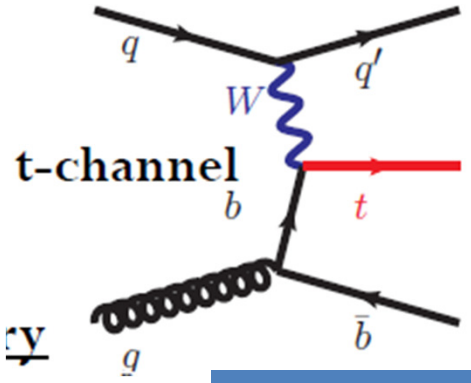
Single top Physics at Hadron Colliders

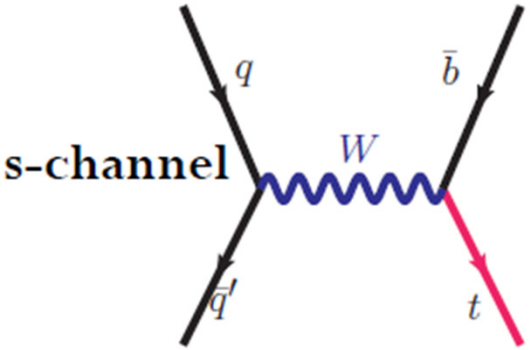
Giorgio Chiarelli
On behalf of
ATLAS CDF CMS D0
AC-DC

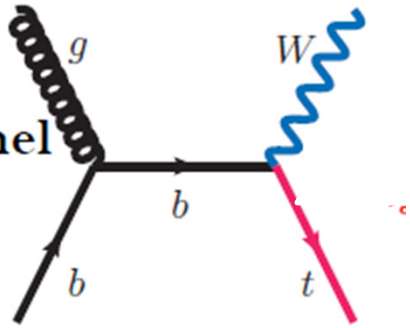
What is single top?

Electroweak production of top quark

- All Feynman diagrams below have a Wtb vertex







	t channel	s channel	Wt
Tevatron(1.96)	2.26	1.04	0.3
LHC (7 TeV)	64.2±2.4	4.6±0.2	15.7±1.1
LHC (8 TeV)	87.8±3.4	5.6±0.3	22.4±1.5

Energy in s channel does non help

Top in ewk production is challenging even at the LHC

History

Top quark discovery in strong production

- CDF, D0 1995,

It took 15 years to see single top (sum of s and t channel)

- Problem is the background

At LHC

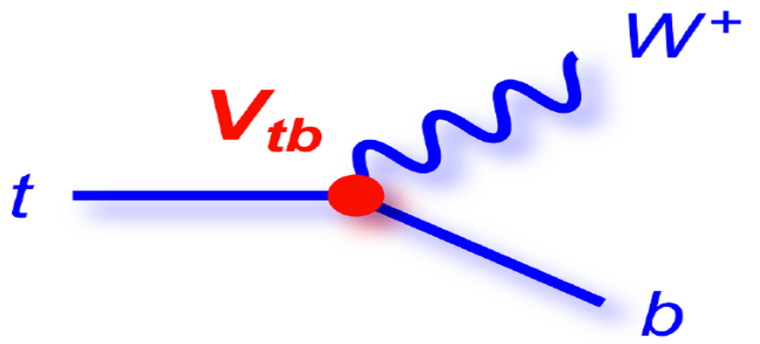
- Single top in t channel already seen in 2010 by both ATLAS and CMS
- Wt channel explored in 2011
  - First evidence(s)
  - 2012 analysis for Wt in progress..

Why fight for? Interest for s-top

Direct way to access the CKM matrix *element* $|V|_{tb}$

- Single-top production can measure $|V_{tb}|$ under the assumption that $|V_{tb}| \gg |V_{td}|, |V_{ts}|$
  - Actually we measure $|f_L \times V_{tb}|$, $f_L=1$ in SM
- Possible 4th generation test as well as other options beyond the standard model
- Anomalous couplings (search for FCNC)

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



More possibilities like

b-quark structure functions

Charged Bosons

Final state

Final state is characterized by

- W + 2-3jets
  - t channel: 2 b jet (1 forward), 1 light jet
  - s channel: 2 b jets
- 2W+1 b jet (Wt channel)

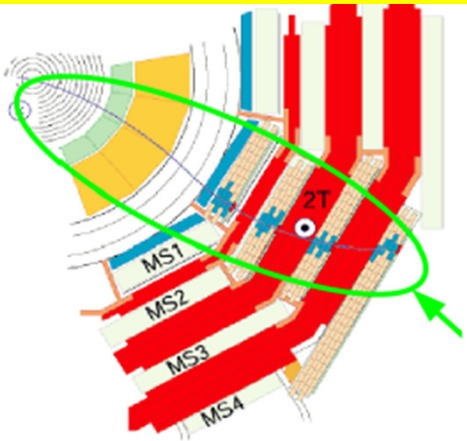
Include figure

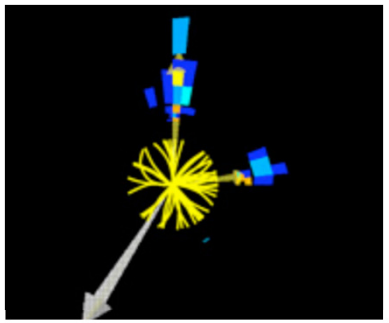
Single top in s and t channel has a final state topology resembling WH

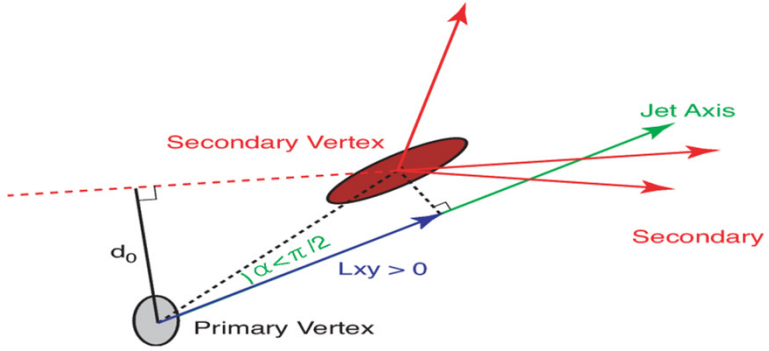
- Important for Higgs in associate production
- W^*, H^+

Tools: physics objects

- Hight Pt lepton (e or mu)
  - Isolated as coming from W
- 2 or 3 Jet with large E_T
  - 20 GeV at CDF, 30 at ATLAS
  - $|\eta|<2.8$ TeV, 4.5 @ LHC
- Missing E_T (MET)
  - 25 GeV (CDF), 20/25 (D0)
    30 (ATLAS), 35 (CMS)
- b-tagging of secondary vertices
  - With a variety of tools (from tracks displaced from the primary to NN algorithms)



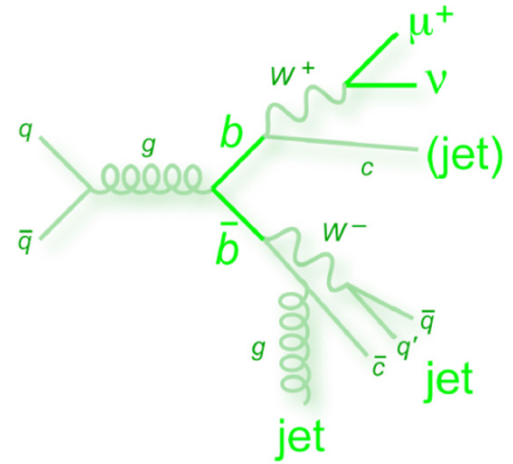


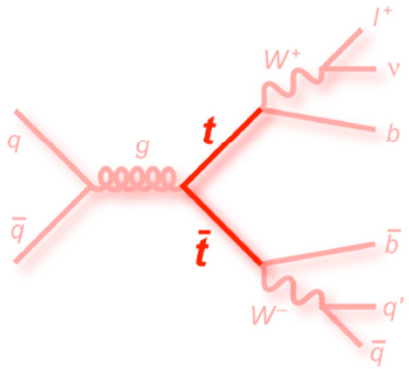


Backgrounds

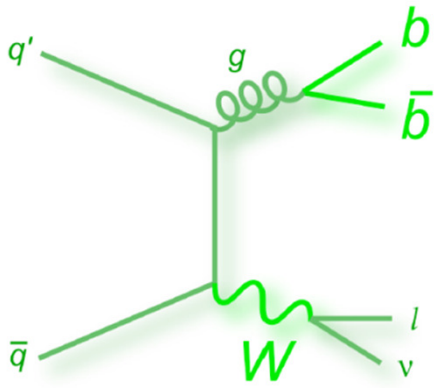
In a final state with W+2/3 jets (1-2 b-tagged)

- Multijet background
  - Data driven (see next slide)
- ttbar (+EWK processes)
  - From MC



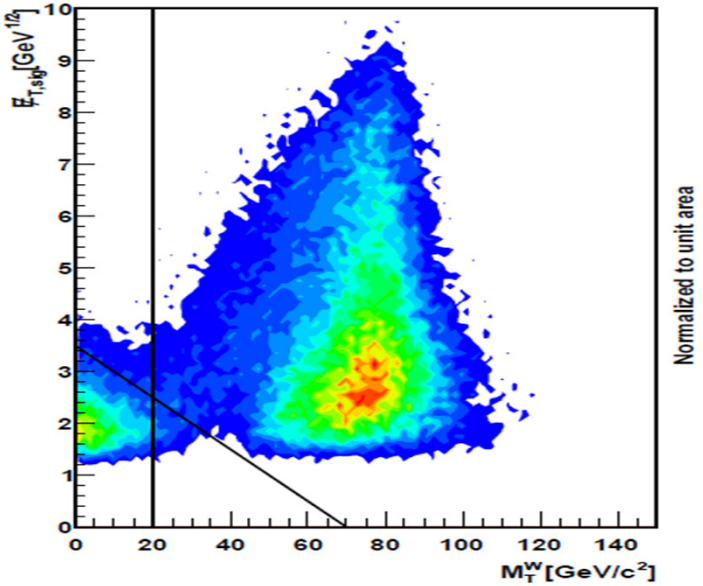


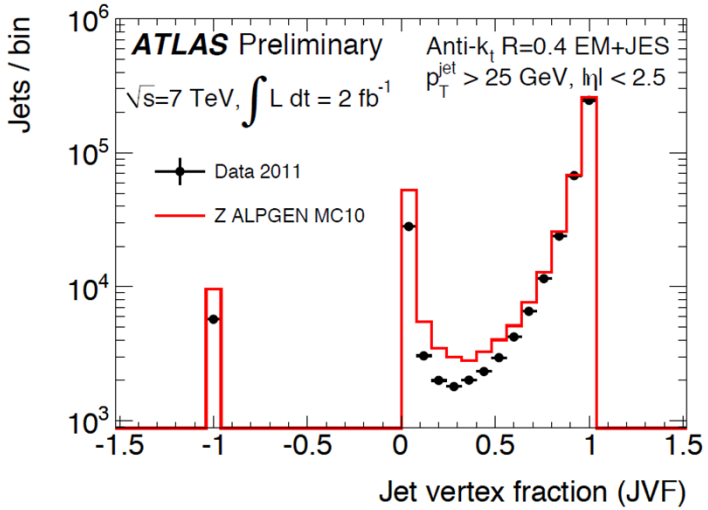
- W/Z+HF
  - Combination of data and MC
- W/Z+light flavour (mistagging)
  - As for W+HF



More on backgrounds…

- QCD removal using ad-hoc requirements
  - CDF, ATLAS, CMS use a cut in the MET-M_T (W) plane
  - D0 with a cut in H_T and in $\Delta\varphi$(MET,l)
- Veto cosmics, Z etc
- ATLAS, CMS fight PileUp using tracking
  - Specific requirements for jets to have
    - JVF>0.75 (ATLAS @7 TeV)
    - JVF>0.5 (ATLAS @8 TeV)





Situation after all requirements

Tevatron and LHC are different environments

- Signal swamped by background and its uncertainties
- s and t channel almost equal at the Tevatron in the 2jets
- LHC:
  - t channel : 50% of ttbar, s: 3% of t, Wt: 50% of t

D0

Source	2 jets	3 jets	4 jets
tb	104 ± 16	44 ± 7.8	13 ± 3.5
tqb	140 ± 13	72 ± 9.4	26 ± 6.4
$t\bar{t}$	433 ± 87	830 ± 133	860 ± 163
W + jets	$3,560 \pm 354$	$1,099 \pm 169$	284 ± 76
Z + jets & dibosons	400 ± 55	142 ± 41	35 ± 18
Multijets	277 ± 34	130 ± 17	43 ± 5.2
Sum of above sources	$4,914 \pm 558$	$2,317 \pm 377$	$1,261 \pm 272$
Data	4881	2307	1283

ATLAS 8 TeV

	Signal region	
	2 jets	3 jets
t-channel	5210 ± 210	1959 ± 78
s-channel	343 ± 14	100 ± 4
Wt	1570 ± 110	1363 ± 95
$t\bar{t}$	11700 ± 1200	15300 ± 1500
W+light flavour	5500 ± 1700	1160 ± 350
W+heavy flavour	12000 ± 6000	3900 ± 2000
Z+jets, diboson	1200 ± 720	410 ± 240
QCD multijet	3000 ± 1500	1650 ± 830
Total Expectation	41600 ± 6600	25800 ± 2700
Data	40663	23687

Finding the needle in the haystack

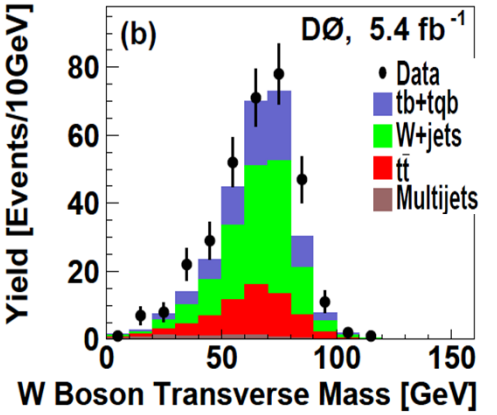
low S^2/B →use of MVA

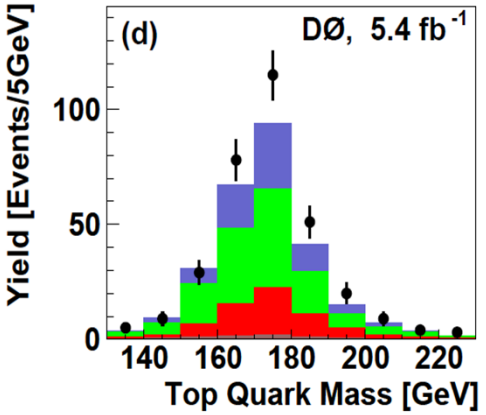
- This was done by CDF and D0 at the Tevatron
  - Detailed studies of large number of variables
- ATLAS and CMS:
  - both cut-based and MVA analyses
    - Signal extraction easier for t-channel
    - MVAs are an additional tool

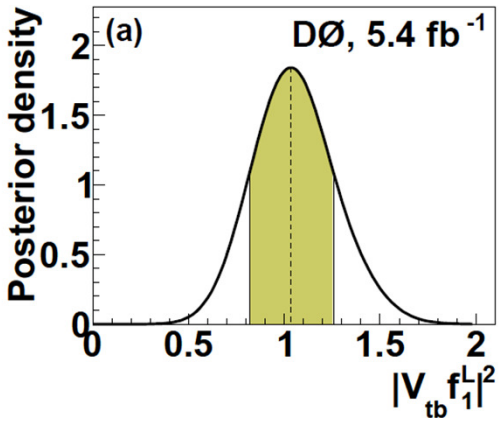
	2-jet		3-jet	
variable	1-tag	2-tag	1-tag	2-tag
$M_{\ell\nu b}$	✓	✓	✓	
$M_{\ell\nu bb}$		✓		✓
$M_{\mathrm{t}}^{\ell\nu b}$	✓	✓	✓	✓
M_{jj}	✓	✓	✓	✓
M_{t}^{w}	✓	✓		
$E_{\mathrm{t}}^{b_{\mathrm{top}}}$		✓	✓	
$E_{\mathrm{t}}^{b_{\mathrm{other}}}$				✓
$\sum e_{\mathrm{t}}^{jj}$			✓	✓
$E_{\mathrm{t}}^{\mathrm{light}}$	✓			✓
p_{t}^{ℓ}	✓			
$p_{\mathrm{t}}^{\ell\nu jj}$			✓	✓
H_{t}	✓		✓	
$\not{E}_T$		✓		
$\not{E}_{T\,\mathrm{sig}}$			✓	
$\cos\theta_{\ell j}$	✓		✓	✓
$\cos\theta_{\ell w}^{w}$	✓			
$\cos\theta_{\ell w}^{t}$	✓			
$\cos\theta_{jj}^{t}$		✓		✓
$Q \times \eta$	✓		✓	✓
η_{ℓ}		✓		
η_{w}	✓	✓		
$\sum \eta_j$	✓		✓	
$\Delta\eta_{jj}$			✓	✓
$\Delta\eta_{t,\mathrm{light}}$			✓	
$\sqrt{\hat{s}}$				✓
Centrality				✓
Jet flavor separator	✓	✓	✓	

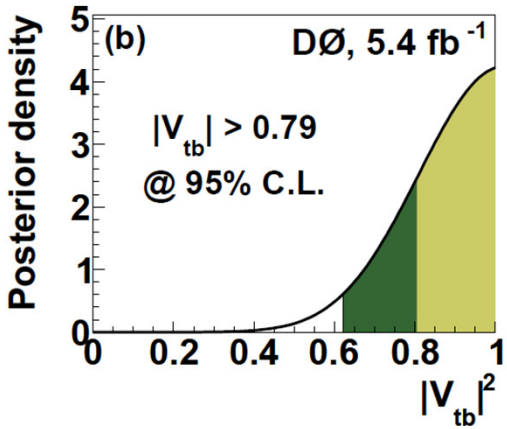
5.4 fb^{-1} result

- DO measures (s+t) Signal extraction proceeds by using:
  - 3 different MVA (BNN, BDT, NEAT) which are trained for s and t channel separately
    - Their output is feed to a BNN(s+t) discriminant









$\sigma(s+t)=3.43\pm0.74$pb

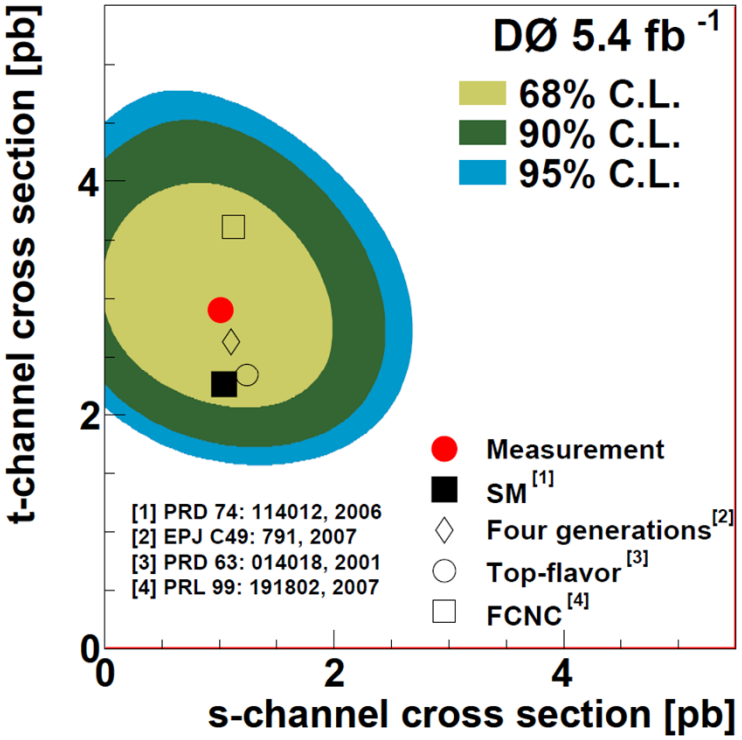
Fixing the ratio t/s to SM value:

$\sigma(t)=2.86\pm0.66$pb $\sigma(t)=0.68\pm0.36$

More…

Leaving s and t free

- t channel at 2.9±0.59 pb
- S channel 0.98±0.63 pb

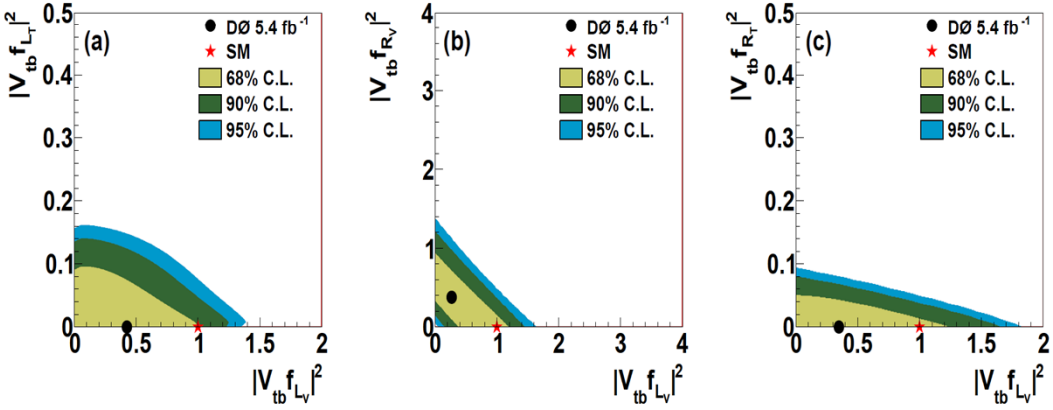


Use the same data to set limit for anomalous Wtb couplings

$$\mathcal{L} = -\frac{g}{\sqrt{2}} b\gamma^{\mu}(L_V P_L + R_V P_R) t W_{\mu}^{-}$$

$$-\frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_{\nu}}{M_W} (L_T P_L + R_T P_R) t W_{\mu}^{-} + h.c.,$$

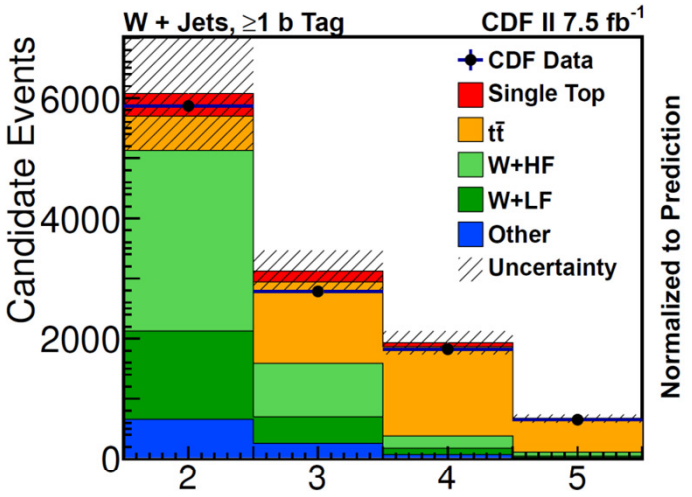
- In SM $L_V \cong 1$, $R_V, R_T, L_T = 0$



7.5 fb^{-1} analysis

CDF updated its 3.4 fb^{-1} result with 7.5

- s+t optimized, 2/3 jets, 1-2 tags
- Use more triggers and lepton reconstruction algorithms
  - Improve acceptance
- New QCD background suppression

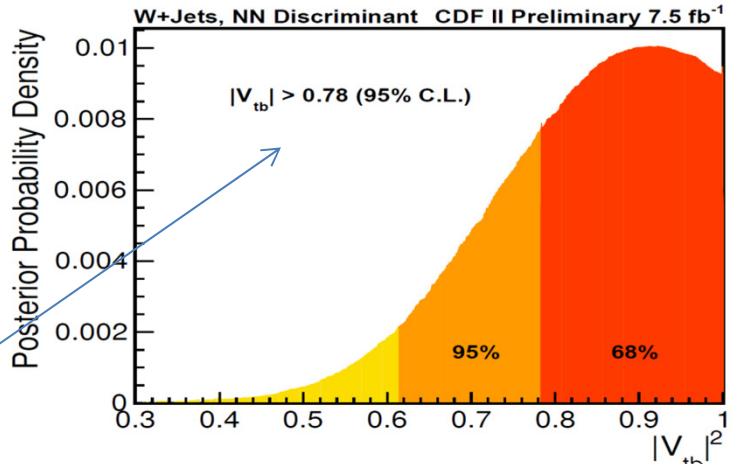


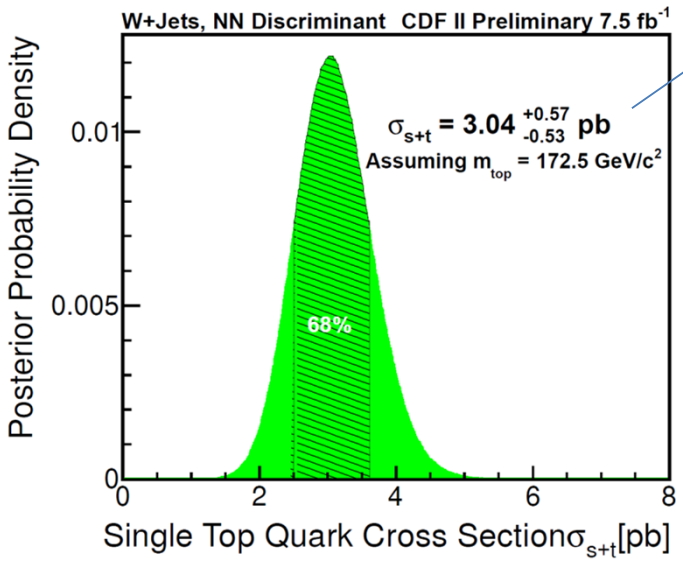
Process	W+2jets, 1 tag	W+3jets, 1 tag	W+2jets, 2 tag	W+3jets, 2 tag
$t\bar{t}$	474 ± 49	1067 ± 109	98 ± 14	284 ± 42
WW	148 ± 21	48 ± 7	1.1 ± 0.3	1.2 ± 0.3
WZ	53 ± 6	14 ± 2	8.8 ± 1.3	2.4 ± 0.4
ZZ	1.7 ± 0.2	0.7 ± 0.1	0.3 ± 0.0	0.1 ± 0.0
Z+Jets	118 ± 15	46 ± 6	4.8 ± 0.7	2.7 ± 0.4
Wbb	1452 ± 437	434 ± 131	183 ± 56	65 ± 20
Wcc	766 ± 233	254 ± 77	10 ± 3	7 ± 2
Wcj	583 ± 177	128 ± 39	7.8 ± 2.4	3.5 ± 1.1
W+Mistags	1459 ± 148	433 ± 47	7.4 ± 1.5	5.4 ± 1.1
Non-W	316 ± 126	141 ± 57	6.8 ± 3.5	3.4 ± 3.2
t-channel	193 ± 25	84 ± 11	6 ± 1	15 ± 2.4
s-channel	128 ± 11	43 ± 4	32 ± 4	12 ± 1.6
Wt-channel	16 ± 4	26 ± 7	0.7 ± 0.2	2.3 ± 0.6
Total Prediction	5707 ± 877	2719 ± 293	367 ± 66	403 ± 53
Observed	5533	2432	335	355

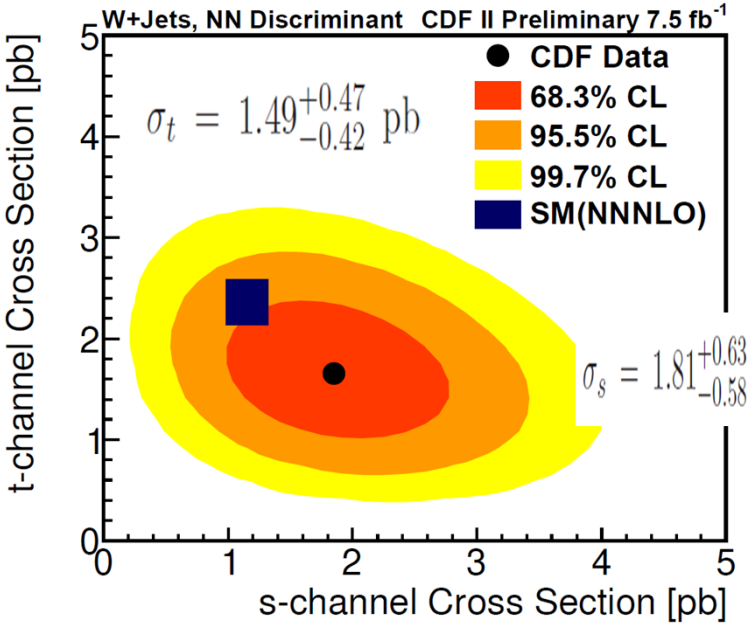
Results

Not sensitive to Wt

- First fit s+t combined
- Then move to a 2-D s-t discriminant



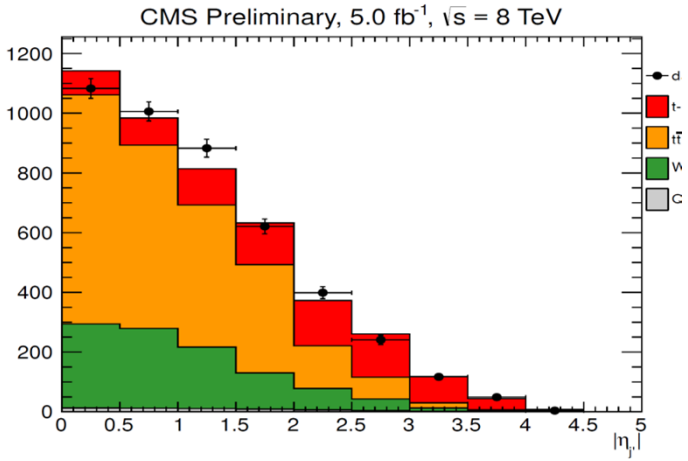




7& 8 TeV-$|\eta_{j'}|$

- Divide l+jets sample in $n_{jet}(2,3)$, $m_{tag}(0,1,2)$
  - Red is signal region blue control regions
- 130<M(lvb)<220 GeV
  - For the non-btagged jet fit $|\eta_{j'}|$ distribution with templates

Process	muon yield	electron yield
t-channel	604.1 ± 2.6	332.9 ± 2.1
tW channel	107.0 ± 1.0	70.13 ± 0.89
s-channel	25.38 ± 0.46	14.70 ± 0.38
$t\bar{t}$	637.1 ± 5.4	472.7 ± 5.0
W + light partons	90.0 ± 6.9	48.2 ± 5.5
$Wc(\bar{c})$	437 ± 14	213.8 ± 9.9
$Wb(\bar{b})$	528 ± 15	244 ± 10
Z + jets	81.5 ± 2.7	11.35 ± 0.90
Dibosons	23.54 ± 0.36	11.03 ± 0.26
QCD	76.1 ± 2.9	61.2 ± 3.3
Total	2610 ± 22	1480 ± 17
Data	3108	1581



t-channel xsec: Results

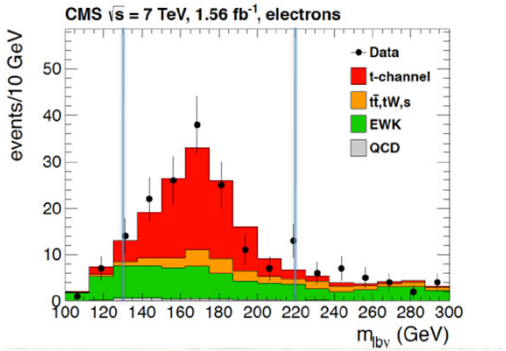
7 TeV: several analyses:

- $\eta_{j'}$
- Neural Net
- Boosted Decision Tree

$$\sigma = 67 \pm 4(\text{stat.}) \pm 3(\text{syst.}) \pm 4(\text{theo.}) \pm 2(\text{lumi.})\ \text{pb}$$

$$V_{tb} = 1.02 \pm 0.05 \pm 0.02\ (\text{theo.})$$

$$V_{tb} > 0.92\ @95\%\text{CL for } V_{tb} \text{ in } [0,1]$$



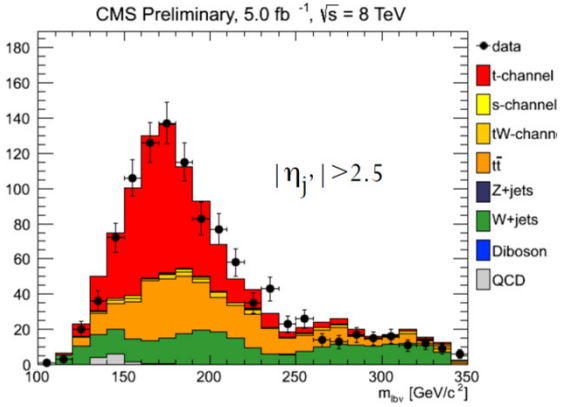
8 TeV:

- $\eta_{j'}$: more stringent cuts than at 7 TeV

$$\sigma = 80 \pm 6(\text{stat.}) \pm 11(\text{syst.}) \pm 4(\text{lumi.})\ \text{pb}$$

$$V_{tb} = 0.96 \pm 0.08 \pm 0.02(\text{theo.})$$

$$V_{tb} > 0.81\ @95\%\text{CL in } [0,1]$$

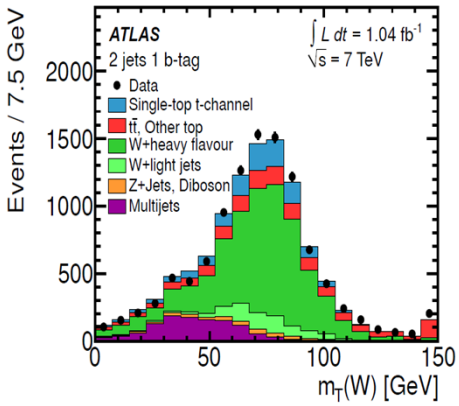


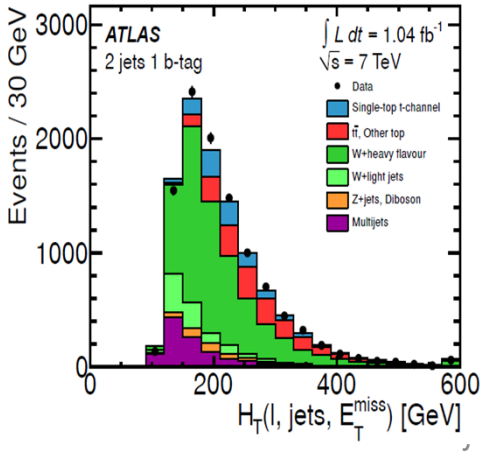
t channel @ 7 TeV

«Easy» channel

- Forward jets, softer b jet
- Events with 2/3 jets ⊕1 b tag
- MET+M_T(W)>60 GeV

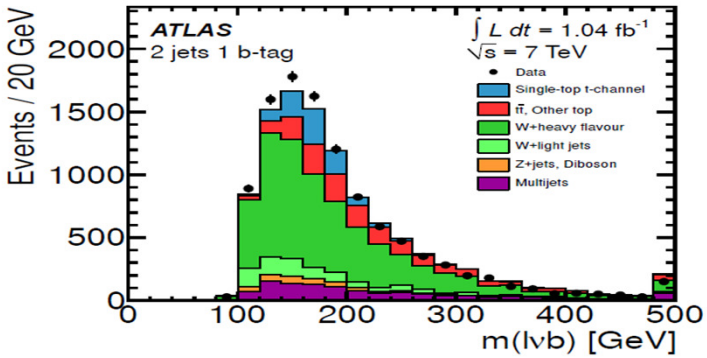
S/B~1/9

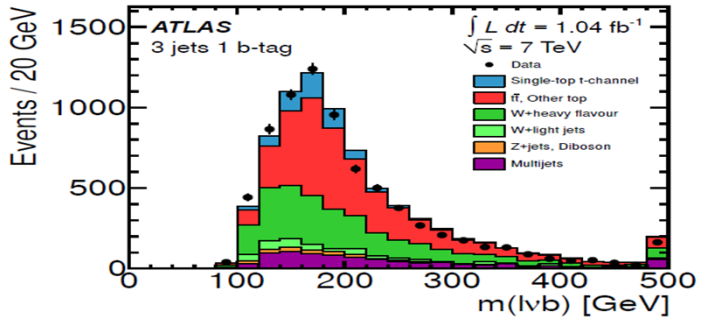




Background estimate:

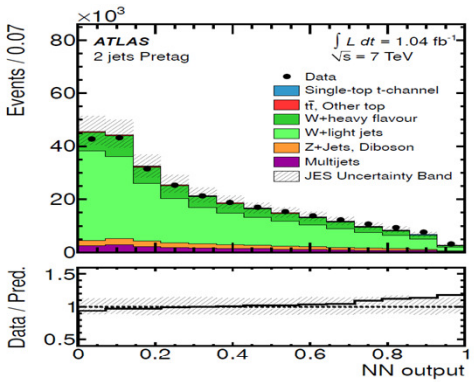
- MC samples
- Data driven models

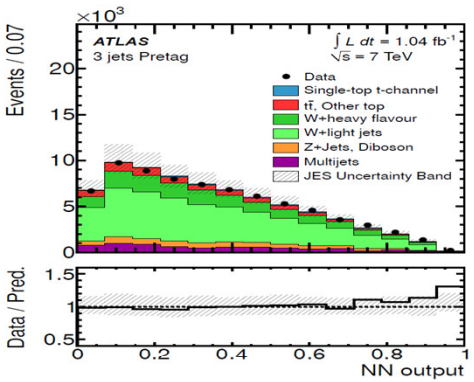




Result at 7 TeV (1.04 fb^{-1})

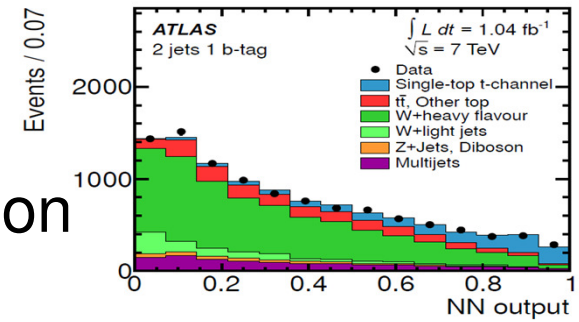
PLB 717 (2012), 330-350

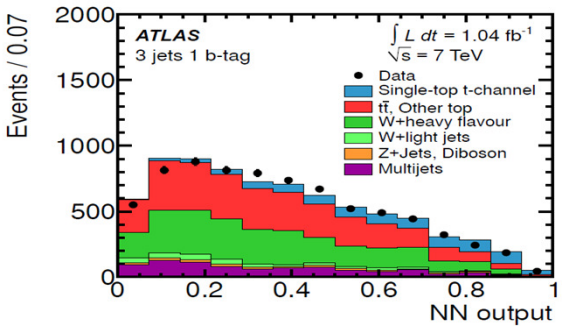




Control region

Signal region





$\sigma_t = 83 \pm 4(\text{stat})\ ^{+20}_{-19}(\text{syst})\text{pb} = 83 \pm 20\ \text{pb}$

$|V_{tb}| = 1.13 +- 0.14$

$|V_{tb}| > 0.75$ @ 95 % CL

t channel @8 TeV

Increase wrt 7 TeV:

- Signal by 35%
- ttbar by 40%
- W+jets: 25-35%

	Signal region	
	2 jets	3 jets
t-channel	5210 ± 210	1959 ± 78
s-channel	343 ± 14	100 ± 4
Wt	1570 ± 110	1363 ± 95
$t\bar{t}$	11700 ± 1200	15300 ± 1500
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W+heavy flavour	12000 ± 6000	3900 ± 2000
Z+jets, diboson	1200 ± 720	410 ± 240
QCD multijet	3000 ± 1500	1650 ± 830
Total Expectation	41600 ± 6600	25800 ± 2700
Data	40663	23687

Instrumental conditions

- More pileup (increased L)
- Lepton triggers requires harder isolation cut
- Multijet fraction higher

Change some cuts

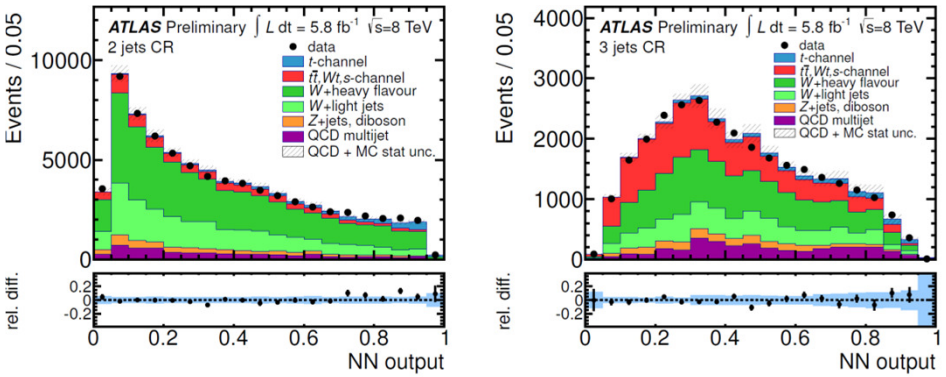
- JVF (see slide 8)
- Jet P_T>30 GeV, MET>30 GeV, $M_T(W)$>50 GeV
  - Expect S/B~1/9

ATLAS-CONF-2012-132

ATLAS-CONF-2012-056

Results

NN in control regions for 2,3 jets



σ_t= 95 ±2 (stat) ±18 (syst) pb

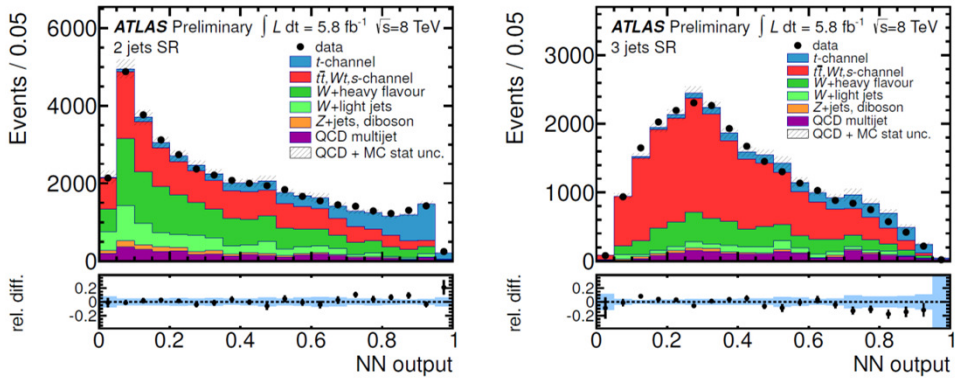
$|V_{tb}|=1.04^{+0.1}_{-0.11}$

Under usual assumption

($|V_{tb}|>>|V_{ts}|, |V_{td}|$)

($|V_{tb}|>0.80$ at 95 % CL)

NN in signal region for 2,3 jets



Splitting the sample in *t* and *tbar* (l charge)

$\sigma_t(t)$= 53±10.8 pb

$\sigma_t(t)= 29.5^{+7.4}_{-7.5}$ pb

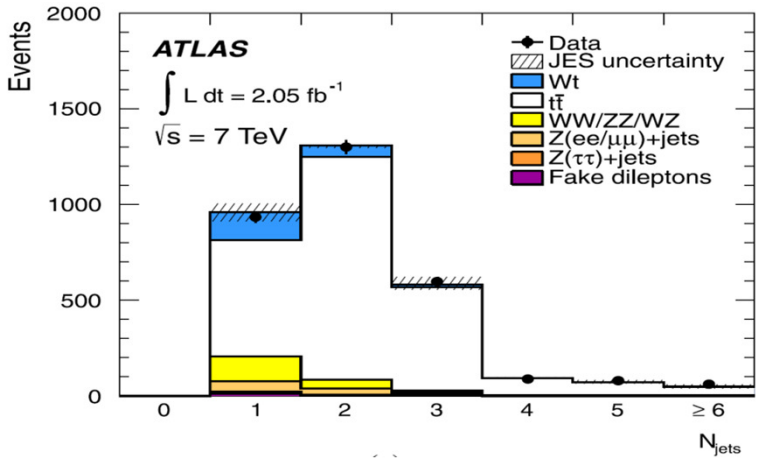
$Rt=1.81^{+0.23}_{-0.22}$

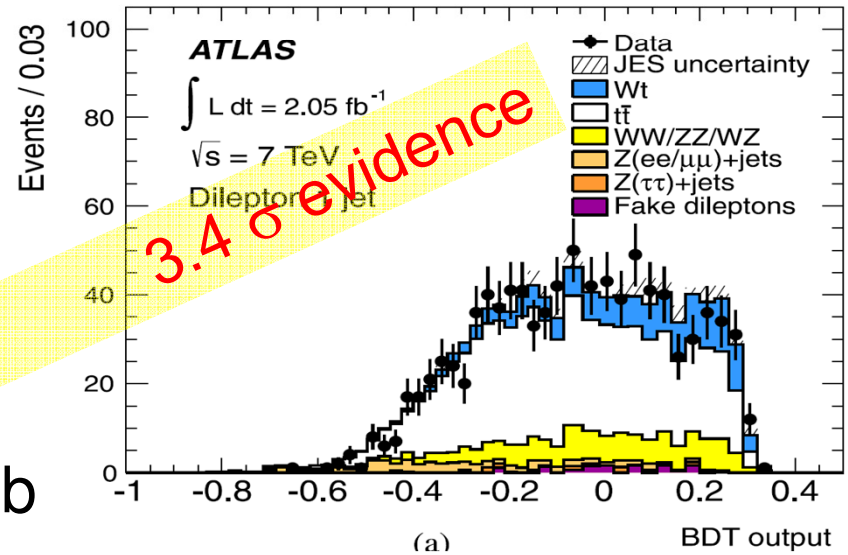
Wt @7 TeV & 2.05 fb^{-1}

Dilepton channel

- Wt→lnlnb
  - Large ttbar background
- Most signal in N_{jet}=1 bin,
  - Use BDT

	1-jet	2-jet	⩾3-jet
Wt	147 ± 13	60 ± 9	17 ± 5
$t\bar{t}$	610 ± 110	1160 ± 140	740 ± 130
Diboson	130 ± 17	47 ± 5	17 ± 4
$Z \to ee$	20 ± 2	11 ± 2	5 ± 2
$Z \to \mu\mu$	29 ± 3	28 ± 3	12 ± 3
$Z \to \tau\tau$	9 ± 6	4 ± 3	2 ± 1
Fake dileptons	11 ± 11	5 ± 5	negl.
Total bkgd.	810 ± 120	1260 ± 140	780 ± 130
Total expected	960 ± 120	1320 ± 140	790 ± 130
Data observed	934	1300	825





$\sigma(Wt)=16.8\pm2.9(stat)\ \pm2.9(syst)pb$

$|V_{tb}|=1.03^{+0.16}_{-0.19}$

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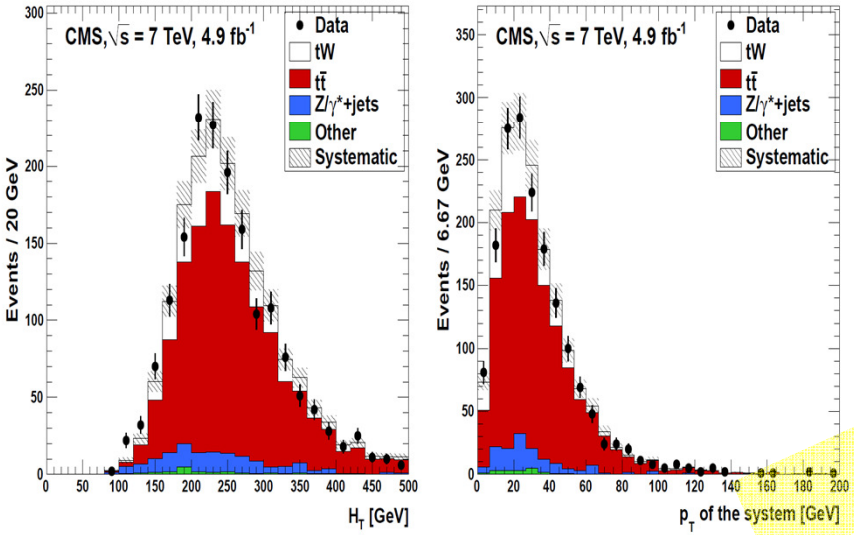
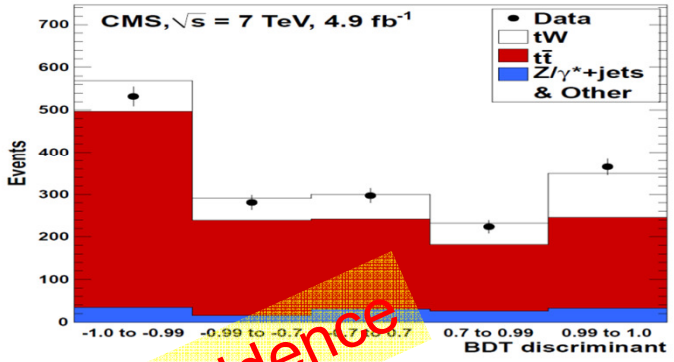
Wt @7 TeV & 4.9 fb^{-1}

Use dilepton channel

- Define signal (1j1tag)
  - ..and control regions (2j1tag,2j2tags)
- BDT with 4 variables

	1j1t	2j1t	2j2t
tW	336±5±16	180±3±16	45±1±6
$t\bar{t}$	1263±19±138	2775±28±205	1488±21±222
Z/γ^* +jets	128±12±28	113±10±22	8.5±1.8±1.8
Other	19±3	8.8±0.7±0.2	4±3
Total estimated	1746±23±141	3077±30±207	1546±21±222
Total data	1699	2878	1507





4 σ evidence

$\sigma(Wt)=16.\ ^{+5}_{-4}$pb

arXiv:1209.3489

$$|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma^{th}_{tW}}} = 1.01^{+0.16}_{-0.13}(\text{exp.})^{+0.03}_{-0.04}(\text{th.})$$

s-channel challenge

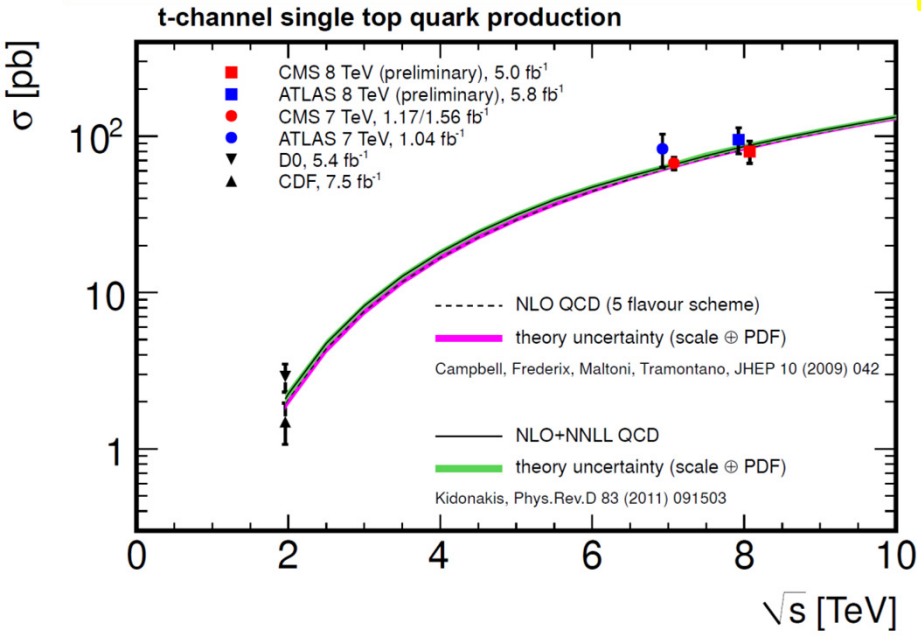
Tevatron:

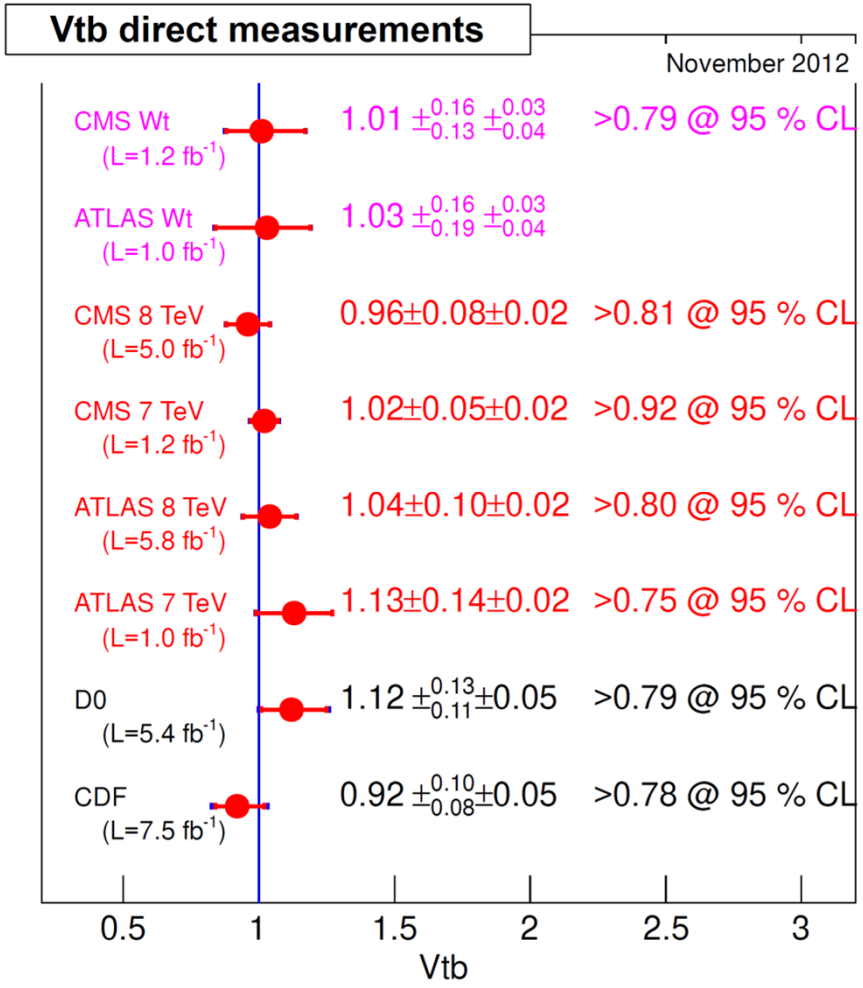
- So far we optimized for observation of (s+t)
- Re-optimize analysis
  - Add statistics (more triggers)
    - Use best taggers (CDF)
    - Add «anti» t-channel requirements?
    - Smart ideas?

LHC:

- Challenging scenario:
  - Very large ttbar
  - Wbb channel to be understood
  - W+lf to be reduced
  - Time will tell

Summary of results





s channel (Tevatron only)

CDF=$1.81^{+0.63}_{-0.58}$ pb

D0=0.98±0.63 pb

Wt (LHC only, 7 TeV)

ATLAS 16.8±5.7 pb

CMS 16^{+5}_{-4} pb

Conclusions

Single top physics in the t-channel is now

- Mature for precise measurements
  - Systematics is by far dominating
    - Better understanding of the detectors will help

We are on the verge of a full observation of Wt

- My prediction: 2012 data (Winter conferences)

ΔV_{tb} is still at 10%

- Need to tackle systematics
  - JES/JER
  - b-tagging,
  - pdf
  - **MC statistics**

s-channel is a long shot for LHC

- Still room for D0 and CDF. Tevatron Heritage?