top physics beyond the LHC

Mini-review of future collider top prospects

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

42nd Johns Hopkins workshop

Beyond Standard Model: Where do we go from here?

Galileo Galilei Institute, Florence,

October 3rd 2018

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Direct searches

Hadron colliders reach up to a fraction of √s

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

Tevatron (1.96 TeV) discovered top, but not Higgs

LHC run I&II (13 TeV) discovered Higgs, but not SUSY (?)

New hadron collider projects, HL-LHC, HE-LHC and SPPC/FCChh to kick the ball further

Lepton colliders cover (nearly) m < √s(/2)

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

New e^+e^- colliders (and possibly a muon collider) can extend the mass reach to TeV regime

Focus of e^+e^- projects is on Higgs factory operation at 250 GeV (except CLIC: 380 GeV)

See: McCullough, Curtin

Direct searches vs. Indirect sensitivity

Indirect sensititivity

Indirect sensitivity can exceed √s significantly

LEP EW fit is sensitive to top and Higgs

B-factories probe high scales

Complete SMEFT characterization

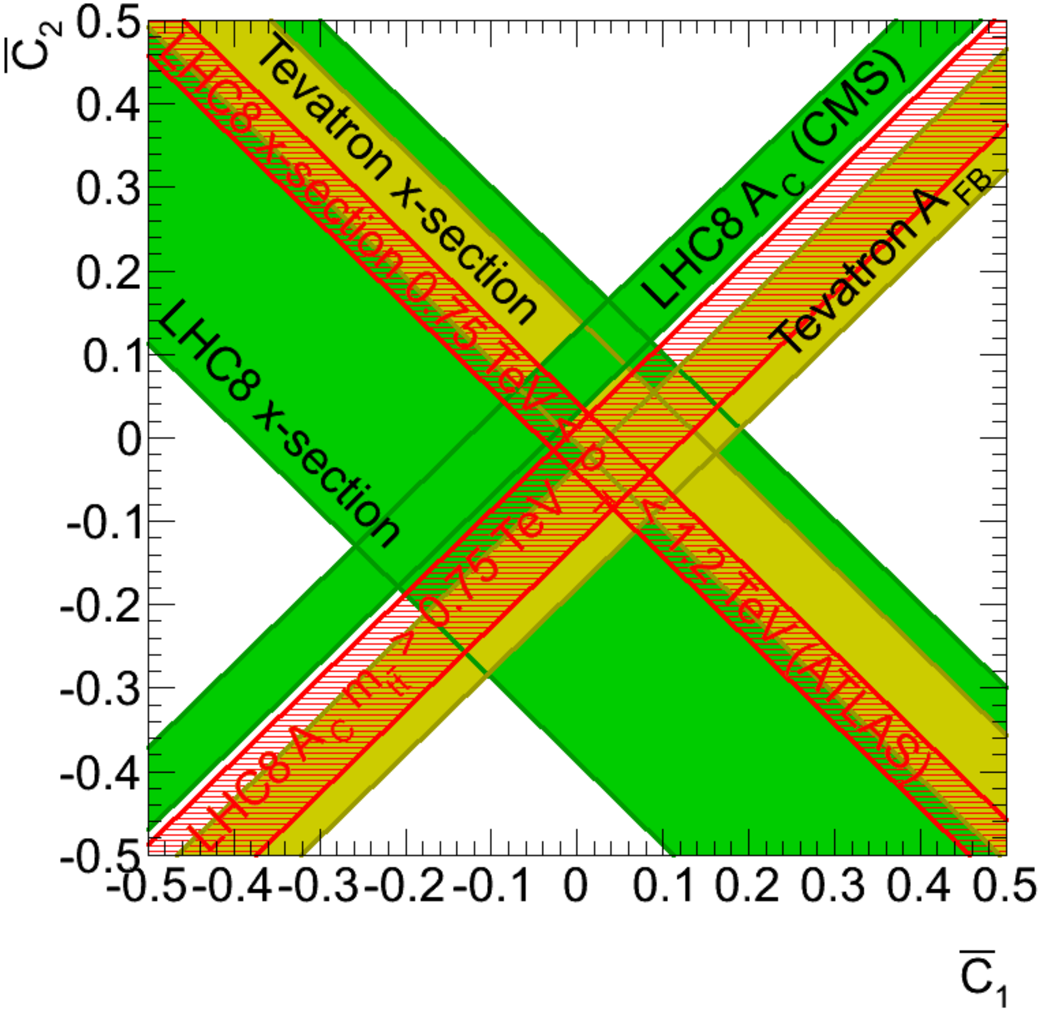
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

Quantify BSM sensitivity with limits on anomalous D6 operators coefficients in EFT

This talk is heavily biased towards precision measurements

Energy vs. accuracy

"Energy helps accuracy" M. Farina et al., arXiv:1609.08157, arXiv:1712.0131



Sensitivity of A_c and x-sec to $q\bar{q}t\bar{t}$ operators at Tevatron and LHC

Tevatron: predominantly $q\bar{q}$ initial state

LHC: statistics and energy reach

M. Perelló, M.V., arXiv:1512.07542

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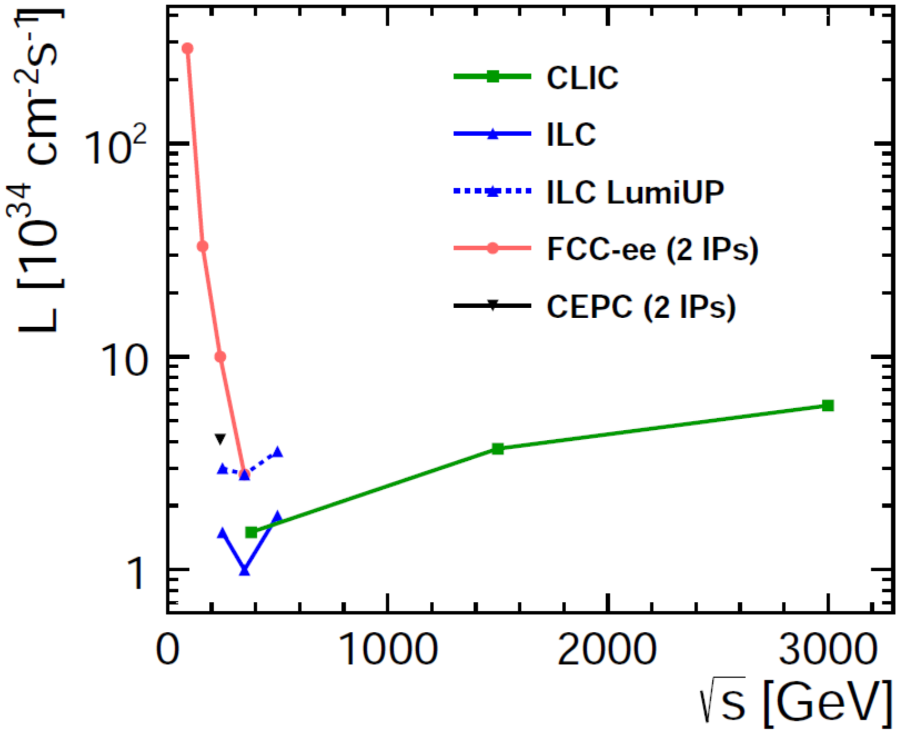
See: F. Simon (linear),
P. Janot (circular) later today

Lepton collider projects:

- ILC (TDR, negotiations):
  250, 550, 1000 GeV
- CLIC (CDR):
  380, 1500, 3000 GeV
- CEPC (CDR 2018):
  90, 160, 250 GeV → no $t\bar{t}$
- FCC-ee (CDR 2018):
  90, 160, 240, 350, 370 GeV



Detailed designs for ILC/CLIC
CEPC/FCC-ee provide CDRs

Will plasma-wakefield acceleration arrive in time? (see: Gessner, Peskin)

Can MICE, LEMMA, etc. revive interest in a muon collider? (see: M. Zanetti)

Top production at e^+e^- colliders

Thresholds:

160 GeV WW

240 GeV ZH

350 GeV $t\bar{t}$

500 GeV ZHH

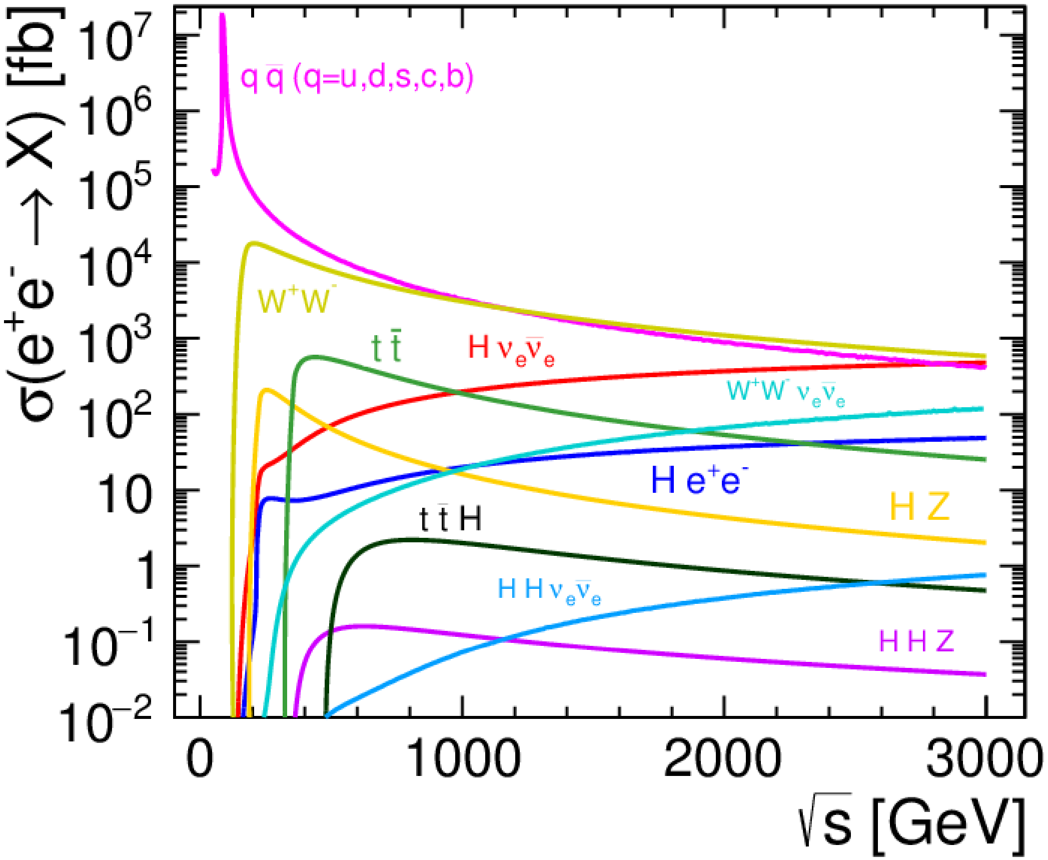
550 GeV $t\bar{t}$H

t-channel processes:

Vector-boson fusion

Hνν, HHνν

WWνν, $t\bar{t}$νν



Key advantages: democratic rates, calculability, control over initial state
→ precision can reach sub-% or per mil level

Cross sections at e^+e^- colliders

Thresholds:

160 GeV WW

240 GeV ZH

350 GeV $t\bar{t}$

500 GeV ZHH

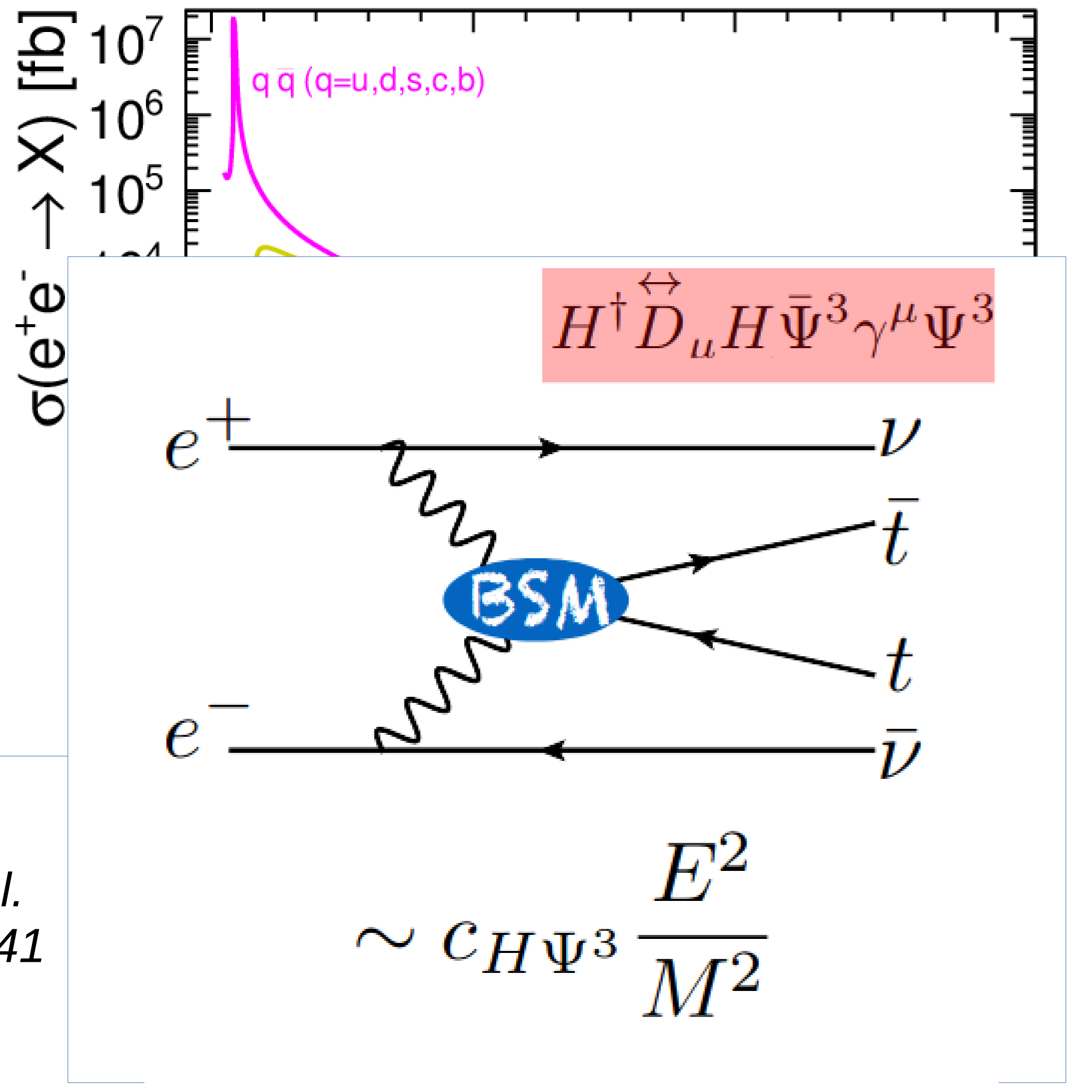
550 GeV $t\bar{t}H$

t-channel processes:

Vector-boson fusion

$H\nu\nu$, $HH\nu\nu$

$WW\nu\nu$, $t\bar{t}\nu\nu$



Work in progress by Wulzer et al.
CLIC top paper, arXiv:1807.02441

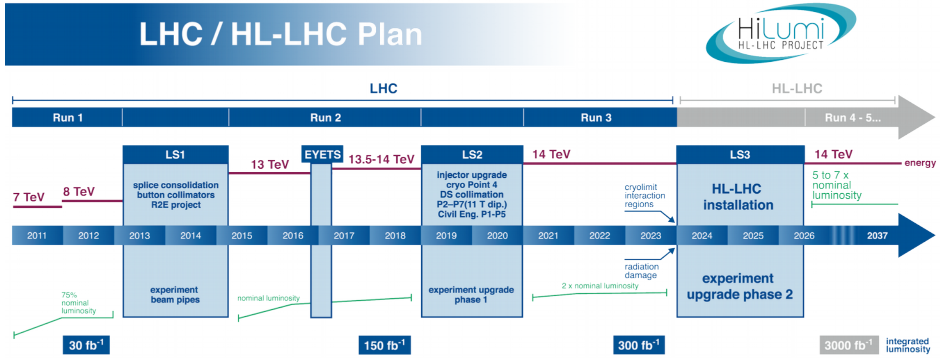
Projects for the next hadron collider

Assume 16 Tesla magnets: $\sqrt{s}/L \sim 1$ TeV/km (see: T. Chen)

- **SPPC (China)**
  100 km (TeV)
- **FCChh (CERN)**
  100 km (TeV)
- **High-E LHC (CERN)**
  27 km (TeV)

See: M. Mangano later today

HL-LHC



There is plenty of LHC left...

And that includes a lot more top physics than what was prospected back in 2002

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]

"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."

Hadron collider potential: challenges

Example: tt inclusive cross section at 13 TeV (arXiv:1606.02699)

Experiment:
Statistical uncertainty: << 0.1% (with 3.2 fb^{-1})
Systematic uncertainty: 3.3% (2.8% had.)
Luminosity: 2.3%

Theory:
Scale uncertainty: ~3% (NNLO+NNLL)
PDF 4.2% (PDF4LHC)

Systematics limit many measurements already today. Progress in precision physics at hadron colliders requires new developments.

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"

Top physics at hadron colliders

Hadron colliders: 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**

The increase in statistics in the high-energy tail is much more pronounced than of the total cross section

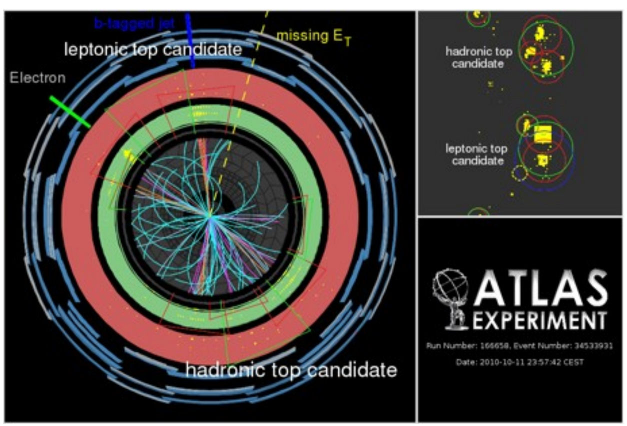
HL-LHC, HE-LHC access remote and unexplored corners of phase space

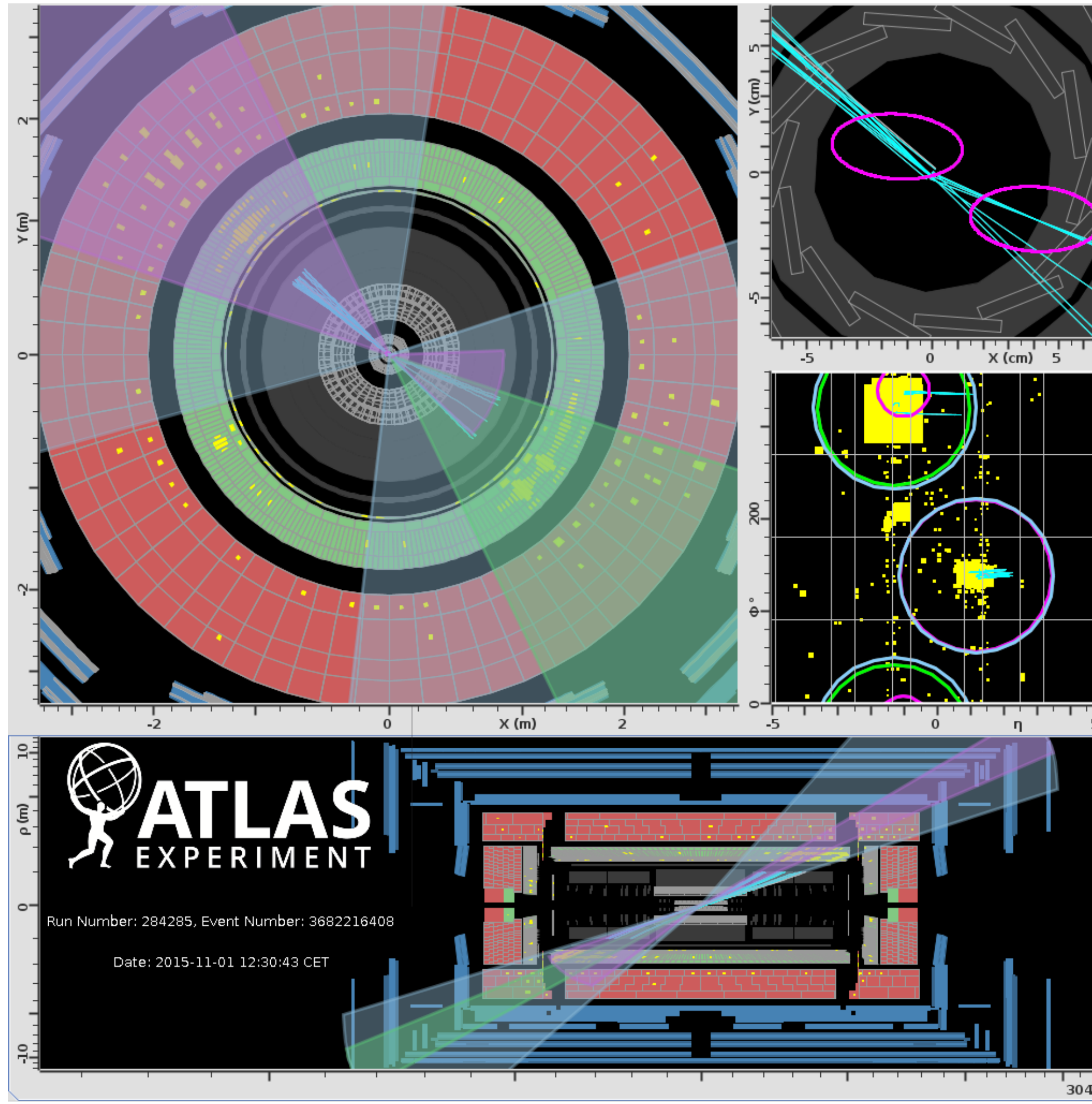
FCChh/SPPC could produce 10^{12} top quark pairs!!

The sheer brute force of hadron colliders

Fully hadronic $t\bar{t}$ event
Invariant mass: 3.3 TeV
Run 2 at 13 TeV

Note: first boosted object
ever at BOOST 2011!!





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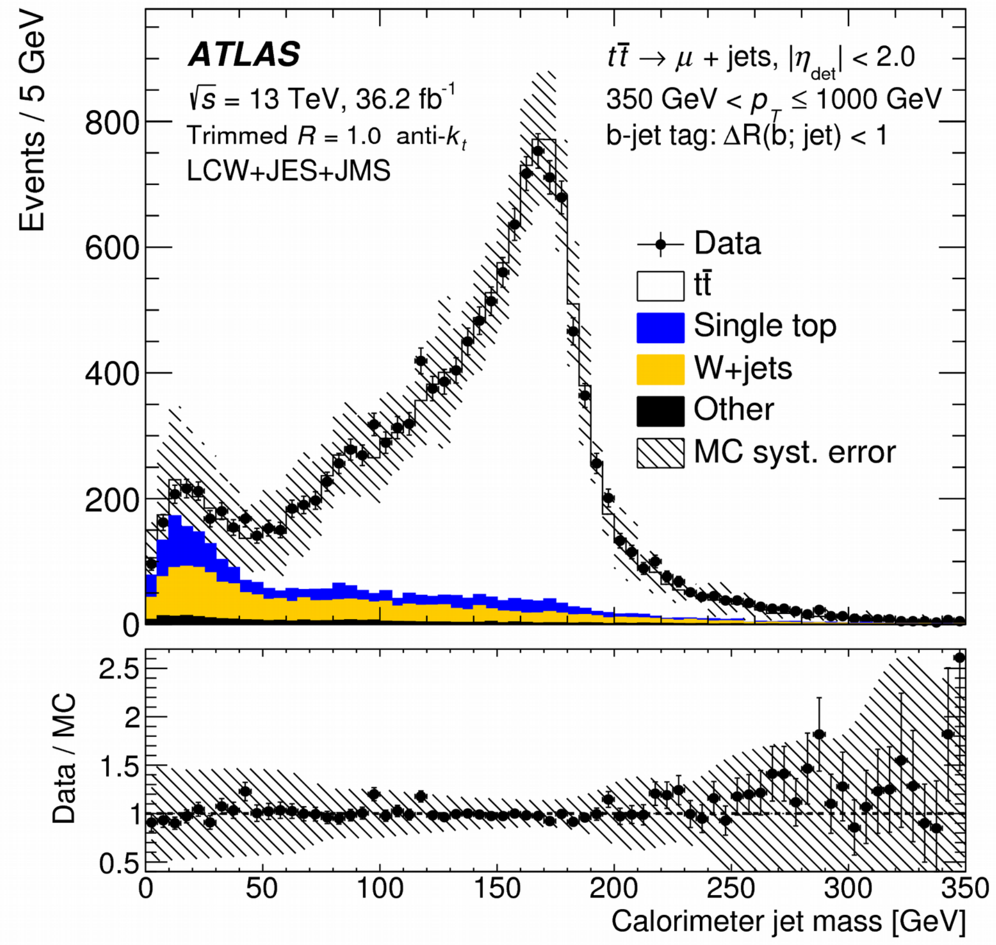
Boosted objects for calibration!



Jet mass peak of boosted top quarks used to calibrate calorimeter response

ATLAS in-situ calibration
arXiv:1807.09477

Who's afraid of boosted top quarks?

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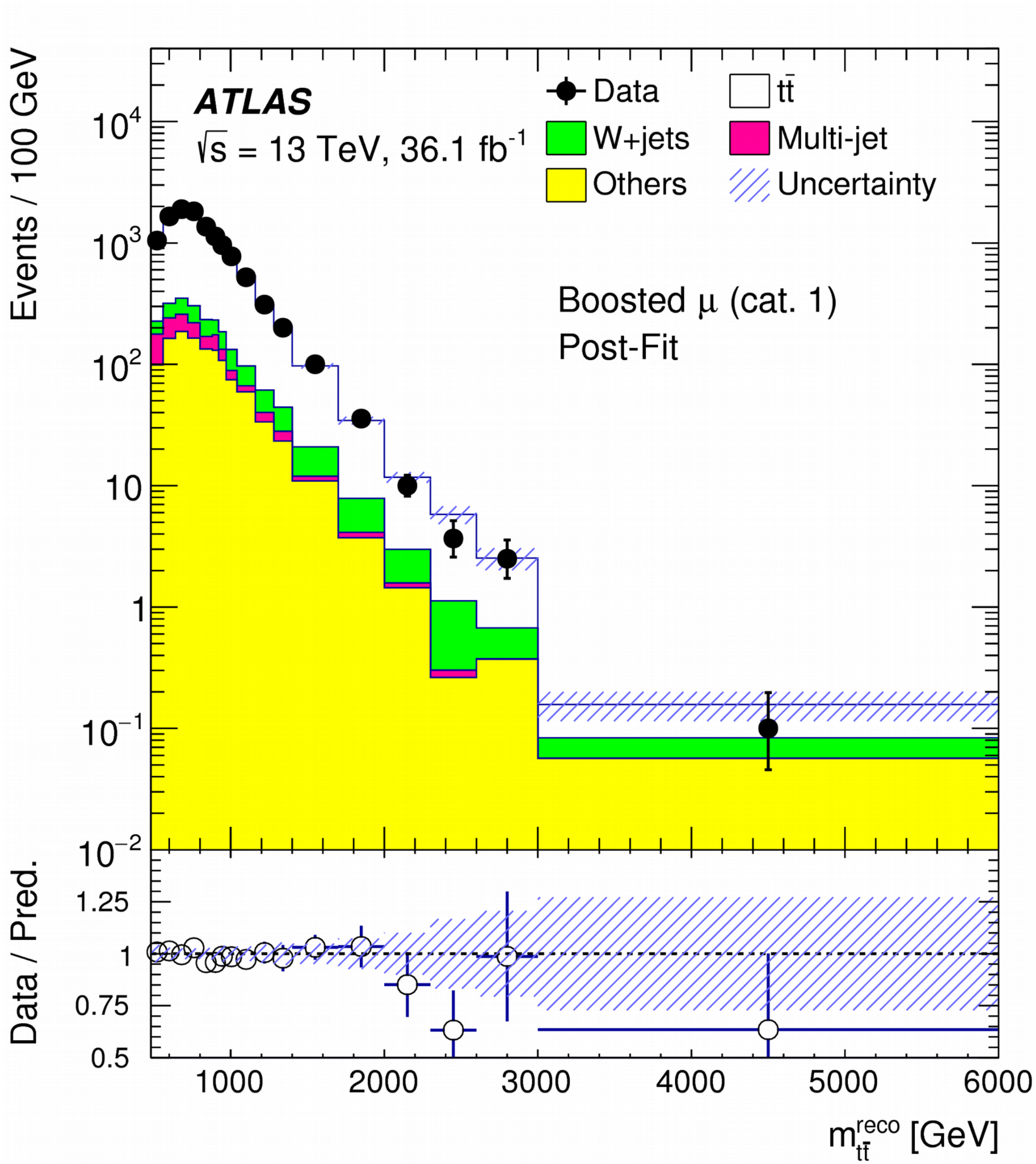
Hadron colliders: brute force



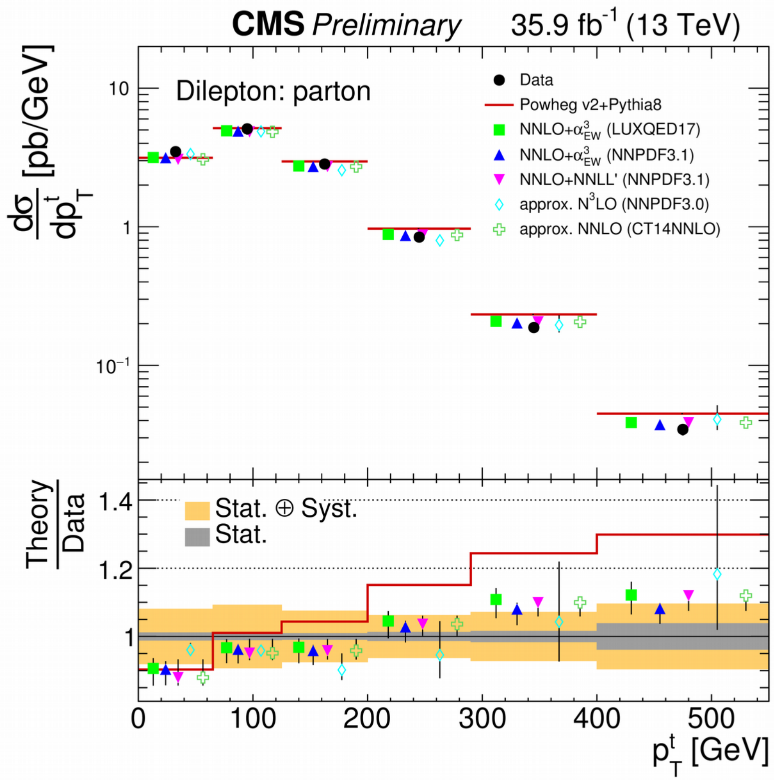
KK gluon limits reach 3.7 TeV
ATLAS 36 fb^{-1}, arXiv:1804.10823
CMS 3 fb^{-1}, JHEP07 (2017) 001

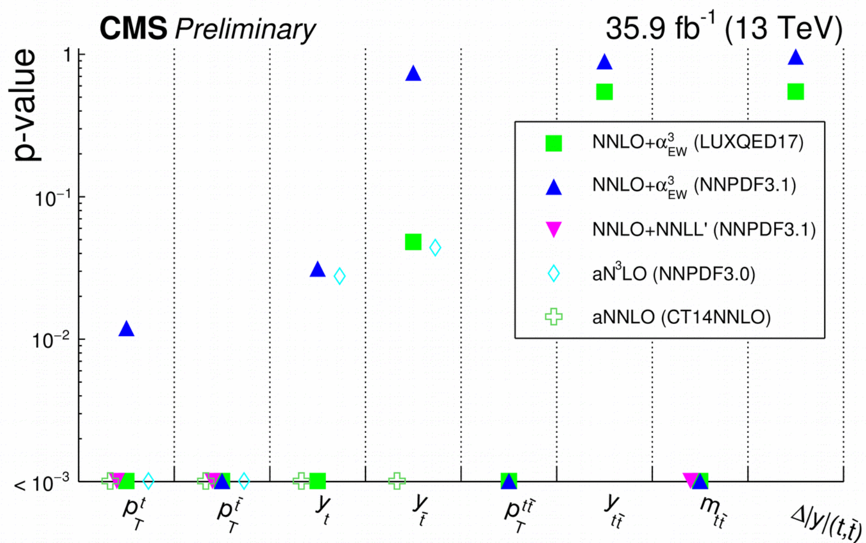
Differential cross section

CMS TOP-17-014

13 TeV, 36 fb^{-1} data vs. MC and NNLO and aN^{3}LO calculations

Monte Carlo prediction is known to be off since a long time



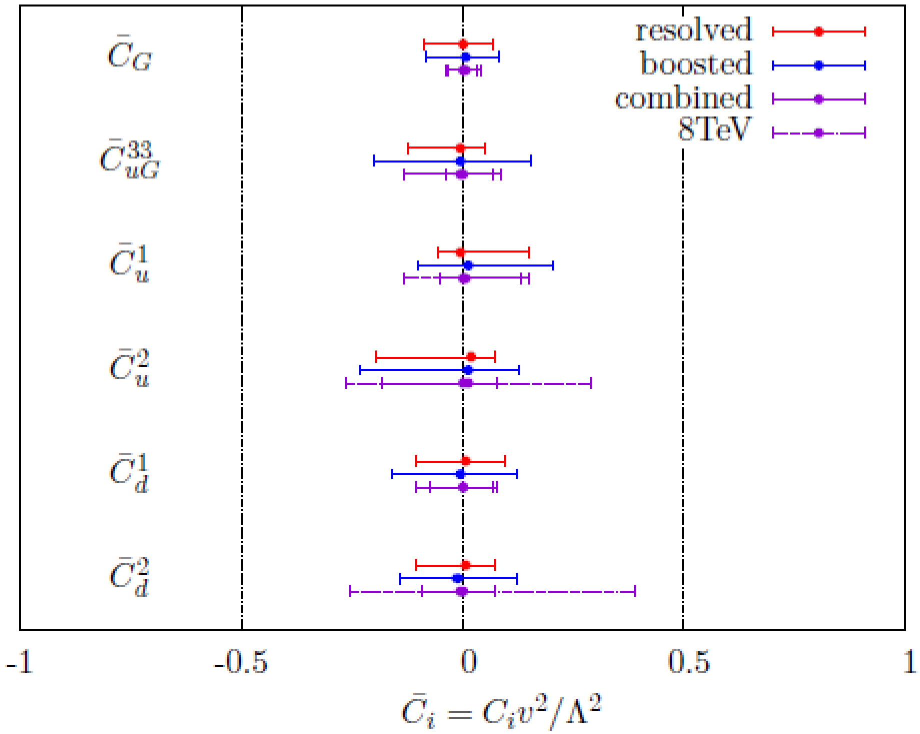


Fixed-order calculations do better, but do not agree with data:

p(SM) < 10^{-3}

What does it mean?

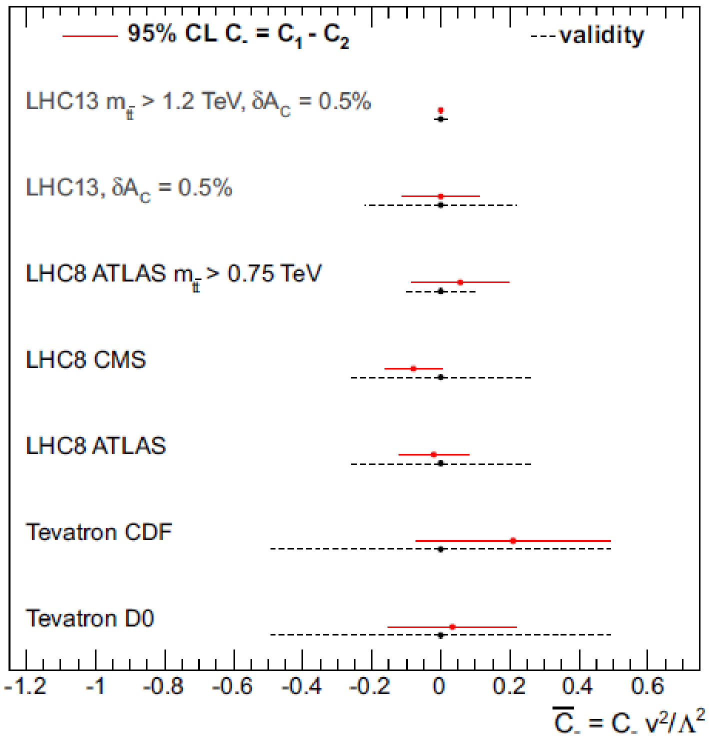
EFT constraints from boosted top quark production



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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Ultra-boosted top quark production

Consequences of “top as a light quark” at 100 TeV

Forward production

- dedicated experiment? M. Mangano, TOP2015

Theory progress

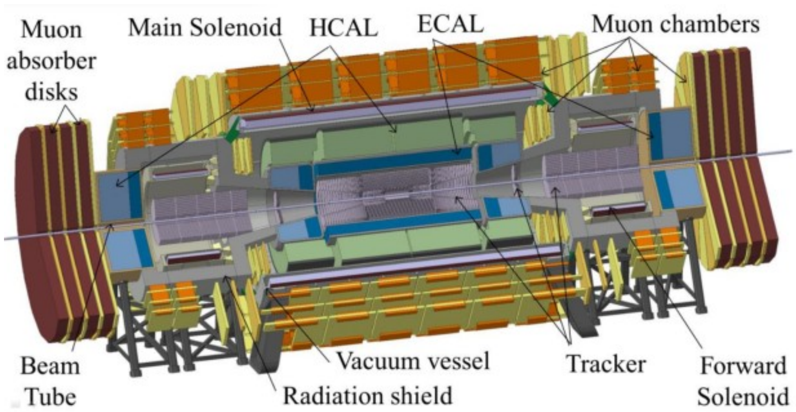
- g $\rightarrow t\bar{t}$ splitting, top quark PDF, J. Rojo/NNPDF, arXiv:1607.01831

Ultra-boosted decay topologies

- Lepton-in-jet, Aguilar-Saavedra et al. arXiv:1412.6654
- Charged substructure, A. Larkoski, arXiv:1511.06495
- Pushing calorimeter granularity, arXiv:1412.5951
- BOOST Review arXiv:1803.06991

Detector requirements

- *GEANT4 studies for calorimeter*
- *9-11 λ, small constant term*
- *Granularity for boosted objects*
- J. Faltova 2018 JINST 13 C03016
- C. Neubuesser, Springer Proc. Phys. 212 (2018)



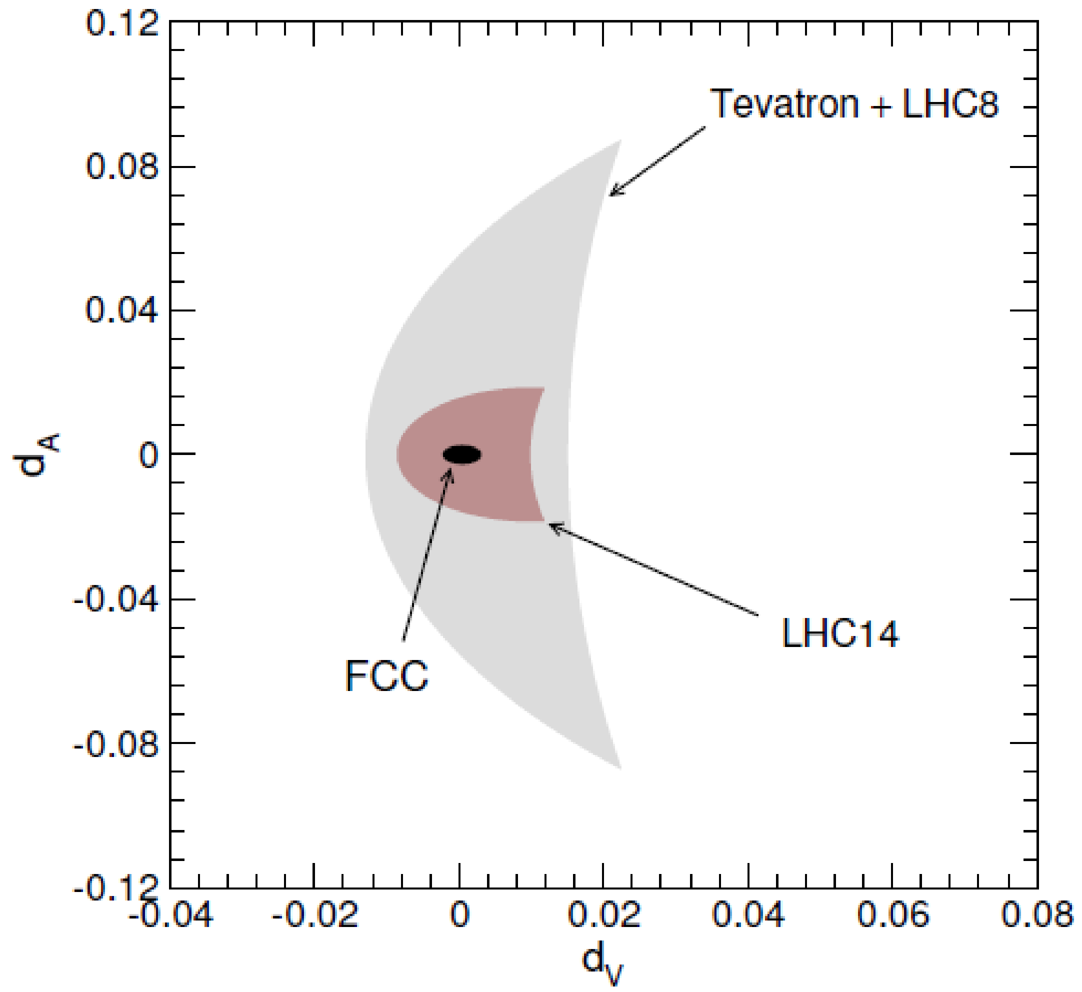
Ultra-boosted top quark production

Aguilar-Saavedra et al., arXiv:1412.6654

Top quark chromomagnetic and chromoelectric dipole moments

$$d_V = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} \Re C_{uG\phi}^{33} \qquad d_A = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} \Im C_{uG\phi}^{33}$$

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



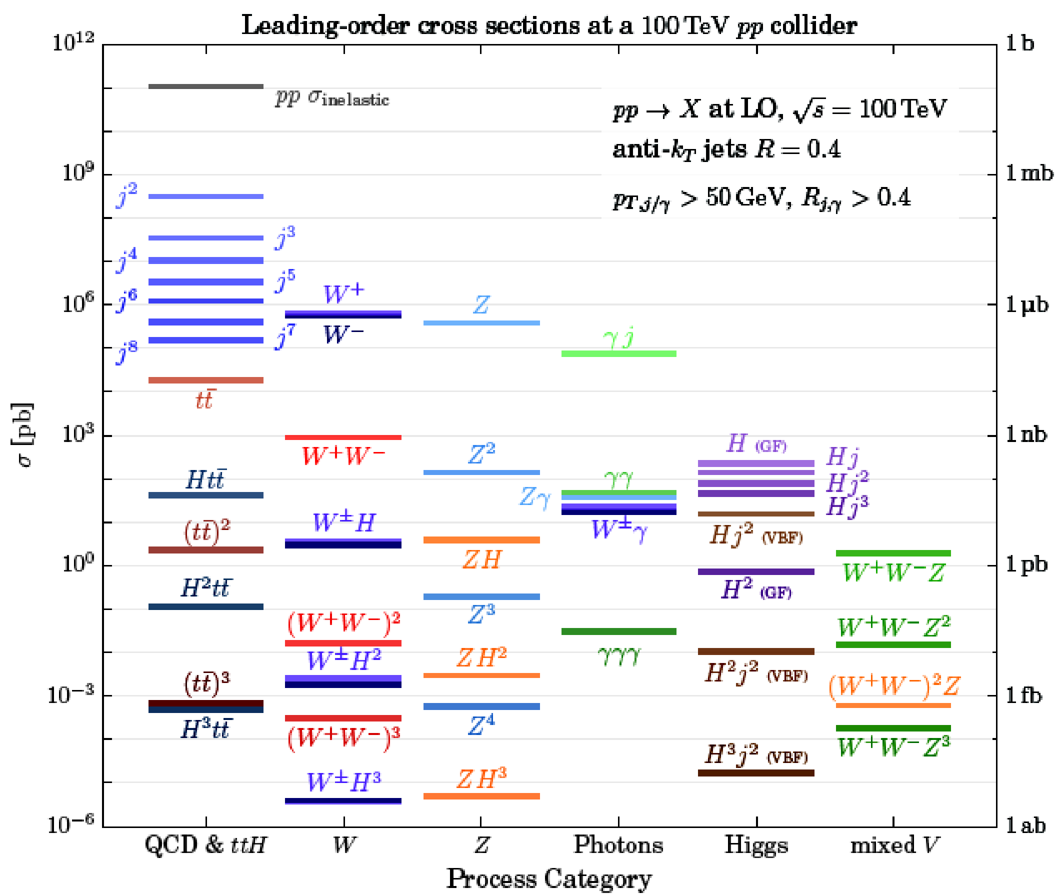
FCChh yields an order of magnitude improvement

Further studies would also be desirable to evaluate the complementarity of the measurements [...] with e^+e^- collisions

Top physics at hadron colliders: rare processes

rare processes (associated production of top and gauge bosons, $t\bar{t}H$, tttt, FCNC decays) become accessible

ArXiv:1605.00617



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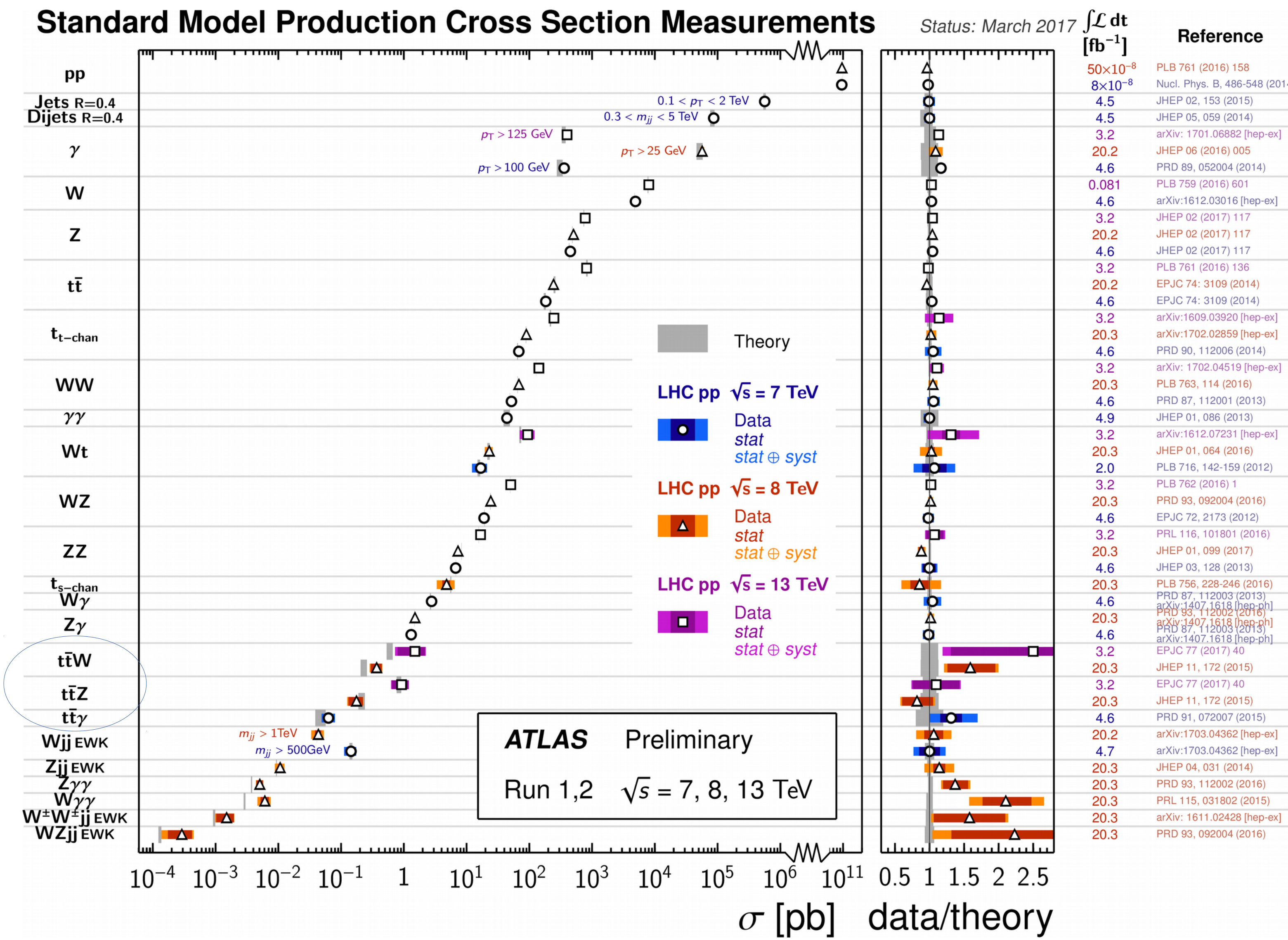
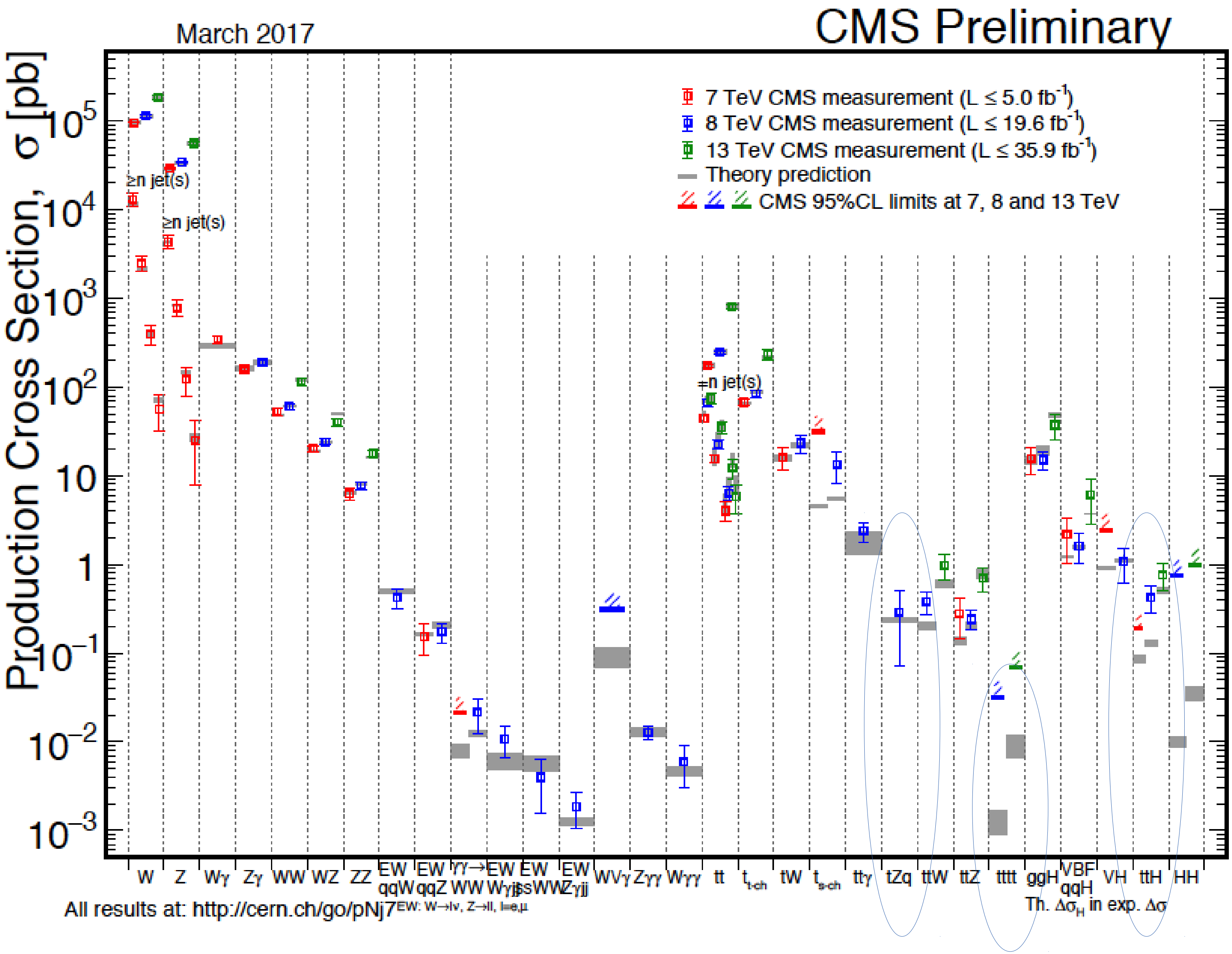
Rare processes



Rare processes

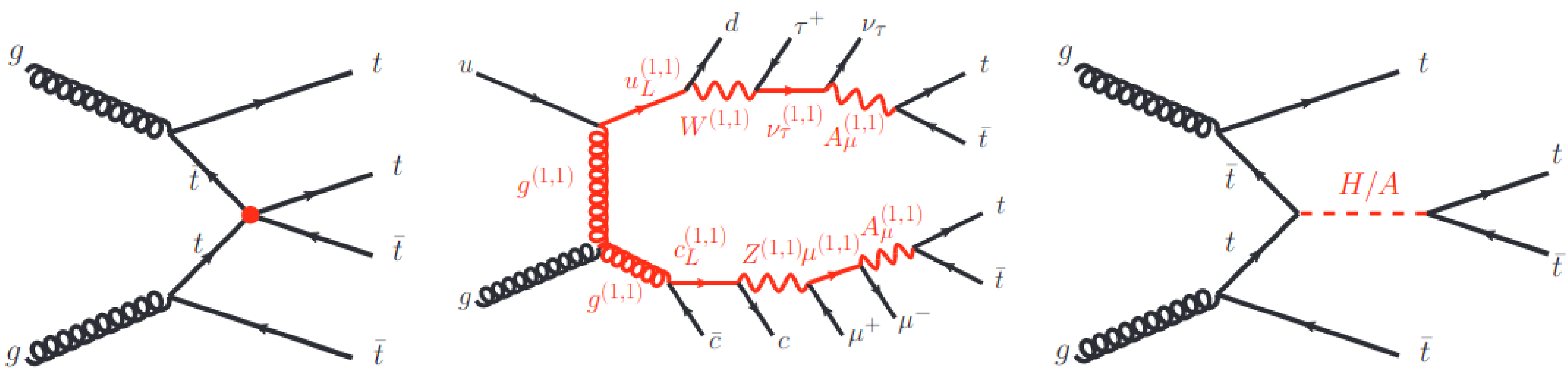


Rare processes, next target: $t\bar{t}t\bar{t}$

ATLAS search for same-sign leptons + b-jets, arXiv:1807.11883

Sensitive to a large number of BSM scenarios (feel free to pick your prejudice)

Sensitivity approaches SM rate for 4-top production



Upper limit on four-top production rate (assuming SM kinematics):

Observed: **69 fb**

Expected: **29 fb**

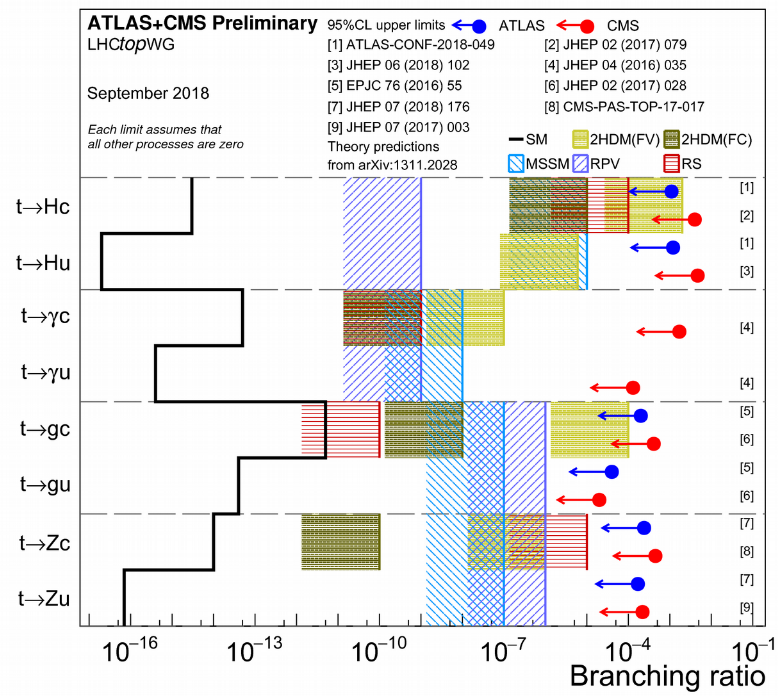
SM prediction: **9.2 fb**

A slight excess

Sensitivity = 3x SM

Top and FCNC

The ultimate rare process

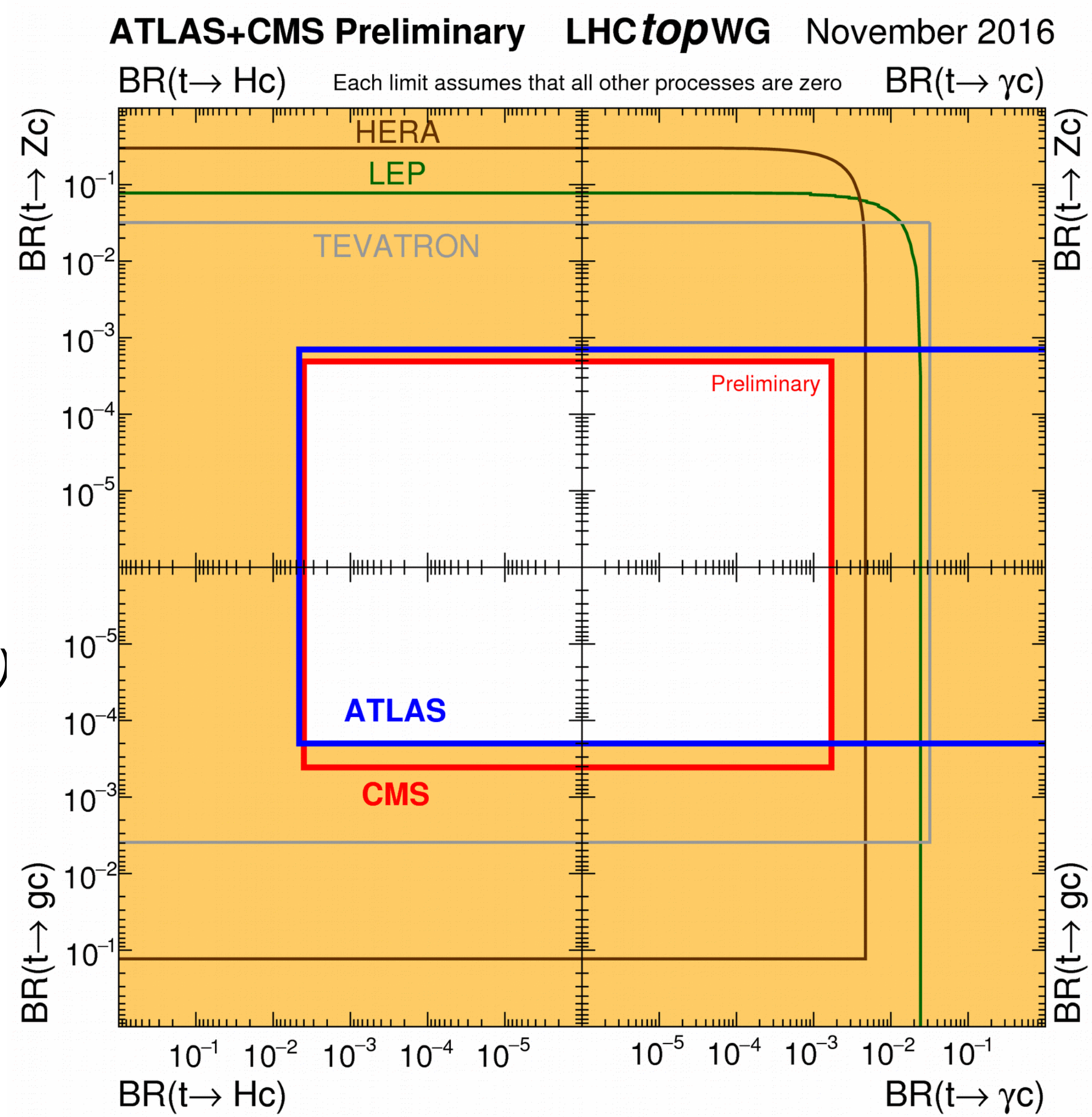


Not covered: lepton-flavour violating top decays → arXiv:1507.07163

FCNC interactions

tXc

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



FCNC interactions

tXc

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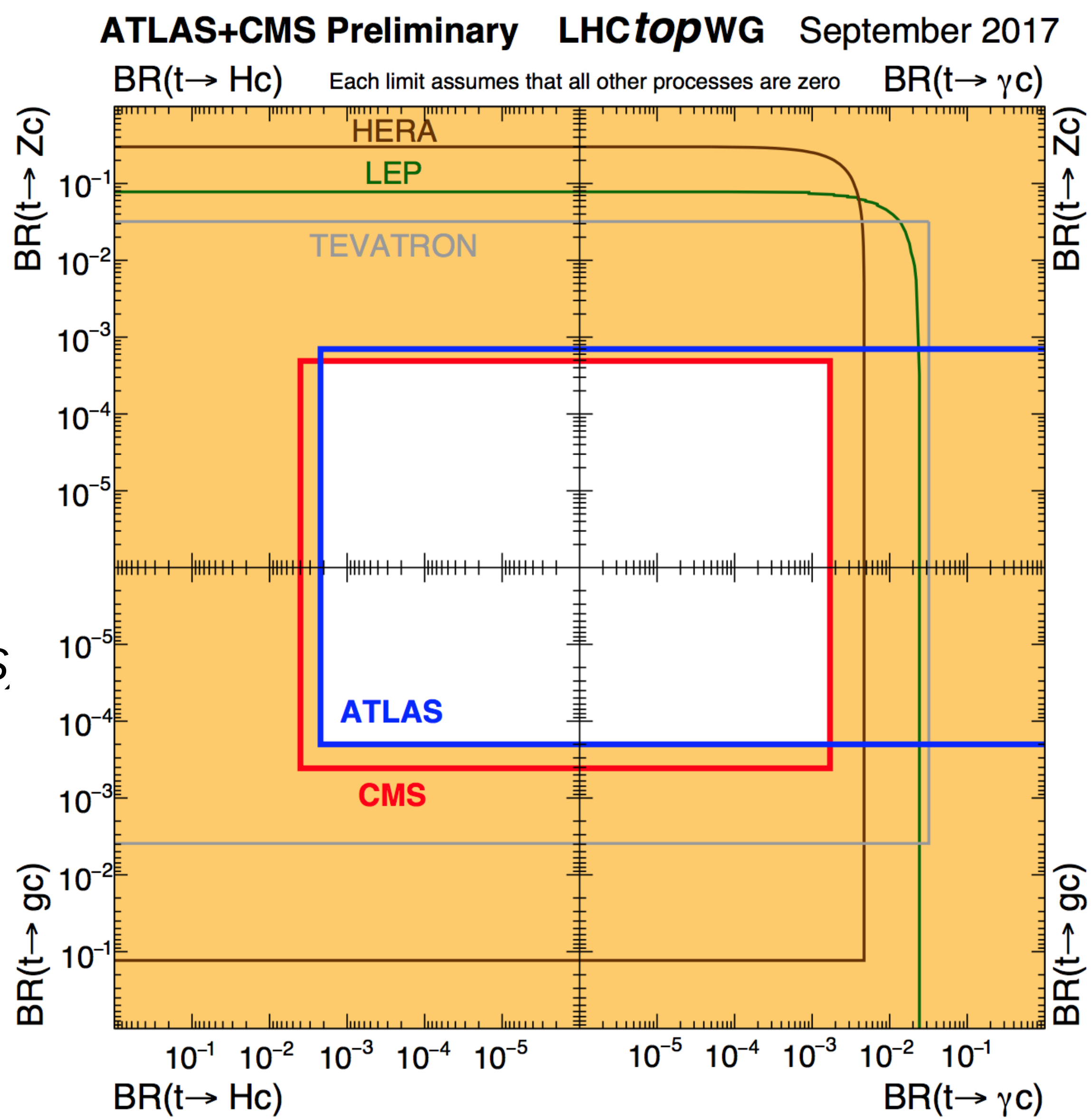
$e^+e^- \rightarrow tj$ (LEP2)
$ep \rightarrow et$ (HERA)
$t \rightarrow j\gamma/ll$ (CDF/D0/ATLAS/CMS)
$t \rightarrow jh$ (ATLAS/CMS)



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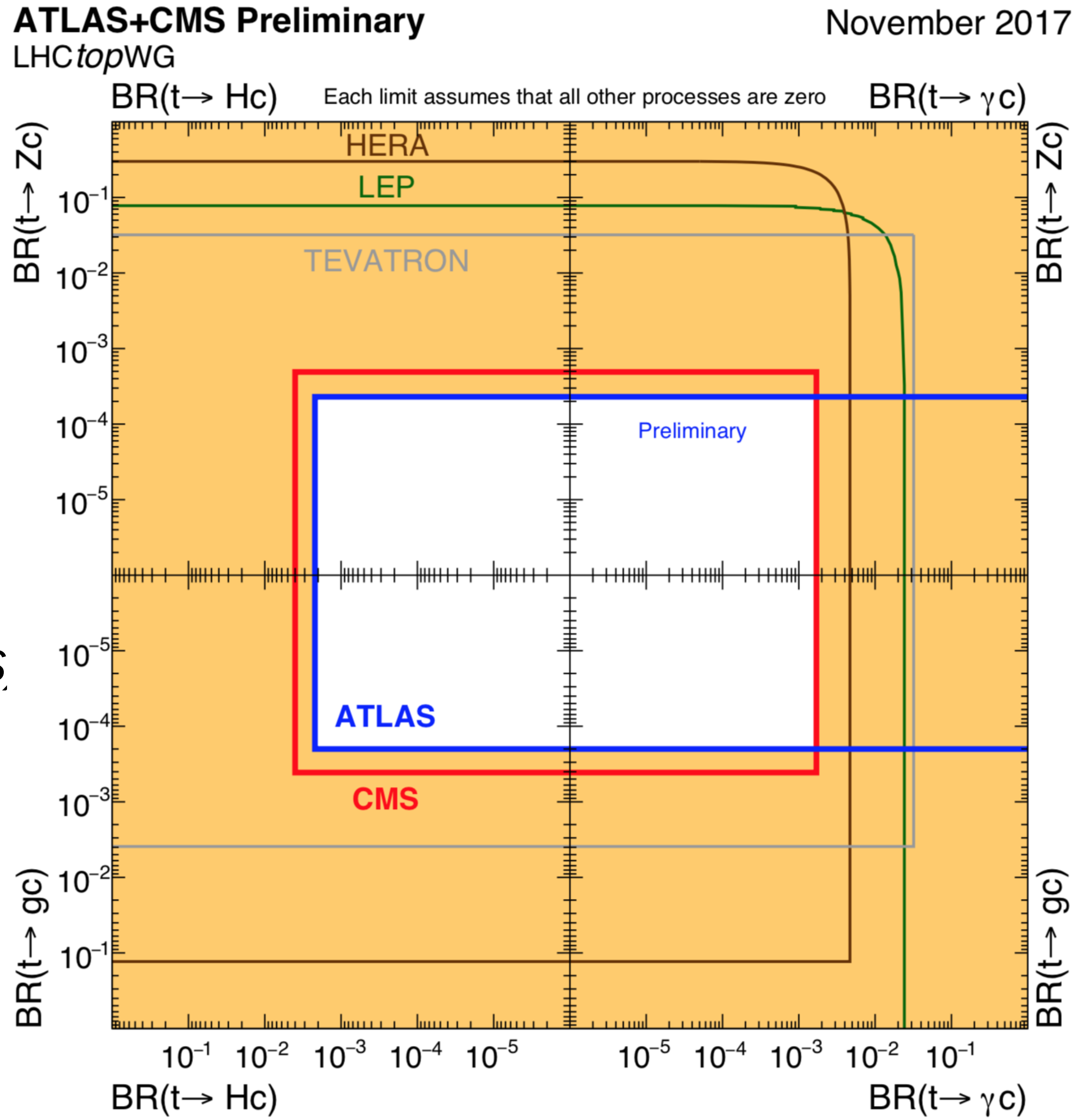

FCNC interactions

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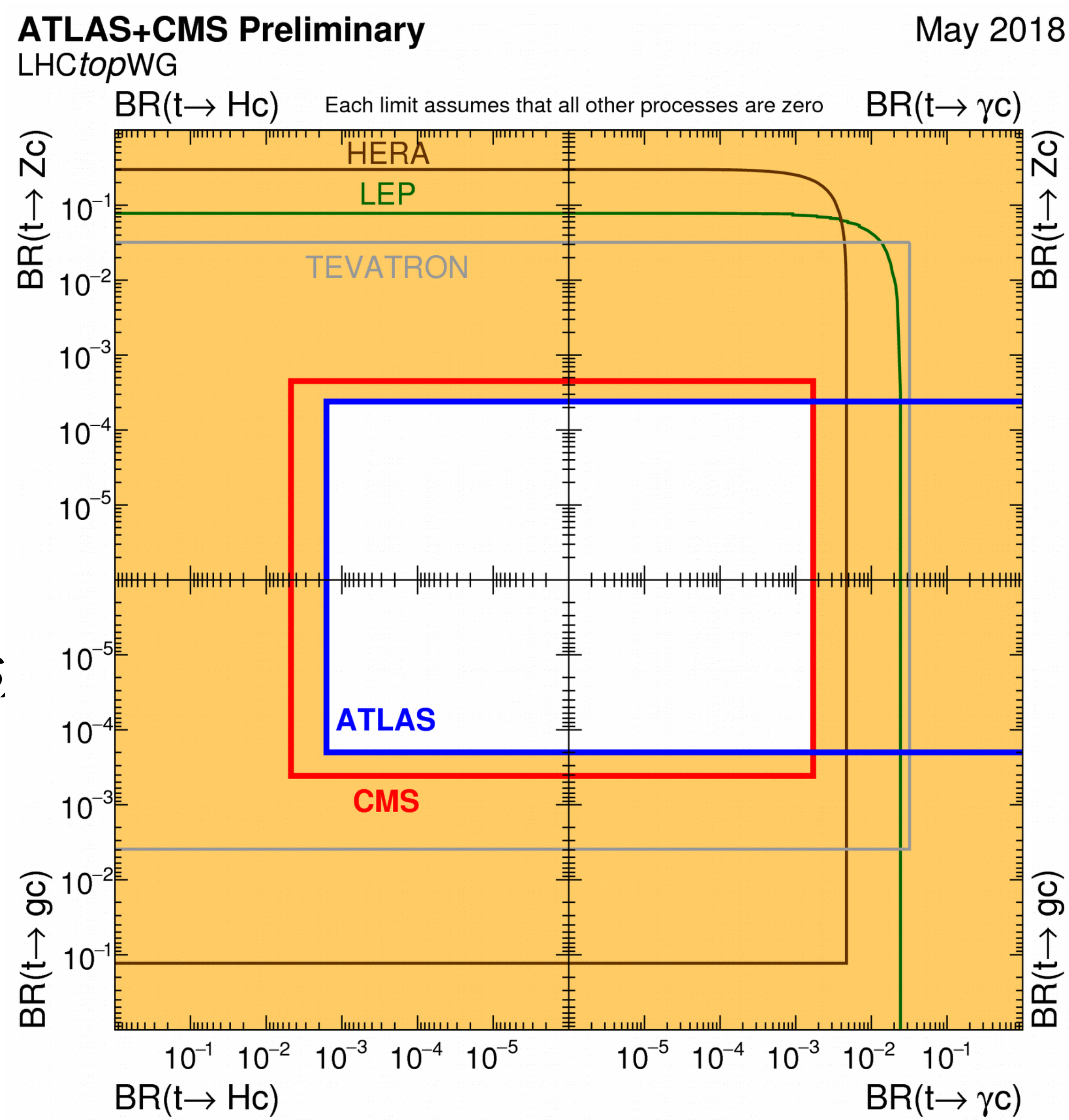

FCNC interactions

tXc

pp → *t* (CDF/ATLAS)
pp → *tj* (D0/CMS)
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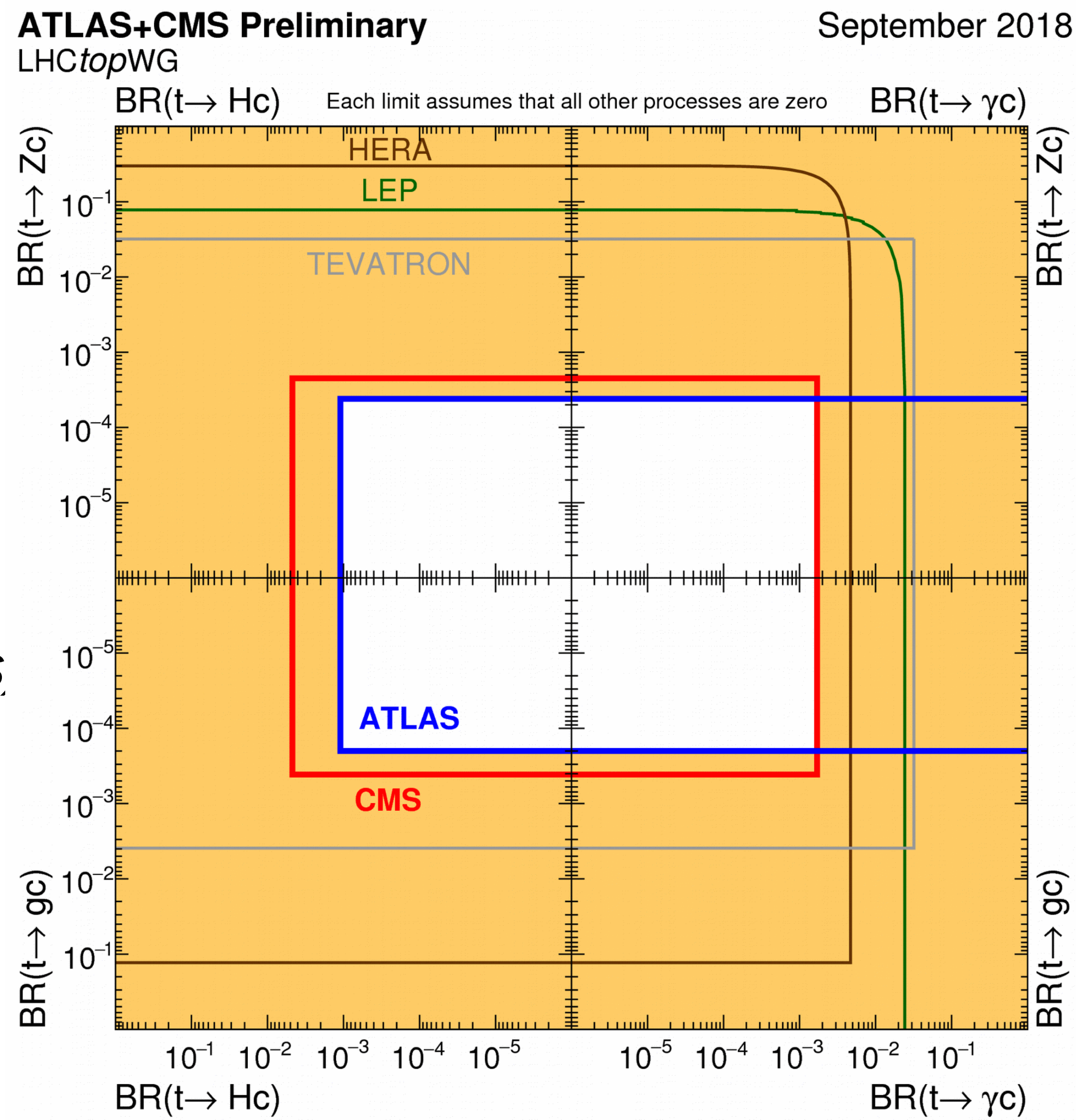


FCNC Prospects

Rare decays seem like an obvious motivation to keep the top factory running

J. A. Aguilar-Saavedra, arXiv:1709.03975
“At future facilities, limits on top FCN interactions resulting from $t\bar{t}$ production will not significantly improve over the current ones” [as they are limited by systematics]

HL-LHC prospects for FCNC decay searches
3000 fb^{-1} at 14 TeV, ATL-PHYS-PUB-2016-019

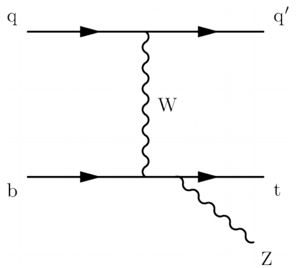
$$BR(t \to Zq) \lesssim 10^{-4}$$
$$BR(t \to Hq) \lesssim 10^{-4}$$

Note: Systematic-aware prospects, with three different scenarios for systematics.

However, dedicated FCC-hh pheno study predicts sensitivity BR ($t \to Hc$) < 10^{-5}, Papaefstathiou & Tetlalmatzi-Xolocotz, arXiv:1712.06332

More data on rare processes

More constraints coming in from rare top production processes (arXiv:1804.07773)



Single top tZ(j) production
(3.7 σ signal Dec. 2017)

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ELSEVIER

Measurement of the associated production of a single top quark and a Z boson in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration *

CERN, Switzerland

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ABSTRACT

A measurement is presented of the associated production of a single top quark and a Z boson. The study uses data from proton–proton collisions at $\sqrt{s} = 13$ TeV recorded by the CMS experiment, corresponding to an integrated luminosity of 35.9 fb^{-1}. Using final states with three leptons (electrons or muons), the tZq production cross section is measured to be $\sigma(pp \to tZq \to Wb\ell^+\ell^-q) = 123^{+33}_{-31}(stat)^{+29}_{-23}(syst)$ fb, where ℓ stands for electrons, muons, or τ leptons, with observed and expected significances of 3.7 and 3.1 standard deviations, respectively.

CMS-TOP-17-016

CERN-EP-2018-206
2018/08/10

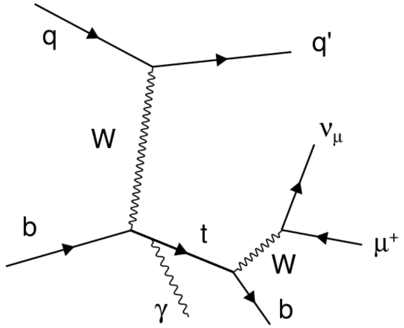
8 Aug 2018

Evidence for the associated production of a single top quark and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

Single top tγ(j) production
(4.4 σ signal Aug. 2018)



FCNC prospects FCChh

FCChh SM summary, arXiv:1607.01831

"Performing a naive rescaling of the LHC expectations one would expect an improvement of almost two orders of magnitude, reaching a sensitivity of Br(t → qZ; t → qg) ~ 10^{-7}

J. A. Aguilar-Saavedra, arXiv:1709.03975

"At future facilities, limits on top FCN interactions resulting from $t\bar{t}$ production will not significantly improve over the current ones" [as they are limited by systematics]

Consider pp → Zt and pp → γt production at FCChh

Semi-leptonic analysis in ultra-boosted top quarks:

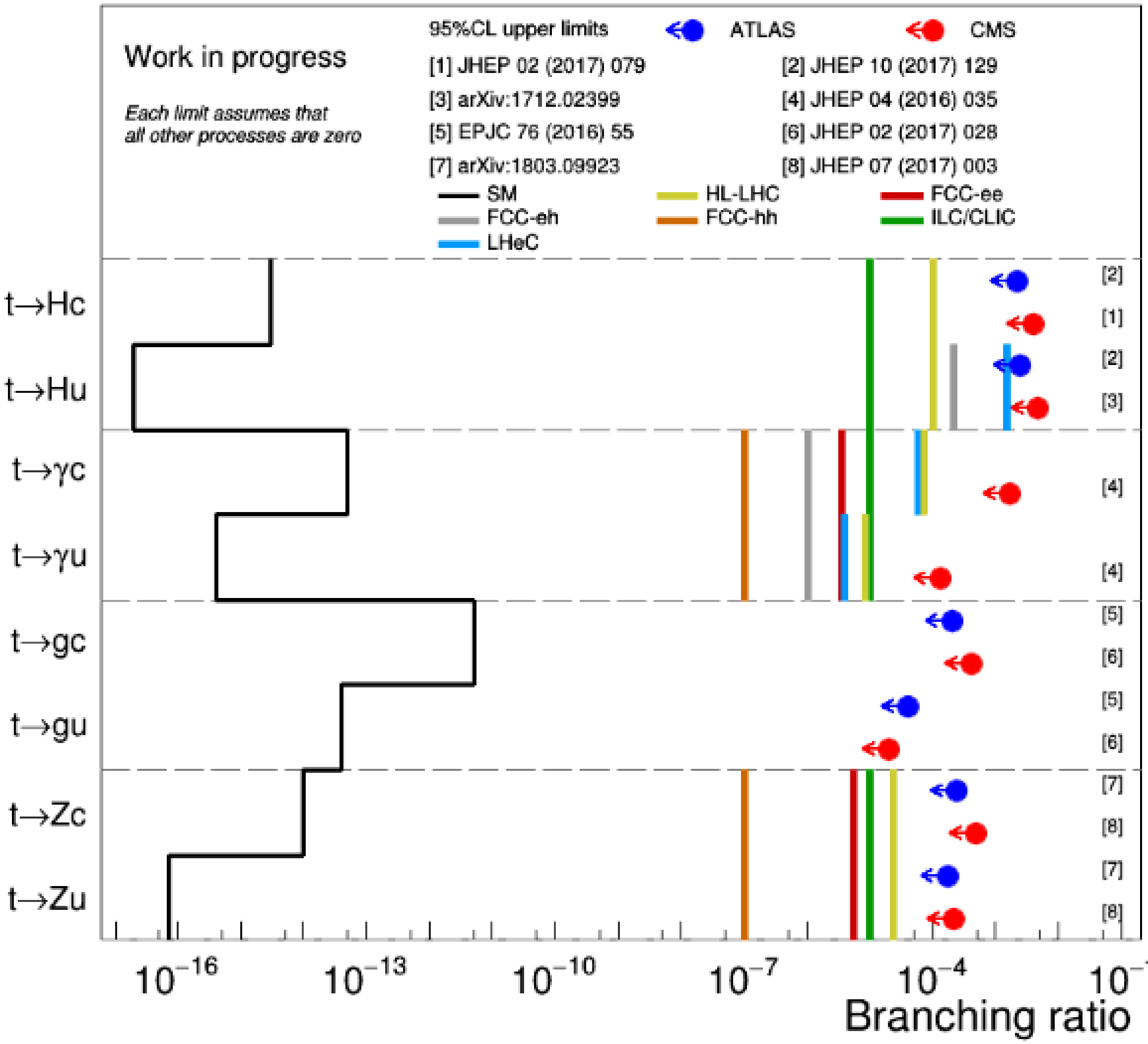
$$\mathrm{Br}(t \to uZ) < 2.7 \times 10^{-6}$$
$$\mathrm{Br}(t \to cZ) < 5.0 \times 10^{-5}$$
$$\mathrm{Br}(t \to u\gamma) < 9.1 \times 10^{-7}$$
$$\mathrm{Br}(t \to c\gamma) < 2.3 \times 10^{-5}$$

Cf. HL-LHC prospects
ATL-PHYS-PUB-2016-019
$\mathrm{BR}(t \to Zq) \lesssim 10^{-4}$
$\mathrm{BR}(t \to Hq) \lesssim 10^{-4}$

"searches for Zt and γt production in the ultraboosted regime will provide competitive limits on top FCN interactions"

FCNC: the rarest processes of all

So rare in the SM, we won't get anywhere near the SM sensitivity soon

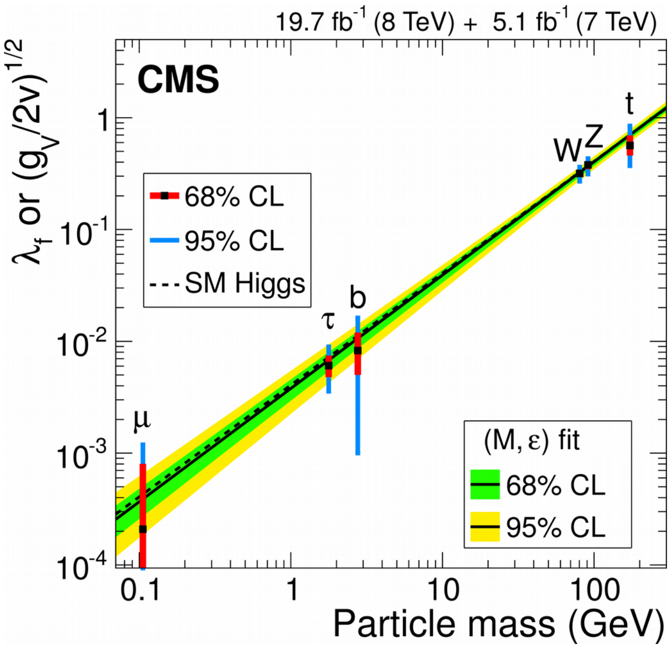


Unique attempt to make a comprehensive summary plot comparing all future projects

Note: e^+e^- makes up for slower top production rate with clean environment and charm-tagging performance in some channels

From:
Freya Blekman, TOP2018

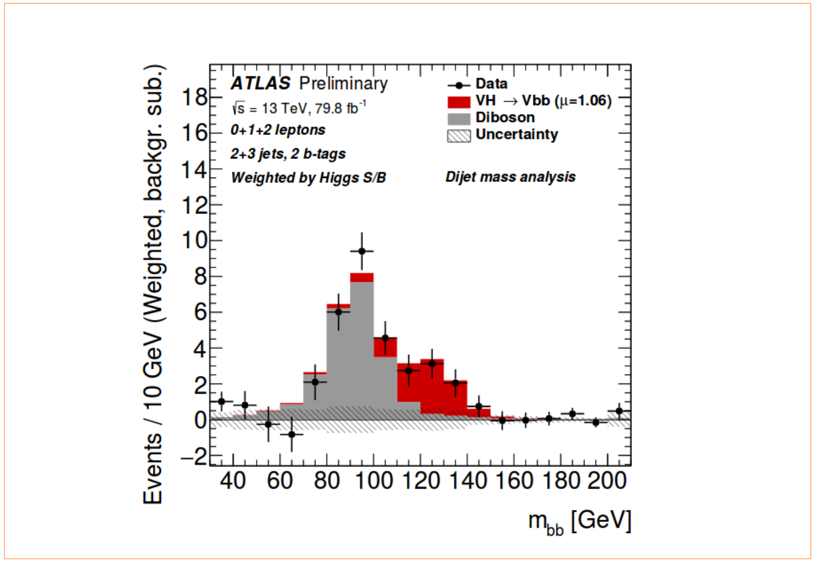
Top and Higgs

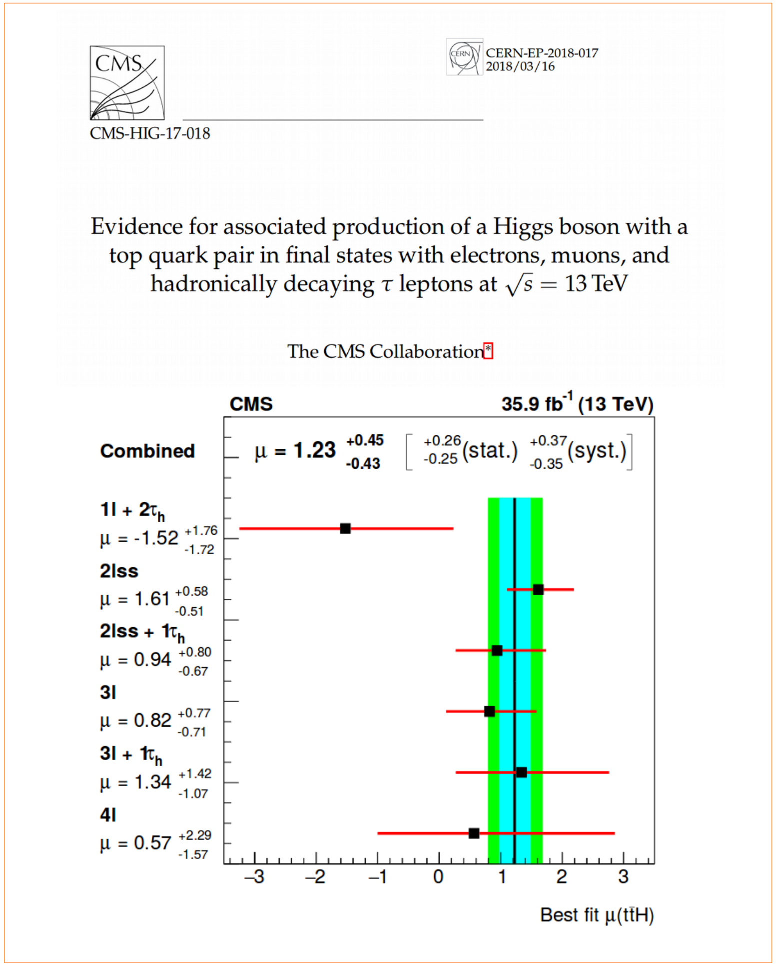


Rare processes: LHC establishes $t\bar{t}H$ production!

$t\bar{t}H$ production observed with >5 σ in both ATLAS and CMS
“New physics”. Even if it is predicted by the SM, it is a process that has never been observed before, and is proof of a new interaction

Together with observations of $H \rightarrow b\bar{b}$ and $H \rightarrow \tau\tau$ decay this is solid evidence that Yukawa couplings are responsible for mass of (third-generation) fermions





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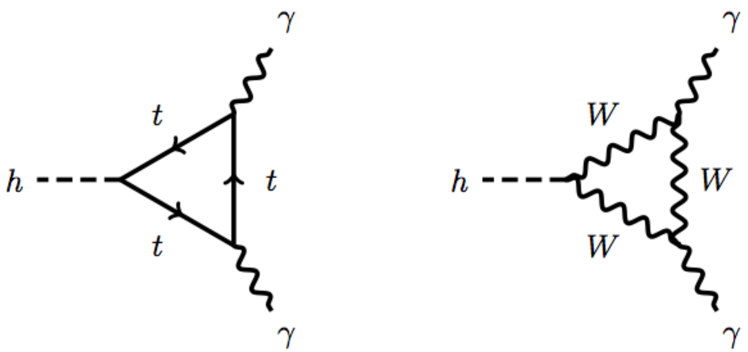
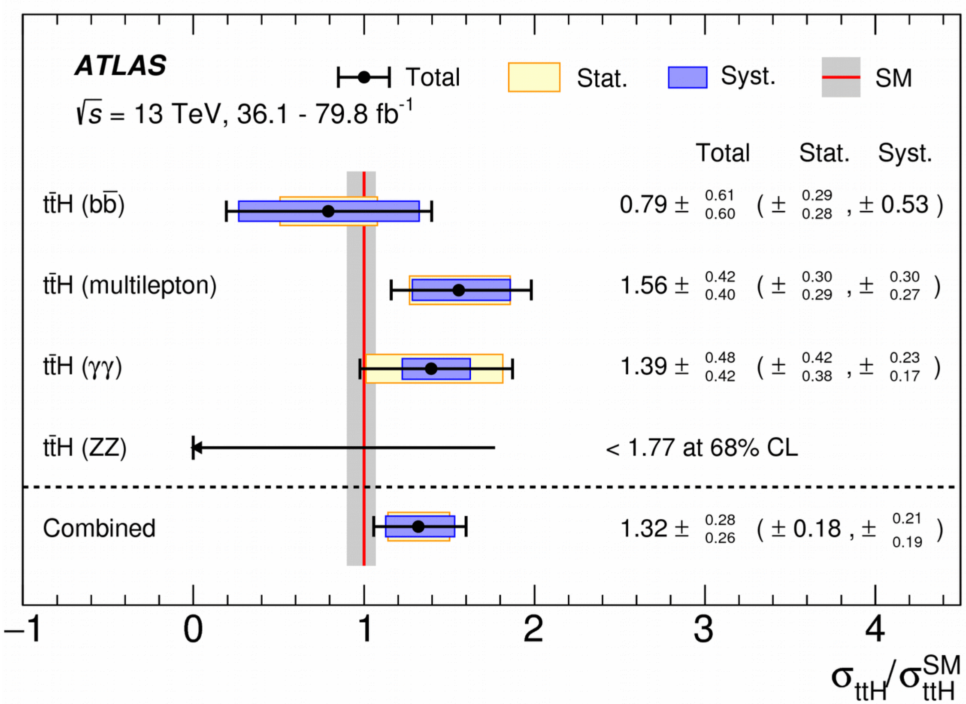
Top Yukawa coupling

Prospects for full LHC program:
K_u → 7-10% (3/ab)
Snowmass Higgs report

Indirect: the top quark Yukawa coupling is inferred from gg → H and H → γγ decay rates.
Run I: k_t = 1.43 ± 0.23.





Direct: measurement in ttH production.
Run I: μ_{ttH} = 2.3 ± 0.7

New 13 TeV data

CMS: μ_{ttH} = 1.26 ± 0.3
ATLAS: μ_{ttH} = 1.32 ± 0.3

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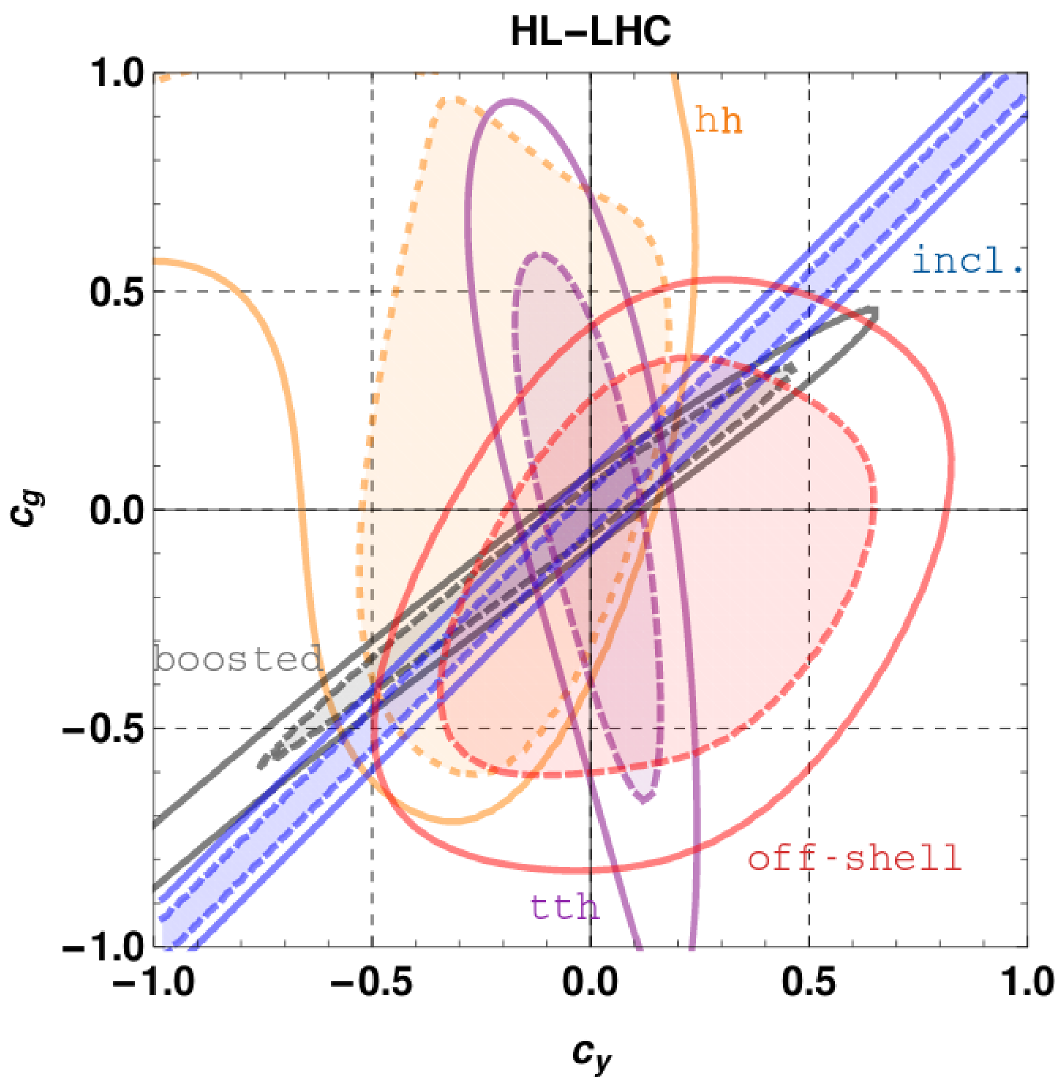
The top Yukawa coupling: global analysis

The indirect constraint on the top Yukawa coupling from top loops in gg → H (and H → γγ) is quite powerful

In a global EFT analysis it is very hard to distinguish the effect of a direct Hgg coupling (c_g) from that of the operator that modifies the top Yukawa coupling (c_y)

Direct measurement in ttH remains most powerful handle

Azatov et al., arXiv:1608.00977



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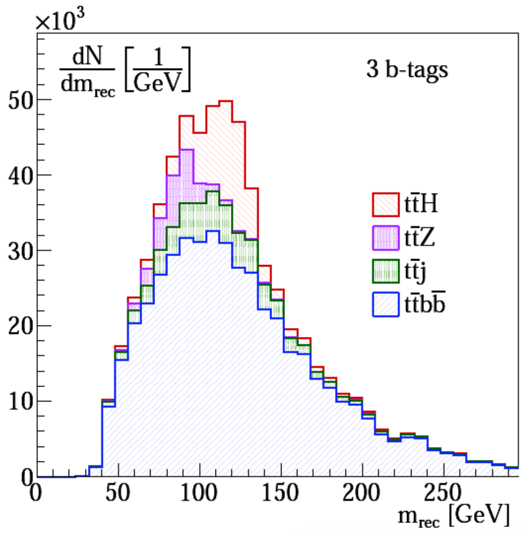
Top quark Yukawa coupling at hadron colliders

Deal with theory cross section by using a wisely chosen ratio:

	$\sigma(t\bar{t}H)[\mathrm{pb}]$	$\sigma(t\bar{t}Z)[\mathrm{pb}]$	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
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	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

High rate allows to focus on events where H → bb and hadronic top decay are sufficiently boosted to reconstruct them as “fat” jets

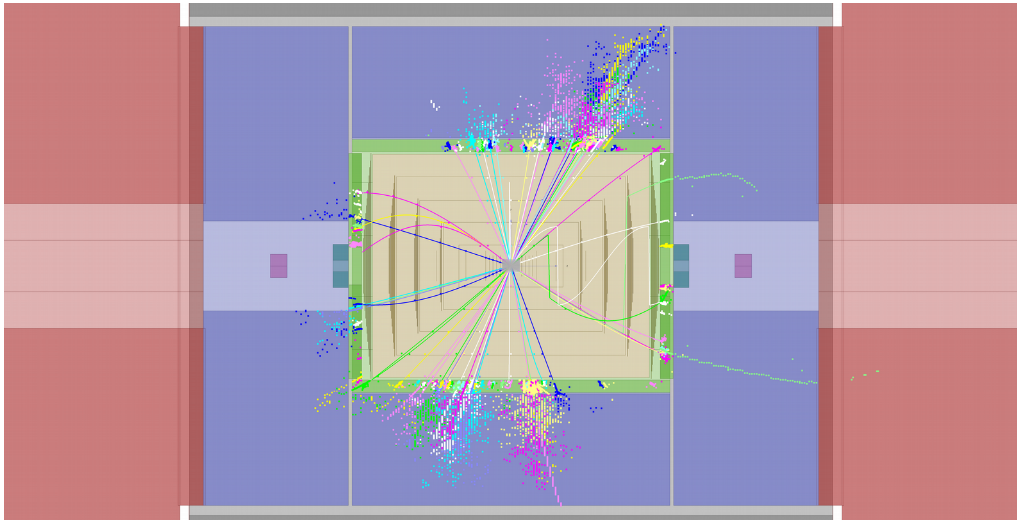
Fast simulation analysis achieves S/B~1/3.
Good mass resolution for H and Z candidates
Side-bands to control background normalization.



FCChh could achieve down to 1% precision on the top Yukawa coupling (20/ab, 100 TeV)
Mangano, Plehn, Reimitz, Schell, Shao, 2015

Full simulation required to make a solid claim

Top quark Yukawa coupling



Challenges:

Small signal sample
Large (x100) background rejection
Jet reconstruction and pairing

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 : 3.8% with 1.5 ab^{-1} at 1.4 TeV *arXiv:1807.02441*

Bonus: CP properties of the Higgs
arXiv:1809.07127, arXiv:1807.02441

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Indirect top Yukawa coupling

Mitov et al., arXiv:1805.12027

$$\mu_{h\to gg} = \frac{\Gamma_{h\to gg}}{\Gamma^{SM}_{h\to gg}} = 1 + 2\Delta y_t \, ,$$

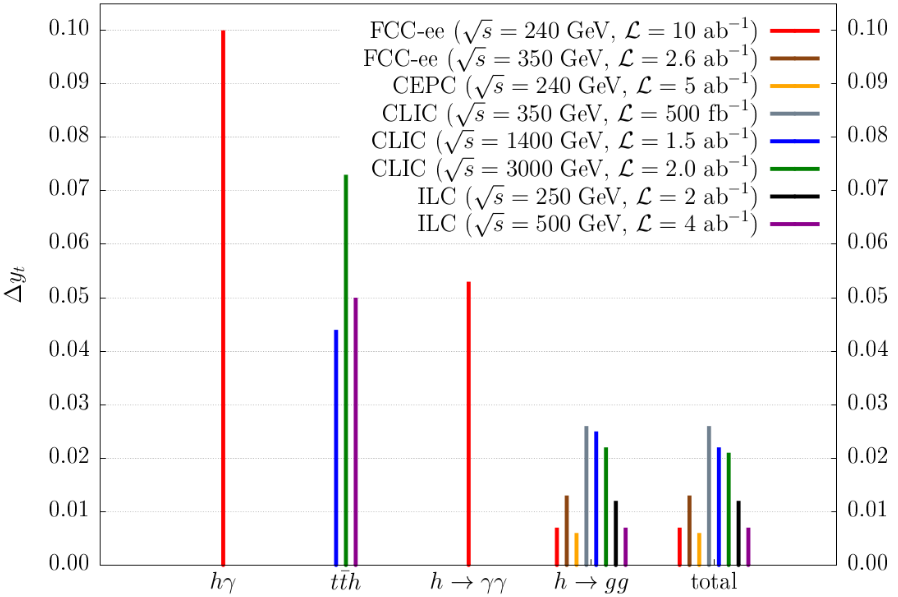
$$\mu_{h\to\gamma\gamma} = \frac{\Gamma_{h\to\gamma\gamma}}{\Gamma^{SM}_{h\to\gamma\gamma}} = 1 - 0.56\Delta y_t \, .$$

Fit of H → gg and H → γγ rates:

1% precision at 250 GeV

Note: one-parameter fit!!

How robust are indirect constraints?



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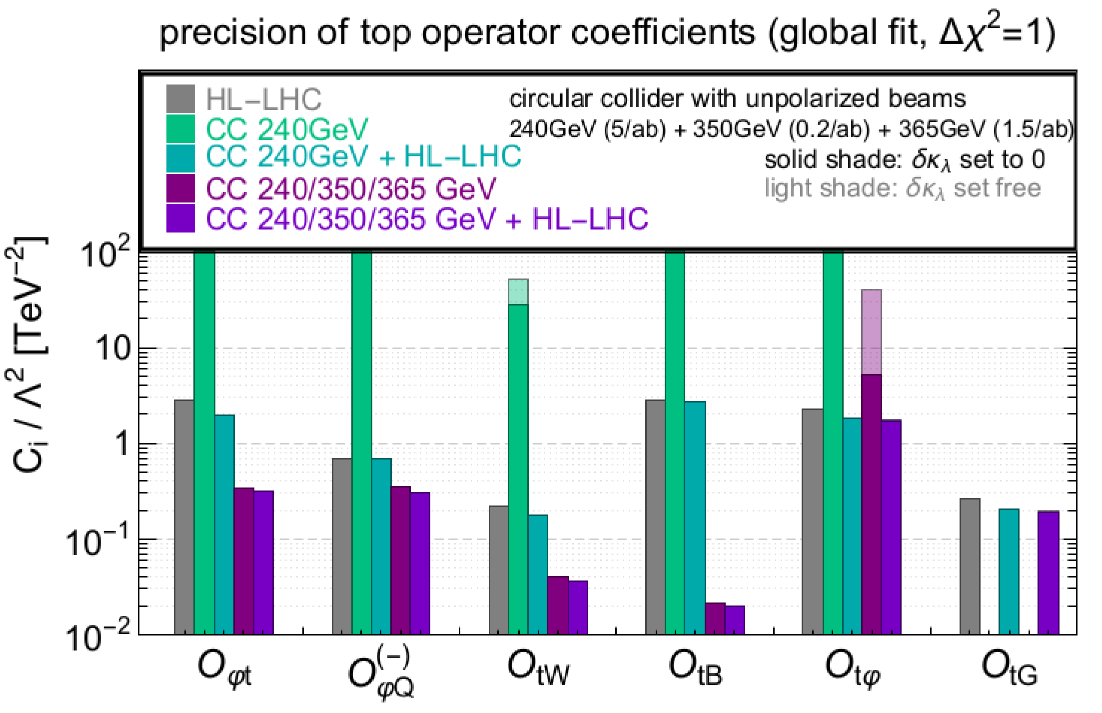
Top Yukawa coupling: global analyis at lepton colliders

Global limits on top operators from 250 GeV measurements are rather weak
Vryonidou & Zhang, arXiv:1804.09766, Durieux et al., arXiv:1809.03520

240 GeV run improves over HL-LHC
but does not get anywhere near 1-2%

Including tt̄ data helps!

Direct ttH production (>550 GeV)
remains desirable



EW couplings of the top quark

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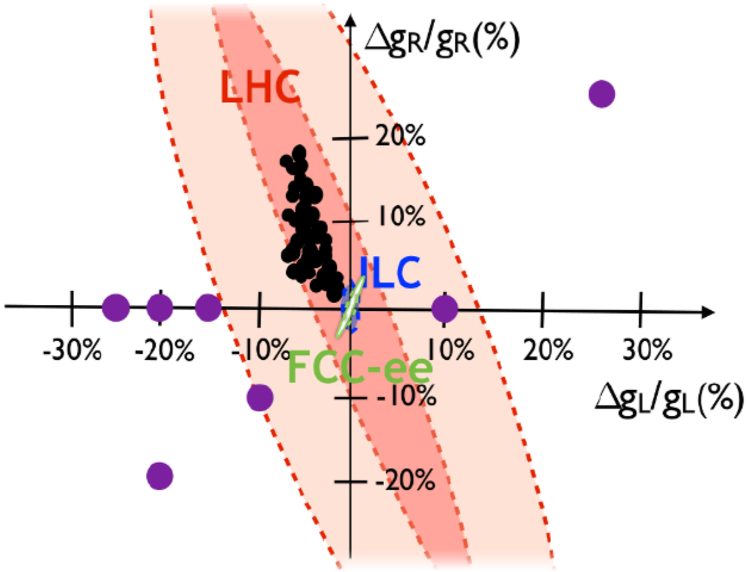
Top quark EW couplings

Genuine “world first”: there are no LEP constraints on top (right-handed) coupling

BSM sensitivity: large family of (composite Higgs/RS) models predict sizeable deviations from SM prediction

- 5D models by several authors
  Richard, arXiv:1403.2893
- 4D Composite Higgs Model
  Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)



Proposal for a (weak) no-loose argument: a measurement of top EW couplings to sub-% precision provides an answer to the question whether Composite Higgs/RS models are realized at their natural scale

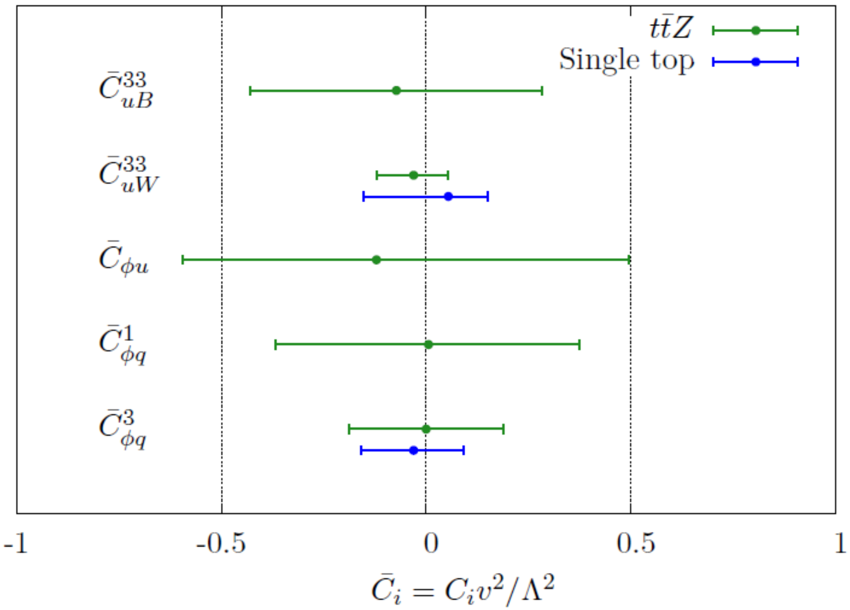
Top EW couplings: LHC status

Neutral current: ttZ, ttγ associated production (tZ, tγ)
→ processes "discovered", cross section measurements 10-20%

Charged current: single top production, top decay observables
→ precision top physics at the LHC

Fit to Tevatron and LHC data
arXiv:1506.08845, arXiv:1512.03360

2015: first attempt to fit all top data



Top EW couplings: LHC status

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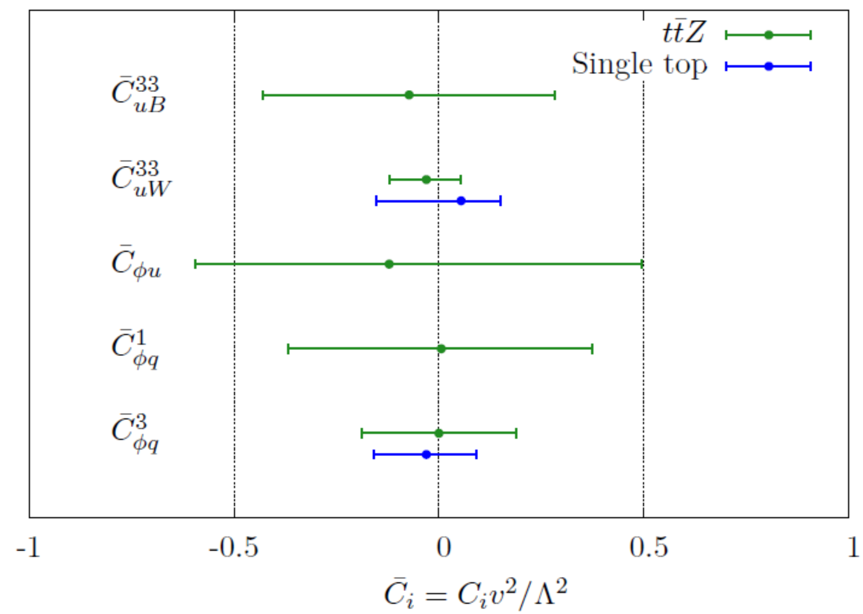
→ precision top physics at the LHC

Fit to Tevatron and LHC data
arXiv:1506.08845, arXiv:1512.03360

Weak limits on the edge of EFT validity
Truly global analysis not yet feasible



Top EW couplings: LHC status

Neutral current: ttZ, ttγ associated production (tZ, tγ)
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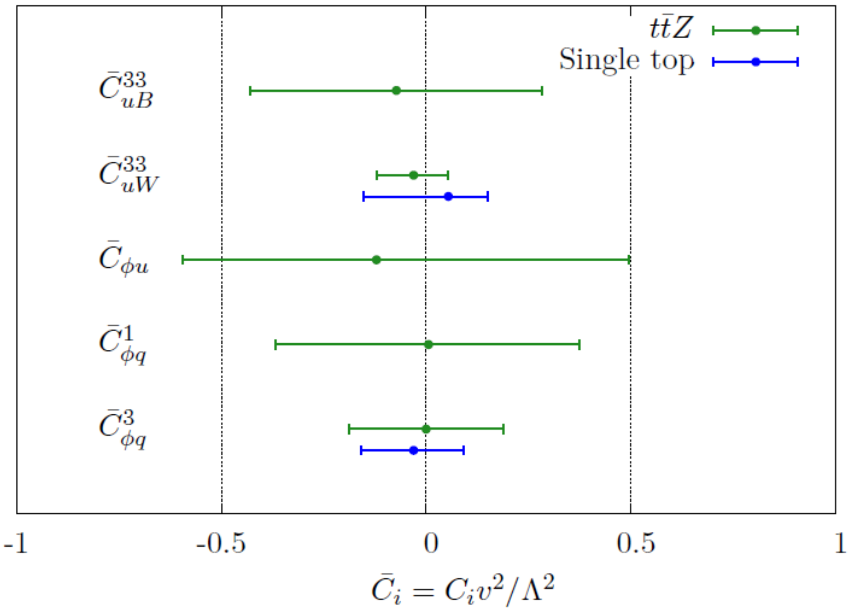
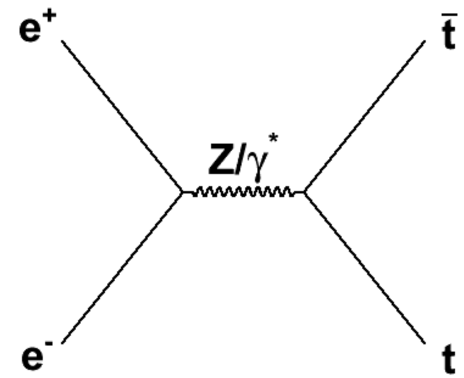


Prospects:
BSM sensitivity rougly independent of $\sqrt{s}$
Gain at HL-LHC, HE-LHC, FCChh/SPPC must come from control of systematics

Rontsch & Schulze, arXiv:1501.05939
Schulze & Soreq, arXiv:1603.08911
FCChh SM study, arXiv:1607.01831

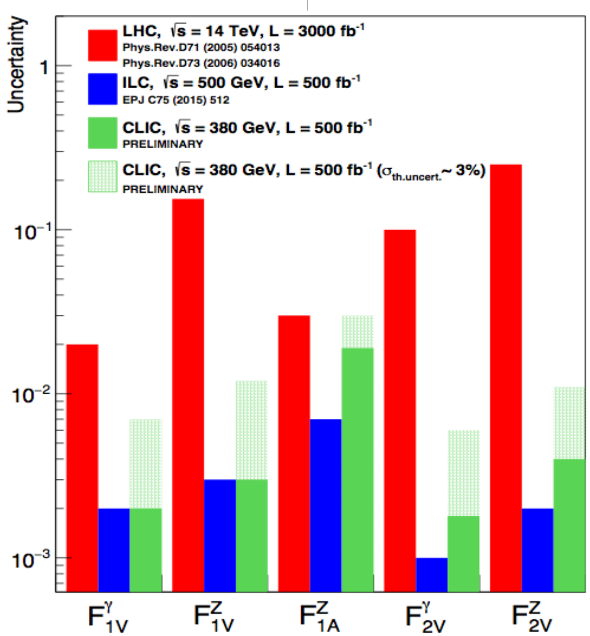
Top EW couplings at lepton colliders

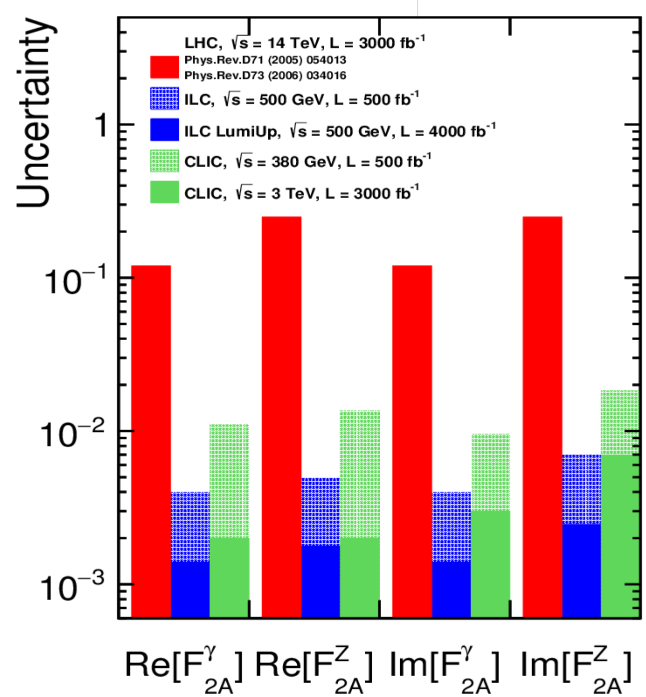


The best laboratory to test $\gamma t\bar{t}$ and $Zt\bar{t}$ vertices

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

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





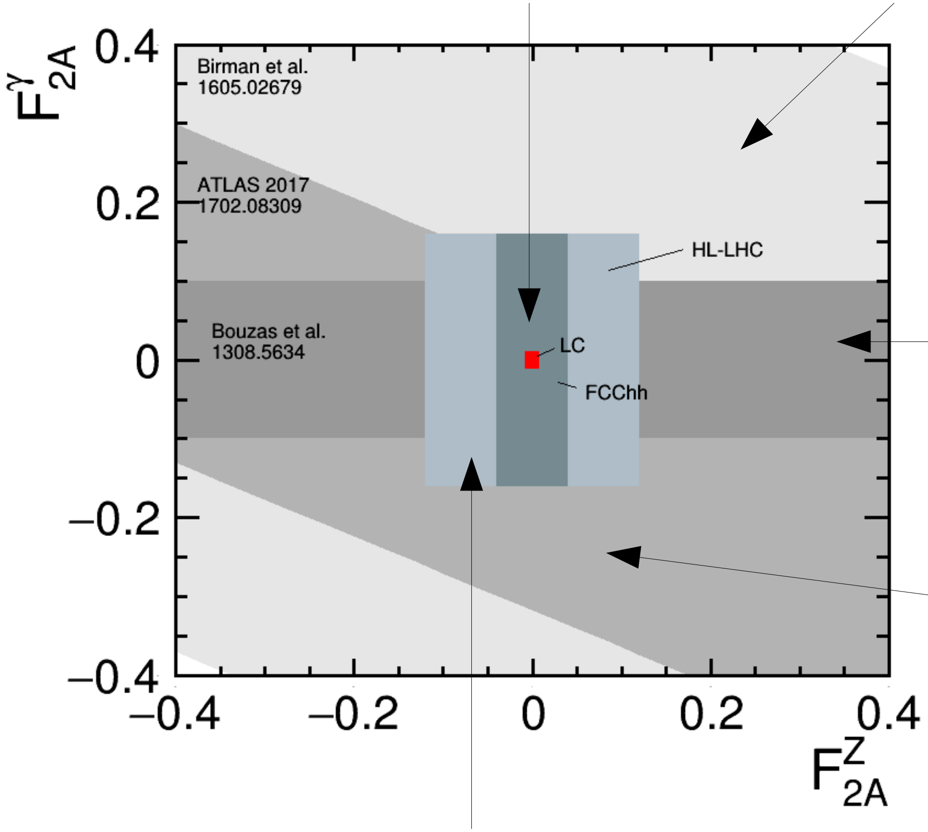
Prospects for HL-LHC/ILC500/CLIC380

arXiv:1307.8102, arXiv:1505.0620

EFT: relate many angles to approach the problem

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

Top decay $t \to Wb$



LHeC $eg \to t\bar{t}$

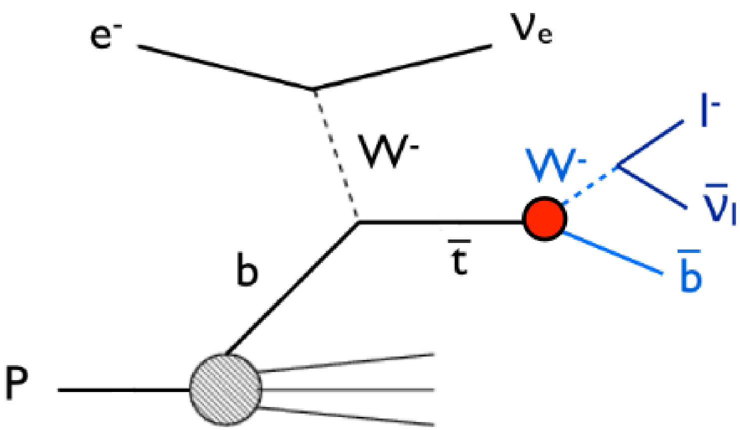
Single top production

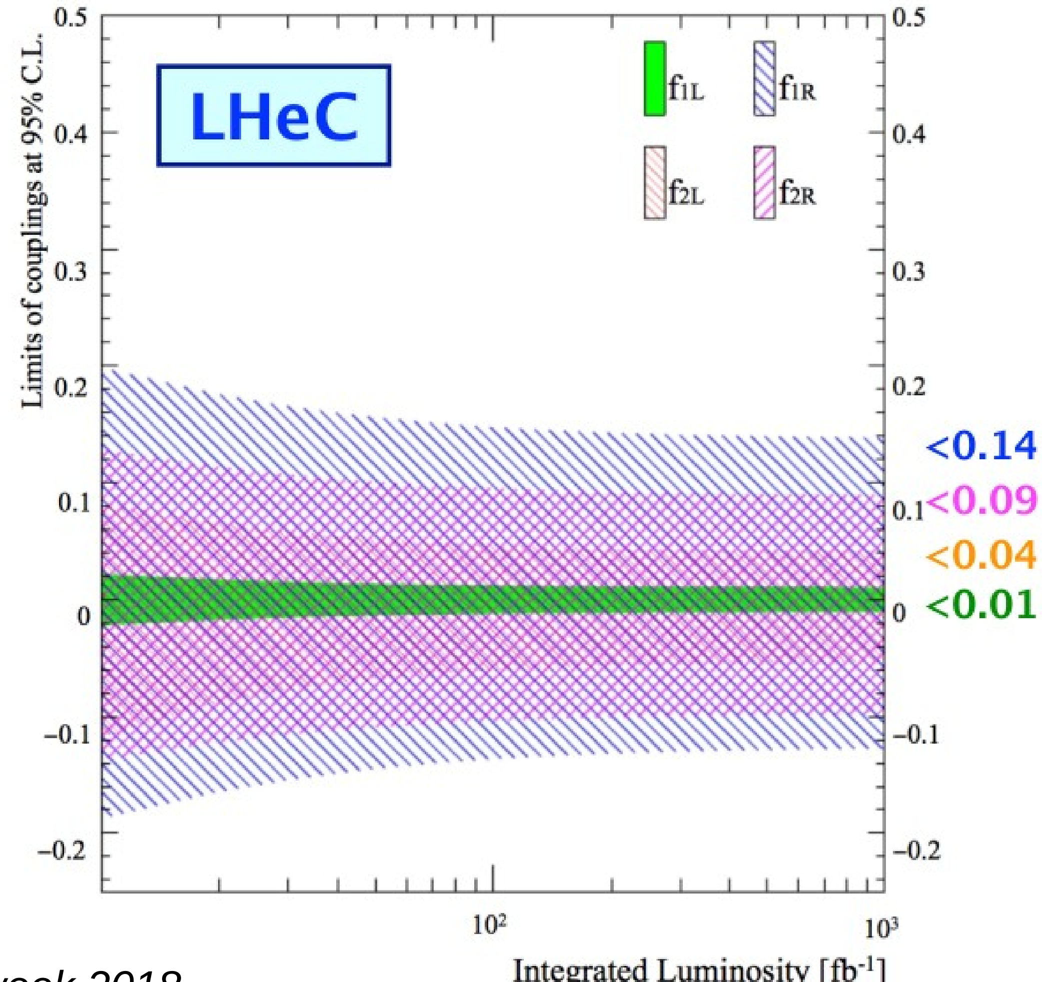
Associated production: $pp \to t\bar{t}Z$

constraints from different processes and colliders on top electric dipole moment $=f(\mathrm{Im}(C_{tW}), \mathrm{Im}(C_{tB}))$

LheC potential for top EW couplings

Dutta, Goyal, Kumar, Mellado, Eur. Phys. J. C75 (2015) no. 12, 577
Kumar, Ruan, to be publ.



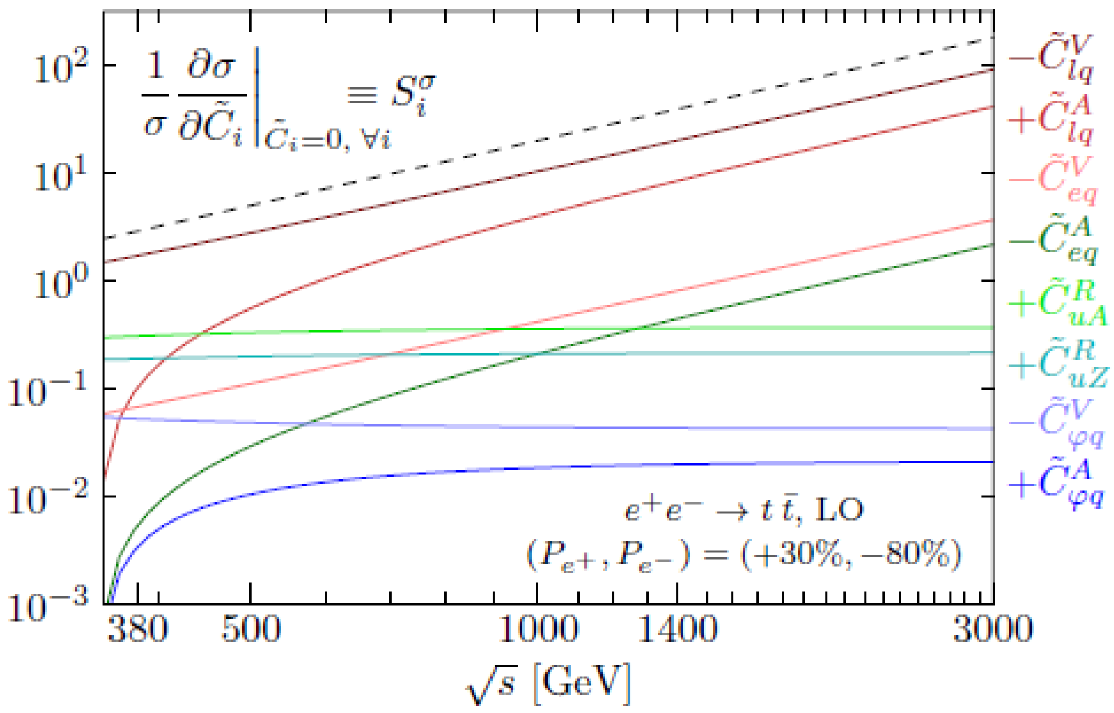


= 1 in SM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

See also: C. Schwanenberger, FCC week 2018

EFT: characterize sensitivity vs. energy



Effect of four-fermion operators felt most strongly at high energy

Effect of two-fermion operators best probed at ~400-500 GeV

(See also Fiolhiais et al., arXiv:1206.1033)

Global EFT fit

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLIC top paper, arXiv:1807.02441

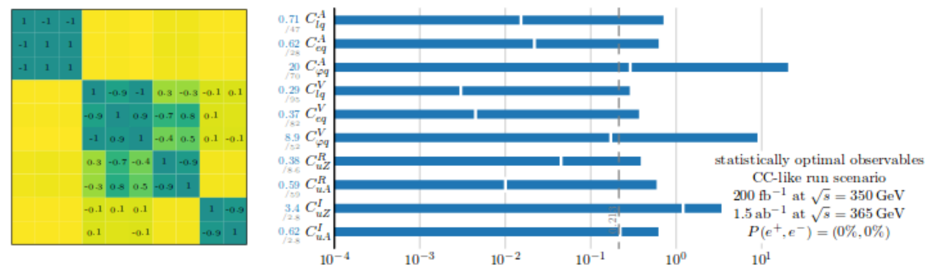


Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

Sensitivity to four-fermion operators increases strongly with energy

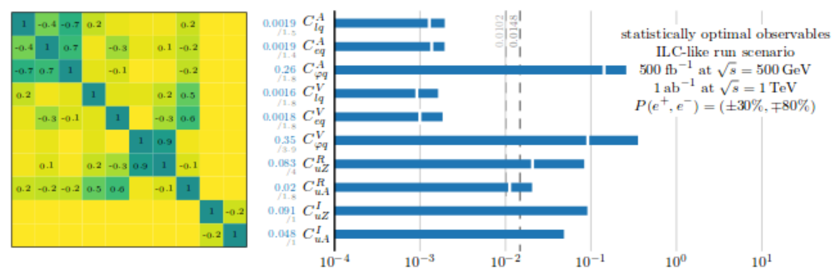


Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.

Ultimate precision in global 10-parameter fit requires a collider, with two energy stages and beam polarization

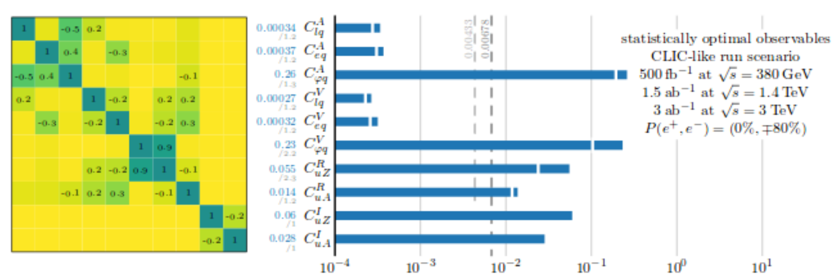
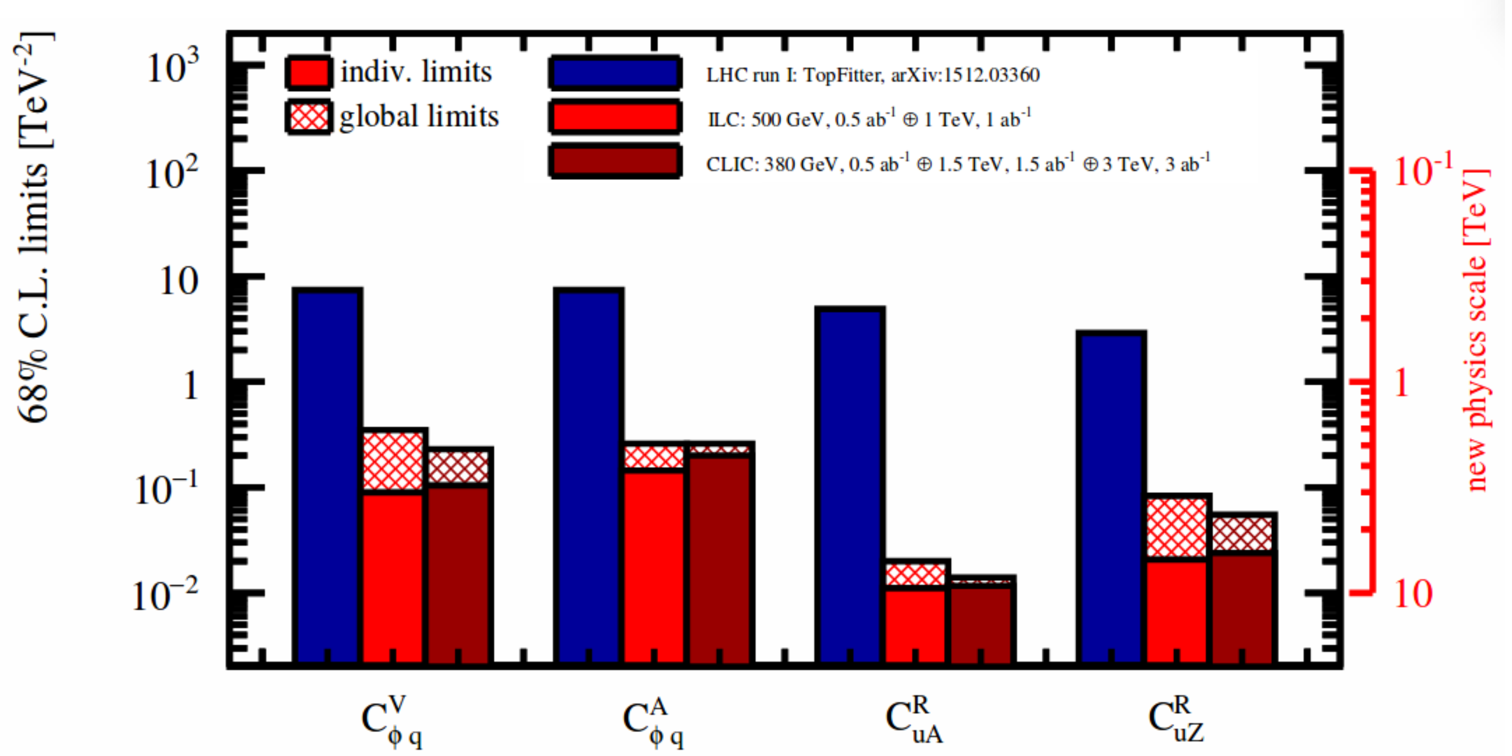


Figure 25. Global one-sigma constraints and correlation matrix arising from the measurement of statistically optimal observables in a CLIC-like benchmark run scenario.

Global EFT fit

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLICdp top paper, arXiv:1807.02441



Two-fermion operator limits exceed HL-LHC prospects by a large factor

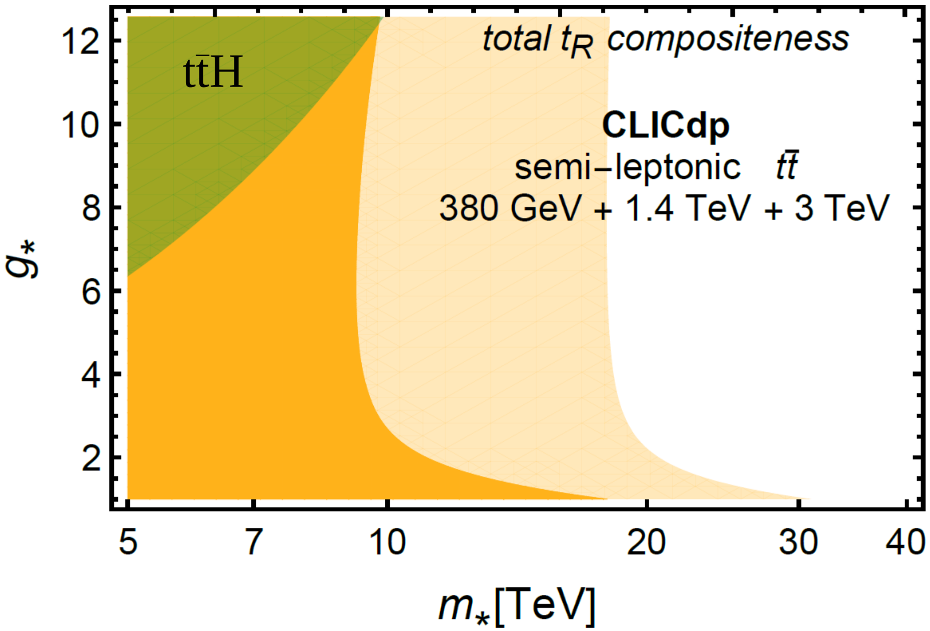
Constraints on 4-fermion and dipole moment operators probe very high scale
- TeV LC competitive with qq → tt at the LHC and possibly FCChh

From EFT to concrete scenario

Re-express EFT constraints as limits on the canonical composite Higgs scenario, characterized by a coupling strength g_* and NP scale m_* (*Giudice 2007*)

The top quark is naturally composite in this framework (*Pomarol 2008*), the only viable option to generate the top Yukawa coupling (*Ratazzi 2008*)

Benchmarks: partial (t_L and t_R composite) & total (t_R maximally composite)
Pessimistic 5σ discovery contours reach 7-15 TeV, in favourable cases > 20 TeV

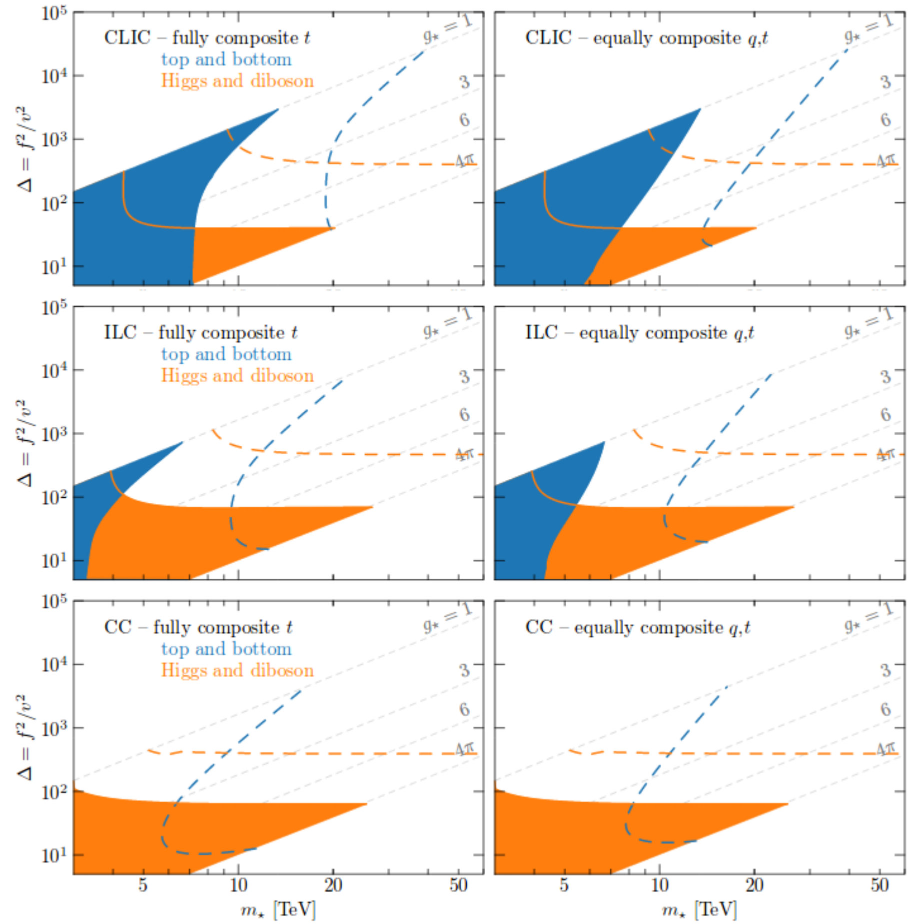


Durieux, Matsedonskiy, arXiv:1807.10273

Comparing projects and channels

Measurements in top and Higgs/di-boson sector yield complementary constraints

Four-fermion operators and high-energy operation can enhance the reach to tens of TeV



"Our results show that one can probe a significant fraction of the natural CH parameter space through the top portal, especially at TeV centre-of-mass energies"

Top mass

If top physics should ever get boring,
just ask a random group of theorists
"does the direct mass measurement yield the pole mass?"

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The top quark mass and the EW fit

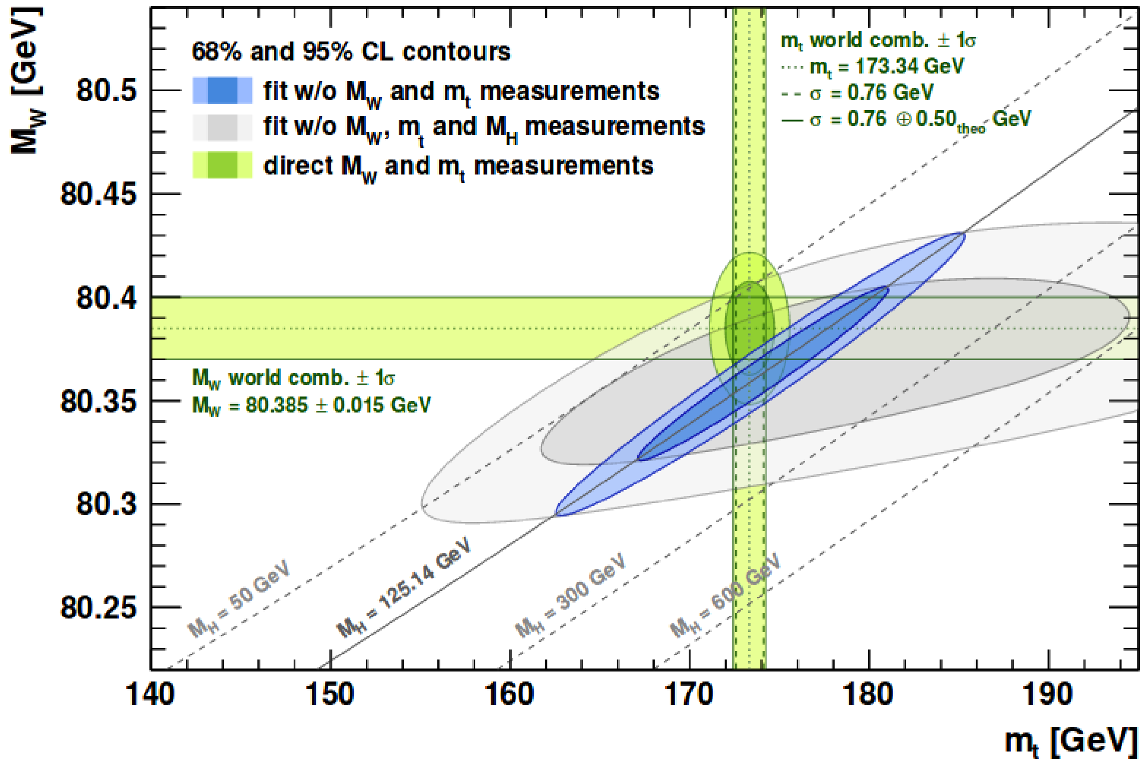
arXiv:1407.3792

New e^+e^- machines can **take the EW fit to next level**

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

Requires theory progress and precise top quark mass

See: F. Riva



Progress at the LHC: top quark mass revisited

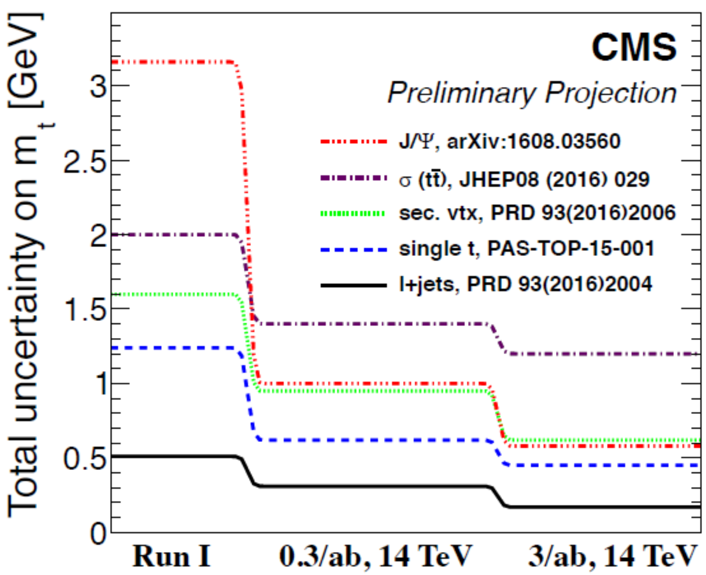
Direct mass measurent can reach 200-300 MeV precision (CMS)

Interpretation of direct top mass measurements is hotly debated.

Calibrate MC mass parameter:	*Hoang et al., PRL117*
Parton shower analytics:	*Hoang et al., arXiv:1807.06617*
Improve MC precision:	*Nason et al., arXiv:1607.04538, arXiv:1801.03944*
Renormalon ambiguity:	*Beneke et al., arXiv:1605.03609*

*Status quo: distinguish “**direct mass**” measurements and **“pole mass”** extractions from (differential) cross section measurements*

Progress beyond 500 MeV requires significant experimental and theory work
arXiv:1310.0799



Top quark pole mass

Inclusive cross section

Well-defined mass scheme & theory unc.

Limited sensitivity: Δm/m ~ 0.2 Δσ/σ

NEW CMS TOP-17-001

36 fb^{-1} at 13 TeV

cross-section, M_t^{pole}, α_s

Flexible mass scheme:

$\overline{\text{MS}}$ mass

Table 6: Extraction of $m_t(m_t)$ at NNLO from $\sigma_{t\bar{t}}$ using different PDF sets.

PDF set (NNLO)	$m_t(m_t)$ [GeV]
ABMP16	161.6 ± 1.6 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
NNPDF3.1	164.5 ± 1.5 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
CT14	165.0 ± 1.7 (fit + PDF) ± 0.6 (α_S) $^{+0.1}_{-1.0}$ (scale)
MMHT14	164.9 ± 1.7 (fit + PDF) ± 0.5 (α_S) $^{+0.1}_{-1.1}$ (scale)

Pole mass

Table 7: Extraction of m_t^{pole} at NNLO from $\sigma_{t\bar{t}}$ using different PDF sets.

PDF set (NNLO)	m_t^{pole} [GeV]
ABMP16	169.1 ± 1.8 (fit + PDF + α_S) $^{+1.3}_{-1.9}$ (scale)
NNPDF3.1	172.4 ± 1.6 (fit + PDF + α_S) $^{+1.3}_{-2.0}$ (scale)
CT14	172.9 ± 1.8 (fit + PDF) ± 0.7 (α_S) $^{+1.4}_{-2.0}$ (scale)
MMHT14	172.8 ± 1.7 (fit + PDF) ± 0.6 (α_S) $^{+1.3}_{-2.0}$ (scale)

Recent D0 pole mass result (arXiv:1605.06168):

$m_t = 172.8 \pm 1.1$ (theo.) $^{+3.2}_{-3.4}$ (exp.) GeV

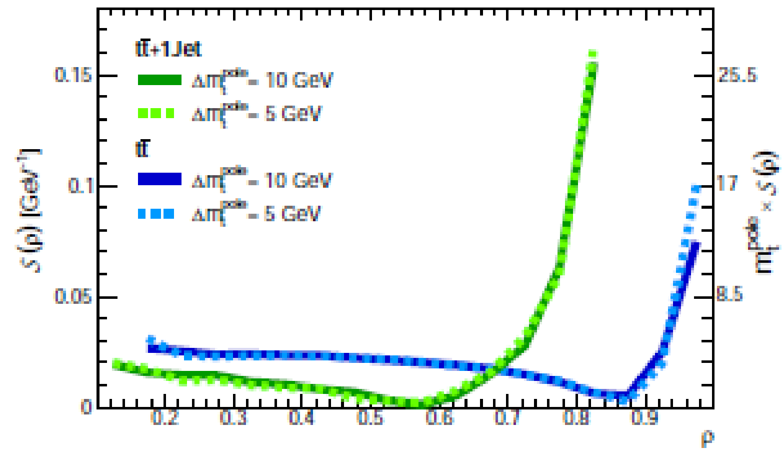
Top quark pole mass

$t\bar{t}g$ diff. cross-section

Alioli, Moch, Uwer, Fuster, Irles, Vos, arXiv:1303.6415

ATLAS, arXiv:1507.01769

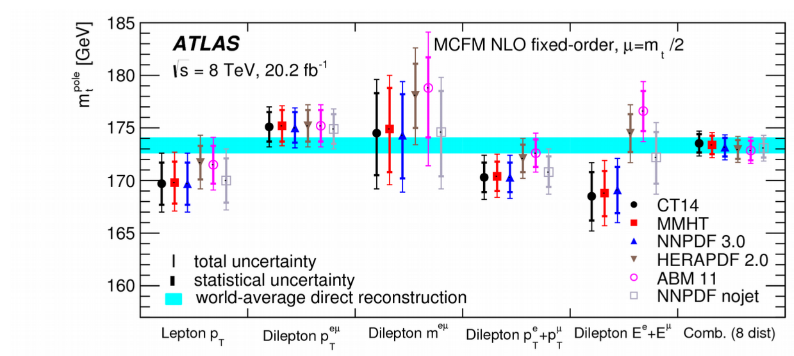
M_t^{pole}= 173.7 ± 1.5 (stat) ± 1.4 (syst) $^{+1.0}_{-0.5}$ (theory) GeV



Di-lepton diff. x-section

ATLAS 8 TeV, *EPJC77 (2017) 804*

M_t^{pole} = 173.2 ± 0.9 (stat.) ± 0.8 (theo.) ± 1.2 GeV (exp.)

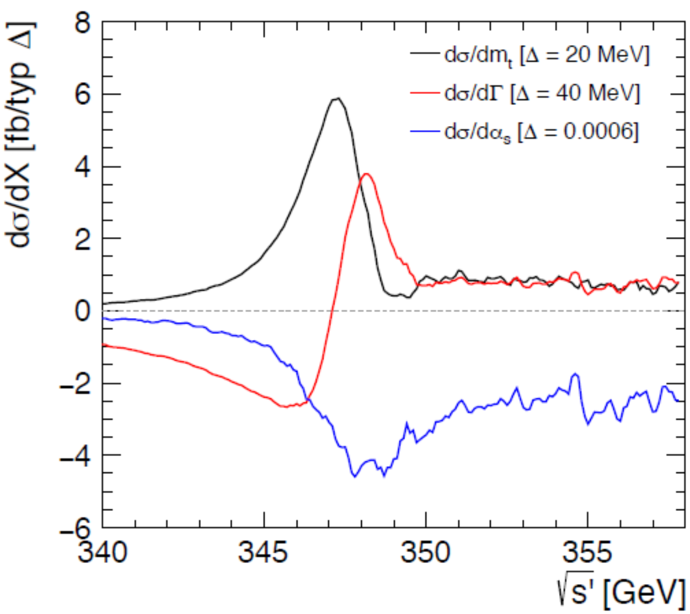


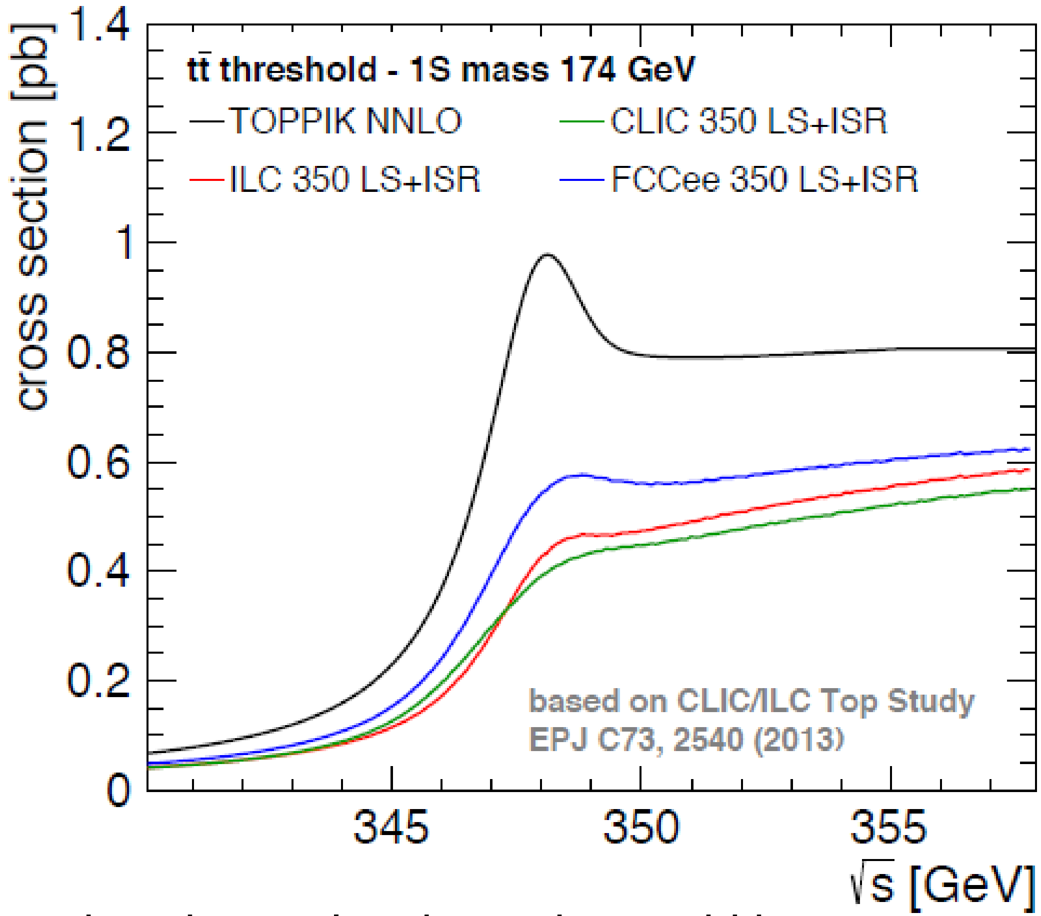
Approaching 1 GeV precision, incl. theory

Top quark mass from e^+e^- threshold scan

Threshold shape reveals the top quark mass

Kuhn, Acta Phys.Polon. B12 (1981)





Line shape also depends on width,
Normalization sensitive to α_s and y_t

Detailed estimates of the precision in multi-parameter fits

Martinez, Miquel, EPJ C27, 49 (2003), Horiguchi et al., arXiv:1310.0563, Seidel, Simon, Tesar, Poss, EPJ C73 (2013)

Top quark mass from e+e- threshold scan

A multi-parameter fit can extract the PS mass with excellent precision

Statistical uncertainty:	~20 MeV	*100 fb^{-1}*
Scale uncertainty:	~40 MeV	*N^3LO QCD, arXiv:1506.06864*
Parametric uncertainty:	~30 MeV	*α_s world average, arXiv:1604.08122*
Experimental systematics:	25-50 MeV	*including LS, arXiv:1309.0372*

This threshold mass can be converted to the $\overline{\text{MS}}$ scheme with ~10 MeV precision

Marquard et al., PRL114, arXiv:1502.01030

A very competitive top quark mass measurement:

$\Delta m_t \sim 50$ *MeV* (= 3×10^{-4}, cf. Δ**m_b ~1%)**

(nearly) independently of machine design and parameters.

Note: this is a prospect, not a target!

The future (of top physics) is bright

Be very critical of any prospect studies!

Top precision physics has a real shot at delivering the transformative discovery that high-energy physics needs

Future facilities offer exquisite sensitivity to high-scale new physics through the top portal

Mapping out the complementary among different projects and between top, Higgs/EW and other parts of the programme

A summary for a general audience

1973: The top quark is conceived

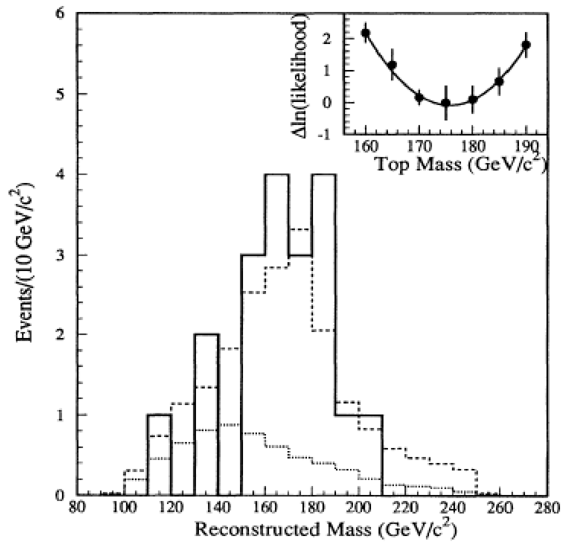
Kobayashi and Maskawa postulate the third generation

Particle physics was so easy back then!

1972 A 5M$ collider on the SLAC parking lot

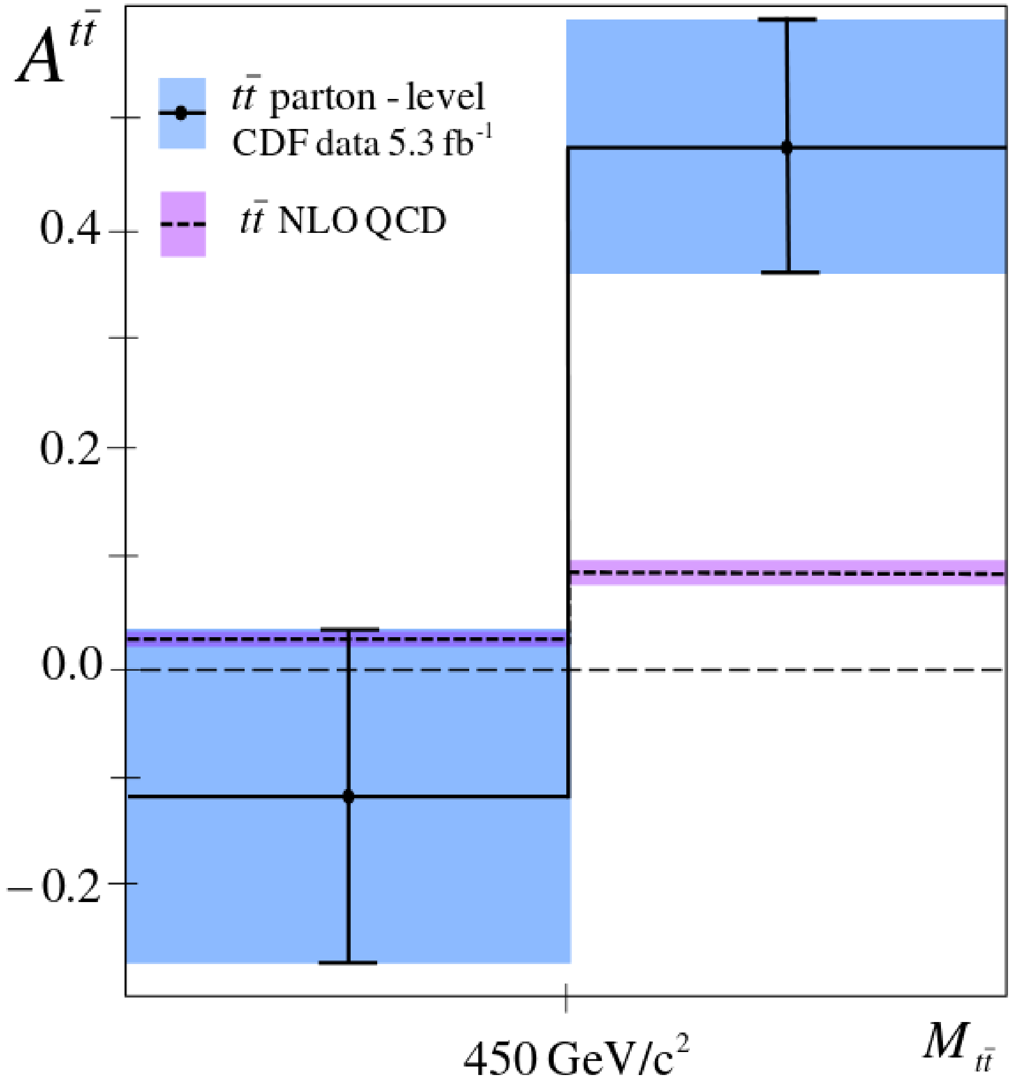
1974 Two colliders in one country discover the same particle

1995: The top quark is born



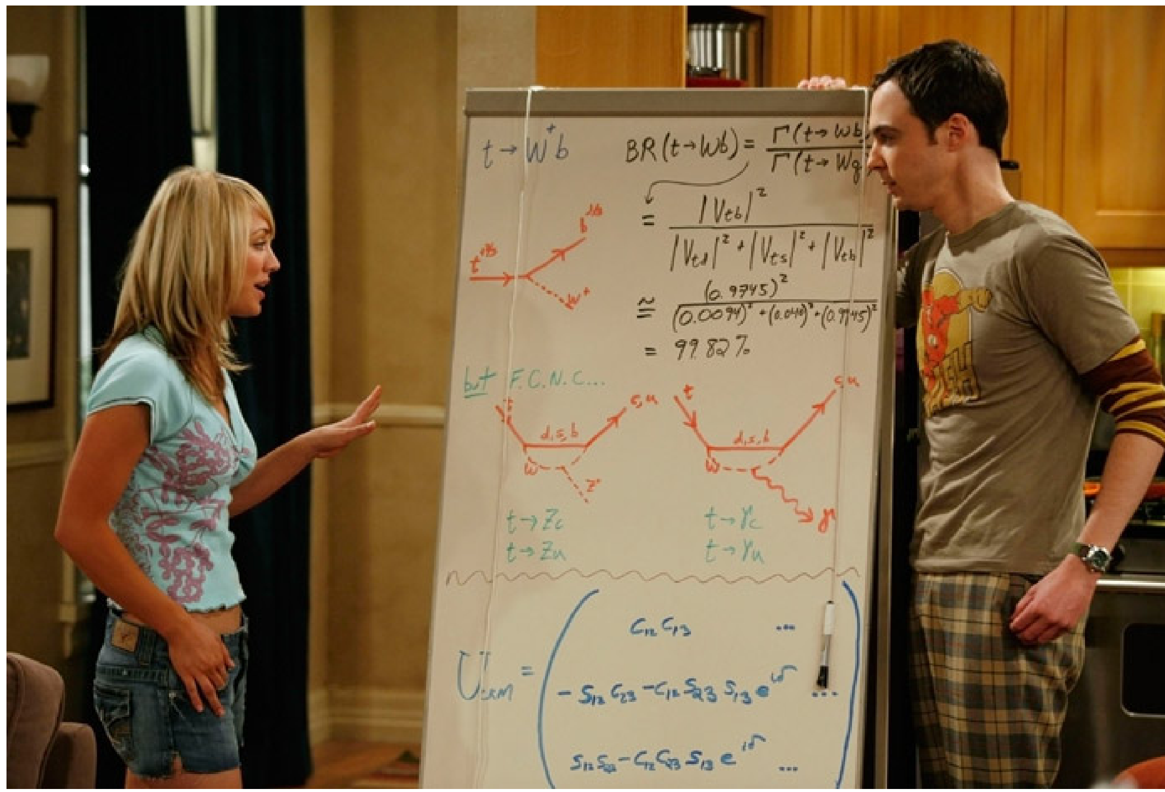
CDF and D0 collaborations, Observation of the top quark
PRL 75 (1995) 2632-2637, 2626-2631

2011: top turns 16
puberty (sigh)



2015: The top quark turns 20

2015: Life is great at 20!



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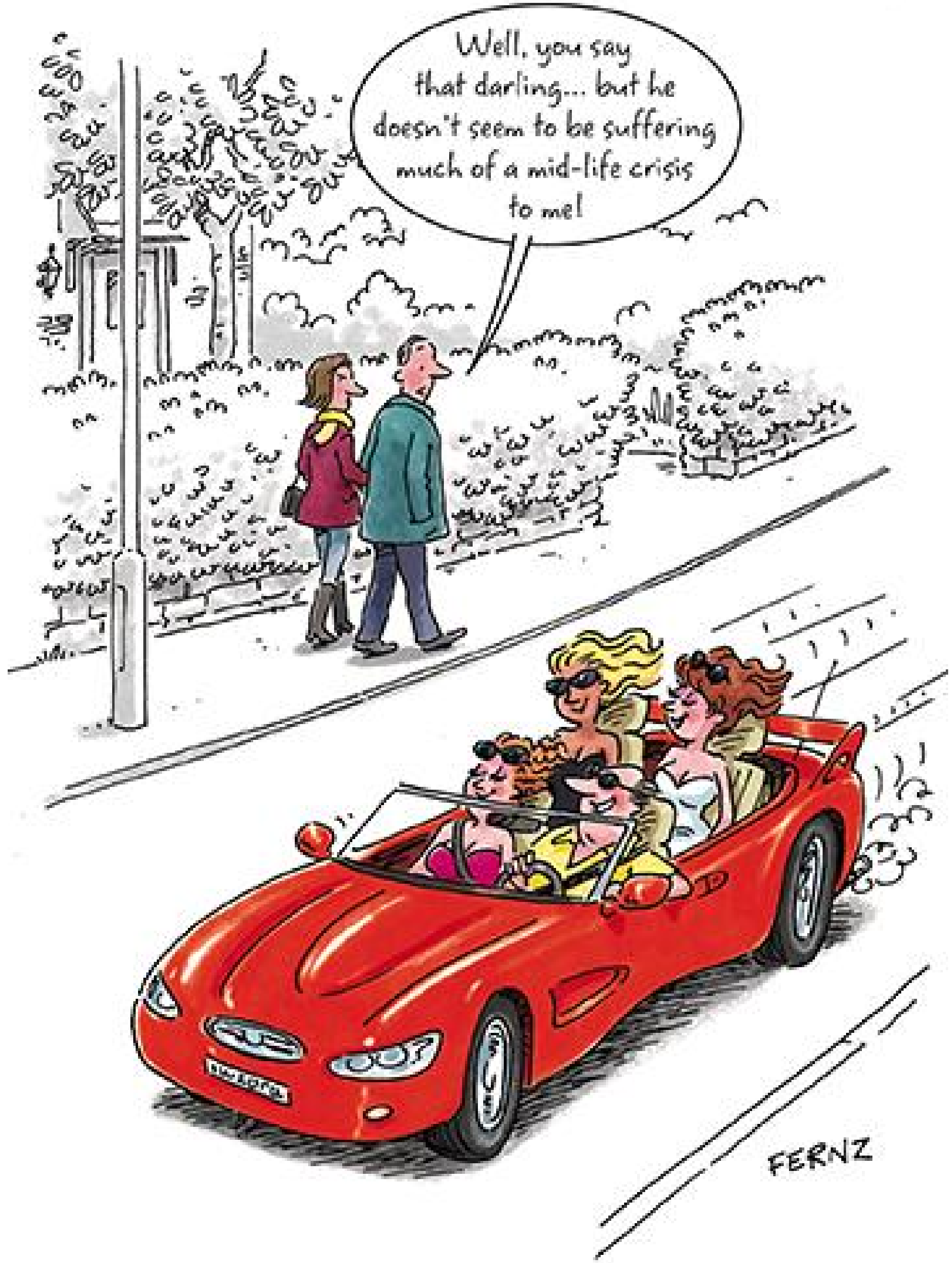
2016: top (finally) grows up...
Another day at the top factory

2018: top meets Higgs

2037: top turns 42

The factory closes: looking for a new job

Mid-life crisis?



2037: or happily ever after?

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