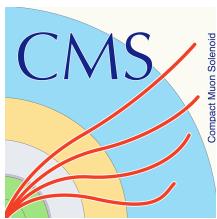


Overview of single top physics in CMS with Run-1 data



Rebeca Gonzalez Suarez
University of Nebraska, Lincoln

19th of June 2015
University of Göttingen, II. Physikalisches Institut

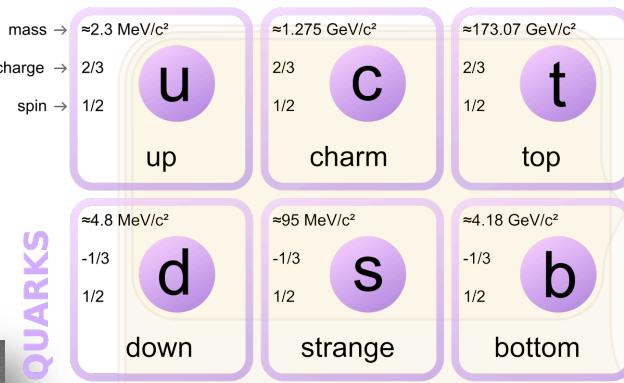


Feb. 24, 1995

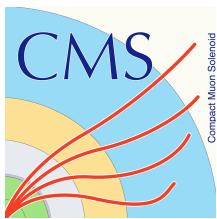
2



- 20 years ago, the two Tevatron collaborations, CDF and DZero, submitted their Top Discovery papers to PRL:
 - [PRL 74, 2626–2631](#), [PRL 74, 2632–2637](#)
- Exactly 6 months before Windows 95 was released **the quark family picture was completed**



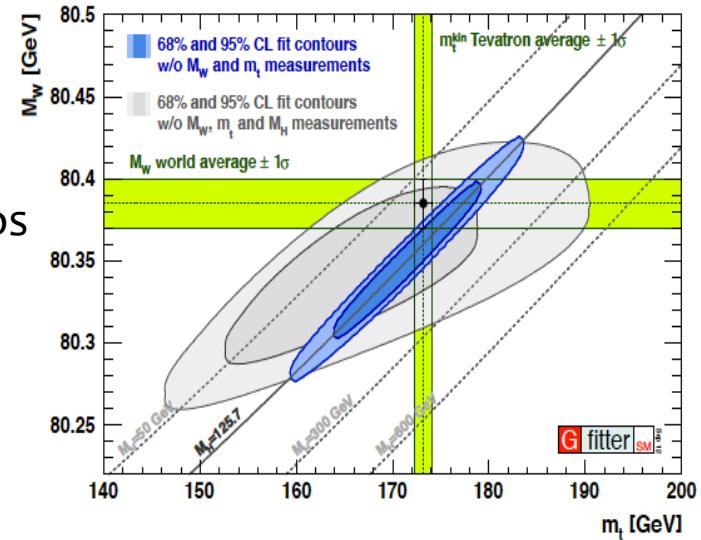
And I was 13 years old...

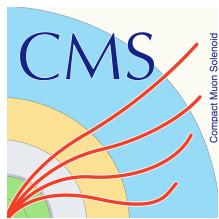


The top quark

3

- Today, we are getting to know the top quark really well → **Tevatron legacy** of central importance
- It is the **heaviest elementary particle known**
 - $m_{top} = 173.34 \pm 0.27(\text{stat}) \pm 0.71(\text{syst}) \text{ GeV}$
- 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)
- Characteristic experimental signature:
 - Decays almost exclusively as $t \rightarrow W b$



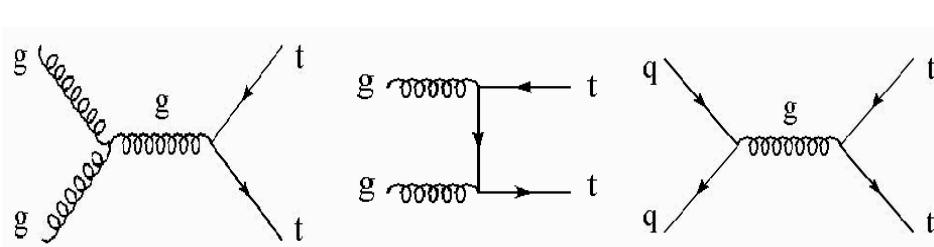


Top quarks at the LHC

4



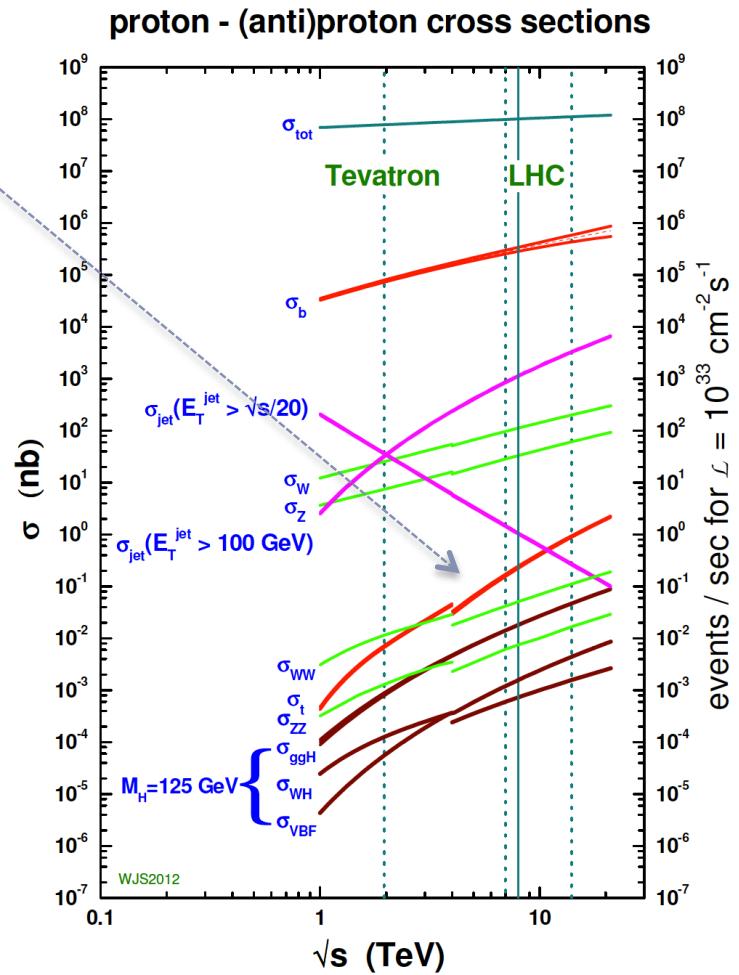
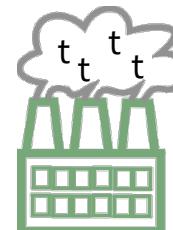
- At the **LHC**, top quarks are produced at a **very high rate**

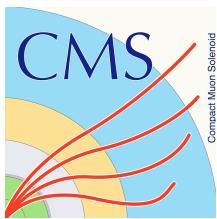


Main mode: **ttbar pairs**, via **strong interaction**

x-sec (pb)	ttbar
Tevatron (1.96TeV)	7.08 approx. NNLO
LHC @ 7TeV	177.31 NNLO+NNLL
LHC @ 8TeV	252.89 NNLO+NNLL
LHC @ 13TeV	831.76 NNLO+NNLL

"The LHC is a top quark factory!"



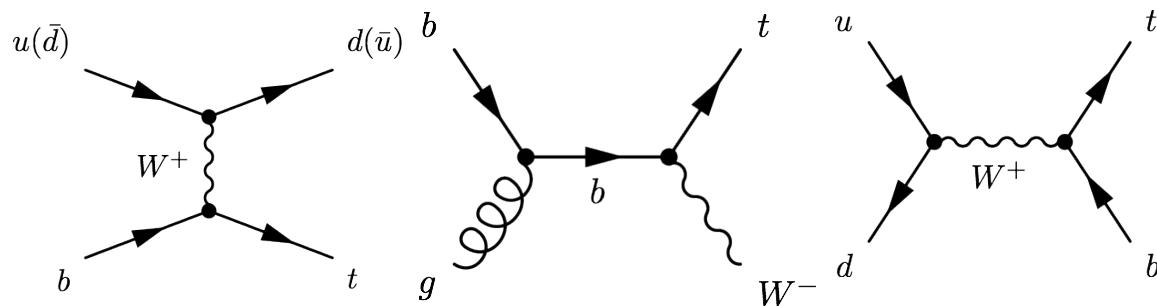


Single top production

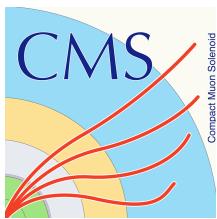
5



- There is an alternative mode, at a 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 (1.96TeV)	2.08	0.22	1.046
LHC @ 7TeV	63.89	15.74	4.29
LHC @ 8TeV	84.69	22.2	5.24
LHC @ 13TeV	216.99	71.2	10.32



Single top timeline

6

- Single top quarks were also **observed for the first time 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
- 2009 Single top discovery
2010 LHC starts colliding
2011 First single top results at the LHC

"The LHC is a SINGLE top quark factory!"

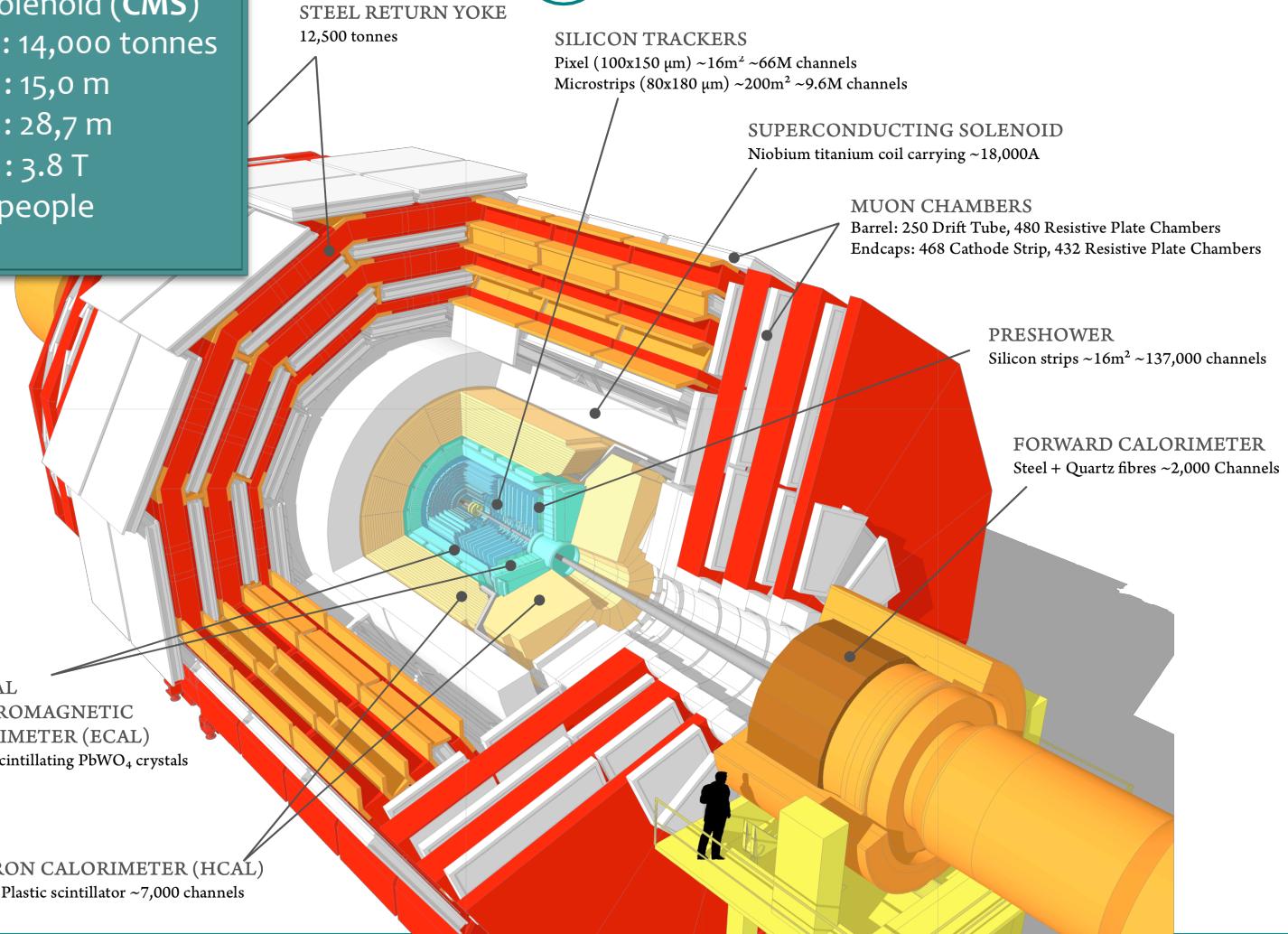


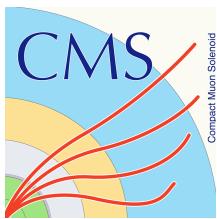
Compact Muon Solenoid (CMS)

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

7



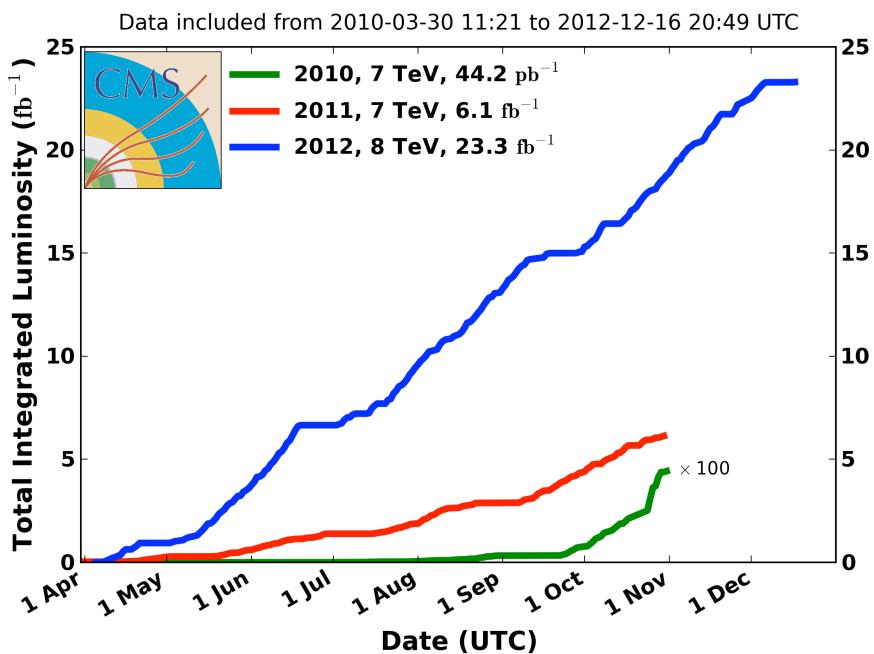


Run-1 in tops



8

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: $\sim 5\text{fb}^{-1}$ of pp collisions at 7TeV and $\sim 20\text{fb}^{-1}$ at 8TeV

This means that CMS has recorded:

- More than 5M $t\bar{t}$ pairs
- Around 2M of single top quarks (via t-channel)

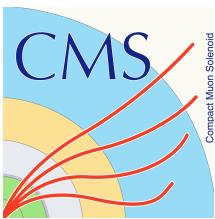
And also:

- Half a million of tW events and a bit more than 100K of s-channel events
- What have we done with them?

Step 1



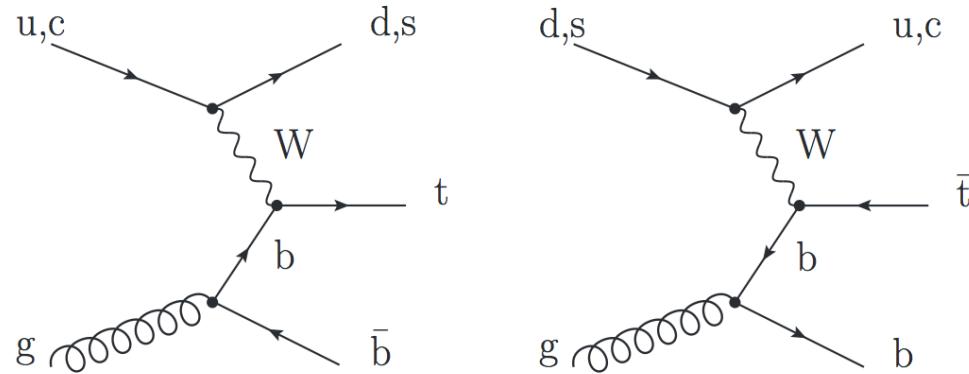
Study the three single top production modes and
measure their production cross section



t-channel

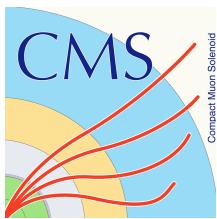
10

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



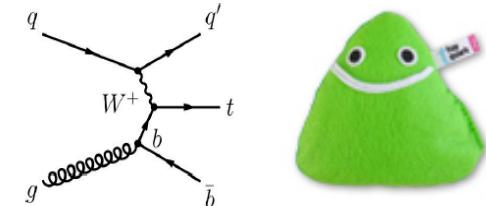
- Final state studied: **lepton + jets signature**
- Signal events characterized by:
 - One isolated **muon or electron**
 - Missing transverse energy (**MET**)
 - A central **b jet**
 - light-quark jet from the hard scattering process (often **forward**)
 - Additionally, a second b jet produced in association to the top quark
- **Main backgrounds: W+jets, ttbar, multijet**

} Leptonic top decay

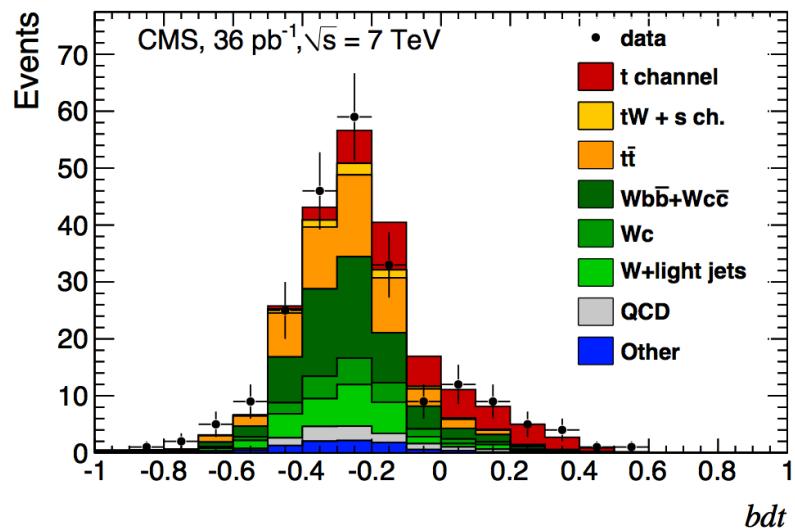


t-channel

11



- Before the start of the Run-1
 - ✖ only t-channel production had been observed at the Tevatron
- In 2011, barely a year into collisions, CMS published its first t-channel paper



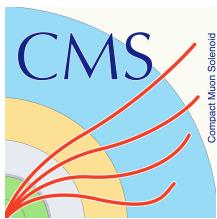
Jun 2011

Phys. Rev. Lett. 107:091802, 2011

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

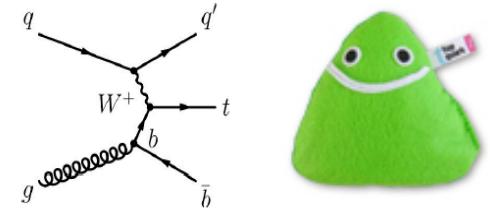
36pb^{-1}

In one year, power to explore processes that had taken decades before

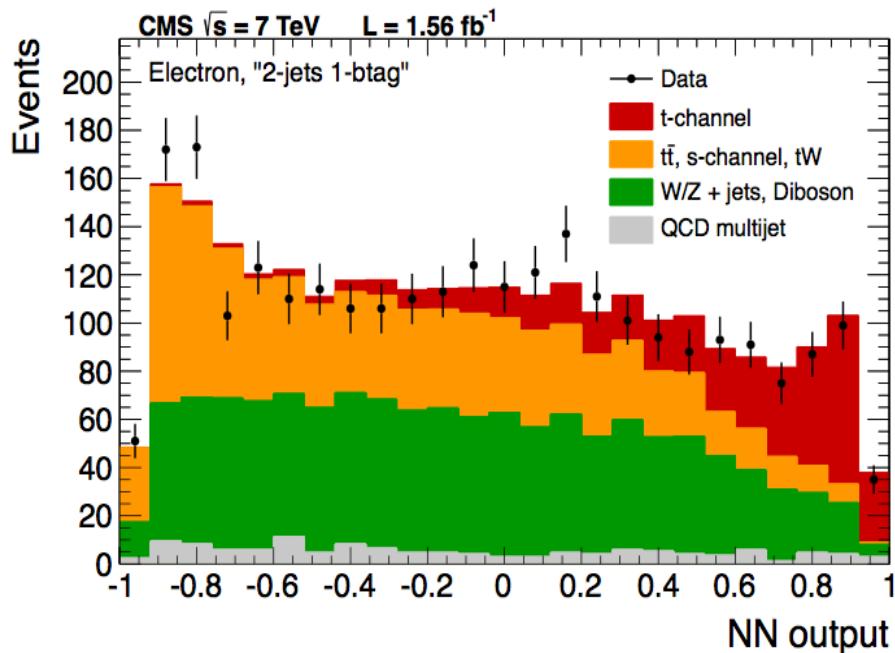


t-channel (7TeV)

12



- 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, $|\eta_{j'}|$

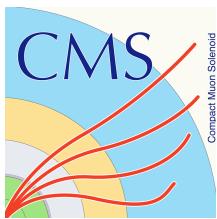


Different regions defined (jets, b-tag)
Multijet and W+jets background
estimated from data

Statistical, systematic, and theory
uncertainties on the same level

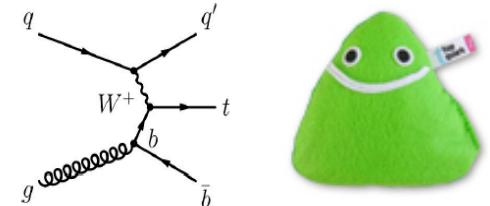
September 2012

JHEP 12 (2012) 035, [arXiv:1209.4533](https://arxiv.org/abs/1209.4533)
7TeV - 1.17 and 1.56 fb^{-1}

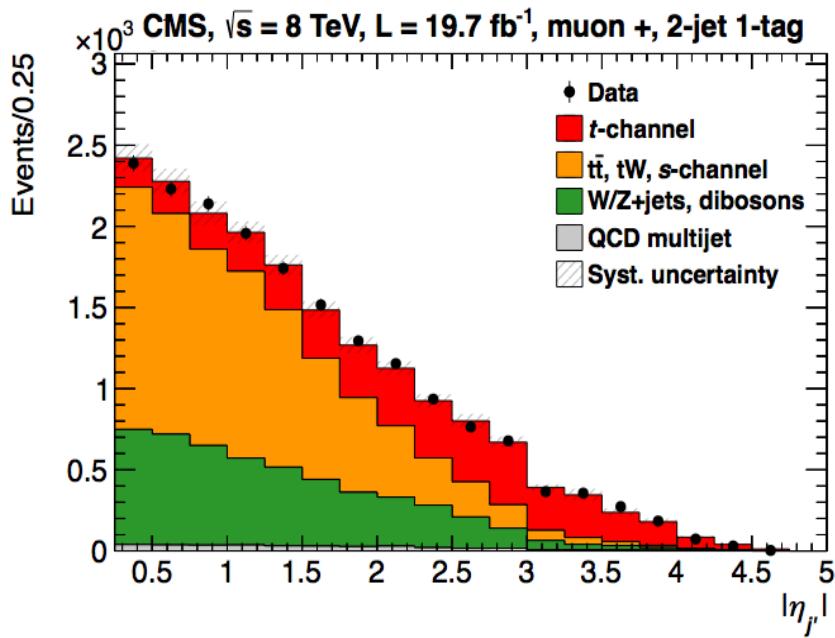


t-channel (8TeV)

13



- At 8 TeV, the measurement was done using the $|\eta_j|$ analysis alone



March 2014

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

8 TeV - 19.7fb^{-1}

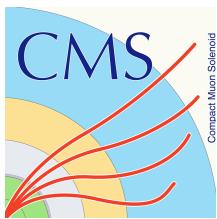
Similar approach as for 7TeV, more data-driven (Multijet, $W+jets$, $t\bar{t}$ bar)

Full luminosity

Systematic dominated

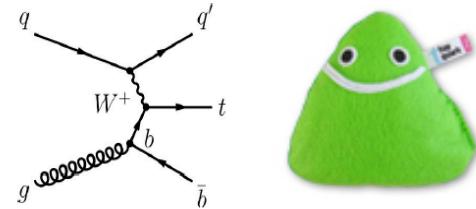
main uncertainties:

Signal modeling ($\sim 6\%$)
and JES/JER/MET ($\sim 4\%$)

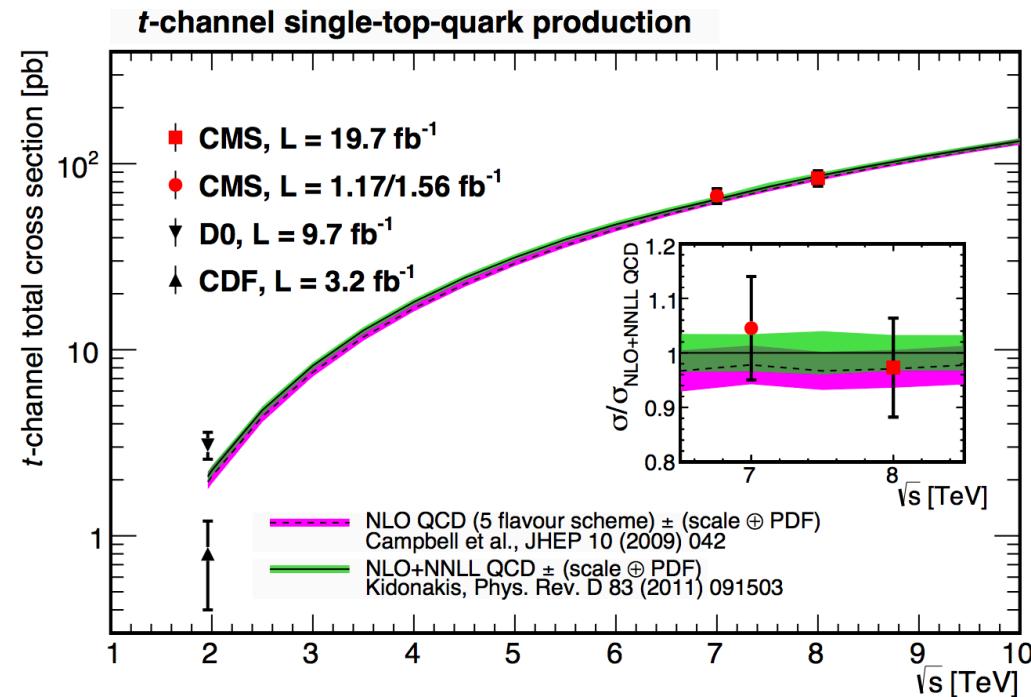


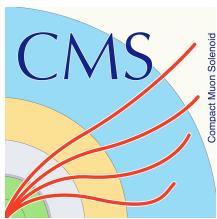
t-channel: results

14



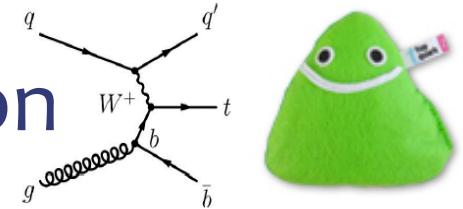
7TeV	Measured	$67.2 \pm 3.7(\text{stat}) \pm 3.0(\text{syst}) \pm 3.5(\text{th}) \pm 1.5(\text{lumi}) \text{ pb} = 67.2 \pm 6.1 \text{ pb}$
	Prediction	$63.89 + 2.91 - 2.52 \text{ (NLO, latest calculation)}$
8TeV	Measured	$83.6 \pm 2.3 \text{ (stat)} \pm 7.4 \text{ (syst) pb}$
	Prediction	$84.69 + 3.76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



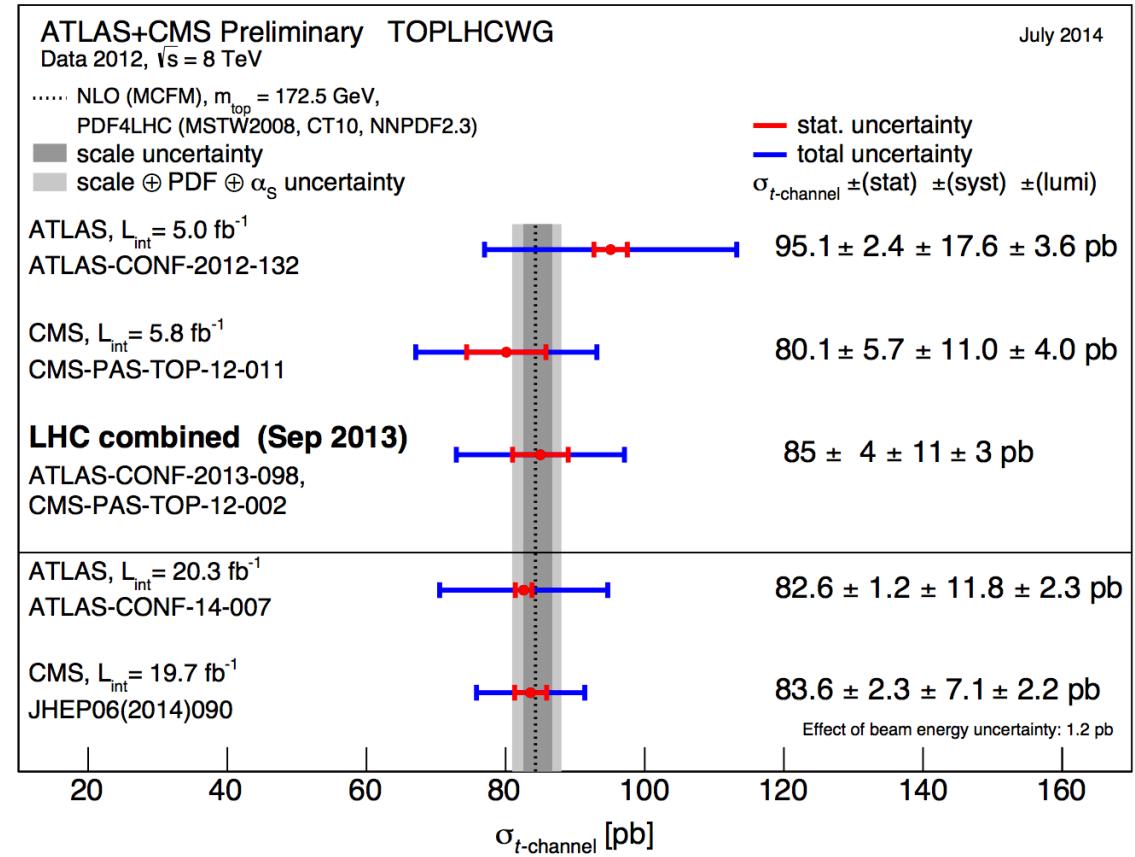


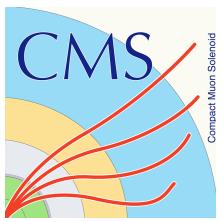
t-channel: LHC combination

15



- At 8TeV, an LHC (ATLAS+CMS) combination was made
- It was the first LHC single top combination
 - Sept. 2013
 - [CMS-PAS-TOP-12-002](#)



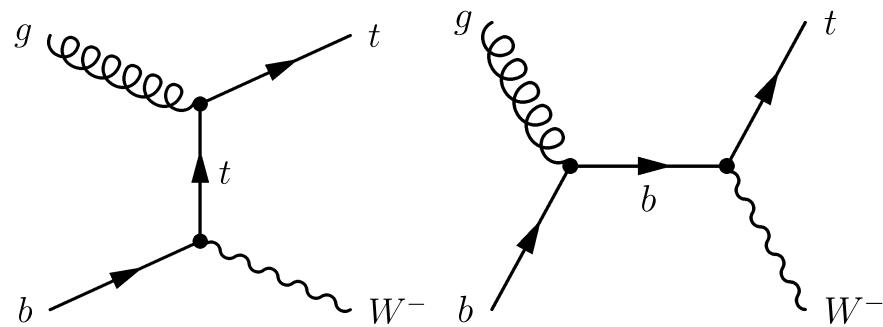


tW associated production

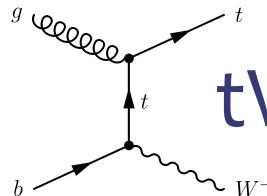
16



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

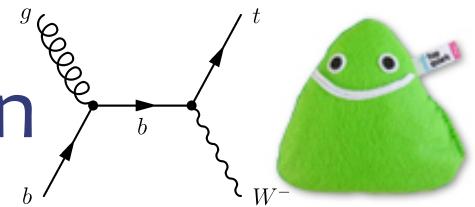


- Final state studied: **dilepton signature**
- Signal events are characterized by:
 - **Two** opposite-sign, isolated **leptons**
 - Missing transverse energy (2 neutrinos in the final state)
 - A jet coming from a **b** decay
- **Backgrounds: ttbar (main challenge), DY**

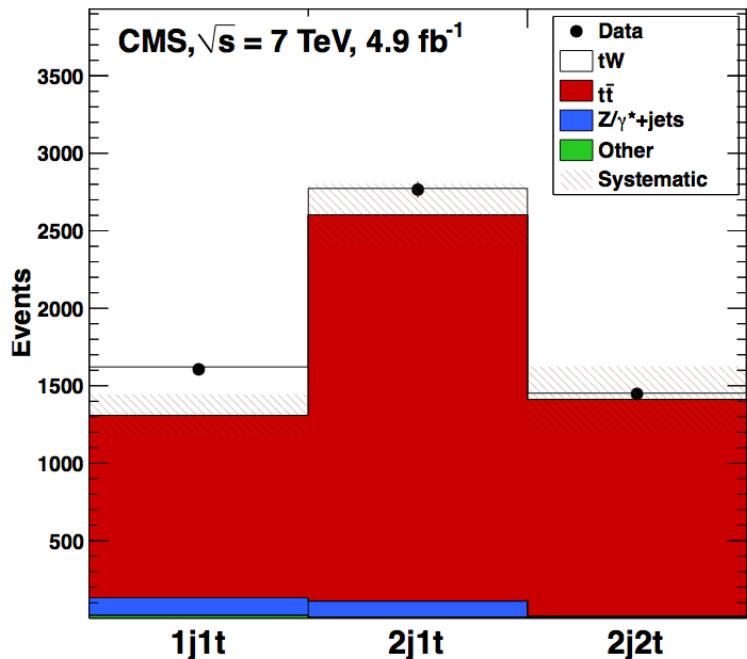


tW associated production

17

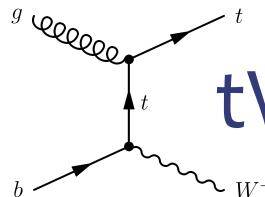


- The low cross section of this process at the Tevatron made it **impossible to study before the LHC** → At the LHC is still not easy
- CMS reported Evidence at 7TeV



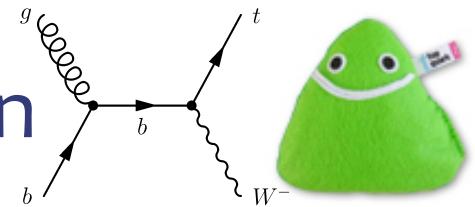
September 2012
Phys. Rev. Lett. 110 (2013) 022003
[arXiv:1209.3489](https://arxiv.org/abs/1209.3489)

4.0σ
 $7\text{TeV} - 4.9\text{fb}^{-1}$

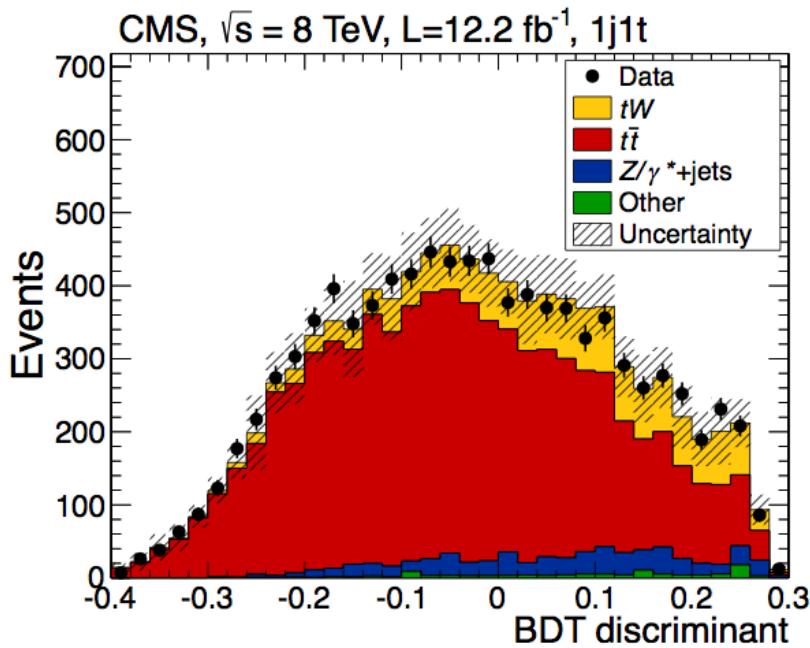


tW associated production

18



- And discovery at 8TeV → Achieving observation ($> 5 \sigma$)



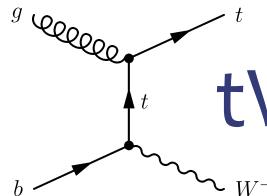
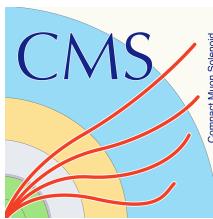
January 2014
Phys. Rev. Lett. 112 (2014) 231802
[arXiv:1401.2942](https://arxiv.org/abs/1401.2942)

6.1σ

8TeV - 12.2 fb^{-1}

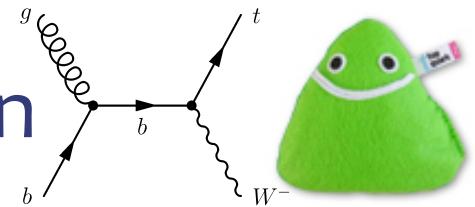
7 TeV → cut-based, basic BDT
8TeV → cut-based, shape-based, more sophisticated BDT

At 8TeV the analysis is already not statistically limited

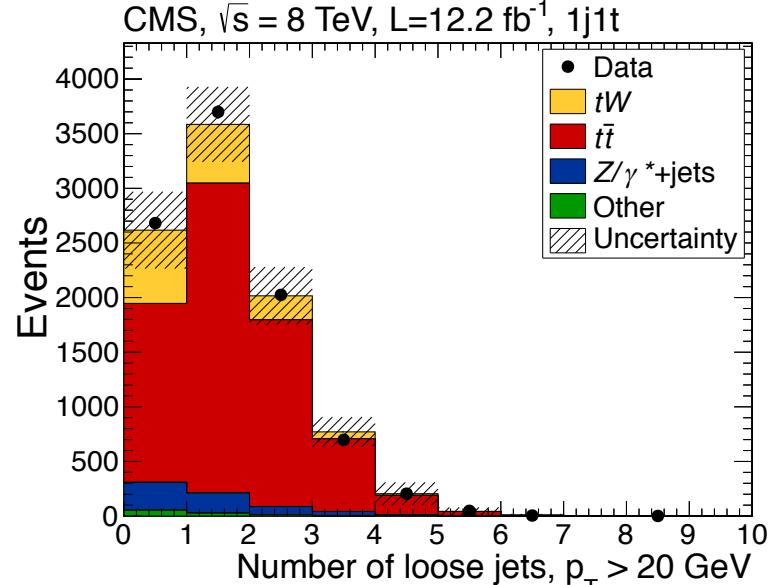


tW associated production

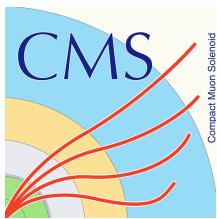
19



- 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

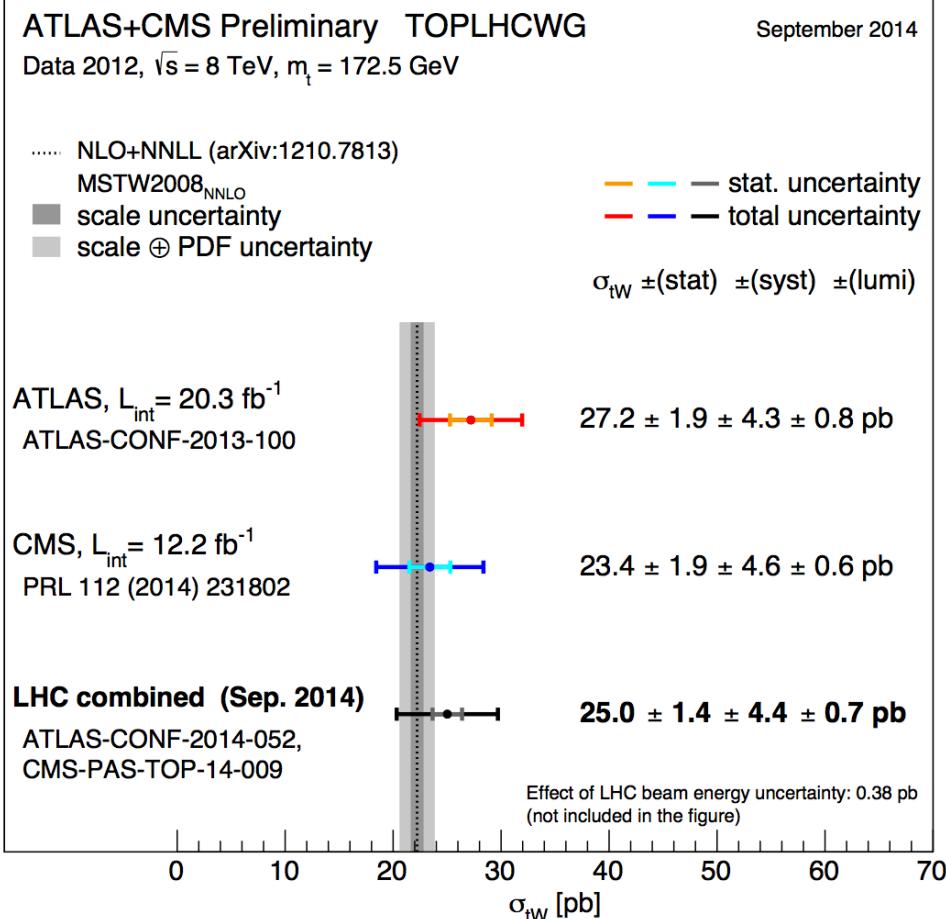


7TeV	Measured	$\sigma_{tW} = 16+5-4 \text{ pb}$
	Prediction	$\sigma_{tW} = 15.6 \pm 0.4 \pm 1.1 \text{ pb}$
8TeV	Measured	$\sigma_{tW} = 23.4 \pm 5.4 \text{ pb}$
	Prediction	$\sigma_{tW} = 22.2 \pm 0.6 \pm 1.4 \text{ pb}$



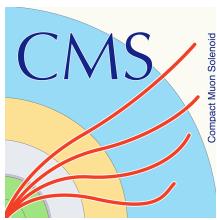
tW Combination with ATLAS

20



Recently, an ATLAS+CMS tW combination at 8TeV was also made public

September 2014
PAS TOP-14-009



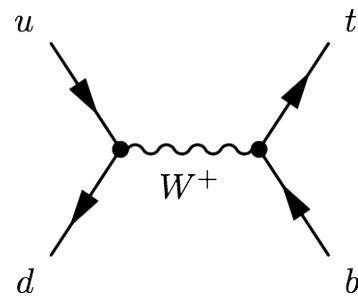
s-channel

21

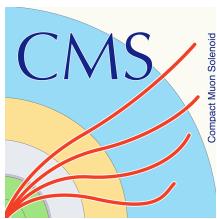
- Lowest cross-section at the LHC, more important at the **Tevatron** (where the study of data **after** the shutdown allowed for the **observation of the process**)

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



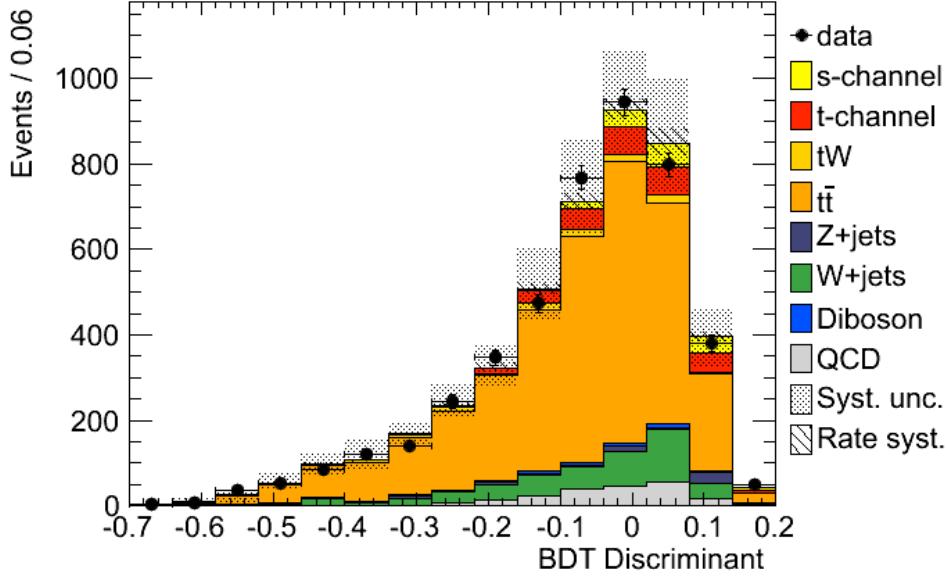
- Signal signature: **lepton + jets**
 - **A lepton** (e, μ) and **MET** from the decay of a W boson
 - **Two jets** with high transverse momentum originating from **b-quarks**
- **Main backgrounds:** $W+jets$ and $t\bar{t}$, multijet



s-channel

22

- 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

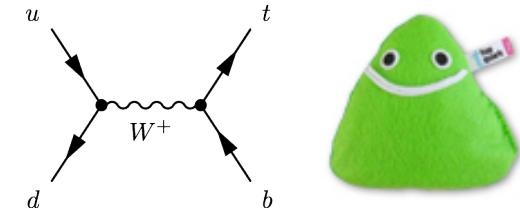
In Run-2 will be even harder

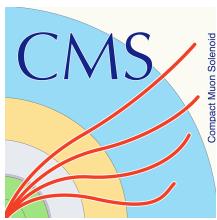
σ [pb]	t-channel	tW	s-channel
LHC (7 TeV)	63.89	15.74	4.29
LHC (8 TeV)	84.69	22.2	5.24
LHC (13 TeV)	216.99	71.2	10.32

$$\sigma_{\text{s-channel}} = 6.2 \pm 5.4(\text{exp.}) \pm 5.9(\text{th}) \text{ pb} = 6.2 + 8.0 - 5.1 \text{ pb (FC)}$$

$$\sigma^{\text{th}}_{\text{s-channel}} = 5.55 \pm 0.08 \text{ (scale)} \pm 0.21 \text{ (PDF) pb (NNLL)}$$

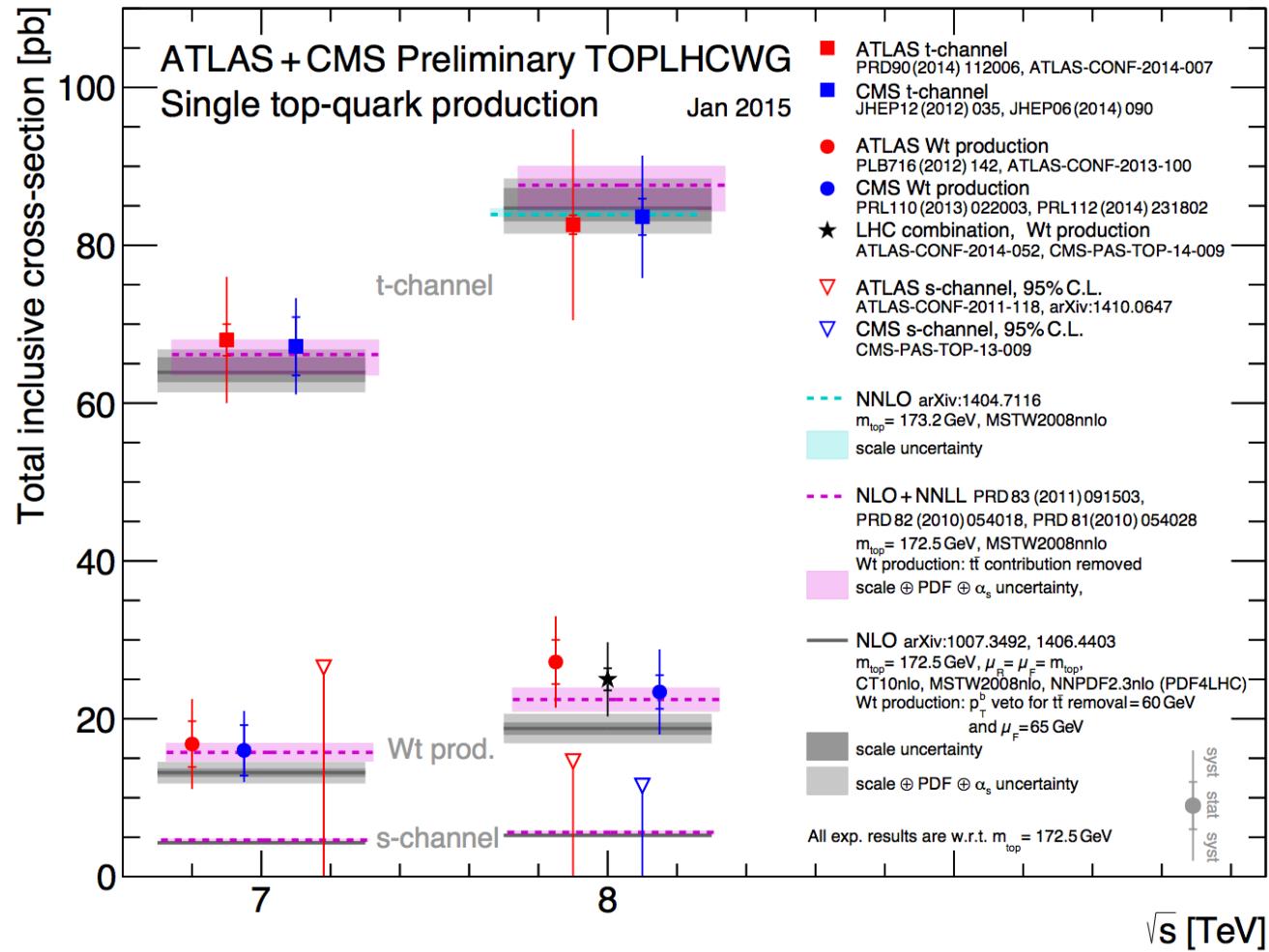
Upper limit of 2.1 (3.1, 1.6) times the SM





Run-1 Summary

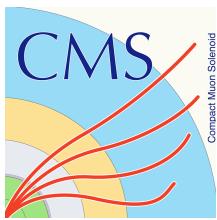
23



Step 2



Measure SM properties in single top signatures



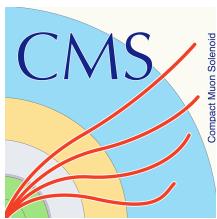
Measurements

25



- Tevatron + LHC established the three single top modes:
 - **Discovery era is over → Enter the measurements age**
- During Run-1, Different SM measurements in the top sector performed in ttbar
 - Competitive measurements since early data taking
- **The single top production at the LHC is large enough to measure top properties in single top signatures**
 - Complementary to ttbar
 - Another handle to tests potential BSM phenomena
 - Valuable to get the **full picture**



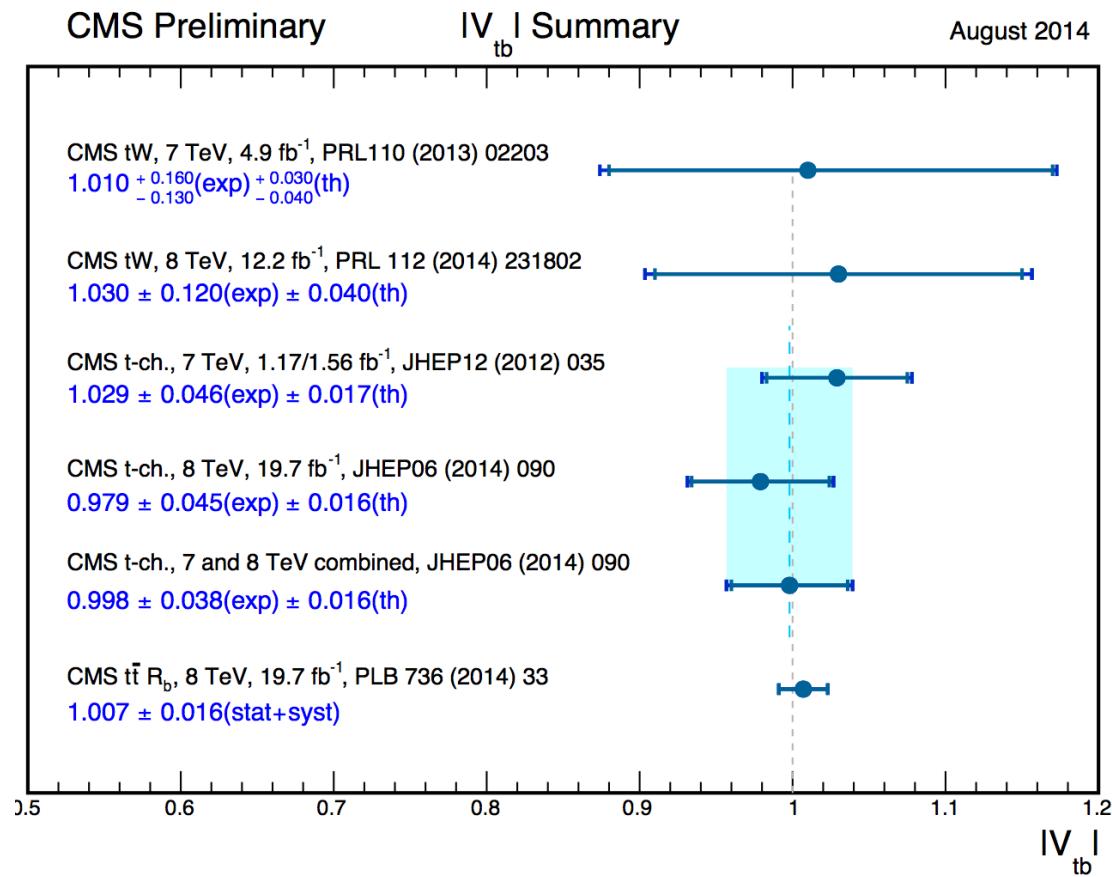
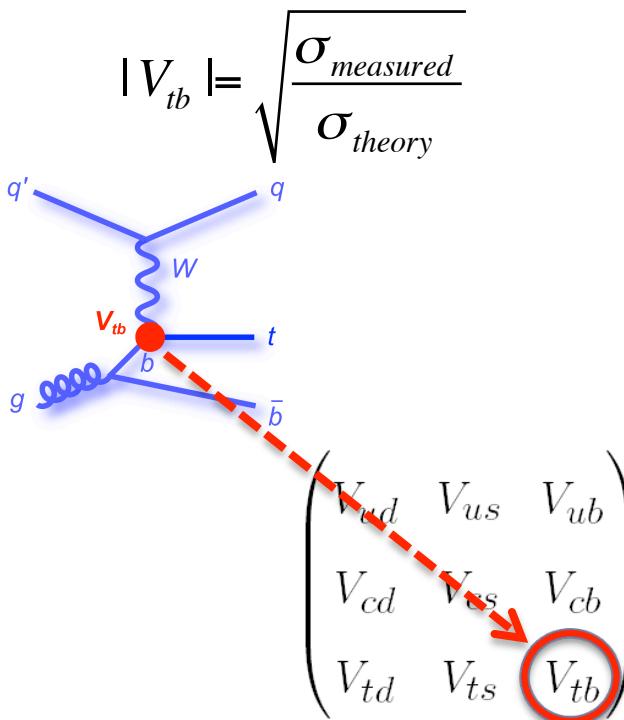


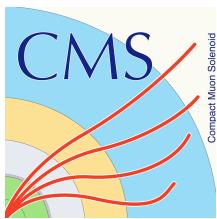
Cross-section and $|V_{tb}|$



26

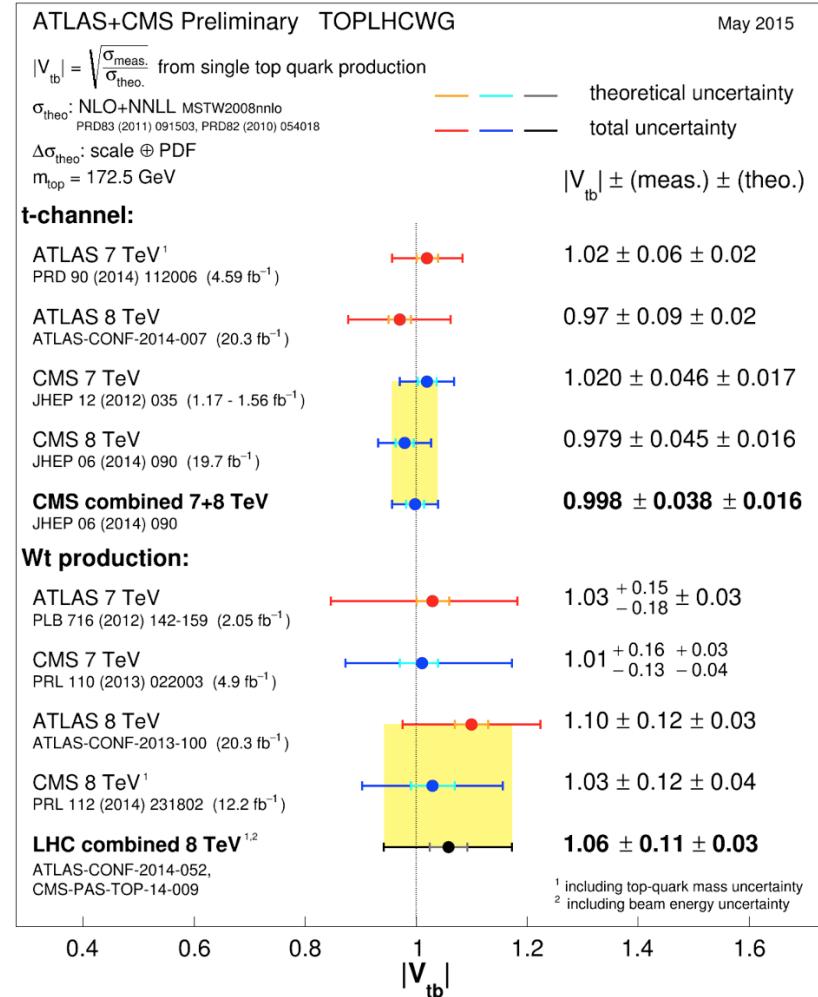
- From the inclusive production cross section of single top (**t-channel, tW**), a value of the **CKM matrix element**, $|V_{tb}|$, can be extracted
- Considering $|V_{td}|, |V_{ts}| \ll |V_{tb}|$
- Cross section $\sim |V_{tb}|^2$



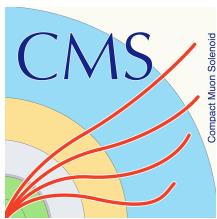


LHC $|V_{tb}|$ combination

27



TOPLHCWG made this summary plot public last month
May 2015

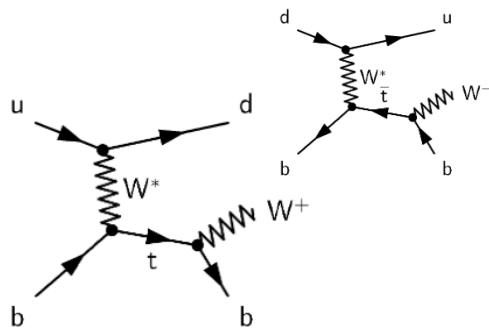
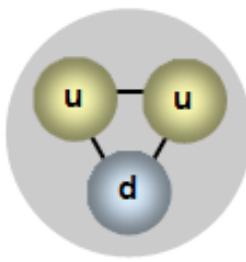


t-channel: R

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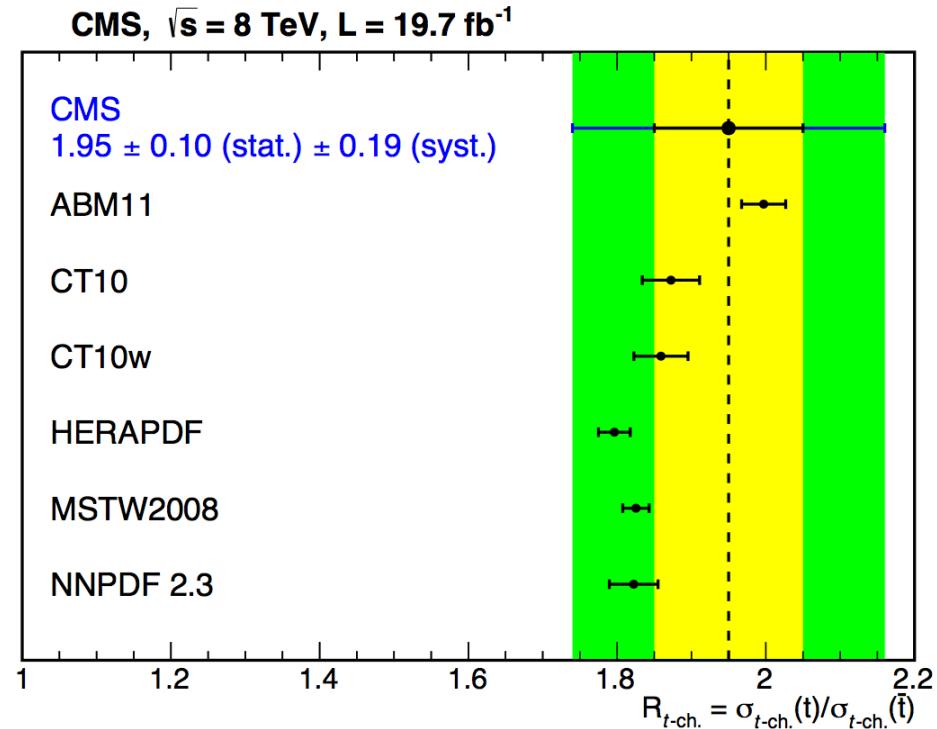


- Within the measurement of the **t-channel** cross-section at 8TeV, we measure the **top/anti-top asymmetry, R**



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

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



$$R = 1.95 \pm 0.10 \text{ (stat)} \pm 0.19 \text{ (syst)}$$

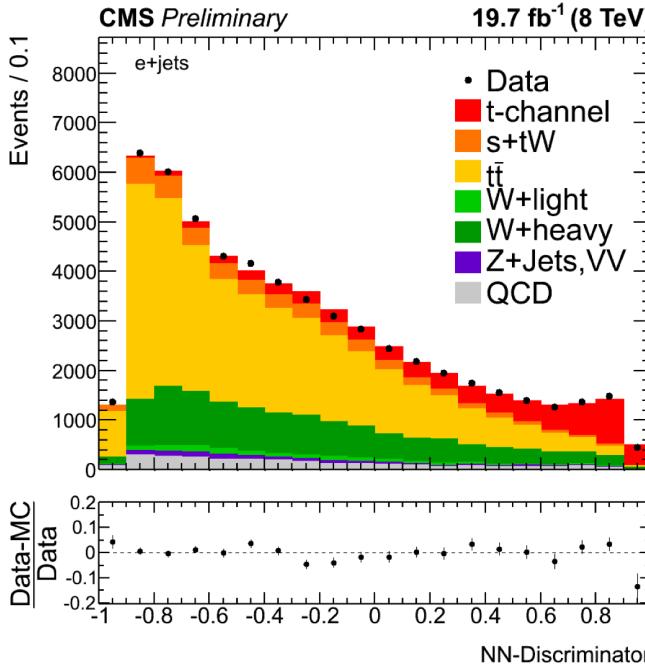
JHEP 06 (2014) 090, [arXiv:1403.7366](https://arxiv.org/abs/1403.7366)



t-channel: differential x-sec

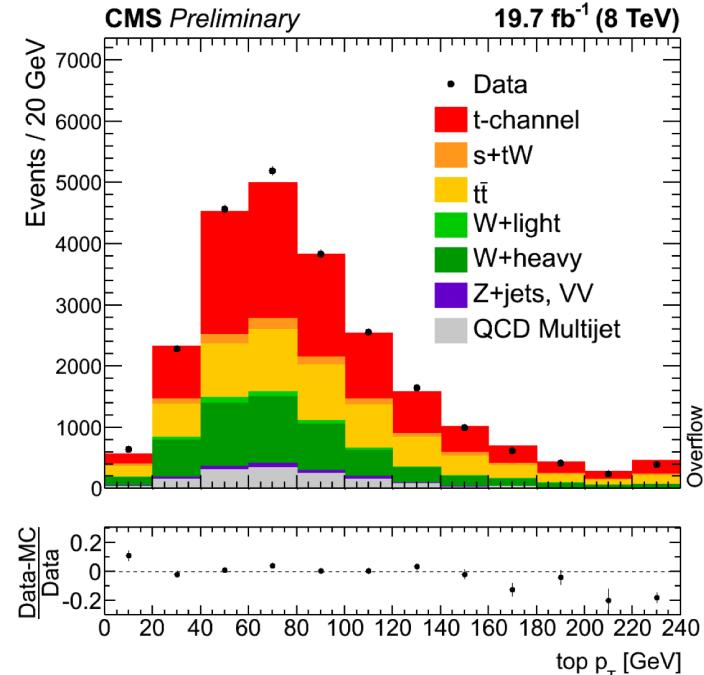
29

- 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 isolate a purer t-channel sample



September 2014
[CMS PAS TOP-14-004](#)

Events are selected by cutting on an optimal NN discriminant value

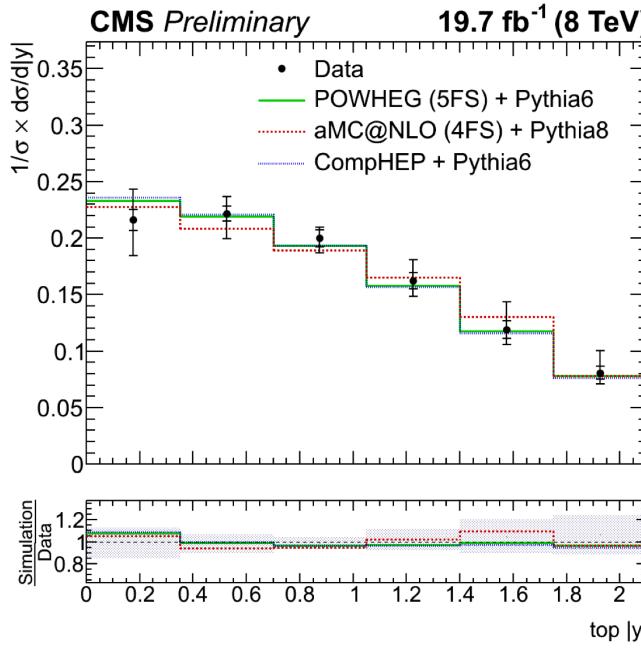
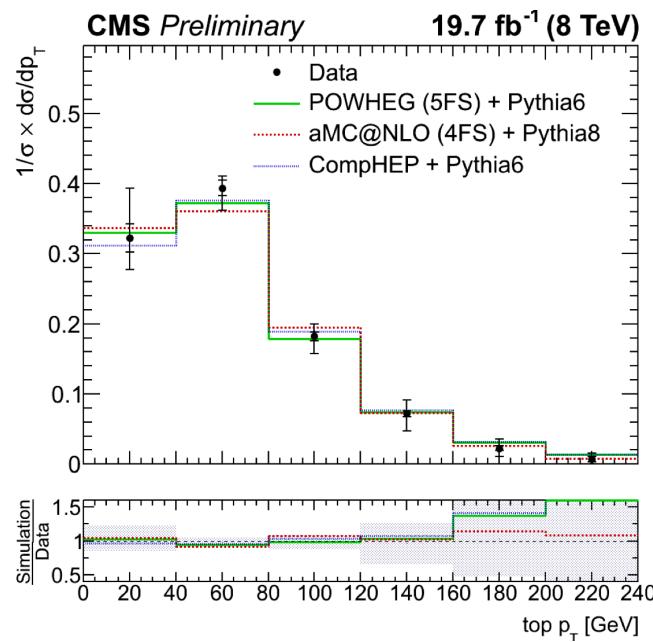




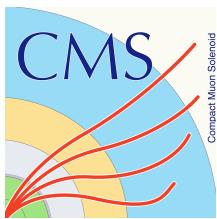
t-channel: differential x-sec

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



[CMS PAS TOP-14-004](#)

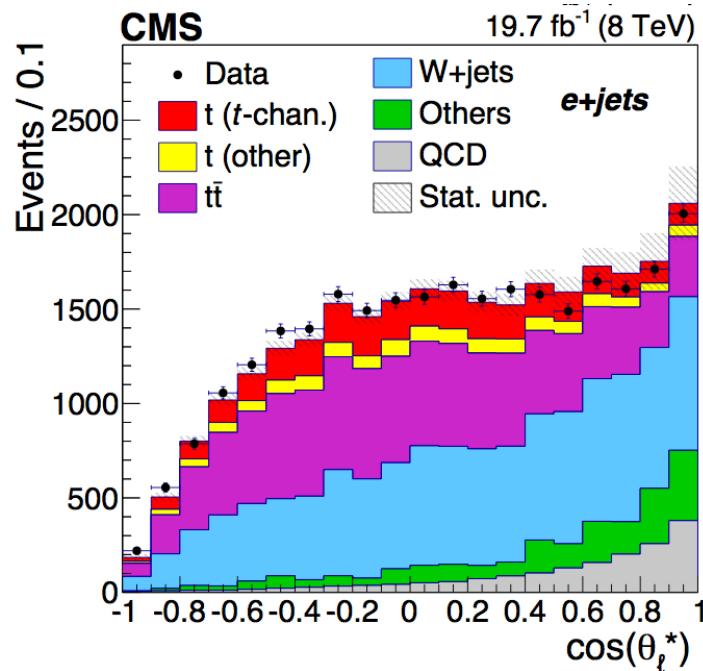


t-channel: W-helicity



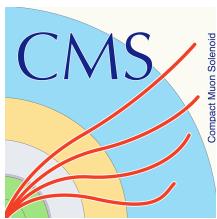
31

- Going further than cross section measurements → measurement of the W-helicity fractions
- Exact same selection and background estimation as the standard t-channel inclusive cross section measurement



θ^* : angle between the W boson in the top rest frame and the lepton in the W rest frame → related to the W-helicity fractions (F_o, F_L, F_R)

October 2014
JHEP 01 (2015) 053, [arXiv:1410.1154](https://arxiv.org/abs/1410.1154)
W boson helicity in t-channel



t-channel: W-helicity (II)



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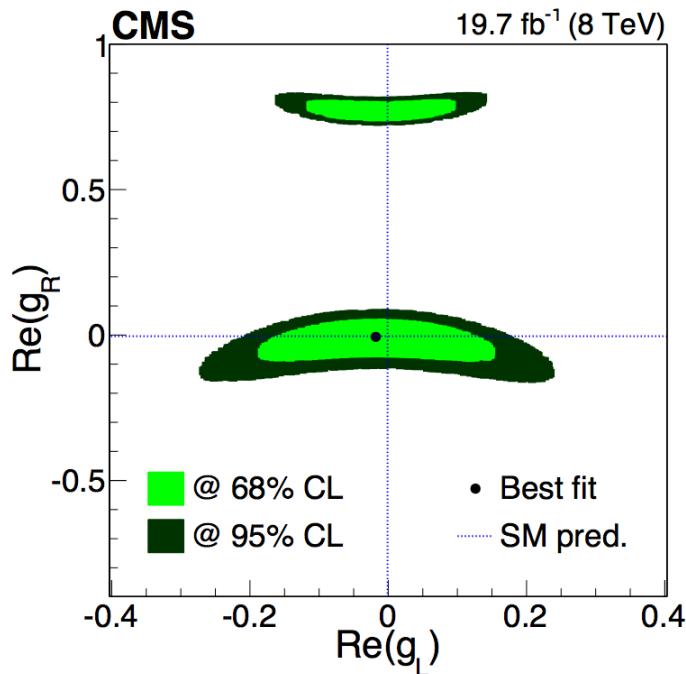
Theory prediction (NNLO)

$$\begin{aligned}F_L &= 0.311 \pm 0.005 \\F_R &= 0.0017 \pm 0.0001 \\F_o &= 0.687 \pm 0.005\end{aligned}$$

PRD 81, 111503(R) (2010)

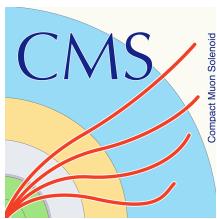
Measured

$$\begin{aligned}F_L &= 0.298 \pm 0.028 \text{ (stat)} \pm 0.032 \text{ (syst)} \\F_R &= -0.018 \pm 0.019 \text{ (stat)} \pm 0.011 \text{ (syst)} \\F_o &= 0.720 \pm 0.039 \text{ (stat)} \pm 0.037 \text{ (syst)}\end{aligned}$$



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](https://arxiv.org/abs/1410.1154)
W boson helicity in t-channel



t-channel: top polarization

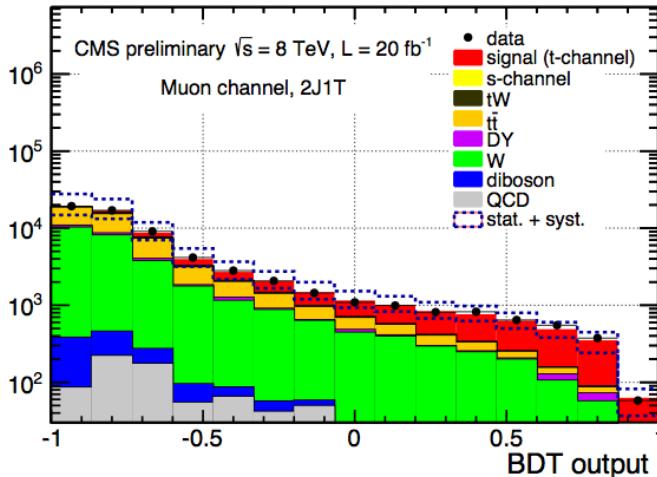


33

- Single top quarks are highly polarized, spin aligned with the recoiling light jet
- The top quark polarization relates to the spin asymmetry
- Which can be extracted from the **$\cos\theta^*$ distribution**

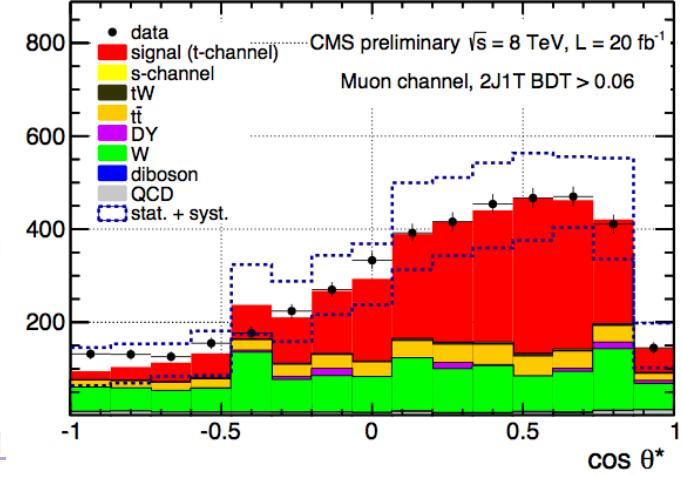
$$A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l$$

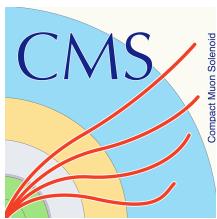
$$A_l = \frac{N(\cos\theta_{unfolded}^* > 0) - N(\cos\theta_{unfolded}^* < 0)}{N(\cos\theta_{unfolded}^* > 0) + N(\cos\theta_{unfolded}^* < 0)}$$



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

August 2013
[CMS-PAS-TOP-13-001](#)

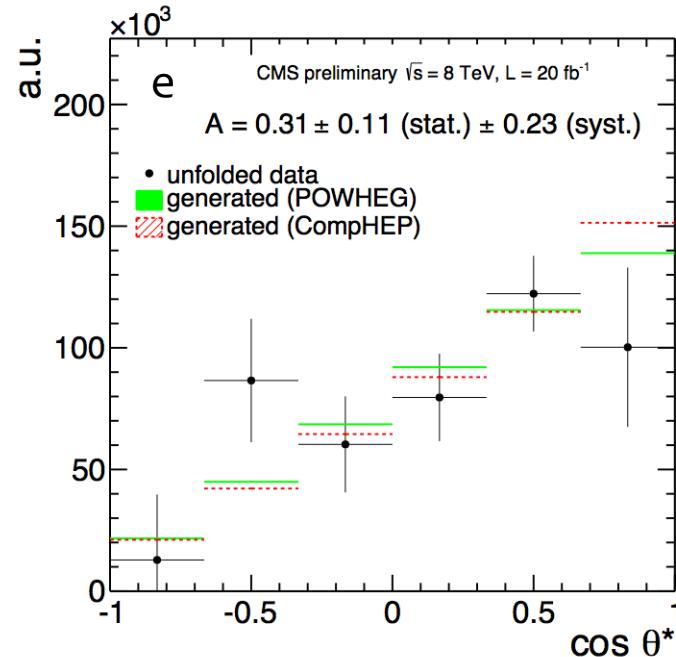
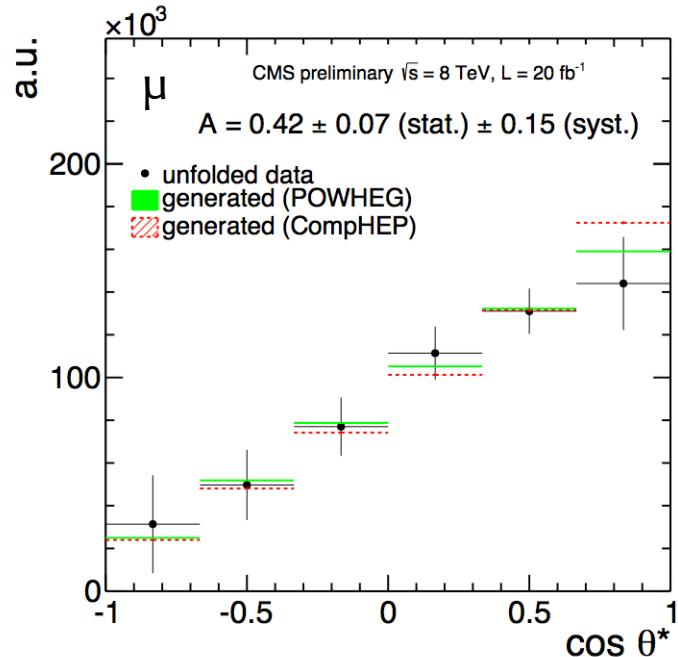




t-channel: top polarization (II)

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Asymmetry and polarization are obtained from the **unfolded** distributions



$A_t = 0.41 \pm 0.06 \text{ (stat.)} \pm 0.16 \text{ (syst.)}$
(SM expectation 0.44)

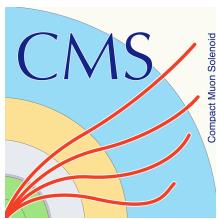
$P_t = 0.82 \pm 0.12 \text{ (stat.)} \pm 0.32 \text{ (syst.)}$

August 2013
[CMS-PAS-TOP-13-001](#)

Step 3



Search for FCNC and Anomalous Couplings



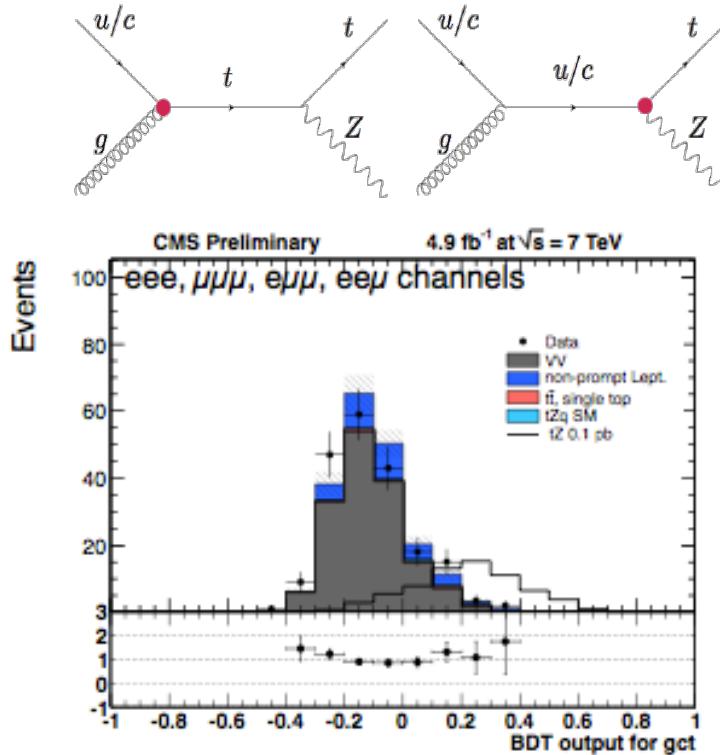
FCNC tZq

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

July 2013

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



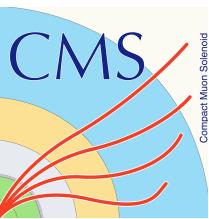
FCNC tZq

Three-lepton signature, 7TeV

BDT (gut, gct, Zut, Zct)

Simulated samples with different scenarios

No excess → Limits on couplings and branching fractions



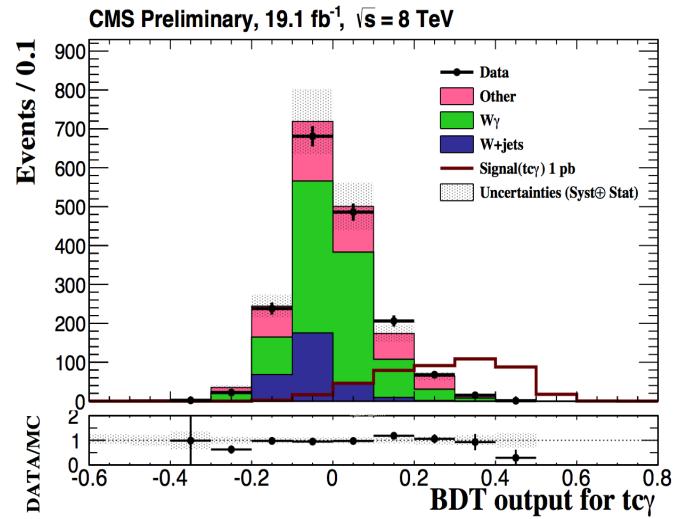
FCNC $t\gamma$

37

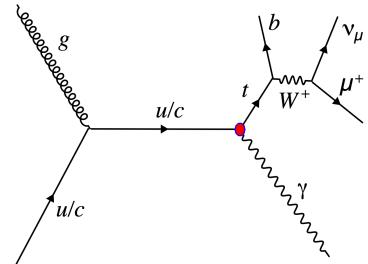


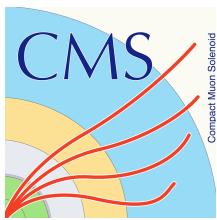
- Preliminary result from Spring last year
- **$t\gamma$, single top produced in association with a photon**
 - Enhancement on $t \rightarrow u(c)\gamma$ BR due to FCNC
 - Samples with anomalous $t u\gamma$, $t c\gamma$ couplings
 - 8TeV, μ only
 - Dedicated BDTs
 - No excess → Limits on couplings and branching fractions

May 2014
CMS PAS-TOP-14-003



	Exp. limit (LO)	Obs. limit (LO)	Exp. limit (NLO)	Obs. limit (NLO)
$\sigma_{tu\gamma} \times Br(W \rightarrow l\nu_l)$	0.0404 pb	0.0234 pb	0.0408 pb	0.0217 pb
$\sigma_{tc\gamma} \times Br(W \rightarrow l\nu_l)$	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
$Br(t \rightarrow u\gamma)$	0.0279%	0.0161%	0.0205%	0.0108%
$Br(t \rightarrow c\gamma)$	0.261%	0.182%	0.193%	0.132%



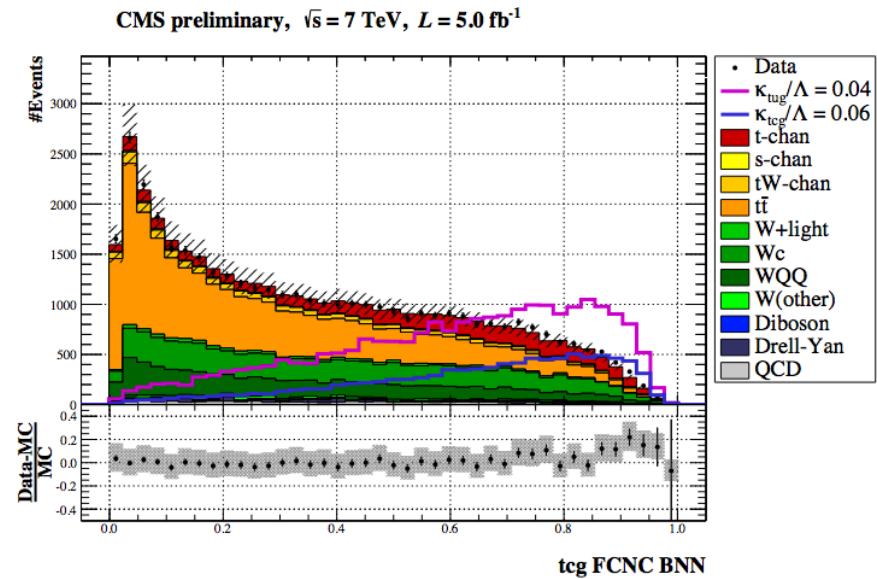
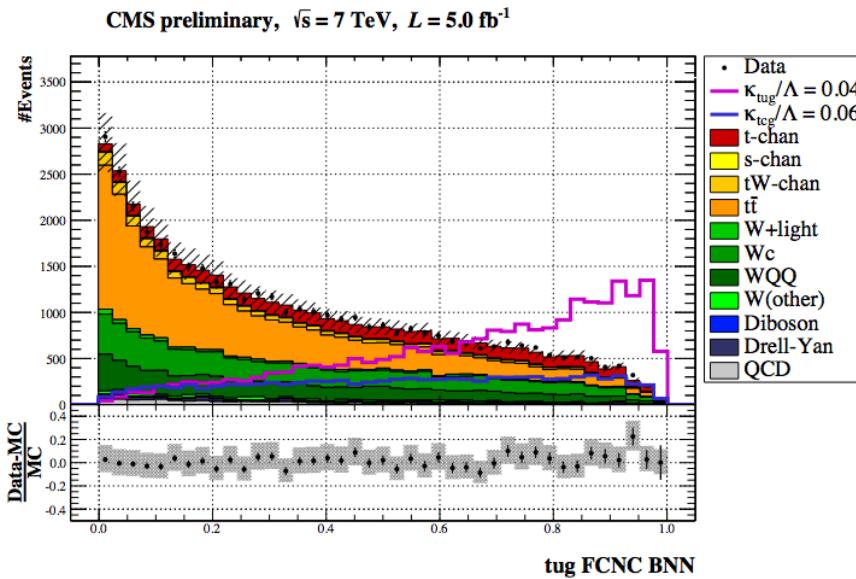


FCNC and AC in t-channel

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- Another preliminary result from Spring last year
- **FCNC and anomalous couplings in t-channel**
 - Anomalous operators in the Wtb vertex and tcg/tug FCNC couplings
 - 7TeV, μ
 - NN to separate different scenarios considered Vs SM
 - No excess → Limits on couplings and branching fractions

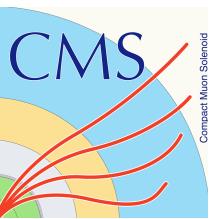
May 2014

CMS PAS-TOP-14-007

Step 4



Explore unusual single top signatures



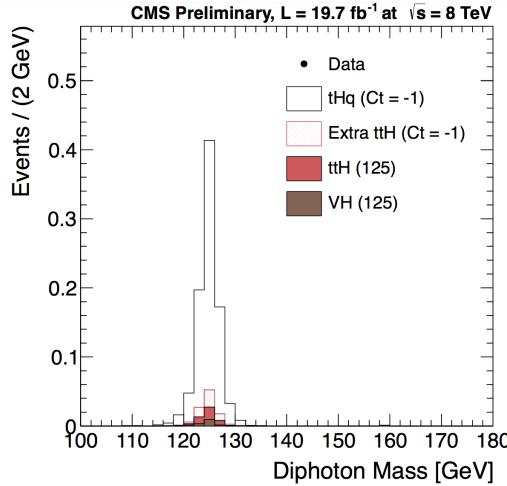
Top+ Higgs

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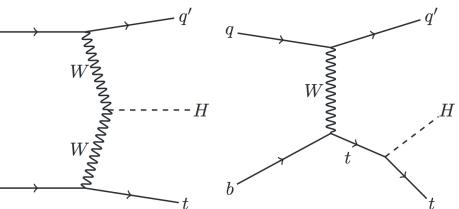
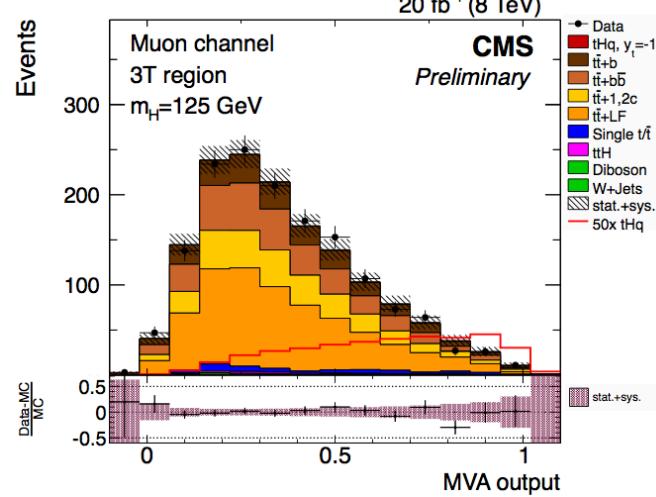


- **single top + Higgs (complementary to ttH)**
 - tH production highly suppressed in the SM
 - If top Higgs Yukawa coupling is negative → enhanced
 - Several decays investigated, more to come, all preliminary
 - ✖ Need Run-2 to become sensitive

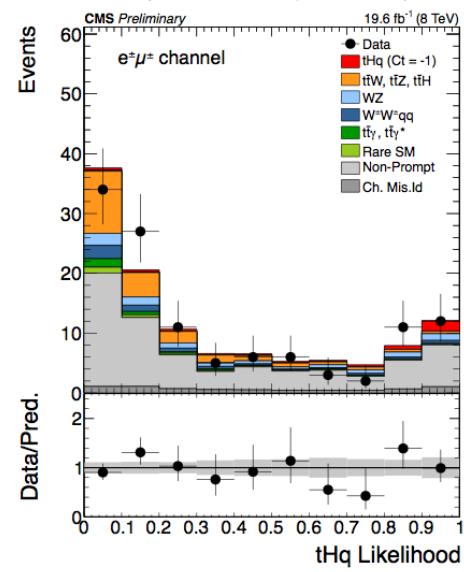
tH, H $\rightarrow\gamma\gamma$
CMS PAS-HIG-14-001
(March 2013)

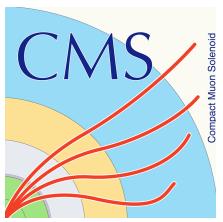


tH, H $\rightarrow bb$
CMS PAS-HIG-14-015
(October 2014)



tH, H $\rightarrow WW$
CMS PAS-HIG-14-026
(February 2015)





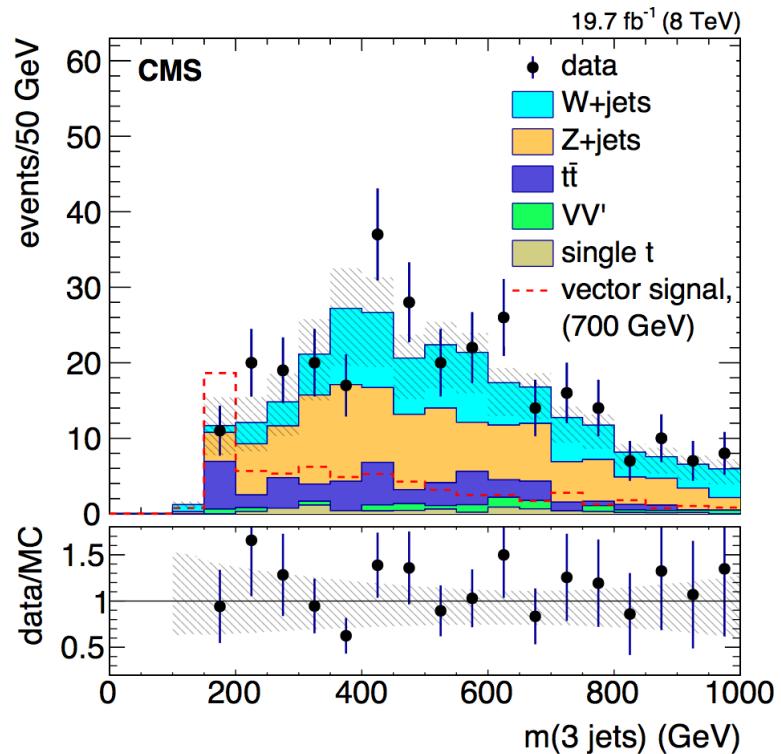
BSM top + X

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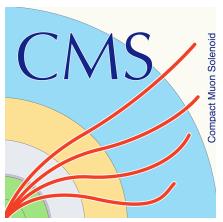
- There are many other BSM channels that involve top quarks and/or similar signatures to single top:
 - classic example: $W' \rightarrow tb$ ([arXiv:1402.2176](https://arxiv.org/abs/1402.2176))
- Some feature truly “single” top quarks

Monotop
Dark Matter search using top + MET
[arXiv:1410.1149](https://arxiv.org/abs/1410.1149)
Phys.Rev.Lett. 114 101801(2015)
(October 2014)



Next steps?





Run-2

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- **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 is just starting now! → 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 accessible (SM tZq and tγq)
- More BSM channels to explore
- New approaches: Single top in heavy ions! (?) [arXiv:1502.04875](https://arxiv.org/abs/1502.04875)



Summary

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- Single top signatures were very rare and largely unknown until recently
- In less than 10 years we have made incredible progress
→ **the LHC is very powerful for top, and single top in particular**
- We have studied the **three main production modes**
- There are so many single top quarks produced via t-channel that we can use them to make **measurements**:
 - W-helicity fractions, top polarization, $|V_{tb}|...$
- We have used conventional and rare single top production modes to look for **FCNC and Anomalous Couplings**
- We have started 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**