ELEMENTARY PARTICLE PHYSICS
Current Topics in Particle Physics
Laurea Magistrale in Fisica,
curriculum Fisica Nucleare e Subnucleare
Lecture 9

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Preliminaries

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Bibliography

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♠ Other basic bibliography:

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♠ Particle Detectors bibliography:

- William R. Leo *Techniques for Nuclear and Particle Physics Experiments*,
  Springer Verlag (1994)(LEO)
- C. Grupen, B. Shawartz *Particle Detectors*,
  Cambridge University Press (2008)(CS)
- *The Particle Detector Brief Book*,(BB)
  http://physics.web.cern.ch/Physics/ParticleDetector/Briefbook/

Specific bibliography is given in each lecture

Lecture Contents - 1 part

1. Introduction. Lep Legacy
2. Proton Structure
3. Hard interactions of quarks and gluons: Introduction to LHC Physics
4. Collider phenomenolgy
5. The machine LHC
6. Inelastic cros section pp
7. W and Z Physics at LHC
8. Top Physics: Inclusive and Differential cross section $t\bar{t}$ W, $t\bar{t}$ Z
9. Top Physics: quark top mass, single top production
10. Dark matter

Specific Bibliography

♠ Bibliography of this Lecture

- T.Han,*Collider Phenomenology: Basic Knowledge and Techniques*, arXiv:hep-ph/0508097 (TAO)

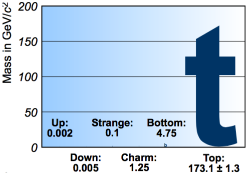
Contents

Introduction

Top quarks are special

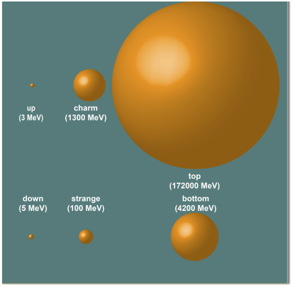
- Top quark mass
  - The heaviest known particle mass : $m_{top} = 173.21 \pm 0.51 \pm 0.71$ GeV
  - Pointlike particle with mass of gold atom, 35x heavier than bottom quark →why?
  - Being heavier than a W boson, it is the only quark that decays semi-weakly, i.e., into a real W boson and a b quark
- It is the only quark whose Yukawa coupling to the Higgs boson is order of unity.
- charge 2/3
- spin 1/2

Understanding the origin of mass is a major open problem.



- Top quark lifetime: $\tau \approx 5 \cdot 10^{-25}$ s
  - $\Gamma = 141^{+0.19}_{-0.15}$GeV.
  - Compare with hadronization scale $\Lambda_{QCD} \approx 250$ MeV.
  - A very short lifetime and decays before hadronization can occur.

- Important consequence of top τ: top decay before hadronization.
  - Top = the only *free* quark $\Longrightarrow$ no bound states (e.g. toponium, top mesons/baryons).
  - The only place where to study property of bare quark.
  - Spin/polarization passed on to decay productions without dilution/direct access to quark properties.



  - Particularly if new particle couples to mass
- First place a new particle could be observed
- **Top is background of many searches**

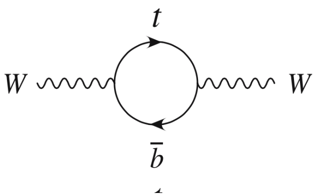
- An accurate knowledge of its properties (mass, couplings, production cross section, decay branching ratios, etc.) can bring **key information on fundamental interactions and beyond**.

Contents

Radiative corrections- Weak radiative corrections - top mass

The main cause of the weak radiative corrections is the W vacuum polarization diagram, affecting m_W and m_Z.The contribution of this kind of diagrams is proportional to the **difference of the squared masses of the two fermions**.

Weak isospin symmetry breaking by fermion doublets with large mass splitting modifies the ρ parameter, which is unity in lowest order.



$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_w} \quad \text{(LO)}$$

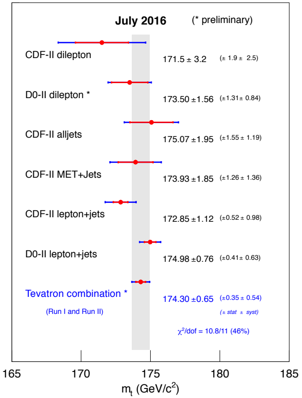
$$\bar{\rho} = 1 + \Delta\rho$$

$$\Delta\rho_t = \frac{3G_F}{8\pi^2\sqrt{2}}\boldsymbol{m_t^2} + \; ..$$ is a quadratic dependence

Top mass at Tevatron

The first measurements of top mass gave been performed at Tevatron By CDF & D0 Collaborations in $p\bar{p}$ collisions($\int \mathcal{L}dt = 9.7 fb^{-1}$).
Using all data sample and taking the correlated uncertainties properly the Tevatron average mass of the top quark is (2016):

$$\begin{aligned} \mathrm{M_{top}} &= 174.30 \pm 0.35(\mathrm{stat}) \\ &\pm 0.54(\mathrm{syst})\ \mathrm{GeV} \end{aligned}$$



summing uncertainties in quadrature:

$$\mathrm{M_{top}} = 174.30 \pm 0.65\ \mathrm{GeV}$$

corresponding to a relative precision of 0.37%.

[a]

[a]CDF and D0 Collaboration, *Combination of CDF and D0 results on the mass of the top quark using up to 9.7 fb^{-1} at the Tevatron*, arXiv:1608.01881v1

We can do **better**.

Pair production:qq and gg-fusion

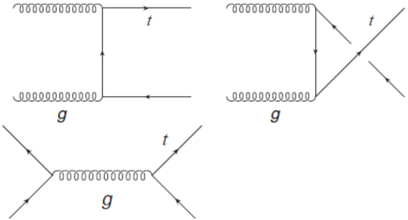


Figure :

Top quarks pair in the Born approximation

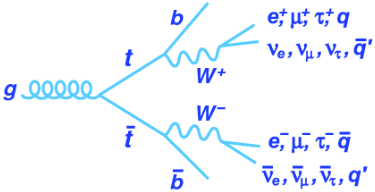
Table : Tevatron and LHC cross section

	Tevatron 1.96 TeV	LHC 14 TeV
qq	85%	5%
gg	15%	95%
σ(pb)	7.0 pb	887 pb

Larger cross section than Tevatron

Top quark decays

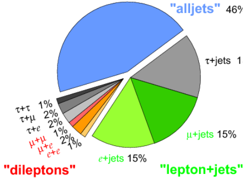
- Most of the time, the top quark is produced in pairs $t\bar{t}$.
- Each quark t or $\bar{t}$ **decays in a W** boson and b-quark $\sim$ **100%** of the time.
- Then the topology of $t\bar{t}$ events is characterized by decay of W-boson



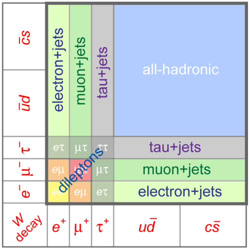
Top quark decays

♠ Then the topology of $t\bar{t}$ events is characterized by **decay of W-boson**:

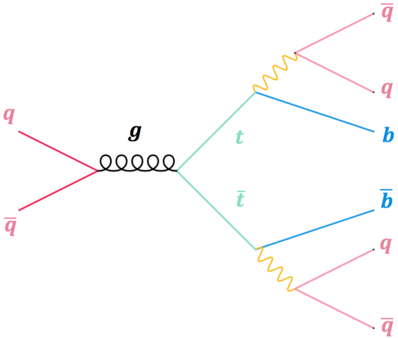
- **Fully hadronic**:
  Both Ws decay into two quarks.
- **Boosteed hadronic**:
  Boosted tops have their decay products within a large-R jet.
- **Dilepton channel**:
  Both Ws decay into a lepton and a neutrino.
- **Lepton + jet** :
  One W decays into two quarks and the other one into a lepton and a neutrino.



Top Pair Decay Channels



Fully hadronic channel



- Advantages
  - No neutrinos, both top decay quarks can be reconstructed.
  - Largest top decay channel branching ratio $\sim 46\%$.
- Disadvantages
  - 6 or more (due to initial and final state radiation) jets in the final state
  - Large multi jet QCD background $\rightarrow$ Signal/bckg $\sim 1/6$.
  - Background composition and modelling.
  - High combinatorial background. Many ways to combine jets to top-antitop pair: 90 combinations

Fully hadronic channel: Event selection

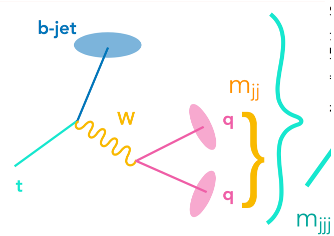
ATLAS Collaboration analysis:[1]

Event selection criteria

- At least 5 of the reconstructed central jets ($\eta < 2.5$) with $p_T > 60$ GeV. Additional central jets must have $p_T > 25$ GeV.
- Any pairing of jets must be separated by $\Delta R(j_i, j_k) > 0.6$.
- No neutrino in the event: $E_T^{miss} < 60$ GeV.
- No isolated electrons with $E_T > 25$ GeV and no isolated muon with $p_T > 20$ GeV.
- At least two of the six leading transverse momentum jets are tagged as coming from b quarks.
- Highest two b-weight jets must satisfy $\Delta\phi(b_i, b_j) > 1.5$.
- W candidate and associated b jets must satisfy $\Delta\phi(b,W) < 2$.

[1] ATLAS Coll., *Top-quark mass measurement in the all-hadronic $t\bar{t}$ decay channel at $\sqrt{s} = 8$ TeV with the ATLAS detector*, submitted JHEP, arXiv:1702.07546v1

Fully hadronic channel: variables



In each event the $t\bar{t}$ final state is reconstructed using all the jets from the all-hadronic $t\bar{t}$ decay chain:$t\bar{t} \rightarrow bWbW \rightarrow b_1 j_1 j_2 b_2 j_3 j_4$

- jets are sensitive to QCD modelling, R parameters.... difficult objects.
- The m_{top} measurement is obtained from template fits to the distribution of the top ratio of three-jet to dijet masses:

$$R_{3/2} = m_{jjj}/mjj$$

- a partial cancellation of systematic effects common to m_{top} and associated m_{W} boson, *e.g.*the significant uncertainty on the Jet Energy Scale (JES).

Fully hadronic channel

$$R_{3/2} = m_{jjj}/mjj$$

- The three-jet mass is obtained from the three jets assigned to the top quark decay.
- From the selected three jets the dijet mass is obtained using the two jets assigned to the W boson decay.
- The jet assignment is accomplished by using a χ^2 fit to the $t\bar{t}$ system, so there are two values of $R_{3/2}$ measured in each. event.

$t\bar{t}$ event reconstruction:

$t\bar{t} \to bWbW \to b_1 j_1 j_2 b_2 j_3 j_4$

To determine the mass a minimum χ^2 approach is adopted:

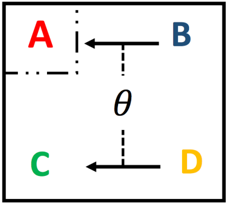
$$\chi^2 = \frac{(m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4})^2}{\sigma^2_{\Delta m_{bjj}}} + \frac{(m_{j_1 j_2} - M_W^{\mathrm{MC}})^2}{\sigma^2_{M_W^{\mathrm{MC}}}} + \frac{(m_{j_3 j_4} - M_W^{\mathrm{MC}})^2}{\sigma^2_{M_W^{\mathrm{MC}}}}$$

- Two of the reconstructed jets are associated with the bottom-type quarks produced directly from the top quark and antitop quark decays (b_1 and b_2), the other four jets are assumed to be u/d/c/s-quark jets from the W boson hadronic decay.
- All possible **permutations** of the **six** or more reconstructed **jets in each** event.
- The permutation resulting in the lowest χ^2 value is kept, assumed consistent $t\bar{t}$ hypothesis.
- First term minimization $t\bar{t}$, second and third Ws.

Fully hadronic channel : background estimation

- Only leading order theory calculations for final states with up to six partons.
- $\Longrightarrow$ dominant multi-jet background determined directly from the data (**Data driven method**)
- 4 control regions
- The background is determined in the control regions and extrapolated to the signal region.
- 2 uncorrelated variables: $N_{b_{tag}}$, number of b-tag jets, $< \Delta\phi(b, W) >$ average of the 2 angular separations.

4 control region **A,B,C,(background) D (signal)**.



ABCD region and definition			Estimated signal fractio
Region	$N_{b_{\text{tag}}}$	$\langle\Delta\phi(b, W)\rangle$	$t\bar{t}$ MC/data [%]
A	< 2	≥ 2.0	2.06 ± 0.02
B	< 2	< 2.0	2.60 ± 0.02
C	≥ 2	≥ 2.0	24.71 ± 0.55
D	≥ 2	< 2.0	34.05 ± 0.57

Fully hadronic channel: background estimation

The estimated background in a given bin i of $R_{3/2}$ for signal region D (SR)($N^{\text{SR D}}{}_{\text{background}}$) :

$$N^{\text{SR D}}{}_{\text{background,i}} = \left(\frac{N^{\text{SR C}}{}_{\text{background}}}{N^{\text{SR A}}{}_{\text{background}}} \right) \cdot N^{\text{SR B}}{}_{\text{background,i}}$$

©

The background in a given bin i of the $R_{3/2}$ spectrum of control region CR B ($N^{\text{SR B}}{}_{\text{background,i}}$) is estimated after subtraction of the signal contamination and after scaling by the ratio of the number events in control regions C ($N^{\text{SR C}}{}_{\text{background}}$) and A ($N^{\text{SR A}}{}_{\text{background}}$), also after signal removal.

Fully hadronic channel: top quark mass determination

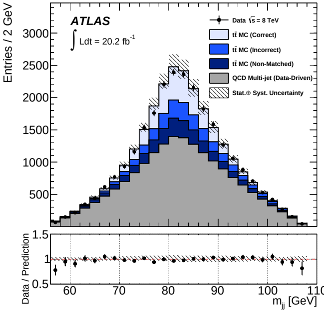


Figure : m_{jj} for W boson candidates

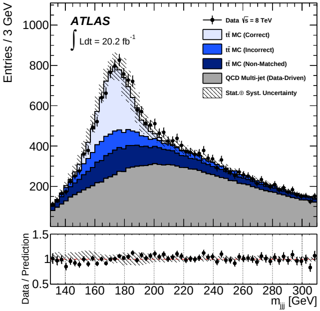


Figure : m_{jjj} for top candidates

For each $t\bar{t}$ event two $R_{3/2}$ are obtained, one for each top-quark measurement. Dividing :

$$R_{3/2} = m_{jjj}/mjj$$

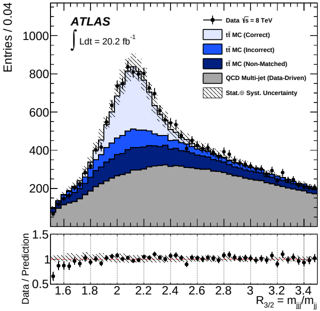


Figure : $R_{3/2}$ before χ^2 applied

Uncertainty	Δm_{top} [GeV]
Monte Carlo Generator	0.18 ± 0.21
Hadronisation Modelling	0.64 ± 0.15
Parton Distribution Functions	0.04 ± 0.00
Initial/Final-State Radiation	0.10 ± 0.28
Underlying Event	0.13 ± 0.16
Colour Reconnection	0.12 ± 0.16
Template Method Non-Closure	0.06
Signal and Bkgd Parameterisation	0.09
Non All-Hadronic $t\bar{t}$ Contribution	0.06
ABCD *vs.* ABCDEF	0.16
Trigger Efficiency	0.08 ± 0.01
Pile-Up Reweighting	0.01 ± 0.00
Lepton/E_T^{miss} Calibration	0.02 ± 0.01
Overall Flavour Tagging	0.10 ± 0.00
Jet Energy Scale (JES)	0.60 ± 0.05
b-Jet Energy Scale (bJES)	0.34 ± 0.02
Jet Energy Resolution	0.10 ± 0.04
Jet Vertex Fraction	0.03 ± 0.01
Jet Reconstruction Efficiency	0.00 ± 0.00
Total Systematic	1.01
Total Statistical	0.55
Total	1.15

Figure : $R_{3/2}$ before χ^2 applied

Largest uncertainties due to jet energy scale and hadronisation.

$R_{3/2} = m_{jjj}/mjj$is a powerful magentatop quark **mass estimator**.

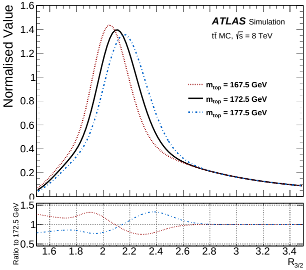


Figure : Template distributions

- Create templates for simulated signal and modelled background.
- Use multi-jet background derived from data (m_t independent)
- Obtain an m_t dependent representation of template.
- The top mass is obtained by fit $R_{3/2}$ distribution.

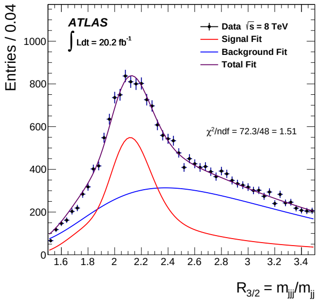


Figure : $R_{3/2}$ distribution total fit(magenta) signal (red) multi-jet background(blue).

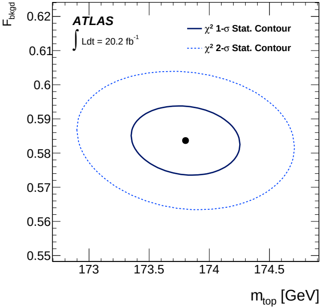
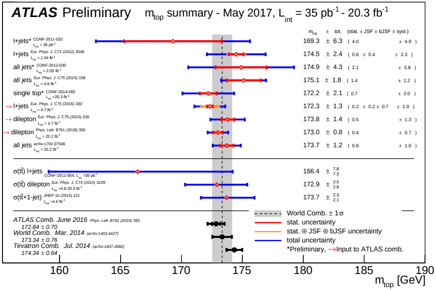


Figure : The central point in the figure indicates the values obtained for m_t on the x-axis, and the fitted background fraction, F_{bkgd}, obtained within the fit range of the $R_{3/2}$ distribution on the y-xis

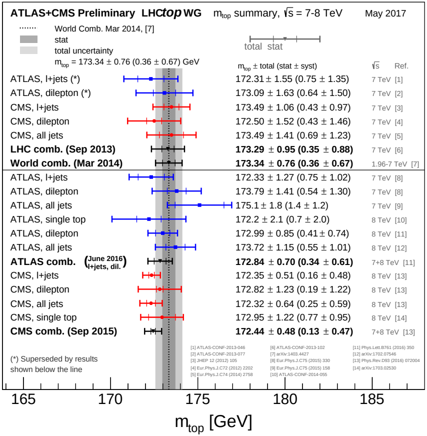
ATLAS Top mass from full hadronic channel

From 20.2 fb^{-1} of data at $\sqrt{s}8 = \text{TeV}$ATLAS determined from all-hadronic decay channel of $t\bar{t}$ pairs:

$$m_{\text{top}} = 173.72 \pm 0.55(\text{stat}) \pm 1.01(\text{sys})\ \text{GeV}$$



ATLAS + CMS: Top mass from full hadronic channel

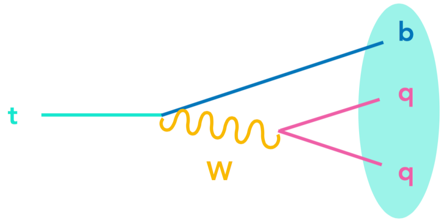


Boosted hadronic channel

When the **top quark** is produced with a **very high momentum** , its **decay products** are **collimated**, affecting the reconstruction efficiency of each individual decay product(*boosted regime*).

- A boosted topology study can complement a resolved analysis by **recovering events** otherwise mis-reconstructed,
- Additional advantages: **reduction of the combinatorial background** due to less final state objects.
- Property of boosted object decays: the **decay products appear collimated in the momentum direction** of the boosted mother particle in the rest frame of the detector. $\longrightarrow$ the decay products merge into a single large radius (large-R) jet with a characteristic substructure

Jet mass in boosted $t\bar{t}$ events(CMS)



CMS analysis:

- Boosted top-quark became collimated $\rightarrow$ reconstructed one large-R jet.
- It needs a special jet treatment.
- Select highly boosted $t\bar{t} \rightarrow (bjj)b\ell\nu$

2

[2] CMS Coll.,*Measurement of the jet mass in highly boosted $t\bar{t}$ events from pp collisions at at $\sqrt{s}$= 8 TeV, EPJ C 77,7,467,arXiv:1703.06330v2*

Jet mass in boosted $t\bar{t}$ events(CMS)

Measurement strategy:
$t\bar{t} \rightarrow (bjj)b\ell\nu$

- A boosted leptonic top quark decay, where the **lepton** is close in ΔR to the ***bjet***.
- **An additional high-p_T jet** is selected, which is assumed to originate from the hadronic top quark decay
- A veto on additional jets is employed which ensures that the hadronic decay is **merged into a single jet**
- An event selection on reconstruction level objects is carried out ensuring high efficiency for events in the fiducial region.
- Finally, the m_{jet} distribution is unfolded for experimental effects and compared to different predictions on particle level.
- A measurement of the normalised m_{jet} distribution is performed as well

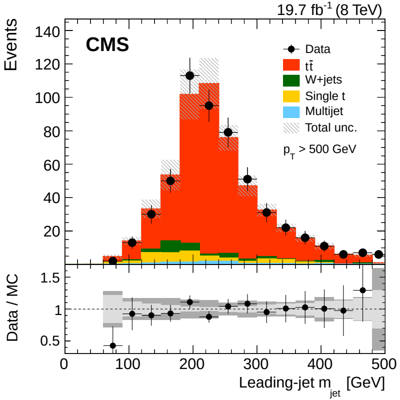
Jet mass in boosted $t\bar{t}$ events(CMS)

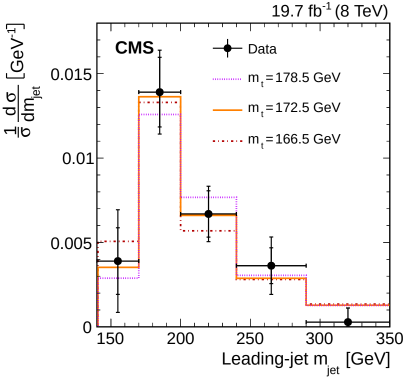
Event selection:

$t\bar{t} \rightarrow (bjj)b\ell\nu$

- Channel ℓ + jets channels.
- Only one electron or muon $p_{\mathrm{T}}>$ 45 GeVand $|\eta|<$ 2.1.
- At least one jet with $p_{\mathrm{T}}>$ 400 GeV in $|\eta|<$ 2.5 originate from the $t \rightarrow Wb \rightarrow q\bar{q}'b$ decay, merged into a single jet.
- A second jet with $p_{\mathrm{T}} >$ 150 GeV from the fragmented b quark of the leptonic decay leg.
- A veto on additional jets with $p_{\mathrm{T}} > 150 GeV$.
- The distance between the lepton and the second jet ΔR<1.2 . This, together with the veto on additional jets, ensures that the top quarks were produced back- to-back in the azimuthal angle ϕ.
- The invariant mass of the leading jet and leptonhas to be greater than the invariant mass of the combination of the second jet and the lepton. This improves the choice of the leading jet to originate from the fully hadronic top quark decay.

Results:





At left the normalised [3] particle-level $t\bar{t}$ differential cross section in the fiducial region as a function of the leading-jet mass. The measurement is compared to predictions from MadGraph+PYTHIA for three values of m_t

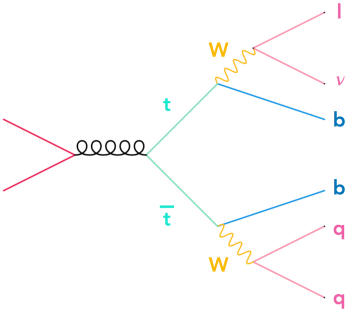
Jet mass in boosted $t\bar{t}$ events(CMS): top quark mass derivation

$m_{\text{top}} = 170.8 \pm 6.00(\text{stat}) \pm 2.8(\text{sys}) \pm 4.6(\text{model}) \pm 4.0(\text{theo})$ GeV

$\text{m}_{\text{top}} = 170.8 \pm 9.00$ GeV

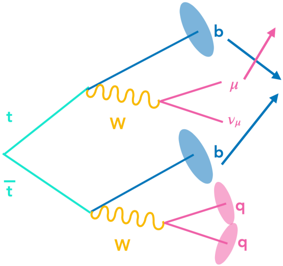
Precision not comparable with other methods.

Lepton + jets channel



$t\bar{t} \to (Wb)(Wb) \to (\ell\nu b)(q\bar{q}b)$

- One of the channels with the **most precise** measurements.
- Still requires template fit modelling.
- The presence of **neutrino** implies **not all decay products are reconstructed.**



CMS analysis :

$t\bar{t} \rightarrow (Wb)(Wb) \rightarrow (\mu\nu b)(q\bar{q}b)$

- Exactly **one μ** with $p_T > 25$ GeVand $|\eta| < 2.1$
- At least **4 jets** with $p_T > 30$ GeVand $|\eta| < 2.4$. The response and the resolution of the jets is corrected to match the data
- Exactly **two b-jets** among the among the four leading ones.

$t\bar{t}$ events, the parton-jet assignments: correct permutations (cp), wrong permutations (wp), and unmatched permutations (un), where, at least one quark from the $t\bar{t}$ decay is not unambiguously matched with a distance of $\Delta R < 0.3$ in the $\eta - \phi$ space to any of the four selected jets. [4]

[4] CMS Coll., *Measurement of the top quark mass with muon+jets final states in pp collisions at* $\sqrt{s}$=*13 TeV*, CMS PAS TO-16-022

μ + jets channel

W

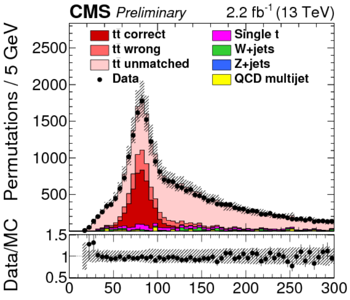


Figure : Invariant mass $m_{\mathrm{W}}^{\mathrm{reco}}$ of the **two untagged jets** .black

top

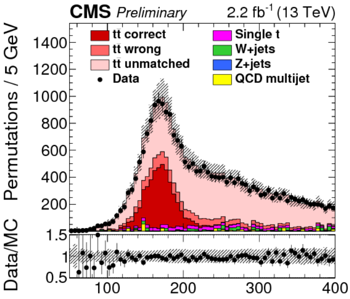


Figure : The invariant mass $m_{\mathrm{t}}^{\mathrm{reco}}$ the **two untagged jets and one of the b-tagged jets** after the b tagging requirement

$\boldsymbol{\mu}$ + jets channel: fit

The **compatibility of an event with the $t\bar{t}$** hypothesis and to **improve the resolution of the reconstructed quantities**, a **kinematic fit** is applied to the events. Inputs for each event:

- four-momenta of the lepton.
- four-momenta of the four leading jets.
- the missing transverse momentum,$\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$

with their resolution.

Constrains: The fit constrains these to the hypothesis of the production of two heavy particles of equal mass, each one decaying to a W boson with its invariant mass constrained to 80.4 GeV and a b quark:

- $m(t \to \ell\nu b) \;=\; m(\bar{t} \to q\bar{q}\bar{b})$
- $m(\ell\nu) \;=\; M_W$
- $m(q\bar{q}) \;=\; M_W$

μ + jets channel: after fit

W

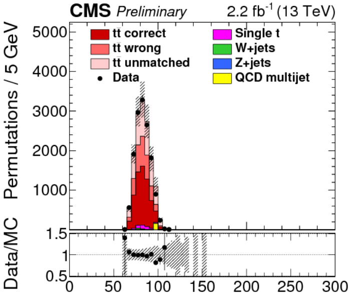


Figure : The reconstructed W boson masses $m_{\mathrm{W}}^{\mathrm{reco}}$

top

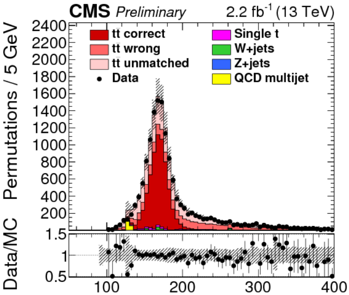


Figure : the fitted top quark $m_{\mathrm{t}}^{\mathrm{fit}}$ after the goodness-of-fit selection and the weighting by goodness-of-fit probability for the kinematic fit

The remaining background consists mostly of single top quark events (3.0%), while W+jets, Z+jets, and QCD multijet contributions are found to be negligible

μ + jets channel: Ideogram fit

- Jet energy scale (JES) and and top quark mass are derived with a joint likelihood fit.
- $m_{\mathrm{W}}^{\mathrm{reco}}$ before it is constrained by the kinematic fit, as an estimator for measuring in situ a JSF(jet energy scale factor).
- The distributions of $m_{\mathrm{t}}^{\mathrm{fit}}$ and $m_{\mathrm{W}}^{\mathrm{reco}}$ are obtained from simulation for five different m_{t} and five different JSF values.
- From these distributions, probability density functions P_j are derived separately for the different permutation cases j: cp, wp, un
- These functions depend on m_{t} and JSF and are labeled $P_j(m_{\mathrm{t}}^{\mathrm{fit}}|m_{\mathrm{t}}, \mathrm{JSF})$ and $P_j(m_{\mathrm{W}}^{\mathrm{reco}}, \mathrm{JSF})$ respectively for the ith permutation of an event in the final likelihood.
- The most likely m_{t} and JSF values are obtained by maximizing $-2ln[\mathcal{L}(m_{\mathrm{t}}, \mathrm{JSF}|\mathrm{sample})]$.

μ + jets channel: Ideogram fit

$$[\mathcal{L}(m_{\rm t}, {\rm JSF}|{\rm sample}) \; = \\ P({\rm JSF}) \cdot \prod_{i={\rm events}}^{N} \left(\sum_{i=1}^{n} P_{\rm gof}(i) \Big(\sum_j f_j P_j(m_{\rm t}^{\rm fit}|m_{\rm t}, {\rm JSF}) \times \\ P_j(m_{\rm W}^{\rm reco}, {\rm JSF}) \Big) \right)^{\rm w_{event}}$$

- n denotes the number of permutations in each event, j labels the permutation cases, f_j relative fraction.
- $P_{\rm gof}$ Probability of goodness of fit.
- $w_{\rm event}$, reduce the impact of events without correct permutations, where c is a normalization constant.
- P(JSF) is chosen to reflect the knowledge on the jet scale factor from the CMS.

μ + jets channel: Mass quark top

The top mass and JSF are measured simultaeously.

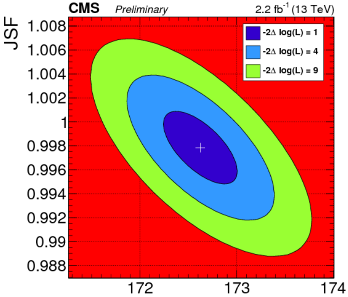
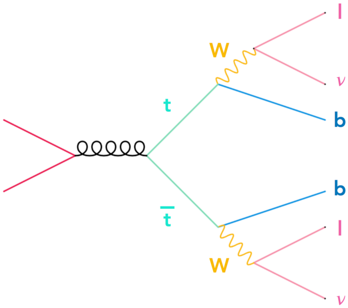


Figure : The likelihood$(-2\Delta log(\mathcal{L}))$measured for the muon+jets final state.The ellipses correspond to contours of $-2\Delta log(\mathcal{L})$ = (1,4, 9) allowing the construction one (two, three) σ statistical intervals of m_{top}.



$t\bar{t} \rightarrow (Wb)(Wb) \rightarrow (\ell\nu b)(\ell\nu b)$

- One of the channels with **the most precise** measurements,
- Doesn't require require template fit modelling.
- The presence of **neutrino** implies **not all decay products are reconstructed.**

$$t\bar{t} \to (W^+b)(W^-\bar{b}) \to (\ell^+\nu b)(\ell^-\bar{\nu}\bar{b})$$

$\ell\ell = ee, e\mu, \mu\mu$ (including $\tau \to e\mu$)

Preselection

- Electron E_{T}>25 GeVand $|\eta|$ <2.47, transition region barrel-endcap excluded
- Muon p_{T}>25 GeV$|\eta|$ <2.5
- Isolation criteria to reduce the contamination by leptons from heavy-flavour decays inside jets or from photon conversions (non prompt lepton,NP).
- Jets p_{T}>25 GeV$|\eta|$ <2.5.
- The identification of jets containing b-hadrons, b-tagging
- Exactly two oppositely charged leptons are required
- Same-lepton-flavour channels, ee and $\mu\mu$,$E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV,$m_{\ell\ell} > 15$ GeV, out of Z mass within 10 GeV

5

[5] ATLAS Coll.,*Measurement of the top quark mass in the $t\bar{t} \to$dilepton channel from $\sqrt{s}$=8 TeV ATLAS data*, Physics Letters B 761 (2016) 350,arXiv:1606.02179

$$t\bar{t} \to (W^+b)(W^-\bar{b}) \to (\ell^+\nu b)(\ell^-\bar{\nu}\bar{b})$$

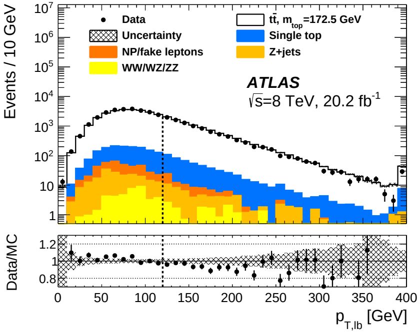
$\ell\ell = ee, e\mu, \mu\mu$ (including $\tau \to e\mu$)

Preselection (cont)

- $e\mu$ channel scalar sum of p_{T} of the two selected leptons and all jets > 130 GeV.
- At least two jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$.
- At least one of these jets has to be b-tagged.

Assuming a top quark mass of $m_{\mathrm{t}} = 172.5$ GeV, the predicted number of events is consistent with the one observed in the data within uncertainties.

dilepton channel



After preselection

The smallest uncertainty in m_t is obtained for:

$\Longrightarrow p_{T\ell b} > 120$ GeV

(1^{st}) additional selection criterion

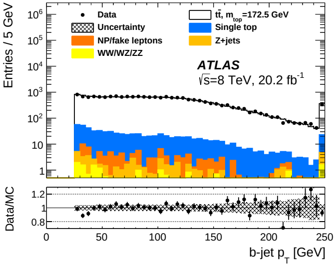
+

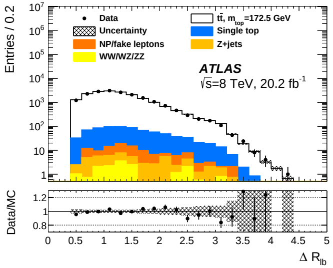
30 GeV $< m_{\ell b}^{reco} <$ 170 GeV

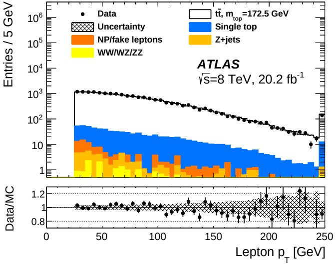
(2^{nd}) additional selection criterion

Applying both restrictions, the **matching efficiency and the sample purity are much improved**. Using this selection, and the objects assigned to the two lepton-b-jet pairs, the kinematic distributions in the data are well described by the predictions.

dilepton channel







After final selection

the objects assigned to the two lepton-b-jet pairs, the kinematic distributions in the data are well described by the predictions.

dilepton channel: template fit

- Kinematics are under-constrained due to the presences of neutrinos.
- The templates are simulated distributions of $m_{\ell b}^{\mathrm{reco}}$, constructed for a number of discrete values of m_t.
- The resulting template fit function has m_t as the only free parameter. A sum of Gaussian and a Landau function gives a good description of shape $m_{\ell b}^{\mathrm{reco}}$.

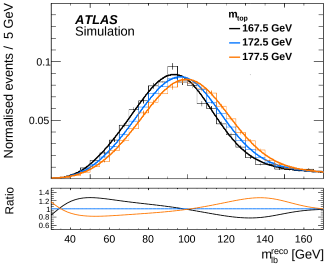


Figure : Simulated signal templates with statistical uncertainties (histograms) for different values of m_t together with the template fits (curves).

- An unbinned likelihood maximisation gives the value of m_t that best describes the data.
- A Gaussian distribution and a Landau function gives a good description of the shape of the $m_{\ell b}^{reco}$.
- The background distribution is independent of m_t, and a Landau function is fitted to it.
- The sum of the signal template at $m_t = 172.5$ GeV and the background is compared to data .

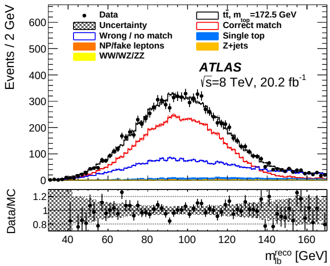


Figure : The $m_{\ell b}^{reco}$ distribution observed in data with statistical uncertainties in comparison to the prediction. The background contributions are too small to be distinguished

dilepton channel: template fit

- The expected statistical precision as well as all systematic uncertainties are obtained from 1000 pseudo-experiments generated per mass point from MC simulated samples mimicking ATLAS data.
- The expected statistical uncertainty is obtained from the distribution of the statistical uncertainty in the fitted m_t of the pseudo-experiments. Value obtained $m_t = 172.99 \pm 0.41$ (stat) GeV.

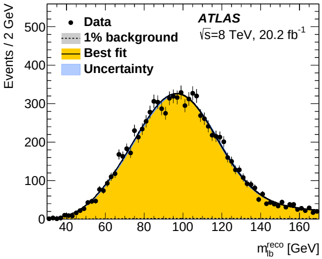


Figure : The $m_{\ell b}^{\rm reco}$ distribution is shown for data with statistical uncertainties together with the fitted probability density functions for the background alone (barely visible at the bottom of the figure) and for the sum of signal and background. The uncertainty band corresponds to the total uncertainty in m_t

dilepton channel: Final results

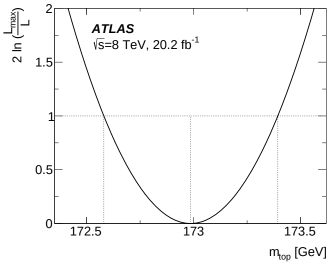
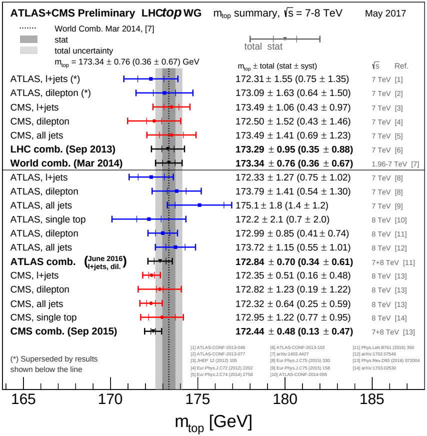


Figure : The logarithm of the likelihood corresponding to the fit in previous figure as a function of m_t.

The statistical uncertainty in m_t is $m_t \;=\; 172.99 \pm 0.41$ (stat) GeV

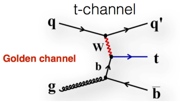
$$m_{\text{top}} \;=\; 172.99 \pm 0.41(\text{stat}) \pm\; 0.74(\text{sys})\;\text{GeV}$$

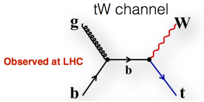
ATLAS + CMS: Top mass from full hadronic channel

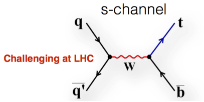


Contents

Single top production







Processes involving single top quarks provide direct probes of electroweak interactions:

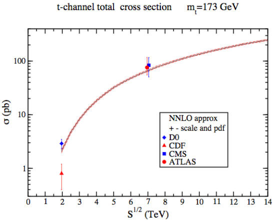
- Important tests of the SM predictions $\rightarrow$ excellent opportunities for searching for New Physics(NP).
- Matrix element $|V_{tb}|$ can be determined from measured cross sections.
- measurement of b-PDF

Single top production

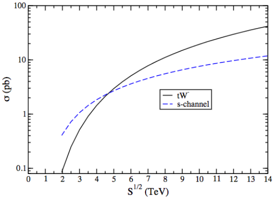
- t- and s-channels, specific to pp collisions, is the difference between production cross sections of single t and $\bar{t}$ that results from a difference in parton distribution functions (PDF) of incident up and down quarks involved in the hard scattering. The **ratio of t over $\bar{t}$ production cross sections** in the t-channel (R($t/\bar{t}$)) is therefore **sensitive to the PDF**of the up- and down-type quarks in the proton.
- Sensitivity of (R($t/\bar{t}$)) to physics beyond the SM manifesting as anomalous couplings in the Wtb vertex.

Single top production teoretica prediction

NKidonakis, NLO+NNLL calculations:



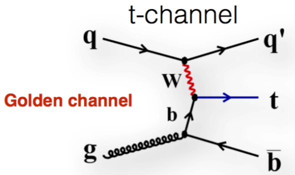
t-channel LHC	t	$\bar{t}$	Total
7 TeV	$43.0^{+1.6}_{-0.2} \pm 0.8$	$22.9 \pm 0.5^{+0.7}_{-0.9}$	$65.9^{+2.1}_{-0.7}{}^{+1.5}_{-1.7}$
8 TeV	$56.4^{+2.1}_{-0.3} \pm 1.1$	$30.7 \pm 0.7^{+0.9}_{-1.1}$	$87.2^{+2.8}_{-1.0}{}^{+2.0}_{-2.2}$
14 TeV	$154^{+4}_{-1} \pm 3$	$94^{+2}_{-1}{}^{+2}_{-3}$	$248^{+6}_{-2}{}^{+5}_{-6}$



s-channel LHC	t	$\bar{t}$	Total
7 TeV	$3.14 \pm 0.06^{+0.12}_{-0.10}$	$1.42 \pm 0.01^{+0.06}_{-0.07}$	$4.56 \pm 0.07^{+0.18}_{-0.17}$
8 TeV	$3.79 \pm 0.07 \pm 0.13$	$1.76 \pm 0.01 \pm 0.08$	$5.55 \pm 0.08 \pm 0.21$
14 TeV	$7.87 \pm 0.14^{+0.31}_{-0.28}$	$3.99 \pm 0.05^{+0.14}_{-0.21}$	$11.86 \pm 0.19^{+0.45}_{-0.49}$

[6]

[6] N Kidonakis. *Differential and total cross sections for top pair and single top production.* arXiv:1205.3453v1; t-channel:PRD 83(2001) 091503, s-channel PRD 81 (2010) 054028, tW-channel PRD 82(2010) 054018



$$\sigma(8\ \text{TeV}) = 87.7^{+3.4}_{-1.9}\text{pb}$$

$$\sigma(13\ \text{TeV}) = 217.0^{+9.1}_{-7.7}\text{pb}$$

Golden t-channel

- Has the largest cross section.
- has the largest S/B.
- Discovered at Tevatron 2009
- Observed at LHC 2011

- An example of signal with leptons, Missing Transverse Energy (MET), b-tag & jets.
- Good agreement with SM prediction. Leading systematics:Parton shower,b-tagging efficiency.

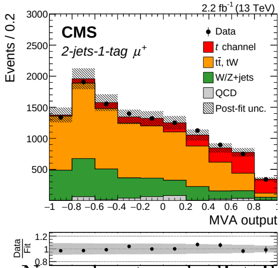


Figure : Neural network distributions. The ratio between data and simulated distributions. The hatched areas

The CMS results on t-channel cross section of single top-quark σ [7].

$$\begin{aligned}
\sigma(t-ch., t) &= 154 \pm 8(stat) \pm 9(exp) \pm 19(theo) \pm 4(lumi)pb \\
&= 154 \pm 22pb, \\
\sigma(t-ch., t) &= 85 \pm 10(stat) \pm 4(exp) \pm 11(theo) \pm 2(lumi)pb \\
&= 85 \pm 16pb, \\
\sigma(t-ch., t+\bar{t}) &= 238 \pm 13(stat) \pm 12(exp) \pm 26(theo) \pm 5(lumi)pb \\
&= 238 \pm 32pb \\
R(t/\bar{t}) &= 1.81 \pm 0.18(stat) \pm 0.15(syst)
\end{aligned}$$

[7] ATLAS Coll., *Fiducial, total and differential cross-section measurements of t-channel single top-quark production in pp collisions at 8 TeV using data collected by the ATLAS detector*, Eur. Phys. J. C 77 (2017) 531, arXiv:1702.02859
ATLAS Coll., *Measurement of the inclusive cross-sections of single top-quark and top-antiquark t-channel production in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, JHEP04(2017)086, arXiv:1609.03920
CMS Coll. *Cross section measurement of t-channel single top quark production in pp collisions at t $\sqrt{s}$ = 13 TeV*, Submitted to Phys. Let. B, arXiv:1610.00678

single top production: t-channel

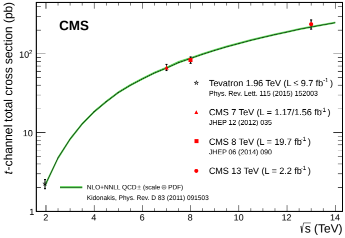


Figure : The summary of the most precise CMS measurements for the total t-channel single top quark cross section, in comparison with NLO+NNLL QCD calculations. The combination of the Tevatron measurements [56] is also shown.

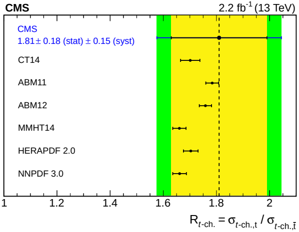


Figure : Comparison of the measured R_{t-ch}.(dotted line) with the prediction from different PDF sets.For the measurement, the inner and outer error bars correspond to the statistical and total uncertainties, respectively.

V_{tb}

Matrix element **$|V_{tb}|$**can be determined **from measured cross section**.

- The presence of a W_{tb} vertex allows for an **interpretation of the cross section measurement in terms of the parameters regulating the strength of this coupling**, most notably the CKM matrix element $|V_{tb}|$.
- The presence of **anomalous couplings at theW_{tb} vertex** can produce anomalous form factors, with parameter $\mathcal{F}$, that would modify the interaction strength.
- Assuming $|V_{td}|, |Vt_{ts}| \ll |V_{tb}|$,
- Considering top-quark decay branching fraction into Wb,$\mathcal{B} \simeq 1$:

$$|\mathcal{F} \times V_{tb}| = \sqrt{\frac{\sigma_{t-ch,t+\bar{t}}}{\sigma^{th}_{t-ch,t+\bar{t}}}}$$

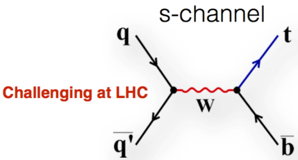
that **several scenarios beyond the SM predict a deviation of the measured value of $\mathcal{F}$ from 1**.

V_{tb} at 13 TeV

$$\begin{aligned}
|\mathcal{F} \times V_{tb}| &= 1.07 \pm 0.01(stat) \pm 0.09(sys) \pm 0.02(theo) \pm 0.01(lumi) = \\
&= 1.07 \pm 0.09 \text{ ATLAS} \\
|\mathcal{F} \times V_{tb}| &= 1.05 \pm 0.07(exp) \pm 0.02(theo) \text{ CMS} \\
& \text{can be directly compared with:} \\
|V_{tb}| &= 1.009 \pm 0.031 \text{ PDG2016}
\end{aligned}$$

Summary of all top LHC mesurements can found in LHCTopWG

single top production: s-channel



$$\sigma(8\ \mathrm{TeV}) = 5.6 \pm 0.2\mathrm{pb}$$

$$\sigma(13\ \mathrm{TeV}) = 10.3 \pm 0.4\mathrm{pb}$$

Challenging channel Measurements have been performed for s-channel:

CMS

$$\sigma_s^{7TeV} = 7.1 \pm 8.1(stat + syst)pb$$

$$\sigma_s^{8TeV} = 13.4 \pm 7.3(stat + syst)pb$$

ATLAS

$$\sigma_s^{8TeV} = 4.8 \pm 0.8(stat) +^{1.6}_{-1.3} (syst)pb$$

[8]

s-channel at 7-8 TeV

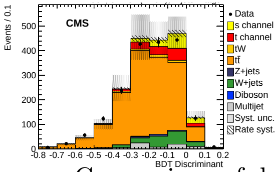
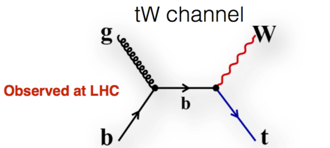


Figure : Comparison of data with simulation for distributions of the BDT discriminants in the 2-jets 2-tags,

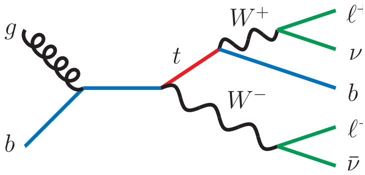
Limited by stat., signal and $t\bar{t}$ modelling

[8] ATLAS Coll., Evidence for single top-quark production in the s-channel in proton-proton collisions at



$\sigma(8\text{ TeV}) = 22.4 \pm 1.5\text{pb}$

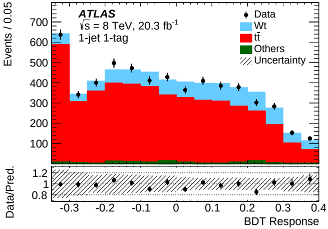
$\sigma(13\text{ TeV}) = 71.7 \pm 3.8\text{pb}$

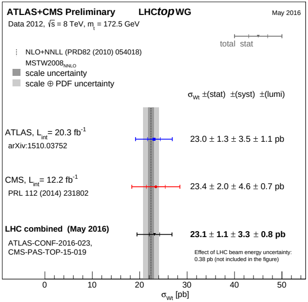


Observed at LHC. [a] Signatures:

- 2 opposite sign isolated leptons
- E^T_{miss} from 2 neutrinos
- 1 high P_T b-tagged jets
- Main backgrounds $t\bar{t}$, X+ Jets
- Leading systematics: $t\bar{t}$ normalization, jet reconstruction, ISR/FSR

[a]ATLAS Coll. ,*Measurement of the production c association with a W boson at 8 TeV with the AT* JHEP01(2016)064,arXiv:1510.03752
CMS Coll.*Observation of the Associated Productio Boson in pp Collisions at* $\sqrt{s}$= *8??TeV*, Phys. Rev. Lett. 112, 231802,PRL112,231802





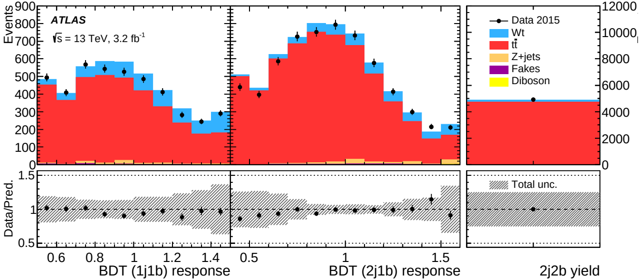
$$\sigma_{tW} = 23.0 \pm 1.3(stat)^{+3.2}_{-3.5}(sys) \pm 1.1(lumi) pb (ATLAS)$$

$$\sigma_{tW} = 23.4 \pm 5.4 pb (CMS) \rightarrow \pm 24\%$$

Combination LHCtopWG:$\sim 10\%$ improvement on measurement.

ATLAS performed as well preliminary measurement at $\sqrt{s}$ 13 TeV. Using 2 separate BDT, trained in two signal region 1jet1 b-jet and 2j1b-jet. [9]

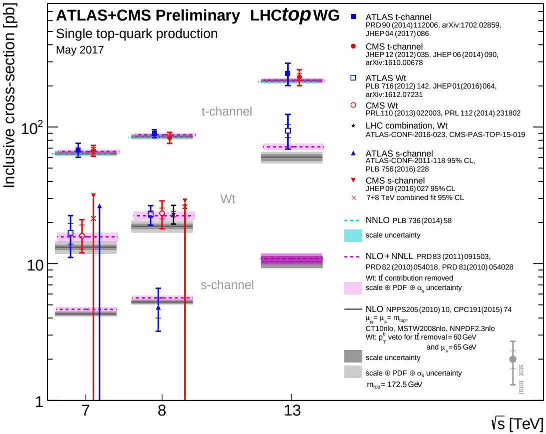
$$\sigma_{tW} = 94.0 \pm 10(stat)^{+28}_{-22}(sys) \pm 2(lumi)pb(ATLAS)$$



Pre-fit distributions of the signal and control regions 1j1b(control), 2j1b (control), and 2j2b(signal).

[9] ATLAS Coll. ,*Measurement of the cross-section for producing a W boson in association with a single top quark in pp collisions at s?=13TeV with ATLAS*, JHEP01(2016)064,arXiv:1612.07231

single top production: Summary of cross section measurements



Summary of all top LHC mesurements can found in LHCTopWG