The future of top physics

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

Seminar

University College London

November 2016

marcel.vos@ific.uv.es

Top physics prehistory

1973: The top quark is born as a hypothetical particle

Kobayashi and Maskawa postulate the third generation

Particle physics was so easy then!

1972 A 5M$ collider starts operation on the SLAC parking lot

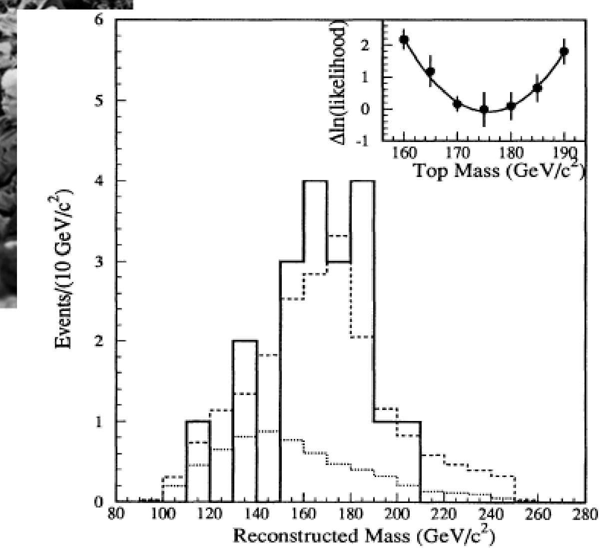
1974 Two colliders in the same country discover the same particle

Top physics in 1995

The Tevatron was the most powerful collider in the world

Expectation was mounting...

And indeed...

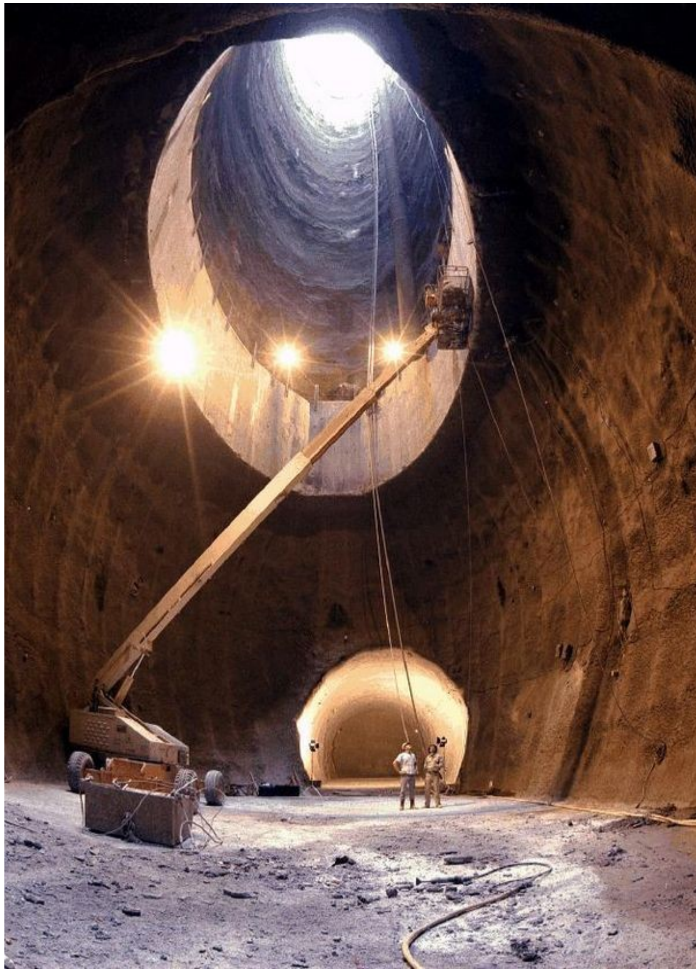


CDF and D0 collaborations, Observation of the top quark
PRL 75 (1995) 2632-2637, 2626-2631

Note that there was still plenty of choice to pick a PhD project:
HERA@DESY, LEP@CERN, SLC@SLAC, or Tevatron@FNAL

Top physics alternative history

Ronald Reagan: “*throw deep*”



“*The super collider is one of the greatest scientific projects in the entire world. This place attracts scientific genius the way our U.S. basketball players attract autograph seekers over there in Barcelona.*” George Bush sr. 1992

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

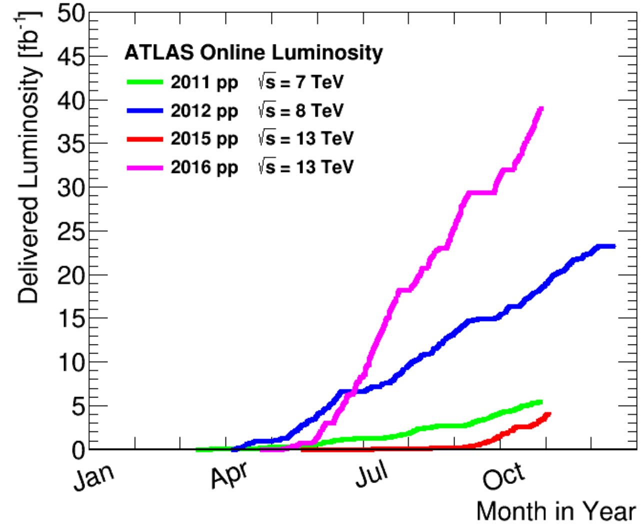
The SSC: could have gained 20 years, but ultimately a bridge too far

(M. Riordan, tunnel visions...)

Top physics today

Thank God for the LHC

Uncertainties in tt production	ATLAS 13 TeV arXiv:1606.02699
Experiment: stat.	0.1% (3.2 fb^{-1}!)
Experiment: syst.	3.3 % (2.8 % had.)
Experiment: luminosity	2.3 %
Experiment: beam energy	1.5 %
Experiment: result	818 pb ± 36 pb
Theory: scale (NNLO+NNLL)	$^{+2.4\%}_{-3.5\%}$
Theory: PDF (PDF4LHC)	4.2 %
Theory: prediction	832 pb $^{+40}_{-46}$ pb



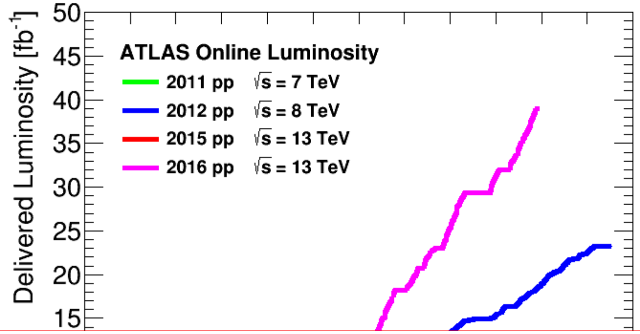
Now also fully differential: arXiv:1606.03350

For a not-too-outdated review, see: Cristianzini & Mulders, arXiv:1606.00327

Top physics today

Thank God for the LHC

Uncertainties in tt production	ATLAS 13 TeV arXiv:1606.02699
Experiment: stat.	0.1% (3.2 fb^{-1}!)
Experiment: syst.	3.3 % (2.8 % had.)
Theory: scale (NNLO+NNLL)	$^{+2.4\%}_{-3.5\%}$
Theory: PDF (PDF4LHC)	4.2 %
Theory: prediction	832 pb $^{+40}_{-46}$ pb



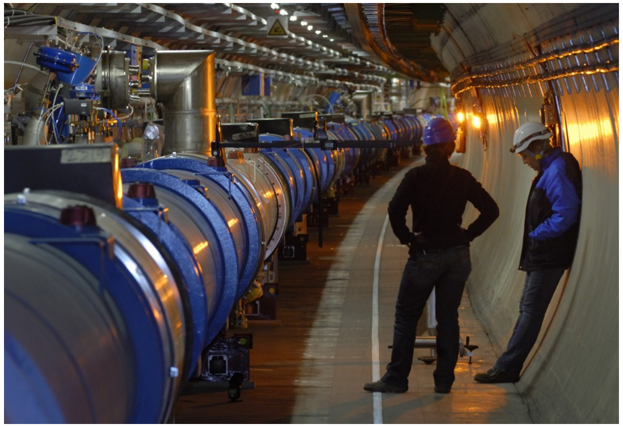
arXiv:1507.08169: "one of the key obstacles to exploiting the immense statics available at hadron colliders for precision measurements, is the intrinsic difficulty in performing accurate absolute rate predictions"

Now also fully differential: arXiv:1606.03350

For a not-too-outdated review, see: Cristianzini & Mulders, arXiv:1606.00327

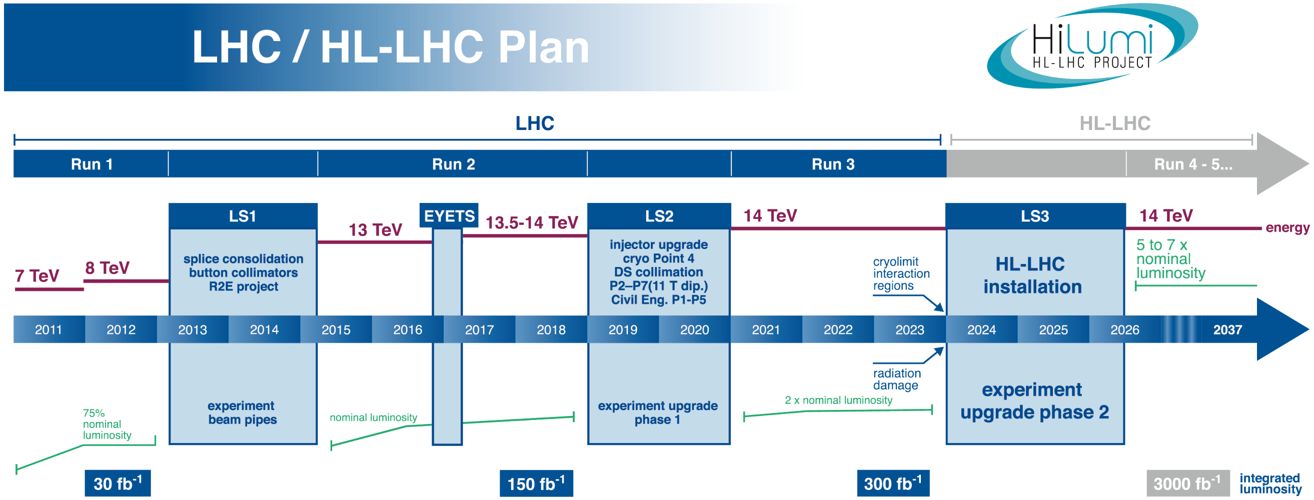
Top physics in the next decades

Thank God for the LHC



The full exploitation of the LHC is the highest priority in the European Strategy for Particle Physics, adopted by the CERN Council and integrated into the ESFRI Roadmap.

The HL-LHC project funding was approved by the CERN Council in June 2014.



HL-LHC top physics case


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

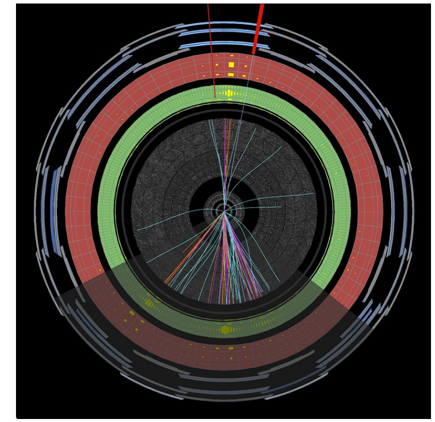
PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

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!!

Top physics: the next decades (revisited)



Find ways around systematics:

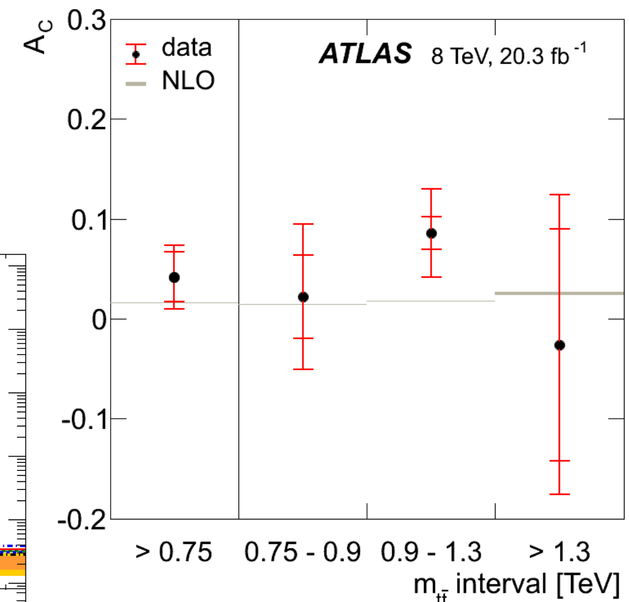
Aggressive targets for the top mass (CMS)

Differential cross sections & cross section ratios (Mangano et al.)

Plenty of statistics-limited analyses left:

Boosted top production (BOOST series)

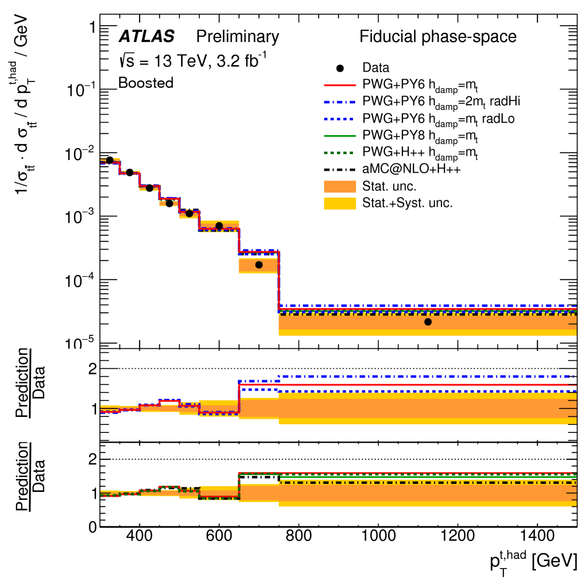
Rare associated production process (ttW/Z/γ/H)



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

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

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



See: M. Cristianzini, P. Azzi, TOP2016

Colliders for the post-LHC era

The post-LHC era

If we want to build a next collider that goes online by 2035, we need:

- technology

- vigorous R&D programme in magnets and cavities
- be prepared for surprises!

- time

- Long lead time – cf. the LHC took 20 years from CERN council decision to physics
- At the time of the European Strategy in 2020 we're on the critical path

- funding

- None of our projects is cheaper than 10 billion → global coordination

- faith

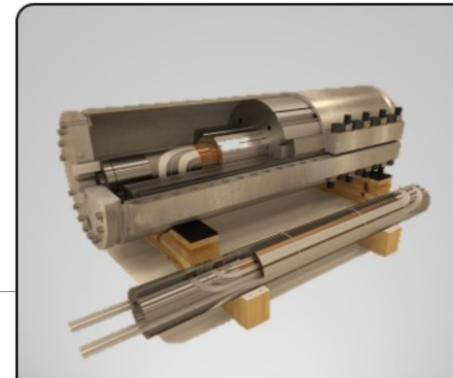
- Big science requires big results: can we guarantee a profound transformation of HEP?
- physics case to convince the field, other fields, the public and politicians
- SM is ~complete, no “obvious” extension

Standard Model physics - and agnosticly defined BSM sensitivity - is an important benchmark

For a big leap in center-of-mass energy

Bending magnets (circular)

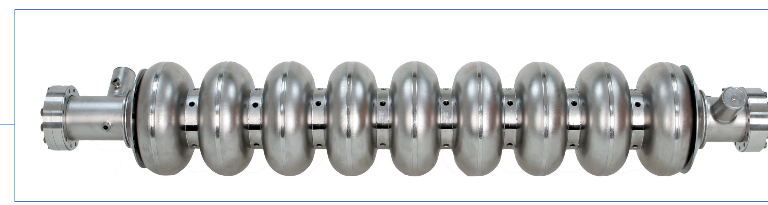
→ 4 Tesla (Tevatron)
→ 8 Tesla (LHC)
→ 16 Tesla (VLHC, SPPC, FCChh)
Key R&D programme in EU strategy

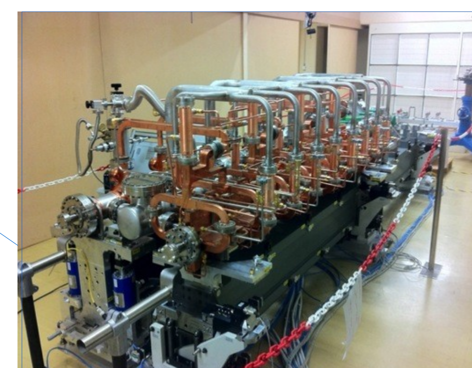


High Field Magnet

Accelerating cavities (linear)

→ 17 MV/m cavities (SLC)
→ 35 MV/m (industry, XFEL/ILC)
→ 100 MV/m (concept proven, CLIC)
→ Plasma wakefield (when?)





Key question: so, when will project X/Y/Z be approved?

Answer: unfortunately, it's not in my – or even our – hands. We depend on high-level politics for projects of this scale.

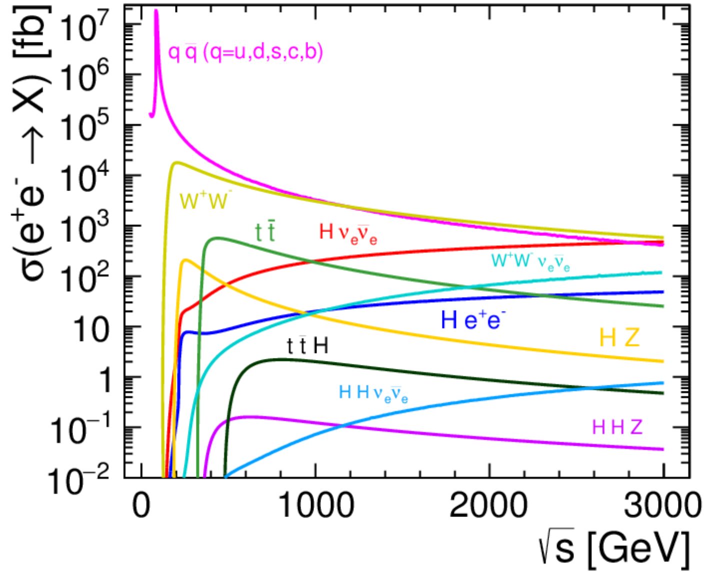
And, unfortunately, politics can be quite unpredictable...

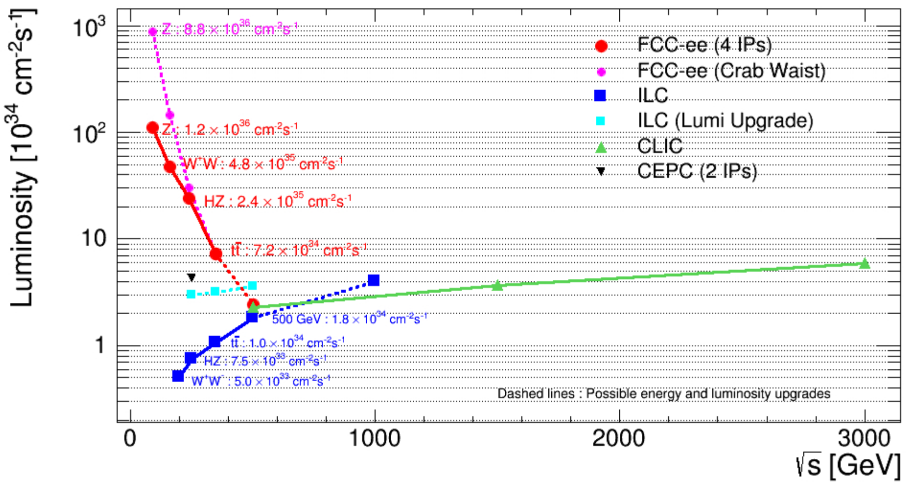
Top physics at a lepton collider?

Lepton collider projects:

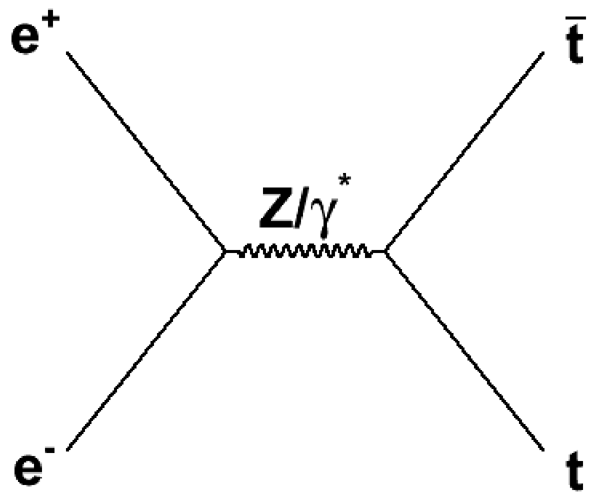
- ILC (TDR, negotiations):
  250, 500, 1000 GeV
- CLIC (CDR):
  380, 1500, 3000 GeV
- CEPC (pre-CDR, TDR ~2020):
  250 GeV → no $t\bar{t}$ production
- FCC-ee (CDR ~2018):
  365 GeV

Technology exists today
Detailed designs for ILC/CLIC





Top quark production at lepton colliders



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

Machine: per mil level luminosity, polarization and beam energy calibration

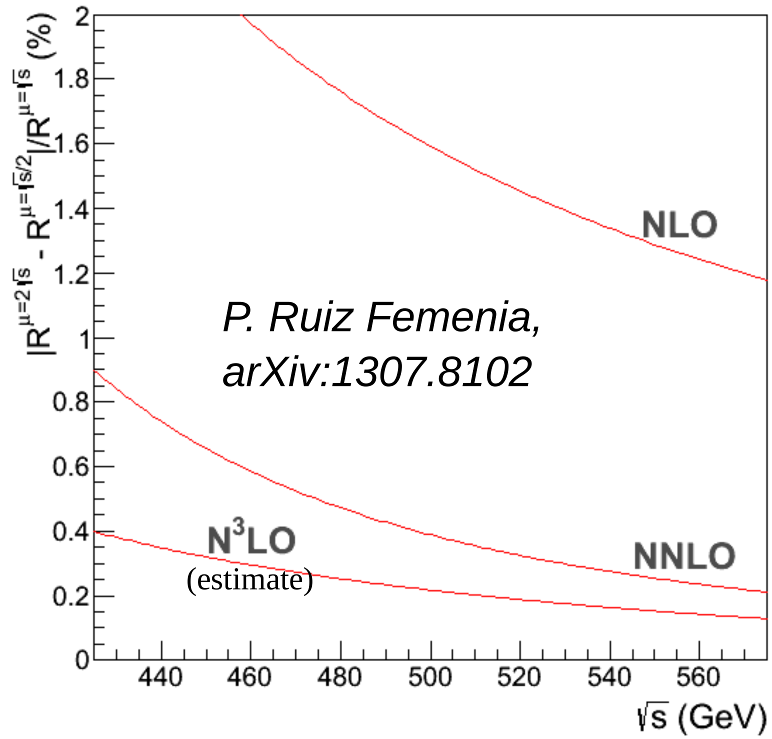
Theory: no PDFs, small QCD corrections
Predictions at few per-mil level already today!

Truly inclusive measurements!

Statistics: few 100.000 events, less at high energy

Experiment must match few per mil precision

Variation in x-section due to scale variations



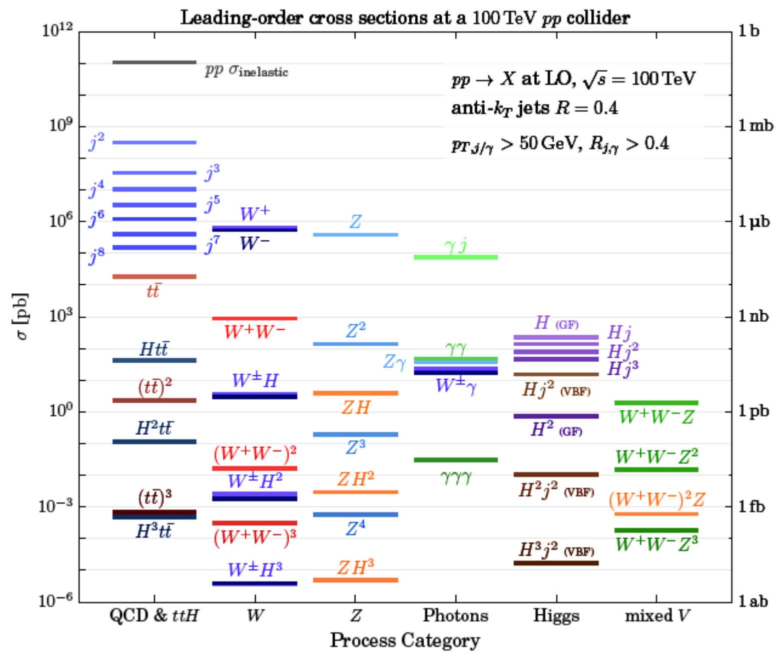
See also: Chokoufé et al., arXiv:1609.03390

Top physics at the next hadron collider?

Projects for the next very large hadron collider

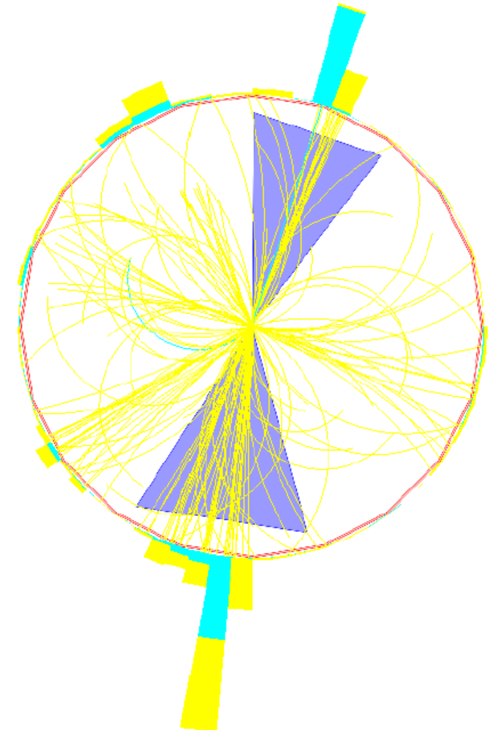
16 Tesla Nb3Sn magnet R&D to allow √s/L ~1 TeV/km

- **SPPC (China, conceptual design end 2016)**
  50-80 km (TeV)
- **FCChh (CERN, CDR ~2018)**
  Up to 100 km (TeV)
- **High-E LHC**
  LEP/LHC tunnel 27 km (or TeV)



ArXiv:1605.00617

80-100 TeV pp collisions



Consequences of “top as a light quark”

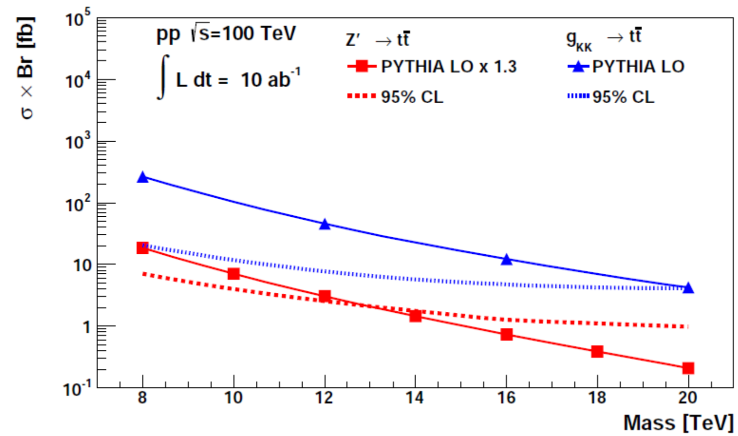
Production much more forward → dedicated experiment a la LHCb?
M. Mangano, TOP2015

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

Ambition

Lepton requirement
Saavedra et al. arXiv:1412.6654
Charged substructure
A. Larkoski, arXiv:1511.06495
jet substructure, pushing calorimeter granularity
$t\bar{t}$ resonance section of arXiv:1606.00947
(Argonne study with DELPHES, arXiv:1412.5951)
Chekanov @ ICHEP full GEANT4 simulation



FCChh BSM summary: *arXiv:1606.00947*

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

Precision physics at hadron colliders

Cross-section for $t\bar{t}$+X at 100 TeV is 60 times larger than at the LHC

Statistics no longer a problem. Can we work around the theory uncertainty?
Move towards relative cross sections or ratios of processes ttH/ttZ

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

Ratio turns O(10%) uncertainty into an O(1%) uncertainty
Even differential: cuts on p_T (Z/H, top, tt) lead to small increase only

Is this the key to precision physics in pp?
verify degree of cancellation and establish robust uncertainties
- theory: verify with NNLO calculation for both processes
- experiment: verify in **ratio of 7 and 8 TeV cross sections:**

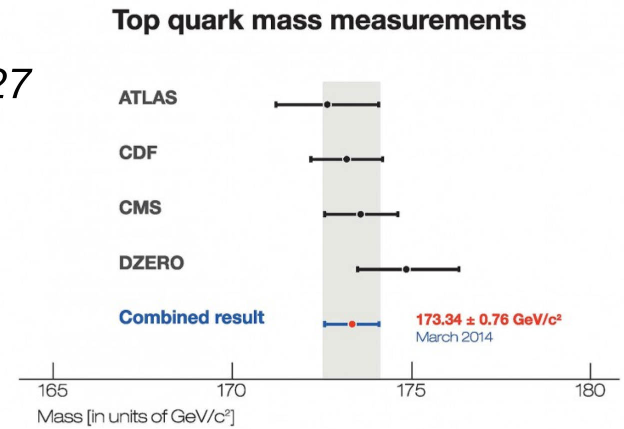
ATLAS: R = 1.326 ± 0.024 (stat.) ± 0.015 (syst.) ± 0.049 (lumi.) ± 0.001 (E)
Theory: R = 1.430 ± 0.013 (scale + PDF + α_s < 1%)

CMS: R(ttbb/ttjj), R(ttγ/tt) in CMS-PAS-TOP-13-010/11 to ~25%
ATLAS: R(tt/Z) in ATLAS-CONF-2015-049 to 9%

Objetive I: top quark mass

Top quark mass

arXiv:1403.4427



Direct measurement: first ever LHC/Tevatron Combination

Consistent results across experiments, initial and final states

A quark mass measurement to better than 0.5%

How much further can we go?

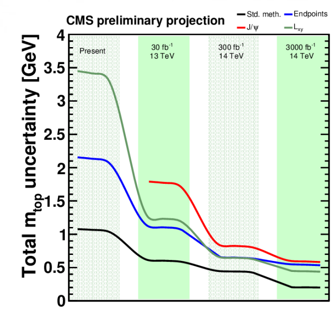
Snowmass, arXiv:1310.0799: *"a top mass extraction with uncertainty as low as 500-600 MeV"*

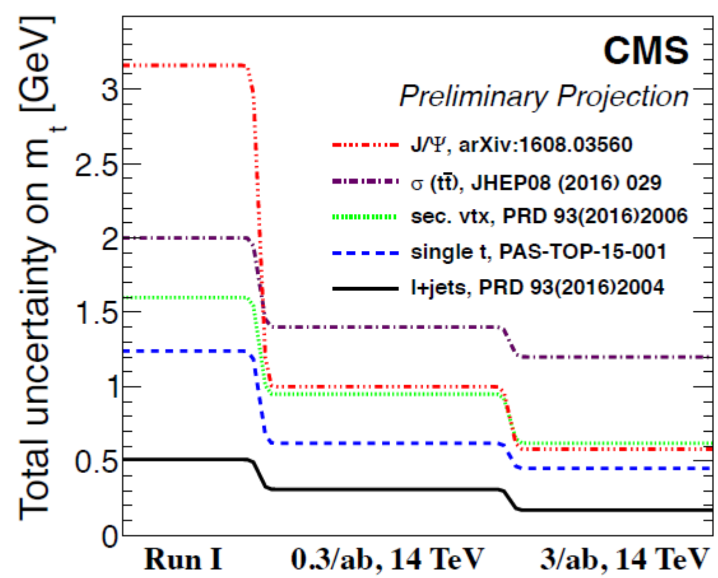
CMS-FTR-13-017-PAS: "200 MeV, based on "assumptions [that] are optimistic but not unrealistic."

CMS-DP-2016-064: "Conventional methods, which are the most precise ones, are expected to yield an ultimate relative precision below 0.1%."

These are experimental uncertainties only!

*Mangano et al., arXiv:1607.01831: "**We avoid here a discussion of the determination of the top mass at 100 TeV**: any progress relative to what will be known at the end of the LHC will depend on theoretical progress that is hard to anticipate"*





The top quark mass combination, small print

Direct mass measurements are calibrated against MC templates

→ **yield MC mass parameter**

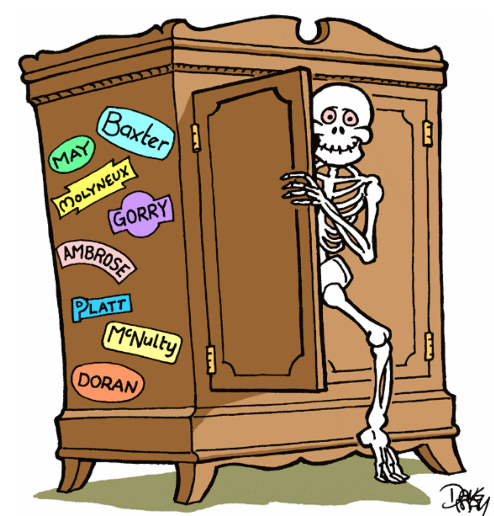
= pole mass in NLO Matrix Element

situation less clear after PS/hadronization

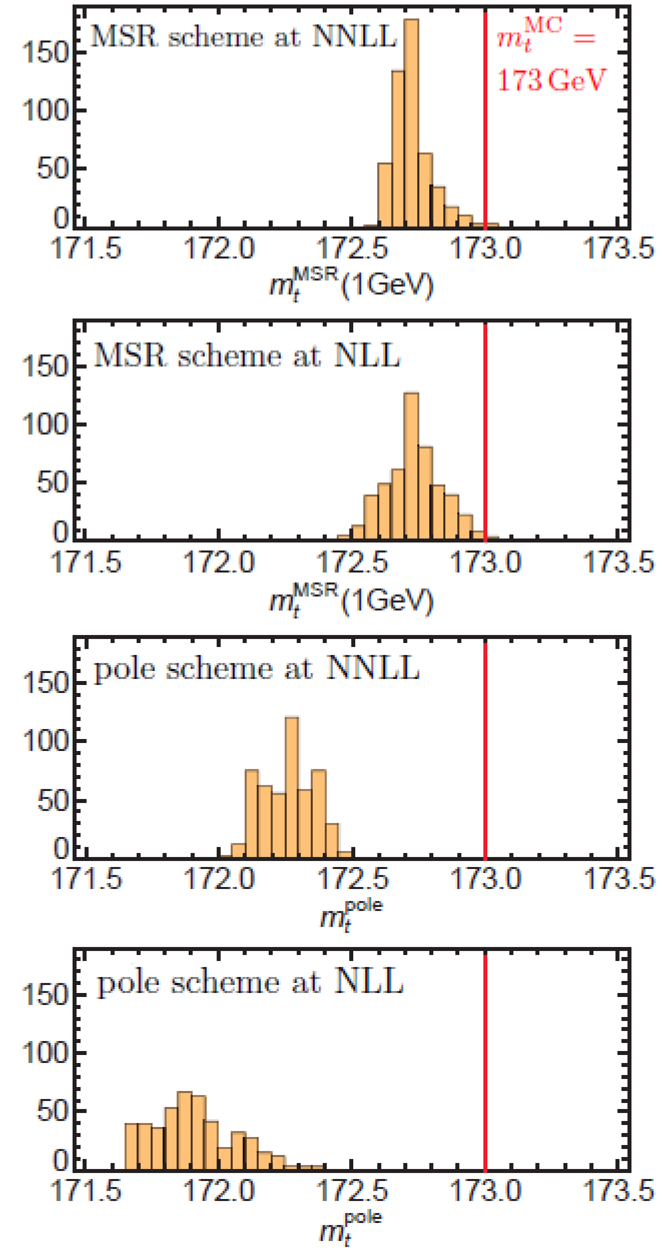
all measurements considered in the present combination, the analyses are calibrated to the Monte Carlo (MC) top-quark mass definition. It is expected that the difference between the MC mass definition and the formal pole mass of the top quark is up to the order of 1 GeV (see Refs. [19, 20] and references therein).

to jet calibration and modelling of the $t\bar{t}$ events. Given the current experimental uncertainty on m_{top}, clarifying the relation between the top quark mass implemented in the MC and the formal top quark pole mass demands further theoretical investigations. The dependence of the result on the correlation assumptions between mea-

Note: it's likely that that 1 GeV uncertainty is at least partially accounted for in current modelling uncertainty



Top quark mass - interpretation



Calibration to field-theoretical mass

(A. Hoang, I. Stewart et al., arXiv:1608.01318)

Compare Pythia and NNLL calculation for thrust distribution in $e^+e^- \rightarrow t\bar{t}$

Generate MC curve, fit it with NNLL curve for different mass schemes and values

Pole mass shows signficant shift

MSR scheme closer and more stable

For calibration: need to show the relation is universal and holds in pp collisions

Top quark mass

Extraction from cross section

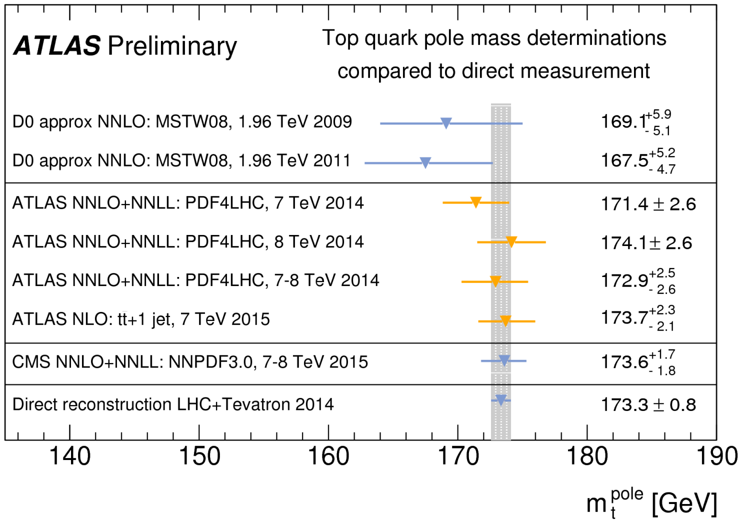
Well-defined mass scheme (pole mass, $\overline{\text{MS}}$ mass)

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

ATLAS and CMS ~2 GeV uncertainty

Recent D0 result (arXiv:1605.06168):

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



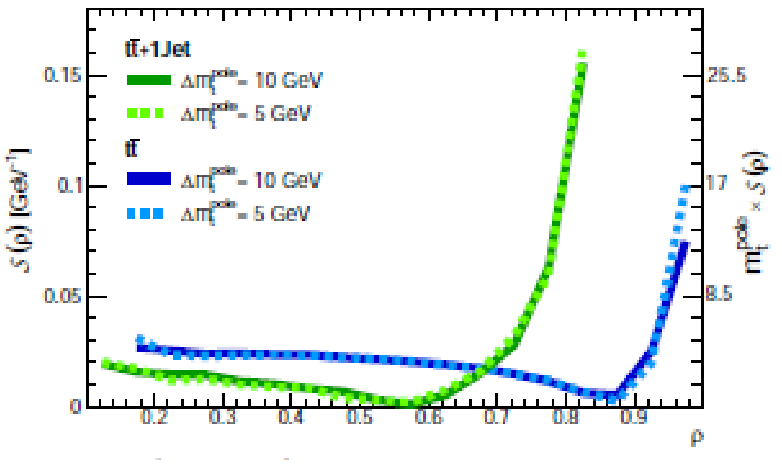
Consider the $t\bar{t}g$ cross-section

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

ATLAS, arXiv:1507.01769

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

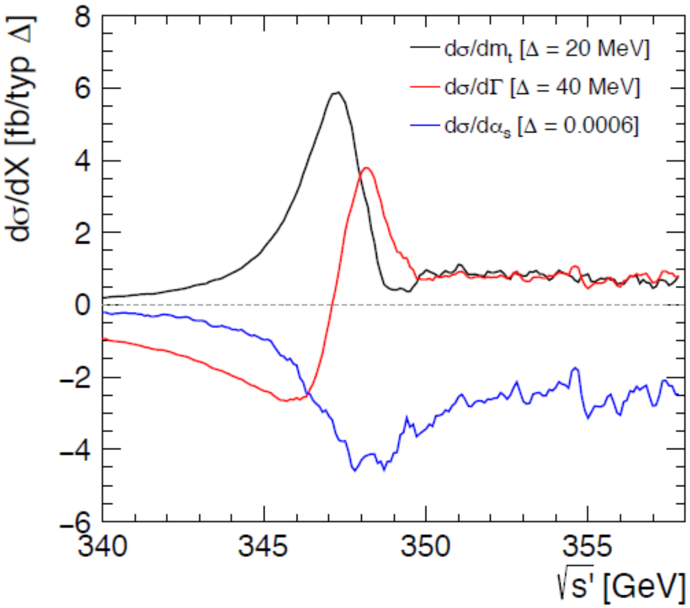
Can achieve 1 GeV precision with existing data and thec

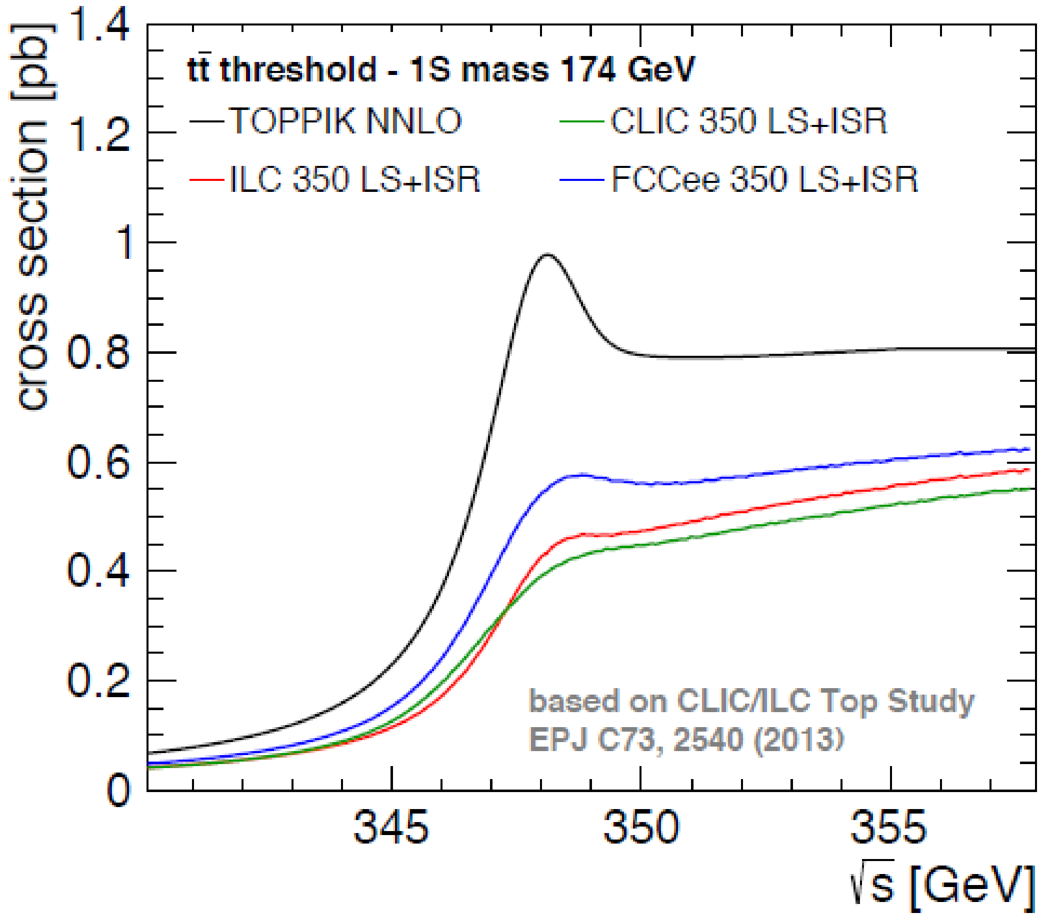


Top quark mass from e+e- threshold scan

Threshold shape reveals the top quark mass

Kuhn, Acta Phys.Polon. B12 (1981)





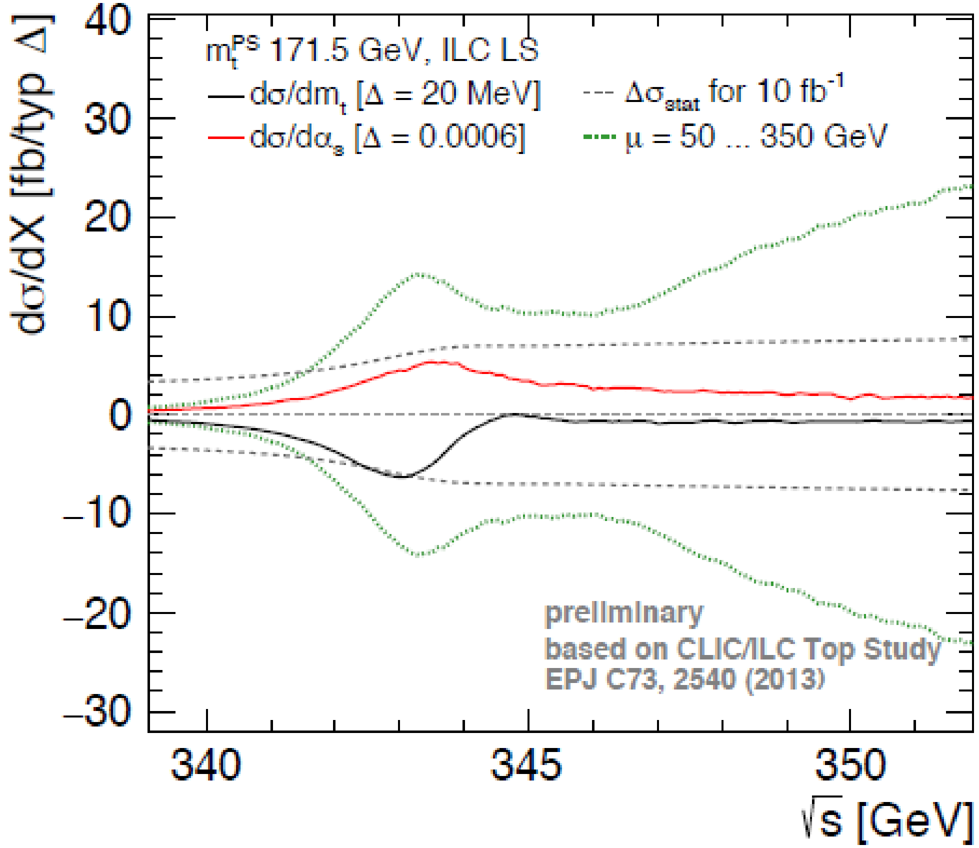
Line shape also depends on width, Normalization sensitive to α_s and y_t

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

Stat. precision 1S/PS mass:
~20 MeV
(assuming 10 x 10/fb)
Martinez, Miquel, EPJ C27, 49 (2003)
Seidel, Simon, Tesar, Poss, EPJ C73 (2013)
Horiguchi et al., arXiv:1310.0563

Experimental systematics:
O(30 MeV)

Theory uncertainty:
50 MeV
(shape fit + 1S → $\overline{MS}$ conversion)
Beneke et al., 1506.06864 [hep-ph]
F. Simon, arXiv:1603.04764, arXiv:1611.03399
P. Marquard et al., arXiv:1502.01030, PRL114 (2015)



arXiv:1604.08122

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 mass from cross-section

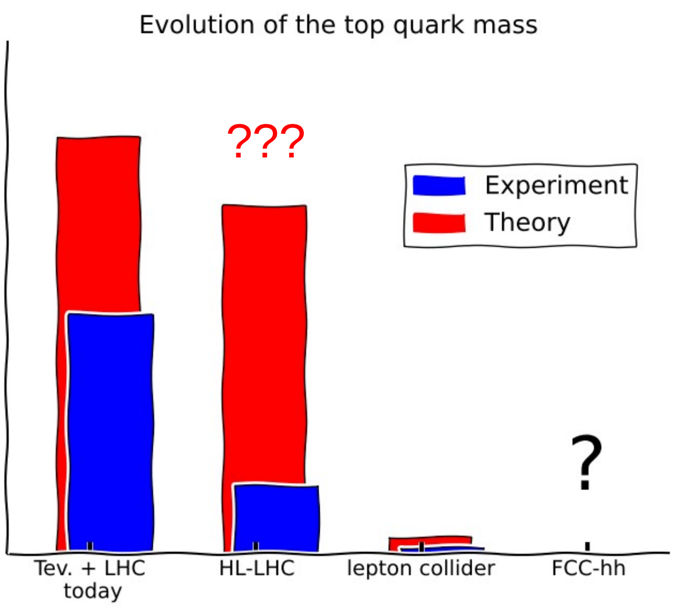
– *Today: δm_t ~ 2 GeV*
– *Rigorous interpretation*
– *Can reach ~1 GeV precision*

Future lepton collider

– *threshold scan*
– *50 MeV precision!*

Future 100 TeV pp collider:

– *?*



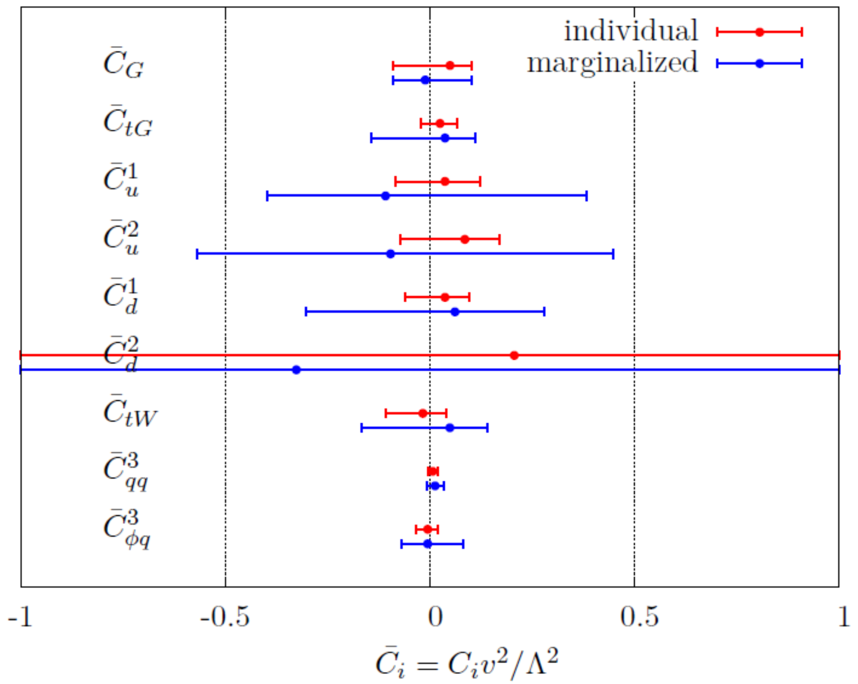
Top and BSM physiscs

Comparative study of the BSM discovery potential of precision measurements

A framework to compare projects?

Simultaneous fit to ~ all data
TopFitter collaboration – U. Glasgow
arXiv:1506.08845, arXiv:1512.03360

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



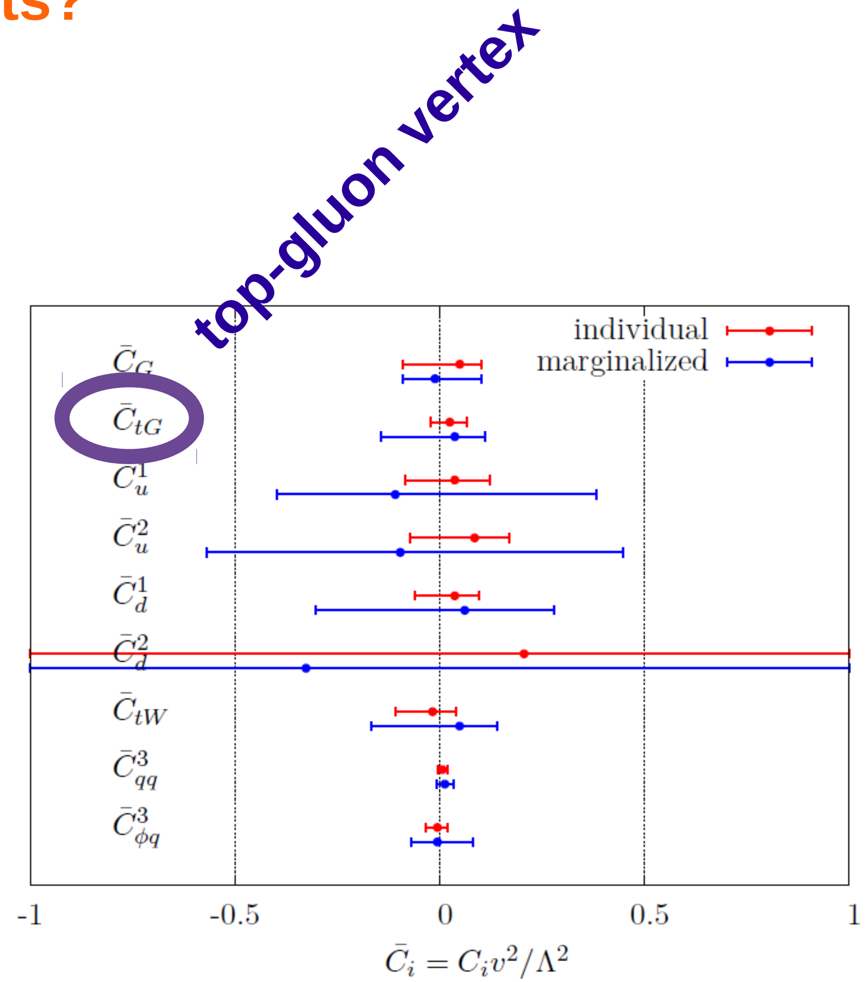
EFT analyses to keep the score (i.e. quantify potential and study complementarity)

Machinery for automated NLO treatment appearing in MG5 (Durieux, Maltoni, Vryonidou, Zhang)

A framework to compare projects?

Simultaneous fit to ~ all data
arXiv:1506.08845, arXiv:1512.03360

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



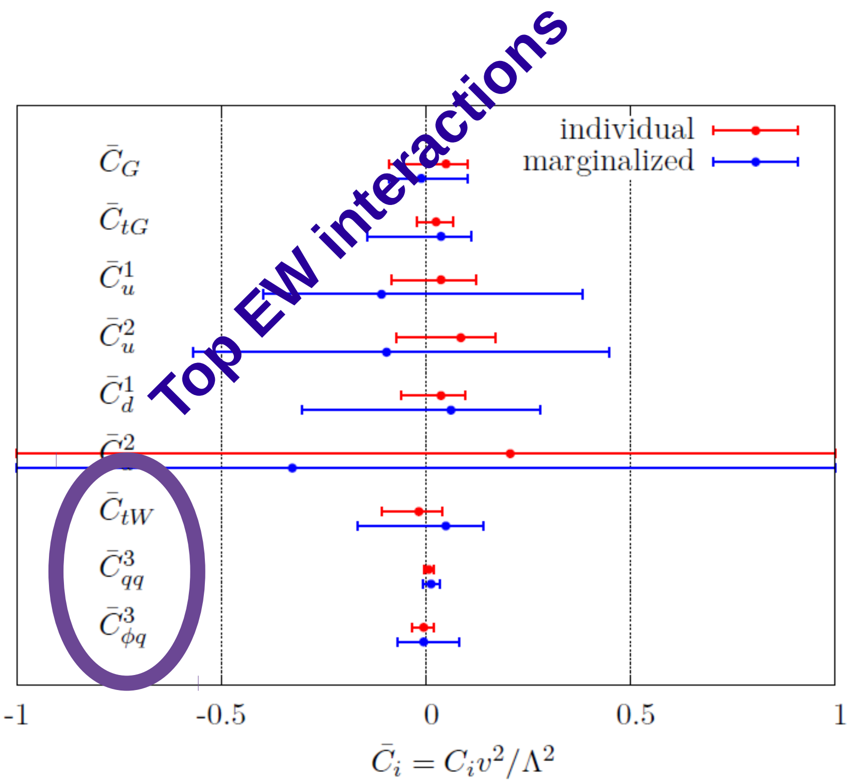
Composite top – non-zero chromo-magnetic and chromo-electric moments

A framework to compare projects?

Simultaneous fit to ~ all data

arXiv:1506.08845, arXiv:1512.03360

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



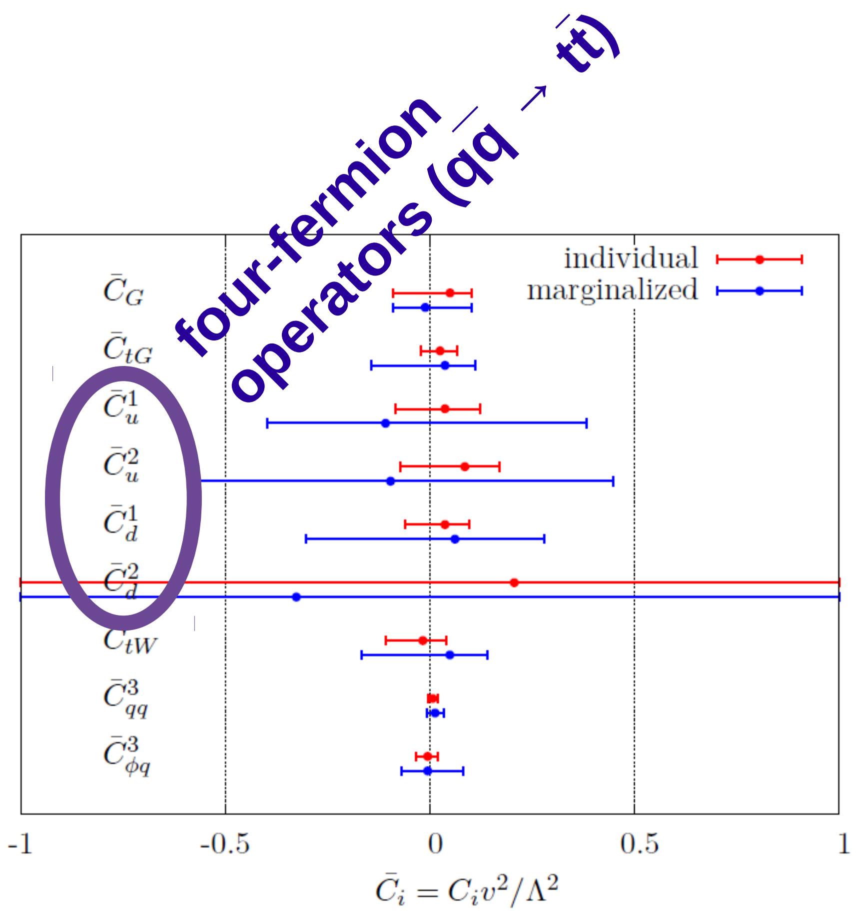
RS and composite Higgs models

A framework to compare projects?

Simultaneous fit to ~ all data
arXiv:1506.08845, arXiv:1512.03360

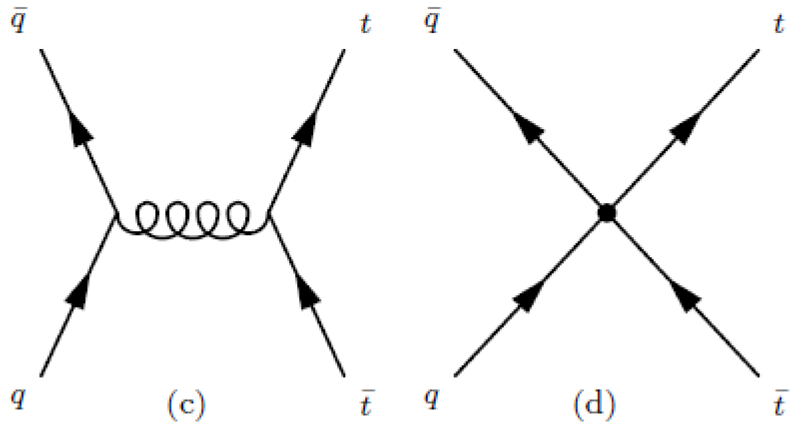
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

Massive mediator (heavy gluon)



marcel.vos@ific.uv.es

Example: comparison of the Tevatron-LHC potential

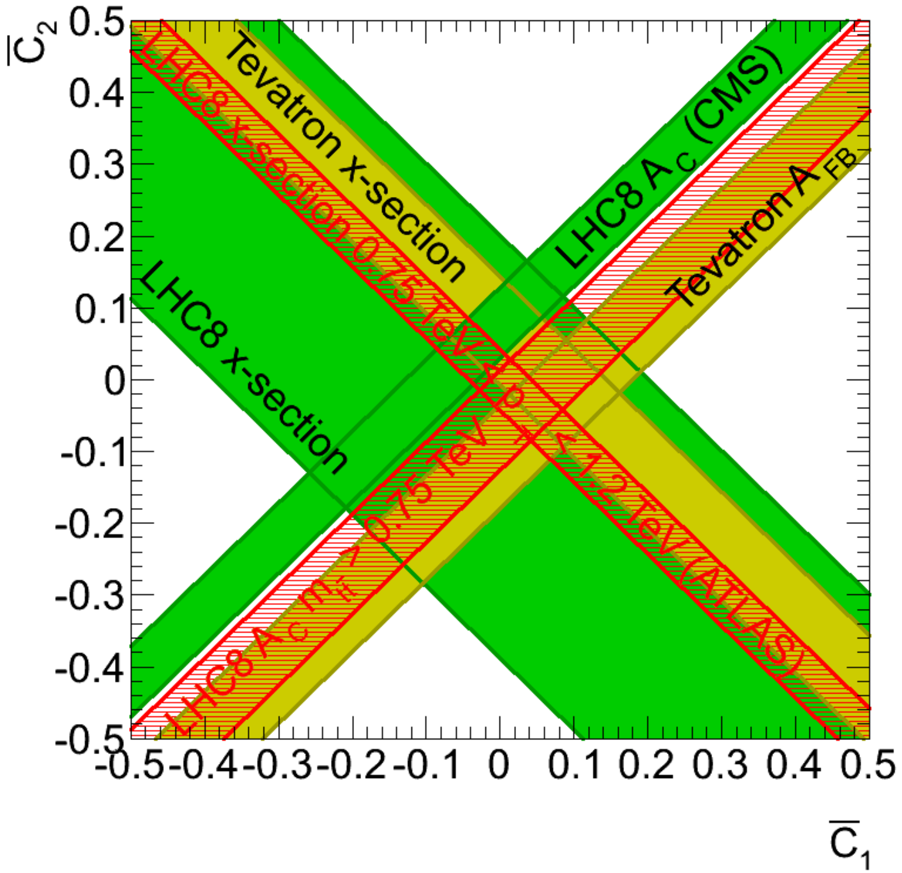


Heavy gluon exchange represented by dimension-6 four-fermion operators

Cross-section and A_C provide complementary constraints

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

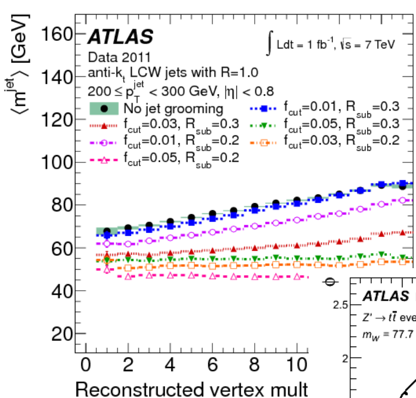
M. Perelló, M. Vos, arXiv:1512.07542

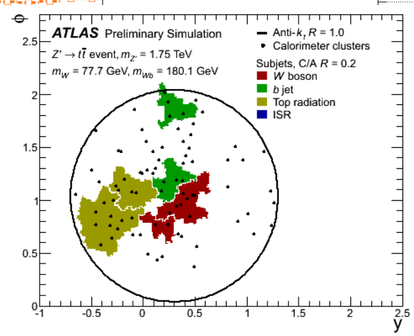


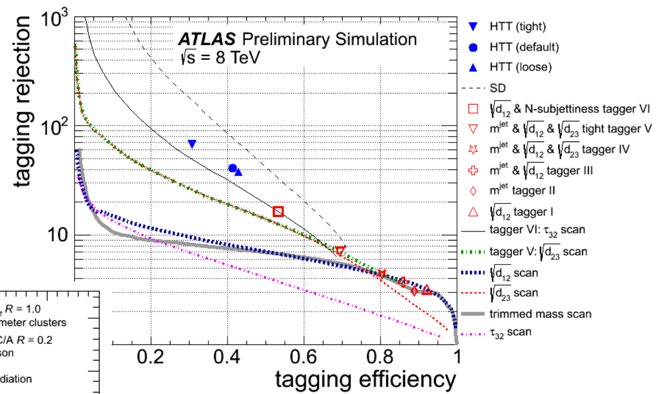
Top and QCD

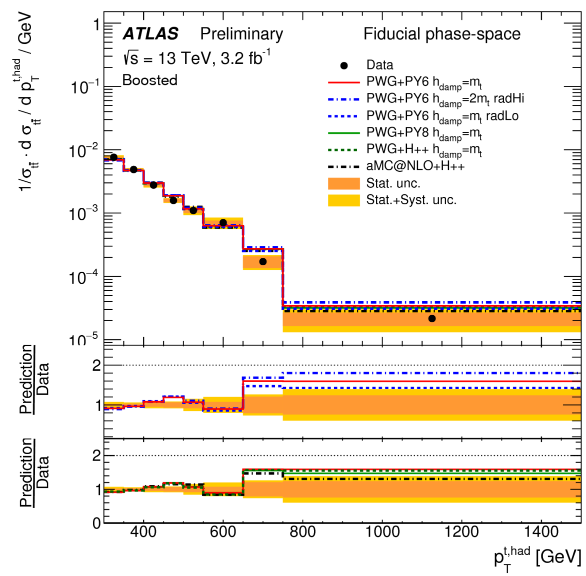
Boosted top quarks

Birth of the boosted object, Seymour, Z. Phys C62 (1994) 127-138
Renewed interest, Butterworth et al., PRL 100 (2008) 242001
First top-tagging paper, PRL 101 (2008) 142001
First BOOST conference (SLAC)
ATLAS boosted top reconstruction developed in ATL-PHYS-PUB-2010-008
First ATLAS jet substructure measurement: JHEP 1205 (2012) 128
First boosted top quarks in an ATLAS search: JHEP 1209 (2012) 041
ATLAS Jet substructure performance paper: JHEP 1309 (2013) 076
2014/15: Boosted objects in many searches
2015/16: Standard Model measurements on boosted top quarks!

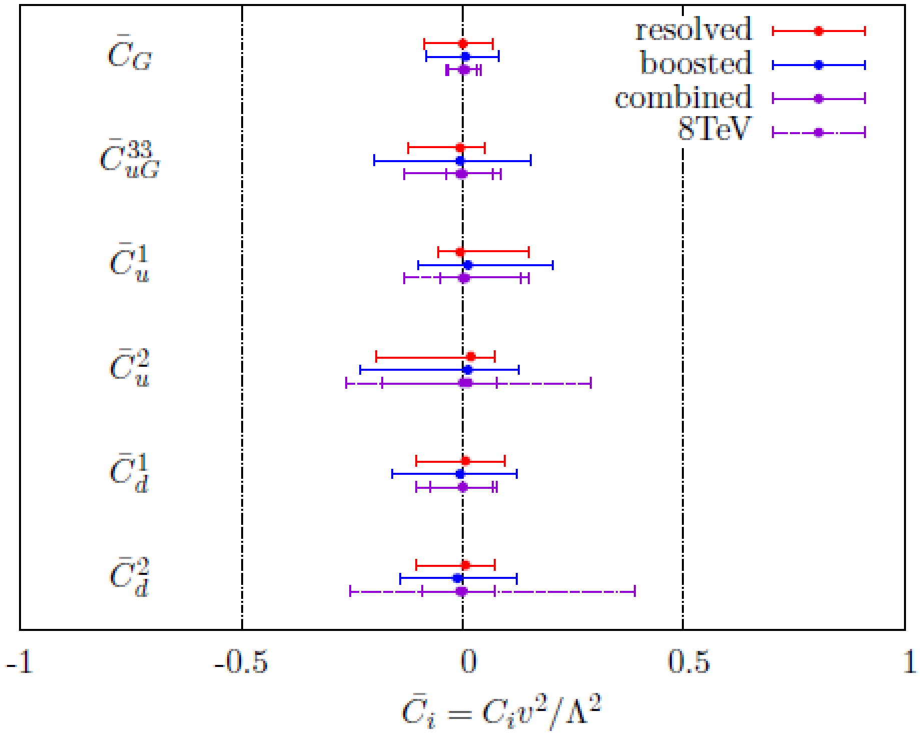




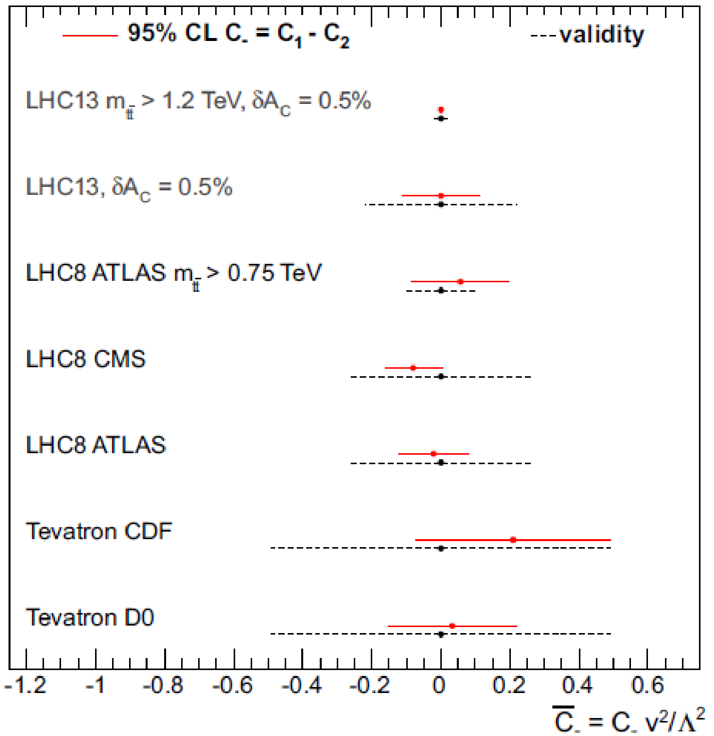




Top and QCD



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



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

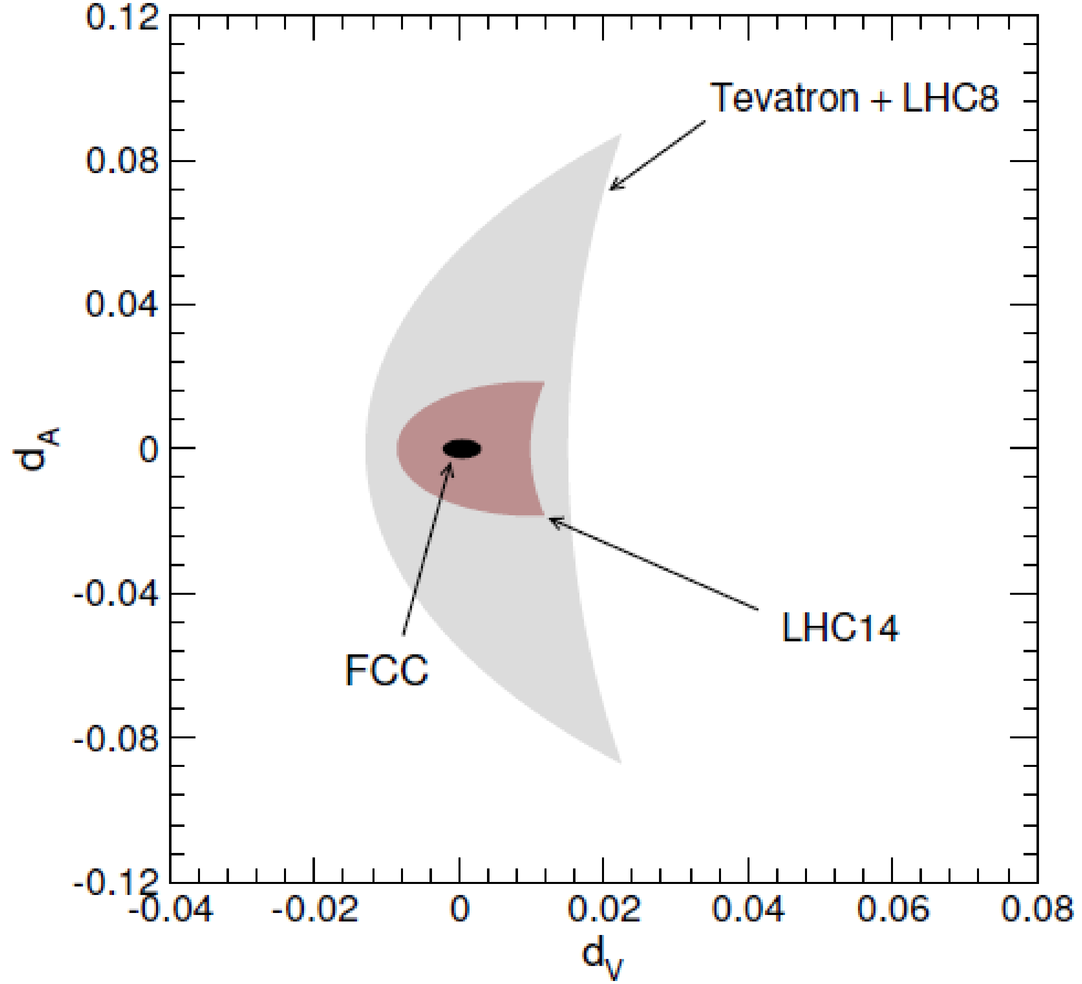
Top and QCD

Aguilar-Saavedra et al., arXiv:1412.6654

Top quark chromomagnetic and chromoelectric dipole moments

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

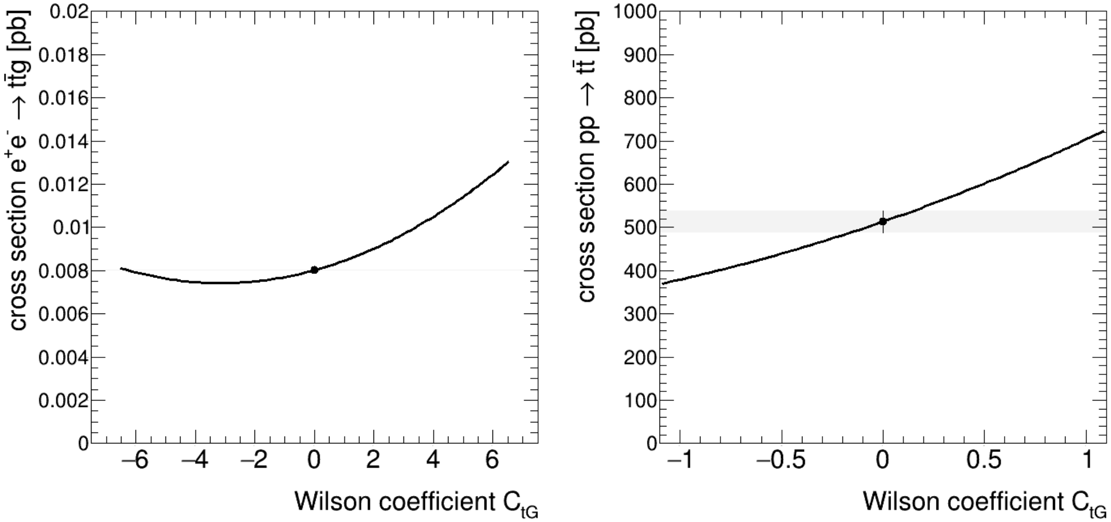
Ultra-boosted: $m(t\bar{t}) > 10$ TeV
Top decay to bμν
Assume 5% systematic



Order of magnitude improvement

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

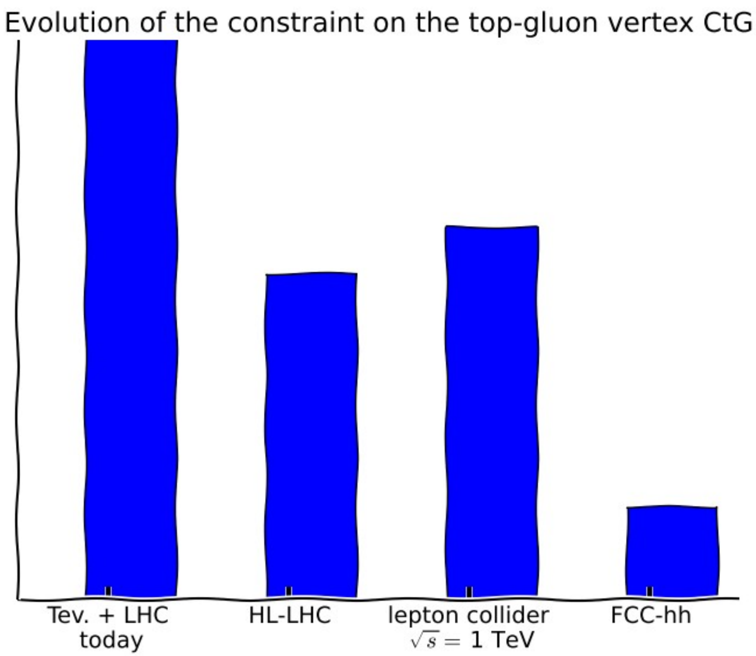
Top-gluon couplings at lepton colliders



$e^+e^- \to$ 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



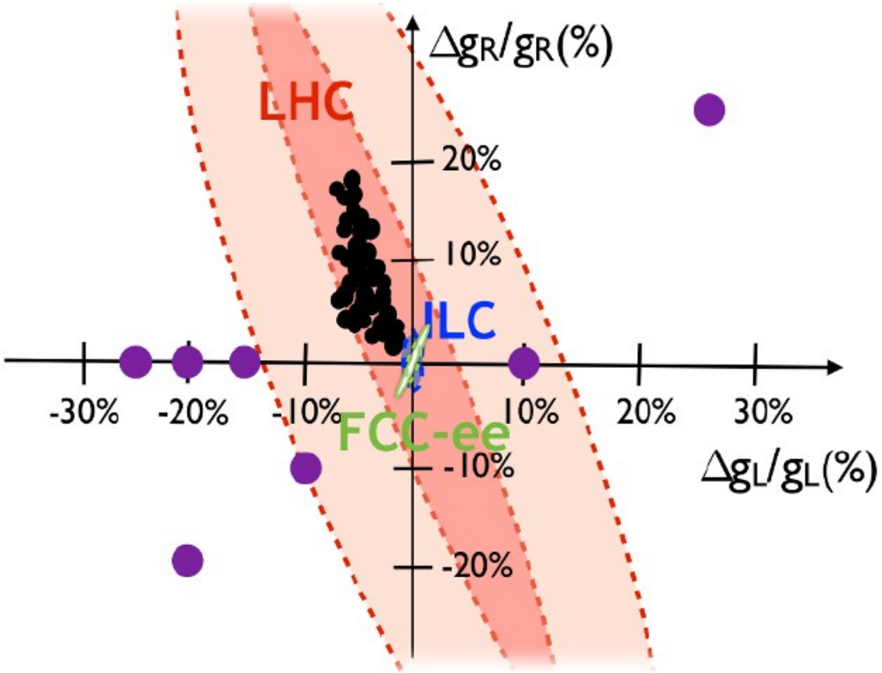
Top EW couplings

Top EW couplings

Certain classes 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 $\Lambda \sim 1$ TeV

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



5D models by several authors
Richard, arXiv:1403.2893

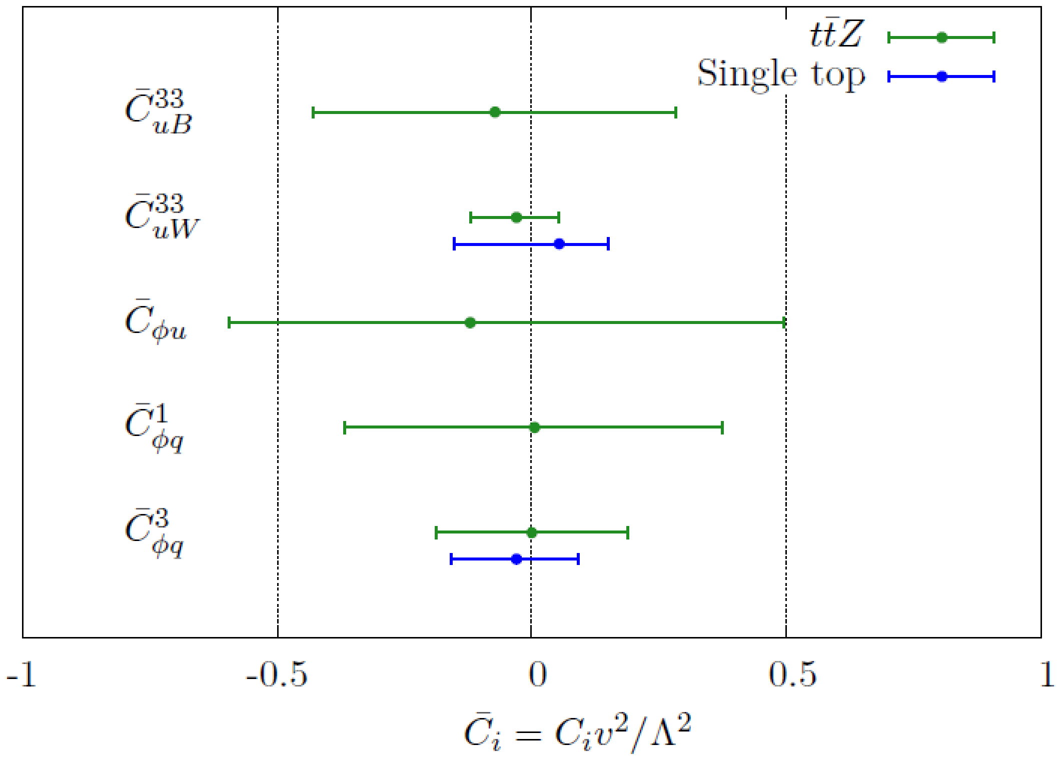
4D Composite Higgs Model
Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)

Top EW couplings: LHC status

Simultaneous fit to Tevatron and LHC data

arXiv:1506.08845, arXiv:1512.03360

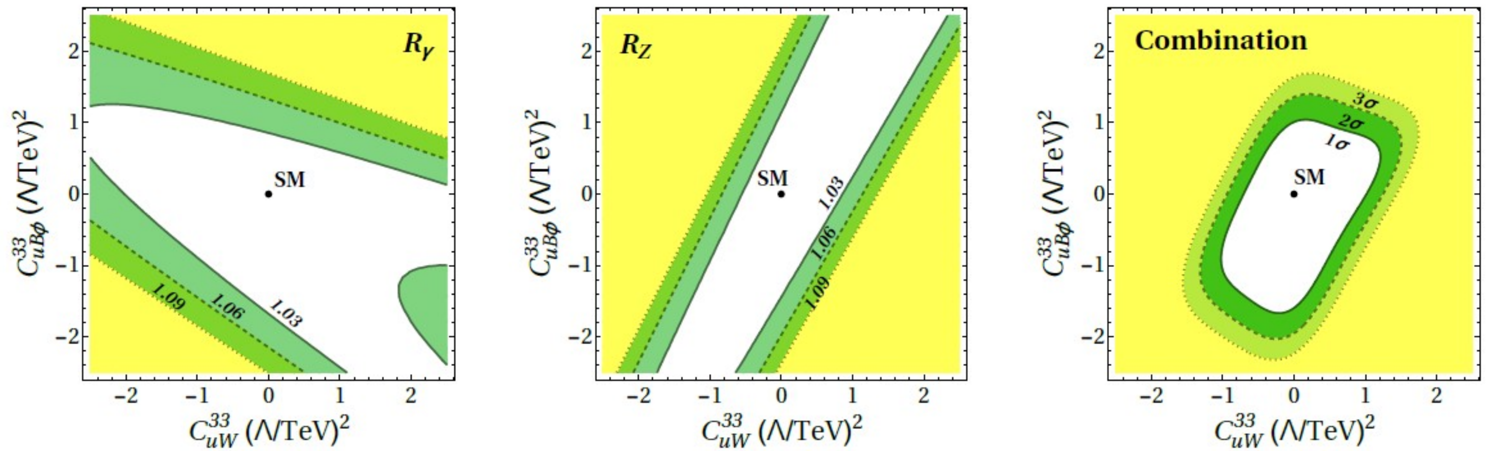
Single top production, ttZ



$t\bar{t}Z$ associated production

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

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



Differential cross section to boost sensitivity: *pT(Z)*
Baur, Juste, Orr, Rainwater, 2004, Rontsch, Schulze, 2014/2015

C_{2V} = weak magnetic dipole moment = $\sqrt{(2)}[\frac{v^2}{\Lambda^2}]\Re(c_W C^{33}_{uW} - s_W C^{33}_{uB\varphi})$

C_{2A} = (CP violating) weak electric dipole moment = $\sqrt{(2)}[\frac{v^2}{\Lambda^2}]\Im(c_W C^{33}_{uW} - s_W C^{33}_{uB\varphi})$

FCChh has the potential to boost the constraints on EW dipole moments

arXiv:1607.01831

	$C_{1,V}$	$C_{1,A}$	$C_{2,V}$	$C_{2,A}$
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]

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:

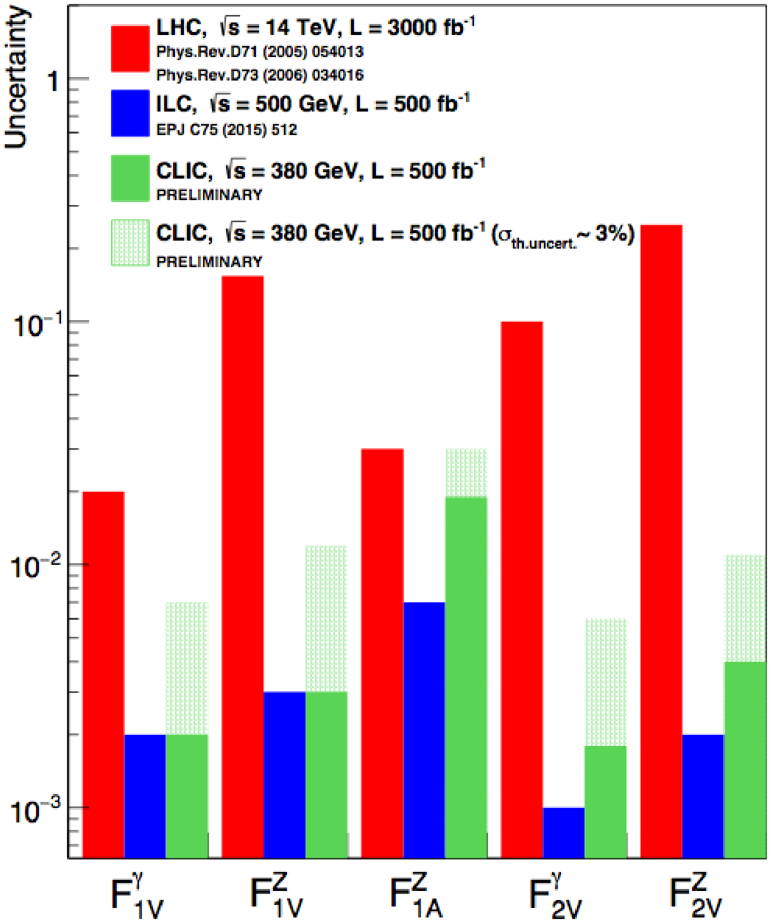
$$\begin{matrix}\sigma(+) & A_{FB}(+) \\ \sigma(-) & A_{FB}(-)\end{matrix} \qquad \left.\begin{matrix}(+=e^-_R) \\ (-=e^-_L)\end{matrix}\right\} \Rightarrow \left\{\begin{matrix}F_{1V}^\gamma & * & F_{2V}^\gamma \\ F_{1V}^Z & F_{1A}^Z & F_{2V}^Z\end{matrix}\right\}$$

Measure **Extract**

380 GeV collider has similar sensitivity

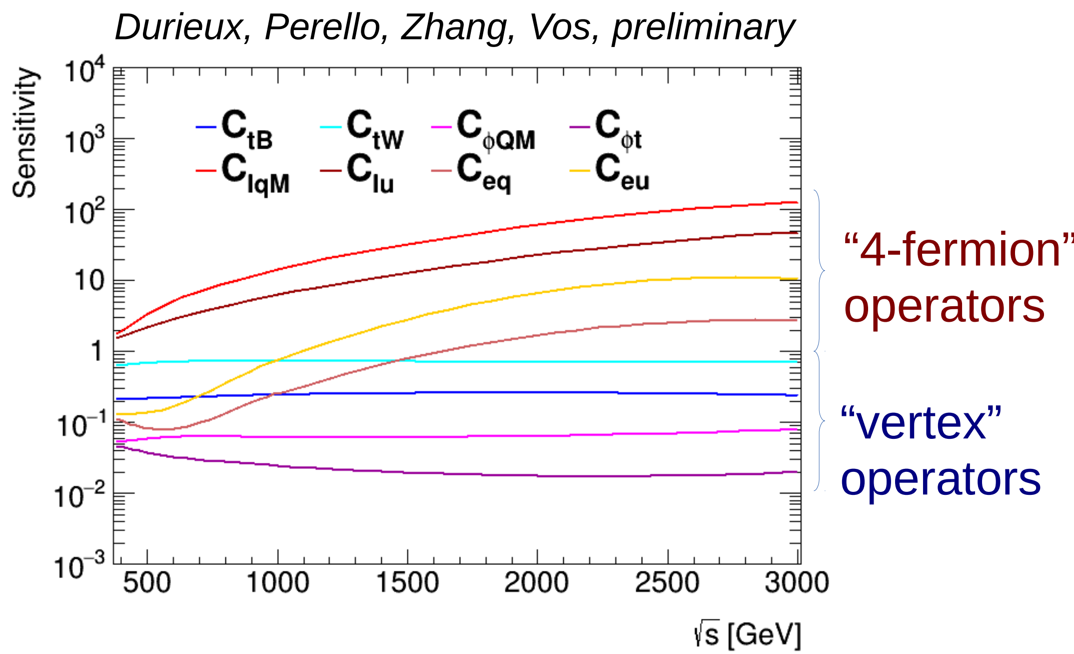
Caveat: theory unc. Exception: Z-F_{1A}

FCC-ee, Janot et al., arXiv:1503.01325, 1509.09056
ILC ME method, arXiv:1503.04247
Study of CP violating form factors coming soon!



Towards a complete comparison

Sensitivity to four-fermion operators grows strongly at high energy → CLIC 3 TeV operation provides tightest constraint

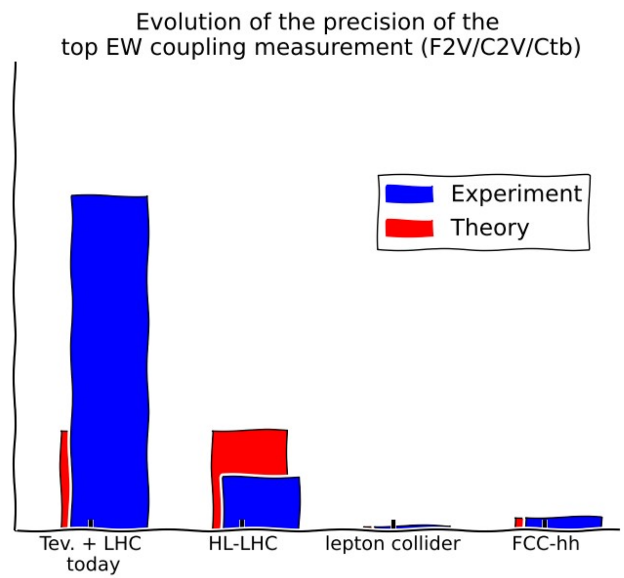


Comparison to current LHC result (TopFitter)

ILC/CLIC full-simultion result (M.V., IFIC/LAL)

Updated LHC (HighLumi) prospects (Rontsch & Schulze)

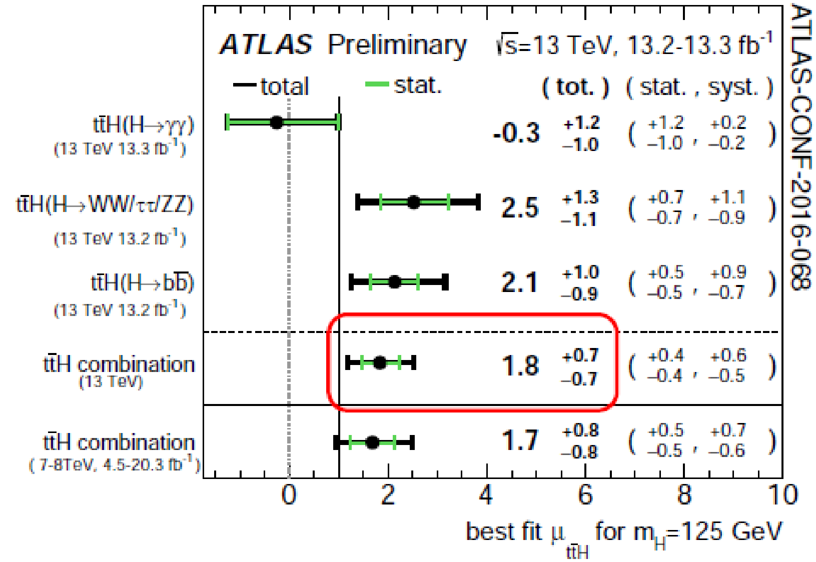
FCChh prospects (Schulze et al., Aparisi)

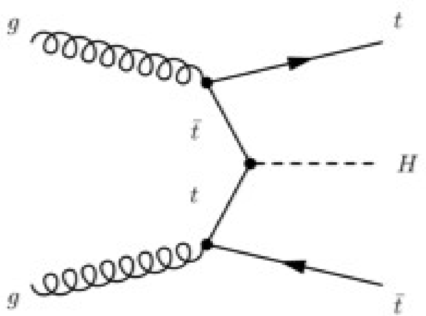


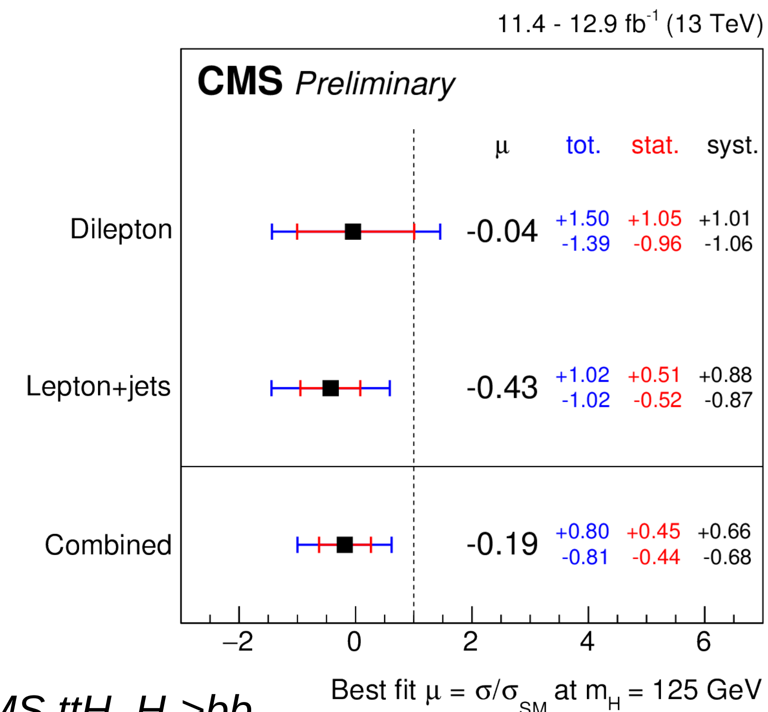
Top and Higgs

Top quark Yukawa coupling

The golden couple of the SM ttH searches in all main Higgs decay modes at 7,8,13 TeV







Prospects for full LHC programme:

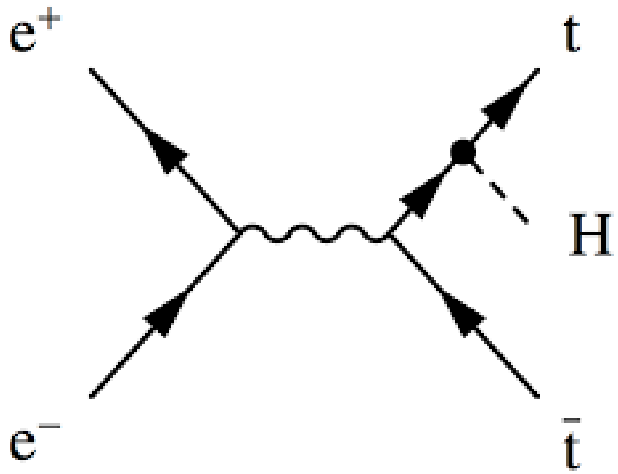
K_u → 14-15% (300/fb)

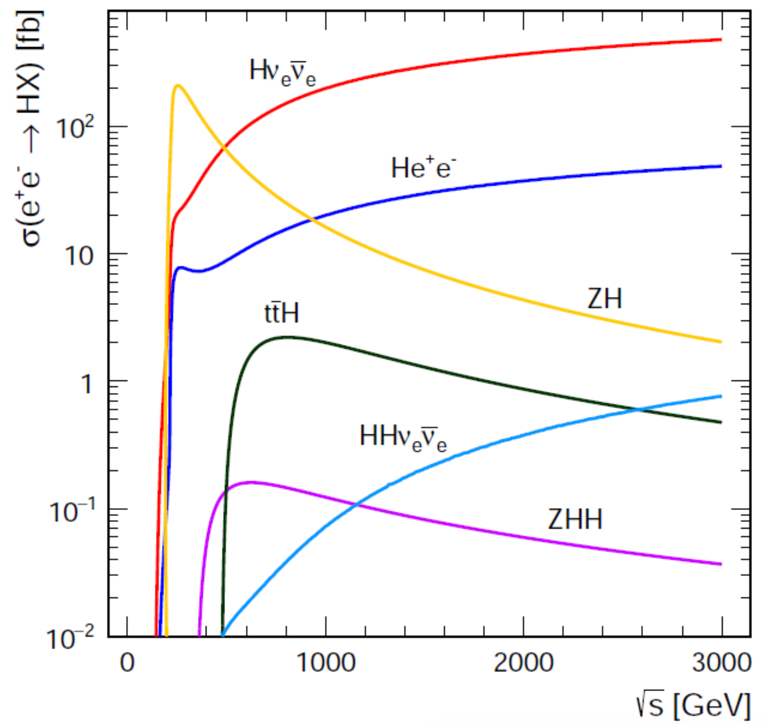
K_u → 7-10% (3000/fb)

Snowmass Higgs report

CMS ttH, H->bb
CMS-PAS-2016-038

Top quark Yukawa coupling at lepton colliders





1608.07538

Bound-state effects strongly enhance cross section at threshold

→ rate at 550 GeV is three times larger than at 500 GeV

→ broad maximum around 800GeV

Top quark Yukawa coupling at lepton colliders

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

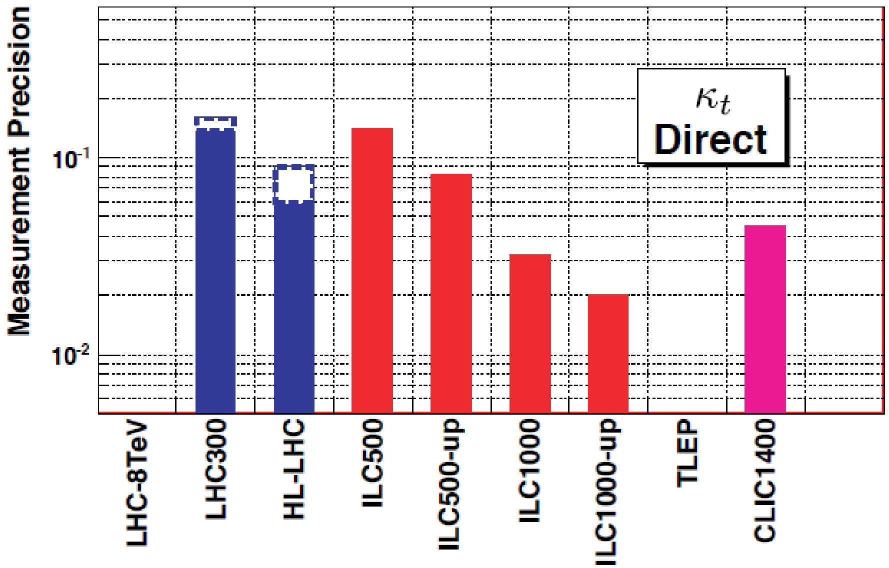
ArXiv:1506.05992

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

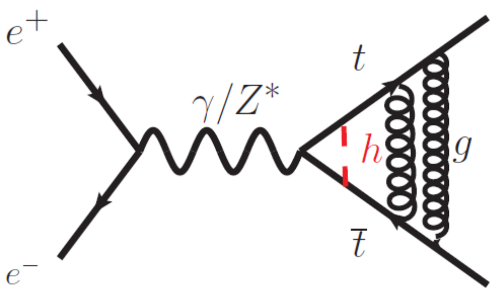
ArXiv:1409.7157

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

ArXiv:1608.07538



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



Horiguchi et al., arXiv:1310.0563

Top quark Yukawa coupling at hadron colliders

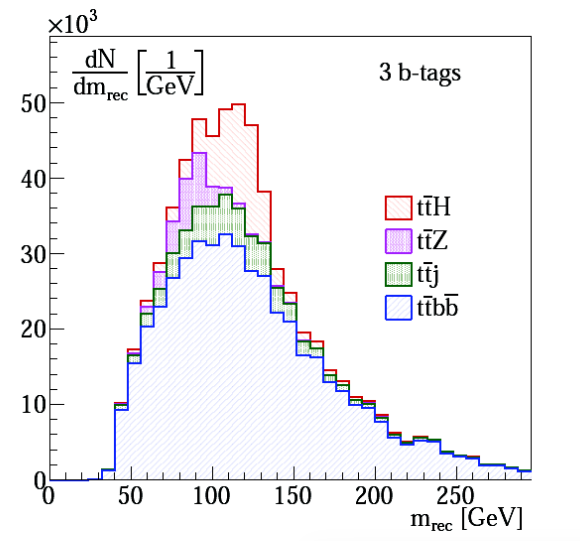
Deal with theory cross section by using a wisely chosen ratio:

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

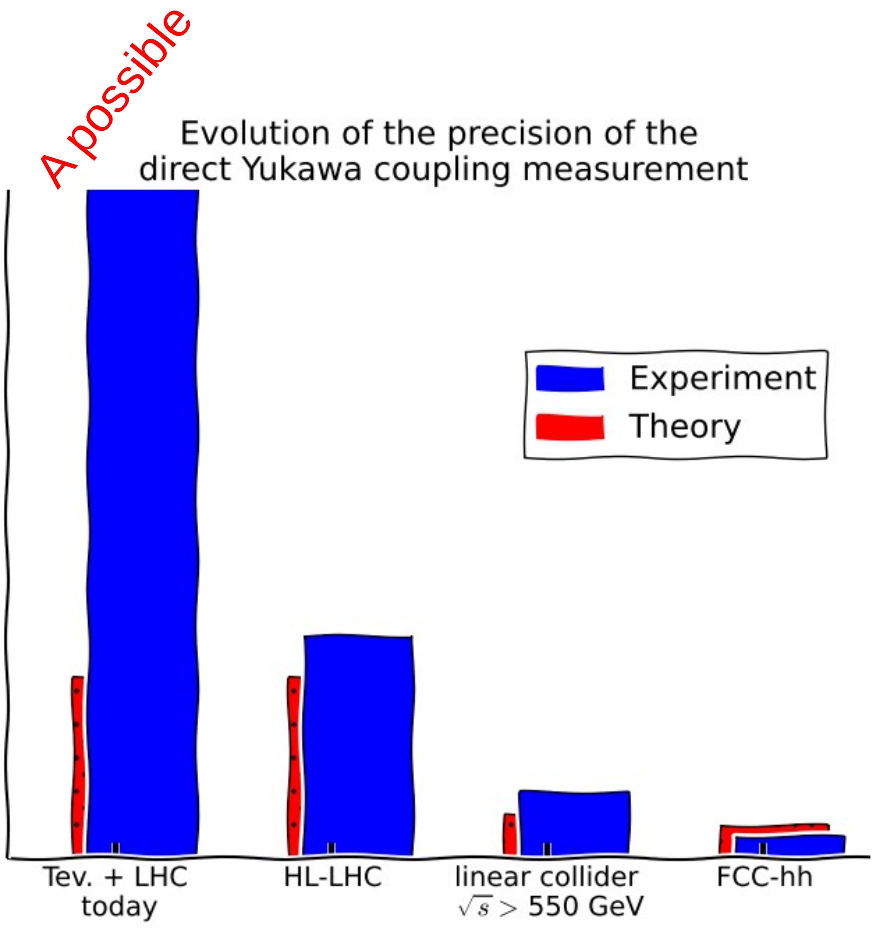
High rate allows to focus on events where H → bb and hadronic top decay are sufficiently boosted to reconstruct them as "fat" jets

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

FCChh: achieve 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

The future of top physics: highlights

Top physics at the LHC is in full swing. 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 mil level

100 TeV hadron collider targets:

Greatly enhanced mass reach → very tight constraint on top QCD interactions
Top Yukawa coupling to 1%

Challenges: control of 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

Bibliography

Report from Top@LC15 workshop at IFIC Valencia

An up-to-date, consensuated summary
with an extensive bibliograpy

arXiv:1604.08122

27 Apr 2016

Top physics at high-energy lepton colliders

Summary of TopLC15, IFIC Valencia, 30^{th} June - 2^{nd} 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)

+ agenda of TopLC16 at KEK!
https://agenda.linearcollider.org/event/7020/

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):

http://arxiv.org/abs/arXiv:0805.1333

Experimentalist review of the first years

Int. J. Mod. Phys. A27 (2012) 1230016

ArXiv:1606.00327

Top quark mass: how can we make further progress?

Determination of the top quark mass circa 2013: methods, subtleties, perspective,

arXiv:1310.0799

A new observable to measure the top quark mass at hadron colliders,

EPJC 73 (2013) 2438

ATLAS top quark pole mass measurement

JHEP 1510 (2015) 121

Boosted top quark production: a new window

Boosted objects: a probe of new physics,

EPJC71 (2011) 1661

Boosted top quarks and jet structure,

EPJ C75 (2015) 9, 415, EPJ C74 (2015) 74, 2792

ATLAS differential cross-section and AC measurements

PLB756 (2016) 52-71, PRD93 (2016) 3, 032009, EPJ C76 (2016) 4,200

Bibliography

Top quark electro-weak couplings:

Determination at the LHC (associated production)

A new observable to measure the top quark mass at hadron colliders,
EPJC 73 (2013) 2438
ATLAS top quark pole mass measurement
JHEP 1510 (2015) 121

Boosted top quark production: a new window

Boosted objects: a probe of new physics,
EPJC71 (2011) 1661
Boosted top quarks and jet structure,
EPJ C75 (2015) 9, 415, EPJ C74 (2015) 74, 2792
ATLAS differential cross-section and AC measurements
PLB756 (2016) 52-71, PRD93 (2016) 3, 032009, EPJ C76 (2016) 4,200