Understanding the top quark properties

Fabrizio Margaroli (Sapienza and INFN)
on behalf of ATLAS/CMS/CDF/D0
collaborations

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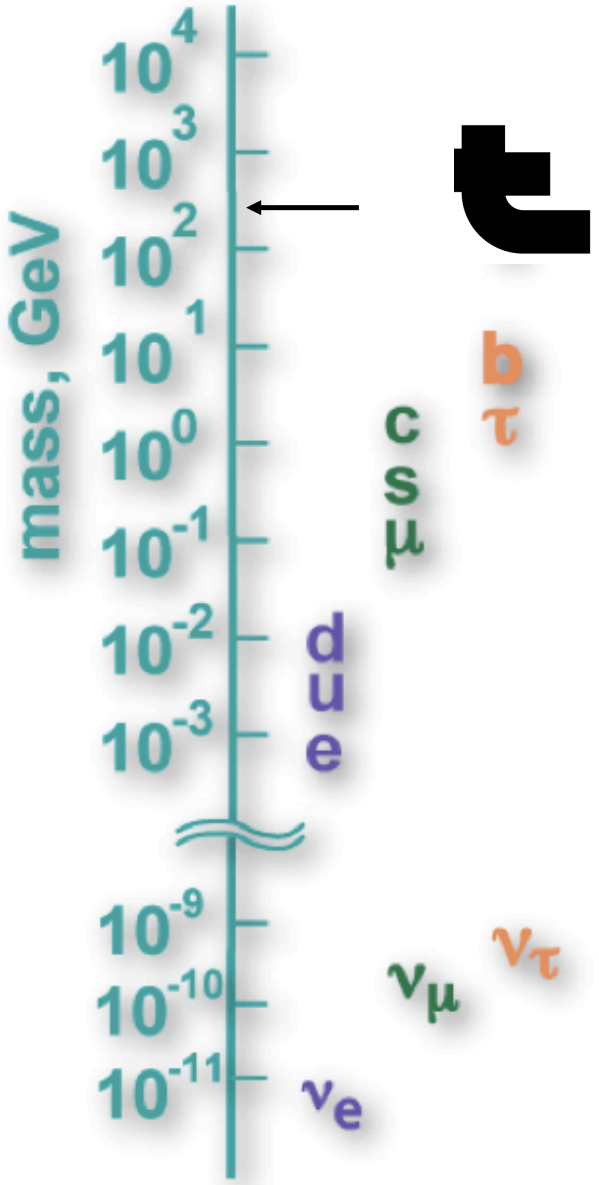
THE TOP QUARK

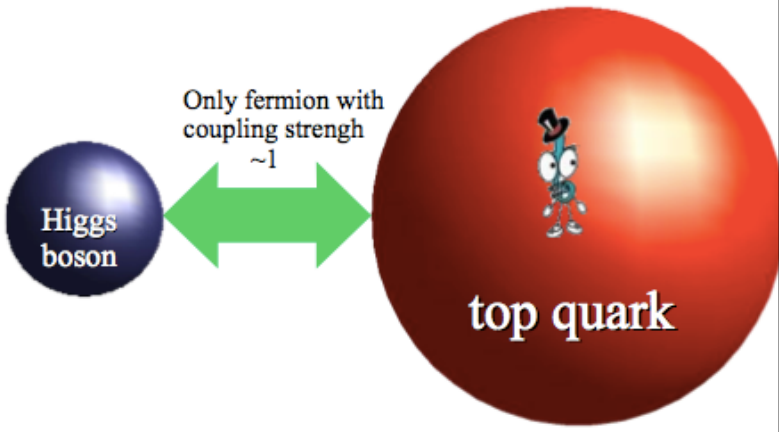
- Top quark was discovered at Fermilab in 1995
- Its mass was found to be much larger than the one of any other fermion
- In fact, so large that its lifetime (10-25s) shorter than hadronization time (10-24s) so only quark that decays before hadronizing



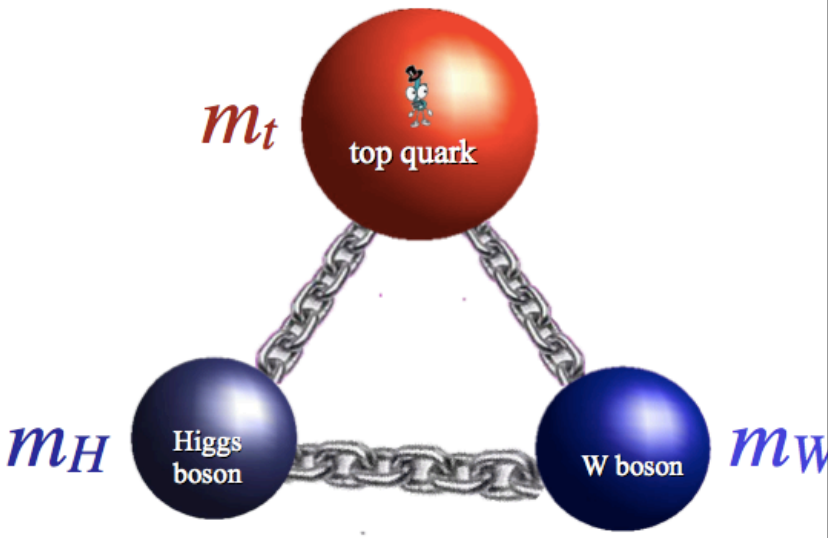
- Unique opportunity to study the properties of a "bare" quark!
- Its "heaviness" suggests a special role in the electroweak symmetry breaking mechanism

A SPECIAL RELATIONSHIP

- Higgs coupling to fermions not established yet
  - proceeds via a different lagrangian - interesting!
- Top is the only quark with large coupling to Higgs
- Our current indirect knowledge: $Y_t = \sqrt{2}M_t/vev = 0.996 \pm 0.005$ using latest Tevatron and/or LHC Mtop
  - Does $Y_t=1$ mean a special role of the top quark in EWSB?
- we know very little about flavor and top



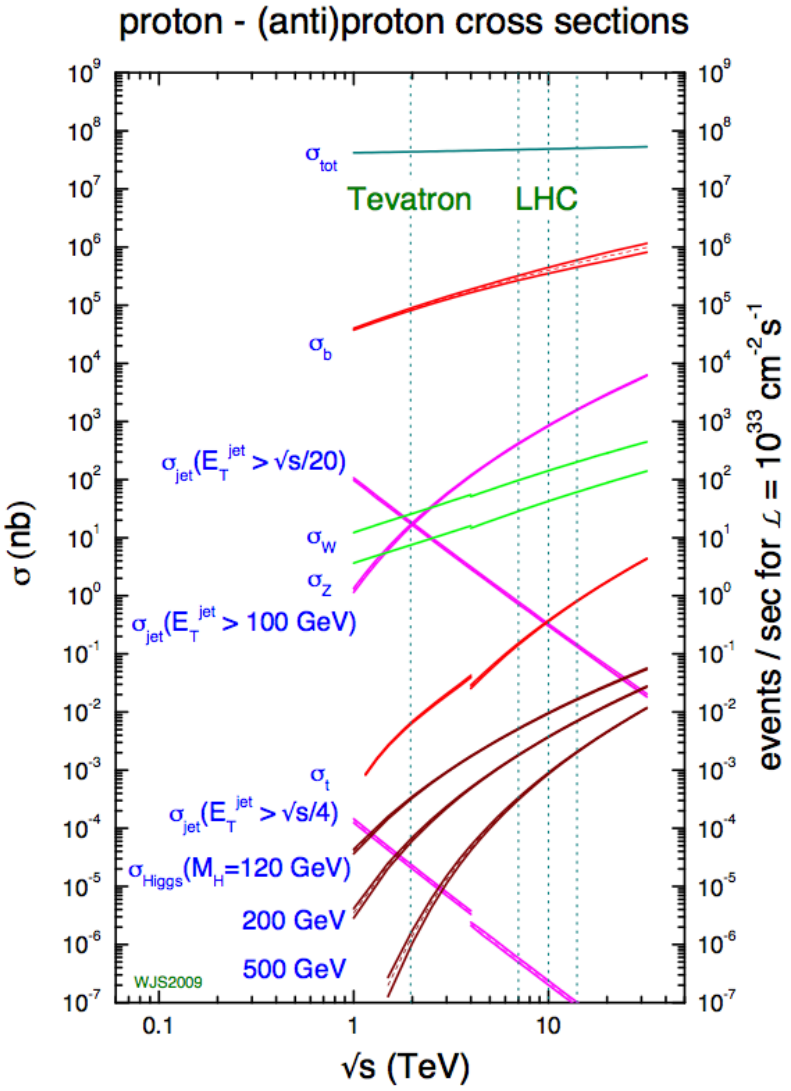
- In most natural models top is linked to EW symmetry breaking.
  - Sets indirect contraint on Higgs mass
  - Creates the hierarchy problem
  - Is involved in its solutions: SUSY (stops) composite Higgs (top partners)

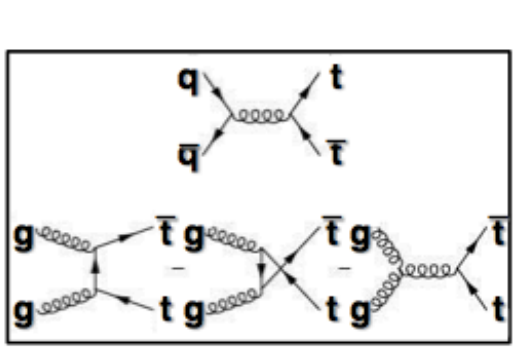


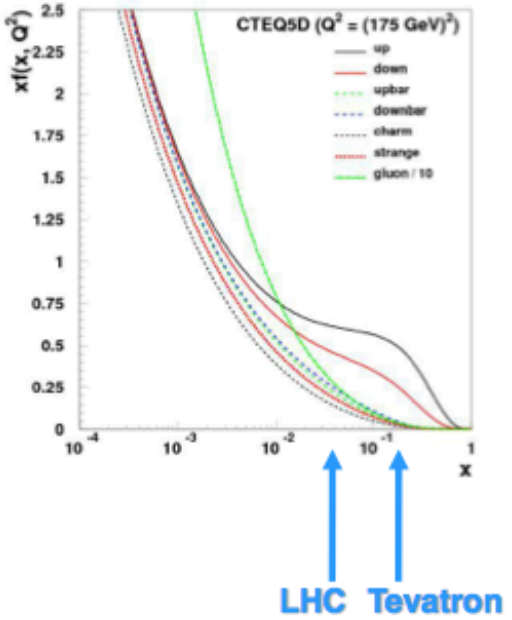
From Tevatron to LHC

~O(10^5) tops produced, at Tevatron, about 10^4 analyzed at the Tevatron

~O(10^7) tops produced at LHC (7+8TeV), yet to analyze full datasets

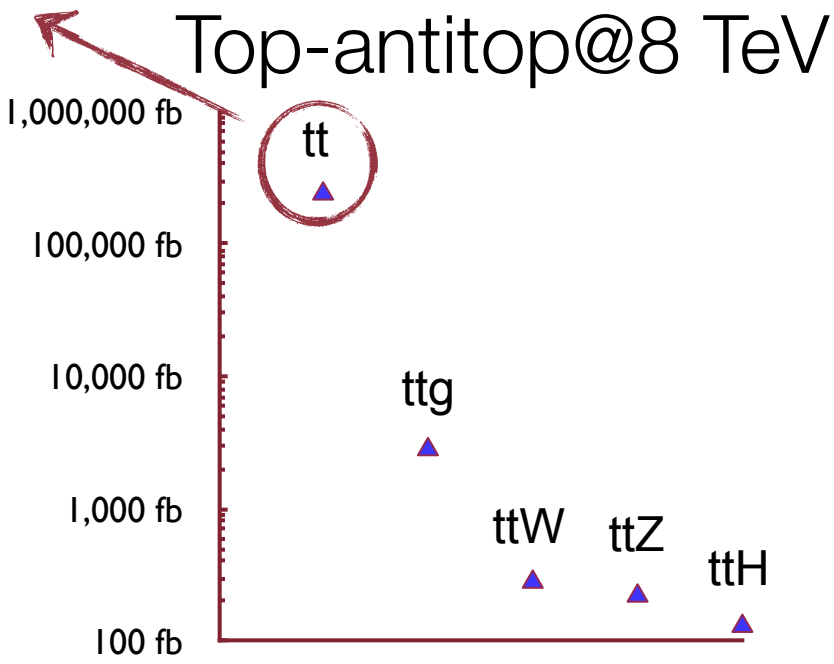






WHAT TO MEASURE

Mass, charge, width, spin correlation, alpha_s, jet shapes, forward-backward asymmetry, FCNC, B violation, CPT violation



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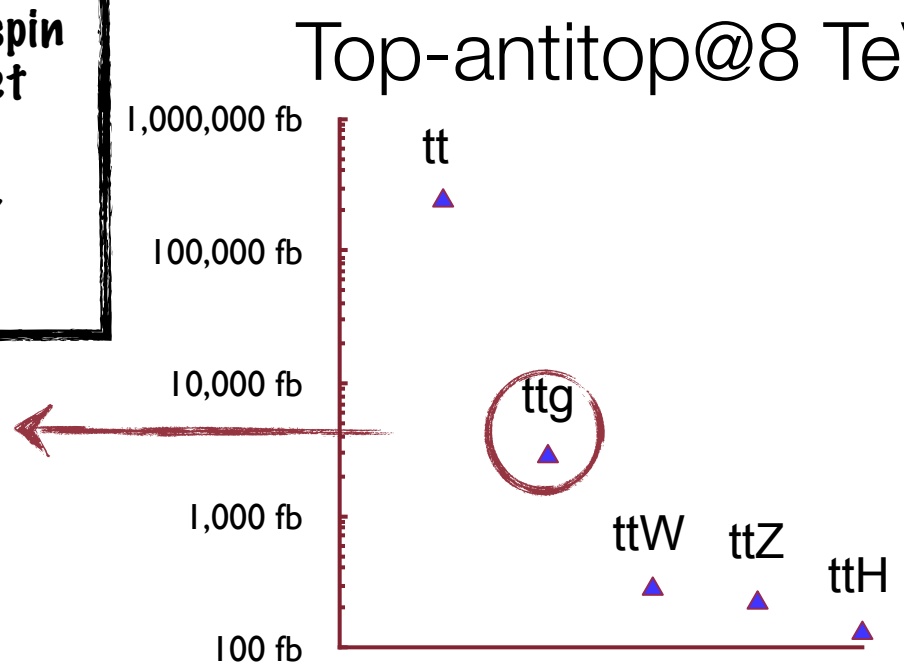
Charge, background to ttH



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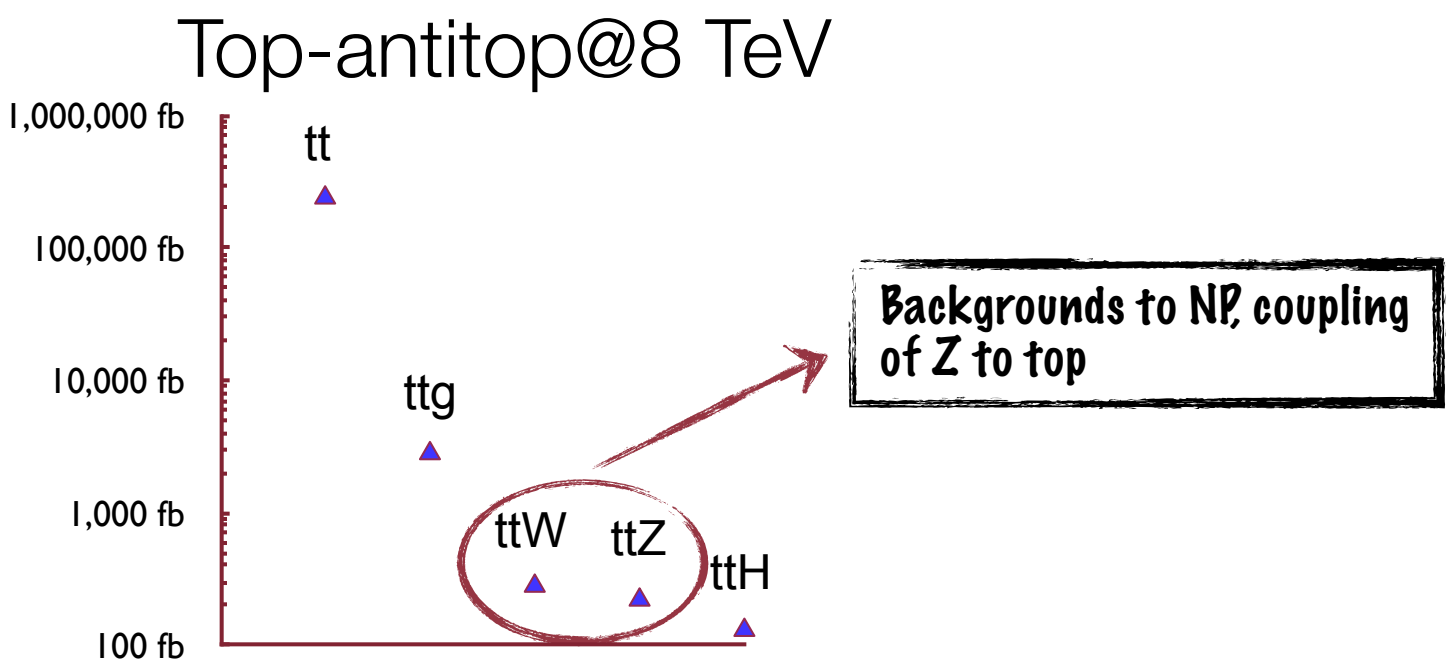

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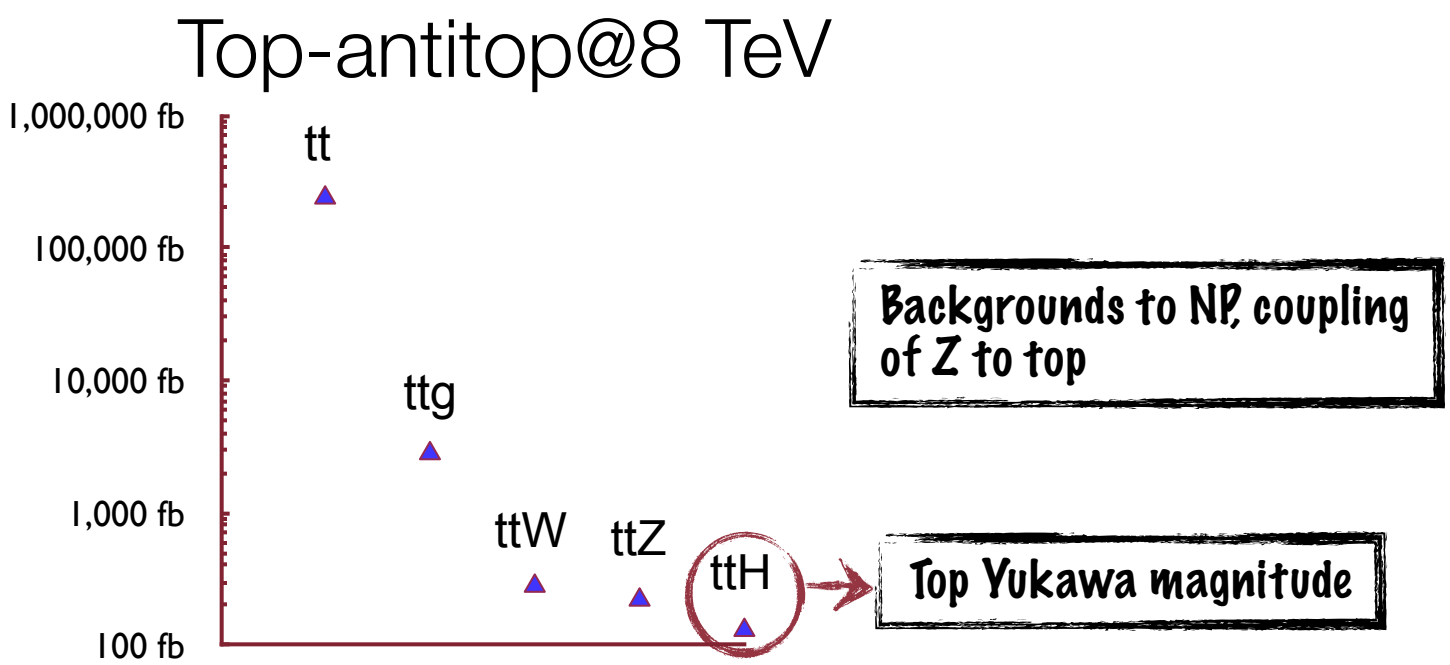


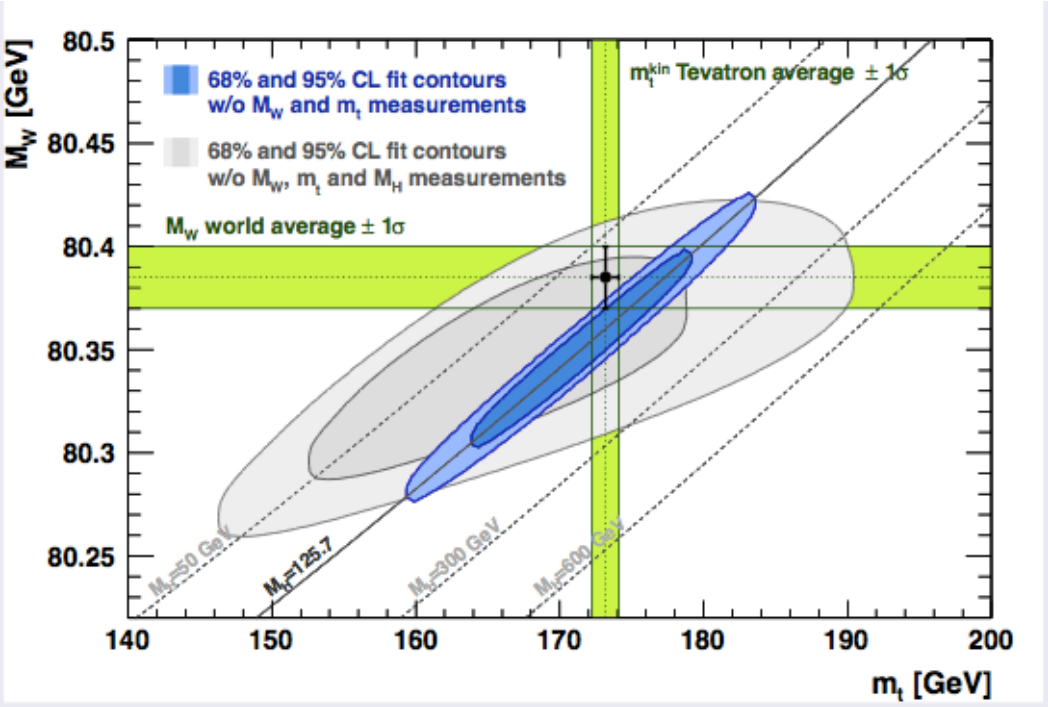
Backgrounds to NP, coupling of Z to top

Top Yukawa magnitude

WHERE TO MEASURE IT

TOP, HIGGS, AND ALL OF US

- W,Z, even Higgs(!) masses already known with amazing precision: 10-3 to 10-5 precision, no ambiguity on mass definition
- Measuring a quark mass is a pretty different business
- Precise top quark mass provides additional predictions: mH=94±24GeV



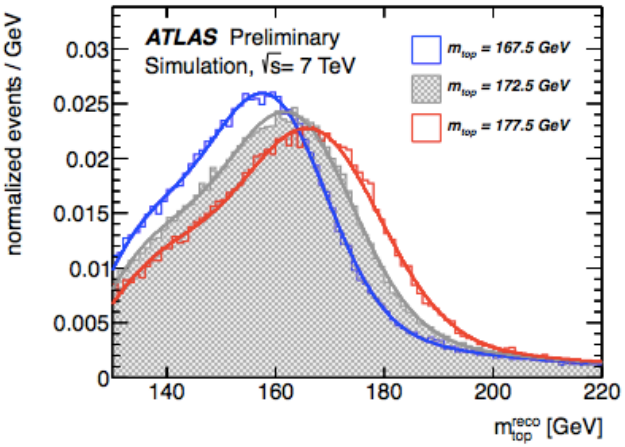
EPJ C72 2205

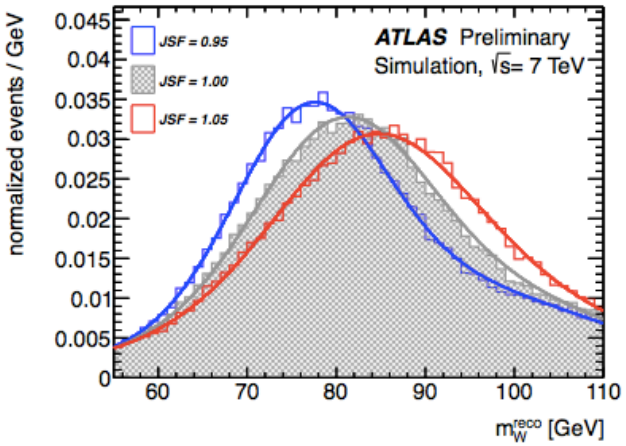
- predicted Higgs boson to be within 1sigma to where we found it!
- knowledge of Higgs mass allows prediction of Mtop to 1% level: Mtop=175.8±2.5GeV

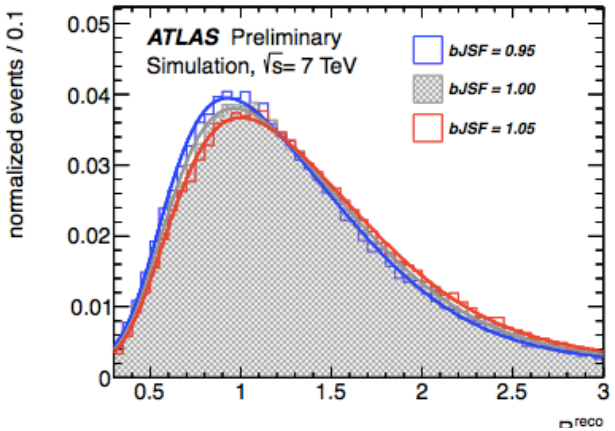
NEW ATLAS MEASUREMENT

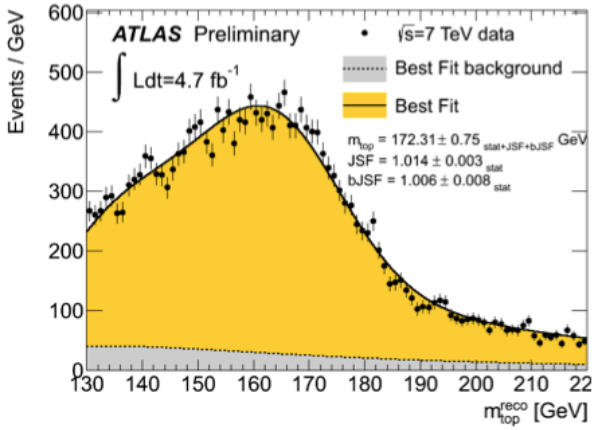
ATLAS-CONF-2013-046

- Typically most performing analyses fit to
  - an observable sensitive to Mtop
  - an observable sensitive to Jet Scale Factor(JSF) in order to limit its systematic
- ATLAS adds a third observable, ratio between Pt of b-jets and Pt of light jets, in order to limit the effect of bJSF





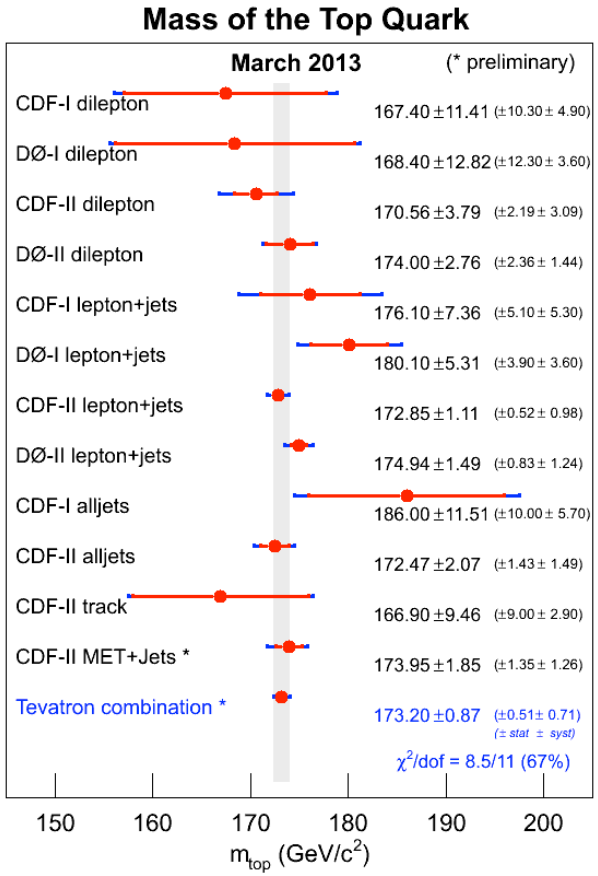




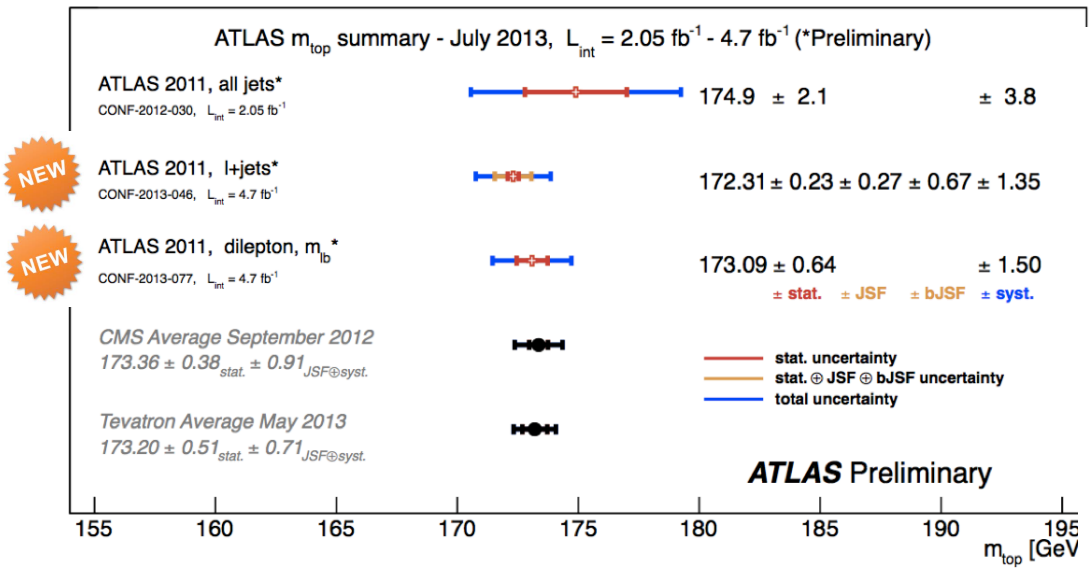
- m_{top}=172.31±0.23(stat)±0.27(JSF)±0.67(bJSF)±1.35(syst)GeV
- Sensibly reduced the impact of bJSF
- Fit for JSF and bJSF compatible with a priori knowledge

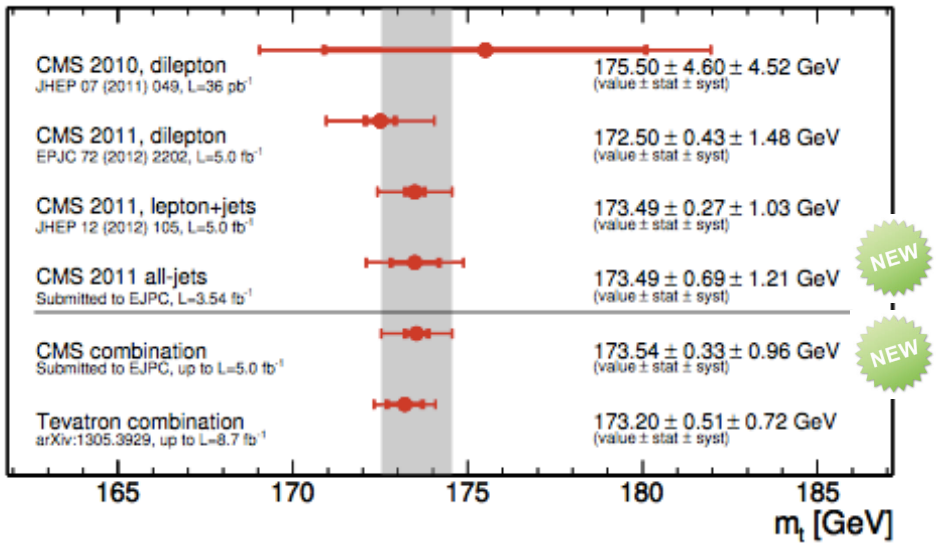
DIRECT MTOP RESULTS

- A very long story...and one still on the making
- All four collaboration measured Mtop directly by reconstructing (in several ways) the top resonance in all the main ttbar final states
- Tevatron still providing best results, CMS gives single best result per channel
- All collaborations agree remarkably well (within 1 sigma) with each other



arXiv:1305.3939





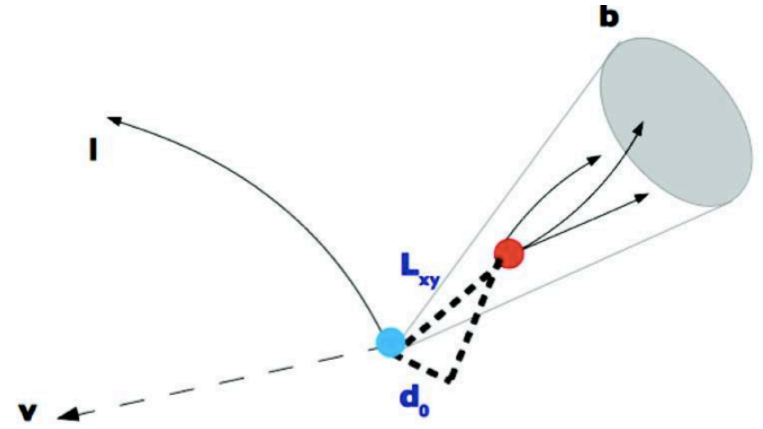
MTOP VIA B LIFETIME

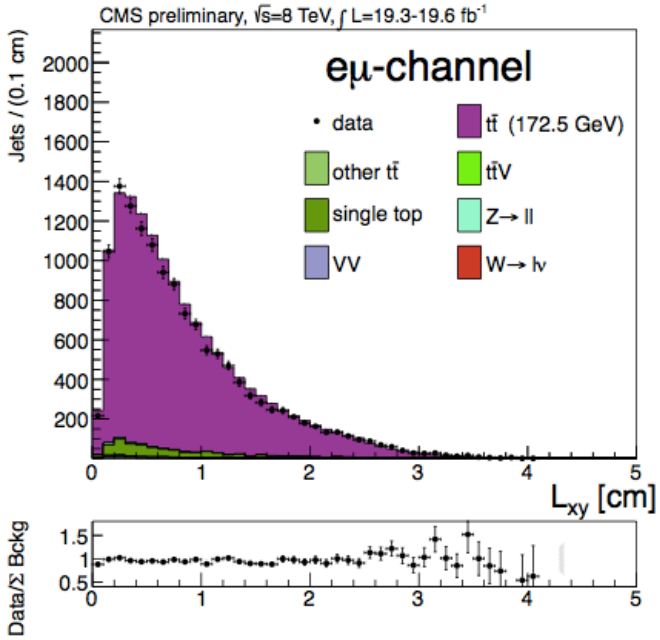
CMS-PAS-TOP-12-030

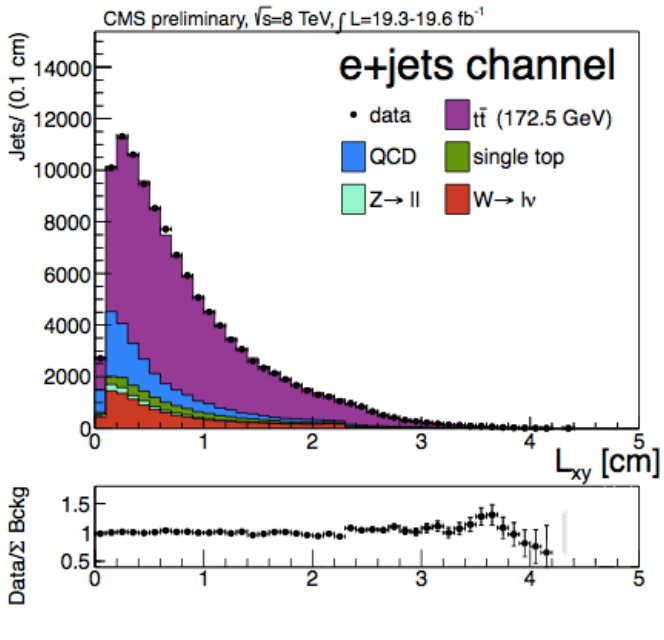
- Boost of b-quark correlated with mt

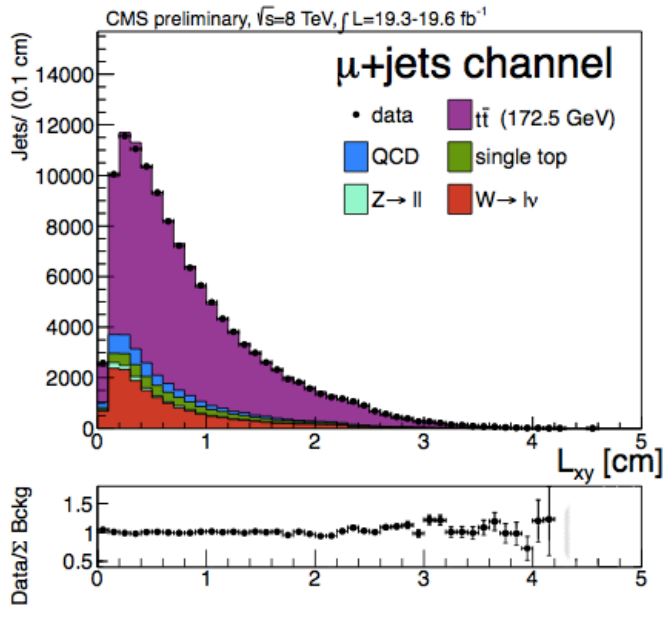
$$L_{xy} = \gamma_b \beta_B \tau_B \approx 0.4 \cdot \frac{m_t}{m_B} \beta_B \tau_B.$$

- Technique similar to previous CDF publication:
  - take the Lxy of the b-jet
  - @good approx linear dependence from Mtop
  - extract Mtop from median Lxy





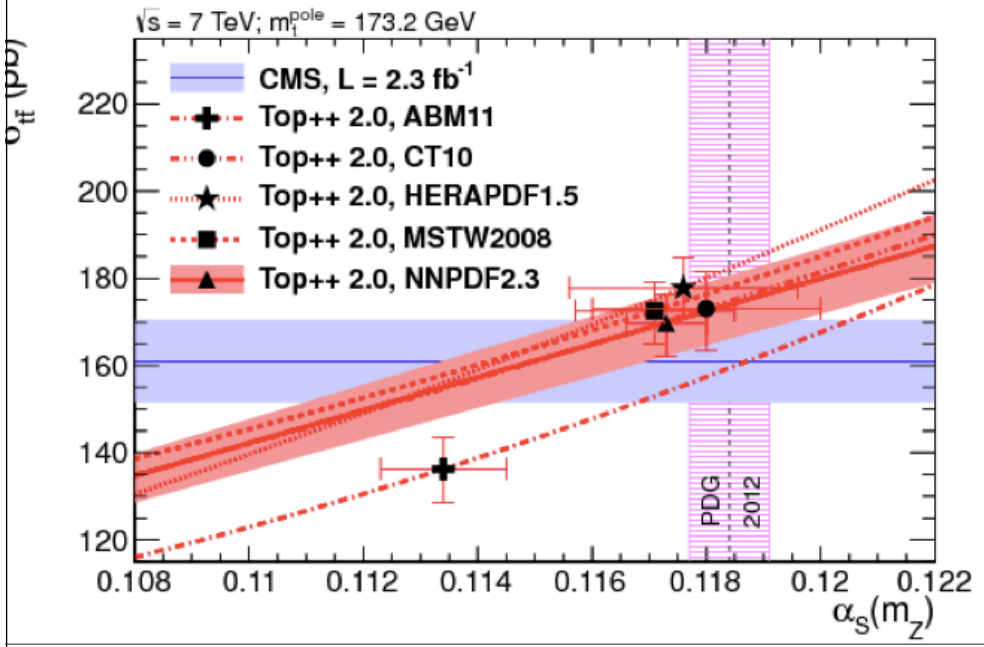


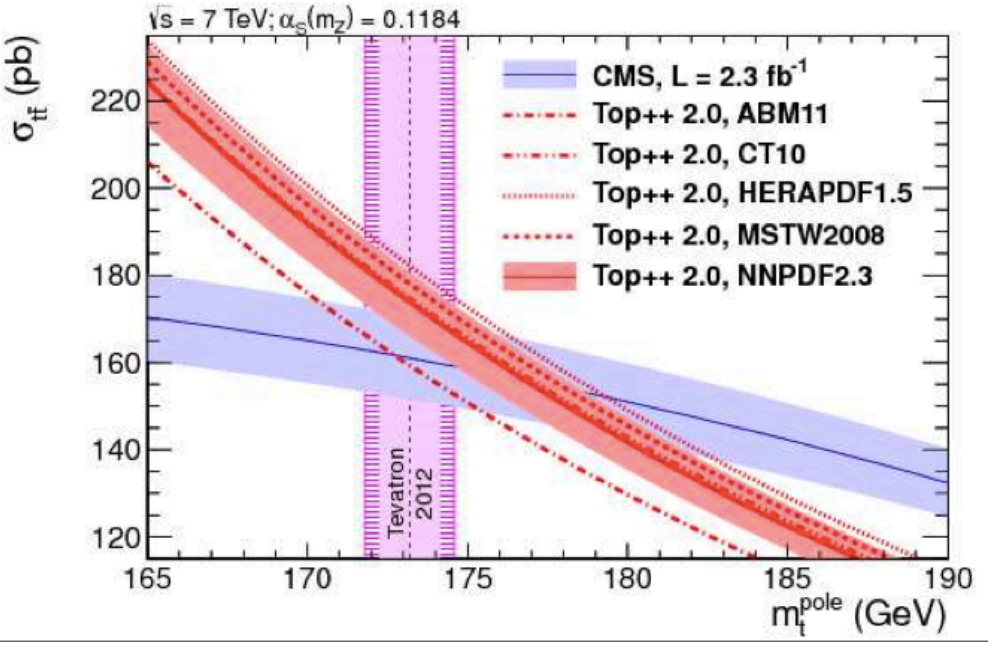


- Mtop = 173.5±1.5(stat) ±1.3(syst) ±2.6(top pt)GeV

MTOP (AND ALPHA_S) FROM SIGMA

- Cross section dependence on α_S and m^{pole} is used to constrain the strong coupling constant or the top quark pole mass.
- Pole mass determination complementary to direct top mass measurements (different systematics and theoretically well defined).





CMS: $m_t^{pole} = 176.7^{+3.8}_{-3.4}$ GeV (NNLO, arXiv:1303.6254) NEW

CMS: $\alpha_s(m_Z) = 0.1151^{+0.0033}_{-0.0032}$ (if m_t^{pole} fixed to measured top quark mass) arXiv:1307.1907 (hep-ex)

D0: $m_t^{pole} = 167.5^{+5.4}_{-4.9}$ GeV (approximate NNLO, Phys. Rev. D 80 (2009) 054009)

ATLAS: $m_t^{pole} = 166.4^{+7.8}_{-7.3}$ GeV (approximate NNLO, Phys. Rev. D 80 (2009) 054009) Phys. Lett. B 703, 422 (2011), ATLAS-CONF-2011-054

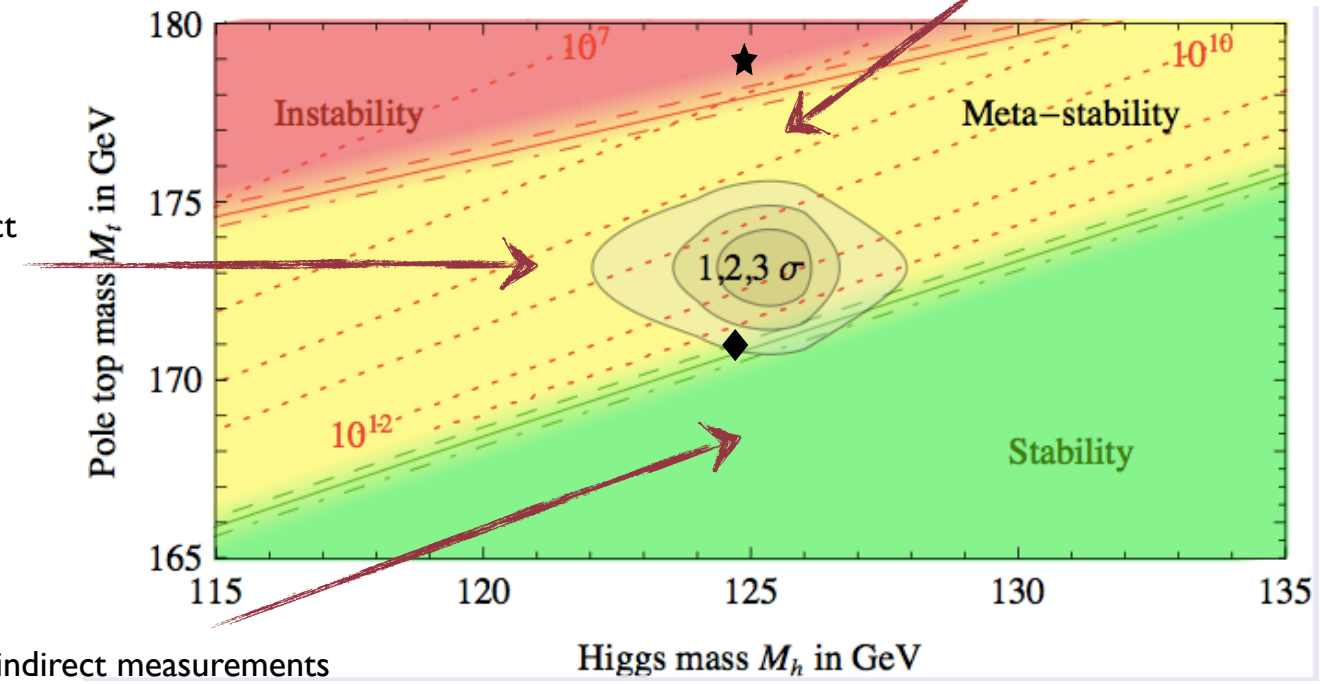
Is the universe truly metastable?

TOP, HIGGS, AND ALL OF US

- W,Z, even Higgs(!) masses already known with amazing precision: 10-3 to 10-5 precision, no ambiguity on mass definition
- Measuring a quark mass is a pretty different business
- Precise top quark mass provides additional predictions: mH=94±24GeV
- Oh BTW, it also helps us predict the fate of the universe...

From EWK fits (incl Higgs)

Mtop from direct measurements

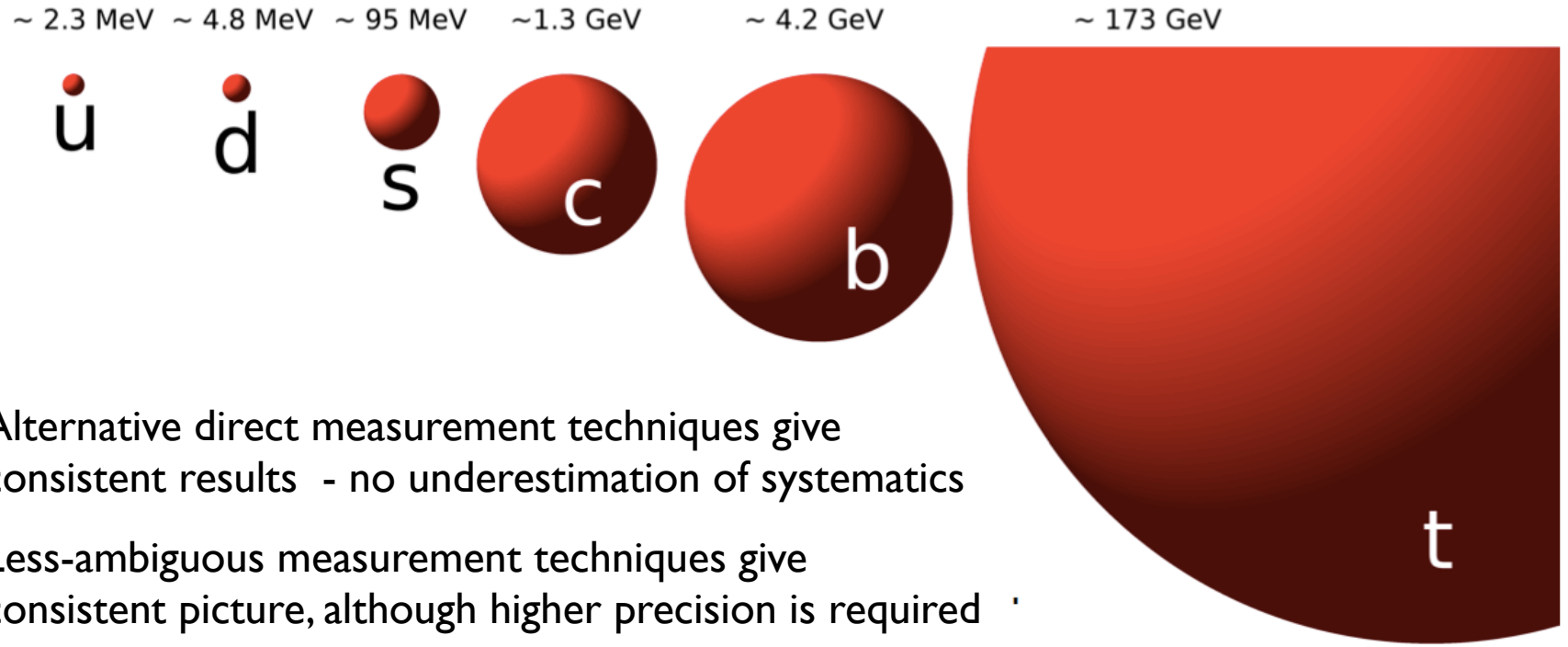


From indirect measurements (until recently)

JHEP 1208 098

MTOP: WHERE ARE WE

- Tevatron still provides the best mass measurement, with an uncertainty of 0.5%.
- Best single LHC measurement (from CMS) reaches 0.6%.
- LHC results mainly coming from 7TeV dataset - lots of room for improvements before LHC reopening!
- Updated LHC mass combination in progress. → Harmonise systematic treatment e.g. generator modeling.

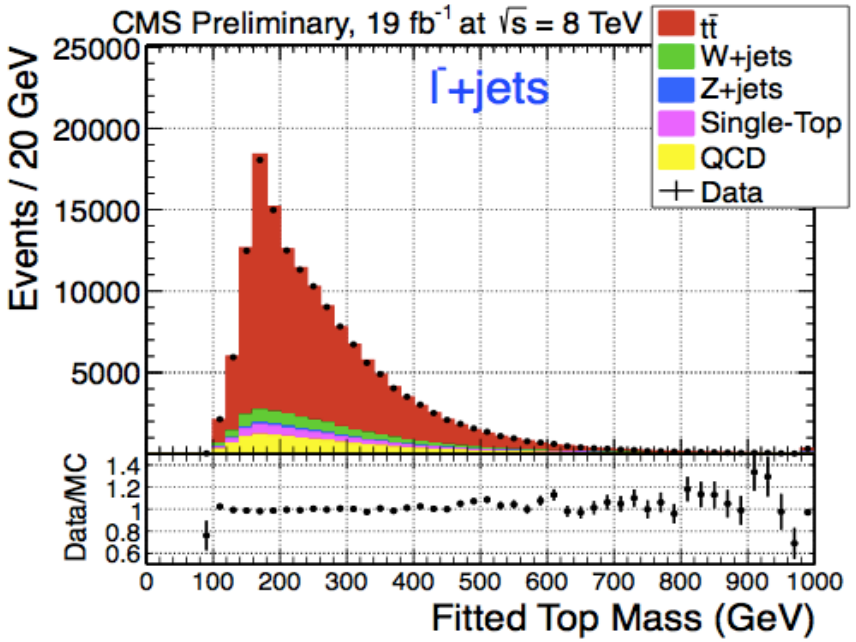


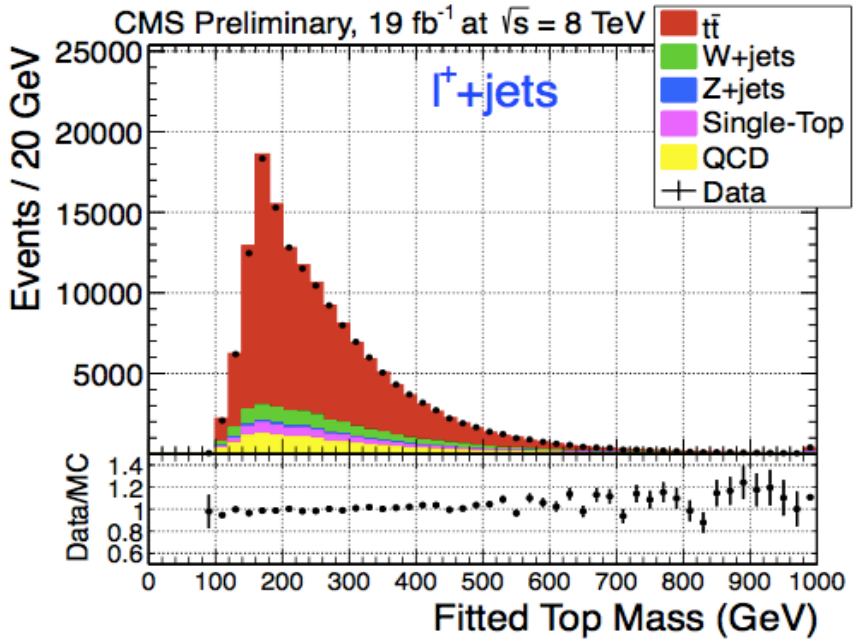
- Alternative direct measurement techniques give consistent results - no underestimation of systematics
- Less-ambiguous measurement techniques give consistent picture, although higher precision is required

CPT VIOLATION

CMS PAS-12-031

- CMS provides the stringent test of CPT violation in top quark physics, by measuring Mtop-Mantitop. Tag leptonic top, reconstruct mass of hadronic top?





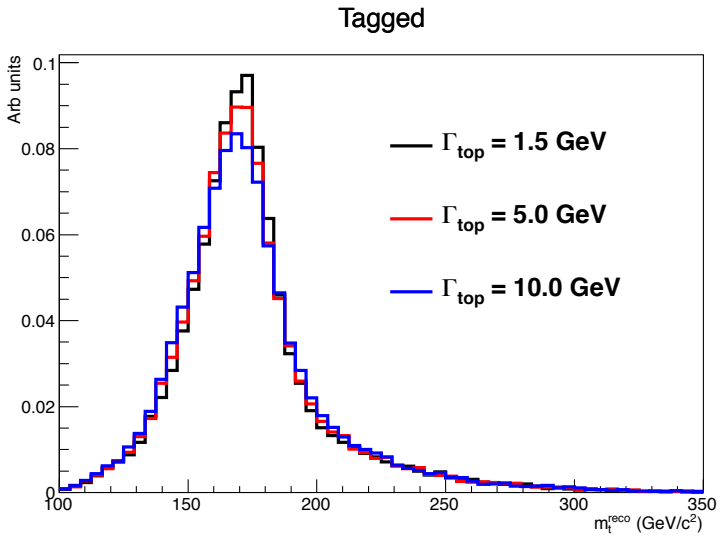
Source	Estimated effect (MeV)
Jet energy scale	$\mathbf{17} \pm 15$
Jet energy resolution	$8 \pm \mathbf{11}$
b vs. $\bar{b}$ jet response	$\mathbf{64} \pm 7$
Signal fraction	$\mathbf{45} \pm 2$
Background charge asymmetry	$\mathbf{12.43} \pm 0.03$
Background composition	$\mathbf{50} \pm 1$
Pileup	$\mathbf{17.4} \pm 0.4$
b-tagging efficiency	$\mathbf{20} \pm 8$
b vs. $\bar{b}$ tagging efficiency	$\mathbf{43} \pm 6$
Method calibration	$15 \pm \mathbf{54}$
Parton distribution functions	$\mathbf{12} \pm 3$
Total	122

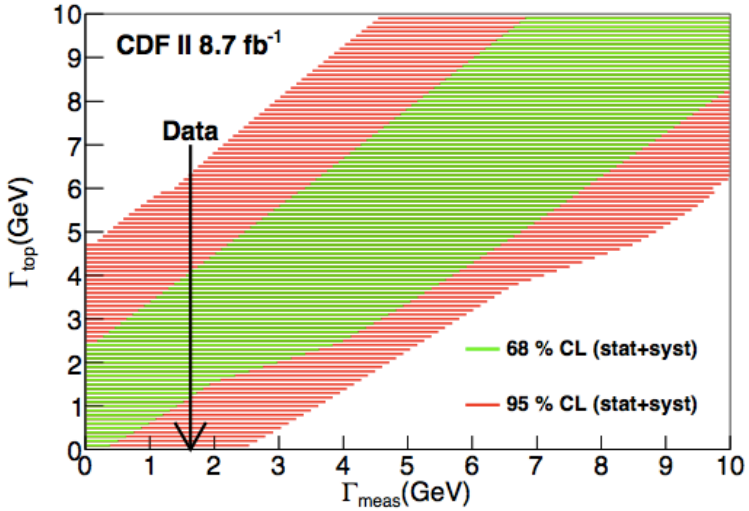
- DeltaMt = -0.27±0.20±0.12 GeV (this result)
- CDF: -1.95±1.26GeV (8.7fb^{-1}) PRD 87 052013
- D0: 0.8±1.9GeV (3.6fb^{-1}) PRD 84 052005

TOP QUARK WIDTH

Just submitted
arxiv:1308.4050v1

- Width has been computed at NNLO = 1.32 GeV (for Mtop=172.5)
- Deviations are model-independent ways to probe for new top decays: H± stops, FCNC
- Analysis strategy: fully reconstruct semileptonic top decays using known MW, Mtop, reduce jet energy resolution through NN-based regression, jet energy scale through W→qq decays, extract from top mass limits on width





- Set a two-sided limit of 1.10 < Γ_{top} < 4.05 GeV at the 68% C.L, or $\Gamma_{top} = 2.2\ ^{+1.8}_{-1.1}$ GeV
- The D0 Collaboration has determined the width to be Γ = 2.00±0.47GeV using a model-dependent, indirect measurement that assumes SM couplings PRD 85, 091104 (2012).

ANATOMY OF AN ANOMALY

- No story is interesting without mistery.....

- Pictures here shows "The Baltic Anomaly": unusual stone formation at the bottom of the baltic sea, battleship rests, UFO, Millennium Falcon???

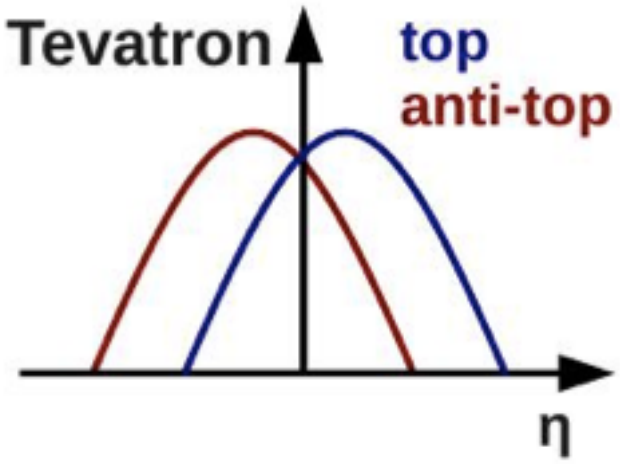
- But you know what I am really referring to (next slide)

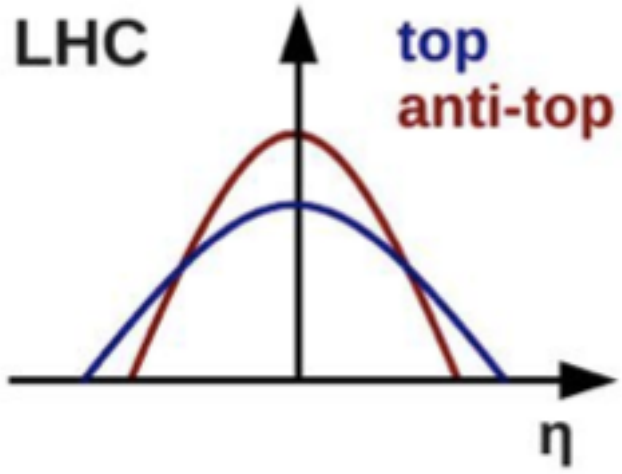
ASYMMETRIES

- Different top quark production modes, different asymmetries at Tev and LHC

Proton-antiproton is a CP eigenstate.
NLO QCD (plus some EW) terms create asymmetry.

Proton-proton not a CP eigenstate.
Small asymmetry comes from PDFs.



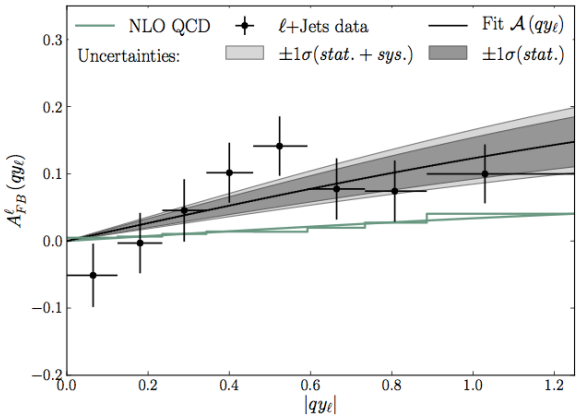


- This is still among hottest TOPics. Want proof? Citation vs time dist. is nearly flat

AT THE TEVATRON

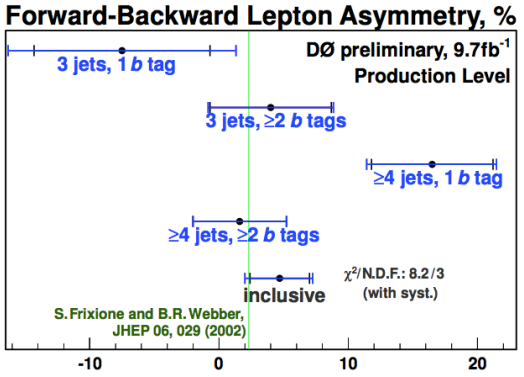
- CDF finds several AFB deviations:
  - deviation depend on mttbar, deltaYt PRD 87 092002
  - not dependent on Pt(ttbar) PRD 87 092002
  - deviation appear mostly in first Legendre poly arxiv:1306.2357
    - more s-channel like new physics
  - leptonic asymmetry gives hints of polarization
    - favors right-handed models

- D0 results are generally between SM and CDF, no significant trends shown
  - latest result analyzes much larger dataset
  - deviation remain only in a subset of data
  - overall good agreement with SM
- Update analysis on lepton asymmetry in dilepton events as well
  - now closer to SM predictions



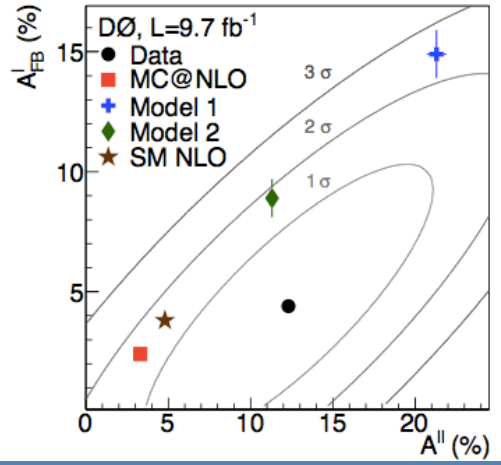
NEW

arxiv:1308.1120



NEW

D0 CONF-6394

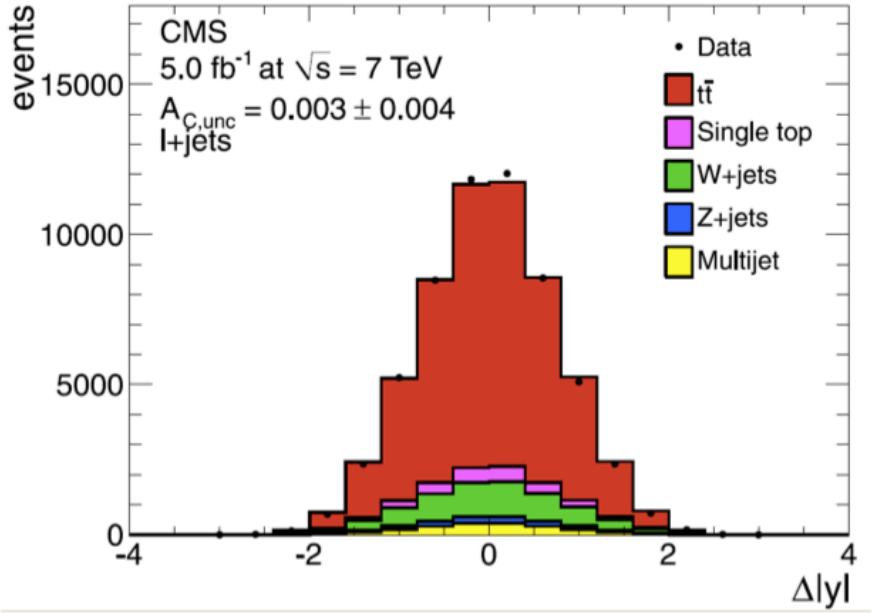


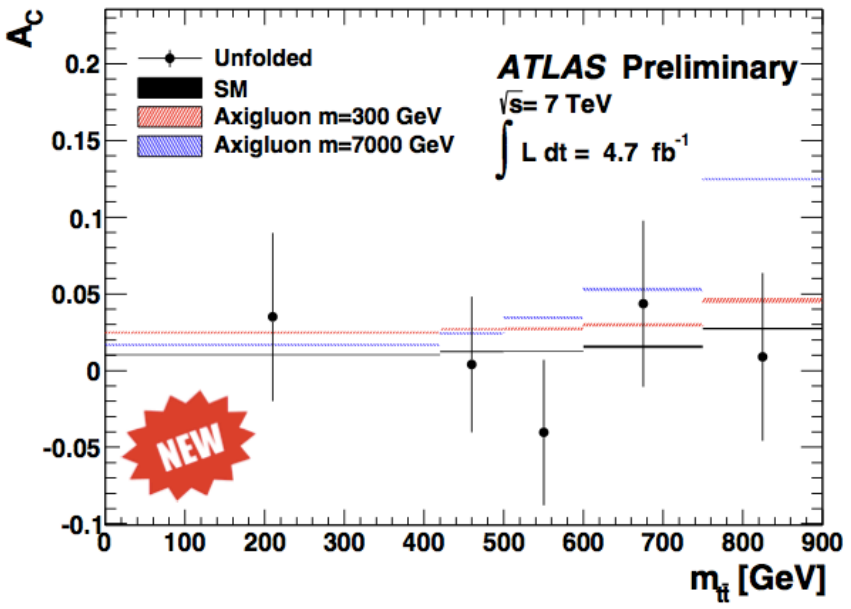
NEW

arxiv:1308.6690

AT THE LHC

- CMS and ATLAS study both inclusive and differential charge asymmetries
- very difficult measurement as theory prediction ~1%, requires very large precision





CMS PAS TOP-12-004
PLB 717 (2012) 109

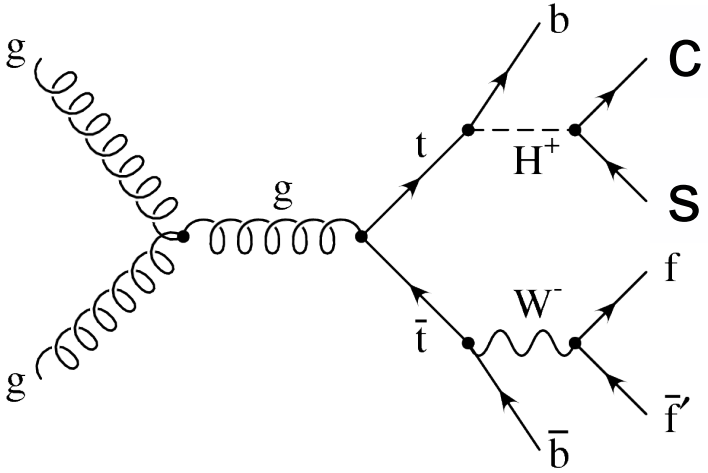
ATLAS-CONF-2013-078
ATLAS-CONF-2012-057

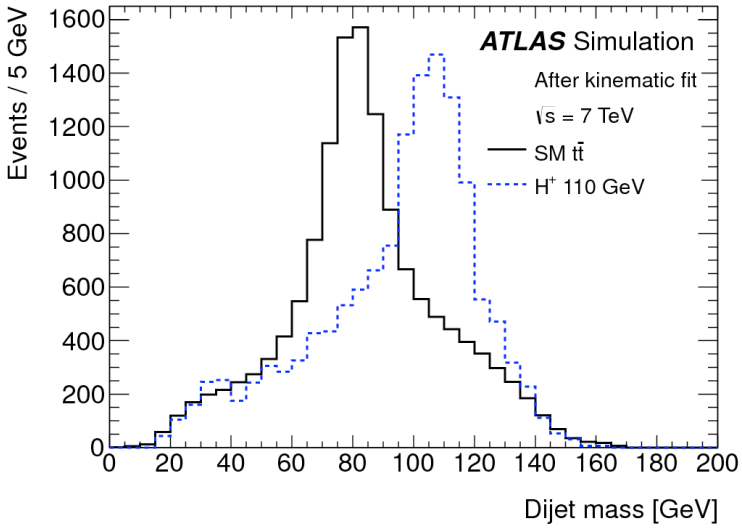
- results consistent with SM, but must be noted that AC and AFB correlate only under assumptions

CHARGED HIGGS FROM TOP

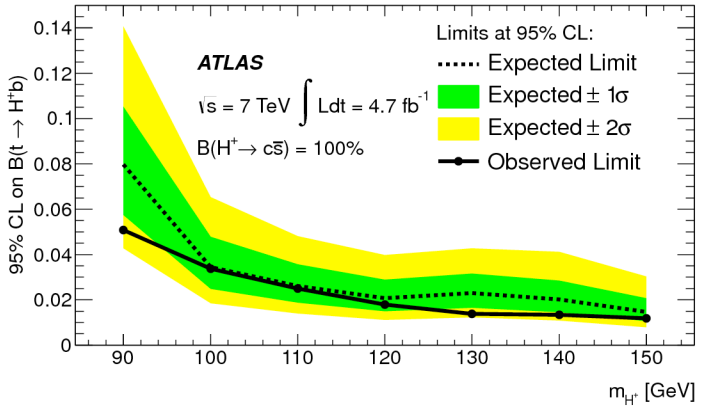
Eur. Phys. J. C, 73 6 (2013) 2465

- Charged Higgs appearing in two Higgs doublet models (2HDM) such as SUSY or triplets
- For H± mass < m(t-b), then decays might appear from top events
- In SUSY, depending on tan(beta), charged Higgses decay dominantly to taunubar, csbar (charge-conjugated processes implied)





- If H± → csbar, then fully reconstruct the event and scan for an hadronic resonance around the W mass
- Set limits on BR(t→Hb) branching ratio of approximately 2% depending on mass hypothesis



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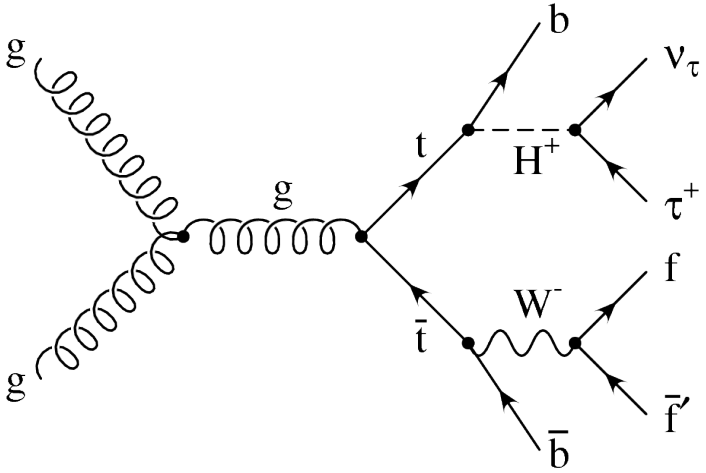
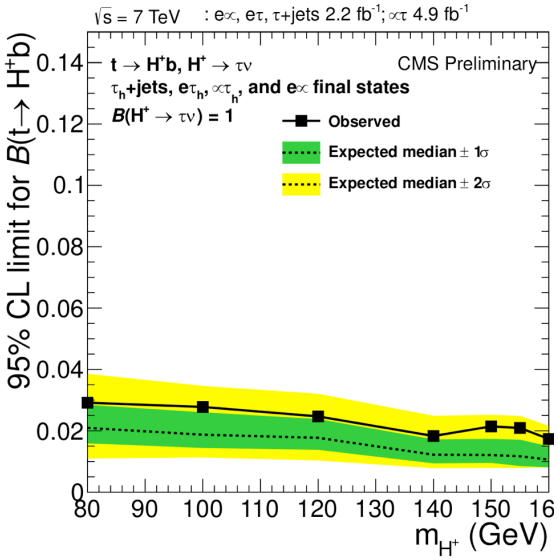
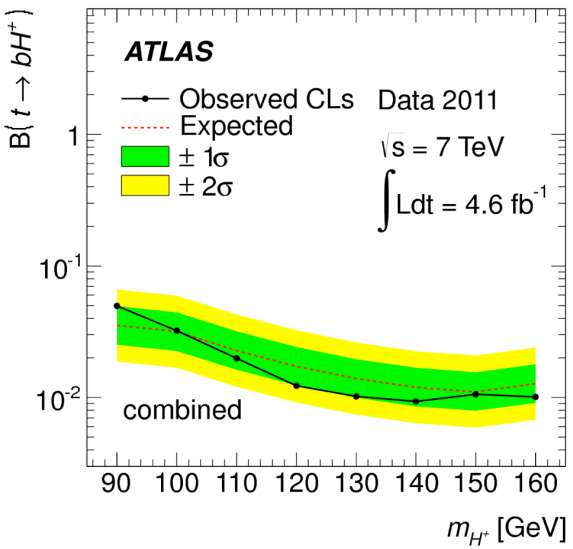
- For H± mass < m(t-b), then decays might appear from top events
- In SUSY, depending on tan(beta), charged Higgses decay dominantly to taunubar, csbar (charge-conjugated processes implied)



CMS-PAS-HIG-12-052



JHEP 1206 (2012) 039

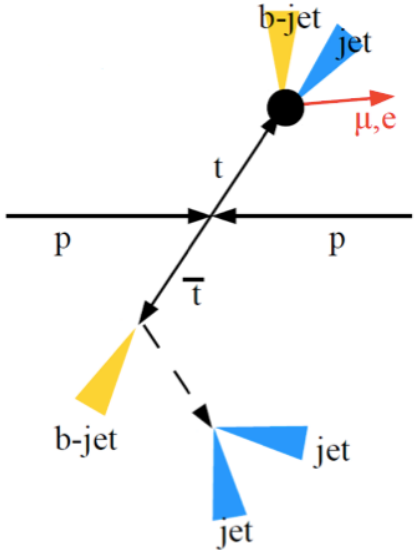


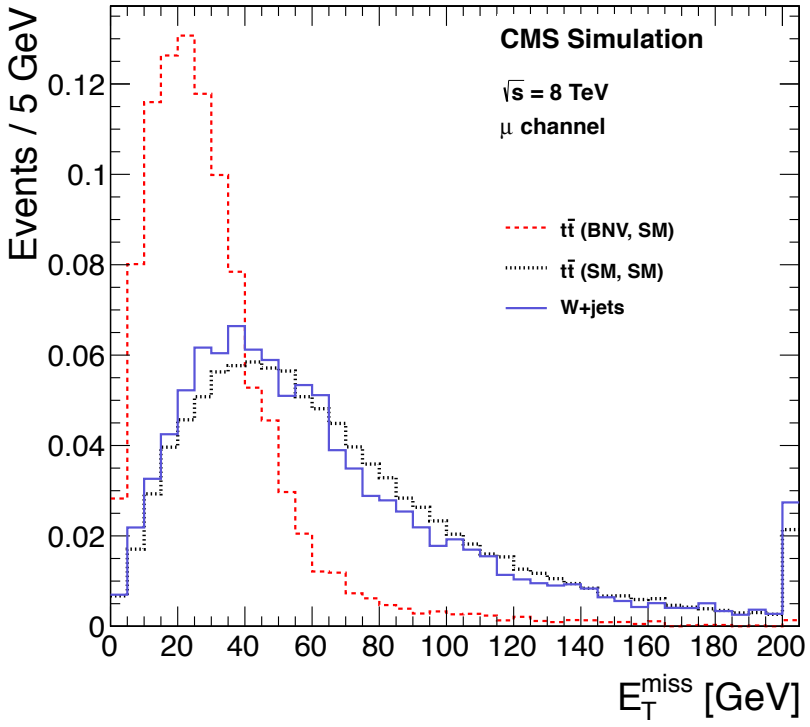
- e-tau, mu-tayu e-mu, tau+jets final states analyzed (here for tau it is assumed hadronic tau decays)
- Both collaboration set limits at the % level

BARYON NUMBER VIOLATION

CMS-PAS-B2G-12-023

- Baryon number violation possible in several BSM scenarios. (SUSY, GUTs, black-hole)
- Limits set on BNV in nucleon, taus, mesons, Z
- Search for $t\bar{t}$ events in which one top decays through $t \to \bar{b}\bar{c}\mu^+$ or $t \to \bar{b}\bar{u}e^+$
  - no neutrinos!





- No significant excess has been found, first uper limits BNV in top events set to be:

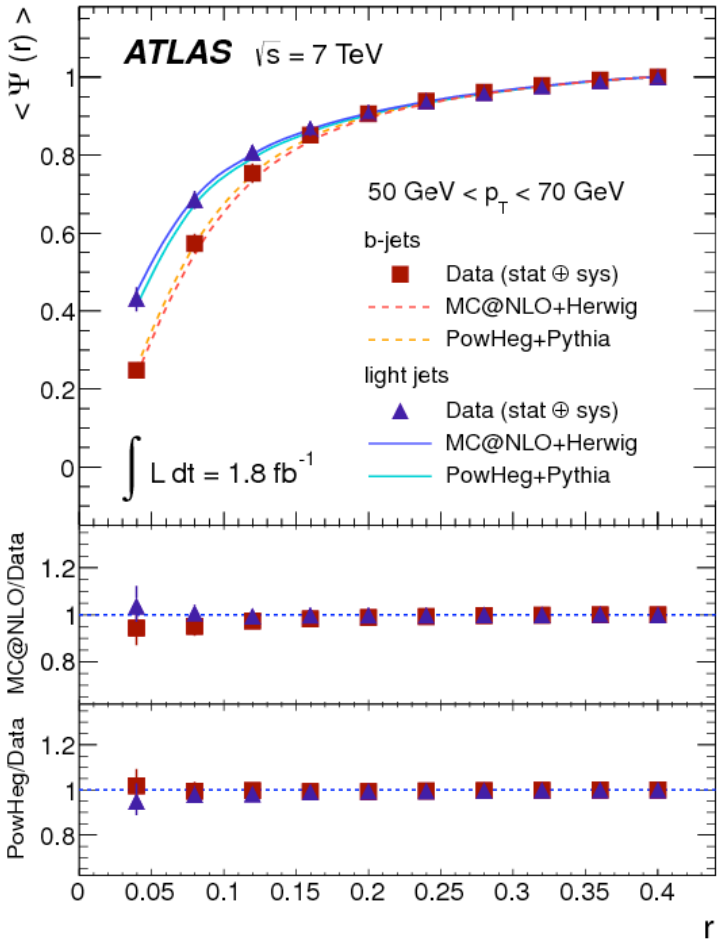
$$BR(t \to \bar{b}\bar{c}\mu^+) < 0.0016 \text{ @ } 95\% \text{ C.L.}$$

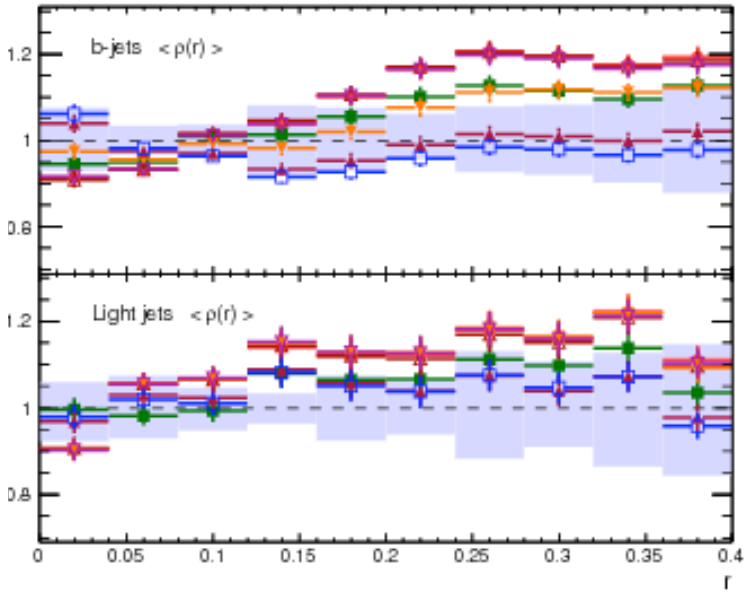
$$BR(t \to \bar{b}\bar{u}e^+) < 0.0017 \text{ @ } 95\% \text{ C.L.}$$

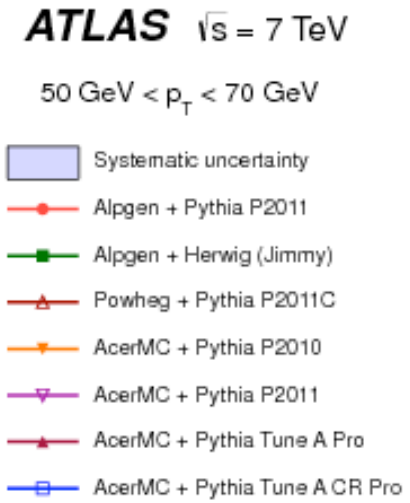
JET SHAPE STUDIES IN TTBAR

arxiv:1307.5749

- Top-antitop events are a very clean source of both b-jets (ttbar in dilepton events) and light flavor jets (from $t \rightarrow Wb, W \rightarrow qq$ decay chain) at hadron colliders
- Interesting test of QCD perturbative (fragmentation) effects



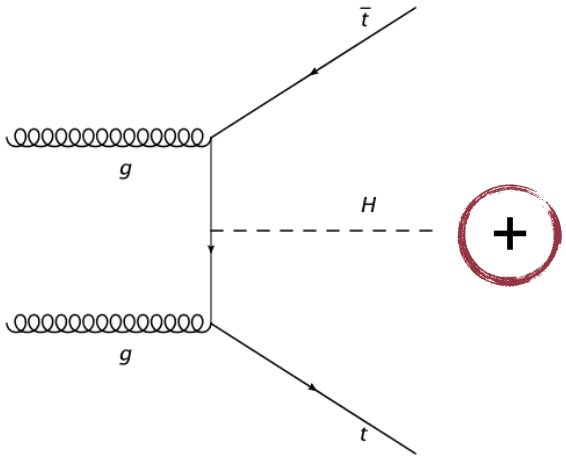


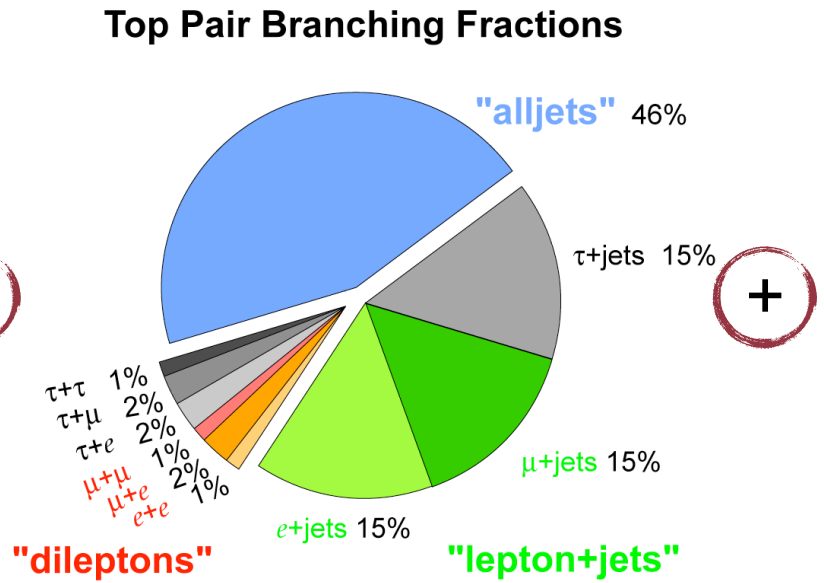


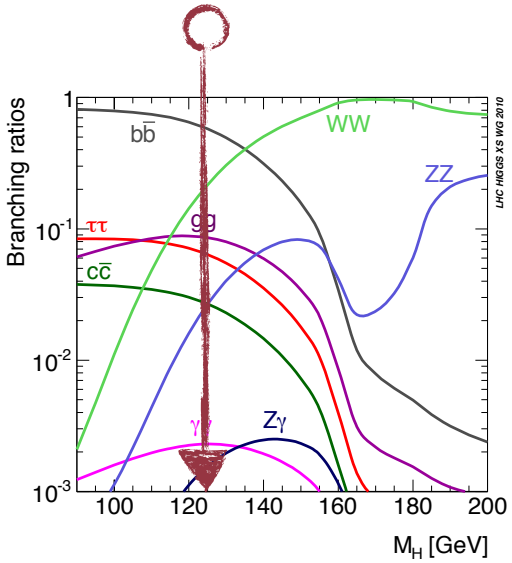
- Although to a smaller extent, jet shapes are sensitive also to non-perturbative QCD: underlying event, color reconnections

TTH: *VERY* COMPLEX FINAL STATE

- Cross section is only ~1/200 of the inclusive Higgs production cross section, ~1/2000 of ttbar production
- Large multiplicity of objects in the final state (signature is dominated by the t/tbar decays)
- Need to find the best combination of top and Higgs decays to isolate the small signal (130fb)



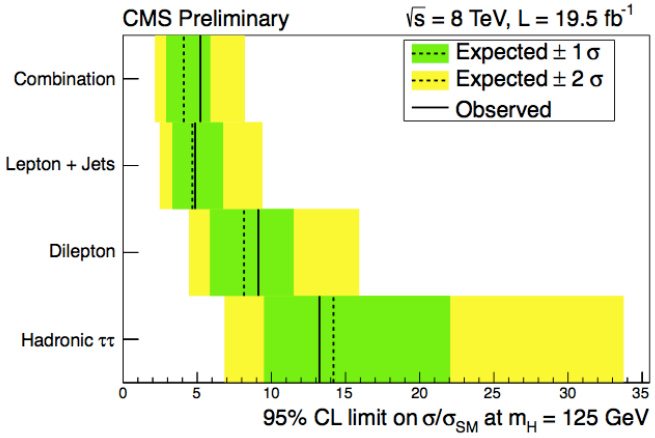


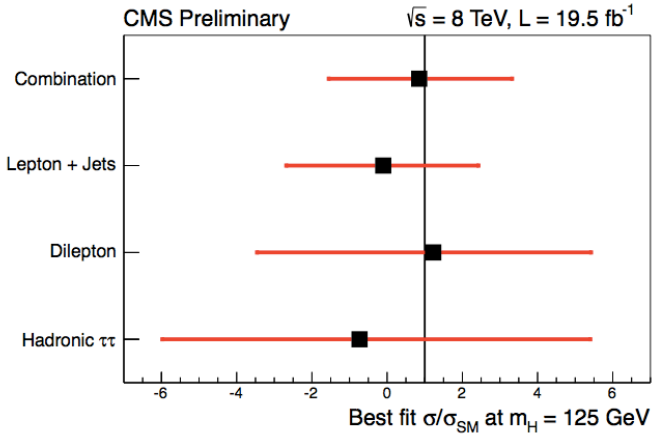


- Studying for now:
  - tt→leptonic, Higgs to bb
  - tt→leptonic, Higgs to tautau
  - tt→anything, Higgs to gamma gamma

TOP YUKAWA MAGNITUDE

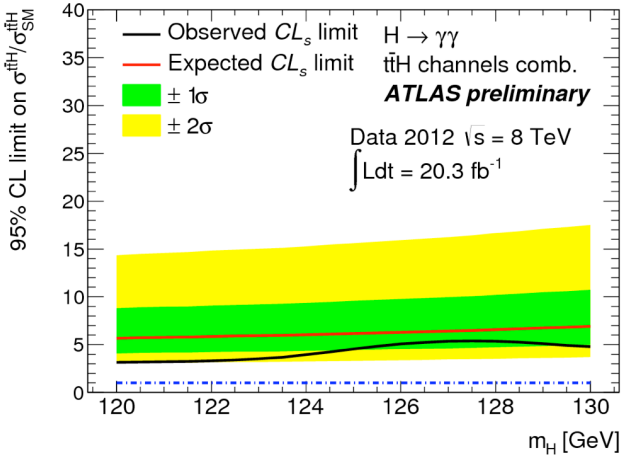
- Searches for ttH production can be directly translated into direct Yt measurements (just as single top can be translated into Vtb measurement).
- Precision on Yt twice the one on sigma(ttH)

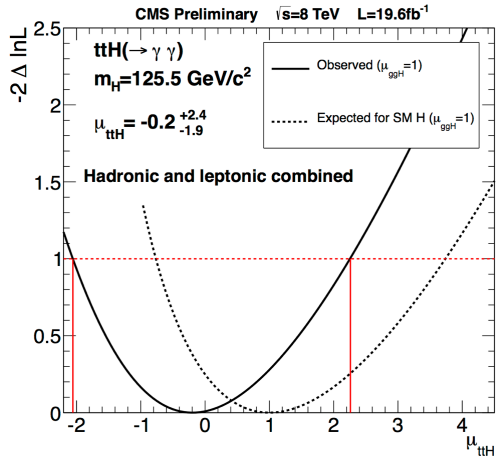




tt->leptonic, H->bb/tautau

CMS-PAS-HIG-13-019
ATLAS-CONF-2012-135





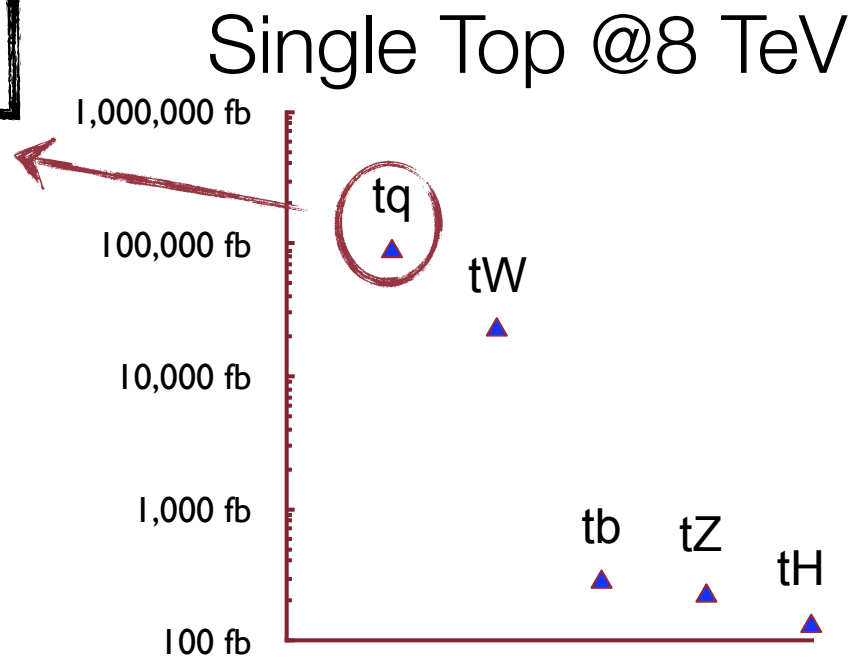
tt->hadronic, leptonic, H->gammagamma

CMS-PAS-HIG-13-015
ATLAS-CONF-2013-080

- Approaching sensitivity to Yt much sooner than originally forecasted!

TOP PROPERTIES FROM SINGLE TOP

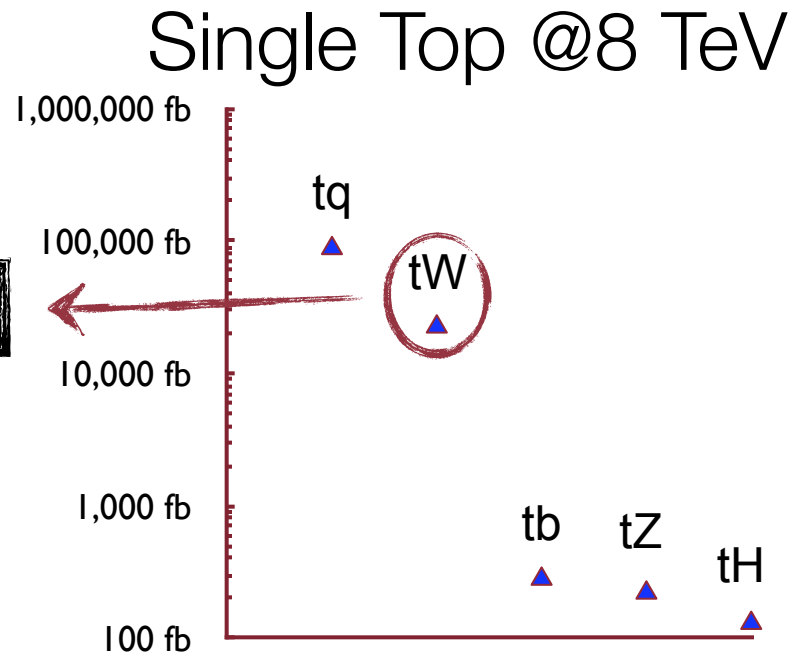
Vtb, polarization, width, CP violation



TOP PROPERTIES FROM SINGLE TOP

Vtb, polarization, width, CP violation

Vtb, background to SUSY

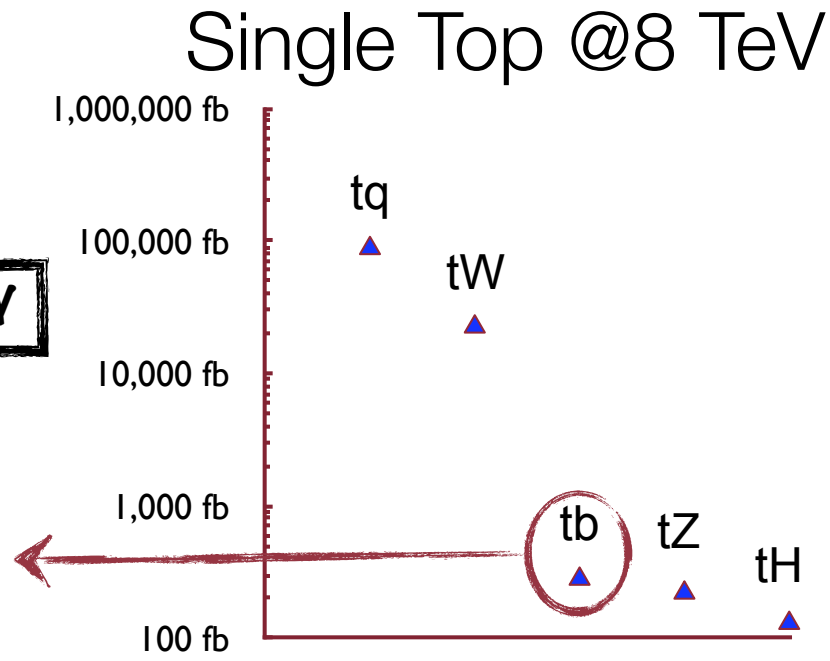


TOP PROPERTIES FROM SINGLE TOP

Vtb, polarization, width, CP violation

Vtb, background to SUSY

Vtb, background to W'/H+-

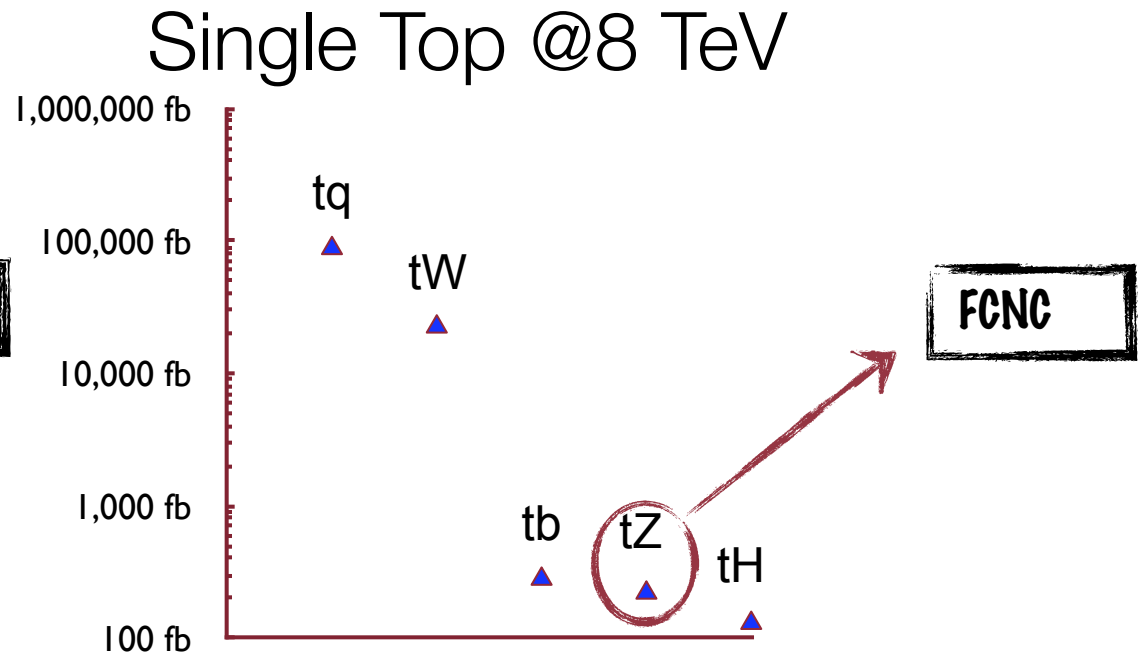


TOP PROPERTIES FROM SINGLE TOP

Vtb, polarization, width, CP violation

Vtb, background to SUSY

Vtb, background to W'/H+-

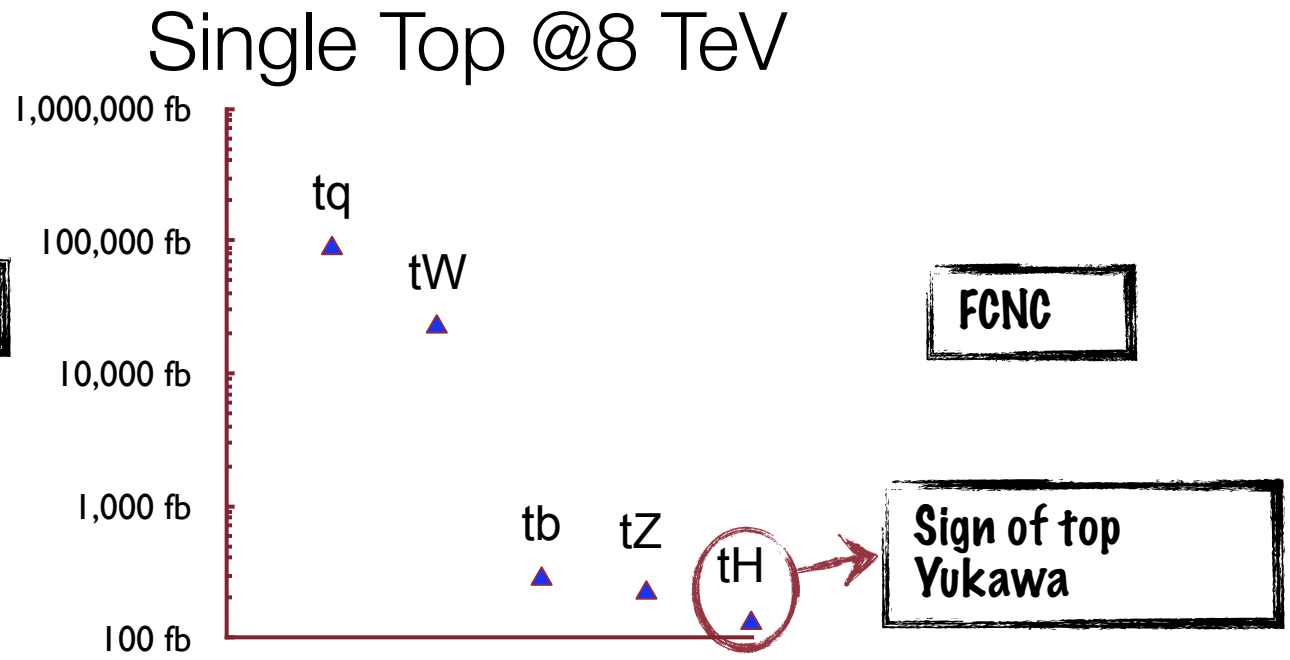


TOP PROPERTIES FROM SINGLE TOP

Vtb, polarization, width, CP violation

Vtb, background to SUSY

Vtb, background to W'/H+-



FCNC

Sign of top Yukawa

VTB EXTRACTION

- Several Vtb results in three different single top production modes (t-channel, s-channel, tW) measured at Tevatron and LHC collaborations,
- all leading to compatible results
- many results do not use yet full dataset
- combination of results could bring additional benefit

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

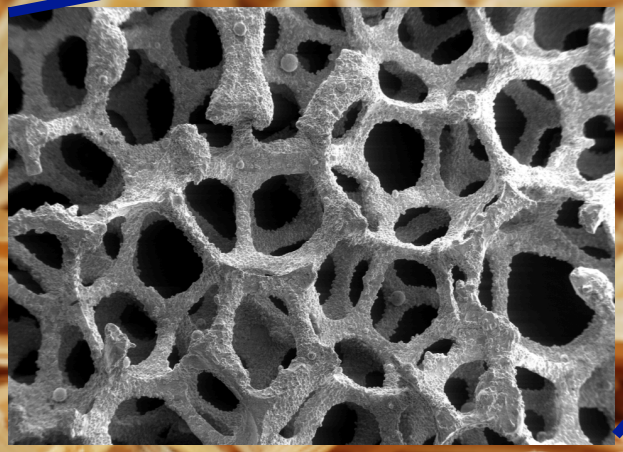
0.91 ± 0.08 (exp+th) s+t channels, Tevatron <3.2fb-1	0908.2171
0.92 ± 0.10(exp)±0.05(theo) s+t channels CDF 7.5fb-1	CDF conf Note 10793
1.12 ± 0.09 s+t channels D0 9. 7fb-1	arXiv: 1307.0731 NEW
1.020 ± 0.046 (meas.) ± 0.017 (theor.) tchannel, CMS 7TeV	JHEP 12(2012)035
0.96 ± 0.08 (exp.) ± 0.02 (theor.) t-channel, CMS 8TeV	CMS-PAS-TOP-12-011
1.04 ± 0.09(exp.) ±0.02(th) t-channel ATLAS 8TeV 6fb-1	ATLAS-CONF-2012-132
1.03 ± 0.12(exp.)±0.04(th.) tW channel 8TeV 13fb-1	CMS PAS TOP-12-040 NEW

RARE DECAYS

- **Take the 1-to-1 billion collisions where top quarks are produced**

RARE DECAYS

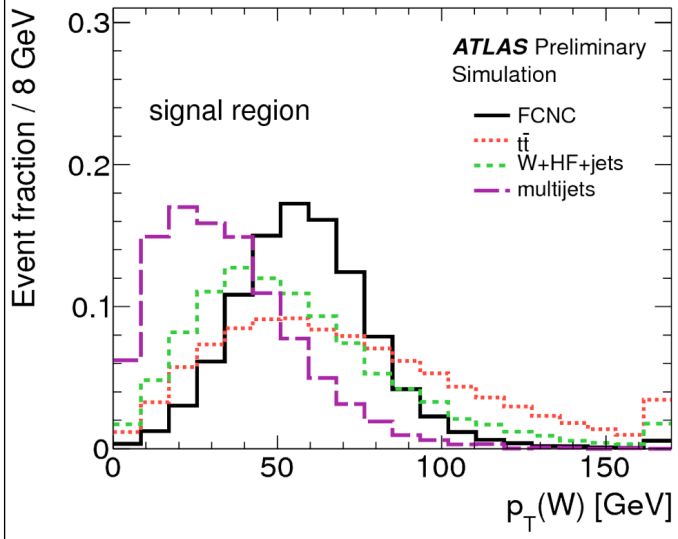
- **Take the 1-to-1 billion collisions where top quarks are produced**
- **investigate scales >=3 orders of magnitude smaller**
- **Is top quark physics already the new b-physics?**

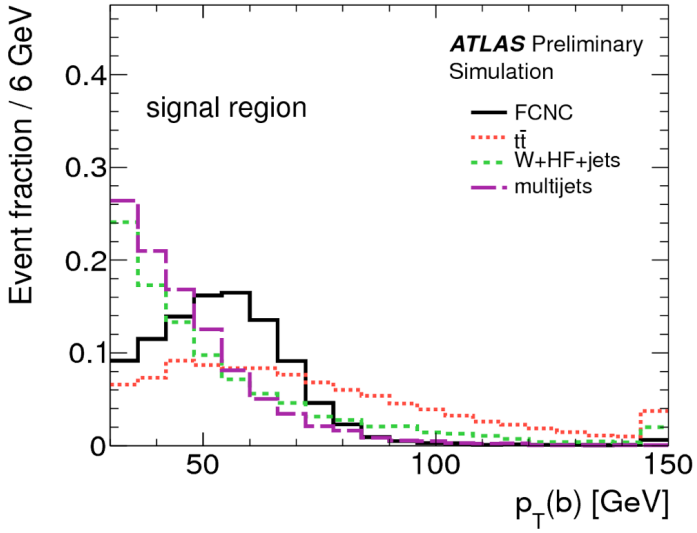


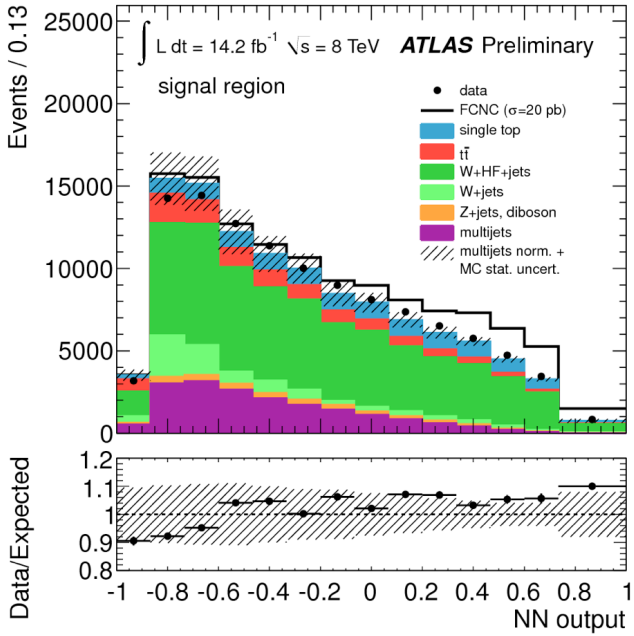
FCNC, GLUONS

ATLAS-CONF-2013-063

- Several NP models (R-parity-violating SUSY/topcolor technicolor), predict enhancements of FCNC decay that lie in LHC sensitivity range (10-3 to 10-5)
- uct, ugt can be better probed from single top production $qg \to t \to Wb \to \ell\nu b \; (q = u, c)$
- top produced alone rather than singly, decay products ~boosted and back to back
  - use NLO predictions and simulations for accurate modeling







- BR(t→ug)<3.1 x 10-5
- BR(t→cg)<1.6 x 10-4
- currently most stringent results

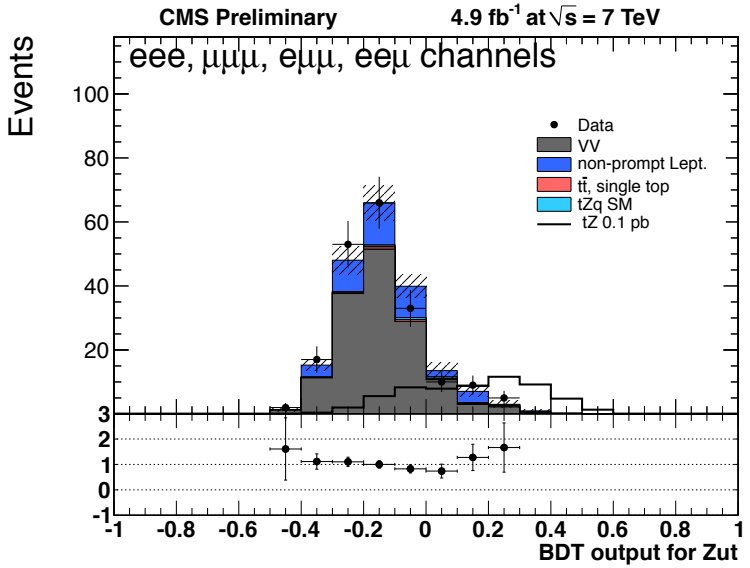
FCNC, Z BOSONS

NEW

CMS-PAS-TOP-12-021

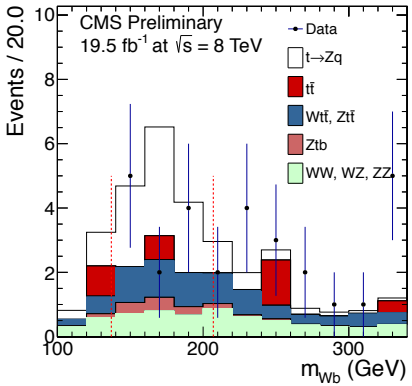
- Use for the first time tZ events to search for FCNC using 7TeV data
  - tZ→trileptons+bjet
- Can identify Z and top separately, use all infos to isolate signal
- Set limits on several anomalous couplings

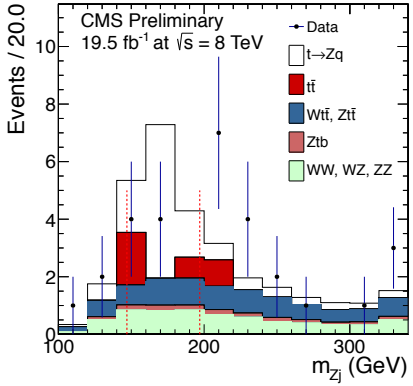
$\mathcal{BR}(t \to Zu) \leq 0.51\%$

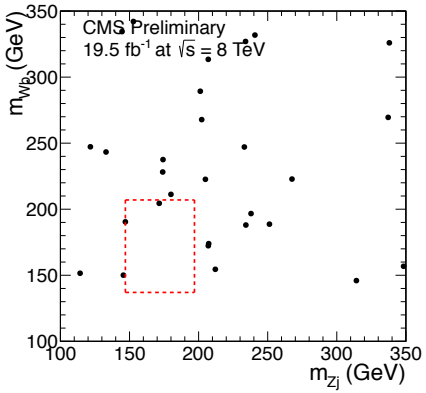


OR

- Use ttbar→bWZq
- Selecting W and Z leptonic decays, full event reconstruction is unambiguous







CMS PAS TOP-12-037

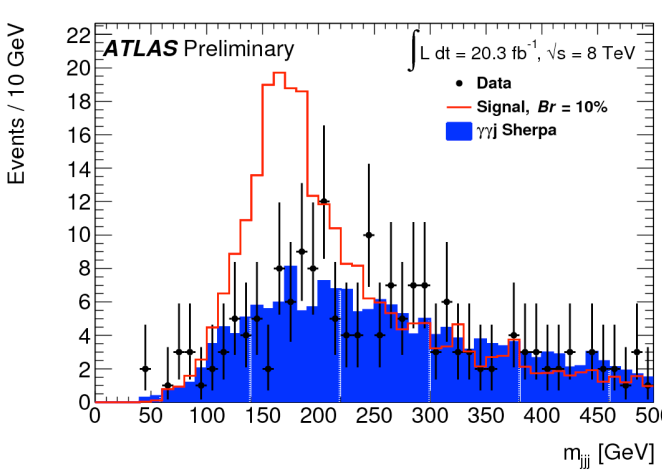
BR(t→Zu)<0.07%

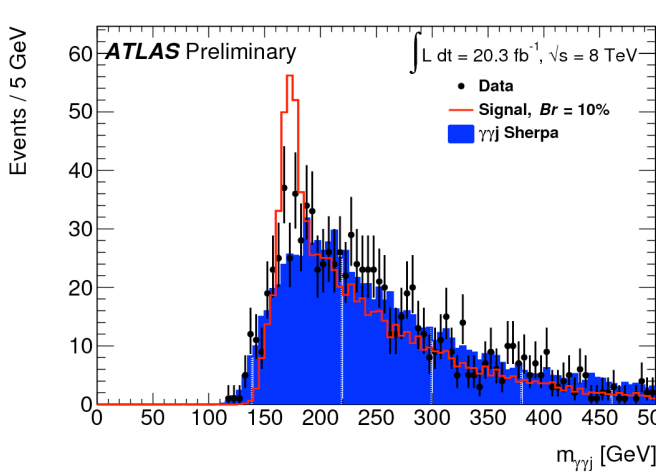
- results are comparable once scaled to same lumi, can be combined in the future

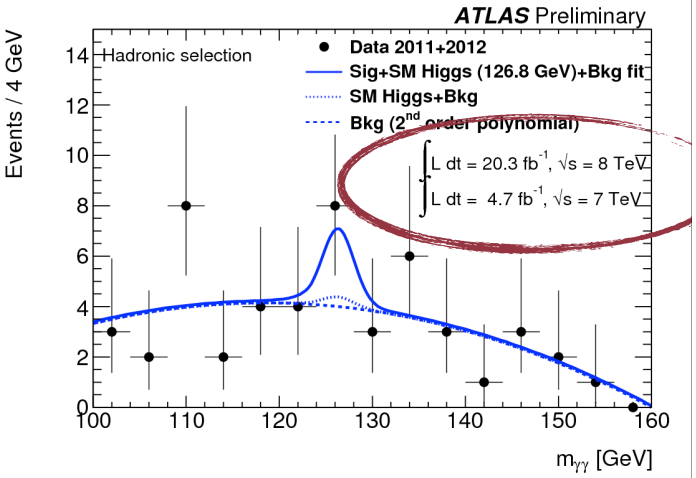
FCNC, HIGGS BOSON

ATLAS-CONF-2013-081

- Take the dominant ttbar production mode, look for events with one FCNC decay of the kind t→Hc
- Split into hadronic (tt→cHWb→cHqqb) events and leptonic (tt→cHWb→cgammagamma lnub) events
  - former contain residual combinatorics, latter unambiguous
- Choose topological and kinematic (top quark mass cuts) final states consistent with the FCNH hypothesis, scan over diphoton spectrum





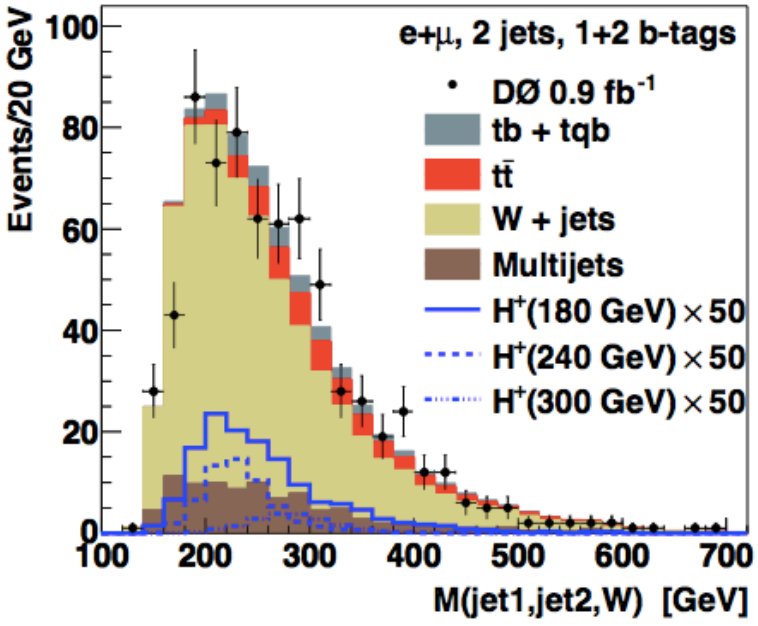


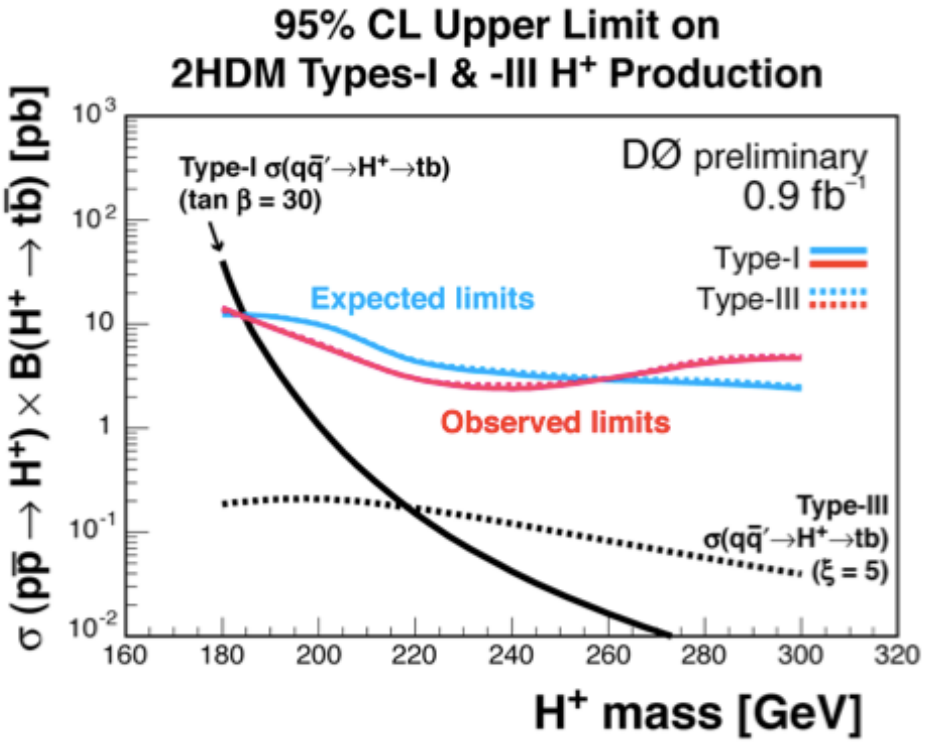
- No significant signal is observed and an upper limit on the branching ratio of 0.83% (0.53% expected) at the 95% confidence level is set. The corresponding limit on the tcH coupling is 0.17 (0.14 expected)

CHARGED HIGGS TO TOP

PRL 102 (2009) 191802

- For a charged Higgs mass above t+b threshold, s-channel single top production can be enhanced by resonant production.
- Tevatron best suited for this search thanks to better S/B
- Scan for resonant production, set limits on Type I, III 2HDM models

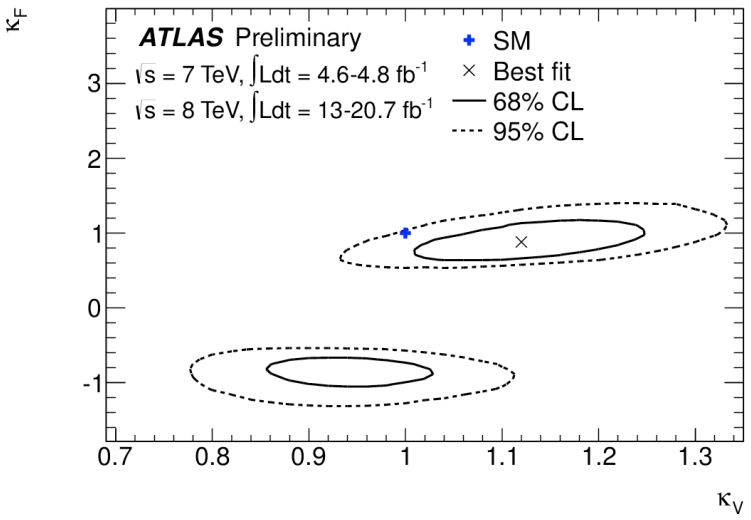


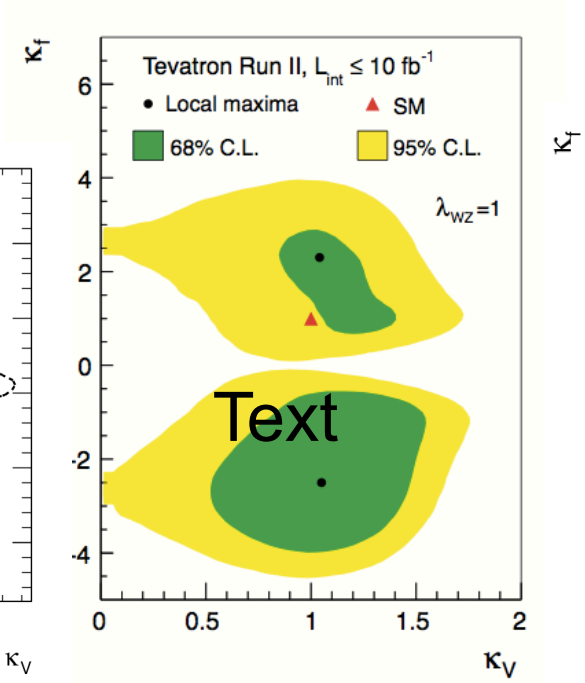


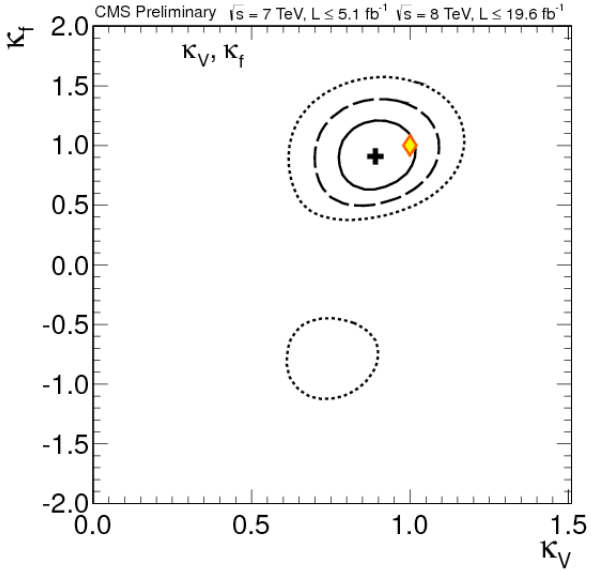
- Limits depend on tan(beta) and 2HDM model

SINGLE TOP QUARK + HIGGS

- Measurement of this production mode would probe ttH/WWH interference
  - same kind of interference that bring current Higgs data to allow negative coupling of Higgs to fermions (ATLAS, Tev)

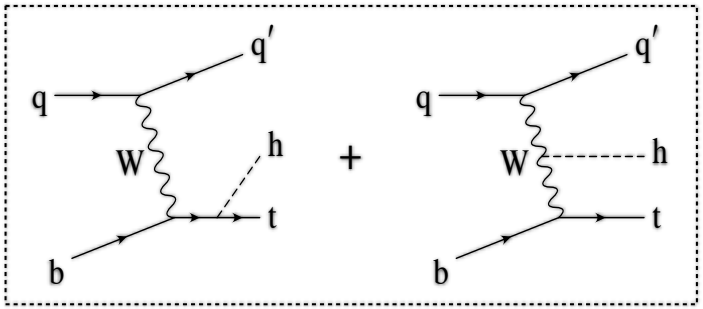




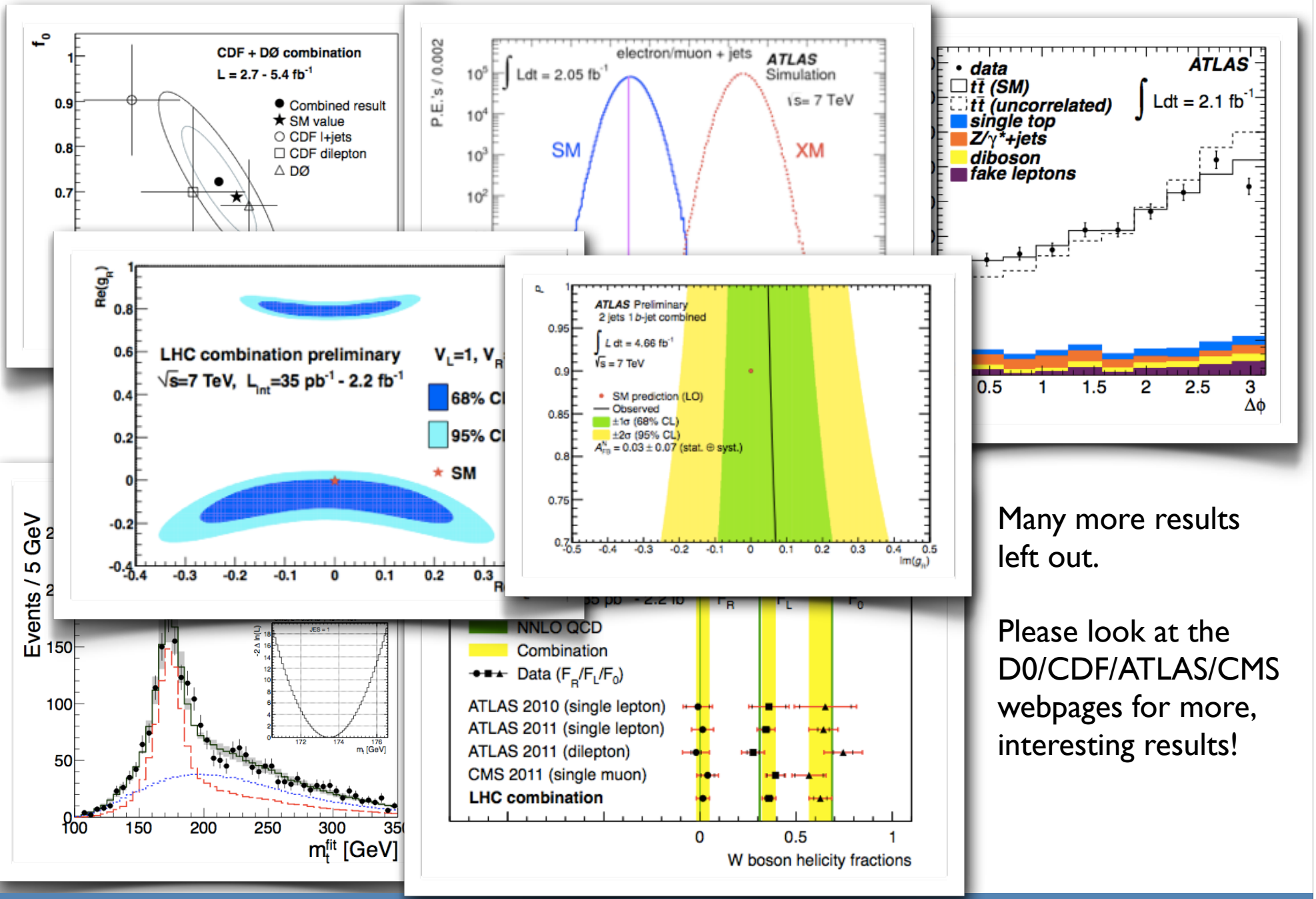


- t-channel tHq production especially sensitive to sign of Yukawa coupling, as it would bring large enhancement in cross section (would exceed ttH production)

S.Biswas et al. JHEP 01 (2013) 088
M.Farina et al. JHEP 05 (2013) 022
S.Biswas et al. JHEP 07 (2013) 073



THERE'S MORE TO THIS



Many more results left out.

Please look at the D0/CDF/ATLAS/CMS webpages for more, interesting results!

CONCLUSIONS

42 slides later....and after the 4th of July 2012 fireworks to celebrate the newcomer,

top is still the heavyweight champion!

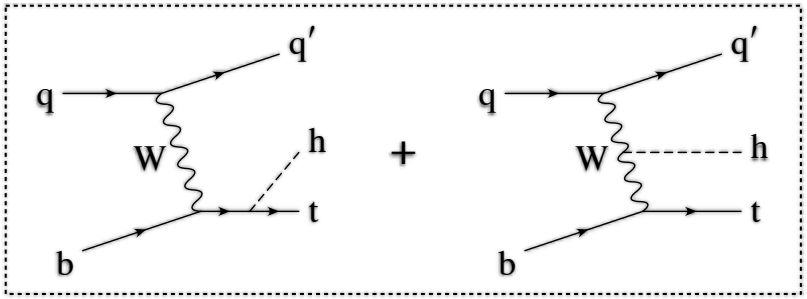
Crucial to predict Higgs mass, check test SM consistency, cosmological implications

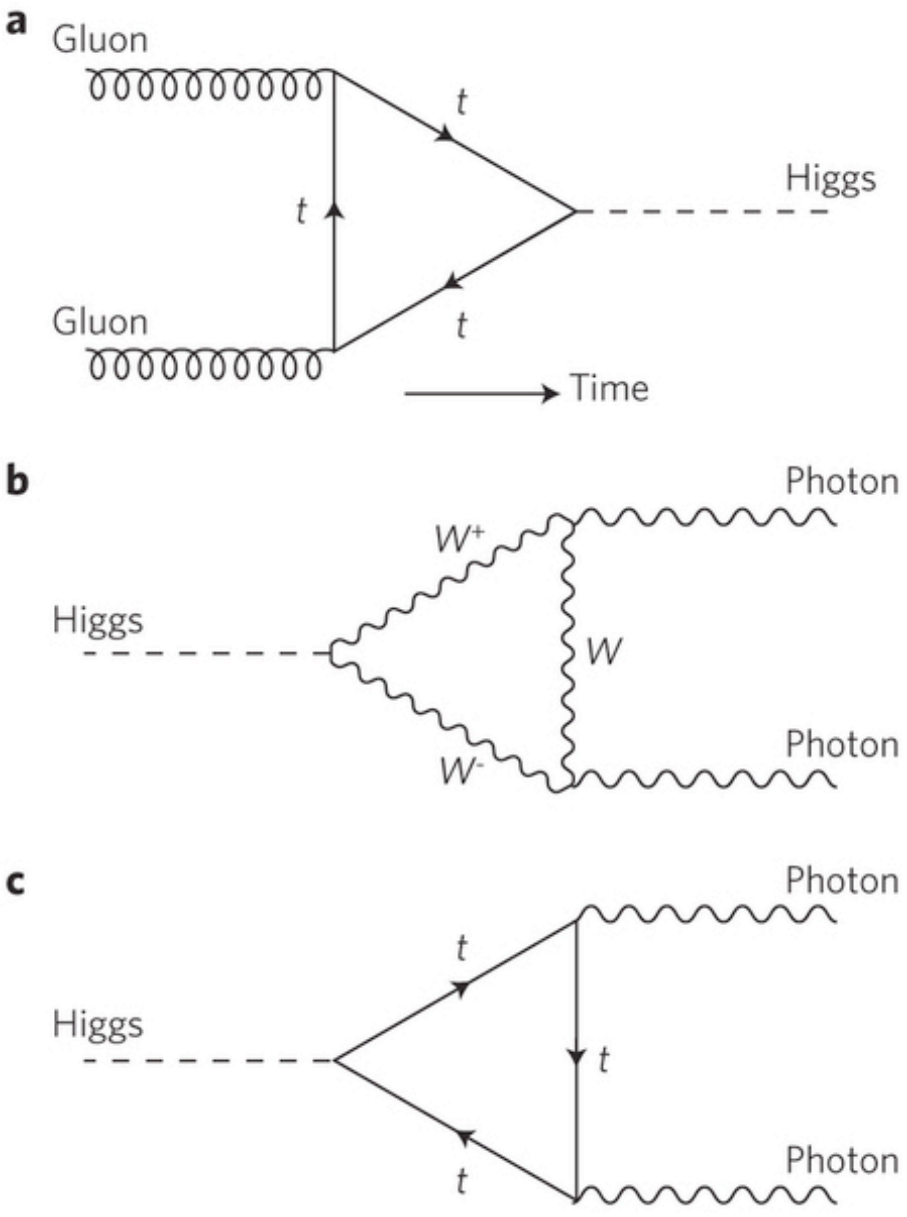
After Higgs discovery, top physics is ESPECIALLY interesting:
testing Higgs Yukawa sector, rare decays to Higgs, charged Higgses

BACKUP

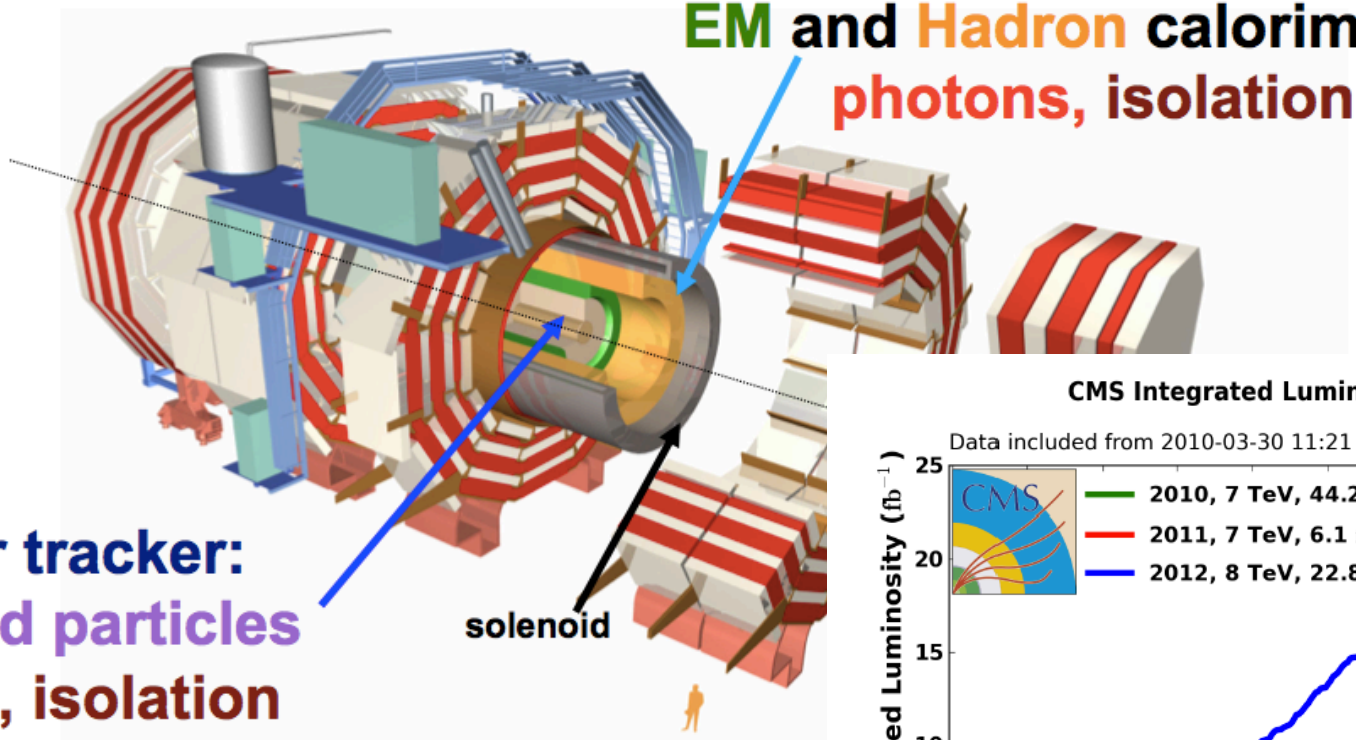
HIGGS AND FERMIONS

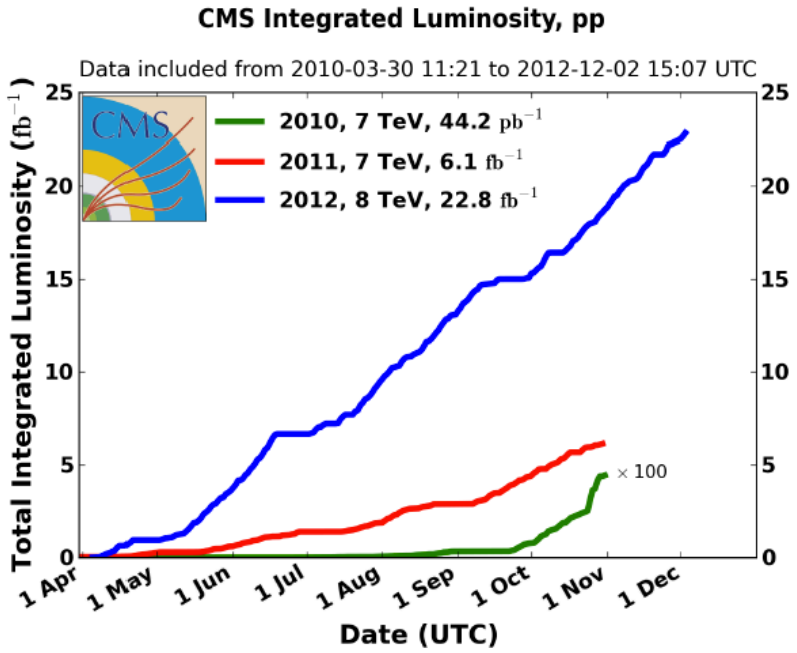
- We know there is a Higgs boson in LHC data
- it first appeared decaying into two bosons
- the big picture is still far from clear, as there are a multitude of loops where new physics might be hiding
- not to mention interference between diagrams...

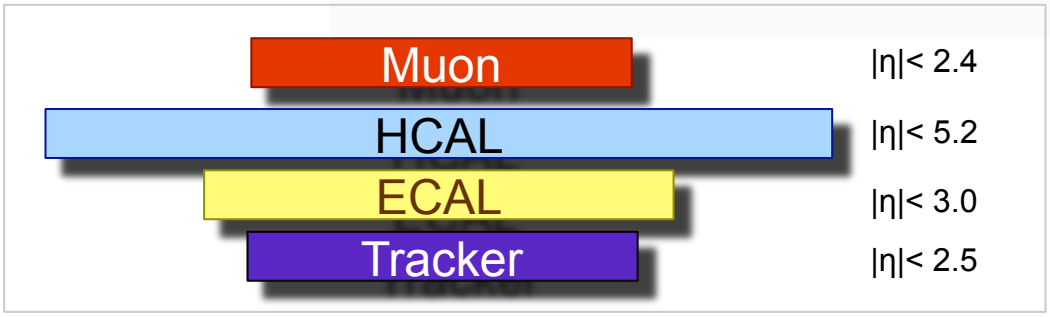




THE CMS DETECTOR



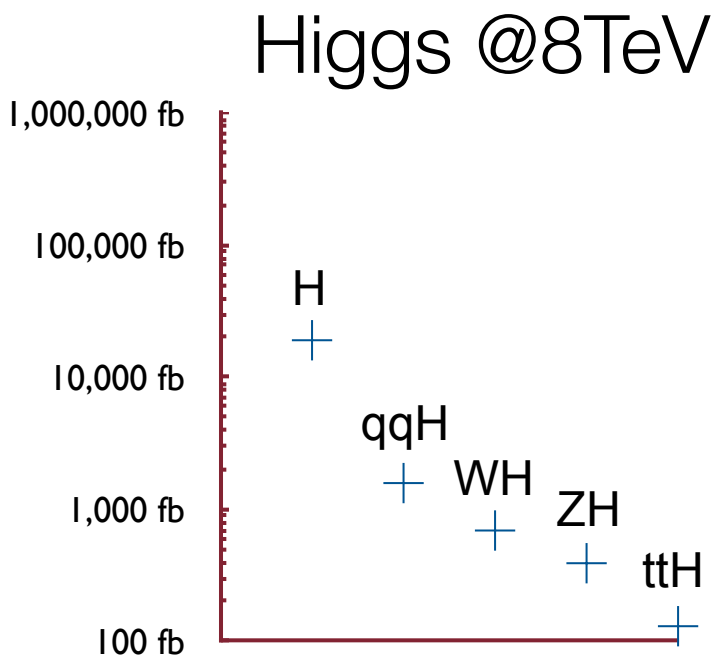


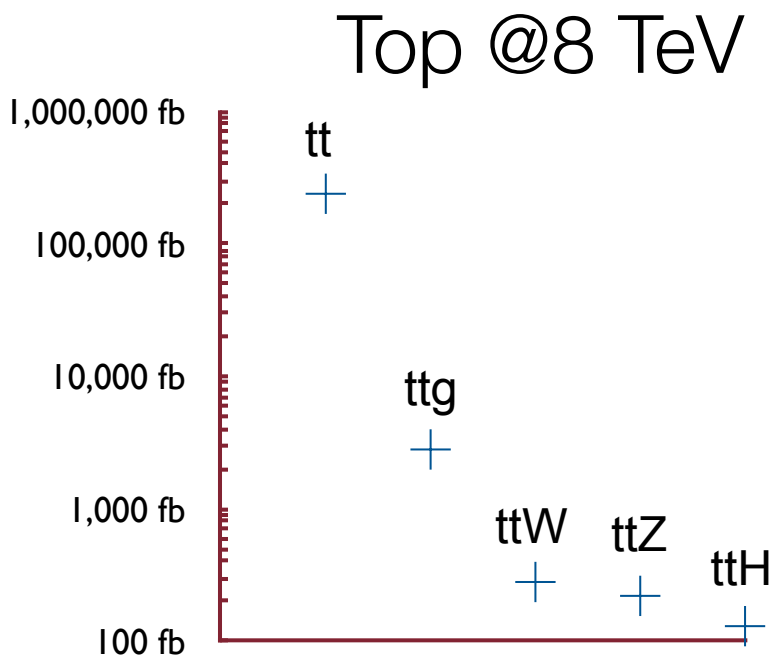


The search for ttH requires all subdetectors!

DIG DEEPER INTO THE LHC GOLD

Higgs and top cross sections at 8 TeV pp collisions





AN. COUPLING AND CP VIOLATION

- We are still left with no solution to the observed baryon asymmetry in the universe

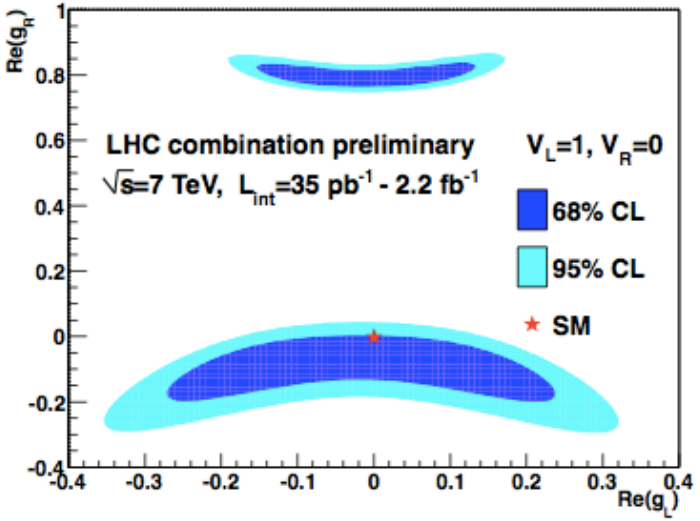
Effective lagrangian for Wtb vertex:

V_R, g_L, g_R anomalous couplings

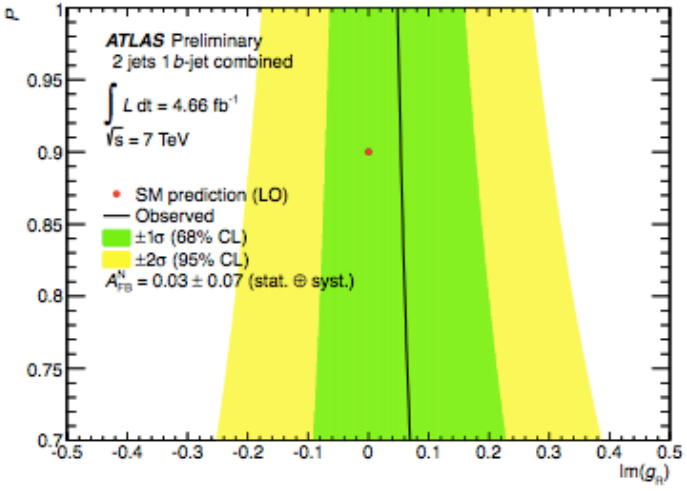
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + \text{h.c.}$$

- Interpret F_R, F_L, F_0 in terms of anomalous couplings.
- Assume $V_L = 1$, $V_R = 0$. Derive limits on g_L and g_R.
- CP violation if $Im(g_R) \neq 0$.
- A_{FB}^{N} in single top t-channel (top $\sim 90\%$ polarized).

$$A_{FB}^{N} = \frac{N(\cos\theta^{N} > 0) - N(\cos\theta^{N} < 0)}{N(\cos\theta^{N} > 0) + N(\cos\theta^{N} < 0)}$$



ATLAS-CONF-2013-033, CMS-PAS-TOP-12-025



ATLAS-CONF-2013-032

TECHNICALITIES

Signal and background modeling

- ttH, WW, WZ, ZZ Pythia
- ttW/ttZ/ttgamma/ttgammagamma/gamma+jets/ gammagamma+jets MadGraph
- tq/tW Powheg

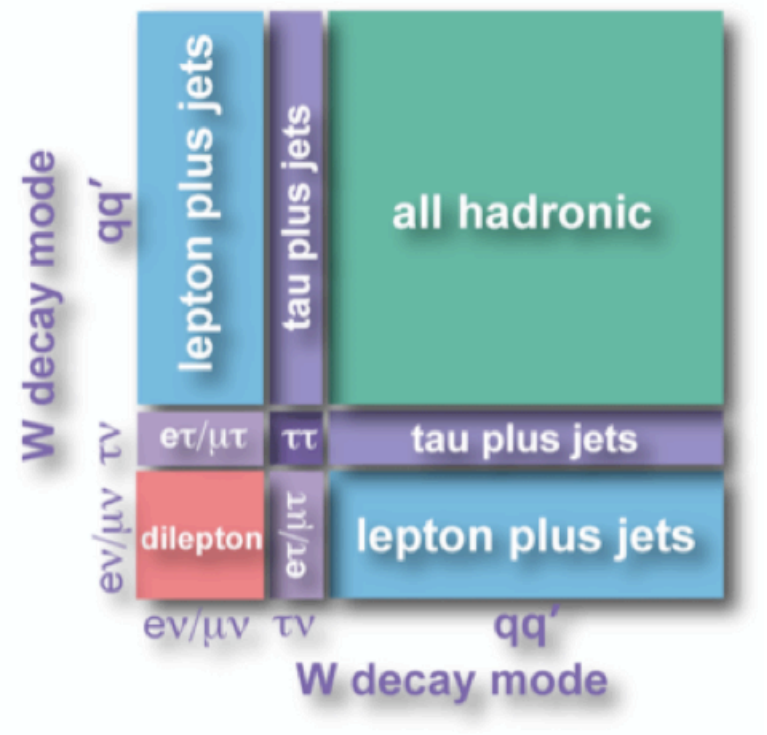
btagging

- Combined secondary vertex, medium OP
- H->bb also uses full CSV spectrum

Triggers used:

- Diphoton trigger
- Electron trigger
- Muon trigger
- ee/emu/mumu triggers

Pair production decay signatures



Total acceptance 13%

Lepton+Jets
- large BR(30%)
- good S/B ratio.

Dileptonic
- Highest S/B
- lowest BR(5%)

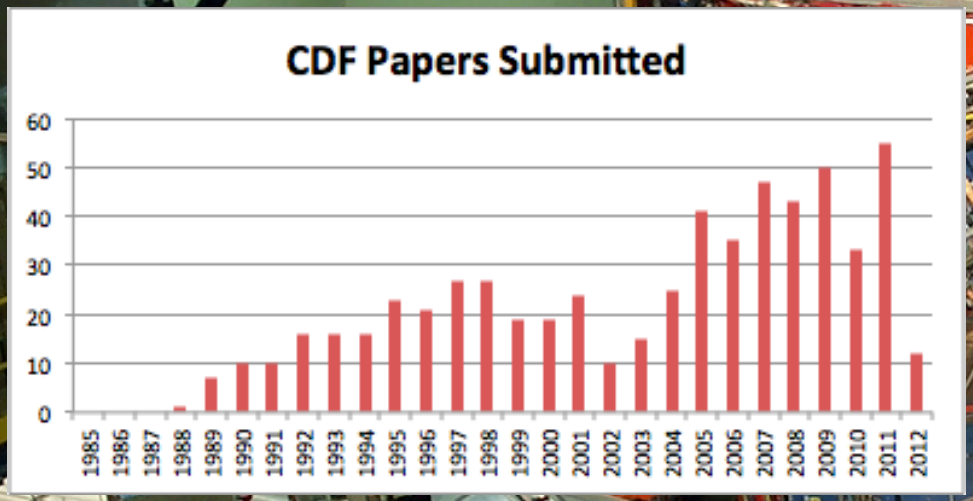
All hadronic
- highest BR(44%)
- Very large QCD background

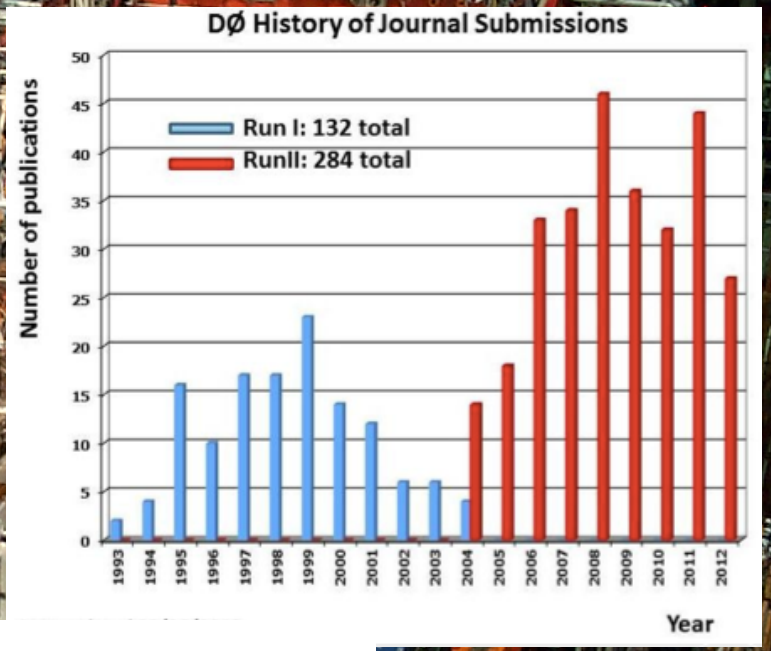
Tau modes
- explicit tau identification

MET + jets
- Lepton+jets and dileptonic decays where electron/muon is not id'ed. Large acceptance to taus

Potential to analyze more than 30 000 top quarks by end 2011

Top at the Tevatron

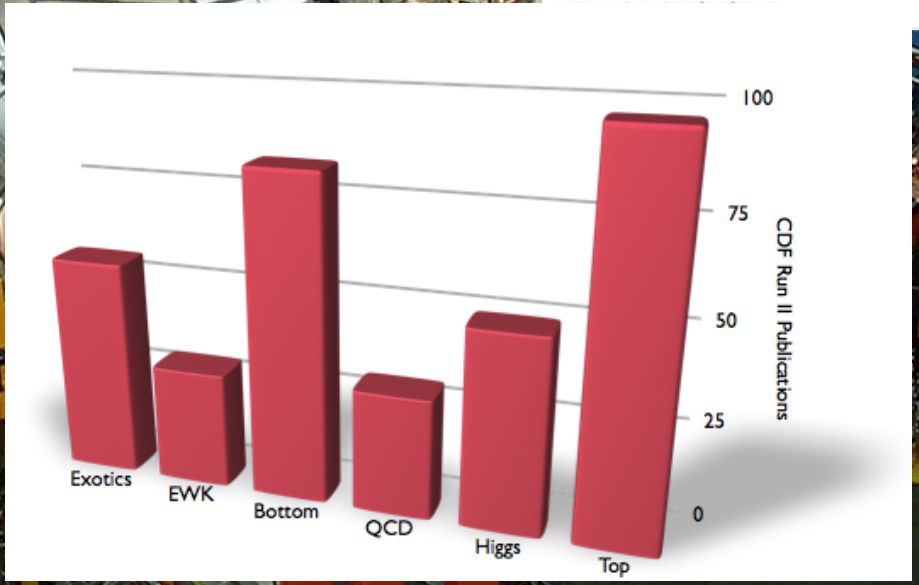




Over 1000 papers total

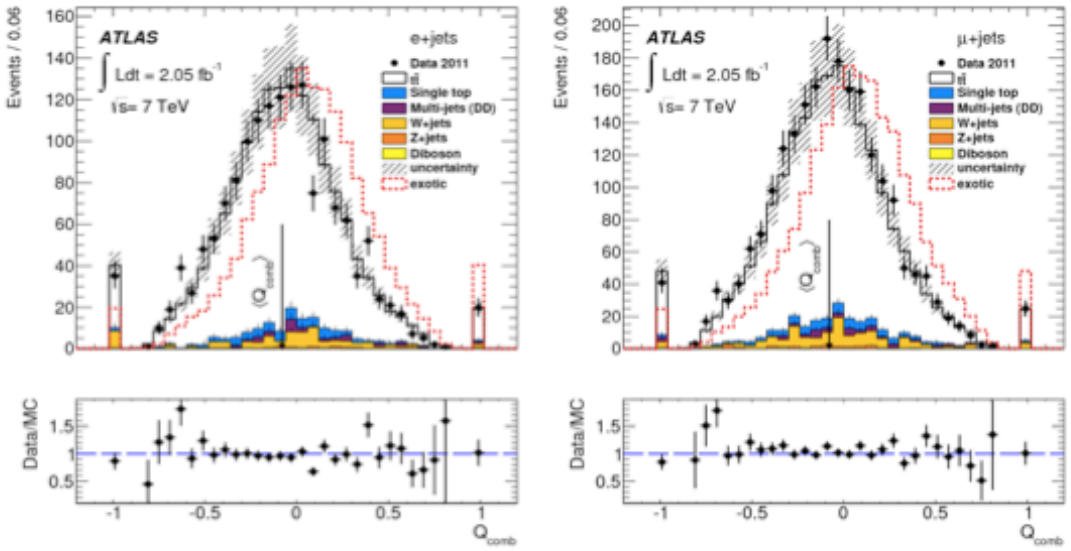
Over 600 RunII papers

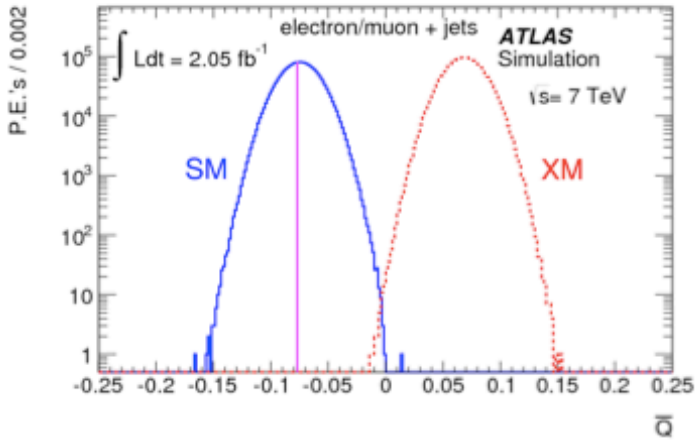
More than a quarter are top results



CDF histo.Similar numbers for D0

Charge: result





arXiv:1307.4568

$$Q_{\text{top}} = 0.64 \pm 0.02\ (\text{stat.}) \pm 0.08\ (\text{syst.})$$

channel	p_{SM}	p_{XM}	σ_{XM}(S.D.)
e	0.715	$< 10^{-7}$	8.7
μ	0.960	$< 10^{-7}$	8.3
$e+\mu$	0.852	$< 10^{-7}$	8.8

Charge compatible with SM top quark
Exotic model excluded at more than 8 sigma

OUTLINE

- Will show you today some of the most interesting results in measurements of top quark properties
  - too many to show all of them: my excuse to the authors of the beatiful results left outside
  - large overlap with other collider topics (new physics searches, flavor, Higgs, etc.) so might be some duplication
- please bear with me
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