# Probing new physics with top quarks at LHC

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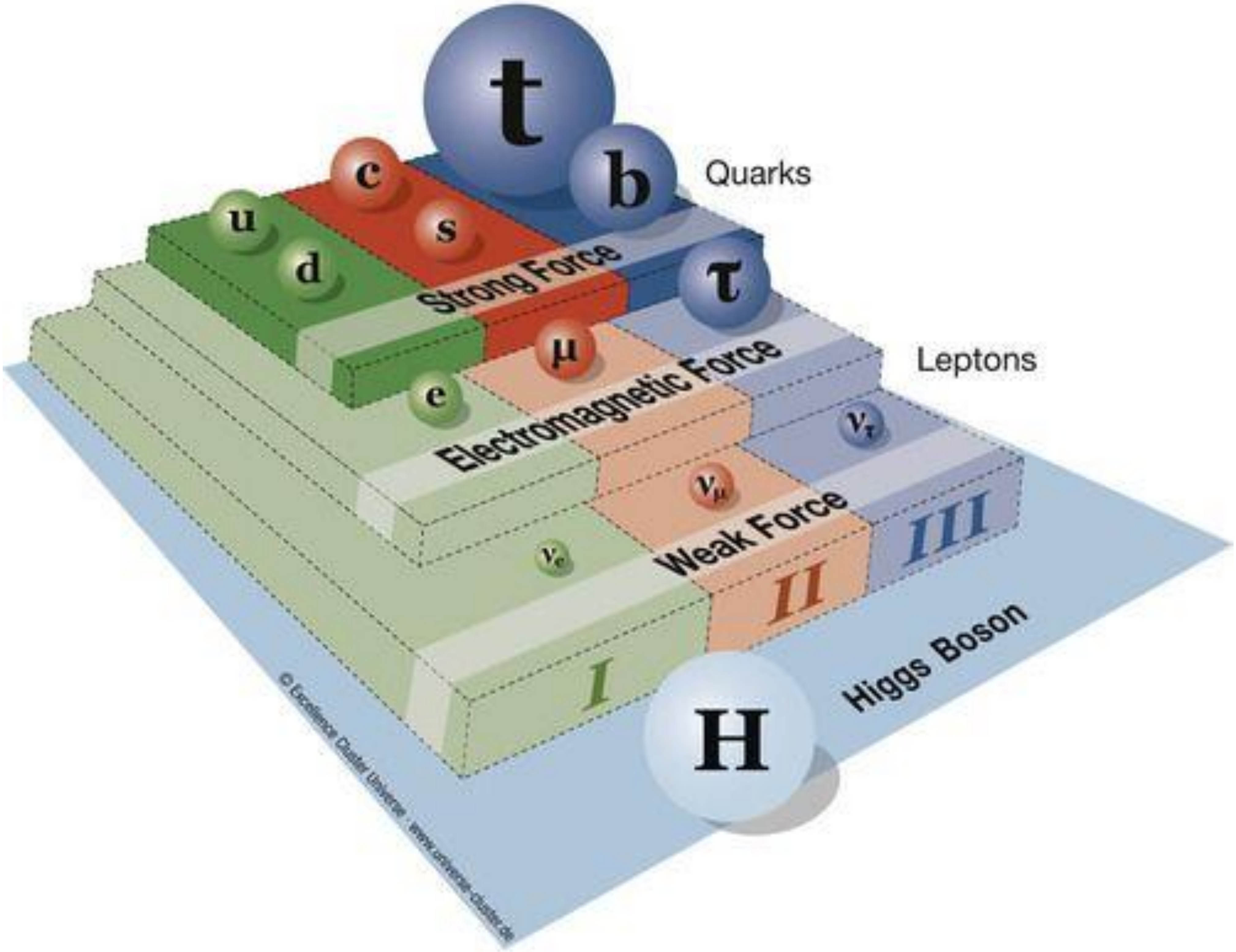


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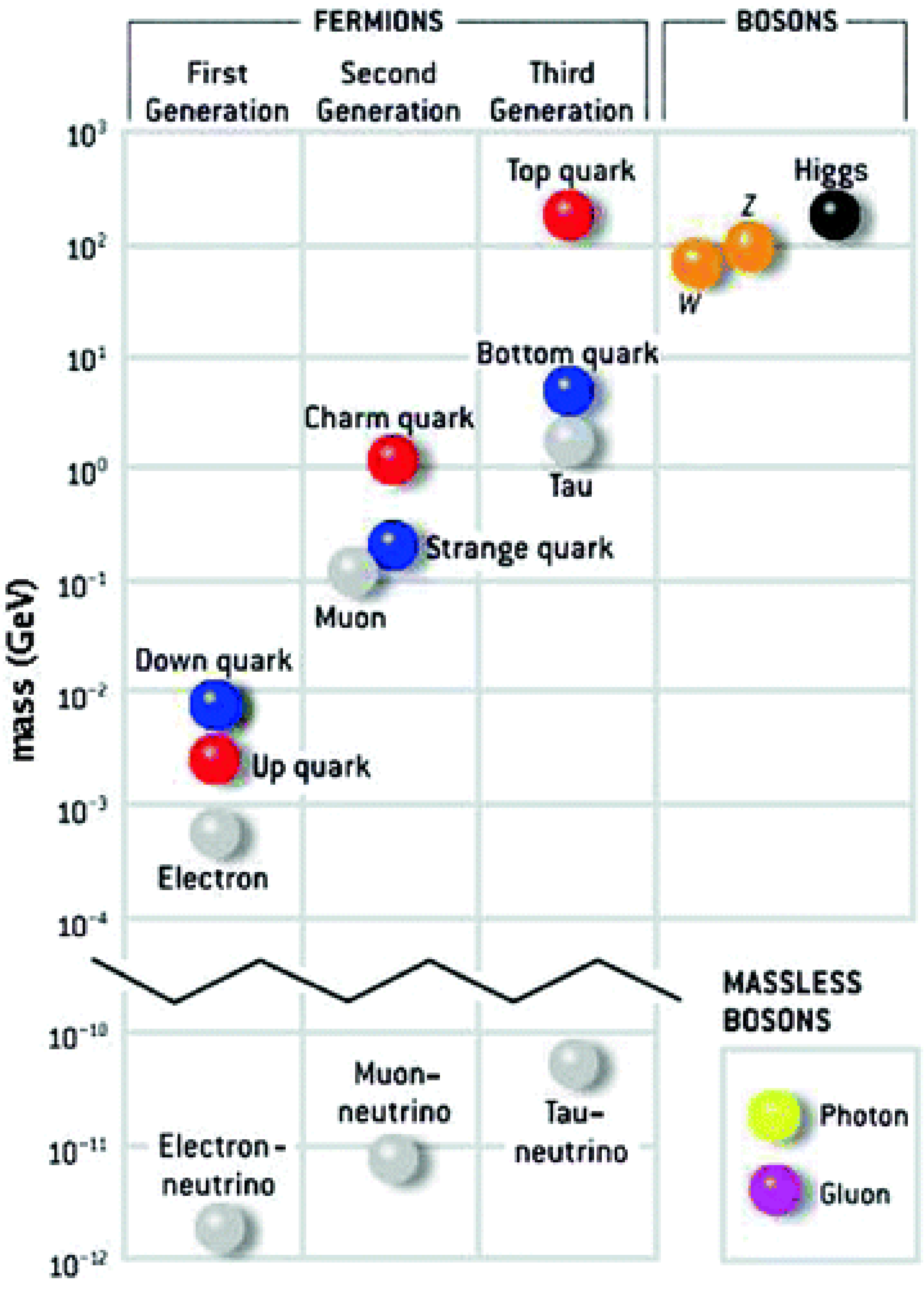
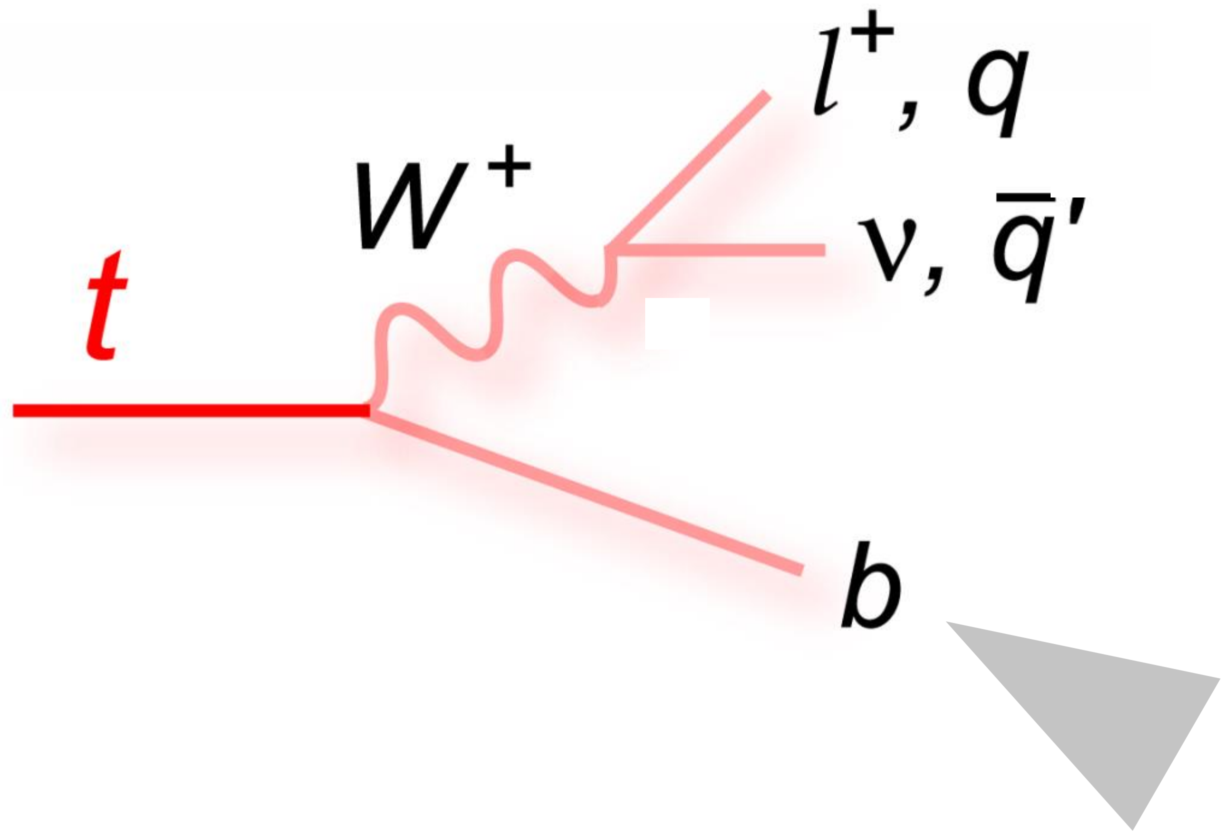
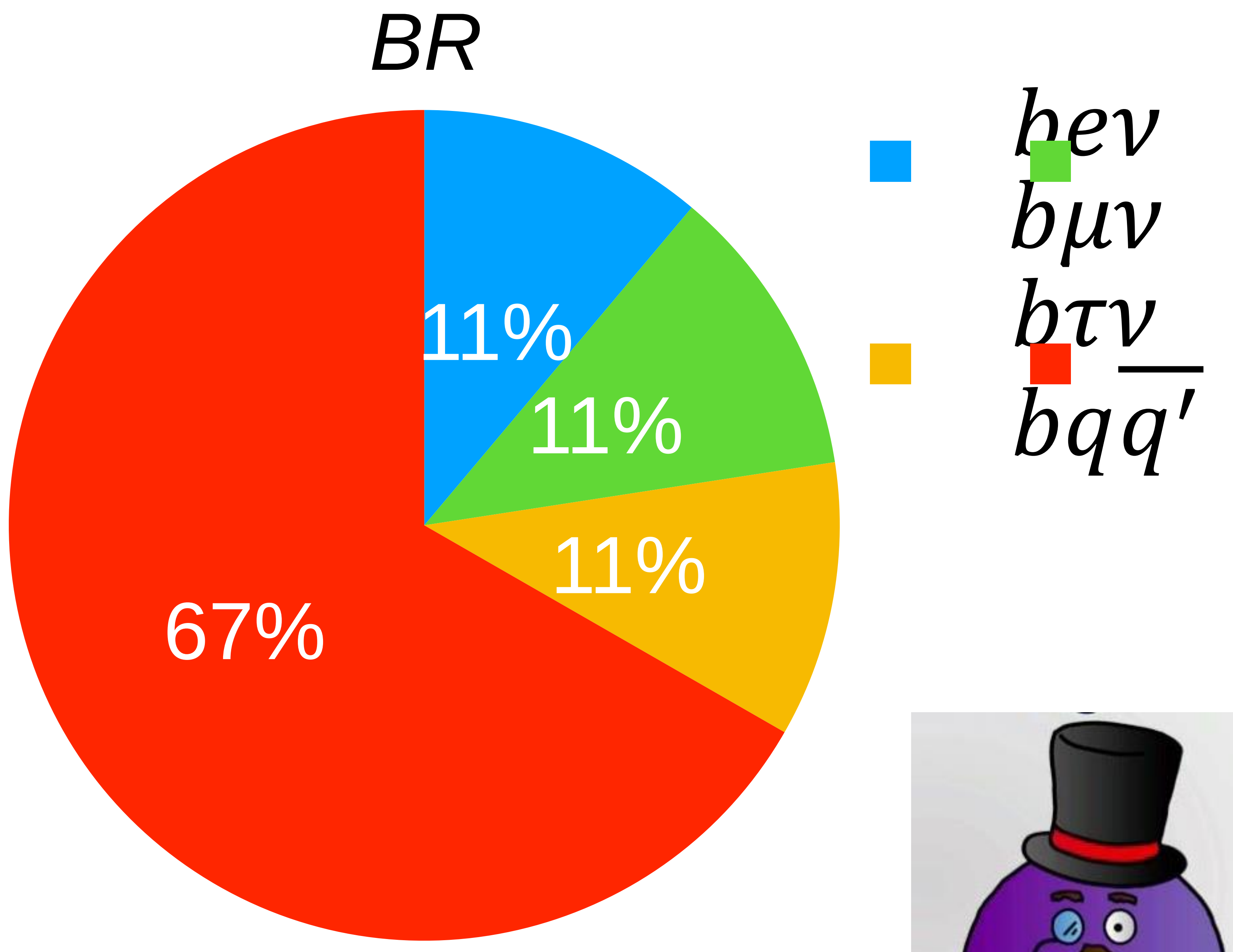
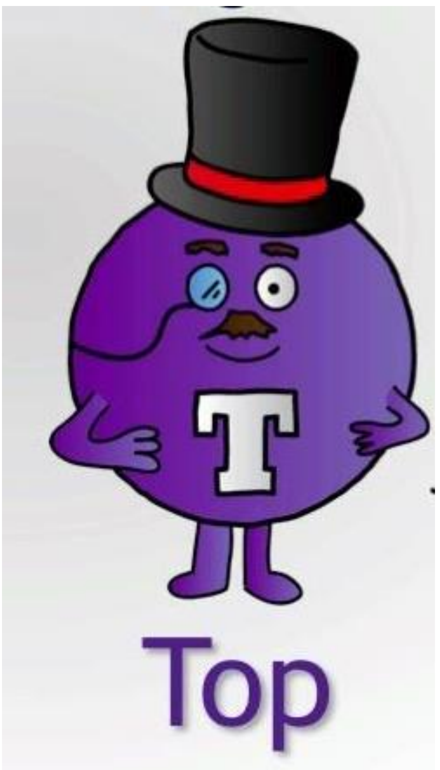
# The *top* quark

- Heaviest known elementary particle ($m_t$ ~ 172 GeV) ➛ largest coupling to the Higgs boson
- Discovered 27 years ago at TeVatron, Fermilab, USA
- Sensitive to stability of EW vacuum
- Decays almost exclusively to *bW* pair
- Unique behavior:
  **$\tau_{decay}$ (≈$10^{-25}$ s) < $\tau_{had.}$ (≈$10^{-24}$ s)** ➛ access to bare quark properties via its daughters

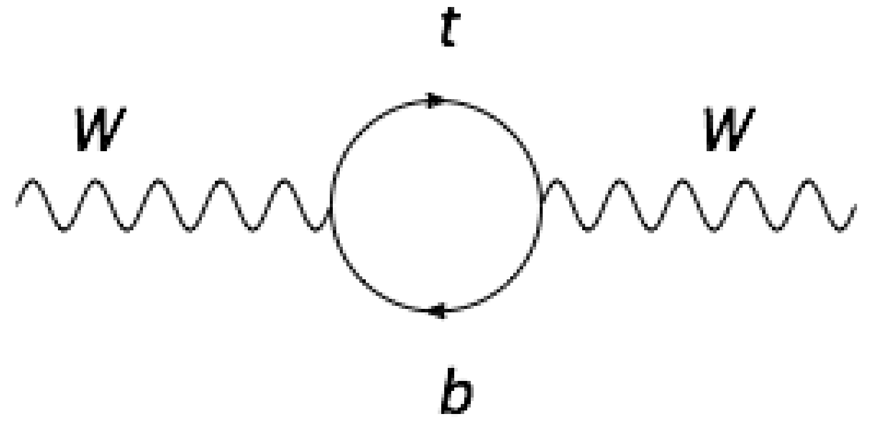


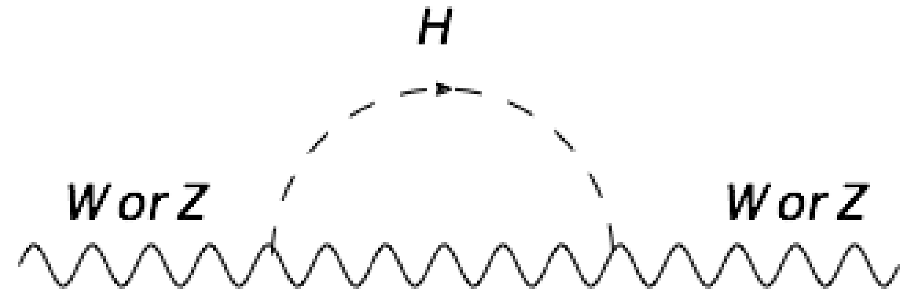



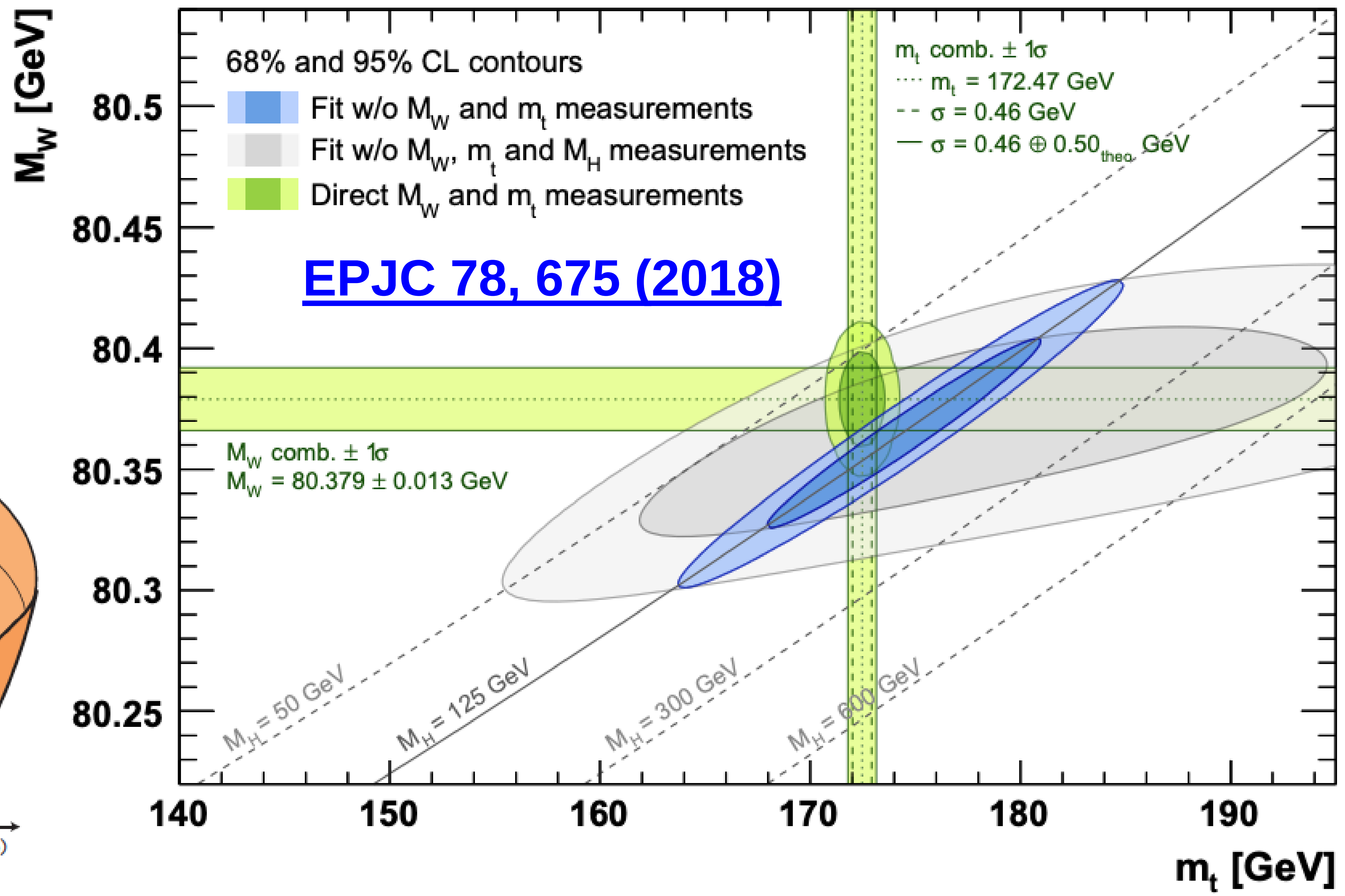
# $m_t$ and EWSB



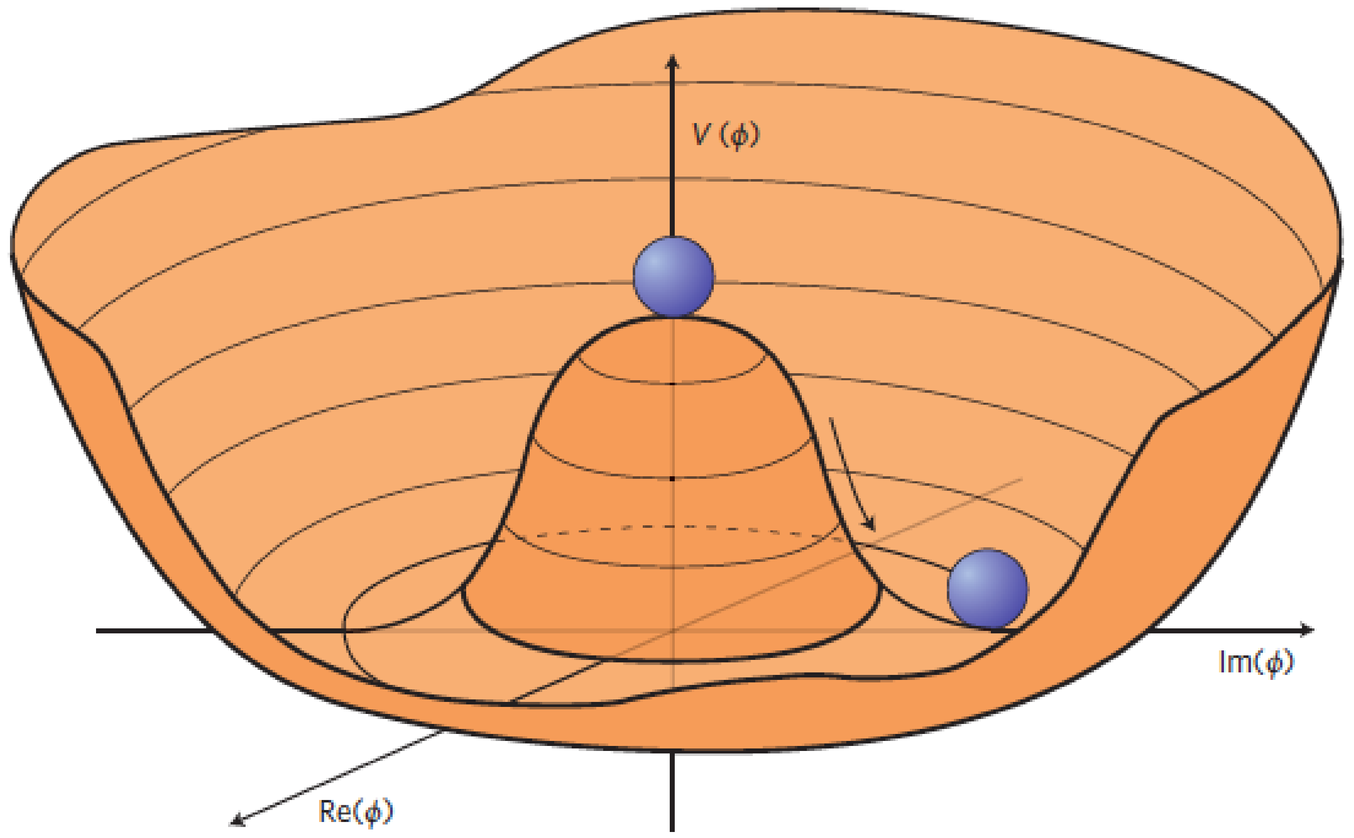

$\Delta M_W \propto m_t^2$

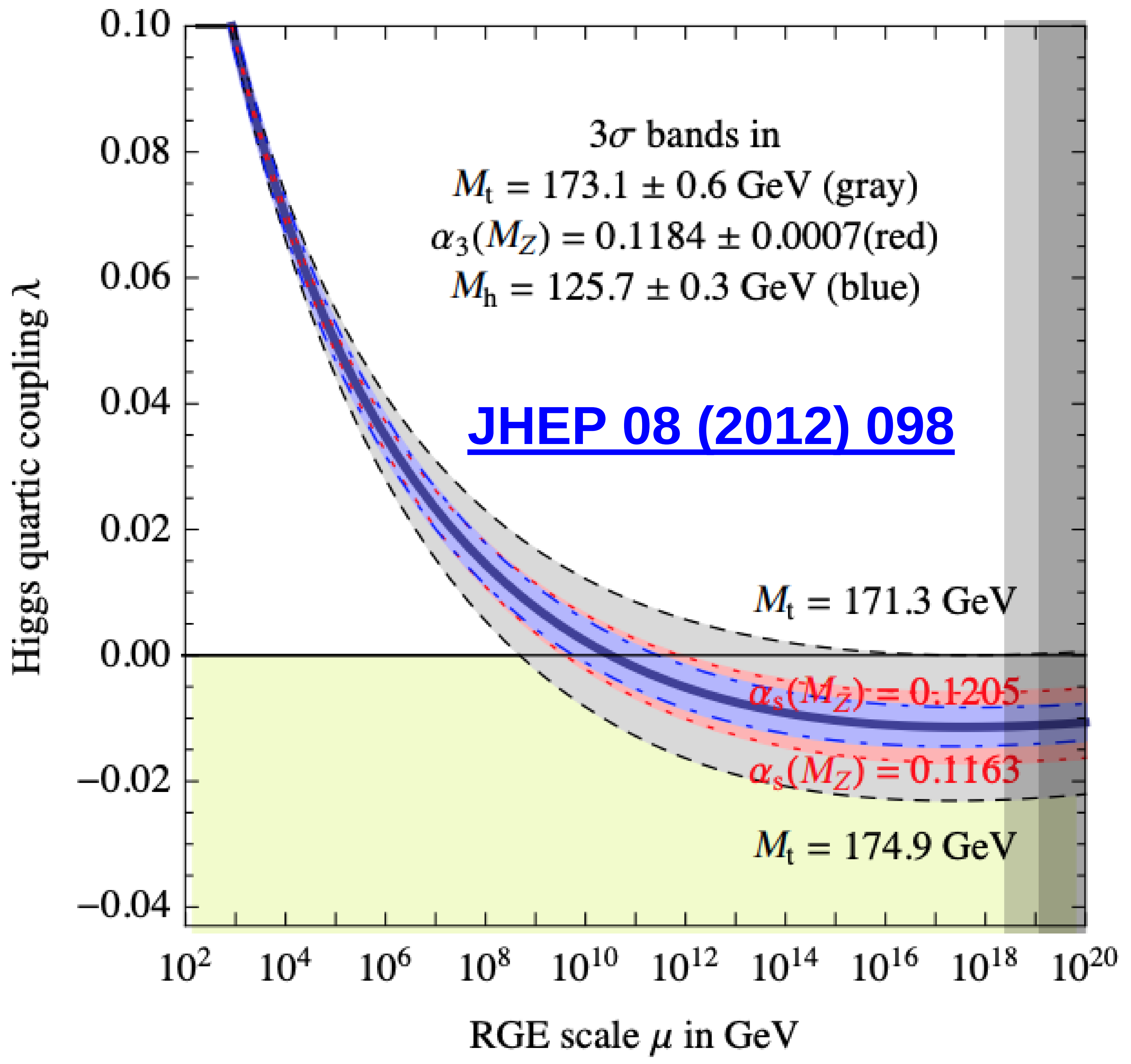



$\Delta M_W \propto \ln M_H$

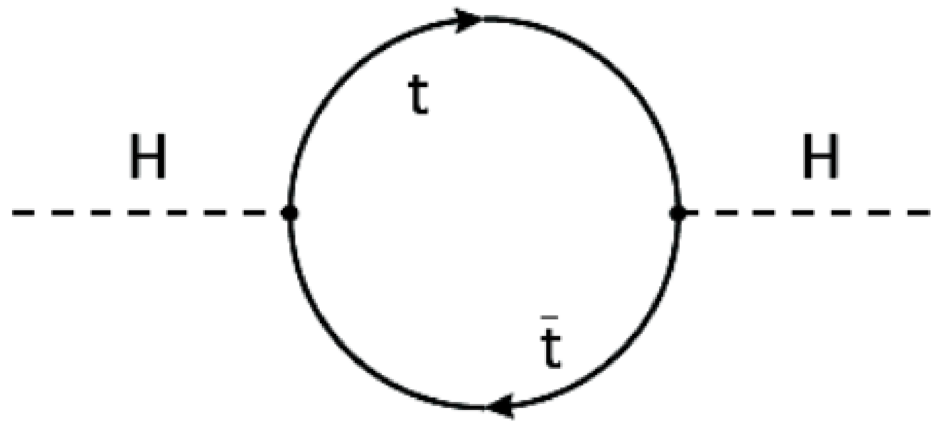



- Higgs Potential: $V(\phi) = -\mu_H^2 \phi^\dagger \phi + \lambda_H (\phi^\dagger \phi)^2$
- Mexican hat only if $\lambda_H > 0$




- $\lambda_H$ receives radiative corrections from all SM particles ➛ mostly from top quark $\Rightarrow \Delta\lambda_H \propto m_t^4$




- Evolve $\lambda_H$ up to Planck scale (~$10^{19}$ GeV)
- Knowing ***$m_t$* accurately** might just reveal the **fate of our universe**

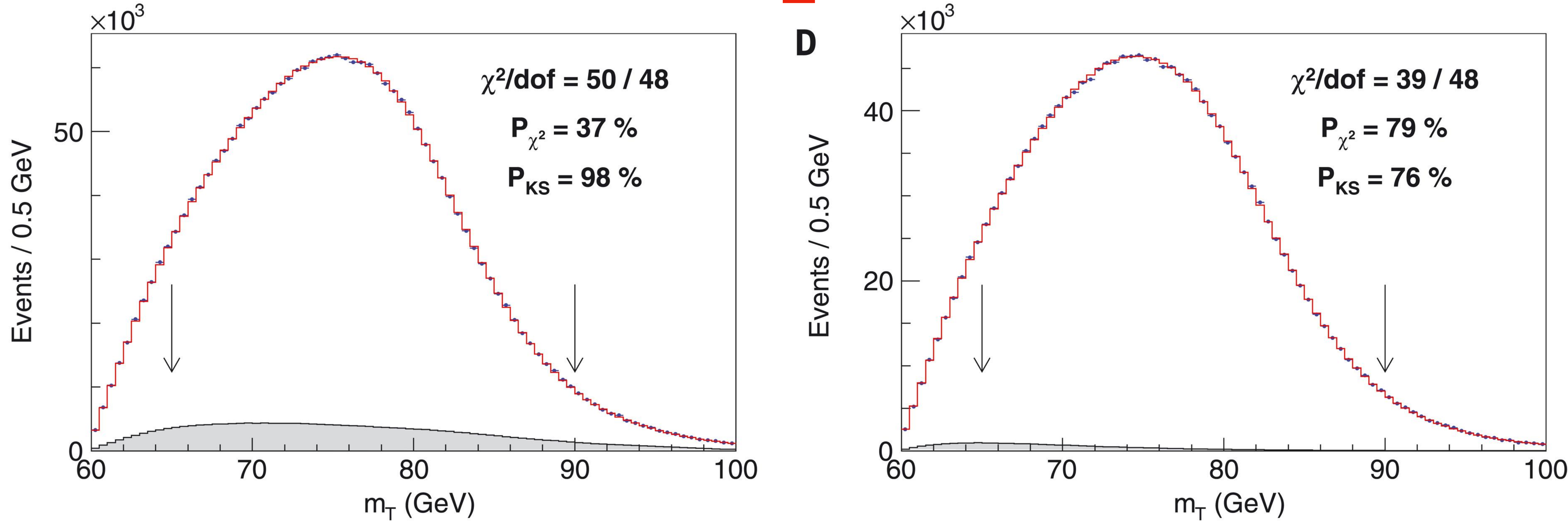
# $m_W$ conundrum

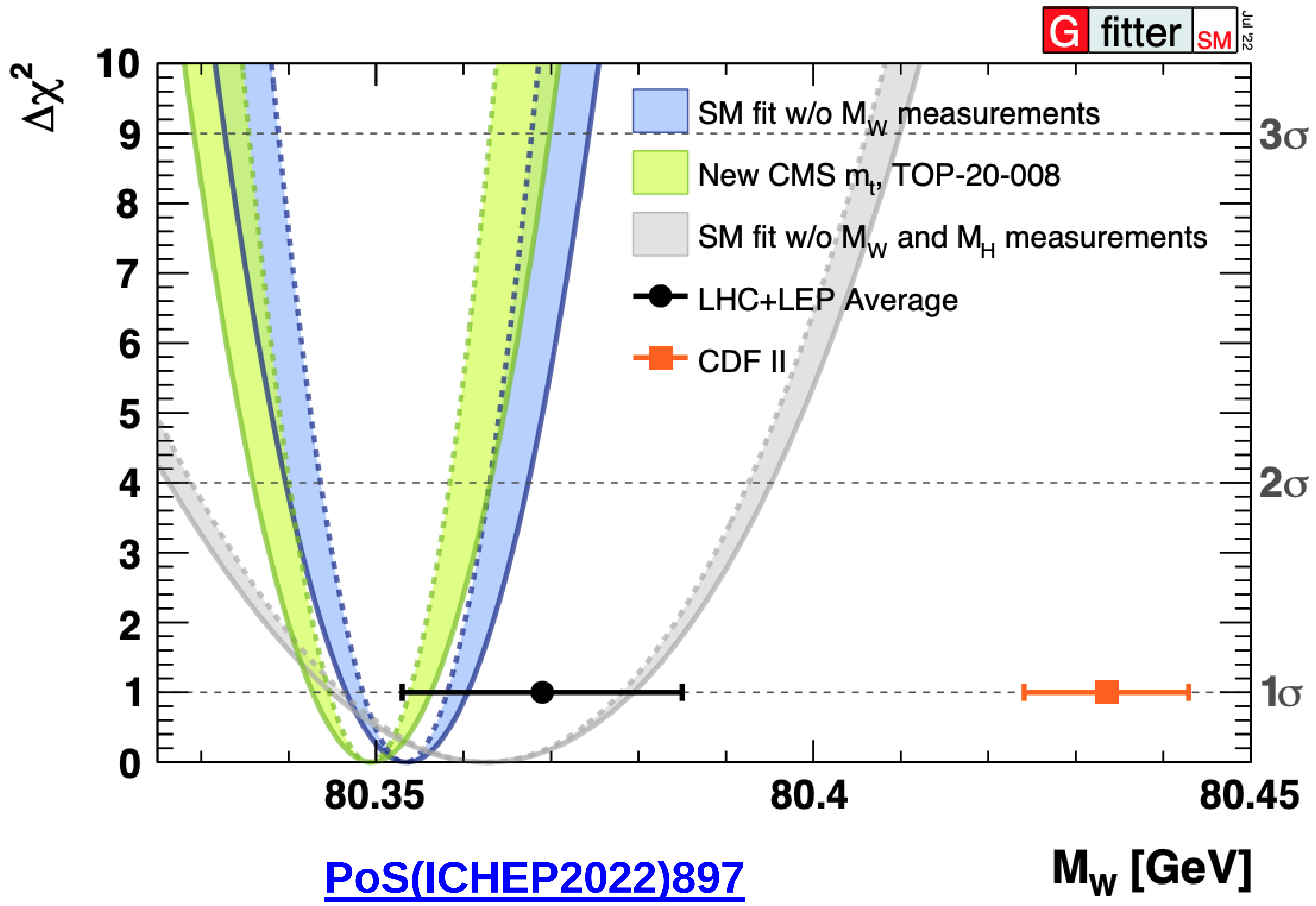
- Life becoming difficult at EW sector with the new CDF measurement of $m_W$

  ➛ 6.8σ deviation from prediction (Blue Band)
- SM predictions consistent with LEP + LHC measurements
- Using $m_t$ from CMS-PAS-TOP-20-008 the deviation is even larger (Green Band)
- PDFs are key inputs ➛ need to resolve differences and harmonize PDF+generators usage in different measurements before combination

Science 376, 170 (2022)

$$m_W^{\text{comb.}} = 80433.5 \pm 6.4(\text{stat}) \pm 6.9(\text{syst})\text{MeV}$$
$$= 80433.5 \pm 9.4\text{MeV}$$

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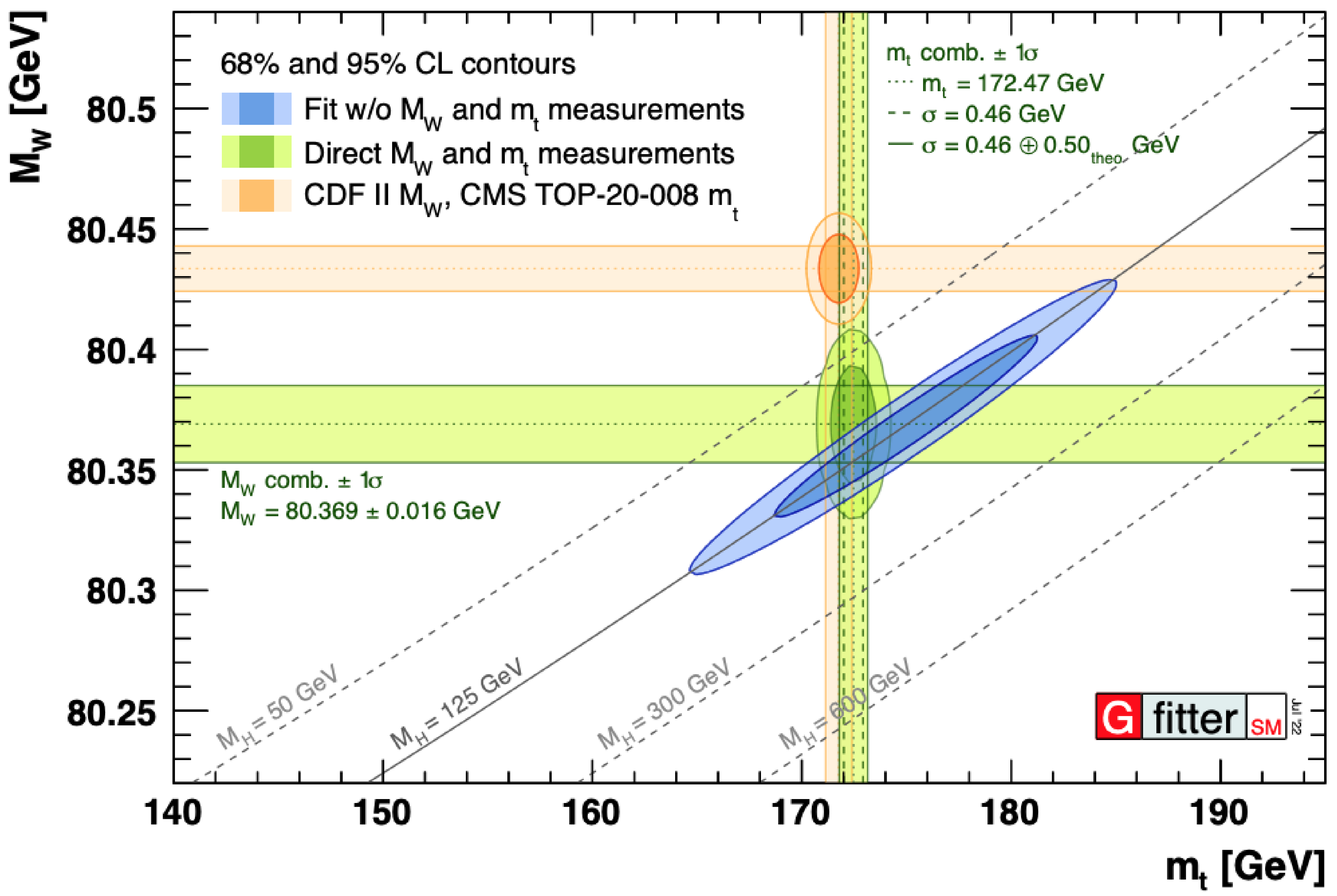
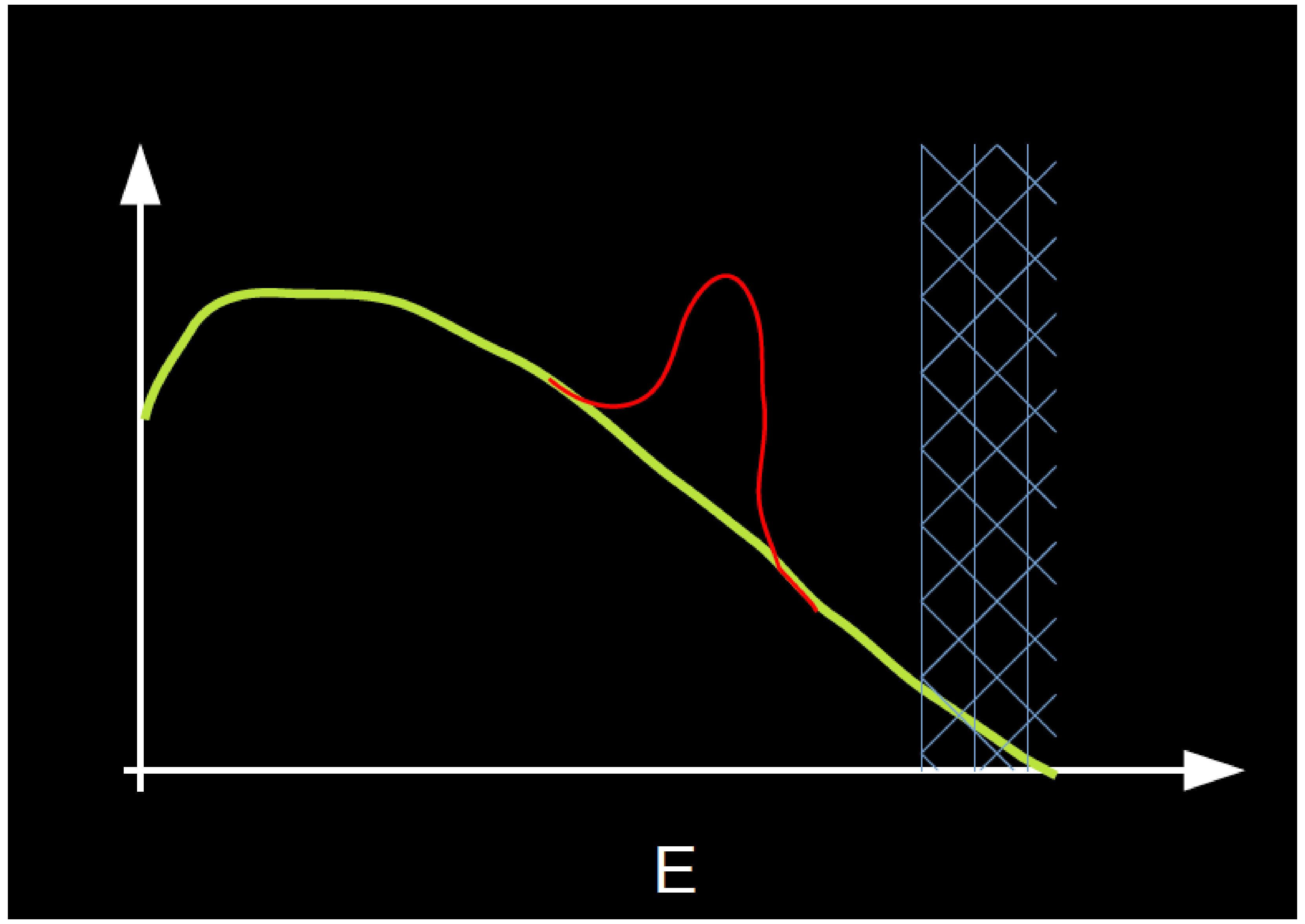
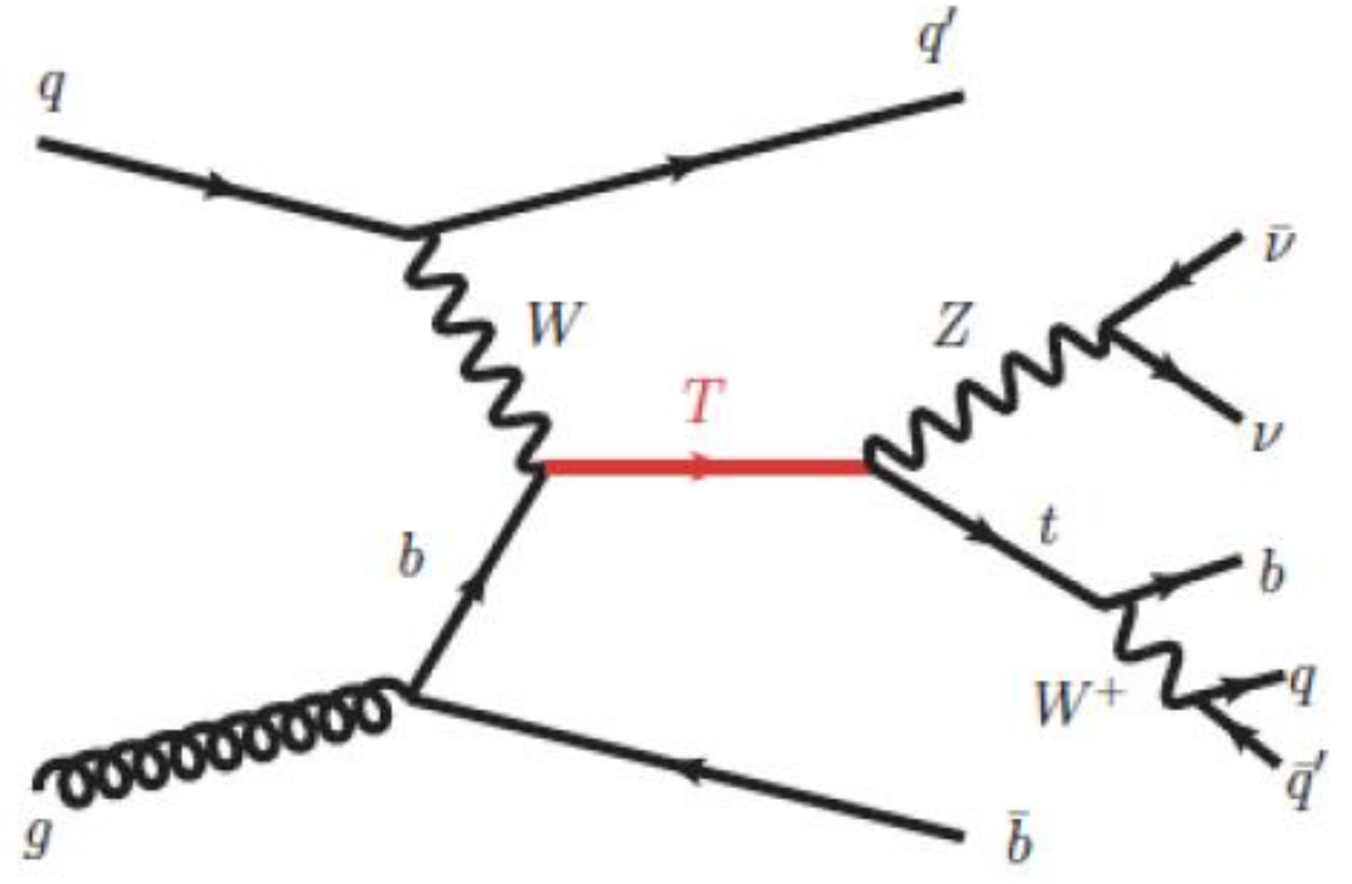


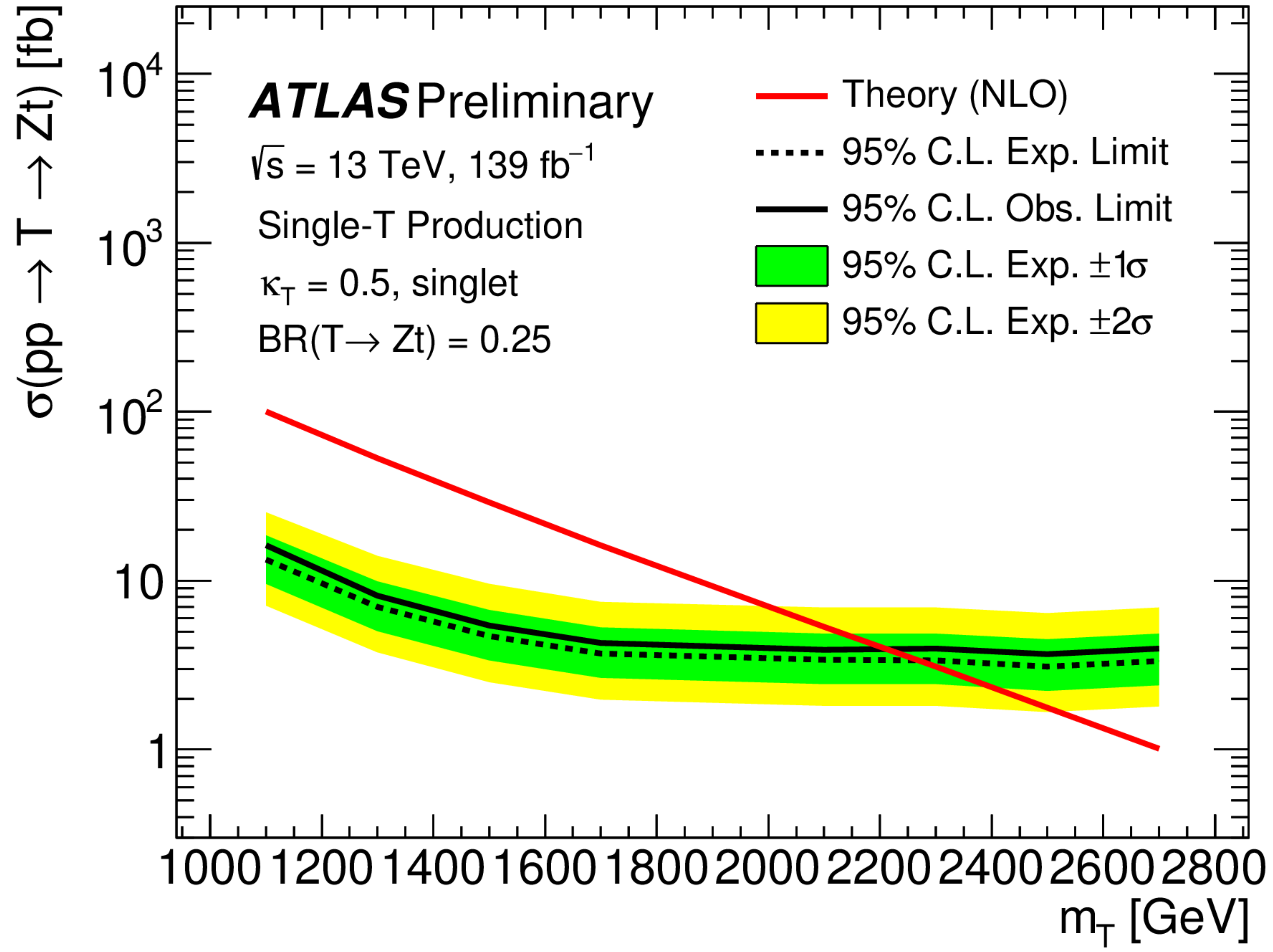
# *Top* portal to new physics - *direct* search strategy

- New resonance such as VLQ with $m < E_{LHC}$ decaying to top quarks
- Accessible at LHC
- Can attempt for a direct search
- Dependent on the new physics model




[ATLAS-CONF-2022-036](ATLAS-CONF-2022-036)

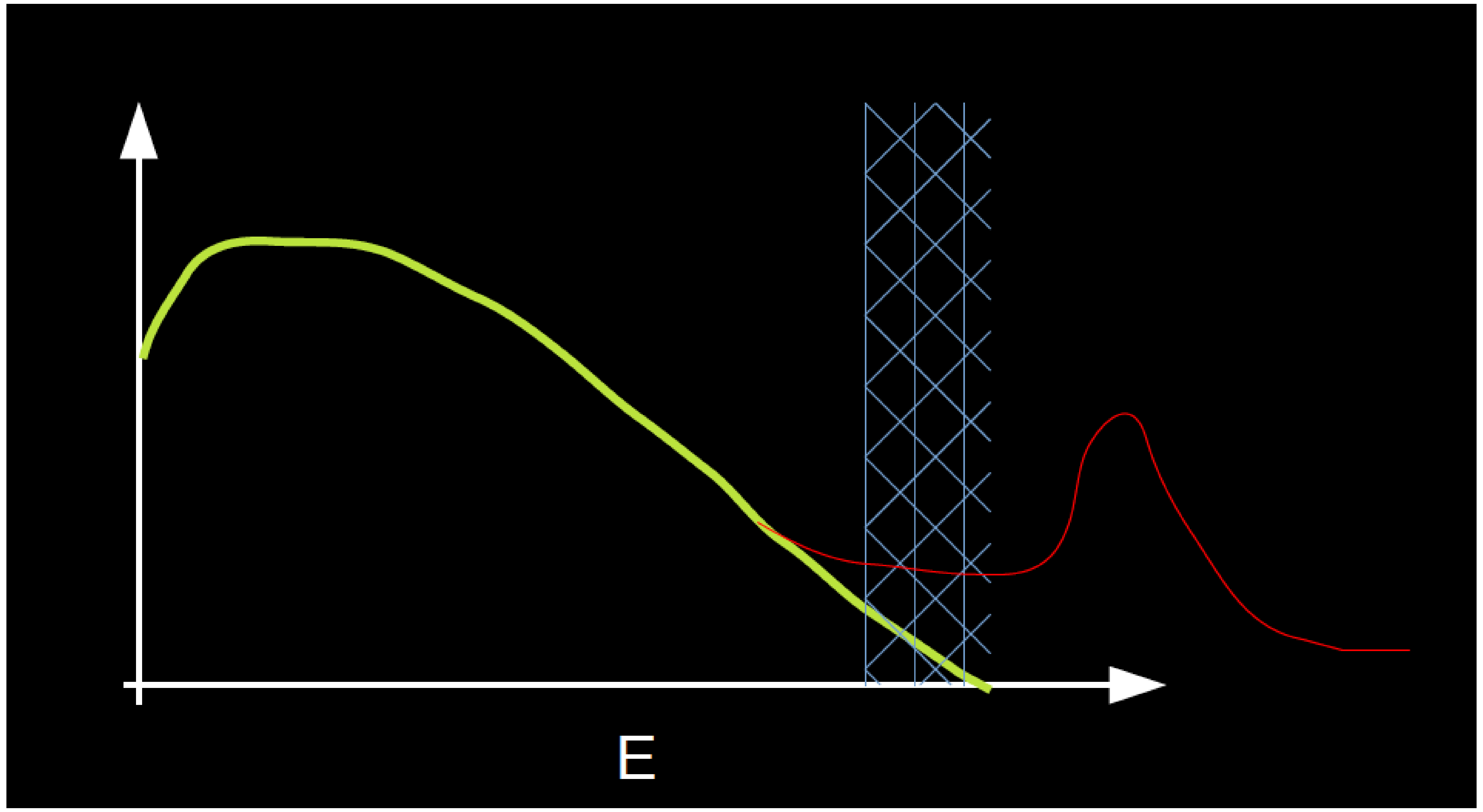



- New search from ATLAS in the mono-top final state
- Benchmark scenario: $k_T$ = 0.5 and BR (T→tZ)= 25%
- $m_T$ > 2.2 TeV @ 95% CL (Gain by 500 GeV ! )

# *Top* portal to new physics - *indirect* search strategy

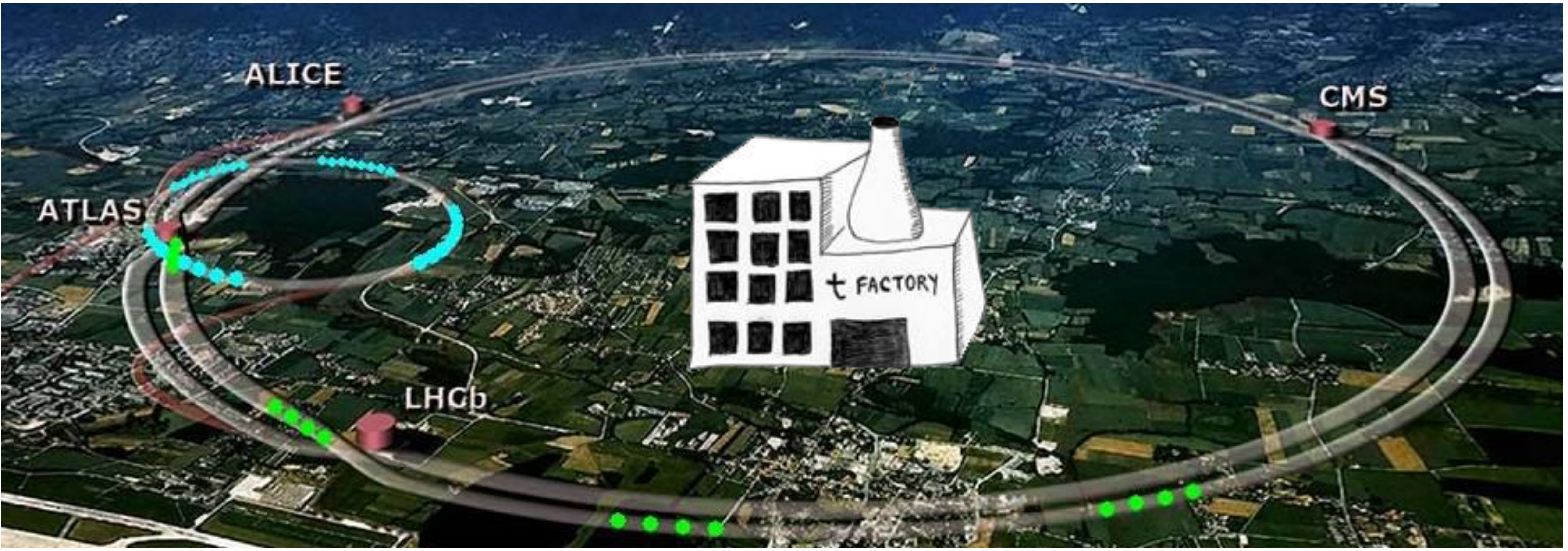


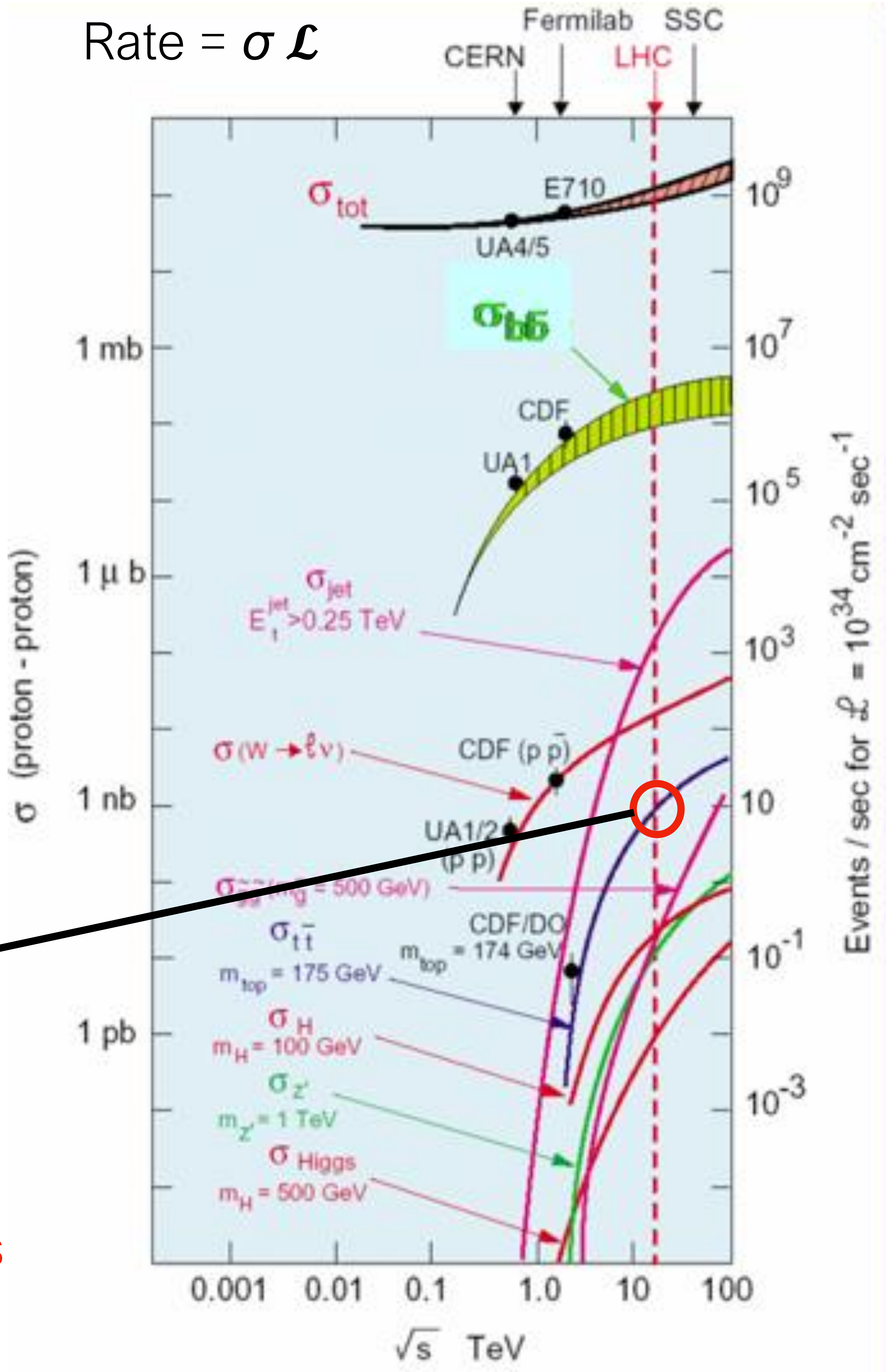
- New physics scale out of range $\Lambda \gg E_{LHC}$
- Expand SM: $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$ (D = 6 so far)
- Wilson coefficients $c_i$ modify SM vertices
  - ➛ Deviations from SM in precision measurements
- Independent of new physics model
- In the top sector, EFT effects visible in various final states: $t\bar{t}, t\bar{t}V, t\bar{t}q\bar{q}, tZq$ etc.
- Two ways of using EFT:
  - ☞ Re-parametrization of cross section measurements
  - ☞ Dedicated estimation of EFT couplings




**This talk primarily focusses on <u>this approach</u> for probing physics beyond the SM**

# LHC - The *top* Factory



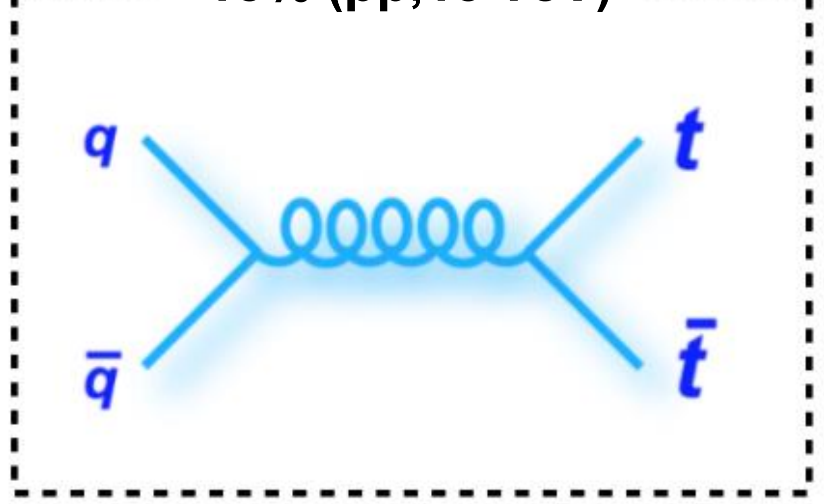




- Top quarks are produced in abundance at the LHC
- Dominant production modes:
  - ➢ Pair production via QCD interactions ~ 10 Hz @13 TeV
  - ➢ Single top quark production via EW interactions ~ 1 Hz @13TeV

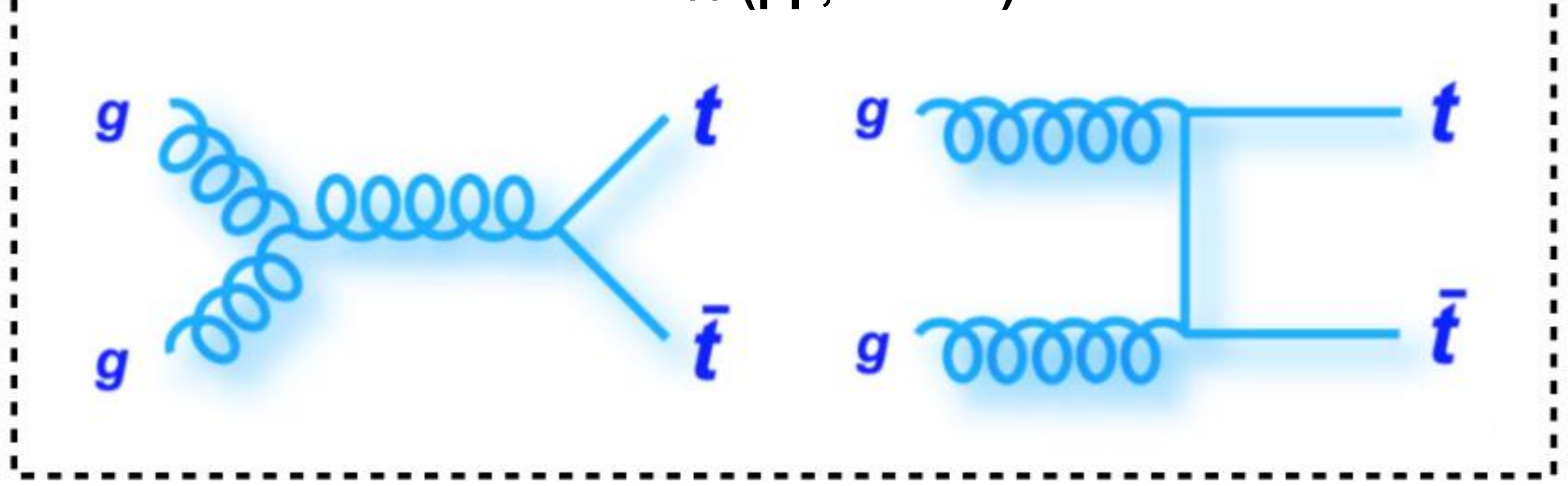
This talk focuses mostly on the cherry-picked results from the latest measurements

# $t\bar{t}$ production

≈15% (pp,13 TeV)




≈ 85% (pp,13 TeV)




- Theoretical uncertainties due to variations in $\mu_R$ & $\mu_F$ scales, PDF and $\alpha_S$
- Most precise (2.4%) inclusive $\sigma_{t\bar{t}}$ meas. (EPJC 80 (2020) 528) in events with OS eμ pair + 1 or 2 b-tagged jets

$$\sigma_{t\bar{t}} = 826.4 \pm 3.6\,(\text{stat}) \pm 11.5\,(\text{syst}) \pm 15.7\,(\text{lumi}) \pm 1.9\,(\text{beam})\,\text{pb}$$

- Dominant systematics:
  - ➢ Luminosity(1.9%)
  - ➢ *tW* bkg. cross-section (0.52%)
  - ➢ hadronization model (0.49%)
  - ➢ PDF (0.45%)
  - ➢ ISR/FSR model (0.45%)

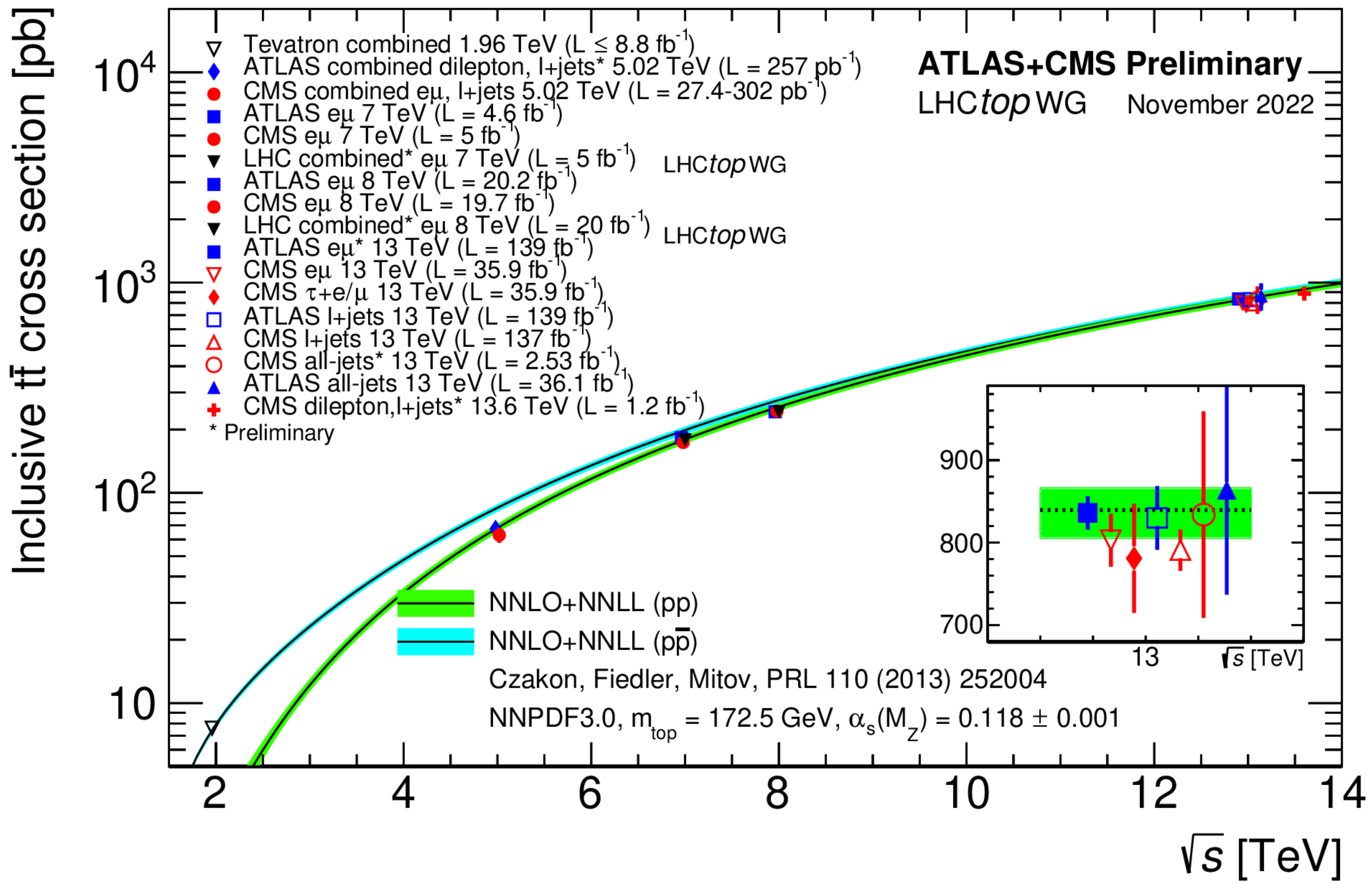
$$\sigma_{t\bar{t}} = 887^{+43}_{-41}(\text{stat}+\text{syst}) \pm 53(\text{lumi})\text{pb@13.6TeV}$$

New

CMS-PAS-TOP-22-012

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

| √s | $\sigma_{t\bar{t}}$ (NNLO + NNLL) |
|---|---|
| 7 TeV | $177.3^{+10.1}_{-10.8}$pb(6.6%) |
| 8 TeV | $252.9^{+15.3}_{-16.3}$pb(6.2%) |
| 13 TeV | $831.8^{+45.5}_{-49.9}$pb(5.7%) |




LHCTOPWGSummaryPlots

# $t\bar{t}$ asymmetry at LHC

- Production of top quark pairs charge symmetric at LO
- No charge asymmetry in gg ➛ $t\bar{t}$ at all orders ⇒ dilutes measurable asymmetry
- Small charge asymmetry at NLO due to QCD $q\bar{q}$ annihilation allowed in SM

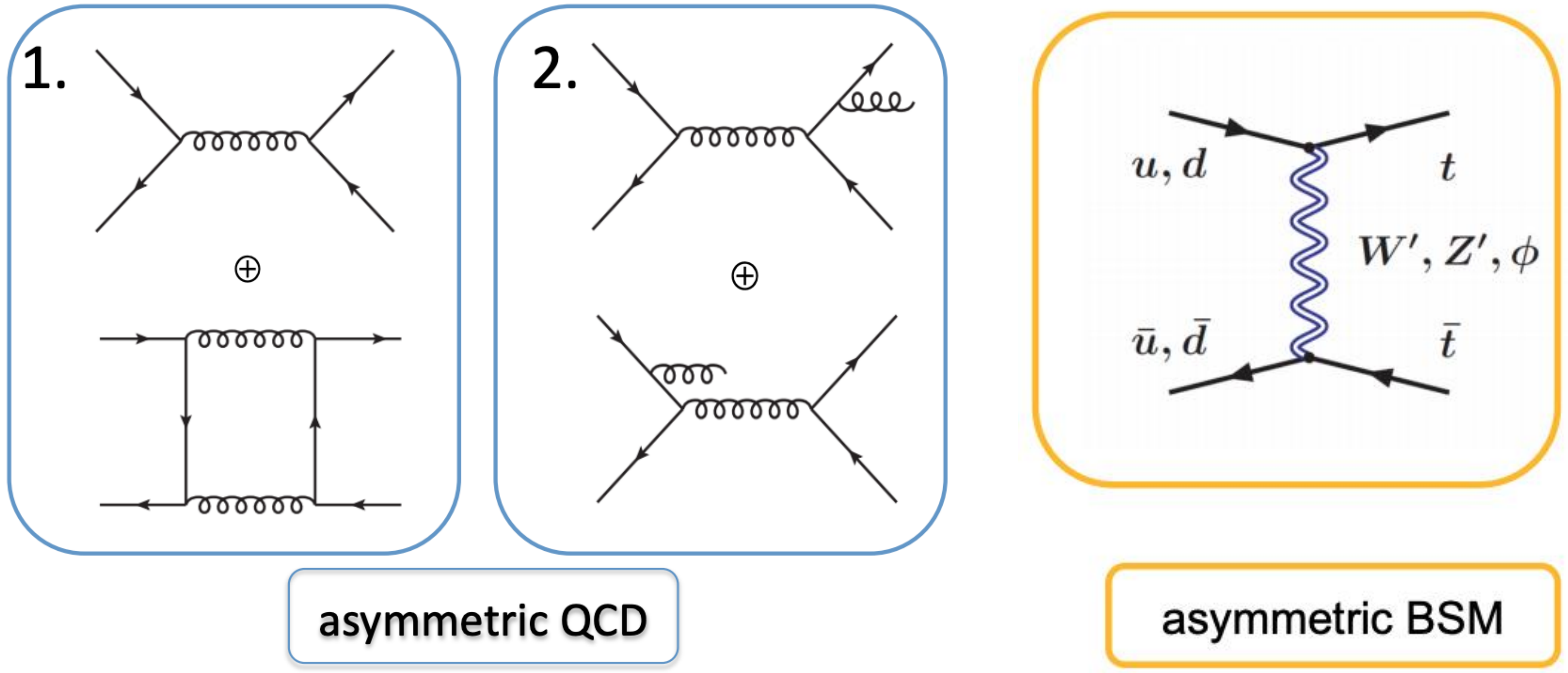
  ➛ interference between tree and box diagram

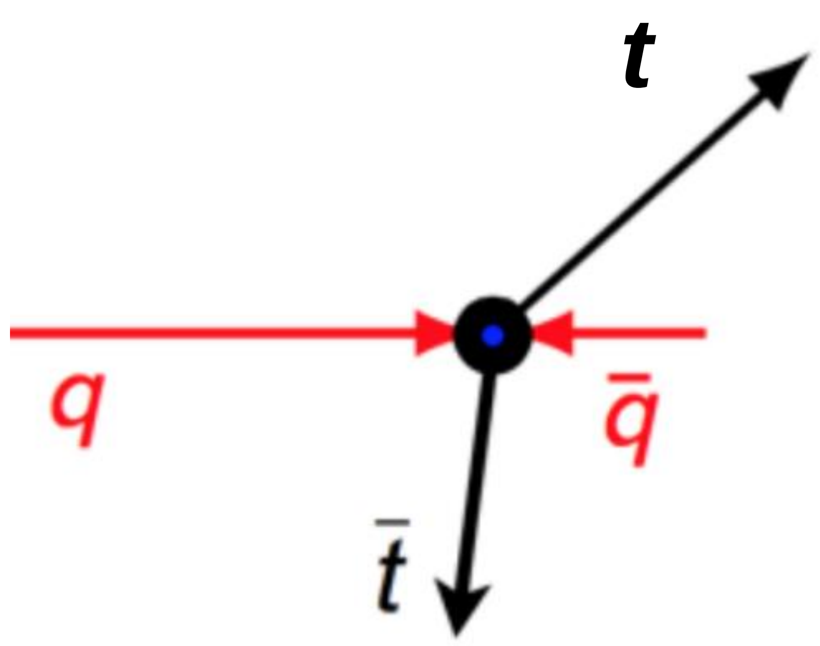
➛ interference between gluon ISR and FSR diagrams

- LHC, a pp collider ➛ no preferential direction for the incoming (anti-) partons
- High momenta valence quarks collide with lower momenta sea anti-quarks ➛ More forward top quarks & more central anti-top quarks leading to charge asymmetry ($A_C$)

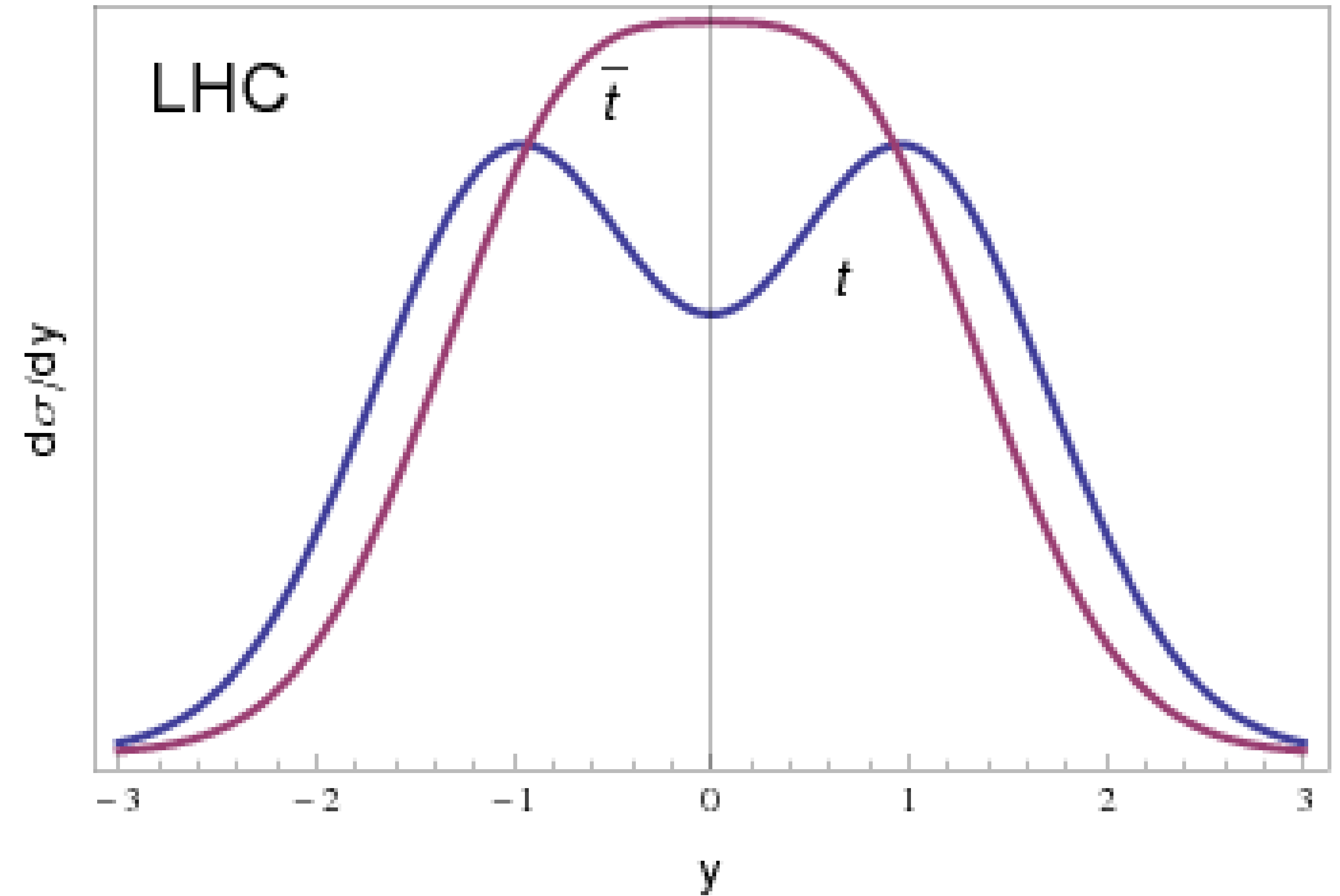
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}, \Delta|y| = |y_t| - |y_{\bar{t}}|$$

- New Physics models can enhance $A_c$ ➛ indirect search for new physics



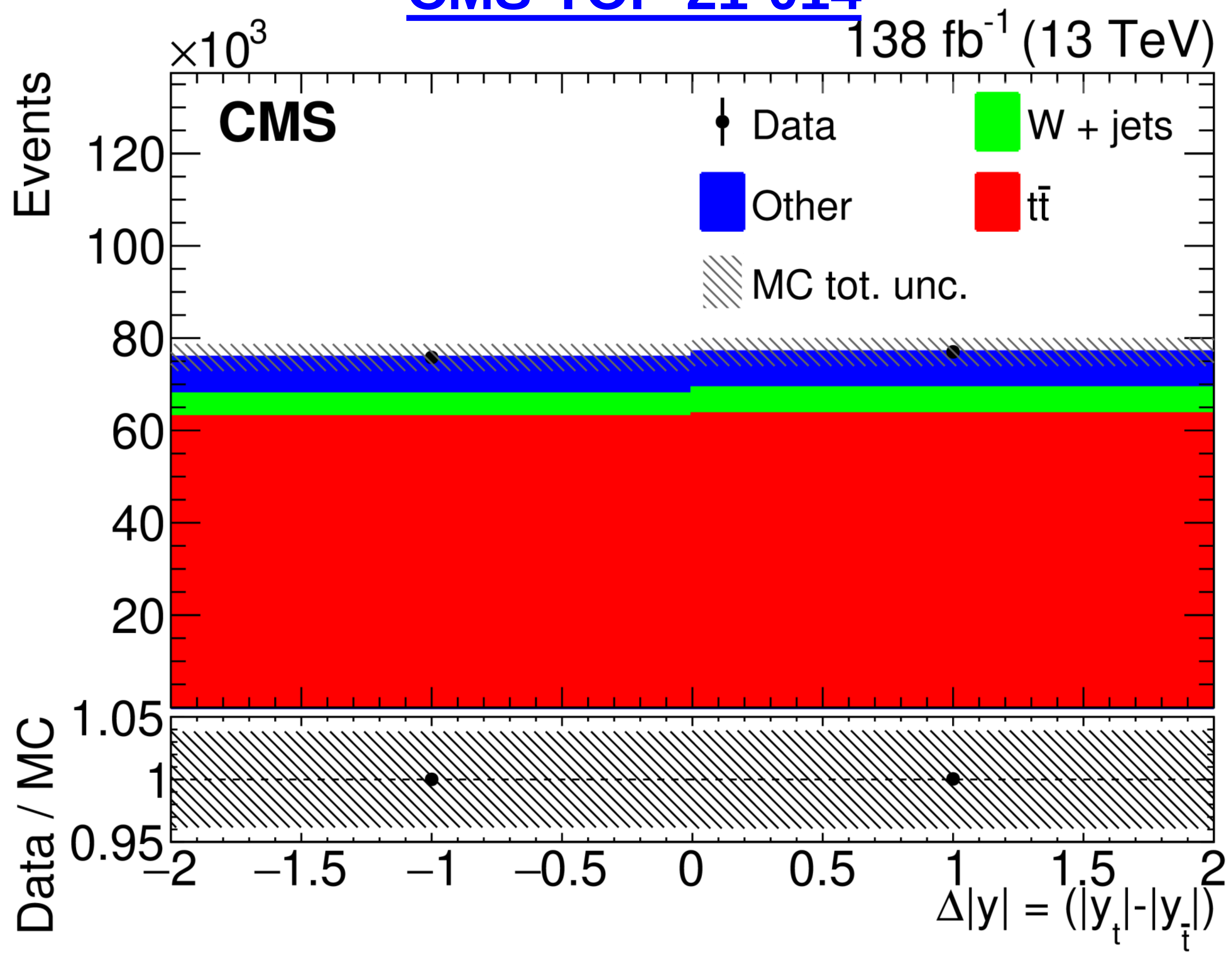

arXiv:1207.0331

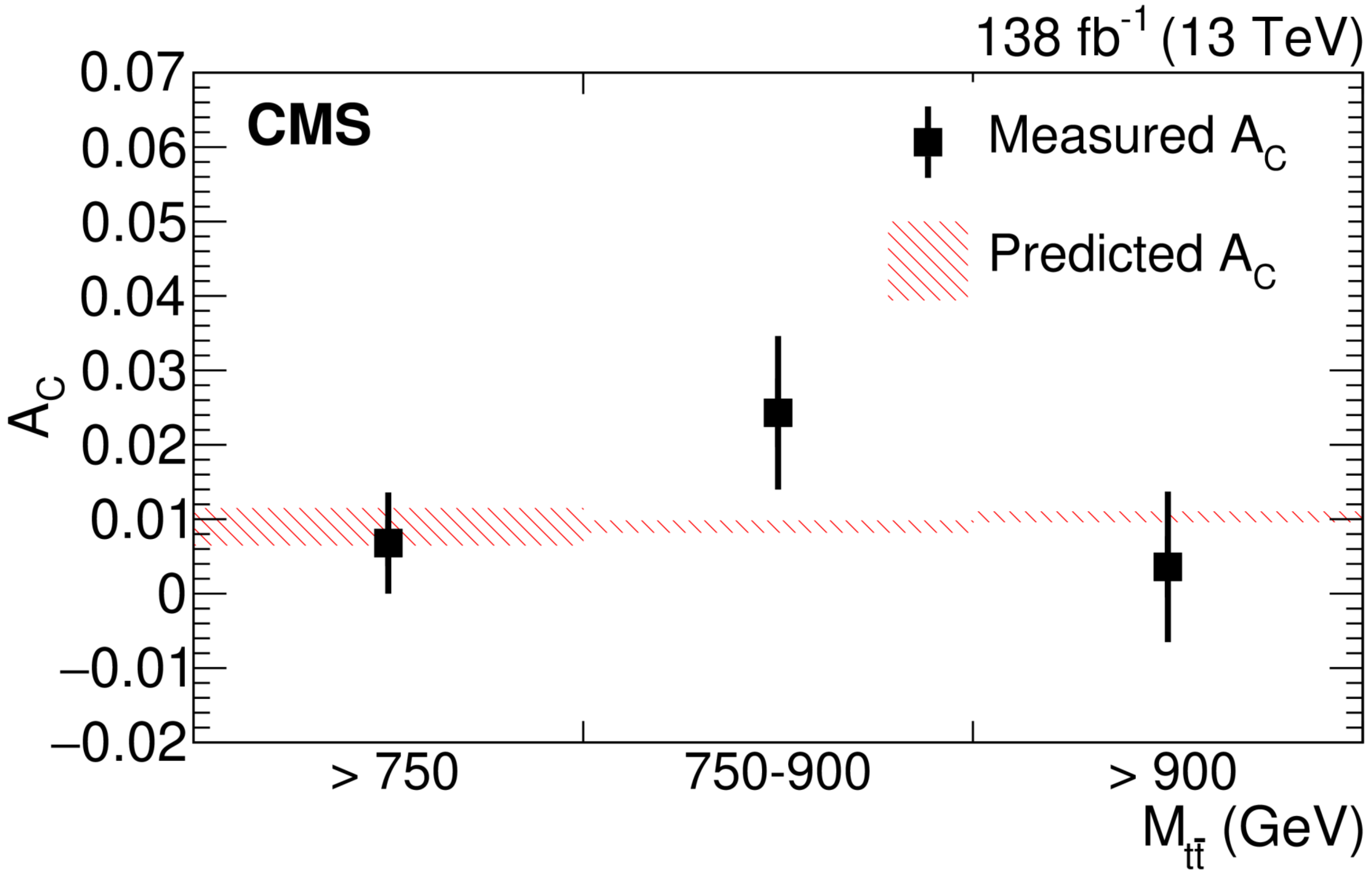


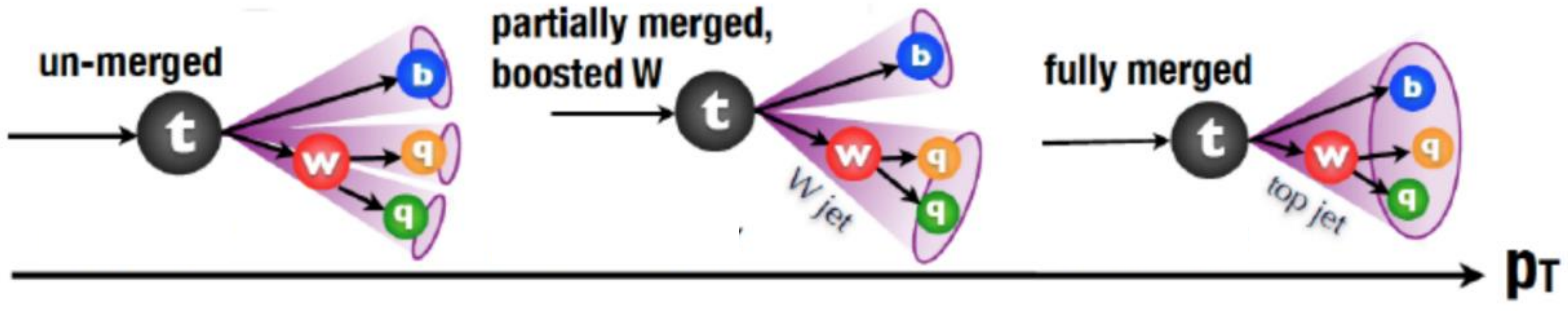
# $t\bar{t}$ charge asymmetry with boosted tops

- Final state consists of $1\ell$ $(e, \mu)$, 1 AK8 jet , 1 b-tagged jet (AK4)
- Event categories based on the boosted jet tagging
- Measurement performed inclusively as well as in bins of $M_{t\bar{t}} \in [750{,}900]\text{or} > 900\text{GeV}$
- Bkg. rate is determined directly from the fit
- Inclusive measurement agrees well with SM prediction
- Dominant sources: $\mu_F$ scale, PDF etc.

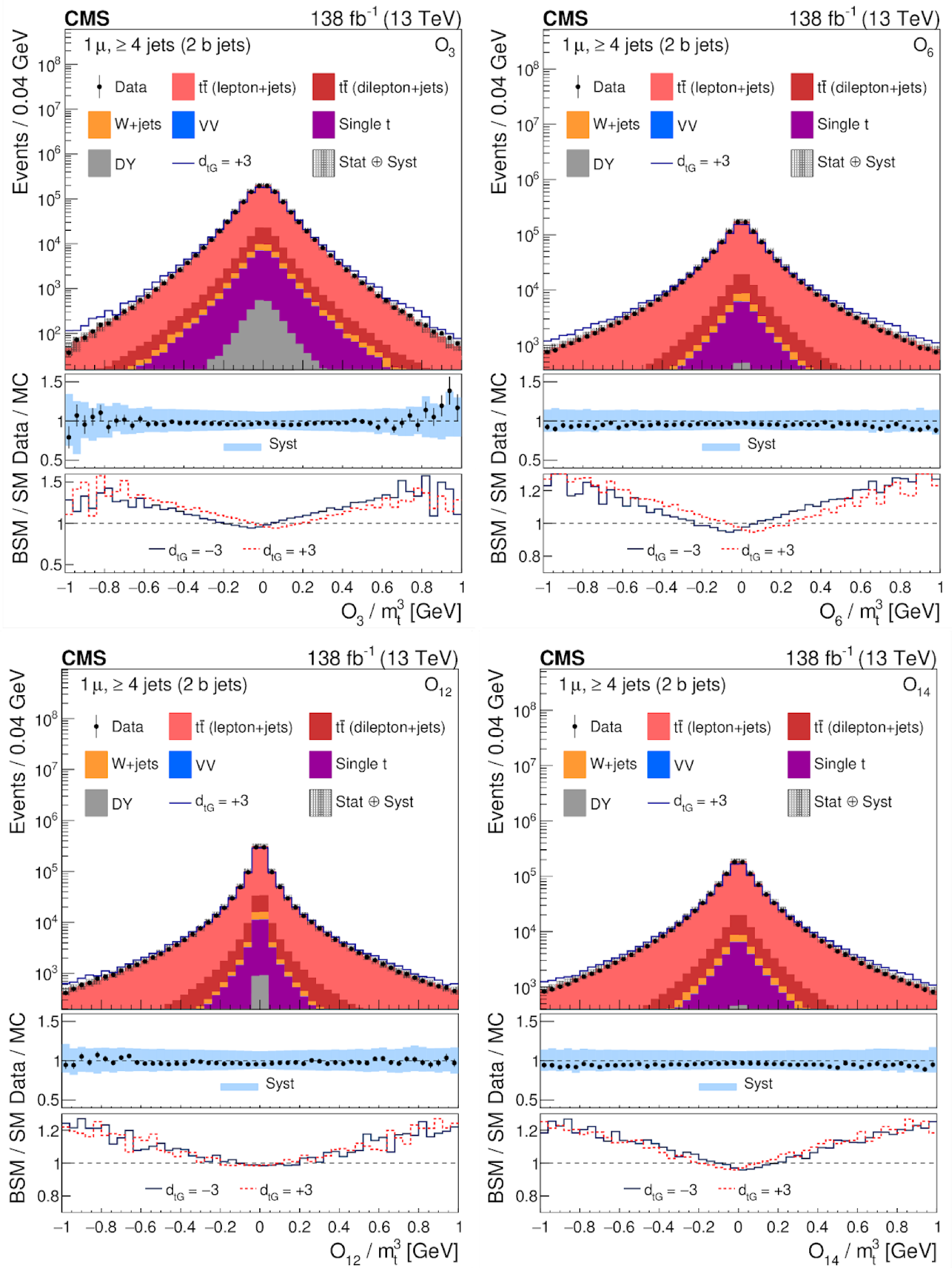
CMS-TOP-21-014



# Search for CP violation in $t\bar{t}$ lepton + jets events




- BSM interaction modifies $tg$ coupling
  - ☞ invokes Chromo-electric-dipole-moment (CEDM) $d_{tG}$ [ref]
  - ☞ possible source of CP violation in strong interaction
- Following Dim-6 operators are considered

$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p}_b^{\,*} \cdot (\vec{p}_\ell^{\,*} \times \vec{p}_{j_1}^{\,*}),$$

$$O_6 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

$$O_{12} = q \cdot (p_b - p_{\bar{b}}) \epsilon(P, q, p_b, p_{\bar{b}}) \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})_z,$$

$$O_{14} = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}).$$

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}, \quad i = 3, 6, 12, 14.$$

- CEDM contribution can be ~ 8% & 0.4% for $A_{CP}(O_3)$ & $A_{CP}(O_{12})$

CMS-TOP-20-005

# Search for CP violation in $t\bar{t}$ lepton + jets events

$$\chi^2 = \left(\frac{m_{jjb} - m_t}{\sigma_t}\right)^2 + \left(\frac{m_{jj} - m_W}{\sigma_W}\right)^2$$

- Hadronic top quark reco. based on min. $\chi^2$
- Data-driven bkg. estimation
- ML fit to data using the $m_{\ell b}$ template
- Measured $A'_{CP}$ calibrated w.r.t $A_{CP}$ at truth level
- $d_{tG}$ determined from $A_{CP}$ : $A_{CP} = \frac{d_{tG}+a}{bd_{tG}^2+cd_{tG}+d}$
- $d_{tG} = 0.04 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{syst})$

☞ consistent with SM prediction $d_{tG} = 0$

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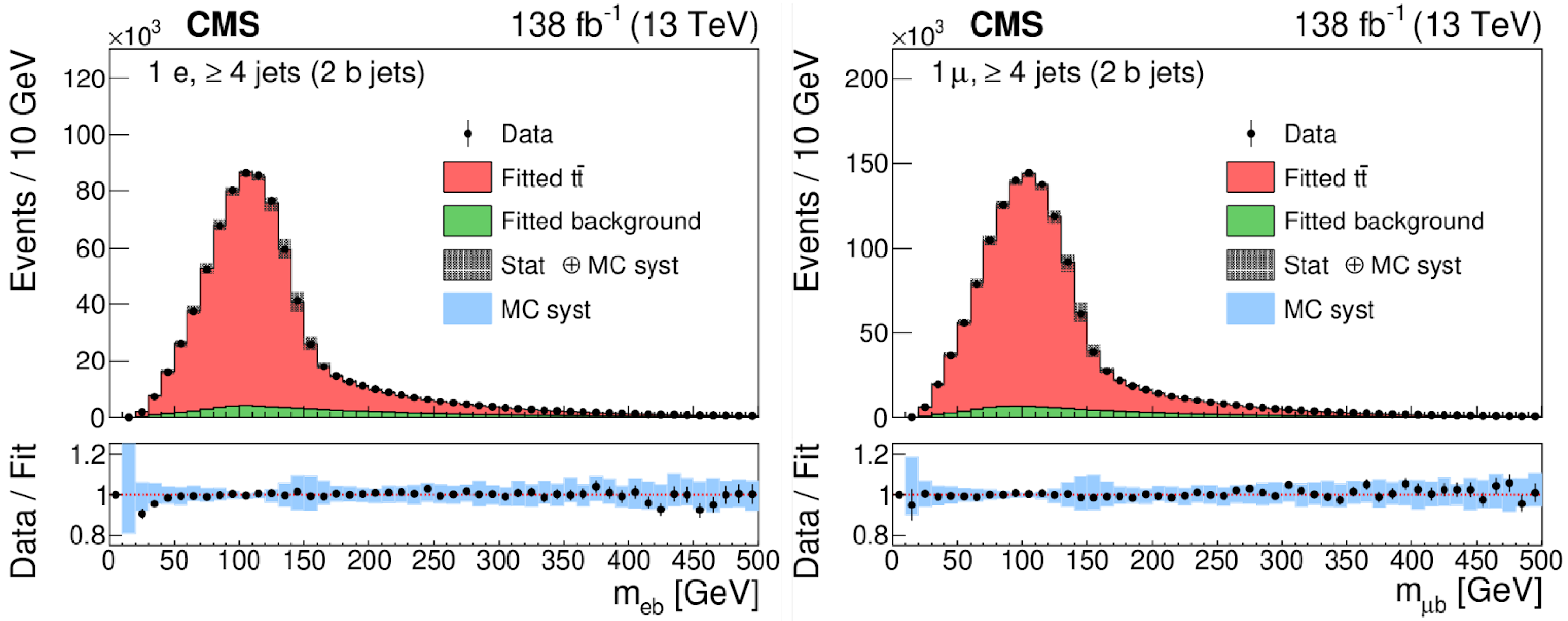


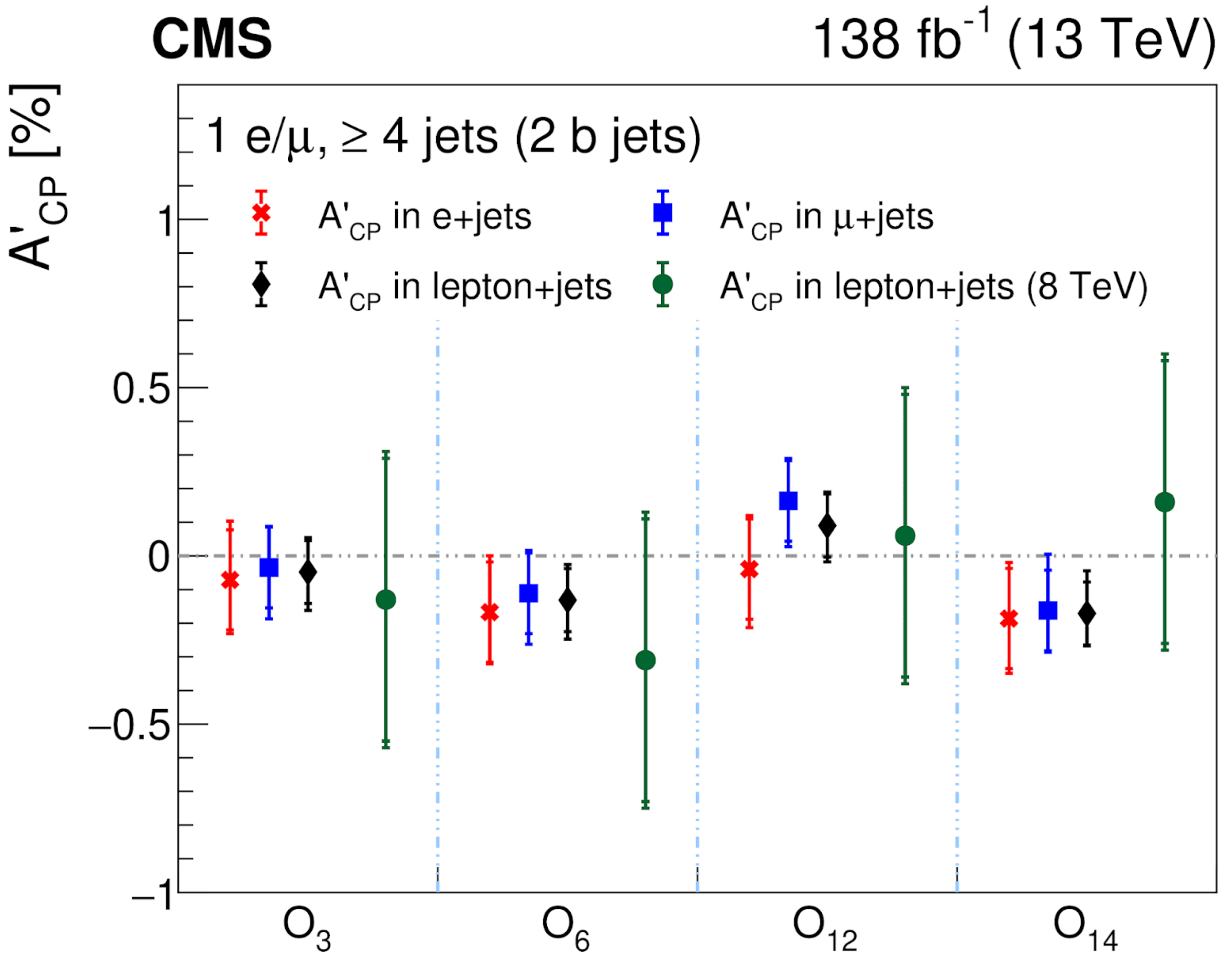


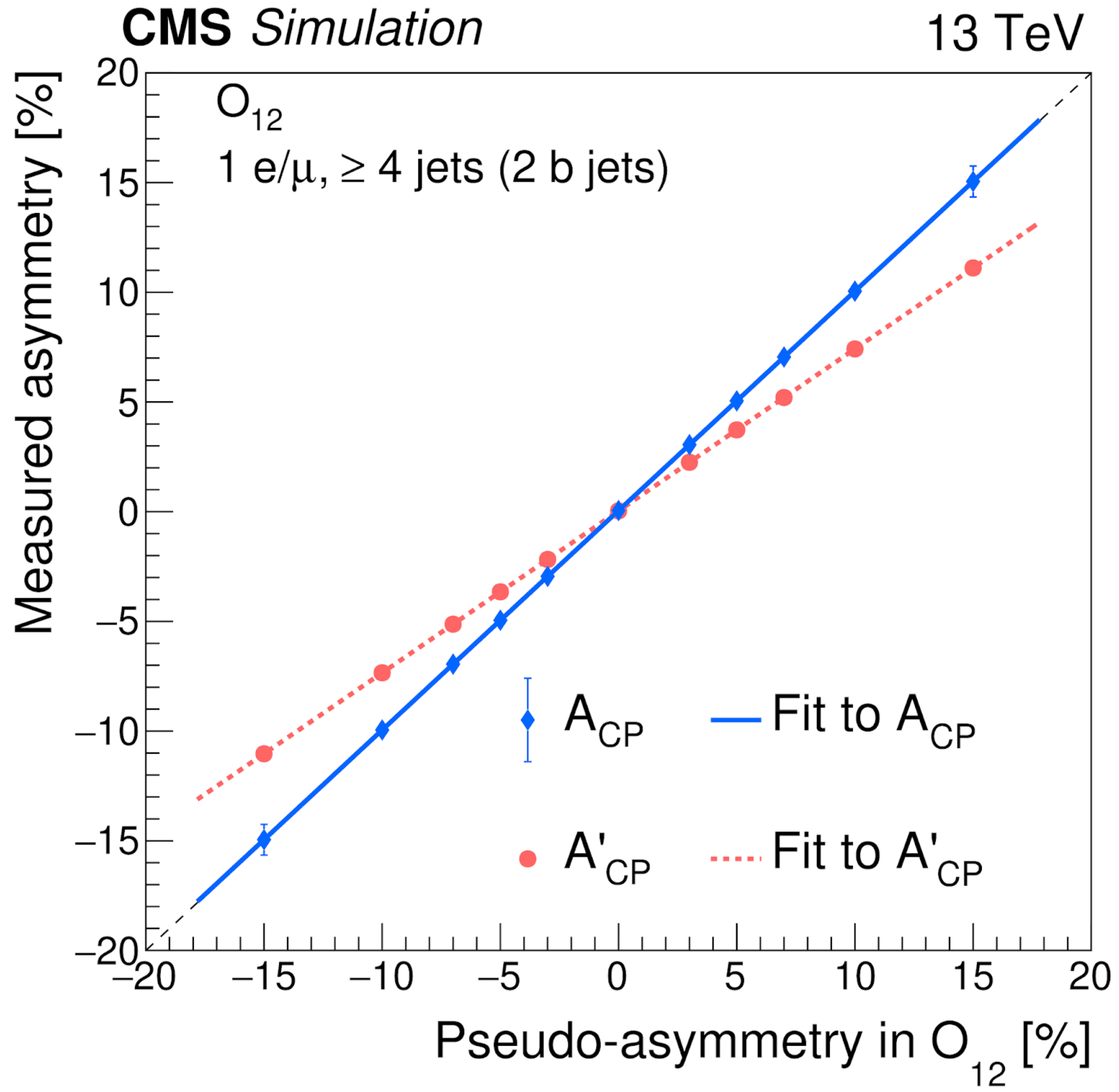

# Inclusive and differential $t\bar{t}\gamma$ cross section - 2$\ell$

- NLO prediction: $\sigma_{t\bar{t}\gamma} = 155 \pm 27\text{fb}[p_T(\gamma) > 20\text{GeV}\ |\eta(\gamma)| < 1.442]$

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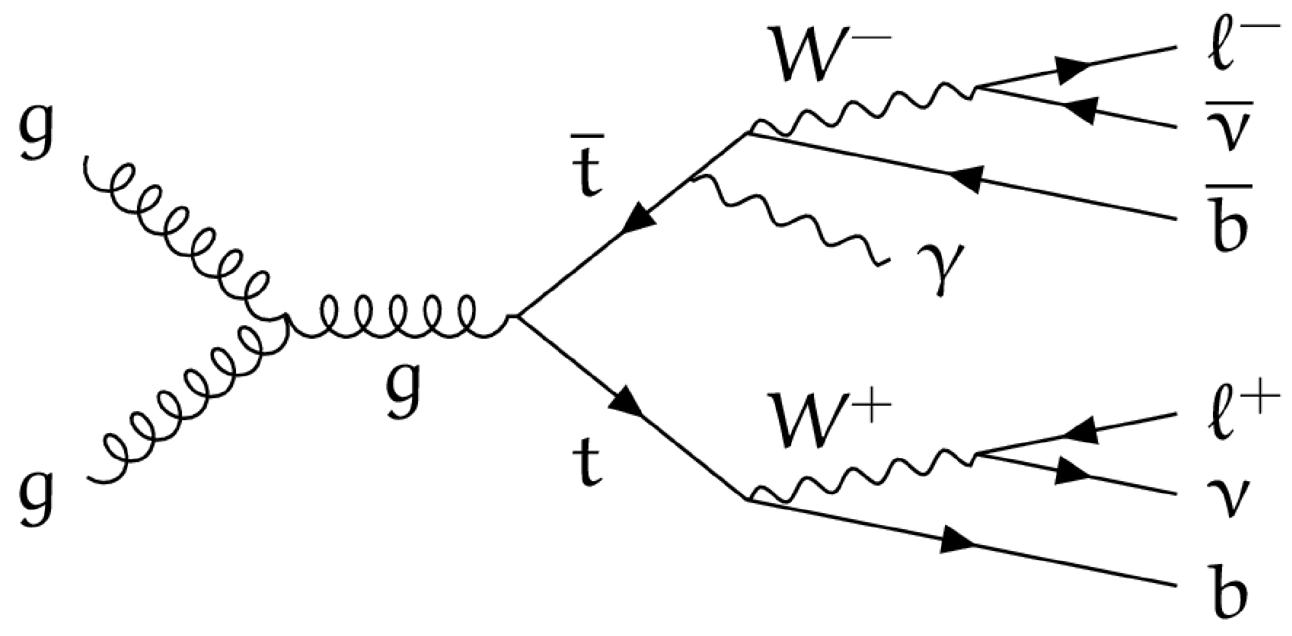
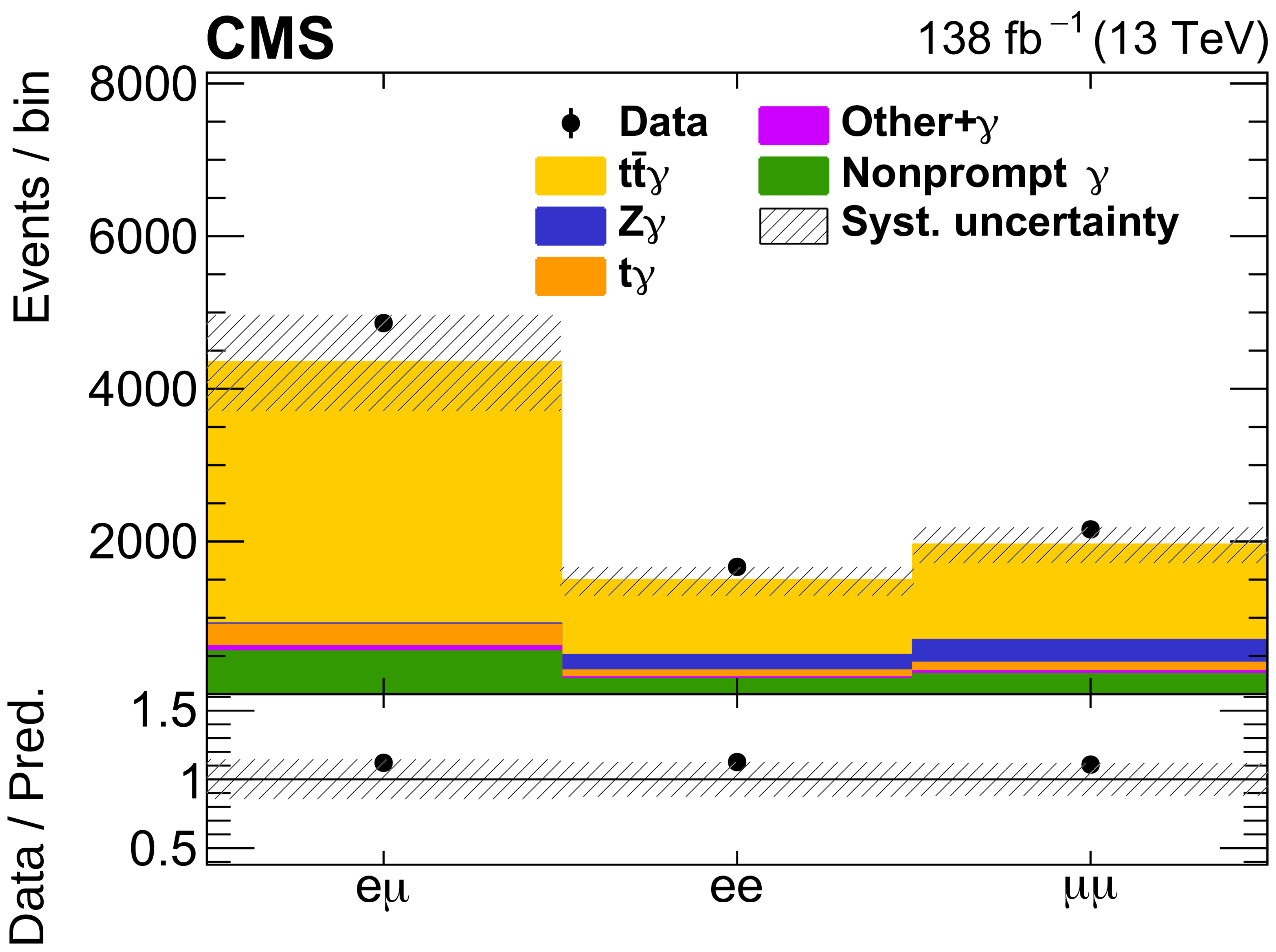
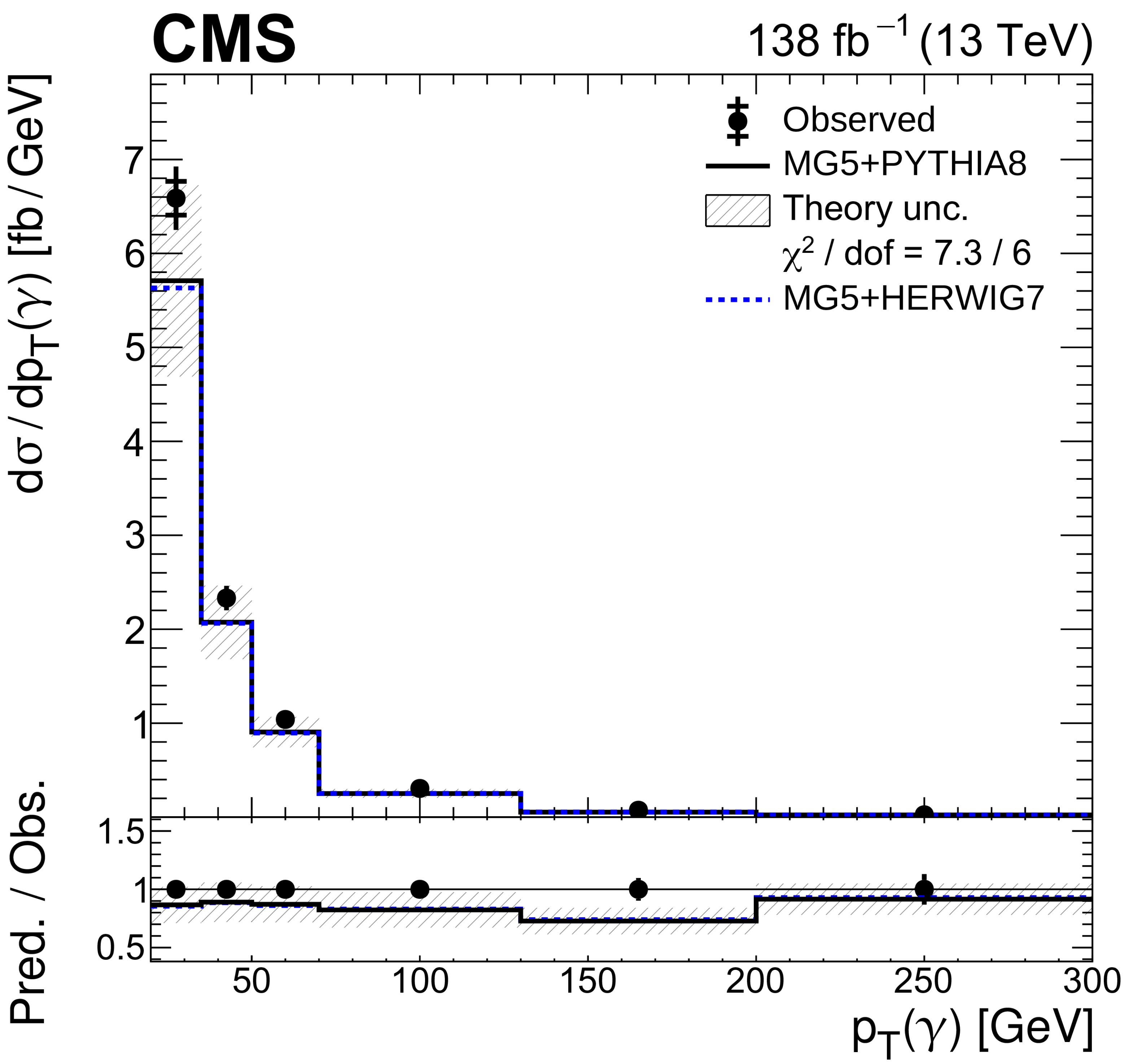
- Exactly 1 $\gamma$, exactly 2 OS $\ell$, ≥ 1 b-tagged jet in the final state
  - ➤ Bkgs.: Non-prompt $\gamma$ (data-driven), Z$\gamma$ (from Z peak), others from simulation

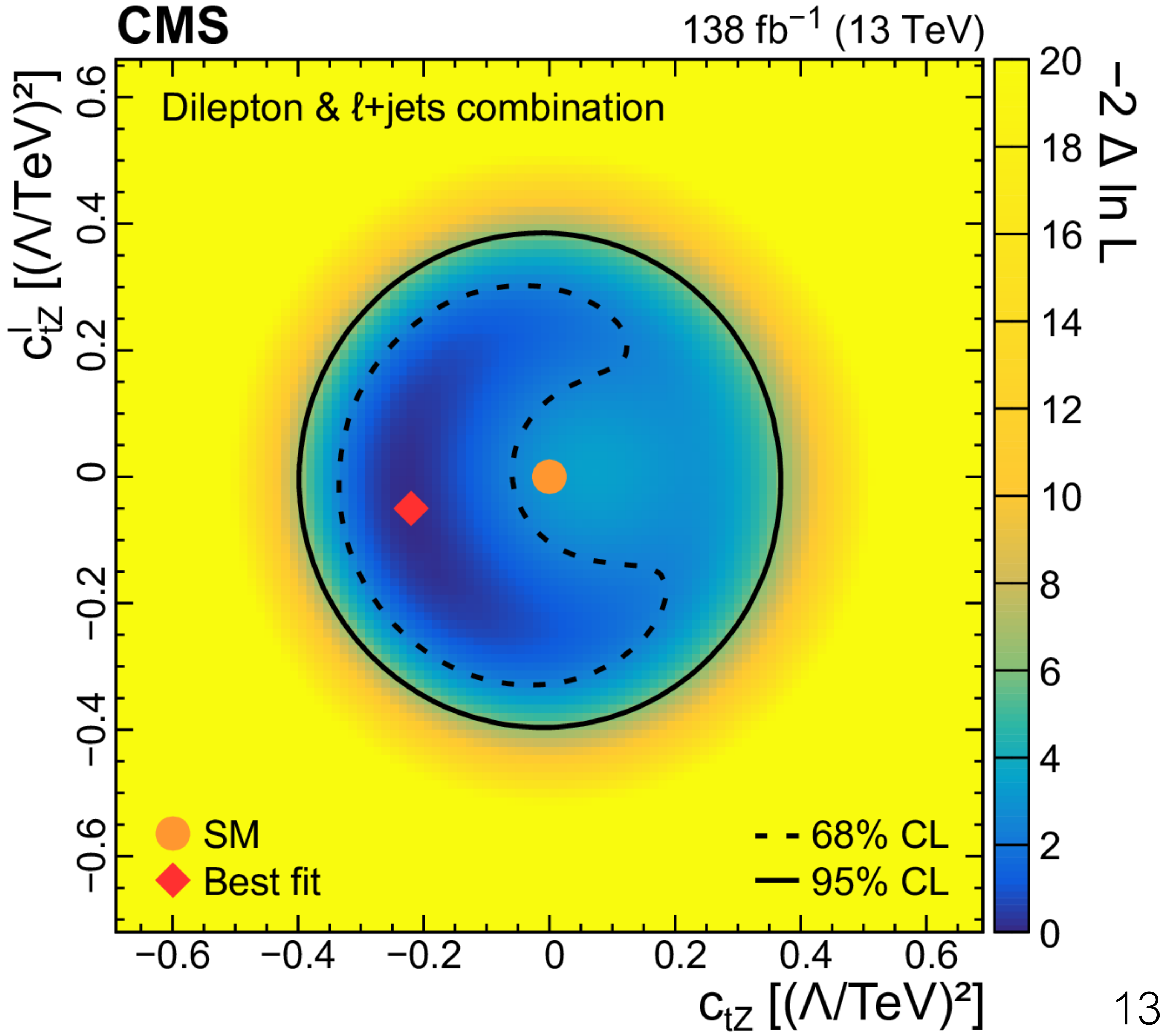



- Measured: $\sigma_{t\bar{t}\gamma} = 175.2 \pm 2.5(\text{stat}) \pm 6.3(\text{syst})\text{fb}(4\%)$
  - ➤ Dominant sources: Luminosity, signal model, bkg. normalization

- Differential measurements used to extract combined (2$\ell$ & $\ell$ + jets ) limits on EFT coupling $C_{tZ}$

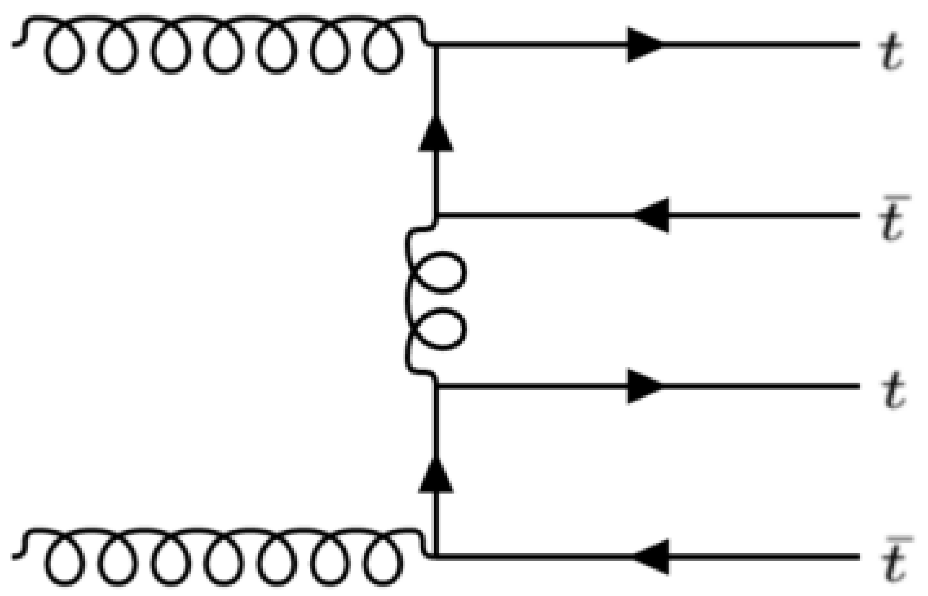


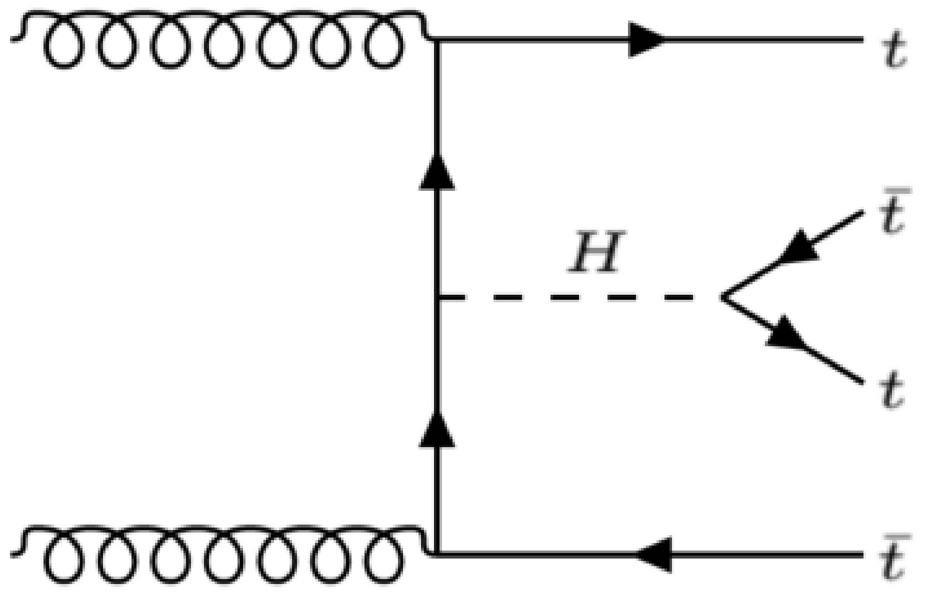



# Production of 4 tops ($t\bar{t}t\bar{t}$)

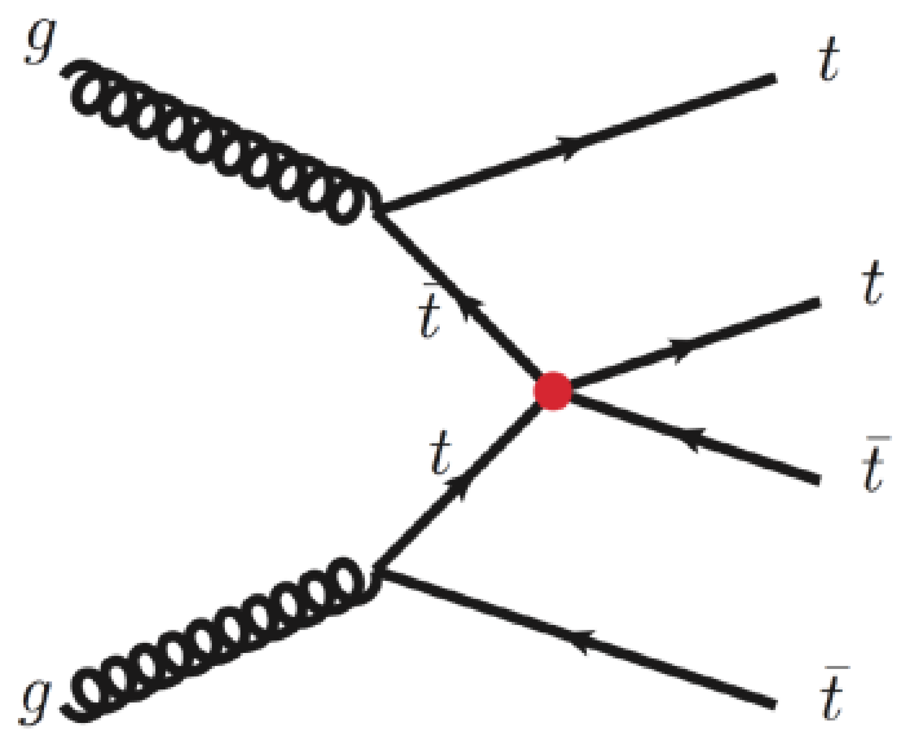
QCD



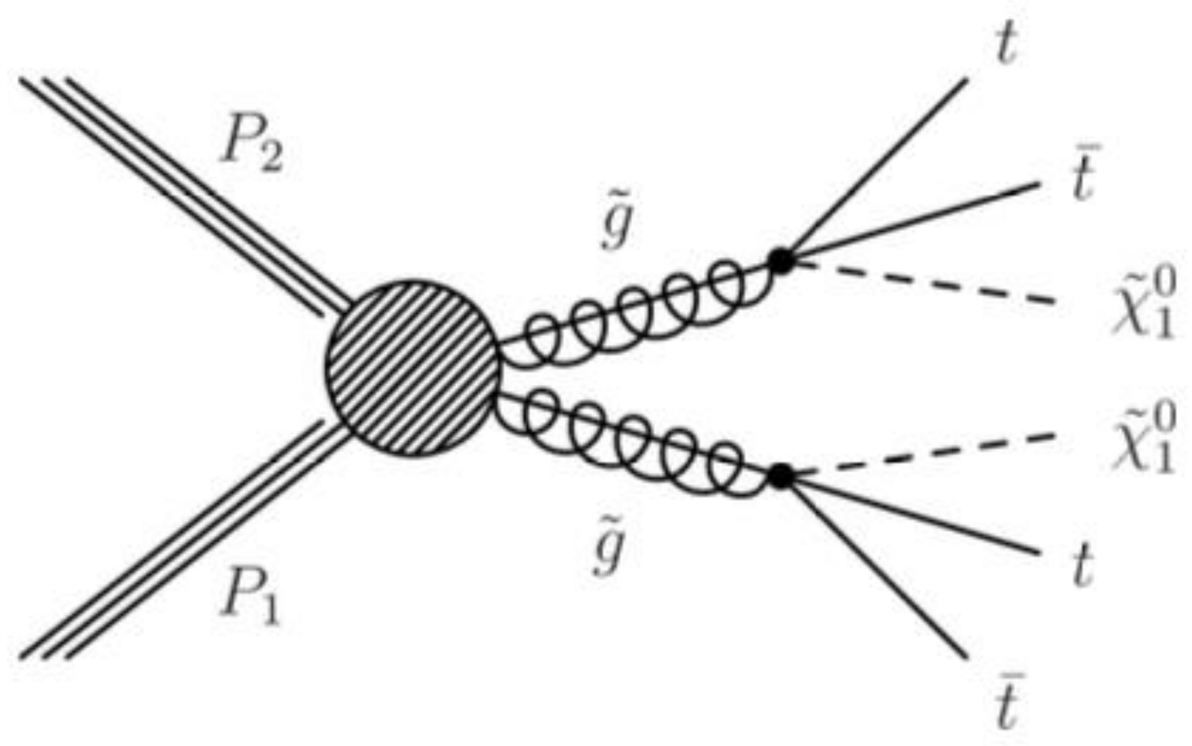

EWK




Four-fermion EFT coupling




SUSY



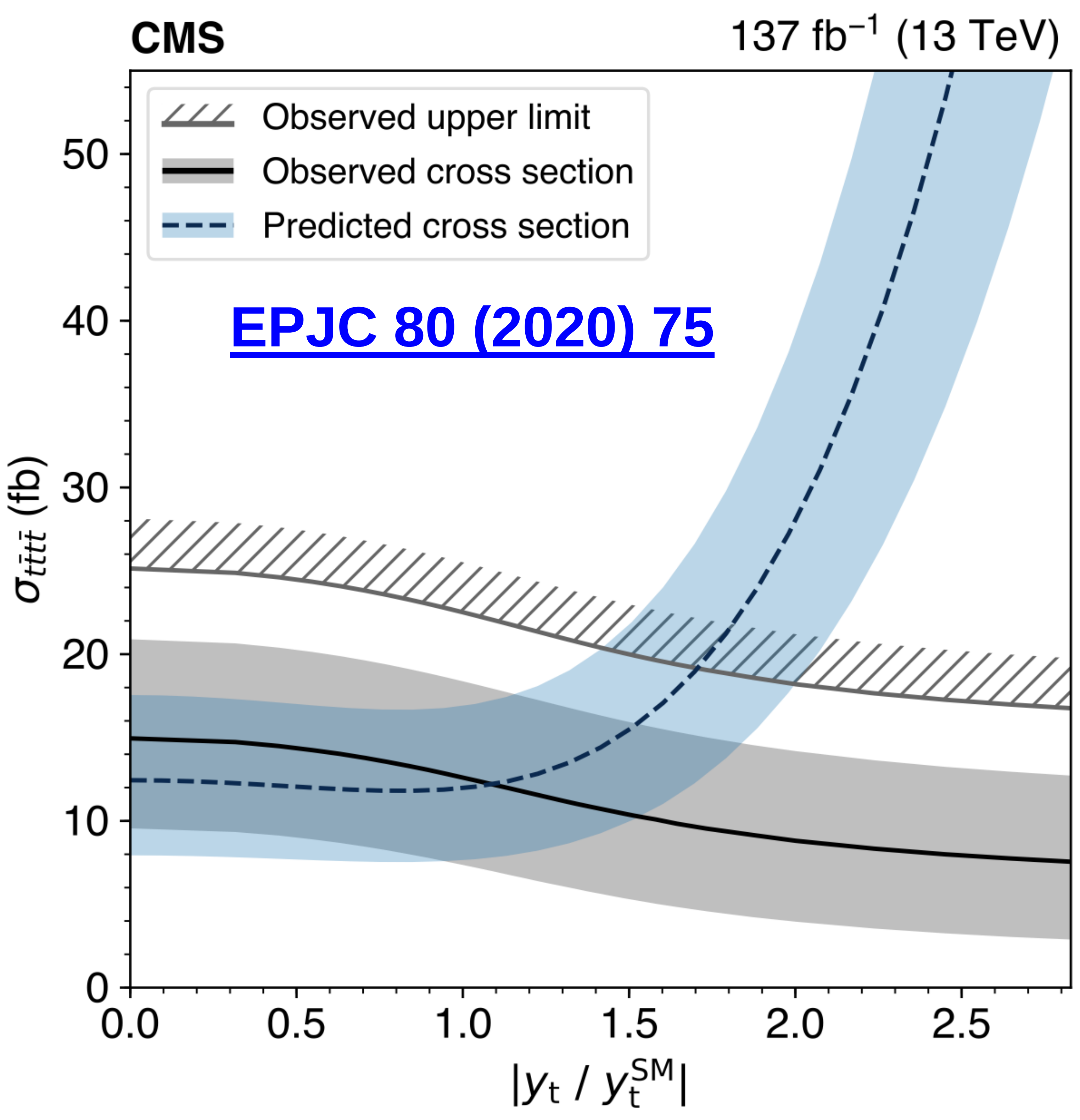

- Prediction: $\sigma_{t\bar{t}t\bar{t}} = 12\text{fb} \pm 20\%$ JHEP 02 (2018) 031
- Final state consists of 4 b-jets, other jets and leptons

| $1\ell$ or $2\ell$ (OS) | SSML: $2\ell$(SS) or $\geq 3\ell$ |
|---|---|
| Combined BR ~ 57% | Combined BR ~13% |
| Dominant $t\bar{t}$ + HF bkg. | Dominant $t\bar{t}$V bkg |
| Negligible fake or non-prompt $\ell$ | Fake or non-prompt $\ell$ significant |

| Topology | Branching ratio |
|---|---|
| $0\ell$ | 31% |
| $1\ell$ | 42% |
| $2\ell$(OS) | 14% |
| $2\ell$(SS) | 7% |
| $\geq 3\ell$ | 5% |

- Extensive use of MVA techniques to extract signal in both types of final states
- SSML: limits on top-Yukawa coupling
- $1\ell/2\ell$OS : EFT interpretation with limits on Wilson coefficients

# Production of 4 tops ($t\bar{t}t\bar{t}$)

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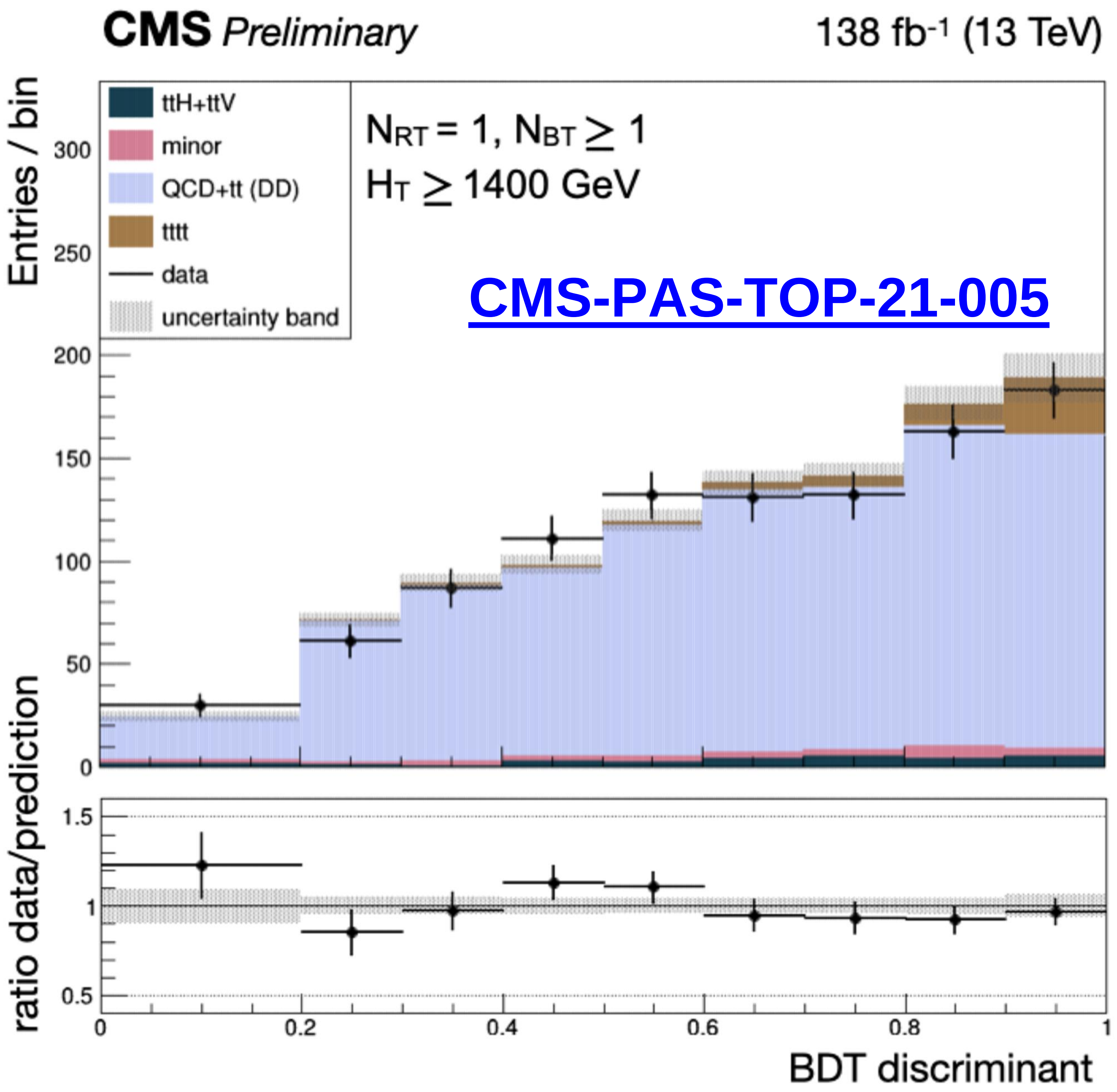
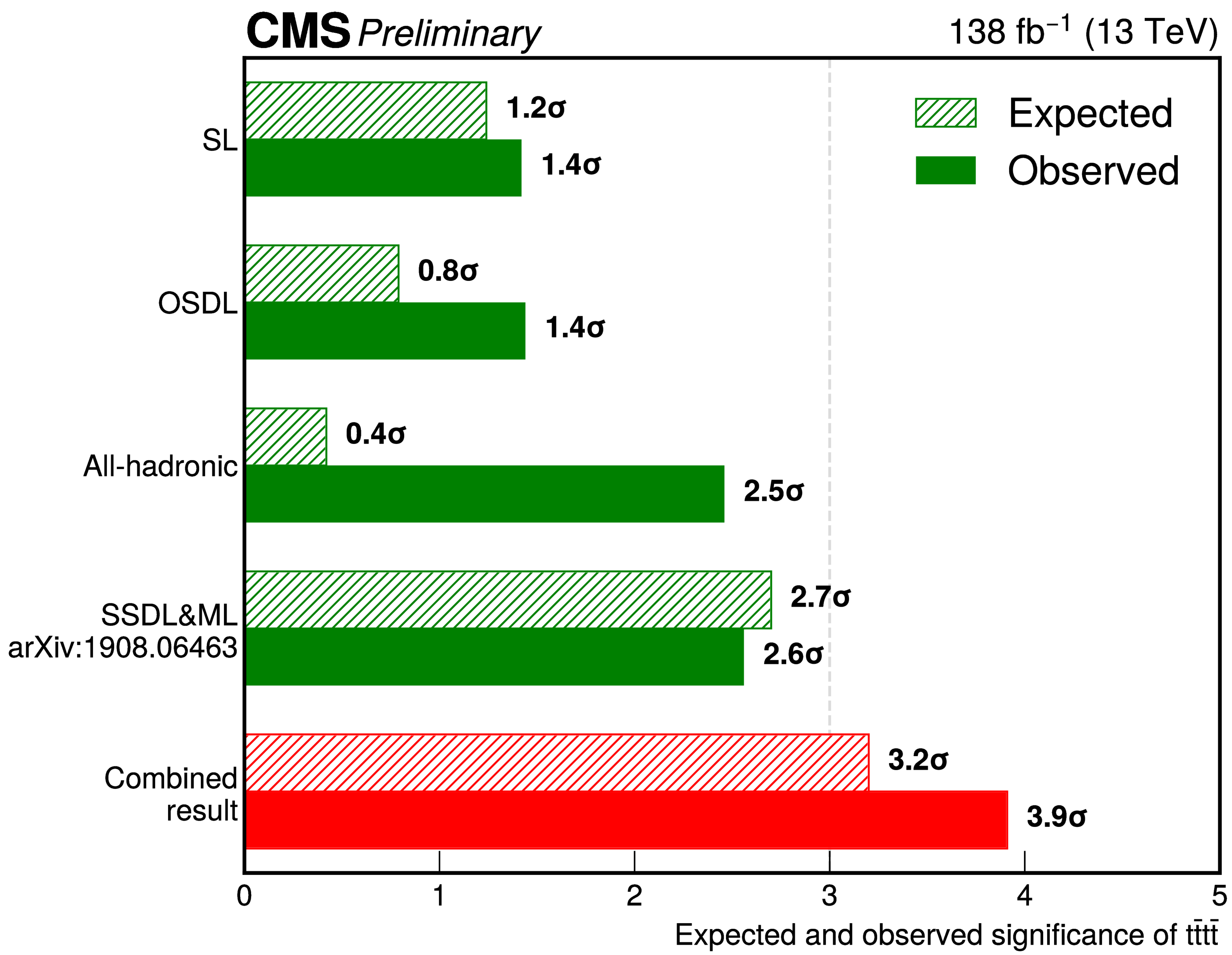
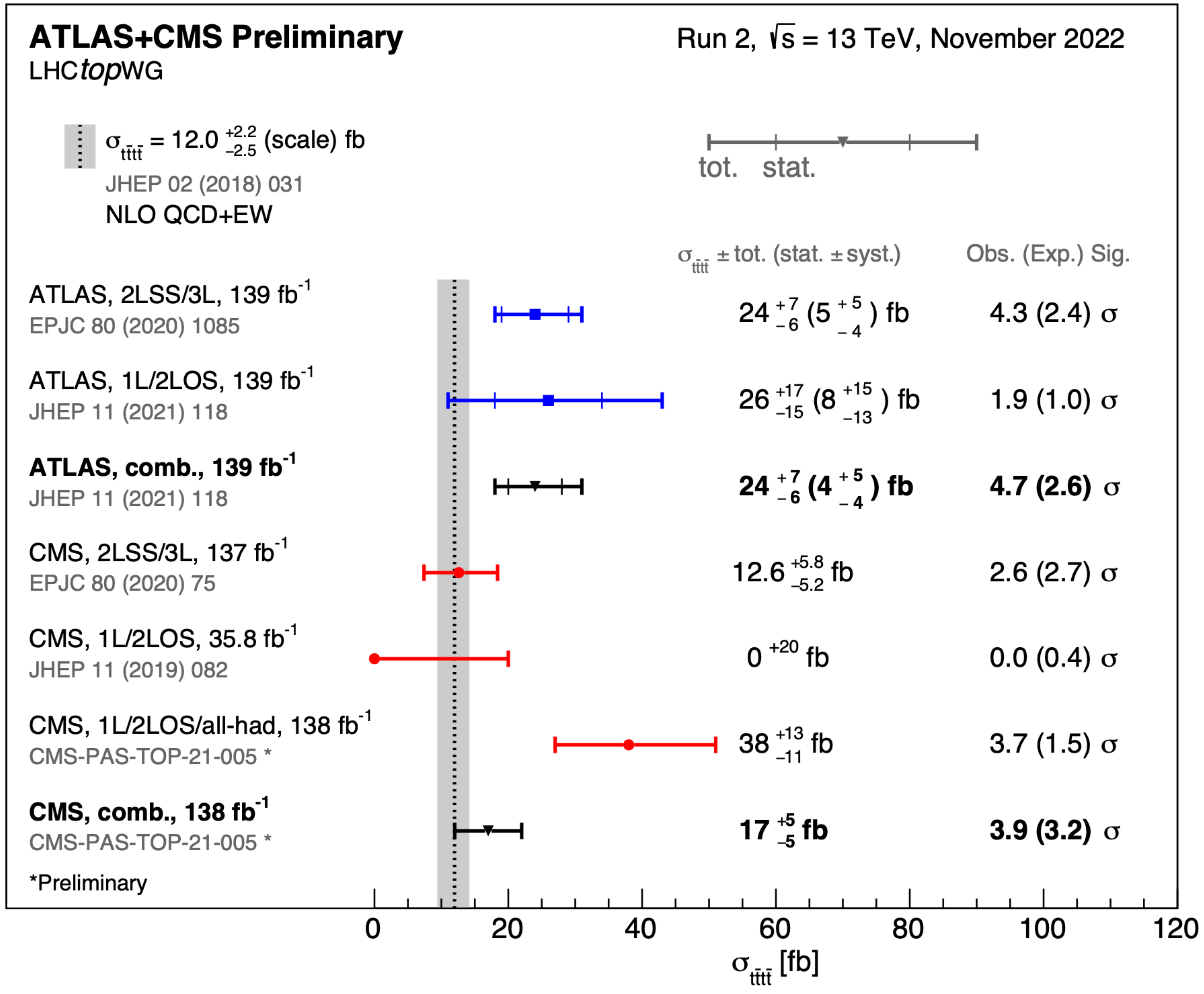
| Operator | Expected $C_k/\Lambda^2$ (TeV$^{-2}$) | Observed (TeV$^{-2}$) |
|---|---|---|
| $\mathcal{O}^1_{tt}$ | [−2.0, 1.9] | [−2.2, 2.1] |
| $\mathcal{O}^1_{QQ}$ | [−2.0, 1.9] | [−2.2, 2.0] |
| $\mathcal{O}^1_{Qt}$ | [−3.4, 3.3] | [−3.7, 3.5] |
| $\mathcal{O}^8_{Qt}$ | [−7.4, 6.3] | [−8.0, 6.8] |




- First time the all-hadronic channel is used in 4 top searches!
- Fit to BDT score for signal / multijet separation
- Event categories of based on resolved / boosted top candidates and $H_T$
- Data-driven estimation of multijet / tt+jets backgrounds

# Production of 4 tops ($t\bar{t}t\bar{t}$)



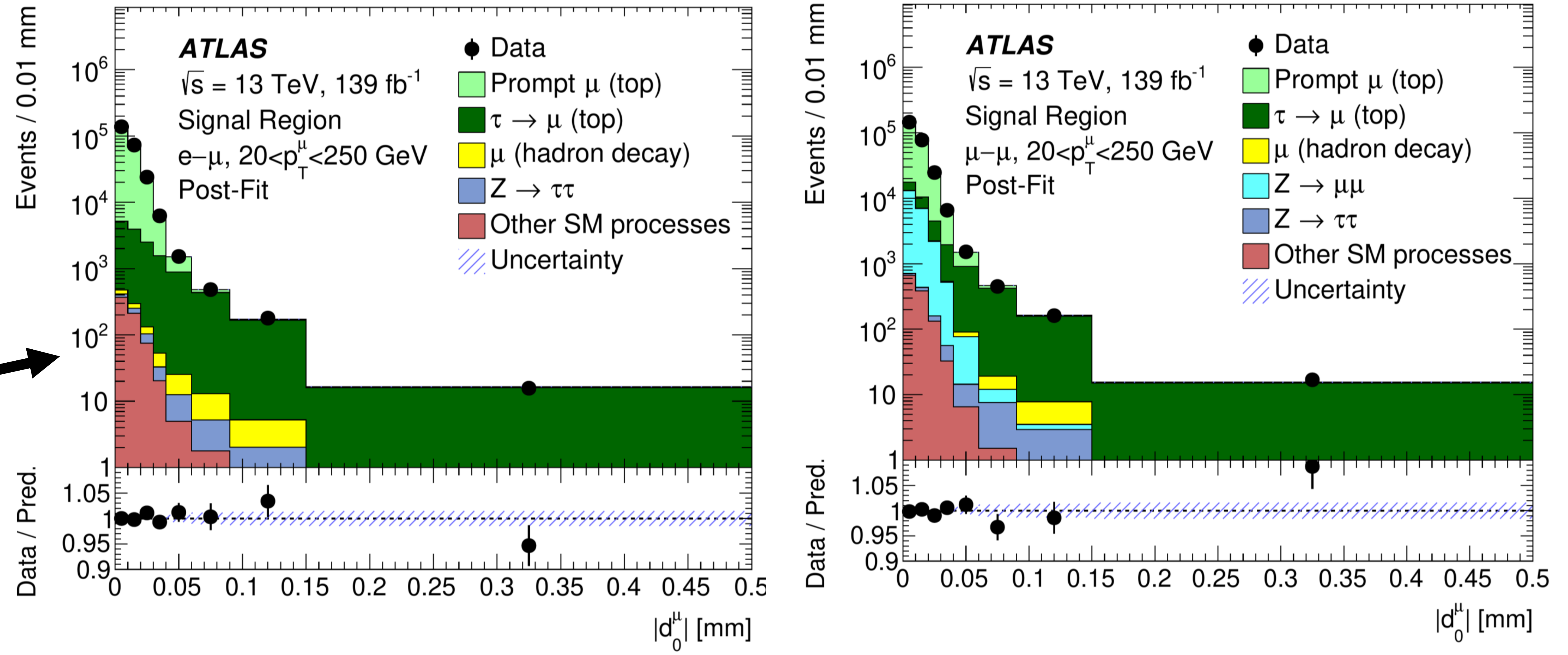

[CMS-PAS-TOP-21-005](#)

[LHCTOPWGSummaryPlots](#)

# Lepton flavor universality using $t\bar{t}$ events

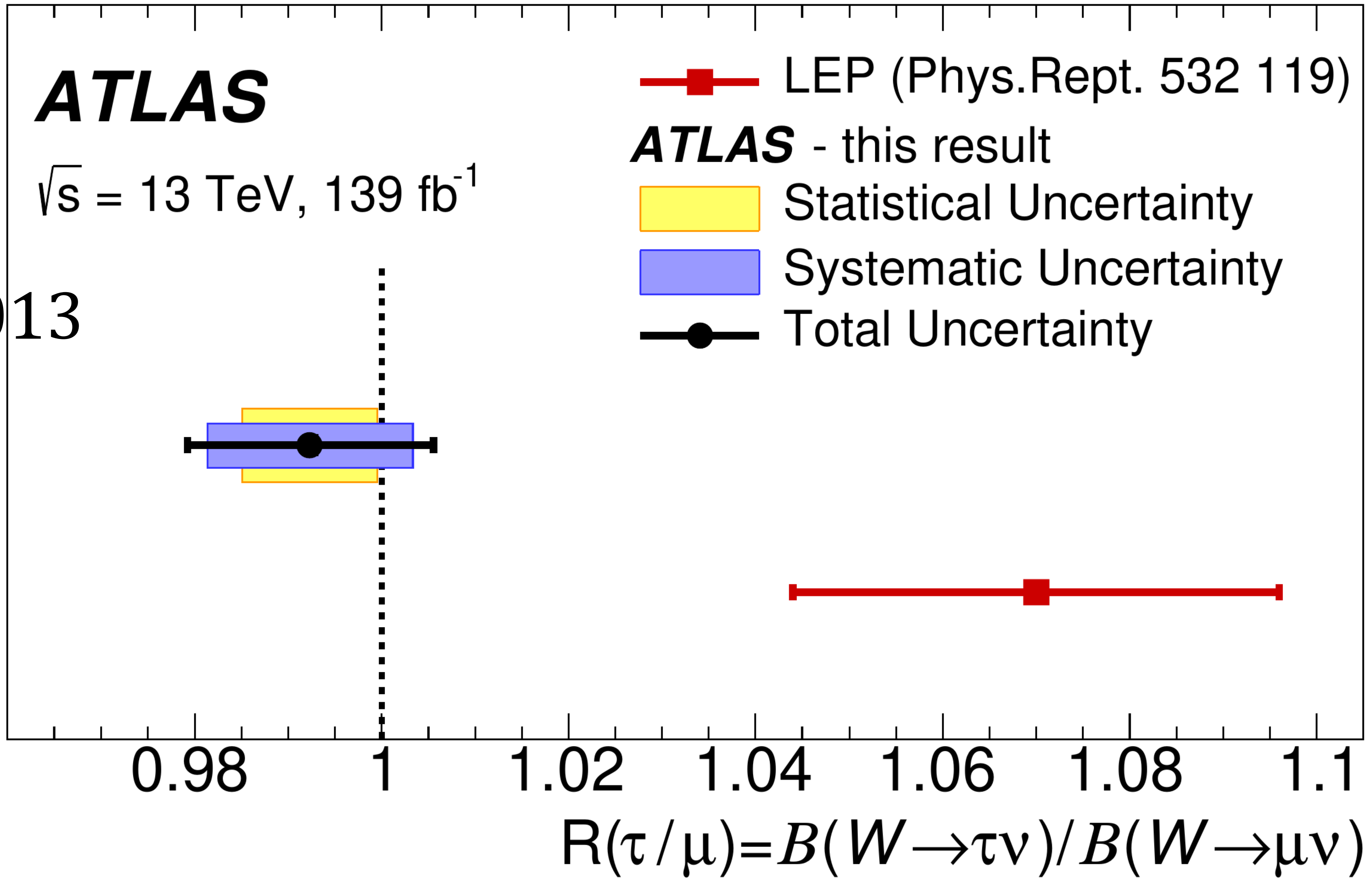
$$R(\tau/\mu) = B(W \to \tau\nu)/B(W \to \mu\nu)$$

- Previous LEP result 2.7$\sigma$ away from SM prediction
- Measurement in $t\bar{t}$ dilepton events using Tag&Probe
  ➢ tight *e*/*μ* , *check second μ*
- Impact parameter ( $d_0$ ) discriminant
  low $d_0$ : Likely *W* ➢ *μ*
  high $d_0$ : Likely W ➢ *τ* ➢ *μ*




- $d_0$ calibrated using *Z* ➢ *μ μ*
- Most Precise result : Unc. dominated by syst.

$$R(\tau/\mu) = 0.992 \pm 0.007(\text{stat}) \pm 0.011(\text{syst}) = 0.992 \pm 0.013$$



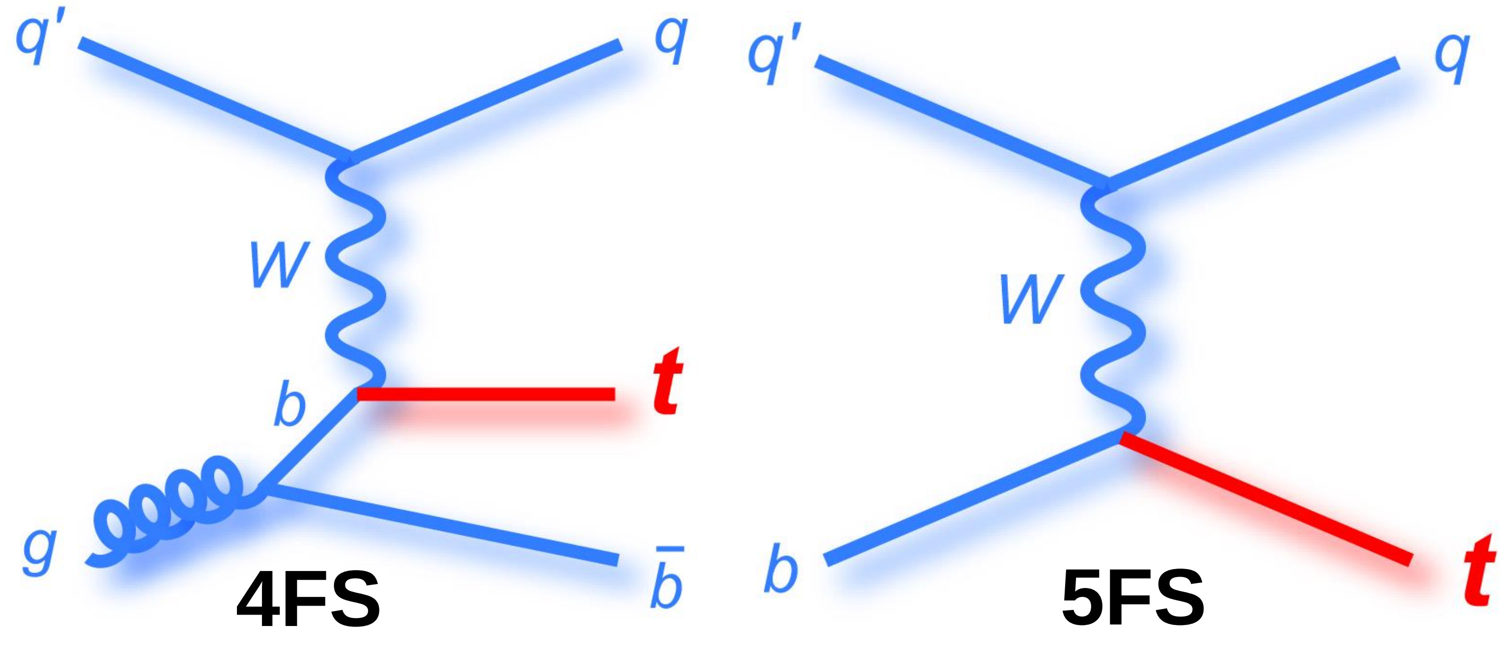

- Dominant syst. sources
  ➢ $d_0$ template modelling
  ➢ *μ* isolation and reconstruction

NP 17, 813–818 (2021)

# Electroweak production

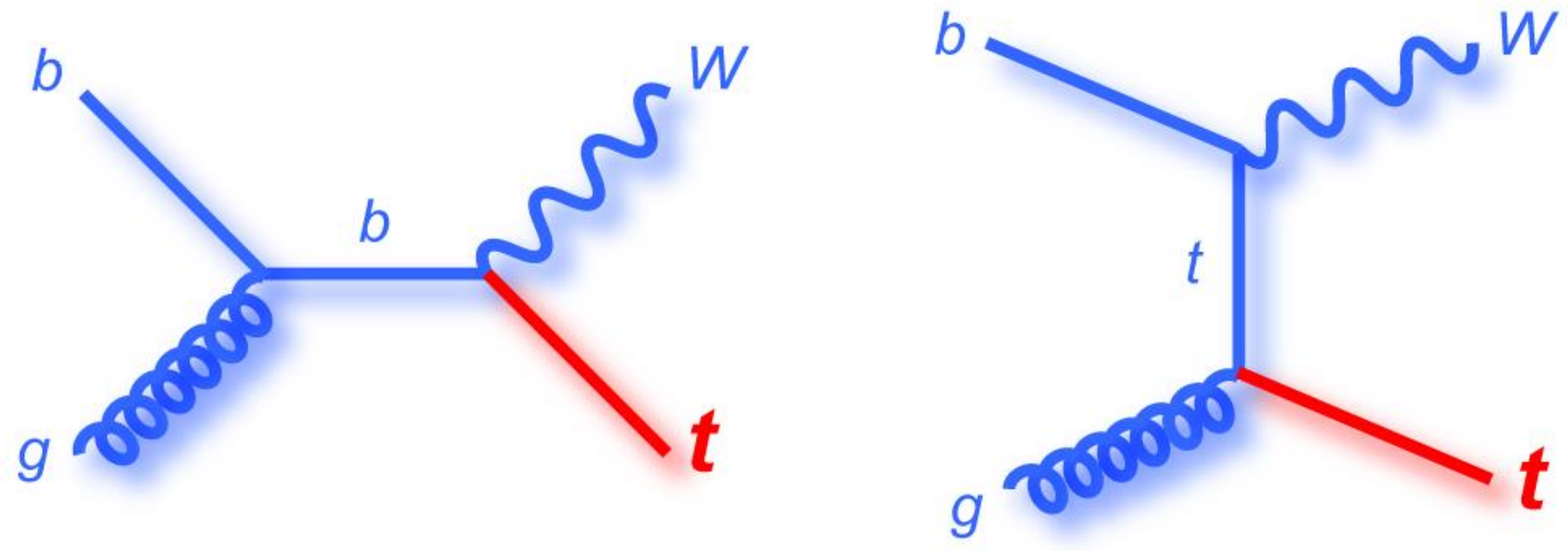
*t*-channel (~ 73% at LHC)

**Golden Channel, sensitive to FCNC**



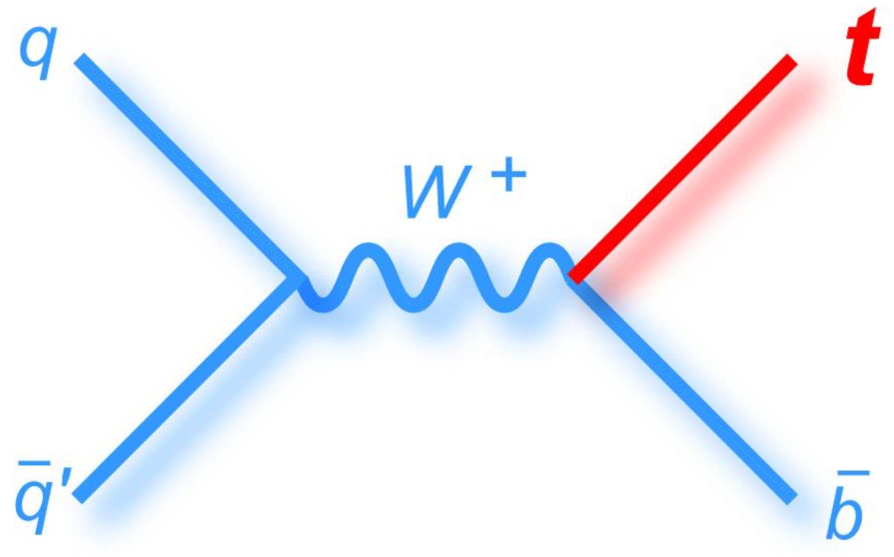

tW (~ 24% at LHC)

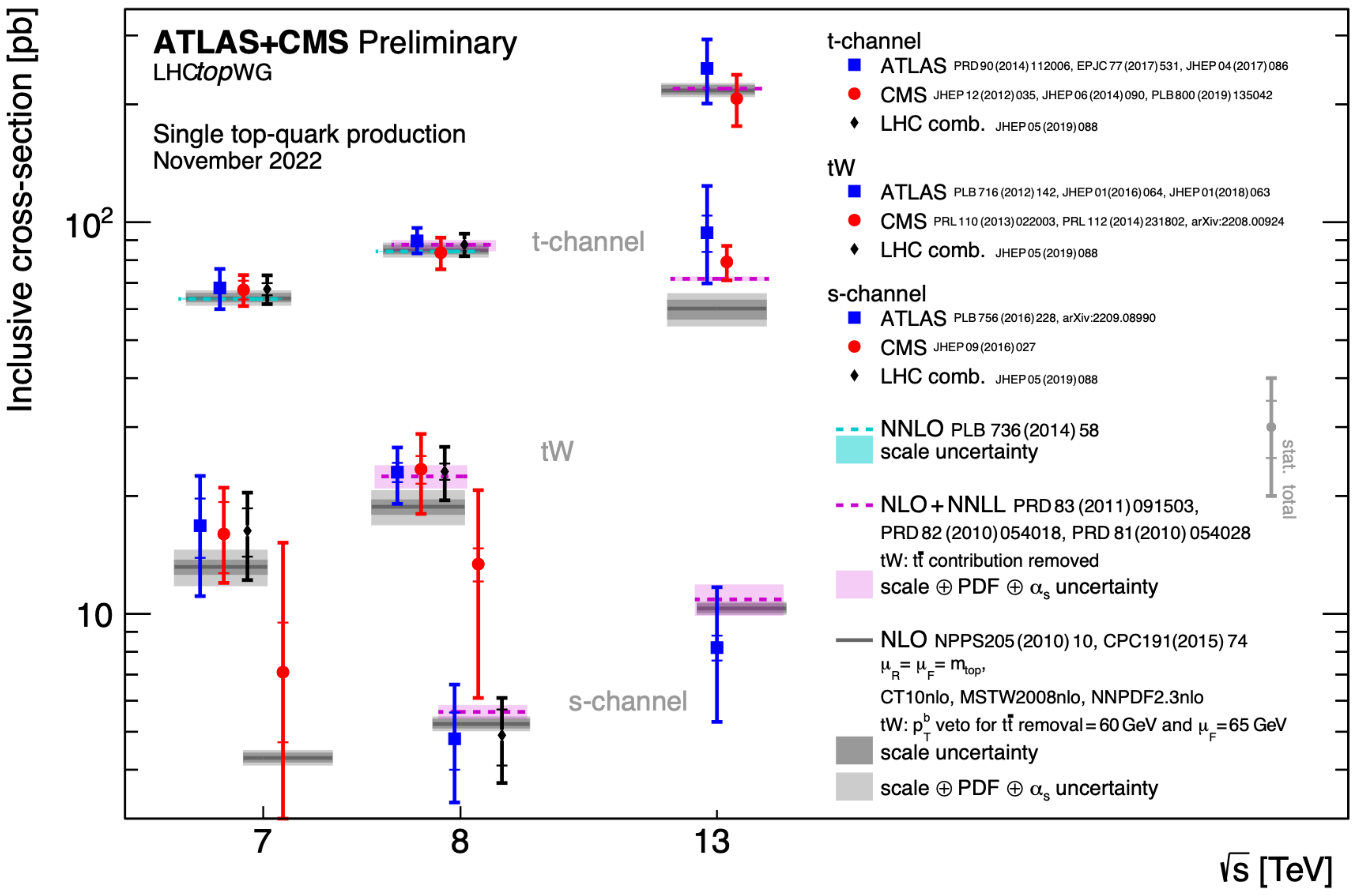
**Observed at LHC, sensitive to BSM couplings**




*s*-channel (~ 3% at LHC)

**Challenging at LHC**




[LHCTOPWGSummaryPlots]

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\sigma \propto |V_{\text{tb}}|^2$$

$$|f_{LV} V_{\text{tb}}| = \sqrt{\frac{\sigma_{meas.}}{\sigma_{theo.}(|V_{\text{tb}}| = 1)}}, \text{Assuming} |V_{\text{td}}|, |V_{\text{ts}}| \ll |V_{\text{tb}}|$$

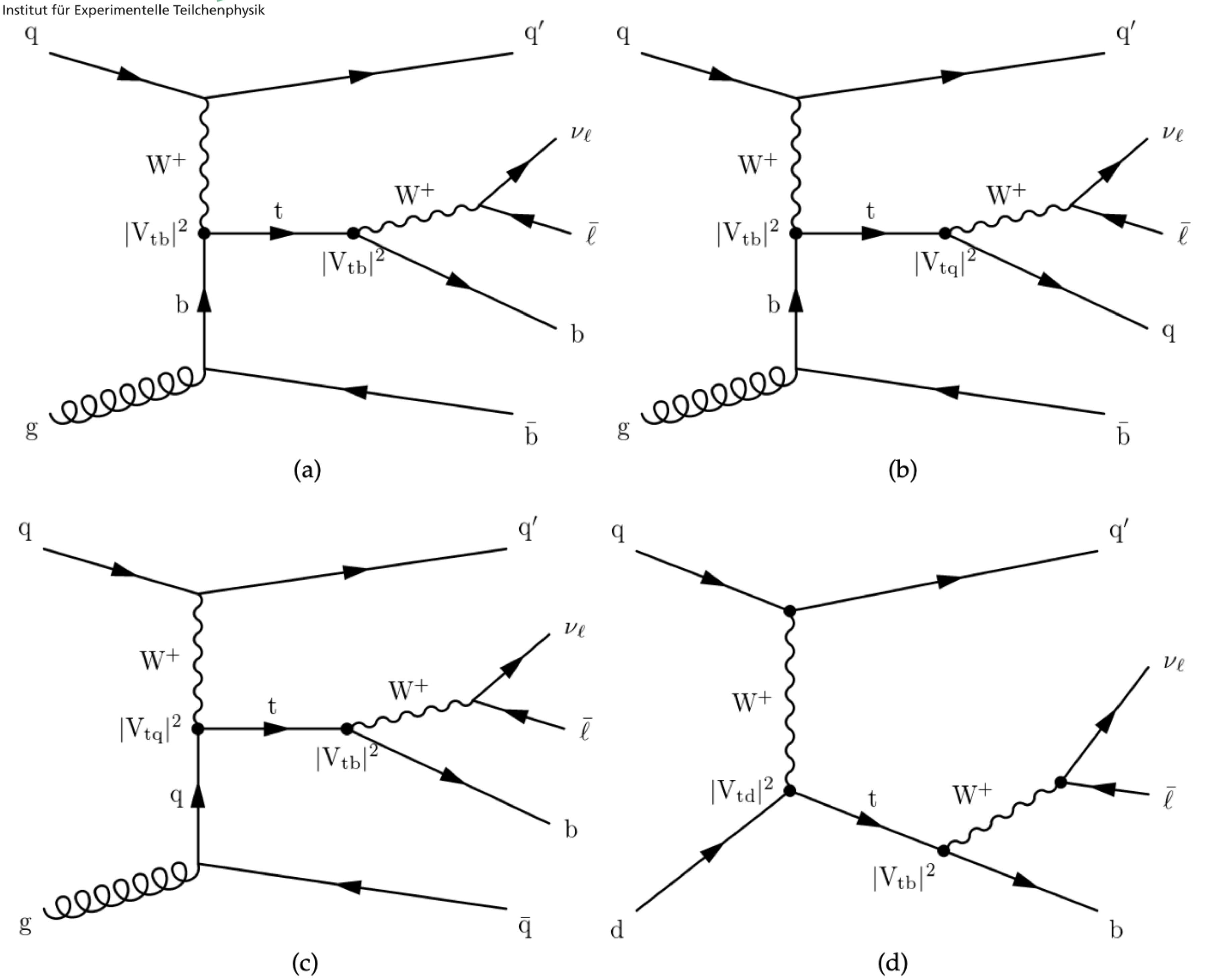
$f_{LV}$ accounts for possible BSM contribution ➛ $f_{LV}$ = 1 for SM

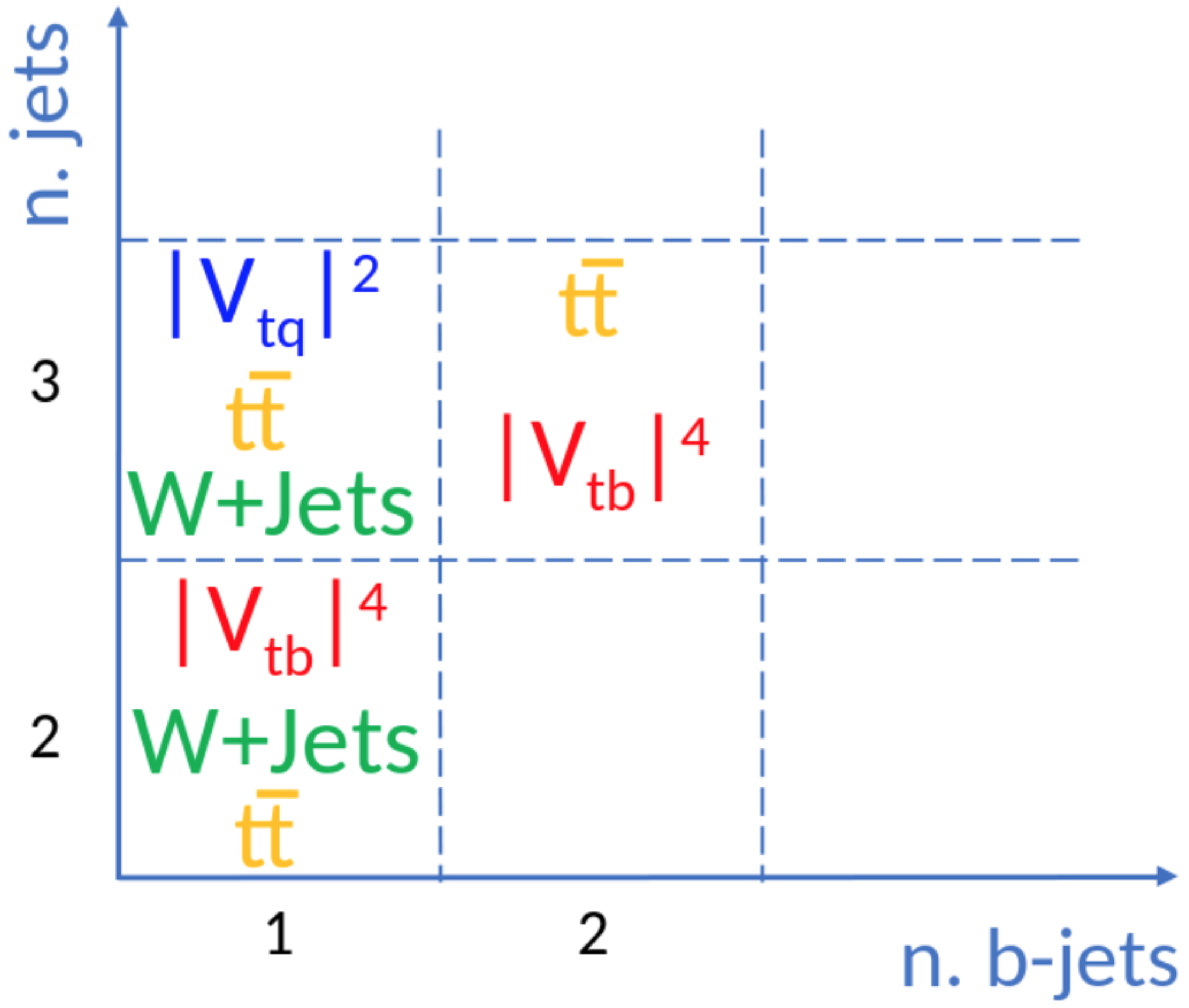
$$\sigma^{t-\text{ch}}_{\text{t}+\bar{\text{t}}}(13\text{TeV}) = 207 \pm 2(\text{stat}) \pm 31(\text{syst})\text{pb} = 207 \pm 31\text{p}$$

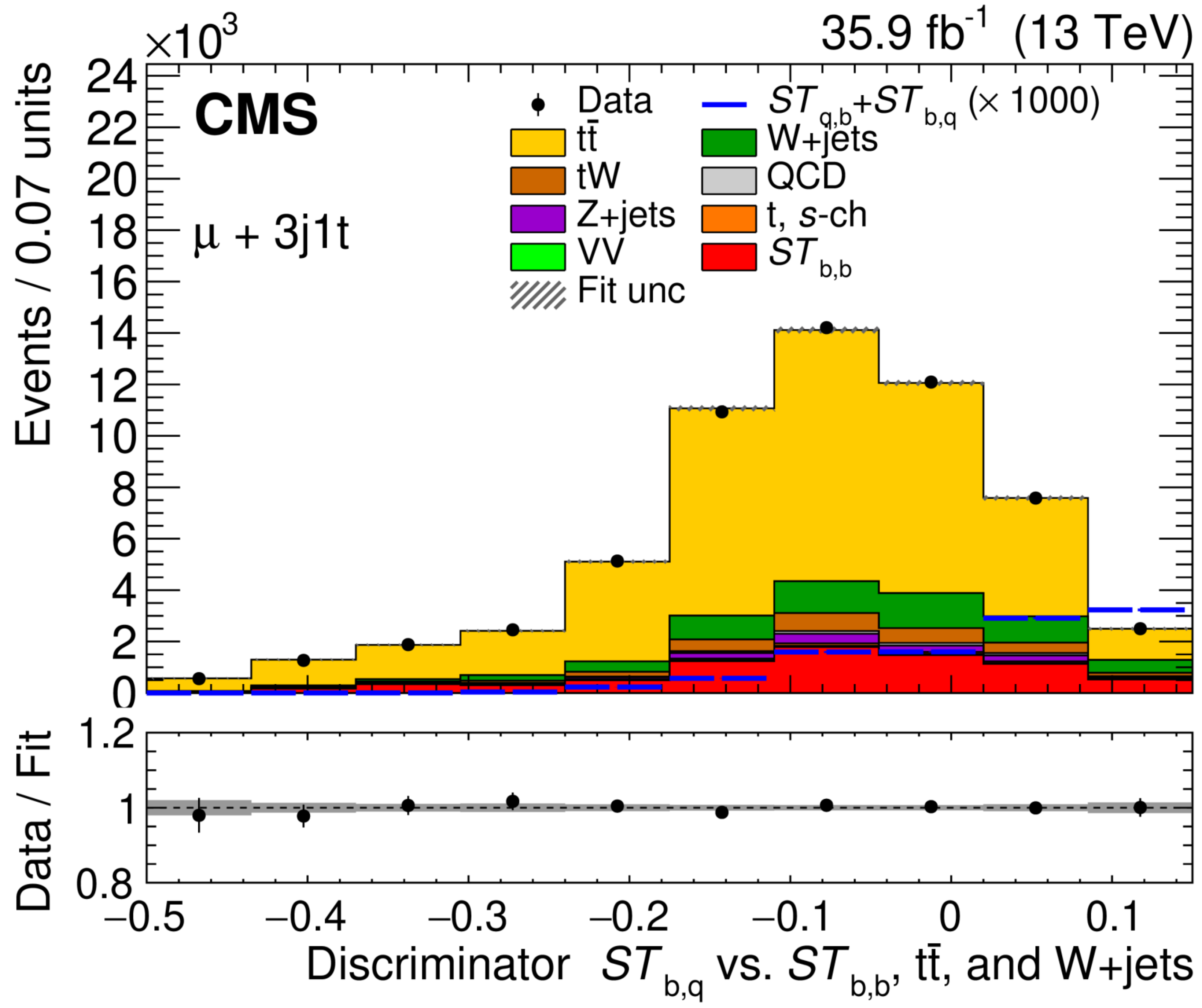


[PLB 800 (2019) 135042]

# $|V_{tq}|$ in $t$-channel




[PLB 808 (2020) 135609](PLB 808 (2020) 135609)

## SM scenario

$$\sum_{q=b,s,d} |V_{tq}|^2 = 1$$

$$|V_{tb}| > 0.9$$

$$|V_{td}|^2 + |V_{ts}|^2 < 0.057$$

## BSM scenario 1

Only partial widths altered (keeping total width fixed) because of modified CKM matrix elements

$$|V_{tb}| = 0.988 \pm 0.051$$

$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$$

## BSM scenario 2

Partial widths unchanged, but the total width increases due to BSM decays

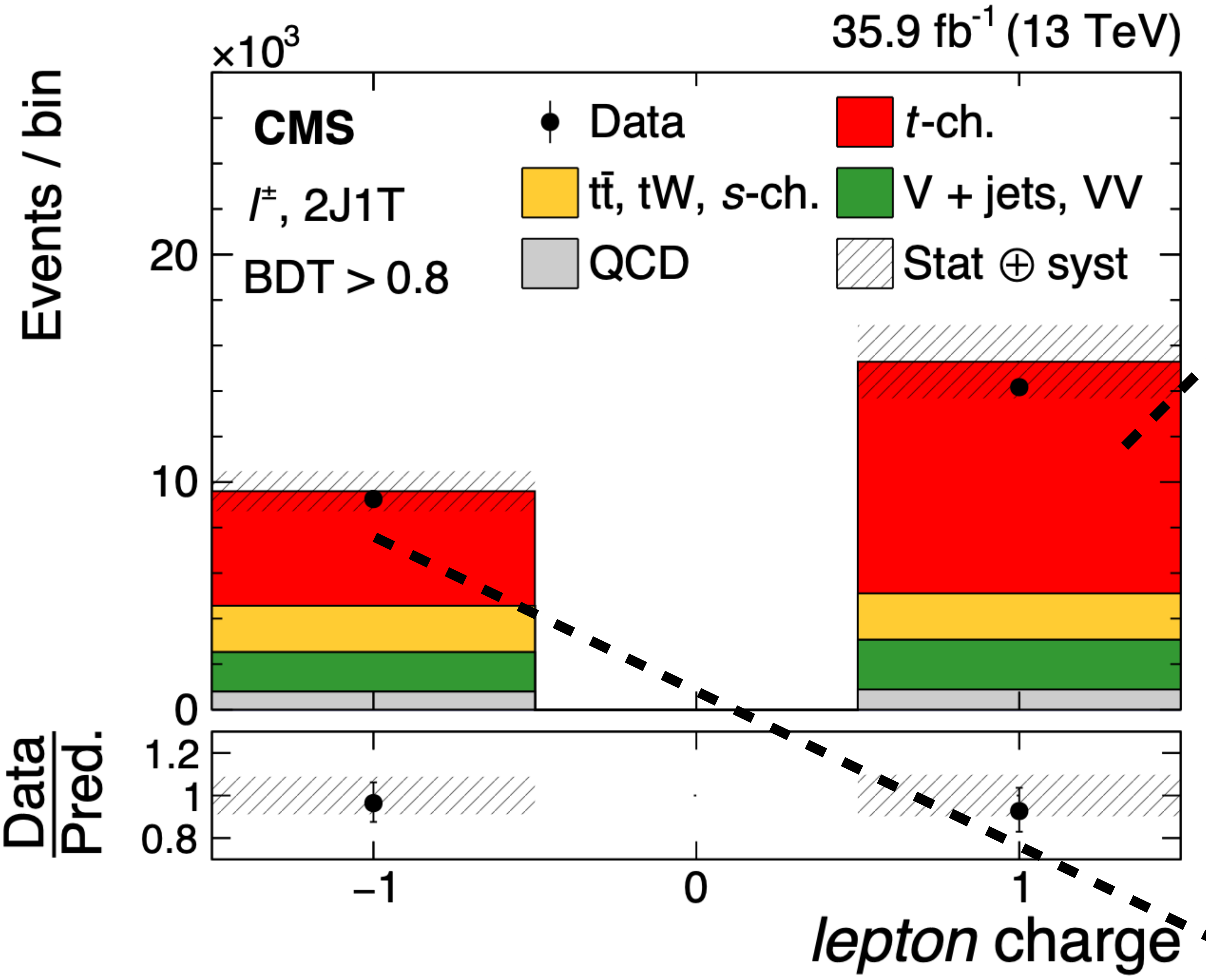
$$|V_{tb}| = 0.988 \pm 0.024$$

$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$$

$$\Gamma_t^{Obs}/\Gamma_t = 0.99 \pm 0.42$$

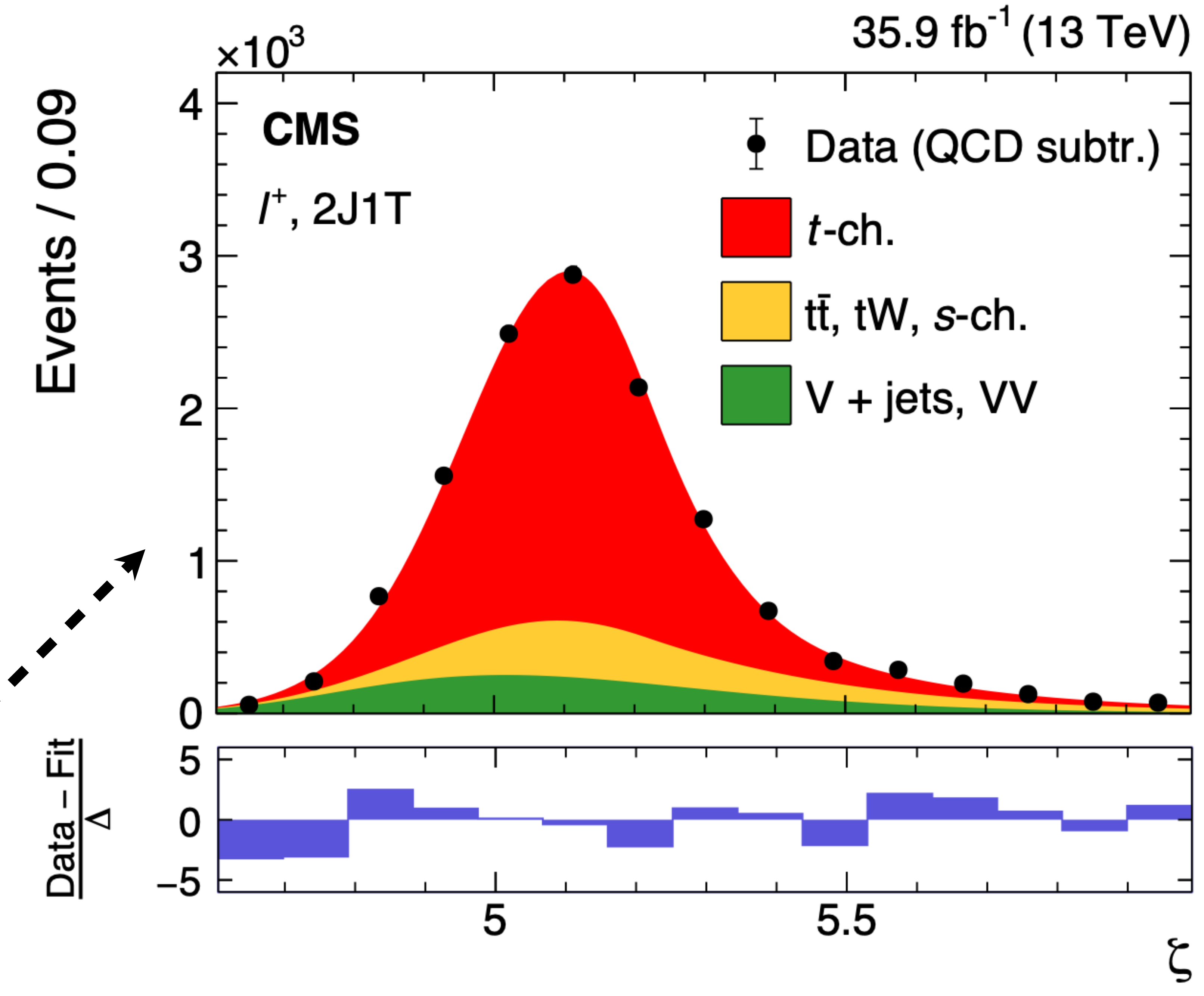
# Test of *CPT invariance* in single top events

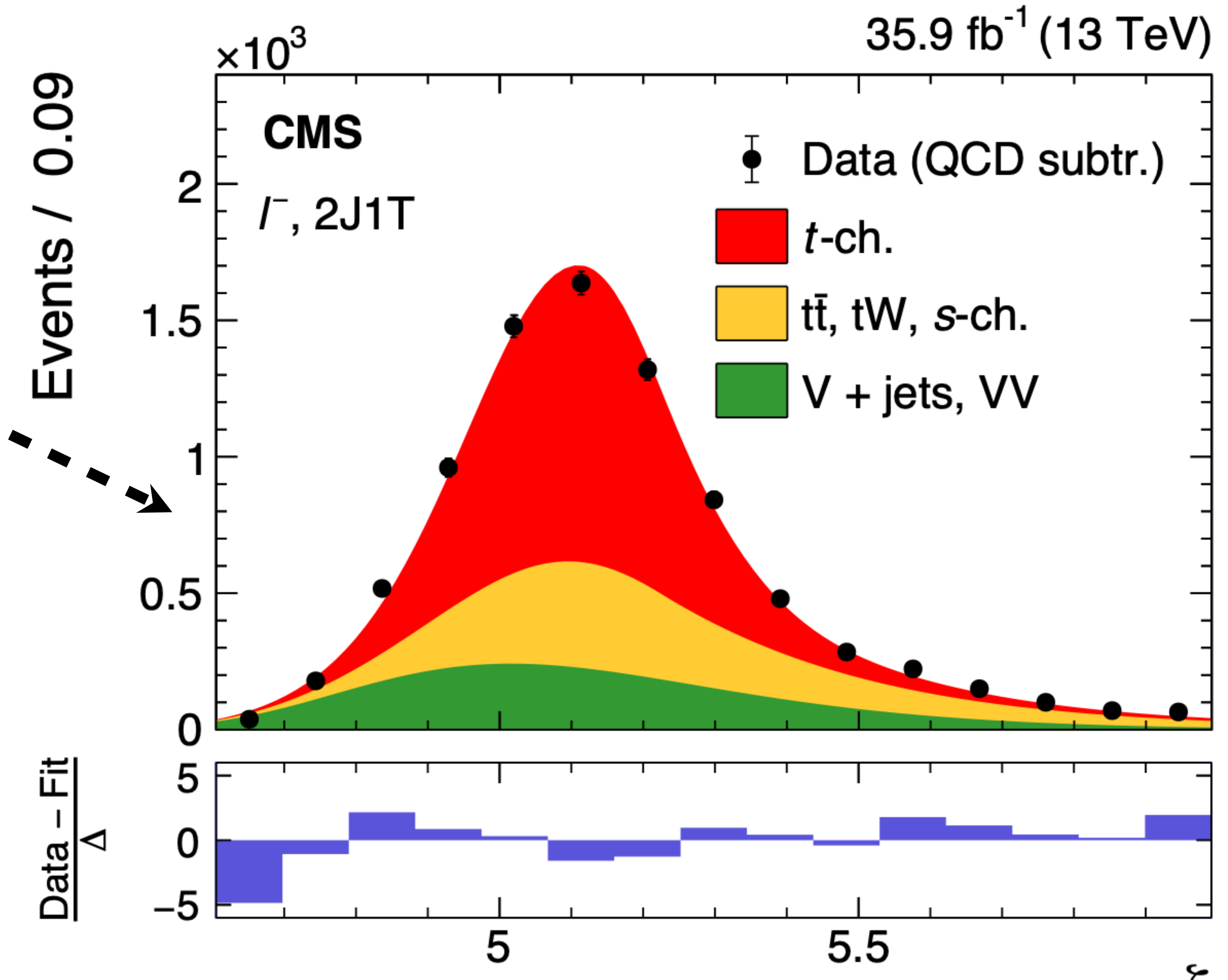
- Separate meas. of top quark and antiquark masses based on the **charge** of the *lepton*

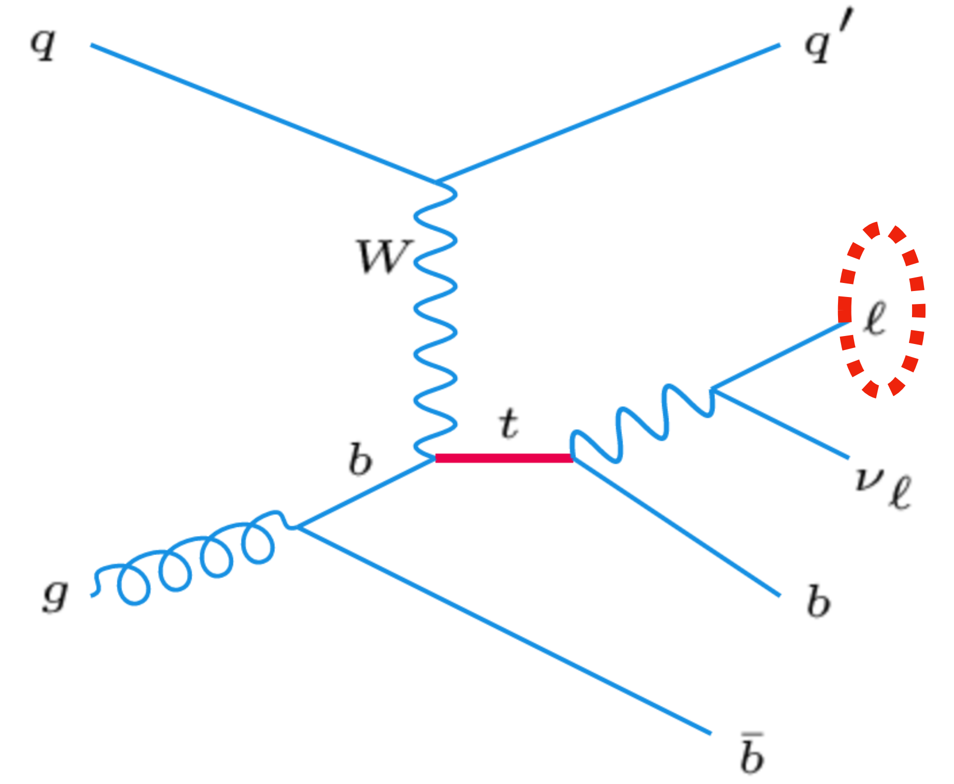


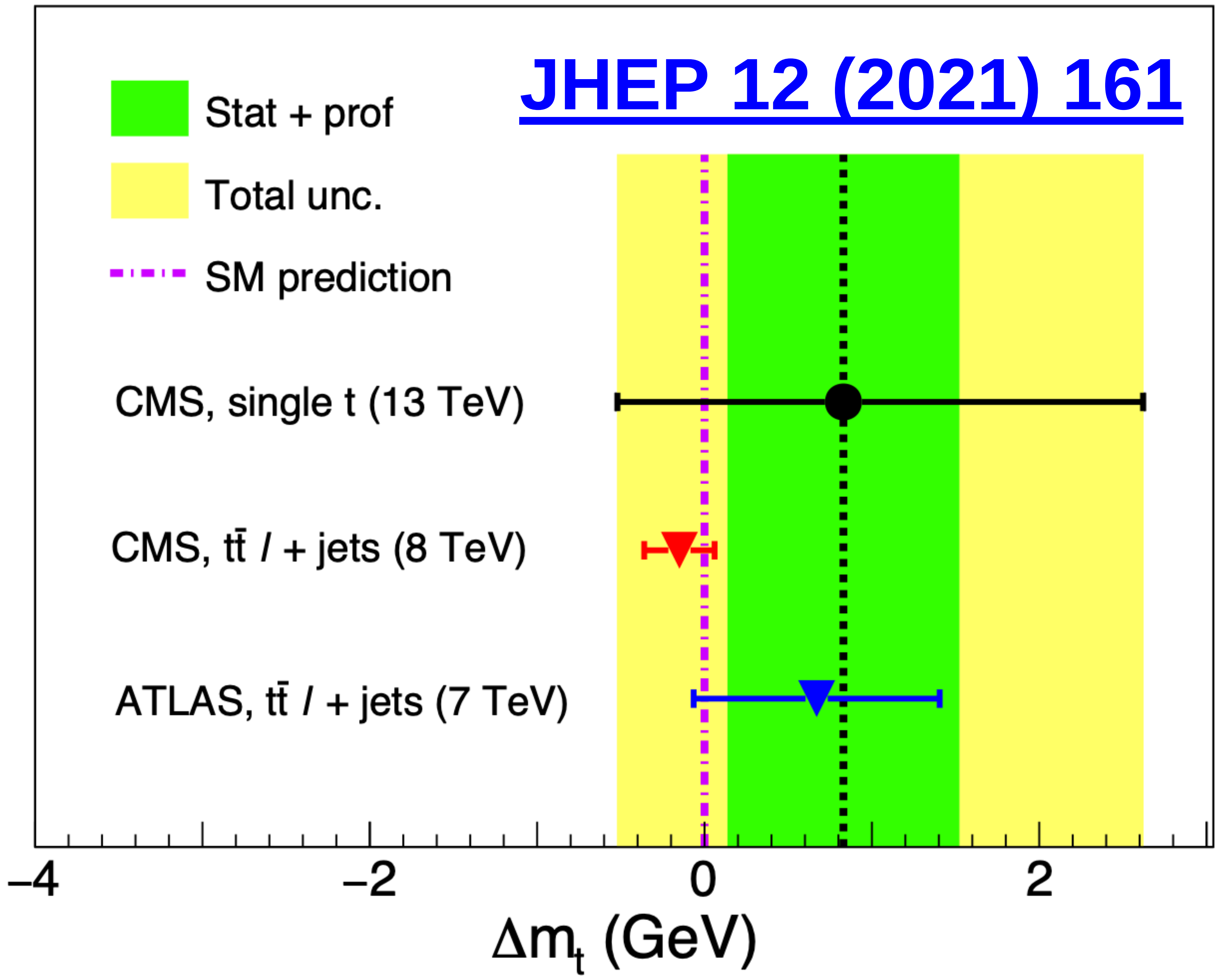

- Optimized selection threshold on BDT discriminants to select event sample with high (≈ 60 %) signal purity

- ML fit to $\zeta = \ln(\frac{m_t}{1\,\mathrm{GeV}})$ using analytic templates to extract mass



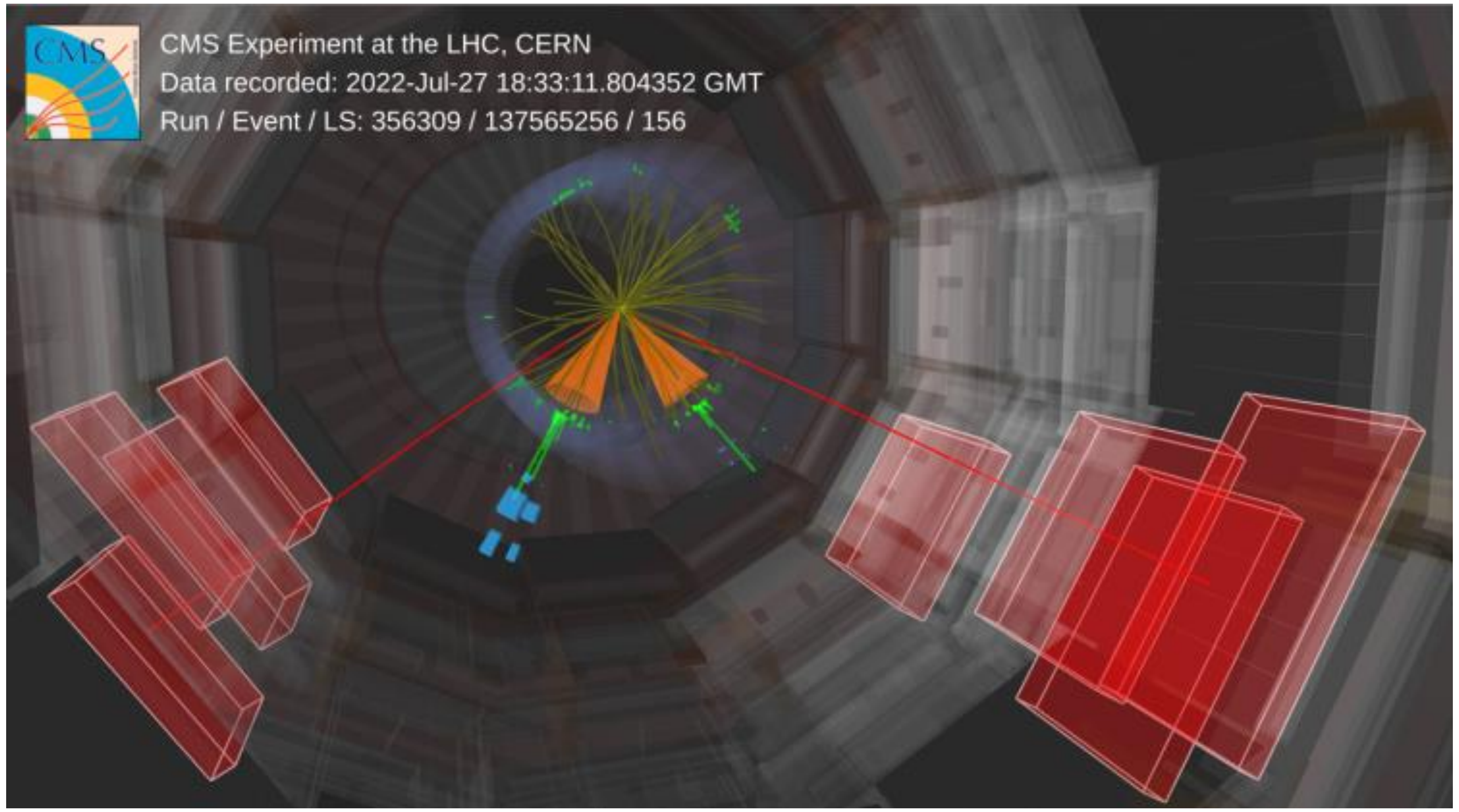




$$\Delta m_t = m_t - m_{\bar{t}} = 0.83^{+1.79}_{-1.35}\,\mathrm{GeV}$$

➛ sensitive to violation of local gauge invariance and/or Lorentz symmetry

# Summary

- LHC ≡ top quark Factory ⇒ precision lab for studying top quark production and properties ⇒ portal to new physics beyond SM
- Most measurements agree with SM prediction within uncertainties
- Provides good understanding of the various modeling aspects such as PDF, PS, UE and CR etc.
- Stringent limits on couplings are placed with EFT interpretation using Run2 data
- Rare processes involving top quarks waiting to be fully exploited during Run3 and HL-LHC
- More information : ATLAS Top Public Results , CMS Top Public Results, LHC Top WG



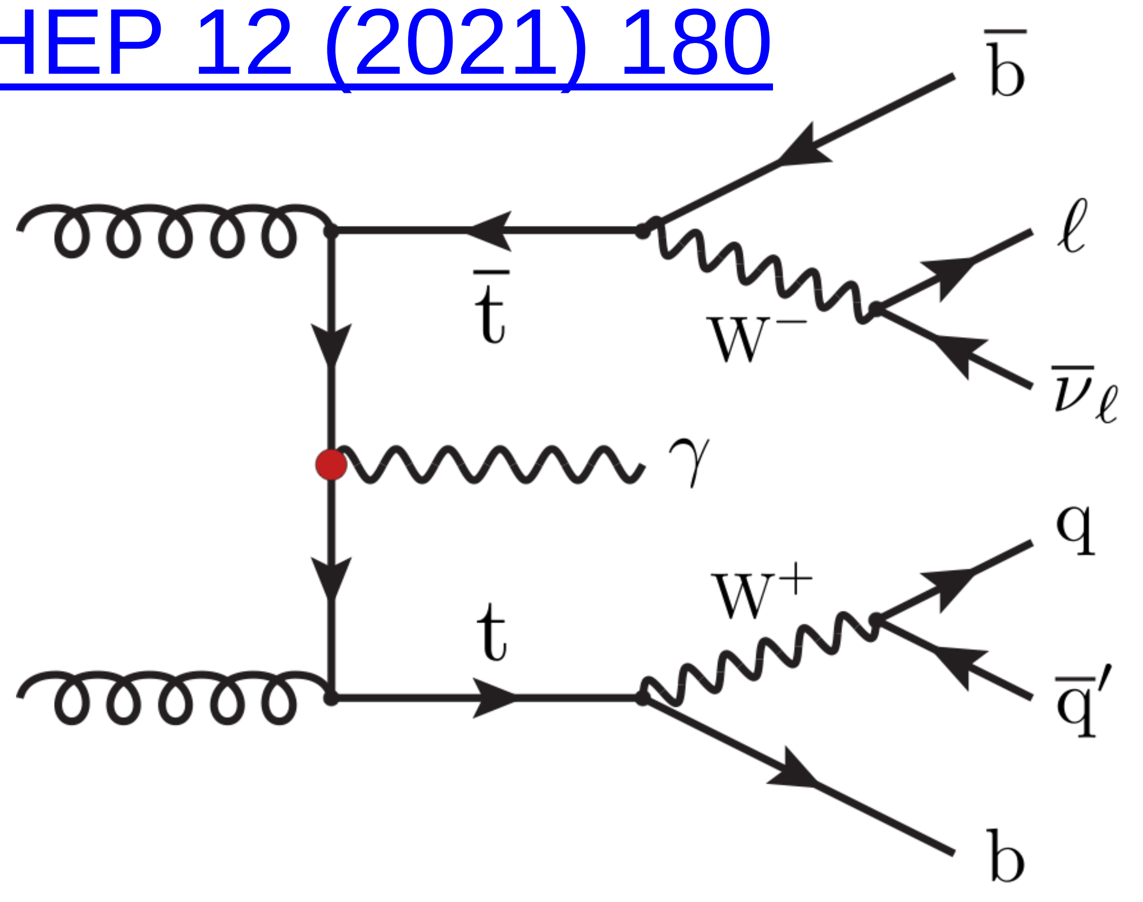

*Thank you for your attention*

# Back up

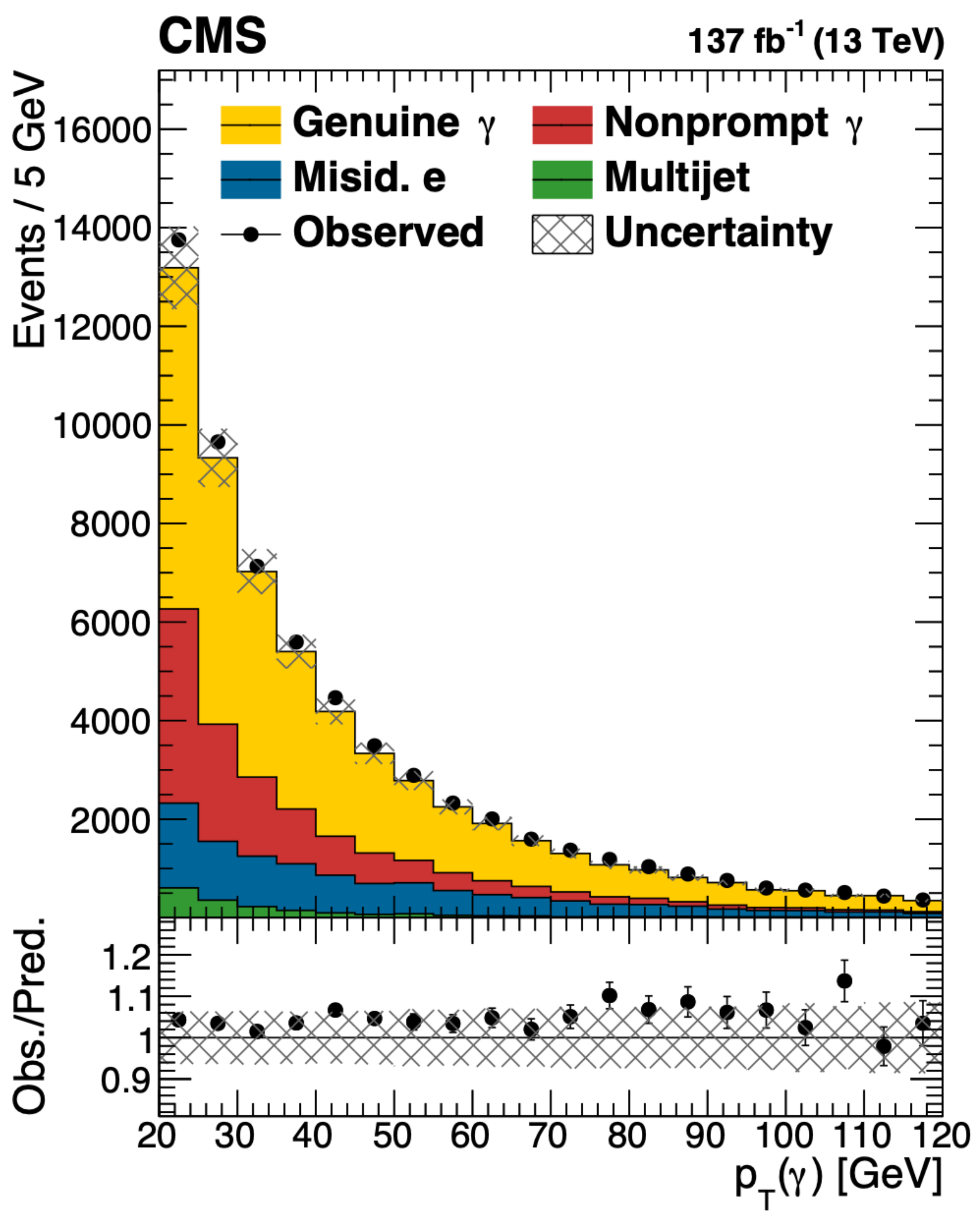
# Inclusive and differential $t\bar{t}\gamma$ cross section - $\ell$ + jets

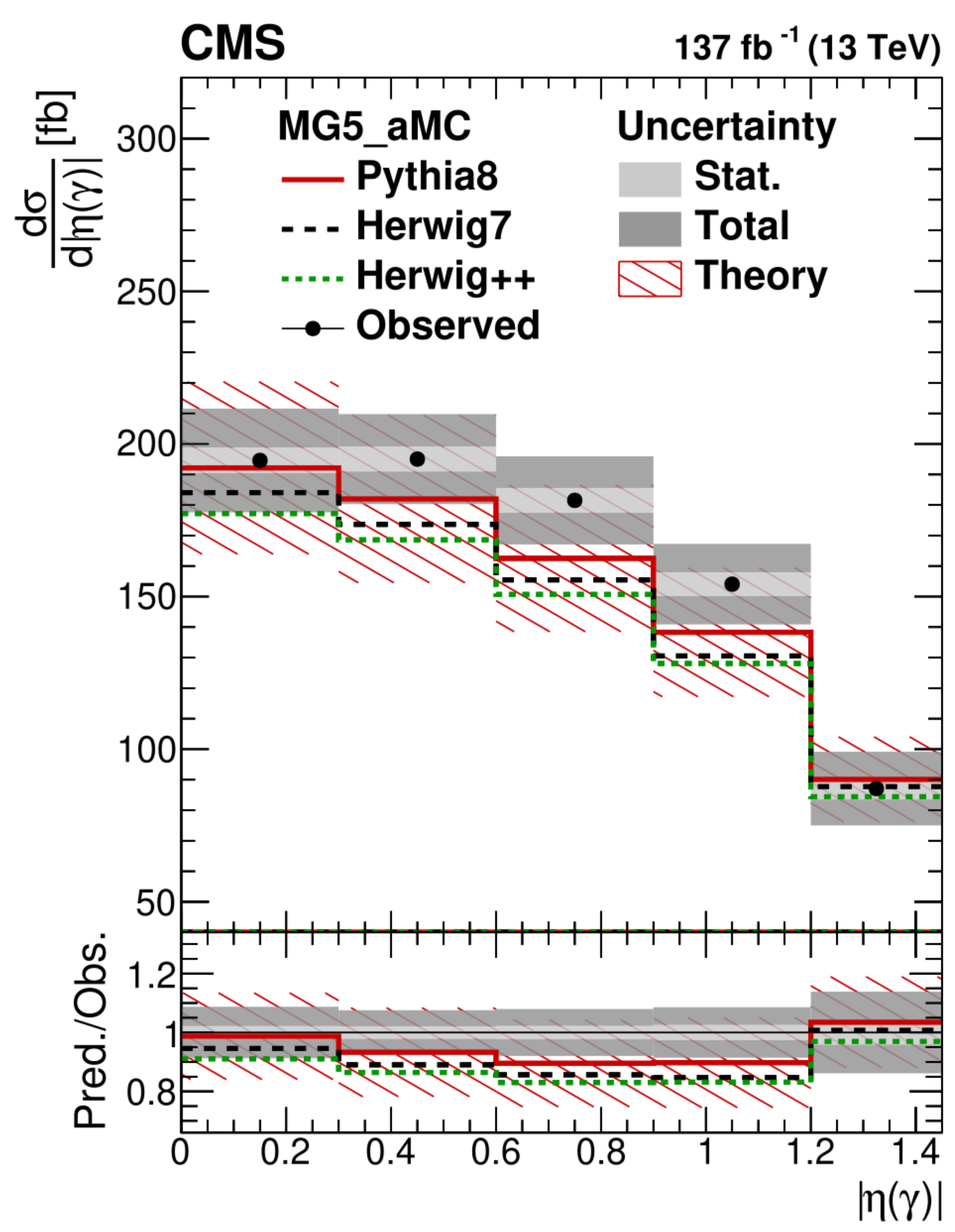
- NLO Prediction: $\sigma_{t\bar{t}\gamma} = 773 \pm 135\text{fb}[p_T(\gamma) > 20\text{GeV}\ |\eta(\gamma)| < 1.442]$

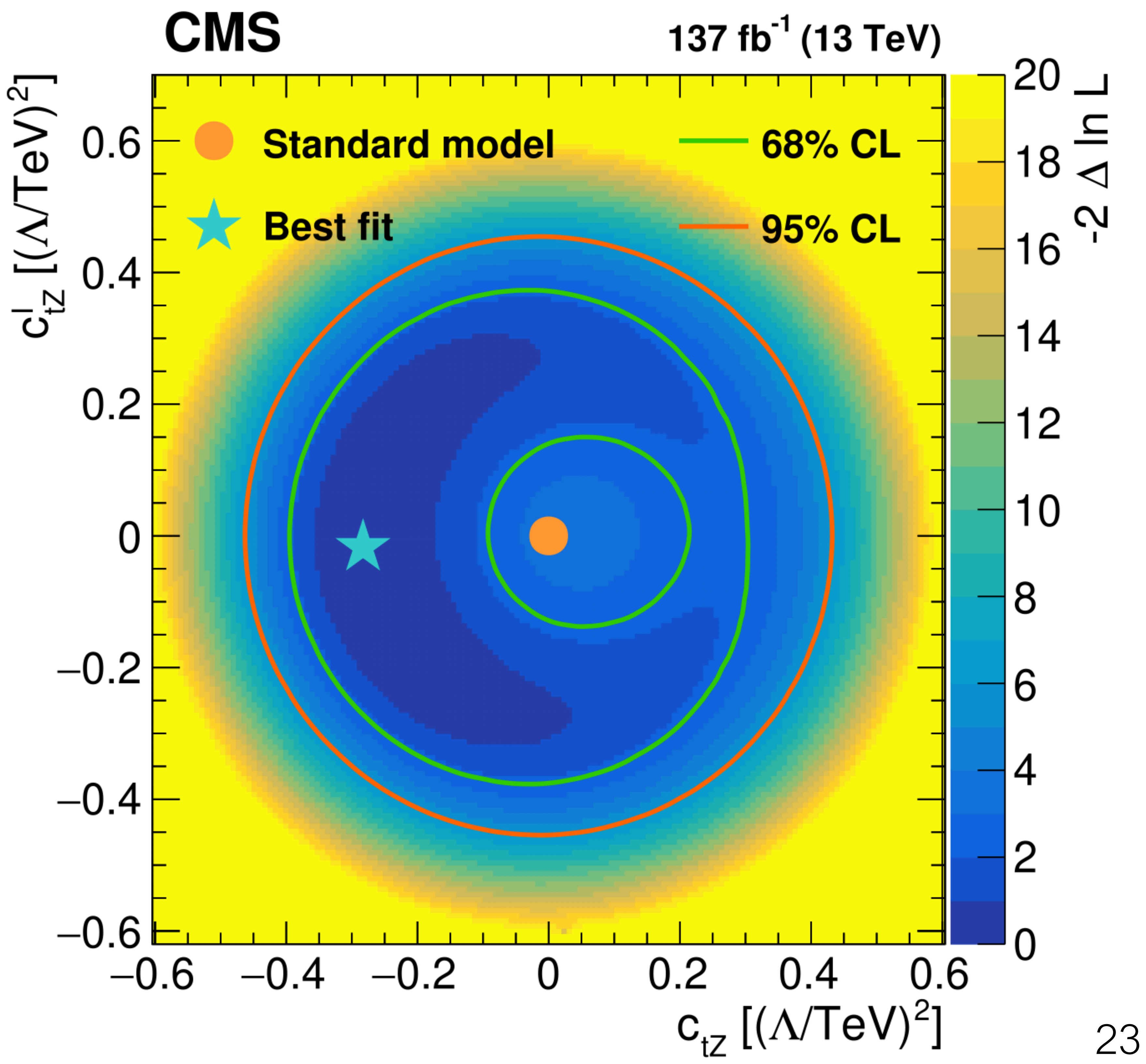
[JHEP 12 (2021) 180]



- Final state consists of exactly 1 $\gamma$, exactly 1 $\ell$, ≥ 3 jets, ≥ 1 b-tagged jet
- Measured inclusive cross section: $\sigma_{t\bar{t}\gamma} = 798 \pm 7(\text{stat}) \pm 48(\text{syst})\text{fb}$
- Differential measurements used to extract limits on EFT coupling $C_{tZ}$

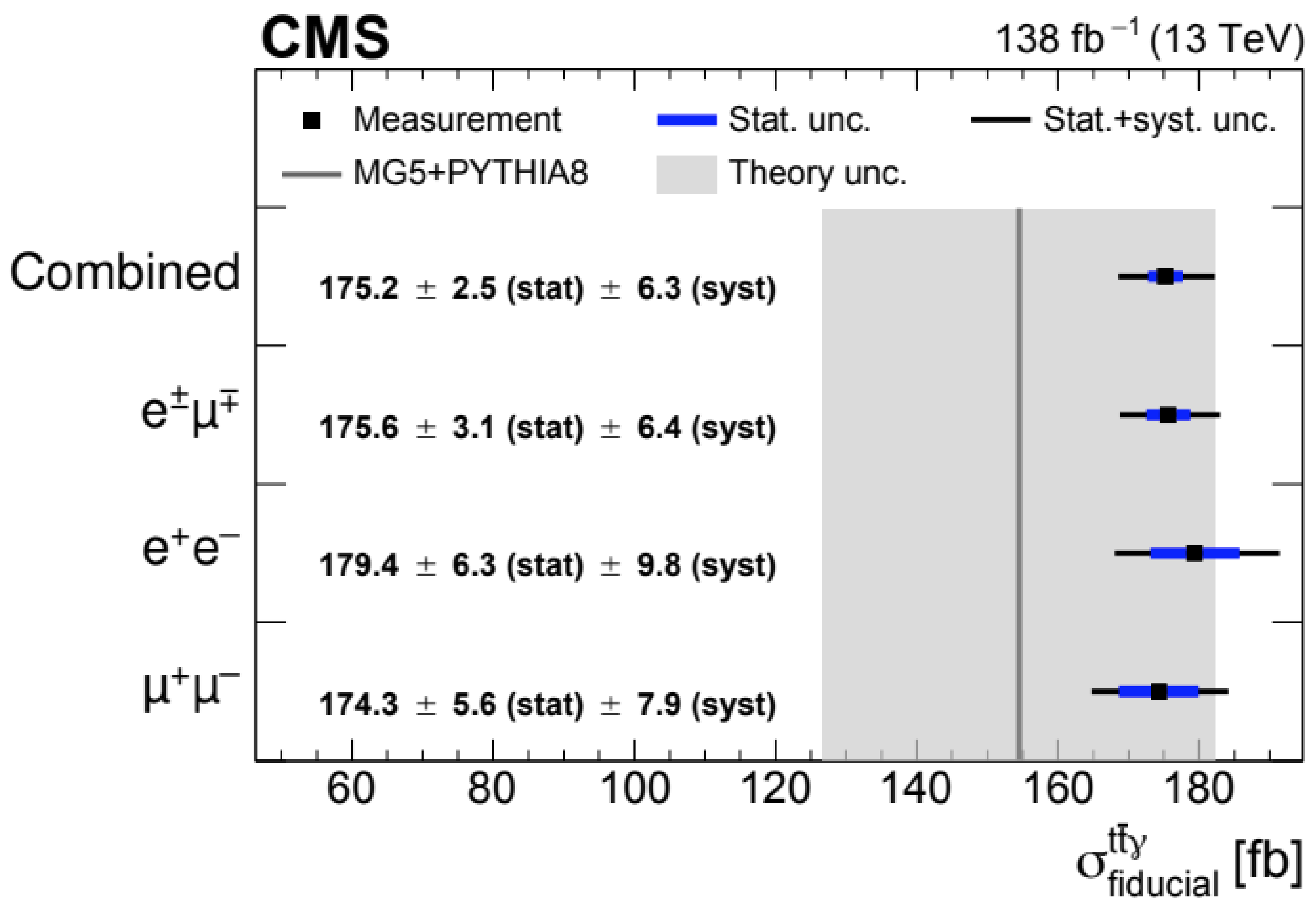






| | Source | Correlation | Uncertainty [%] Prefit range | Postfit |
|---|---|---|---|---|
| Experimental | Integrated luminosity | ~ | 1.3–3.2 | 1.7 |
| | Pileup | ✓ | 0.1–1.4 | 0.7 |
| | Trigger efficiency | × | 0.6–1.7 | 0.6 |
| | Electron selection efficiency | ~ | 1.0–1.3 | 1.0 |
| | Muon selection efficiency | ~ | 0.3–0.5 | 0.5 |
| | Photon selection efficiency | ~ | 0.4–3.6 | 1.1 |
| | Electron & photon energy | ✓ | 0.0–1.1 | 0.1 |
| | Jet energy scale | ~ | 0.1–1.3 | 0.5 |
| | Jet energy resolution | ✓ | 0.0–0.6 | <0.1 |
| | b tagging efficiency | ~ | 0.9–1.4 | 1.1 |
| | L1 prefiring | ✓ | 0.0–0.8 | 0.3 |
| Theoretical | Values of $\mu_F$ and $\mu_R$ | ✓ | 0.3–3.5 | 1.3 |
| | PDF choice | ✓ | 0.3–4.5 | 0.3 |
| | PS modelling: ISR & FSR scale | ✓ | 0.3–3.5 | 1.3 |
| | PS modelling: colour reconnection | ✓ | 0.0–8.4 | 0.2 |
| | PS modelling: b fragmentation | ✓ | 0.0–2.2 | 0.7 |
| | Underlying-event tune | ✓ | 0.5 | 0.5 |
| Background | Zγ correction & normalization | ✓ | 0.0–0.2 | 0.1 |
| | tγ normalization | ✓ | 0.0–0.9 | 0.8 |
| | Other+γ normalization | ✓ | 0.3–1.0 | 0.8 |
| | Nonprompt γ normalization | ✓ | 0.0–1.8 | 0.7 |
| | Size of background samples | × | 1.5–7.6 | 0.9 |
| | Total systematic uncertainty | | | 3.6 |
| | Statistical uncertainty | | | 1.4 |
| | Total uncertainty | | | 3.9 |

JHEP 05 (2022) 091



## JHEP 12 (2021) 161

| Source | | $\delta m_{l^\pm}$ | $\delta m_{l^+}$ | $\delta m_{l^-}$ |
|---|---|---|---|---|
| Statistical | | ±0.19 | ±0.23 | ±0.33 |
| 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 |
| | $\mu_R$ and $\mu_F$ scales | ±0.09 | ±0.13 | ±0.03 |
| | PDF+$\alpha_S$ | ±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) |
| | $\mu_R$ and $\mu_F$ scales | ±0.03 | ±0.03 | ±0.01 |
| | PDF+$\alpha_S$ | <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 |

## NP 17, 813–818 (2021)

| **Source** | **Impact on $R(\tau/\mu)$** |
|---|---|
| Prompt $d_0^\mu$ templates | 0.0038 |
| $\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ parton shower variations | 0.0036 |
| Muon isolation efficiency | 0.0033 |
| Muon identification and reconstruction | 0.0030 |
| $\mu_{(had.)}$ normalisation | 0.0028 |
| $t\bar{t}$ scale and matching variations | 0.0027 |
| Top $p_T$ spectum variation | 0.0026 |
| $\mu_{(had.)}$ parton shower variations | 0.0021 |
| Monte Carlo statistics | 0.0018 |
| Pile-up | 0.0017 |
| $\mu_{(\tau\to\mu)}$ and $\mu_{(had.)}$ $d_0^\mu$ shape | 0.0017 |
| Other detector systematic uncertainties | 0.0016 |
| $Z$+jet normalisation | 0.0009 |
| Other sources | 0.0004 |
| $B(\tau \to \mu\nu_\tau\nu_\mu)$ | 0.0023 |
| Total systematic uncertainty | 0.0109 |
| Data statistics | 0.0072 |
| **Total** | **0.013** |

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| Systematic sources | $A'_{CP}$ (%) $O_3$ | $O_6$ | $O_{12}$ | $O_{14}$ |
|---|---|---|---|---|
| Pileup | $-0.0008$<br>$+0.0010$ | $-0.0003$<br>$+0.0007$ | $+0.0023$<br>$-0.0017$ | $+0.0040$<br>$-0.0044$ |
| b tagging scale factor (b and c quarks) | $+0.0002$<br>$-0.0002$ | $+0.0001$<br>$-0.0003$ | $<0.0001$<br>$<0.0001$ | $<0.0001$<br>$-0.0002$ |
| b tagging scale factor (light-flavor quarks and gluons) | $-0.0003$<br>$+0.0004$ | $-0.0003$<br>$<0.0001$ | $-0.0009$<br>$+0.0007$ | $-0.0007$<br>$+0.0005$ |
| Lepton efficiencies | $-0.0002$<br>$+0.0002$ | $-0.0001$<br>$-0.0001$ | $-0.0001$<br>$<0.0001$ | $-0.0004$<br>$+0.0001$ |
| Jet energy resolution | $-0.0028$<br>$-0.0029$ | $-0.0069$<br>$+0.0032$ | $-0.0024$<br>$-0.0021$ | $-0.0070$<br>$+0.0026$ |
| Jet energy scale | $-0.0051$<br>$-0.0018$ | $-0.0046$<br>$+0.0065$ | $-0.0046$<br>$+0.0011$ | $-0.0062$<br>$+0.0041$ |
| Background template | $+0.0061$ | $+0.0050$ | $+0.0139$ | $+0.0016$ |
| PDF | $+0.0008$<br>$-0.0008$ | $-0.0008$<br>$+0.0006$ | $+0.0003$<br>$-0.0004$ | $+0.0003$<br>$-0.0006$ |
| QCD renormalization and factorization | $+0.0008$<br>$+0.0012$ | $+0.0008$<br>$-0.0002$ | $+0.0013$<br>$-0.0033$ | $+0.0007$<br>$-0.0004$ |
| Initial-state QCD radiation | $+0.0006$<br>$-0.0004$ | $-0.0005$<br>$+0.0004$ | $+0.0017$<br>$-0.0015$ | $+0.0024$<br>$-0.0021$ |
| Final-state QCD radiation | $-0.0001$<br>$-0.0008$ | $-0.0215$<br>$+0.0122$ | $+0.0053$<br>$-0.0017$ | $-0.0129$<br>$+0.0060$ |
| Color reconnection | $-0.0162$<br>$<0.0001$ | $+0.0186$<br>$-0.0206$ | $+0.0091$<br>$-0.0464$ | $+0.0384$<br>$+0.0304$ |
| ME-PS matching | $-0.0235$<br>$+0.0399$ | $-0.0043$<br>$+0.0177$ | $-0.0185$<br>$+0.0139$ | $+0.0352$<br>$+0.0376$ |
| Underlying event | $-0.0515$<br>$-0.0099$ | $-0.0576$<br>$+0.0355$ | $-0.0082$<br>$+0.0218$ | $+0.0116$<br>$+0.0424$ |
| Flavor response | $-0.0017$<br>$-0.0024$ | $-0.0007$<br>$+0.0024$ | $-0.0033$<br>$-0.0004$ | $-0.0105$<br>$+0.0070$ |
| Top quark mass variation | $+0.0049$<br>$-0.0179$ | $+0.0152$<br>$-0.0118$ | $+0.0119$<br>$-0.0097$ | $+0.0082$<br>$-0.0046$ |
| Per-event resolution | $-0.0027$<br>$-0.0004$ | $-0.0022$<br>$+0.0040$ | $+0.0023$<br>$+0.0014$ | $-0.0005$<br>$+0.0048$ |
| W+HF fraction | $-0.0174$ | $-0.0132$ | $-0.0102$ | $-0.0098$ |

| CP observable | $A_{CP}$ (%) | $d_{tG}$ |
|---|---|---|
| $O_3$ | $-0.10 \pm 0.20 \pm 0.14$ | $+0.04 \pm 0.11 \pm 0.07$ |
| $O_6$ | $-0.30 \pm 0.21 \pm 0.16$ | $+0.25 \pm 0.20 \pm 0.15$ |
| $O_{12}$ | $+0.12 \pm 0.13 \pm 0.07$ | $+0.45 \pm 0.47 \pm 0.27$ |
| $O_{14}$ | $-0.29 \pm 0.16 \pm 0.14$ | $-0.81 \pm 0.48 \pm 0.44$ |

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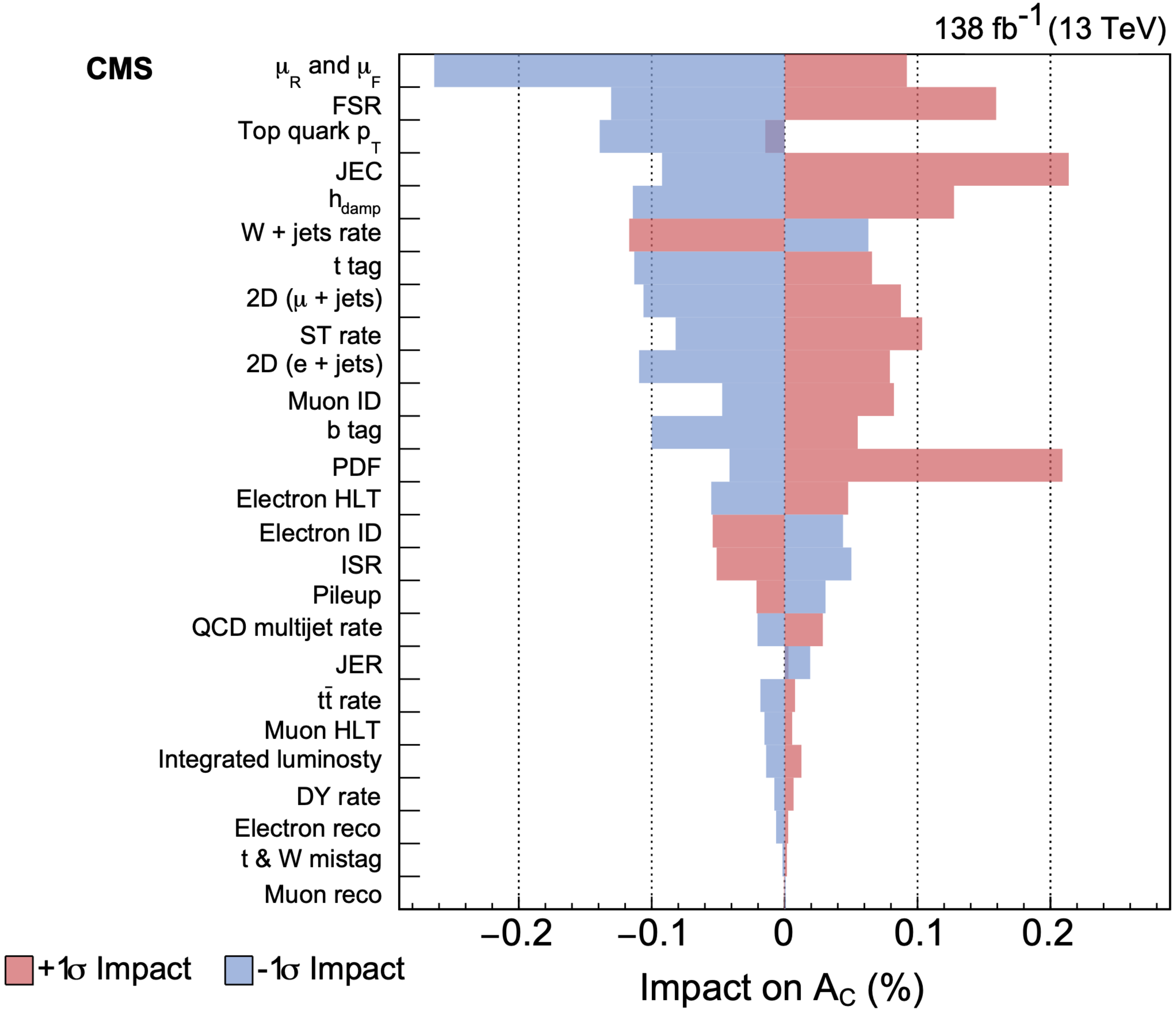
| Source | Uncertainty (MeV) |
|---|---|
| Lepton energy scale | 3.0 |
| Lepton energy resolution | 1.2 |
| Recoil energy scale | 1.2 |
| Recoil energy resolution | 1.8 |
| Lepton efficiency | 0.4 |
| Lepton removal | 1.2 |
| Backgrounds | 3.3 |
| $p_T^Z$ model | 1.8 |
| $p_T^W/p_T^Z$ model | 1.3 |
| Parton distributions | 3.9 |
| QED radiation | 2.7 |
| $W$ boson statistics | 6.4 |
| Total | 9.4 |

CMS-TOP-21-014

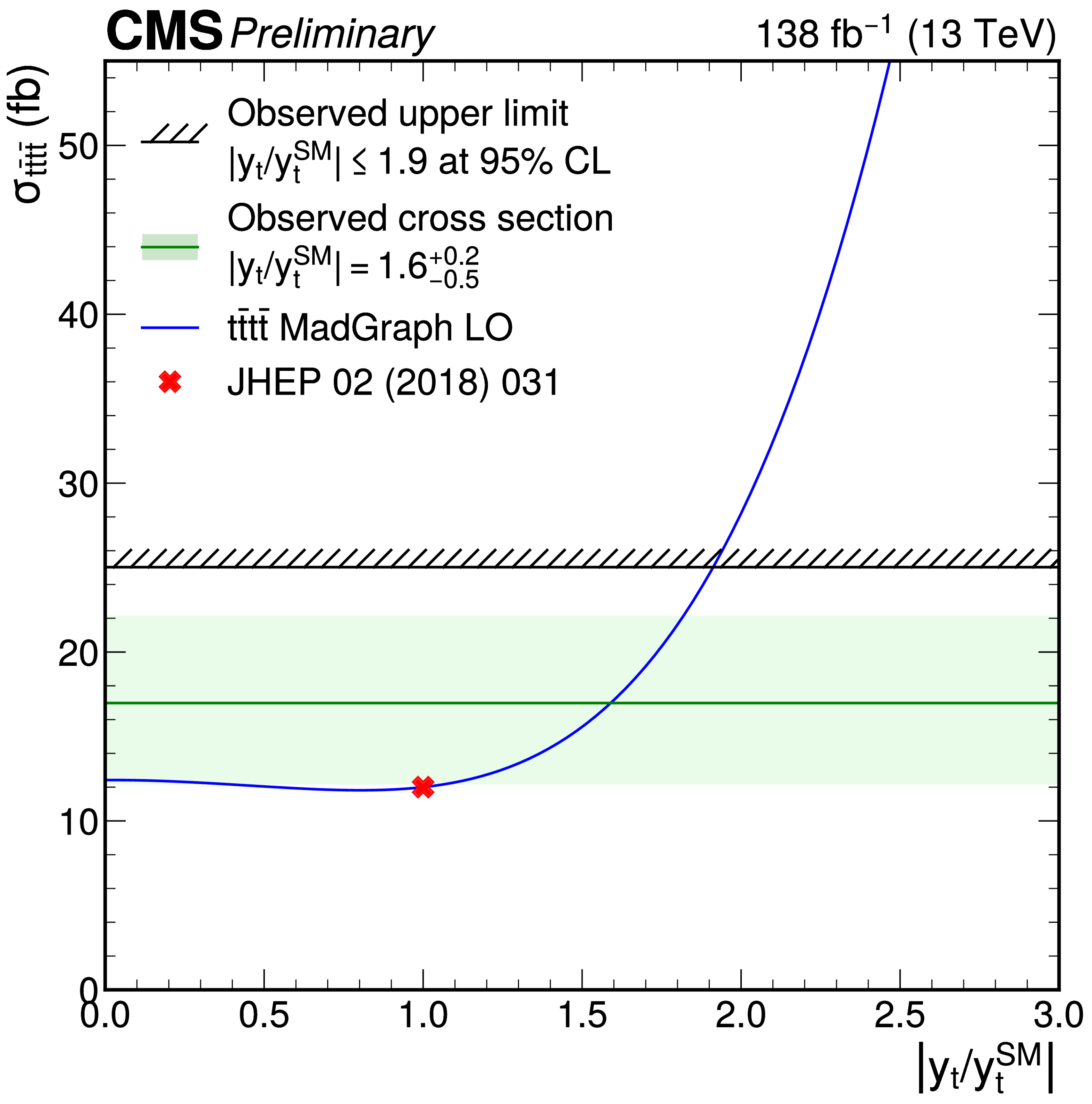
PLB 808 (2020) 135609



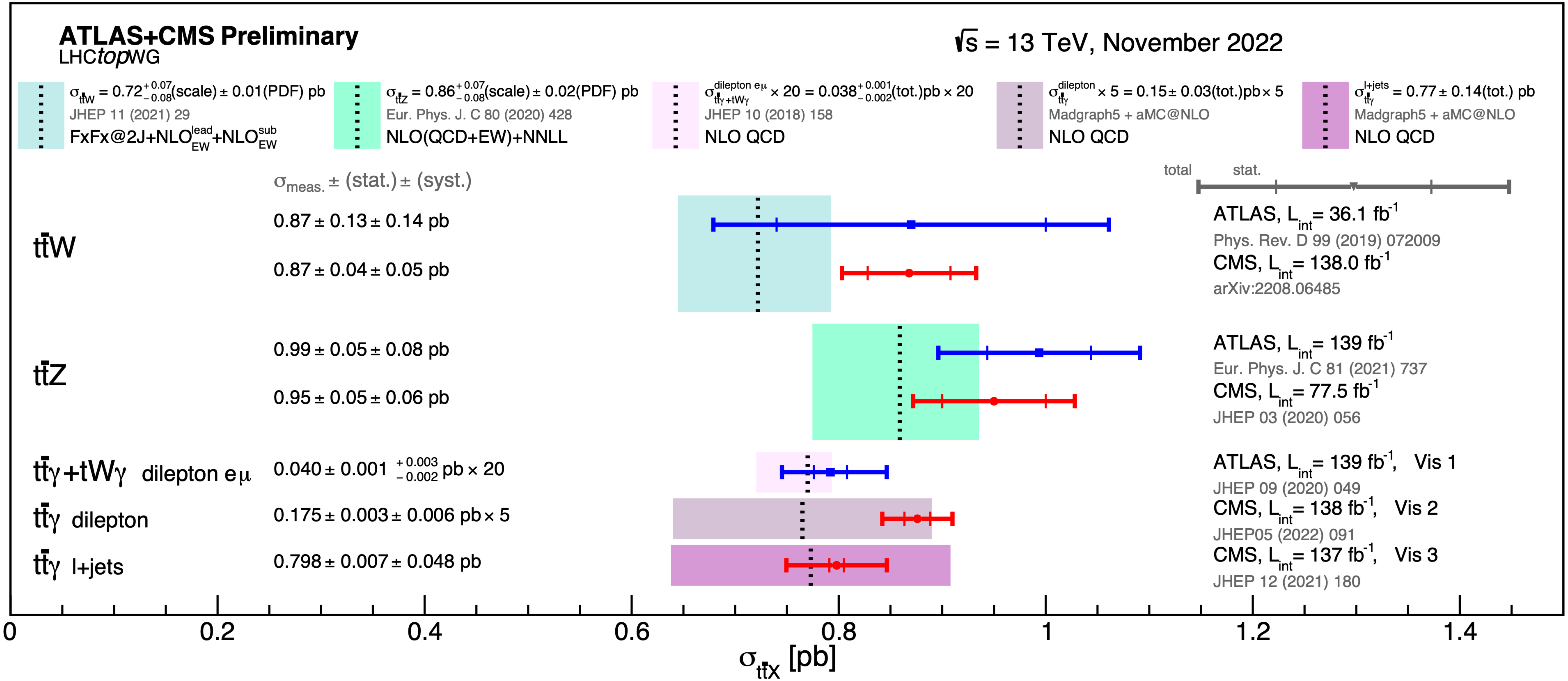

| Treatment | Uncertainty | $\Delta\sigma_{ST_{b,b}}/\sigma$ (%) |
|---|---|---|
| Profiled | Lepton trigger and reconstruction | 0.50 |
| | Limited size of simulated event samples | 3.13 |
| | $t\bar{t}$ modelling | 0.66 |
| | Pileup | 0.35 |
| | QCD background normalisation | 0.08 |
| | W+jets composition | 0.13 |
| | Other backgrounds $\mu_R/\mu_F$ | 0.44 |
| | PDF for background processes | 0.42 |
| | b tagging | 0.73 |
| | Total profiled | 3.4 |
| Nonprofiled | Integrated luminosity | 2.5 |
| | JER | 2.8 |
| | JES | 8.0 |
| | PDF for signal process | 3.8 |
| | Signal $\mu_R/\mu_F$ | 2.4 |
| | ME-PS matching | 3.7 |
| | Parton shower scale | 6.1 |
| | Total nonprofiled | 11.5 |
| Total uncertainty | | 12.0 |

## CMS-PAS-TOP-21-005

| Source | Uncertainty | Process | Final state | correlated (years) | correlated (Process) |
|---|---|---|---|---|---|
| Normalization only | | | | | |
| Luminosity | 1–2% | All | All | | ✓ |
| Electron Id/Isolation/Trigger | 3% | All | OSDL+SL | | ✓ |
| Muon Id/Isolation/Trigger | 3% | All | OSDL+SL | | ✓ |
| Modelling $t\bar{t}$ + HF | 4–8% | $t\bar{t} + b\bar{b}$ | OSDL+SL | ✓ | ✓ |
| ME-PS matching | +7.5%/-9.6% | $t\bar{t}$ | OSDL | | |
| Cross section $t\bar{t}$ +bb | +4.8%/-5.5% | $t\bar{t}$ +bb | OSDL+SL | ✓ | |
| Cross section $t\bar{t}$ +light jets | +4.8%/-5.5% | $t\bar{t}$ +light jets | OSDL+SL | ✓ | |
| Cross section TOP | 4% | TOP | SL | ✓ | |
| Cross section $t\bar{t}$ +H | 20% | $t\bar{t}$ H | All | ✓ | |
| Cross section $t\bar{t}$ +V | 50% | $t\bar{t}$ V | OSDL | ✓ | |
| Cross section $t\bar{t}$ +rare | 50% | $t\bar{t}$ Rare | OSDL | ✓ | |
| Cross section EWK | 3.8% | EWK | OSDL+SL | ✓ | |
| Shape and Normalization | | | | | |
| Prefire | $\pm\sigma$ | All | All, 2016+2017 only | | |
| Pileup | $\sigma_{minbias} \pm 4.6\%$ | All | All | ✓ | ✓ |
| Jet Energy Scale | $\pm\sigma(p_T, \eta)$ | All | All | | ✓ |
| Jet Energy Resolution | $\pm\sigma(\eta)$ | All | All | | ✓ |
| DeepCSV tagging | $\pm\sigma(p_T)$ | All | SL | | ✓ |
| DeepCSV tagging stats | $\pm\sigma$ | All | SL | | ✓ |
| DeepJet tagging | $\pm\sigma$ | All | OSDL, hadronic | | ✓ |
| DeepJet tagging stats | $\pm\sigma$ | All | OSDL, hadronic | | ✓ |
| resolved t tagging: statistical | $\pm\sigma$ | All | SL, hadronic | | |
| resolved t tagging: CS purity | $\pm\sigma(p_T)$ | All | SL | | |
| resolved t tagging: closure | $\pm\sigma(N_{jet})$ | All | SL | | |
| PDF | $\pm\sigma$ | $t\bar{t}$ | All | ✓ | ✓ |
| Renorm./Fact. Energy Scale | envelope($\times 2$, $\times 0.5$) | All | SL, hadronic | ✓ | |
| Renorm./Fact. Energy Scale | $\times 2$, $\times 0.5$ | All | OSDL | ✓ | |
| Shape only | | | | | |
| ISR | $\pm\sigma$ | All | All | ✓ | |
| FSR | $\pm\sigma$ | All | All | ✓ | |

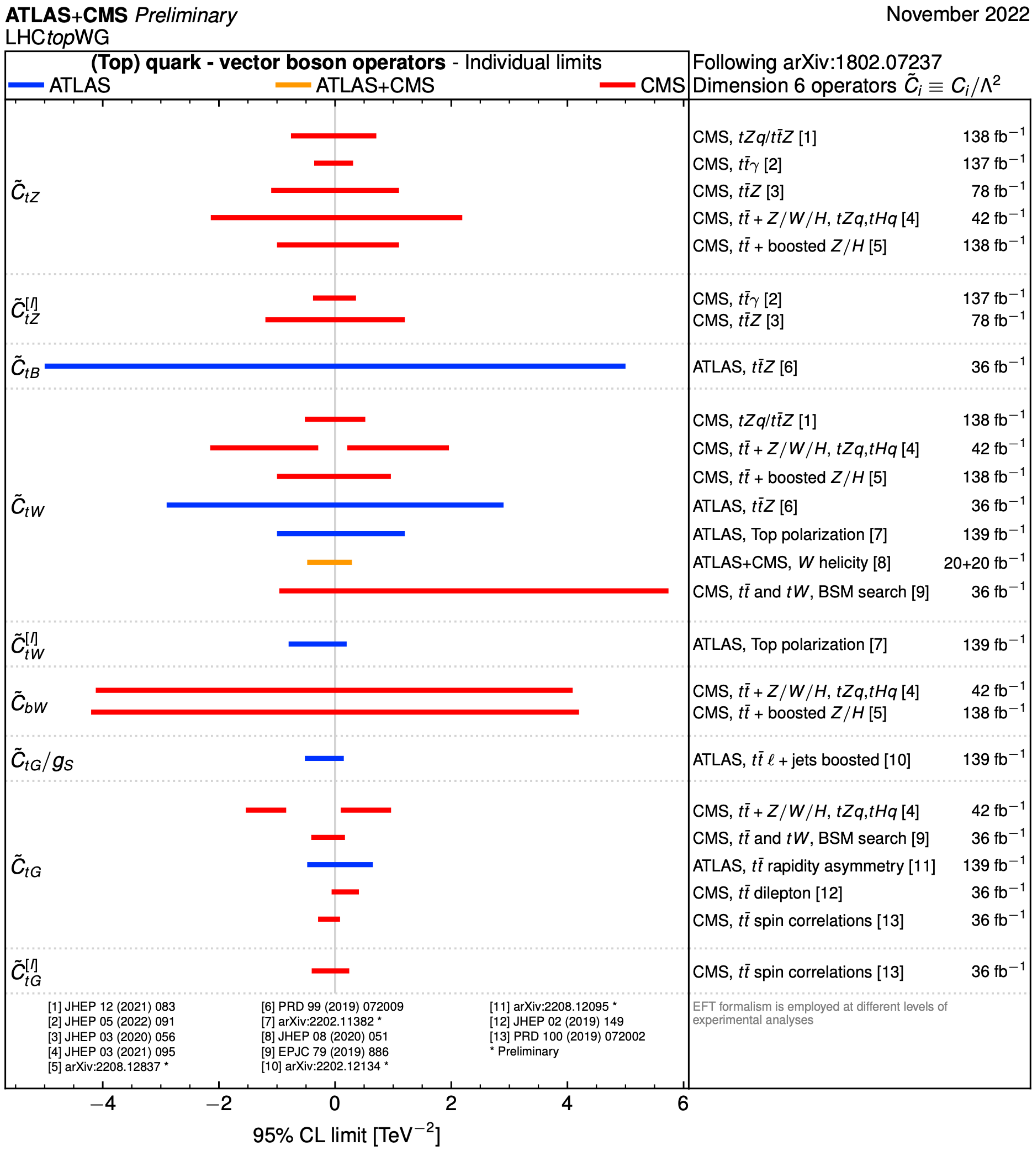


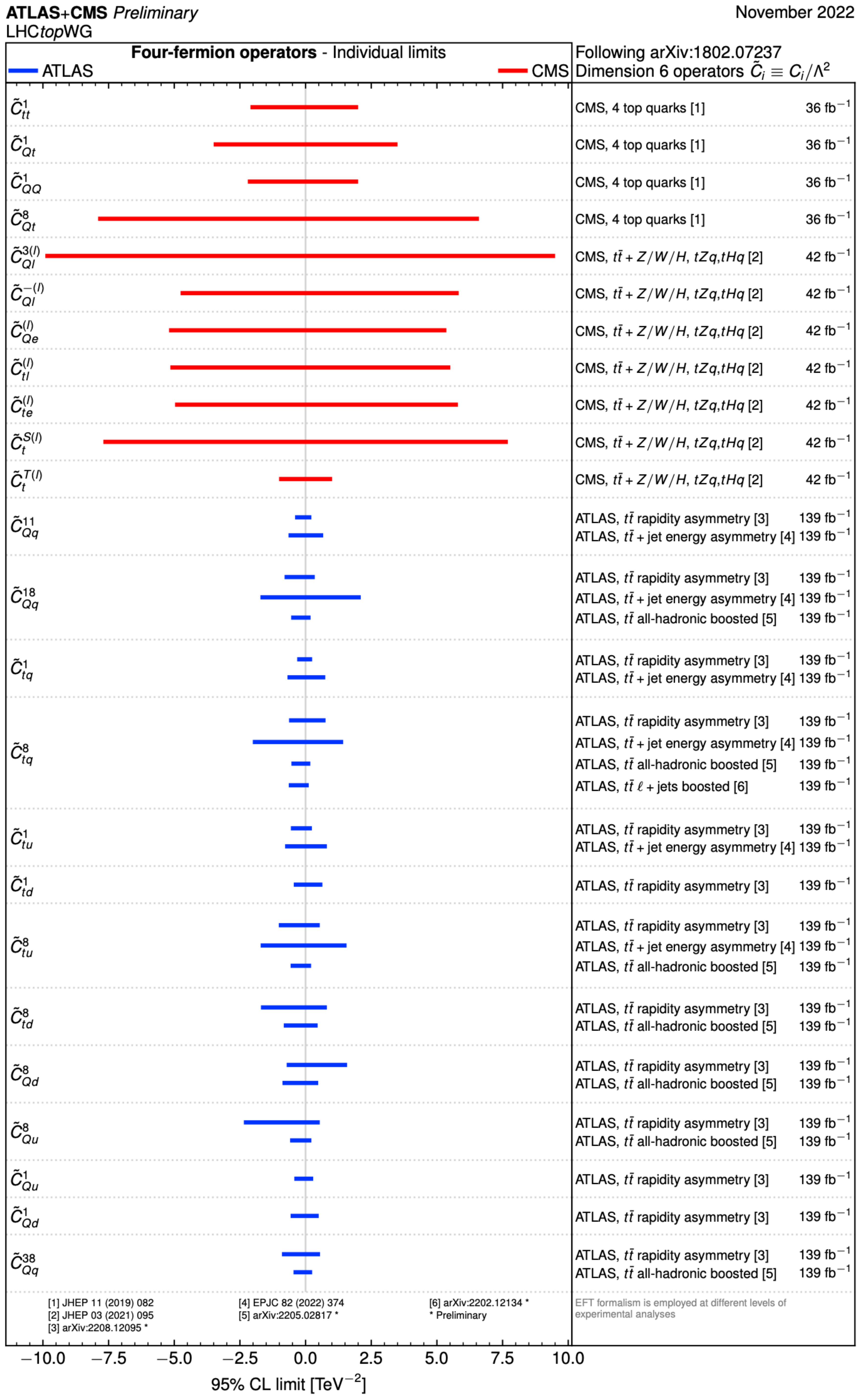
# Summary of $t\bar{t}V$ measurements



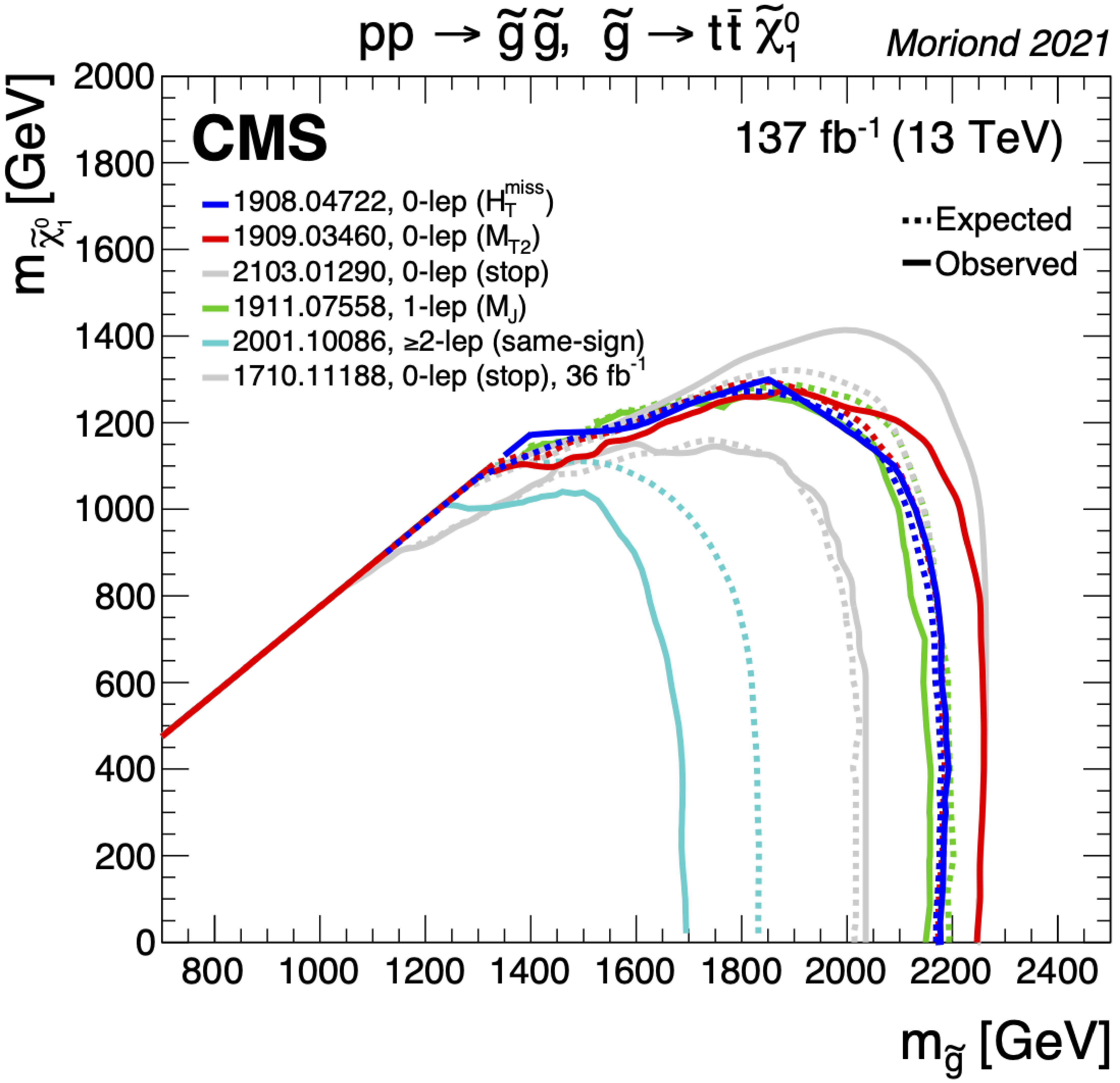

[LHCTOPWGSummaryPlots]

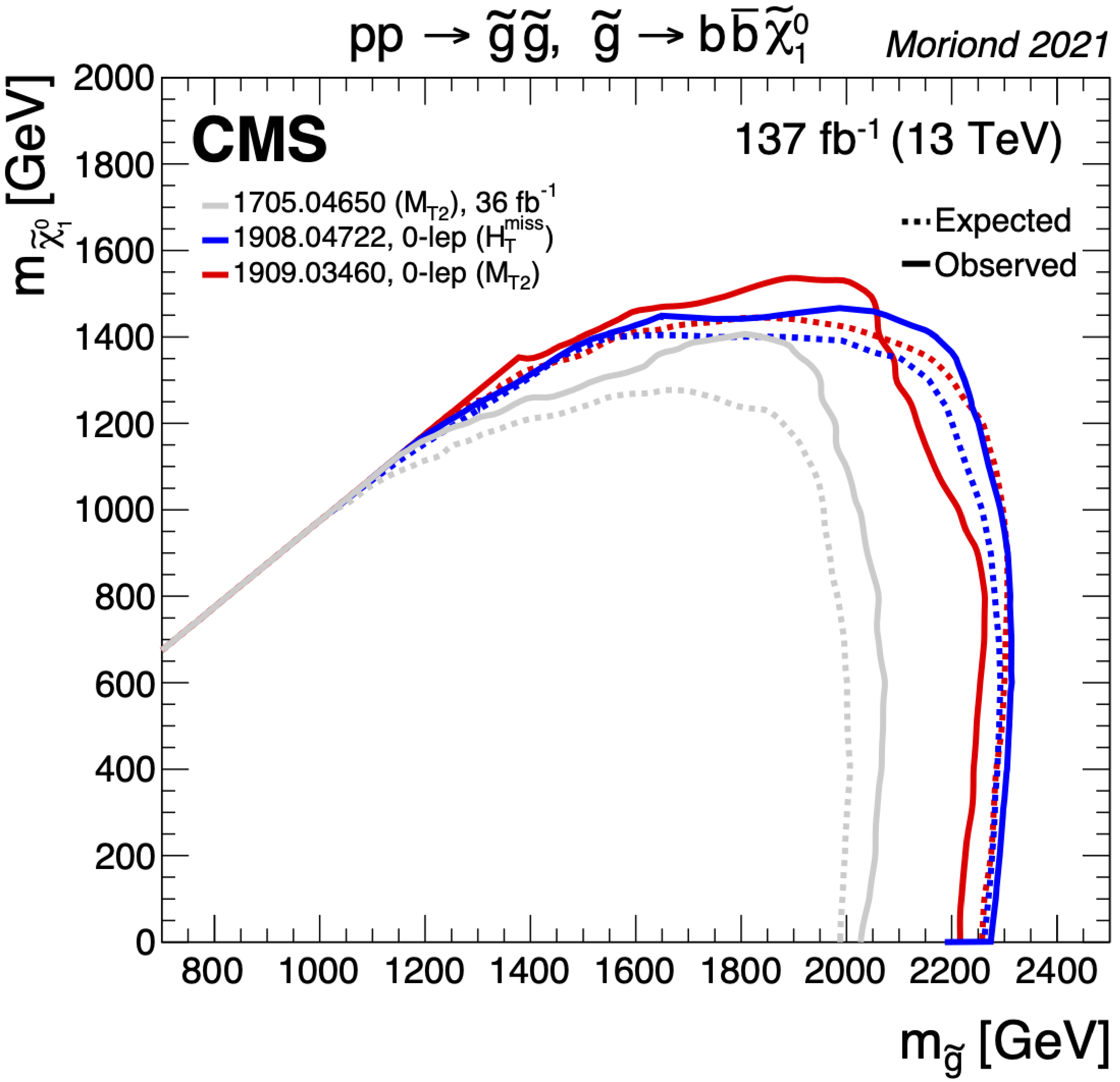
# LHCTOPWGSummaryPlots



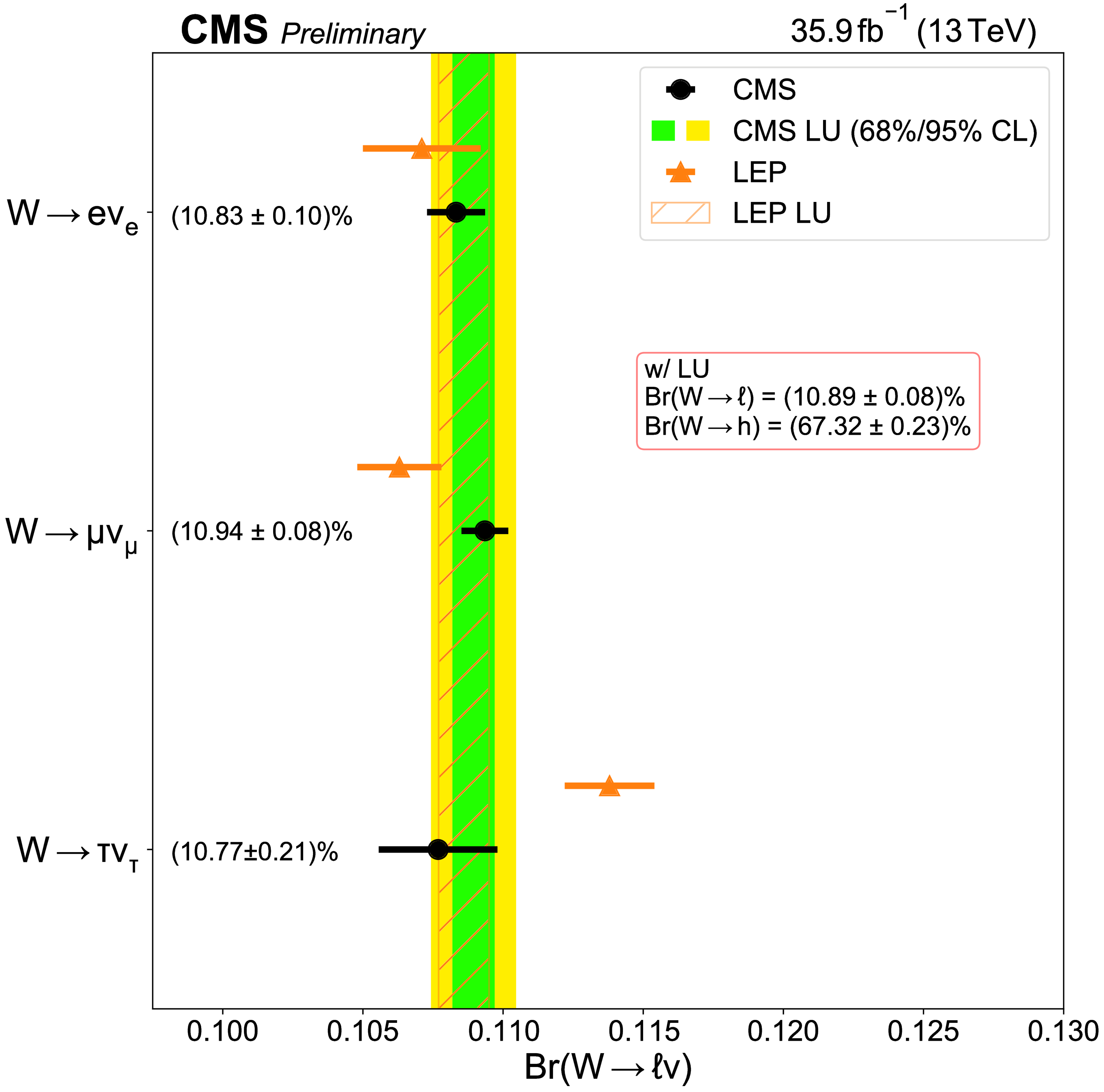



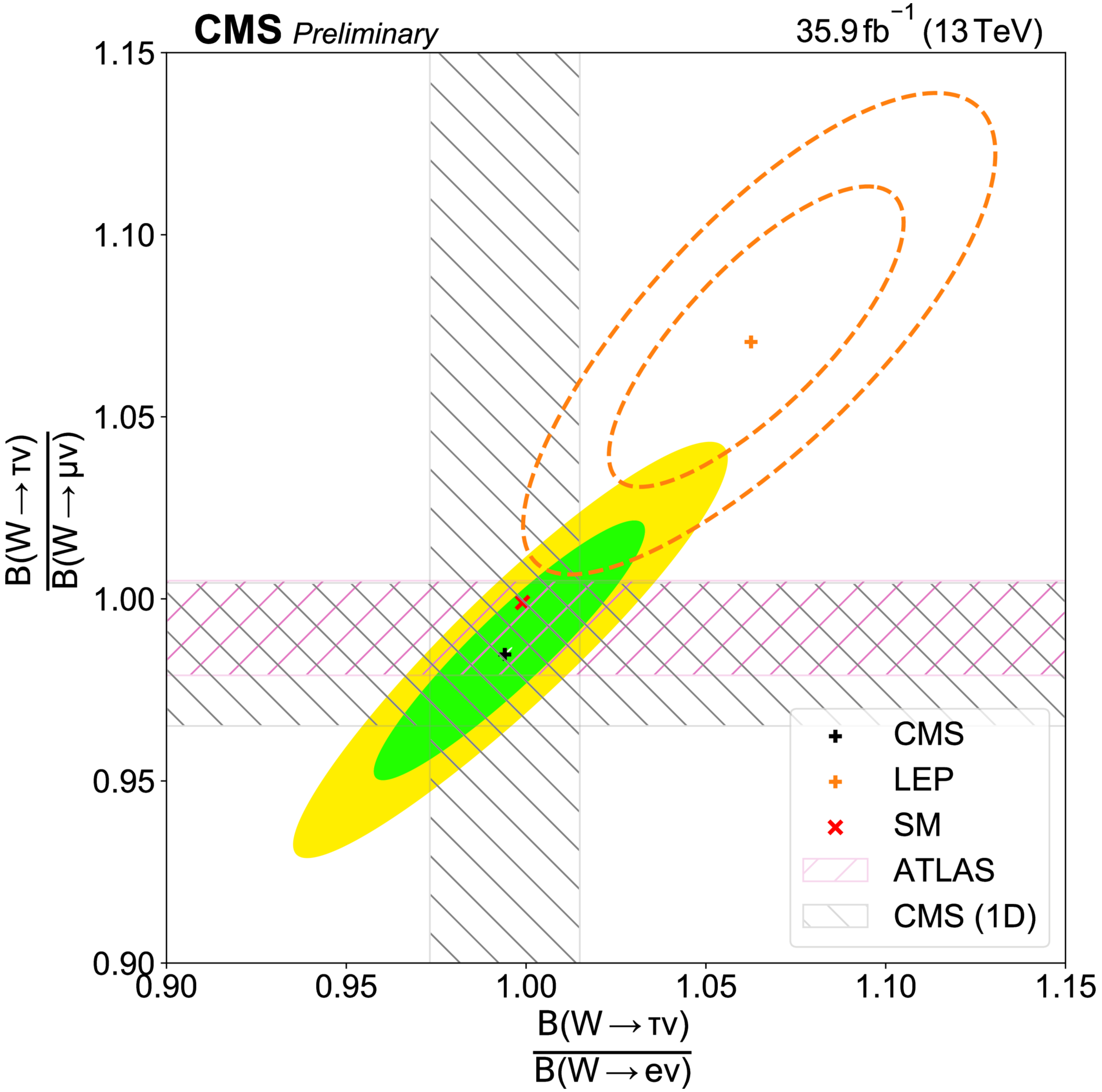
CMS-SUSY-Summary-Plots



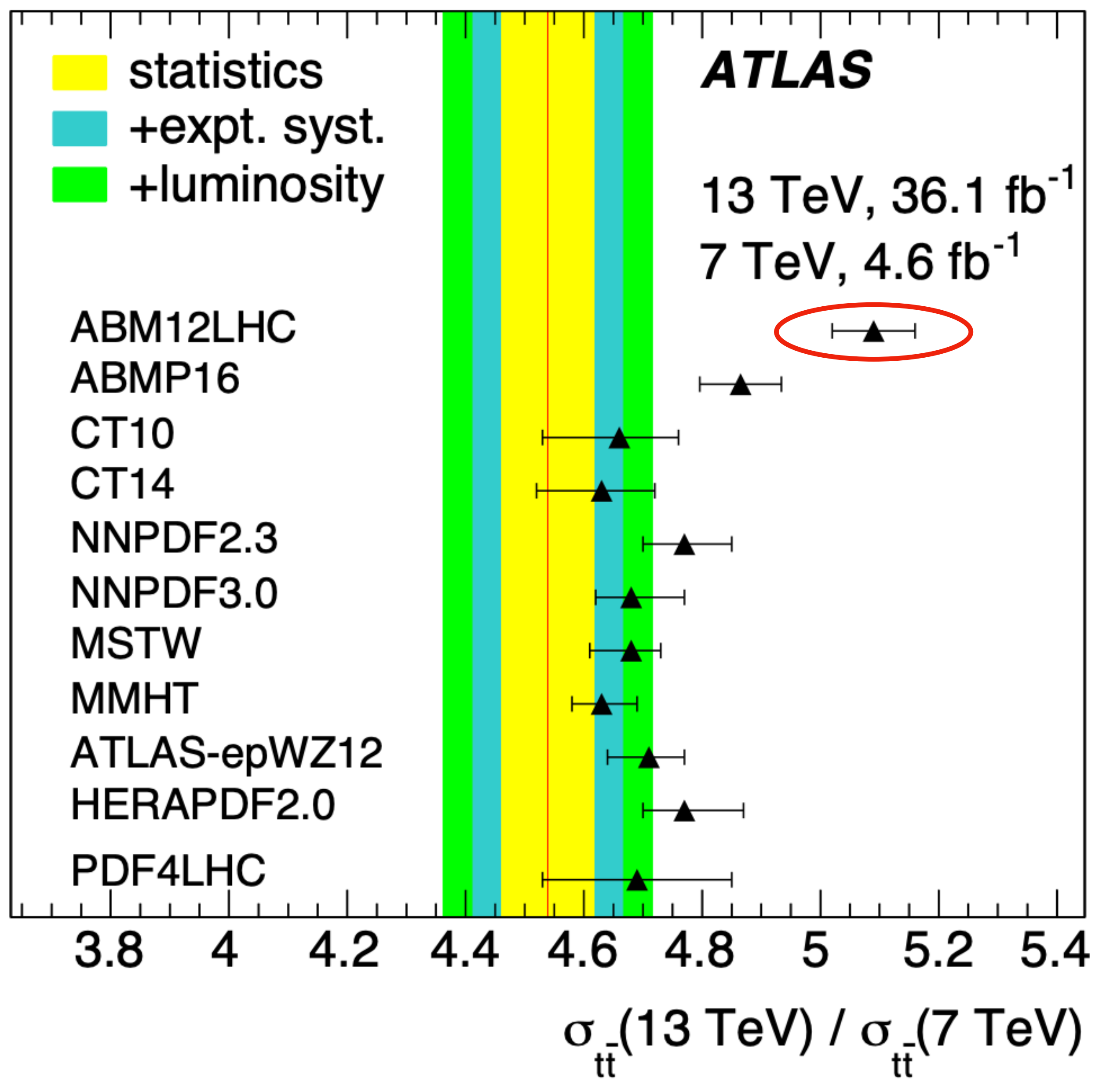
# *Lepton flavor universality* using *WW and W+jets* events

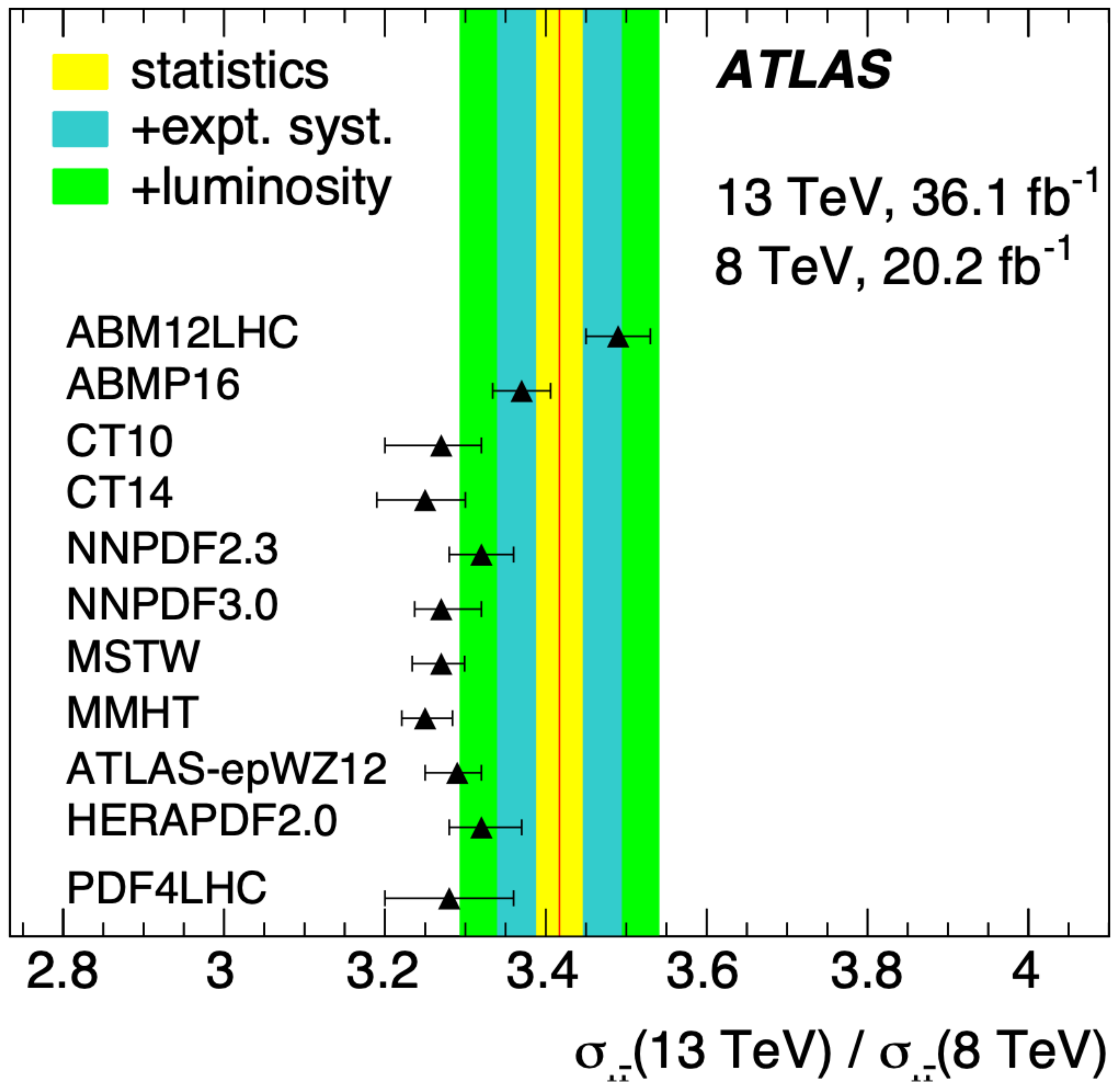


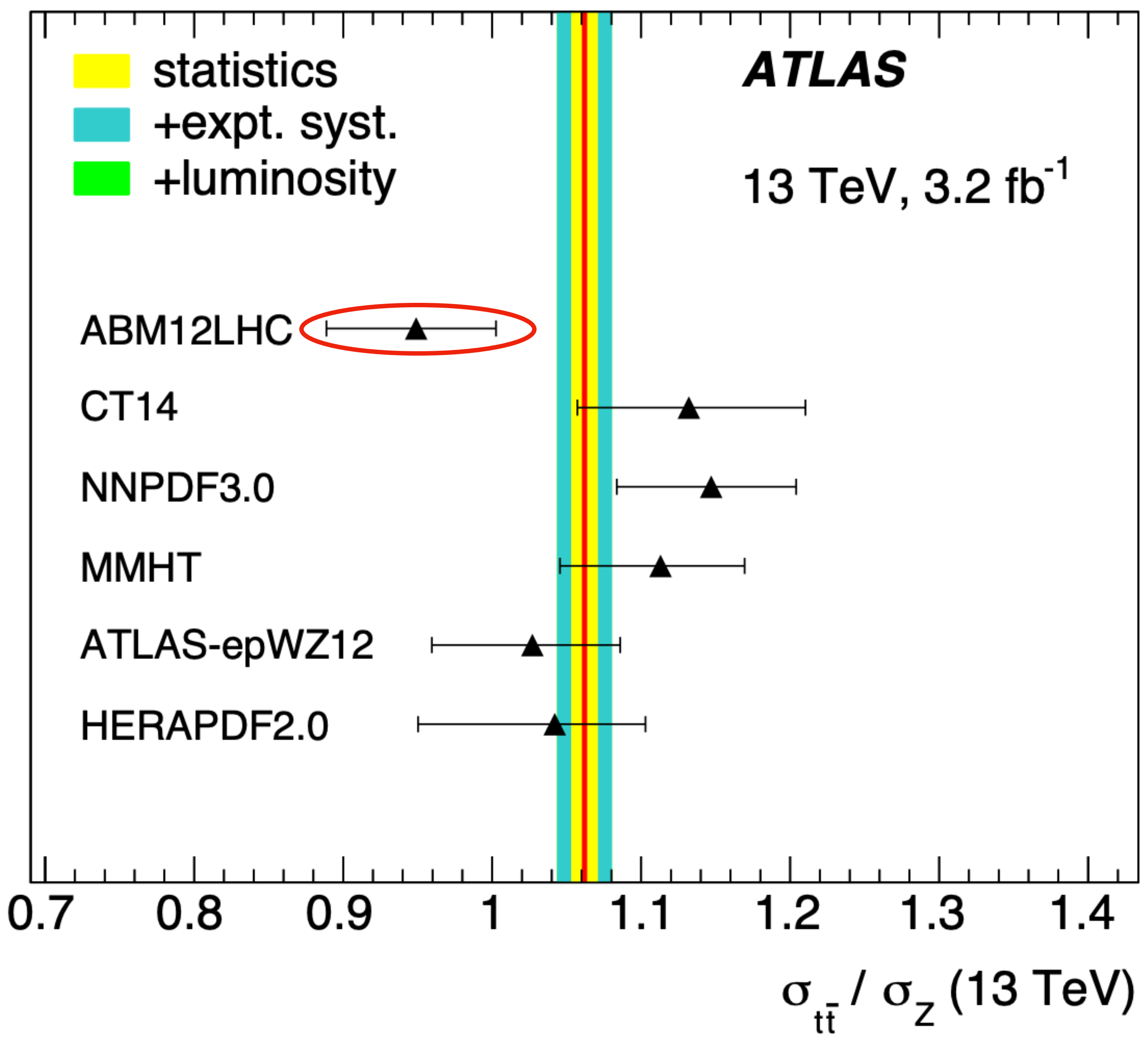



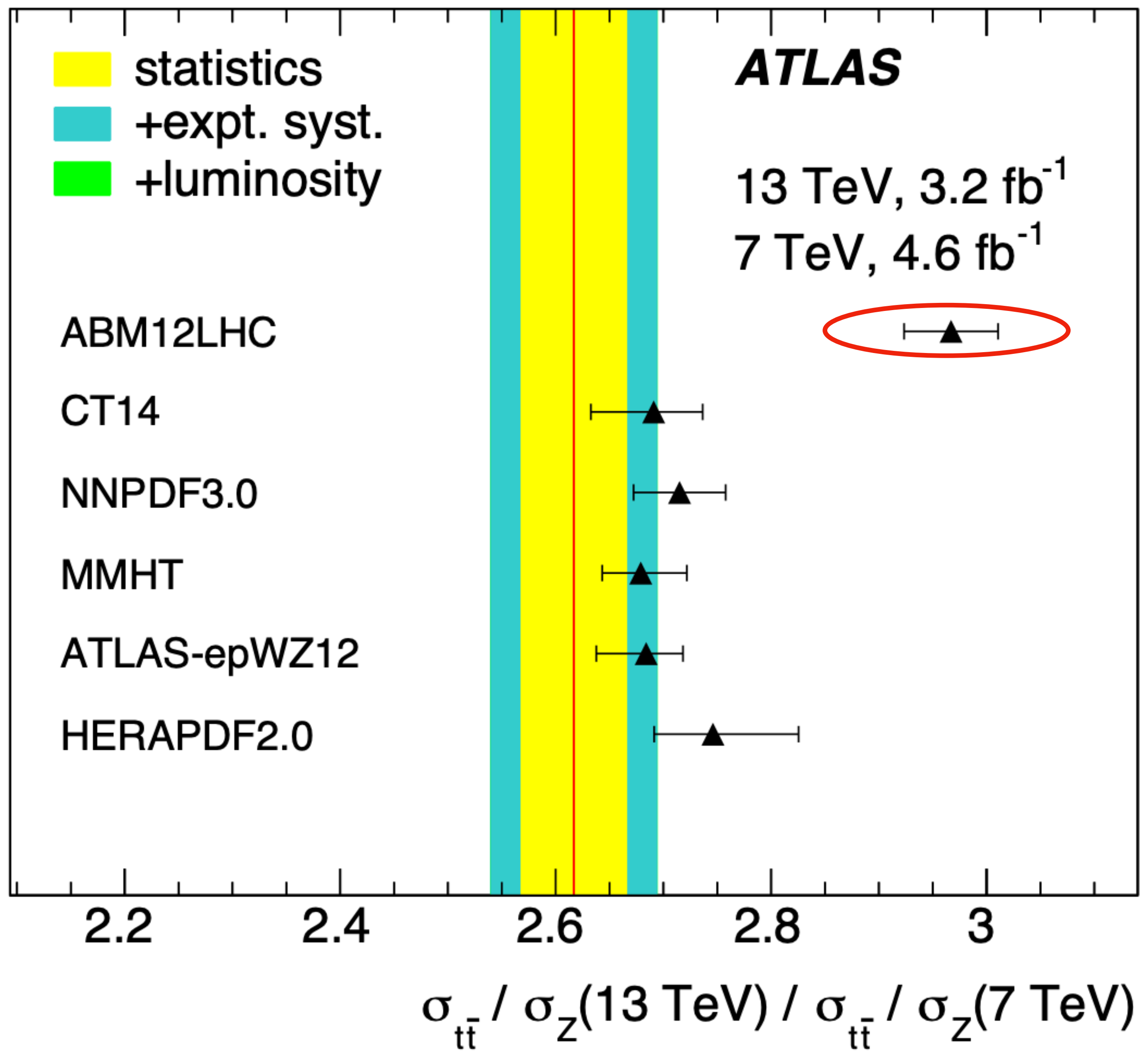

[PRD 105 (2022) 072008]

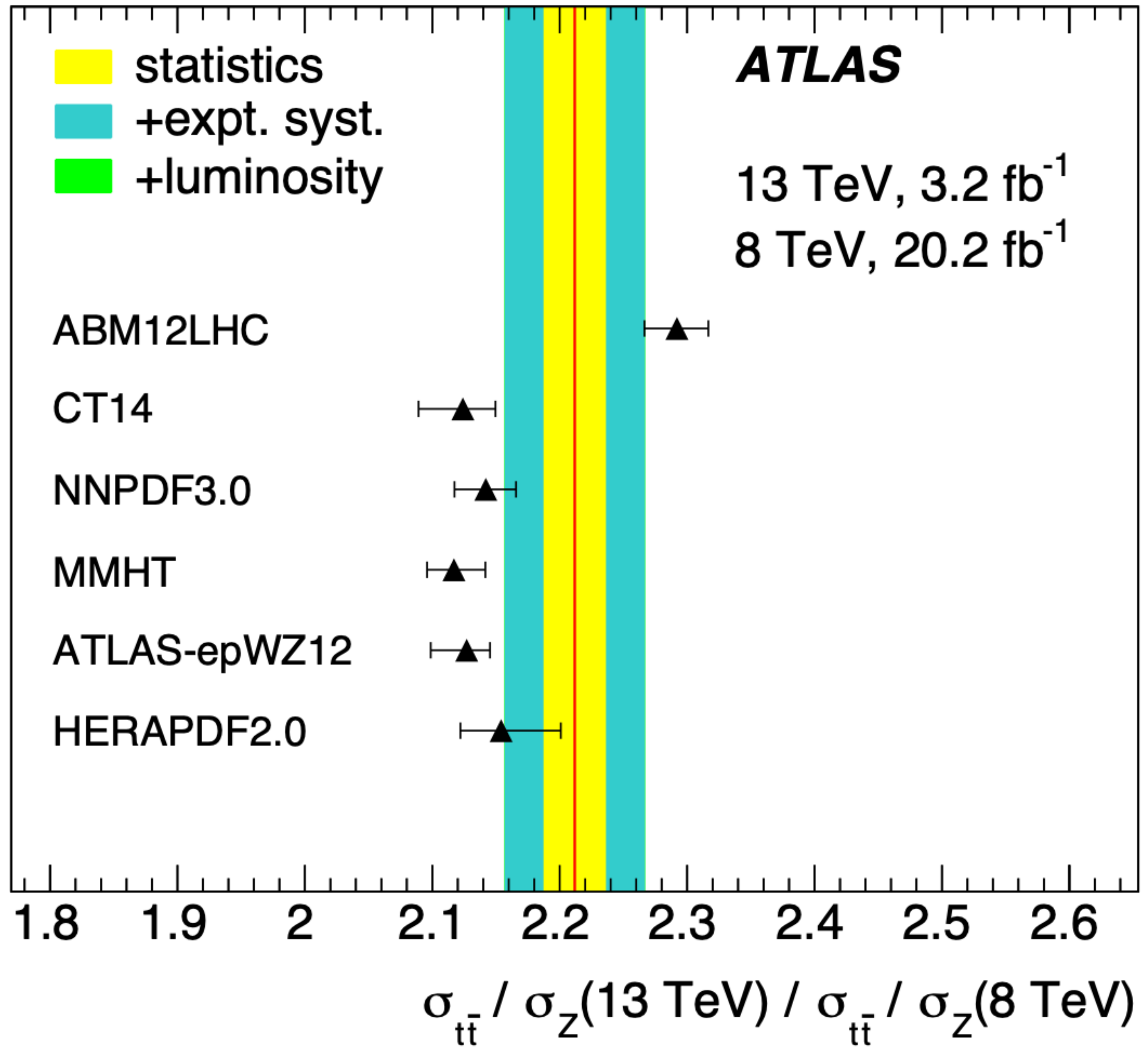
# Cross section ratios




- $t\bar{t}$ cross section ratios and double ratios ( $t\bar{t}$ / Z ) estimated at different $\sqrt{s}$ & compared with various PDF predictions
- Results mostly agree within 2 s.d with predictions with the exception of ABM12LHC ➛ lower gluon density at high Bjorken-x for ABM12LHC compared to others

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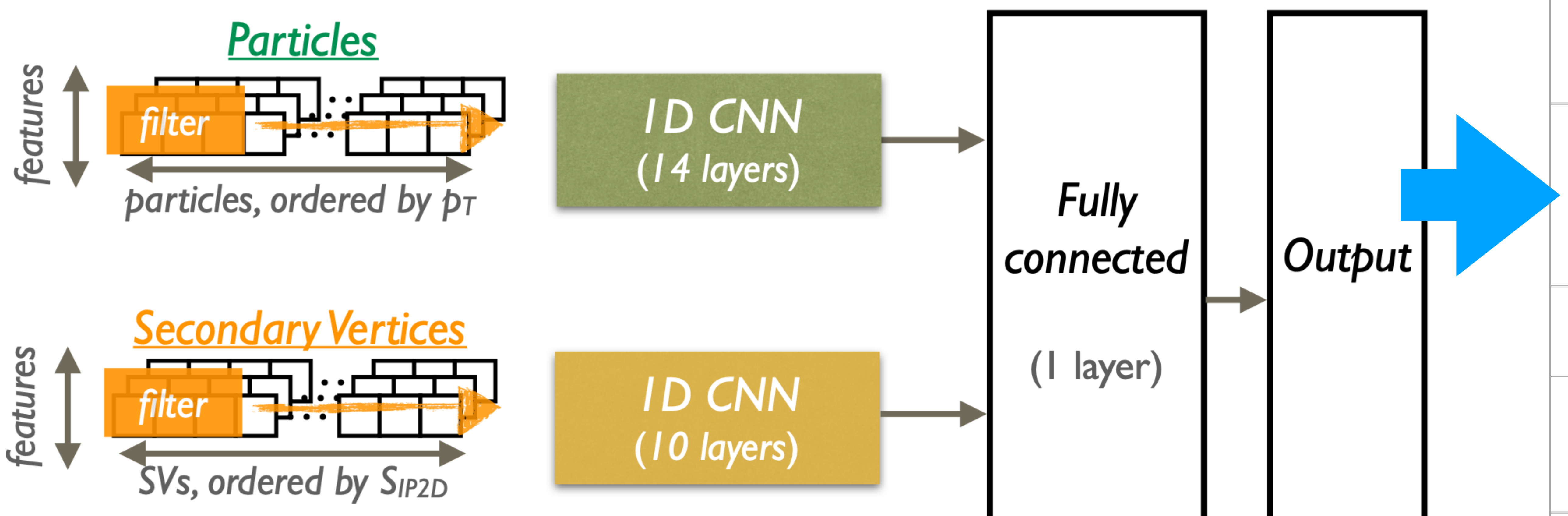
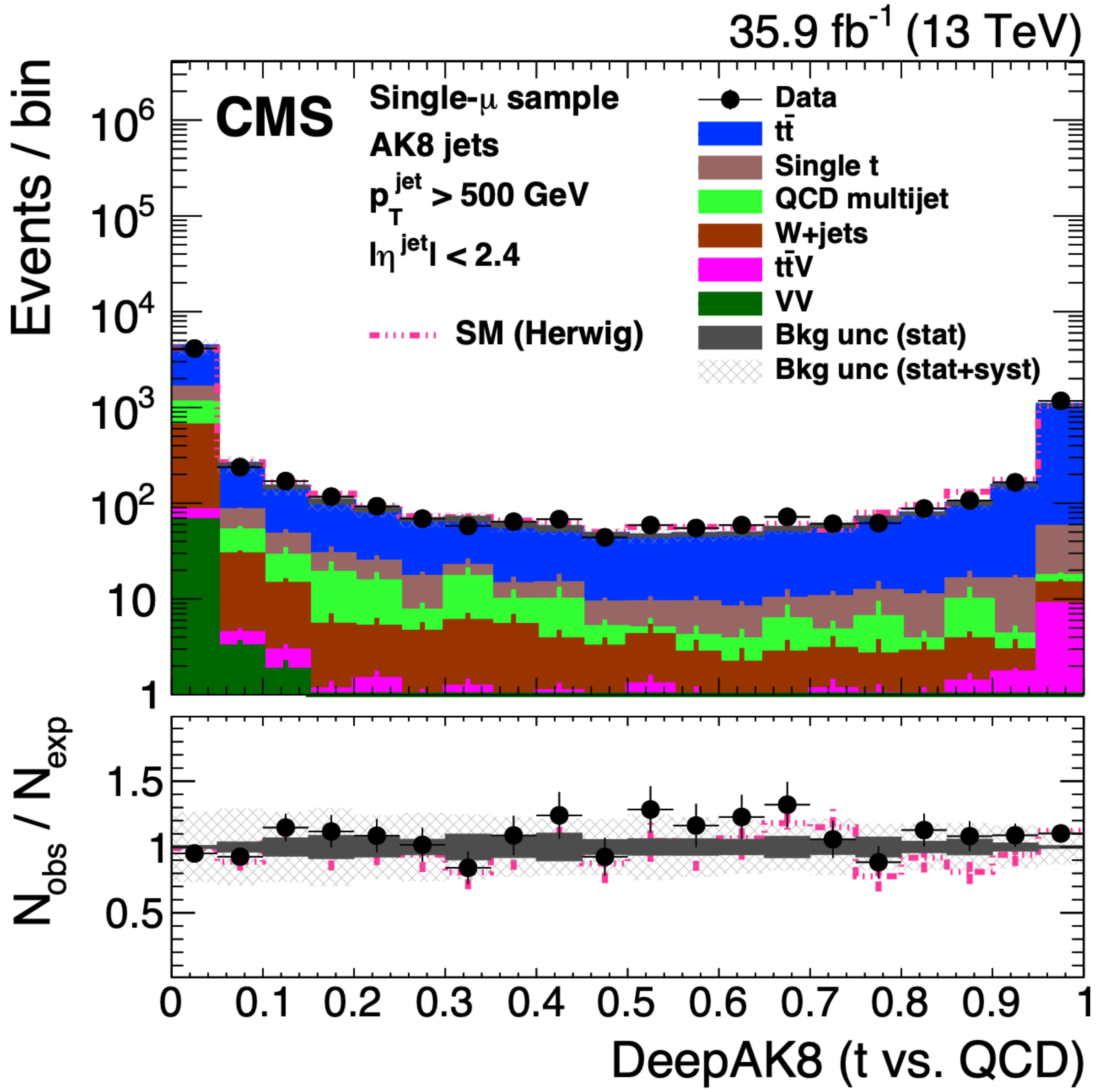
# DeepAK8

- DeepAK8 is a multi-classification algorithm for the identification of hadronically decaying particles, with five main categories ☞ W/Z/H/t/QCD
- PF candidates and secondary vertex information as inputs.
- It is a one-dimensional CNN based on the ResNet architecture




**Output**

| Category | Label |
|---|---|
| Higgs | H (bb) |
| | H (cc) |
| | H (VV*→qqqq) |
| Top | top (bcq) |
| | top (bqq) |
| | top (bc) |
| | top (bq) |
| W | W (cq) |
| | W (qq) |
| Z | Z (bb) |
| | Z (cc) |
| | Z (qq) |
| QCD | QCD (bb) |
| | QCD (cc) |
| | QCD (b) |
| | QCD (c) |
| | QCD (others) |

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