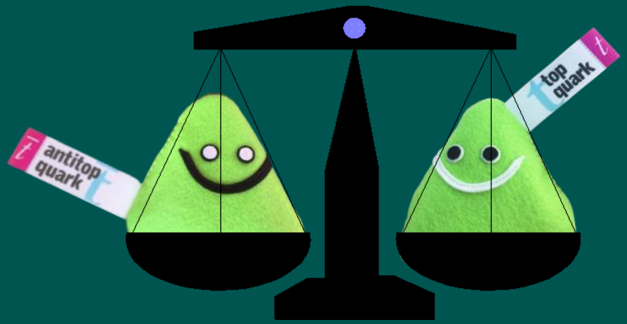
RIGA TECHNICAL UNIVERSITY
Institute of Particle Physics and Accelerator Technologies



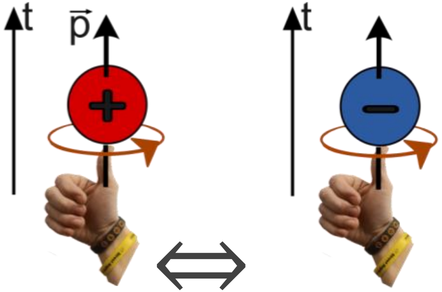
The measurement of the mass difference between the top quark and antiquark at 13 TeV

Thesis endorsement
TOP PAG Meeting

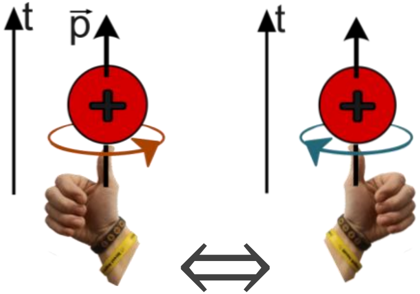
Kārlis Dreimanis, Markus Seidel, Martijn Mulders,
Andris Potrebko

04.03.2025

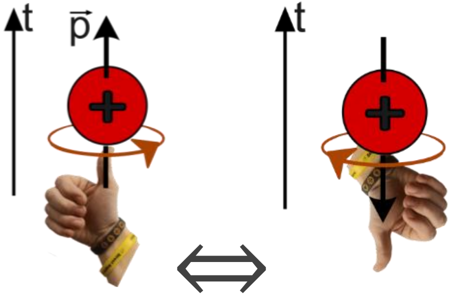
The purpose – test the CPT symmetry



Charge
conjugation (C)

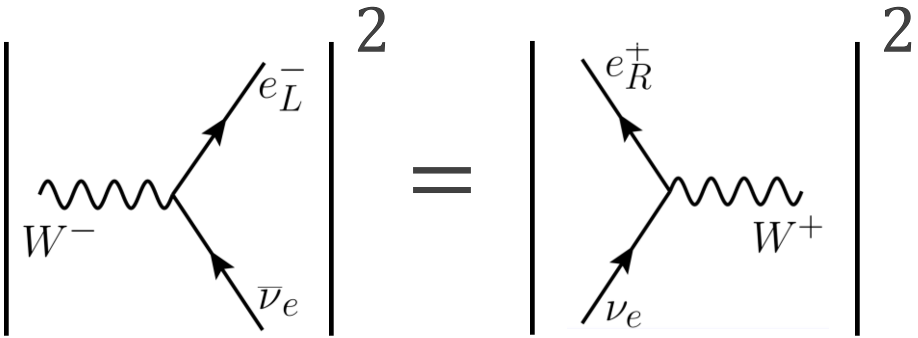


Parity
transformation (P)



Time
reversal (T)

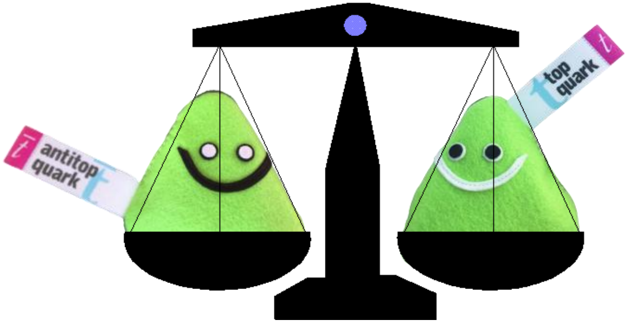
- C, P, T and the combined CP symmetries are violated in weak interactions in the SM, but no deviation from the exact CPT symmetry is found
- CPT symmetry predicts equality of particles and antiparticles
- Right-handed antiparticles behave like left-handed particles moving backwards in time



CPT symmetry predicts equal top quark-antiquark mass

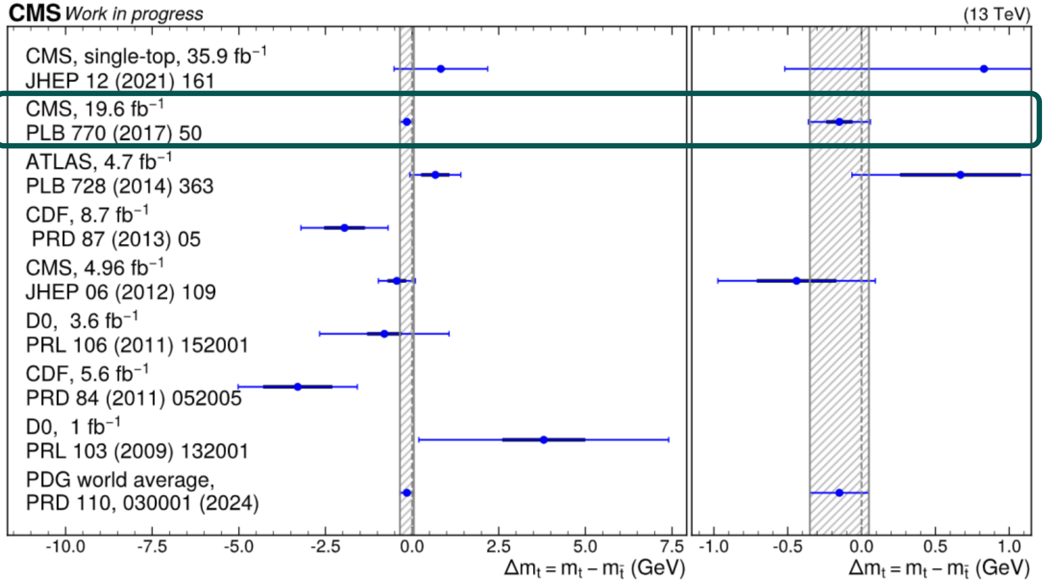
- CPT-violation can be incorporated in the SM through, e.g., string theory or in the neutrino sector
- The CPT symmetry can be tested by measuring

$$\Delta m_t = m_t - m_{\bar{t}}$$



- The current world best measurement ($t\bar{t}$, $\sqrt{s} = 8$ TeV, $19.6\ \mathrm{fb}^{-1}$):

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



Aim: reduce uncertainty by a factor of 3

The current world best measurement ($t\bar{t}$, $\sqrt{s} = 8$ TeV, $19.6\ \mathrm{fb}^{-1}$):

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

10x more data in full Run 2 ⇒ uncertainty reduced by a factor of 3

Uncertainty breakdown in the Run 1 Δm_t measurement

Source	Uncertainty in Δm_t (MeV)
Jet energy scale	7 ± **16**
Jet energy resolution	7 ± **11**
b vs. $\bar{b}$ jet response	**51** ± 1
Signal fraction	**27** ± 2
Background charge asymmetry	**11.9** ± 0.1
Background composition	**28** ± 1
Pileup	**9.1** ± 0.3
b tagging efficiency	**24** ± 7
b vs. $\bar{b}$ tagging efficiency	**11** ± 7
Method calibration	3 ± **53**
Parton distribution functions	**9** ± 3
Total	91

Derivation improved in this thesis (b vs. $\bar{b}$ jet response)

Reduced in this thesis due to a tighter event selection (signal fraction, background charge asymmetry, background composition)

The trigger used

Datasets and event selection borrowed from UL m_t analyses:

AN-2020-147 (Hannu Siikonen); AN-2024/119 (Mikael Myllymaki)

Changes highlighted.

Analysis based on the Hamburg code for top mass

The HLT trigger paths used for this analysis

Channel	Trigger	HLT p_T threshold [GeV]	Reco p_T threshold [GeV]
2016 APV e	HLT_Ele27_WPTight_Gsf	27	29
2016 APV μ	HLT_IsoMu24 and HLT_IsoTkMu24	24	26
2016 nonAPV e	HLT_Ele27_WPTight_Gsf	27	29
2016 nonAPV μ	HLT_IsoMu24 and HLT_IsoTkMu24	24	26
2017 e	HLT_Ele32_WPTight_Gsf_L1DoubleEG	32	35
2017 μ	HLT_IsoMu27	27	29
2018 e	HLT_Ele32_WPTight_Gsf	32	35
2018 μ	HLT_IsoMu24	24	26

Datafiles used

UL16-UL18 MiniAODv2 versions of the following datasets (newest available subversions):

Data (2016APV)
SingleMuon/Run2016[B-ver2, C, D, E,F]-HIPM
SingleElectron/Run2016[B-ver2, C, D, E,F]-HIPM

Data (2016 non-APV)
SingleMuon/Run2016[F-H]
SingleElectron/Run2016[F-G]

Data (2017)
SingleMuon/Run2017[B-F]
SingleElectron/Run2017[B-F]

Data (2018)
SingleMuon/Run2017[B-F]
SingleElectron/Run2017[B-F]

Datafiles used

Summer20UL16-UL18 MiniAODv2 versions of the following datasets:

$t\bar{t}$ samples: Tune CP5 (POWHEG+PYTHIA8 NLO)
TTToSemiLeptonic
TTTo2L2Nu
TTToHadronic

Single top: Tune CP5 (NLO)	
ST_tW_[top, antitop]_5f_NoFullyHadronicDecays	POWHEG+PYTHIA8
ST_t-channel_[top, antitop]_4f_InclusiveDecays	POW+MADSPIN+PY8
ST_s-channel_4f_leptonDecays	aMC@NLO+PY8

Vector boson: Tune CP5 (MADGRAPH-MLM+PYTHIA8 LO)
WJetsToLNu_HT-[*]
DYJetsToLL_M-50_HT-[*]

Diboson: Tune CP5 (PYTHIA8 LO)
WW
WZ
ZZ

QCD: Tune CP5 (Pythia 8 LO)
QCD_Pt-[*]_MuEnrichedPt5
QCD_Pt-[30to80, etc]_EMEnriched

Event selection

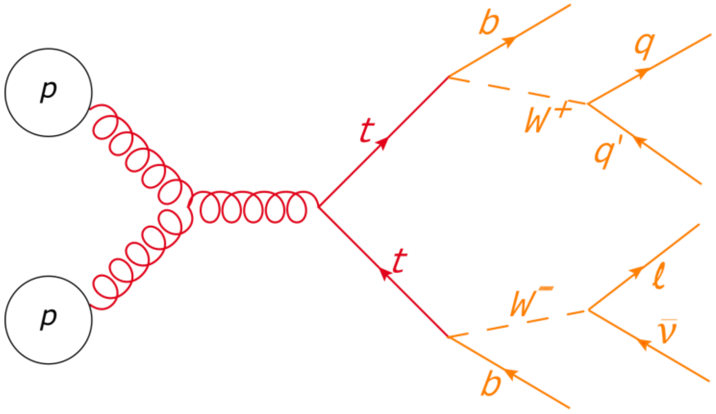
Electron channel: one signal electron, no additional veto lepton
Muon channel: one signal muon, no additional veto lepton

	Signal electron	Veto electron	Signal muon	Veto muon
Max $\|\eta\|$ (2016)	2.4	2.4	2.4	2.4
Max $\|\eta\|$ (2017-2018)	2.5	2.5	2.4	2.4
Min p_T [GeV] (2016)	29	15	26	15
Min p_T [GeV] (2017-2018)	35	15	29	15
ID	Tight	Loose	Tight	Loose
ID version	Cut basedElectronID-Fall17-94X-V2		CutBased	CutBased
Isolation	Within ID	Within ID	PFIso Tight	PFIso Tight
Extra η cuts	EE/EB transition	-	-	-
Impact parameter cut	(*)	-	Within ID	-
Energy corrections	pat::Electron	pat::Electron	Rochester	Rochester
Trigger SF	Yes	-	Yes	-
Reco SF	Yes	-	-	-
ID SF	Yes	-	Yes	-
Isolation SF	Missing for 2016	-	Yes	-

(*): $|d_{xy}| < 1$ mm, $|d_z| < 2$ mm at $|\eta| \leq 1.479$; $|d_{xy}| < 0.5$ mm, $|d_z| < 1$ mm at $|\eta| > 1.479$

Jet selection

- AK4PFchs jets: $p_T > 30$ GeV, $|\eta| < 2.4$ (2016)
  $|\eta| < 2.5$ (2017-18), tight jet ID, lepton veto
- b jets: above the DeepJet Medium WP
- At least 4 jets, out of which exactly 2 b jets
  b jets: searched within the 8 leading jets.
  In Run 1: at least 1 b jet among 4 leading.
- Jet veto maps
- Veto events with any jet with $p_T > 1000$ GeV
- Noise filter

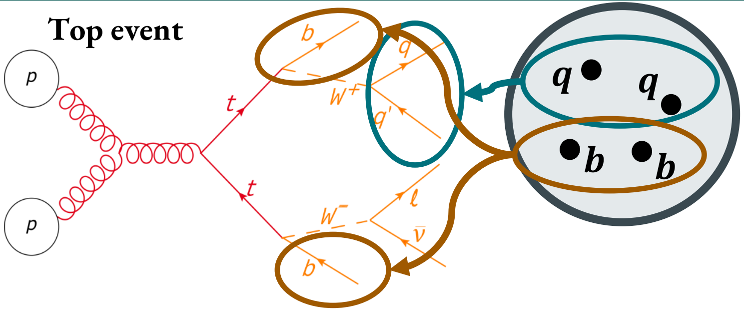


Corrections:

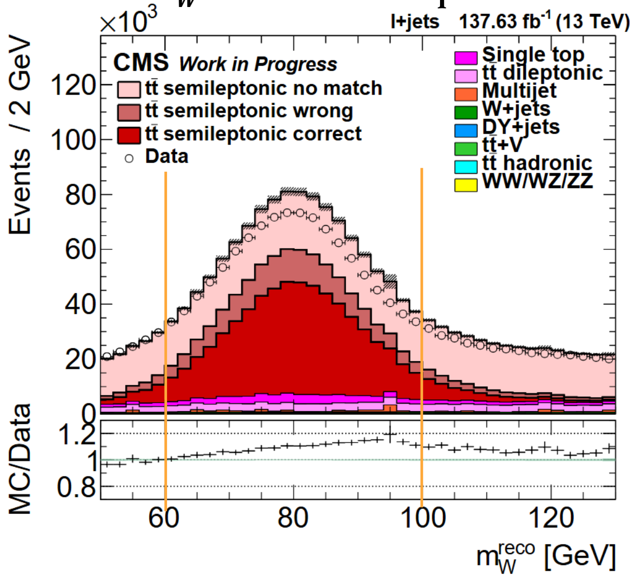
- L1FastJet+L2Relative+L3Absolute
  L5 (flavor-dependent) corrections (see further)

Event reconstruction

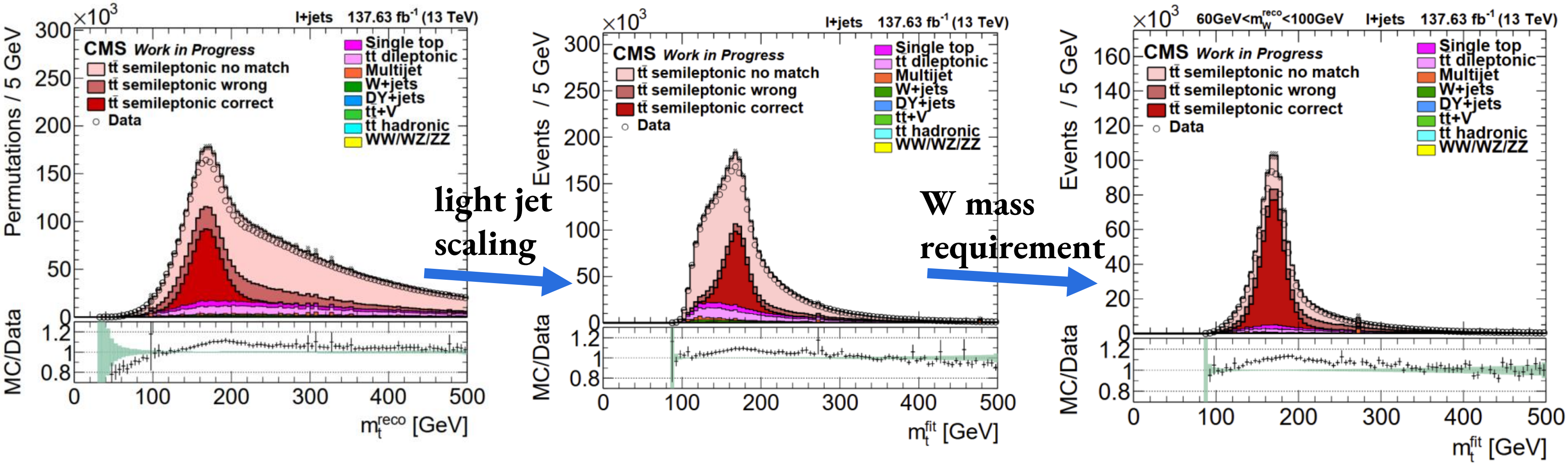
- Kinematic fit cannot be used for the Δm_t measurement because of the $m_{t\ had} = m_{t\ lep}$ constraint
- *HitFit* analyzer is replaced with *WMassDeltaTopMass [link]*:
  1. 2 leading light jets (q) assigned to W_{had} boson
  2. Scale the q jet p_T to match exactly $m_W^{pdg} = 80.40$ GeV
  3. 2 permutation for b-tagged (b) jet combinations with each W boson
  4. Keep the b permutation with the smallest $\Delta m_t^{reco} = m_{t,had}^{reco} - m_{t,lep}^{reco}$
  5. add a W mass requirement $\mathbf{60 < m_W^{reco} < 100}$ GeV



Reconstructed W boson mass and the $60 < m_W^{reco} < 100$ GeV requirement



Hadronic top mass m_t^{fit} peak is improved with the W mass requirement and scaling the light jet invariant mass to m_W^{pdg}



- Data yields are higher by around 10 %: consistent with the HitFit results in the m_t analysis, see TOP-20-008

Event yields (all run 2)

The dataset is split according to the lepton charge.

	No m_W^{reco} requirement				With the m_W^{reco} requirement			
	l^-+jets run 2		l^++jets run 2		l^-+jets run 2		l^++jets run 2	
Dataset	Events [k]	Ratio to signal, %	Events [k]	Ratio to signal, %	Events [k]	Ratio to signal, %	Events [k]	Ratio to signal, %
$t\bar{t}$ l+jets total	1239.7	84.0	1240.6	84.5	530.6	89.4	531.6	89.5
l+jets correct	289.1	19.6	289.5	19.7	255.9	43.1	256.3	43.1
l+jets wrong	115.7	7.8	115.8	7.9	83.0	14.0	83.0	14.0
l+jets no match	834.8	56.6	835.3	56.9	191.7	32.3	192.3	32.4
dilepton	113.3	7.7	113.4	7.7	26.3	4.4	26.4	4.4
all hadronic	1.2	0.1	1.3	0.1	0.4	0.1	0.4	0.1
$t\bar{t}$+V	3.1	0.2	2.7	0.2	0.9	0.2	0.8	0.1
single-top	70.3	4.8	61.0	4.2	25.4	4.3	23.3	3.9
DY+jets	4.2	0.3	4.1	0.3	1.0	0.2	1.0	0.2
W+jets	23.4	1.6	17.8	1.2	4.7	0.8	3.7	0.6
VV	1.0	0.1	0.8	0.1	0.3	0.0	0.3	0.0
Multijet	18.8	1.3	26.3	1.8	4.0	0.7	6.8	1.1
Simulation total	1474.9	100.0	1468.0	100.0	593.5	100.0	594.2	100.0
Data	1390.6	94.3	1378.7	93.9	542.8	91.5	540.3	90.9

43 % of correct permutations, only slightly lower than for HitFit (49%).

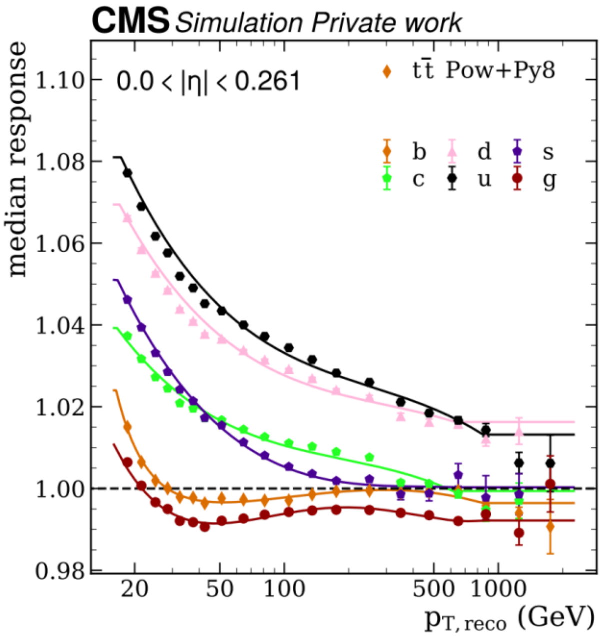
Symmetric for most datasets.
Asymmetric for single-top, W+jets, multijet.
Data: slightly asymmetric vs MC.

Flavour-dependent jet energy corrections

Flavour-dependent jet energy corrections are obtained for Run 2 for $t\bar{t}$, QCD samples and using a simultaneous fit of $t\bar{t}$, QCD and DY

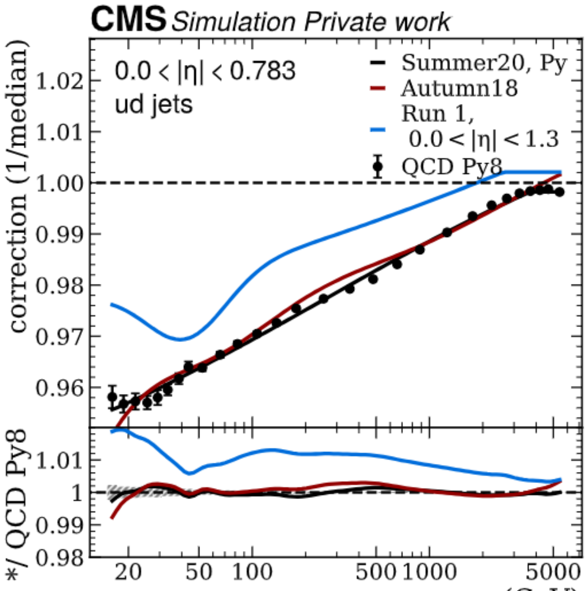
Large differences with Run 1 flavour corrections:

- Pythia 6 → Pythia 8,
- Physics definition → parton flavour,
- reduced statistical uncertainties



Up, down response → larger,

Gluon and bottom response → lower than QCD mix



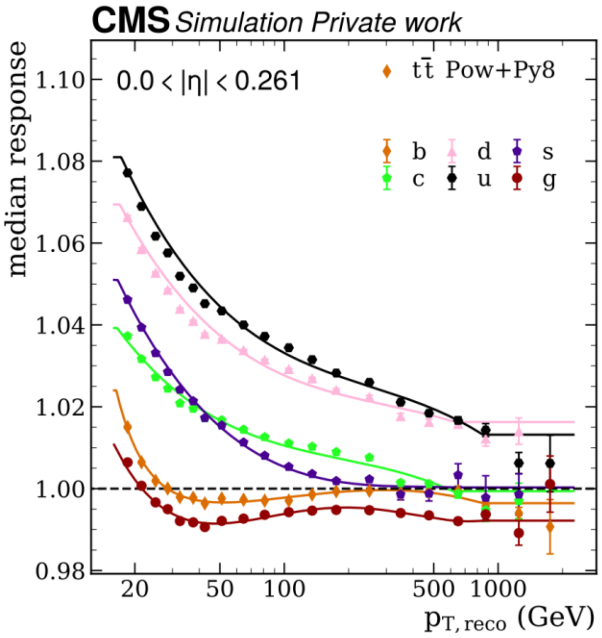
Work described in AN-23-074

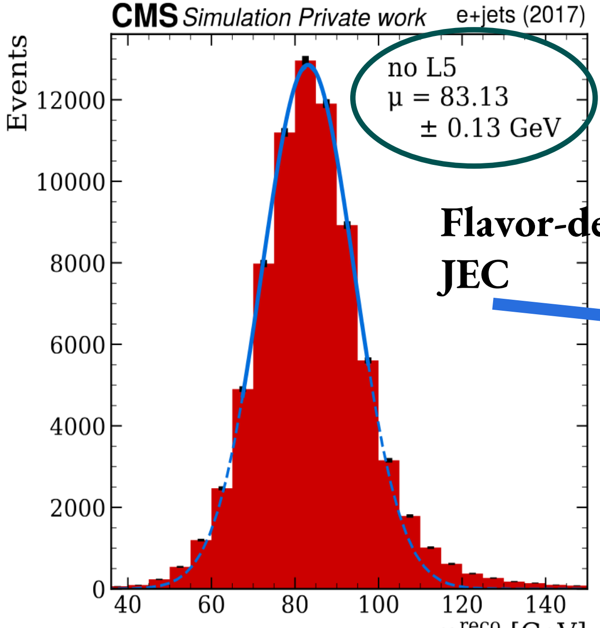
Flavour-dependent jet energy corrections

Flavour-dependent corrections applied on both MC and data

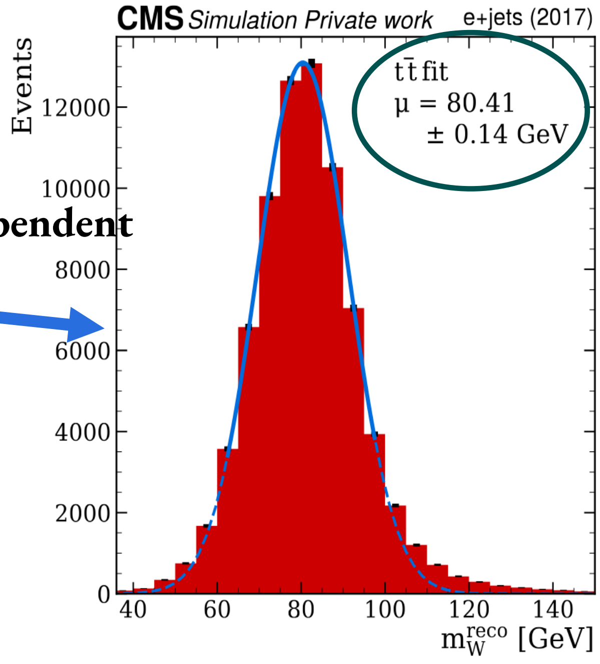
- b correction on b jets
- light correction on light jets

Light-flavor correction brings the W peak lower to 80.4 GeV





Flavor-dependent JEC

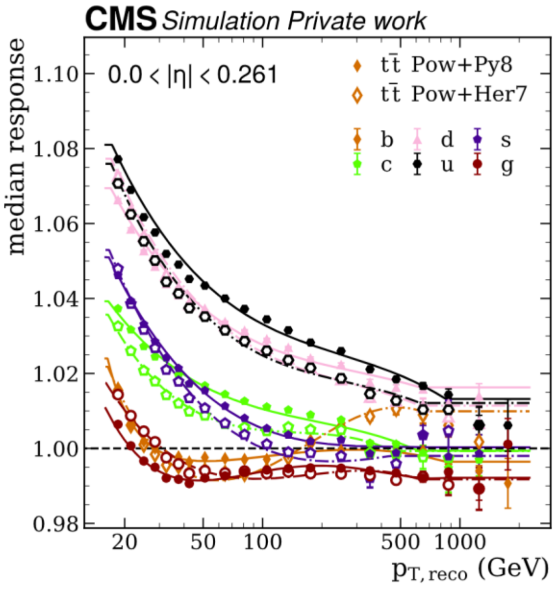


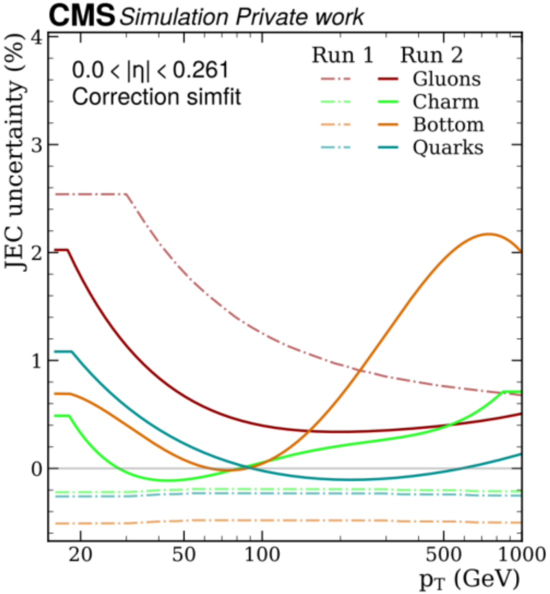
Work described in [AN-23-074]

Flavour uncertainties

- Flavour uncertainty estimates the jet response mismodelling for different flavours
- Obtained from Pythia 8 - Herwig 7 and normalized to the reference point of the global fit (Z+Jets mix at 200GeV and $\eta = 0$ should have a 0 uncertainty)

Work described in [AN-23-074]





- Gluon uncertainty decreased more than twice since Run 1; quark uncertainty slightly increased
- Bottom: in Run1 was fit with a straight line due to large stat. uncertainties. In Run2: shows a large bump at $p_T > 200$ GeV. Possibly due to b hadron lifetime mismodelling in Herwig 7

Flavor-antiflavor uncertainties

Work described in [AN-23-074]

Flavor-antiflavor uncertainty obtained using a similar principle as for the flavor uncertainty: comparison of the predictions by Herwig7 and Pythia8

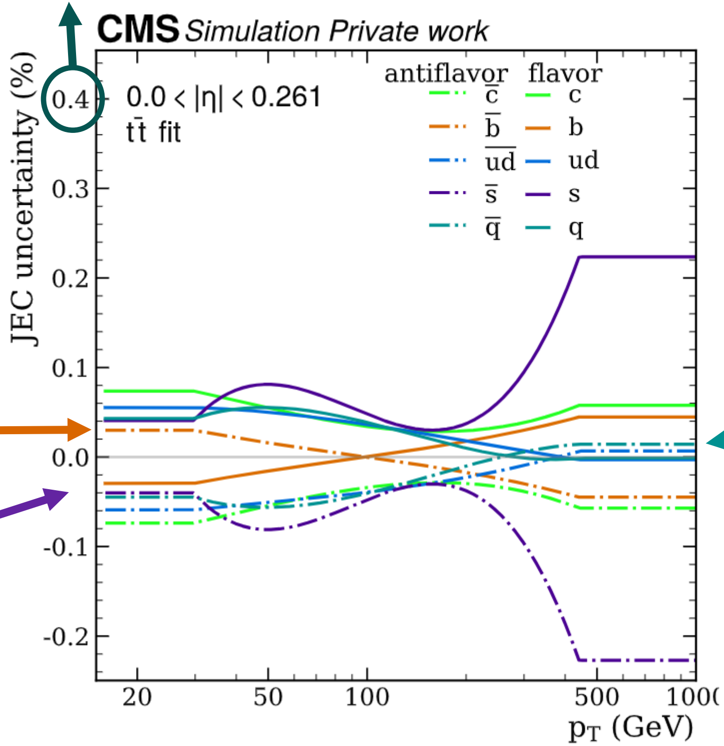
In Run 1: full b vs $\bar{b}$ in Pythia was taken as uncertainty
⇒ 0.078 % constant shift

b vs $\bar{b}$ uncertainty is small:
Her7 and Py8 predict b vs $\bar{b}$ response similarly

Large s vs $\bar{s}$ uncertainty:

Her7 and Py8 predict it differently

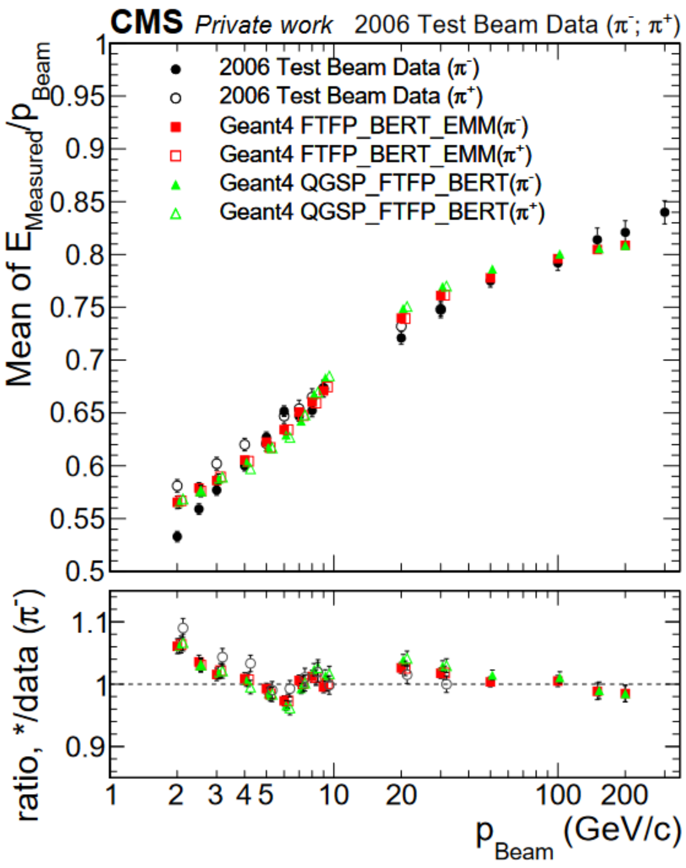
O(10) smaller than flavor uncertainties



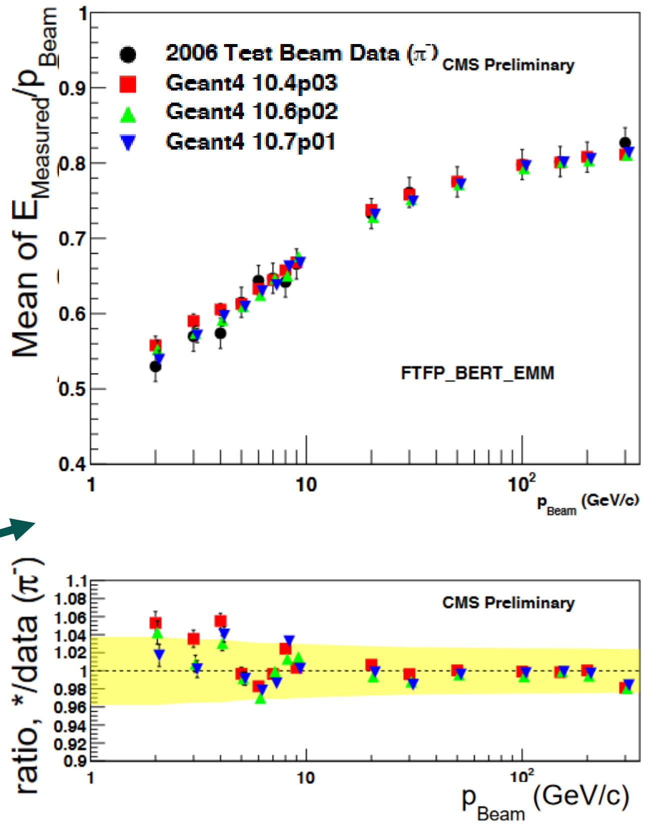
Slightly asymmetric for q vs $\bar{q}$ due to more q jets than $\bar{q}$ jets in pp collisions

Correction of pion response mismodelling

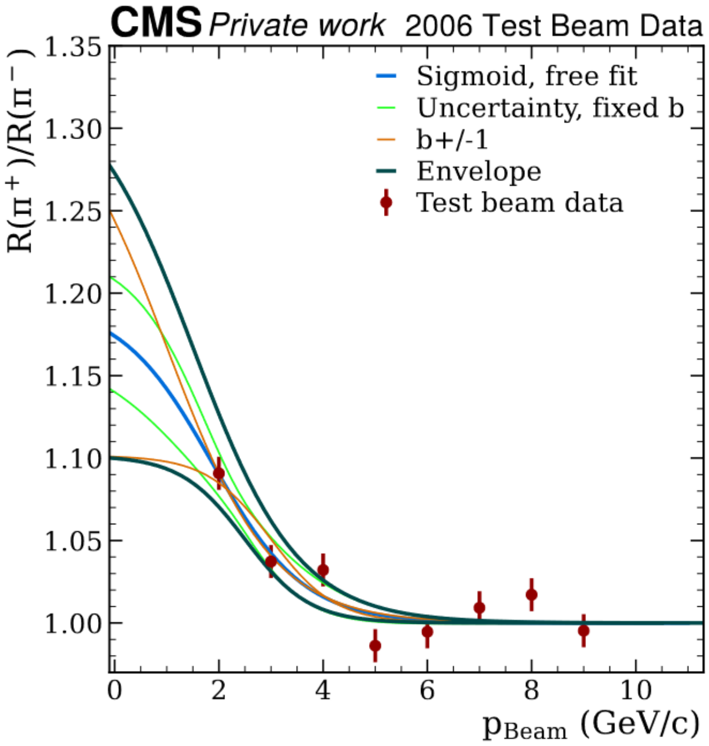
See, EPJ CONF 251, 03010 (2021)



- GEANT4 describes the π^+ response in HCAL test beam data well
- No physics list describes the π^- response well ⇒ additional uncertainty on the mismodelling of π^- response
- GEANT 4 v10.4p03 used: default in CMSSW106X
- Results differ for other GEANT 4 version



Correction of pion response mismodelling



- Ratio was fit with a sigmoid function.

$$y = 1 - a + \frac{a}{1 + \exp(-c \cdot (x - b))}$$

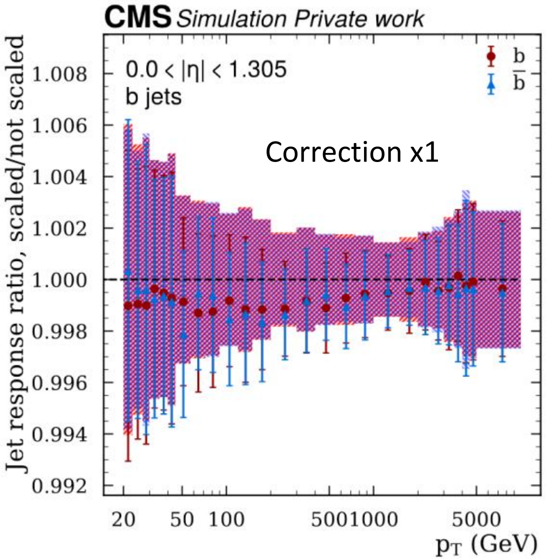
- Correction was taken as the highest envelope.
  Correction was applied to π^-: the response was in the MC to match data.
  It was propagated trough the particle flow code.
- Differences in response when a new neutral particle is created/removed.

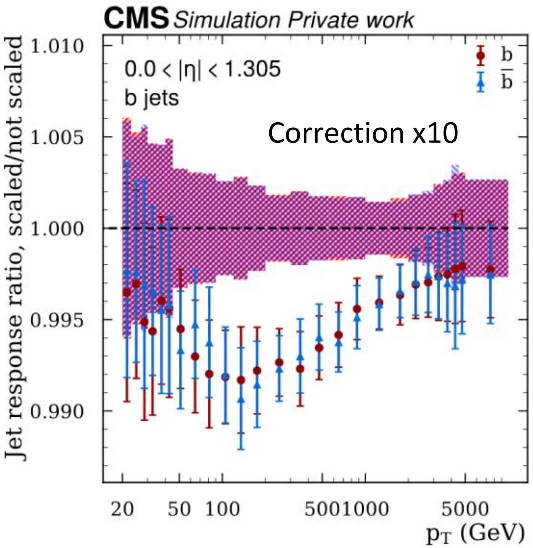
q vs qbar from pi+ correction

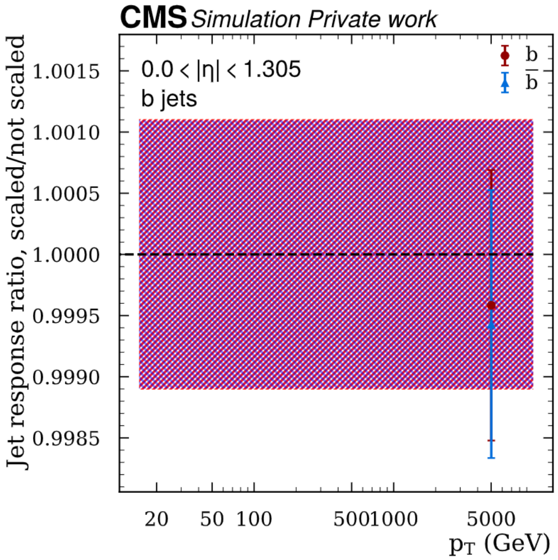
- An O(0.1%) effect on the jet response, but similar on b and $\bar{b}$

- Statistical uncertainty is large (only 2M events used)
- The correlation was 1.000 (correction applied on the same GEN-SIM events)
  ⇒ only the central values taken as the uncertainty

Uncertainty taken in 4 η bins, inclusively in p_T as the difference between the central values

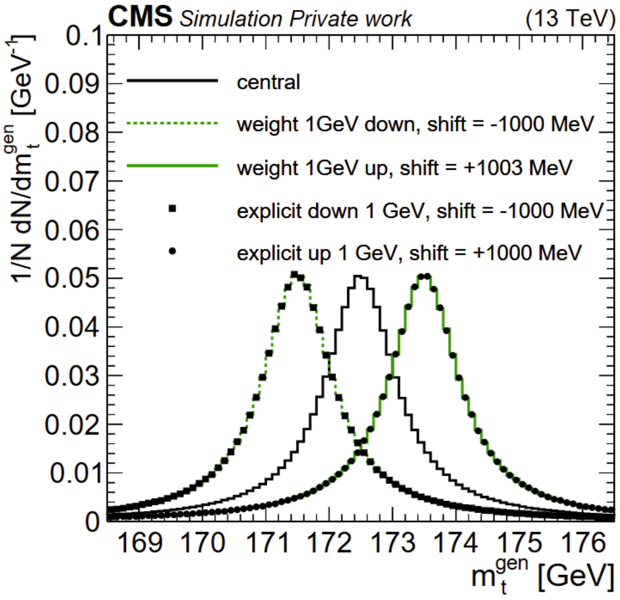


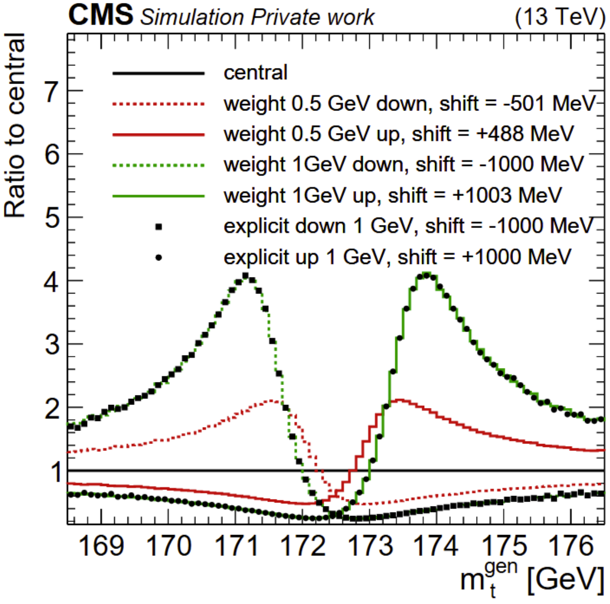




Reweighting events to create $\Delta m_t > 0$ in MC

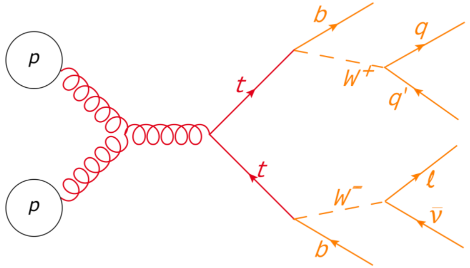
- Δm_t difference in the signal MC is obtained using reweighting, applying weight proportional to $\frac{BW(m_{t,new})}{BW(m_{t,old})}$
- Breit-Wigner (BW) distribution $BW(m_t) = \frac{k}{(E^2 - m^2) + m^2\Gamma^2}$
- m_t^{gen} distribution reweighted to $\Delta m_t = 2$ GeV agrees with the distributions for MC samples generated with $m_t = 171.5$ GeV and $m_t = 173.5$ GeV
- For profiled likelihood we use $\Delta m_t = 400$ MeV: covers the uncertainties of the previous measurement



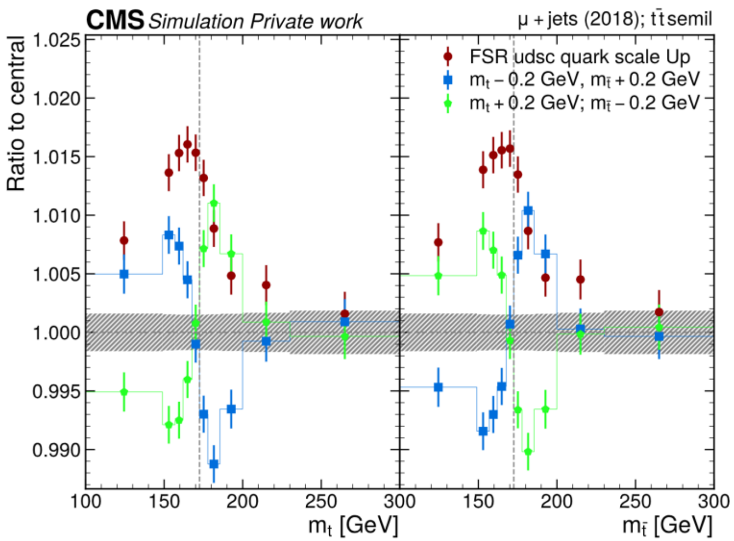


Preparations for a profile-likelihood fit in combine

Events are split into 10 bins of equal number of events and then split into t and $\bar{t}$ according to the lepton charge, q: (m_t^{fit}, q) distribution

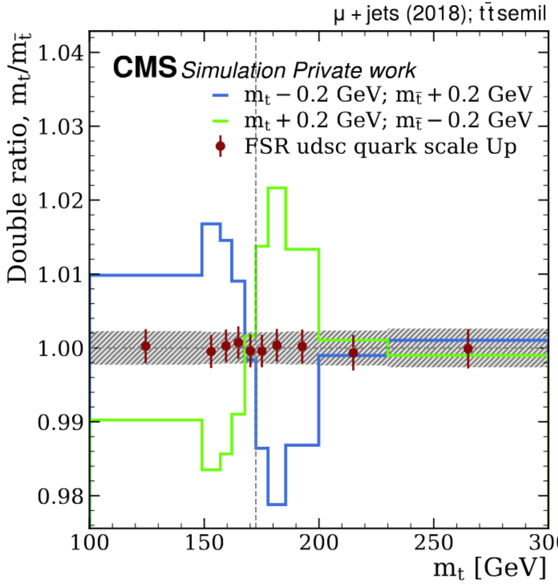


Impact of light-quark FSR: large but correlated for m_t and $m_{\bar{t}}$



Blue and green: effect of the $\Delta m_t = 400$ MeV reweighting up and down

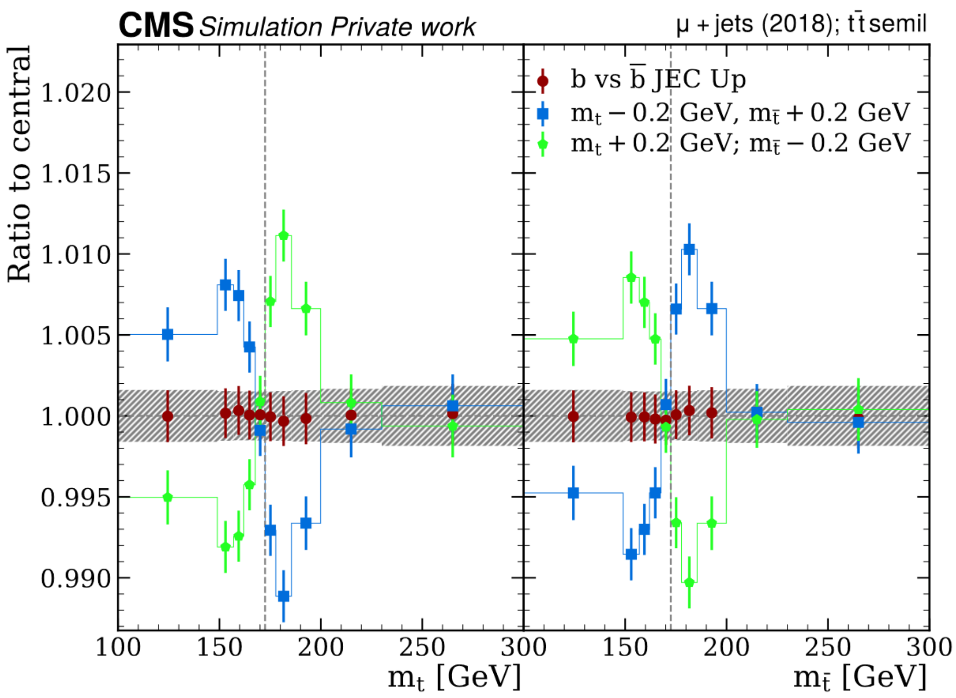
Dividing m_t^{reco} over $m_{\bar{t}}^{reco}$, the variation mostly cancels out

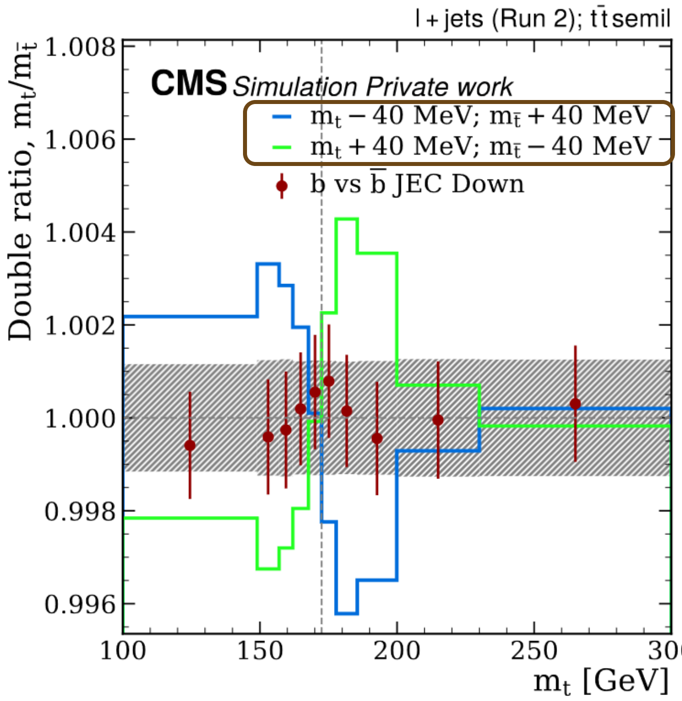


c vs cbar/ q vs qbar jet JEC

Effect of b vs $\bar{b}$ variation: very small (due to the uncertainty crossing 0), but in the opposite directions for m_t and $m_{\bar{t}}$. The double ratio shows an effect on m_t.

Note: here Δm_t reweighting is scaled by 1/5 for visibility





Systematic uncertainties (experimental)

The recommendations under the TOP PAG are used
https://twiki.cern.ch/twiki/bin/viewauth/CMS/TopSystematics

- Jet energy scale uncertainty
- Jet energy resolution
- Jet flavour uncertainty: from Run 2 MC
- Missing transverse momentum
- b-tagging scale factors
- Pileup
- Electron and muon scales factors
- L1 ECAL and muon prefiring
- Luminosity
- Cross-section uncertainty

Additionally

- Jet flavour-antiflavour uncertainty:
  - Pythia vs Herwig from flavor uncertainty machinery
  - π^+/π^- response mismodelling seen in HCAL test beam

Systematic uncertainties (modelling)

The recommendations under the TOP PAG are used
https://twiki.cern.ch/twiki/bin/viewauth/CMS/TopSystematics

Applied as weights:

- PDF variations
- QCD scale variations:
  - Matrix element variaitons
  - ISR variations
  - FSR variation for each splitting (16 variations)
- b jet fragmentation
- Semileptonic branching ratio of the b hadron decays
- Top p_t mismodelling

Obtained from additional samples:

- Matrix element to parton shower scale (ME-PS scale = hdamp)
- CP5 tune (UE tune)
- Colour reconnection (CR) and early resonance decays on (ERD on)

Expected and observed uncertainties

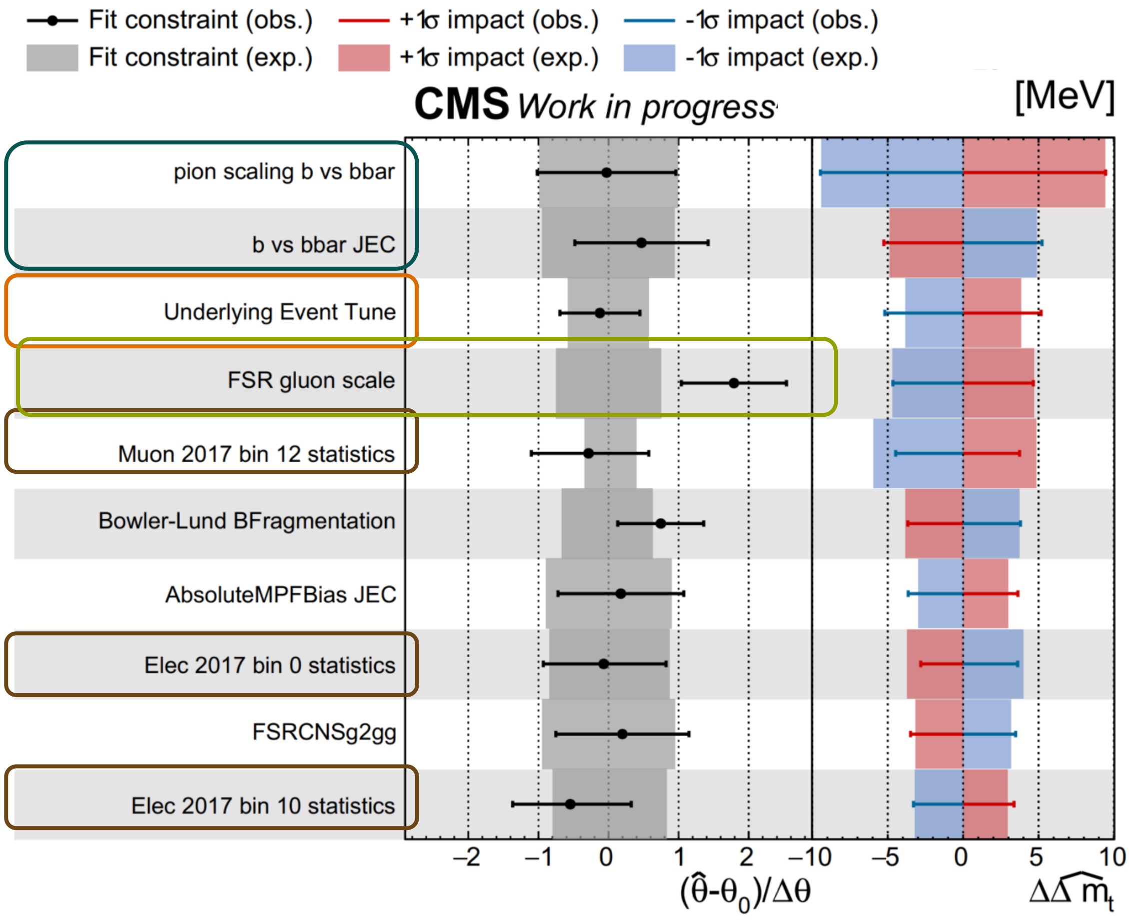
Result from the $(m_t, \Delta m_t)$ fit

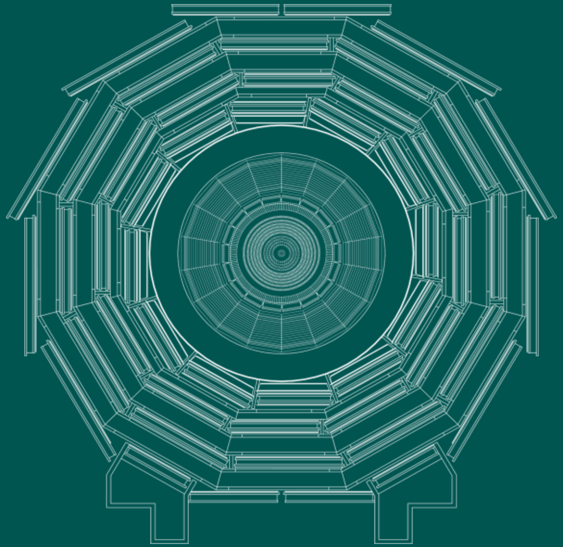
The flavour-antiflavour uncertainties among the leading.

Large statistical uncertainties. The analysis is still statistics limited (± 62 MeV)

Large uncertainties due to the large statistical uncertainties in the variation datasets

Large pull for the final state radiation (FSR) consistent with the m_t measurement



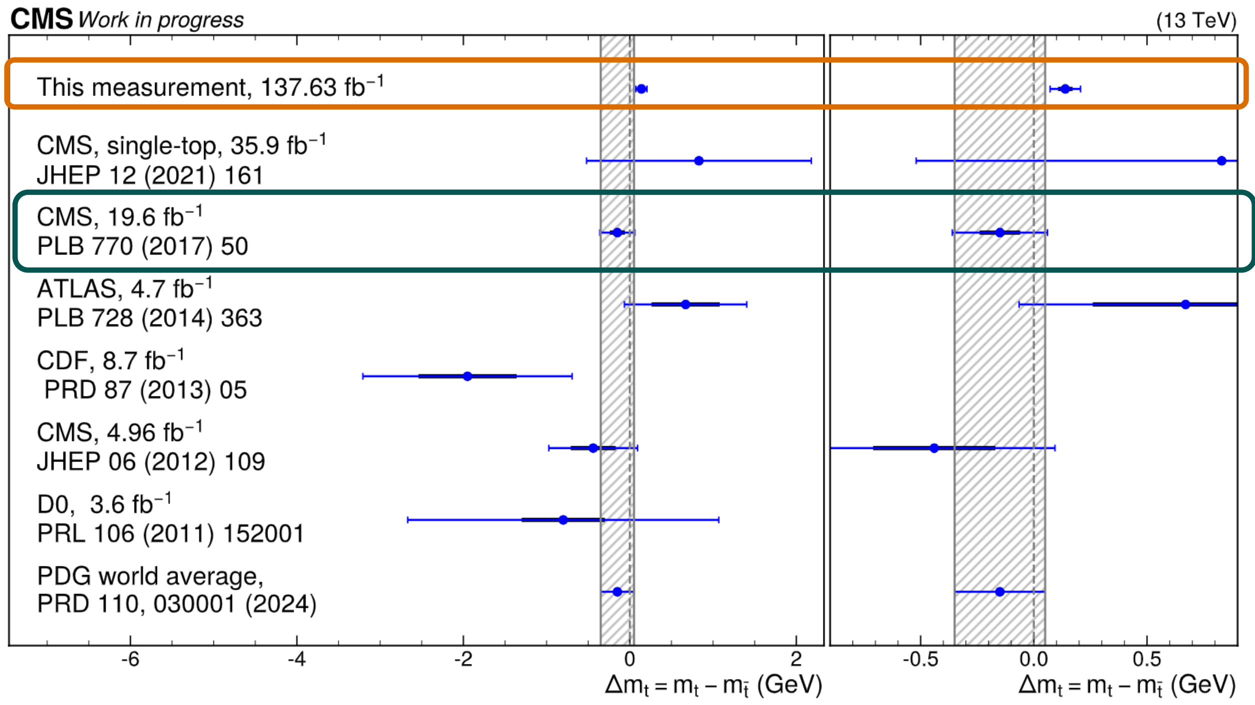


The result

Result

The result of the profile likelihood fit provided
$\Delta m_t = 139 \pm 25\ (syst.) \pm 62(stat.)$ MeV $= 139 \pm 67$ MeV

- 2.1 standard deviation disagreement from $\Delta m_t = 0$, but not significant to claim an evidence for New Physics
- Statistical uncertainty **190 MeV** → **62 MeV** with respect to the Run 1 measurement
- Systematic uncertainty **90 MeV** → **25 MeV**



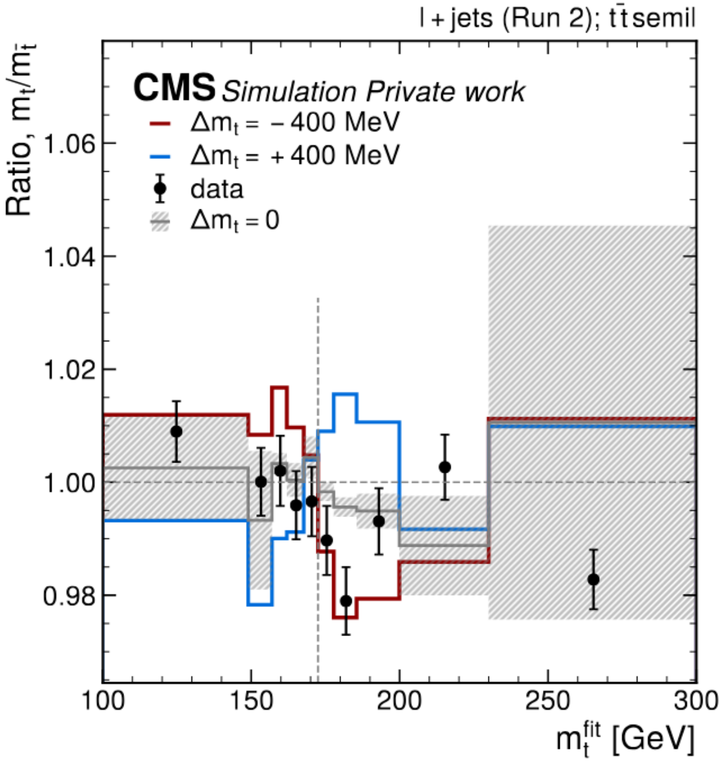
Summary

- Competitive measurement of Δm_t:
  - Statistical uncertainty reduced from 190 MeV to 59 MeV with respect to the Run 1 measurement.
  - Systematic uncertainty reduced from 90 MeV to 36 MeV.
- Estimated quark vs antiquark jet response uncertainty using
  - Pythia vs Herwig from flavor uncertainty machinery
  - π^+/π^- response mismodelling seen in HCAL test beam

Backup

Ratio of m_t^{fit} for l^- and l^+

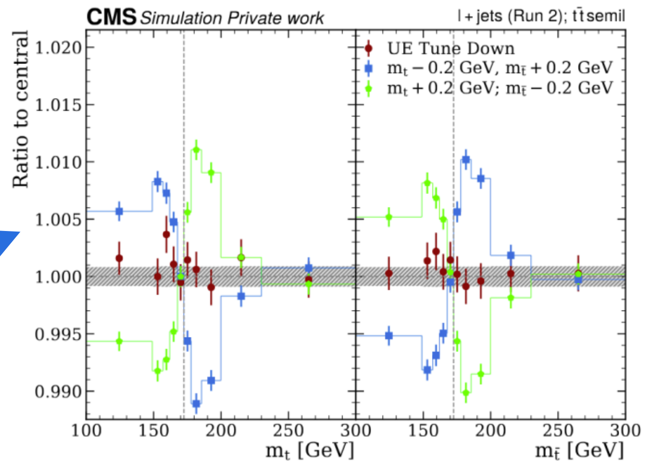
- Slight asymmetry: mostly due to backgrounds
- Some data points are more aligned with $\Delta m_t = +400$ MeV and some with $\Delta m_t = -400$ MeV



Preparation of the systematic uncertainties

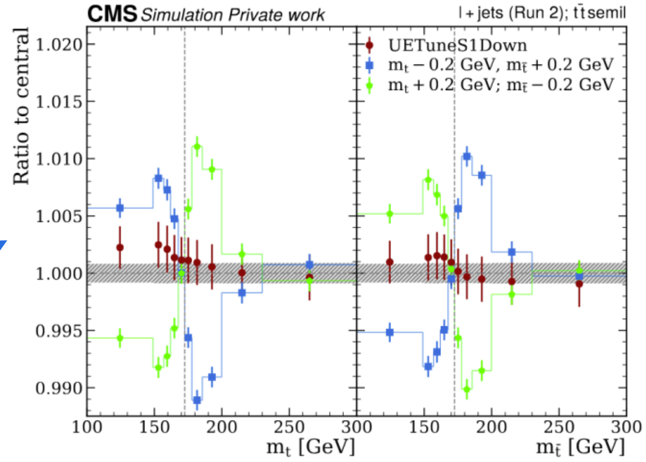
- All the variations are symmetrized around the central.
- Effectively doubles the number of events
- Most important for UE tune

Only symmetrized



- Variations obtained from separate MC samples are smoothed assuming a physical effect should be continuous.
- 353QH method used within TH1F.Smooth is used.

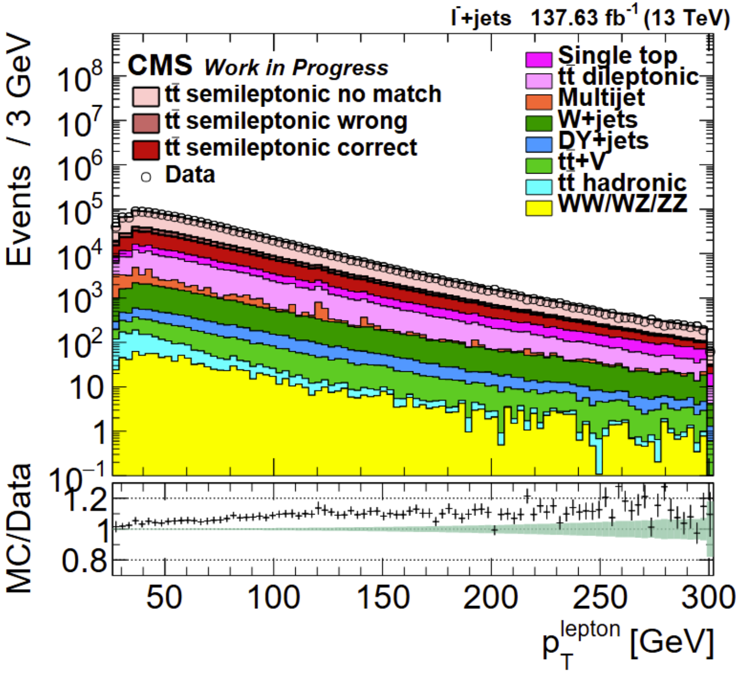
Symmetrized and smoothed



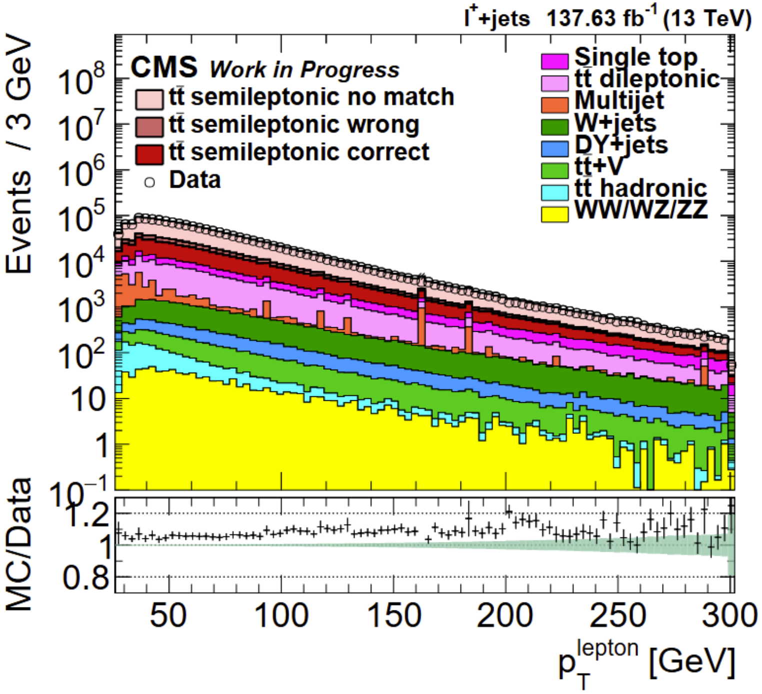
Control plots, split in charge

Warning: MC variations not estimated in the control plots

Lepton transverse momentum, l^-



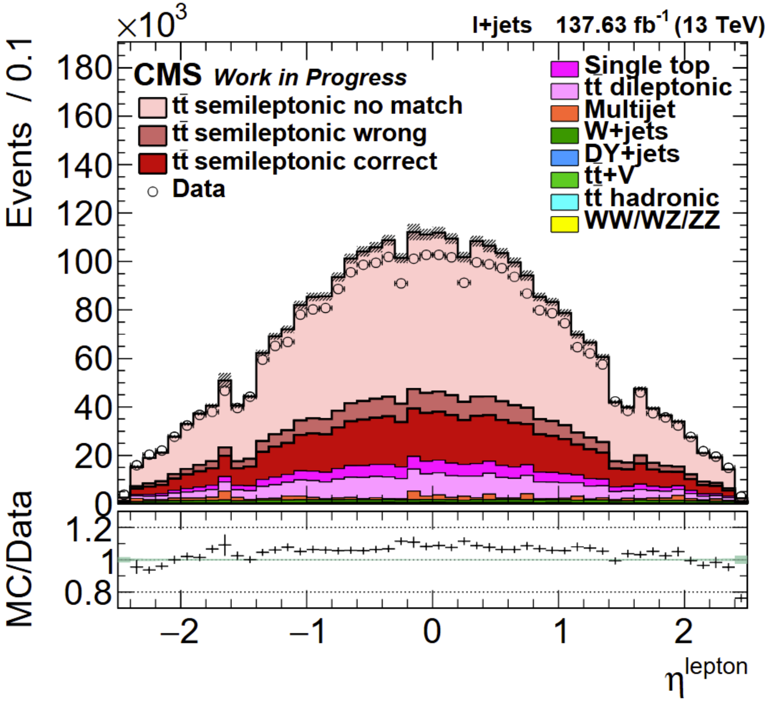
Lepton transverse momentum, l^+



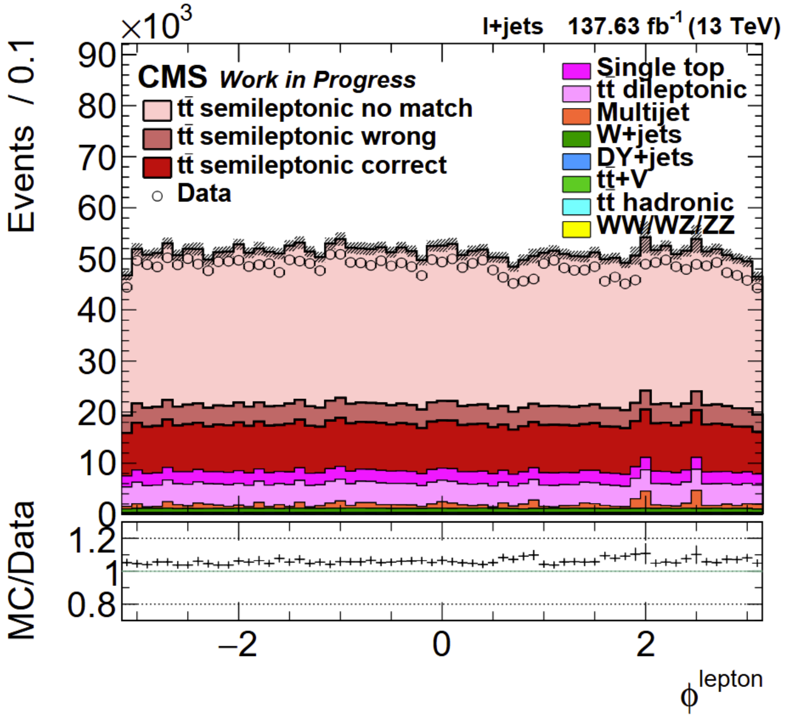
Control plots, lepton

Warning: MC variations not estimated in the control plots

Electron η



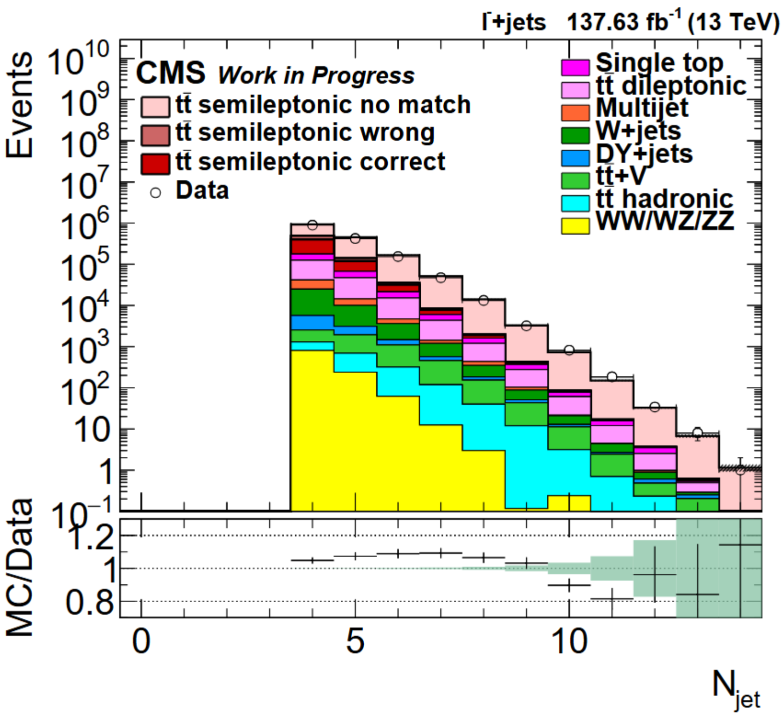
Electron ϕ



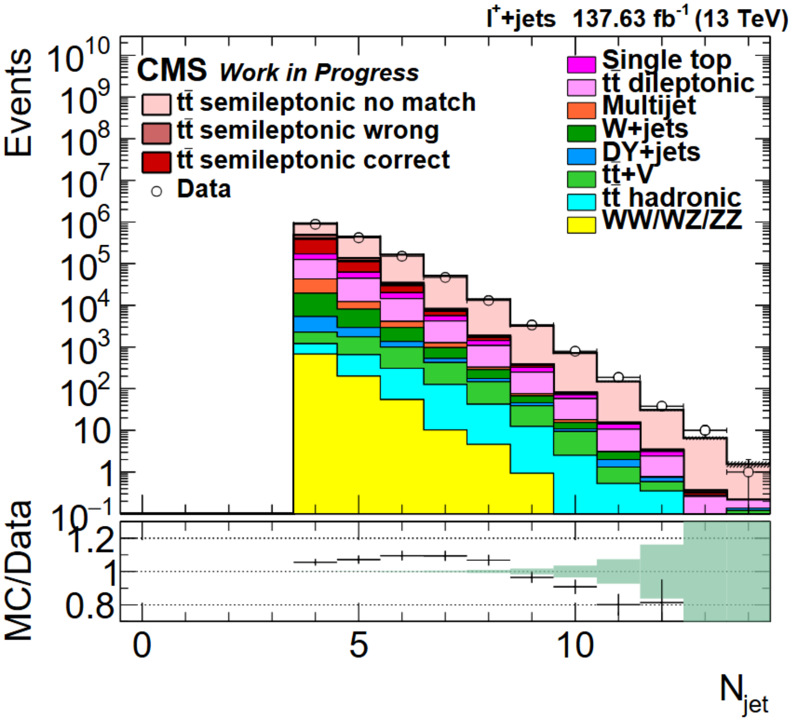
Control plots, split in charge

Warning: MC variations not estimated in the control plots

Number of jets, for l^-



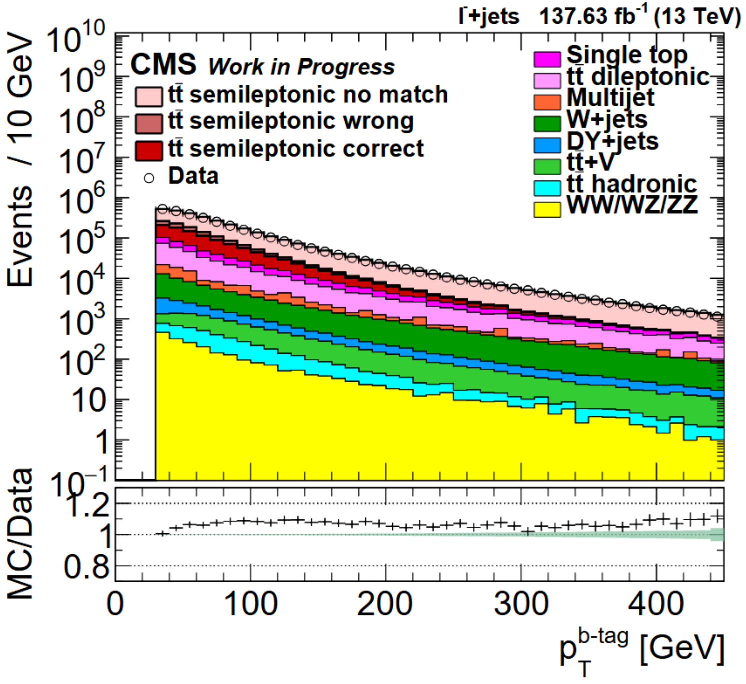
Number of jets, for l^+



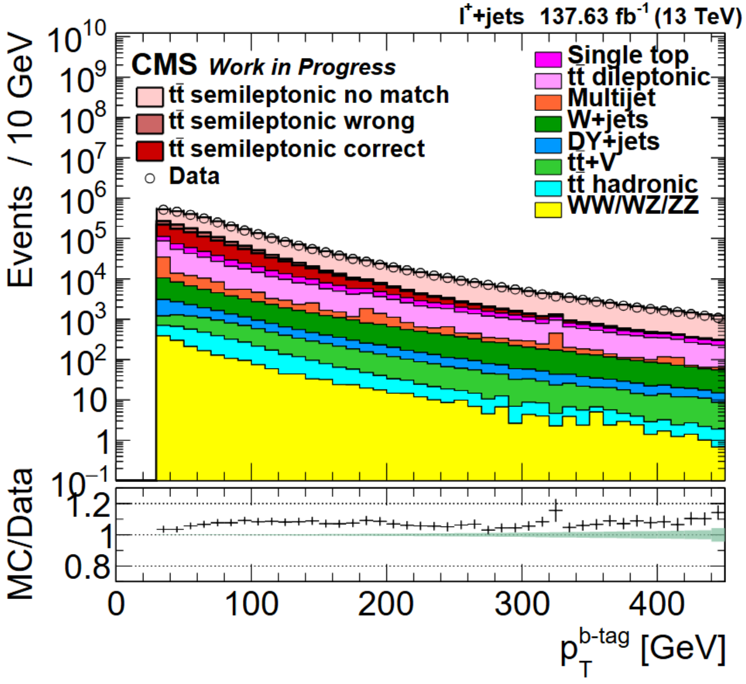
Control plots, split in charge

Warning: MC variations not estimated in the control plots

Transverse momentum of b-tagged jet, for l^-



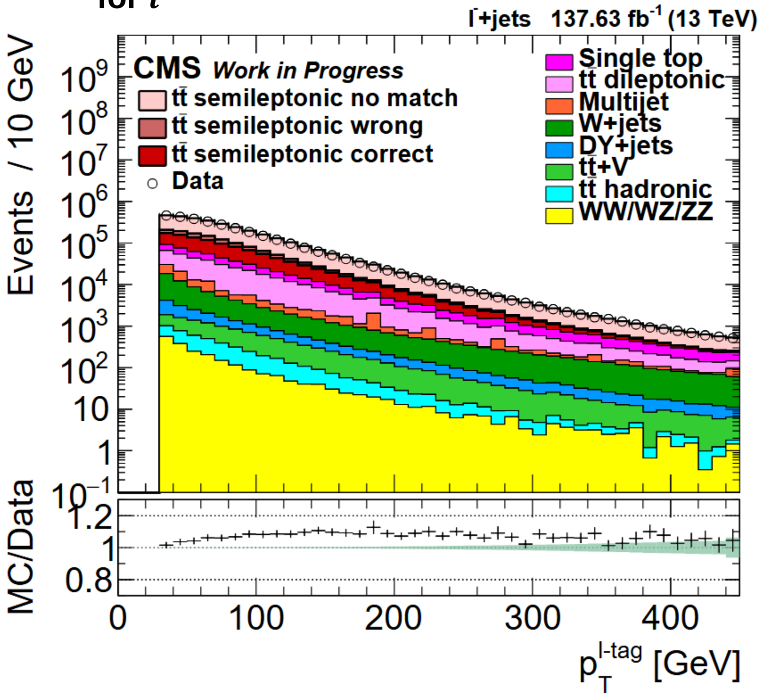
Transverse momentum of b-tagged jet, for l^+



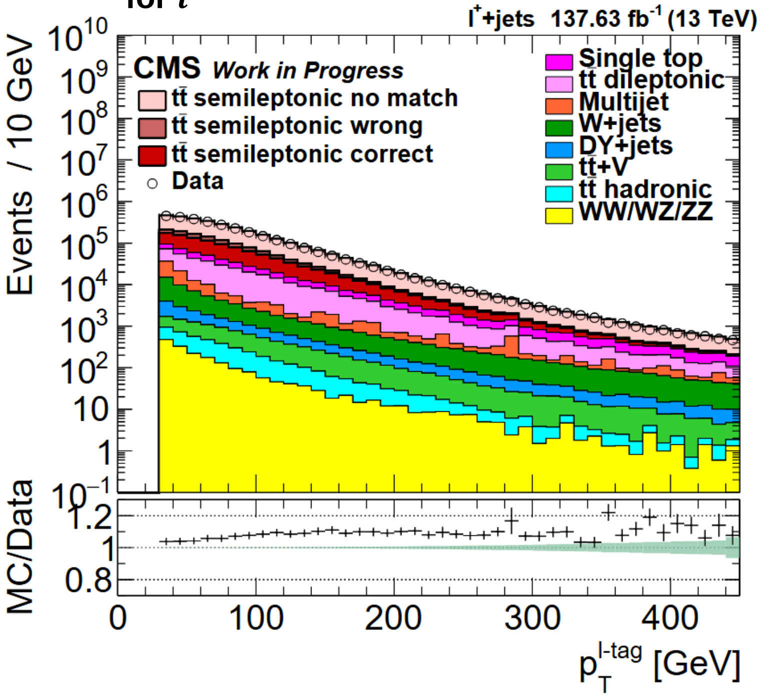
Control plots, split in charge

Warning: MC variations not estimated in the control plots

Transverse momentum of l-tagged jet, for l^-



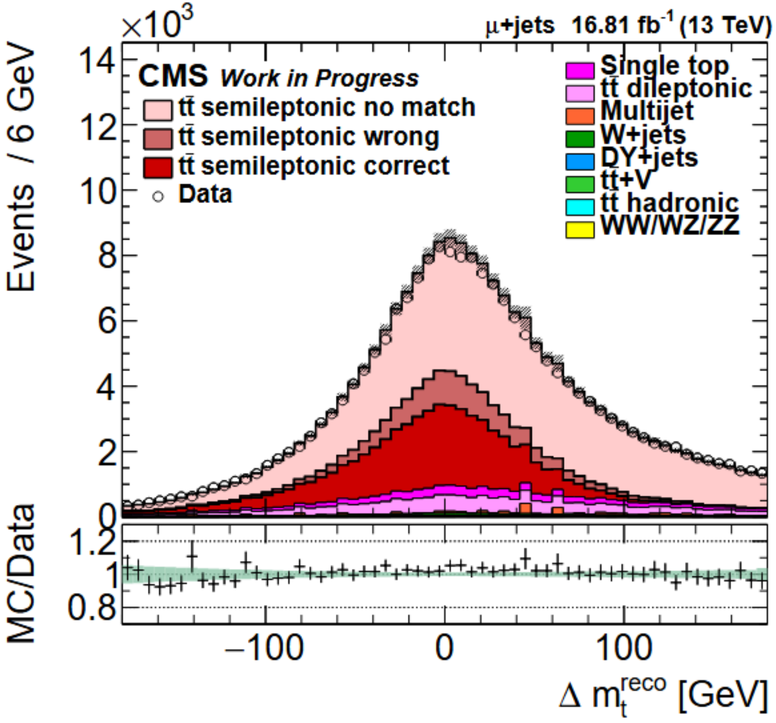
Transverse momentum of l-tagged jet, for l^+



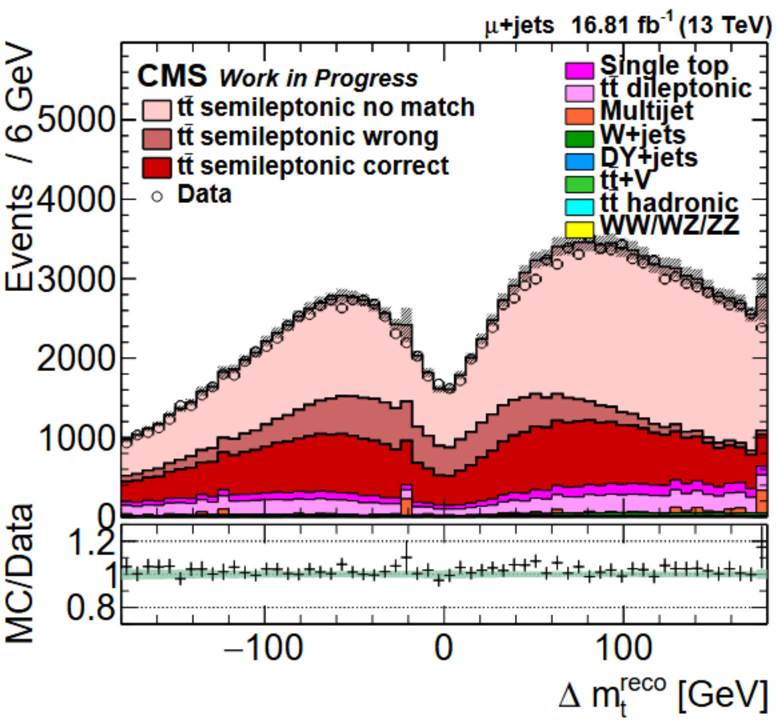
Control plots

Warning: MC variations not estimated in the control plots

$\Delta m_t^{reco} = m_{t,had}^{reco} - m_{t,lep}^{reco}$ **for the permutation with the smallest** Δm_t^{reco}



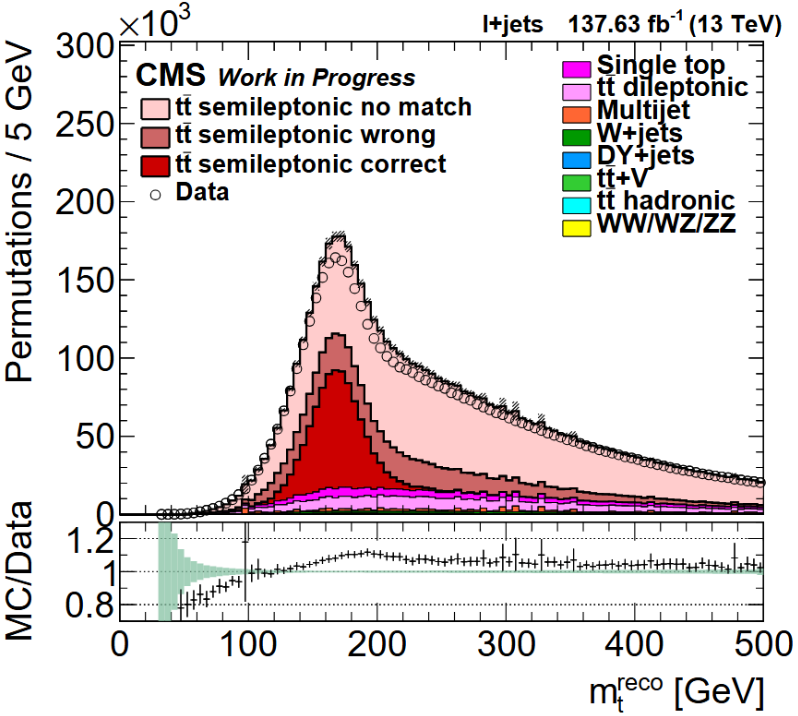
$\Delta m_t^{reco} = m_{t,had}^{reco} - m_{t,lep}^{reco}$ **for the permutation with the largest** Δm_t^{reco}



Control plots

Warning: MC variations not estimated in the control plots

Hadronic reconstructed top quark mass



Leptonic reconstructed top quark mass