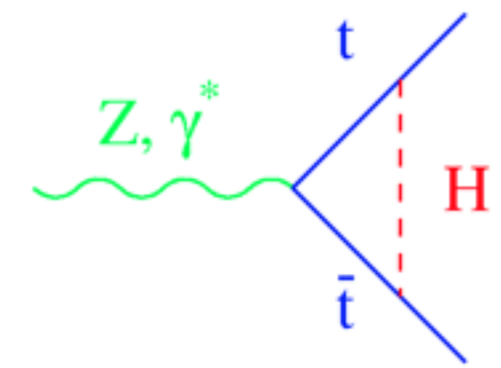
PROSPECTIVES EWK T-W FITS AFTER FCC-EE



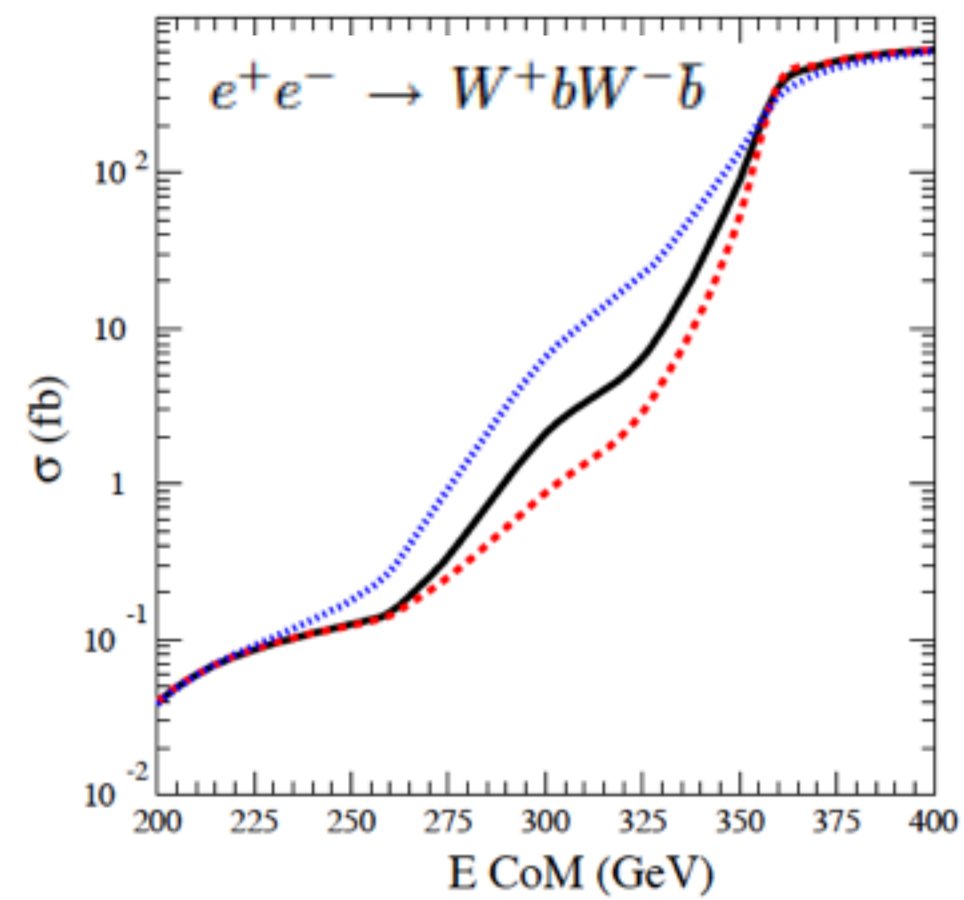
- ➤**Improvements m_{top}, α_S, M_W at FCC-ee**
  - ➤ Would improve understanding consistency SM in top-W-H radiative corrections
- ➤**Standard Model line uncertainty dominated by Z boson mass error**
  - ➤ Without FCC-ee it's 2.2 MeV!
- ➤**Sensitivity up to NP scales up to 100 TeV**

EWK COUPLINGS OF THE TOP QUARK

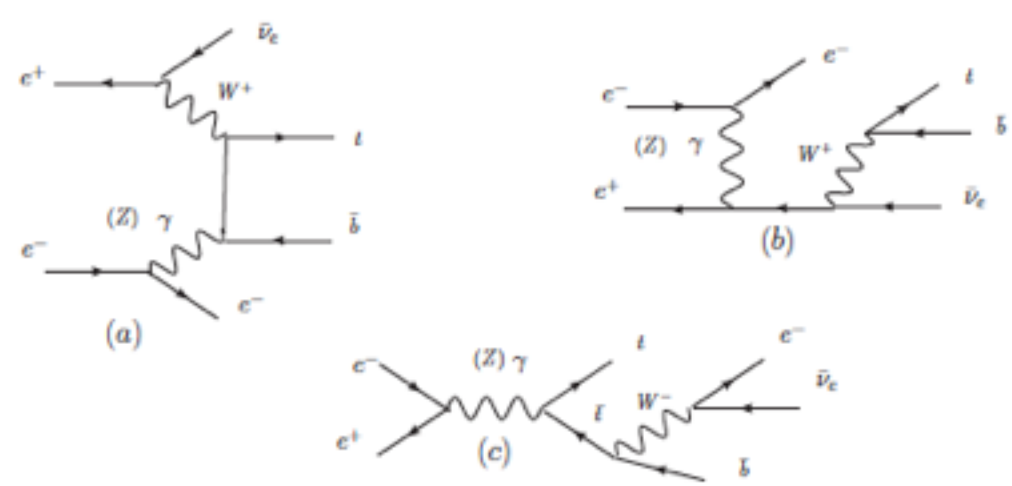
- **λ_{top}: indirect measurement via threshold scan of 13% @FCCee**
  - [to be compared with 10% @HL-LHC, and will need the full upgrade high energy ILC to get <10%]
  - reaching the sub-% will be a job for FCChh!



- **g_{tWb} can be measured:**
  - in top decays in pair production
  - single top production: threshold scan from mtop top 2mtop.
    - Expect 2% on gtWb with Γ(t)~100MeV @ILC √s=340 GeV (Snowmass 2005 Top Report)
    - can extrapolate to ~per mil for FCCee Γ(t)~12MeV: to be done!



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



ELECTROWEAK COUPLINGS TO TOP

- **ttZ**, **ttγ** couplings can be enhanced in extra dimensions and (particularly) composite Higgs models
  - Directly probed as **production** process FCC-ee
- Use lepton energy and angular distributions top decay to disentangle ttZ from ttγ in l+jets
  - Large luminosity more than compensates for lack beam longitudinal polarisation
- Sensitivity investigated in optimal observable analysis in arXiv:1503.01325 using form factor approach:

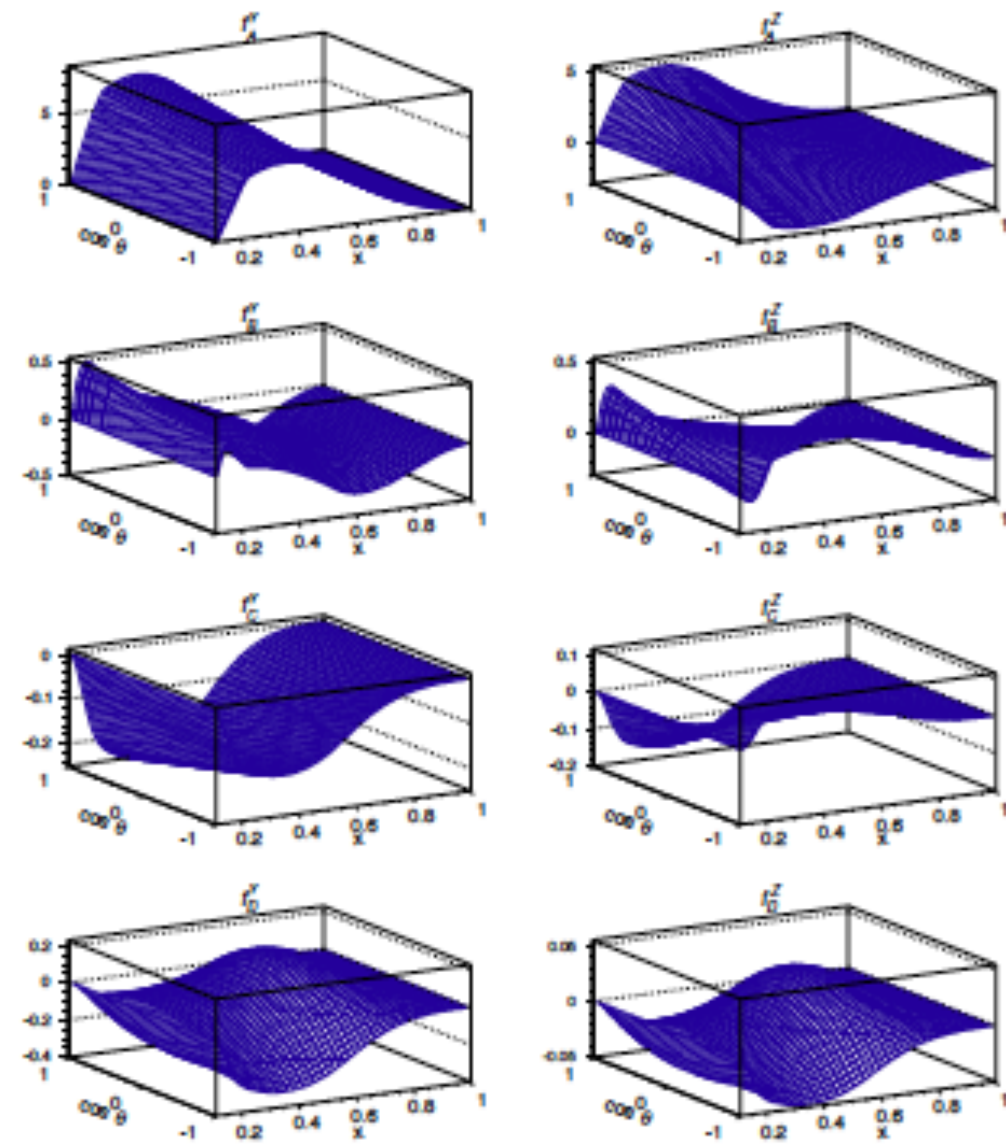
$$\Gamma^{\mu}_{ttv} = \frac{g}{2}\left[\gamma^{\mu}\left\{(A_v + \delta A_v) - \gamma_5(B_v + \delta B_v)\right\} + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t}(\delta C_v - \delta D_v\gamma_5)\right]$$

P. Janot | Reference: arXiv: 1503.01325

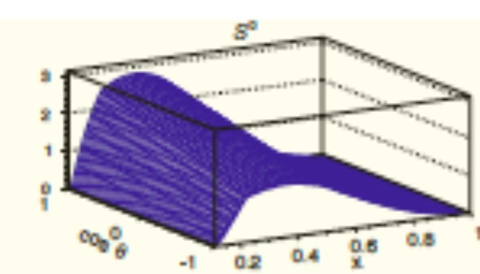
EXPLOITING THE FINAL STATE

- ➤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 (θ) and its reduced energy (χ)
  - ➤ main systematic comes from predicted event rate
- ➤More final state variables can be considered

Angular modifications

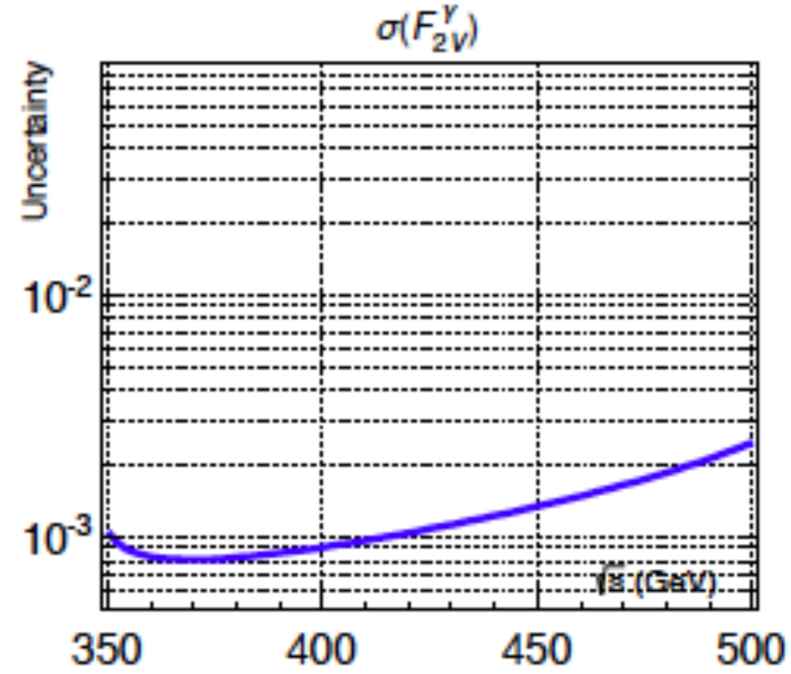


Standard Model



ANALYTICAL ANALYSIS RESULTS

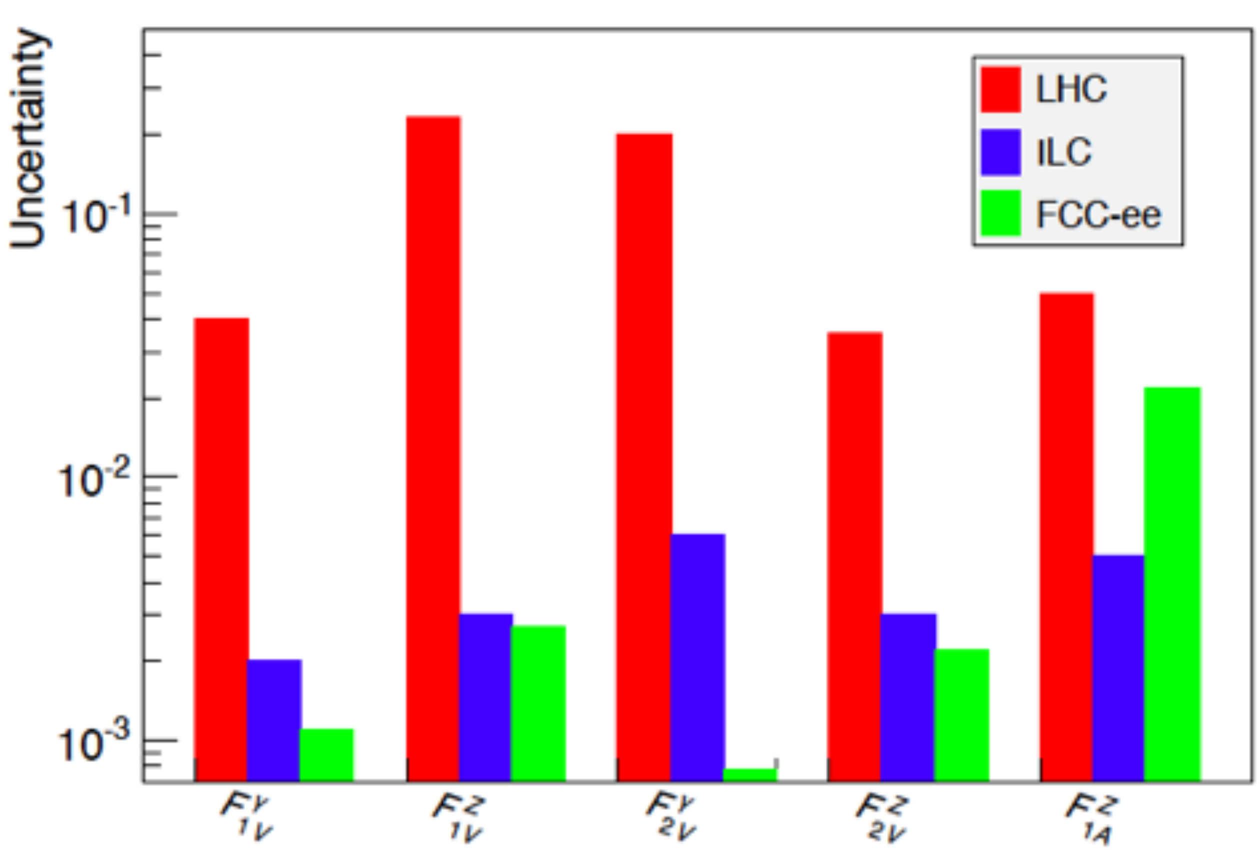
- Fit includes conservative assumptions detector performance such as b-tagging, lepton identification and angular/ momentum resolution
- Expected precision of order 10^{-2} to 10^{-3}



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

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

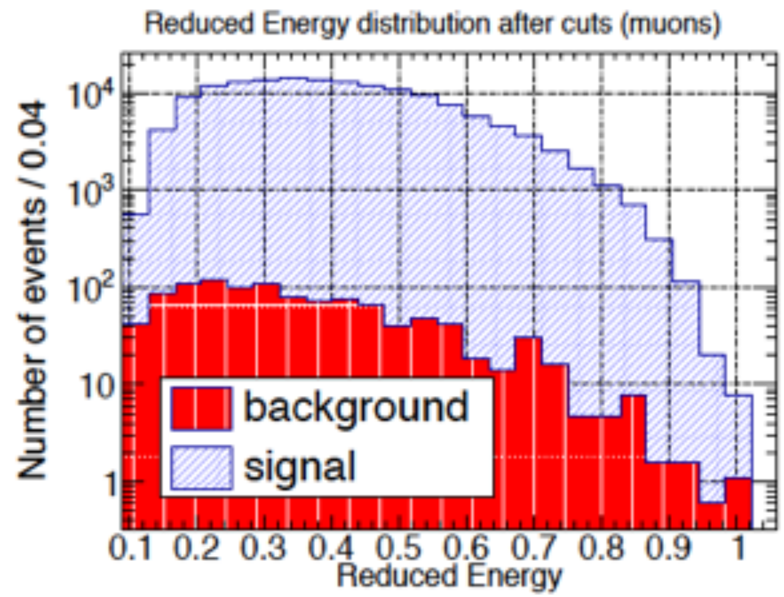
FCC-ee = $\sqrt{s}$=365 GeV, 2.4 ab^{-1}

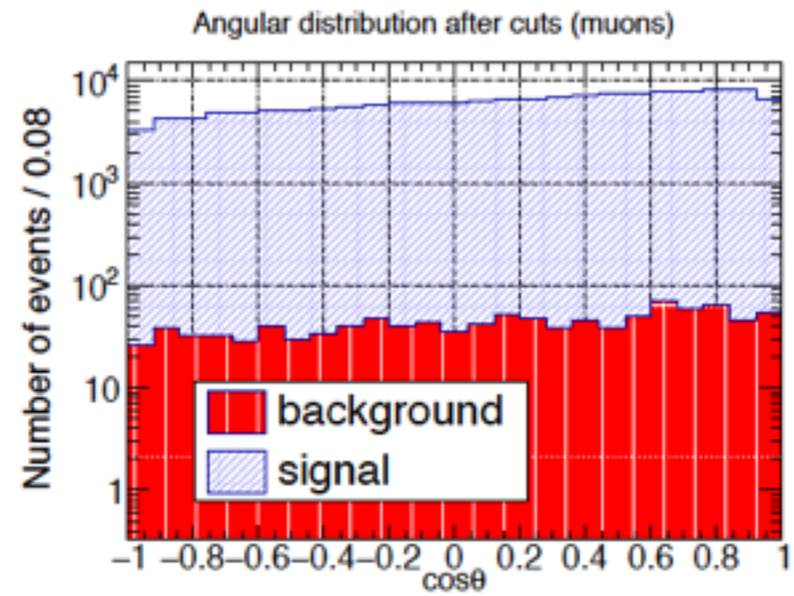


- Expected uncertainty on bounds ttZ/ ttγ couplings dominated by theory uncertainty on prediction mechanism
- Also confirmed by full sim analysis using Whizard and assumed FCC-ee detector performance
- **Optimal centre-of-mass energy is 365-370 GeV**
- **NO need for polarization to disentagle the initial state**

A FULL SIMULATION STUDY

Reduced charged lepton energy and angular distributions after the cuts





The analytical results have been proven with full detector simulation considering signal and backgrounds.

Good agreement with the predictions in Arxiv 1503.01325

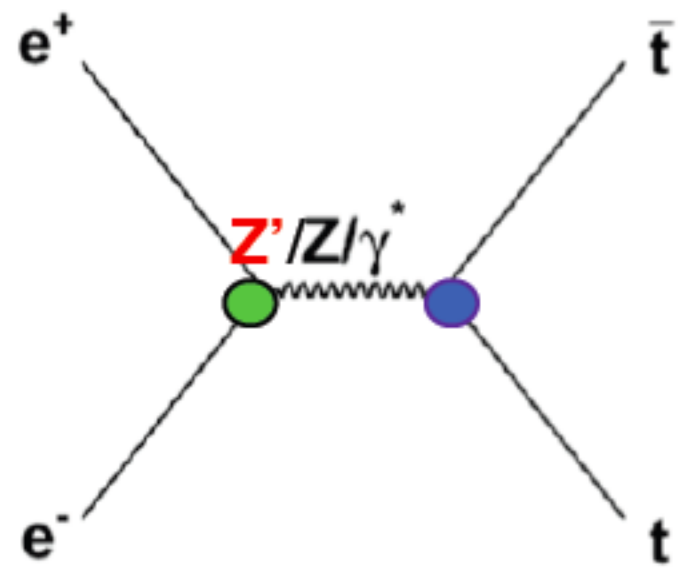
	Whizard full simulation	Arxiv 1503.01325
$\sigma(\delta A_Z)$	$1.8 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
$\sigma(\delta B_Z)$	$1.6 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$

Assumptions in arXiv:1503.1325

- selection efficiency $\simeq 0.5$
- complete rejection of the background
- included also the fully leptonic final state analysis in its estimates

P. Janot, N. Foppiani, T. Pajero

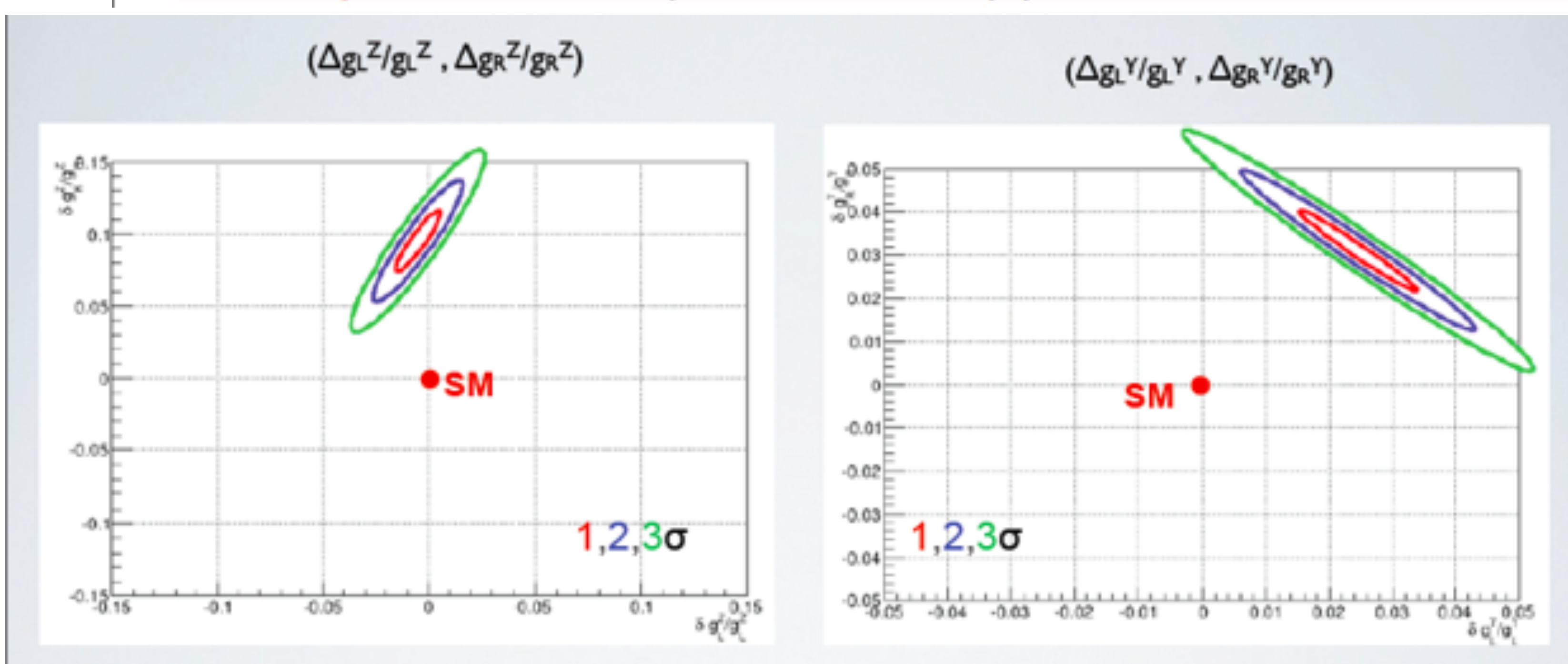
BSM POTENTIAL: COMPOSITE HIGGS MODEL



The CHM modifications of the process arise via 3 effects:

- ☑ modification of the Zee coupling (negligible)
- ☑ modification of the Ztt coupling from: mixing between top and extra fermions (partial compositeness), mixing between Z and Z's
- ☑ the s-channel exchange of the new Z's (interference) - commonly neglected BUT can be very important also for large $M_{Z'}$

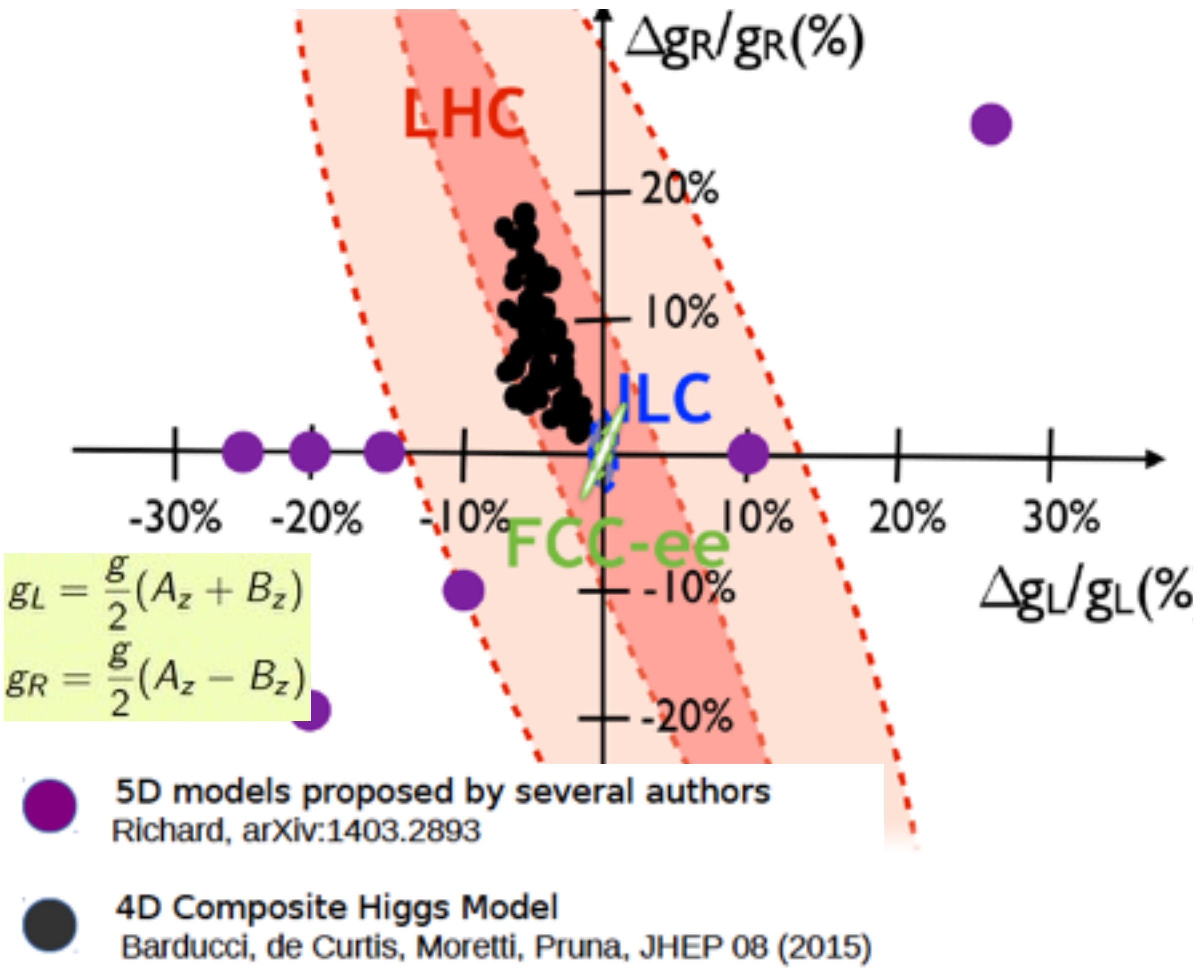
$e^+e^- \rightarrow t\bar{t}$ production is one of the most prominent 6f process, strong sensitivity also to new particles. Asymmetries O(1)

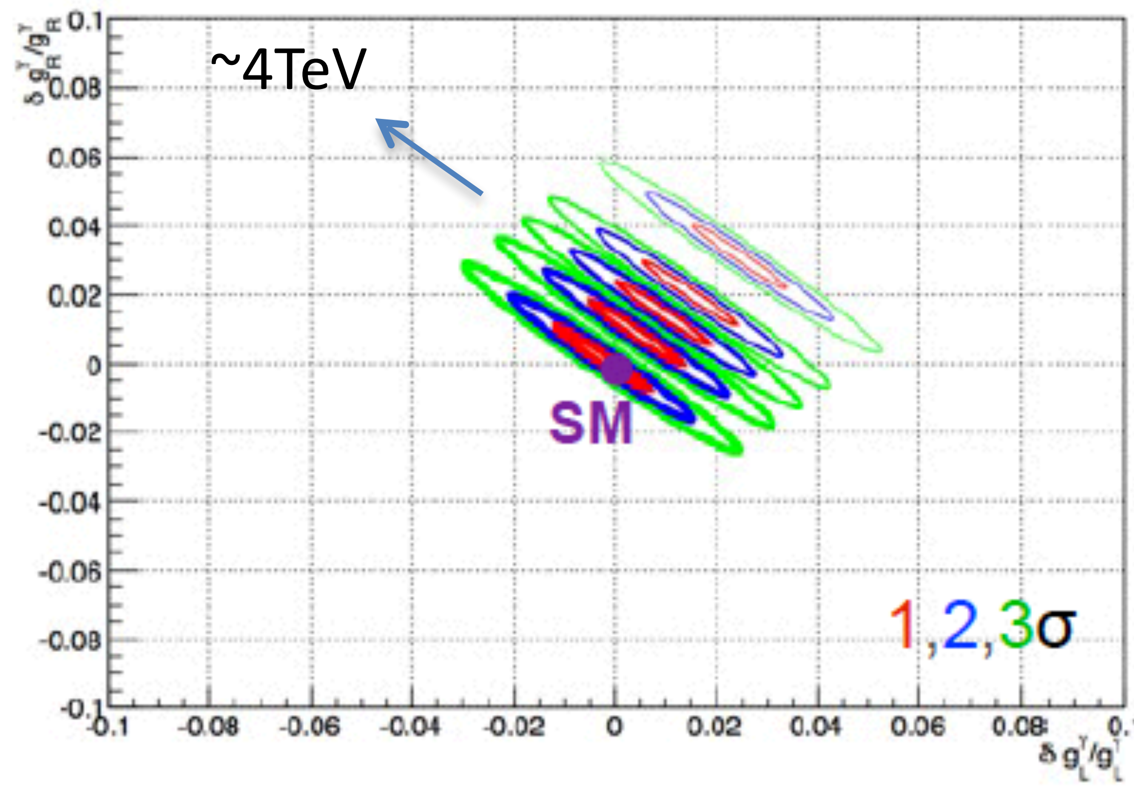


Barducci, De Curtis,Moretti, Pruna 1311.3305

NEW PHYSICS SENSITIVITY

In CHM, the Z-t-t coupling is modified from: mixing between top and extra fermions (partial compositeness), mixing between Z and Z's.





Typical deviations of the Zt_Lt_L and Zt_Rt_R couplings for various NP models (purple points) and for the 4D-CHM (black points) together with the sensitivity expected at LHC-13 with 300 and 3000/fb , outer and inner red lines, from ILC-500, blue dashed lines, and FCC-ee green lines.

FLAVOUR CHANGING NEUTRAL CURRENTS

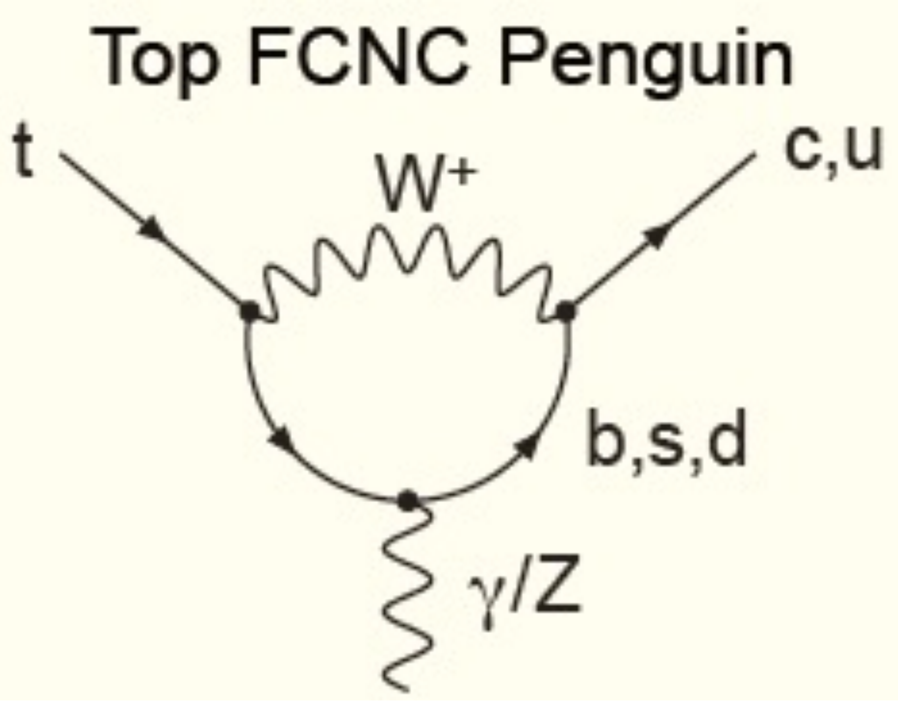
- FCNC are one of the best handles on constraining SM/indirectly discovering BSM in the top sector
- Almost all popular BSM extensions predict increased rare decays of the top quark

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}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

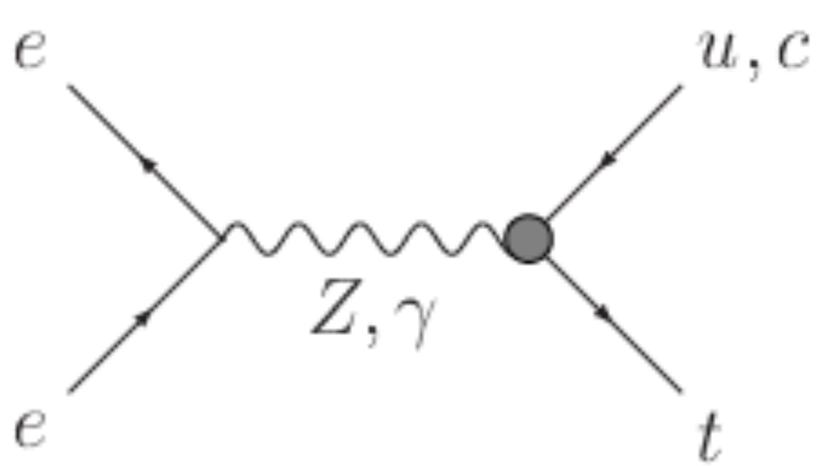
arXiv:1311.2028

FCNC: SINGLE TOP FINAL STATE @√S=240 TEV

- **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 using Delphes+ILD**



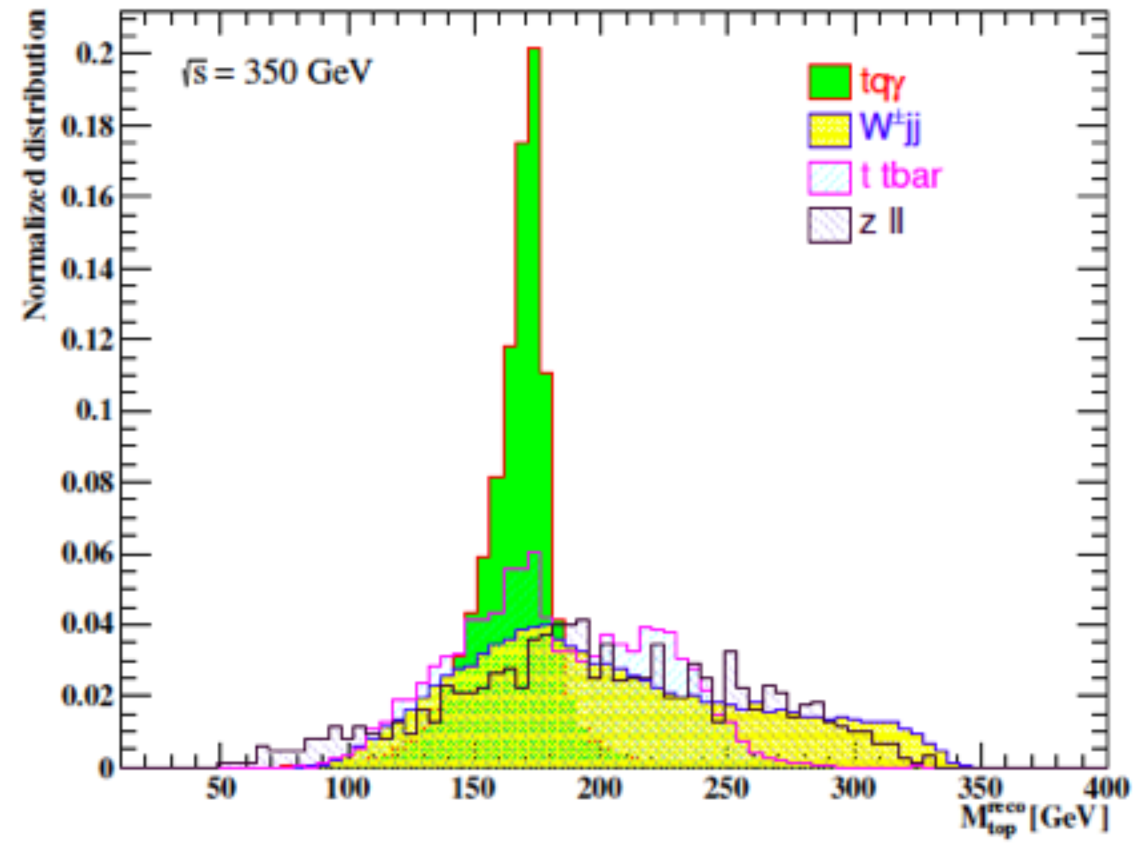
Process	SM
$t \to Zu$	7×10^{-17}
$t \to Zc$	1×10^{-14}
$t \to gu$	4×10^{-14}
$t \to gc$	5×10^{-12}
$t \to \gamma u$	4×10^{-16}
$t \to \gamma c$	5×10^{-14}
$t \to hu$	2×10^{-17}
$t \to hc$	3×10^{-15}



FCNC: LEPTON+JETS

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

- ➤Signal final state: e+e- —> lvb+jet
- ➤Backgrounds from: W^+W^->lvjj, 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 (ε=70%, rej_c=10%, rej_l=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)
- Background rejection rates improves from 10^{-1} to 10^{-2} from √s=240 GeV to 350 GeV
- Only first look at systematics (not included in the result): with 5%(10) change of ΔBr~0.5(6)x10^{-5}



√s(GeV)	240(l+jets) 10ab^{-1}	350(l+jets) 3ab^{-1}
Br(t->qγ)	2x10^{-5}	9.86x10^{-6}
Br(t->qZ)($\sigma_{\mu\nu}$)	2.44x10^{-5}	1.41x10^{-5}
Br(t->qZ)(γ_μ)	5.02x10^{-5}	5.27x10^{-5}

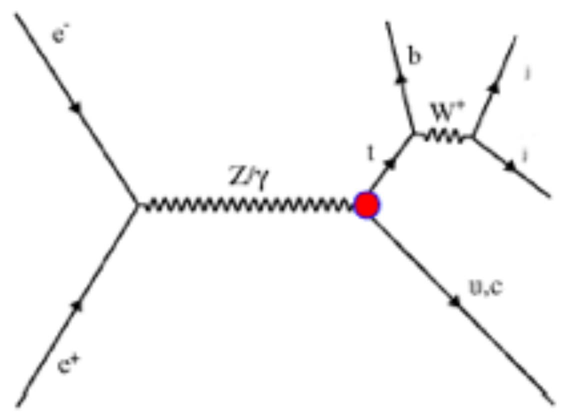
FCNC: ALL HADRONIC

S. Biswas, F. Margaroli, B. Mele

Signal

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

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 $e^+e^- \to Wjj \to jjjj$

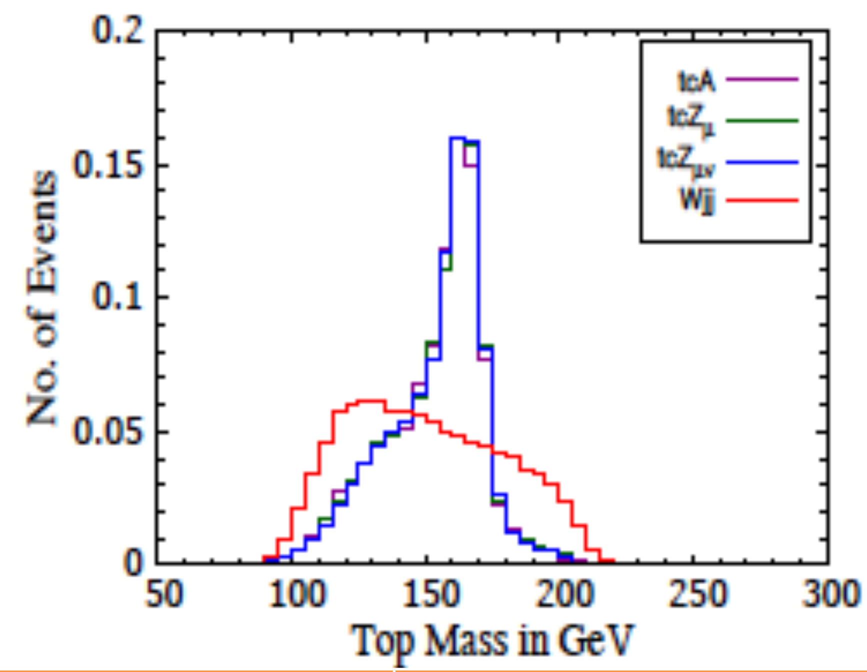
Other 4-jets background ($e.g.$ $q\bar{q}b\bar{b}$) checked to be small.

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

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

udsg rejection factor 1000

- **Selection of 4 jet events to explicitly reconstruct and cut on m(t) and m(W).**
  - signal eff ~47%, bkg ~5%
  - **very preliminary look, simple cut&count analysis**
- **Plan to combine analyses and push sensitivity further**



Sqrt(s) and lumi	240 GeV 10 ab-1
BR(t->qγ) all hadronic	**3.17 x 10-5**
BR(t->qγ) semileptonic	2.01 x 10-5
BR(t->qZ) ($\sigma_{\mu\nu}$) All hadronic	**4.12 x 10-5**
BR(t->qZ) ($\sigma_{\mu\nu}$) semileptonic	2.44 x 10-5
BR(t->qZ) ($\gamma_{\mu\nu}$) All hadronic	**8.22 x 10-5**
BR(t->qZ) ($\gamma_{\mu\nu}$) semileptonic	5.02 x 10-5

EFFECT OF DETECTOR PERFORMANCE

- **This is not only a very important physics channel, but it's a very useful benchmark for detector design studies as b-tag and c-tag performance can enhance the result significantly.**

l+jets analysis 95% limit with b-tagging ε=85% and mistag=5%

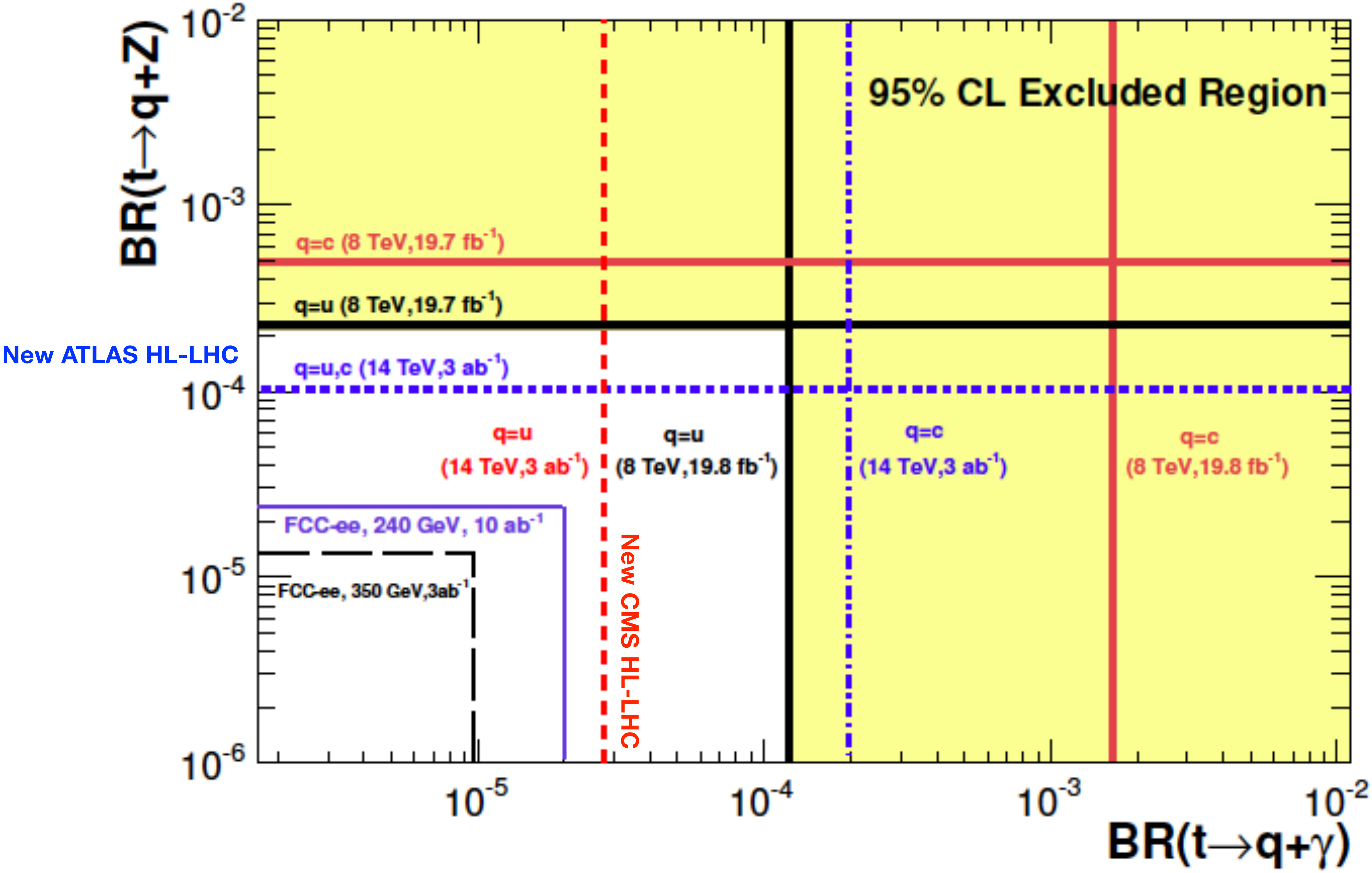
Improvement of about a factor 2 (300 fb^{-1})

$\sqrt{s}$	$Br(t \to q\gamma)$	$Br(t \to qZ)$ $(\sigma_{\mu\nu})$	$Br(t \to qZ)$ (γ_μ)
350 GeV	2.19×10^{-5}	3.12×10^{-5}	1.22×10^{-4}

l+jets analysis 95% limit with different charm tagging performance

Integrated luminosity	$\sqrt{s}$ =240 (GeV)	10% c-tagging	30% c-tagging	50% c-tagging
300 fb^{-1}	$Br(t \to c\gamma)$	1.18×10^{-3}	3.95×10^{-4}	2.37×10^{-4}
3 ab^{-1}	$Br(t \to c\gamma)$	3.39×10^{-4}	1.13×10^{-4}	6.74×10^{-5}
10 ab^{-1}	$Br(t \to c\gamma)$	1.81×10^{-4}	6.05×10^{-5}	3.62×10^{-5}

SUMMARY FOR FCNC (WITH COMPARISON WITH HL-LHC)



SUMMARY OF TOP @FCC-EE

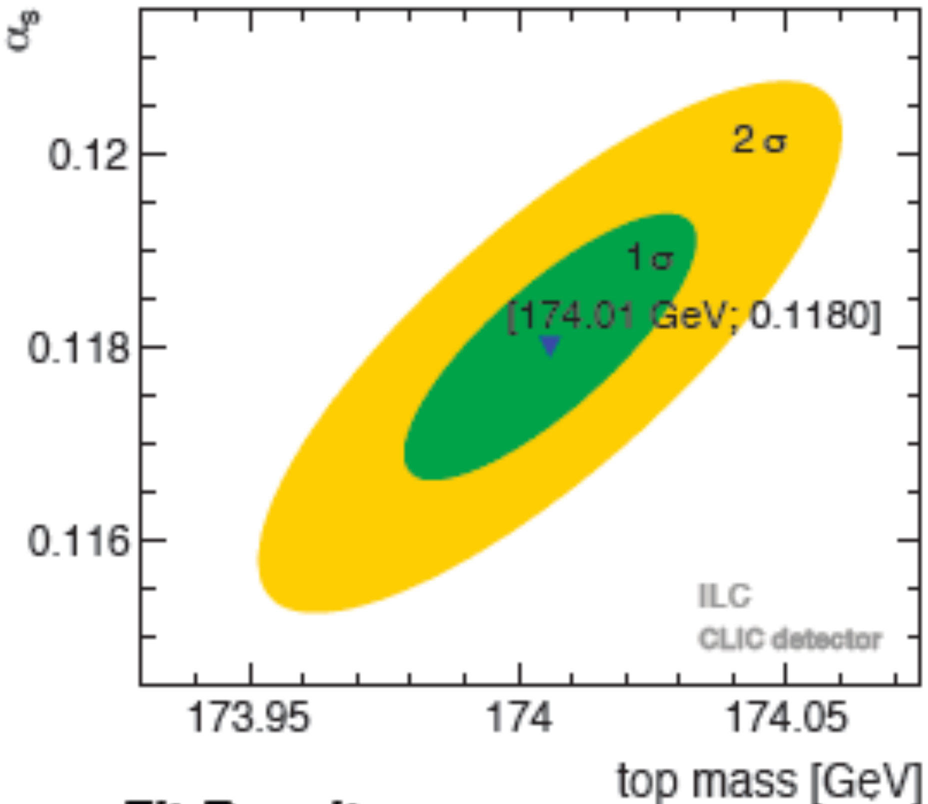
- **FCC-ee great machine for precision measurements in the top quark sector**
  - Very high luminosity up to 2 ab-1 (baseline: 1 ab-1)
    - with 0.5 pb ttbar cross section
  - Different center-of-mass-energies (Z, WW,ZH, ttbar) possible
  - Properties and indirect BSM constraints competitive
    - Nb: FCC-ee precision can probe scales up to 100 TeV
  - Most measurements top sector at this point limited by theory
- **FCC-ee can measure top quark mass with threshold scan:**
  - Statistical uncertainty: 10 MeV
  - Total uncertainty dominated by theoretical input
  - plus possibility of measuring also width and Yukawa
- **Top couplings ttZ and ttγ can be measured to ~ 1% accuracy**
  - And substantial BSM sensitivity for Composite Higgs-like models
- **Limits FCNC of order 10^{-5} - 10^{-6}**
  - still have not pushed fully the potential

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 (top 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 FCC-ee is able to achieve excellent precision on fundamental Top related measurements and:**
    - **very large $\sqrt{s}$ energy running does not seem necessary**
    - **beam polarization does not seem necessary**
- **let's define the run plan for top physics for the CDR**

BACKUP

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

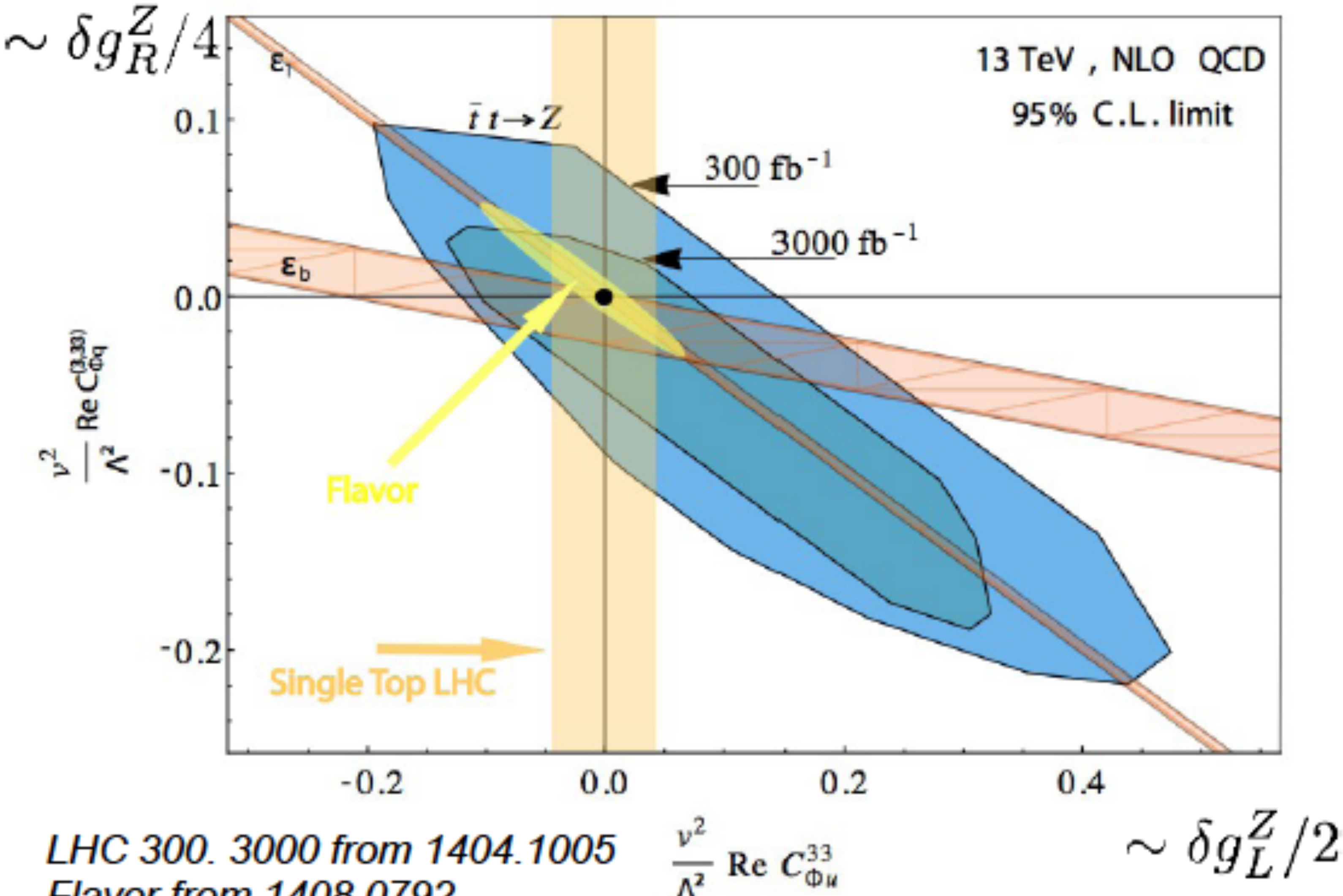
So if $\Delta\alpha_s$~0.0002 this can be divided by 3.

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

EWK COUPLINGS OF THE TOP QUARK

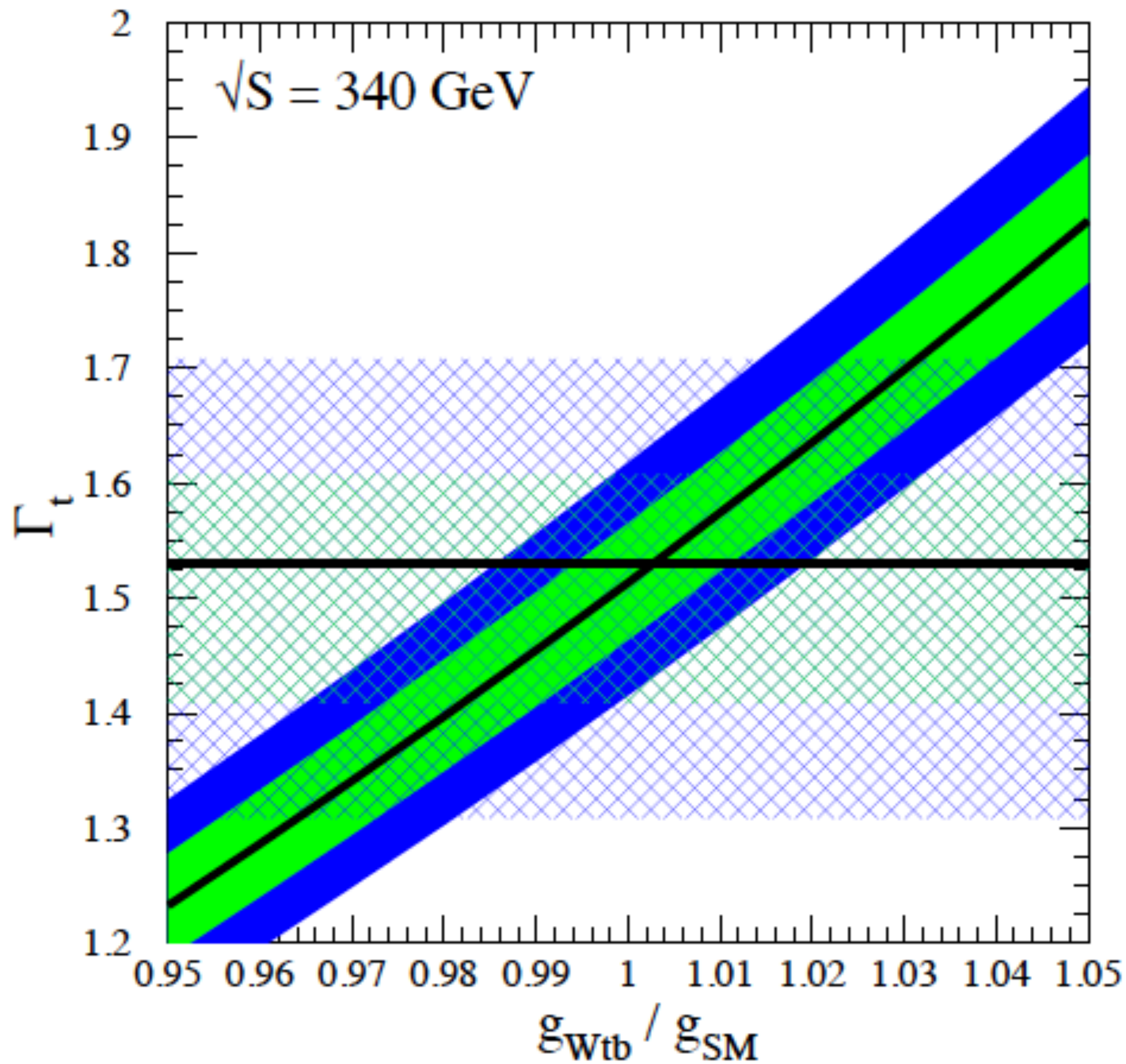


Figure 2: Curve corresponding to the SM rate and its 1σ and 2σ deviations in the plane of g_{Wtb} and Γ_t. Also overlaid is an expected measurement of Γ_t from the on-shell threshold scan with an uncertainty of 100 MeV.