

# Run 1 analyses end-game TOP PAG



# The top quark

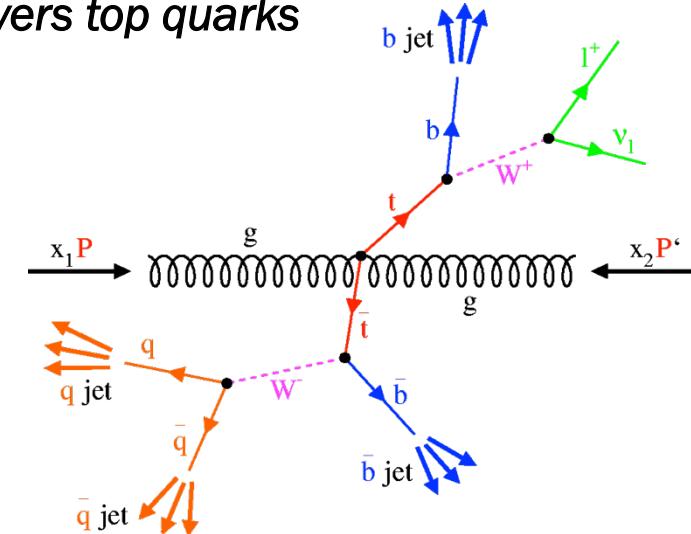


*“The top quark is special”*

– *Every speaker at every talk that covers top quarks*

But it is indeed very special:

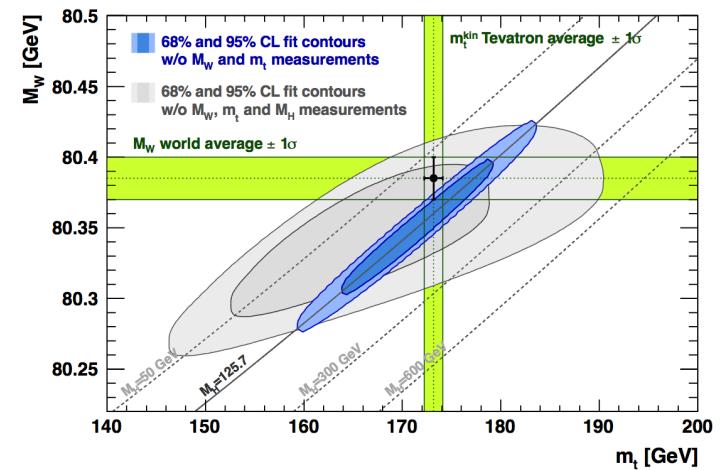
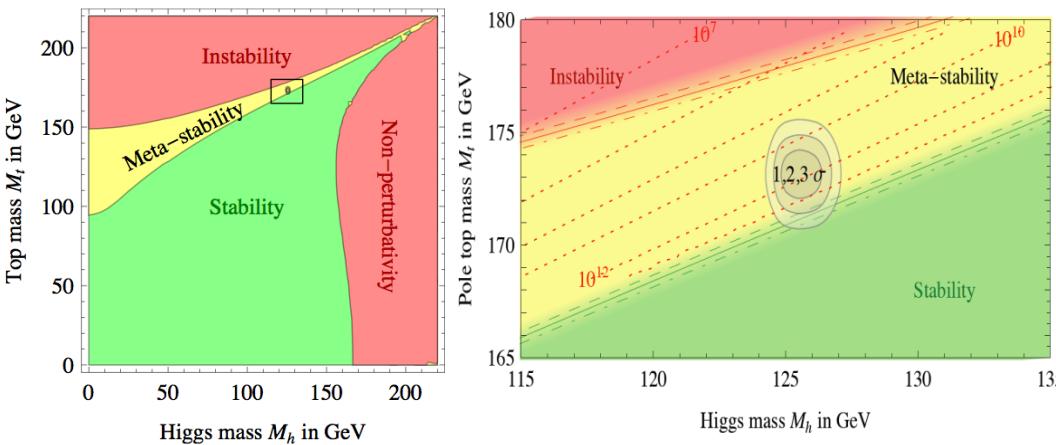
- It is the **heaviest elementary particle known**
  - $m_{top} = 173.34 \text{ GeV}$
  - But it is still point-like
  
- It has a strong **coupling to the Higgs boson**
  - Hints a role on the electroweak symmetry breaking
  - $m_{top}$  largely affects the stability of the Higgs mass
  
- It is the only quark that **decays before hadronizing**
  - By studying its decay products we have direct access to properties (spin, charge, polarization)





# Top? Physics

- Top is connected to QCD, EWK, flavor physics, and in particular Higgs  
The top quark is key to explore the Higgs sector
- Clear motivation for precision measurements (SM)  
Mass, width, cross sections, differential distributions...
- Top analyses require the development of tools and expertise useful beyond top  
i.e b-tag
- Natural way to go towards BSM physics (SUSY/EXO/B2G)

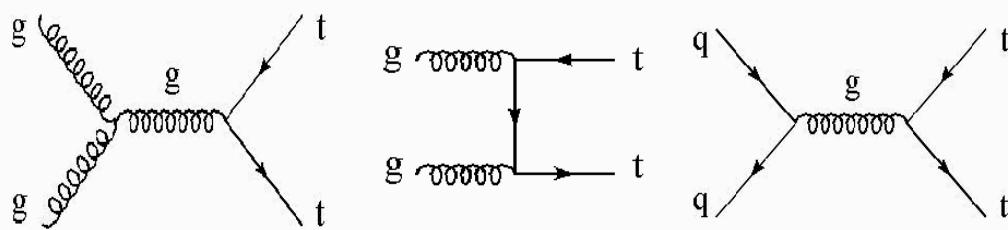




# Top quark production

Main production mode:

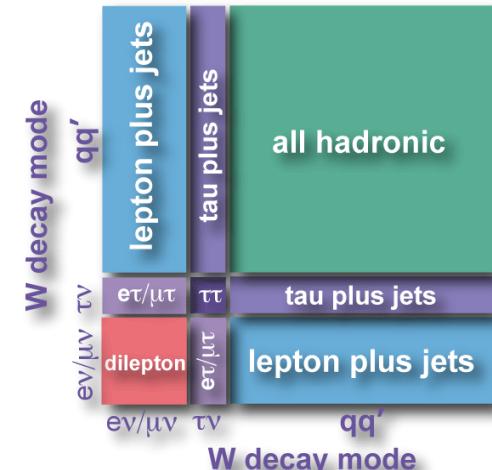
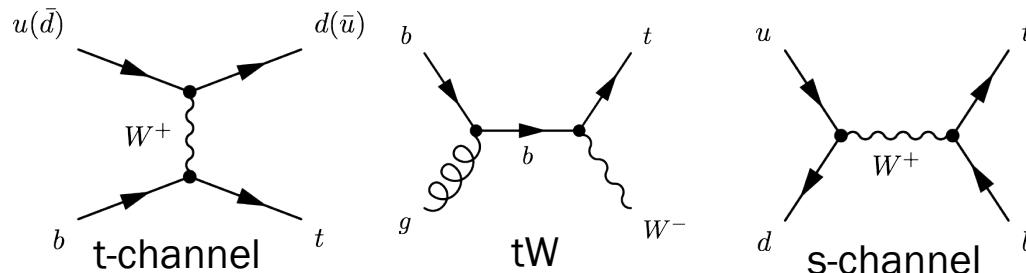
→ ttbar pairs, via strong interaction (QCD)



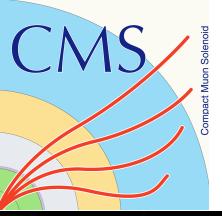
In the SM:  
 $t \rightarrow W b$  ( $\sim 100\%$ )

Alternative:

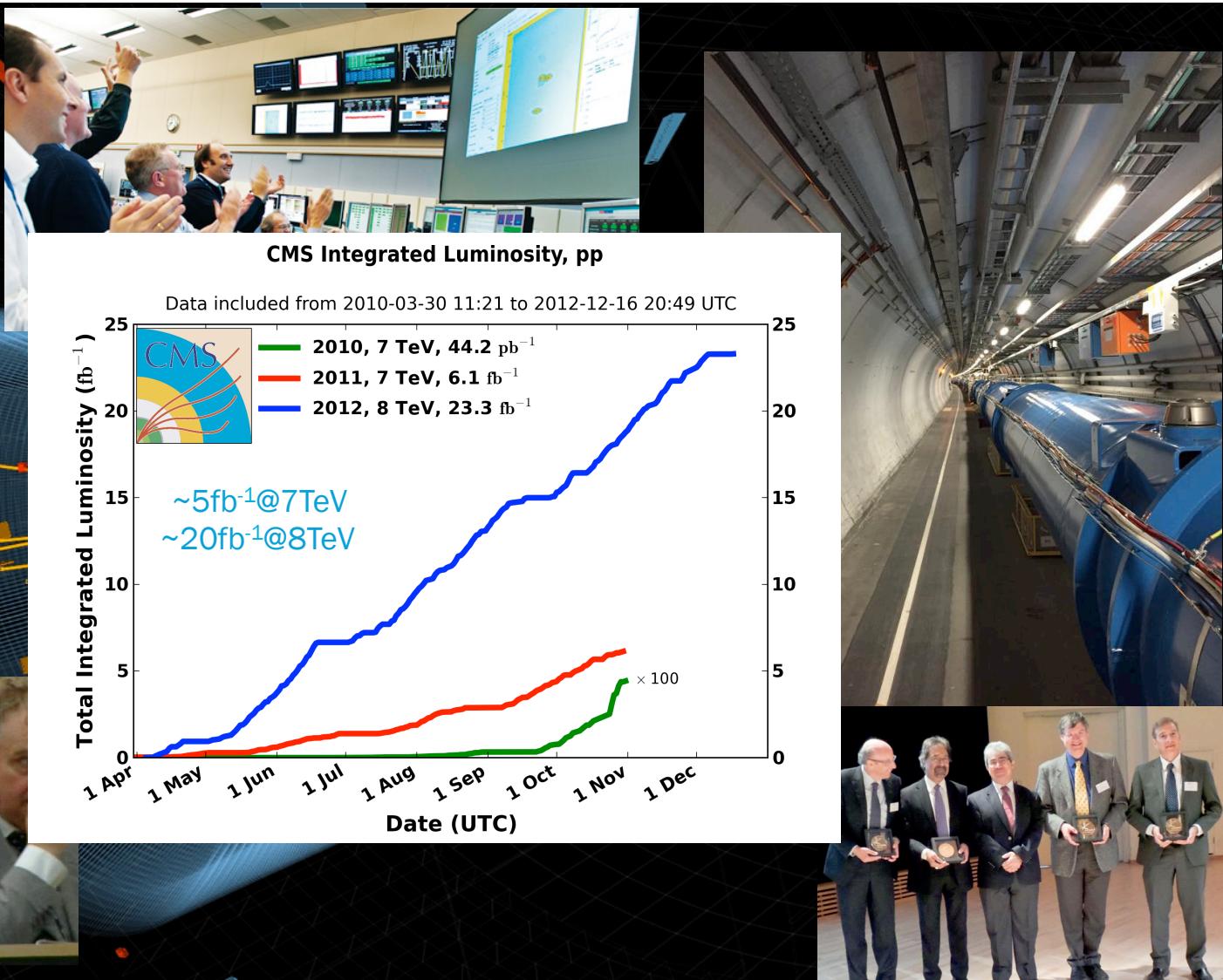
→ single top quarks (EWK production), much smaller rate

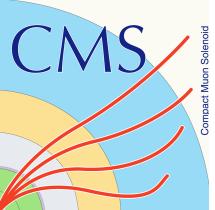


$\sigma$ [pb]	ttbar	t-channel	tW	s-channel
LHC (7 TeV)	163	64.6	15.6	4.59
LHC (8 TeV)	234	87.1	22.2	5.55

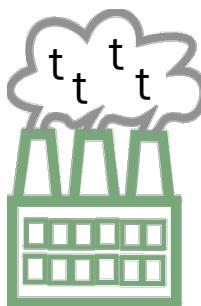
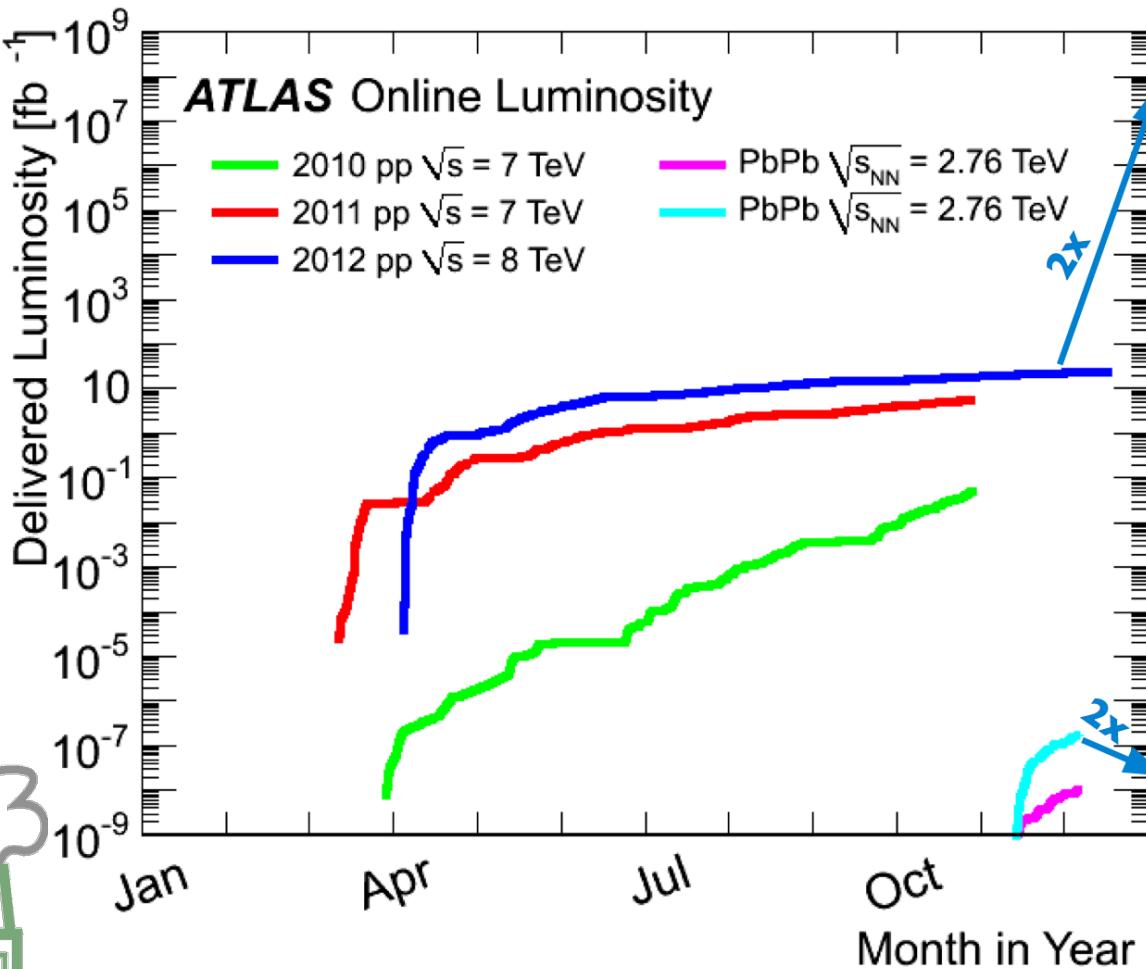


# LHC Run 1 (2009 - 2013)



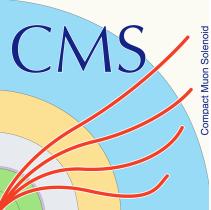


# Run-1 in top quarks



LHC: Certified top factory

Stolen from Pedro's talk on TOP2014 ([slides](#))



# A bit more than 4 years ago...

**Top-Quark Studies at CMS**

Tim Christiansen (CERN)  
on behalf of the CMS Collaboration

ICHEP 2010, Paris  
35th International Conference on  
High-Energy Physics  
22–28 July 2010

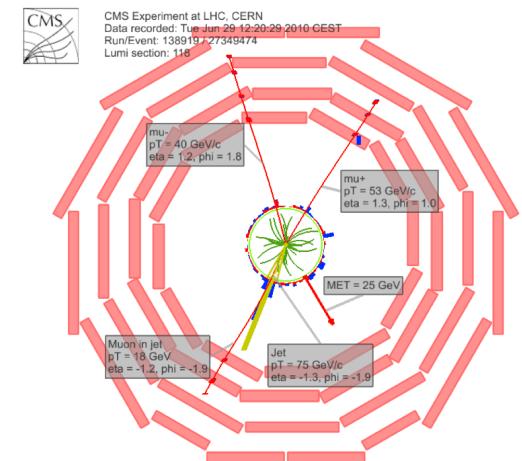
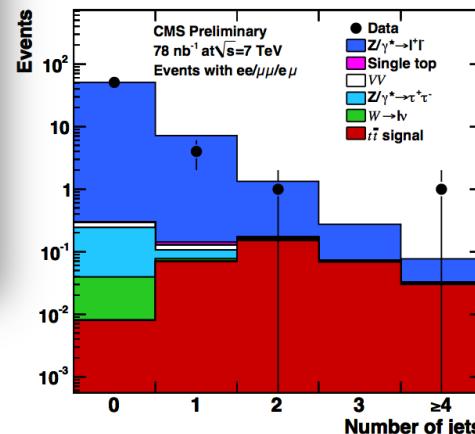
**ICHEP PARIS 2010**

**Follow all the way to Top to get new directions**

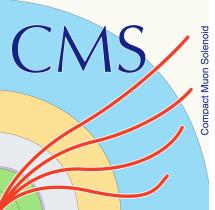
ICHEP 2010 in Paris Featured  
**CMS PAS TOP-10-004**

<http://cds.cern.ch/record/1280706>

‘Selection of Top-Like Events in the Dilepton and Lepton-plus-Jets Channels in Early 7 TeV Data’  
A preliminary result with just 78.5 nb<sup>-1</sup>



Our first PAS with data



# ... and just some days ago

TOP 2014 in Cannes, France (28 Sep. – 3 Oct.) THE conference for top physics

- <https://indico.in2p3.fr/event/10114/>

We presented several new results in TOP this year:

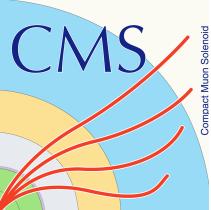
- 2 papers
  - TOP-12-020 [arXiv:1410.1154](#) (submitted to JHEP)
  - TOP-13-012 [arXiv:1409.7339](#) (submitted to JHEP)
- 6 PAses
  - TOP-14-014, TOP-14-004, TOP-14-015, TOP-14-009, TOP-14-016, TOP-14-010

## CMS ruled the poster session

- 3 . James with TOP-13-012 (ex-aequo)
- 2 . Markus with TOP-14-001 ‘[Palme d’Argent](#)’
- 1. Benjamin with TOP-13-007 ‘[Palme d’Or!](#)’**



PALME D'OR  
FESTIVAL DE CANNES



# Some numbers

- 82 Public Analysis Summaries in cds
- 38 Papers submitted journals
  - 36 of them already published
- Planned ~38 more Run-1 publications
  - Most cases work already ongoing
  - 1 FR, 2 post-CWR

The European Physical Journal  
volume 74 number 4 april - 2014

**EPJ C**  
Recognized by European Physical Society

Particles and Fields

CMS,  $\sqrt{s} = 7 \text{ TeV}$

CMS 2011, dilepton  $\Delta m^2 < 0.11 \text{ GeV}$ ,  $L_3 + L_2 + p_T$   
 $175.60 \pm 4.50 \pm 4.82 \text{ GeV}$

CMS 2011, dilepton  $\Delta m^2 < 0.11 \text{ GeV}$ ,  $L_3 + L_2 + p_T$   
 $172.50 \pm 0.45 \pm 1.48 \text{ GeV}$

CMS 2011, dilepton jets  $\Delta m^2 < 0.11 \text{ GeV}$ ,  $L_3 + L_2 + p_T$   
 $173.49 \pm 0.27 \pm 1.08 \text{ GeV}$

CMS 2011, dilepton jets  $\Delta m^2 < 0.11 \text{ GeV}$ ,  $L_3 + L_2 + p_T$   
 $172.54 \pm 0.30 \pm 1.21 \text{ GeV}$

CMS combination  $\Delta m^2 < 0.11 \text{ GeV}$ ,  $L_3 + L_2 + p_T$   
 $173.18 \pm 0.32 \pm 0.96 \text{ GeV}$

Tevatron combination  $\Delta m^2 < 0.11 \text{ GeV}$ ,  $L_3 + L_2 + p_T$   
 $173.18 \pm 0.70 \pm 0.78 \text{ GeV}$

Overview of the different measurements combining the CMS and Tevatron data. The shaded band shows the combined CMS result. The error bars include all systematic uncertainties. From the CMS Collaboration: Measurement of the top quark mass in  $\ell\ell\nu\bar{\nu}$  events at  $\sqrt{s} = 7 \text{ TeV}$ . *Phys. Rev. D* 89 (2014) 031301, arXiv:1308.4445.

Springer

**Physics** spotlighting exceptional research

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**Viewpoint: Top Quarks Go Solo in Rare Events**

**Richard Hawkins**, CERN, Geneva, Switzerland

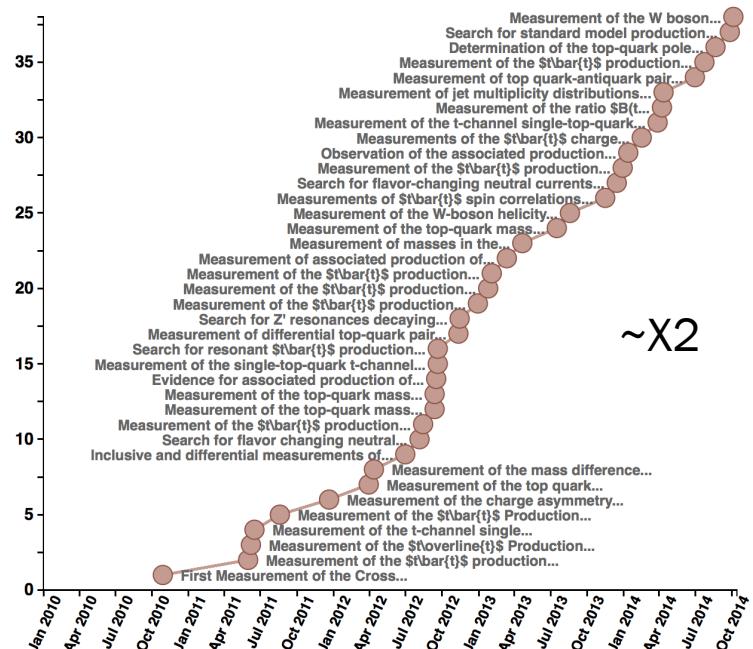
Published June 9, 2014 | Physics 7, 61 (2014) | DOI: 10.1103/Physics.7.61

Separate collider experiments observe the top quark without its usual antiparticle partner in unique processes that could give insight into new physics, such as additional sets of quarks.

The subatomic elementary particles known as quarks are among the building blocks of the standard model (SM) of particle physics. Protons and neutrons are made of the lightest, up and down quarks, but the unstable strange, charm, bottom, and top quarks can also be produced in high-energy particle accelerators. This enigmatic top

Observation of  $t$ -Channel Production of Single Top Quarks at the Tevatron T. Aaltonen et al. (CDF Collaboration); T. D0 Collaboration

38 papers submitted as of 2014-10-10



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**Best value for top quark's mass: Tevatron and LHC scientists announces first joint result**



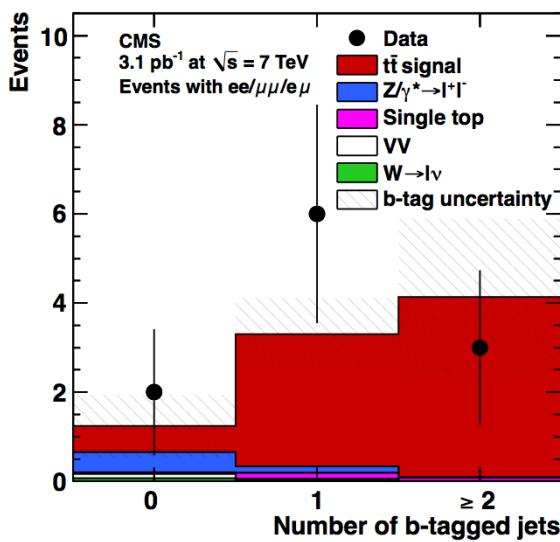
# Organization

Ending 2014  
Starting 2015

- The current top PAG conveners are
  - **Martijn Mulders**, Andreas Meyer, and **Andrea Giammanco**
- TOP has at the moment 4 top subgroups:
  - **cross sections:** **Akram Khan**, Mara Senghi Soares, **James Keaveney**
  - **mass:** **Pedro Silva**, Benjamin Stieger, **Hartmut Stadie**
  - **properties:** **Efe Yazgan**, Jacob Linacre, **Thorsten Chwalek**
  - **single top:** **Rebeca Gonzalez Suarez**, Orso Iorio, **Nadjieh Jafari**
- And works together with ATLAS and the theory community in the context of the **TOP LHC Working Group**
- More info, including contact persons for different tasks and POGs:
  - <https://twiki.cern.ch/twiki/bin/view/CMS/TWikiTopQuark>



# Top cross sections



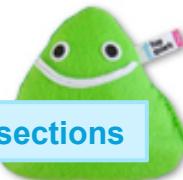
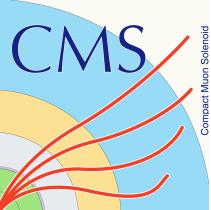
October 2010  
 PLB 695 (2011) 424  
[arXiv:1010.5994](https://arxiv.org/abs/1010.5994)

First TOP paper

'First Measurement of the Cross Section for Top-Quark Pair Production in Proton-Proton Collisions at  $\sqrt{s}=7$  TeV'

$3.1\text{pb}^{-1}$  dilepton ( $e,\mu$ )

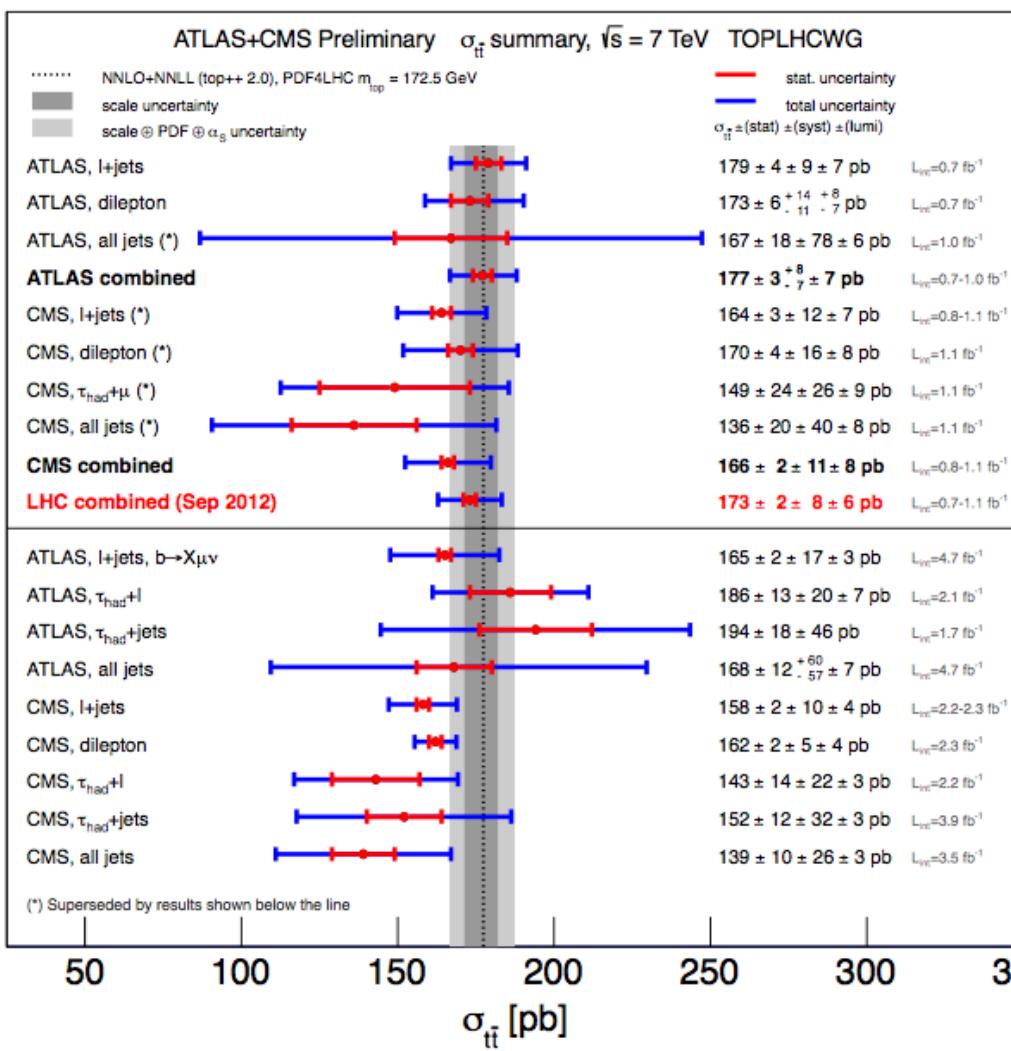
$\sigma_{tt} = 194 \pm 72 \text{ (stat.)} \pm 24 \text{ (syst.)} \pm 21 \text{ (lumi.) pb}$



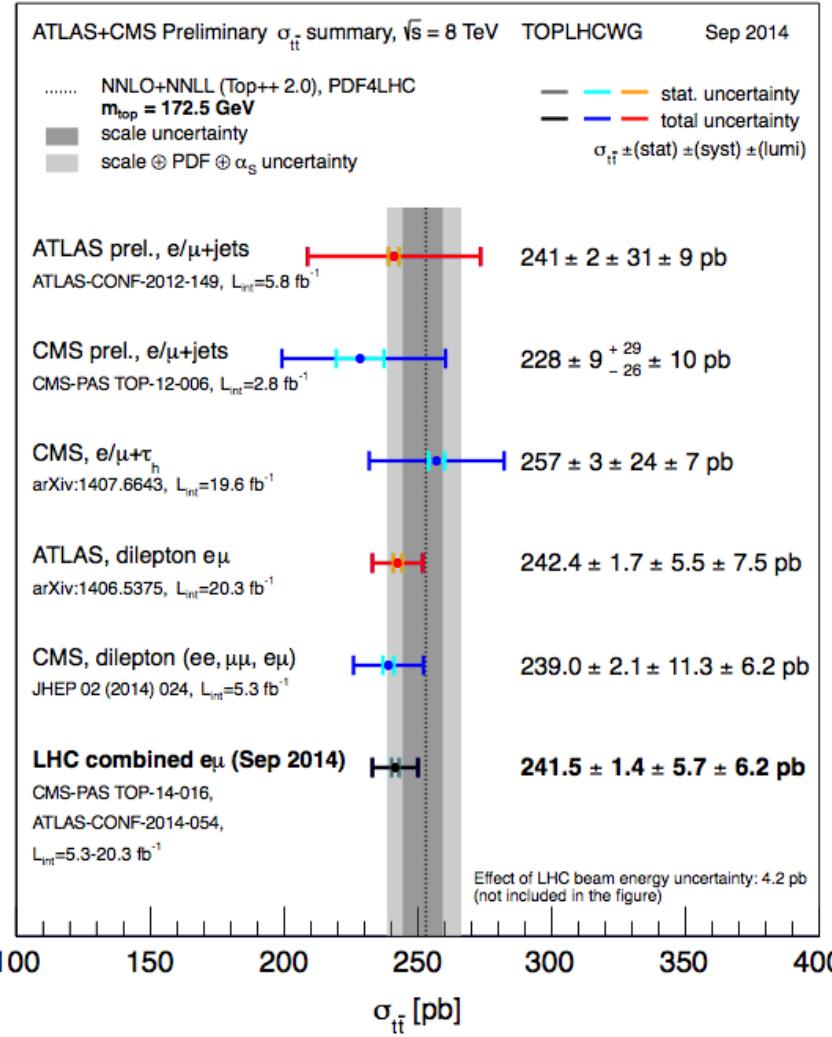
# Inclusive

Cross sections

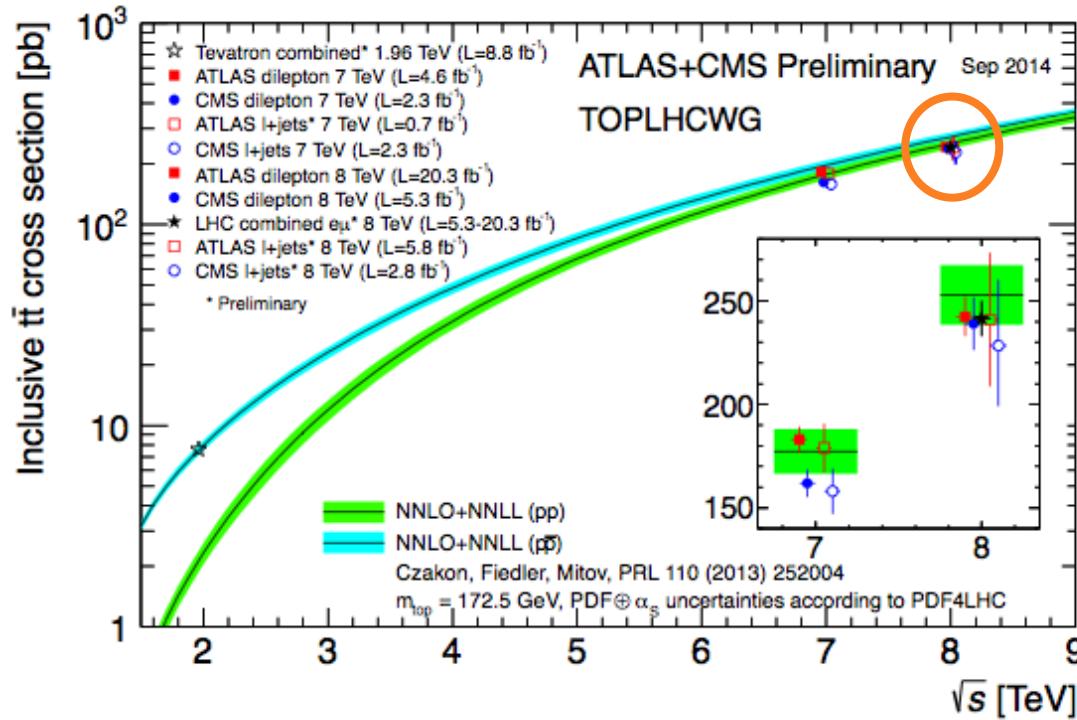
7TeV



8TeV



# Inclusive Legacy 8TeV

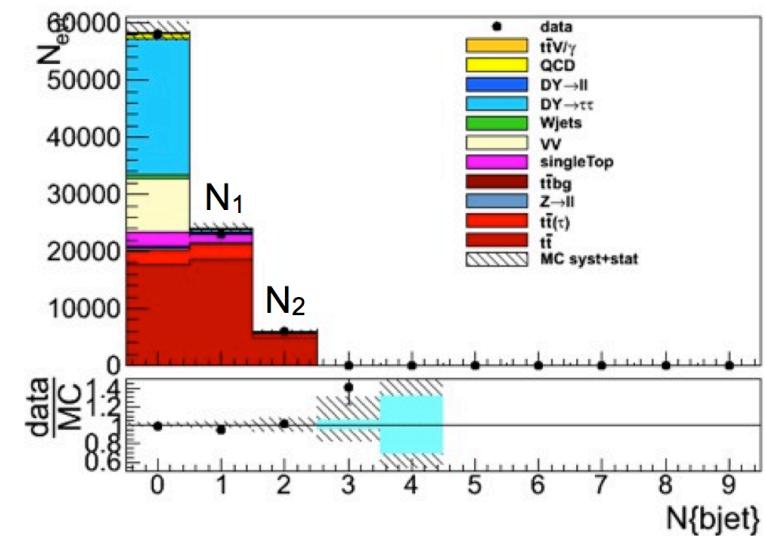


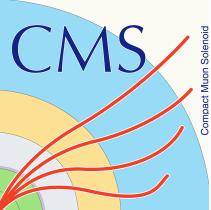
The legacy papers will include ratios, will focus on achieving the best precision possible

→ Dilepton (TOP-13-004) will include 1btag category to constrain b-tag systematics

## 8TeV HPA

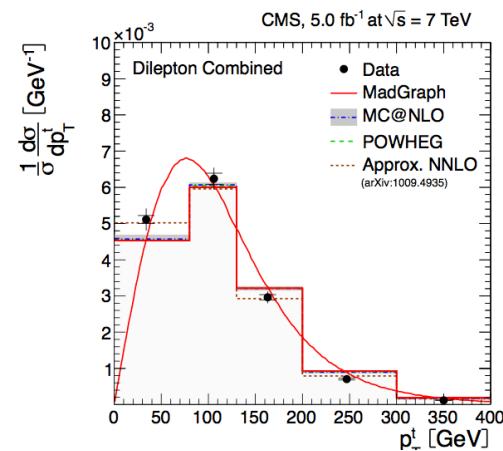
- **dilepton** published → legacy paper in preparation
- **I+jets** preliminary → Extended paper draft in progress (TOP-12-006)





# Differential

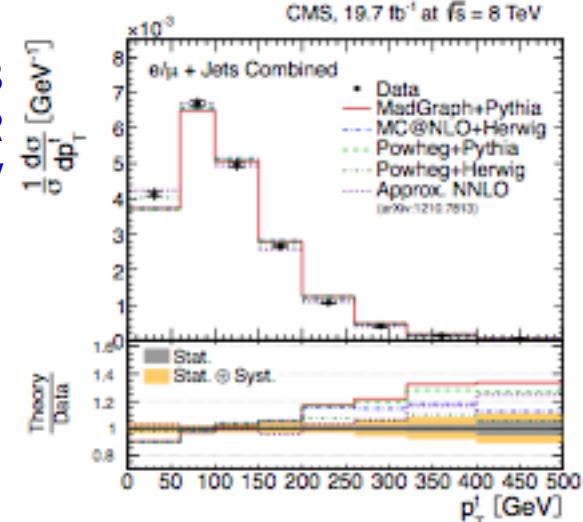
Cross sections



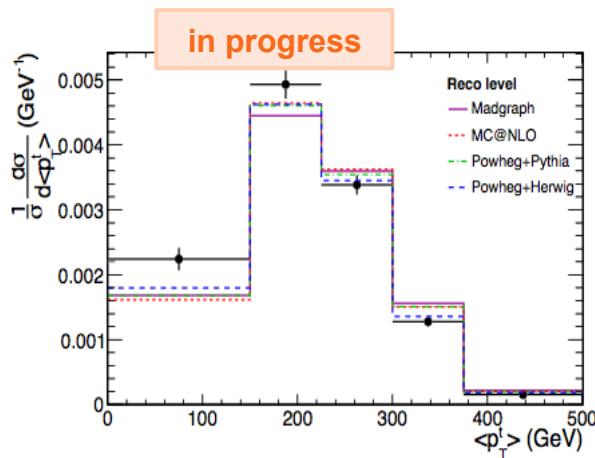
November 2012  
 EPJC 73 (2013) 2339  
[arXiv:1211.2220](https://arxiv.org/abs/1211.2220)  
 Dilepton, l+jets  
 7TeV 5fb $^{-1}$

First differential

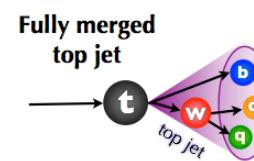
TOP-12-028  
 Post CWR  
 Dilepton 8TeV



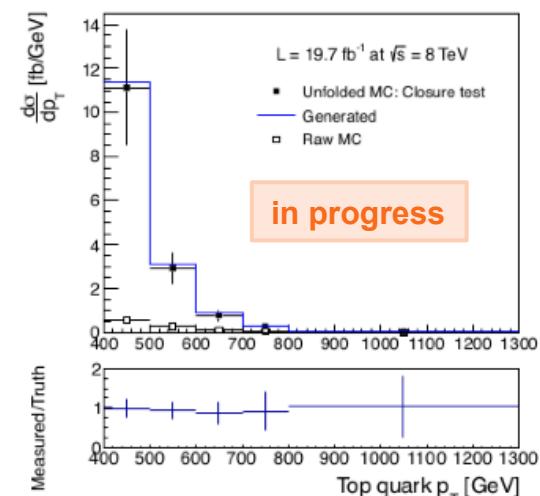
- Differential cross sections studied at 7 and 8 TeV, in all channels.
- Slope discrepancy found at large  $p_T$  (confirmed by ATLAS), still to be understood by the theory → top  $p_T$  reweighting (widely used in top-related analyses)



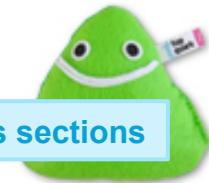
All had.  
 TOP-14-018



Boosted top  
 TOP-14-012



New: Exploring directly large  $p_T$   
 (background free)



# Publication plans

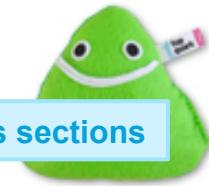
Cross sections

Inclusive cross sections (7TeV done):

- **TOP-12-006** Top pair cross section in  $e/\mu+jets$  at 8 TeV (Fall 2014)
  - Legacy paper  $t+jets$
  - analysis being finalized, paper draft in review
- **TOP-13-004** Legacy Run I inclusive cross-section including 8/7 TeV ratios (Fall 2014)
  - Legacy paper dileptons, full 2012 statistics, ultimate precision
  - Includes extraction of pole mass and limits on SUSY

Differential cross sections

- **TOP-12-028** ttbar Differential cross sections at 8 TeV (NOW)
  - dilepton and  $t+jets$ , paper draft post-CWR (includes TOP-12-027)
- **TOP-12-042** Measurement of MET,  $H_T$  and other global distributions in top pair events at 7 and 8 TeV (Fall 2014)
  - first paper draft available (includes TOP-12-019)
- **TOP-14-013** Double differential top pair cross-section at 8 TeV
  - analysis started



# Publication plans (II)

Cross sections

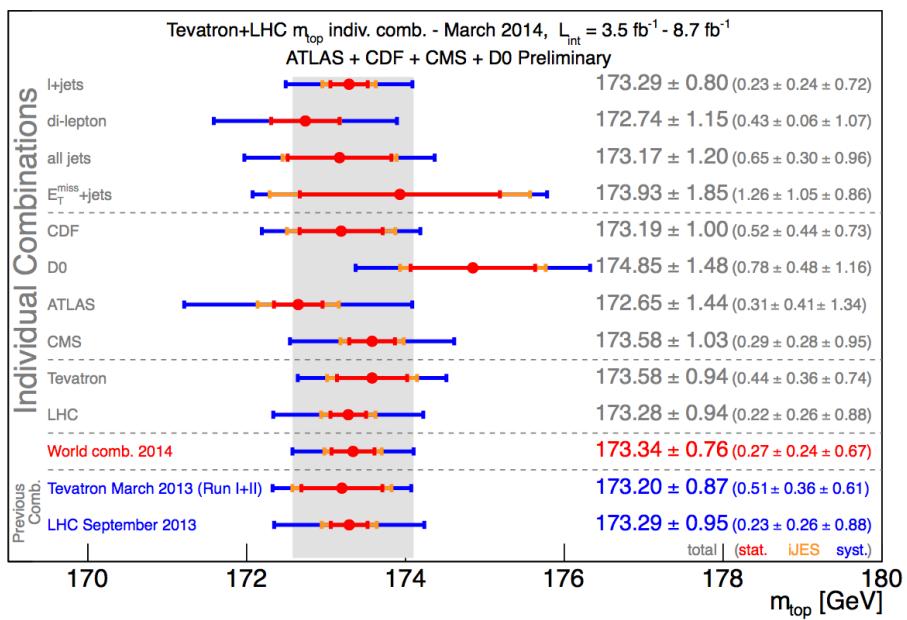
- **TOP-14-018** ttbar inclusive and differential cross section in the **fully hadronic final state**
- **TOP-14-012** ttbar differential cross section in **boosted topologies**
  - Both analyses aiming for paper end of 2014

There are other analyses covered by top cross sections (tt+jets, ttbb...) that have provided very interesting public results, more to come:

- **TOP-12-041** Measurement of jet multiplicity in top pair events at 8 TeV (Winter 2014)
  - dilepton, preliminary since Spring 2013
- **TOP-XX-YYY** 8 TeV tt+jets
  - l+jets, analysis starting
- **TOP-13-010** Measurement of ttbb cross section at 8 TeV (NOW)
  - dilepton, In Final Reading
- **TOP-13-016** Measurement of tt+bb in l+jets channel at 8 TeV (Fall 2014)
- **TOP-XX-YYY** Pseudo-Top (RIVET optimized) differential cross-section analysis



# Top mass

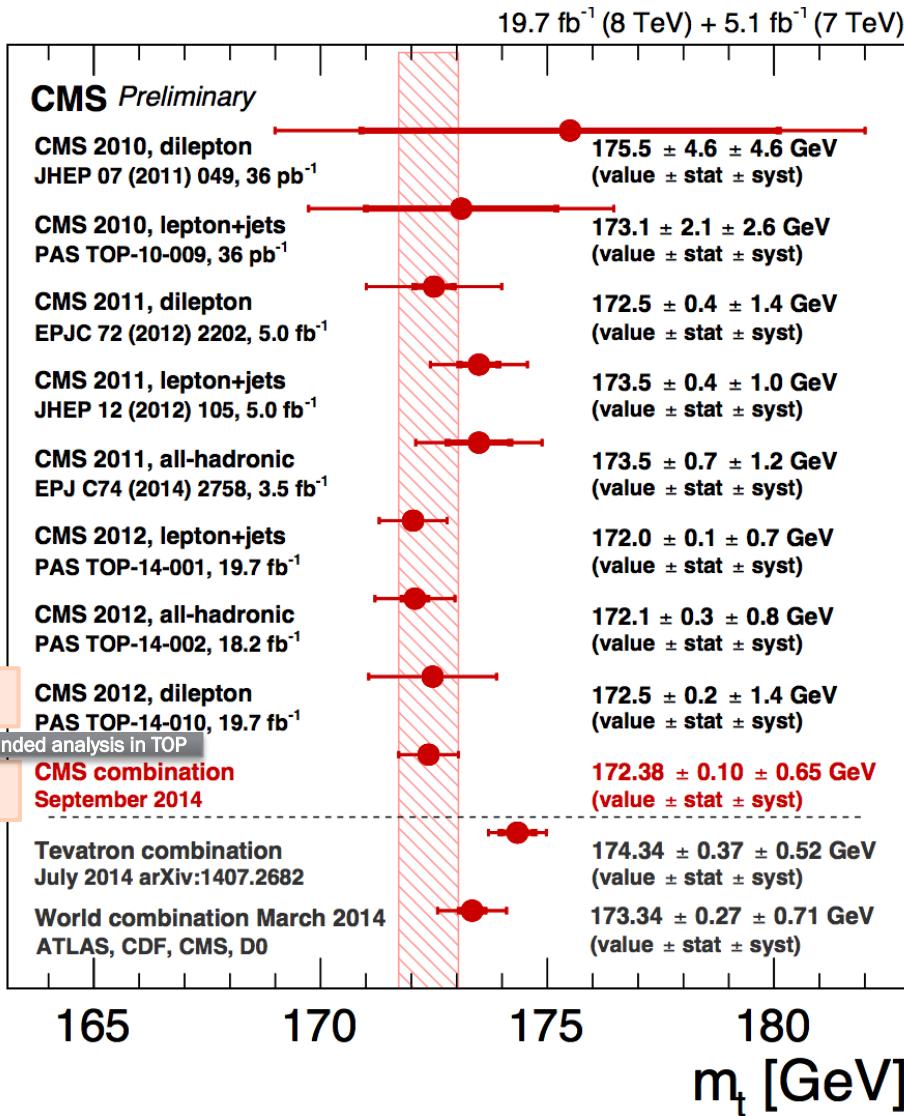


First Tevatron-LHC combination

March 2014  
[arXiv:1403.4427](https://arxiv.org/abs/1403.4427)

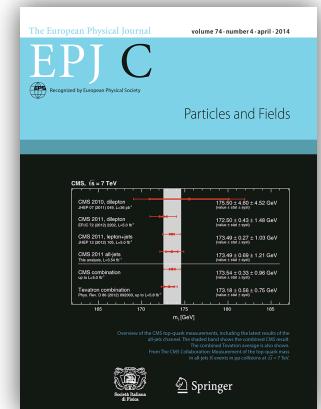


# Standard methods



- CMS is the **most precise** experiment

7 TeV:  
All published  
(4 papers)



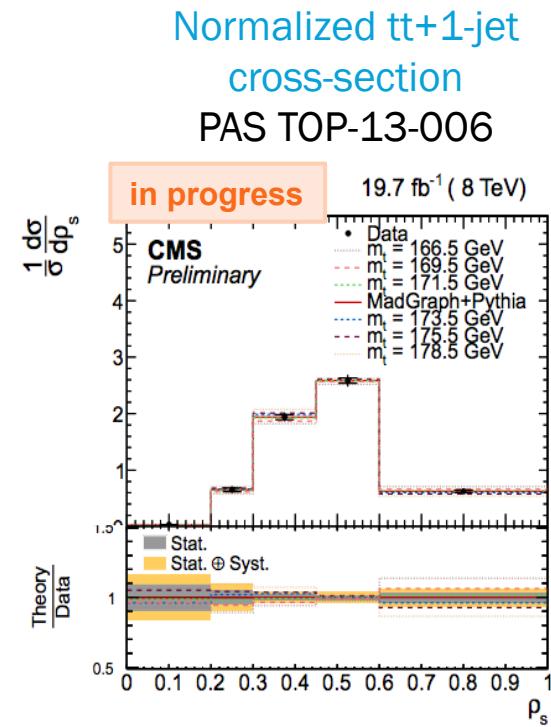
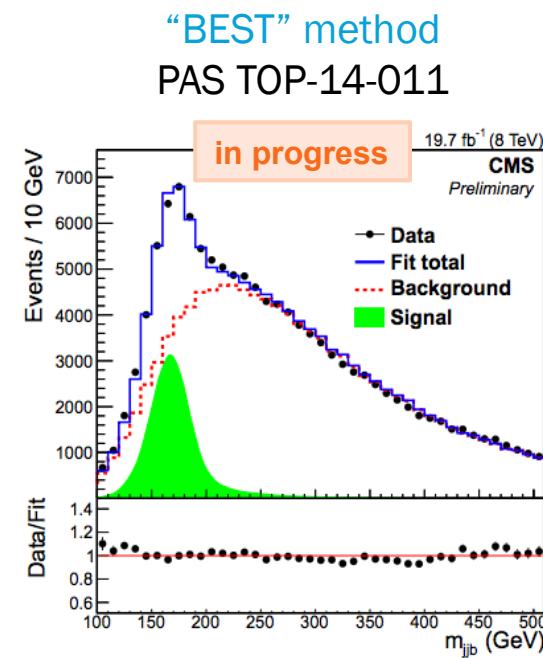
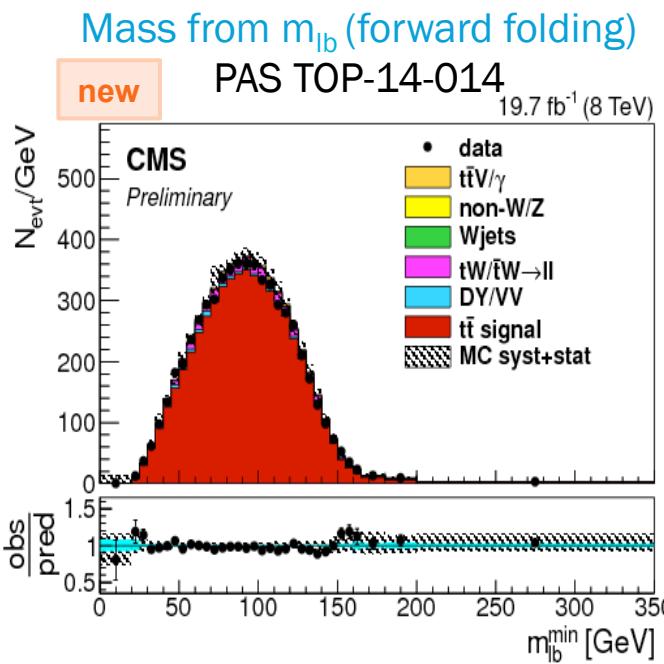
8 TeV:  
1 legacy paper planned  
includes CMS 7+8 TeV  
combination

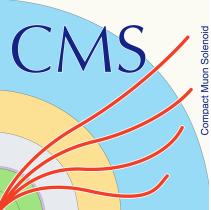
End of 2014 - TOP-14-022  
(merges TOP-14-001/02/10/15)



# Alternative methods

- We also have a **complete** set of alternative mass methods
  - Goal: to improve our **understanding** of measured top observable
- Already Published:** mass from cross-section, mass from endpoints
  - Various PAses ready + new methods still being added





# Publication Plan

Standard methods (7TeV all done)

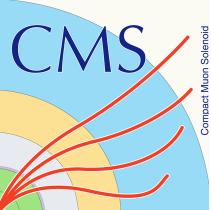
- **TOP-14-022** Legacy Run I top mass (standard methods) (Fall 2014)
  - merges **14-001/02/10/15**
  - PAS (4x) public, paper draft in preparation

Top/antitop mass difference (published at 7TeV)

- **TOP-12-031** Top anti-top mass difference at 8 TeV
  - [POST CWR](#)

Alternative methods

- **TOP-12-030** Top mass from B hadron life time (Fall 2014)
  - PAS public, improved method in development
- **TOP-13-007** Study of Underlying Event in top pair events (Spring 2015)
  - PAS public, work ongoing

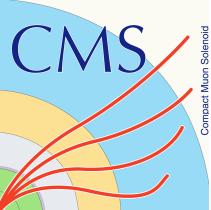


# Publication Plan (II)

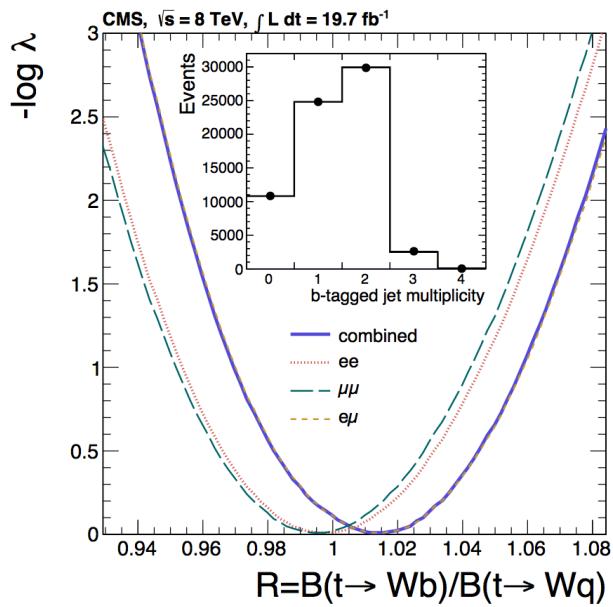
More alternative methods:

- TOP-13-006 Top mass from tt+1 jet events (Fall 2014)
  - PAS pre-approved
- TOP-14-011 Top mass using the BEST method (Fall 2014)
  - PAS pre-approved
- TOP-14-014 Measurement of top mass from  $m_{lb}$ 
  - PAS approved
- TOP-XX-YYY Measurement of the top mass using kinematic endpoints at 8 TeV
  - Work ongoing
- TOP-XX-YYY Measurement of the top mass using the J/psi method at 8 TeV
  - Work ongoing

Round table of publication plan and preparation for Run II  
will occur next week during the top mass meeting



# Top Properties



April 2014

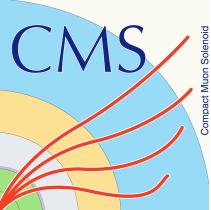
Phys. Lett. B 736 (2014) 33  
[arXiv:1404.2292](https://arxiv.org/abs/1404.2292)

Ratio R

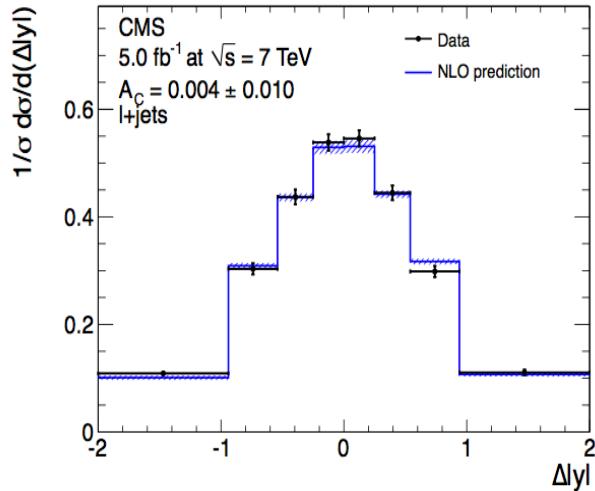
$B(t \rightarrow Wb)/B(t \rightarrow Wq)$

8TeV,  $19.7\text{fb}^{-1}$

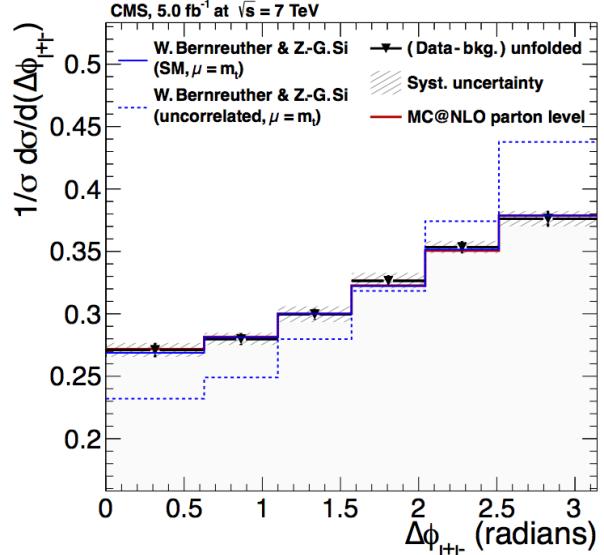
dilepton



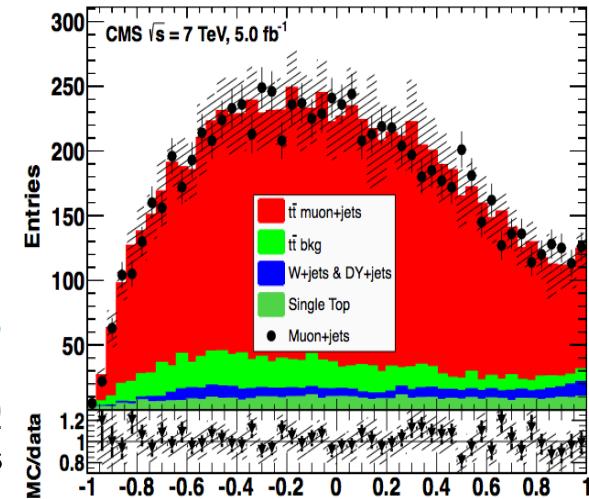
# Angular distributions



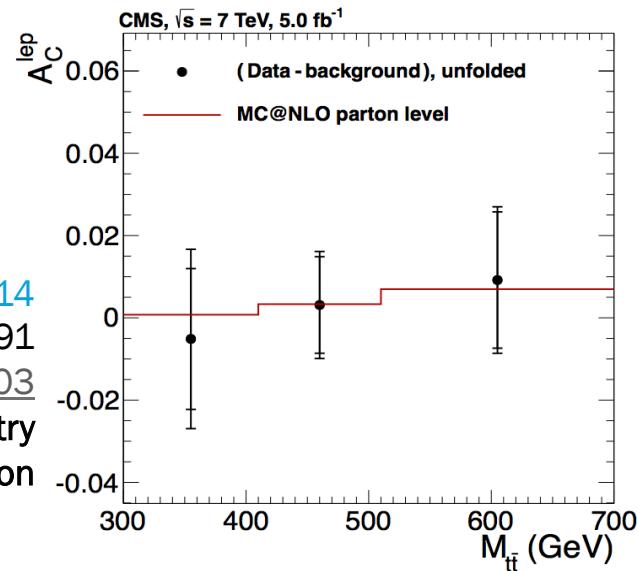
June 2012  
Phys. Lett. B 717 (2012) 129  
[arXiv:1207.0065](https://arxiv.org/abs/1207.0065)  
charge asymmetry, l+jets



November 2013  
Phys. Rev. Lett. 112 (2004) 182001  
[arXiv:1311.3924](https://arxiv.org/abs/1311.3924)  
spin correlations  
and top-quark  
polarization  
Dilepton



August 2013  
JHEP 10 (2013) 167  
[arXiv:1308.3879](https://arxiv.org/abs/1308.3879)  
W-helicity l+jets

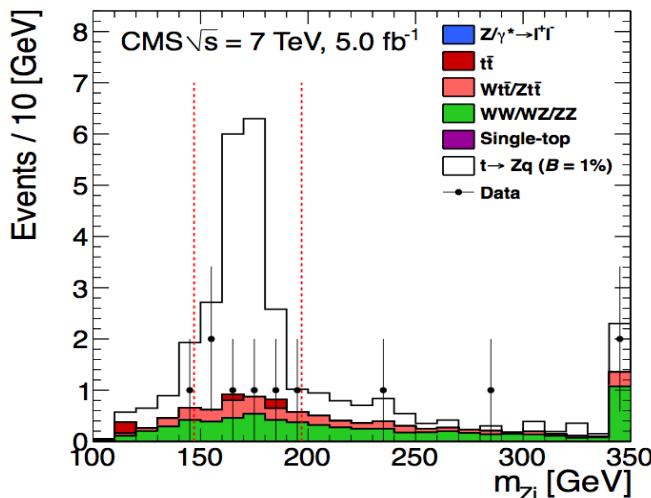


February 2014  
JHEP 04 (2014) 191  
[arXiv:1402.3803](https://arxiv.org/abs/1402.3803)  
charge asymmetry  
Dilepton

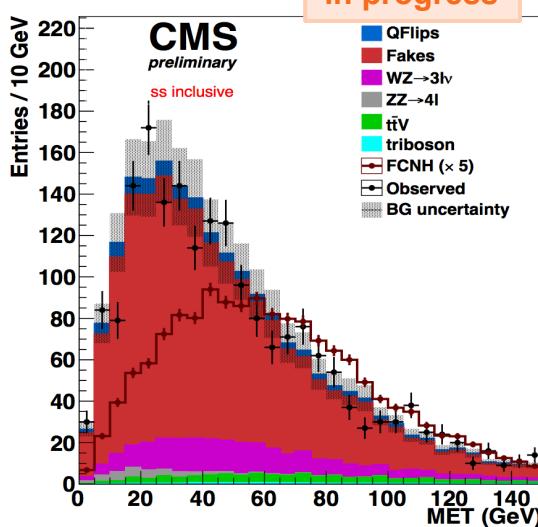
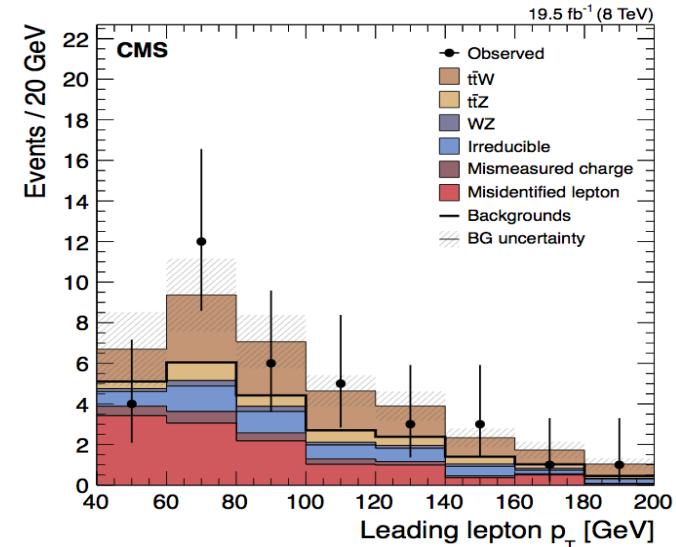


# Everything else (FCNC, $t\bar{t} + X$ , $t \rightarrow X \dots$ )

Properties



August 2012  
 Phys. Lett. B 718  
 (2013) 1252  
[arXiv:1208.0957](https://arxiv.org/abs/1208.0957)  
 FCNC  $tZq$  decay, 3 leptons



Search for flavor changing neutral Higgs (FCNH)  
 Three PAses, may be merged into one paper (tbd)  
 → TOP-13-017 pre-approved yesterday  
 (multilepton  $H \rightarrow WW, ZZ, TT$ )



# Publication Plan

## Charge asymmetry

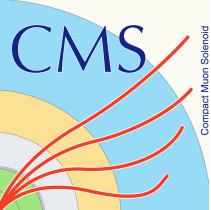
- **TOP-12-033** Measurement of the ttbar charge asymmetry at 8 TeV (Fall 2014)
  - includes **TOP-12-034**
- **TOP-13-013** Determination of initial-state-dependent charge asymmetries in l +jet events at 8 TeV (Winter 2015)

## W-helicities

- **TOP-13-008** W helicity and anomalous couplings (8 TeV, l+jets + 7/8 combined) (Winter 2015)
- **TOP-14-017** W helicity and anomalous couplings (8 TeV, dilepton + 7/8 combined) (Winter 2015)

## Spin correlations

- **TOP-13-015** ttbar spin correlations using **Matrix Element Methods** (8 TeV, l+jets) (Winter 2015)
- **TOP-XX-YYY** 8 TeV reprise of the 7 TeV dilepton analysis (TOP-13-003 for 7 TeV) including limits on top chromo moments (TOP-14-005 for 7 TeV)



# Publication Plan (II)

## tt+X

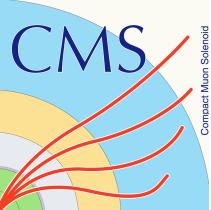
- **TOP-14-008** ttbar+ $\gamma\gamma$  in l+jet and dileptons at 8 TeV (Winter 2015)
  - includes **TOP-13-011**
- **TOP-14-021** (?) tt+W/Z analysis for improved sensitivity
  - On going

## FCNH

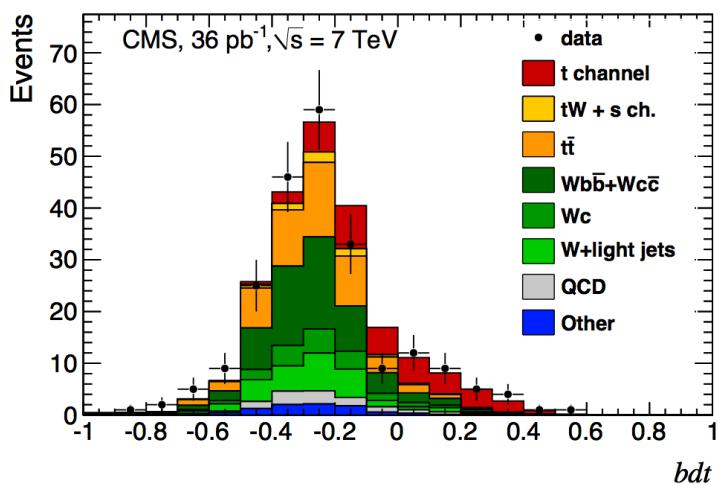
- **TOP-14-019** FCNH- $\rightarrow\gamma\gamma$  (Winter 2015)
  - merge with **TOP-14-020** (FCNH- $\rightarrow bb$ ) and **TOP-13-017** (multilepton H $\rightarrow WW, ZZ, \tau\tau$ ) (tbd)

## Other

- **TOP-XX-YYY** Extraction of top pole mass, alpha\_s from (differential) cross sections at 8 TeV (pole mass also could be a part of the cross section legacy paper)
- **TOP-XX-YYY** Direct measurement of the Top Width



# Single top



Jun 2011

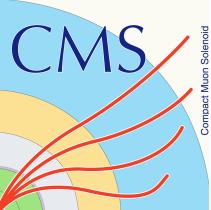
Phys.Rev.Lett.107:091802,2011  
[arXiv:1106.3052](https://arxiv.org/abs/1106.3052)

t-channel

36pb<sup>-1</sup>

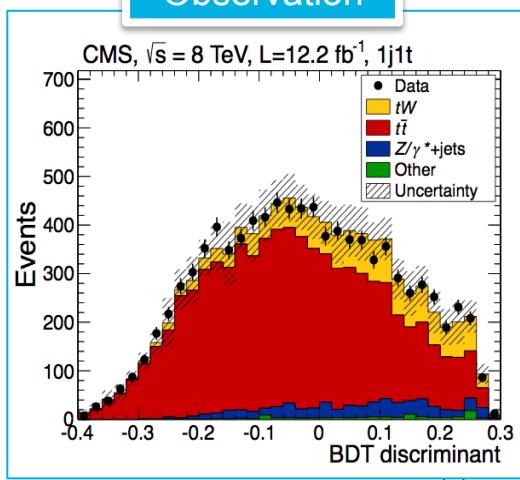
2D ( $\cos\theta^*$ ,  $\eta_{j'}$ ) and BDT

LHC Milestone



# t-channel, tW, and s-channel

## Observation



January 2014

Phys. Rev. Lett. 112  
(2014) 231802  
[arXiv:1401.2942](https://arxiv.org/abs/1401.2942)

$tW$  (BDT, shape, cut)  
 $6.1\sigma$

September 2012

Phys. Rev. Lett. 110 (2013) 022003  
[arXiv:1209.3489](https://arxiv.org/abs/1209.3489)

CMS Preliminary

Single top-quark production

September 2012

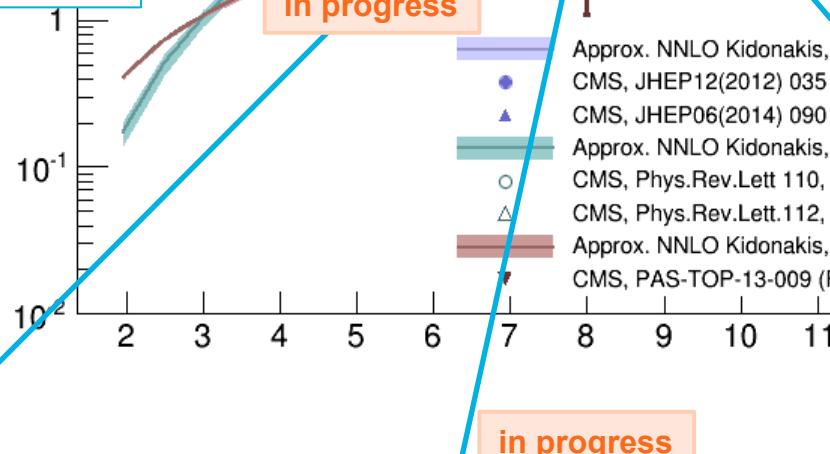
JHEP 12 (2012) 035  
[arXiv:1209.4533](https://arxiv.org/abs/1209.4533)

t-channel

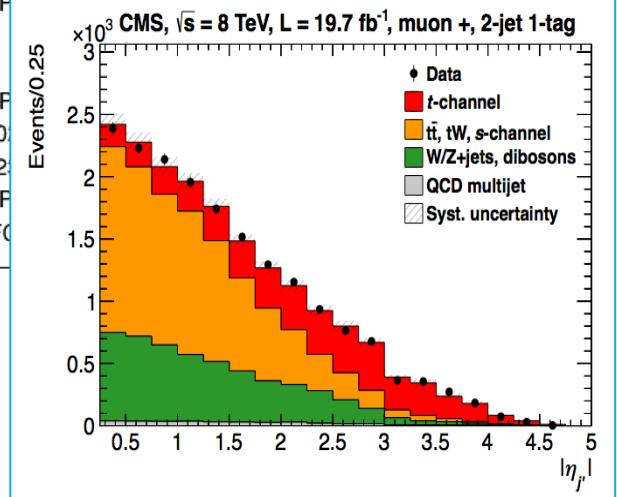
tW

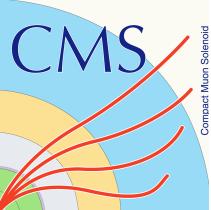
s-channel

in progress

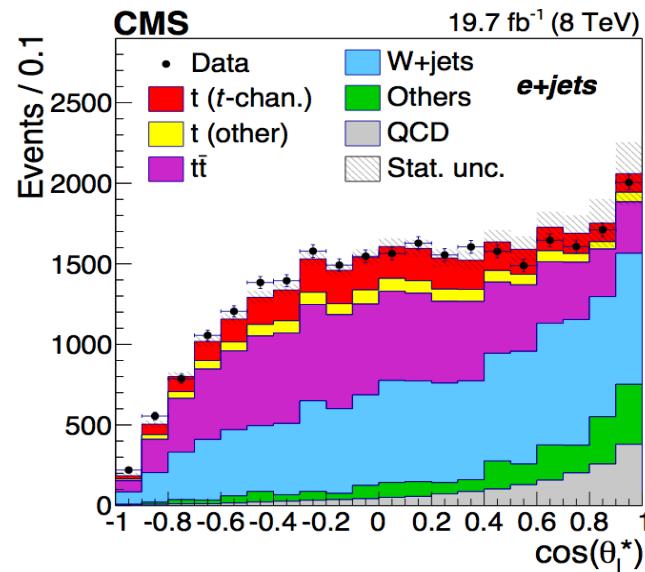


November 2013  
[PAS TOP-13-009](https://cds.cern.ch/record/1600000)





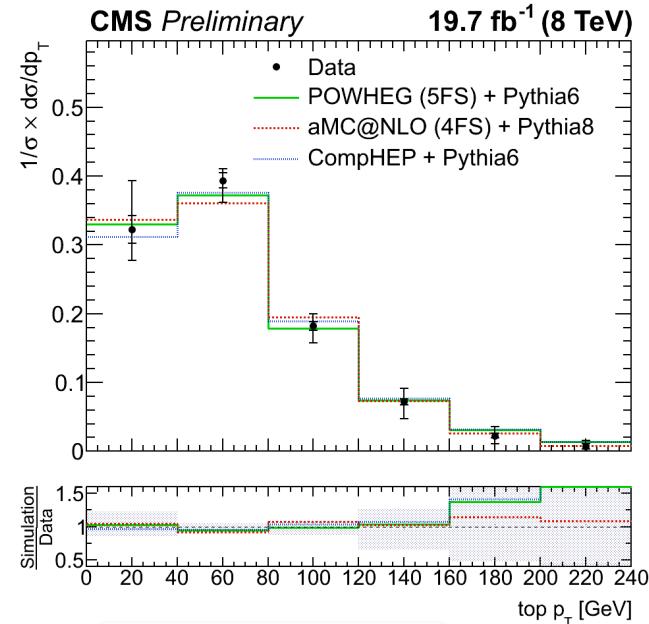
# Most Recent - 8TeV 19.7fb<sup>-1</sup>



First CMS paper of top properties in single top

September 2014  
CMS PAS TOP-14-004  
differential single top quark t channel cross sections  
 $p_T$  and  $y$

October 2014  
Sub. to JHEP  
[arXiv:1410.1154](https://arxiv.org/abs/1410.1154)  
W boson helicity in t-channel



First CMS single top differential

t-channel well known, cross section well measured (inclusive and differential), already being used for measuring **top properties** (top polarization, W-helicities, mass)  
FCNC and Anomalous couplings in different single top signatures also under study



# Publication plans

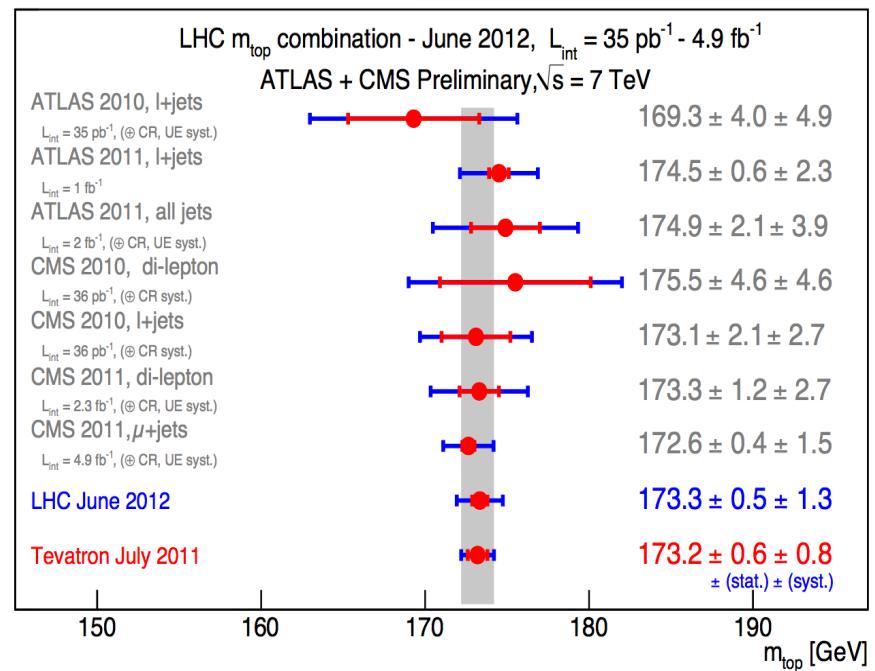
- TOP-13-001 Measurement of **top polarization** in single top (Fall 2014)
  - PAS public, t-channel, work ongoing
- TOP-13-009 Single top production in the s-channel (Winter 2014)
  - PAS public, work ongoing
- TOP-12-039 Search for FCNC in single top events at 8 TeV (Winter 2014)
  - PAS at 7TeV, tZq (FCNC and SM), work ongoing
- TOP-14-003 Search for FCNC in single top events at 8 TeV (Winter 2014)
  - PAS public, ty, work ongoing
- TOP-14-007 Search for Anomalous Couplings and FCNC in single top events at 8 TeV (Winter 2014)
  - PAS public, t-channel, work ongoing
- TOP-14-004 Measurement of single top t-channel differential cross sections
  - PAS public
- Also ongoing:
  - Top mass in single top, t-channel **fiducial cross-sections**, tW l+jets



# TOPLHCWG

- Ongoing ATLAS+CMS effort to do **LHC combinations**, some of the combinations may be published
  - Top mass (post-legacy papers), single top...
  
- CMS contact person for the TOPLHCWG:
  - **Roberto Chierici**
  
- The contacts of the working groups are:
  - ✓ cross section: Maria Aldaya
  - ✓ single top: Luca Lista
  - ✓ top mass: Steve Wimpenny
  - ✓ W helicity: Mara Senghi
  - ✓ Charge asymm.: Thorsten Chwalek
  - Differential: Maria Aldaya

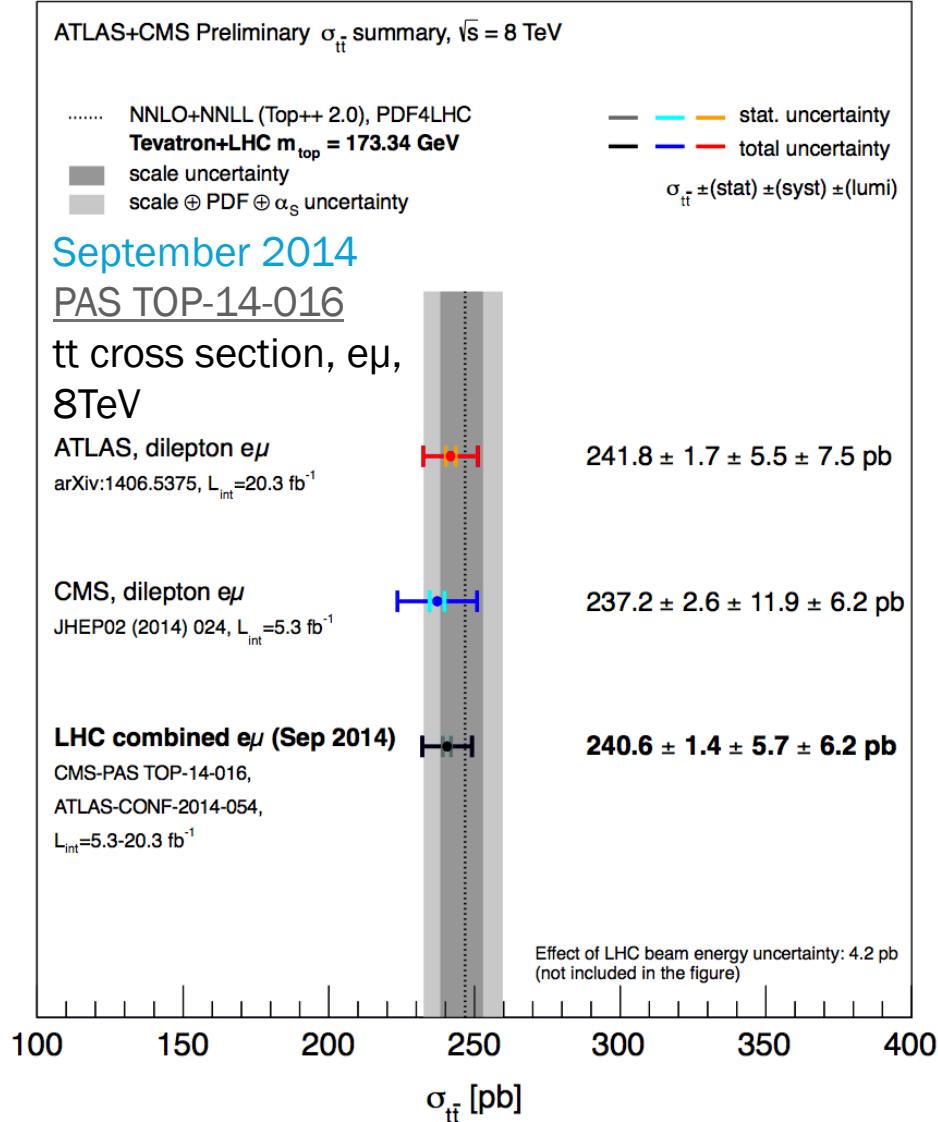
First TOP LHC combination



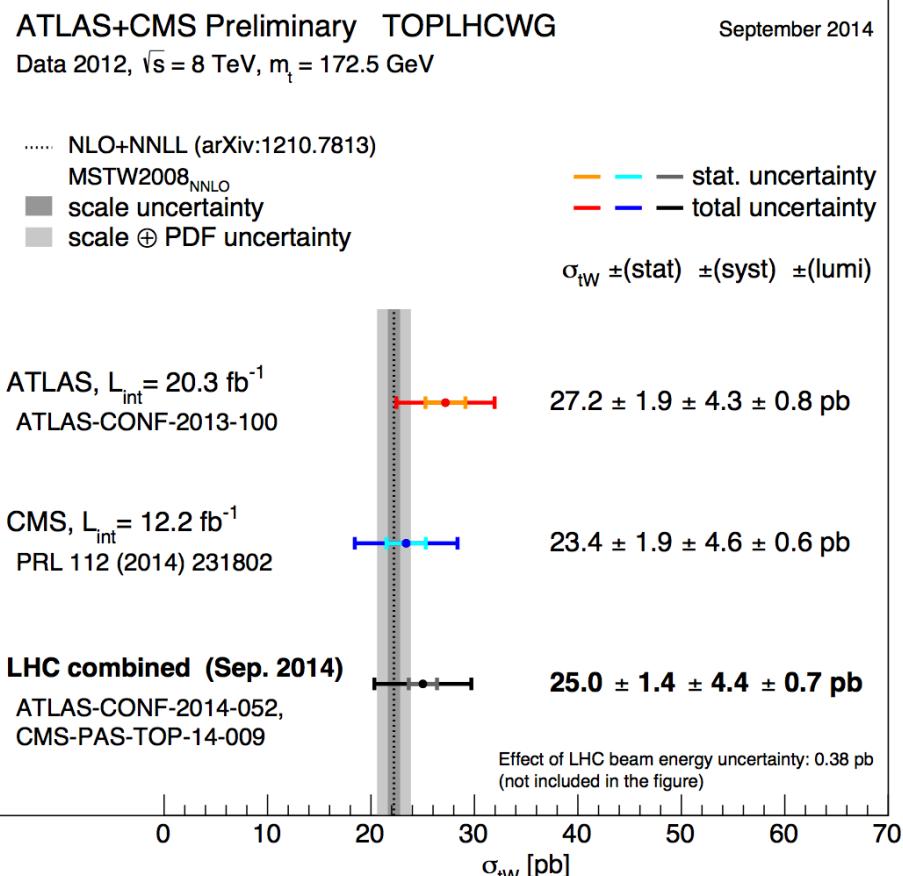
- More info [[Twiki](#)]

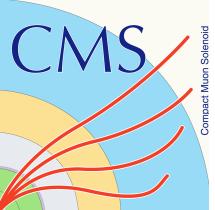
July 2012  
PAS TOP-12-001  
 Top mass combination

# Latest



**September 2014**  
PAS TOP-14-009  
tW combination, 8TeV





# Summary

- Top quark physics had a **very prolific and successful Run-1**
- **38 Run-1 TOP papers** and 82 public PASes
  - Enormous amount of work already public
  - All info available in:
    - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP>
- While we are getting ready for Run-2, **we are not finished yet with Run-1**
  - Many analyses ongoing
    - ~38 new papers already planned
  - Several important publications are still to come
    - <https://twiki.cern.ch/twiki/bin/viewauth/CMS/Internal/PublicationPlan2014#TOP>
- Some topics that could still be explored with Run-1 are uncovered, and some would profit from more manpower → Join us!