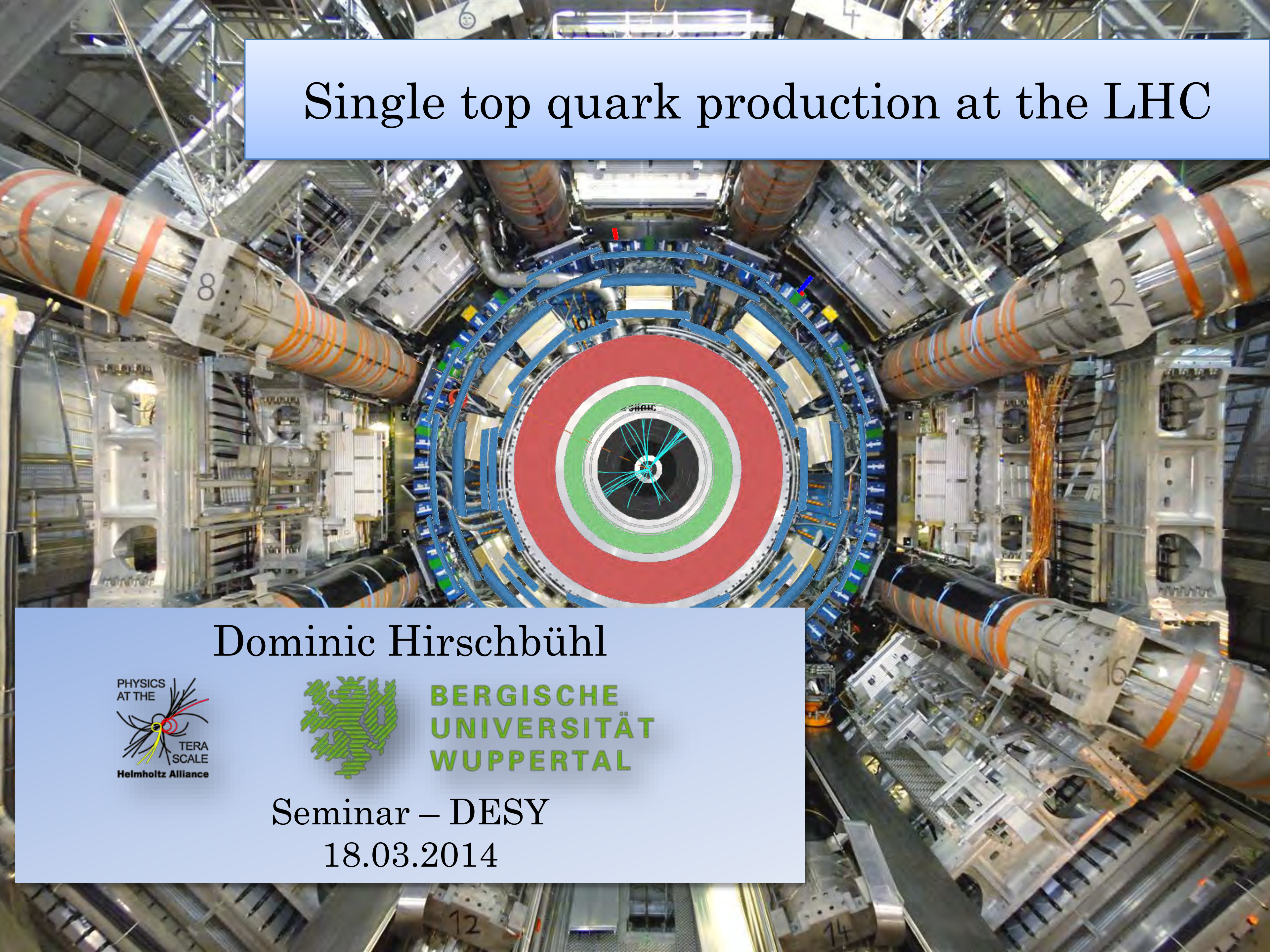


Single top quark production at the LHC

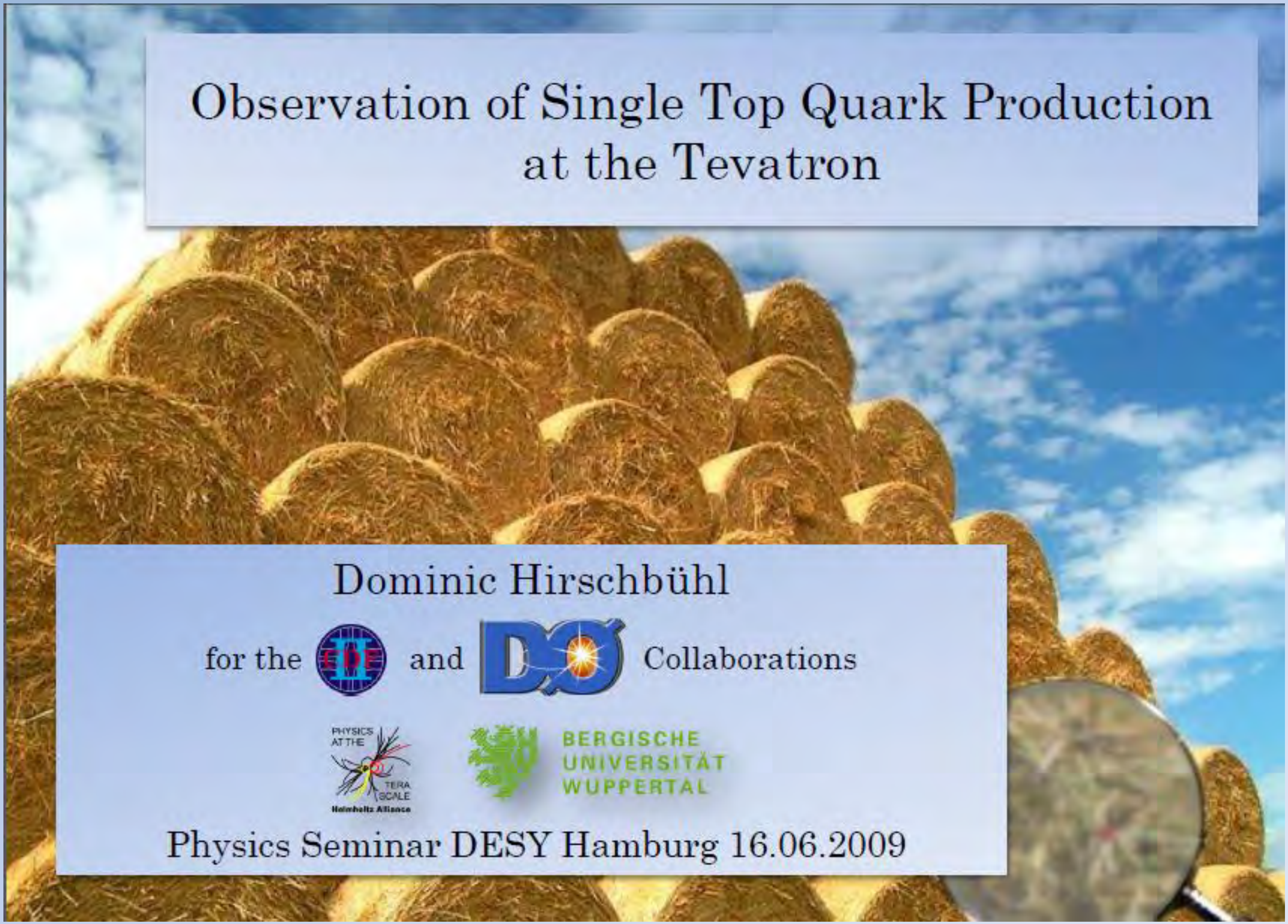
Dominic Hirschbühl

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

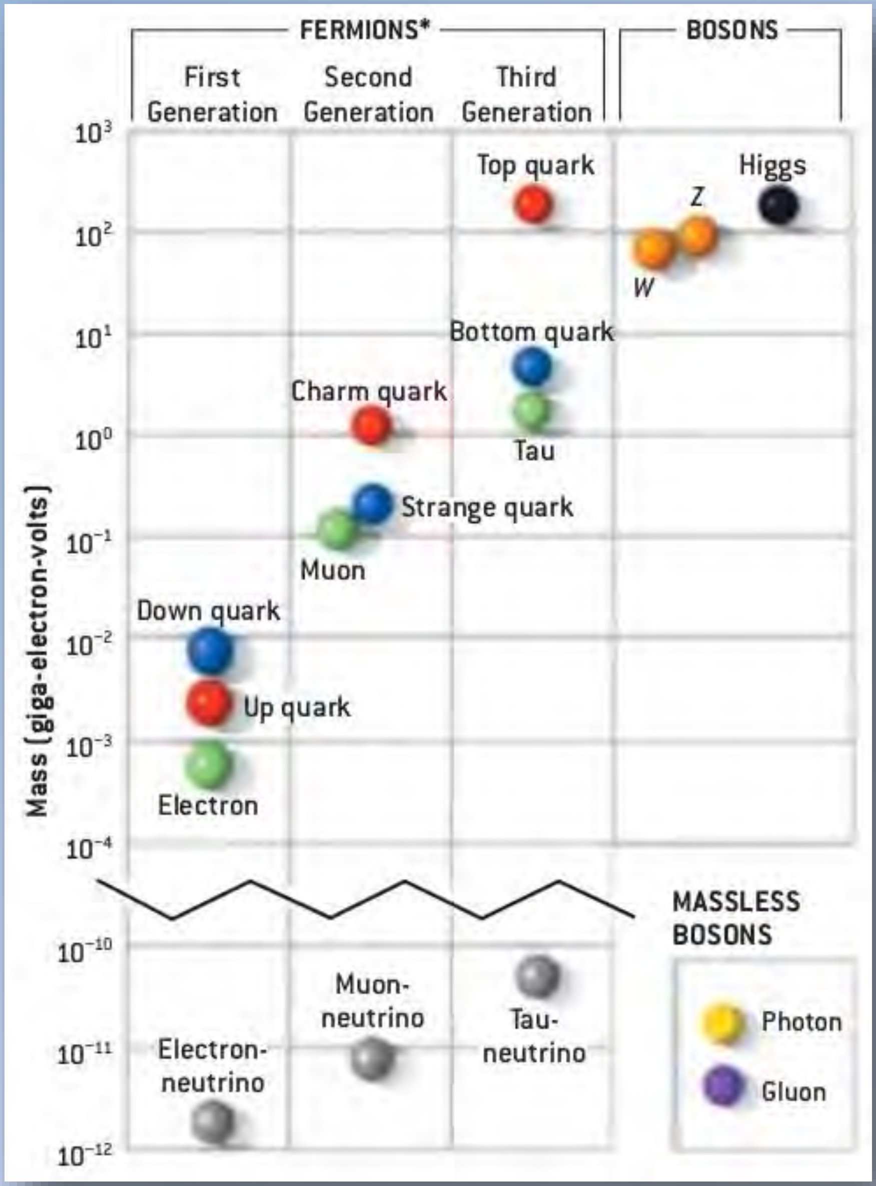
BERGISCHE UNIVERSITÄT WUPPERTAL

Seminar – DESY
18.03.2014

Last time ...


Observation of Single Top Quark Production
at the Tevatron
Dominic Hirschbühl
for the CDF and DØ Collaborations
PHYSICS AT THE TERA SCALE
Helmholtz Alliance
BERGISCHE UNIVERSITÄT WUPPERTAL
Physics Seminar DESY Hamburg 16.06.2009

The top quark



The heaviest know elementary particle.

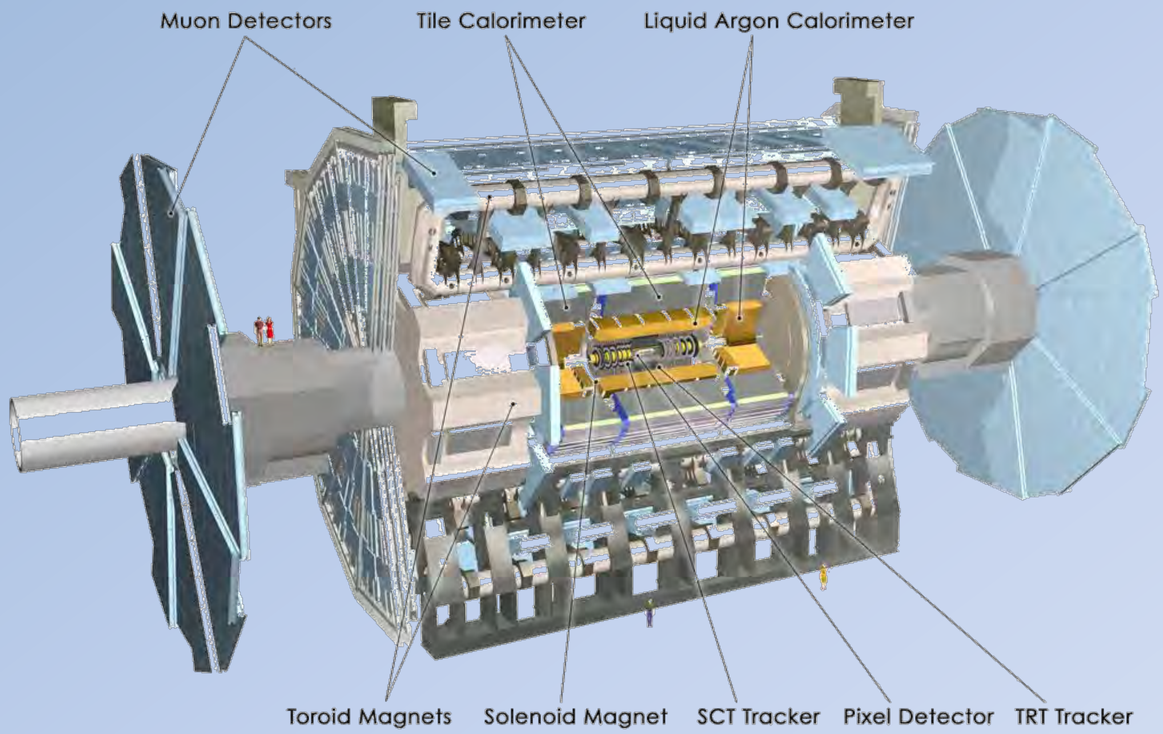
Tight connection to the Higgs-Boson and Electroweak Symmetry Breaking

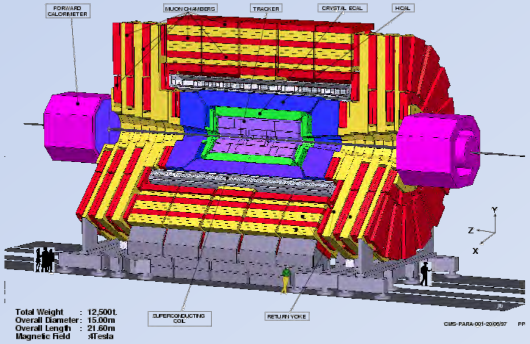
It decays before it hadronizes.

It is still a (old) teenager, discovered in 1995, and we just got recently many of them

The experiments

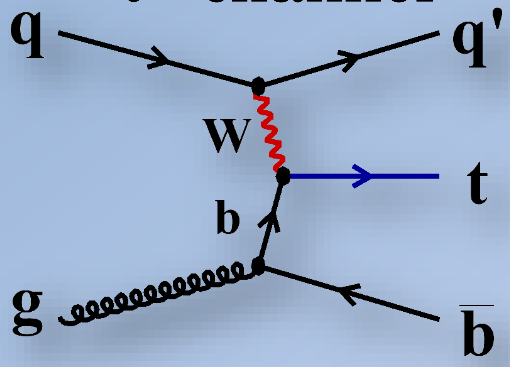
Focus on ATLAS



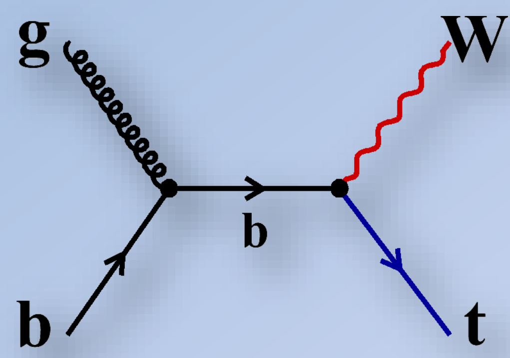


Single top quark production

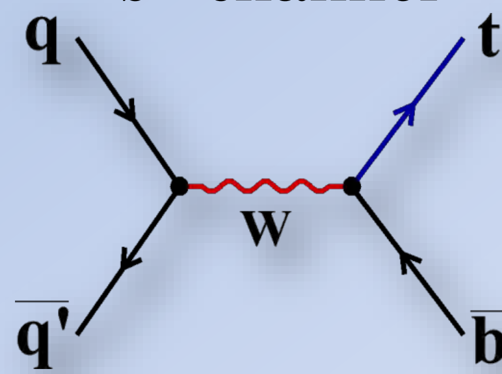
t - channel



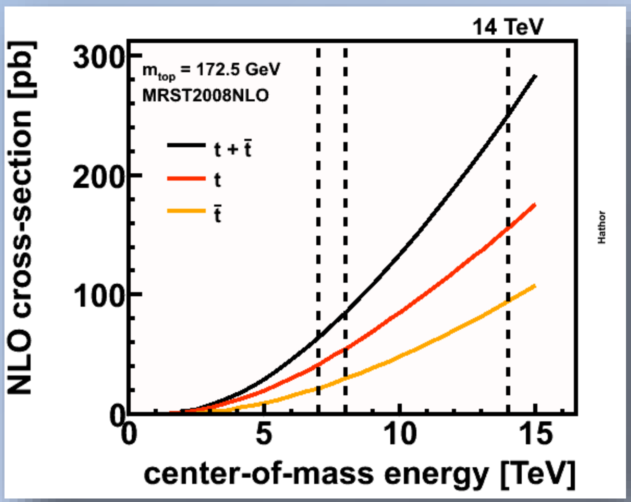
Wt



s - channel



t-channel



Calculations using MCFM @ NLO

Cross section	1.96 TeV	7 TeV	8 TeV
t – channel	2.1 ± 0.1 pb	64.6 ± 2.4 pb	87.8 ± 3.4 pb
Wt	0.25 ± 0.03 pb	15.7 ± 1.1 pb	22.4 ± 1.5 pb
s - channel	1.05 ± 0.05 pb	4.6 ± 0.2 pb	5.6 ± 0.2 pb

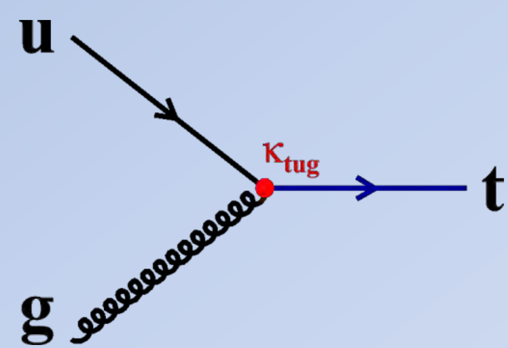
Single-top-quark and antiquark cross sections are different for t- and s-channel at the LHC!

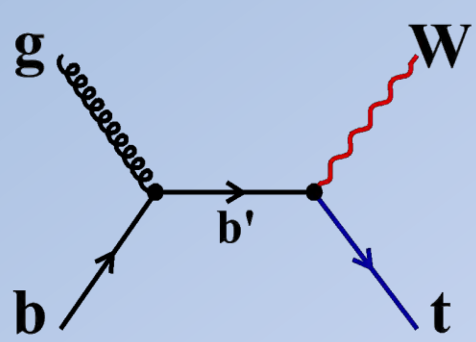
Calculations by N. Kidonakis:
Phys.Rev.D83 (2011) 091503, Phys.Rev.D82 (2010) 054018,2010, Phys.Rev.D81 (2010) 054028
@ NLO + NNLL resummation

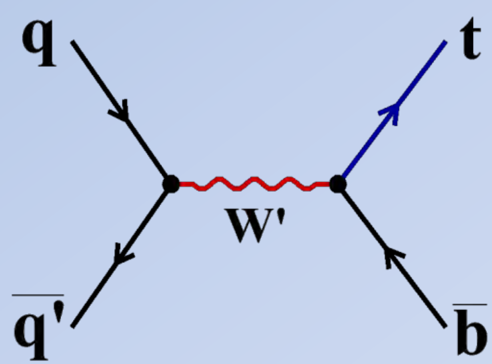
Single top quark production in new physics

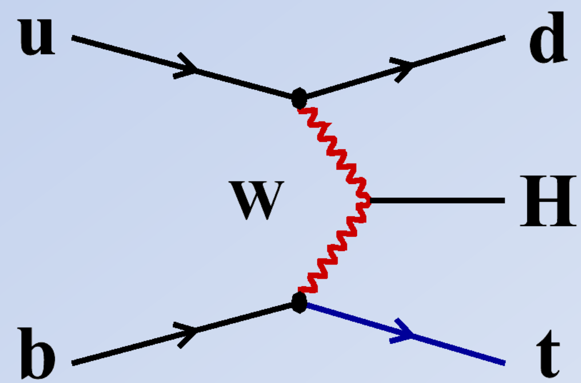
There are a variaty of new physics processes producing only one top quark anomalous Wtb couplings

- charged heavy Bosons W', H+ etc.
- 4th generation fermions b'
- FCNC, Monotops









But I won't tell you anything about them today.
The short summary:

Single top quark production in new physics

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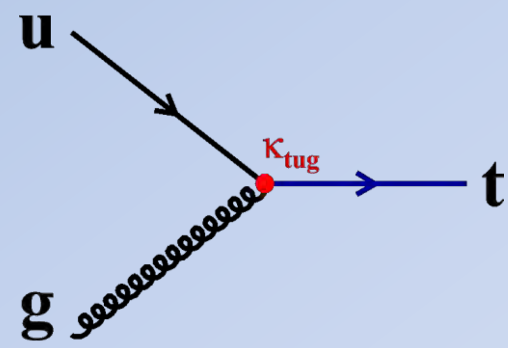
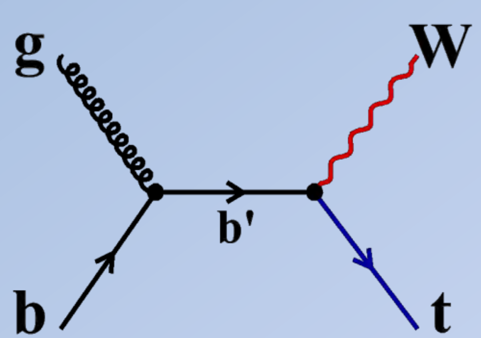
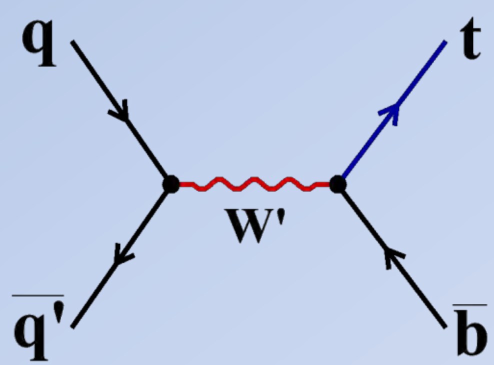
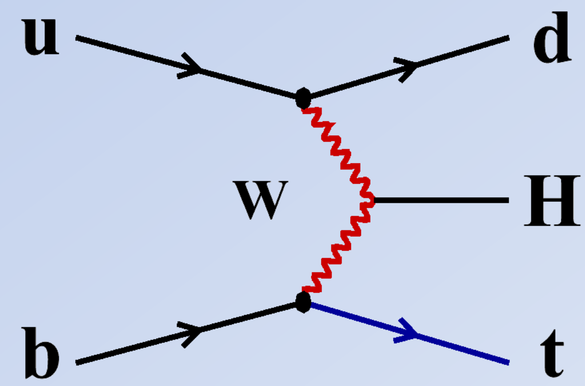


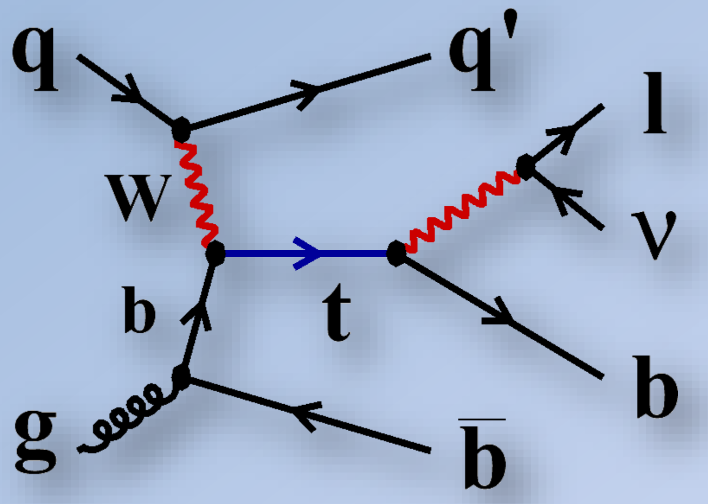






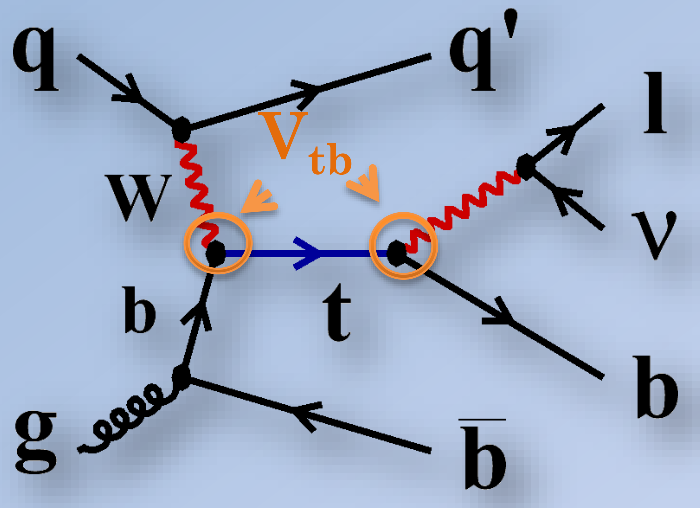
But I won't tell you anything about them today.
The short summary: Nothing found yet

t-channel single top quark production



Why study t-channel single top?

Cross section $\propto |V_{tb}|^2$
$\rightarrow$ test of the unitarity of the CKM Matrix



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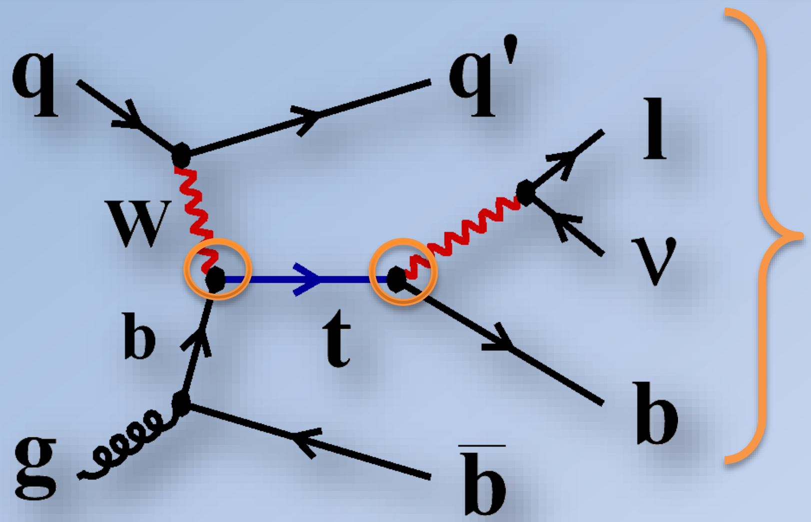

Test of the V-A structure of the Wtb vertex, e.g. using the top polarisation or W helicity

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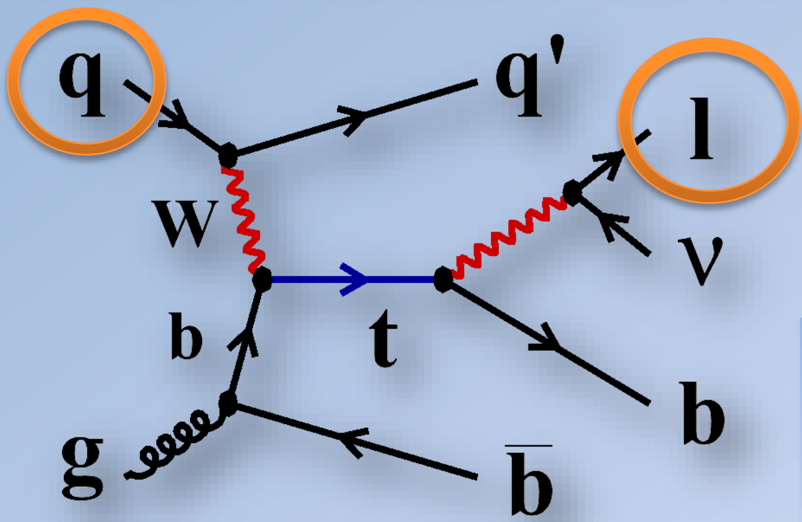

Test of the V-A structure of the Wtb vertex, e.g. using the top polarisation or W helicity

The cross-section ratio top-quark/top-antiquark production is sensitive to the u/d-quark ratio in the PDF sets.

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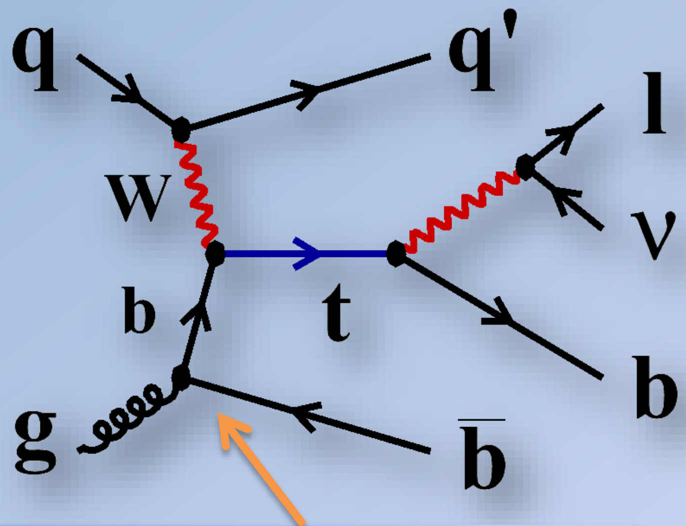

Test of the b-quark PDF

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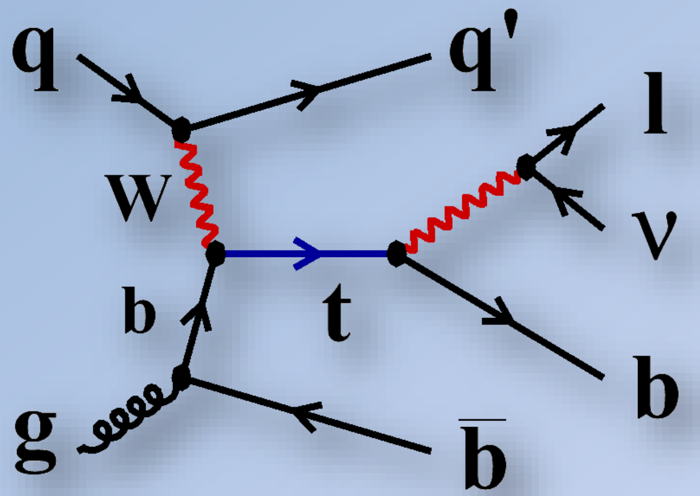


Test of the V-A structure of the Wtb vertex, e.g. using the top polarisation or W helicity

The cross-section ratio top-quark/top-antiquark production is sensitive to the u/d-quark ratio in the PDF sets.

Test of the b-quark PDF

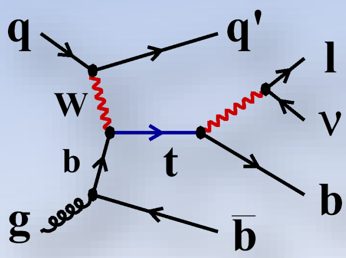
Single top quark events as complementary environment:
different color structure, less reocnstruction ambiguities, different energy scale

- „Repetition of top quark properties measurements“
  top quark mass, W helicity in the top quark decay, ...

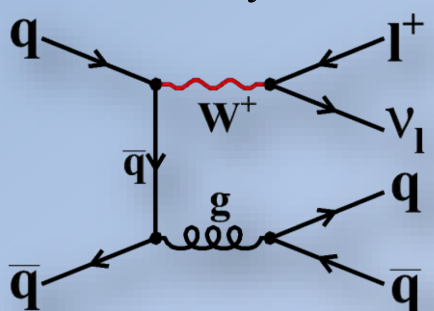
Background processes

Event signature

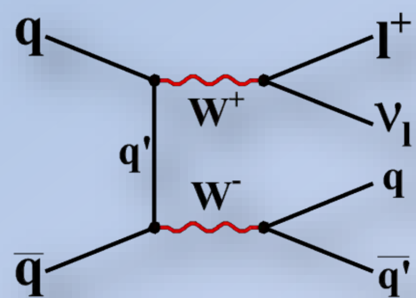
- One real **W boson**
- One central **b-quark jet** (from the top quark)
- One or two additional **jets**

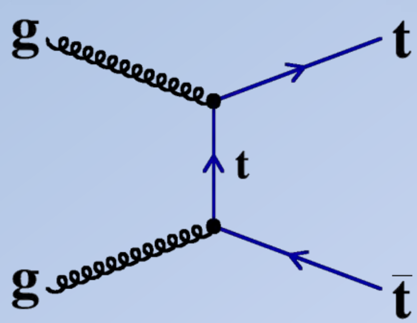


W/Z + jets

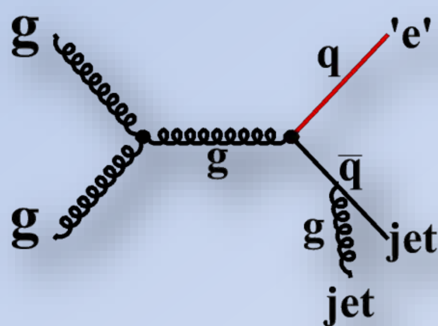


WW/WZ/ZZ

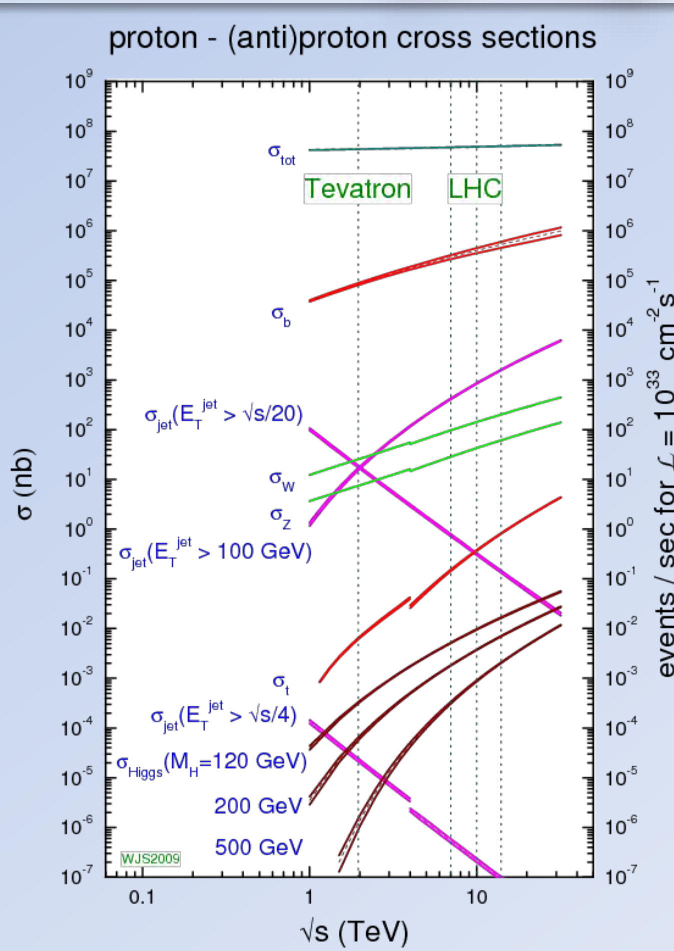




top-quark pair-production



QCD-multijet production ("fake" leptons)



Background estimation

Using MC acceptance and modeling

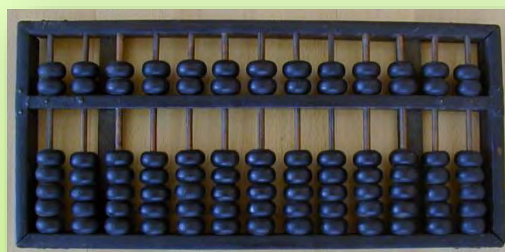
$N = \sigma \cdot \varepsilon \cdot \mathcal{L}$

Using MC modeling but normalization from data

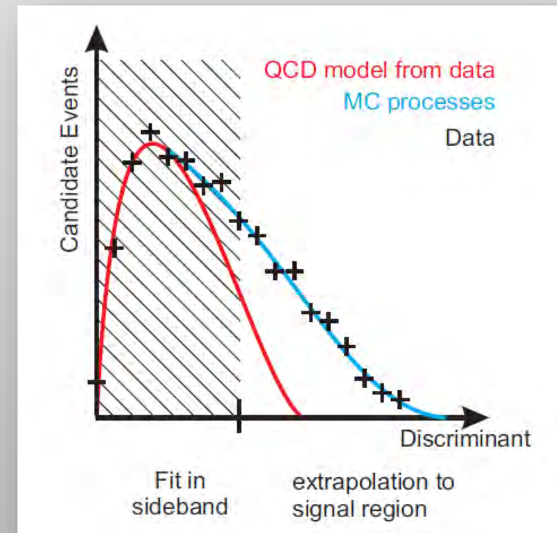
$$N_{W+jets}^{pretag} = N_{data}^{pretag} - N_{qcd}^{pretag} - N_{MC}^{pretag}$$

$$N_{\Phi,n}^{tag} = N^{pretag} F_{\Phi,n}^{pretag} P_{\Phi,n}^{tag} .$$

$$N_{data-bkg,2}^{tag} = N_{data-bkg,2}^{pretag} \cdot (F_{bb,2}^{pretag} \cdot P_{bb,2}^{tag} + k_{cctobb}^{pretag} \cdot F_{bb,2}^{pretag} \cdot P_{cc,2}^{tag} + F_{c,2}^{pretag} \cdot P_{c,2}^{tag} + F_{l,2}^{pretag} \cdot P_{l,2}^{tag}) = N_{data-bkg,2}^{pretag} \cdot (k_{bb1to2}^{pretag} \cdot F_{bb,1}^{pretag} \cdot P_{bb,2}^{tag} + k_{cctobb}^{pretag} \cdot k_{bb1to2}^{pretag} \cdot F_{bb,1}^{pretag} \cdot P_{cc,2}^{tag} + k_{c1to2}^{pretag} \cdot F_{c,1}^{pretag} \cdot P_{c,2}^{tag} + k_{l1to2}^{pretag} \cdot F_{l,1}^{pretag} \cdot P_{l,2}^{tag}).$$

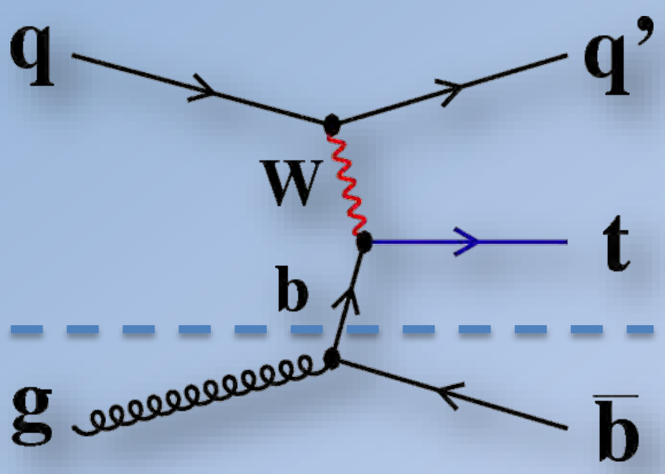


Using modeling and normalization from data (Mostly „fake“ backgrounds)



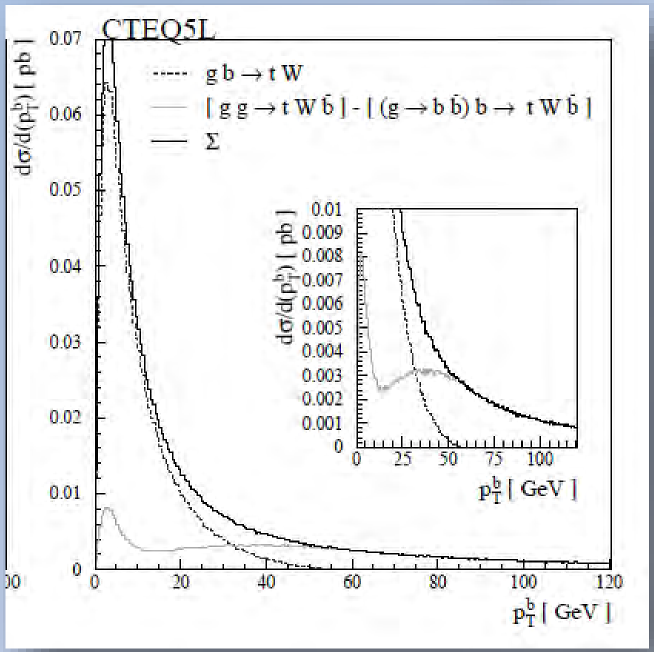
Similar approaches of both experiments – details are different

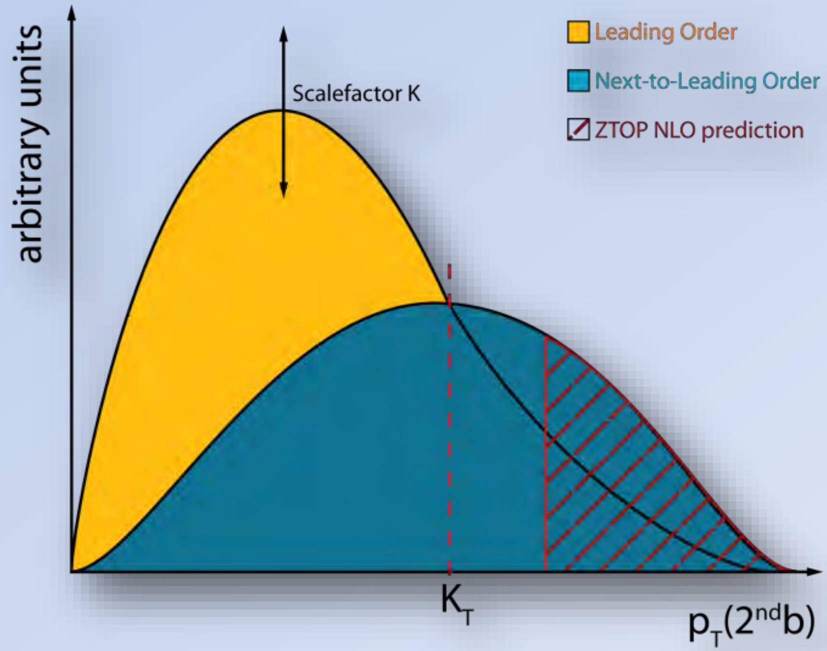
Signal modeling – traditional approach



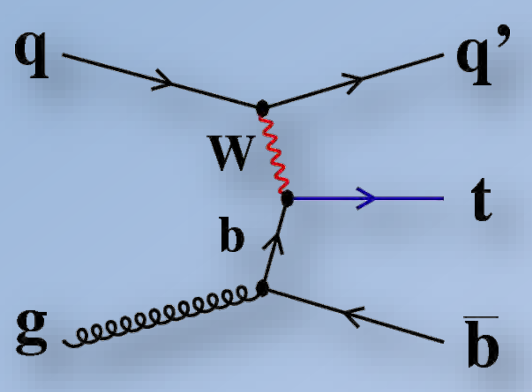
Two approaches for matching 2→2 & 2→3:

- Matching of second b-quark p_T
  (Comphep, Madgraph) → CMS
- Subtraction of double counting in the PDF (ACOT)
  (AcerMC) → ATLAS



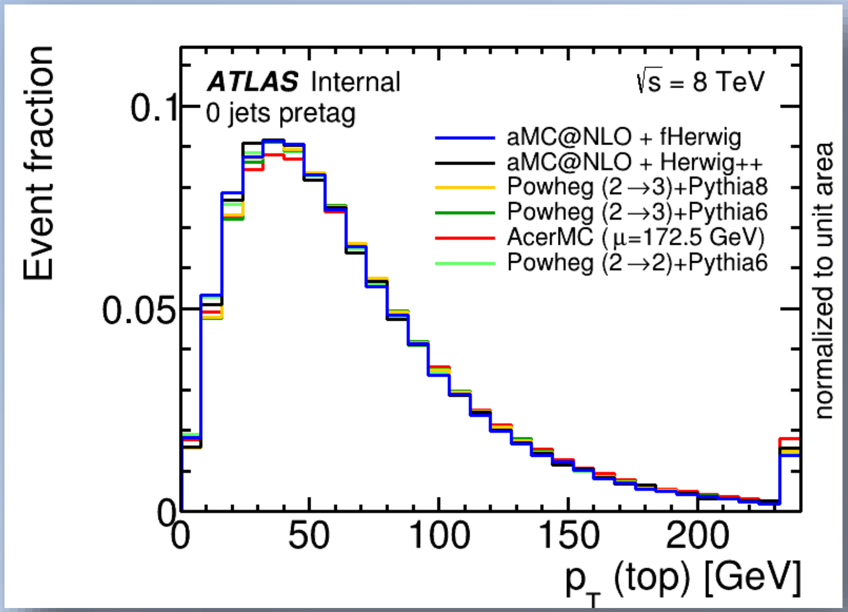


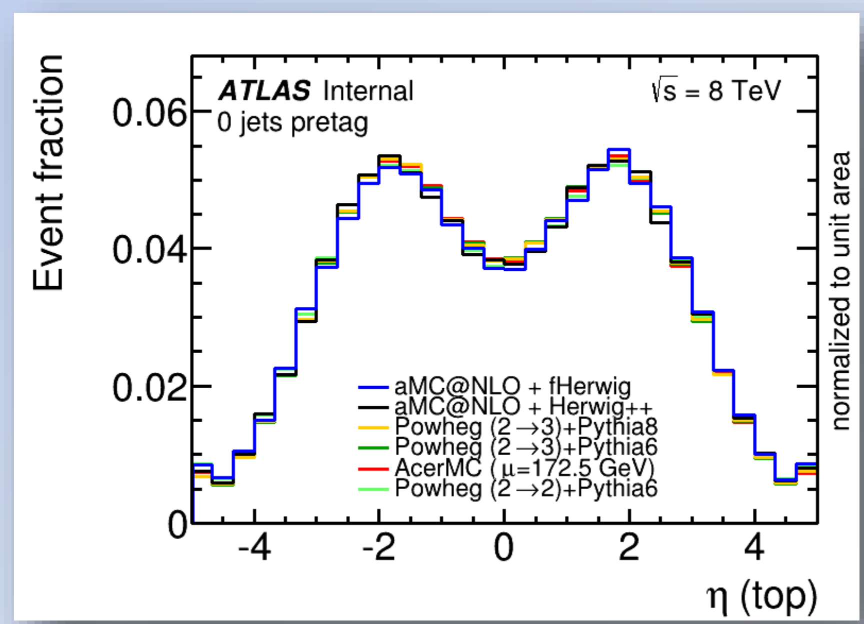
Signal modeling – new NLO generators



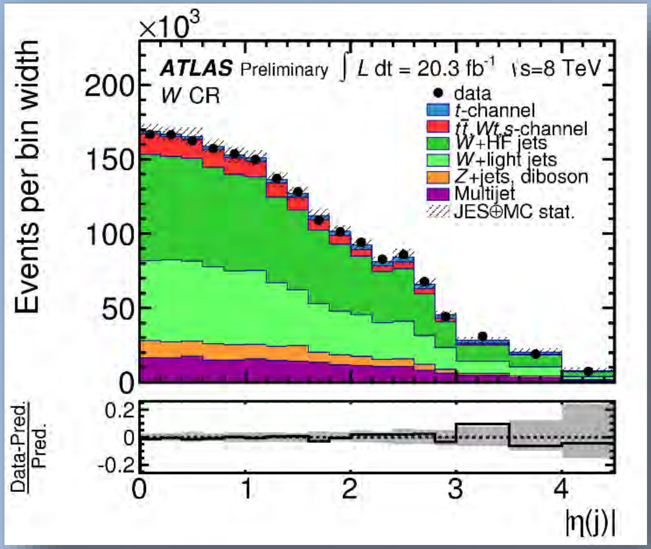
Two generators available for 2→3 @ NLO:

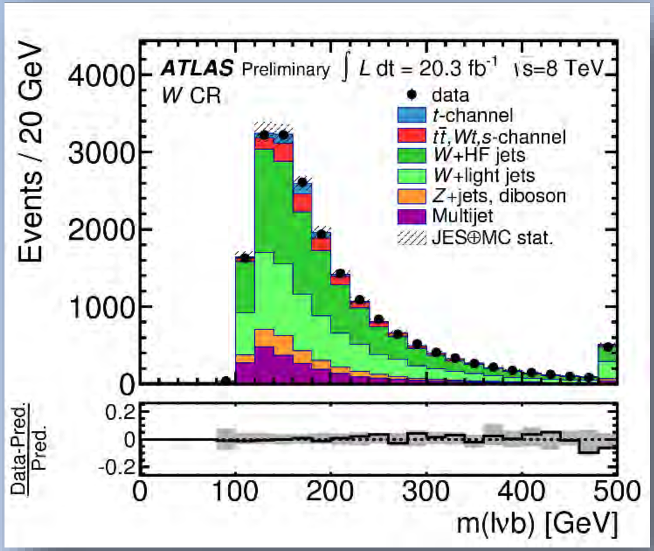
- aMC@NLO
  → can be interfaced to Herwig/Herwig++ and just recently Pythia8
- Powheg
  → can be interfaced to Pythia6/Pythia8, Herwig/Herwig++





W + jets background





Used MC generators:

Alpgen/Madgraph + Herwig/Pythia or Sherpa

- Models multiple gluon radiation with LO matrix elements (ME) + parton shower (PS)
  → LO+LL accuracy
- Overlap between ME and PS needs to be removed
  → MLM or CKKW matching
- „hard" jets are modeled by the ME,
  „soft" jets by the PS
- Each process is then built from several different „parton" processes, e.g.:
  W+$b\bar{b}$, W+$b\bar{b}$+0p, W+$b\bar{b}$+1p mit W→ eν, ...
- Remaining overlap between processes with b- und c-quarks needs to be removed by hand (for Alpgen/Madgraph)

Check modelling in a W+jets dominated region

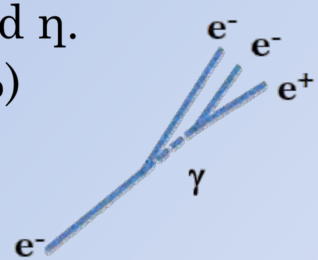
Models for QCD-multijet background

Jet lepton model:

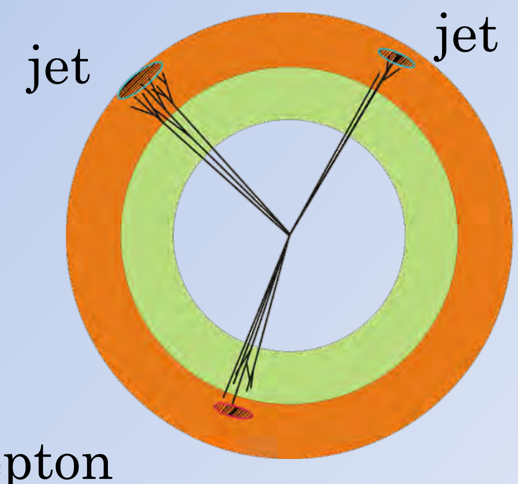
Use jet triggered data or di-jet MC

Identification of a jet as a "fake" lepton:

- Use same acceptance as real electrons / muons in p_T und η.
- High em fraction (80% - 95%)
- At least 3 tracks



- Events with real (signal) leptons are rejected

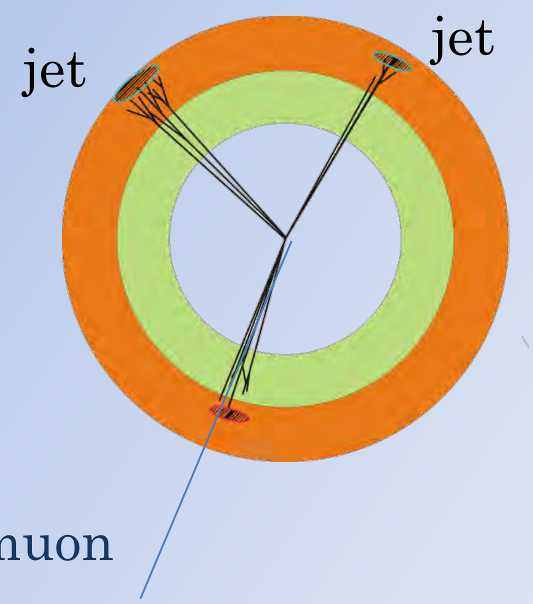


Anti-muon / Anti-electron:

Use lepton triggered data

Revert some ID cuts, e.g.:

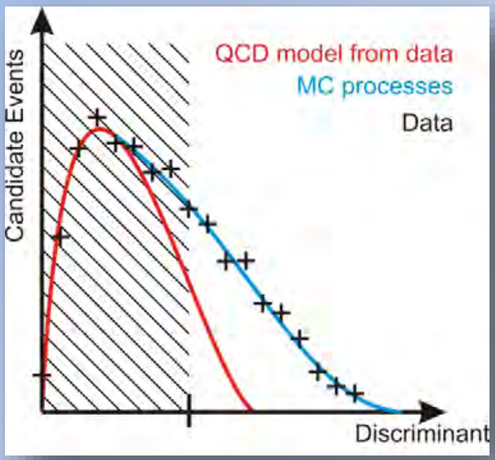
- Impact parameter
- Isolation
- Energy loss type

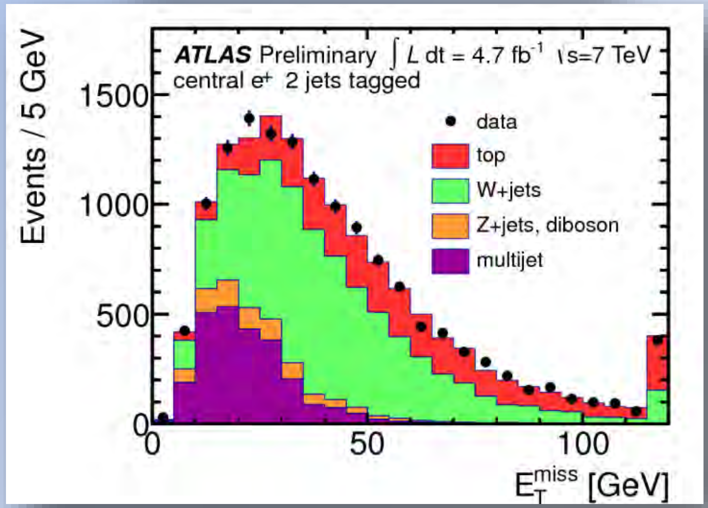


Determination of the QCD-multijet background

ATLAS:

Binned Likelihood fit to the E_T^{miss} distribution





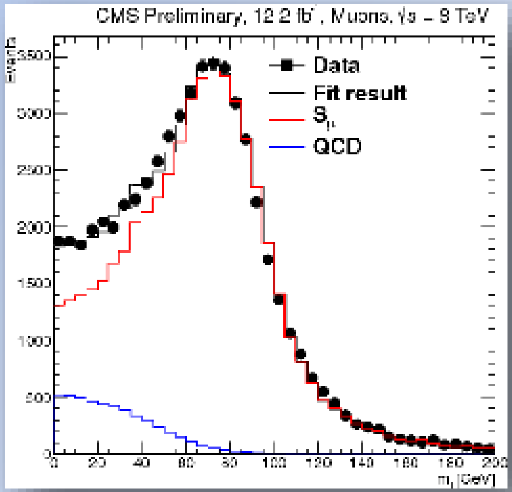
CMS:

Likelihood fit to the E_T^{miss} (electrons) or $m_T(W)$ (muons) distribution

Parameterisation:

$$F(x) = a \cdot S(x) + b \cdot B(x)$$

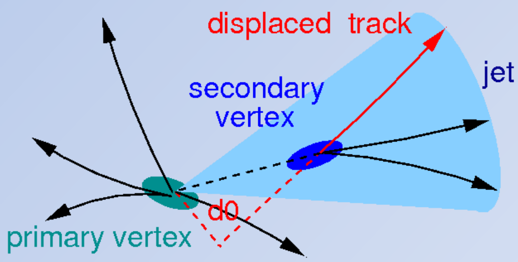
W-Boson processes (from MC) — QCD model



t – channel event selection

- Lepton selection (electron / muon):
  - Isolated
  - Also some acceptance from leptonic tau decays

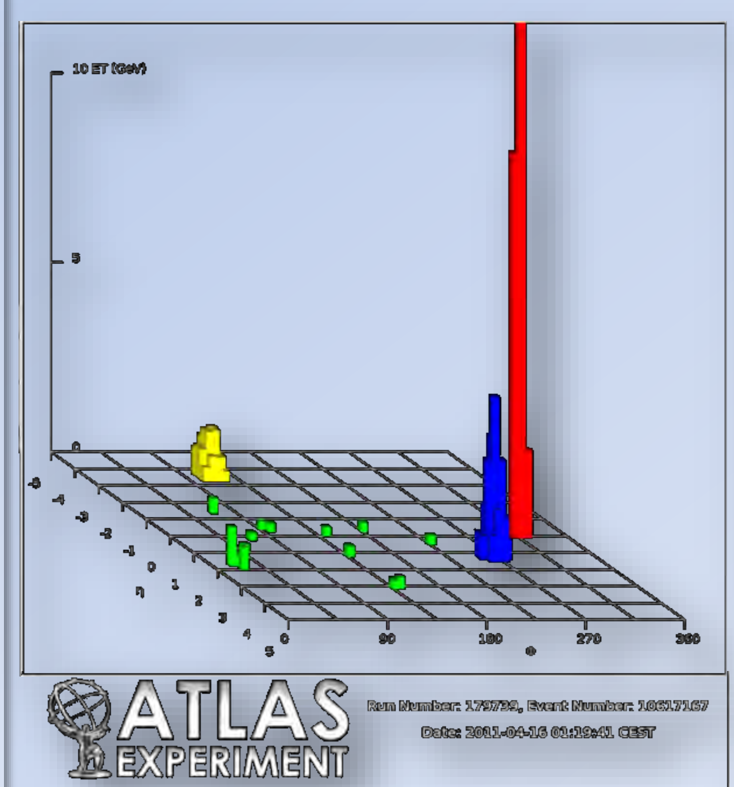
- Jets
  - Anti-k_T algorithm
  - Including forward calorimeters (|η|<4.5)
  - Identification of b-quark jets (including sufficient c-quark suppression)



  - Number of jets: 2 - 4

- Missing transverse energy

- QCD multijet veto



Typical event yields

Numbers are for 20 fb^{-1} @ 8 TeV

Process	W CR	$t\bar{t}$ CR	SR
t-channel	9580 ± 960	647 ± 65	18100 ± 1800
$t\bar{t}$, Wt, s-channel	25500 ± 2000	9560 ± 770	54200 ± 4300
W+jets	285000 ± 156000	2000 ± 1100	51000 ± 28000
Z+jets, diboson	25000 ± 6000	328 ± 79	6900 ± 1700
Multijet	44000 ± 22000	650 ± 320	11800 ± 5900
Total expectation	390000 ± 158000	13000 ± 1400	142000 ± 29000
Data	389919	13041	143332

Purity:

2 jet channel: S/B = 13%

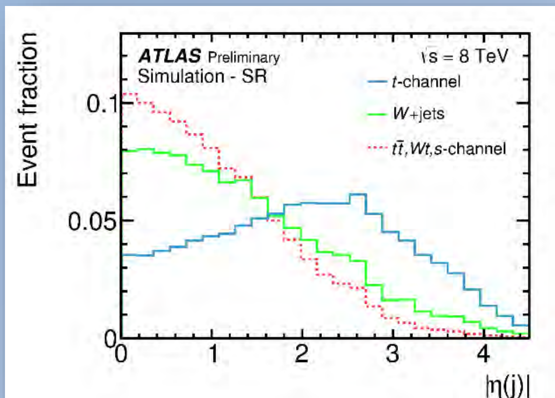
3 jet channel: S/B = 9%

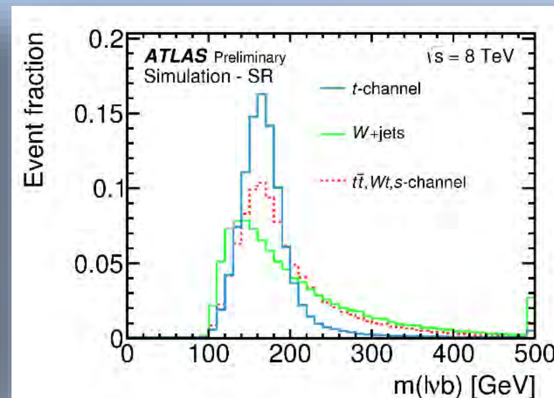
→ Usage of neural networks to further enhance the signal, but cut-based is also possible

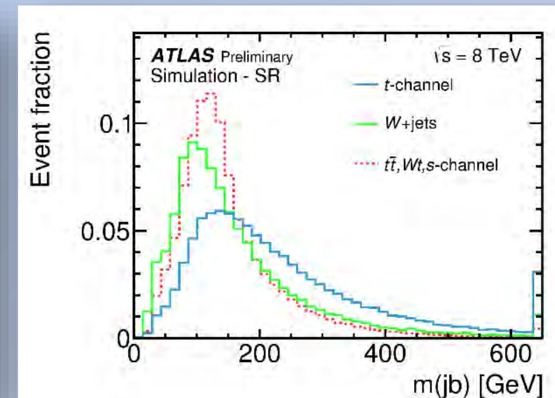
Process	Fraction
t-channel	13%
s-channel, Wt, tt	38%
W+jets	36%
Z+jets,Diboson	5%
Multijet	8%

Multivariate Analyses

Idea: Combine many variables including correlations in one discriminate







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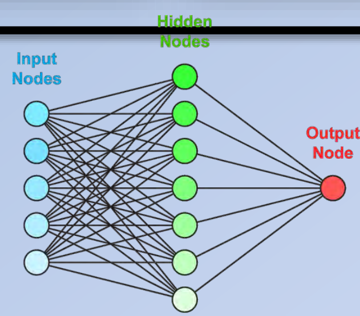
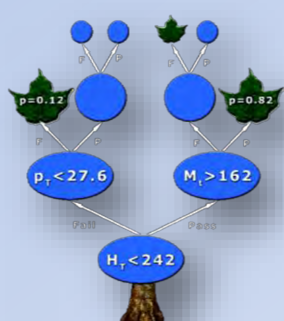
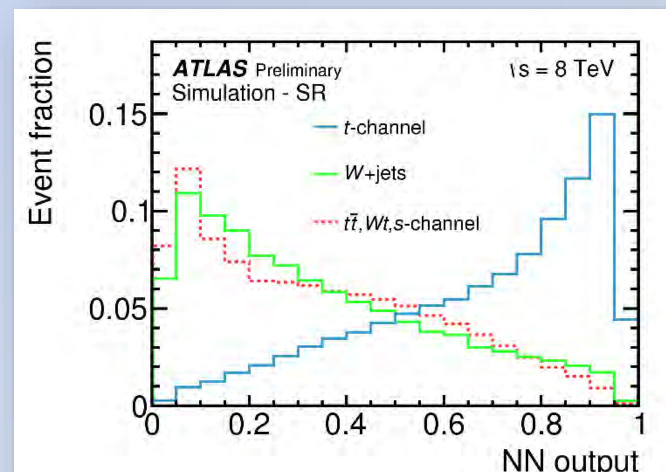
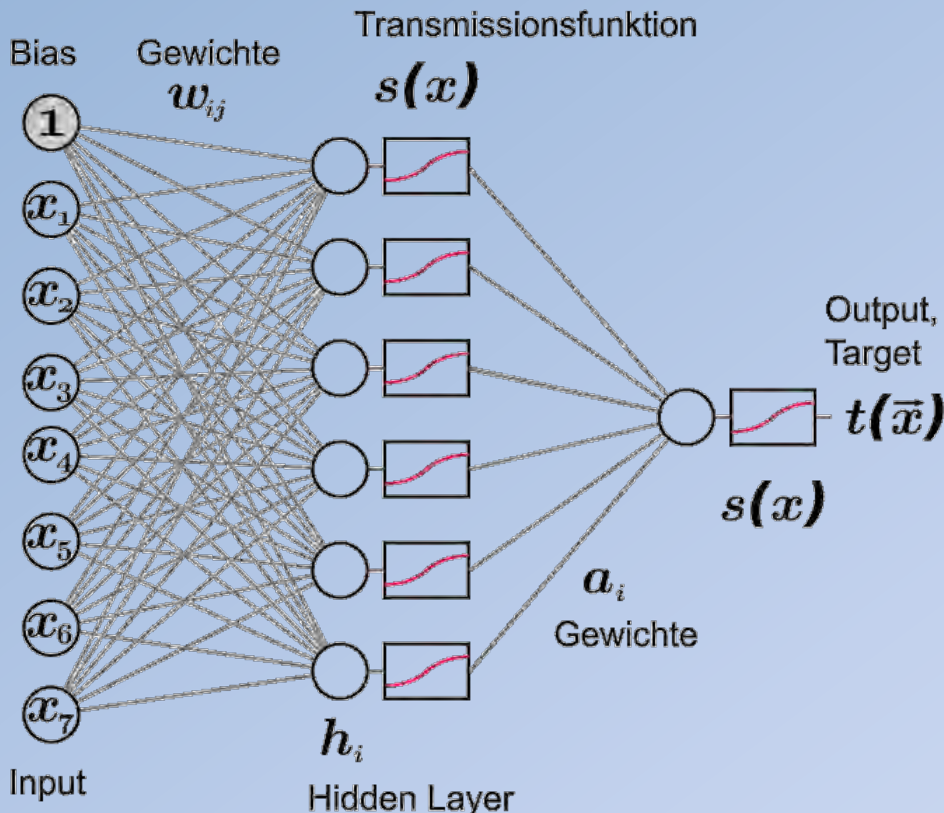


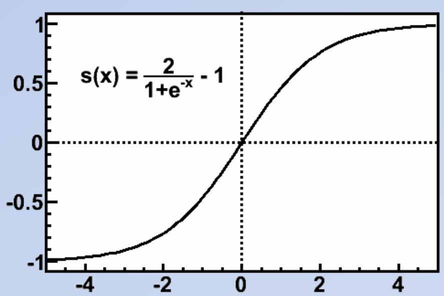




Analysis technique – neural networks



$$(-\infty, +\infty) \overset{s(x)}{\longmapsto} [-1, +1]$$



Implementation in NeuroBayes

Construction of a continuous discriminate from several variables using a neural network

Training with simulated events:

- Training target:
  signal = 1, background = 0.
- Modification of the weights between different nodes for a optimal separation.

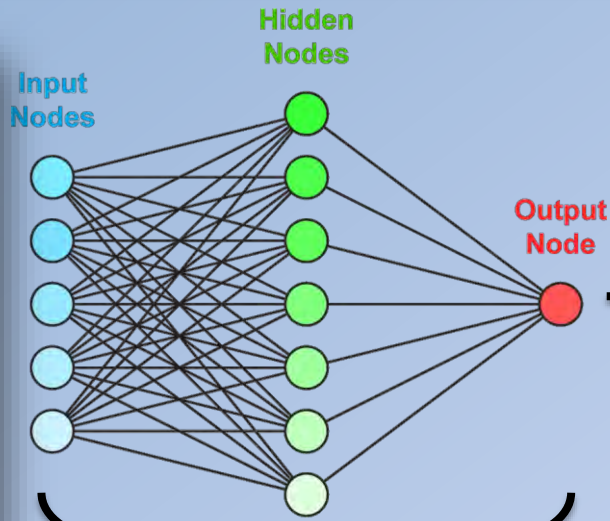
- Minimizing the „quadratic loss-function “:

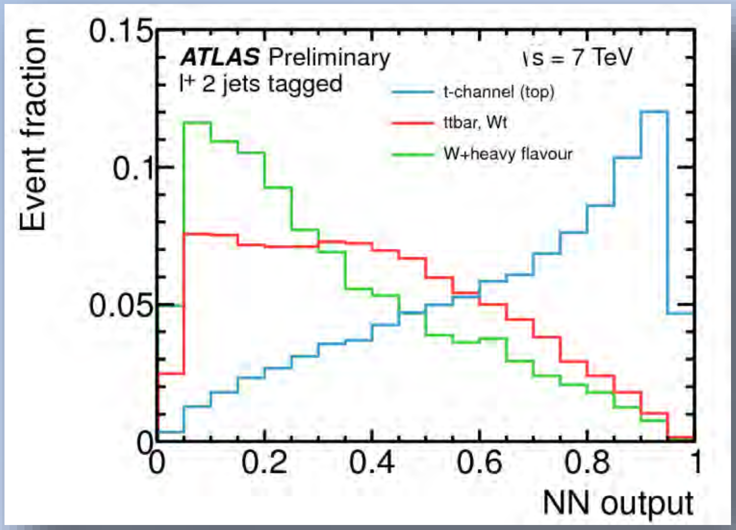
$$E = \frac{1}{2} \sum_i (t(\vec{x}_i) - T_i)^2$$

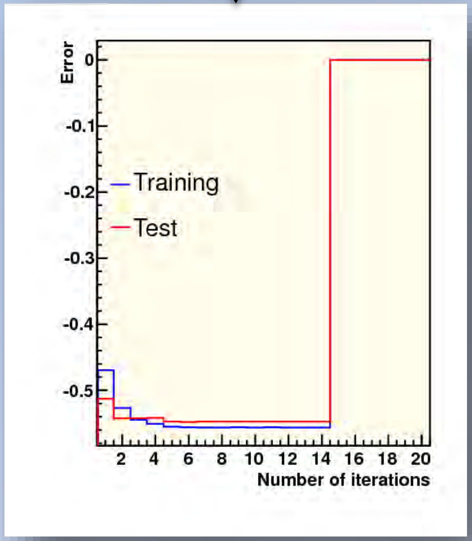
Known target

Training / validation of neural networks

Variable
$m(jb)$
$m(\ell b)$
$\lvert\eta(j)\rvert$
$m(\ell \nu b)$
$\cos\theta(\nu, W)$
H_T
polarization
$\lvert\Delta\eta(b,\ell)\rvert$
$m(b)$
sphericity
$E_T(j)$
$\lvert\Delta\eta(j,\ell)\rvert$
$m(jt)$
$\lvert\Delta\eta(\nu, b)\rvert$
$\lvert\Delta\eta(j, b)\rvert$







Choice of the variables:

- Good data/MC agreement
- Good separation power

Typical training parameters

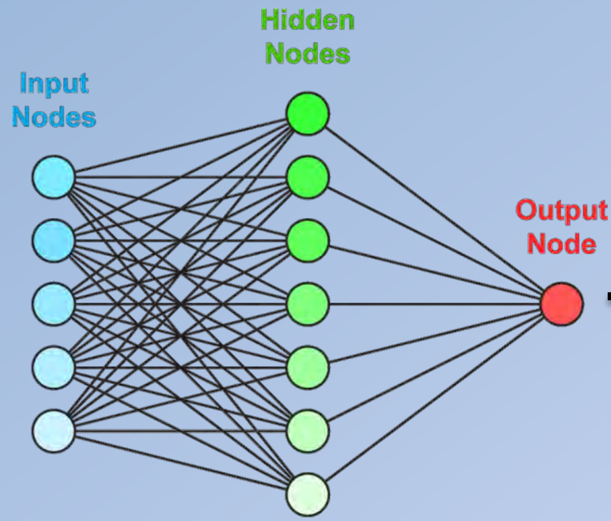
- 50% signal / 50% background
- 10-15 nodes in the hidden layer
- 50k – 150k trainig events

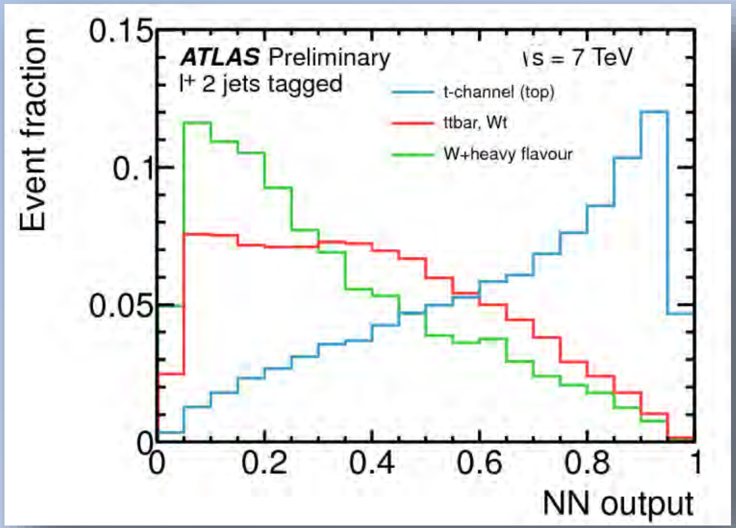
Validation of the networks

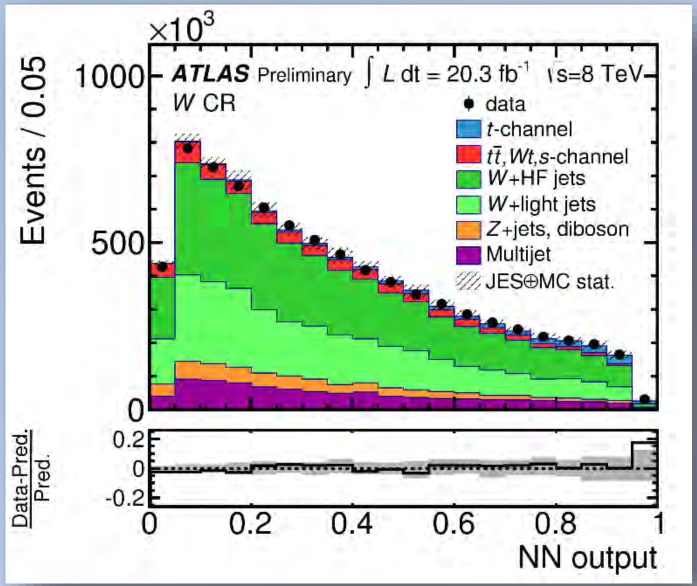
- Overtraining test

Training / Validierung von Neuronalen Netzen

Variable
$m(jb)$
$m(\ell b)$
$\lvert\eta(j)\rvert$
$m(\ell\nu b)$
$\cos\theta(\nu, W)$
H_T
polarization
$\lvert\Delta\eta(b,\ell)\rvert$
$m(b)$
sphericity
$E_T(j)$
$\lvert\Delta\eta(j,\ell)\rvert$
$m(jt)$
$\lvert\Delta\eta(\nu, b)\rvert$
$\lvert\Delta\eta(j, b)\rvert$







Choice of the variables:

- Good data/MC agreement
- Good separation power

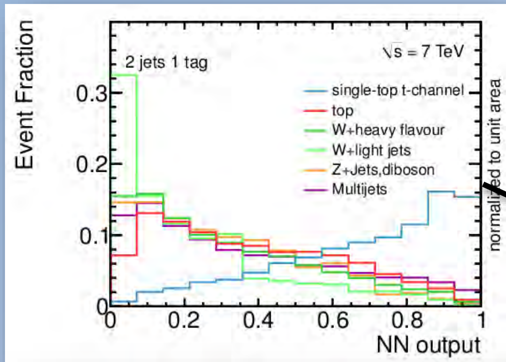
Typical training parameters

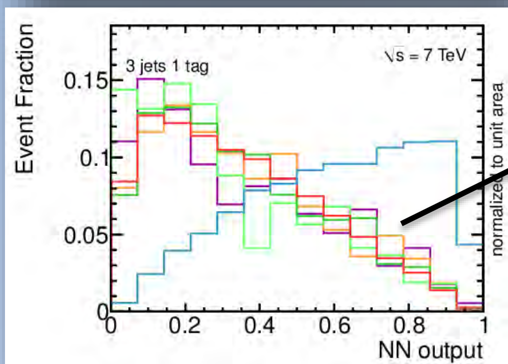
- 50% signal / 50% background
- 10-15 nodes in the hidden layer
- 50k – 150k trainig events

Validation of the networks

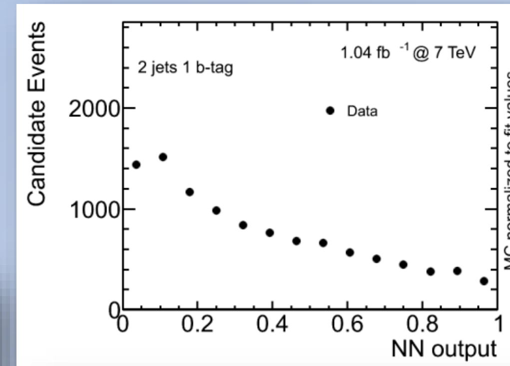
- Overtraining test
- Application in control regions

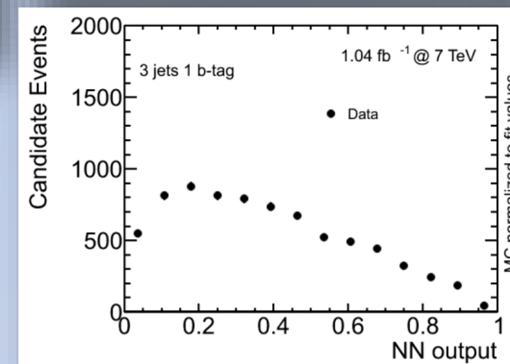
Measurement of the cross section





$$L(\beta^s; \beta_1^b, \ldots, \beta_B^b)$$



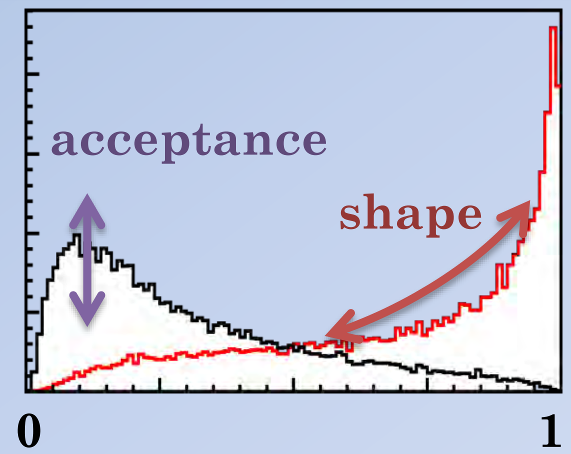


- Simultanious fit of all analysis channels to extract the signal events
- Free parameter in the likelihood function $\beta = \nu_{obs}/\nu_{exp}$.

$$L(\beta^s; \beta_1^b, \ldots, \beta_B^b) = \prod_{k=1}^{M} P(n_k; \mu_k) \cdot \prod_{j=1}^{B} G(\beta_j^b; 1.0, \Delta_j).$$

$$P(n_k; \mu_k) = \frac{e^{-\mu_k} \cdot \mu_k^{n_k}}{n_k!} \qquad G(\beta_j^b; 1.0, \Delta_j) = \frac{1}{\sqrt{2\pi\Delta_j^2}} \cdot \exp\frac{-\left(\beta_j^b - 1\right)^2}{2\Delta_j^2}$$

Treatment of systematic uncertainties

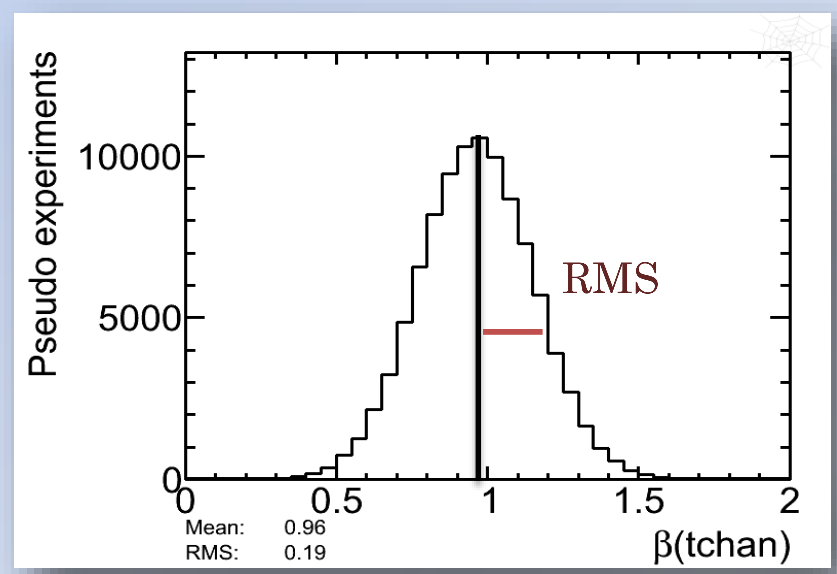


Effect of systematic uncertainties

- Acceptance
- Shape of the network distribution

Ensemble tests

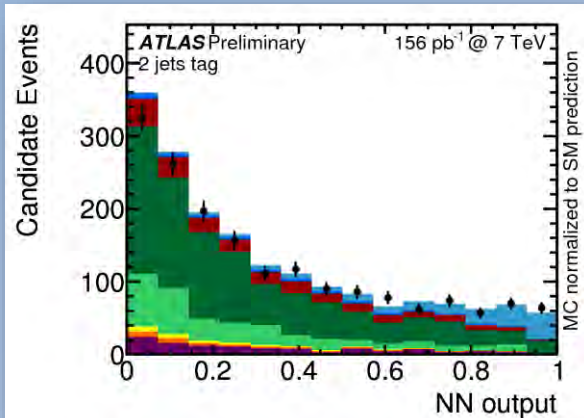
- Construction of pseudo data from template distributions
- Variation of systematic effect in acceptance and shape
- RMS of the ß-distribution is a measure of the size of the systematic effect.



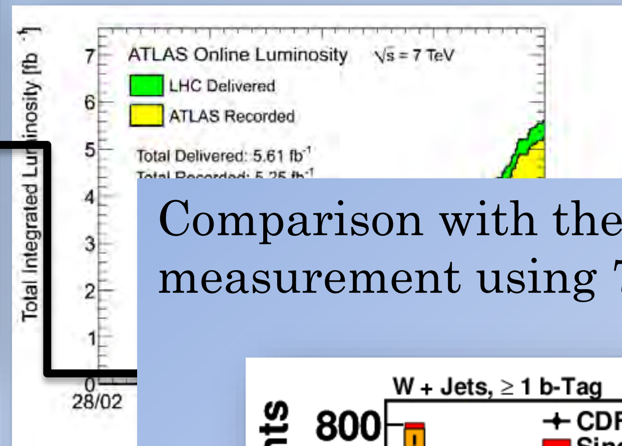
Sources of systematic uncertainties

- Reconstruction / calibration
- Event simulation
- Background estimation

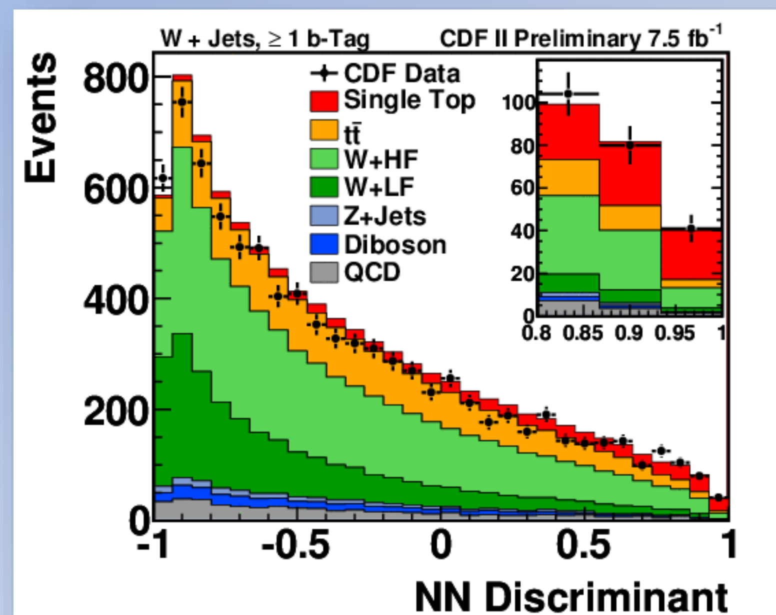
Some history



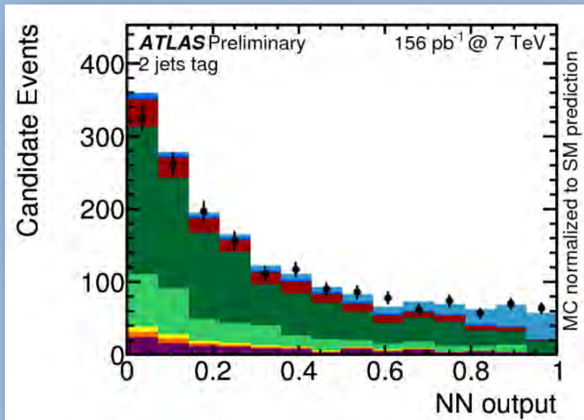
ATLAS-CONF-2011-088



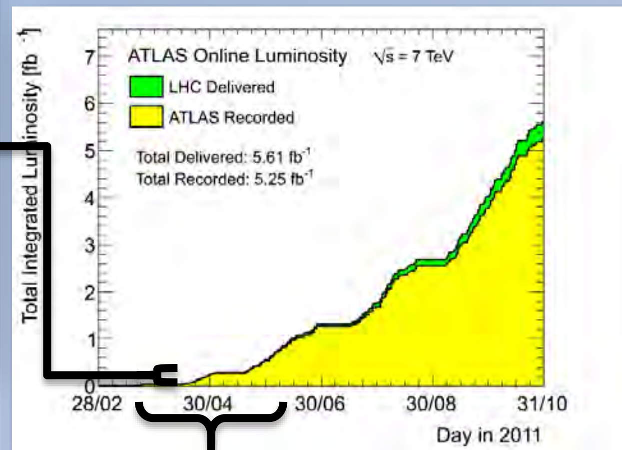
Comparison with the most recent CDF measurement using 7.5 pb^{-1}

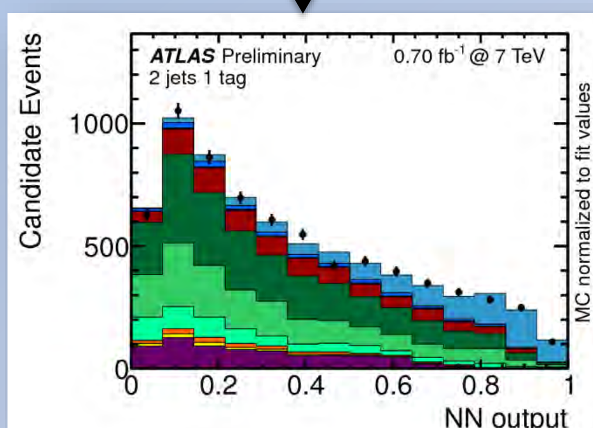


Some history



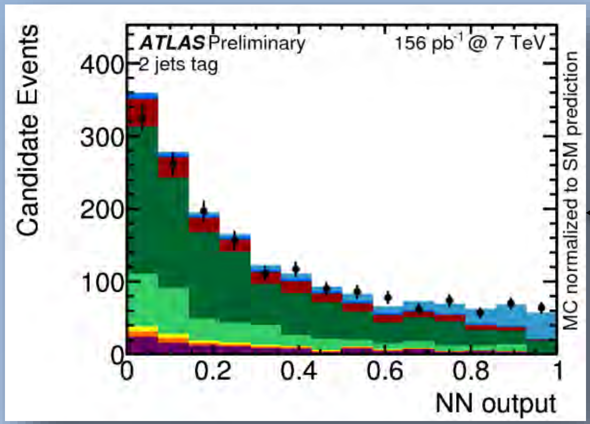
ATLAS-CONF-2011-088



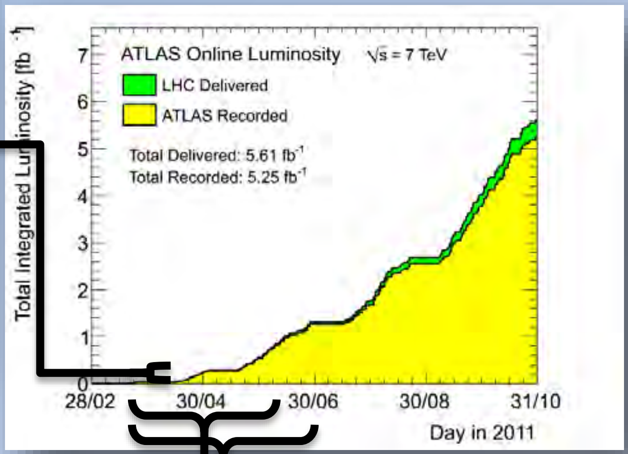


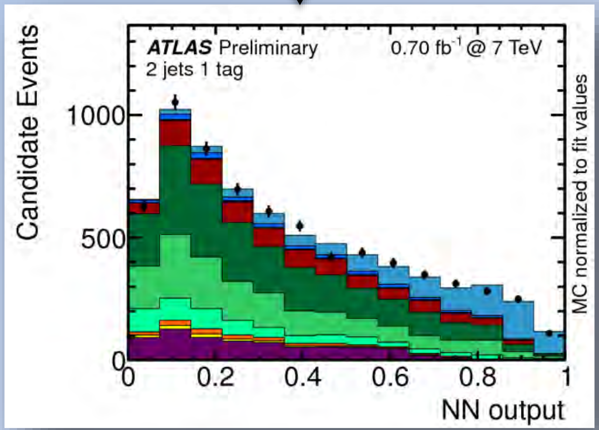
ATLAS-CONF-2011-101

Some history @ 7 TeV

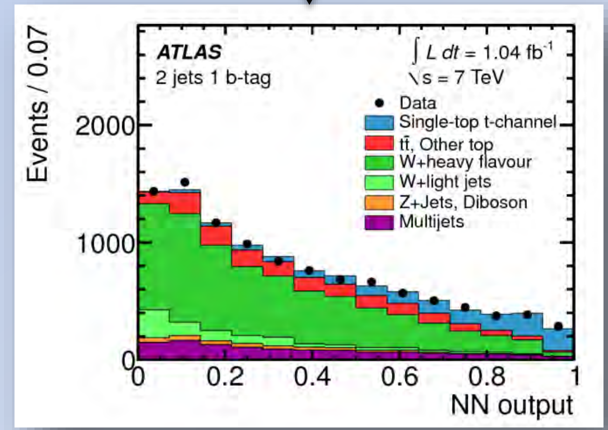


ATLAS-CONF-2011-088



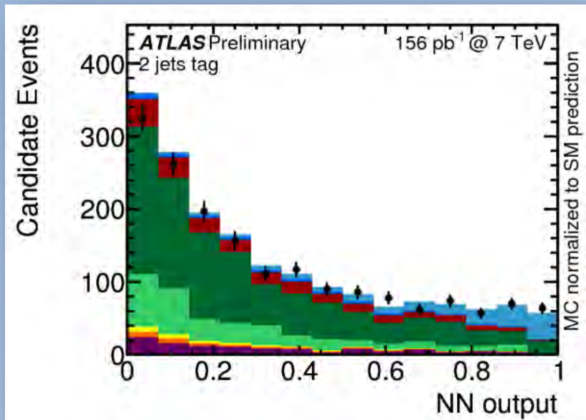


ATLAS-CONF-2011-101

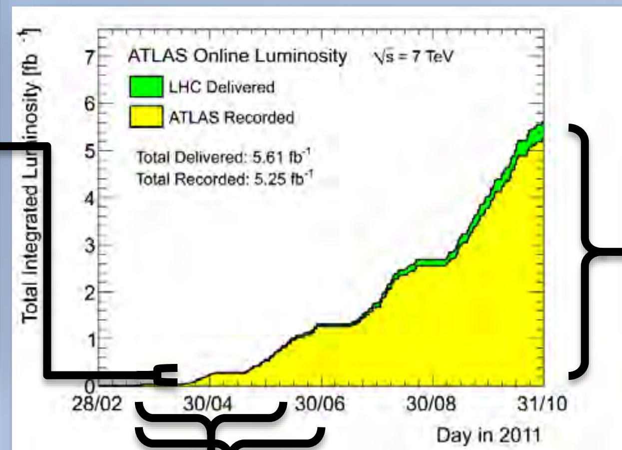


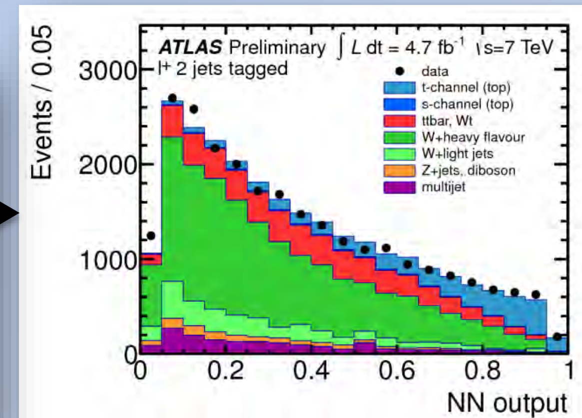
Phys. Lett. B 717, 330-350

Some history

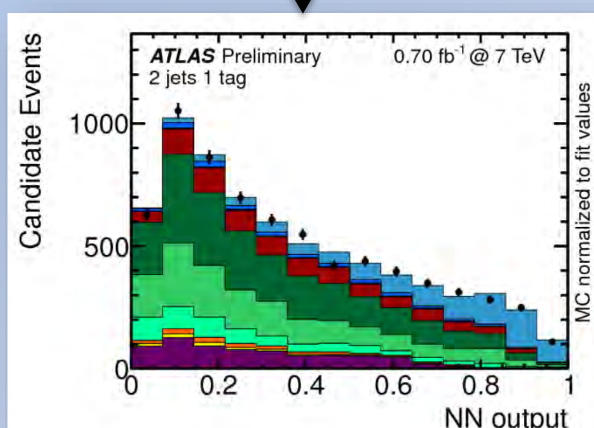


ATLAS-CONF-2011-088

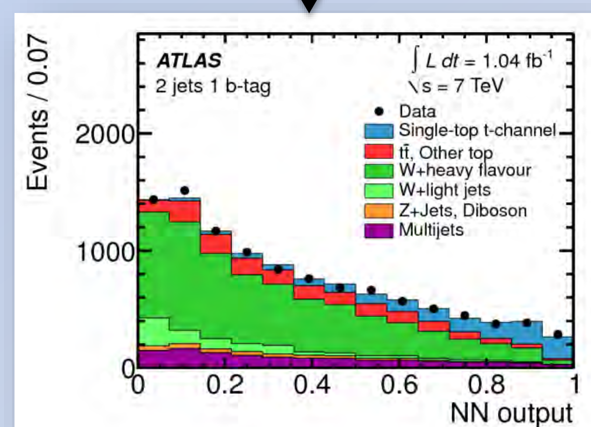




ATLAS-CONF-2012-056
(to be updated soon)



ATLAS-CONF-2011-101



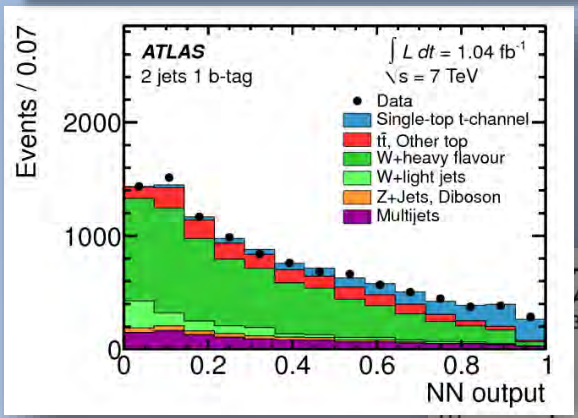
Phys. Lett. B 717, 330-350

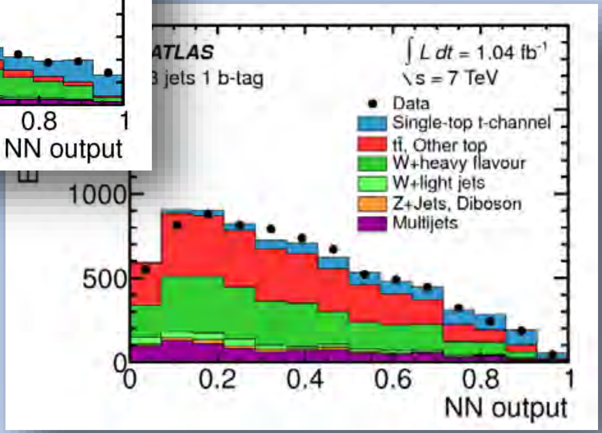
Inclusive cross section @ 7 TeV from ATLAS

Used 1.04 fb-1 of the 2011 data set

Two neural networks

- 2 jet channel – 12 variables
- 3 jet channel – 18 variables





Source	$\Delta\sigma_{exp}/\sigma_{exp}$ [%]	$\Delta\sigma_{obs}/\sigma_{obs}$ [%]
Data Statistics	±6.1	±5.1
MC Statistics	±3.8	±3.4
Object Modelling		
Jet Energy Scale	±4.7	±5.3
Jet Energy Resolution	±1.7	±1.5
Jet Reconstruction	±0.5	±0.2
b-Tagging Scale Factor	±13	±13
Mistag Scale Factor	±0.6	±0.4
Lepton Efficiencies	±1.9	±2.0
Lepton Energy Resolution	±0.4	±0.3
Electron Energy Scale	+0.5/−0.6	0.2/−0.4
E_T^{Miss}	±1.0	±0.8
Pileup E_T^{Miss}	±1.0	±0.9
Liquid Argon	±0.9	±0.9
Event Modelling		
PDF	±3.3	±3.3
W Shape	+0.5/−0.3	+0.5/−0.3
Top Generator	±3.3	±2.3
t-Channel Generator	±3.5	±3.5
ISR/FSR	±14	±14
Parton Shower	±4.5	±5.0
η-Reweighting	+6.9/−4.2	+6.4/−3.9
Normalisation		
Background Normalisation	±1.1	±0.9
QCD	±5.7	±4.4
Luminosity	±3.9	±3.8
Total Systematic	+25/−24	+24/−23
Total Systematic + Statistic	+26/−24	+24/−24

Measured cross section:

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

SM: $\sigma_t = 64.6$ pb

Significance 7.2 σ

Inclusive cross section @ 7 TeV from CMS

Used 1.17 / 1.56 fb^{-1} of the 2011 data set

Three different methods

- Neural network
  - Two networks
  - 37 / 38 variables for electron/muon channel
- BDT
  - 4 BDTs
  - 10 variables
- Cut based
  - fit to light jet |η|

- Combination of all three using BLUE

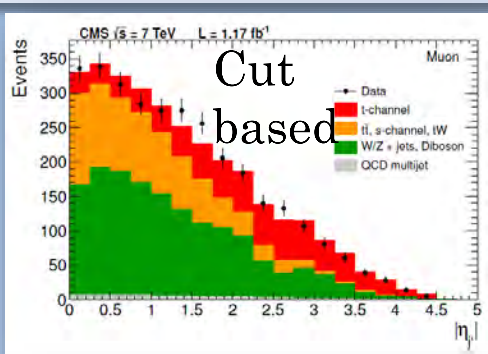
Event yield of cut based analysis

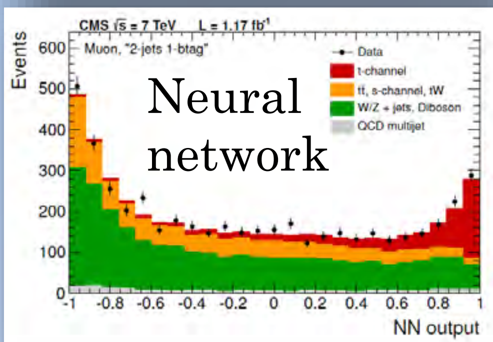
Process	Muon yield	Electron yield
t-channel	617 ± 3	337 ± 2
tW channel	107 ± 1	70.2 ± 0.9
s-channel	25.6 ± 0.5	14.7 ± 0.4
$t\bar{t}$	661 ± 6	484 ± 5
W + light partons	92 ± 7	38 ± 4
$Wc(\bar{c})$	432 ± 14	201 ± 9
$Wb(\bar{b})$	504 ± 14	236 ± 10
Z + jets	87 ± 3	13 ± 1
Dibosons	23.3 ± 0.4	10.7 ± 0.3
QCD multijet	77 ± 3	62 ± 3
Total	2626 ± 22	1468 ± 16
Data	3076	1588

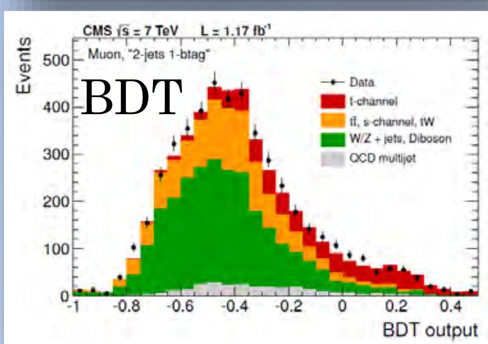
	2 jets	3 jets	4 jets
0 tag	W+jets CR	W+jets CR	$t\bar{t}$ CR
1 tag	Signal Region	Signal Region	$t\bar{t}$ CR
2 tags		$t\bar{t}$ CR	$t\bar{t}$ CR

} Used in the signal extraction

Inclusive cross section @ 7 TeV from CMS







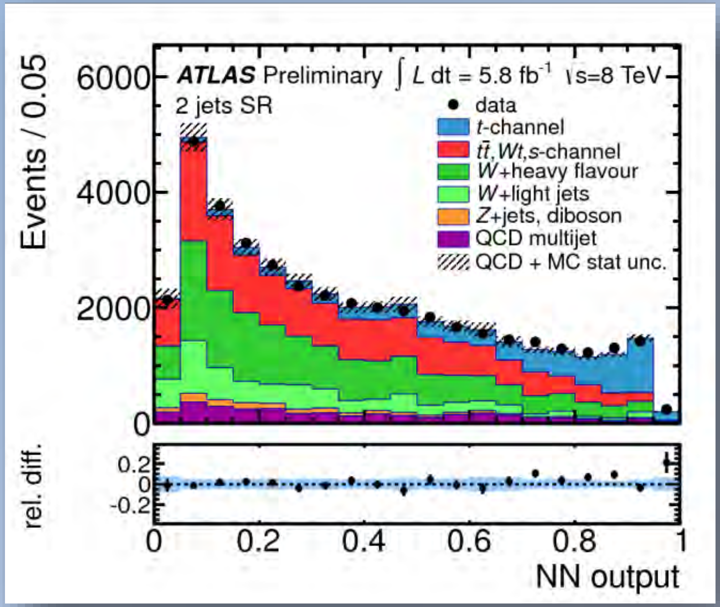
		Uncertainty source	NN	BDT	$\lvert\eta_{j'}\rvert$
Marginalised (NN, BDT)	Experimental uncert.	Statistical	$-6.1/+5.5\%$	$-4.7/+5.4\%$	$\pm8.5\%$
		Limited MC data	$-1.7/+2.3\%$	$\pm3.1\%$	$\pm0.9\%$
		Jet energy scale	$-0.3/+1.9\%$	$\pm0.6\%$	$-3.9/+4.1\%$
		Jet energy resolution	$-0.3/+0.6\%$	$\pm0.1\%$	$-0.7/+1.2\%$
		b tagging	$-2.7/+3.1\%$	$\pm1.6\%$	$\pm3.1\%$
		Muon trigger + reco.	$-2.2/+2.3\%$	$\pm1.9\%$	$-1.5/+1.7\%$
		Electron trigger + reco.	$-0.6/+0.7\%$	$\pm1.2\%$	$-0.8/+0.9\%$
		Hadronic trigger	$-1.3/+1.2\%$	$\pm1.5\%$	$\pm3.0\%$
		Pileup	$-1.0/+0.9\%$	$\pm0.4\%$	$-0.3/+0.2\%$
		$\not{E}_T$ modelling	$-0.0/+0.2\%$	$\pm0.2\%$	$\pm0.5\%$
	Backg. rates	W+jets	$-2.0/+3.0\%$	$-3.5/+2.5\%$	$\pm5.9\%$
		light flavour (u, d, s, g)	$-0.2/+0.3\%$	$\pm0.4\%$	n/a
		heavy flavour (b, c)	$-1.9/+2.9\%$	$-3.5/+2.5\%$	n/a
		$t\bar{t}$	$-0.9/+0.8\%$	$\pm1.0\%$	$\pm3.3\%$
		QCD, muon	$\pm0.8\%$	$\pm1.7\%$	$\pm0.9\%$
		QCD, electron	$\pm0.4\%$	$\pm0.8\%$	$-0.4/+0.3\%$
		s-, tW ch., dibosons, Z+jets	$\pm0.3\%$	$\pm0.6\%$	$\pm0.5\%$
	Total marginalised uncertainty		$-7.7/+7.9\%$	$-7.7/+7.8\%$	n/a
Not marginalised		Luminosity		$\pm2.2\%$	
	Theor. uncert.	Scale, $t\bar{t}$	$-3.3/+1.0\%$	$\pm0.9\%$	$-4.0/+2.1\%$
		Scale, W+jets	$-2.8/+0.3\%$	$-0.0/+3.4\%$	n/a
		Scale, t-, s-, tW channels	$-0.4/+1.0\%$	$\pm0.2\%$	$-2.2/+2.3\%$
		Matching, $t\bar{t}$	$\pm1.3\%$	$\pm0.4\%$	$\pm0.4\%$
		t-channel generator	$\pm4.2\%$	$\pm4.6\%$	$\pm2.5\%$
		PDF	$\pm1.3\%$	$\pm1.3\%$	$\pm2.5\%$
		Total theor. uncertainty	$-6.3/+4.8\%$	$-4.9/+5.9\%$	$-5.6/+4.9\%$
Syst. + theor. + luminosity uncert.			$-8.1/+7.8\%$	$-8.1/+8.4\%$	$\pm10.8\%$
Total (stat. + syst. + theor. + lum.)			$-10.1/+9.5\%$	$-9.4/+10.0\%$	$\pm13.8\%$

Cross section from combination

$\sigma_t = 67.2 \pm 3.7$ (stat.) ± 3.0 (syst.) ± 3.0 (theor.) ± 1.5 (lumi) pb

Inclusive cross section @ 8 TeV - History

Used 5.8 fb^{-1} of the 2012 data set

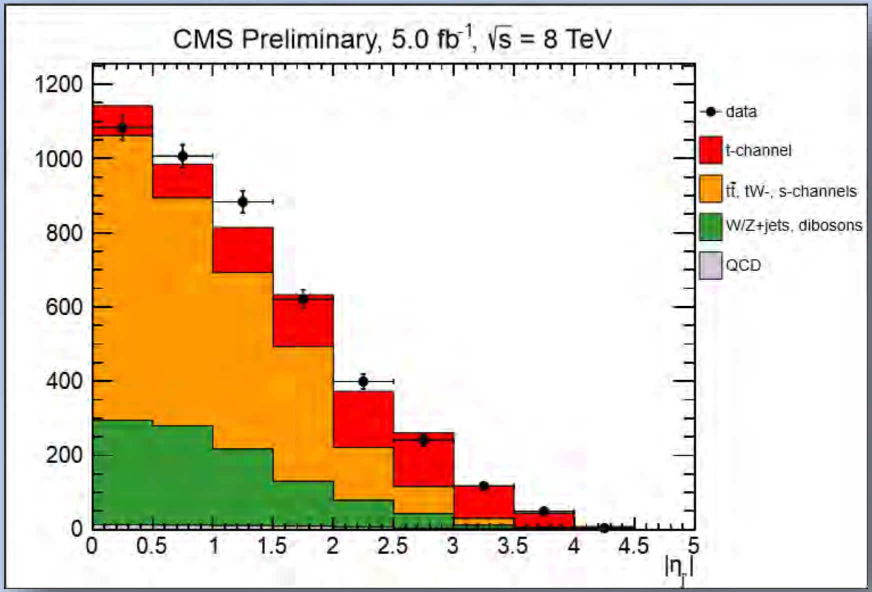


Measured cross section:

$\sigma_t = 95 \pm 2$ (stat.) ± 18 (syst.) pb

Dominate uncertainty:
b-tagging, JES, signal generator

Used 5.0 fb^{-1} of the 2012 data set



Measured cross section:

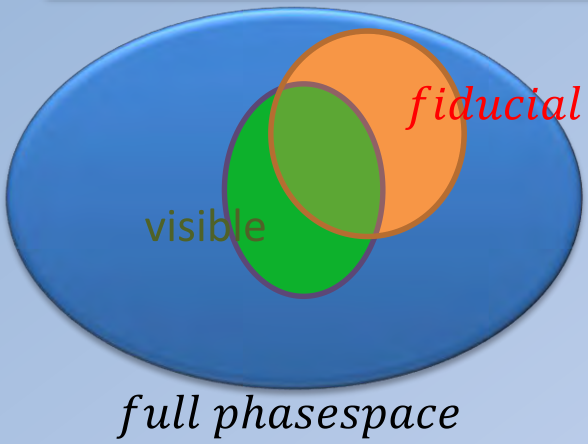
$\sigma_t = 80 \pm 6$ (stat.) ± 11 (syst.) ± 11 (lumi.) pb

Dominate uncertainty:
JES, theoretical uncertainties
(generator, PDF)

SM: $\sigma_t = 87.8$ pb

Fiducial cross section measurment

Idea: Measure cross section only in visible phase space, don't add theoretical uncertainties from the extrapolation to the measurement.



$$\vec{N}_{\text{part}} = \vec{f}_{\text{part!reco}} \cdot \mathrm{M}^{\text{reco}}_{\text{part}} \cdot \vec{f}_{\text{reco!part}} \cdot \vec{f}_{\text{accpt}} \cdot (\vec{N}_{\text{reco}} - \vec{N}_{\text{bgnd}})$$

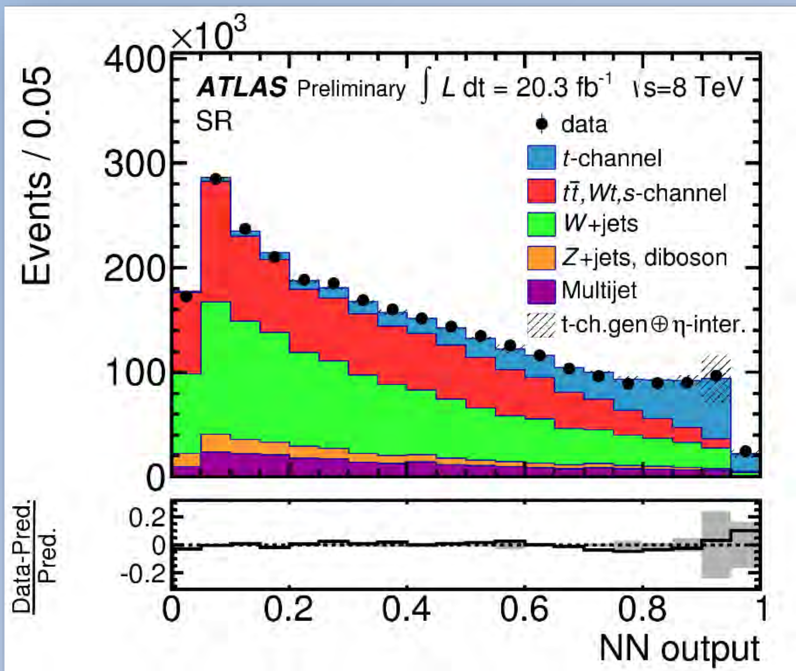
$$\sigma^{fid}(\vec{N}_{\text{part}}) = \frac{\vec{N}_{\text{part}}}{\int L dt},$$

Define a fiducial phase space close to the phase space of the selected data events

Object	Cut
Electrons	$p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
Muons	$p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
Jets	$p_{\mathrm{T}} > 30$ GeV and $\lvert\eta\rvert < 4.5$
	$p_{\mathrm{T}} > 35$ GeV, if $2.75 < \lvert\eta\rvert < 3.5$
Lepton (ℓ), Jets (j_i)	$\Delta R(\ell, j_i) > 0.4$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV
Transverse W-boson mass	$m_{\mathrm{T}}(W) > 50$ GeV
Lepton (ℓ), jet with the highest p_{T} (j_1)	$p_{\mathrm{T}}(\ell) > 40$ GeV $\left(1 - \frac{\pi - \lvert\Delta\phi(j_1,\ell)\rvert}{\pi - 1}\right)$

Fiducial cross section measurment

Used 20.3 fb^{-1} of the 2012 data set
One neural network in the 2 jet channel, 14 variables



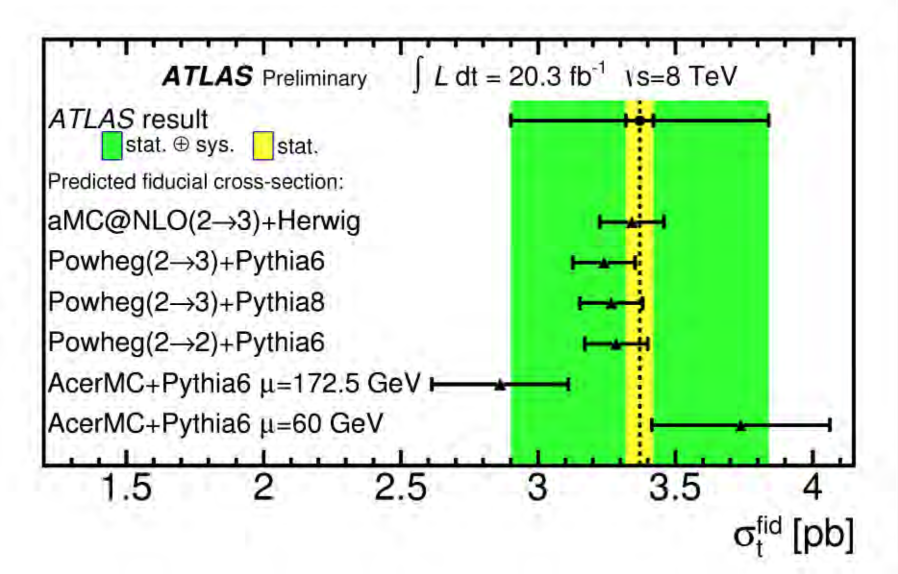
Measured fiducial cross section:

$$\sigma_{\text{fid}} = 3.37 \pm 0.05\ (stat.) \pm 0.47\ (\text{syst.}) \pm 0.09\ (\text{lumi.})\ \text{pb}$$

Source	$\Delta\sigma_{\text{fid}}/\sigma_{\text{fid}}$ [%]
Data statistics	±1.5
MC statistics	±1.1
Multijet normalisation	+2.3 -1.4
Other background normalization	±0.8
JES η intercalibration	±7.9
JES physics modelling	±3.0
JES detector	< 0.5
JES statistical	< 0.5
JES mixed detector and modelling	< 0.5
JES single particle	< 0.5
JES pile-up	< 0.5
JES flavor composition	±0.8
JES flavor response	±0.5
b-JES	< 0.5
Lepton uncertainties	±2.9
E_T^{miss} modelling	±3.0
b-tagging efficiency	±3.5
c-tagging efficiency	< 0.5
Mistag efficiency	< 0.5
Jet energy resolution	±1.7
Jet reconstruction eff.	< 0.5
Jet vertex fraction	< 0.5
t-channel generator	±7.9
W+jets generator	±1.4
PDF	±1.1
$t\bar{t}$, Wt and s-channel generator	< 0.5
ISR / FSR ($t\bar{t}$)	< 0.5
Total Systematic	±14
Total	±14

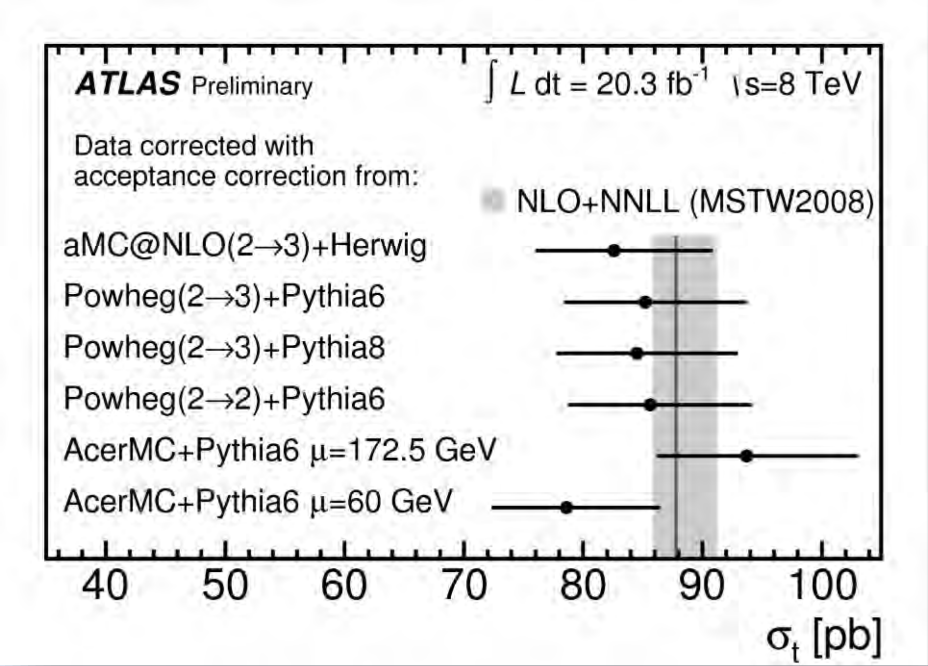
Fiducial and extrapolated cross section

Comparison of different of generator predictions



- Inclusive cross section for each generator calculated accordingly
- Uncertainy includes scale variations and PDF uncertainty (PDF4LHC description)

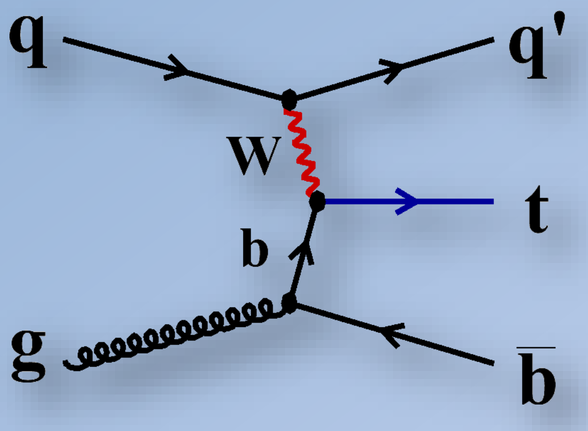
Extrapolated inclusive cross section



Uncertainty includes measured uncertainty plus PDF uncertainty of the extrapolation

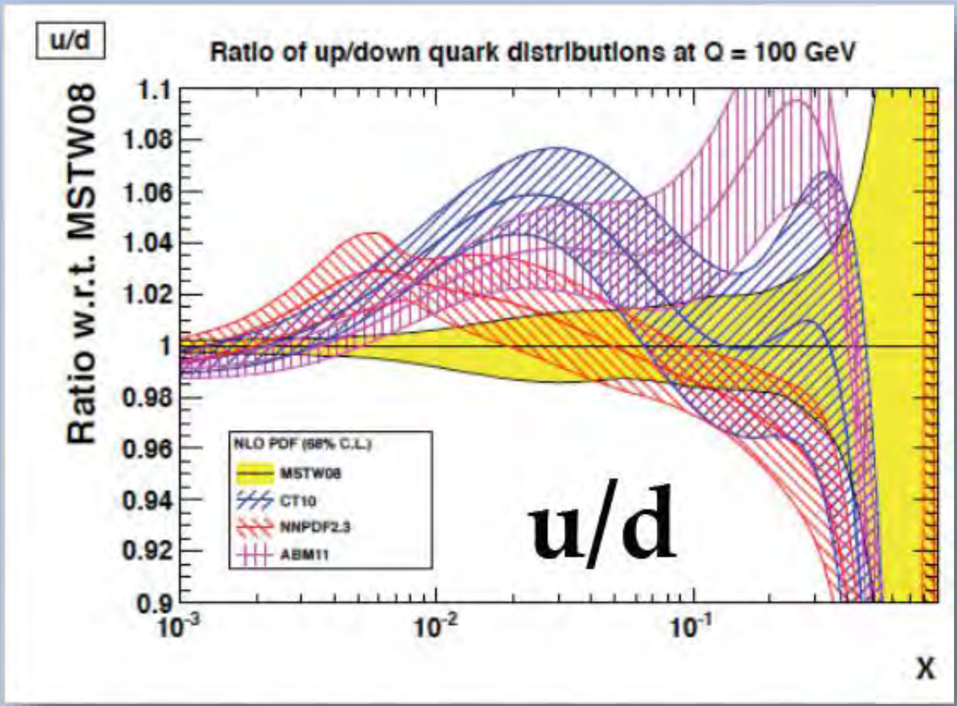
First time, that signal modelling can be studied in data!

t-channel cross section ratio



The charge of the top quark is connected to the type of the incoming light-flavour quark
→ Measure cross-section ratio top-quark/top-antiquark production is sensitive to d/u-quark ratio

$$R_t = \frac{\sigma(tq)}{\sigma(\bar{t}q)}$$



Cross section ratios @ 7 TeV

PDF set	R_t	scale unc.	PDF unc.	α_s	4- / 5-flavour
ABM11 (5 flav.)	2.06	-0.2% / 0.1%	-1.2% / 0.9%	-0.9% / 0.8%	± 0.7%
CT10	1.93	-0.2% / 0.1%	-4.1% / 3.5%	-0.4% / 0.3%	± 0.3%
CT10 (+ D0 W asym.)	1.86	-0.2% / 0.1%	-2.7% / 2.3%	-0.4% / 0.4%	± 0.1%
GJR08 (VF)	1.88	-0.1% / 0.1%	-2.5% / 2.7%	—	± 0.2%
HERAPDF 1.5	1.98	-0.1% / 0.1%	-3.5% / 2.0%	-0.2% / 0.2%	± 0.1%
MSTW2008 (68% C.L.)	1.89	-0.2% / 0.0%	-1.4% / 1.7%		± 0.3%
NNPDF 2.3	1.87	-0.2% / 0.1%	-1.1% / 1.1%	-1.3% / 0.2%	± 0.3%

Calculations are done using MCFM and Hathor

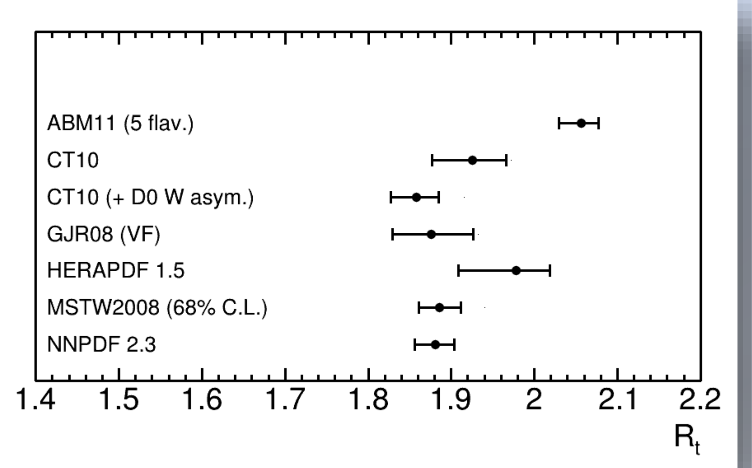
Statistical uncertainty
- from integration → 0.2% for R_t

Scale uncertainty
- Scan μ_r,μ_f plane between ½ and 2 x nominal

2 → 2 vs. 2 → 3
- Use difference between the two calculations

PDF internal uncertainties
- Calculations are done according to respective recommendations

α_s
- ± 0.002 or correlated with PDF unc. (MSTW)



Quite large variations of Rt for different PDFs

Cross section ratio

Used the complete 7 TeV dataset (4.7 fb-1)

Analysis needs to be separated into 4 channels:

Charge of the top quark results from the charge of the lepton

→ Split analysis into + und – of the lepton chareg

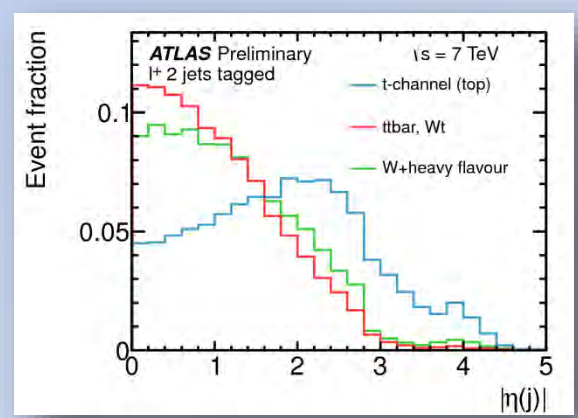
Use 2 and 3 jet channel

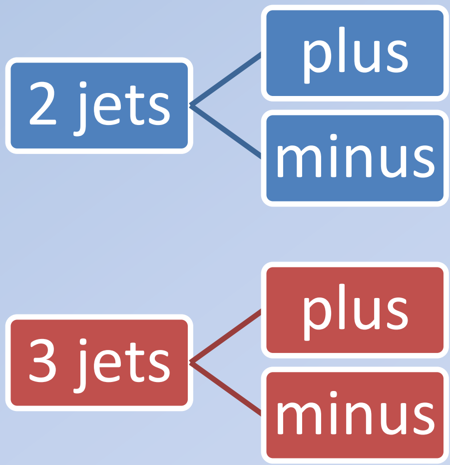
For each channel one separate network

Common choice of variables per jet bin

- 2 jet channel – 15 variables
- 3 jet channel – 19 variables

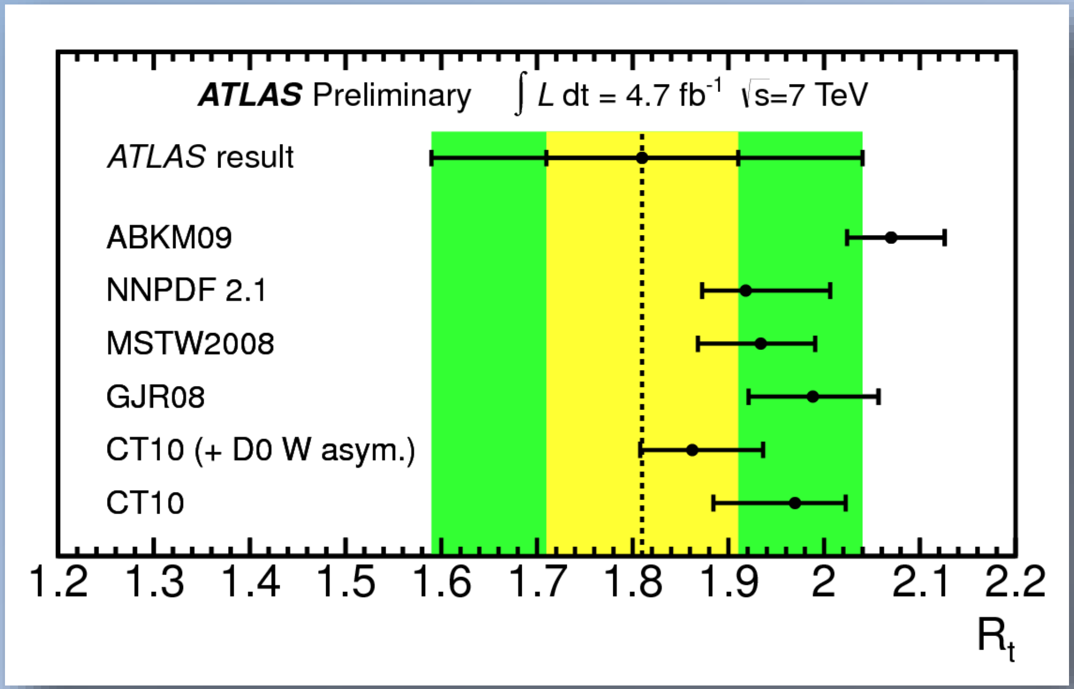
Measurement of $\sigma(t)$, $\sigma(\bar{t})$, $\sigma(t) / \sigma(\bar{t})$



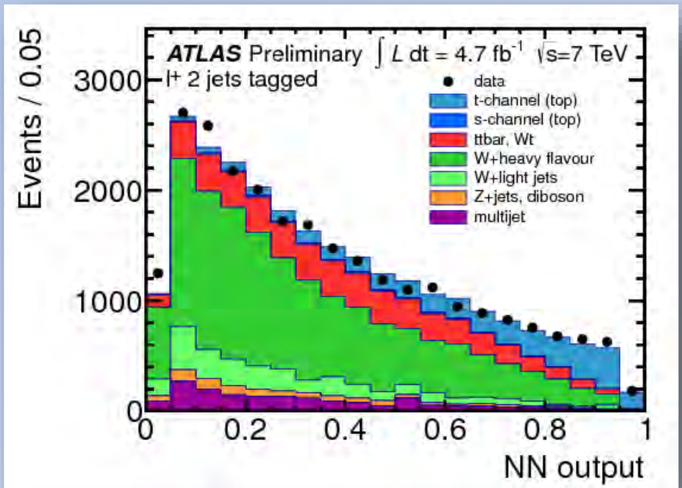


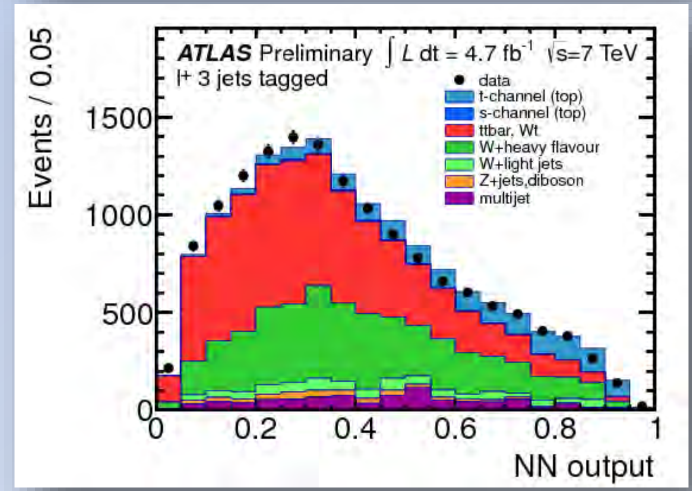
2 Jet channel	3 Jet channel
$\lvert\eta(j_u)\rvert$	$\eta(l\nu)$
$E_T(j_u)$	$p_T(l)$
H_T	$p_T(j_{u2})$
$\lvert\Delta\eta(bl)\rvert$	H_T
$\lvert\Delta\eta(j_u l)\rvert$	$\lvert\Delta\eta(j_1 j_2)\rvert$

Cross section ratio



Old PDF sets and old uncertainty calculation!





Measured values:

$\sigma_t(t) = 53.2 \pm 10.8$ pb

$\sigma_t(\bar{t}) = 29.5 \pm 7.5$ pb

$R_t = 1.81^{+0.23}_{-0.22}$ $(^{+12.8\%}_{-12.4\%})$

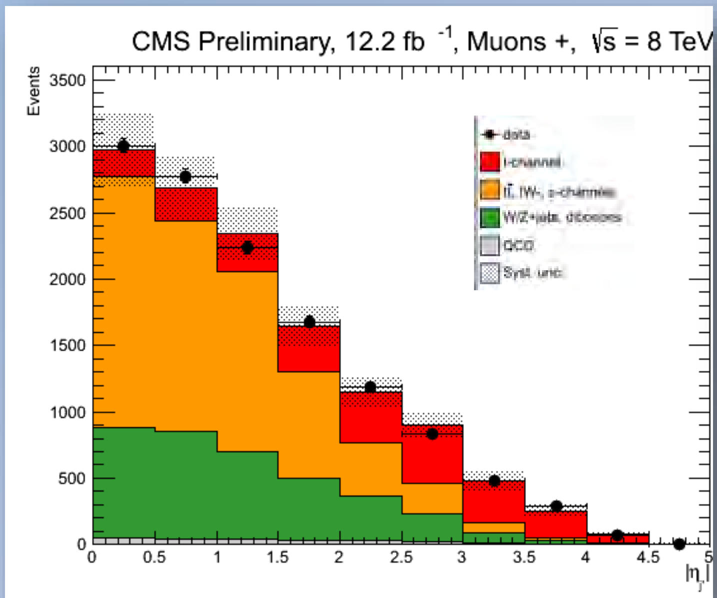
Update will come soon!

Dominate uncertainty:

- Data statistic
- QCD normalization

t-channel cross section ratio CMS

Used 12 fb^{-1} of the 2012 data set
Cut based analysis



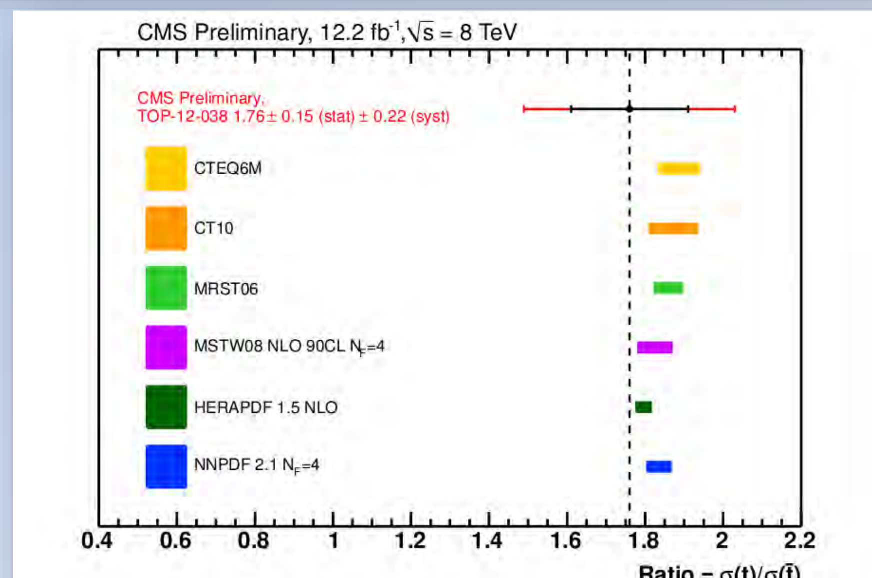
Uncertainty source	$\sigma_{t-ch,antitop}$ (%)	$\sigma_{t-ch,top}$ (%)	$R_{t-channel}$ (%)
stat. uncertainty	± 8.6	± 3.9	± 8.8
JES,JER, and MET	± 4.9	± 4.2	± 2.6
b-tagging and mis-tag	± 4.3	± 3.7	± 0.9
backgrounds ratio	± 0.6	± 0.5	± 1.1
lepton reconstruction/trig.	± 1.9	± 1.8	± 3.6
qcd extraction	± 6.4	± 3.4	± 0.9
W+Jets, $t\bar{t}$ extraction	± 5.9	± 2.4	± 6.8
signal modeling	± 11.4	± 15.4	± 5.4
pdf uncertainty	± 5.8	± 2.8	± 7.5
simulation statistics	± 1.1	± 0.6	± 1.1
luminosity	± 4.4	± 4.4	-
total systematics	± 17.4	± 17.8	± 12.6
total relative uncertainty	± 19.4	± 18.3	± 15.3
Scale factor w.r.t. SM ± uncertainty	0.92±0.18	0.88±0.16	0.96±0.15

Measured values:

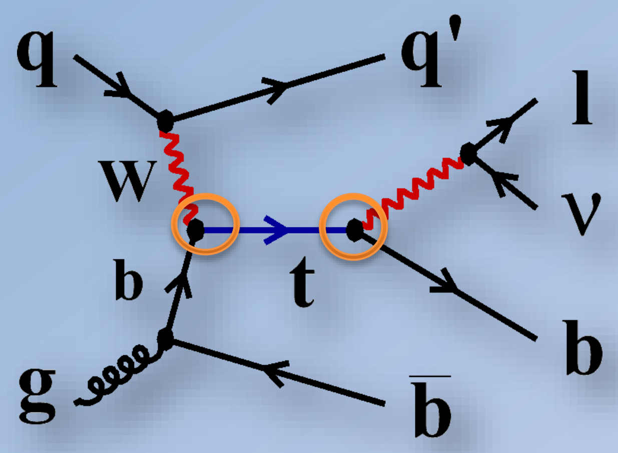
$\sigma_t(t) = 49.9 \pm 9.1$ pb

$\sigma_t(\bar{t}) = 28.3 \pm 5.5$ pb

$R_t = 1.76 \pm 0.27$ (± 15.3%)



Introduction couplings

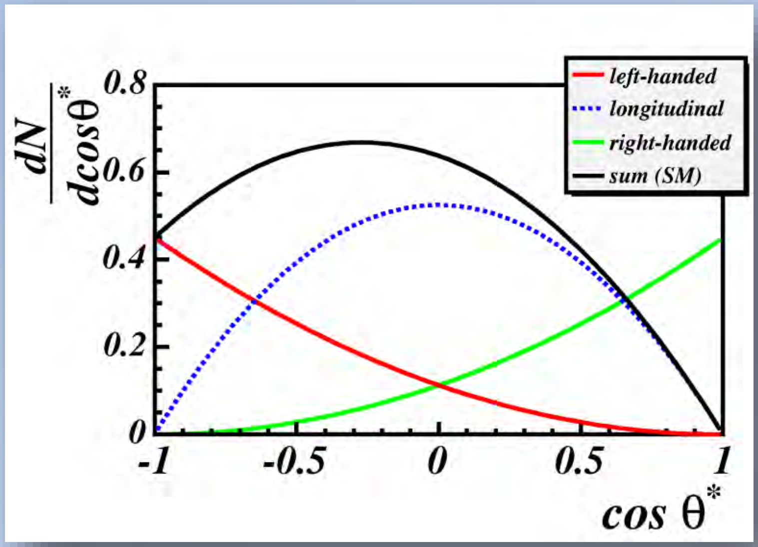


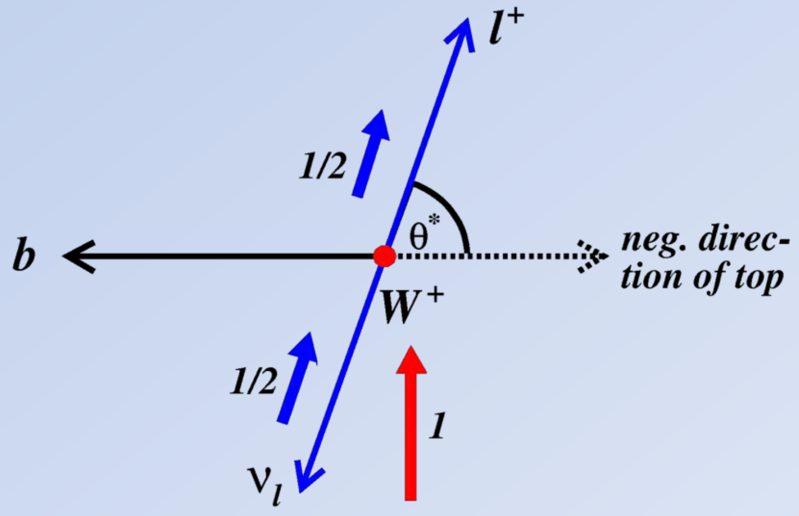
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.}$$

$V_L \equiv V_{tb} \sim 1$ (within SM)

$V_R, g_R, g_L \Rightarrow$ anomalous couplings

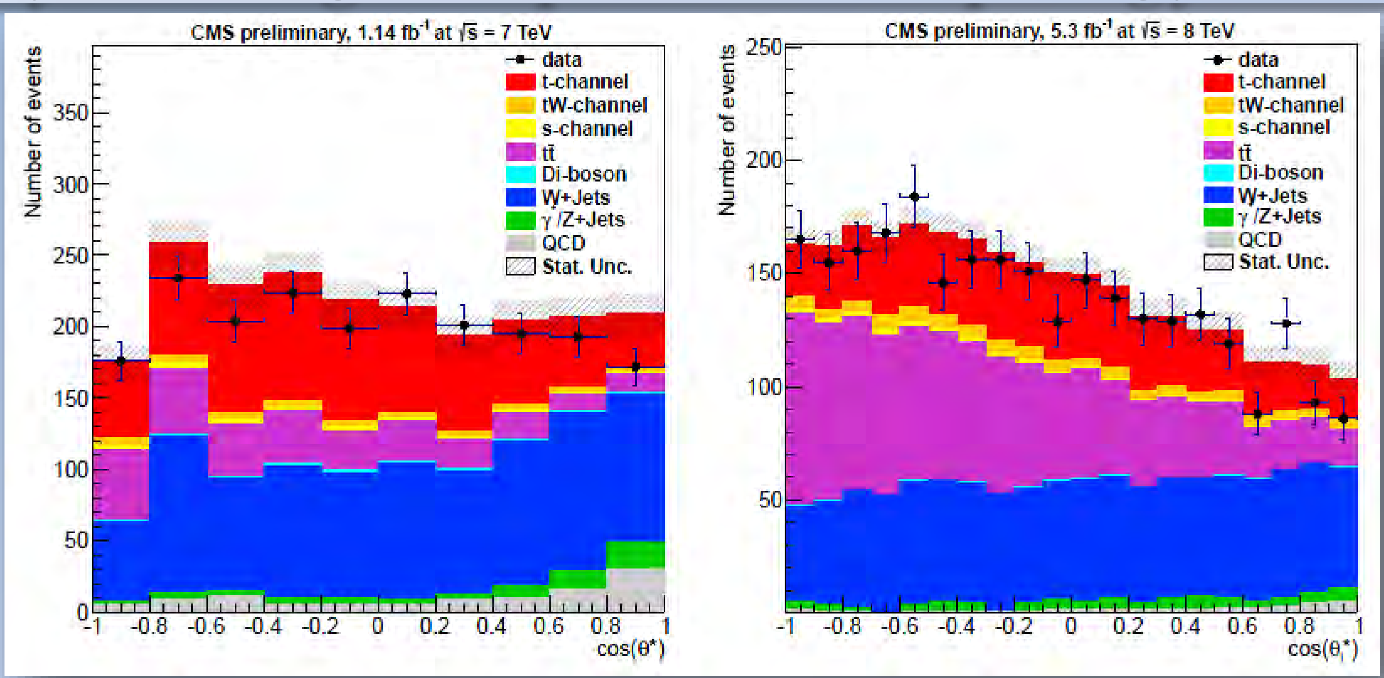
[EPJC50 (2007) 519, NPB804 (2008) 160, NPB812 (2009) 181]





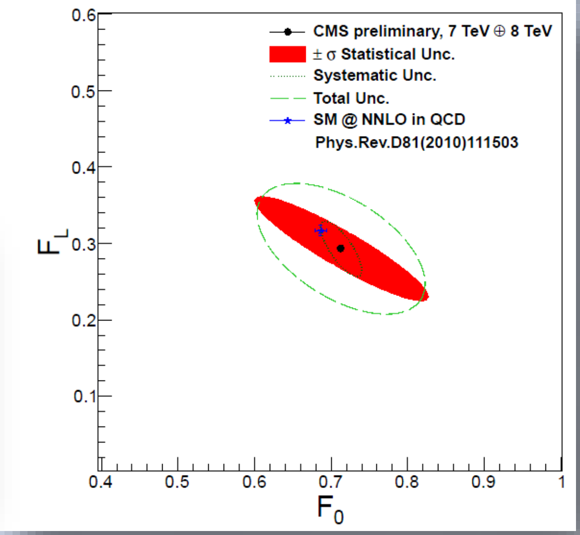
W helicity in single top events topology

Analyses done for
7 TeV with 1.14 fb^{-1}
8 TeV with 5.3 fb^{-1}



Combination of 7 and 8 TeV analysis
using a combined likelihood

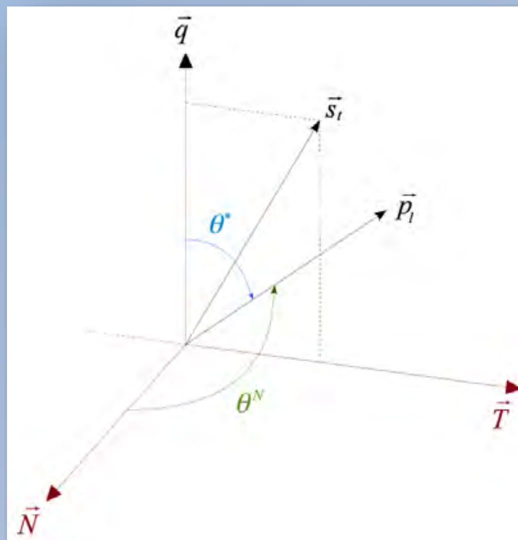
$$F_L = 0.293 \pm 0.069(\text{stat.}) \pm 0.030(\text{syst.}),$$
$$F_0 = 0.713 \pm 0.114(\text{stat.}) \pm 0.023(\text{syst.}),$$
$$F_R = -0.006 \pm 0.057(\text{stat.}) \pm 0.027(\text{syst.}).$$



W polarization beyond helicity fraction

[NPB840 (2010) 349]

☞ consider transverse and normal directions



$\vec{q}$ ➔ W mom in t rest frame

$\vec{s}_t$ ➔ top spin

$$\vec{N} = \vec{s}_t \times \vec{q}$$

$$\vec{T} = \vec{q} \times \vec{N}$$

meaningful for polarised t decays (e.g. in single top production)

θ^*_ℓ ➔ angle between ℓ, $\vec{q}$ determine F_+, F_0, F_-

θ^T_ℓ ➔ angle between ℓ, $\vec{T}$ determine F^T_+, F^T_0, F^T_-

θ^N_ℓ ➔ angle between ℓ, $\vec{N}$ determine F^N_+, F^N_0, F^N_-

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^X_\ell} = \frac{3}{8}(1+\cos\theta^X_\ell)^2 F^X_+ + \frac{3}{8}(1-\cos\theta^X_\ell)^2 F^X_- + \frac{3}{4}\sin^2\theta^X_\ell\, F^X_0$$

$$A^N_{FB} = \frac{3}{4}\left[F^N_+ - F^N_-\right]$$

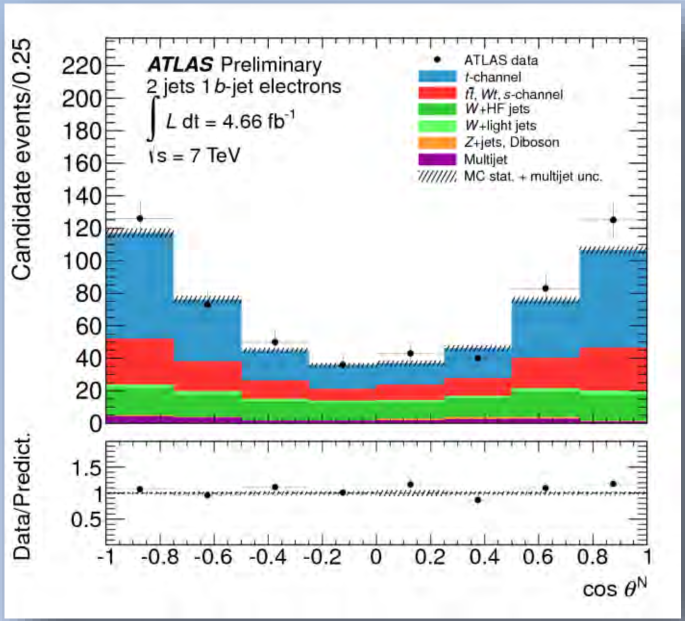
$$A^N_{FB} \simeq 0.64\, P\, \mathrm{Im}\, g_R$$

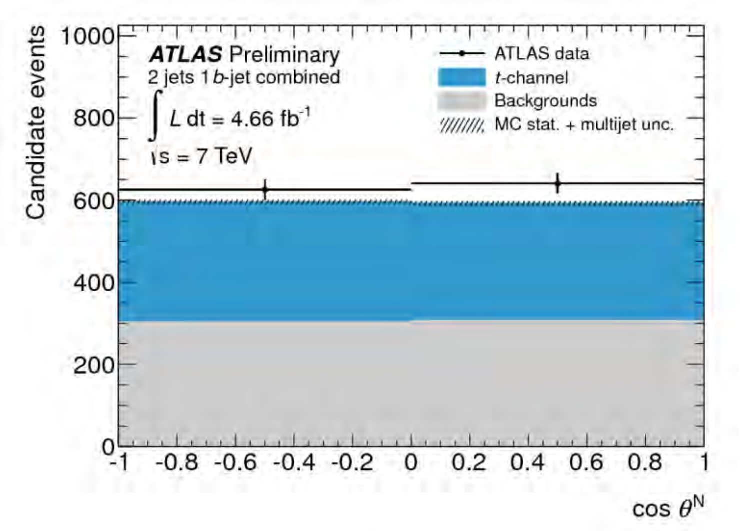
Unfolding of cos θ_N

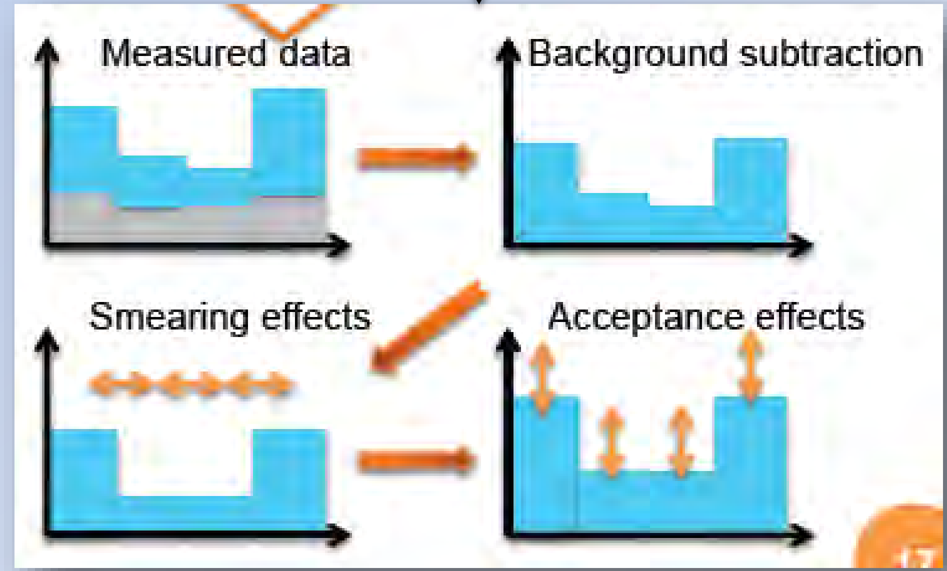
Used 5.8 fb^{-1} of 2012 data set

- Additional cuts to enrich t-channel signal
- To measure A_N^{FB} the cos θ_N distribution is unfolded
- Uncertainties are estimated using pseudo experiments

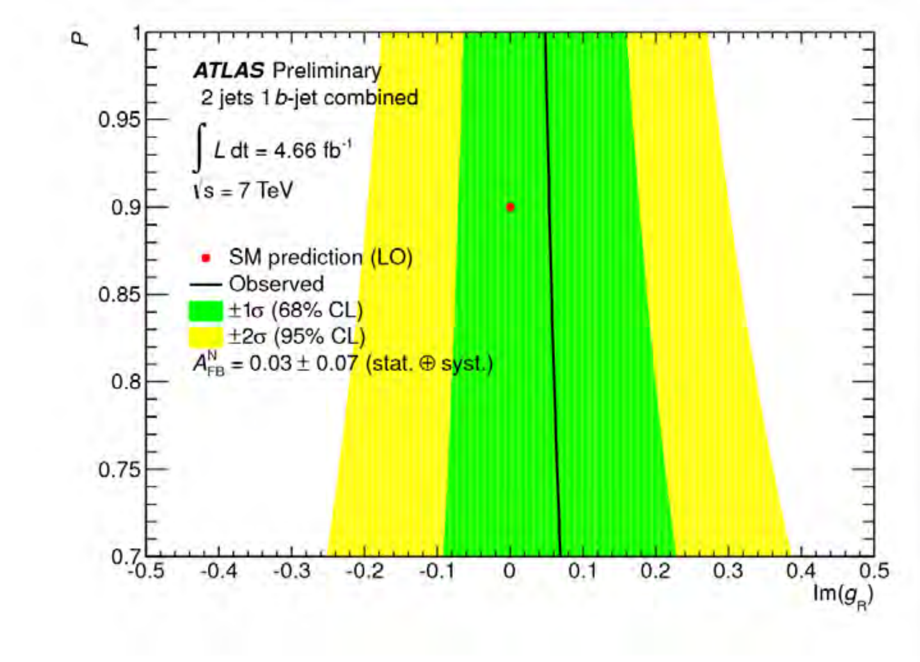
cos θ_N after final selection







Result



Source	$\Delta A_{\mathrm{FB}}^{\mathrm{N}}$
t-channel generator	+0.024 / −0.024
$t\bar{t}$ generator and parton shower	+0.010 / −0.010
Background normalisation	+0.008 / −0.008
Jet energy resolution	+0.007 / −0.007
Jet energy scale	+0.005 / −0.009
Lepton id, reco., trigger and scale	+0.004 / −0.006
PDFs	+0.003 / −0.003
Unfolding	+0.003 / −0.003
$E_{\mathrm{T}}^{\mathrm{miss}}$	+0.002 / −0.004
b-tagging	+0.002 / −0.002
W+jets shape	+0.001 / −0.001
ISR/FSR	+0.001 / −0.001
Jet reconstruction efficiency	+0.001 / −0.001
Luminosity	+0.001 / −0.001
Jet vertex fraction	<0.001 / <0.001
Total systematic	+0.029 / −0.031

$$A_{FB}^{N} = \frac{N_{+}^{unfold} - N_{-}^{unfold}}{N_{+}^{unfold} + N_{-}^{unfold}}$$

Measured values:

Data unfolded: A_N^{FB} = 0.031 ± 0.065 (stat.) ± 0.030 (syst.)

Assuming P ~ 0.9 (SM) (Polarization)

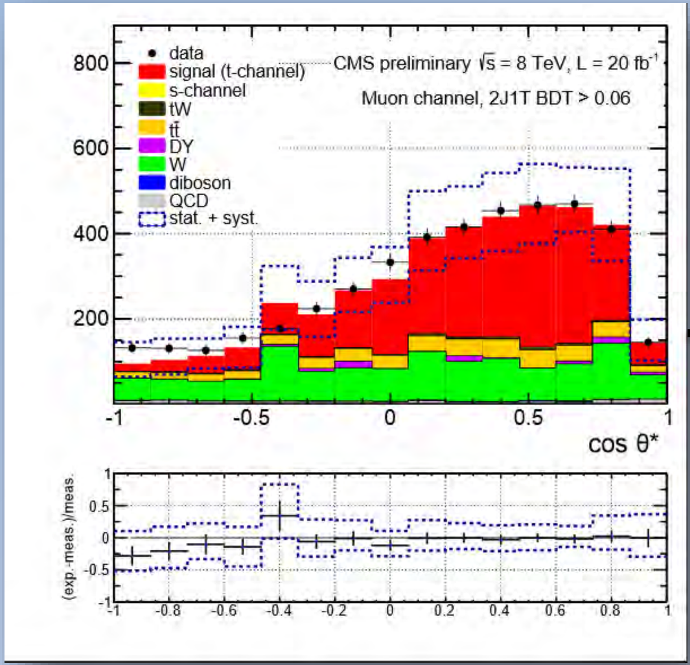
68% C.L.: $-0.07 < \mathrm{Im}(g_R) < 0.18$

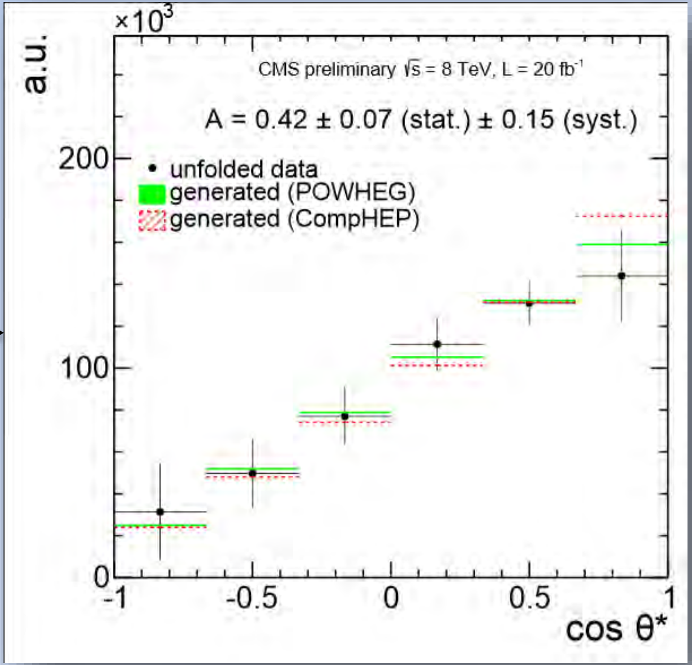
95% C.L.: $-0.20 < \mathrm{Im}(g_R) < 0.30$

Polarization

Used 20 fb^{-1} of 2012 data set

- Regularized unfolding of $cos\theta^*$ distribution, after selection based on BDT discriminante



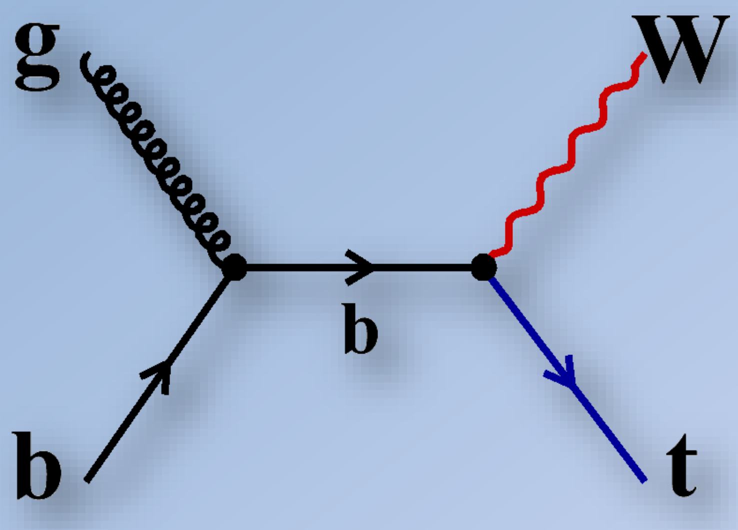


$$A_l = \frac{1}{2} \cdot P_t \alpha_l = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

Result:

- Top Spin asymmetry: $A_l = 0.41 \pm 0.06$ (stat.) $\pm\, 0.16$ (syst.)
- Top Polarization: $P_t = 0.82 \pm 0.12$ (stat.) $\pm\, 0.32$ (syst.)

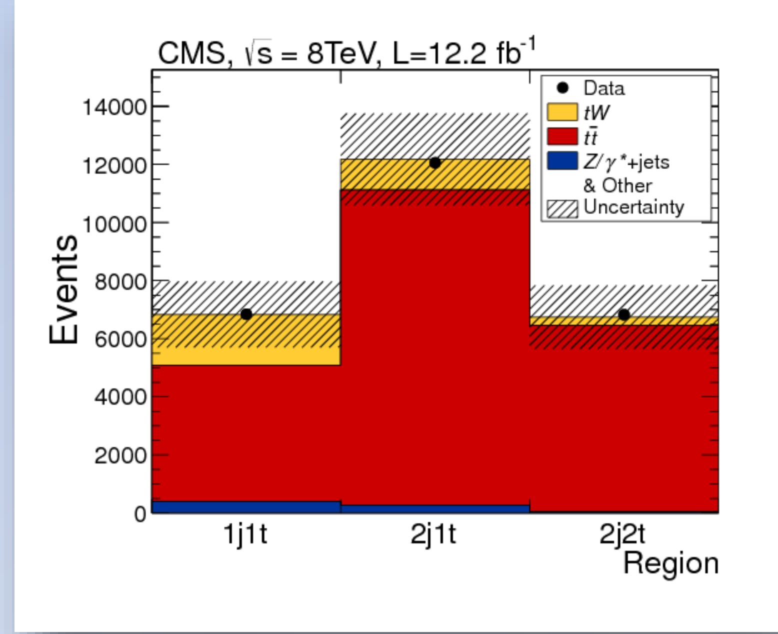
Wt single top quark production



Two decay modes:
- Lep+jets: On W boson decay leptonically one hadronically
- Di-lepton: Both W bosons decay leptonically

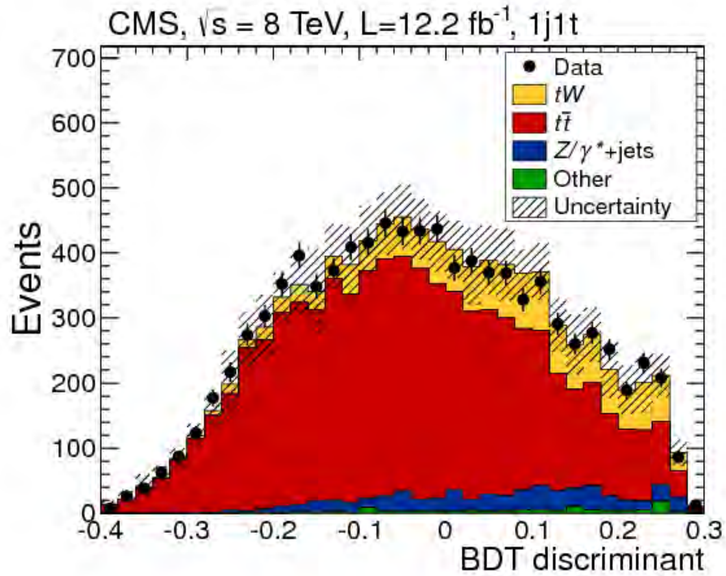
Interference with $t\bar{t}$ @ NLO

Main background: $t\bar{t}$ production
- Both experiments reported evidence with 7 TeV
- Both experiments reported evidence with 7 TeV



Wt single top quark production

Used 12.2 fb^{-1} of the 2012 data set
BDT in the dilepton channel



Systematic uncertainty	$\Delta\sigma$ (pb)	$\Delta\sigma/\sigma$
ME/PS matching thresholds	3.3	14%
Renormalization/factorization scale	2.9	12%
Top-quark mass	2.2	9%
Fit statistical	1.9	8%
Jet energy scale	0.9	4%
Luminosity	0.7	3%
Z+jets data/simulation scale factor	0.6	3%
tW DR/DS scheme	0.5	2%
$t\bar{t}$ cross section	0.4	2%
Lepton identification	0.4	2%
PDF	0.4	2%
Jet energy resolution	0.2	1%
b-tagging data/simulation scale factor	0.2	<1%
$t\bar{t}$ spin correlations	0.1	<1%
Pileup	0.1	<1%
Top-quark p_T reweighting	0.1	<1%
E_T^{miss} modeling	0.1	<1%
Lepton energy scale	0.1	<1%
Total	5.5	24%

Measured cross section:
$\sigma_t = 23.4 \pm 5.4$ pb
SM: $\sigma_t = 22.2$ pb

Significance 6.1 σ

Summary

- All three production modes of single top are now observed
- Measurements in the t-channel starts to enter precision measurement area
  - Measurements of cross section ratio
  - First fiducial cross section measurement
  - Measurement of W helicity
  - Measurement of CP violation

Are already done, more to come …. stay tuned