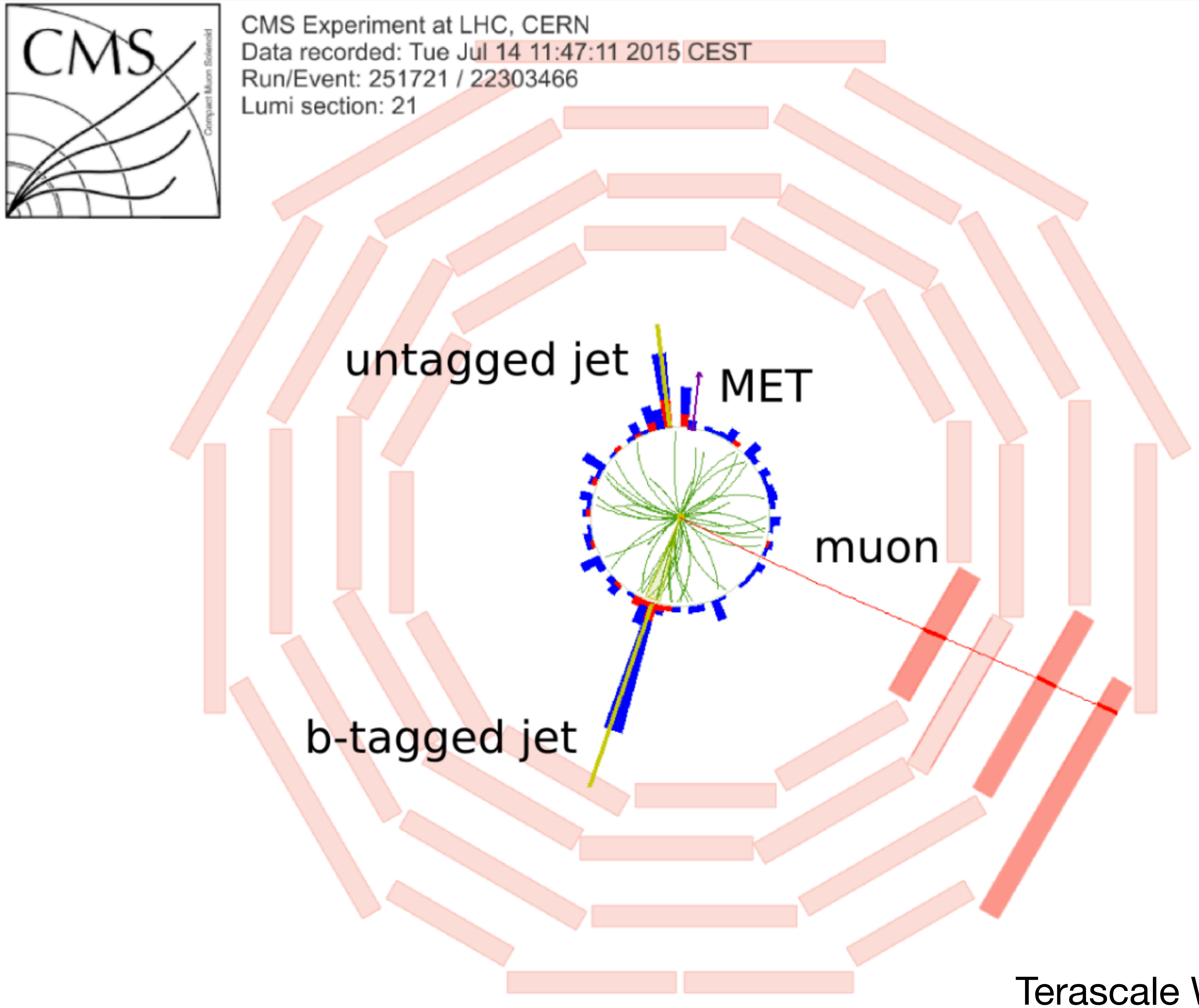
Top quark mass (m_t) measurement in single top events



CMS-TOP-19-009, arXiv:2108.10407

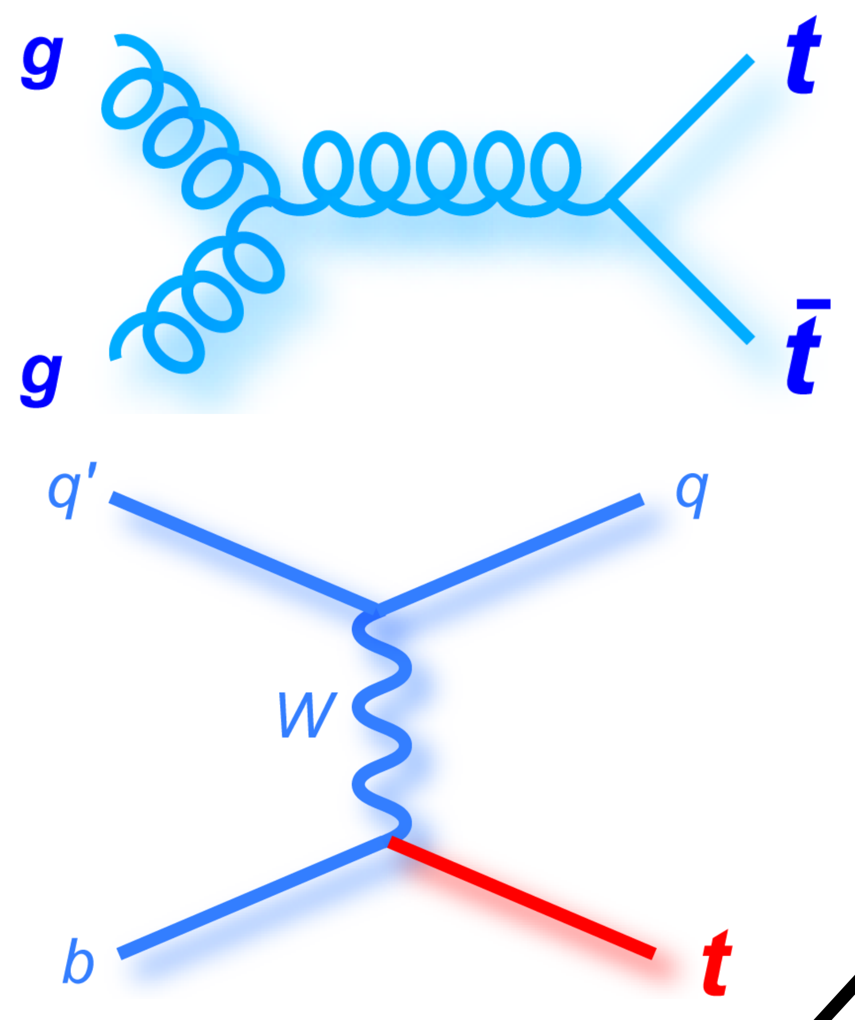
Submitted to JHEP

Soureek Mitra
On behalf of the CMS Collaboration

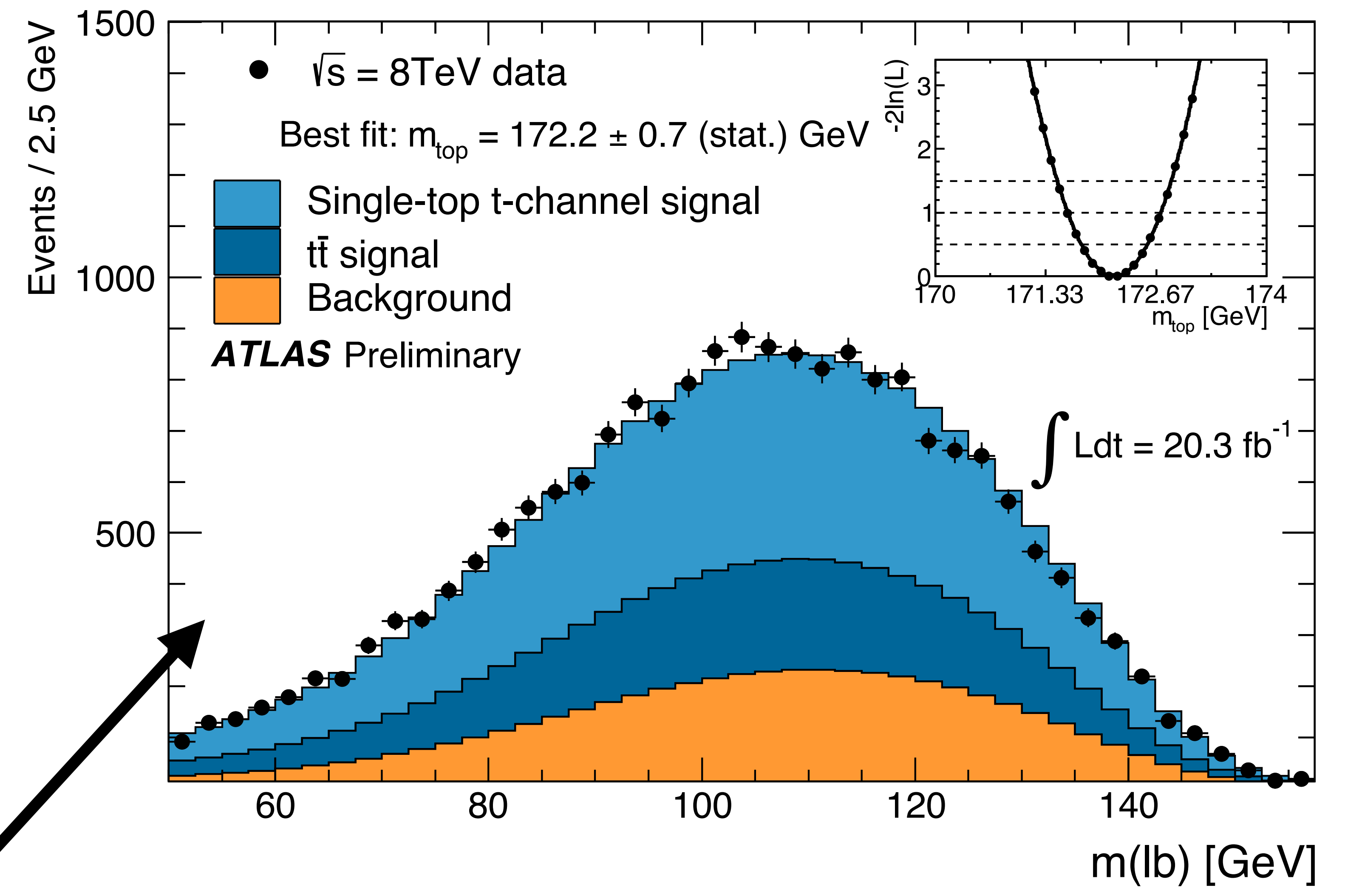
Terascale Workshop, 2021

Motivation

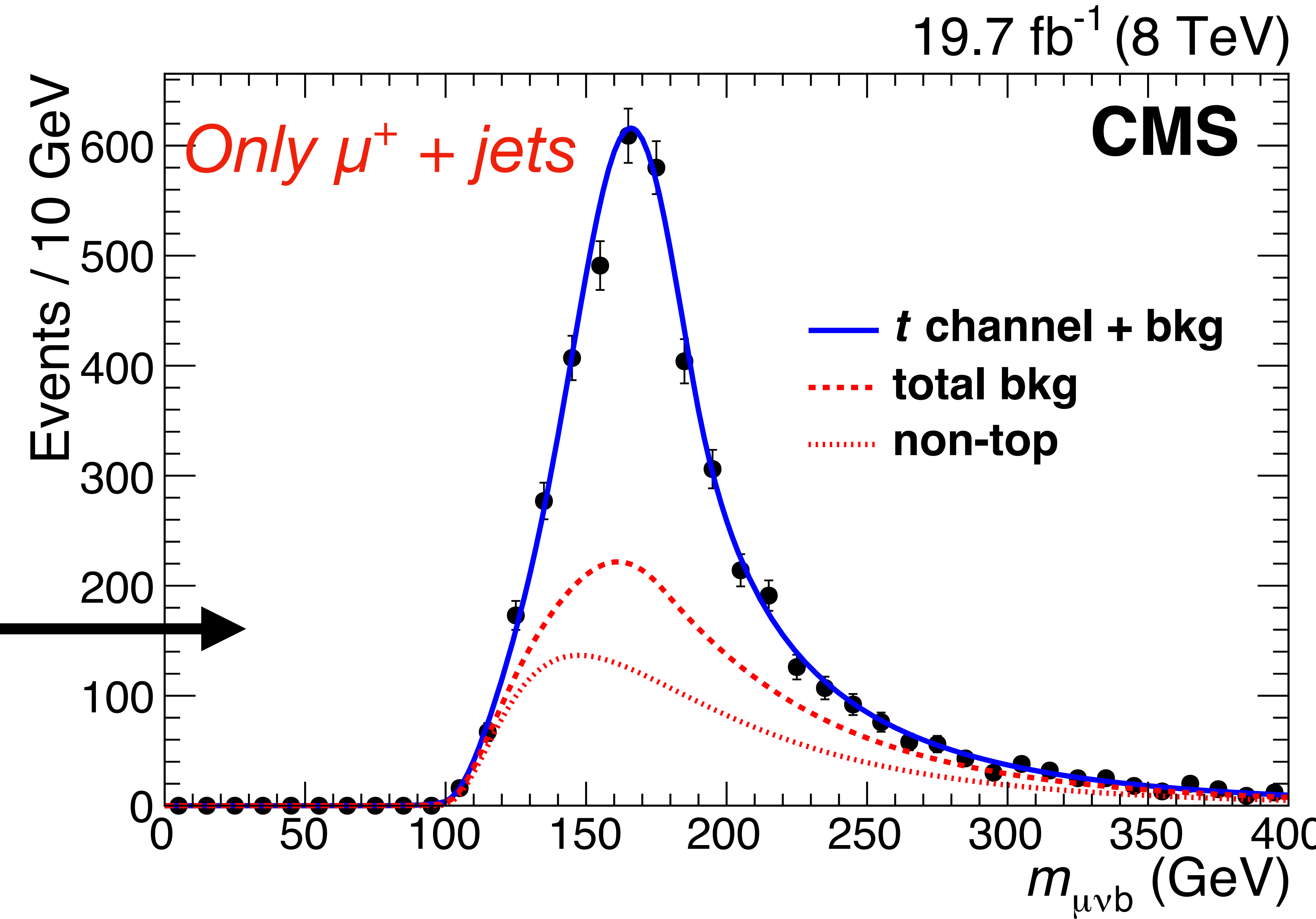
- Top quark mass (m_t) is an important parameter of SM
  - ➢ Largest contributor to the radiative corrections to m_W and λ_H among SM particles ⇒ stability of EW vacuum
- $\Delta m_t = m_t - m_{\bar{t}}$ ➢ test of *CPT* invariance ⇒ *Lorentz symmetry* (PRL 89:231602,2002)
- Measurement in single top provides
  - ➢ meas. in an independent process (*EWK* production)
  - ➢ lower Q^2 (∈ [170, 340] GeV) scale than $t\bar{t}$ (> 340 GeV)
  - ➢ partially uncorrelated syst. from $t\bar{t}$ measurements



- ATLAS@8TeV (ATLAS-CONF-2014-055) :
  - ➢ Measurement: $m_t = 172.2 \pm 0.7\,(\mathrm{stat.}) \pm 2.0\,(\mathrm{syst.})\,\mathrm{GeV} = 172.2 \pm 2.1\,\mathrm{GeV}$
  - ➢ Dominant Unc.: JES (± 1.5 GeV) , t − ch . Had . modeling (± 0.7 GeV)



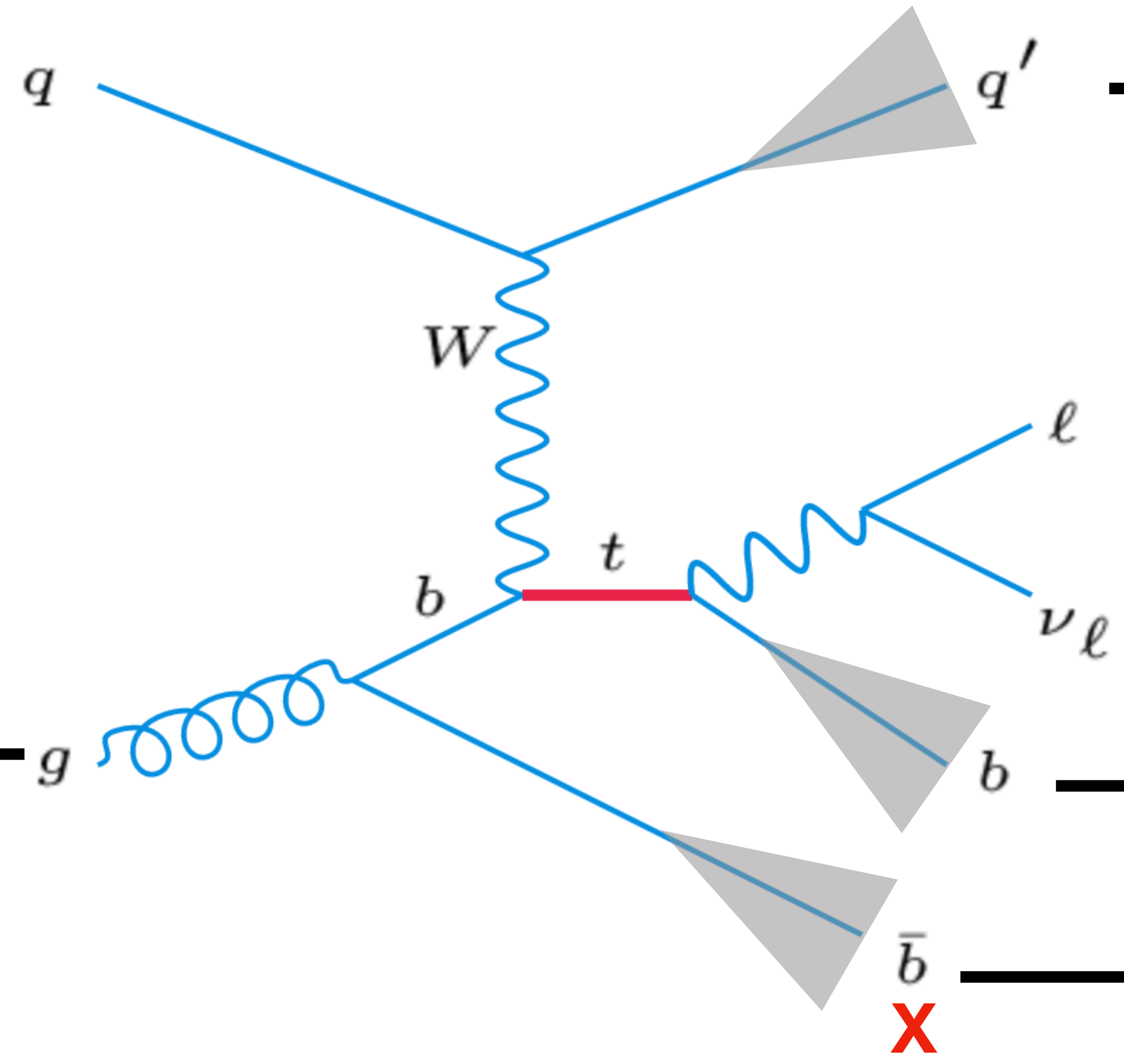
- CMS@8TeV (EPJC 77 (2017) 354) :
  - ➢ Measurement: $m_t = 172.95 \pm 0.77\,(\mathrm{stat.})\,^{+0.97}_{-0.93}(\mathrm{syst.})\,\mathrm{GeV} = 172.95^{+1.24}_{-1.21}\,\mathrm{GeV}$
  - ➢ Dominant Unc.: JES ($^{+0.68}_{-0.61}$ GeV) , Fit Calibration (± 0.39 GeV)



Event Topology and Dominant bkgs.

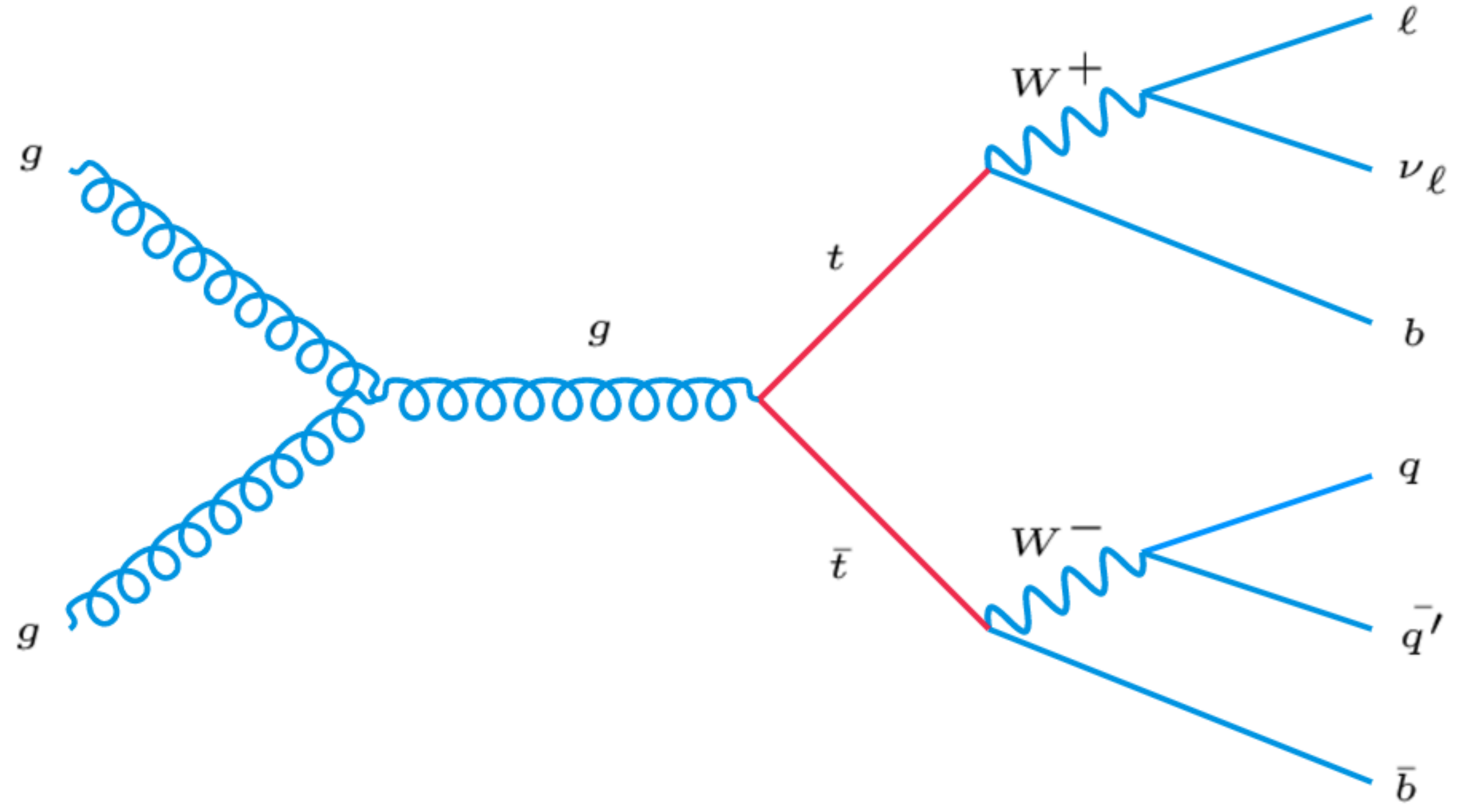
$t-\mathrm{ch}:\sigma(13\,\mathrm{TeV})=217.0^{+9.1}_{-7.7}\,\mathrm{pb}$

2-jets-1-tagged (2J1T)

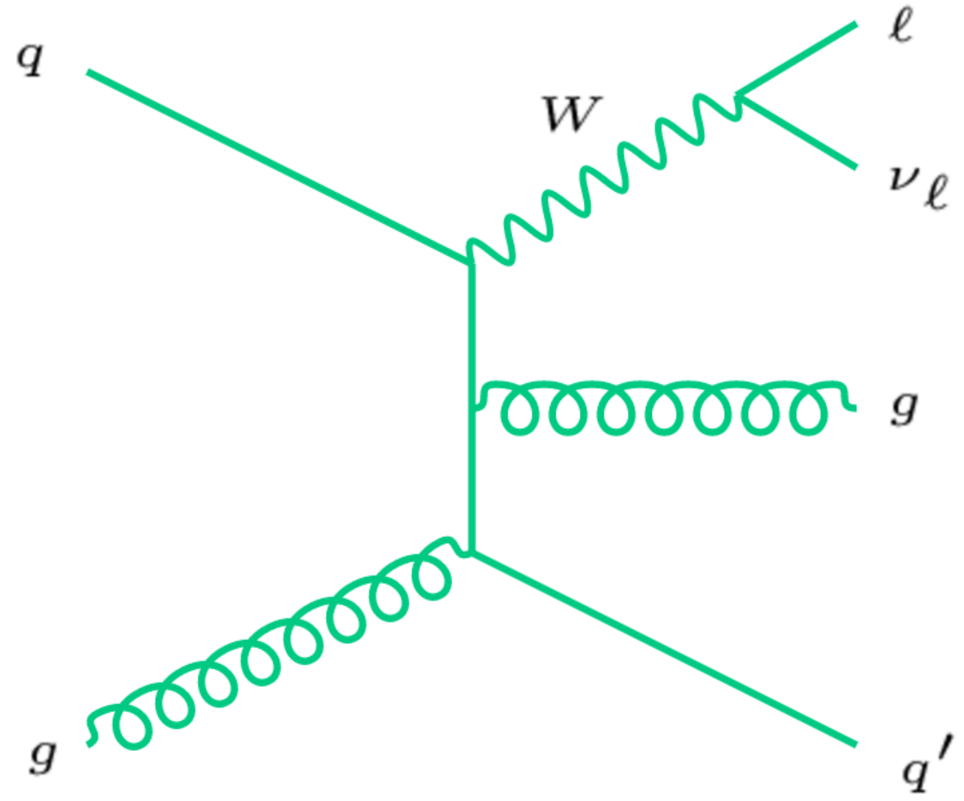


- Spectator light-flavor jet with $p_T > 40$ GeV and $|\eta| < 4.7$
- Exactly 1 isolated high-p_T (> 26 [35] GeV) μ [e] ; $|\eta| < 2.4$ (2.1)
- Missing p_T
- High-p_T (> 40 GeV), central ($|\eta| < 2.4$) b-jet (tight-tagged)
- 2nd b-jet: mostly out of tracker acceptance or has very low p_T

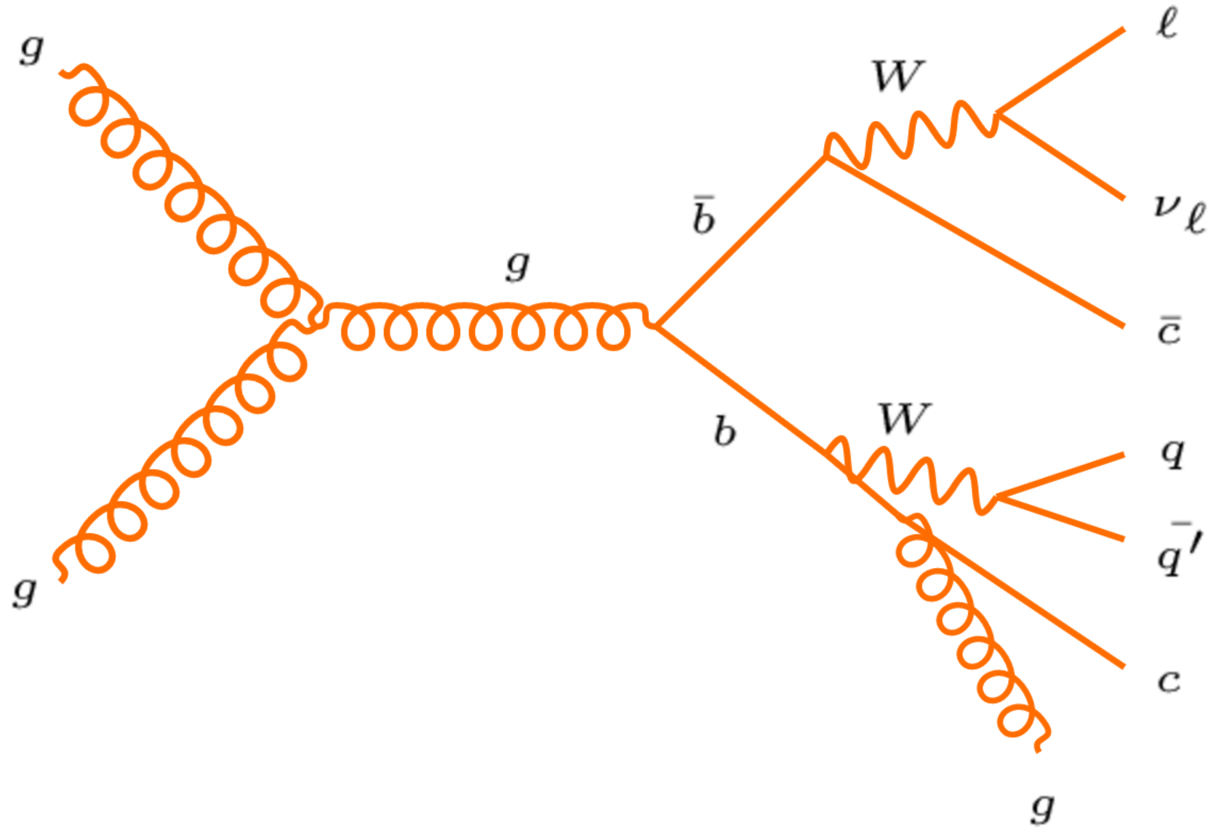
No b-quark at initial state (4FS ME)



$\mathrm{t\bar{t}}:\sigma(13\,\mathrm{TeV})\approx 832\,\mathrm{pb}$



$W+\mathrm{jets}:\sigma(13\,\mathrm{TeV})\approx 6\times10^{4}\,\mathrm{pb}$



QCD multijets (heavy flavor) : $\sigma(13\,\mathrm{TeV})\approx 10^{6}\,\mathrm{pb}$

Estimation of QCD multijet bkg.

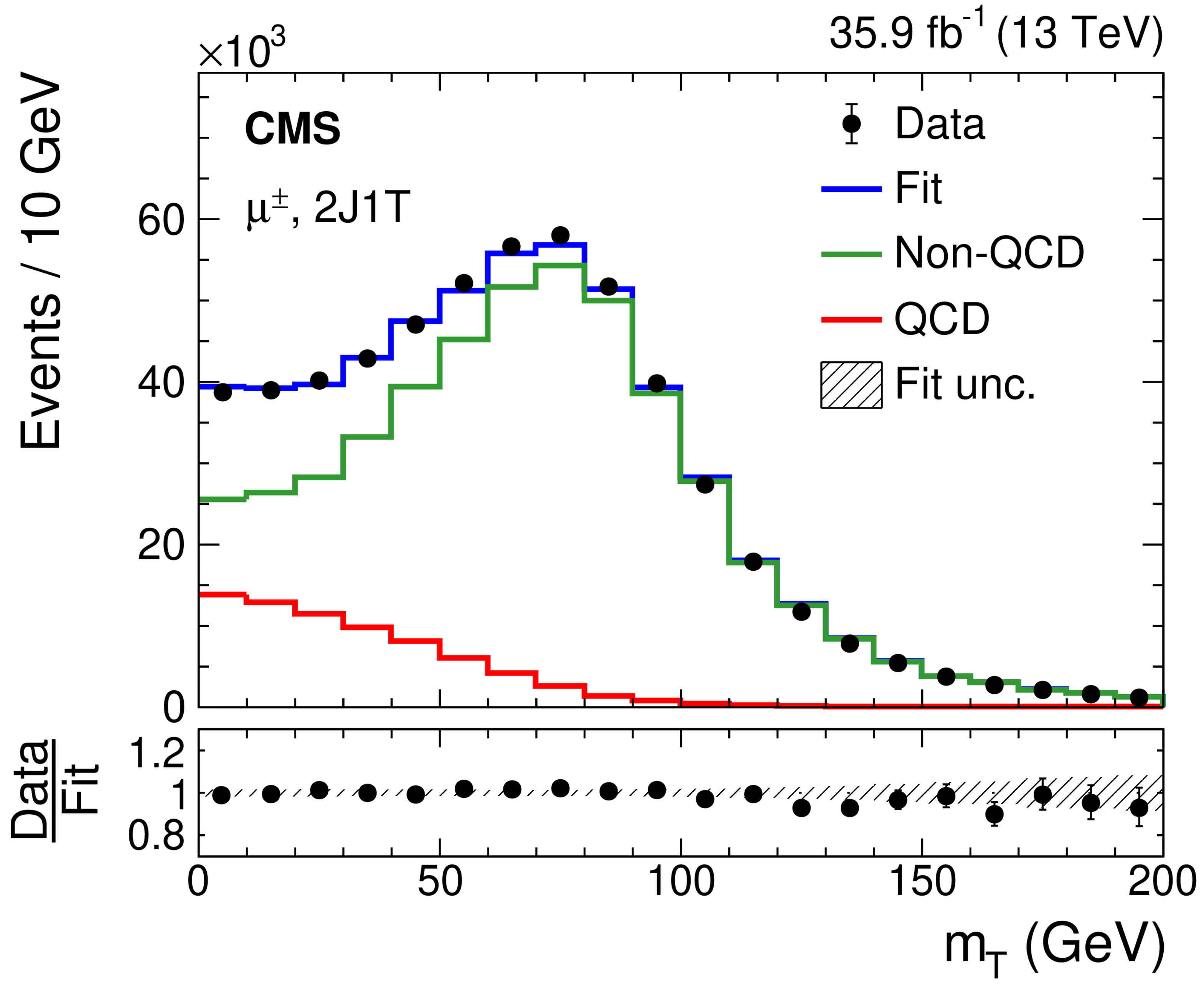
- Large cross section but low selection efficiency ⇒ require very high stat. MC sample for accurate templates after event selection

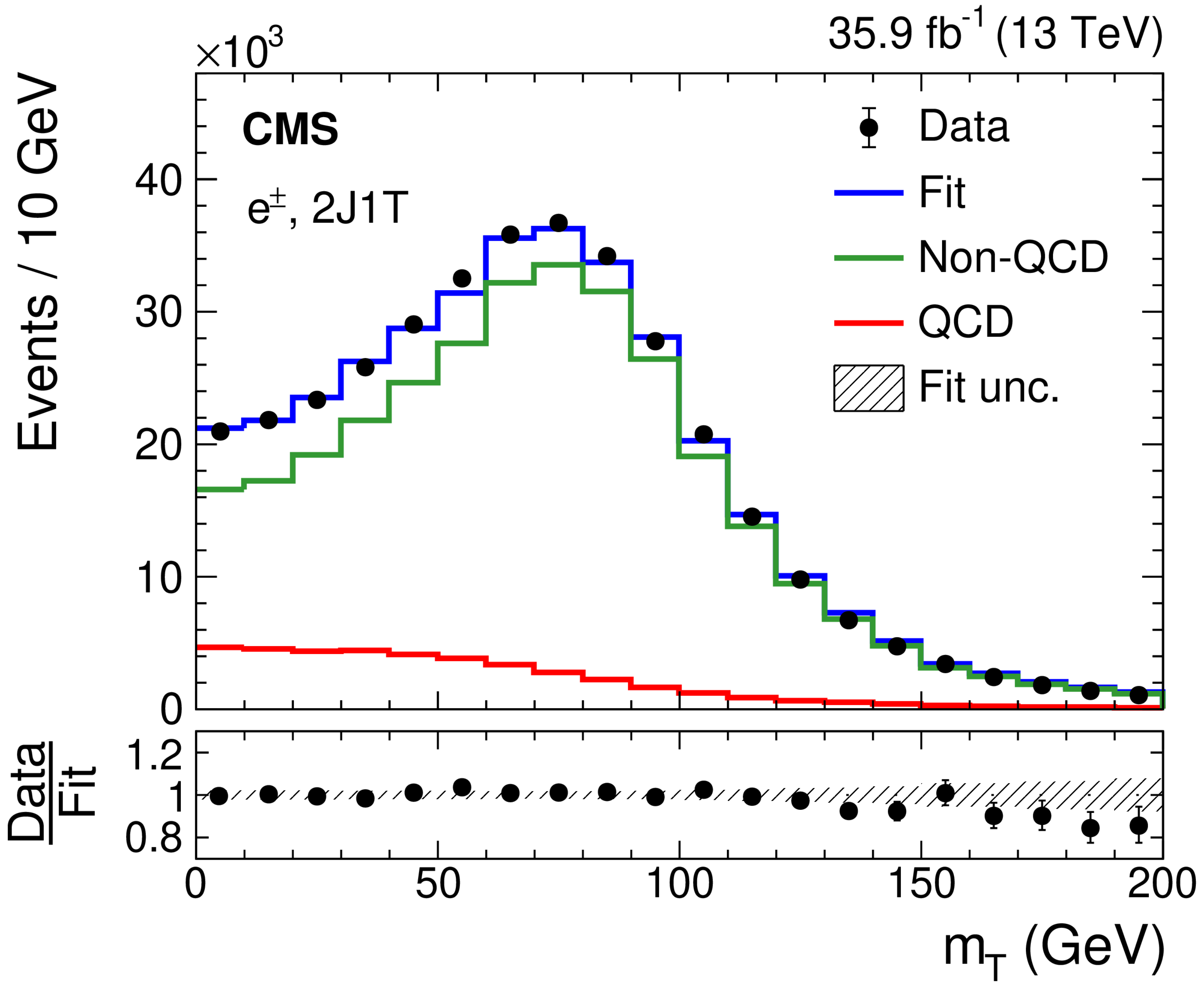
- QCD-enriched side-band (SB) in data as alternative
  ➛ invert I_{rel} (*ID*) criteria of the μ (e) in the final state

- ML fit to data in Signal region to extract normalization using QCD template from SB
  ➛ Proof of concept in 2J0T and estimation in 2J1T

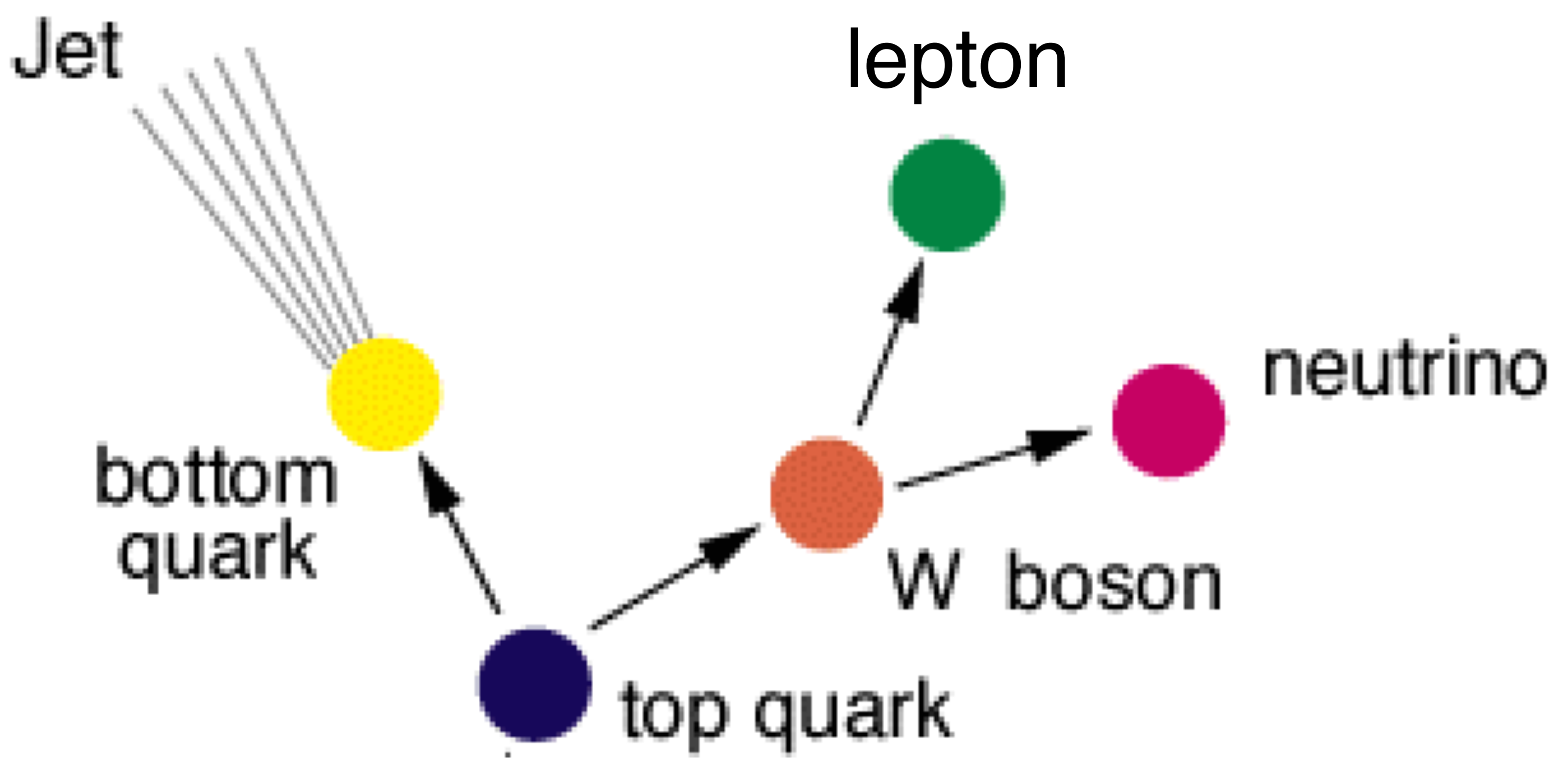
- Shape derived from SB and post-fit yield $m_T > 50$ GeV for QCD bkg. considered for further analysis

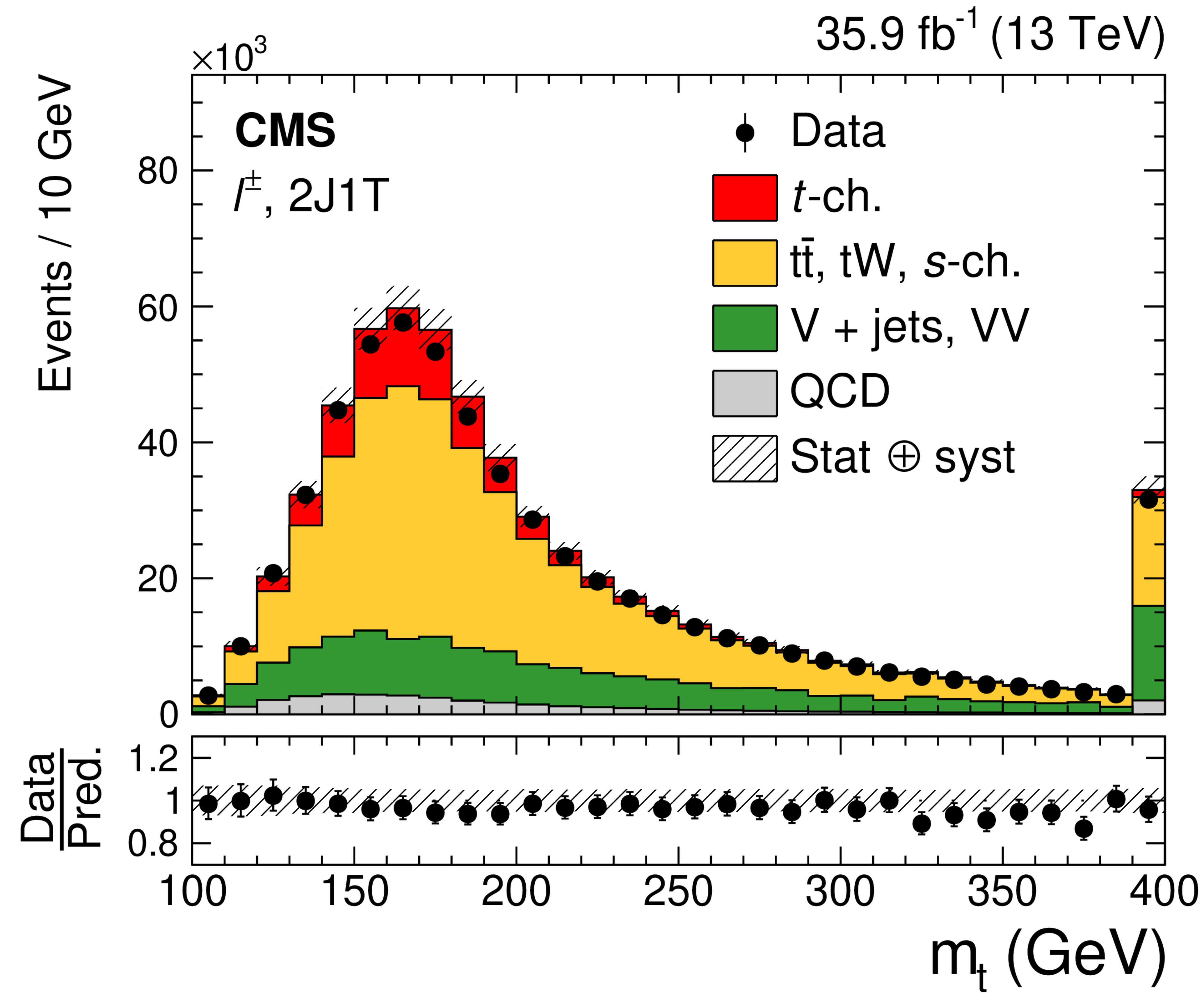
- 50% variation (shape + norm.) on the estimated QCD bkg. contribution as a systematic for final meas.





Top Quark Reconstruction





- Estimate neutrino p_z from lepton 4-momenta and Missing p_T

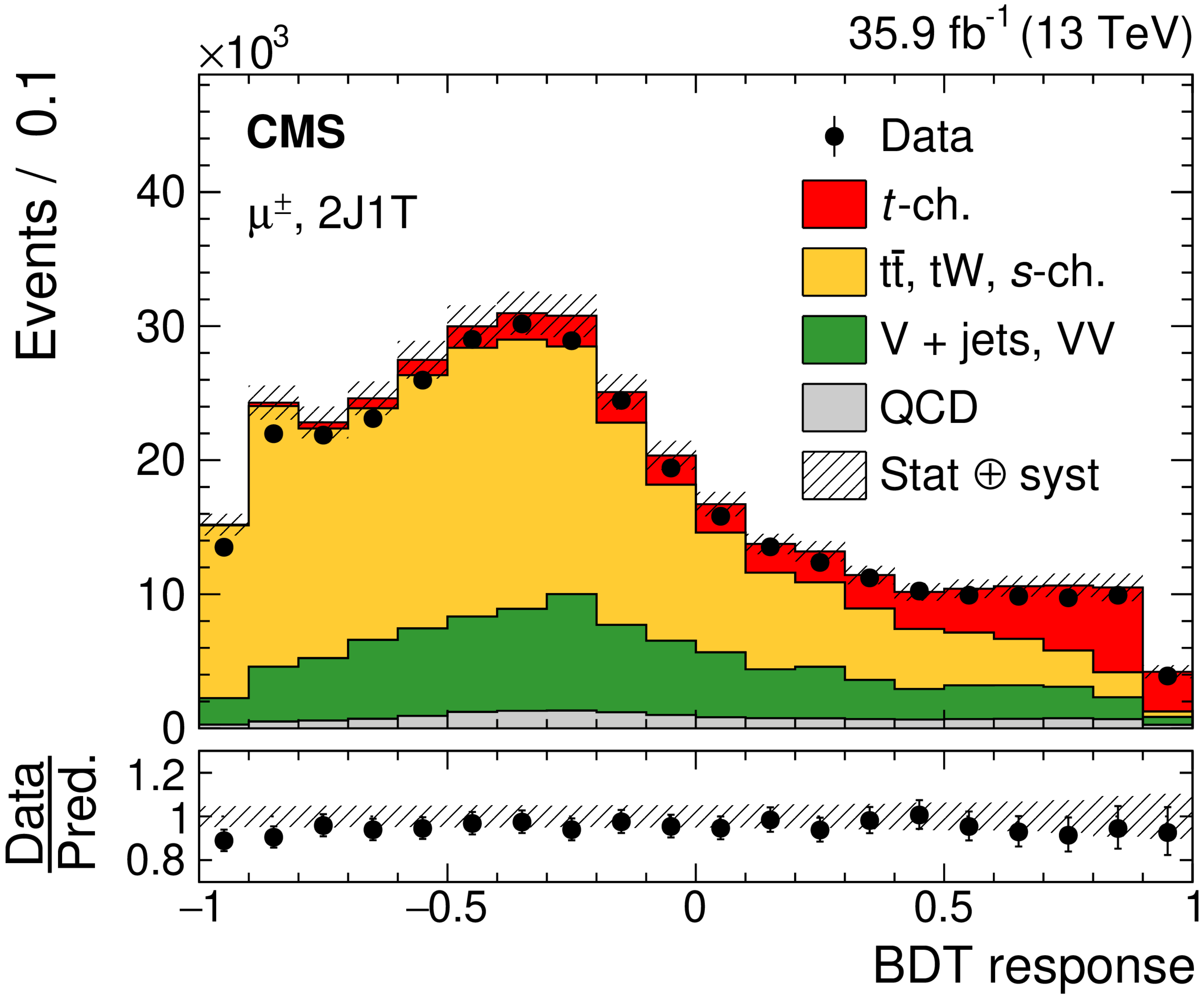
$$m_W^2 = \left(E_l + \sqrt{(p_T^{\text{miss}})^2 + p_{z,\nu}^2}\right)^2 - (\vec{p}_{T,l} + \vec{p}_T^{\text{miss}})^2 - (p_{z,l} + p_{z,\nu})^2$$

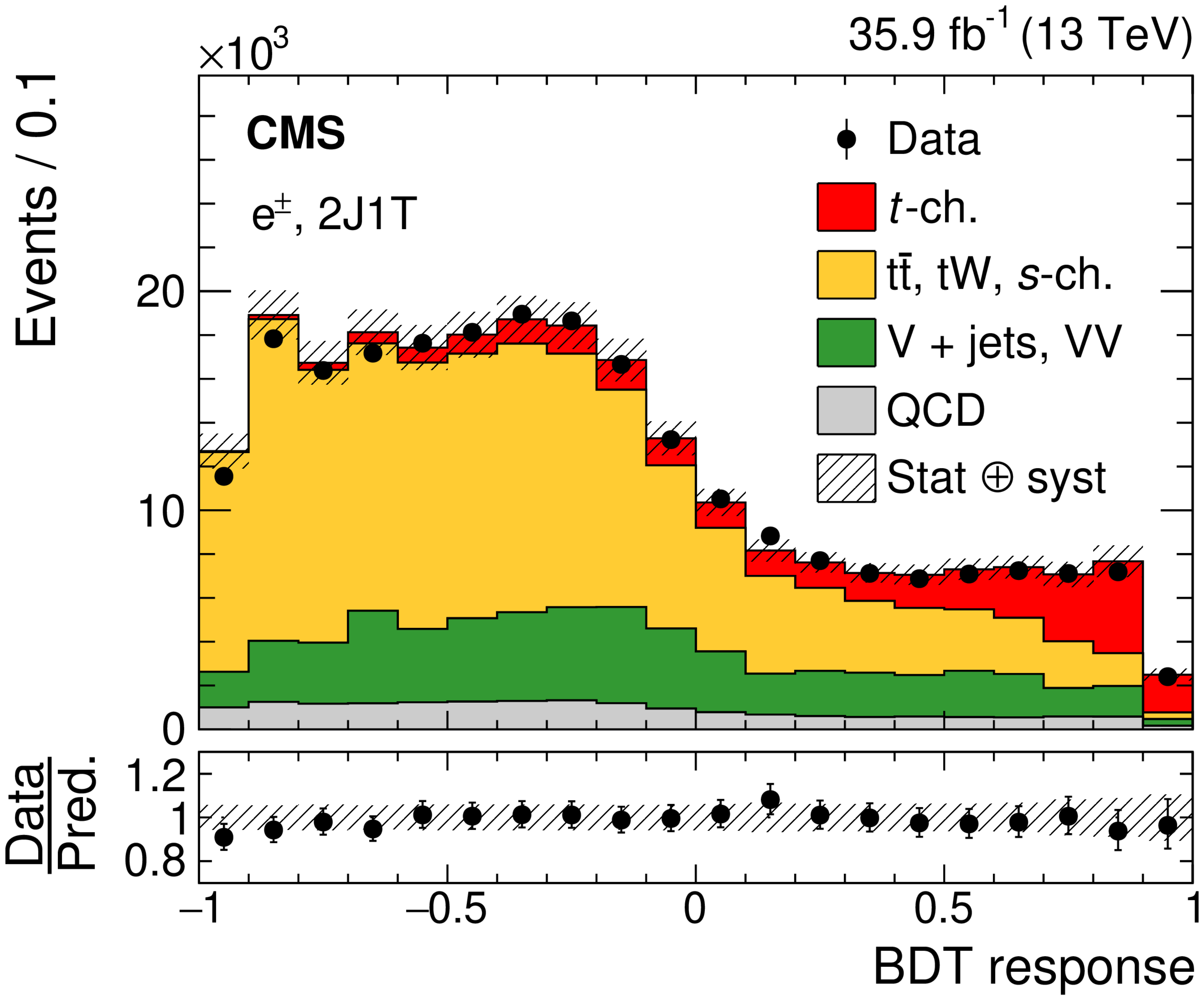
- Quadratic solution for neutrino p_z :
  - ☞ For real case (~ 65%):
    - ➛ choose the one with lowest | p_z | (accuracy ~ 64%)
  - ☞ For imaginary case (~ 35%):
    - ➛ Set radical equal to 0 ⇒ quadratic Eqn. in neutrino p_x and p_y
    - ➛ vary neutrino p_x and p_y keeping above Eqn. satisfied so that neutrino p_T has lowest $\Delta\varphi$ with Missing p_T

4-momenta of the b-quark from top quark decay approximated using b-tagged jet ⇒ m_t^{MC}

- Reconstruct W-boson from lepton and neutrino 4-momenta
- Combine b-jet and W-boson 4-momenta to reconstruct the top quark

BDT discriminants

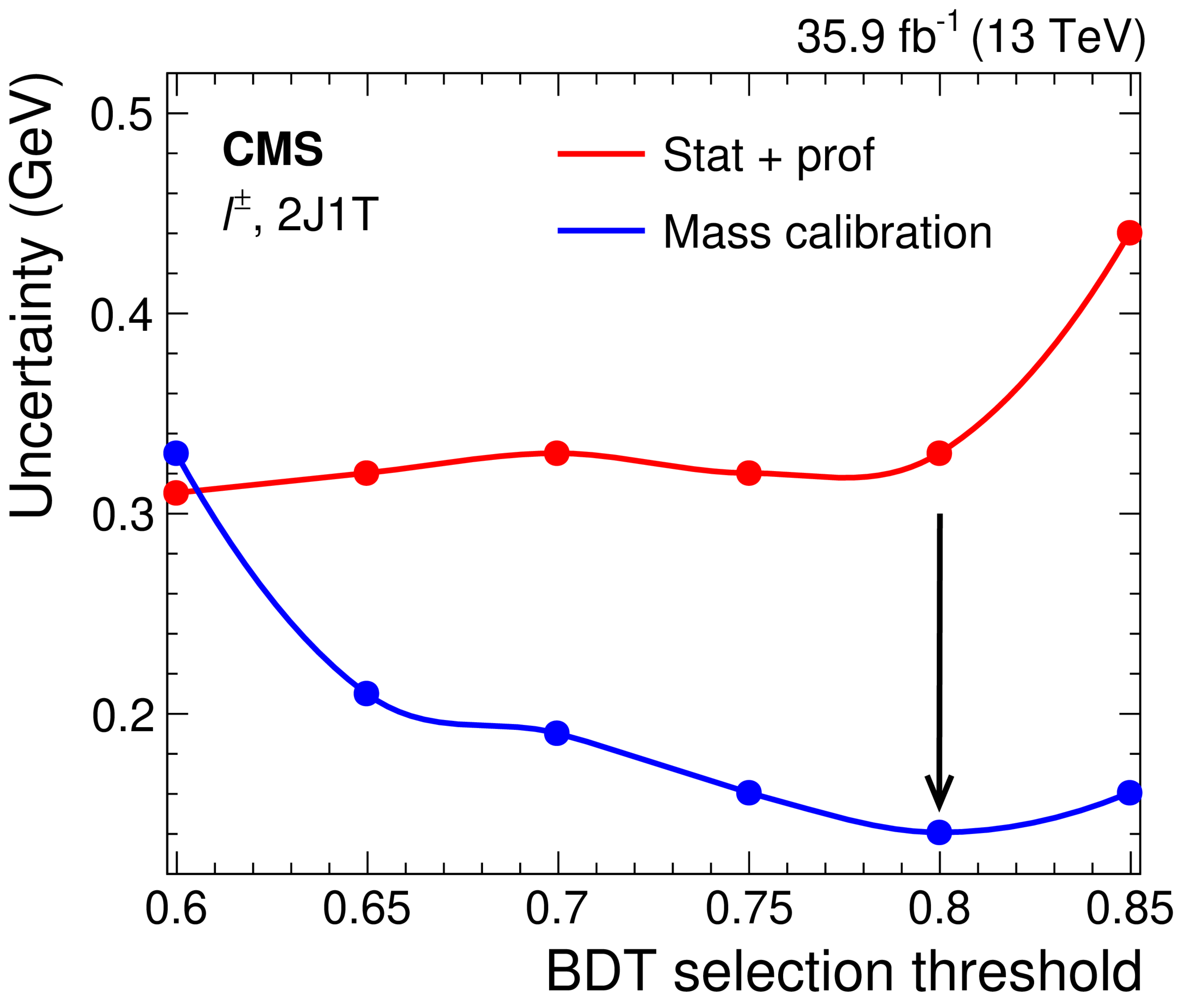


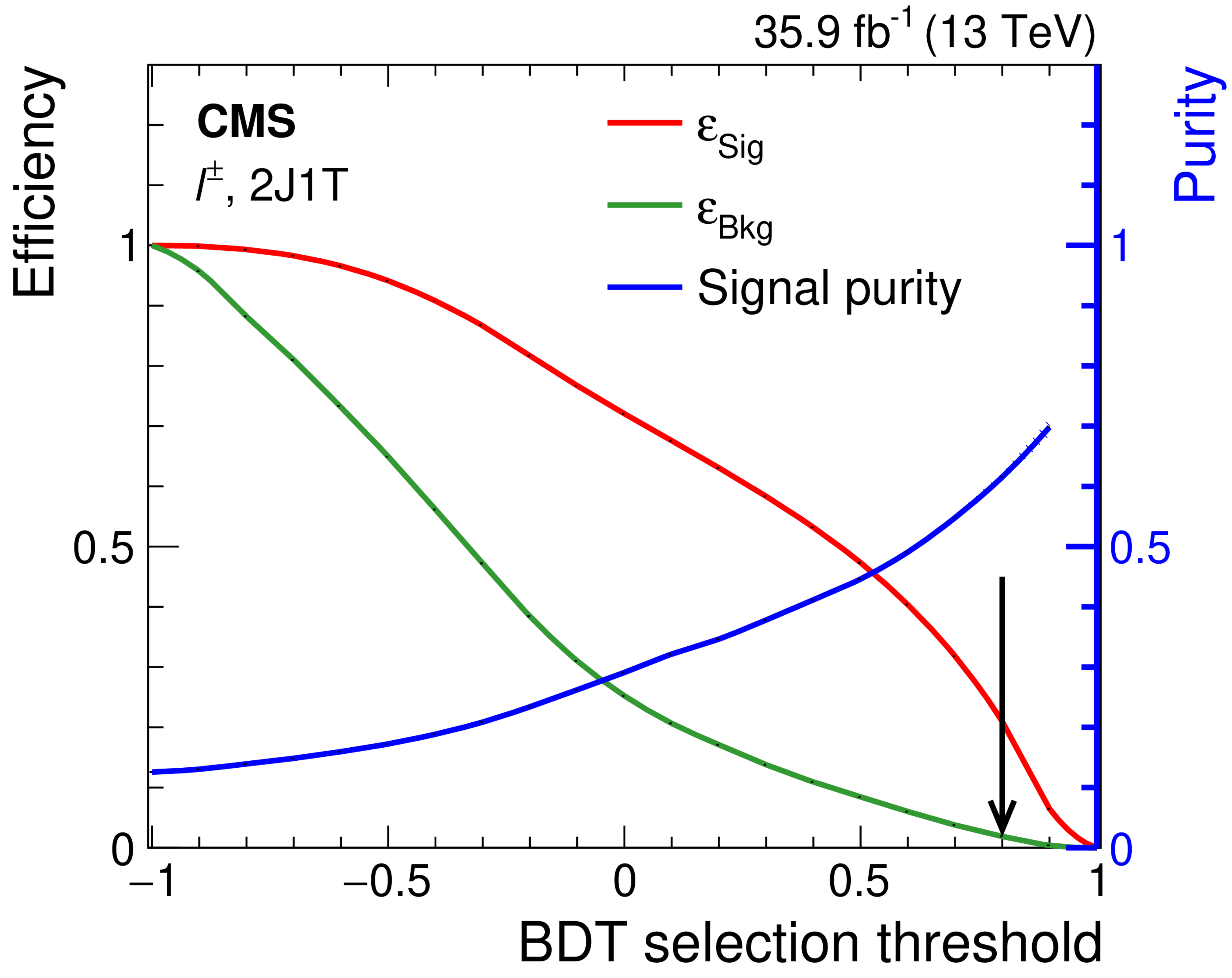


- Data and prediction agree within uncertainties along BDT response
- BDT response has <u>low corr.</u> (≈ -13%) with m_t for signal

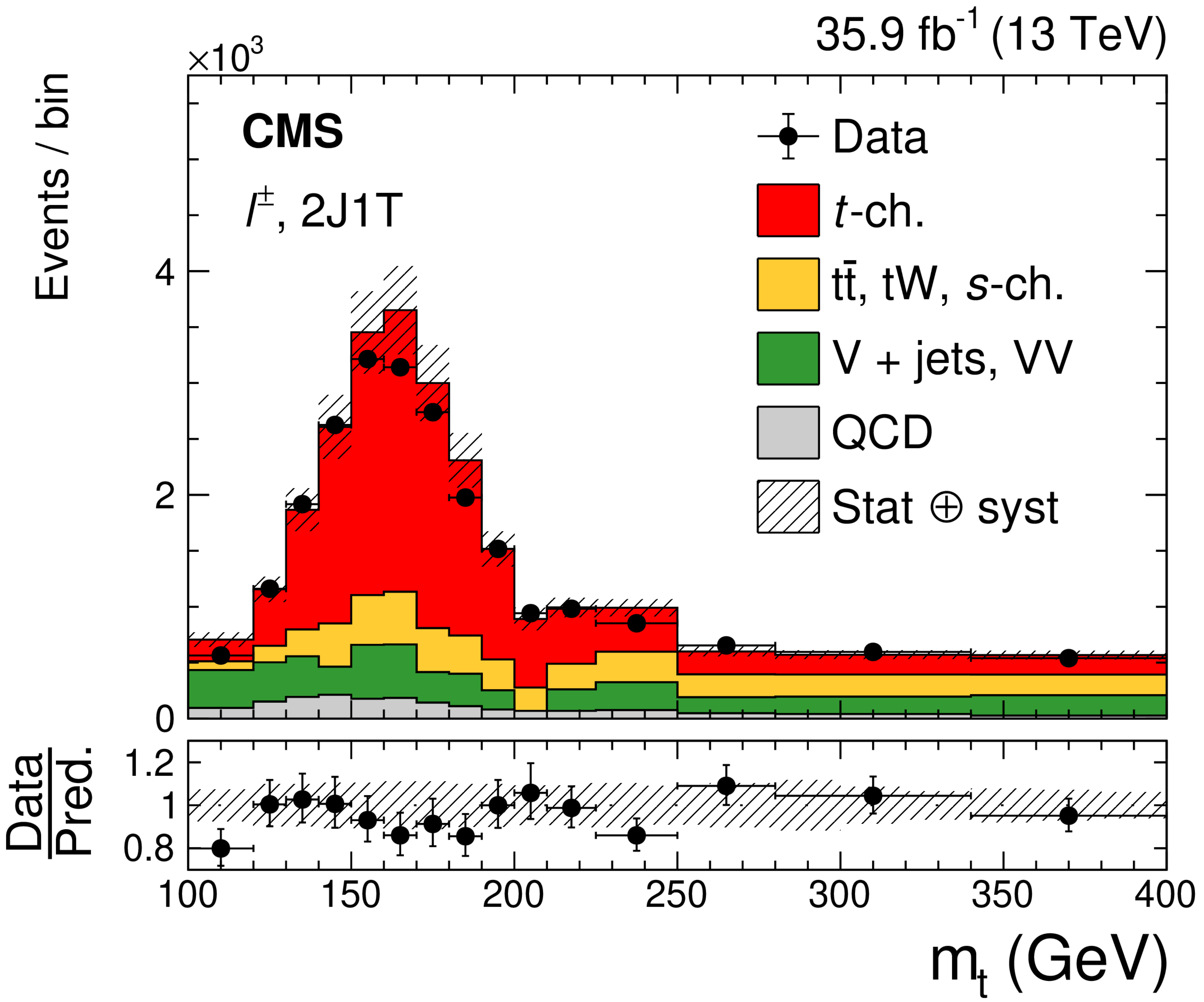
Optimization of BDT cut

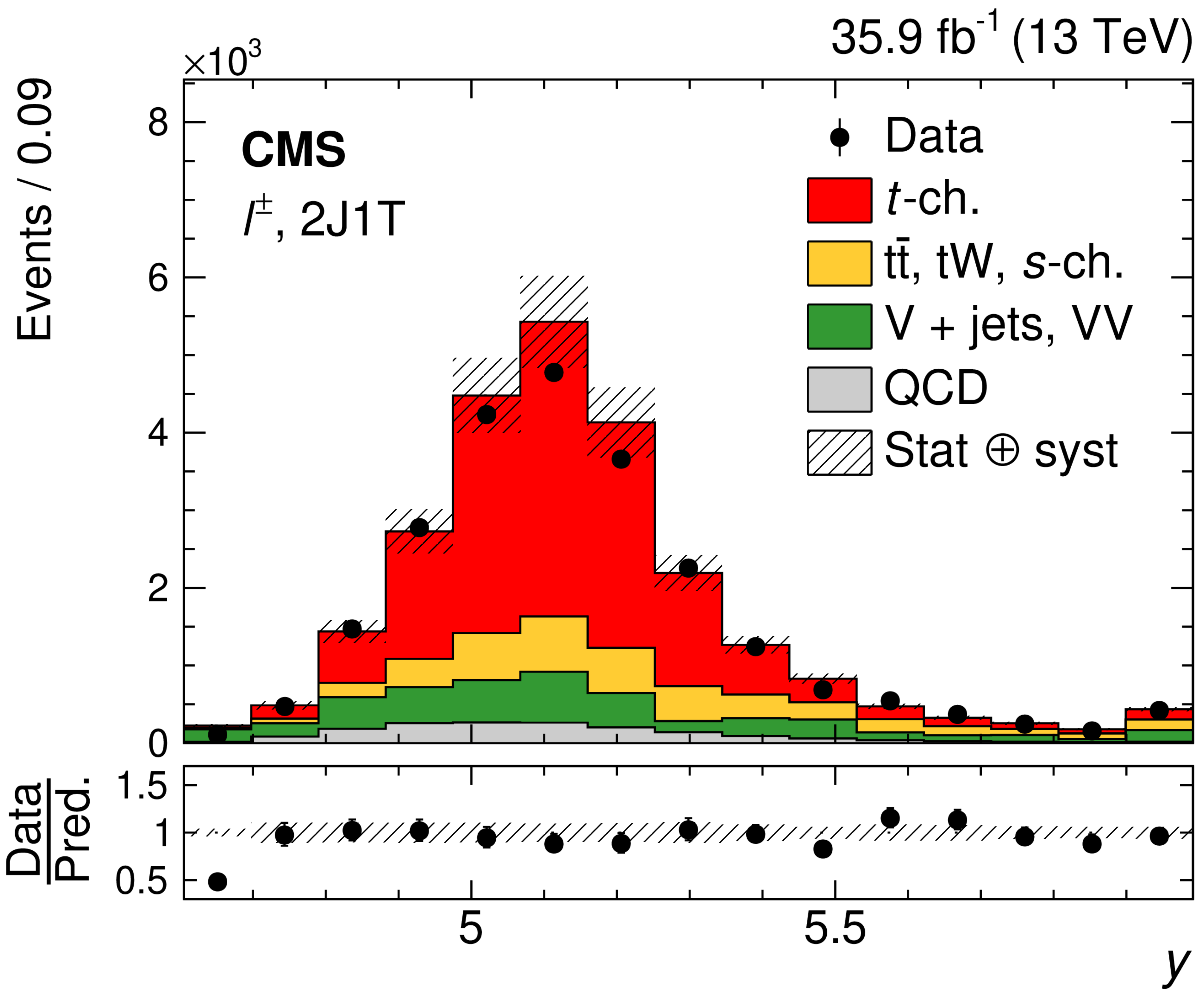
- BDT selection threshold optimized at minimum unc. due to calibration w.r.t *true* mass
- Selected cut value corresponds to ≈ 60% signal purity





m_t after BDT selection



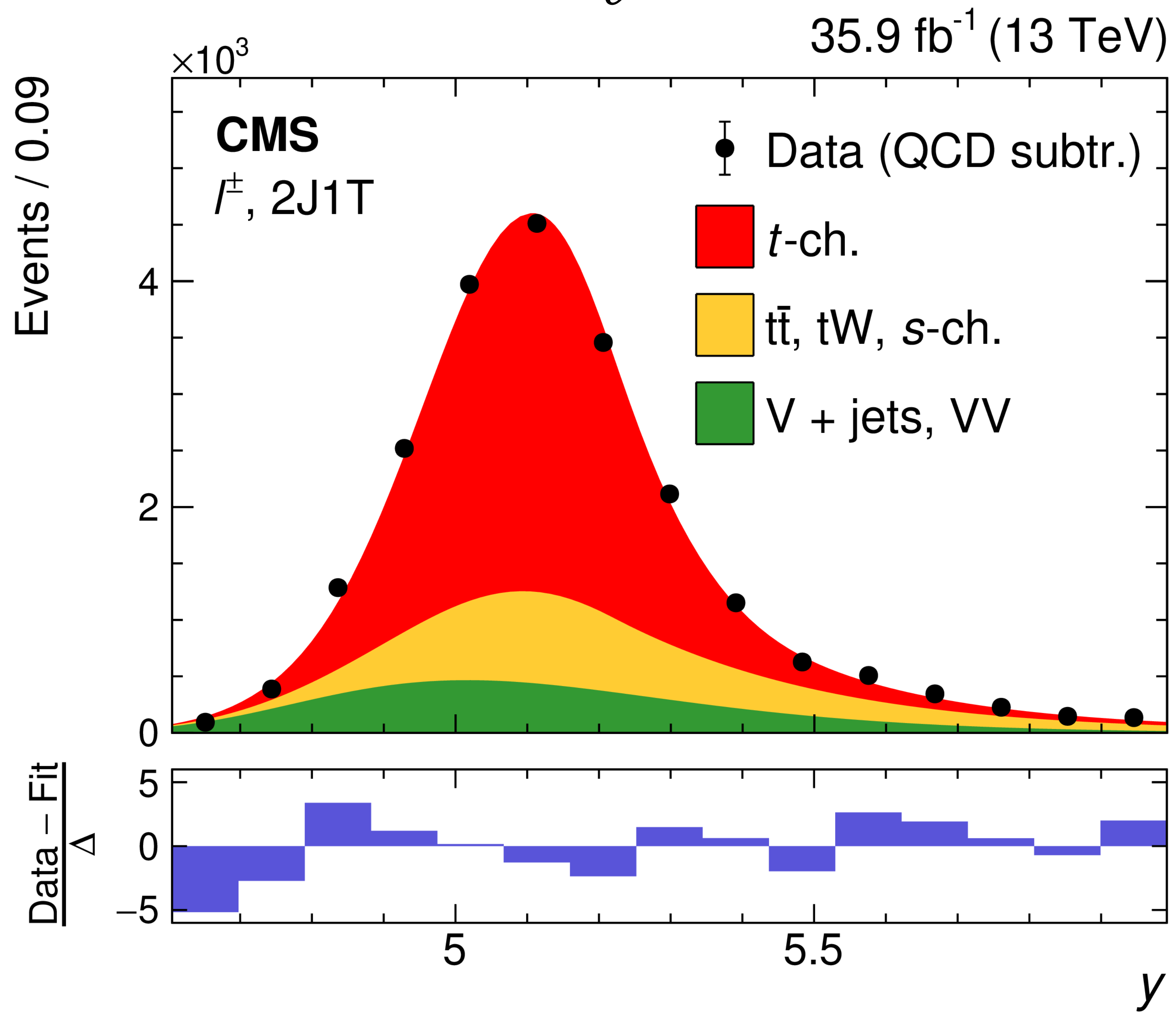


- m_t distribution *highly asymmetric* ➤ difficult to model accurately using parametric shapes

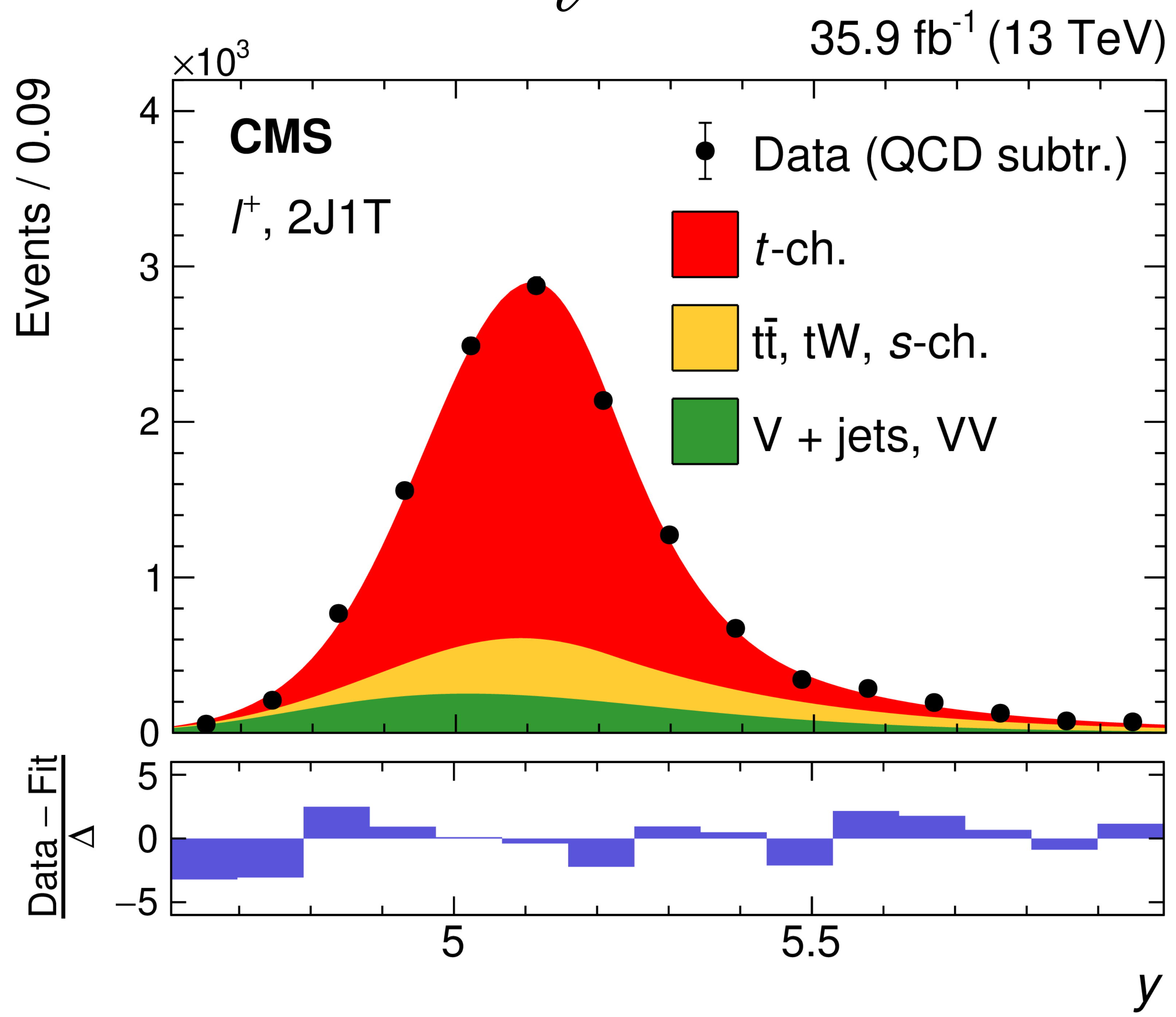
⇒ Use $y = \ln\,(m_t/\ 1\ \text{GeV})$ for fit ➤ more symmetric and easy to model

Postfit distributions

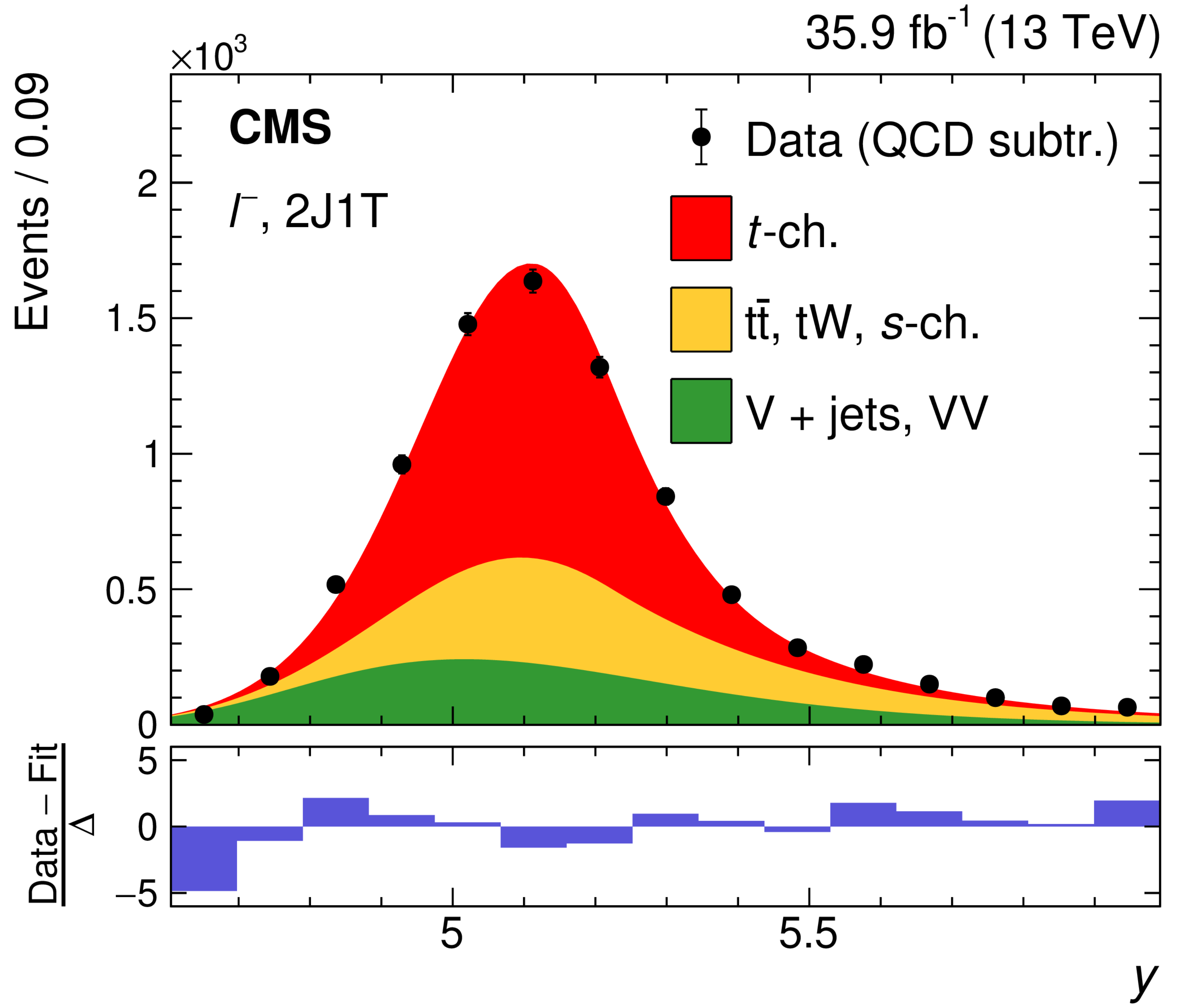
$\ell^{\pm}$



ℓ^{+}



ℓ^{-}



- *Simultaneous* ML fit in μ and e final states with *signal and bkg. rates constrained* using nuisance parameters
- Peak (y_0) well-modeled by fit
- Higher relative bkg. contribution in the ℓ^{-} final state
  - ➛ charge asymmetry of W boson radiated from the initial state quark in the signal process
- m_{fit} = *Exp* (y_0) calibrated for different *true* m_t values considered for signal & ttbar together and separately for ℓ^{+}, ℓ^{-}, $\ell^{\pm}$ final sates

Uncertainty Table

- *Signal and bkg. rates added as nuisance parameters* in the fit ➛ *profiled*
- All other syst. sources *externalized* ➛ fit repeated with templates obtained after syst. source variation (conservative approach)
- Largest shift w.r.t nominal result quoted in case of one-sided impact (conservative approach)
- Dominant sources on the $\ell^{\pm}$ case marked by shaded region
- Larger syst. uncertainties in case of ℓ^{-} final state due to higher relative bkg. contribution

Experimental Syst.

Modeling Syst.

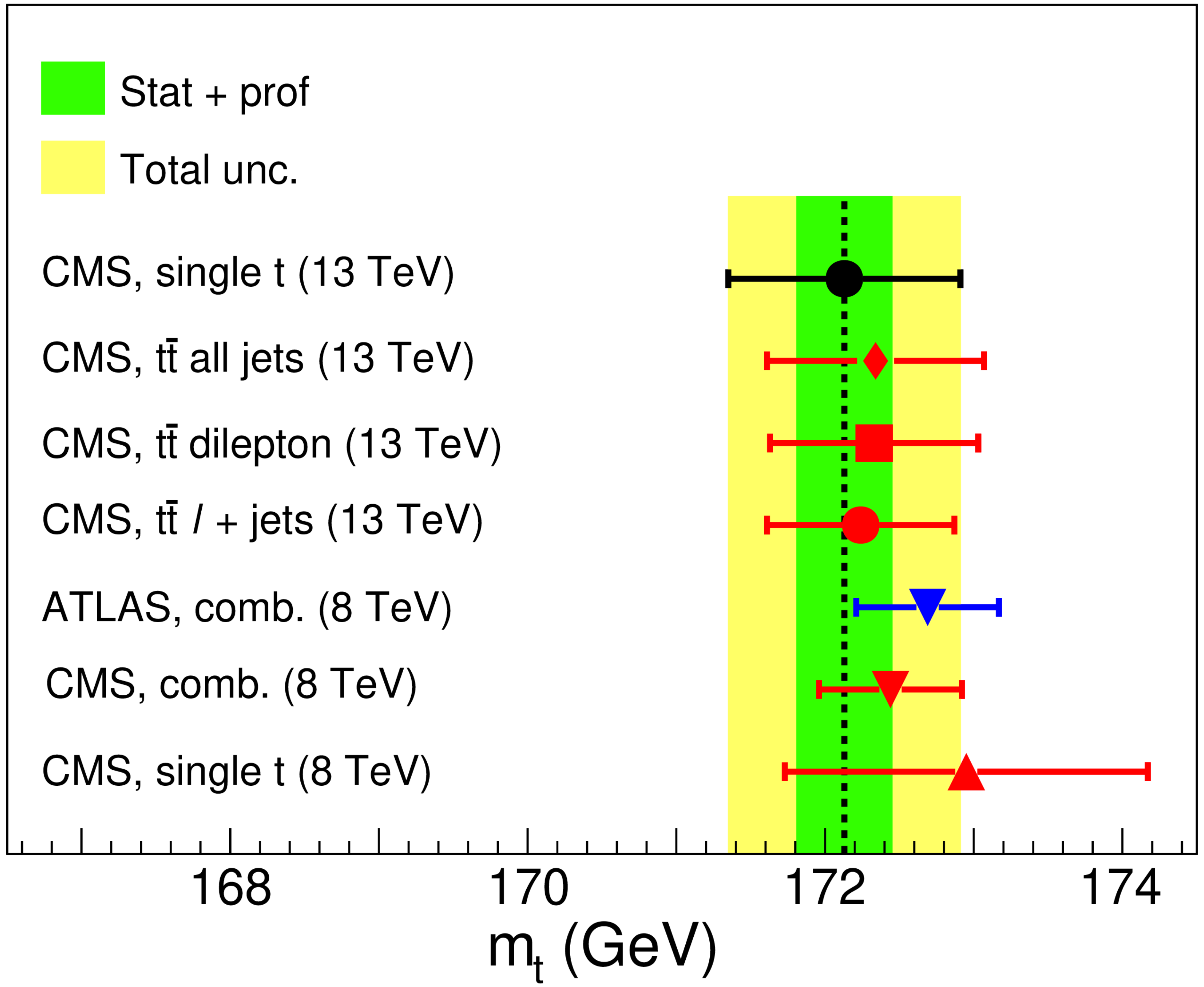
Source		$\delta m_{l^\pm}$	δm_{l^+}	δm_{l^-}
Statistical + profiled systematic		±0.32	±0.37	±0.58
JES	Correlation group intercalibration	±0.09	±0.07	±0.12
	Correlation group MPFInSitu	±0.02	±0.02	±0.01
	Correlation group uncorrelated	±0.39	±0.17	±0.83
	Total (quadrature sum)	±0.40	±0.18	±0.84
JER		<|0.01|	<|0.01|	<|0.01|
Unclustered energy		<|0.01|	<|0.01|	<|0.01|
Muon efficiencies		<|0.01|	<|0.01|	<|0.01|
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
Mass calibration		±0.11	±0.13	±0.20
Int. luminosity		<|0.01|	<|0.01|	±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 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	<|0.01|
	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	<|0.01|	<|0.01|	<|0.01|
	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

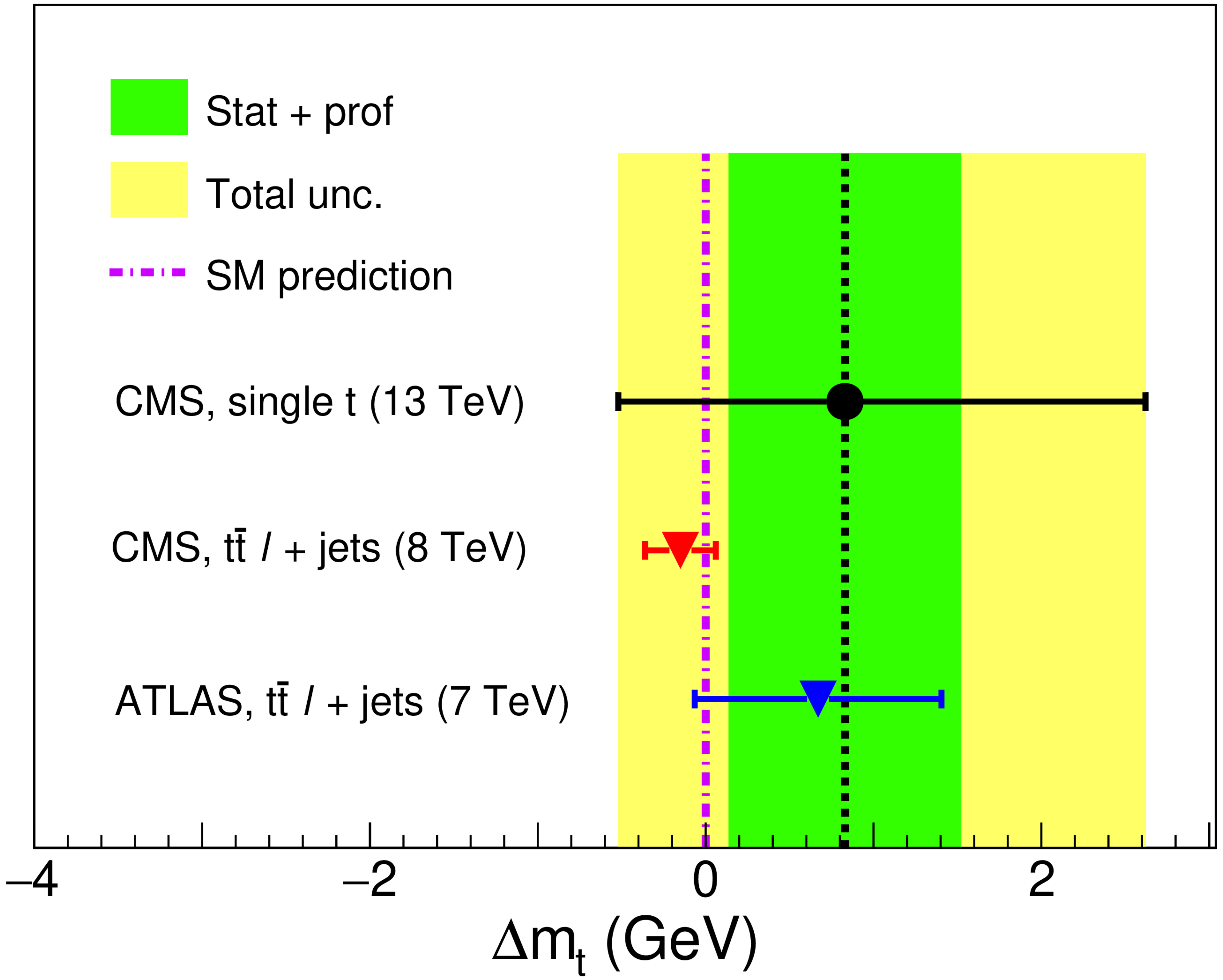
Results

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

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

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

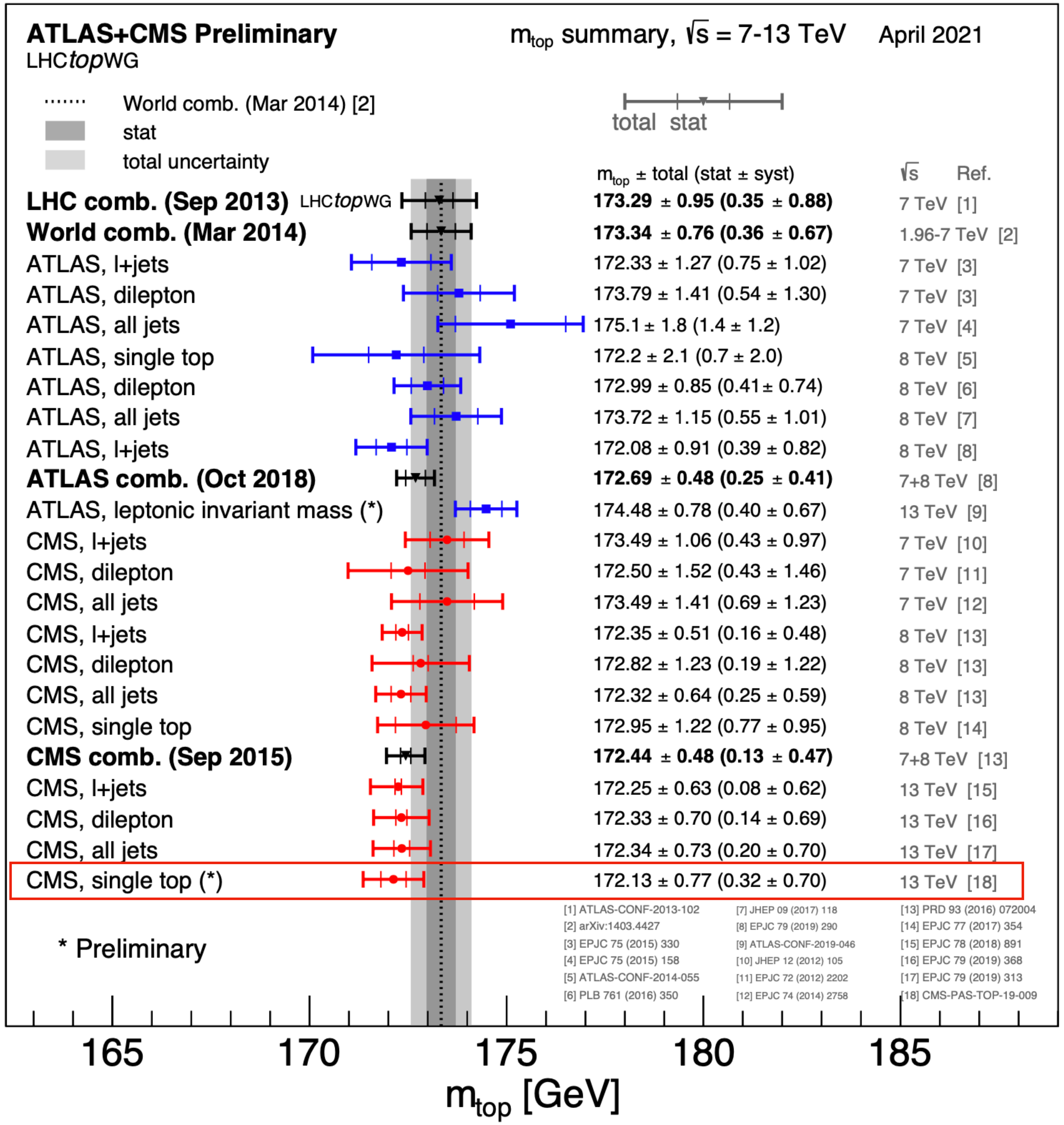




Summary and Outlook

- First m_t measurement at $\sqrt{s}$ = 13 TeV in single top enriched event sample with 35.9 fb^{-1} data
- First m_t measurement to achieve sub-GeV precision in single top enriched event sample
- First measurement of R_{m_t} and Δm_t in single top enriched phase space ➛ test of CPT invariance; *no violation observed*
- Dominant uncertainties in the $\ell^{\pm}$ result:
  - ➛ JES (± 0.40 GeV)
  - ➛ signal FSR scale (± 0.28 GeV)
  - ➛ color reconnection (± 0.24 GeV)
  - ➛ b-quark had. model ($^{+0.23}_{-0.18}$ GeV)

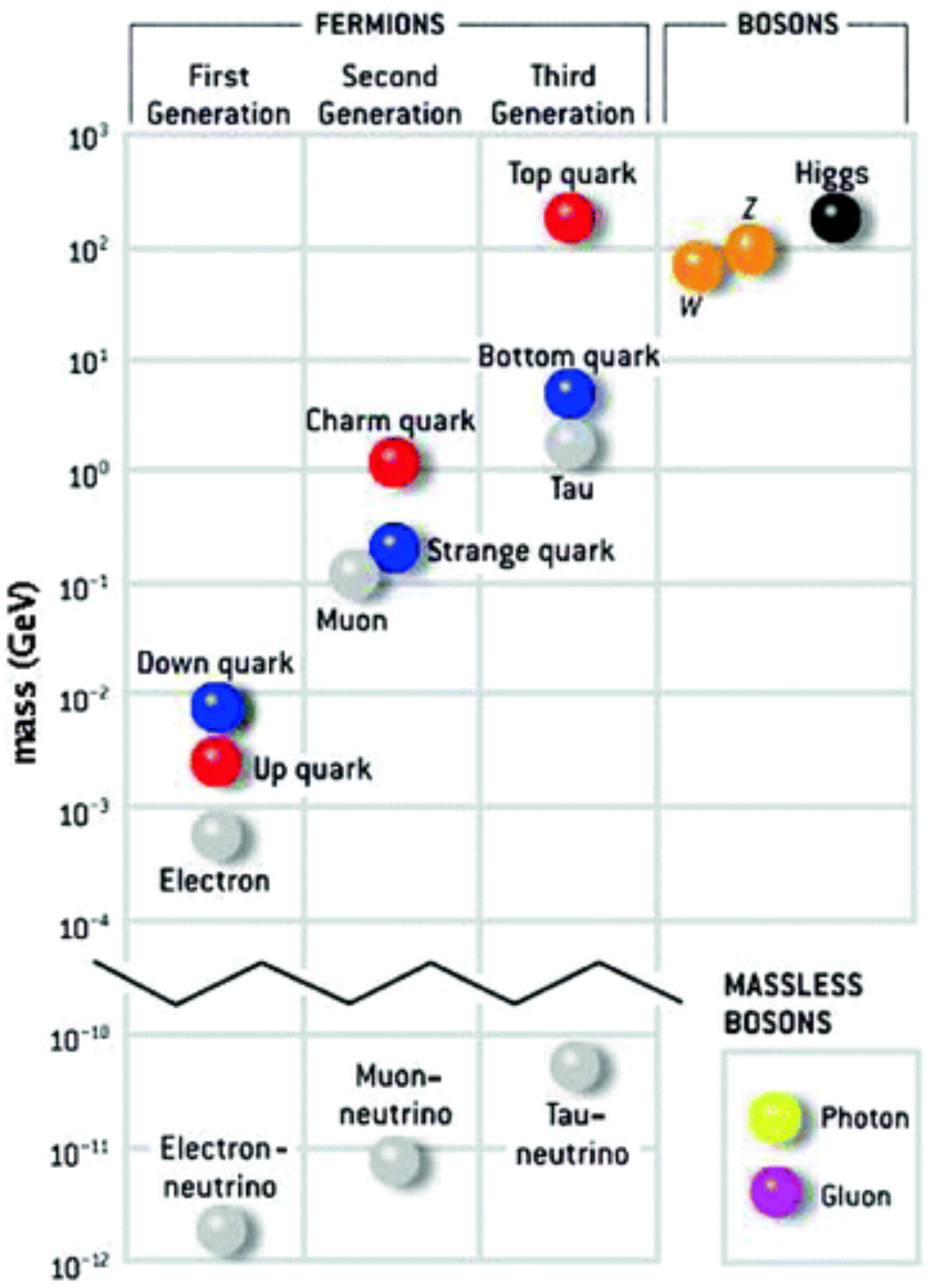
LHC top WG Summary Plots

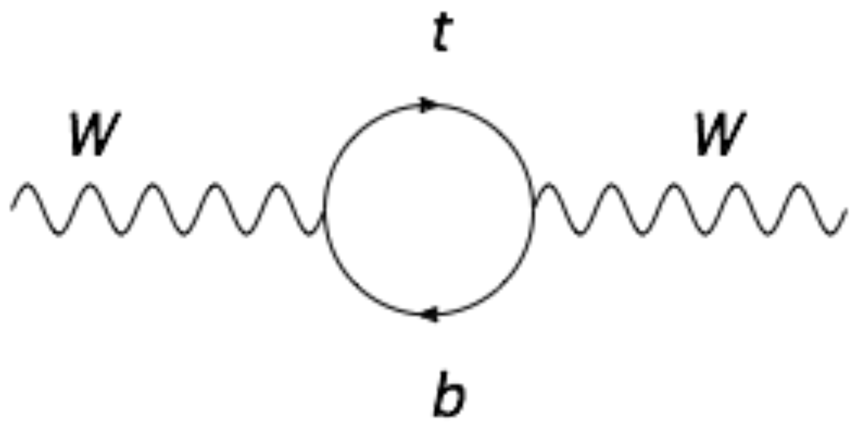


Thank You

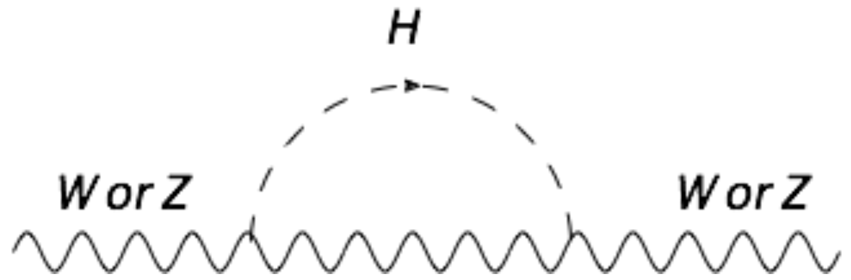
Back Up

m_t & Electroweak symmetry

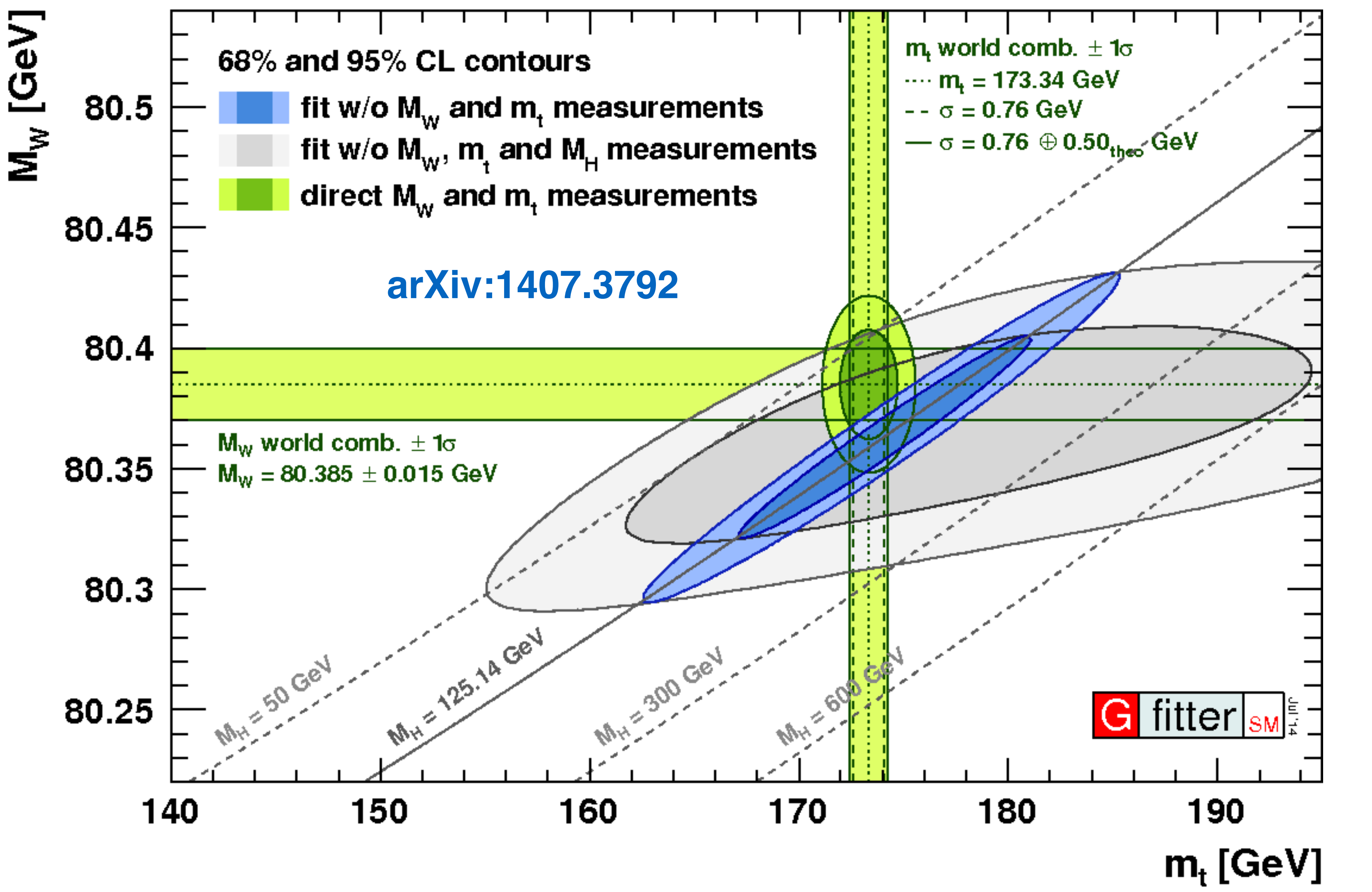




$$\Delta m_W \propto m_t^2$$



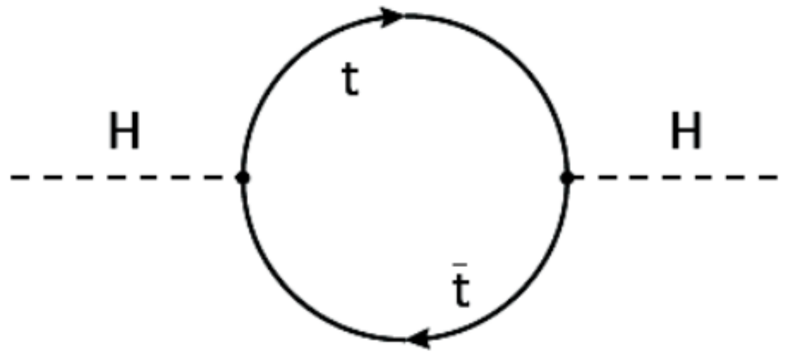
$$\Delta m_W \propto \ln m_H$$



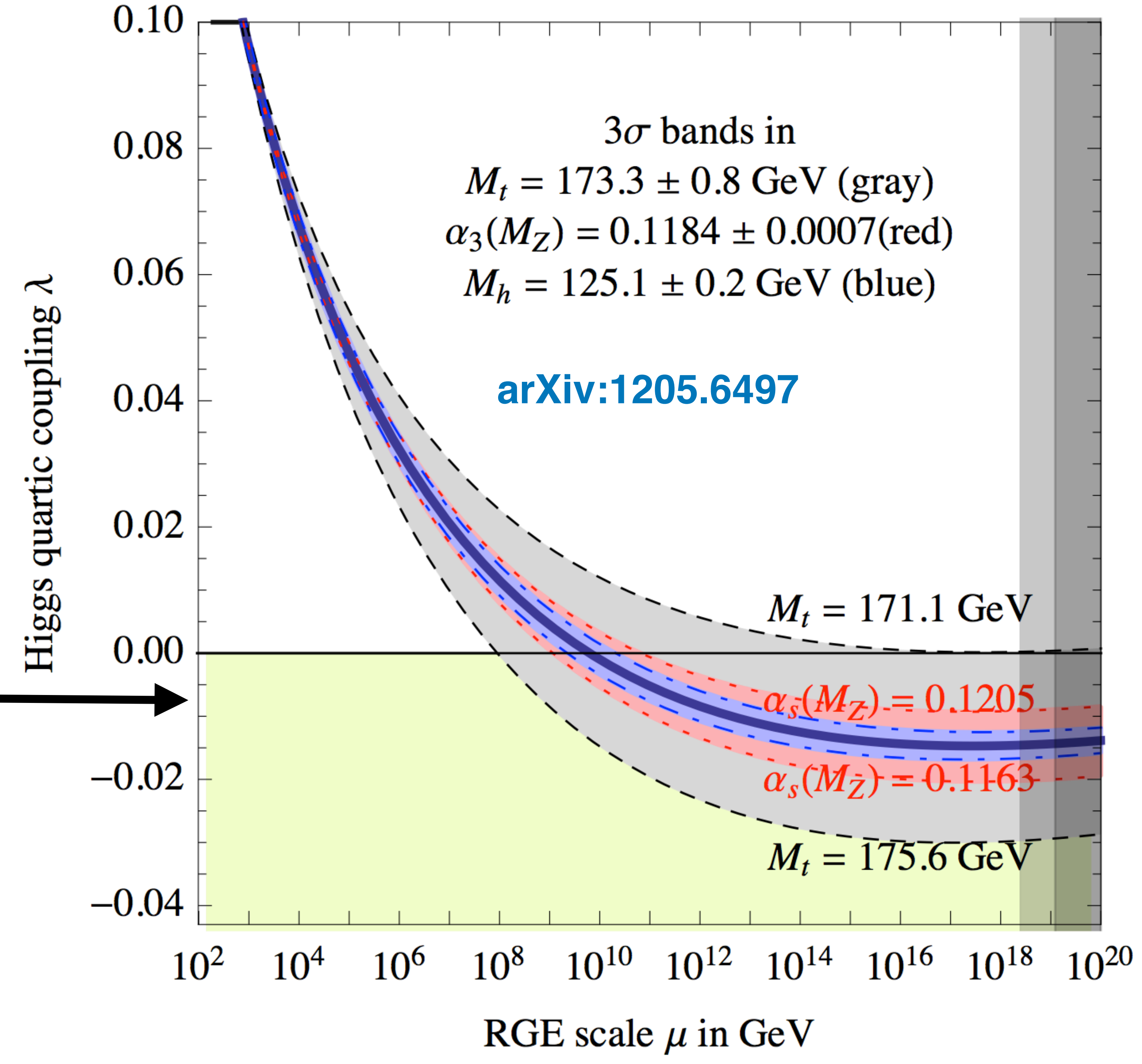
- Higgs Potential:

$$V(\phi) = -\mu_H^2\phi^\dagger\phi + \lambda_H(\phi^\dagger\phi)^2$$

- Mexican hat only if $\lambda_H > 0$
- λ_H receives radiative corrections from all SM particles ➛ mostly from top



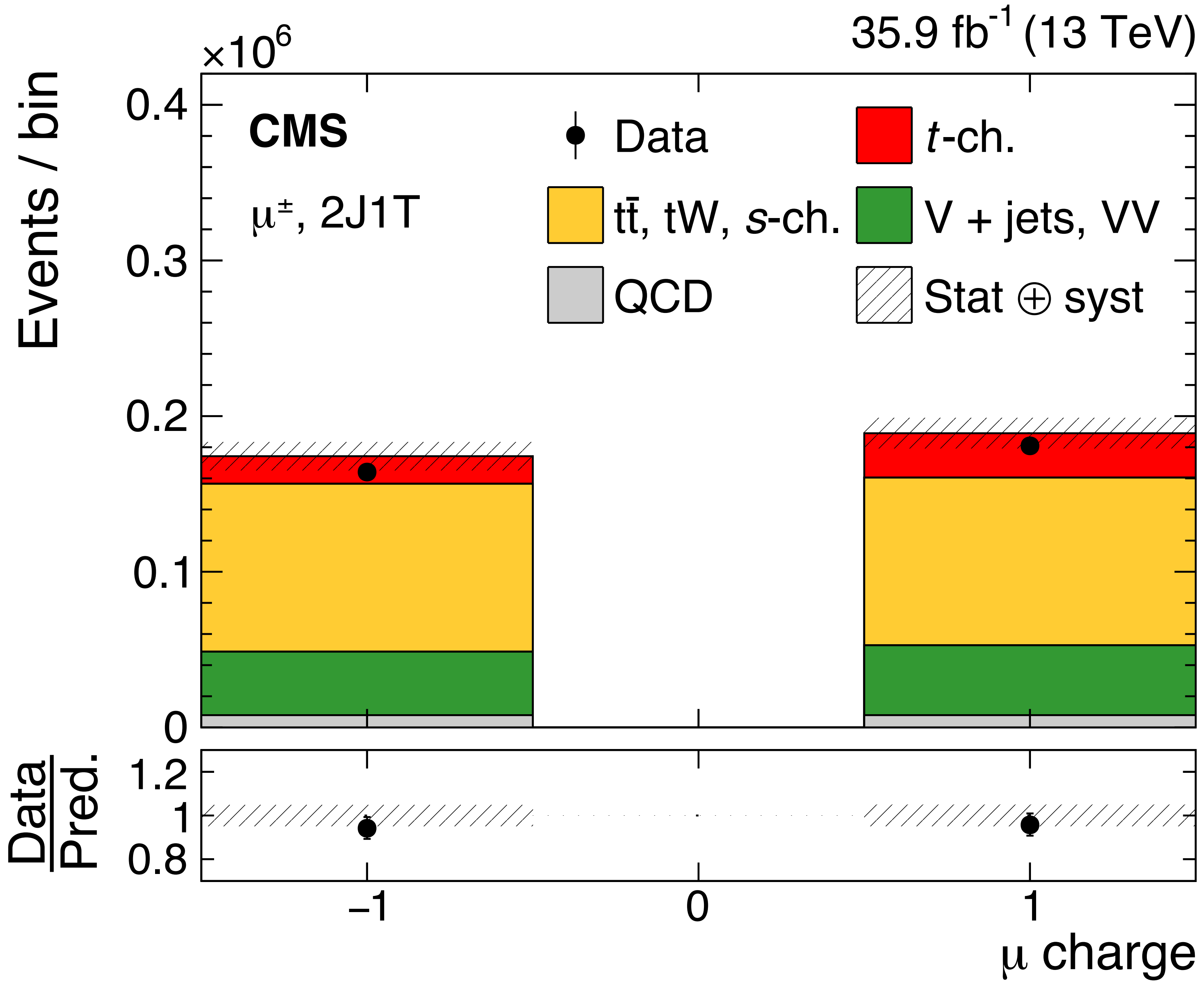
$$\lambda_H(\mu) = \lambda_H(v) - \frac{3m_t^4}{2\pi^2 v^4}\log\frac{\mu}{v}$$

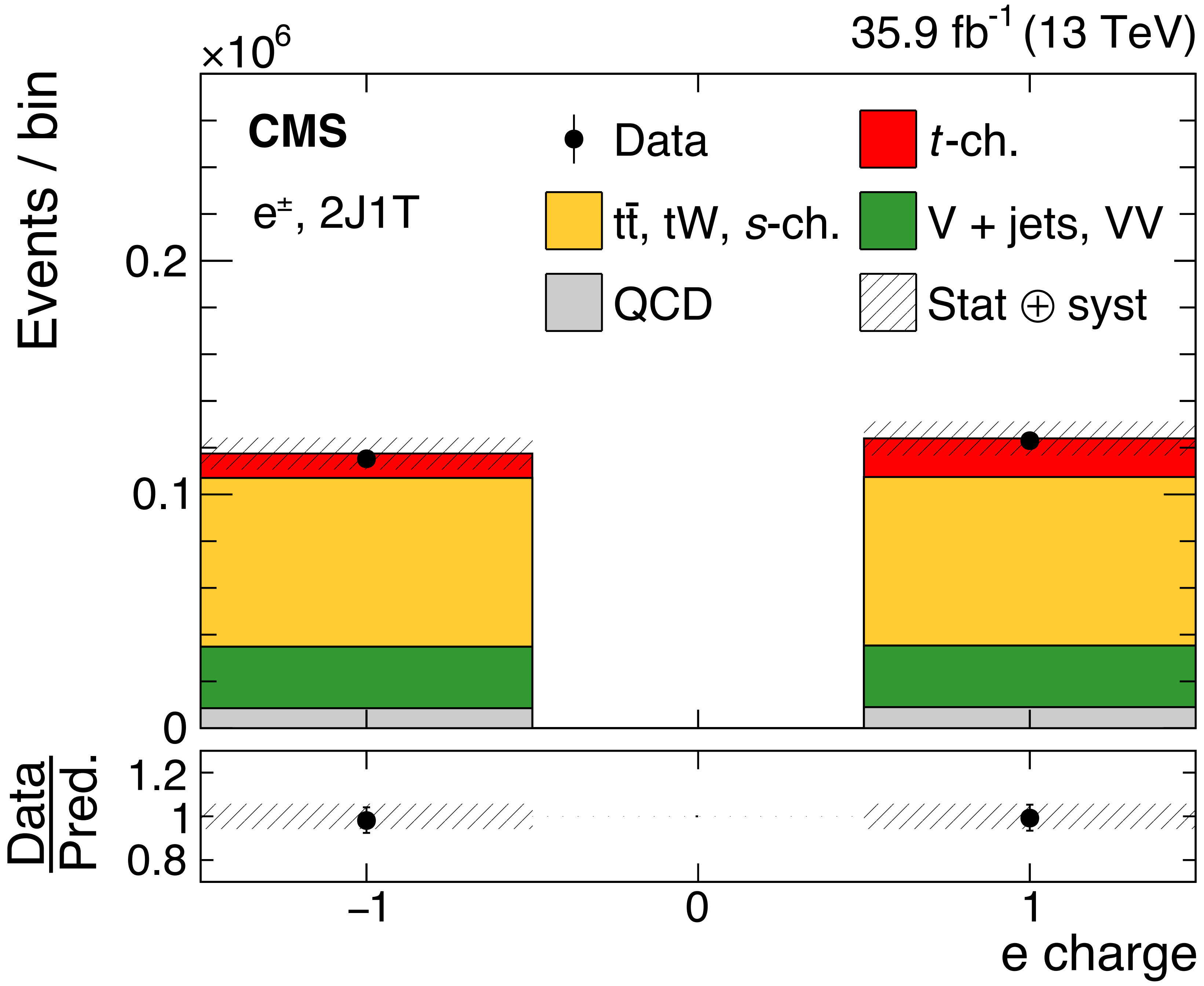


- Evolve λ_H up to Planck scale (~10^{19} GeV)
- Knowing the top mass **accurately** might just reveal the **fate of our universe**
- $\Delta m_t = m_t - m_{\bar{t}}$ ➛ test of CPT invariance ⇒ Lorentz symmetry

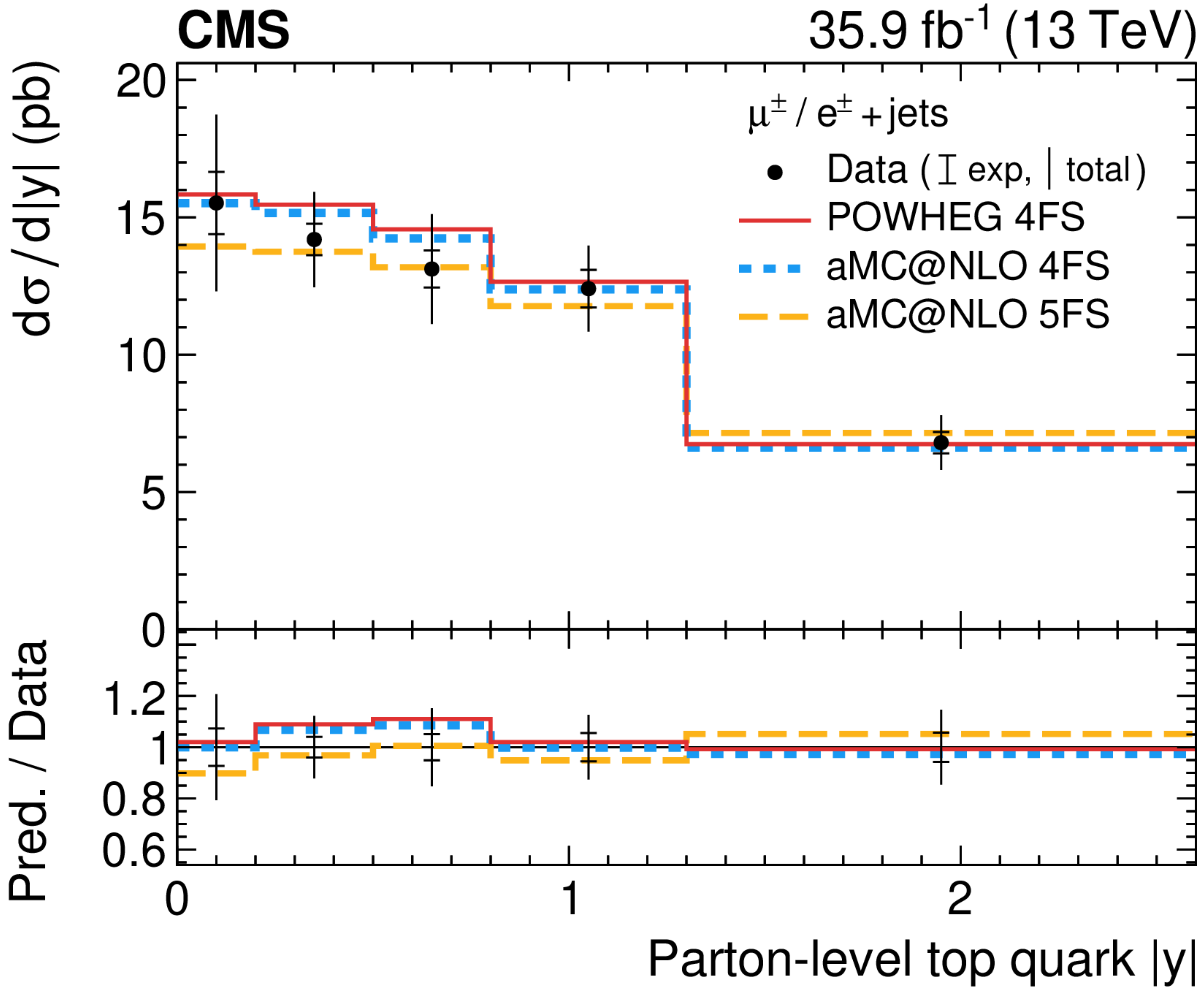
Event selection and yield

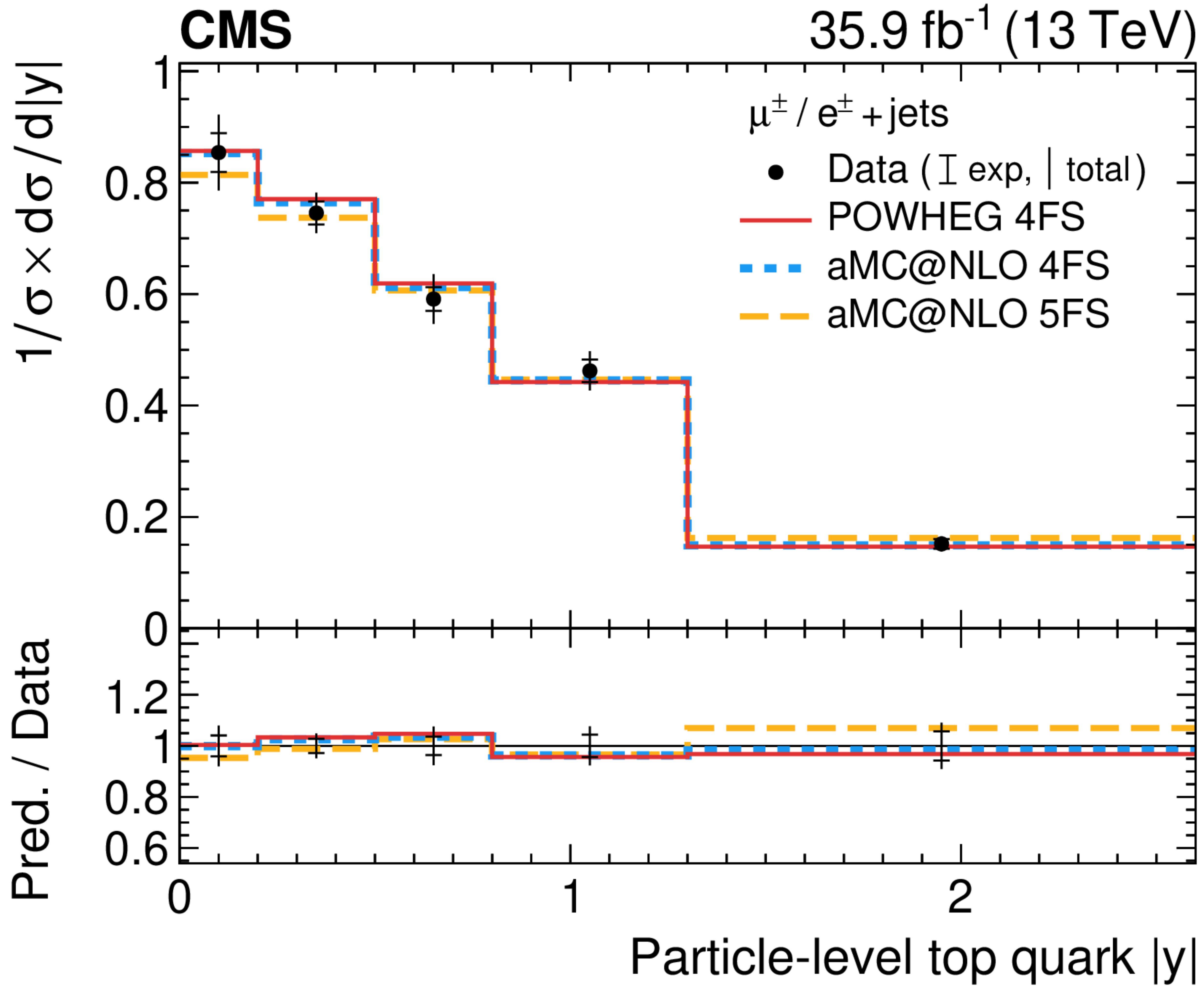
Selection Step	Criteria for μ + jets	Criteria for e + jets
Trigger	HLT_IsoMu24 OR HLT_IsoTkMu24	HLT_Ele32_eta2p1_WPTight_Gsf
Tight lepton selection	$p_T \geq 26$ GeV, $\lvert\eta\rvert \leq 2.4$ cut-based tight Id. $I_{rel} \leq 0.06$ - $\lvert d_{xy}\rvert < 0.2$ cm, $\lvert d_z\rvert < 0.5$ cm (included in tight Id.)	$p_T \geq 35$ GeV, $\lvert\eta\rvert \leq 2.1$ cut-based tight Id. $I_{rel} \leq 0.0588(0.0571)$ in EB (EE) (included in tight Id.) $\lvert\eta_{sc}\rvert \leq 1.4442$ OR $\lvert\eta_{sc}\rvert \geq 1.566$ $\lvert d_{xy}\rvert < 0.05(0.1)$ cm , $\lvert d_z\rvert < 0.1(0.2)$ cm in EB (EE)
Loose μ veto	$p_T \geq 10$ GeV, $\lvert\eta\rvert \leq 2.4$, loose Id.	
Loose e veto	$p_T \geq 15$ GeV, $\lvert\eta\rvert \leq 2.5$, veto Id.	
Jet selection	$p_T \geq 40$ GeV, $\lvert\eta\rvert \leq 4.7$, loose Id., ΔR(tight lepton, jet) > 0.4 , no. of jets = 2	
b-tagging	$\lvert\eta\rvert \leq 2.4$, cMVAv2 tight WP (discriminator > 0.9432), no. of b-tagged jets =1	
QCD rejection	$m_T^W \geq 50$ GeV	





4FS vs 5FS modeling





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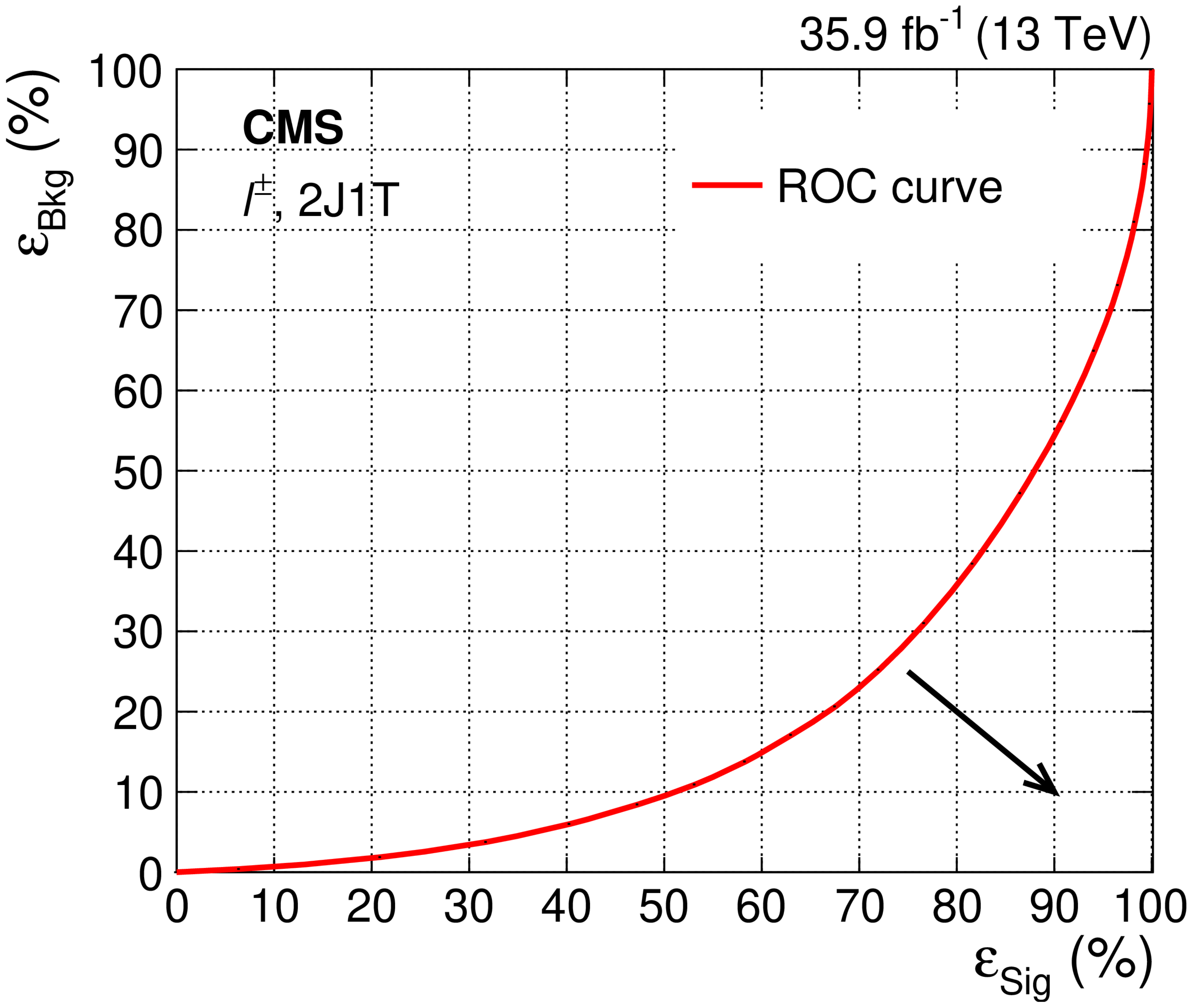
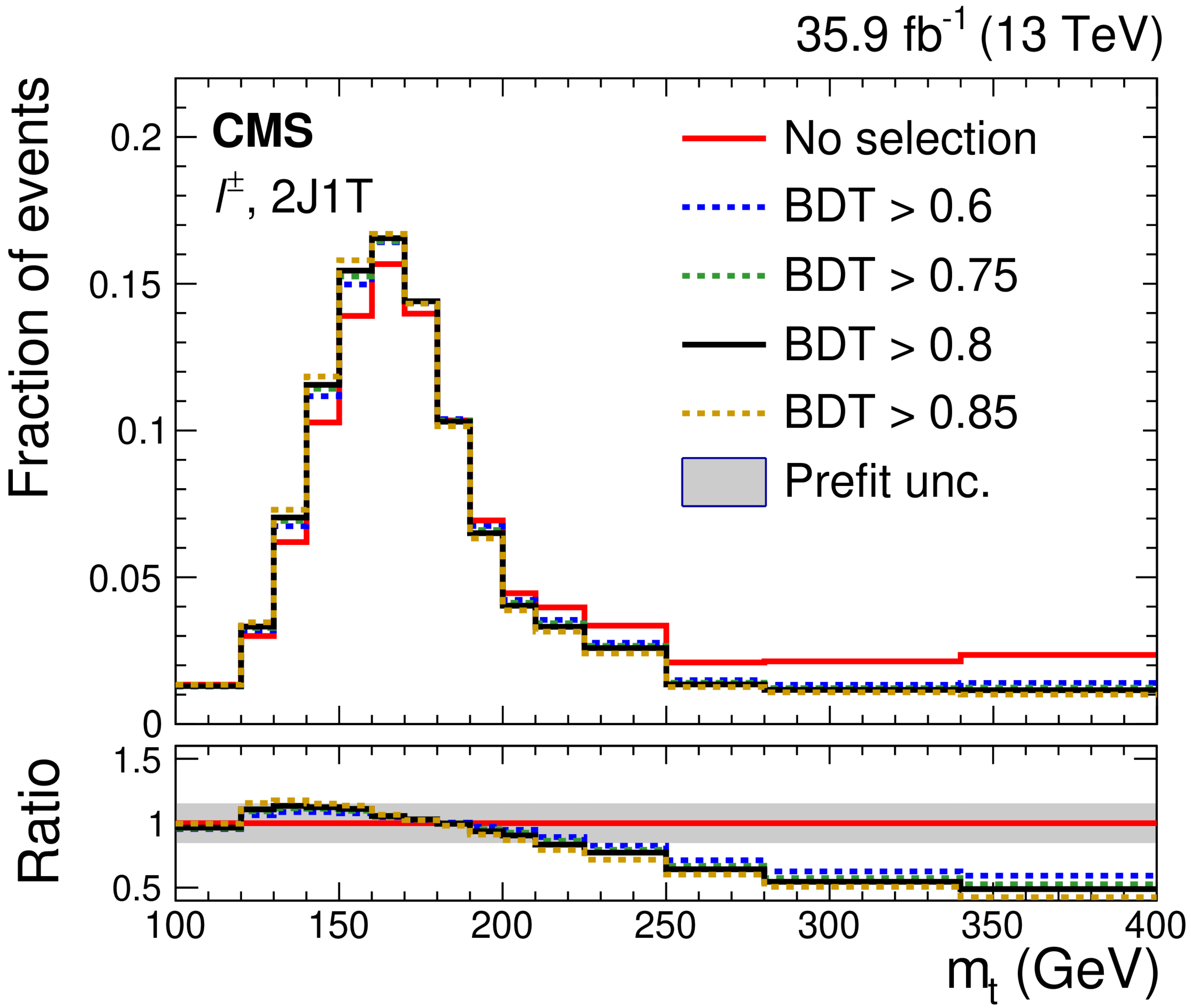
BDT inputs

Variable	Rank Muon	Rank Electron	Description
$\Delta R_{\mathrm{bj'}}$	1	1	Angular separation in (η, ϕ) space between the b-tagged and untagged jets
Untagged jet $\lvert\eta\rvert$ ($\lvert\eta_{\mathrm{j'}}\rvert$)	2	2	Absolute pseudorapidity of the untagged jet
$m_{\mathrm{bj'}}$	3	3	Invariant mass of the system comprising 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}	5	5	Transverse mass as defined in Eq. (1)
FW1	—	6	First-order Fox–Wolfram moment [64, 65] (electron final state)
$\lvert\Delta\eta_{l\mathrm{b}}\rvert$	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 the p_{T} of the b-tagged and untagged jets
$\lvert\eta_l\rvert$	8	—	Absolute pseudorapidity of the lepton (muon final state)

BDT performance

- Arrow indicate region of better separation between signal and bkgs.
- Area under ROC ~ 16 % (Lower is Better)





Extraction of m_t

- QCD bkg. contribution is subtracted from data ➛ 50% variation (shape + norm.) in estimated QCD bkg. contribution added as separate systematic source
- Simultaneous ML fit using ***y* = *ln* m$_t$** distributions in μ and e final states

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

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

- Signal and bkg. rates added as nuisance parameters to the fit & constrained using log-normal priors based on respective cross sections

$$f_{t-ch} \rightarrow 15\,\%\,, f_{Top} \rightarrow 6\,\%\,\&\, f_{EWK} \rightarrow 10\,\%$$

- Parametric fit model validated in bkg. enriched control region defined by $-0.2 < BDT < 0.8$
- Separate fits for ℓ^+ , ℓ^- , $\ell^\pm$ final states

Results

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

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

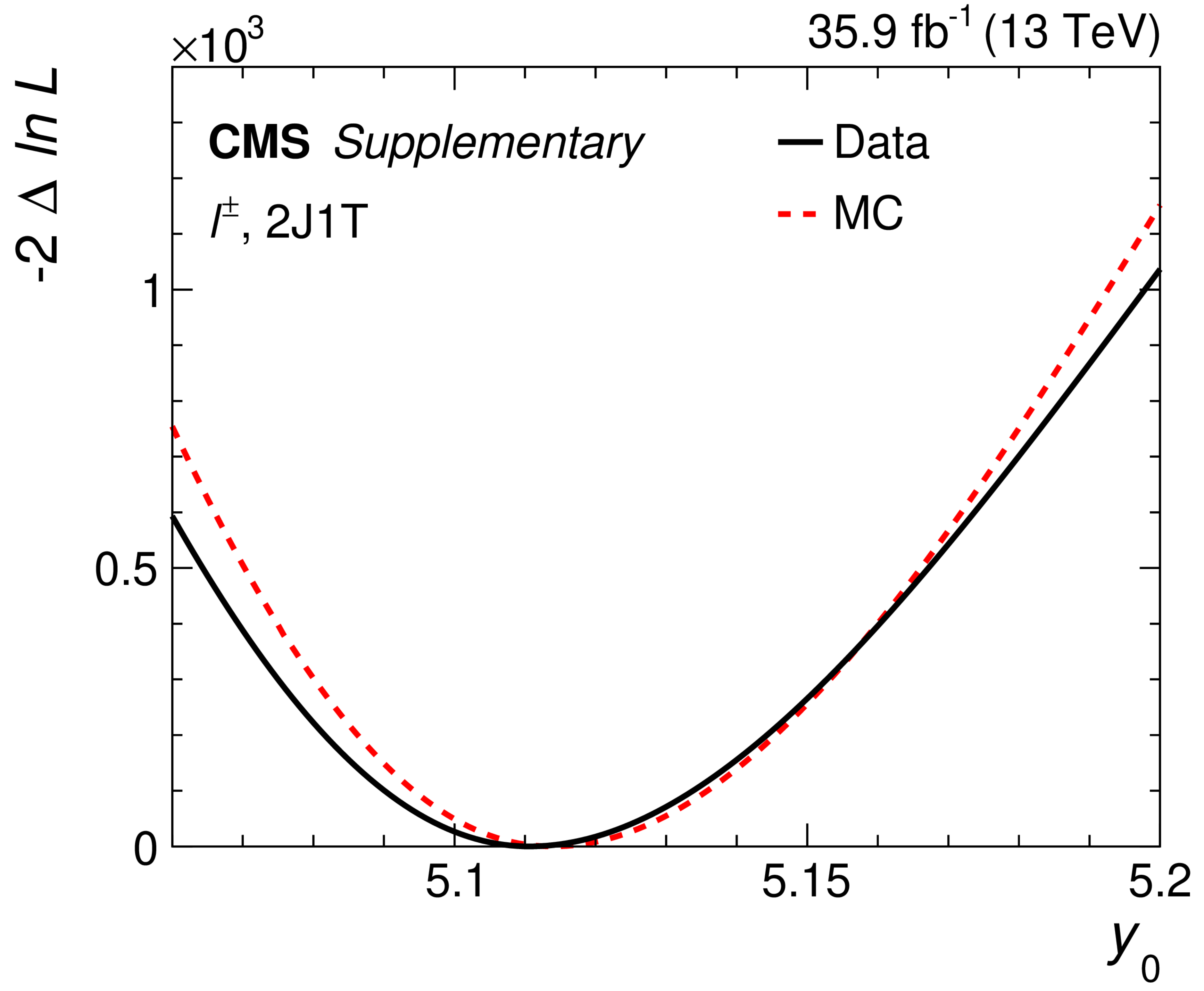
$$m_{\bar{t}} = 171.79 \pm 0.58\,(\text{stat} + \text{prof})\,^{+1.32}_{-1.39}\,(\text{ext})\,\text{GeV} = 171.79^{+1.44}_{-1.51}\,\text{GeV}$$

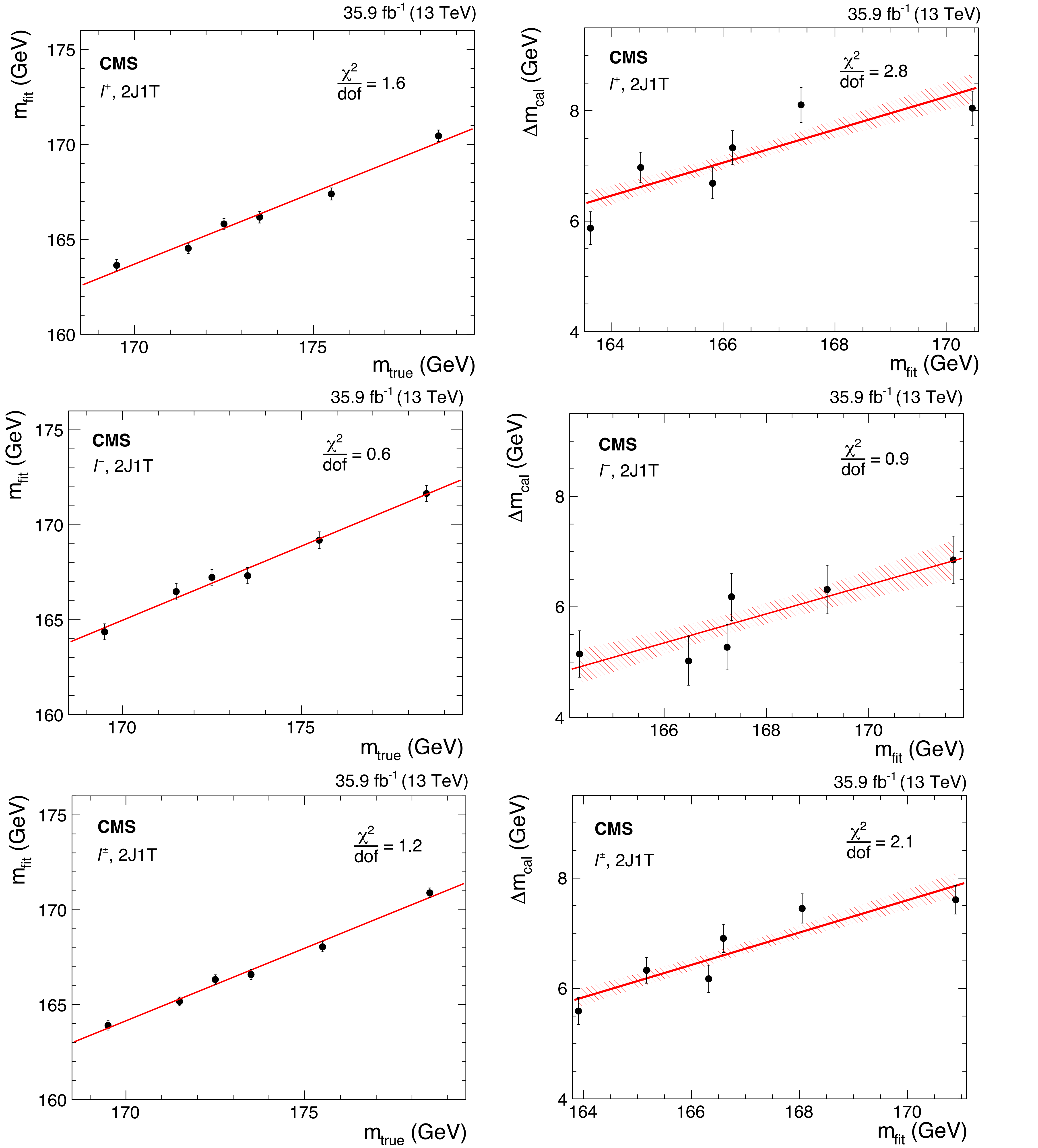
$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.9952 \pm 0.0040\,(\text{stat} + \text{prof})\,^{+0.0068}_{-0.0096}\,(\text{ext}) = 0.9952^{+0.0079}_{-0.0104}$$

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

Consistent with CPT invariance

Likelihood scan and mass calibration





- Different *true* m_t hypotheses considered for <u>*t-ch.* and $t\bar{t}$ simultaneously</u>
- Fit output (m_{Fit}) compared to *true* m_t & <u>offset is derived as a function of m_{Fit}</u> separately for ℓ^+ , ℓ^- , $\ell^\pm$
- Unc. due to offset calibration derived from $\pm 1\sigma$ band and considered as a separate systematic

Systematic Uncertainty Estimation

- Signal and bkg. rates are added as nuisance parameters in the fit (profiled systematic source)
- All other sources externalized ➛ fit repeated with varied templates (conservative approach)

Experimental

☞ **JES**: sub-categorized into different correlation groups according to JME-15-001

☞ **JER**

☞ **Unclustered energy:** 10% variation

☞ **Lepton efficiencies**: Total unc. on the efficiency SFs due to identification, isolation and trigger

☞ **Pileup re-weighting**: 4.6% unc. on $\sigma_{\text{min. bias}}$= 69.2 mb

☞ **b-tagging**: unc. on efficiency SFs based on jet kinematics and tagger discriminators

☞ **QCD bkg.**: 50% unc. on the estimated QCD bkg.

☞ **offset correction**: $\pm1\sigma$ unc. from the offset calibration curve

☞ **Luminosity**: 2.5% unc. according to LUM-17-001

Modeling

☞ **Flavor-dependent JES**: Correlated across *jet flavors* (gluon, light [uds], charm and bottom) as well as *signal and bkg. processes*

☞ **b-quark had. model:** Dedicated *event weights* for

- ➛ $\pm1\sigma$ variations of Bowler-Lund parameters
- ➛ comparison with Peterson parameterization
- ➛ unc. on semi-leptonic branching ratio of B hadrons *from PDG*

☞ **Color Reconnection (CR):** 2 alternate CR models considered for *t - ch.* and $t\bar{t}$ simultaneously using *dedicated MC samples*

☞ **Signal modeling:** Dedicated *event weights* corresponding to

- ➛ **ISR and FSR scale** variations
- ➛ μ_R/μ_F **scale** variations
- ➛ **PDF (NNPDF3.0) +** α_S variations

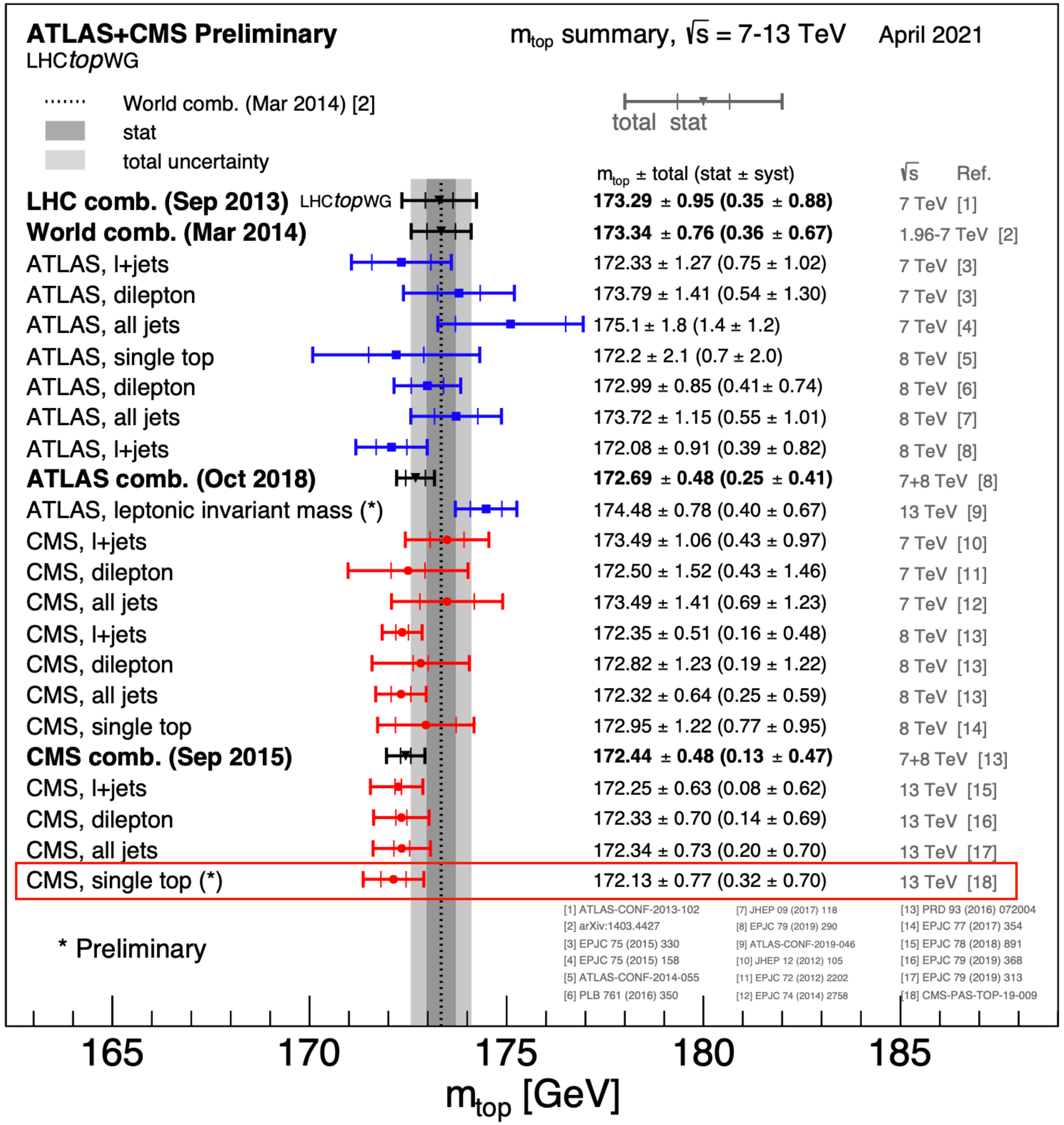
☞ $t\bar{t}$ **Modeling:**

- ➛ using *dedicated MC samples* for variations of **ISR & FSR scales, ME-PS matching scale** & **UE tune**
- ➛ *event weights* for μ_R/μ_F **scale, PDF+** α_S & **top** p_T **re-weighting**

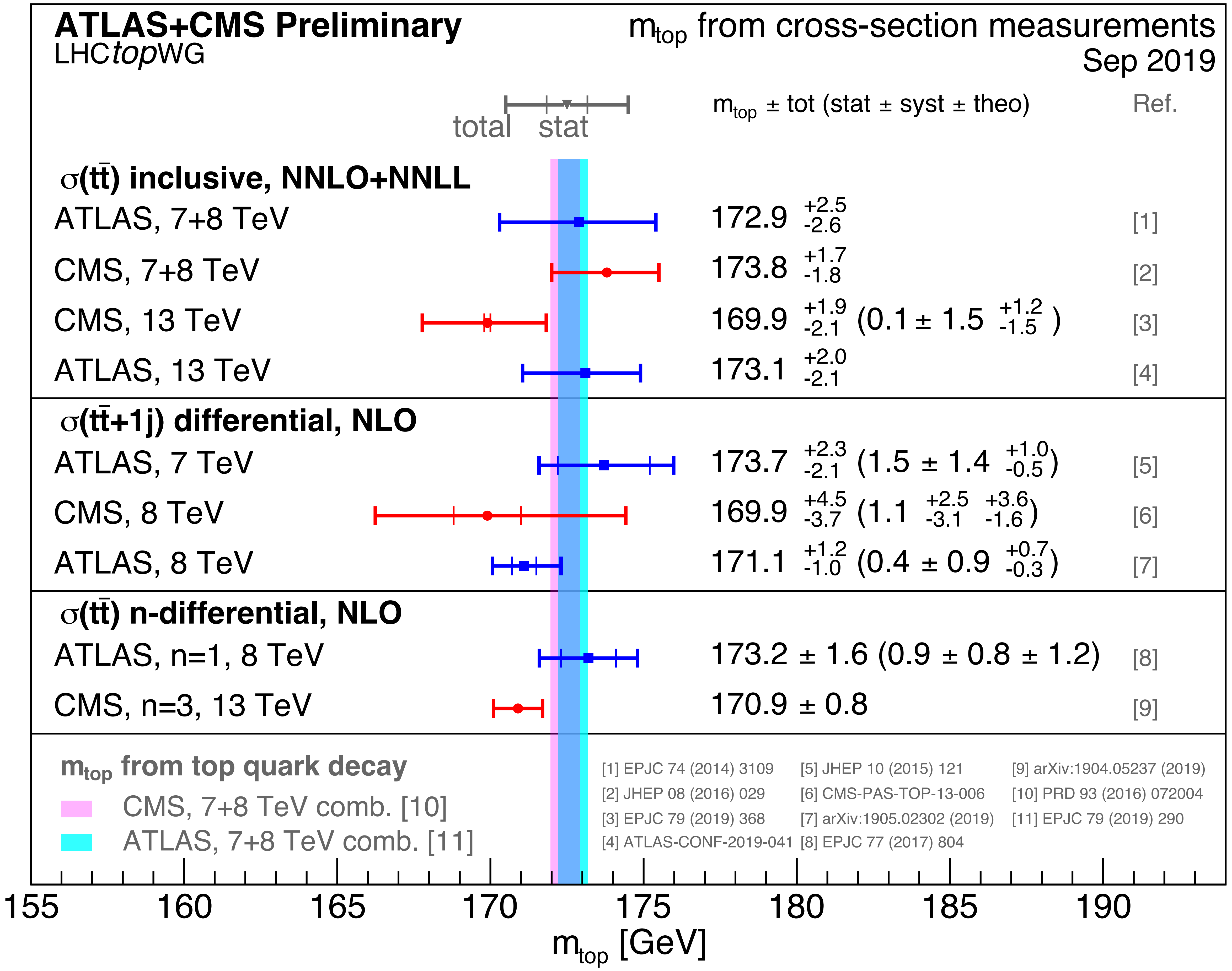
☞ **Signal and bkg. shape:** $\pm3\sigma$ variation of shape parameters

Summary of m_t measurements

Direct measurements



Indirect measurements



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots