A simultaneous measurement of the top quark mass and decay width with single top quark events at CMS

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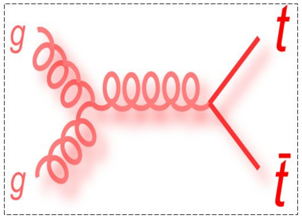
On the behalf of the CMS Collaboration

Top quark production at LHC

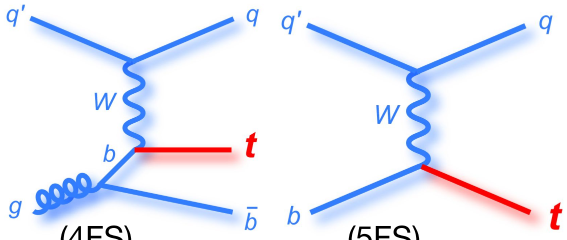
- Top quark is the heaviest particle of the SM
- Largest Yukawa coupling with the Higgs boson
- Major impact on the stability of EWK vacuum
- 13 TeV center mass energy ➨ top quark factory LHC
- Precision lab for measuring the top quark properties such as its mass (m_t)

Top pair



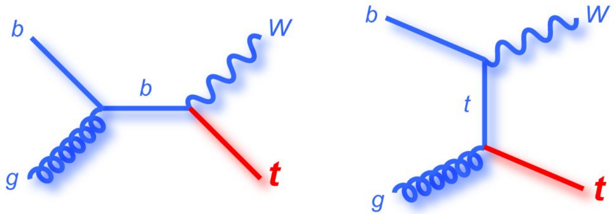
≅ 831 pb

t-channel (~73% at LHC)



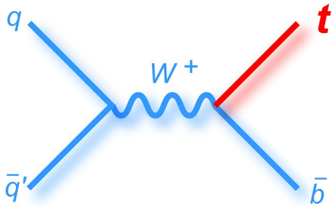
≅ 217 pb

tW (~24% at LHC)

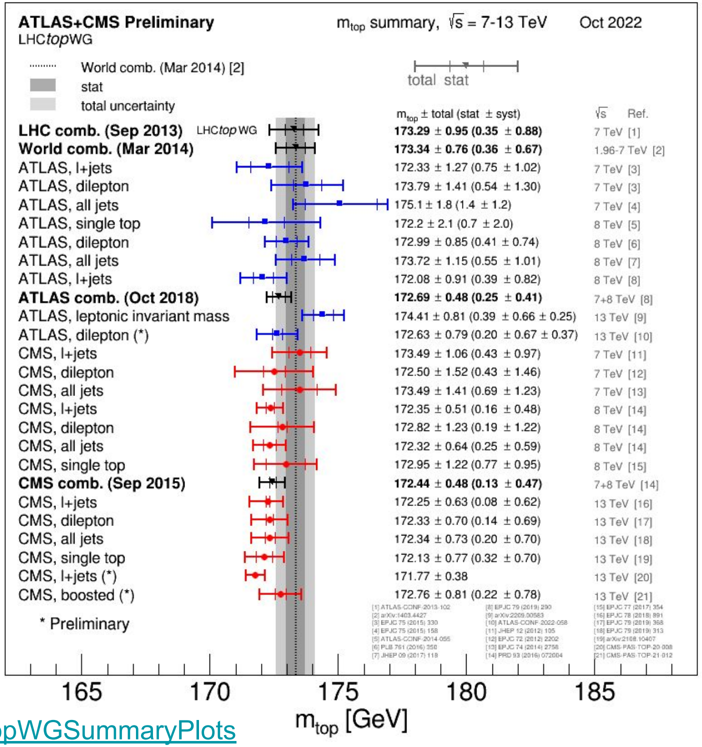


≅ 72 pb

s-channel (~3% at LHC)



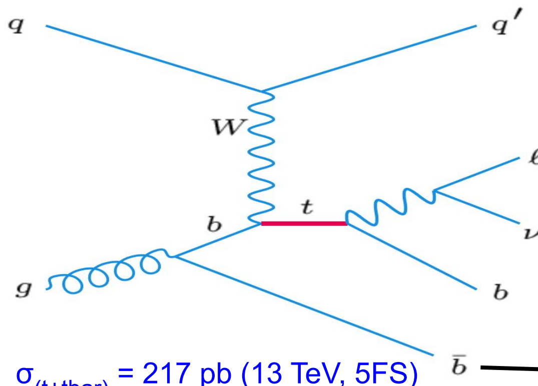
≅ 10 pb



[LHCTopWGSummaryPlots]

*FS -> Flavour Scheme

Event topology and categories

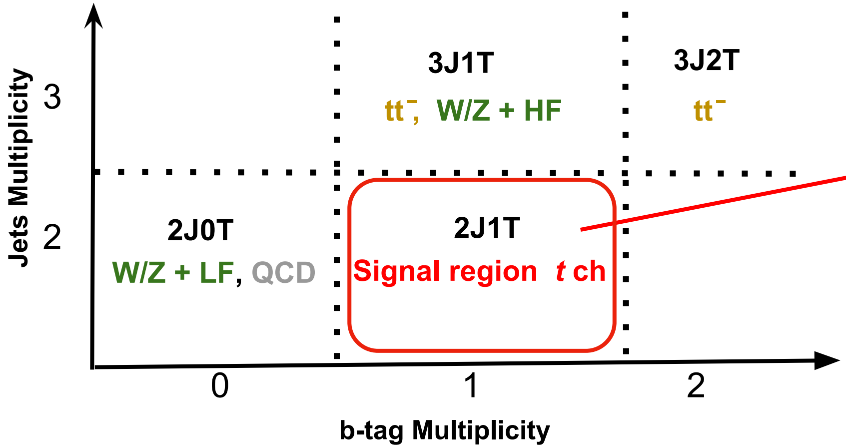


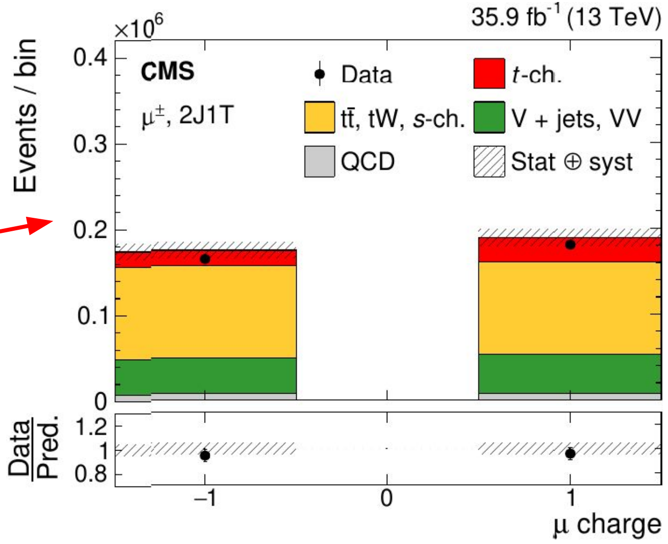
(4FS)

- Spectator light-flavor jet (p_T > 40 GeV) at high |η|
- Exactly one 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



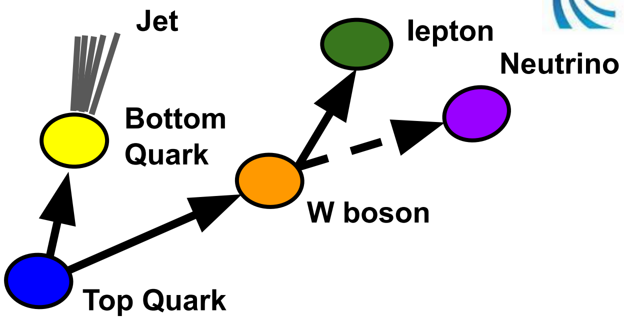


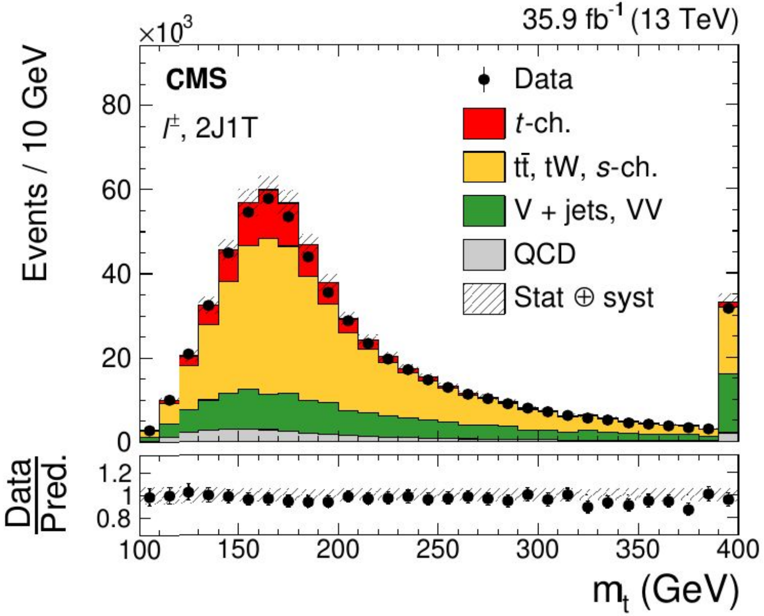
Analysis strategy

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

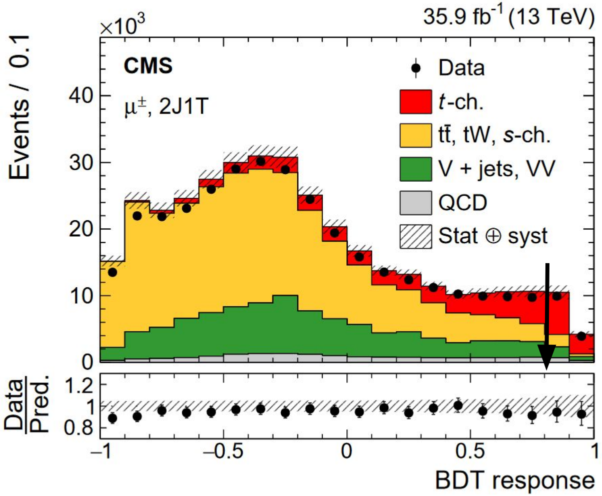
$$m_W^2 = \left(E_\ell^2 + \sqrt{\not{p}_T^2 + p_{z,\nu}^2}\right)^2 - \left(\vec{p}_{T,\ell} + \vec{\not{p}}_T\right)^2 - \left(p_{z,\ell} + p_{z,\nu}\right)^2$$

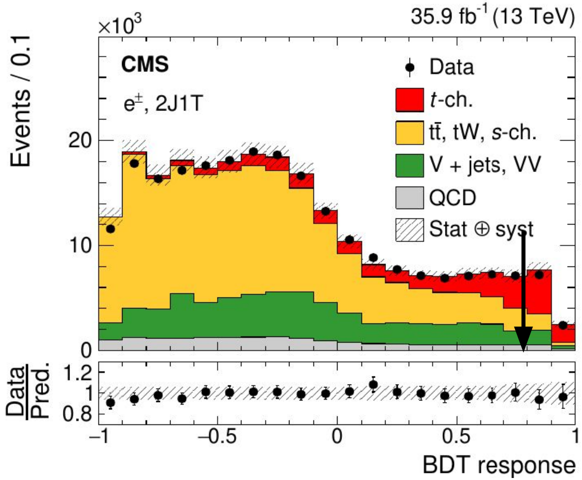
- Reconstruct the W boson from charged lepton and neutrino
- Reconstruct the top quark from b-tagged jet and W boson
- Use a boosted decision tree (BDT) to separate signal from backgrounds
- Optimize the criterion on the BDT response such that the expected uncertainty on top quark mass is minimum
- Fit the top quark mass distribution to get the measured top quark mass

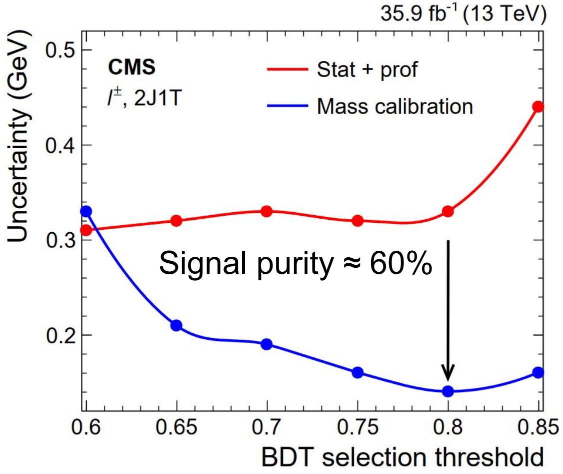


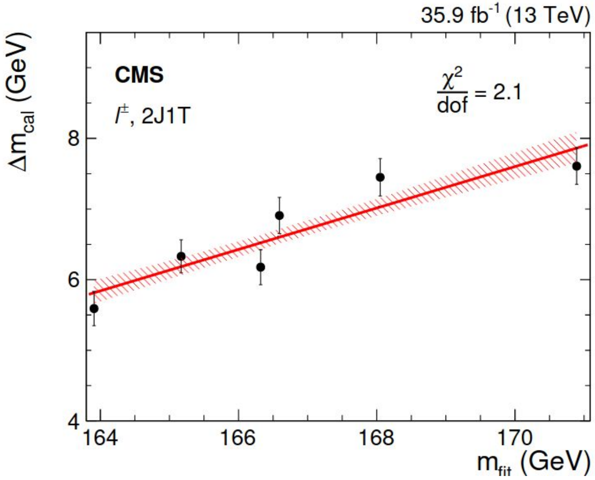


BDT discriminator and cut optimization









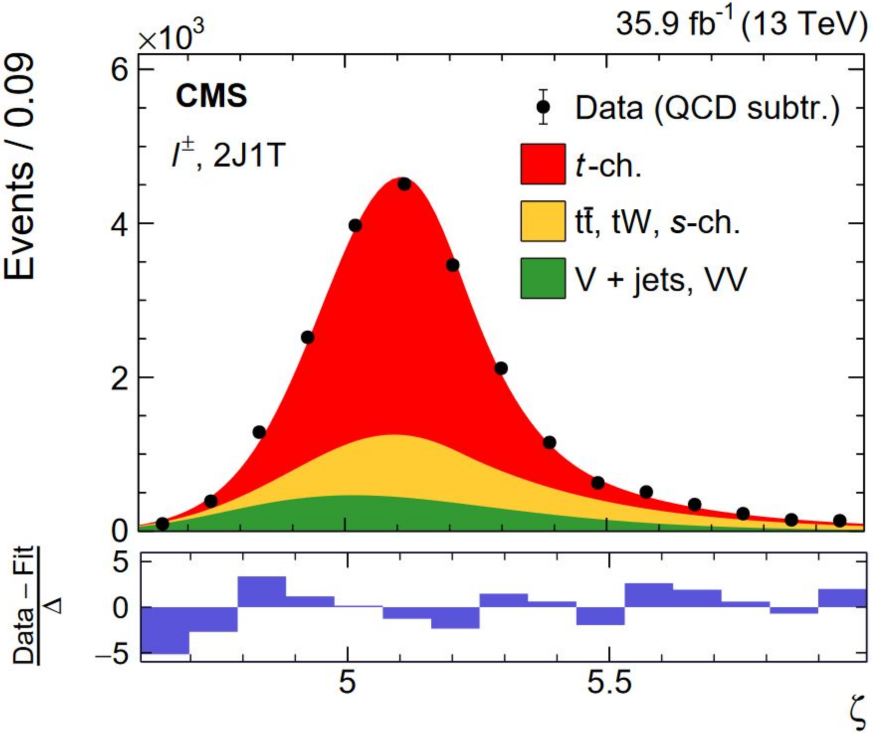
Extraction of m_t

- QCD is subtracted from the data
- 50% uncertainty (shape+rate) propagated on the estimated QCD bkg.
- Simultaneous ML fit with the **ζ = *ln*(m_t /1 GeV)** distributions in μ and e final states

$$\mathcal{L}_{\rm tot} = \prod_{l} \mathcal{L}_l \quad \text{with} \quad \mathcal{L}_l = \prod_{i,\ j} \mathcal{P}[N_{i,\ l}^{\rm obs} \mid F_l(\zeta;\ \zeta_0,\ f_j)]\ \Theta(f_j),$$

  - ➢ ζ_0 : POI, represents the peak position of the combined *t*-channel and Top templates
  - ➢ **m_{Fit} extracted from exp(ζ_0)**; calibrated against *true* **m_t**
  - ➢ $F_{t\text{-}ch}$ = asymmetric Gaussian core + Landau tail
  - ➢ F_{Top} = Crystal ball
  - ➢ F_{EWK} = Novosibirsk

- ζ_0 , f_{t-ch}, f_{Top} ,and f_{EWK} are allowed to float in the fit
- Constraint on the rates added as nuisance parameters to the fit
  $f_{t-ch} \rightarrow 15\%,\ f_{Top} \rightarrow 6\%$ and $f_{EWK} \rightarrow 10\%$



Fit model is validated in control region:

-0.2 < BDT response < 0.8

Results

Sub-GeV precision

Inclusive mass results:

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

Source	$\delta m_{inclu.}$(GeV)
JES	± 0.40
Signal modeling	± 0.30
CR model	± 0.24
b-quark hadronization model	$^{+0.23}_{-0.18}$

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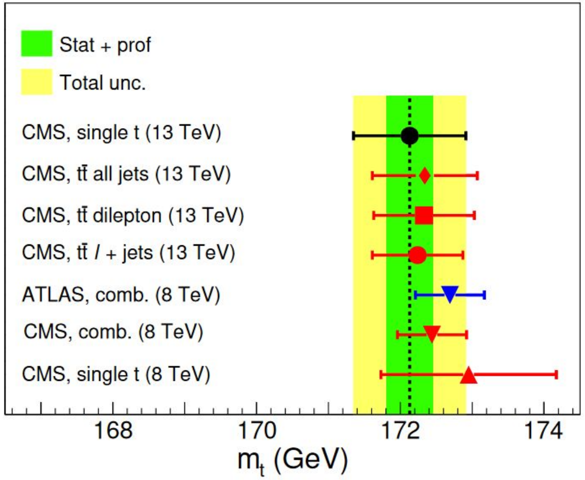
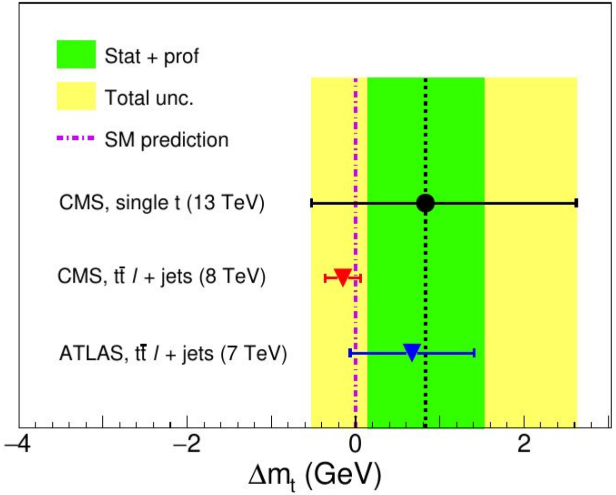
Masses of the top quark and antiquark:

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

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

Mass ratio and difference (a check for CPT Invariance)





VALUE (GeV)	DOCUMENT ID	TECN
172.69 ± 0.30 OUR AVERAGE Error includes scale fact below.		
$172.13^{+0.76}_{-0.77}$	[1] TUMASYAN 21G	CMS

VALUE (GeV)	DOCUMENT ID	TECN
−0.15 ± 0.20 OUR AVERAGE Error includes scale factor of		
$0.83^{+1.79}_{-1.35}$	[1] TUMASYAN 21G	CMS

https://doi.org/10.1093/ptep/ptac097

Width measurement

- Simultaneous measurement of $\mathbf{m_{top}}$ and $\mathbf{\Gamma_{top}}$ using **full Run-2 data** (~ 137 fb-1) and latest recommended MC samples ➨ Strategy: Fit with **parametric shapes** (JHEP 12 (2021) 161)
- Improvements:
  - Use the Deepjet discriminant to tag b jets
  - Determination of QCD bkg. rate simultaneously in both lepton flavours
  - Estimation of other bkg. contributions from the dedicated control regions
  - Multi-classification with DNN to separate signal from combinatorial bkgs.
  - Usage of Higgs combine tool → shape systematics as a nuisance parameters in the fit to obtain a precise width measurement

Preliminary results for $\mathbf{m_{top}}$ and $\mathbf{\Gamma_{top}}$ in a ttbar-enriched control region to validate the new fit set-up

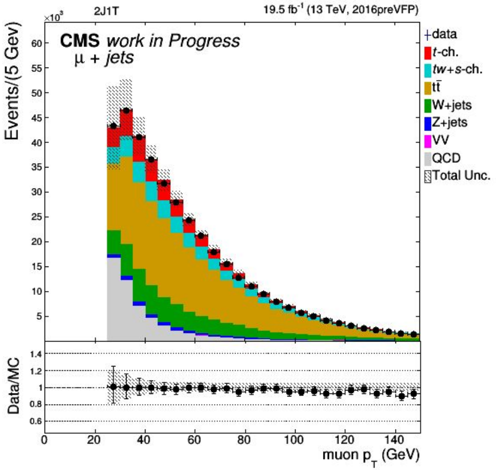
→

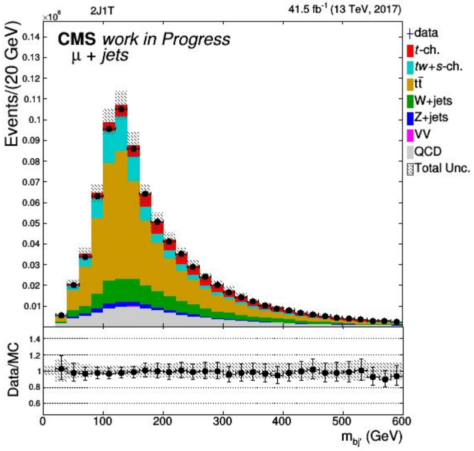
$\mathbf{m_{top}}$ = 172.1 ± 1.209 (offset only) GeV*

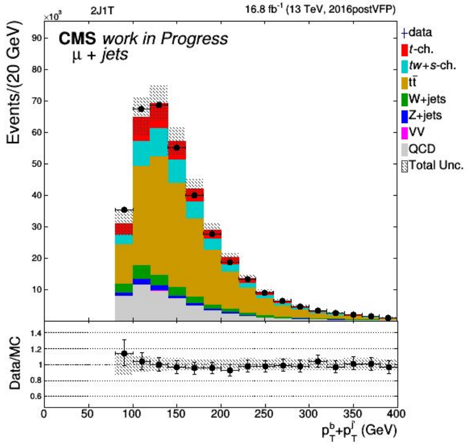
$\mathbf{\Gamma_{top}}$ = 1.47 ± 0.1 (offset only) GeV*

Current status

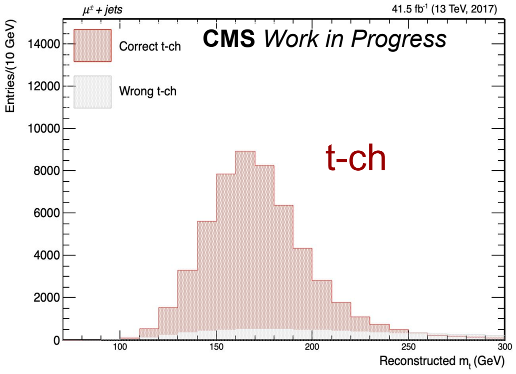
In general, a good data-MC agreement observed with data collected during 2016 and 2017

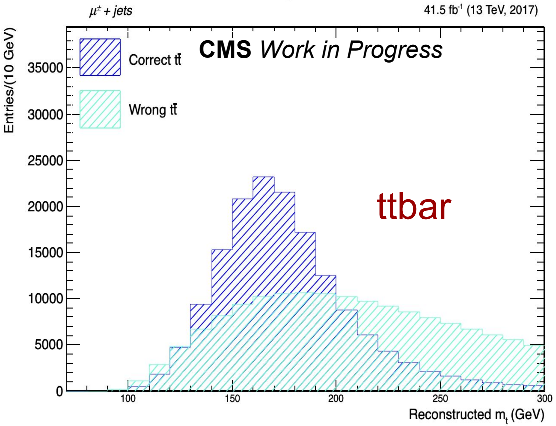


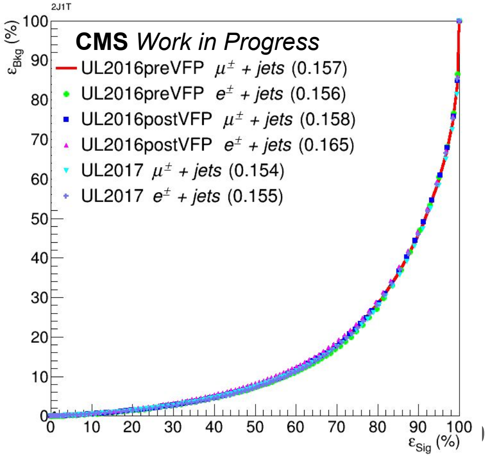




DNN is trained and tested with MC sample for 2016 and 2017







Summary and outlook

- Top quark mass measured with data collected during 2016 is already published JHEP 12 (2021) 161
- We have achieved a sub-GeV precision for the first time in single top topologies
- Simultaneous mass and width extraction is aimed based on the full Run-2 data
- Targeting for **summer conferences in 2023** for a public result

Back up

DNN details

- Input variables to the network
  - 4-momenta of the lepton, b jet, light jet, and the reco. neutrino
  - First Fox-Wolfram moments
  - deepJet scores of b-jet and light jet

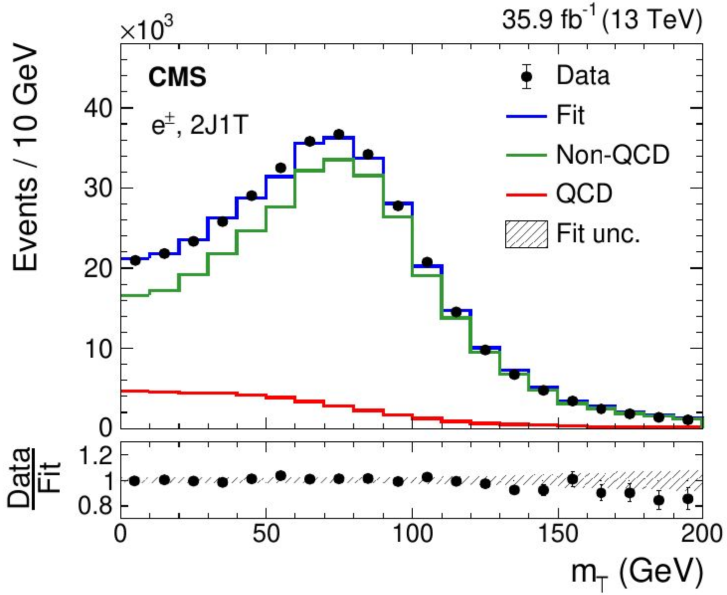
- The events are distinguished into 6 output classes
  - *t*-ch. single top correct assignment
  - *t*-ch. single top incorrect assignment
  - Top ($t\bar{t}$ + tW + *s*-ch.) bkg. correct assignment
  - Top bkg. incorrect assignment
  - Electroweak bkg. (V+jets and VV)
  - QCD

QCD estimation

- 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)
    ⇒ derive QCD template using SB data
- 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



Analysis strategy

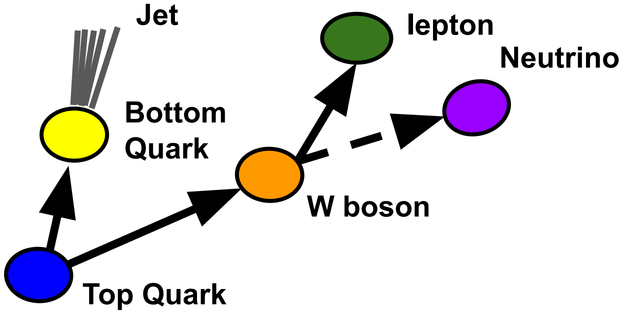
- Estimate $p_{z,\nu}$ from energy-momentum conservation using the m_W (= 80.4 GeV) constraint

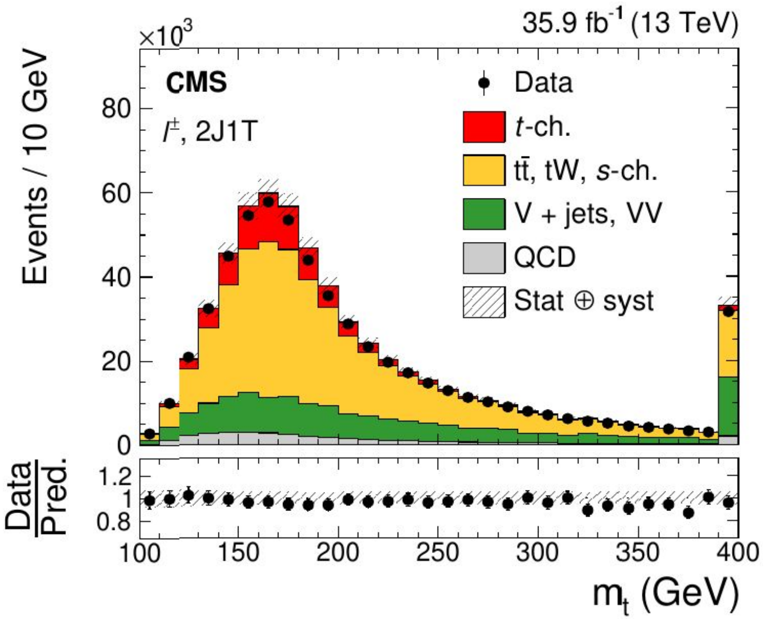
$$m_W^2 = \left(E_\ell^2 + \sqrt{\not{p}_T^2 + p_{z,\nu}^2}\right)^2 - \left(\vec{p}_{T,\ell} + \vec{\not{p}}_T\right)^2 - (p_{z,\ell} + p_{z,\nu})^2$$

- Leads to a 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 $p_{y,\nu}$ while keeping the m_W constraint satisfied so that neutrino $p_{T,\nu}$ has lowest Δφ with missing p_T

- Reconstruct the W boson from charged lepton and neutrino

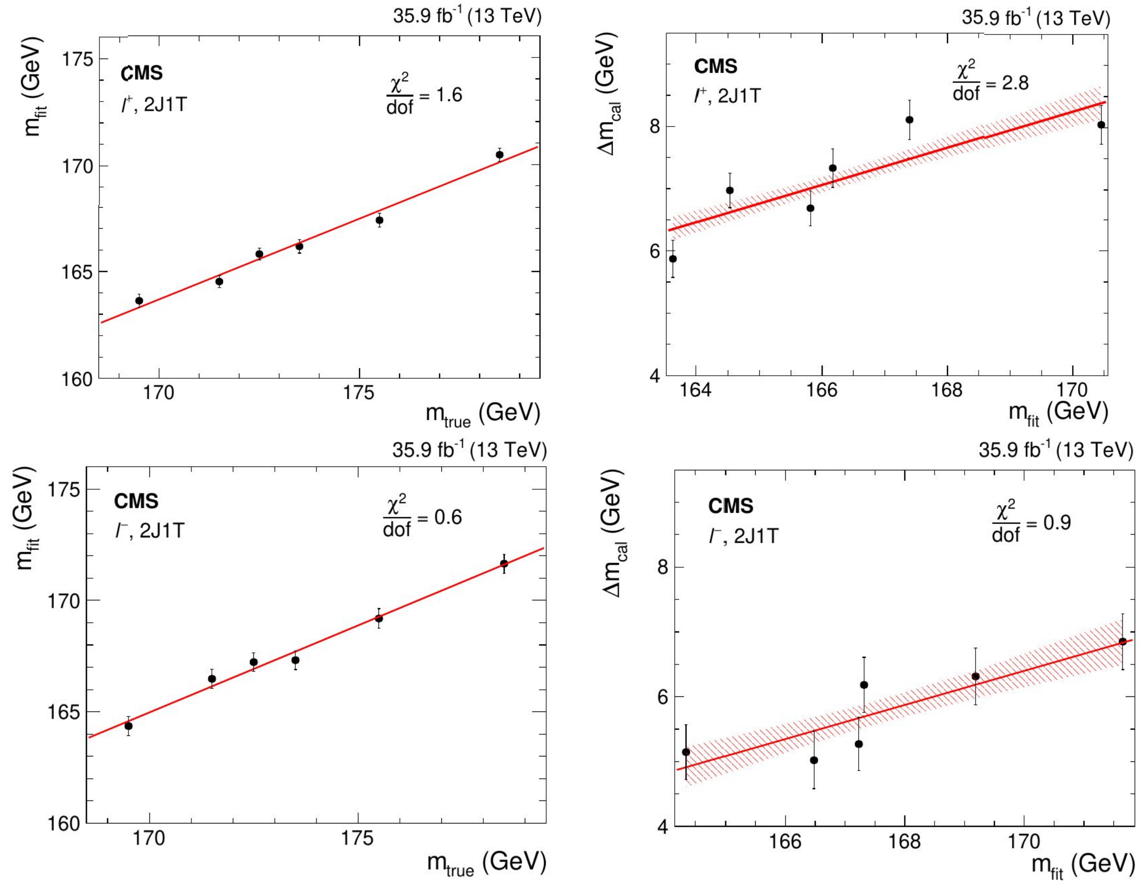
- Reconstruct top quark from b-tagged jet and W boson





Mass linearity and calibration

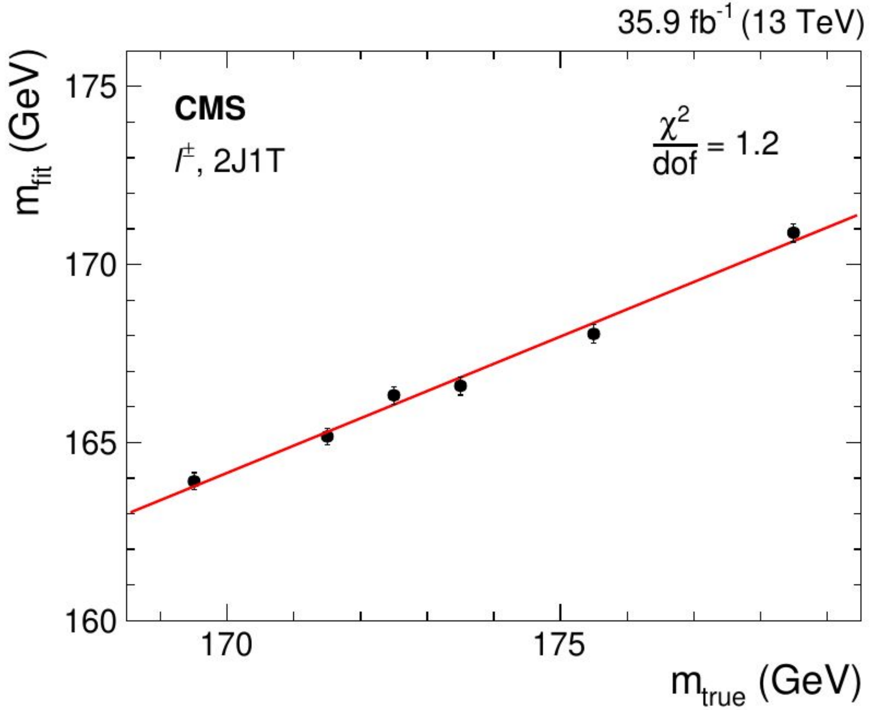
m_t hypothesis considered simultaneously for *t* - ch. and $t\bar{t}$ using dedicated MC samples

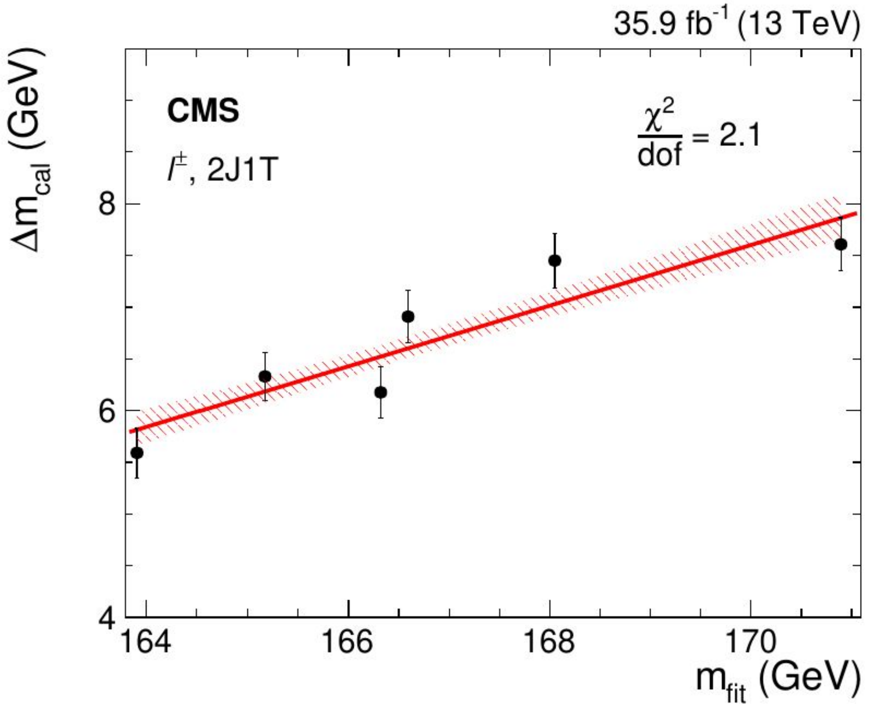


- Calibration performed separately for the ℓ^+ and ℓ^- case also
- Mass calibration is done using the relationship $\Delta m_{offset} = |m_{True} - m_{Fit}|$ vs. m_{Fit}

Mass linearity and calibration

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

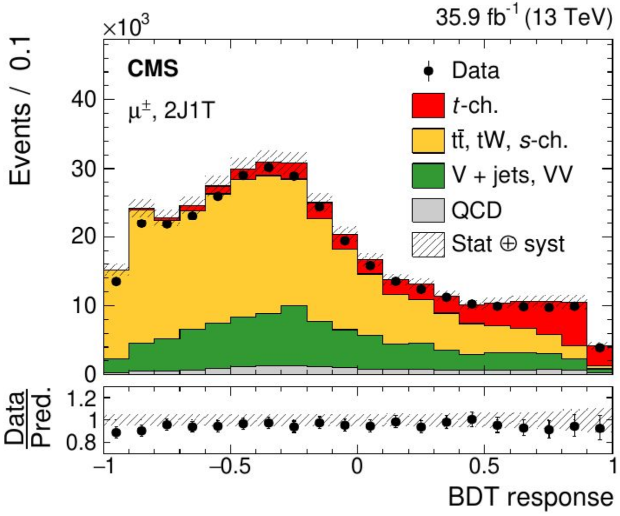


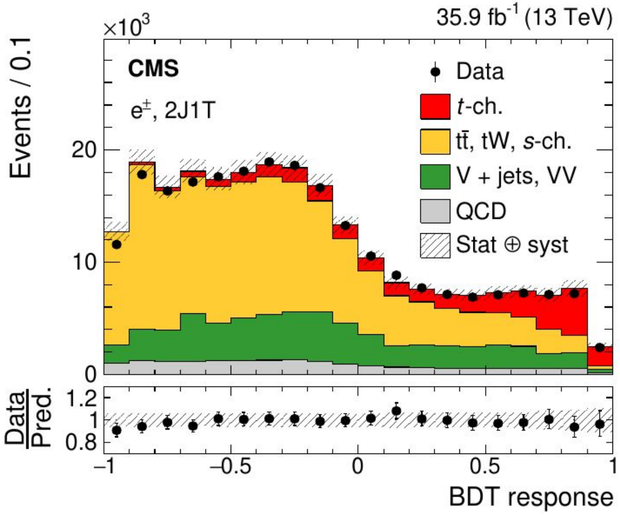


- Calibration performed separately for the ℓ^+ and ℓ^- case also
- Mass calibration is done using the relationship $\Delta m_{offset} = |m_{True} - m_{Fit}|$ vs. m_{Fit}

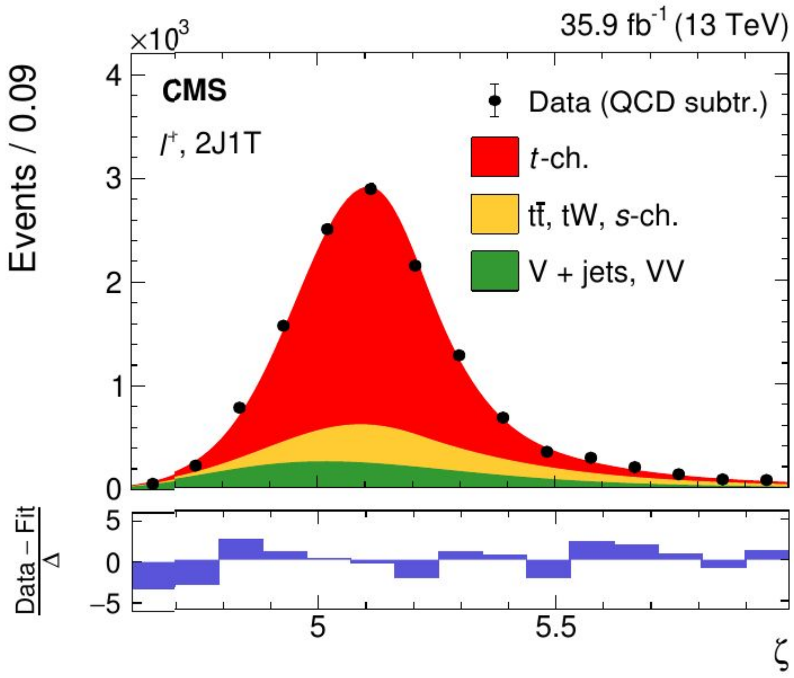
BDT variables (TOP-19-009)

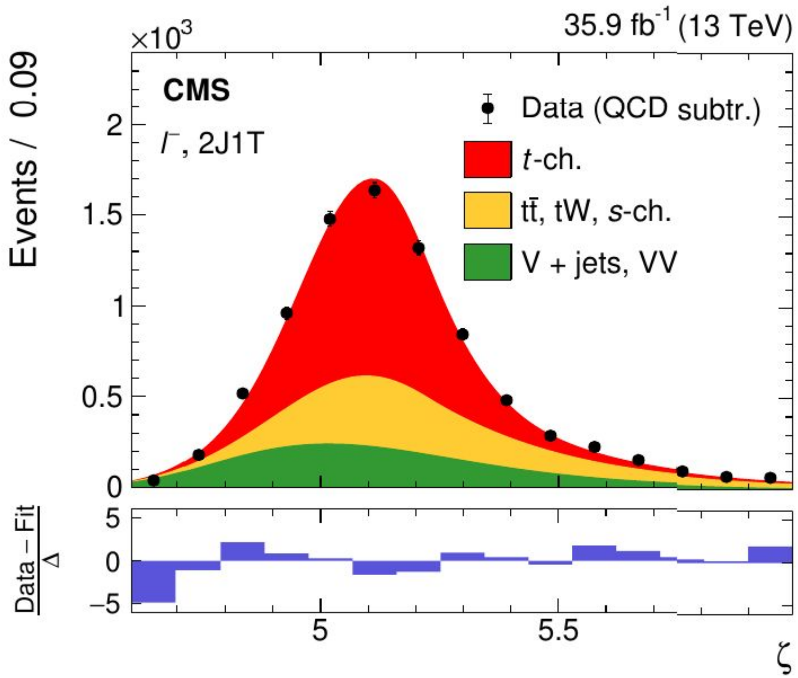
Variable	Rank μ	Rank e	Description
$\Delta R_{bj'}$	1	1	Angular separation in $\eta - \phi$ space between the b-tagged and untagged jets
light jet $\lvert\eta\rvert$	2	2	Absolute pseudorapidity of the untagged jet
$m_{bj'}$	3	3	Invariant mass of the system comprising of the b-tagged and untagged jets
$\cos\ \theta^*$	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)



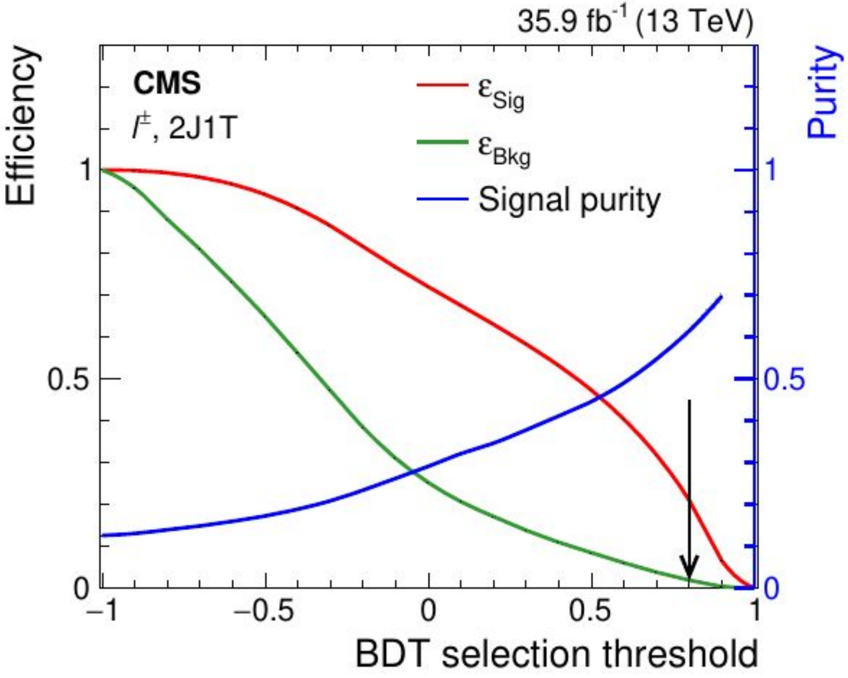


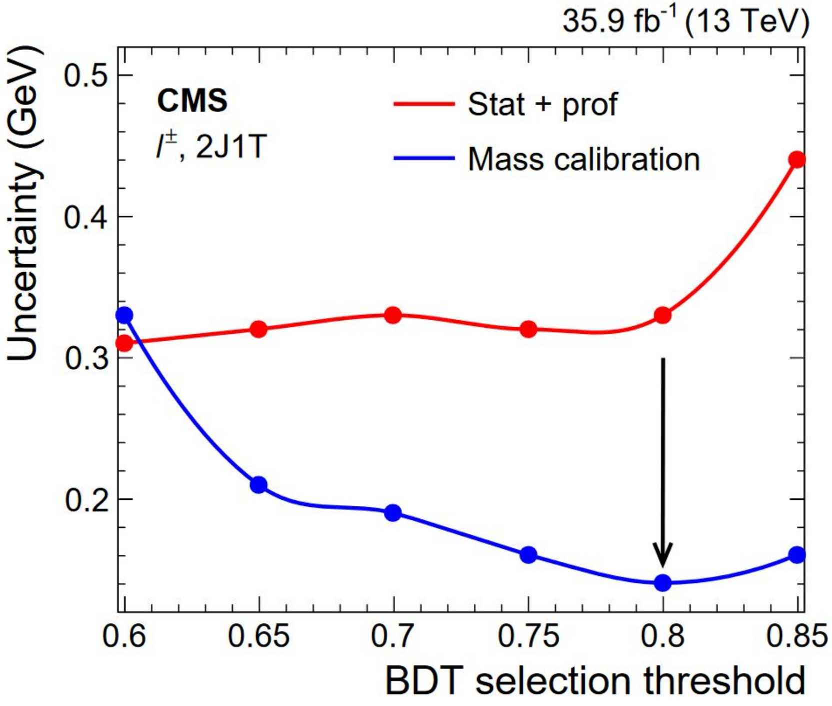
Lepton charge - dependent fits





BDT performance





- One BDT is trained per channel (electron/Muon)
- At BDT response = 0.8
  - Signal purity ≈ 60%

Systematics

Source		$\delta m_{\ell^\pm}$	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		$< \pm0.01$	$< \pm0.01$	$< \pm0.01$
Unclustered energy		$< \pm0.01$	$< \pm0.01$	$< \pm0.01$
Muon efficiencies		$< \pm0.01$	$< \pm0.01$	$< \pm0.01$
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
Offset correction		±0.11	±0.13	±0.20
Luminosity		$< \pm0.01$	$< \pm0.01$	±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 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	$< \pm0.01$
	FSR	±0.28	±0.31	±0.20
	μ_R / μ_F scale	±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 / μ_F scale	±0.03	±0.03	±0.01
	PDF + α_S	$< \pm0.01$	$< \pm0.01$	$< \pm0.01$
	Top p_T- reweighting	-0.04	-0.08	-0.04
	Underlying event	±0.07 (0.005)	±0.04 (0.003)	±0.17 (0.012)
	total (quadrature sum)	±0.20	$^{+0.18}_{-0.20}$	±0.50
Signal and background shape	signal shape	±0.05	±0.03	±0.04
	Top bkg. shape	±0.07	±0.04	±0.05
	EWK bkg. shape	±0.03	±0.01	±0.02
	total (quadrature sum)	±0.09	±0.05	±0.07
Total systematic		$^{+0.69}_{-0.71}$	$^{+0.97}_{-0.65}$	$^{+1.32}_{-1.39}$
Grand total		$^{+0.76}_{-0.77}$	$^{+1.04}_{-0.75}$	$^{+1.44}_{-1.51}$

CMS-PAS-TOP-19-009

Systematics charge dependent(TOP-19-009)

- Unc. other than Signal and Bkg normalization are externalized
- 2.5% uncertainty in luminosity propagated
- 4.6% uncertainty in $\sigma_{\text{min. bias}}$ = 69.2 mb propagated as unc. due to pileup
- Alternate CR tune models and top mass hypothesis considered for t-ch and ttbar simultaneously
- Unc. due to QCD scale, PDF, ISR, FSR effects are calculated using reweighted templates

Source	$\delta m_{\text{inclu.}}$(GeV)
JES	± 0.40
Signal modeling	± 0.30
CR model	± 0.24
b-quark hadronization model	$^{+0.23}_{-0.18}$
Total syst.	$^{+0.69}_{-0.71}$
Stat. + Rate	±0.32
Grand total	±0.77

Source	δm_{l+} (GeV)
Flavor-dependent JES	+0.72
CR model	± 0.39
Signal modeling	± 0.34
b-quark hadronization model	$^{+0.21}_{-0.18}$
Total syst.	$^{+0.97}_{-0.65}$
Stat. + Rate	± 0.37
Grand total	± 0.75

Source	δm_{l-} (GeV)
JES	± 0.84
CR model	± 0.68
$t\bar{t}$ modeling	± 0.50
Flavor-dependent JES	- 0.46
Total syst.	$^{+1.32}_{-1.39}$
Stat. + Rate	±0.58
Grand total	±1.51

CMS-PAS-TOP-19-009

DeepJet efficiency