Overview of single top physics in CMS with Run-1 data

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2d of March 2015
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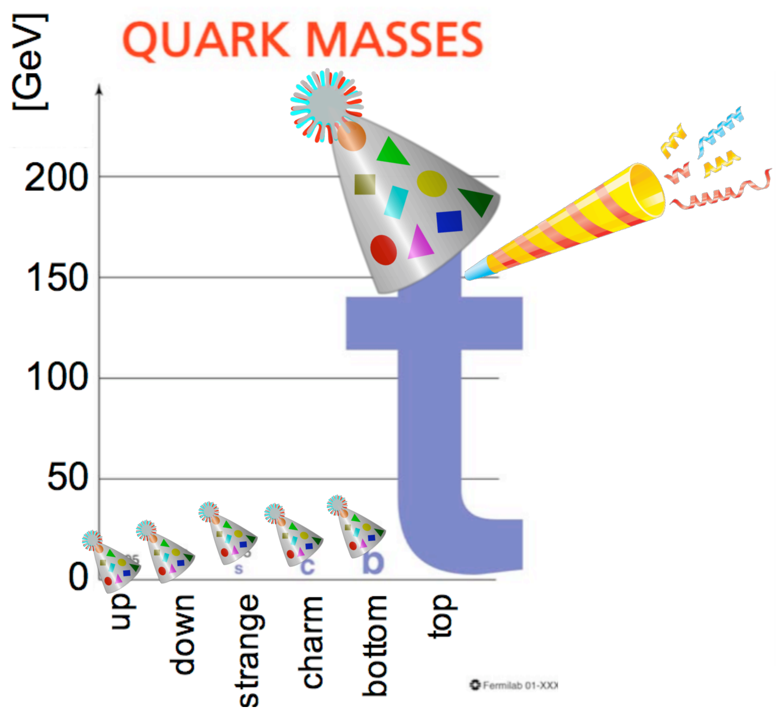
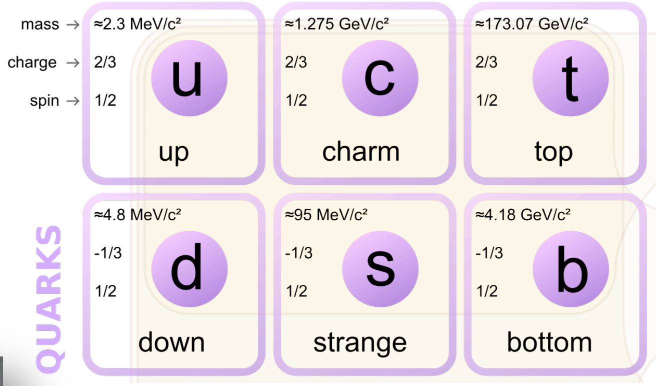
Last Tuesday

- **Last Tuesday was the 20th anniversary of the discovery of the top quark**



Feb. 24, 1995

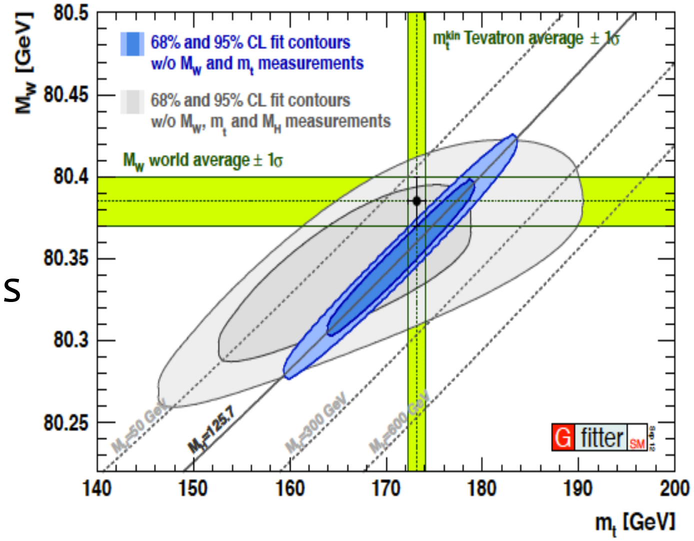
- On Feb. 24, 1995 the two Tevatron collaborations, CDF and DZero, submitted their Top Discovery papers to PRL:
  - PRL 74, 2626–2631, PRL 74, 2632–2637
- **The quark family picture was completed** exactly 6 months before Windows 95 was released



And I was 13 years old…

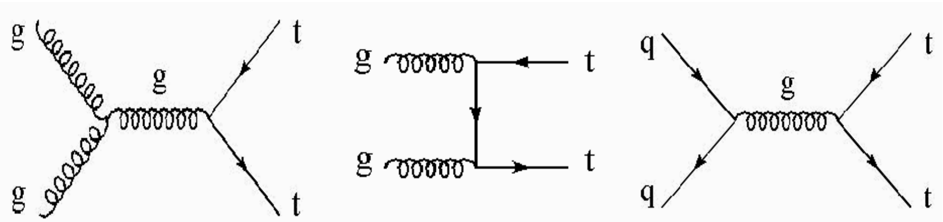
The top quark

- **Tevatron legacy** has been of central importance
- In 20 years we are getting to know the top quark really well
- It is the **heaviest elementary particle known**
  - **m**$_{top}$ = 173.34±0.27(stat)±0.71(syst) GeV
  - arXiv:1403.4427
- Short lived → only quark that decays before hadronizing
  - **direct access to properties** (spin, charge, polarization…)
- Has a strong coupling to the Higgs boson
- It is a good candidate to play a role in many scenarios of physics beyond the SM (BSM)
- Experimental signature:
  - Decays almost exclusively as **t→ Wb**



Top quarks at the LHC

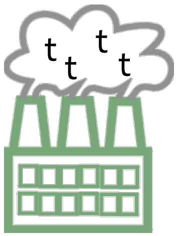
- At the **LHC** top quarks are produced at a **very high rate**

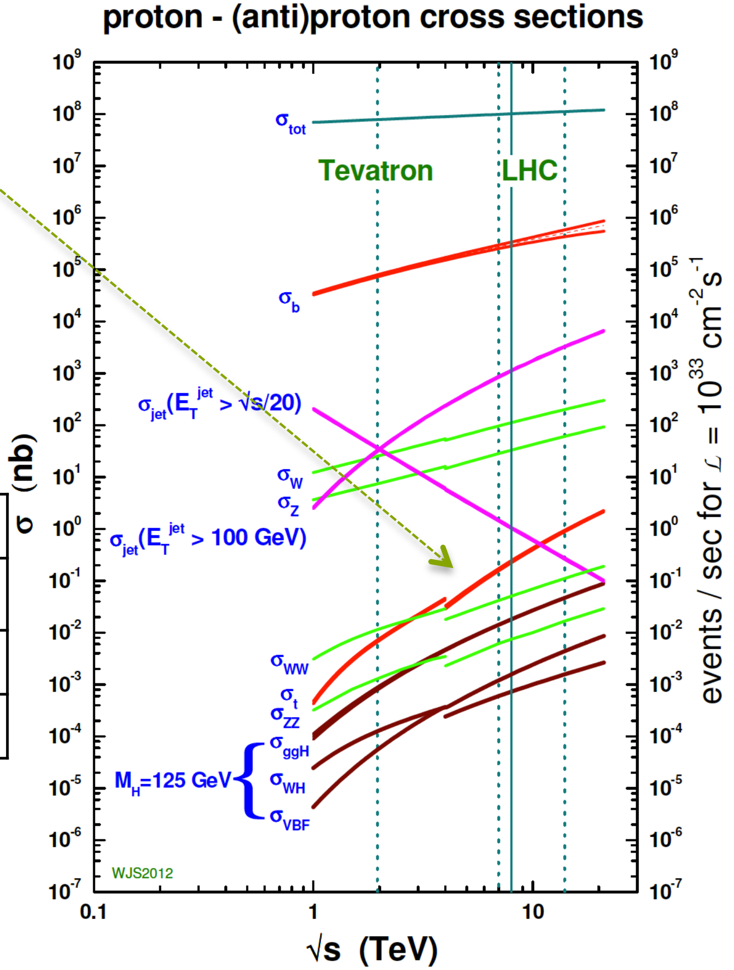


Main mode: **ttbar pairs,** via **strong interaction**

x-sec (pb)	ttbar
Tevatron	7.08 (+0.00-0.24) (+0.36-0.27) approx. NNLO
LHC @ 7TeV	163 (+7-5)(±9) approx. NNLO
LHC @ 8TeV	234 (+10-7)(±12) approx. NNLO

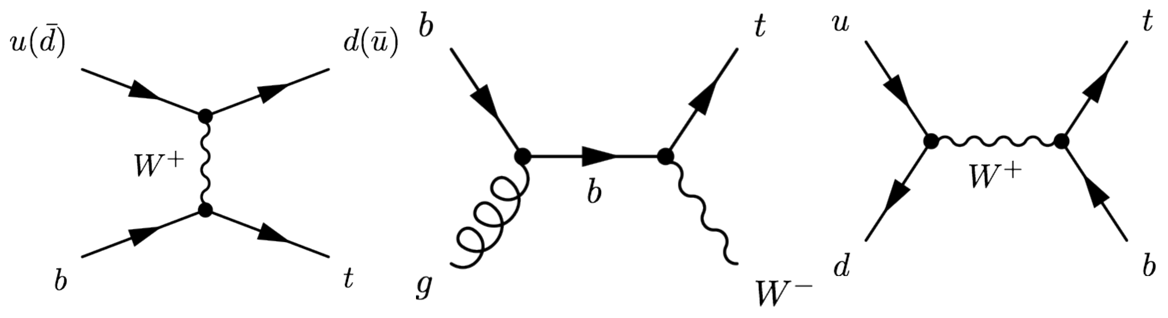
"The LHC is a top quark factory!"





Single top production

- There is an alternative mode, at a much lower rate: **Single top quark production**
- Via **electroweak interaction**, involving a Wtb vertex
- Three main process: **t-channel, tW associated production, s-channel**



σ [pb]	t-channel	tW	s-channel
Tevatron (1.96 TeV)	2.08	0.22	1.046
LHC (7 TeV)	63.9	15.7	4.63
LHC (8 TeV)	84.7	22.2	5.55

Single top timeline

1986 Tevatron starts colliding

1995 Top quark discovery

2009 Single top discovery

2010 LHC starts colliding

2011 First single top results at the LHC

- Single top quarks were also **observed at the Tevatron**, in March 2009

  PRL103:092002, PRL.103:092001

- **ATLAS and CMS** presented their first t-channel studies with 7TeV data early 2011

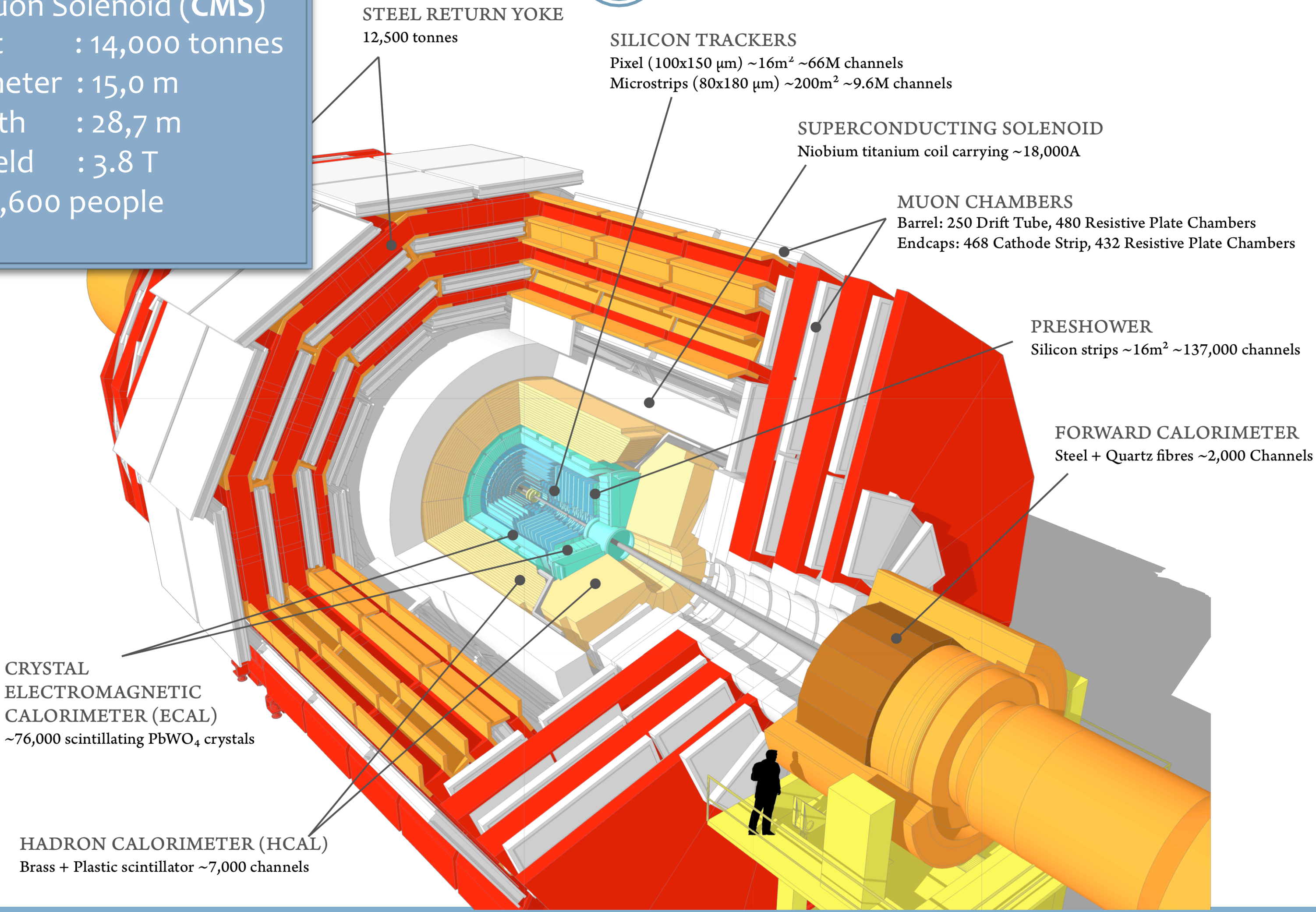
  CMS-PAS-TOP-11-021, ATLAS-CONF-2011-088

- Since then, **all the main modes have been studied,** the t-channel has been used to measure SM properties, and several single top related signatures have been used to study new physics

"The LHC is a SINGLE top quark factory!"

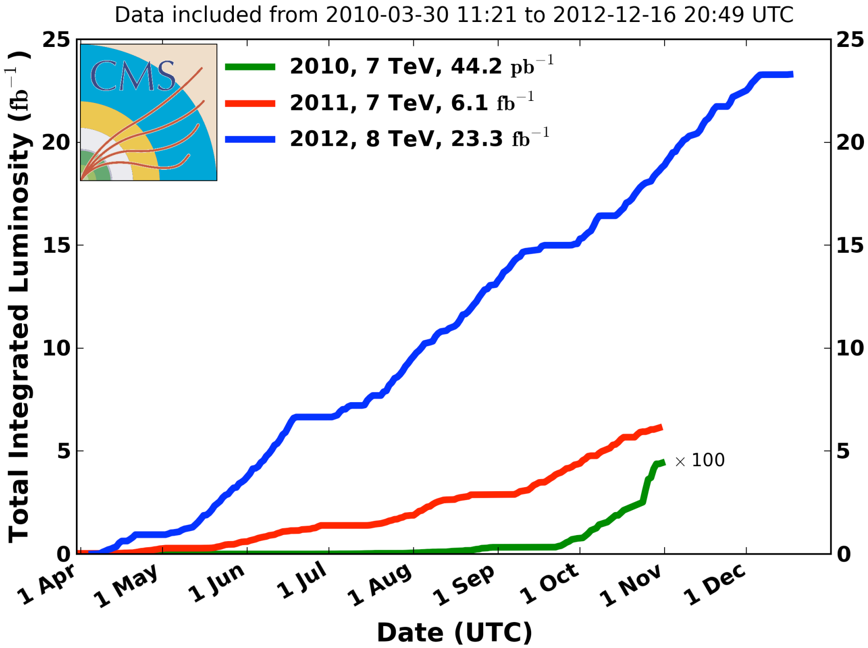
Compact Muon Solenoid (CMS)

Compact Muon Solenoid (**CMS**)
Total weight : 14,000 tonnes
Overall diameter : 15,0 m
Overall length : 28,7 m
Magnetic Field : 3.8 T
More than 2,600 people
41 countries



Run-1 in tops

Year	Overview	COM energy	Integrated luminosity [fb^{-1}]
2010	Commissioning	7 TeV	0.04
2011	Exploring limits	7 TeV	6.1
2012	Production	8 TeV	23.1



- The Run-1 of the LHC started in March 2010 and ended in February 2013
- During three years: **~5fb^{-1} of pp collisions at 7TeV and ~20fb^{-1} at 8TeV**

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

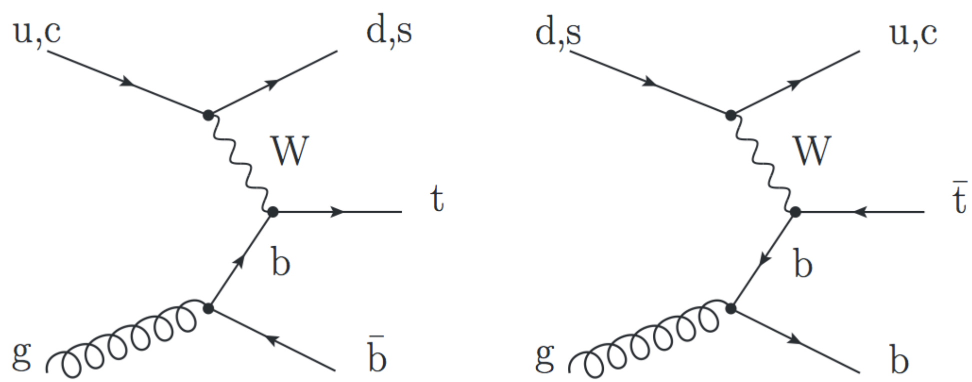
- What have we done with them?

Step 1

Study the three single top production modes and measure their production cross section

t-channel

- **Dominant process** with the highest cross section at the Tevatron and the LHC

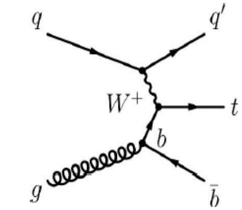


- The final state studied is a **lepton + jets signature**
- Signal events characterized by:
  - One isolated **muon or electron**
  - Missing transverse energy (**MET**)
  - A central **b jet**

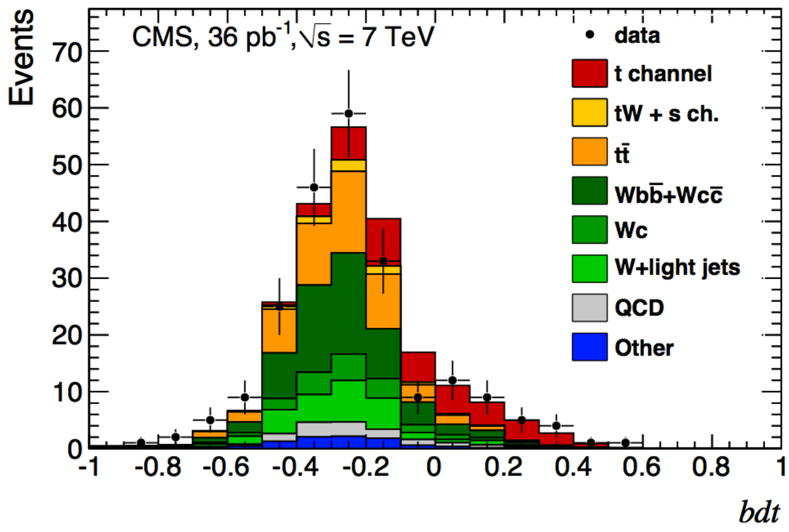
  Leptonic top decay

  - light-quark jet from the hard scattering process (often forward)
  - Additionally, a second b jet produced in association to the top quark
- **Main backgrounds: W+jets, ttbar, multijet**

t-channel



- Before the start of the Run-1
  - only t-channel production was observed at the Tevatron
- 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

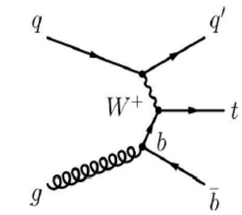
t-channel

36pb^{-1}

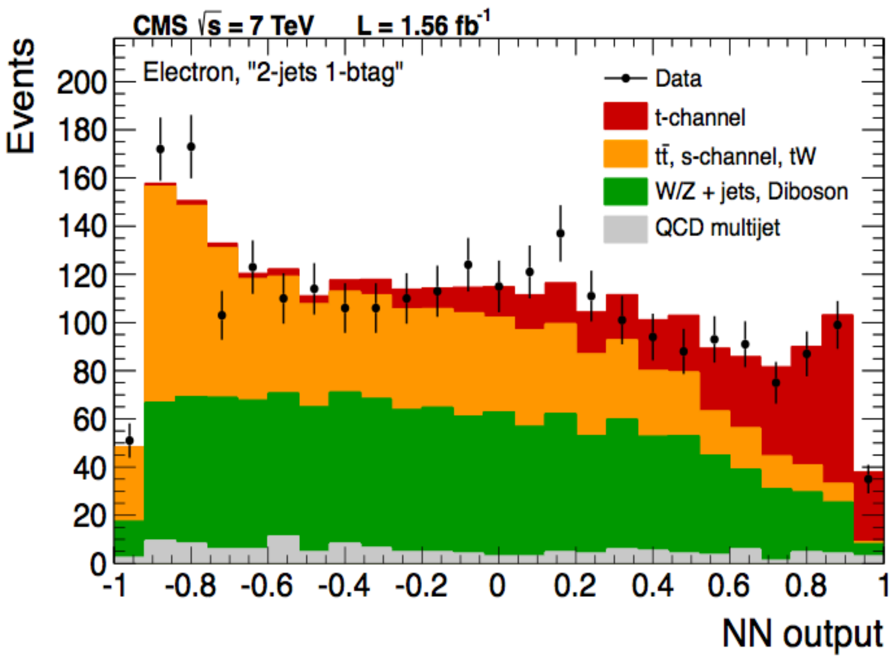
2D shape analysis ($\cos\theta^*$ $\eta_{j'}$) and BDT

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

t-channel (7TeV)



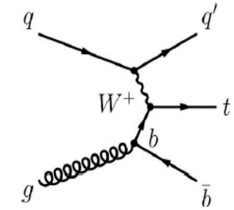
- At 7 TeV CMS measured the inclusive **t-channel cross section**
- Using Multivariate methods (BDT, NN) and the shape of the pseudorapidity of the light jet, $|\eta_{j'}|$



Different regions defined (jets, b-tag)
Multijet and W+jets background estimated from data

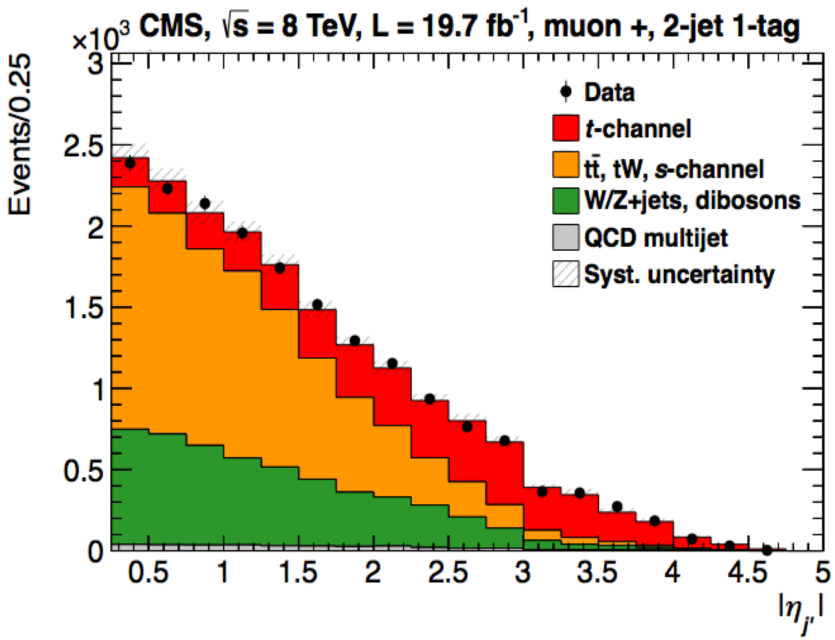
Statistical, systematic, and theory uncertainties on the same level

September 2012
JHEP 12 (2012) 035, arXiv:1209.4533
t-channel ($|\eta_j|$', NN, BDT)
7TeV - 1.17 and 1.56 fb^{-1}



t-channel (8TeV)

- At 8 TeV, this was made just with the $|\eta_{j'}|$ analysis



March 2014

JHEP 06 (2014) 090, arXiv:1403.7366

t-channel, $\eta_{j'}$

8 TeV - $19.7 fb^{-1}$

Similar approach as for 7TeV, more data-driven (Multijet, W+jets, ttbar)

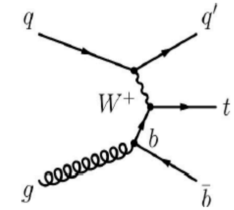
Full luminosity

Systematic dominated

main uncertainties:

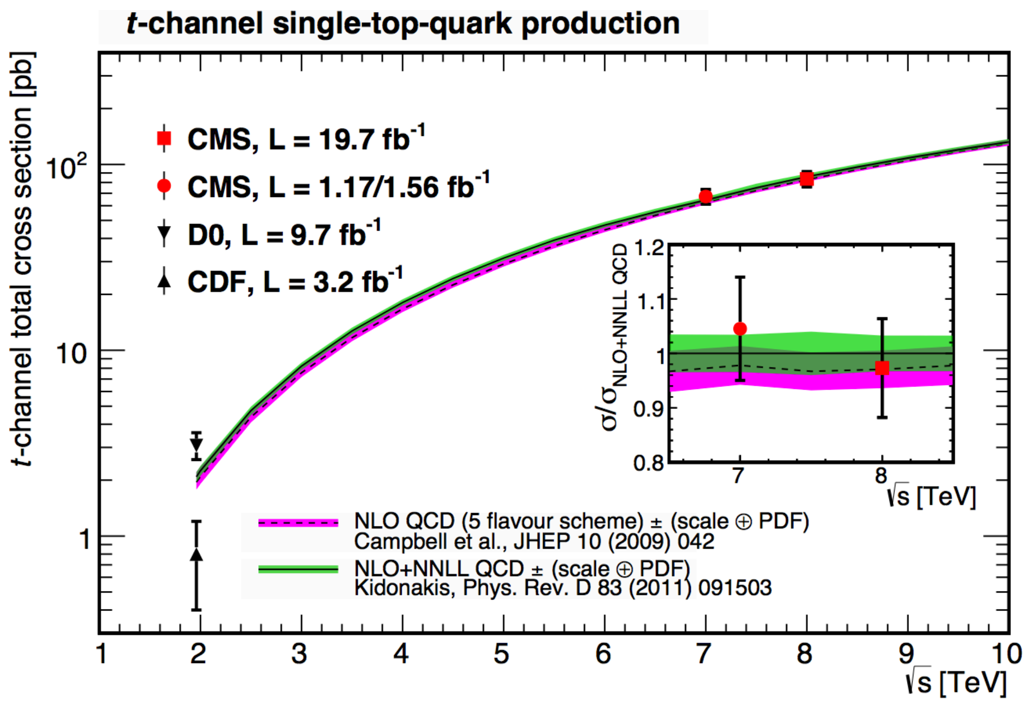
Signal modeling (~6%)

and JES/JER/MET (~4%)

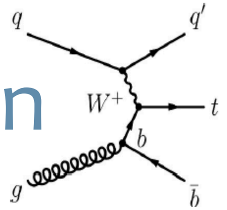


t-channel: results

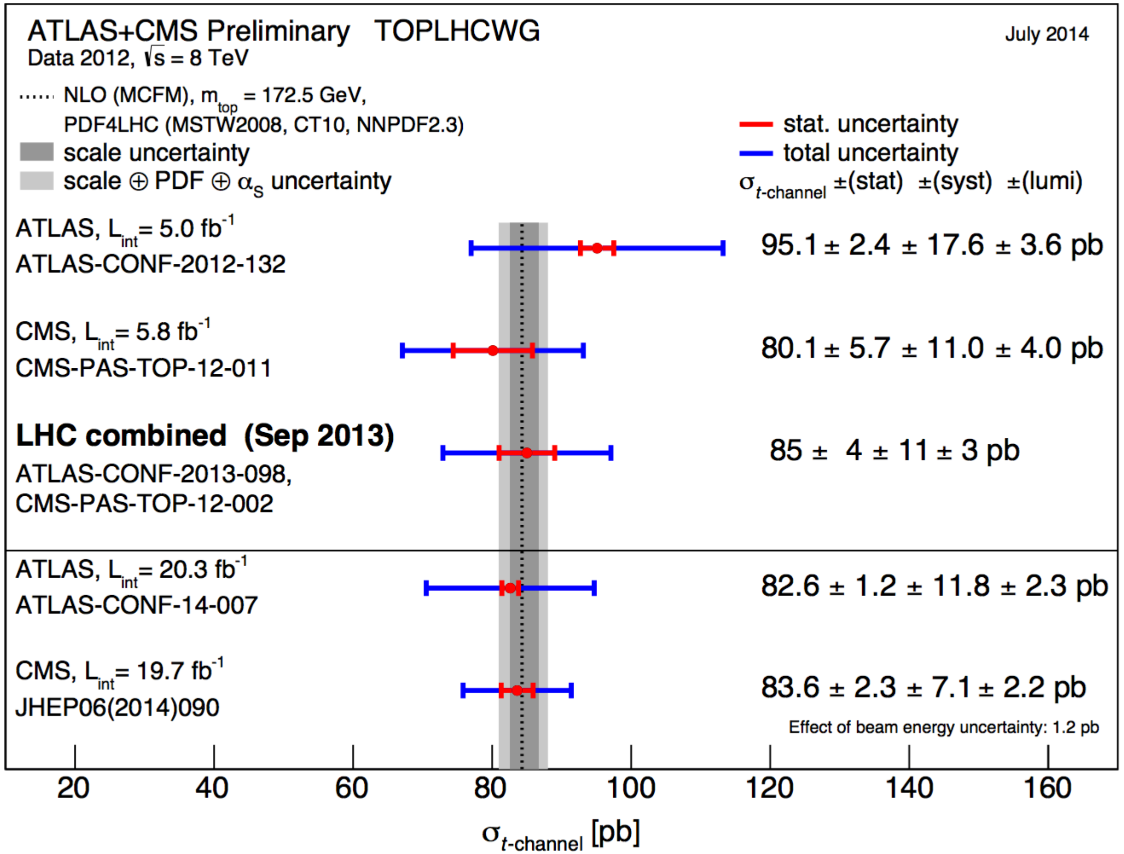
7TeV	Measured	67.2±3.7(stat)±3.0(syst)±3.5(th)±1.5(lumi) pb = 67.2±6.1 pb
	Prediction	63.89+2.91-2.52 (NLO, latest calculation)
8TeV	Measured	83.6±2.3 (stat) ±7.4 (syst) pb
	Prediction	84.69+3.76 -3.23 (NLO, latest calculation)



t-channel: LHC combination

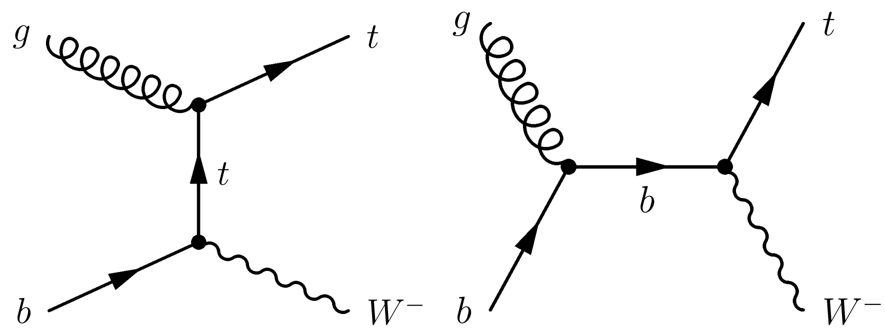


- **At 8TeV, there was an LHC (ATLAS+CMS) combination**
- First LHC single top combination
  - Sept. 2013
  - CMS-PAS-TOP-12-002

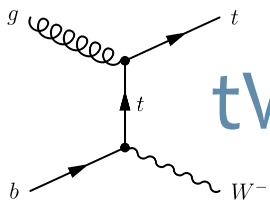


tW associated production

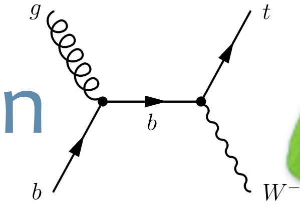
- Single top process with the second largest cross-section at the LHC



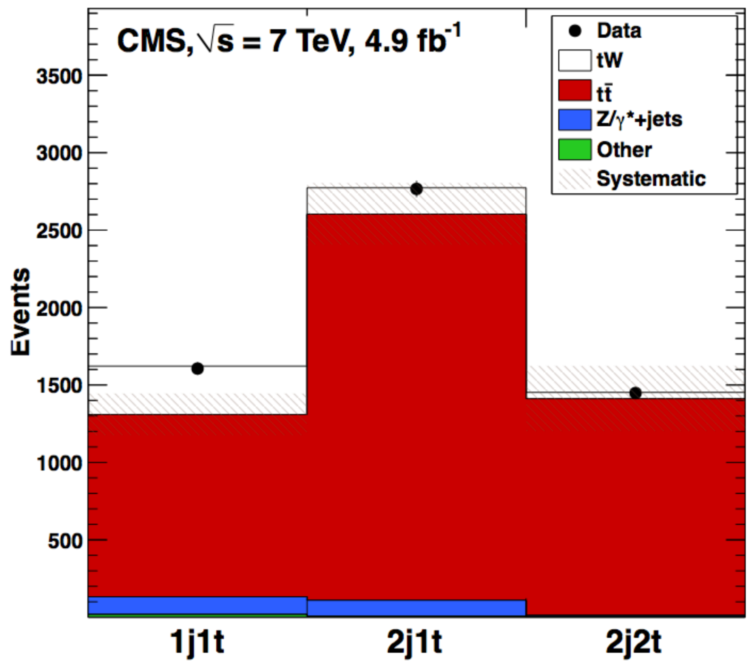
- The final state studied is a **dilepton signature**
- Signal events are characterized by:
  - **Two** opposite-sign, isolated **leptons**
  - Missing transverse energy (2 neutrinos in the final state)
  - A jet coming from a **b decay**
- **Backgrounds: ttbar (main challenge), DY**



tW associated production



- 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
- CMS reported Evidence at 7TeV

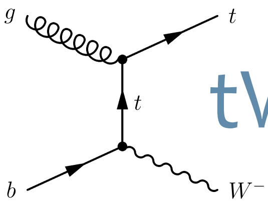


September 2012

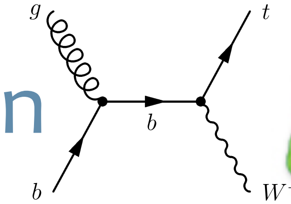
Phys. Rev. Lett. 110 (2013) 022003

arXiv:1209.3489

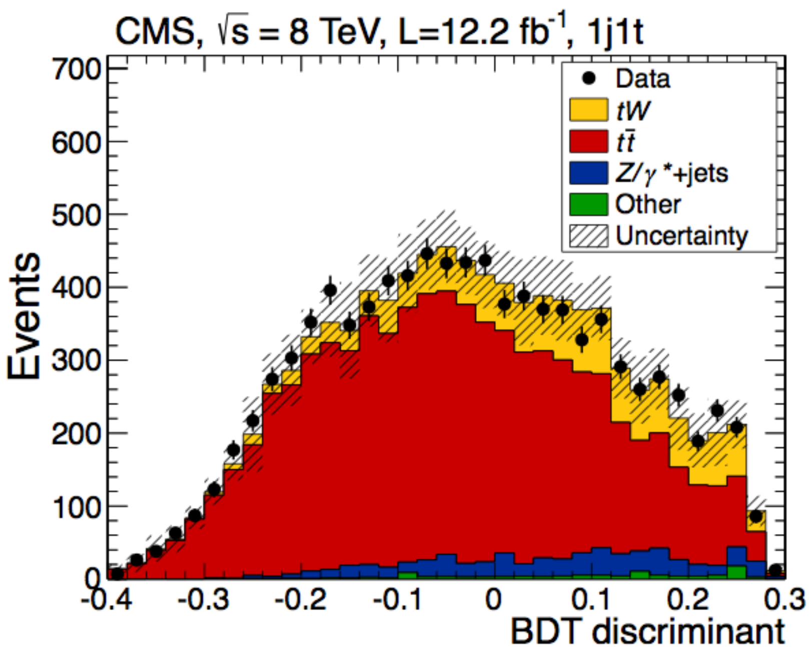
(cut, BDT) 4.0σ 7TeV - 4.9fb^{-1}



tW associated production



- **And discovery at 8TeV → Only observation (> 5 σ) so far**



January 2014

Phys. Rev. Lett. 112 (2014) 231802

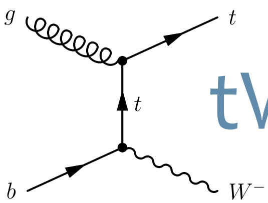
arXiv:1401.2942

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

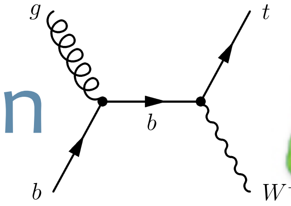
7 TeV → cut-based, basic BDT

8TeV → cut-based, shape-based, more sophisticated BDT

At 8TeV the analysis is already not statistically limited



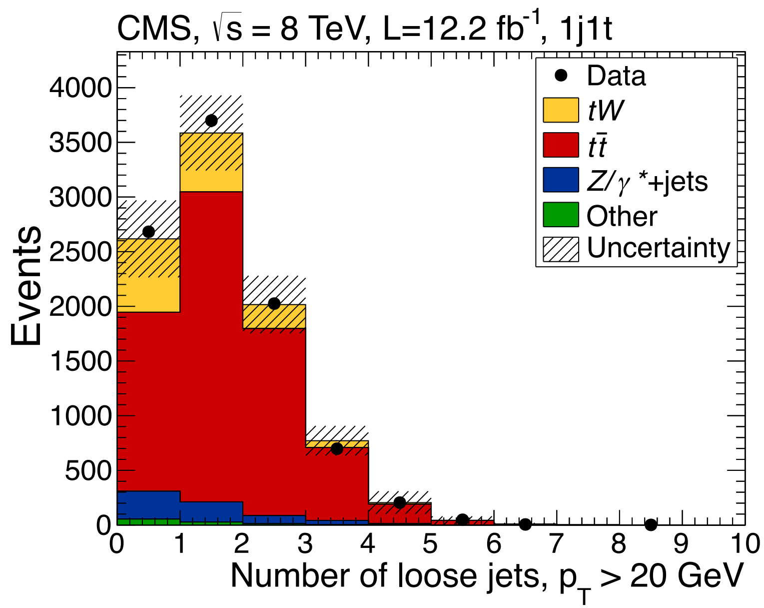
tW associated production



- The main challenge is the **ttbar background**
  - ttbar with 1 jet outside acceptance or miss-reconstructed → main background

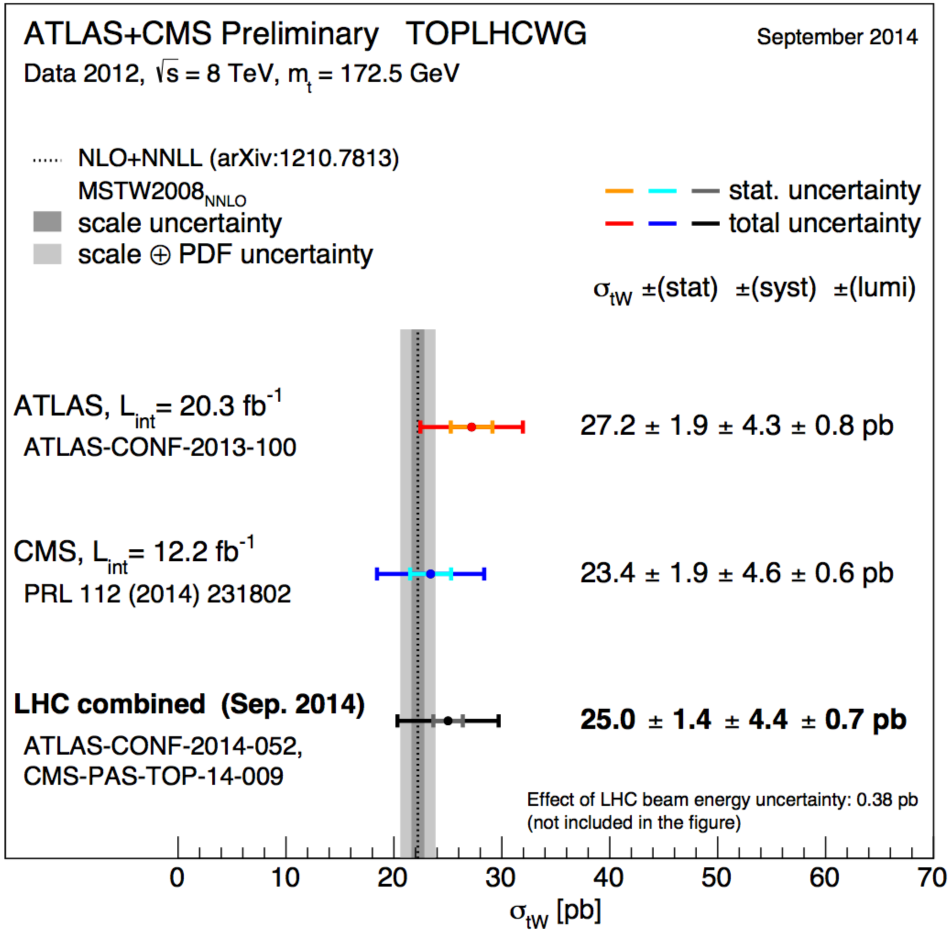
  → Very similar final states and their diagrams mix at NLO

  → Main uncertainties come from theory modeling of ttbar
- 2 control regions were established



7TeV	Measured	σ_{tW} =16+5-4 pb
	Prediction	σ_{tW} = 15.6±0.4±1.1 pb
8TeV	Measured	σ_{tW} = 23.4±5.4 pb
	Prediction	σ_{tW} = 22.2±0.6±1.4 pb

tW Combination with ATLAS



Recently, we also made public the ATLAS+CMS tW combination at 8TeV

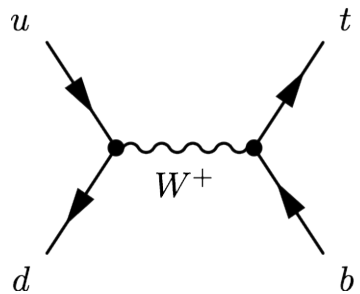
September 2014
[PAS TOP-14-009]

s-channel

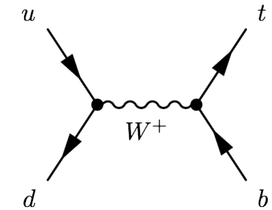
- Lowest cross-section at the LHC, more important at the **Tevatron** (where the study of data **after** the shutdown allowed for the **observation of the process**)

Phys. Rev. Lett. 112, 231803 (2014)

- Production mode **sensitive to new physics: W' bosons, charged Higgs bosons**
- **Very challenging final state:** low cross-section, difficult to separate from backgrounds

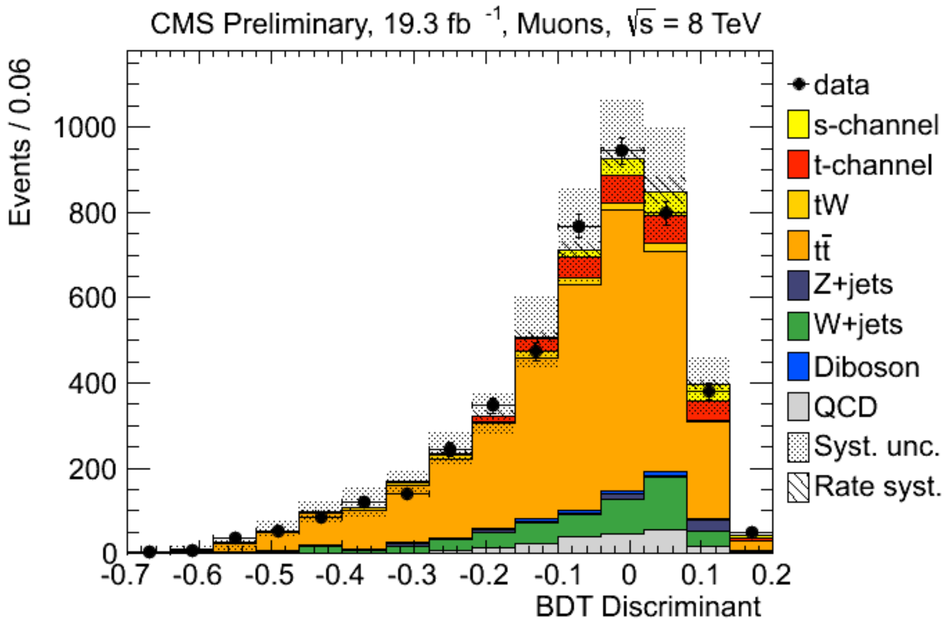


- Signal signature: **lepton + jets**
  - **A lepton** (e,μ) and **MET** from the decay of a W boson
  - **Two jets** with high transverse momentum originating from **b-quarks**
- **Main backgrounds:** W+jets and ttbar, multijet



s-channel

- CMS has a preliminary result at 8TeV



CMS-PAS-TOP-13-009

(November 2013)

Full lumi, e and μ

BDT

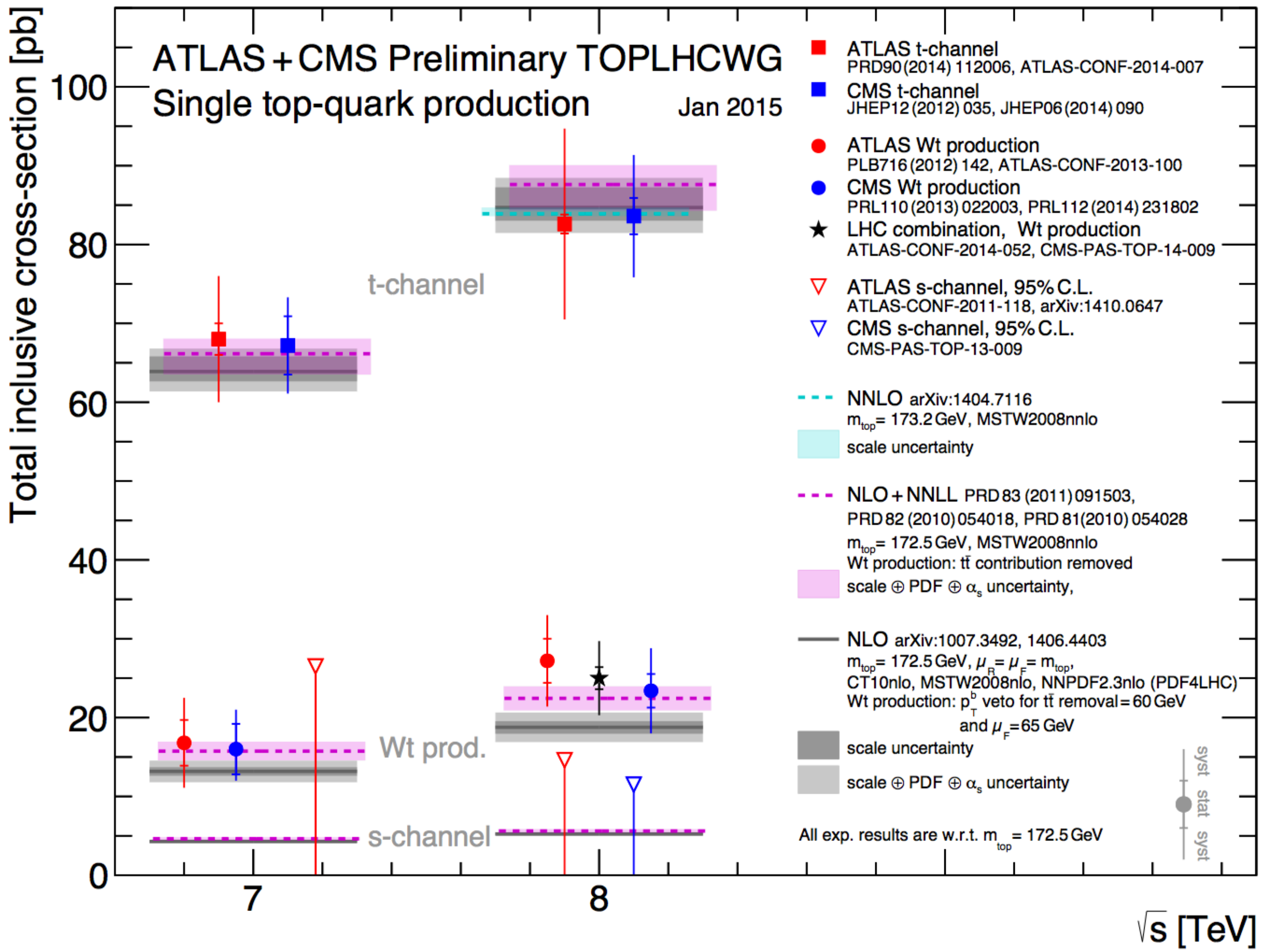
S/B is a bit better at 7TeV

In Run-2 will be even harder

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

$\sigma_{\text{s-channel}}$ = 6.2±5.4(exp.)±5.9(th)pb = 6.2+8.0-5.1 pb (FC)
$\sigma^{th}_{\text{s-channel}}$ = 5.55 ± 0.08 (scale) ± 0.21(PDF) pb (NNLL)
Upper limit of 2.1 (3.1,1.6) times the SM

Run-1 Summary



Step 2

Measure SM properties in single top signatures

Measurements

- Tevatron + LHC established the three single top modes:
  - **Discovery era is over → Enter the Measurements age**

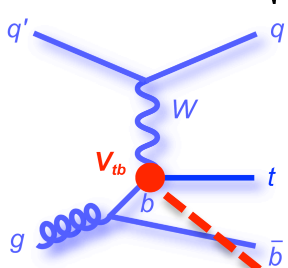
- Different SM measurements can be performed in the top sector and many have been performed already during Run-1 in CMS, mostly in ttbar
  - Competitive measurements since early data taking
  - To fully characterize the top quark and **test consistency of SM predictions**

- **The single top production at the LHC is large enough to measure top properties**
  - Complementary approach to ttbar
  - Another handle to tests potential BSM phenomena
  - Valuable to get the **full picture**

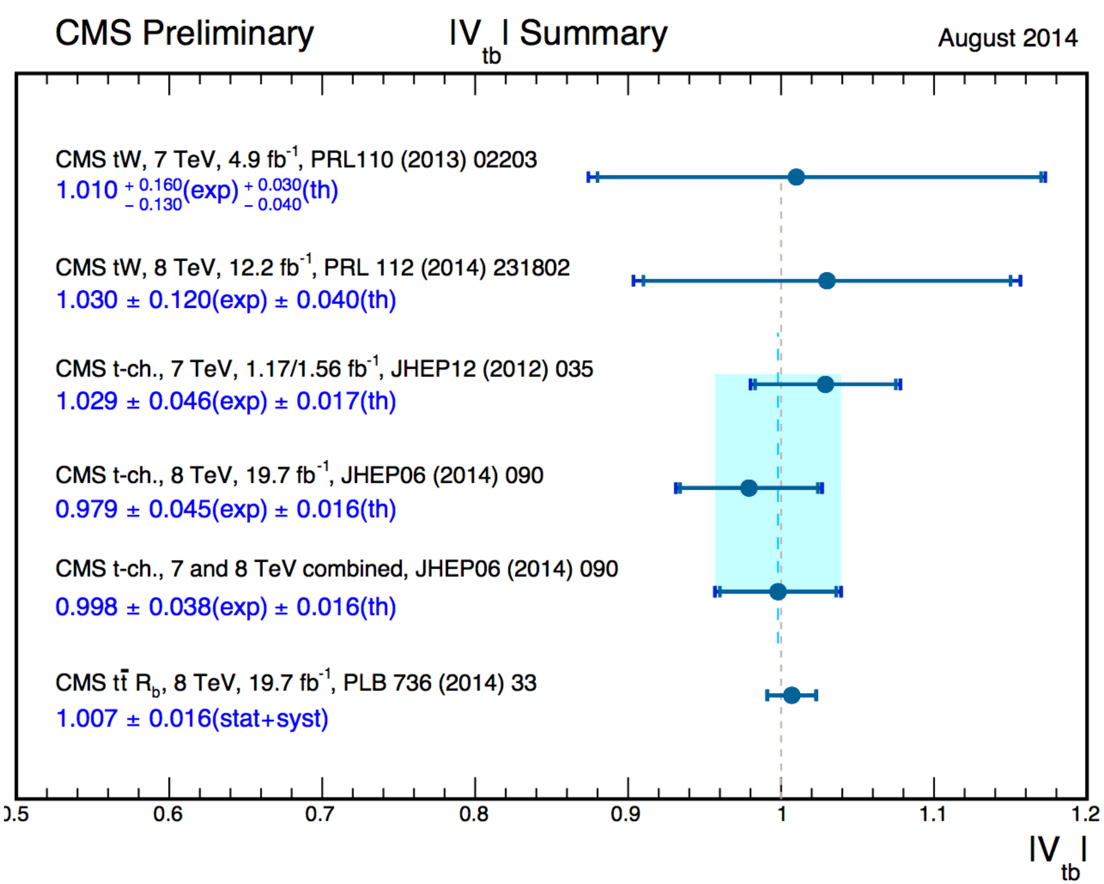
Cross-section and $|V_{tb}|$

- From the inclusive production cross section of single top (**t-channel, tW**), a value of the **CKM matrix element, $|V_{tb}|$**, can be extracted
- Considering $|V_{td}|, |V_{ts}| << |V_{tb}|$
- Cross section ~ $|V_{tb}|^2$

$$|V_{tb}| = \sqrt{\frac{\sigma_{measured}}{\sigma_{theory}}}$$

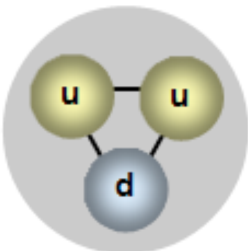


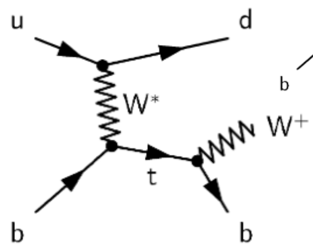
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

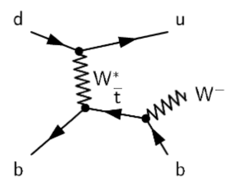


t-channel: R

- Within the measurement of the **t-channel** cross-section at 8TeV , we measure the **top/anti-top asymmetry, R**

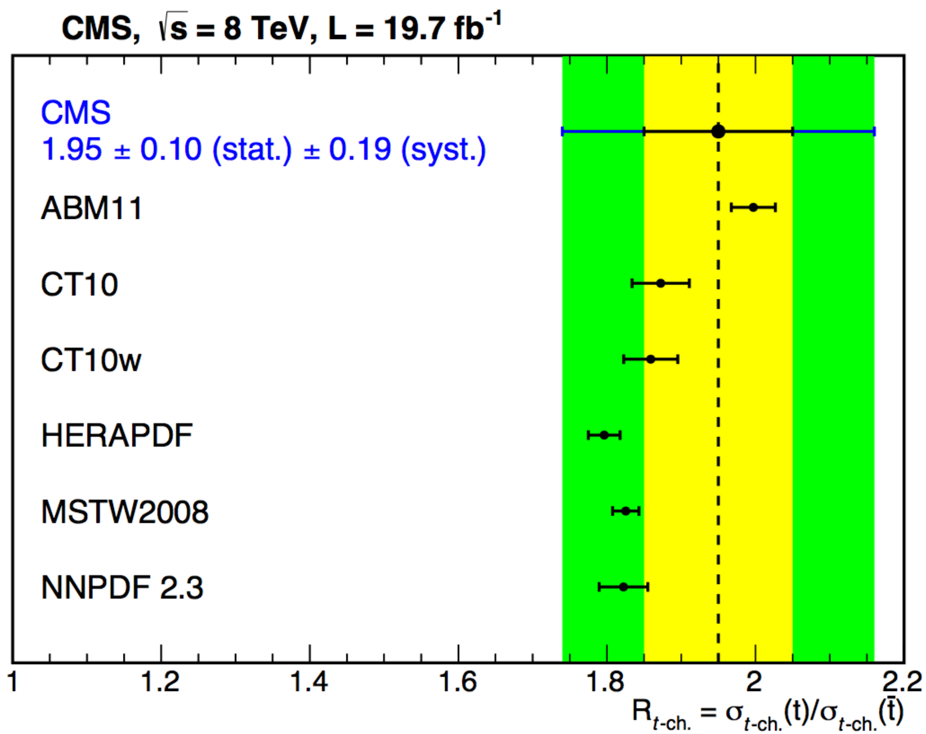






Due to the relative proportion of u and d quarks in the proton, more tops than anti-tops are expected to be produced

σ_{top} = 53.8±1.5(stat.)±4.4(syst)pb
σ^{th}_{top} = 54.87 +2.29 -1.94 pb (NLO, latest calculation)
$\sigma_{anti\text{-}top}$ = 27.6±1.3(stat.)±4.4(syst)pb
$\sigma^{th}_{anti\text{-}top}$ = 29.74 +1.67 -1.51 pb (NLO, latest calculation)

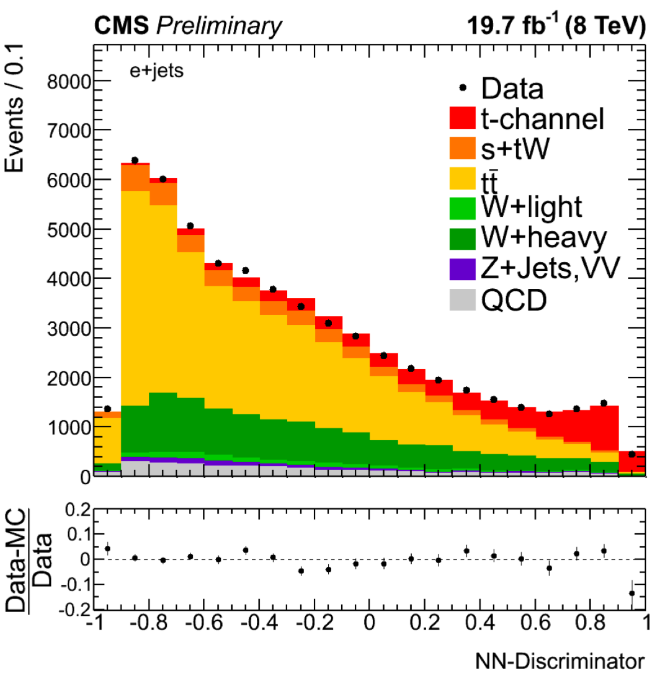


R = 1.95±0.10(stat)±0.19(syst)

JHEP 06 (2014) 090, arXiv:1403.7366

t-channel: differential x-sec

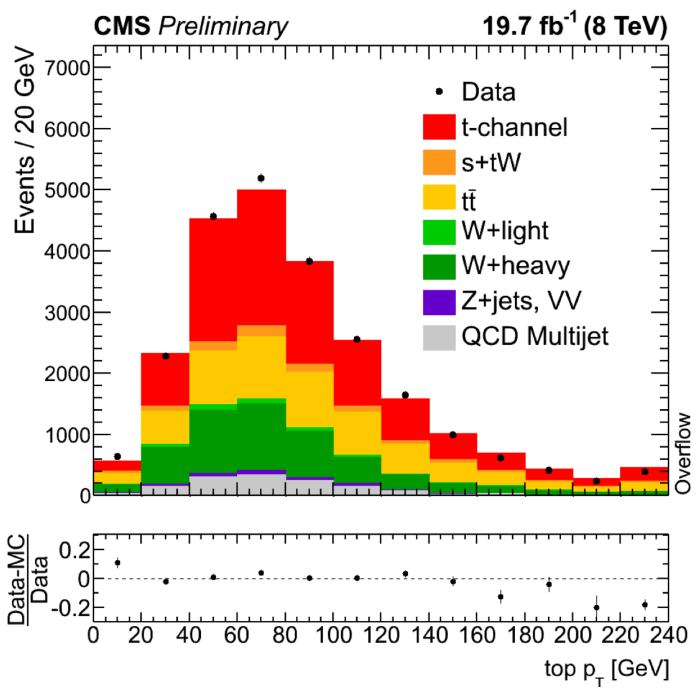
- t-channel **differential cross section** came last September, still preliminary
- 8 TeV, full luminosity
- Starting in the same way as the inclusive cross section, the analysis uses a NN to obtain a purer t-channel sample



September 2014

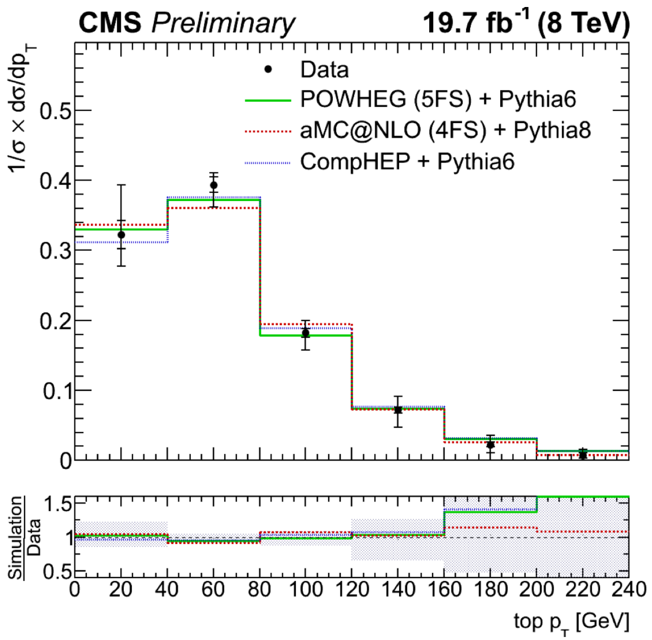
[CMS PAS TOP-14-004]

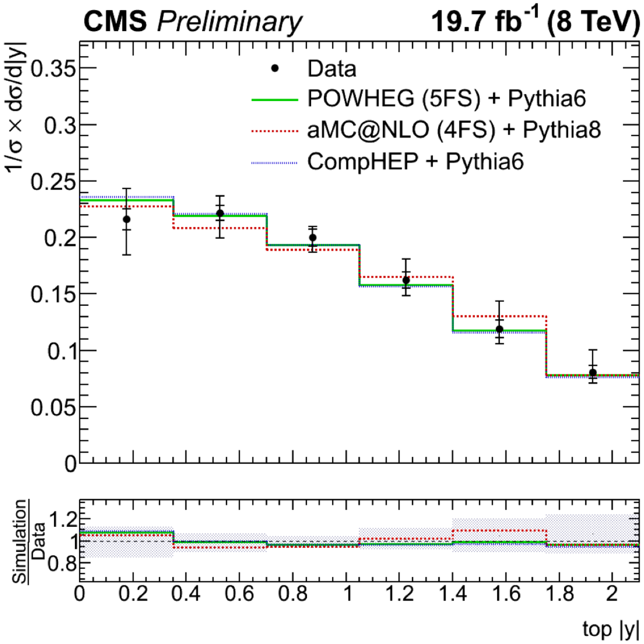
Events are selected by cutting on an optimal NN discriminant value



t-channel: differential x-sec

- Distributions are then corrected for detector effects allowing for direct comparison with theoretical predictions (**Unfolded**)
- p_T and rapidity of the top quarks compared with different predictions:
  - PowHeg+Pythia (solid), aMC@NLO+Pythia (dotted), and CompHEP (dashed)

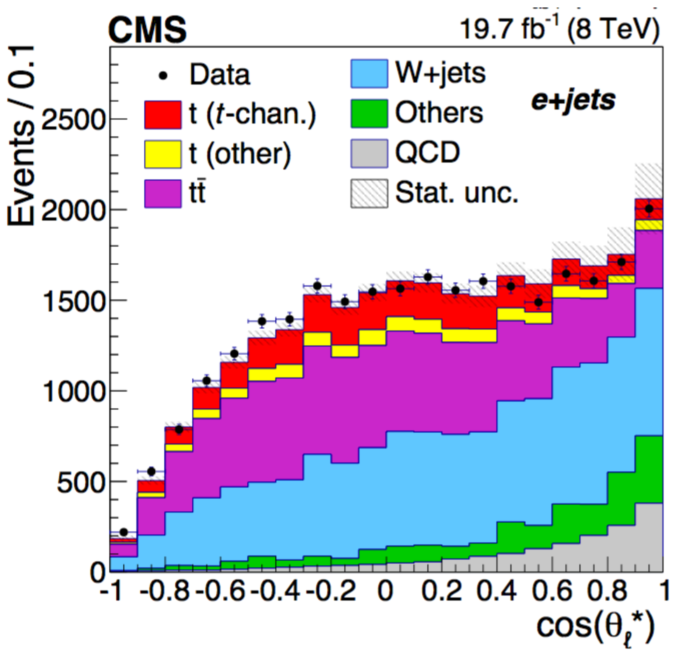




CMS PAS TOP-14-004

t-channel: W-helicity

- Further than cross section measurements → measurement of the W-helicity fractions is the **first published measurement of top properties in single top signatures at the LHC**
- Exact same selection and background estimation as the standard t-channel inclusive cross section measurement



θ*: angle between the W boson in the top quark rest frame and the down-type decay fermion in the W rest frame → related to the W-helicity fractions **(F_0, F_L, F_R)**

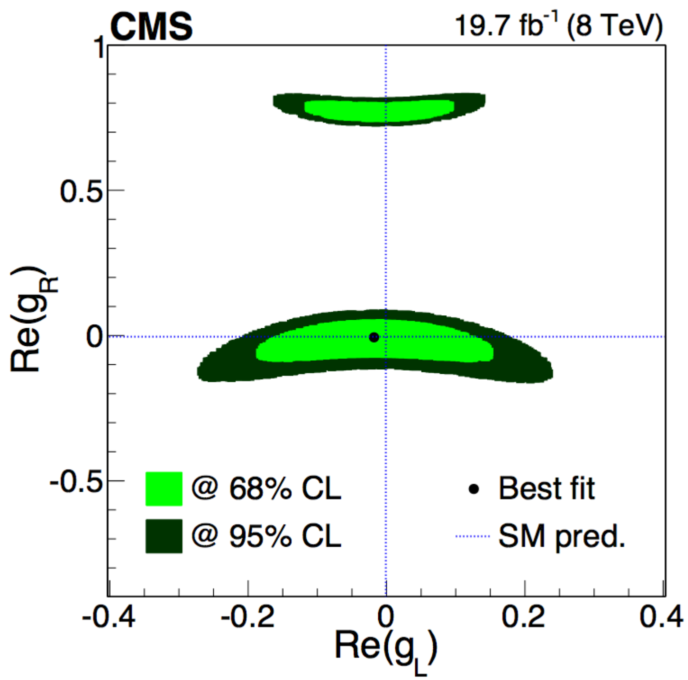
October 2014

JHEP 01 (2015) 053, arXiv:1410.1154

W boson helicity in t-channel

t-channel: W-helicity (II)

Theory prediction (NNLO)	Measured
$F_L = 0.311 \pm 0.005$ $F_R = 0.0017 \pm 0.0001$ $F_0 = 0.687 \pm 0.005$ PRD 81, 111503(R) (2010)	$F_L = 0.298 \pm 0.028\ (\text{stat}) \pm 0.032\ (\text{syst})$ $F_R = -0.018 \pm 0.019\ (\text{stat}) \pm 0.011\ (\text{syst})$ $F_0 = 0.720 \pm 0.039\ (\text{stat}) \pm 0.037\ (\text{syst})$



Using the helicity fractions measured → exclude the tensor terms of the tWb anomalous couplings, g_L and g_R

October 2014

JHEP 01 (2015) 053, arXiv:1410.1154

W boson helicity in t-channel

t-channel: top polarization

- **Single top quarks are highly polarized,** spin aligned with the recoiling light jet
- Polarization ~ spin asymmetry

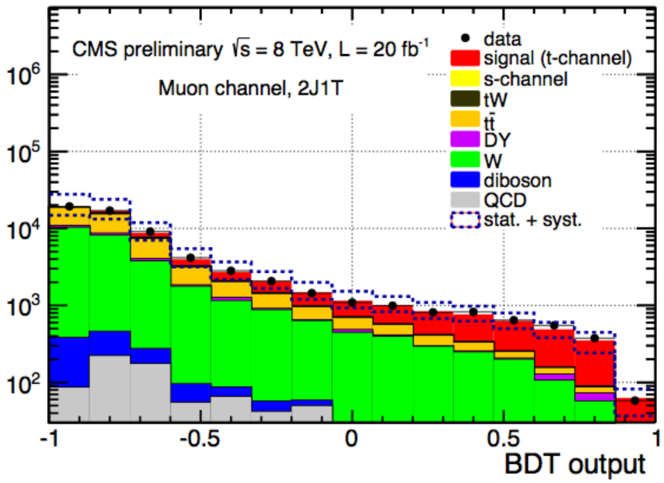
$$A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l$$

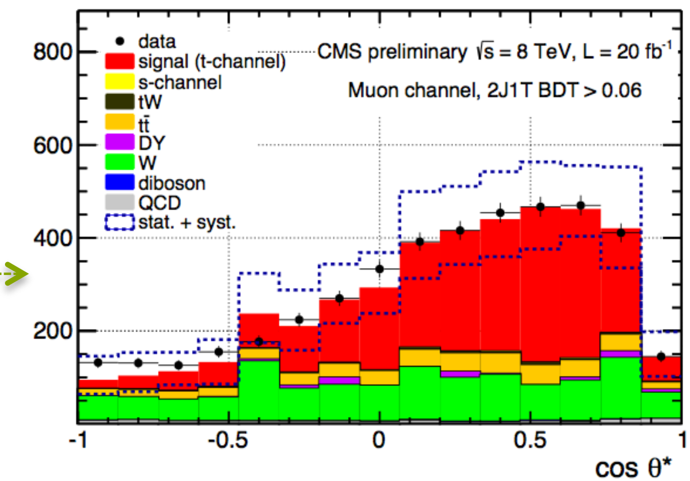
- From **unfolded cosθ*$_l$ distribution**

$$A_l = \frac{N(\cos\theta^*_{unfolded} > 0) - N(\cos\theta^*_{unfolded} < 0)}{N(\cos\theta^*_{unfolded} > 0) + N(\cos\theta^*_{unfolded} < 0)}$$

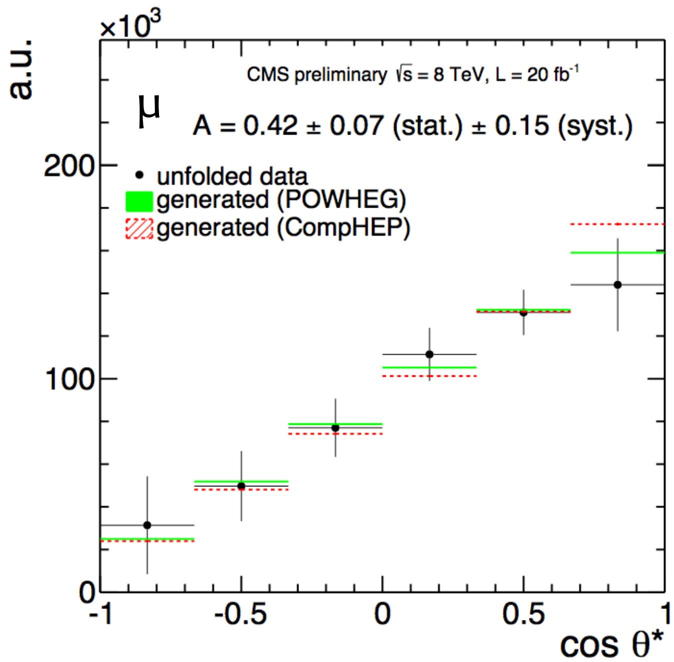
- A BDT is used to get a t-channel enriched sample

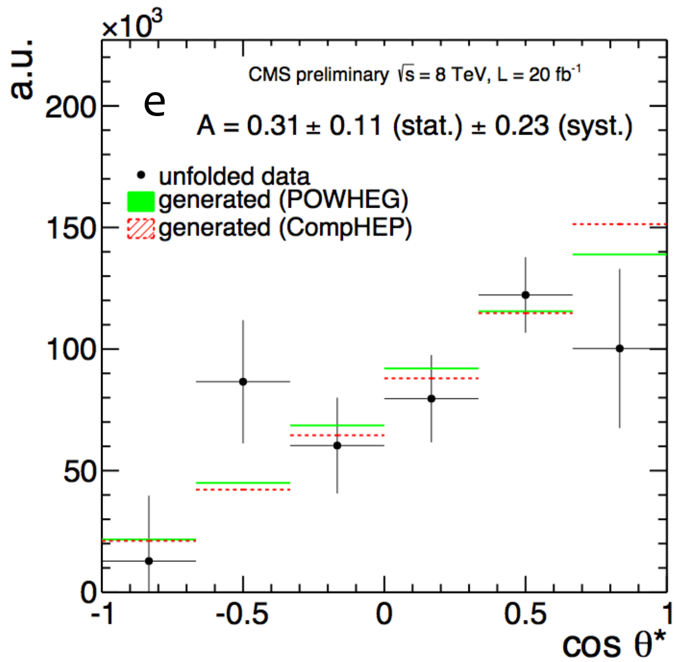
August 2013
CMS-PAS-TOP-13-001





t-channel: top polarization (II)





A_l=0.41±0.06(stat.)±0.16(syst.) (SM expectation 0.44)
P_t=0.82±0.12(stat.)±0.32(syst.)

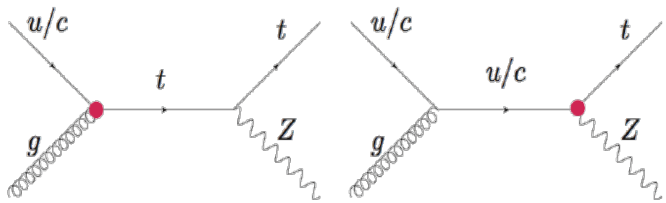
August 2013
CMS-PAS-TOP-13-001

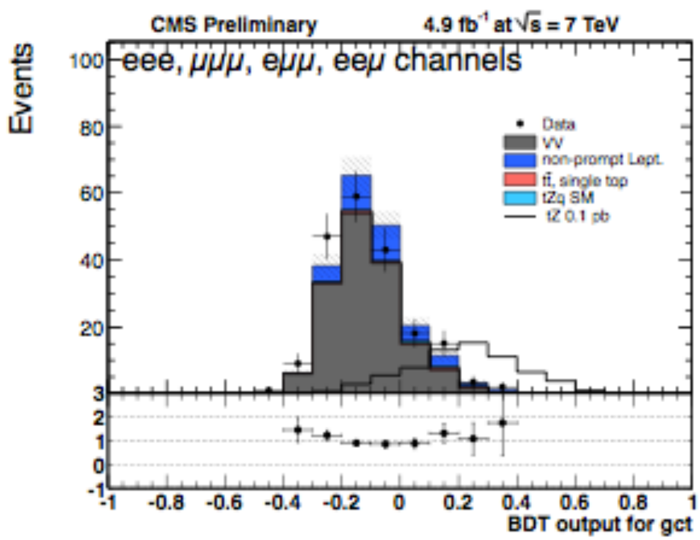
Step 3

Search for FCNC and Anomalous Couplings

FCNC tZ

- Limits on anomalous Wtb couplings can be extracted from SM measurements (W-helicity fractions, top polarization)
- Dedicated analysis searching for **FCNC in many single top signatures** are also in place





FCNC tZ

BDT (gut, gct, Zut, Zct) 7TeV

Limits on couplings and branching fractions

Three-lepton signature

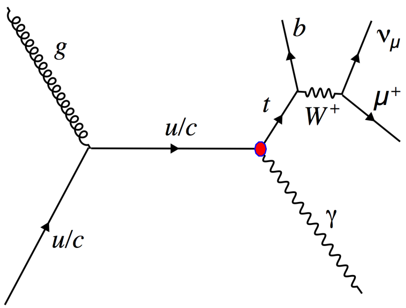
couplings	Expected	Observed	$\mathcal{B}(t \to gq/Zq)$
κ_{gut}/Λ	0.096	0.096	0.56 %
κ_{gct}/Λ	0.427	0.354	7.12 %
κ_{Zut}/Λ	0.492	0.451	0.51 %
κ_{Zct}/Λ	2.701	2.267	11.40 %

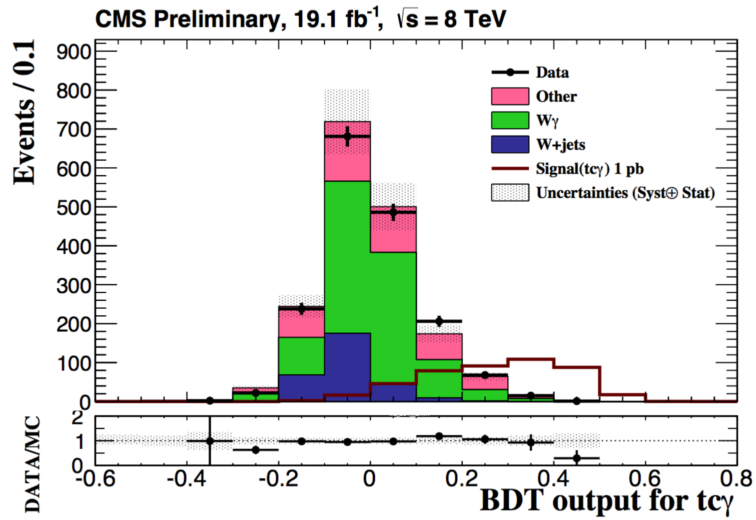
July 2013

CMS-PAS-TOP-12-021

FCNC tγ

- Another preliminary result from Spring last year
- **tqγ**
  - tuγ, tcγ couplings
  - BDT 8TeV, μ





May 2014

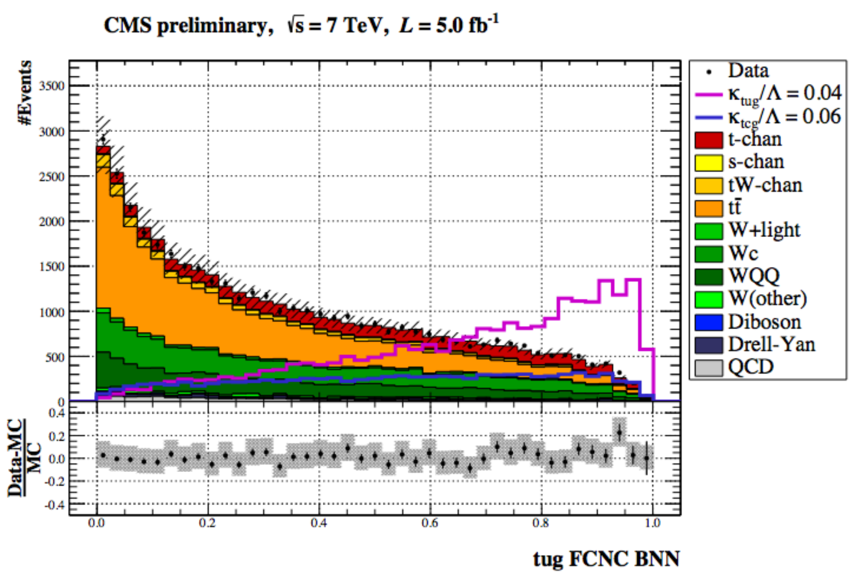
CMS PAS-TOP-14-003

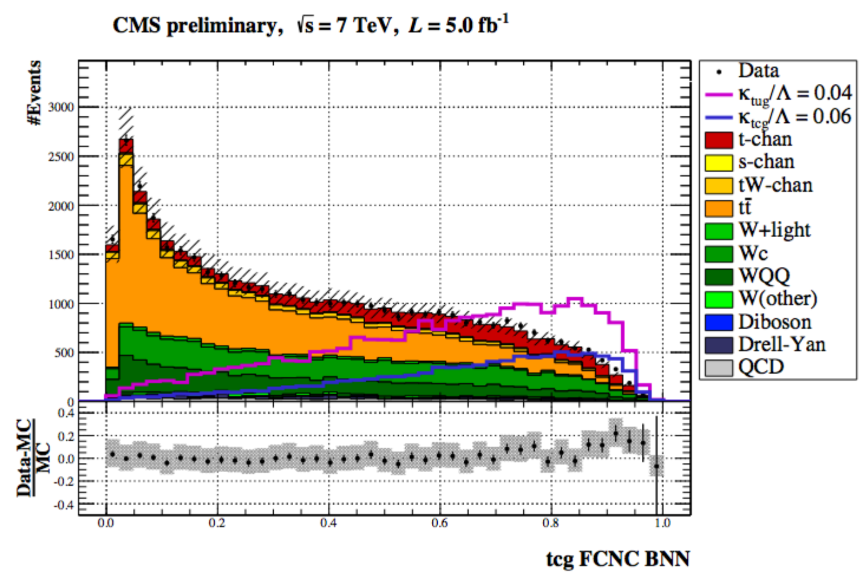
	Exp. limit (LO)	Obs. limit (LO)	Exp. limit (NLO)	Obs. limit (NLO)
$\sigma_{tu\gamma} \times Br(W \to l\nu_l)$	0.0404 pb	0.0234 pb	0.0408 pb	0.0217 pb
$\sigma_{tc\gamma} \times Br(W \to l\nu_l)$	0.0411 pb	0.0281 pb	0.0410 pb	0.0279 pb
$\kappa_{tu\gamma}$	0.0367	0.0279	0.0315	0.0229
$\kappa_{tc\gamma}$	0.113	0.094	0.0790	0.0652
$Br(t \to u\gamma)$	0.0279%	0.0161%	0.0205%	0.0108%
$Br(t \to c\gamma)$	0.261%	0.182%	0.193%	0.132%

FCNC and AC in t-channel

- It is possible to optimize an analysis to explore FCNC and anomalous couplings in t-channel directly
- Another preliminary result from last Spring
- **FCNC in t-channel**
- 7TeV, tcg and tug
- NN using different anomalous samples to separate hypotheses

May 2014
CMS PAS-TOP-14-007



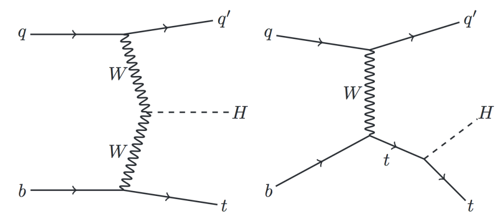


Step 4

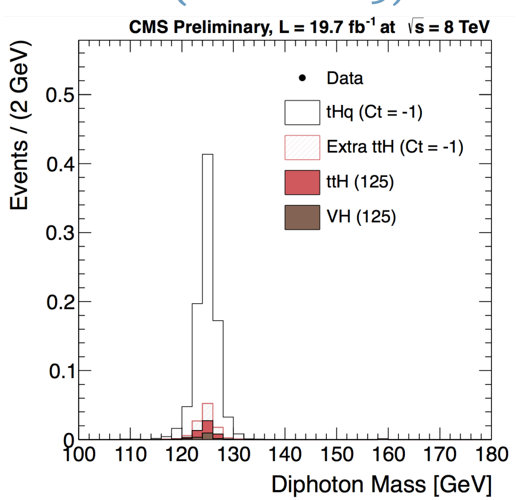
Explore unusual single top signatures

Top+ Higgs

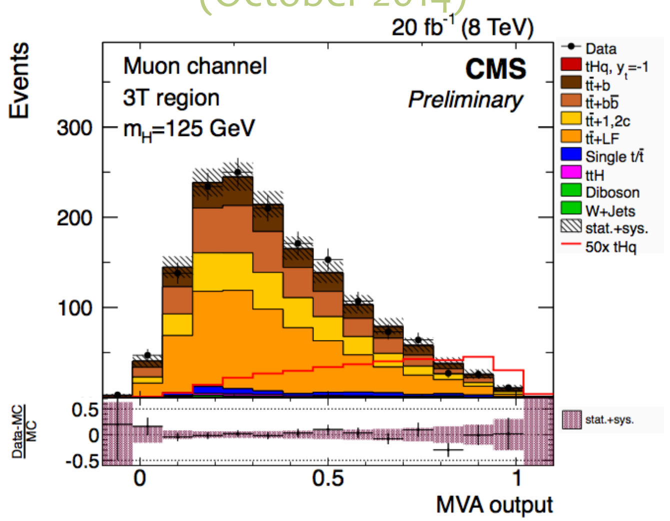
- **single top + Higgs (complementary to ttH)**
  - tH production highly suppressed in the SM
  - If top Higgs Yukawa coupling is negative → enhanced
  - Several decays investigated, more to come, all preliminary
    - Need Run-2 to become sensitive



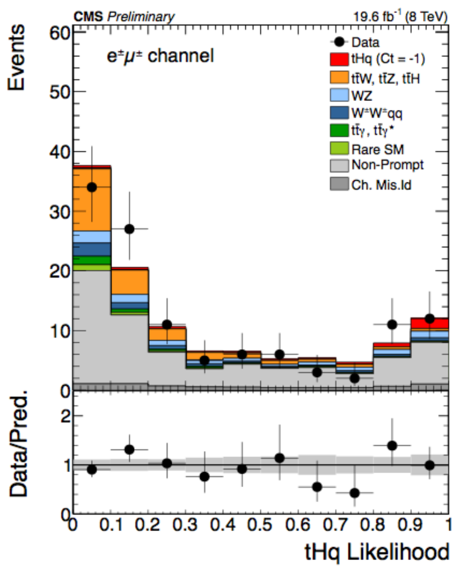
tH, H→γγ
CMS PAS-HIG-14-001
(March 2013)



tH, H→bb
CMS PAS-HIG-14-015
(October 2014)

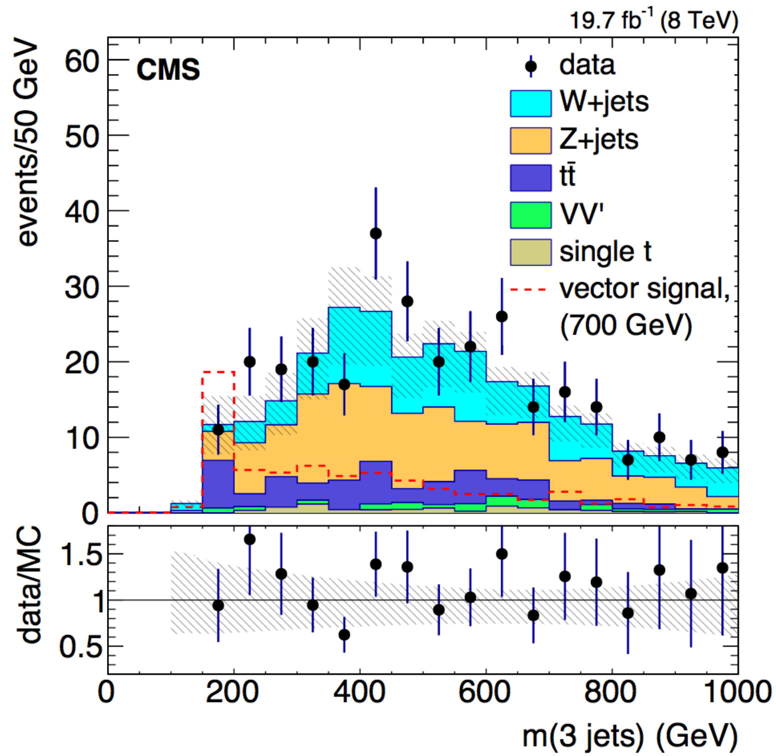


tH, H→WW
CMS PAS-HIG-14-026
(February 2015)



BSM top + X

- There are many other BSM channels that involve top quarks and/or similar signatures to single top:
  - classic example: **W'⟶tb** (arXiv:1402.2176)
- Some feature truly "single" top quarks



Monotop

Dark Matter search using top + MET

arXiv:1410.1149

Accepted by PRL for publication

(October 2014)

Next steps?

Run-2

- **There are still open topics still to be explored by CMS with Run-1**
  - Top mass in single top signatures, fiducial cross sections…

- Run-2 will start late Spring 2015 → Will run ~3 years [**300fb^{-1} at 13 (14) TeV**]
  - **t-channel:** Has become a SM candle (early analysis~1fb^{-1})
  - tW and tt interplay → Run-2 goal

- With **higher luminosity and center of mass energies**
  - Work on systematics and modeling
  - Face new challenges (high pileup)
  - Moving towards "**precision**" era
  - Rare SM processes accesible (SM tZq and tγq)

- More BSM channels to explore
- New approaches: Single top in heavy ions! (?) arXiv:1502.04875

Summary

- Single top signatures were very rare and largely unknown until recently
- In less than 10 years we have made incredible progress

  → **the LHC is extremely powerful for top, and single top in particular**
- In CMS we have studied the **three main production modes:**
  - t-channel
  - tW associated production
  - s-channel
- We have so many single top quarks produced via t-channel that we can use them to make **measurements:**
  - W-helicity fractions, top polarization, |Vtb|…
- We have used conventional and rare single top production modes to look for **FCNC and Anomalous Couplings**
- We have starting the exploration of more exotic single top processes looking for new phenomena
- **Run-2 will be the time to fully explore single top signatures, in particular to look for physics beyond the standard model**