



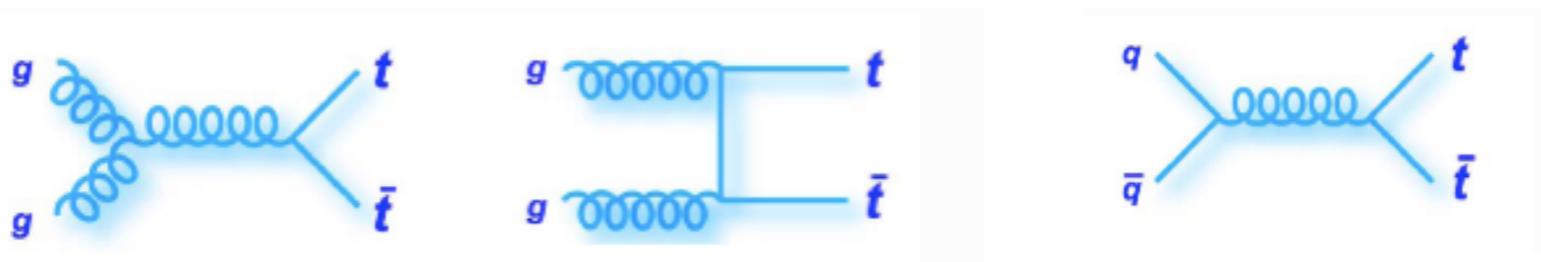
# Top pair cross section with lepton+jets

Anne-Catherine Le Bihan - IPHC Strasbourg  
LHC-France, 2-6 april 2013



# Top pair production at the LHC

- $t\bar{t}$  production dominated by gluon fusion at the LHC ( $\sim 85\%$  @ 7 & 8 TeV) :



- Results presented in this talk compared to approx. NNLO :

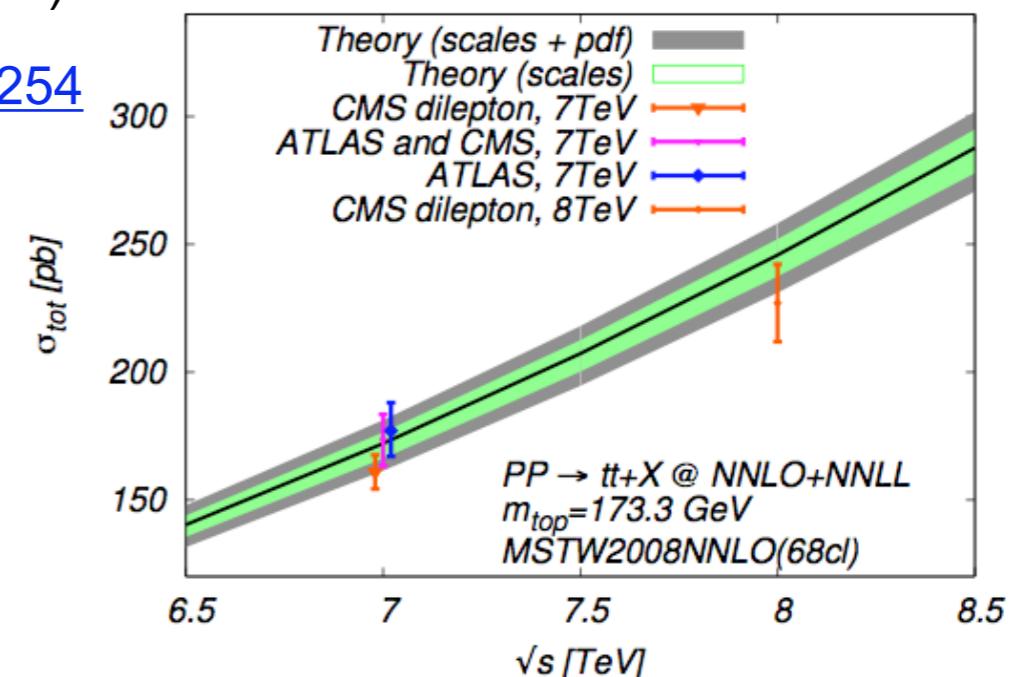
[arXiv:1208.5578](https://arxiv.org/abs/1208.5578)

	LHC 7 TeV	LHC 8 TeV
$\sigma(t\bar{t})$ [pb]	$163^{+7}_{-5} \pm 9$	$234^{+10}_{-7} \pm 12$

- Full NNLO+NNLL (including NNLO correction for  $gg \rightarrow t\bar{t}$ ) calculation now available :

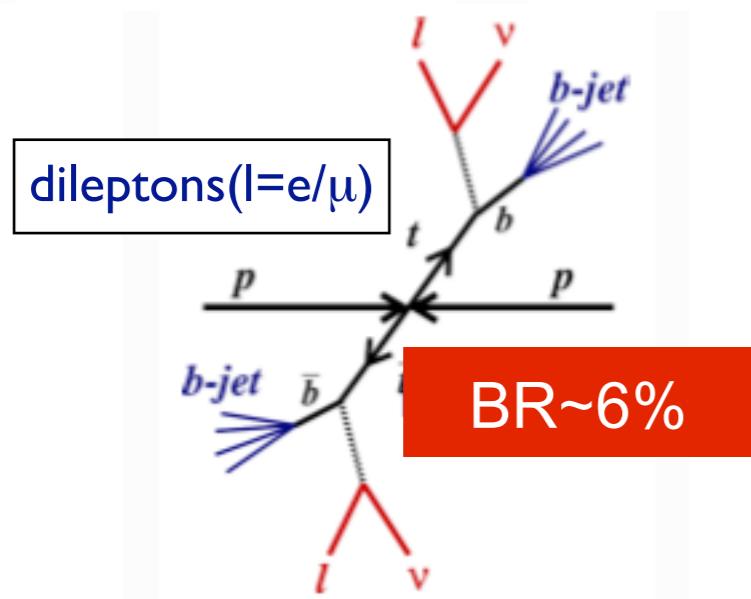
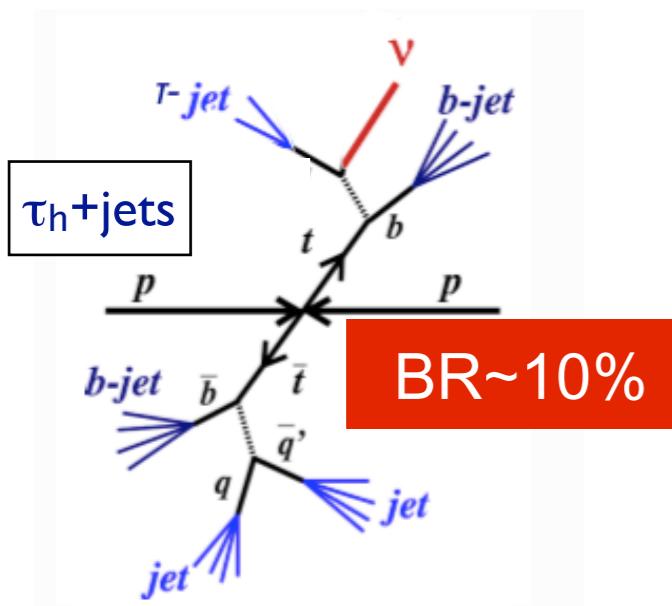
[arXiv:1303.6254](https://arxiv.org/abs/1303.6254)

Collider	$\sigma_{\text{tot}}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) -0.200(2.8%)	+0.169(2.4%) -0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) -5.8(3.4%)	+4.7(2.7%) -4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) -8.4(3.4%)	+6.2(2.5%) -6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) -33.9(3.6%)	+16.2(1.7%) -17.8(1.9%)

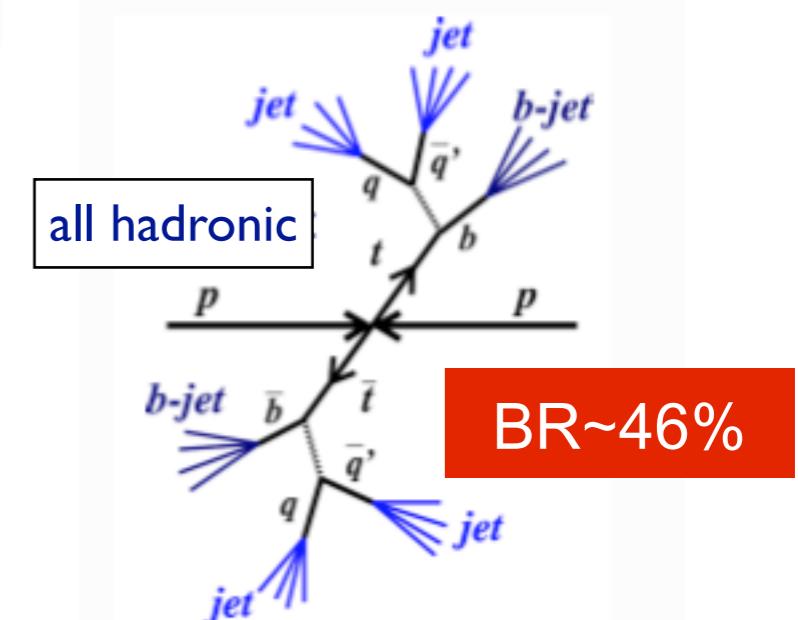
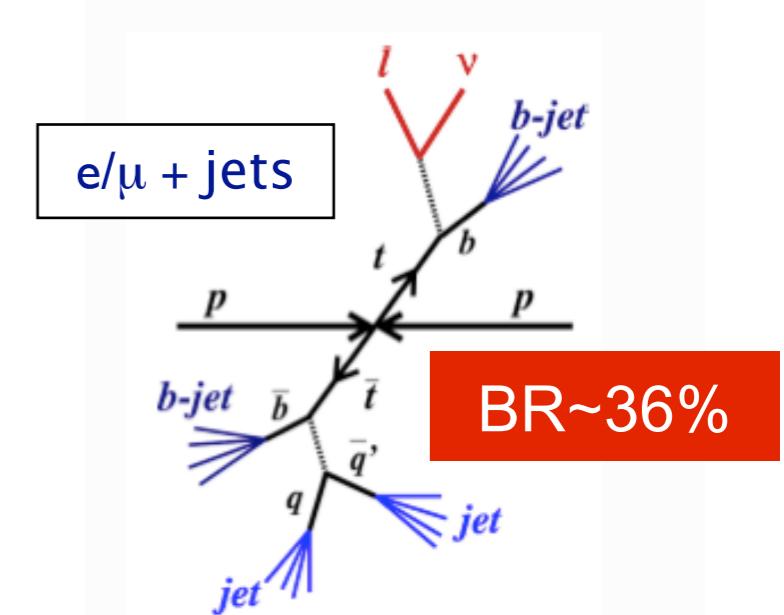
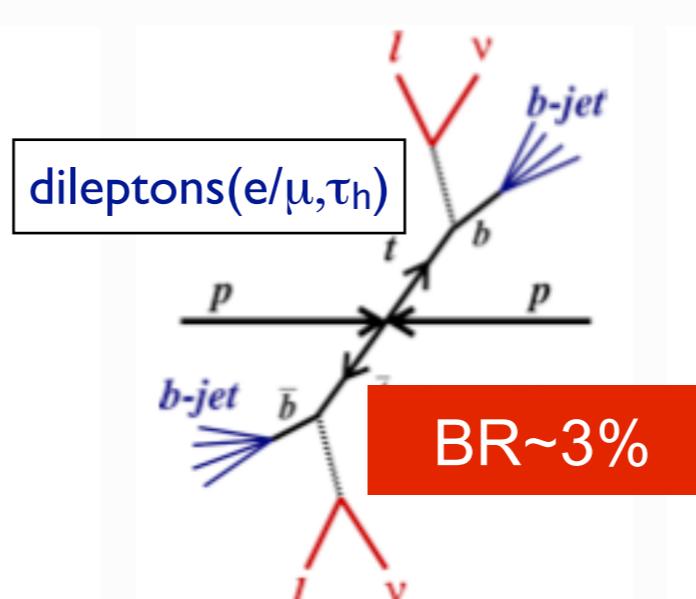


# Top pairs in lepton+jets

- We identify top pairs mainly through the top decay :  $t \rightarrow W b$ ,  $BR \sim 100\%$  in SM



$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic
$\bar{u}d$				
$e\tau$	electron+jets	muon+jets	tau+jets	all-hadronic
$\mu\tau$				
$e\mu$	dileptons	muon+jets		
$\mu\tau$				
$e\tau$	dileptons	electron+jets		
$\nu$ decay	$e^+$	$\mu^+$	$\tau^+$	$u\bar{d}$
				$c\bar{s}$



- ATLAS and CMS have measured  $t\bar{t}$  in all final states (except in  $\tau_h\tau_h$ )
- In this talk : cross section measurements in  $e/\mu + \text{jets}$  and  $\tau_h + \text{jets}$  !

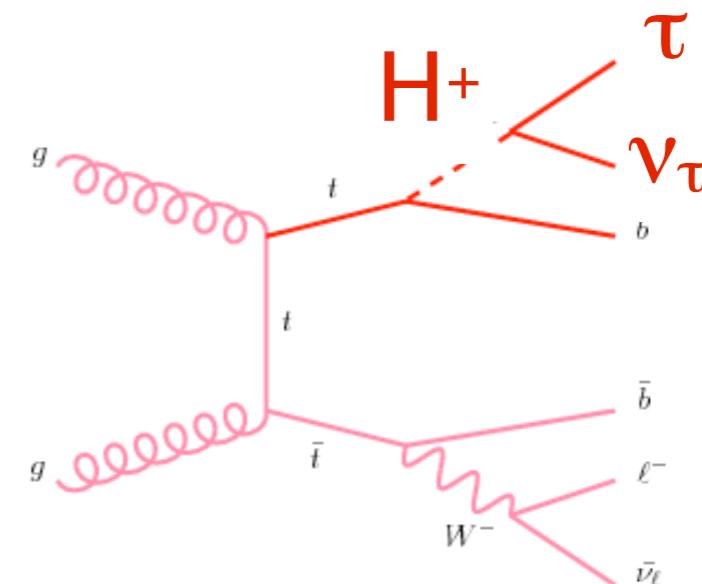
# Top pair cross section measurement in $\tau_h + \text{jets}$

CMS : [arXiv:1301.5755](https://arxiv.org/abs/1301.5755), submitted to EPJC (7 TeV, L=3.9 fb<sup>-1</sup>)

ATLAS : [EPJC 73 3 \(2013\) 2328](https://doi.org/10.1140/epjc/s10050-013-2328-1) (7 TeV, L =1.67 fb<sup>-1</sup>)

# Motivation

- Important background to charged Higgs searches



- Cross section in di-lepton final states including a  $\tau$  lepton already measured at the LHC

[CMS : Phys. Rev. D 85 \(2012\) 112007](#)

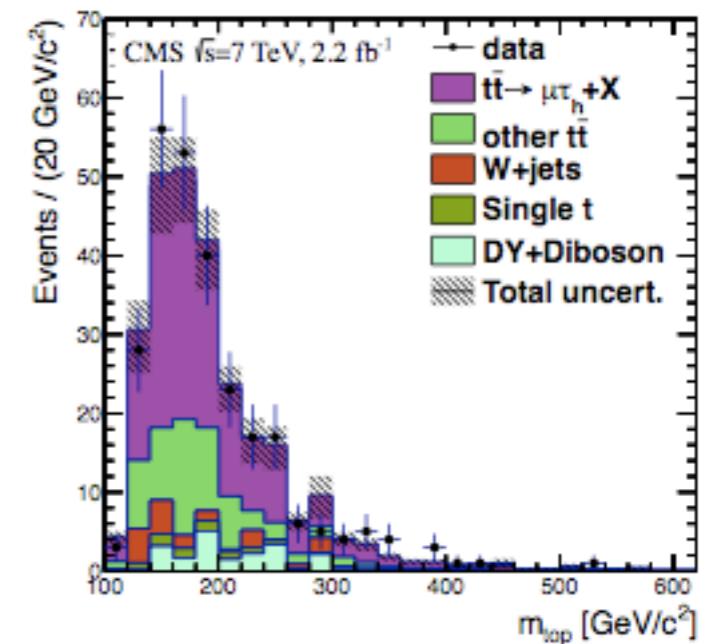
$$\sigma_{t\bar{t}} = 143 \pm 14 \text{ (stat.)} \pm 22 \text{ (syst.)} \pm 3 \text{ (lumi.) pb}$$

18%

[ATLAS : Phys. Lett. B 717 \(2012\) 89-108](#)

$$\sigma_{t\bar{t}} = 186 \pm 13 \text{ (stat.)} \pm 20 \text{ (syst.)} \pm 7 \text{ (lumi.) pb}$$

13%

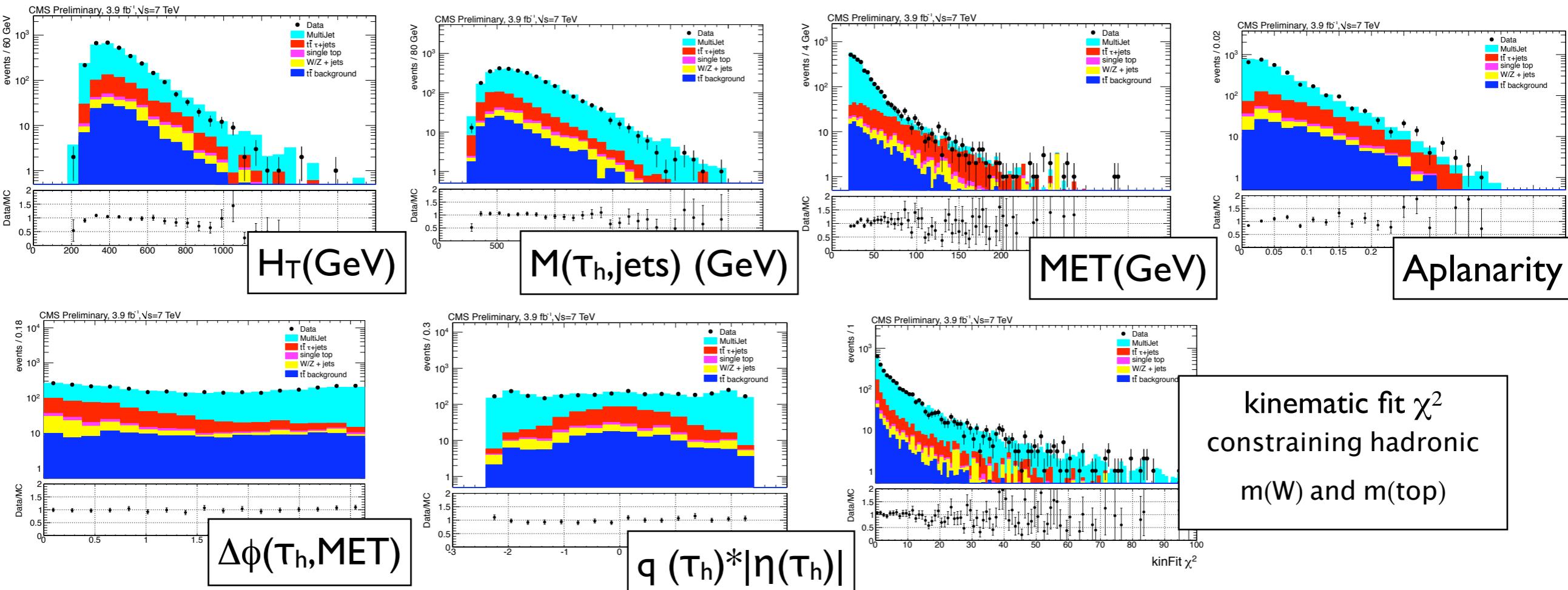


isolated e/ $\mu$  +  $\tau_h$  + 1 b-jet  
largest background :  $\tau_h$  fakes

- But  $t\bar{t} \rightarrow \tau_h + jets$  is the largest contribution including a  $\tau$  in the final state

# $t\bar{t} \rightarrow \tau_h + \text{jets}$ – analysis strategy

- Dedicated trigger : 4 jets ( $E_T > 40/45$  GeV), one identified as  $\tau_h$ , particle flow used online for  $\tau$ -id
- Final state preselection :
  - 3 jets,  $E_T > 45$  GeV + 1 jet,  $E_T > 20$  GeV
  - 1  $\tau_h$ ,  $E_T > 45$  GeV (HPS)
  - dedicated MVAs to separate  $\tau_h$  from e/ $\mu$
  - lepton veto
  - $\text{MET} > 20$  GeV
  - at least one b-jet (Jet Probability)
- High fake rate for  $\tau_h$ , neural network approach with 7 variables :

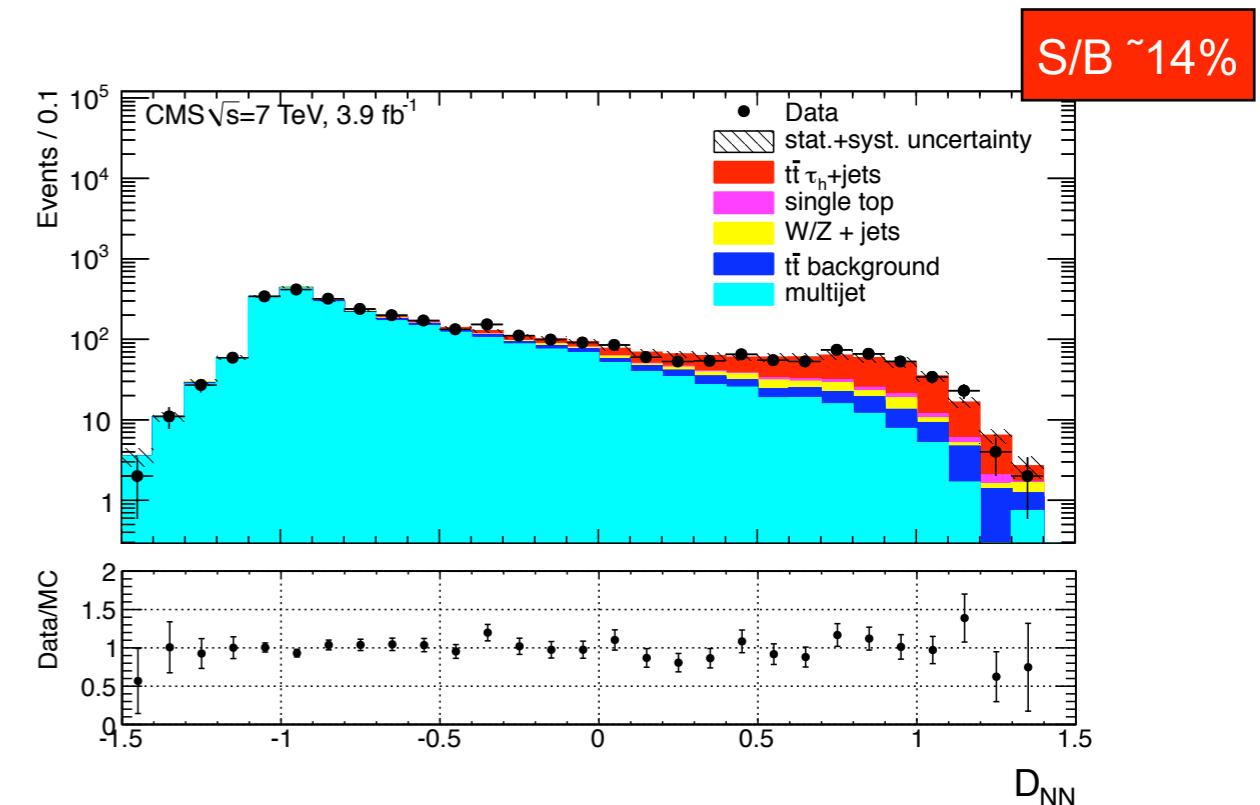


# $t\bar{t} \rightarrow \tau_h + \text{jets}$ – signal extraction

$L_{\text{int}} = 3.9 \text{ fb}^{-1}$

- Signal yield extracted using a template fit to the NN output distribution :

Source	Events
Signal $t\bar{t} \rightarrow \tau_h + \text{jets}$	$383 \pm 29 \text{ (fit)}$
Multijet	$2392 \pm 29 \text{ (fit)} \pm 120 \text{ (syst.)}$
Other $t\bar{t}$	$151 \pm 4 \text{ (stat.)} \pm 37 \text{ (syst.)}$
$W + \text{jets}$	$62 \pm 8 \text{ (stat.)} \pm 14 \text{ (syst.)}$
Single top	$41 \pm 1 \text{ (stat.)} \pm 8 \text{ (syst.)}$
$Z + \text{jets}$	$21 \pm 2 \text{ (stat.)} \pm 4 \text{ (syst.)}$
Total backgrounds	$2667 \pm 31 \text{ (stat.)} \pm 127 \text{ (syst.)}$
Data	3050



- Important multijet background, modelled from 0-b-tagged sideband, EWK backgrounds from MC

# $t\bar{t} \rightarrow \tau_h + \text{jets}$ – cross section measurement

- Cross section & branching ratio measurements :

$$\sigma_{t\bar{t}} = \frac{N - N_B}{A_{\text{tot}} \cdot \mathcal{B} \cdot \int \mathcal{L} dt}$$

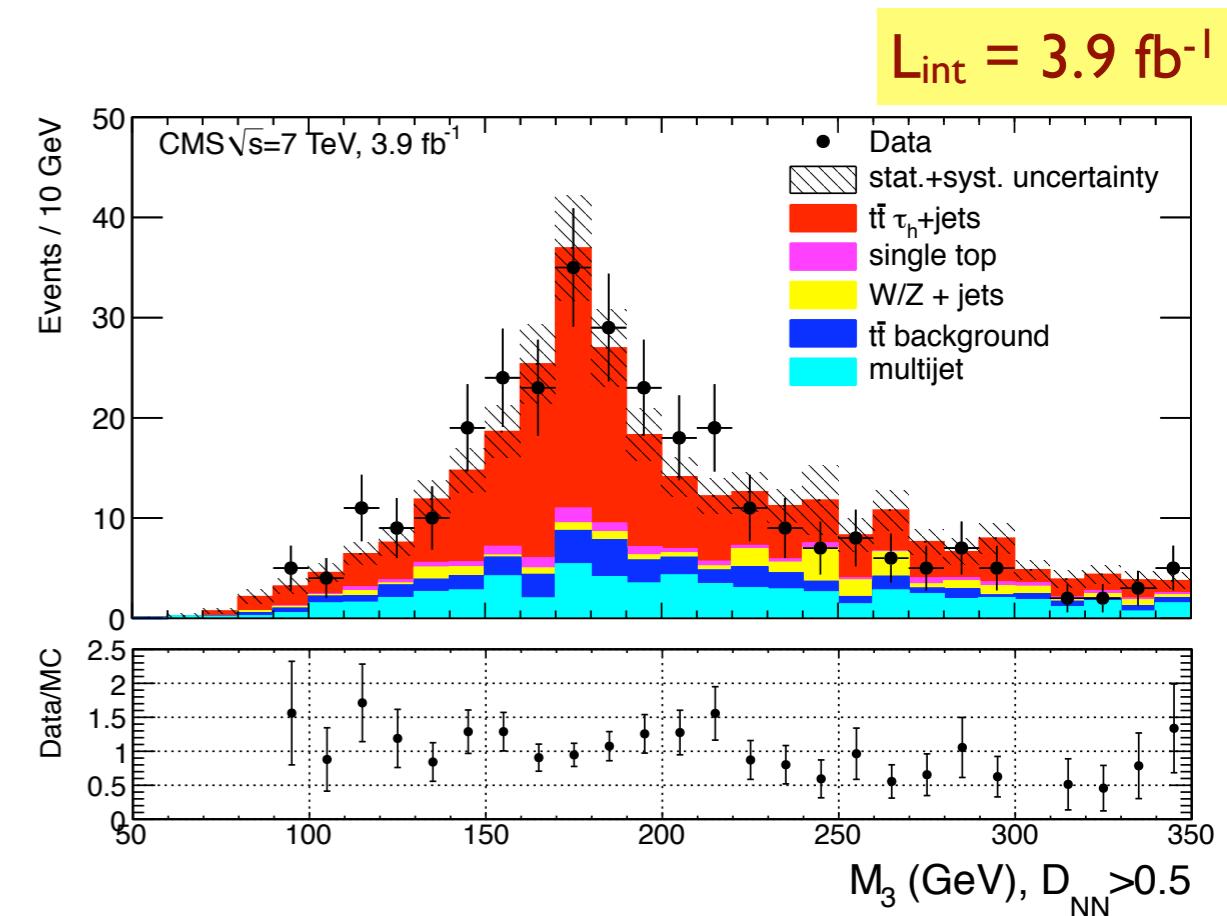
$$\sigma_{t\bar{t}} = 152 \pm 12 \text{ (stat.)} \pm 32 \text{ (syst.)} \pm 3 \text{ (lum.) pb}$$

22%

$$\mathcal{B} = 0.091 \pm 0.007 \text{ (stat.)} \pm 0.020 \text{ (syst.)} \pm 0.002 \text{ (lum.)}$$

- Largest uncertainties from :

- jet energy scale
- $\tau_h$  identification and energy scale
- trigger efficiency



$M_3$  : invariant mass of the three-jet system with highest transverse momentum in enriched signal region,  
 $D_{NN}>0.5$



# $t\bar{t} \rightarrow \tau_h + \text{jets}$ at ATLAS

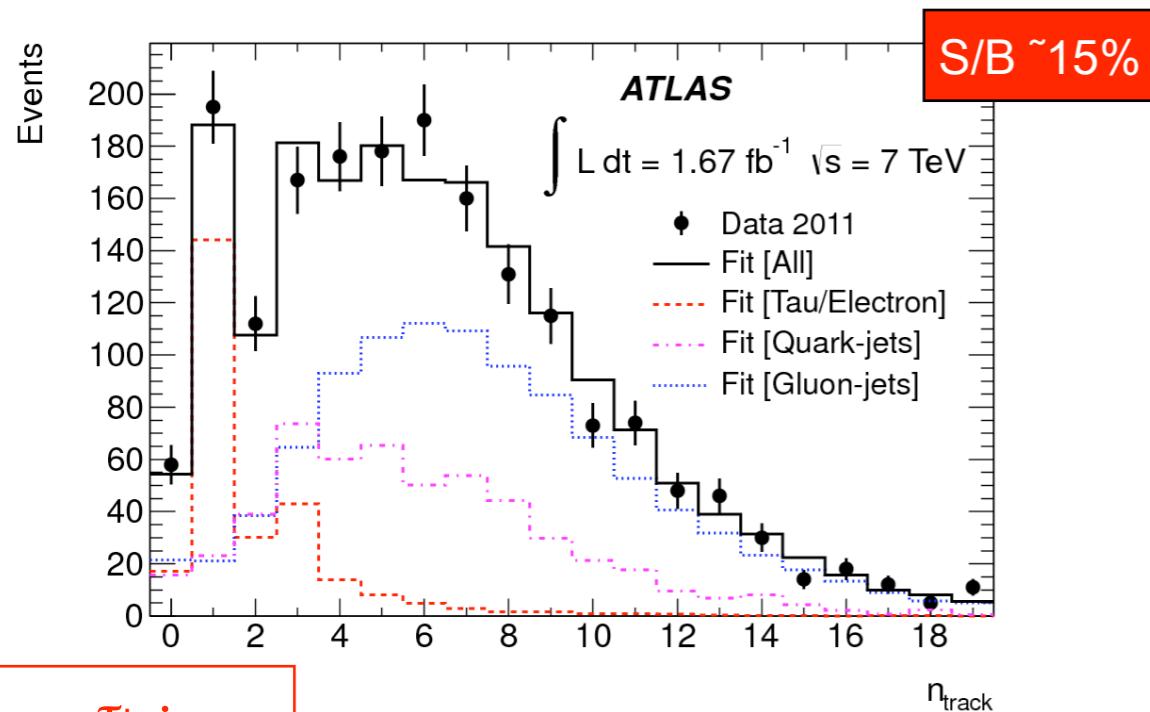
- Trigger : at least 4 jets with  $E_T > 10$  GeV and  $|\eta| < 3.2$ , 2 jets identified as b-jets

$L_{\text{int}} = 1.67 \text{ fb}^{-1}$

- Final state selection :

5 jets  $E_T > 20$  GeV,  $|\eta| < 2.5$   
 2 jets identified as b-jets  
 2 jets associated to hadronic W  
 remaining leading jet ( $E_T > 40$  GeV) selected as  $\tau_h$  candidate  
 MET significance,  $\text{SET} > 8$   
 lepton veto

- Signal extracted using a template fit to the number of tracks associated to the  $\tau_h$  candidate



$\tau_h$  :  
 $n_{\text{trk}} = 1$  or 3

Number of signal events using  $N(\tau_h)/N(e) + N(\tau_h)$   
 measured in simulation

9

$\tau_h/e$  template from simulated  $t\bar{t}$   
 gluon initiated jet template (QCD multijet)  
 from sideband in data with  $3 < \text{SET} < 4$   
 quark initiated jet template ( $t\bar{t}$ , W+jets, single-top)  
 from  $t\bar{t}$  control sample with muon

$\sigma_{t\bar{t}} = 194 \pm 18 \text{ (stat.)} \pm 46 \text{ (syst.) pb}$

25%

# Top pair cross section measurement in e/ $\mu$ +jets

ATLAS : ATLAS-CONF-2011-121 (7 TeV, 0.7 fb $^{-1}$ )  
ATLAS-CONF-2012-149 (8 TeV, 5.8 fb $^{-1}$ )

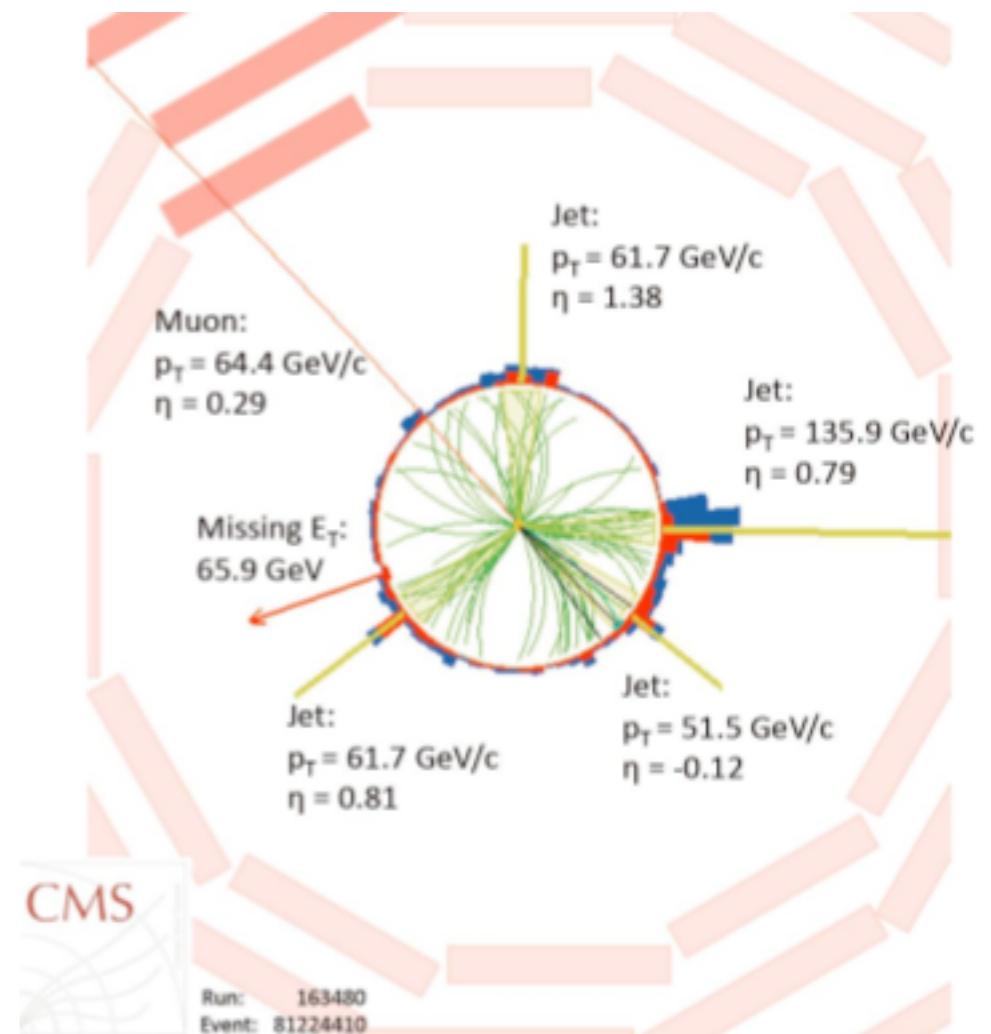
CMS : [Phys. Lett. B 720 \(2013\) 83](#) (7 TeV, 2.3 fb $^{-1}$ )  
CMS-PAS-TOP-12-006 (8 TeV, 2.8 fb $^{-1}$ )

Differential cross-sections :

ATLAS : [EPJC \(2013\) 73:2261](#) (7 TeV, 2.05 fb $^{-1}$ )

# Motivation

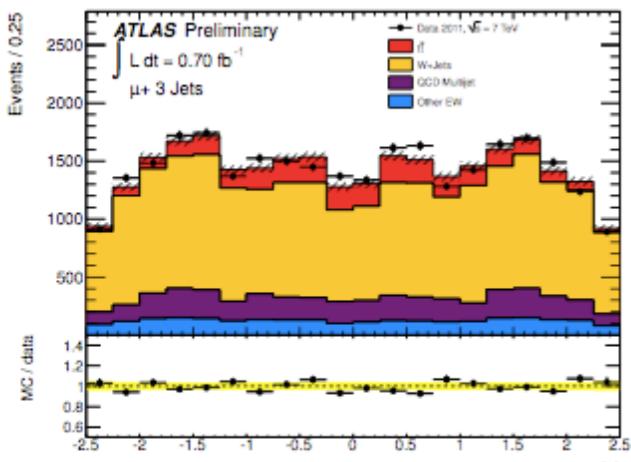
- final state with largest BR
  - verify theoretical cross section calculations
  - primary background in many searches for physics beyond the standard model
  - inclusive measurement : gate to new physics, additional processes may modify the production rate
- 
- **Analysis strategy :**  
one single isolated  $e$  or  $\mu$ , 1 to 4 jets usually 1 b-tagged, possibly MET
  - **Main backgrounds :**  $W+jets$  and QCD multijets



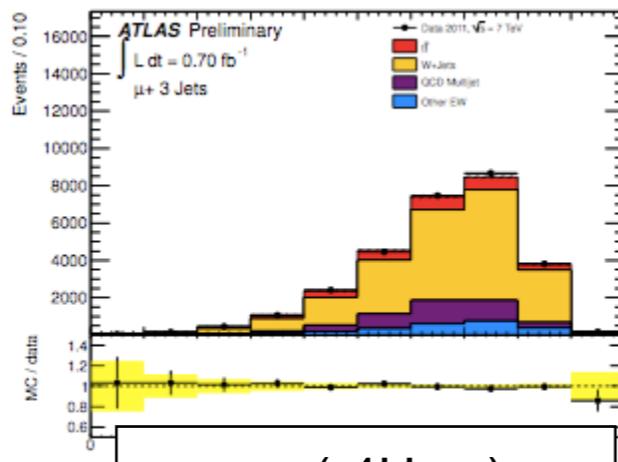
# l+jets analysis @ 7 TeV (1/2)



- Event selection :
  - Single lepton trigger
  - 1 isolated e/ $\mu$  with  $E_T/p_T > 25/20$  GeV,  $|\eta| < 2.5$
  - at least 3 jets with  $p_T > 25$  GeV
  - $MET > 35$  GeV,  $m_T(W) > 25$  GeV (e+jets channel)
  - $MET > 25$  GeV,  $m_T(W) + MET > 60$  GeV ( $\mu$ +jets channel)
- no b-jet identification to avoid additional systematics
- W+jets background estimated using W charge asymmetry
- QCD multijet background estimated from matrix method, real/fake lepton efficiencies measured from Z events/control samples with small MET in data
- Projective likelihood discriminant function constructed using simulated W+jets as background and 4 variables :

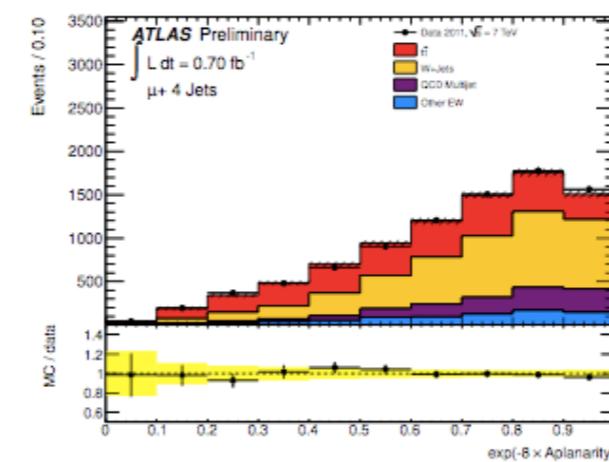


$\eta(l)$

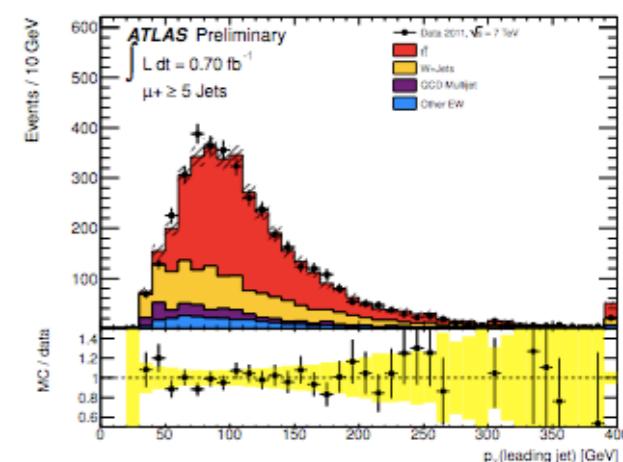


$\exp(-4H_{T,3p})$

$$H_{T,3p} = \frac{\sum_{i=3}^{N_{\text{jets}}} |p_{T,i}|}{\sum_{j=1}^{N_{\text{objects}}} |p_{z,j}|}$$



modified event aplanarity  
 $A' = \exp(-8A)$



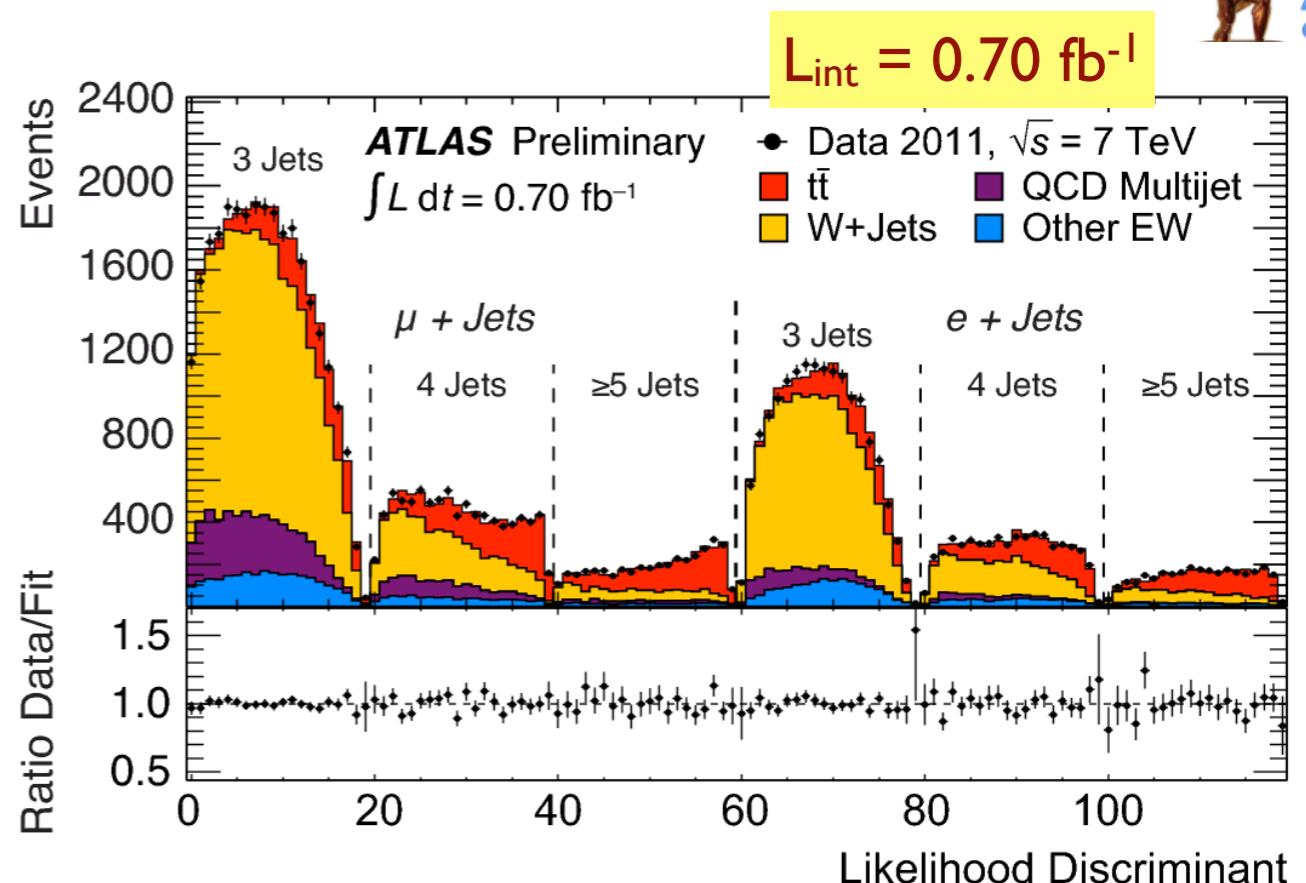
$p_T$  of leading jet

# I+jets analysis @ 7 TeV (2/2)



- Maximum likelihood fit to the 6 likelihood discriminants
- Fit input :
  - data driven normalization and shape for QCD multijet
  - data driven W+jets normalization, shape from MC
  - other backgrounds (Z+jets, single-top, di-bosons) from simulation, normalized to  $\sigma^* L$
- Main systematics :  
MC modelling, luminosity, muon id

$$\sigma_{t\bar{t}} = 179.0 \pm 3.9 \text{ (stat)} \pm 9.0 \text{ (syst)} \pm 6.6 \text{ (lumi)} \text{ pb}$$



Uncertainty	up (pb)	down (pb)	up (%)	down (%)
Statistical	3.9	-3.9	2.2	-2.2
Detector simulation				
Jets	3.2	-4.3	1.8	-2.4
Muon	4.1	-4.1	2.3	-2.3
Electron	2.7	-3.0	1.5	-1.7
$E_T^{\text{miss}}$	2.0	-1.6	1.1	-0.9
Signal model				
Generator <sup>*)</sup>	5.4	-5.4	3.0	-3.0
Hadronization <sup>*)</sup>	0.9	-0.9	0.5	-0.5
ISR/FSR	3.0	-2.3	1.7	-1.3
PDF <sup>*)</sup>	1.8	-1.8	1.0	-1.0
Background model				
QCD shape <sup>*)</sup>	0.7	-0.7	0.4	-0.4
W shape <sup>*)</sup>	0.9	-0.9	0.5	-0.5
Monte Carlo statistics <sup>*)</sup>	3.2	-3.2	1.8	-1.8
Systematic	9.0	-9.0	5.0	-5.0
Stat. & Syst.	9.8	-9.8	5.4	-5.4
Luminosity	6.6	-6.6	3.7	-3.7
Total	11.8	-11.8	6.6	-6.6

\* : uncertainties evaluated outside the fit

7 %

# I+jets analysis @ 8 TeV



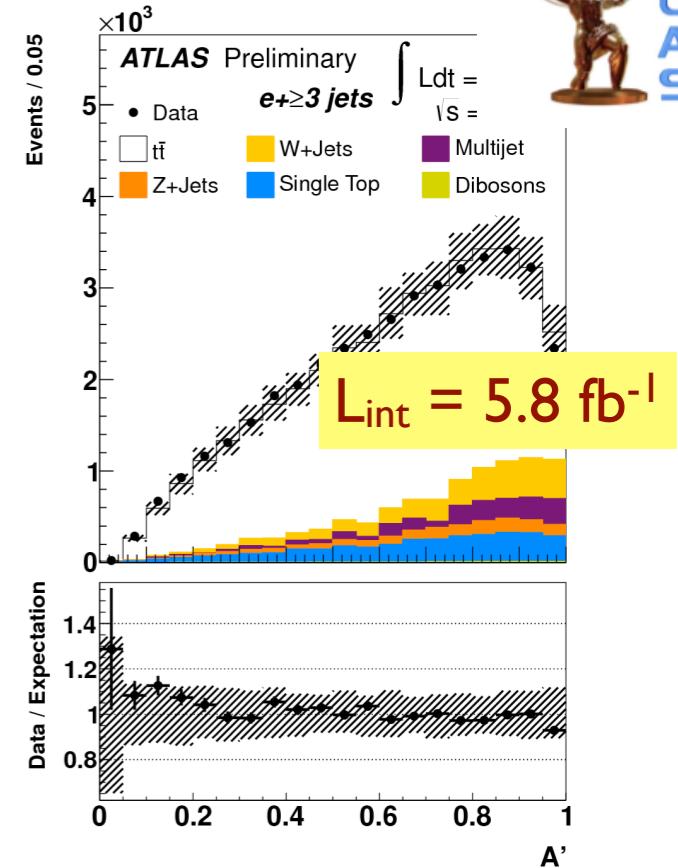
- Similar preselection to 7 TeV analysis :
  - one single isolated e/ $\mu$  with  $E_T/p_T > 40$  GeV,  $|\eta| < 2.5$
  - at least 3 jets with  $p_T > 25$  GeV
  - $MET > 30$  GeV,  $m_T(W) > 30$  GeV (e+jets channel)
  - $MET > 20$  GeV,  $m_T(W) + MET > 60$  GeV ( $\mu$ +jets channel)
  - at least one b-jet (MV1)
- Similar data driven technique for QCD multijet estimate
- Signal and W+jets from fit to the likelihood discriminant
- Main systematics : MC modelling, JES

$$\sigma_{t\bar{t}} = 241 \pm 2 \text{ (stat.)} \pm 31 \text{ (syst.)} \pm 9 \text{ (lumi.) pb}$$

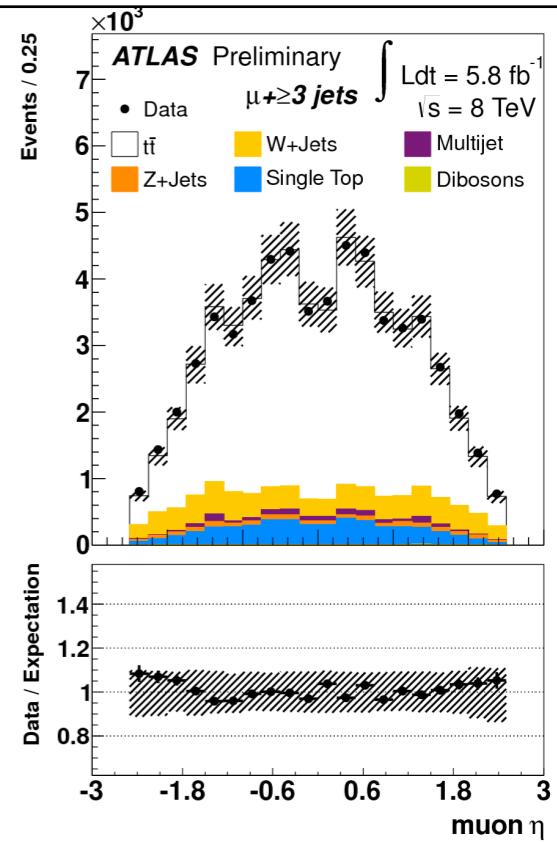
13%

LHC is a top factory :  
76k of selected  $t\bar{t}$  !

Channel	$N_{t\bar{t}}$	$\sigma_{t\bar{t}}$ (pb)
$e + \geq 3$ jets	$31050 \pm 350$	$239 \pm 3$
$\mu + \geq 3$ jets	$45000 \pm 400$	$242 \pm 2$
$l + \geq 3$ jets	$76000 \pm 500$	$241 \pm 2$



Likelihood constructed  
with 2 variables :  $A'$  and  $\eta(l)$



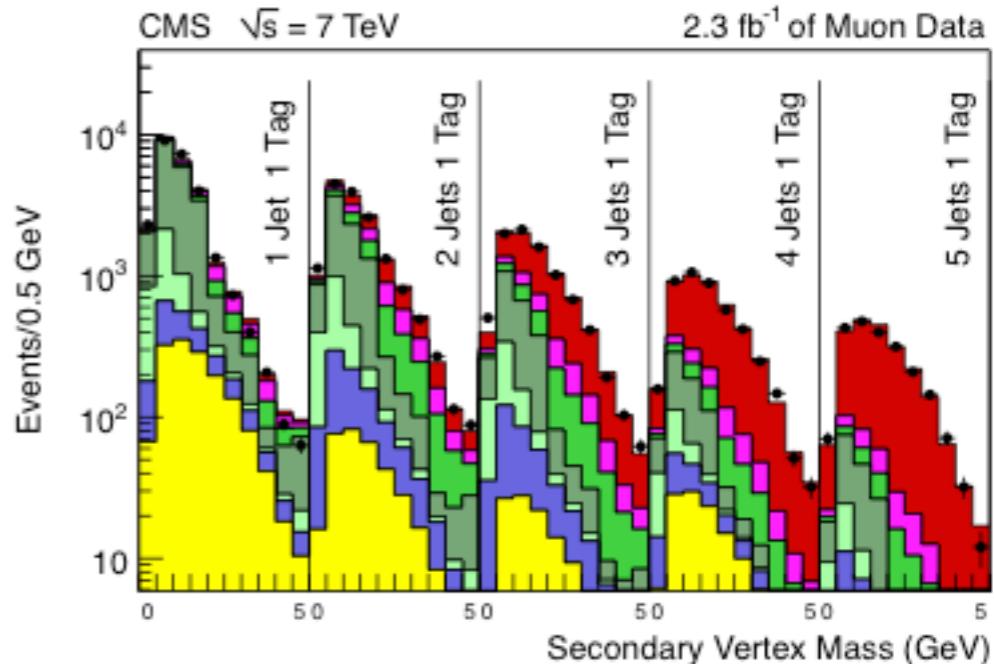
# I+jets analysis @ 7 TeV & 8 TeV

- Event selection :

single lepton and lepton+jets triggers  
 one single isolated e or  $\mu$ ,  $E_T/p_T > 35$  GeV  
 at least one jet  $E_T > 35$  GeV,  
 one or two b-jets (Simple SV)  
 MET $>20$  GeV

7 TeV

$L_{\text{int}} = 2.3 \text{ fb}^{-1}$



$$\sigma_{t\bar{t}} = 158.1 \pm 2.1 \text{ (stat.)} \pm 10.2 \text{ (syst.)} \pm 3.5 \text{ (lum.) pb}$$

- Profile likelihood fit to the number of reconstructed jets, number of b-tagged jets and secondary vertex mass distributions
- Background normalizations and main systematics (JES,  $Q^2$  scale, b-tagging) constrained from fit

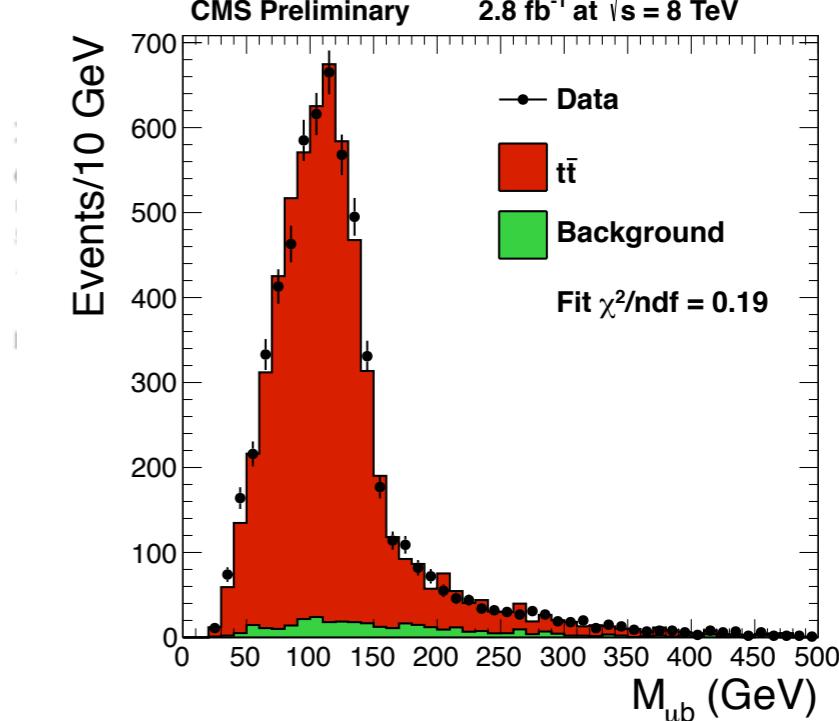
- Event selection :

lepton+jets triggers  
 one single isolated e or  $\mu$ ,  $E_T/p_T > 26/30$  GeV  
 at least four jets  $E_T > 45, 45, 35, 35$  GeV  
 at least one b-jet (Jet Probability)

8 TeV

$L_{\text{int}} = 2.8 \text{ fb}^{-1}$

- Signal extracted by template fit to  $M(l,b)$  distribution
- Multijet template from anti-isolated lepton side band in data, other backgrounds from simulation
- Main systematics : JES, b-tagging efficiency



$$\sigma_{t\bar{t}} = 228.4 \pm 9.0 \text{ (stat.)}^{+29.0}_{-26.0} \text{ (syst.)} \pm 10.0 \text{ (lum.) pb}$$

7 %

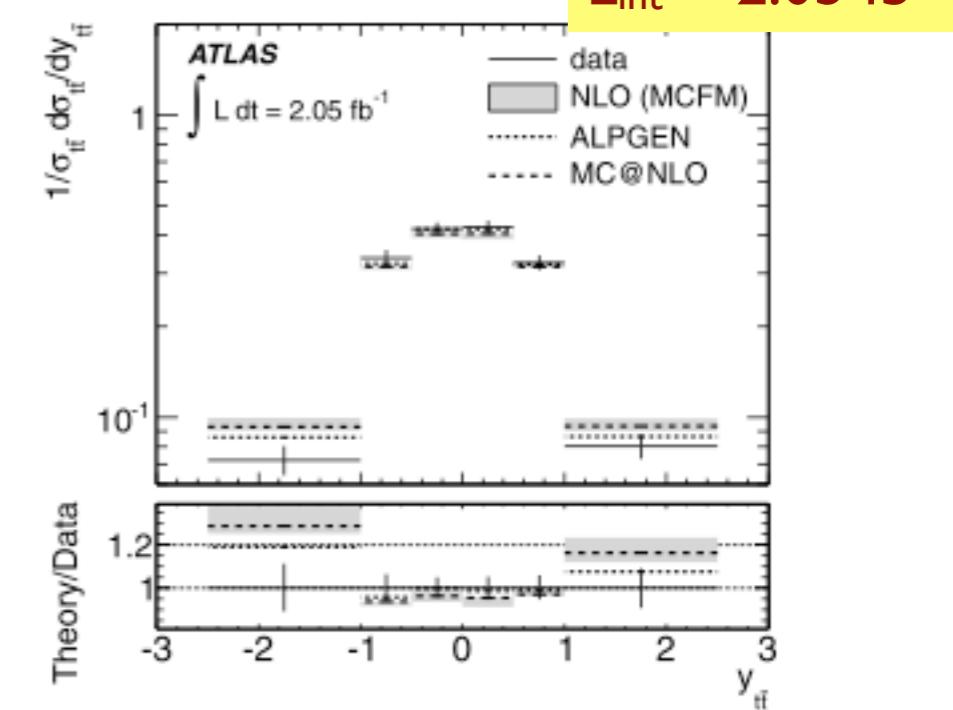
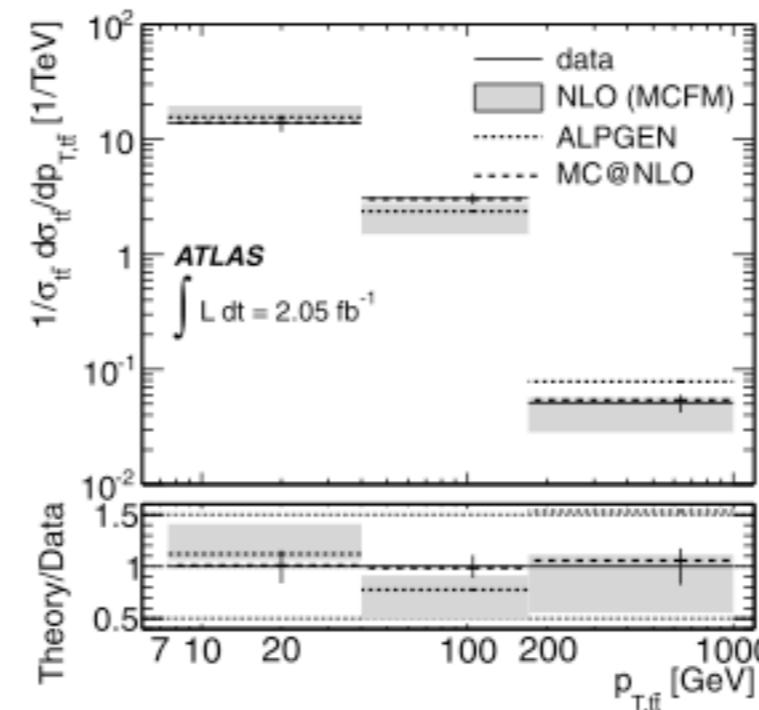
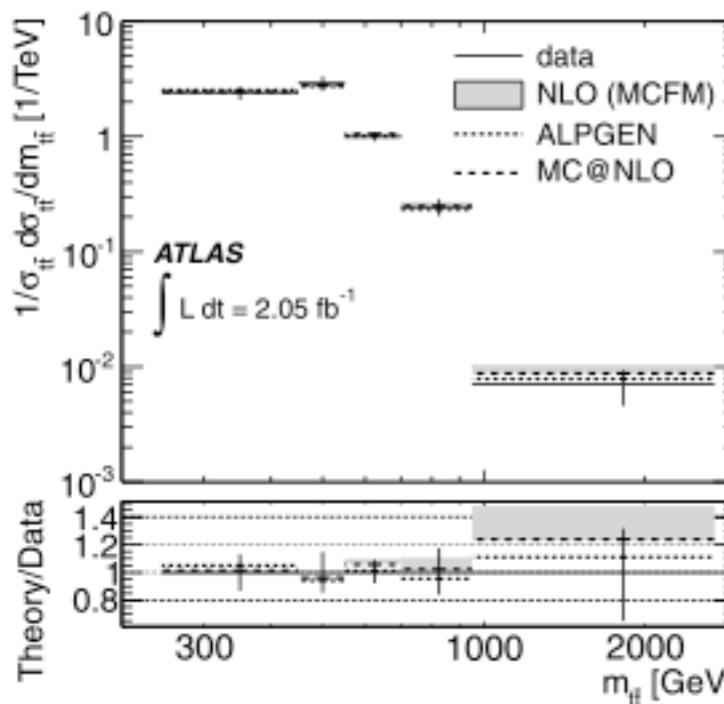
13 %

# Differential cross sections in l+jets



- Enhances sensitivity to new physics, allows to test pQCD, dependence to ME-parton matching, QCD scales, PDFs, ...
- Analysis strategy : one isolated e/ $\mu$ , 4 jets, one b-jet, MET and **full kinematic reconstruction**
- Differential distributions unfolded for detector effects
- Kinematic properties ( $m$ ,  $p_T$ ,  $y$ ) of  $t\bar{t}$  considered
- Uncertainties : 10-20 %, **no significant deviations from SM expectations, good agreement with generators**

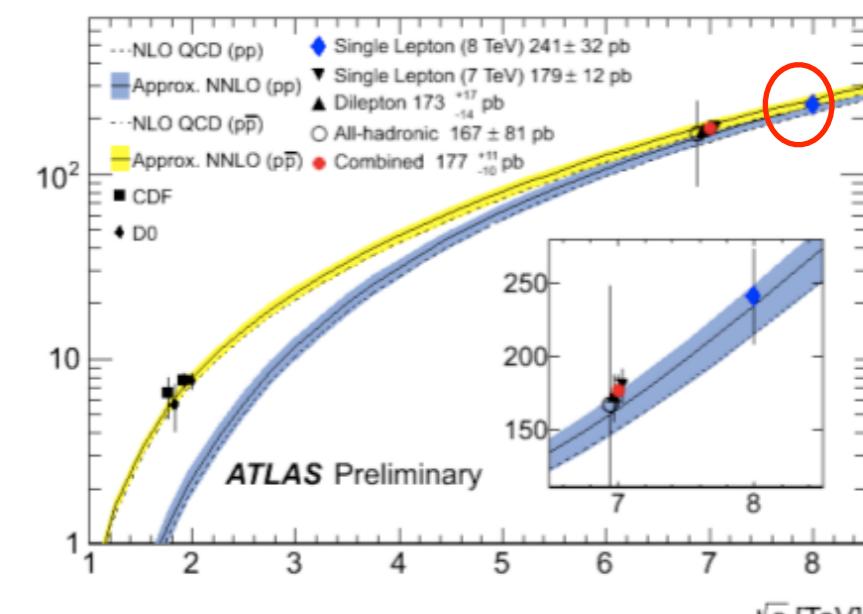
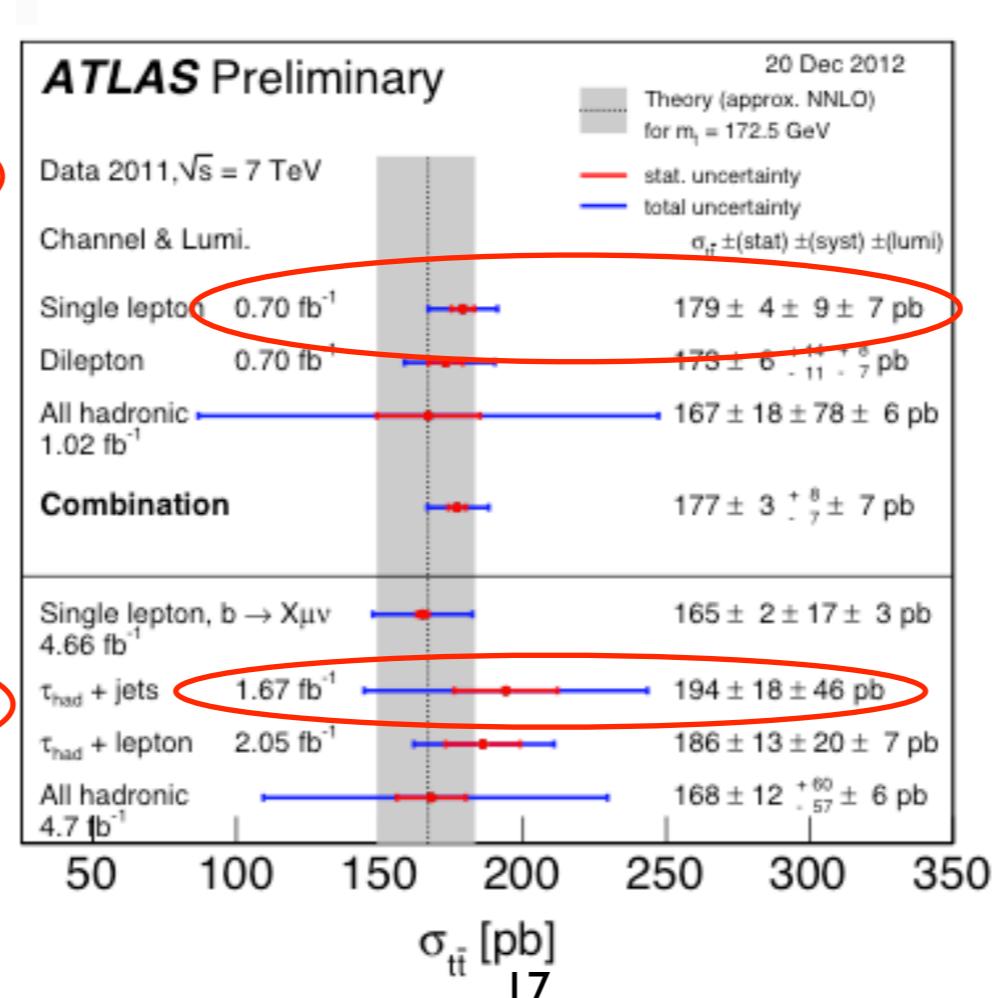
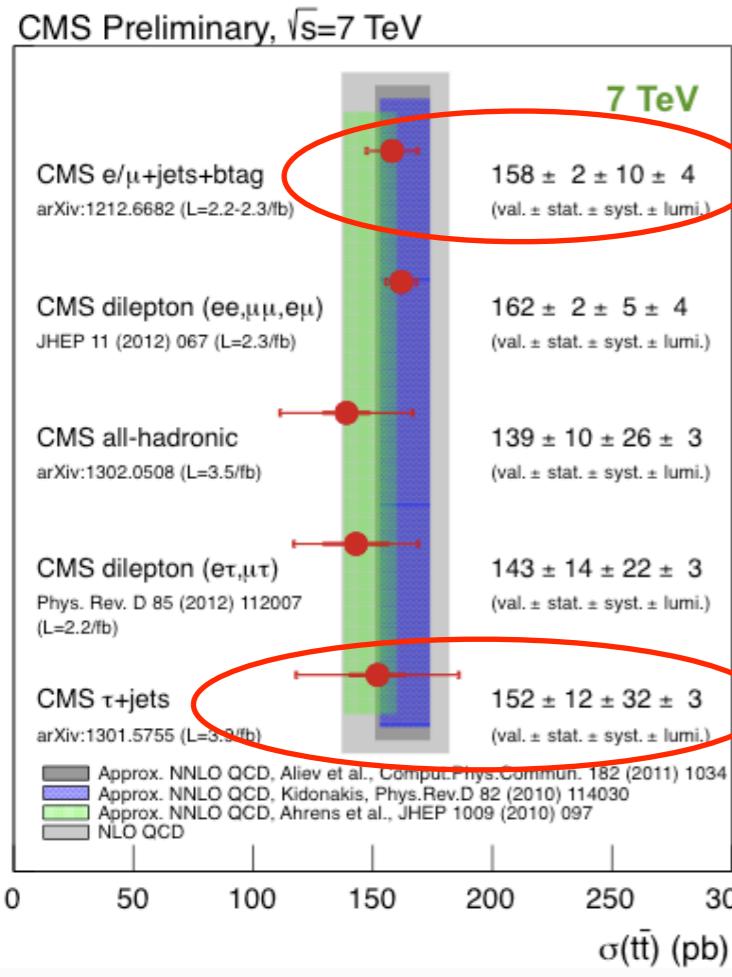
$$\frac{1}{\sigma} \frac{d\sigma(x_i)}{dx_i}$$



(Similar measurements at CMS : TOP-12-027 (l+jets), TOP-12-028 (di-lepton))

# Summary

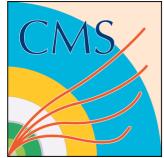
- ATLAS and CMS have measured the top pair cross sections in “all possible” lepton+jets channels, namely  $e+jets$ ,  $\mu+jets$  and  $\tau_h+jets$
- French labs are involved in the  $\tau_h+jets$  ([IPHC-CMS](#)),  $e/\mu+jets$  ([IRFU-ATLAS](#)) and differential ([CPPM-ATLAS](#)) cross section measurements
- Cross section measurements in very good agreement with approx. NNLO calculations (and full NNLO+NNLL calculations)





# Additional slides

# Systematics $t\bar{t} \rightarrow \tau_h + \text{jets}$



7 TeV

Source	Rel. uncert. [%]
W/Z/ $t\bar{t}$ backgr. cross section uncert.	$\pm 3$
Top-quark mass	$\pm 3$
Renormalization/factorization scale	$\pm 2$
Parton matching	$\pm 3$
PDF	$\pm 5$
$\tau_h$ trigger efficiency	$\pm 7$
Pileup	$+5 -1$
$\tau_h$ energy correction	$\pm 7$
$\tau_h$ identification	$\pm 9$
Jet energy scale	$\pm 11$
Jet energy resolution	$\pm 2$
Unclustered $E_T^{\text{miss}}$	$\pm 7$
b-tagging	$\pm 3$
Multijet background reweighting	$\pm 5$
Syst. uncertainty	$\pm 21$
Stat. uncert. from fit and MC samples	$\pm 8$
Stat. uncert. from trigger	$\pm 0.4$
Total stat. uncert.	$\pm 8$

7 TeV

Source of uncertainty	Relative uncertainty
ISR/FSR	15%
Event generator	11%
Hadronisation model	6%
PDFs	2%
Pile-up	1%
$b$ -jet tagging efficiency	9%
Jet energy scale	5%
$E_T^{\text{miss}}$ significance mismodelling	5%
$b$ -jet trigger efficiency	3%
Jet energy resolution	2%
Fit systematic uncertainties	4%
Luminosity	4%
Total uncertainty	24%





# Systematics $t\bar{t} \rightarrow l + \text{jets}$

7 TeV

Source	Electron channel	Muon channel	Combined analysis
Quantity	Uncertainty (%)		
Lepton ID/reconstruction/trigger efficiency	3.0	2.0	3.0
$\cancel{E}_T$ resolution due to unclustered energy	0.9	0.3	0.8
Jet energy resolution	0.5	0.5	0.6
$t\bar{t}$ + jets renorm./fact. scales	3.5	4.3	4.3
$t\bar{t}$ + jets ME to PS matching	2.2	1.8	2.2
Pileup	0.5	0.2	0.6
Parton distribution function choice	0.3	0.3	0.3
QCD multijet SVM distribution	1.4	0.4	0.6
Subtotal	5.5	5.1	5.9
Nuisance parameter	Uncertainty (%)		
Jet energy scale	3.9	3.0	2.4
b-tagging efficiency and mistag rate	3.5	2.8	2.1
W + jets renorm./fact. scale	1.6	1.5	1.6
Total systematic uncertainty	7.0	6.2	6.5

8 TeV

Systematic	Combined fit $\delta\sigma_{t\bar{t}}$ (%)
Jet Energy Scale	+4.3 -5.0
Jet Energy Resolution	+0.5 -1.1
Pileup	+0.7 -0.7
Background Composition	+0.1 -0.1
W + Jets template shape from unweighted 7 TeV	+0.9 -0.9
Normalisation of data-driven multijet shape	+0.9 -0.9
b tagging efficiency measurement	+8.0 -8.0
Trigger Efficiency	+3.2 -2.8
Lepton selection	+2.8 -2.4
Factorization scale (*)	+6.2 -2.1
ME-PS Matching threshold (*)	+4.6 -3.1
PDF uncertainties (*)	+1.6 -2.0
Top Quark Mass (*)	+0.3 -1.4
Total	+12.7 -11.4
Luminosity	+4.4 -4.4

\* : uncertainties from 7 TeV data

# Differential cross sections in l+jets

- Measurements performed in l+jets and di-lepton final states
- normalized differential tt cross section as function of  $p_T$ ,  $\eta$  of leptons and b-jets in visible phase space,  $m(l,b)$
- as function of  $t$  and  $tt$  in full phase space
- Prediction at approx NNLO gives particularly good description of  $p_T(t)$

$$\frac{1}{\sigma} \frac{d\sigma(x_i)}{dx_i}$$

