The future of top physics

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EXCELENCIA SEVERO OCHOA

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Brief recap of future collider projects

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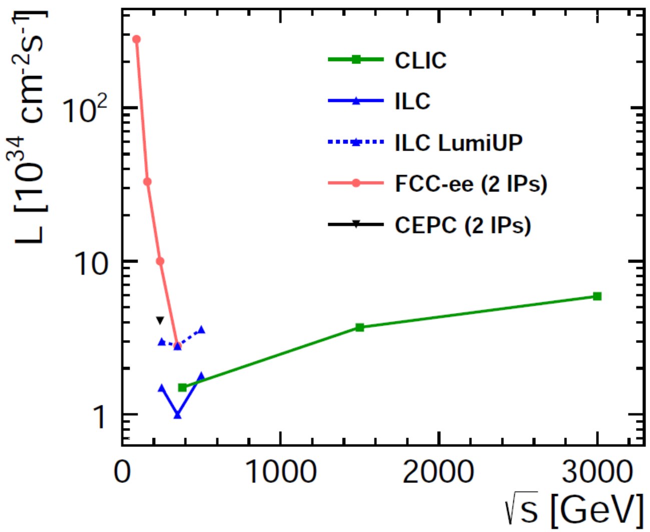
Future lepton colliders

Cavities key tech. for LC:
35 MV/m ILC
100 MV/m CLIC
(cf. 17 MV/m at SLC)

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

The next hadron collider?

Projects for the next very large hadron collider

- SPPC (China, CDR ~2018)
  100 km (TeV)
- FCChh (CERN, CDR ~2018)
  100 km (TeV)
- High-E LHC
  LEP/LHC tunnel 27 km (or TeV)

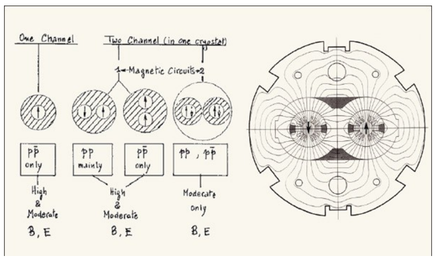
$\sqrt{s}/L \sim 1$ TeV/km

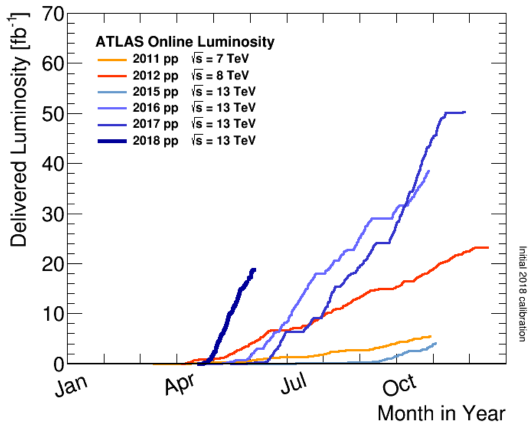
New 16 T magnets (cf. 4 T Tev., 8 T LHC) are essential technology for all these projects

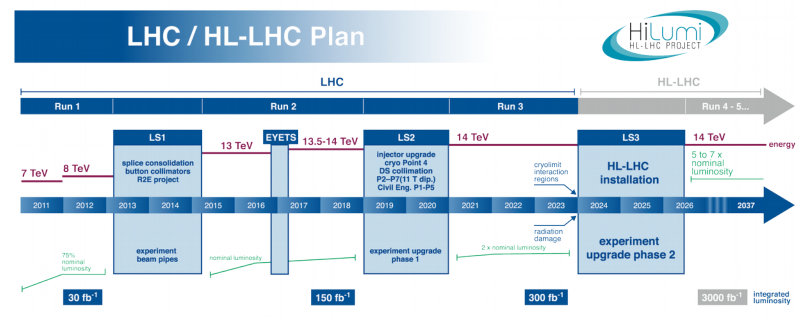
Nb3Sn magnets are a key R&D program in current European strategy

Top physics today

One energy frontier collider: the LHC







1984 ...	1995 ...	2010	2015	2018	2023	2026	2037
1st LHC workshop	LHC approval	data!! 7 TeV	13 TeV	150 fb^{-1}	14 TeV 300 fb^{-1}	start HL-LHC	3 ab^{-1}

Top discovered at FNAL

Top turns 20

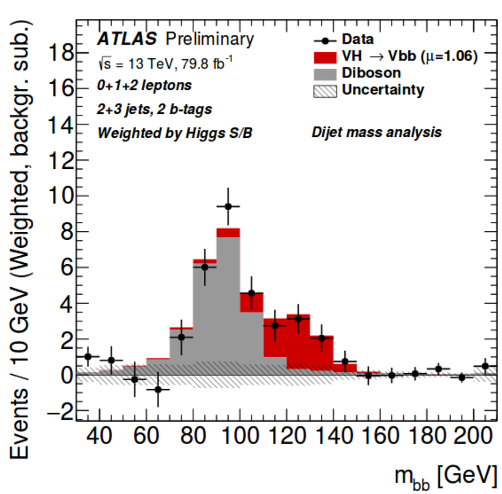
For a not-too-outdated review (so far) see: Cristianzini & Mulders, arXiv:1606.00327

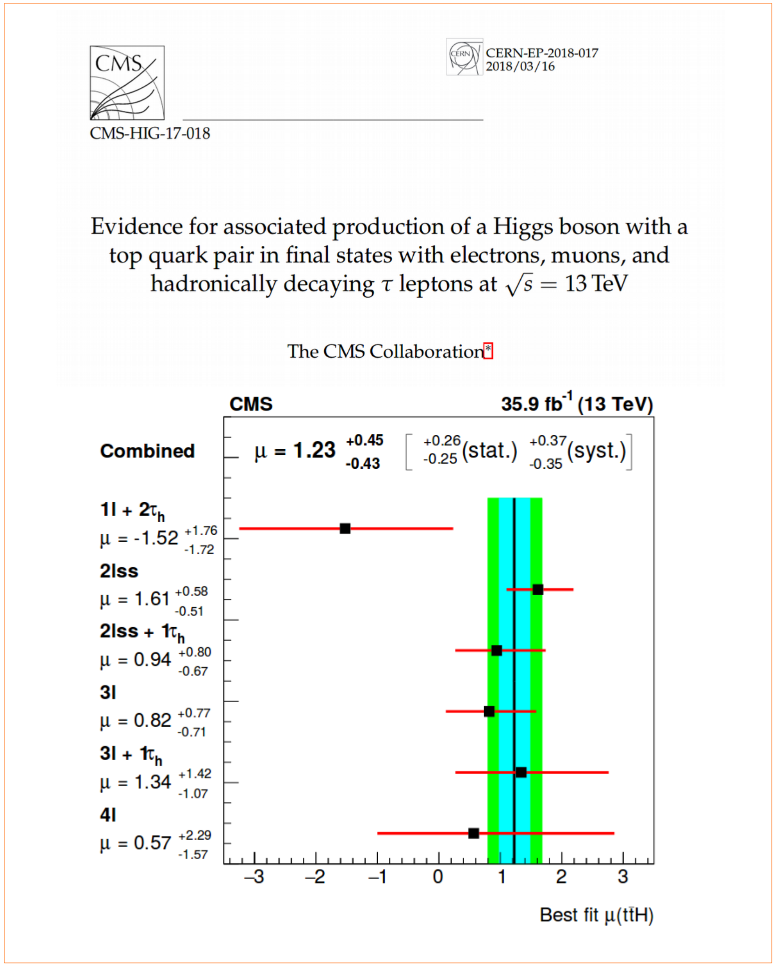
LHC establishes $t\bar{t}H$ production and $H \to b\bar{b}$ decay !

$t\bar{t}H$ 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 $H \to b\bar{b}$ and $H \to \tau\tau$ decay this is solid evidence that Yukawa coupling is responsible for mass of (third-generation) fermions





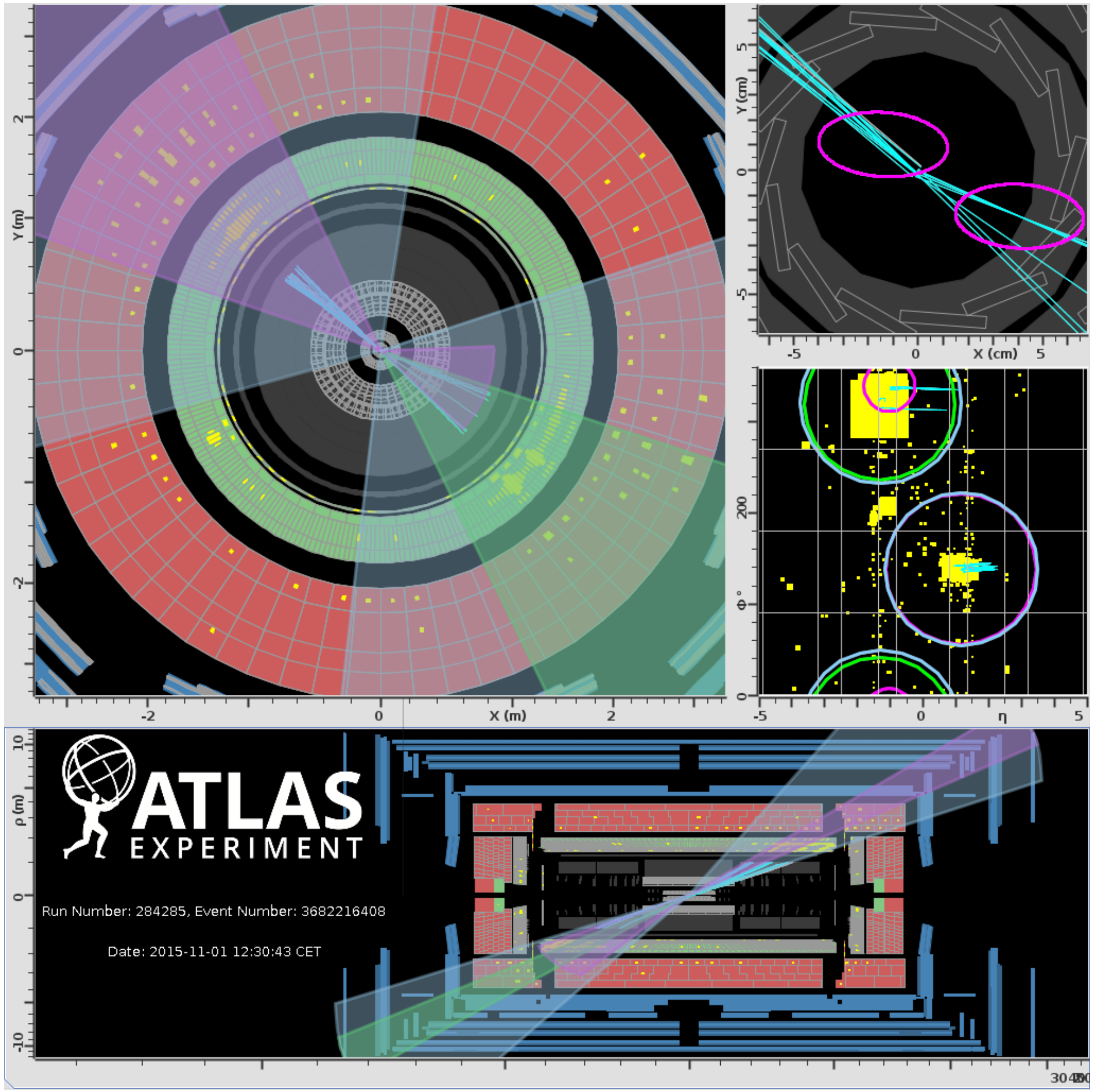
Lepton vs. hadron colliders

Hadron colliders: brute force

Run 2 at 13 TeV

Fully hadronic $t\bar{t}$ event

Invariant mass: 3.3 TeV



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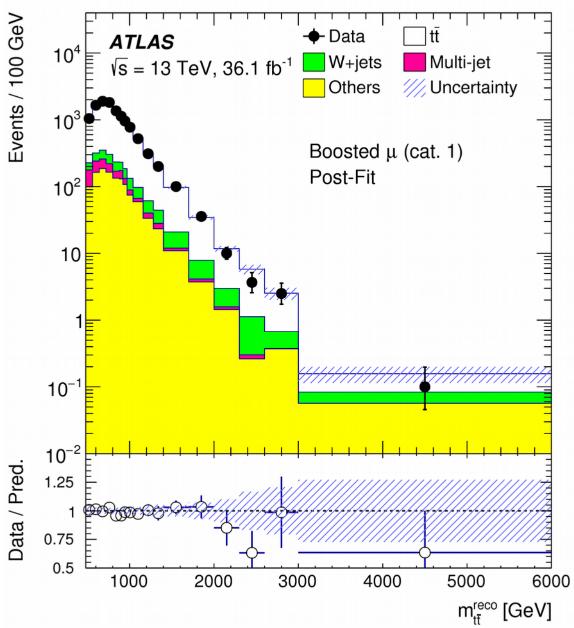
Hadron colliders: brute force

ArXiv:1605.00617

Hadron colliders are top quark factories

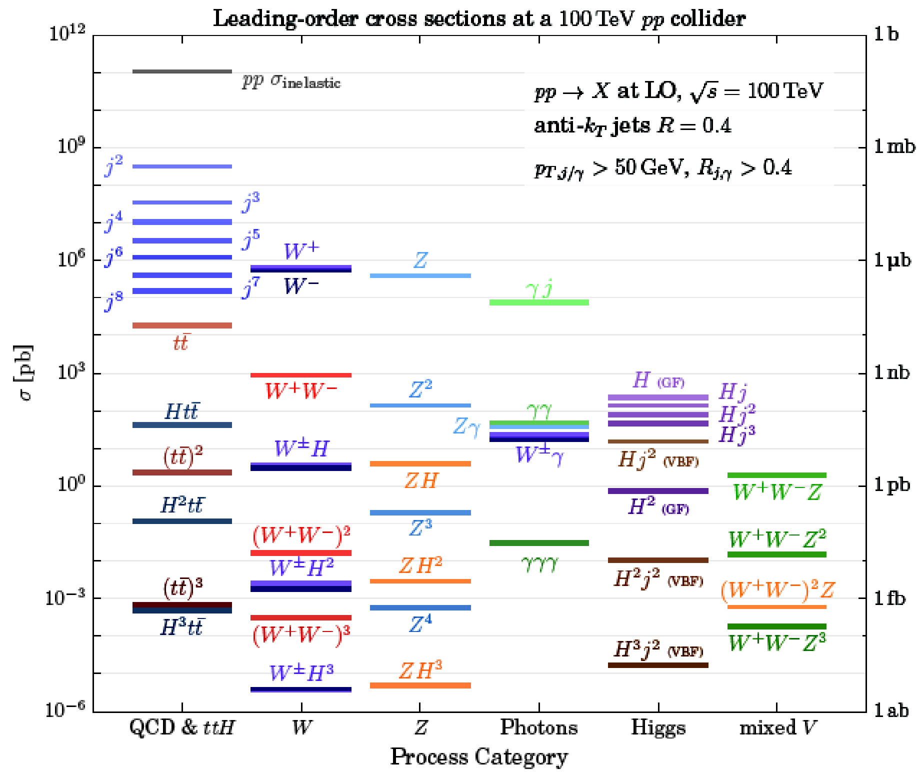
Data sample	*Tevatron* *10 fb⁻¹ @ 1.96 TeV*	*LHC 2012* *20 fb⁻¹ @ 8 TeV*	LHC 2016 *30 fb⁻¹ @ 13 TeV*	*LHC design* *300 fb⁻¹ @ 13 TeV*	*HL-LHC* *3 ab⁻¹ @ 13/14 TeV*	*HE-LHC* *3 ab⁻¹ @ 27 TeV*	*FCChh* *10 ab⁻¹ @ 100 TeV*
# tt events	10^5	10^6	10^7	10^8	10^9	10^{10}	10^{12}

Production in new kinematic regime



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

Production of new rare processes



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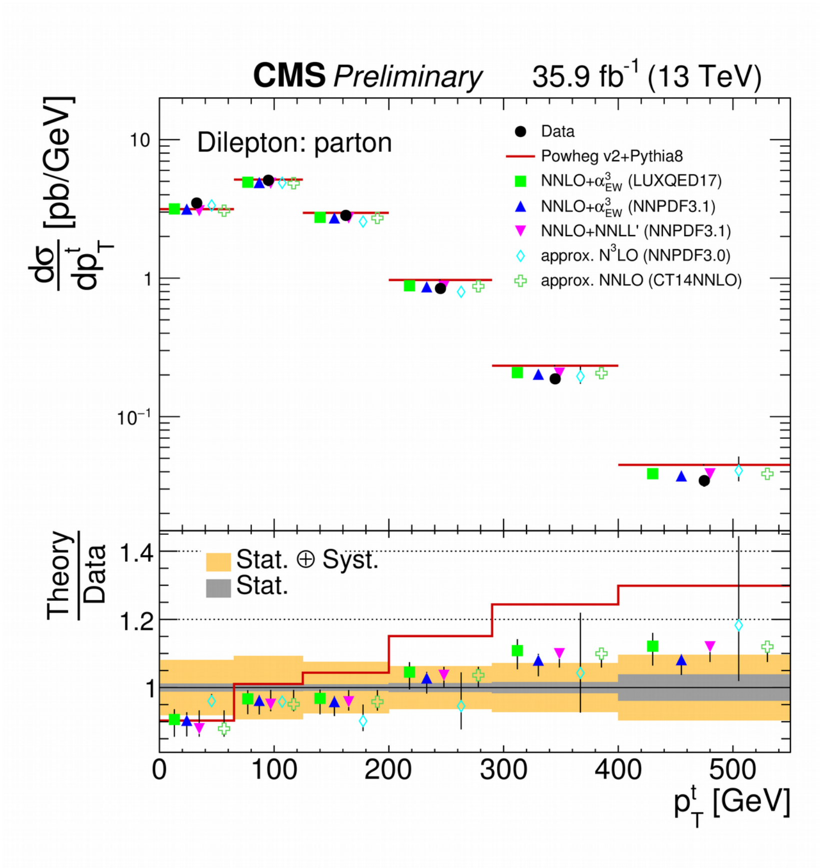
Differential cross section

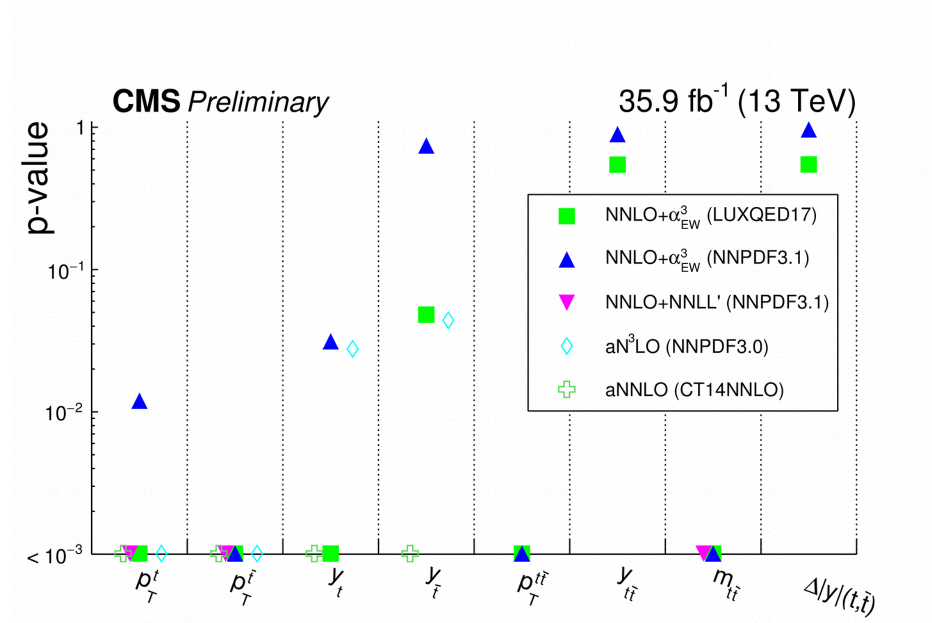
NEW: CMS TOP-17-014



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: p(SM) < 10^{-3}



What does it mean?

Error in the measurement?

Mistake in the calculations??

The SM is broken???

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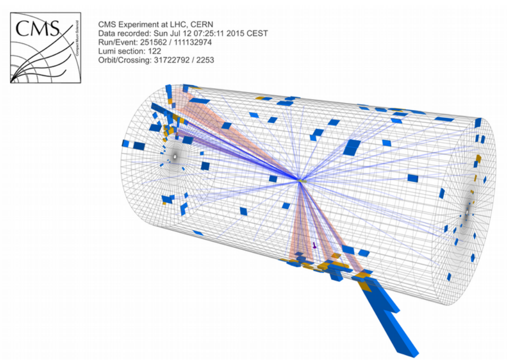
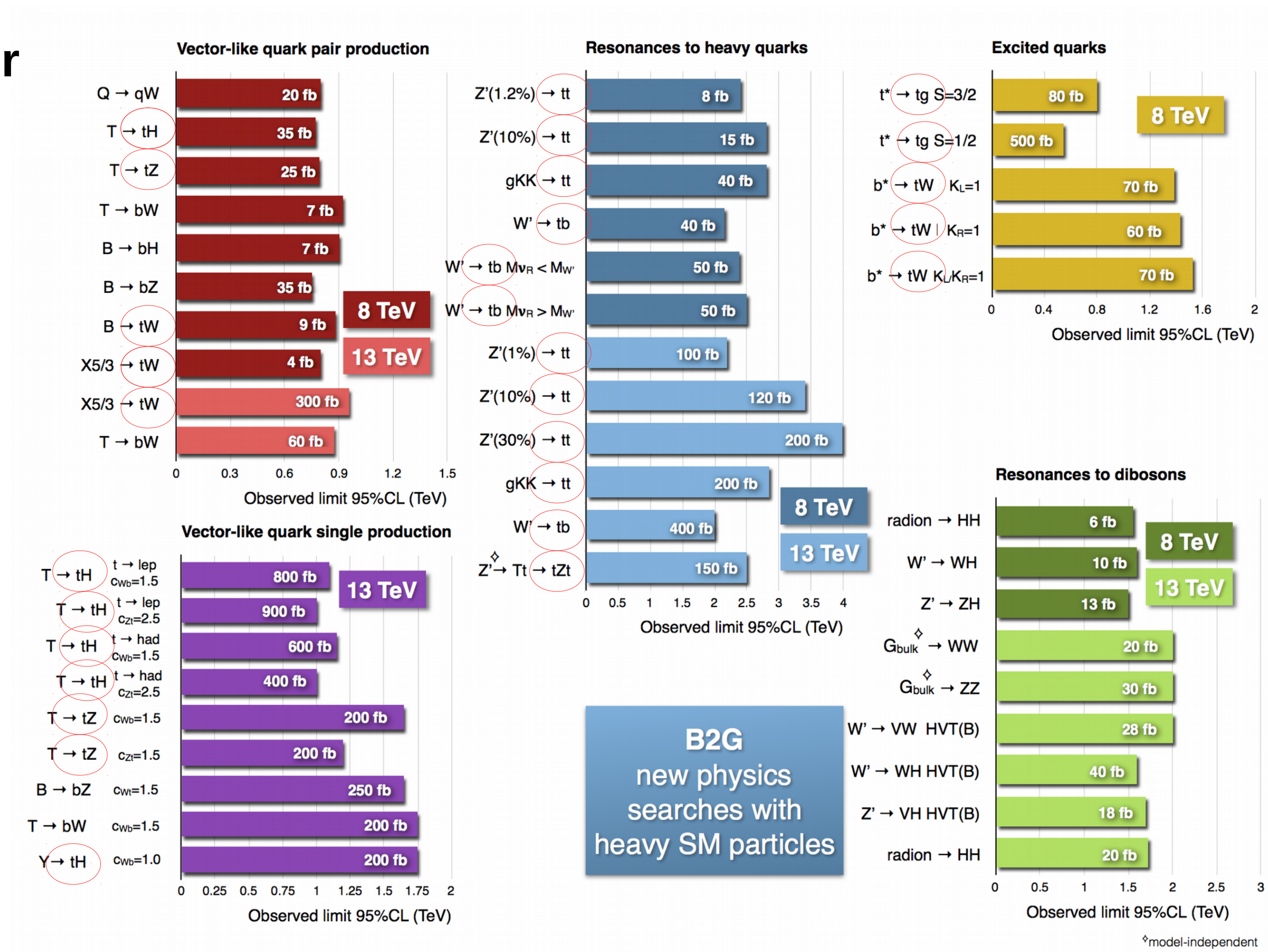
New physics with top quarks?

A plethora of searches for massive, new states decaying to final states involving top quarks



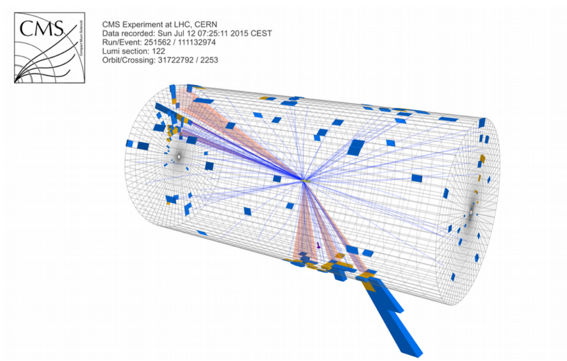
Boosted top quark reconstruction is “bread-and-butter” physics now



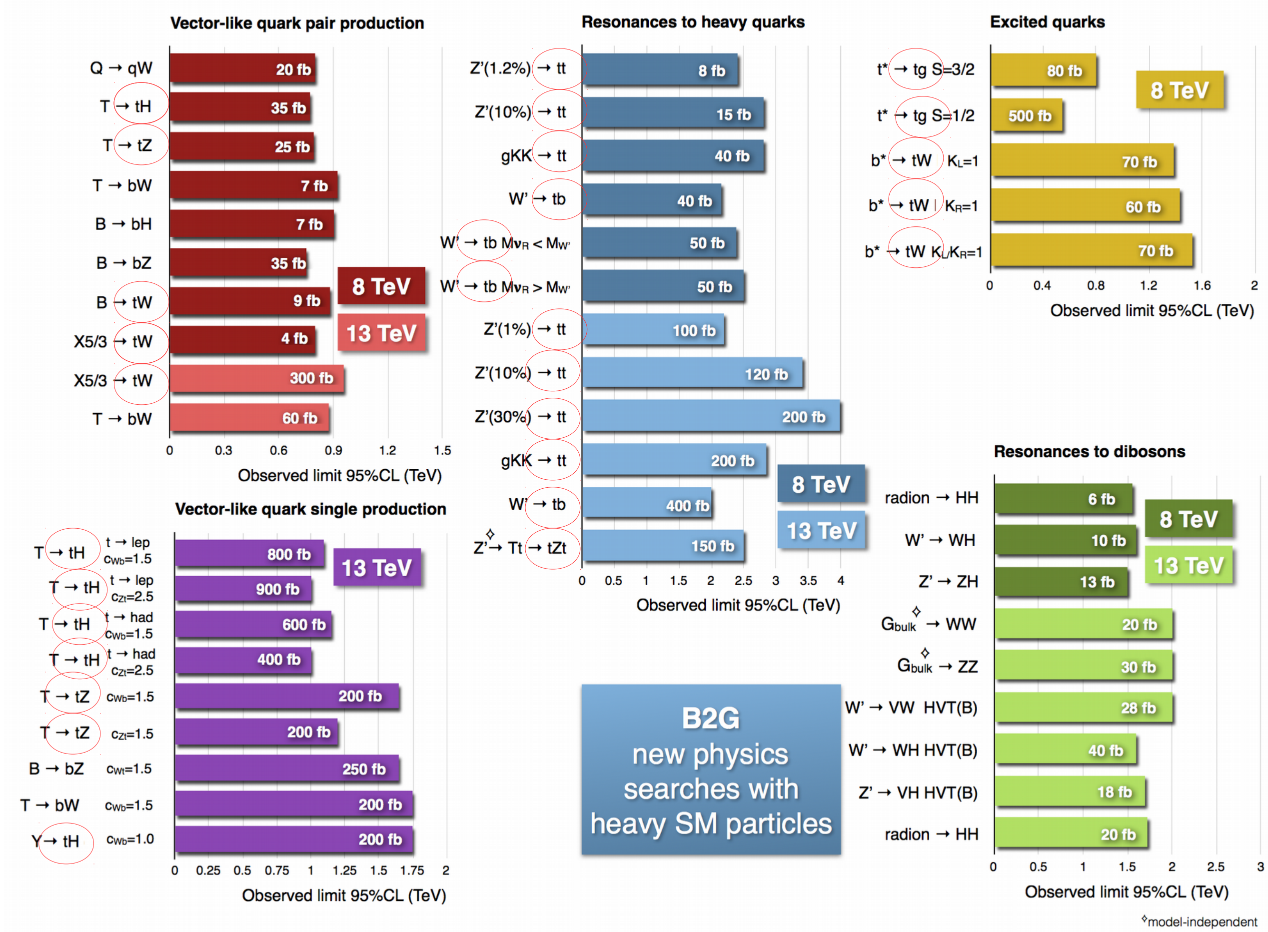
New physics with top quarks?

Unfortunately, no sign of BSM physics So far! Still a lot of LHC data to come

A plethora of searches for massive, new states decaying to final states involving top quarks



Boosted top quark reconstruction is “bread-and-butter” physics now



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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%

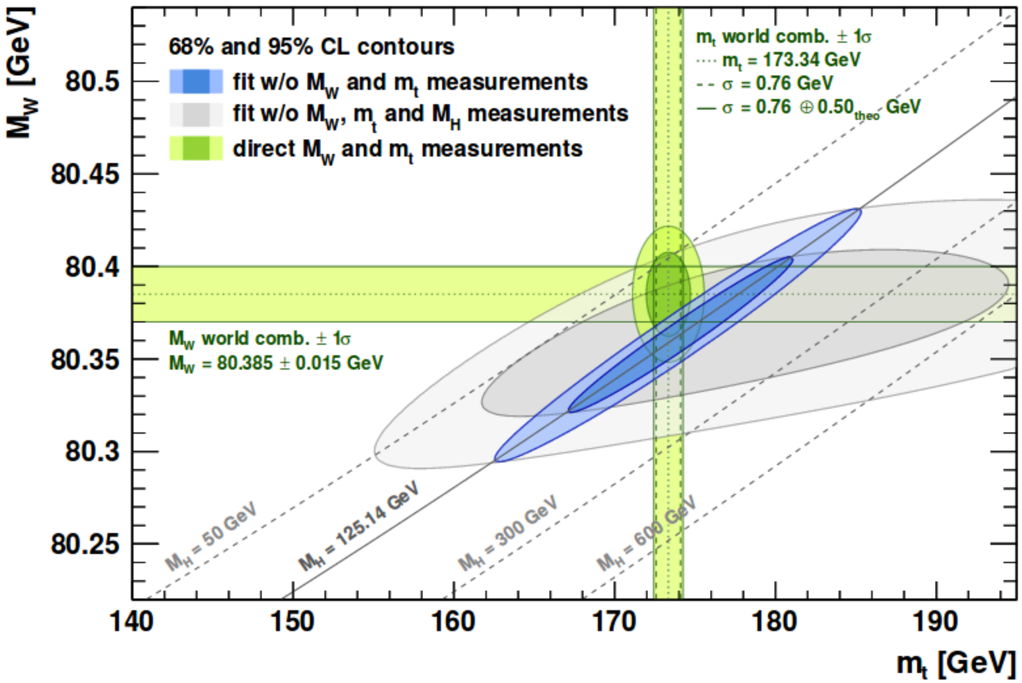
Theory:

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

Systematics limit many measurements already today. 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"

Lepton colliders: stringent precision tests



M. Baak et al., arXiv:1407.3792

Electroweak fit yields indirect m_W = 80.354 ± 8 MeV

More precise than actual W mass measurement

Precision BSM physics. Precise measurements, precise theory & BSM sensitivity

- Higgs couplings
- Vector boson scattering
- Top EW production → Top is one of two SM particles to escape scrutiny at LEP/SLC and the top sector remains relatively unconstrained.

Closure tests of the Standard Model

- EW fit
- vacuum stability → Error budget dominated by m_t

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

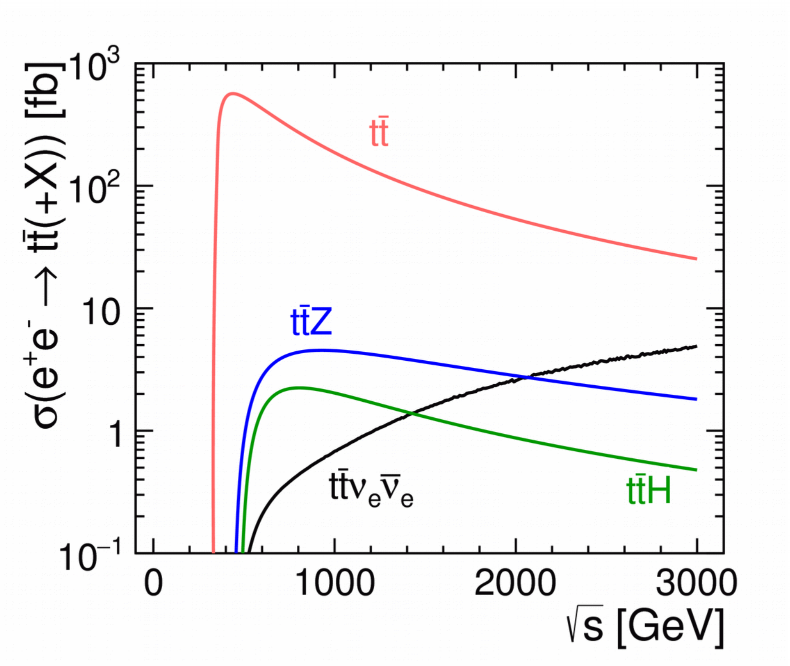
Theory: no PDFs, small QCD corrections
Predictions at few per-mille level already today!

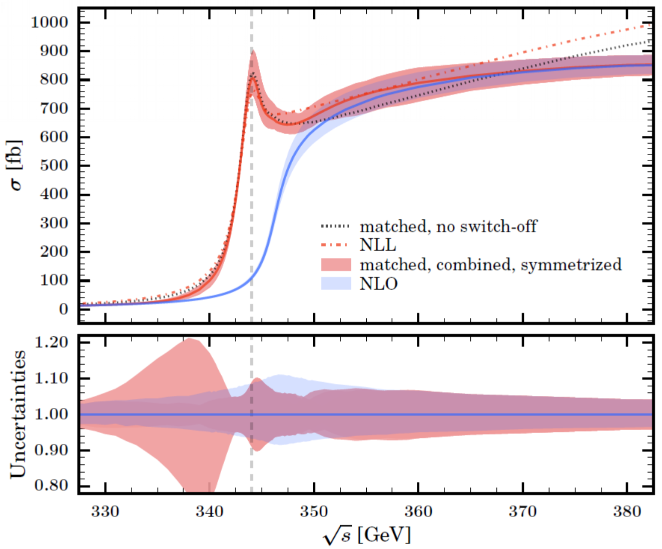
Selection: democratic cross sections allow for truly inclusive measurements (no trigger!)

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



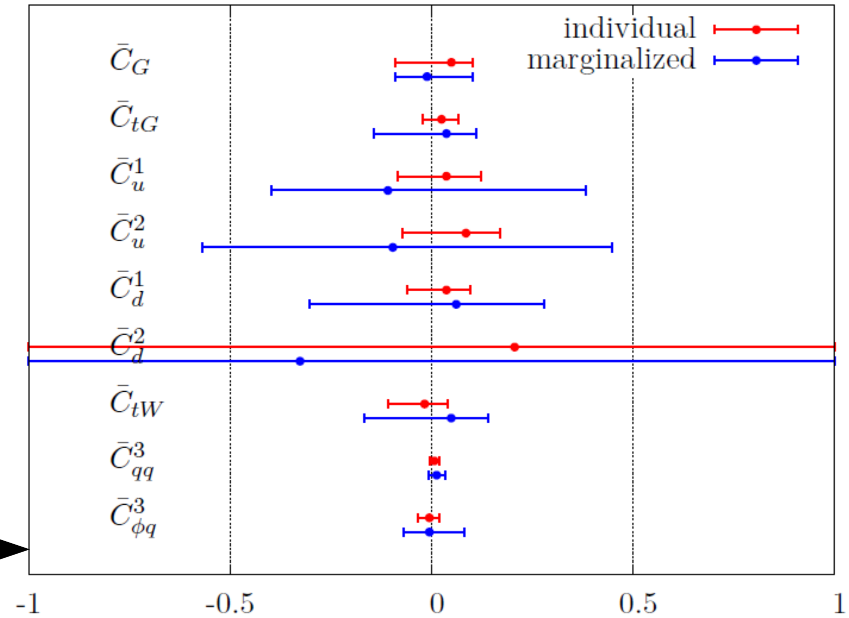


Precision BSM physics

Treat high-energy colliders as low-energy probes:

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

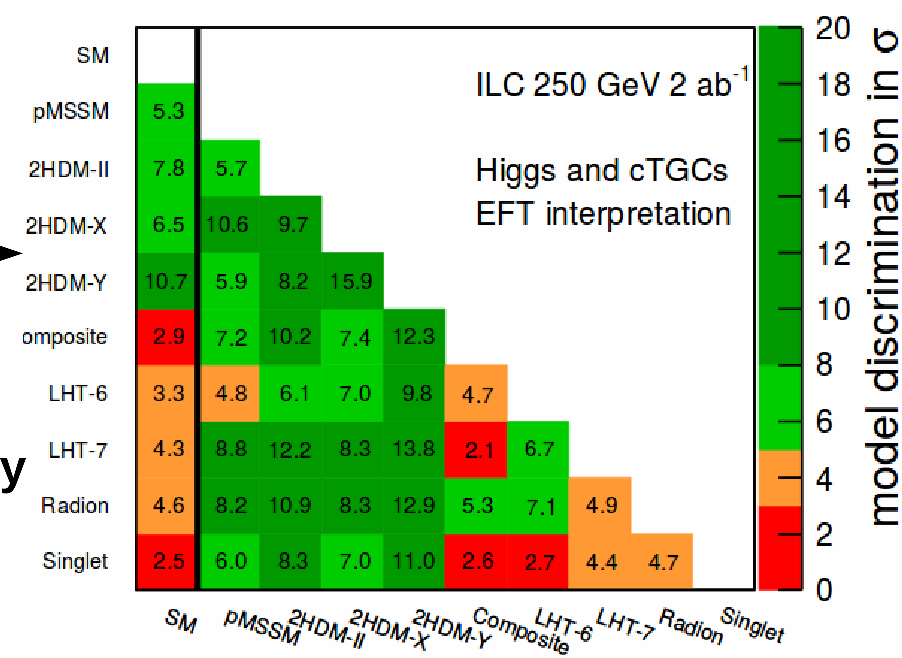
Simultaneous fit to all (relevant) effective D6 operators provides general set of constraints on (nearly) any BSM physics



LHC fit top sector arXiv:1506.08845

Results can easily be translated into limits on concrete new physics models

ILC fit Higgs sector arXiv:1708.08912



EFT fits are thriving at the LHC, but a truly global fit may require a lepton collider

Top quark mass

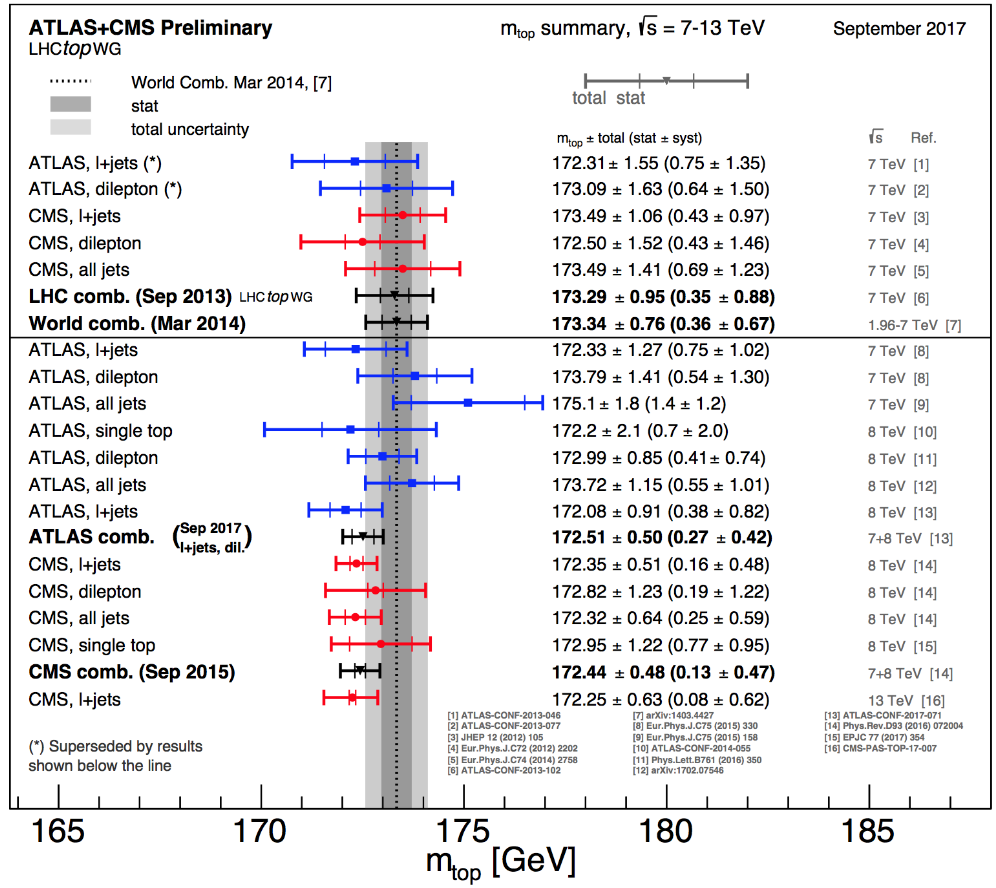
Top quark mass: direct

The top quark mass

LHC + Tevatron 2014:
m_t = 173.3 ± 0.7 GeV
(arXiv:1403.4427)

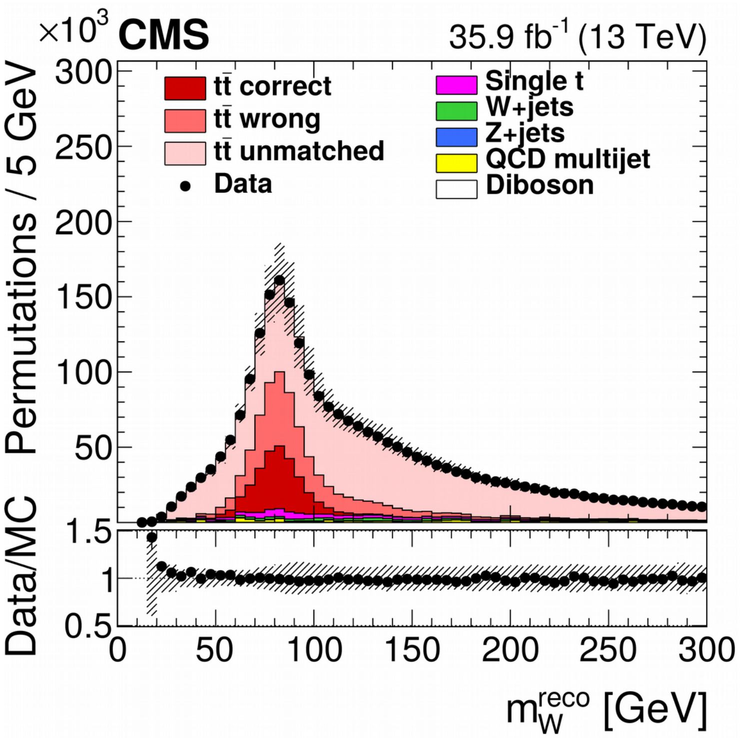
ATLAS combination (2017)
m_t = 172.5 ± 0.5 GeV

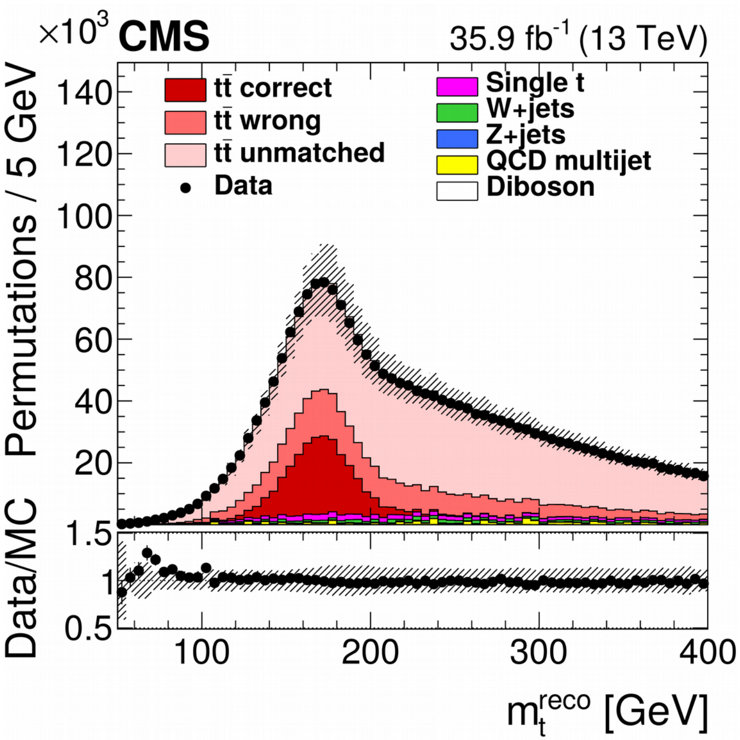
CMS combination (2015)
m_t = 172.4 ± 0.5 GeV



13 TeV, CMS l+jets, arXiv:1805.01428 (36 fb^{-1}, 600 MeV)

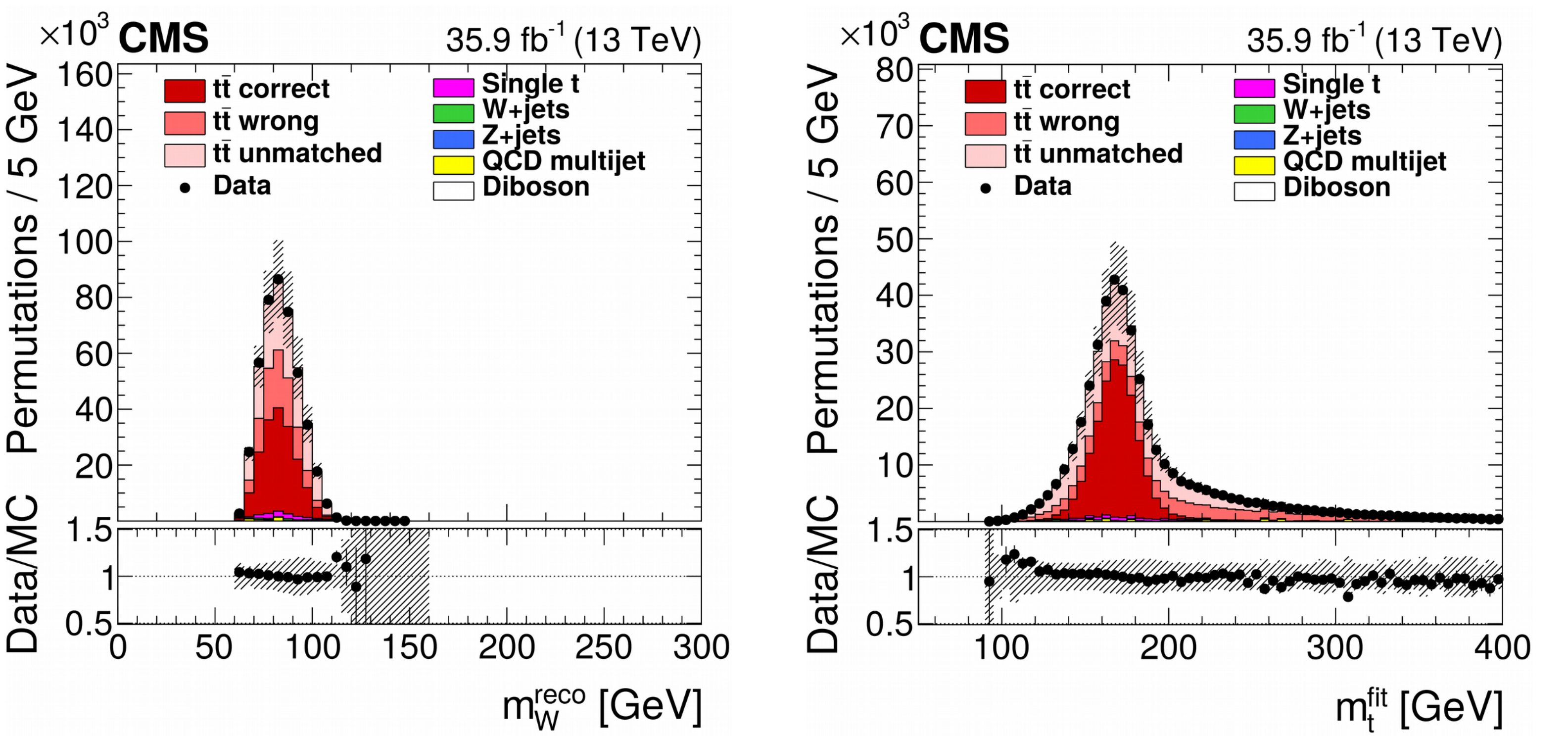
CMS direct top mass at 13 TeV





Mass peaks of 2- and 3-jet system that are selected as W and top candidates
W-peak is crucial to control jet energy response in situ → 2D (3D) fit of mt, JES, (bJES)

CMS direct top mass at 13 TeV



W and top mass peaks after the fit

arXiv:1805.01428

36 fb^{-1} at 13 TeV (lepton+jets)
172.24 ± 0.08 (stat.) ± 0.62 (syst.)
cf. 20 fb^{-1} at 8 TeV (lepton+jets)
172.35 ± 0.16 (stat) ± 0.48 (syst) GeV

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Progress at the LHC: top quark mass revisited

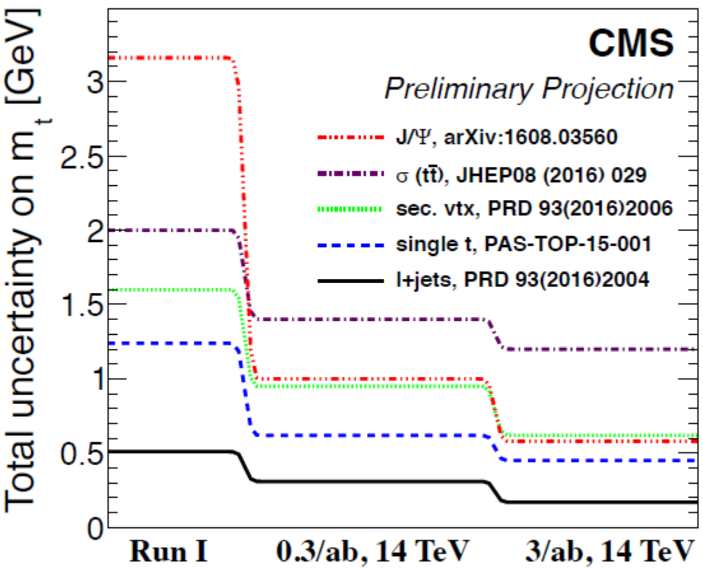
Direct mass can reach 200-300 MeV precision (CMS), well beyond 1 GeV envisaged before the start of the LHC.

Interpretation of top mass measurements is hotly debated. The direct top mass is probably close to, but definitely not identical to the pole mass...

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

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

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

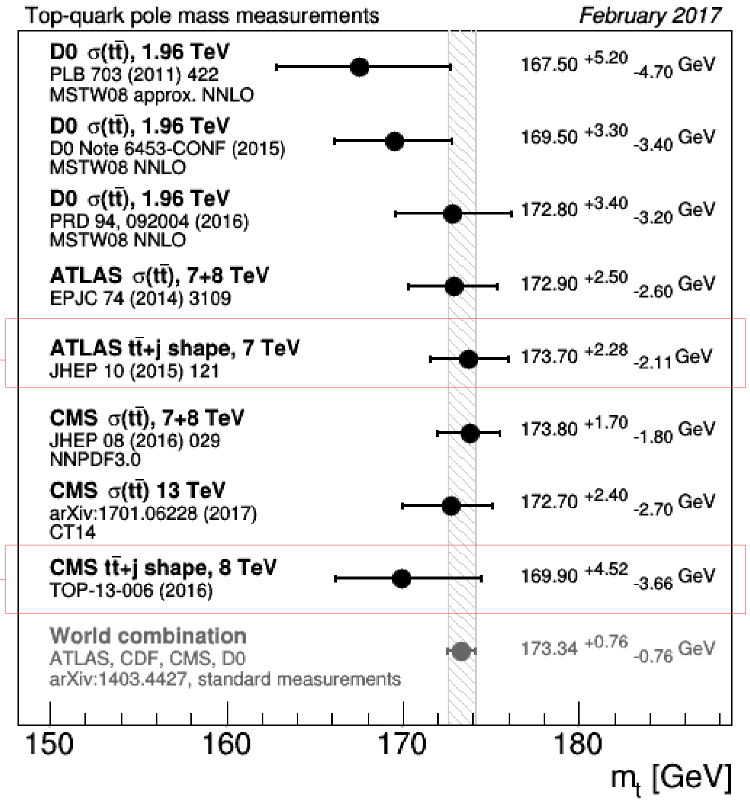


Alternative methods: pole mass

The top quark pole mass is extracted from a (differential) cross section measurement with sufficient mass sensitivity
Control over mass scheme, provided unfolding is independent of MC mass

Differential cross section
Enhanced sensitivity
+ shape analysis

NNLO+EWK corrections for $t\bar{t}$
NLO precision for tt+1 jet
NLO for lepton observables



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Top quark pole mass

Inclusive cross section

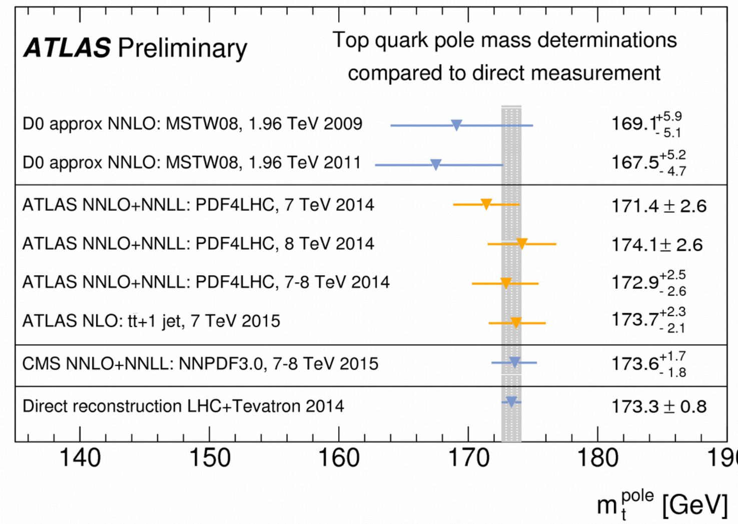
Well-defined mass scheme (pole mass, $\overline{\text{MS}}$ mass)

Limited sensitivity: $\Delta m/m \sim 0.2\ \Delta\sigma/\sigma$

ATLAS and CMS ~2 GeV uncertainty

Recent D0 result (arXiv:1605.06168):

mt = 172.8 ± 1.1 (theo.) $^{+3.2}_{-3.4}$ (exp.) GeV

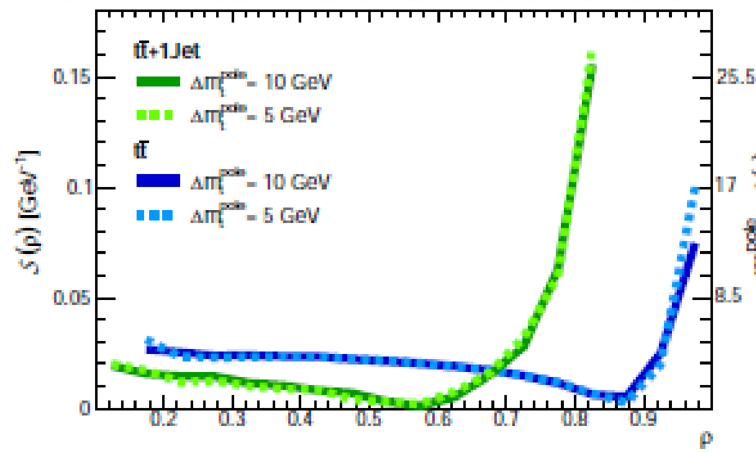


$t\bar{t}g$ cross-section

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

ATLAS, arXiv:1507.01769

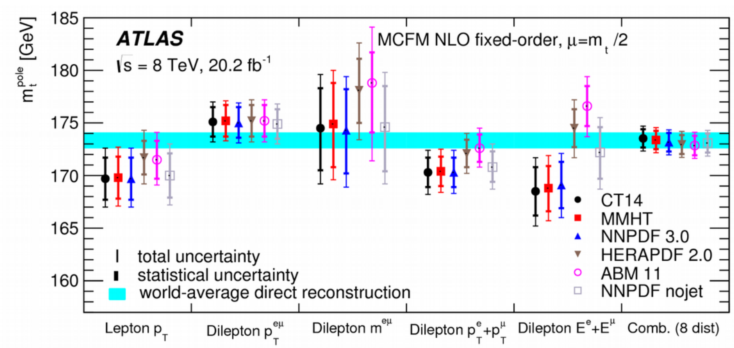
Mt = 173.7 ± 1.5 (stat) ± 1.4 (syst) $^{+1.0}_{-0.5}$ (theory) GeV



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.)

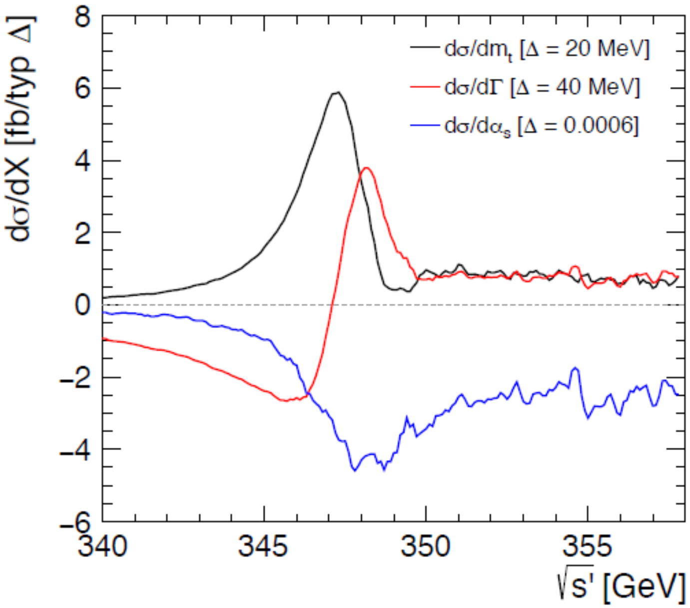


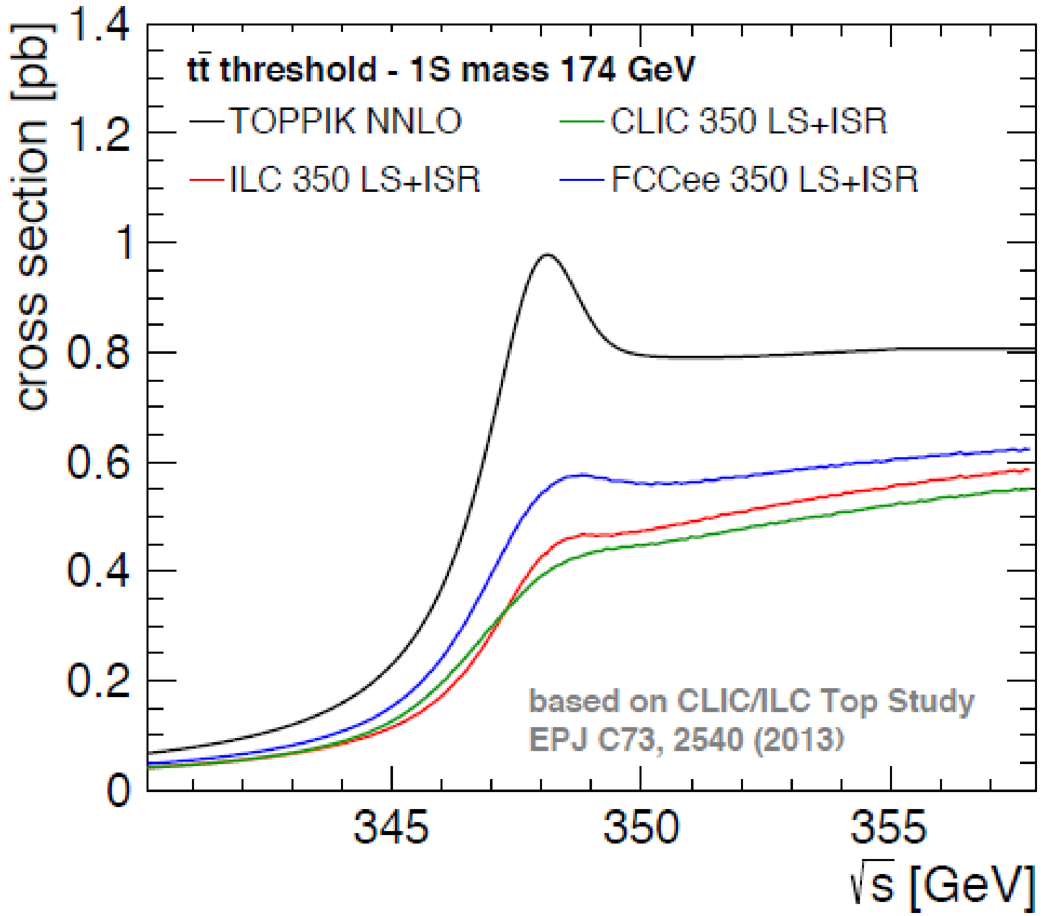
Approaching 1 GeV precision

Top quark mass from e+e- threshold scan

Threshold shape reveals the top quark mass

Kuhn, Acta Phys.Polon. B12 (1981)





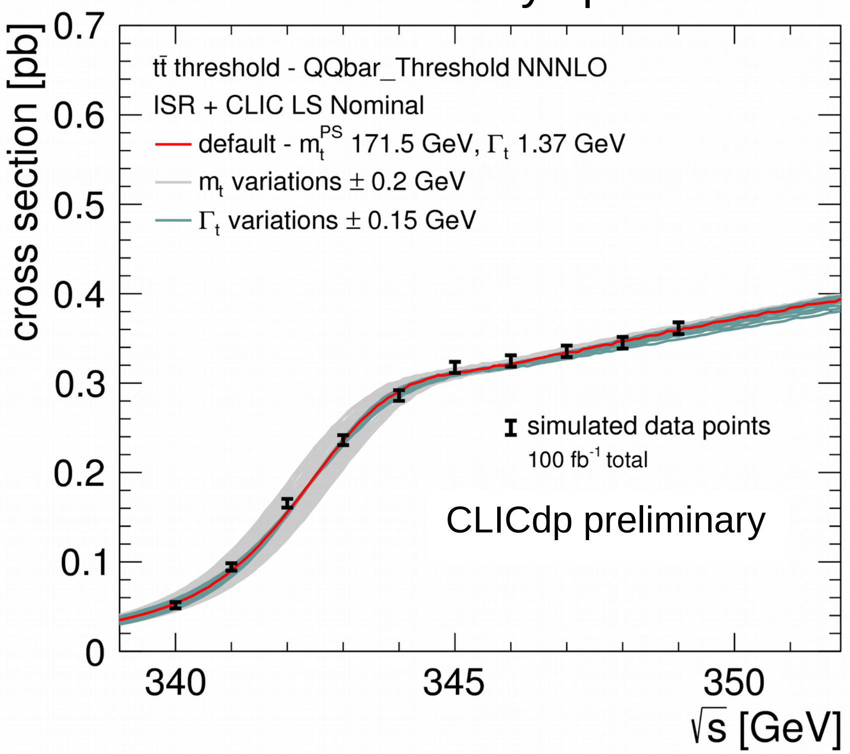
Line shape also depends on width,
Normalization sensitive to α_s and y_t

Threshold scan: experiment

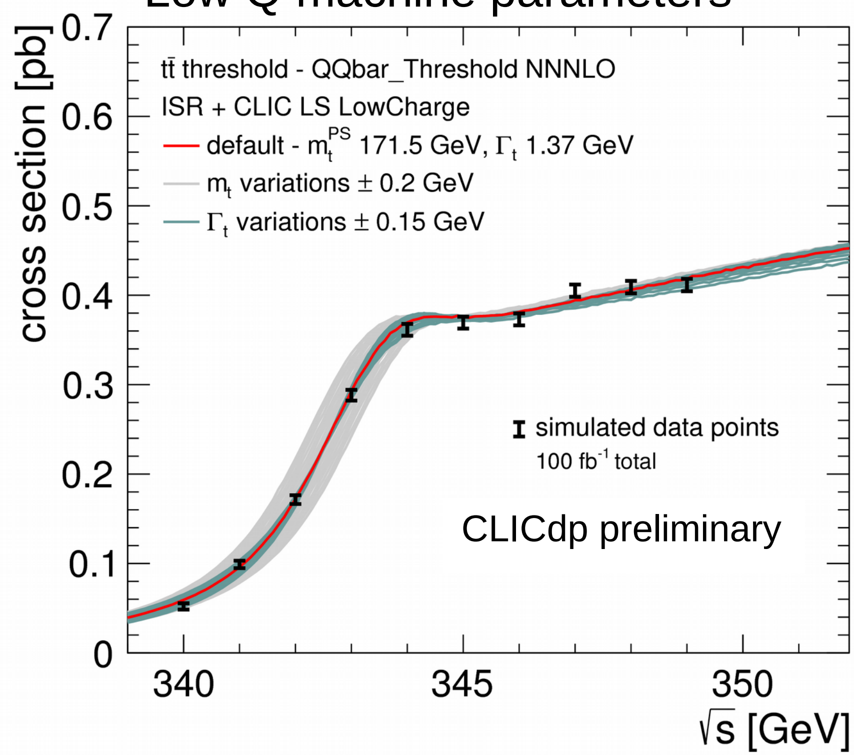
Detailed estimates of the precision in multi-parameter fits

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

Nominal luminosity spectrum



Low Q machine parameters



The machine parameters can be tuned (at a cost in instantaneous luminosity) to minimize the impact of the luminosity spectrum on the threshold shape
Higher precision - per unit luminosity – in the mass extraction + potential gain in the width measurement. The details of the scan can be further optimized.

Threshold scan: potential

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

Statistical uncertainty:	~20 MeV	*100 fb^{-1}*
Scale uncertainty:	~40 MeV	*N^{3}LO 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 x 10^{-4}, cf. Δm_b ~1%)*

This is a real prospect, not a target! Build the machine and we perform the measurement.

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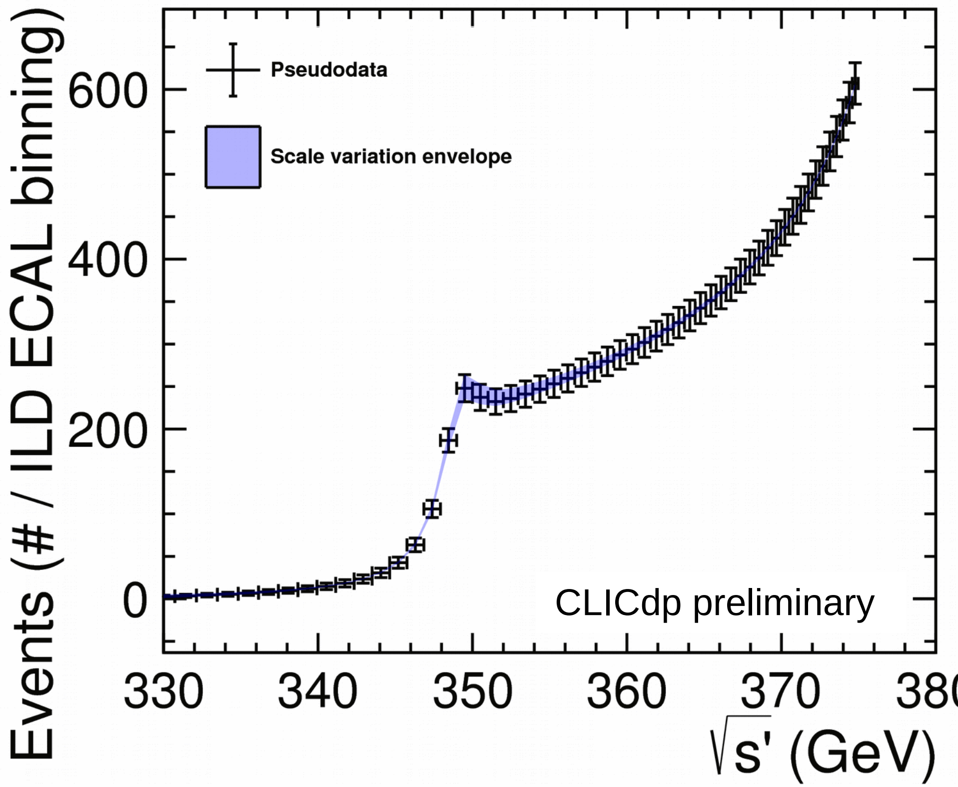
Top quark mass: alternatives

Radiative events:

“return-to-threshold”

Cross section depends strongly on top quark mass

Matched threshold-continuum calculation by Hoang et al.



Radiative $t\bar{t}\gamma$ events give access to the top quark mass in continuum runs:

~100 MeV uncertainty with 500 fb^{-1} of 380 GeV data
~100 MeV uncertainty with 4 ab^{-1} of 500 GeV data

Rigorous and flexible control over theory → access to the running of the mass

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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

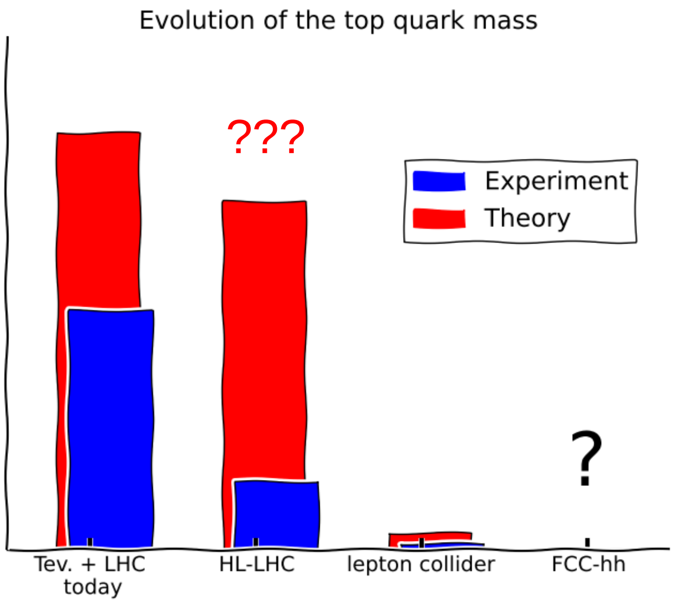
- *Today: $\delta m_t \sim 2$ GeV*
- *Rigorous interpretation*
- *Can reach ~1 GeV precision*

Future lepton collider

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

Future 100 TeV pp collider:

- *?*



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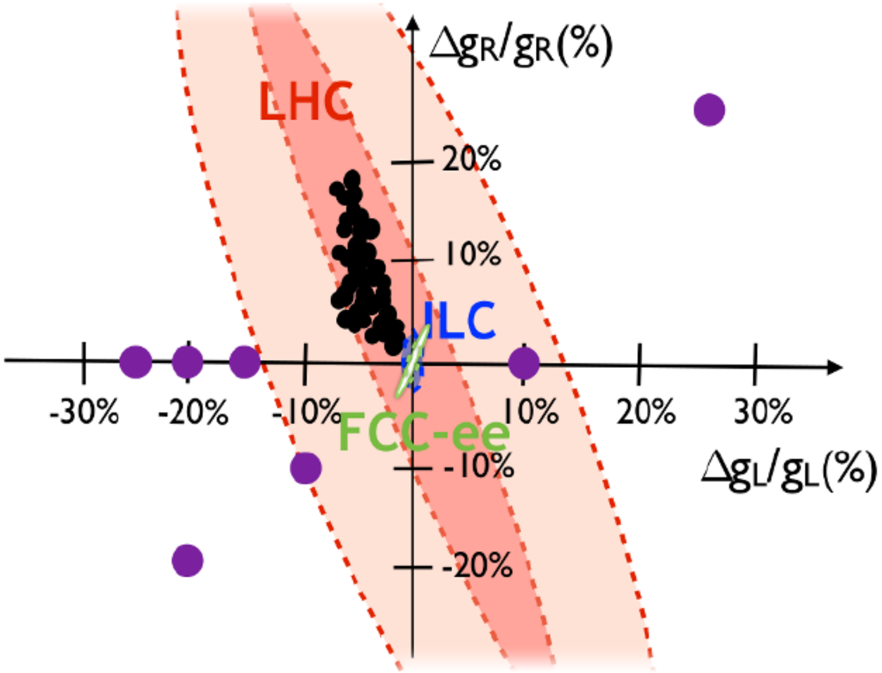
Top EW couplings

Top EW couplings

RS/composite Higgs type of SM extensions predict sizable deviations from the SM prediction for the $t\bar{t}Z$ coupling

Extra dimension models typically yield order 10% deviations for Λ ~ 1 TeV

A %-level measurement can pick up signals from very high scale, O(10 TeV)



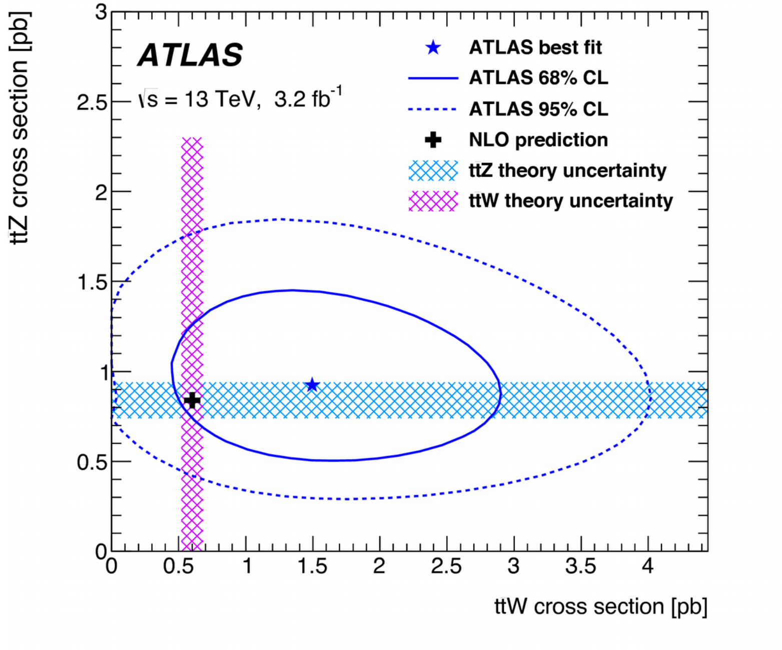
5D models by several authors
Richard, arXiv:1403.2893

4D Composite Higgs Model
Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)

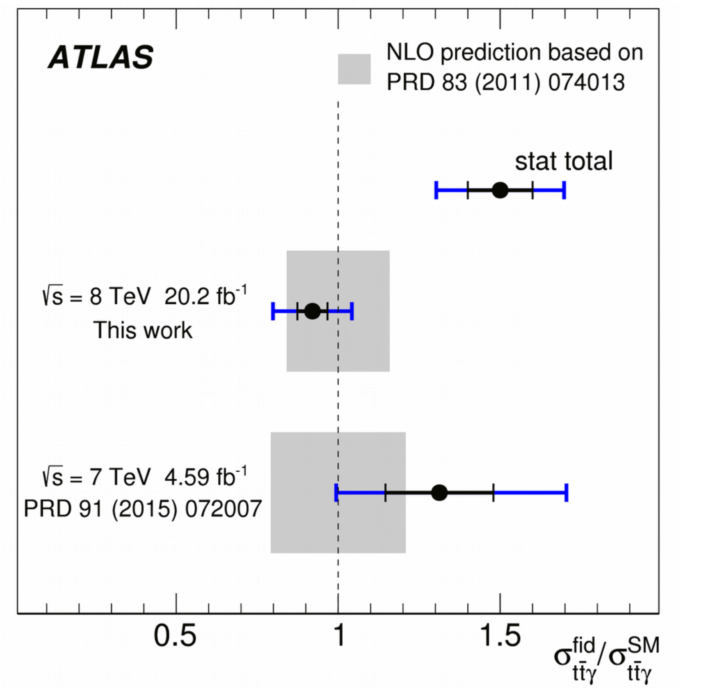
Rare processes

Top and friends: $t\bar{t}\gamma$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, tttt

(and single-top associated production)



ATLAS ttZ/ttW at 13 TeV:
statistics still 2-3 times the systematics
(with approximately 1/10th of today's data)
arXiv:1609.01599



ATLAS $tt\gamma$ at 8 TeV
Systematic dominant,
theory comparable
arXiv:1706.03046

Cf. CMS 8 TeV ttX results
(arXiv:1406.7830)

$\sigma_{ttW} = 170^{+90}_{-80}$ (stat.) $\pm$ 70 (syst.) fb

$\sigma_{ttZ} = 200^{+80}_{-70}$ (stat.) $\pm$ 40 (syst.) fb

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Top EW couplings: LHC status

Simultaneous fit to Tevatron and LHC data
arXiv:1506.08845, arXiv:1512.03360

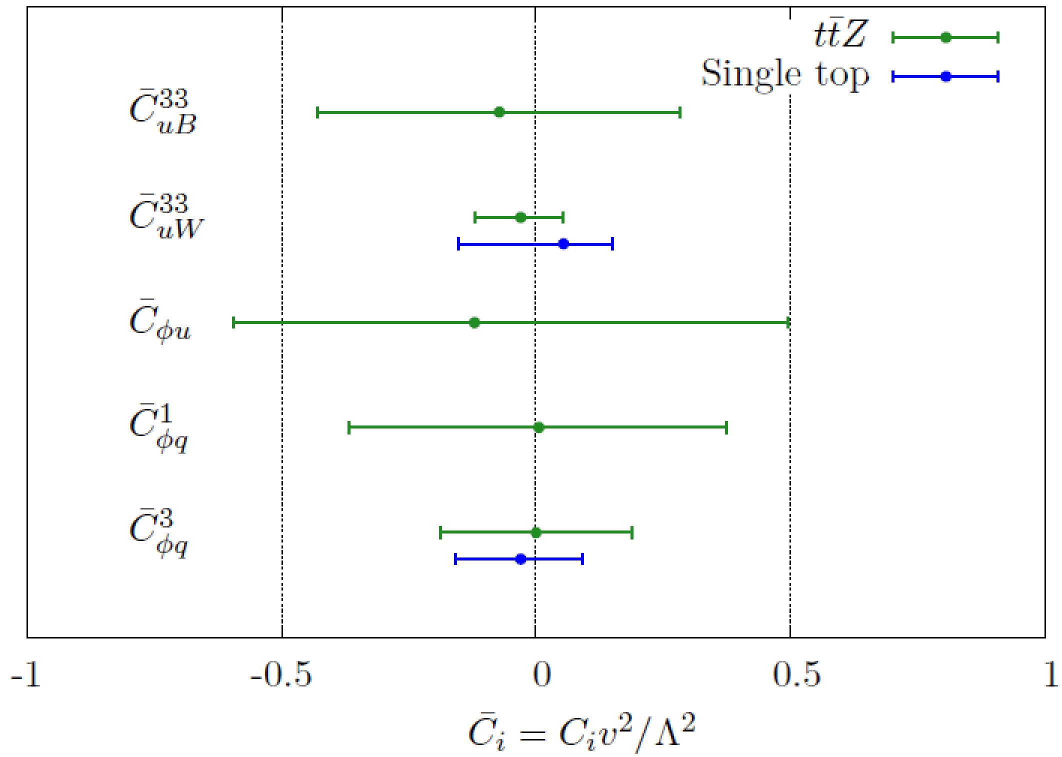
Single top production, ttZ

First EFT fit in top sector

Limits are still weak

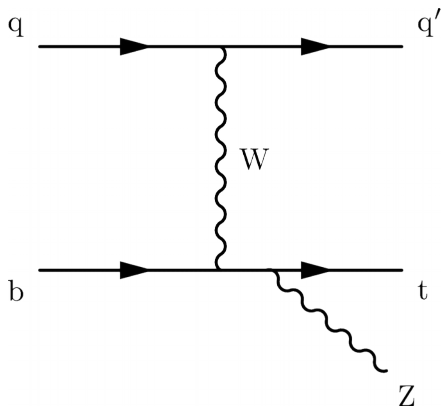
Validity of EFT marginal

1-parameter fit for EW coupling



More data on rare processes

More constraints coming in from rare top production processes



Single top tZ production
(3.7 σ signal in CMS)

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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

ARTICLE INFO

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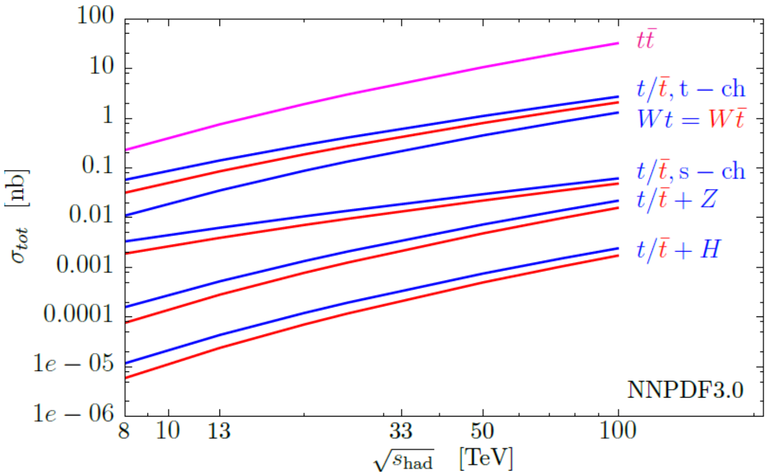
ABSTRACT

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.

Associated production at 100 TeV

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



Factor 50 increase in ttZ rate;
tZ and tH become accessible

ArXiv:1607.01831

Form cross section ratios (ttZ/tt and ttγ/tt) to cancel theory uncertainty (~20%)
Resulting uncertainty from scale variations = 3% in Schulze & Soreq, 2016

arXiv:1607.01831

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

	$C_{1,V}$	$C_{1,A}$	$C_{2,V}$	$C_{2,A}$
SM value	0.24	−0.60	< 0.001	≪ 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]

FCChh boosts constraints on EW dipole moments

Top EW couplings at lepton colliders

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

Prospects for 500 GeV ILC

ArXiv:1307.8102, arXiv:1505.0620

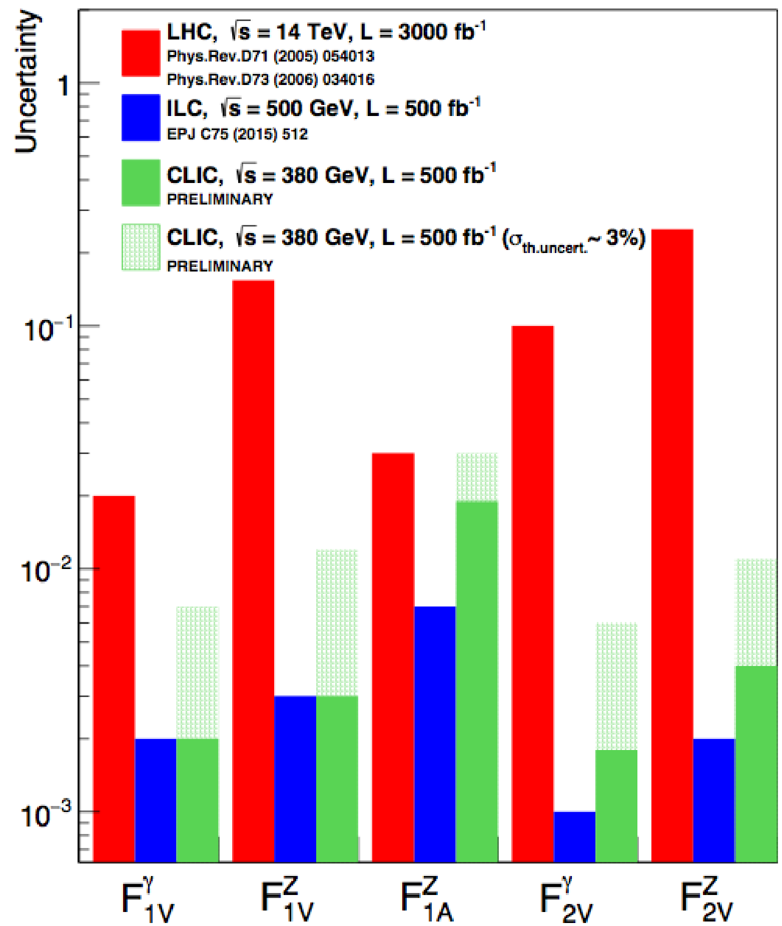
Measure 2 observables for 2 beam polarizations at ILC500 or CLIC380:

$$\begin{array}{ll} \sigma(+) & A_{FB}(+) \\ \sigma(-) & A_{FB}(-) \end{array} \quad \left.\begin{array}{l}(+ = e_R^-) \\ (- = e_L^-)\end{array}\right\} \Rightarrow \left\{\begin{array}{ccc} F_{1V}^\gamma & * & F_{2V}^\gamma \\ F_{1V}^Z & F_{1A}^Z & F_{2V}^Z \end{array}\right\}$$

Measure **Extract**

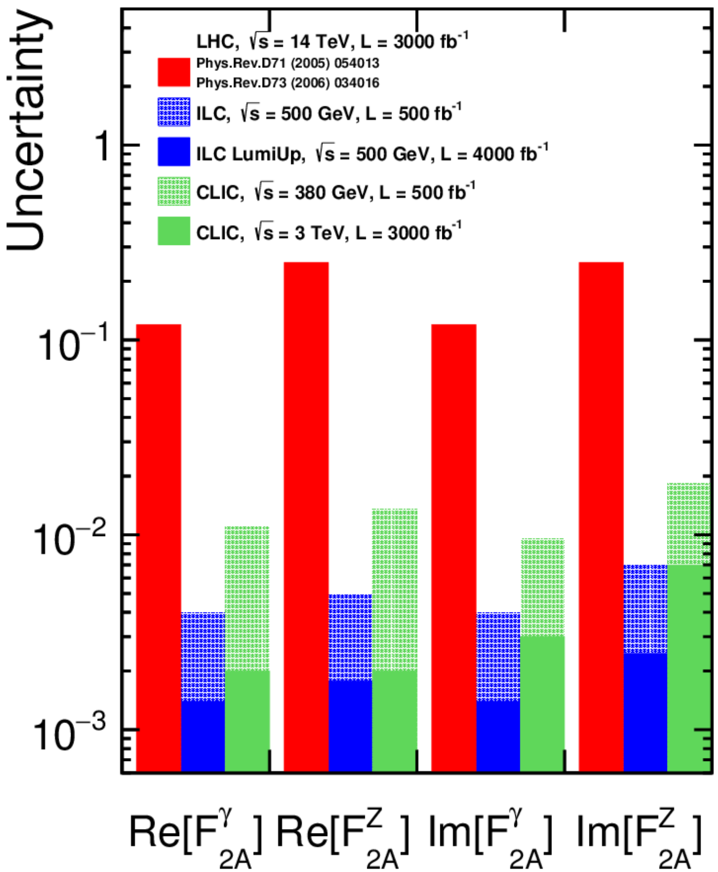
380 GeV collider has similar sensitivity
Caveat: theory unc. Exception: Z-F_{1A}

FCC-ee, Janot et al., arXiv:1503.01325, 1509.09056
ILC ME method, arXiv:1503.04247

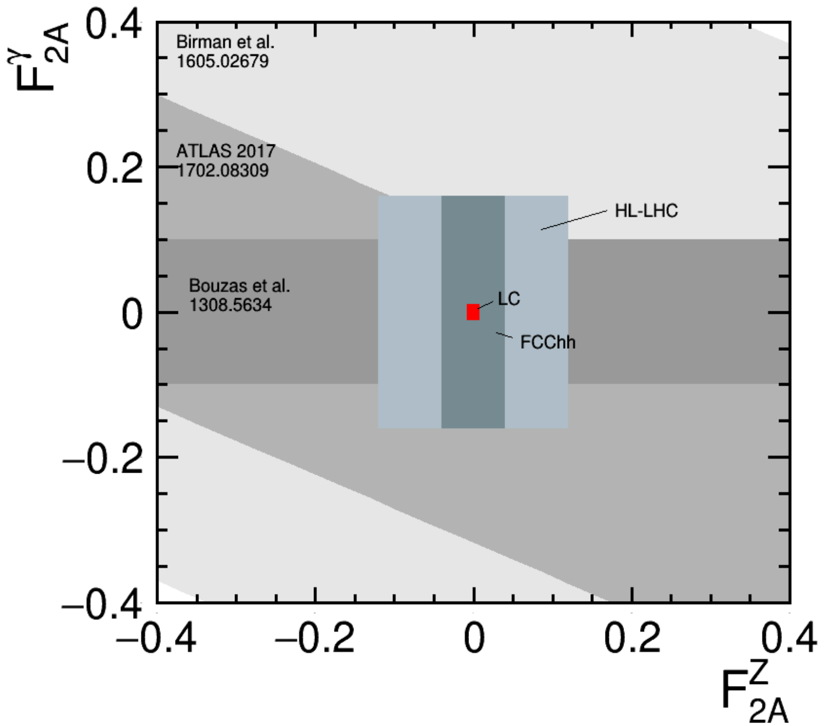


CP violating interactions

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

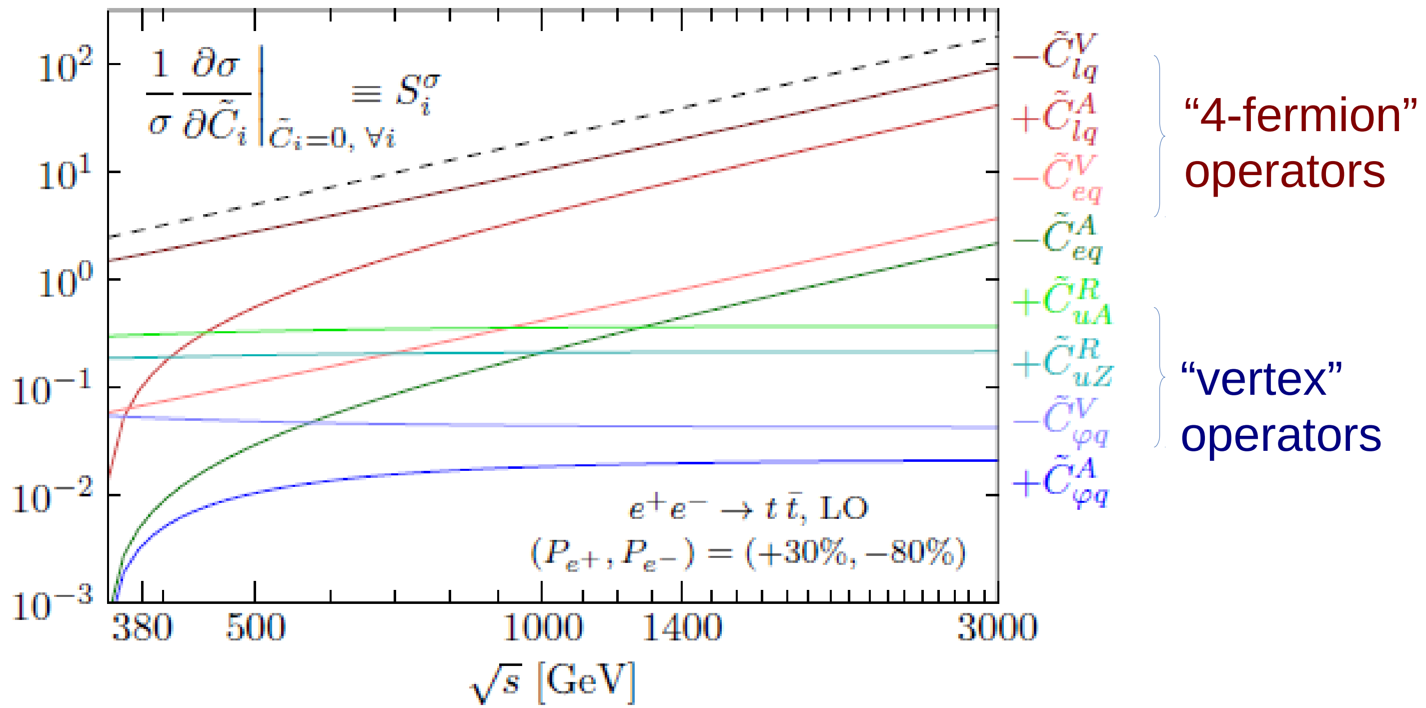


Reconstruction of optimal CP observables yields very tight constraints → sensitive to deviations predicted by viable 2HDM models
Bernreuther, Richard et al., arXiv:1710.06737



Towards a global EFT fit

Durieux, Perello, Zhang, Vos, arXiv:1807.02121



Sensitivity to 4-fermion operators (~new mediators) grows strongly with energy
→ CLIC 3 TeV operation provides tightest constraint
Sensitivity to 2-fermion (~loop effects) is flat
→ low-energy operation yields superior constraints

Global EFT fit

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLICdp top paper, arXiv:1807.02441

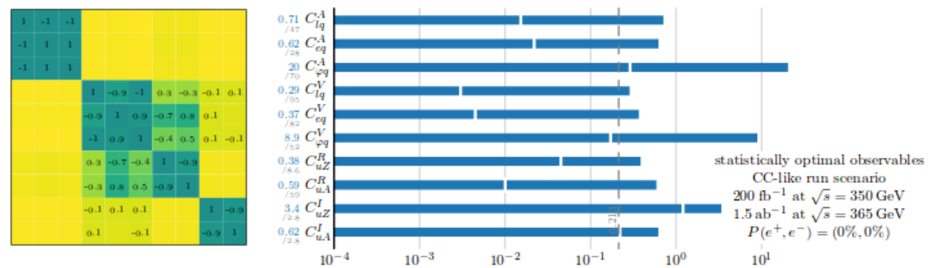


Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

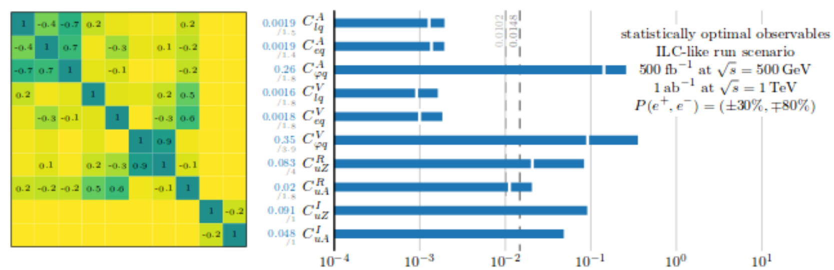


Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.

Global 10-parameter fit requires a linear collider, with two energy stages and beam polarization

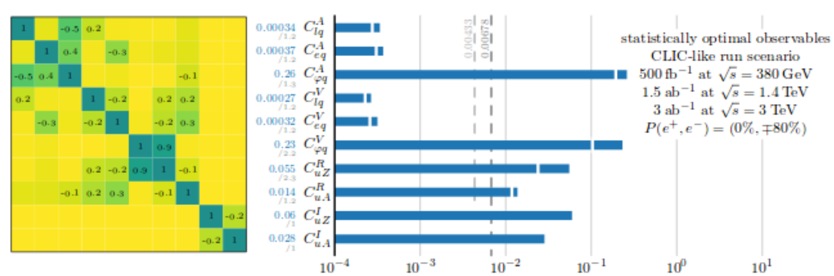
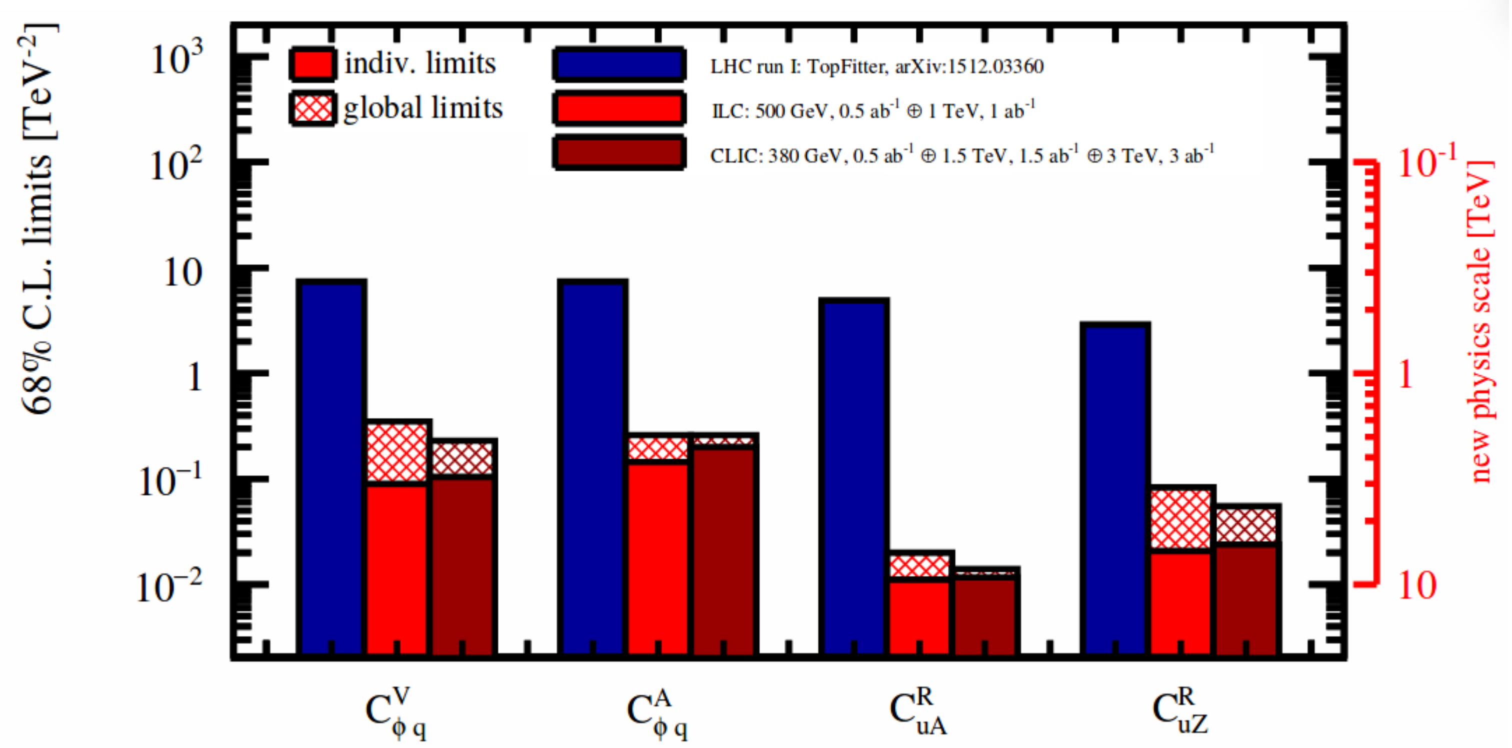


Figure 25. Global one-sigma constraints and correlation matrix arising from the measurement of statistically optimal observables in a CLIC-like benchmark run scenario.

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

Durieux, Matsedonskiy, arXiv:1807.10273

CLICdp top paper, *arXiv:1807.02441*

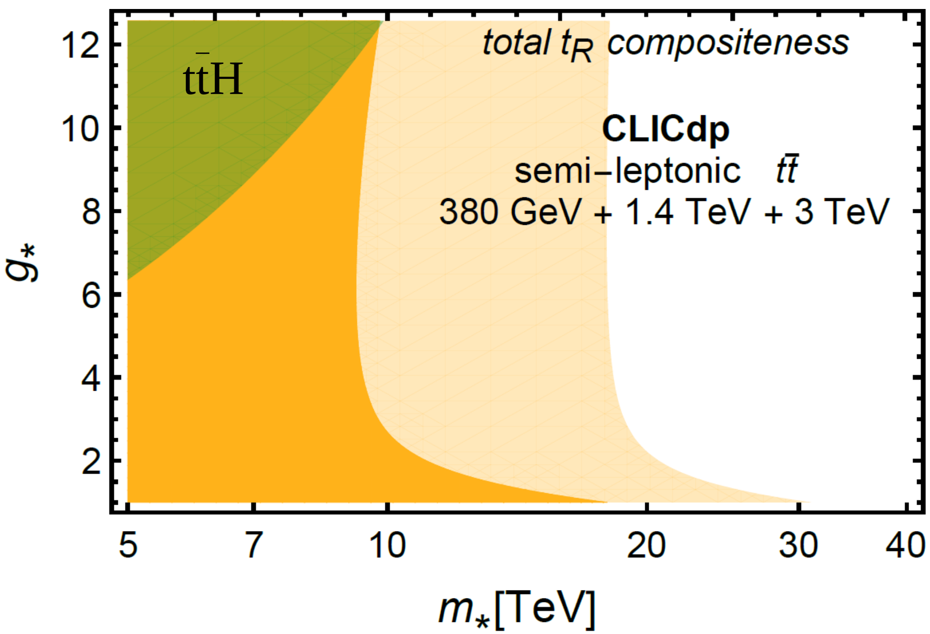
From EFT to concrete scenario

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



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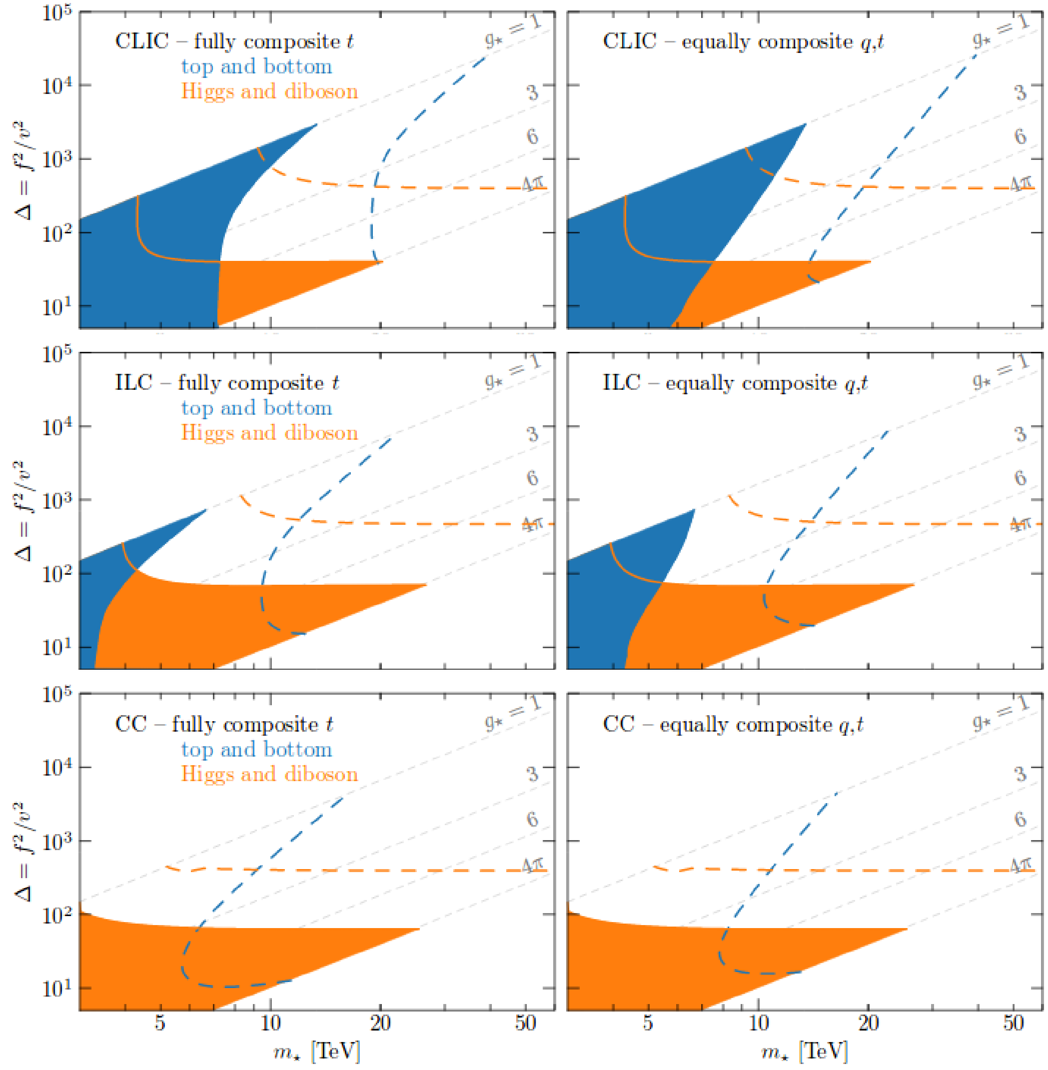
Durieux, Matsedonskiy, arXiv:1807.10273

Comparing projects and channels

Remember: EFT study mapped onto “generic” Composite Higgs scenario

Measurements in top and Higgs sector yield complementary constraints at linear colliders



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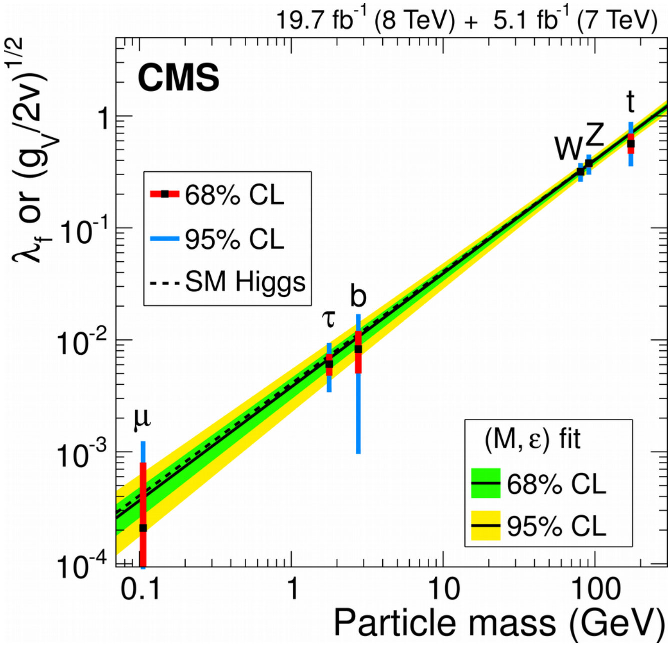
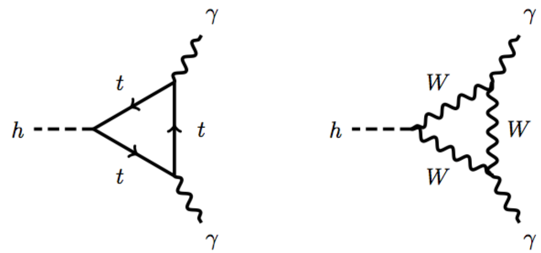
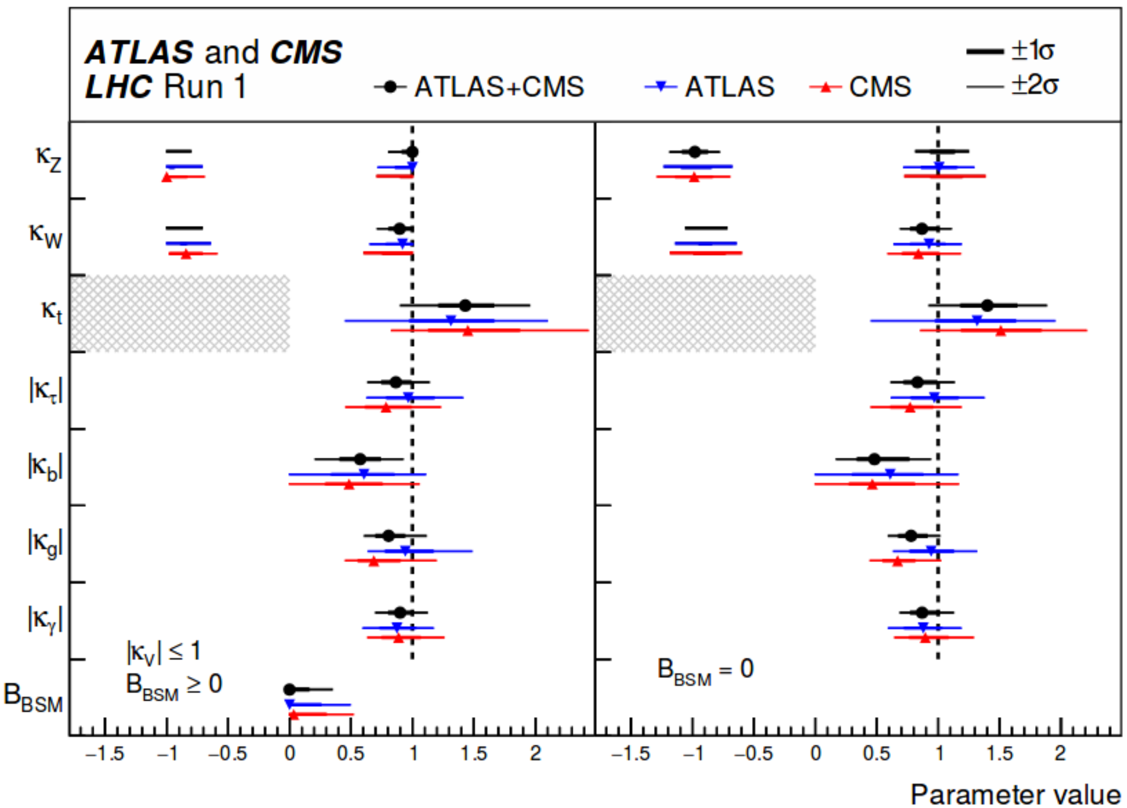
Top and Higgs



Top Yukawa coupling

At the LHC the top quark Yukawa coupling is inferred from the observed gg → H and H → γγ decay rates. Legacy combined run I result: $k_t = 1.43 \pm 0.23$.





Prospects for full LHC program:

K_u → 14-15% (300/fb)

K_u → 7-10% (3/ab) *Snowmass Higgs report*

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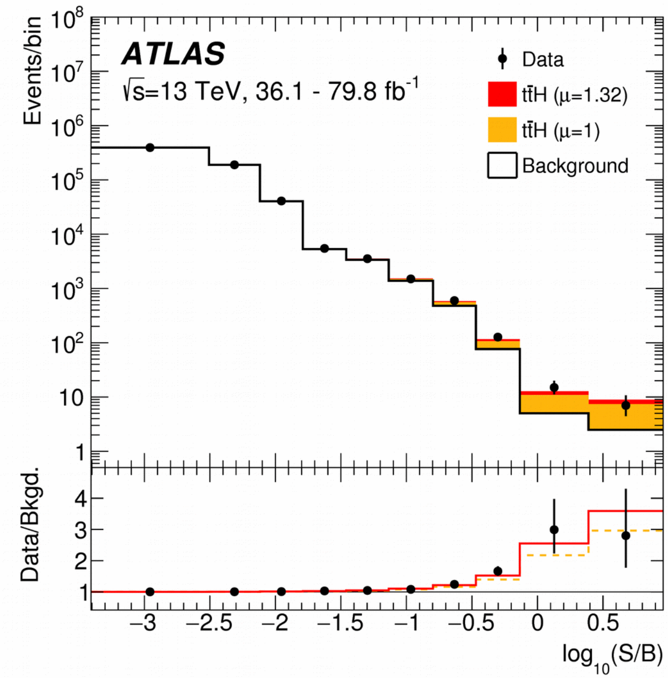
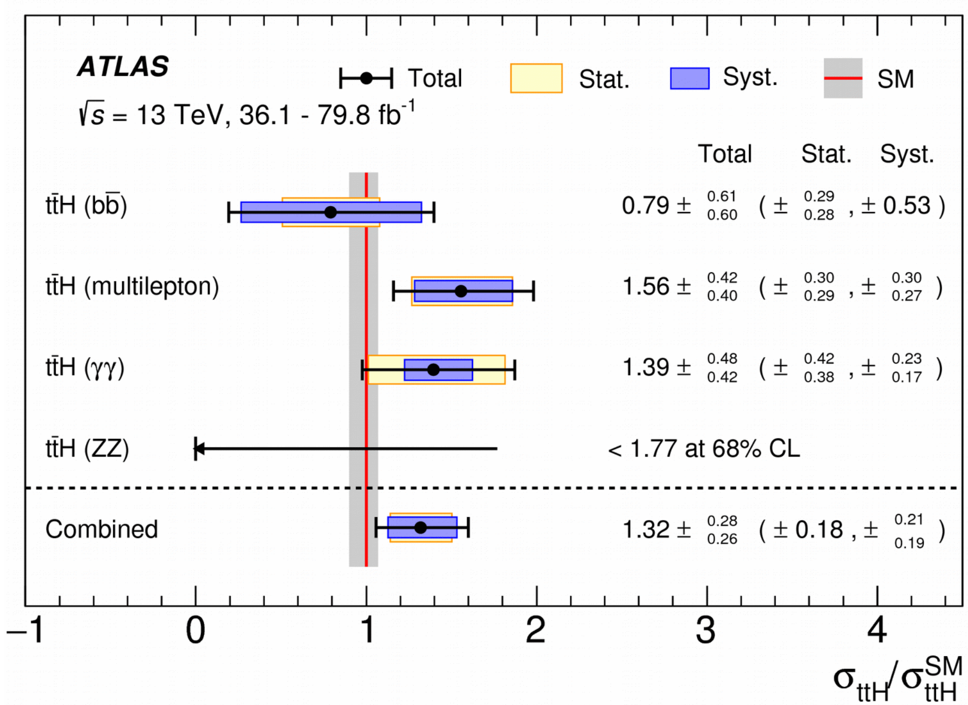
Top Yukawa coupling at the LHC

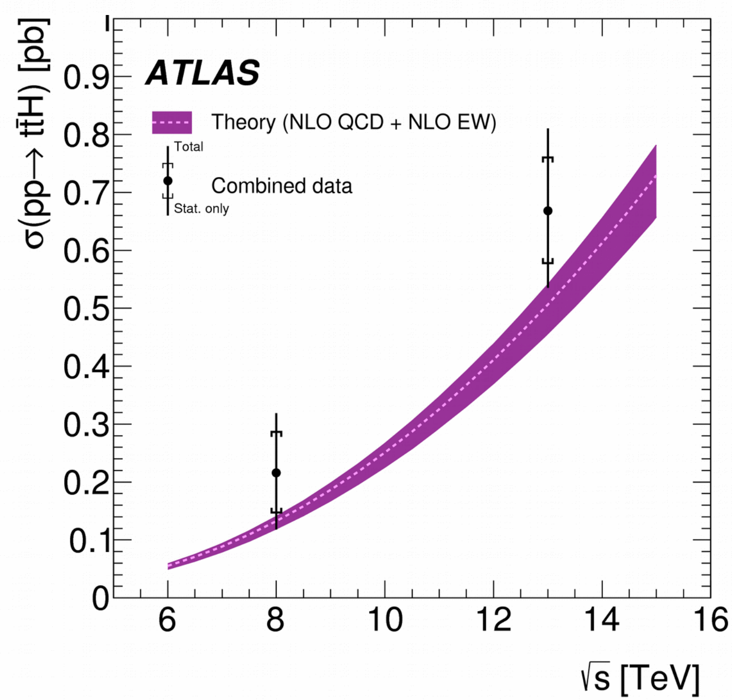
The LHC adds yet another discovery

Results compatible with the predictions for a Standard Model Higgs boson

Direct probe of the most interesting Yukawa coupling

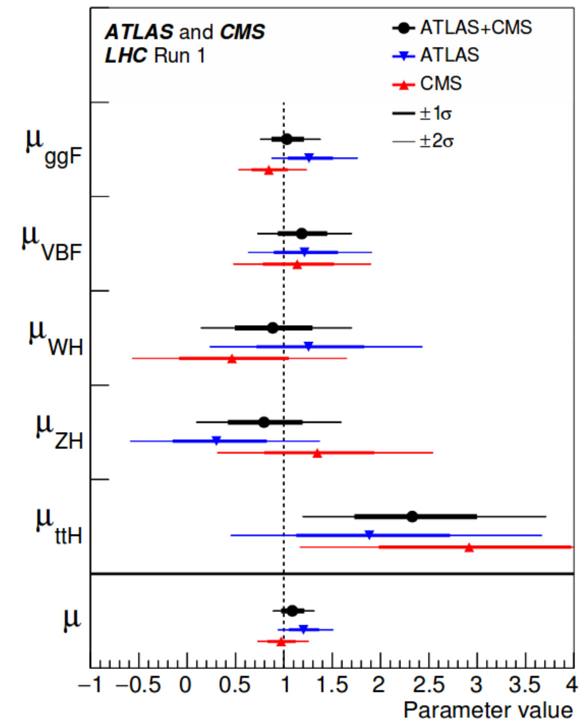


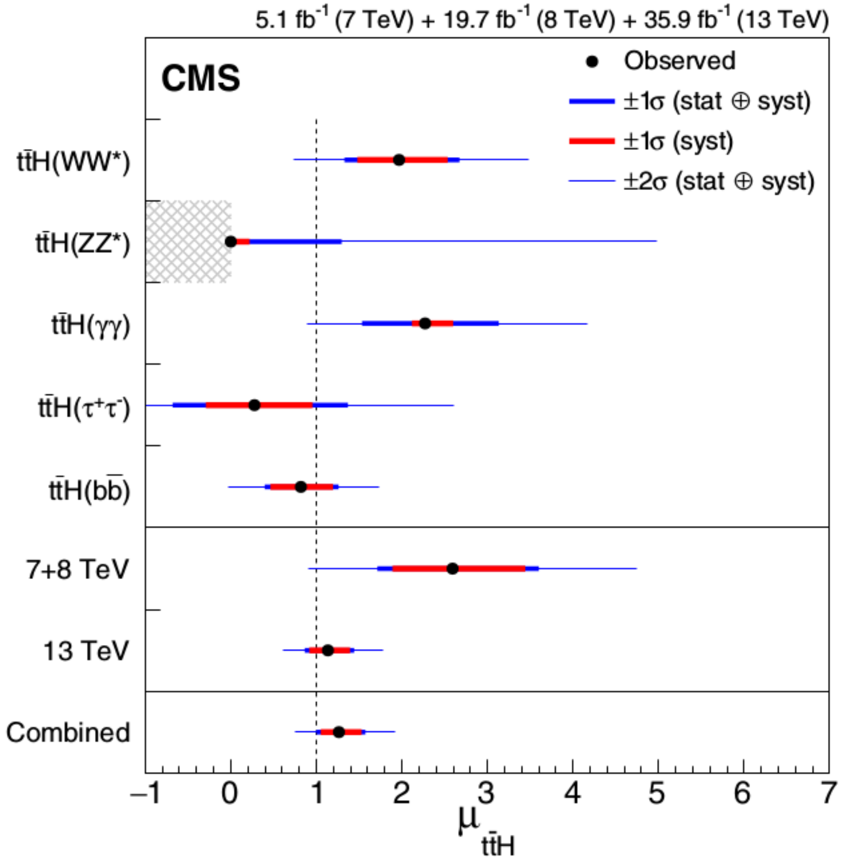




Top Yukawa coupling

The top Yukawa coupling is measured directly in associated ttH production.
Run I result: $\mu_{ttH} = 2.3 \pm 0.7$





New 13 TeV data

CMS: $\mu_{ttH} = 1.26 \pm 0.3$

ATLAS: $\mu_{ttH} = 1.32 \pm 0.3$

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Indirect top Yukawa coupling

Mitov et al., arXiv:1805.12027

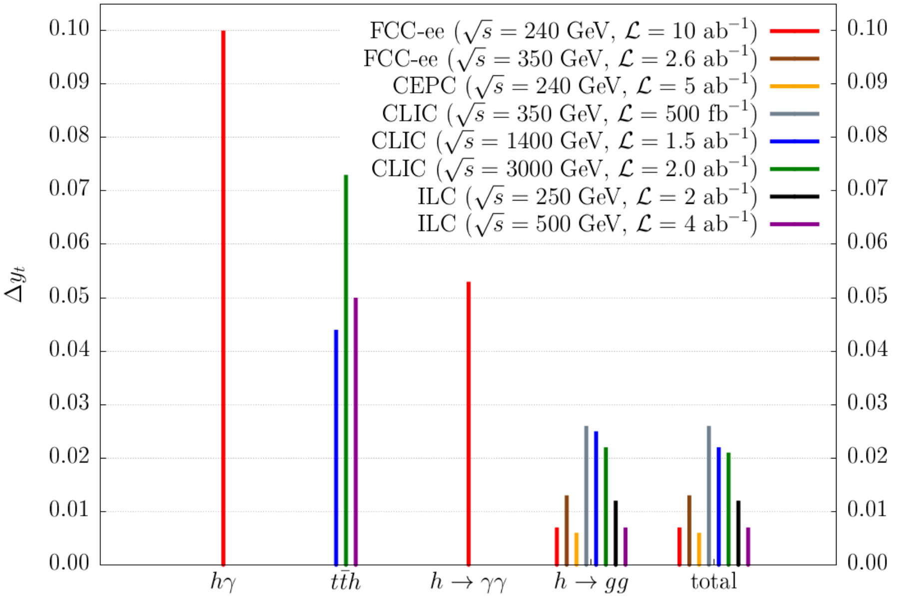
$$\mu_{h\to gg} = \frac{\Gamma_{h\to gg}}{\Gamma^{\rm SM}_{h\to gg}} = 1 + 2\Delta y_t \, ,$$

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

One-parameter fit of H → gg and H → γγ rates yields 1-2% precision already in the low-energy stage

More complex general case:
Vryonidou & Zhang, arXiv:1804.09766
Perello & Tian, in progress

CP properties in ttH
See *arXiv:1807.02441*



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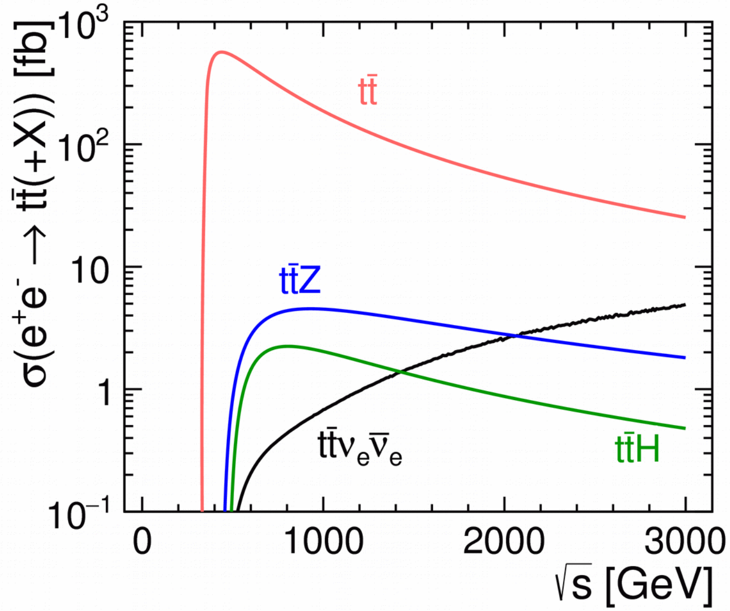
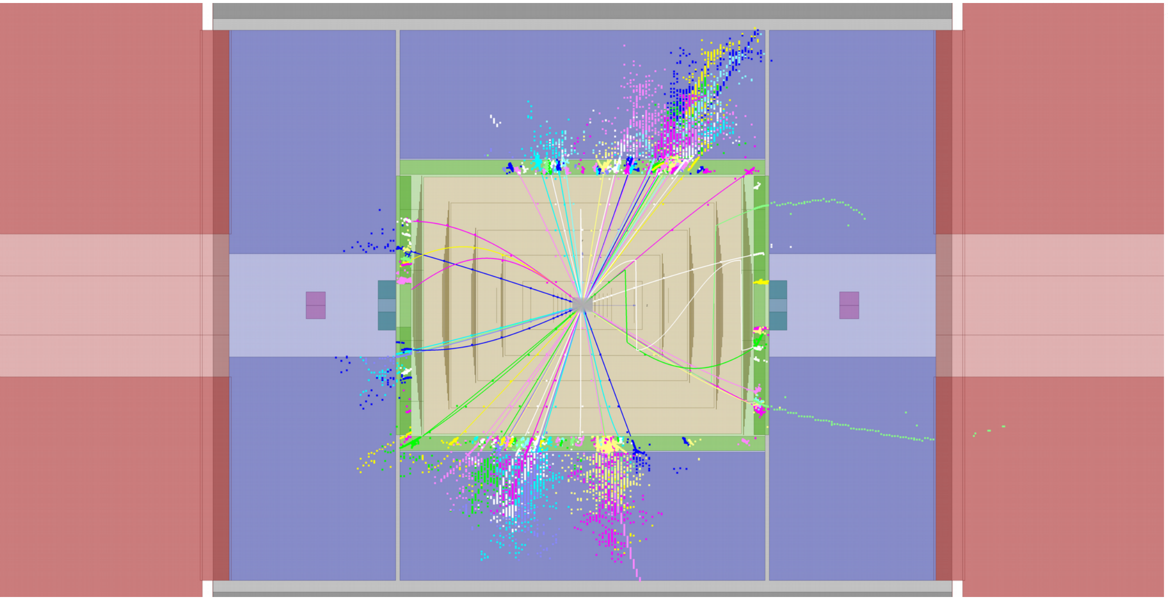
$t\bar{t}H$ at lepton colliders

Requires at least 500 GeV
(550 GeV has 3x higher rate)





Complex multi-jet events:
$t\bar{t}H$, $H \to b\bar{b}$
0 leptons → 8 jets,
1 lepton → 6 jets

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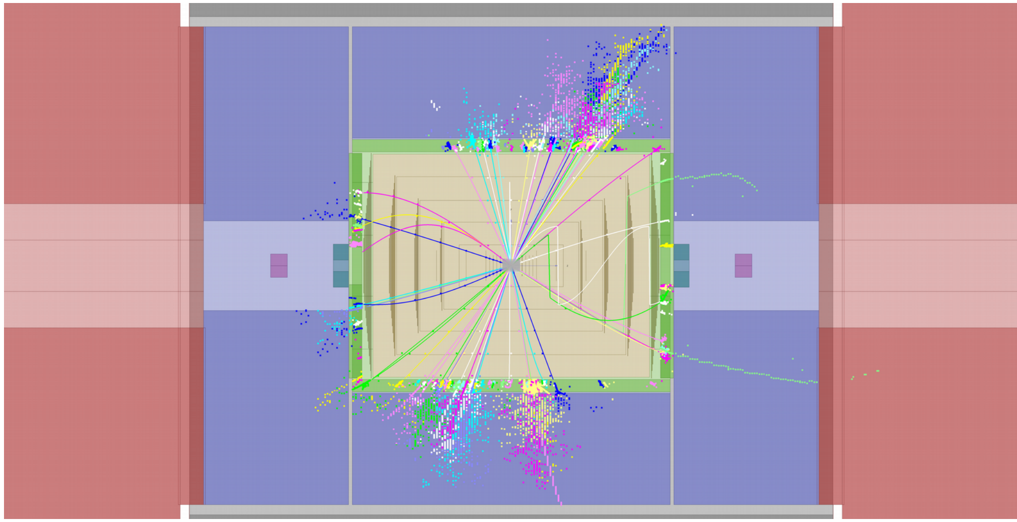
Top quark Yukawa coupling



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*

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Top quark Yukawa coupling at hadron colliders

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

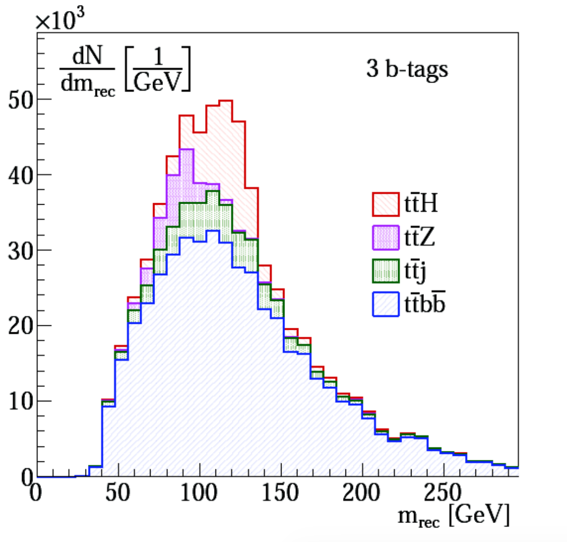
	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$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

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

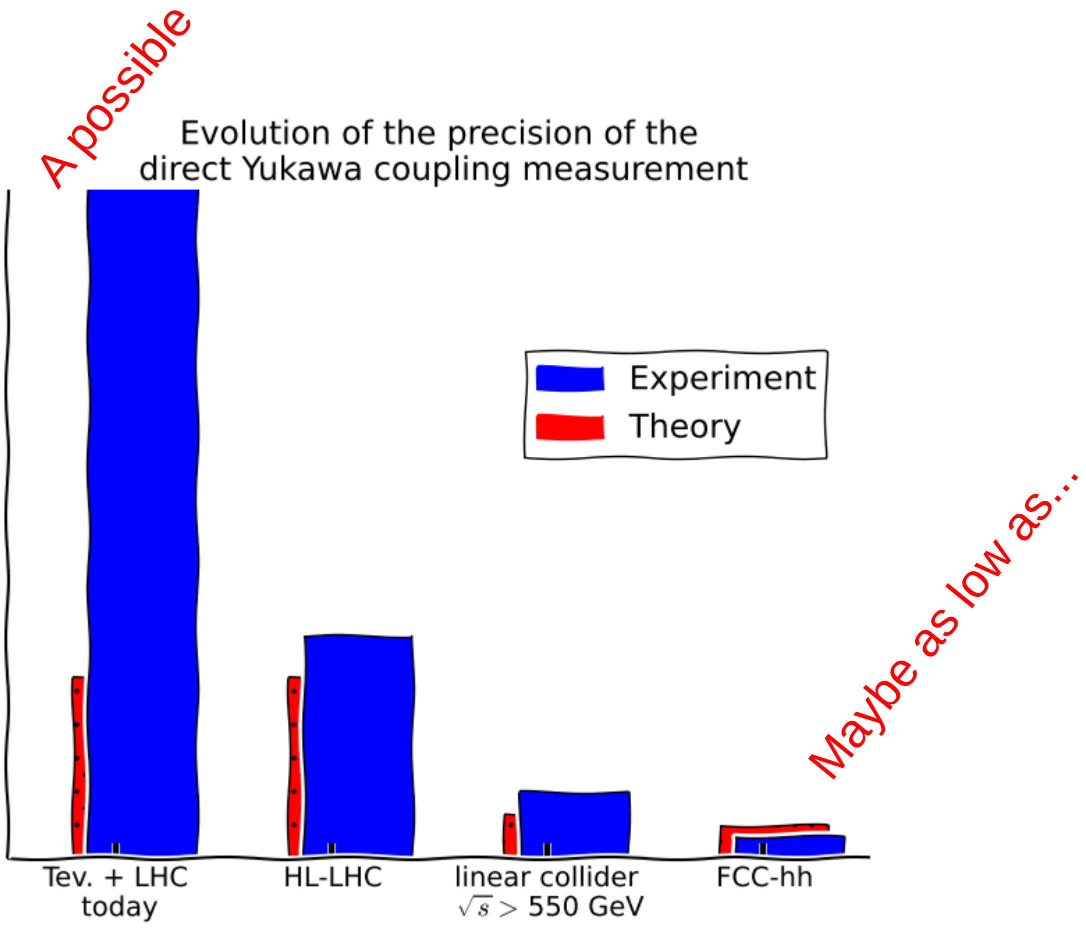
Fast simulation analysis achieves S/B~1/3.
Good mass resolution for H and Z candidates
Side-bands to control background normalization.

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

Full simulation results not yet available



Direct top Yukawa coupling measurement - summary



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The future of top physics: highlights

Top physics at the LHC is in full swing. So much is going on, it is hard to keep up. BSM constraints derived from top physics measurements will continue to improve until 2035.

Top quark studies at future facilities have the potential to deliver the transformation that this field needs

Lepton collider prospects:

= 350 GeV: top mass measurement to 50 MeV precision
> 350 GeV: Unrivalled sensitivity to ttZ and ttγ vertices
> 500 GeV: direct top Yukawa coupling to 4%

Challenges: control of systematics to per mille level

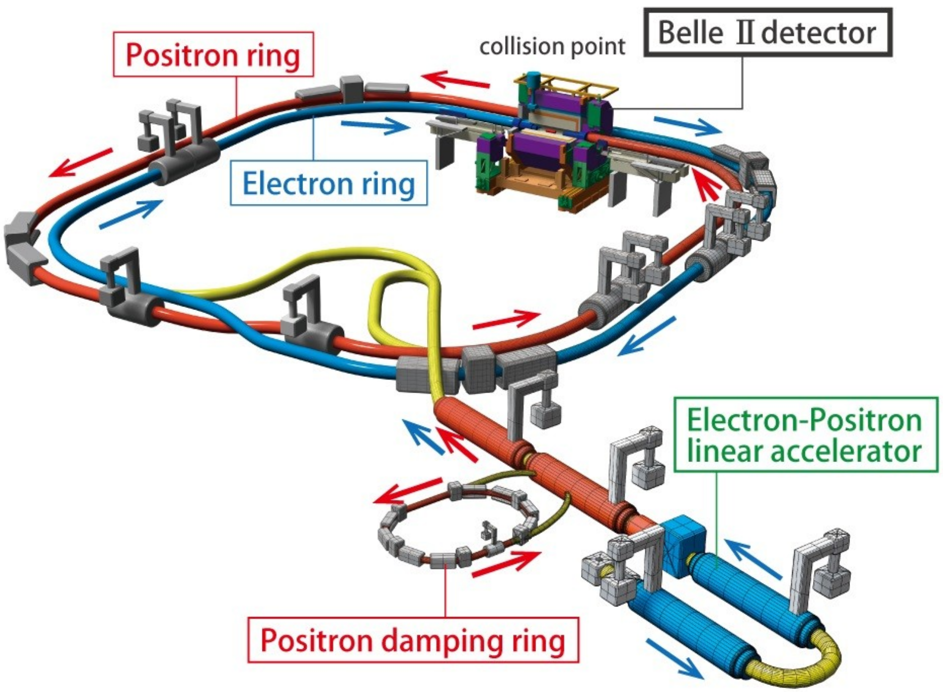
100 TeV hadron collider targets:

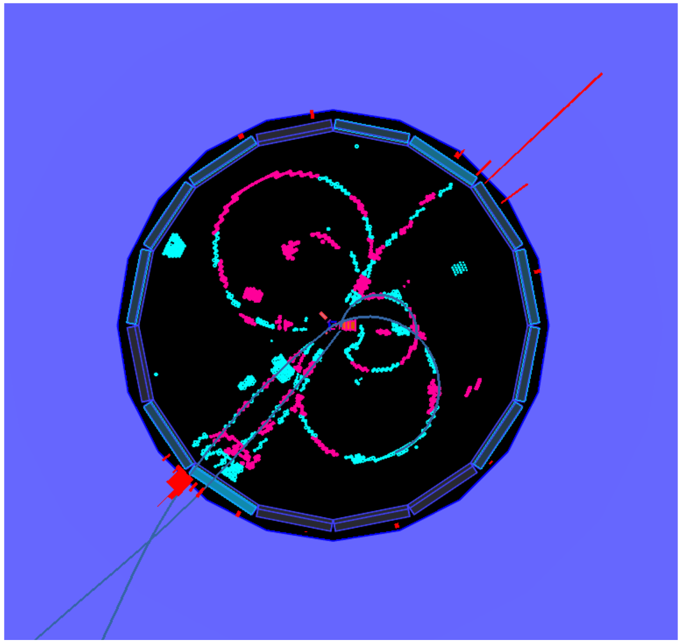
Greatly enhanced mass reach for searches
Very tight constraint on top QCD interactions
Top Yukawa coupling to 1% ?

Challenges: control of (theory) systematics to % level, ultra-boosted production

Progress on EFT machinery enable a comparison of the BSM potential of top precision measurements at different colliders → deliver by the time of the European Strategy update

Let’s just do it!





Japan and KEK are now officially in charge of the study of the bottom quark

Let’s just do it!!

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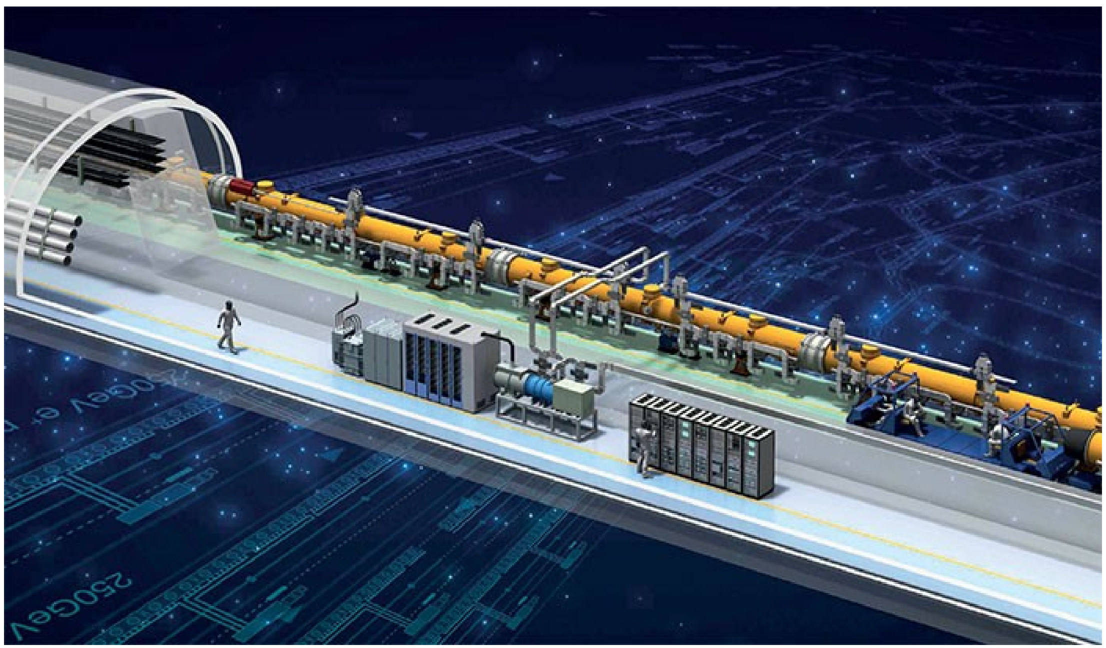
NEWS

International committee backs 250 GeV ILC

15 January 2018



Japan can host the machine that studies the Higgs boson

With the rest of the world, Japan can reach the top

Let’s just do it!!!

With the rest of the world, Japan can reach the top, sooner or later!!

The future of Higgs and top physics in Japan?

There is a real chance that the International Linear Collider can be realized in Japan, with important international contributions.

Initial phase at 250 GeV is very good for Higgs physics. Energy extendability is key at linear colliders: the time for top physics will come.

Time is running out: we need to move forward before the European strategy update.

ILC 福岡宣言「国際リニアコライダーの実現を目指して- 更新版」

2018 年5 月31 日、福岡

2015 年に東京で行われたリニアコライダーワークショップに集まった科学者は、国際リニアコライダー（ILC）の迅速な実現の科学的正当性に対する強い支持を確認する声明を発表した。リニアコライダーコラボレーション（LCC）と2018 アジアリニアライダーワークショップ（ALCW2018）に世界から集まった参加者は、ILC の科学的重要性を再確認する。我々はプロジェクトの実現に近づいており、今は決定的に重大な段階である。

（1）欧州合同原子核研究機関(CERN) の大型ハドロンコライダー(LHC) の結果は、我々が宇宙の起源と歴史を明らかにするための探求の岐路に立っていることを示唆している。現在、精密測定、特にヒッグス粒子の特性の測定は、我々が宇宙の理解を深めるために不可欠な次のステップであることがわかっている。250 ギガ電子ボルト(GeV) の重心系エネルギーにおけるILC での電子 - 陽電子相互作用の正確な測定は、我々の科学的知見に飛躍をもたらし、LHC とSuperKEKB の今後の成果とともに、素粒子物理学の究極の理論と、宇宙の深い理解に向け研究を進展させるであろう。

（2）我々は長年にわたり、産業界と協力し、世界各国の政府と協議を行なってILC の準備を進めてきた。ILC は現在最も成熟し、かつ実現可能な電子･陽電子衝突加速器のプロジェクトであり、線形加速器としてのエネルギー拡張性も有している。ハンブルクの欧州自由電子レーザー(XFEL) の運用の成功、シカゴ近郊のフェルミ国立加速器研究所や他研究所における超伝導研究開発の最近の進歩、また重心系エネルギーを250GeV に変更することによるコスト削減は、当該エネルギーにおける物理実験の能力を維持しつつ、ILC の技術的および財務的な実現可能性を向上させた。ILC のために開発された超伝導技術は、加速器産業および医療用途において大きな波及効果をもたらすものだ。我々は、新しいILC の設計に基づく提案に対する日本政府の評価プロセスに深く謝意を表する。

（3）ILC は国際プロジェクトとしてのみ実現することができる計画であり、本プロジェクトのホスト国が国際交渉を導くべきであると考える。ILC 建設への協力を含む、素粒子物理学における欧州の未来戦略の更新作業が来年初めに始まるため、今年、日本政府からの議論の開始に前向きの姿勢が示される肯定的なメッセージが提示されることが非常に重要となる。この更新作業は、世界中の高エネルギー物理学計画の将来について、欧州以外の地域にも大きな影響を与えるものである。更新作業に関する議論においては、我々はILC の科学的論拠を強く主張する予定であるが、日本政府から積極的なメッセージが時宜を得て伝えられることが不可欠である。

リン･エバンス

LCC ディレクター

LCC とALCW2018 の科学者

注: これは研究者による日本語訳であり、正文は英語版である。

Bibliography

Report from Top@LC15 workshop at IFIC Valencia

An up-to-date, consensuated summary of LC top physics, with an extensive bibliograpy

arXiv:1604.08122

27 Apr 2016

Top physics at high-energy lepton colliders

Summary of TopLC15, IFIC Valencia, 30th June - 2nd July, 2015

M. Vos (IFIC, editor)
Attendants of the workshop:
G. Abbas (IFIC), M. Beneke (TUM), S. Bilokin (LAL), M.J. Costa (IFIC), S. de Curtis (U. & INFN Firenze), K. Fujii (KEK), J. Fuster (IFIC), I. Garcia Garcia (IFIC), P. Gomis (IFIC), A. Hoang (U. Vienna), A. Irles (DESY), Y. Kiyo (Yuntendo), M. Kurata (Tokyo), L. Linssen (CERN), J. List (DESY), M. Nebot (Lisboa), M. Perello (IFIC), R. Pöschl (LAL), N. Quach (KEK), J. Reuter (DESY), F. Richard (LAL), G. Rodrigo (IFIC), Ph. Roloff (CERN), E. Ros (IFIC), F. Simon (MPI Munich), J. Tian (KEK), A.F. Żarnecki (Univ. of Warsaw)

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IFIC/17-01
January 24, 2017

Top physics beyond the LHC

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C./Catedratico Jose Beltran 2, Paterna, E-46980, Spain

Bibliography

This is not a review, find good top quark physics reviews here:

Bernreuther on LHC top quark theory (before the start of the LHC):
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ArXiv:1606.00327

Top quark mass: how can we make further progress?

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