A measurement of the inclusive $t\bar{t}$ production cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV using events with one isolated charge lepton and at least one jet

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- Approval
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  - Michele Gallinaro
  - Gaetano-Marco Dallavalle
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Available on the CMS information server **CMS TOP-16-006**

CMS Draft Analysis Note

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A measurement of the inclusive $t\bar{t}$ production cross section in proton-proton collisions at $\sqrt{s}$=13 TeV using events with one isolated charged lepton and at least one jet

Abstract

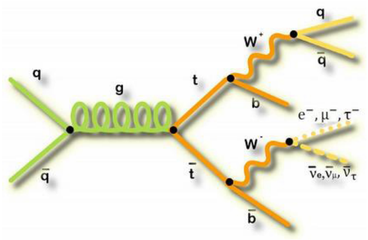
A measurement of the $t\bar{t}$ production cross section at $\sqrt{s}$=13 TeV is presented using 2.3 fb^{-1} of proton-proton collision data acquired by the CMS detector. Final states including one isolated charged lepton (electron or muon) and at least one jet are selected and categorized according to the multiplicity of jets. From a likelihood fit to the invariant mass of the isolated lepton and a jet identified as stemming from the fragmentation and hadronization of b quark, the cross section is measured to be $\sigma(t\bar{t}) = 834.6 \pm 2.5\,(\mathrm{stat}) \pm 19.1\,(\mathrm{syst}) \pm 22.5\,(\mathrm{lumi})\ \pm 12.5\,(\mathrm{extrapol.})$ pb in agreement with the standard model prediction. A measurement of the top quark pole mass is also reported.

Scope

- We aim to measure the cross section at 13 TeV
  - how precise can we measure it in the l+jets final state
  - precise measurement of the cross section opens the possibility to perform
    - precision measurements (PDFs, α_S)
    - extrapolating the pole mass http://arxiv.org/abs/1511.00841
  - search for physics beyond the standard model is particularly relevant at Run 2
    - A deviation in the ratio of cross section at 13 TeV/ 8TeV http://arxiv.org/abs/1206.3557
    - by setting limit on stop production http://arxiv.org/abs/1407.1043
    - A deviation in the branching ratios of different final states (test lepton universality in ttbar decays)
    - For this preliminary result, we shall measure σ only

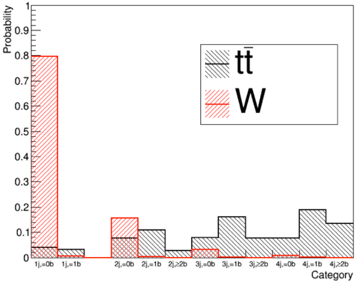
L+Jets Final State

- The l+jets final state is chosen
- High statistics, moderate background
- Branching ratio ($t\bar{t} \rightarrow l\nu q\bar{q}b\bar{b}$) = 30% + 5.3% from $tau \rightarrow l\nu\nu$ decays
- Expect 1 lepton, $\not{E}_T$ and 4 jets including at least 2 b-tags
- We start the analysis with 1 jet (next slide)



Analysis Strategy

- We divide the analysis in different categories by counting the jets and b-tags
- Low jet/btag categories to constrain backgrounds while high jet/btag to fit the signal
- Analysis is also divided according to lepton charge
  - charge asymmetry is expected for W+Jets
- We don't subdivide the simulation per heavy flavor
  - As we are not having the enough statistics
- similar approach of TOP-11-004/TOP-13-004 ($SH_{Y}FT$, legacy Run-I)



Physics object selection

Muon Selection

- IsoMu20||IsoTkMu20
- Exactly one muon
  - p_T >30 GeV, $|\eta|$ <2.1, tight ID
  - dB <0.2, dZ <0.5, relIso <0.15
  - SIP3D <4
- Loose Muon Veto
  - p_T >15 GeV, $|\eta|$ <2.4, relIso <0.25

Electron Selection

- Ele22_eta2p1_WPLoose_Gsf
- Exactly one electron
  - Using official electron tight ID
  - p_T >30 GeV, $|\eta|$ <2.1
  - SIP3D <4
- Using recommended electron veto ID

Jet Selection

- We require at least one jet
  - LOOSE jet ID is applied
  - p_T >30 GeV, $|\eta|$ <2.4, Fall15_25nsV2
- Count number of jets identified as b's
  - CSV Discriminator value >0.800 (medium working point)

Data and MC samples

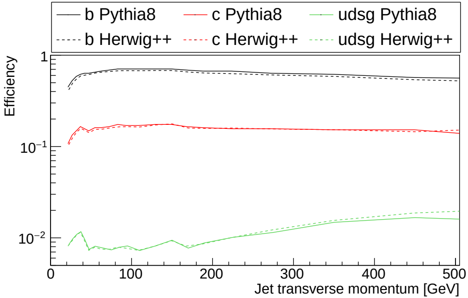
Data samples	Integrated Luminosity
/SingleMuon/Run2015C_25ns-16Dec2015-v1/MINIAOD /SingleElectron/Run2015C_25ns-16Dec2015-v1/MINIAOD /SingleMuon/Run2015D-16Dec2015-v1/MINIAOD /SingleElectron/Run2015D-16Dec2015-v1/MINIAOD	2.3 fb^{-1}

MC samples	Process	Cross section[pb]	Events
/TT_TuneCUETP8M1_13TeV-powheg-pythia8	$t\bar{t}$	831.76	97994442
/TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	$t\bar{t}$+V	0.2043	250307
/TTWJetsToQQ_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	$t\bar{t}$+V	0.4062	831847
/TTZToQQ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	$t\bar{t}$+V	0.5297	747000
/TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8	$t\bar{t}$+V	0.2529	394200
/ZZ_TuneCUETP8M1_13TeV-pythia8	Multiboson	16.523	985600
/WWToLNuQQ_13TeV-powheg	Multiboson	49.497	6996000
/WWTo2L2Nu_13TeV-powheg	Multiboson	12.178	1979988
/WZ_TuneCUETP8M1_13TeV-pythia8	Multiboson	47.13	100000
/WJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	W	61526.7	199037280
/ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	tW	35.6	1000000
/ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	tW	35.6	999400
/ST_t-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	t-ch	44.33	3299200
/ST_t-channel_antitop_4f_leptonDecays_13TeV-powheg-pythia8_TuneCUETP8M1	t-ch	26.38	1630900
/DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	DY	6025.0	247512446
/DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	DY	18610	76558711
/Multijets (data)			

- MC samples are normalized by: $\hat{N} = \mathcal{L} \cdot \sigma \cdot \frac{\sum_{i=1}^{\mathrm{N_{sel}}} w_i}{\sum_{i=1}^{\mathrm{N_{gen}}} w_i}$

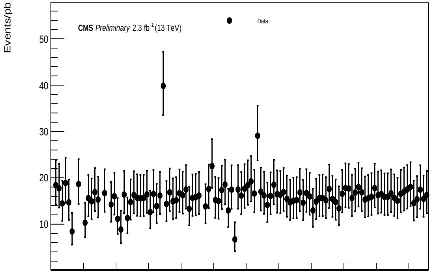
Correction Factors applied to Simulation

- PU reweighting based on 69 minimum bias cross section
- b-Tag scale factors (76X)
  - we scale Herwig++ efficiency to match pythia8 and apply the BTV scale factors to that
- Lepton SF (Official POG), cross checked in this analysis
- JEC (Fall15_25nsV2)
- JES sources
  uncertainties broken in 29 sources
- JER JER twiki

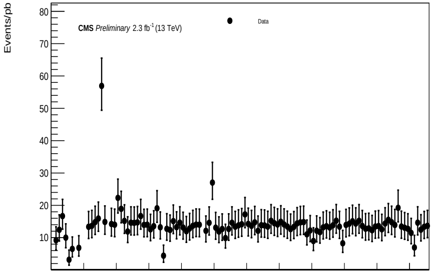


Stability of the Selection

- The rate of events is very stable as function of run number
- A couple of runs identified with anomalous rates have very low luminosity ($\sim 1pb^{-1}$)

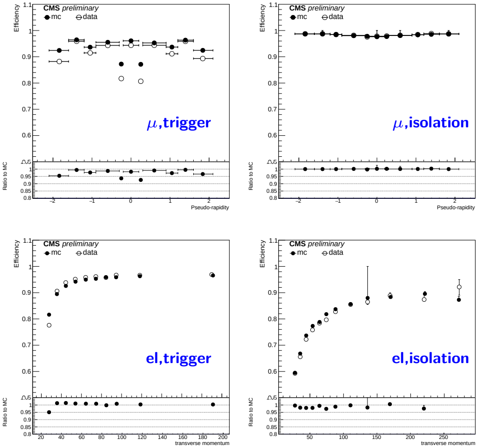


4J, μ^+



4J, el^+

Trigger Efficiency Measurements



- Using official TnP trees adopted for our selection (Different fitting models tried)
- Results are used as a cross check of the official SFs

Background estimation

Background Estimation: W+Jets

- Modelled from simulation
- Analysis in each lepton channel is sub-divided according to lepton charge
- $t\bar{t}$ production is expected to be symmetric
- W production is expected to asymmetric due to PDF composition of protons
- Assign the corresponding uncertainties from the choice of the QCD scales and PDFs.
  - The templates are currently derived from the MG5_aMC@NLO
  - Large fraction of negative weights, sufficient statistics to provide positive defined and fairly smooth templates
- Compared MG5_aMC@NLO with MADGRAPH in different categories
- Difference in normalization is observed but the shape of the distributions is fairly similar

W+Jets Normalization and Charge Asymmetry

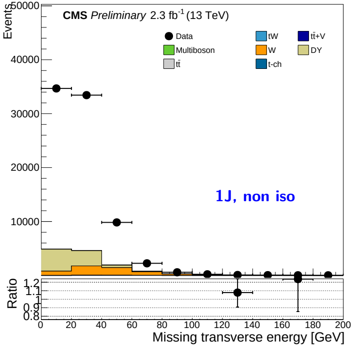
Category	=1 jet	=2 jets	=3 jets	$\geq$4 jets
μ^+	1.112$\pm$0.002	1.184$\pm$0.006	1.20$\pm$0.01	0.96$\pm$0.02
μ^-	1.095$\pm$0.003	1.170$\pm$0.006	1.19$\pm$0.01	0.97$\pm$0.02
e^+	1.102$\pm$0.003	1.196$\pm$0.007	1.21$\pm$0.02	0.96$\pm$0.02
e^-	1.288$\pm$0.004	1.38$\pm$0.008	1.40$\pm$0.02	1.09$\pm$0.03

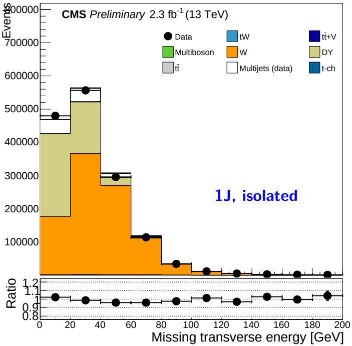
- Ratio of the events predicted by MG5_aMC@NLO wrt MADGRAPH
- Predicts $\sim$ 20% more events wrt to madgraph for Njets $<$4
- Predicts $\sim$ 5% less events for Njets $>$4
- As a consequence of this observation, different charge asymmetry is predicted

Background Estimation: QCD Multijets

- Normalization is determined from events with low $\not{E}_T$ ($<$20 GeV)
  - Expect to be dominated by QCD
  - Extract QCD shape from events with relIso $>$0.4
  - Normalized from:

$$N_{\rm SR}(QCD) = [N_{\rm CR}(obs) - N_{\rm CR}(non - QCD)] \cdot \frac{N_{\rm SR}^{E_T^{miss}<20}(obs) - N_{\rm SR}^{E_T^{miss}<20}(non - QCD)}{N_{\rm CR}^{E_T^{miss}<20}(obs) - N_{\rm CR}^{E_T^{miss}<20}(non - QCD)}$$





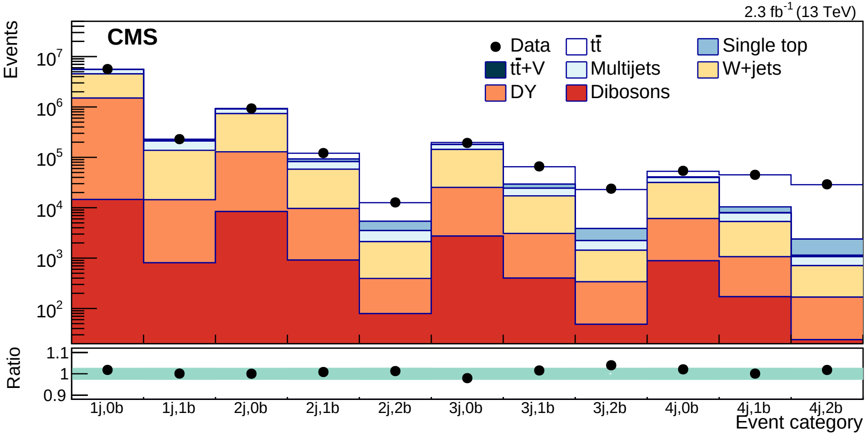
Background Estimation: QCD Multijets

Category	=1 jet	=2 jets	=3 jets	≥4 jets
μ^+	1.89 ± 0.09	1.63 ± 0.14	2.77 ± 0.24	2.17 ± 0.23
μ^-	1.59 ± 0.05	1.19 ± 0.05	2.64 ± 0.22	2.01 ± 0.15
e^+	2.71 ± 0.09	2.29 ± 0.10	2.60 ± 0.13	2.14 ± 0.30
e^-	2.50 ± 0.12	2.06 ± 0.05	2.56 ± 0.13	2.03 ± 0.10

- Scale factors to be applied to the control region distributions for QCD to normalize them in the signal region
- Overall the scale factors are approximately constant across the different jet multiplicity categories
- tend to increase for higher jet multiplicities
  - Due to NON QCD contamination in control region
- Uncertainty is higher in the positively charged lepton sample (as a consequence of charge asymmetry)
- All scale factors are close to two, data is triggered by isolated lepton triggers
- We capture only a portion of non-isolated leptons

Control distributions
(pre-fit, stats only uncertainty)

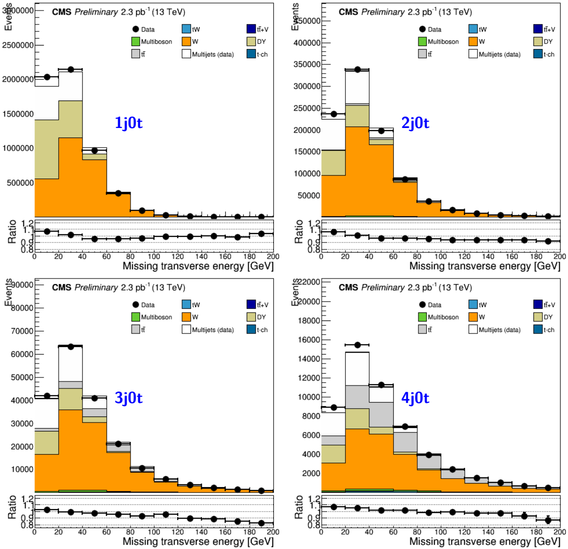
Events count



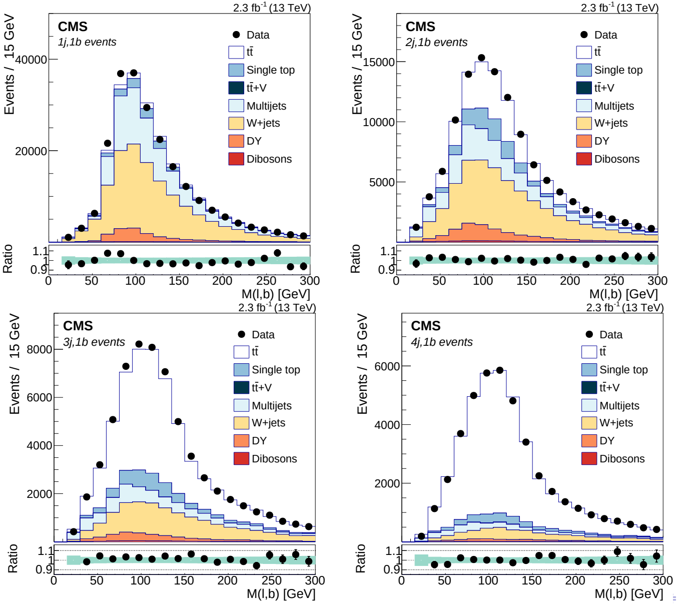
- e/mu+jets combined for positive/negative charged leptons
- Statistical uncertainty only

MET distributions

- At pre-approval (74X), we were using these distributions to constrain backgrounds
- Not so well modelled in 76X (electron channel)
  - we count simply the number of events with 0-btags

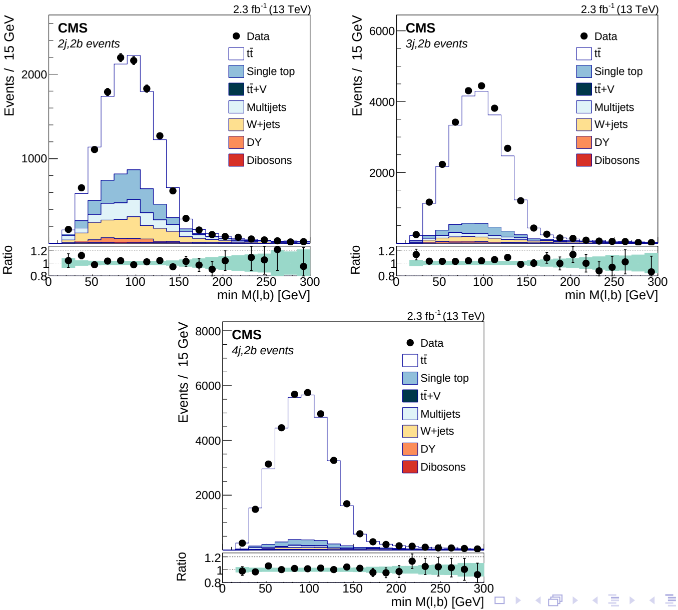


M(l,b)



2.3 fb^{-1} (13 TeV)
CMS
1j,1b events
2j,1b events
3j,1b events
4j,1b events
Data
$t\bar{t}$
Single top
$t\bar{t}$+V
Multijets
W+jets
DY
Dibosons
Events / 15 GeV
Ratio
M(l,b) [GeV]

minM(l,b)



2.3 fb^{-1} (13 TeV)
CMS
2j,2b events
3j,2b events
4j,2b events
Data
$t\bar{t}$
Single top
$t\bar{t}$+V
Multijets
W+jets
DY
Dibosons
Events / 15 GeV
Ratio
min M(l,b) [GeV]

Fit results and cross section measurement

Cross Section Measurement

- The $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ is extracted from the following expression

$$\sigma = \frac{\boxed{N_{obs} - N_{bkg}}}{A\varepsilon\mathcal{L}}$$

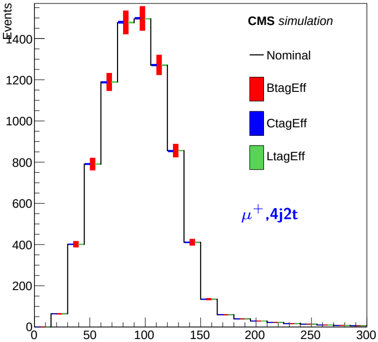
- We make use of Higgs Combination tool
- Use all categories to fit the signal and adjust initial background estimation
- In the fit, uncertainties are included

$$N^{bkg} \to N^{bkg}_{nom} \cdot (1 + \theta_{btag}) \cdot (1 + \theta_{jes}) \cdot \ldots..$$

- Use the profile likelihood method (PLR) to fit the signal strength

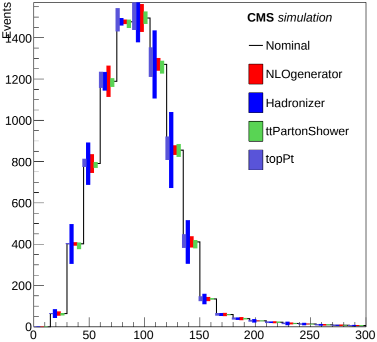
$$\mu = \sigma_{obs}/\sigma_{th}$$

Experimental uncertainties



- b-tagging efficiency is expected to have the largest impact on the signal shapes.
- nuisances are constrained by log-normal distributions

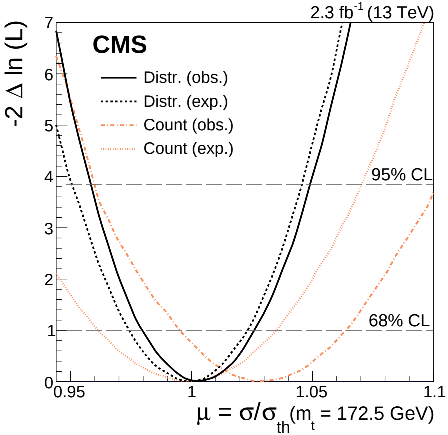
Uncertainty group	Name	Type	Prior	Range
JES	AbsoluteFlavMap			1.0-1.14
	AbsoluteMPFBias			1.0-1.18
	AbsoluteScale			1.0-1.3
	AbsoluteStat			1.0-1.2
	FlavorPureBottom			1.0-1.084
	FlavorPureCharm			1.0-1.144
	FlavorPureGluon			1.0-1.156
	FlavorPureQuark			1.0-1.073
	Fragmentation			1.0-1.106
	PileUpDataMC			1.0-1.12
	PileUpPtBB			1.0-1.17
	PileUpPtEC1			1.0-1.15
	PileUpPtEC2			1.0-1.13
	PileUpPtHF			1.0-1.12
	PileUpPtRef	shape+rate	lnN	1.0-1.14
	RelativeFSR			1.0-1.2
	RelativeJEREC1			1.0-1.10
	RelativeJEREC2			1.0-1.14
	RelativeJERHF			1.0-1.17
	RelativePtBB			1.0-1.19
	RelativePtEC1			1.0-1.11
	RelativePtEC2			1.0-1.12
	RelativePtHF			1.0-1.13
	RelativeStatEC			1.0-1.07
	RelativeStatHF			1.0-1.12
	SinglePionECAL			1.0-1.1
	SinglePionHCAL			1.0-1.12
	TimeEta			1.0-1.12
	TimePt			1.0-1.20
JER	JER	shape+rate	lnN	1.0-1.16
	BtagEff			1.0-1.17
b-tagging efficiency	CtagEff	shape+rate	lnN	1.0-1.13
	LtagEff			1.0-1.16
Luminosity	lumi_13TeV	rate	lnN	1.027
Pileup	Pileup	shape	lnN	
	EleEfficiency			0.98-1.027
	EleScale			1.0-1.016
	EleTrigger			0.97-1.032
Lepton efficiencies	MuEfficiency	shape+rate	lnN	1.0-1.003
	MuScale			1.0-1.045
	MuTrigger			1.0-1.003
QCD multijets	MultiJetsNorm*	rate	lnN	1.0-1.5
	MultiJetsShape*	shape	lnN	



Uncertainty group	Name	Type	Prior	Range
Theoretical cross sections	DYnorm_th	rate	lnN	1.038
	VVnorm_th			1.2
	Wnorm_th			1.037
	tWnorm_th			1.054
	tnorm_th			1.044
$t\bar{t}$ modelling	Hadronizer	shape+rate	lnN	1.0-1.344
	NLOgenerator	shape+rate	lnN	1.0-1.20
	topPt	shape+rate	lnN	1.0-1.055
	Mtop	shape	lnN	
	ttCombScale	shape	lnN	
	ttFactScale	shape	lnN	
	ttPartonShower	shape	lnN	
	ttRenScale	shape	lnN	
tW modelling	tWscale	shape+rate	lnN	1.0-1.14
	tWttinterf	shape+rate	lnN	1.00-1.30
W+jets modelling	wCombScale	shape+rate	lnN	1.05-1.13
	wFactScale (shape)			1.0-1.039
	wRenScale (shape)			1.0-1.15

- Distributions for the signal shapes
- Hadronizer is expected to have the largest impact on the signal shapes

Fit result

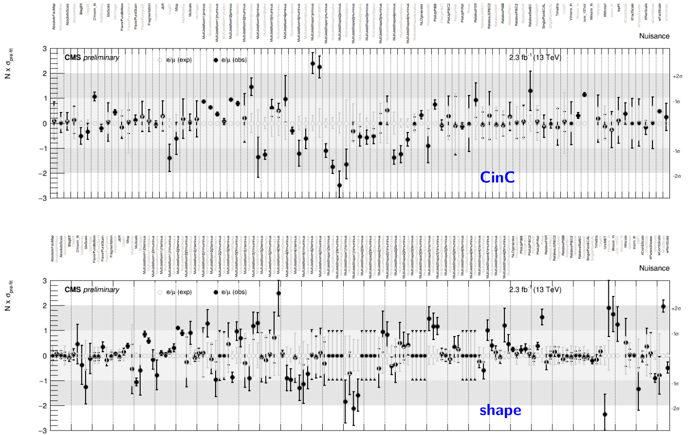


- Expected/observed for the cut-in-categories and and the shape analysis

$$\mu = 1.003 \pm 0.003(stat) \pm 0.023(syst)$$

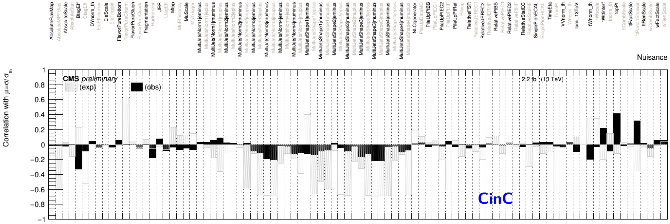
$$\mu = 1.030 \pm 0.004(stat) \pm 0.034(syst)$$

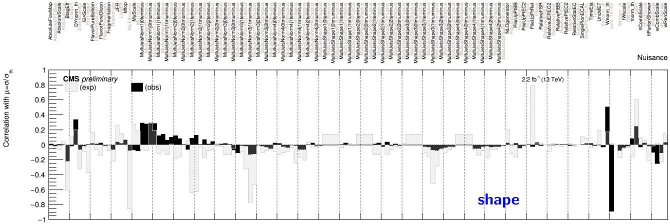
post-fit nuisances (expected & observed)



- Largest pulls are observed for the main backgrounds W and QCD multijets
- All the rest with in 1 σ
- Post fit uncertainties smaller in shapes as expected

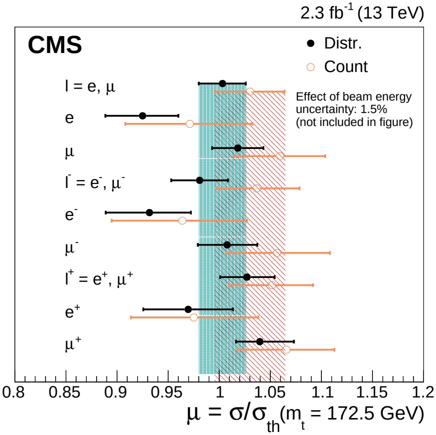
correlation factor between each nuisance and the signal strength





- Largest correlations in main backgrounds W, QCD multijets and luminosity

Fit in different categories



- Slight tension (1σ) between electron and muon channels
- Enhanced after combination
- Fair agreement between shape and cut-in-categories

Systematics

Source	Cut-in-Categories	Shape
Statistics	0.004	0.003
Experimental uncertainties		
Jet energy scale/resolution	0.003	0.001
b-tagging	0.004	0.004
Other backgrounds	0.004	0.004
Pileup	0.001	< 0.001
Lepton efficiency	$<$0.001	$<$0.001
Lepton energy scale	0.002	0.001
W model	0.020	0.020
QCD multijets	0.018	0.009
Theory uncertainties		
Top quark mass	< 0.001	0.001
$t\bar{t}$ model	0.011	0.002
Single top quark model	0.008	0.002
$t\bar{t}$ top p_T	0.006	0.005
Parton shower scale	0.012	0.001
$t\bar{t}$ QCD scale	0.004	0.002
Total	**0.034**	**0.023**

- The impacts of the systematic uncertainties on the likelihood are evaluated using the following prescription:
  - fix the nuisances to their post-fit values
  - repeat the fit freezing several times adding at a time a nuisance (or a group of nuisances)

Cross Section Measurement

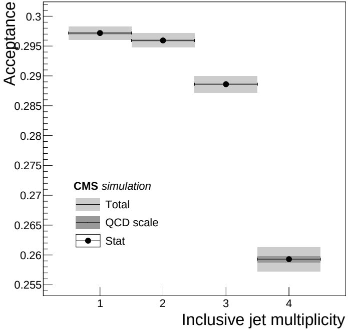
- The $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ is extracted from the following expression

$$\sigma = \frac{N_{obs} - N_{bkg}}{A\varepsilon\mathcal{L}}$$

- Acceptance is estimated from Powheg+Pythia8 $m_t = 172.5$ GeV
  - central value affected by the MC choice, hadronizer, parton shower scale
  - PDF uncertainties
  - QCD scale choice at ME level
- Uncertainty on the luminosity is intrinsic to the measurement 2.7 % (LUM-15-001)

Acceptance Measurement

Uncertainty	Procedure	Impact
PDF+α_s	RMS of the 100 NNPDF3.0 variations with $\Delta\alpha_s = \pm 0.001$	± 0.0006
QCD scale	Envelope of the variations (μ_R, μ_F)	± 0.0017
PS scale	Difference between nominal PS scale POWHEG+PYTHIA8 and 2,1/2 variations	
Hadronizer	Difference between PYTHIA8 and HERWIG++	± 0.0039
Integrated luminosity	2.7%	



$$\boxed{Acceptance = 0.2972 \pm 0.0001(stat) \pm 0.0043(syst)}$$

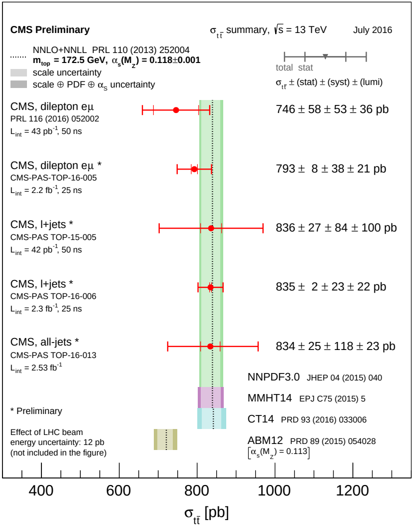
- Table indicates the uncertainties considered in the extrapolation to full phase space
- Dependence on the mass enhanced by the reqquirement of extra jets

$t\bar{t}$ cross-section summary

$$\boxed{\sigma = 834.7 \pm 2.5(stat) \pm 20.7(syst) \pm 22.6(lumi) \pm 12.5(extrapol)}$$

$$\boxed{\Delta\sigma/\sigma = 3.98\%}$$

- Thanks J.Kieseler for such a nice plot



Conclusion

- We have presented a measurement of the inclusive cross section in the l+jets channel
  - focus on optimizing the data to understand the signal in the visible region
  - uncertainty in the extrapolation reduced by requiring only one jet in the selection
- We measure:

$$\boxed{\sigma = 834.7 \pm 2.5(stat) \pm 20.7(syst) \pm 22.6(lumi) \pm 12.5(extrapol)}$$

$$\boxed{m_{\mathrm{t}} = 172.3 + 2.7/-2.3 GeV}$$

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THE END