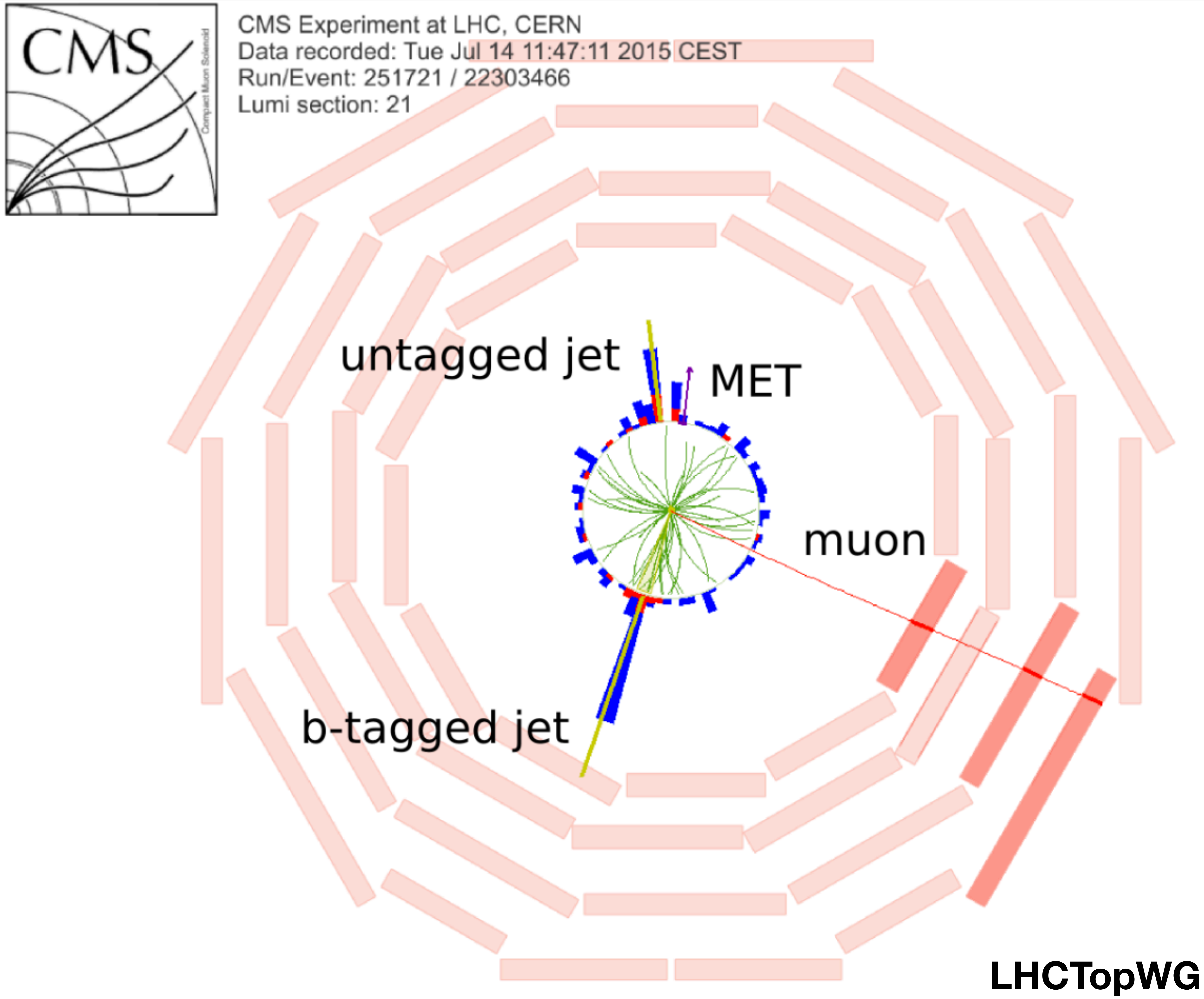
Measurement of the top quark mass (m_t) in single top enriched events at $\sqrt{s}$ = 13 TeV



CMS-PAS-TOP-19-009

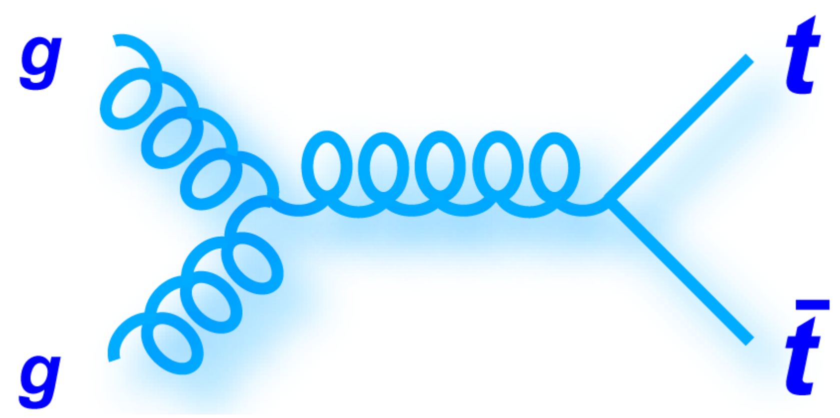
Soureek Mitra (Karlsruher Institut für Technologie)

On behalf of CMS collaboration

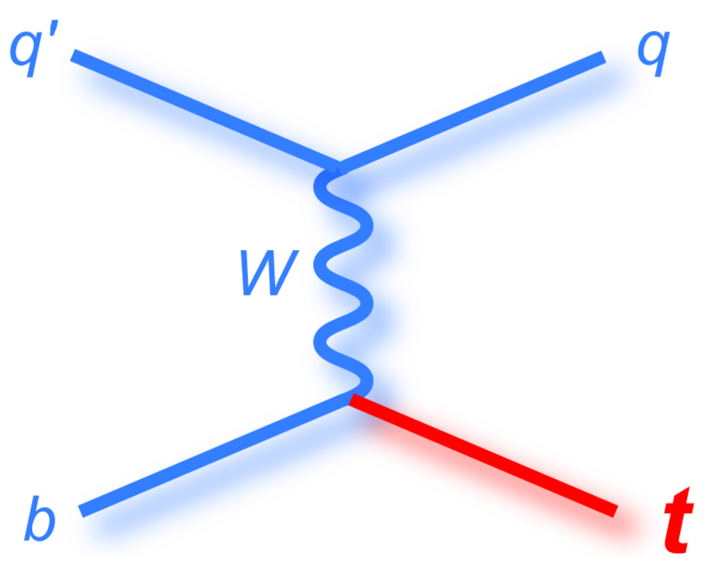
LHCTopWG Meeting, 2021

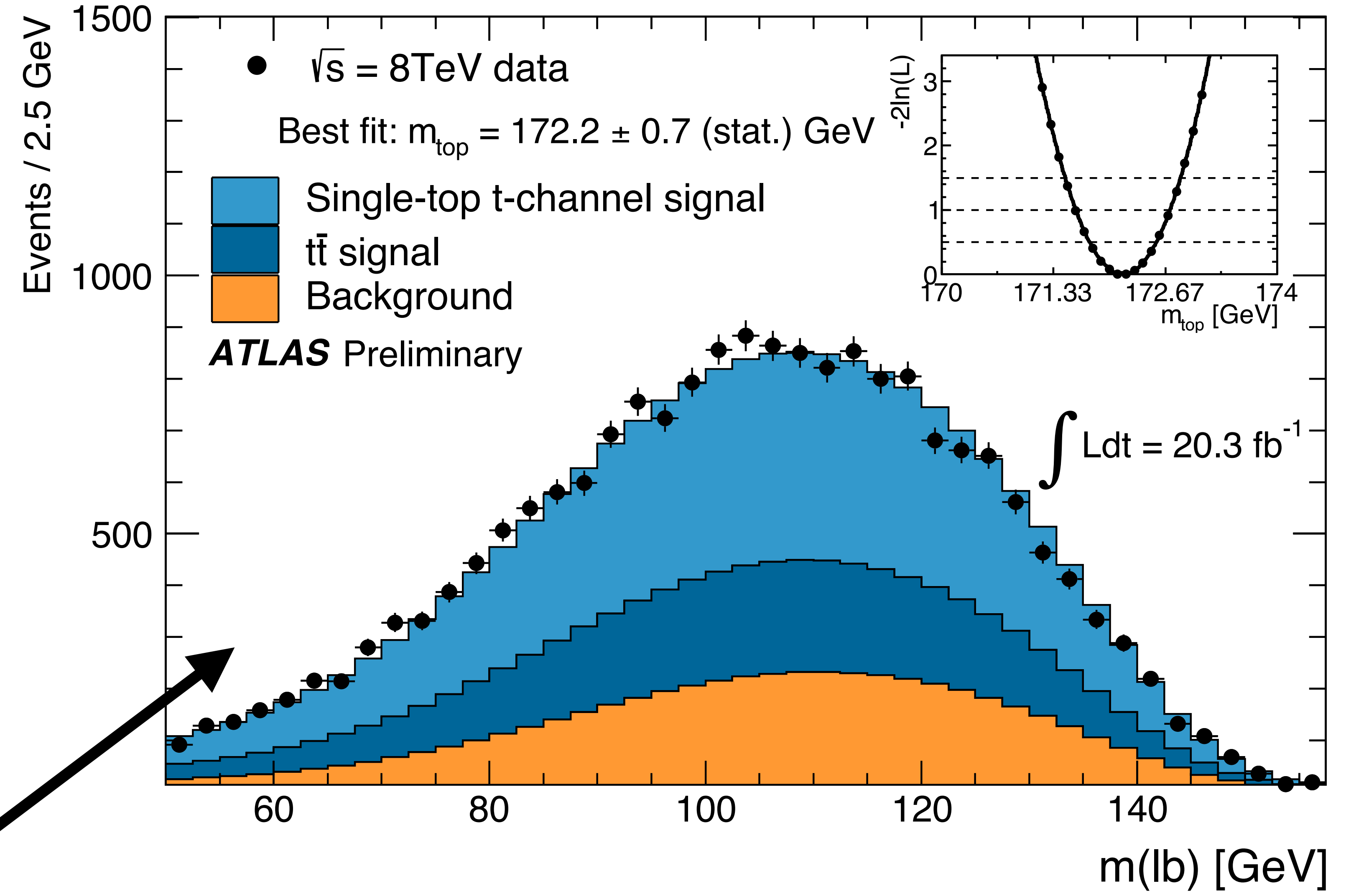
Motivation

- Top quark mass (m_t) is an important parameter of SM
  - ➛ Largest contributor in radiative corrections to W mass and Higgs self-coupling among SM particles ⇒ stability of EW vacuum
- $\Delta m_t = m_t - m_{\bar{t}}$ ➛ test of CPT invariance ⇒ Lorentz symmetry
- Traditionally m_t measurements performed with $t\bar{t}$ events

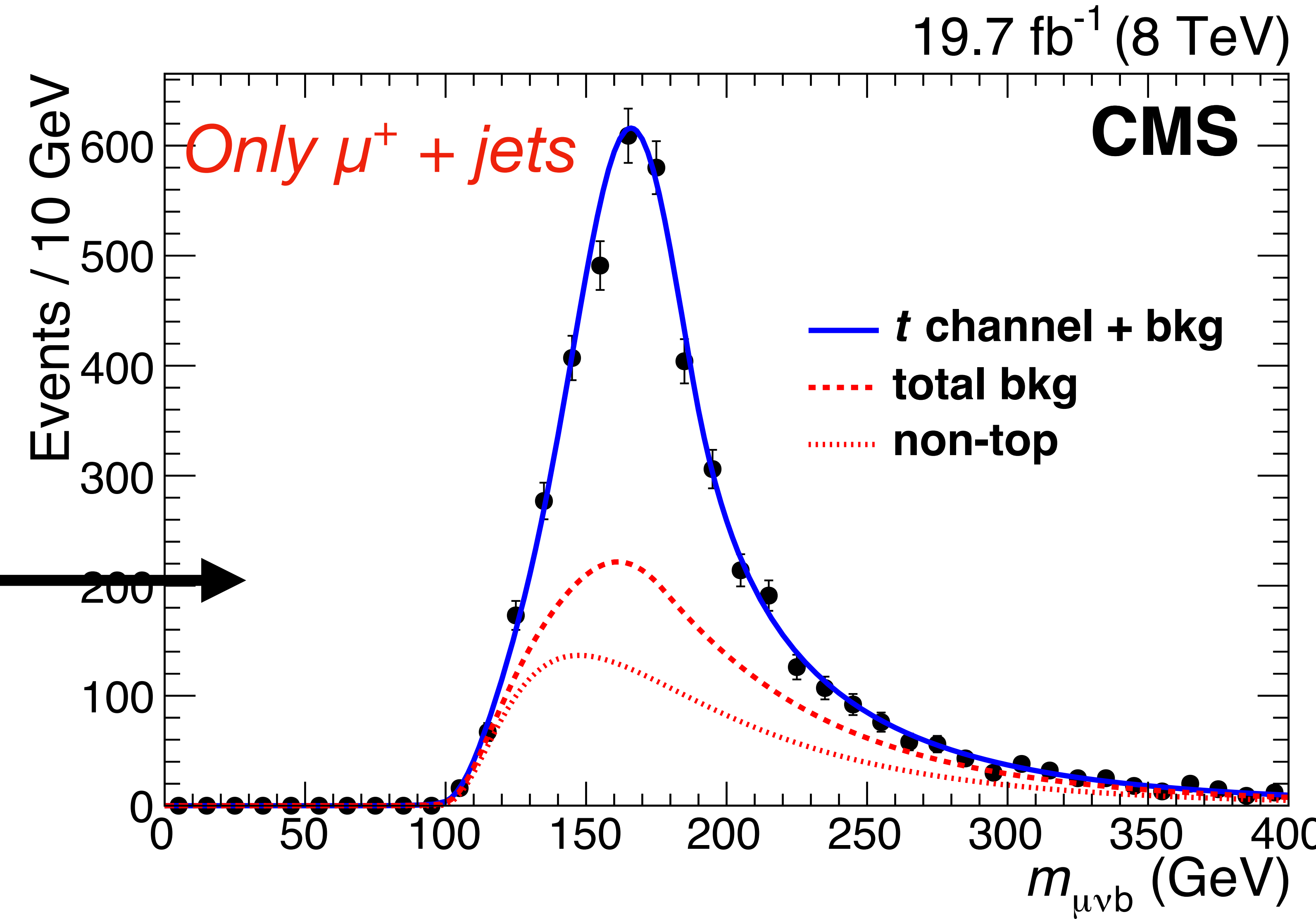


- Measurement in single top provides
  - ➛ measurement in an independent process
  - ➛ lower energy scale (>170 GeV) compared to $t\bar{t}$ (> 300 GeV)
  - ➛ partially uncorrelated systematics from $t\bar{t}$ measurements





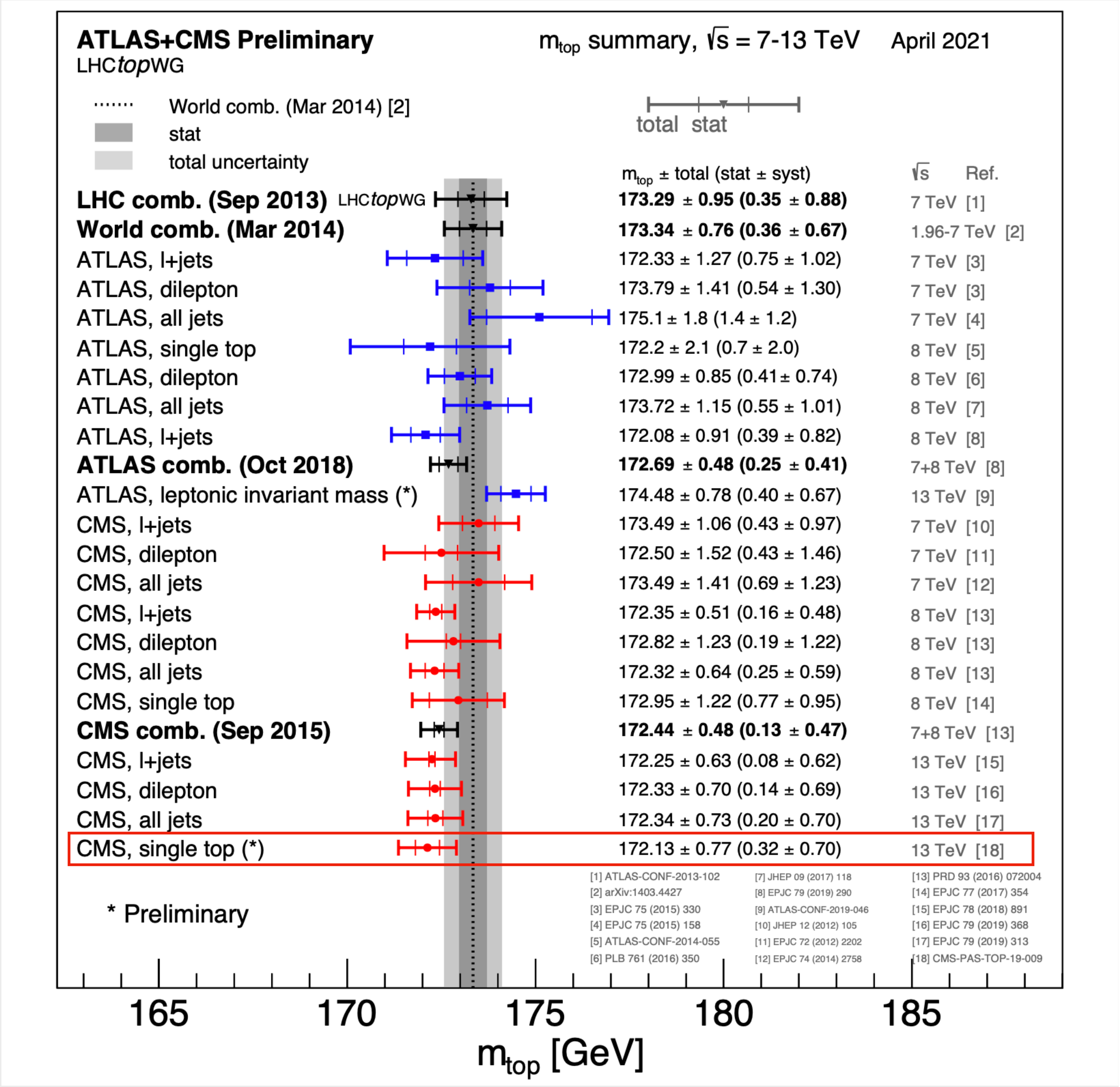
- ATLAS@8TeV (ATLAS-CONF-2014-055) :
  - ➛ Measurement: $\boxed{m_t = 172.2 \pm 0.7\,(\text{stat.}) \pm 2.0\,(\text{syst.})\,\text{GeV} = 172.2 \pm 2.1\,\text{GeV}}$
  - ➛ Dominant Unc.: $\text{JES}\,(\pm 1.5\,\text{GeV})$, $\text{t-ch. Had. modeling}\,(\pm 0.7\,\text{GeV})$
- CMS@8TeV (EPJC 77 (2017) 354) :
  - ➛ Measurement: $\boxed{m_t = 172.95 \pm 0.77\,(\text{stat.})\,^{+0.97}_{-0.93}(\text{syst.})\,\text{GeV} = 172.95^{+1.24}_{-1.21}\,\text{GeV}}$
  - ➛ Dominant Unc.: $\text{JES}\,(^{+0.68}_{-0.61}\,\text{GeV})$, $\text{Fit Calibration}\,(\pm 0.39\,\text{GeV})$



Summary of m_t measurements (so far)

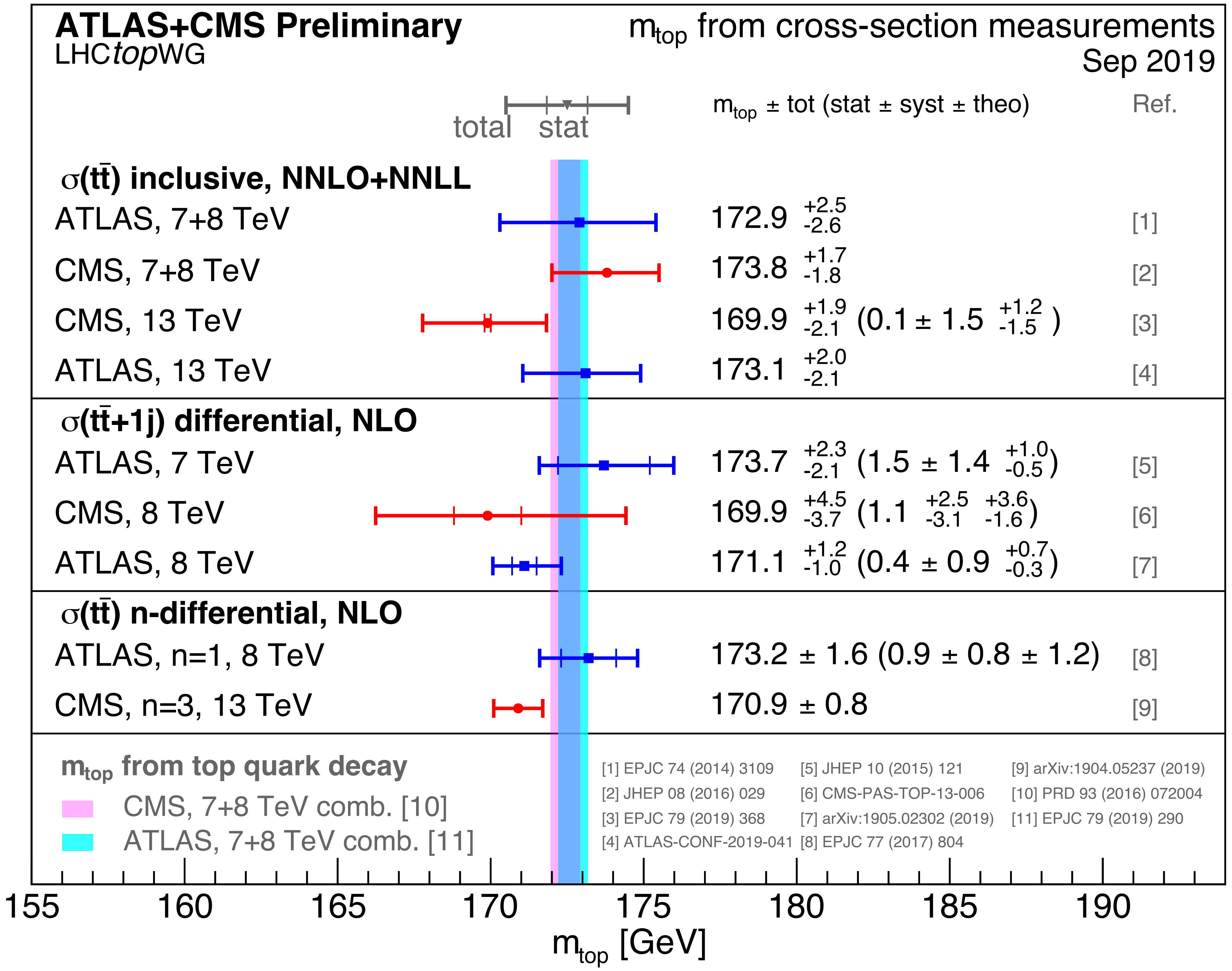
Direct measurements

➛ m_t reconstructed from daughters ⇒ running mass



Indirect measurements

➛ m_t^{pole} determined from cross section measurements

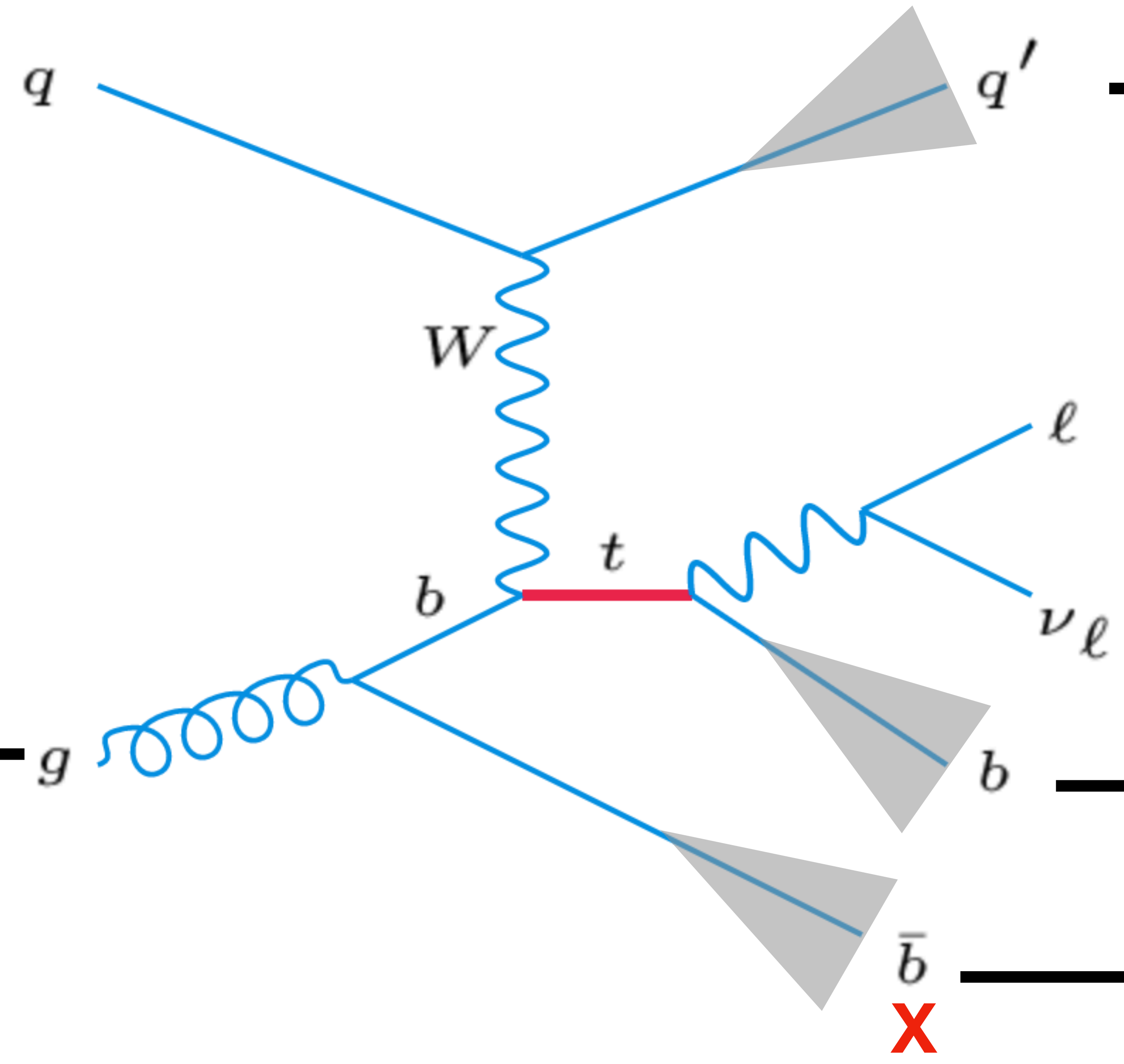


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

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 $|\eta| < 4.7$

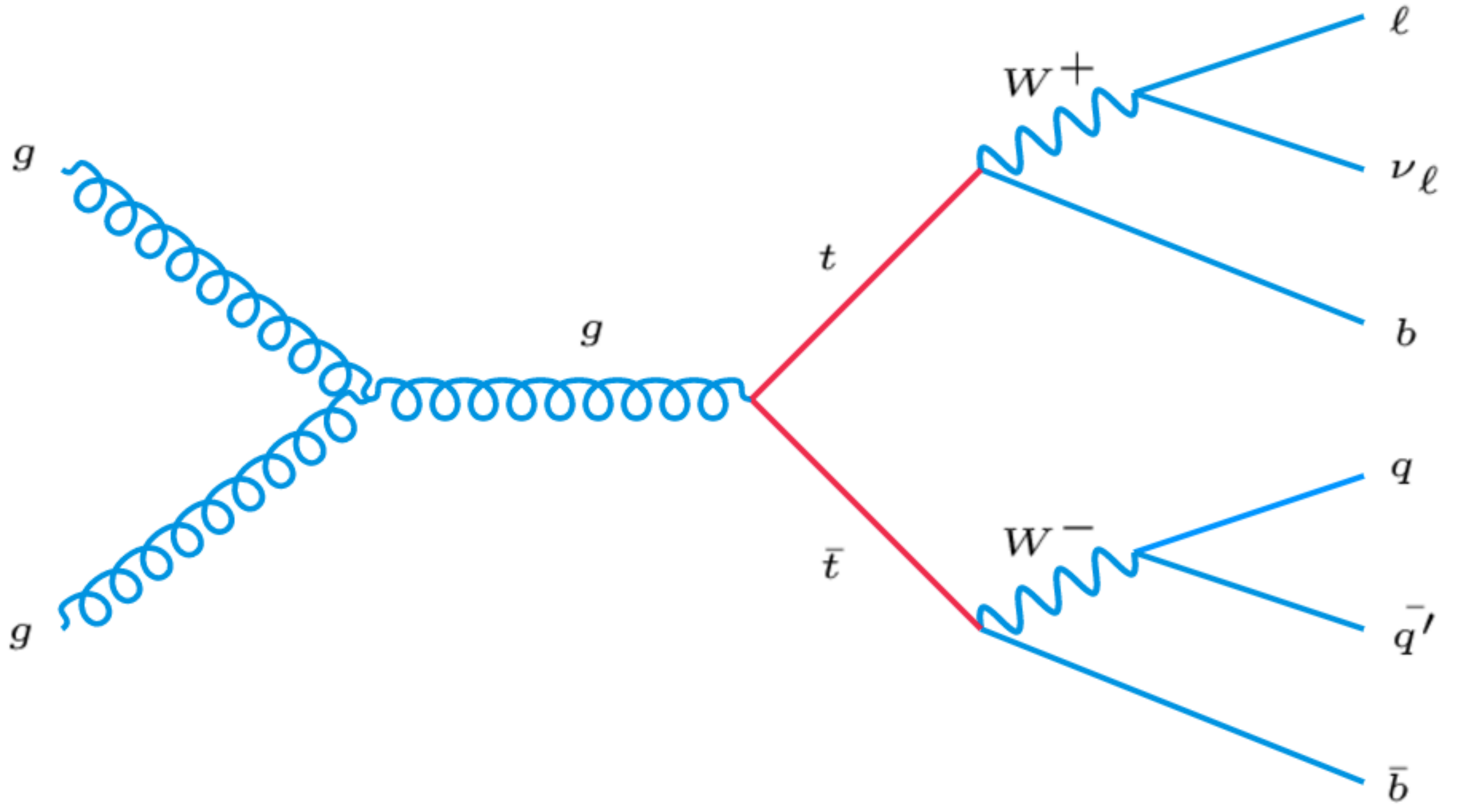
→ Exactly 1 isolated high-p_T (> 26 [35] GeV) μ [e] ; $|\eta| < 2.4$ (2.1)

→ Missing p_T

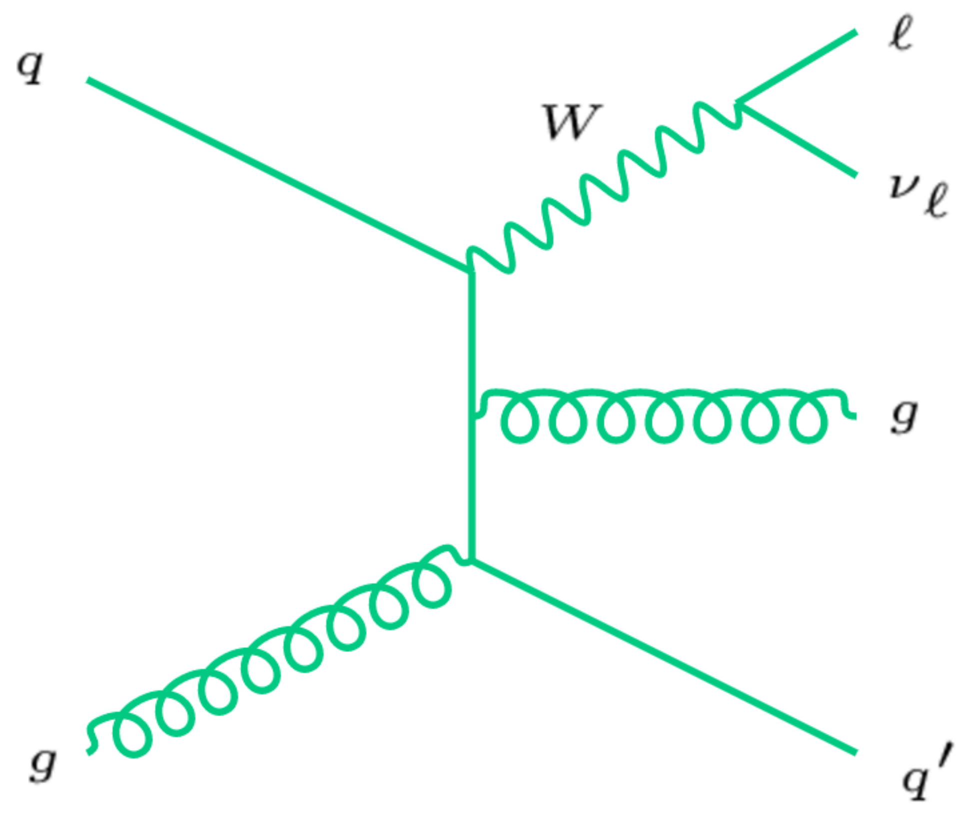
→ High-p_T (> 40 GeV), central ($|\eta| < 2.4$) b-jet (tight-tagged)

→ 2nd b-jet: mostly out of tracker acceptance or has very low p_T

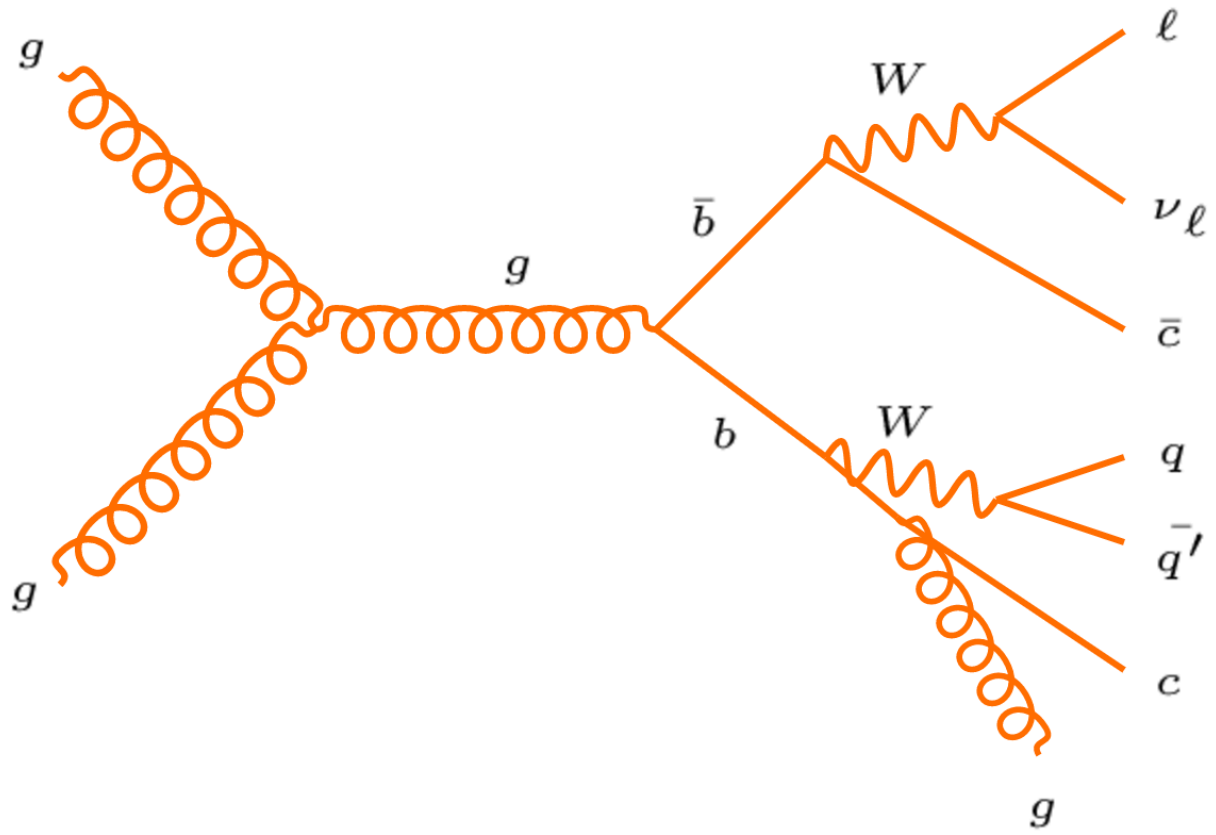
No b-quark at initial state (4FS ME) ←



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



$W + \mathrm{jets}: \sigma(13\,\mathrm{TeV}) \approx 6 \times 10^4\,\mathrm{pb}$



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

Estimation of QCD multijet bkg.

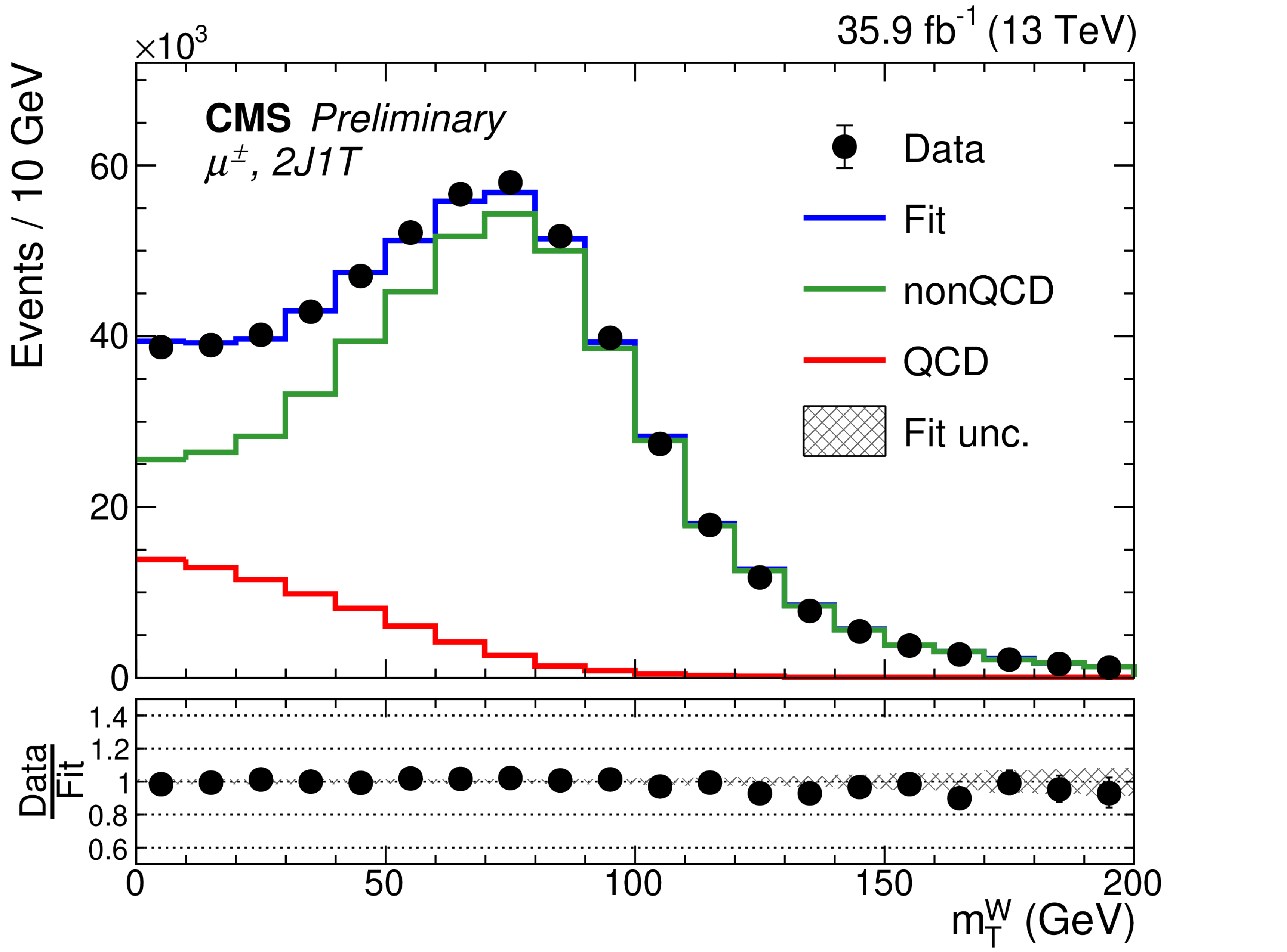
- Large cross section but low selection efficiency ⇒ require very high stat. MC sample for accurate templates after event selection

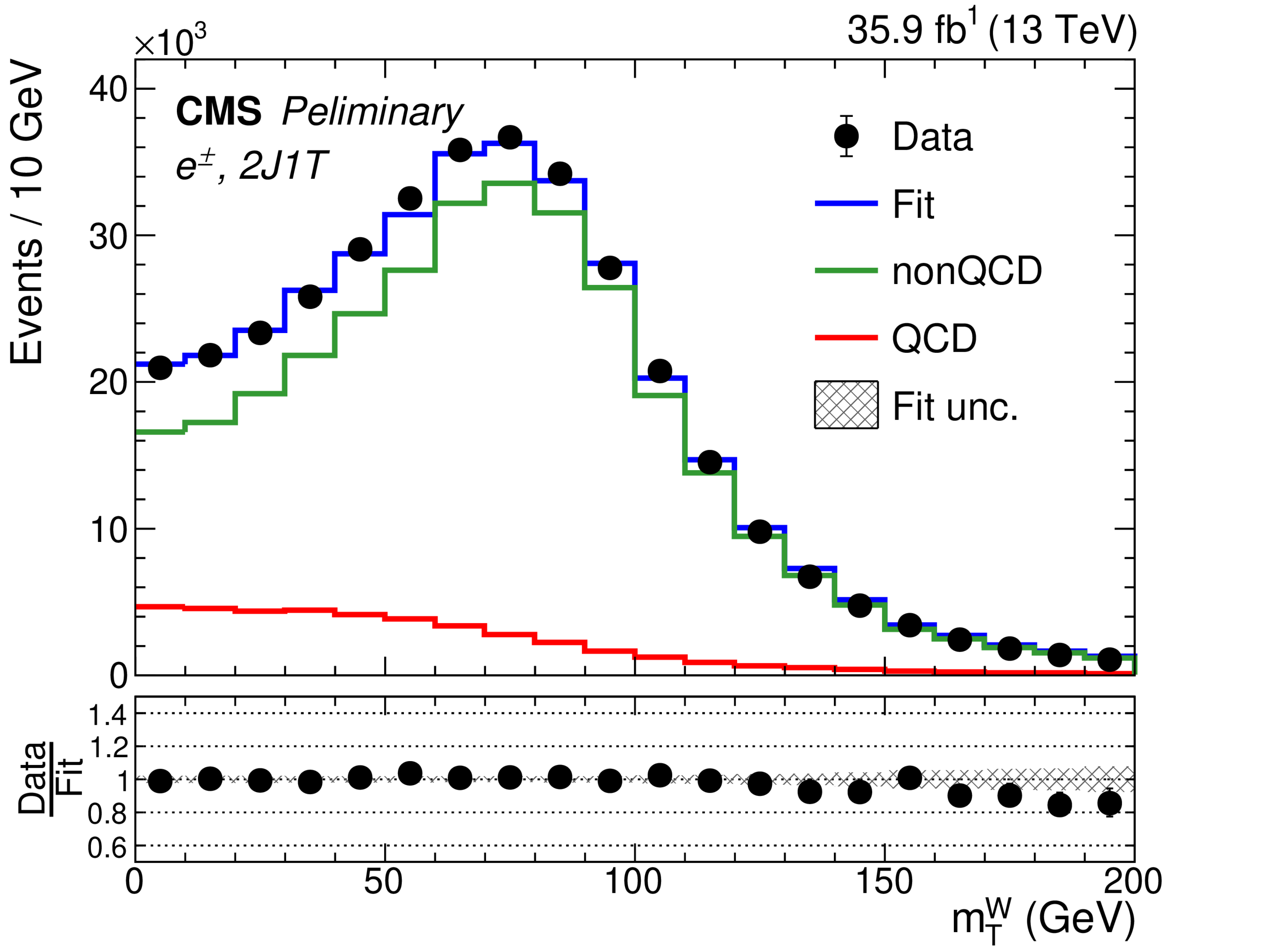
- QCD-enriched side-band (SB) in data ➛ invert rel. isolation (identification) criteria of the muon (electron) in the final state

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

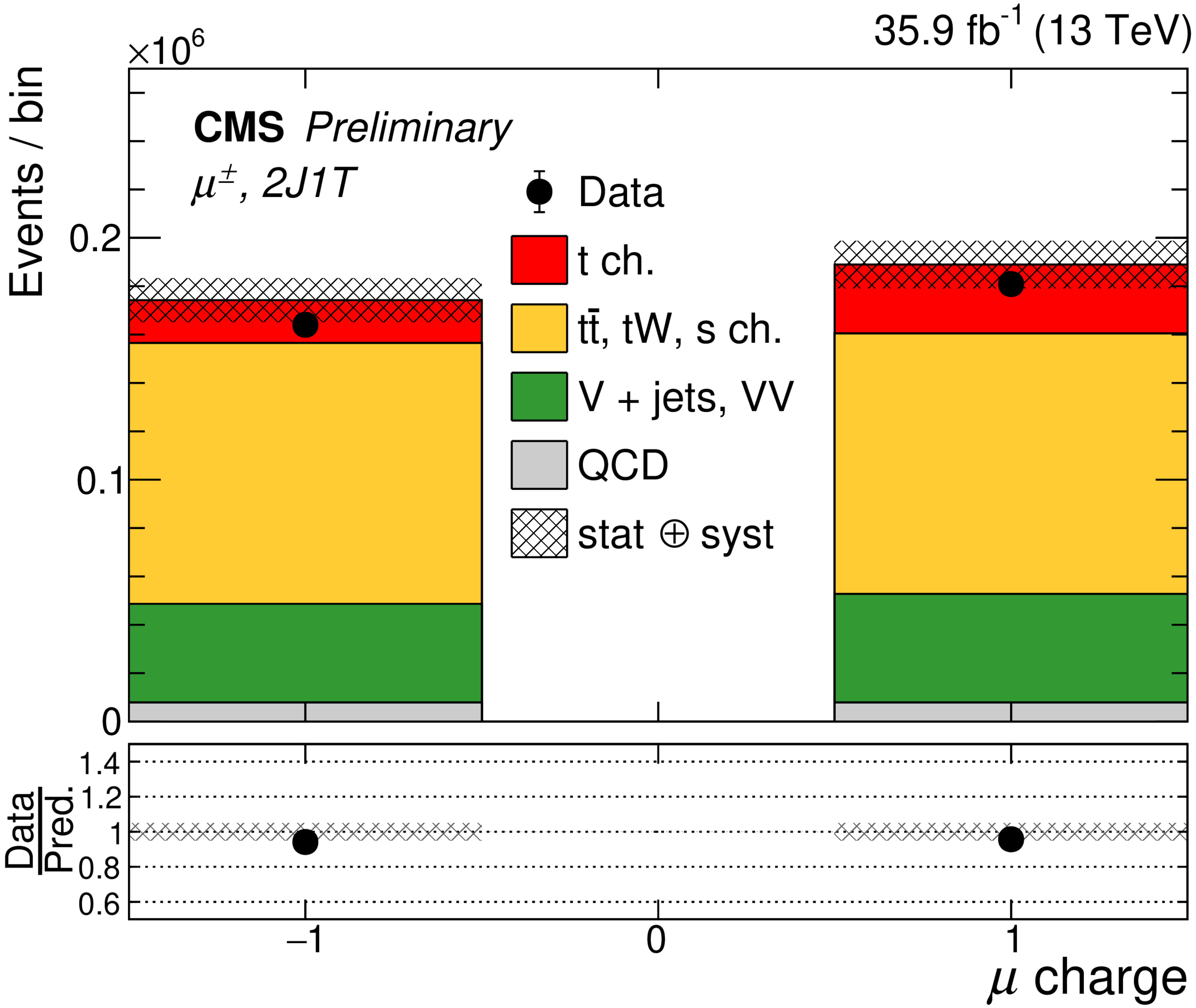
- Shape derived from SB and post-fit yield $m_T^W > 50$ GeV for QCD bkg. considered for further analysis

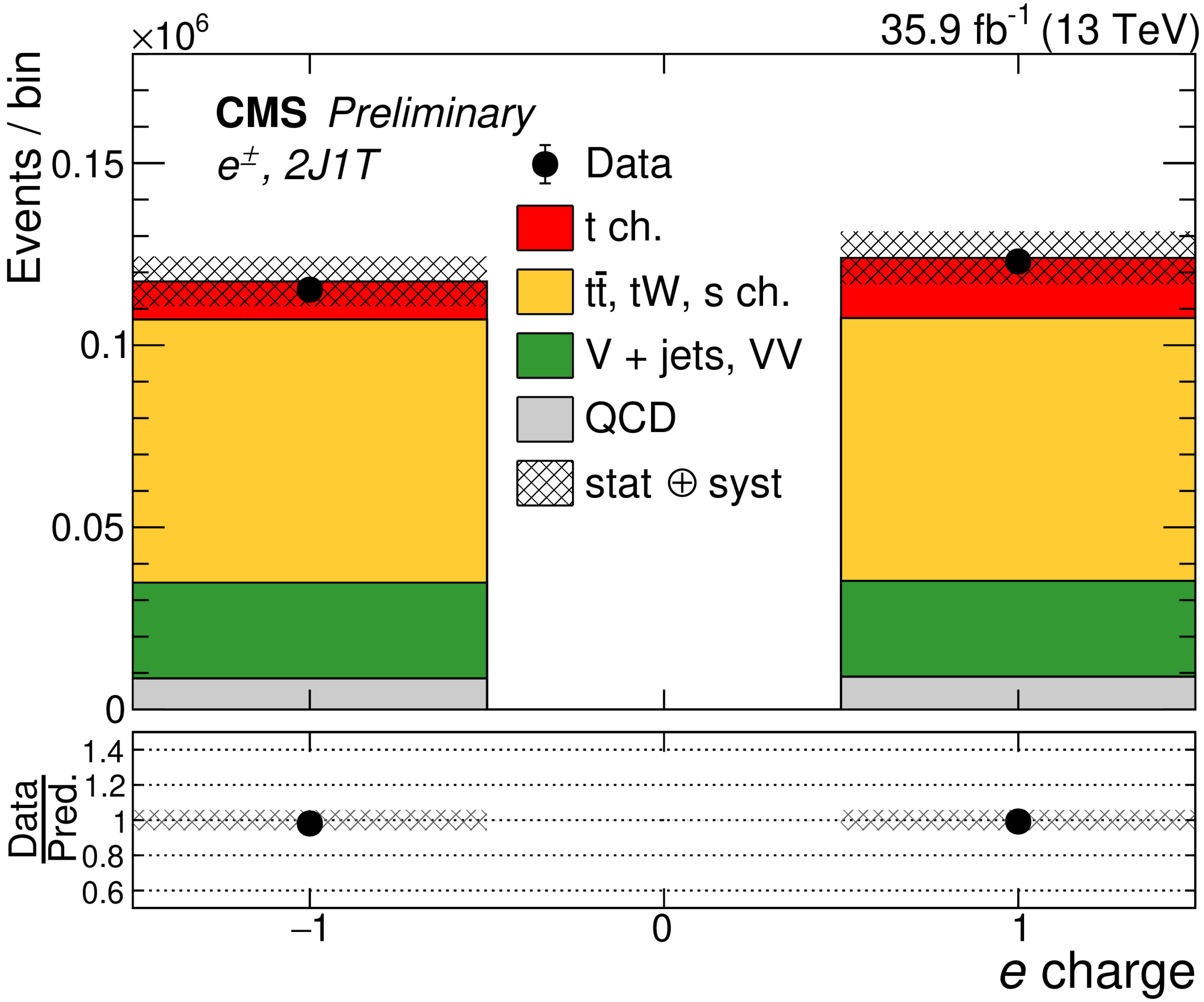
- 50% variation (shape + normalization) on the estimated QCD bkg. contribution as a systematic for final measurement



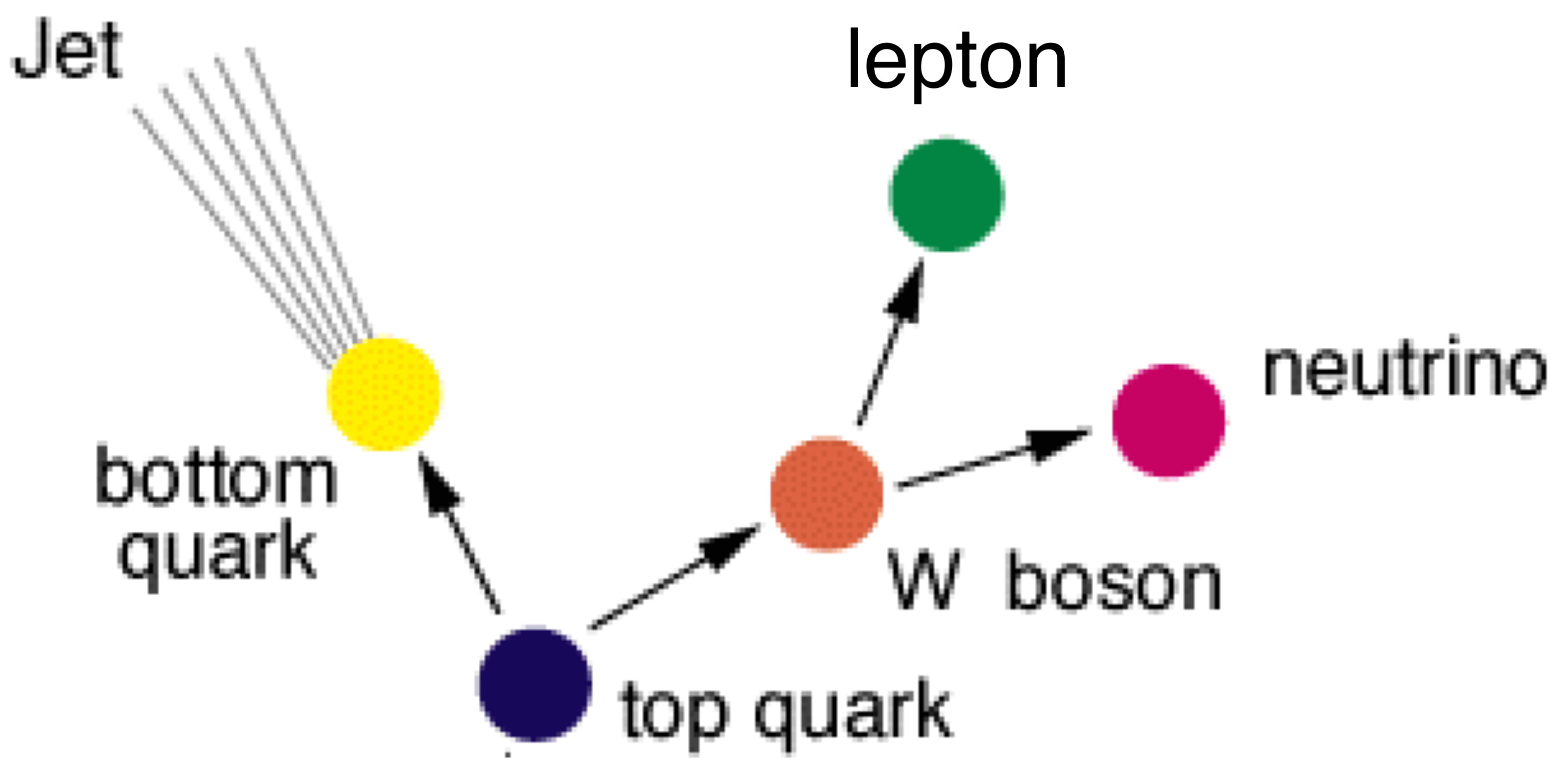


Event yields separated by lepton charge and flavor





Top Quark Reconstruction

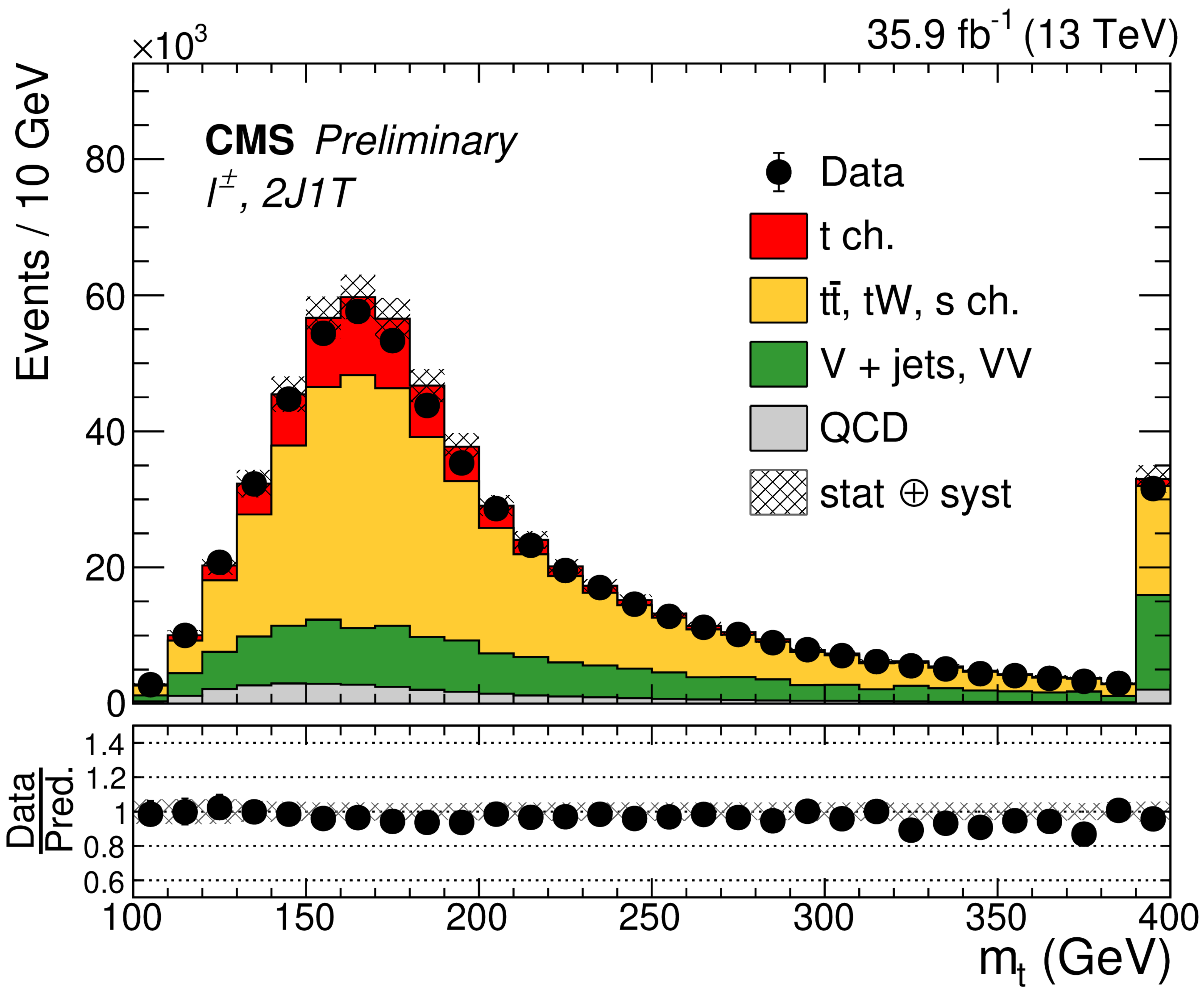


- Determine neutrino four-momenta from lepton and Missing p_T
- Estimate neutrino p_z from lepton four-momentum and Missing p_T

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

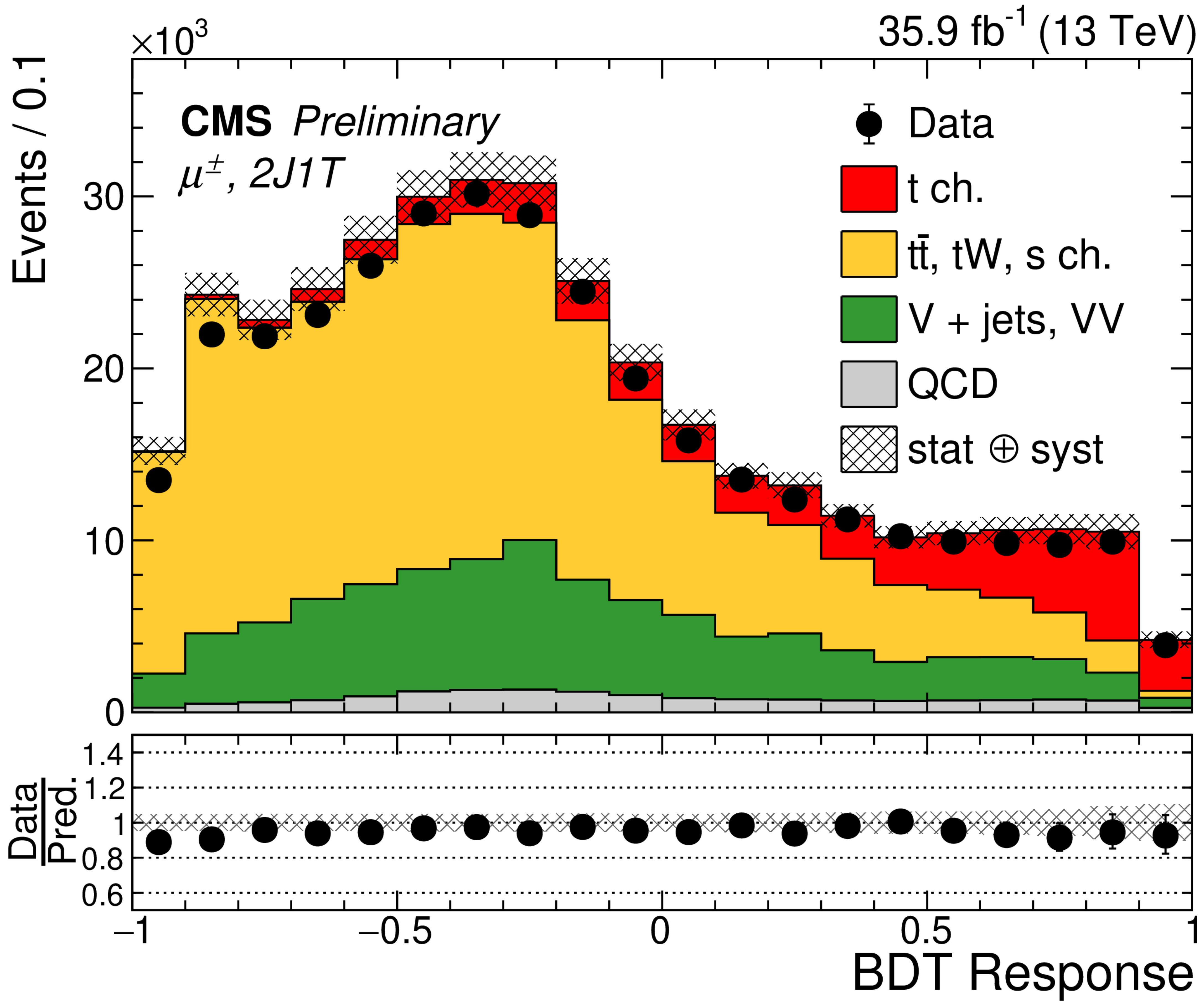
- Quadratic solution for neutrino p_z :
  - ☞ For real case (~ 65%):
    - ➛ choose the one with lowest | p_z | (accuracy ~ 64%)
  - ☞ For imaginary case (~ 35%):
    - ➛ Set radical equal to 0 ⇒ quadratic Eqn. in neutrino p_x and p_y
    - ➛ vary neutrino p_x and p_y keeping above Eqn. satisfied so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

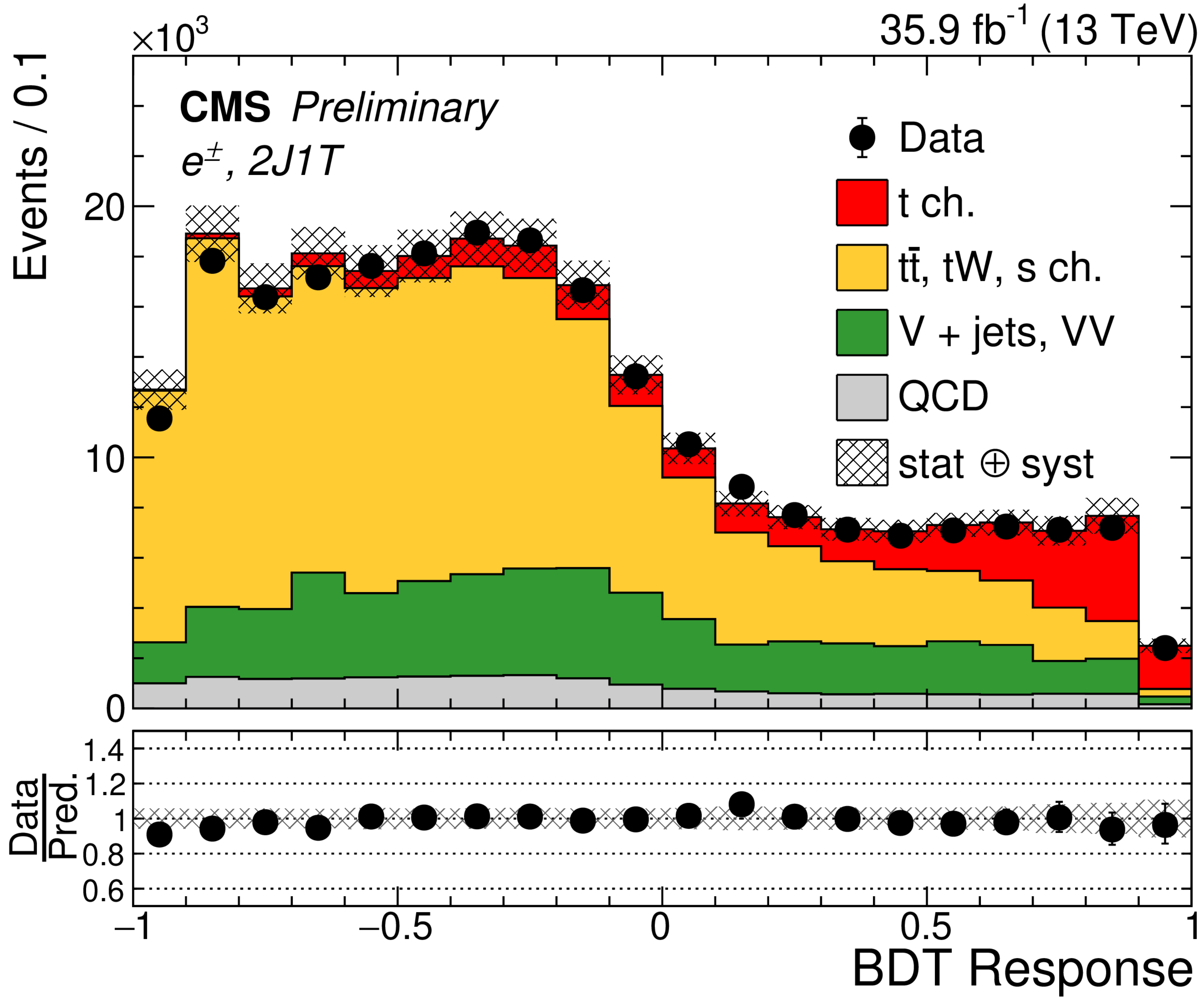
- Reconstruct W-boson from lepton and neutrino four-momenta
- Reconstruct top quark from b-jet and W-boson four-momenta



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

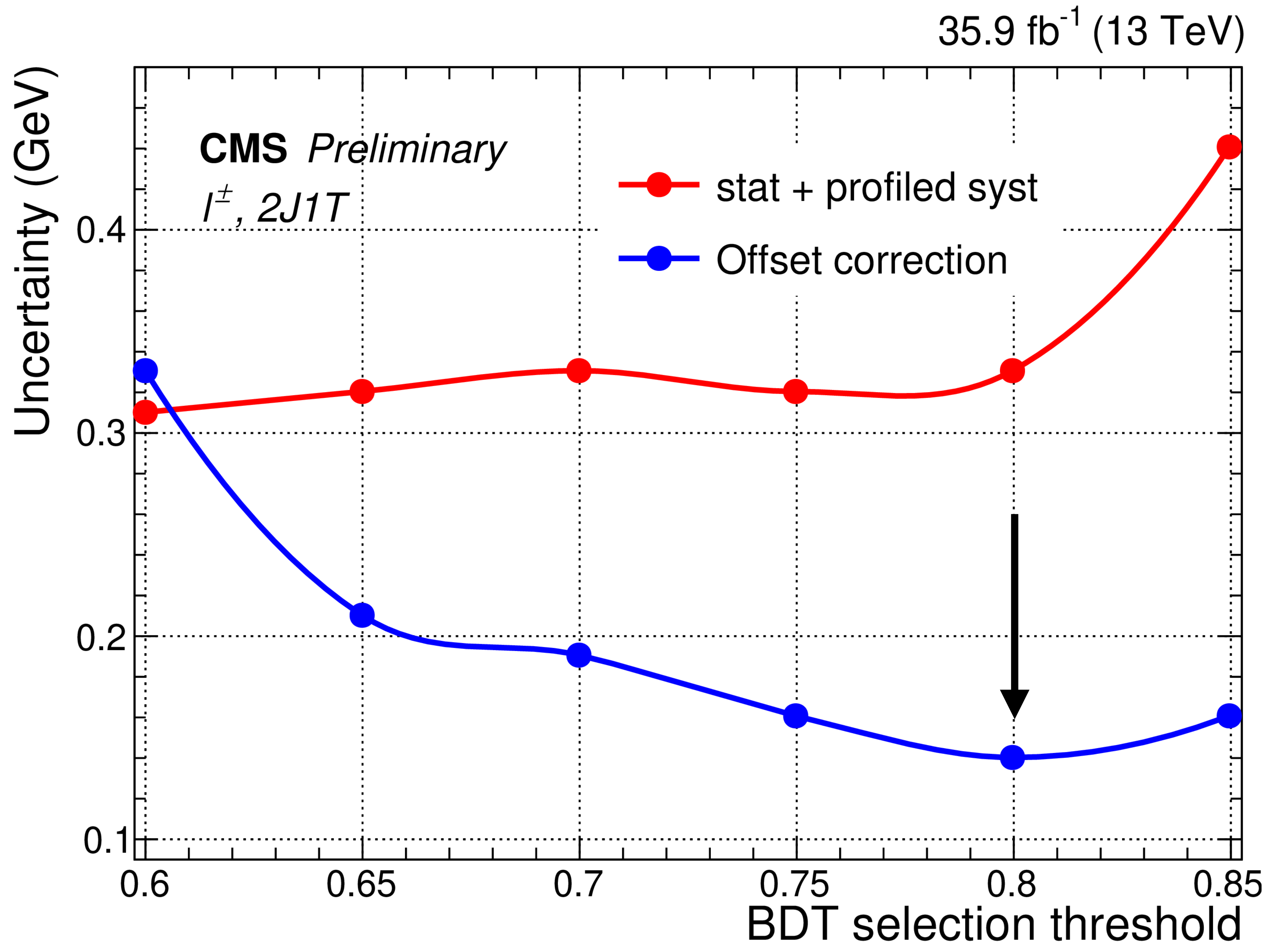
BDT discriminators

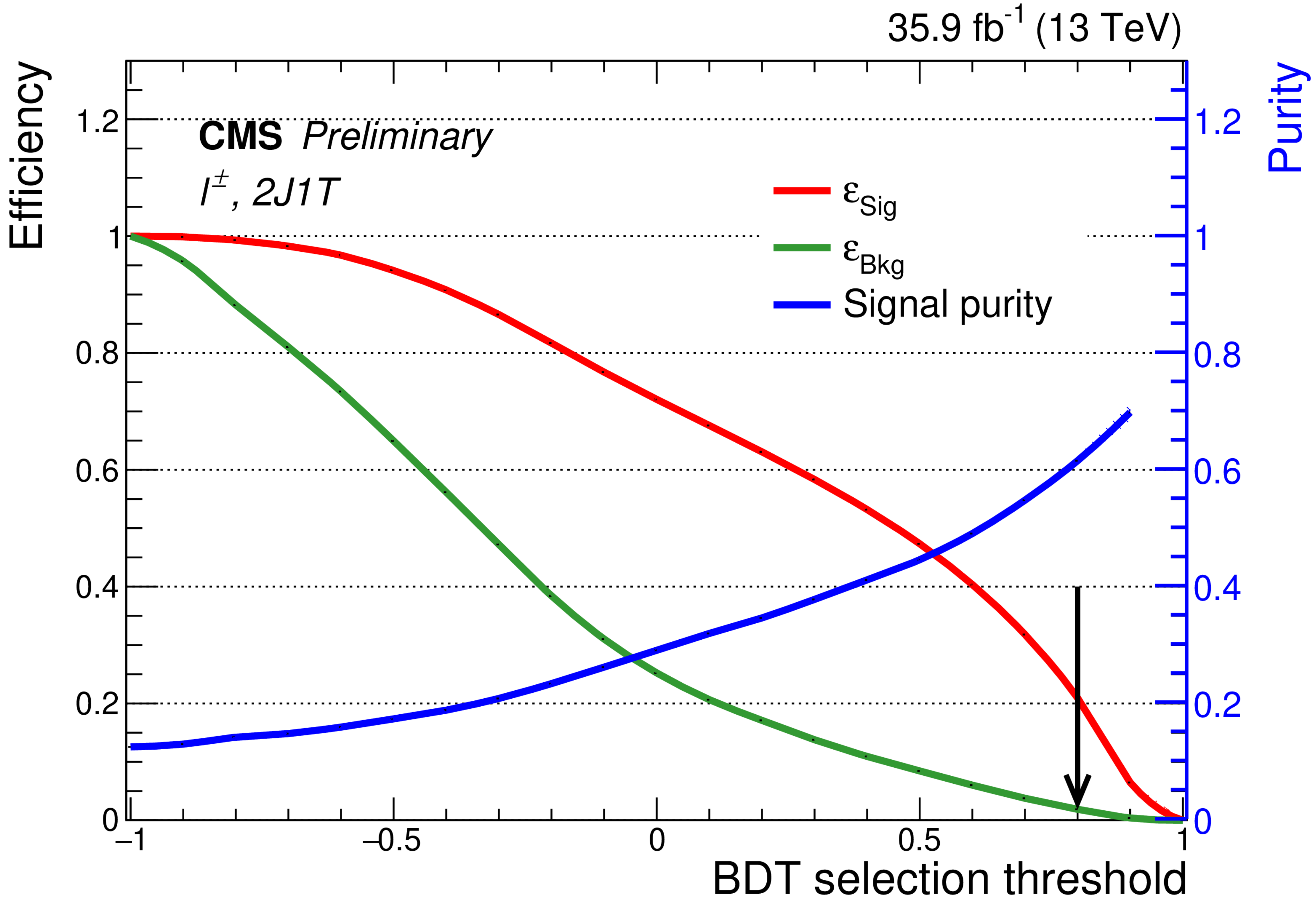




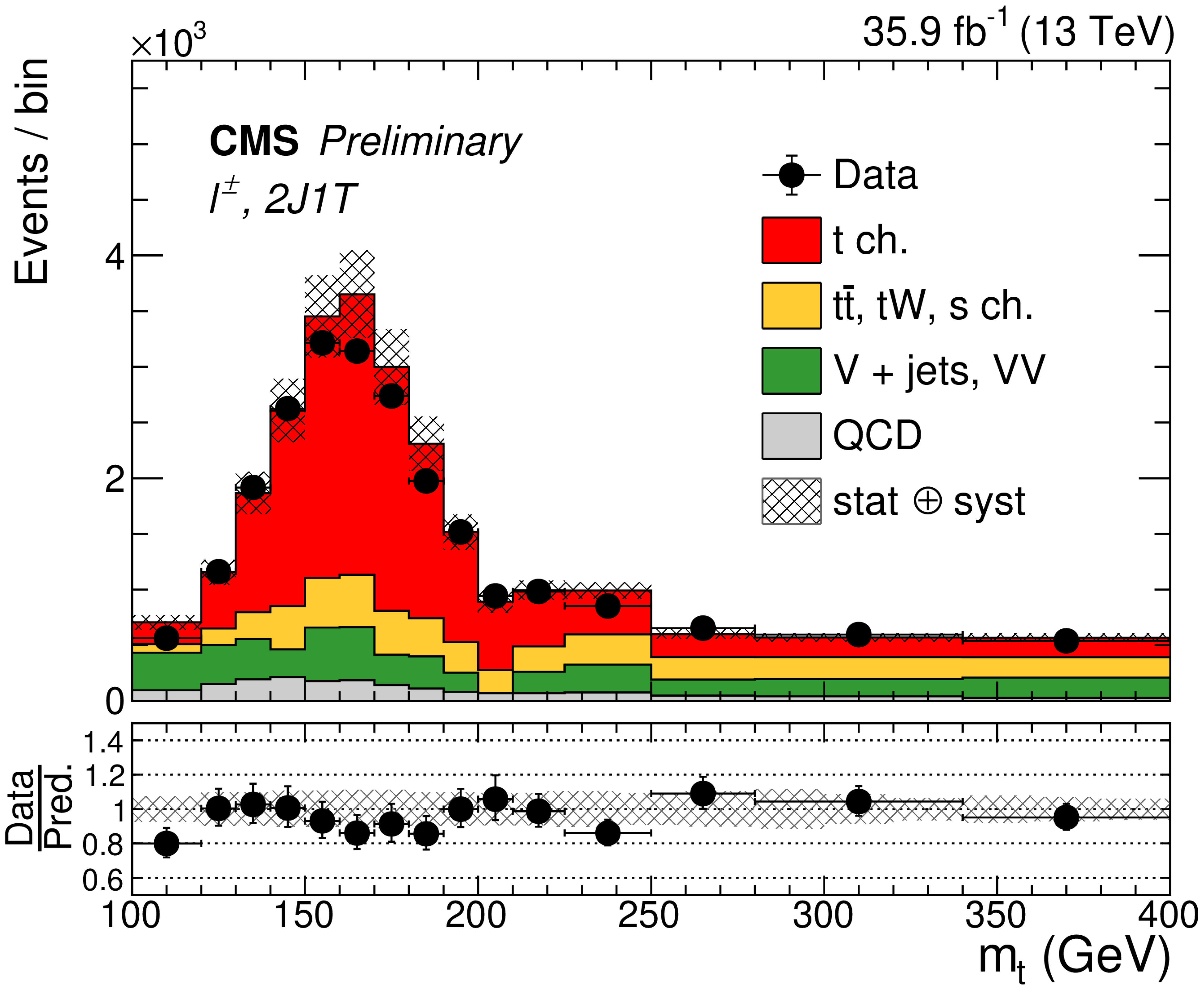
Optimization of BDT cut

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





m_t after BDT selection



- m_t distribution *highly skewed* ➛ difficult to model accurately using parametric shapes
  ⇒ Use $\ln m_t$ for fit ➛ low skewness, more symmetric and easy to model

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
  - ➢ ***m_{Fit} = TMath::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

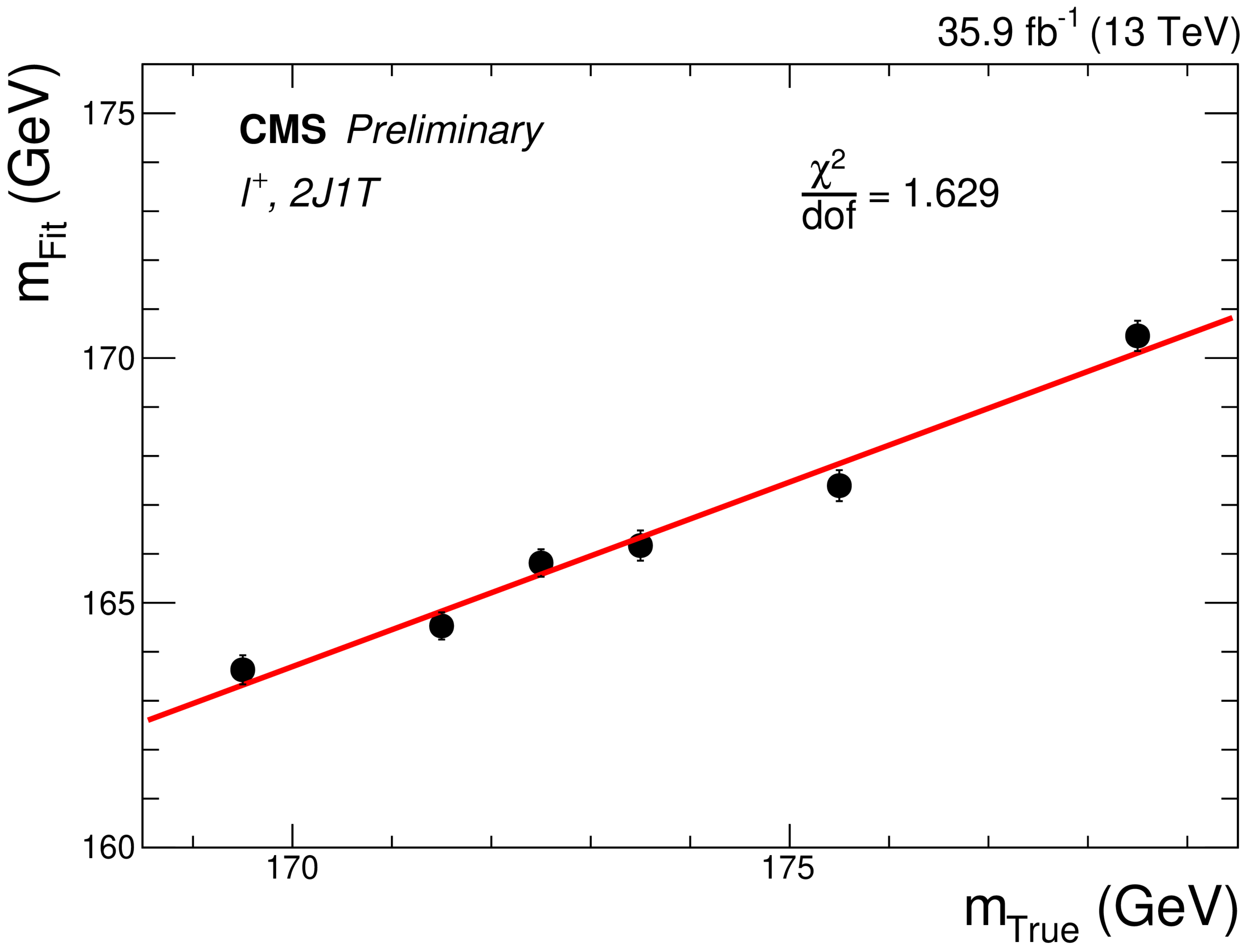
Postfit distributions

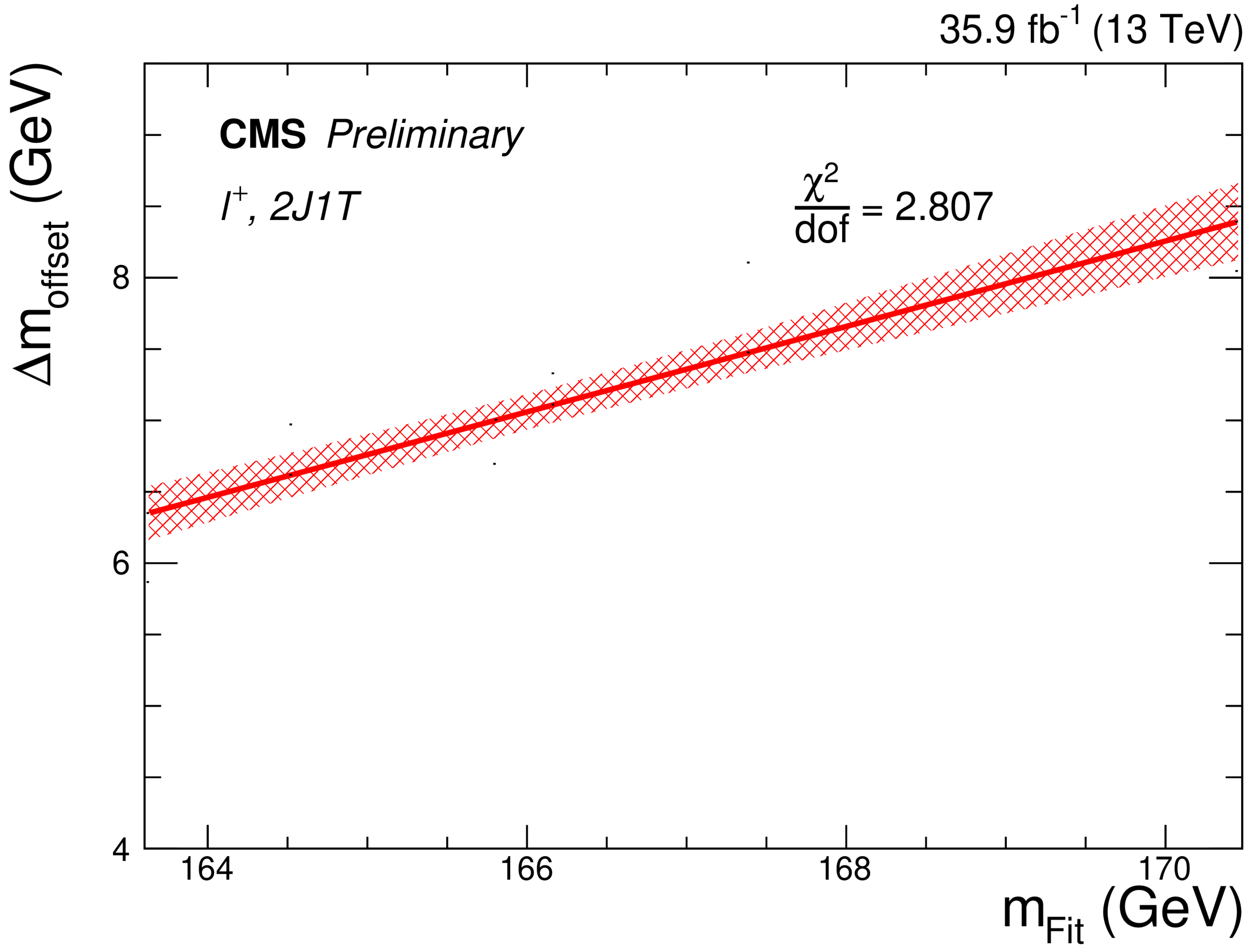
- Peak region well-modeled by fit
- Higher relative bkg. contribution in the ℓ^- final state

➛ charge asymmetry of W boson radiated from the initial state quark in the signal process

Offset calibration w.r.t *true* m_t

- 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





Uncertainty Table

- Signal and bkg. rates are added as nuisance parameters in the fit (profiled systematic sources)
- All other syst. sources externalized ➛ fit repeated with varied templates (conservative approach)
- Asymmetric uncertainties on the measurements
- Largest shift relative to the nominal result quoted in case of one-sided impact (conservative approach)
- Dominant sources on the $\ell^{\pm}$ case highlighted by shaded region
- Larger syst. uncertainties in case of ℓ^{-} final state due to higher relative bkg. contribution

	Source		$\delta m_{\ell\pm}$	$\delta m_{\ell+}$	$\delta m_{\ell-}$
	Statistical + profiled systematic		±0.32	±0.37	±0.58
Experimental Syst.	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 normalization		±0.02	±0.01	±0.02
	Offset correction		±0.11	±0.13	±0.20
	Luminosity		$< \pm0.01$	$< \pm0.01$	±0.01
Modeling Syst.	CR model and ERD		±0.24	±0.39	±0.68
	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	±0.02	±0.22
		FSR	±0.10	±0.14	±0.40
		ME/PS matching scale	±0.10	±0.10	±0.10
		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	±0.04	±0.17
		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		${}^{+0.76}_{-0.77}$	${}^{+1.04}_{-0.75}$	${}^{+1.44}_{-1.51}$

Institut für Experimentelle Teilchenphysik

Final Results

Karlsruher Institut für Technologie

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

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

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

$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.995 \pm 0.004\,(\mathrm{stat} + \mathrm{prof})\,^{+0.002}_{-0.004}\,(\mathrm{syst}) = 0.995^{+0.005}_{-0.006}$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83 \pm 0.69\,(\mathrm{stat} + \mathrm{prof})\,^{+0.35}_{-0.74}\,(\mathrm{syst})\,\mathrm{GeV} = 0.83^{+0.77}_{-1.01}\,\mathrm{GeV}$$

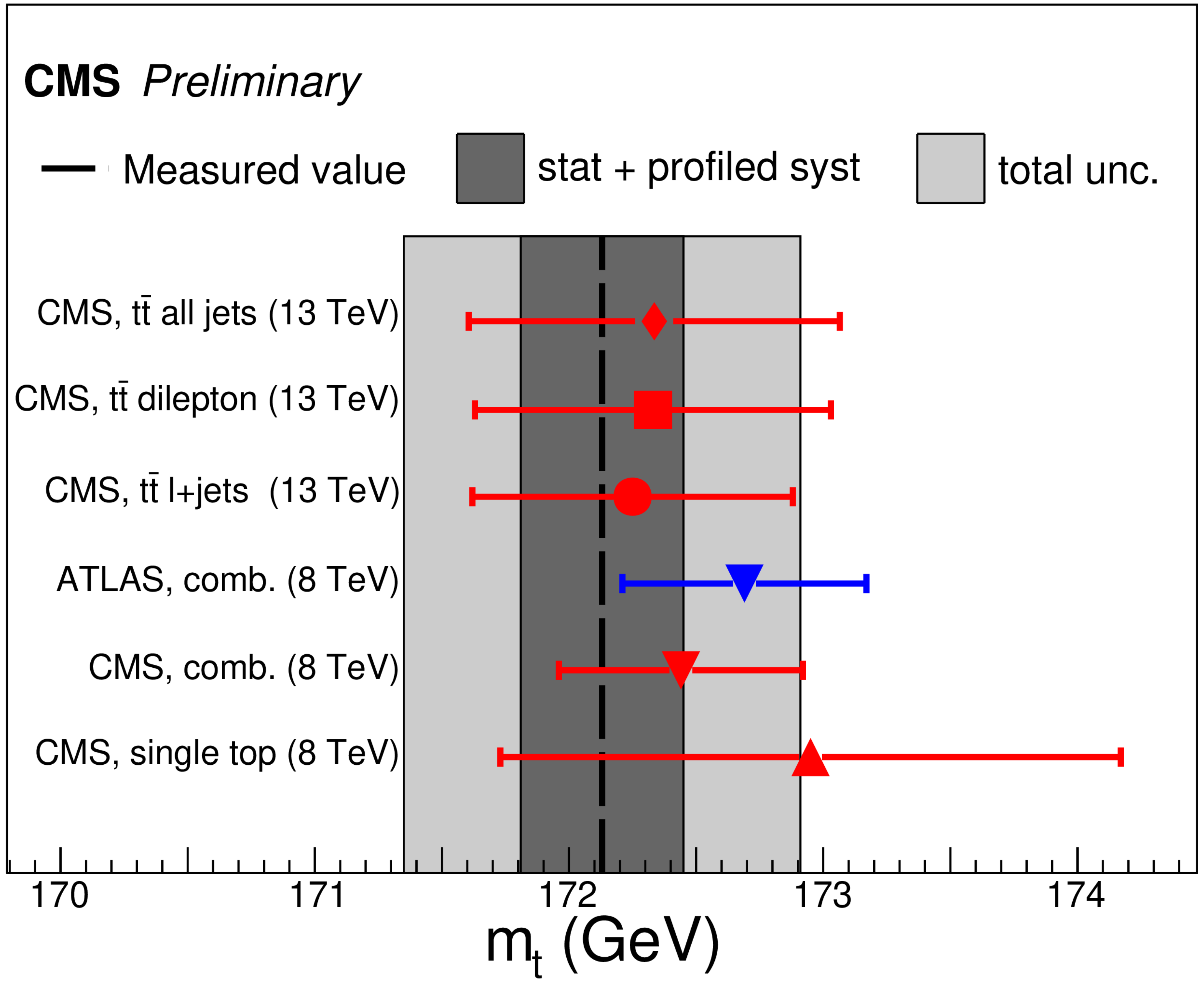
Consistent with CPT invariance

Δm_t measured by CMS at $\sqrt{s} = 8$ TeV using $t\bar{t}$ events Phys. Lett. B 770 (2017) 50

$$\Delta m_\mathrm{t} = -0.15 \pm 0.19\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst})\,\mathrm{GeV}$$

Summary

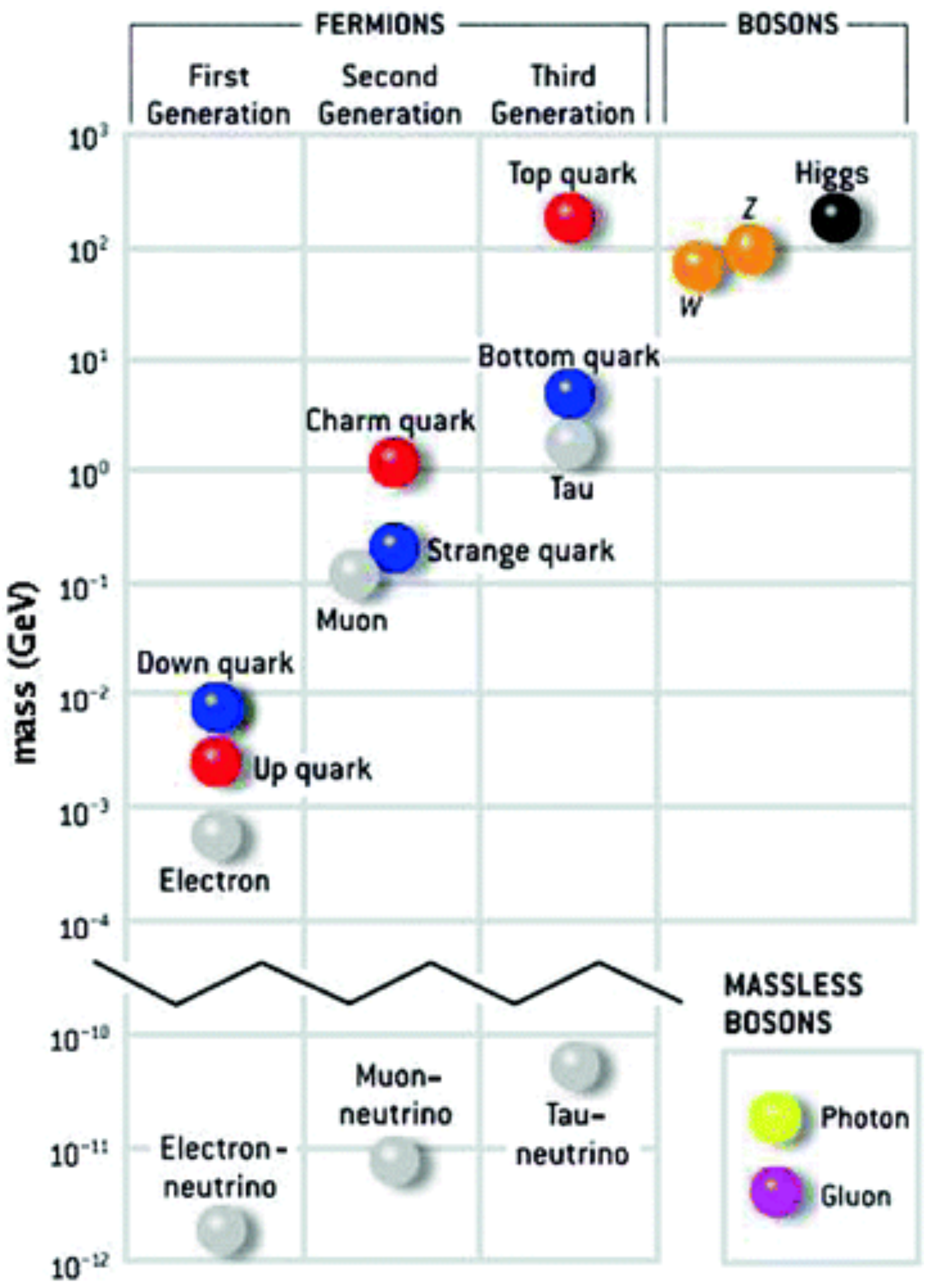
- First m_t measurement with data taken at $\sqrt{s}$ = 13 TeV in single top enriched event sample
- First m_t measurement to achieve sub-GeV precision in single top enriched event sample
- First measurement of R_{m_t} and Δm_t in single top enriched phase space
  - ➢ test of CPT invariance and no violation is 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)

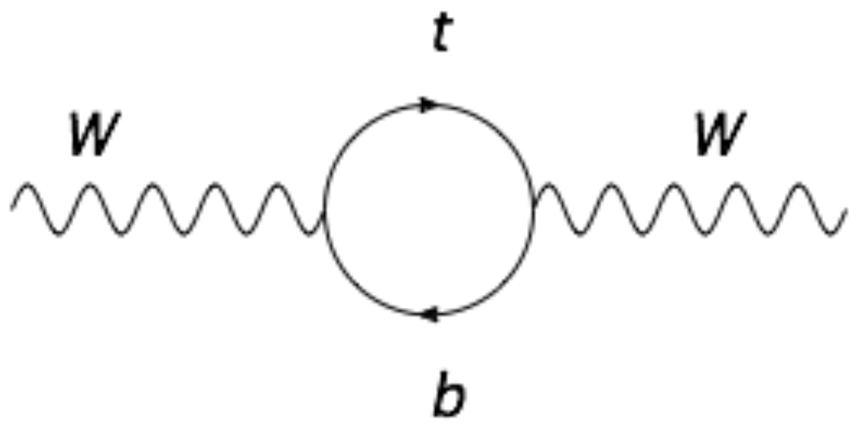


Thank You

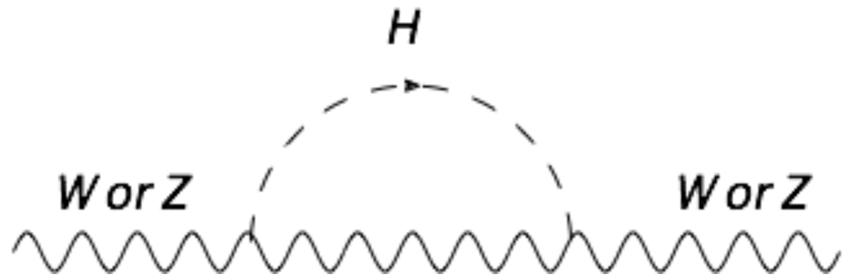
Back Up

m_t & Electroweak symmetry





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

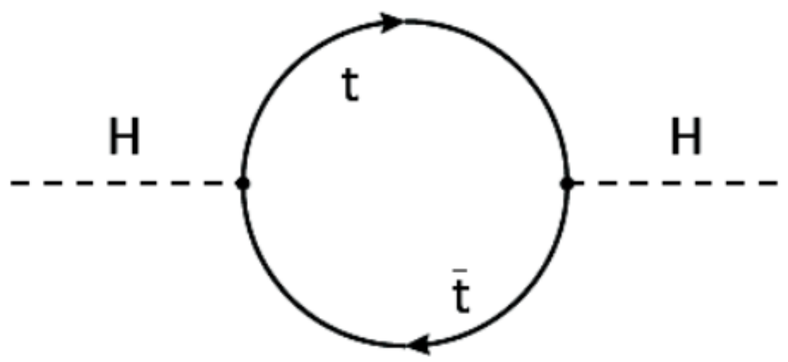


$$\Delta m_W \propto \ln m_H$$

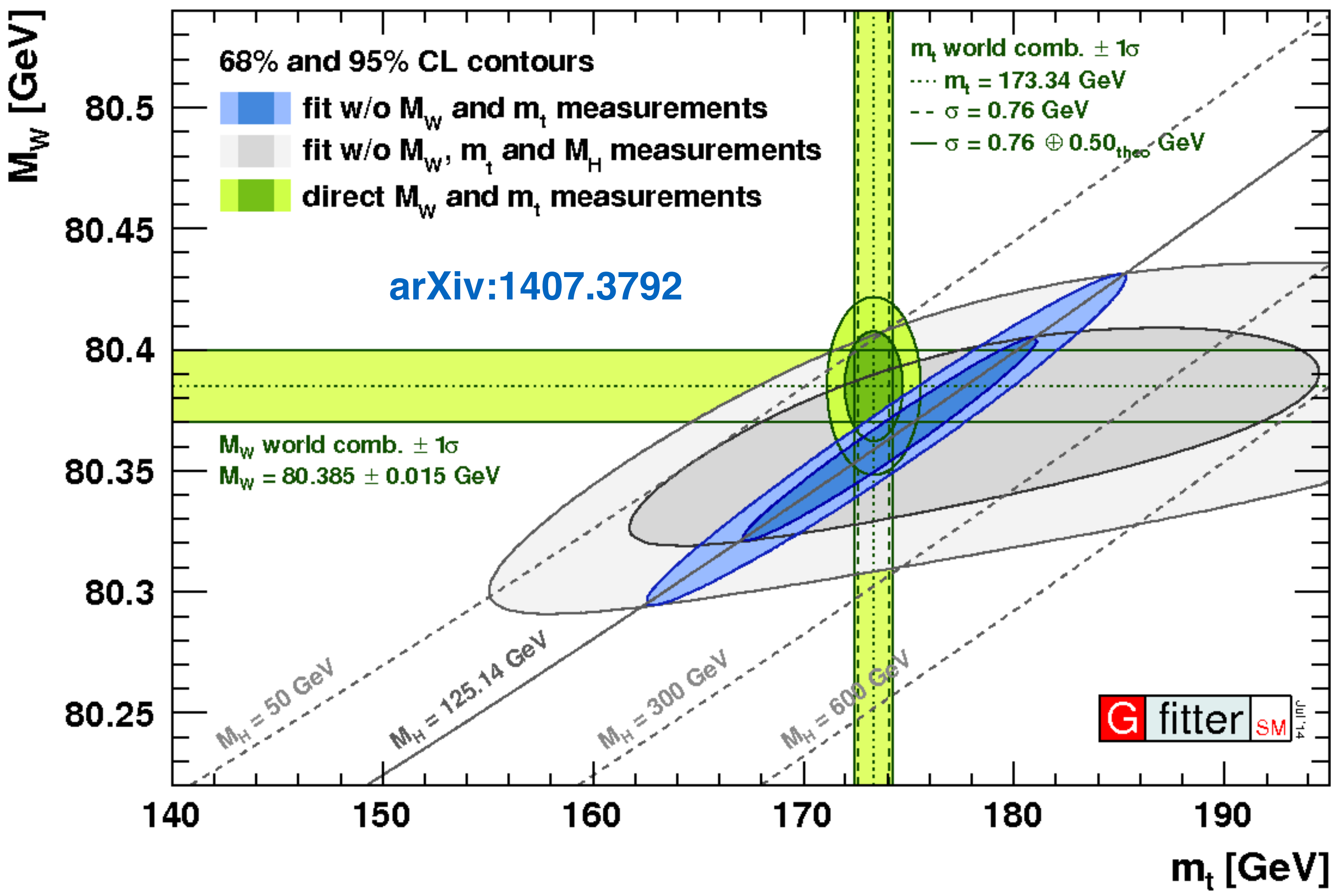
- Higgs Potential:

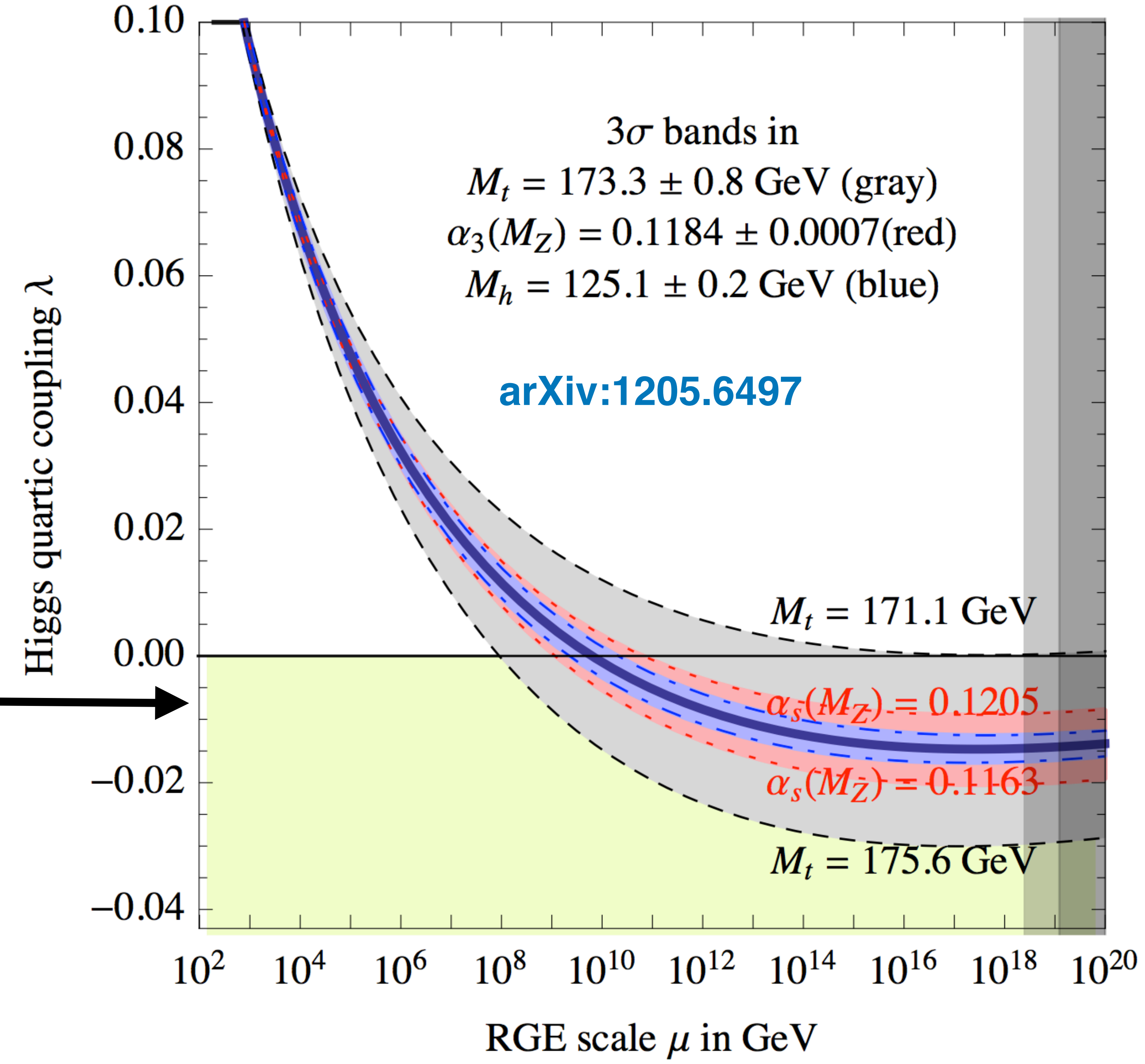
$$V(\phi) = -\mu_H^2 \phi^\dagger \phi + \lambda_H (\phi^\dagger \phi)^2$$

- 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

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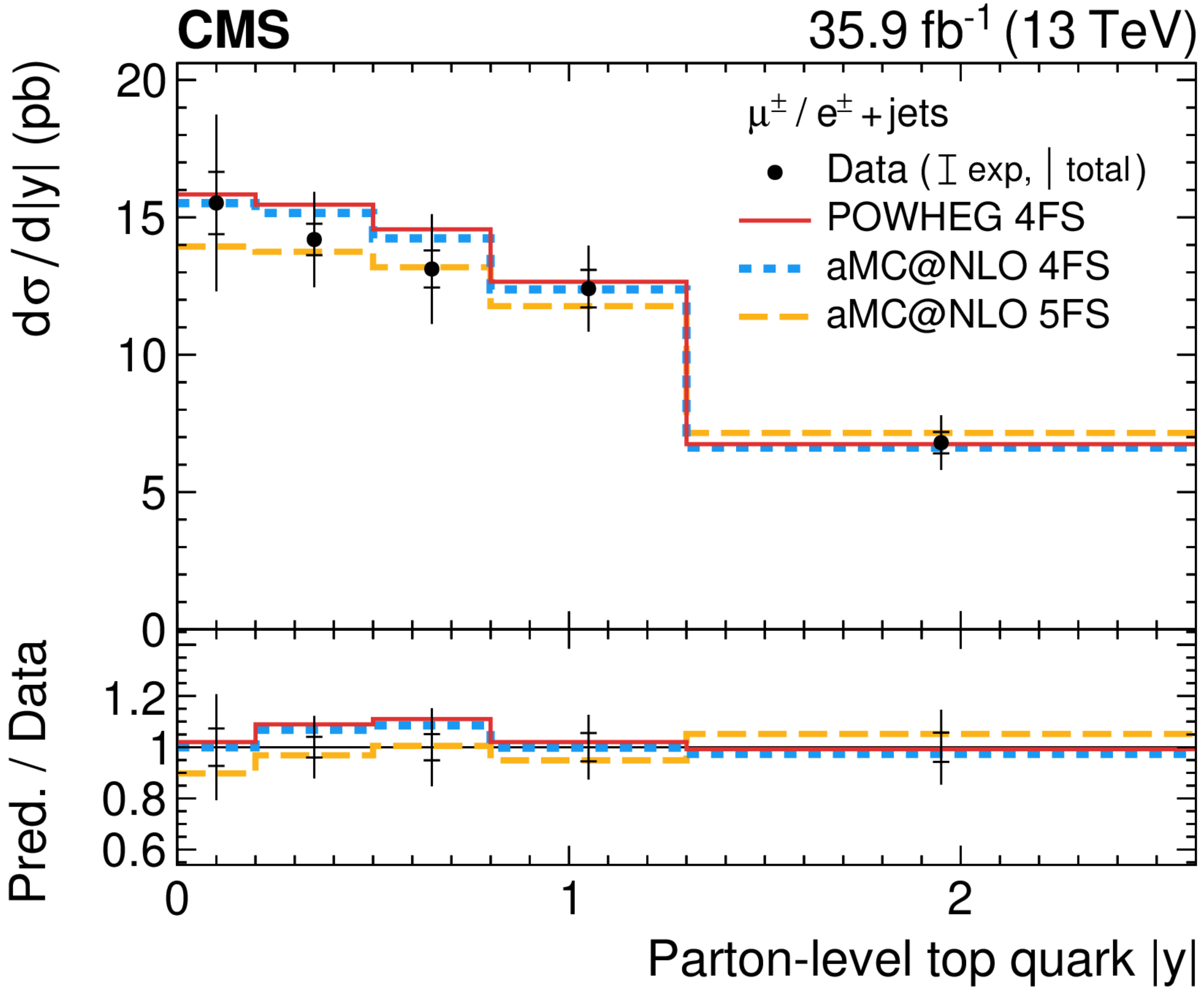
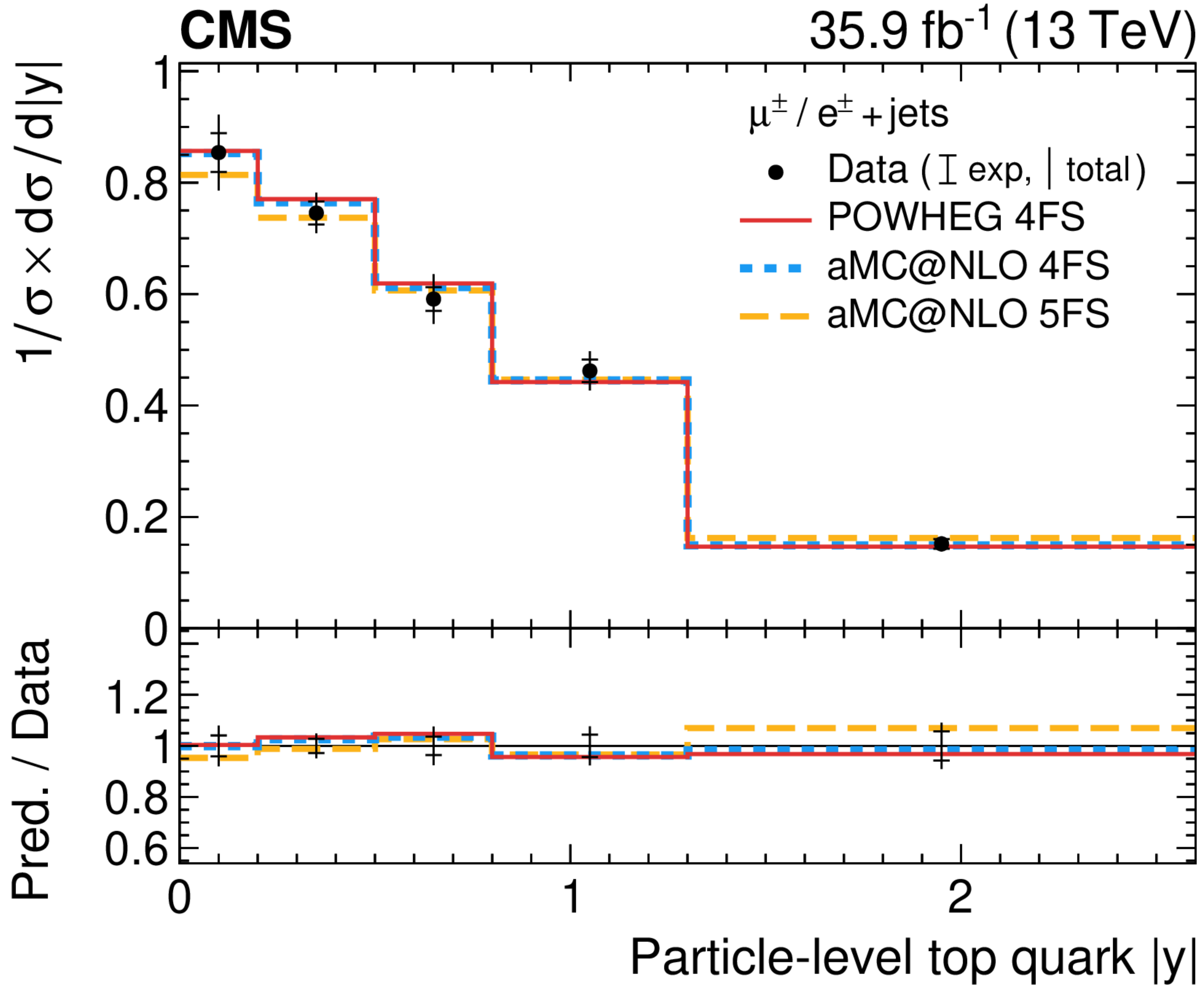


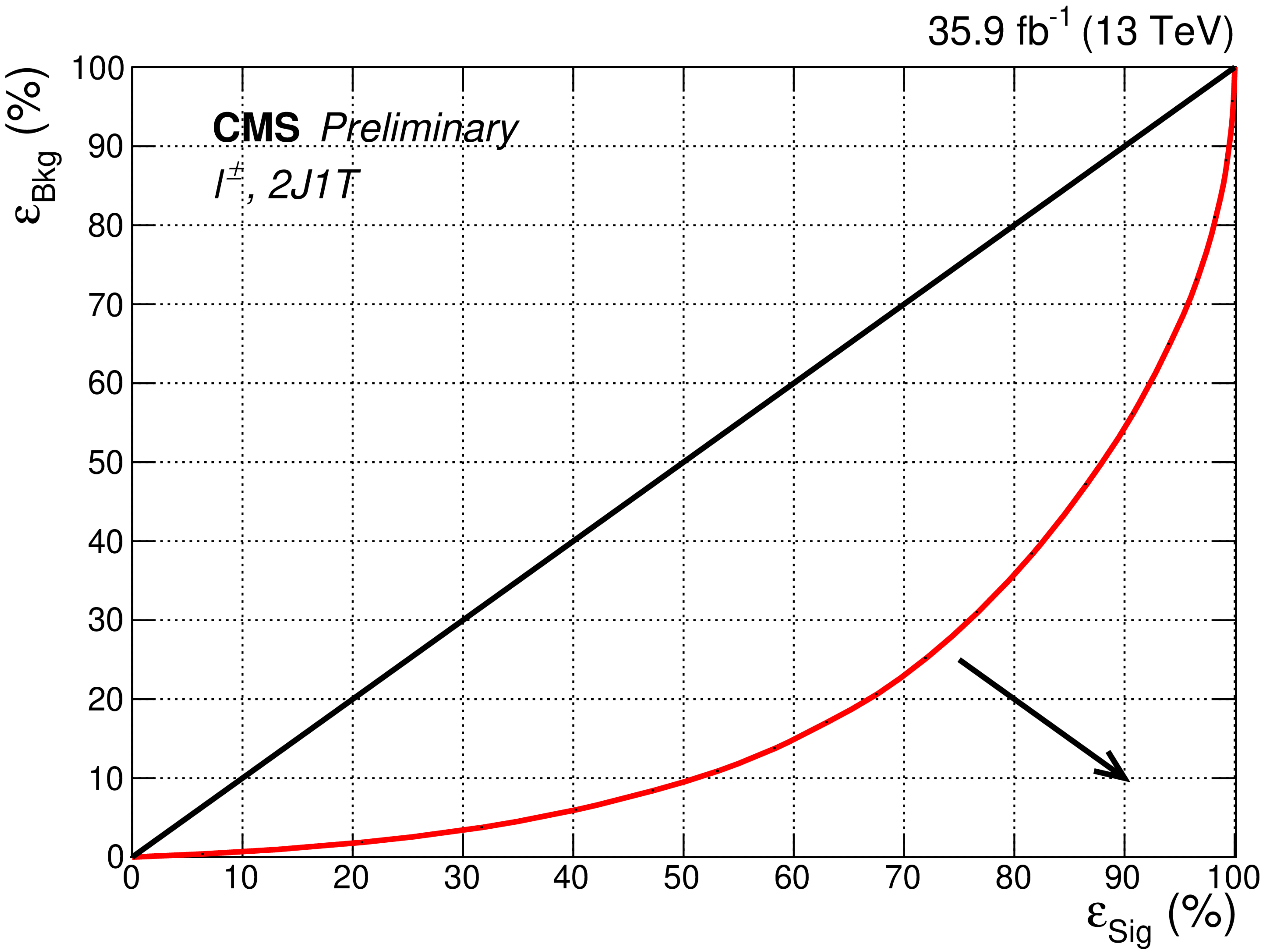


BDT discriminator

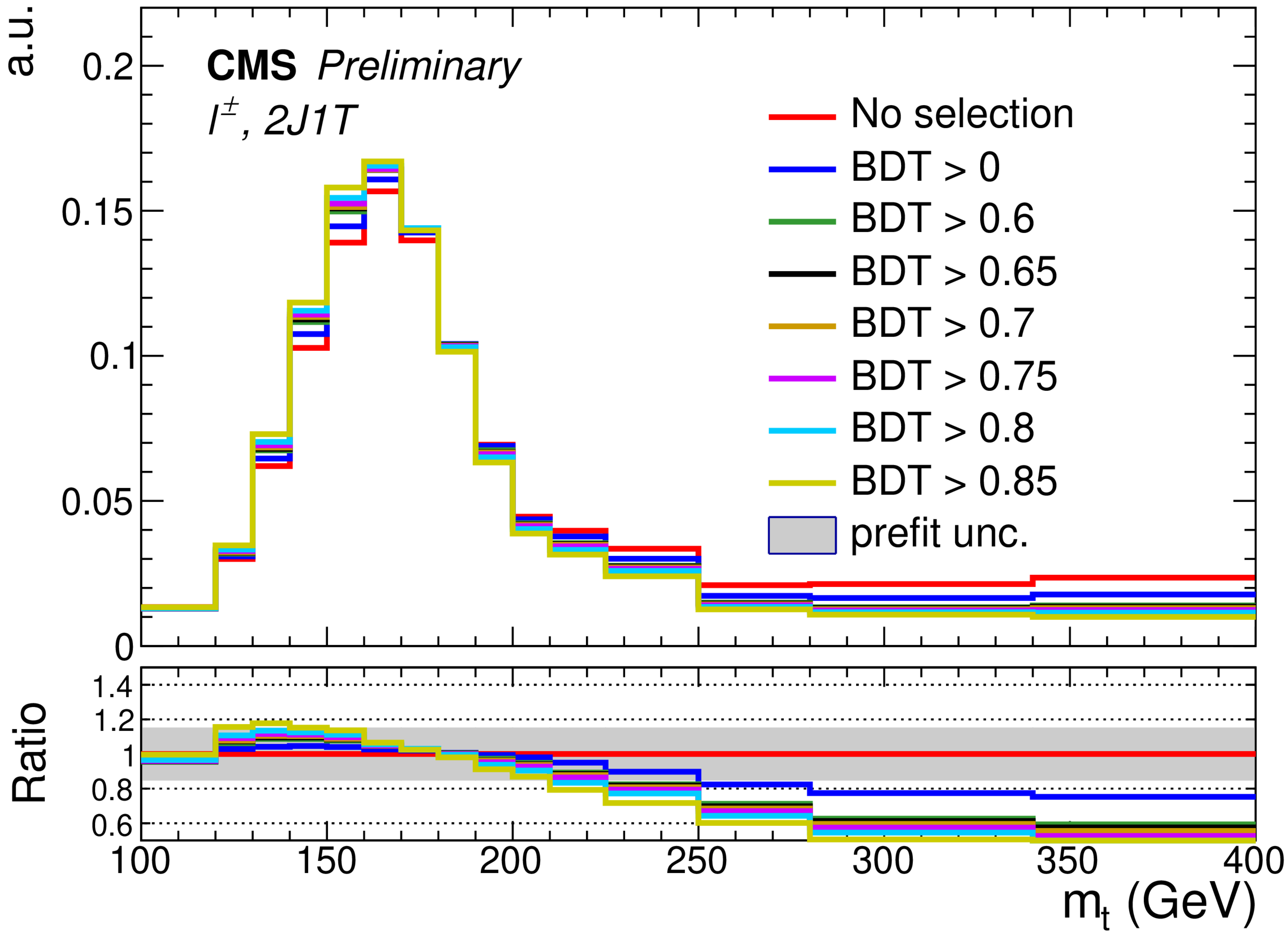
Variable	Rank μ	Rank e	Description
$\Delta R_{\mathrm{bj'}}$	1	1	Angular separation in $\eta - \phi$ space between the b-tagged and untagged jets
light jet $\lvert\eta\rvert$	2	2	Absolute pseudorapidity of the untagged jet
$m_{\mathrm{bj'}}$	3	3	Invariant mass of the system comprising of the b-tagged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

ROC curve

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



Signal m_t shape due to different BDT cut



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**: $\pm 1\sigma$ 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

➛ $\pm 1\sigma$ 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:** $\pm 3\sigma$ variation of shape parameters