Measurement of Top Quark Mass and Production Cross-Section using tt-bar pairs with Semi-Leptonic Decay Channel

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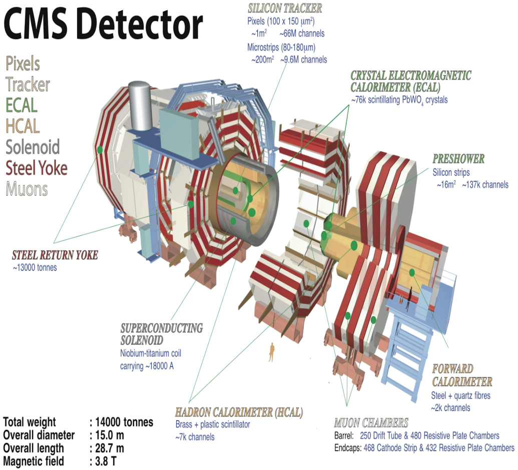
Large Hadron Collider (LHC)

- the LHC is a discovery machine
- the LHC will determine the future course of high energy physics
- to smash protons moving at 99.999999% to the speed of light
- to create conditions a fraction of a second after the big bang
- High energies allows us:
  - to look deeper into nature (E α 1/size), ("powerful microscopes")
  - to discover new particles with high(er) mass (E=mc^2)
  - to study the early universe (E=kT)
  - revisit the earlier, hotter, history of our universe, searching for a new simplicity ("powerful telescopes") by observing phenomena and particles no longer observable in our everyday experience

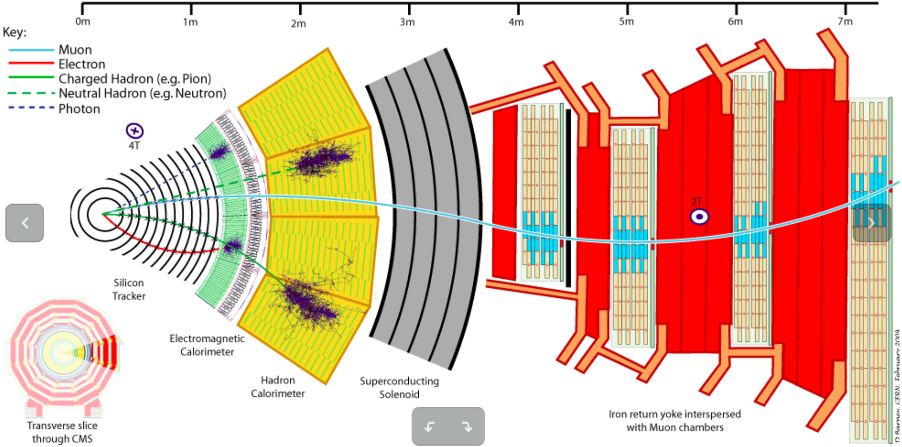
Compact Muon Solenoid (CMS)



- Distinct features are compact size and superconducting solenoid (3.8 T)
- Tracker and calorimeters are located inside the solenoid
- Muon detectors are out side the solenoid
- All these sub-detectors are arranged in layers around the interaction point

- Multi-purpose detector

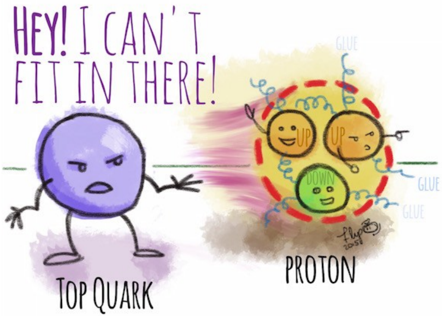
Compact Muon Solenoid (CMS)



- Particle identification: Various types of particles interact with matter differently, leaving a typical or no signal in specific subdetectors.

TOP quark physics

- The heaviest quark in the SM, discovered in 1995 at Tevatron.
- Charge of $+2/3$, weak isospin of $+1/2$ and life-time is 5×10^{-25} sec, so decays before hadronization.
- The spin information is kept by its decay products and its only quark which provides opportunity to study the properties of a bare quark.
- Major backgrounds to many important searches beyond the Standard Model (BSM) processes.

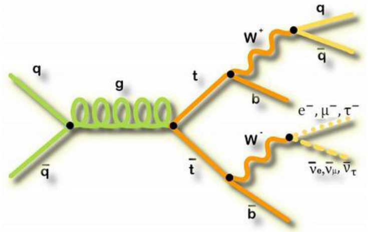


Scope

- 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

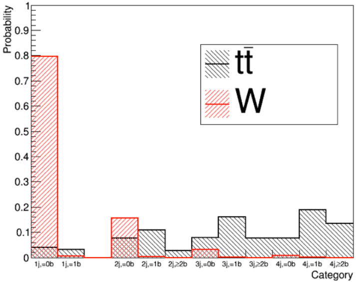
L+Jets Final State

- The l+jets final state is chosen
- High statistics, moderate background
- Branching ratio ($t\bar{t} \to l\nu q\bar{q}b\bar{b}$) = 30% + 5.3% from $tau \to l\nu\nu$ 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

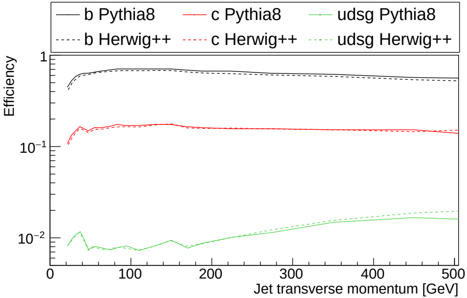
Data samples	Integrated Luminosity
/SingleMuon/Run2015C_25ns-16Dec2015-v1/MINIAOD /SingleElectron/Run2015C_25ns-16Dec2015-v1/MINIAOD /SingleMuon/Run2015D-16Dec2015-v1/MINIAOD /SingleElectron/Run2015D-16Dec2015-v1/MINIAOD	2.2 fb^{-1}

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: $\hat{N} = \mathcal{L} \cdot \sigma \cdot \frac{\sum_{i=1}^{\mathrm{N_{sel}}} w_i}{\sum_{i=1}^{\mathrm{N_{gen}}} w_i}$

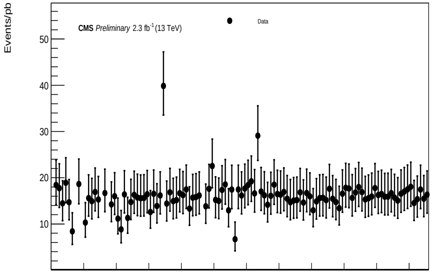
Correction Factors applied to Simulation

- 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

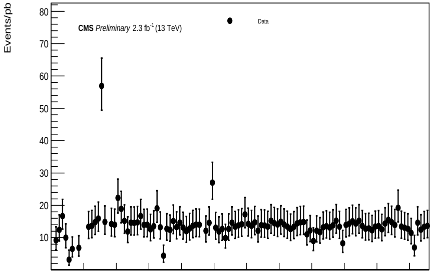


Stability of the Selection

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

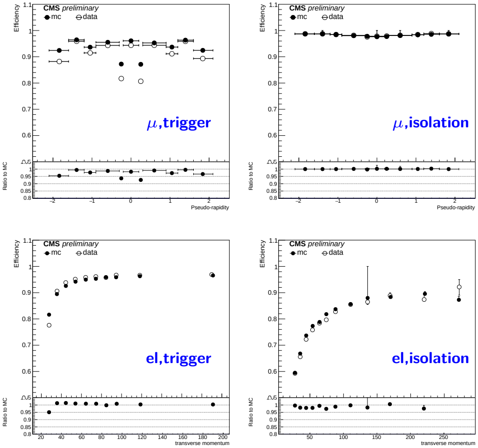


4J,μ^+



4J, el^+

Trigger Efficiency Measurements



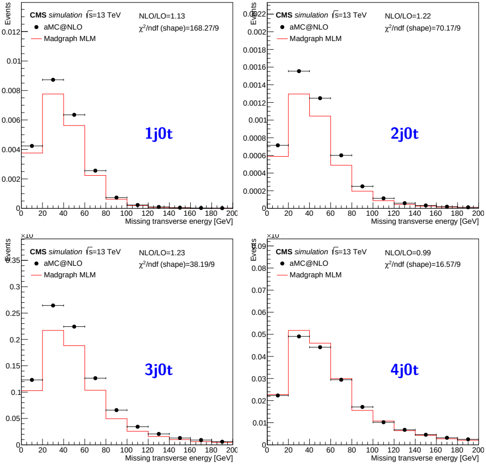
- Using official TnP trees adopted for our selection (Different fitting models tried)
- Results are used as a cross check of the official SFs

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

MET Distributions



W+Jets Normalization and Charge Asymmetry

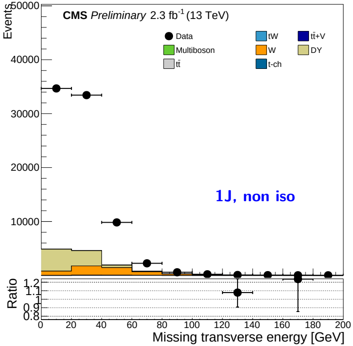
Category	=1 jet	=2 jets	=3 jets	≥4 jets
μ^+	1.112±0.002	1.184±0.006	1.20±0.01	0.96±0.02
μ^-	1.095±0.003	1.170±0.006	1.19±0.01	0.97±0.02
e^+	1.102±0.003	1.196±0.007	1.21±0.02	0.96±0.02
e^-	1.288±0.004	1.38±0.008	1.40±0.02	1.09±0.03

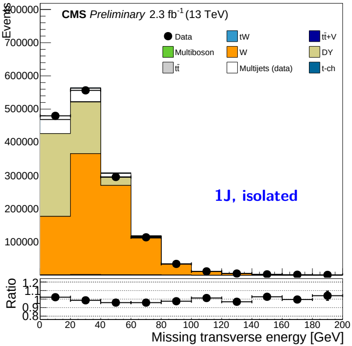
- Ratio of the events predicted by MG5_aMC@NLO wrt MADGRAPH
- Predicts $\sim$ 20% more events wrt to madgraph for Njets $<$4
- Predicts $\sim$ 5% less events for Njets $>$4
- As a consequence of this observation, different charge asymmetry is predicted

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

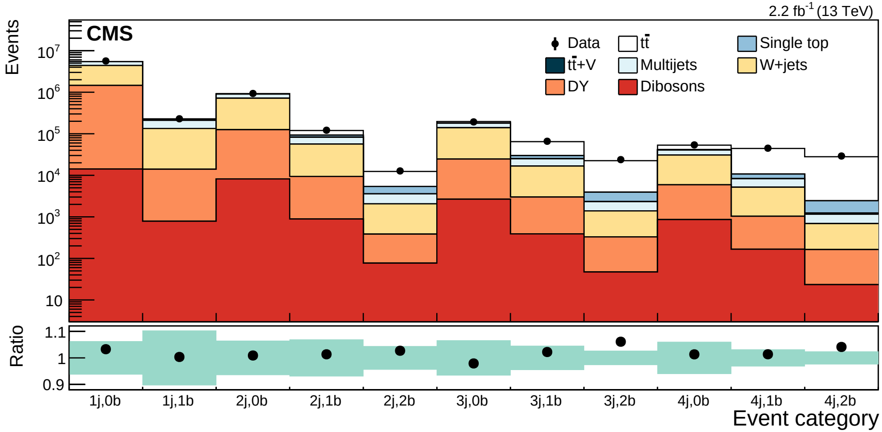
Category	=1 jet	=2 jets	=3 jets	≥4 jets
μ^+	1.89 ± 0.09	1.63 ± 0.14	2.77 ± 0.24	2.17 ± 0.23
μ^-	1.59 ± 0.05	1.19 ± 0.05	2.64 ± 0.22	2.01 ± 0.15
e^+	2.71 ± 0.09	2.29 ± 0.10	2.60 ± 0.13	2.14 ± 0.30
e^-	2.50 ± 0.12	2.06 ± 0.05	2.56 ± 0.13	2.03 ± 0.10

- 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)

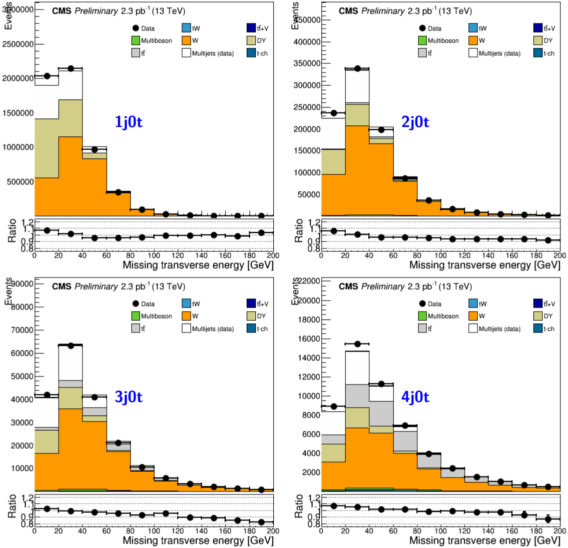
Events count



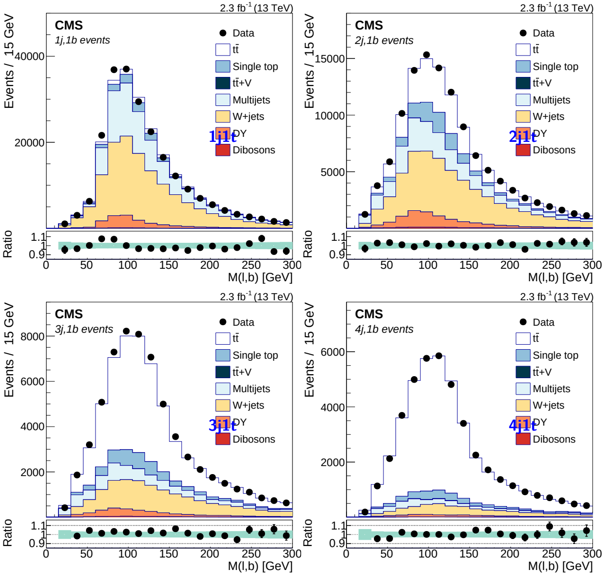
- e/mu+jets combined for positive/negative charged leptons
- Statistical uncertainty only

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

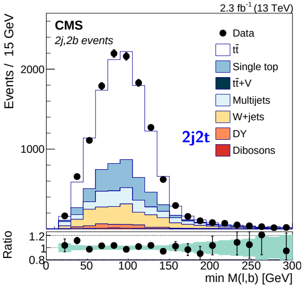


M(l,b)

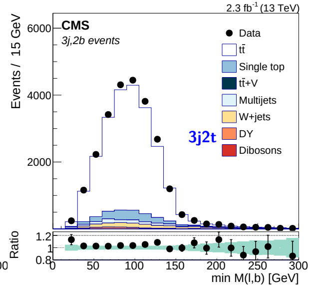


2.3 fb^{-1} (13 TeV)
CMS
1j,1b events
2j,1b events
3j,1b events
4j,1b events
Data
$t\bar{t}$
Single top
$t\bar{t}$+V
Multijets
W+jets
DY
Dibosons
1j1t
2j1t
3j1t
4j1t
Events / 15 GeV
Ratio
M(l,b) [GeV]

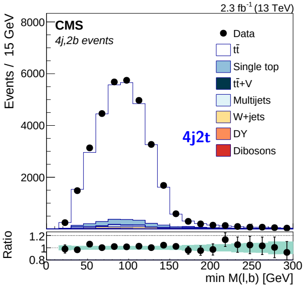
minM(l,b)



2.3 fb^{-1} (13 TeV)
CMS
2j,2b events
Data
$t\bar{t}$
Single top
$t\bar{t}$+V
Multijets
W+jets
DY
Dibosons
2j2t
Events / 15 GeV
Ratio
min M(l,b) [GeV]



2.3 fb^{-1} (13 TeV)
CMS
3j,2b events
Data
$t\bar{t}$
Single top
$t\bar{t}$+V
Multijets
W+jets
DY
Dibosons
3j2t
Events / 15 GeV
Ratio
min M(l,b) [GeV]



2.3 fb^{-1} (13 TeV)
CMS
4j,2b events
Data
$t\bar{t}$
Single top
$t\bar{t}$+V
Multijets
W+jets
DY
Dibosons
4j2t
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

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

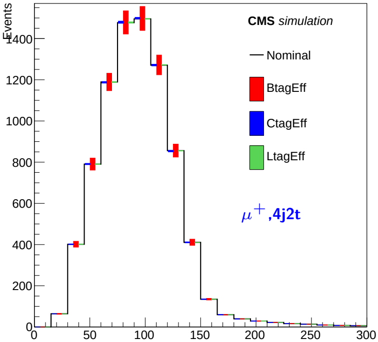
- We make use of Higgs Combination tool
- Use all categories to fit the signal and adjust initial background estimation
- In the fit, uncertainties are included

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

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

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

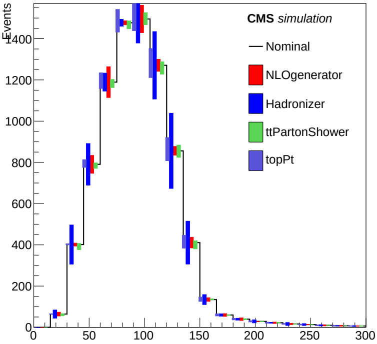
Experimental uncertainties



- 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	

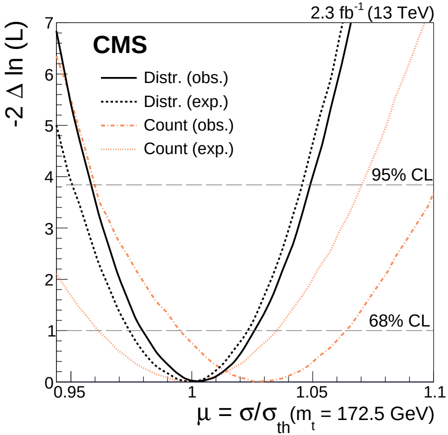
Theory uncertainties



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		lnN	1.05-1.13
	wFactScale (shape)	shape+rate		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

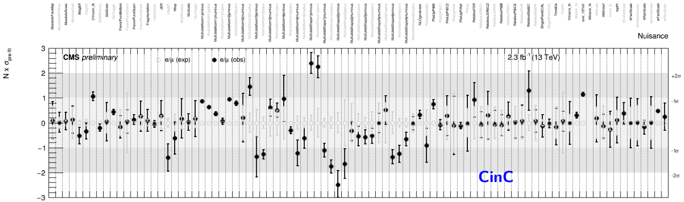
Fit result

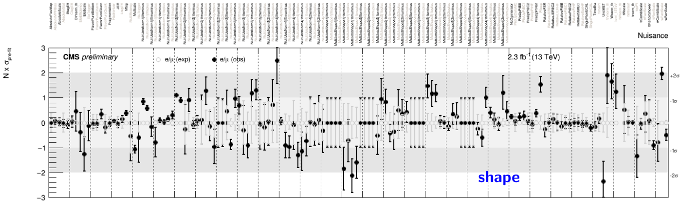


- Expected/observed for the cut-in-categories and and the shape analysis

$\mu = 1.003 \pm 0.003(stat) \pm 0.023(syst)$
$\mu = 1.030 \pm 0.004(stat) \pm 0.034(syst)$

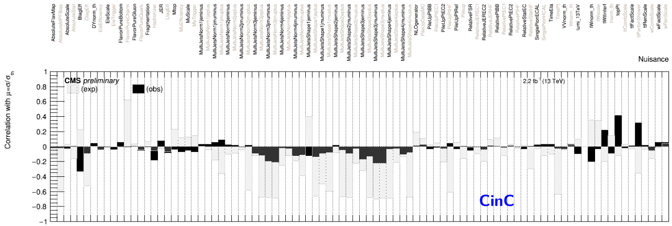
post-fit nuisances (expected & observed)

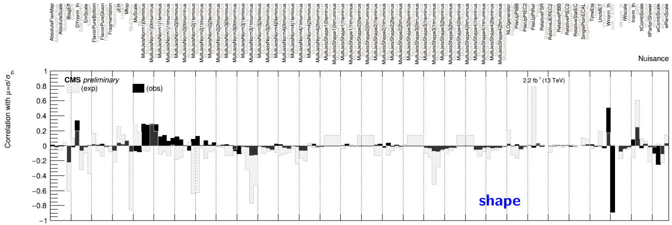




- Largest pulls are observed for the main backgrounds W and QCD multijets
- All the rest with in 1 σ
- Post fit uncertainties smaller in shapes as expected

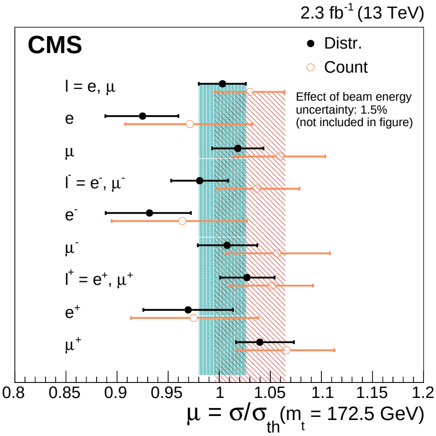
correlation factor between each nuisance and the signal strength





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

Fit in different categories



- The QCD contamination makes the W+jets background being pulled by the fit slightly differently in each channel.
- Difference observed is within uncertainties.
- Fair agreement between shape and cut-in-categories.

Systematics

Source	Distributions	Count
Statistical	0.003	0.004
Experimental uncertainties		
Jet energy scale/resolution	0.001	0.007
b tagging	0.005	0.011
Pileup	$<$ 0.001	$<$ 0.001
Lepton trigger/selection efficiency	0.002	0.001
Lepton energy scale	0.001	$<$ 0.001
W+jets model	0.019	0.022
multijet	0.011	0.021
Other backgrounds	0.001	0.001
Theoretical uncertainties		
$t\bar{t}$ model	0.002	0.001
Top quark p_T	0.004	0.003
Parton shower scales	0.001	0.005
$\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$	0.002	0.003
Single top quark model	0.002	0.003
Top quark mass	$<$ 0.001	0.001
Total	**0.023**	**0.034**

- 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

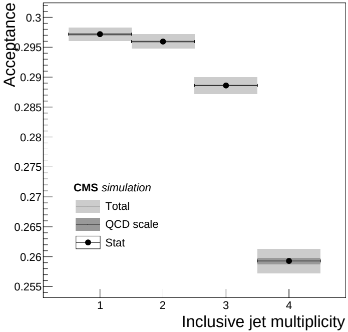
- The $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ is extracted from the following expression

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

- 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%	



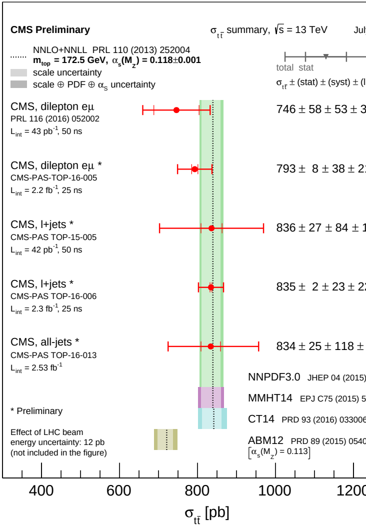
$$\boxed{Acceptance = 0.2972 \pm 0.0001(stat) \pm 0.0043(syst)}$$

- 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

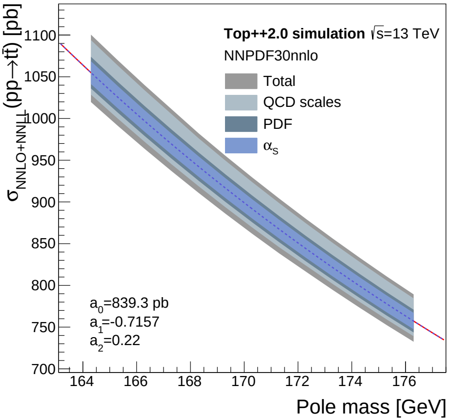
$$\boxed{\sigma \;=\; 834.7 \pm 2.5(stat) \pm 20.7(syst) \pm 22.6(lumi) \pm 12.5(extrapol)}$$

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



Pole mass extraction

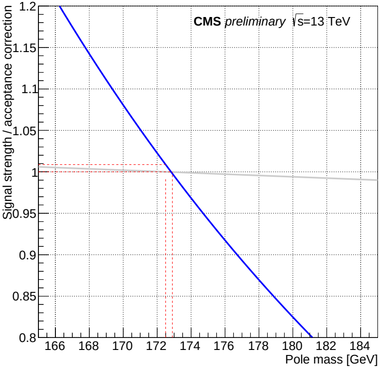
top^{++} prediction



$$\boxed{\sigma(m_t) = \sigma(m_{ref})(\frac{m_{ref}}{m_t})^4 \times [1 + a_1(\frac{m - m_{ref}}{m_{ref}}) + a_2(\frac{m - m_{ref}}{m_{ref}})^2]}$$

- We parameterize the cross section dependency on the pole mass using TOP^{++} v2.0
- Thanks J.Kieseler for cross-checking our numbers with top^{++}

Model for the Pole Mass Extraction



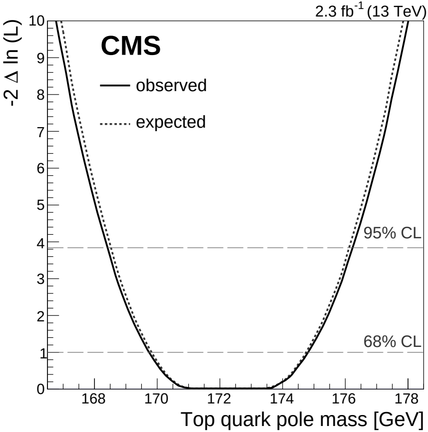
- The signal strength is re-parametrized as function of the top pole mass
  - model includes an acceptance correction estimated from MC simulation
  - extra correction to bring the LHCTOPWG reference value to NNPDF 3.0 central value
- Thanks to A. David for his help in cross checking our implementation in Higgs combine tool

Extra uncertainties in the extraction of pole mass

- In addition to the nuisances added to standard fit in the visible phase space we include:
- 1.5% extrapolation (lnN)
- 2.7% lumi (lnN)
- QCD scale (lnU)
- PDF+α_s (lnN)
- Beam energy (lnN)

Source	Δm_t [GeV]
Scales+α_S	+1.1/-0.9
Beam energy	+0.8/-0.5
Extrapolation to full phase space	+1.1/-0.7
Uncertainties from fit in the fiducial region	+2.1/-2.0
Total	+2.7/-2.3

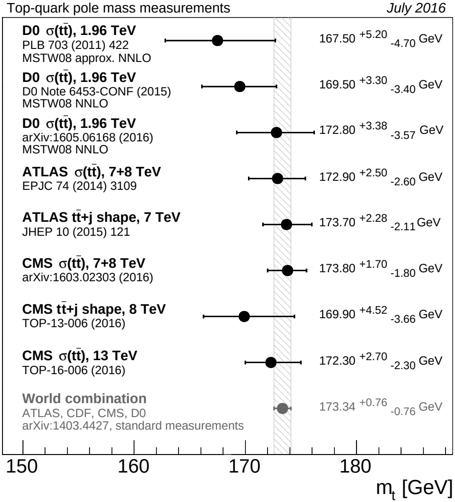
Measured top mass



- We measure 172.3 +2.7/-2.3 GeV while we expect an uncertainty +2.3/2.7 GeV notice the flatness of the likelihood around the minimum. That's induced by a flat prior on the QCD scale uncertainty. The QCD scale uncertainty is assymetric so it also induces an asymmetry in the uncertainty

$t\bar{t}$ mass summary

- Thanks Benjamin Stieger for this nice summary 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:

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

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

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THE END