top physics beyond the LHC

Mini-review of future collider top physics prospects

ECT* workshop,

Old and new strong interactions from the LHC to future colliders,

Trento, 13 September 2017

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

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Why am I inderested in top physics?

Top escaped direct scrutiny at LEP
→ more room for surprises

Top is massive:
→ tight connection with the Higgs boson
→ predilected quark in BSM?

Top is a fun quark
→ bare quark
→ readily isolated with W → lν
→ polarization accessible
→ quark-anti-quark tagging (CP violation)

A brief history of top quark physics

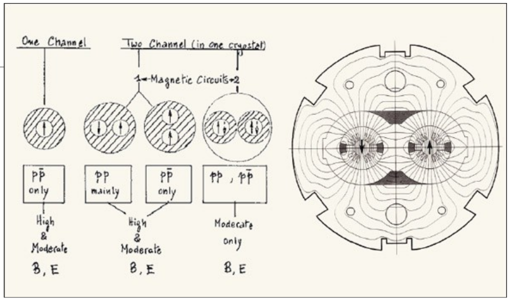
Particle physics was so easy back then!

1972: a 5M$ collider starts operation on a SLAC parking lot

1973: The top quark is born as a hypothetical particle

1974: Two colliders in one country discover the same particle

1984: First LHC workshop



1994: SSC canceled

1995: top quark discovery at FNAL

"*Abandoning the SSC at this point would signal that the United States is compromising its position of leadership in basic science*", Bill Clinton, 1993

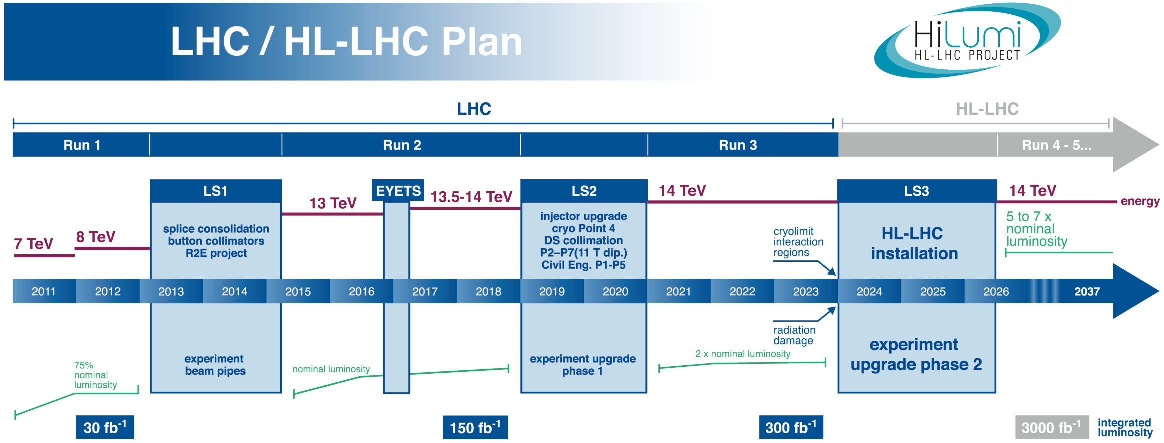
2010: start of the LHC (top turns 25)

2020: decision on next collider?

2035: start of operation

Future projects

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 - show a detailed engineering design & costing
- c - make a compelling physics case

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

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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

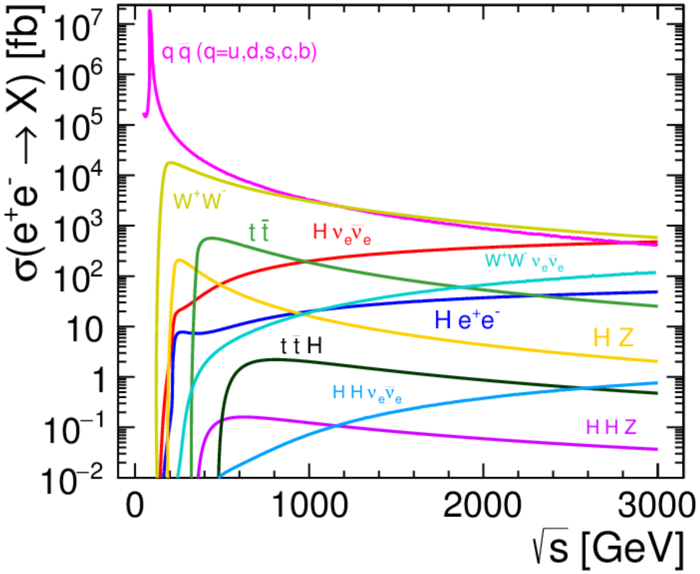
Theory: no PDFs, small QCD corrections
Predictions at few per-mille level already today!

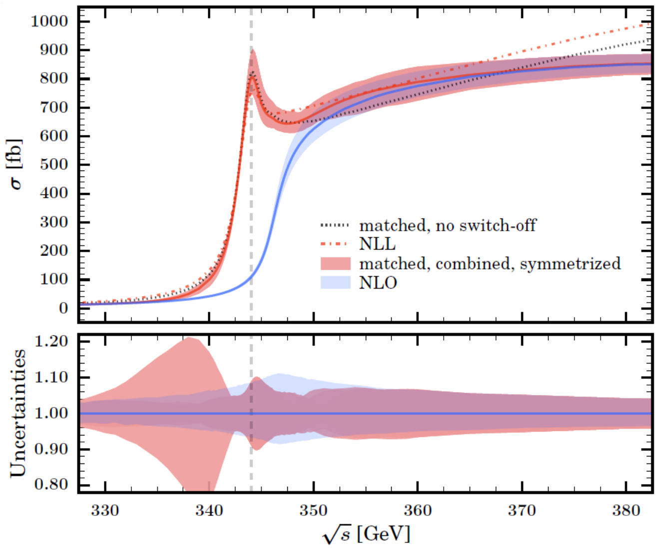
Selection: democratic cross sections allow for truly inclusive measurements (no trigger!)

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

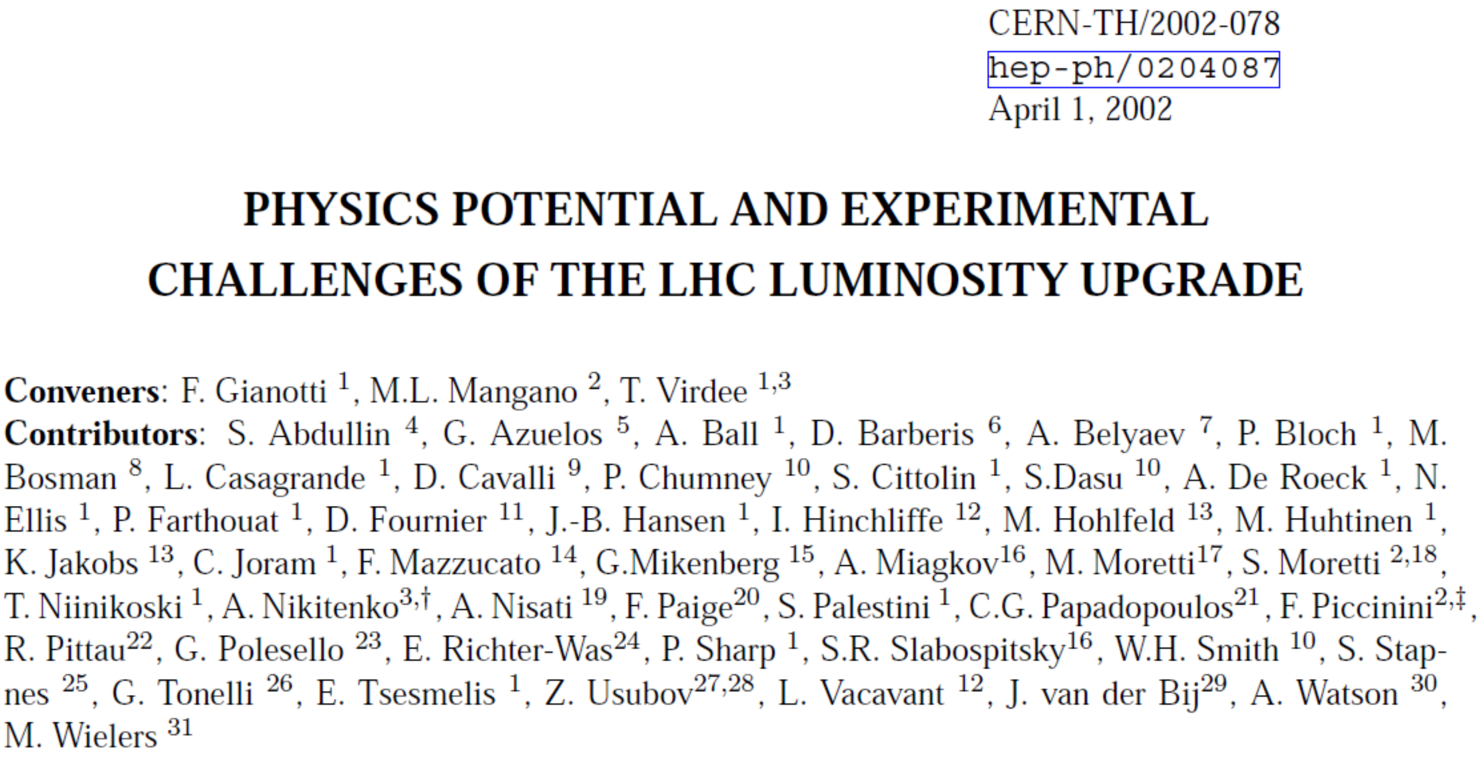
Challenge: excellent detectors to make sure the experiment matches few per mille theory precision

See also: Chokoufé et al., arXiv:1609.03390





LHC + HL-LHC top physics expectations



CERN-TH/2002-078
hep-ph/0204087
April 1, 2002

PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

Conveners: F. Gianotti [1], M.L. Mangano [2], T. Virdee [1,3]
Contributors: S. Abdullin [4], G. Azuelos [5], A. Ball [1], D. Barberis [6], A. Belyaev [7], P. Bloch [1], M. Bosman [8], L. Casagrande [1], D. Cavalli [9], P. Chumney [10], S. Cittolin [1], S.Dasu [10], A. De Roeck [1], N. Ellis [1], P. Farthouat [1], D. Fournier [11], J.-B. Hansen [1], I. Hinchliffe [12], M. Hohlfeld [13], M. Huhtinen [1], K. Jakobs [13], C. Joram [1], F. Mazzucato [14], G.Mikenberg [15], A. Miagkov[16], M. Moretti[17], S. Moretti [2,18], T. Niinikoski [1], A. Nikitenko[3,†], A. Nisati [19], F. Paige[20], S. Palestini [1], C.G. Papadopoulos[21], F. Piccinini[2,‡], R. Pittau[22], G. Polesello [23], E. Richter-Was[24], P. Sharp [1], S.R. Slabospitsky[16], W.H. Smith [10], S. Stapnes [25], G. Tonelli [26], E. Tsesmelis [1], Z. Usubov[27,28], L. Vacavant [12], J. van der Bij[29], A. Watson [30], M. Wielers [31]

The top quark physics chapter starts: “Given the large top quark cross-section, most of the top physics programme should be completed during the first few years of LHC operation [32]. In particular, **the $t\bar{t}$ and the single-top production cross-sections should be measured more precisely than the expected theoretical uncertainties**, and the determination of the **top mass should reach an uncertainty (dominated by systematics) of ∼ 1 GeV, beyond which more data offer no obvious improvement.”**

Promise: the remainder of the LHC programme will be more exciting than that!!

For an updated HL-LHC case, see: M. Cristianzini, P. Azzi, TOP2016

Top 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

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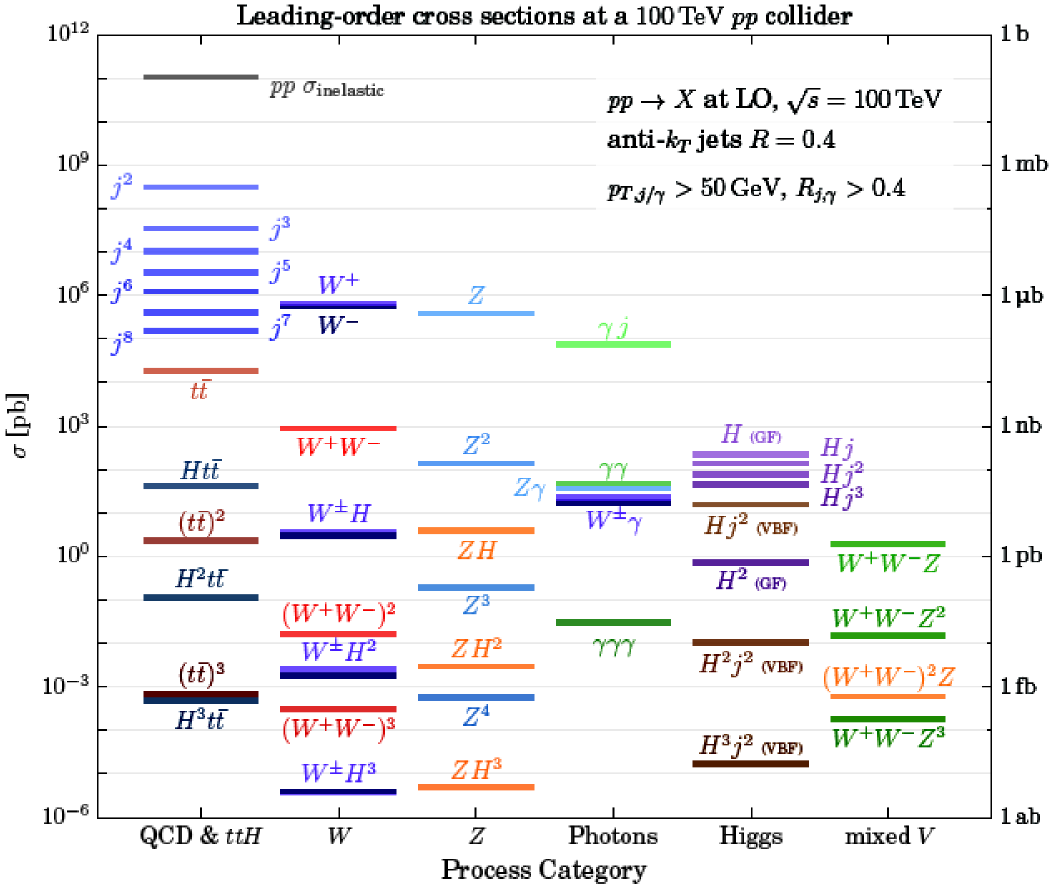
tt production	**57 k**	**2.6 M**	**15.5 M**	**155 M**	**1.55 G**

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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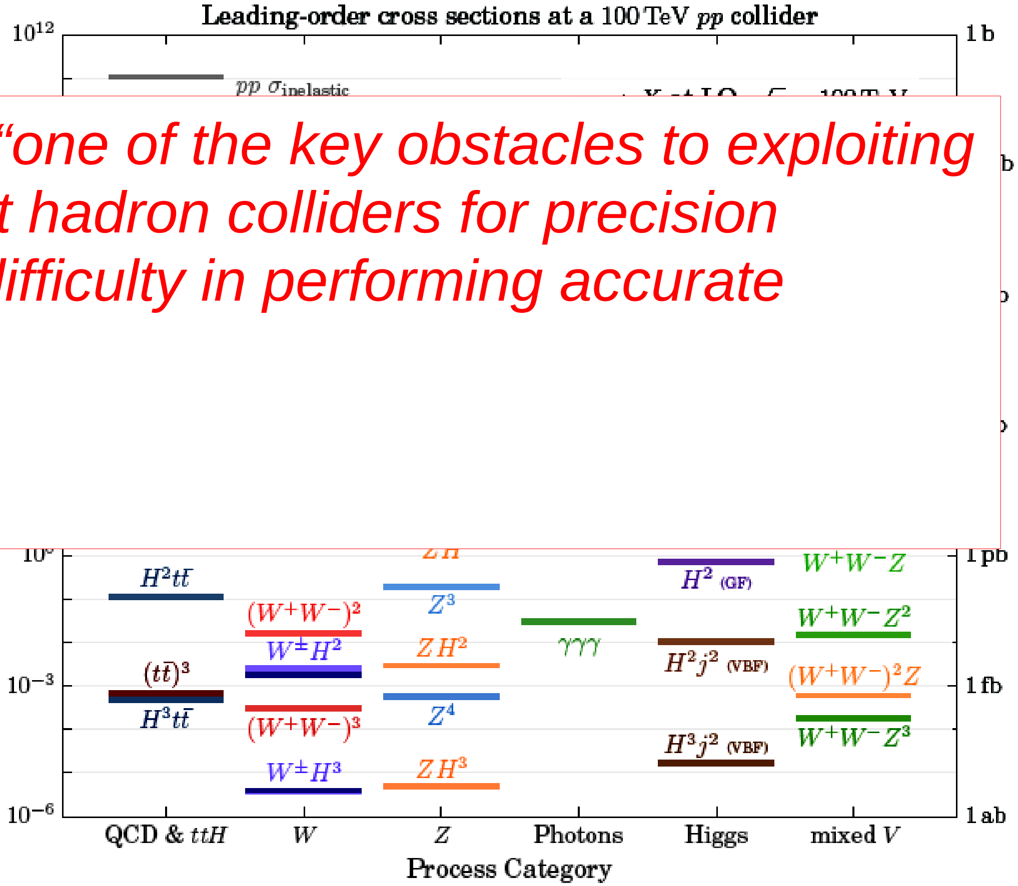
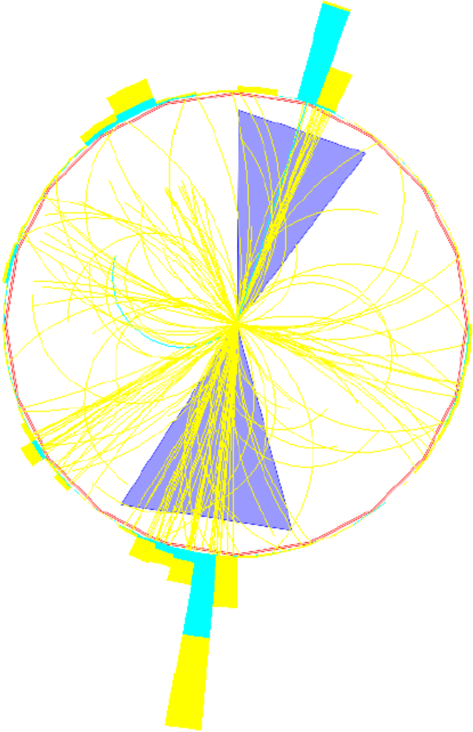
FCChh and SPPC



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

FCChh BSM summary: *arXiv:1606.00947*

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

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)

Indirect sensitivity can exceed √s significantly

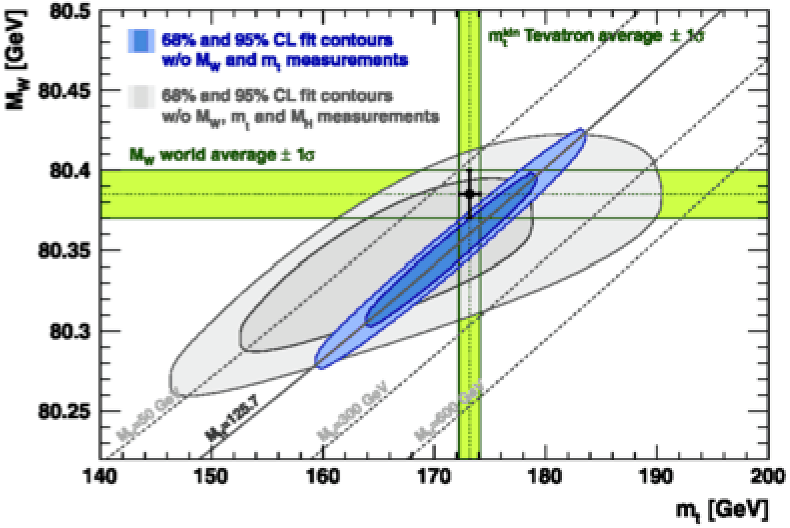
LEP EW fit felt the top quark and Higgs bosons, B-factories probe high scales

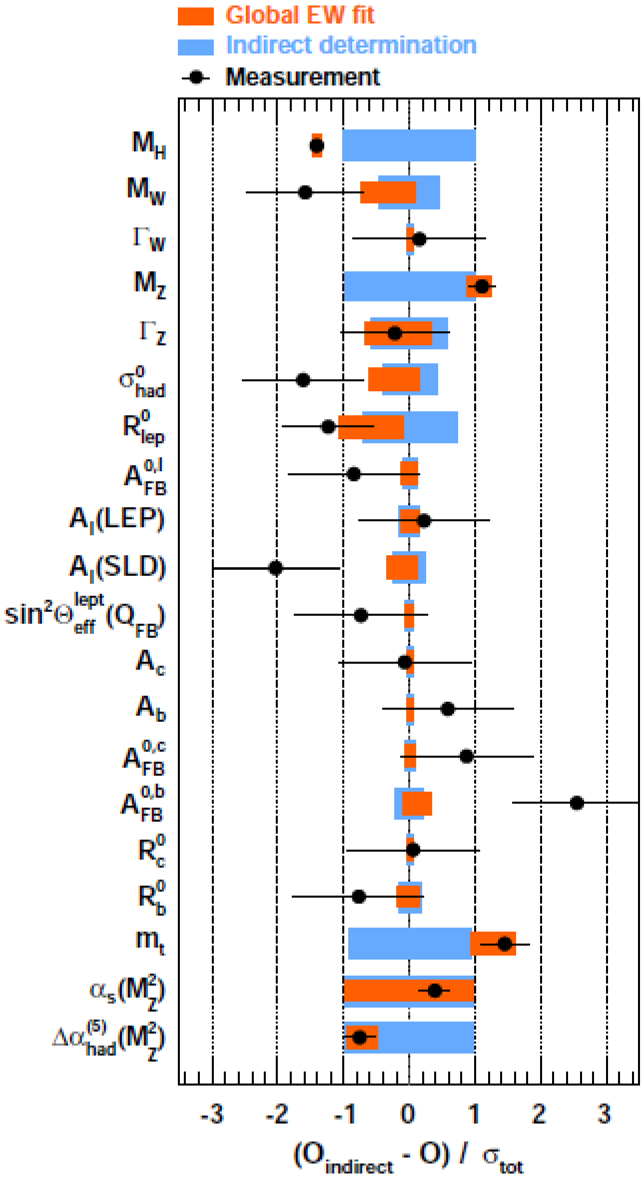
EW fit

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

top quark mass revisited

Precision already well beyond 1 GeV. Direct mass can reach 200-300 MeV

(CMS-FTR-13-007-PAS, CMS-FTR-16-006, “*optimistic, but not unrealistic*”)

Needs a reliable recipe for hadronization uncertainties
→ go beyond Pythia vs. Herwig

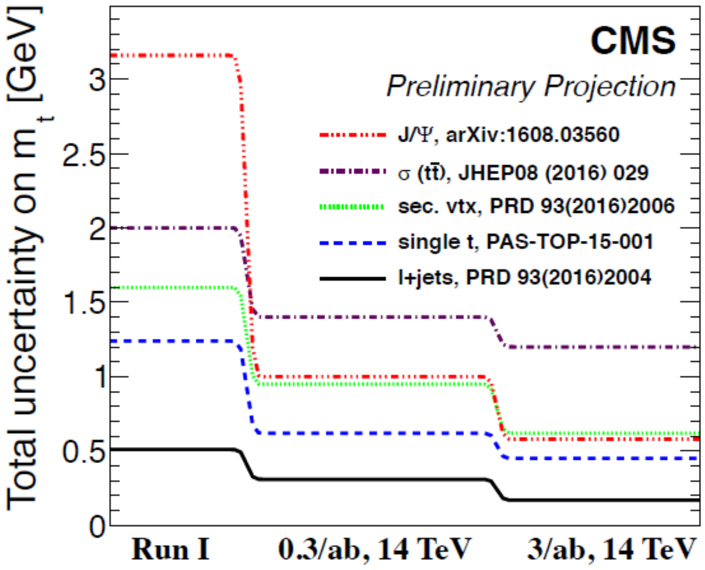
Interpretation of direct mass measurement hotly debated

(Hoang et al., PRL117, Beneke et al., arXiv:1605.03609)

See P. Nason in this session and
G. Corcella's talk at EPS2017

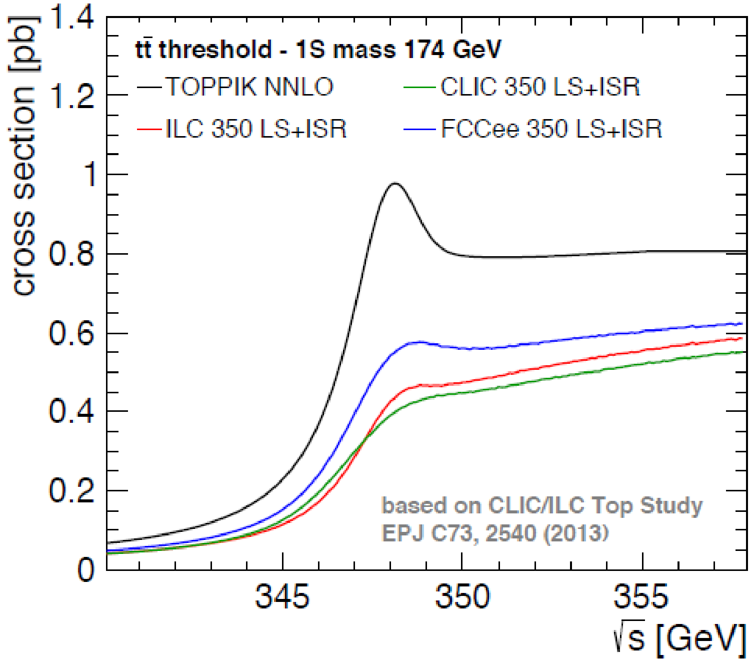
*Status quo: distinguish between **“mass”** measurements (that need an additional theory uncertainty) and proper **“pole mass”** measurements*

Progress below 500 MeV requires significant experimental and theory work *(arXiv:1310.0799)*



Can extractions with unambiguous interpretation reach competitive precision?
Here, I'm more optimistic than CMS.

Top quark mass



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: F. Simon on Monday.
Recent review: arXiv:1604.08122

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3 decades of top quark mass measurements...

Tevatron: discovery (1995) and first characterization

- Legacy δm_t < 1 GeV

LHC: direct measurements

- *Today: 500 MeV*
- *Exp. Prospects: 200 MeV*
- *Interpretation to match this precision...*

LHC: extract top pole mass from cross-section

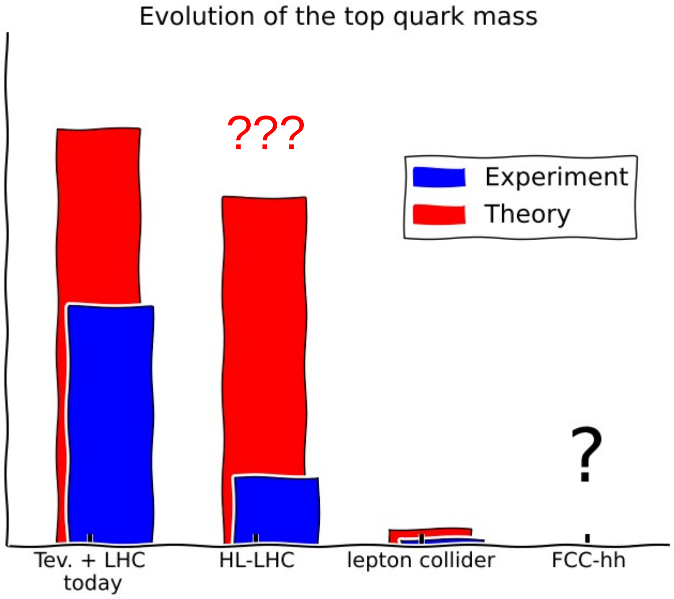
- *Today: δm_t < 2 GeV*
- *Rigorous interpretation*
- *Can reach ~1 GeV precision*

Future lepton collider

- *threshold scan*
- *50 MeV precision!*

Future 100 TeV pp collider:

- *?*



Top and QCD

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Global SM (+BSM) fit

EFT offers a systematically improvable approach to perform (sector-by-sector semi-) global fits

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

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

This is not a post-processing of the data. EFT sensitivity should inform the experimental strategy → design BSM-oriented SM measurements

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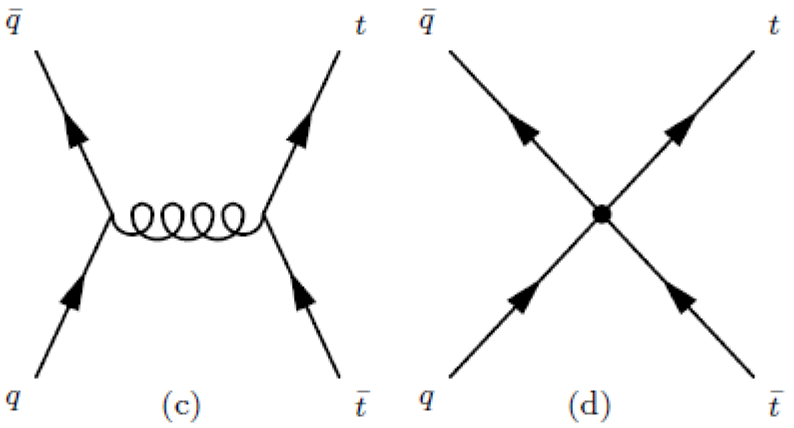
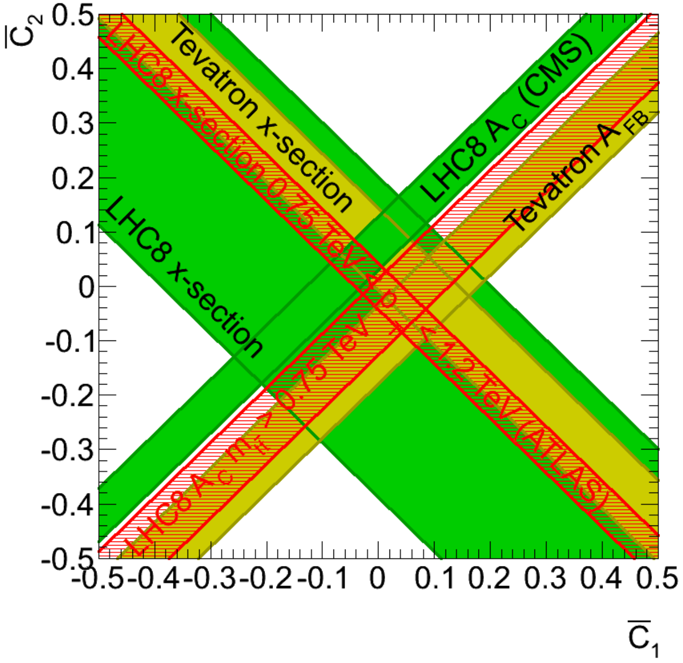
Tevatron-LHC potential to constrain four-fermion operators

BSM exchange represented by D6 4-fermion operators



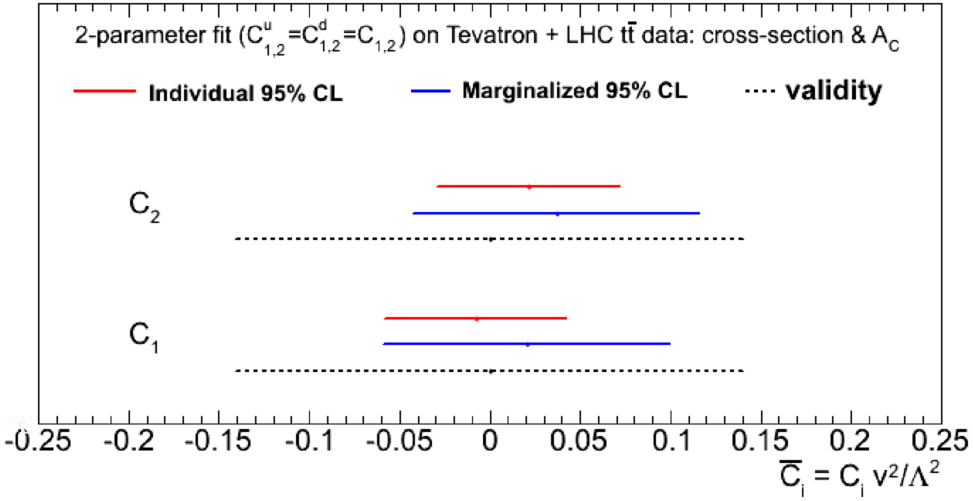


Cross-section and A_C provide complementary constraints

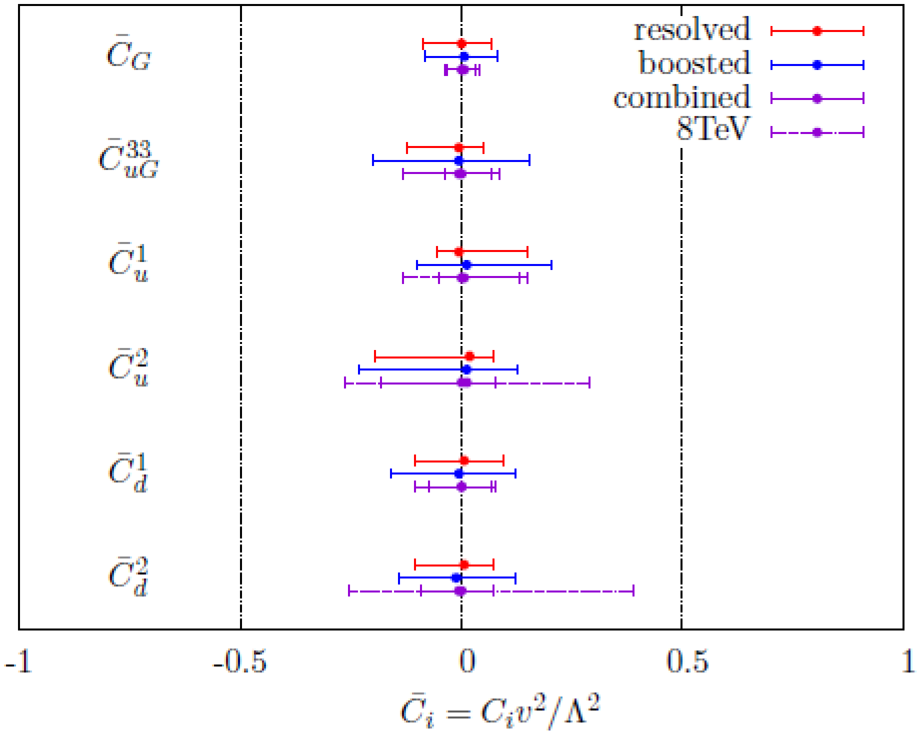
Charge asymmetry is a ratio: not limited by theory uncertainty

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

M. Perelló, M.V., arXiv:1512.07542



Top and QCD

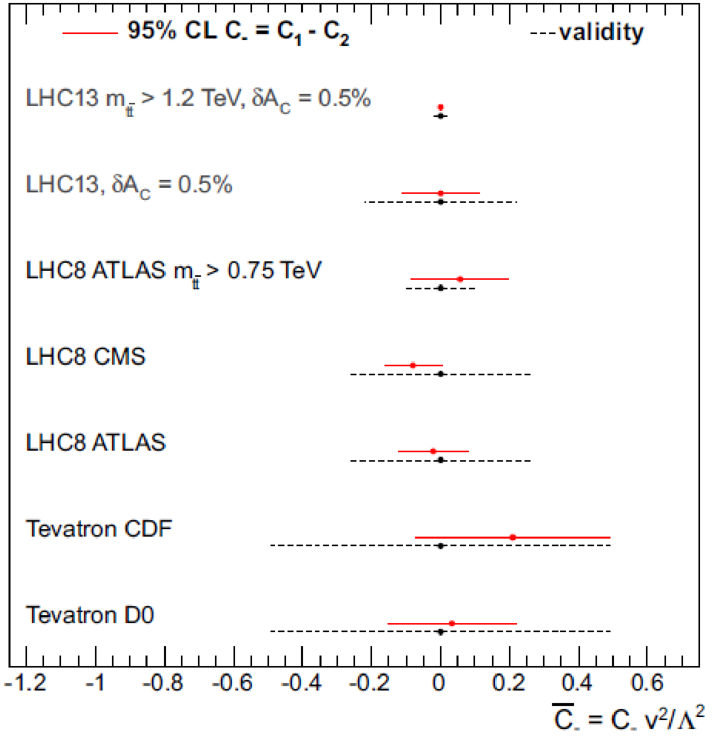


Today (8 TeV fit): resolved and boosted category offer similar sensitivity
Englert et al., arXiv:1607.04304

Inclusive measurement syst-limited
Boosted expected to improve quicker

Not-too-distant future:

measurement of the charge asymmetry with m(tt)>1.2 TeV and 0.5% precision shrinks the allowed region for Wilson coefficients C_1 and C_2 of 4-fermion operators by a factor 10
arXiv:1512.07542



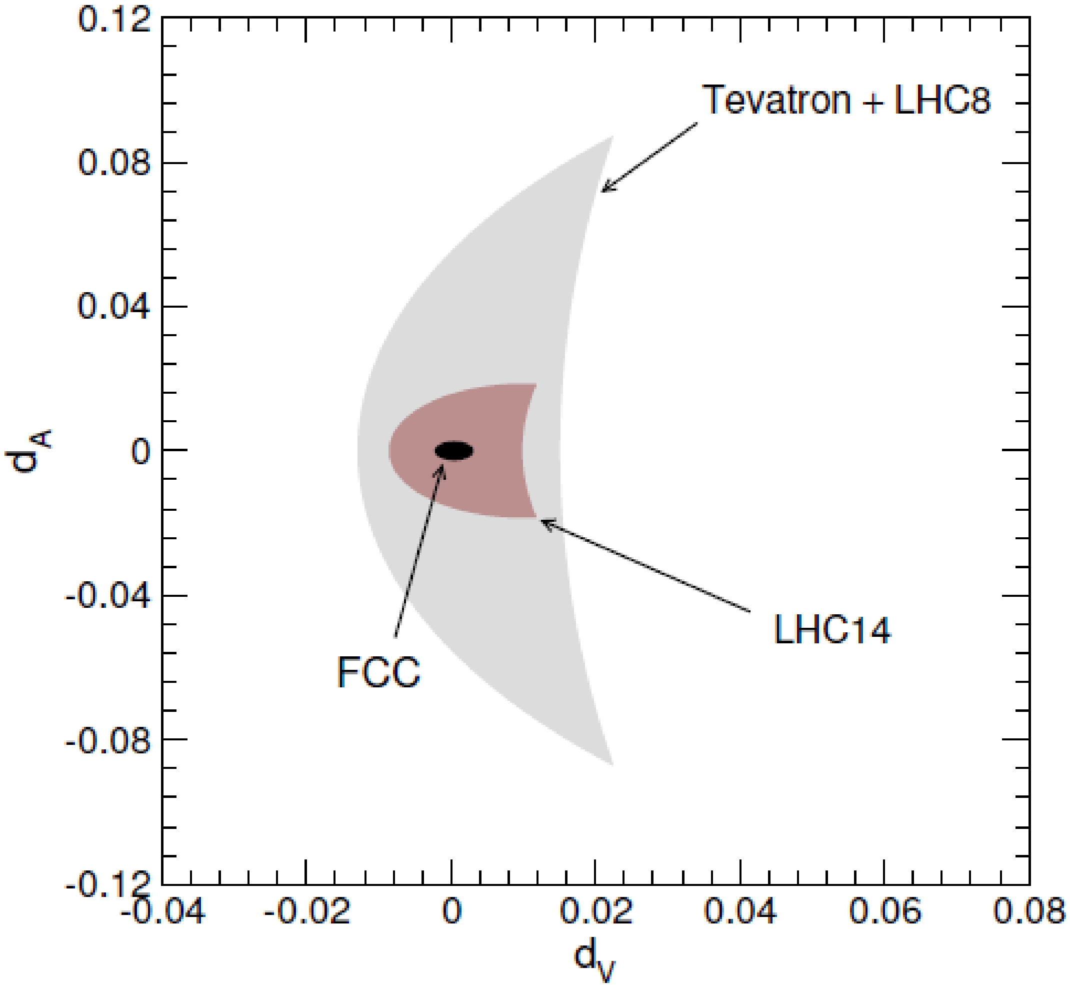
Top and QCD

Aguilar-Saavedra et al.,
arXiv:1412.6654

Top quark chromomagnetic and chromoelectric dipole moments

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

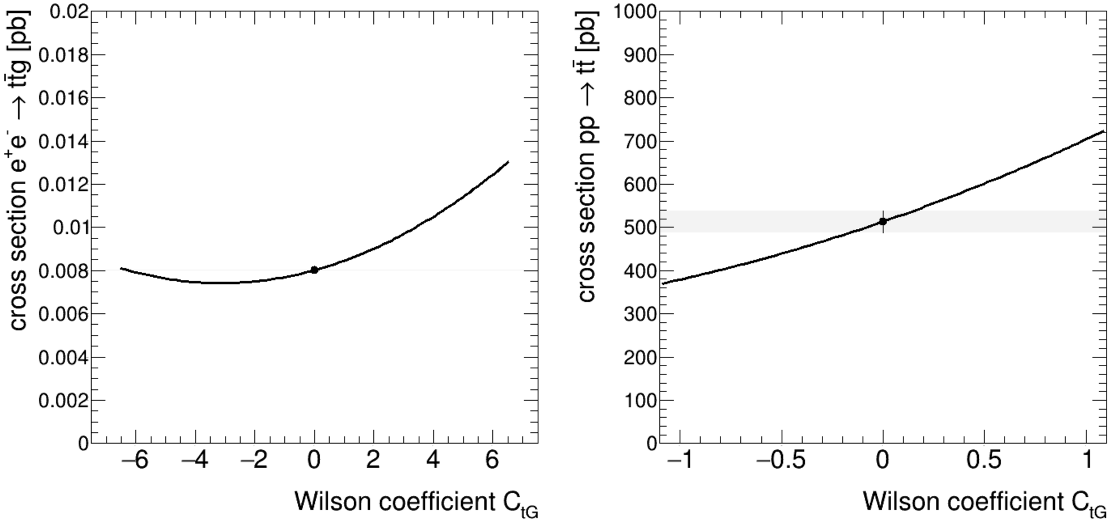
Ultra-boosted: m($t\bar{t}$) > 10 TeV
Top decay to bμν
Assume 5% systematic

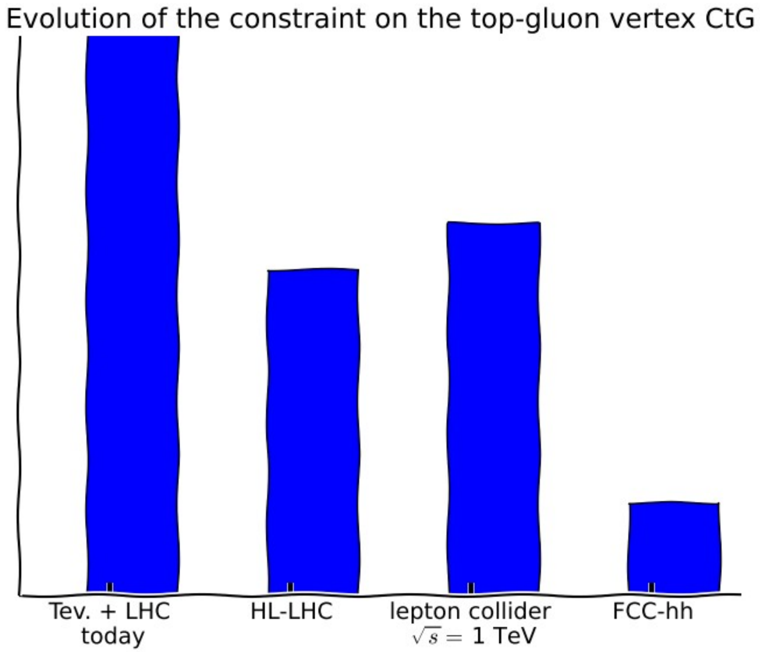


Further studies would also be desirable to evaluate the complementarity of the measurements discussed in this paper, with those possible with e^+e^- collisions

HL-LHC still has an order of magnitude to go
100 TeV collider can gain another order

Top-gluon couplings at lepton colliders





$e^+e^- \to$ ttg can be competitive with HL-LHC provided precision goes well below a %.

NLO scale uncertainties are O(1%) level at $\sqrt{s}$ = 1 TeV, E_g > 200 GeV

Update (M.V., M. Perelló) of old study T. Rizzo, hep-ph/9506351, hep-ph/9605370

Top and Higgs

Top quark Yukawa coupling

Prospects at lepton colliders

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

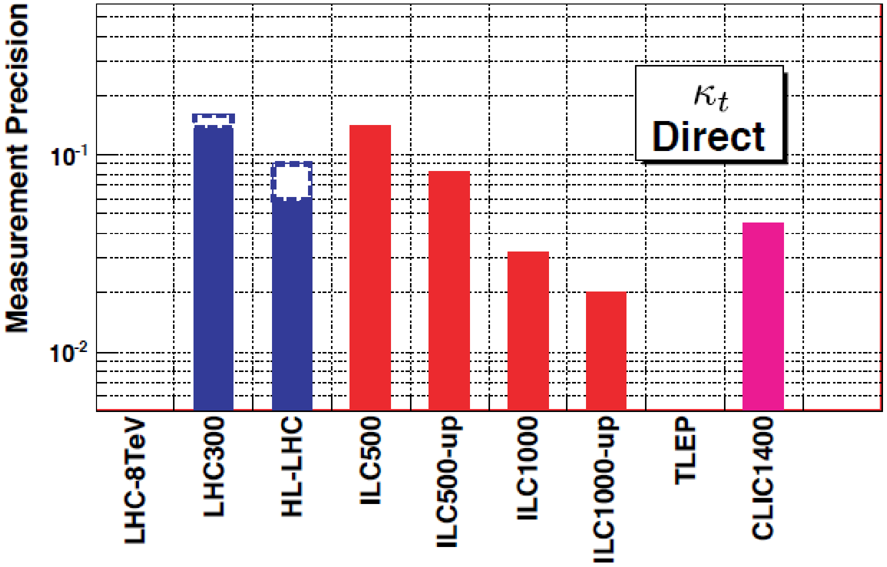
arXiv:1506.05992

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

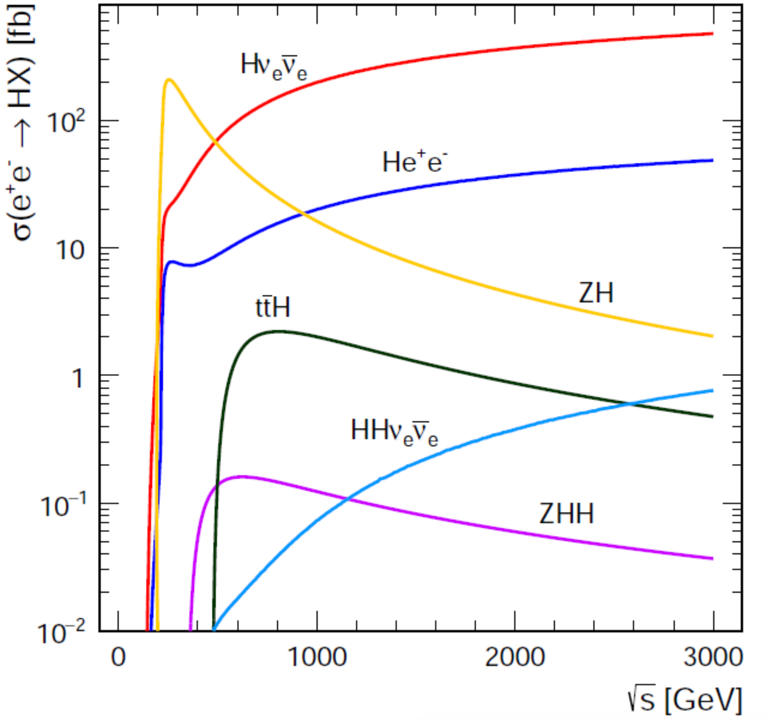


Prospects for full LHC programme:

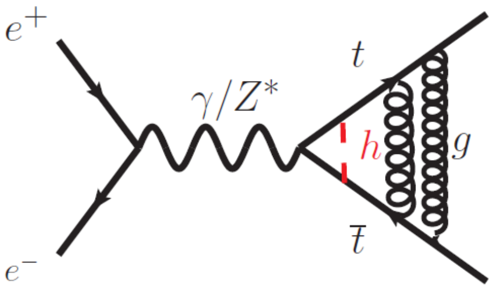
K_u → 14-15% (300/fb)

K_u → 7-10% (3/ab)

Snowmass Higgs report



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

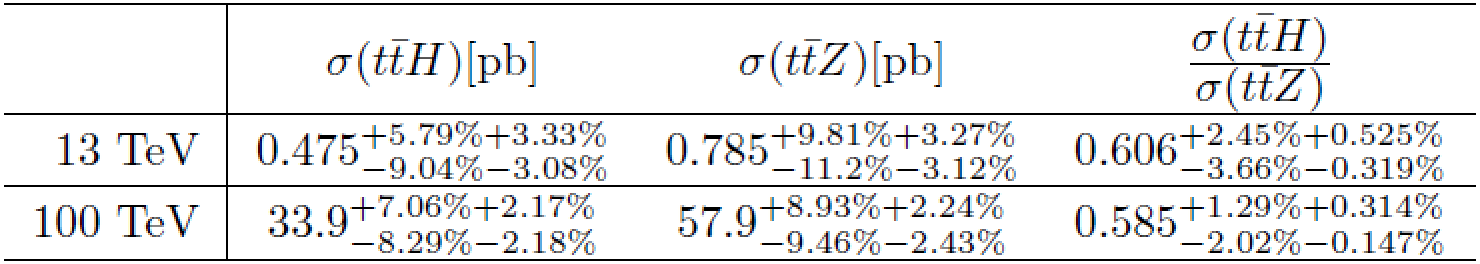


Horiguchi et al., arXiv:1310.0563

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:

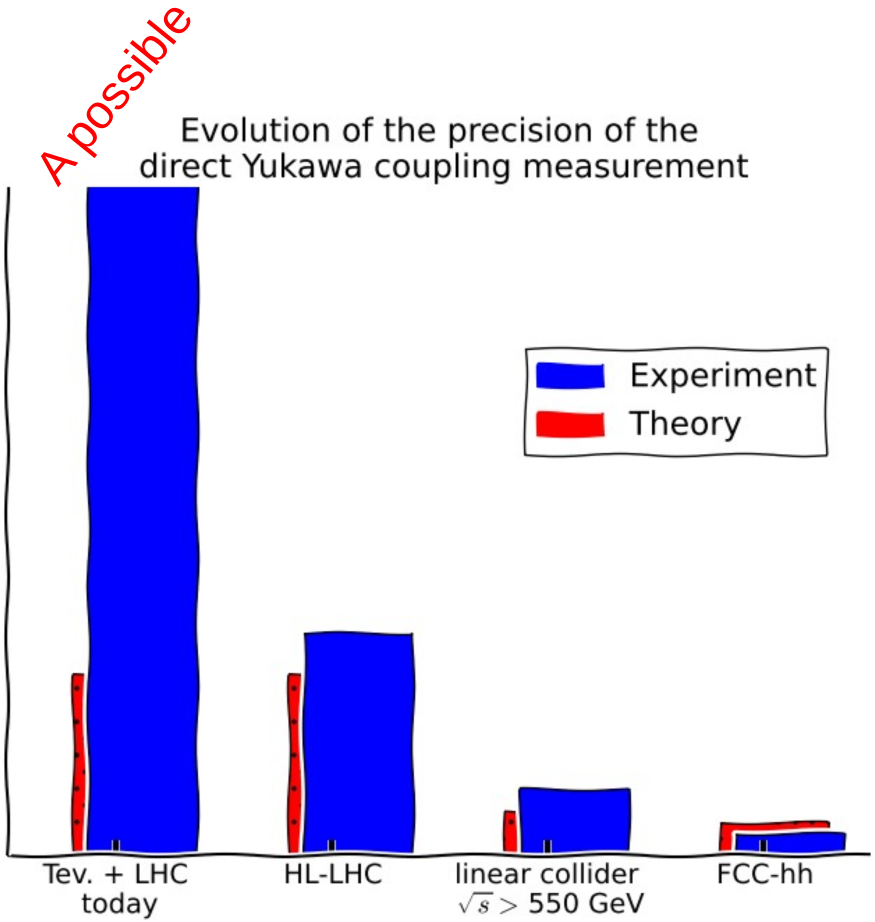
Tevatron A_{FB}, recent ATLAS $t\bar{t}$/Z ratio (*arXiv:1612.03636*)

FCChh fast simulation study:

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

Mangano, Plehn, Reimitz, Schell, Shao, 2015

Top and Higgs - summary

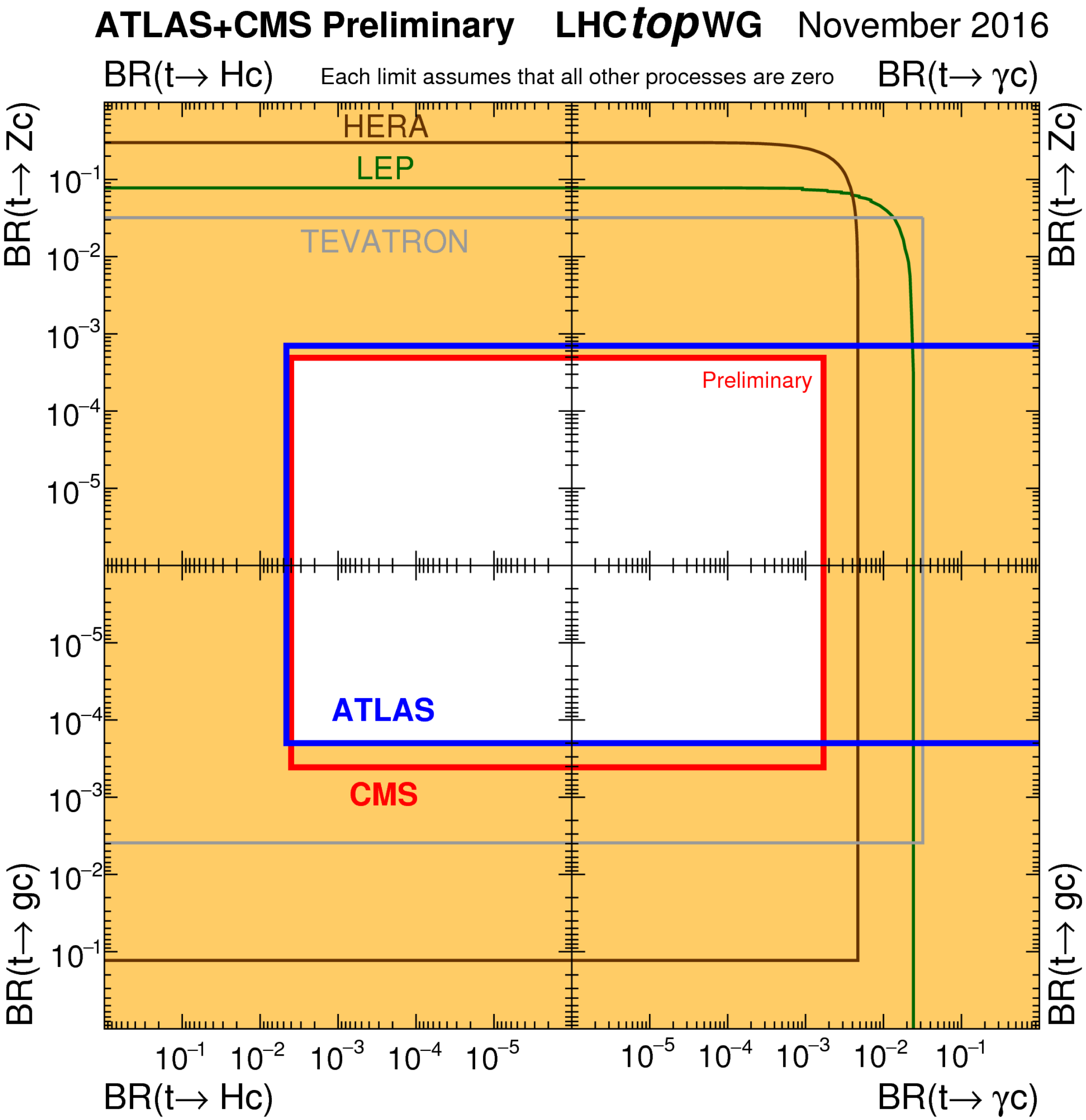


Note: sensitivity similar at FCChh and HL-LHC
theory uncertainty can be reduced also at HL-LHC

Top and FCNC

FCNC interactions

tXc

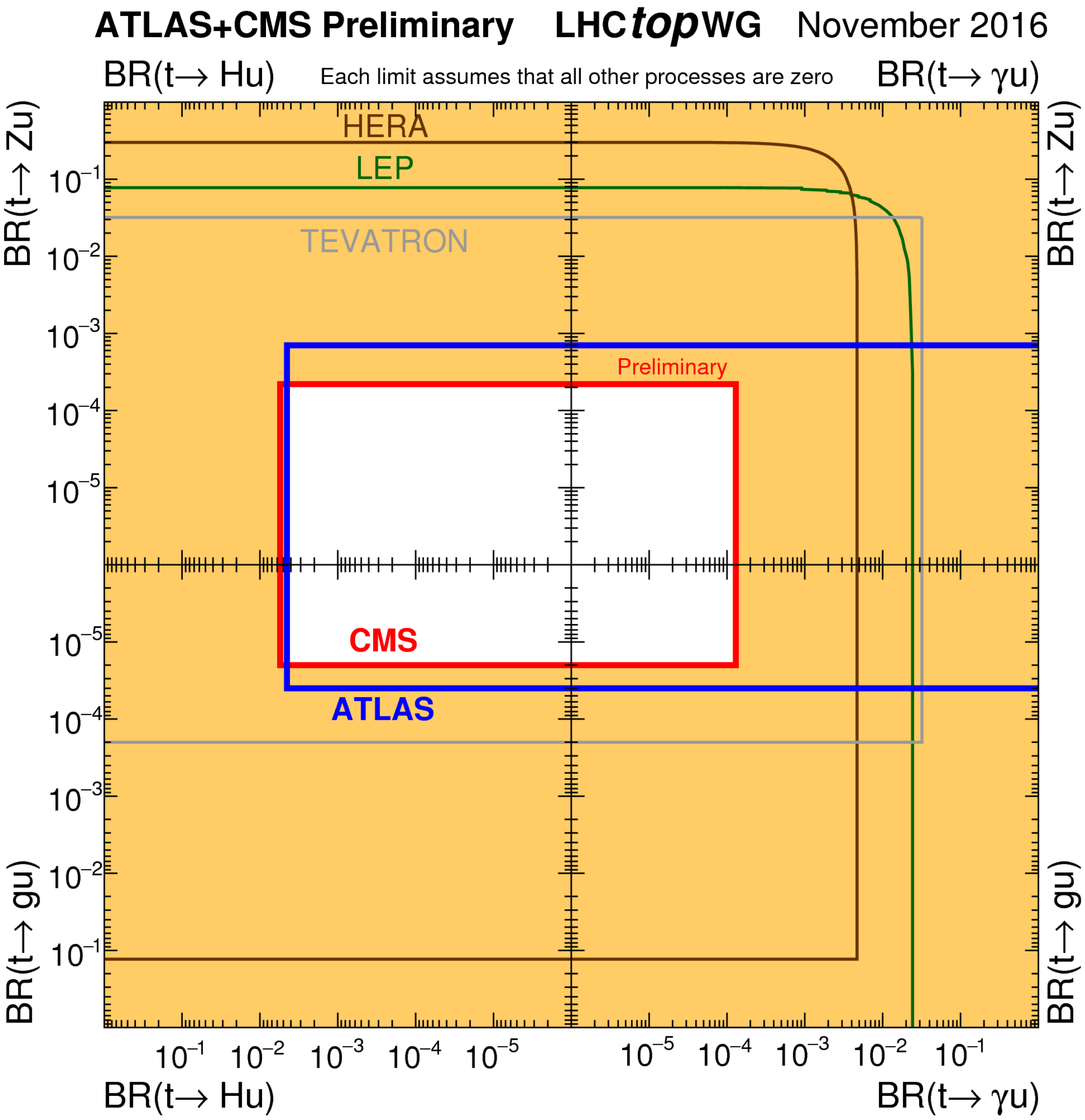


pp → *t* (CDF/ATLAS)
pp → *tj* (D0/CMS)
pp → *tγ/ll* (CMS)
e^+e^- → *tj* (LEP2)
ep → *et* (HERA)
t → *jγ/ll* (CDF/D0/ATLAS/CMS)
t → *jh* (ATLAS/CMS)

FCNC interactions

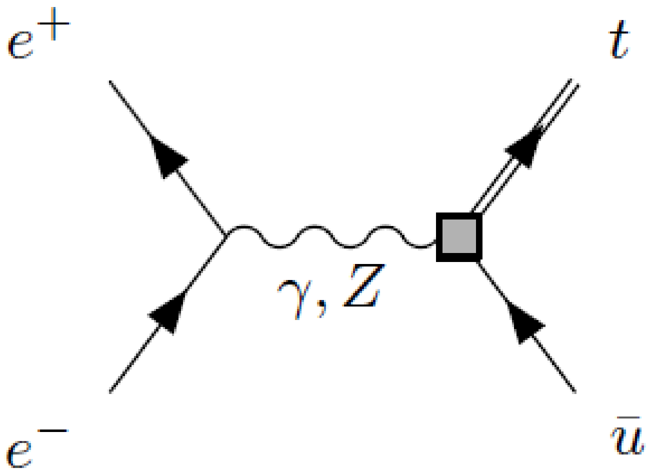
tXu

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

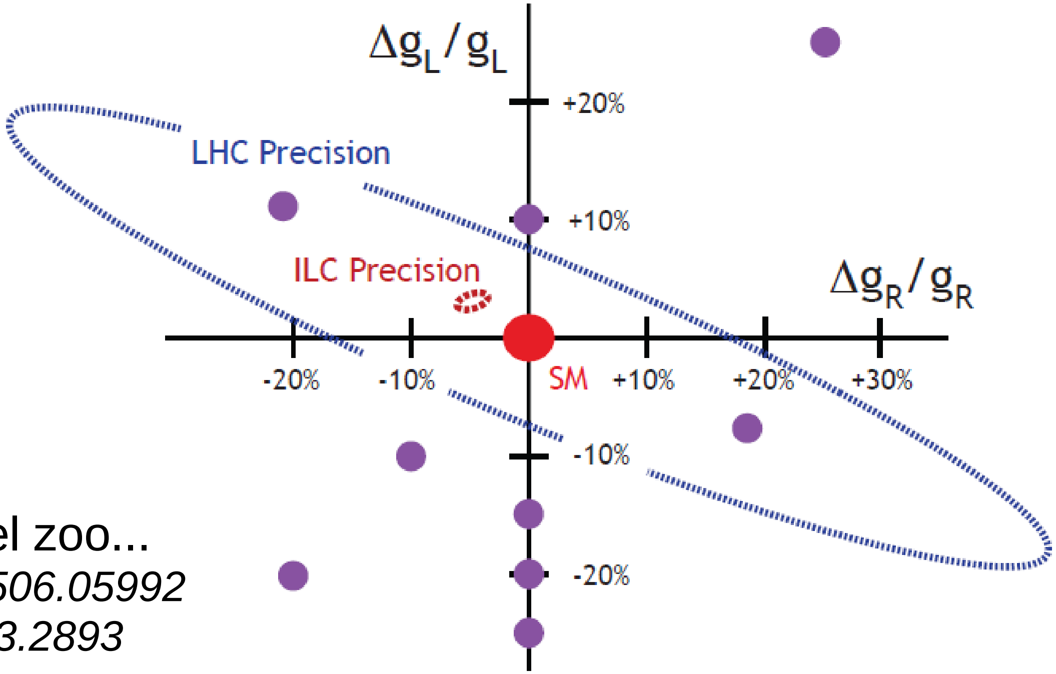
From FCChh SM physics summary (arXiv:1607.01831)
“Performing a naive rescaling of the LHC expectations [...] and assuming a luminosity of 10 ab^{-1} *for the FCC, one would expect an improvement of almost two orders of magnitude, reaching a sensitivity of Br(t → qZ; t → q*γ*) ~ 10*$^{-7}$
However, at 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 at LHC

BSM motiviation: strongly interacting high-scale physics predicts large deviations in $t\bar{t}Z$ coupling

Question to tomorrow's session:
Can one make such general statements more robust?

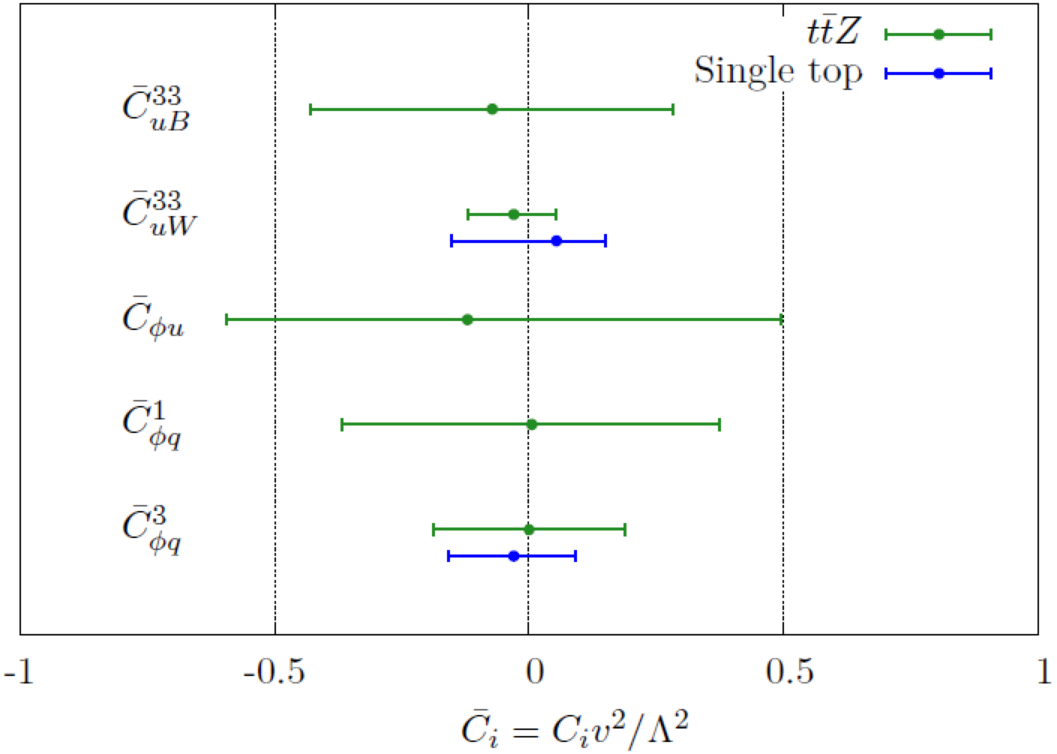


Scatter plot of the model zoo...
ILC Physics case, arXiv:1506.05992
Richard/Wulzer, arXiv:1403.2893

Top EW couplings at LHC

Top EW couplings are accessible in several ways at hadron colliders:
- *single top production, associated ttZ/ttγ/ttW production, top decay*
- *$f\bar{f}$ → Z/γ→ $t\bar{t}$ swamped at the LHC (but dominant channel at lepton colliders)*

Simultaneous fit to Tevatron and LHC yields first (rather poor) constraints
arXiv:1506.08845, arXiv:1512.03360

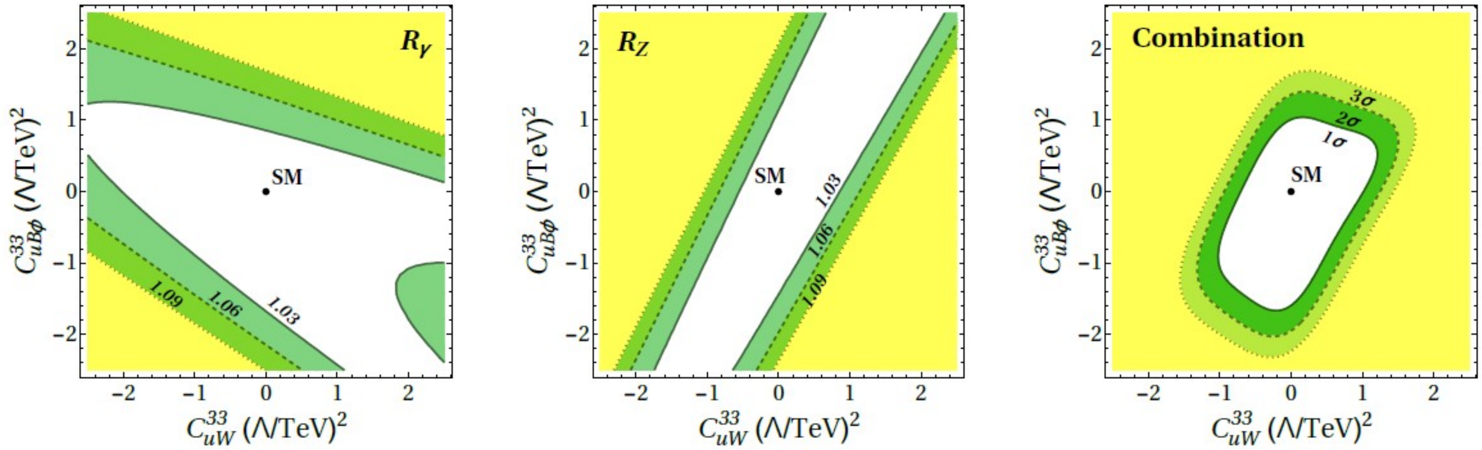


Associated production at 100 TeV

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

Cross-section at √s = 100 TeV

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



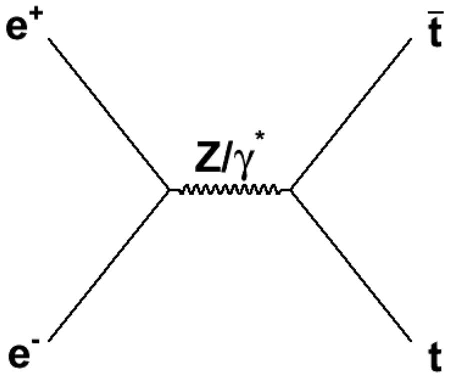
Expect rapid improvement at LHC, HL-LHC, FCC

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

arXiv:1607.01831

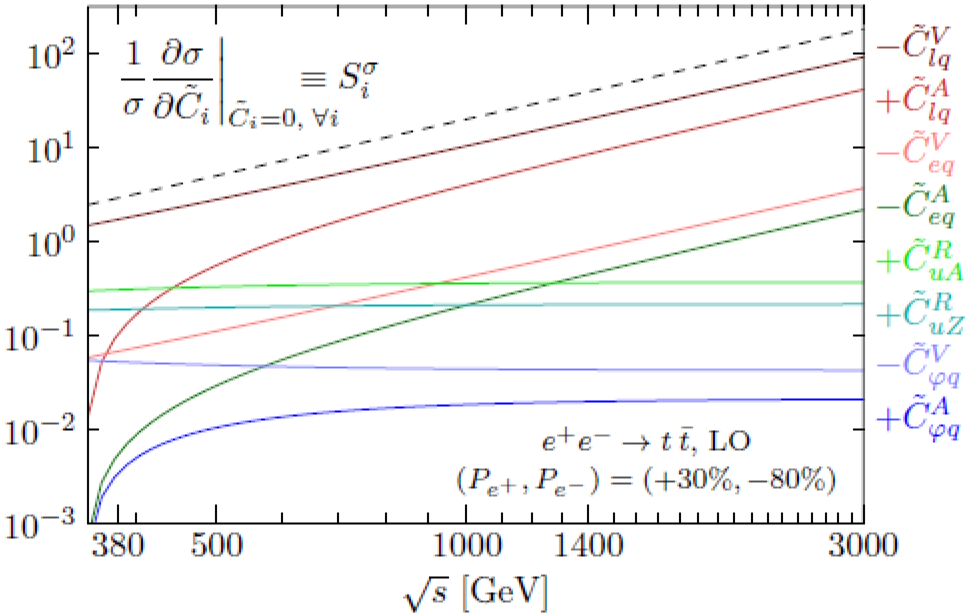
	$C_{1,V}$	$C_{1,A}$	$C_{2,V}$	$C_{2,A}$
SM value	0.24	−0.60	< 0.001	$\ll 0.001$
13 TeV, 3 ab^{-1}	[−0.4, +0.5]	[−0.5, −0.7]	[−0.08, +0.08]	[−0.08, +0.08]
100 TeV, 10 ab^{-1}	[+0.2, +0.28]	[−0.63, −0.57]	[−0.02, +0.02]	[−0.02, +0.02]

Lepton colliders



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

Measurements with two beam polarizations allow to disentangle γ and Z contributions



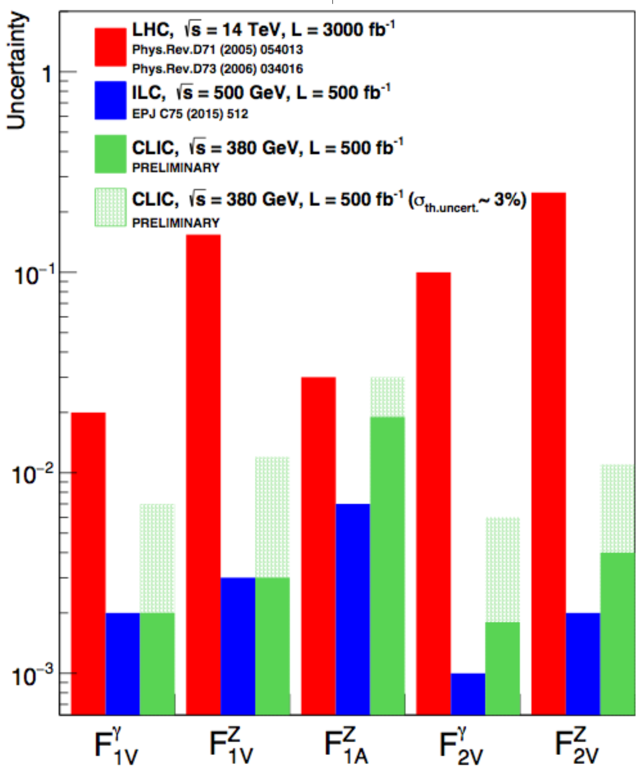
Effect of four-fermion operators (i.e. new massive mediator) best felt at high energy

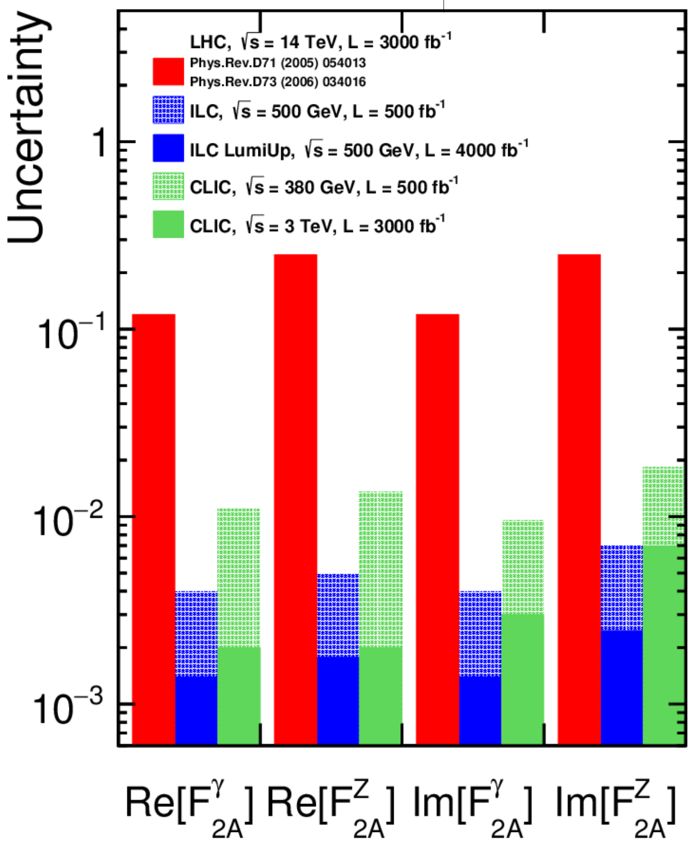
Effect of two-fermion operators (i.e. loop effects on $t\bar{t}X$ vertex) best probed at ~500 GeV

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

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





Prospects for HL-LHC/ILC500/CLIC380

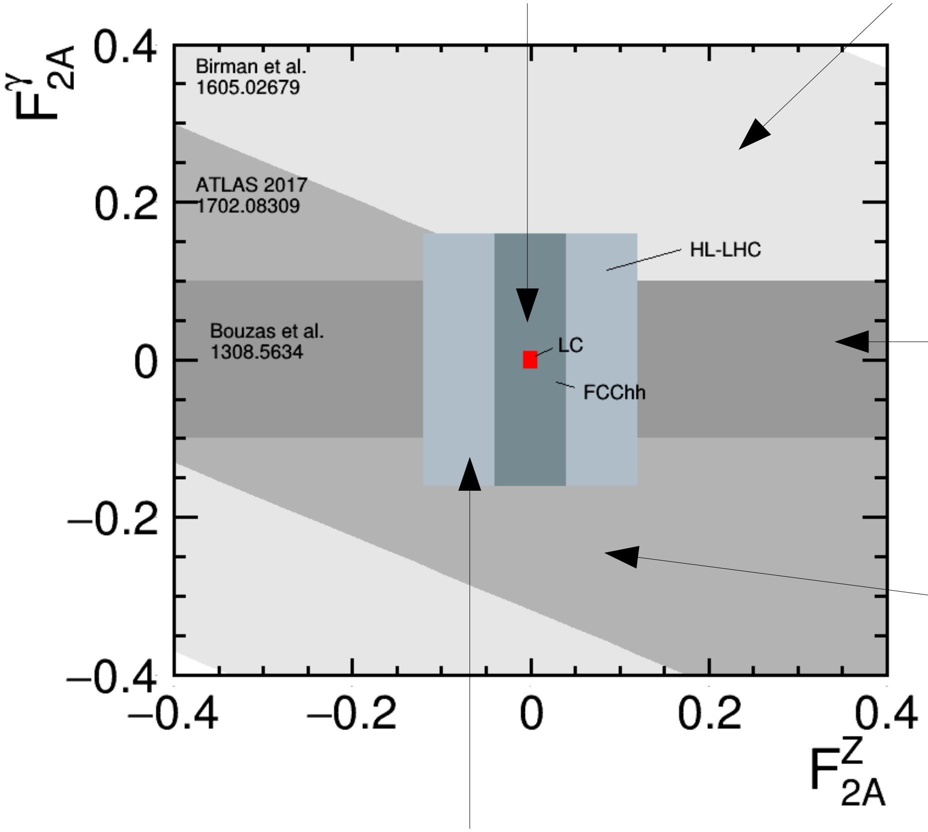
arXiv:1307.8102, arXiv:1505.0620

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

Many directions to approach the problem

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

Top decay $t \to Wb$



$e\gamma \to t\bar{t}$

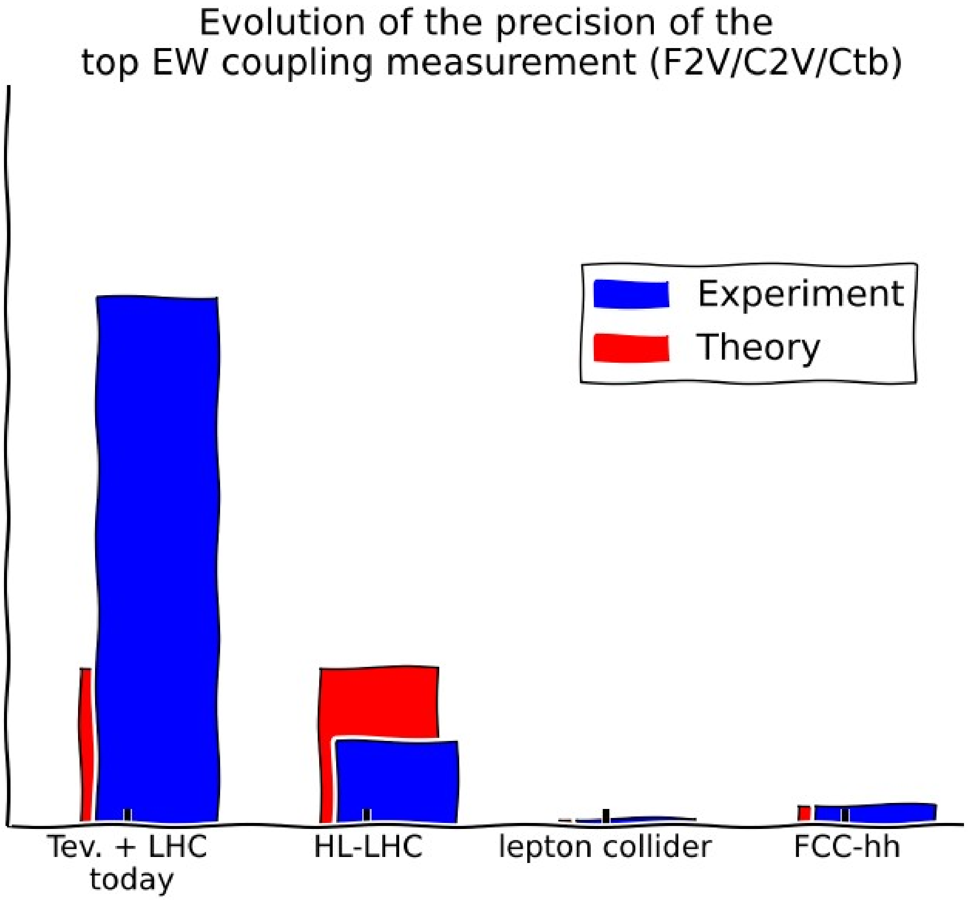
Single top production

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(C_{tW}), Im(C_{tB}))

Towards a comparison of global fits

Perform a fit to D6 operators of pseudo-measurements of the top EW sector to "score" each project



Current LHC result
    (TopFitter)

ILC/CLIC full-simultion result
    (Perello, Strom, M.V.)

Updated LHC (HighLumi) prospe
    (Rontsch & Schulze)

FCChh prospects
    (Schulze et al., Aparisi)

The future of 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: Higgs physics, searches for exotic single-top production

Circular machine

= 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 couplings
Challenges: control of systematics to per mille level

Linear machine

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 and top mass potential to be evaluated
Challenges: control of systematics to % level, ultra-boosted production

Lessons and future work

Top 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

Much more work is needed to make an informed decision. Take advantage of EFT machinery for a systematic comparison of the potential of different processes/machines

EW fit

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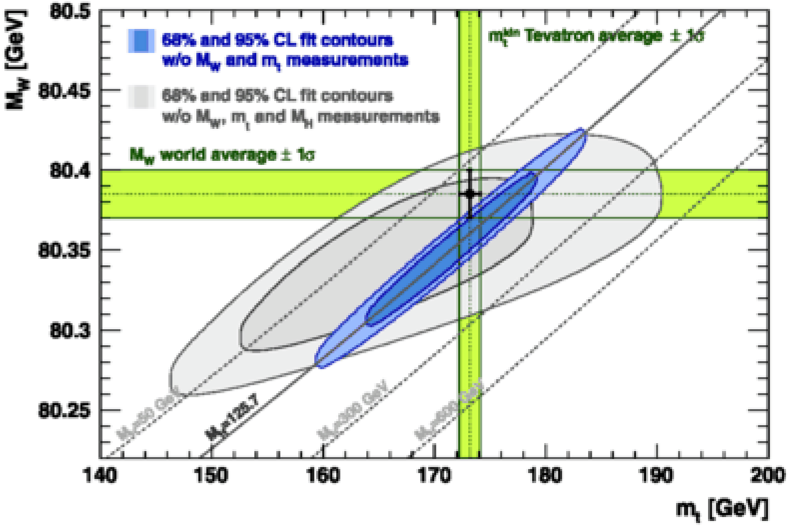
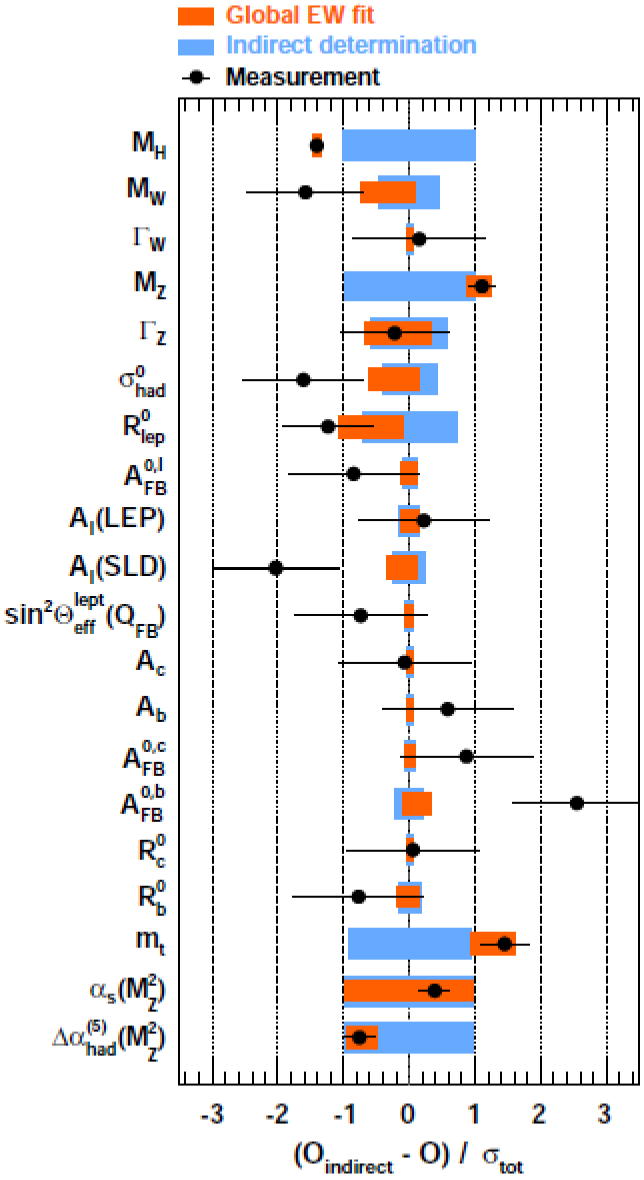
EW fit

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

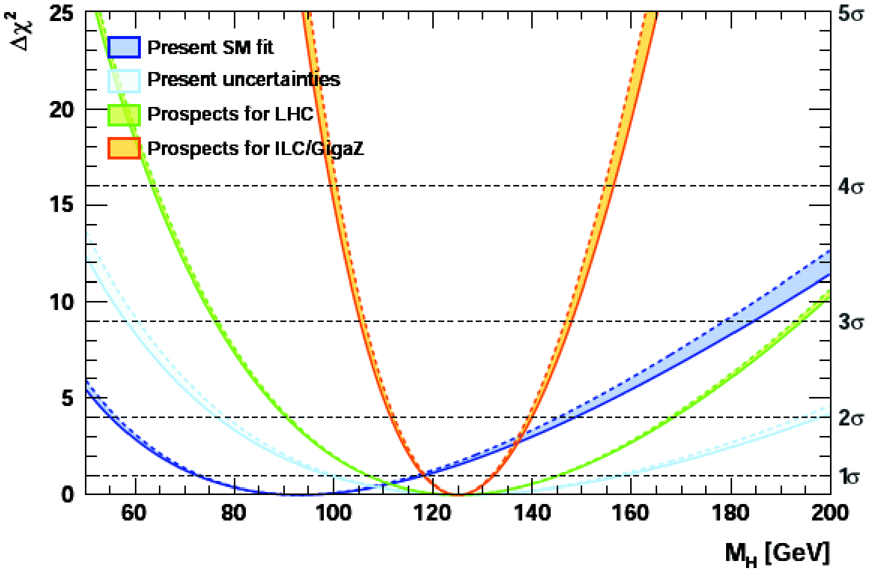
New e^+e^- machines exceed LEP and SLC luminosity by orders of magnitude (ILC GigaZ or FCC-ee TeraZ)

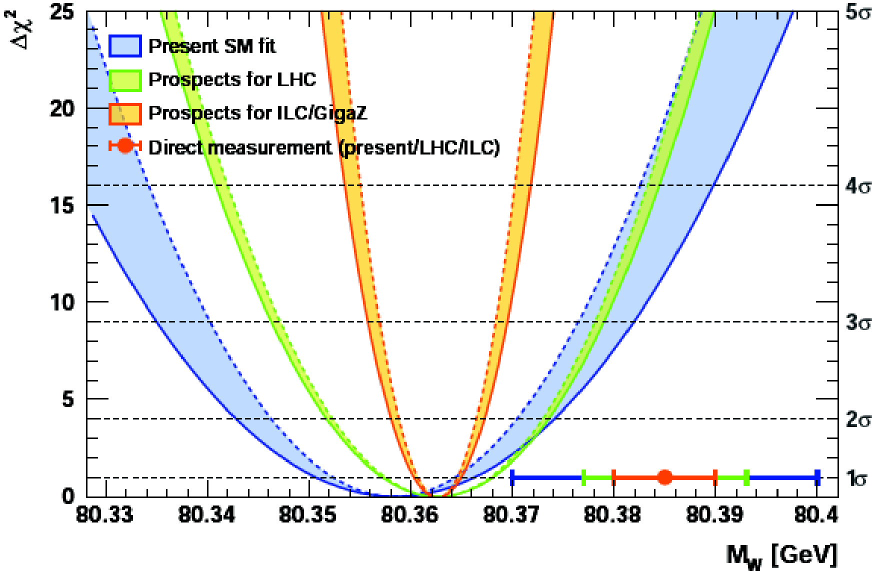
Higher-performance detectors and more sophisticated theory/Monte Carlo

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)





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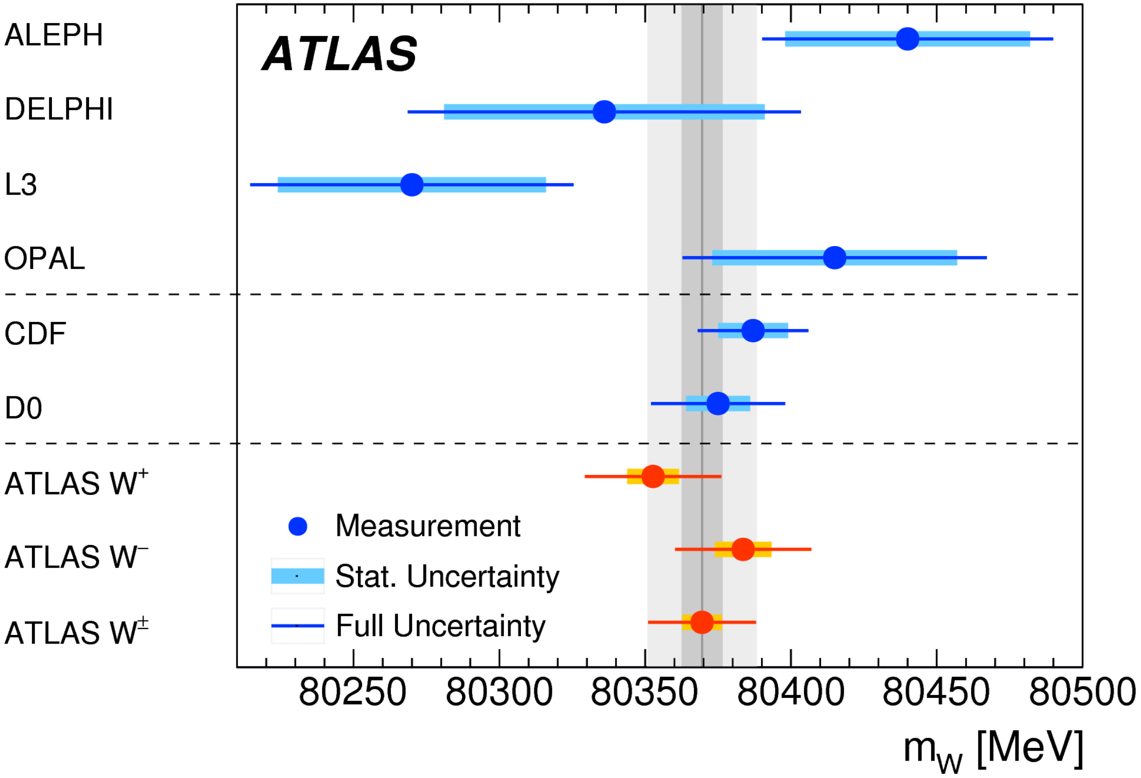
W-boson mass



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

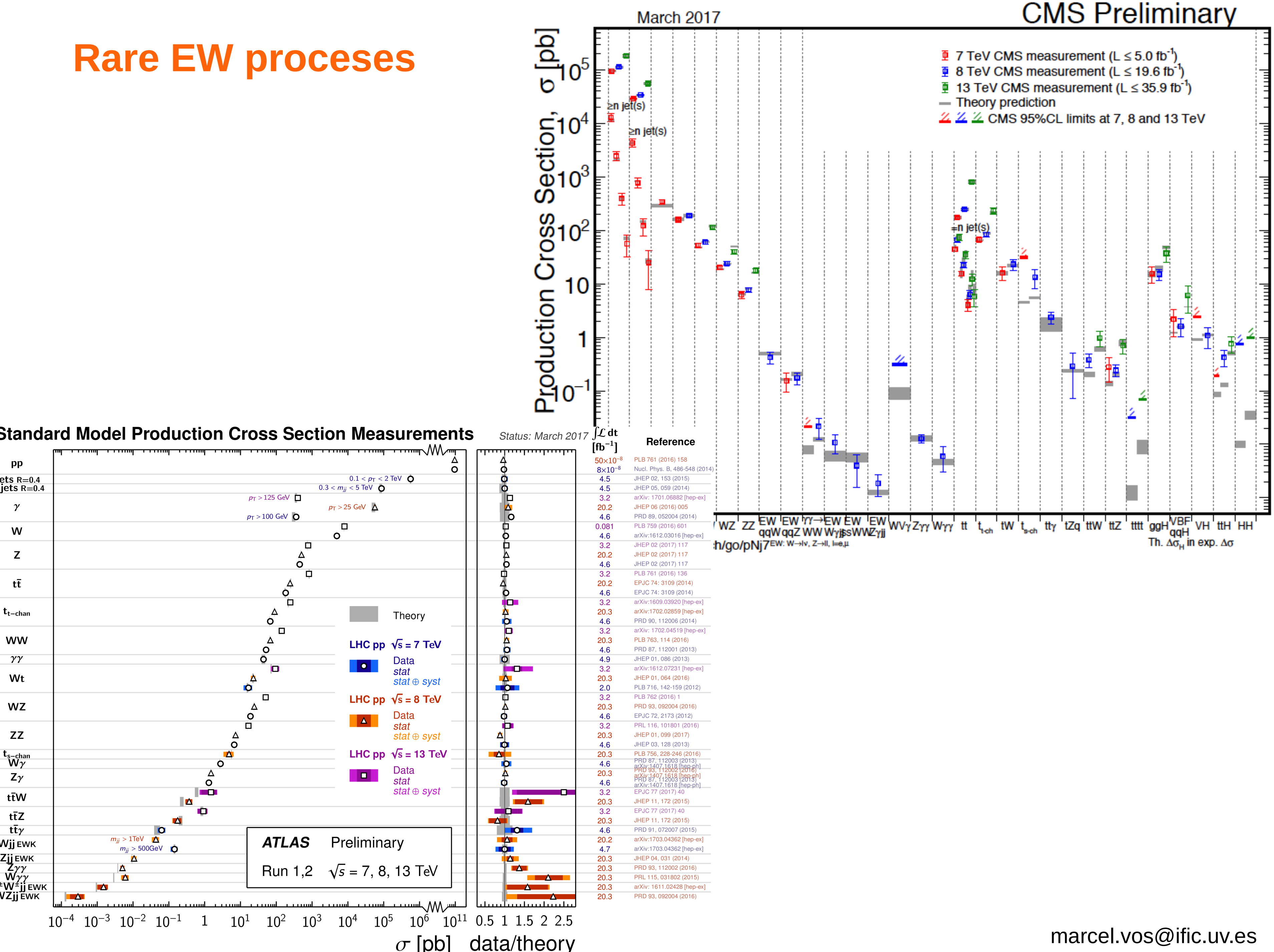
Lepton colliders: direct measurement or WW threshold

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

Rare EW proceses



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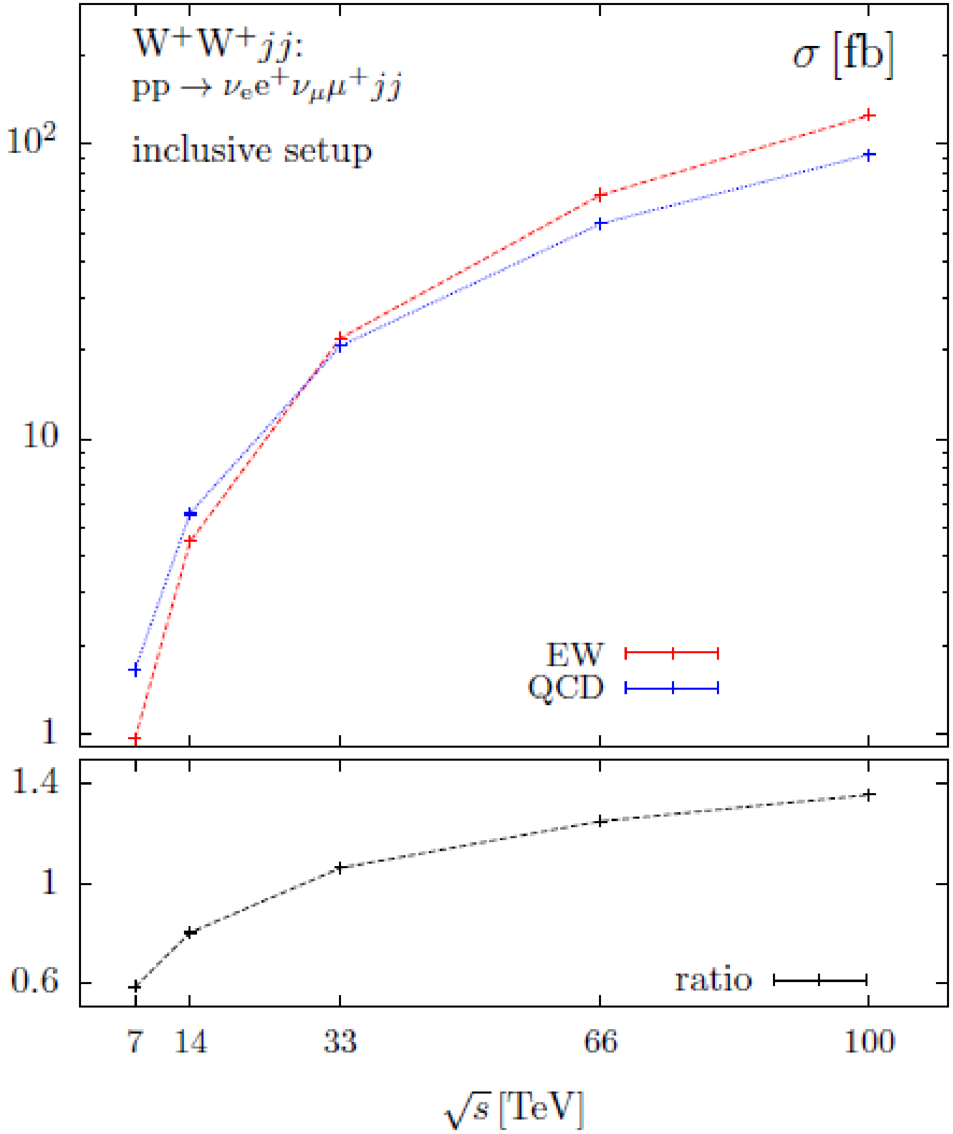
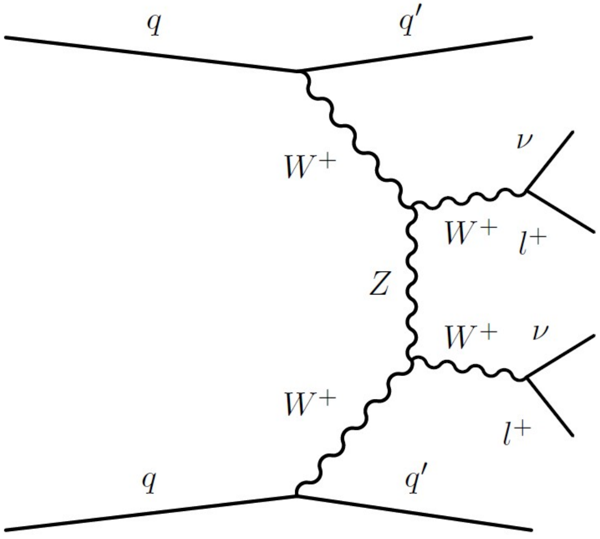
Vector boson scattering – future hadron colliders

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

Vector boson scattering

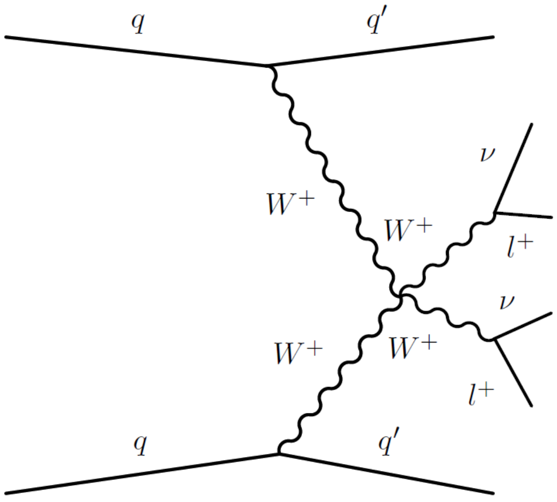


The measurement that demanded a Higgs boson...

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

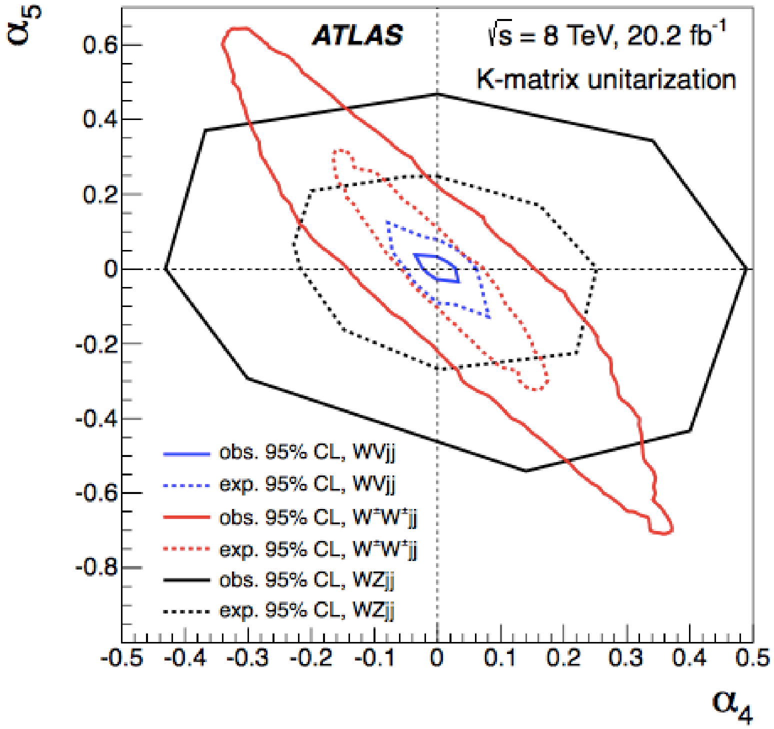
See: updates by ATLAS and CMS

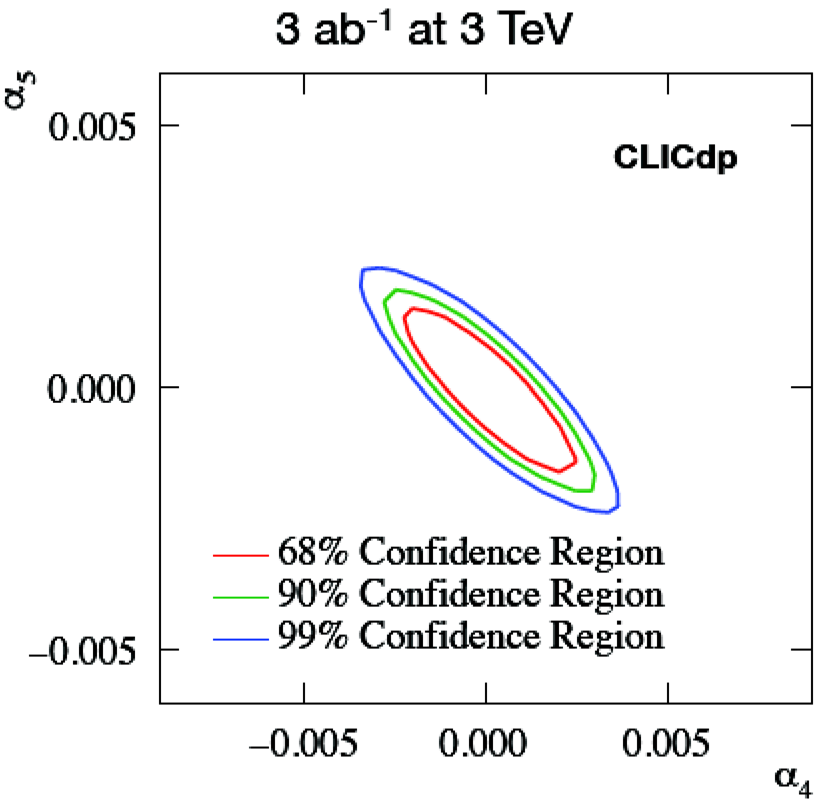


Test Higgs-suppression of longitudinal VBS, constrain anomalous couplings (aTGC and aQGC), measure Higgs properties, Campbell, Ellis arXiv:1502.02990

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

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*