Top Physics @FCC-ee

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and

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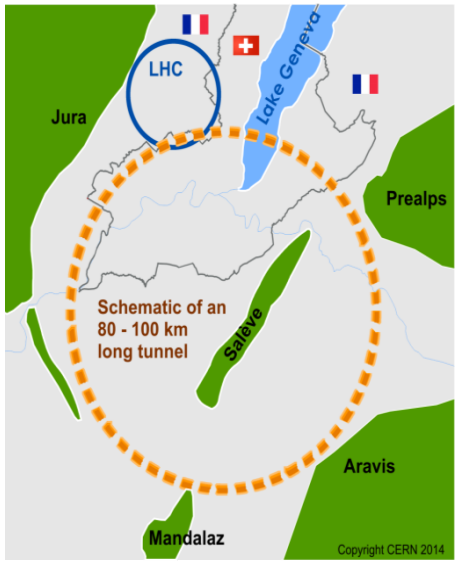
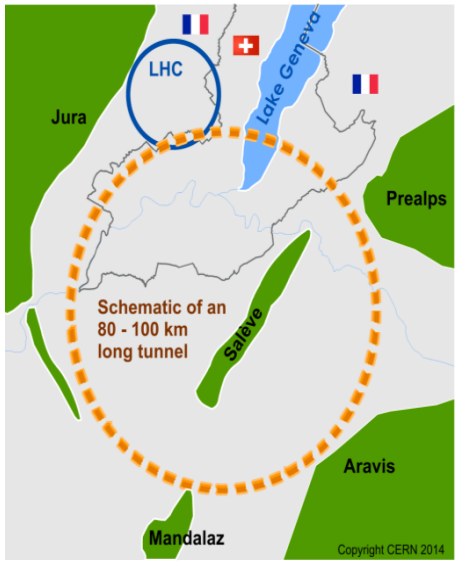
FCC-ee: Introduction

- High-luminosity **ee circular collider** proposed in new 80-100 km tunnel near CERN
- **Flexible** centre-of-mass-energy from **90 to 400 GeV**
- Schedule (and physics) **complementary** and in synergy with FCC-hh (pp @ 100 TeV)



FCC-ee: Introduction

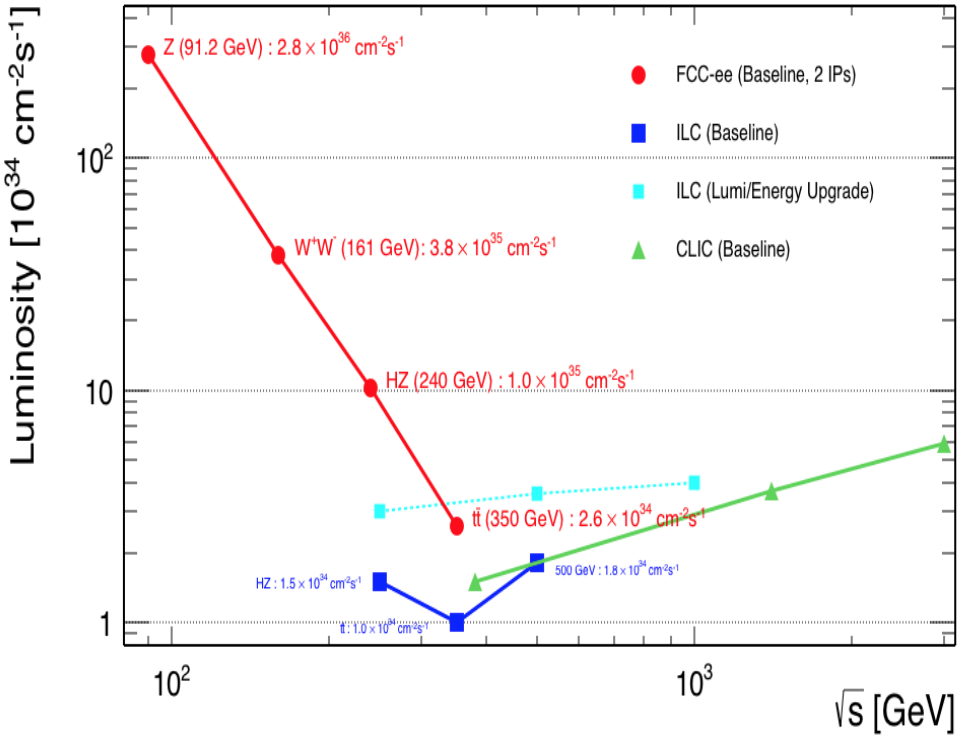
- Explore energy scales to at **least10 TeV**
  - With precision measurements, 20-50 fold improvement on many SM parameters such as
    - m_Z m_W m_{top} $\sin^2\theta_W^{eff}$ R_B, α_{QED} α_S, top and Higgs couplings
- Potential to directly or indirectly **discover** BSM physics
    - Understand BSM through quantum effects in loops
    - DM as invisible decay of H as Higgs factory
    - FCNC in Z and ttbar, flavour physics
    - Very diverse exotica programme



Disclaimer for ee-collider audience:
Obviously, the majority of these arguments hold for any ee-machine

Top physics at the FCC-ee

- The strength of the FCC-ee program:
  - span several centre-of-mass energies: **from Tera-Z to 350 GeV**
  - Using separate e+ and e- storage rings and target $\beta^*\gamma \sim 1$-2 mm means high luminosity at all energies
- Where/when does **top** physics come in the program?



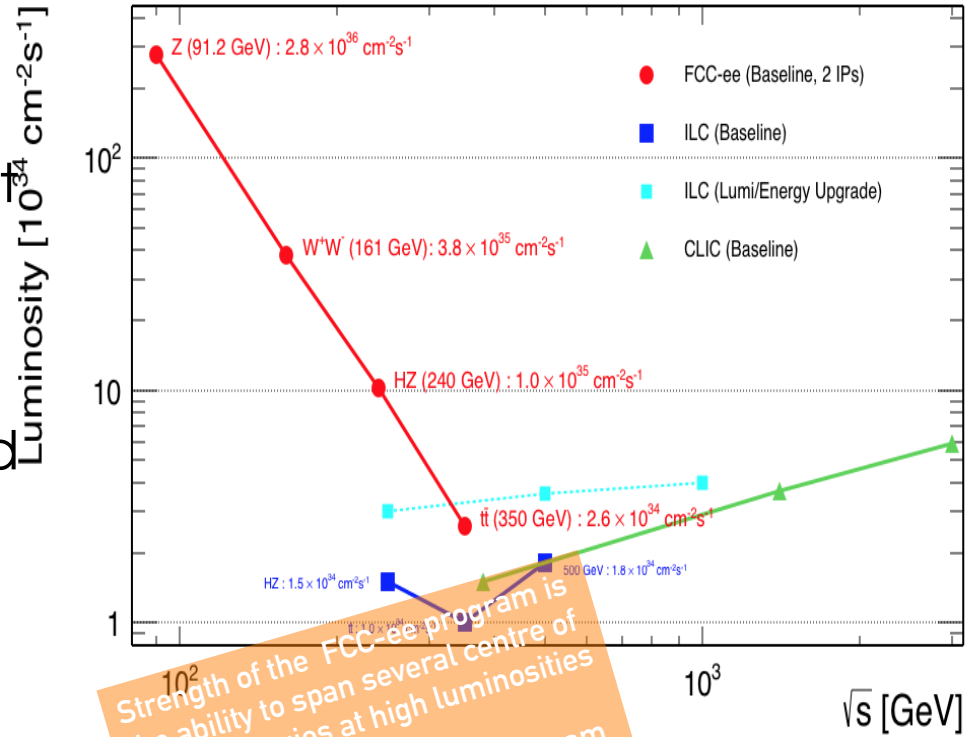
See: arXiv:1308.6176

Physics meetings public:

https://indico.cern.ch/category/5259

Top physics at the FCC-ee

- @350 GeV & just above threshold @370 GeV:
- Dedicated run of ~1.5 ab-1 at and around tt threshold @350GeV « Mega-Top »
  - 0.2 ab-1 for mass measurement from threshold scan
  - higher energy runs for top coupling measurement (ttZ,ttγ,ttH)
- **Single top quark** sample: by product of 240 GeV run (5 ab^{-1})
  - at H+Z mass



Strength of the FCC-ee program is the ability to span several centre of mass energies at high luminosities

Top physics comes in the program in several places

See: arXiv:1308.6176

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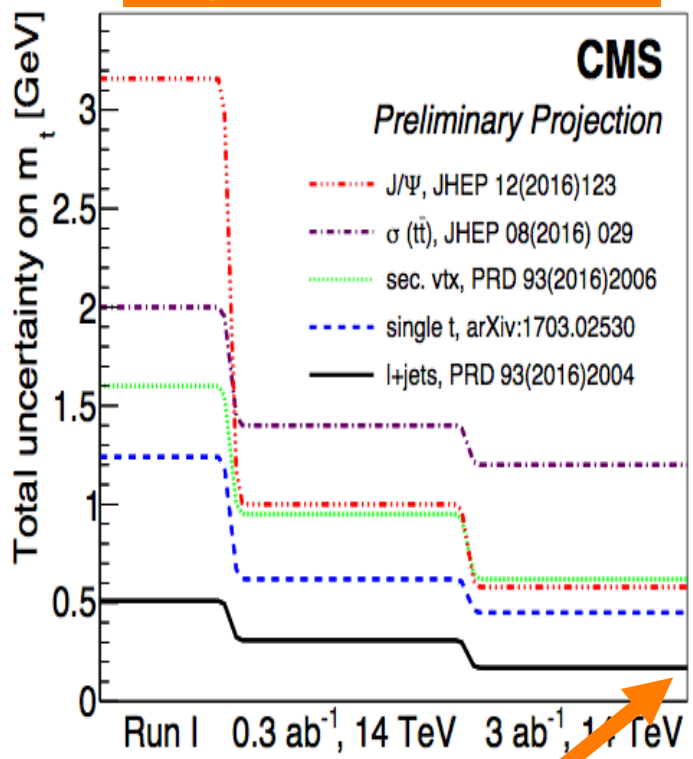
Top Mass measurement

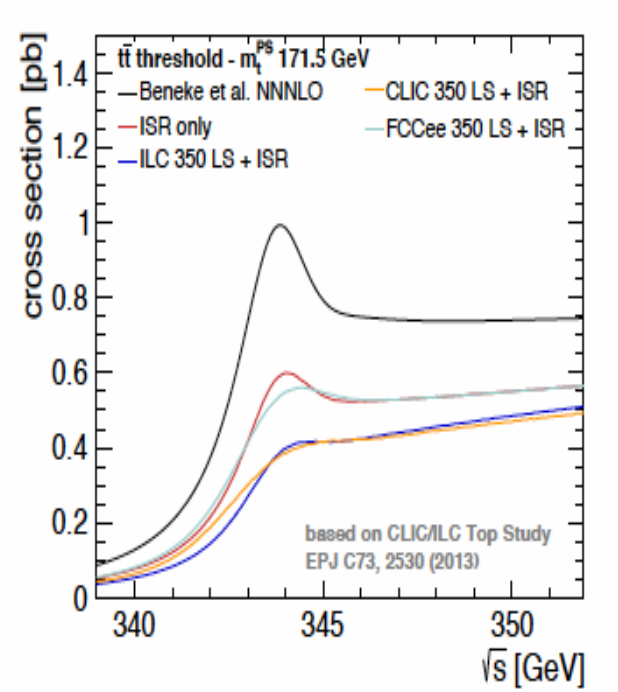
- Methods for top mass reconstruction are characterized by different experimental and theoretical issues and uncertainties:
  - Reconstructed mass: fit to the decay products
    - Most precise way (for now) at hadron colliders. Well defined experimentally, not so well theoretically.
    - New HL-LHC extrapolation ~0.17 in l+jets
    - at lepton collider could obtain precision of ~80MeV (CLIC study)
  - other methods considered for HL-LHC could reach ~500MeV with different systematics.

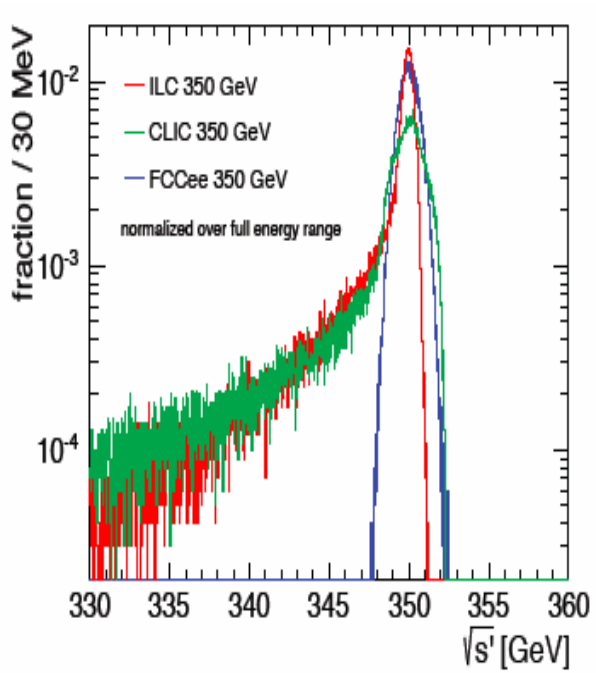
Projections for HL-LHC



l+jets Δm~0.17

Top Mass measurement

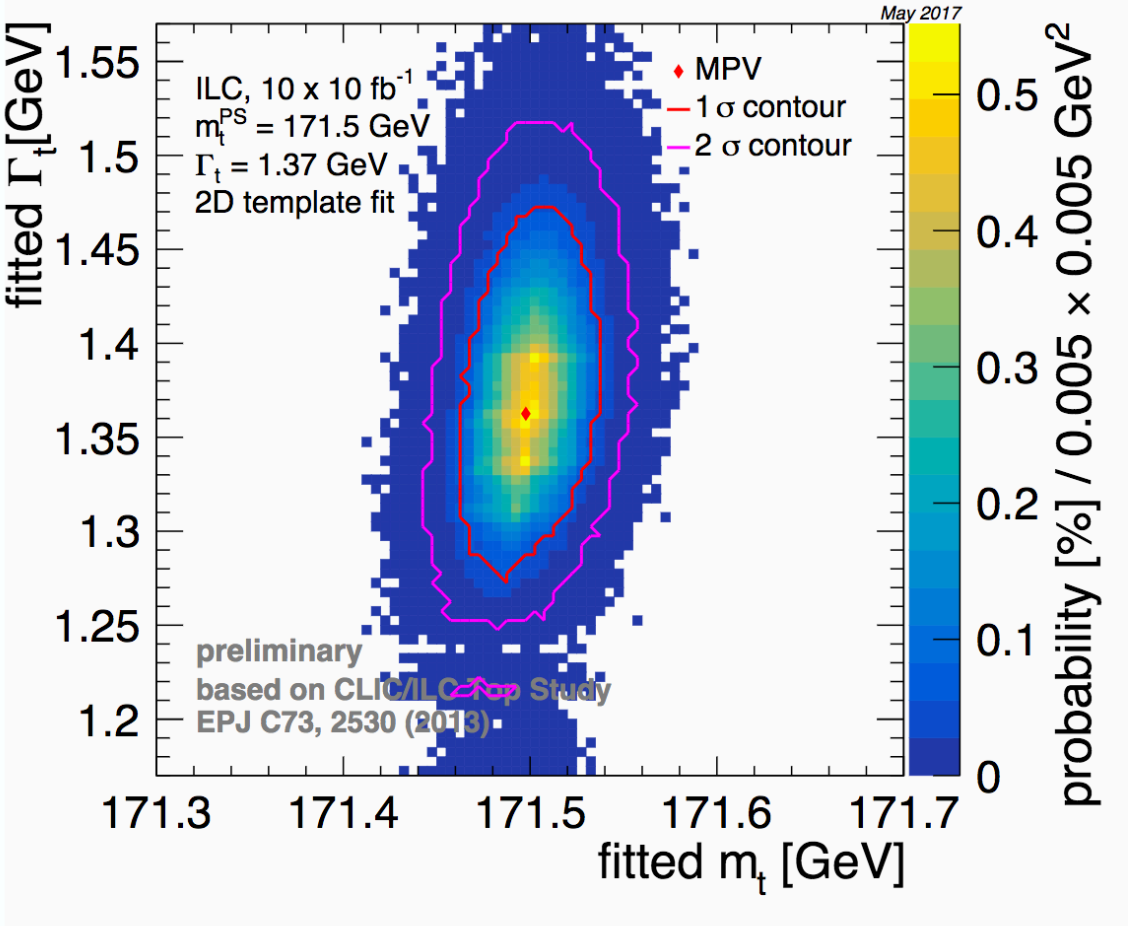




- Cross section shape depends strongly on top quark mass, width, α_s and Y_t
  - Top mass can then be extracted directly with a threshold scan
- The threshold shape is affected by ISR and machine beam energy spread
  - The FCC-ee has very steep luminosity profile, enhancing size of top sample
  - **corresponds to about a 20% improvement in statistics compared to ILC**

From F. Simon's excellent talk on Wednesday

Mass & Width: 2D Template Fit ILC, CLIC, FCCee

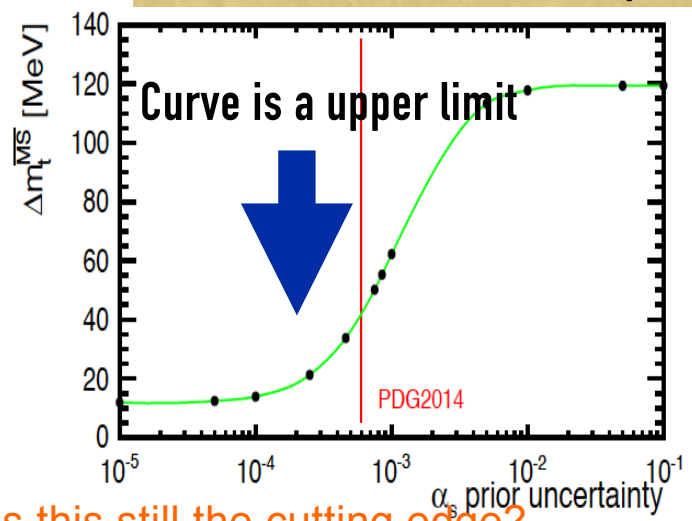


- 1D mass resolution (assuming def. Γ_t)
  18 MeV (ILC)
  21 MeV (CLIC)
  16 MeV (FCCee)
- 1D width resolution (assuming def. m_t)
  43 MeV (ILC)
  51 MeV (CLIC)
  37 MeV (FCCee)
- Extension of 1 σ contour:
  m_t +39 -35 MeV **(ILC)**
  Γ_t +90 -45 MeV
  m_t +40 -45 MeV **(CLIC)**
  Γ_t +130 -95 MeV
  m_t +35 -30 MeV **(FCCee)**
  Γ_t +95 -65 MeV

Mass measurement from threshold: α_S

- Experimental Uncertainties:
  - Beam energy uncertainty of few MeV & beam energy spread: $\Delta m<5$MeV
  - α_S: $\Delta\alpha_s$(@FCC)~0.0002 -> Δm <20MeV
- Theory uncertainties:
  - 1S/PS->$\overline{\text{M}}$S@4th loop: Δm~10MeV
  - other scale uncertainties under study

M. Perello', M. Vos (2015)



Is this still the cutting edge?

- FCC-ee will measure α_S with unprecedented precision at Z pole and WW threshold runs: $\Delta\alpha_S < 0.0002$
  - **Improved α_s drastically improves correlations m_t, Γ_t and Y_t**

With 200 fb-1 and a CLIC-style detector FCC-ee can measure the top quark mass with ~10 MeV statistical accuracy

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

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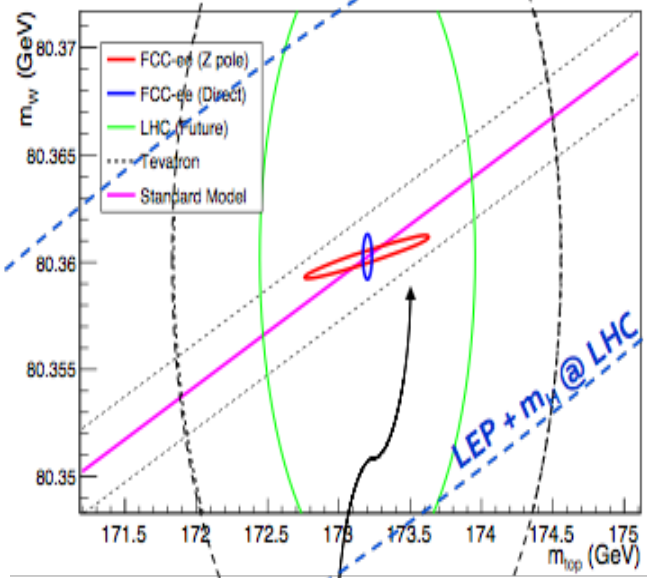
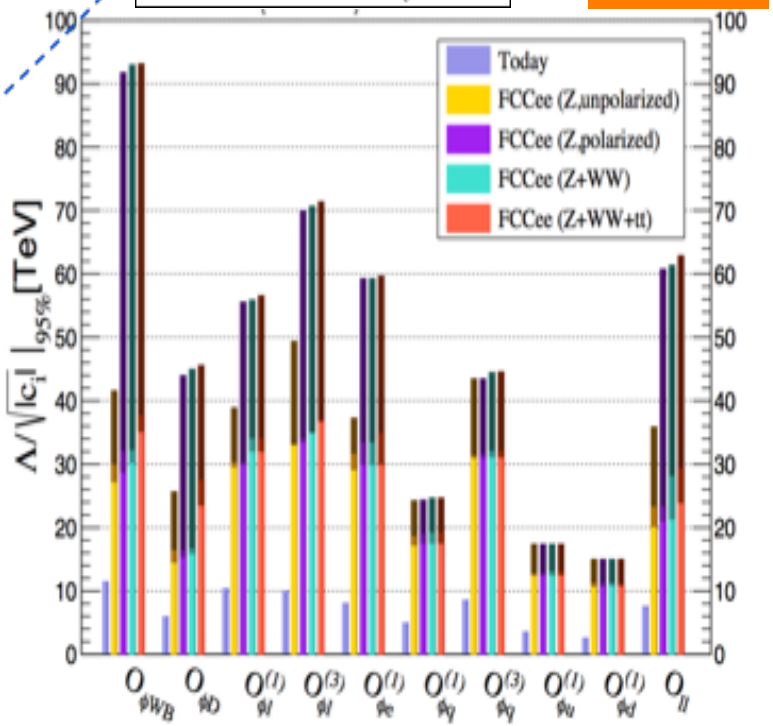
The electroweak fit in the top sector



Without $m_Z(\alpha_{QED})$@FCC-ee, the SM line would have a 2.6 (1.8) MeV width
FCC-ee sensitivity severely drops without POLARIZATION + STATISTICS
(and improved theory calculations)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

de Blas



- Improvements in m_{top}, α_S, M_W at FCC-ee will improve understanding consistency SM in top-W-H radiative corrections
- Sensitivity for NP scale extended up to 100 TeV

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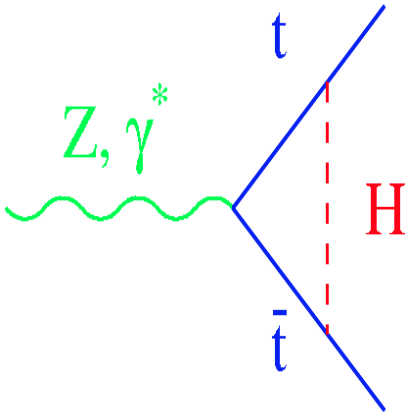
Top yukawa coupling

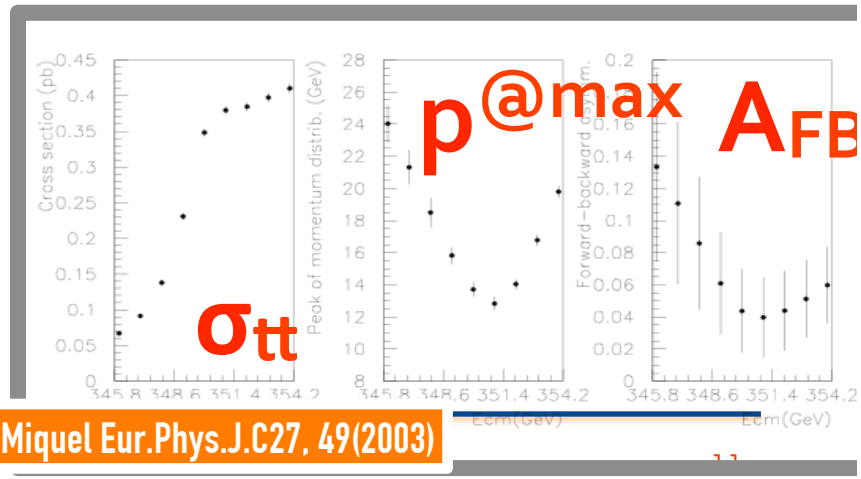


- The coupling between the top and Higgs is important SM test and only precision measurements will allow full understanding
  - **The HL-LHC is expected to reach a precision of ~7-10%. Reaching the sub-% will be a job for FCChh!**
- At the FCC-ee the λ_{top} is accessible only indirectly: at threshold the virtual Higgs boson exchange that can give an effect up to 9% on the cross section
- **A new ILC study @350 GeV with 220fb^{-1}(pol) finds $\Delta y/y$~4.2%(stat)**
  - optimistic, maybe, but it reopens the case for the indirect measurement
- **and the challenge to theory (now around 30%)**

Horiguchi, et al. arXiv:1310.0563

Fitting several variables such as σ, p_T, A_{fb} can be used to extract the top mass, the width and the Yukawa at the same time.

Expected reach of ΔΓ~20 MeV for FCC-ee, will need to be reevaluated.

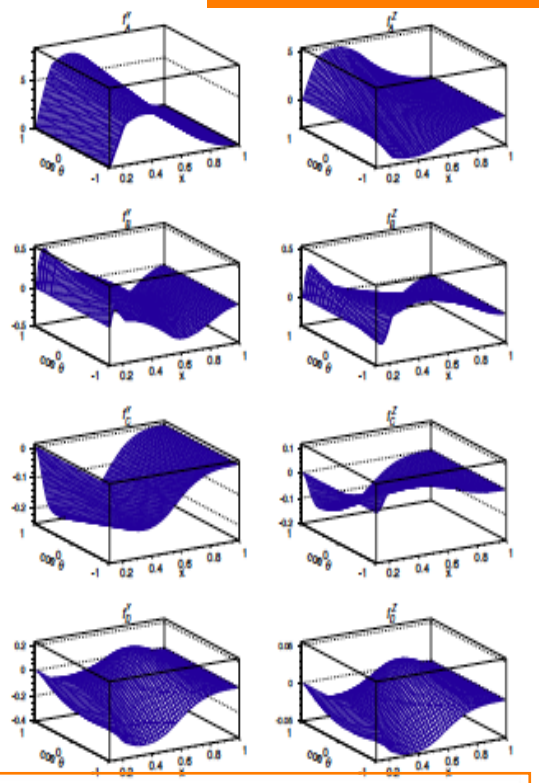


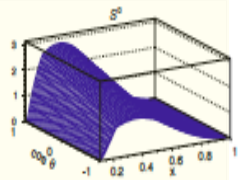
Martinez, Miquel Eur.Phys.J.C27, 49(2003)

Electroweak couplings of the top quark (1)

- ttZ, ttγ couplings can be enhanced in extra dimensions and (particularly) composite Higgs models
  - Directly probed in the tt production process at FCC-ee
- Profit of the fact that top polarization information is maximally transferred to its final state particles via the weak decay
- Use lepton energy and angular distributions in top decay to disentangle ttZ from ttγ in l+jets
  - Sensitivity investigated in optimal observable analysis (confirmed by full simulation analysis)

P. Janot arXiv: 1503.01325





Standard Model

Pajero, Foppiani, Janot

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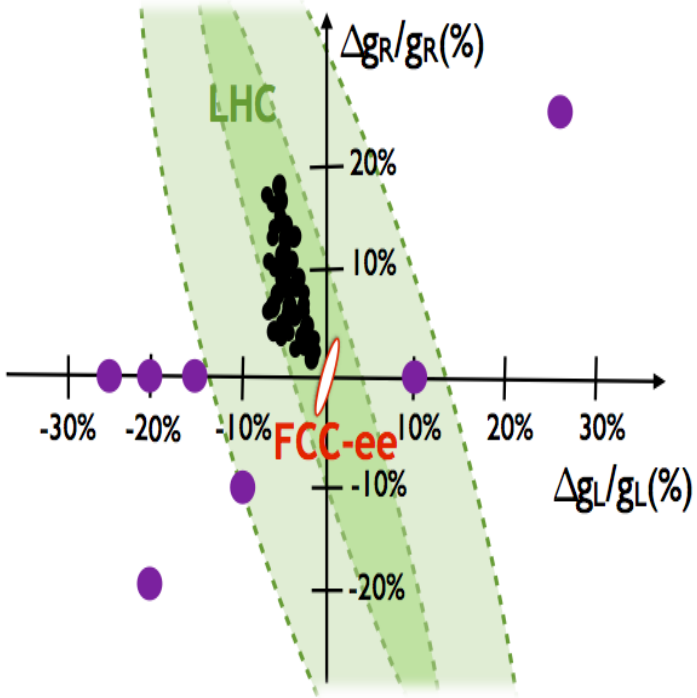
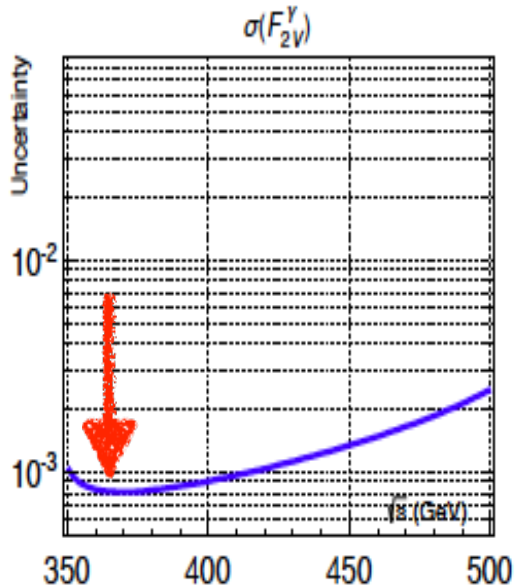
Electroweak couplings of the top quark(2)

- Large statistics and final state polarization allow a full separation of the ttZ/γ couplings with **NO need for polarization in the initial state.**
- **Optimal √s= 365-370 GeV**





- ➤ Fit includes conservative assumptions detector performance
- ➤ Theory uncertainty on production mechanism dominates

FCC-ee expected precision of order 10^{-2} to 10^{-3}

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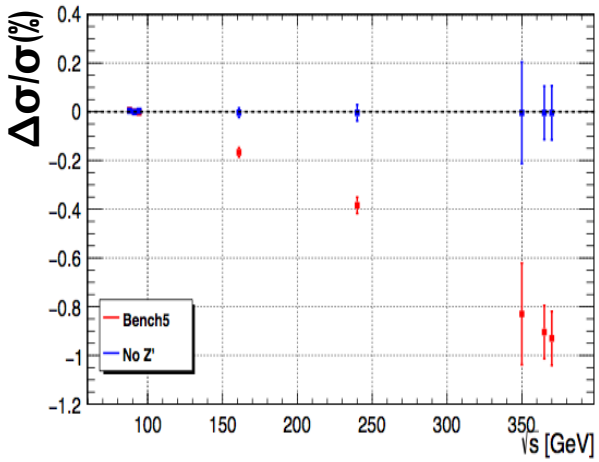
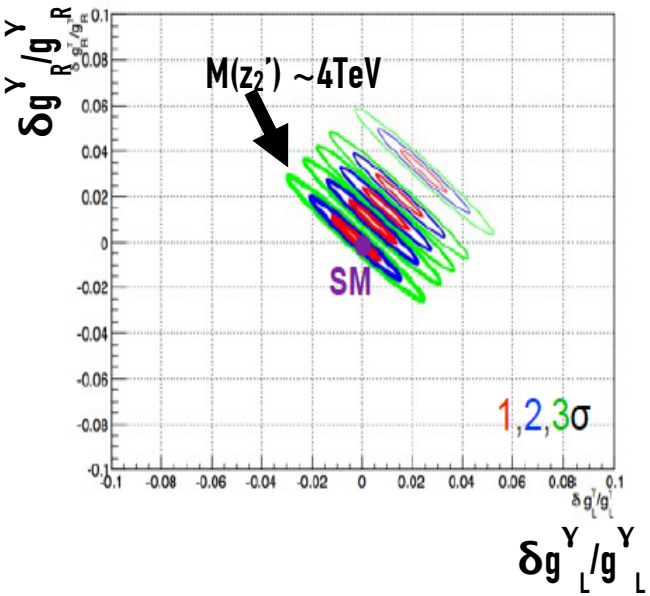
Constraining Composite Higgs

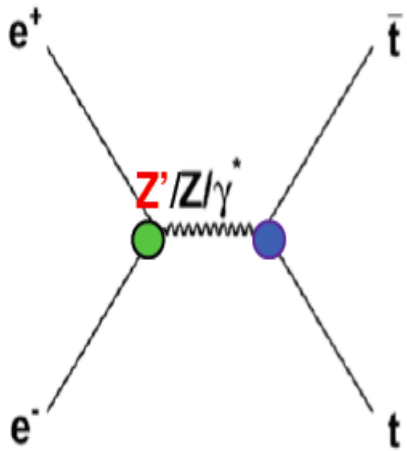
Barducci, De Curtis,Moretti, Pruna 1311.3305

- The CHM modification 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, mixing between Z and Z's
  - s-channel exchange of the Z's (interference)

$$e^+e^- \to \gamma, Z, Z' \to \mu^+\mu^-$$







One more step!
By combining muon cross-sections and A_{FB} with the top optimal observables **the model can be fully characterized @FCCee**

With FCC-ee precision sensitivity up to ~4 TeV Z' mass

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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

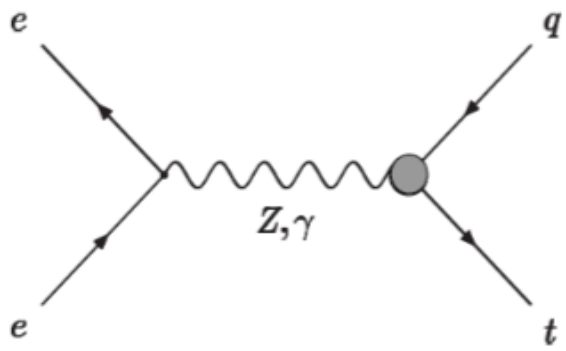
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$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

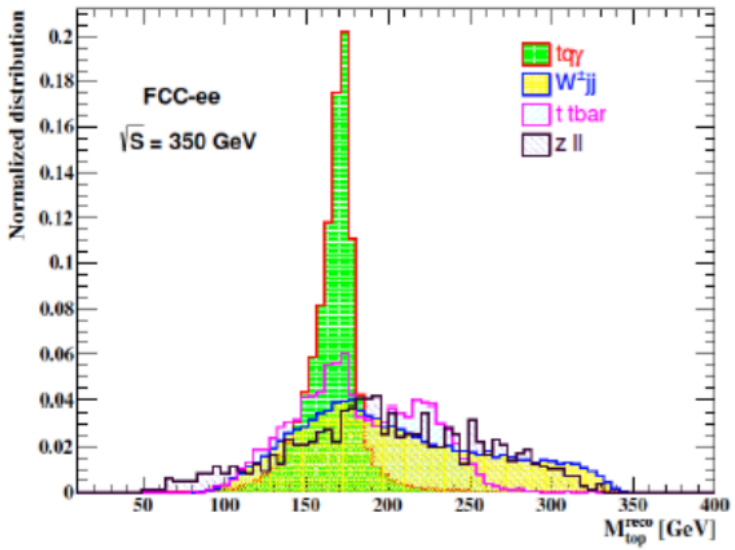
Large and pure 'MegaTop' sample good for FCNC

- As usual in FCNC analyses, taking an **effective Lagrangean** approach

$$\mathcal{L}_{eff} = \sum_{q=u,c} \Big[e\lambda_{tq}\bar{t}(\lambda^v - \lambda^a\gamma^5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}qA^\mu + \frac{g_W}{2c_W}\kappa_{tq}\bar{t}(\kappa^v - \kappa^a\gamma^5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}q\ Z^{\mu\nu} + \frac{g_W}{2c_W}X_{tq}\ \bar{t}\gamma_\mu(x^L P_L + x^R P_R)q\ Z^\mu \Big] + \text{h.c.}$$



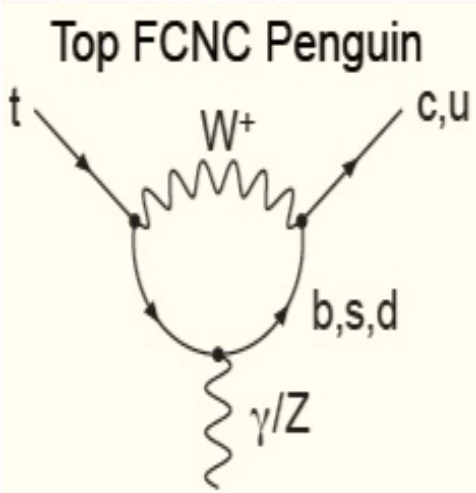
- FCNC tqZ and tqγ: top quark+light quark jet final states
  - Due to lower total mass, already **sensitivity at 240 GeV** FCC-ee run (ee --> HZ)
  - Can be analysed in **full hadronic** and **semileptonic** top decays

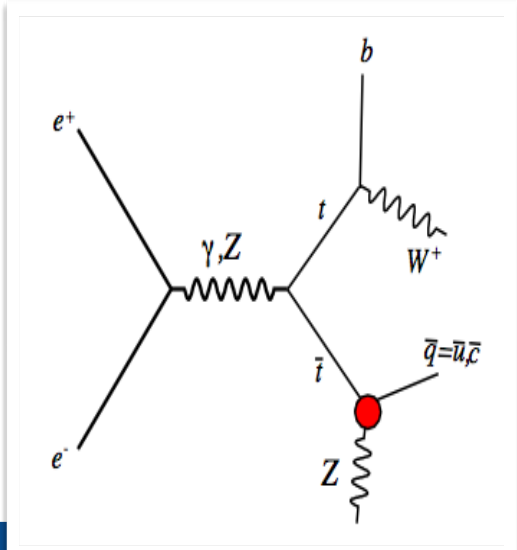


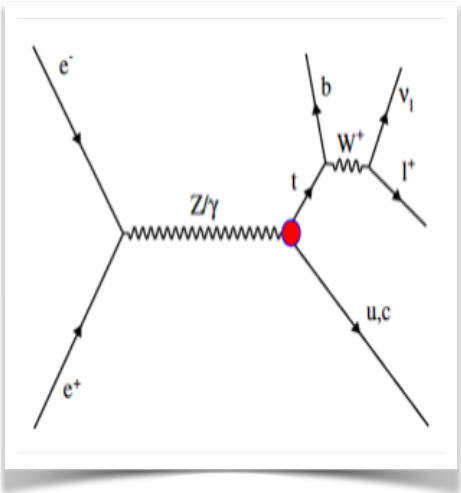
Clear distinction between tqγ and ttbar in semileptonic final state

FCNC also sensitivity in single top @ 240 GeV

- 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
- At the FCC-ee they can be studied:
  - at decay vertex in pair production at √s=350 GeV
  - at production vertex in single top events at √s=240 GeV and √s=350 GeV







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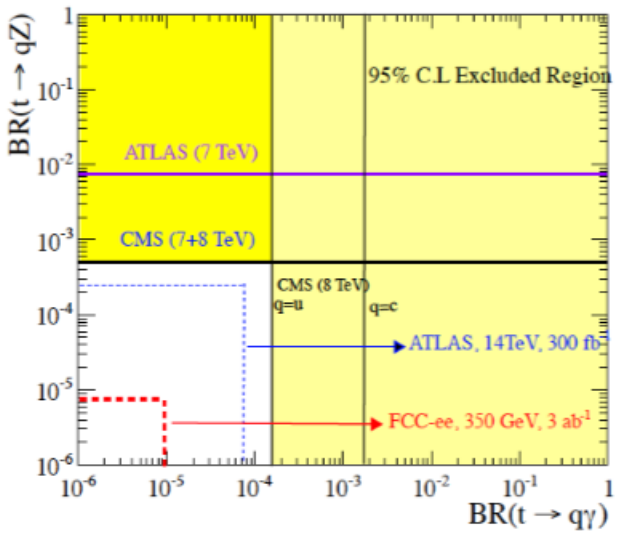
$t \to \gamma c$	5×10^{-14}
$t \to hu$	2×10^{-17}
$t \to hc$	3×10^{-15}

Sensitivity FCNC: 95% CL exclusion limits

- Limits in all-hadronic and lepton+jets channel compatible, as are 240-350 GeV runs

	Single top	Pair of tops
Sqrt(s) and lumi	**240 GeV 5 ab-1**	**350 GeV 5 ab-1**
BR(t->qγ) all hadronic	1.5 x 10-4	
BR(t->qγ) semileptonic	2.84 x 10-5	1.39 x 10-5
BR(t->qZ) ($\sigma_{\mu\nu}$) All hadronic	3.9 x 10-4	
BR(t->qZ) ($\sigma_{\mu\nu}$) semileptonic	3.45 x 10-5	1.99 x 10-5
BR(t->qZ) ($\gamma_{\mu\nu}$) All hadronic	1.9 x 10-4	
BR(t->qZ) ($\gamma_{\mu\nu}$) semileptonic	7.09 x 10-5	7.45 x 10-5



FCC-ee expected to substantially improve beyond HL-LHC

H. Khanpour, S. Khatibi, M. Khatiri, M. M. Najafabadi arXiv:1408:2090
(these new preliminary results from same group)
B. Mele, S. Biswas

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) √s
- the measurement of the main parameters of the SM with unprecedented precision is a priority:

top mass precision at 10MeV | ttZ/ttγ couplings at ~% | indirect ttH coupling

- the opportunities offered for indirect effect of new physics in rare/forbidden/ FCNC processes are extremely interesting

sensitivity to CHM m(Z')~4 TeV | FCNC limits on tq(c)Z ~10-4/10-5

- These preliminary studies show that FCC-ee is able to achieve excellent precision on fundamental Top related measurements while:
  - **Many other opportunities for top quark physics at FCCee**
  - **beam polarizatio advantage can be compensated with optimal variables**

Actively writing CDR this summer – if you want to redo your analysis at 350 or 240 GeV: let Patrizia or me know, we love to help you get the most of your analysis effort

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