# Advanced measurement of four-top-quark production and search for new physics in ATLAS

CEA/SJTU project

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17th workshop of the FCPPN/L
1 July 2026

# The top quark

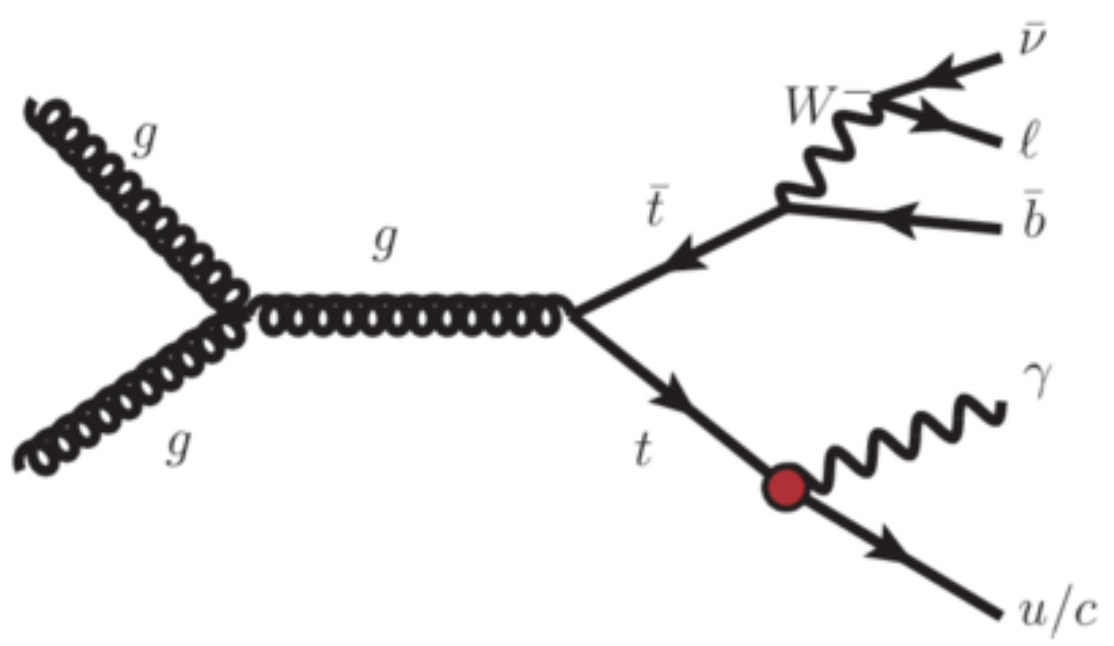
- The heaviest elementary particle
  - Coupling to the Higgs boson close to 1: special role in the electroweak symmetry breaking ?
  - Decay before hadronizing: unique opportunity to observe a bare quark
  - Window to physics beyond the Standard Model

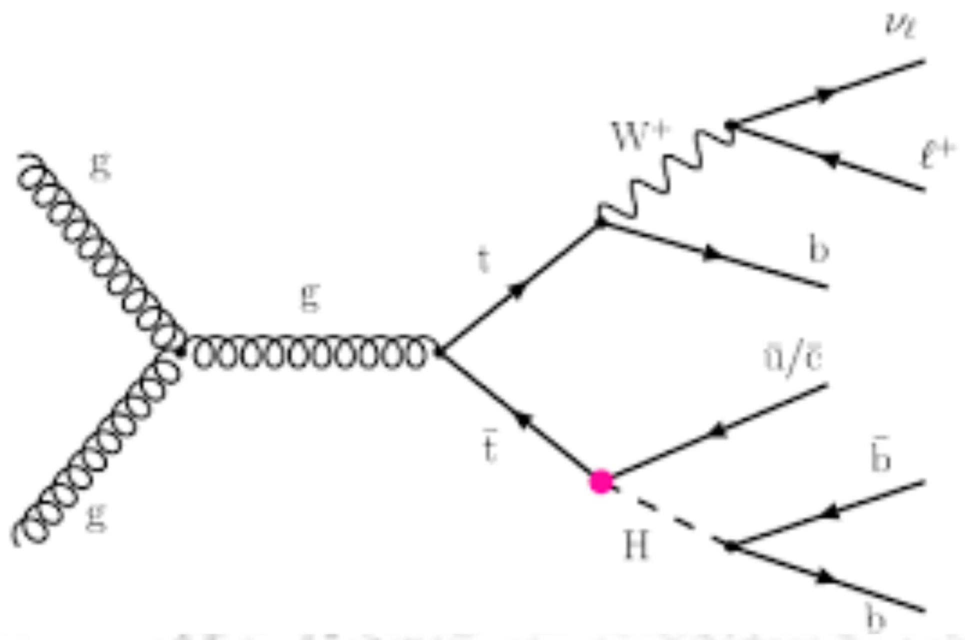
$$\mathcal{L}_{\text{Yukawa}} = -\lambda_t \overline{\psi_{Lt}} \Phi \psi_{Rt}$$

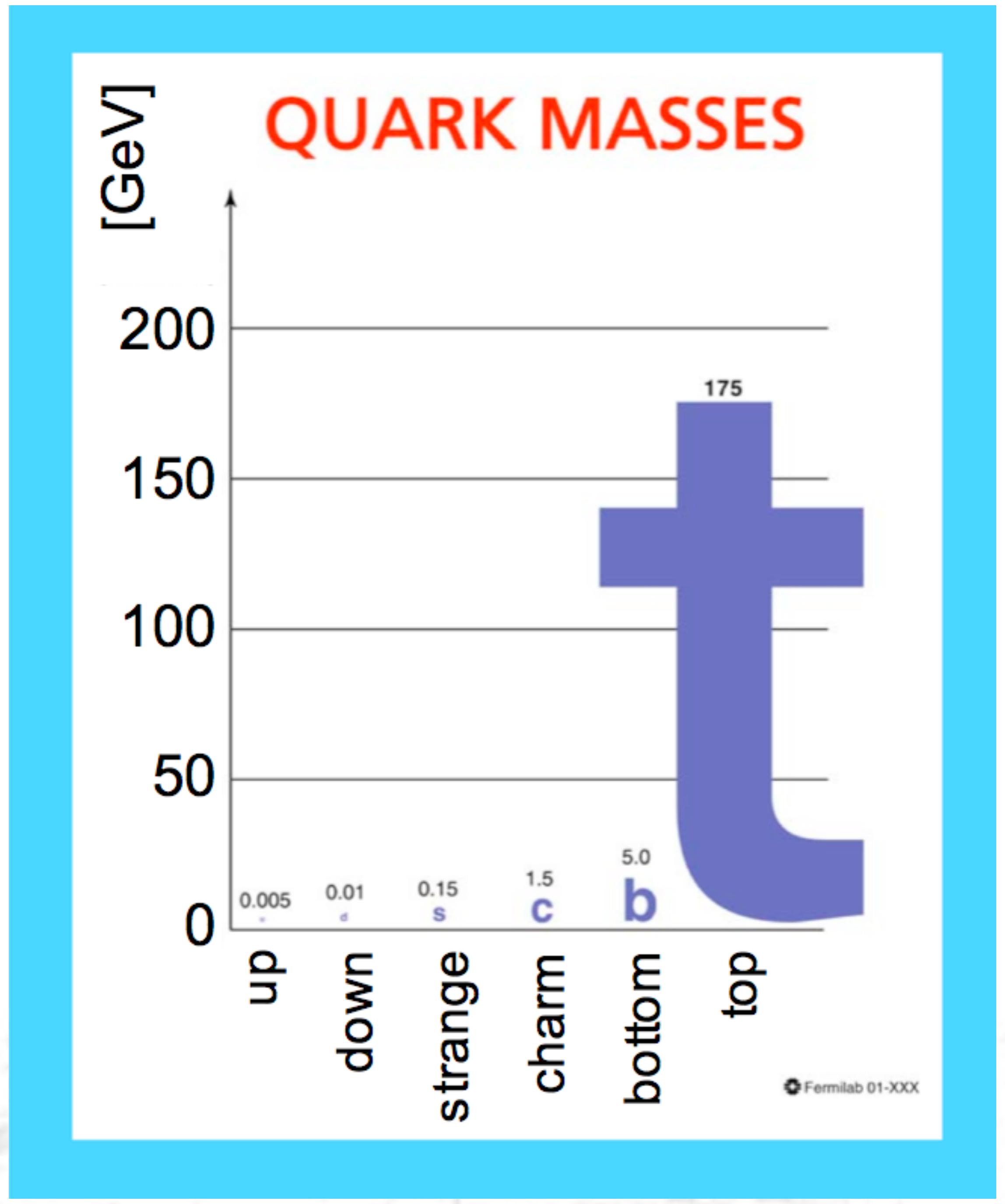
$$\lambda_t \approx 1$$

$$m_t >> m_b$$

$$\tau \approx 5.10^{-25}\text{s} << \Lambda_{\text{QCD}}^{-1}$$



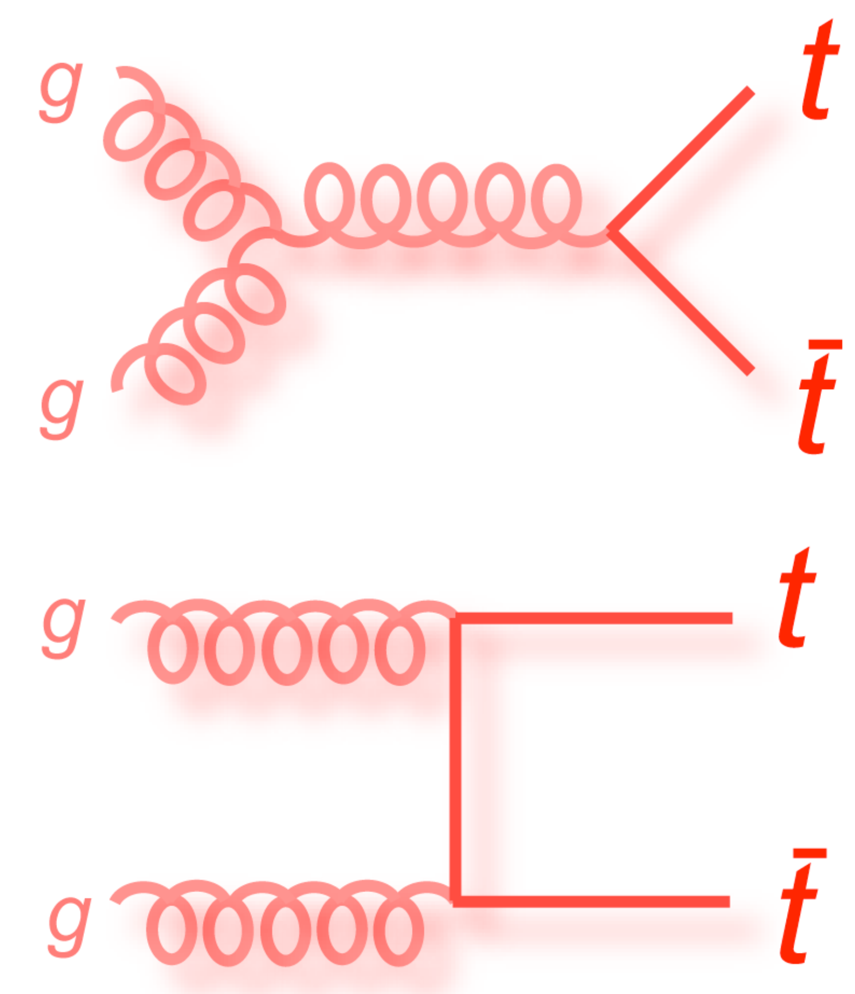



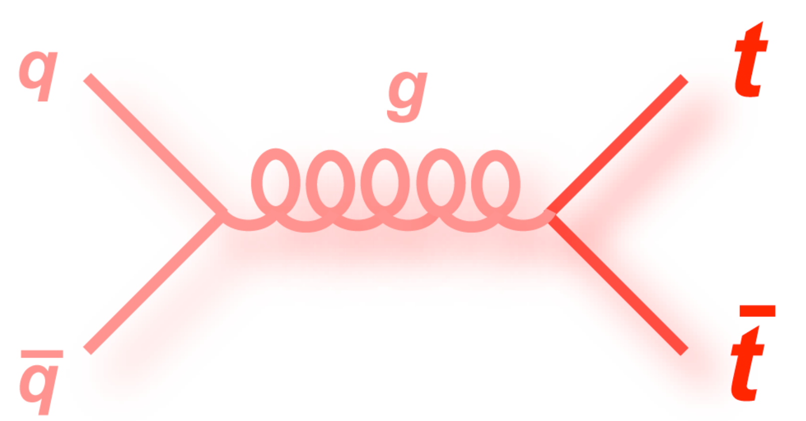
# Top-quark production and decay at the LHC

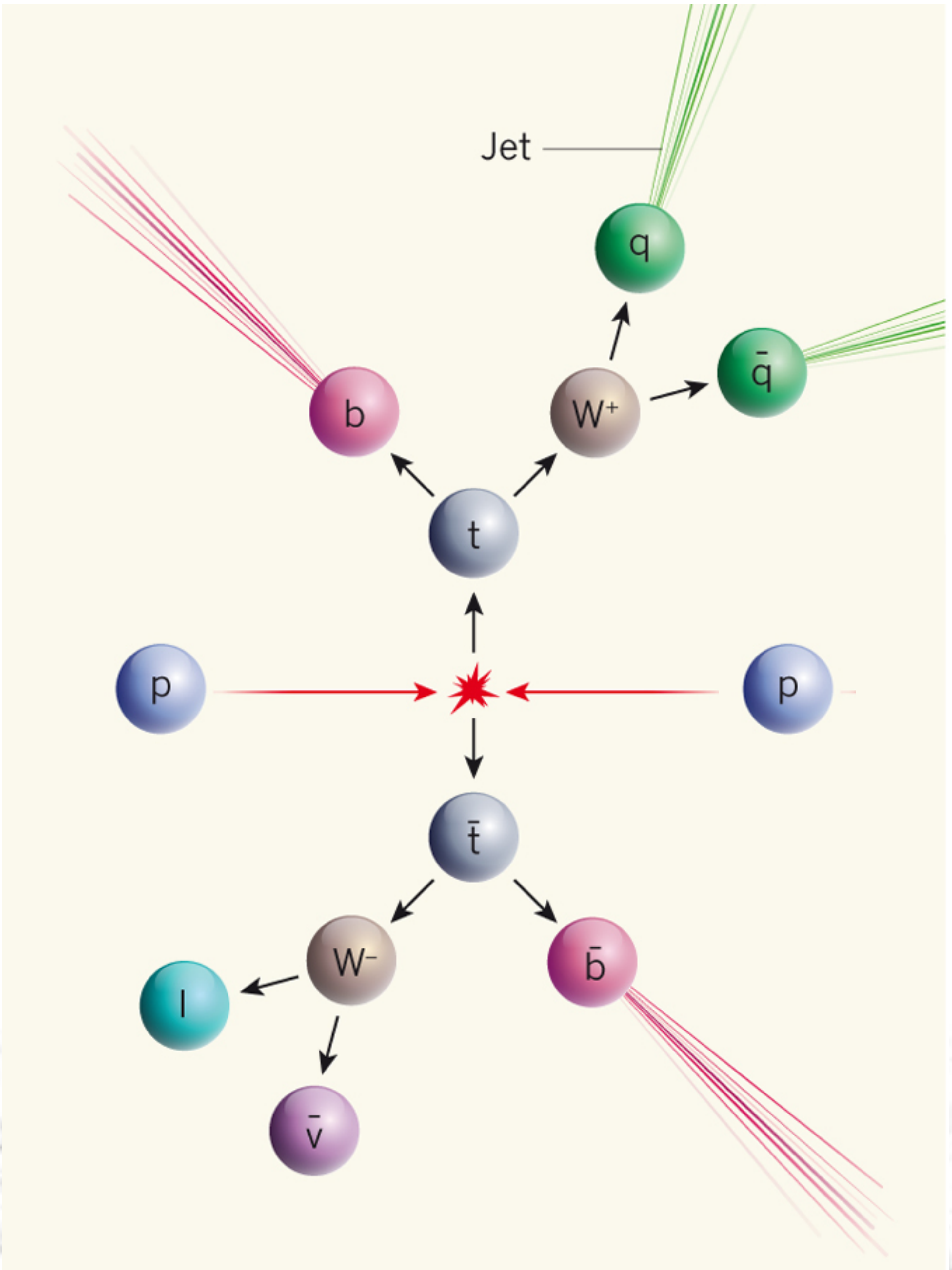
Strong production: $\sigma_{t\bar{t}} \sim 830$ pb (13 TeV)

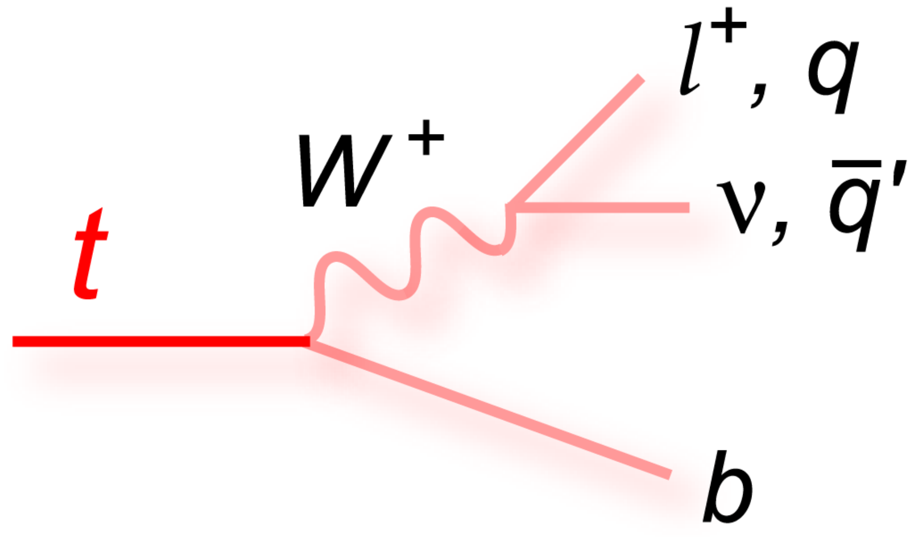
~ 90%




~ 10%



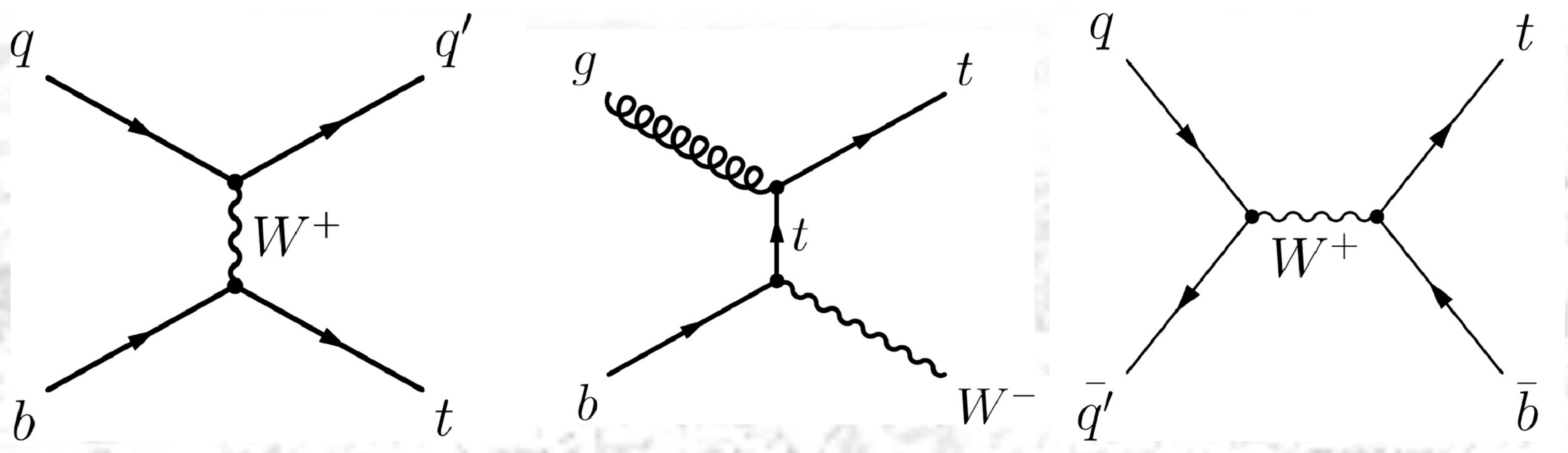



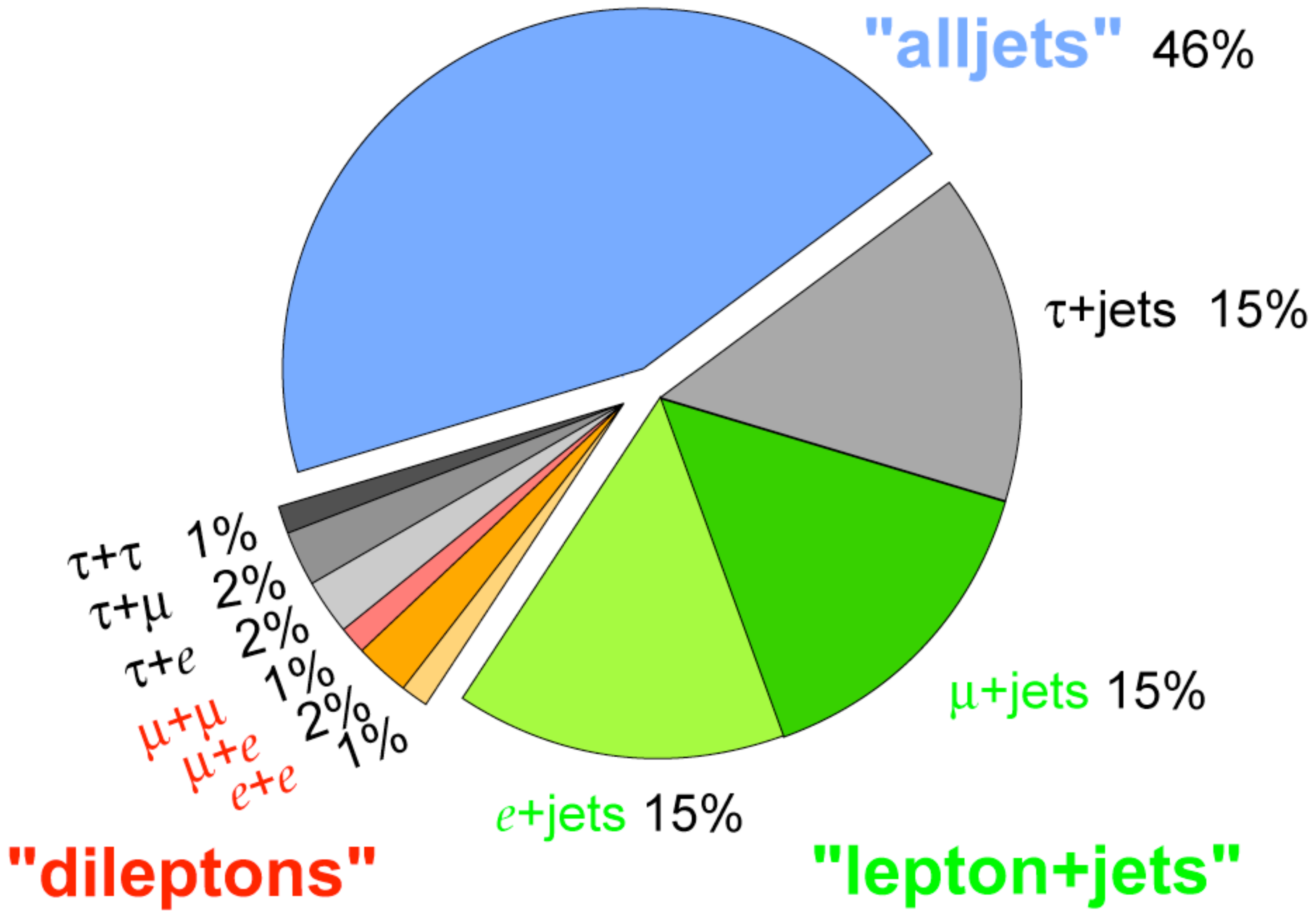




~ 100% in the Standard Model

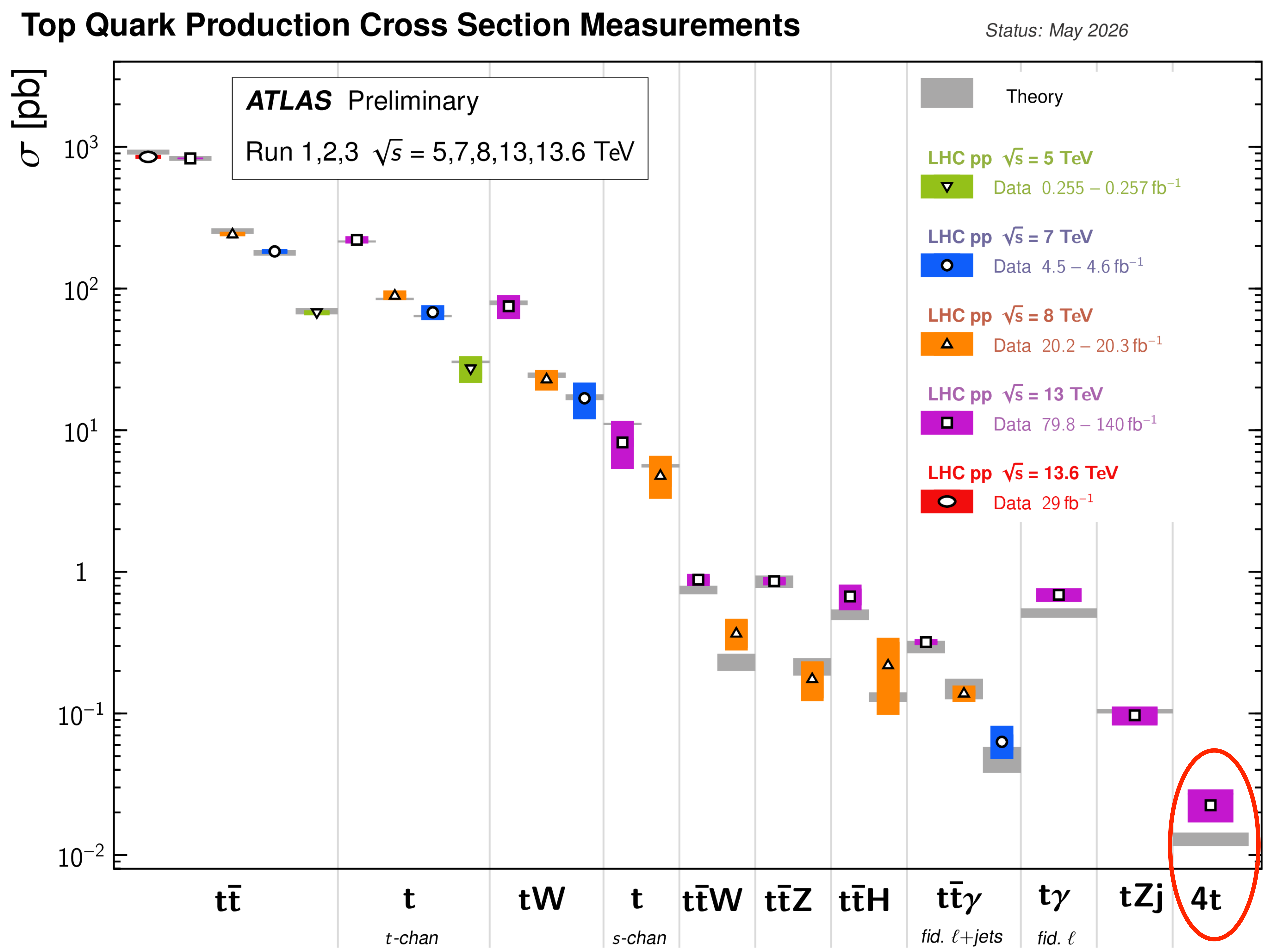
Electroweak production (13 TeV):

~ 217 pb ~ 72 pb ~ 10 pb



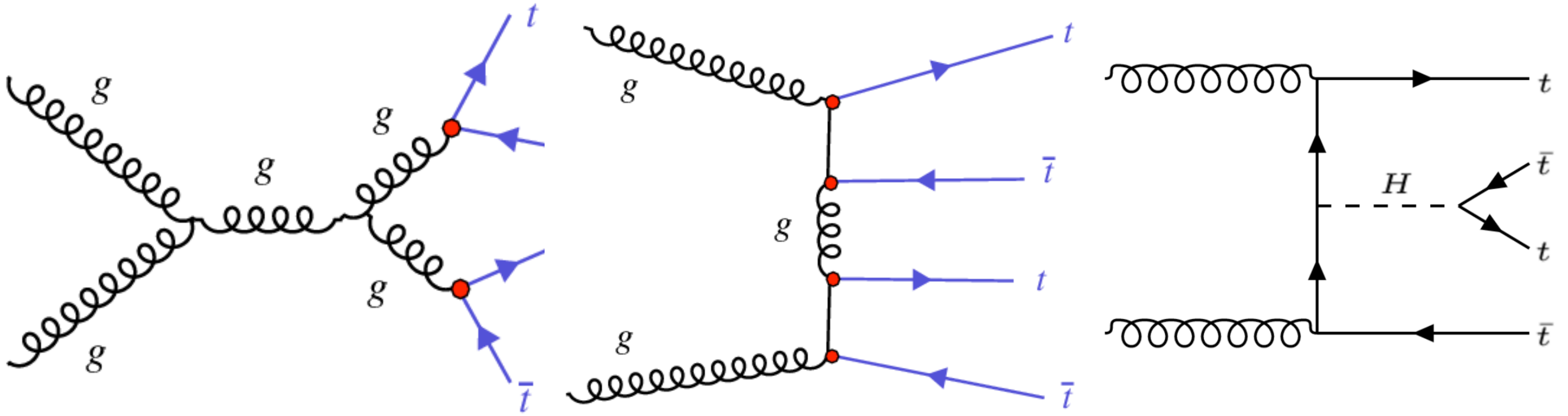



# Rare top-quark processes

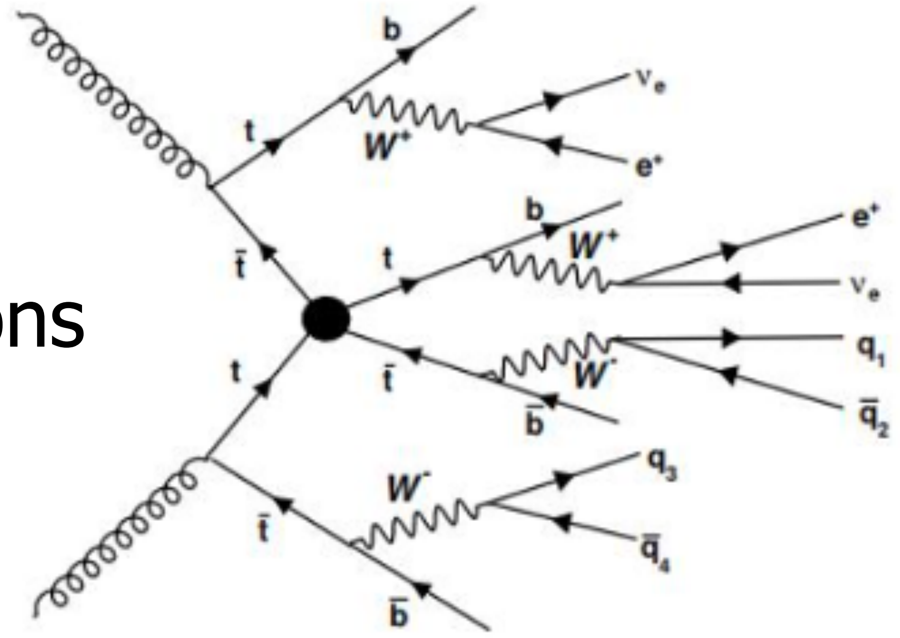


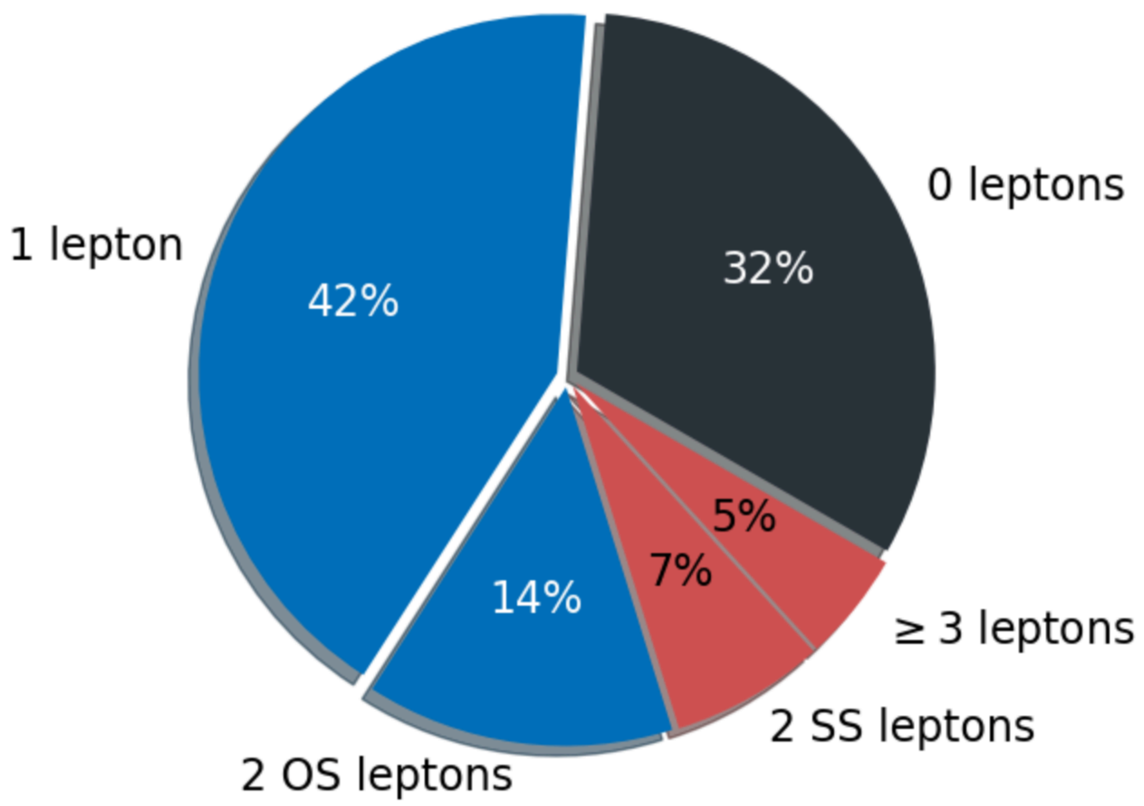
# Four top-quark production at the LHC

- One of the heaviest final states accessible at the LHC
  - NLO QCD: $\sigma(t\bar{t}t\bar{t})$ = 12 fb ±20% @ 13 TeV [JHEP 02 (2018) 031]
  - NLO+NLL: $\sigma(t\bar{t}t\bar{t})$ = 13.4 fb ±11% @ 13 TeV [PRL131 (2023) 211901]
  - Increased by ~ 20% @ 13.6 TeV
- Naturally sensitive to many BSM models
  - top Higgs Yukawa coupling and its CP properties
  - Effective Field Theory (EFT) four heavy fermion operators

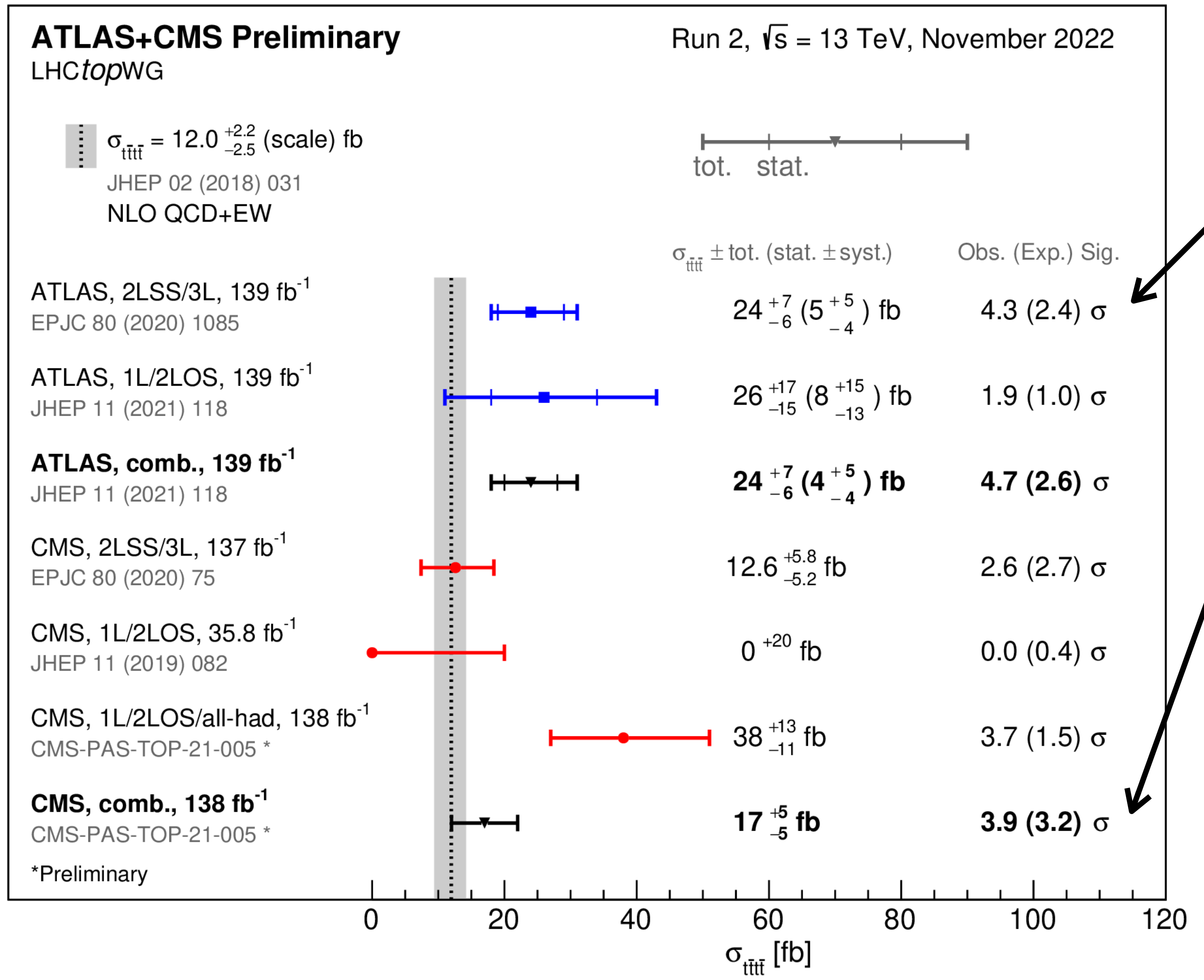



- Final states: high jets and b-jets multiplicity
  - Analysis strategy depends on the number of leptons from the top decays




Summary of $t\bar{t}t\bar{t}$ results until winter 23

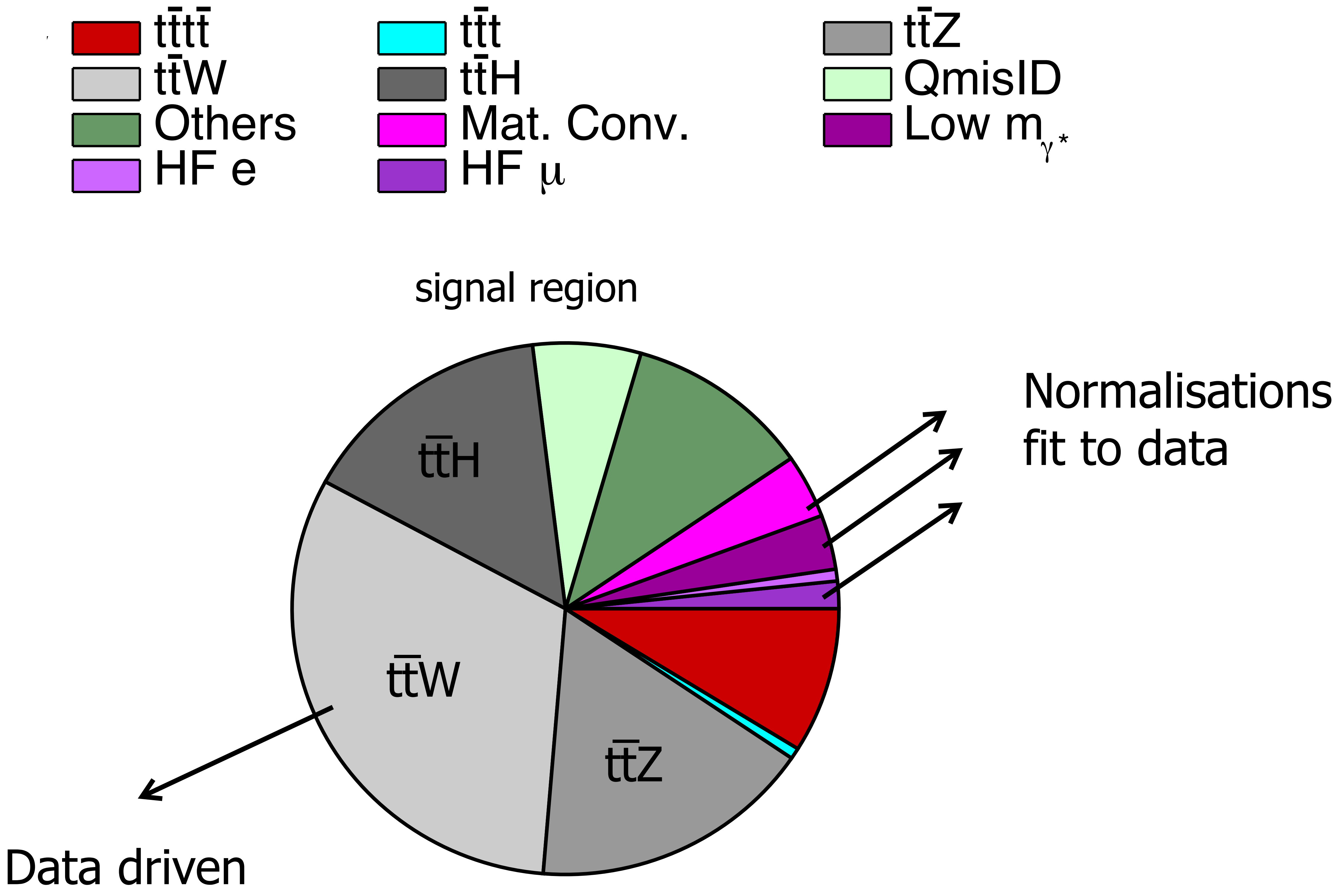



evidence

# Analysis Strategy

- Multilepton final state, signal region:
  - 2 isolated same-sign leptons or 3 leptons
  - $\geq$ 6 jets $\geq$ 2 b-jets
  - HT = $\Sigma$pT(lepton) + $\Sigma$pT(jets) $\geq$ 500 GeV

- Main backgrounds:
  - Physical background (~85%):
    - $t\bar{t}Z$ + jets, $t\bar{t}H$ + jets, $t\bar{t}W$+jets
  - Instrumental background (~15%):
    - Process with electron charge mis-identified
    - Events with non prompt or fake leptons




$t\bar{t}W$ is the main background
Key process to estimate

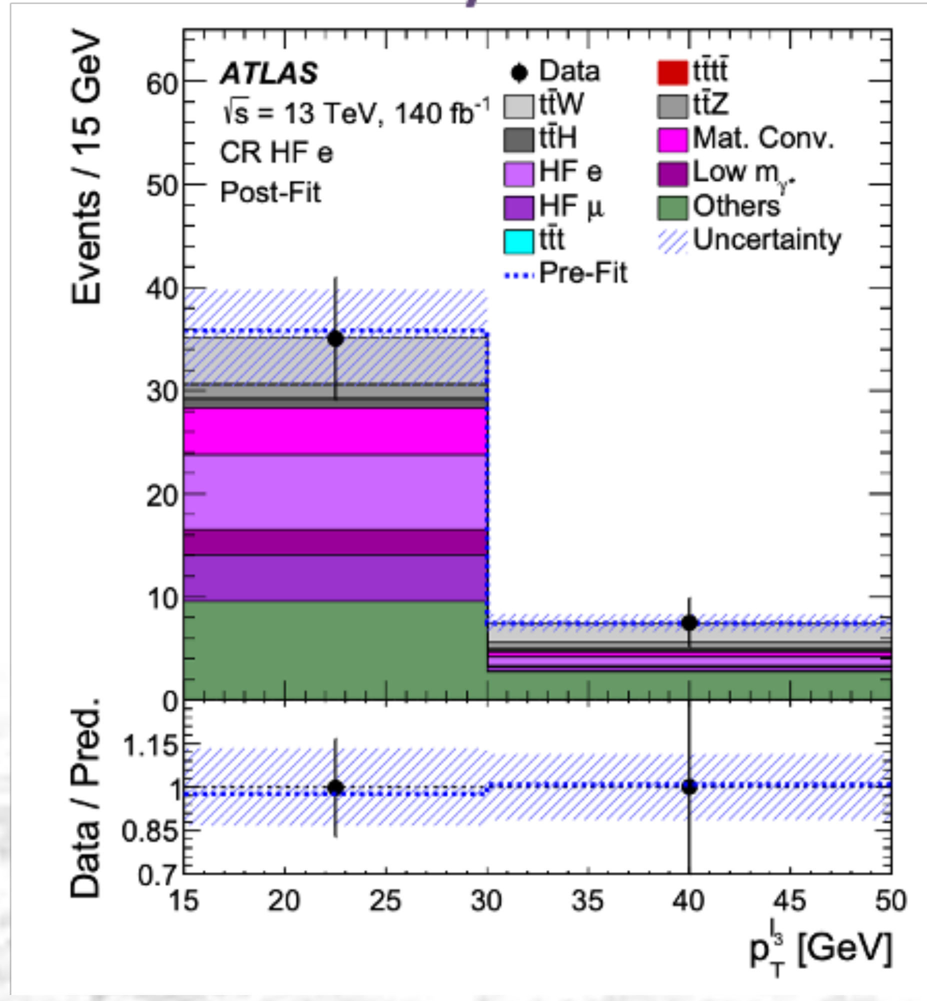
# Fake, non-prompt lepton background estimation

- Fake lepton or non-prompt lepton background :
  - Difficult to accurately simulate using MC

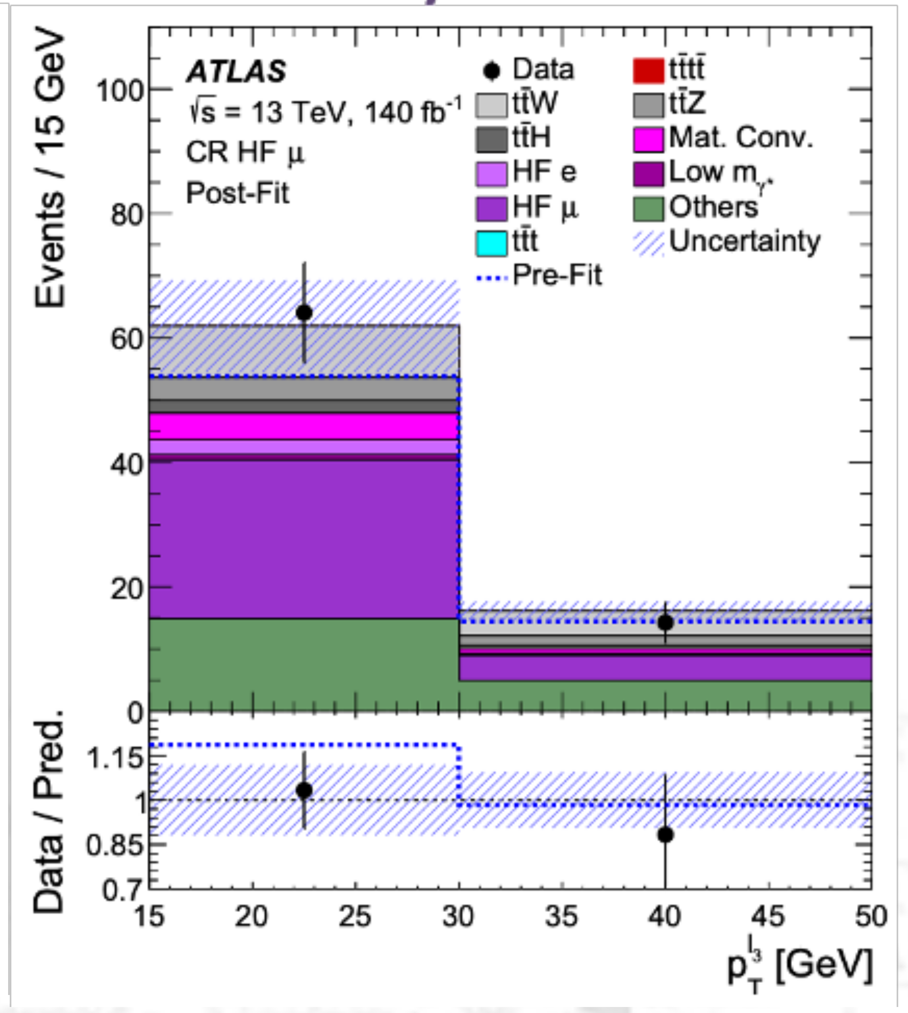
| $NF_{\text{Mat. Conv.}}$ | $NF_{\text{Low } m_{\gamma^*}}$ | $NF_{\text{HF } e}$ | $NF_{\text{HF } \mu}$ |
|---|---|---|---|
| $1.80^{+0.47}_{-0.41}$ | $1.08^{+0.37}_{-0.31}$ | $0.66^{+0.75}_{-0.46}$ | $1.27^{+0.53}_{-0.46}$ |

- Normalisations of these background fit to data:
  - Define control regions enhanced in these components
  - Normalisation adjusted together with the signal strength for :
    - Conversions in the material
    - Virtual photon conversions
    - Electrons from decays of heavy flavor jets
    - Muons from decays of heavy flavor jets

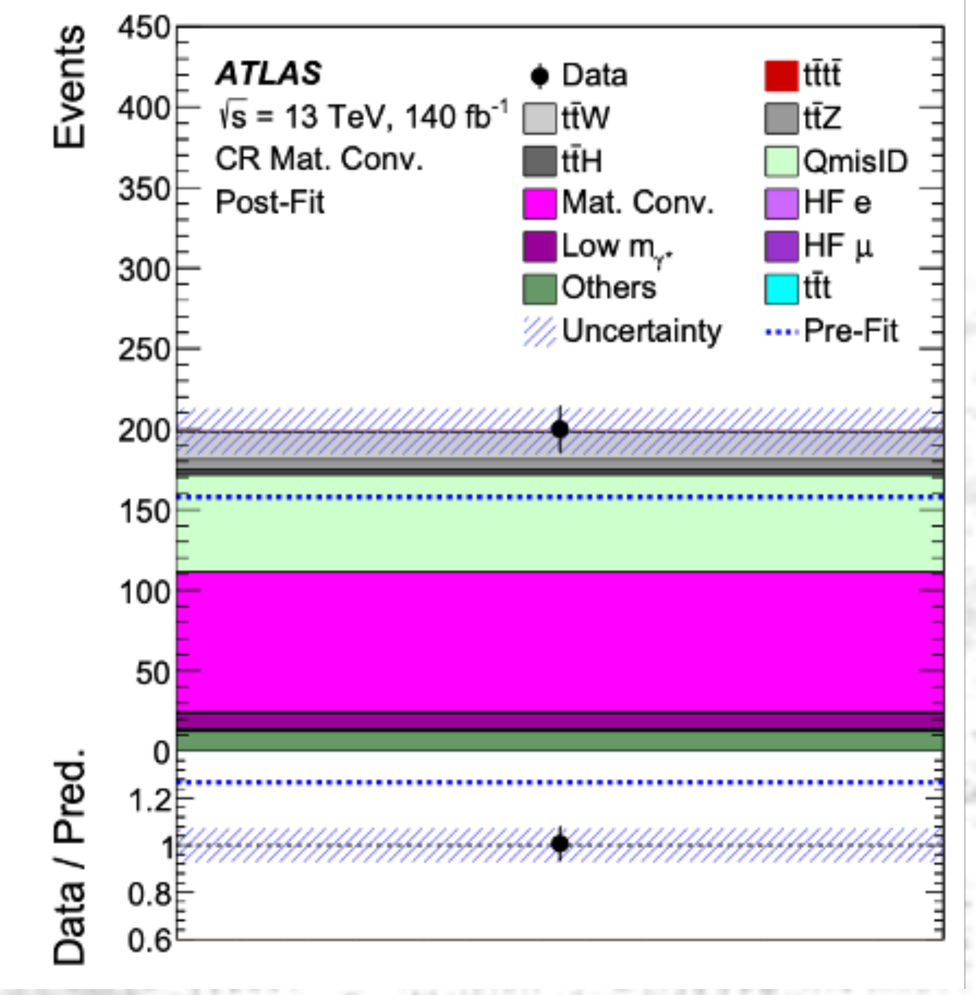
Heavy flavor e



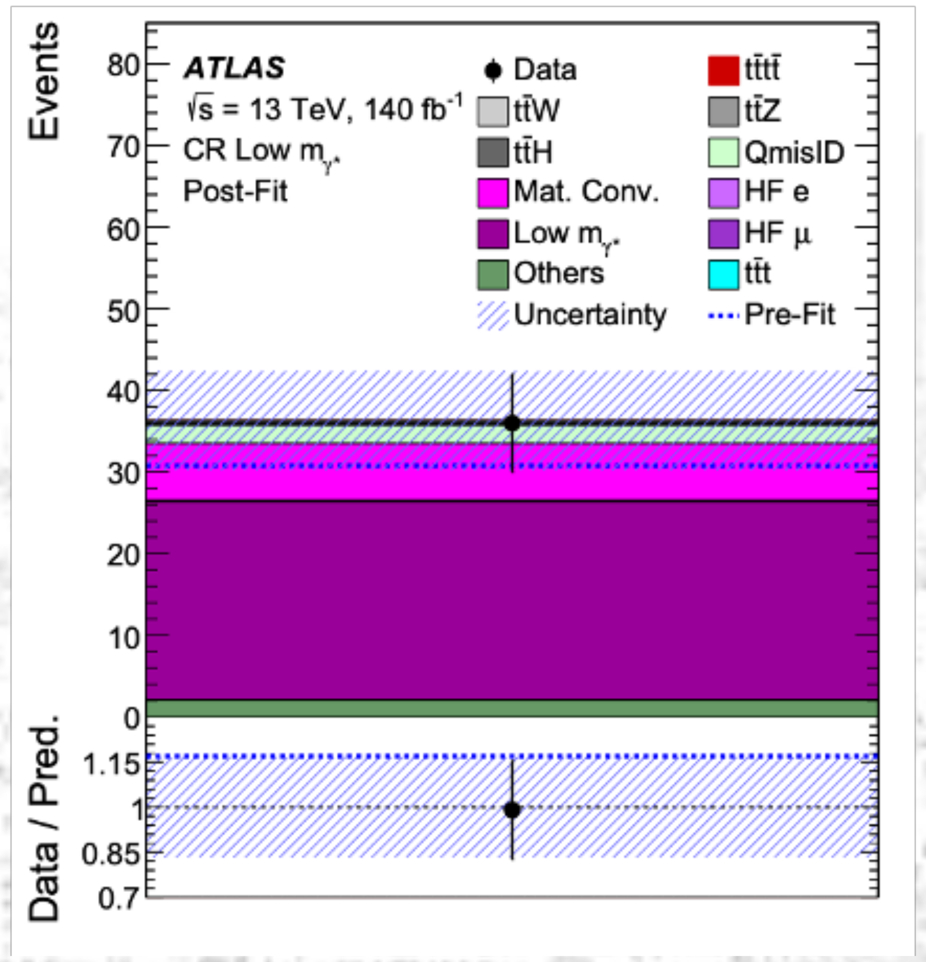

Heavy flavor mu




Material conversions

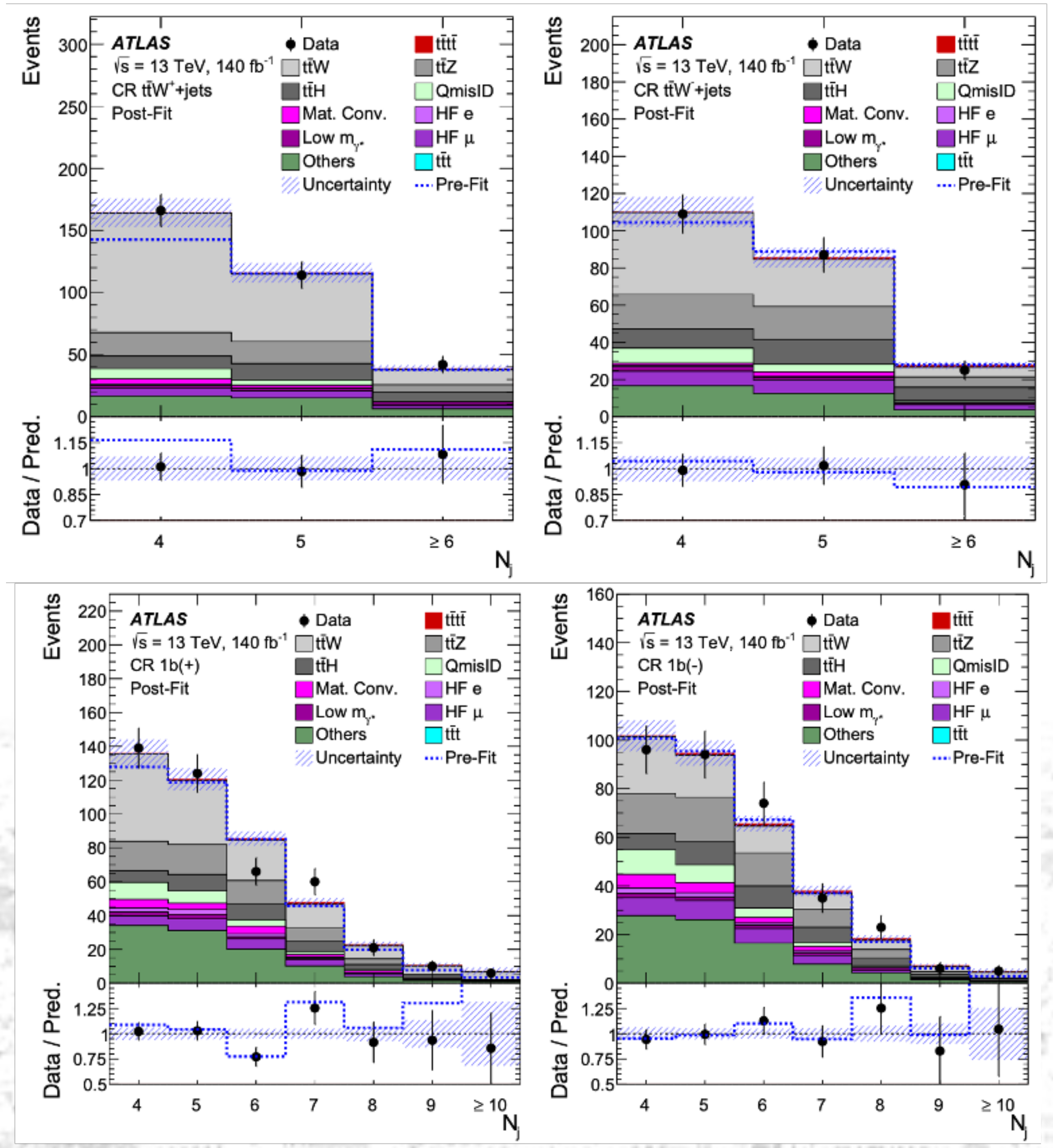



Virtual photon conversion



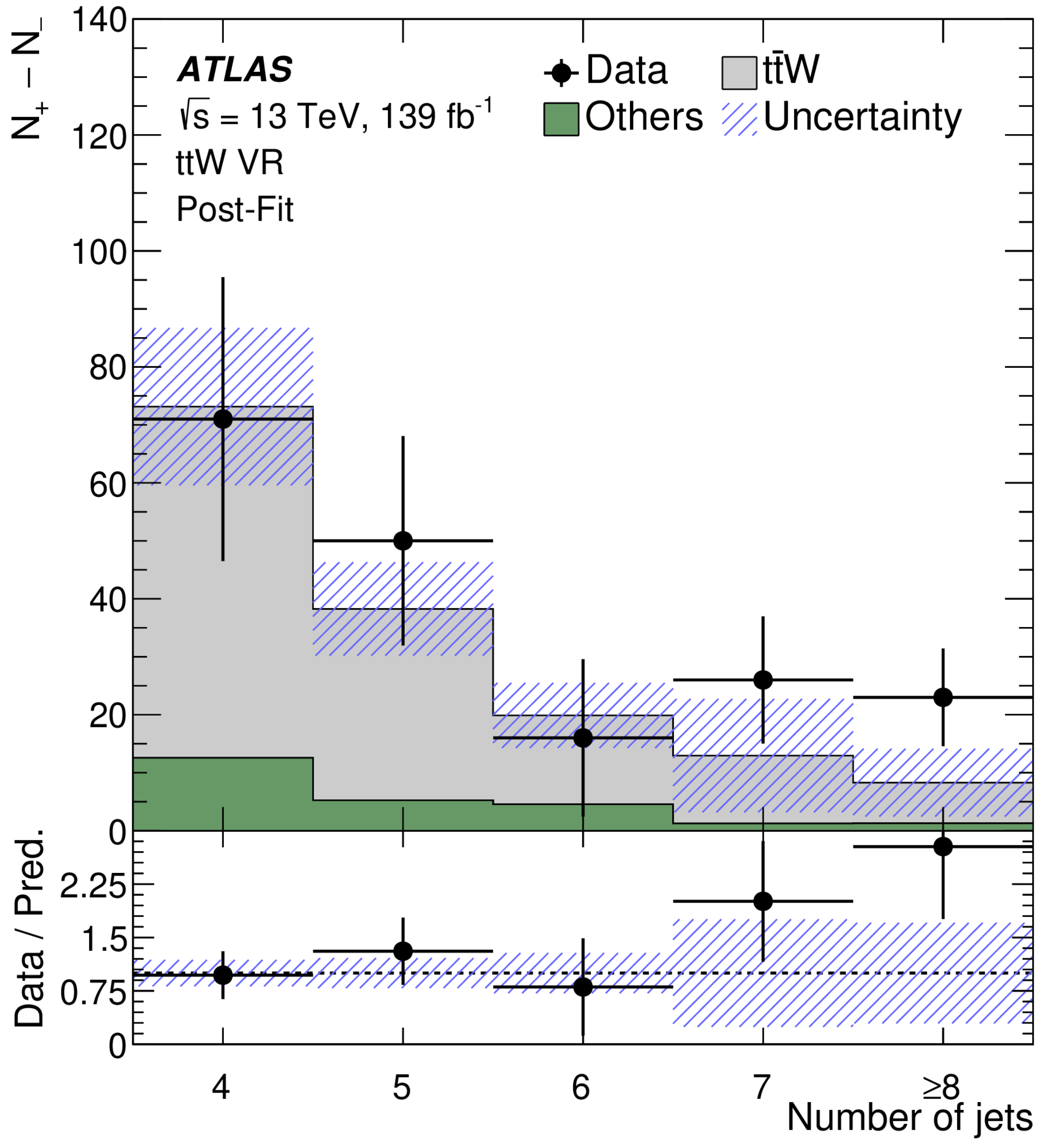
# $t\bar{t}W$ background estimation

- $t\bar{t}W$+jets background:
  - In the evidence analysis, large uncertainties were assigned to $t\bar{t}W$+jets
  - Instead a data-driven estimation was developed
  - Njets dependence fitted to data using 4 free parameters ($a_0$,$a_1$, $ttW^+$4jets, $ttW^-$4jets) with four control regions

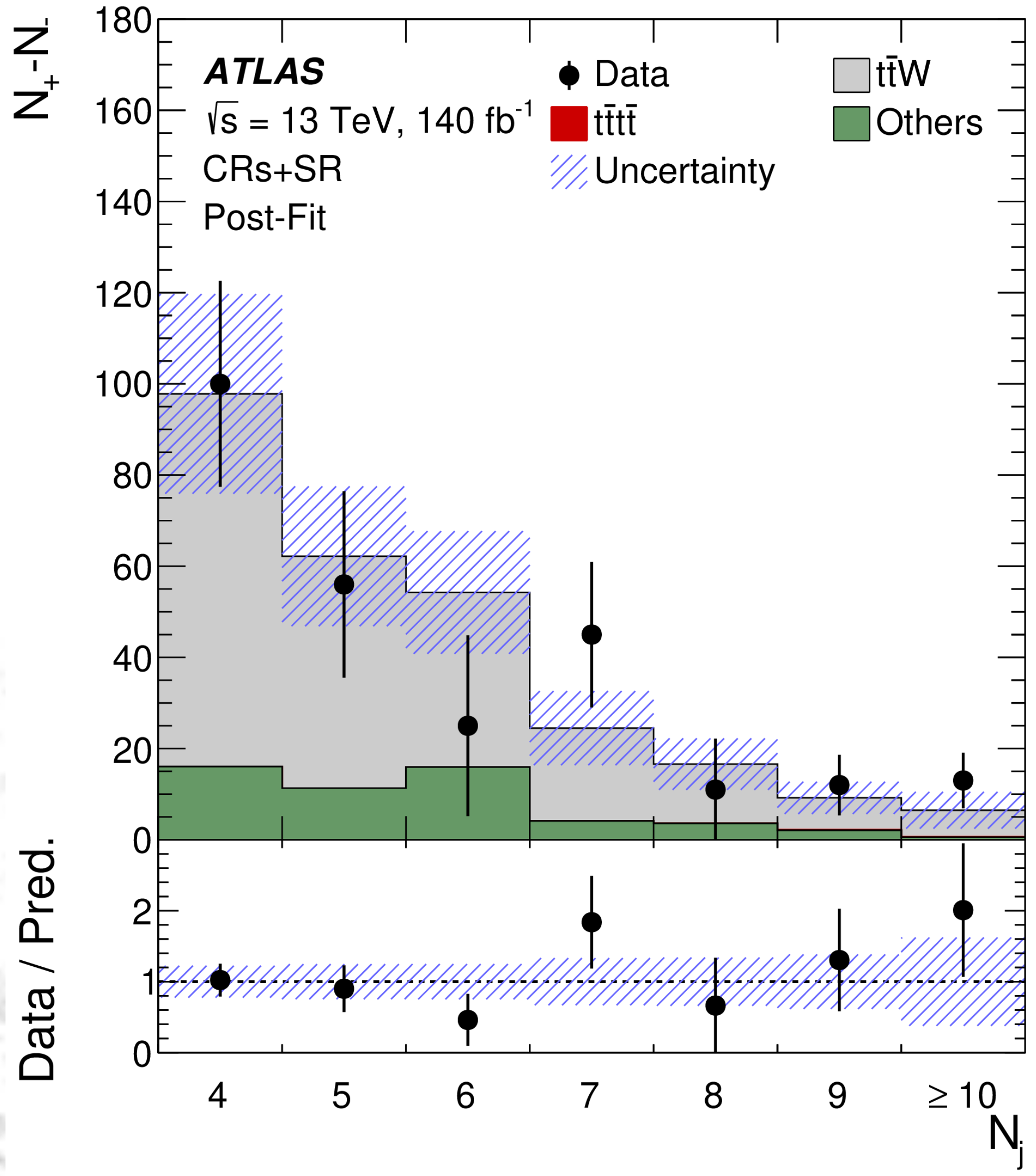



| $t\bar{t}W$ background | $a_0$ | $a_1$ | $\mathrm{NF}_{t\bar{t}W^+(4\mathrm{jet})}$ | $\mathrm{NF}_{t\bar{t}W^-(4\mathrm{jet})}$ |
|---|---|---|---|---|
| Value | $0.51 \pm 0.10$ | $0.22^{+0.25}_{-0.22}$ | $1.27^{+0.25}_{-0.22}$ | $1.11^{+0.31}_{-0.28}$ |

difference between positive and negative SS dilepton events to suppress symmetric processes




$t\bar{t}W$ validation region in the evidence analysis

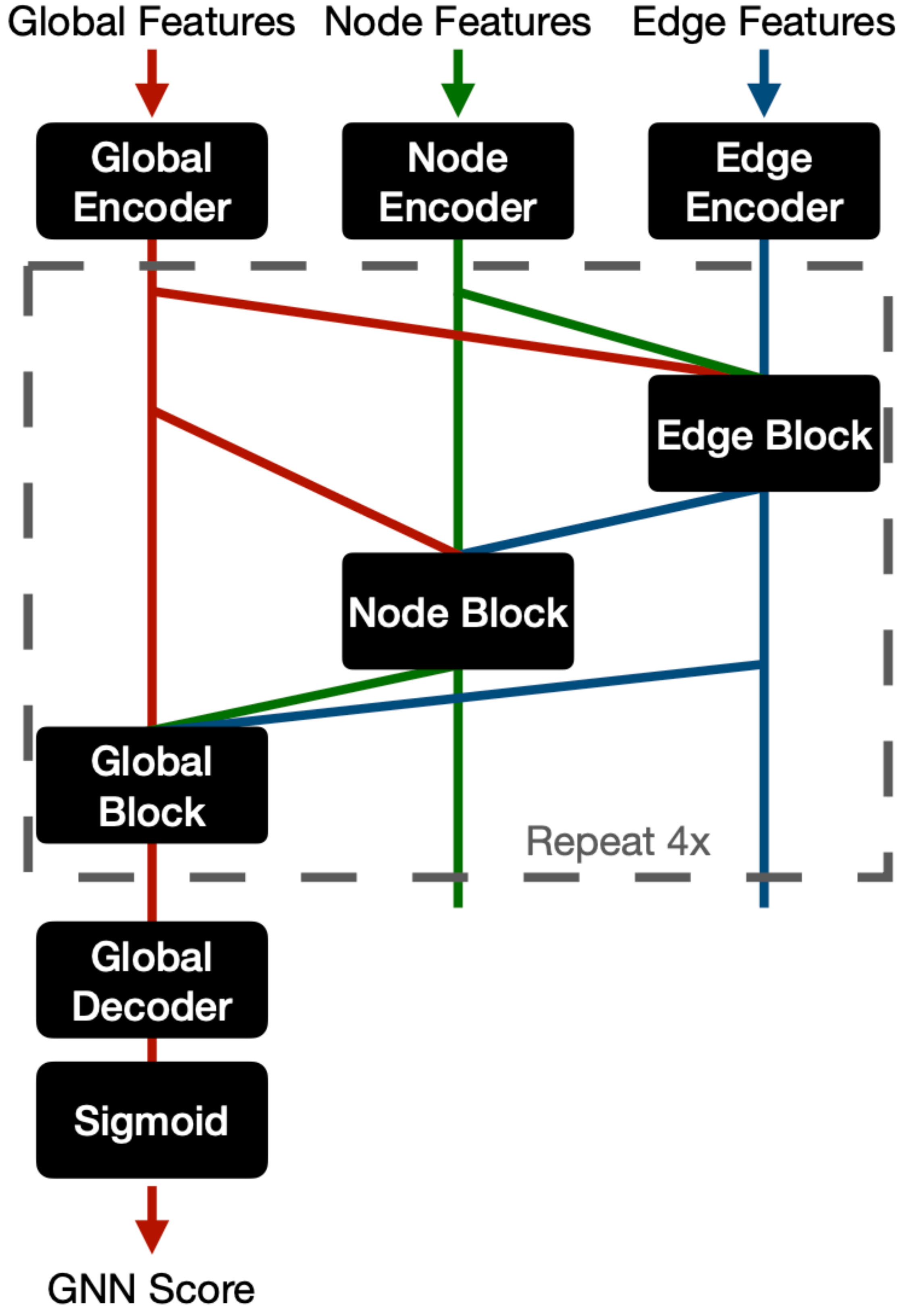



$t\bar{t}W$ validation region with data-driven estimation in the new analysis

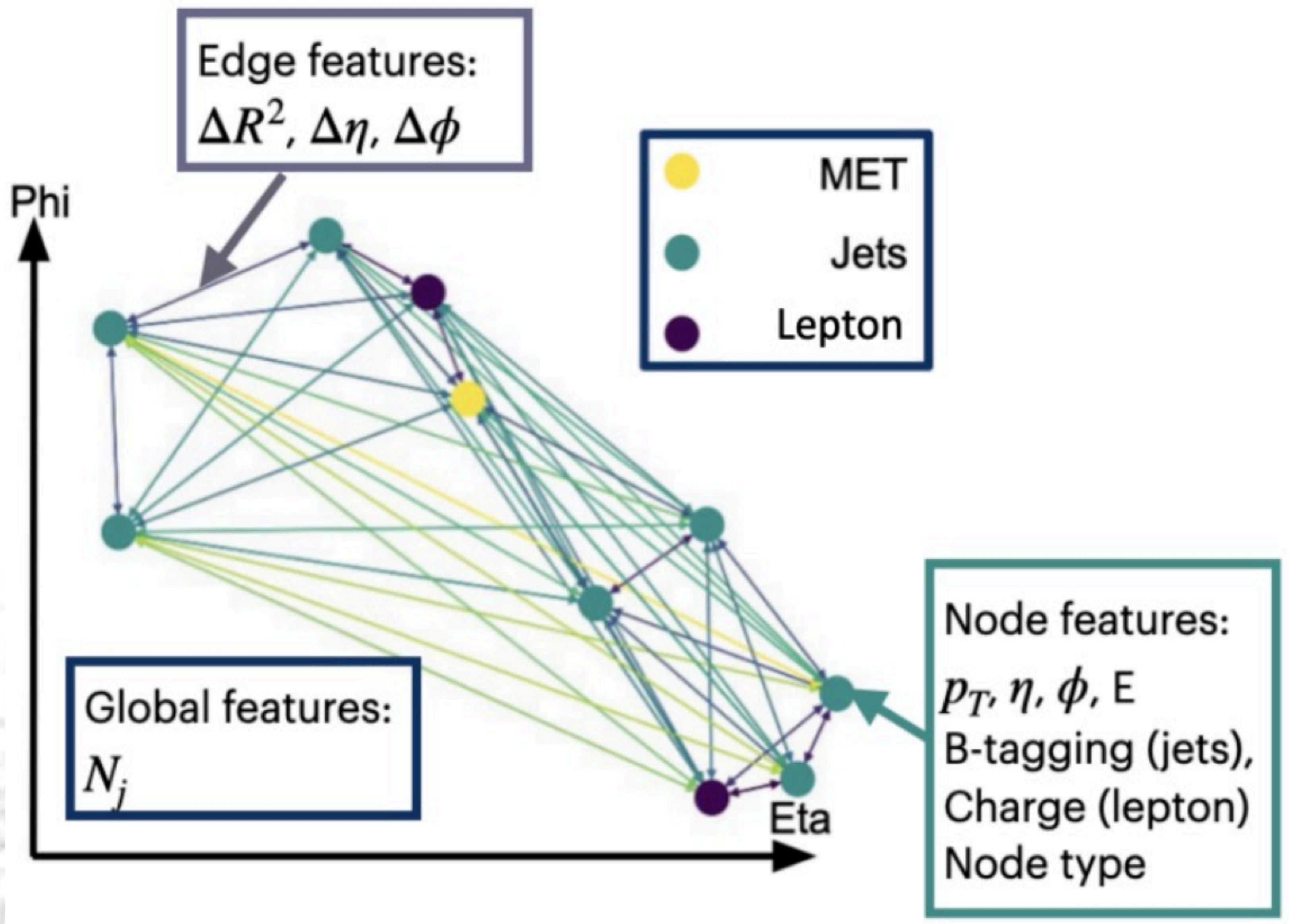
# Separation between signal and background

- Signal vs background separation performed using machine learning :
  - Graph neural network (GNN)
  - Combine objects information (jets, lepton, MET) from an event into graphs, with node, edge, and global properties

GNN structure




GNN inputs



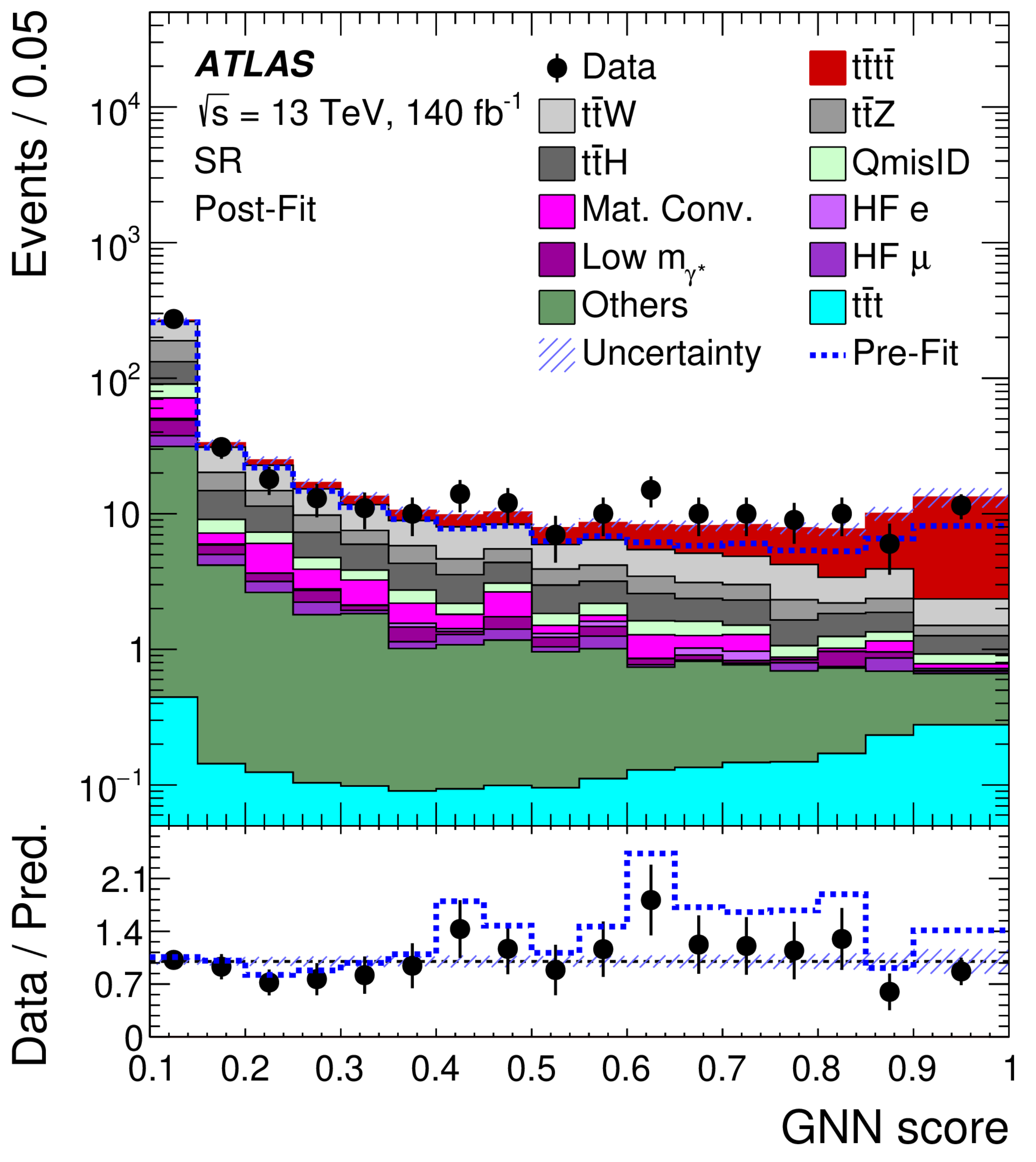
# Observation of four top-quark production

EPJ C83 (2023) 496
See PhD from Xiang Chen (2025)

- Simultaneous profile likelihood fit to data in the signal region and the 8 control regions

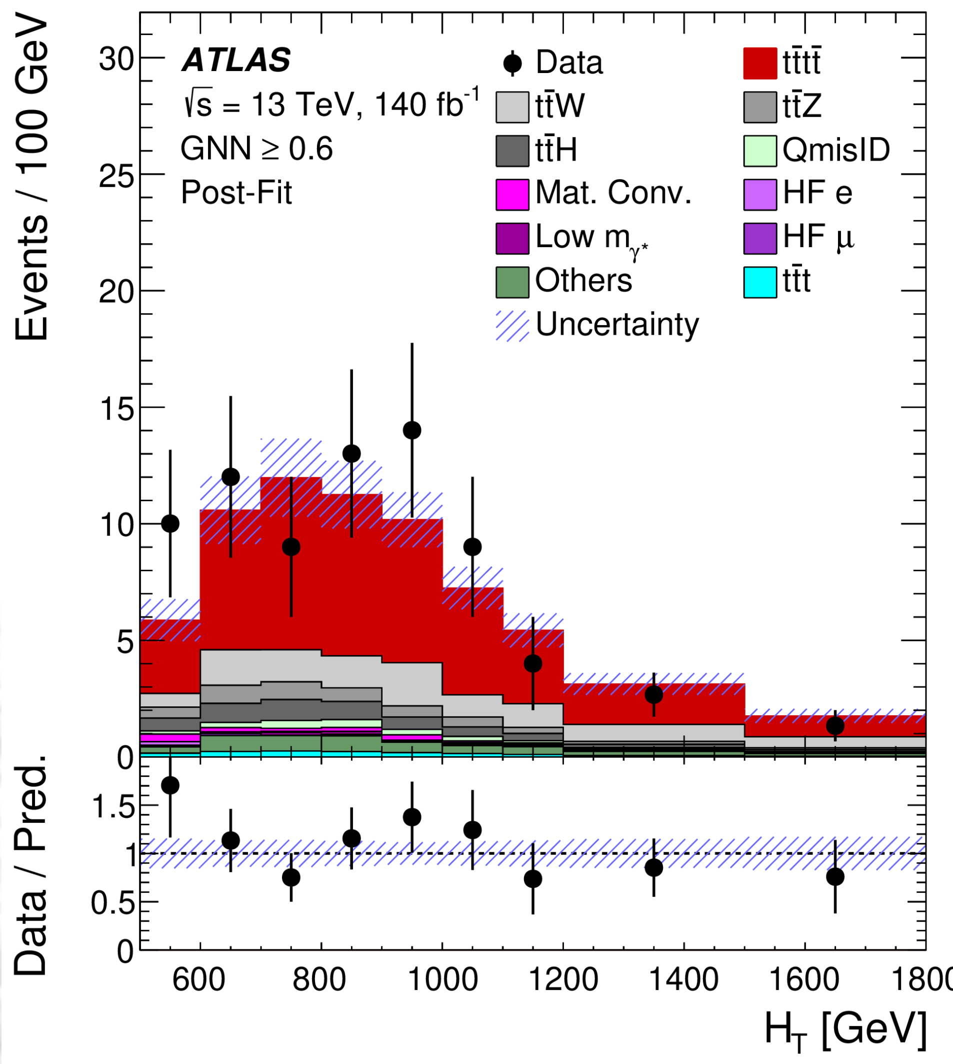
$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\ \text{fb}$$

Compatible at 1.8 σ with the SM prediction but measurement twice higher than the SM expectation.
Largest systematic uncertainties on signal modelling

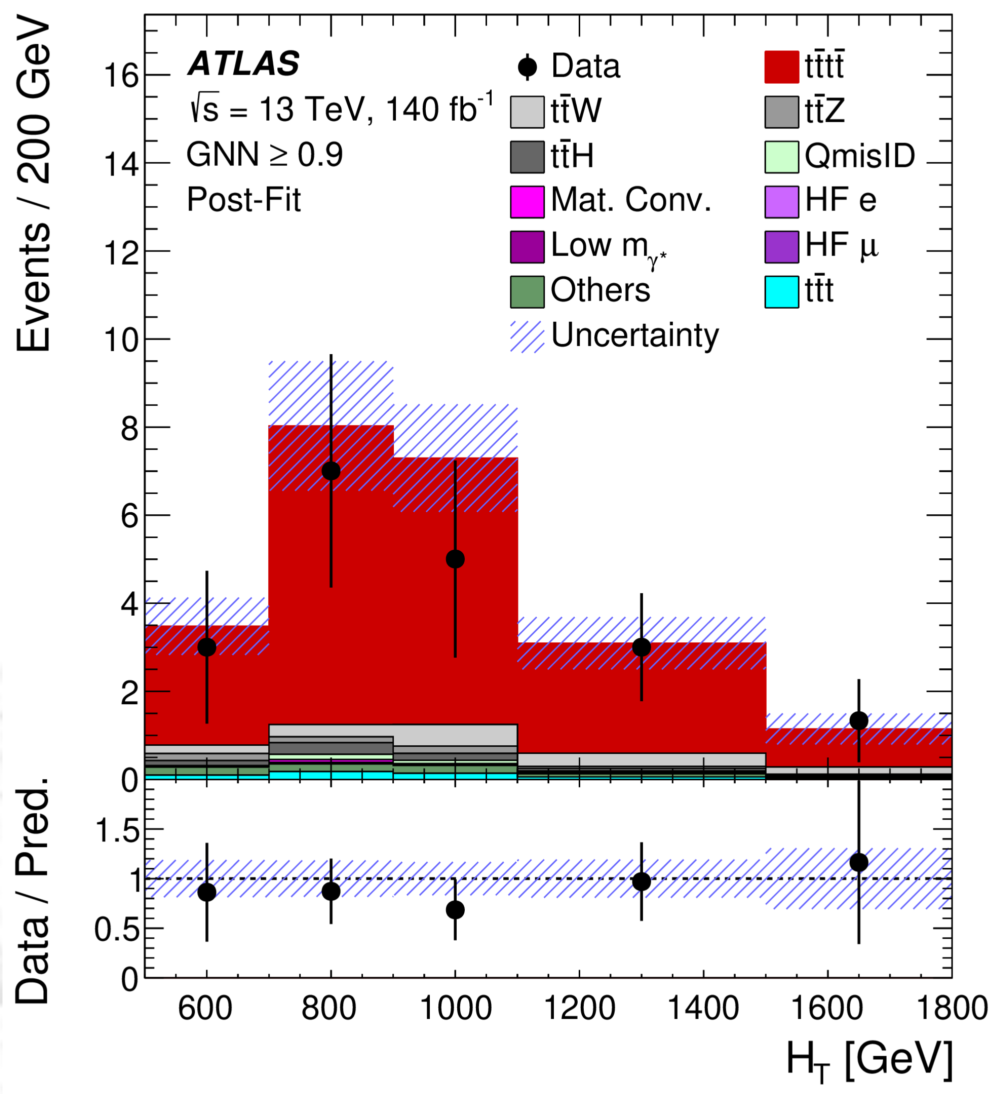



Expected significance: 4.3 σ
Observed significance: 6.1σ

GNN>0.6



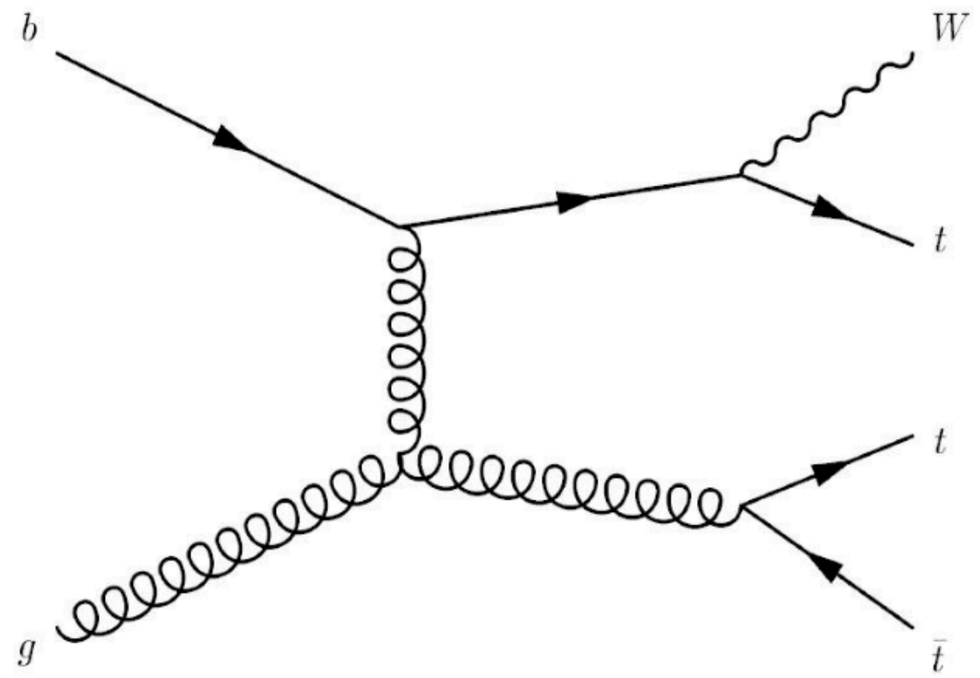

GNN>0.9



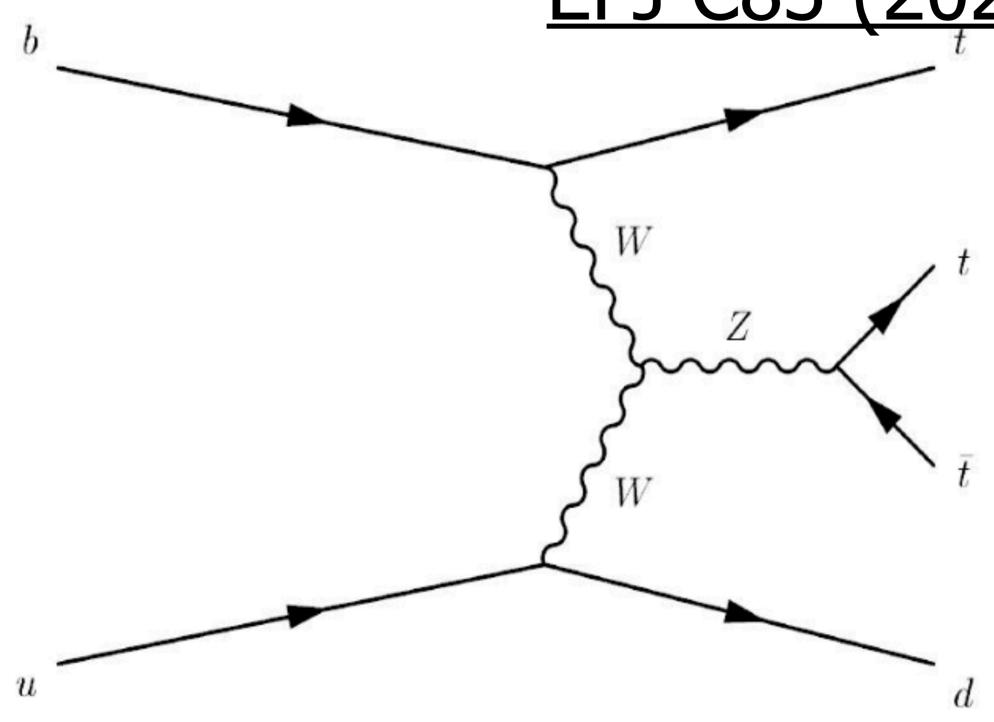
# Four top as a path to three top

EPJ C83 (2023) 496

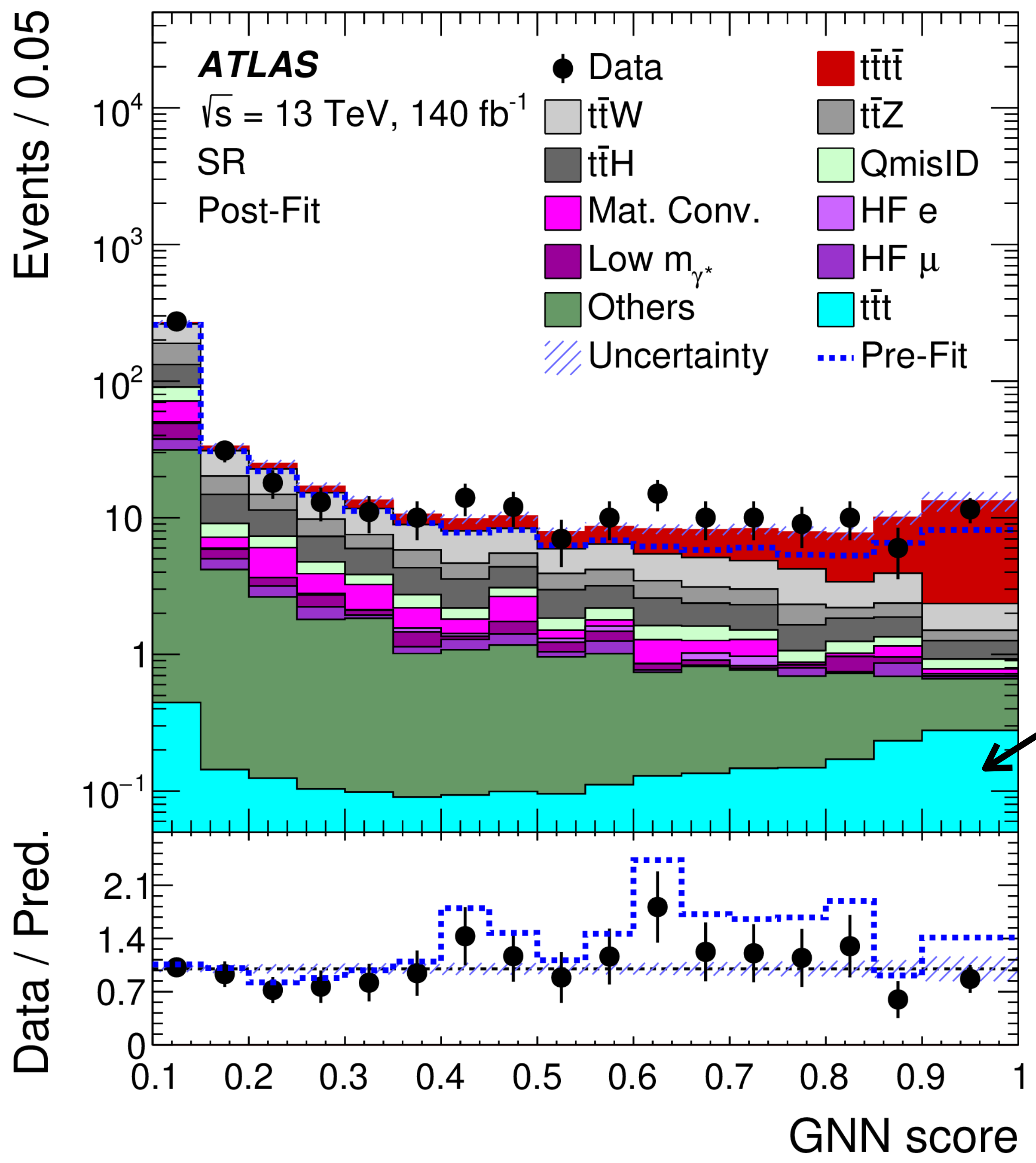
- SM three top production
  - Cross section ~ 10 times smaller than the four top process
  - Still very signal like
  - Currently no experimental constraints
- Free floating both $t\bar{t}t\bar{t}$ and $t\bar{t}t$ in the fit
  - Very large correlation between the 2 processes : - 93%

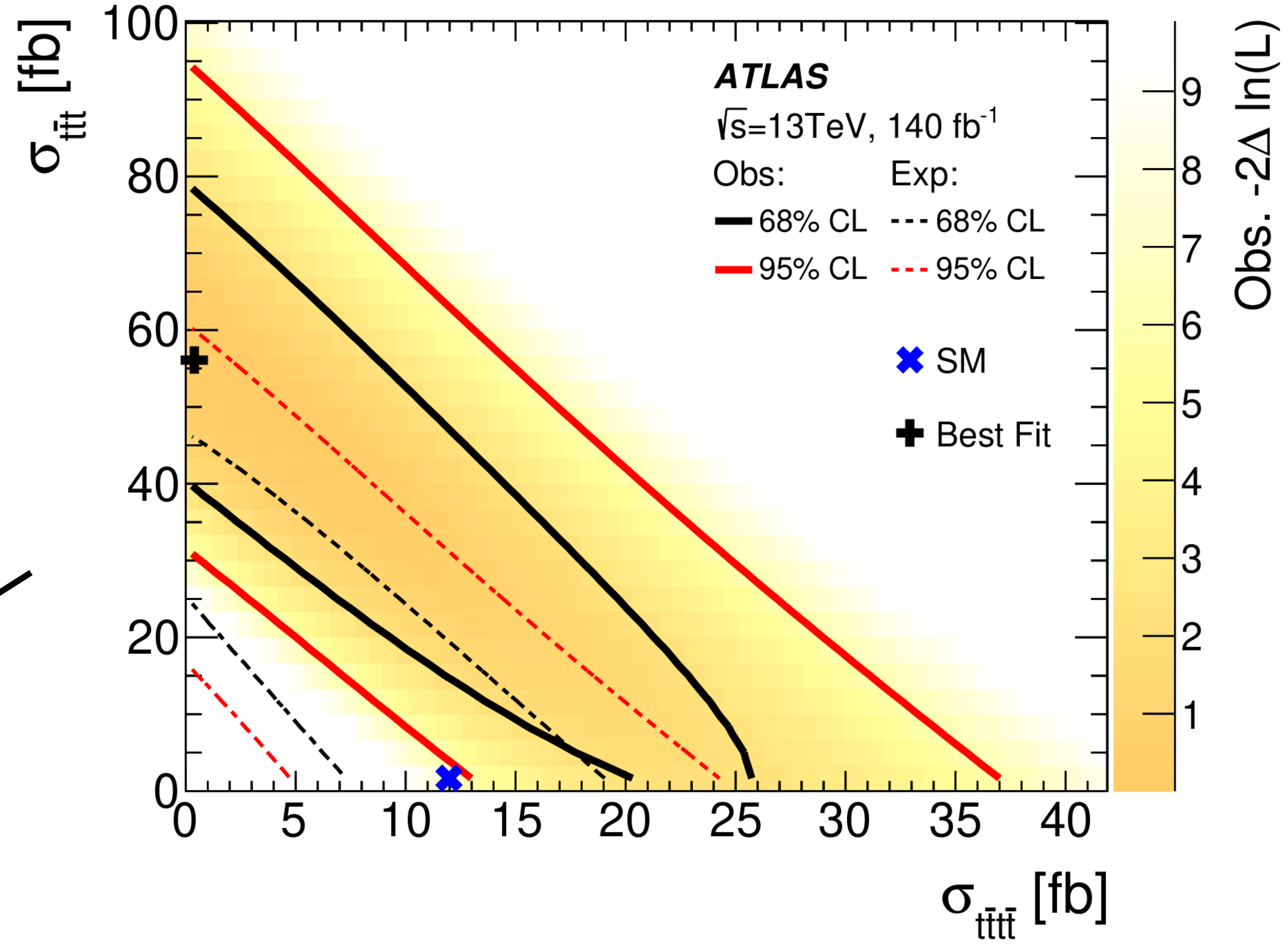



σ(tt̄t W) ~ 1 fb




σ(tt̄t q) ~ 0.6 fb



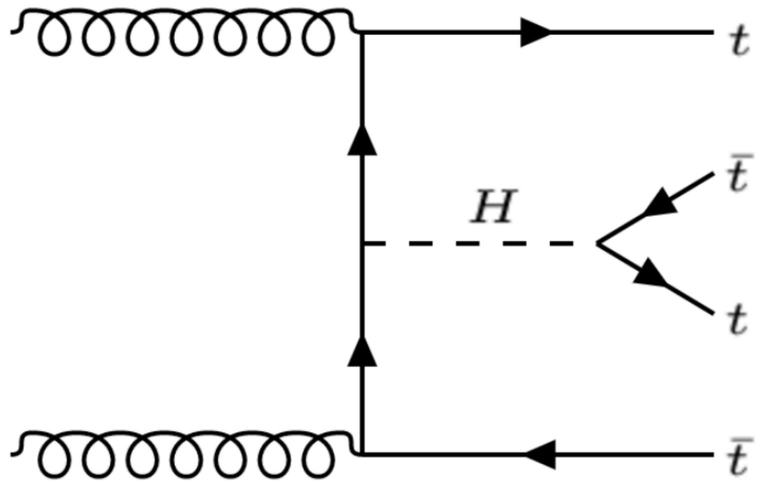

Use the 2D likelihood scan to set limit on $t\bar{t}t$ production

| Processes | 95% CL cross section interval [fb] with $\mu_{t\bar{t}t\bar{t}} = 1$ | 95% CL cross section interval [fb] with $\mu_{t\bar{t}t\bar{t}} = 1.9$ |
|---|---|---|
| $t\bar{t}t$ | [4.7, 60] | [0, 41] |
| $t\bar{t}tW$ | [3.1, 43] | [0, 30] |
| $t\bar{t}tq$ | [0, 144] | [0, 100] |

# Four top links to Higgs physics

EPJ C83 (2023) 496

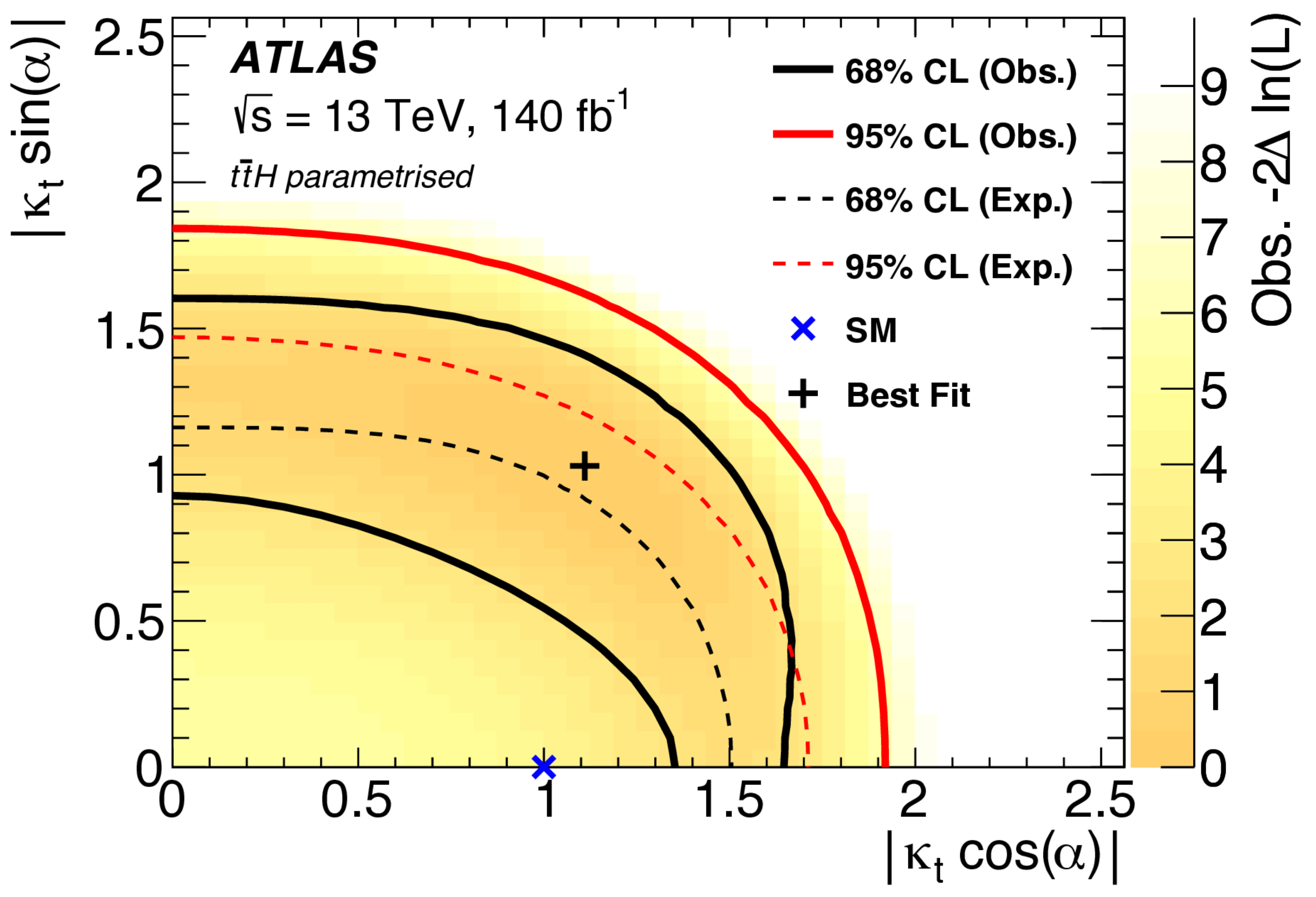
- Top Yukawa coupling
  - Four top production sensitive to modification of the Higgs-top coupling
  - Need also to take into account the changes of $t\bar{t}H$ background yield



$$\mathscr{L} = -\frac{1}{\sqrt{2}}\kappa_t \bar{t}(\cos(\alpha) + i\sin(\alpha)\gamma_5)th$$

CP even CP odd

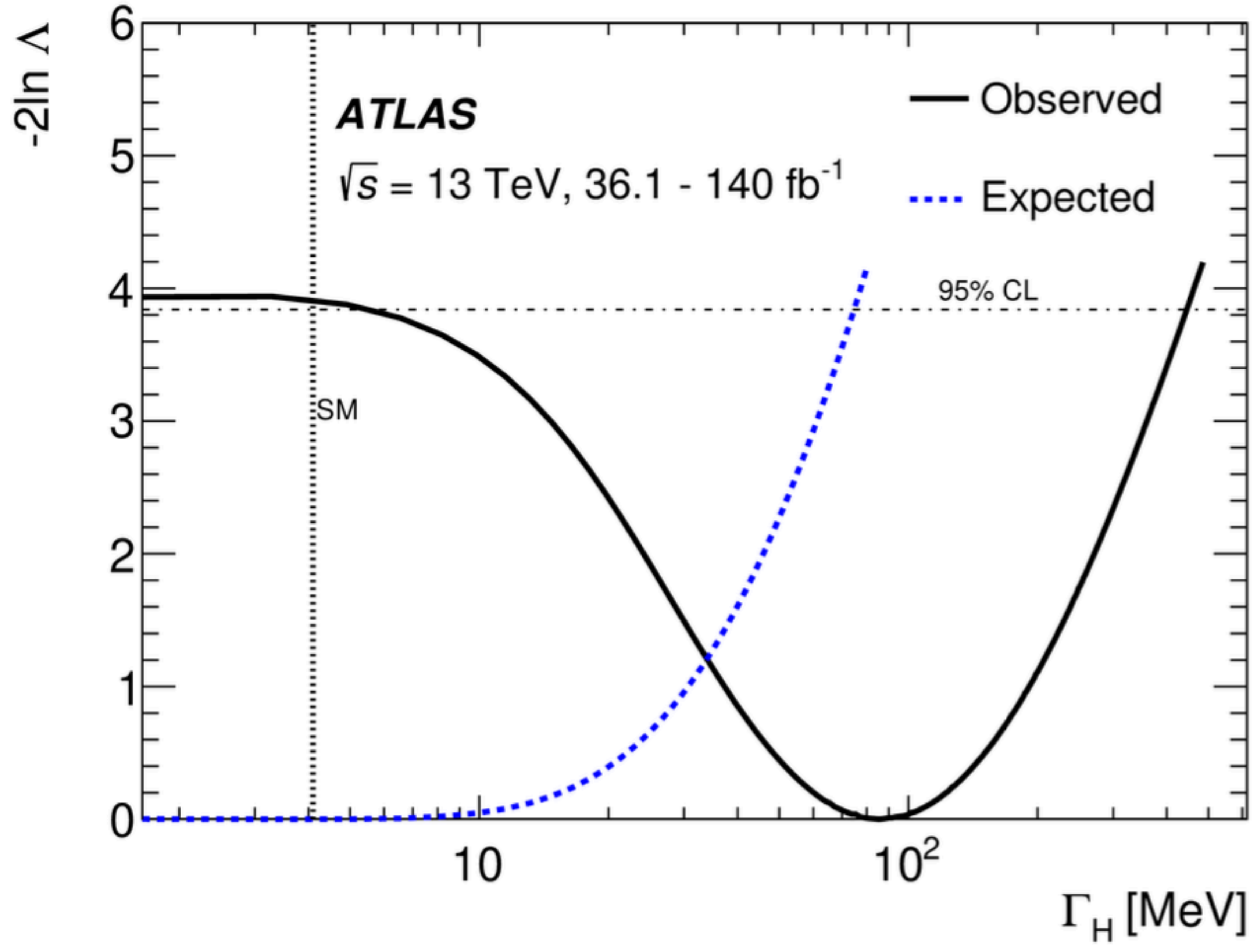
Obs (exp) limit with $\alpha = 0$: $|\kappa_t| < 1.9$ (1.6)




PLB 861 (2025) 139277

- Higgs width from the top Yukawa coupling
  - combination of on- (Higgs analyses) and off-shell (4top) measurements
  - Observed (expected) 95% CL limit: $\Gamma_H < 450$ (75) MeV

$$\mu_{i\to H\to f} = \frac{\sigma_i \times \mathrm{B}(H\to f)}{\sigma_i^{\mathrm{SM}} \times \mathrm{B}^{\mathrm{SM}}(H\to f)} = \frac{\kappa_i^2\kappa_f^2}{R_\Gamma}$$

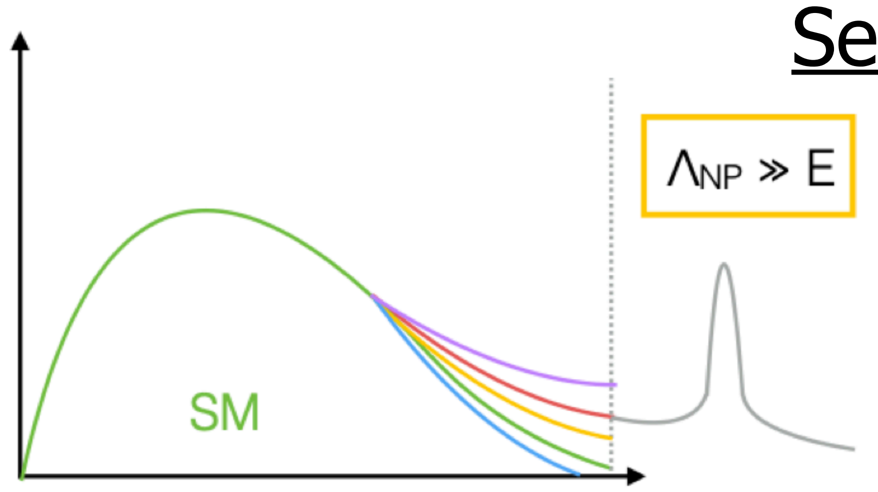


# Using four top to constrain new physics

See PhD from Xiang Chen (2025)

EPJ C83 (2023) 496

- Effective field theory approach
  - Parametrization of new physics effects that can not be directly produced
  - Four top production uniquely sensitive to modification of the four heavy-fermion operators: cQQ1, cQt1, ctt1, cQt8
  - Parametrization of the changes induced by these operators in each bin of the GNN

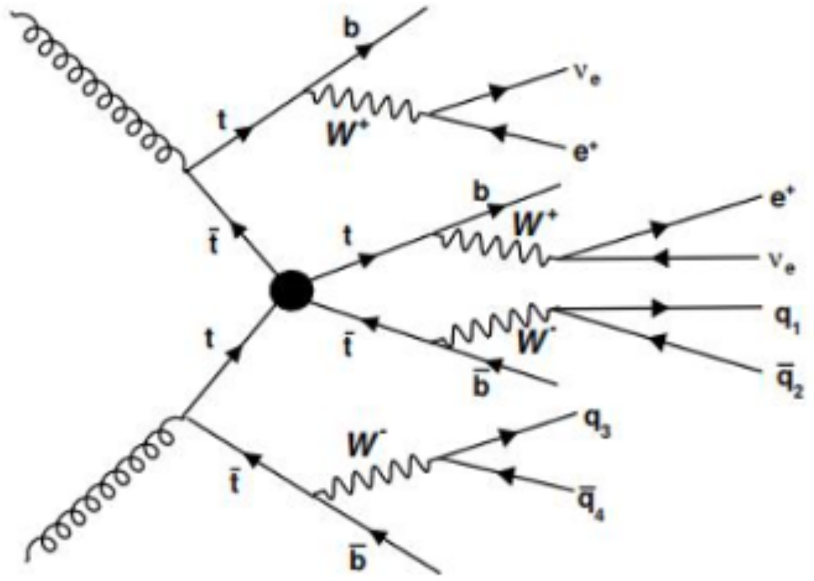



Operators with new interactions

Coupling Strength

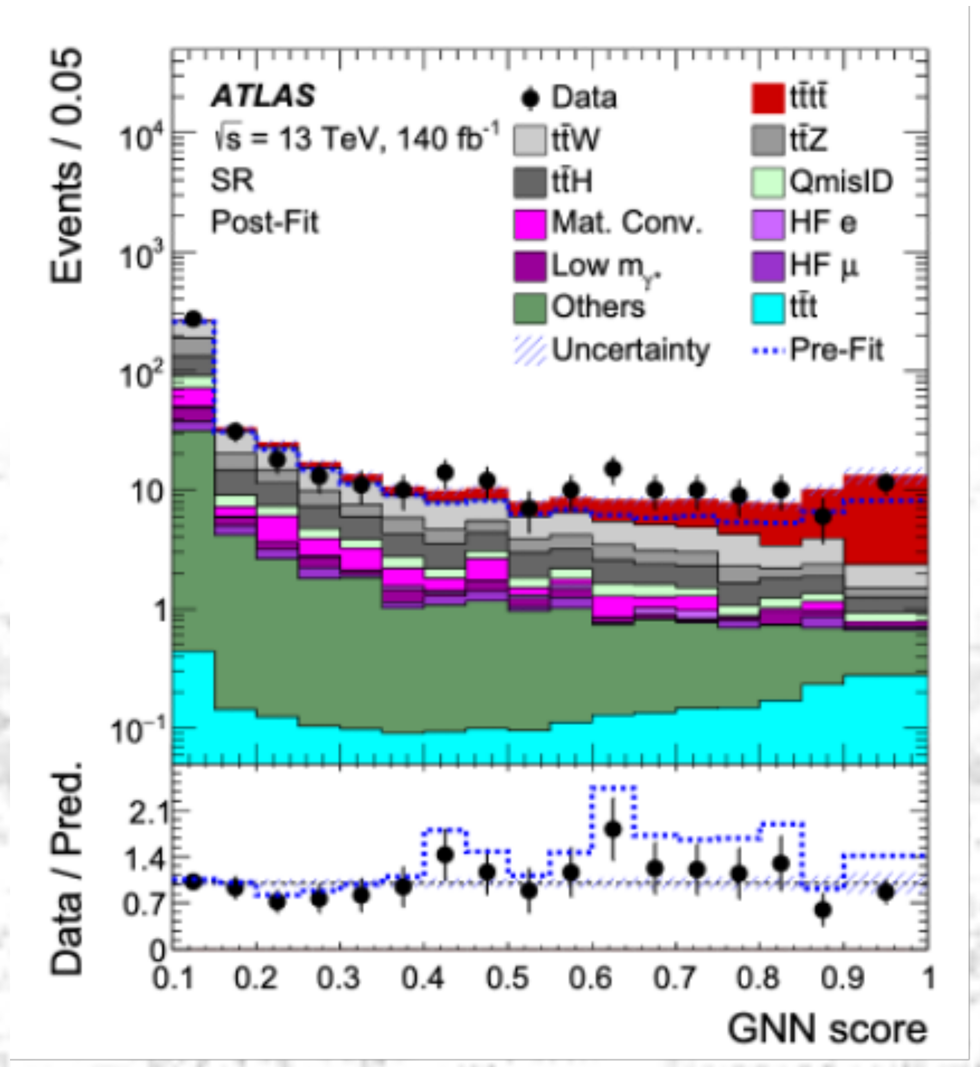
$$\mathscr{L}_{SMEFT} = \mathscr{L}^{SM}_{d\leq 4} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

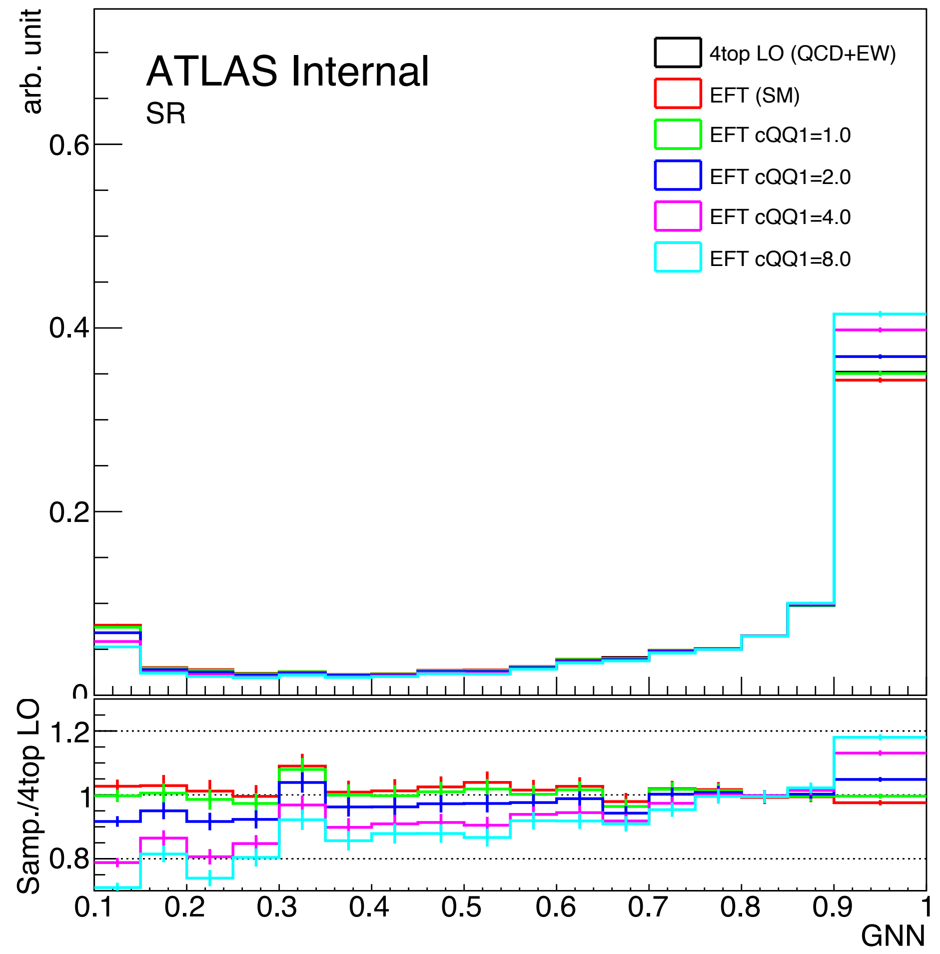
Standard Model

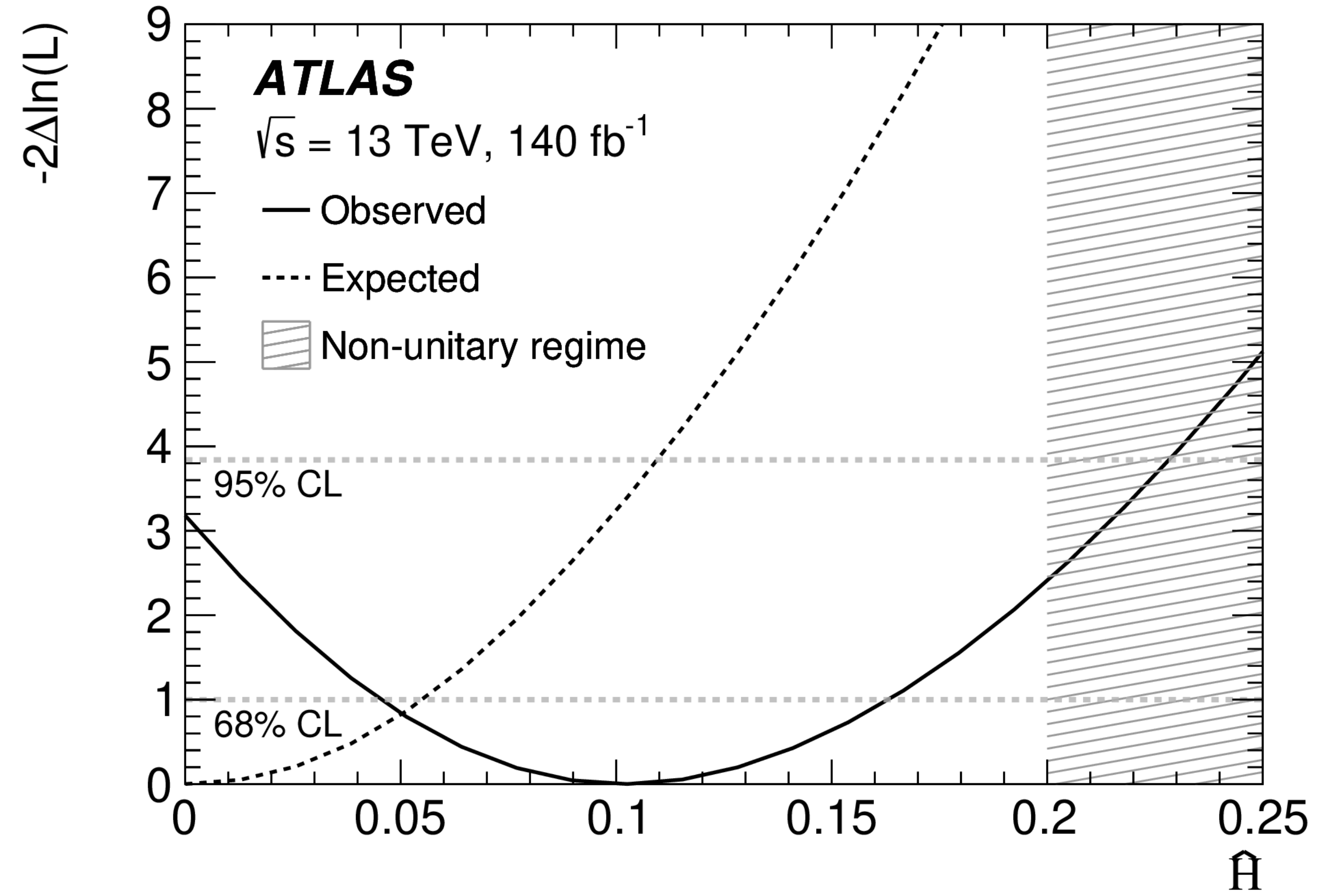


Limits of four heavy-fermion operators (one operator at a time)

| Operators | Expected $C_i/\Lambda^2$ [TeV $^{-2}$] | Observed $C_i/\Lambda^2$ [TeV $^{-2}$] |
|---|---|---|
| $O^1_{QQ}$ | [-2.5, 3.2] | [-4.0, 4.5] |
| $O^1_{Qt}$ | [-2.6, 2.1] | [-3.8, 3.4] |
| $O^1_{tt}$ | [-1.2, 1.4] | [-1.9, 2.1] |
| $O^8_{Qt}$ | [-4.3, 5.1] | [-6.9, 7.6] |



# CEA/SJTU Project

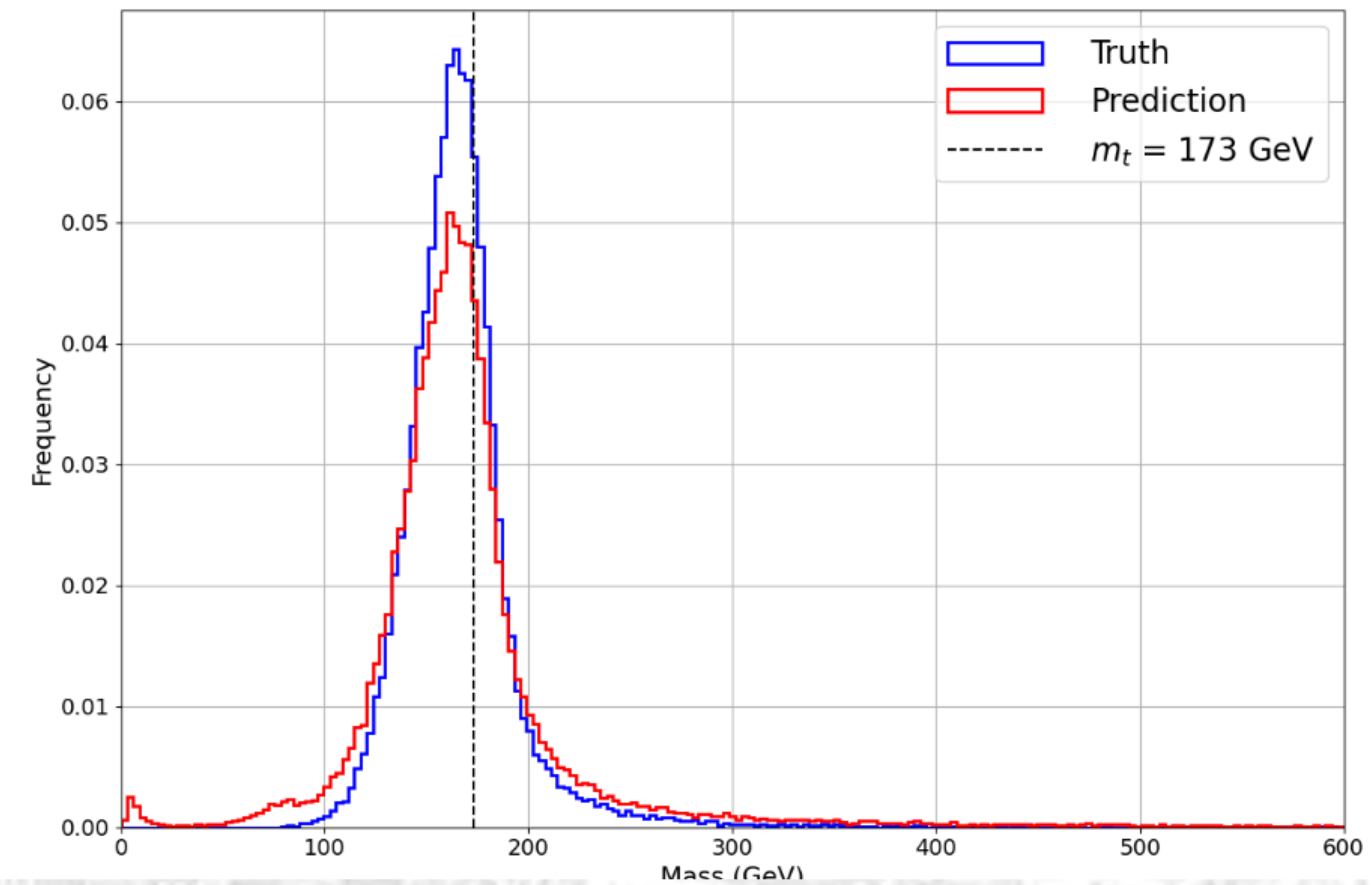
- Project plans
  - measurement the cross-section for four-top-quark production using Run3 data at an enhanced center of mass energy (20% more cross section)
    - Do we still see a factor of 2 excess compared to the Standard Model prediction ?
  - Search for new physics through effective field theory
- Project innovations
  - Better handle of the 3top process (highly correlated with 4top production)
  - Try to reconstruct the final state to help signal discrimination using machine learning
    - Very challenging because of large multiplicity in the final state and underconstraint coming from escaping neutrinos
  - Treat new physics effects on the background as well

Performance comparaison of different reconstruction method

| $N_{jets}$ | Event Fraction | SPA-NET Efficiency | | $\chi^2$ Efficiency |
|---|---|---|---|---|
| | | $t_h$ | $t_l$ | $t_h$ Only |
| 6 | 7.9% | 0.326 | 0.745 | 0.081 |
| 7 | 19.8% | 0.371 | 0.721 | 0.139 |
| ≥8 | 72.3% | 0.376 | 0.681 | 0.143 |
| **Inclusive** | **100%** | **0.373** | **0.693** | **0.138** |

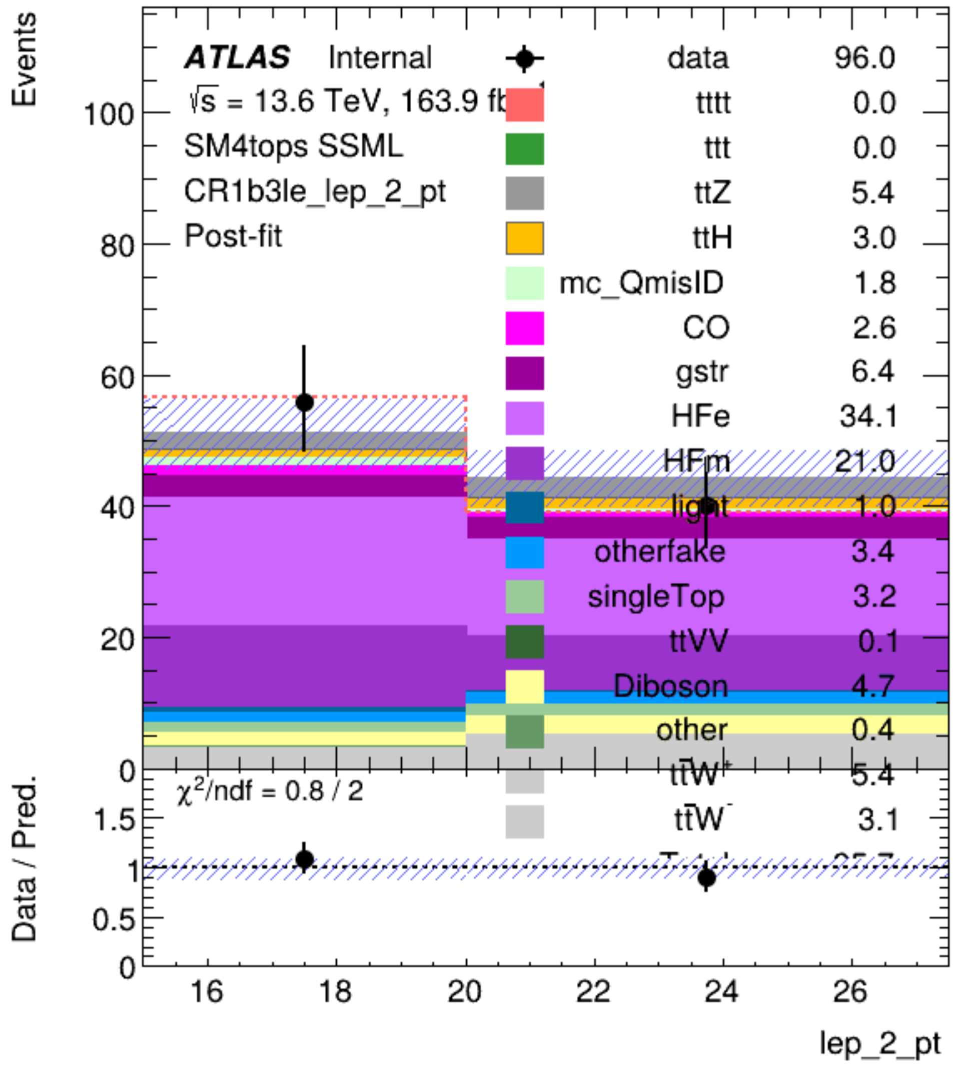
- $t_h$: assign one b quark and two light quarks
- $t_l$: assign only one b quark

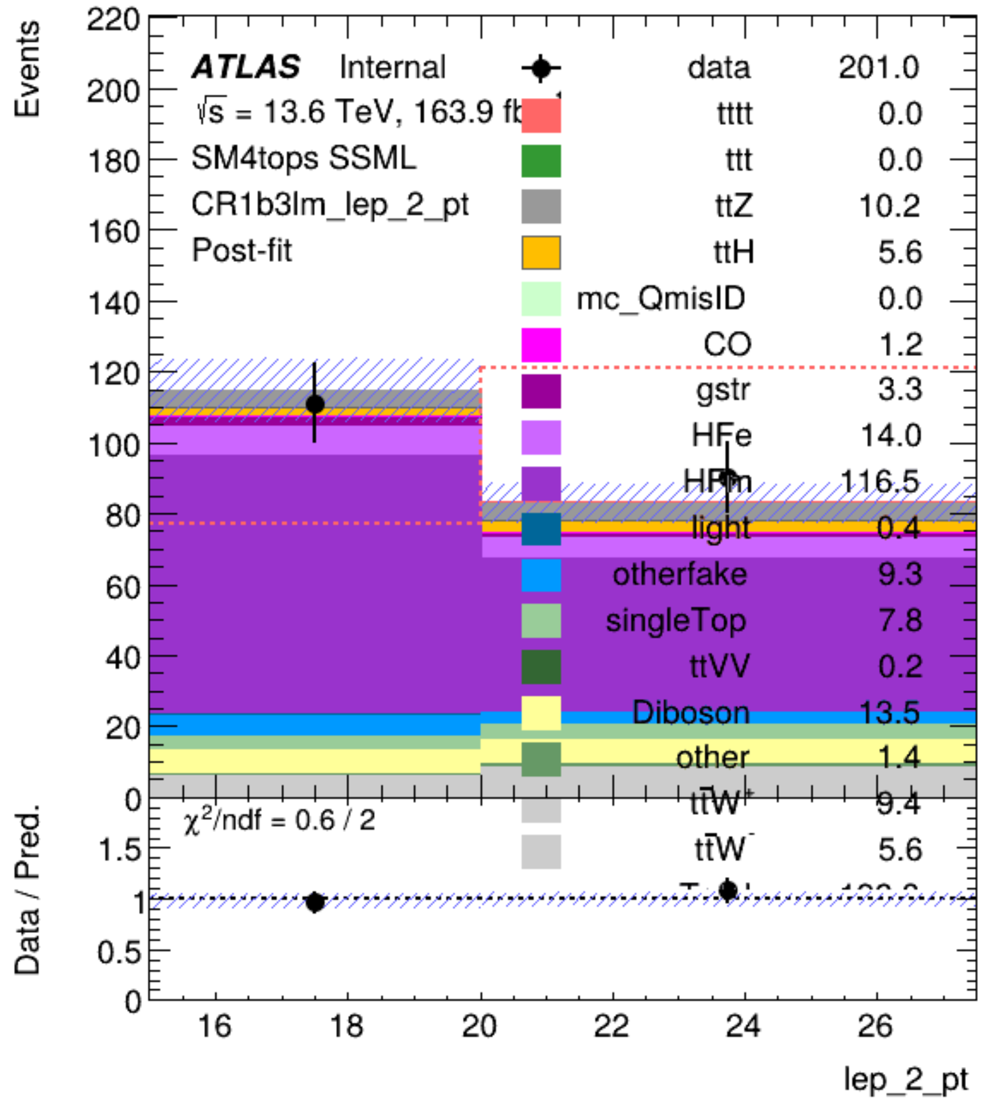
Reconstruction of the hadronically decaying top quark mass



# On-going control region definitions

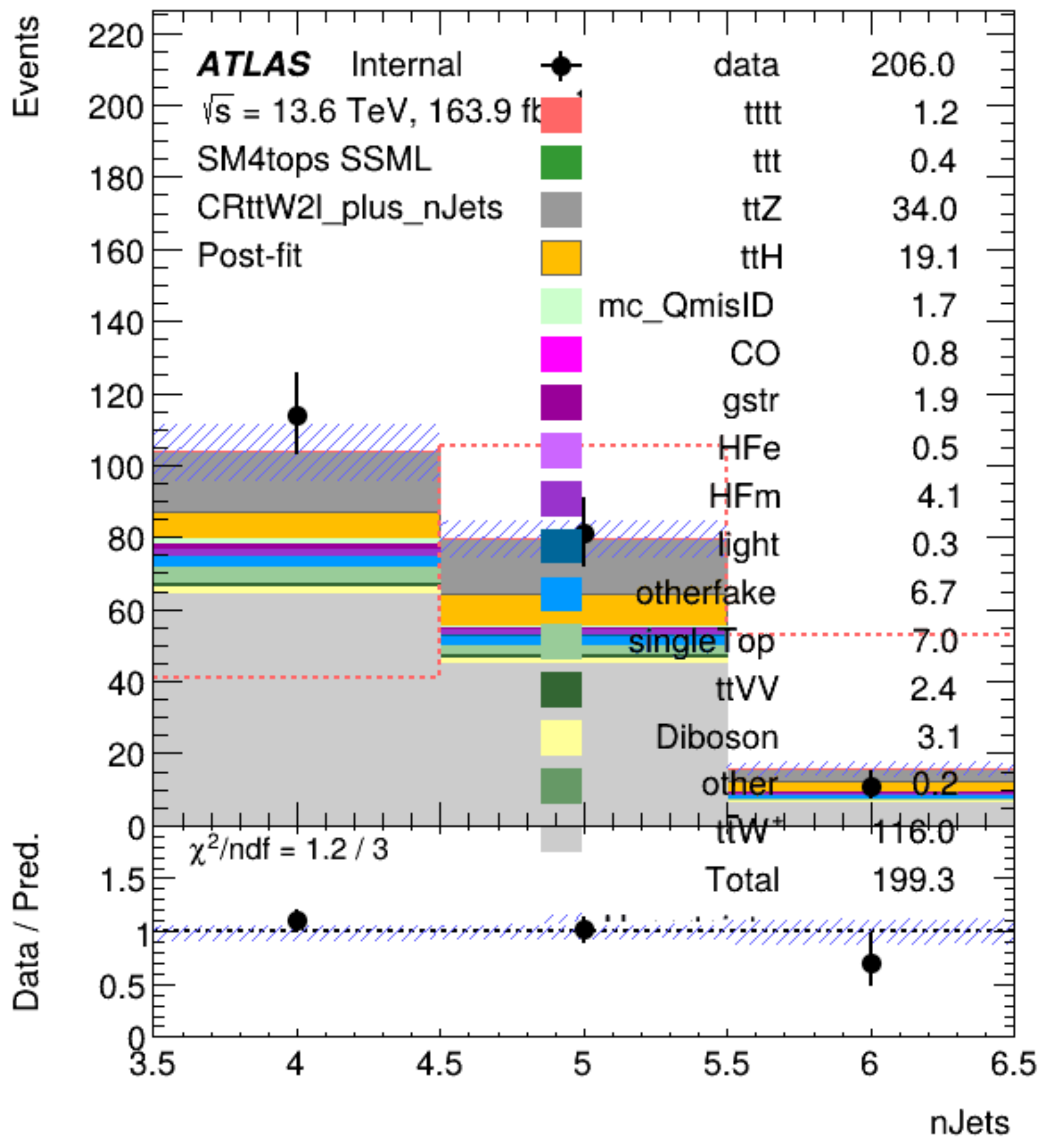
- Re-optimisation of the control regions enhanced in specific background components from Run3
  - Normalisation to be fitted together with the signal strength

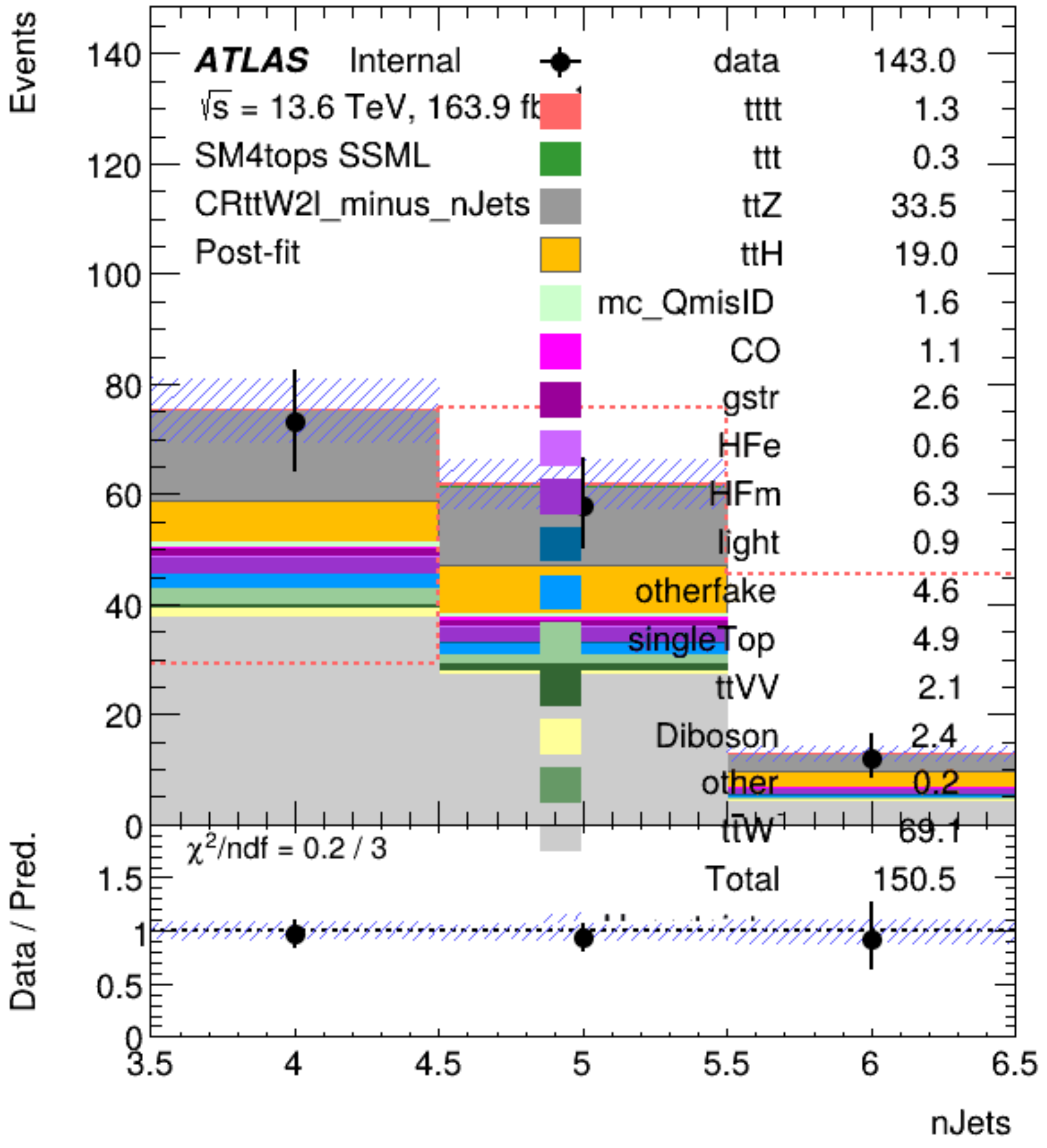


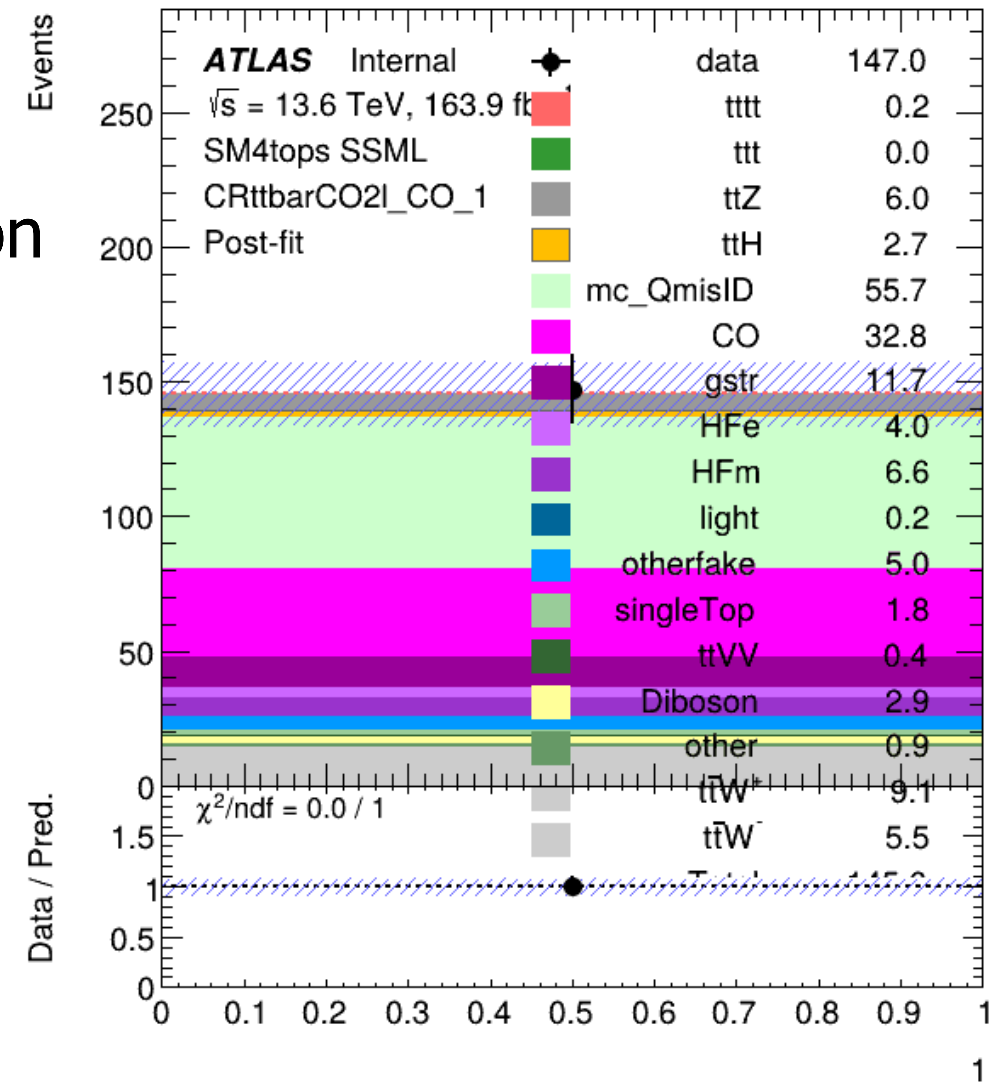

Control regions for non-prompt leptons from heavy flavour jets

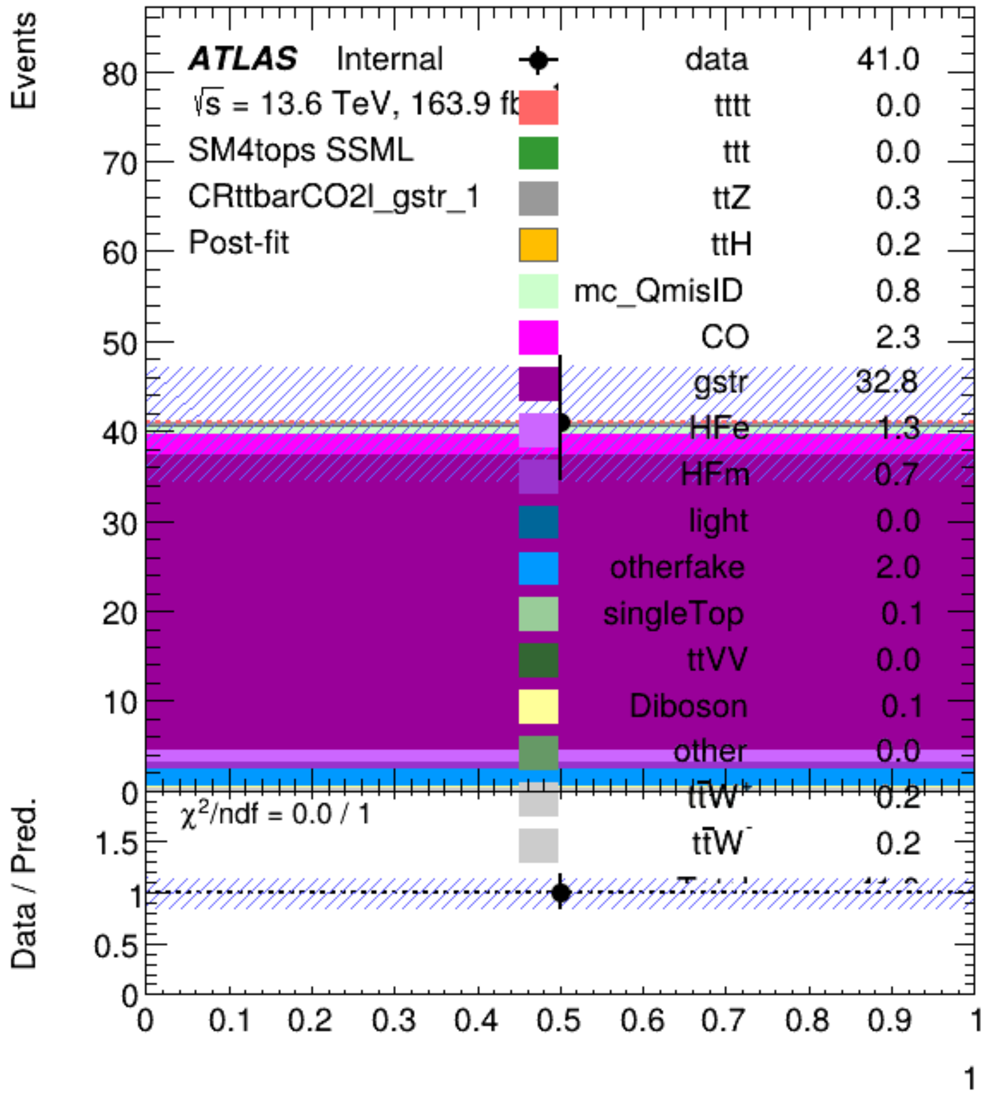
$t\bar{t}W$ control regions




Electron conversion control regions



# Conclusion

- Four top-quark production
  - One of the heaviest processes accessible at the LHC
  - Just being observed with some excess compared to the prediction
  - Ideal place to search for new physics

- CEA/SJTU Project
  - Measure four top-quark production at a new center of mass energy to see if the excess persists
    - Based on the CEA and SJTU team expertise from the 4top observation analysis
  - Several innovations foreseen to enhance the analysis sensitivity
  - Status: analysis infrastructure in place, control region definition to be optimized