



# Top quark physics at FCC-ee

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**for FCC-ee project**



**38th INTERNATIONAL CONFERENCE  
ON HIGH ENERGY PHYSICS**

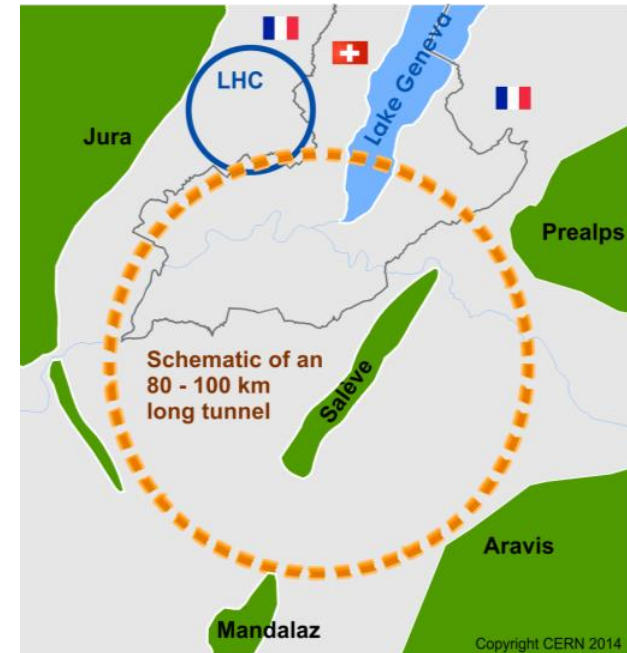
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# Outline

- The **FCC-ee collider** expected to produce large, clean top quark pair sample
- **Top quark mass and width** important parameters SM and contribution loops
- Probing electroweak couplings **ttZ** and **ttγ** with unprecedented precision
- FCC-ee can pin down role of the **top quark** in physics beyond the Standard Model, also at higher scales:
  - tested by measuring **Flavour Changing Neutral Currents**

# 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)
- Explore energy scales to at **least 10 TeV**
  - With precision measurements, 20-50 fold improvement on many SM parameters such as
    - $m_Z$   $m_W$   $m_{\text{top}}$   $\sin^2\theta_W^{\text{eff}}$   $R_B$ ,  $\alpha_{\text{QED}}$   $\alpha_S$ , 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  $t\bar{t}$ , flavour physics

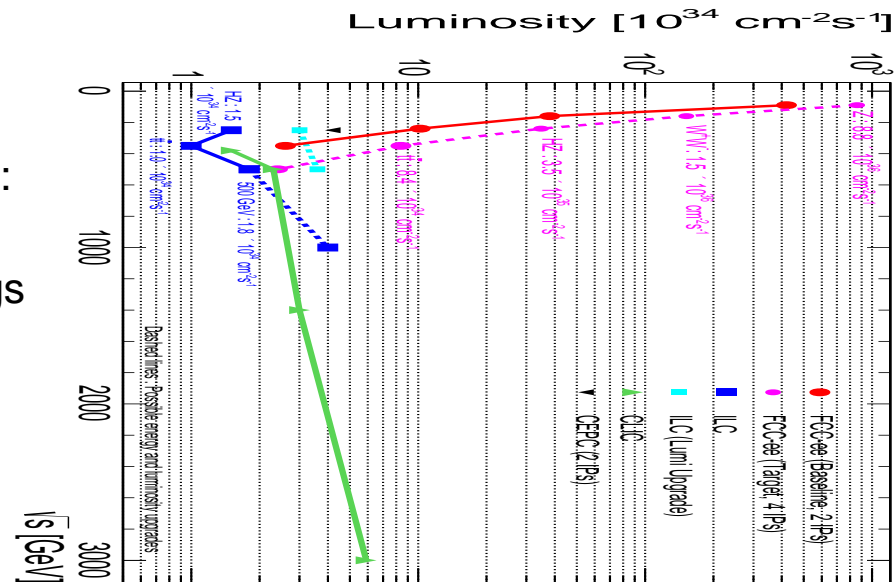


# Top physics at the FCC-ee

- 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  $\beta^*\gamma \sim 1\text{-}2\text{ mm}$  means high luminosity at all energies

- Where/when does **top** physics come in the program?



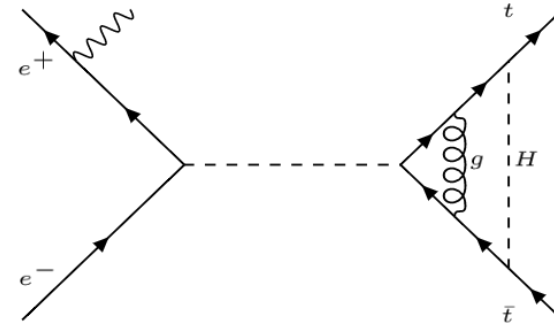
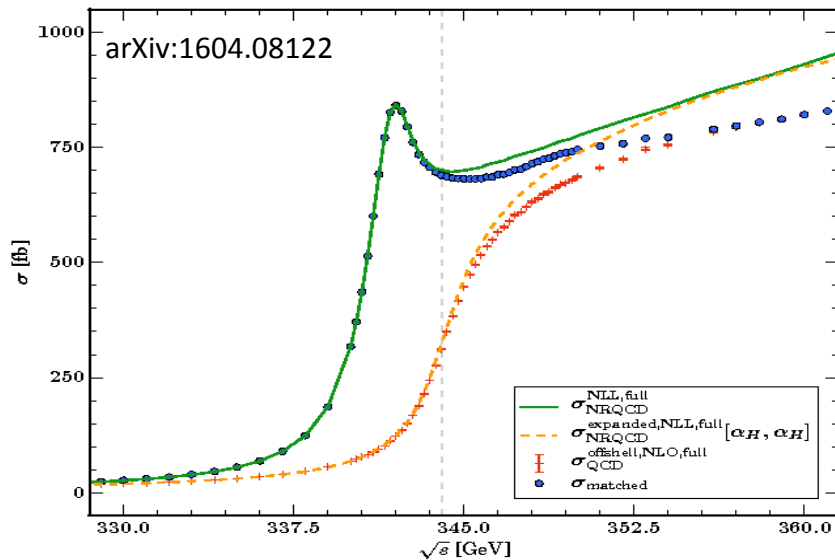
- @350 GeV and just above threshold @370 GeV:
  - cross section  $t\bar{t}$ :  $\sim 0.5\text{ pb}$
  - dedicated run at/around  $2m_{\text{top}}$  **'Mega-Top'**
  - $2\text{ ab}^{-1} = 1\text{M top pairs}$ 
    - with 4 IP: 0.5 year/IP (arxiv:1601.06640)
  - Dedicated run at 370 GeV for top electroweak couplings
- Single top quark** sample: byproduct of 240 GeV run
  - at H+Z mass

See: arXiv:1308.6176

Physics meetings public:

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

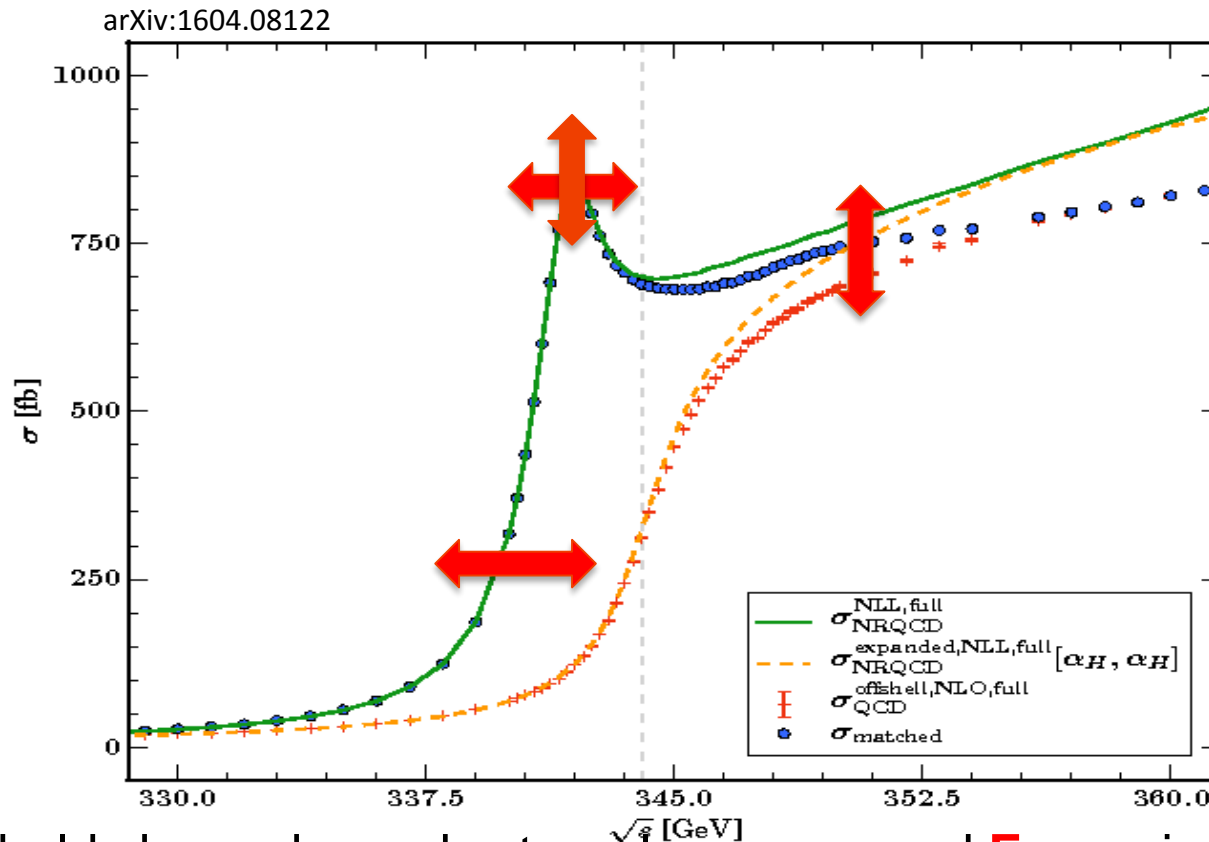
# merit of $m_{\text{top}}$ threshold scan



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

- FCC-ee will measure  $\alpha_s$  with unprecedented precision at Z pole and WW threshold
- Cross section shape depends strongly on top quark mass and width,  $\alpha_s$  and  $Y_t$
- Top mass and width can be measured directly with an accurate top cross section threshold scan
  - Improved  $\alpha_s$  drastically improves correlations  $m_t$ ,  $\Gamma_t$  and  $Y_t$

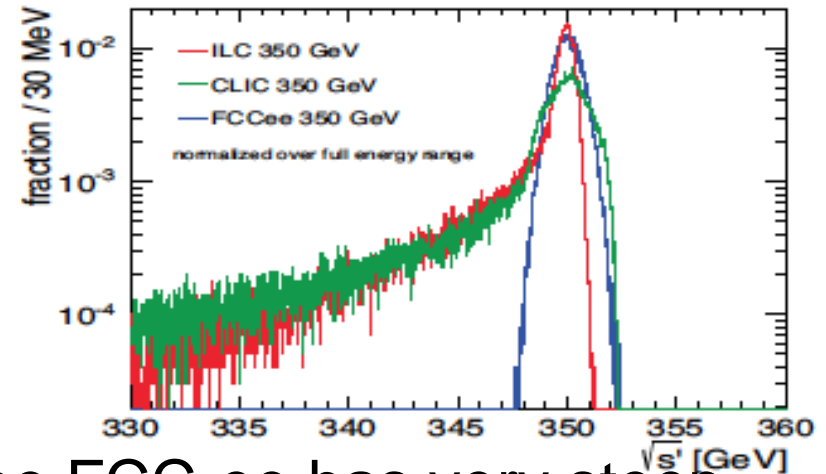
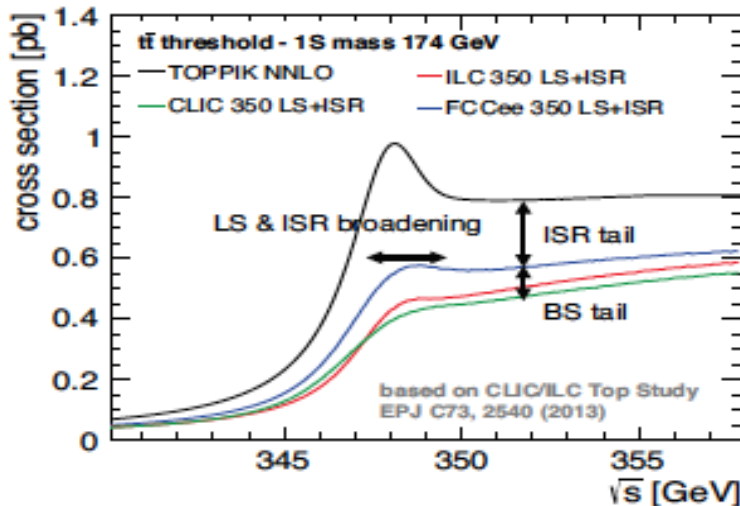
# $m_{\text{top}}$ threshold scan



- Threshold shape depends strongly on  $m_{\text{top}}$  and  $\Gamma_{\text{top}}$  so indirectly  $V_{\text{tb}}$
- Size of resonance behavior at and above threshold can be used to indirectly constrain  $Y_{\text{top}}$

# Top mass and threshold scan

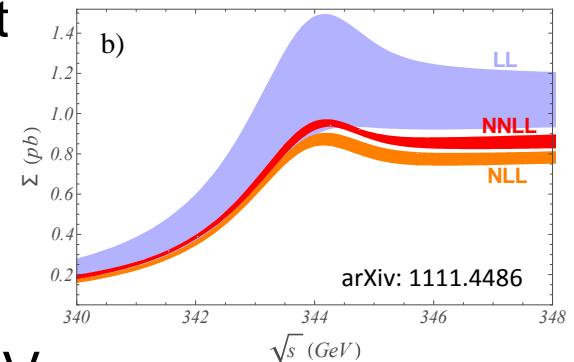
- The threshold shape is affected by ISR and luminosity profile
  - Width of turn-on affected by width luminosity peak
  - Possibility to shift below threshold energy means reduction in effective cross section



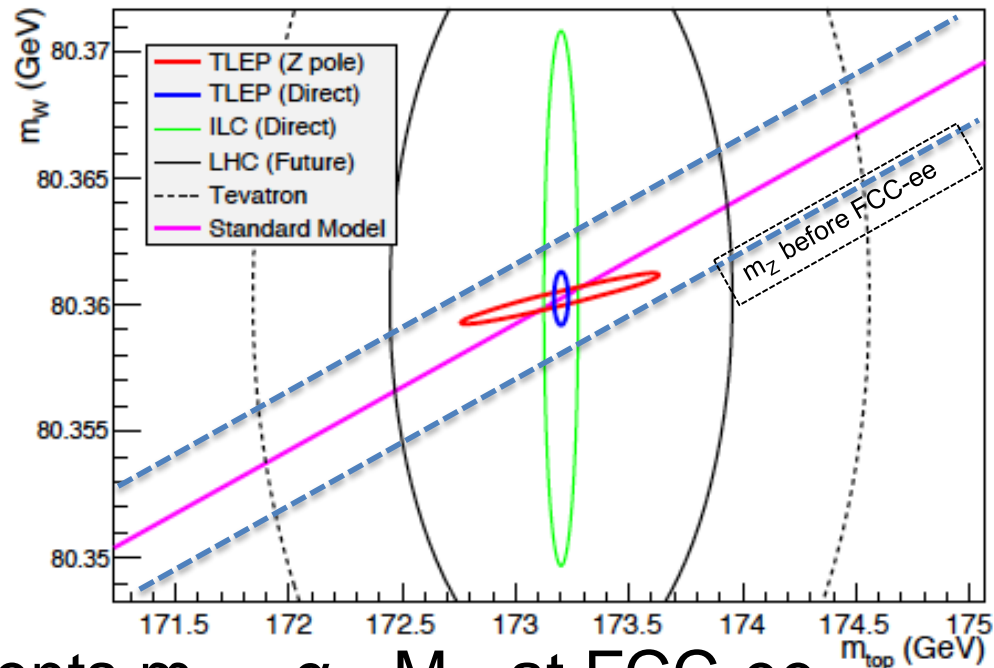
- The FCC-ee has very steep luminosity profile, enhancing **size of top sample** and knowledge of centre-of-mass
- With 100 fb-1 and a ILD/CLIC-style detector FCC-ee can **measure top quark mass** with **16 MeV statistical accuracy!**

# Uncertainties on $m_{\text{top}}$

- Uncertainty due to  $\alpha_s$ :
  - $\Delta m_{\text{top}} = 2.7 \text{ MeV} \times (\Delta\alpha_s/0.0001) \rightarrow \mathbf{5.4 \text{ MeV}}$
  - Input measured (at FCC-ee) with precision of  $\mathbf{\Delta\alpha_s < 0.0002}$  using W/Z boson hadronic branching fraction
    - See talk Mario Antonelli at ICHEP2016
- Theory uncertainty:
  - Description shape  $e^+e^-$  to  $bWbW$  calculated at NNLL
  - Most important NNLL dependence
    - 1S-MSbar scheme top mass
  - Recent developmenst:
    - Uncertainty  $m_{\text{top}}$   $\mathbf{23 \text{ MeV}}$  (parton shower level)
- Experimental (statistics) uncertainty 8-14 MeV depending on 1D or 2D fit
  - $\mathbf{10 \text{ MeV stat uncertainty}}$   $m_{\text{top}}$  within reach if theory improvement continues



# Prospectives EWK t-W fits after FCC-ee



- Improvements  $m_{\text{top}}$ ,  $\alpha_S$ ,  $M_W$  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!

# Electroweak couplings to top

- **ttZ**, **tty** 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 tty 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:

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

# Electroweak couplings to top

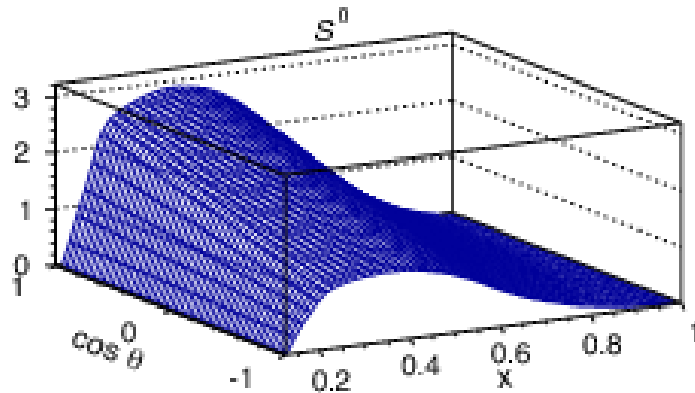
$$\Gamma_{ttv}^{\mu} = \frac{g}{2} \left[ \gamma^{\mu} \{ (A_v + \delta A_v) - \gamma_5 (B_v + \delta B_v) \} + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t} (\delta C_v - \delta D_v \gamma_5) \right]$$

- Each contributes differently to double-differential cross section

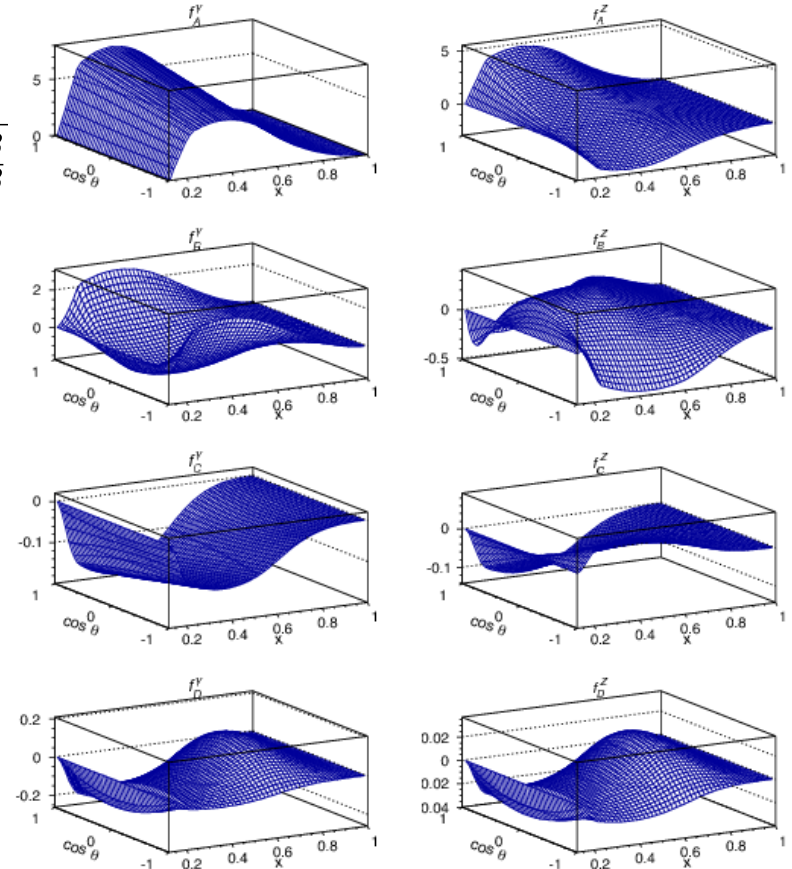
- Lepton angle ( $\cos \theta$ )
- $x$  (reduced lepton energy)

- Sum contributions fitted to data  
SM +  $\delta A_{Z/\gamma}$  +  $\delta B_{Z/\gamma}$

$$x = \frac{2E_{\ell}}{m_t} \sqrt{\frac{1-\beta}{1+\beta}}$$



Standard Model

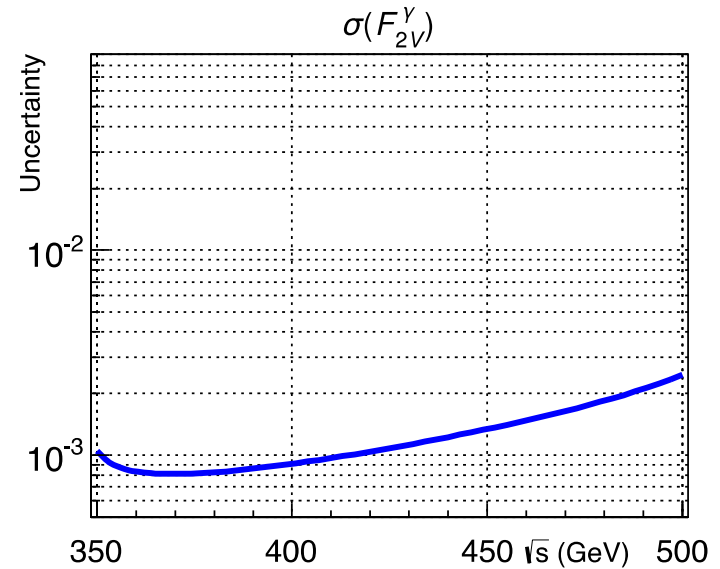
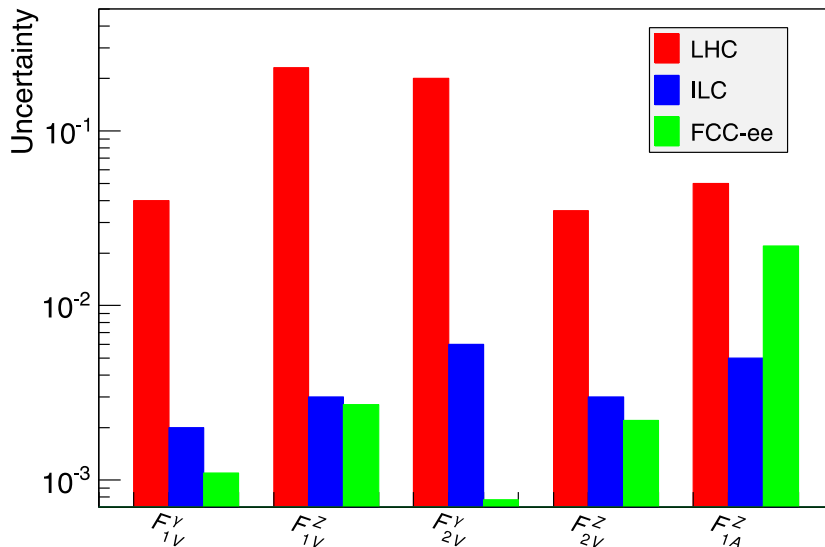


Angular modifications

Reference: arXiv: 1503.01325

# Electroweak couplings to top

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



- Expected uncertainty on bounds  $ttZ/tt\gamma$  couplings dominated by theory uncertainty on prediction mechanism
- **Optimal centre-of-mass energy is 365-370 GeV**
- Also confirmed by full analysis using Whizard and assumed FCC-ee detector performance

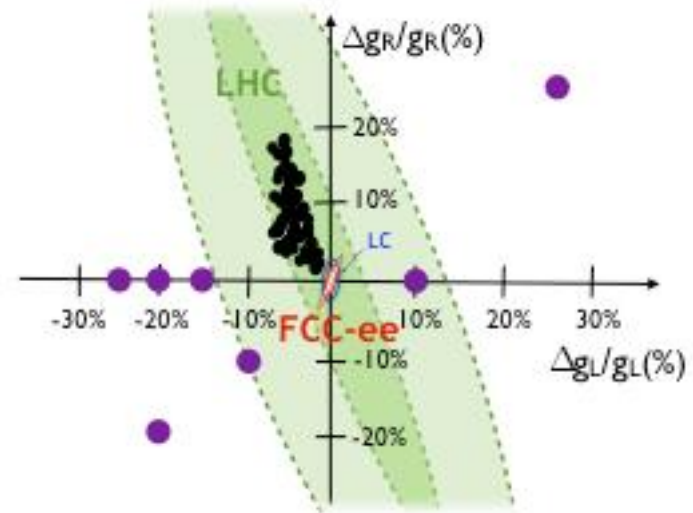
# Constraining BSM with Z/ $\gamma$ to $t\bar{t}$

- Precision measurement has great potential to constrain BSM
  - $A_{Z/\gamma}$  and  $B_{Z/\gamma}$  parameters can be interpreted as  $g_R$  and  $g_L$

$$g_L = \frac{g}{2} (A_z + B_z)$$

$$g_R = \frac{g}{2} (A_z - B_z)$$

- Cross section constraint of  $\sim 2\%$  can be used to constrain BSM well beyond LHC precisions
  - in this case Composite Higgs models



- Note: 2% uncertainty cross section depends on controlling large QCD uncertainties near threshold!
- Currently theory uncertainty at 370 GeV is about 3-4%
  - Larger at 350 GeV
  - We are not far from 2% needed

# 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

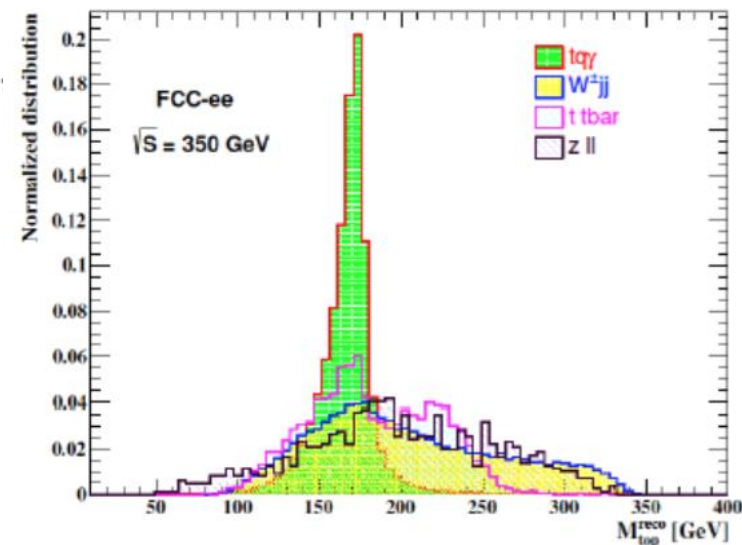
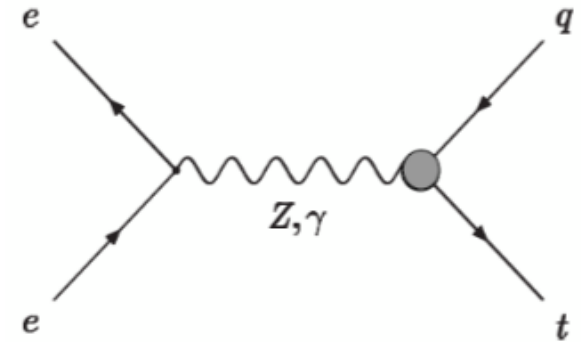
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \rightarrow Zu$	$7 \times 10^{-17}$	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \rightarrow Zc$	$1 \times 10^{-14}$	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \rightarrow gu$	$4 \times 10^{-14}$	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$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

# Large and pure 'MegaTop' sample good for FCNC

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

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

- FCNC tqZ and tq $\gamma$ : 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

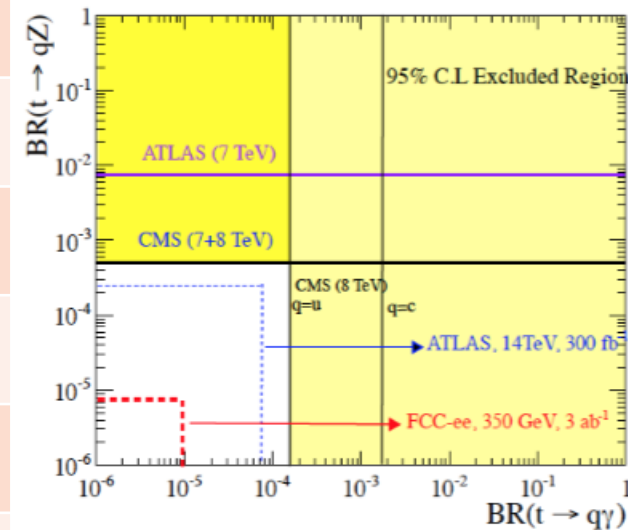


Clear distinction between tq $\gamma$  and t $\bar{t}$  in semileptonic final state

# Sensitivity FCNC: 95% CL exclusion limits

- Limits in all-hadronic and lepton+jets channel compatible

Sqrt(s) and lumi	240 GeV 100 fb <sup>-1</sup>	240 GeV 10 ab <sup>-1</sup>	350 GeV 3 ab <sup>-1</sup>
BR(t→qγ) all hadronic	1.43 × 10 <sup>-4</sup>	3.17 × 10 <sup>-5</sup>	
BR(t→qγ) semileptonic	-	2.01 × 10 <sup>-5</sup>	9.86 × 10 <sup>-6</sup>
BR(t→qZ) (σ <sub>μν</sub> ) All hadronic	1.86 × 10 <sup>-4</sup>	4.12 × 10 <sup>-5</sup>	
BR(t→qZ) (σ <sub>μν</sub> ) semileptonic	-	2.44 × 10 <sup>-5</sup>	1.41 × 10 <sup>-6</sup>
BR(t→qZ) (γ <sub>μν</sub> ) All hadronic	3.78 × 10 <sup>-4</sup>	8.22 × 10 <sup>-5</sup>	
BR(t→qZ) (γ <sub>μν</sub> ) semileptonic	-	5.02 × 10 <sup>-5</sup>	5.27 × 10 <sup>-5</sup>



FCC-ee expected to substantially improve beyond HL-LHC

# Summary

- **FCC-ee** great machine for precision measurements in the top quark sector
  - **Very high luminosity** up to  $2 \text{ ab}^{-1}$  (baseline:  $1 \text{ ab}^{-1}$ )
    - with  $0.5 \text{ pb}$   $t\bar{t}$  cross section
  - Different center-of-mass-energies (Z, WW, ZH,  $t\bar{t}$ ) possible
  - Properties and indirect BSM constraints competitive
  - Nb: FCC-ee precision can probe **scales up to 100 TeV**
    - **not discussed here, see M. Antonelli's talk**
  - 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
- Top couplings  **$t\bar{t}Z$**  and  **$t\bar{t}Y$**  can be measured to  **$\sim 1\%$  accuracy**
  - And substantial BSM sensitivity for Composite Higgs-like models
- Limits **FCNC** of order  $10^{-5} - 10^{-6}$

# Outlook

- Top physics = **Precision** physics with **BSM** sensitivity at **FCC-ee**
  - Many **opportunities** for interesting short (and not-so-short) studies for the FCC technical design report due **2018**
  - Ask me after the talk, we are always **happy to train interested physicists!**

**Thank you for your attention!**

# Backup

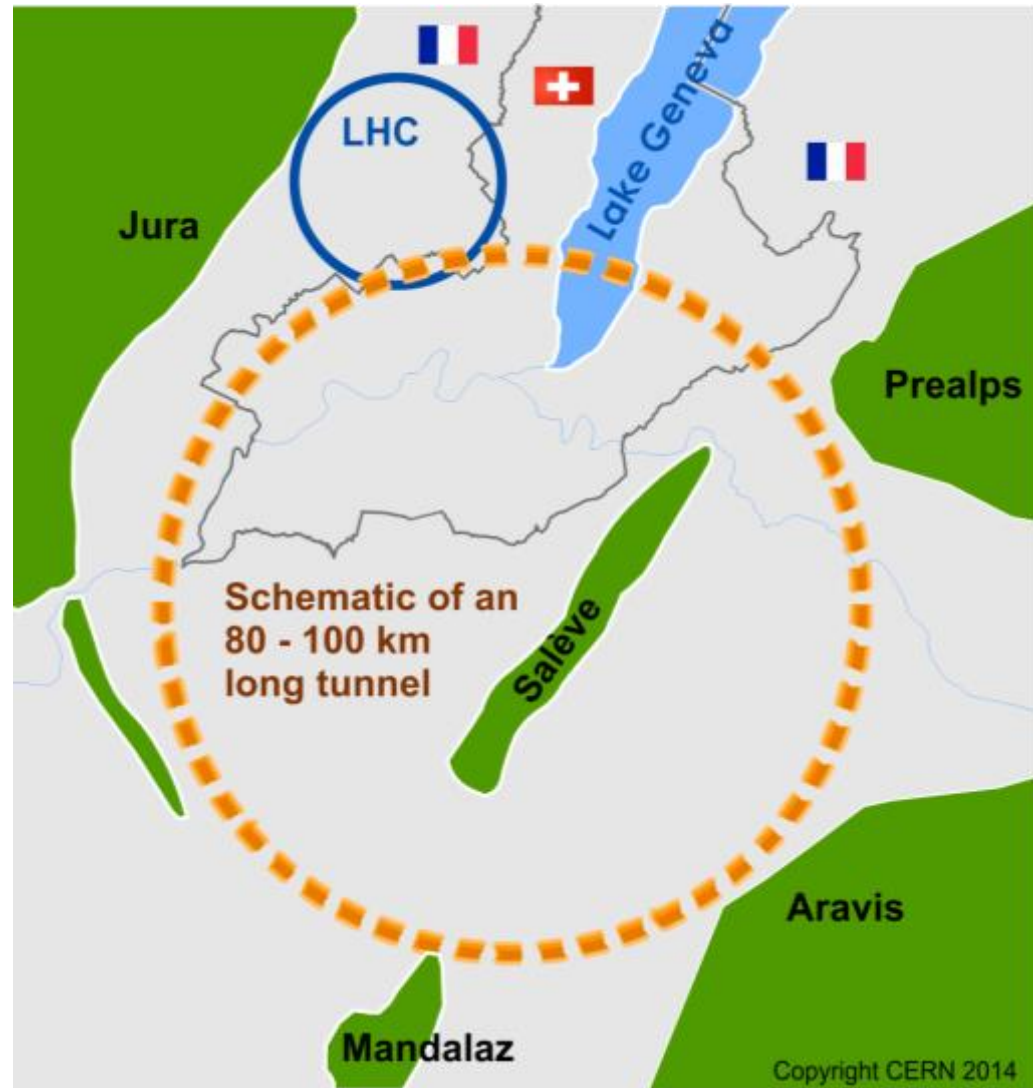
# Potential physics studies

- FCC-ee at  $2m_{\text{top}}$  350 GeV:
  - top **mass** measurement around threshold @350GeV
  - intertwined with mass but dedicated measurement could improve sensitivity:
    - top  $Y_t$  measurement
    - top **width**
  - **Rare** decays
  - **FCNC**
  - **Anomalous** couplings
  - Forward-backward asymmetry
- **Single top** physics @240GeV:
  - higher integrated luminosity will really help here
  - direct measurement  $V_{tb}$
  - **Anomalous** couplings **FCNC**
    - also @240 GeV
- Interference  $t\bar{t}/WbWb$  and single top production is open topic
  - needs further exploration and interaction with pheno group
- The case for 500 GeV run
  - direct extraction of  $Y_t$  from  **$t\bar{t}H$**
  - any other BSM signal to look for?

# FFC-ee -> FCC-hh

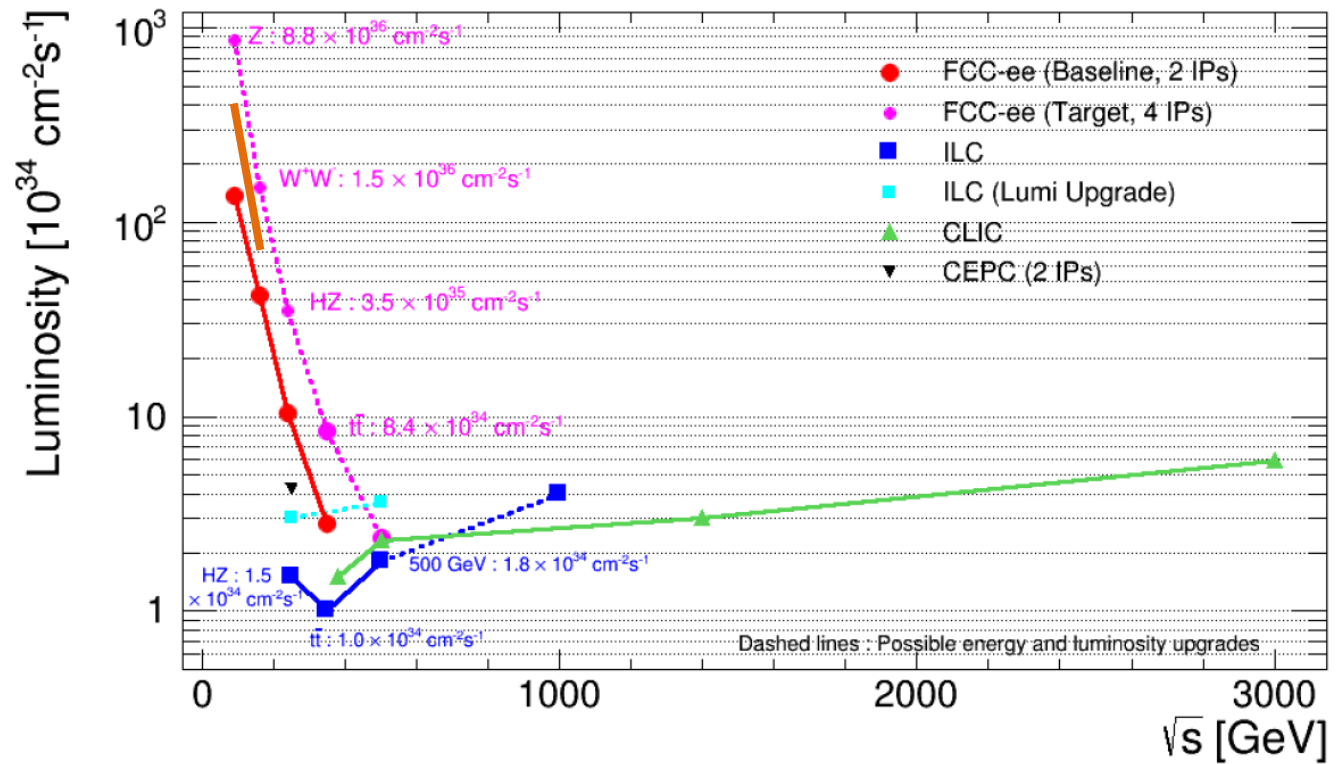
Forming an international collaboration to study:

- ***pp-collider (FCC-hh)***  
→ defining infrastructure requirements
- ***e<sup>+</sup>e<sup>-</sup> collider (FCC-ee)*** as potential first step  
ECM=90-400 GeV
- ***p-e (FCC-he)*** option
- **80-100 km infrastructure** in Geneva area



Provide highest possible luminosity from Z to tt by exploiting b-factory technologies:

- separate e- and e+ storage rings
- very strong focussing:  $\beta^* \gamma = 1 - 2$  mm (target, baseline -- work in progress!)
- top-up injection
- crab-waist crossing



Event statistics :

Z peak	$E_{\text{cm}}$ : 91 GeV	$5 \times 10^{12}$	$e^+e^- \rightarrow Z$	LEP $\times 10^5$
WW threshold	$E_{\text{cm}}$ : 161 GeV	$10^8$	$e^+e^- \rightarrow WW$	LEP $\times 2.10^3$
ZH threshold	$E_{\text{cm}}$ : 240 GeV	$10^6$	$e^+e^- \rightarrow ZH$	Never done
$t\bar{t}$ threshold	$E_{\text{cm}}$ : 350 GeV	$10^6$	$e^+e^- \rightarrow t\bar{t}$	Never done



# CERN Circular Colliders and FCC

