Measurement of single top production in pp collisions at 7 TeV with the CMS detector

2011 Europhysics Conference on High-Energy Physics

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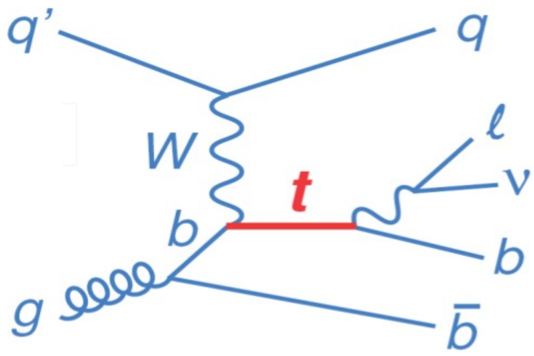
On behalf of the CMS collaboration



Based on:
CMS PAS TOP-10-008
Preprint arXiv:1106.3052

The CMS detector

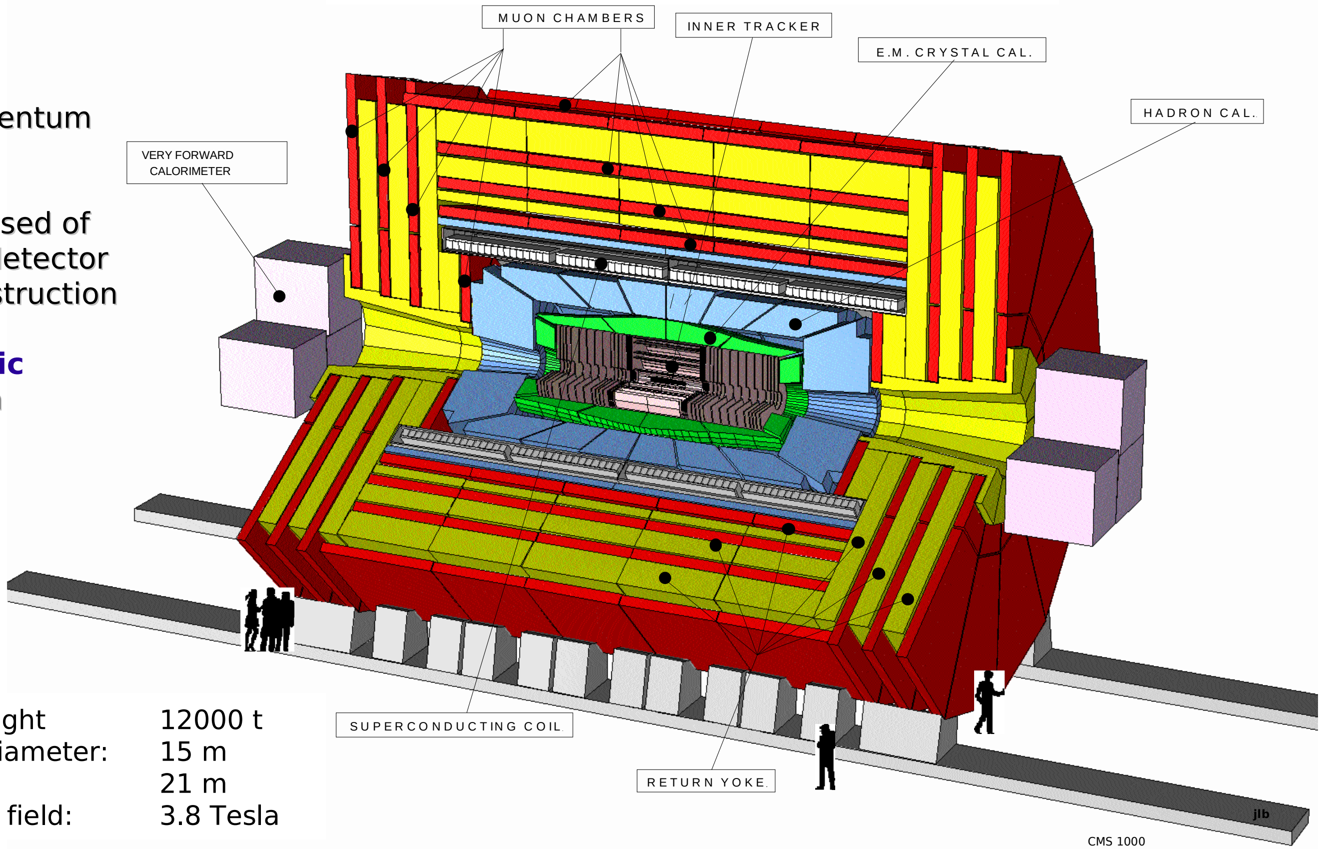
- **Compact design** thanks to 3.8 Tesla superconducting magnet

- **Muon detector**
For muon identification and momentum reconstruction

- **Inner tracking system** composed of a silicon pixel and a silicon strip detector for charged particle tracks reconstruction

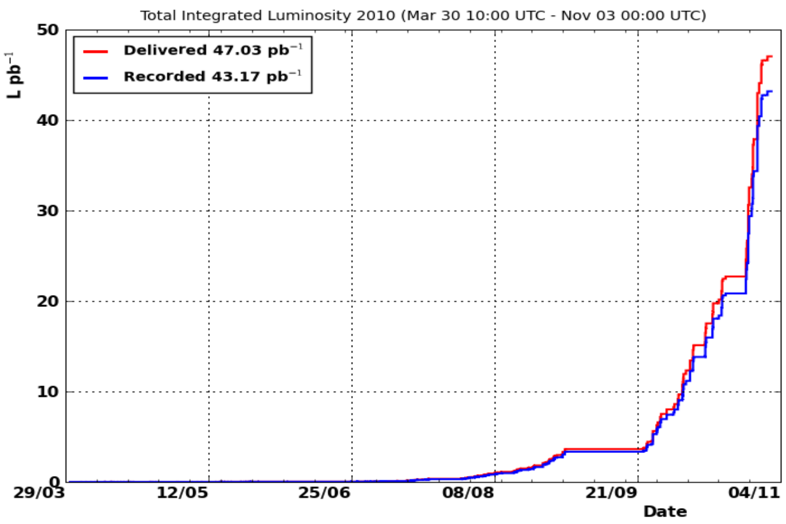
- **Electromagnetic and hadronic** calorimeters for electron, photon and jets reconstruction

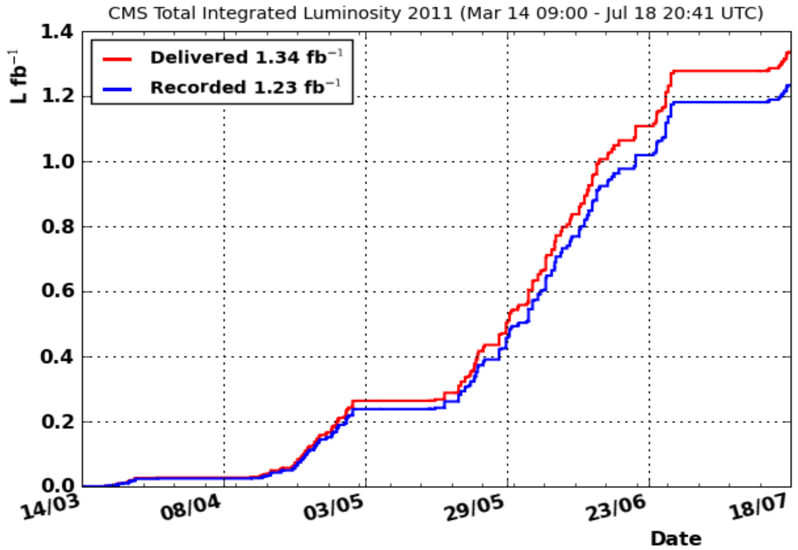
CMS
Compact Muon Solenoid



Total Weight	12000 t
Overall diameter:	15 m
Length:	21 m
Magnetic field:	3.8 Tesla

The CMS detector: data taking at 7 TeV





2010:

Up to december '10:
43 pb^{-1} on tape
peak instant luminosity:
204.78 μb^{-1} s^{-1}

2011

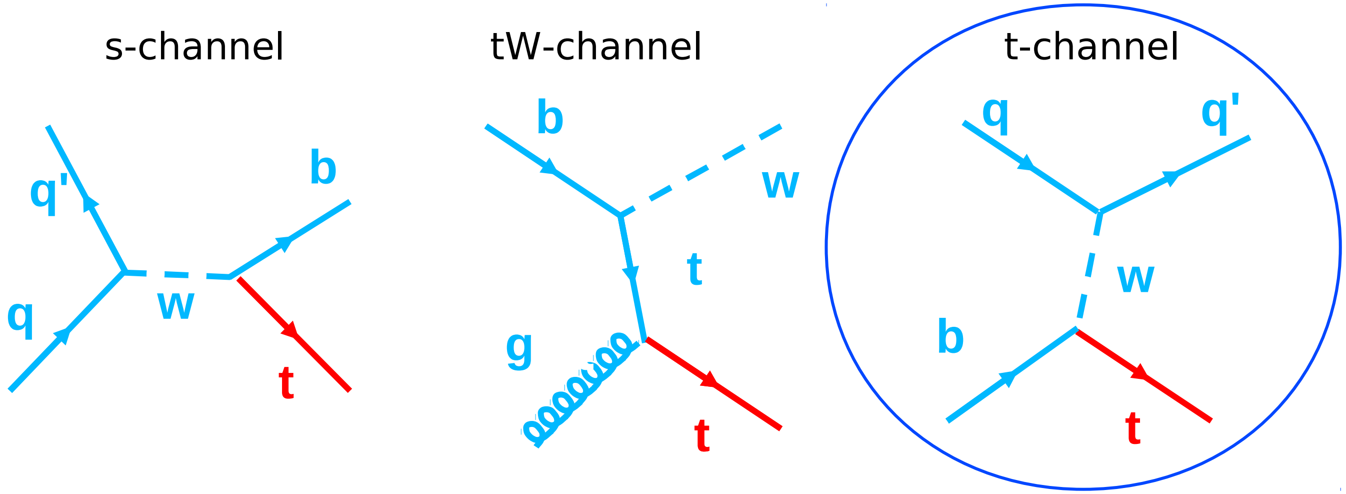
Up to July '11:
> 1 fb^{-1} on tape
peak instant luminosity:
1.57 nb^{-1} s^{-1}

Note: the analysis henceforth described uses the 2010 dataset.

Single top processes

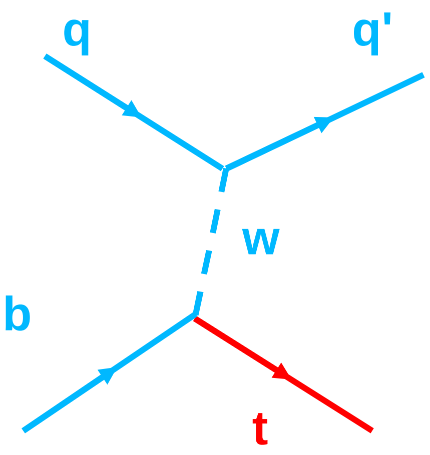
3 single top processes:

Focus on **t-channel**:
-highest cross section
-most favorable s/b ratio

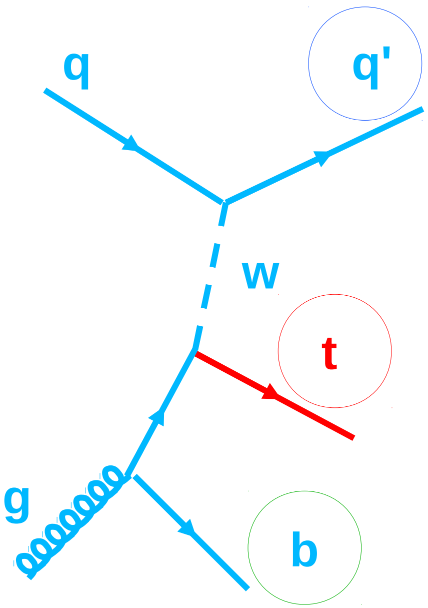


Cross sections(pb) (top mass =173)	***s-channel*** NLO, Phys. Rev. D 81, 054028 (2010), N. Kidonakis	***tW channel*** NNLO,Phys. Rev. D 82, 054018 (2010), N. Kidonakis	***t channel*** NNLO,Phys. Rev. D 83, 091503(R) (2011) N. Kidonakis	***$t\bar{t}$*** NNLO,arxiv.org/pdf/0909.0037 , N. Kidonakis
LHC: *pp* @7 TeV	4.59	15.6	63.2	165
Tevatron *$p\bar{p}$* @1.96 TeV	1.04	0.22 (arxiv.org/pdf/0909.0037)	2.08	7.2
LHC *pp* @14 TeV	11.9	83.6	243	894

Single top t-channel



(2) → (2)



(2) → (3)

light quark q' scattered at low angle wrt beam axis

t : decays to
$Wb \rightarrow bqq'$
$Wb \rightarrow bl\nu$

quark b :
low p_T → outside cuts acceptance

Main backgrounds ($t \rightarrow bl\nu$ decay mode):

- $t\bar{t}$ ($\sigma = 165$ pb): same kinematic region as t-channel
- **$W(\rightarrow l\nu)$+jets** ($\sigma \sim 31$ nb) : different behavior from $W+(u,s,d,g)$ and $W+(c,b)$
- **Multijet QCD** $\rightarrow l$ + jets : extreme kinematic regions → use data driven estimation

Analysis strategy

Baseline selection + QCD background estimation

(lepton, b-jet, light jet, M_T) (fit to M_T)

Top quark 4-momentum reconstruction

“2D analysis”
Based on template fits for signal extraction

“BDT analysis”
Multivariate analysis using boosted decision trees

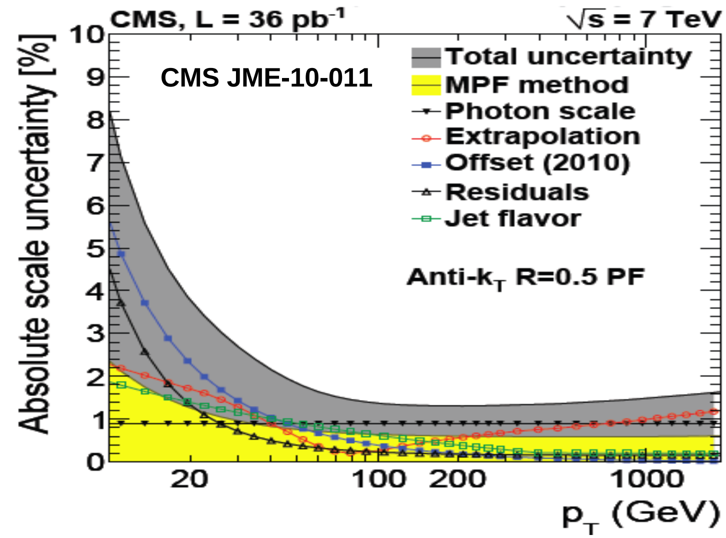
Combination of the results

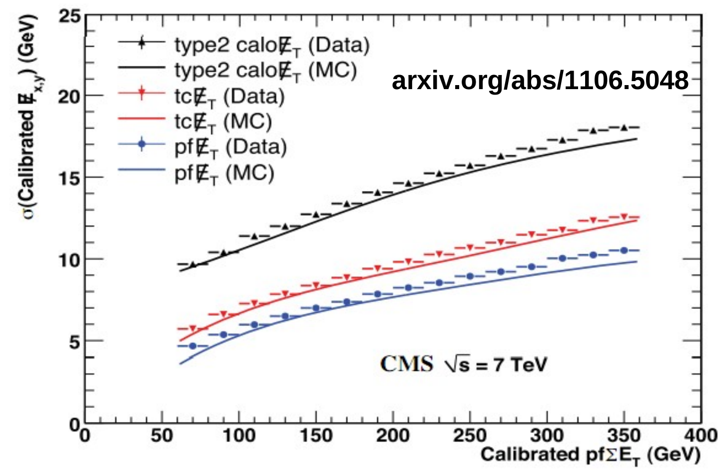
Event selection: physics objects and Particle Flow

- **Particle Flow:**
Algorithm which uses information from all the sub-detectors to reconstruct leptons, jets, missing energy.

- **JET momentum resolution** greatly benefits of the inclusion of the tracking system.

- **Missing energy resolution**
Increases due to Intrinsicly inclusive nature of the Particle Flow algorithm





Event selection

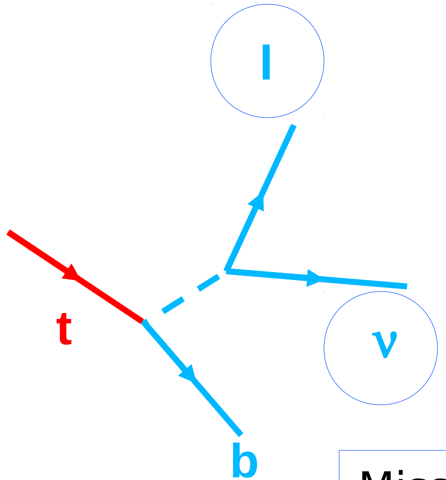
Leptons:

- **Exactly 1 muon(electron)** with p_T (E_T) > 20(30) GeV, $|\eta|$ < 2.1 (2.5)

- **relative isolation for the μ(e):**
  RelIso = (trackIso+ caloIso)/p_T(E_T) < 0.05(0.1)
  trackIso and caloIso are the sum of p_T of the tracks and of calorimetric deposits
  In a cone of $\Delta R = \sqrt{\Delta\Phi^2 + \Delta\eta^2} < 0.3$ around the lepton momentum

- **veto extra "loose" μ(e)** with p_T(E_T)>10(15) GeV and RelIso < 0.2

Only leptonic decays are considered ($t \rightarrow l b \nu$)

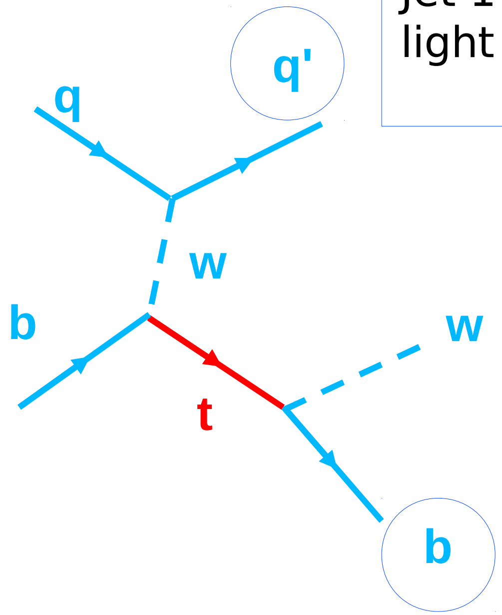


Missing energy due to neutrino.

Event selection

Jets

-Jets reconstructed through the anti-kt algorithm with 0.5 cones
-Exactly **2 jets with p_T > 30 GeV,|η|< 5**
- jets overlapping in $\Delta R < 0.1$ with electrons are discarded.
- veto leptons at $\Delta R < 0.3$ from jets



Jet 1 stems from the light quark q'

Jet 2 comes from top quark decay.

b-tagging

- exactly **1 b-tagged jet** using an algorithm that measures the impact parameter of tracks associated to the jet

- exactly **1 b-vetoed jet** using the same algorithm, with a looser requirement (2D only)

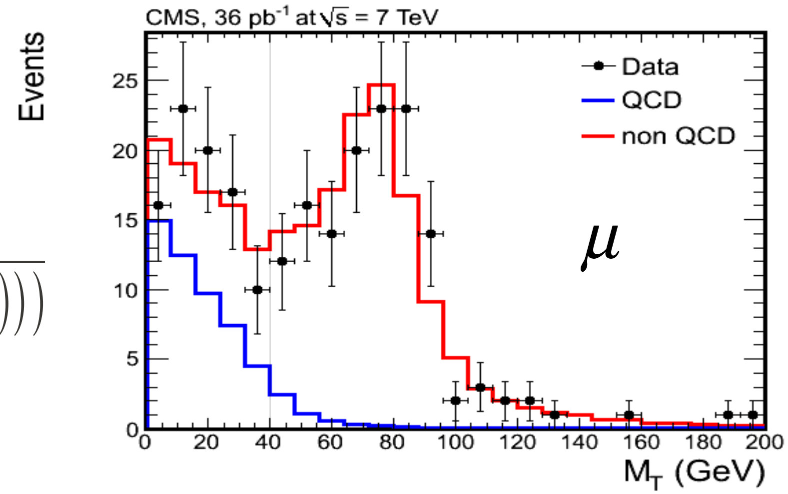
QCD estimation method

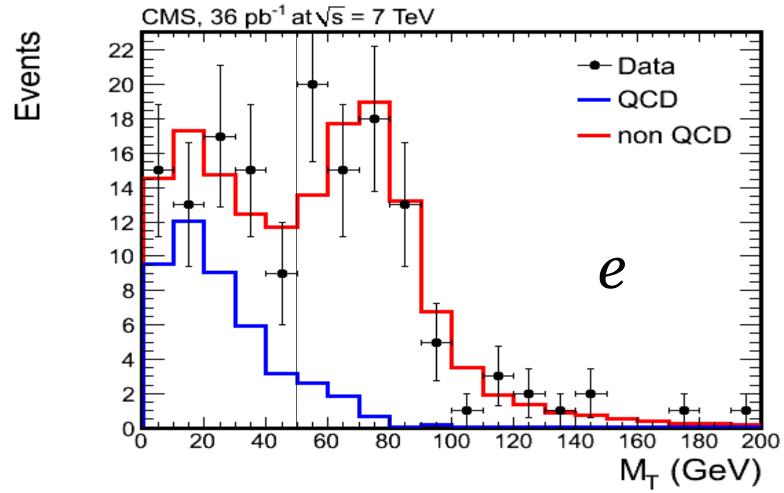
A maximum likelihood fit is performed on M_T defined as

$$M_T = \sqrt{\left(2 \cdot P_{T,lepton} \cdot MET \left(1 - \cos\left(\varphi_{lepton} - \varphi_{MET}\right)\right)\right)}$$

To determine the amount of QCD after all the cuts.

The shape of the QCD is extracted from an orthogonal control sample obtained **inverting the relIso cut**



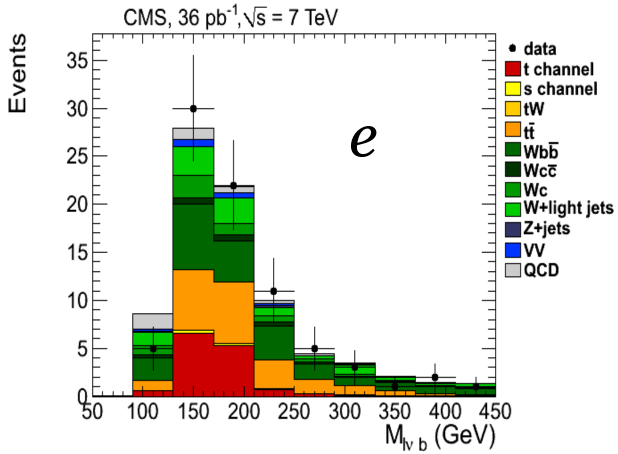


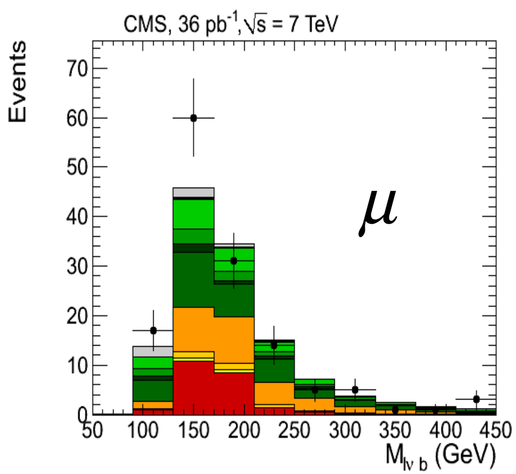
Selection and QCD fit results

Process	2D, μ channel	2D, e channel	BDT, μ channel	BDT, e channel
single top, t channel	17.6 ± 0.7 (†)	11.2 ± 0.4 (†)	17.6 ± 0.7 (†)	10.7 ± 0.5 (†)
single top, s channel	0.9 ± 0.3	0.6 ± 0.2	1.4 ± 0.5	1.0 ± 0.3
single top, tW	3.1 ± 0.9	2.4 ± 0.7	3.8 ± 1.1	< 0.1
WW	0.29 ± 0.09	0.23 ± 0.07	0.32 ± 0.10	0.23 ± 0.07
WZ	0.24 ± 0.07	0.17 ± 0.05	0.33 ± 0.10	1.5 ± 0.4
ZZ	0.018 ± 0.005	0.011 ± 0.003	0.020 ± 0.006	< 0.1
$W+$ light partons	18.2 ± 5.5	11.6 ± 2.3	8.4 ± 4.2	7.0 ± 3.5
$Z+X$	1.7 ± 0.5	1.6 ± 0.3	0.7 ± 0.2	0.05 ± 0.03
QCD	0.6 ± 0.3	$2.6^{+3.4}_{-2.6}$	4.9 ± 2.5	5.3 ± 5.3
$VQ\bar{Q}$	20.4 ± 10.2	14.1 ± 7.1	17.6 ± 8.8	11.7 ± 5.8
Wc	$12.9^{+12.9}_{-6.5}$	$9.4^{+9.4}_{-4.7}$	$9.2^{+9.2}_{-4.6}$	$5.9^{+5.9}_{-2.9}$
$t\bar{t}$	20.3 ± 3.6	15.6 ± 2.8	34.9 ± 4.9	22.9 ± 3.2
Total background	78.6 ± 15.2	58.4 ± 11.0	82.4 ± 13.1	55.9 ± 10.2
Signal + background	96.2 ± 15.3	69.6 ± 11.0	100.0 ± 13.2	66.6 ± 10.2
Data	112	72	139	82

- S/B ratio ~ 1/4 , 1/5
- Some differences in the BDT / 2D event yield:
  - Different algorithms used for physics objects reconstruction
  - 2D analysis: partially derives W normalization from orthogonal samples
  - BDT analysis: no second b-veto, extra cuts o n $\Delta\Phi > 0.3$

Top quark 4-momentum reconstruction





(plots from BDT selection)

Reconstructed taking 4 momenta of the lepton and the b-tagged jet and the MET:

1) take **$(p_{x,\nu}, p_{y,\nu}) = (MET_x, MET_y)$**

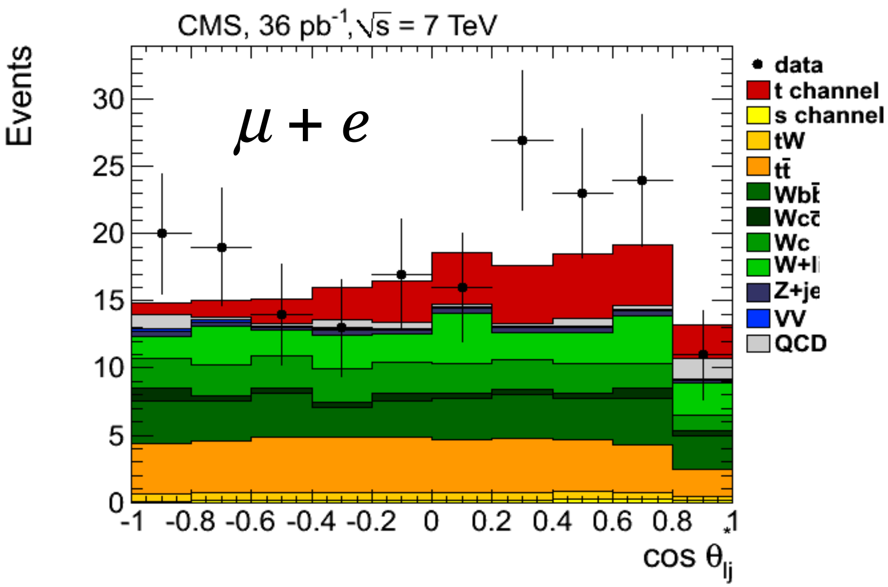
2) costrain the mass of the lν pair In to the PDG value of M_w : **get 2ndorder equation in $p_{z,\nu}$**

3)two real solutions:take the one with lowest $|p_{z,\nu}|$

4)two imaginary solutions: put discriminant to 0. In this case the 1) is not valid anymore, but **we can still impose 2**.

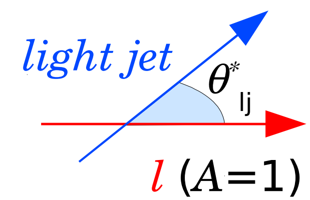
5)Chose $p_{x,\nu}$,$p_{y,\nu}$ with minimum distance from the MET in the p_x/p_y plane

2D analysis: $\cos\theta_{lj}^{*}$ and η_{lj}



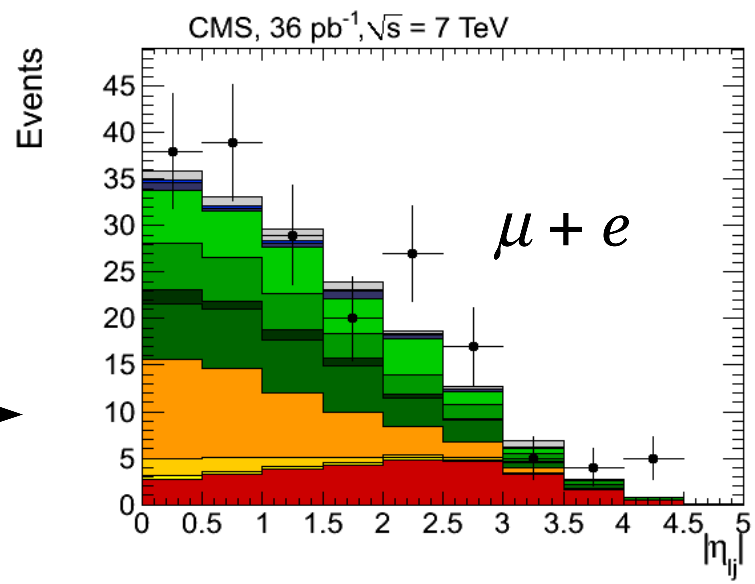
100 % left (right) **polarization** of $t(\bar{t})$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^{*}_{lj}} = \frac{1}{2}(1 + A\cos\theta^{*}_{lj})$$

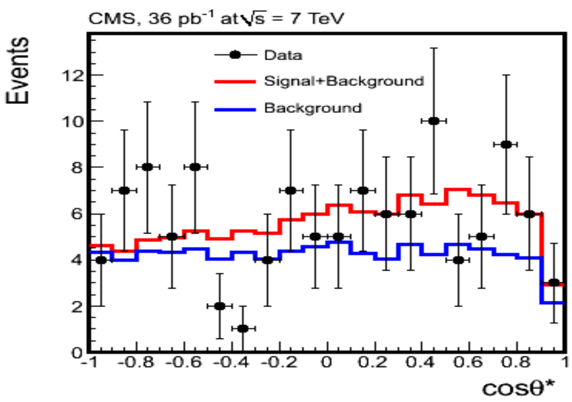


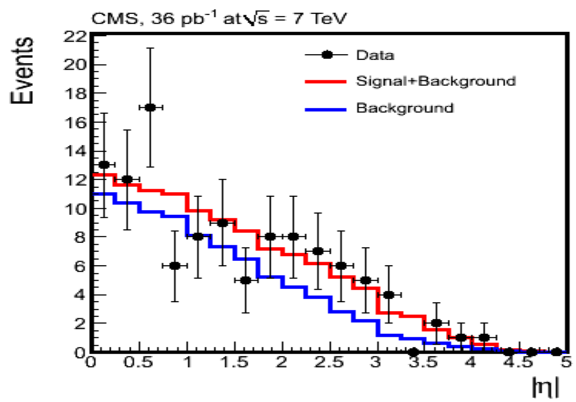
light quark recoiling against much more massive top: non central distribution of η_{lj}

- High discriminating power
- model – independent.



2D analysis: fit to the 2D templates





Muon only fit:

$$\sigma_\mu = 104.1 \pm 42.3(stat)^{+24.8}_{-28.0}(syst)\,pb^{-1}$$

$$Events = 27.7$$

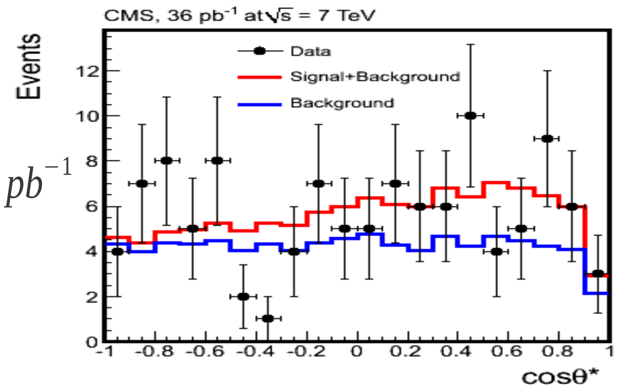
Extended Maximum Likelihood fit to the 2D template of cosθ* and $|\eta_{lj}|$.

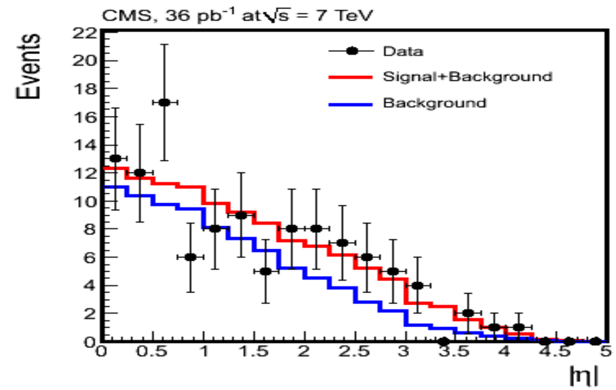
Dice pseudo-experiment to evaluate impact instrumental and theoreticals ystematics

Electron only fit:

$$\sigma_\mu = 154.2 \pm 56.0(stat)^{+40.6}_{-40.6}(syst)\,pb^{-1}$$

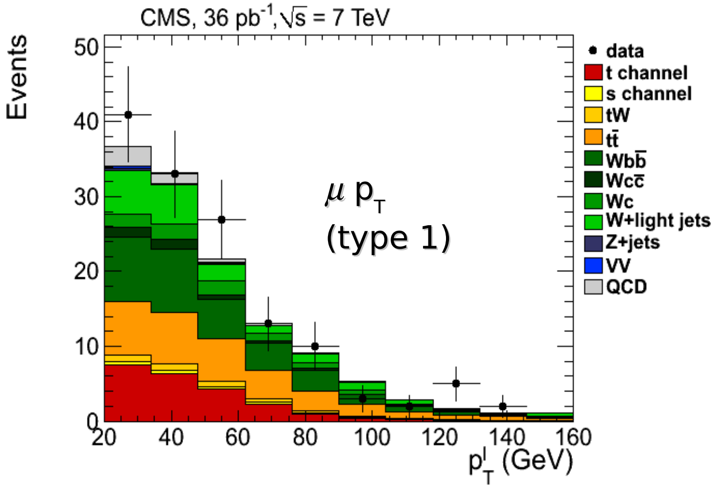
$$Events = 25.9$$

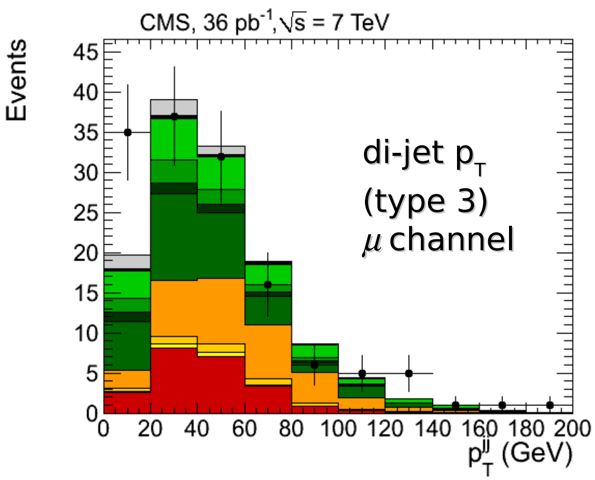


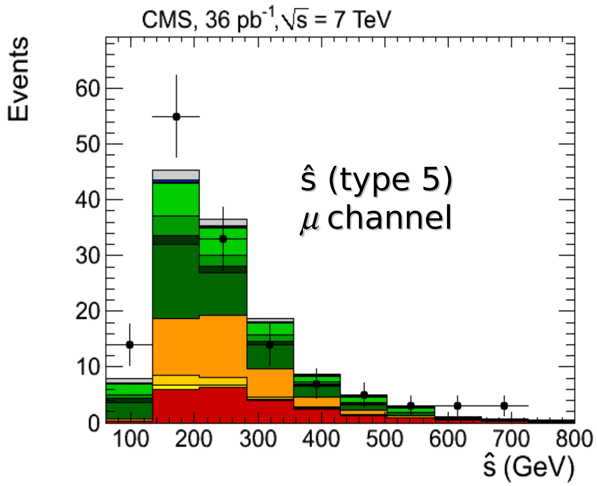


BDT analysis: choice of the variables

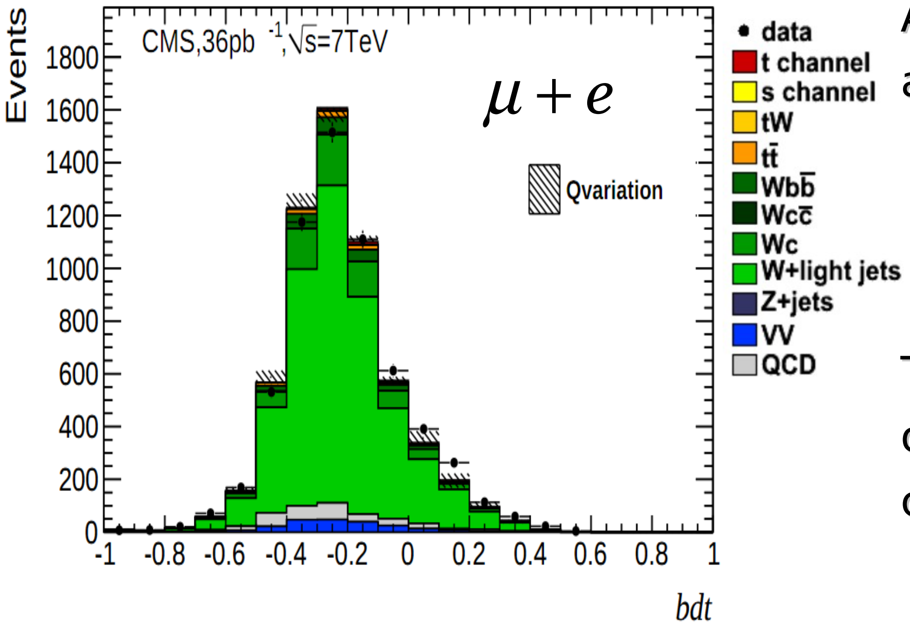
- 37 variables combined → 1 discriminator
  with Boosted Decision Trees
- five categories :
  1) Kinematic variables (lepton and jets p_T,η etc)
  2) Properties of correlation between objects in 1)
  3) Combination of objects in 1)
  4) Angular properties (e.g.: $\cos\theta_{lj}$)
  5) Overall event properties (total E_T, sphericity)







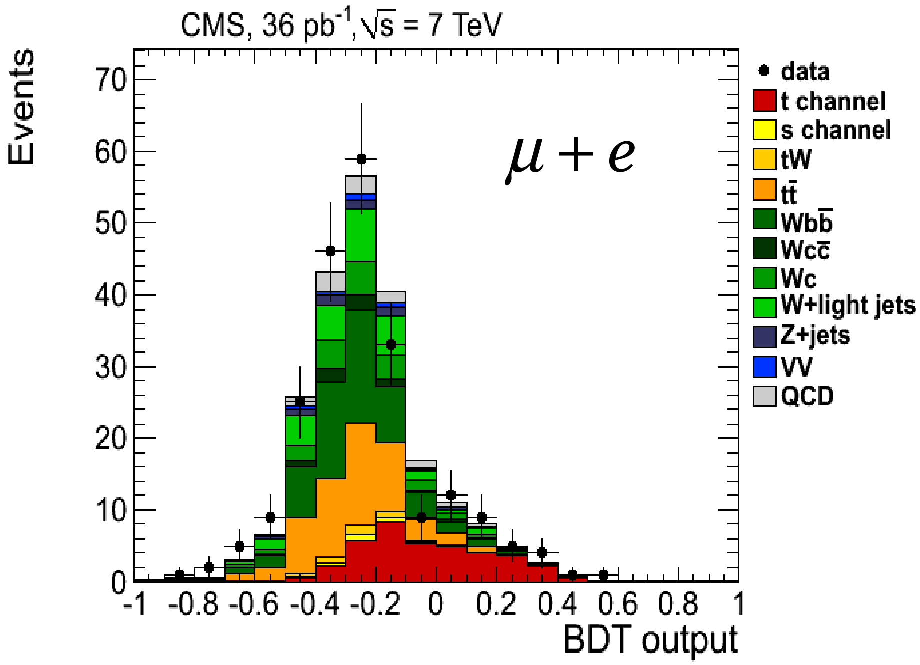
BDT analysis: validation on data



All variables and BDT output validated in a control region with 0 b-tagged jets

The effect of systematics, like the scaling of the Q^2 of the interaction, could be checked on such orthogonal sample

BDT analysis: Signal extraction



Background rates and systematics effects parametrized as **nuisance parameters.**

Signal was extracted by **marginalization of the nuisance parameters** using Markov Chain Monte Carlo technique

Muon:

$$\sigma_{\mu} = 89.8 \pm 40.4 \, (stat + syst) \, pb^{-1}$$

Electron:

$$\sigma_{\mu} = 59.2 \pm 37.8 \, (stat + syst) \, pb^{-1}$$

Impact of systematics

- Most important sources of uncertainty:

- **b-tagging**
- **Q^2 scaling**
- **JES**

- Other notable sources:

- Different signal generators (LO matched vs NLO)
- Different hadronization models
- Different initial and final state radiation scenarios

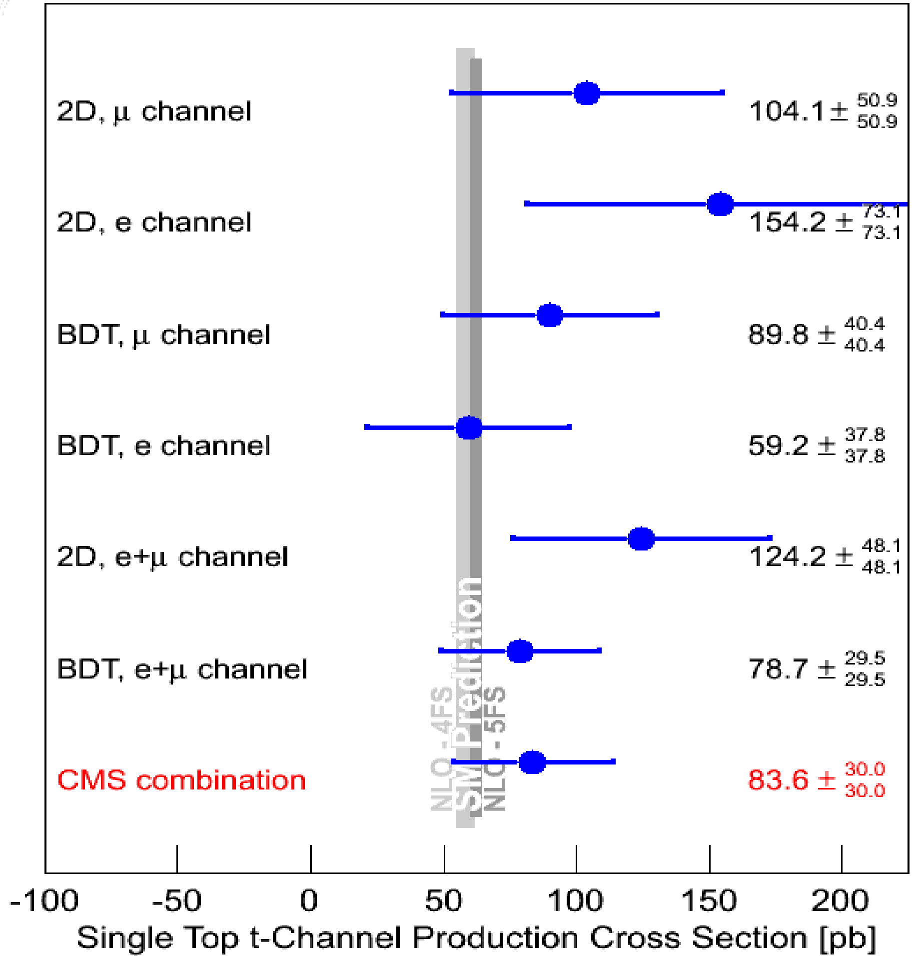
uncertainty	correlation	impact on 2D −	impact on 2D +	impact on BDT −	impact on BDT +
statistical only	60	52		39	
shared shape/rate uncertainties:					
ISR/FSR for $t\bar{t}$	100	−1.0	+1.5	< 0.2	< 0.2
Q^2 for $t\bar{t}$	100	+3.5	−3.5	+0.3	−0.4
Q^2 for V+jets	100	+5.7	−12.0	+2.6	−4.5
Jet energy scale	100	−8.8	+3.6	−5.1	+1.2
b tagging efficiency	100	−19.6	+19.8	−15.2	+14.6
MET (uncl. energy)	100	−5.7	+3.7	−3.9	−0.5
shared rate-only uncertainties:					
$t\bar{t}$ (±14%)	100	+2.0	−1.9	+0.5	−0.6
single top s (±30%)	100	−0.4	+0.5	−0.4	+0.4
single top tW (±30%)	100	+1.1	−1.0	< 0.2	< 0.2
$Wb\bar{b}$, $Wc\bar{c}$ (±50%)	100	−3.0	+2.9	+1.7	−1.9
Wc ($^{+100\%}_{-50\%}$)	100	−3.0	+6.1	−2.4	+4.4
Z+jets (±30%)	100	−0.6	+0.7	+0.4	−0.2
electron QCD (BDT: ±100%, 2D: $^{+130\%}_{-100\%}$)	50	+2.9	−3.7	−1.7	+1.7
muon QCD (BDT: ±50%, 2D: ±50%)	50	< 0.2	< 0.2	−2.1	+2.1
signal model	100	−5.0	+5.0	−4.0	+4.0
BDT-only uncertainties:					
electron efficiency (±5%)	0	—	—	−1.4	+1.4
muon efficiency (±5%)	0	—	—	−3.6	+3.5
V+jets (±50%)	0	—	—	−1.5	< 0.2
2D-only uncertainties:					
muon W+light (±30%)	0	−1.4	+1.4	—	—
electron W+light (±20%)	0	−0.6	+0.7	—	—
W+light model uncertainties	0	−5.4	+5.4	—	—

Combination: Correlation of the analyses

- Correlation evaluated drawing **pseudo-experiments** from the overlapping datasets

- Differences in the BDT / 2D :
  - Event selection
  - Data-driven shape and background normalization extraction for 2D

- Most important systematics 100% correlated between 2D-BDT



Combined results and V_{tb} extraction

Measured cross section:

$$\boxed{\sigma = 83.6 \pm 29.8\,(stat+syst) \pm 3.3\,(lumi)\; pb}$$

Standard model prediction :

$$\sigma = 64.57^{+2.09}_{-0.71}\,(scale)^{+1.51}_{-1.74}\,(pdf)\; pb$$

with a significance of **3.7(3.5)** standard deviations for the 2D (BDT) analysis.

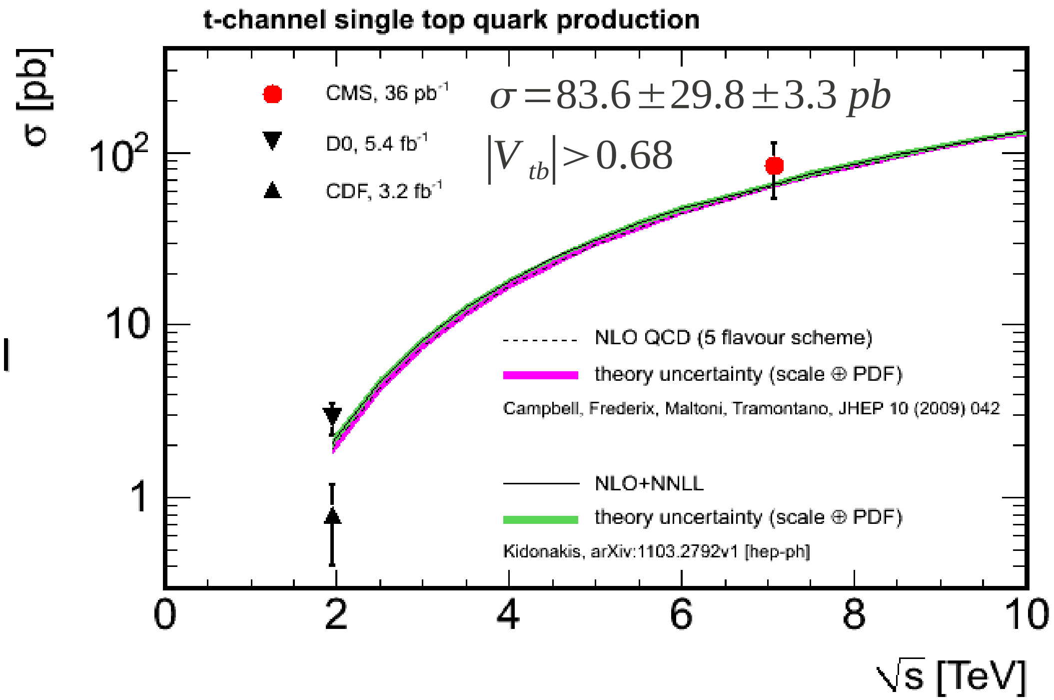
Assuming $|V_{td}|,|V_{ts}| \ll |V_{tb}|$ yields $|V_{tb}| = \sqrt{\frac{\sigma^{exp}}{\sigma^{th}}}$ and: $\boxed{|V_{tb}| = 1.14 \pm 0.22\,(\exp) \pm 0.02\,(th)}$

Taking $0<|V_{tb}|\leq 1$ yields a lower limit at 95% confidence level of $\boxed{|V_{tb}| > 0.62\,(0.68)}$ for the 2D(BDT) analysis respectively

Conclusions

In 2010 with 36 pb^{-1} of data:

- Evidence of single top t-channel
- Cross section measurement consistent with the standard model prediction
- Measurement of $|V_{tb}|$



Higher statistics and rich opportunities for single top studies in 2011:

- t-channel properties like charge asymmetry, differential cross section ...
- Study of other single top channels, FCNC, W' resonances and much more ...

THANKS!

Backup slides

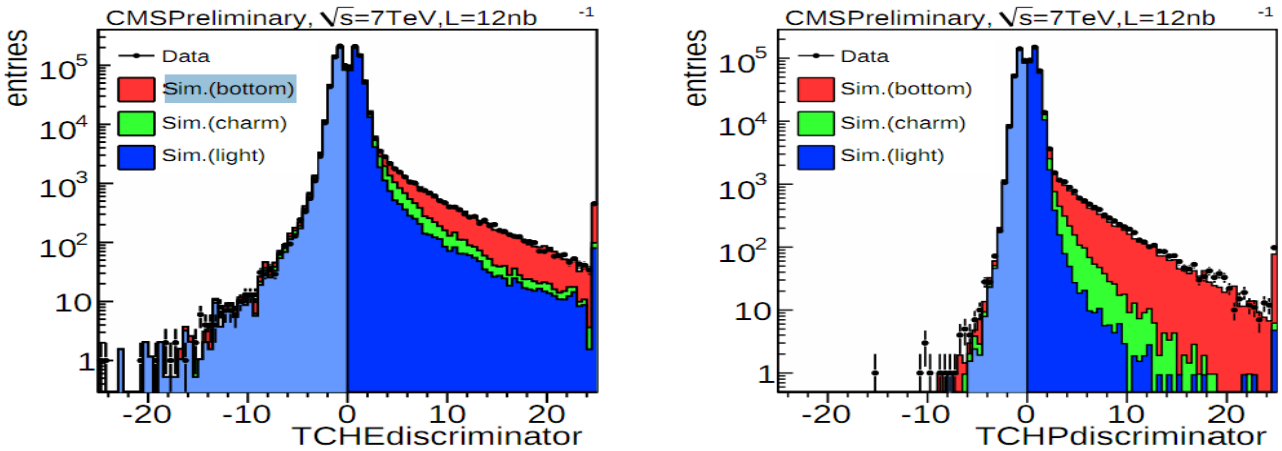
Physics object reconstruction: b-tagging

- **b jets** stem from decays of long lived B mesons, coming from by b quarks produced in the pp interaction

- **They can be identified** since the vertex of the particles that compose such jet differs from the primary interaction vertex

- **Track Counting algorithms**
Used in the presented analysis counts the 2(3) best tracks associated to the jets and uses as high efficiency(purity) discriminator the the lowest value of the significance of the impact parameter amongst the two(three)

TC distribution →
data-mc comparison



Physics object reconstruction: Particle Flow

- **Particle Flow** is the algorithm used to reconstruct physics objects in the presented analysis

- **Each physics object** is reconstructed using information from all sub-detectors of CMS

- **Muons** have the cleanest signature and are identified first: they pass through the muon detector of CMS and can be discriminated from other particles

- **Electrons** are identified after muons through their releases in the Electromagnetic calorimeter in association to a track and through tight quality cuts

- **Jets** are reconstructed with the anti-kt algorythm taking information from all the sub-detectors. Jets are required not to overlap with the already identified muons and electrons and pass through quality cuts

- **Missing energy** in PF can be measured taking into account all information From sub-detectors in a coherent way

Single top t-channel: backgrounds

Main processes reproducing the same event topology:

- $t\bar{t}$ (cross section: 165 pb):

- $t\bar{t} \rightarrow bl\nu\; bqq'$: two of the jets not passing the transverse momentum or quality cuts.

- $t\bar{t} \rightarrow bl\nu\; bl\nu$: the second lepton is outside the detector acceptance/not identified.

Remarks: one top has same decay chain as single top.

- ***W*+jets** (cross section 31314 pb with MCFM):

- W + light partons (u,d,s quarks,gluon) → $l\nu+$jets, one of the jets reproduces the behavior of a b-jet.

- W + heavy partons (c,b quarks) → $l\nu+$jets.

Remarks: W + light partons and W + heavy partons have different behavor, high cross section with respect to single top.

- **Multijet QCD** → l + jets

Remarks: high cross section with respect to single top, signal region in the tail of Monte Carlo distributions → data driven methods to keep it under control

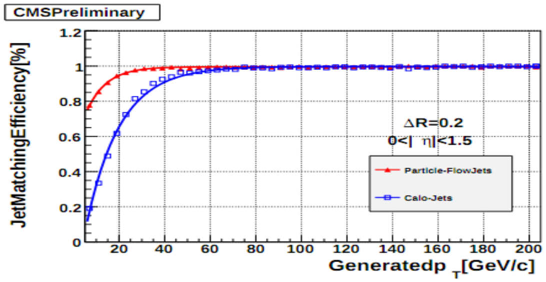
Systematics sources and effects

Type	Source	Affects	Correlation 2D-BDT
Theoretical and modeling	Q2 of the interaction, $t\bar{t}$ and WJets	Background event selection, distributions	100%
	Initial/Final state radiation, $t\bar{t}$	Event selection, distributions	100%
	Background processes ($t\bar{t}$, W+Jets, etc) rate	Background normalizations, overall variables distributions, Signal extraction	100%
	Signal model	Signal event selection and distribution, signal extraction	100%
Instrumental	Jet energy scale	Event selection, distributions	100%
	b-tagging	Event selection, distributions	100%
	Unclustered missing energy	Event selection, distributions	100%
	Lepton efficiencies	Event selection, distributions	100%
Analysis specific	Data driven procedures (e.g.: QCD estimation)	Signal extraction	Uncorrelated or conservative 50%

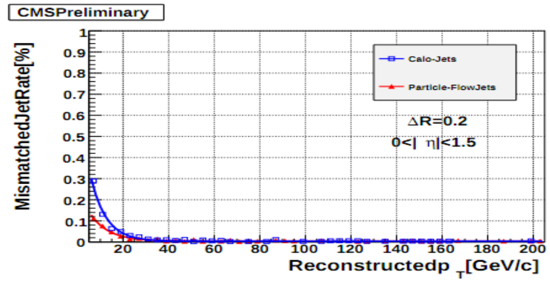
- Most of the systematics are shared by both analyses and 100% correlated

- Most of them are 100% correlated between μ and e channels.

Physics object reconstruction: Particle Flow performances



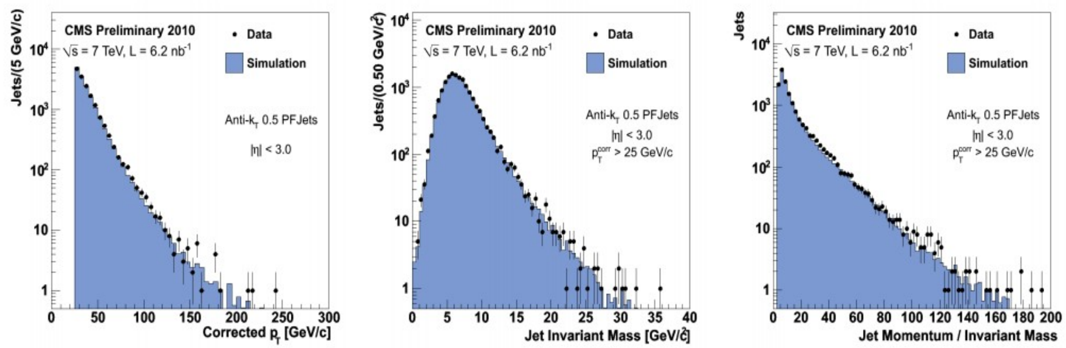
(a) $\Delta R = 0.2$

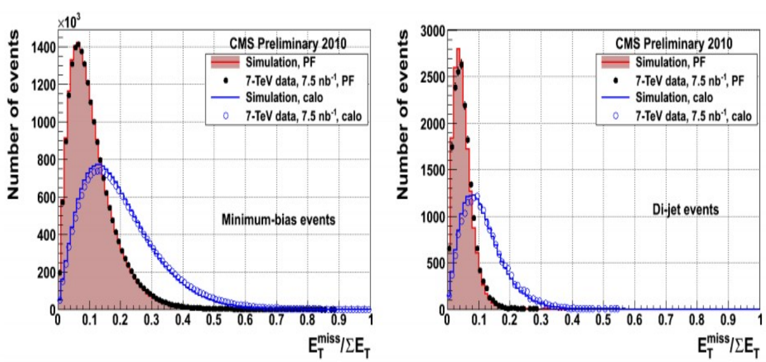


(b) $\Delta R = 0.2$

← PF **Jets** matching efficiency (MC)

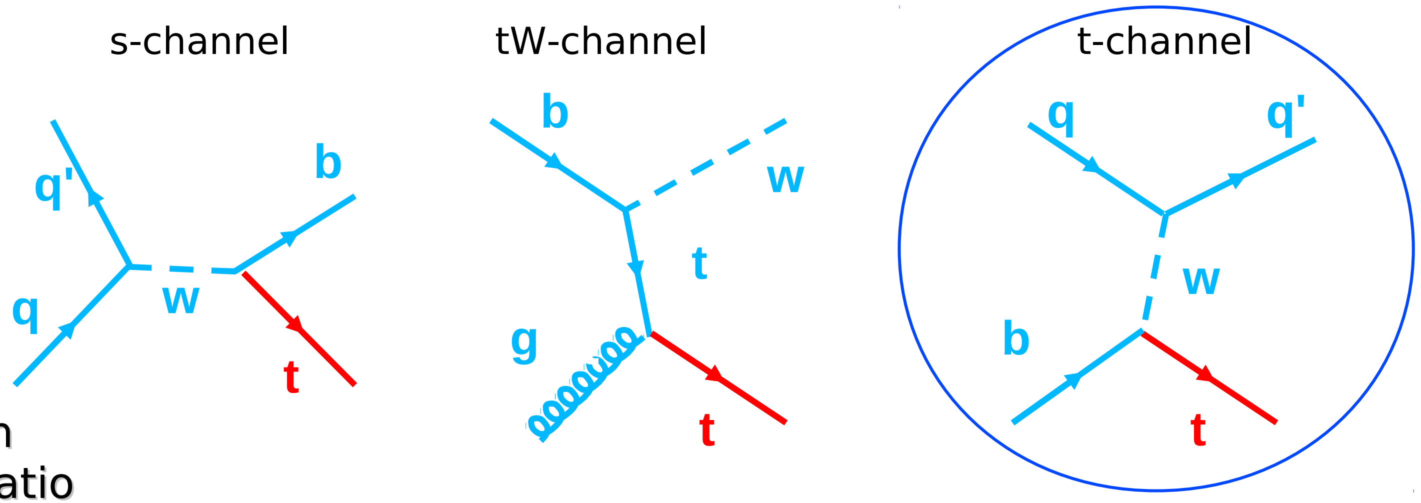
PF Jets data-mc comparison → on minimum bias data





← **Transverse missing energy** relative resolution

Single top t-channel physics



Focus on
t-channel:

-highest cross section
-most favorable s/b ratio

most suitable for early, low statistics studies

Physics of *t*-channel:

- $\sigma_{(\text{t-channel})}$ related to CKM element Vtb
- asymmetry in the production of $t\backslash\bar{t}$
- sensitive to W'
- study of Flavour Changing Neutral Currents

QCD estimation method: Cut optimization

A maximum likelihood fit is performed on M_T defined as

$$M_T = \sqrt{\left(2 \cdot P_{T,lepton} \cdot MET \left(1 - \cos\left(\varphi_{lepton} - \varphi_{MET}\right)\right)\right)}$$

To determine the amount of QCD after all the cuts.

The cut on MT after optimizing the figure of merit:

$$W / \sqrt{\left(W + Q + k^2 Q^2\right)}$$