Top Physics @FCCee(TLEP): first thoughts on the challenges ahead

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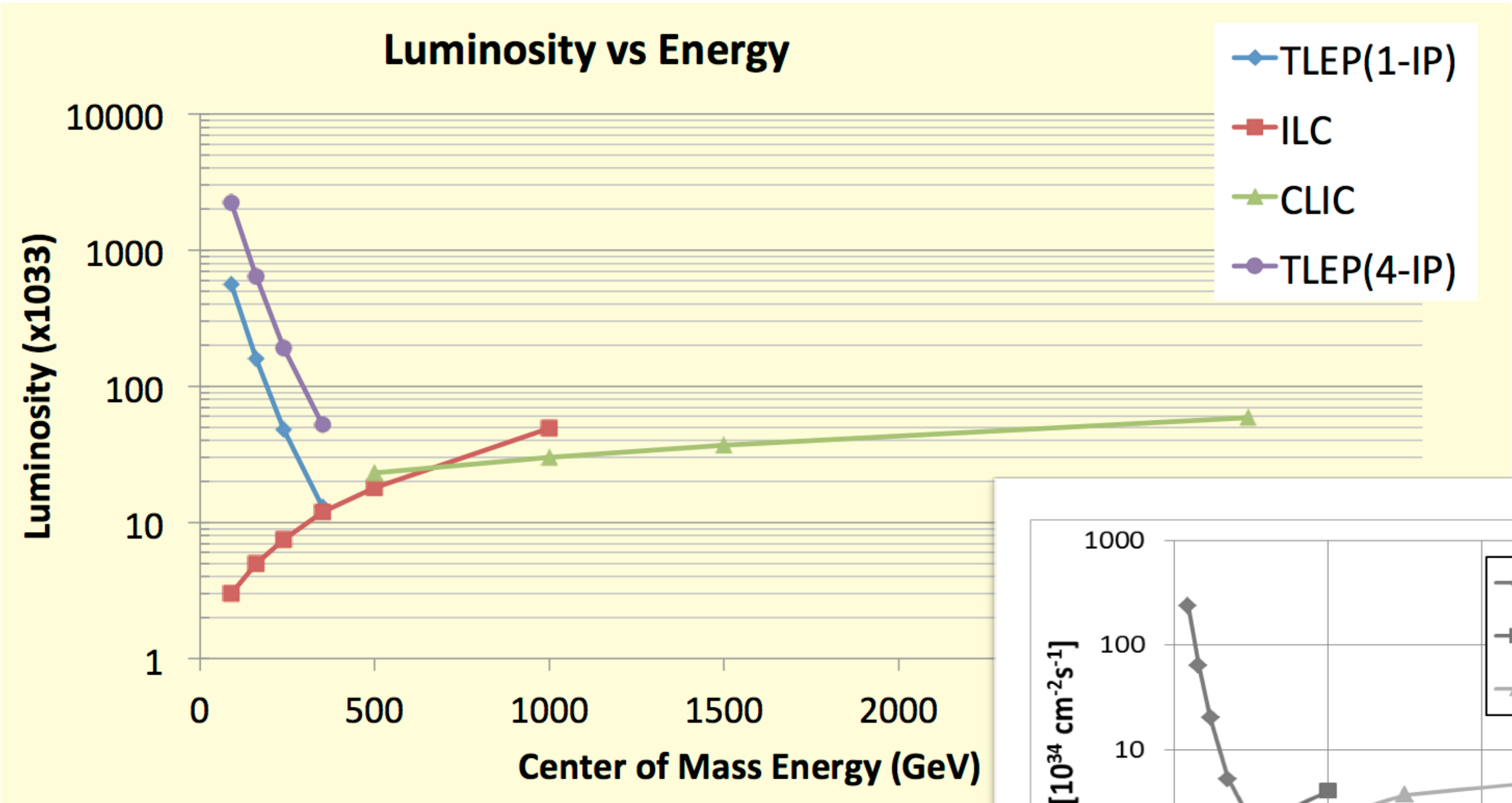
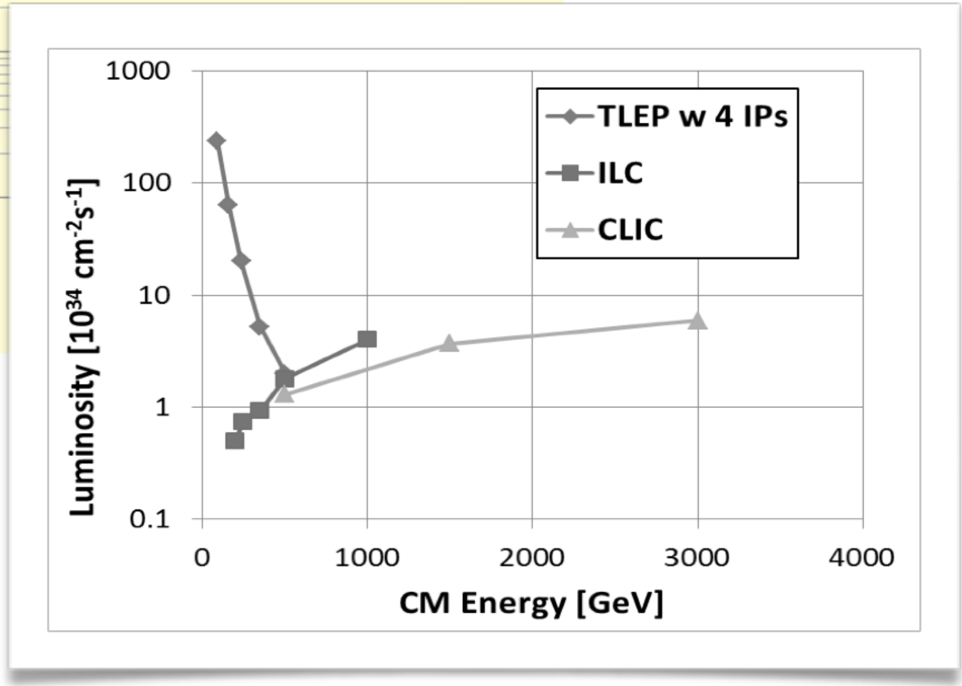
Energy and luminosity at FCCee





	Lumi / 5 years	# top pairs
TLEP	**4 × 650 fb^{-1}**	**1,000,000**
ILC	350 fb^{-1}	100,000

Possible upgrade to 500GeV?

the basics

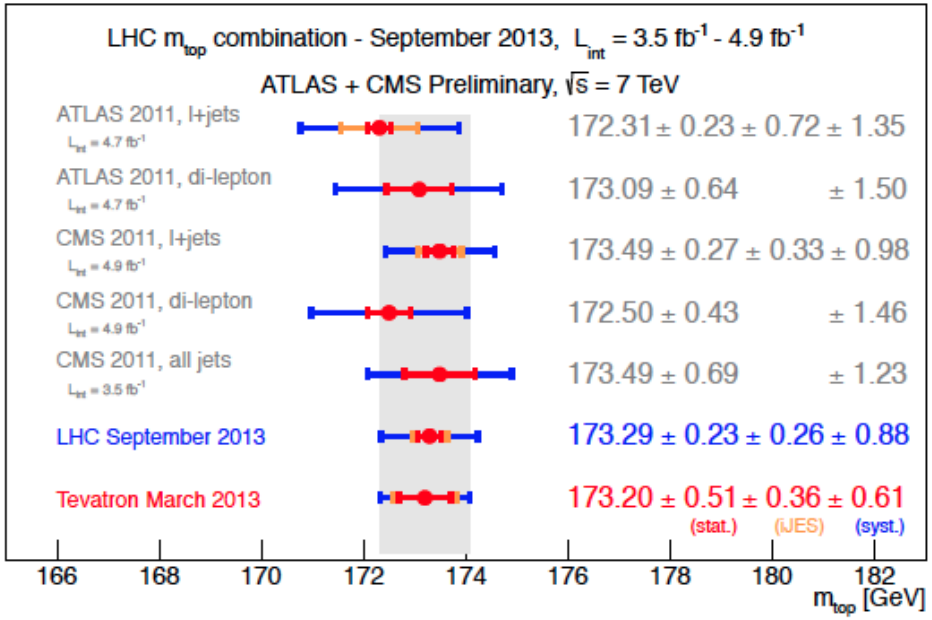
- plan to run for 5 years at the $t\bar{t}$ threshold
  - sqrt(s)=350 GeV, $L_{inst}=1.3\times10^{34}\ cm^{-2}s^{-1}$ at each IP
  - $130 fb^{-1}$ /year*IP
  - « Mega-Top » accumulated statistics
  - periodic returns at the Z peak (in TLEP-t conditions) for calibration
- NOTE: **effective duration of running at each energy** and the **order** is not fixed and it will depend on the physics needs and the advanced knowledge acquired in the next years
- Possible energy upgrades to sqrt(s)=500 GeV should be also considered.

	Lumi / 5 years	# top pairs
TLEP	**$4 \times 650\ fb^{-1}$**	**1,000,000**
ILC	$350\ fb^{-1}$	100,000

ILC-350 baseline

how is top physics doing now?

- FALSE myth! *« cannot do precision top physics at hadron colliders »*
- LHC experiments have shown that precision top physics can be achieved at a hadron collider:
  - a true top factory
  - very pure samples
  - impressive results
  - trampoline for BSM



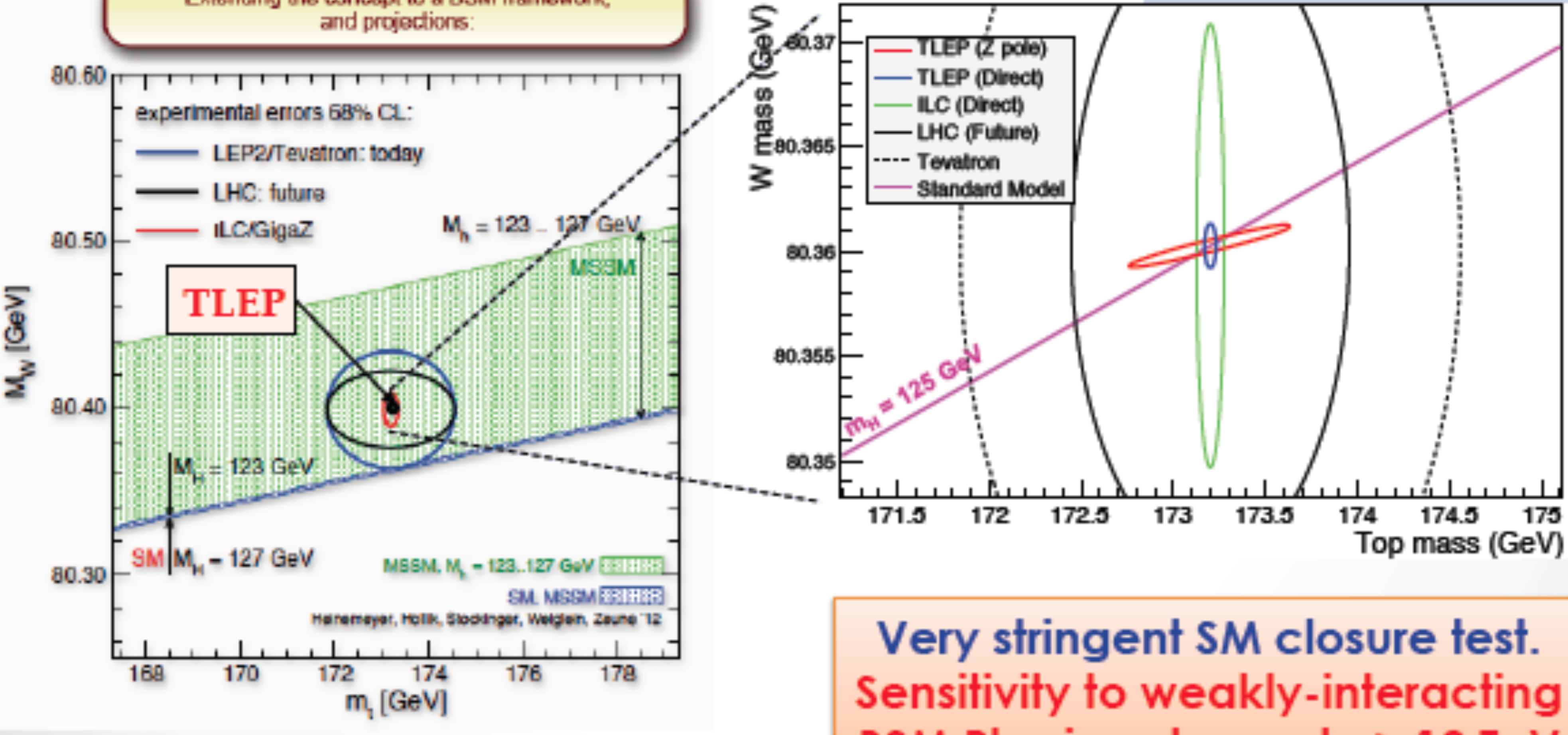
- top measurements now a « standard candle » for calibration: jet energy scale and b-tagging efficiencies!
- LHC-Run2 challenge: profit of the higher CM energy without suffering of the harsher running conditions: work in progress

but why? (I)

- When m_W, m_{top} and m_H are known with precision …
  - … The standard model has nowhere to go !

Extending the concept to a BSM framework, and projections:

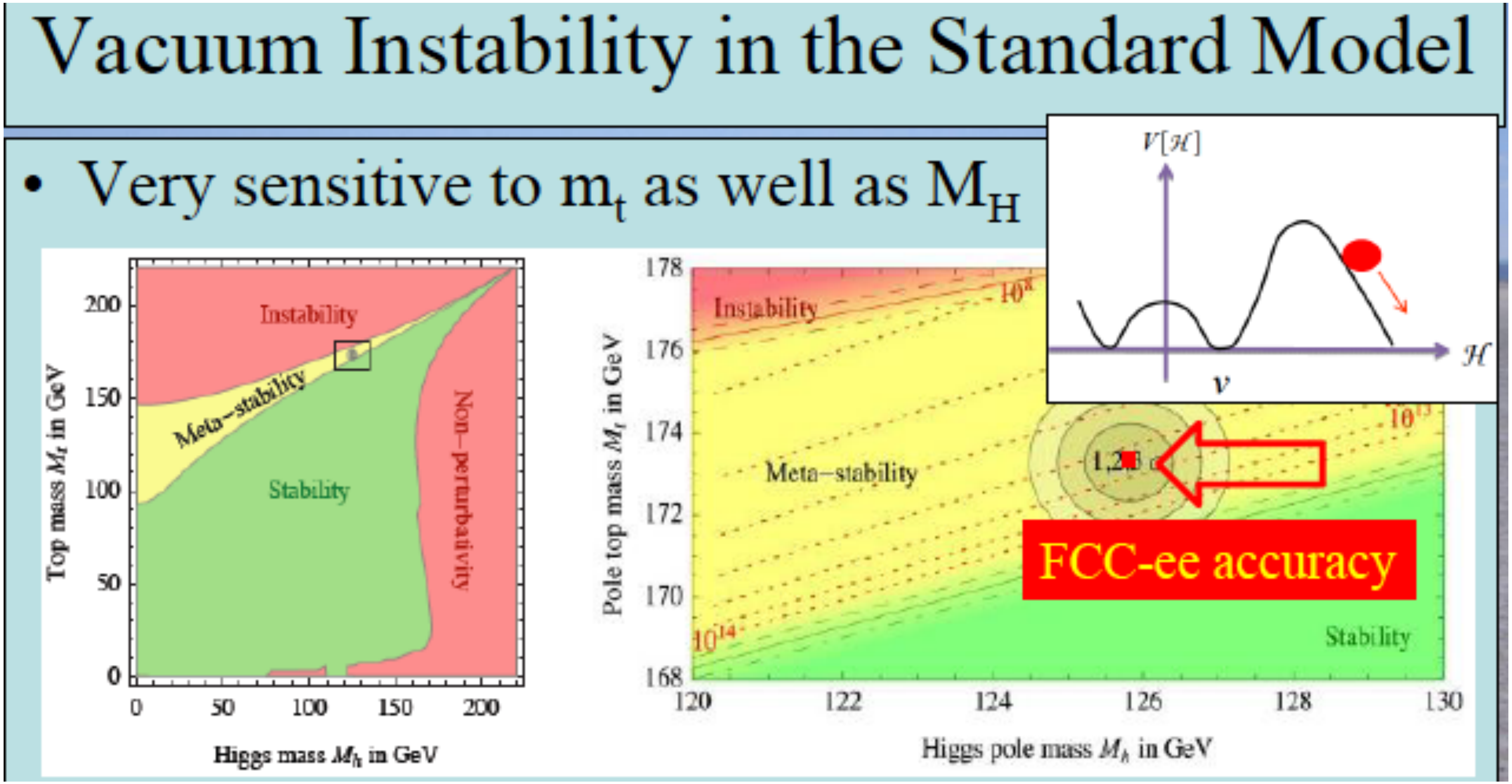
Obtained with Gfitter (matching theory uncertainties)



Very stringent SM closure test.
Sensitivity to weakly-interacting BSM Physics at a scale > 10 TeV

but why? (2)

- top mass is still a fundamental parameter: can tell us the fate of the Universe



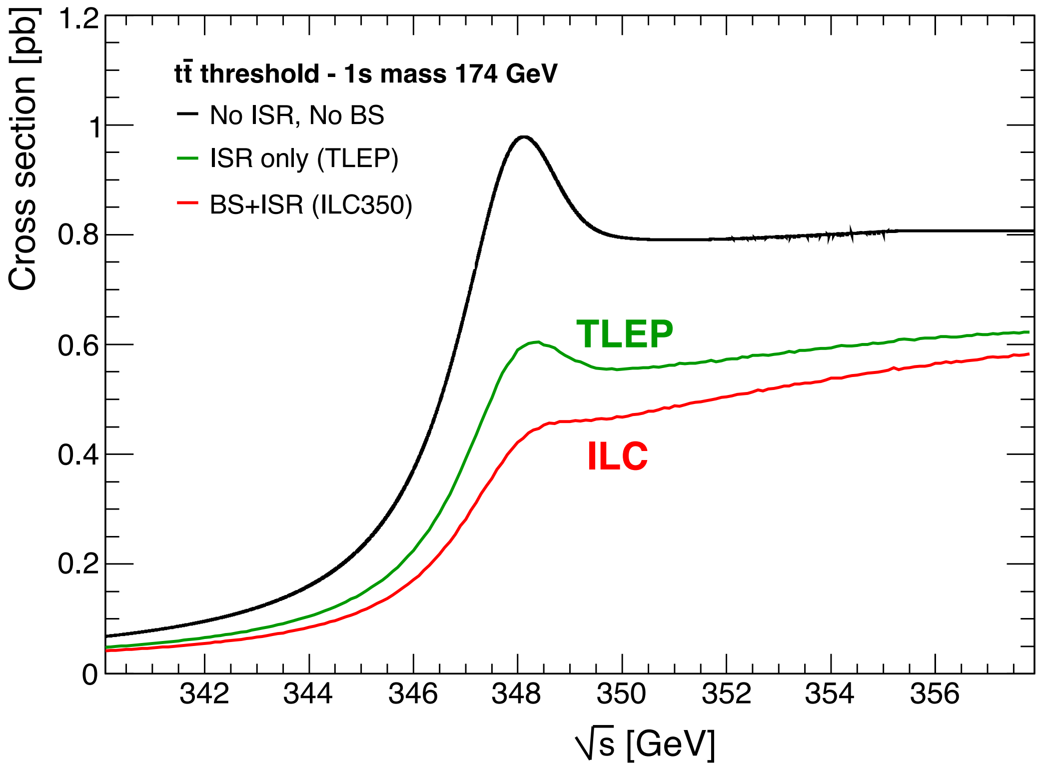
(stolen from J. Ellis, one of the most shown plots at this meeting…)

but why? (3)

- top as a portal to new physics effects: large statistics allows to probe rare decays and top (anomalous) couplings
  - possibility to see indirect effects from loop contributions
  - at FCCee no direct production of heavier objects
    - and given the actual experimental exclusion limits the possibility that other planned lepton colliders have a sufficient energy is very small
- *standing on the shoulder of LHC-Run2 results for all the new physics connections!*

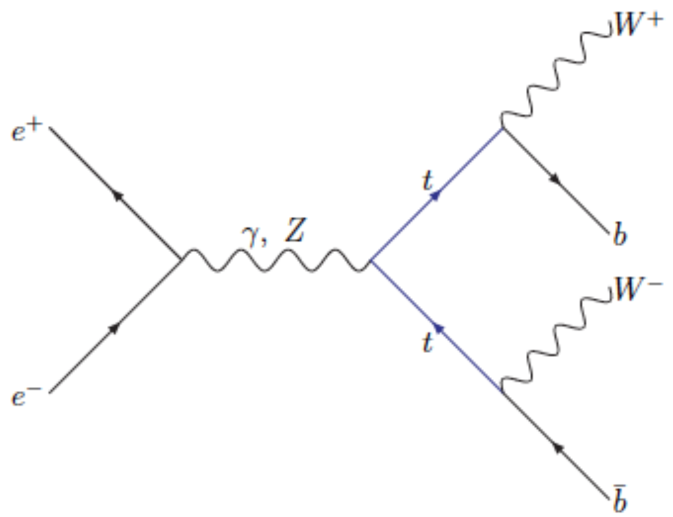
Experimental Conditions

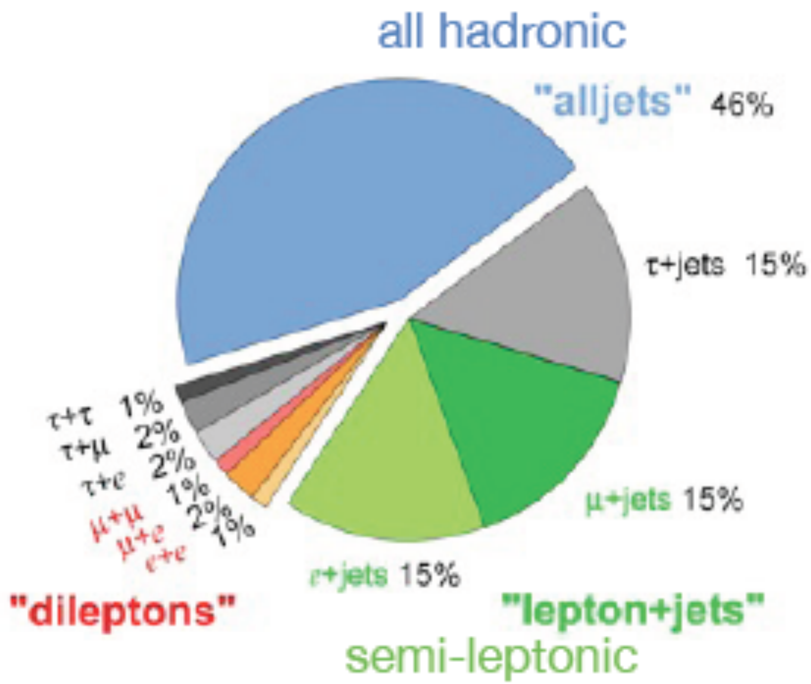
- Production cross section at threshold at NNLO
- the absence of beamstrahlung at TLEP (typical of linear collider configuration) has two effects:
  - enhances the steepness of the threshold profile
  - enhances the absolute value of the production cross section
- *Disclaimer: No studies are available yet for TLEP and the results and (the few) extrapolation here are taken from previous literature (from ILC, CLIC, TESLA, etc).*



Production & decay

- analysis driven by production and decays modes
  - at threshold pair production dominates
  - at lower energies can enhance also the single production wrt to background

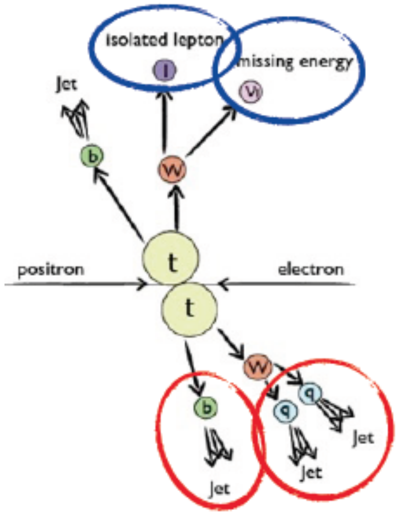




  - ~100% BR in Wb
  - final states classified on the basis of the W decay

Analysis & Detector requirements

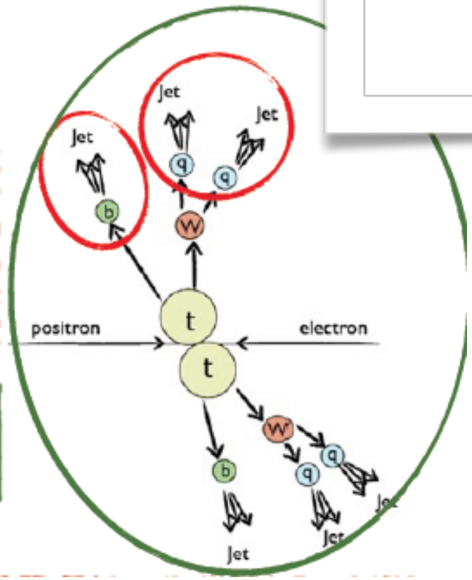
- Strategy depends on targeted ttbar final state



Semi-leptonic:
- isolated lepton ID, momentum measurement
- missing energy measurement

Universal
- Flavor tagging:
  - b - identification
  - b/c separation
- b-Jet energy measurement
- light Jet reconstruction & energy measurement

All-hadronic
- global hadronic energy reconstruction



type	final state	σ 500 GeV	σ 352 GeV
Signal (m_{top} = 174 GeV)	$t\bar{t}$	530 fb	450 fb
Background	WW	7.1 pb	11.5 pb
Background	ZZ	410 fb	865 fb
Background	$q\bar{q}$	2.6 pb	25.2 pb
Background	WWZ	40 fb	10 fb

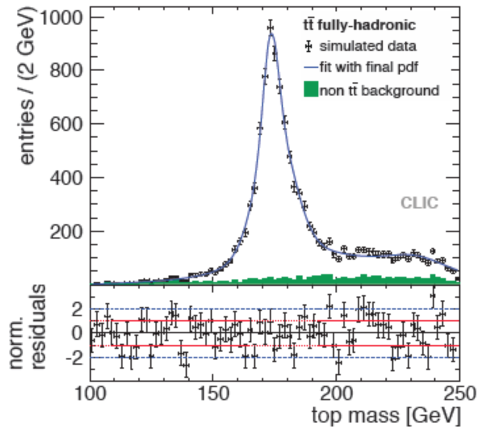
from CLIC study

slide taken
from F. Simon
« top studies@CLIC »

- as detector requirements are concerned the top reconstruction and identification would not make stronger requirement than the Higgs physics program already demands.
- possibly, in the case of a single top program (never discussed before) there would be higher concern about fwd object reconstruction (but this again is also part of the Higgs needs)
- plus no QCD multijet background here

Which mass to measure?

- 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
- **« @threshold »: unique at lepton collider, easier experimentally**
  - it is a counting experiment
  - clearly theoretically connected to a theoretically well defined mass



	Ref.[13]	Projections				
CM Energy	7 TeV	14 TeV				
Luminosity	$5 fb^{-1}$	$100 fb^{-1}$		$300 fb^{-1}$		$3000 fb^{-1}$
Pileup	9.3	19	30	19	30	95
Syst. (GeV)	0.95	0.7	0.7	0.6	0.6	0.6
Stat. (GeV)	0.43	0.04	0.04	0.03	0.03	0.01
Total, GeV	**1.04**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**

reco mass extrapolation @LHC

	Lumi / 5 years	# top pairs	Δm_{top}
TLEP	4×650 fb^{-1}	1,000,000	10 MeV
ILC	350 fb^{-1}	100,000	30 MeV

threshold method

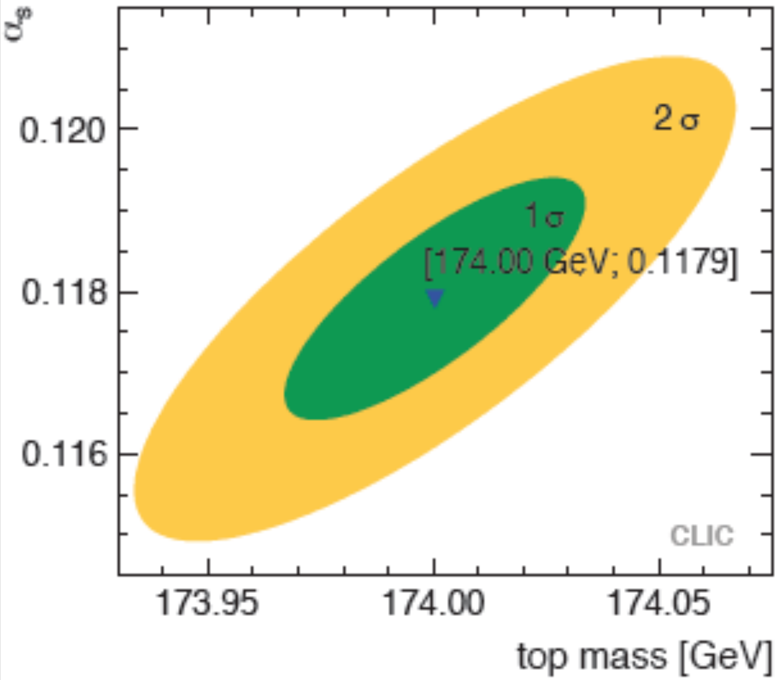
systematics!

- statistics is clearly not the issue at TLEP.
- Two main systematics on the threshold measurement:
  - Beam energy measurement: need to know beam energy to a fraction of MeV.
  - can use the precision Z mass measurement from the Z pole. or better the m(W) and WW measurements?
    - With $3{\times}10^{7}$ Z(γ) events (Z e^+e^-, $\mu^+\mu^-$) / experimentt at TLEP(W)
    - With $2{\times}10^{6}$ Z pairs and $5{\times}10^{6}$ Z(γ) events (Z e^+e^-, $\mu^+\mu^-$) / expt at TLEP(H)
    - Can reach combined statistical precision on E_{beam} of 0.3 MeV and 0.4 MeV
- αs : can profit of the measurement with Tera-Z (if it comes first in run planning) or can do a simultaneous fit

2D fit to m_{top} and α_s

Measuring Top Mass and Strong Coupling

from CLIC



- 2D template fit to cross section

1S top mass and α_s combined 2D fit	
m_t stat. error	34 MeV
m_t theory syst. (1%/3%)	5 MeV / 8 MeV
α_s stat. error	0.0009
α_s theory syst. (1%/3%)	0.0008 / 0.0022

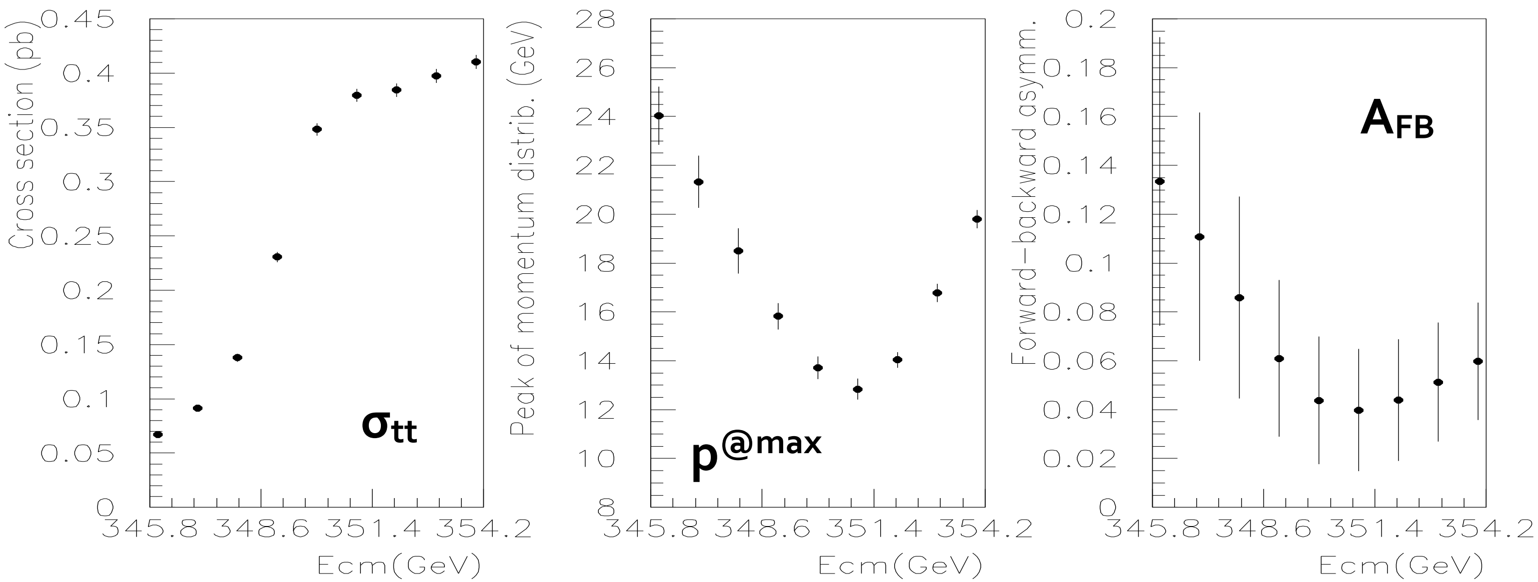
- Alternative: 1D fit - Taking α_s as input with current WA uncertainties

$$\Delta m_t = (\pm 22 \text{ (stat)} \pm 20\ (\alpha_s)\ \pm 18 / 56 \text{ (theory 1\%/3\%)}) \text{ MeV}$$

Differences to ILC due to different luminosity spectrum small:
10% to 20% reduction of statistical uncertainties

other methods

- other methods proposed for ILC: properties of decay kinematics in threshold scan
- simultaneous fit of observables (σ_{tt}, A_{fb} and <p@max>) sensitive to m_{top}, Γ_{top} and λ_{top} from study with ILC
    - scaled to the TLEP case (there is no beamstrahlung bkg and higher luminosity)

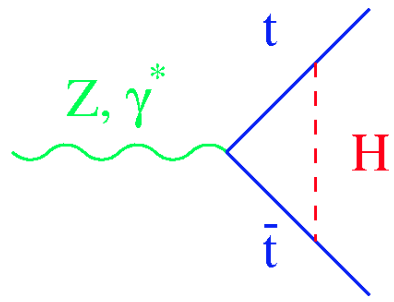


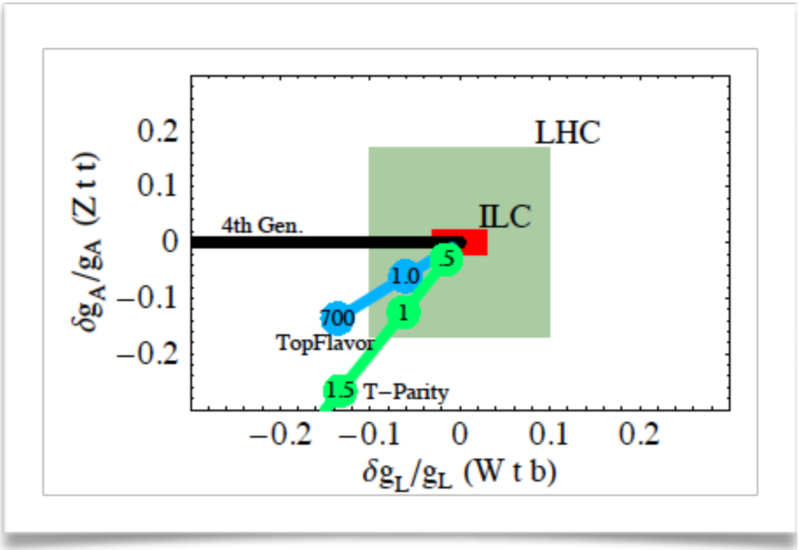
	Lumi / 5 years	# top pairs	Δm_{top}	$\Delta\Gamma_{top}$	$\Delta\lambda_{top}/\lambda_{top}$
TLEP	4 × 650 fb^{-1}	1,000,000	10 MeV	12 MeV	13%
ILC	350 fb^{-1}	100,000	30 MeV	35 MeV	40%

*from M. Martinez and R. Miquel, Eur. Phys. J. C27, 49 (2003), hep-ph/0207315.

Couplings

- λ_{top}: indirect measurement via threshold scan of 13%(30%) TLEP(ILC-indirect)
    - [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} (ILC, Snowmass 2005)
- ttZ/ttγ: measurable with excellent precision at e+e- collider.
    - expect about one order of magnitude better than LHC
    - TLEP expected combined better due to higher statistics
    - Question: do we really need polarization to disentangle the two???





this plot (from 2005!) is now outdated, but its part of the homework!

rare decays: the gold mine!

FCC hh ee he

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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.

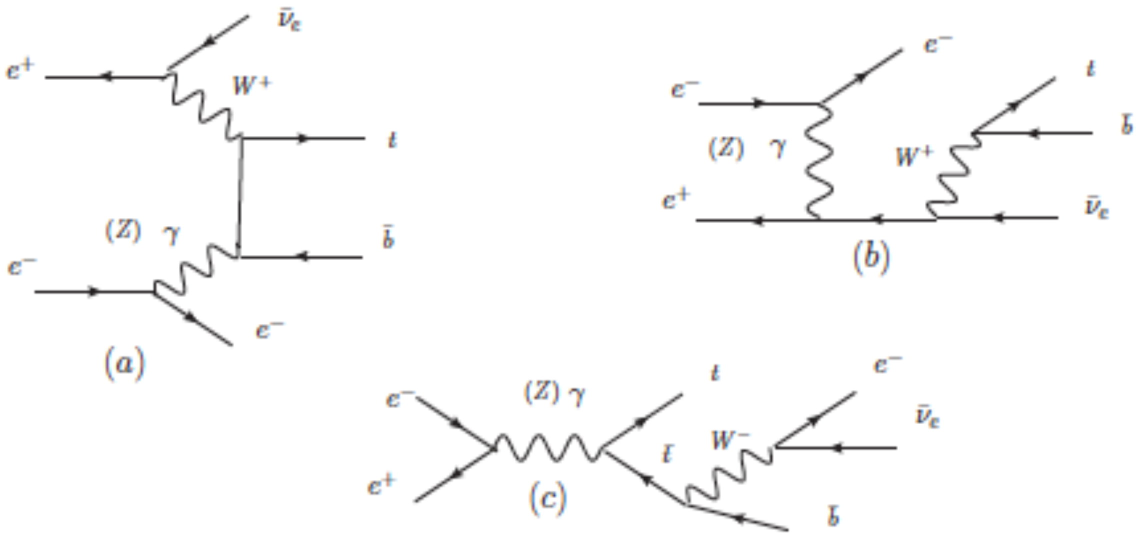
extrapolations

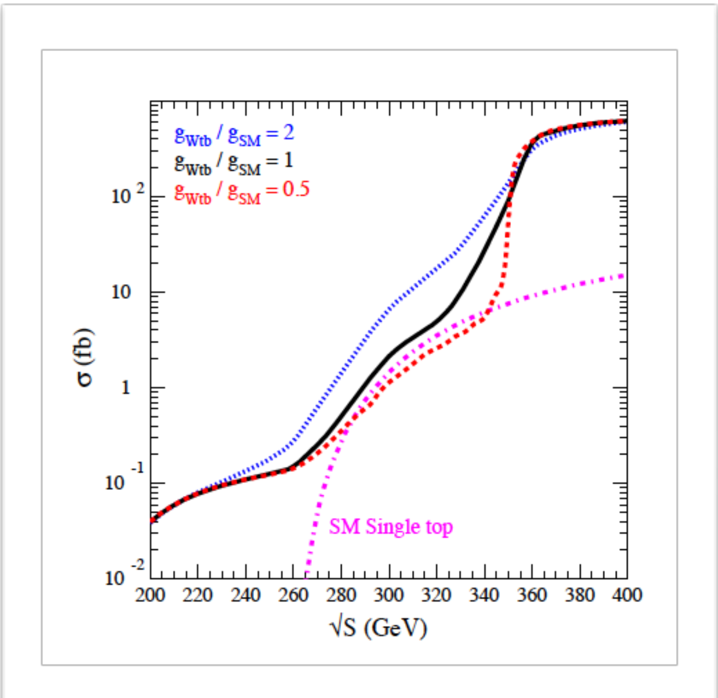
t->Zq, γq, Zc

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

single top production?

- just a couple of words…not seen much of this in literature anymore.
- the single top case could make use of different running energies:
  - could use the run at the Higgs or energies in between for g_{tWb}
- needs to be added to the things to study!





inclusive rate

for e^+e^- —>WbWb

time to get to work?

- the proposed FCCee machine and its « Mega-Top » program seems an ideal place for the study of precision top physics. Outcome could span from cornering the standard model for good to finding new physics, or at least defining its scale.
  - the Top physics chapter should cover at least all that was shown here and possibly more?
- first actions on my to-do list:
  - get a co-convener(s) to share the fun
  - define few subgroups with specific topics
  - define interaction with other (sub)groups
  - important! analysis framework to start the studies: collaboration with Offline/Software
- not the biggest interest group for now, but why? this is so much fun!
  - would be good to build on the previous experience and have synergy also with hh colliders studies
  - contact me! (also for comments/questions/suggestions…)

Measurements/topics

- Mass (various reconstruction methods) & Γ_t
- couplings: λ_t , g_{tWb}, $g_{Ztt/\gamma tt}$
- decay kinematics
- rare decays
- measurements with single top
- running energy optimization
- Study and define the requirements on:
  - machine
  - theory
  - detector
  - reconstruction