Electro-weak and top physics beyond the LHC

Mini-review of future collider top/EW prospects

Marcel Vos (IFIC, CSIC/UV, Valencia, Spain)

EPS-HEP, Venice, 2017

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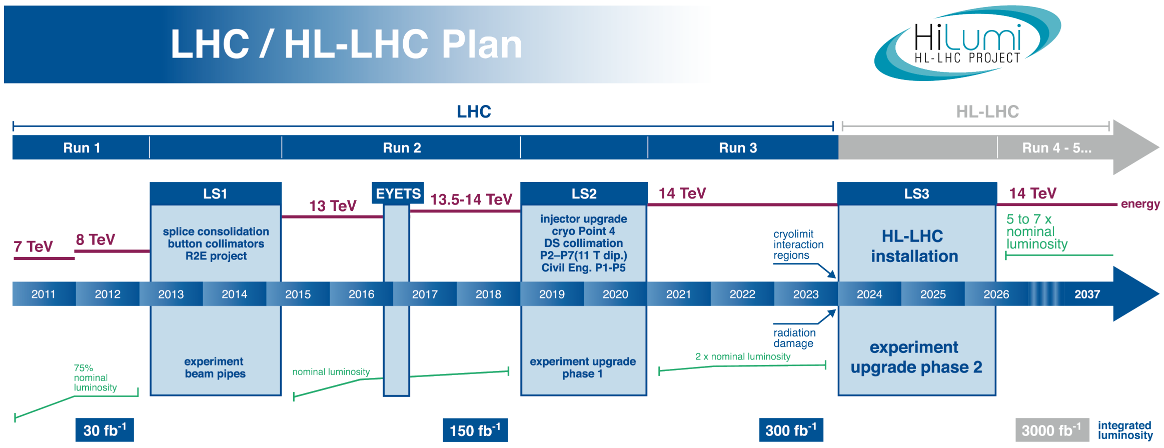
Future projects

See: F. Hosseinabadi in this track

Particle physics' new energy-frontier installation



HL-LHC program runs until 2037

Lead time is ~15 years. Need to approve a project soon to minimize the Ph.D. gap between the end of the HL-LHC and the start of the new project.

For consideration by funding agencies proposals must:
- a - be based on completed R&D and industrialization
- b - perform a detailed engineering design & costing

(a) excludes e.g. a muon collider from the current discussion
(b) is our homework towards the European strategy update in 2019L

Linear e^+e^- colliders

Accelerating cavities

SLC was built with 17 MV/m cavities (1989-1998)

Intense R&D and industrialization program to improve acceleration gradient

→ 35 MV/m super-conducting cavities
(mature & industrialized, XFEL/ILC)

Niobium Superconducting Cavities
1.3 GHz 9-Cell ILC/TESLA

Niobium in stock for quick delivery!

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*Entry level niobium cavity delivered in 3 months (other options available).

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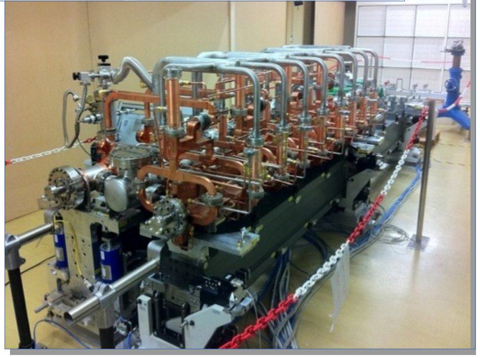
→ 100 MV/m "warm" cavities
(concept proven in large-scale tests, CLIC)



→ Plasma wakefield (when?)

Excellent overview of the future of cold and warm technology

Note: there is more to a machine....positron source, final focus

Circular pp/e^+e^- colliders

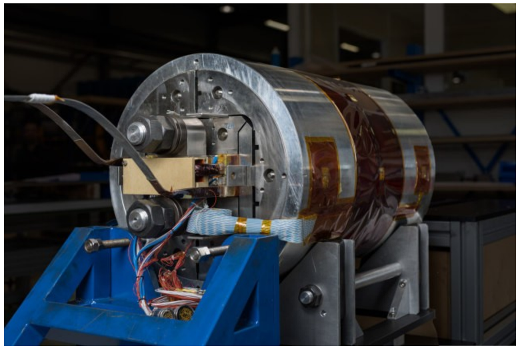
Bending magnets

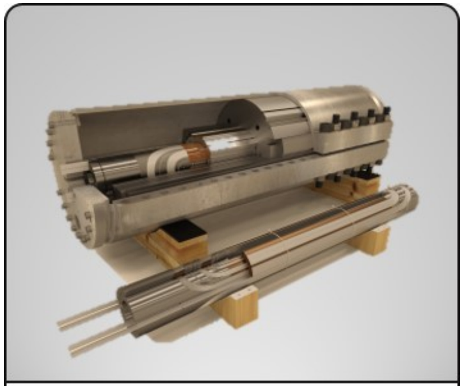
Tevatron had 4 Tesla superconducting magnets (1990-95, 2001-11)
LHC has 8 Tesla superconducting double-channel magnets

Nb3Sn magnets are a key R&D program in current European strategy

16 T - as assumed for HL-LHC, HE-LHC, SPPC, FCChh - was achieved in short racetrack magnet, "accelerator-like" magnet to reach 14-15 T soon

Recent status update here and by F. Savary in session on accelerators





High Field Magnet

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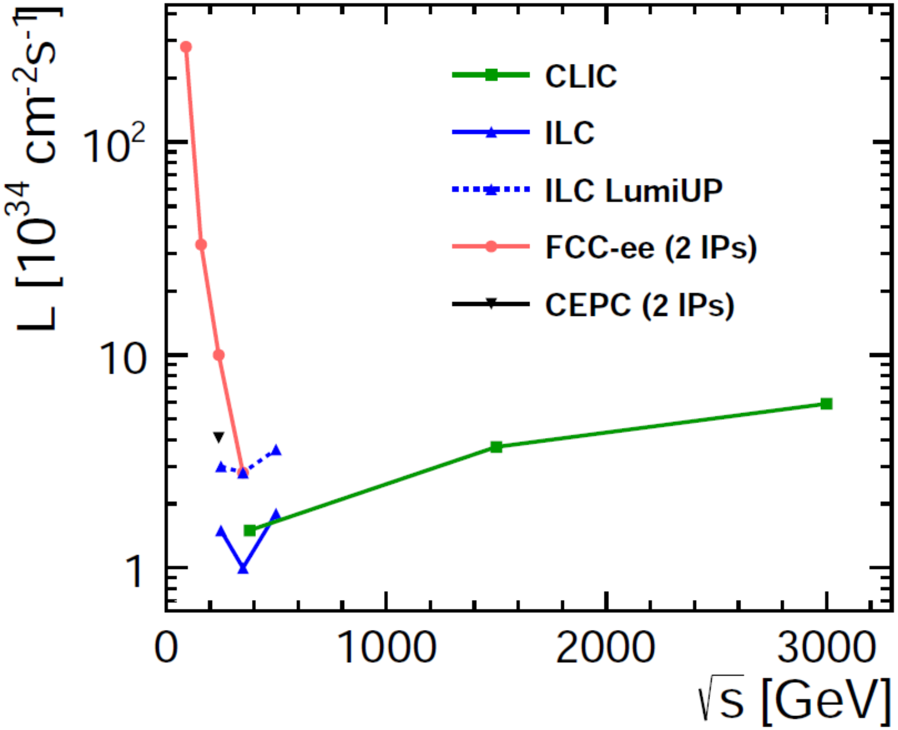
Top and EW physics at a lepton collider

Lepton collider projects:

- ILC (TDR, negotiations):
  250, 500, 1000 GeV
- CLIC (CDR):
  380, 1500, 3000 GeV
- CEPC (pre-CDR, TDR ~2020):
  250 GeV → no $t\bar{t}$ production
- FCC-ee (CDR 2018):
  90, 160, 240, 350, 370 GeV



Detailed designs for ILC/CLIC
CEPC/FCC-ee to provide CDR

Clear complementarity:

Circular is superior at low energy, linear is the only option at high energy

Precision physics at lepton colliders

For precision there is nothing like e^+e^-

Machine: per mille level control over luminosity, polarization and beam energy calibration

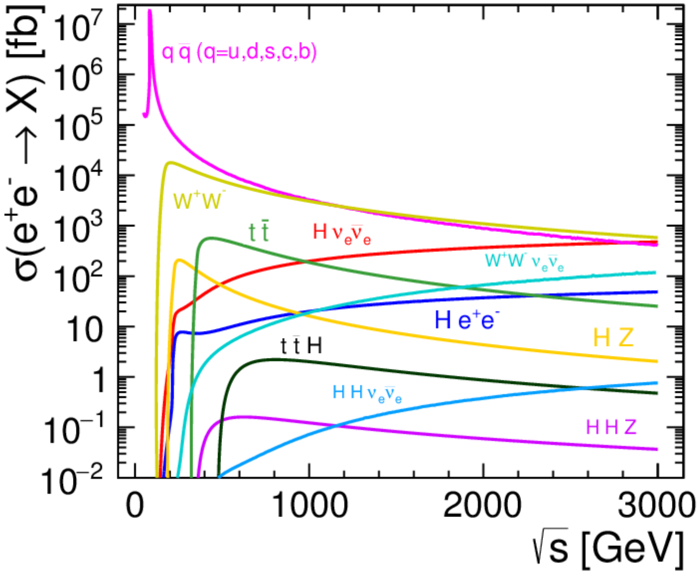
Theory: no PDFs, small QCD corrections
Predictions at few per-mille level already today!

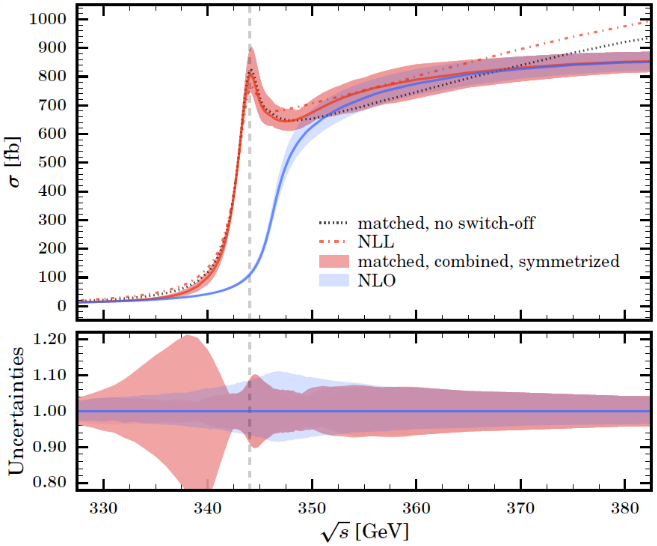
Selection: democratic cross sections allow for truly inclusive measurements (no trigger!)

Statistics: smaller samples (decreasing with energy for s-channel processes, increasing for t-channel)

Challenge: excellent detectors to make sure the experiment matches few per mille theory precision

See also: Chokoufé et al., arXiv:1609.03390





Top and EW physics at the next hadron collider?

Projects for the next very large hadron collider

16 Tesla magnets: $\sqrt{s}/L \sim 1$ TeV/km

- SPPC (China, conceptual design end 2016)

100 km (TeV)

- FCChh (CERN, CDR ~2018)

100 km (TeV)

- High-E LHC

LEP/LHC tunnel 27 km (or TeV)

Physics at hadron colliders: HL-LHC

Hadron colliders are top quark factories

# tt events	***Tevatron run II*** ***10 fb^{-1} @ 1.96 TeV***	***LHC 2012*** ***20 fb^{-1} @ 8 TeV***	**LHC sep-2016** ***30 fb^{-1} @ 13 TeV***	***LHC design*** ***300 fb^{-1} @ 13 TeV***	***HL-LHC*** ***3 ab^{-1} @ 13/14 TeV***
tt production	**57 k**	**2.6 M**	**15.5 M**	**155 M**	**1.55 G**

Access to remote corners of phase space and rare processes

The increase in the high-energy tail is even more pronounced: analyses of boosted top quark pair production are on their way to become bread-and-butter physics

For many rare processes (associated production of top and gauge bosons, $t\bar{t}H$, FCNC decays, vector boson scattering) analyses are still statistics-limited. We'll just let the machine do the dirty work and collect the benefits..

Still many areas where we probe top quark and gauge boson interactions in new ways. There might be surprises. Optimize analyses for BSM sensitivity (informed by EFT or concrete models)

HL-LHC prospect studies for top and EW physics are rare (but increasing).

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Physics at hadron colliders: brute force

ArXiv:1605.00617

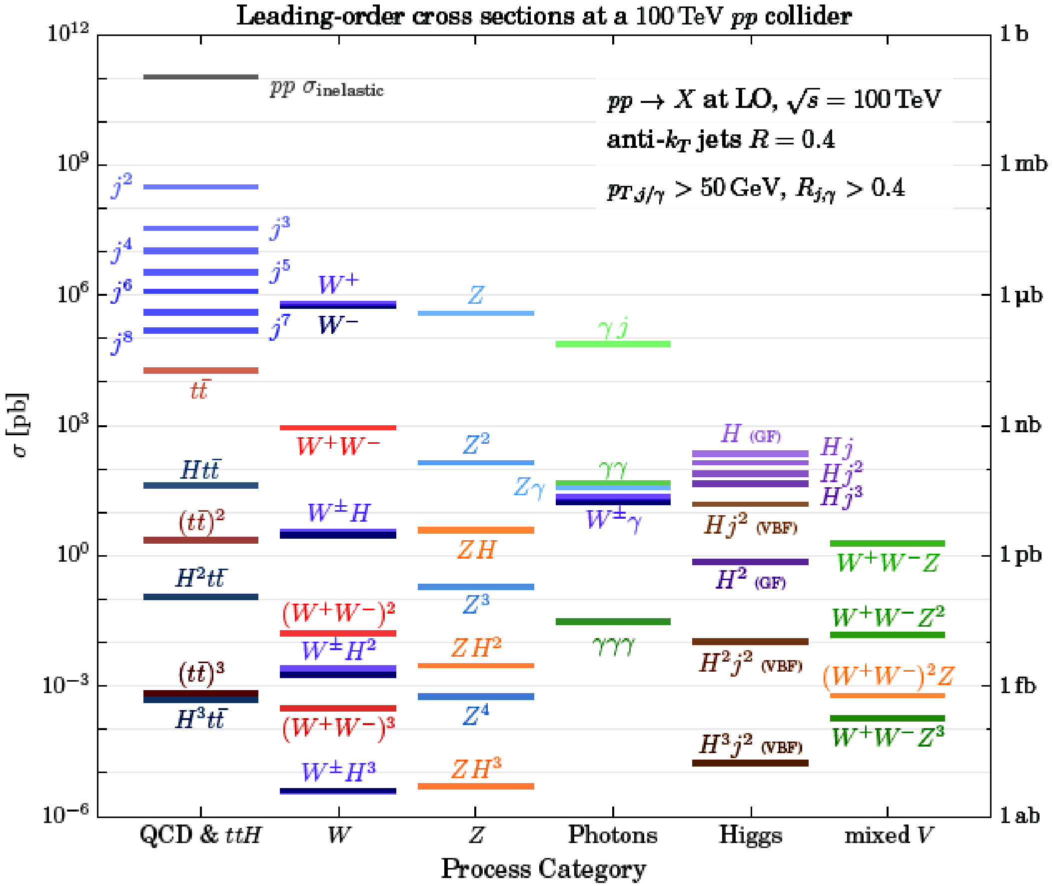
Hadron colliders are top quark factories

# tt events	*Tevatron run II* *10 fb^{-1} @ 1.96 TeV*	*LHC 2012* *20 fb^{-1} @ 8 TeV*	LHC sep-2016 *30 fb^{-1} @ 13 TeV*	*LHC design* *300 fb^{-1} @ 13 TeV*	*HL-LHC* *3 ab^{-1} @ 13/14 TeV*
tt production	57 k	2.6 M	15.5 M	155 M	1.55 G

Top and W/Z production rates of FCChh and SPPC are off the chart!

10 ab^{-1} at 100 TeV yields
10^{12} top quark pairs

Access to √s= 10-20 TeV and processes you wouldn't dream of elsewhere



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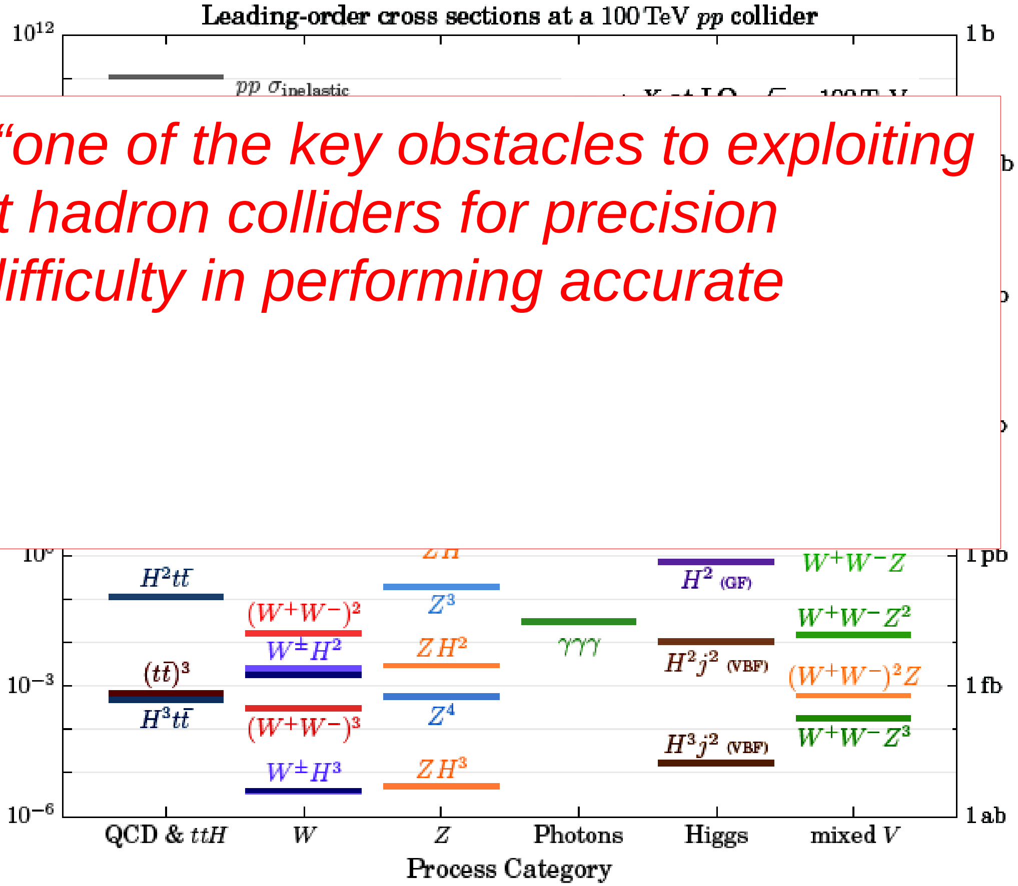
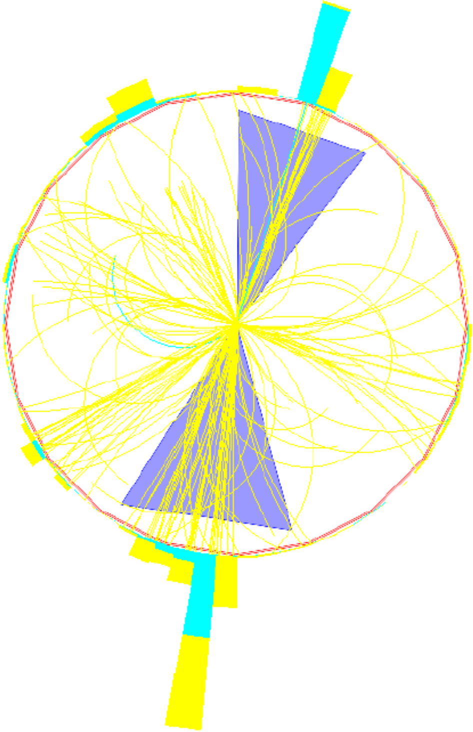
FCChh and SPPC



Challenge (arXiv:1507.08169): “one of the key obstacles to exploiting the immense statics available at hadron colliders for precision measurements, is the intrinsic difficulty in performing accurate absolute rate predictions”

Work-arounds later in the talk

80-100 TeV pp collisions



Consequences of “top as a light quark”

Production much more forward→ dedicated experiment a la LHCb?
M. Mangano, TOP2015

Must treat production differently: g → $t\bar{t}$ splitting, top quark PDF
J. Rojo/NNPDF, arXiv:1607.01831

Must deal with ultra-boosted decay topologies
Lepton-in-jet, Saavedra et al. arXiv:1412.6654
Charged substructure, A. Larkoski, arXiv:1511.06495
Pushing calorimeter granularity, arXiv:1412.5951
Full simulation starting → Chekanov @ ICHEP

See: M. Selvaggi, in this track

FCChh BSM summary: *arXiv:1606.00947*

Mass reach (2.5-3 TeV today) expected to scale with center-of-mass energy

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Direct searches vs. Indirect sensitivity

A new collider's primary aim: discovery → searches

Searches a $p\bar{p}$ colliders provide mass reach up to fraction of √s

Sp$\bar{p}$S (540 GeV) discovered W, but not top

Tevatron (1.96 TeV) discovered top, but not Higgs boson

Even lepton colliders cannot fully cover everything up to m = √s

LEP (208 GeV) missed the Higgs boson (125 GeV)

Higgs and
NP session

Indirect sensitivity can exceed √s significantly

LEP EW fit felt the top quark and Higgs bosons, B-factories probe high scales

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

Express BSM sensitivity in terms of expected limits on anomalous form factors or D6/D8 operators coefficients in EFT

EW fit

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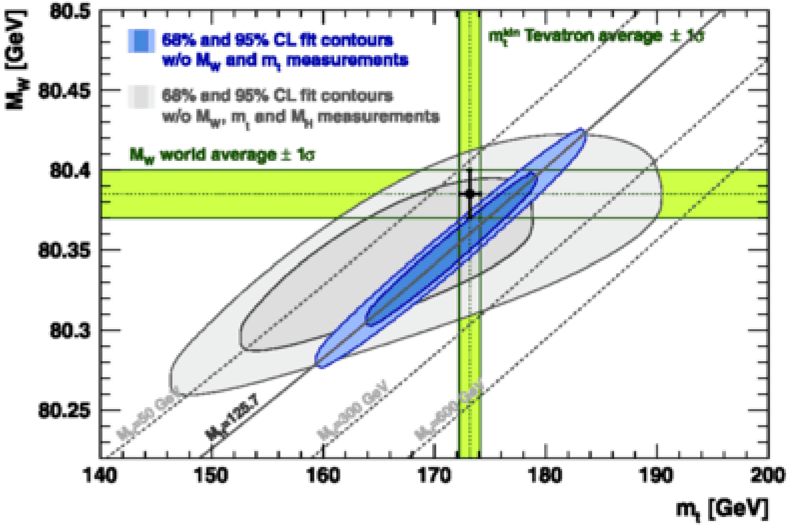
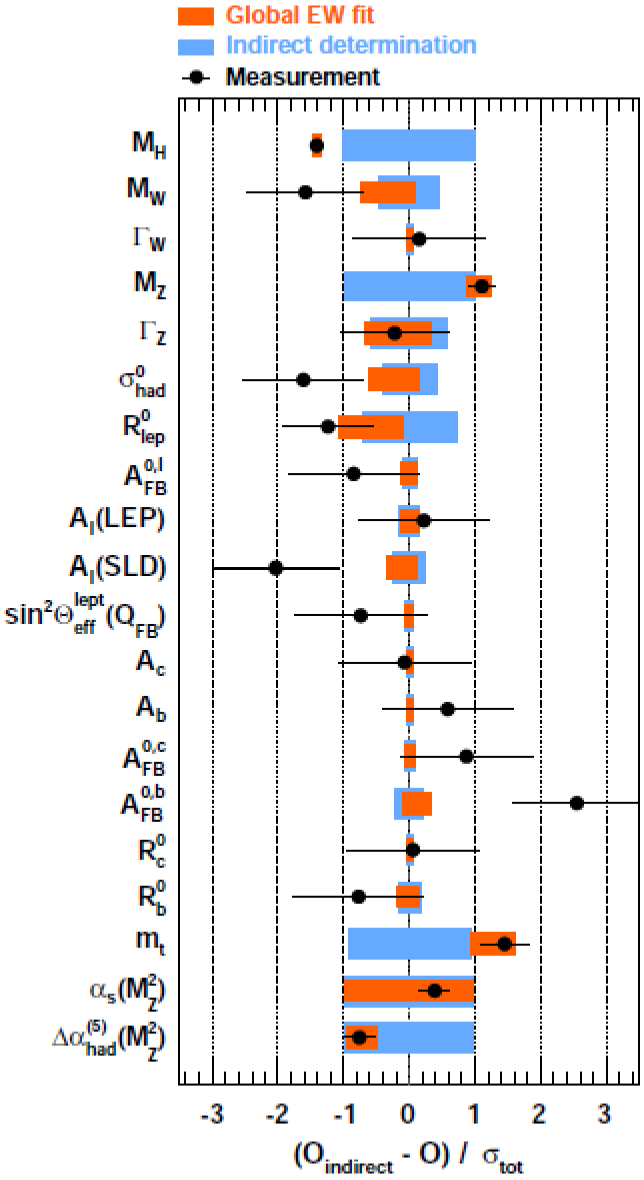
EW fit

LEP/SLD legacy results completed by Tevatron/LHC:
precise measurements of W-boson and top quark mass
Discovery of the Higgs boson



Gfitter, arXiv:1407.3792
Snowmass EW, arXiv:1310.6708



EW parameters: LHC and future colliders

arXiv:1407.3792

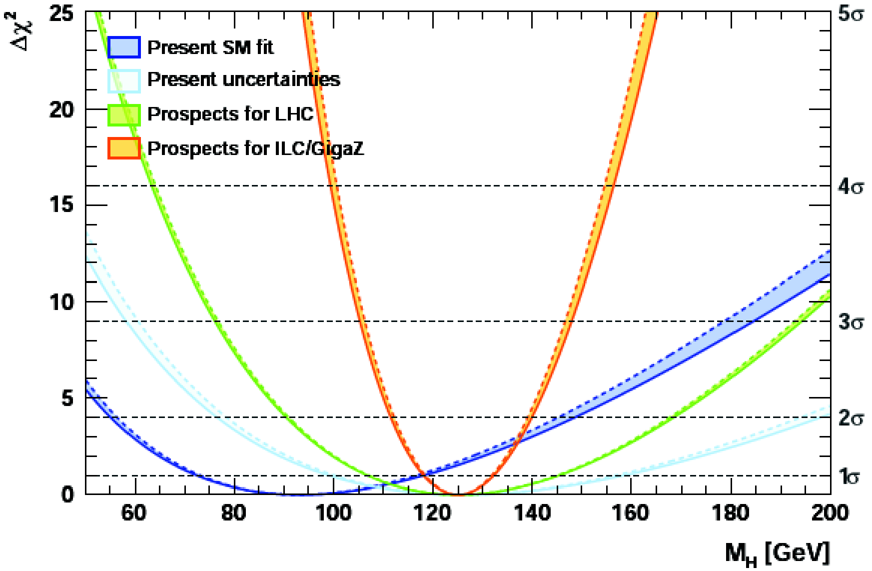
New e^+e^- machines exceed LEP and SLC luminosity by orders of magnitude (ILC GigaZ or FCC-ee TeraZ)

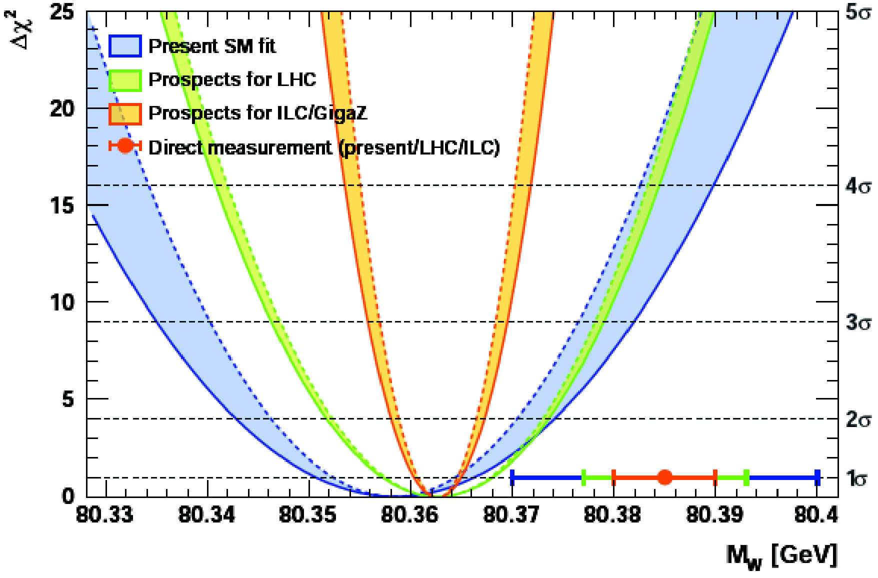
Higher-performance detectors and more sophisticated theory/Monte Carlo

We can take EW fit to next level

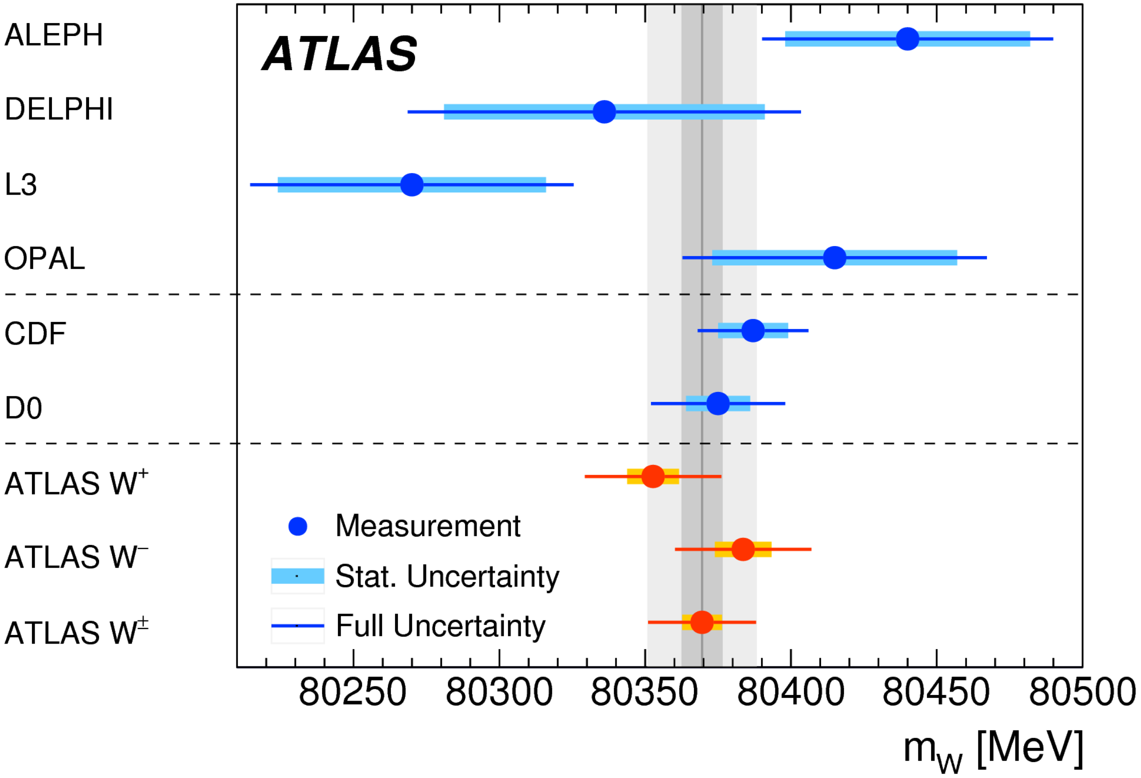
TLEP physics case, arXiv:1308.6176
Snowmass EW, arXiv:1310.6708

Exactly how far we get depends on theory progress (see Piccinini, FCC week Berlin)





W-boson mass



W-boson mass extracted from transverse mass distribution of decay products at Tevatron/LHC

Lepton colliders: direct measurement or WW threshold

LEP Electroweak Working Group, Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP," arXiv:1302.3415

Prospects for W-boson mass measurements, according to TLEP study:

~ 5 MeV at hadron colliders, down to 1 MeV at lepton colliders

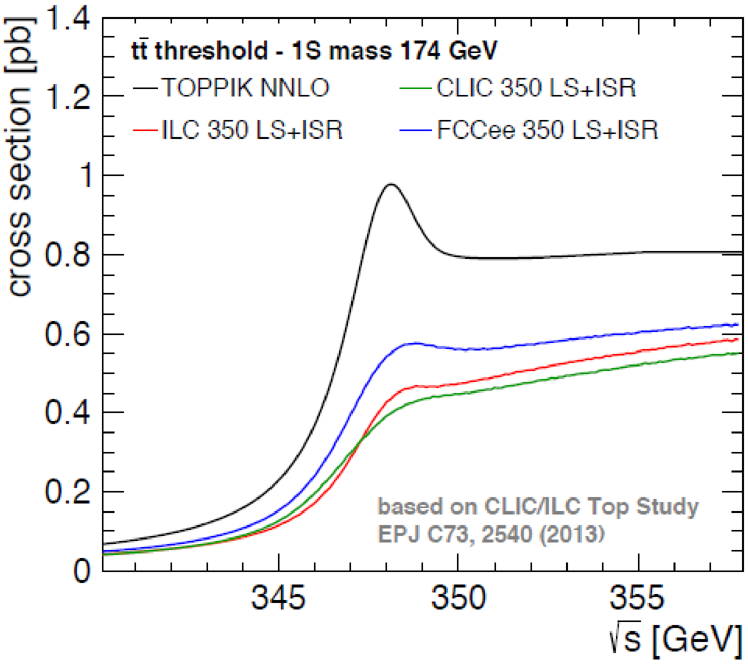
See: E. Locci in this track

Top quark mass

See G. Corcella's talk in this track

Experiment:
Tevatron/LHC direct measurements today **~500 MeV.**
HL-LHC can reach **200-300 MeV** (CMS-FTR-13-007-PAS "*optimistic, but not unrealistic*")

Theory:
Additional uncertainty for "interpretation" in mass scheme: *Hoang et al., arXiv:1608.01318*
Challenge: can pole or MS mass extractions reach competitive precision?



Ultimate top quark mass measurement

$e^+e^- \rightarrow t\bar{t}$ threshold scan

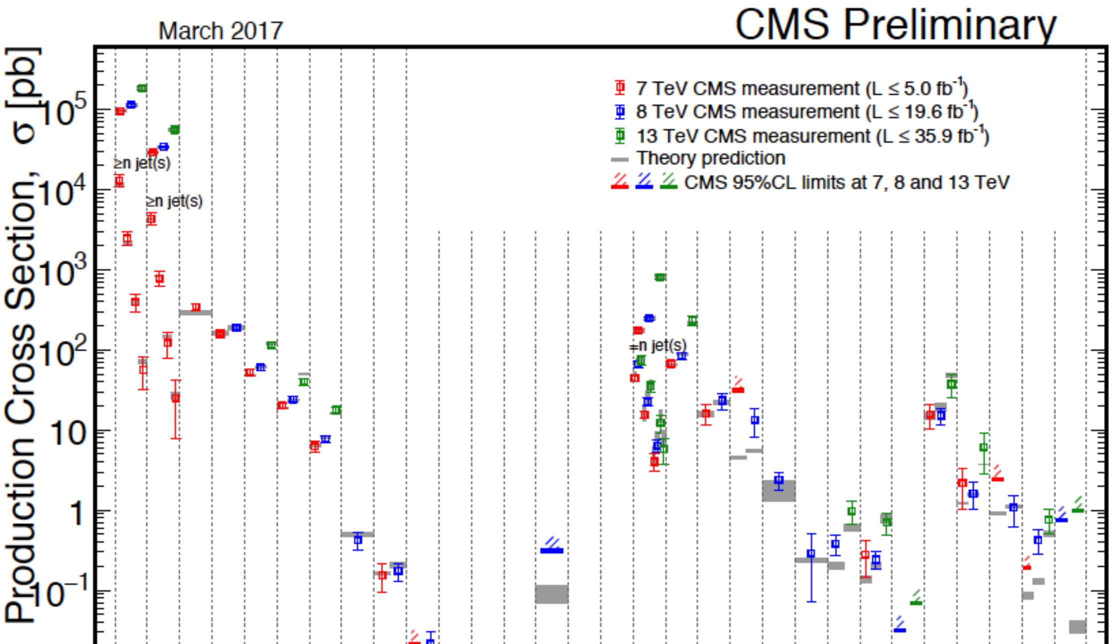
Kuhn, Acta Phys.Polon. B12 (1981)

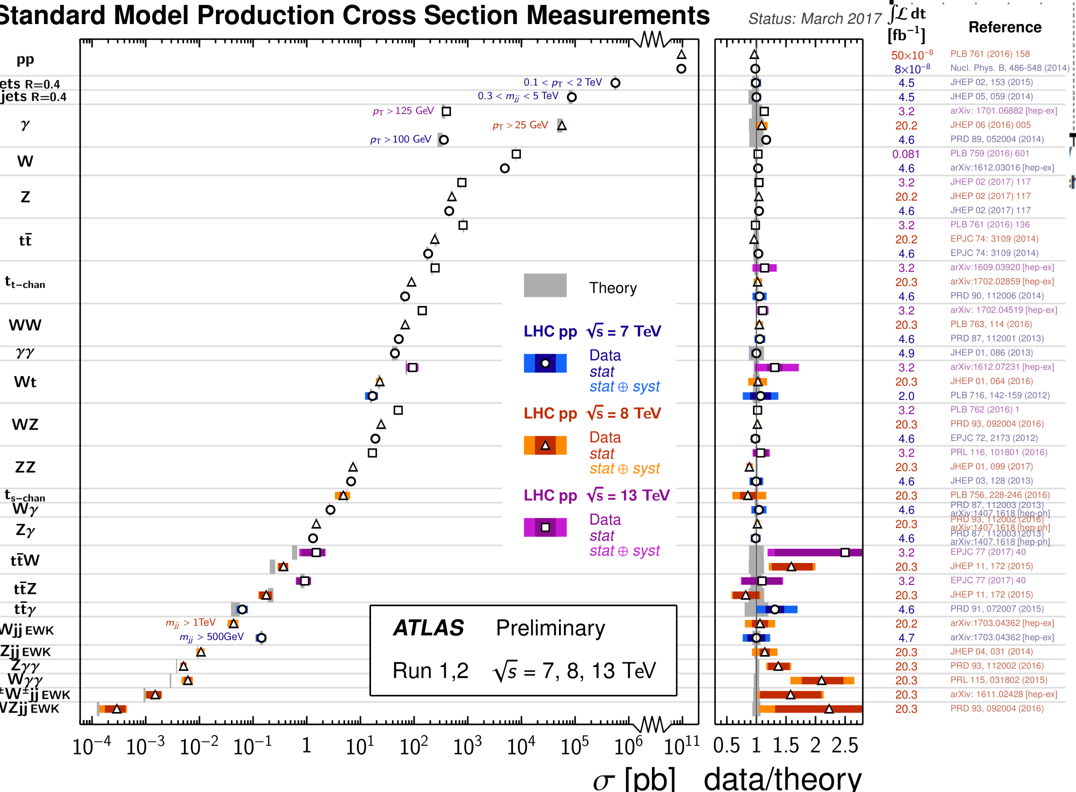
Stat. precision 1S/PS mass: ~20 MeV
Experimental systematics: O(30 MeV)
Theory uncertainty: 50 MeV
Requires precise value of α_s

(shape fit + 1S → $\overline{\text{MS}}$ conversion)
Beneke et al., 1506.06864 [hep-ph]
P. Marquard et al., arXiv:1502.01030
F. Simon, arXiv:1603.04764

See: N. v.d. Kolk in this track.
Recent review: arXiv:1604.08122

Rare EW proceses





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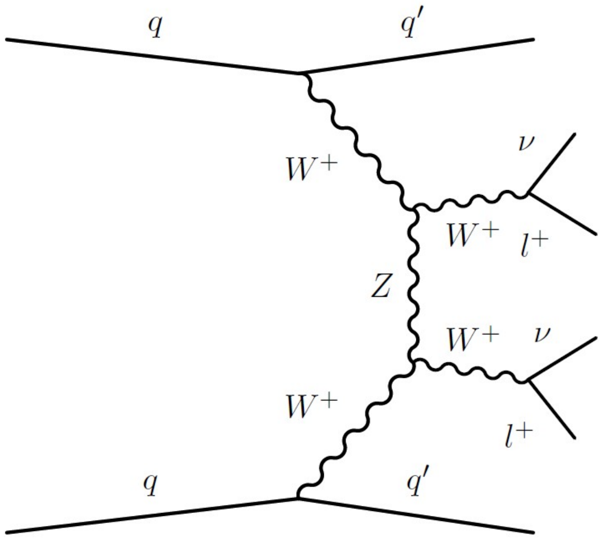
Vector boson scattering

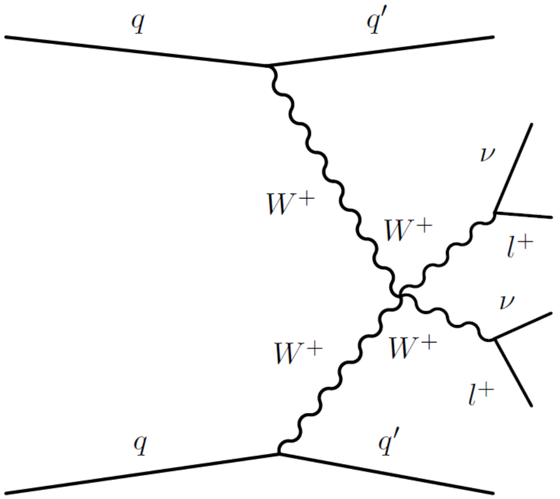


The measurement that demanded a Higgs boson...

EWK process isolated during run I at the LHC using same-sign WW and WZ production

Forward “tag” jets, high-mass VV' system
ATLAS arXiv:1611.02428
CMS arXiv:1410.6315

See: updates by ATLAS and CMS



Test Higgs-suppression of longitudinal VBS, constrain anomalous couplings (aTGC and aQGC), measure Higgs properties, Campbell, Ellis arXiv:1502.02990

Towards a global fit of a complete vector boson EFT, including all relevant aTGC and aQGCs, and Higgs operators

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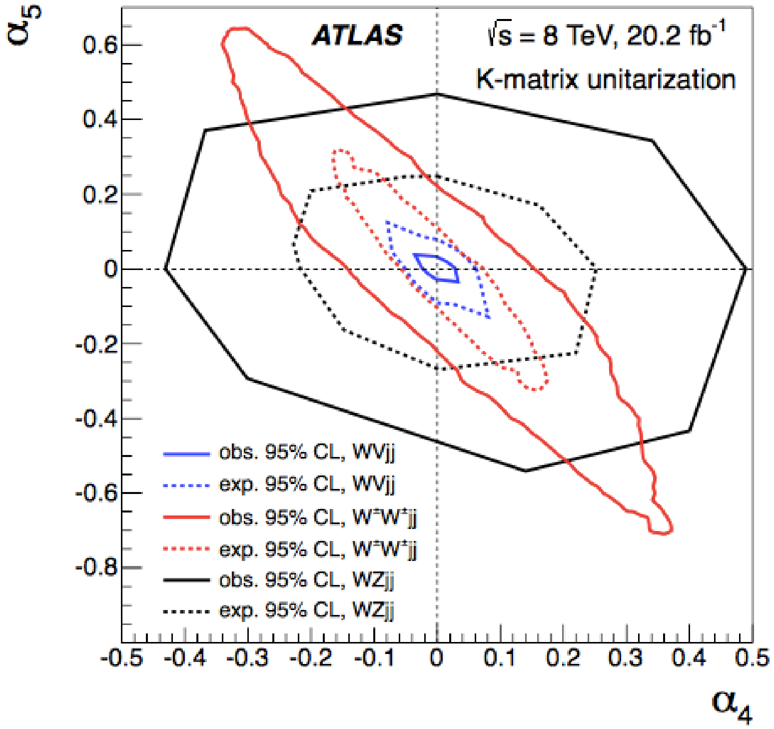
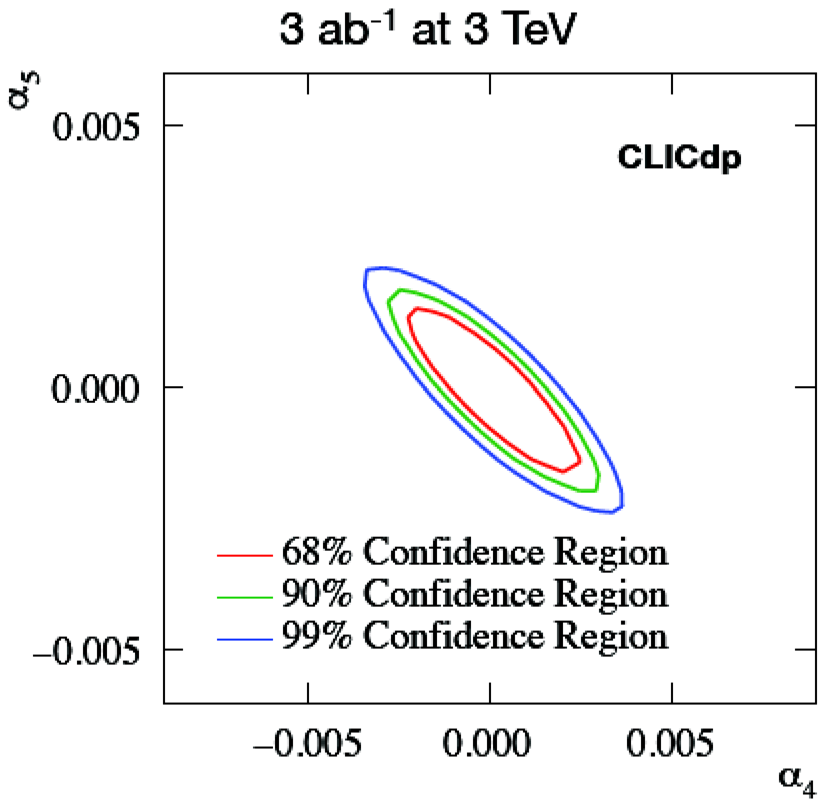
Limits on anomalous quartic couplings: LHC vs. CLIC



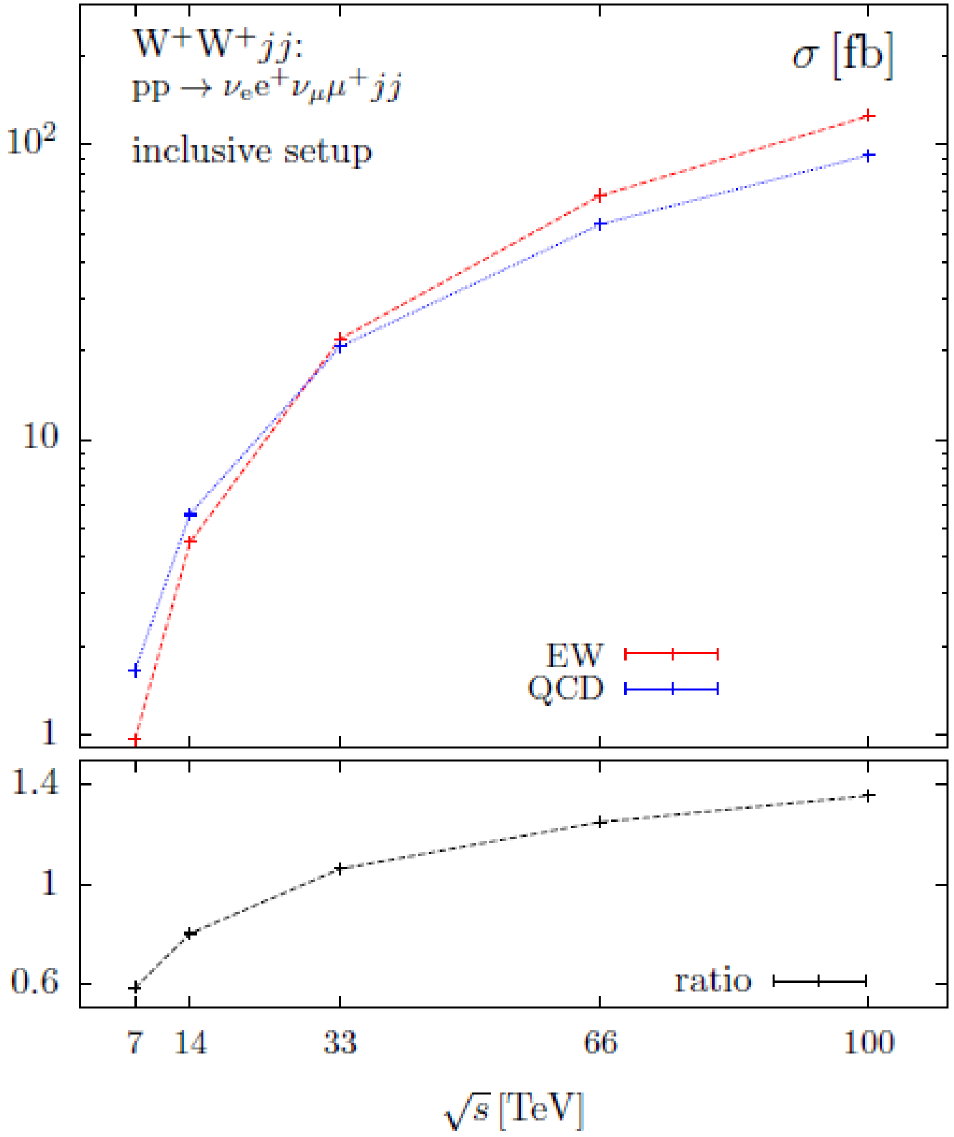
ATLAS run-I, *from Green, Meade, Pleier, arXiv:1610.07572*



CLICdp prospects for 3 TeV, *see poster Matthias Weber*

Vector boson scattering – future hadron colliders

Prospects for HL-LHC: the precision in the measurement of the EWK component cross-section is 10% or better after 3 ab^{-1}. Isolate tiny longitudinal component. Limits on aTGCs and aQGC order of magnitude better.
SMP-14-008-PAS



Prospects for FCChh/SPPC, Probing high-mass VV production yields very competitive limits on D8 operators
arXiv:1704.04911

Top and QCD

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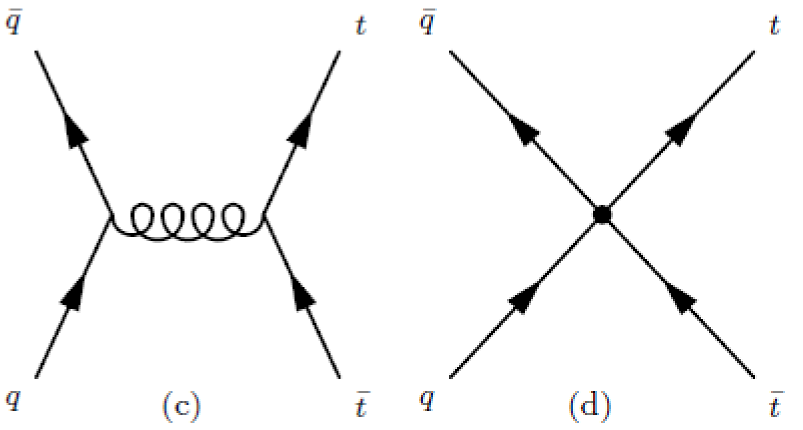
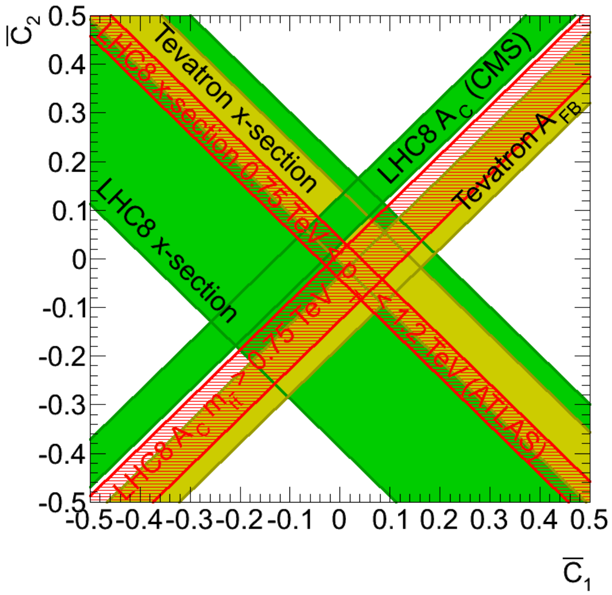
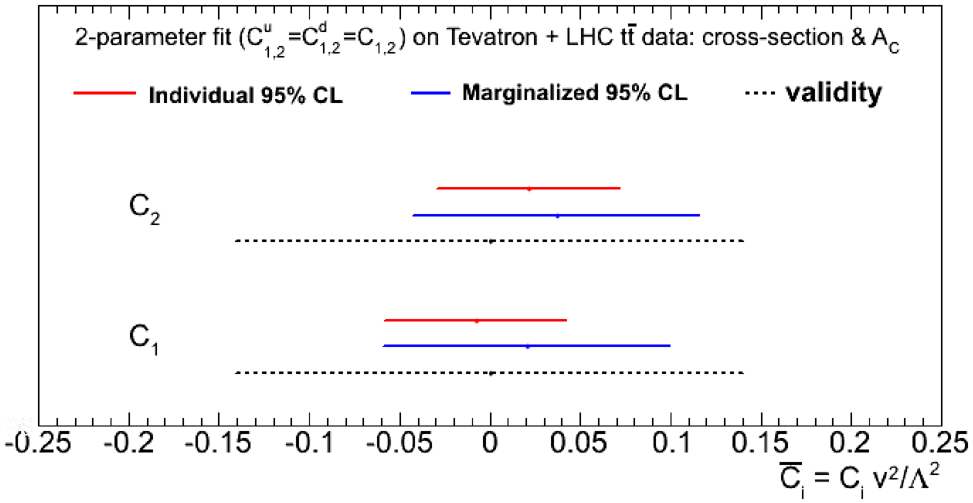
Tevatron-LHC potential to constrain four-fermion operators







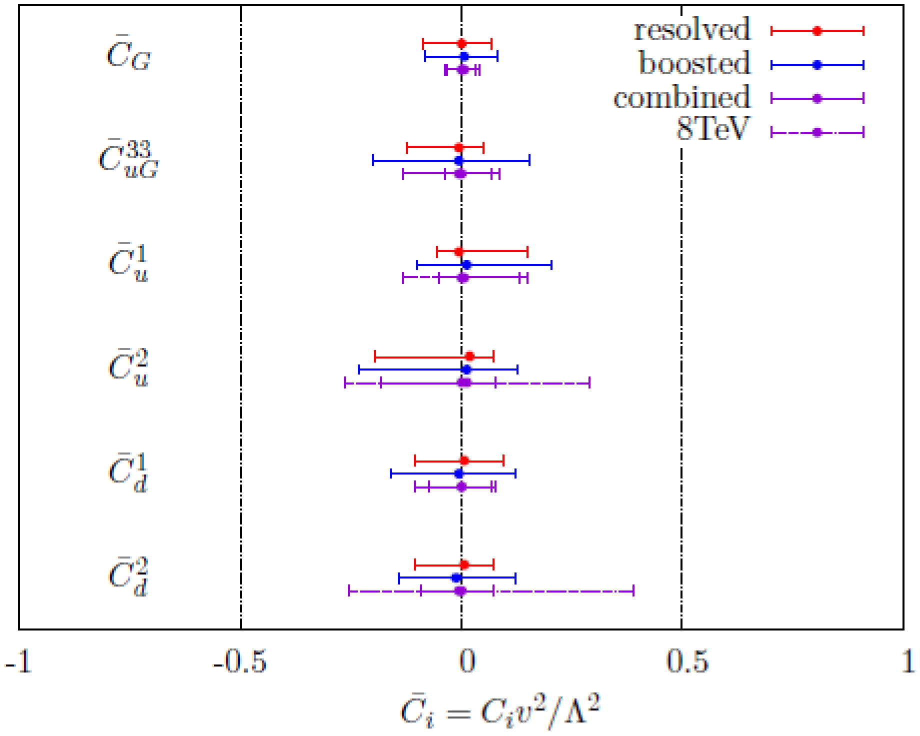
Heavy gluon exchange represented by dimension-6 four-fermion operators

Cross-section and A_C provide complementary constraints

LHC vs. Tevatron: use higher boost to produce tight constraints

M. Perelló, M.V., arXiv:1512.07542

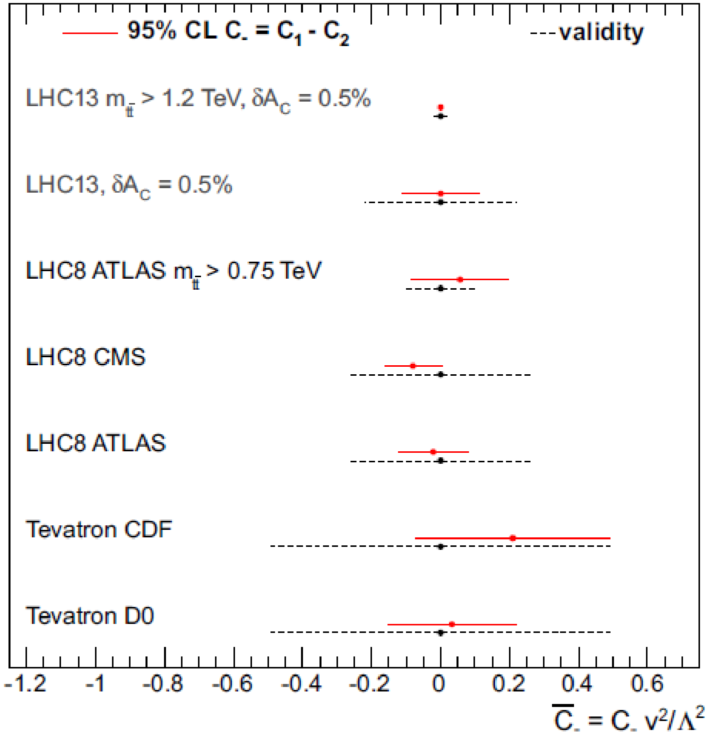
Top and QCD



8 TeV fit: resolved and boosted category offer similar sensitivity
Englert et al., arXiv:1607.04304

Inclusive measurement syst-limited
Boosted expected to improve quicker

Indeed, a measurement of the charge asymmetry with m(tt)>1.2 TeV and 0.5% precision shrinks the allowed region by a factor 10
arXiv:1512.07542



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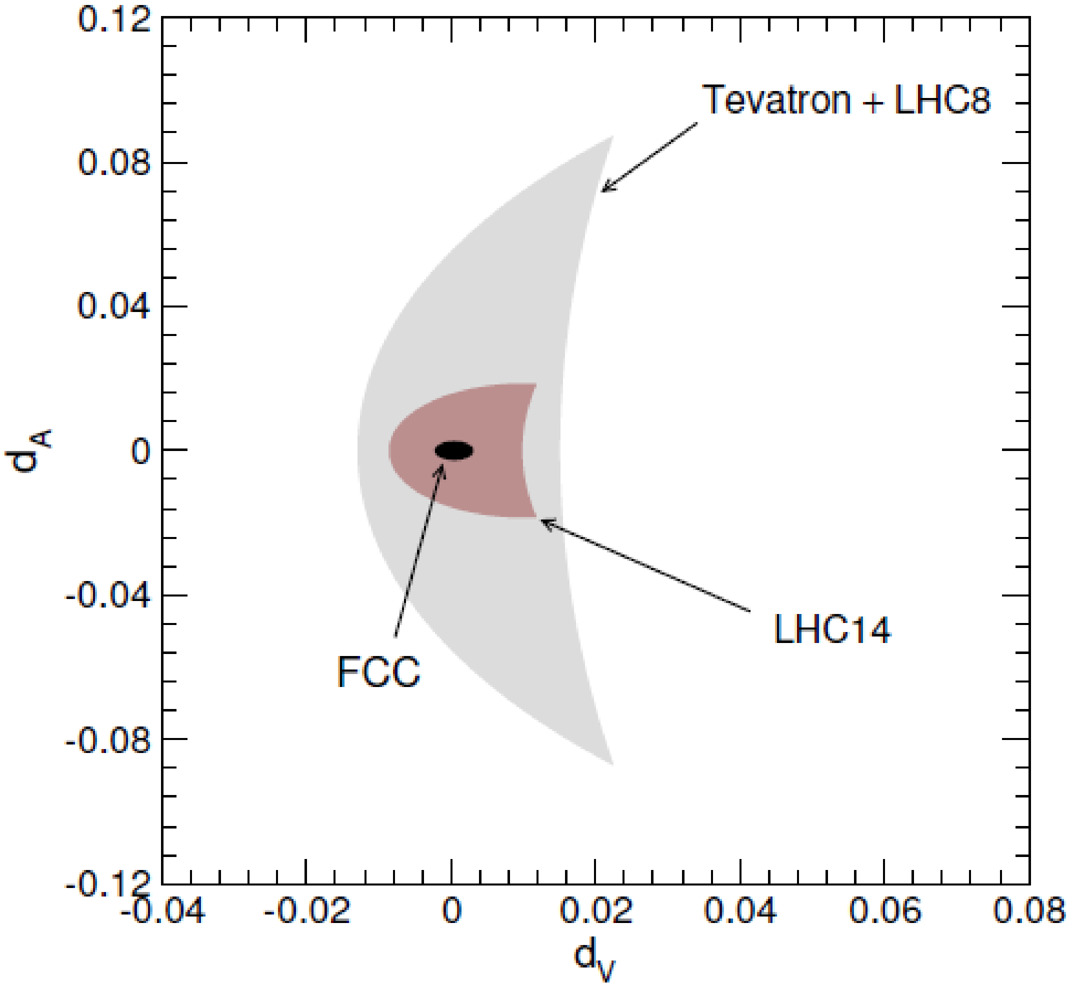
Top and QCD

Aguilar-Saavedra et al., arXiv:1412.6654

Top quark chromomagnetic and chromoelectric dipole moments

$$d_V = \frac{\sqrt{2}\, v\, m_t}{g_s \Lambda^2} \Re\, C^{33}_{uG\varphi} \qquad d_A = \frac{\sqrt{2}\, v\, m_t}{g_s \Lambda^2} \Im\, C^{33}_{uG\varphi}$$

Ultra-boosted: m($t\bar{t}$) > 10 TeV
Top decay to $b\mu\nu$
Assume 5% systematic



Order of magnitude improvement

Further studies would also be desirable to evaluate the complementarity of the measurements discussed in this paper, with those possible with e^+e^- collisions

Top and Higgs

Top quark Yukawa coupling

Prospects at lepton colliders

ILC: 3% with 4 ab^{-1} at 550 GeV

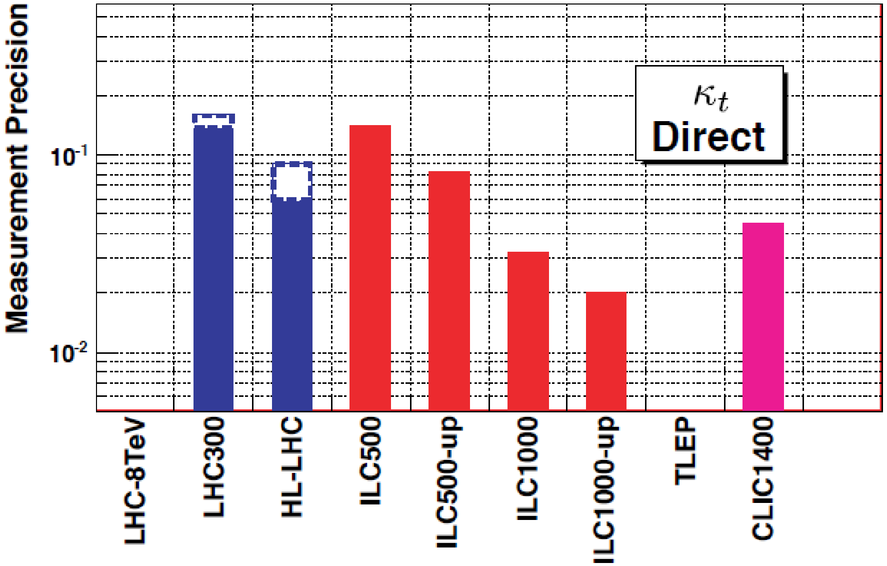
arXiv:1506.05992

ILC: 4% with 1 ab^{-1} at 1 TeV

arXiv:1409.7157

CLIC: 4% with 1.5 ab^{-1} at 1.4 TeV

arXiv:1608.07538

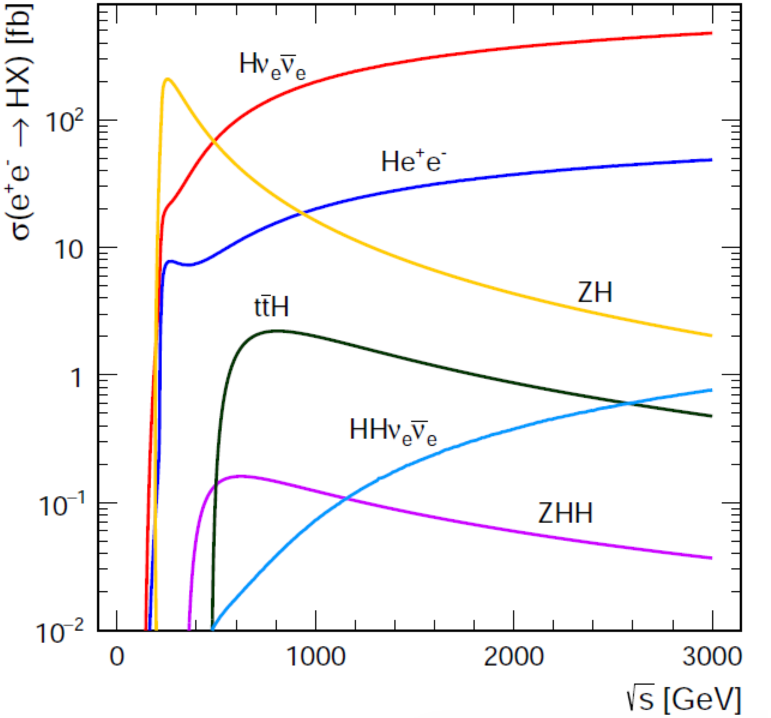


Prospects for full LHC programme:

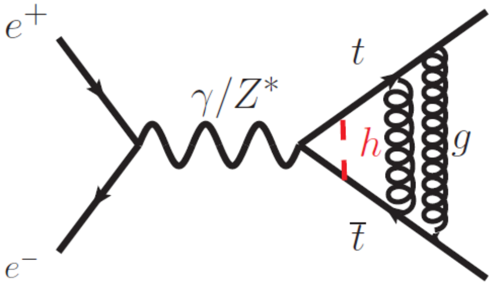
K_u → 14-15% (300/fb)

K_u → 7-10% (3/ab)

Snowmass Higgs report



Note: 4% stat. from threshold scan (but: large theory uncertainty)

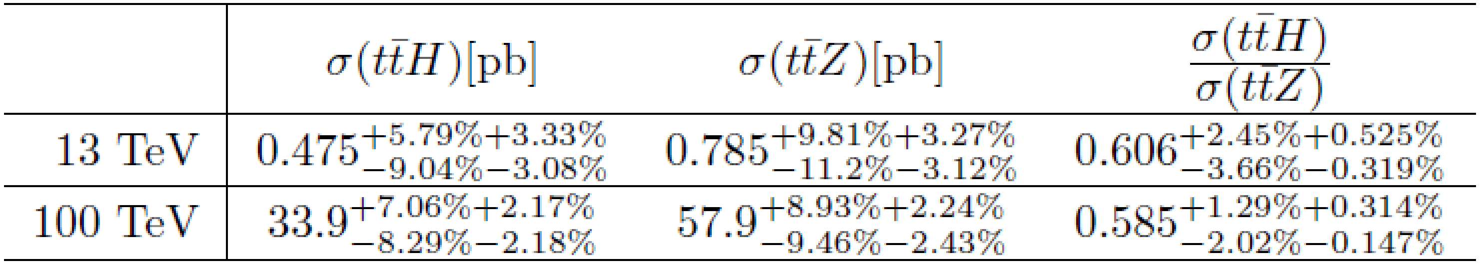


Horiguchi et al., arXiv:1310.0563

Top quark Yukawa coupling at hadron colliders

The ttH cross section at 100 TeV is 60 times larger than at the LHC

Relative cross sections or ratios of processes ttH/ttZ cancel theory uncertainty



	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

Use data to gain confidence with (scale) uncertainties of ratios:

Tevatron A_{FB}, recent ATLAS $t\bar{t}$/Z ratio (*arXiv:1612.03636*)

FCChh fast simulation study:

1% precision on the top Yukawa coupling (20/ab, 100 TeV)

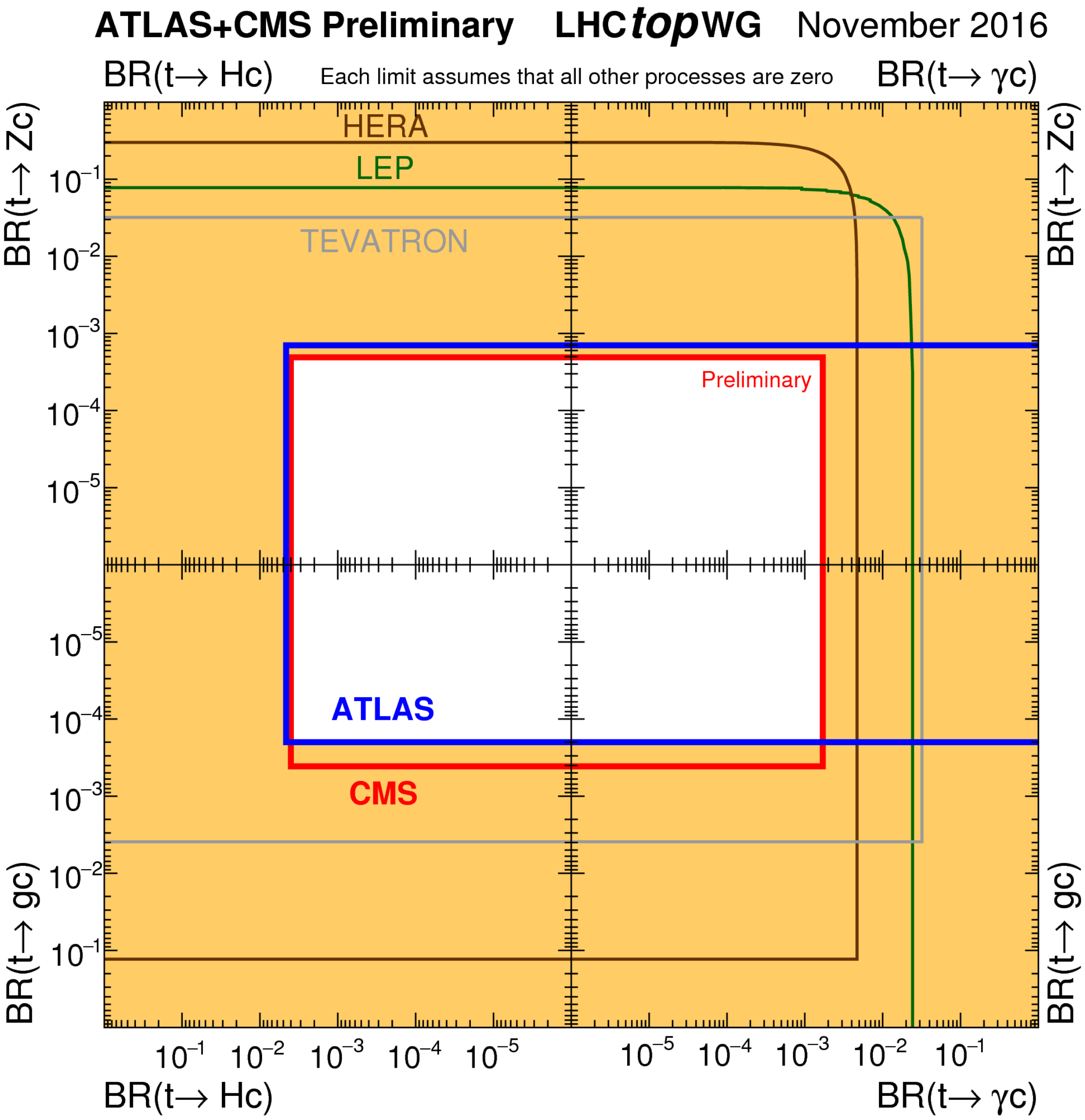
Mangano, Plehn, Reimitz, Schell, Shao, 2015

Top and FCNC

FCNC interactions

tXc

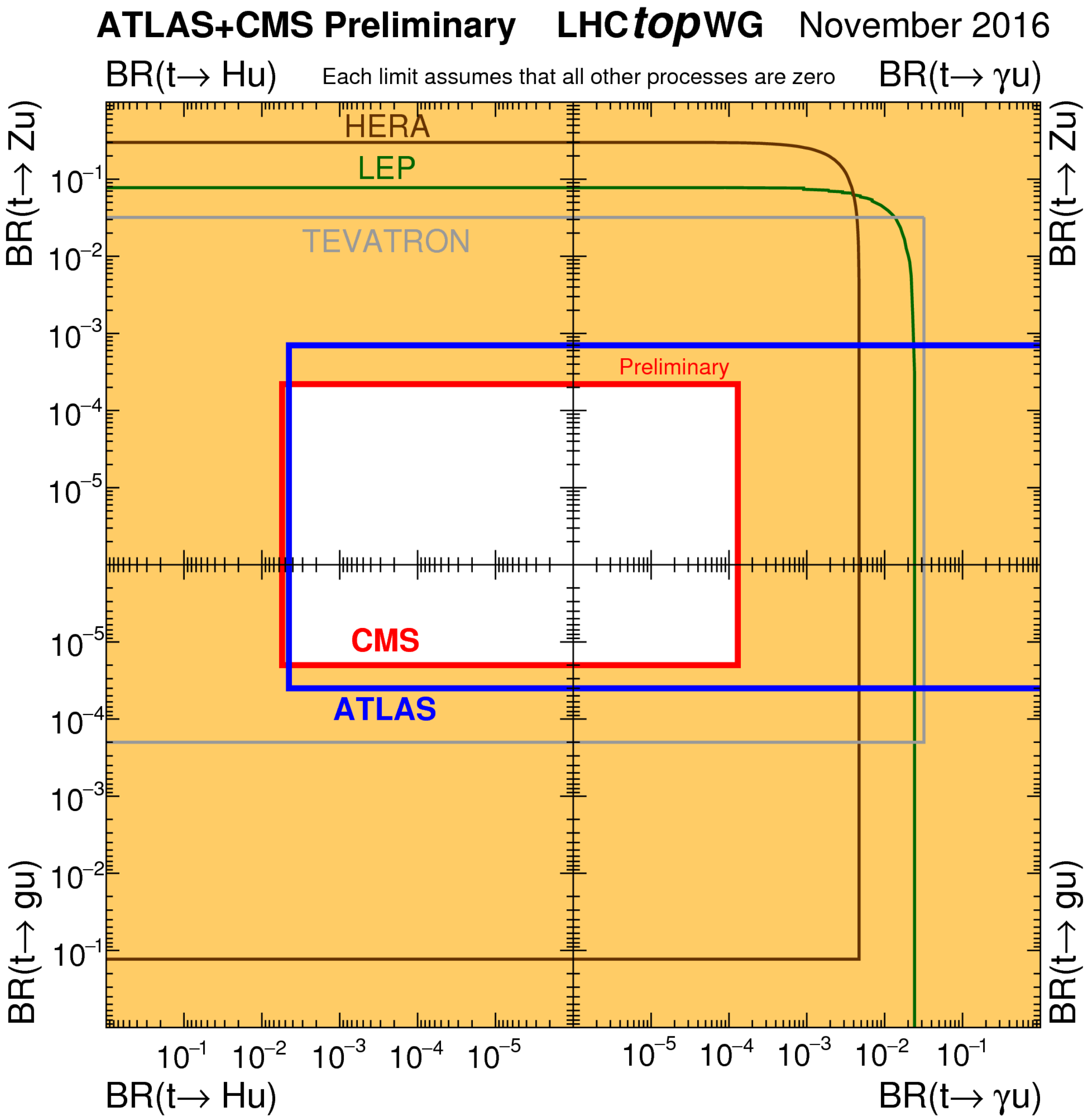
pp → t (CDF/ATLAS)
pp → tj (D0/CMS)
pp → tγ/ll (CMS)
e^+e^- → tj (LEP2)
ep → et (HERA)
t → jγ/ll (CDF/D0/ATLAS/CMS)
t → jh (ATLAS/CMS)



FCNC interactions

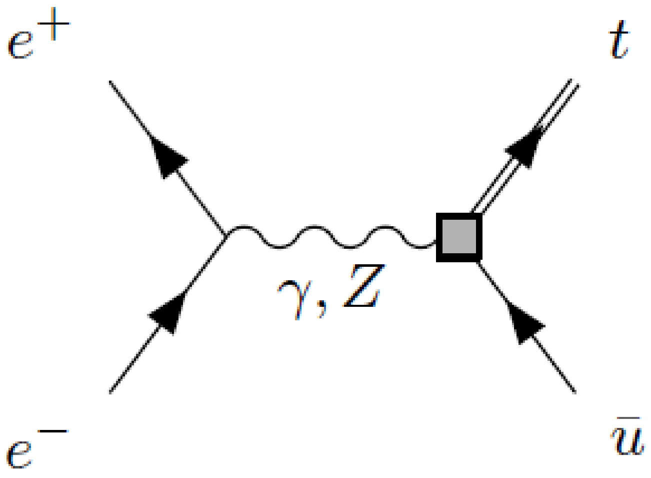
tXu

$pp \to t$ (CDF/ATLAS)
$pp \to tj$ (D0/CMS)
$pp \to t\gamma/ll$ (CMS)
$e^+e^- \to tj$ (LEP2)
$ep \to et$ (HERA)
$t \to j\gamma/ll$ (CDF/D0/ATLAS/CMS)
$t \to jh$ (ATLAS/CMS)



FCNC at lepton colliders

Lepton colliders may provide complementary constraints:



$e^+e^- \rightarrow tj$ production, sensitive to Ztq and γtq

Top physics below $t\bar{t}$ production threshold: limits from LEP2 in arXiv:1412.7166

Prospect studies for ILC (hep-ph/0102197) and FCC-ee (arXiv:1408.2090) indicate potential well beyond equivalent BR < 10^{-4}

Benign experimental environment for “hard” top decays
Expected limits on BR(t → ch) × BR(h → $b\bar{b}$) ~ 10^{-5}
Zarnecki, vd Kolk, preliminary parton-level study

Order of magnitude better than Snowmass expectation for LHC + lumi upgrade

FCNC at future hadron colliders

Searches for rare decays are an obvious strong point for a machine producing billions of top quarks/year

From FCChh SM physics summary (arXiv:1607.01831)
"Performing a naive rescaling of the LHC expectations [...] and assuming a luminosity of 10 ab^{-1} for the FCC, one would expect an improvement of almost two orders of magnitude, reaching a sensitivity of $Br(t \rightarrow qZ; t \rightarrow q\gamma) \sim 10^{-7}$
However, at such a level of precision the systematic uncertainties in the background predictions will likely be dominant, and a more reliable estimation of the sensitivity requires a detailed analysis."

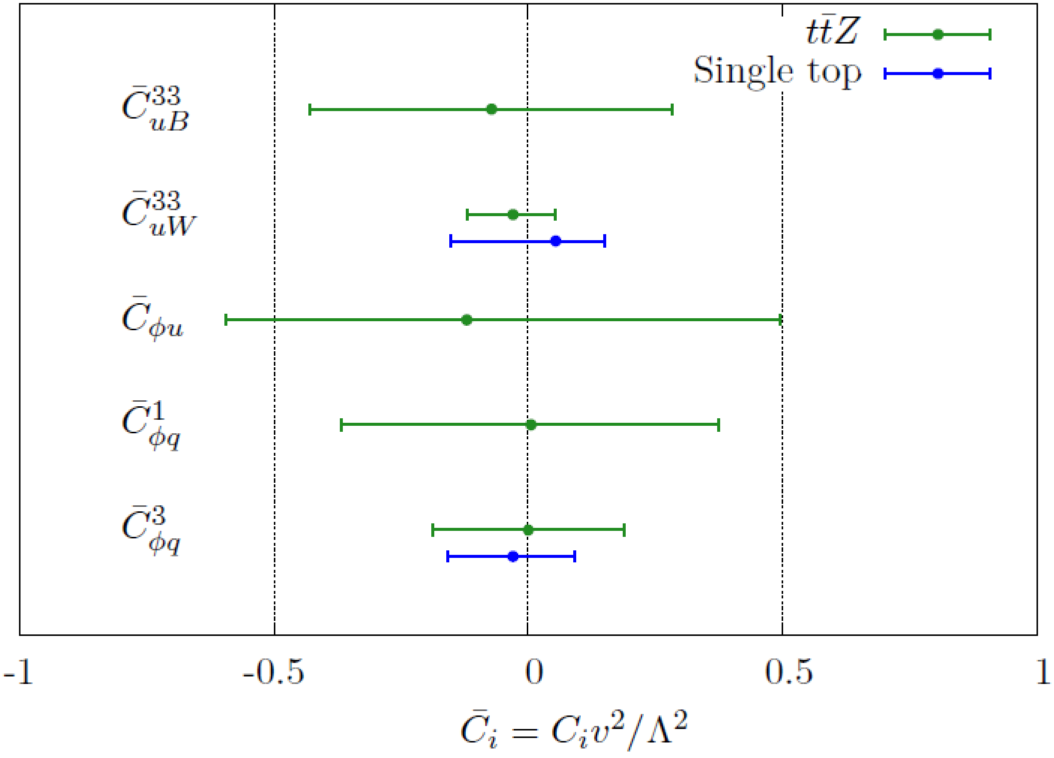
Top EW couplings

Top EW couplings: LHC status

Simultaneous fit to Tevatron and LHC data

arXiv:1506.08845, arXiv:1512.03360

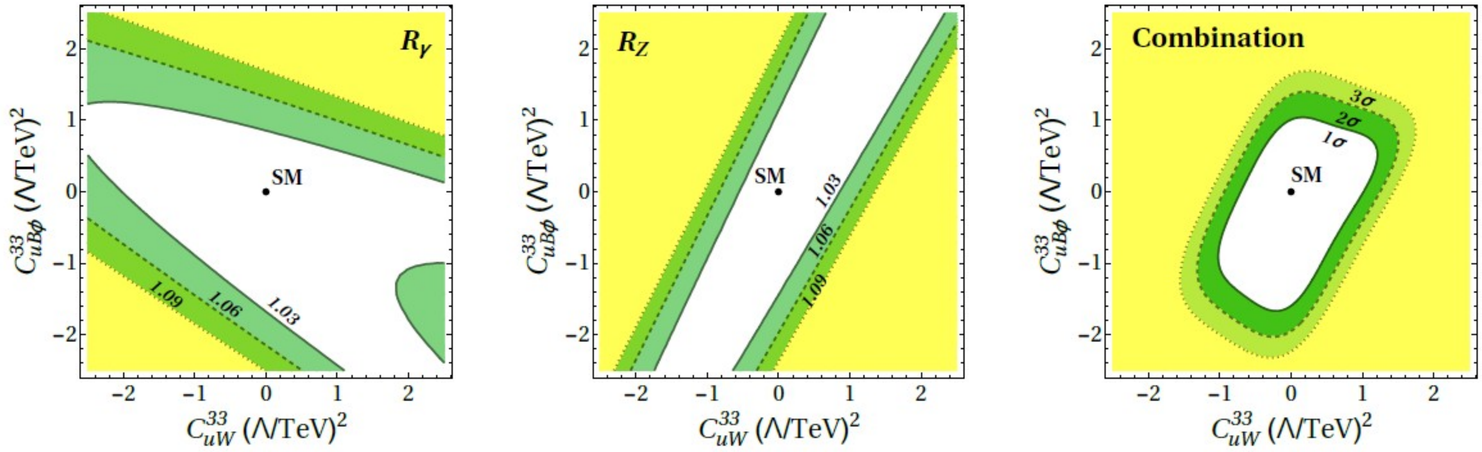
Single top production, ttZ, (top decay)



Associated production at 100 TeV

Analyses of still “rare” processes to profit most from increase in rate.

	$t\bar{t}$	$t\bar{t}t\bar{t}$	$t\bar{t}W^{\pm}$	$t\bar{t}Z^{0}$	$t\bar{t}WW$	$t\bar{t}W^{\pm}Z$	$t\bar{t}ZZ$
σ(pb)	$3.2 \cdot 10^{4}$	4.9	16.8	56.3	1.1	0.17	0.16



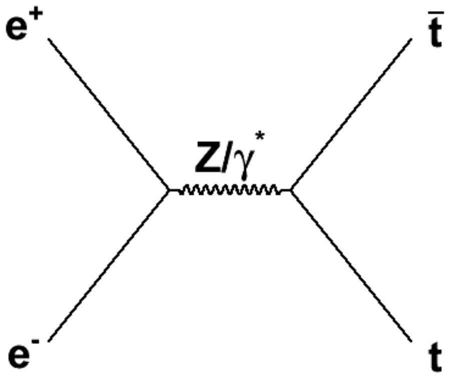
Rontsch & Schulze, arXiv:1501.05939
Schulze & Soreq, arXiv:1603.08911

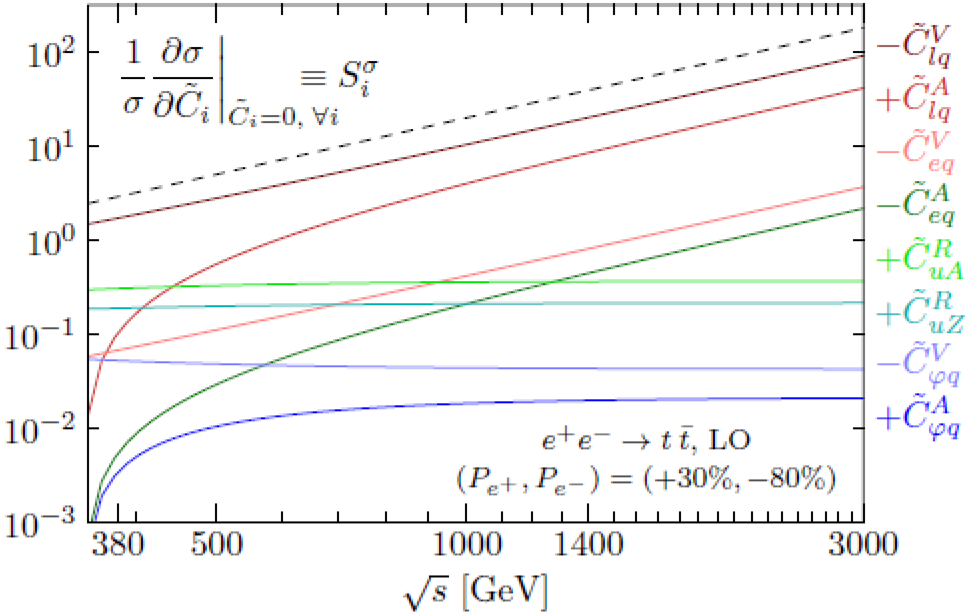
arXiv:1607.01831

	$C_{1,V}$	$C_{1,A}$	$C_{2,V}$	$C_{2,A}$
SM value	0.24	−0.60	< 0.001	$\ll 0.001$
13 TeV, 3 ab^{-1}	[−0.4, +0.5]	[−0.5, −0.7]	[−0.08, +0.08]	[−0.08, +0.08]
100 TeV, 10 ab^{-1}	[+0.2, +0.28]	[−0.63, −0.57]	[−0.02, +0.02]	[−0.02, +0.02]

Lepton colliders

The best laboratory to test $\gamma t\bar{t}$ and $Zt\bar{t}$ vertices





Effect of four-fermion operators (i.e. new massive mediator) best felt at high energy

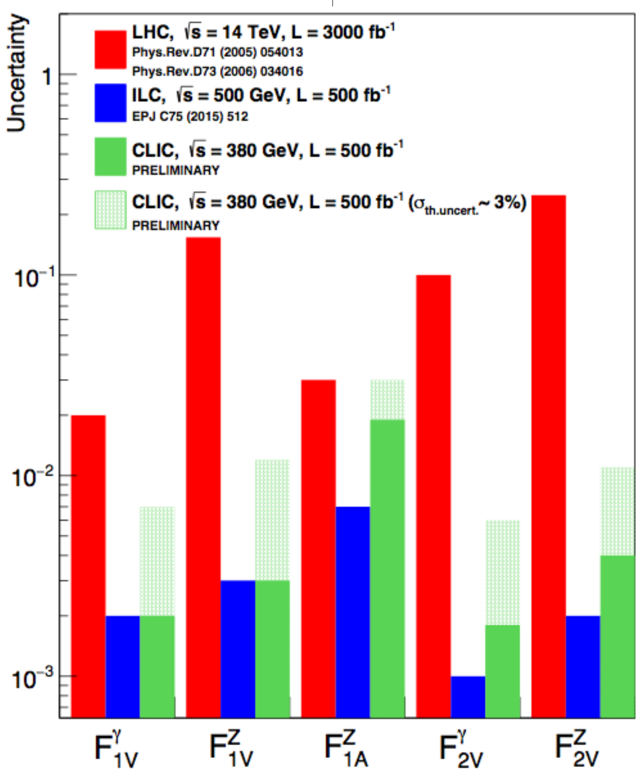
Effect of two-fermion operators (i.e. loop effects on $t\bar{t}X$ vertex) best probed at ~500 GeV

Fit of all operators on measurements of σ, A_{FB} needs two energy points

(Fiolhiais et al., arXiv:1206.1033)

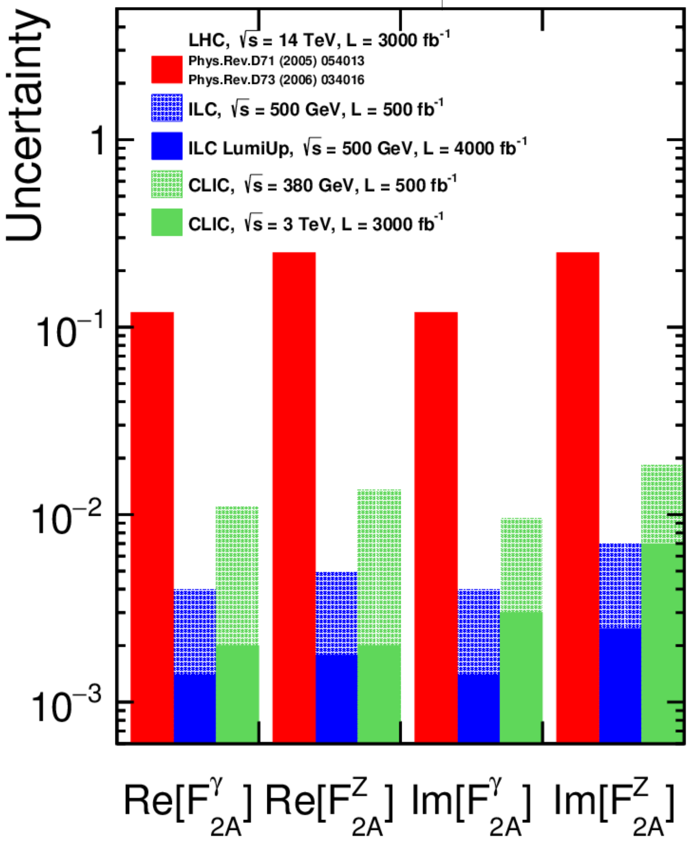
Top EW couplings at lepton colliders

$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(\underline{F_{1V}^X}(k^2)+\gamma_5 \underline{F_{1A}^X}(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(i\underline{F_{2V}^X}(k^2)+\gamma_5 \underline{F_{2A}^X}(k^2)\right)\right\}$$



Prospects for HL-LHC/ILC500/CLIC380

arXiv:1307.8102, arXiv:1505.0620



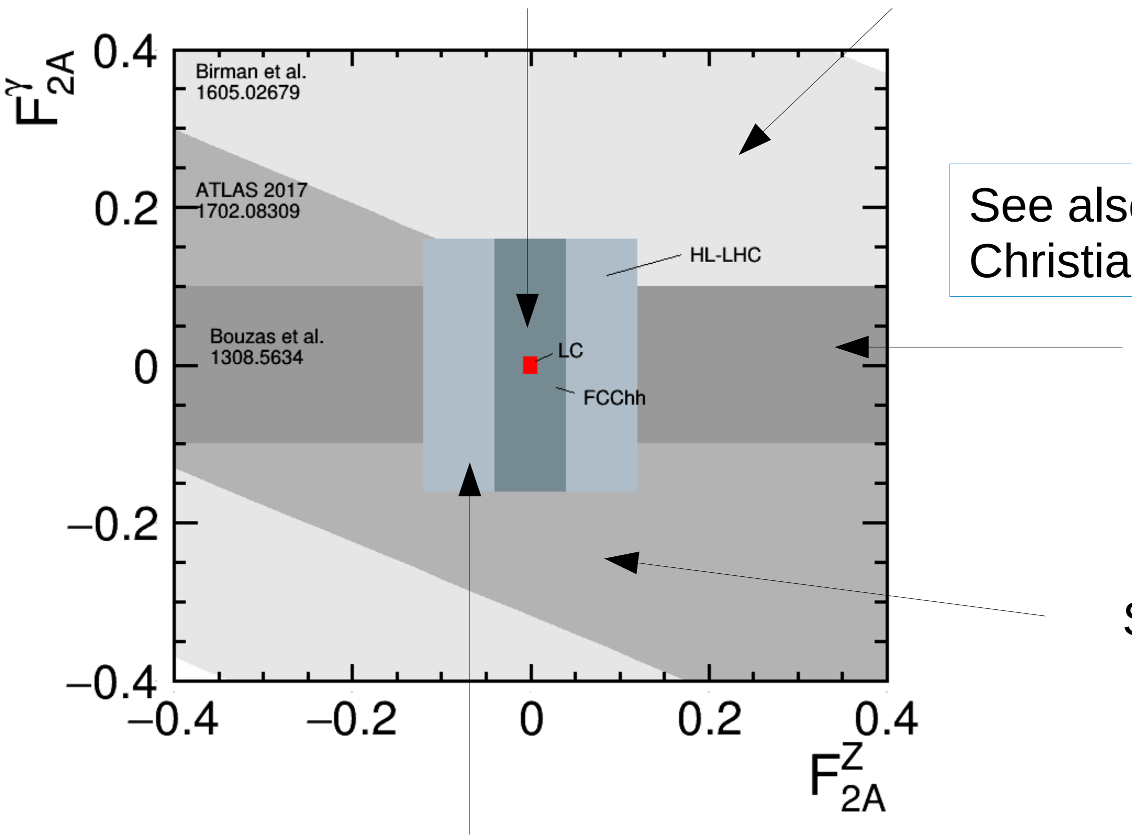
FCC-ee, arXiv:1503.01325, 1509.09056
ILC di-lepton, arXiv:1503.04247

See E. Locci's talk in this track

Many directions to approach the problem

$e^+e^- \to t\bar{t}$

Top decay $t \to Wb$



See also: contribution on ep by Christian Schwanenberger in this track

$eg \to t\bar{t}$

Single top production

Associated production: $pp \to t\bar{t}Z$

Current and future constraints from different processes and colliders on CP violating electric dipole moments of the top quark =f(Im(Ctw), Im(CtB))

The future of EW and top physics: highlights

Lepton collider prospects:

= Z-pole: GigaZ, TeraZ to bring EW fit to the next level
= WW threshold for W mass
Challenges: control of theory/modelling

= 250 GeV: W phyiscs, searches for exotic single-top production

= 350 GeV: top mass measurement to 50 MeV precision
> 350 GeV: Unrivalled sensitivity to ttZ and ttγ vertices
> 550 GeV: direct top Yukawa coupling to 3-4%
>> 1-3 TeV: limits on anomalous top EW, TGC and QGC couplings
Challenges: control of systematics to per mille level

100 TeV hadron collider targets:

Greatly enchaned mass reach for searches, access to rare processes
Constraint of ttg vertex improves by an order of magnitude
(and qqtt 4-fermion operators)
Top Yukawa coupling to 1%
FCNC, top mass, W mass potential to be evaluated
Challenges: control of systematics to % level, ultra-boosted production

Lessons and future work

Top and EW precision physics may deliver the transformative discovery that this field needs

Each of the future facilities offers exciting new possibilities, with quite complementary sensitivity to high-scale new physics

Comparison is hard! Take advantage of EFT machinery to compare the potential different processes/machines