Inclusive Top Pair Cross Section Results at the LHC

International Workshop on Top-Quark Physics, 2014

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Talk prepared with the help of Richard Hawkings

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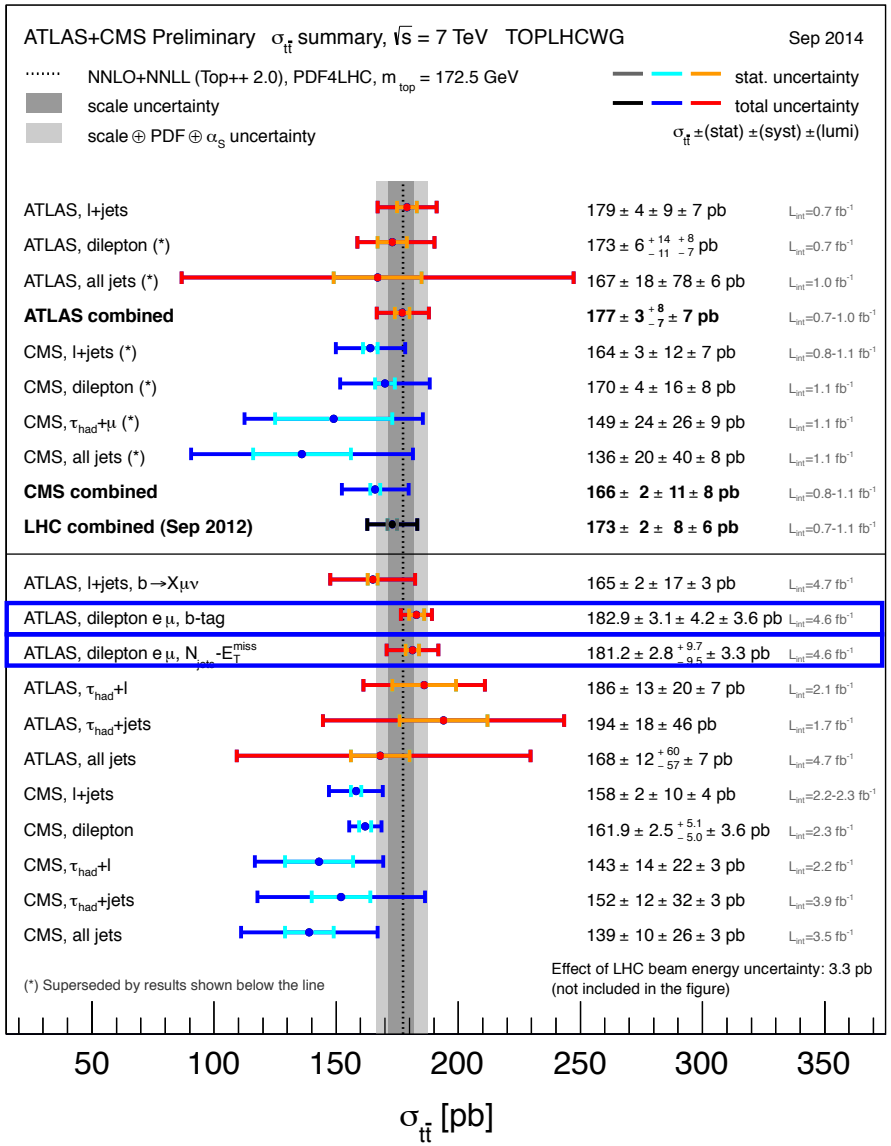
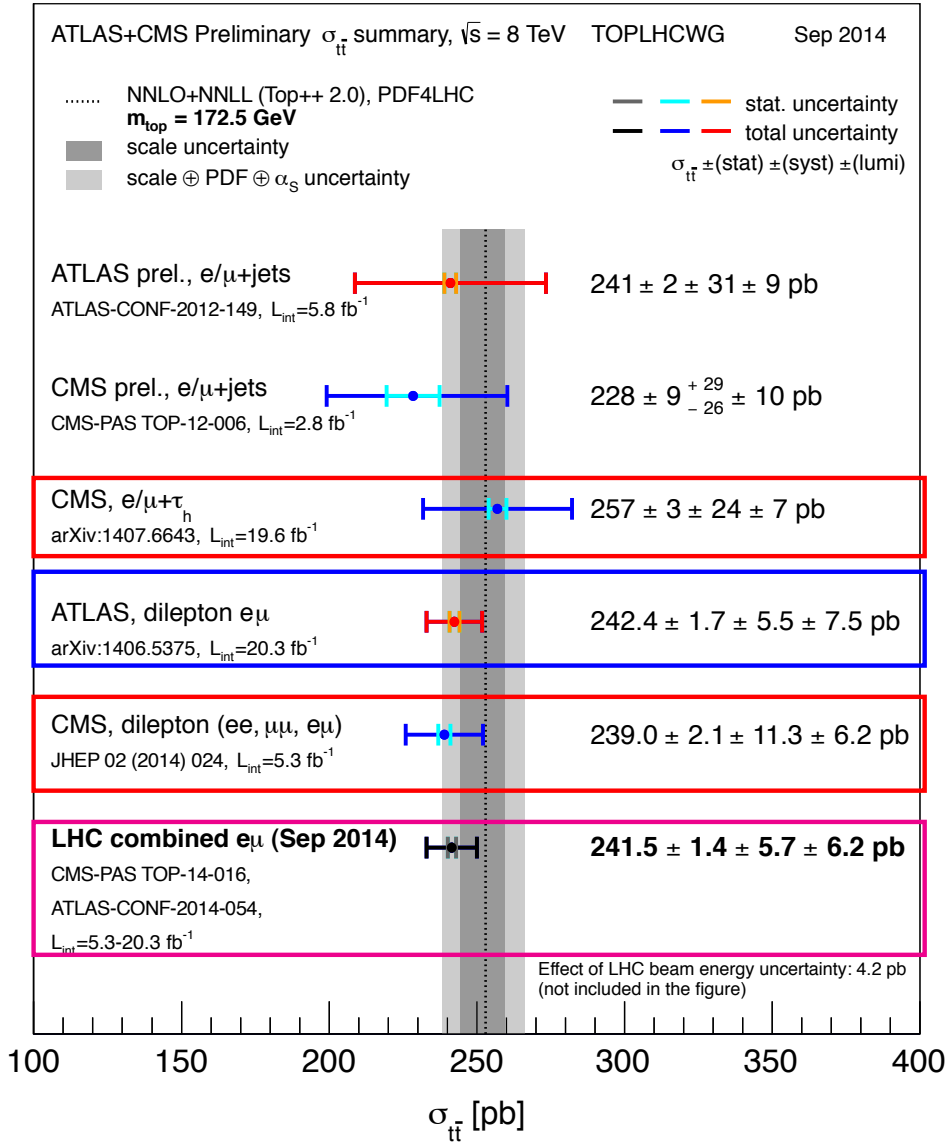
September 29, 2014

Introduction: New and Precise Measurements





Introduction

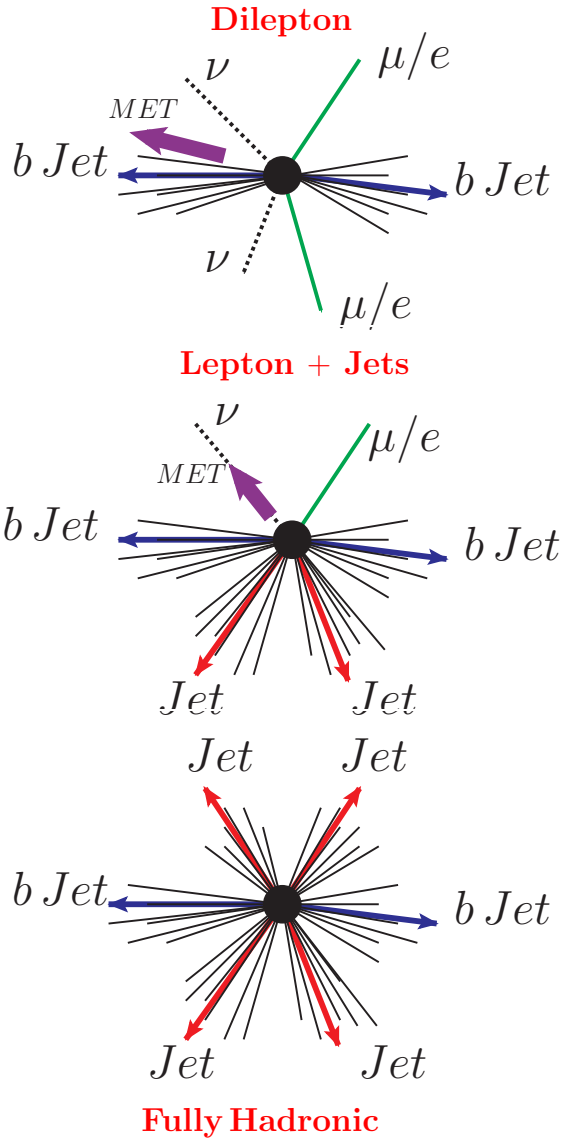
Top Quark

- Top quark production at the LHC is dominated by the gluon-gluon fusion ($\sim 85\%$).
- Until now, it is the heaviest elementary particle $m_t = 173.4\,\mathrm{GeV}$.
- Top quark decays into a W and a b almost 100% of the times.
- $t\bar{t}$ decays: Dilepton(e or μ) ($\sim 5\%$), lepton+jets ($\sim 44\%$) and fully hadronic ($\sim 46\%$).
- Precise $\sigma_{t\bar{t}}$ measurement allows determination of m_t and α_s.

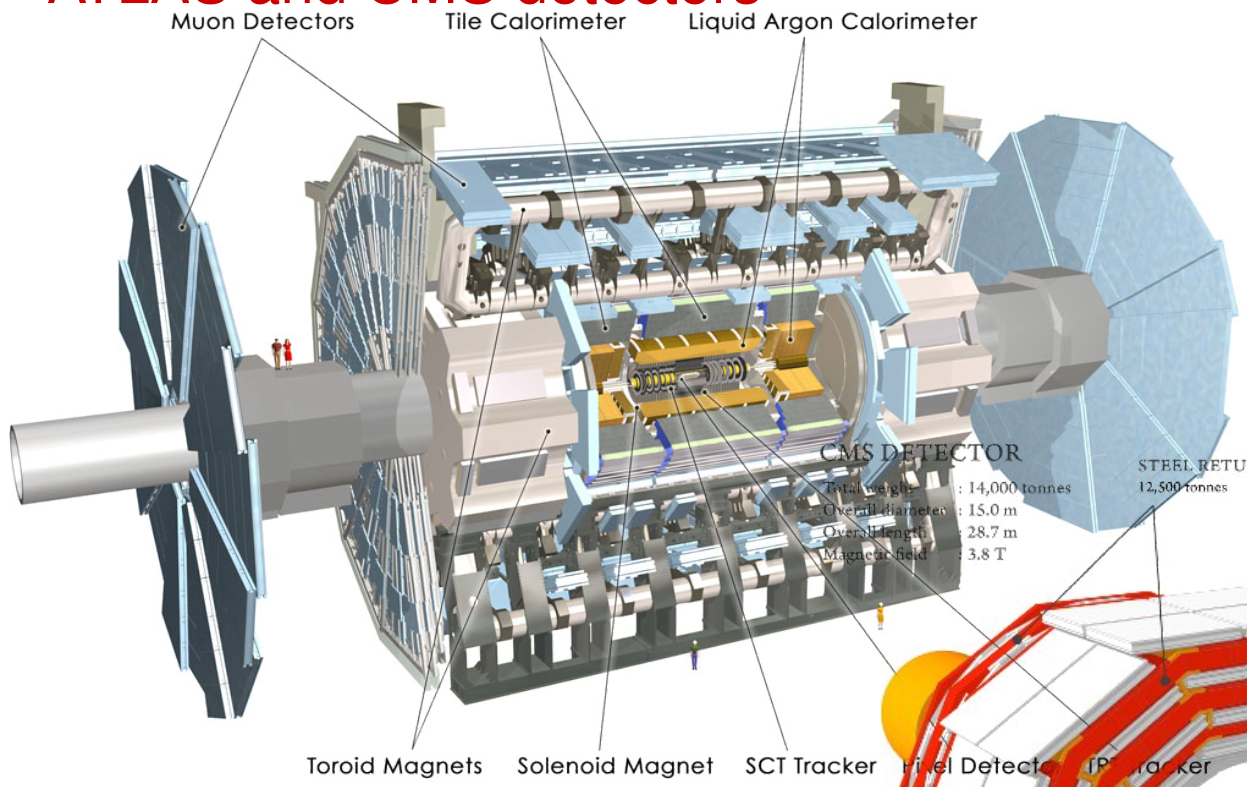
$\sqrt{s}$ [TeV]	$\sigma_{t\bar{t}}$(NNLO+NNLL) [pb]		Scale[1] [%]	PDF[1,2] [%]
	(172.5 GeV)[1]	(173.3 GeV)[1]		
7	177.3	172.0	3.4%	5.1%
8	252.8	245.9	3.4%	4.6%
13	824.2	806.4	3.5%	3.5%
14	974.8	953.6	3.6%	3.5%

[1] $\sigma_{t\bar{t}}$ calculated using `Top++(v2.0)`.

[3] PDF uncertainty calculated following PDF4LHC prescription.



ATLAS and CMS detectors

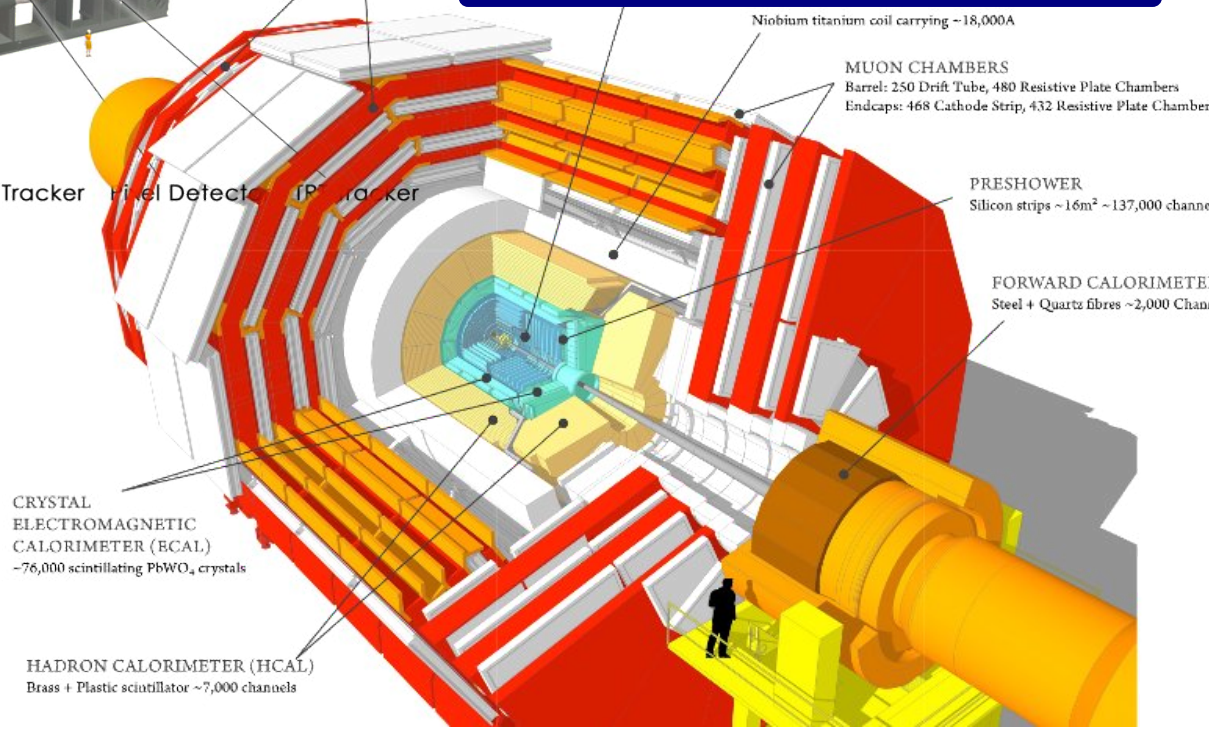


ATLAS Detector

1. Jets: 3D topological clusters.
2. Electron: $|\eta|<2.47$ and $p_T^e>25\,\text{GeV}$
3. Muon: $|\eta|<2.5$ and $p_T^\mu>20/25\,\text{GeV}$
4. b-tagging: MV1 algorithm.
5. Trigger: Single lepton.

CMS Detector

1. Particle Flow.
2. Electron: $|\eta|<2.5$ and $p_T^e>20/35\,\text{GeV}$
3. Muon: $|\eta|<2.4$ and $p_T^e>20/30\,\text{GeV}$
4. b-tagging: CSV algorithm.
5. Trigger: Single lepton/Dilepton.



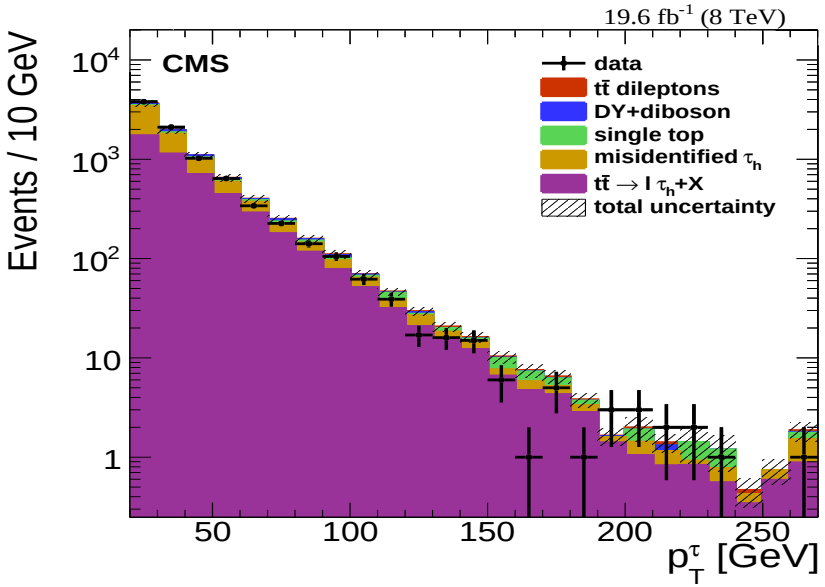
Dilepton Channel: $t\bar{t} \to e/\mu + \tau_h$

arXiv:1407.6643

- Background process in searches of charged Higgs boson.
- Measurement performed with the full 8 TeV data sample.
- τ decaying in hadrons.
- Cut and count.
- The fraction of these events is 4/81 of all $t\bar{t}$ decays.
- $p_T{}^{e} > 35\,\text{GeV}$, $p_T{}^{\mu} > 30\,\text{GeV}$.
- At least 2 jets with $p_T{}^{jet} > 30\,\text{GeV}$ and one $p_T{}^{jet} > 20\,\text{GeV}$.
- At least 1-btagged jet using CSV with a b-tagging efficiency $\sim$ 60%.
- τ_h identification: Eff. $\sim$ 50% with $\sim$ 1% misID eff.
- Signal MC: MadGraph + Pythia

Background

1. Main background: Jet misID as τ_h jet. Mainly $t\bar{t} \to \ell$+jets and $W \to \ell\nu_\ell$+jets.
2. The DD method exploits the probability for each jet to be misidentified as τ_h ($\omega(p_T, \eta, R_{jet})$).
3. $\omega(p_T, \eta, R_{jet})$ is evaluated in W+Jets and QCD control samples.

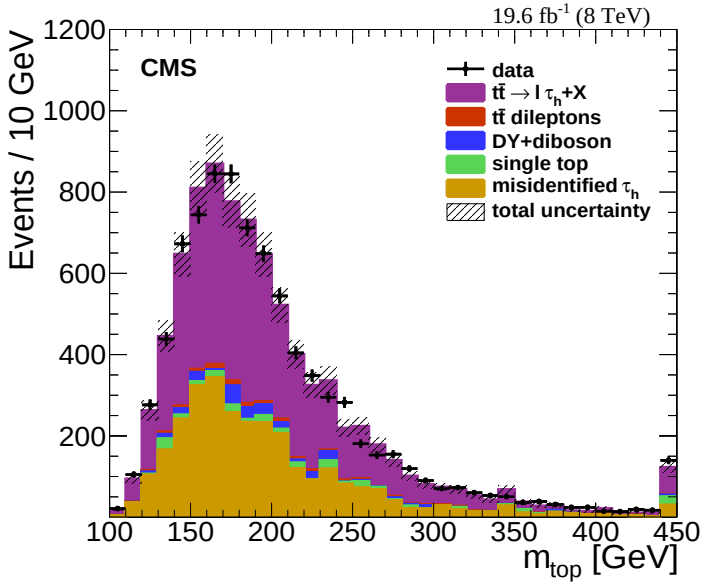


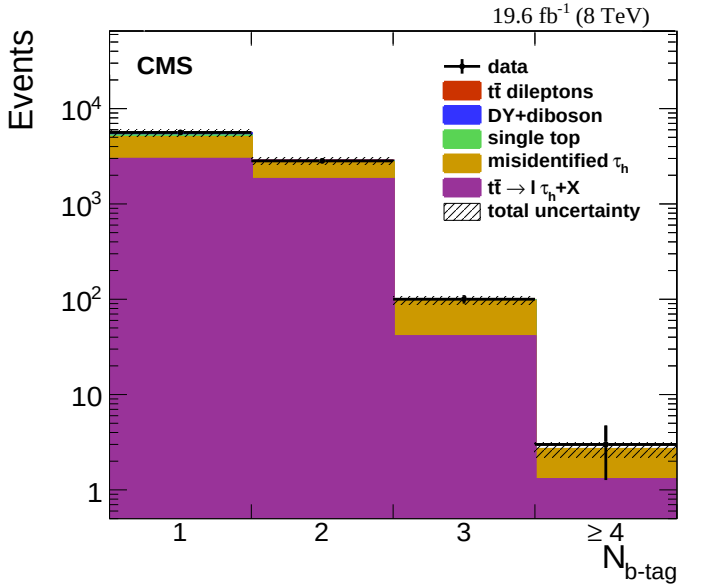
Dilepton Channel: $t\bar{t} \to e/\mu + \tau_h$

arXiv:1407.6643

Source	Uncer. [%]
Experimental	
τ_h jet identification	6.0
τ_h misidentification bkg	4.3
τ_h energy scale	2.5
b-jet tagging, jet misID	1.6
JES, JER, $\not{E}_T$	1.9
lepton reconstruction	0.5
other backgrounds	0.7
luminosity	2.6
Theoretical	
matrix element-parton shower matching	1.5
facto./renor. scale	2.9
generator	1.5
hadronisation	1.7
top-quark p_T modelling	0.6
parton distribution functions	0.7
total systematic uncertainty	9.5

$$\sigma_{t\bar{t}} = 257 \pm 3(\text{stat.}) \pm 24(\text{syst.}) \pm 7(\text{Lumi.})\,\text{pb}$$

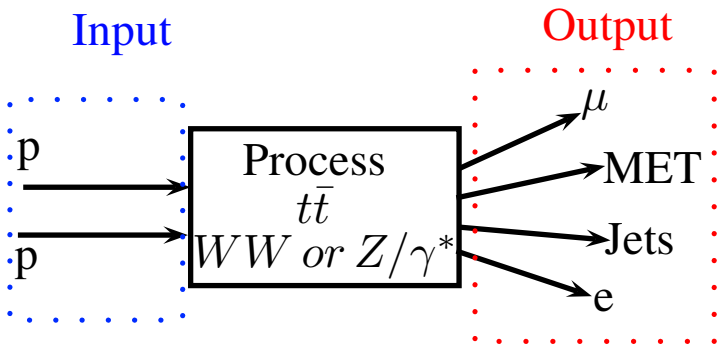




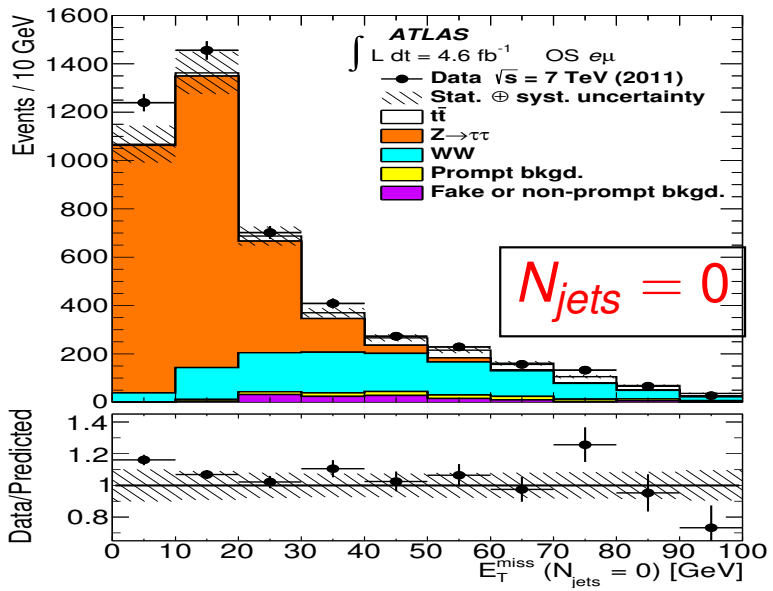
μe Channel: Simultaneous Measurement $t\bar{t}$, WW and Z/γ^*

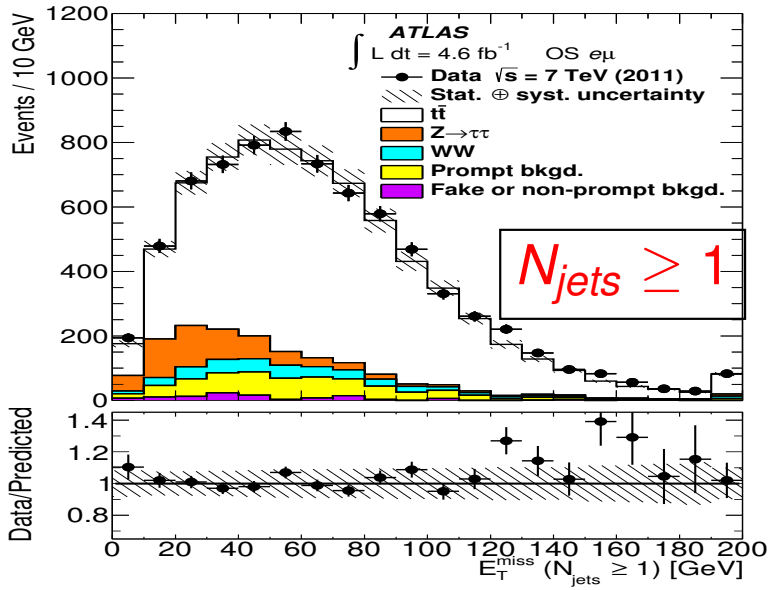
arXiv:1407.0573

- $t\bar{t}$, W^+W^- and $Z/\gamma^* \to \tau\tau$: dominant processes in the $e\mu$ final states.



- Method to extract the $\sigma_{t\bar{t}}$: Template fit over $\not{E}_T$ vs N_{jets} parameter space.
- Normalization parameters of $t\bar{t}$, WW and Z/γ^* are the free parameters of the fit.
- Background: Matrix method to estimate fake and non-prompt leptons.
- Monte Carlo
  1. Central: MC@NLO + HERWIG.
  2. PS studies: POWHEG + PYTHIA/HERWIG.
  3. ISR/FSR: ALPGEN + PYTHIA.





μe Channel: Fiducial $\sigma_{t\bar{t}}$ and Systematic Uncertainties

arXiv:1407.0573

Fiducial Cross Section

- Allows direct comparisons between theoretical calculations and experimental measurements. Most model-independent measurement.
- The $\sigma_{t\bar{t}}^{total}$ is an extrapolation of the fiducial cross section to the full phase space.
- Extraction (fiducial and total $\sigma_{t\bar{t}}$):

$$\sigma_{t\bar{t}}^{fid\,/\,total} = \frac{N_{evt}}{\mathcal{E} \times \mathcal{A} \times Br \times \mathcal{L}} \Rightarrow \sigma_{t\bar{t}}^{total} = \frac{\sigma_{t\bar{t}}^{fid}}{\mathcal{A} \times Br}$$

- Acceptance ($\mathcal{A}$) extrapolates the $\sigma_{t\bar{t}}$ to the full kinematic region. Efficiency ($\mathcal{E}$) includes RECO, ID, ISO, Trigger...

$$\mathcal{A} = \frac{N_{GEN}^{Cuts}}{N_{GEN}} \;\; ; \;\; \mathcal{E} = \frac{N_{RECO}}{N_{GEN}^{Cut}}$$

Where "Cuts": p_T, η...

Systematic Uncertainties

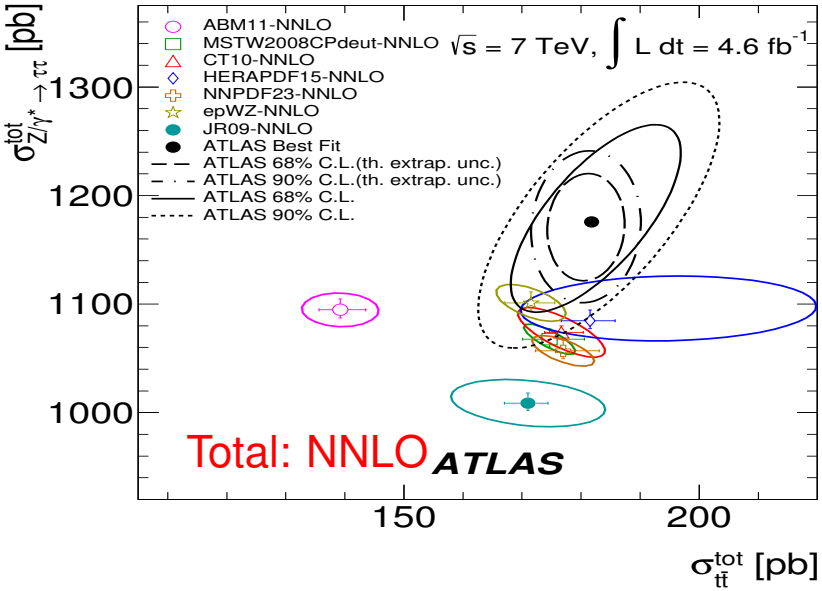
Source	$t\bar{t}$ [%]		
	$\mathcal{E}$	$\mathcal{A} \times \mathcal{E}$	Shape
ISR/FSR+Scale	± 1.1	± 0.4	$+1.0(-1.5)$
Generator	± 0.7	± 0.8	$+0.2(-0.0)$
PS Modeling	± 0.9	± 0.6	$+0.0(-0.1)$
PDF	± 0.6	± 1.7	± 0.5
e reco., ID, ISO	± 3.2		$+0.0(-0.1)$
μ reco	± 0.8		$+0.0(-0.0)$
JES	± 0.8		$+1.4(-1.4)$
JER	± 0.2		$+0.3(-0.0)$
background		± 0.8	

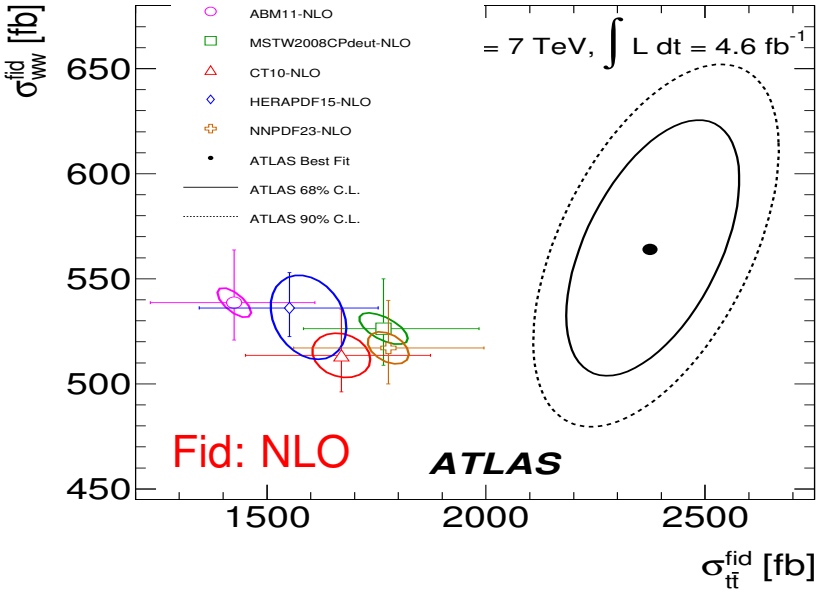
Beam Energy Uncertainty

- Beam energy at 8 TeV was calibrated to be $0.30 \pm 0.66\%$ smaller than the nominal value.
- Propagated to $\sigma_{t\bar{t}} \Rightarrow \sim 1.7\%$ of uncertainty.

μe Channel: Results

arXiv:1407.0573





Results

$$^{a}\sigma_{t\bar{t}}^{fid} = 2730 \pm 40(\text{stat.}) \pm 140(\text{syst.}) \pm 50(\text{Lumi.}) \pm 50(\text{beam}^{b})\ \text{fb}$$

$$\sigma_{t\bar{t}}^{total} = 181.2 \pm 2.8(\text{stat.}) \pm^{9.7}_{9.5}(\text{syst.}) \pm 3.3(\text{Lumi.}) \pm 3.3(\text{beam}^{b})\ \text{pb}$$

[a] Fiducial cuts: $[p_T^{e(\mu)} > 25(20)\ \text{GeV}; |\eta^{e(\mu)}| < 2.5(2.47)]$

[b] beam: Beam energy uncertainty.

μe Channel: Measurement Using Events with b-tagged Jets

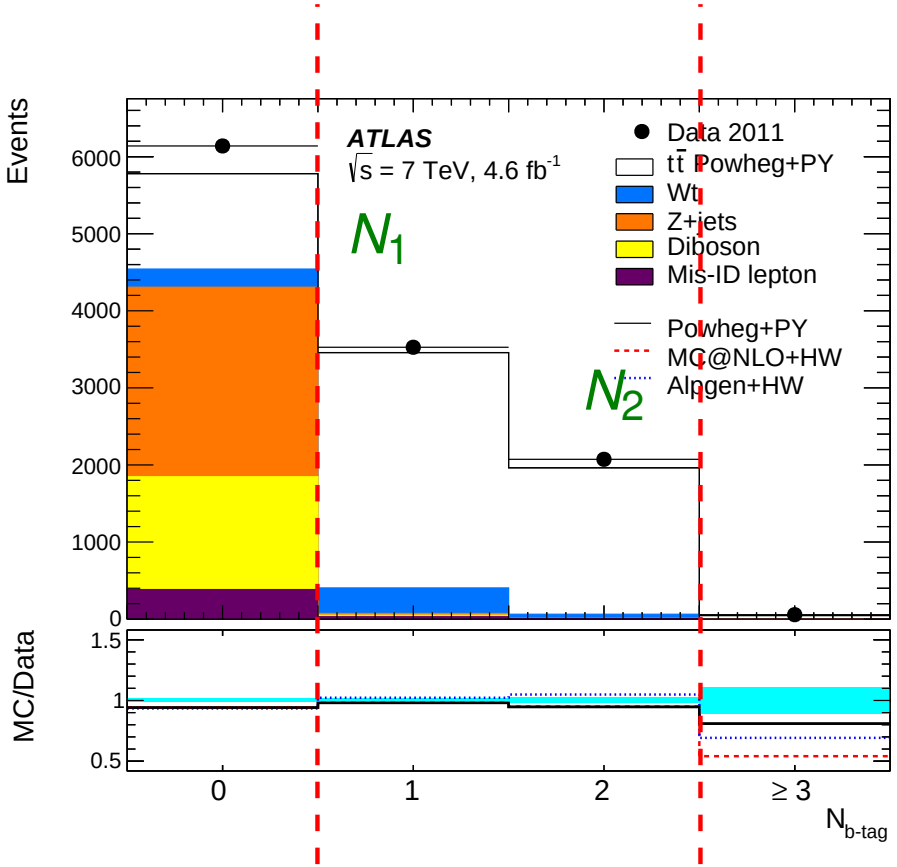
arXiv:1406.5375

Method

- Simultaneous measurement of $\sigma_{t\bar{t}}$ and ϵ_b.

$$N_1 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{bkg}$$
$$N_2 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{bkg}$$

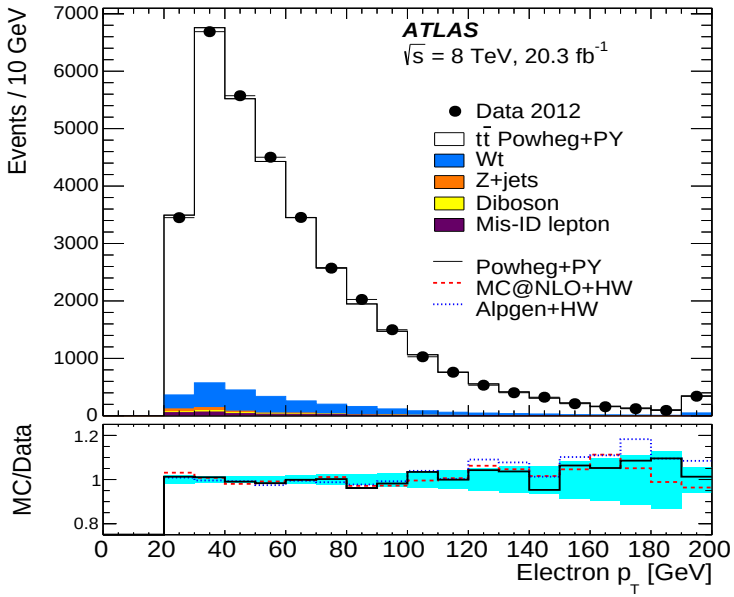
- ϵ_b is the product of b-tagging efficiency and jet kinematic acceptance for $t\bar{t}$ events.
- $\epsilon_{e\mu}$ is the leptonic acceptance.
- C_b is a correlation coefficient of ϵ_b: $C_b = \epsilon_{bb}/\epsilon_b^2 \sim 1$.
- Leptonic acceptance $\epsilon_{e\mu}$ and tagging correlation C_b evaluated from $t\bar{t}$ simulation.
- Simultaneous measurement ($\sigma_{t\bar{t}}$ and ϵ_b) reduces related systematic uncertainties.

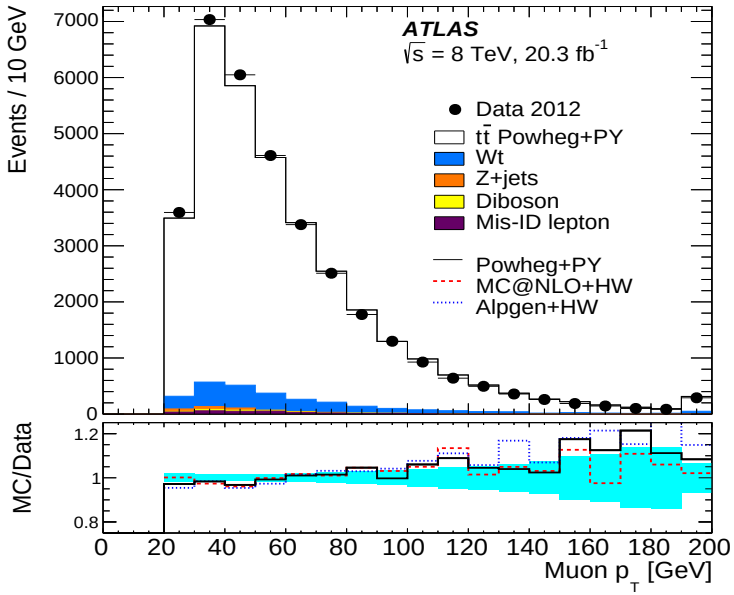


Background content (dominated by **Wt**):
$N_1^{bkg} \sim 12\%$ and $N_2^{bkg} \sim 4\%$.

μe Channel: Measurement Using Events with b-tagged Jets

arXiv:1406.5375





Selection

- An electron and a muon with opposite charge.
- Event selection:
  1. $p_T{}^{e} > 25\,\text{GeV}$
  2. $p_T{}^{\mu} > 25\,\text{GeV}$
  3. $p_T{}^{Jet} > 25\,\text{GeV}$
- Single lepton triggers.
- b-tagging: Multivariate algorithm with 70% of efficiency.
- Central $t\bar{t}$ MC: POWHEG + PYTHIA.
  $t\bar{t}$ modeling: MC@NLO + HERWIG and ALPGEN + HERWIG.

Background

- Drell-Yan: Estimated by the Data/MC ratios of $Z \to \mu\mu$ and $Z \to ee$.
- Non-prompt leptons: Extrapolated from the SS data region using OS/SS simulated ratios.

μe Channel: Results

arXiv:1406.5375

Total Cross Section

$$\sigma_{t\bar{t}}^{\mu e}(\sqrt{s}=7\,\text{TeV}) = 182.9 \pm 3.1(\text{stat.}) \pm 4.2(\text{syst.}) \pm 3.6(\mathcal{L}) \pm 3.3(\text{beam})\,\text{pb}$$

$$\sigma_{t\bar{t}}^{\mu e}(\sqrt{s}=8\,\text{TeV}) = 242.4 \pm 1.7(\text{stat.}) \pm 5.5(\text{syst.}) \pm 7.5(\mathcal{L}) \pm 4.2(\text{beam})\,\text{pb}$$

$$R_{t\bar{t}} = 1.326 \pm 0.024(\text{stat.}) \pm 0.015(\text{syst.}) \pm 0.049(\mathcal{L}) \pm 0.001(\text{beam})$$

p_T^ℓ(GeV)	$\lvert\eta^\ell\rvert$	Fiducial cross section (including $W \to \tau \to \ell\nu$) $\sqrt{s} = 7$ TeV (pb)	$\sqrt{s} = 8$ TeV (pb)
> 25	< 2.5	$2.615 \pm 0.044 \pm 0.056 \pm 0.052 \pm 0.047$	$3.448 \pm 0.025 \pm 0.069 \pm 0.107 \pm 0.059$
> 30	< 2.4	$2.029 \pm 0.034 \pm 0.043 \pm 0.040 \pm 0.036$	$2.662 \pm 0.019 \pm 0.054 \pm 0.083 \pm 0.046$

Uncertainty $\sqrt{s}$	$\Delta\sigma_{t\bar{t}}^{total}/\sigma_{t\bar{t}}^{total}$ (%) 7 TeV	8 TeV
Parton distribution functions	1.04	1.13
QCD scale choice	0.30	0.30
Analysis systematics ($\sigma_{t\bar{t}}$)	2.27	2.26
Uncertainty	$\Delta\sigma_{t\bar{t}}^{fid}/\sigma_{t\bar{t}}^{fid}$ (%)	
Parton distribution functions	0.38	0.28
QCD scale choice	0.00	0.00
Analysis systematics ($\sigma_{t\bar{t}}$)	2.13	2.01

- Includes beam energy uncertainty.
- Most precise measurement (3.9% @ 7 TeV and 4.3% @ 8 TeV).
- $R_{t\bar{t}}^{Theory}(7/8\,\text{TeV}) = 1.430 \pm 0.013(\text{PDF} + \alpha_s) + \pm 0.001(\text{scale})$
- Simultaneous fit reduces jets, b-tagging and modelling of radiation uncertainties.
- $\frac{d\sigma_{t\bar{t}}}{dm_t} = -0.28\%$ per GeV.

Dilepton Channel: CMS Detector

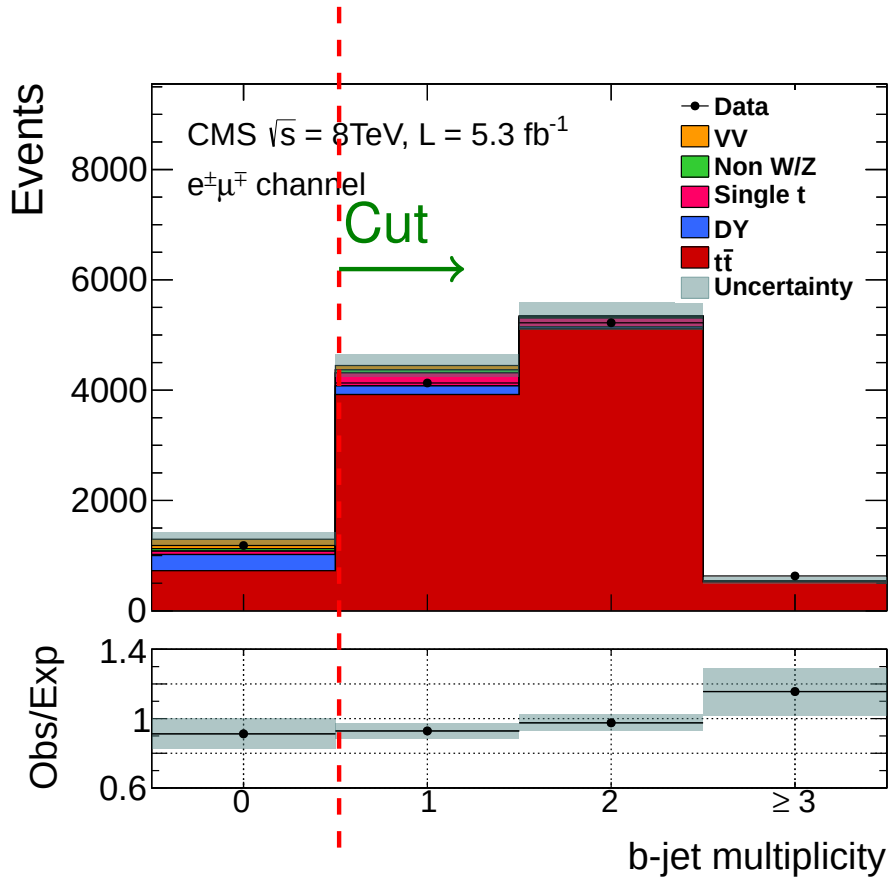
JHEP 02 (2014) 024

- Measurement performed in $\mu\mu$, ee and μe.
- Just 5.3 fb^{-1} of data!
- Cut and count analysis.
- Monte Carlo:
  - Central: MADGRAPH + PYTHIA.
  - Hadronization: POWHEG + PYTHIA/HERWIG
  - PS (cross check): MADGRAPH/POWHEG + PYTHIA
- b-tagging eff.: CSV, 85% misID 10%.
- Mass parametrization.

Background

- Drell-Yan: MC normalization based in the N_Z^{data} events inside m_Z window.
- Non-W/Z: "tight to loose" method.
- VV and single top: MC Simulations.

1. $p_T^{\ell} > 20\,\text{GeV}$ and $p_T^{Jet} > 30\,\text{GeV}$
2. $N^{Jets} \geq 2$ and $N^{b-jets} \geq 1$
3. $\mu\mu$ and *ee* only: $\not{E}_T > 40\,\text{GeV}$ and m_Z veto to reduce DY background.



Systematic Uncertainties and Results

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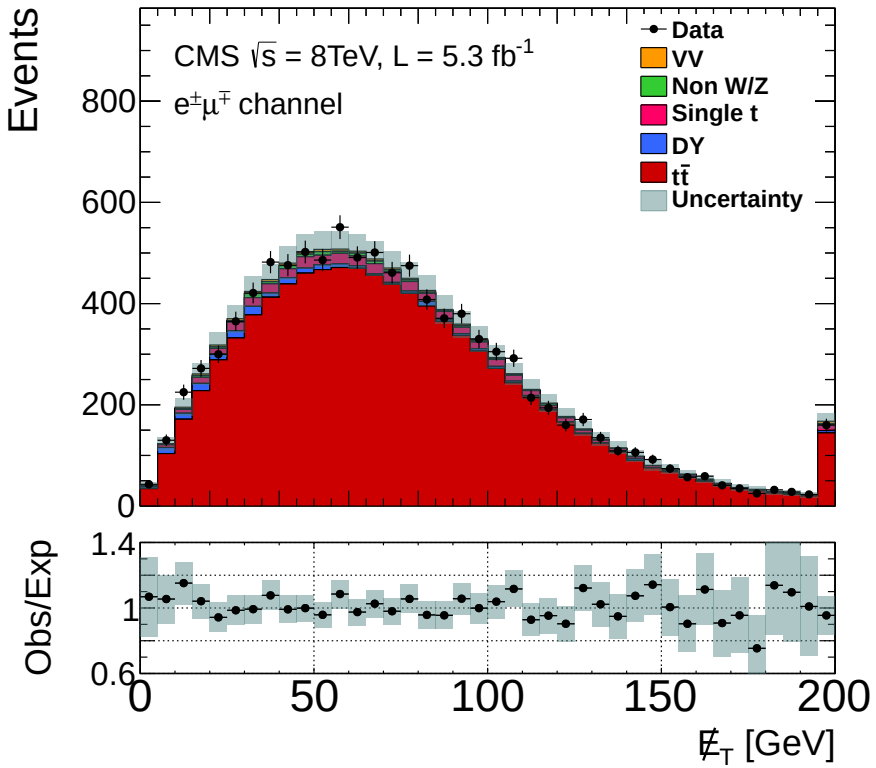


Channel	$\sigma_{t\bar{t}} \pm \text{stat.} \pm \text{syst.} \pm \text{Lumi.}$ [pb]
e^+e^-	$244.3 \pm 5.2 \pm 18.6 \pm 6.4$
$\mu^+\mu^-$	$235.3 \pm 4.5 \pm 18.6 \pm 6.1$
$\mu^{\pm}e^{\mp}$	$239.0 \pm 2.6 \pm 11.4 \pm 6.2$
$\ell^{\pm}\ell^{\mp}$	$239 \pm 2 \pm 11 \pm 6$

Systematic Uncertainties

Source	e^+e^-	$\mu^+\mu^-$	$\mu^{\pm}e^{\mp}$
		[pb]	
Trigger efficiencies	4.1	3.0	3.6
Lepton efficiencies	5.8	5.6	4.0
Lepton energy scale	0.6	0.3	0.2
Jet energy scale	10.3	10.8	5.2
Jet energy resolution	3.2	4.0	3.0
b-jet tagging	1.9	1.9	1.7
Pileup	1.7	1.5	2.0
Scale (μ_F and μ_R)	5.7	5.5	5.6
Matching PS	3.9	3.8	3.8
Single top quark	2.6	2.4	2.3
VV	0.7	0.7	0.5
Drell-Yan	10.8	10.3	1.5
Non-W/Z leptons	0.9	3.2	1.9
Total systematic	18.6	18.6	11.4

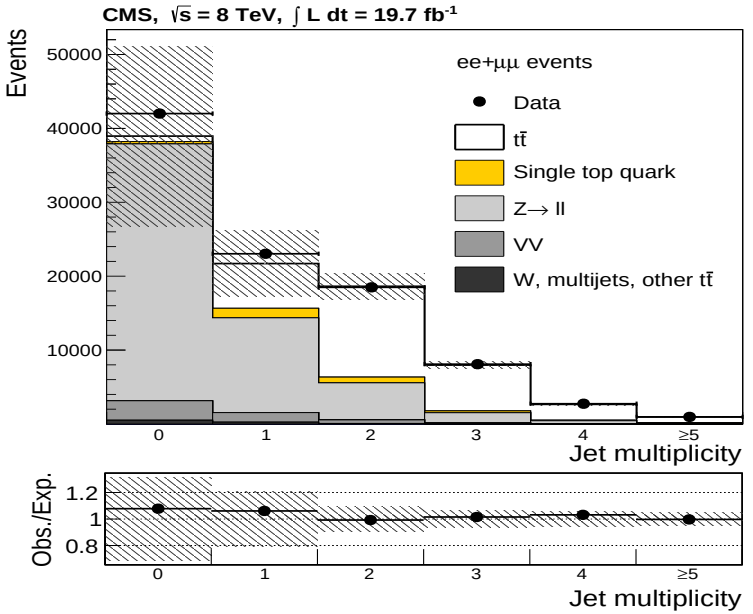
$$\frac{\sigma_{t\bar{t}}(m_t)}{\sigma_{t\bar{t}}(m_t^o)} = 1.00 - 0.009 \times (m_t - m_t^o) - 0.000168 \times (m_t - m_t^o)^2$$

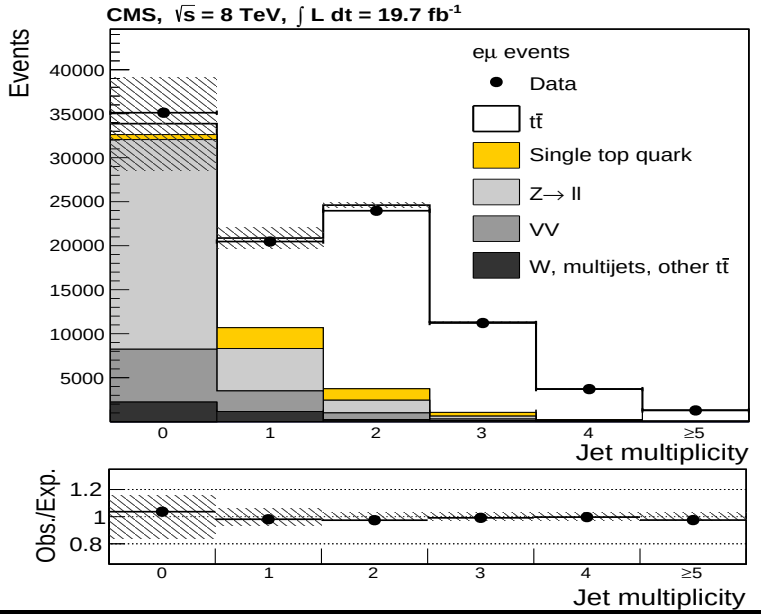
$\sigma_{t\bar{t}}$ in the $\mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$ measurement

PLB 736 (2014) 33

1. Full 8 TeV data sample.
2. Analysis focused in the measurement of $\mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$
3. Measurement performed over the three *dilepton* channels.
4. Profile likelihood method.
5. Background: Drell-Yan estimated from data with Template fit to the angle between the leptons (in ee,$\mu\mu$) and the $\sum M_T$ for eμ channel.
6. Uncertainties affect signal and background expectations as multiplicative factors (nuisances).
   - All uncertainties are distributed according to a log-normal and log-uniform distribution.
7. The systematic uncertainty includes PDF, luminosity, $t\bar{t}$ modeling, etc.

$$\sigma_{t\bar{t}} = 238 \pm 1(\text{stat.}) \pm 15(\text{syst.})\,\text{pb}$$



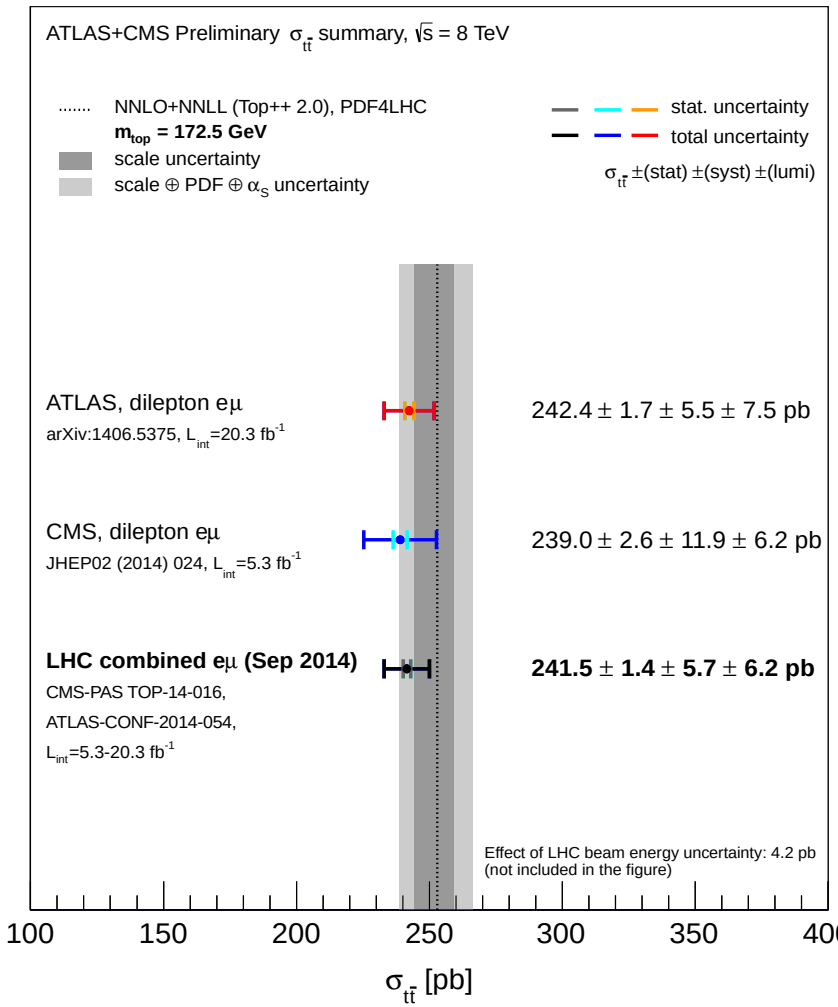


Dilepton Combination: ATLAS + CMS Result

CMS PAS TOP-14-016/ATLAS-CONF-2014-054

	ATLAS	CMS	Corr.	LHC comb.
Detector model				
Trigger	0.4	3.6	0	1.1
LES/LER	1.2	0.2	0	0.9
Lepton ID	1.7	4.0	0	1.7
Jet resolution	1.3	3.0	0	1.2
Jet ID	0.1	–	–	0.1
b-tagging	1.0	1.7	0	0.8
Pileup	–	2.0	–	0.6
non-JES subtotal	2.7	6.7	0	2.7
UncorrJES	0.6	4.3	0	1.3
InsituJES	0.6	0.6	0	0.5
IntercalibJES	0.3	0.1	0.5	0.2
FlavourJES	0.9	2.9	0	1.0
bJES	0.1	n/e	–	0.1
JES subtotal	1.3	5.2	0	1.7
Signal model				
Scale	0.7	5.6	0.5	1.9
Radiation	–	3.8	–	1.1
GEN and PS	3.0	3.4	0.5	2.7
PDF	2.7	0.5	1	2.1
DD-Background				
Z+jets	<0.1	1.5	0	0.4
Lepton misID	0.8	1.9	0	0.8
SIM Background				
Dibosons	0.3	0.5	1	0.4
Single top	2.0	2.3	1	2.1
Luminosity				
VdM scan	2.9	5.0	1	3.5
Luminosity	6.9	3.6	0	5.1
Total systematic	9.3	13.4		8.4
Total	9.5	13.6		8.5

1. Comb. performed with the BLUE method.



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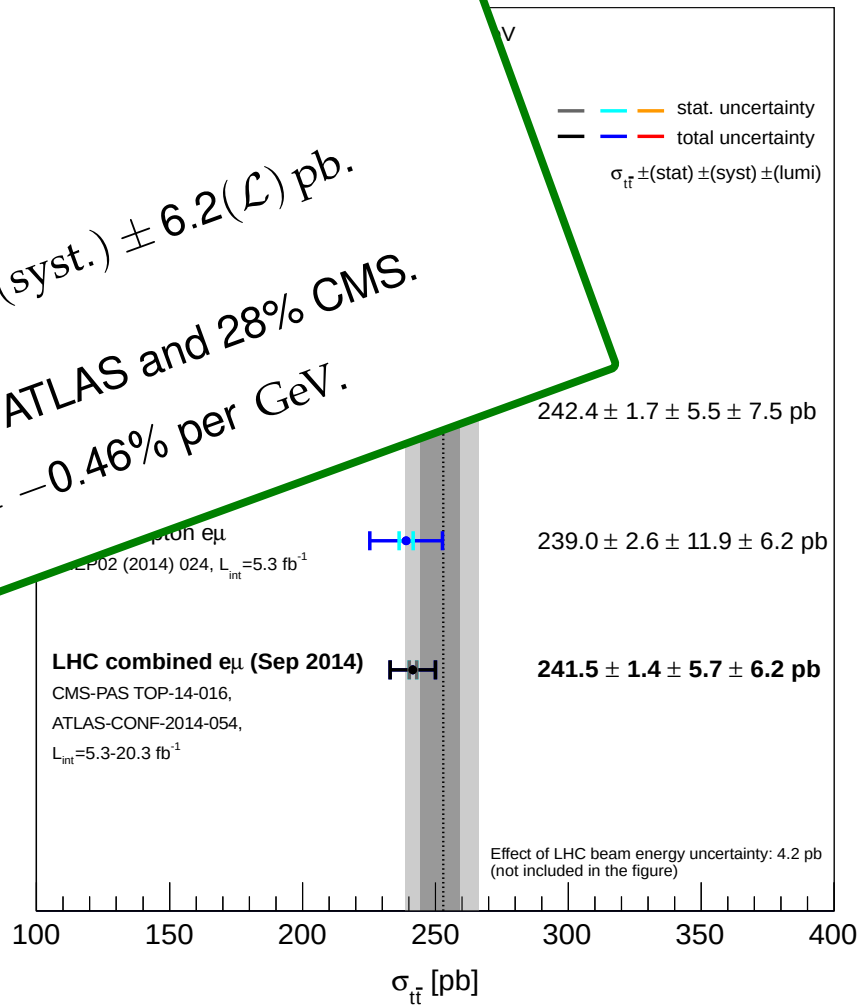
Jet resolution	1.3	3.0	0	
Jet ID	0.1	–	–	
b-tagging	1.0	1.7		
Pileup	–			
non-JES subtotal	2.7			
UncorrJES				
InsituJES				
IntercalibJES				
FlavourJES				
bJES				
JES subtotal				
Signal model				
Scale	0.			
Radiation	–			
GEN and PS	3.0			
PDF	2.7			
DD-Background				
Z+jets	<0.1			
Lepton misID	0.8			0.8
SIM Background				
Dibosons	0.3		1	0.4
Single top	2.0	2.8	1	2.1
Luminosity				
VdM scan	2.9	5.0	1	3.5
Luminosity	6.9	3.6	0	5.1
Total systematic	9.3	13.4		8.4
Total	9.5	13.6		8.5

Cross section combination: ATLAS and CMS

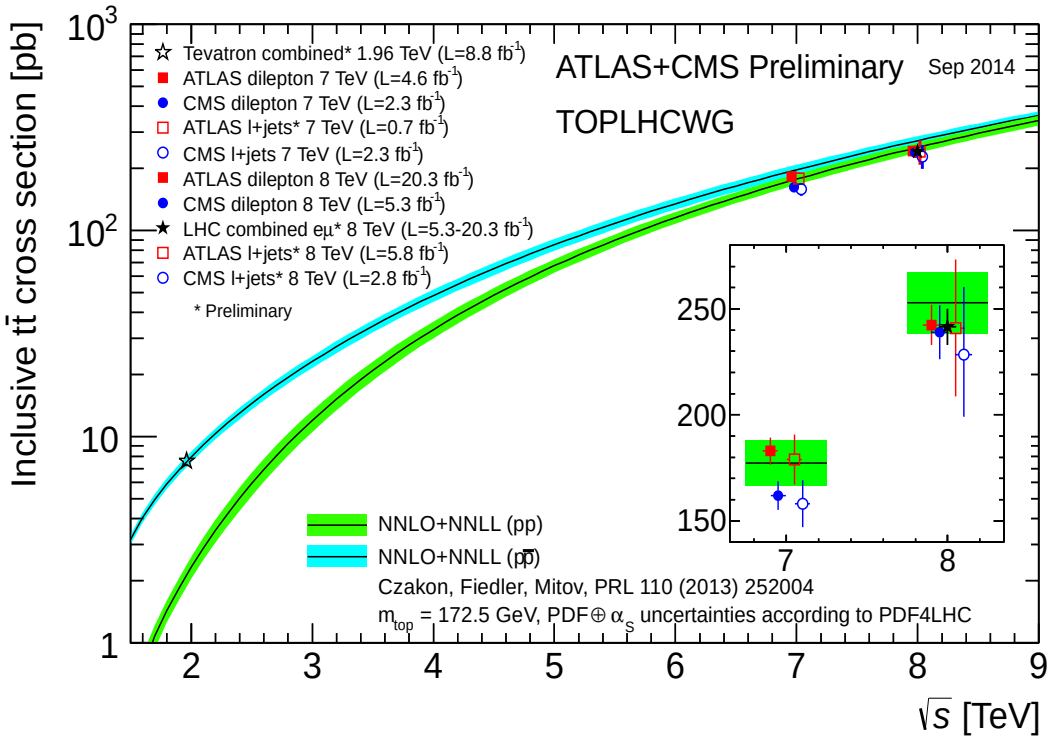
1. ATLAS:
   - $\sigma_{t\bar{t}} = 242.4\,\text{pb} \pm 3.9\%$.
2. CMS:
   - $\sigma_{t\bar{t}} = 239.0\,\text{pb} \pm 5.7\%$.
3. $\sigma_{t\bar{t}} = 241.5 \pm 1.4(\text{stat.}) \pm 5.7(\text{syst.}) \pm 6.2(\mathcal{L})\,\text{pb}$.
   - $\sigma_{t\bar{t}} = 241.5\,\text{pb} \pm 3.5\%$.
4. Combination weights: 72% ATLAS and 28% CMS.
5. Mass dependency: $\frac{d\sigma_{t\bar{t}}}{dm_t} = -0.46\%$ per GeV.

with the BLUE



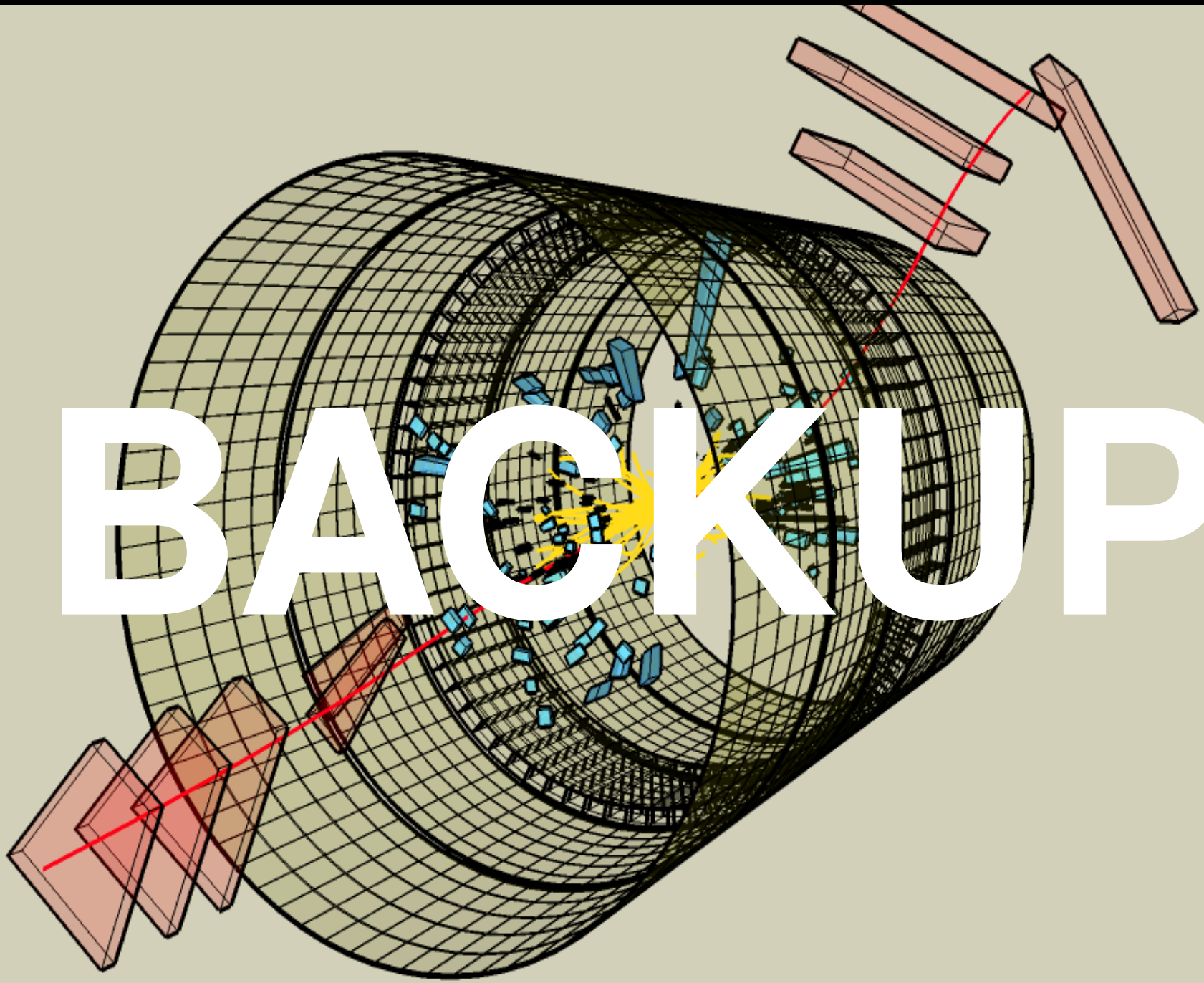
Conclusions

1. $t\bar{t}$ cross section measurements and theory have unprecedented precision.
   - $\sigma_{t\bar{t}}^{Theory} = 245.9\,\mathrm{pb} \pm 5.7\%$
   - $\sigma_{t\bar{t}}^{\mu e} = 241.8\,\mathrm{pb} \pm 3.5\%$
2. $\sigma_{t\bar{t}}$ in fiducial regions is provided in order to avoid model-dependent extrapolations.
   - No NNLO calculation to compare.
3. Precise measurements of the $\sigma_{t\bar{t}}$ allows to perform measurements of other interesting parameters such as m_t, SUSY constrains, etc.
4. New results at 8 TeV are coming (lepton+jets, full hadronic, dilepton, etc).



Latest CMS and ATLAS results

1. ATLAS Simultaneous measurements of the top quark pair, W^+W^-, and $Z/\gamma* \to \tau\tau$ production cross sections in pp collisions with the ATLAS detector at $\sqrt{s} = 7\,\text{TeV}$. arXiv:1407.0573
2. CMS Measurement of the ttbar production cross section in pp collisions at 8 TeV in the $e\tau$ and $\mu\tau$ dilepton final states. arXiv:1407.6643
3. ATLAS Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with b-tagged jets in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector. arXiv:1406.5375
4. CMS Measurement of the ratio B($t \to Wb$)/B($t \to Wq$) in pp collisions at $\sqrt{s} = 8\,\text{TeV}$. PLB 736 (2014) 33
5. CMS Measurement of the $t\bar{t}$ production cross section in the dilepton channel in pp collisions at $\sqrt{s} = 8\,\text{TeV}$. JHEP 02 (2014) 024
6. ATLAS Measurement of the $t\bar{t}$ production cross section in the τ+jets channel using the ATLAS detector. Eur. Phys. J. C, 73 3 (2013)
7. CMS Measurement of the $t\bar{t}$ production cross section in the $\tau + jets$ channel in pp collisions at $\sqrt{s} = 7\,\text{TeV}$. EPJ C73 (2013) 2386



BACKUP

μe Channel: Systematic Uncertainties

arXiv:1406.5375

$\sqrt{s}$	7 TeV			8 TeV		
Uncertainty (inclusive $\sigma_{t\bar{t}}$)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
$t\bar{t}$ modelling	0.71	−0.72	1.43	0.65	−0.57	1.22
Parton distribution functions	1.03	-	1.04	1.12	-	1.13
QCD scale choice	0.30	-	0.30	0.30	-	0.30
Single-top modelling	-	-	0.34	-	-	0.42
Single-top/$t\bar{t}$ interference	-	-	0.22	-	-	0.15
Single-top *Wt* cross-section	-	-	0.72	-	-	0.69
Diboson modelling	-	-	0.12	-	-	0.13
Diboson cross-sections	-	-	0.03	-	-	0.03
Z+jets extrapolation	-	-	0.05	-	-	0.02
Electron energy scale/resolution	0.19	−0.00	0.22	0.46	0.02	0.51
Electron identification	0.12	0.00	0.13	0.36	0.00	0.41
Muon momentum scale/resolution	0.12	0.00	0.14	0.01	0.01	0.02
Muon identification	0.27	0.00	0.30	0.38	0.00	0.42
Lepton isolation	0.74	-	0.74	0.37	-	0.37
Lepton trigger	0.15	−0.02	0.19	0.15	0.00	0.16
Jet energy scale	0.22	0.06	0.27	0.47	0.07	0.52
Jet energy resolution	−0.16	0.08	0.30	−0.36	0.05	0.51
Jet reconstruction/vertex fraction	0.00	0.00	0.06	0.01	0.01	0.03
b-tagging	-	0.18	0.41	-	0.14	0.40
Misidentified leptons	-	-	0.41	-	-	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	1.56	0.75	2.27	1.66	0.59	2.26