Measurement of the top quark mass using events with a single reconstructed top quark in pp collisions at $\sqrt{s}$ = 13 TeV

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Department of High Energy Physics Review Meeting

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Motivation and Summary of previous results

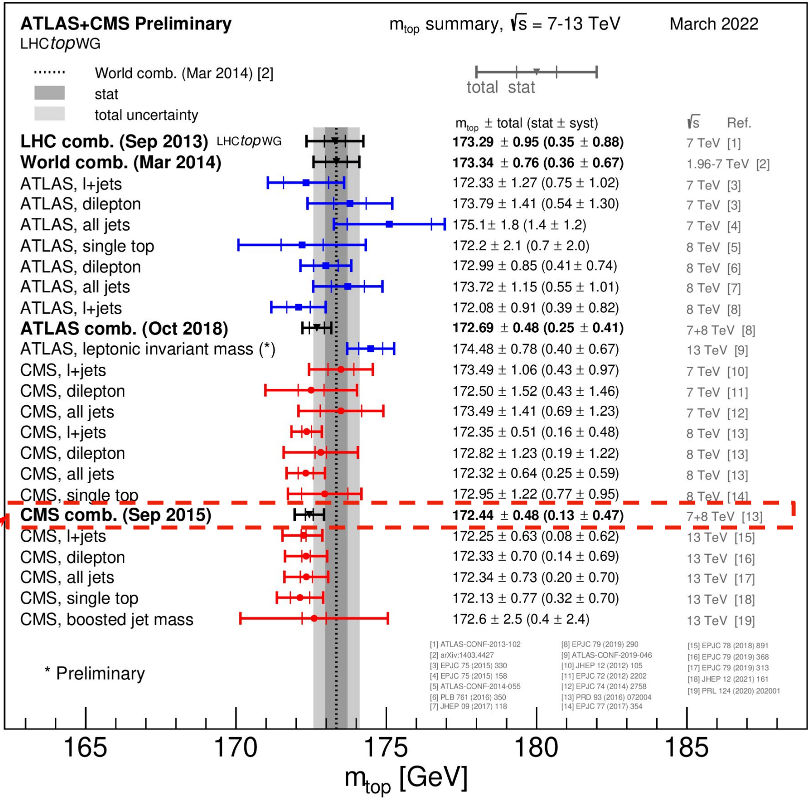
- Top quark:
  - Most massive elementary particle in the Standard Model
  - Largest Yukawa coupling with the Higgs boson
  - Given the matrix element $V_{tb} \cong 1$, it preferentially decays in Wb before it hadronise

- Top quark mass:

  m_t = 172.44 ± 0.13 (stat) ± 0.47 (syst) GeV*
  - Top-quark pair is the largest contributor to this measurement
  - Systematic uncertainty dominates over the statistical one

- *t*-channel:
  - Dominant single top quark production process at the LHC
  - Provides alternate phase space at lower interaction scale
  - Partially independent systematic compare to ttbar

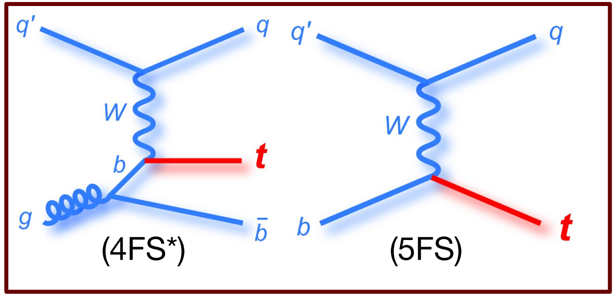
Source	$\delta m_{inclu.}$(GeV)
Jet Energy correction	**0.33**
b Jet modeling	**0.14**
Matrix Element matching	**0.11**



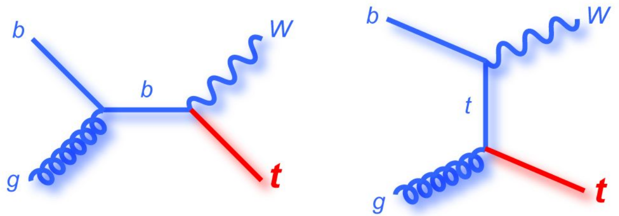
[PRD 93 (2016) 072004](PRD 93 (2016) 072004) LHCTopWGSummaryPlots

Single top quark production

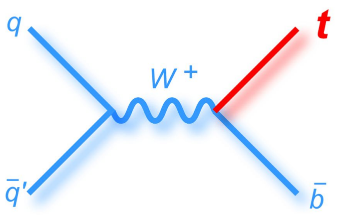
t-channel (~ 73% at LHC)



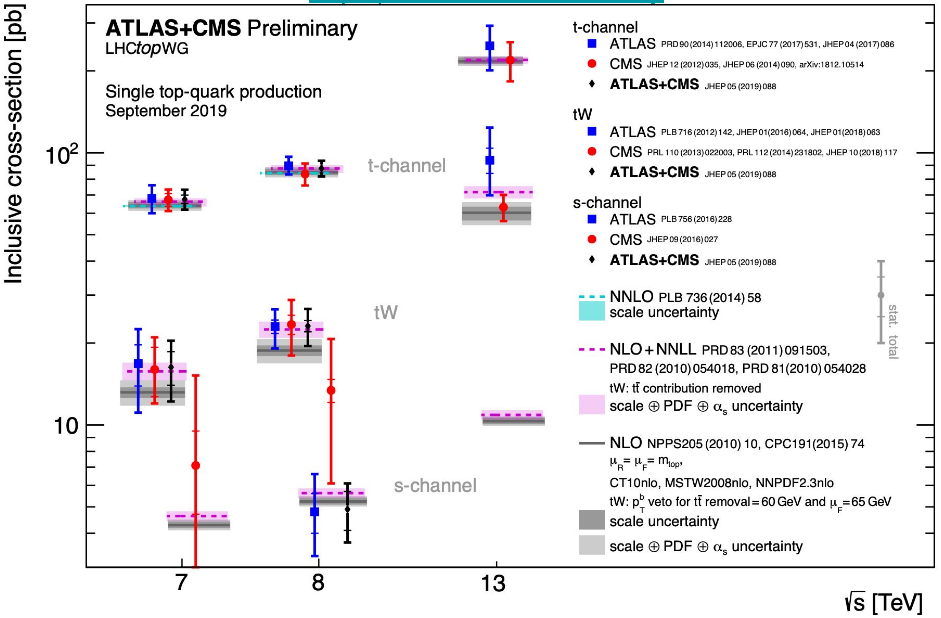
tW (~ 24% at LHC)



s-channel (~ 3% at LHC)



Top quark results summary



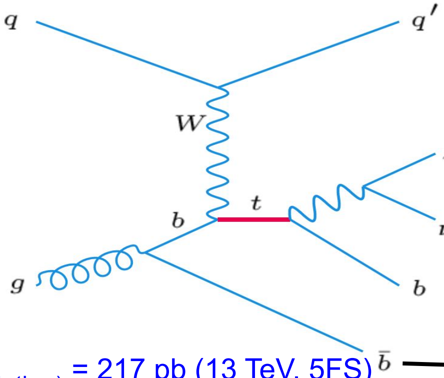
TOP quark cross-section

$\sqrt{s}$	$\sigma_{t\text{-ch.}}$ (NLO)
7 TeV	63.9±2.9pb (4.5%)
8 TeV	84.7±3.8pb (4.4%)
13 TeV	217.0±9.0pb(4.1%)

*FS -> Flavour schemes

Signal event topology and Backgrounds

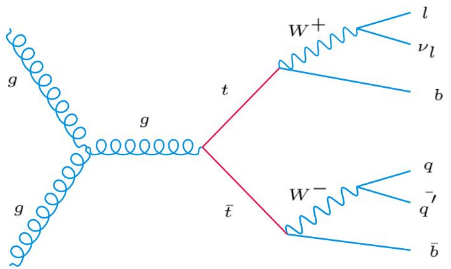
(4FS)



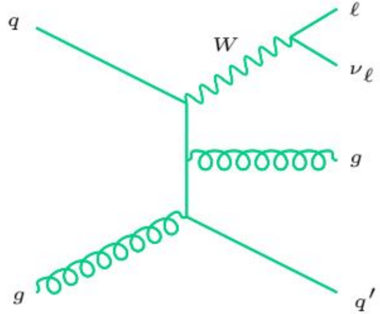
- Spectator light-flavor jet (p_T > 40 GeV) at high |η|
- Exactly 1 isolated lepton μ (e) with p_T >26 (35) GeV
  Separately (μ^- , e^-) and (μ^+ , e^+) considered
- Missing p_T
- Central b-jet from top quark decay (p_T > 40 GeV)
- (not reconstructed) mostly out of tracker acceptance or very low p_T

$\sigma_{(t+tbar)}$ = 217 pb (13 TeV, 5FS)

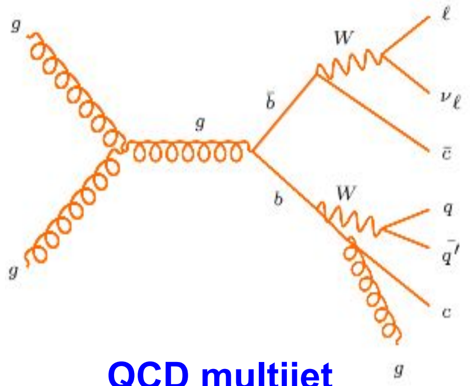
SingleTopRefXsec



top-pair process
σ = ~10^3 pb

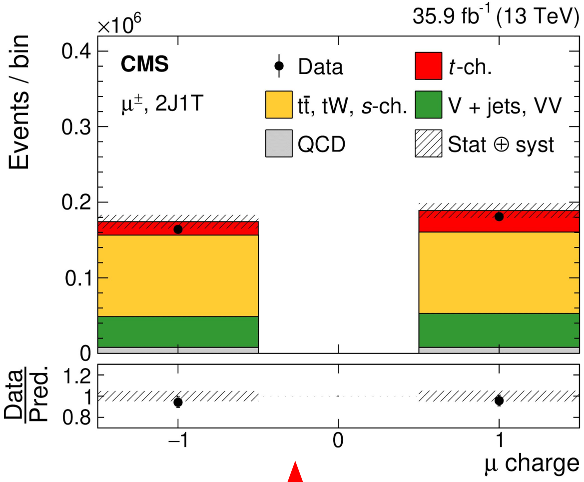


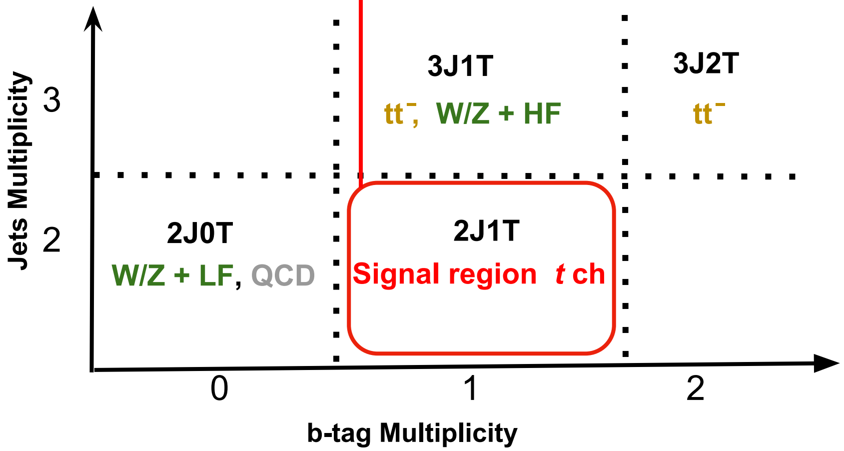
W+jets process
σ = ~10^5 pb

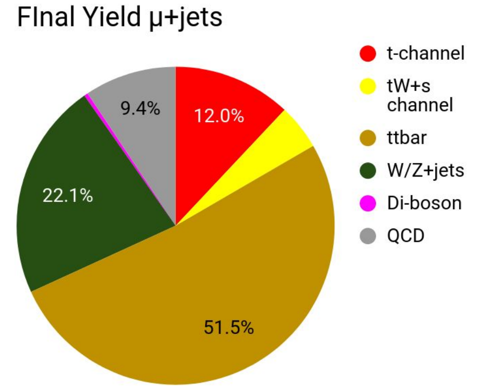


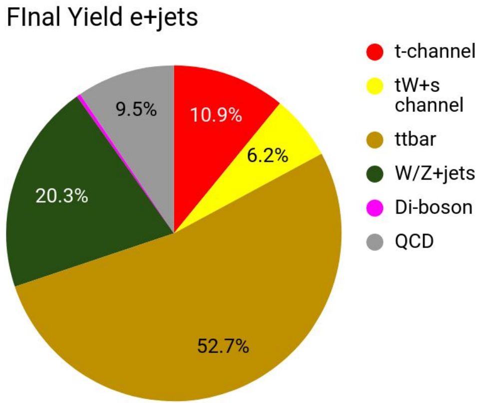
QCD multijet
σ = ~10^6pb

Yields after selection and categorization









Top quark reconstruction

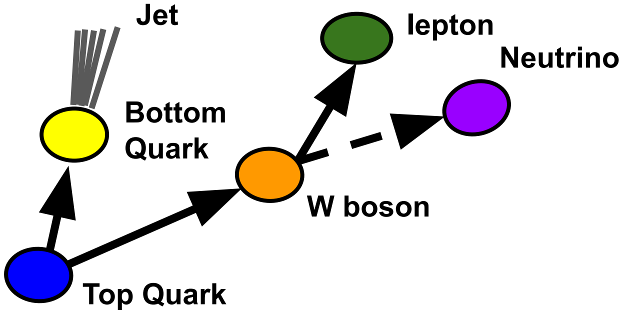
- Estimate $p_{z,\nu}$ from energy-momentum conservation using the m_W = 80.4 GeV constraint

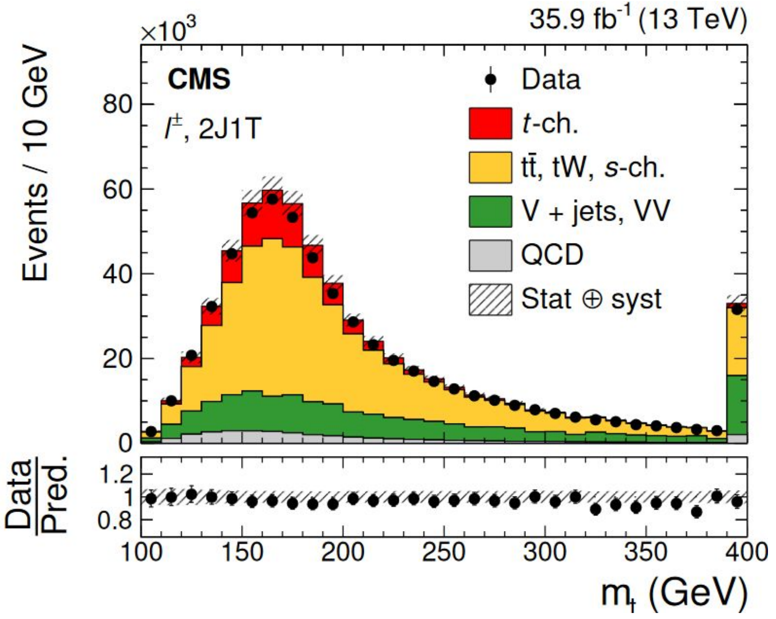
$$m_W^2 = \left(E_\ell^2 + \sqrt{\not{p}_T^2 + p_{z,\nu}^2}\right)^2 - \left(\vec{p}_{T,\ell} + \vec{\not{p}}_T\right)^2 - (p_{z,\ell} + p_{z,\nu})^2$$

- Quadratic solution for neutrino p_z :
  - ☞ For real case (~ 65%), choose the one with lowest $|p_z|$ (accuracy ~ 64%)
  - ☞ For imaginary case (~ 35%)
    - ☞ make the radicand zero ⇒ Quadratic equation in $p_{x,\nu}$ and $p_{y,\nu}$
    - ☞ vary $p_{x,\nu}$ and $p_{y,\nu}$ keeping the m_W constraint satisfied so that neutrino $p_{T,\nu}$ has lowest $\Delta\phi$ with missing p_T

- Reconstruct W boson from lepton and neutrino

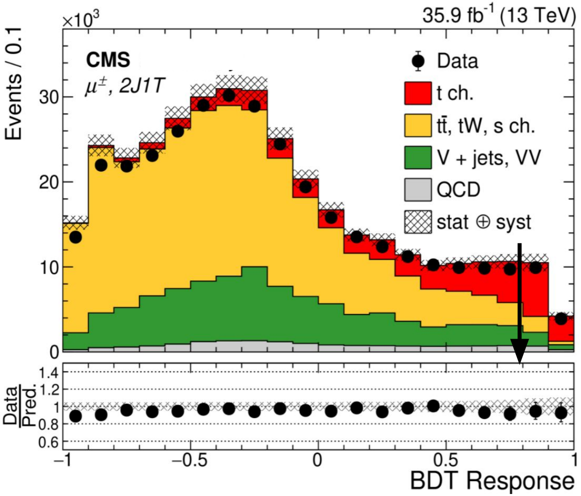
- Reconstruct top quark from b-tagged jet and W boson

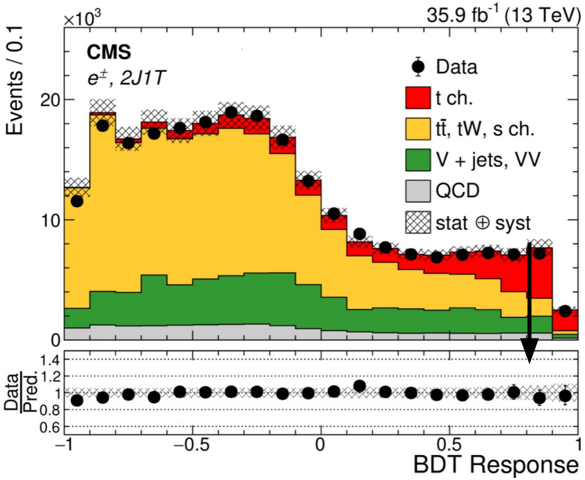


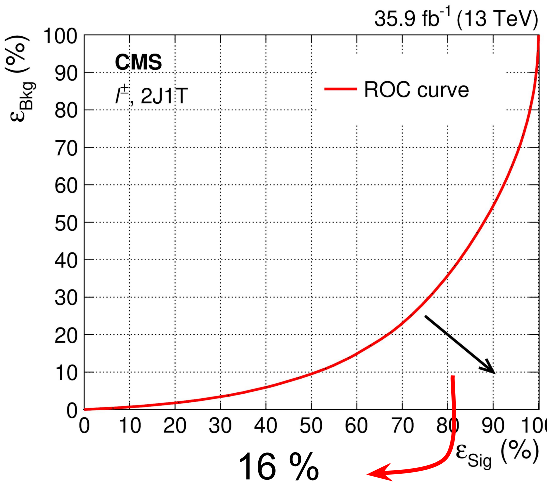


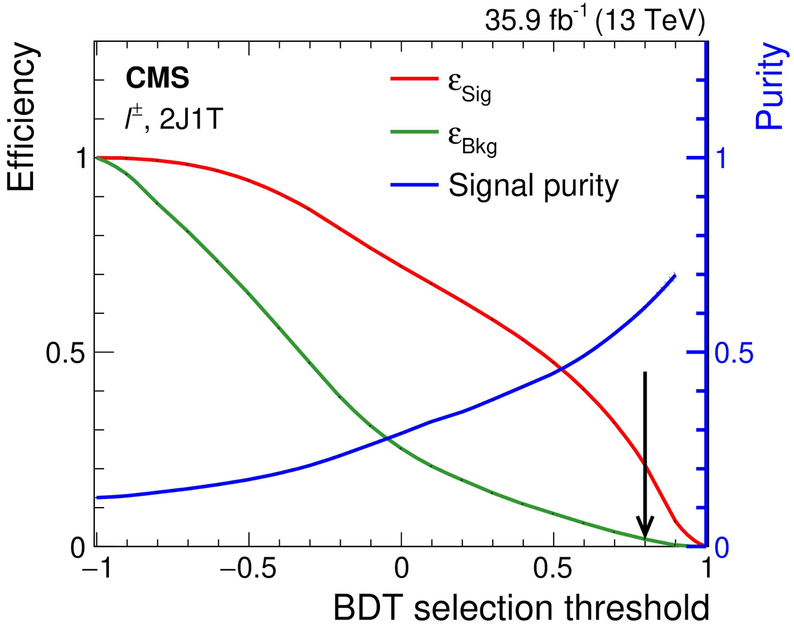
BDT discriminator and ROC

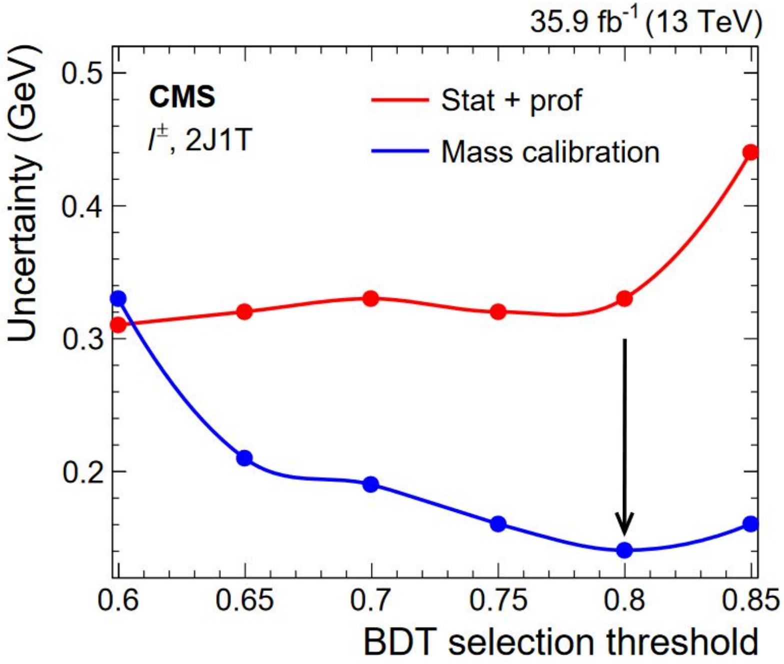
Variable	Rank μ	Rank e	Description
$\Delta R_{\mathrm{bj'}}$	1	1	Angular separation in $\eta - \phi$ space between the b-tagged and untagged jets
light jet $\lvert\eta\rvert$	2	2	Absolute pseudorapidity of the untagged jet
$m_{\mathrm{bj'}}$	3	3	Invariant mass of the system comprising of the b-tagged and untagged jets
$\cos\,\theta^*$	4	4	Cosine of the angle between the lepton and untagged jet in the rest frame of the top quark
$\mathrm{m_T^W}$ (≥ 50 GeV)	5	5	Transverse W boson mass as described in Eq. (6)
FW1	—	6	First-order Fox-Wolfram moment [46, 47]
$\lvert\Delta\eta_{\ell\mathrm{b}}\rvert$	6	7	Absolute pseudorapidity difference between the lepton and b-tagged jet
$p_{\mathrm{T}}^{\mathrm{b}} + p_{\mathrm{T}}^{\mathrm{j'}}$	7	8	Scalar sum of p_{T} of the b-tagged and untagged jets
$\lvert\eta_\ell\rvert$	8	—	Absolute pseudorapidity of the lepton (muon)











- For BDT response > 0.8
  - Signal purity ≈ 60%

Extraction of m_t

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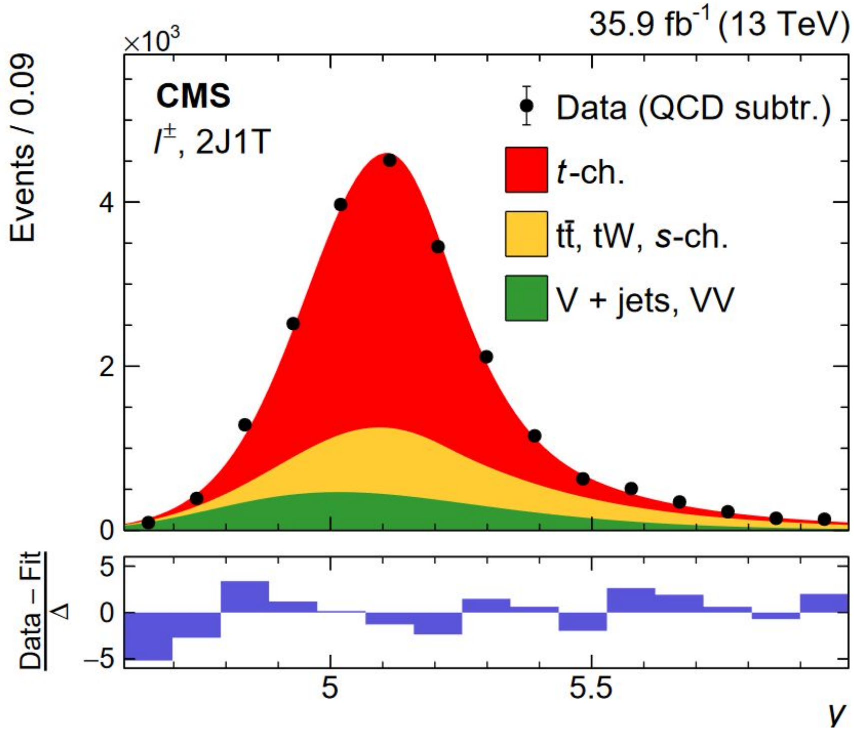
- QCD is subtracted from the data
- 50% uncertainty (shape+rate) propagated on the estimated QCD bkg.
- Simultaneous ML fit using $\boldsymbol{y = \ln(m_t)}$ distributions in μ and e final states

$$F(y) = f_{t-ch}\, F_{t-ch}(y\,;\, y_0) + f_{Top}\, F_{Top}(y\,;\, y_0) + f_{EWK}\, F_{EWK}(y)$$

  - y_0 : POI, represents the peak position of the combined t - ch. and Top templates
  - $\boldsymbol{m_{Fit} = Exp\,(y_0)}$; calibrated against *true mass* in MC
  - $F_{t\text{-}ch}$ = asymm. Gauss. core + Landau tail
  - F_{Top} = Crystal ball
  - F_{EWK} = Novosibirsk

- y_0, f_{t-ch}, f_{Top} and f_{EWK} are allowed to float during the fit
- Constraint on the rates added as nuisance parameters to the fit $f_{t-ch} \rightarrow 15\%$, $f_{Top} \rightarrow 6\%$ and $f_{EWK} \rightarrow 10\%$

uncertainty in the respective cross section measurement are taken into account

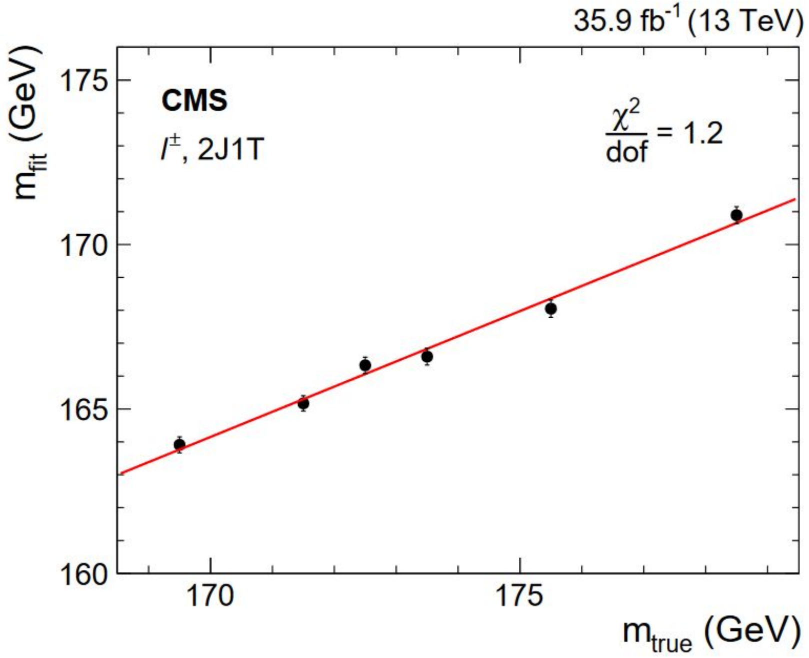


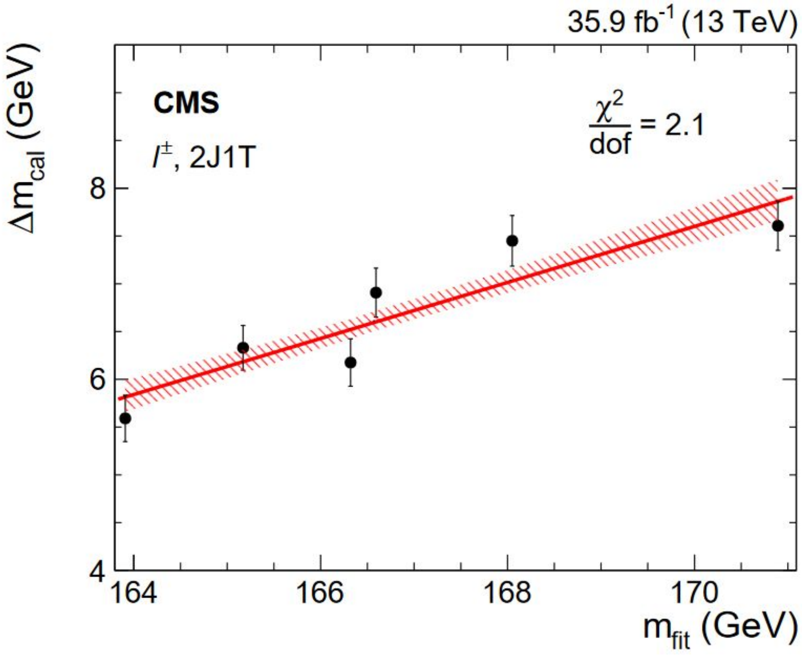
Fit model is validated in control region

-0.2<BDT Response<0.8

Mass linearity and calibration

- m_t hypothesis considered simultaneously for *t* - ch. and $t\bar{t}$ using dedicated MC samples





- Fit output shows a linear behavior
- Calibration performed separately for the ℓ^+ and ℓ^- case also

- Mass calibration is done using the relationship

  $\Delta m_{cali} = |m_{True} - m_{Fit}|$ vs. m_{Fit}
- 1σ uncertainty band is shown in the plot

Systematic Uncertainties

- Signal and Bkg normalization added as nuisance parameters in the fit
- All other unc. are externalized ➛ fit repeated with varied templates
- Max. difference w.r.t nominal quoted as uncertainty for PDF+α_s and μ_R/μ_F scale variations

Source	$\delta m_{inclu.}$(GeV)
Jet Energy scale	**± 0.40**
Signal modeling	**± 0.30**
Color reconnection model	**± 0.24**
b-quark hadronization model	$^{+0.23}_{-0.18}$
Total syst.	$^{+0.69}_{-0.71}$
Stat. + Rate	**±0.32**
Grand total	$^{+0.76}_{-0.77}$

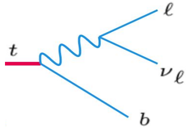
Results

Inclusive mass results:

Sub GeV precision

$$m_t = 172.13 \pm 0.32(\text{stat+prof})^{+0.69}_{-0.70}(\text{ext})\ \text{GeV} = 172.13^{+0.76}_{-0.77}\ \text{GeV}$$

The masses of the top quark and antiquark :



$$m_t = 172.62 \pm 0.37(\text{stat+prof})^{+0.97}_{-0.65}(\text{ext})\ \text{GeV} = 172.62^{+1.04}_{-0.75}\ \text{GeV},$$

$$m_{\bar{t}} = 171.79 \pm 0.58(\text{stat+prof})^{+1.32}_{-1.39}(\text{ext})\ \text{GeV} = 171.79^{+1.44}_{-1.51}\ \text{GeV}.$$

Masses ratio and difference:

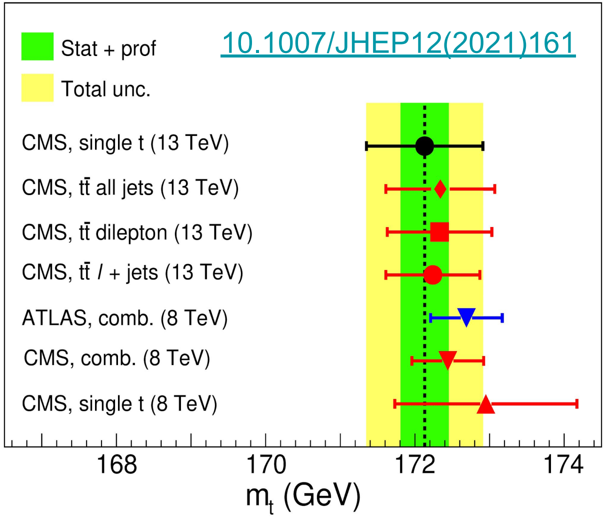
no evidence for violation of CPT invariance

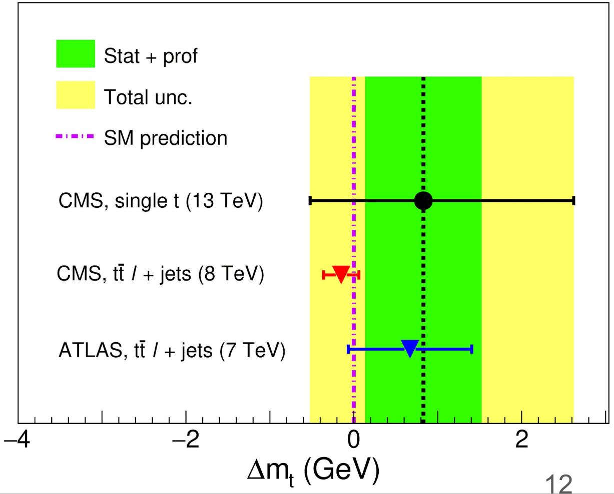
$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.9952 \pm 0.0040(\text{stat+prof})^{+0.0068}_{-0.0096}(\text{ext}) = 0.9952^{+0.0079}_{-0.0104},$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83 \pm 0.69(\text{stat+prof})^{+1.65}_{-1.16}(\text{ext})\ \text{GeV} = 0.83^{+1.79}_{-1.35}\ \text{GeV}$$

Mass difference from ttbar events (PLB 770 (2017) 50–71):

$$\Delta m_t = -0.15 \pm 0.19\ (\text{stat}) \pm 0.09\ (\text{syst})\ \text{GeV}$$





Award in Science Communication Competition

Third Prize In Physical science:
National Level Science Communication Competition, Saransh (सारांश): 3 Mins. Thesis Presentation on 10.1007/JHEP12(2021)161
Organised by :
Indian National Young Academy of Sciences (INYAS)

[Award Ceremony of SARANSH]()

Mass and width measurement with Full Run2

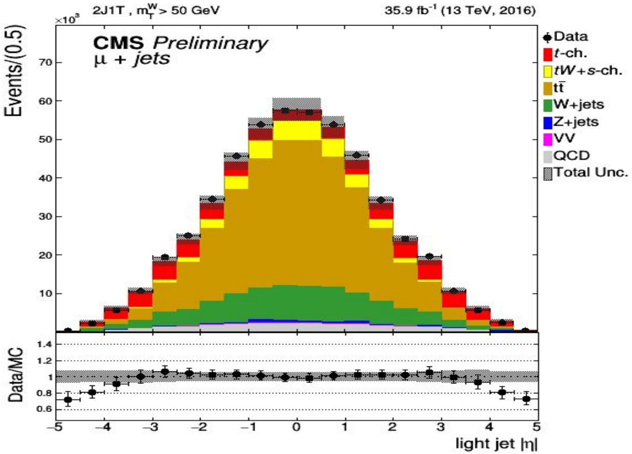
1. Decay width measurement is sensitive to Beyond Standard model effects
2. Top quark decay width will be different than SM prediction If the top quark able decay into some new heavy up/down type quarks doi:10.1140/epjc/s10052-006-0137
3. Top quark width is measured at lower presion(10.40%) @CMS_Run1 compare to it mass presion (0.28%)

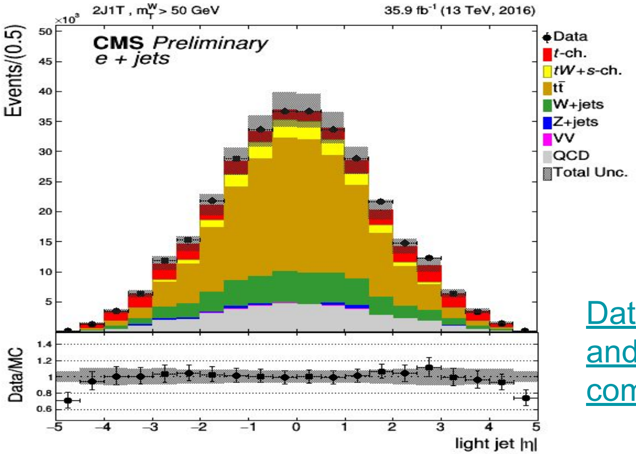
Higgs combine tool

1. It is common framework used by many analyses
2. Data handling is easy
3. Systematics can be floated in the fit as a nuisance parameter
4. Top quark mass and width parameters are floated in the fit as Parameter of interest
5. results are reproduced using mc template from 10.1007/JHEP12(2021)161 for signal and background
6. constraints on the normalization added as nuisance parameters to the fit similar previous measurement

Data MC comparison for newly processed samples

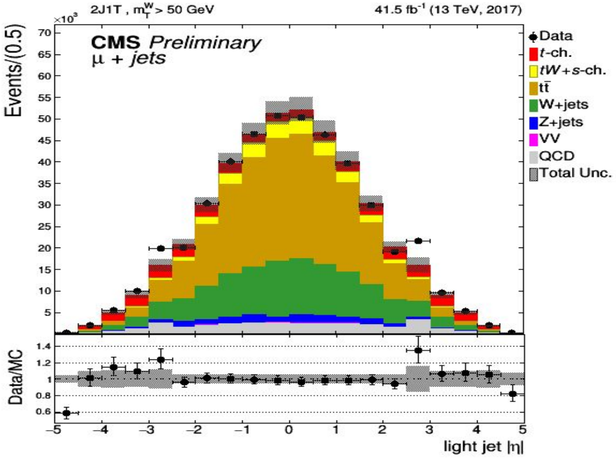
2016

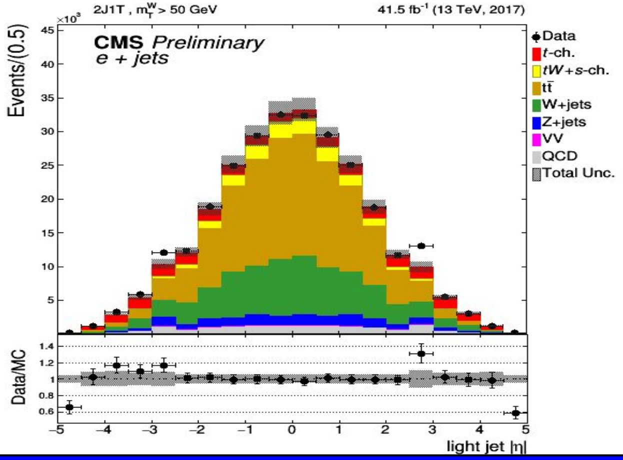




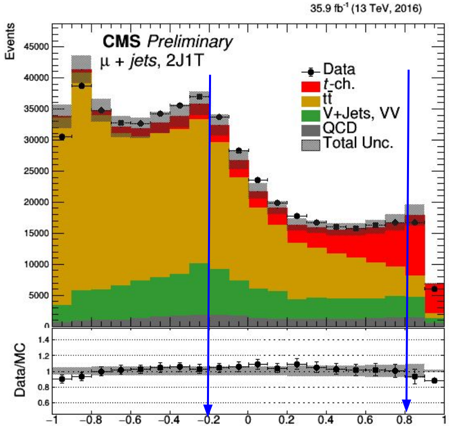
Data Driven QCD and more Data-MC comparison plots

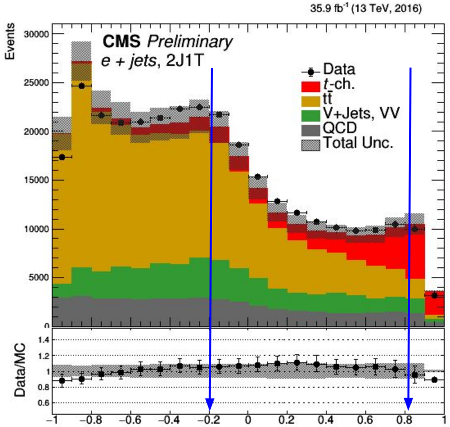
2017



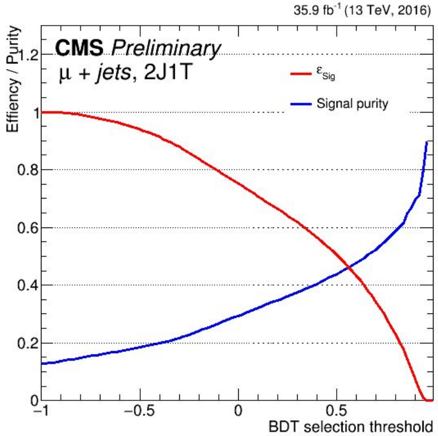


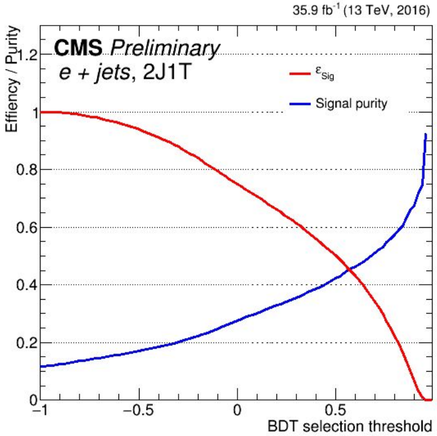
BDT Distribution (2016 legacy samples)





Control region study has been from -0.2<BDT<0.82

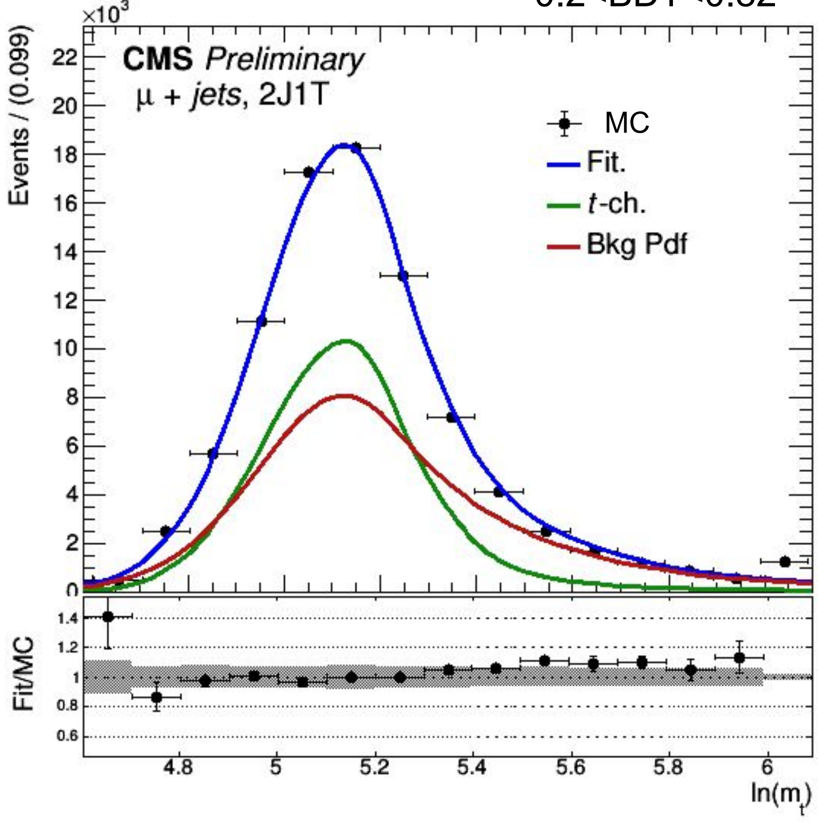




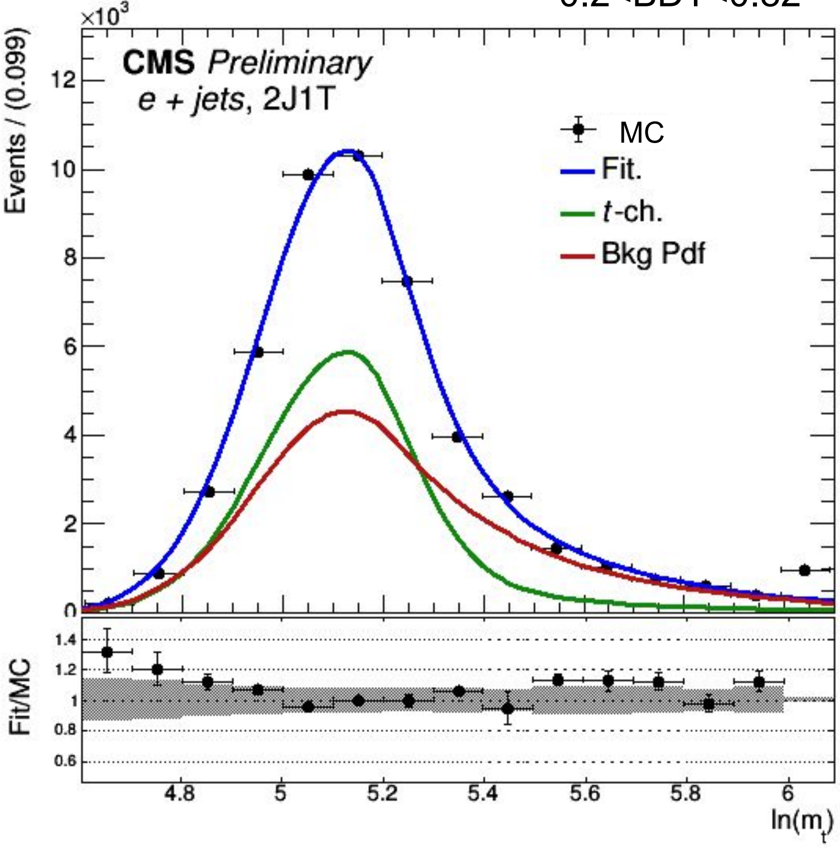
BDT > 0.82
Purity ≃ 60%

Nominal sample fit results (m_t = 172.5 GeV, Γ_t = 1.322 GeV)

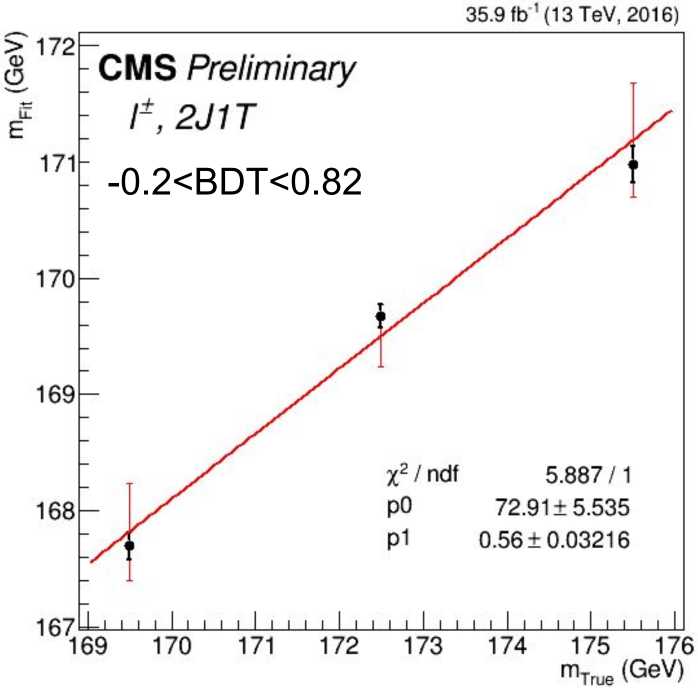
-0.2<BDT<0.82

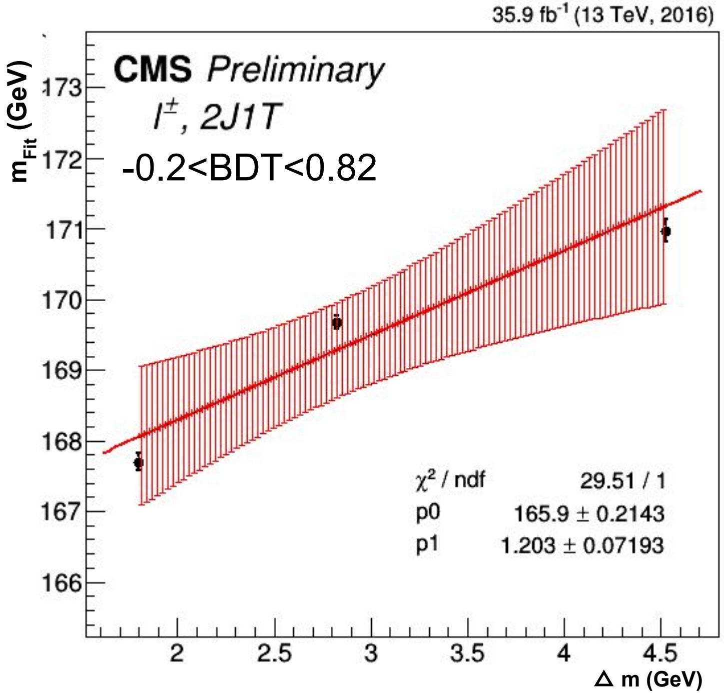


-0.2<BDT<0.82



Mass linearity and Calibration With Alt. Mass samples





- Nominal Sample m_t = 172.5 , Alter mass sample m_t = 169.5, 173.5
- Alternate mass sample for ttbar for m_t = 171.5, 173.5 are not available
- Offset corrected mass = **172.1 ± 0.001 (stat) ± 1.209 (cali. only) GeV**

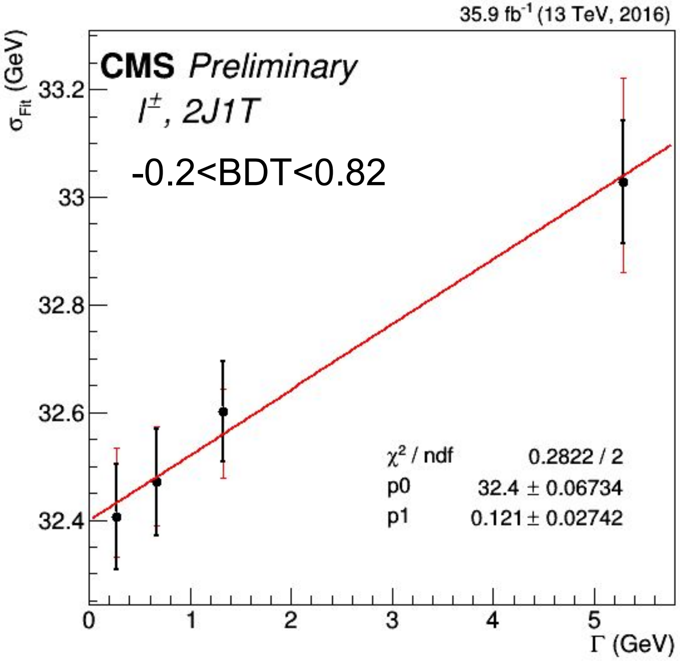
Sigma linearity and calibration With Alt. width samples (control)

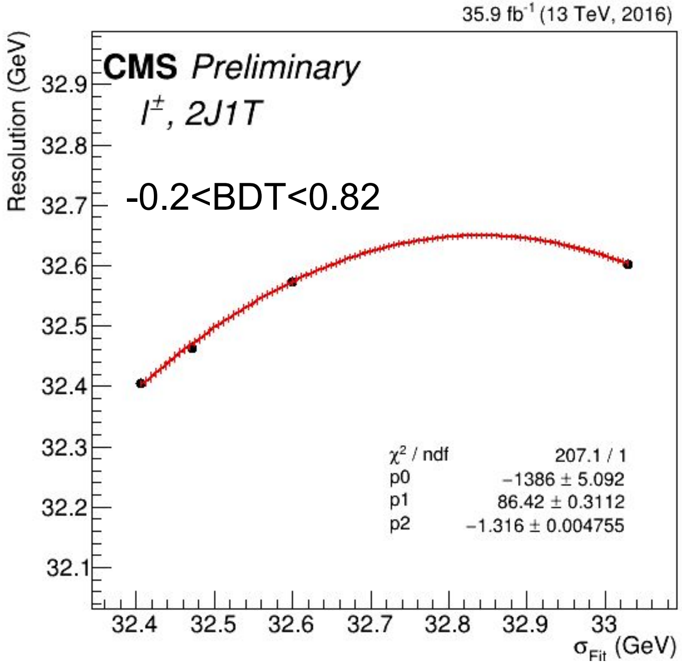
$$\sigma^2 = r^2 + \Gamma_t^{\ 2}$$

σ : is measured quantity which the sigma of the distribution

r : is the detector resolution

Γ_t : is the actual width

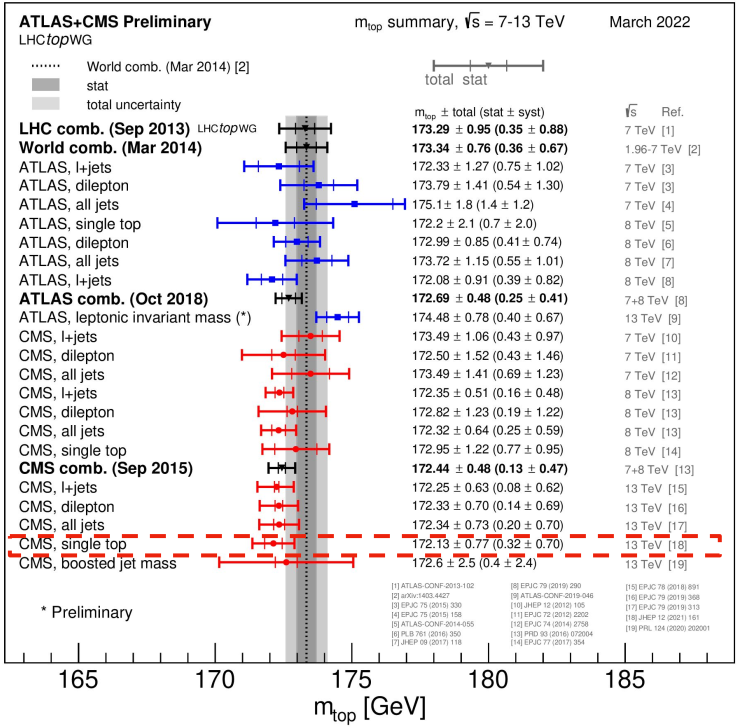




- Nominal Sample Γ_t = 1.322 (NNLo) , Alt. width sample Γ_t = Nomi. Γ_t * (0.2,0.5,4)
- Only Alternate width samples for ttbar used
- Offset corrected width = **1.309 ± 0.001 (stat) ± 0.001 (cali. only) GeV**

Summary

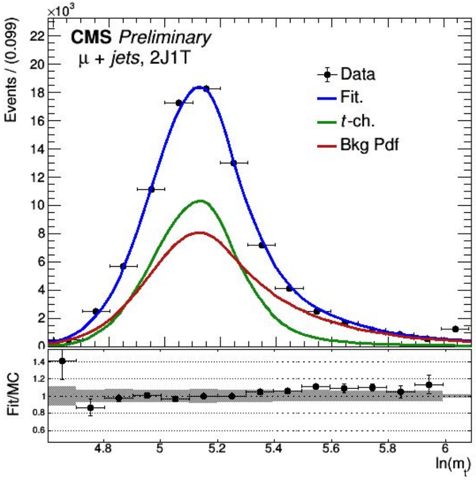
m_t in events with a **single reconstructed top**



[LHCTopWGSummaryPlots]

Our result is dominated by JES, Signal Modeling, CR, b quark modeling

- Top quark mass measurement has been published in JHEP
- Simultaneous measurement of top quark mass and width with full Run2 data is in progress
- A detailed study has been done in control region with new processed samples (2016 only)
- Draft Internal analysis note TOP-21-212 is ready
- Adding more data (2017/2018) to the study
- Systematics effect will be studied with latest processed sample for 16/17/18 data by the end 2022



BACKUP

Changes in Selection criteria for the legacy samples w.r.t previous Analysis

- Trigger use 2016 new processed sample are same but changed for 2017 legacy samples which also lead to change the lepton p_t cut

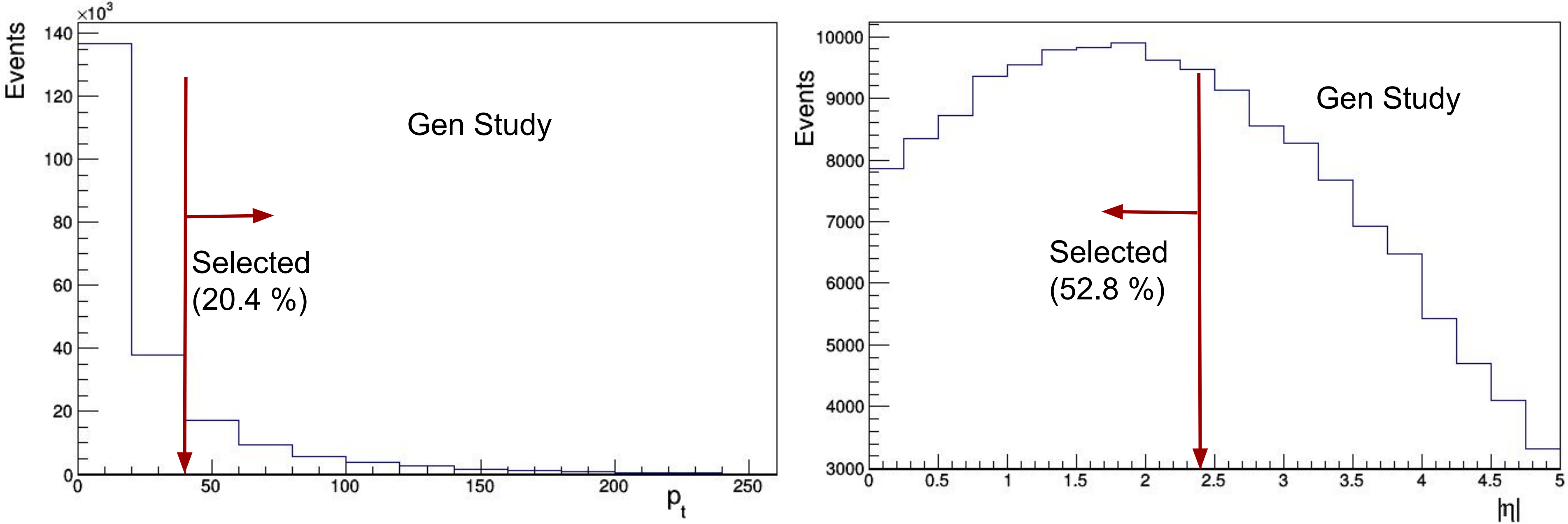
2017	Trigger	Lepton p_t cut on
el	HLT_Ele35_WPTight_Gsf_ _OR_HLT_Ele30_eta2p1_WPTight_Gsf_CentralPFJet35_EleCleaned	p_t > 37 GeV
mu	HLT_IsoMu27	p_t > 30 GeV

- Tagger for be tagging is changed from “CMVAv2” to “DeepCSV”

Year	Discriminator cut	Tagger
2016	Tight Working point (discriminator >0.7527)	DeepCSV
2017	Tight Working point (discriminator >0.8001)	DeepCSV

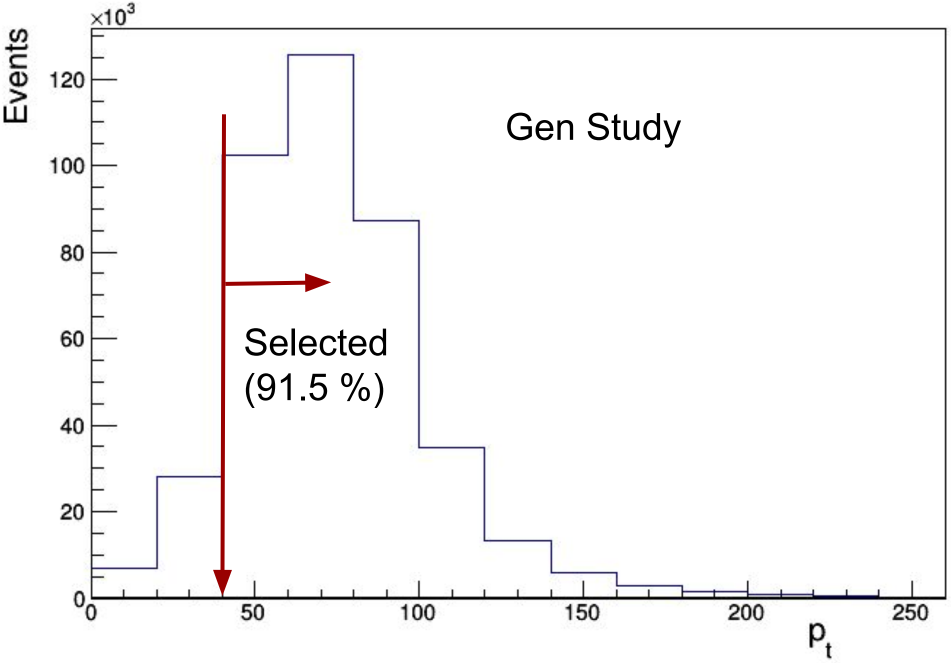
We already shifted to “DeepJet” Tagger for latest processed samples

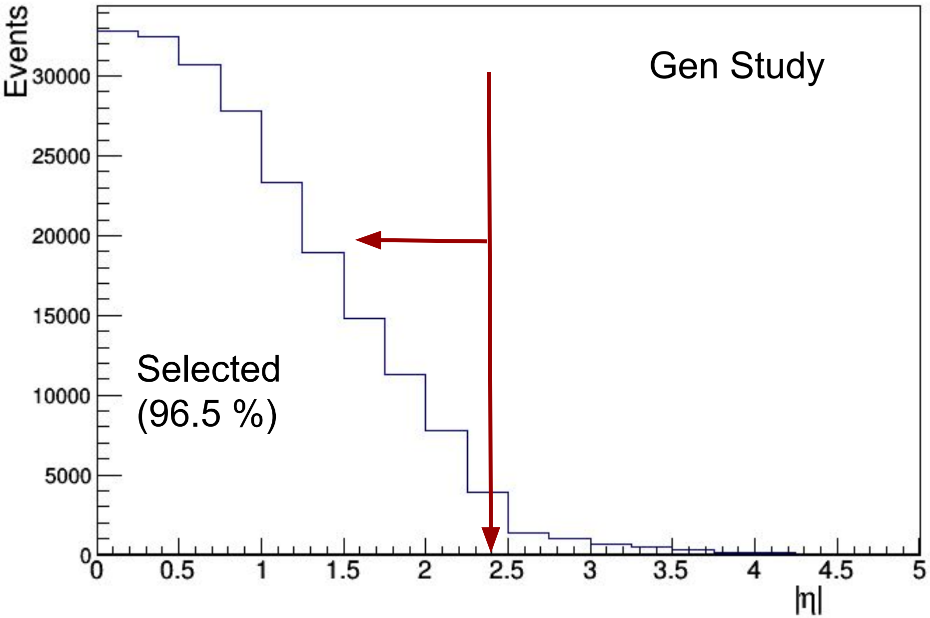
Distributions of the 2nd b quark from gluon that does not participate in top quark production



Efficiency written in the figure are calculated separately for each cut but in analysis both condition require simultaneously which lead to more stringent cut

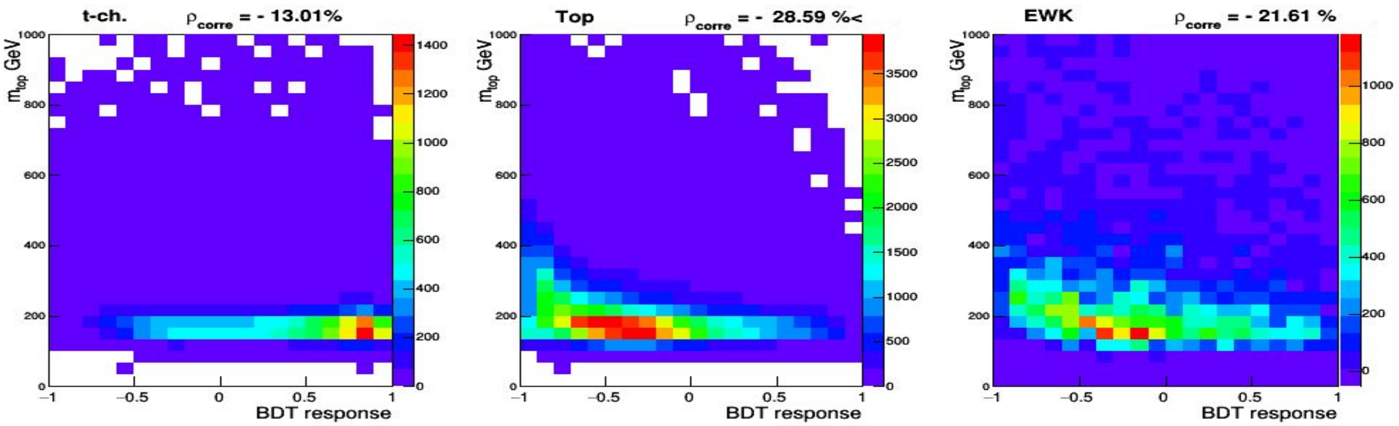
Distributions of b quark from top decay



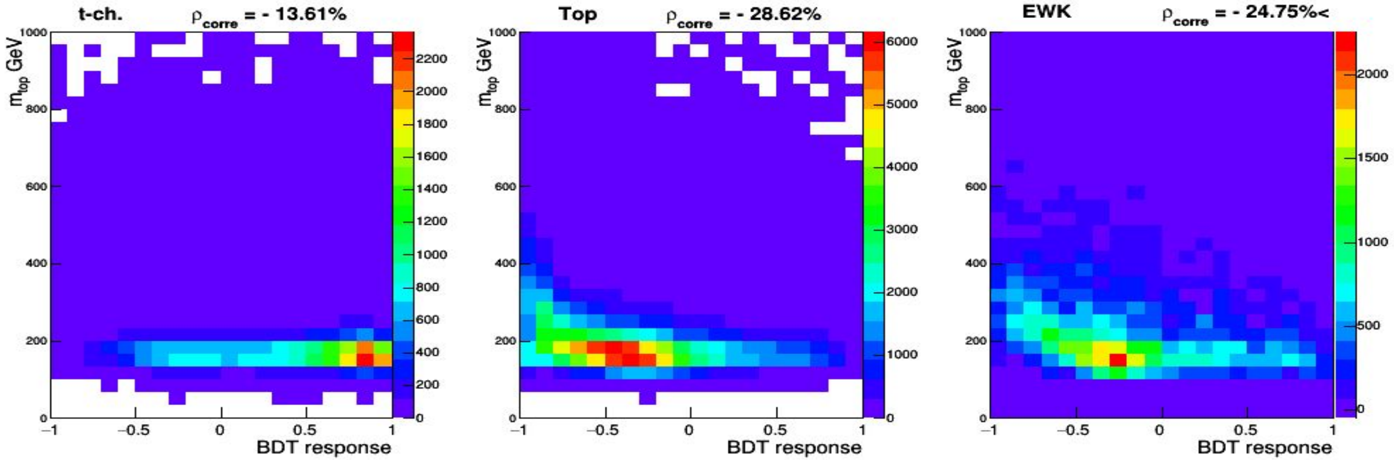


m_{top} correlation with the BDT response

e + jets



μ + jets

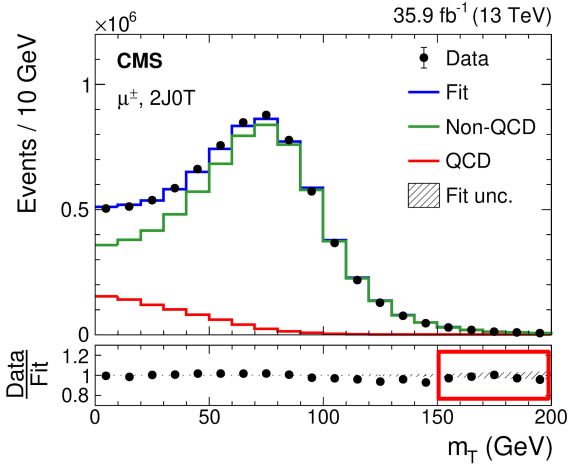


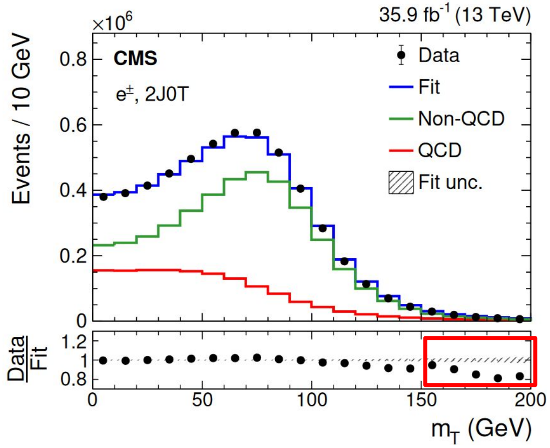
Estimation of Data Driven QCD

- QCD has large cross section but a very low selection efficiency
- Require high stat. MC ⇒ computationally intensive
  - Obtain SB in data by investing iso. (id) ⇒ subtract nonQCD from it ⇒ data-driven QCD template
- ML fit in signal region to estimate QCD bkg. contribution :

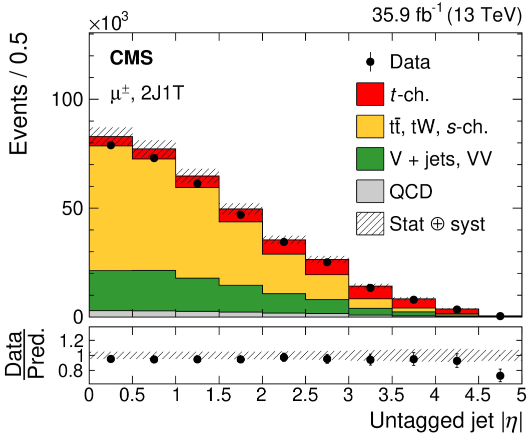
$$F(m_T^W) = N_{QCD} \times Q(m_T^W) + N_{non\text{-}QCD} \times W(m_T^W)$$

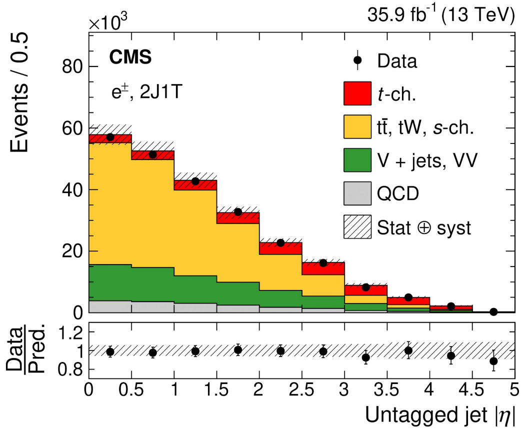
- Data-driven QCD shape and postfit QCD yield $m_T^W > 50$ GeV considered for further analysis for QCD
- 50% uncertainty (shape+rate) on the estimated QCD bkg. propagated as systematic

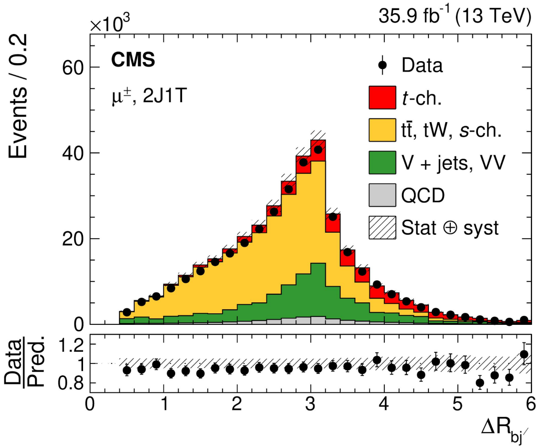


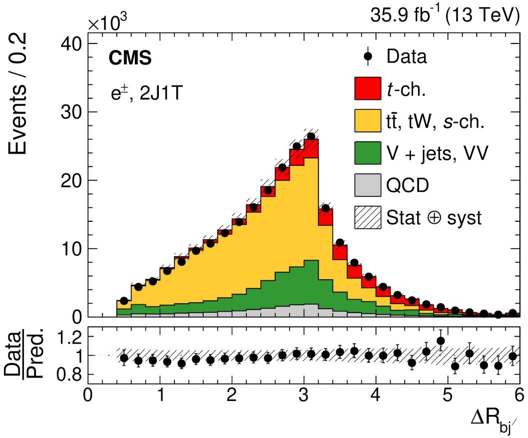


Data MC Agreement



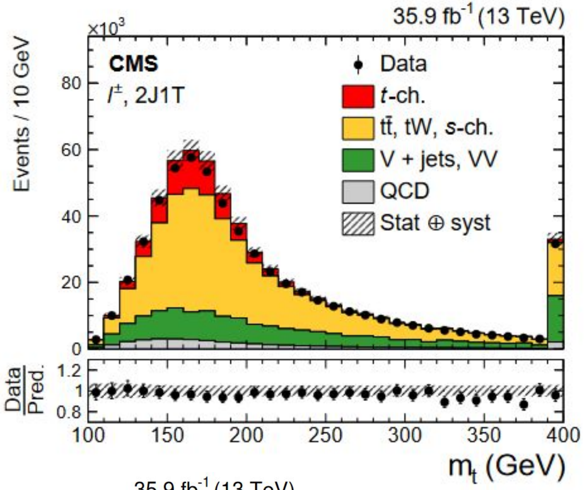






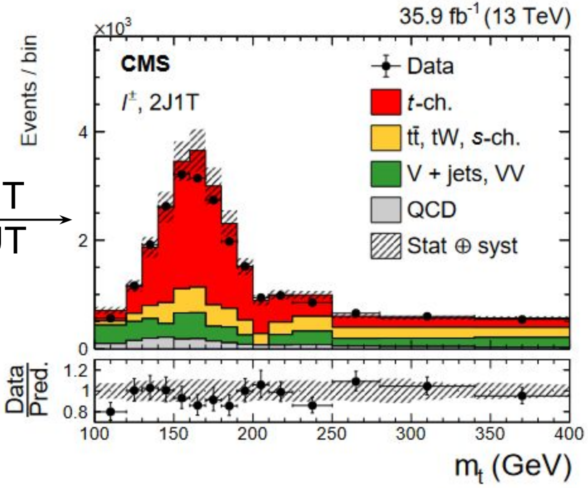
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Prefit Top mass distribution

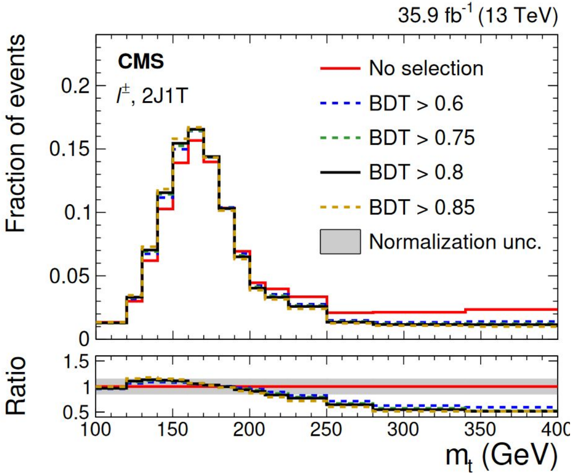


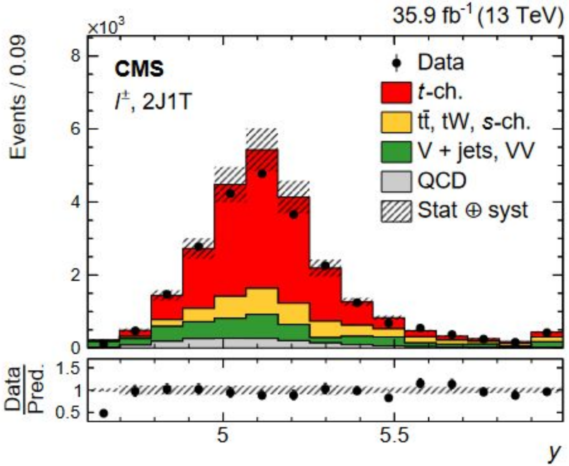
BDT

CUT



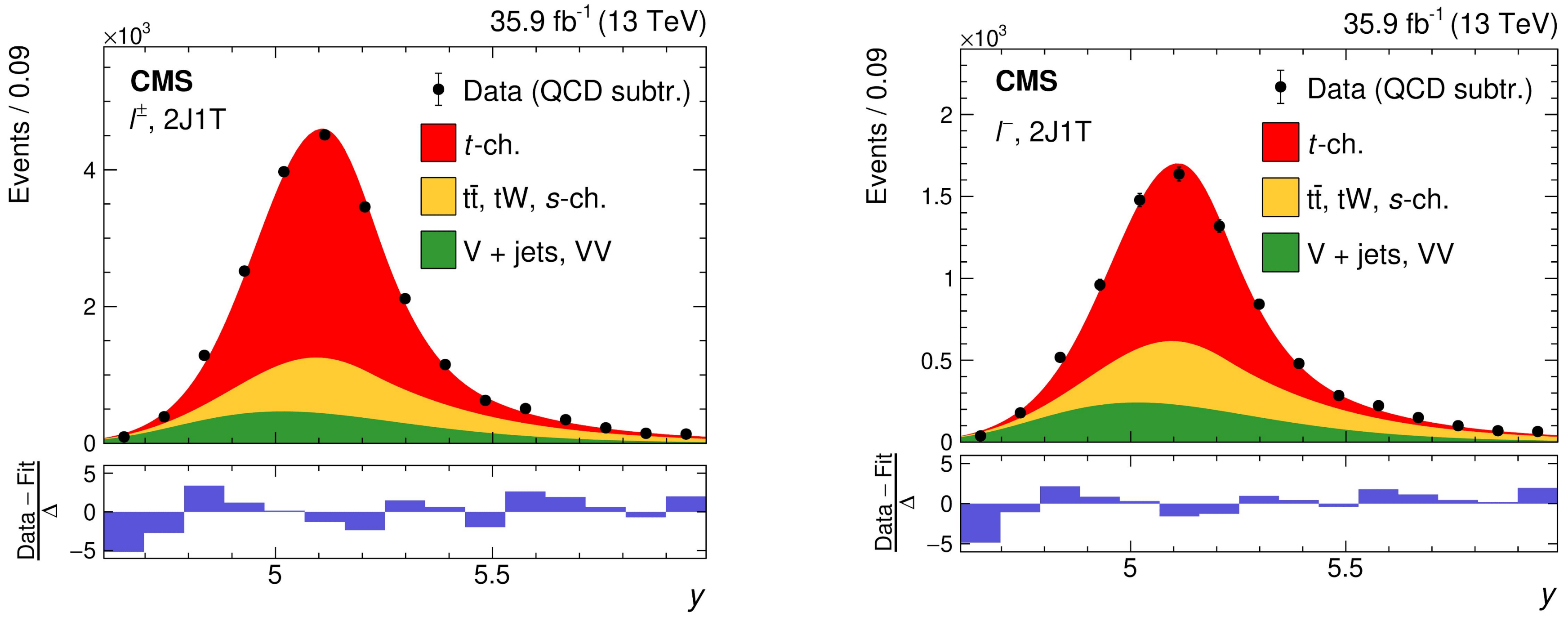
$y = ln(m_t)$





1. More Symmetric Distribution
2. Easy to to model using parametric shapes

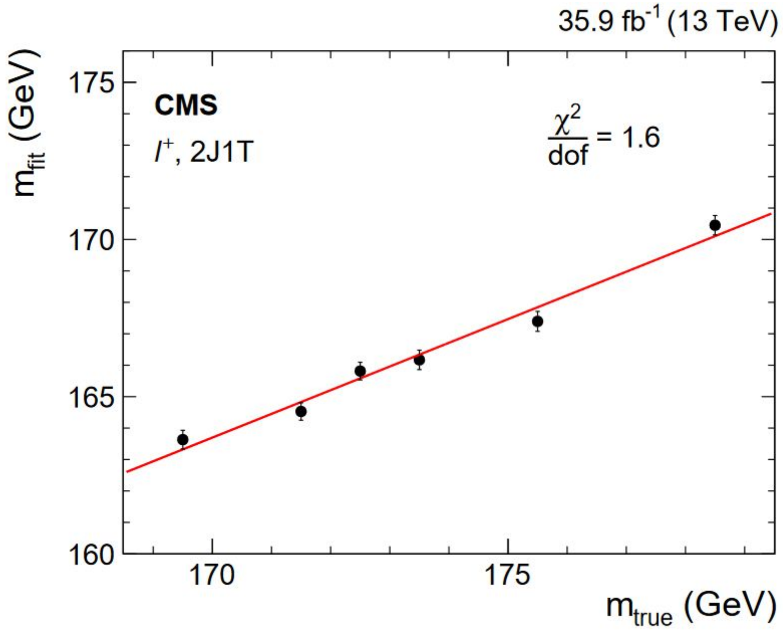
Charge dependent fit m_t

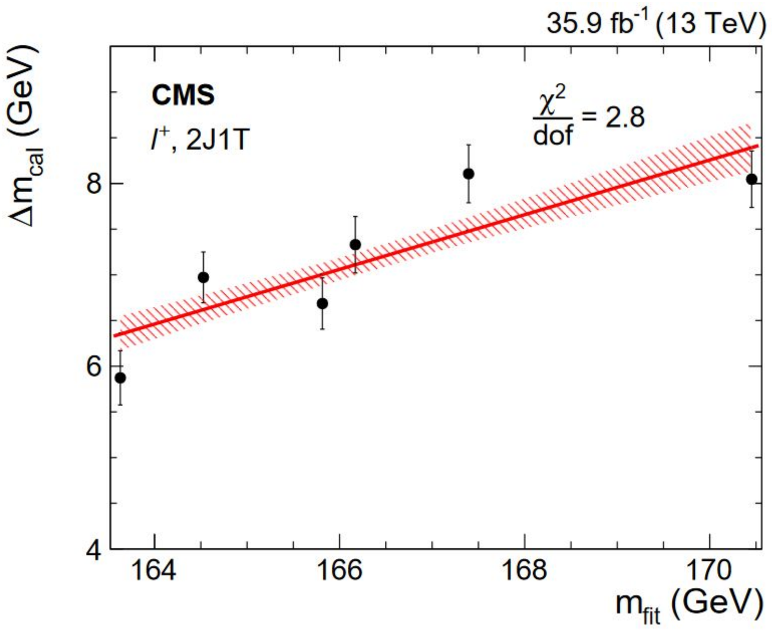


$$m_t = 172.62 \pm 0.37\,(\text{stat} + \text{prof})\,^{+0.97}_{-0.65}\,(\text{syst})\ \text{GeV} = 172.62^{+1.04}_{-0.75}\ \text{GeV},$$
$$m_{\bar{t}} = 171.79 \pm 0.58\,(\text{stat} + \text{prof})\,^{+1.32}_{-1.39}\,(\text{syst})\ \text{GeV} = 171.79^{+1.44}_{-1.51}\ \text{GeV}.$$

Mass linearity and calibration L^+

m_t hypothesis considered simultaneously for *t* - ch. and $t\bar{t}$ using [dedicated MC samples]





- Fit output shows a linear behavior

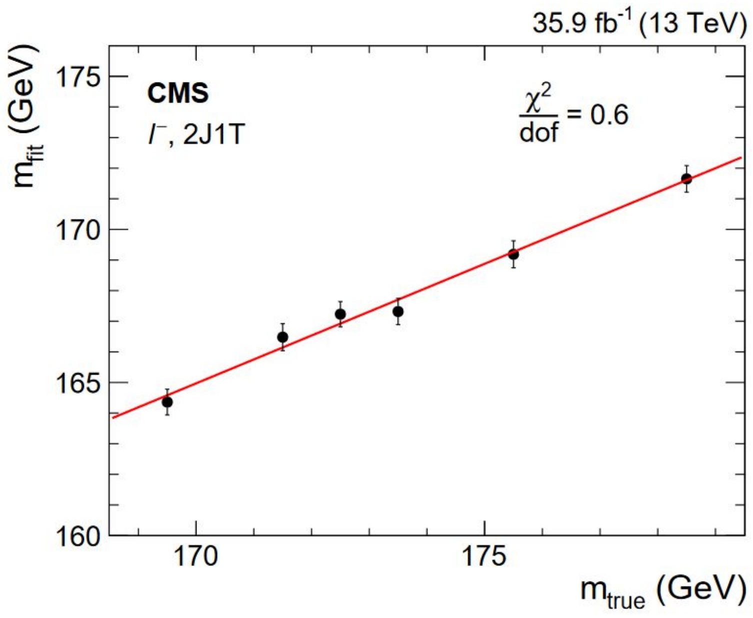
CMS-PAS-TOP-19-009

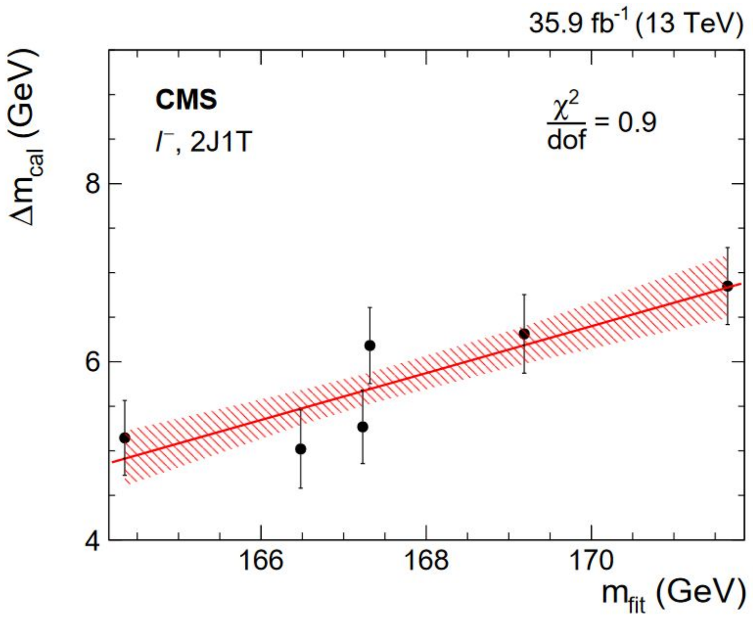
- Mass calibration is done using the relationship

  $\Delta m_{offset} = |m_{True} - m_{Fit}|$ vs. m_{Fit}
- 1σ uncertainty band is shown in the plot

Mass linearity and calibration L^-

m_t hypothesis considered simultaneously for *t* - ch. and $t\bar{t}$ using dedicated MC samples





- Fit output shows a linear behavior

CMS-PAS-TOP-19-009

- Mass calibration is done using the relationship

  $\Delta m_{offset} = |m_{True} - m_{Fit}|$ vs. m_{Fit}
- 1σ uncertainty band is shown in the plot

Selection criteria for the legacy samples

Table 10: Summary of event selection criteria for 2J1T region in 2016 Dataset

Selection Step	Criteria for μ + jets	Criteria for e + jets
Trigger	HLT_IsoMu24 OR HLT_IsoTkMu24	HLT_Ele32_eta2p1_WPTight_Gsf
Tight lepton selection	$p_T \geq 26$ GeV, $\|\eta\| \leq 2.4$ cut-based tight Id. $I_{rel} \leq 0.06$ - $\|d_{xy}\| < 0.2$ cm, $\|d_z\| < 0.5$ cm (included in tight Id.)	$p_T \geq 35$ GeV, $\|\eta\| \leq 2.1$ cut-based tight Id. $I_{rel} \leq 0.0588(0.0571)$ in EB (EE) (included in tight Id.) $\|\eta_{sc}\| \leq 1.4442$ OR $\|\eta_{sc}\| \geq 1.566$ $\|d_{xy}\| < 0.05(0.1)$ cm , $\|d_z\| < 0.1(0.2)$ cm in EB (EE)
Loose μ veto	$p_T \geq 10$ GeV, $\|\eta\| \leq 2.4$, loose Id.	
Loose e veto	$p_T \geq 15$ GeV, $\|\eta\| \leq 2.5$, veto Id.	
Jet selection	$p_T \geq 40$ GeV, $\|\eta\| \leq 4.7$, loose Id., ΔR(tight lepton, jet) > 0.4 , no. of jets = 2	
b-tagging	$\|\eta\| \leq 2.4$, deepCSV tight WP (discriminator > 0.7527), no. of b-tagged jets =1	

Table 11: Summary of event selection criteria for 2J1T region in 2017 Dataset

Selection Step	Criteria for μ + jets	Criteria for e + jets
Trigger	HLT_IsoMu27	HLT_Ele35_WPTight_Gsf OR HLT_Ele30_eta2p1_WPTight_Gsf_CentralPFJet35_EleCleaned
Tight lepton selection	$p_T \geq 30$ GeV, $\|\eta\| \leq 2.4$ cut-based tight Id. $I_{rel} \leq 0.06$ - $\|d_{xy}\| < 0.2$ cm, $\|d_z\| < 0.5$ cm (included in tight Id.)	$p_T \geq 37$ GeV, $\|\eta\| \leq 2.1$ cut-based tight Id. $I_{rel} \leq 0.0588(0.0571)$ in EB (EE) (included in tight Id.) $\|\eta_{sc}\| \leq 1.4442$ OR $\|\eta_{sc}\| \geq 1.566$ $\|d_{xy}\| < 0.05(0.1)$ cm , $\|d_z\| < 0.1(0.2)$ cm in EB (EE)
Loose μ veto	$p_T \geq 10$ GeV, $\|\eta\| \leq 2.4$, loose Id.	
Loose e veto	$p_T \geq 15$ GeV, $\|\eta\| \leq 2.5$, veto Id.	
Jet selection	$p_T \geq 40$ GeV, $\|\eta\| \leq 4.7$, loose Id., ΔR(tight lepton, jet) > 0.4 , no. of jets = 2	
b-tagging	$\|\eta\| \leq 2.4$, deepCSV tight WP (discriminator > 0.8001), no. of b-tagged jets =1	
QCD rejection	$m_T^W \geq 50$ GeV	

Log Normal transformation

What we have proposed $\sigma^2 = r^2 + \Gamma_t^{\ 2}$ Here

σ : is measured quantity which the sigma of the distribution

r : is the detector resolution

Γ_t : is the actual width

$$LN(m_y, \sigma_y^2) = \frac{1}{\sqrt{2\pi}\sigma_x x} Exp\left[-\frac{(\ln x - m_x)^2}{2\sigma_x^2}\right]$$

$$m_y = e^{m_x + \frac{\sigma_x^2}{2}} \quad \sigma_y^2 = e^{2m_x + \sigma_x^2}\left(e^{\sigma_x^2} - 1\right)$$

$$LN(M_{m_t}, \sigma_{m_t}^2) = \frac{1}{\sqrt{2\pi}\sigma_{\ln(m_t)} m_t} Exp\left[-\frac{(\ln m_t - M_{\ln(m_t)})^2}{2\sigma_{\ln(m_t)}^2}\right]$$

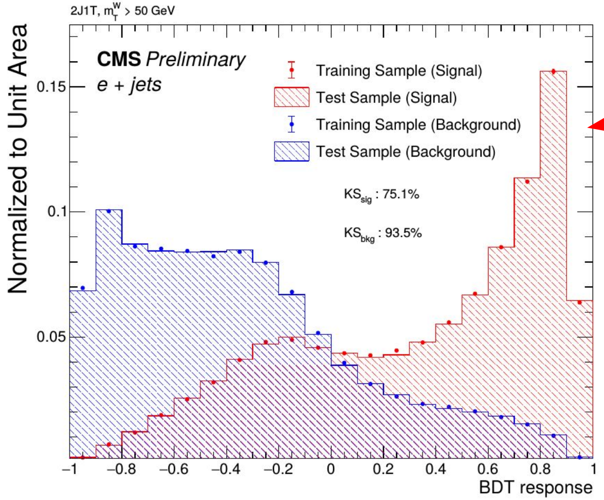
$$M_{m_t} = e^{M_{\ln(m_t)} + \frac{\sigma_{\ln(m_t)}^2}{2}} \quad \sigma_{m_t} = e^{2M_{\ln(m_t)} + \sigma_{\ln(m_t)}^2}\left(e^{\sigma_{\ln(m_t)}^2} - 1\right)$$

Systematic uncertainty estimation

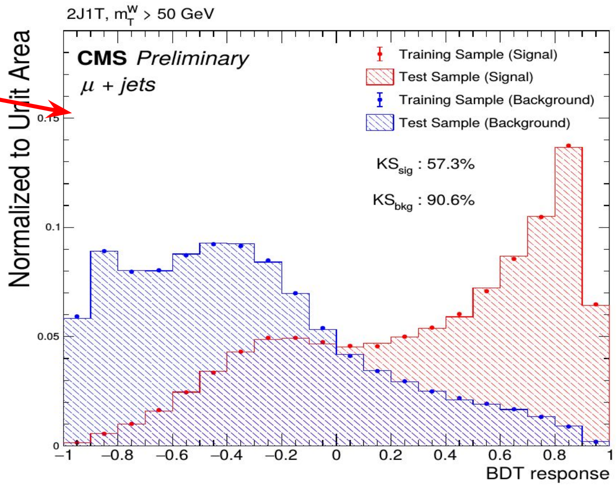
- Signal and Bkg normalization added as nuisance parameters in the fit
- All other unc. are externalized ➛ fit repeated with varied templates
- JES and JER unc. are evaluated according to TopJME recommendation
- JES uncertainty corresponding to different sub-category according to JME-15-001
  cms.cern.ch/iCMS/analysisadmin/get?analysis=JME-15-001-pas-v8.pdf
- 2.5% uncertainty in luminosity propagated
- 4.6% uncertainty in $\sigma_{\text{min. bias}}$ = 69.2 mb propagated as unc. due to pileup
- 50% uncertainty in QCD normalization is propagated
- Top p_T re-weighting applied to ttbar only
- Dedicated samples used for t-ch. and ttbar modeling unc. sources
- Alternate CR tune models and top mass hypothesis considered for t-ch and ttbar simultaneously
- Max. difference w.r.t nominal quoted as uncertainty for PDF+α_s and μ_R/μ_F scale variations

Boosted decision tree performance

Variable	Rank μ	Rank e	Description
$\Delta R_{bj'}$	1	1	Angular separation in $\eta - \phi$ space between the b-tagged and untagged jets
light jet $\lvert\eta\rvert$	2	2	Absolute pseudorapidity of the untagged jet
$m_{bj'}$	3	3	Invariant mass of the system comprising of the b-tagged and untagged jets
$\cos\theta^*$	4	4	Cosine of the angle between the lepton and untagged jet in the rest frame of the top quark
m_T^W (≥ 50 GeV)	5	5	Transverse W boson mass as described in Eq. (6)
FW1	—	6	First-order Fox-Wolfram moment [46, 47]
$\lvert\Delta\eta_{\ell b}\rvert$	6	7	Absolute pseudorapidity difference between the lepton and b-tagged jet
$p_T^b + p_T^{j'}$	7	8	Scalar sum of p_T of the b-tagged and untagged jets
$\lvert\eta_\ell\rvert$	8	—	Absolute pseudorapidity of the lepton (muon)



One BDT is tain per lepton flavour



Event selection TOP-19-009

1. **Trigger:**
   μ: HLT_IsoMu24 OR HLT_IsoTkMu24
   e: HLT_Ele32_eta2p1_WPTight_Gsf

2. **Exactly 1 lepton:**
   μ: p_T > 26 GeV, |η| < 2.4, tight ID, I_{rel}< 0.06 within ΔR=0.4

   e: p_T > 35 GeV, |η| < 2.1, passes tight, EB-EE transition gap excluded,
   IP cuts:
   for $|\eta_{sc}| \leq 1.479$, $|d_{xy}| < 0.05$ cm and $|d_z| < 0.10$ cm,

   for $|\eta_{sc}| \geq 1.479$, $|d_{xy}| < 0.10$ cm and $|d_z| < 0.20$ cm

3. **Veto events with second lepton:**
   p_T > 10 (15) GeV , |η| < 2.4 (2.5), loose (veto) ID, I_{rel} < 0.2 for μ (e)

4. **2 AK4 PF jets with:**
   p_T > 40 GeV, |η| < 4.7, loose ID, ΔR(ℓ,Jets) > 0.4

5. **1 b-tag jet with:**
   |η| < 2.4 passing the CMVAv2 tight working point

6. **m_T^W > 50 GeV**
   To rejet the QCD multijet background

Object selections based on POG recommendations

Moment For Two & Three Jet

$$H_L = \sum_{i,j=1}^{N} w_i w_j P_L \cos(\Omega_{ij})/S = 1/S(\sum_i w_i^2 + 2*\sum_{i<j} w_i\ w_j\ P_L \cos(\Omega_{ij}))$$

For two jets

$$H_L = (w_1^2 + w_2^2 + 2*w_1 w_2\ P_L(\cos(\Omega_{12}))/(w_1+w_2)^2$$

or

$$H_L = \{1+r^2 + 2*r\ *P_L(\cos(\Omega_{12}))\}/(1+r)^2$$ Here $r = w_1/w_2$

And For Three jets

$$H_L = \{1+r_2^2+r_3^2 + 2*r_2 *P_L(\cos(\Omega_{12}))+2*r_3*P_L(\cos(\Omega_{13}))+2*r_2*r_3*P_L(\cos(\Omega_{23}))\}/(1+r_2+r_3)^2$$

Here $r_2=w_2/w_1$ & $r_3=w_3/w_1$ and Ω_{ij} is the angle b/w the jet i and j

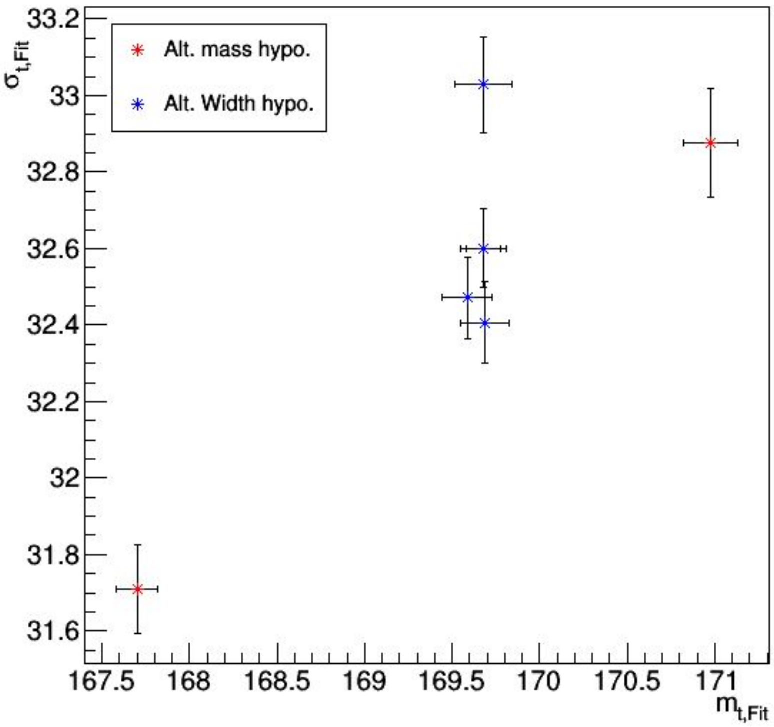
Systematic Breakdown

Source		$\delta m_{l\pm}$	δm_{l+}	δm_{l-}
Statistical + profiled systematic		±0.32	±0.37	±0.58
JES	Correlation group intercalibration	±0.09	±0.07	±0.12
	Correlation group MPFInSitu	±0.02	±0.02	±0.01
	Correlation group uncorrelated	±0.39	±0.17	±0.83
	Total (quadrature sum)	±0.40	±0.18	±0.84
JER		$<\lvert 0.01\rvert$	$<\lvert 0.01\rvert$	$<\lvert 0.01\rvert$
Unclustered energy		$<\lvert 0.01\rvert$	$<\lvert 0.01\rvert$	$<\lvert 0.01\rvert$
Muon efficiencies		$<\lvert 0.01\rvert$	$<\lvert 0.01\rvert$	$<\lvert 0.01\rvert$
Electron efficiencies		±0.01	±0.01	±0.01
Pileup		±0.14	±0.04	±0.34
b tagging		±0.20	±0.18	±0.22
QCD multijet background		±0.02	±0.01	±0.02
Mass calibration		±0.11	±0.13	±0.20
Int. luminosity		$<\lvert 0.01\rvert$	$<\lvert 0.01\rvert$	±0.01
CR model and ERD		±0.24 (0.017)	±0.39 (0.027)	±0.68 (0.048)
Flavor-dependent JES	Gluon	+0.52	+0.75	−0.03
	Light quark (uds)	−0.18	+0.18	−0.23
	Charm	+0.01	+0.08	+0.11
	Bottom	−0.48	−0.29	−0.31
	Total (linear sum)	−0.13	+0.72	−0.46
b quark hadronization model	b frag. Bowler–Lund	±0.03	±0.06	±0.08
	b frag. Peterson	+0.14	+0.11	+0.19
	Semileptonic b hadron decays	±0.18	±0.17	±0.19
	Total (quadrature sum)	+0.23 −0.18	+0.21 −0.18	+0.28 −0.21
Signal modeling	ISR	±0.01	±0.01	$<\lvert 0.01\rvert$
	FSR	±0.28	±0.31	±0.20
	μ_R and μ_F scales	±0.09	±0.13	±0.03
	PDF+α_S	±0.06	±0.06	±0.07
	Total (quadrature sum)	±0.30	±0.34	±0.21
$t\bar{t}$ modeling	ISR	±0.11 (0.008)	±0.02 (0.001)	±0.22 (0.016)
	FSR	±0.10 (0.007)	±0.14 (0.010)	±0.40 (0.028)
	ME-PS matching scale	±0.10 (0.007)	±0.10 (0.006)	±0.10 (0.008)
	μ_R and μ_F scales	±0.03	±0.03	±0.01
	PDF+α_S	$<\lvert 0.01\rvert$	$<\lvert 0.01\rvert$	$<\lvert 0.01\rvert$
	Top quark p_T reweighting	−0.04	−0.08	−0.04
	UE	±0.07 (0.005)	±0.04 (0.003)	±0.17 (0.012)
	Total (quadrature sum)	±0.20	+0.18 −0.20	±0.50
Parametric shapes	Signal shape	±0.05	±0.03	±0.04
	$t\bar{t}$ bkg. shape	±0.07	±0.04	±0.05
	EW bkg. shape	±0.03	±0.01	±0.02
	Total (quadrature sum)	±0.09	±0.05	±0.07
Total externalized systematic		+0.69 −0.71	+0.97 −0.65	+1.32 −1.39
Grand total		+0.76 −0.77	+1.04 −0.75	+1.44 −1.51

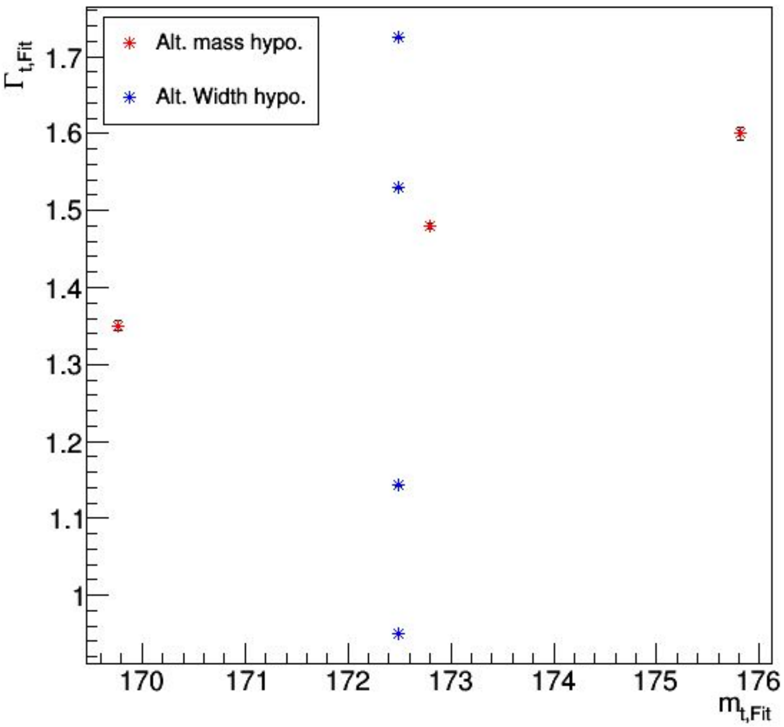
- Signal and Bkg normalization added as nuisance parameters in the fit
- All other unc. are externalized ➢ fit repeated with varied templates
- Max. difference w.r.t nominal quoted as uncertainty for PDF+α_s and μ_R/μ_F scale variations

Source	$\delta m_{inclu.}$(GeV)
Jet Energy scale	**± 0.40**
Signal modeling	**± 0.30**
Color reconnection model	**± 0.24**
b-quark hadronization model	**+0.23 -0.18**
Total syst.	**+0.69 −0.71**
Stat. + Rate	**±0.32**
Grand total	**+0.76 -0.77**

Relation between the mass and the width from fit and Gen level



Measured mass and width of the mass from the fit in ttbar control region



At Gen level form ttbar dilepton final state (fit with breit wigner)

While varying the mass width does not change

But mass varies with the width