



Latest Top Quark Measurements with the CMS Detector

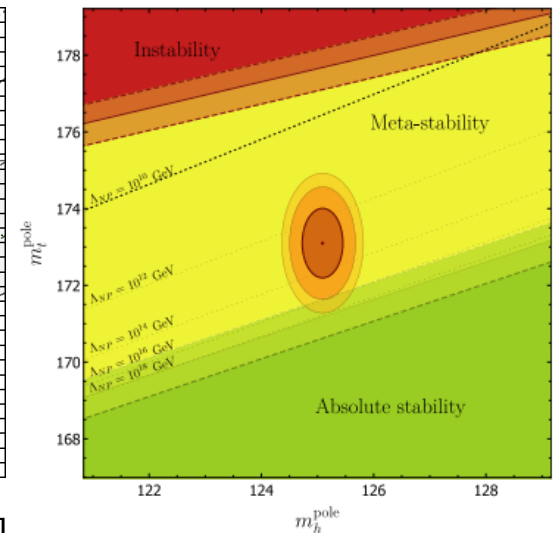
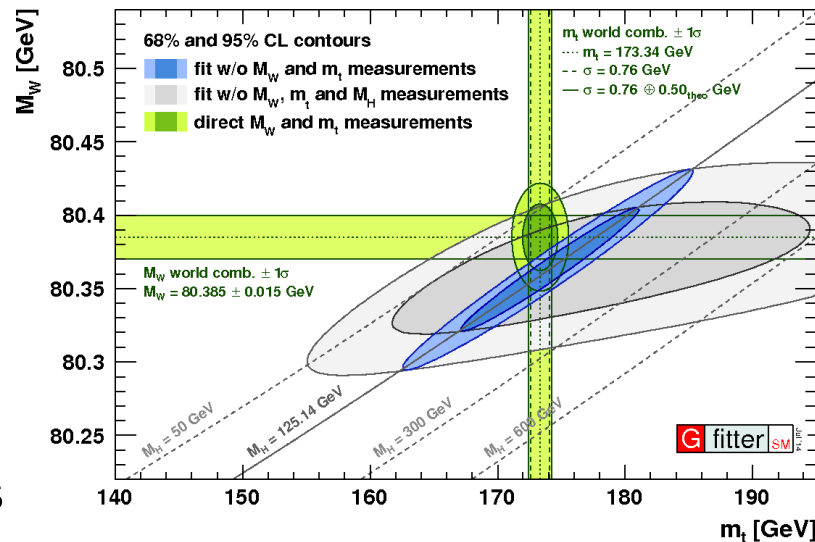
29th Deep-Inelastic Scattering (DIS) and Related Subjects

May 2-6, 2022

**Hideki Okawa for CMS Collaboration
Fudan University**

Top Quark: A Unique Particle

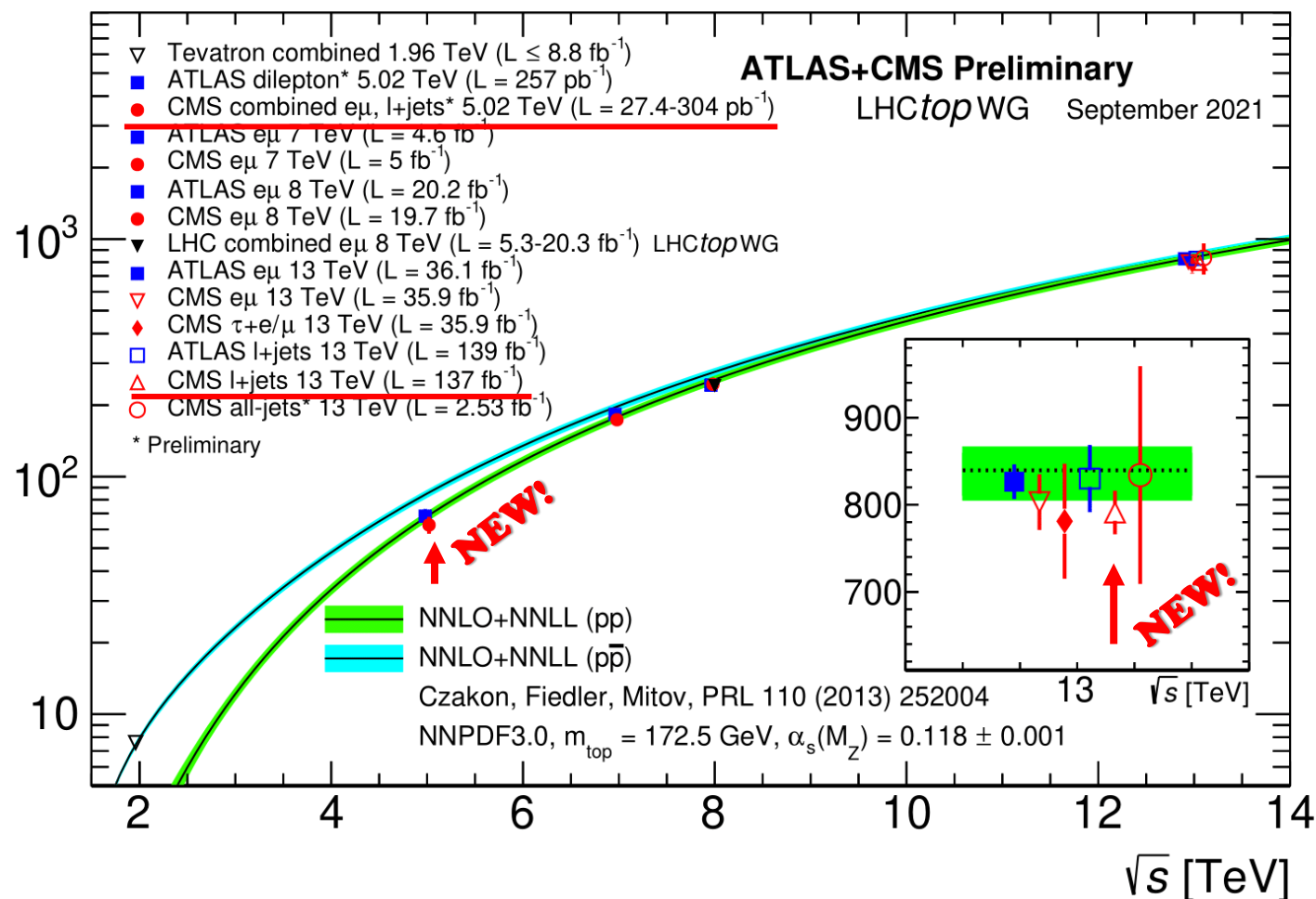
- Top quark is the heaviest elementary particle: **near-unity Yukawa**
- Decays ($\tau_t \sim 0.5 \times 10^{-24} \text{s}$) before hadronizing & spin-decorrelation
→ **Bare quark properties, maintains spin-correlation in decay products**
- Large corrections to EW observables & dominant contributions in the Higgs potential (insights to its origin & life time of the Universe)
- **LHC is a “Top Factory,”** covering $O(10^6)$ range in top production xsec.
 - Allows precise xsec & property measurements, searches for rare processes



Top Inclusive Cross Sections

Recent measurements:
[arXiv:2112.09114](https://arxiv.org/abs/2112.09114), accepted by JHEP
 Phys. Rev. D 104 (2021) 092013

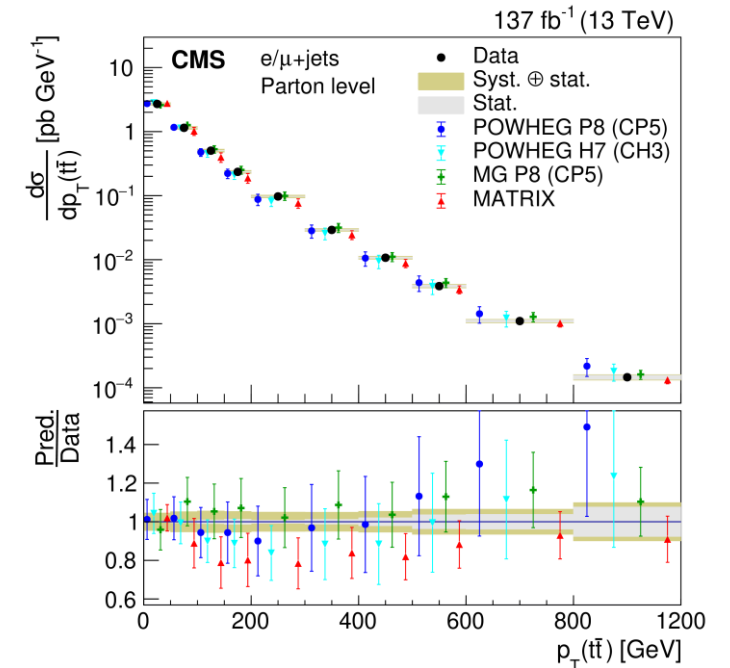
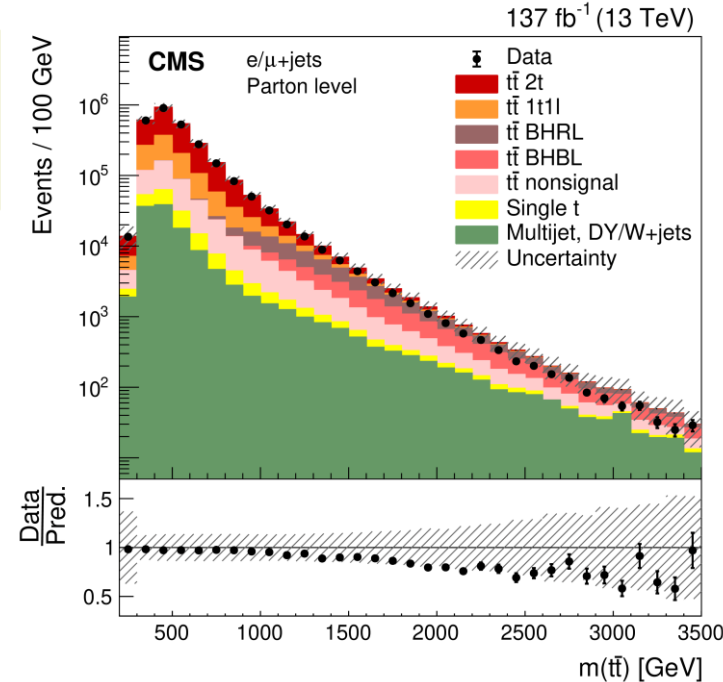
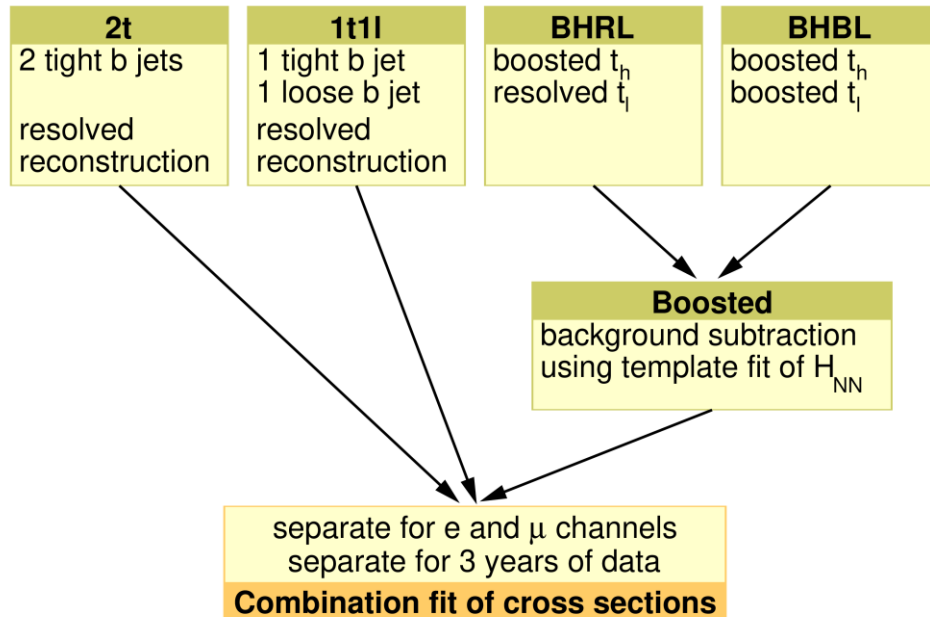
Inclusive $t\bar{t}$ cross section [pb]



- Top-pair production cross section is measured at $\sqrt{s}=5.02, 7, 8, 13 \text{ TeV}$.
- New 2-lepton (& 1-lep combined) measurements at $\sqrt{s}= 5.02 \text{ TeV}$.
 - 4.3% syst. unc., 8.2% stat. unc.
- New 1-lepton measurement with Full Run-2 data (also diff. xsec).
 - 3.2% precision, 1.8% lumi. unc.
- In good agreement with **NNLO QCD+NNLL resummation** (Top++ v2.0).

$t\bar{t}$ Differential Cross Section

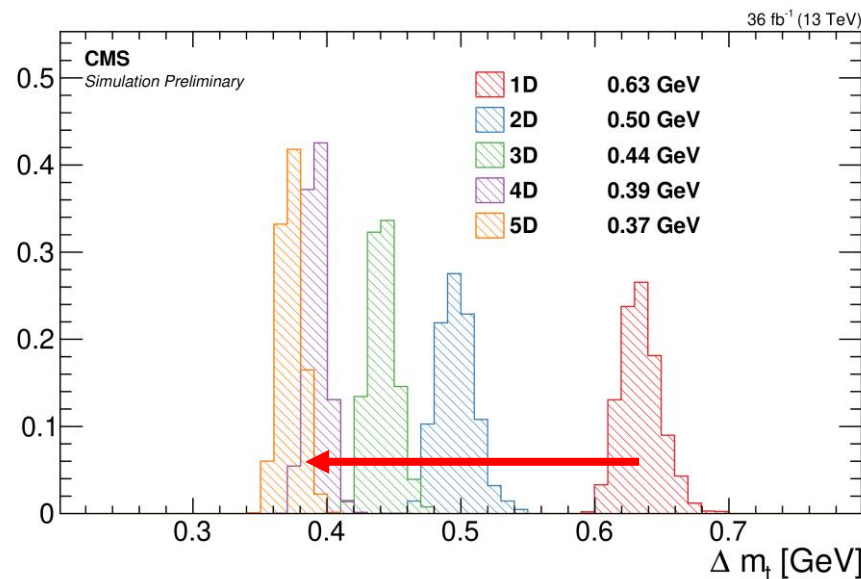
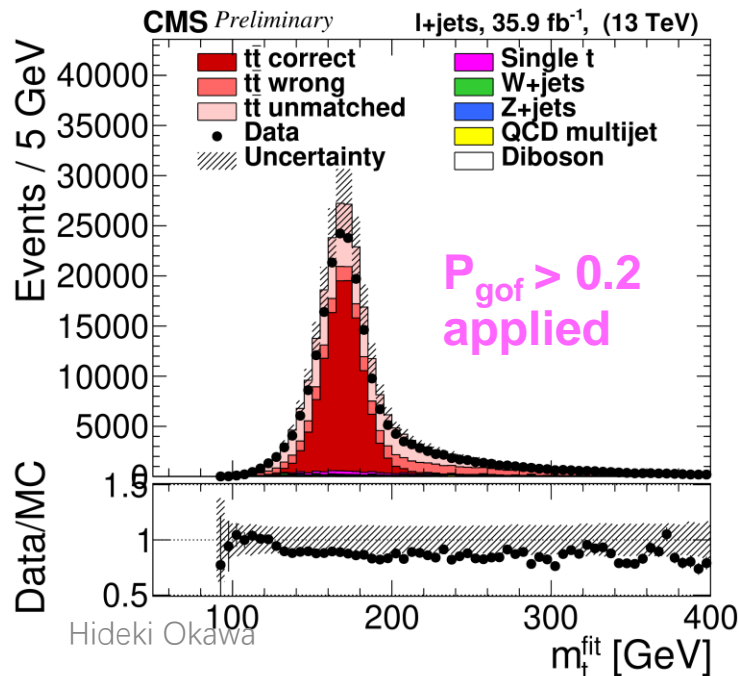
Phys. Rev. D 104 (2021) 092013



- **First combination of resolved & boosted events** in 1-lepton channel.
- Resolved: reconstructed top-pair system with constraints on m_t , m_W using likelihood.
- Boosted: Top-tagger on Anti-kt $R=0.8$ jets with a neural network.
- Fixed-order NNLO prediction (MATRIX) can be directly compared to the parton-level xsec. It generally describes the kinematic distributions, but 2σ discrepancy in $p_T(t\bar{t})$ at low p_T .

Top Mass (Direct Measurement)

- Determines the top mass parameter defined in MC from kinematic observables. the so-called “MC mass”
- Goodness-of-fit defined as $P_{\text{gof}} = \exp(-1/2 \chi^2)$ for jet-parton assignment.
- Profile likelihood w/ 5 variables: $m_t^{\text{reco}}, m_W^{\text{reco}}, R_{b,q}^{\text{reco}}, m_{l,b}^{\text{reco}}/m_t^{\text{reco}}, m_{l,b}^{\text{reco}}|_{P<0.2}$



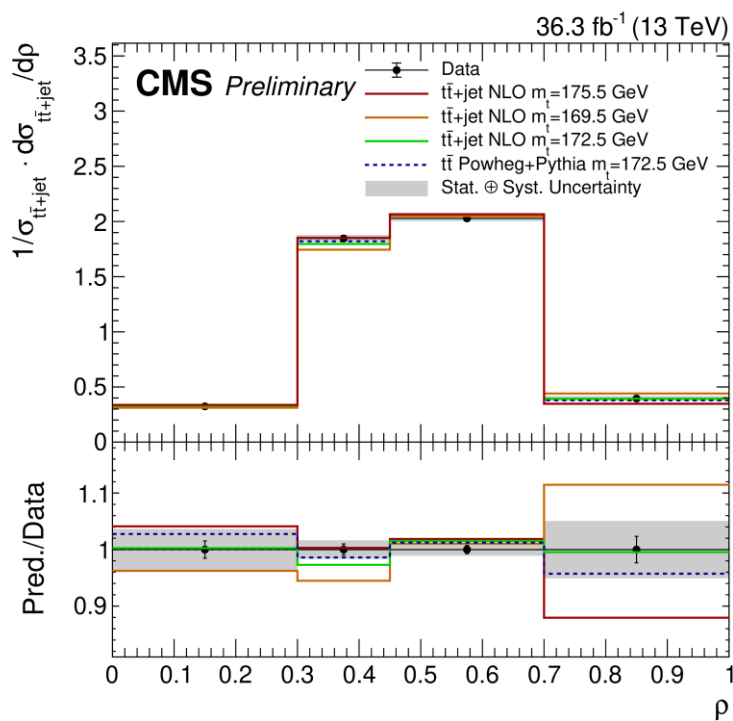
$$R_{b,q}^{\text{reco}} = (p_T^{b1} + p_T^{b2}) / (p_T^{q1} + p_T^{q2})$$

- **Considerable improvement from previous results w/ 5D fit.**
- $m_t^{5D} = \underline{171.77 \pm 0.38 \text{ GeV}}$

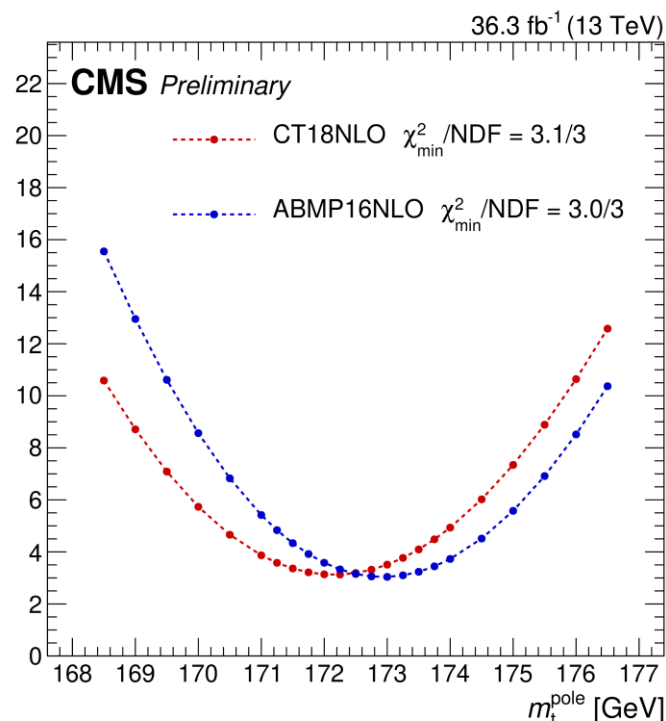
Top Mass (Pole Mass) from $t\bar{t}$ +jets

- **Pole mass: mass defined in parton-level scattering amplitudes.** Self-energy corrections are absorbed in this mass scheme.
- MVA used for kinematic reconstruction on dilepton channel.

$$\rho = \frac{2m_0}{m_{t\bar{t}+\text{jet}}}$$



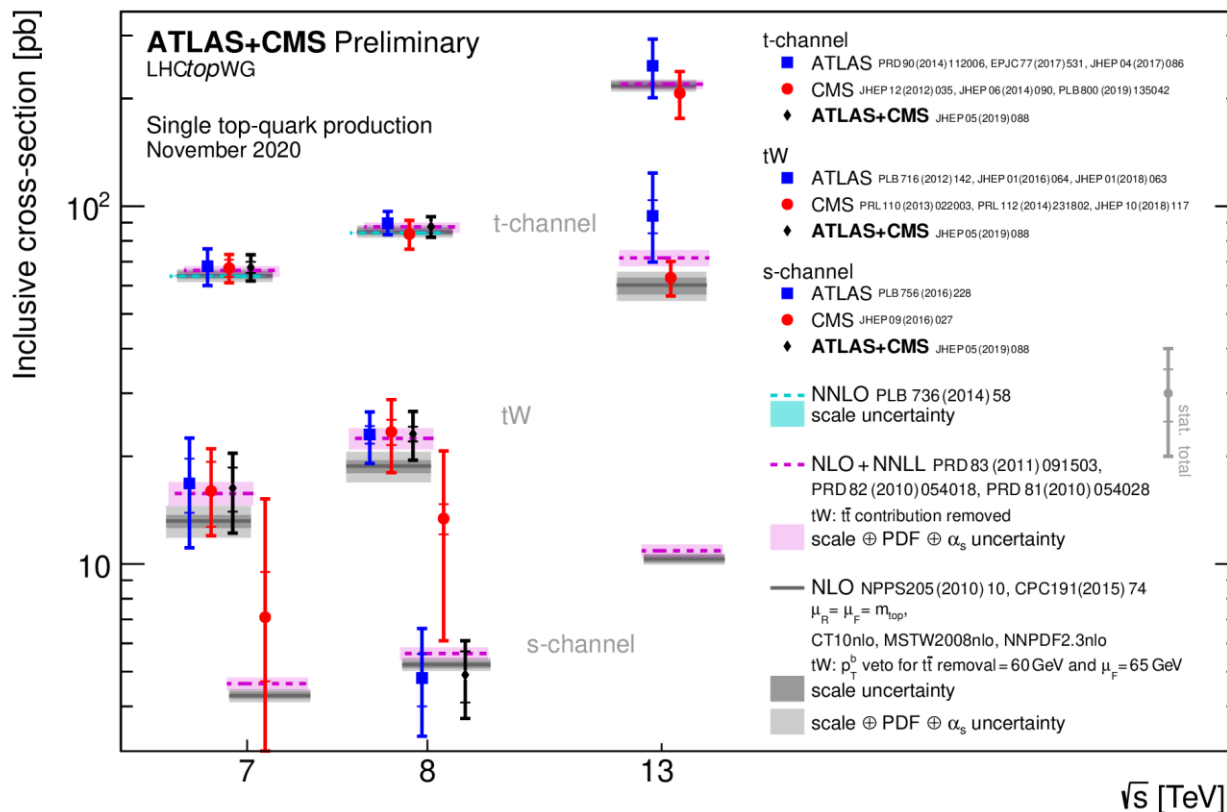
Hideki Okawa



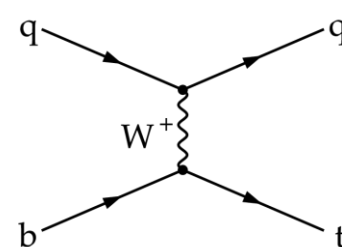
DIS2022

- Mass extracted from inverse invariant mass of $t\bar{t}$ +jets.
- Pole mass with NLO theory prediction.
- **Top pole mass:**
 - $m_t = 172.94 \pm 1.37$ GeV (ABMP16NLO).
 - $m_t = 172.16 \pm 1.44$ GeV (CT18NLO).

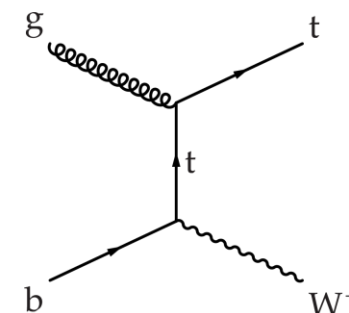
Single Top



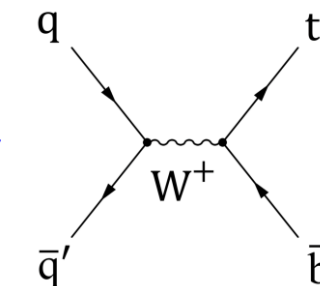
t-Channel



W-association (tW)



s-Channel

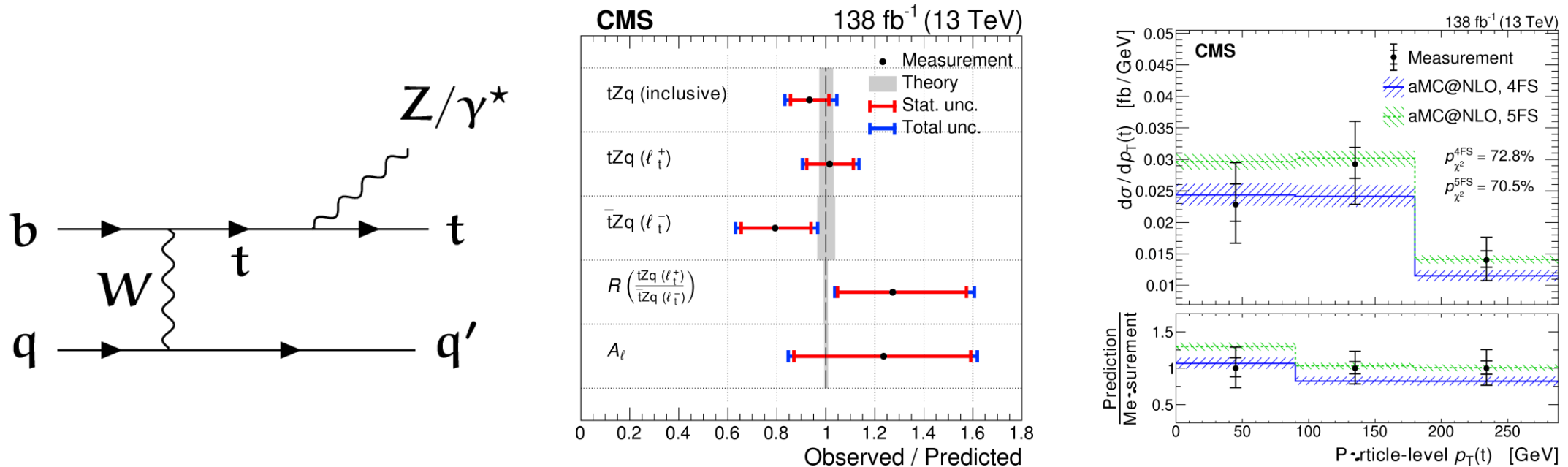


- Inclusive xsec measurements are generally in good agreement w/ NLO+NNLL & NNLO prediction.
- The very rare Z-association mode was observed in 2018.

Single Top Differential (tZq)

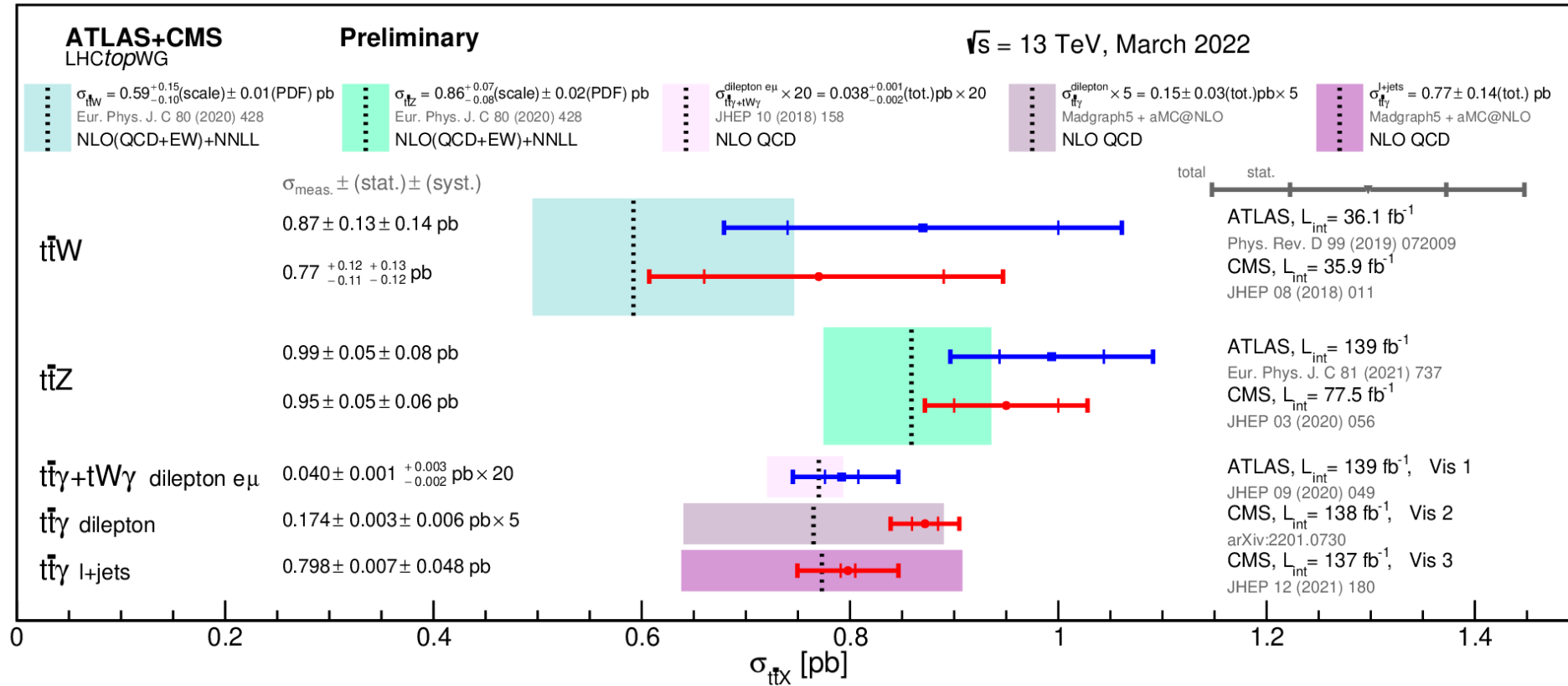
JHEP 02 (2022) 107

- Inclusive & **first** differential xsec measurements for tZq (pure EW production).



- Binned fit to multivariate classifier in 3-lepton events categorized w/ n_{jets} & $n_{\text{b-jets}}$.
- Most precise tZq inclusive xsec so far.** Differential xsec compatible w/ SM & top spin asymmetry also consistent w/ SM.

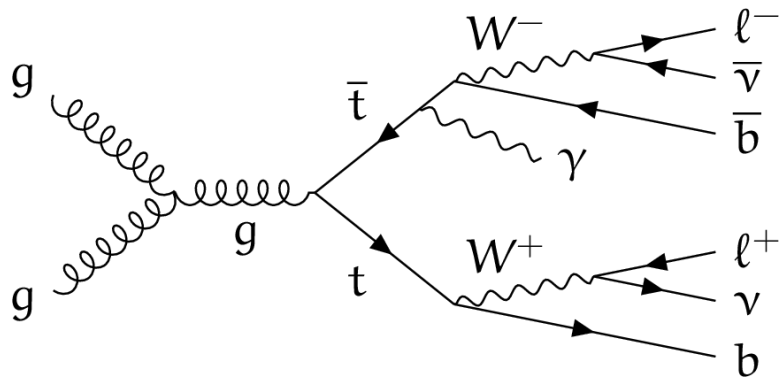
$t\bar{t}+V$



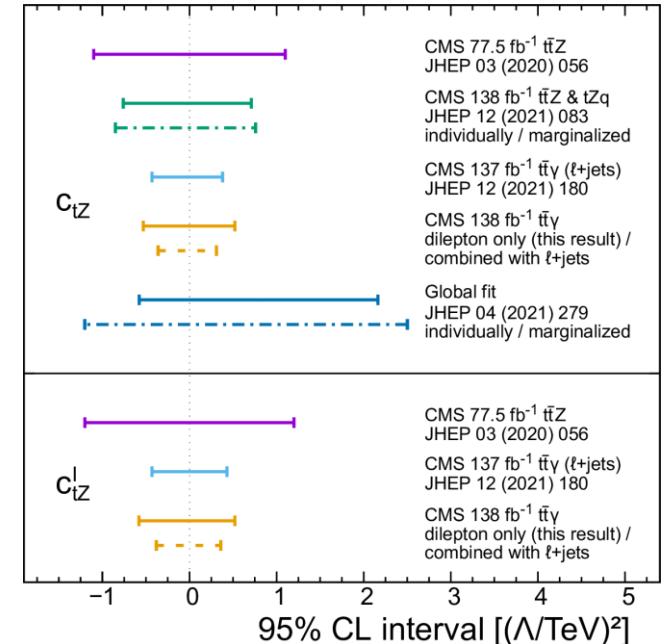
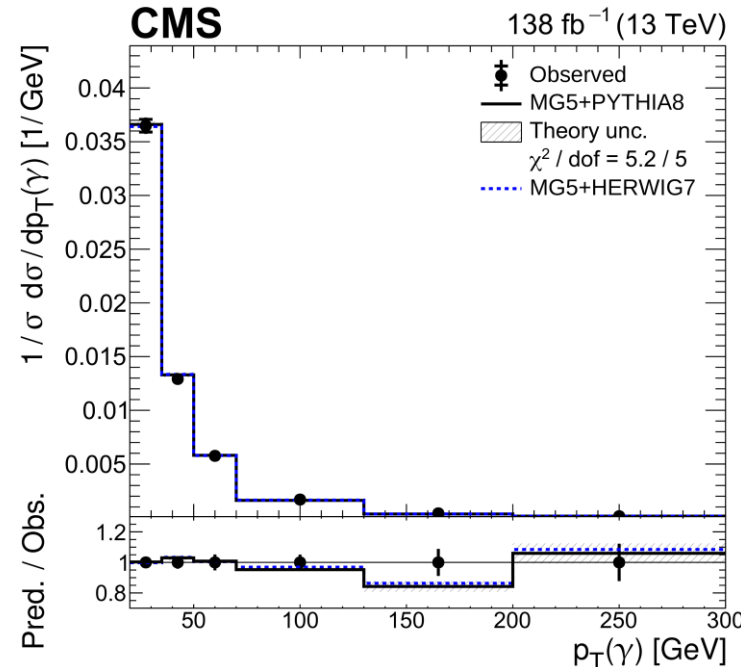
- Direct measurement of top couplings to gauge bosons → inputs to EFT
- $t\bar{t}W$ & $t\bar{t}Z$ are dominant irreducible BG for $t\bar{t}H$.

$t\bar{t}\gamma$ xsec & EFT

arXiv:2201.07301, accepted to JHEP



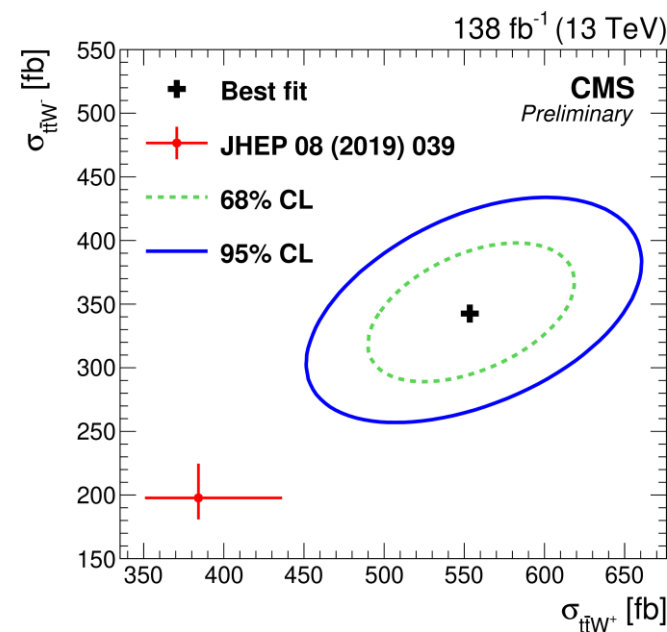
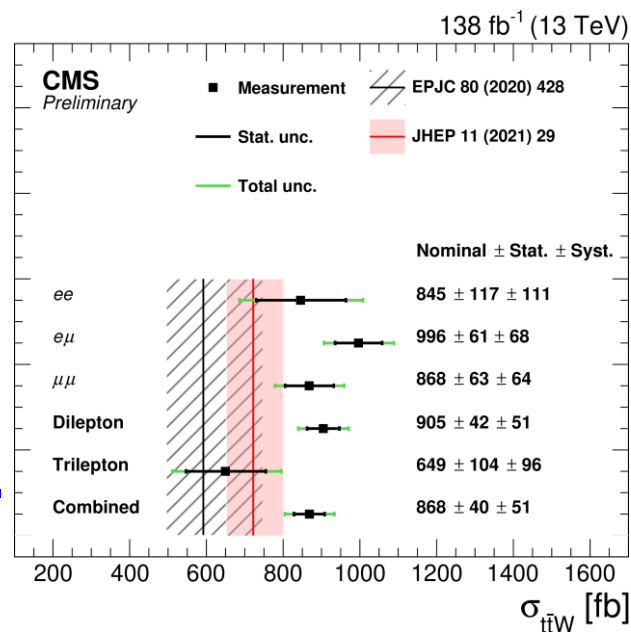
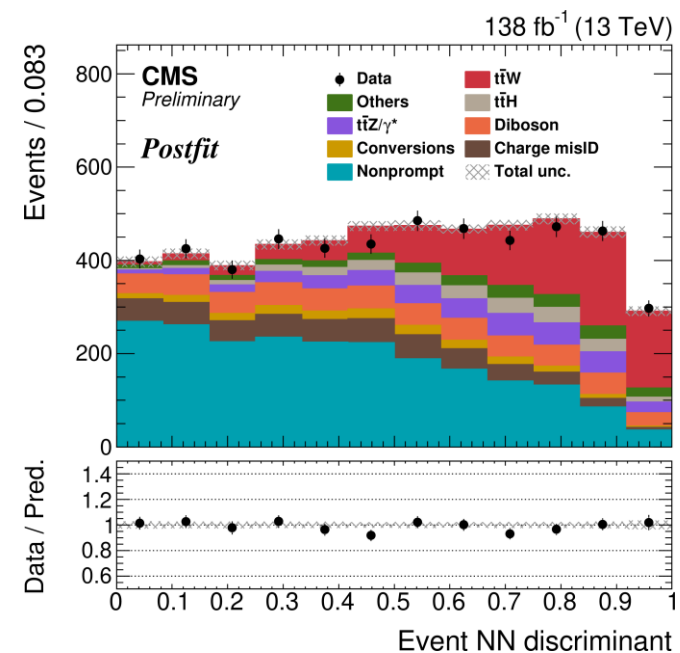
γ can radiate from top or its decays.



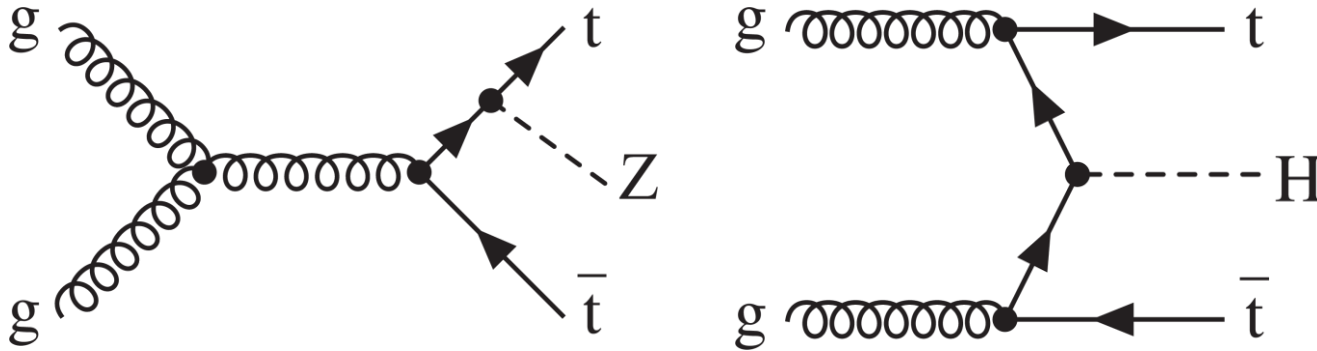
- $t\bar{t}\gamma$ measured in dilepton channel.
- Fiducial xsec: $173.5 \pm 2.5(\text{stat}) \pm 6.3(\text{syst})$ fb, 153 ± 27 fb (theory w/ NLO k-factor)
 - Theory does not include γ contributions from top decays \rightarrow xsec underestimated
- Differential cross section for kinematic observables from leptons, jets & γ .
Complementarity to $t\bar{t}Z$; improved constraints on Wilson coefficients w/ comb.

$t\bar{t}+W$ Cross Section

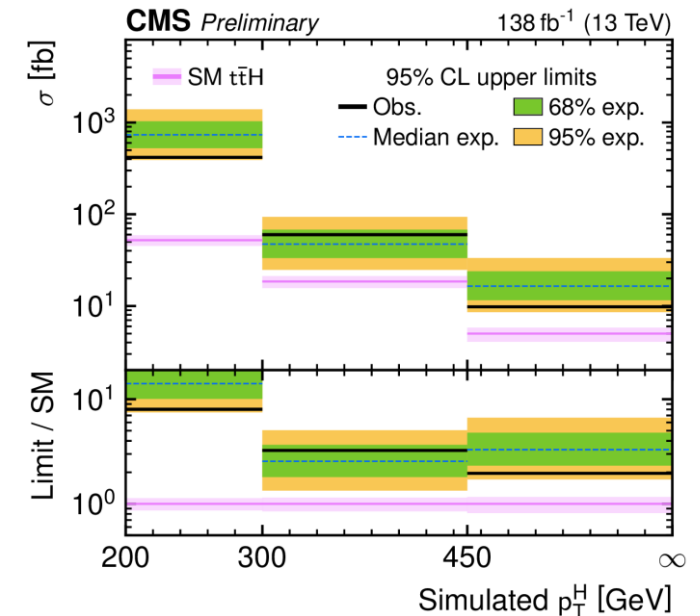
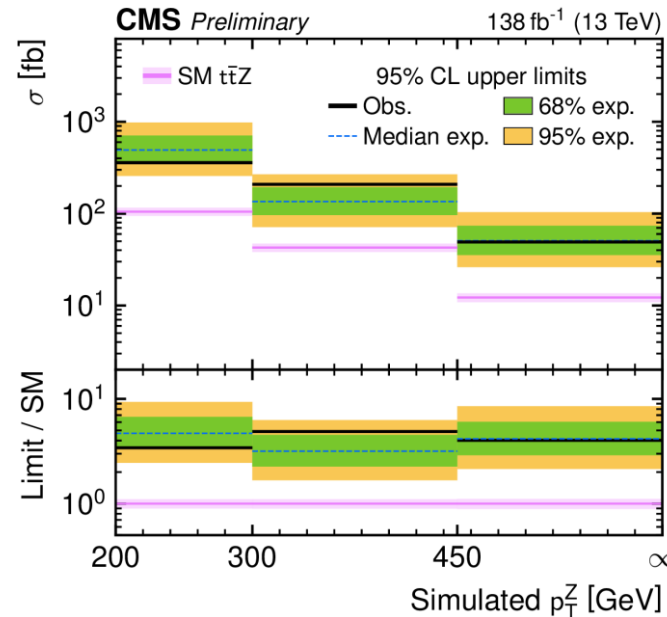
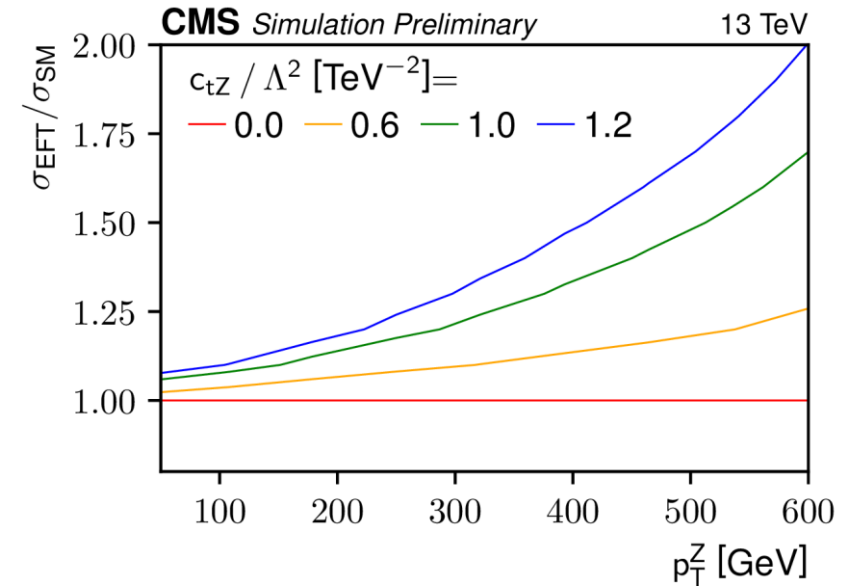
- Measurement w/ SS 2-lepton & 3-lepton events. Multi-classification NN used for SS 2-lepton & m_{3l} as discriminant for 3-lepton.
- Compared to prediction from NLO+NNLL & NLO w/ improved FxFx ME merging.
- Leading systematics: $t\bar{t}H$ norm (2.6%), lumi (1.9%), $t\bar{t}W$ scale (1.8%)
- **Xsec visibly larger than NLO+NNLL prediction.**
- **$R_{t\bar{t}W+/t\bar{t}W-}$ lower than SM by 2σ .**



EFT w/ $t\bar{t}$ +Boosted Z/H



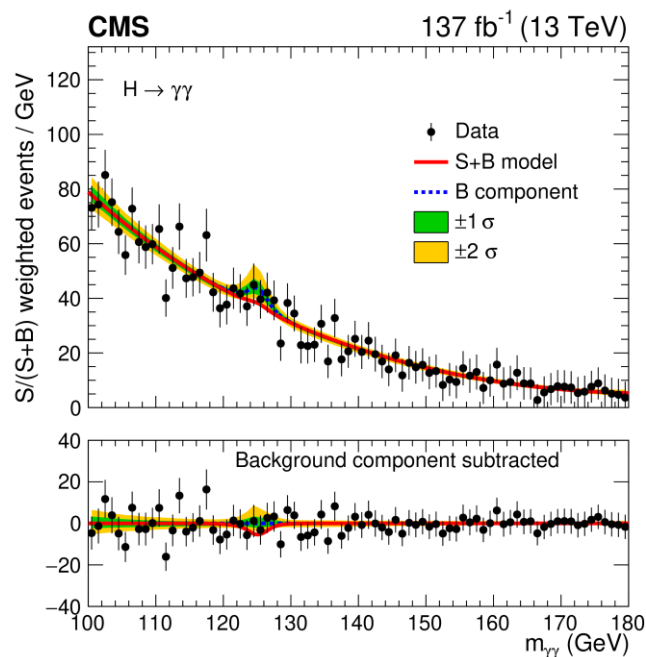
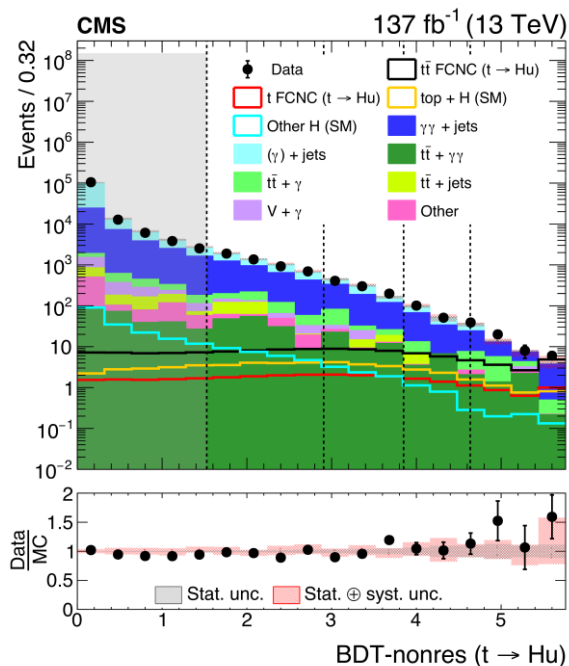
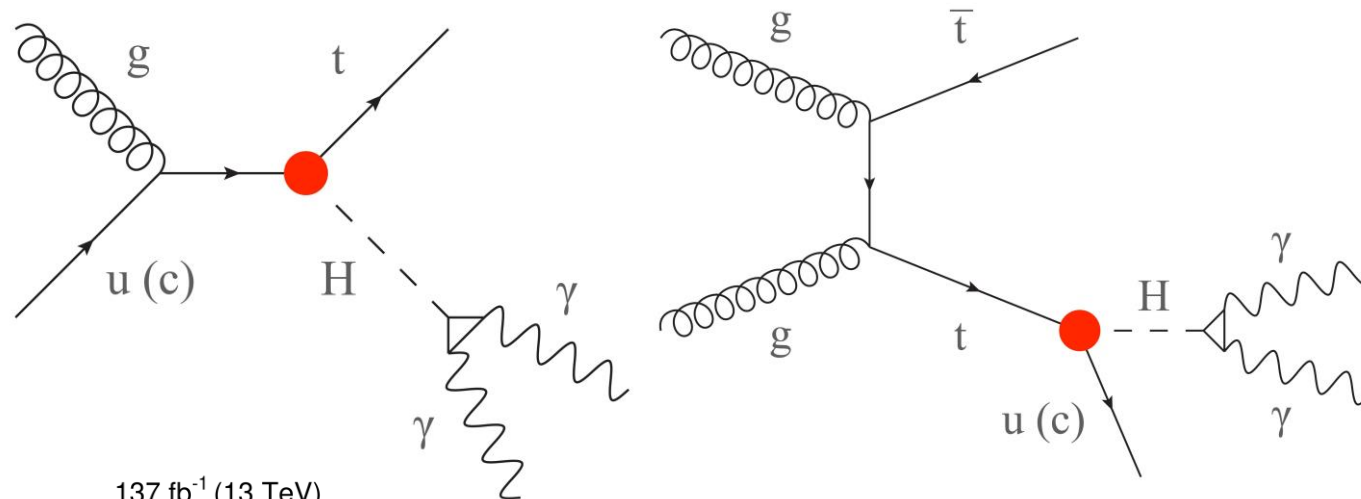
- Higher sensitivity to BSM in boosted Z/H p_T region.
- 1-lepton channel with boosted Z/H($\rightarrow b\bar{b}$) tagged w/ DNN (DeepAK8).
- $\mu_{t\bar{t}Z}^{\text{boost}} = 0.65^{+1.05}_{-0.98}$
- $\mu_{t\bar{t}H}^{\text{boost}} = -0.33^{+0.87}_{-0.85}$



Search for FCNC in $t\bar{t}$

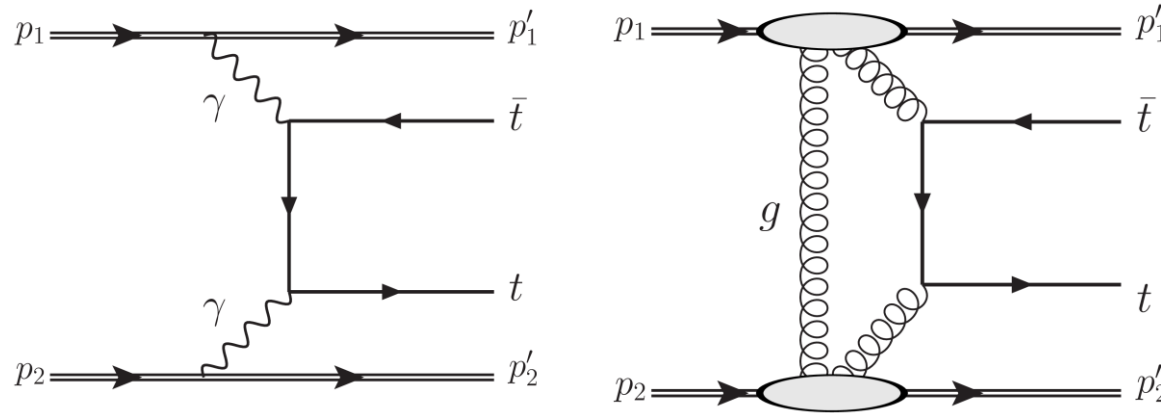
arXiv:2111.02219, submitted to PRL

- FCNC: forbidden at tree-level; highly suppressed at loop-level in SM ($\text{BR} < \mathcal{O}(10^{-12})$)
- 8 BDTs: 0/1-lepton; resonant/non-resonant; tHu/tHc couplings.



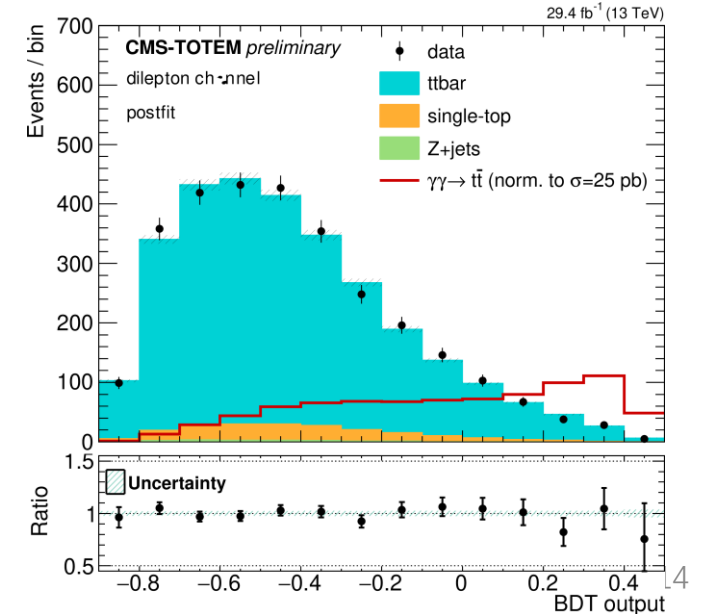
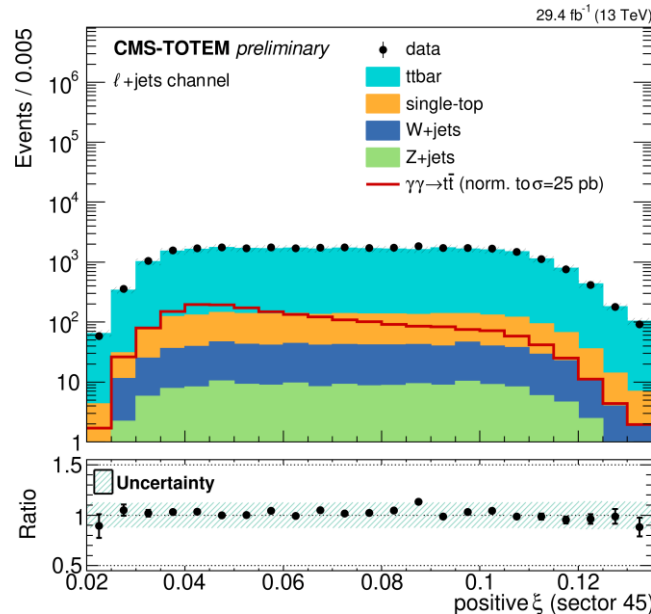
- 7 categories from BDT scores & simultaneous fit of $m_{\gamma\gamma}$ spectrum.
- $\text{BR}(t \rightarrow Hu) < 0.019\% \text{ (0.031\%)}$, $\text{BR}(t \rightarrow Hc) < 0.073\% \text{ (0.051\%)}$ obs (exp) @95%CL
- Currently most stringent limit.**

First Search for Central Exclusive $t\bar{t}$



- Search for central exclusive $t\bar{t}$ production in 1 & 2-lepton channels.
 - **Predicted xsec $\sim \mathcal{O}(0.1 \text{ fb})$.**
BSM can enhance xsec
 - **Presence of 1 or 2 protons remain intact. Tagged by Roman Pots.**

- Fractional momentum loss of protons (ξ) provides key variables to select the signals.
- Cross section limit: $<0.59 \text{ pb}$ [obs], 1.14 pb [exp] at 95%CL.
 - Statistical unc. still dominates.



Summary

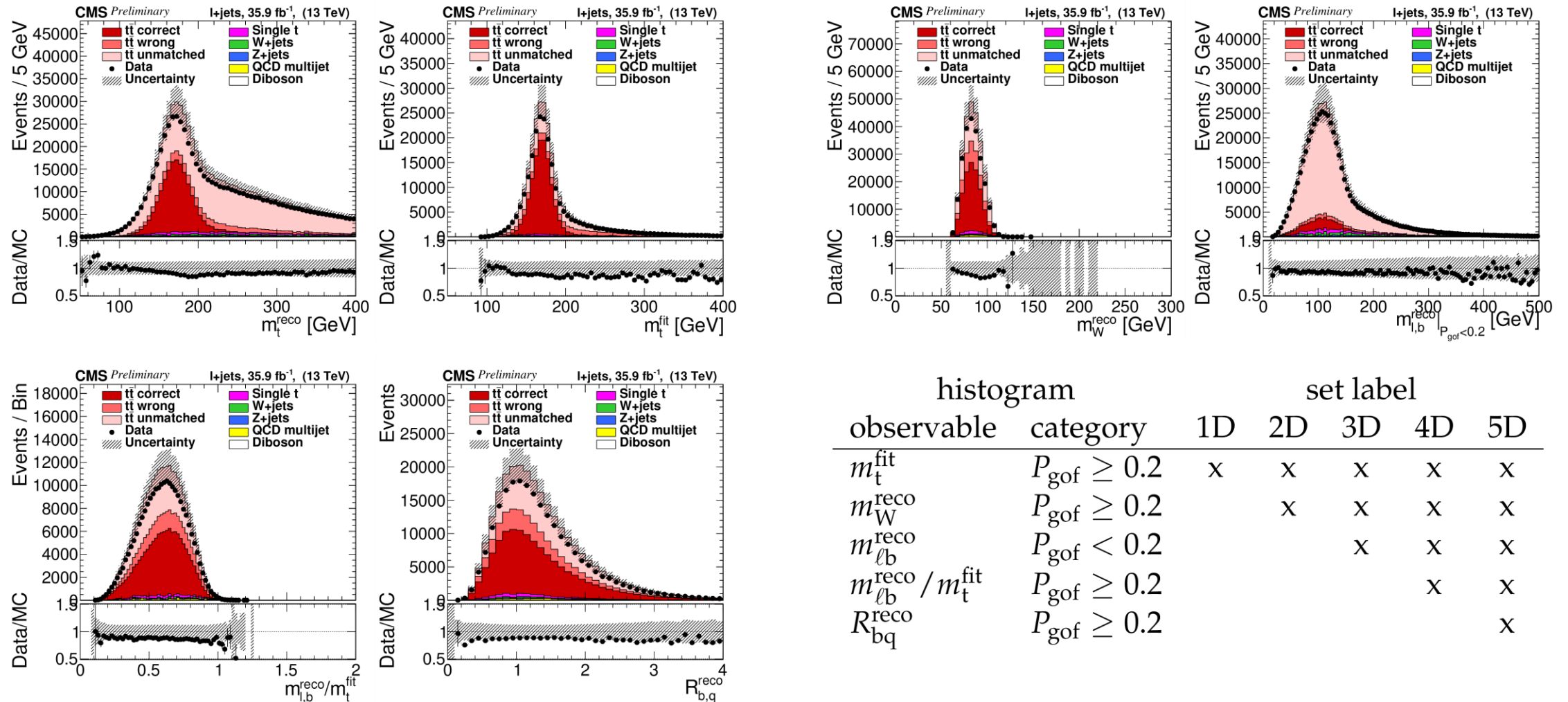
- **Many new results in CMS with Full Run-2 dataset and/or with higher precision.**
 - Inclusive & differential cross section measurements for $t\bar{t}$ production.
 - Top-quark mass precision continues to improve.
 - Starting to have differential cross section measurements in rare productions as well.
 - $t\bar{t}W$ production visibly larger than NLO+NNLL.
 - Searching for BSM with EFT and in direct searches for FCNC processes.
 - First search for central exclusive production of top pairs.
- More analyses are under way. Stay tuned!

CMS Public Results: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP>



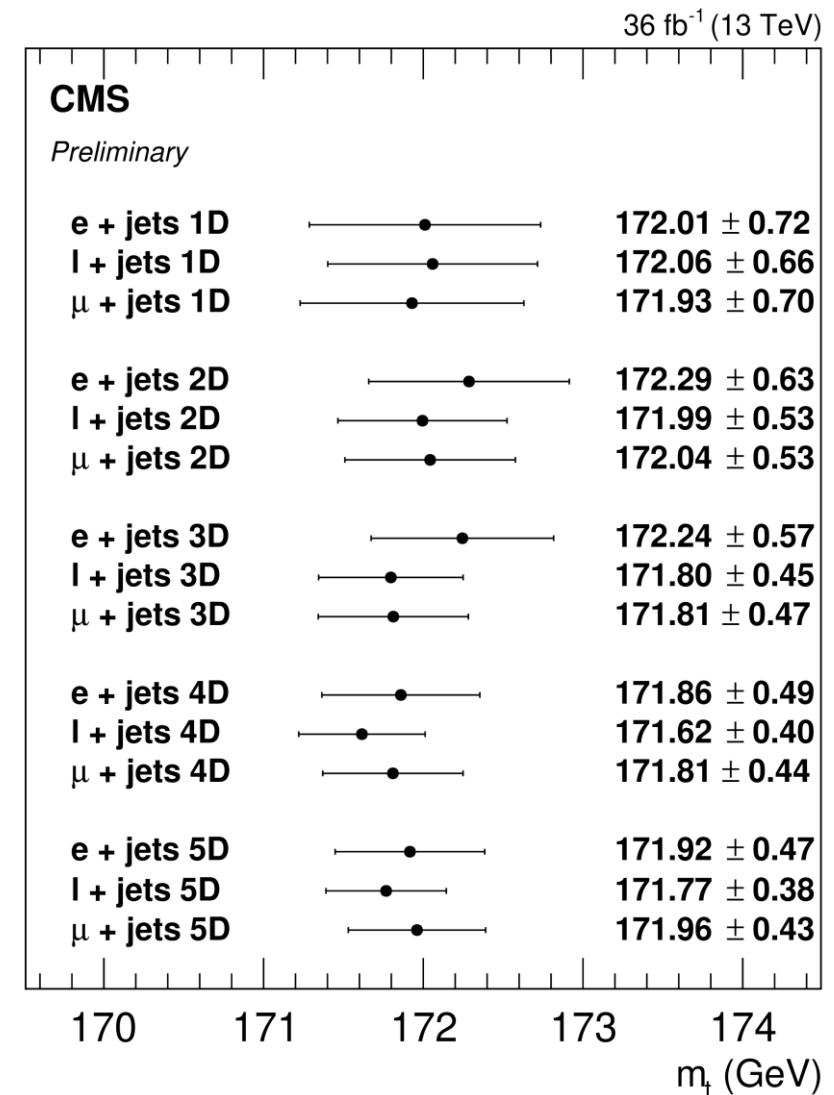
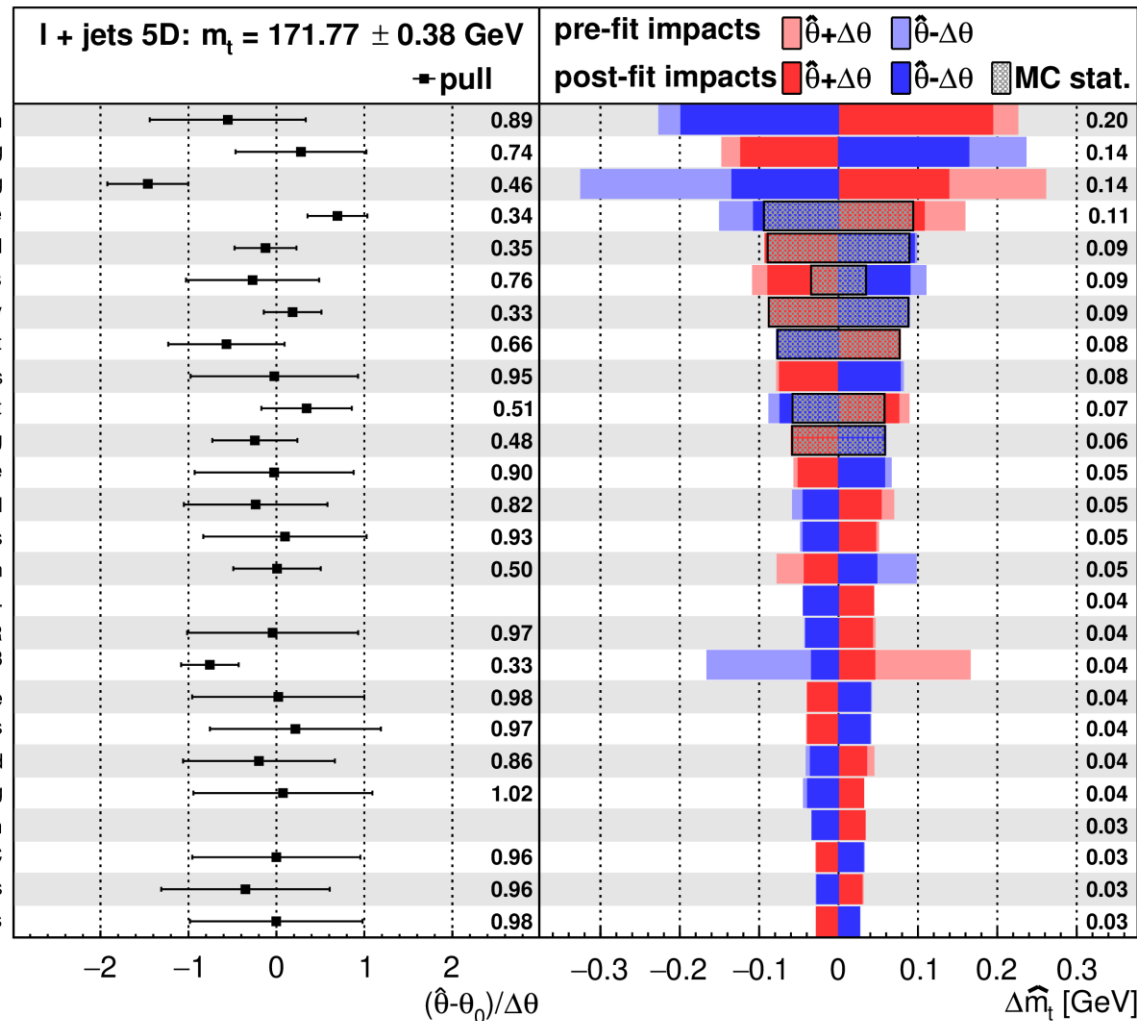
Backup

Top Mass (Direct Measurement)

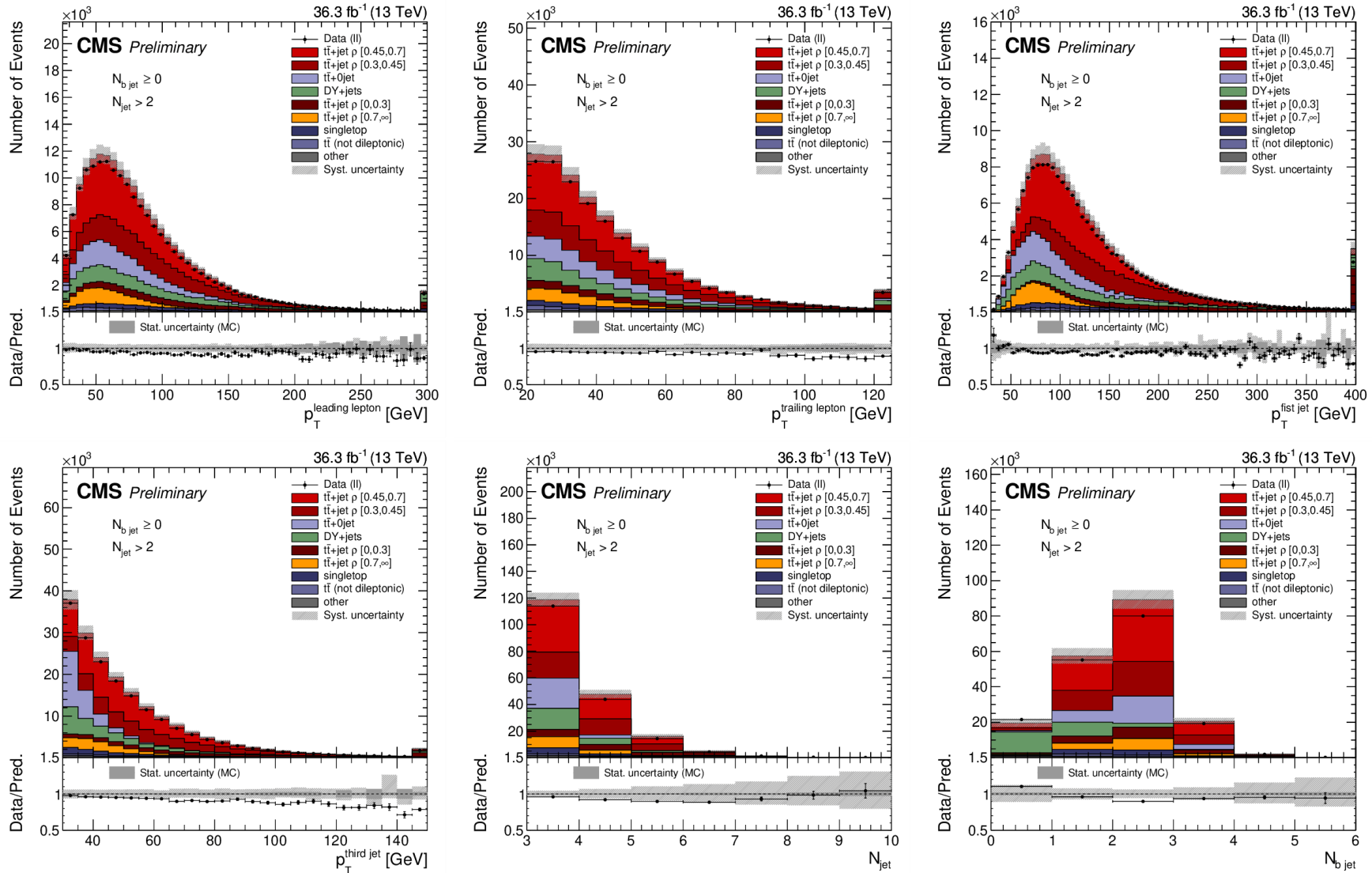


Top Mass (Direct Measurement)

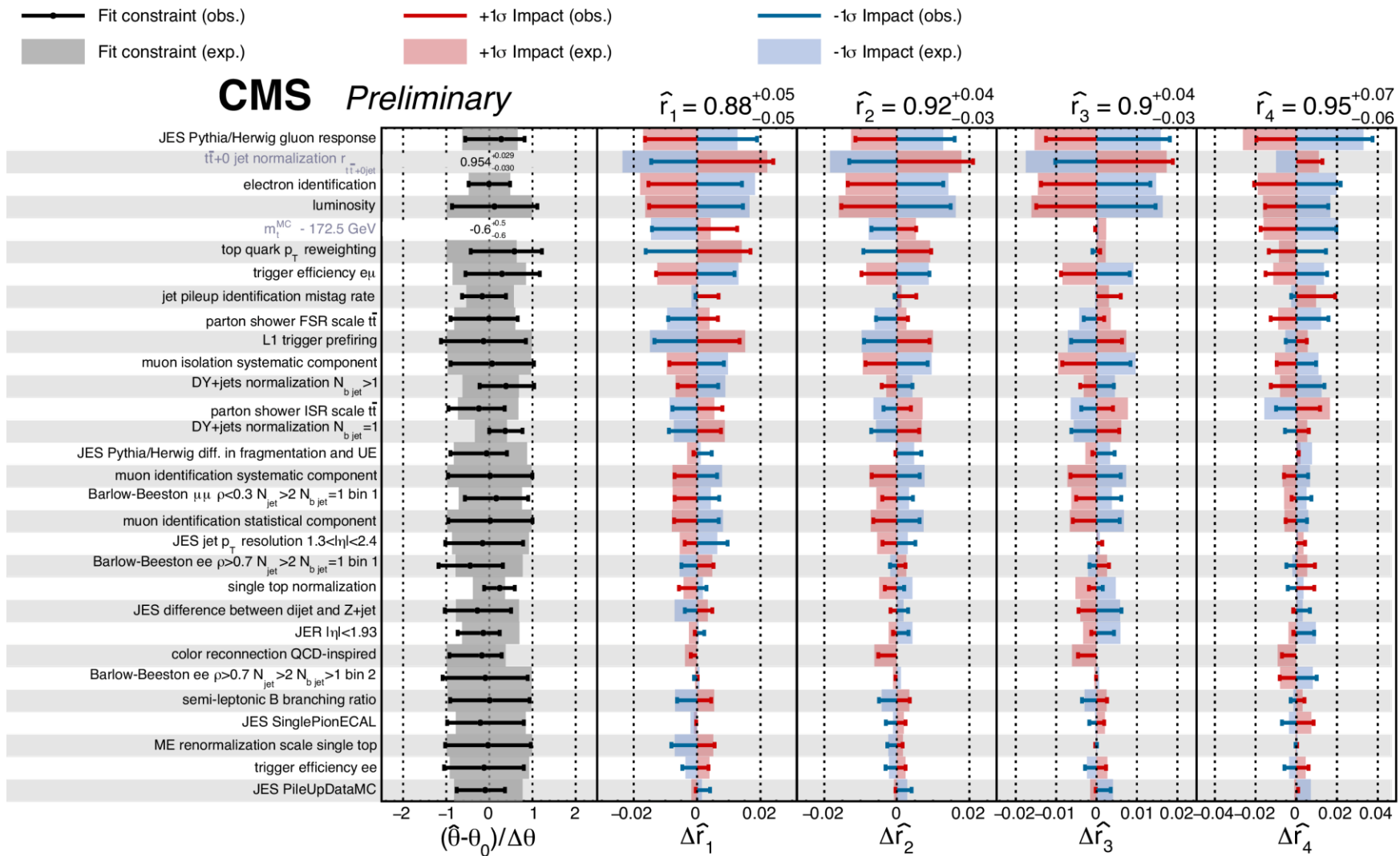
CMS Preliminary

36 fb⁻¹ (13 TeV)

Top Mass (Pole Mass) from $t\bar{t}$ +jets



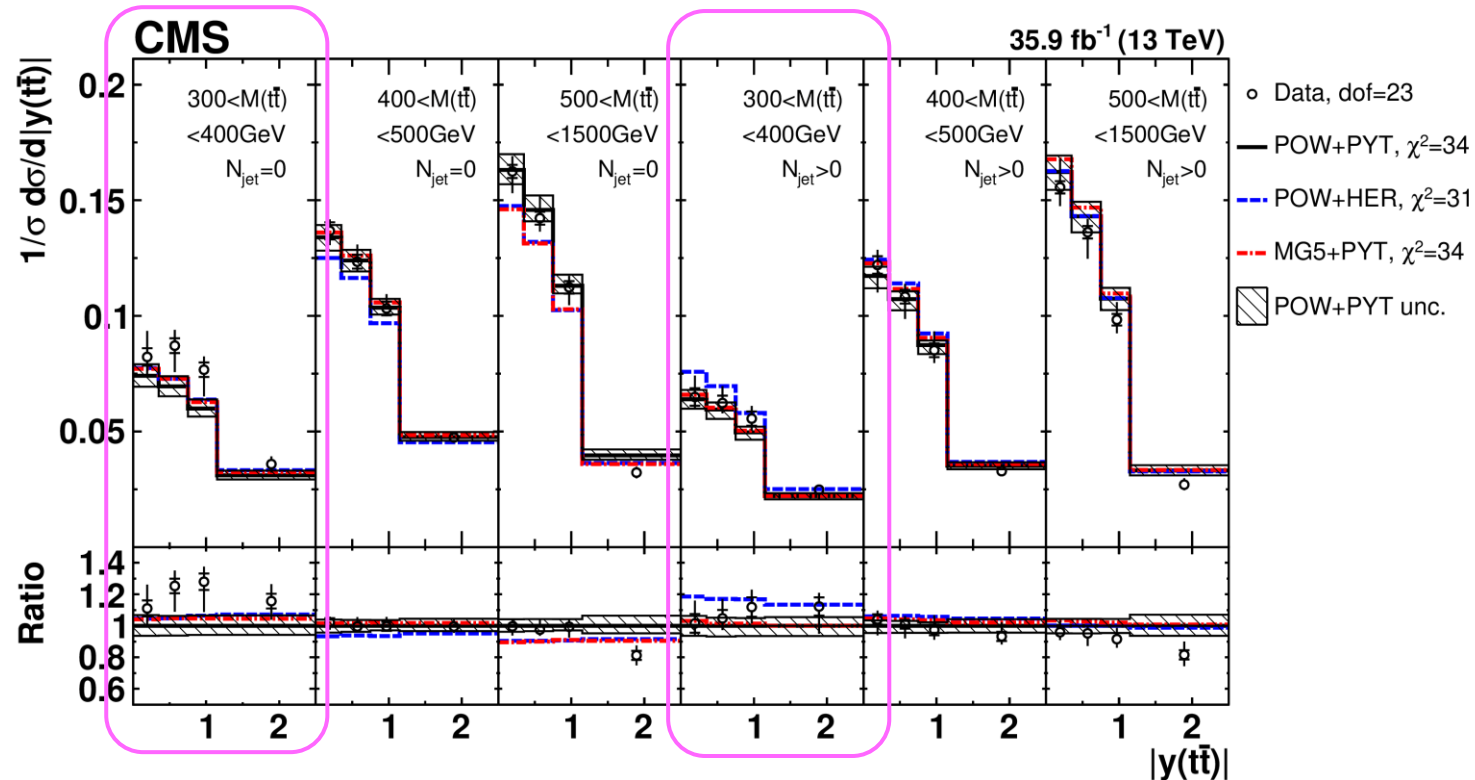
Top Mass (Pole Mass) from $t\bar{t}$ +jets



Top Mass (Pole Mass)

Eur. Phys. J. C 80 (2020) 658

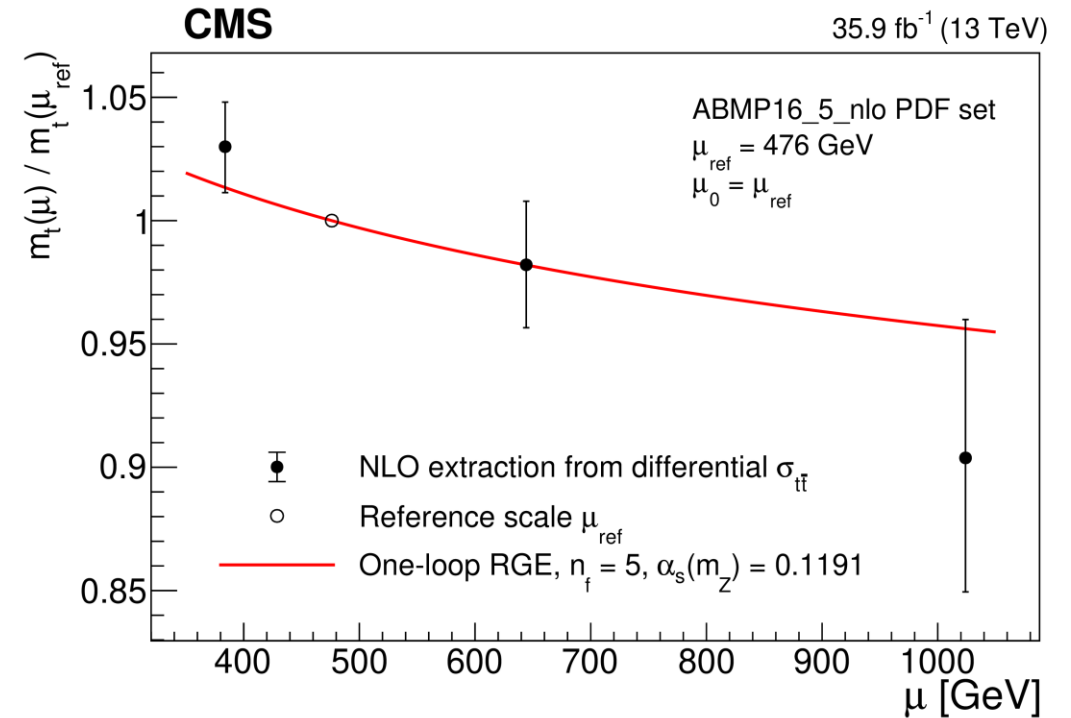
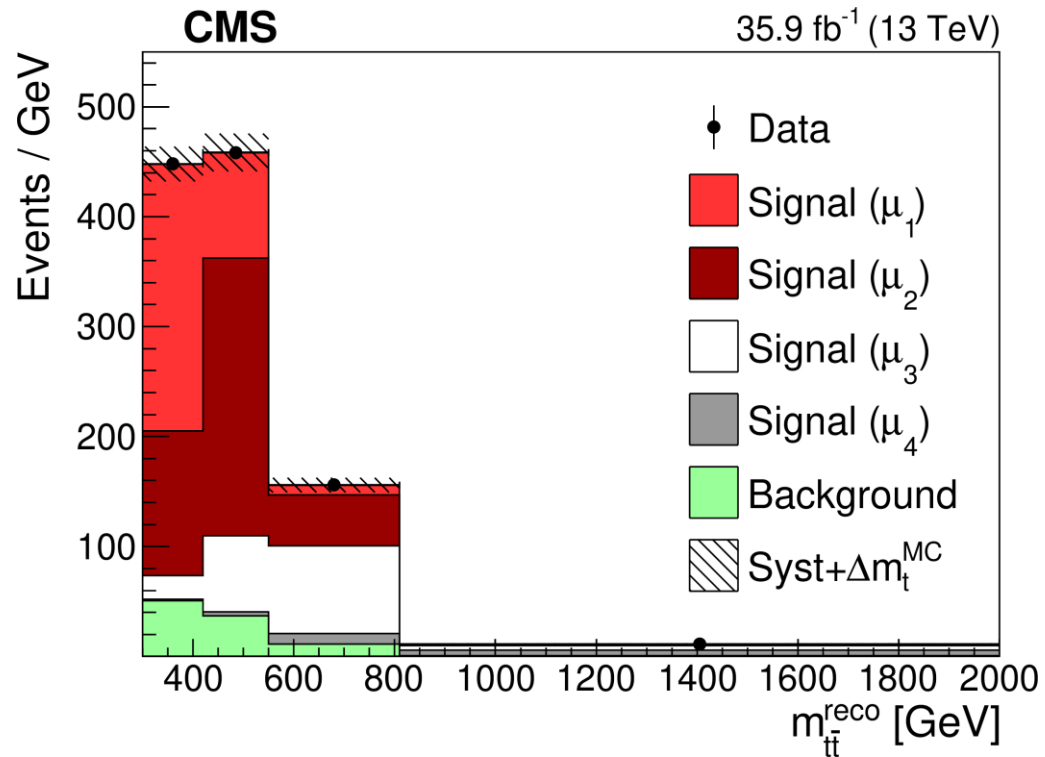
- Pole mass: mass defined in parton-level scattering amplitudes. Self-energy corrections are absorbed in this mass.
- Extracted from total or differential cross sections.



- Triple differential measurements on N_{jet} , M_{tt} , y_{tt} in dilepton channel.
- Simultaneous fit on PDF, α_s & m_t at NLO.
- Most precise measurement of top pole mass: $m_t = 170.5 \pm 0.8$ GeV
- However, higher-order effects near the threshold can give as large as 1.4 GeV effect (W.-L. Ju et al., JHEP06(2020)158).

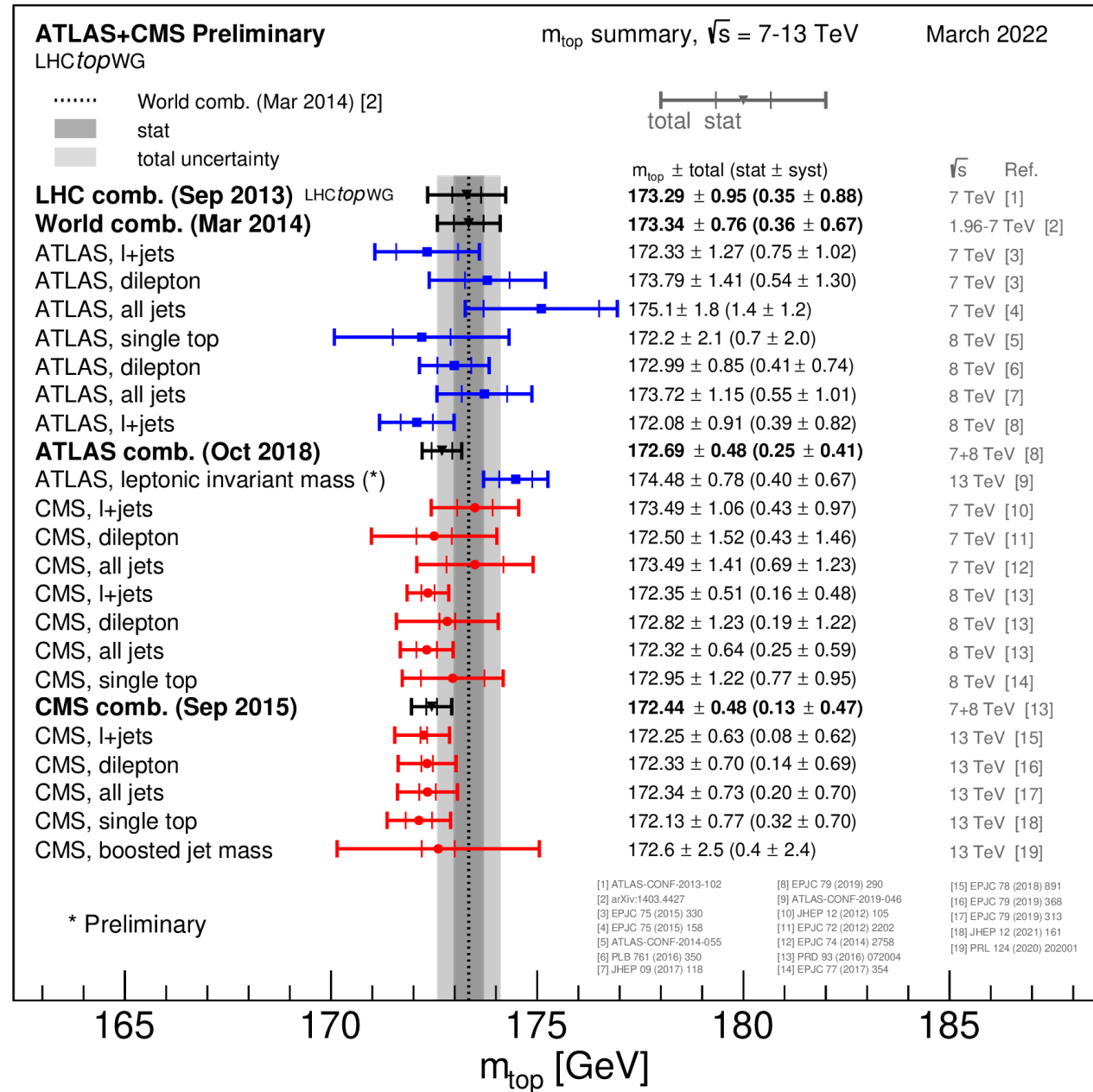
Running of Top Mass

Phys. Lett. B 803 (2020) 135263



- First investigation on “running” of m_t in \overline{MS} scheme.
- $m_t(\mu)$ is extracted from the $m_{t\bar{t}}$ distribution in the dilepton channel.

Top Mass (MC Mass)



Top Pole Mass

