Recent SM results (including Higgs) from ATLAS and CMS

Focusing on rare processes

Nedaa-Alexandra Asbah (CERN)

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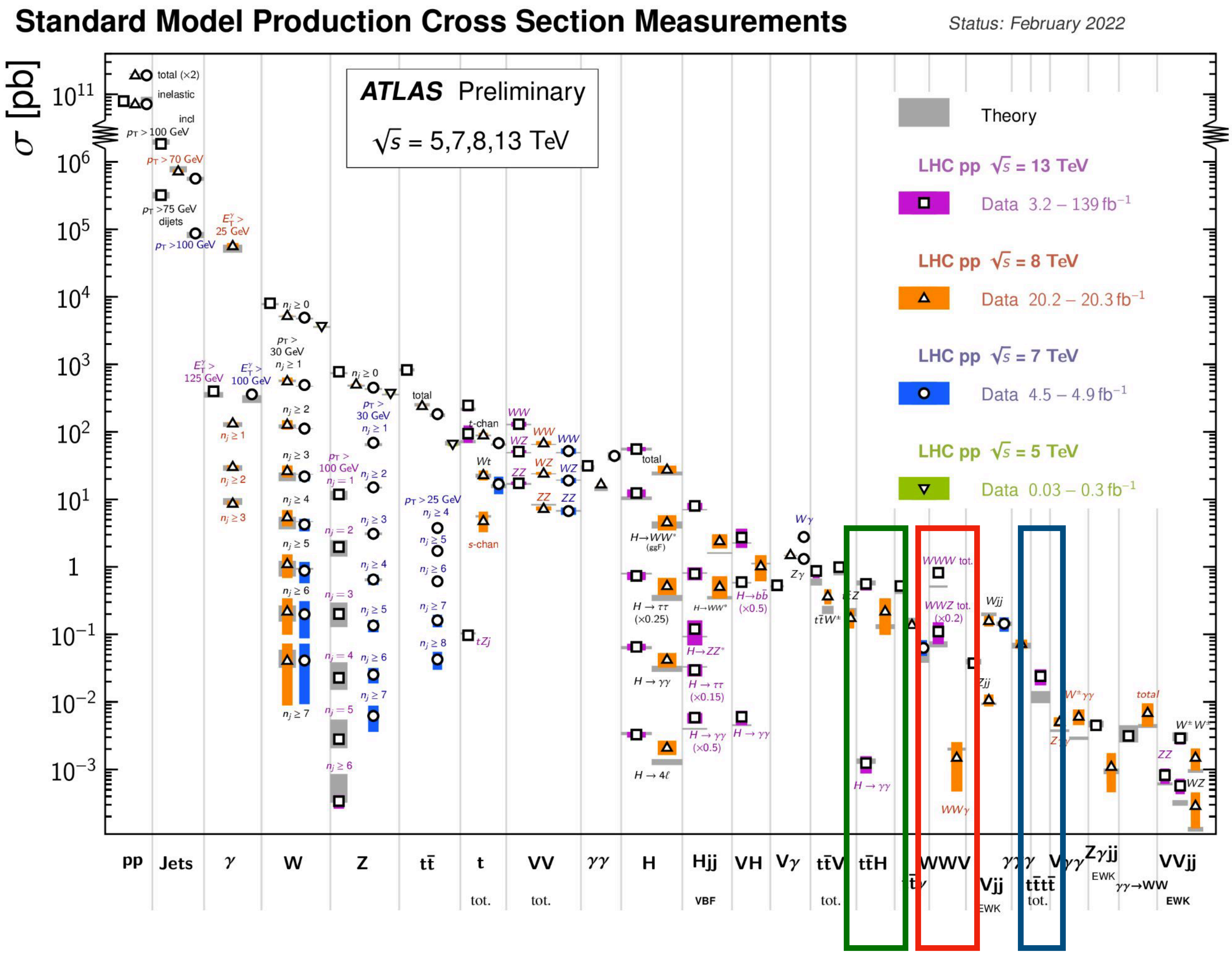
Why rare processes?

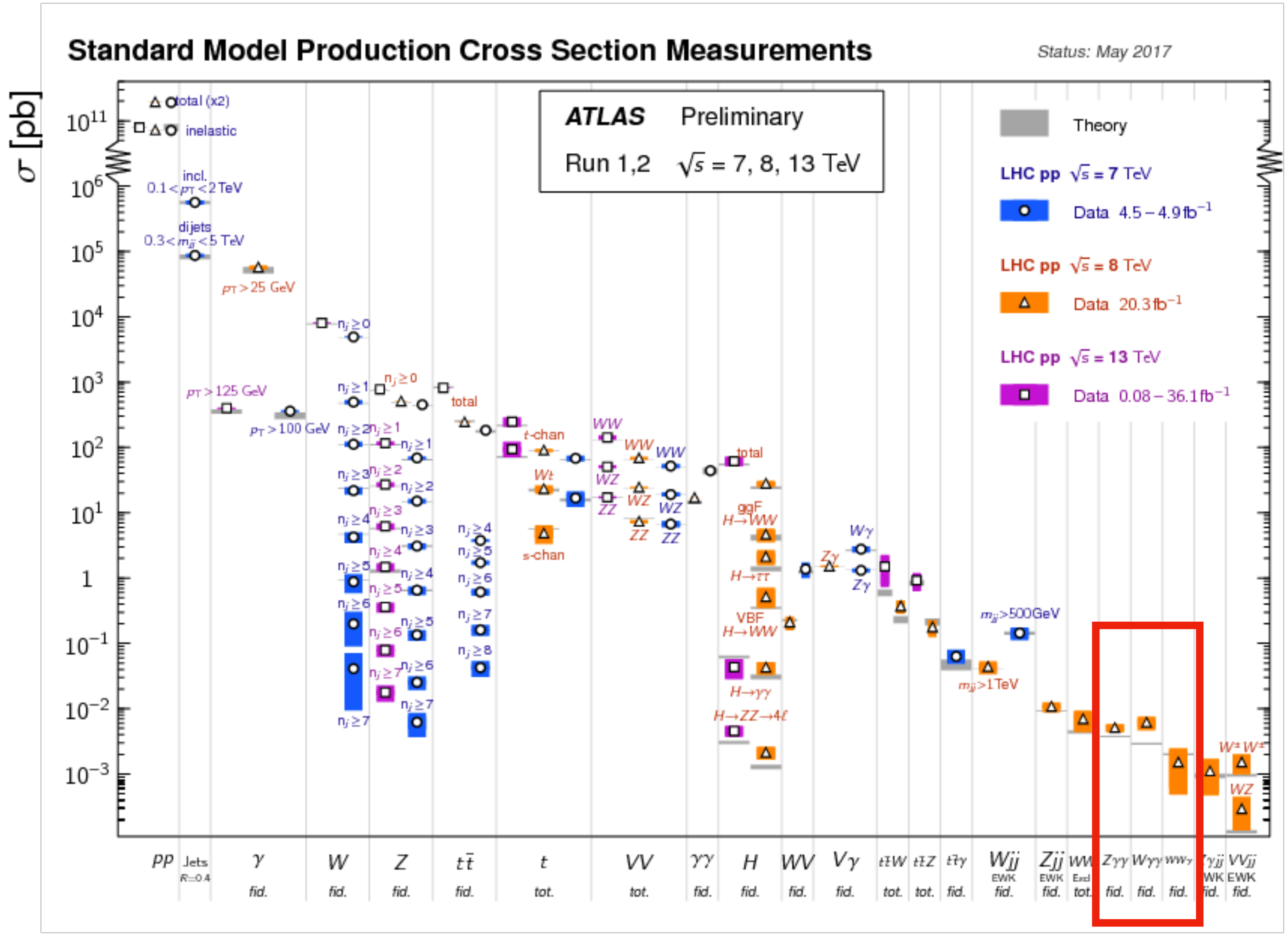


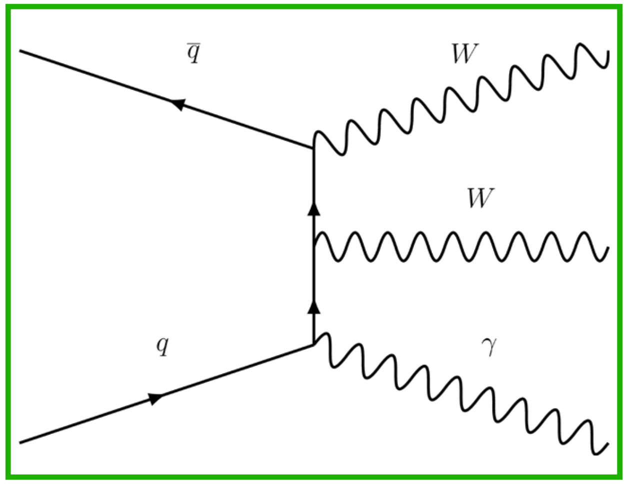
Why rare processes?

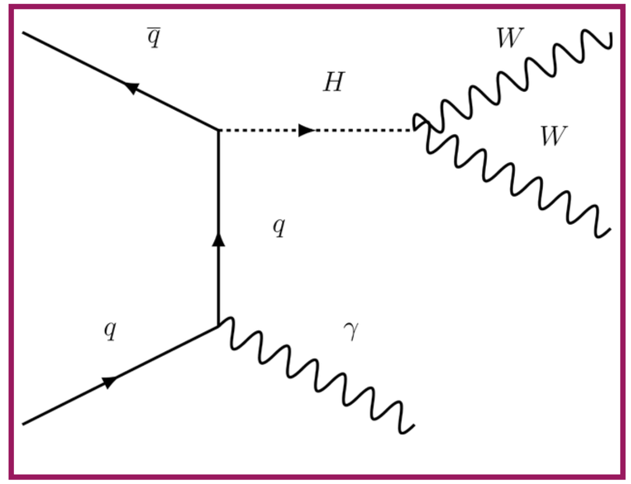
- Rare production modes become fully accessible with Run 2 data
  - Many recent first observations!
- No signs of new physics beyond the SM brought by searches at LHC
- Further test SM by measuring more precisely rare processes which are not yet well measured

Triboson measurements with ATLAS and CMS

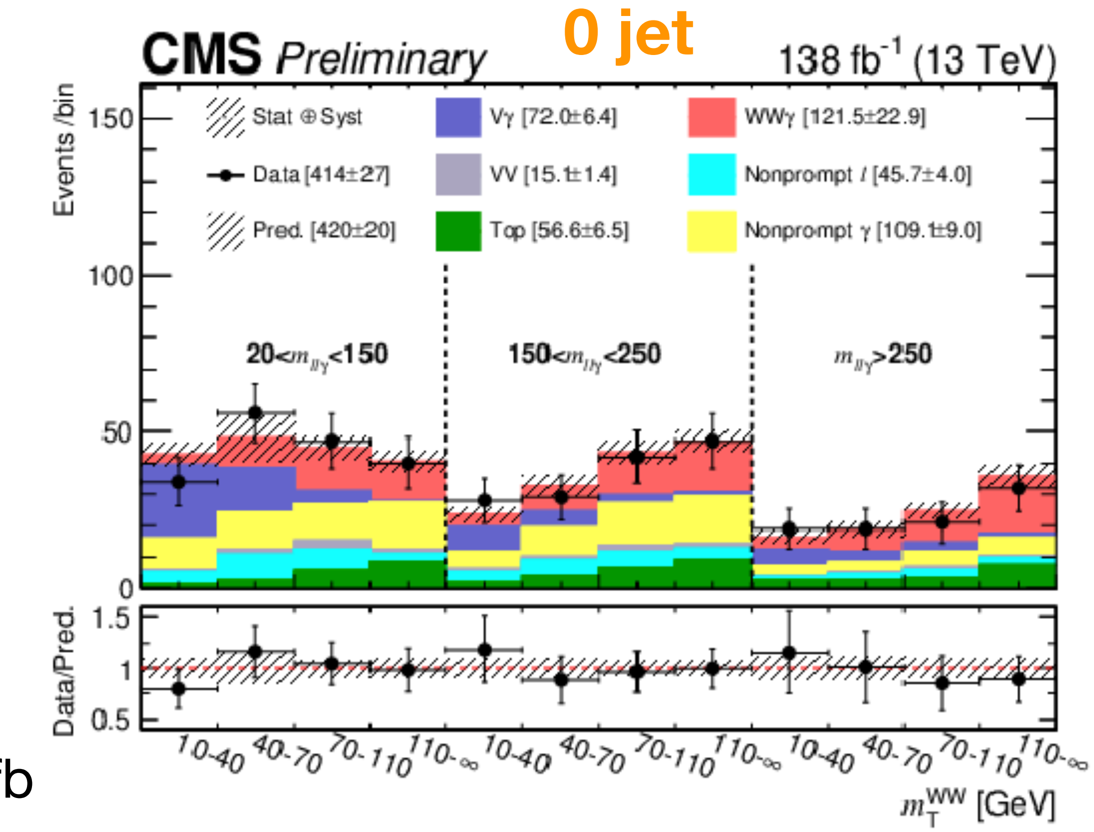
- Triboson final states have small cross section
- Sensitive to Anomalous Quartic Gauge Coupling (AQGC)
- Limit to Effective Field Theories can be set
- Understand those process as they are backgrounds for further analyses in run 3 (ZH(γγ) WH(γγ))

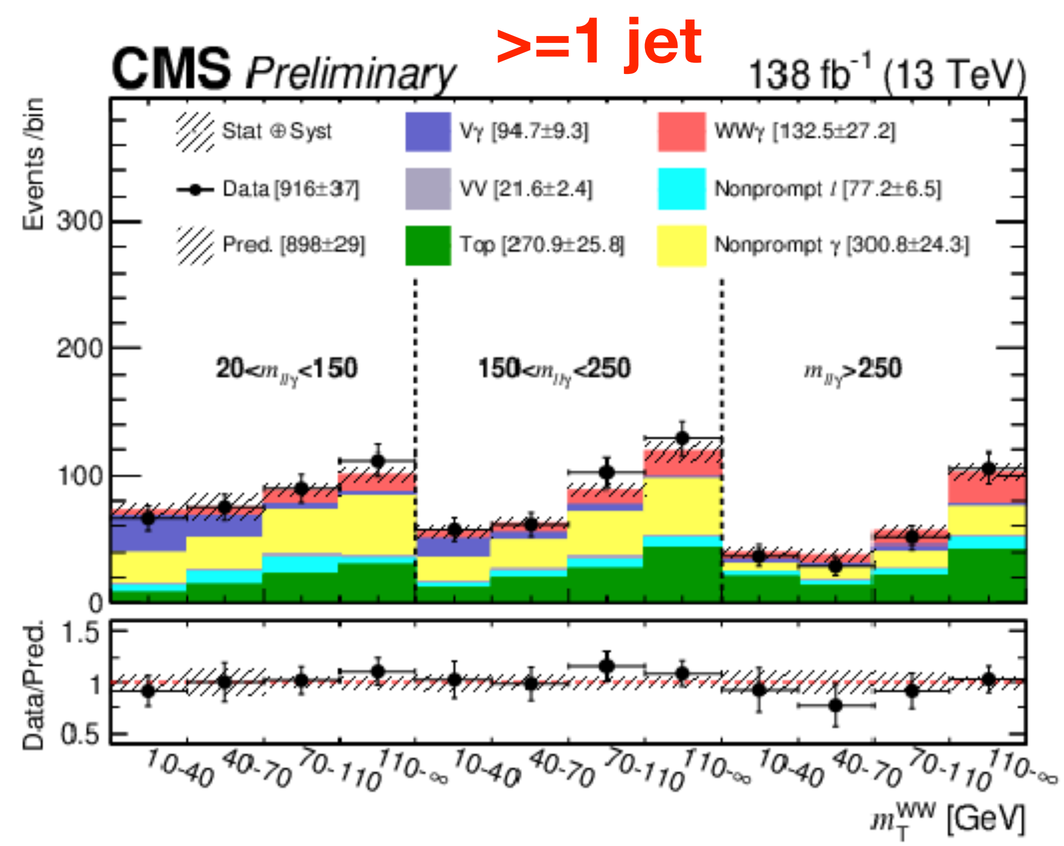






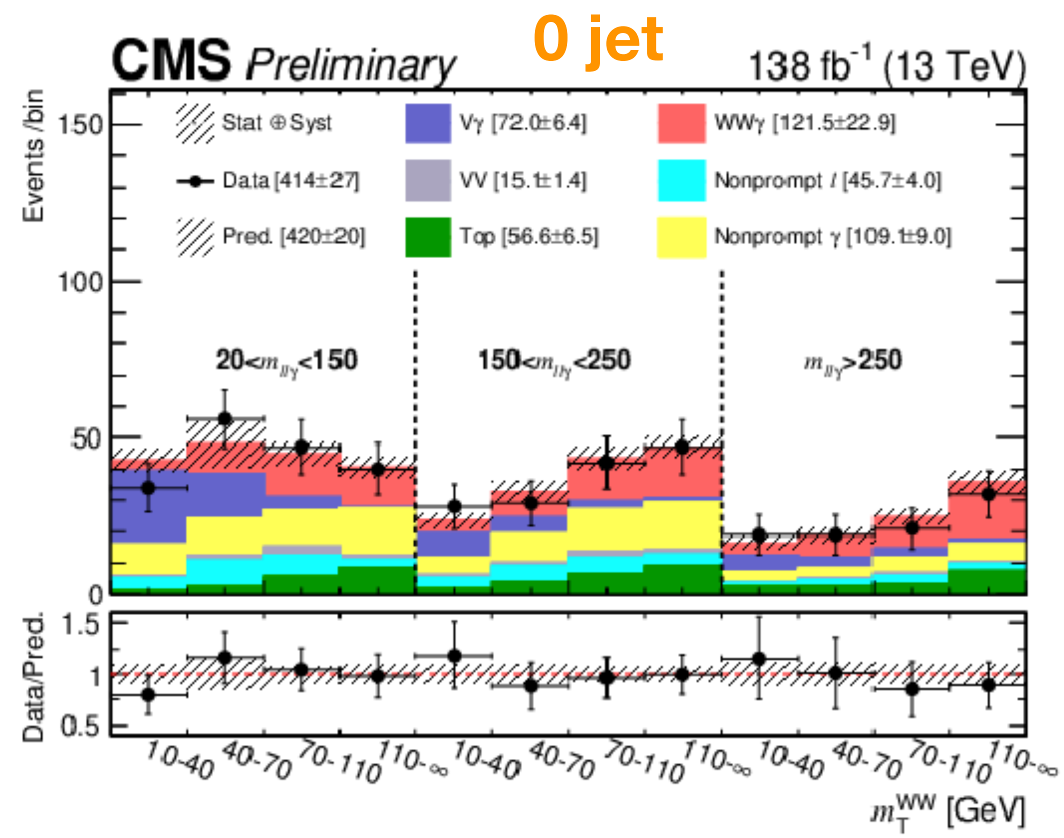
- First measurement of $WW\gamma$ fiducial cross section with 5.6 (4.7) standard deviation observed (expected)
  - $\sigma_{\text{measured}} = 6.0 \pm 1.0\ (\text{stat}) \pm 1.0\ (\text{syst}) \pm 0.9\ (\text{theo})$ fb within 1.5σ of theory prediction
  - $\sigma_{\text{Theory}} = 4.16 \pm 0.34\ (\text{scale}) \pm 0.05\ (\text{PDF})$ fb
- Using opposite charge opposite flavor e/μ channel with 138 fb^{-1} at 13 TeV
  - b-jet veto
  - Likelihood 2D fit on M_T^{WW} and $M_{ll\gamma}$, using SR (splitting 0 jet and >=1 jet) and 2VR
- Limit on Higgs Yukawa couplings with light quarks (u,d,s,c)





$WW\gamma$ [CMS PAS SMP-22-006]

- Background treatment
  - Non prompt photon/lepton
    - $j \to \gamma$ main background; Data driven estimation in W+jets Control Region (CR)
    - $j \to e$ significant background; Data driven fake rate estimate in dijet CR
    - Validation; Top+γ VR with ≥ 1 b-jet for both background; Same flavor lepton final state CR for j→ e background
  - $WZ\gamma$ and top; reduced by b-jet veto



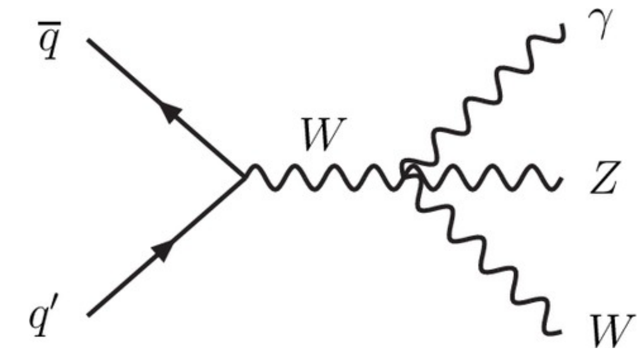
Limit on Higgs Yukawa couplings

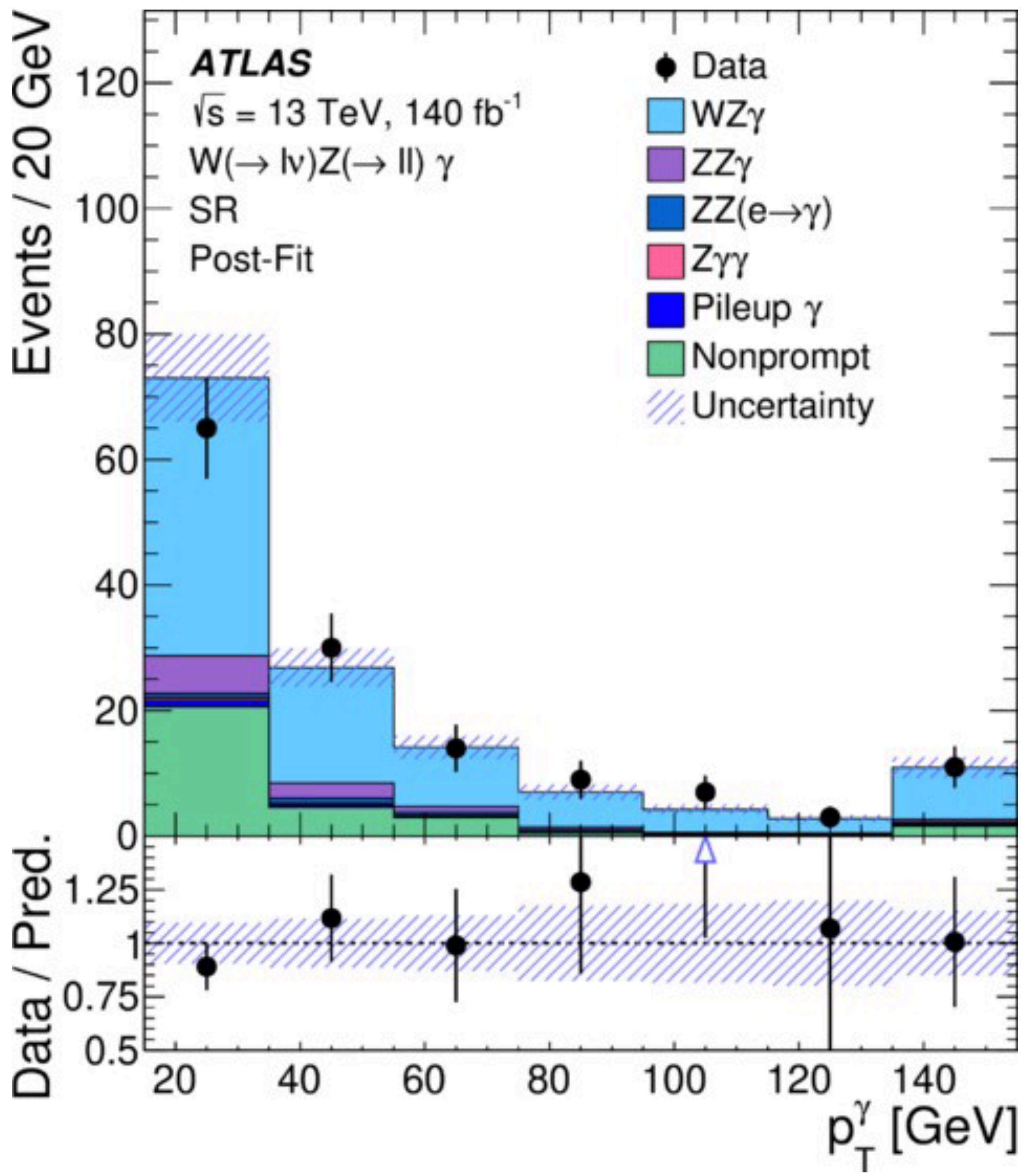
Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq$13000 (16000)
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq$14000 (17000)
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq$1300 (1700)
$c\bar{c} \to H + \gamma \to e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq$110(200)

$WZ\gamma$ [STDM-2019-17]

ATLAS EXPERIMENT

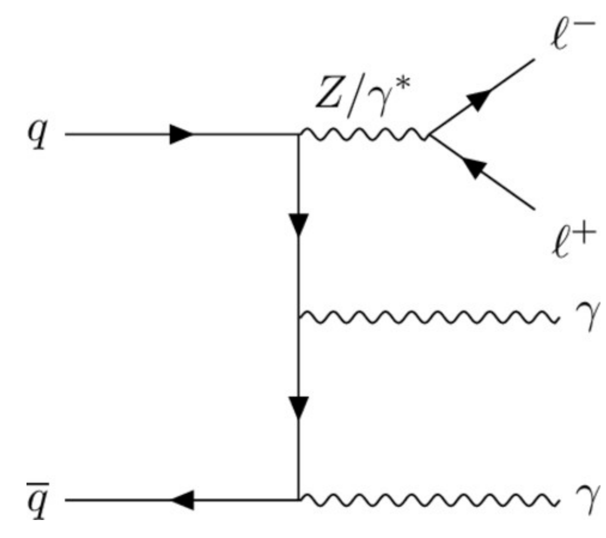
- First measurement of $WZ\gamma$ cross section with 6.3 (5.0) standard deviation observed (expected)
  - $\sigma_{\text{measured}} = 2.01 \pm 0.3$ (stat) ± 0.16 (syst) fb within 1.5σ of theory prediction
  - $\sigma_{\text{Theory}} = 1.5 \pm 0.06$ fb
- Using llly channel one same flavor opposite charge pair with 140fb^{-1} at 13TeV
  - $|m_{e(W)\gamma} - m_Z| > 10$ GeV
  - $m_{l(Z)l(Z)} > 81$ GeV for FSR reduction
  - Profile likelihood fit of the 4 e/μ final states (3 bins, 1SR and 2CR)
- Background treatment
  - $j \to \gamma$ background; reduced by $m_{e(W)\gamma}$ selection; data driven fake rate estimation in looser identification/ isolation selection CD using Z+jets sample
  - $j \to l$ background; data driven fake rate estimation in looser identification/ isolation selection CD using dijet sample
  - $ZZ\gamma$ and $ZZ(e \to \gamma)$; normalized with dedicated CR



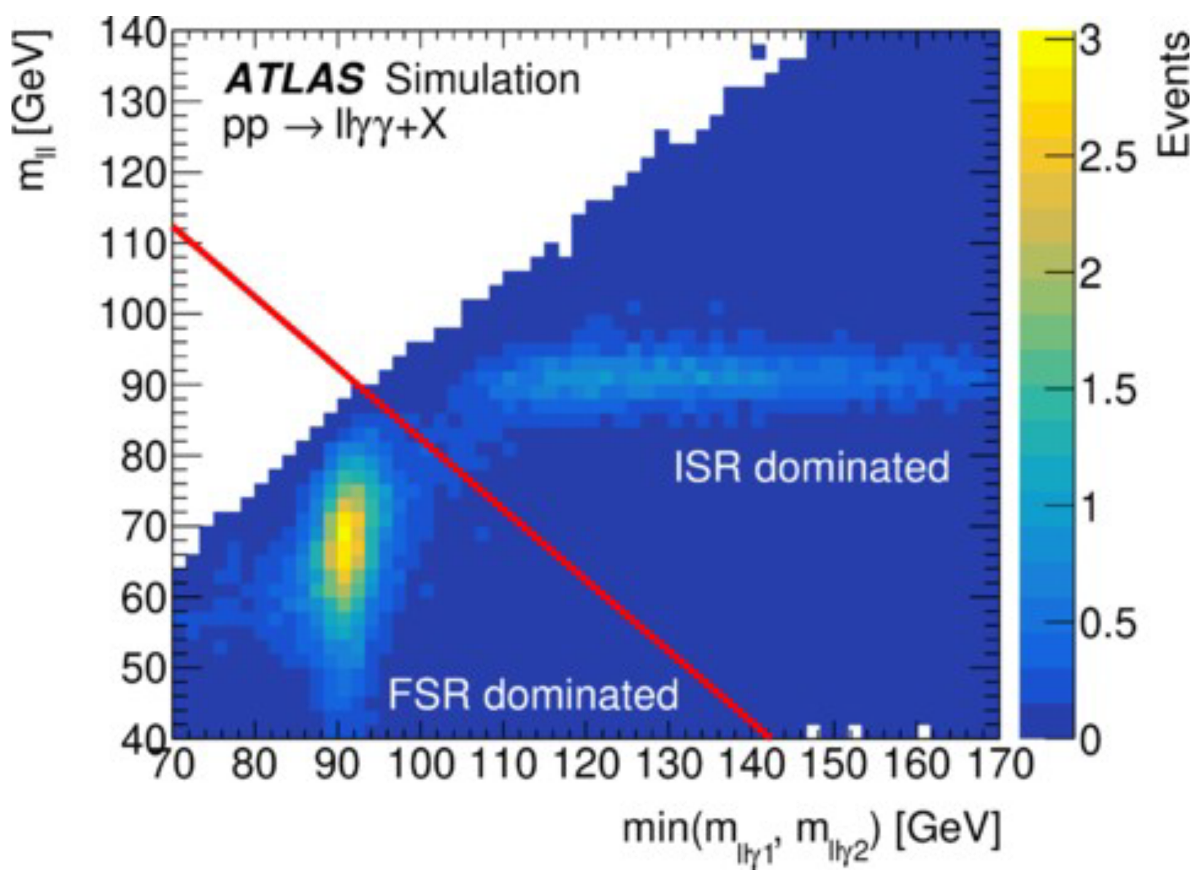


$Z\gamma\gamma$ [Phys. J. C 83, 539]

- Fiducial cross section
  - $\sigma_{\text{measured}} = 2.45 \pm 0.20$ (stat) $\pm\, 0.22$ (syst) $\pm\, 0.04$(lumi) fb measurement with 12% precision
- Using e/μ channel with 139 fb^{-1} at 13 TeV
  - $(m_{ll} + min(m_{ll\gamma,1}, m_{ll\gamma,2})) > 2M_Z$ for FSR contribution
  - Differential cross-sections (6 kinematic observables: $E_T^{\gamma 1}, E_T^{\gamma 2}, p_T^{ll}, p_T^{ll\gamma\gamma}, m_{\gamma\gamma}, m_{ll\gamma\gamma}$
- Background treatment
  - $j \to \gamma$ main background; data driven fake rate estimate using $Z\gamma$+jet and Z+jet
  - $tt\gamma\gamma$ with leptonic decay from top quark (second contribution); normalized using CD with opposite sign e/μ pair
  - $Z\gamma + \gamma$ and $Z + \gamma\gamma$ from pile-up; Uncertainties computed via signal simulation reweighed to pile-up background p_T spectra
  - $e \to \gamma$; Modelled by ZZ and $ZW\gamma$ simulation
  - $Z(ll)H(ll)$; Estimated from simulation

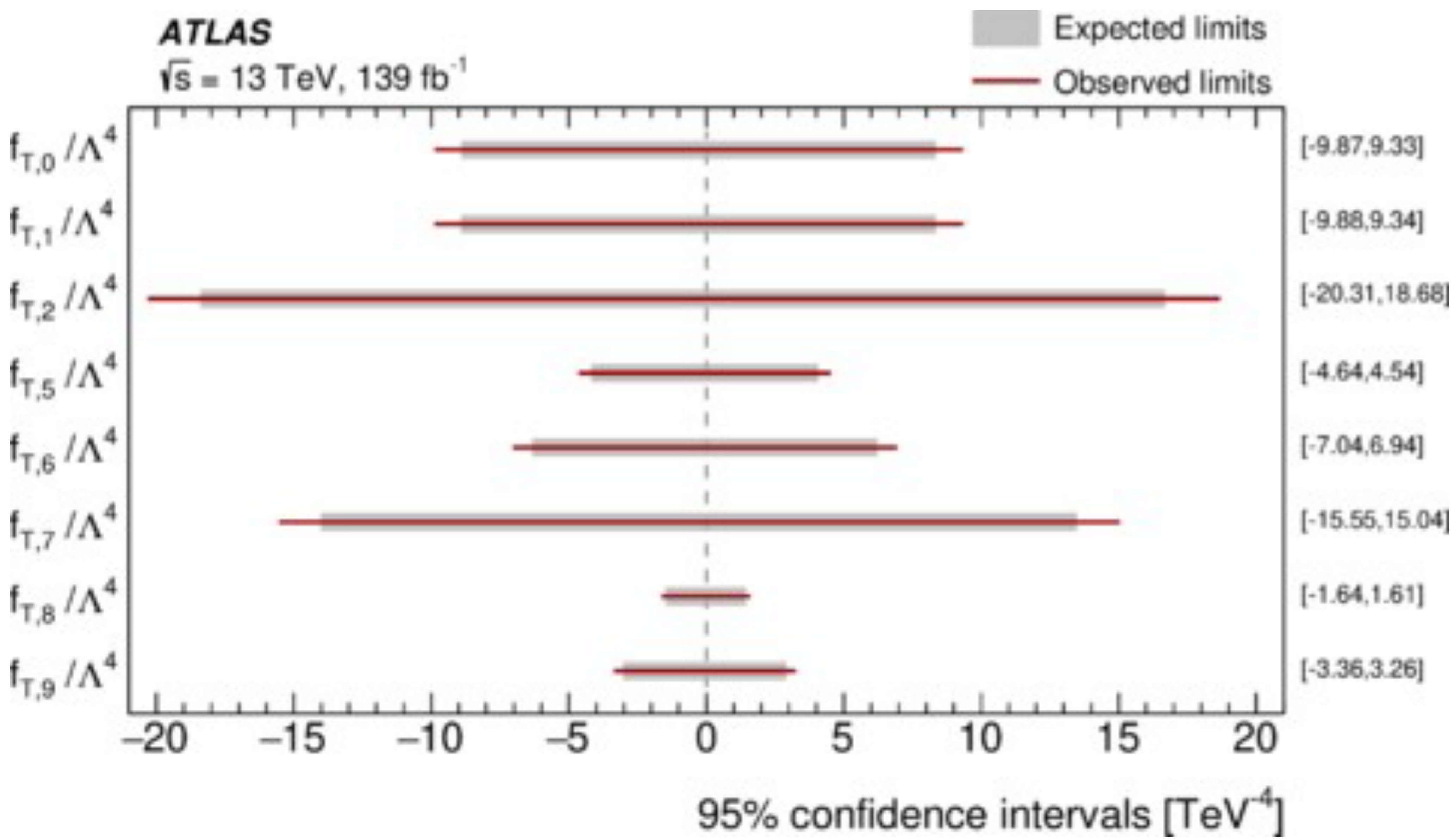


Distinction between ISR and FSR events when the Z boson is on-shell

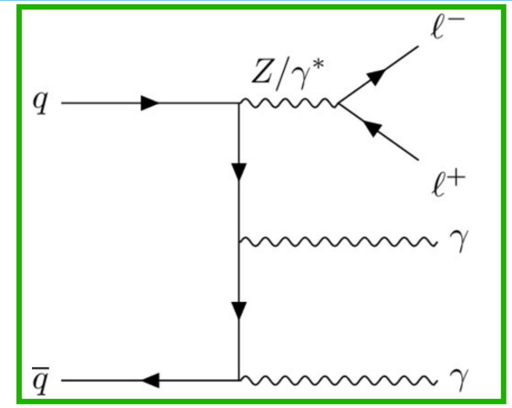


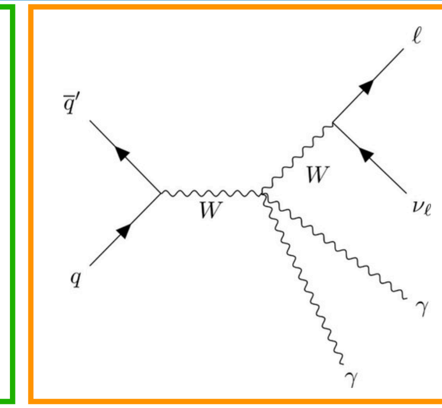
$Z\gamma\gamma$ [Phys. J. C 83, 539]

- Limit set on aQGC operators using EFT approach
- $O8_{T,1}$, $O8_{T,2}$, $O8_{T,6}$, $O8_{T,7}$ reduced up to two order of magnitude at 8 TeV (Phys. Rev. D 93, 112002)



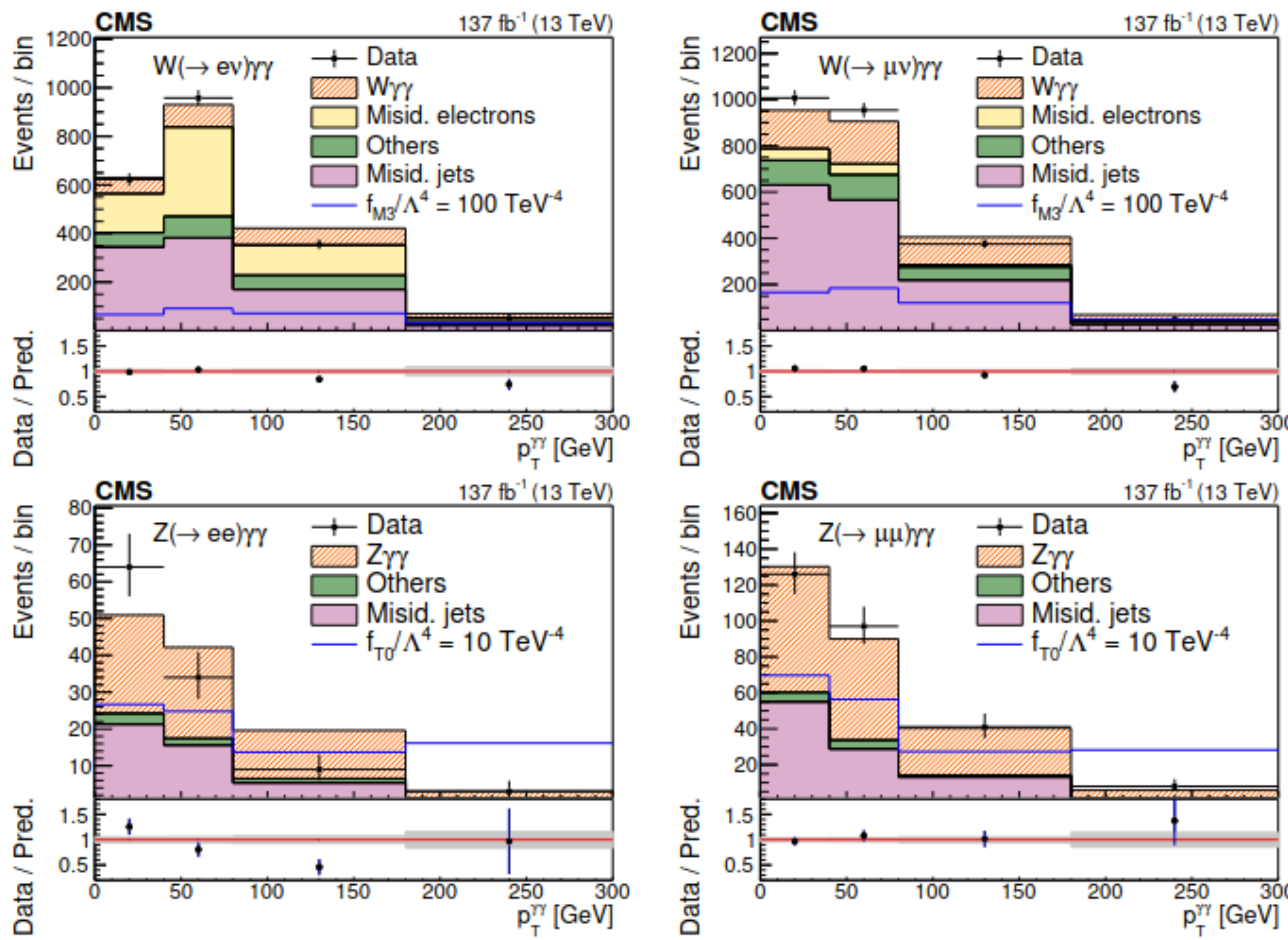
$V\gamma\gamma$ [JHEP10(2021)174]





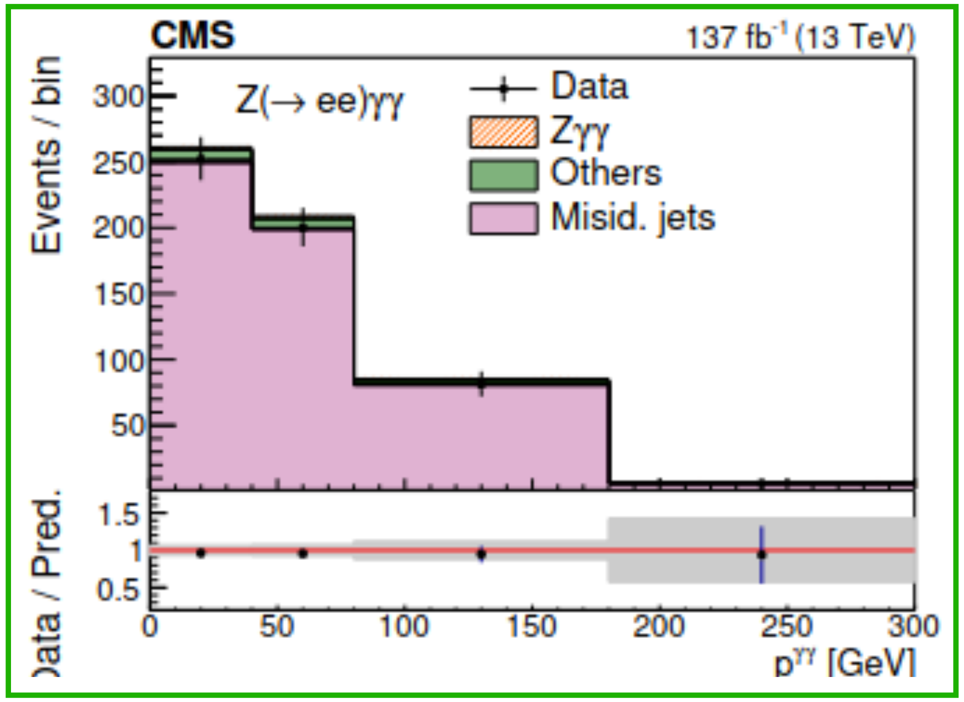
- $Z\gamma\gamma$ fiducial cross section
  - $\sigma(Z\gamma\gamma) = 5.41^{+0.58}_{-0.55}$ (stat)$^{+0.64}_{-0.70}$ (syst) $\pm$ 0.06 (PDF + scale) fb4.8 (5.8) standard deviation observed (expected)
- $W\gamma\gamma$ fiducial cross section
  - $\sigma(W\gamma\gamma)^{\text{meas}} = 13.6 \pm 1.9$ (stat) $\pm$ 0.4 (syst) $\pm$ 0.08 (PDF + scale) fb 3.1 (4.5) standard deviation observed (expected)

- Using e/μ channel with 137 fb^{-1} at 13 TeV
  - Event removed if $|m_{e,\gamma} - m_Z| < 5$ GeV or $|m_{e,\gamma\gamma} - m_Z| < 5$ GeV
  - Binned likelihood fit on diphoton p_T distribution

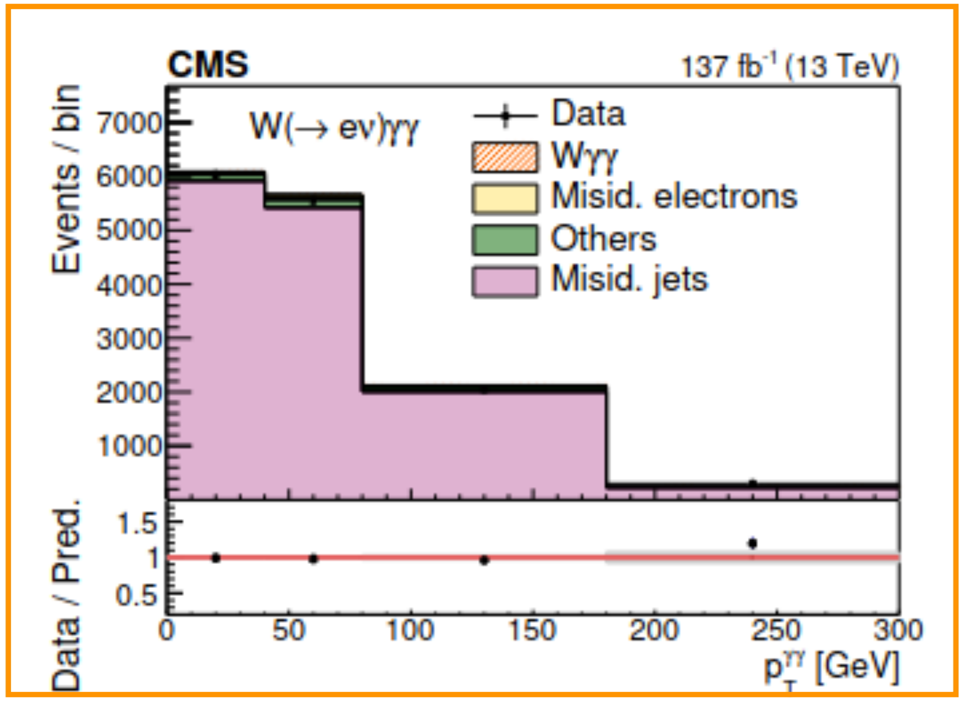


$V\gamma\gamma$ [JHEP10(2021)174]

- Background treatment:
  - $j \to \gamma$, dominant for both $W\gamma\gamma$ and $Z\gamma\gamma$; data-driven fakes rate estimates
  - $e \to \gamma$, important in $W(e)\gamma\gamma$
    - Coming from $Z\gamma$ events
    - Corrector factor computed in CR ($|m_{e,\gamma\text{lead}} - m_Z| < 5$ GeV removed) with fit on $m_{e,\gamma\text{lead}}$
  - $VH(\gamma\gamma)$ neglected
- Limit set on 10 aQGC operators using EFT approach

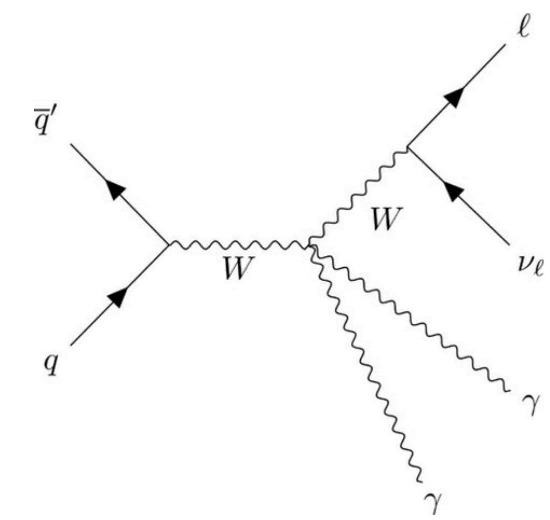


	$W\gamma\gamma$ (TeV^{-4})		$Z\gamma\gamma$ (TeV^{-4})	
Parameter	Expected	Observed	Expected	Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T2}/Λ^4	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
f_{T5}/Λ^4	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
f_{T6}/Λ^4	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
f_{T7}/Λ^4	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
f_{T8}/Λ^4	—	—	[−0.90, 0.94]	[−1.06, 1.10]
f_{T9}/Λ^4	—	—	[−1.54, 1.54]	[−1.82, 1.82]

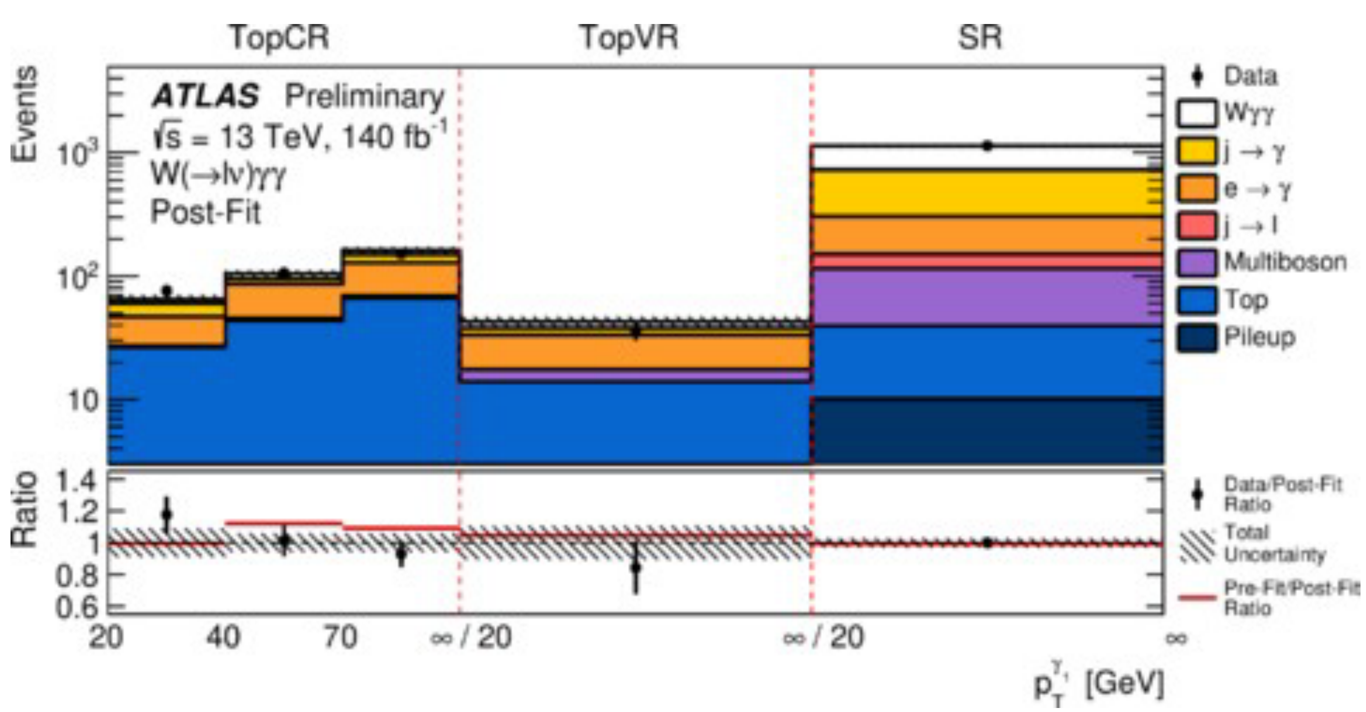


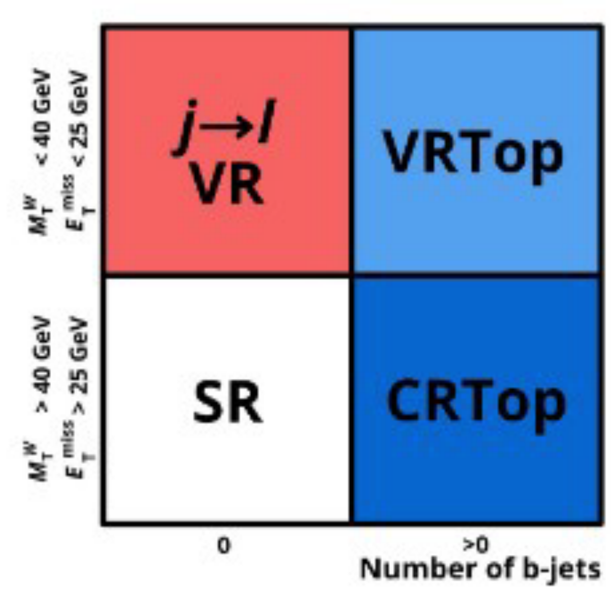
$W\gamma\gamma$ [STDM-2018-33]

- First measurement of $W\gamma\gamma$ at 5.6 (5.6) standard deviation observed (expected)
  - $\sigma_{\text{measured}} = 12.2 \pm 1.0\ (\text{stat}{}^{+1.9}_{-1.8}\ (\text{syst}) \pm 0.01(\text{lumi})$ fb in agreement with the SM prediction
- Using e/μ channel with 140 fb^{-1} at 13 TeV
  - b-jet veto and $E_T$miss > 40 GeV selection
  - 4 bin likelihood fit (using topCR, topVR, and SR)



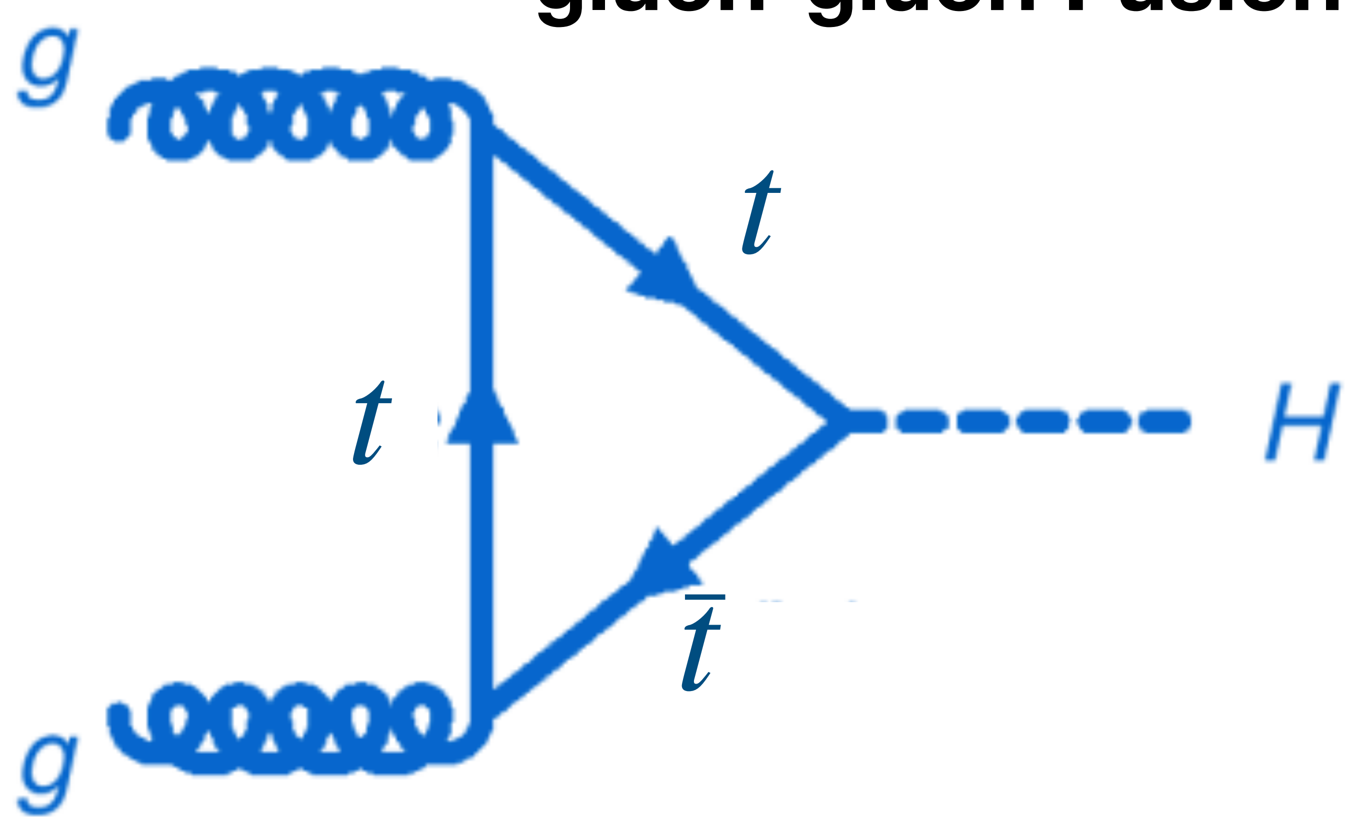
- Background treatment:
  - $j \to \gamma$ main background; 2D (leading/sub-leading) template fit of photon isolation energy in data
  - $e \to \gamma$; Data driven fake rate estimate in Z→ee/eγ CR
  - Top background; Reduced via b veto; Dedicated CR (with >= 1 b-jet) for fit constrain; Low E_{Tmiss} region (with >= 1 b-jet) for validation



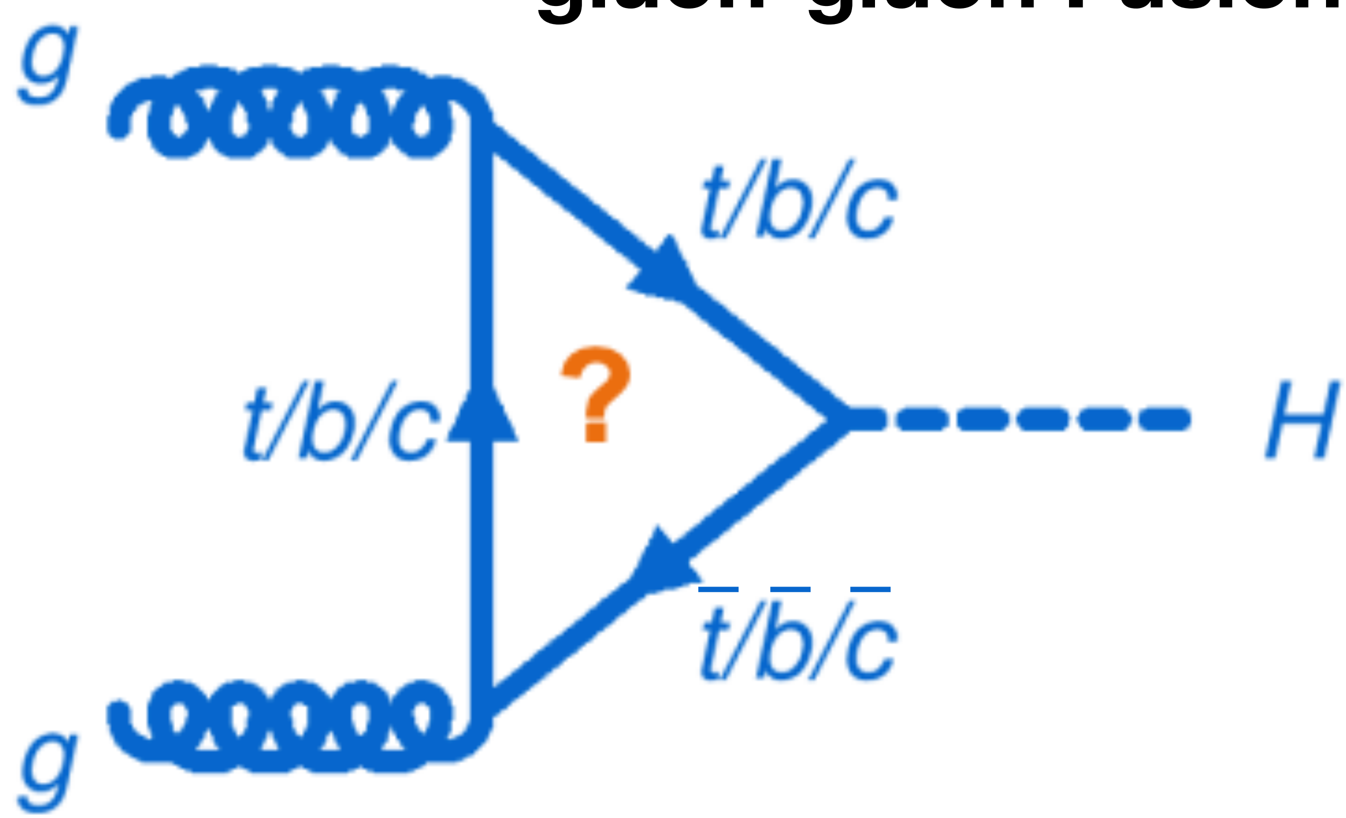


- Two ways to measure top-higgs coupling
- Dominant production mode of the Higgs boson at the LHC
- Proceeds primarily through a top quark loop

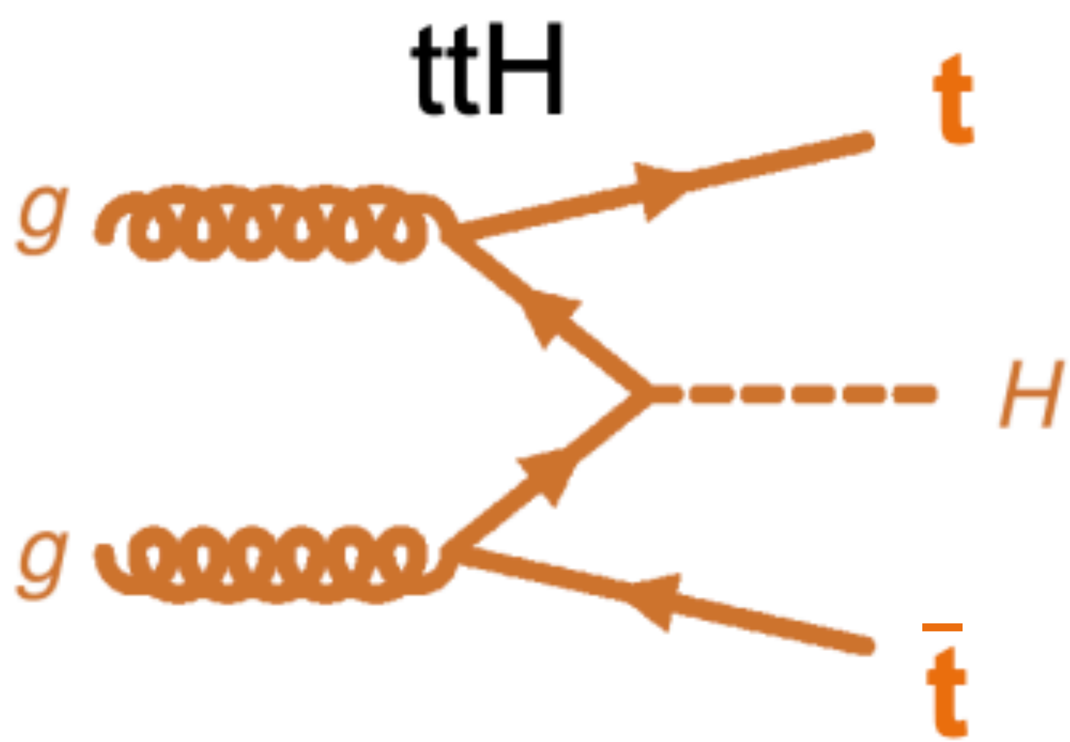
gluon-gluon Fusion

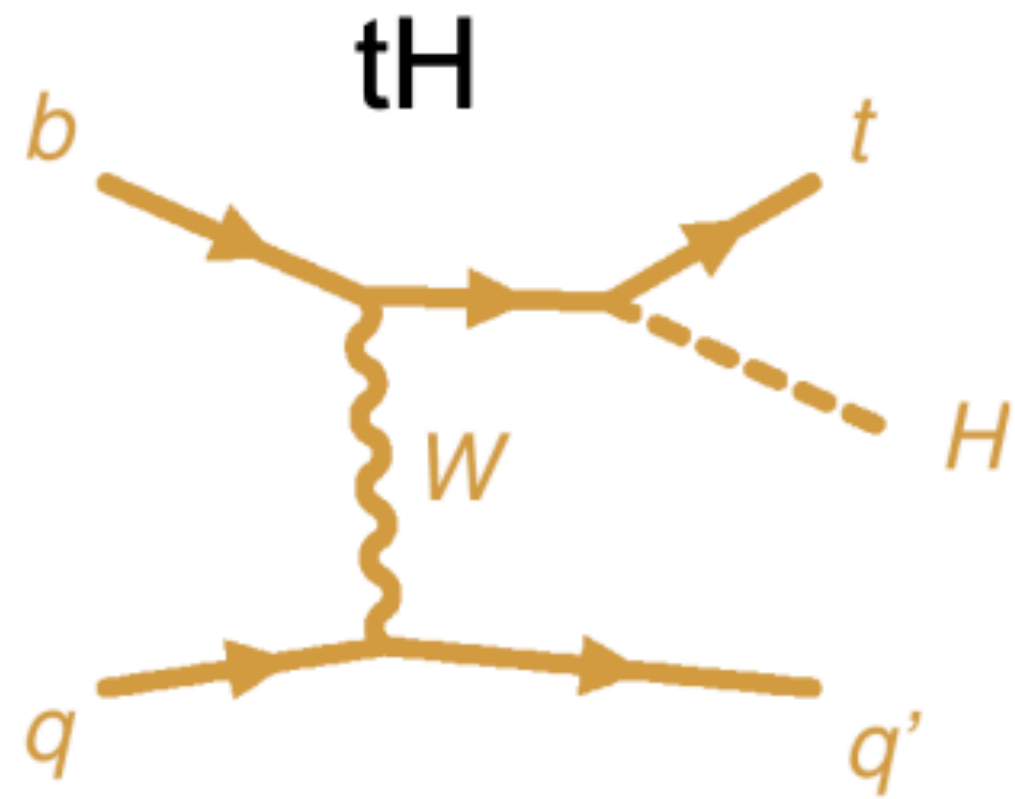


gluon-gluon Fusion



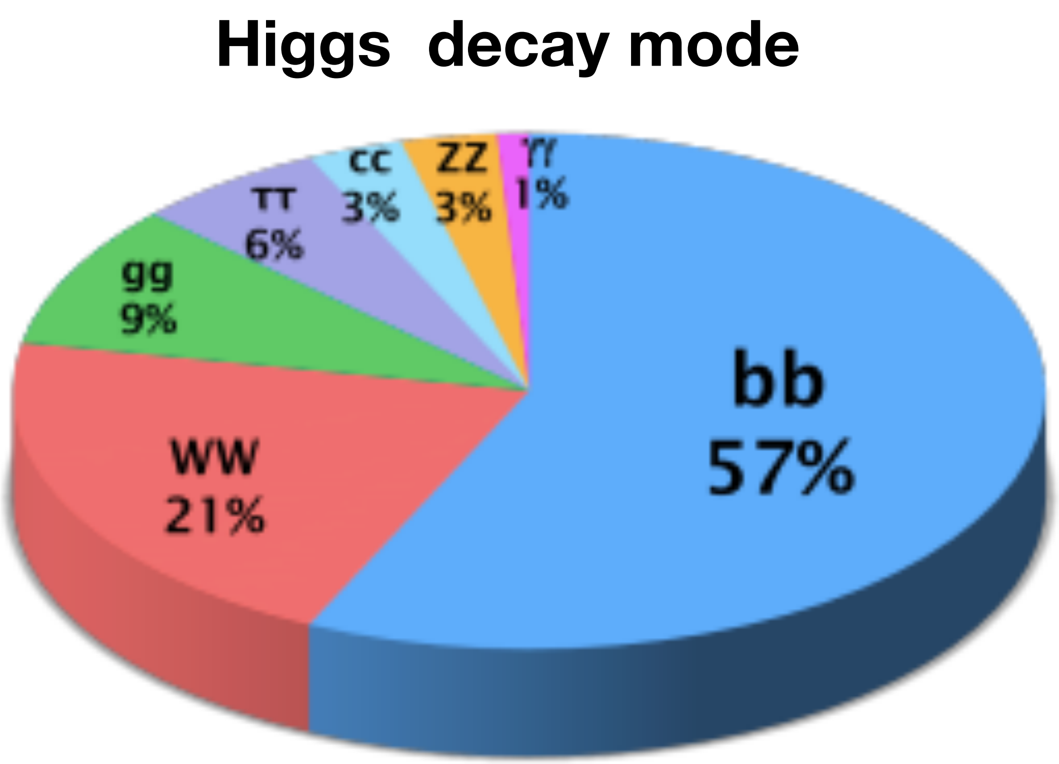
ttH+tH :
probe of top-Higgs coupling

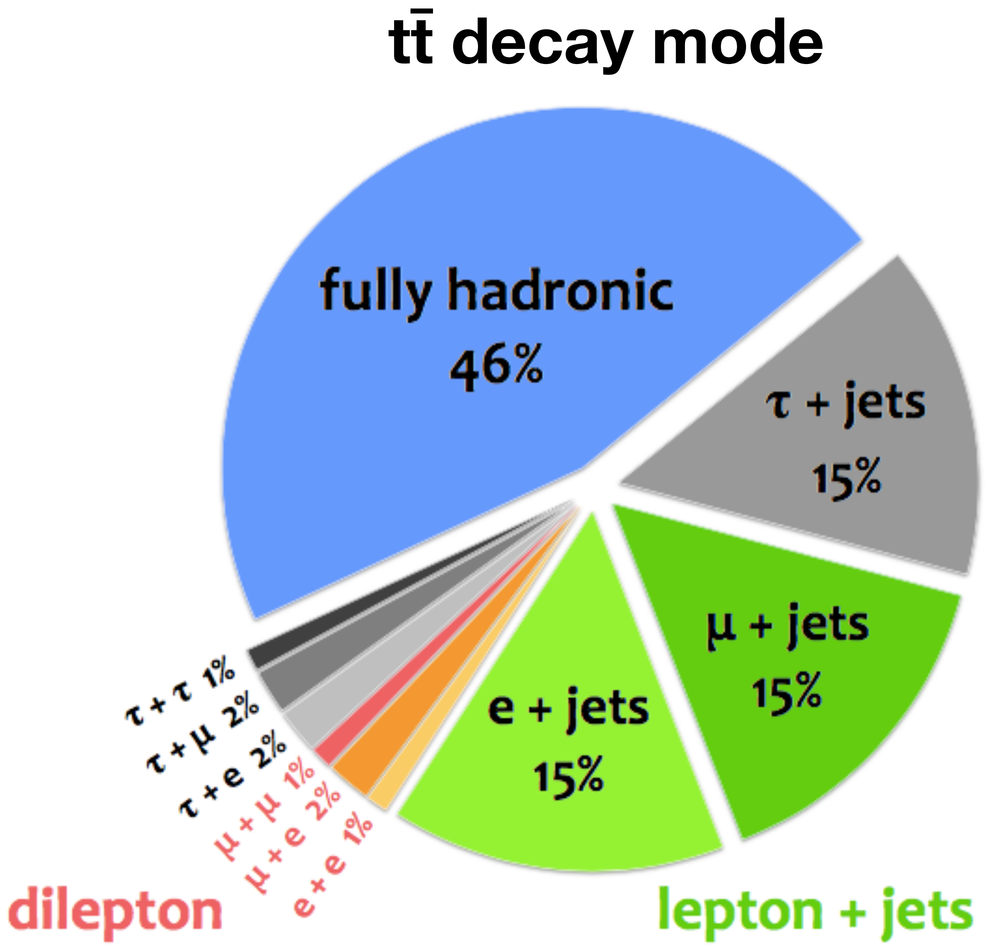




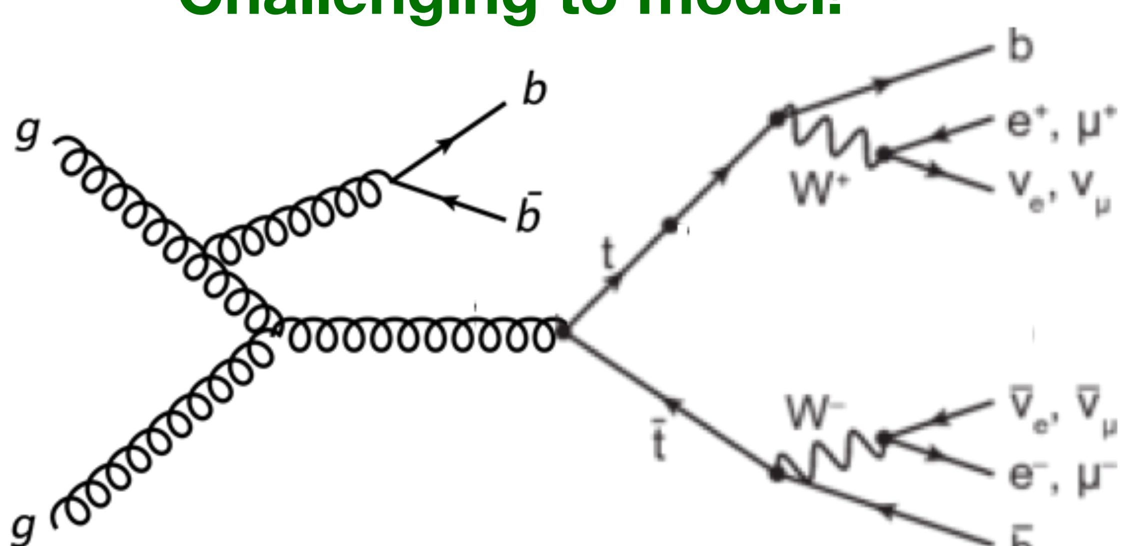
Only 1% of Higgs at LHC

Only 0.1%!!!



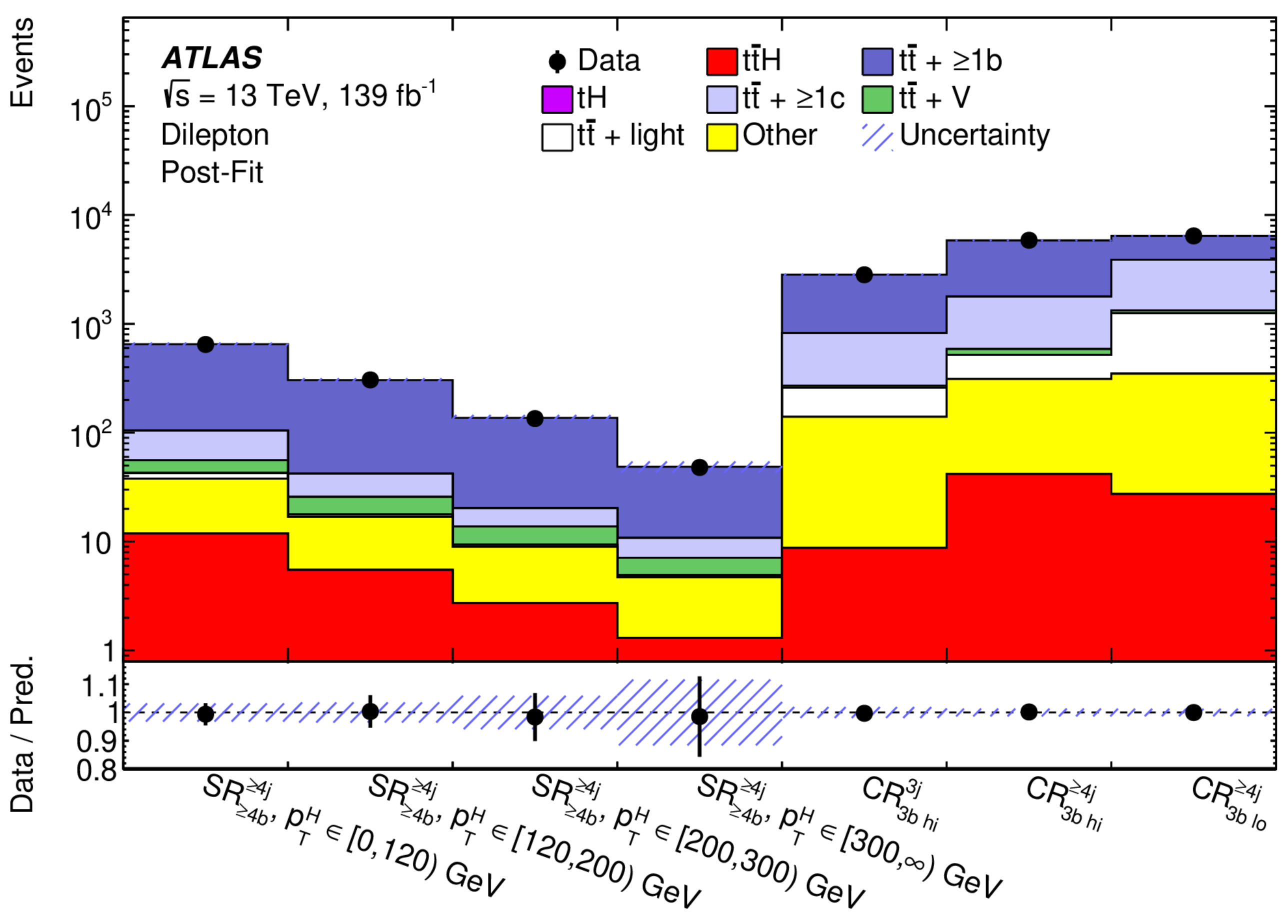


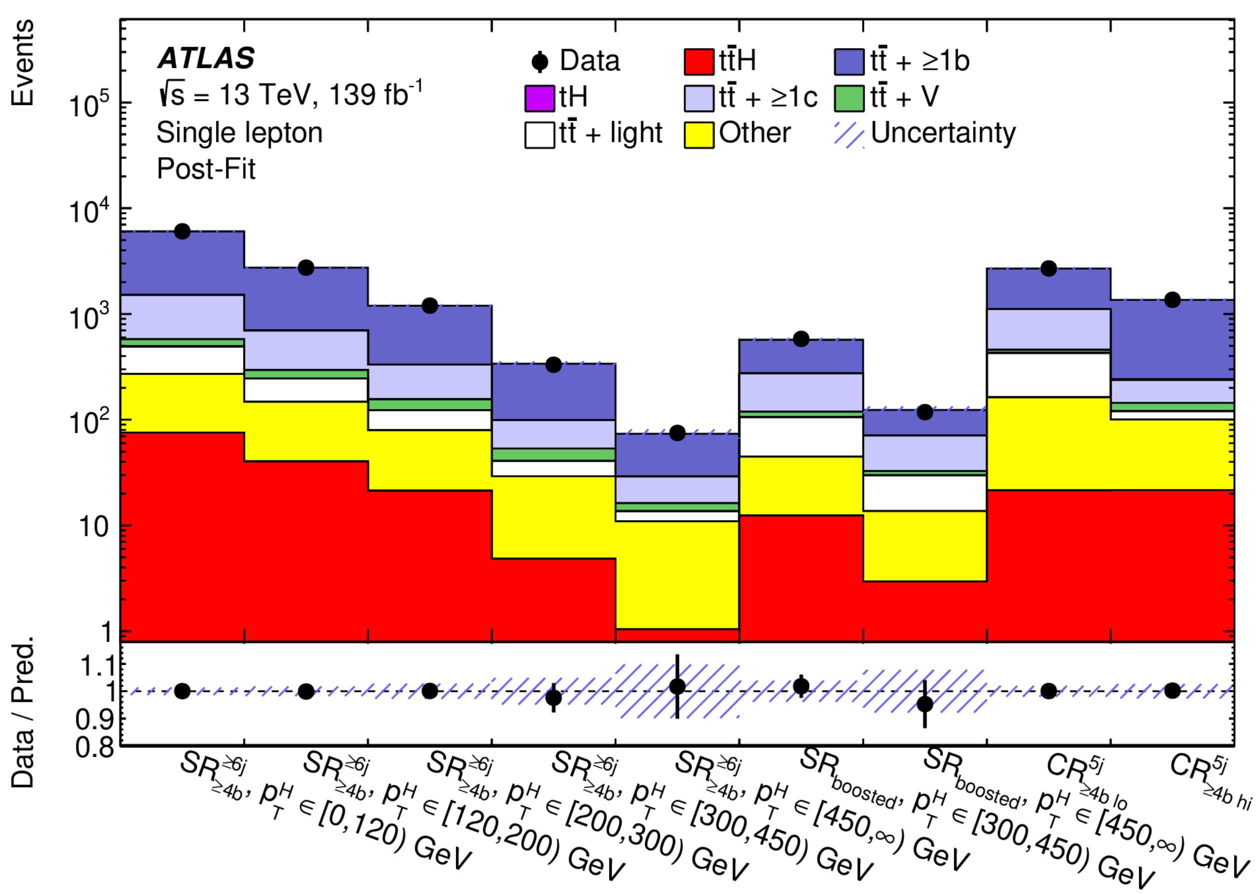
Large background from $t\bar{t}$+jets
Challenging to model!



$t\bar{t}H(H \to b\bar{b})$ [JHEP06(2022)97]

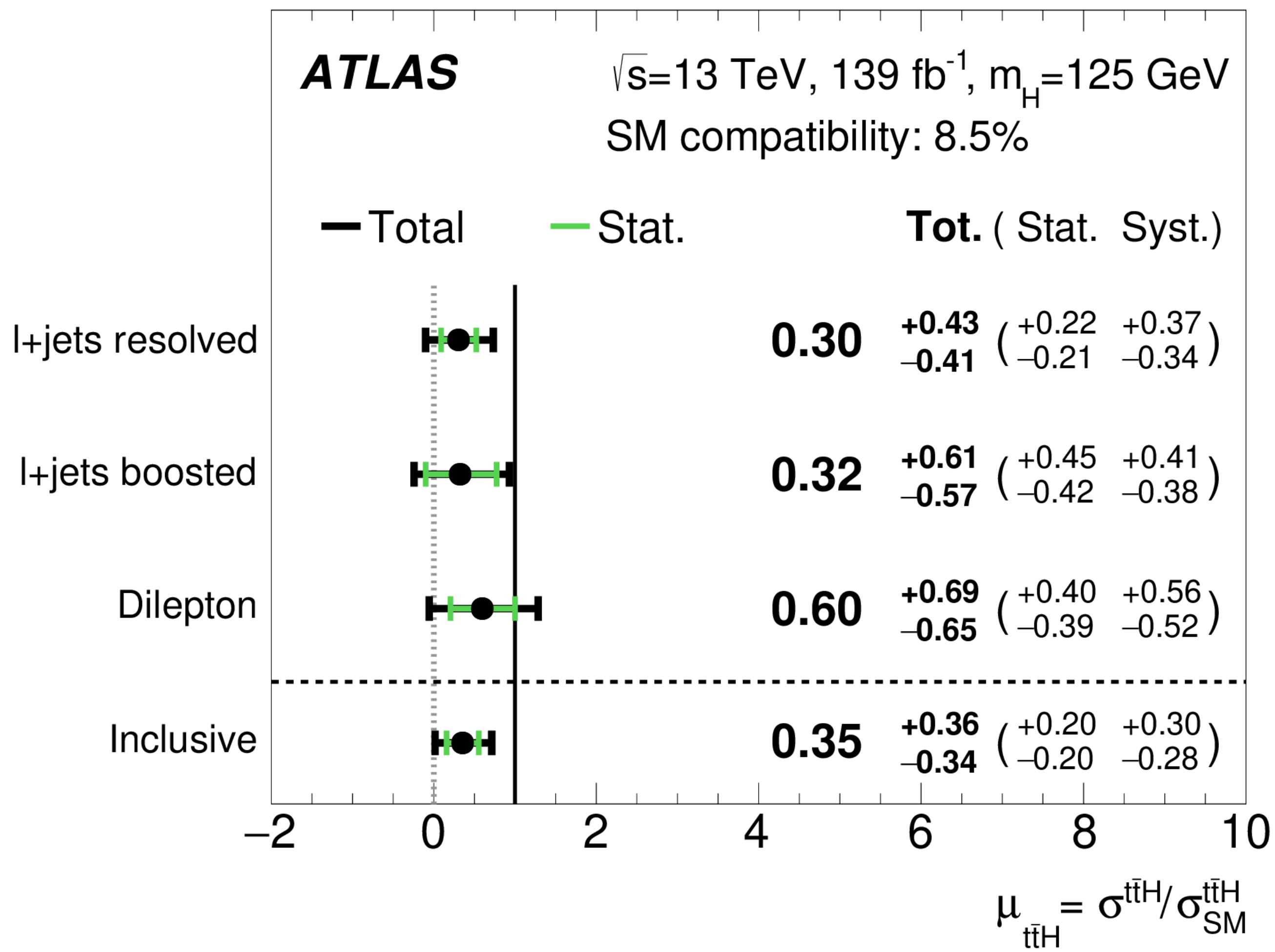
- Single lepton and dilepton regions
- Signal and control regions depending on number of jets and b-jets
- Single lepton boosted for Higgs $p_T > 300$ GeV
- Classification BDT for signal regions and yields for control regions in fit

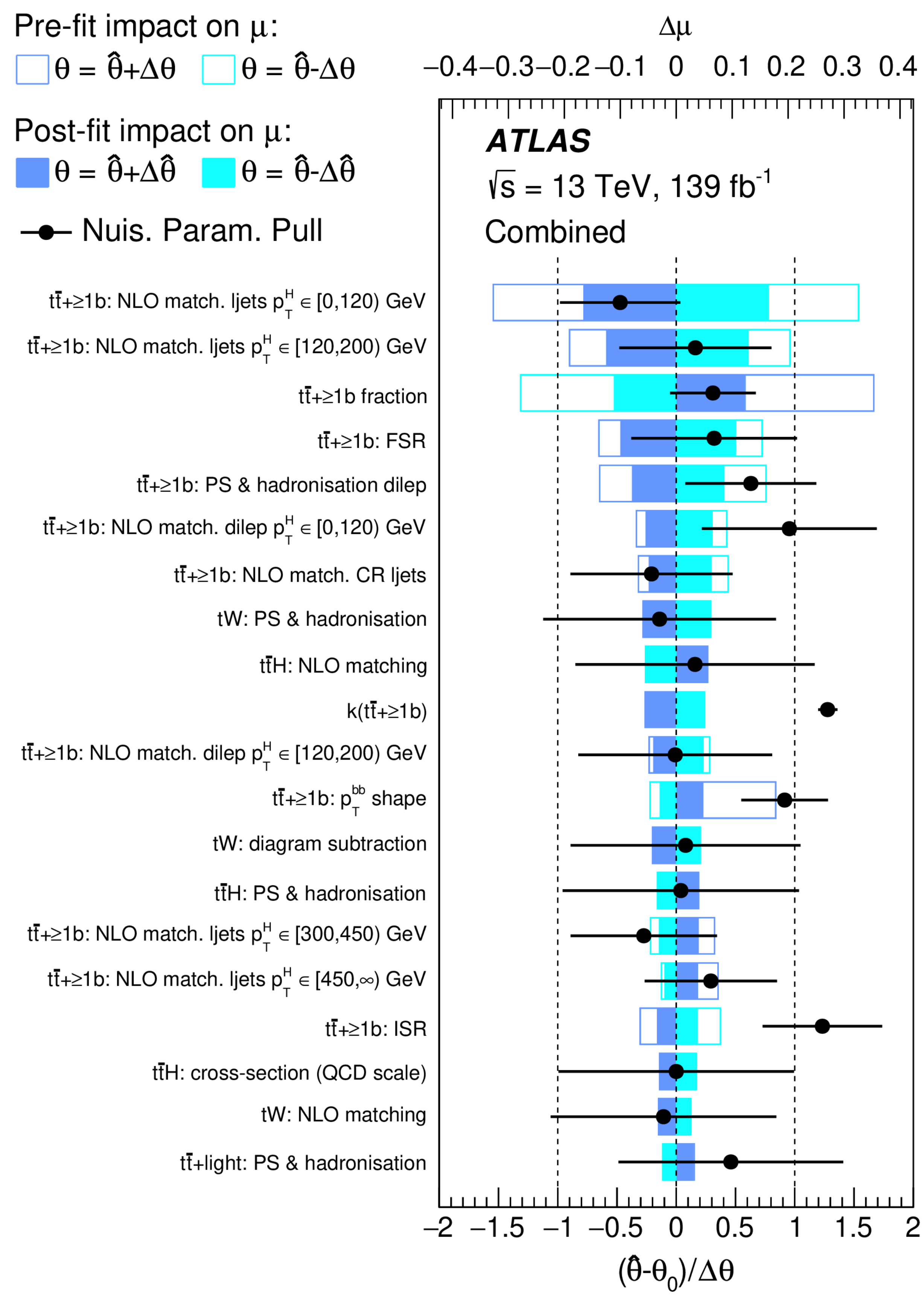




$t\bar{t}H(H \to b\bar{b})$ [JHEP06(2022)97]

Inclusive measurement

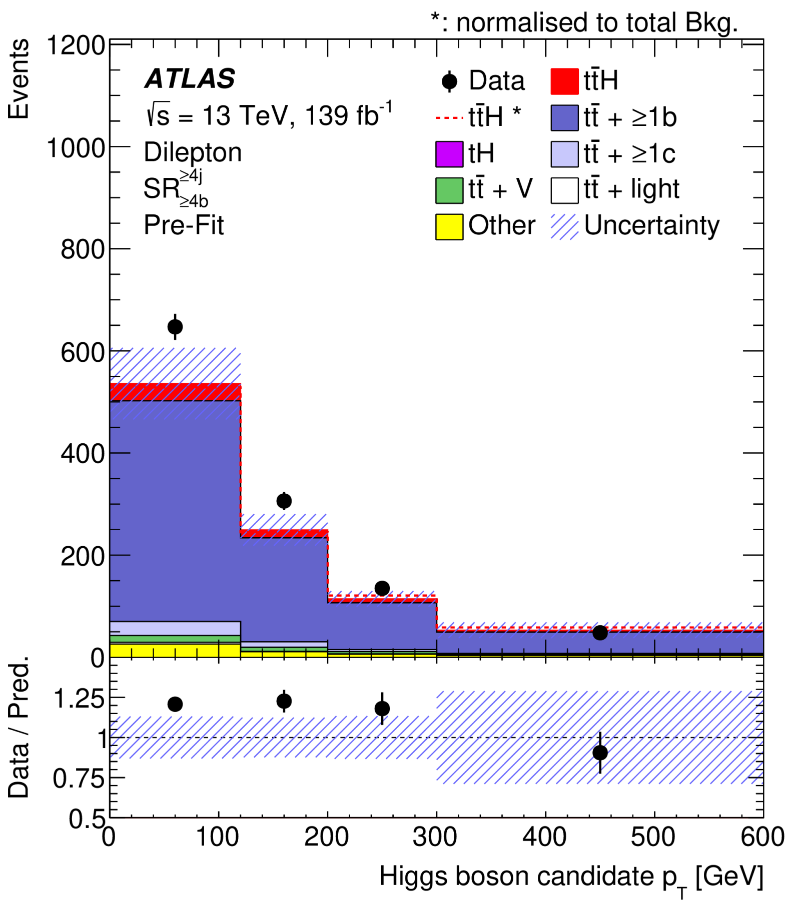


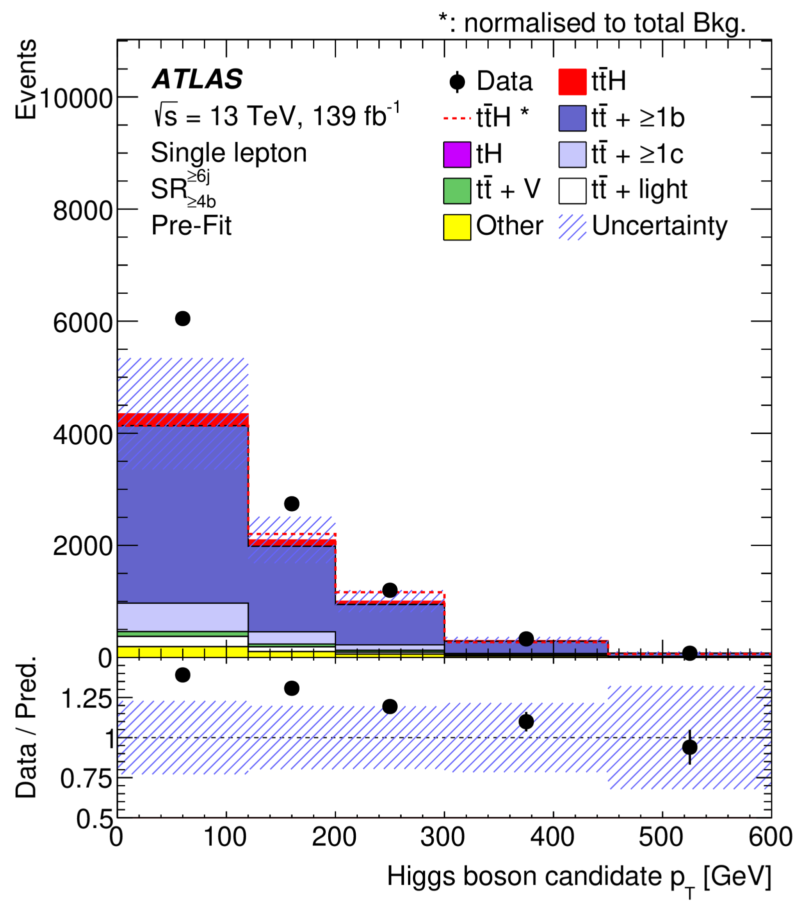


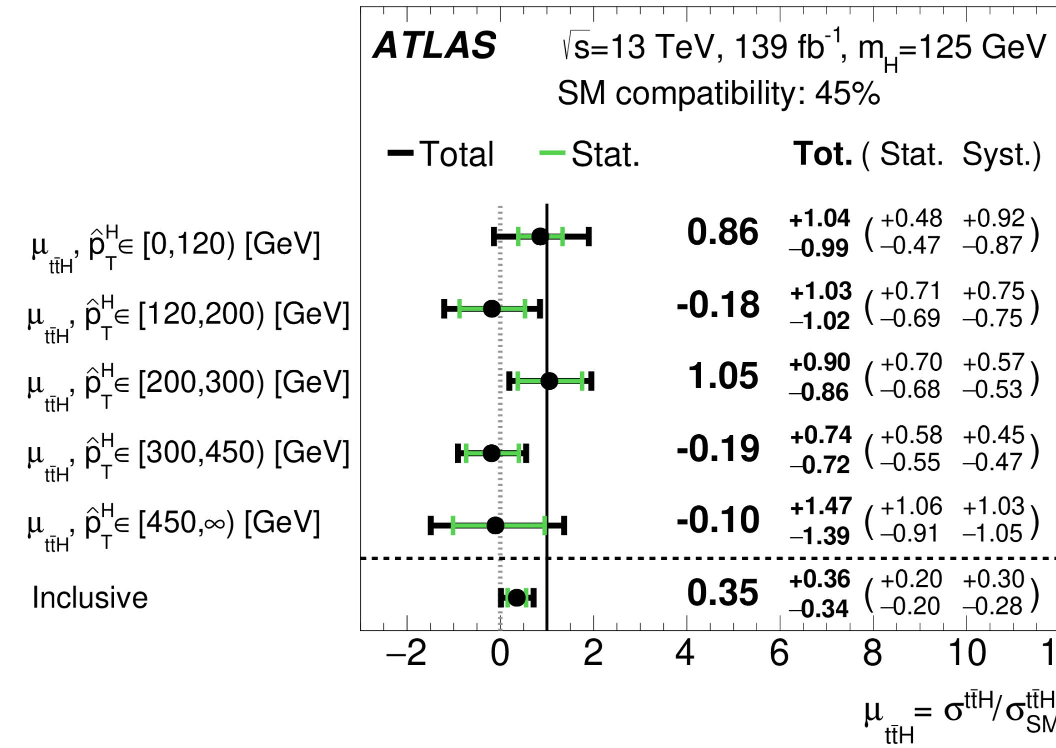
- Total uncertainty dominated by $t\bar{t}+\geq 1b$ modelling systematics
- No theoretical constraints applied to its cross section
- $k(t\bar{t}+\geq b) = 1.28 \pm 0.08$

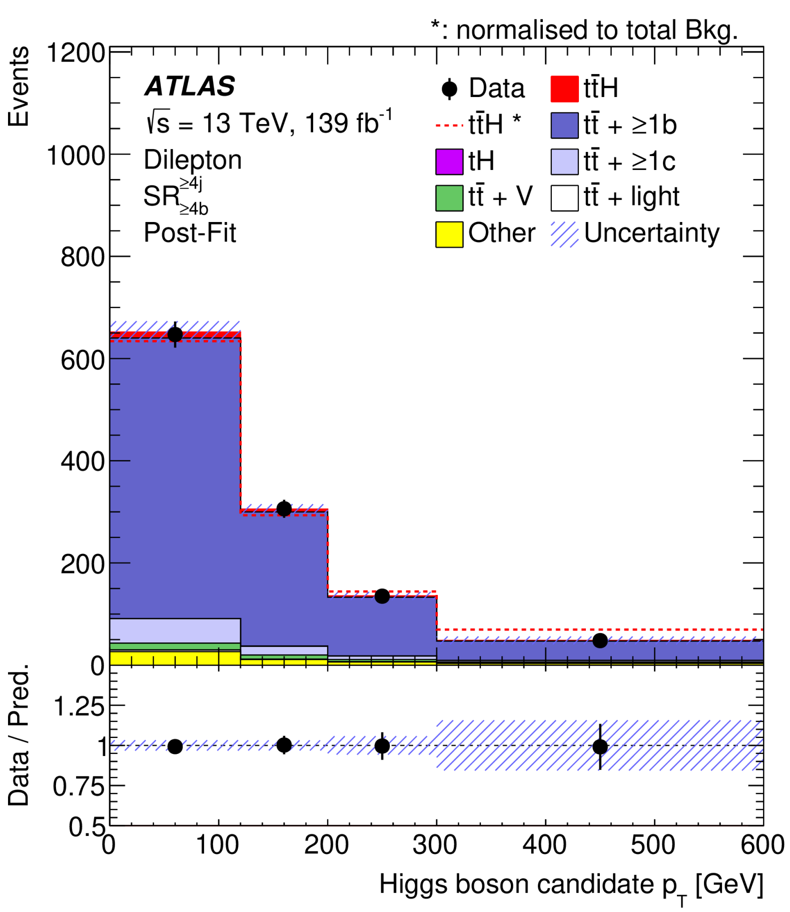
$t\bar{t}H(H \rightarrow b\bar{b})$ [JHEP06(2022)97]

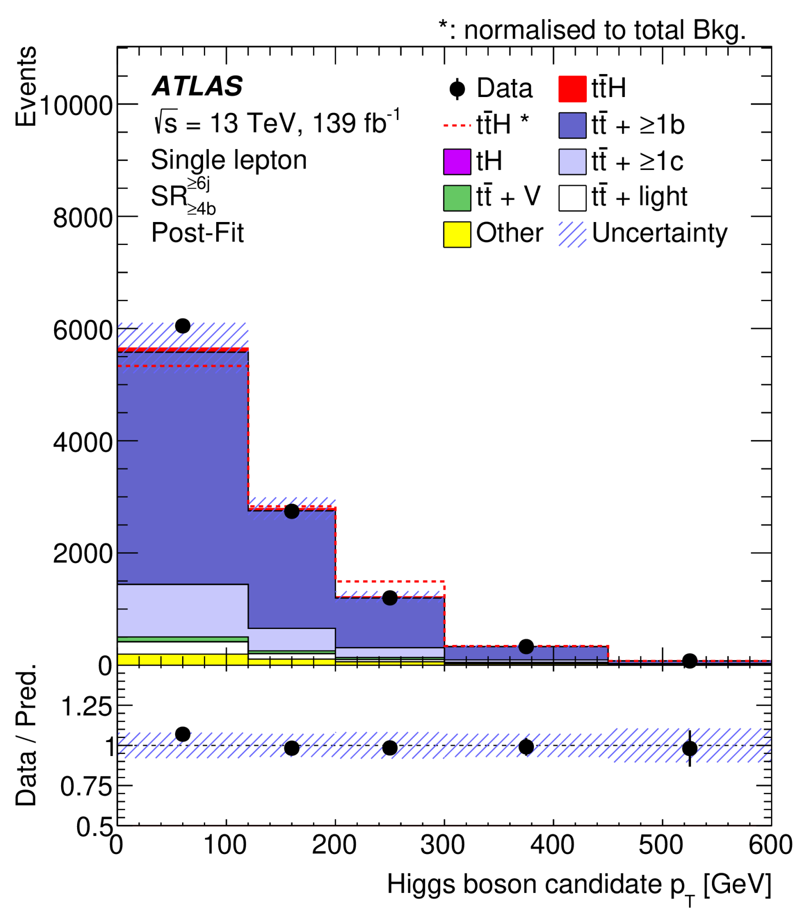
Differential measurement









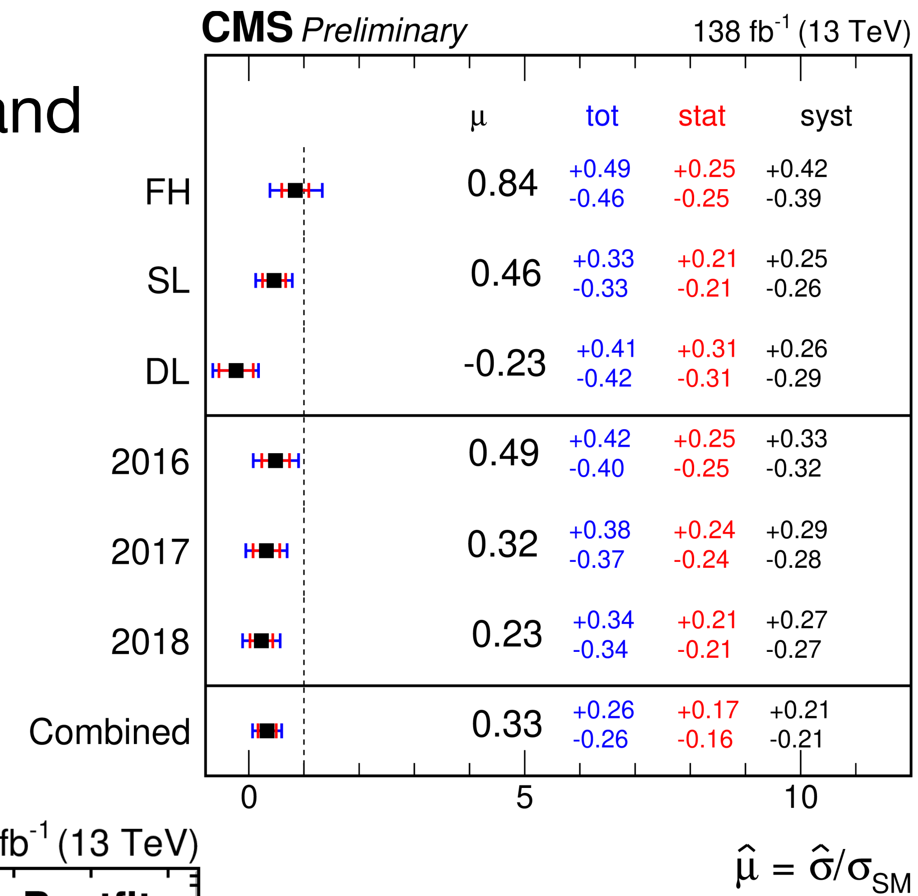


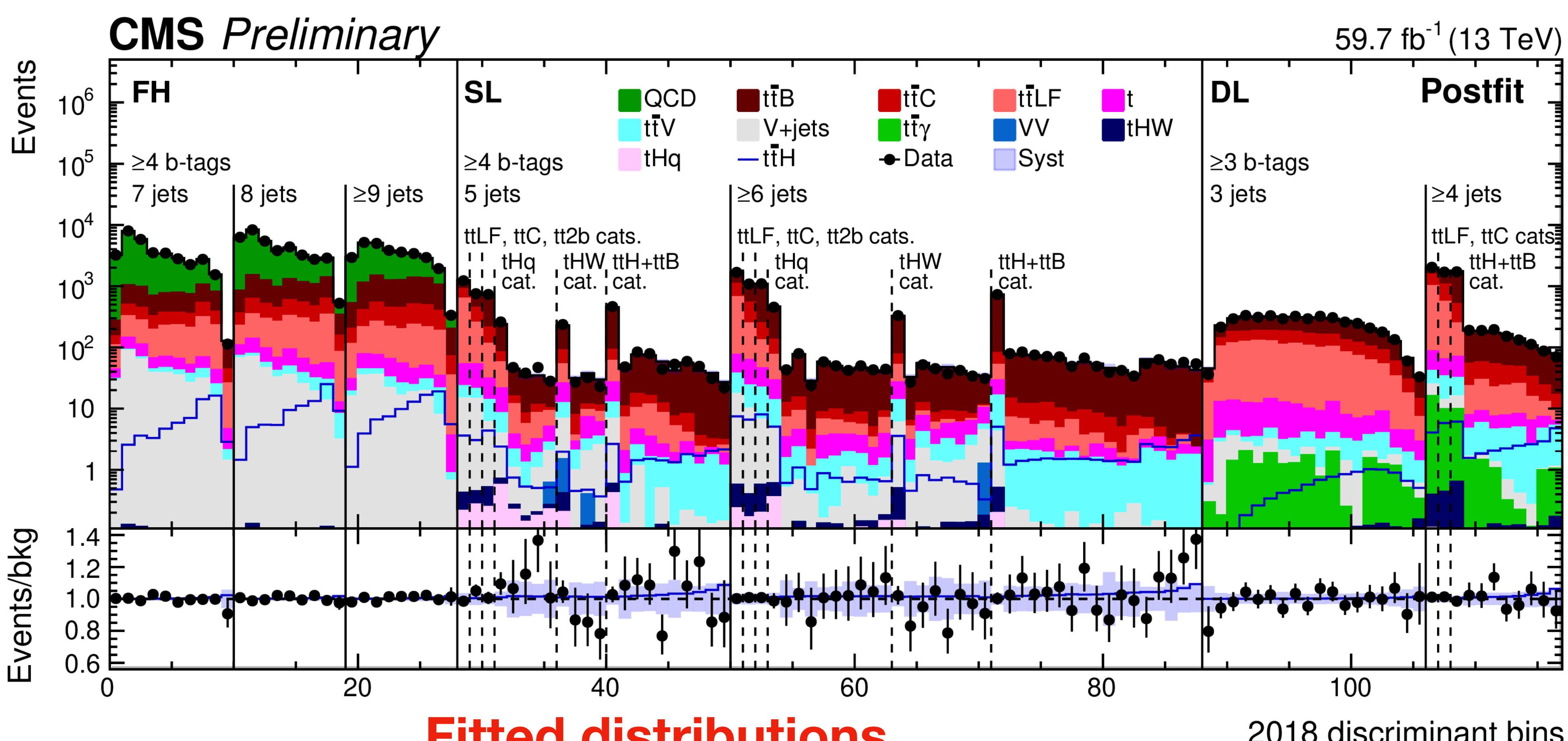
- Statistical and systematic uncertainties of similar size in most bins
- Results compatible with the SM predictions within 1-2 σ (but several negative fit values)

$t\bar{t}H(H \to b\bar{b})$ [CMS-PAS-HIG-19-011]

- Full hadronic, single lepton and dilepton regions
- Signal and control regions depending on number of jets and b-jets
- Multiclass artificial neural networks (ANNs) separately for each year
- ANN output and likelihood ratio of outputs used in fit
- Different treatment of $t\bar{t}$+≥1b background wrt ATLAS

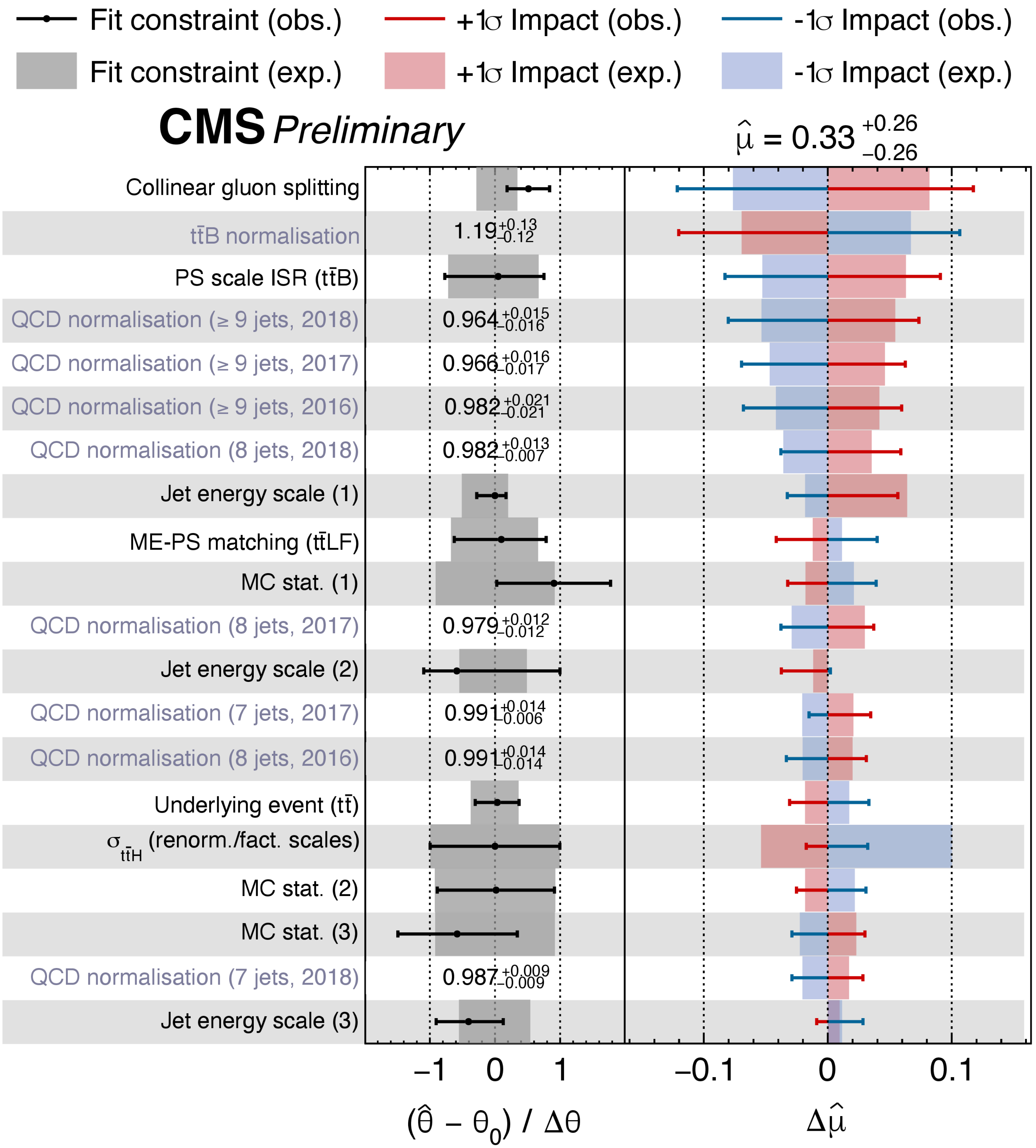
Inclusive measurement

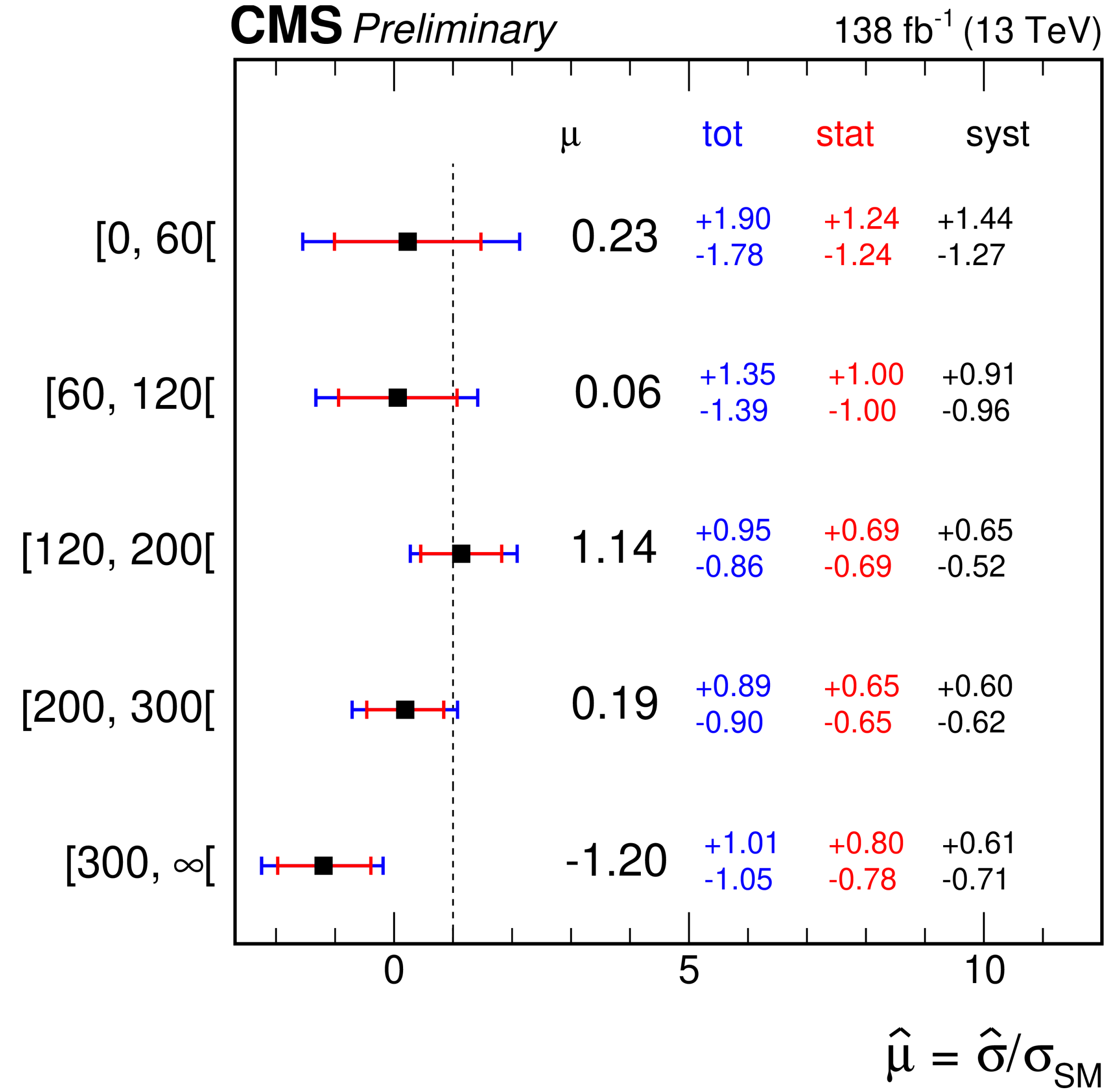




Fitted distributions

$t\bar{t}H(H \rightarrow b\bar{b})$ [CMS-PAS-HIG-19-011]





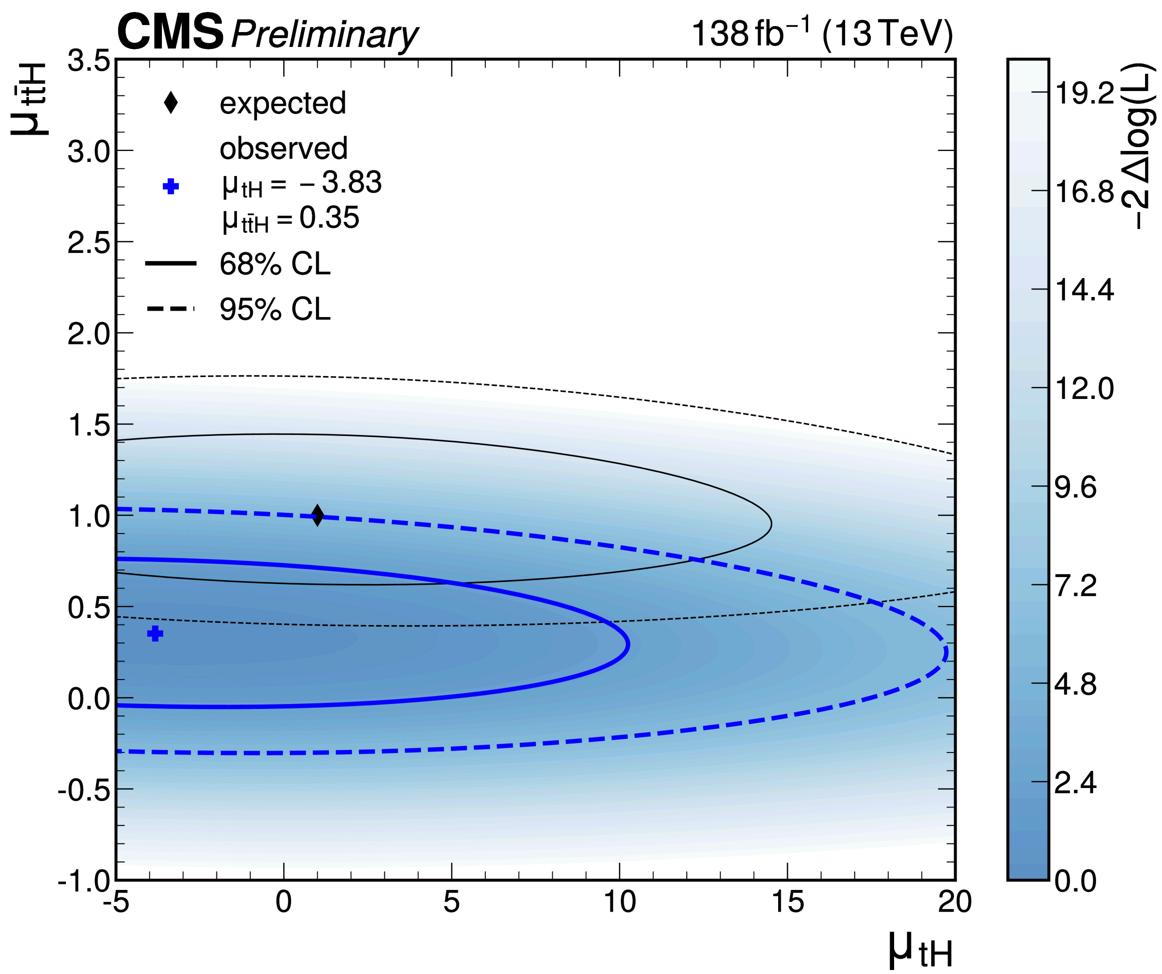
- Results compatible with SM (≤2.4σ) and similar to ATLAS
- Uncertainty dominated by systematics for the inclusive measurement, mostly similar size for differential

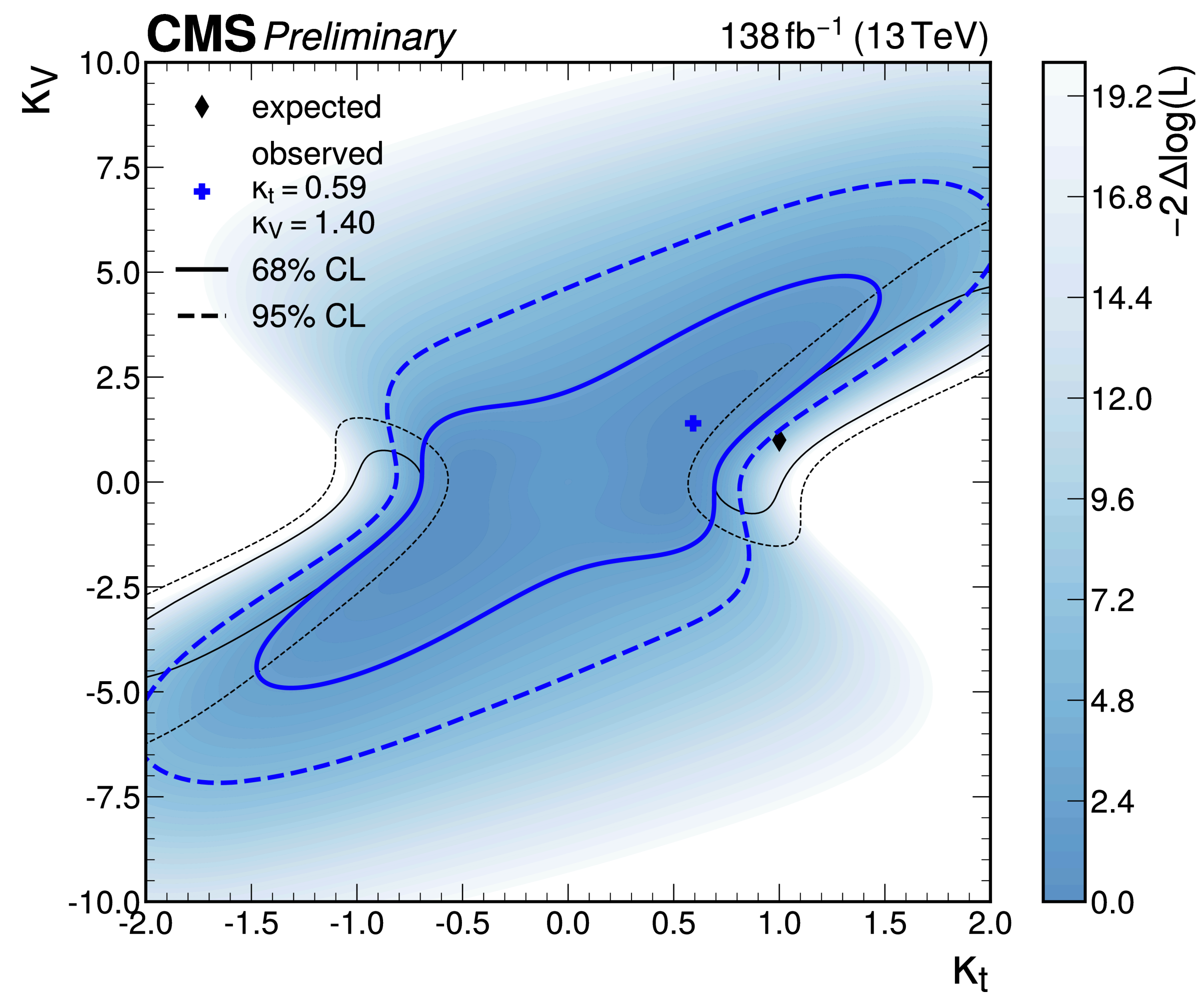
$\mu_{tH} < 14.6$ @ 95%CL With $\mu_{t\bar{t}H}$ fixed to 1 and treated as background

Coupling measurement Assuming SM Higgs boson coupling structure

$$\sigma_{tHq} = (2.63\kappa_t^2 + 3.58\kappa_V^2 - 5.21\kappa_t\kappa_V)\sigma_{tHq}^{SM}$$
$$\sigma_{tHW} = (2.91\kappa_t^2 + 2.40\kappa_V^2 - 4.22\kappa_t\kappa_V)\sigma_{tHW}^{SM}$$

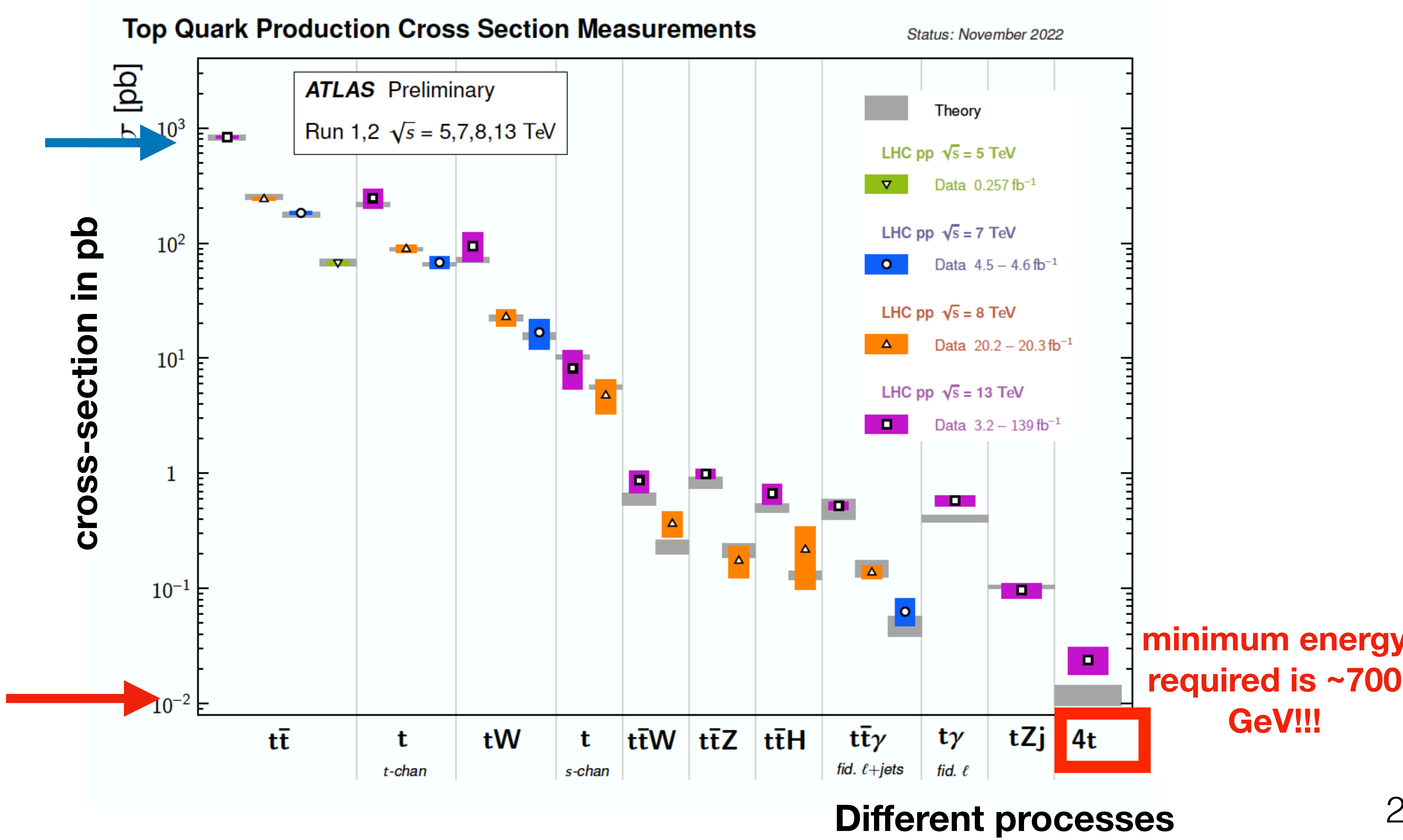
Simultaneous fit





Production of four-top-quarks

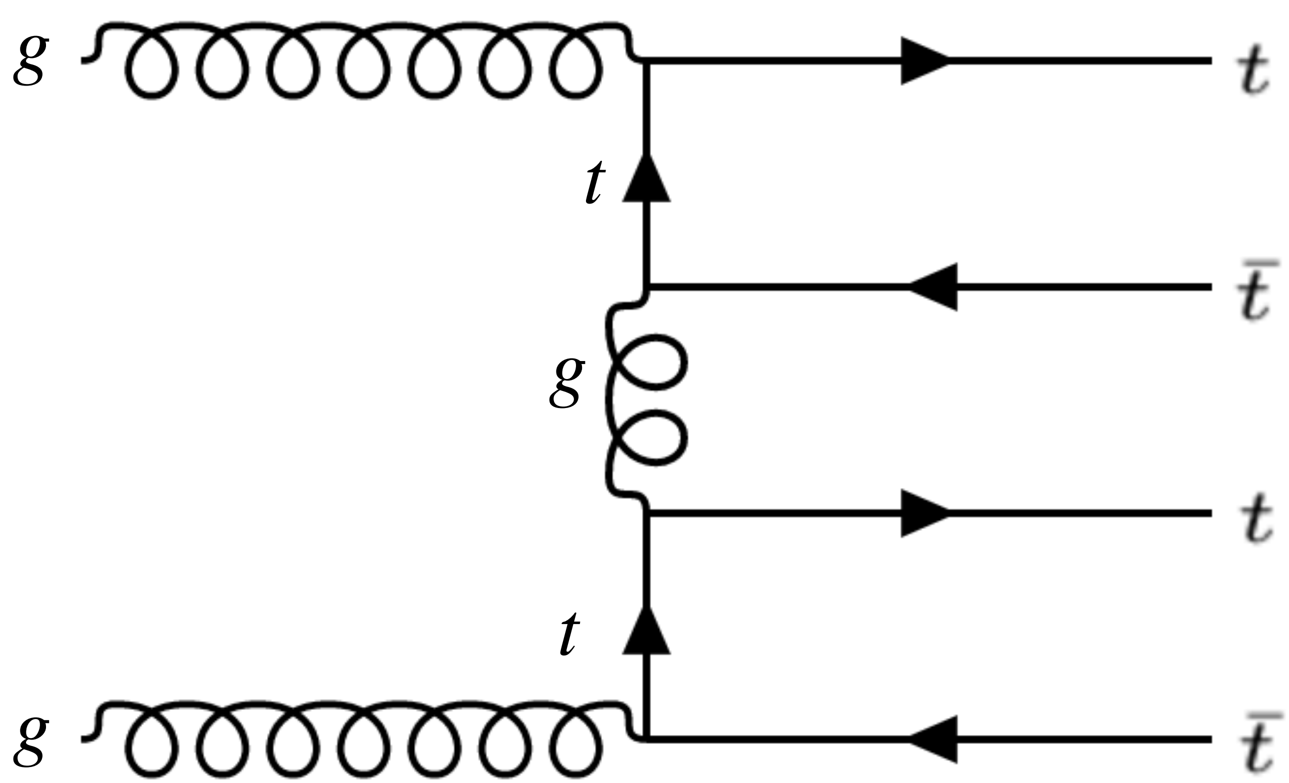
- Heaviest particle final state
- four-top-quark has a **very tiny cross section in the SM**
- $\sigma_{SM}(t\bar{t}t\bar{t})$ ~12 fb



Predictions for four tops

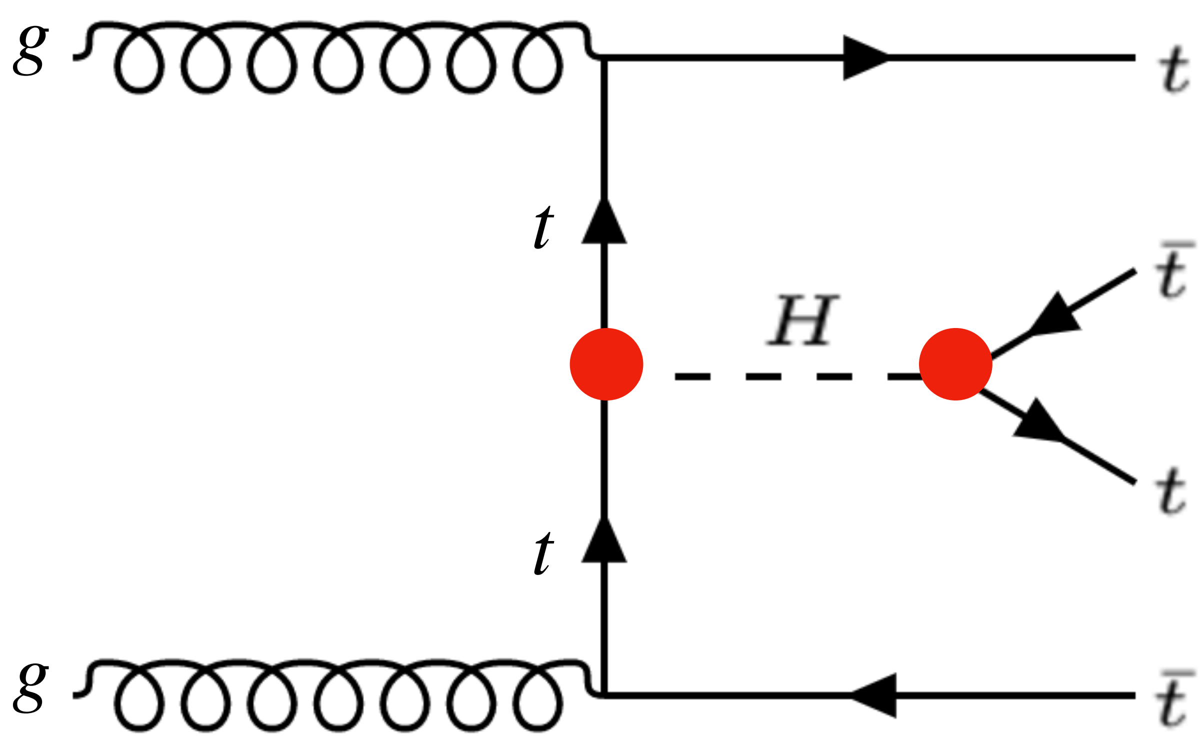
- **Rare** process predicted by the SM and has never been observed

Dominant production of $t\bar{t}t\bar{t}$



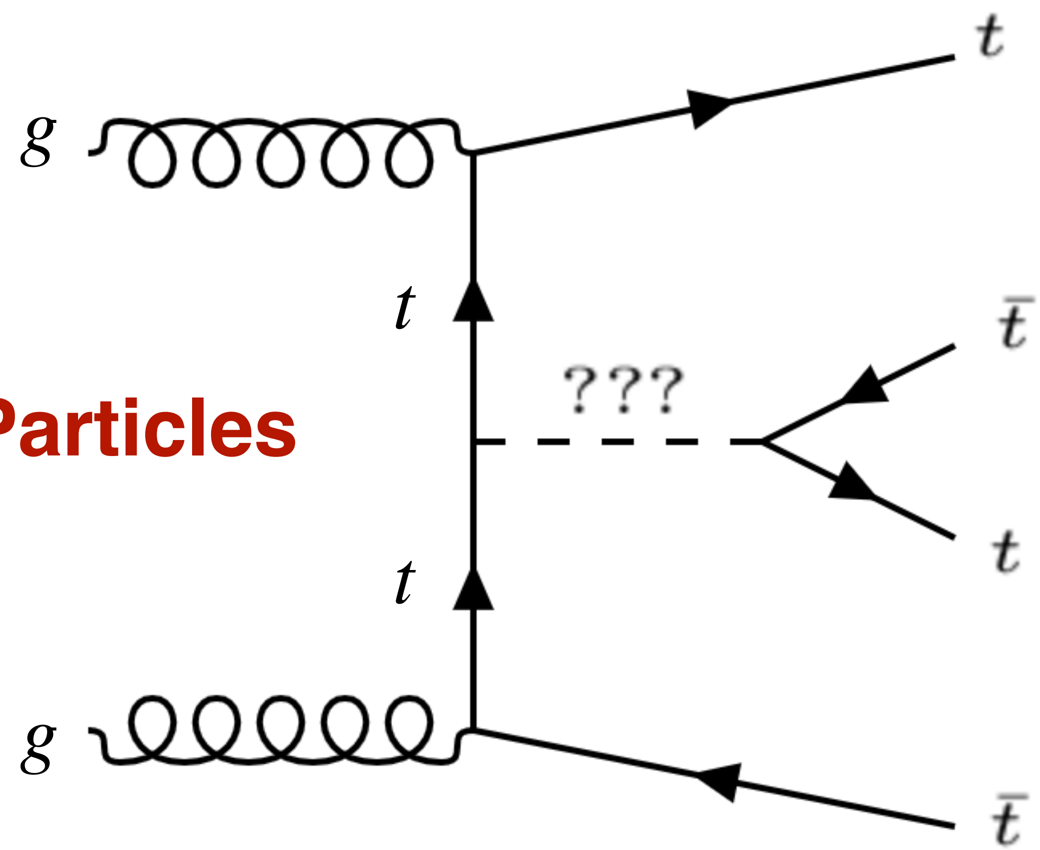
Predictions for four tops

- Four top quarks can be produced via an **offshell SM Higgs boson**
- **Sensitive to the magnitude and CP properties of the Yukawa coupling of the top quark to the Higgs boson**

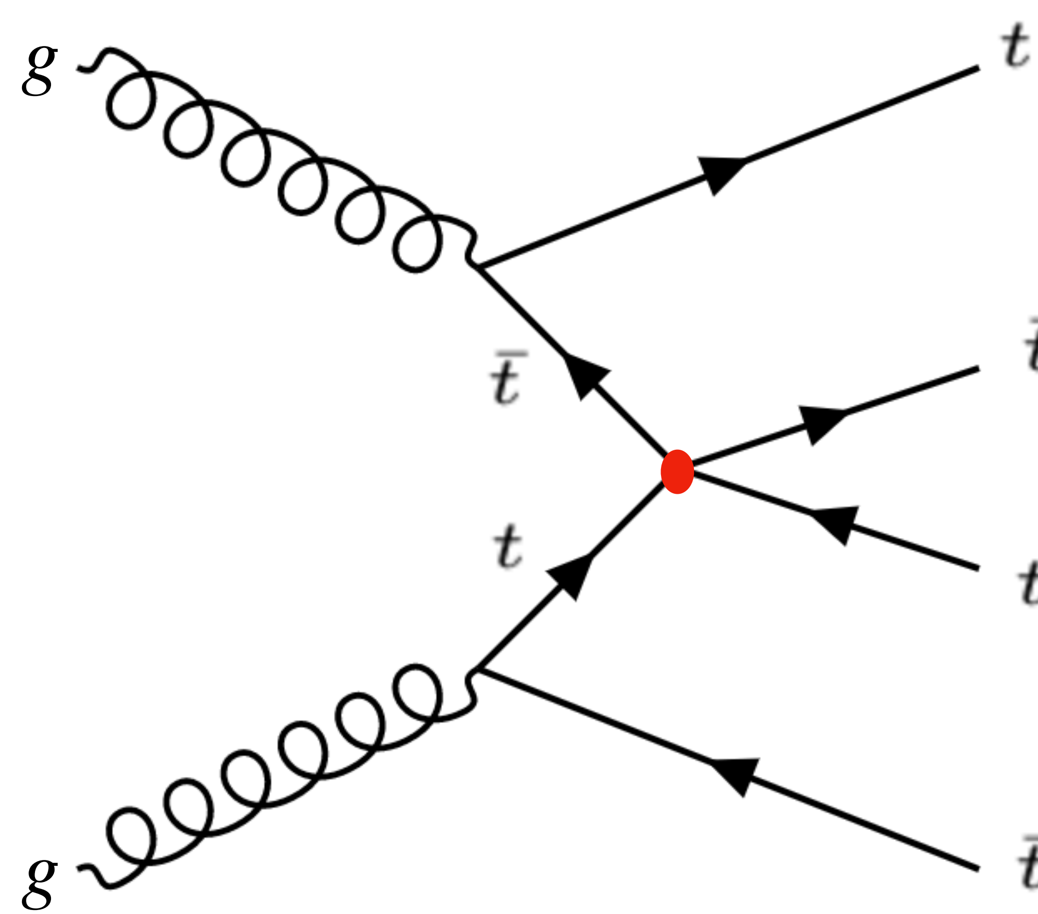


[arXiv:1611.05032 [hep-ph]]

Four top quarks can be sensitive to BSM scenarios



New Particles

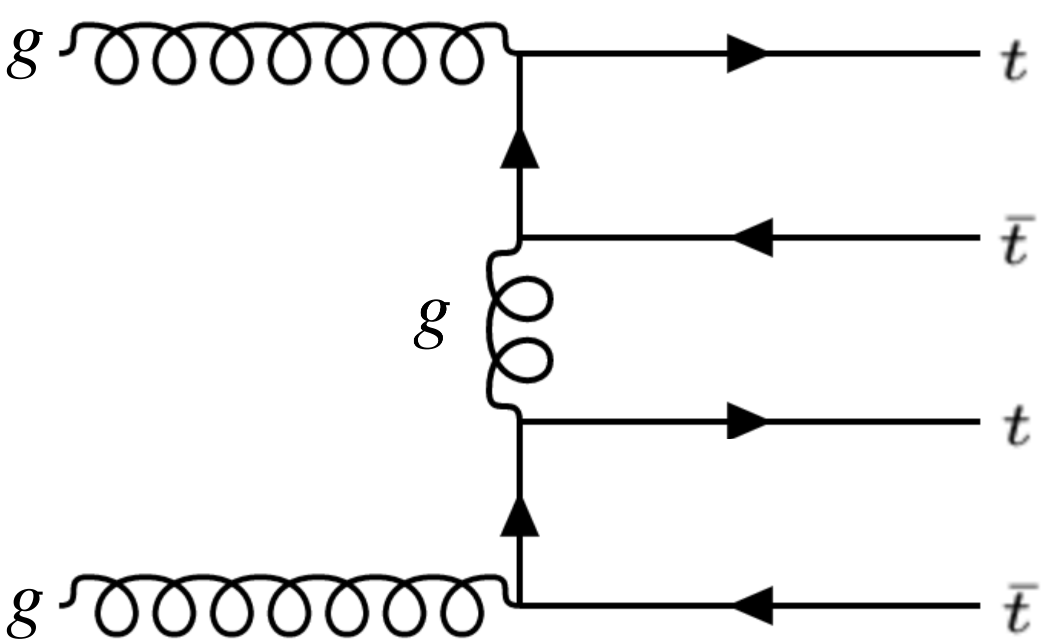


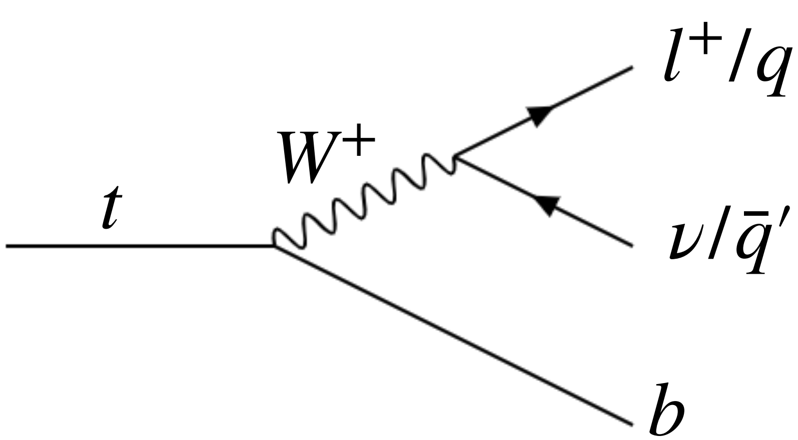
New physics beyond our energy reach

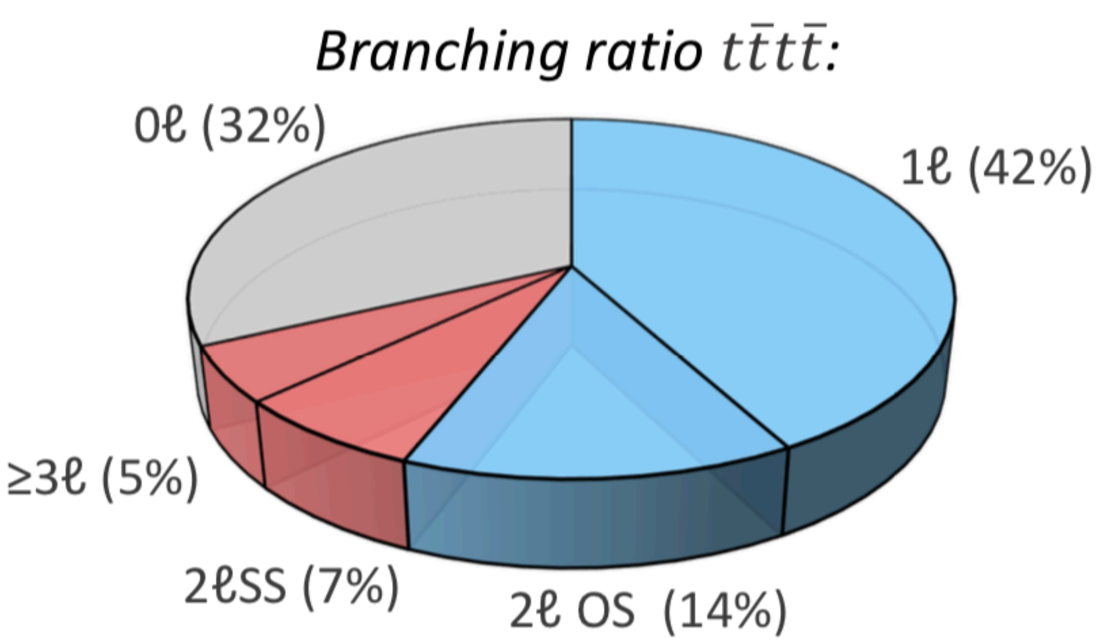
“Four-fermion contact interaction”

Signatures

- We have **four tops** in our final state
- Each **top** decays to **Wb** and the detector signature is defined by:
  - The presence of four b-quarks
  - The decays of the W bosons







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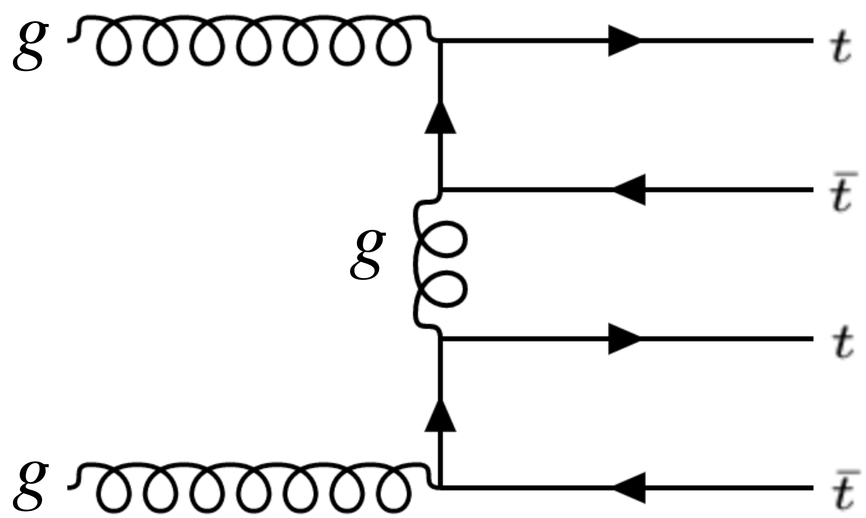
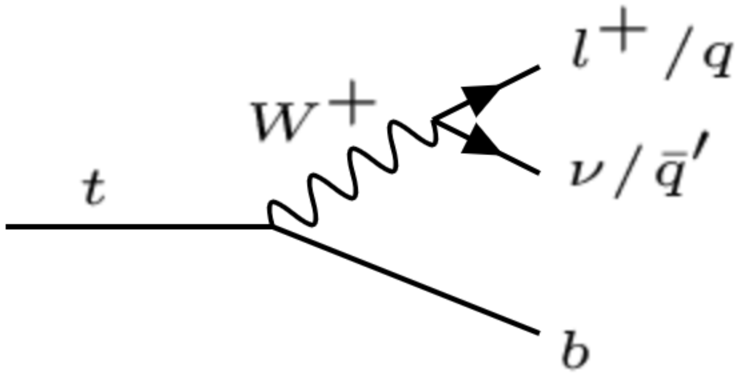
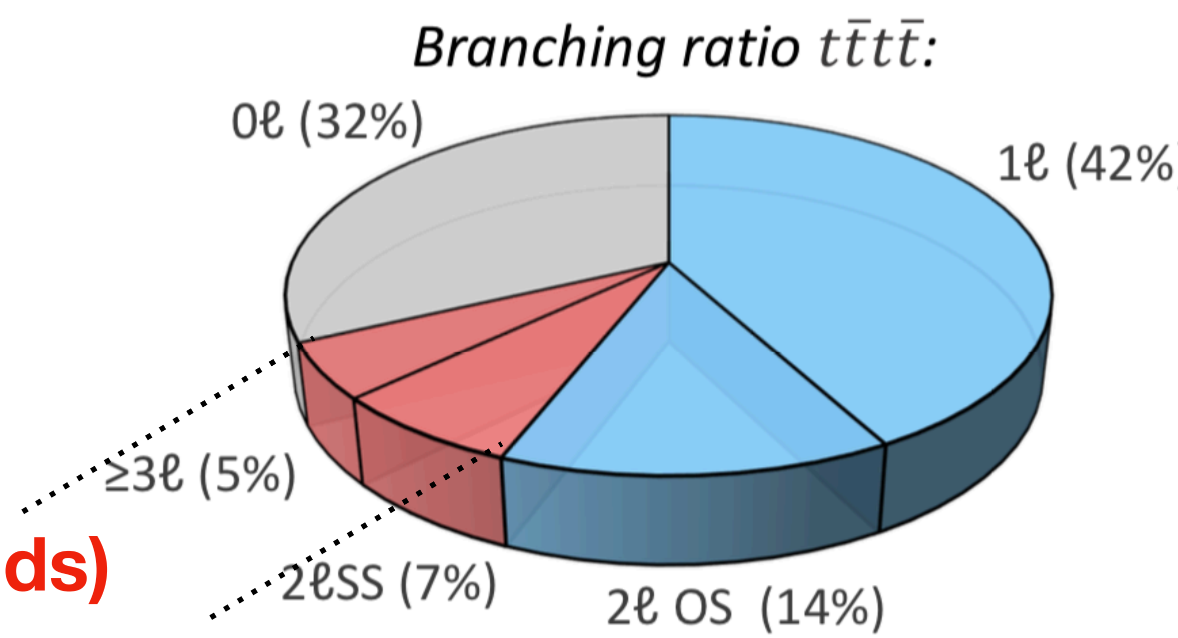
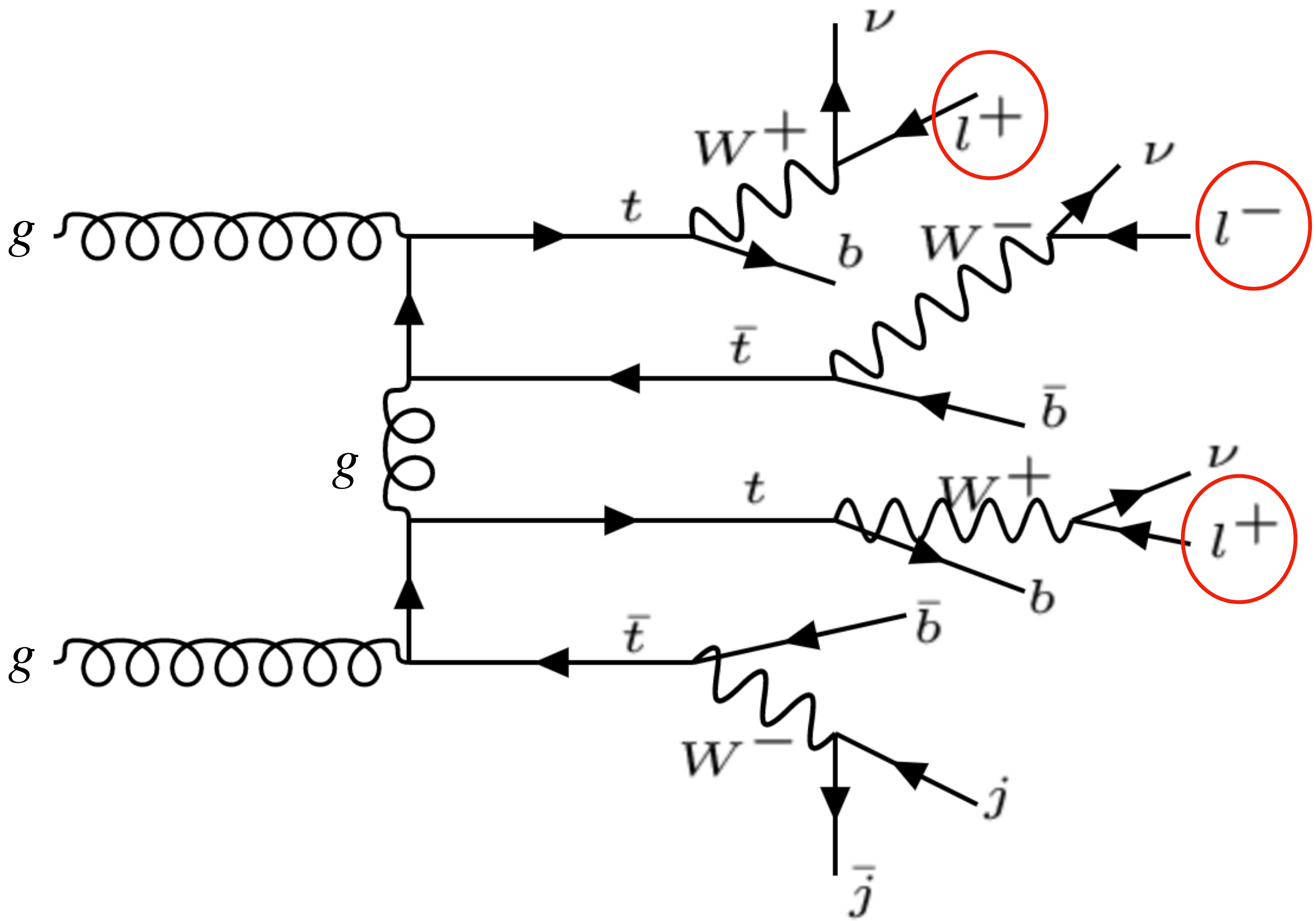




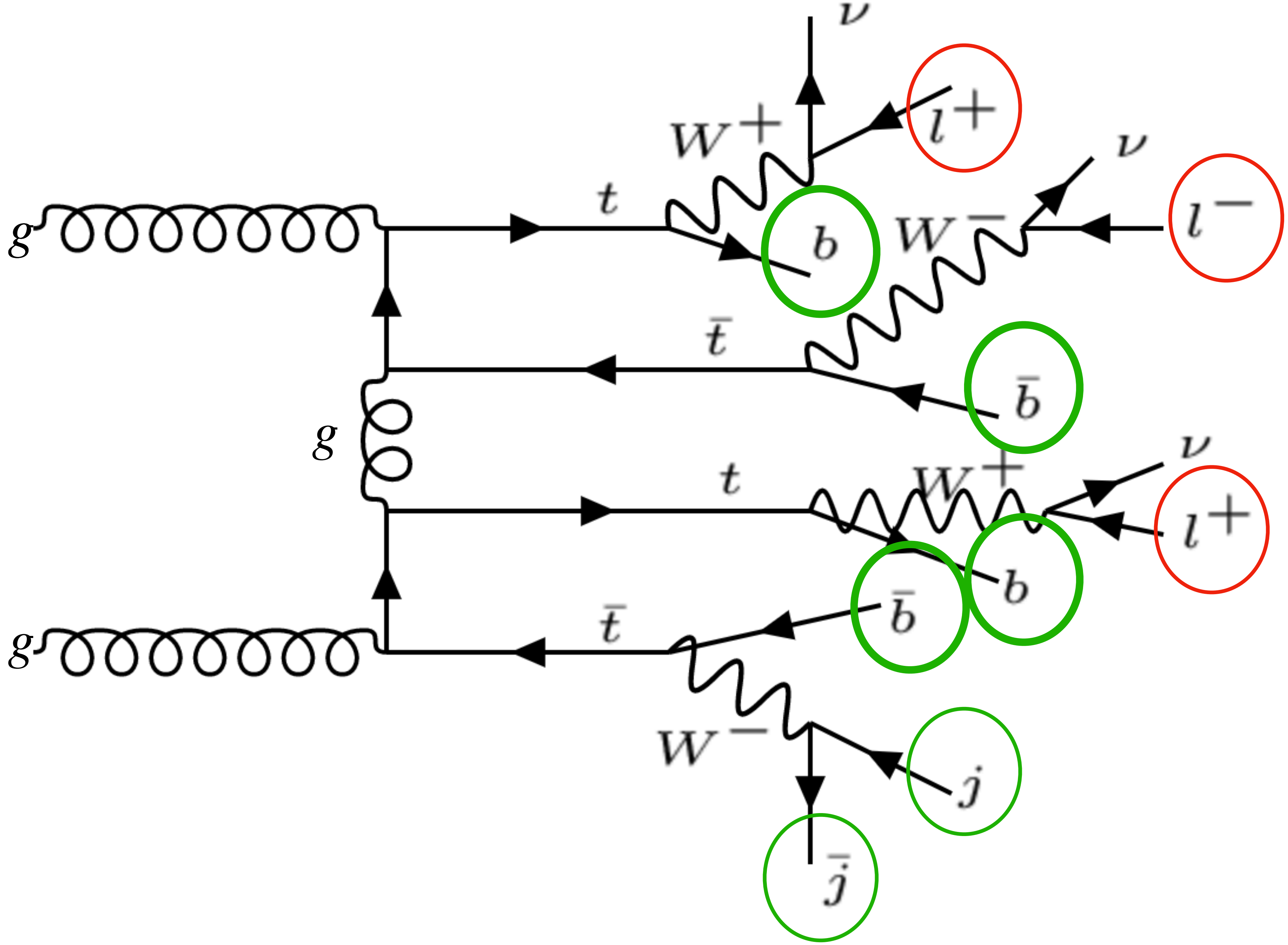


Smallest branching ratio
but very clean (low backgrounds)
Most sensitive channel

Example from the 3l channel



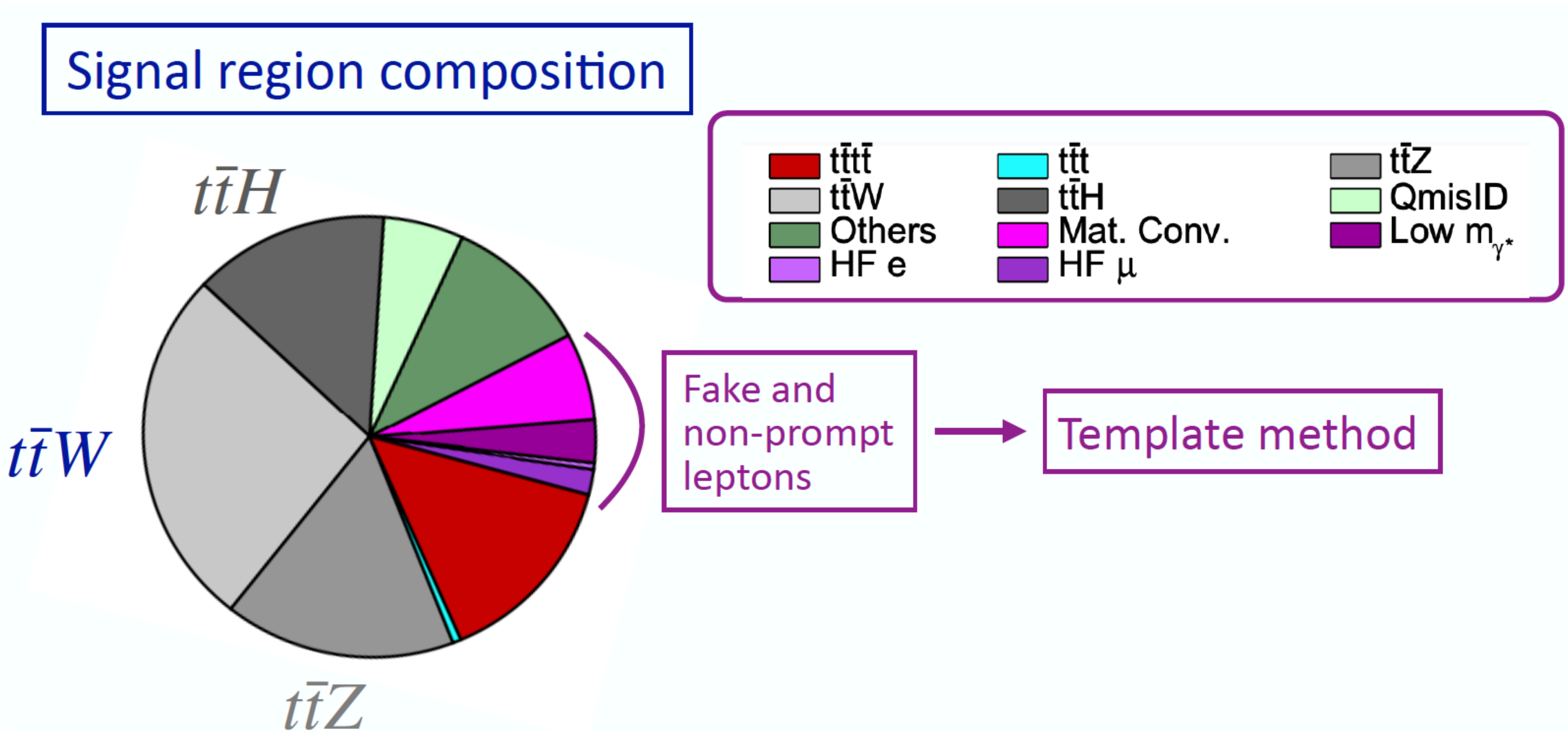
Example from the 3l channel



Signal region selection

- Selection requirements in the **2ℓSS/3ℓ** (signal region):
  - 2 same-sign leptons *or* 3 leptons (ℓ=e,μ)
  - **≥ 6 jets**
  - **≥ 2 b-tagged jets**
  - H_T > 500 GeV ; $H_T = \sum^{leptons} P_T + \sum^{jets} P_T$

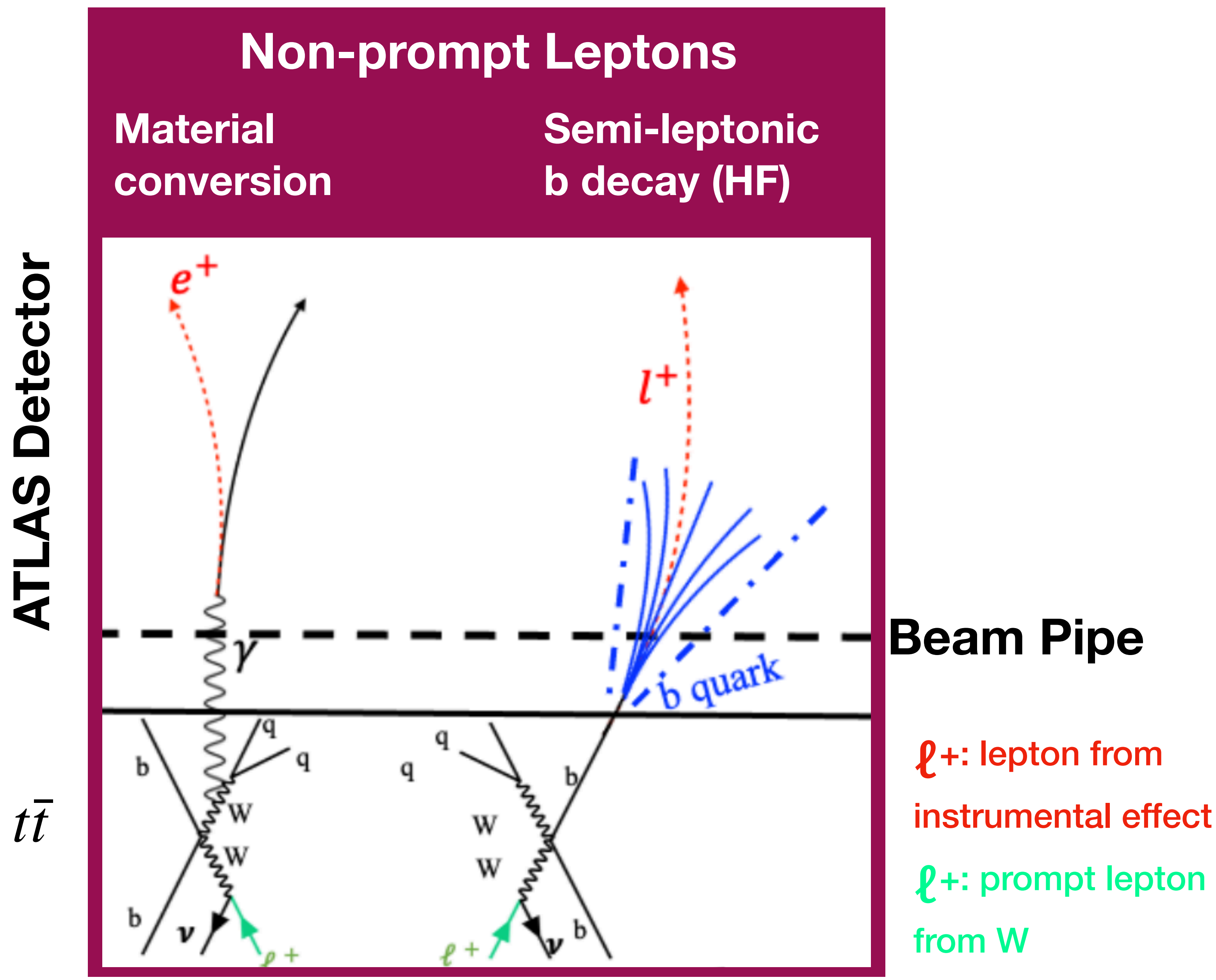
What else can produce many leptons & jets ?



Control regions are designed to evaluate $t\bar{t}W$ and fake/non-prompt background

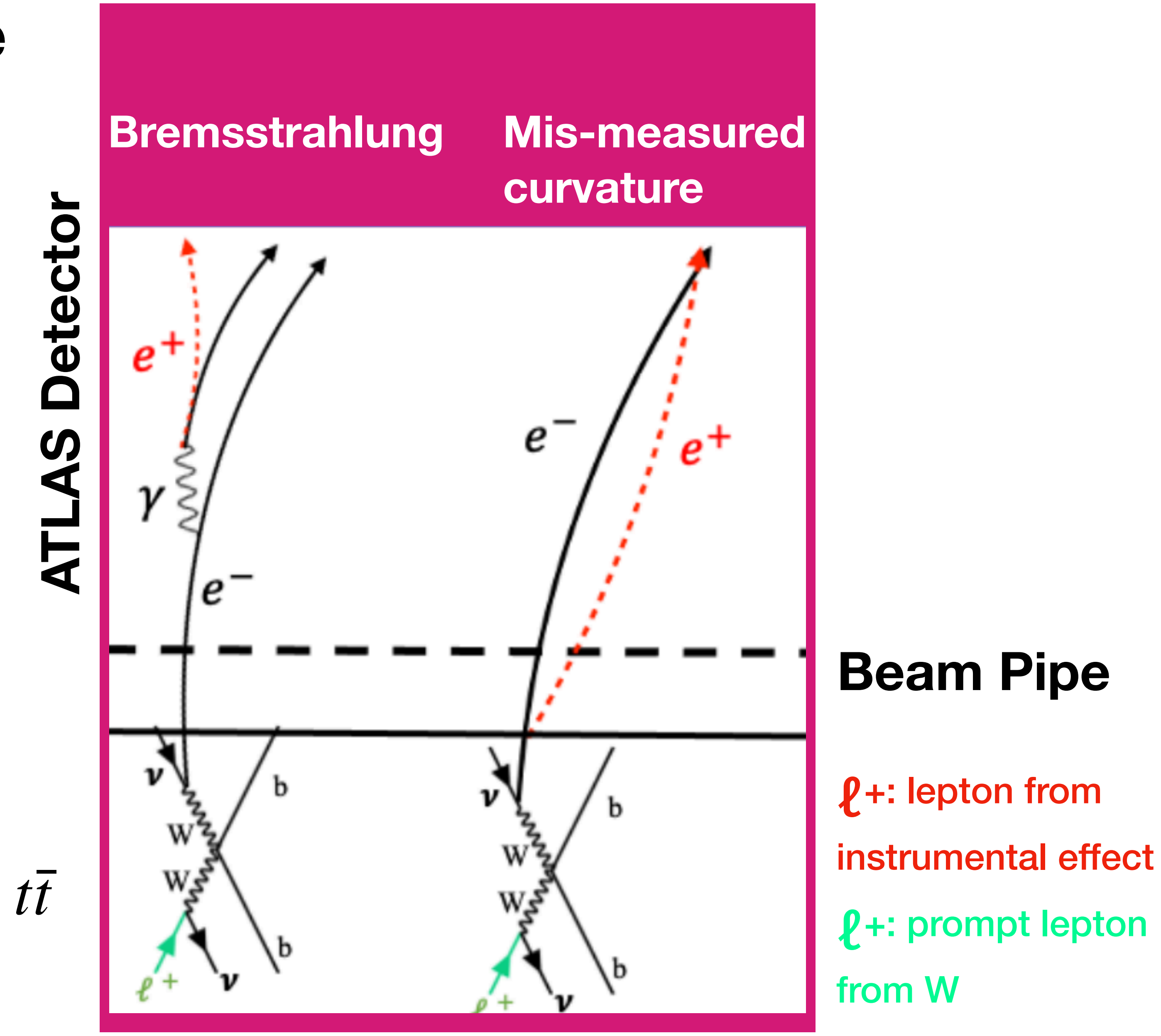
Fake/non-prompt leptons

- electrons from ɣ conversion in detector
- a virtual photon ɣ* leading to an e+e– pair (Low M_{ee})
- electrons (muons) from heavy-flavour (HF) decay



Fake/non-prompt leptons

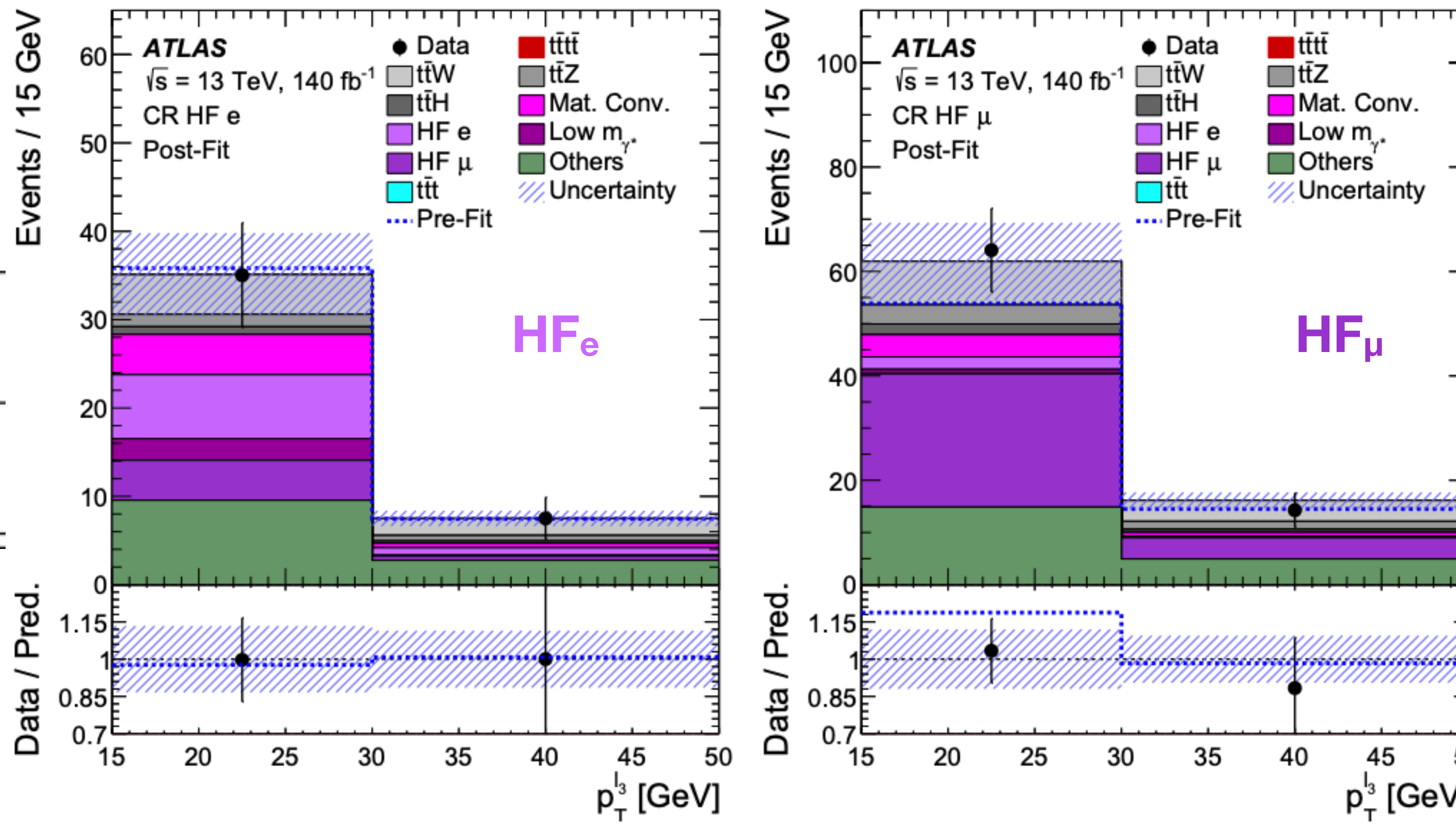
- Charge mis-assignment (relevant for the 2ℓSS channel)
- Charge of electron is mis-measured, caused by:
  - Bremsstrahlung photon emission followed by its conversion
  - Mis-measured track curvature



Template method to estimate fake/non-prompt leptons

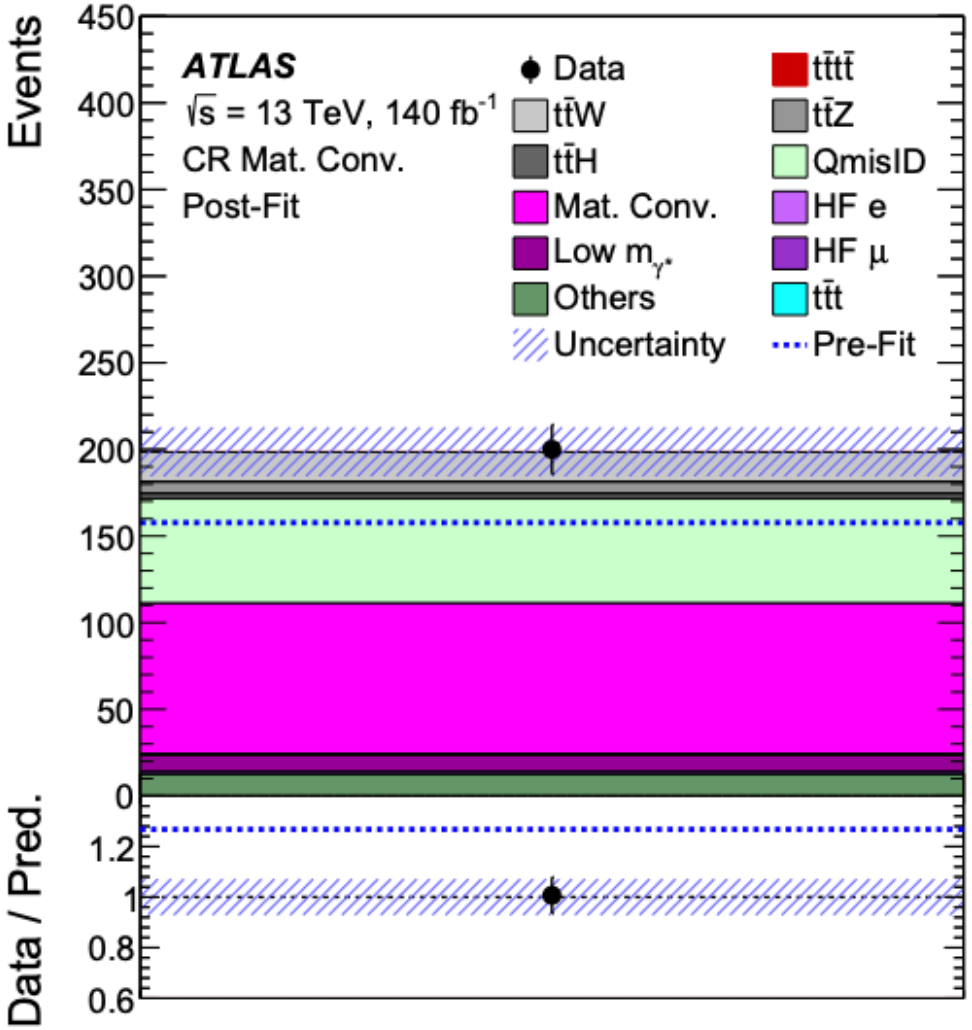
- **Template Method** is used to determine the major backgrounds
  - Background shapes are estimated from MC
  - Normalisation is obtained from the fit
  - 4 free parameters included in the signal extraction fit to determine normalization (HF electron, HF muon, material conversions, virtual photon conversions)

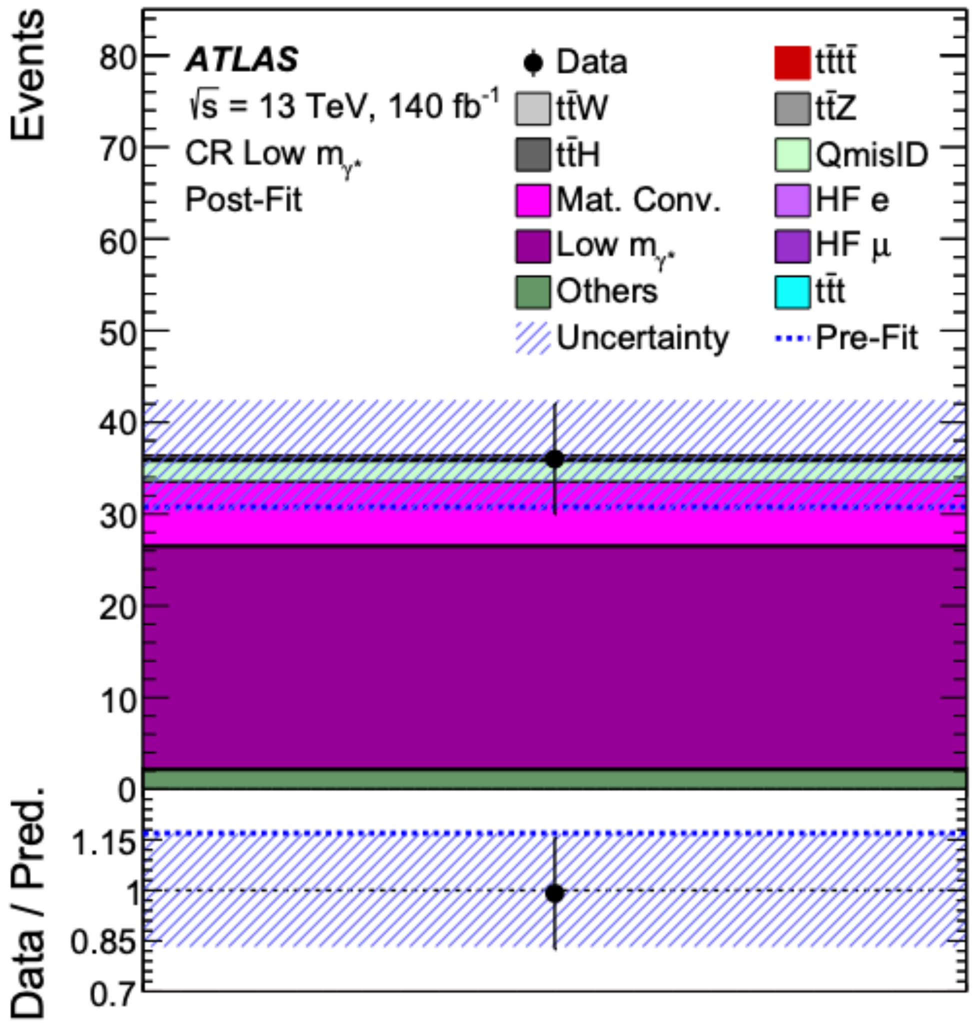
$NF_{HF\ e}$	$NF_{HF\ \mu}$
$0.66^{+0.75}_{-0.46}$	$1.27^{+0.53}_{-0.46}$



[Eur. Phys. J. C 83 (2023) 496]

Template method to estimate fake/non-prompt leptons





material conversions **virtual photon conversions**

$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } m_{\gamma^*}}$
$1.80^{+0.47}_{-0.41}$	$1.08^{+0.37}_{-0.31}$

[Eur. Phys. J. C 83 (2023) 496]

ttW background

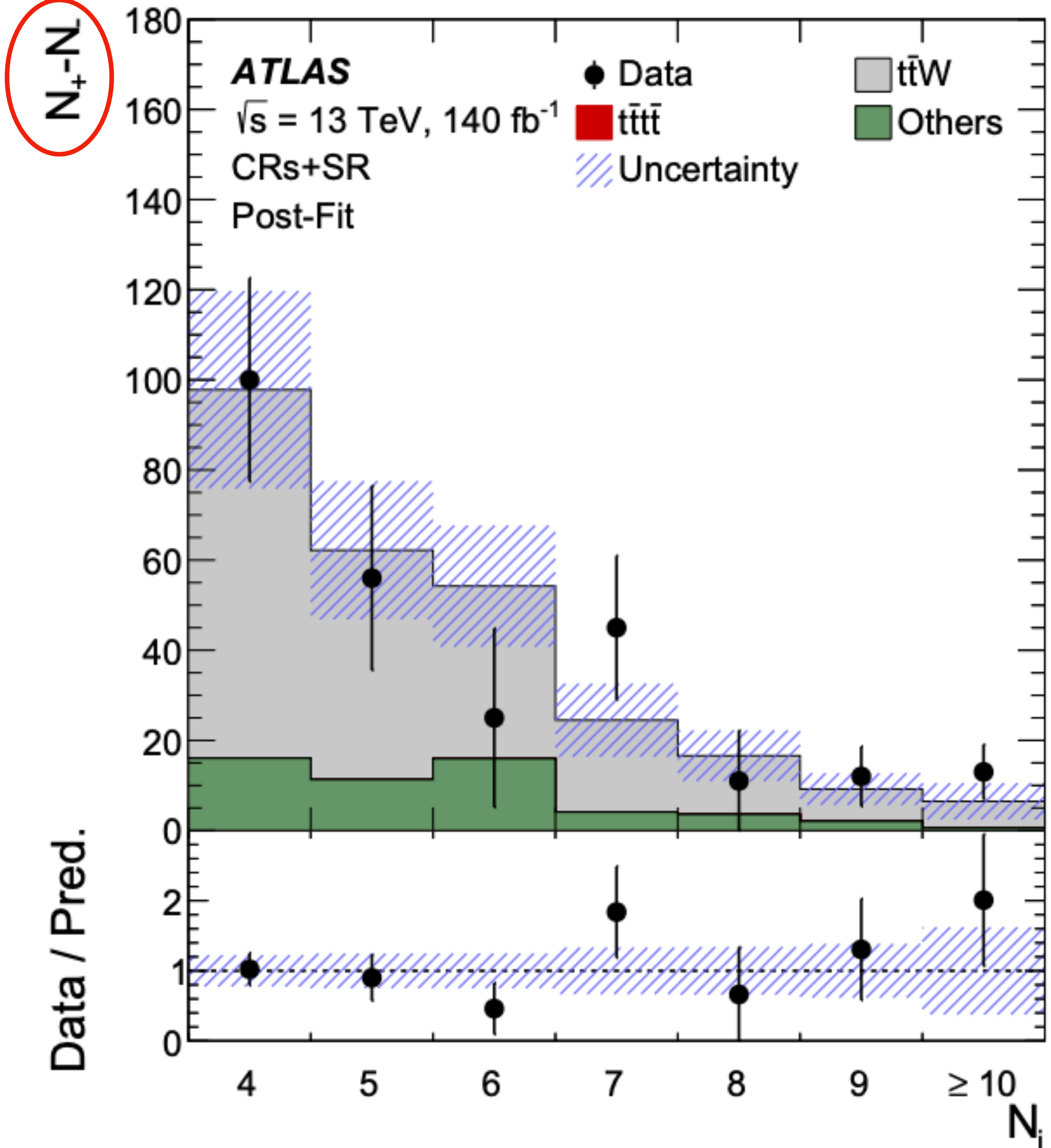
- Estimate ttW background normalization per jet bin from data based on the evolution

$$R(j) = \frac{N(j+1)}{N(j)}$$

  - $R(j) = a_0$ for $j>j_{threshold}$
  - $R(n) = a_1/(n+1)$ for $n<j_{threshold}$ where n=number of additional jets to the hard process

- Shape from MC simulation

Plot $N_+ - N_-$ to suppress all charge symmetric backgrounds

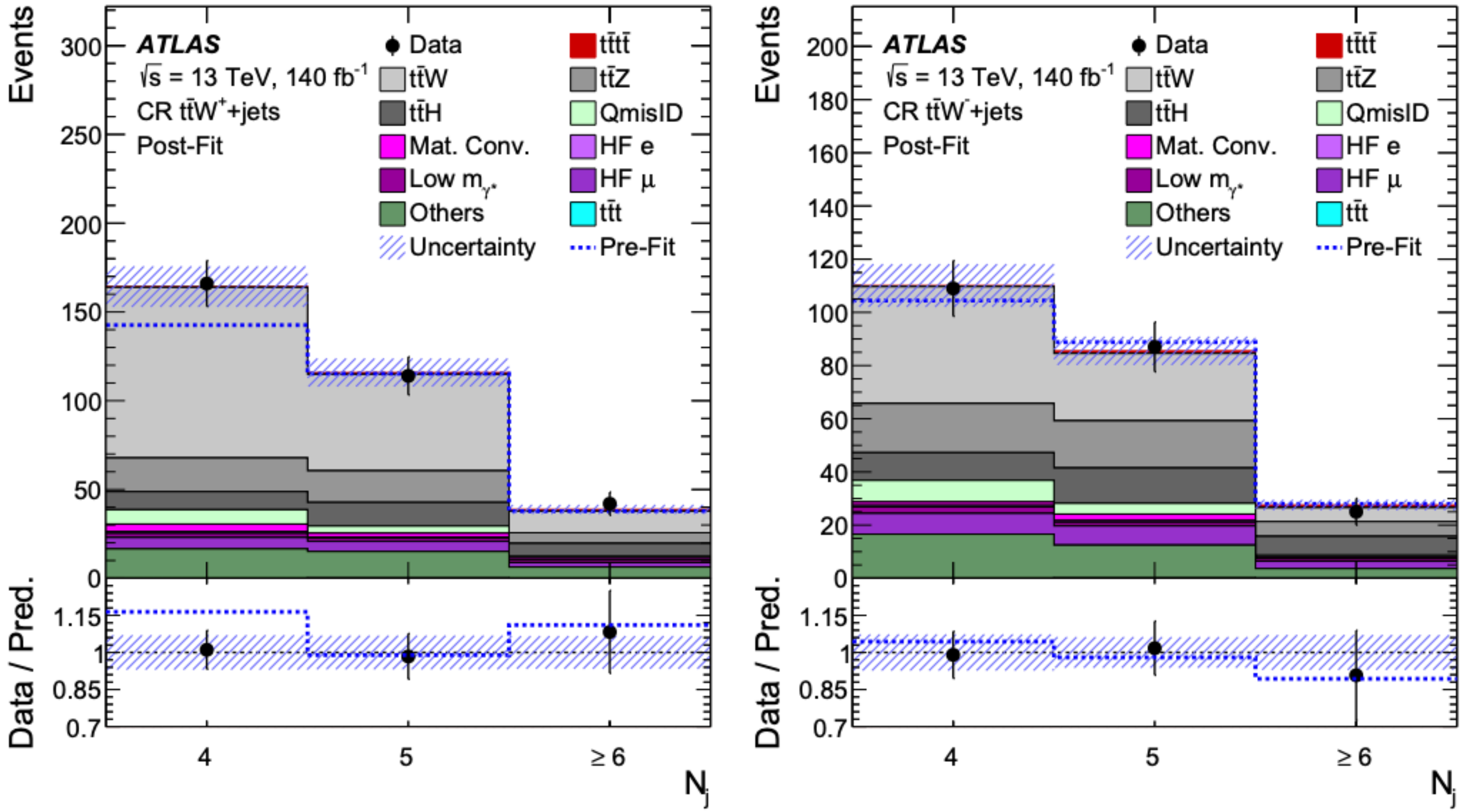


[Eur. Phys. J. C 83 (2023) 496]

ttW background

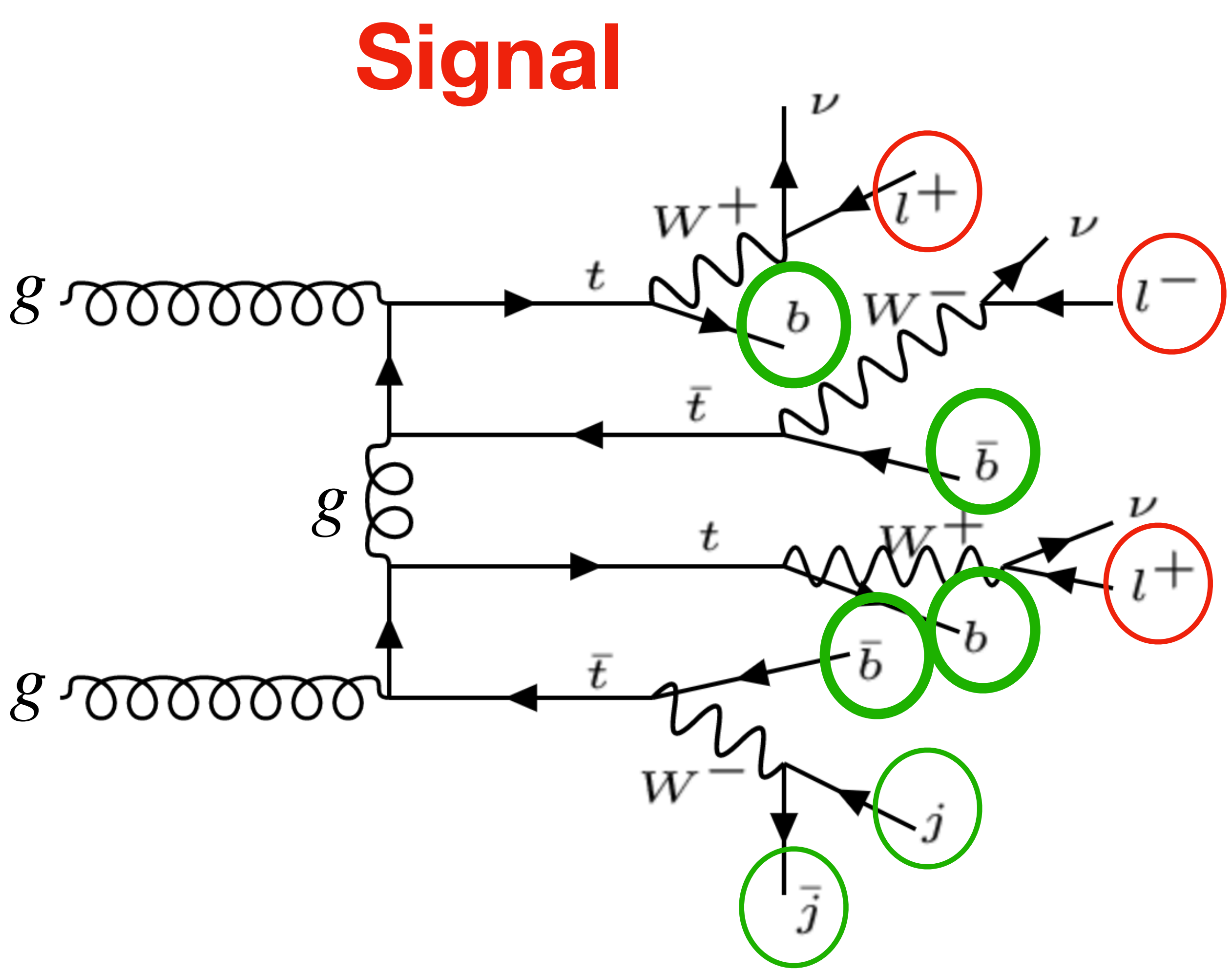
- Four ttW control regions to determine
  - a_0 , a_1
  - $t\bar{t}W^+$ and $t\bar{t}W^-$normalization for j=4

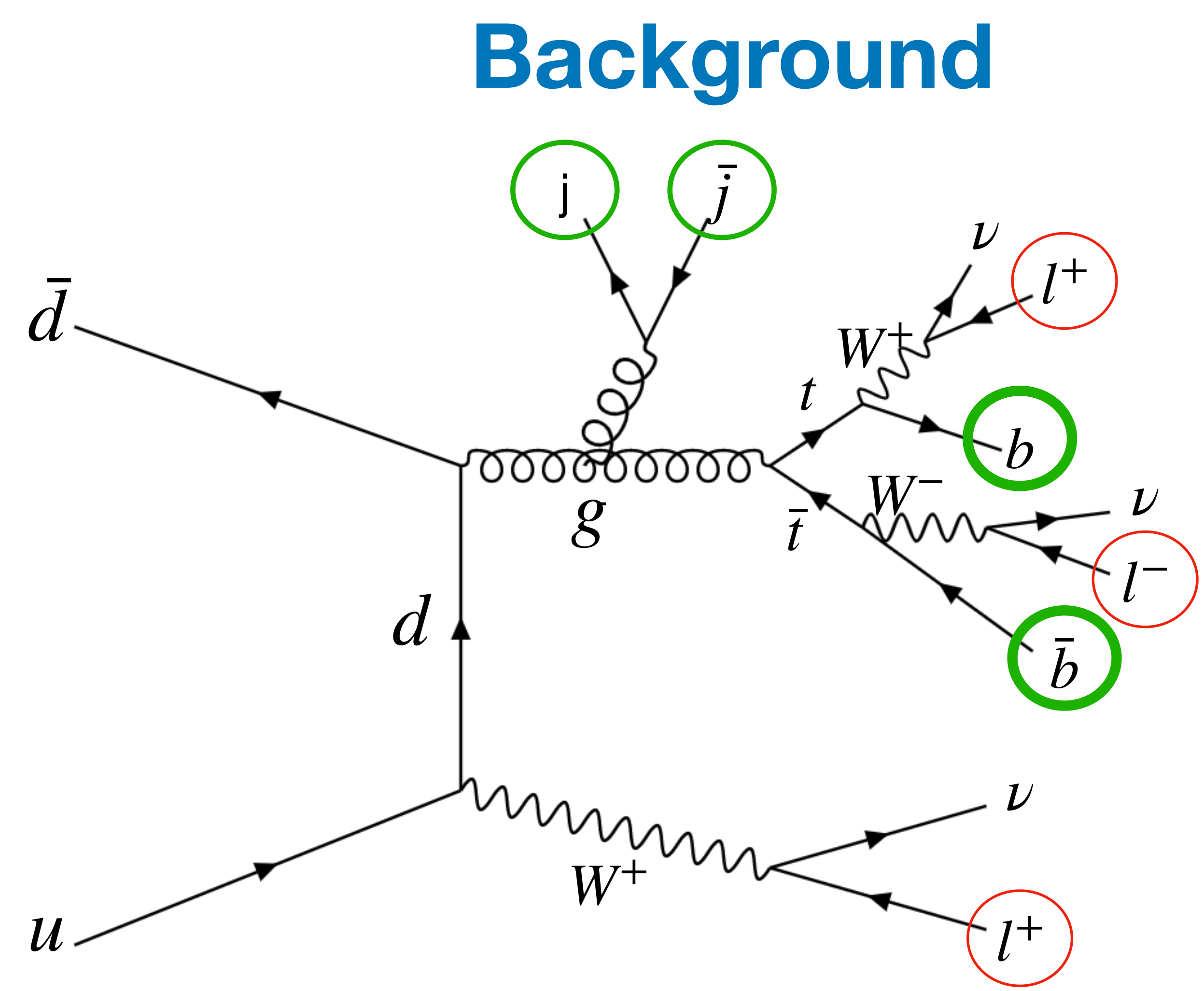
[Eur. Phys. J. C 83 (2023) 496]



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

Disentangling Signal from Background

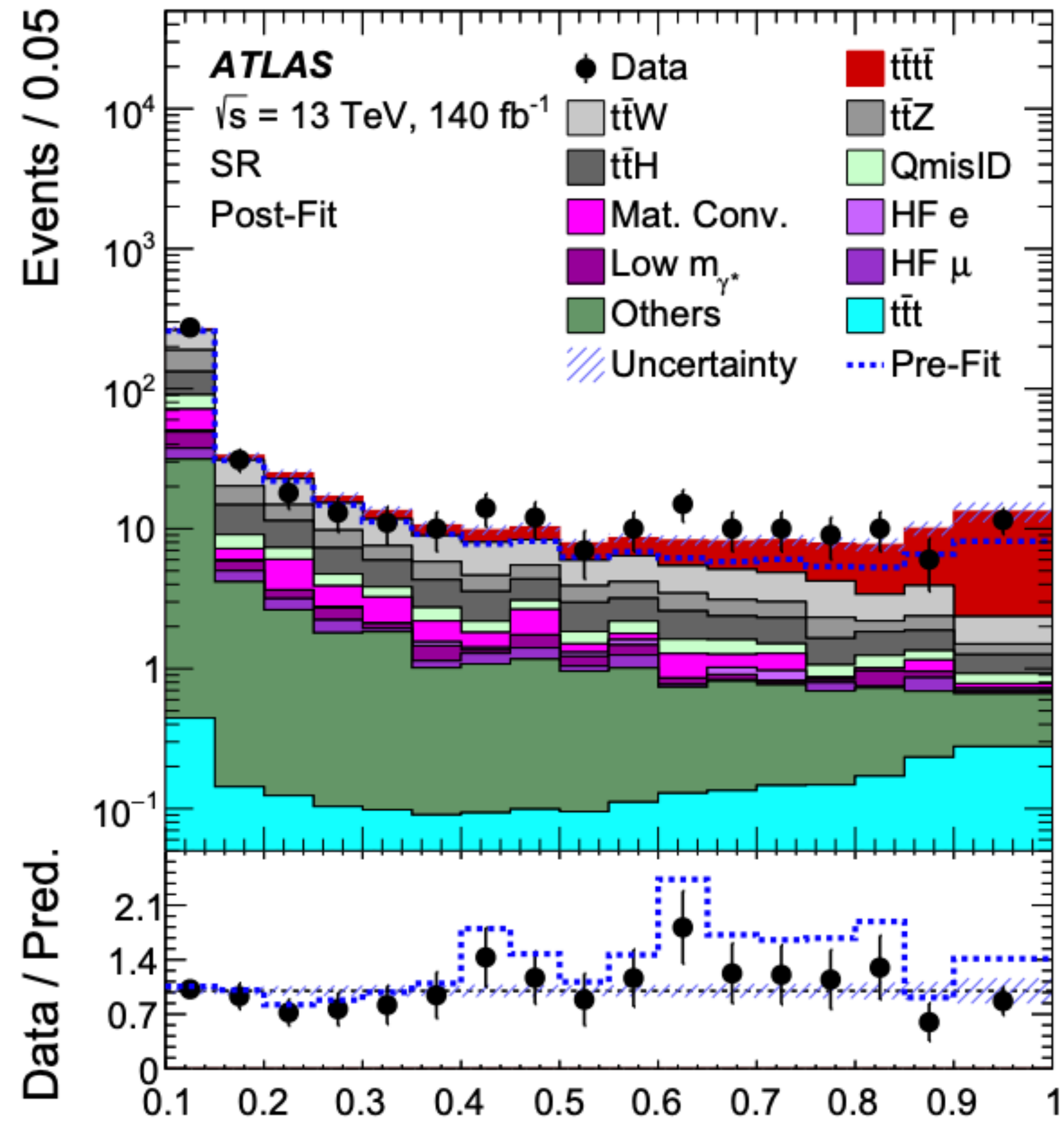




- Look for variables showing kinematic differences between signal and background
  - Many jets, b-jets, leptons
- A multivariate discriminant built with a Graph Neural Network (GNN) is used
- Example: use b-jet “tagging” variable *continuously* and *across all jets*

Four-top cross section result

- Signal extraction
  - simultaneous fit to GNN in SR and distributions in 8 CRs
  - Extract the signal strength $\mu = \sigma_{t\bar{t}t\bar{t}} / \sigma^{SM}_{t\bar{t}t\bar{t}}$
  - $\mu = 1.9 \pm 0.4$ **(stat)** $^{+0.7}_{-0.4}$ **(syst)** ; 6.1σ (4.3σ expected)
- Measured four-top cross-section: $\sigma(t\bar{t}t\bar{t}) = 22.5^{+6.6}_{-5.6}\ fb$
- Observation of the 4-top quark production!
- Consistent with the SM prediction at 1.8/1.7 σ
- Largest systematic uncertainty from 4-top modelling, ttW DD parameters



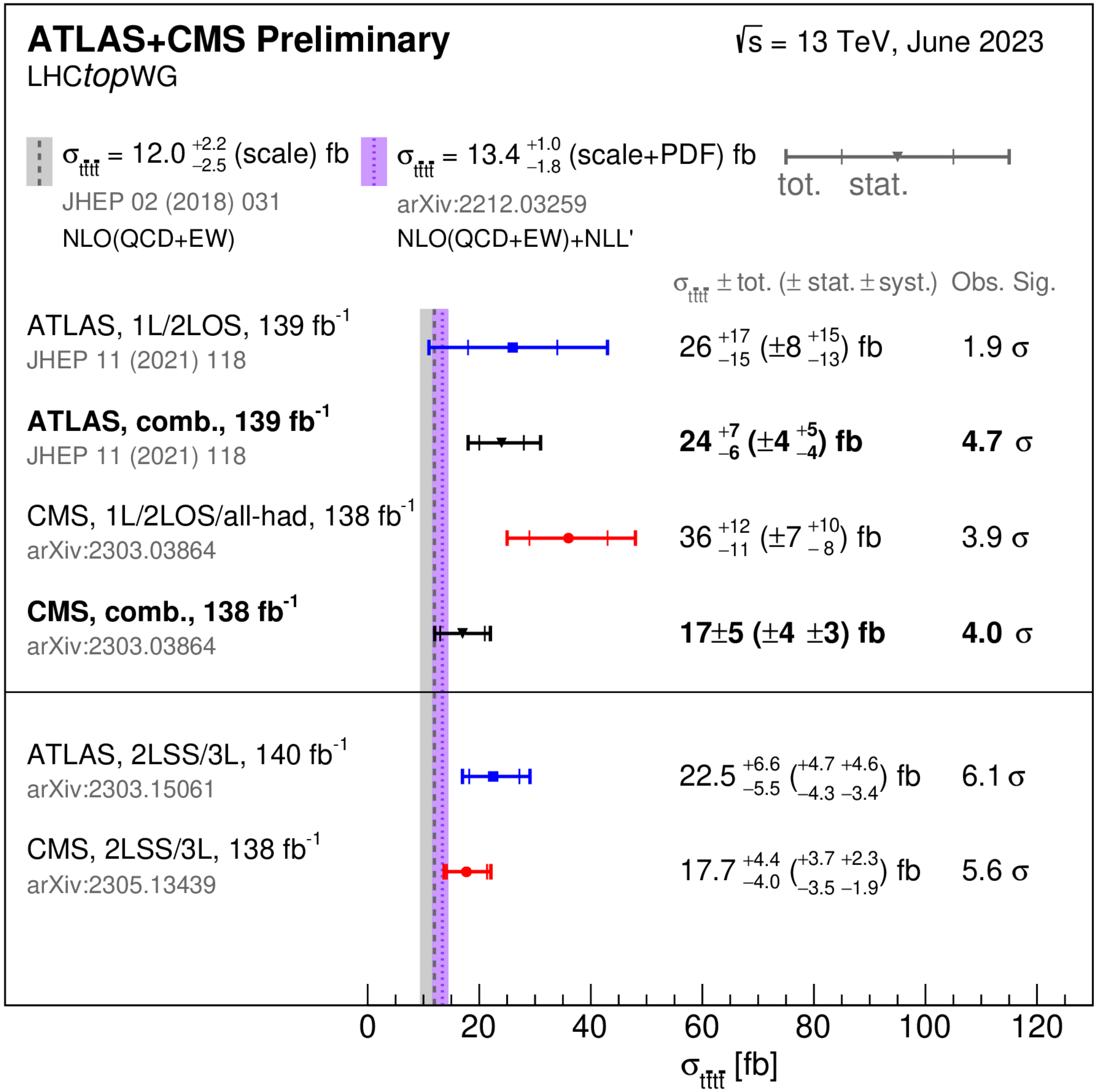
[Eur. Phys. J. C 83 (2023) 496]

SM predictions

JHEP 02 (2018) 031 — NLO (QCD+EW) $\sigma(t\bar{t}t\bar{t}) = 12.0 \pm 2.4$ fb

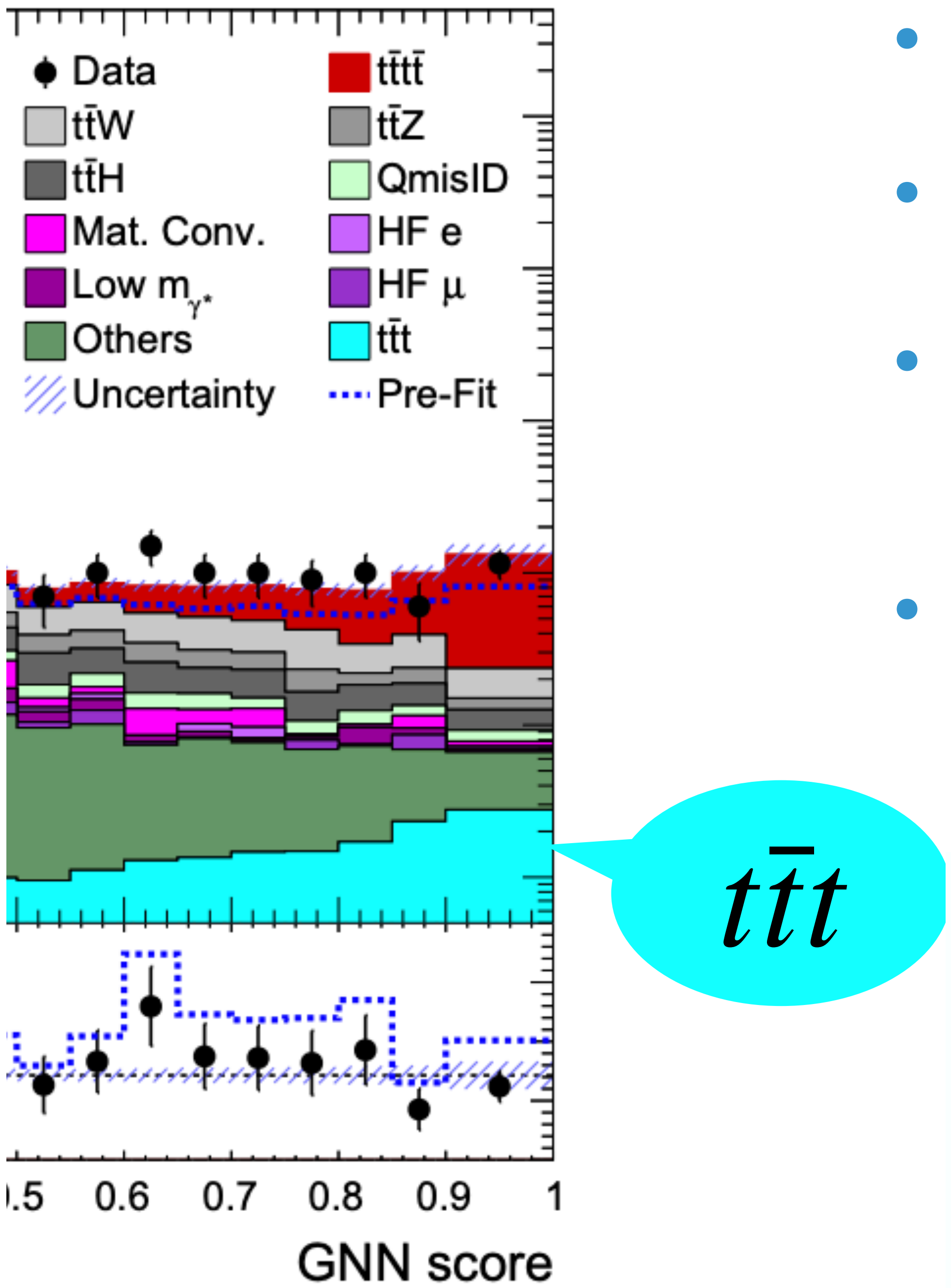
arXiv: 2212.03259 — including NLL′ $\sigma(t\bar{t}t\bar{t}) = 13.4^{+1.0}_{-1.8}$ fb

Summary of ATLAS and CMS measurements

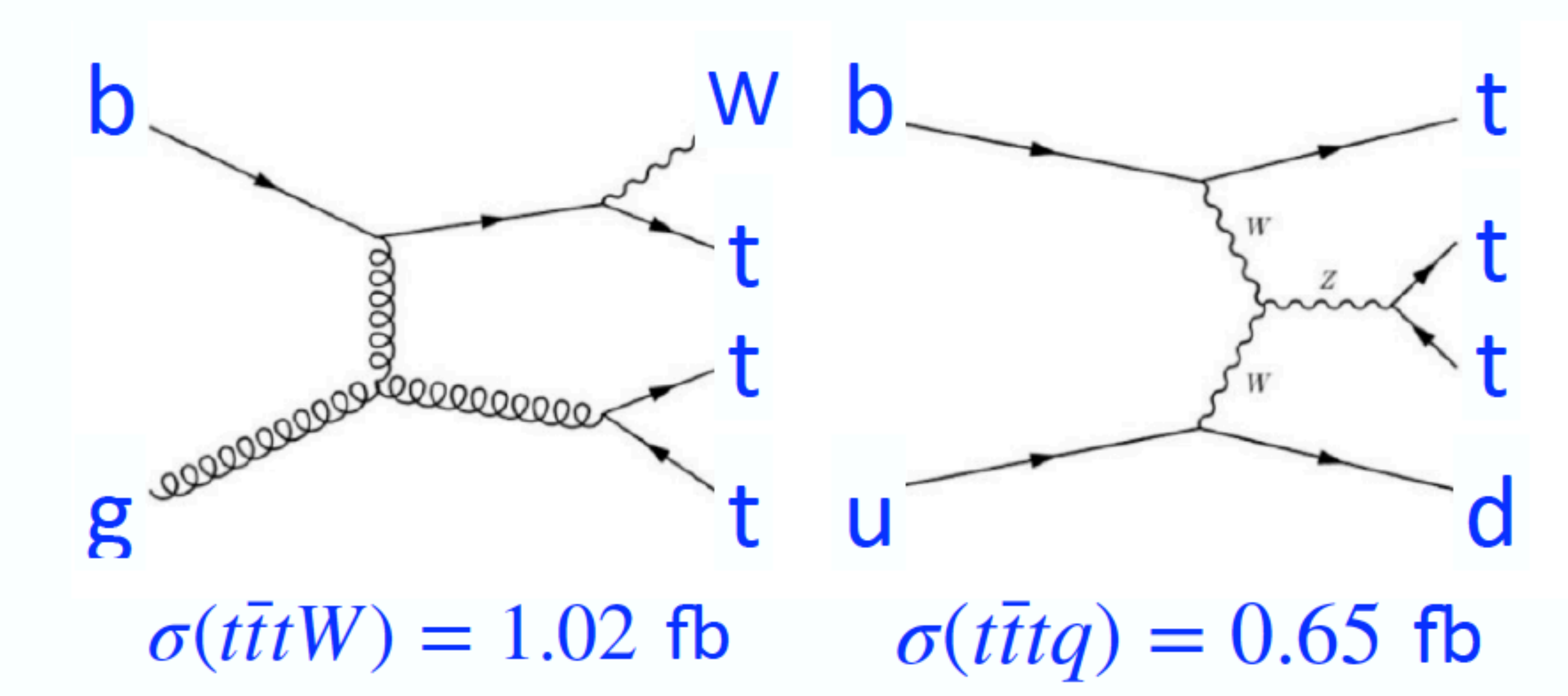


[ATL-PHYS-PUB-2023-013]

Three-top-quark production



- Final state signature is similar to four top signal
- Populates regions of high GNN score
- In SM $t\bar{t}t$ produces always in association with other particles
- 30% uncertainty on $t\bar{t}t$ cross section
  - Big thanks to Gauthier Durieux for these predictions!



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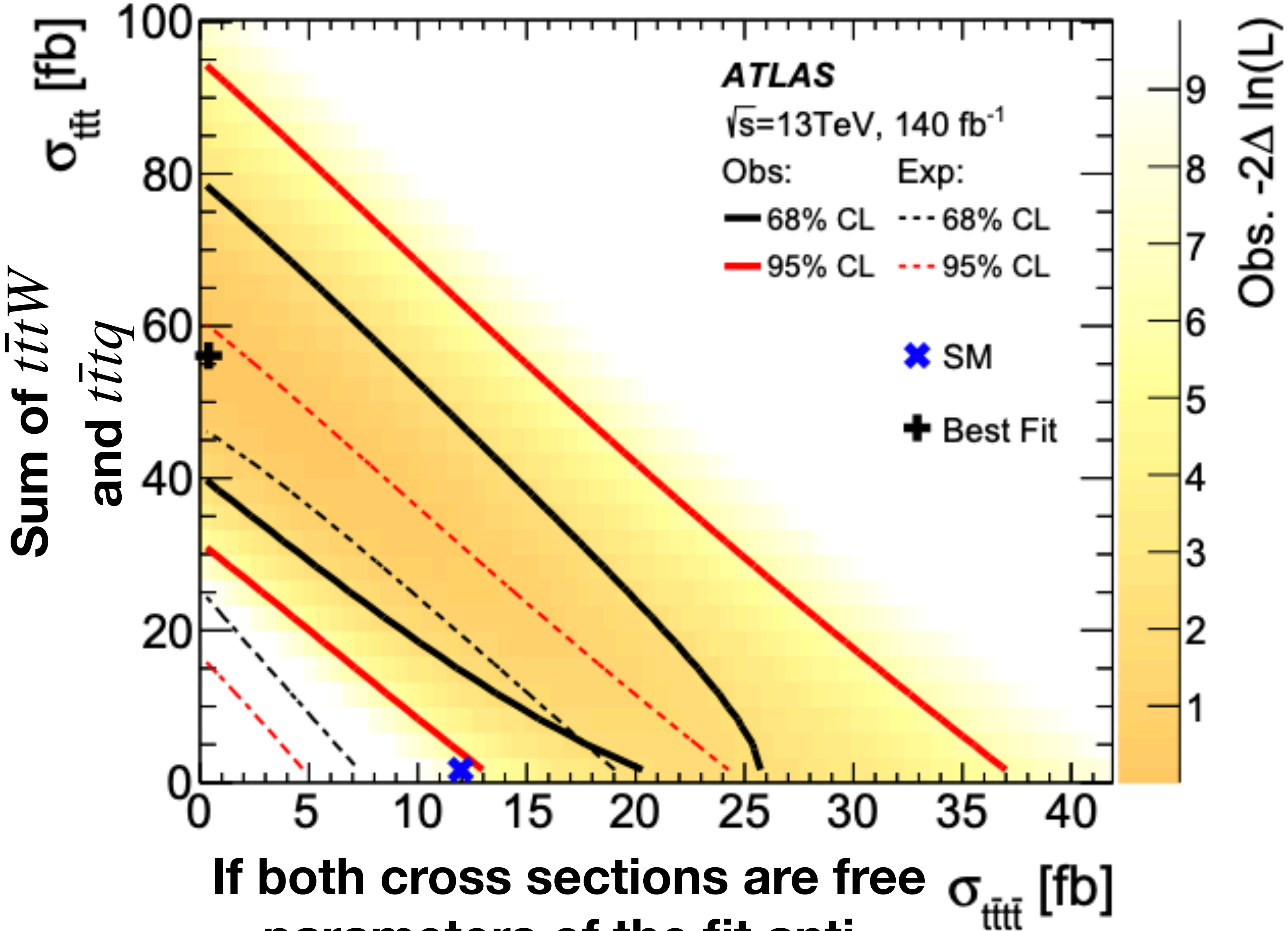

[Eur. Phys. J. C 83 (2023) 496]

If both cross sections are free parameters of the fit anti-correlation is 93%

Limits on $t\bar{t}t$ production

Cross section [fb]	95% CL interval with $\mu_{t\bar{t}t\bar{t}} = 1$	95% CL interval 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]

Interpretations

- Limits on heavy flavour fermion operators in EFT (one parameter variation)

Operators	Expected C_i/Λ^2 [TeV^{-2}]	Observed C_i/Λ^2 [TeV^{-2}]
O^1_{QQ}	[-2.4,3.0]	[-3.5,4.1]
O^1_{Qt}	[-2.5,2.0]	[-3.5,3.0]
O^1_{tt}	[-1.1,1.3]	[-1.7,1.9]
O^8_{Qt}	[-4.2,4.8]	[-6.2,6.9]

Conclusions

- Run 2 brought us to an unprecedented centre-of-mass energy of 13 TeV!
- Opened up measurements to new rare SM processes
  - SM, Top, & Higgs groups working to produce precise & lasting measurements
- Teaches us about the SM
- Improves our theoretical calculations, MC modelling, and understanding of CP calibrations and uncertainties
- Can uncover unexpected deviations from the SM
- ATLAS & CMS published many interesting measurements using full Run 2 data-set at 13 TeV

Thank you!