3rd Single Top Workshop Strasbourg 2-3 June 2016

The future of Top Physics measurements: why - what - and how well?

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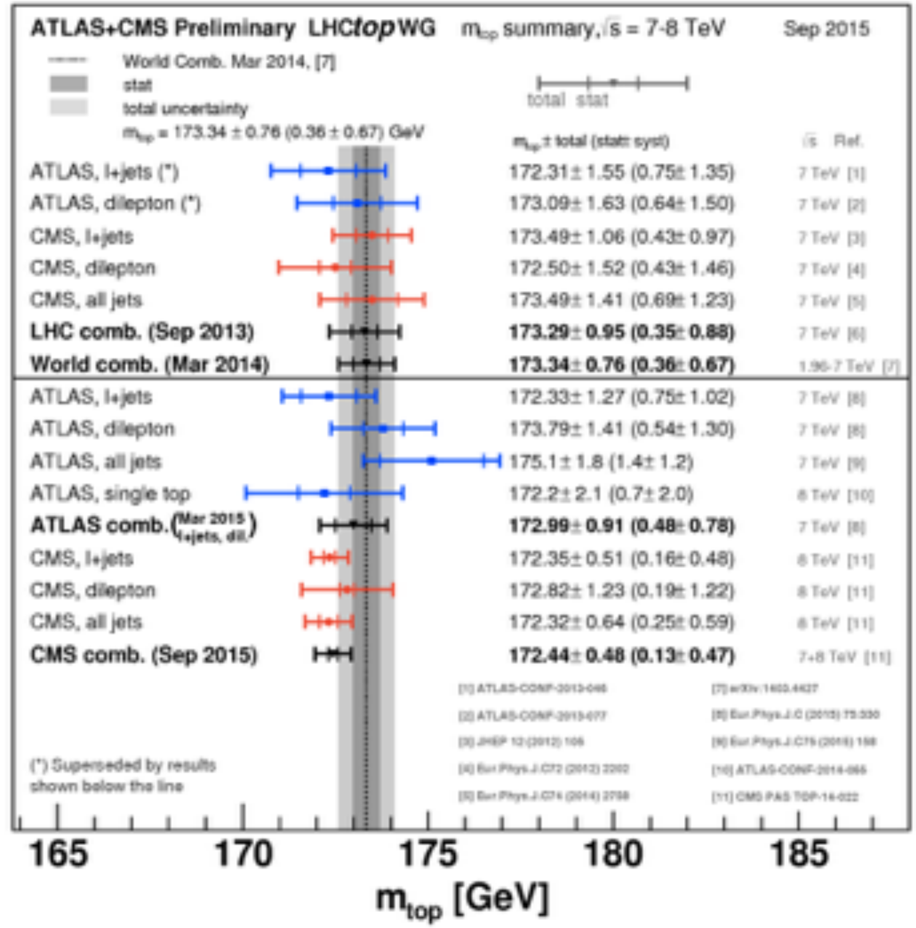
*thanking all my colleagues whose slides I have shamelessy stolen:
M. Vos, MLM, M. Selvaggi, B. Fuks, M. Najafabadi*

how is top physics doing now?

INFN Istituto Nazionale di Fisica Nucleare

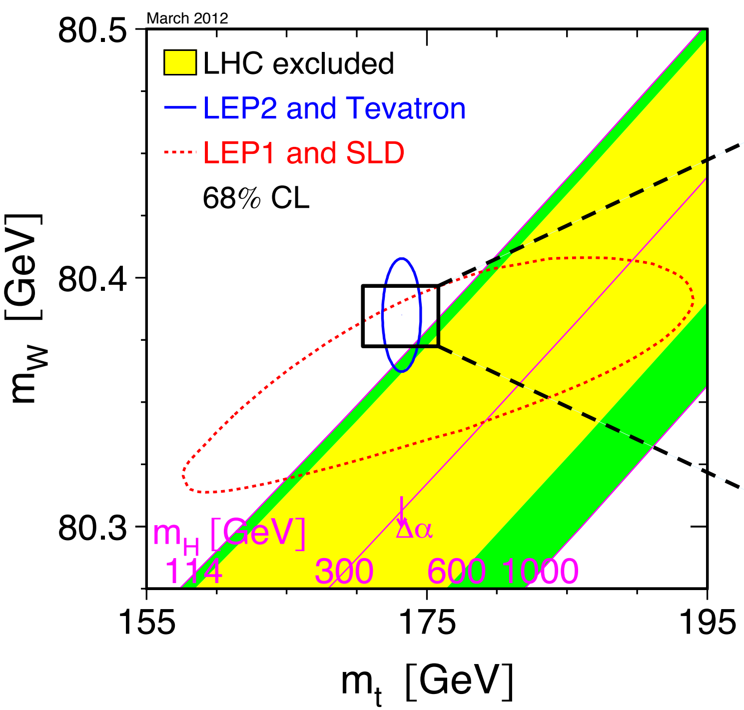
- Tevatron and LHC experiments have shown that *precision top physics can be achieved at a hadron collider*:
  - a true top factory
  - very pure samples
  - impressive results
  - trampoline for BSM
- top measurements now a « standard candle » for calibration: jet energy scale and b-tagging efficiencies!

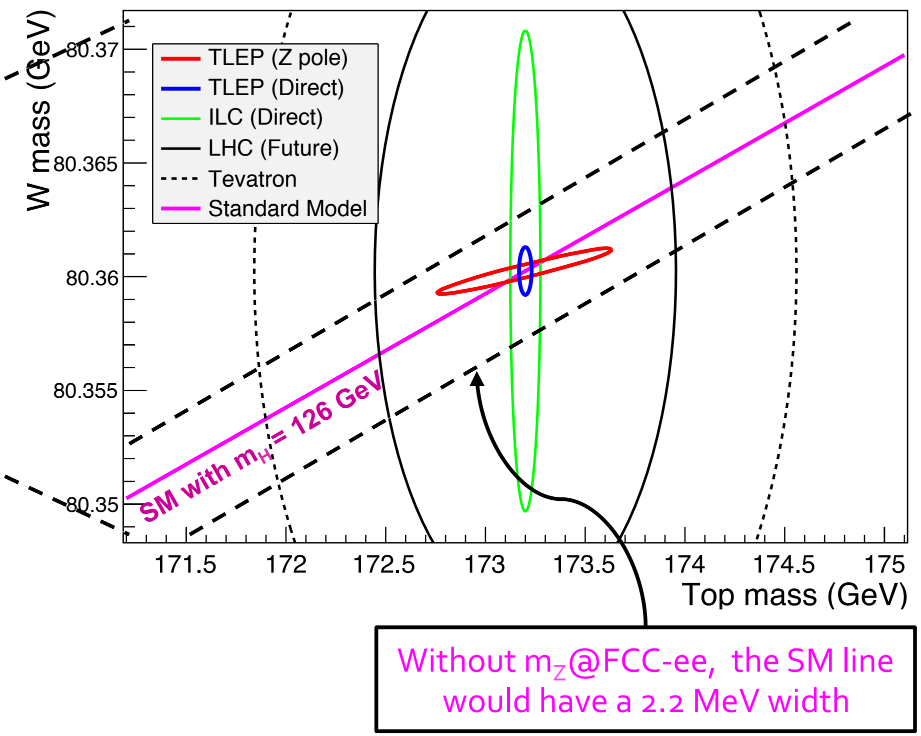


- LHC-Run2 challenge: profit of the higher CM energy without suffering of the harsher running conditions. work in progress!

why? (I)

- **In absence of New Physics the m_{top} vs m_W plot would look like this:**

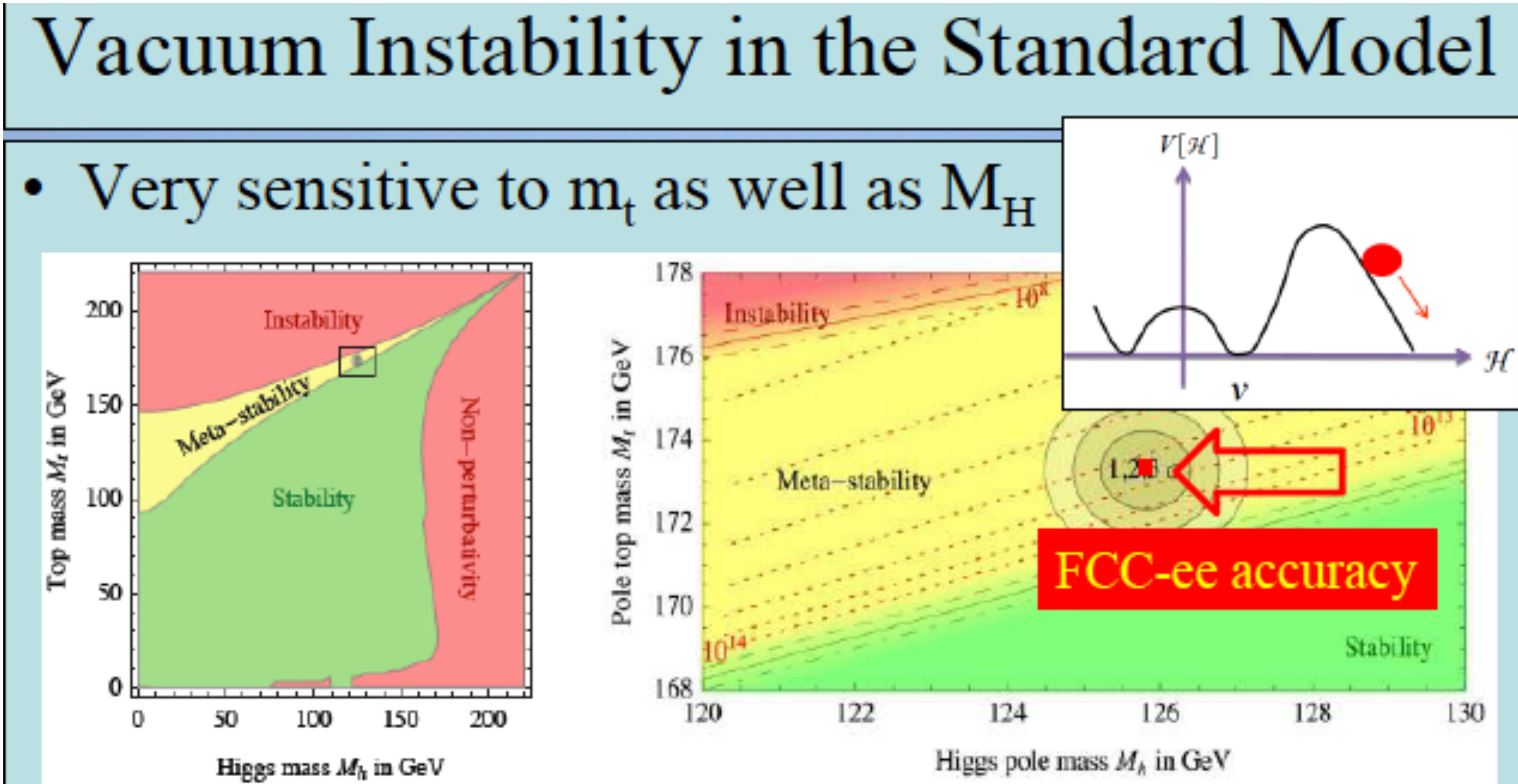




- **Constraints on new physics ?**

why? (2)

- **top mass can tell us the fate of the Universe**



why? (3)

- **top as a portal to new physics:**
  - rare decays and FCNC processes
  - top (anomalous) couplings
  - indirect effects from loop contributions
  - precision study of kinematic properties
  - associated production with other objects (i.e. tt+Z/W/H/DM etc)
  - resonances or other new particles decaying in tt

- *standing on the shoulder of LHC-Run2 results for all the new physics connections!*

What ? (the shopping list)

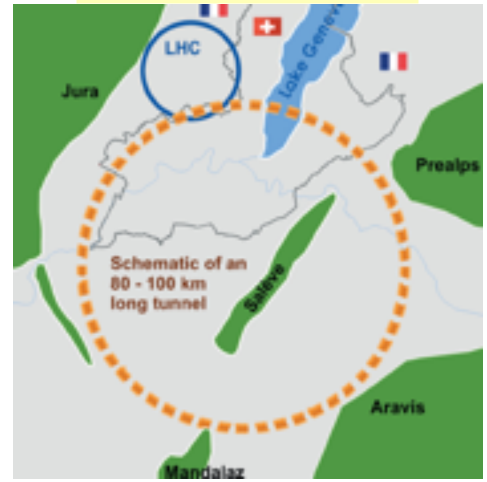
- Mass (various reconstruction methods) & Γ_t
- couplings: λ_t , g_{tWb}, $g_{Ztt/\gamma tt}$
- rare decays & FCNC
- asymmetries
- measurements with single top
- tops in the initial state (top_{PDF})
- physics with/of (hyper-)boosted tops

idea is to identify which future machines would satisfy the requirements to perform the desired studies and achieve the needed precision

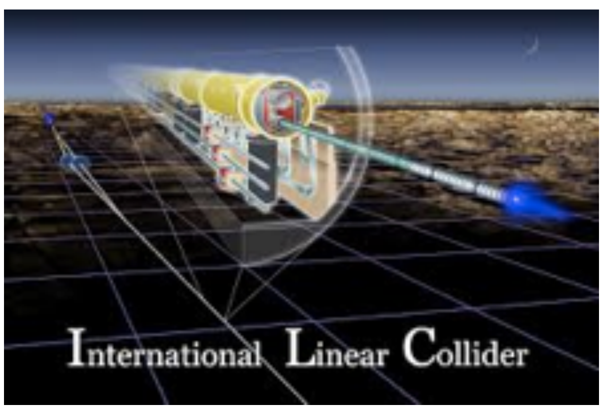
The future colliders

High Luminosity LHC

FCC(CERN)



ILC(Japan)



CLIC(CERN)

CEPC-SPPC(China)

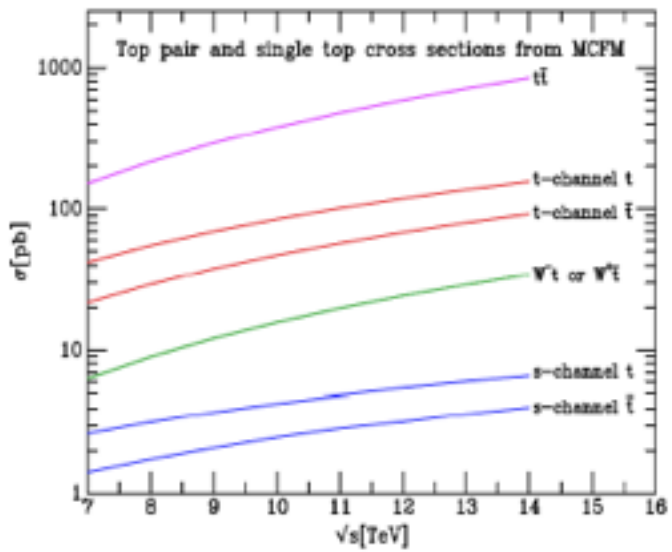
top@HL-LHC

Large number of tops @ LHC, 10x more @ HL-LHC !

$\sqrt{s}=14$ TeV   3 ab^{-1}

$\sigma_{t\bar{t}}$	~ 1 nb	→	3B top pairs
$\sigma_{t\text{-channel}}$	~ 200 pb	→	600M tops
σ_{tW}	~ 75 pb	→	200M tops
$\sigma_{s\text{-channel}}$	~ 10 pb	→	30M tops
$\sigma_{tt\gamma/V/H}$	~ 1 pb	→	3M top pairs
σ_{tZ}	~ 100 fb	→	300k tops
σ_{tH}	~ 10 fb	→	30k tops

Adelman et. al [1309.1947]



HL-LHC is great laboratory for doing high precision top physics   4

top@FCC-hh

10 ab^{-1} at 100 TeV imply:

$\sigma_{tt} \sim 30$ nb

10^{12} top quarks => 5 10^4 x today

=> 10^{12} W bosons from top decays ⇒ rare W decays

=> 10^{12} b hadrons from top decays (particle/antiparticle tagged)

=> 10^{11} $t \rightarrow W \rightarrow$ taus ⇒ rare decays $\tau \rightarrow 3\mu$, $\mu\gamma$, CPV

=> few x10^{11} $t \rightarrow W \rightarrow$ charm hadrons
⇒ rare decays $D \rightarrow \mu^+\mu^-$, ..., CPV

The possibility of detectors dedicated to top physics (more in general, to final states in the 0.1 - 1 TeV region deserves, e.g. for Higgs physics) deserves very serious thinking

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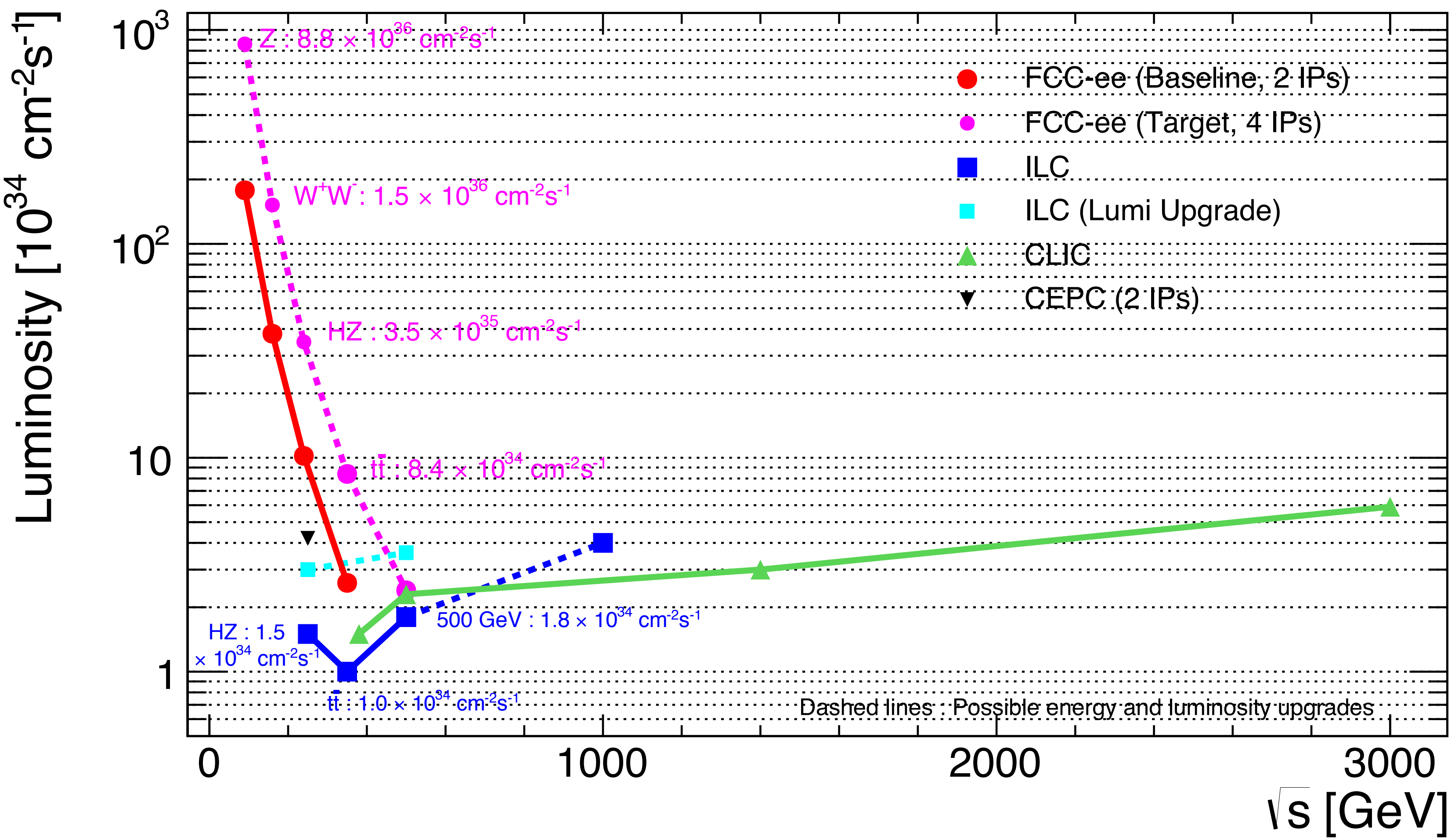
Future lepton colliders Luminosity



Unprecedented precision: a challenge also to theory expectations

Which mass to measure? (1)

- The methods that can be employed for the mass reconstruction are characterized by different experimental and theoretical issues and uncertainties:

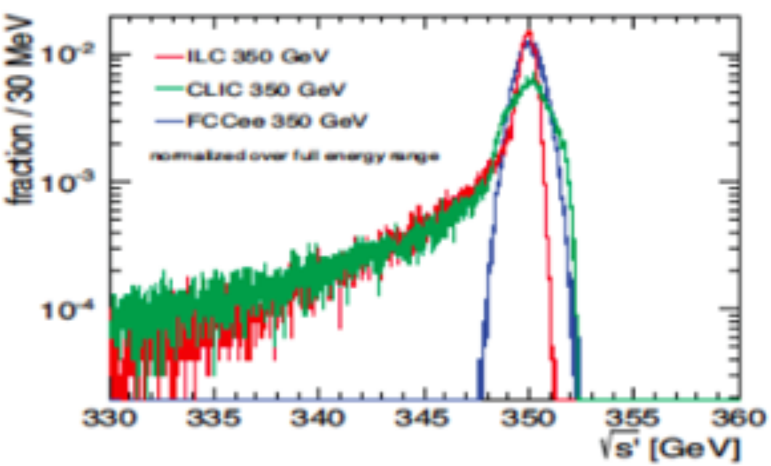
- « Reconstructed » mass: from a fit of the decay products in the various channels.
    - Most precise way (for now) at hadron colliders. Has the problem of being correlated with the real « pole » mass in a way that brings in significant theoretical uncertainties
    - for the lepton collider case this method can be used above threshold (using ttγ or ttj)
    - at lepton collider could obtain precision of ~80MeV (CLIC study) $\sqrt{s}$=500 GeV, 500fb-1

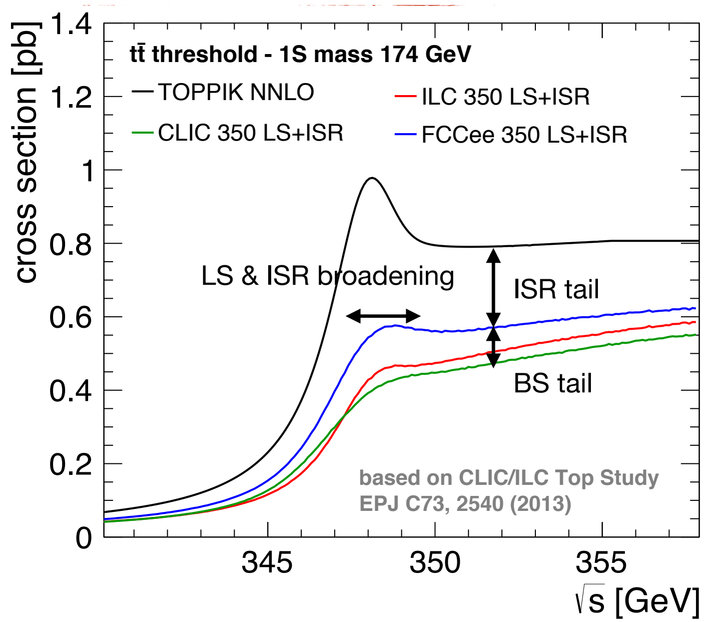
	Current	Future		
Center-of-mass energy	7 TeV l+jets	13 TeV	14 TeV	14 TeV
Integrated luminosity	5 fb^{-1}	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
Fit calibration	0.06	0.03	0.03	0.03
b-JES	0.61	0.27	0.09	0.03
Residual JES	0.28	0.28	*0.2*	*0.06*
Lepton energy scale	0.02	0.02	0.02	0.02
Missing transverse momentum	0.06	0.06	0.06	0.06
Jet energy resolution	0.23	0.23	*0.2*	*0.06*
b tagging	0.12	0.06	0.06	0.06
Pileup	0.07	0.07	0.07	0.07
Non-$t\bar{t}$ background	0.13	0.06	0.06	0.06
Parton distribution functions	0.07	0.04	0.04	0.04
Renormalization and factorization scales	0.24	0.12	0.12	*0.06*
ME-PS matching threshold	0.18	0.09	0.09	*0.06*
Underlying event	0.15	0.15	0.15	*0.06*
Color reconnection effects	0.54	0.27	*0.2*	*0.06*
Systematic	0.98	0.60	0.44	0.20
Statistical	0.43	0.15	0.05	0.01
Total	1.07	0.62	0.44	0.20

FTR-13-017

Which mass to measure? (2)

- « threshold scan»: unique at lepton collider.
  - easier experimentally, it is a counting experiment
  - well connected to a theoretically well defined mass
- Two main systematics on the threshold measurement:
  - Beam energy measurement: need to know beam energy to a fraction of MeV.
    - @ILC: beam energy (30MeV), Lumi spectrum (10MeV), non res contribution(30MeV)
    - @FCC-ee: $\sigma(E_{beam})$=0.3 MeV, from Z pole, or 0.4 MeV (from m(W) and WW)
  - αs : profit of the measurement with Tera-Z (FCC-ee) , or can do a simultaneous 2D fit (ILC)
- With 1M top expect ~10-20 MeV stat uncertainty on M(top) at FCC-ee.





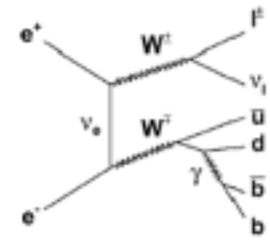
Planning to perform full sim analysis this Summer!

Single top background at ILC

Challenge: selection

Top quark pair production...

...Single top quark production...



...WWγ/Z/h...

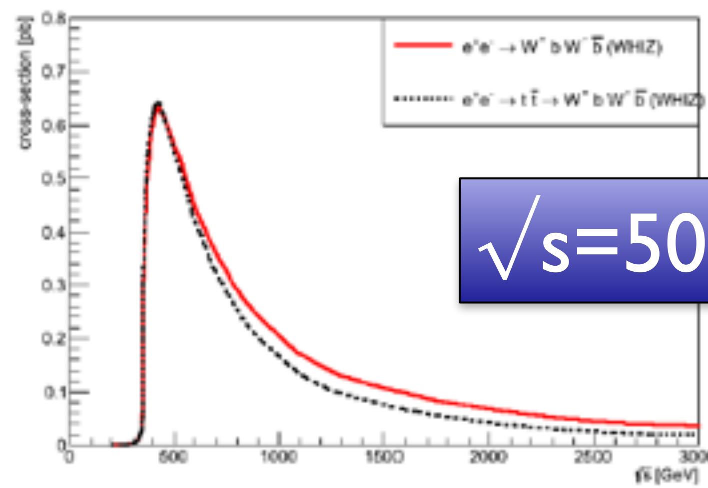
Maximum x-section for pair production ~0.6 pb
peak well above threshold ~ 420 GeV
Drop in (s-channel) cross-section at higher √s
partially compensated by higher luminosity

$e^+e^- \rightarrow WbW\bar{b} \rightarrow$ 6 fermions is "contaminated" by single top production:

- 380 GeV: ~5%
- 500 GeV: ~9%
- 3 TeV: ~50%

As far as we can (at 500 GeV) single top is ~indistinguishable from pair production

See: Garcia, Perello, Ros, Vos, Study of single top production at high energy electron-positron colliders, arXiv:1411.2355

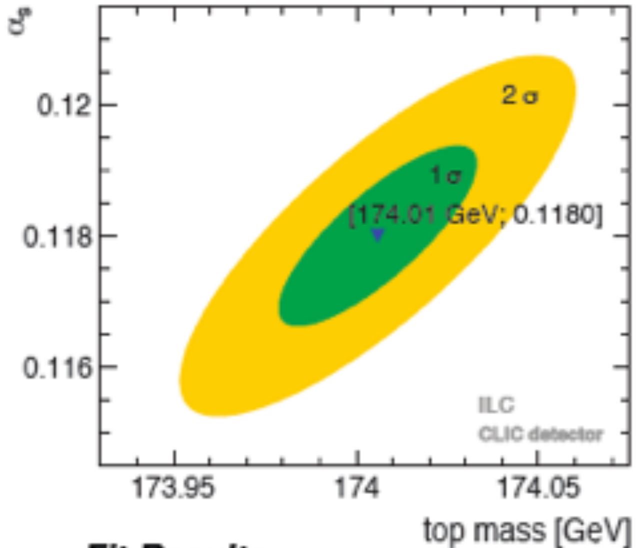


√s=500 geV

Must measure rate and properties of WbWb production. For a precise comparison of data and prediction more theory work is needed!

Behind precision, CERN, feb. 2016 Marcel Vos (marcel.vos@ific.uv.es)

2D fit to m_{top} and α_s



- 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

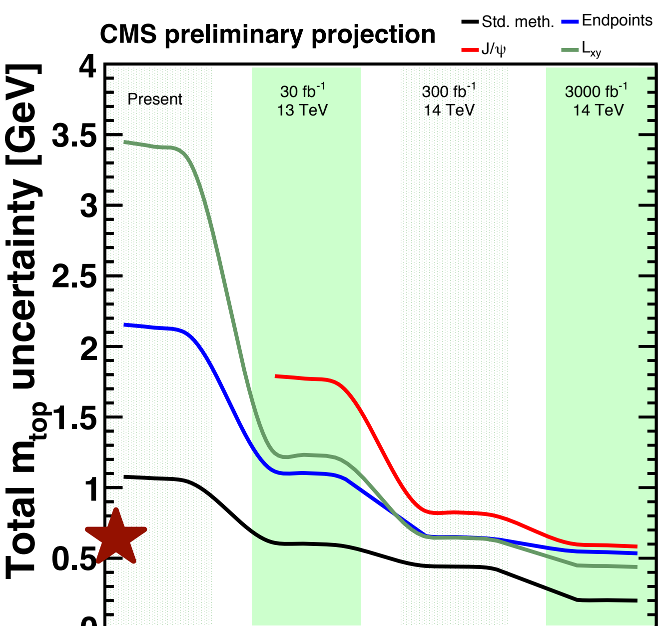
Frank Simon (fsimon@mpp.mpg.de) 14

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

Which mass to measure ? (3)

Gain with statistics!

- « Alternative methods »:
  - obtain a measurement using sensitive variables that allow to better solve the connection between m_{top}^{MC} and theory one m_{pole} or similar
  - right now statistically limited but profit fully of the HL-LHC statistic and theory improvements



	Current	Future		
Center-of-mass energy	7 TeV	13 TeV	14 TeV	14 TeV
Integrated luminosity	5 fb^{-1}	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
Jet energy scale and resolution	1.6	0.9	0.5	0.3
Lepton energy scale	0.4	0.2	0.2	0.2
Jet and lepton efficiencies	0.2	0.2	0.2	0.2
Fit range	0.6	0.2	0.2	0.2
Background shape	0.5	0.2	0.1	0.02
QCD effects	0.6	0.3	0.3	0.3
Pileup	0.1	0.1	0.1	0.1
Systematic	1.9	1.0	0.6	0.5
Statistical	0.9	0.4	0.1	0.04
Total	2.1	1.1	0.6	0.5

M(lb) end-point extrapolation (CMS)

	Ref. analysis	Projections				
CM Energy	8 TeV	14 TeV			33 TeV	100 TeV
Luminosity	$20 fb^{-1}$	$100 fb^{-1}$	$300 fb^{-1}$	$3000 fb^{-1}$	$3000 fb^{-1}$	$3000 fb^{-1}$
Theory (GeV)	-	1.5	1.5	1.0	1.0	0.6
Stat. (GeV)	7.00	1.8	1.0	0.3	0.1	0.1
Total	**-**	**2.3**	**1.8**	**1.1**	**1.0**	**0.6**

« J/psi method » extrapolation (CMS)

Measuring Γ_t

- The top quark width is difficult to measure directly at LHC: however a 2% determination can be useful to constrain new models that predict new particles in top decays.
- At the LHC indirect (new) measurement (CMS: arXiv:1404.2292) from Run1:

  $\Gamma[t]=1.36 \pm 0.02$ (stat.) $+0.14/-0.11$ (syst.) GeV

$$\Gamma_t = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(t\to Wb)} \cdot \frac{\Gamma(t\to Wb)}{\sigma_{t\text{-ch.}}^{\text{theor.}}},$$

- Expected improvement down to 5% at HL-LHC
- However direct measurements down to few % possible with top-pair threshold scan at lepton colliders from simultaneous fit of observables (σ_{tt}, A_{fb} and <p@max>) sensitive to m_{top}, Γ_{top} and λ_{top} u

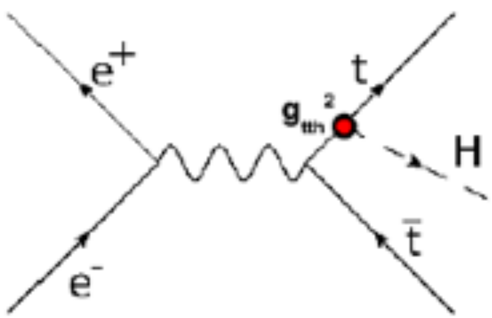
		# top pairs	Δm_{top}	$\Delta\Gamma_{top}$	$\Delta\lambda_{top}/\lambda_{top}$
FCCee		1,000,000	10 MeV	12 MeV	13%
ILC		100,000	30 MeV	35 MeV	40%

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

Top Yukawa Coupling

ttH at the ILC

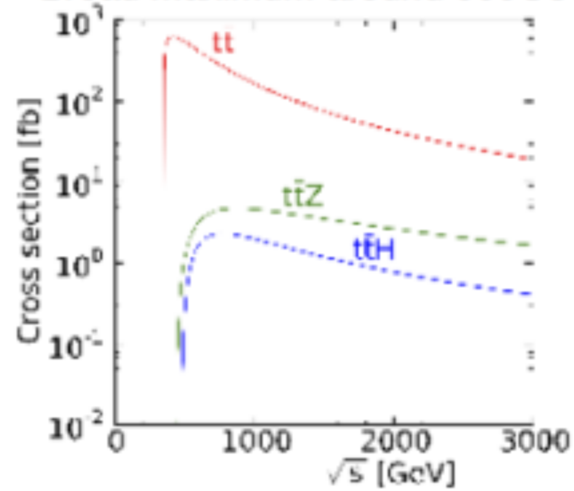
The top Yukawa coupling g_{tth} can be measured directly



$$\frac{\Delta g_{ttH}}{g_{ttH}} = c \cdot \frac{\Delta\sigma}{\sigma}$$

No Higgsstrahlung: c = 0.50
ILC 1 TeV: c = 0.52
CLIC 1.4 TeV: c = 0.53

Broad maximum around 800GeV



About 4% precision on the top Yukawa coupling achievable with 1ab^{-1}

Collider	LHC		ILC	ILC	CLIC
CM Energy [TeV]	14	14	0.5	1.0	1.4
Luminosity [fb^{-1}]	300	3000	1000	1000	1500
Top Yukawa coupling κ_t	(14 – 15)%	(7 – 10)%	10%	4%	4%

from arXiv:1311.2028

Talk by Ph.Roloff at TopLC 2015 - Valencia

ILC: arXiv:1506.05992

√S	350 GeV	500 GeV	+1000 GeV
$L_{nominal}$	200 fb^{-1}	+500 fb^{-1}	+2 ab^{-1}
$\delta h_t/h_t$	20%	18%	3.1%

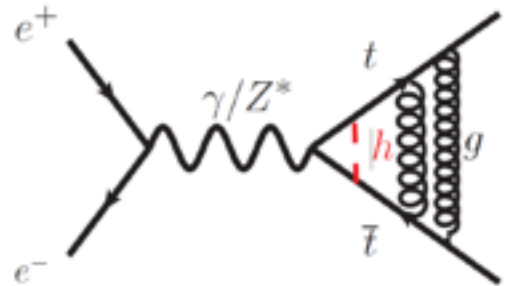
Top Yukawa @threshold

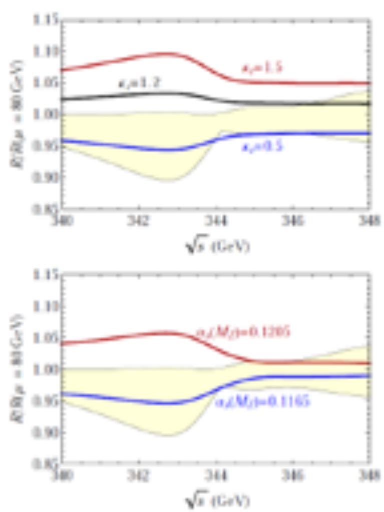
- New calculation, needs to be checked. Good for FCCee

Ishikawa et al., arXiv:1310.0563:
consider several observables (σ, A_{FB}, p)
two polarizations, 220 fb^{-1} in total
extract properties from simultaneous fit

- ΔM ~ 16 MeV
- ΔΓ ~ 21 MeV
- Δy ~ 4.2 %

} Stat. Uncertainty only





Enhancement of 9%
~ independent of √s... no shape information...

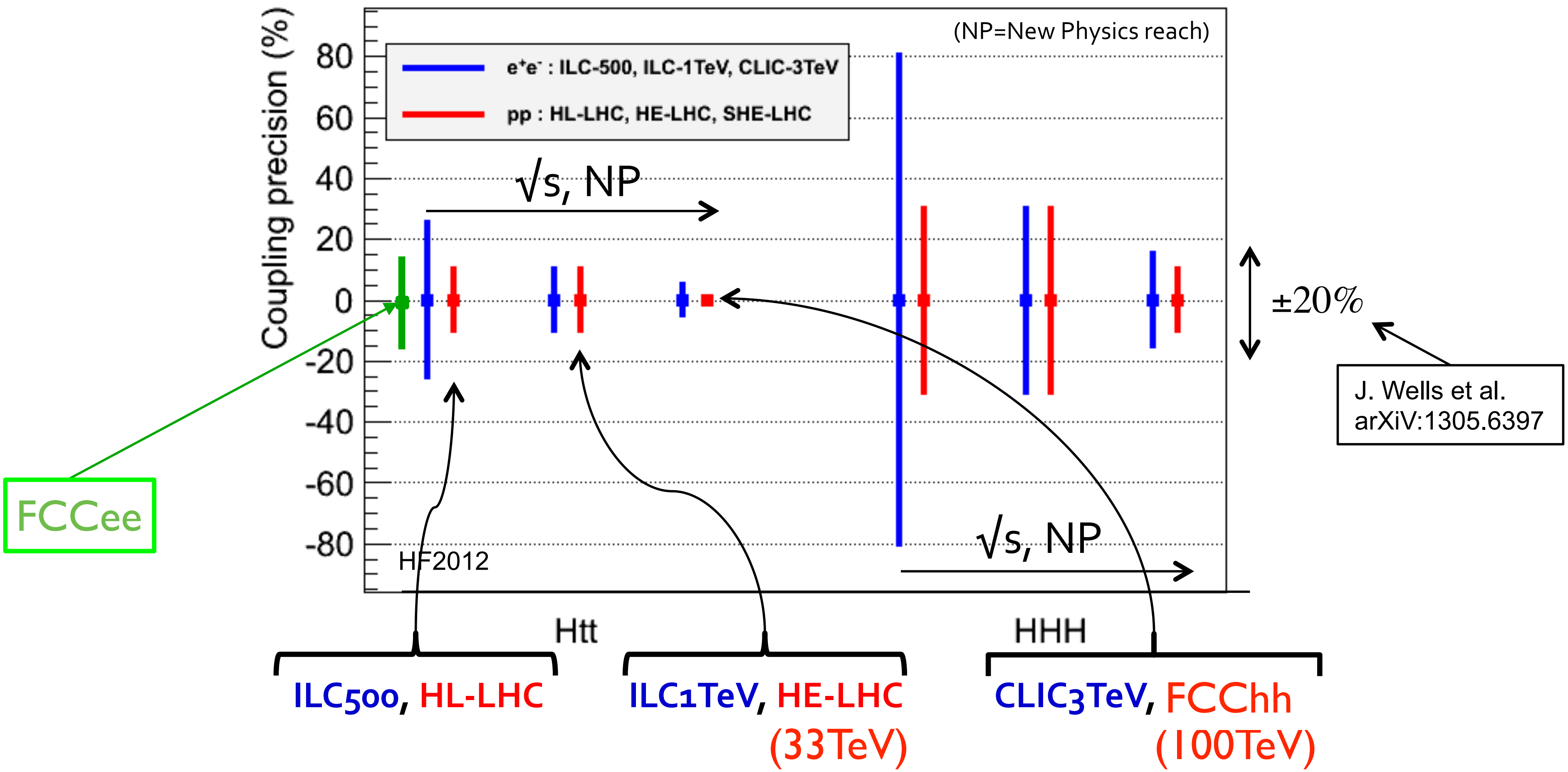
Feature is nearly degenerate with α_s
Have to assume very good α_s
NNNLO uncertainty approx. 3%
Theory uncertainty today: 18%

Beneke et al., Nucl. Phys. B899 (2015) 180-193: "Our results show that once theoretical uncertainties are taken into account, it is unlikely that such a high precision [i.e. 4.2%] can be achieved."

eb. 2016 Marcel Vos (marcel.vos@ific.uv.es) 19

Top Yukawa @hadron colliders

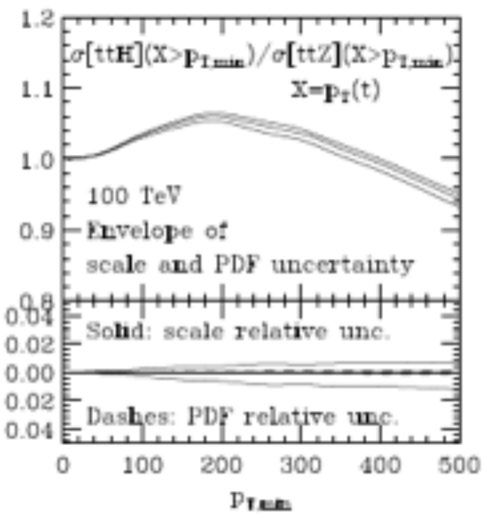
- usually shown in the context of H precision

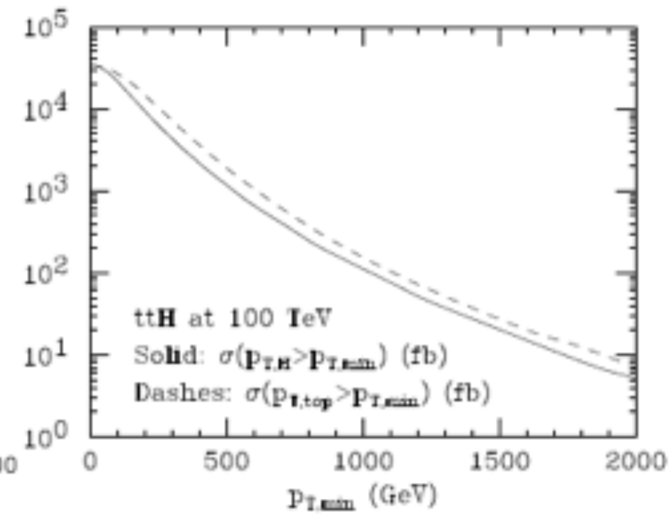


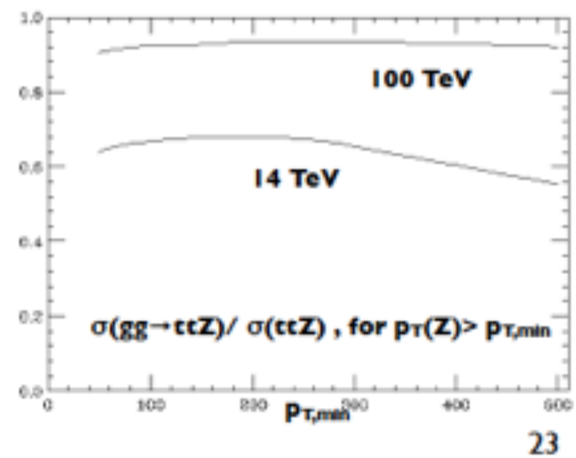
Top Yukawa @FCChh

At 100 TeV:

- greater dominance of gg initial state w.r.t. 14 TeV ⇒ ttH closer to ttZ
- huge production rates (ttH rate@100 TeV ~ 60 x ttH rate@14 TeV)
- large rate at very high $p_T(H)$ and $p_T(top)$ ⇒ effective use of boosted techniques, reduced combinatorial bg, systematics)
- access to "clean" final states ($H\to\gamma\gamma$, $H\to WW^*$)







1% precision on y_{top} within reach
(assuming $B(H\to bb)$ known)
arXiv:1507.08169

Top EWK couplings

measure

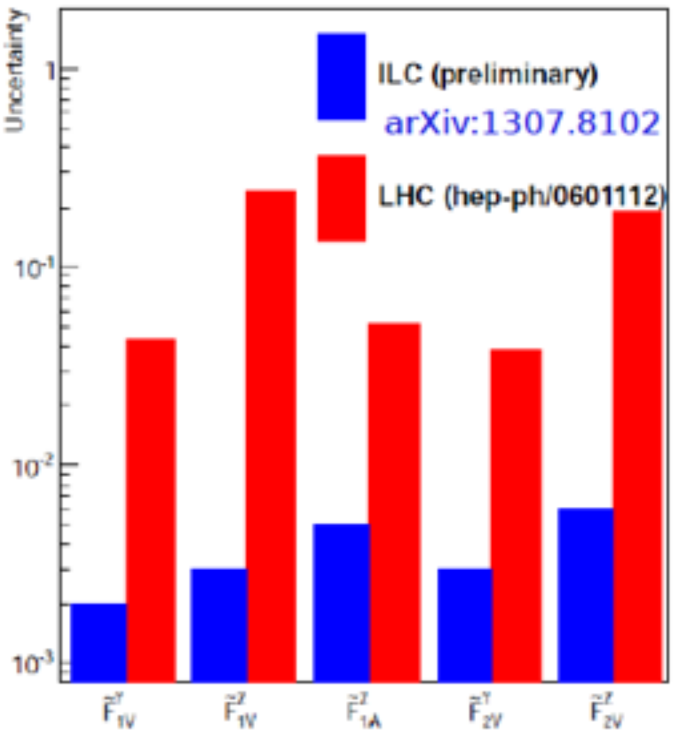
$\sigma(+)\quad A_{FB}(+)$
$\sigma(-)\quad A_{FB}(-)$

extract

$$\left.\begin{matrix}(+=e^-_R)\\(-=e^-_L)\end{matrix}\right\}\Rightarrow\left\{\begin{matrix}F^{\gamma}_{1V} & * & F^{\gamma}_{2V}\\ F^{Z}_{1V} & F^{Z}_{1A} & F^{Z}_{2V}\end{matrix}\right\}$$

Measure 2 observables for 2 beam polarizations:
- x-section
- FB asymmetry

Extract form factors in groups (assuming SM for remaining groups)



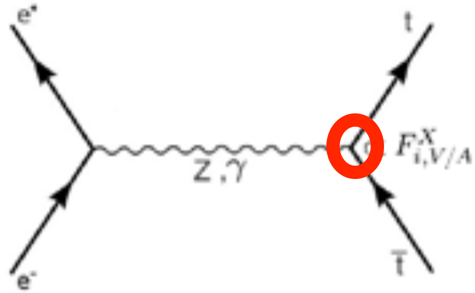
Assumptions:

LHC: 14 TeV, 300/fb
LC: √s = 500 GeV, L = 500/fb
P(e⁻) = +/- 80%, P(e⁺)= -/+ 30%
$\delta\sigma$ ~ 0.5% (stat. + lumi)
δA_{FB} ~ 1.8% (stat., covers systematics?)

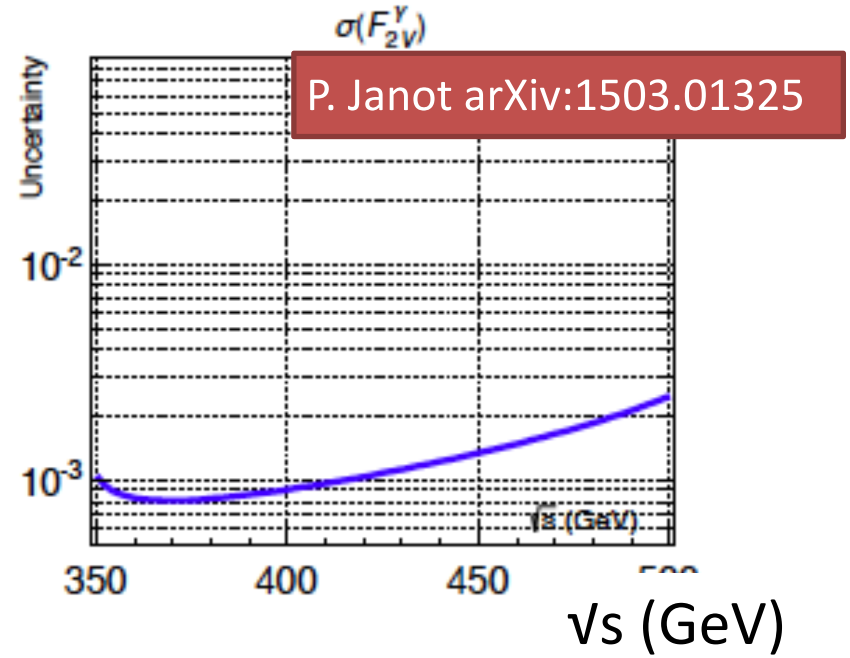
Polarization needed to disentangle photon and Z-boson form factors!

Especially for ttZ LC precision is better than existing (model-dependent) limits from top decay, LEP T-parameter, B-factories (full comparison in progress)

Top Electroweak Couplings @FCCee

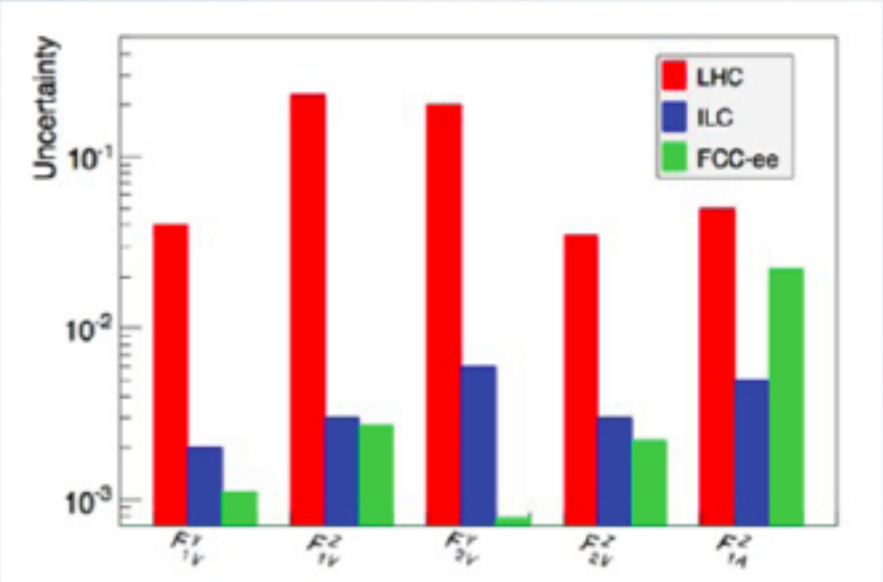


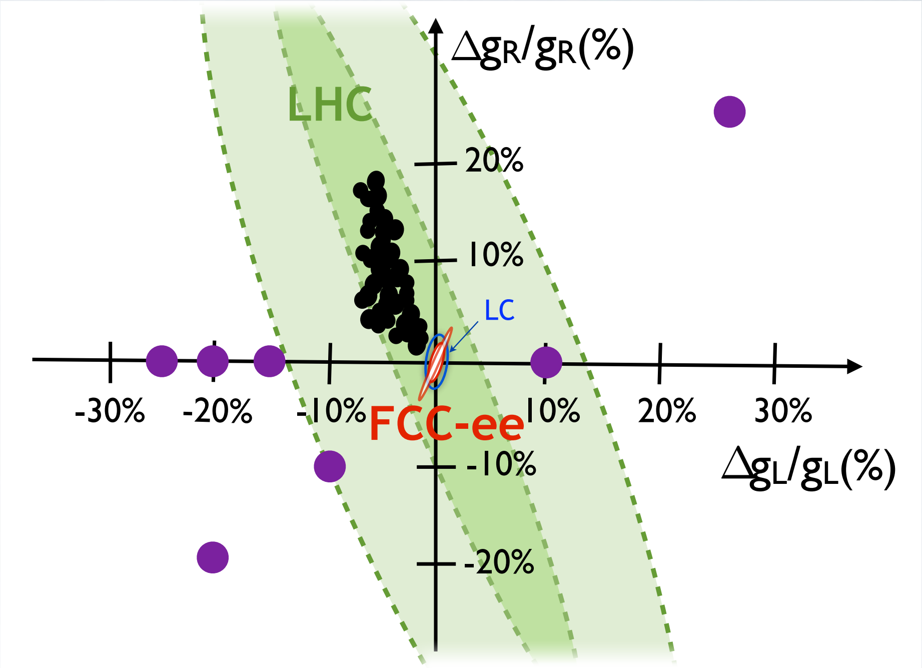
- Access the separate components from the ttZ and ttγ couplings and possible anomalous contributions from the top decay properties.
- Top polarization information is maximally transferred to its final state via the weak decay
    - **the lack of beam polarization is compensated by the final state polarization and by the larger statistics (1.6M top in 3 years)**
- Some optimal observable can be defined. In the case of tt->l+jets: the lepton direction and energy.
- main systematics comes from predicted event rate



- target precision at the per-mil level
- no need for high energy runs, far above the threshold: $\sqrt{s}$=365 GeV is optimal

Accuracy on Top Couplings





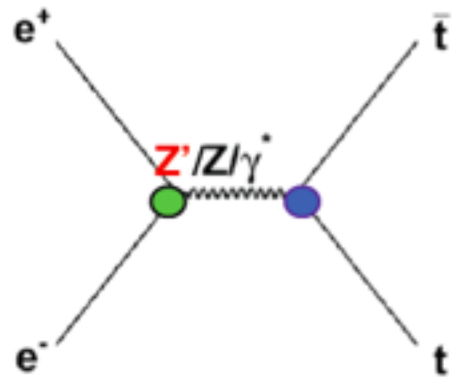
LHC (14 TeV, 300 fb^{-1})
ILC(500GeV, 500 fb^{-1}) with polarized beams
(ILC-TDR 1306.6352; Amjad et al. 1505.06020)
FCC-ee (360GeV, 2.6 ab^{-1}) from lepton angular and energy distributions
(Janot 1503.01325)

continuous(dashed): from angular and energy distributions of leptons (b-quarks)
(Janot, EPS HEP 2015, WhatNext White paper of CSN1)

Analytical results also verified with full simulation analysis in 2015

Foppiani,Pajero

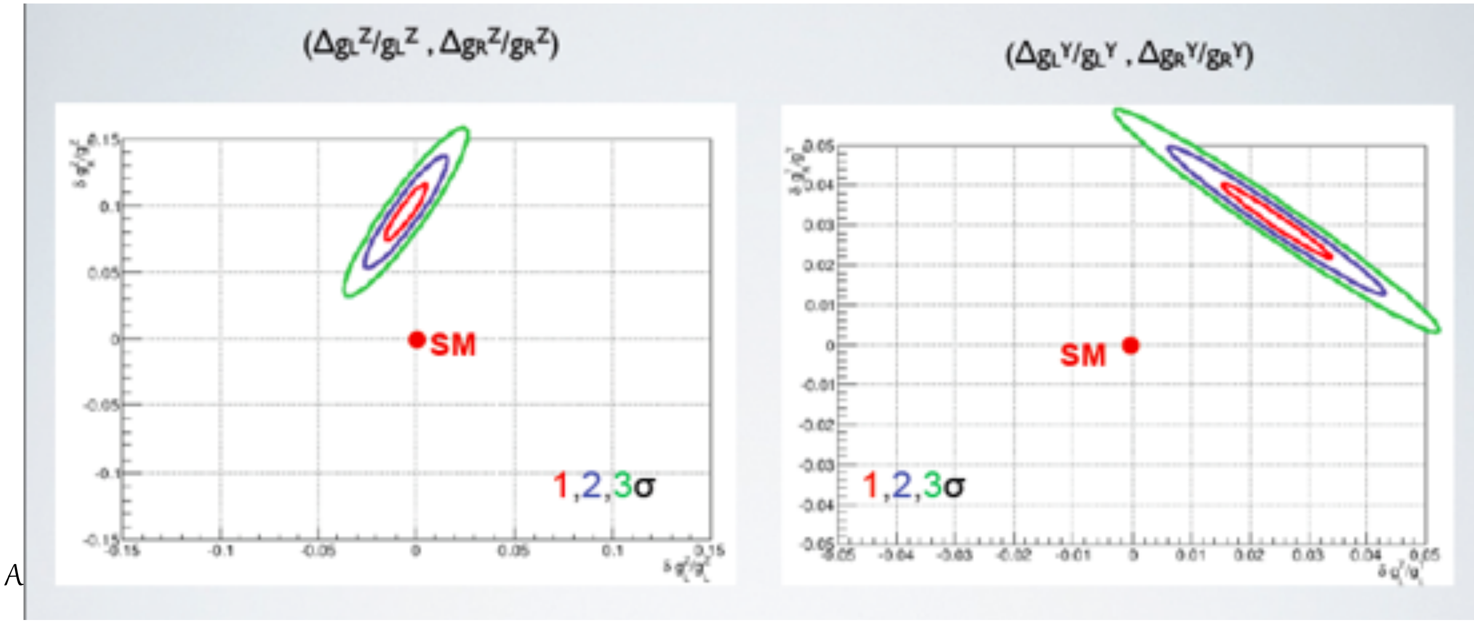
Probing Composite Higgs models



The CHM modifications of the process arise via 3 effects:

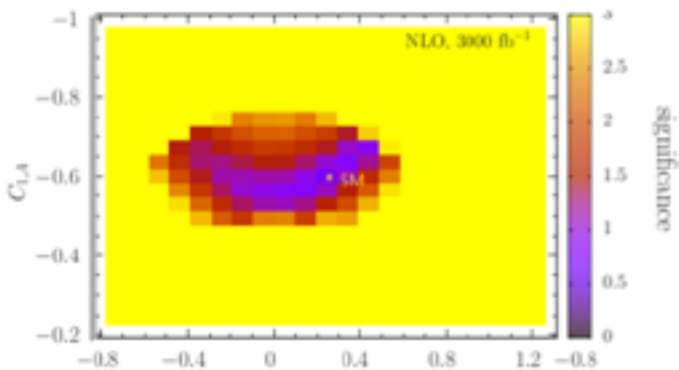
- ☑ modification of the Zee coupling (negligible)
- ☑ modification of the Ztt coupling from: mixing between top and extra fermions (partial compositeness), mixing between Z and Z's
- ☑ the s-channel exchange of the new Z's (interference) - commonly neglected BUT can be very important also for large $M_{Z'}$

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



S. De Curtis, S. Moretti

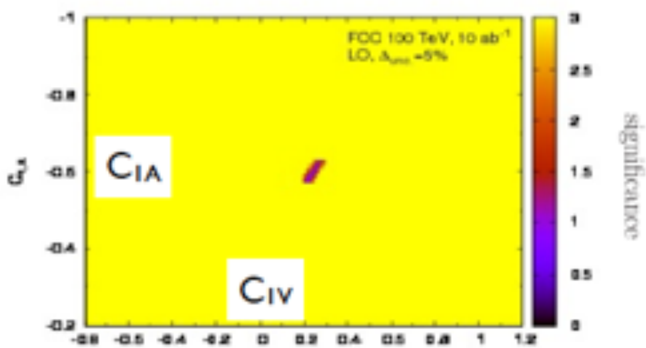
ttZ vector and axial couplings



ttbar + Z

LHC 13 TeV, 3000 fb^{-1}

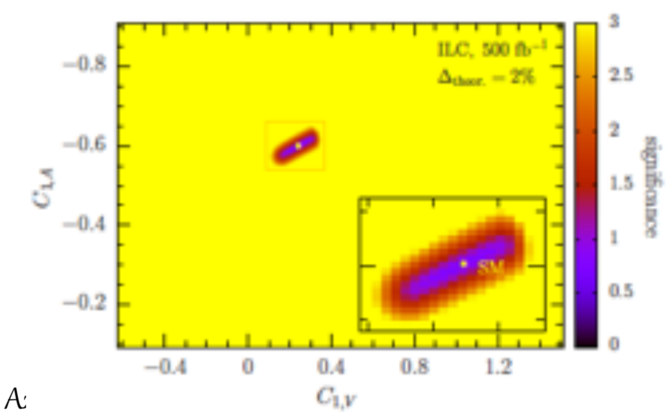
scale+pdfs: ± 15 %



ttbar + Z

FCC 100 TeV, 10 ab^{-1}

scale+pdfs: ± 5 %



ttbar
ILC 500 GeV, 500fb-1
theory 2%

Top chromo magnetic moments (gtt)

$$\mathcal{L}_{tg} = -g_s \bar{t}\gamma^\mu \frac{\lambda_a}{2} t\, G^a_\mu + \frac{g_s}{m_t} \bar{t}\sigma^{\mu\nu}(d_V + i d_A \gamma_5)\frac{\lambda_a}{2} t\, G^a_{\mu\nu}$$

SM (~ α_s)

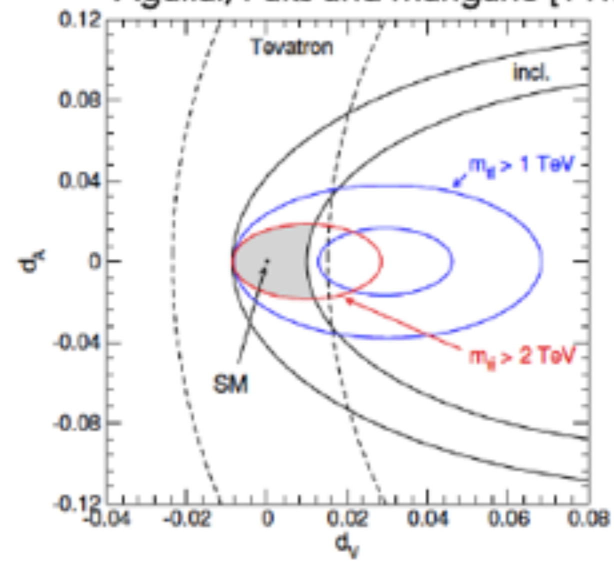
BSM
SM via loop

Enhance chromo-electric/magnetic contribution by going at p > m_t

Strategy:

- use boosted techniques to tag tops and reduce QCD background
- measure σ_{tt} (m > 1(2) TeV) to constrain d_A and d_V

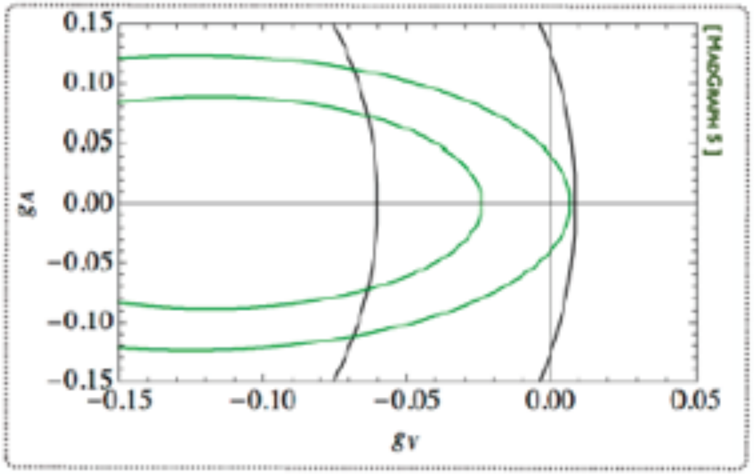
Aguilar, Fuks and Mangano [1412.6654]

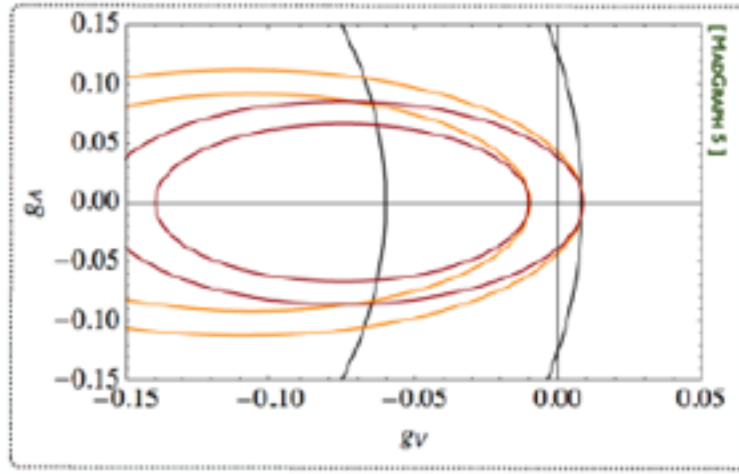


gtt @FCChh

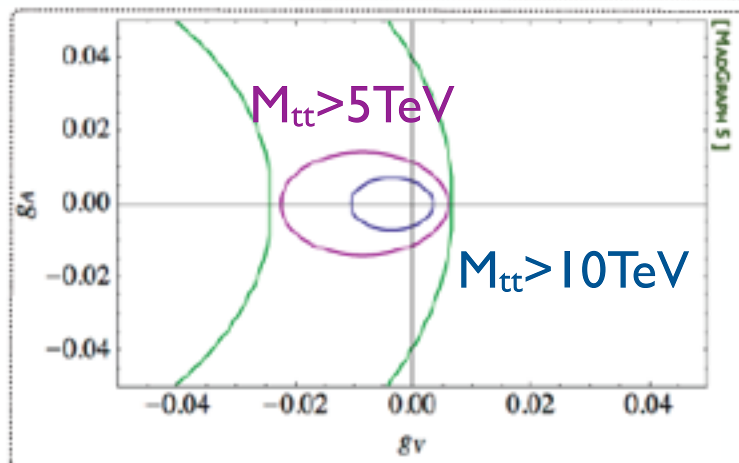
INFN Istituto Nazionale di Fisica Nucleare

✦ Top chromomagnetic and chromoelectric moments $\mathcal{L} = \frac{ig_s}{m_t}\bar{t}\sigma^{\mu\nu}\left[g_V + i g_A \gamma_5\right] T_a t G^a_{\mu\nu}$





- Top pair-production total cross sections
  - ➢ constraints on g_A and g_V
- Existing data: Tevatron; LHC-8
- Predictions: LHC-14; FCC-100
  - ★ Major improvement not foreseen…
  - ★ LHC: assuming 5% syst. + stat. for 100 fb^{-1}
  - ★ FCC: assuming 5% syst. + stat. for 1 ab^{-1}
- Using instead highly massive top pairs
  - ★ M_{tt} > 5 TeV, 10 TeV



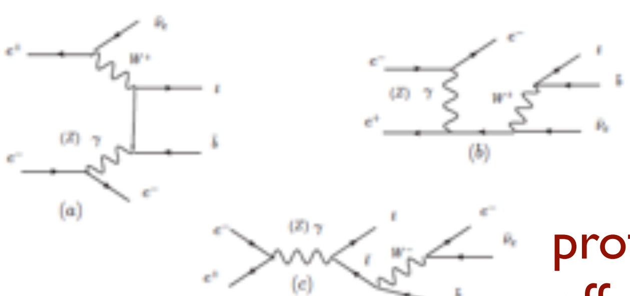
$\Rightarrow \Lambda \gtrsim 17$ TeV

benjamin fuks

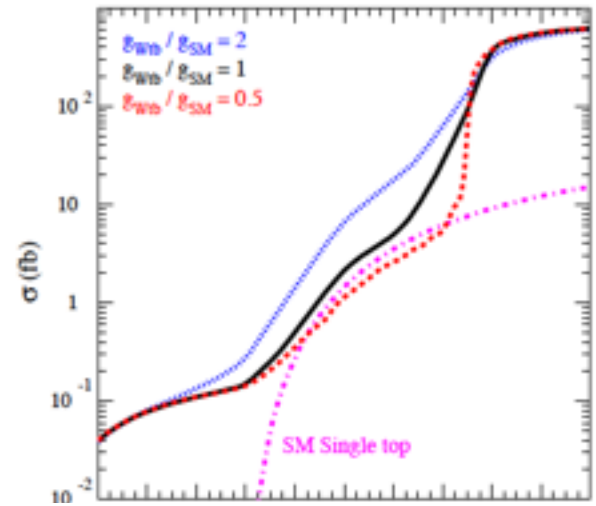
gtWb @LC

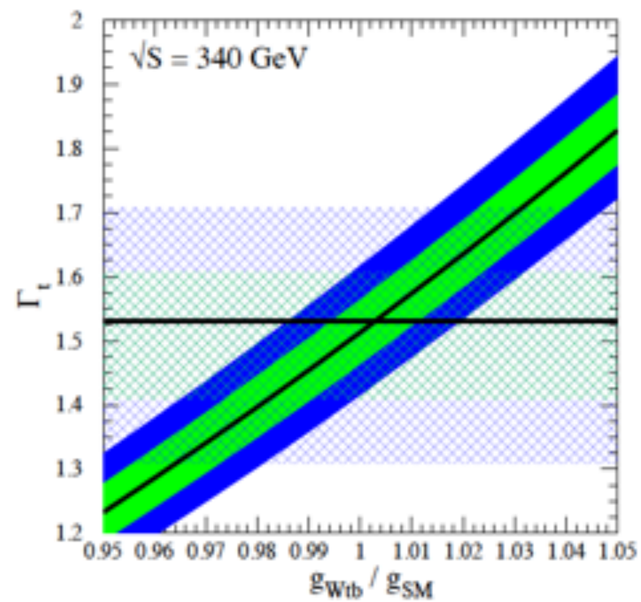
inclusive rate for e^+e^- —>WbWb

- the single top is very interesting for lower energy runs below the tt threshold
    - for FCC-ee could use the run at the Higgs
- Study at ILC (old,2005) for the extraction of gWtb:
    - use the energy scan between $\sqrt{s}$=240 and $\sqrt{s}$=350 for g_{tWb}.
    - Expected uncertainty of 2% with 100fb-1 collected at $\sqrt{s}$=340 GeV (if the Γtop is measured at 100 MeV)



profit of the off-shell top





g_{tWb} coupling @HL-LHC

enhance at q > M_W

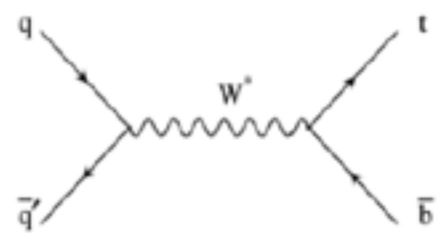
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW^-_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)tW^-_{\mu} + h.c.\,,$$

SM

thanks to F. Demartin and G. Durieux

- $V_L = V_{tb}$ in the SM
- ΔV_{tb} ~ 5 % well constrained
- ΔV_{tb} ~ 2.5 % with 300 fb^{-1} (3 ab^{-1})

Agashe et. al [1311.2028]

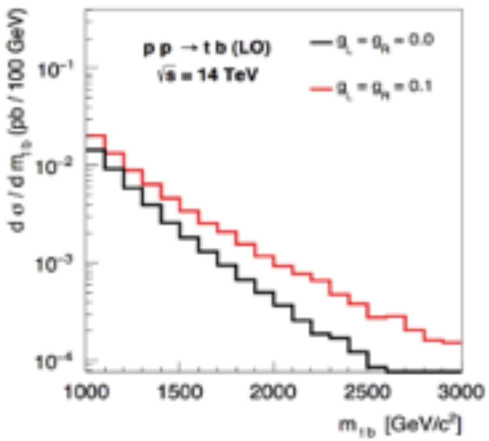


Strategy (*suggested by M.Mangano*):

- s-channel single top production perfect candidate
- probe off-shell region $q^2 >> M_W^2$ by selecting events such that m_{tb} > 1(2) TeV

→ enhance sensitivity of cross section to g_L, g_R

→ reduce QCD backgrounds



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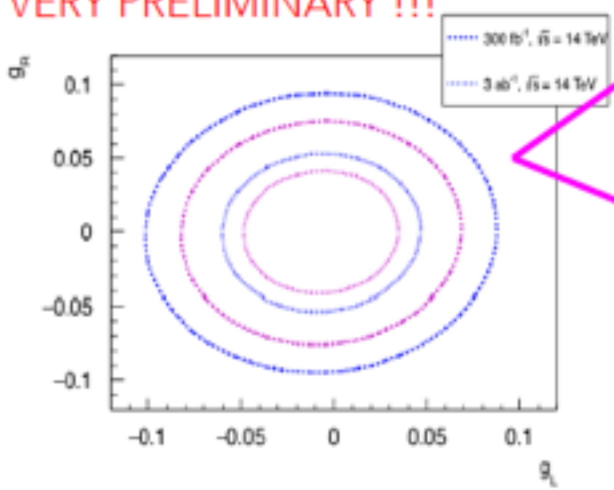
gtWb coupling @HL-LHC

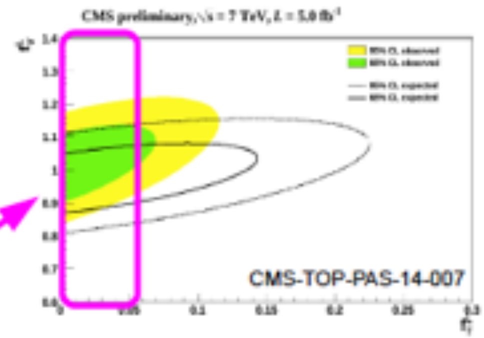
m_{tb} > 2 TeV	s-channel ST	ttbar	dijet
$\sigma_{fiducial}$ (fb)	82 (50) ab	105 (12) ab	750 (80) ab

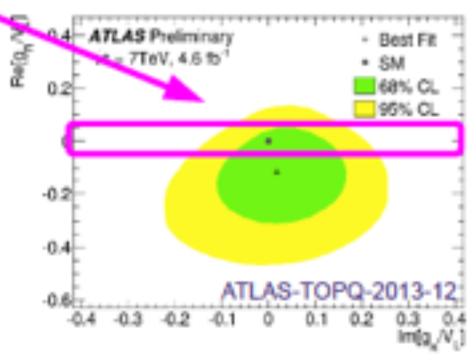
conservative
aggressive

$\Delta\sigma/\sigma_{stat}$ (300 fb $^{-1}$)	$\Delta\sigma/\sigma_{stat}$ (3 ab $^{-1}$)
68 (43) %	21 (13) %

VERY PRELIMINARY !!!





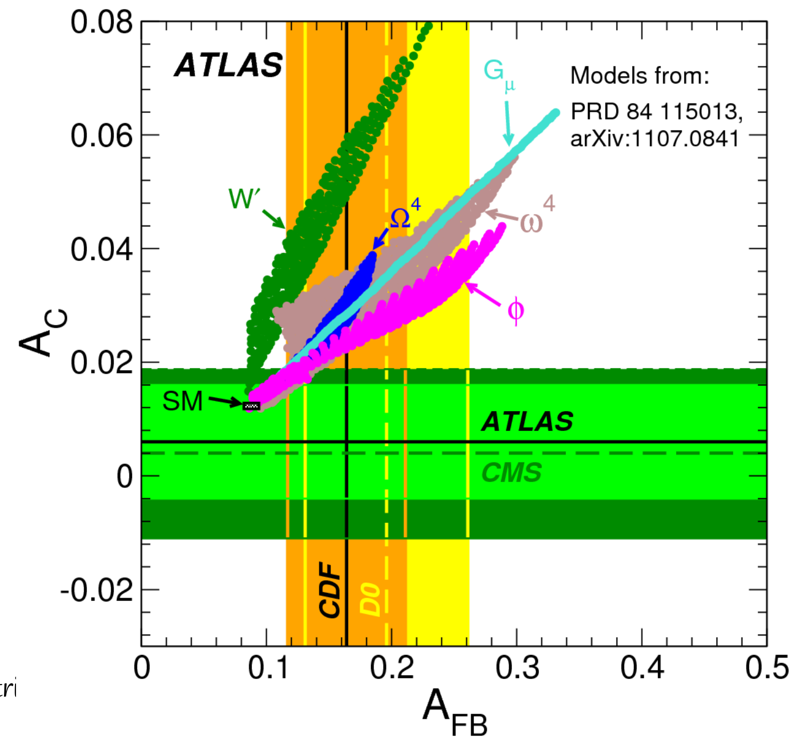


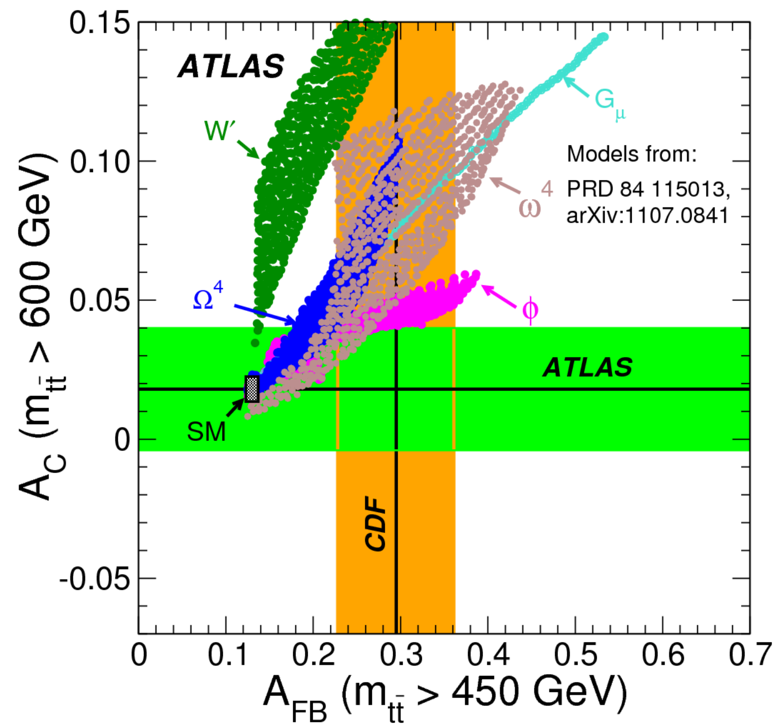
Can do better by:

- going NLO
- include tW channel

Asymmetries

- Asymmetries important to study as they are the only place currently where we see deviation from SM.
- LHC not the best place for A_{FB} especially with the energy increase. But new ideas coming in!
- @LeptonColliders: A_{FB} is sensitive to the chiral structure of the ttX vertex. Can be measured with 2% precision (1TeV, ILC polarized) by measuring top production angle and helicity angle. Polarized beams make the difference.





rare decays& FCNC: 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]

extrapolations

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.

t->Zq, γq, Zc

rare decays seem the best option for discoveries in top physics profiting of the large statistics of future machines

FCNC @FCC-ee

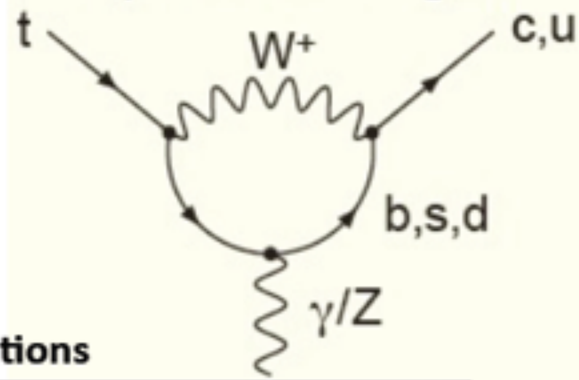
-Flavor-changing neutral current (FCNC) interactions: Transition from a quark with flavor-X and charge-Q to another quark of flavor-Y but with the same charge-Q.

For example: $b \rightarrow s\gamma$, $t \rightarrow u\gamma$, $t \rightarrow uZ$ …

-FCNC are forbidden at tree level and only allowed via higher order corrections such as penguin diagrams and strongly suppressed: due to GIM mechanism and smallness of the related CKM matrix elements.

-Top decays through FCNC are enhanced in many models beyond the SM.
-The enhancement mechanism depends on the model. It can be done via weaker GIM cancellation by new particles in loop corrections.

Top FCNC Penguin



SM Predictions

$Br(t \to cg)$	$\mathcal{O}(10^{-11})$
$Br(t \to cZ)$	$\mathcal{O}(10^{-13})$
$Br(t \to c\gamma)$	$\mathcal{O}(10^{-13})$

Phys. Rev. D 44, 1473 (1991); Phys. Lett. B 435, 401 (1998).

Decay mode	2HDM (FV)	MSSM	ED: RS
Br(t→γ+c)	≤ 10^{-7}	≤ 10^{-8}	≤ 10^{-9}
Br(t→Z+c)	≤ 10^{-6}	≤ 10^{-6}	≤ 10^{-5}
Br(t→g+c)	≤ 10^{-4}	≤ 10^{-7}	≤ 10^{-10}

arXiv:1311.2028

FCNC @FCC-ee

Exclusion limits at 95% CL

Full hadronic channel

$\sqrt{s}$ (GeV)	240, 100 fb^{-1}	240, 10 ab^{-1}
Br(t->qγ)	1.43×10^{-4}	3.17×10^{-5}
Br(t->qZ)($\sigma_{\mu\nu}$)	1.86×10^{-4}	4.12×10^{-5}
Br(t->qZ)(γ_{μ})	3.78×10^{-4}	8.22×10^{-5}

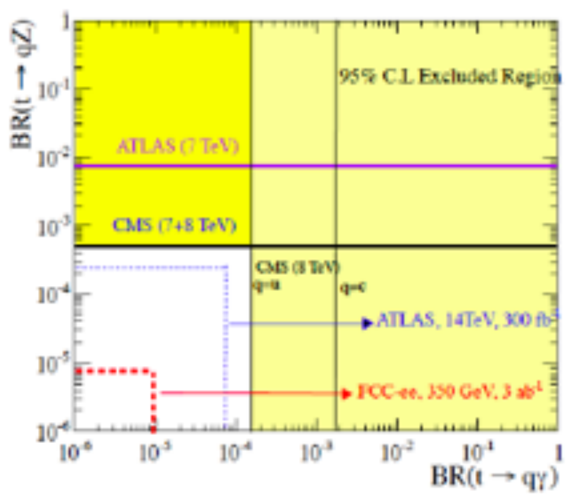
S.Biswas, F.Margaroli, B. Mele; More details can be found in talk by B. Mele:
http://indico.cern.ch/event/438866/session/10/contribution/254/attachments/1256224/1854541/FCCW_Mele.pdf

Semi-leptonic channel

$\sqrt{s}$ (GeV)	240, 10 ab^{-1}	350, 3 ab^{-1}
Br(t->qγ)	2.01×10^{-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}

$\sqrt{s}$=240 GeV means single top final state

Comparison with the LHC experiments



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All are preliminary results→ efforts are going to be done for combination and optimization.

FCNC @ILC

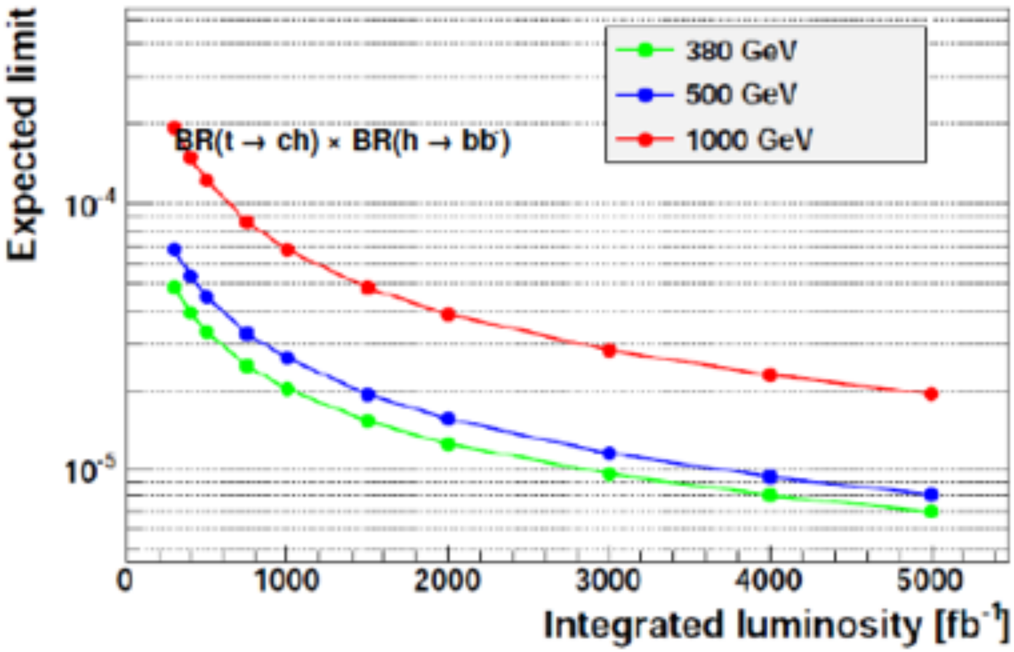
F. Zarnecki: **Measurement of FCNC top decays at ILC/CLIC studied at parton level.**

Top workshop Valencia July 15
https://indico.cern.ch/event/381148/session/5/contribution/4/attachments/759420/1674930/topl c2015.pdf

Decay t → c h is most interesting:

- well constrained kinematics
- test of Higgs boson couplings
- seems to be most difficult for LHC

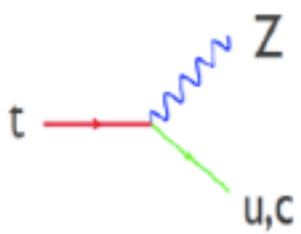
Two Higgs Doublet Model (2HDM) as a test scenario

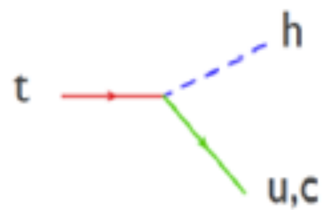


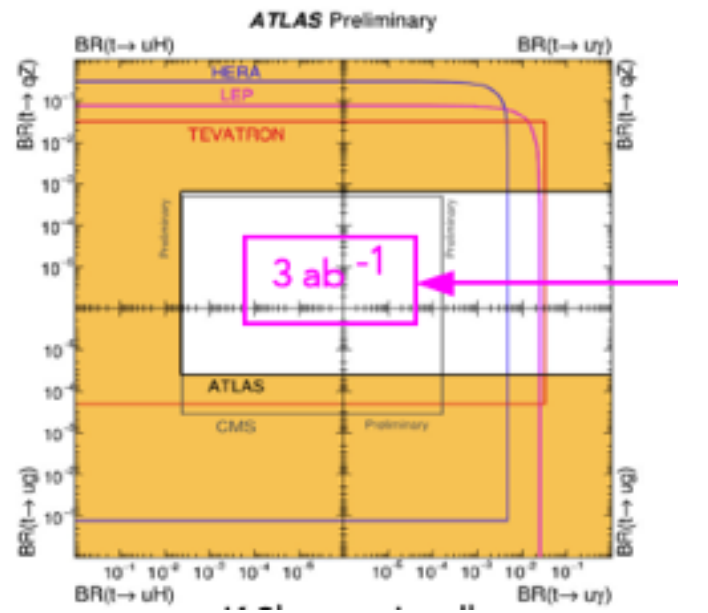
Expected limits on BR(t → ch) × BR(h → bb̄) ~ 10^{-5}
depending on the energy, luminosity and detector parameters in a H-20 LC full program

Order of magnitude improvement wrt Snowmass expectation for LHC + lumi upgrade

FCNC @HL-LHC







- ATLAS-PHYS-PUB-2013-012
- CMS-FTR-13-016

B(t→ c H) < 1.5 10^{-4}

< 0.05 %

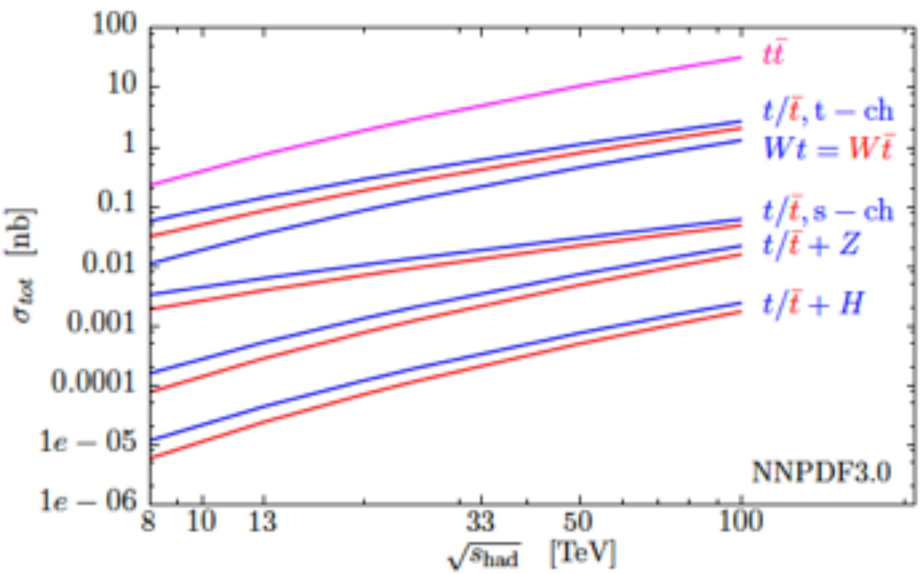
Phys. Rev. Lett. 112 (2014) 171802

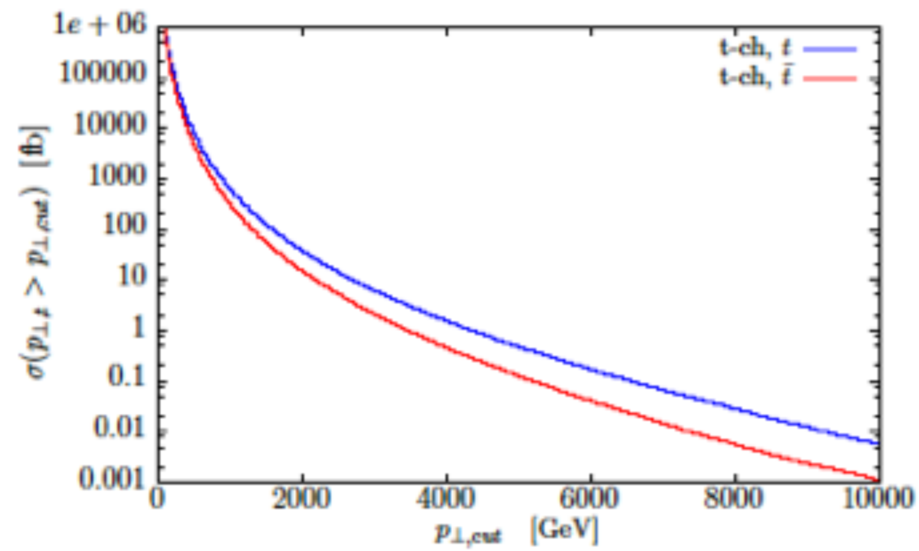
$\mathcal{B}(t \to Zq)$	19.5 fb^{-1} @ 8 TeV	300 fb^{-1} @ 14 TeV	3000 fb^{-1} @ 14 TeV
Exp. bkg. yield	3.2	26.8	268
Expected limit	< 0.10%	< 0.027%	< 0.010%
1 σ range	0.06 – 0.13%	0.018 – 0.038%	0.007 – 0.014%
2 σ range	0.05 – 0.20%	0.013 – 0.051%	0.005 – 0.020%

single top @HC

- @HL-LHC: Important to constrain new physics from the measurement of the three different production modes
- @100 TeV t-channel is x20 and s-channel x10, Wt x35! s-channel becomes 1% of the total. Important to consider the WWbb final state.

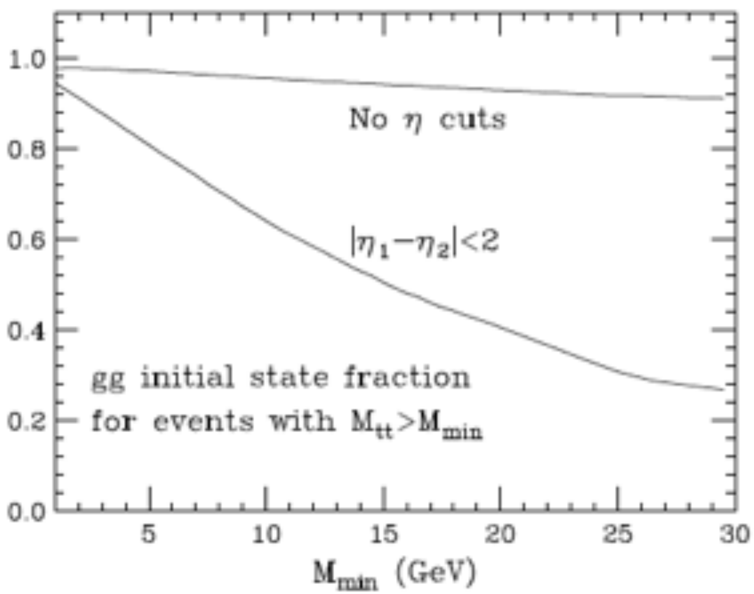
	$p_T^{min} = 0$	$p_T^{min} = 1$ TeV	$p_T^{min} = 5$ TeV
$\sigma_{\rm NLO}^{t,\, t-channel}(p_T > p_T^{min})$ [nb]	2.7 nb	1.0 pb	0.5 fb
$\sigma_{\rm NLO}^{\bar{t},\, t-channel}(p_T > p_T^{min})$ [nb]	2.0 nb	0.57 pb	0.2 fb



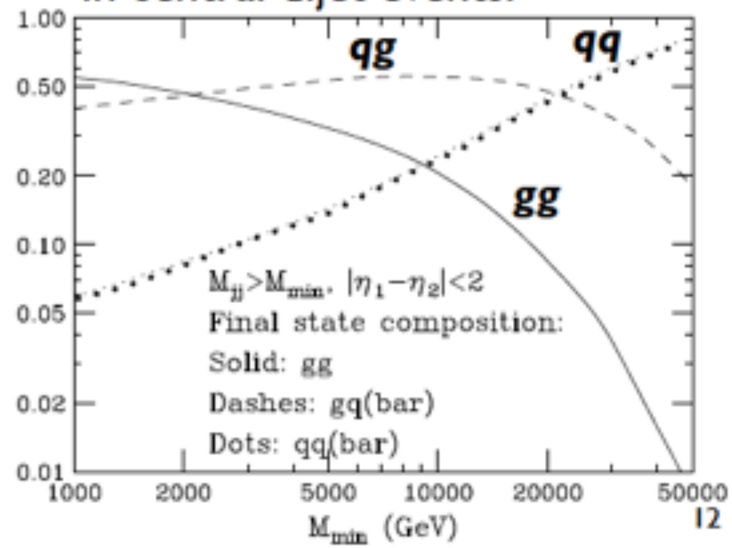


top@100TeV - production

Dominance of gg initial state:
- for all t-tbar masses in inclusive production
- up to M_{tt}~15 TeV for very central production

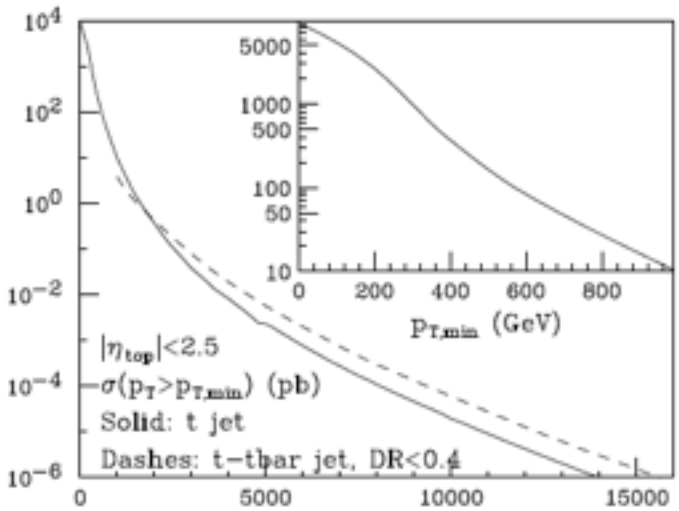


cfr initial-state composition
in central dijet events:



top@100TeV - gluon splitting

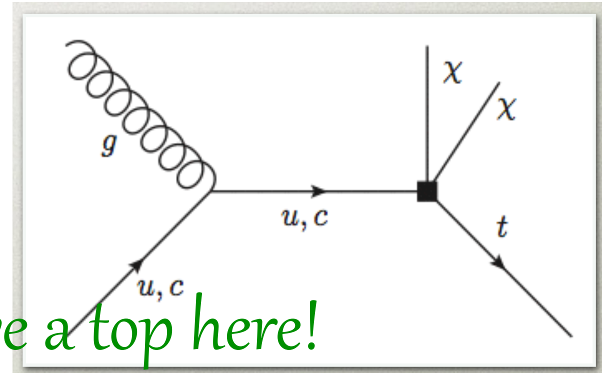
Dominance of g→tt at high p_T



top-merged jets

possible impact on top tagging at high pt ?

- **Monotops:** used to search for DM production. At LHC need FV coupling. Due to large top PDF @100TeV might not need that anymore.



can have a top here!

Conclusions

- very quick excursus into the multitude of top physics studies offered by the new machines on the market
- the top quark is a pillar of the SM. A precise measurement of its parameters is essential for a better knowledge of the SM but also opens the possibility to be sensitive to new physics processes.
- theory has to advance as much as the experiments in order to fully profit of the data collected with these new machines

looking beyond out current data is a necessary excercise to push the potential of our current analyses and to guarantee a prosperous exploration of the high energy frontier

backup

Summary of top properties determinations at ILC/FCC-ee

ILC: arXiv:1506.05992

Parameter	Initial Phase	Full Data Set	units
m_t	50	50	MeV ($m_t(1S)$)
Γ_t	60	60	MeV
g_L^γ	0.8	0.6	%
g_R^γ	0.8	0.6	%
g_L^Z	1.0	0.6	%
g_R^Z	2.5	1.0	%
F_2^γ	0.001	0.001	absolute
F_2^Z	0.002	0.002	absolute

(% units: relative precision)

m_t, Γ_t from runs at threshold
⇒ ultimately dominated by TH

syst, comparable results at FCC-ee

FCC-ee: arXiv:1503.01325 2.4 ab^{-1} at 365 GeV

Absolute Precision on	F_{1V}^γ	F_{1V}^Z	F_{1A}^γ	F_{1A}^Z
Only three $F_{1V,A}^X$	$1.2\,10^{-3}$	$2.9\,10^{-3}$	$0.0\,10^{-2}$	$2.2\,10^{-2}$
All four $F_{1V,A}^X$	$1.2\,10^{-3}$	$3.0\,10^{-3}$	$1.3\,10^{-2}$	$2.4\,10^{-2}$
$\sqrt{s} = 500\,\text{GeV}$	$5.5\,10^{-3}$	$1.5\,10^{-2}$	$1.0\,10^{-2}$	$2.2\,10^{-2}$