

Single Top production in CMS: Lessons learned from Run-1 and future prospects



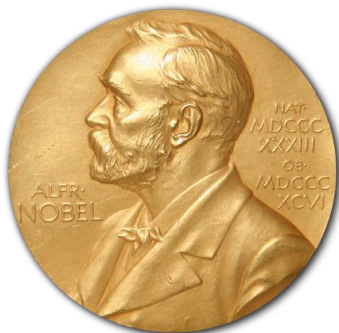
2^d CMS Single top workshop
4-5 December 2014
Naples, Italy

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University of Nebraska, Lincoln

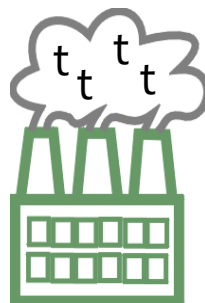
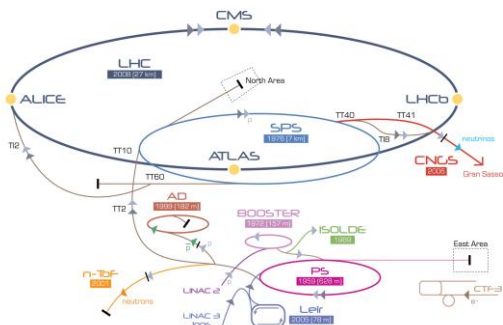


- The Run-1 of the LHC started in March 2010 and ended in February 2013
- During three years:
 - $\sim 5\text{fb}^{-1}$ at 7TeV and $\sim 20\text{fb}^{-1}$ at 8TeV of pp collisions
- It was great for many reasons

Most obvious one, though it was not for 'us'



- For top physics in particular it was really good



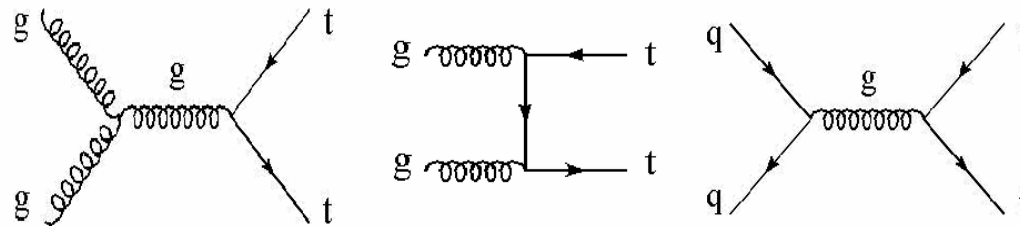
Top quark production at the LHC



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Main production mode

→ $t\bar{t}$ pairs, via strong interaction (QCD)

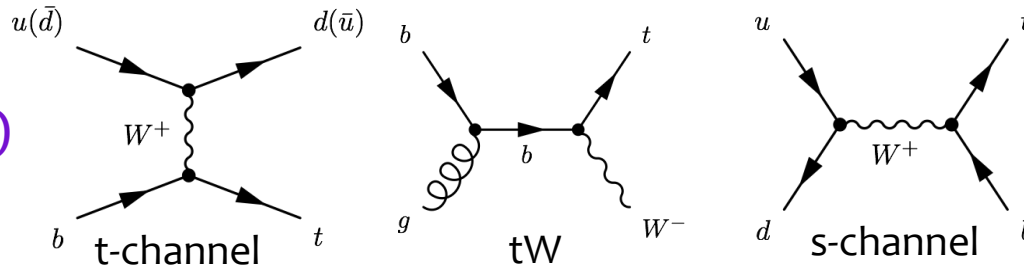


(Tevatron 1995)

Alternative

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

(Tevatron 2009)



σ [pb]	$t\bar{t}$	t-channel	tW	s-channel
LHC (7 TeV)	163	63.9	15.7	4.63
LHC (8 TeV)	234	84.7	22.2	5.55

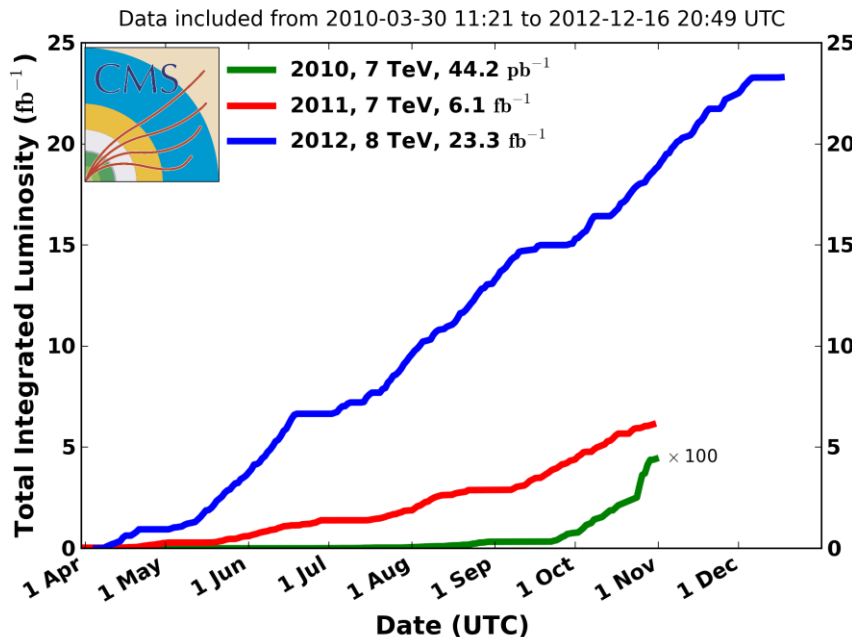


Run-1 in tops



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CMS Integrated Luminosity, pp



This means that CMS has recorded:

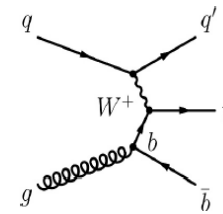
- More than **5M ttbar pairs**
- Around **2M of single top quarks (via t-channel)**

And also:

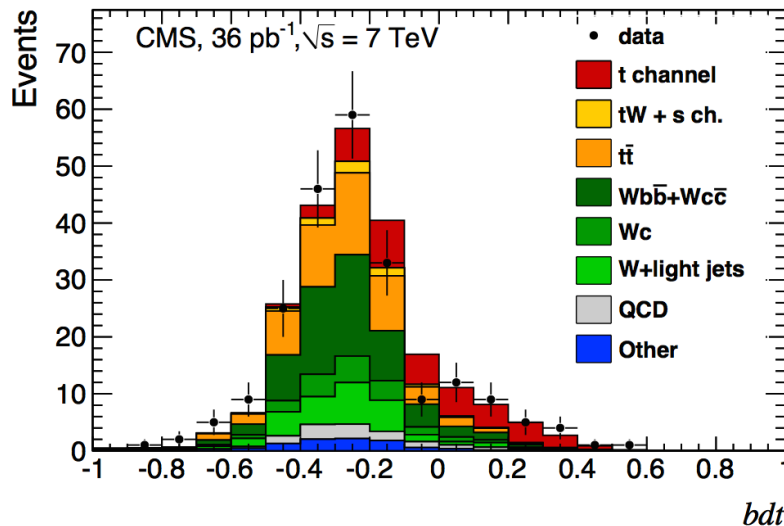
- Half a million of tW events and a bit more than 100K of s-channel events

CMS Single top spoiler alert:

This transforms into 6 papers published, several PASes made public (11 in the last two years), 2 LHC combinations, 1 discovery, and many milestones
And more results are planned before Run-2



- Before the start of the Run-1
 - ✦ only t-channel production was observed at the Tevatron
- It had taken the Tevatron 20 years to explore single top processes
- In 2011, barely a year into collisions, CMS published its first t-channel paper



Jun 2011

Phys. Rev. Lett. 107:091802,2011

[arXiv:1106.3052](https://arxiv.org/abs/1106.3052)

t-channel

36pb⁻¹

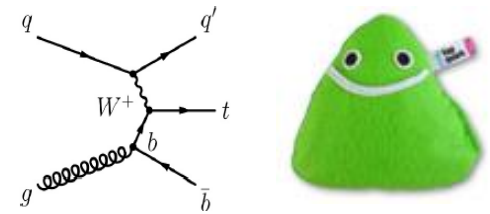
2D (cosθ* η_j) and BDT

1st lesson: the LHC truly is a top factory

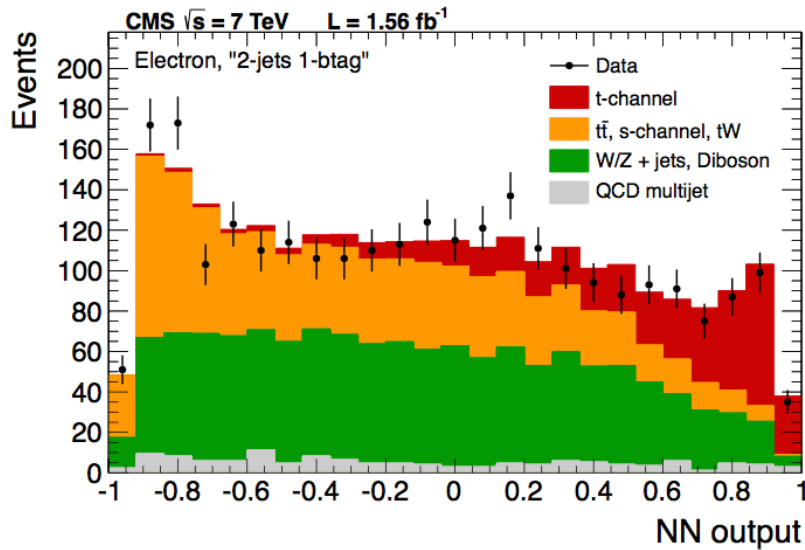
In one year, power to explore processes that took the Tevatron decades

t-channel

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- CMS measured the **inclusive t-channel cross section at 7 and 8 TeV**
- Including the ratio between top and anti-top, the measurement of $|V_{tb}|$ and the ratio between center of mass energies

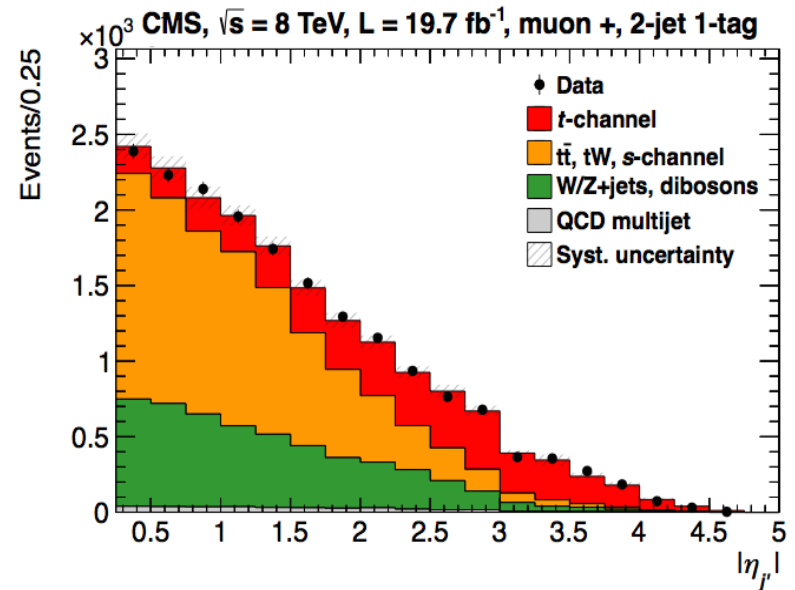


September 2012

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

t-channel ($\eta_{j'}$, NN, BDT)

7TeV - 1.17 and 1.56 fb^{-1}



March 2014

JHEP 06 (2014) 090, [arXiv:1403.7366](https://arxiv.org/abs/1403.7366)

t-channel and $|V_{tb}|$, $\eta_{j'}$

8 TeV - 19.7 fb^{-1}



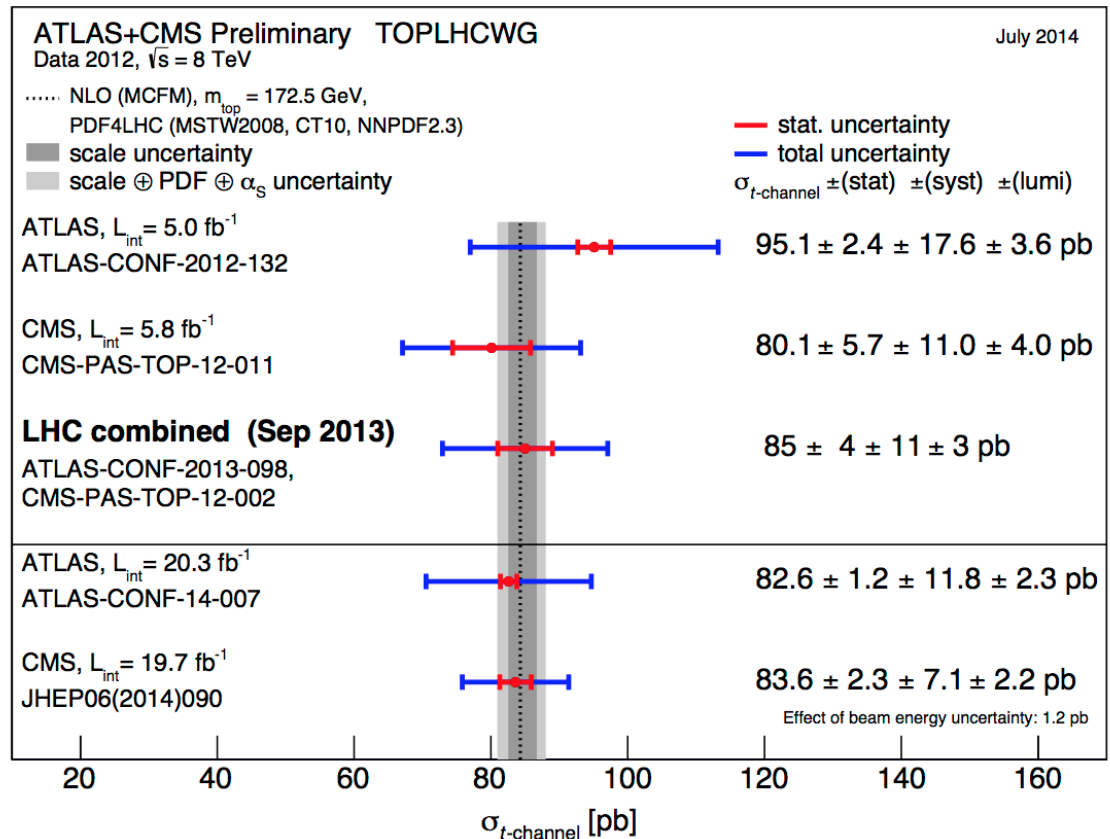
Combination with ATLAS



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- **ATLAS+CMS combination, 8TeV (September 2013)**
 - Using Iterative BLUE
 - [CMS-PAS-TOP-12-002](#)

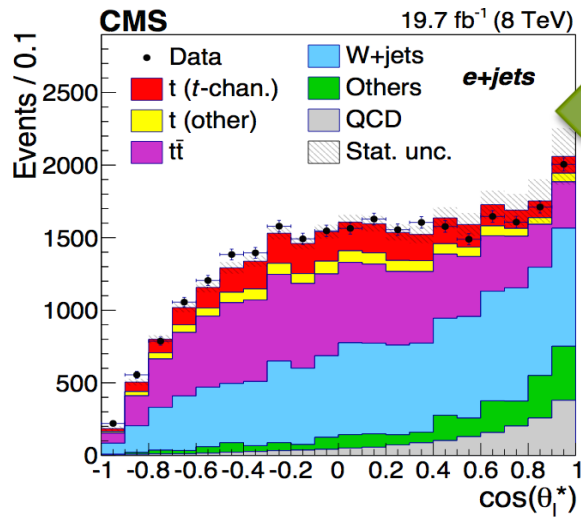
First LHC single top combination, within TOPLHCWG for TOP2013



Lesson: we can cooperate with ATLAS and produce common results, though it takes effort from both sides



- There are enough t-channel events to **measure top properties** in this signature



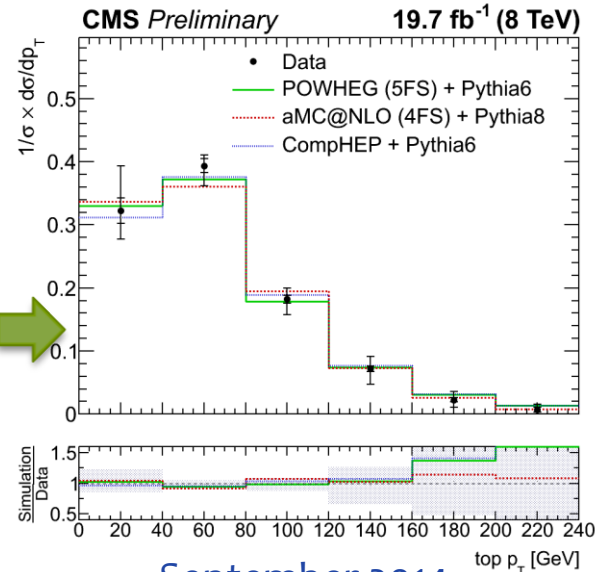
First CMS (PAS and) paper of top properties in single top

First CMS single top differential

October 2014

Accepted by JHEP, [arXiv:1410.1154](https://arxiv.org/abs/1410.1154)

W boson helicity in t-channel



September 2014

CMS PAS TOP-14-004

Differential cross sections

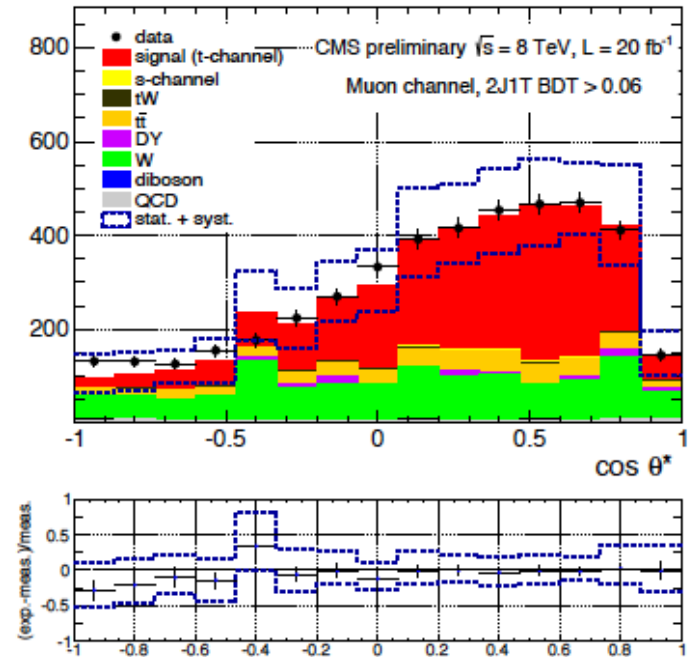
- top width** measurement in tt also used the inclusive t-channel cross-section
 - Phys. Lett. B 736 (2014) 33, [arXiv:1404.2292](https://arxiv.org/abs/1404.2292) (April 2014)



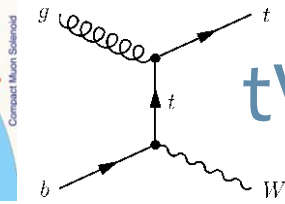
- **Top quark polarization**
 - Paper version of PAS
 - ✦ [CMS-PAS-TOP-13-001](#)
 - ✦ (September 2013)

- **Top mass**
 - Michelangelo Mangano's 2013 Christmas wish
 - ATLAS has a conf note (TOP2014)
 - ✦ [ATLAS-CONF-2014-055](#)

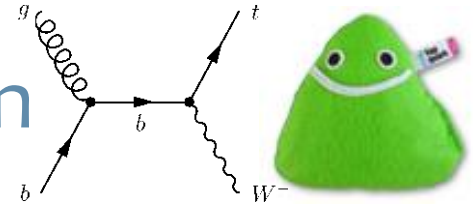
- **Fiducial t-channel cross sections**
 - ATLAS has a conf note (March 2014)
 - ✦ [ATLAS-CONF-2014-007](#)



Lesson: single top t-channel is an excellent signature to make measurements and there's a lot of information to extract from it

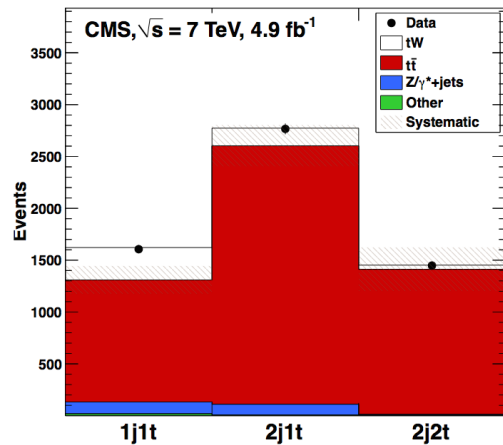


tW associated production



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- The low cross section of this process at the Tevatron made it impossible to study before the LHC
- At the LHC is still not easy → only CMS has managed to observe it ($> 5\sigma$)
- Evidence at 7TeV, discovery at 8TeV

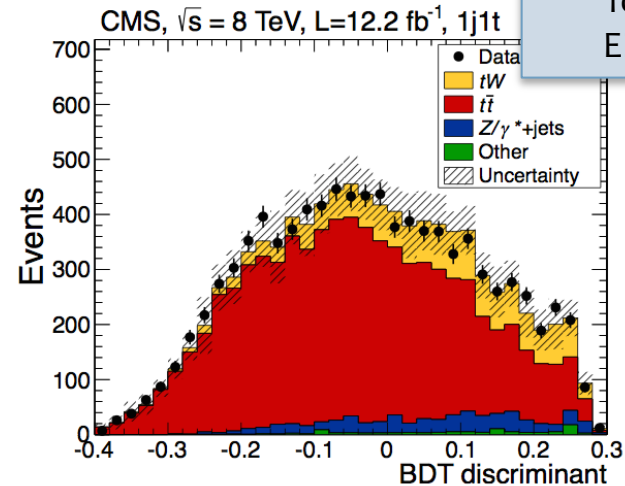


September 2012

Phys. Rev. Lett. 110 (2013) 022003

[arXiv:1209.3489](https://arxiv.org/abs/1209.3489)

(cut, BDT) 4.0σ 7TeV - 4.9fb^{-1}



January 2014

Phys. Rev. Lett. 112 (2014) 231802

[arXiv:1401.2942](https://arxiv.org/abs/1401.2942)

(BDT, shape, cut) 6.1σ 8TeV - 12.2fb^{-1}

2013 Milestone
for CMS
EPS 2013



tW Combination with ATLAS



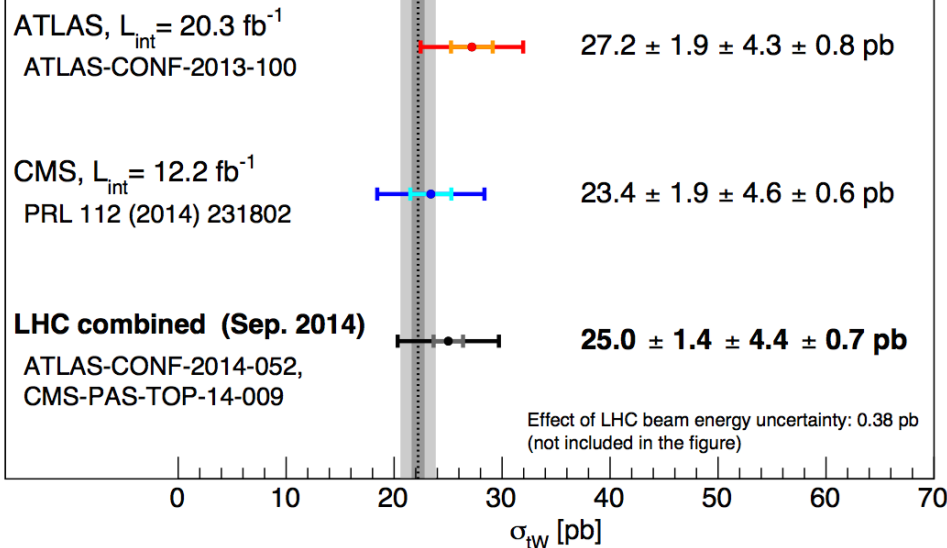
ATLAS+CMS Preliminary TOPLHCWG

September 2014

Data 2012, $\sqrt{s} = 8$ TeV, $m_t = 172.5$ GeV

- NLO+NNLL (arXiv:1210.7813)
- MSTW2008_{NNLO}
- scale uncertainty
- scale ⊕ PDF uncertainty

- stat. uncertainty
 - total uncertainty
- $\sigma_{tW} \pm(\text{stat}) \pm(\text{syst}) \pm(\text{lumi})$

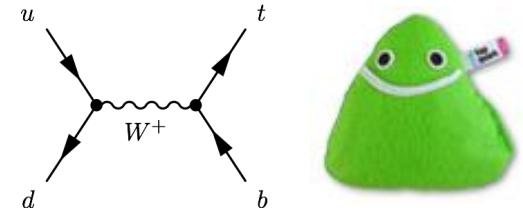


September 2014

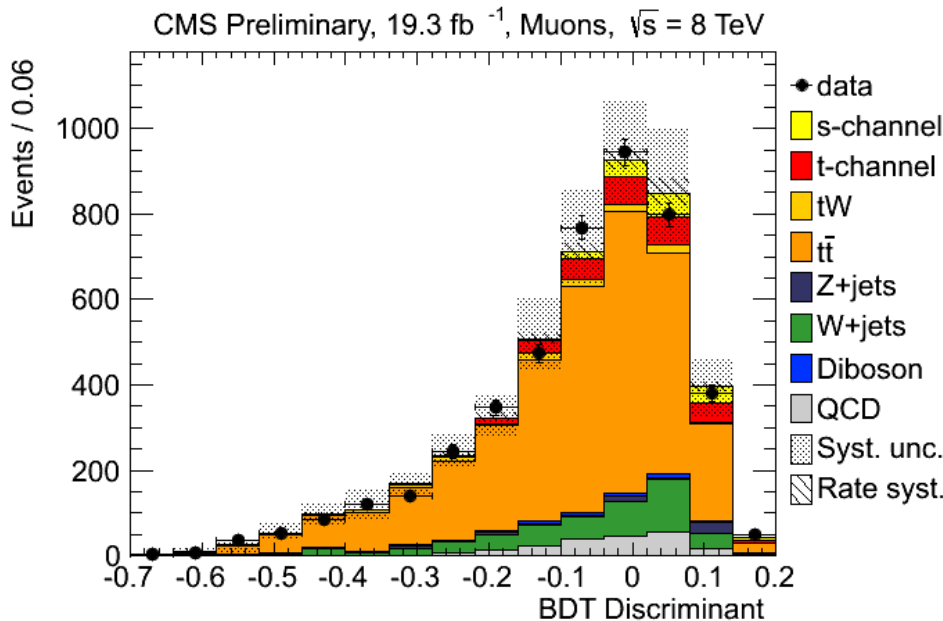
PAS TOP-14-009

tW combination, 8TeV

Lesson: tW and ttbar are not easily separated (practically and theoretically), to understand and properly model the ttbar as background and its interference with the signal is the priority in this channel



- Whereas the tW associated production has a larger production cross section, the **s-channel becomes very challenging at the LHC**



CMS has a PAS at 8TeV

[CMS-PAS-TOP-13-009](#)

(November 2013)

Full lumi, e and μ

S/B is a bit better at 7TeV

In Run-2 will become even harder

Better control of theory systematics would help \rightarrow NLO Monte Carlo samples

Working on the paper version

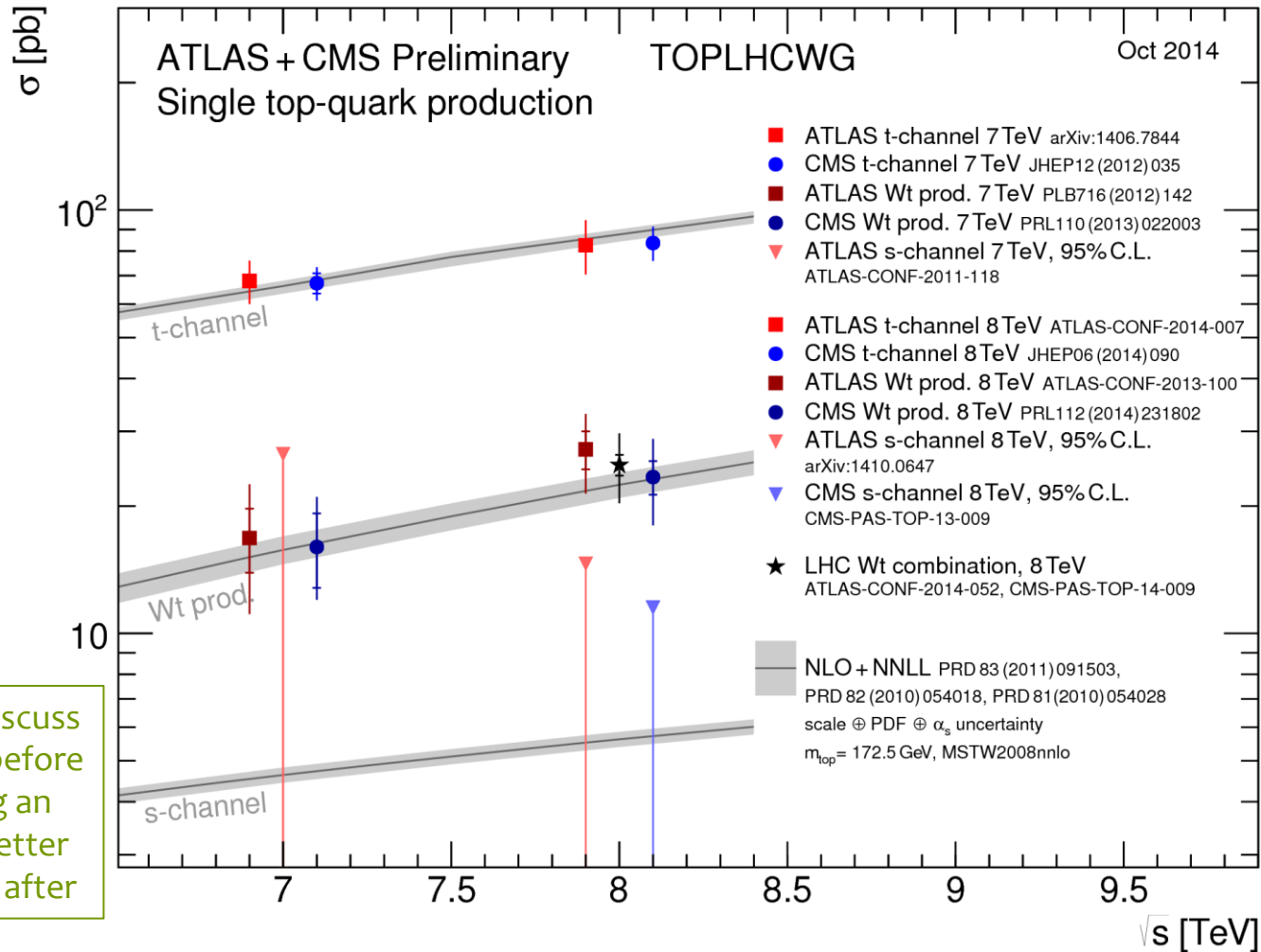
First CMS result
in this channel
PASCOS 2013

Lesson: the s-channel is a complex analysis with large tt background that requires a very good signal extraction

Summary plot



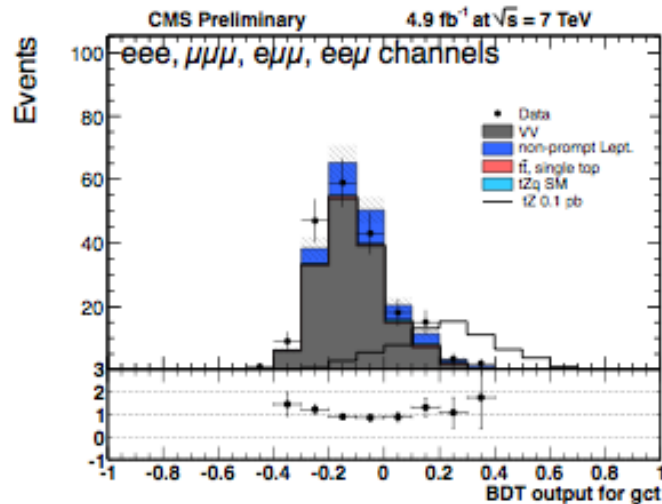
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Lesson: To discuss with ATLAS before performing an analysis is better than to do it after



- As you have seen today, limits on anomalous Wtb couplings can be extracted from SM measurements (W -helicity fractions, top polarization)
- There are also dedicated analysis searching for **FCNC in many signatures**



FCNC tZ

BDT (gut, gct, Z_{ut}, Z_{ct}) 7TeV

Limits on couplings and branching fractions

[CMS-PAS-TOP-12-021](#)

(July 2013)

Work in progress towards a paper

First FCNC PAS in single top



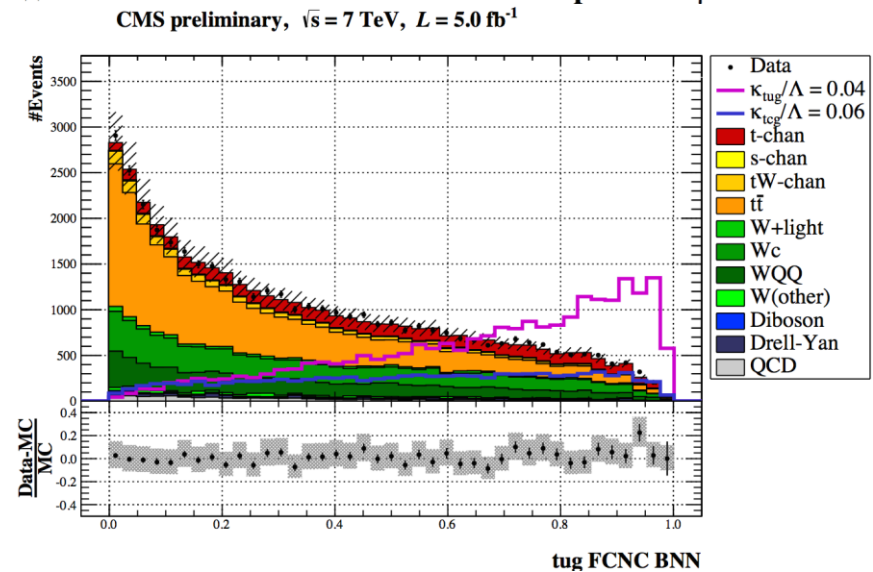
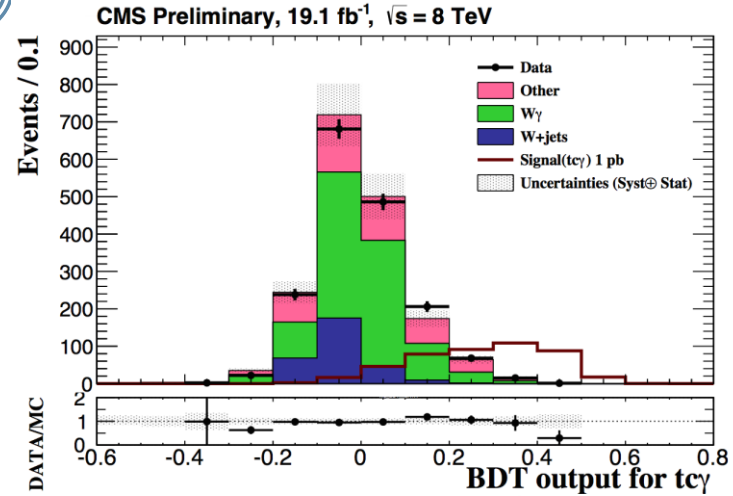
- **FCNC $tq\gamma$**

- [CMS PAS-TOP-14-003](#)
- (May 2014)
- $tq\gamma$, $tc\gamma$ couplings
- BDT 8TeV, μ
- Work in progress towards a paper

Lesson: Single top signatures are ideal for AC and FCNC studies

- **FCNC in t-channel**

- [CMS PAS-TOP-14-007](#)
- (May 2014)
- 7TeV, NN
- $tc\gamma$ and $tq\gamma$
- Work in progress towards a paper



Top + Higgs



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- tH production highly suppressed in the SM
- If top Higgs Yukawa coupling is negative → enhanced

tH, H → γγ

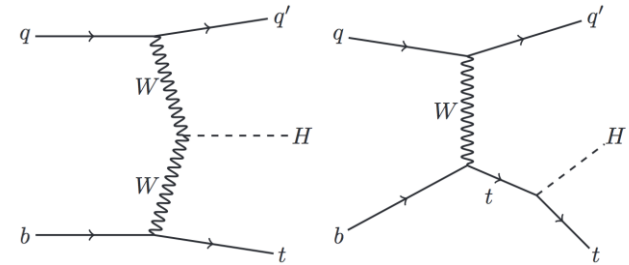
CMS PAS-HIG-14-001

(March 2013)

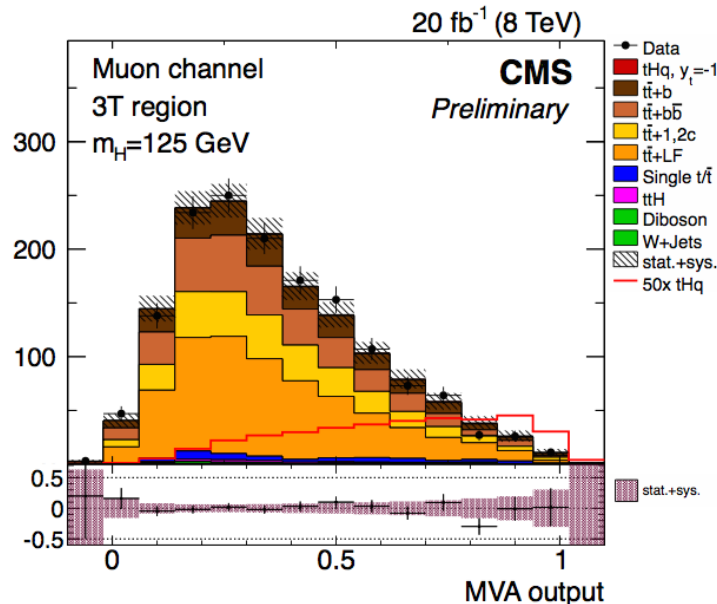
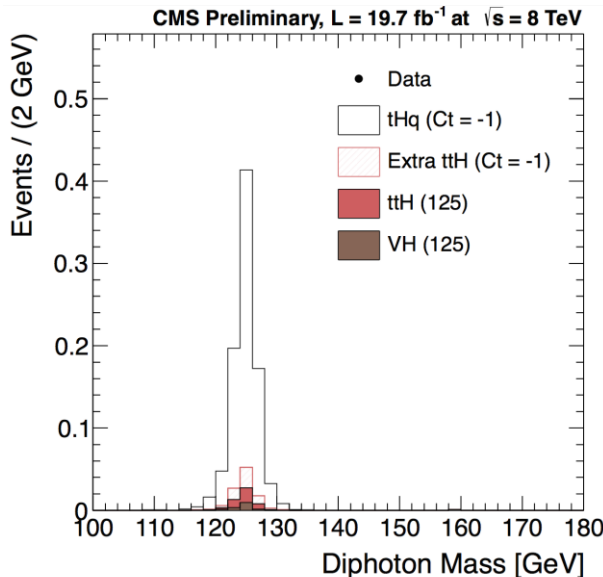
tH, H → bb

CMS PAS-HIG-14-015

(October 2014)



New channels to come!



Lesson: the top Higgs coupling can be studied in single top signature (not only in ttH)



- There are many BSM channels that involve top quarks and/or similar signatures to single top, like $W' \rightarrow tb$ ([arXiv:1402.2176](https://arxiv.org/abs/1402.2176))
- Also some feature “single” top quarks

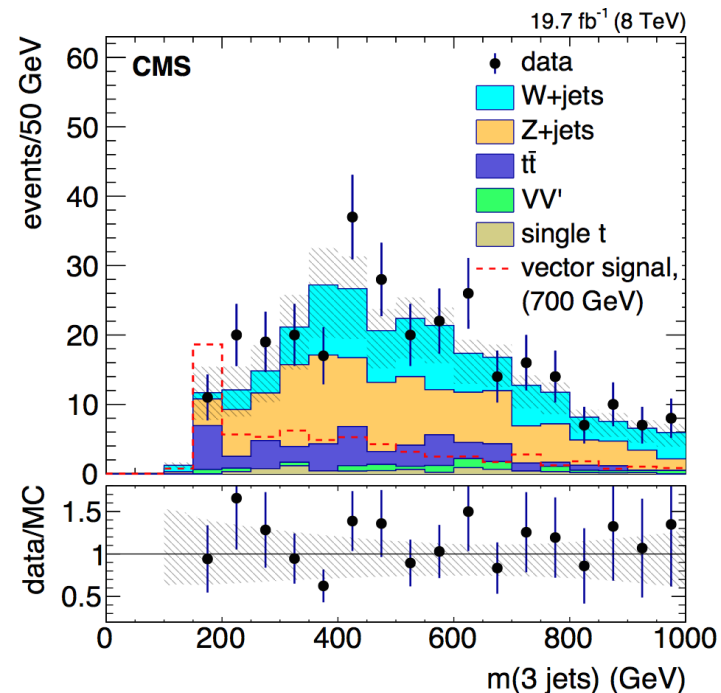
Monotop

DM search using top + MET

[arXiv:1410.1149](https://arxiv.org/abs/1410.1149)

(October 2014)

Lesson: We can already be sensitive to BSM in creative single top like channels with Run-1 data, Run-2 full of opportunities



What's next



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- **Finish the Run-1 analyses** ongoing → several papers projected
- There are **open topics** that could already be studied with Run-1 data and are uncovered, for example
 - Measurement of t and s -channel simultaneously
 - Study of $tW + t\bar{t}$ in dilepton final states simultaneously
 - CP violation measurement in single top decays
- With the higher luminosity and center of mass energies of **Run-2** (Run-3, Run-4...)
 - Minimizing systematics and improve modelling
 - Face new challenges like high pileup scenarios
 - Measurement of properties in purer samples (“precision” era)
 - SM processes with low production rates (tZ for example) will become accessible
 - More BSM channels could also be explored, larger phase space to test



- Run-2 will start late Spring 2015
 - Will run for ~3 years providing about **300fb⁻¹ at 13 (14) TeV**
- **t-channel:**
 - SM candle
 - flagship for the single top group
 - Could be done ~1fb⁻¹ → **High Priority Analysis (HPA) for Run-2**
- Next → tW (~3fb⁻¹)
 - May be the surprise of Run-2 with a larger growth in cross section than the other modes
 - Exploring tt and tW interplay → Run-2 goal
- Properties from 5fb⁻¹

σ [pb]	t-channel	tW	s-channel
LHC (7 TeV)	63.9	15.7	4.63
LHC (8 TeV)	84.7	22.2	5.55
LHC (13TeV)	217	71.2	11.3



Summary



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- The LHC Run-1 has been highly successful for single top physics
- Many public results:
 - **The three main production modes** (t-channel, tW, s-channel)
 - **Top properties in t-channel** (W-helicities, top polarization)
 - **Anomalous couplings and FCNC**
 - **Top+Higgs production** constraining the top-Higgs Yukawa coupling
 - **BSM searches** involving single top quarks
- **ttbar background** omnipresent in all single top studies
 - to model and understand this process (as well as the signal) → priority
- Open **collaboration with ATLAS** in LHC combination
 - Effort in harmonization, improvement in techniques and estimations
- **Wrapping up Run-1 results, getting ready for Run-2**

→ Tune in tomorrow to see the process of the ongoing analyses!