Run-I Single-top measurements at CMS

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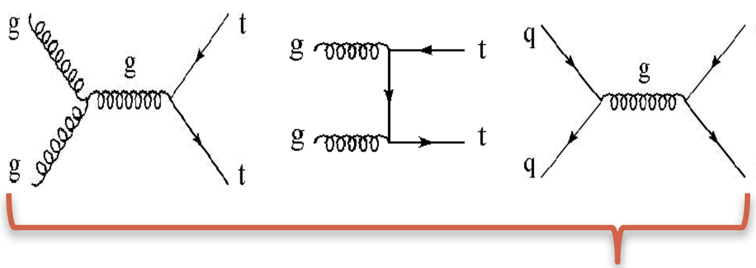
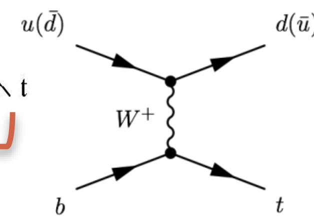
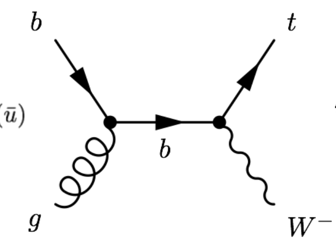
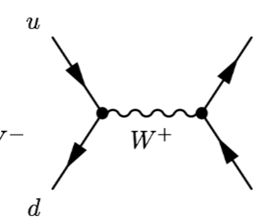
Top quarks at the LHC

- At the **LHC,** top quarks are produced mainly in **ttbar pairs**
  - **strong interaction**
- Alternative mode, at a lower rate: **Single top quark production**
  - **electroweak interaction**
- Three main single top process:
  - **t-channel, tW associated production, s-channel**







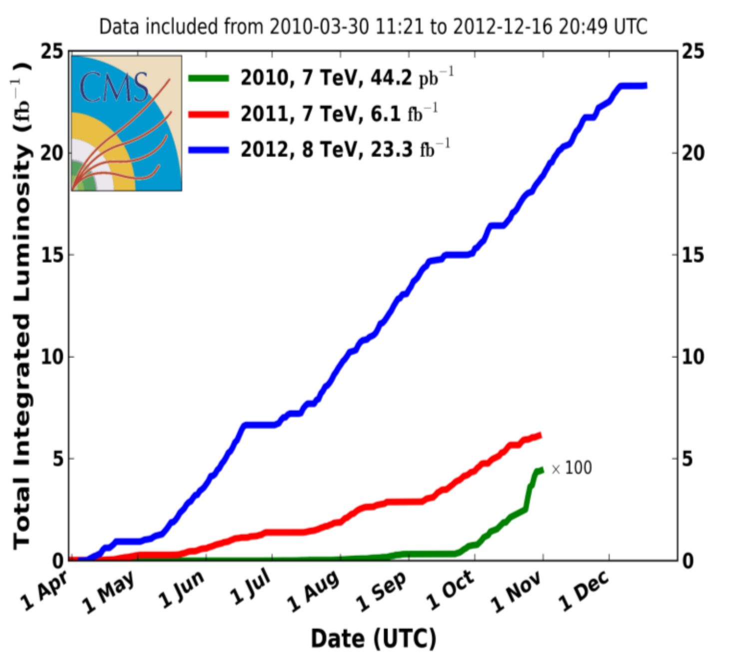


σ [pb]	ttbar	t-channel	tW	s-channel
Tevatron (1.96TeV)	7.08	2.08	0.22	1.046
LHC @ 7TeV	177.31	63.89	15.74	4.29
LHC @ 8TeV	252.89	84.69	22.2	5.24
LHC @ 13TeV	831.76	216.99	71.2	10.32

Run-1 of the LHC in tops

Top quarks were observed for the first time at the Tevatron → in 1995 via ttbar, in 2009 via single top; but the LHC has been competitive since the start (first single top paper in 2011)

"The LHC is a top quark factory!"
- Every speaker at every talk about top quarks at the LHC



- The Run-1 of the LHC lasted three years:
  ~5fb^{-1} of pp collisions at 7TeV
  ~20fb^{-1} at 8TeV

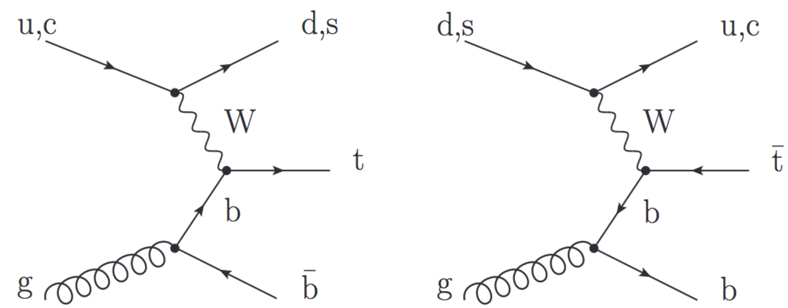
CMS then registered
- More than **5M ttbar pairs**
- Around **2M of single top quarks (via t-channel)**
- **Half a million of tW events**
- a bit more than 100K of s-channel events

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

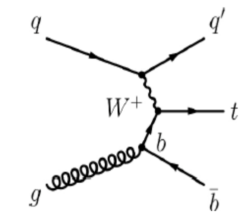


- Final state studied: **lepton + jets signature**
- Signal characterized by:
  - One isolated **muon or electron**
  - Missing transverse energy (**MET**)
  - A central **b jet**

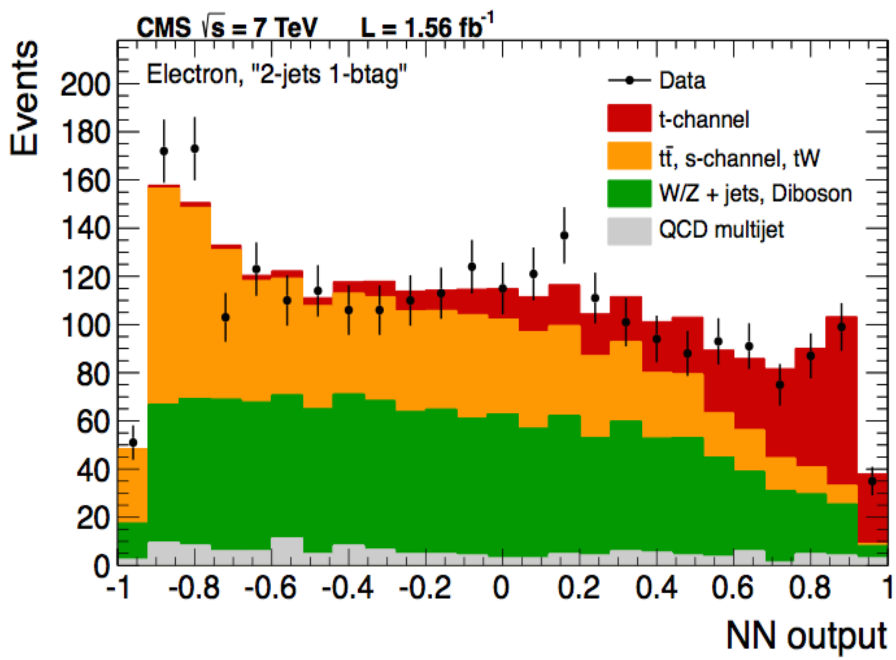
  Leptonic top decay

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

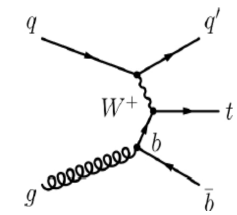


Different regions defined (jets, b-tag)
Multijet and W+jets background estimated from data

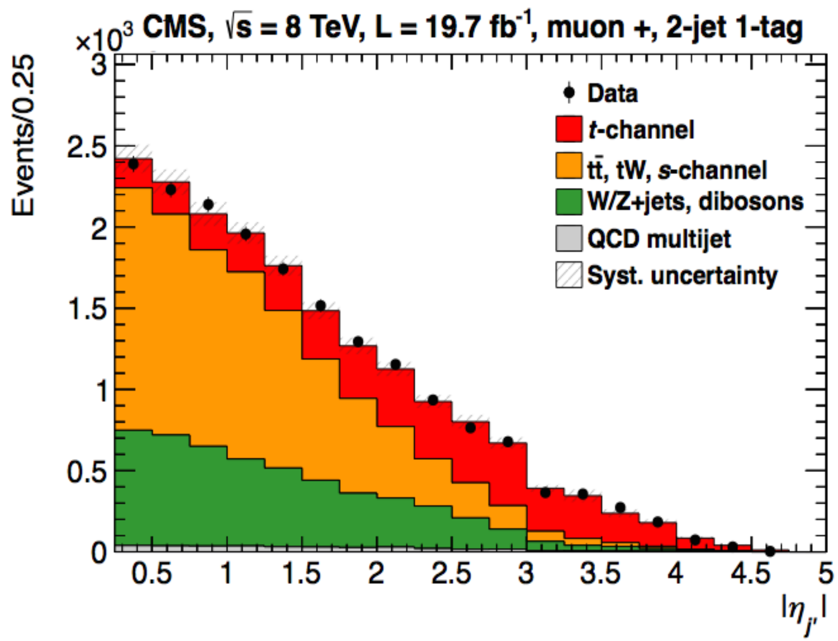
Statistical, systematic, and theory uncertainties on the same level

September 2012
JHEP 12 (2012) 035
arXiv:1209.4533
7TeV - 1.17 and 1.56 fb^{-1}

t-channel (8TeV)



- At 8 TeV, the measurement was done using the $|\eta_{j'}|$ analysis alone



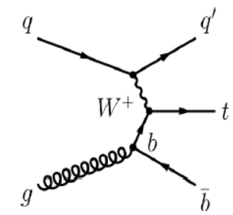
Similar approach as for 7TeV, more data-driven (Multijet, W+jets, ttbar)

Full luminosity

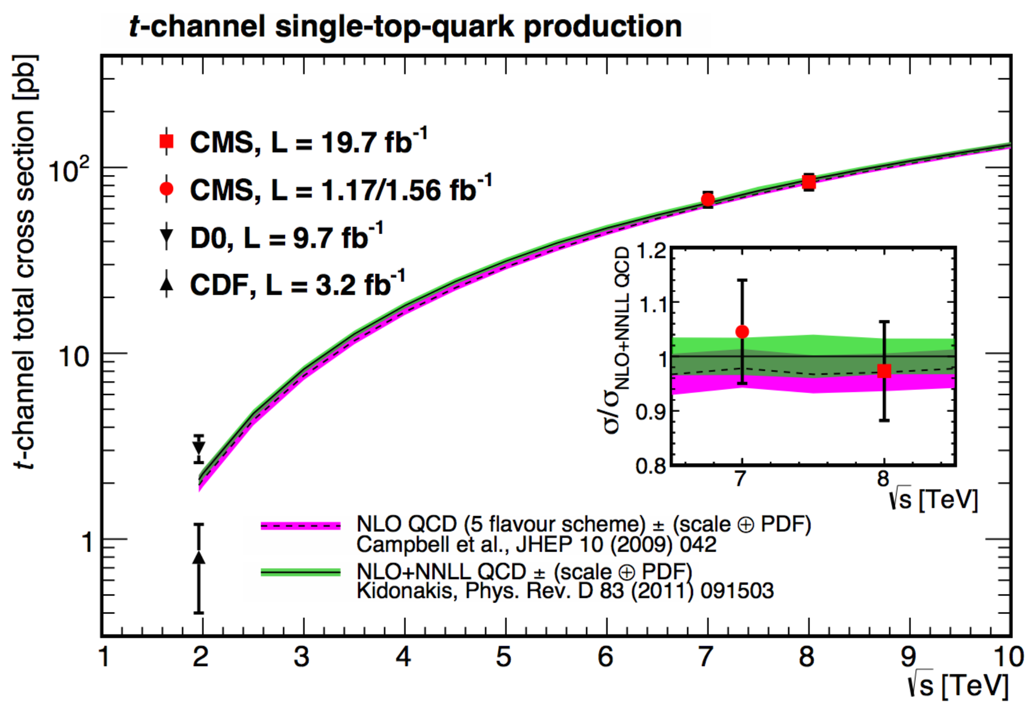
Systematic dominated
main uncertainties:
Signal modeling (~6%)
and JES/JER/MET (~4%)

March 2014
JHEP 06 (2014) 090
arXiv:1403.7366
8 TeV - 19.7fb^{-1}

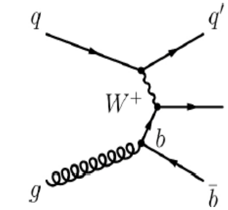
t-channel: results



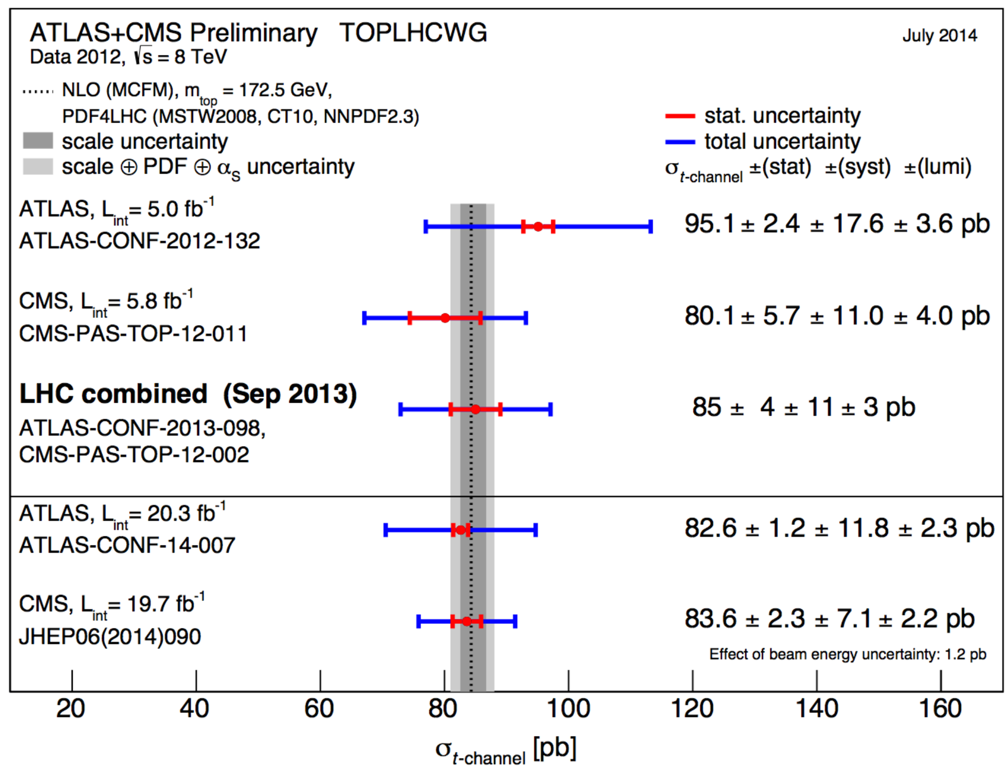
7TeV	Measured	67.2±3.7(stat)±3.0(syst)±3.5(th)±1.5(lumi) pb = 67.2±6.1 pb
	Prediction	63.89+2.91-2.52 (NLO, latest calculation)
8TeV	Measured	83.6±2.3 (stat) ±7.4 (syst) pb
	Prediction	84.69+3.76 -3.23 (NLO, latest calculation)



t-channel: combination

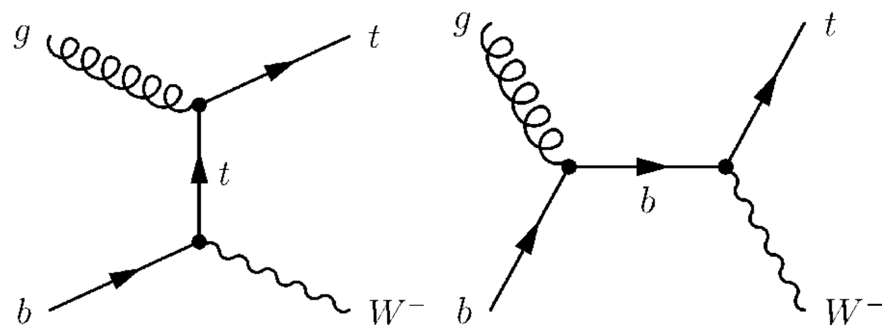


- **An LHC (ATLAS+CMS) combination was made at 8TeV**
- It was the first single top combination of the LHC
  - Sept. 2013
  - CMS-PAS-TOP-12-002



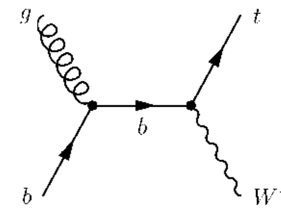
tW associated production

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

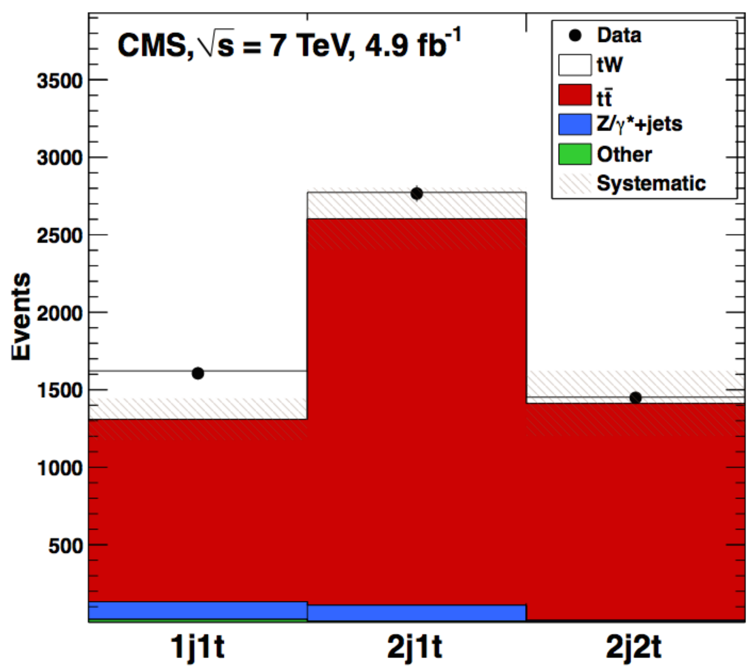


- Final state studied: **dilepton signature**
- Signal events are characterized by:
  - **Two** opposite-sign, isolated **leptons**
  - Missing transverse energy (2 neutrinos in the final state)
  - A jet coming from a **b decay**
- **Backgrounds: ttbar (main challenge), DY**

tW (7TeV)



- Impossible to study before the LHC (very low cross section at he Tevatron) → At the LHC is still not easy
- With 7TeV data, CMS reported evidence for the process



September 2012

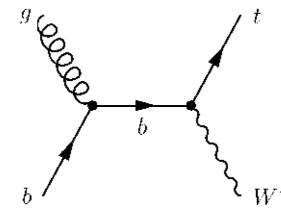
Phys. Rev. Lett. 110 (2013) 022003

arXiv:1209.3489

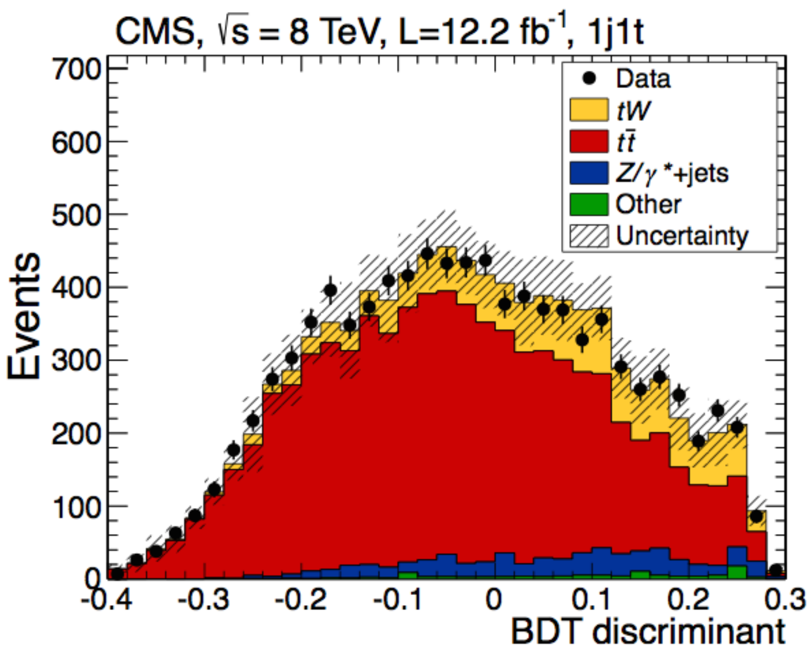
4.0σ

7TeV - 4.9fb^{-1}

tW (8TeV)



- **At 8TeV the process was observed with a significance > 5 σ**

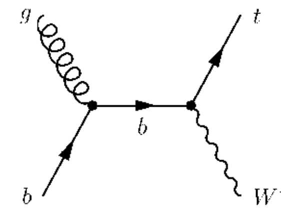


7 TeV → cut-based, basic BDT
8TeV → cut-based, shape-based, more sophisticated BDT

At 8TeV the analysis is already not statistically limited

January 2014
Phys. Rev. Lett. 112 (2014) 231802
arXiv:1401.2942
6.1σ
8TeV - 12.2fb^{-1}

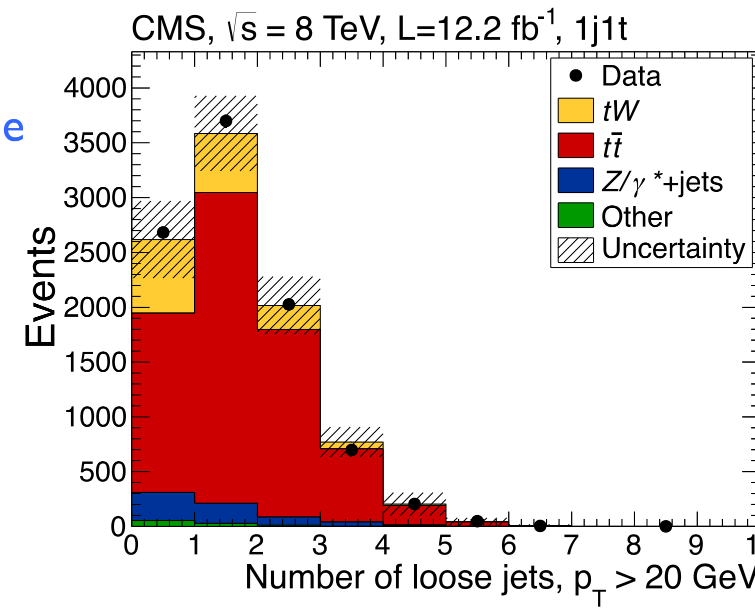
tW: results



- The main challenge is the **ttbar background**
  - ttbar with 1 jet outside acceptance or misreconstructed → mimics perfectly the signal

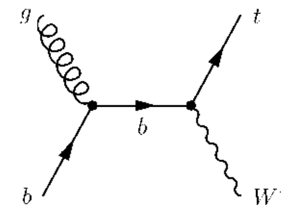
  → not only very similar final states, also their diagrams mix at NLO

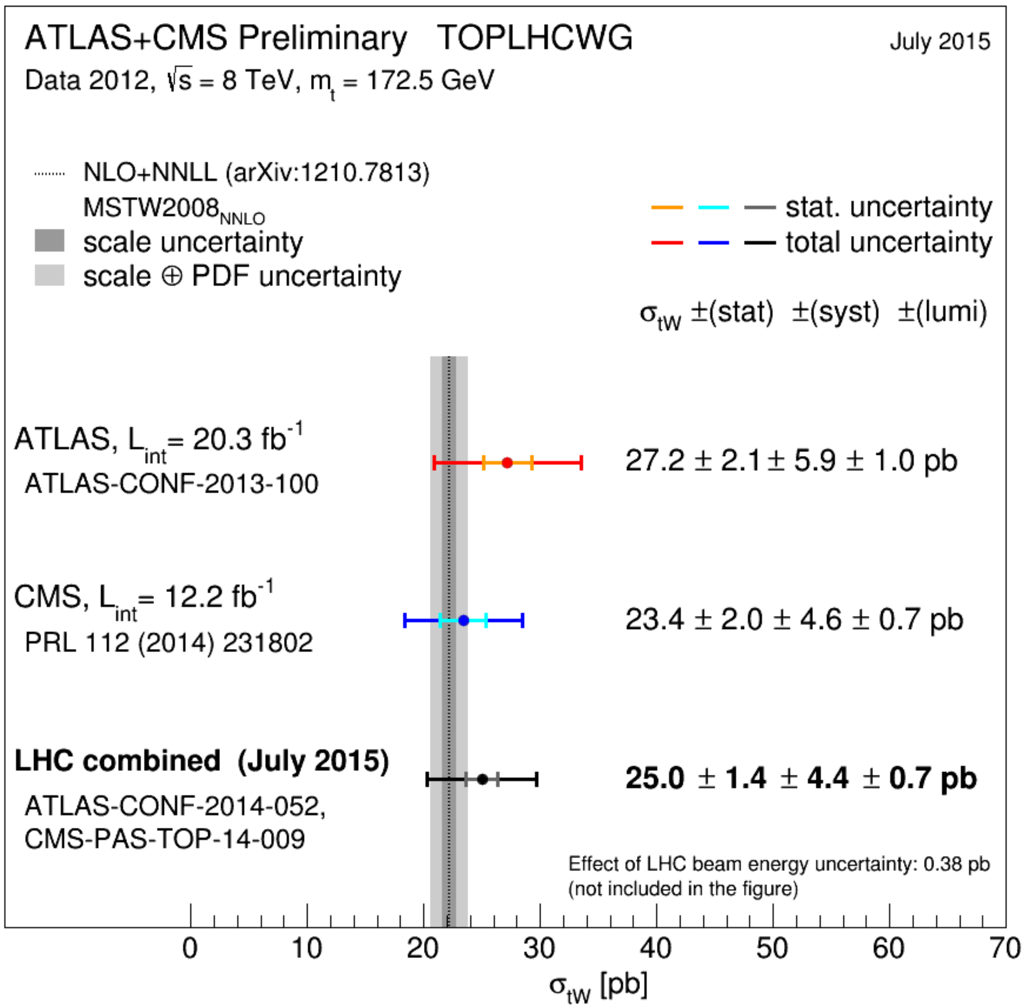
  → Main uncertainties come from theory modeling of ttbar
- 2 control regions were established
- Use of variables related 'loose' jets



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





ATLAS+CMS tW combination at 8TeV also performed

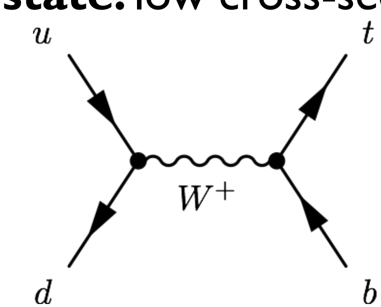
September 2014
CMS-PAS-TOP-14-009

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**

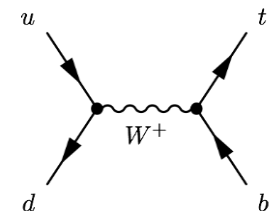
  [Phys. Rev. Lett. 112, 231803 (2014)]

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

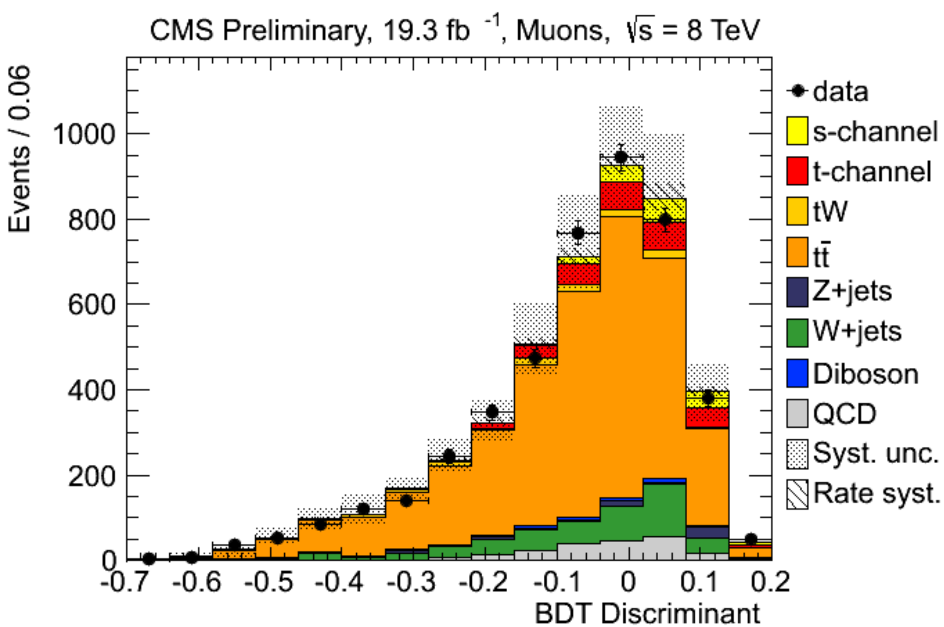


- Signal signature: **lepton + jets**
  - **A lepton** (e,μ) and **MET** from the decay of a W boson
  - **Two jets** with high transverse momentum originating from **b-quarks**
- **Main backgrounds:** ttbar, W+jets, multijet

s-channel



- CMS has a preliminary result at 8TeV



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

(November 2013)

Full lumi, e and μ

BDT

Difficult analysis

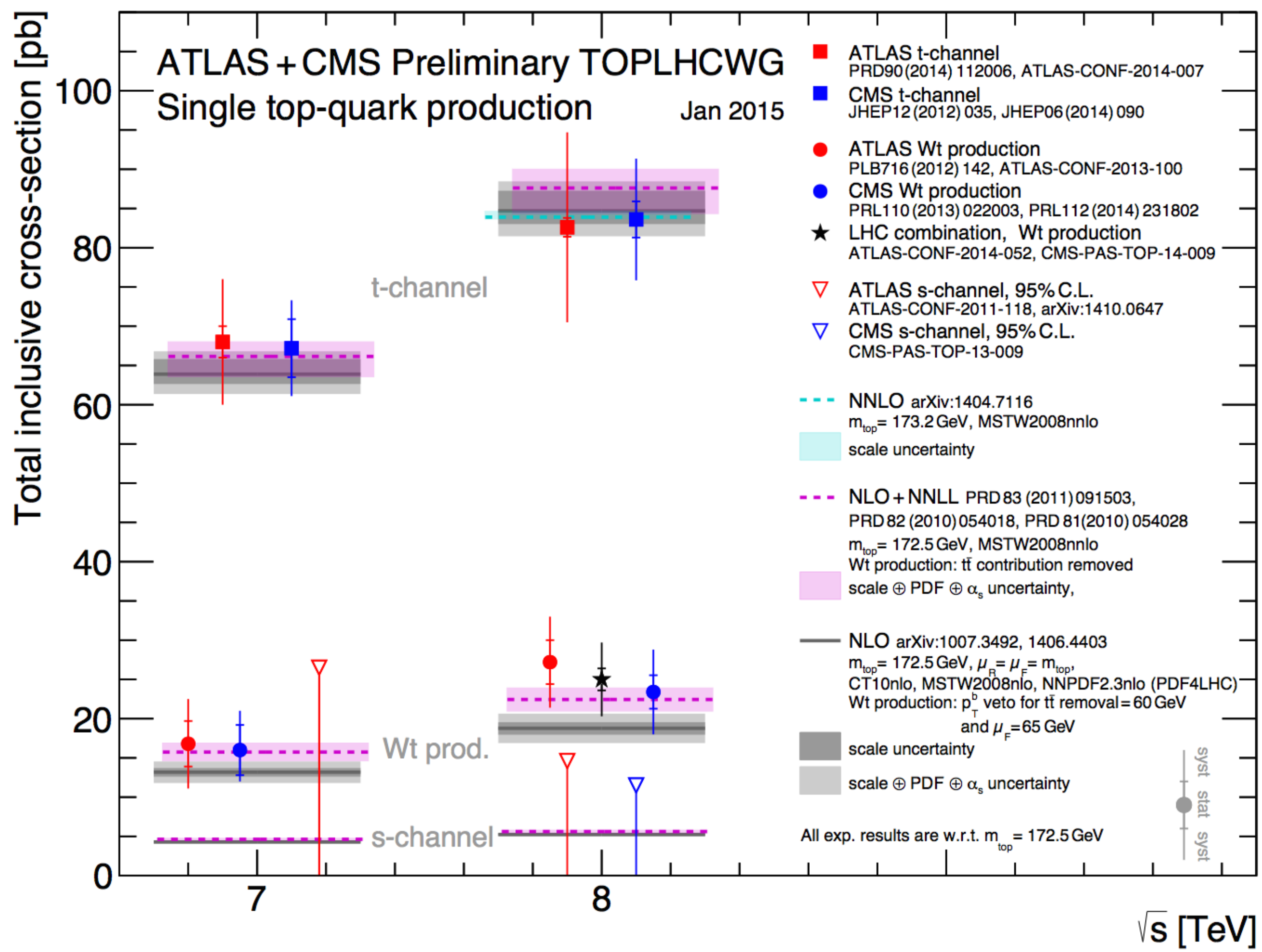
In Run-2 will be even harder

S/B is a bit better at 7TeV

σ [pb]	ttbar	s-channel
LHC (7 TeV)	177.31	4.29
LHC (8 TeV)	252.89	5.24
LHC (13TeV)	831.76	**10.32**

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

Run-1 Summary



Step II

Measure SM properties in single top signatures

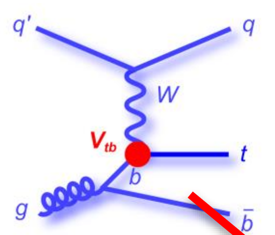
The single top production at the LHC is large enough to measure top properties in single top signatures

- Complementary to ttbar
- Another handle to test potential BSM phenomena
- Valuable to get the **full picture**

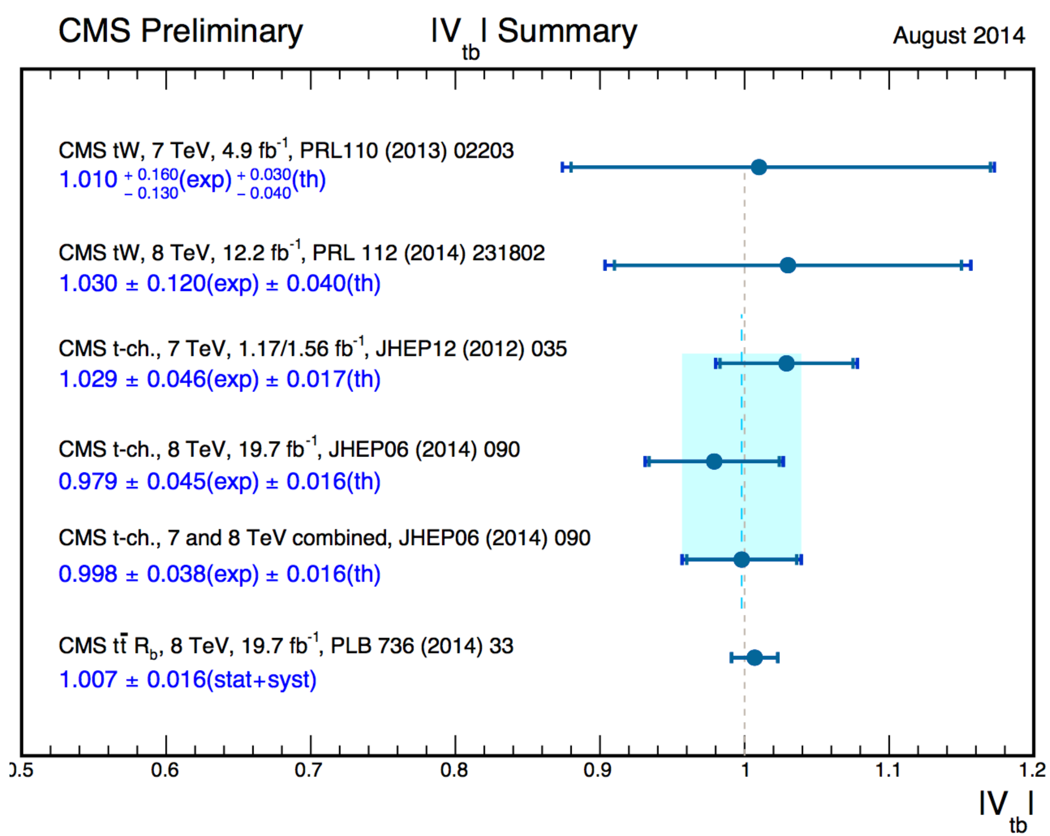
Cross-section and $|V_{tb}|$

- 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 ~ $|V_{tb}|^2$

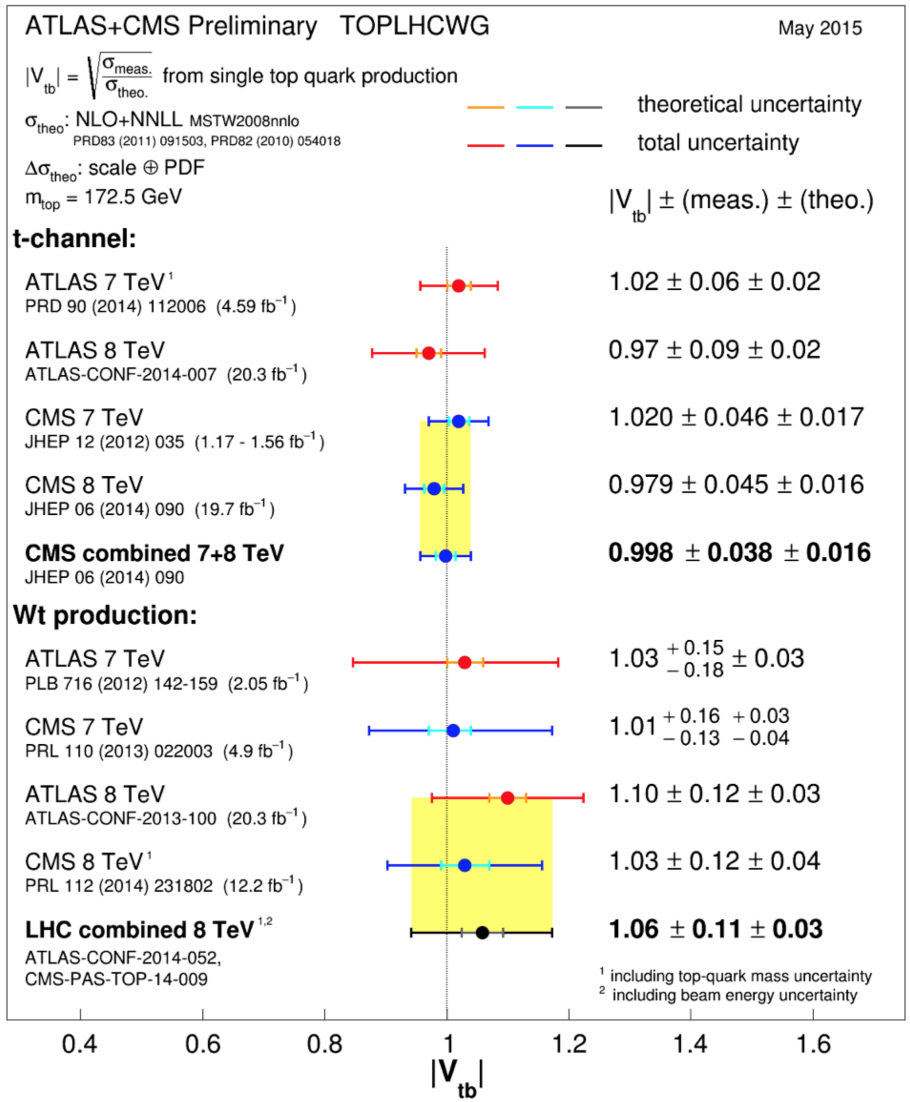
$$|V_{tb}| = \sqrt{\frac{\sigma_{measured}}{\sigma_{theory}}}$$



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



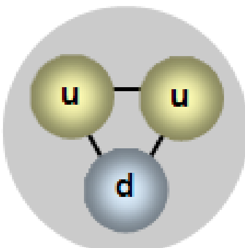
LHC $|V_{tb}|$ summary

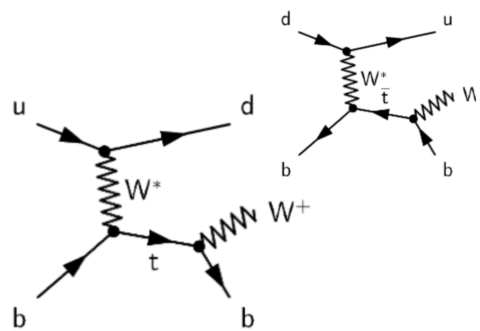


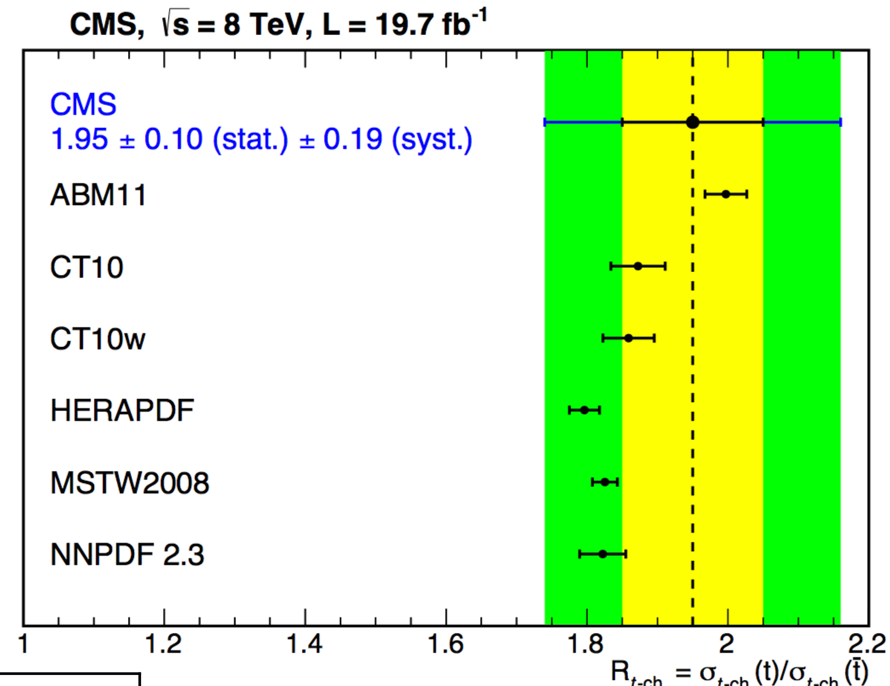
Summary plot from TOPLHCWG
May 2015

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

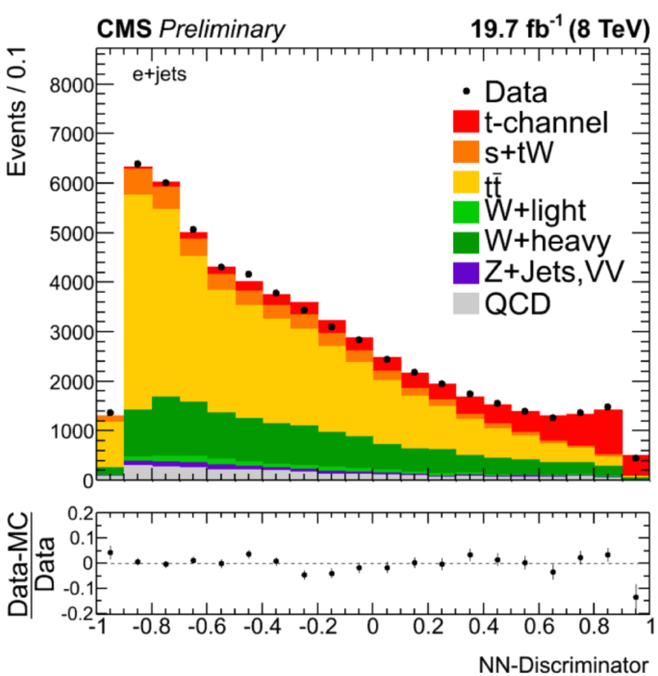
σ_{top} = 53.8±1.5(stat.)±4.4(syst)pb
$\sigma^{th}{}_{top}$ = 54.87 +2.29 -1.94 pb (NLO, latest calculation)
$\sigma_{anti\text{-}top}$ = 27.6±1.3(stat.)±4.4(syst)pb
$\sigma^{th}{}_{anti\text{-}top}$ = 29.74 +1.67 -1.51 pb (NLO, latest calculation)

R = 1.95±0.10(stat)±0.19(syst)

JHEP 06 (2014) 090
arXiv:1403.7366

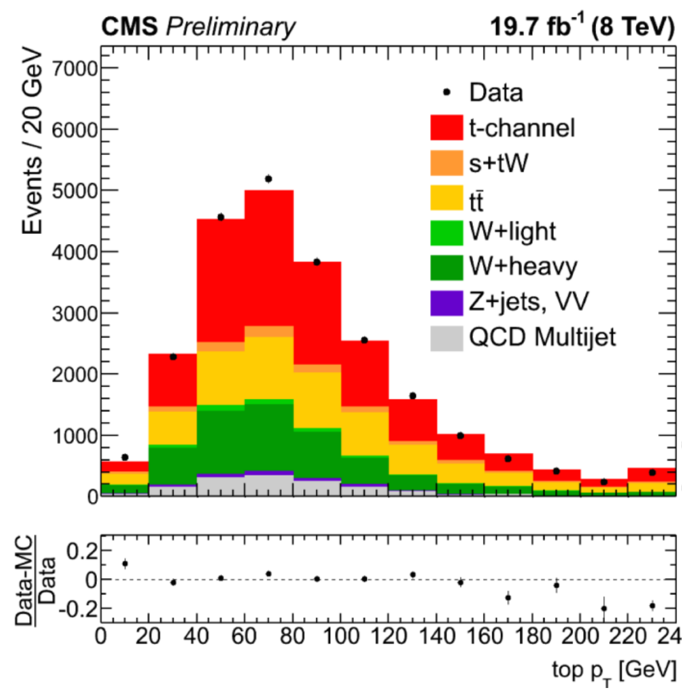
t-channel: differential x-sec

- t-channel **differential cross section** came last September, 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



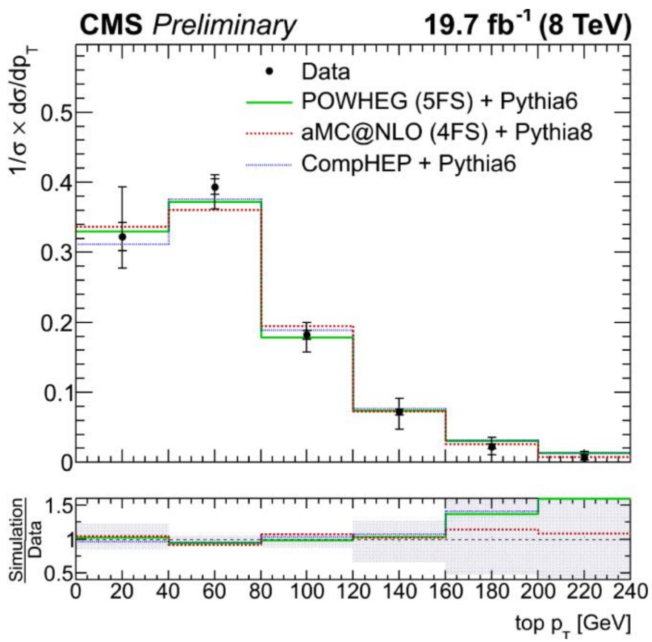
September 2014
[CMS-PAS-TOP-14-004]

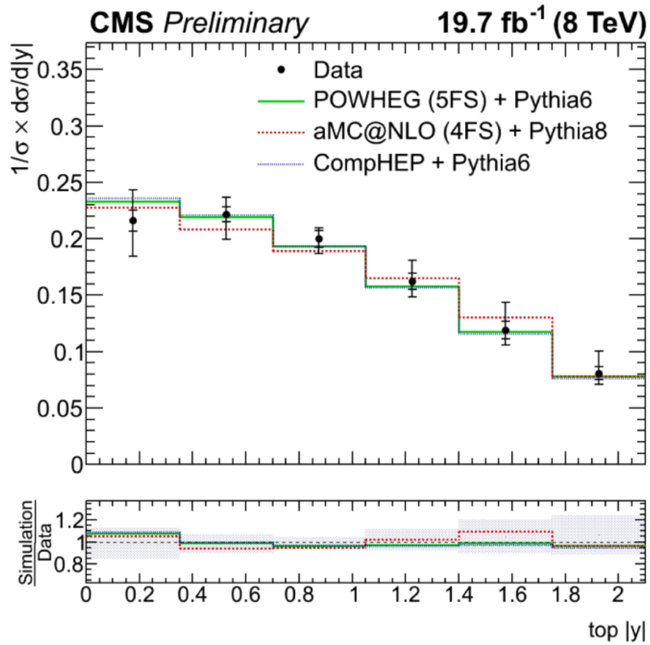
Events are selected by cutting on an optimal NN discriminant value



t-channel: differential x-sec

- 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)

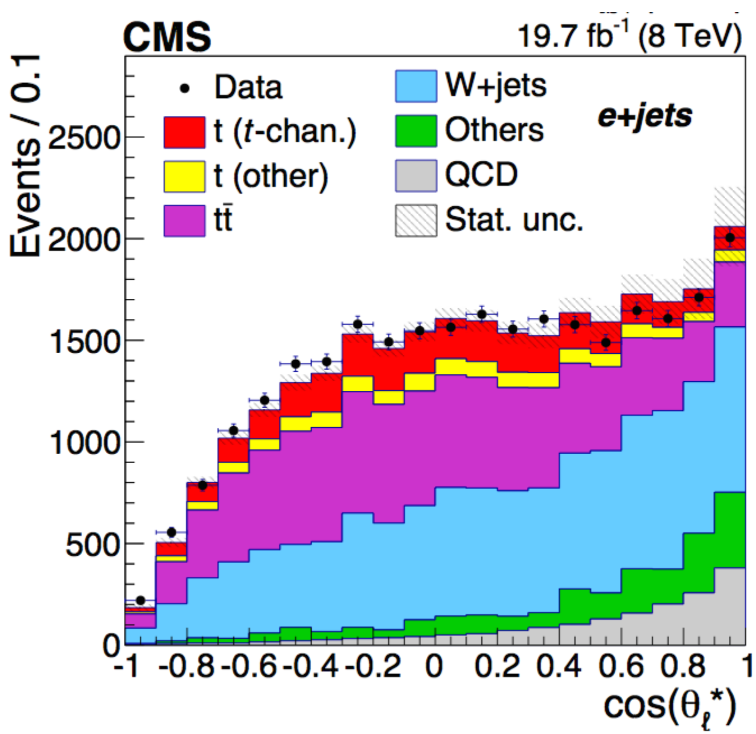




CMS-PAS-TOP-14-004

t-channel: W-helicity

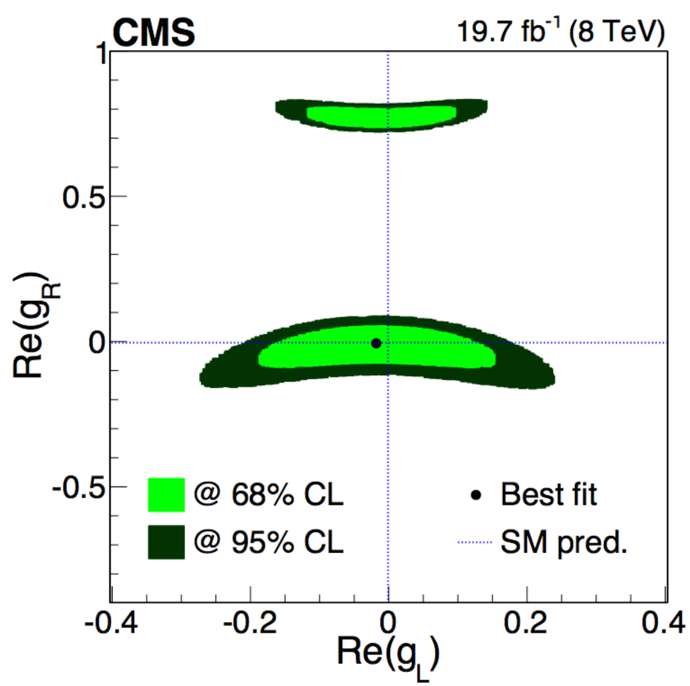
- Going further than cross section measurements → measurement of the W-helicity fractions
- Exact same selection and background estimation as the standard t-channel inclusive cross section measurement



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_0, F_L, F_R)**

t-channel: W-helicity

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)	$F_L = 0.298 \pm 0.028$ (stat) ± 0.032 (syst) $F_R = -0.018 \pm 0.019$ (stat) ± 0.011 (syst) $F_0 = 0.720 \pm 0.039$ (stat) ± 0.037 (syst)



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

October 2014

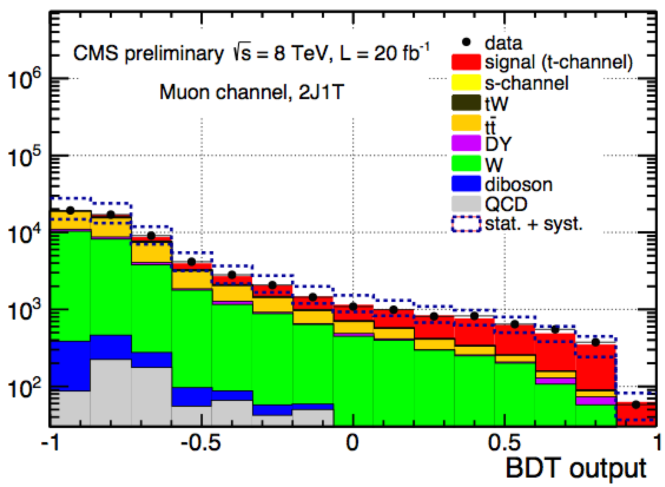
JHEP 01 (2015) 053

arXiv:1410.1154

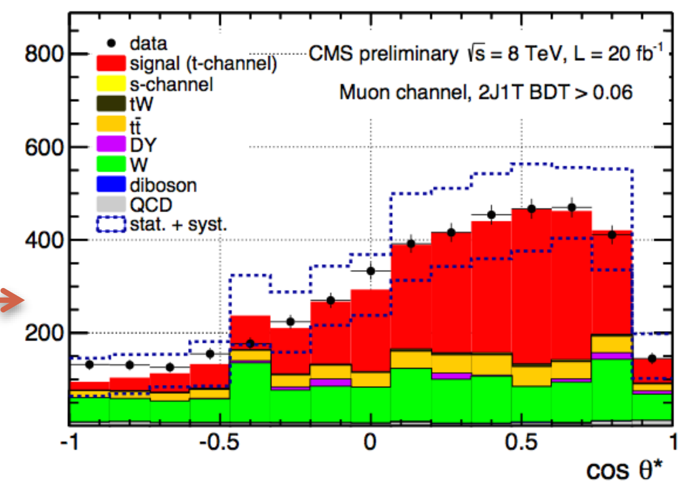
t-channel: top polarization

- **Single top quarks are highly polarized**
  - spin aligned with the recoiling light jet
- The top quark polarization relates to the spin asymmetry $A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l$
- Which can be extracted from the **$\cos\theta^*_l$ distribution**

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



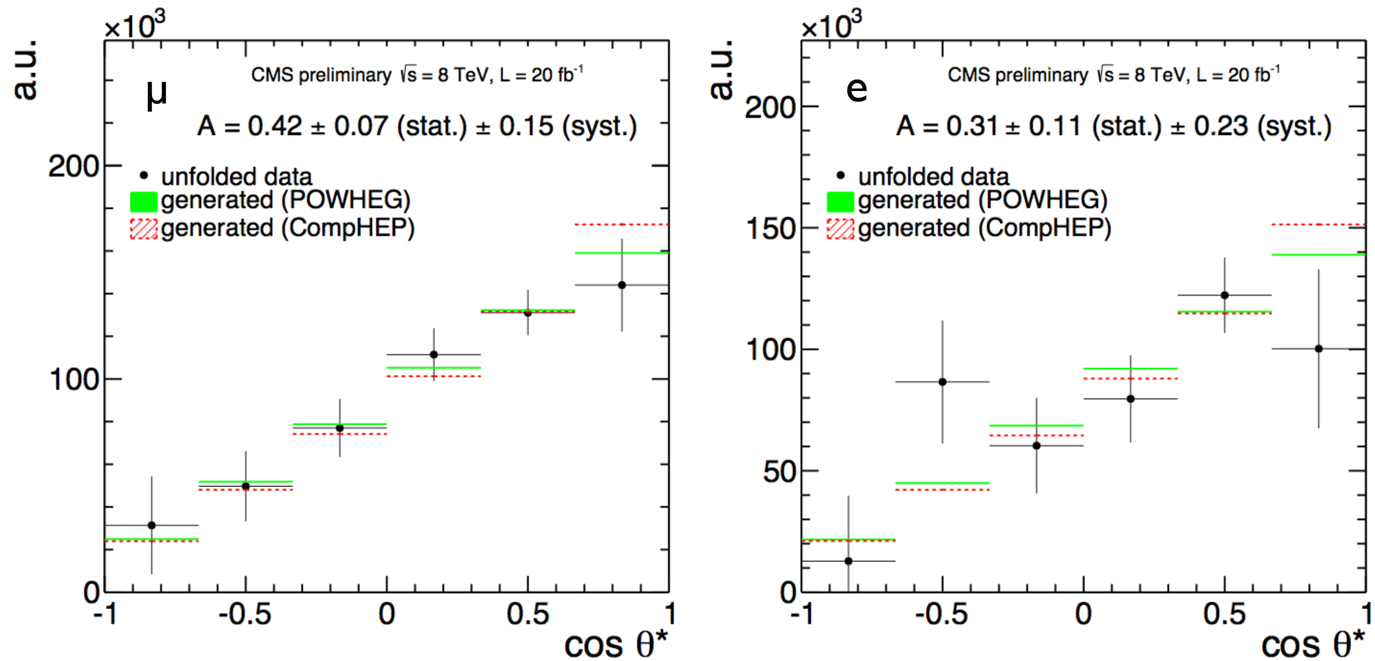
A BDT is used to get a t-channel enriched sample



August 2013
CMS-PAS-TOP-13-001

t-channel: top polarization

The asymmetry is obtained from the **unfolded** distributions in the e and μ channels separately and combined using BLUE



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

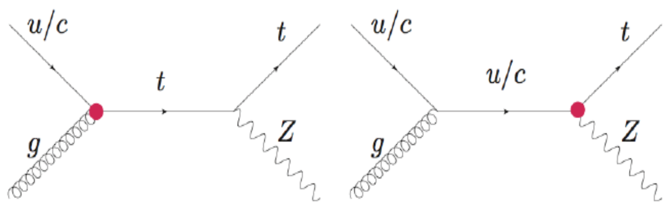
Step III

Search for FCNC and Anomalous Couplings

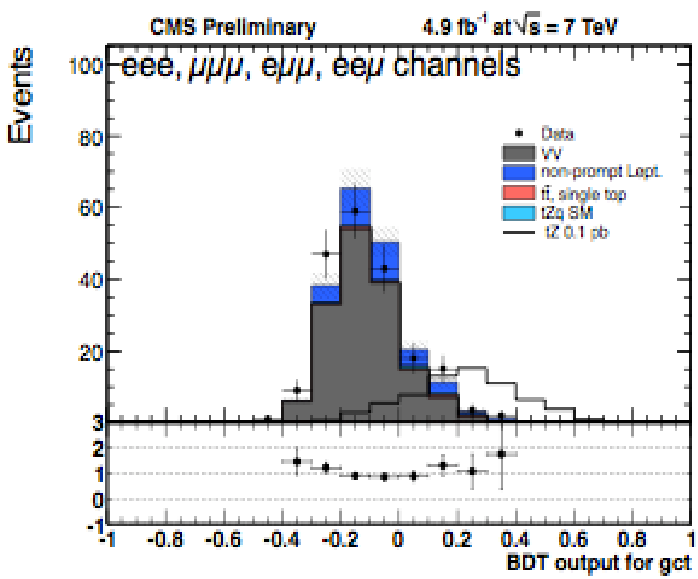
Limits on anomalous Wtb couplings can be extracted from SM measurements (W-helicity fractions, top polarization)

→ Dedicated analyses searching for deviations from the SM are also in place in single top signatures

FCNC tZ



July 2013
[CMS-PAS-TOP-12-021]



FCNC tZ

7TeV

Three-lepton signature

Simulated samples with different scenarios

BDT (gut, gct, Zut, Zct)

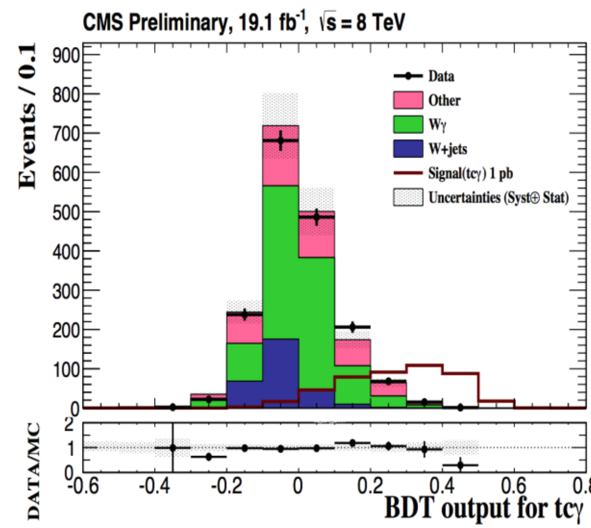
No excess → Limits on couplings and branching fractions

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 %

FCNC tγ

- **tqγ, single top produced in association with a photon**
  - Enhancement on t→u(c)γ BR due to FCNC
  - 8TeV, μ only
  - Samples with anomalous tuγ, tcγ couplings
  - Dedicated BDTs
  - No excess

  → Limits on couplings and branching fractions



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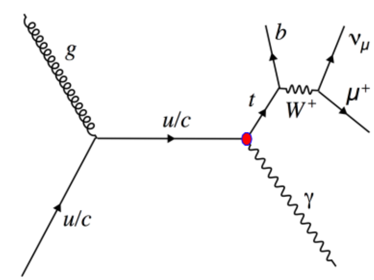
	Exp. limit (LO)	Obs. limit (LO)	Exp. limit (NLO)	Obs. limit (NLO)
$\sigma_{tu\gamma} \times Br(W \to l\nu_l)$	0.0404 pb	0.0234 pb	0.0408 pb	0.0217 pb
$\sigma_{tc\gamma} \times Br(W \to l\nu_l)$	0.0411 pb	0.0281 pb	0.0410 pb	0.0279 pb
$\kappa_{tu\gamma}$	0.0367	0.0279	0.0315	0.0229
$\kappa_{tc\gamma}$	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

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

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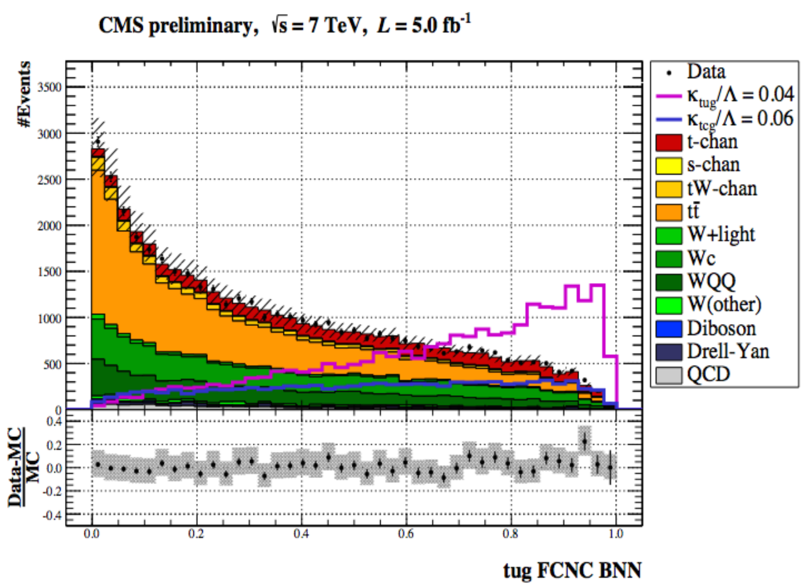
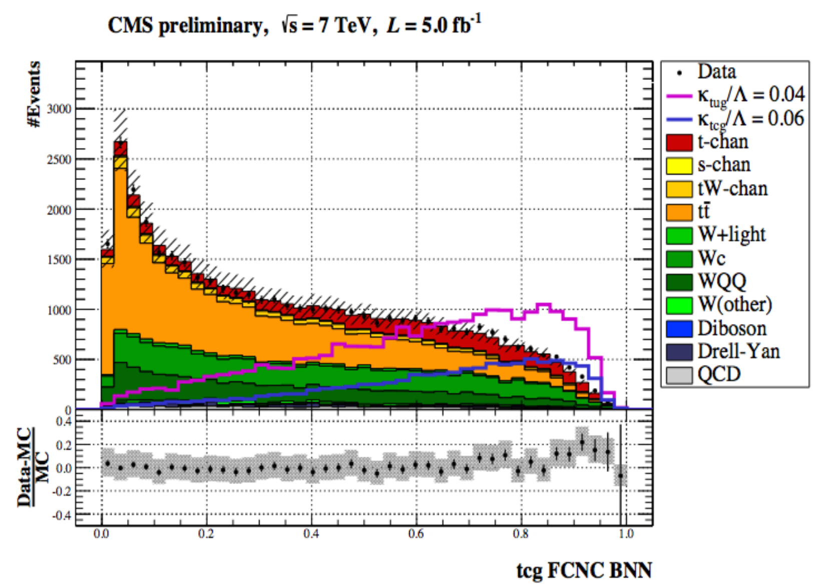
[CMS-PAS-TOP-14-007]





Summary

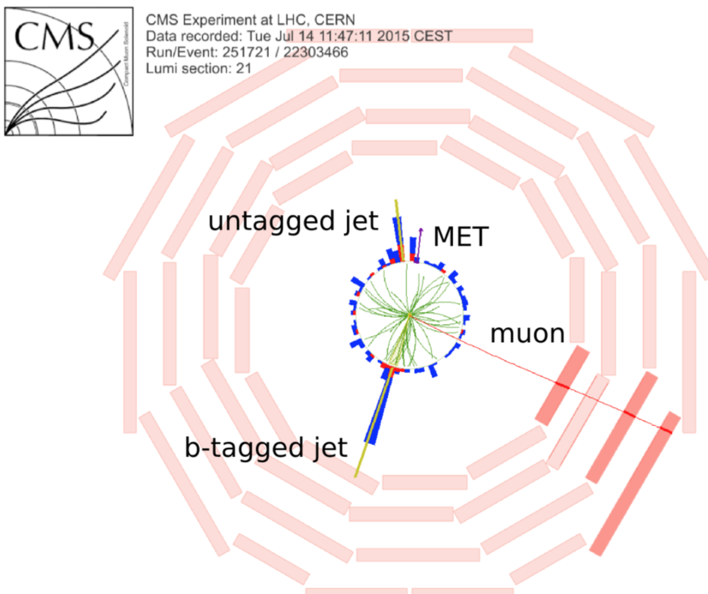
- Single top signatures were largely unknown until recently
- In the last 5 years we have made very good progress

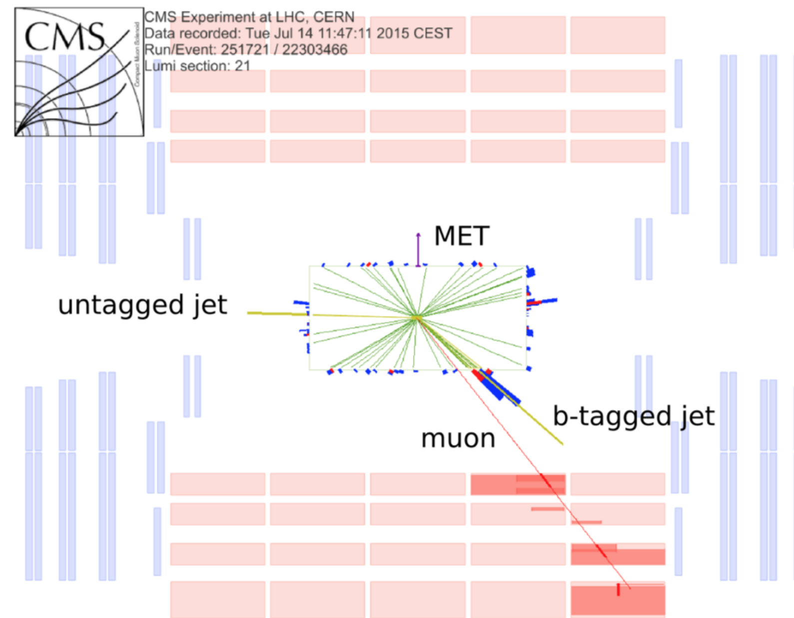
  → **the LHC is very powerful for top, and single top in particular**

- In CMS we have studied the **three main production modes**
- We have used single top quarks produced via t-channel for **measurements**:
  - W-helicity fractions, top polarization, $|V_{tb}|$…
- We have explored conventional and rare single top production modes to look for BSM physics: **FCNC and Anomalous Couplings**
  - Also (not in this talk): single top+Higgs (see Ken Bloom's talk on Thursday!), monotops (DM)

- **Run-2 will be the time to fully explore single top signatures, in particular to look for physics beyond the standard model**

Stay tuned!





Single top candidate event (t-channel, μ)

[CMS DP -2015/019](CMS DP -2015/019)
22 July 2015