ATLAS results on rare top quark processes

CERN LHC Seminar
29.03.2022

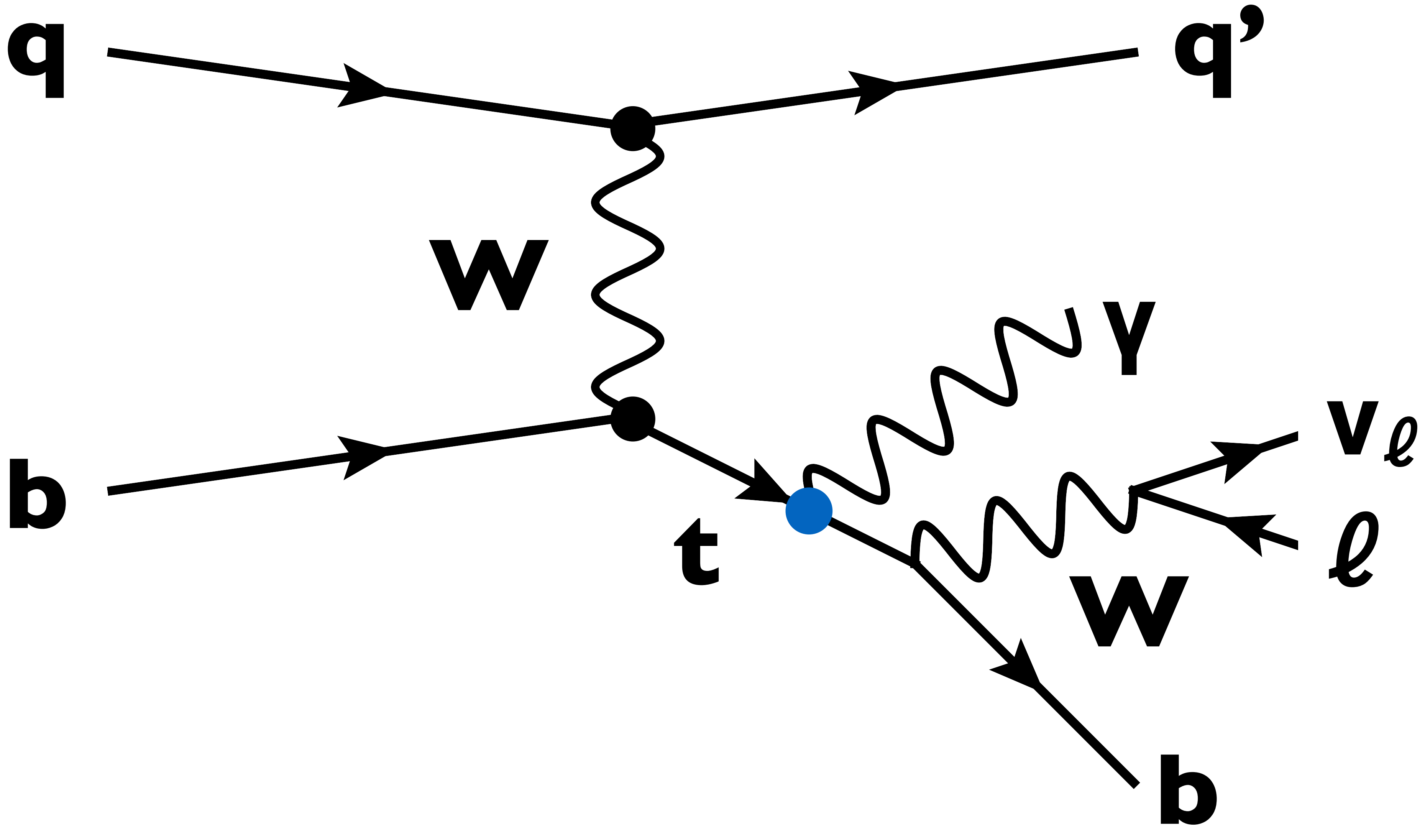
Johannes Erdmann
TU Dortmund University

on behalf of the ATLAS Collaboration

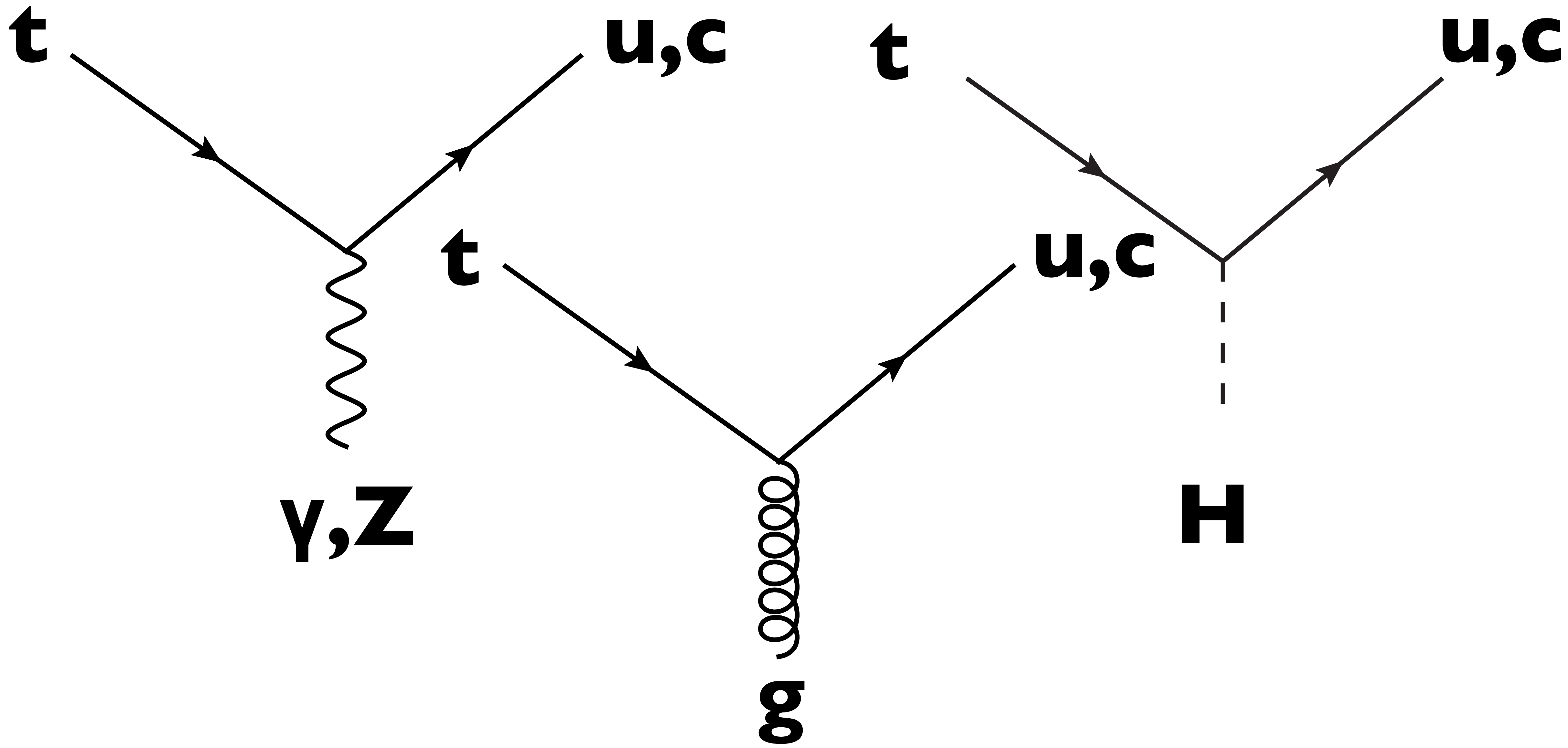
Outline

particlezoo.net

Single-Top+Photon Production



Flavour Changing Neutral Currents



What's In Common / Different ?

Common Points

- Full Run-2 data
- Single-lepton triggers (except $\tau\tau$)
- Search for rare processes

  → Background suppression using machine learning

  → Background validation using data in background-enriched regions
- Statistical uncertainties matter

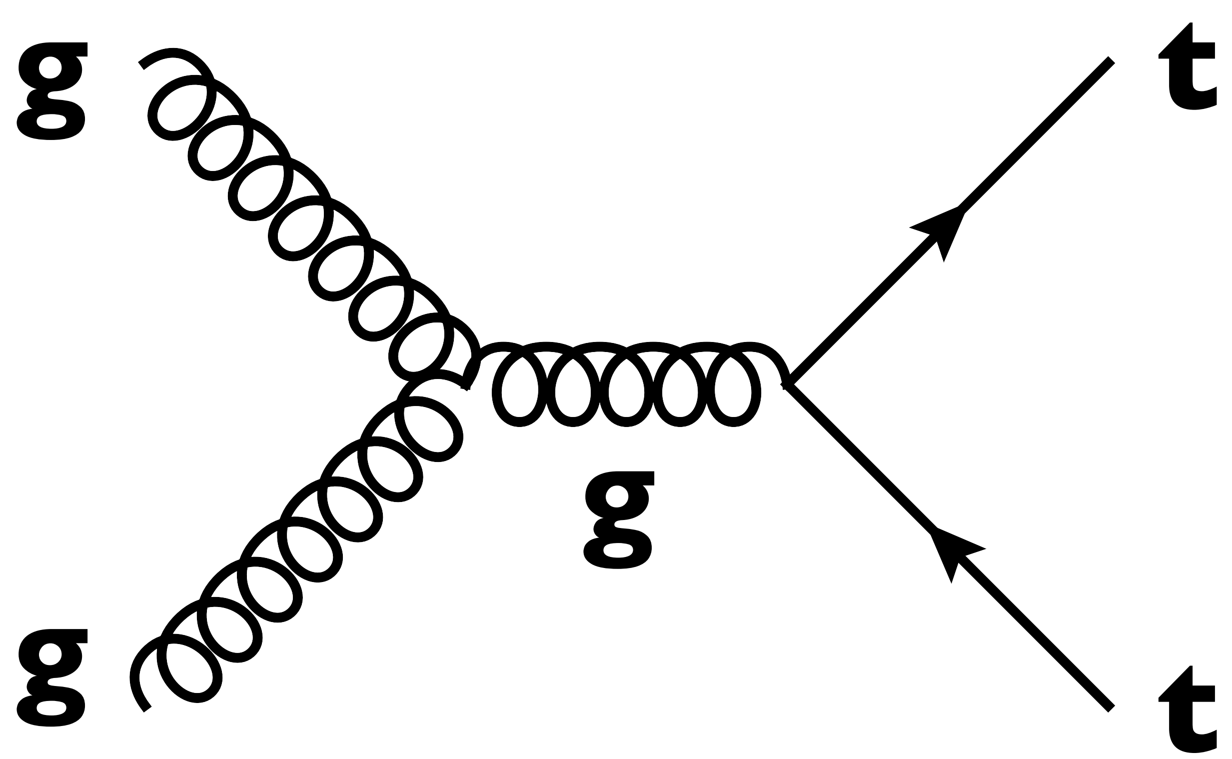
Differences

- Final state
- Machine-learning classifier
- Background estimation techniques
- SM process (top+photon) vs. BSM process (FCNC)
- Statistics vs. Systematics

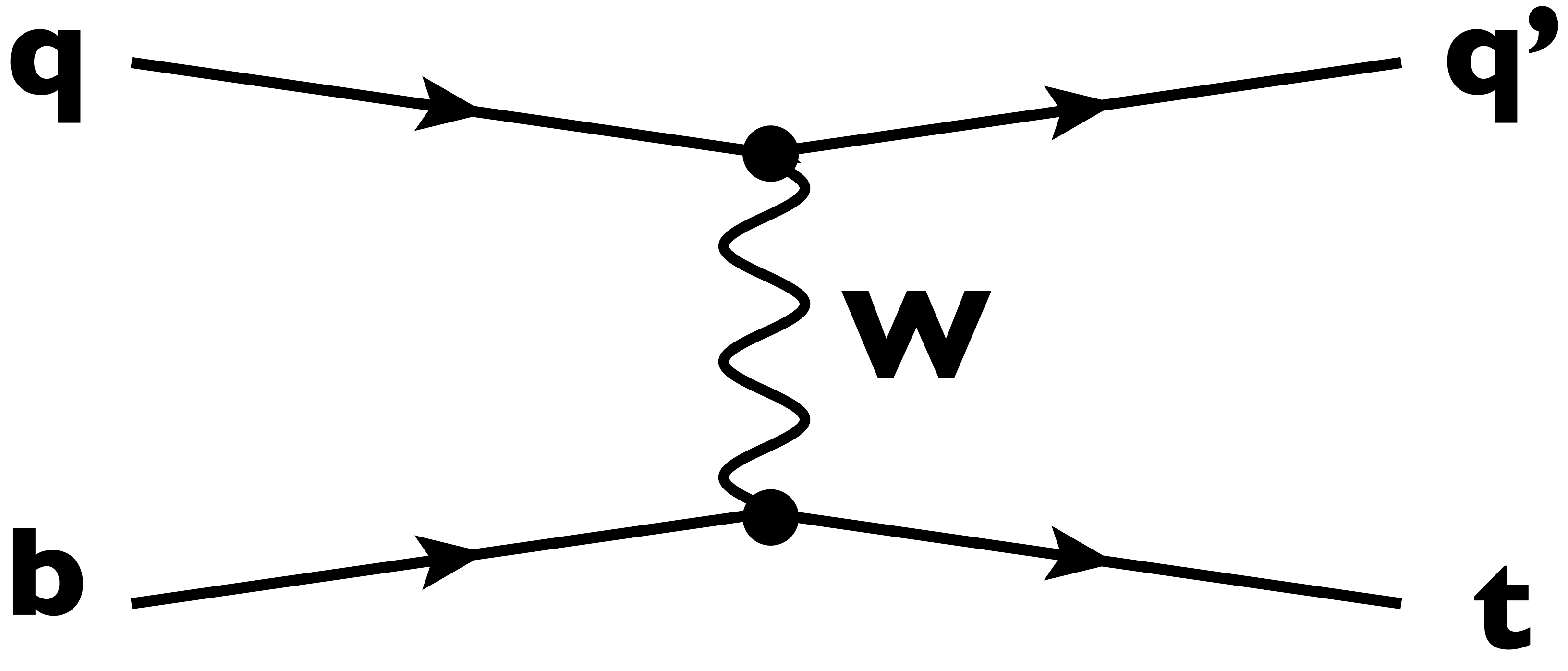
Search for single-top+γ production

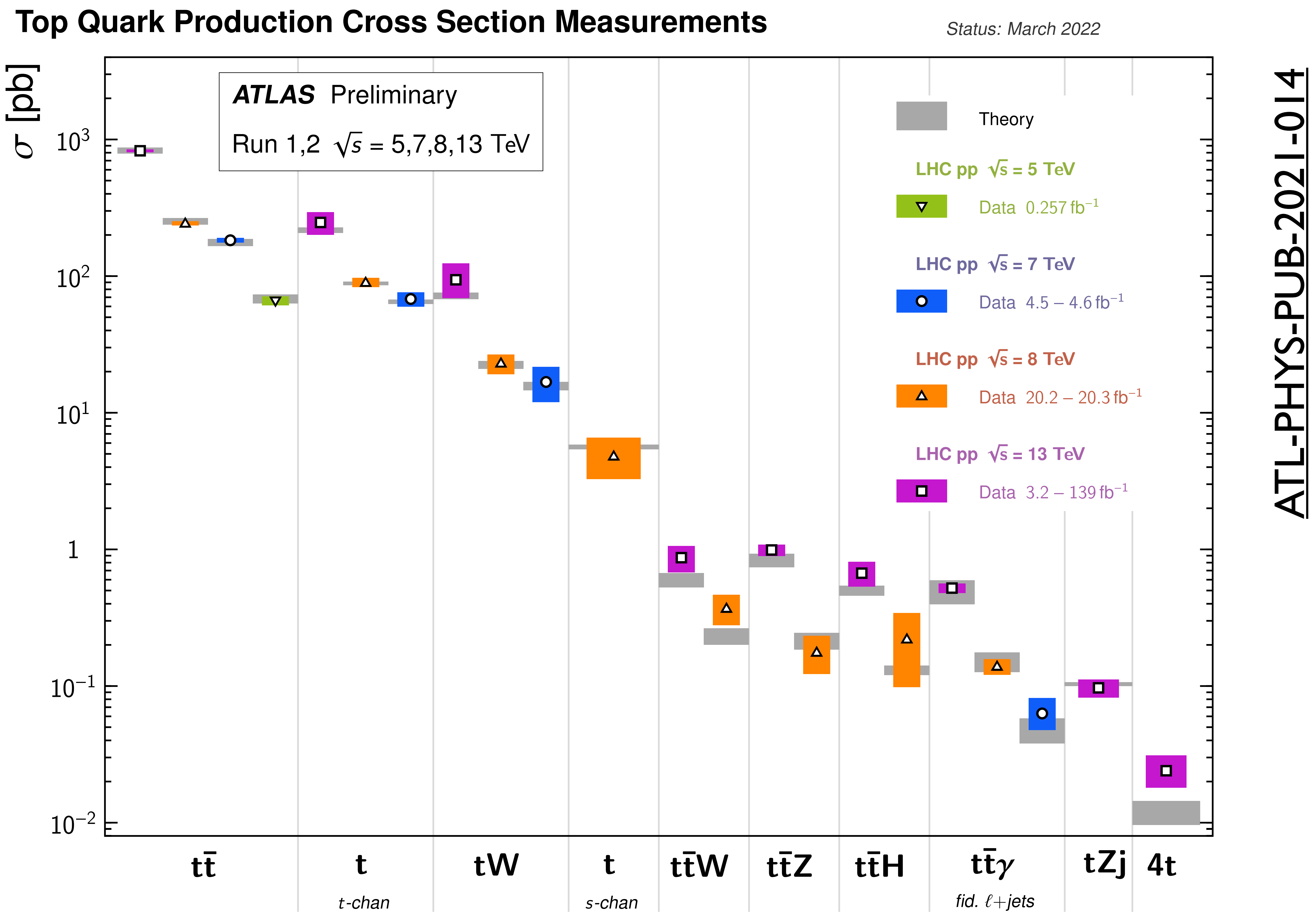
The Quest for Rare Top Processes

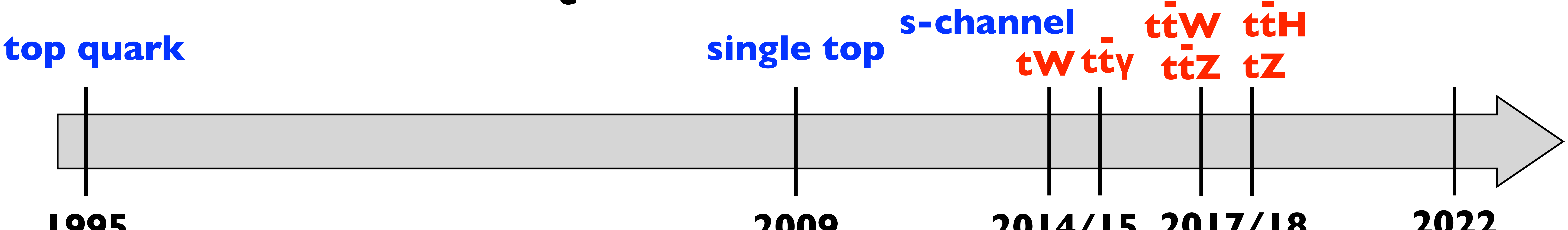
- Tops mainly produced in pairs



- Single top via EW production







A Missing Piece

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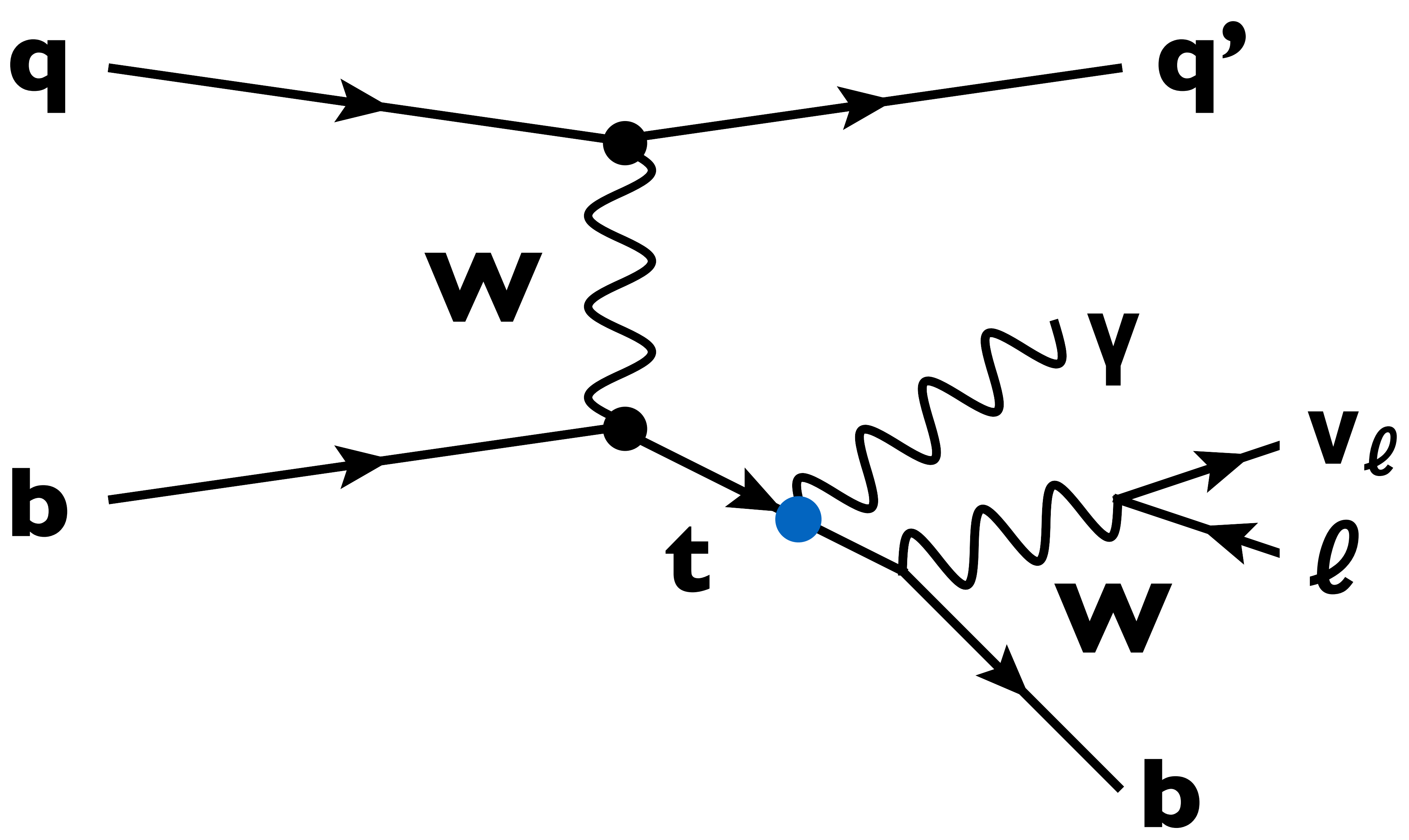
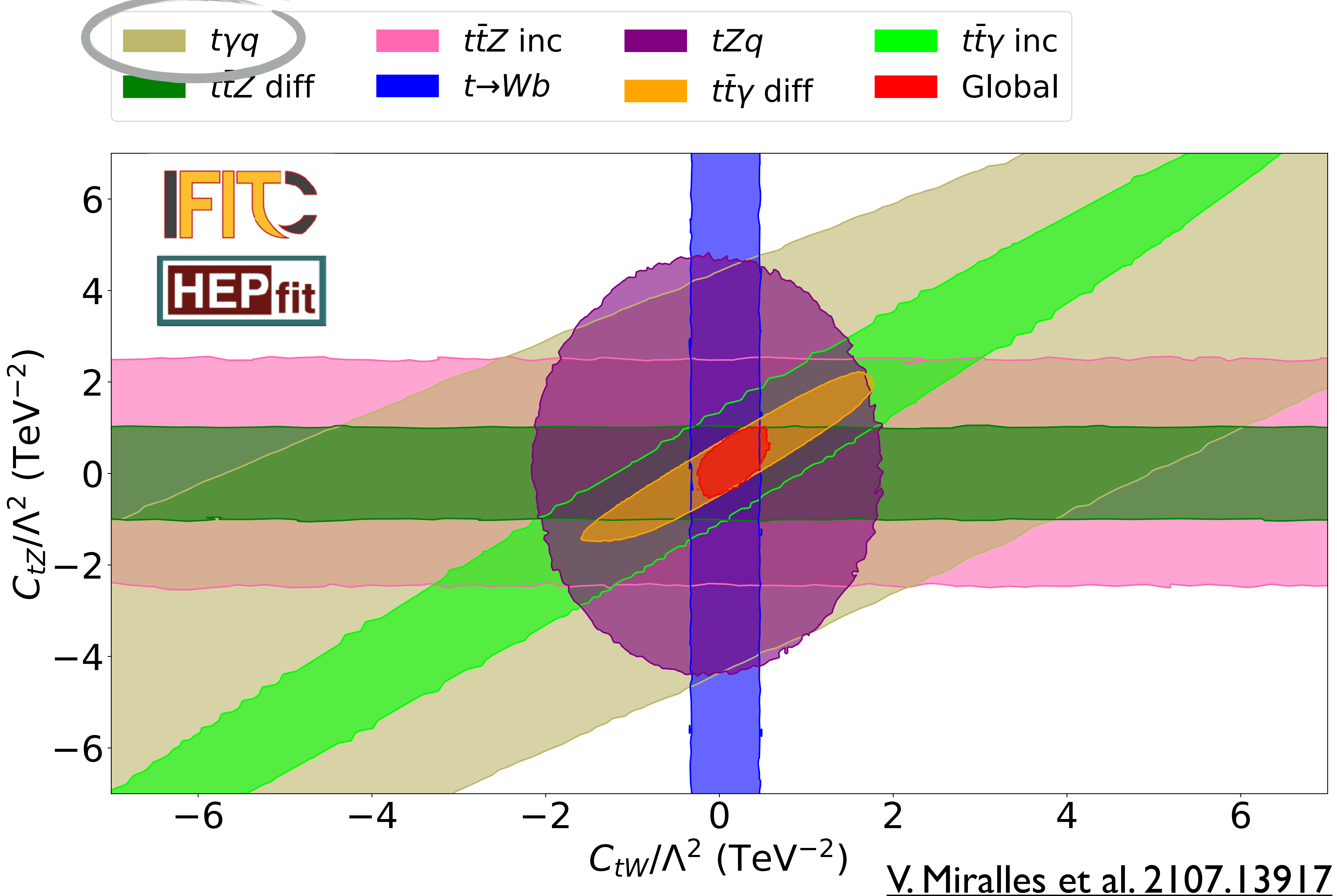
- Single top + photon not observed, yet



from CMS evidence analysis



V. Miralles et al. 2107.13917

- Evidence by CMS with 36 fb^{-1} 1808.02913
- Top+γ/Z probes electroweak vertex

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{\sum_i C_i \mathcal{O}_i}{\Lambda^2} + \ldots$$

How Rare Is it?

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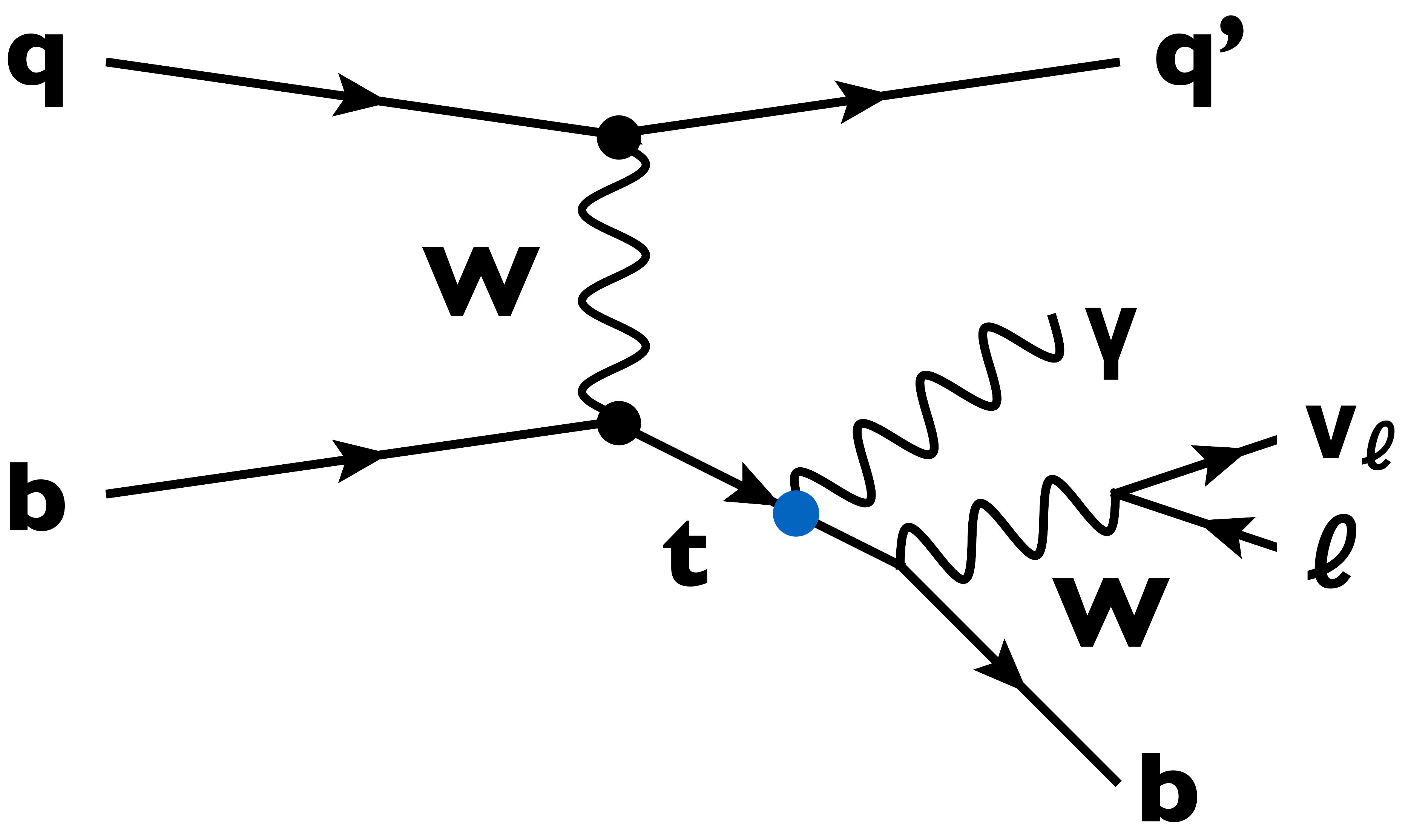

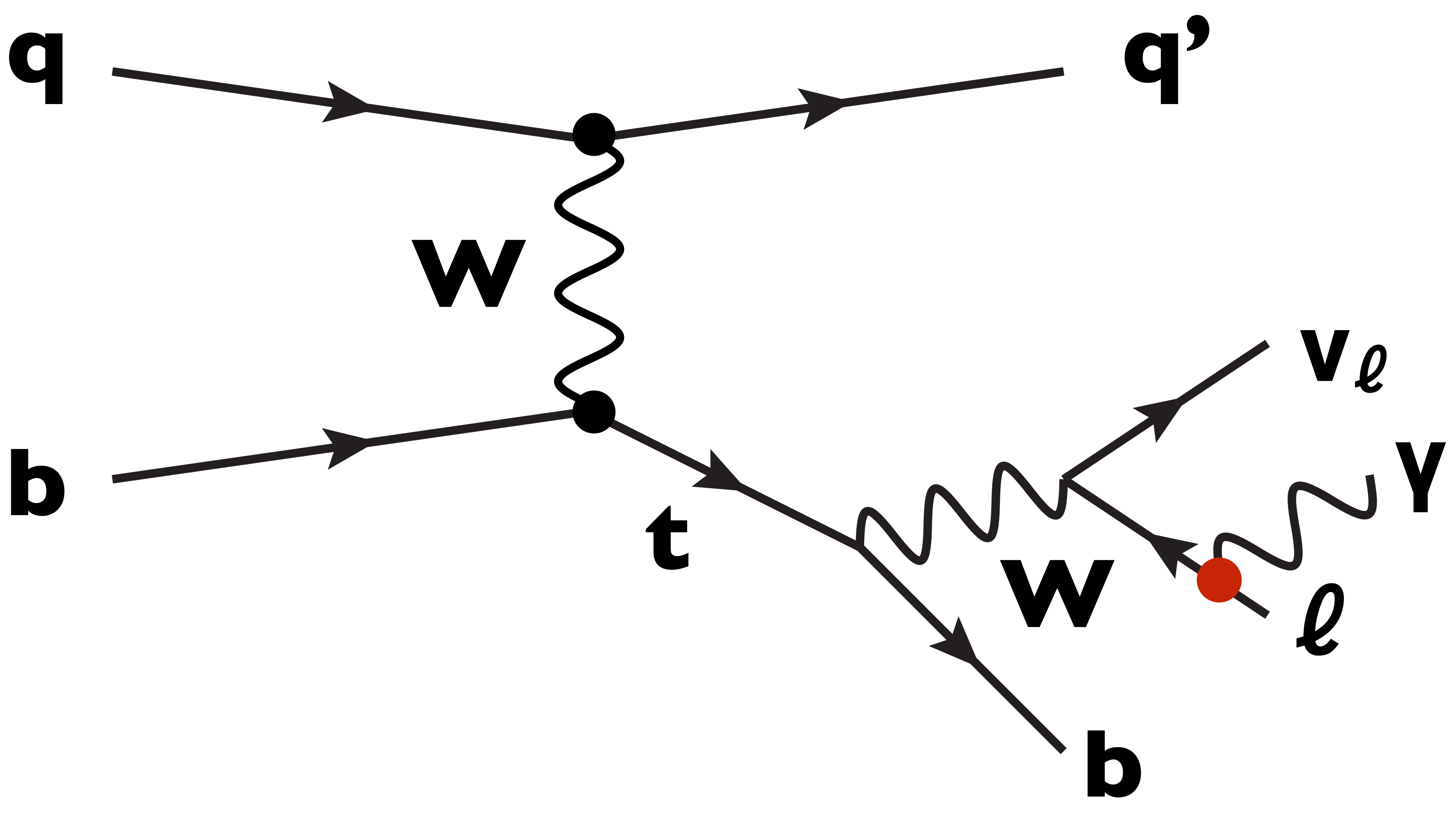

- tqγ sensitive to top EW coupling
- Fiducial phase space at parton level: $p_T(\gamma) > 20$ GeV , $|\eta_\ell| < 2.5$, $\Delta R(\gamma, X) > 0.4$
- $\sigma_{tq\gamma} \times \mathcal{B}\,(t \to \ell\nu b) = 406\,^{+25}_{-32}$ fb (NLO QCD, 4FNS, scale: $\frac{1}{2}\sum_i \sqrt{m_i^2 + p_{\mathrm{T}\,i}^2}$)
- Ratio of "tqγ" and "t→ℓνbγ" is ~ 4:1

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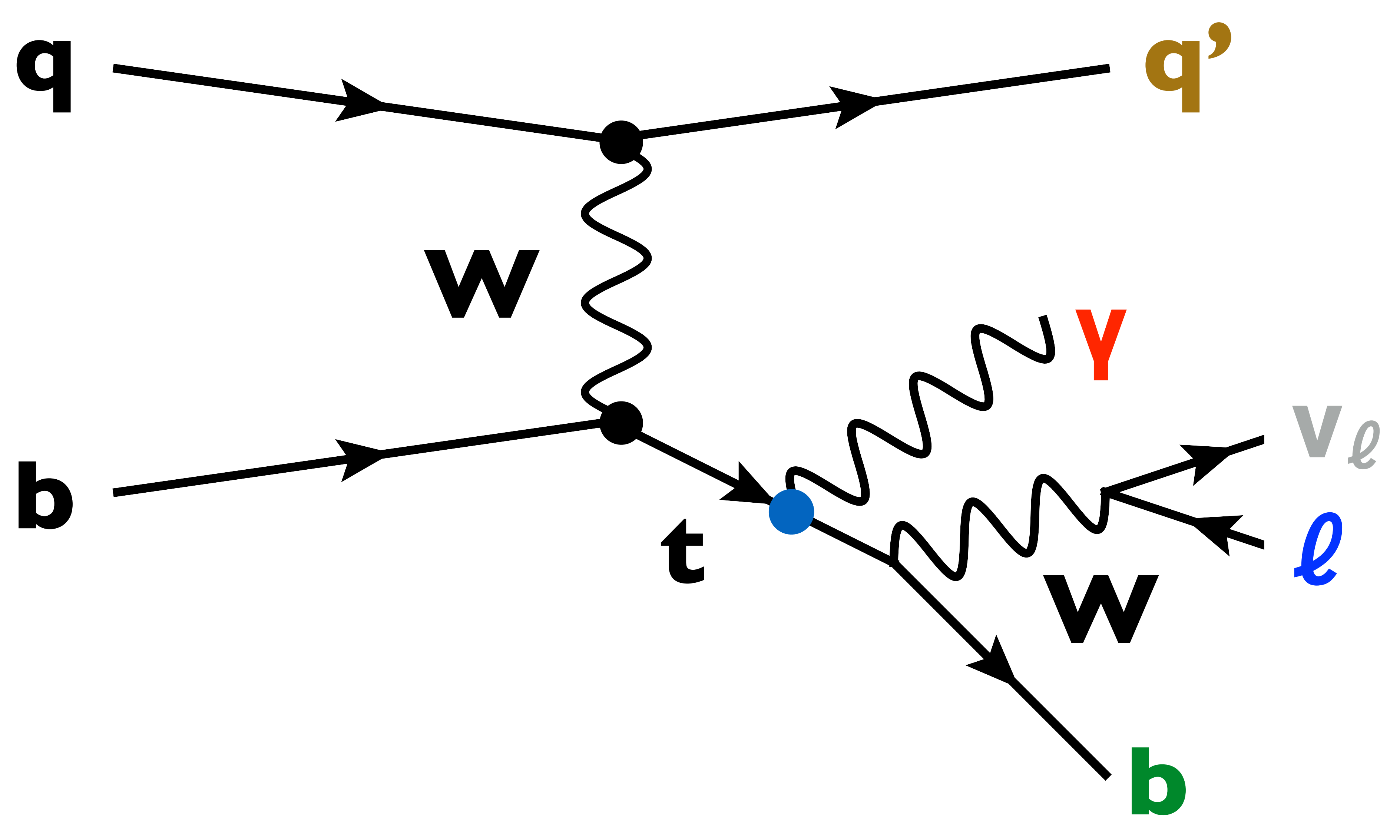
Event selection

- One central γ with $p_T > 20$ GeV
- One central **e/μ** with $p_T > 27$ GeV
- One **b-tagged jet** with $p_T > 25$ GeV

  + no additional jet with loose b-tag
- $E_T^{miss} > 30$ GeV
- m(eγ) outside 80-100 GeV
- **Forward jet** $(2.5 < |\eta| < 4.5)$?

0fj SR **≥1fj SR**



Background Estimates

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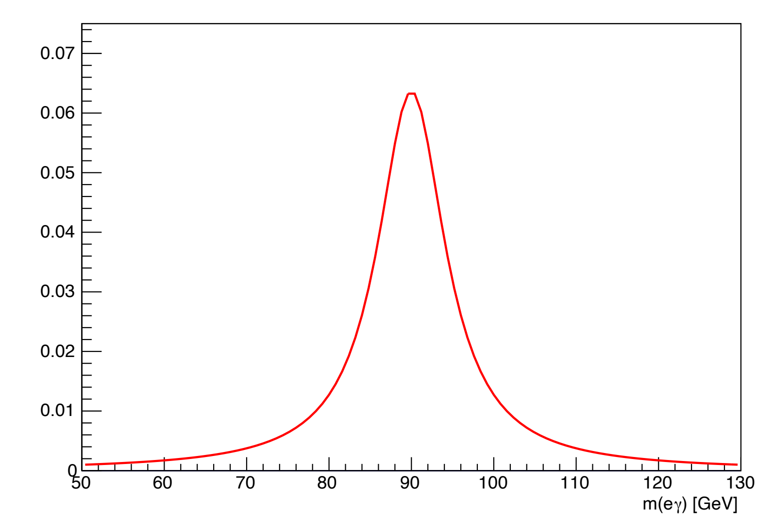
Process	0fj SR	≥1fj SR	Background Strategy
Signal	5%	10%	
$t\bar{t}\gamma$	29%	34%	data control region with 1 tight + 1 loose b-tag
Wγ+jets	20%	12%	data control region with 1 loose b-tag
e→γ fakes (mostly dileptonic $t\bar{t}$)	24%	25%	data-MC scale factors (Z→e+fake)
h→γ fakes (mostly lepton+jets $t\bar{t}$)	7%	7%	data-MC scale factors (ABCD)
Additional backgrounds with real γ	15%	12%	MC + matrix method for lepton fakes

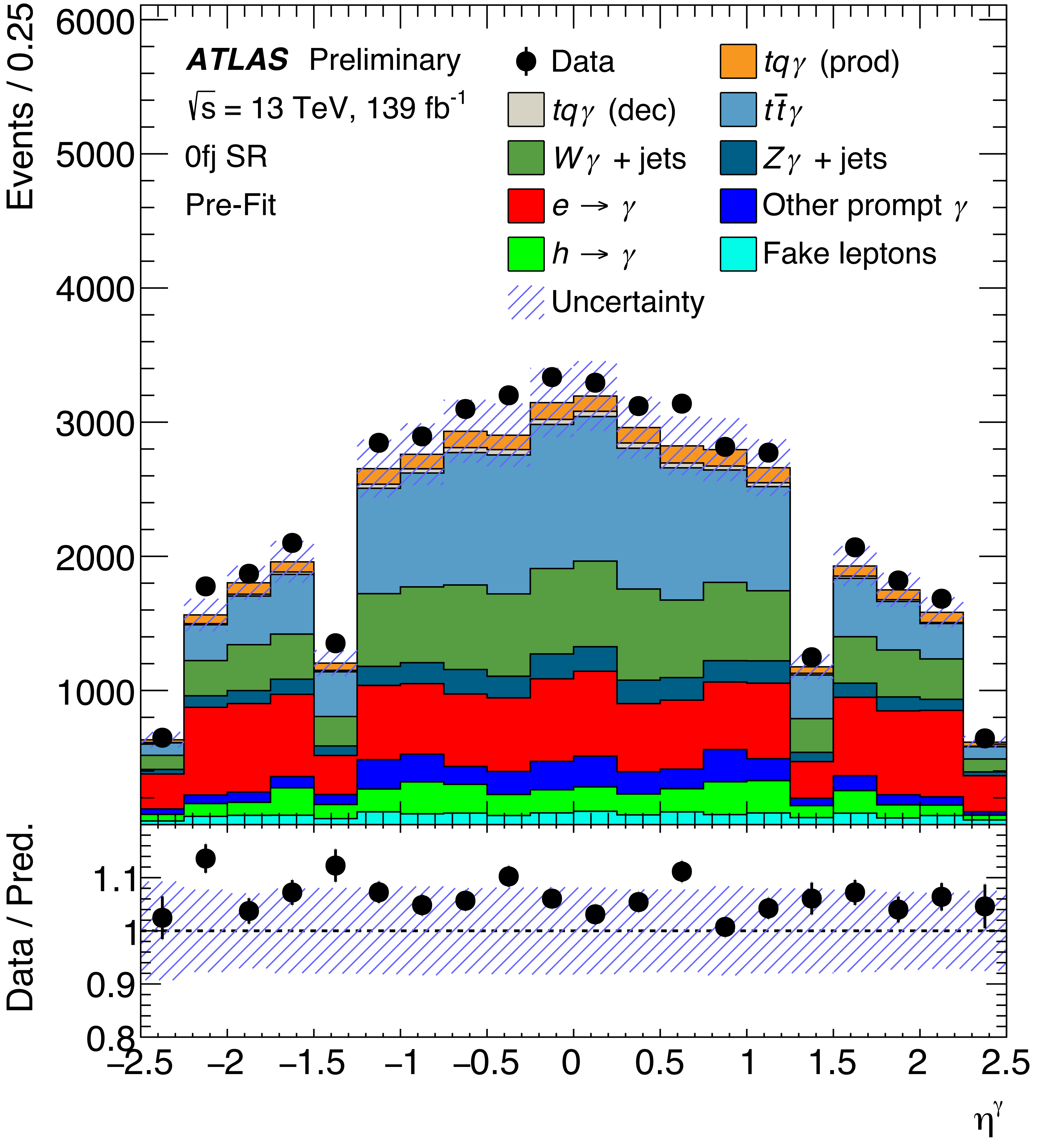
- e^+e^- and eγ events close to m_Z
- Correct MC in bins of photon η and separately for the different γ → e^+e^- reconstruction types

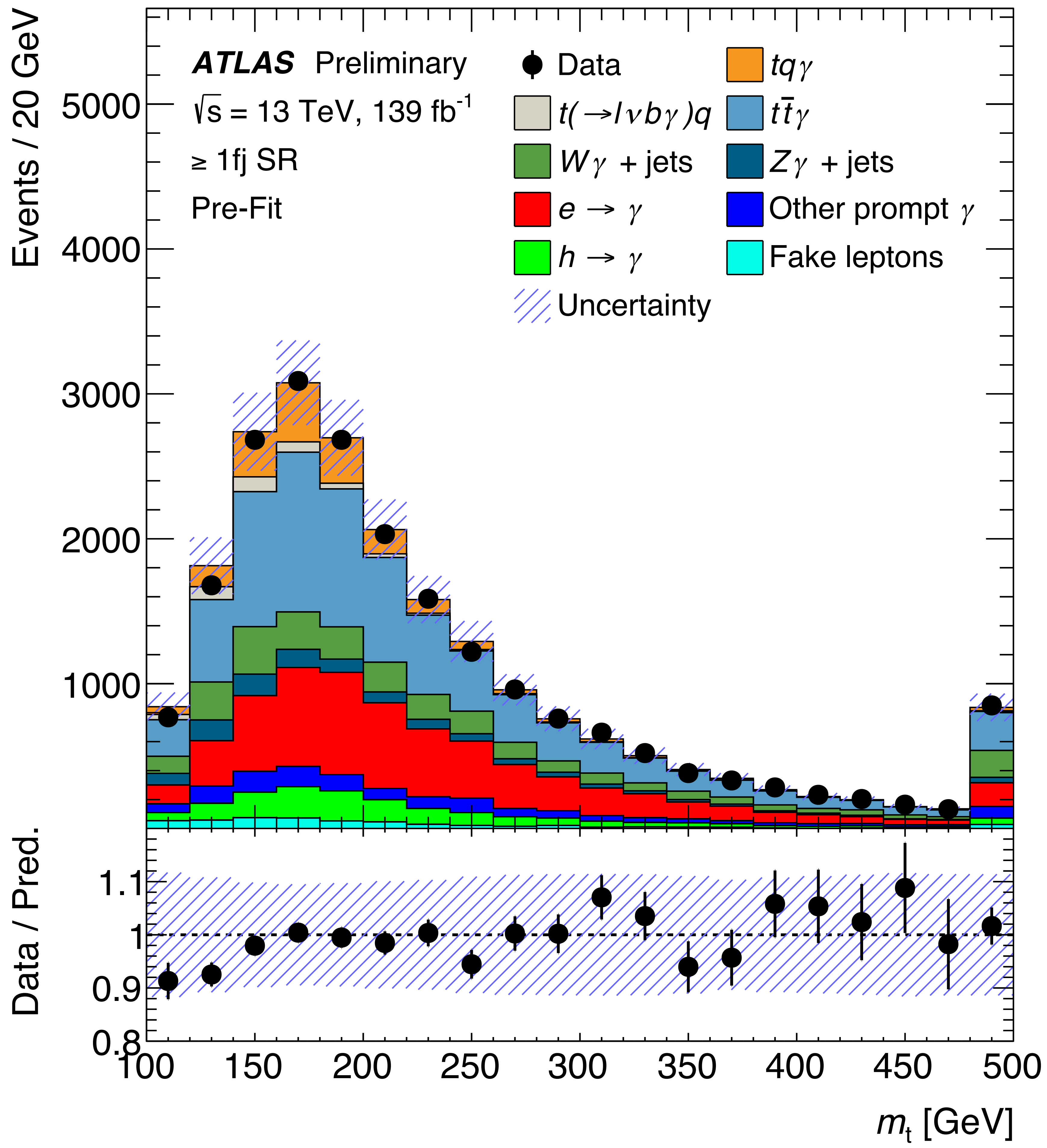


- Signal/control region selection with reverted photon criteria
- In bins of η, two bins of photon p_T and for converted/unconverted γ

Neural Network

- NNs trained in SRs with 12/15 inputs based on final-state kinematics and b-tag properties
- Shapes of input variables well modeled in data

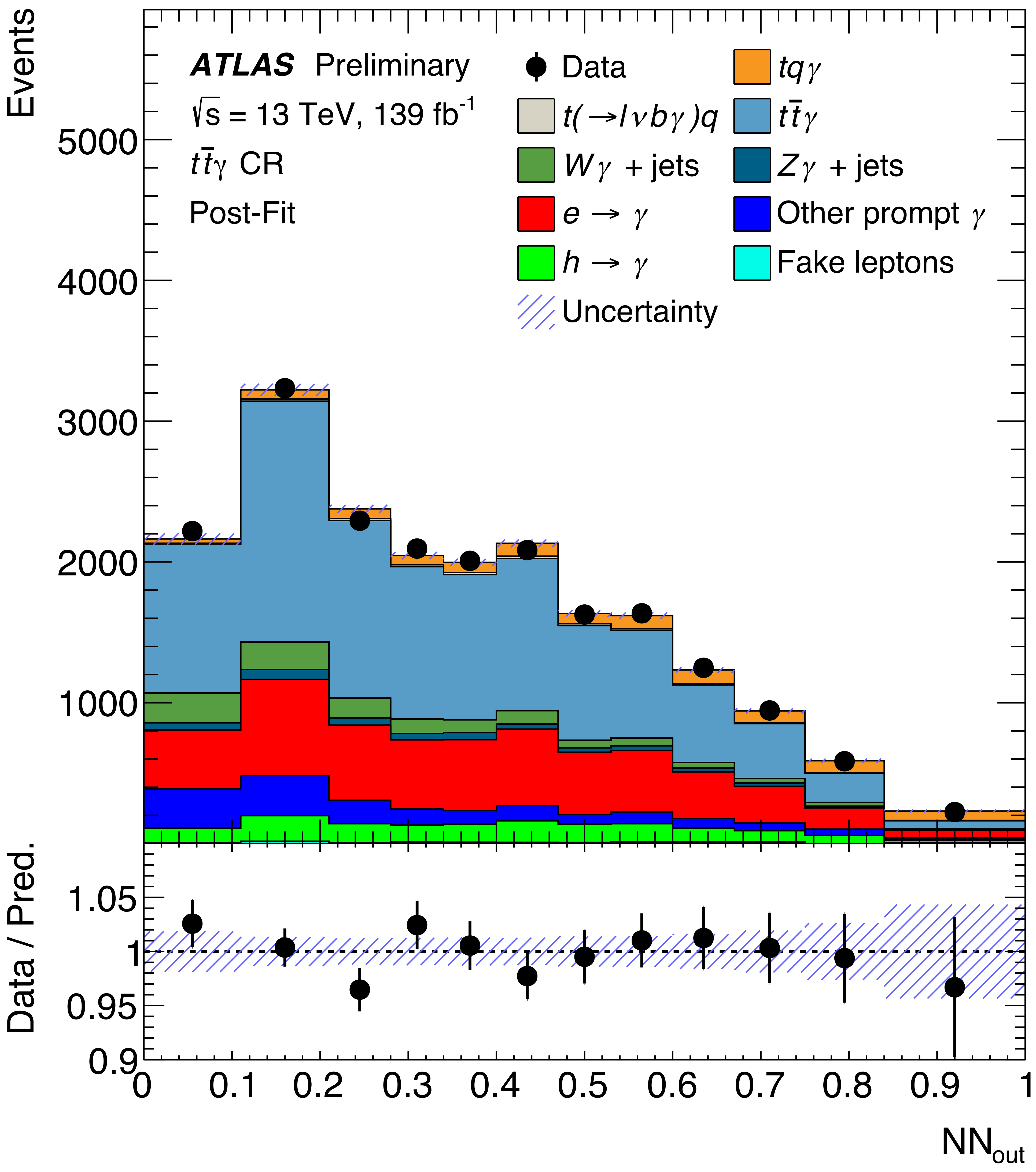




Background Prediction

- Profile-likelihood fit to SRs and CRs
- NN output in SRs and $t\bar{t}\gamma$ CR, total yield in $W\gamma$ CR
- ~21,000 / ~46,000 events in the SRs

	≥ 1fj SR	0fj SR	$t\bar{t}\gamma$ CR	$W\gamma$ CR
$tq\gamma$	2390 ± 260	2480 ± 320	890 ± 120	1280 ± 150
$t(\rightarrow \ell\nu b\gamma)q$	360 ± 150	460 ± 240	120 ± 50	230 ± 110
$t\bar{t}\gamma$ (production)	3100 ± 400	4800 ± 700	4300 ± 600	2720 ± 350
$t\bar{t}\gamma$ (radiative decay)	3800 ± 600	9300 ± 1400	5700 ± 600	4300 ± 900
$W\gamma$+jets	2500 ± 400	9300 ± 1300	1050 ± 190	31 900 ± 3000
$Z\gamma$+jets	990 ± 310	2800 ± 800	440 ± 150	7900 ± 2400
$e \rightarrow \gamma$ fake photons	5200 ± 500	10 300 ± 800	4800 ± 400	5400 ± 500
$h \rightarrow \gamma$ fake photons	1100 ± 400	2700 ± 800	1300 ± 500	2500 ± 800
Other prompt γ	1360 ± 350	2600 ± 900	1400 ± 400	4100 ± 500
Fake leptons	350 ± 170	900 ± 400	100 ± 50	3300 ± 1600
Total	21 250 ± 150	45 720 ± 240	20 180 ± 140	63 590 ± 310
Data	21 227	45 723	20 194	63 592



Uncertainties

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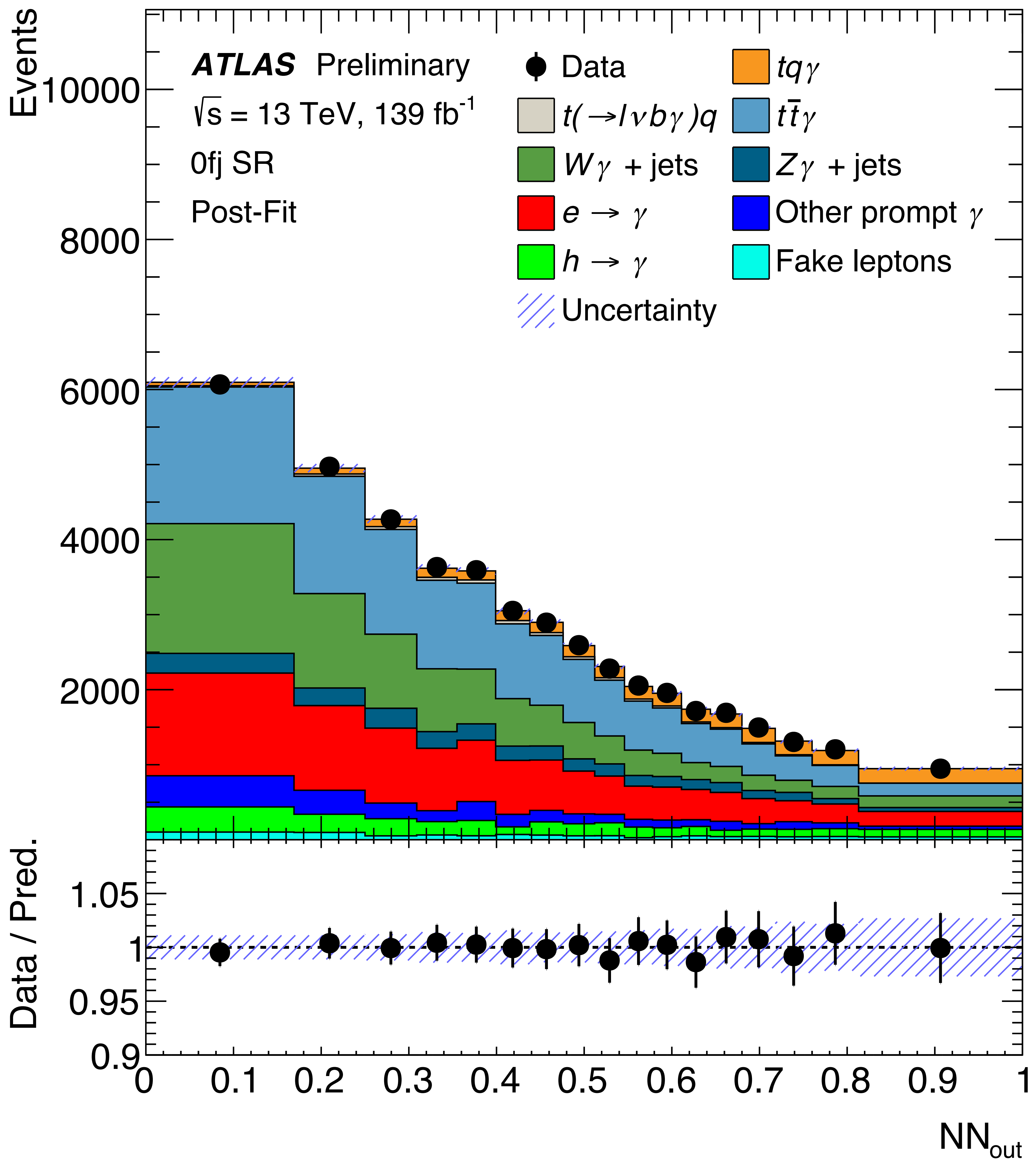
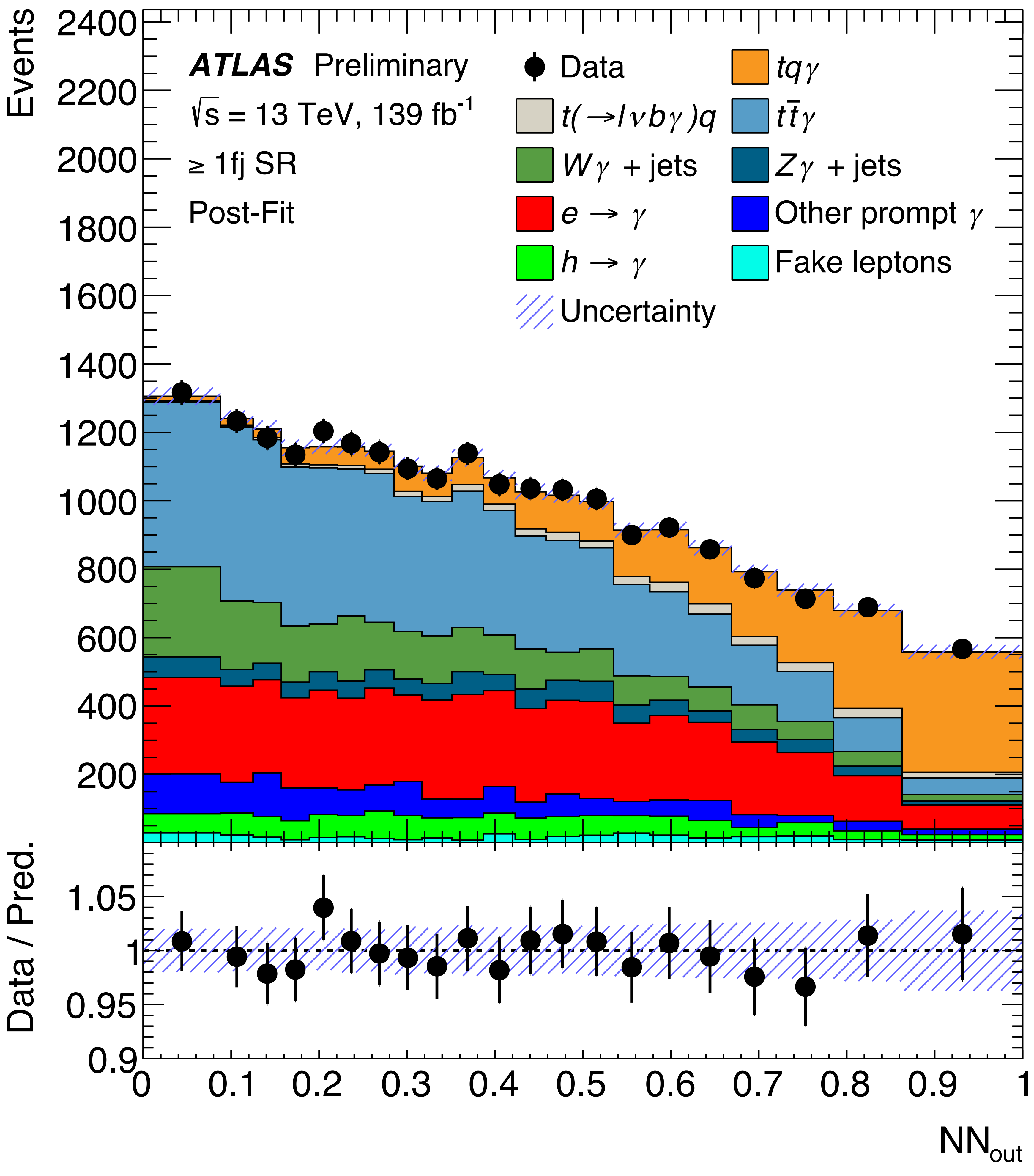
- Statistical uncertainty: 3.3%
- Not a single culprit
- Main systematics from background modelling
  - $t\bar{t}\gamma$ and $t\bar{t}$
- Uncertainties from limited MC statistics
  - A major challenge for $t\bar{t}$ production
- Fake uncertainties are small in comparison

Uncertainty	$\Delta\sigma/\sigma$
$tt\gamma$ modelling	±5.6%
Background MC statistics	±3.5%
$t\bar{t}$ modelling	±3.4%
$tq\gamma$ MC statistics	±3.4%
$t\,(\to \ell\nu b\gamma)\,q$ modelling	±1.9%
Additional background uncertainties	±1.9%
$tq\gamma$ modelling	±1.8%
$t\,(\to \ell\nu b\gamma)\,q$ MC statistics	±0.3%
Lepton fakes	±2.2%
$h \to \gamma$ photon fakes	±2.2%
$e \to \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.2%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±4.0%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.8%
Total systematic uncertainty	±10.9%

Observation

- tqγ production clearly visible on top of the background
- Significance: 9.1σ observed / 6.7σ expected





- Parton-level fiducial cross section → compare to fixed-order SM and EFT tqγ

$$\sigma_{tq\gamma} \times \mathcal{B}(t \to \ell\nu b) = 580 \pm 19\,(\text{stat.}) \pm 63\,(\text{syst.})\ \text{fb}$$

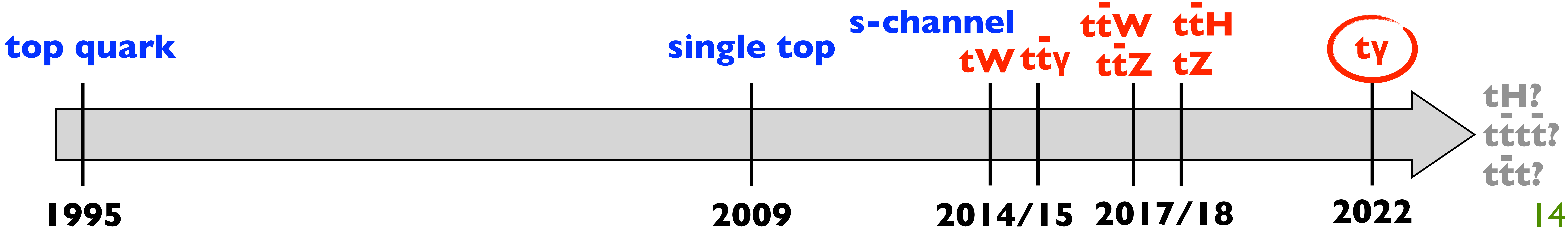
  - ~40% higher than the prediction: $406\,^{+25}_{-32}$ fb

- Particle-level fiducial cross section → minimal extrapolation of tqγ and t→ℓνbγ

$$\sigma_{tq\gamma} \times \mathcal{B}(t \to \ell\nu b) + \sigma_{t(\to\ell\nu b\gamma)q} = 287 \pm 8\,(\text{stat.}) \pm 31(\text{syst.})\ \text{fb}$$

  - ~equally high compared to prediction: $207\,^{+26}_{-11}$ fb

- Compatibility: 2.5σ / 1.9σ at parton/particle level



Parton / Particle Level Cross Sections

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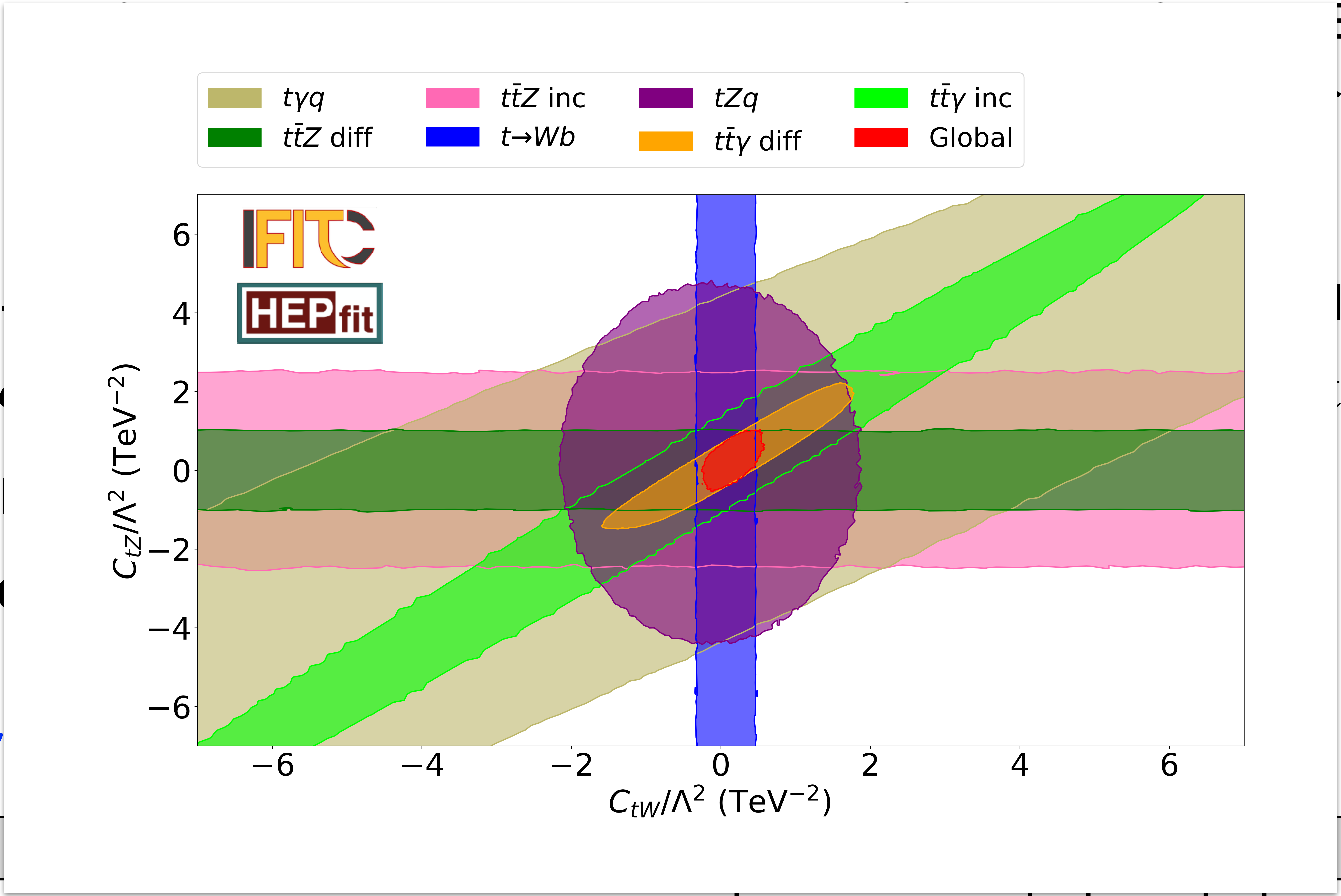
- Parton- … EFT tqγ
  … b
  - ~40%
- Particle- … l t→ℓνbγ
  … .) fb
  - ~equal
- Compat



top quar

tγ

tH?
tt̄tt̄?
tt̄t?

1995 2009 2014/15 2017/18 2022

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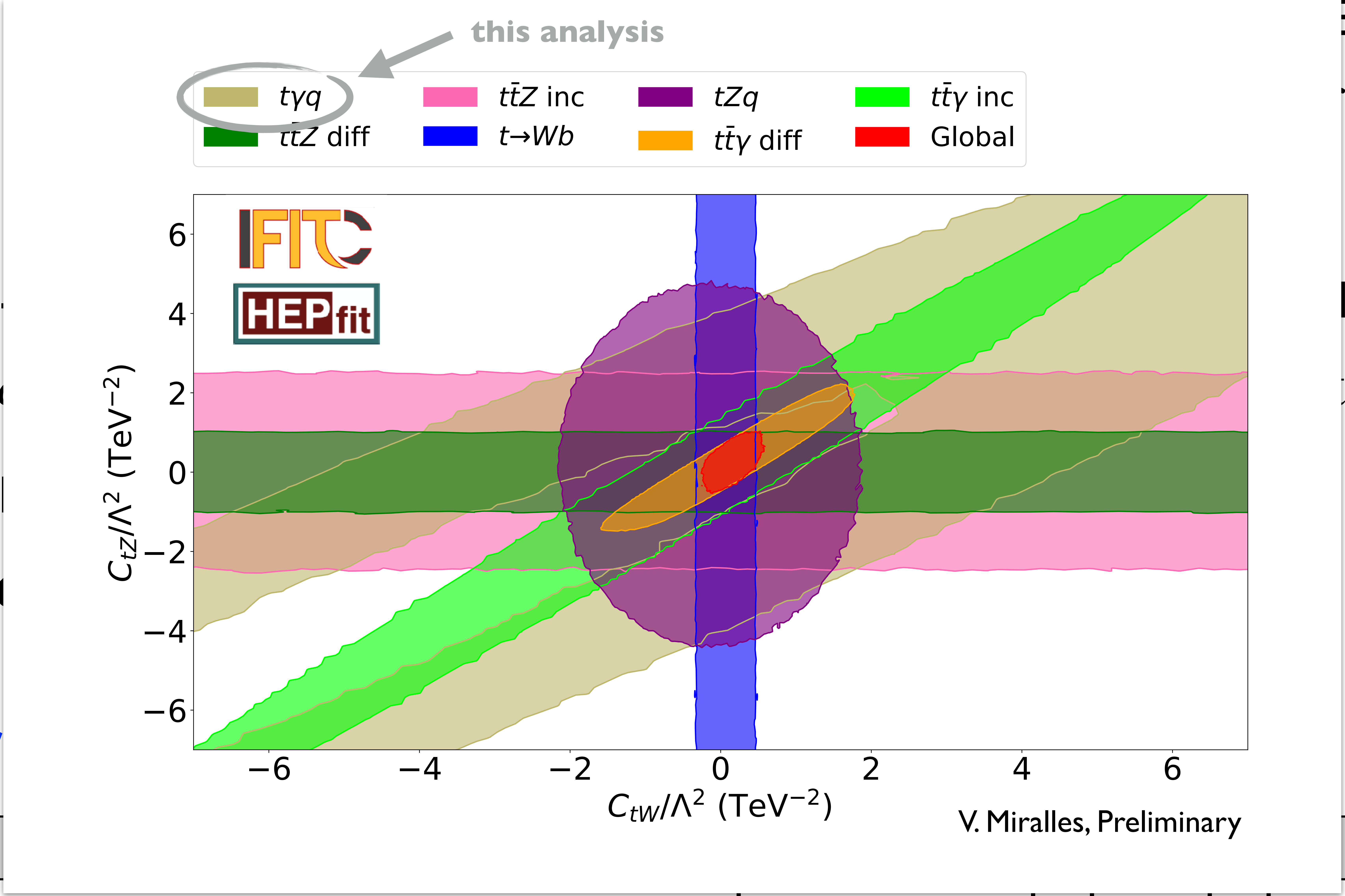

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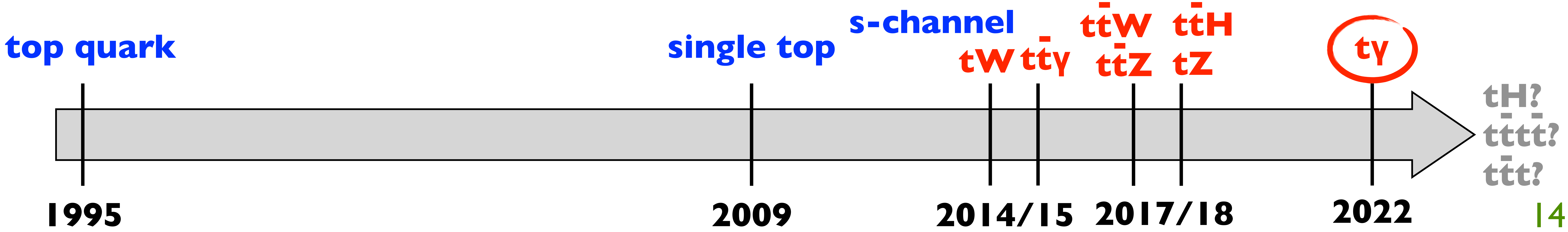
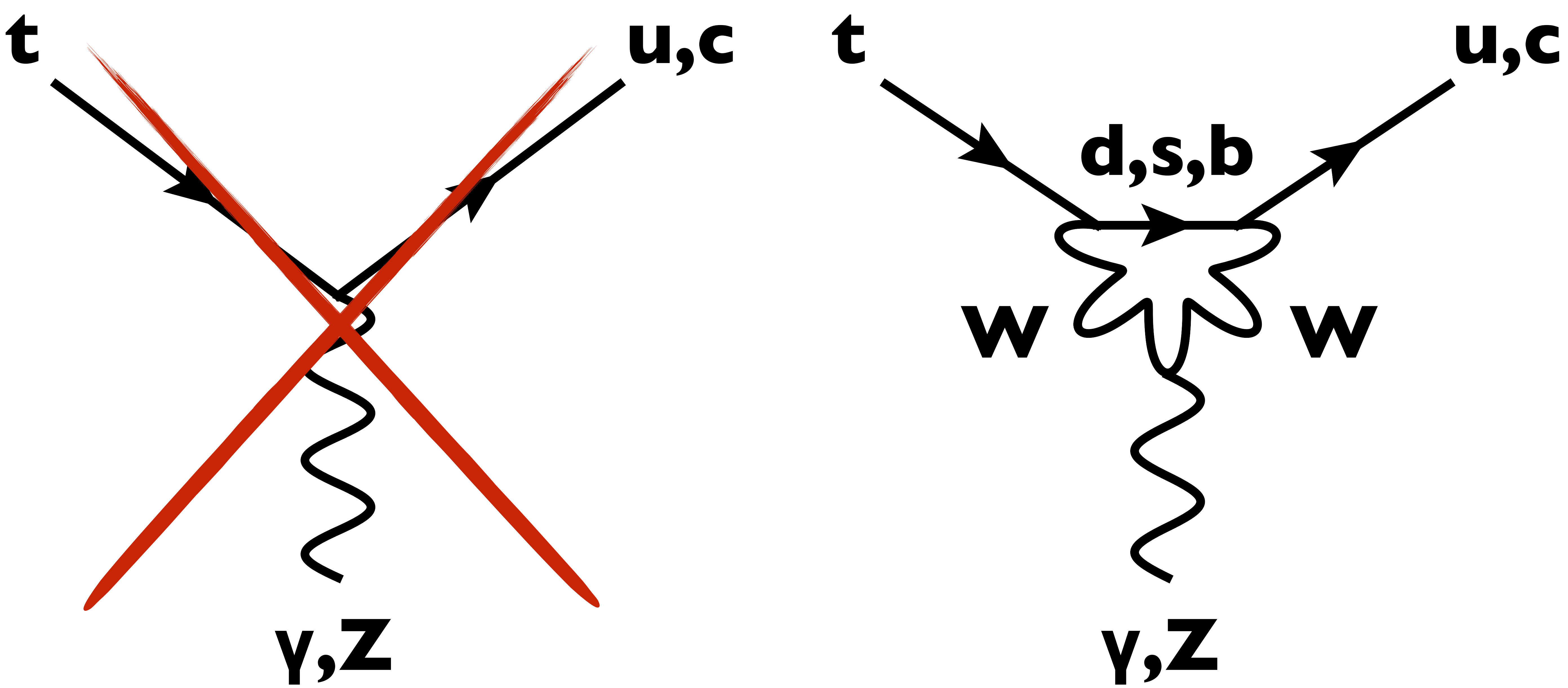


News on top-quark FCNC

Top Quark FCNCs

- FCNC in the SM only at loop level
- Highly suppressed due to GIM

hep-ph/0409342	SM BR (u)	SM BR (c)
$t \to \gamma + u/c$	4×10^{-16}	5×10^{-14}
$t \to Z + u/c$	8×10^{-17}	1×10^{-14}
$t \to H + u/c$	2×10^{-17}	3×10^{-15}
$t \to g + u/c$	4×10^{-14}	5×10^{-12}



- BR also suppressed by large $\Gamma(t \to Wb)$
- Mild constraints from flavour/EW precision (e.g. $BR(t \to cH) < 5\text{-}7 \times 10^{-4}$ from D mixing)

$BR(t \to cH) < 2 \times 10^{-3}$ from $Z \to c\bar{c}$)

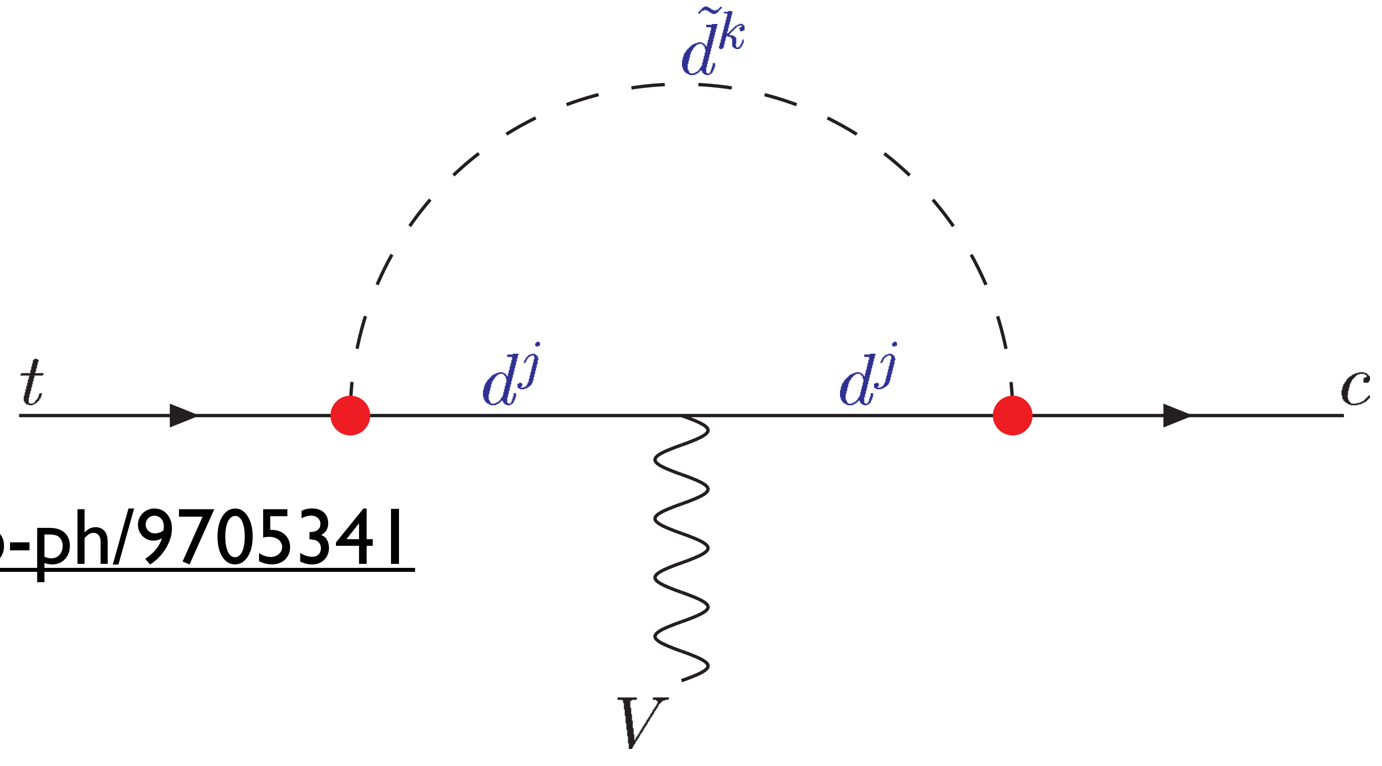
H. Hesari et al., 1508.07579

- Any observation of top FCNC = BSM physics !

Top FCNCs in BSM Theories

- Top FCNC searches = searches for a highly suppressed experimental signature
- Comprehensive survey of enhancements in BSM theories done in J.A.Aguilar-Saavedra, hep-ph/0409342
  - Models that break 3x3 CKM unitarity (quark singlet)
  - Models with flavour-changing charged bosons (2HDM)
  - Models with baryon number violation (RPV SUSY)
  - …

J. M. Yang et al., hep-ph/9705341

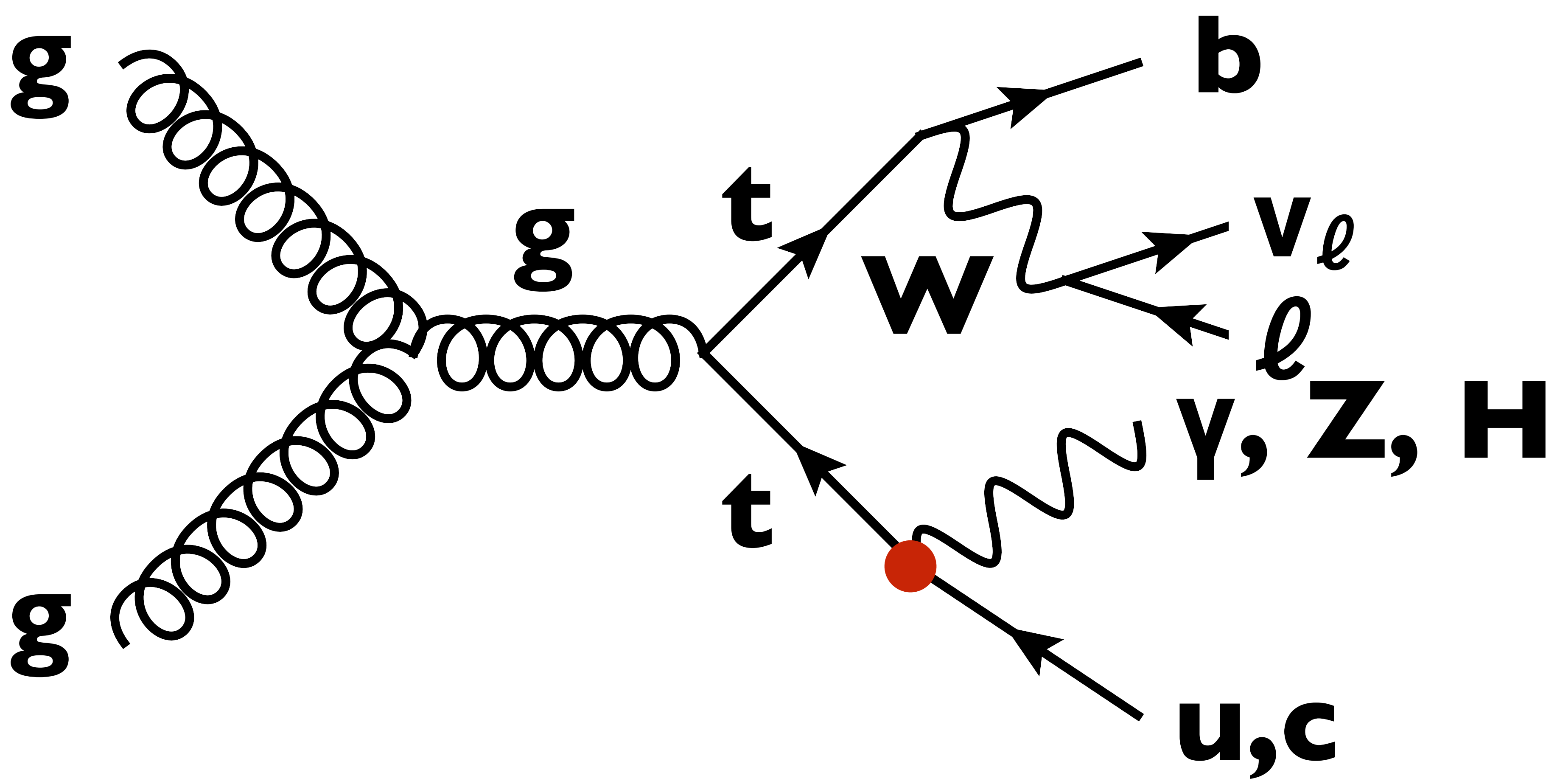


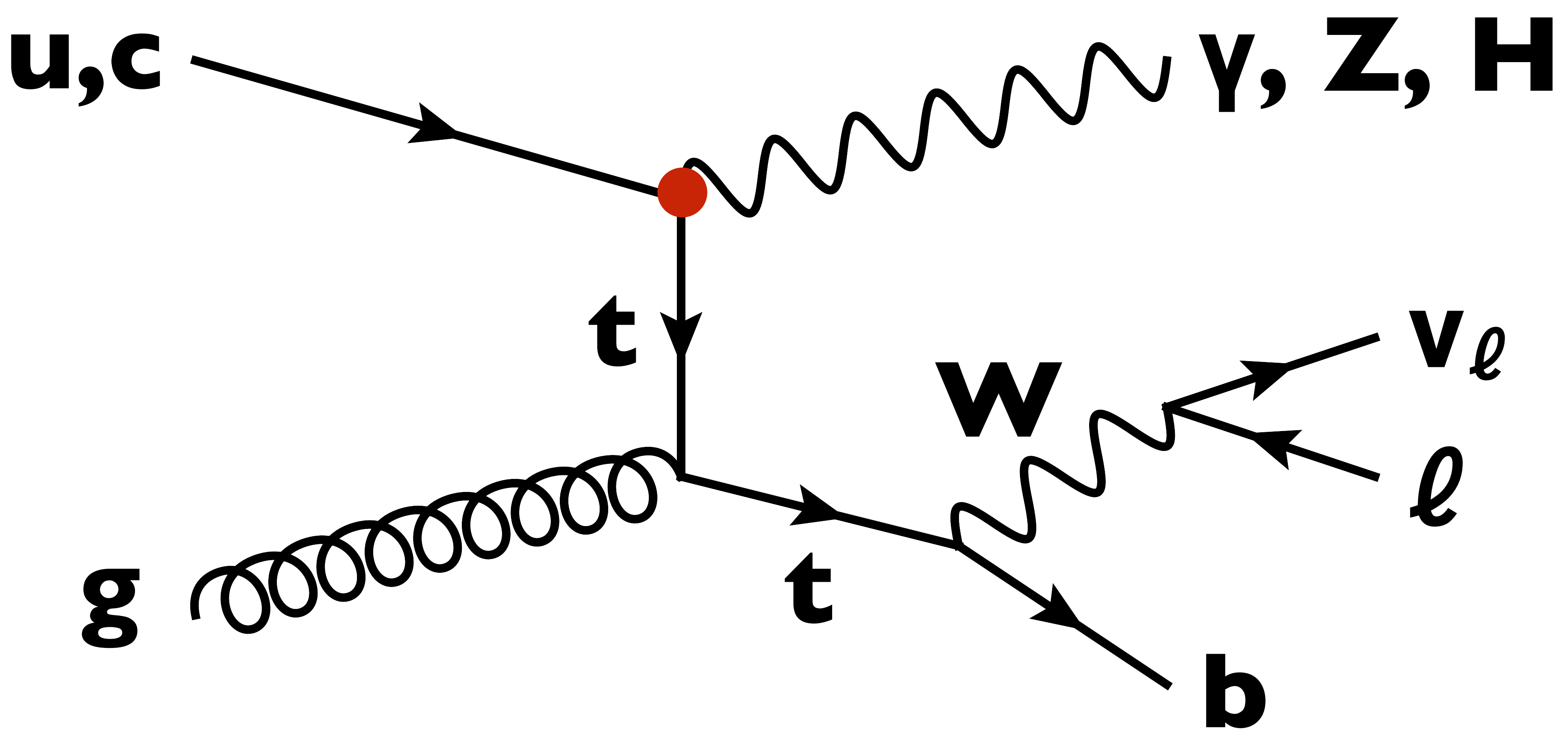
- A couple examples of post-Higgs-discovery works:
  - MSSM + B-L symmetry J.-L. Yang et al., 1806.01476 — BR(cg) ~10^{-6}, BR(cγ) ~10^{-7}, BR(cZ) ~10^{-7}
  - Extended mirror fermion model P. Q. Hung et al., 1709.01690 — BR(cZ) ~10^{-6}-10^{-8}, BR(cγ) ~10^{-7}-10^{-9}
  - Composite Higgs A. Azatov et al., 1408.4525 — BR(cZ) ~10^{-5} and similar for BR(cH)

FCNC Decay and Production

- FCNC vertex → FCNC top decay in $t\bar{t}$ — characterized by BR(t→q+boson)

  → FCNC single-top production — characterized by $\sigma_{t+boson}$



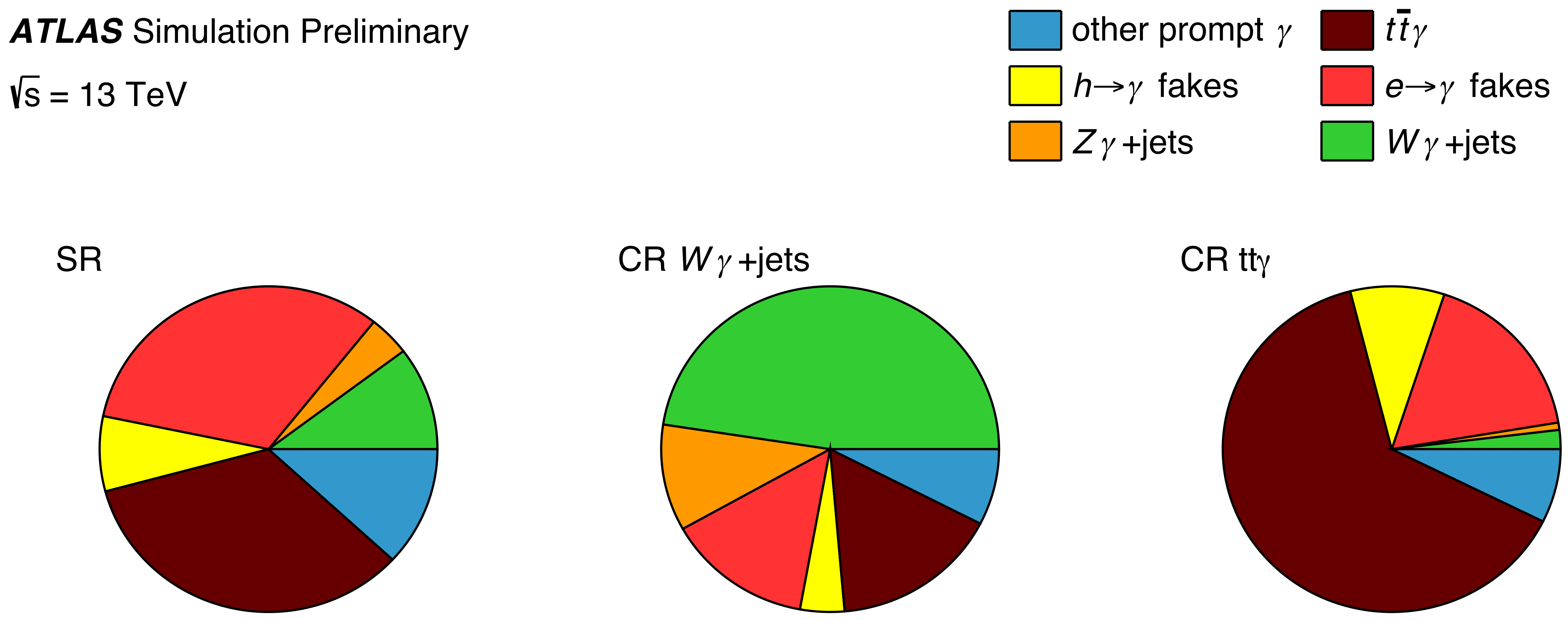


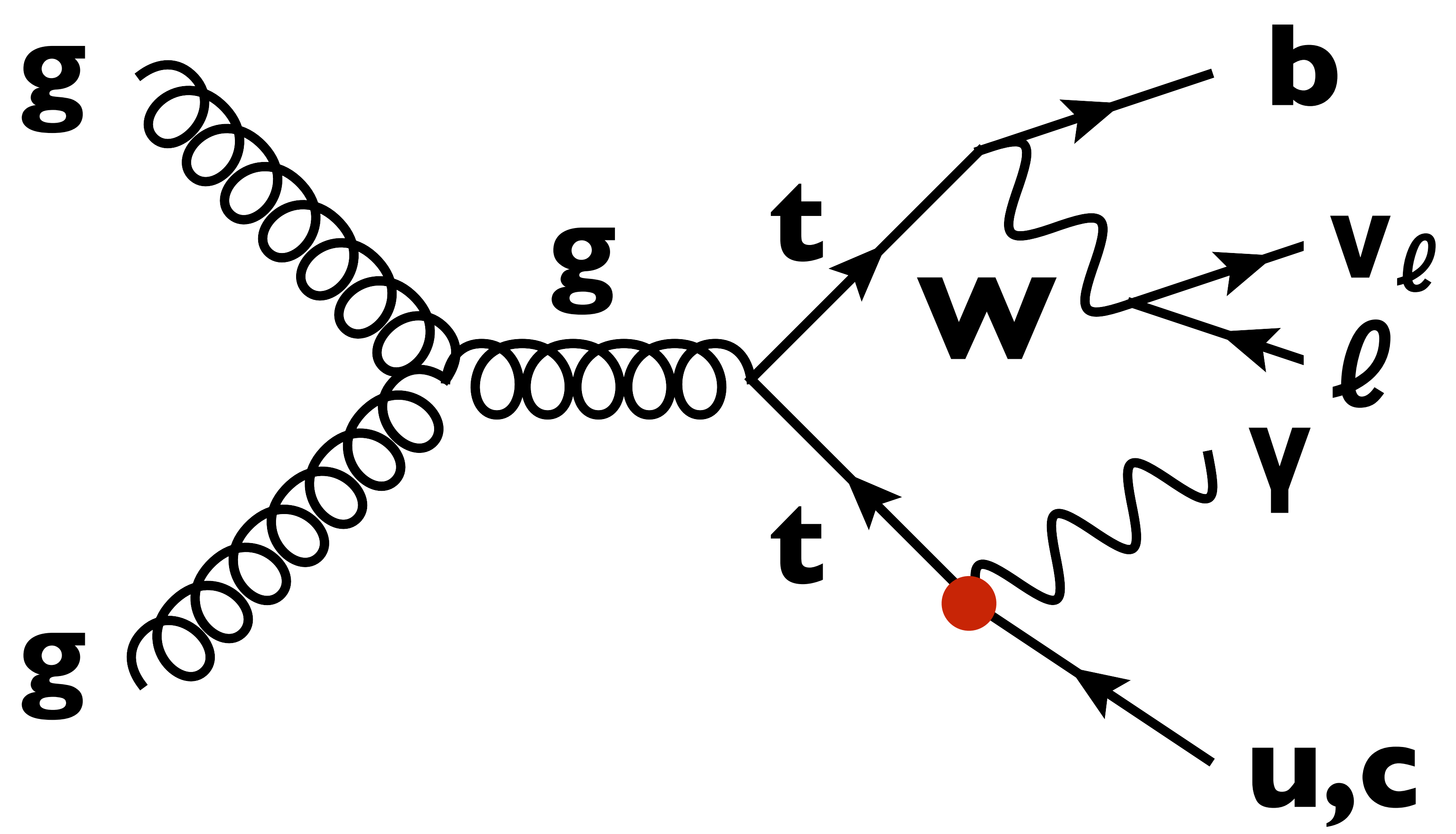
- EFT Wilson coefficients link BR and σ

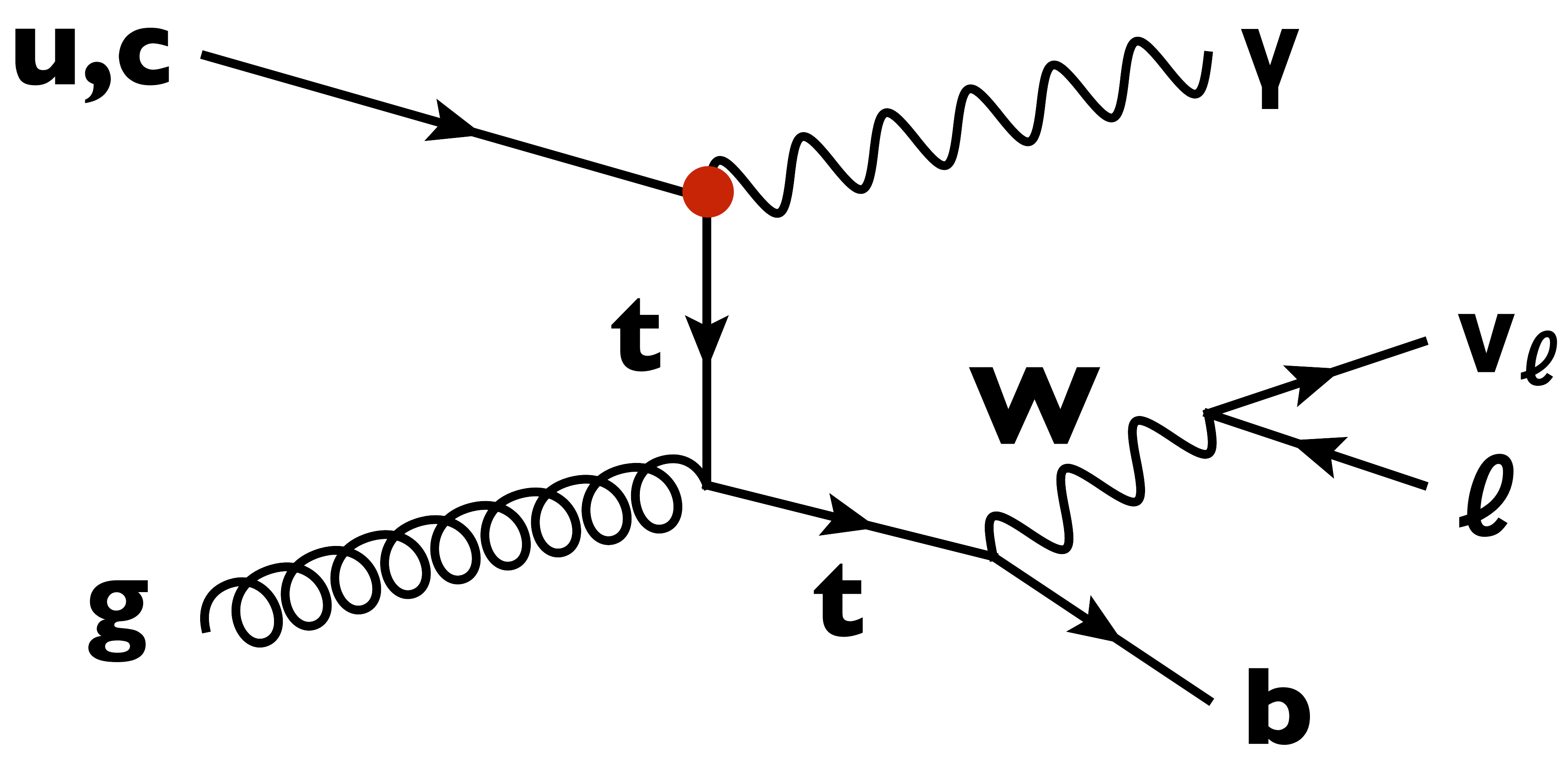
Boson	Best Limit on the BR (95% CL)		
γ	ATLAS 81 fb^{-1}, focus on $\sigma_{t+boson}$	~0.3 x 10^{-4} (up)	~2 x 10^{-4} (charm)
Z	ATLAS 36 fb^{-1}, focus on BR	~2 x 10^{-4} (up)	~2 x 10^{-4} (charm)
Higgs	CMS 137 fb^{-1}, H→γγ	~2 x 10^{-4} (up)	~7 x 10^{-4} (charm)
gluon	CMS Run-1, top+jet production	~0.2 x 10^{-4} (up)	~4 x 10^{-4} (charm)

FCNC γ — Analysis Strategy

- Optimize for FCNC production & decay
- Final state similar to SM tqγ process
  - → same basic selection without forward-jet split
  - → same techniques for background estimates ($t\bar{t}\gamma$ & Wγ+jets CRs and fake estimates)







FCNC γ — Multiclass Neural Network

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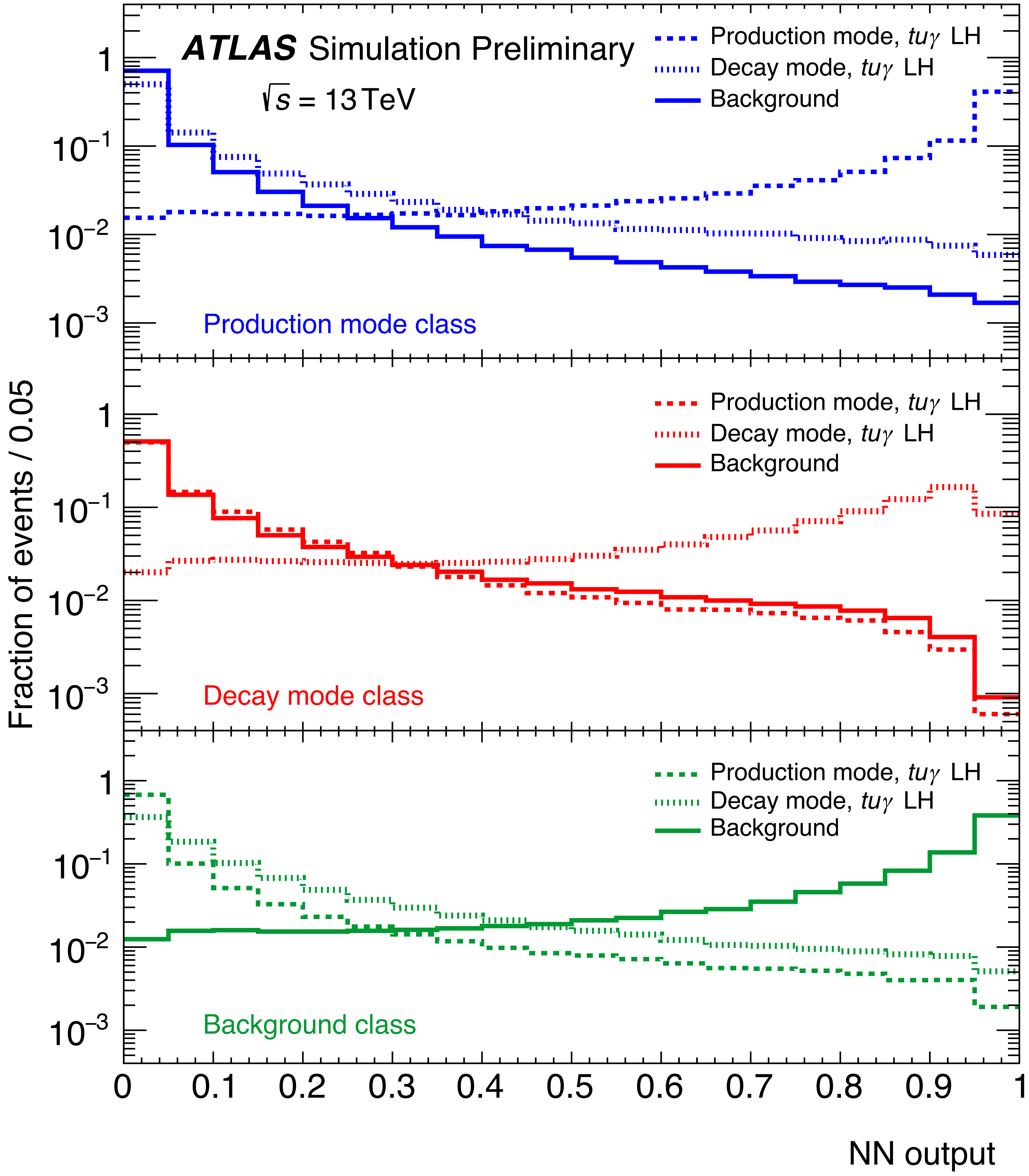
- Deep NN (6 hidden layers)
- 37 input variables:
  final-state kinematics, photon conversion
- 3 output nodes with values:
  $y_{\text{prod}} \quad y_{\text{dec}} \quad y_{\text{bkg}}$
- Signal outputs combined in 'likelihood ratio'

$$\mathcal{D} = \ln \frac{a \cdot y_{\text{prod}} + (1-a) \cdot y_{\text{dec}}}{y_{\text{bkg}}}$$

- Separate networks for up & charm
- Multiclass approach ~30% better than optimized binary classifier



FCNC γ — Data vs Prediction

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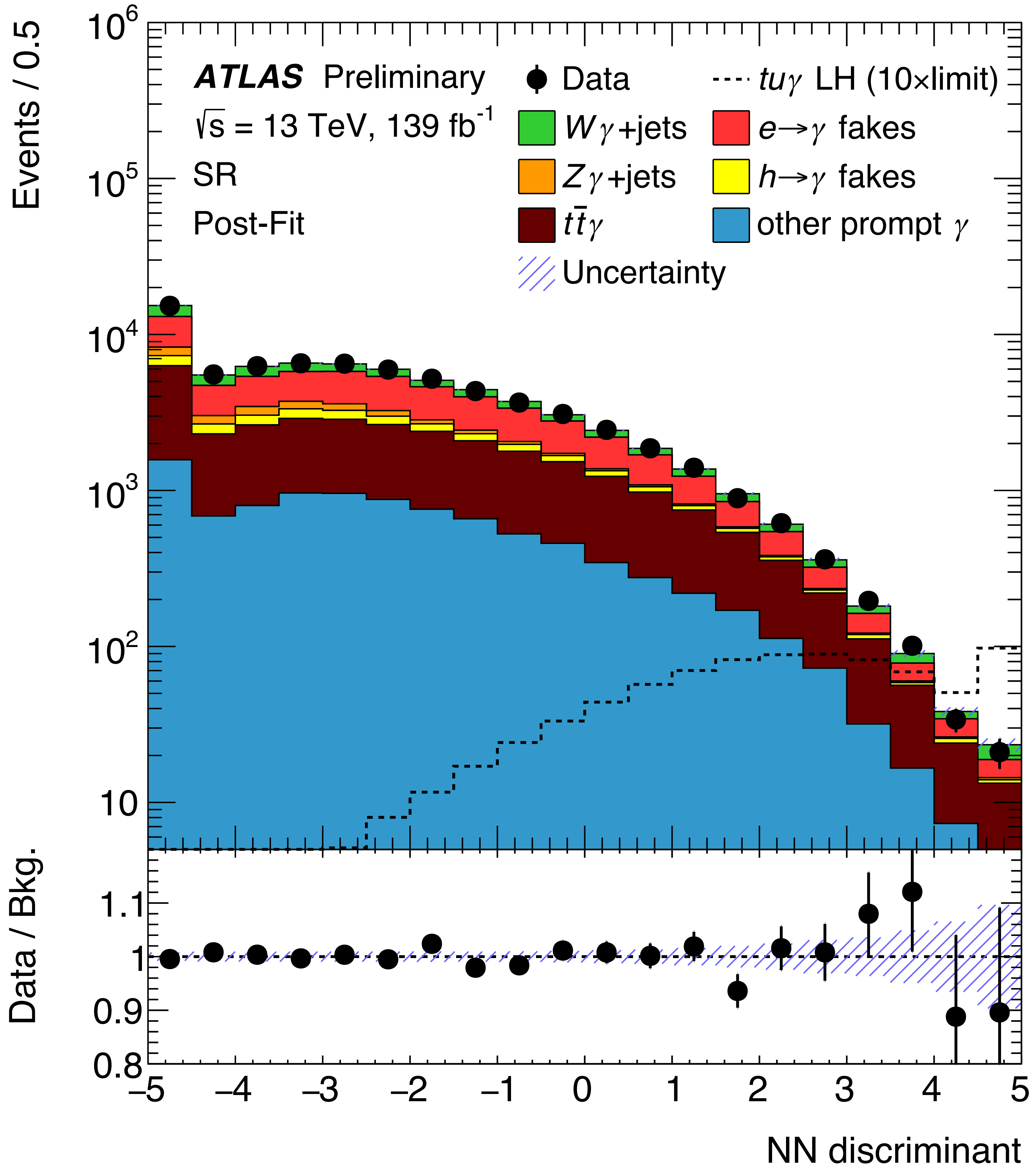
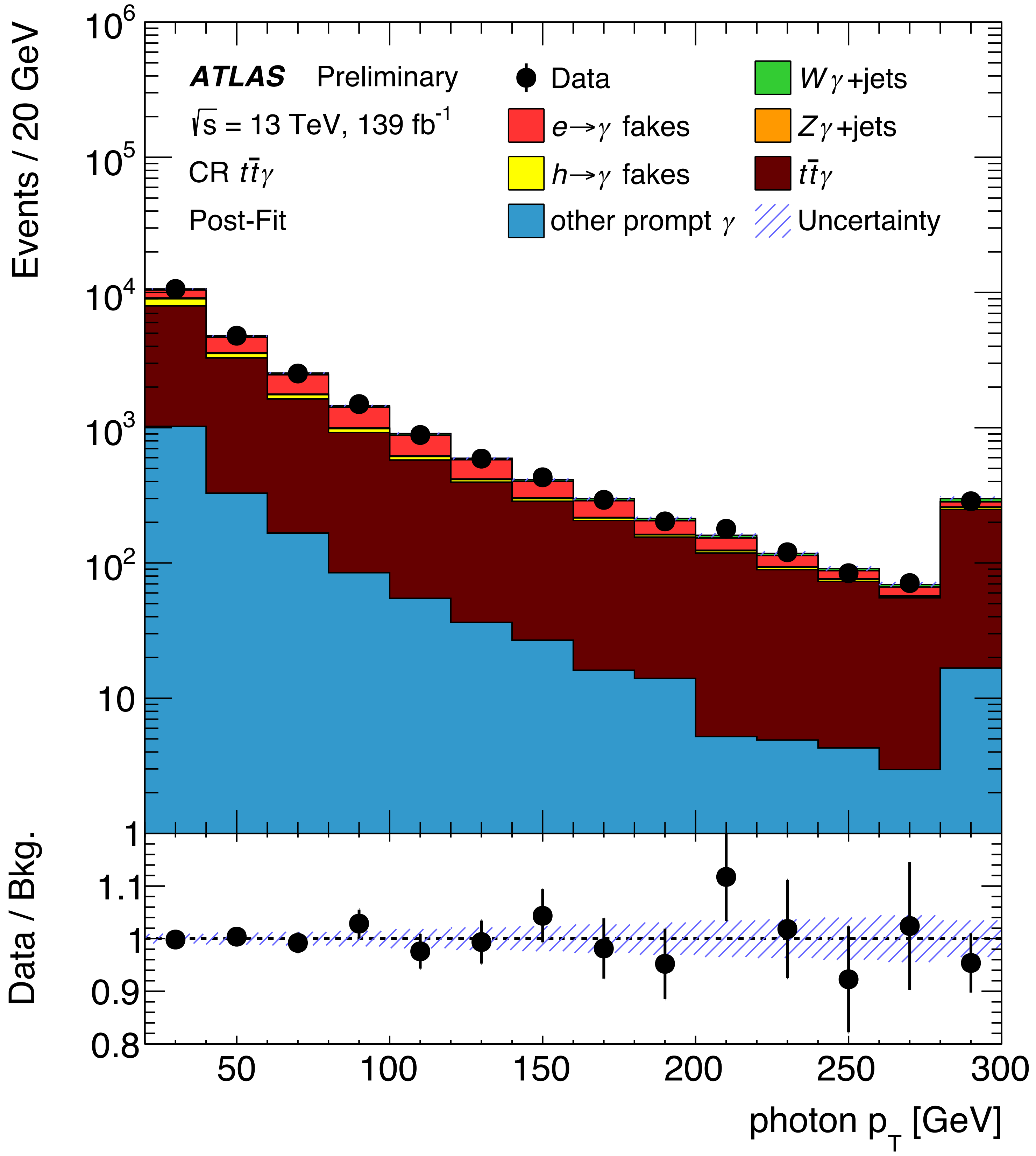
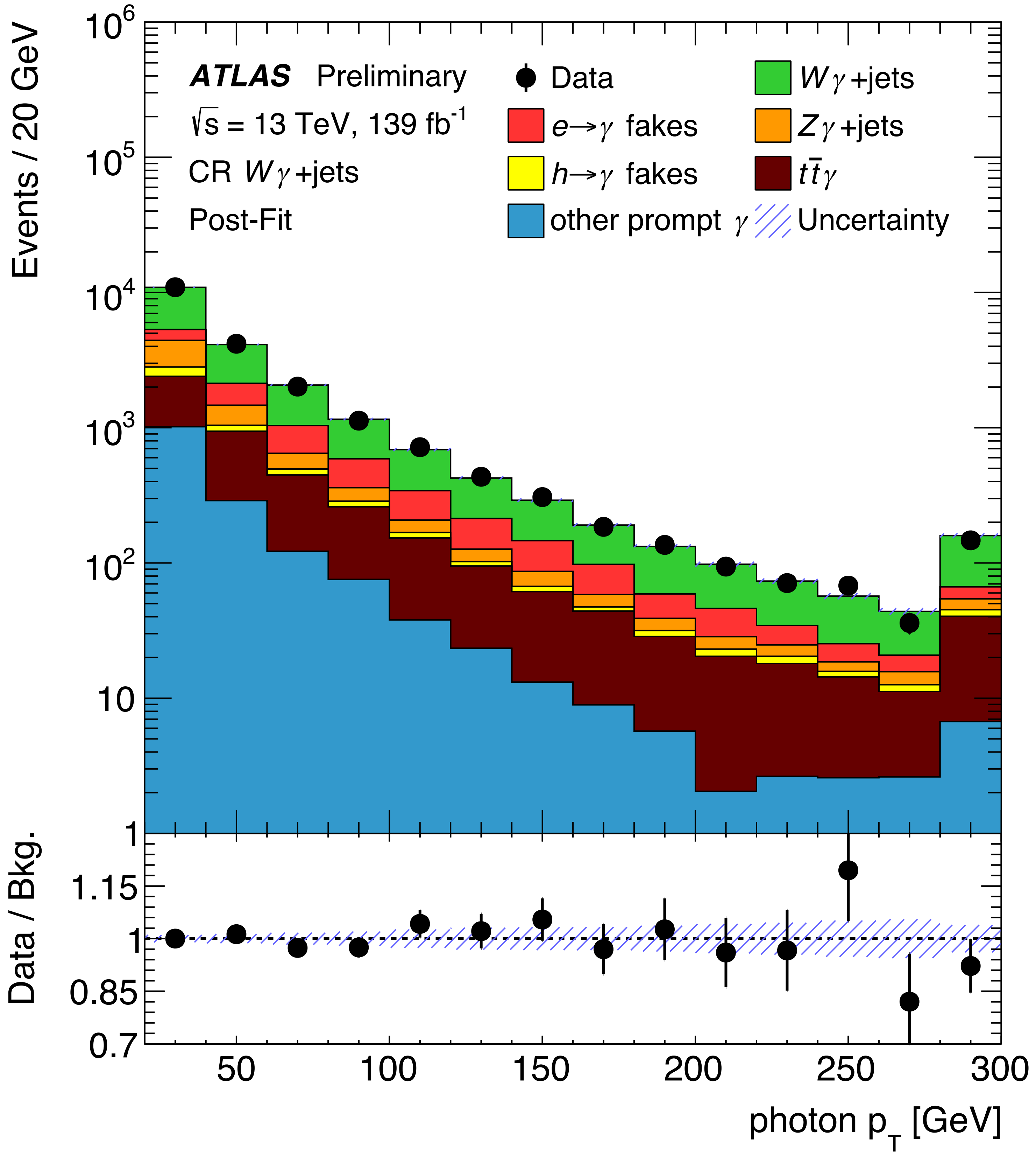
Signal Region



tt̄γ CR



Wγ+jets CR

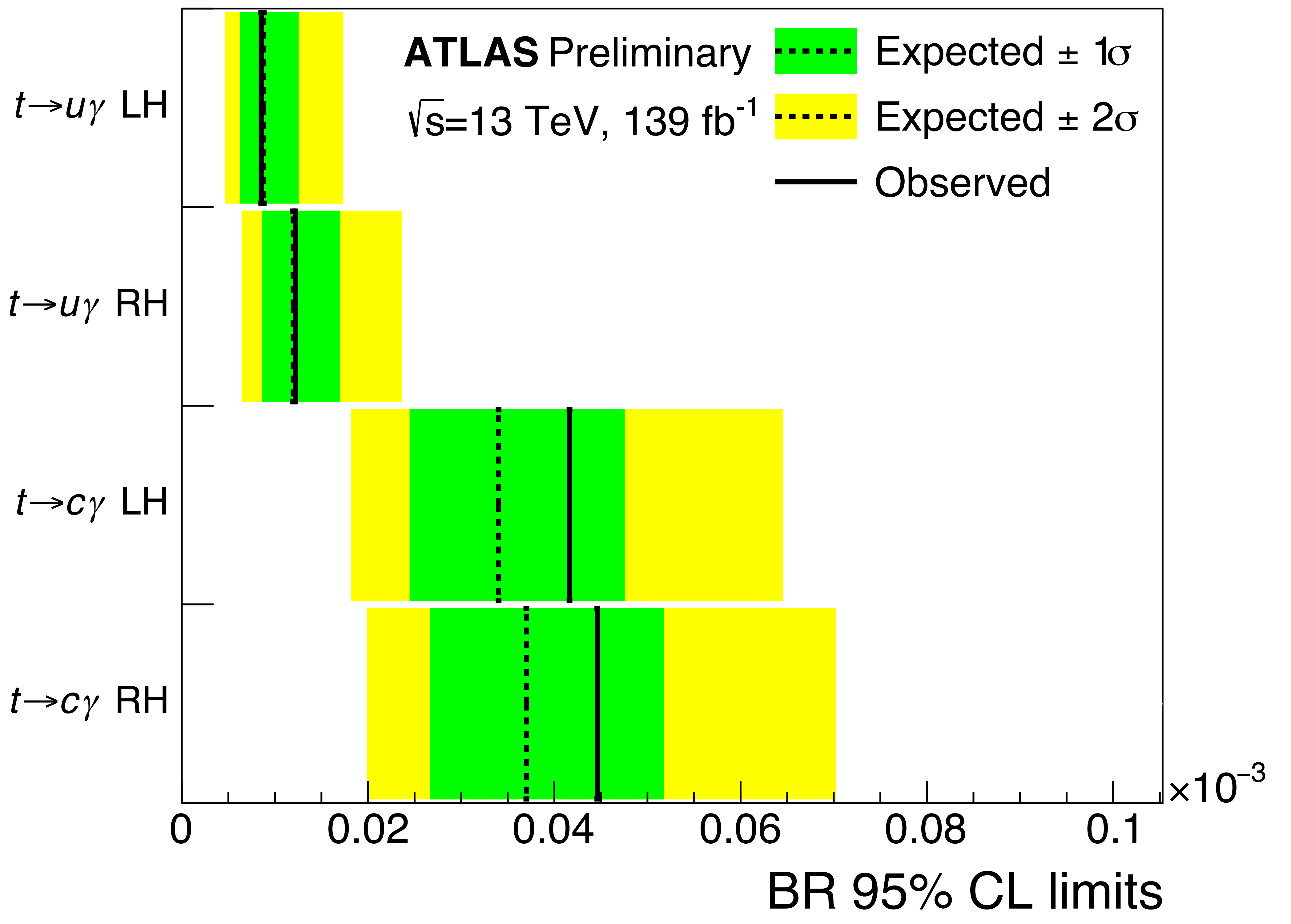


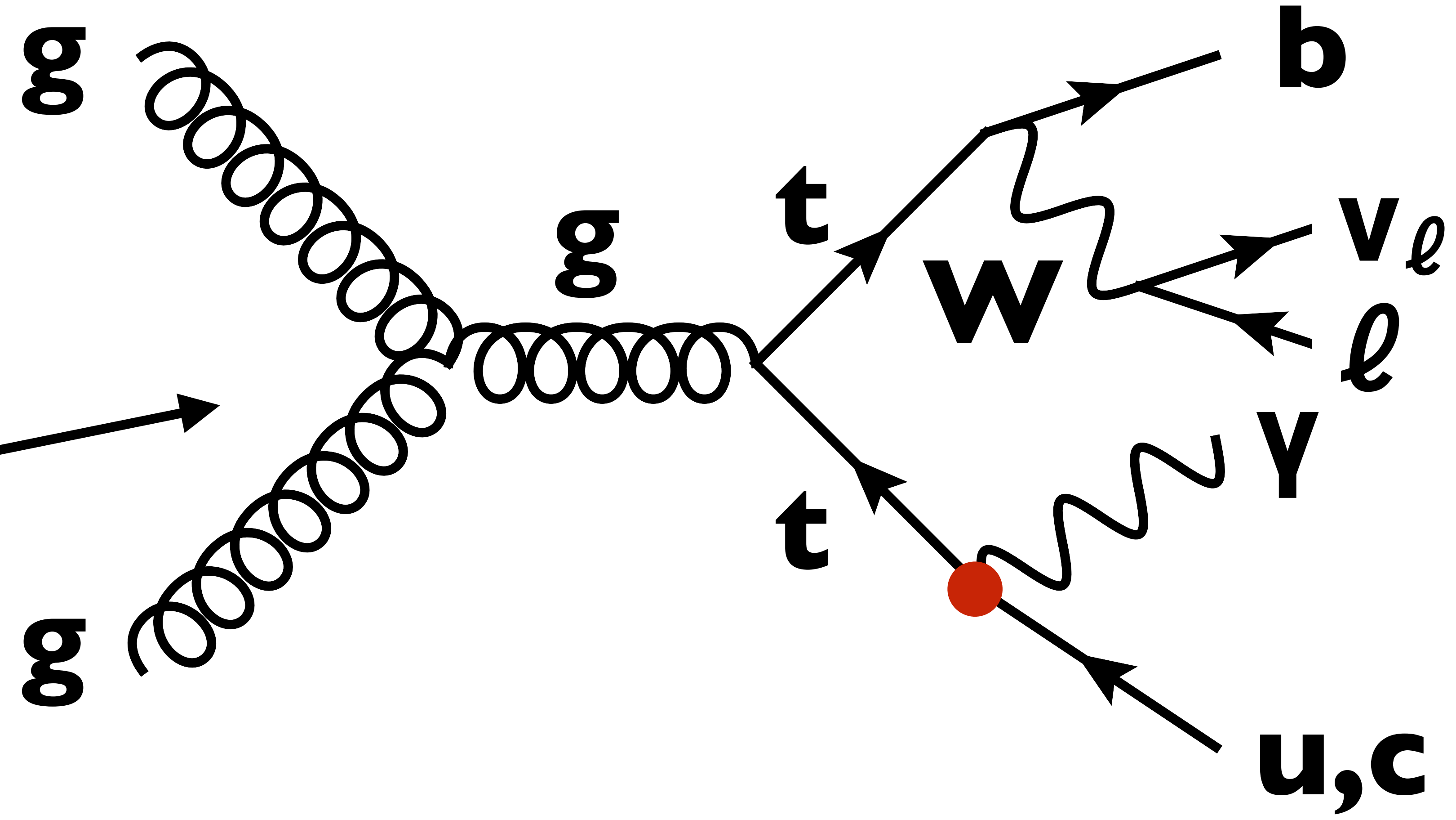
- Profile-likelihood fit → Background model in agreement with the data

FCNC γ — Results

- Limits at 95% CL
  - on Wilson coefficients for dim-6 operators
  - interpreted as BR limits
- Statistical uncertainties dominate
  - All systematics together worsen limits by ~20% (tuγ) or ~40% (tcγ)
- Factor 3.2 - 6.5 more sensitive than 81 fb^{-1} analysis
  - Reason: adding events with more than one jet

arXiv:1908.08461





FCNC Z — Analysis Strategy

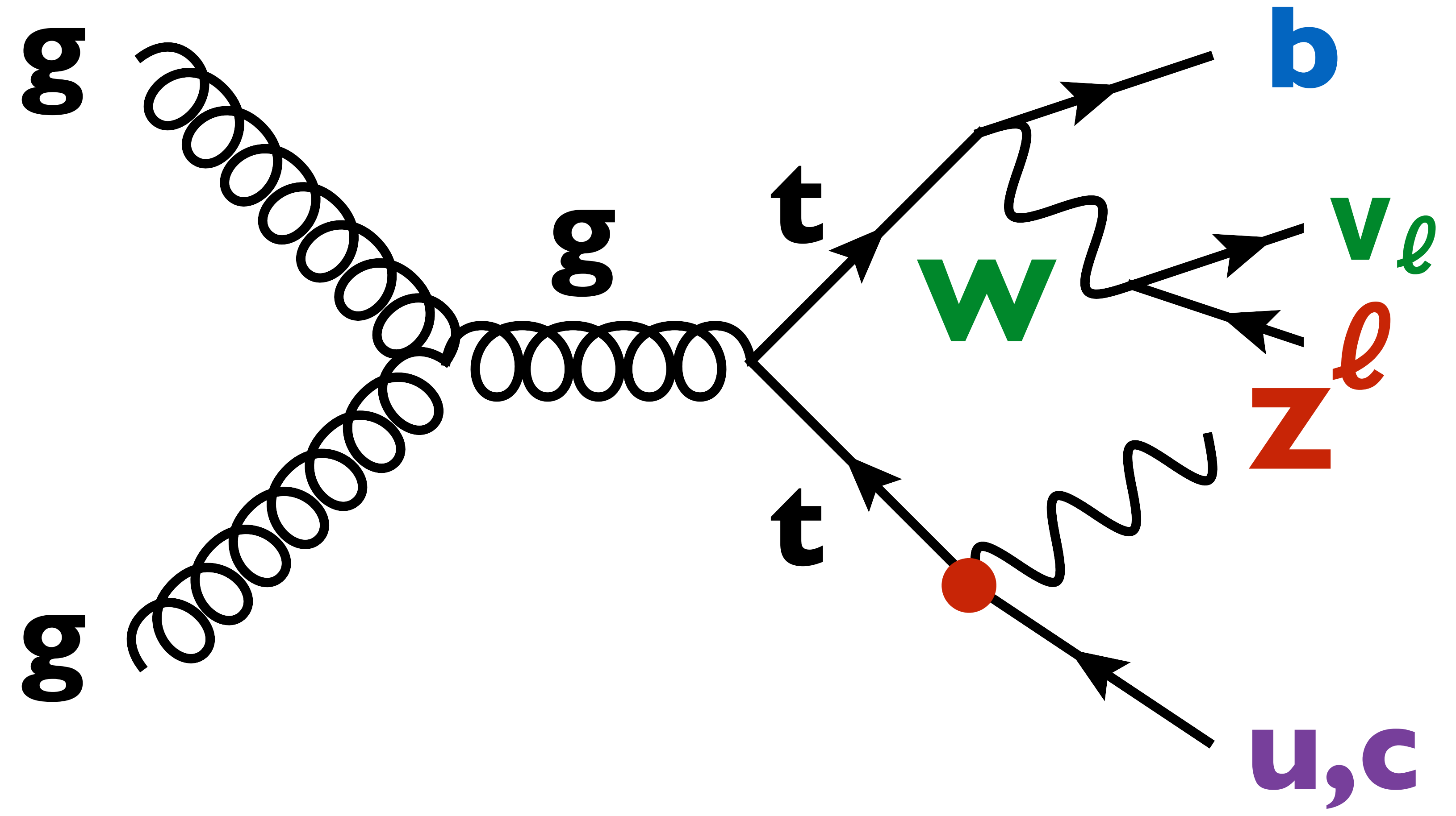
- Event selection:
  - $Z \rightarrow \ell\ell$ with $\ell = e,\mu$
  - 3 isolated ℓ with $p_T > 27 / 15 / 15$ GeV and $m_{\ell\ell} \sim m_Z$
  - 1 b-jet
  - Target FCNC decay or production?

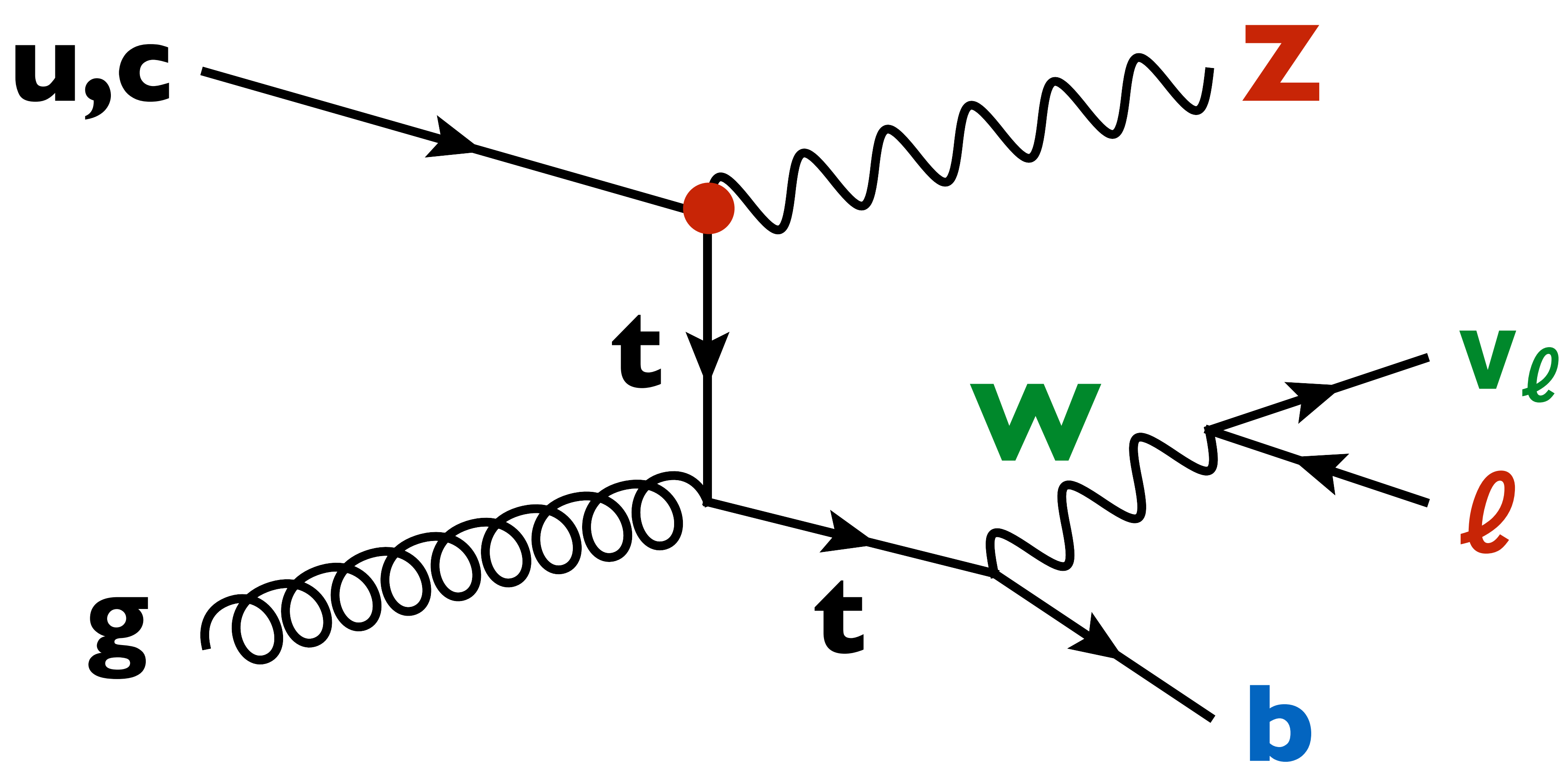
SR1

- ≥1 additional jet
- Reconstruct FCNC and SM decays

SR2

- $m_T(\ell\nu) > 40$ GeV
- Reconstruct SM decay
- 0 or 1 additional jets (then veto SR1 events)

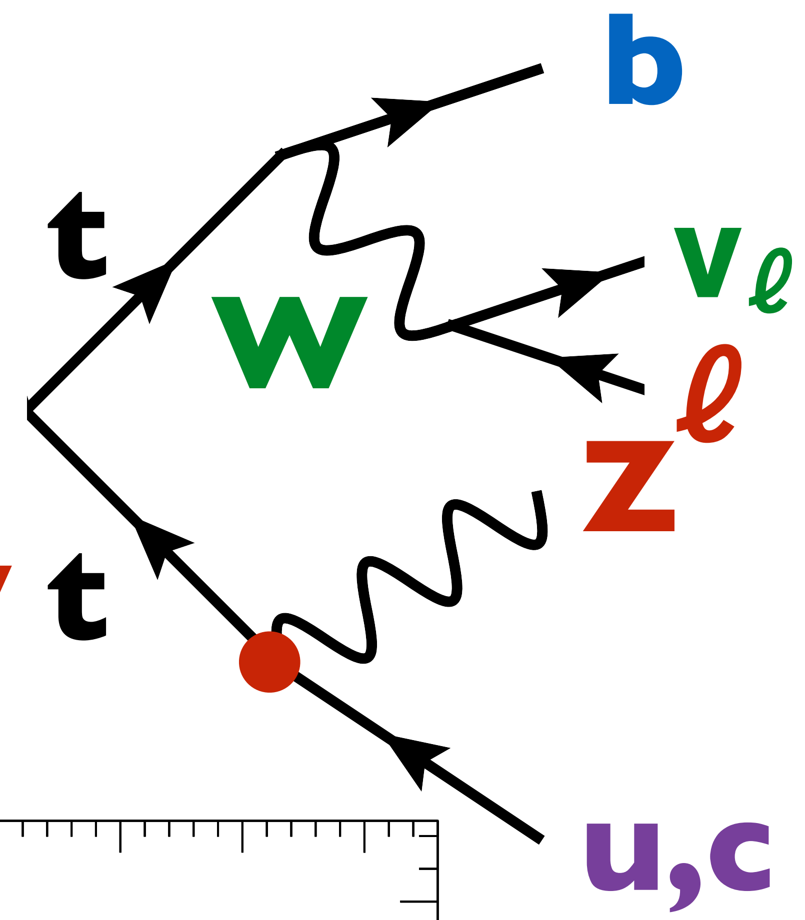




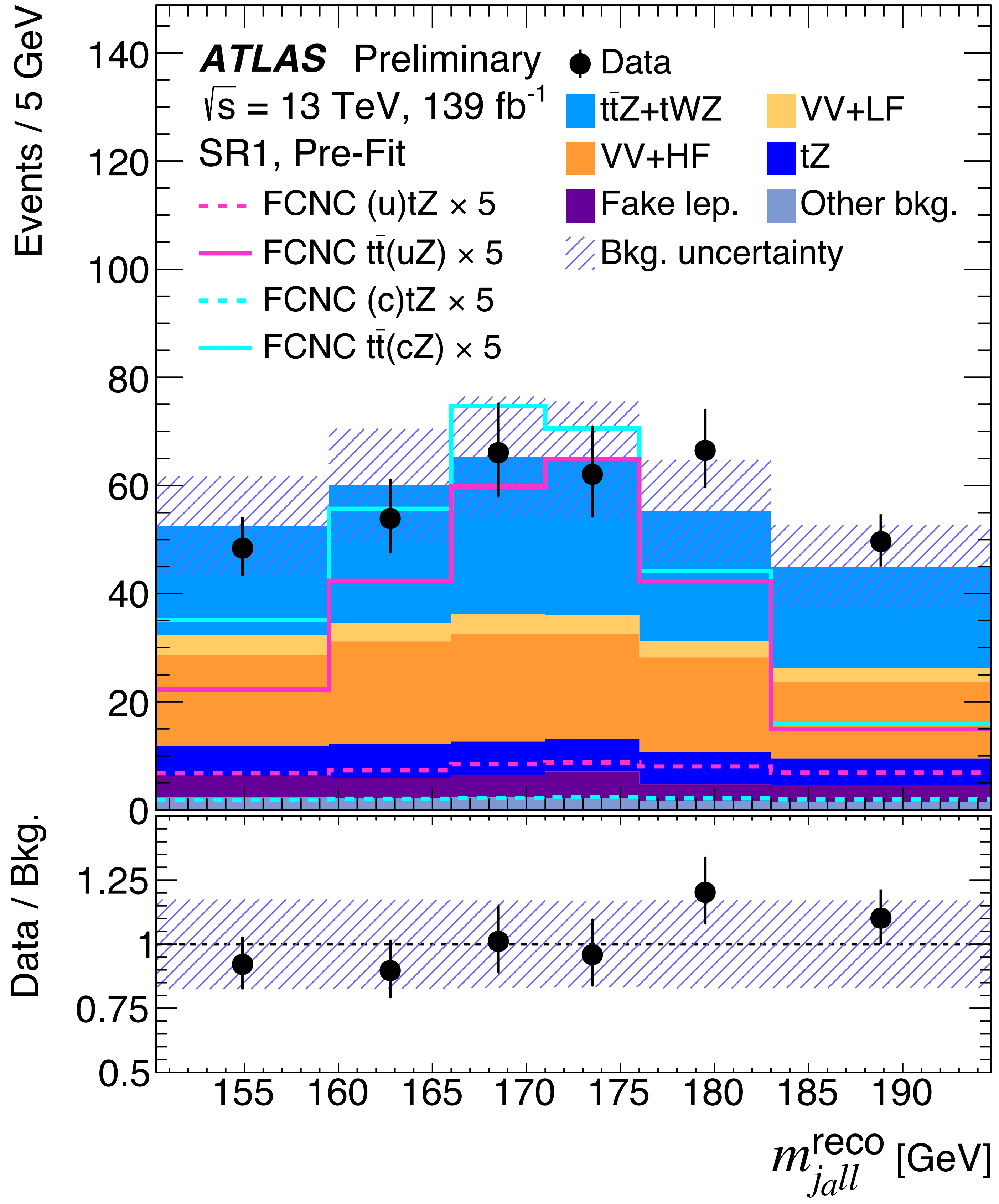
- χ2 minimization to
  - select light jet j_a (only for FCNC decay)

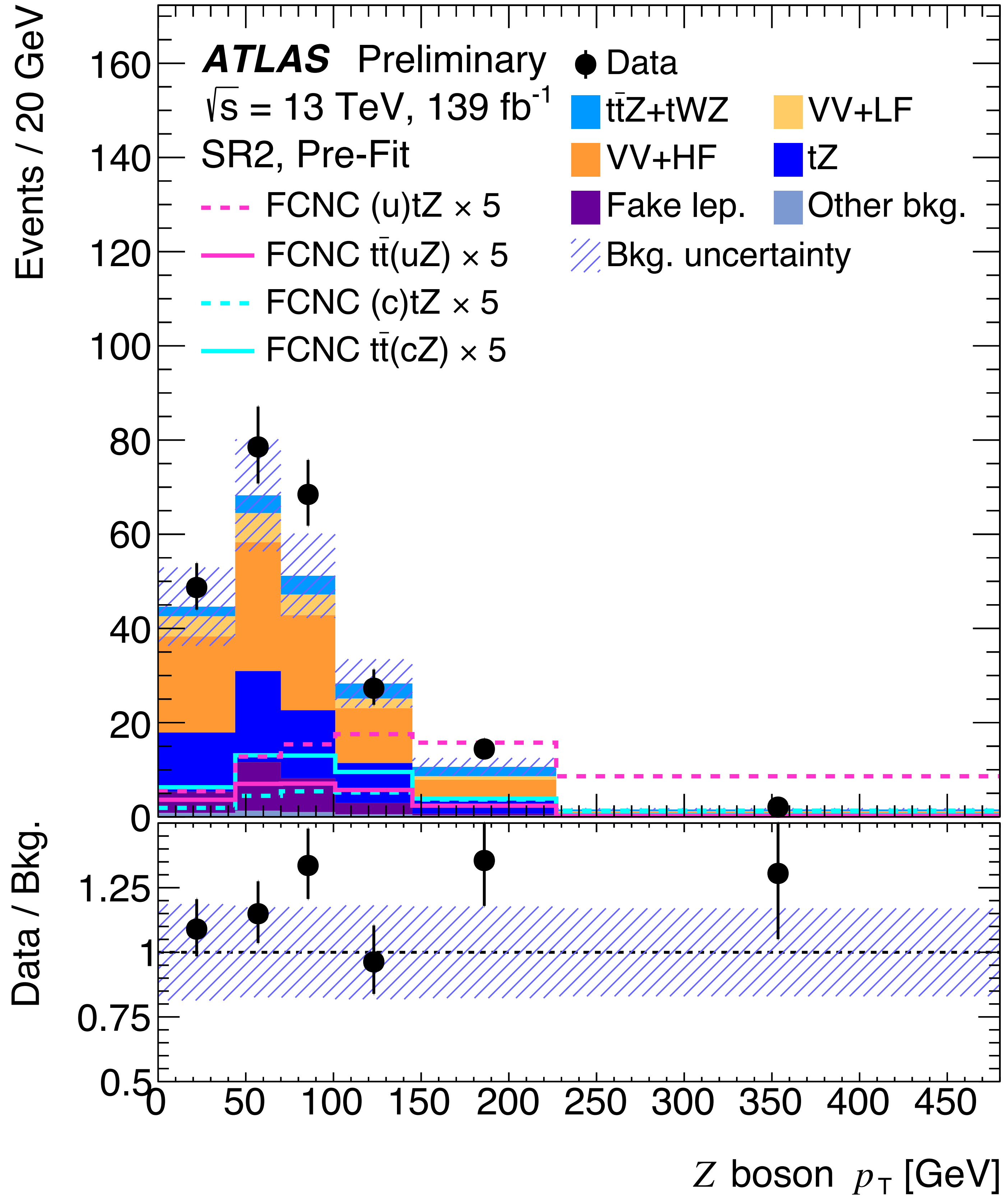
$$\chi^2_{t\bar{t}} = \frac{\left(m^{\text{reco}}_{j_a\ell\ell} - m_{t_{\text{FCNC}}}\right)^2}{\sigma^2_{t_{\text{FCNC}}}} + \frac{\left(m^{\text{reco}}_{j_b\ell_W\nu} - m_{t_{\text{SM}}}\right)^2}{\sigma^2_{t_{\text{SM}}}} + \frac{\left(m^{\text{reco}}_{\ell_W\nu} - m_W\right)^2}{\sigma^2_W}$$

~11 GeV ($\sigma_{t_{\text{FCNC}}}$) **~23 GeV** ($\sigma_{t_{\text{SM}}}$) **~15 GeV** (σ_W)



  - fit $p_z(\nu)$
- SR1: $|m^{\text{reco}}_{j_a\ell\ell} - m_t| < 2\sigma_{t_{\text{FCNC}}}$
- SR2: $|m^{\text{reco}}_{j_b\ell_W\nu} - m_t| < 2\sigma_{t_{\text{SM}}}$
- Train BDTs for:
  - SR1 (FCNC decay)
  - SR2 (production via up)
  - SR2 (production/decay with charm)

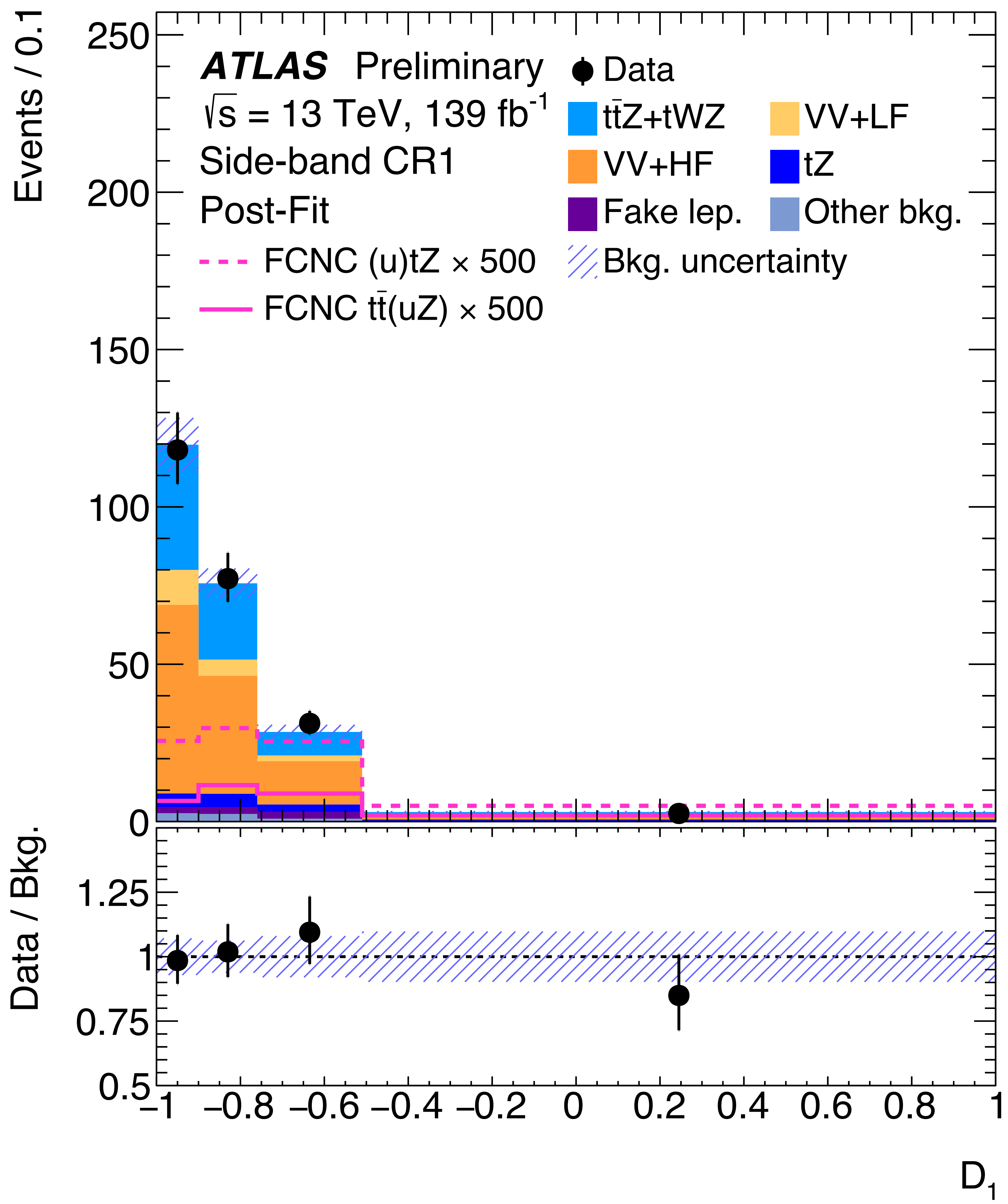




FCNC Z — Background Control and Validation

	SR1 (D_1 > -0.6)	SR2 (D_2^u > -0.7 or D_2^c > -0.4)
$t\bar{t}Z + tWZ$	137 ± 12	36 ± 6
VV + LF	18 ± 7	24 ± 8
VV + HF	114 ± 19	162 ± 26
tZ	46 ± 7	108 ± 18
$t\bar{t} + tW$ fakes	14 ± 4	27 ± 8
Other fakes	7 ± 8	5 ± 6
$t\bar{t}W$	4.2 ± 2.1	3.1 ± 1.6
$t\bar{t}H$	4.8 ± 0.7	0.89 ± 0.17
Other bkg.	2.0 ± 1.0	2.5 ± 2.9
FCNC $(u)tZ$	0.9 ± 1.7	4 ± 8
FCNC $t\bar{t}(uZ)$	5 ± 9	0.8 ± 1.5
Total background	348 ± 15	369 ± 21
Data	345	380

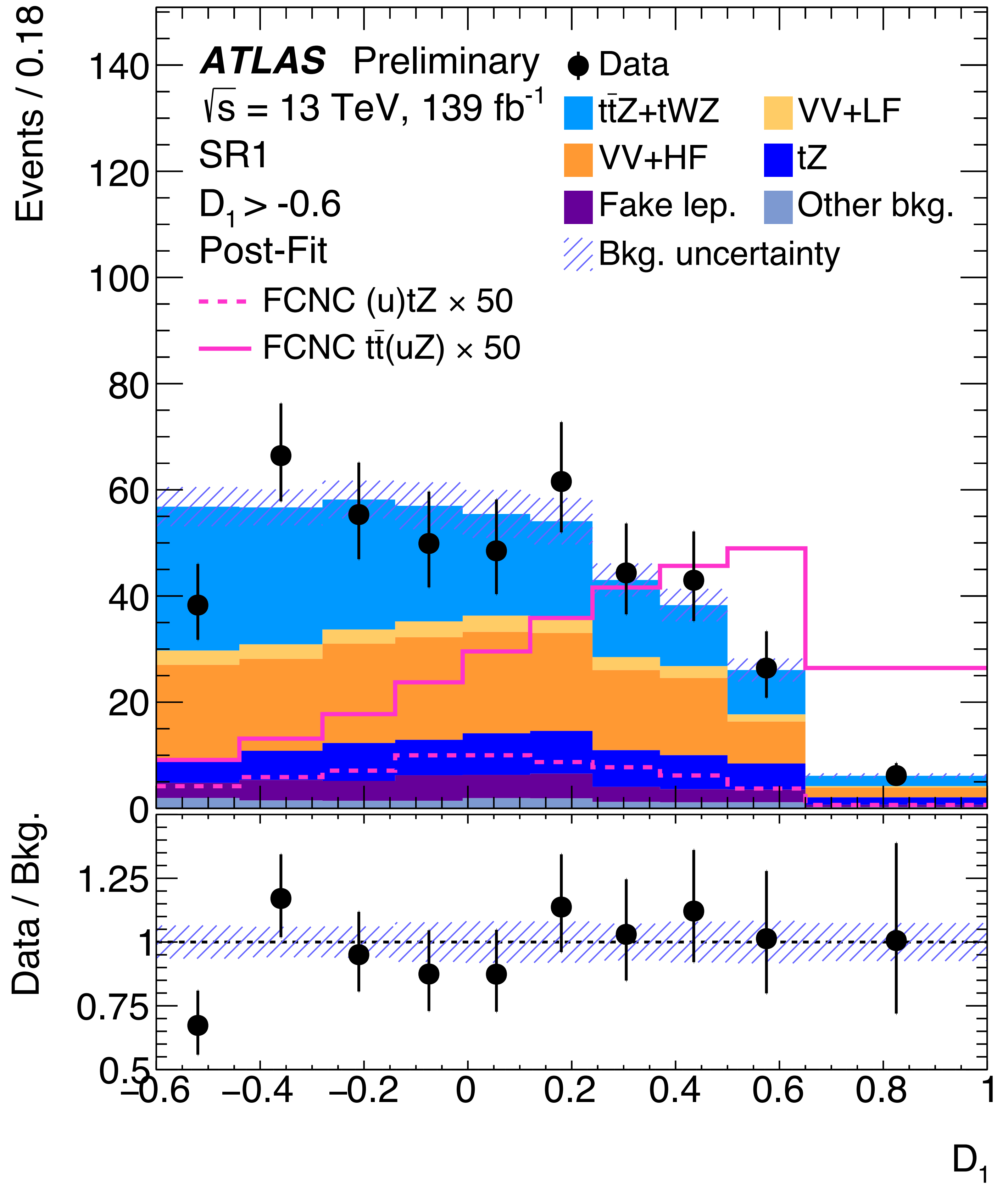
- $t\bar{t}$ CR without Z candidate
- $t\bar{t}Z$ CR with 2 b-jets and ≥2 extra jets
- SR sidebands in reconstructed masses



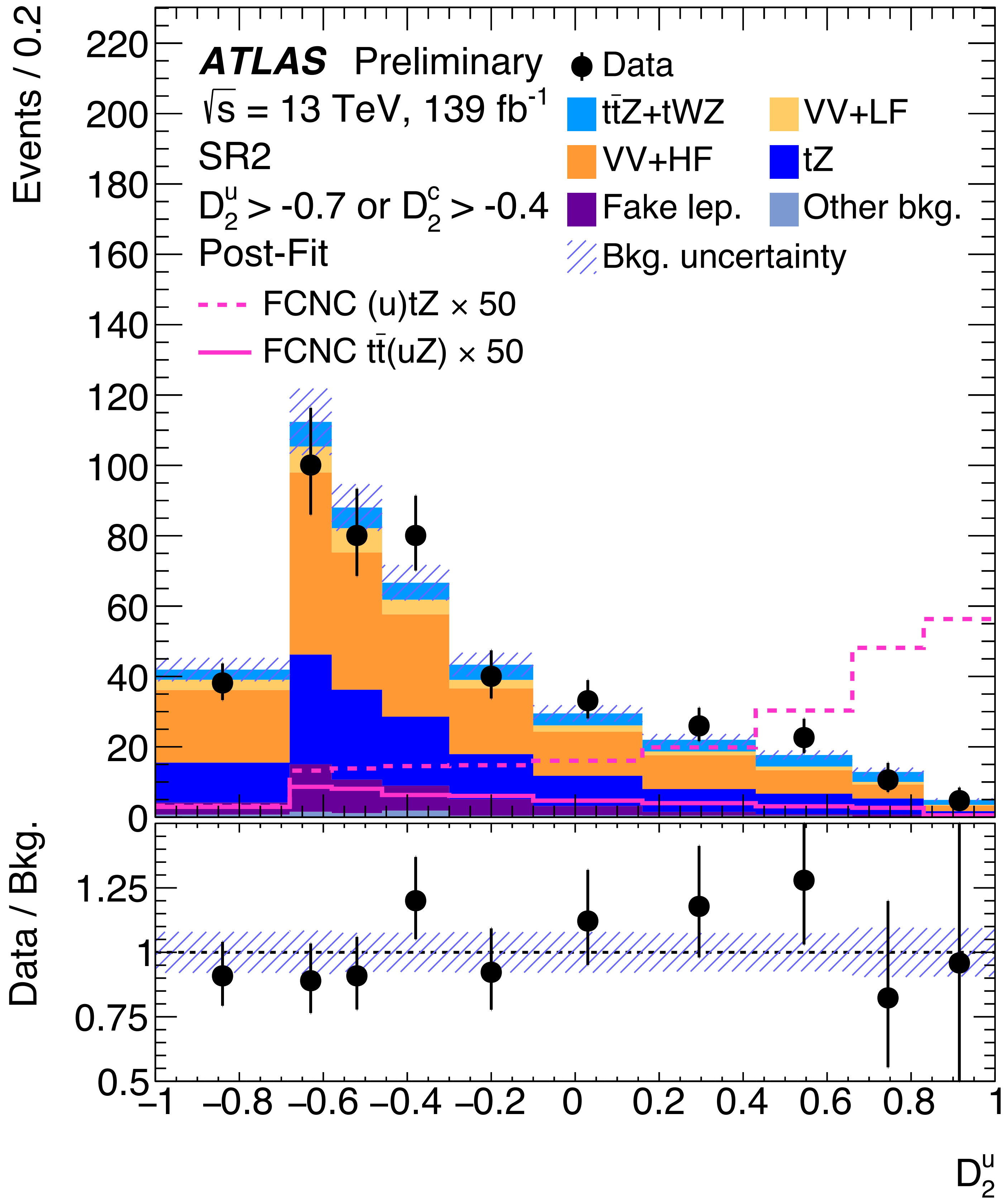
FCNC Z — Results

ATLAS-CONF-2021-049

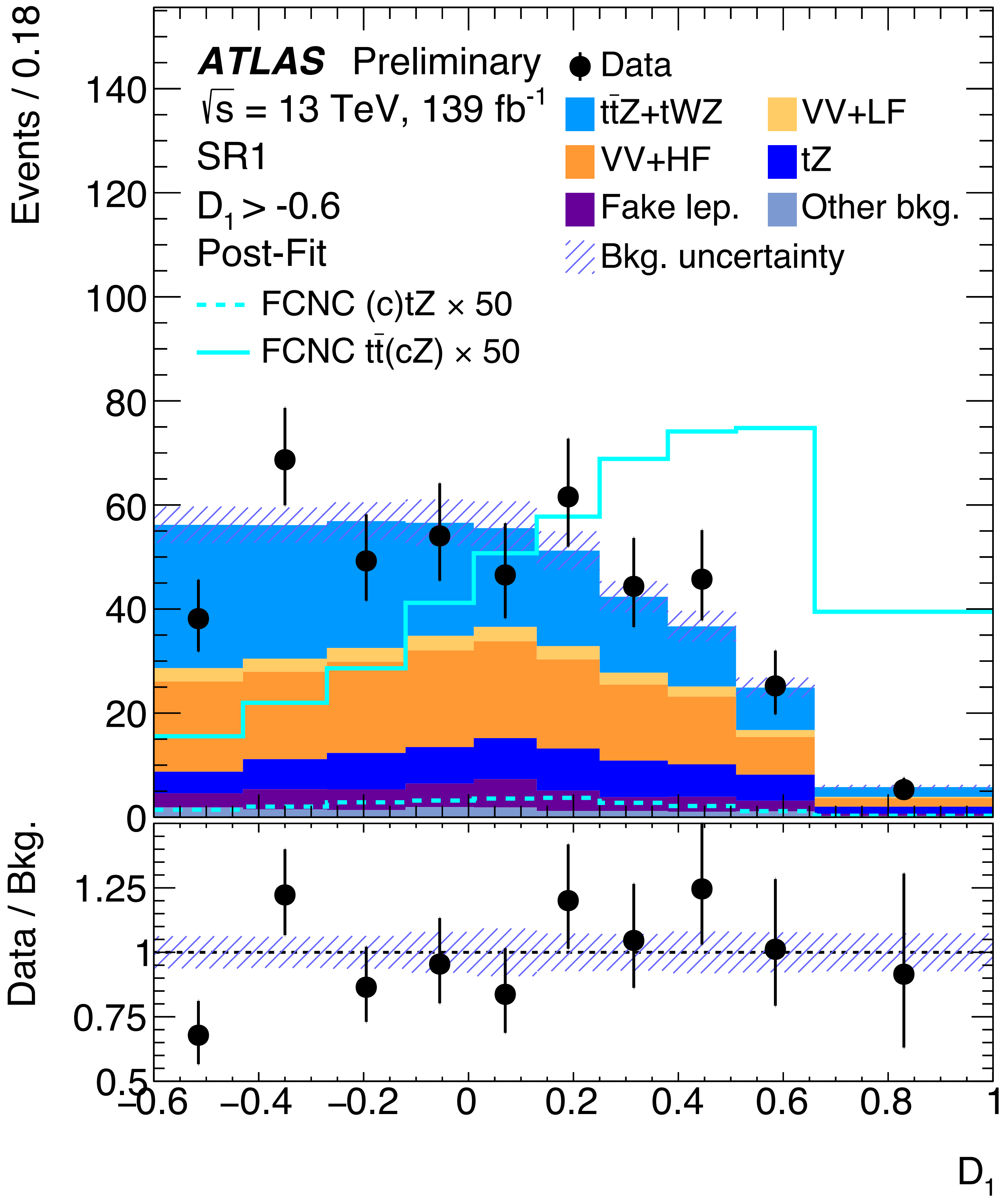
SR1 (up quark)



SR2 (up quark)



SR2 (charm quark)



- Systematics worsen limits by ~20% (tuZ) or ~25% (tcZ)
- BR(t→uZ) < 6.2/6.6 x 10^{-5} [LH/RH]

  BR(t→cZ) < 13/12 x 10^{-5} [LH/RH]

- Sensitivity improved by

  t→uZ: ~ 4.7-4.9

  t→cZ: ~ 2.9-3.2

FCNC H(ττ) — Analysis Strategy

- Targeting leptonic and hadronic top & tau decays
  - 1 b-jet
  - 1 electron or muon OR none

t_{lep} or τ_{lep}

$\geq 2\ \tau_{had}$

OR 1 τ_{had} and 1 or 2 extra jets

(& ℓ, τ_{had} have same charge)

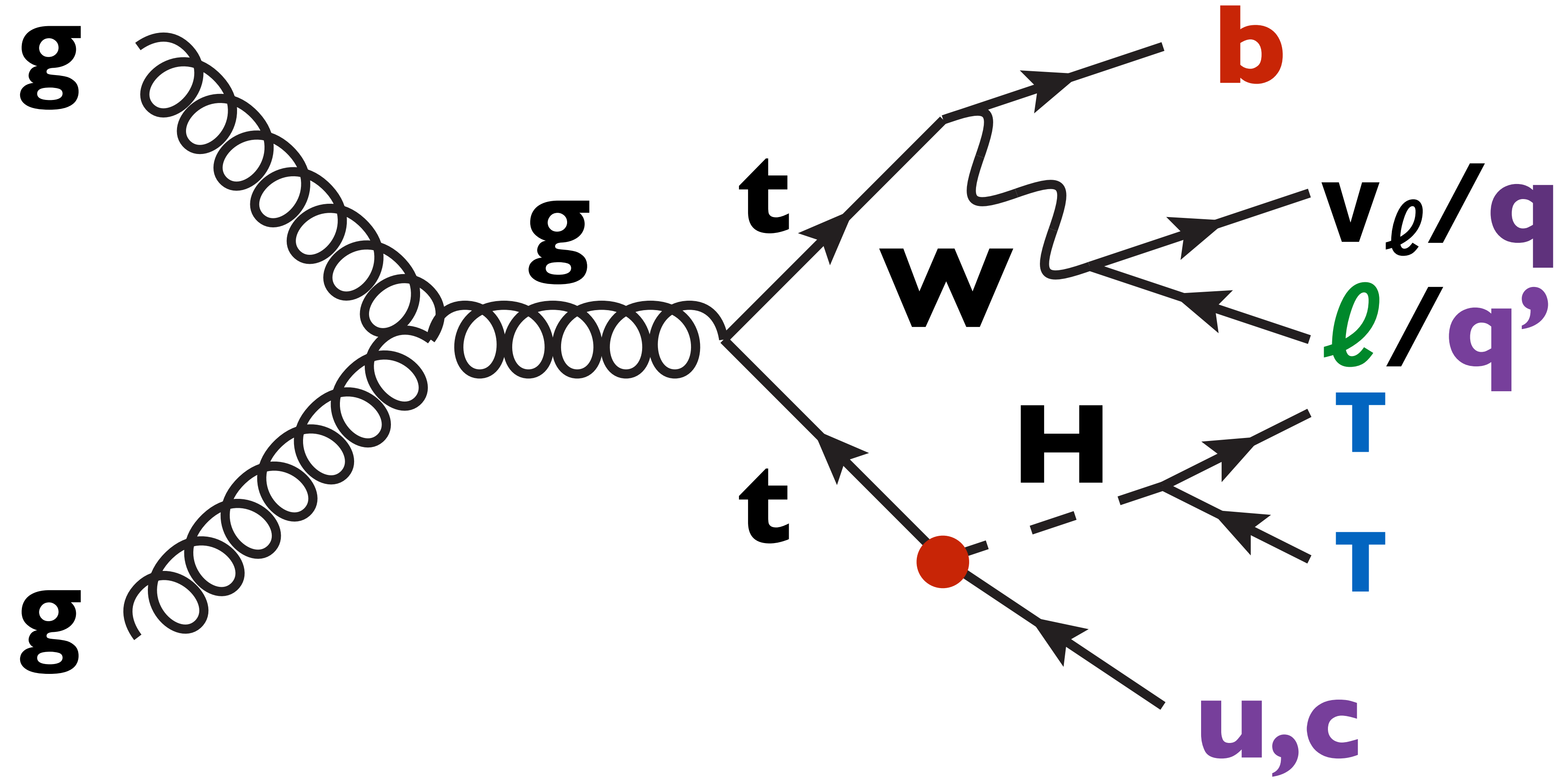
1 τ_{had}

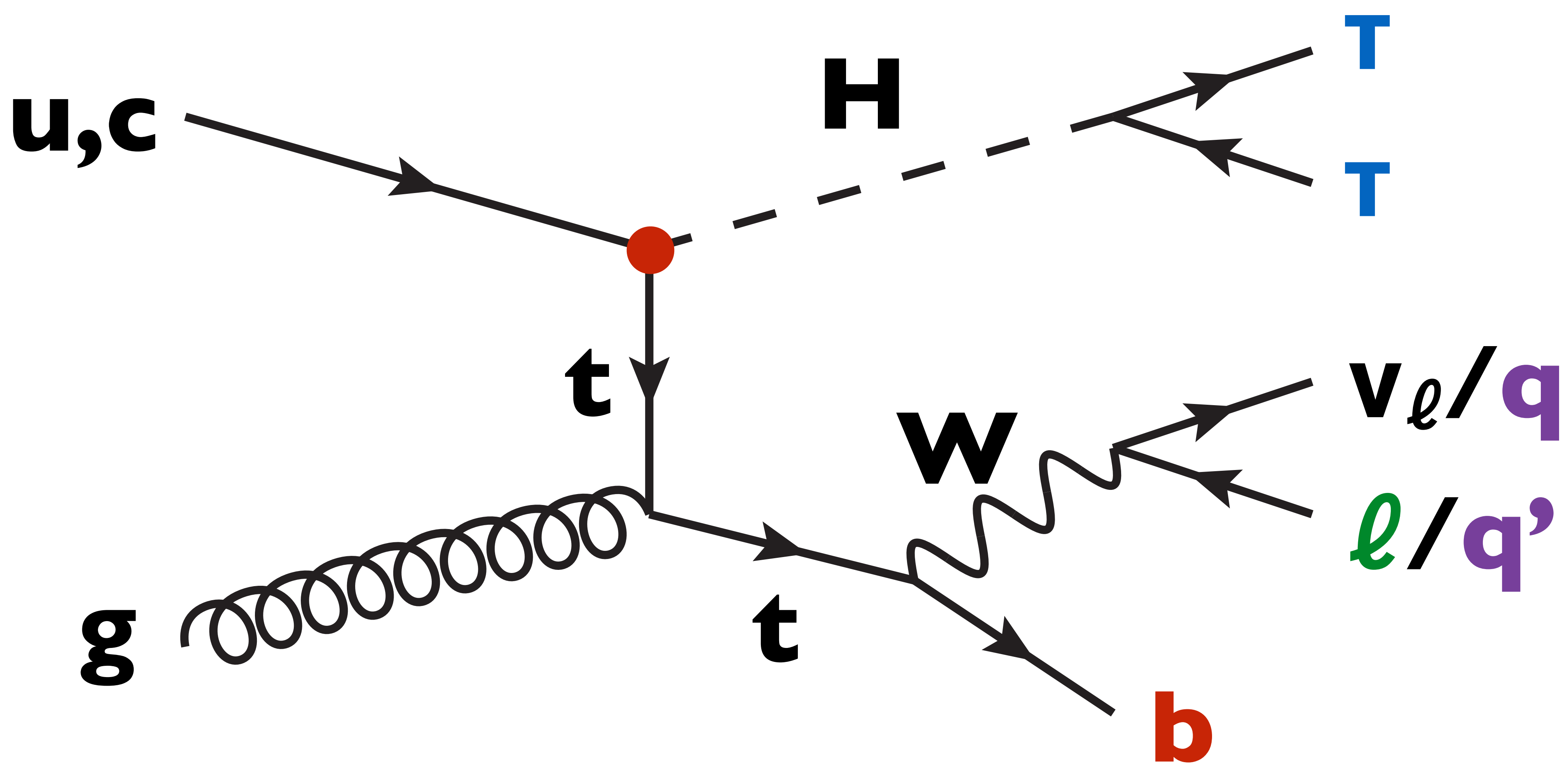
2/≥3 extra jets

$t_{had}\tau_{had}\tau_{had}$

$\geq 2\ \tau_{had}$

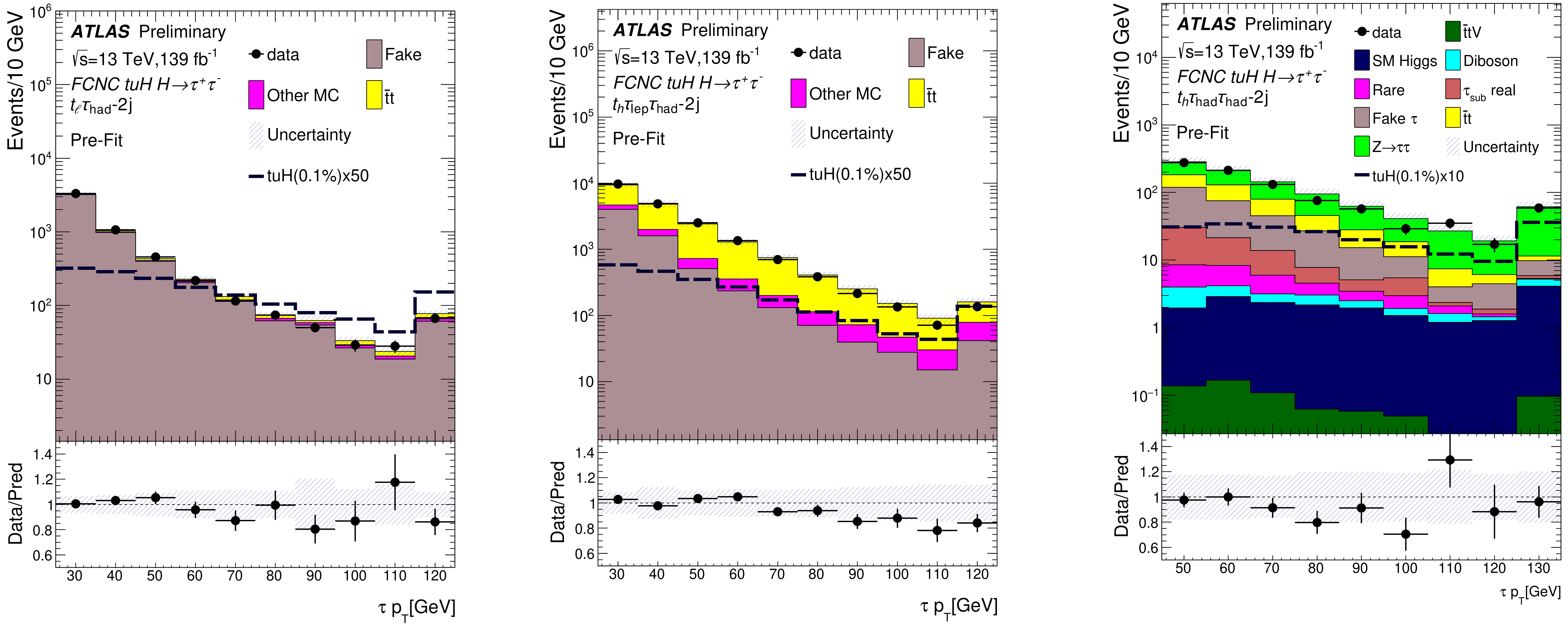
2/≥3 extra jets





FCNC H(ττ) — Fake Tau Estimates

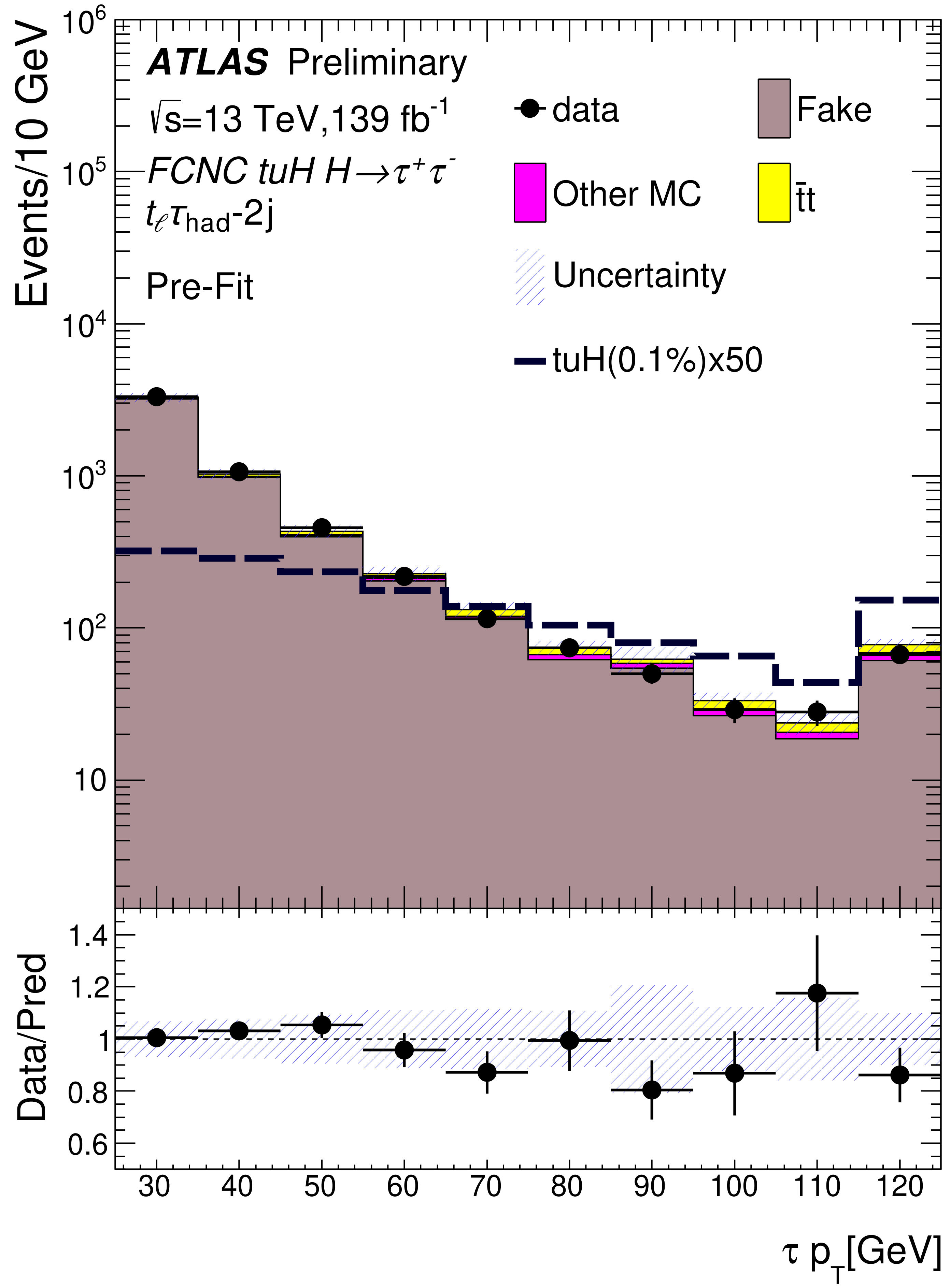
- Leptonic channels: data-MC scale factors from $t\bar{t}$ CRs (2 b-tags or 2 leptons)
- Hadronic channels: events with looser τ ID multiplied with fake factors (from W+jets CR)



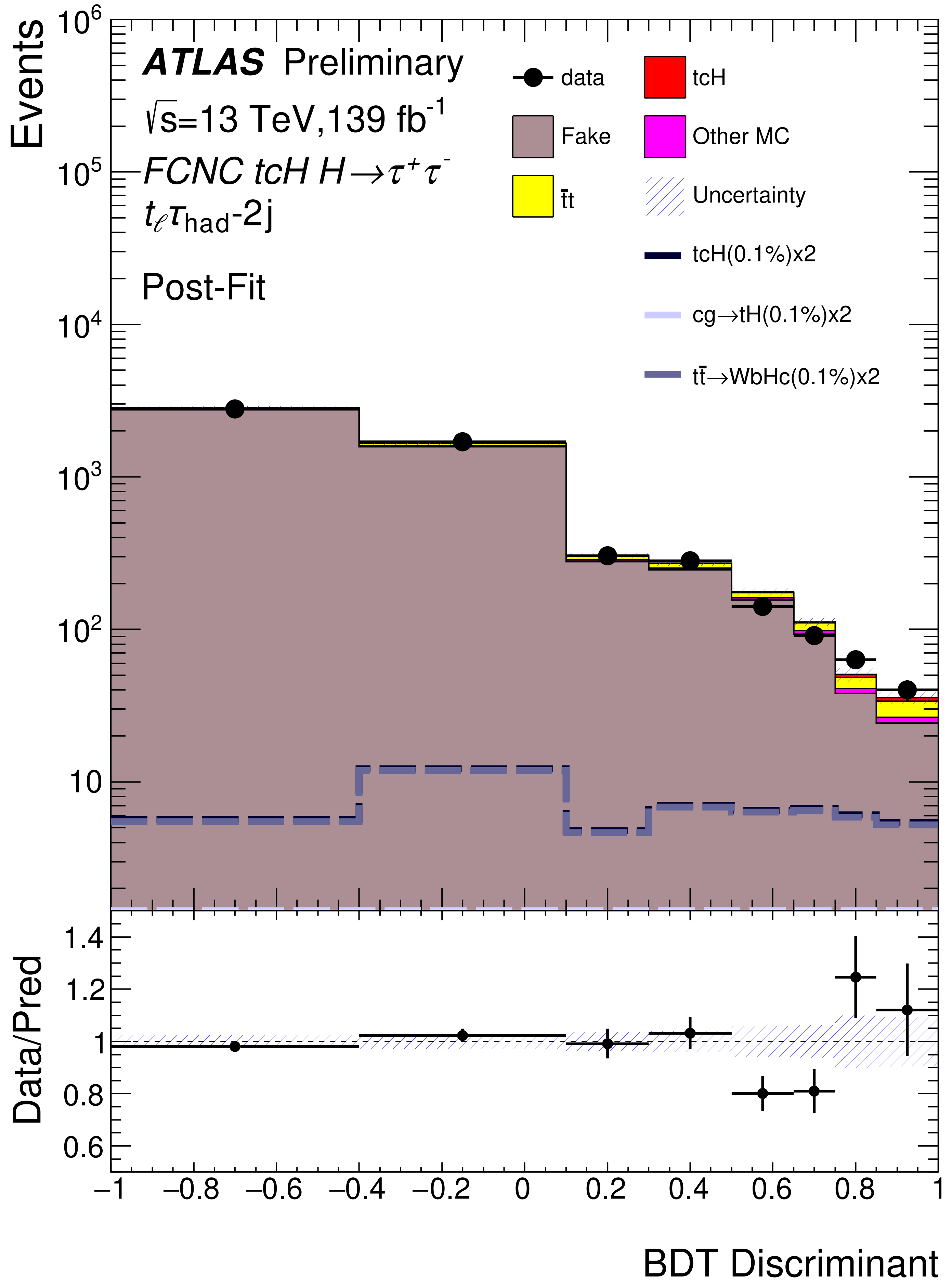
FCNC H(ττ) — Boosted Decision Trees

- One BDT per signal region with 12-17 kinematic input features
- Generally important: p_T of leading τ, $m_{\tau\tau}$, m_{bjj} (hadronic top regions)

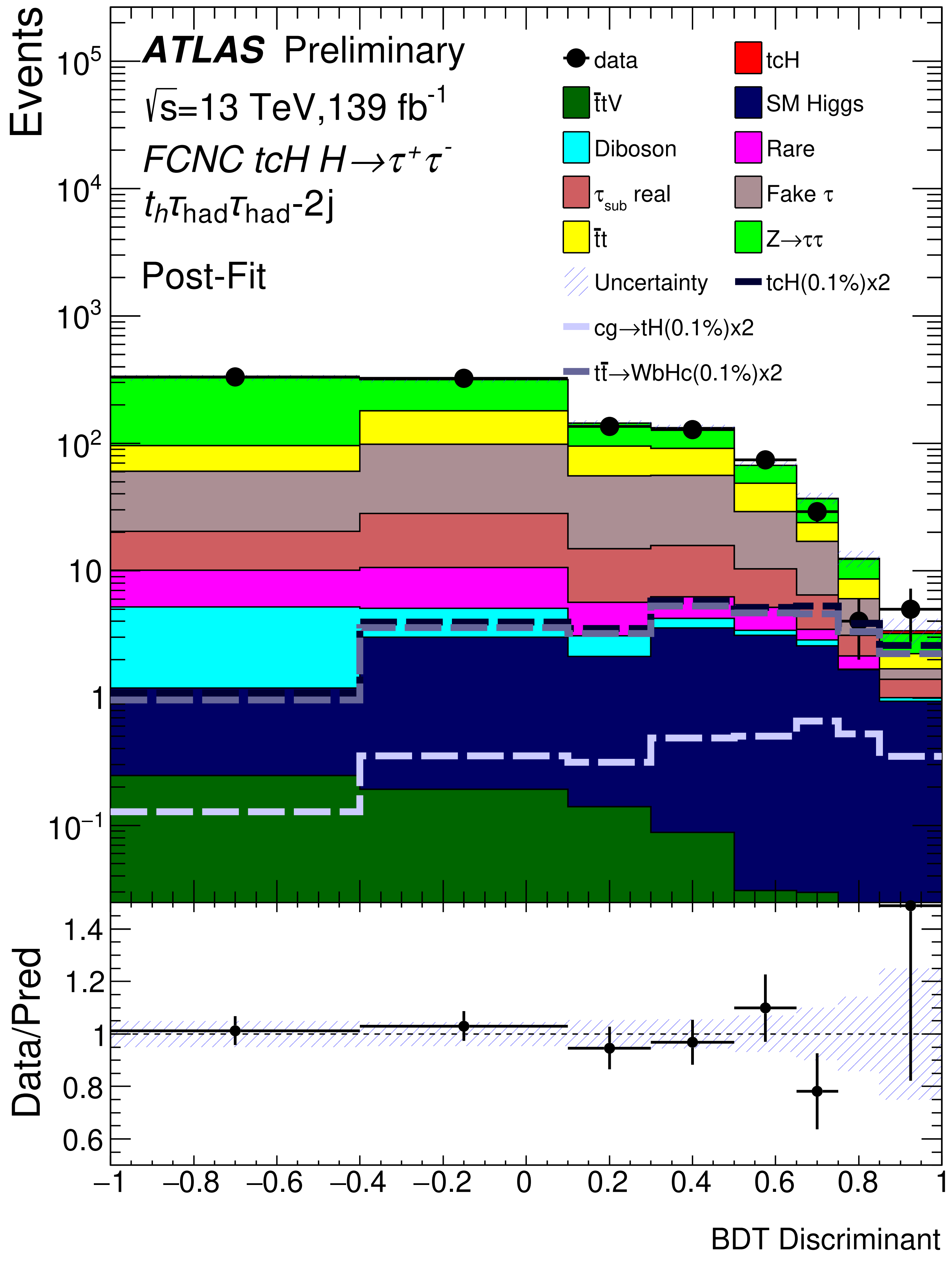
leading-τ p_T



least sensitive leptonic SR

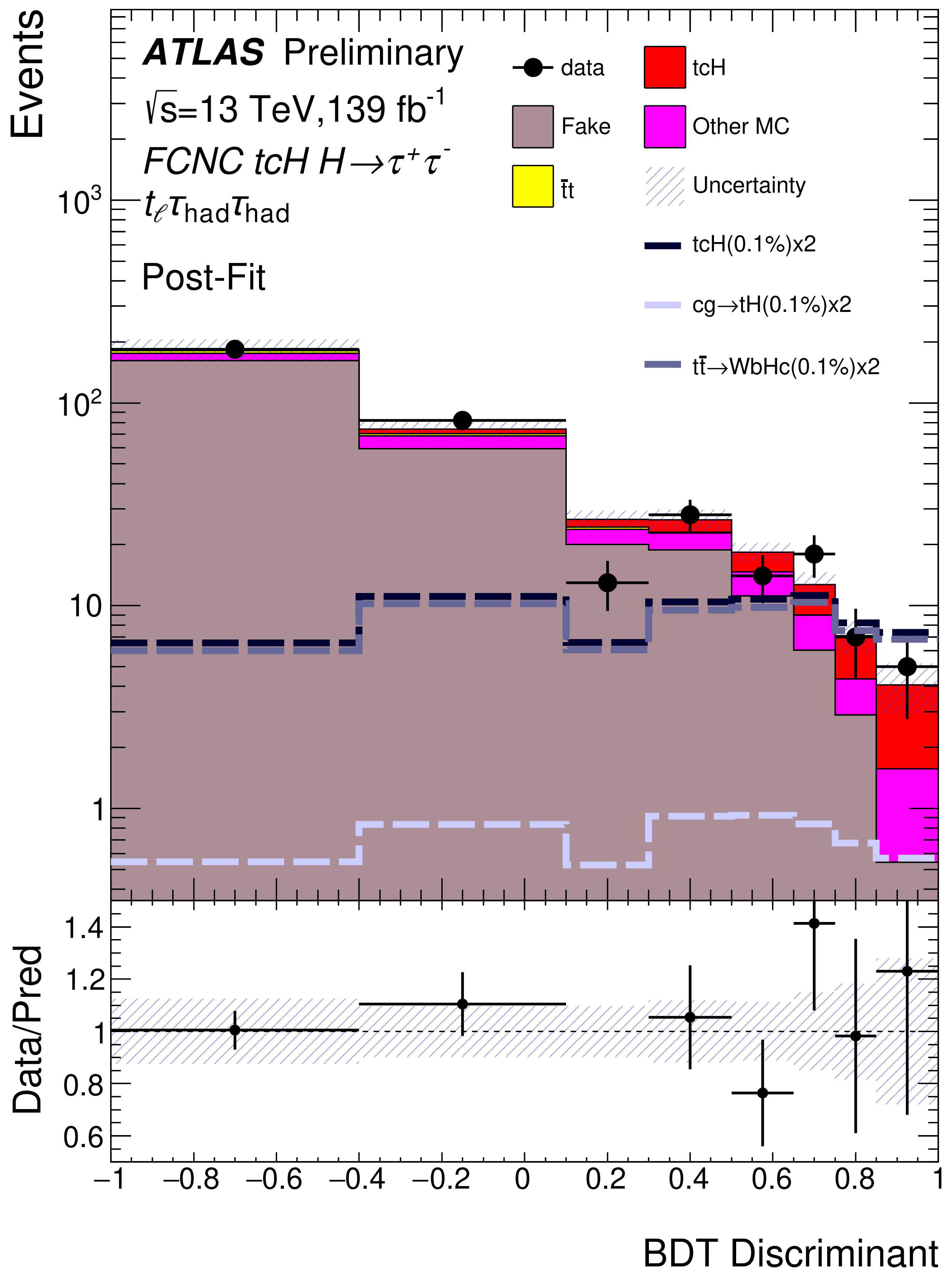


least sensitive hadronic SR

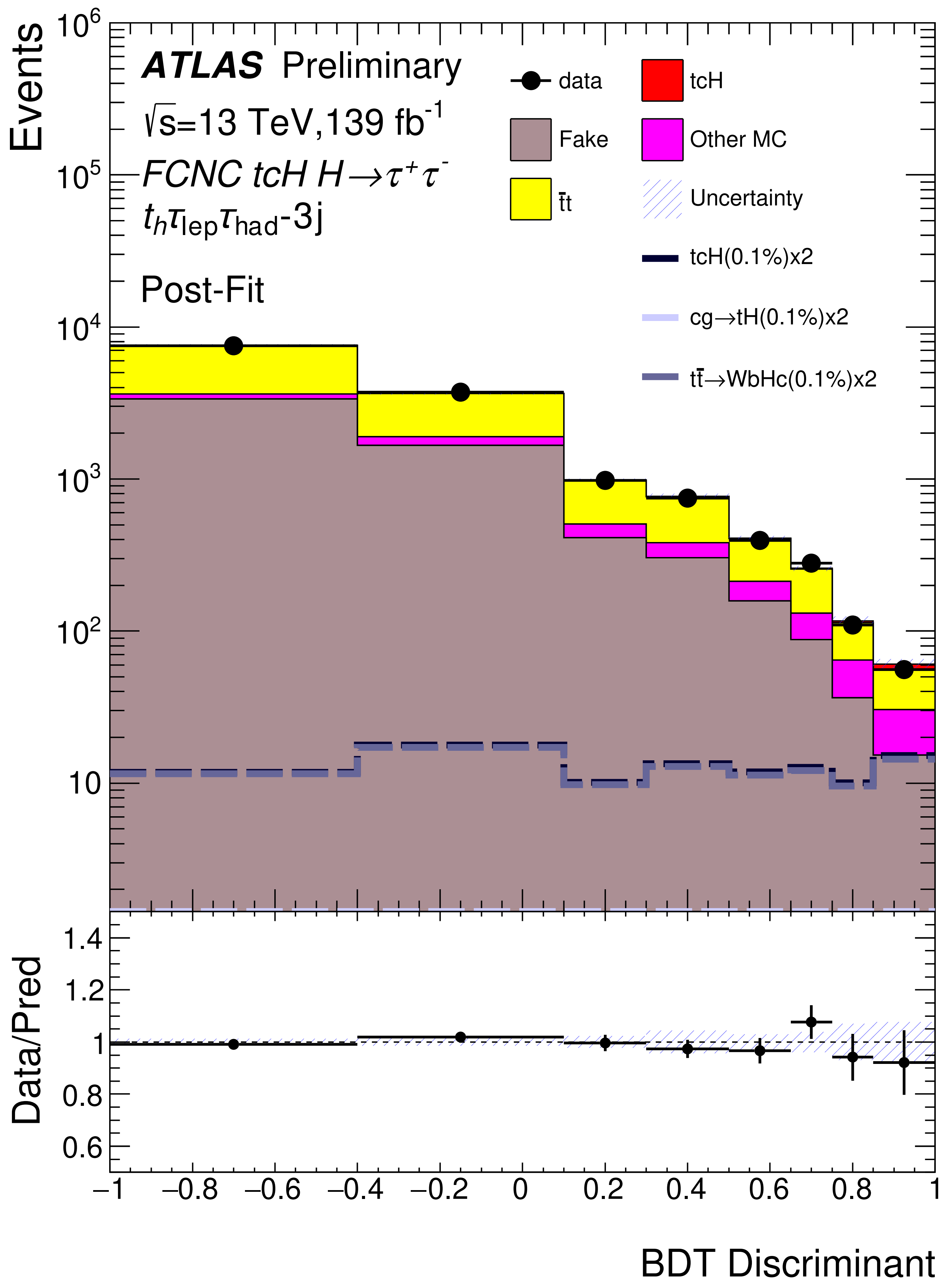


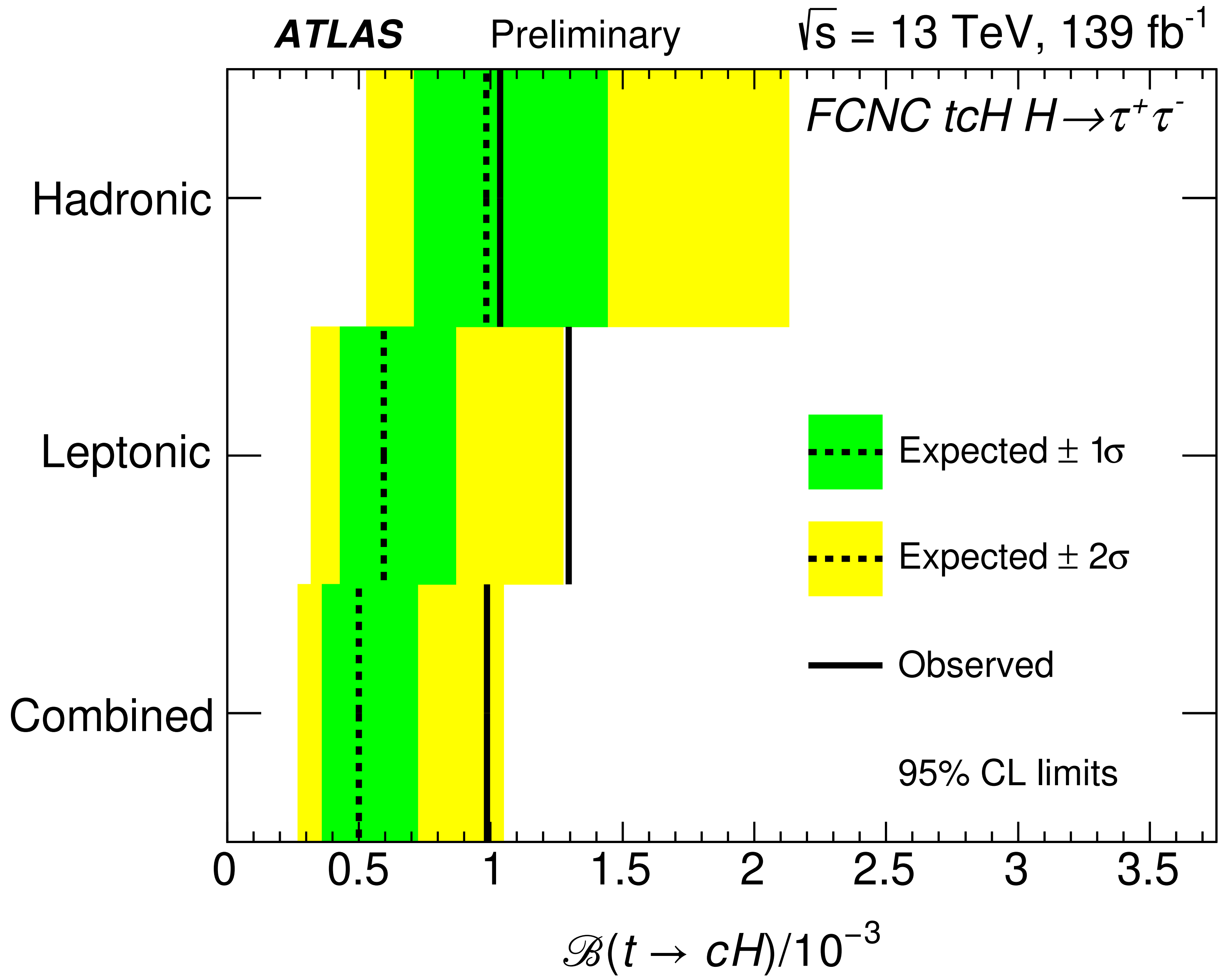
FCNC H(ττ) — Results

Most sensitive leptonic SR



Most sensitive hadronic SR





Expected Limits

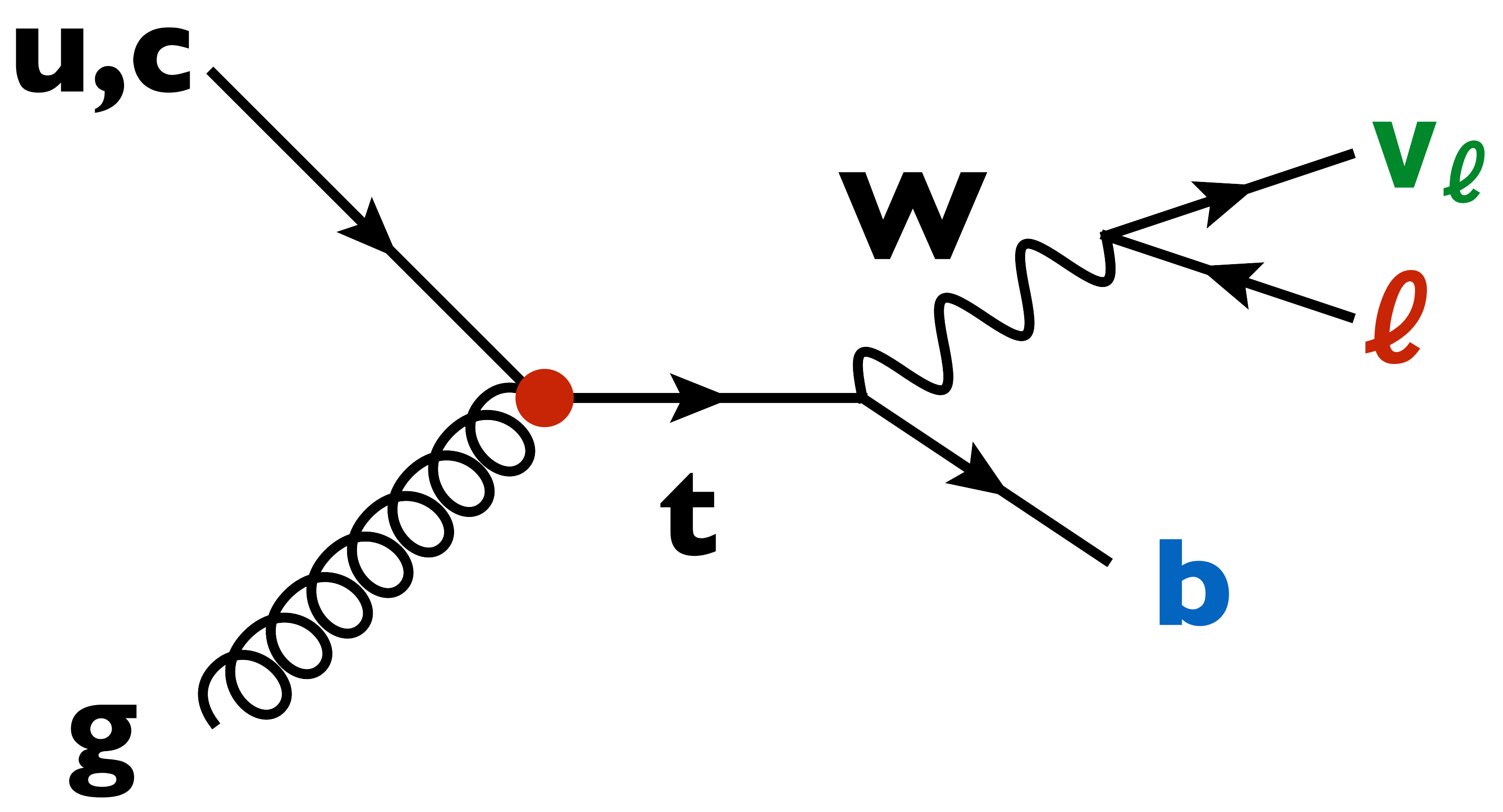
95% CL [10^{-3}]	BR(uH)	BR(cH)
This analysis	0.36	0.50
ATLAS 36 fb-1 H→ττ	2.0	2.1
ATLAS 36 fb-1 ττ+bb+γγ+ML	0.83	0.83
CMS 139 fb-1 H→γγ	0.31	0.51

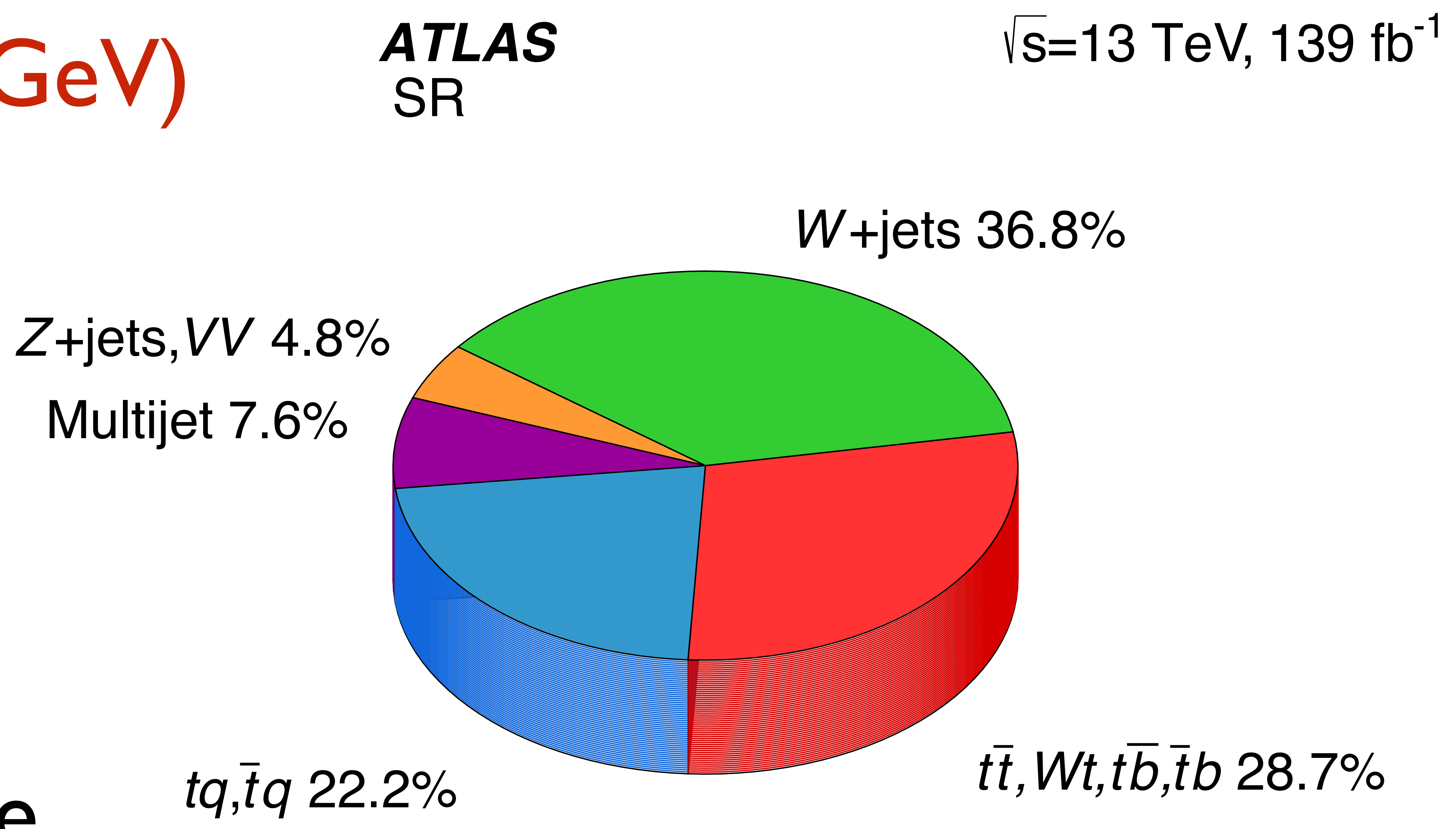
- Excess 2.3σ significant
- Statistical uncertainties dominate over systematics

FCNC g — Analysis Strategy

arXiv:2112.01302

- FCNC decay hopeless
  → anomalous single-top production
- Just one top
  - Swamped by W+jets, SM single top, QCD multijet & $t\bar{t}$
- Selection:
  - 1 e or μ with p_T > 27 GeV + dilepton veto (10 GeV)
  - E_T^{miss} > 30 GeV & $m_T(\ell\nu)$ > 50 GeV
  - 1 b-jet with 30% (!) efficiency
  - No additional jet with $|\eta|$ < 4.5
  - Increase lepton p_T requirement if $\Delta\Phi(\ell,\text{jet})$ large



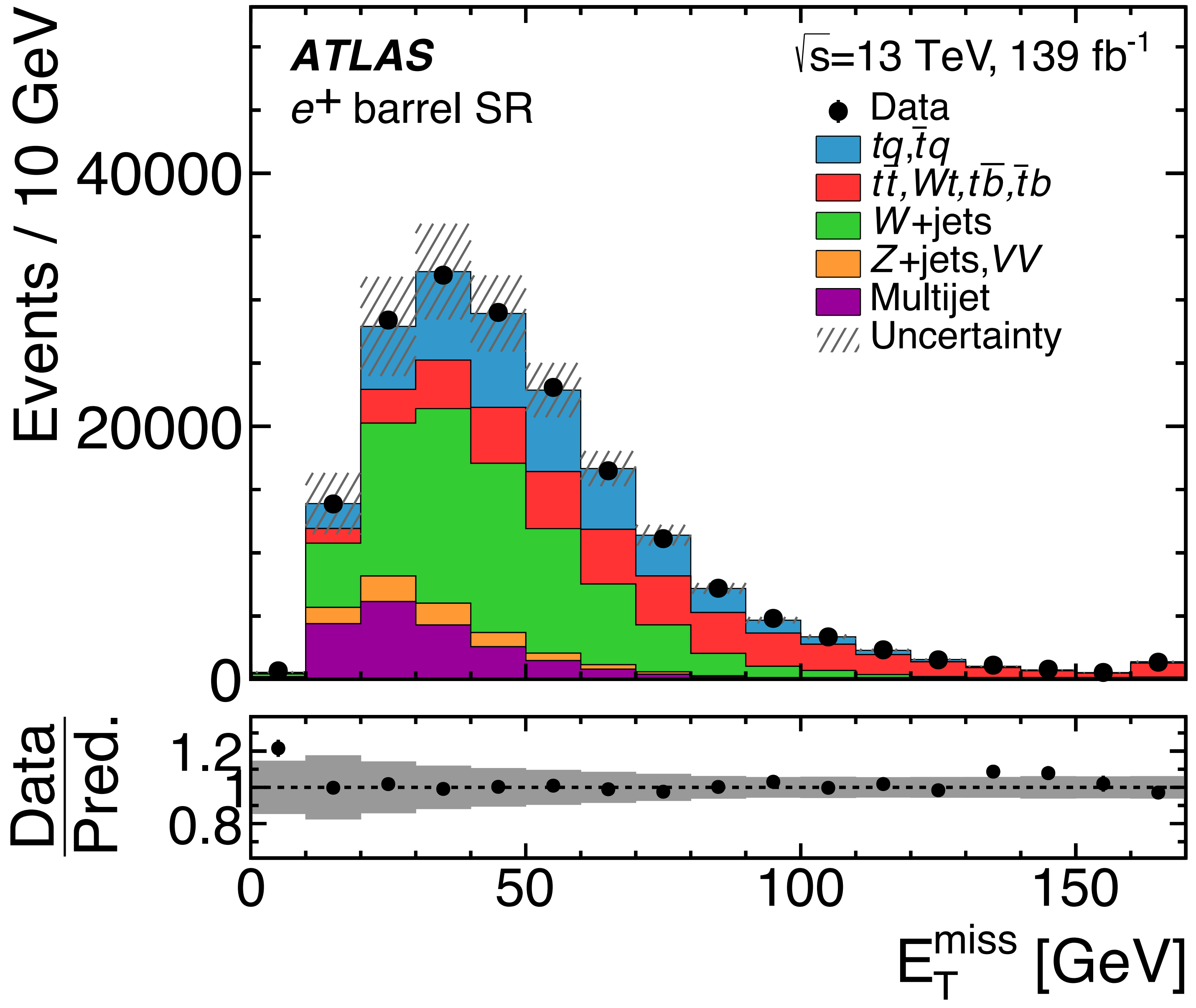


FCNC g — Background Estimation and Validation

arXiv:2112.01302

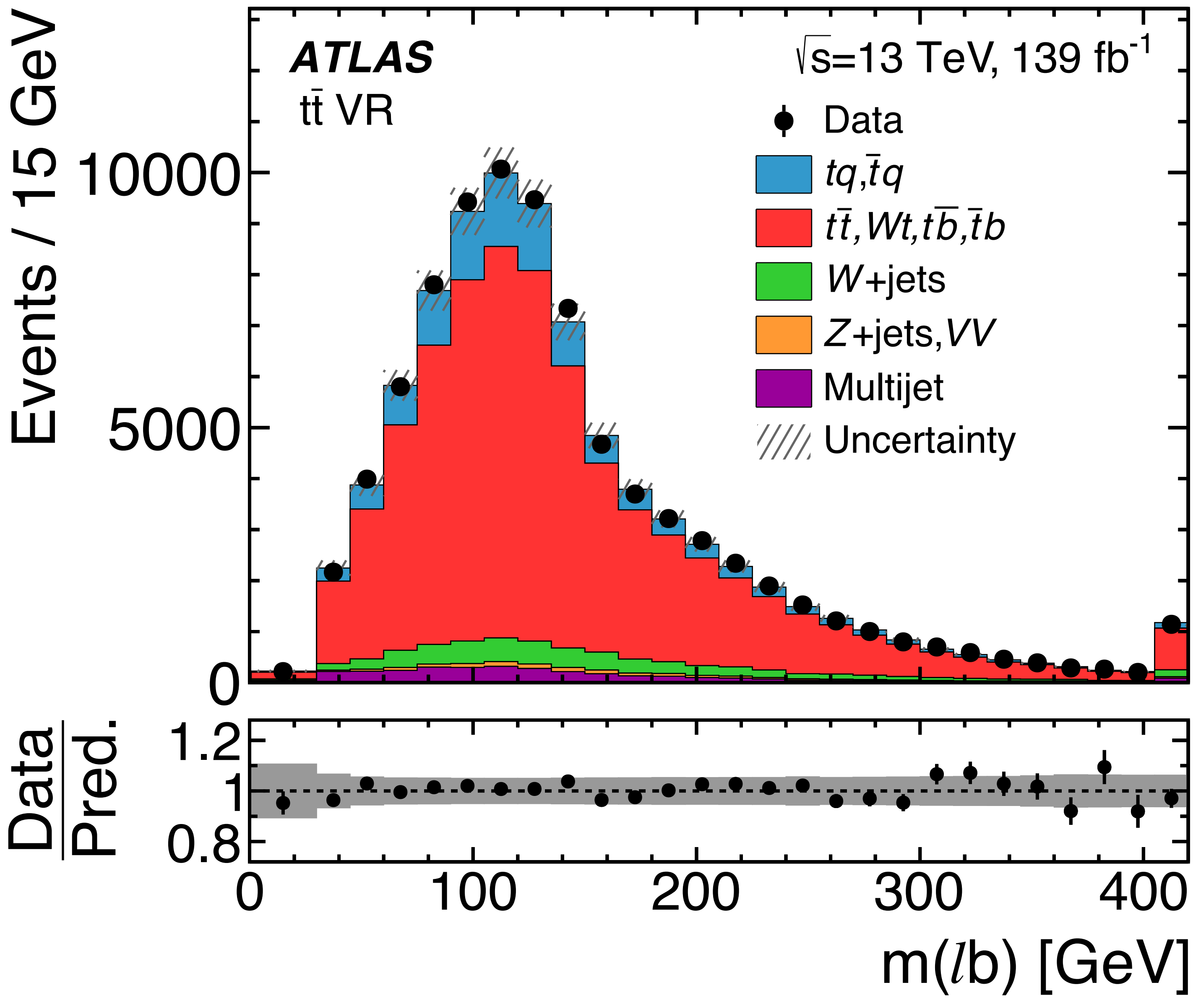
Multijet estimate:

- Matrix method



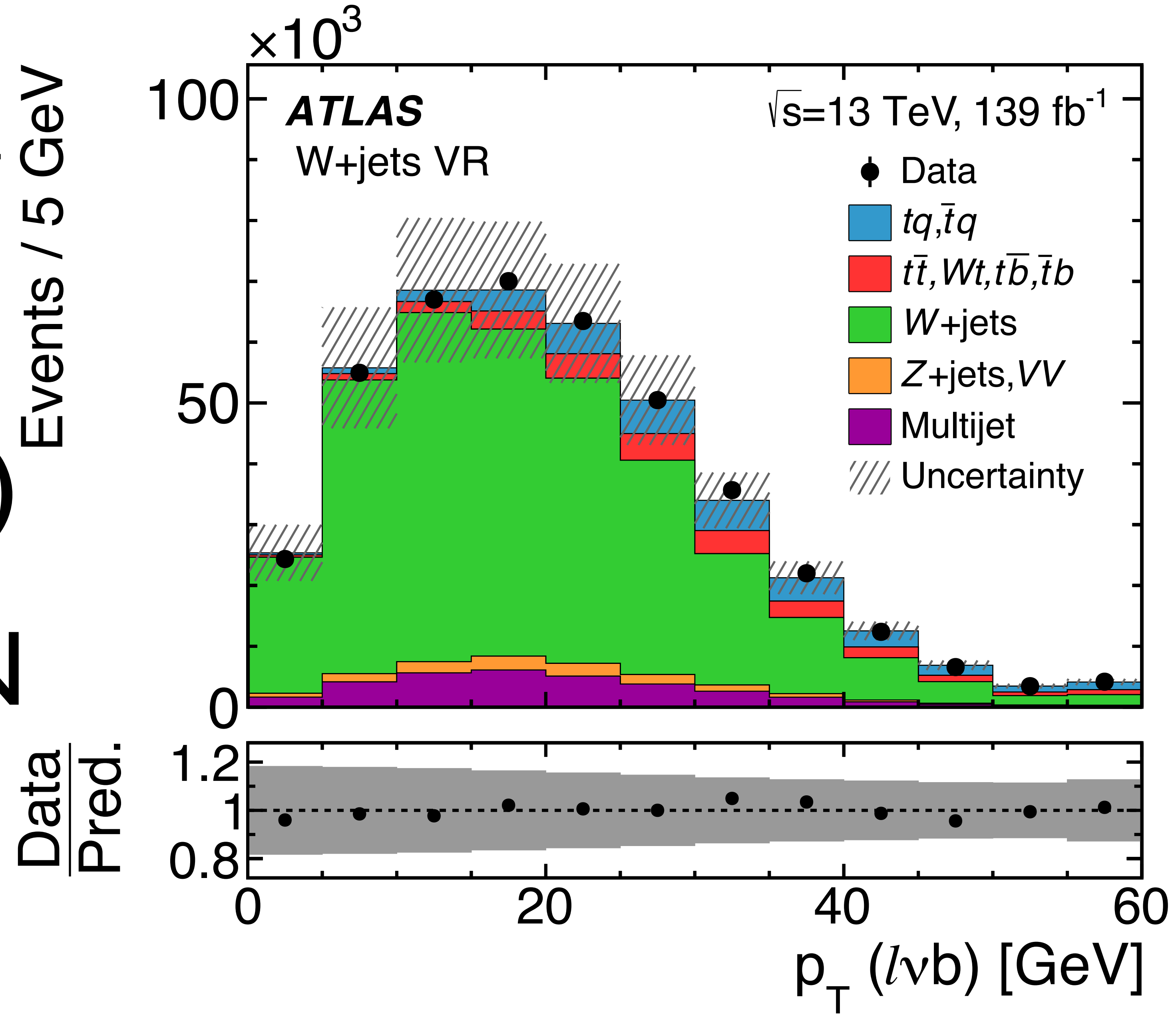
$t\bar{t}$ validation:

- 2 jets
- both b-tagged



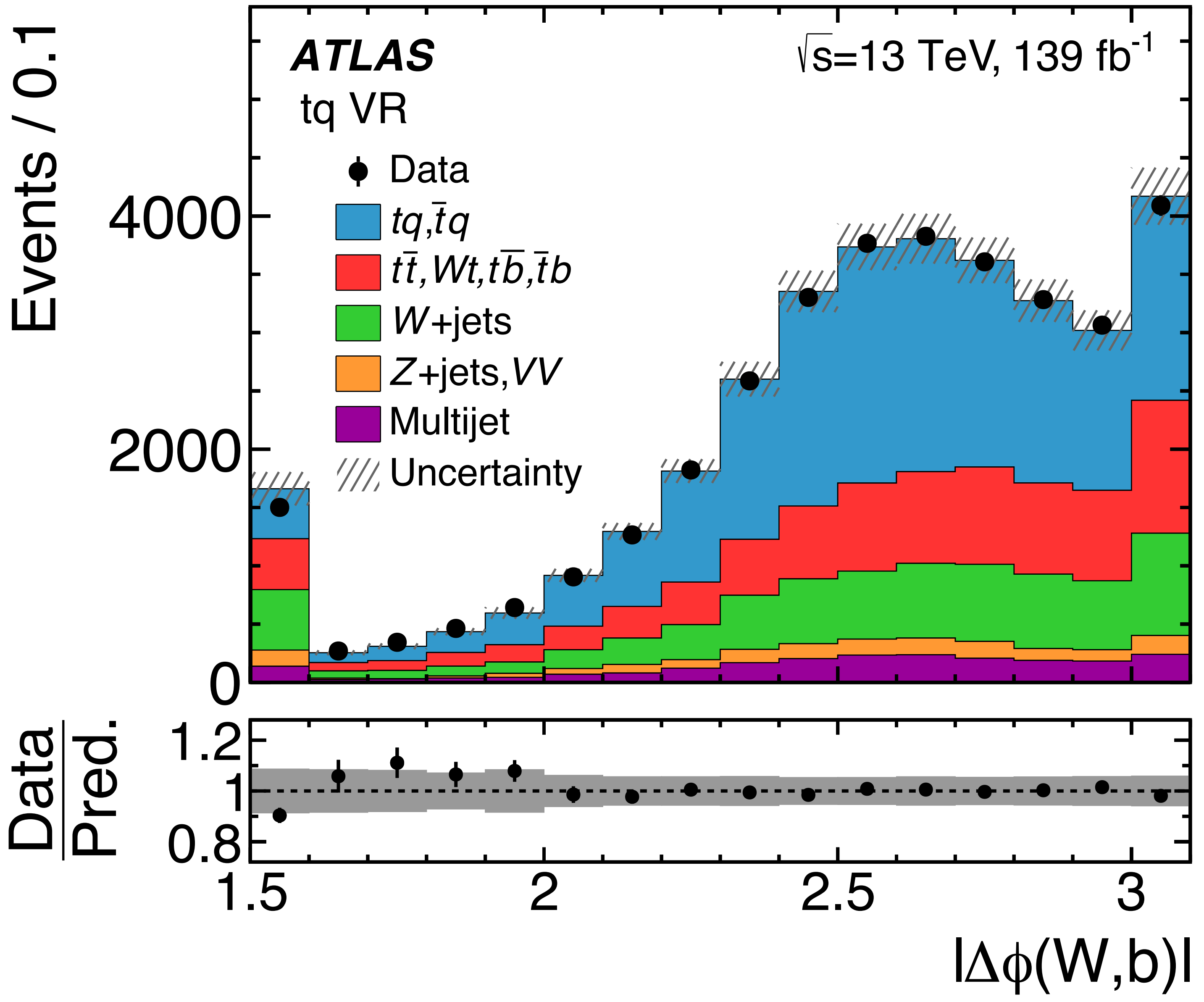
W+jets validation:

- 1 b-jet but with 60% (+30% veto)
- intermediate NN



single-t validation:

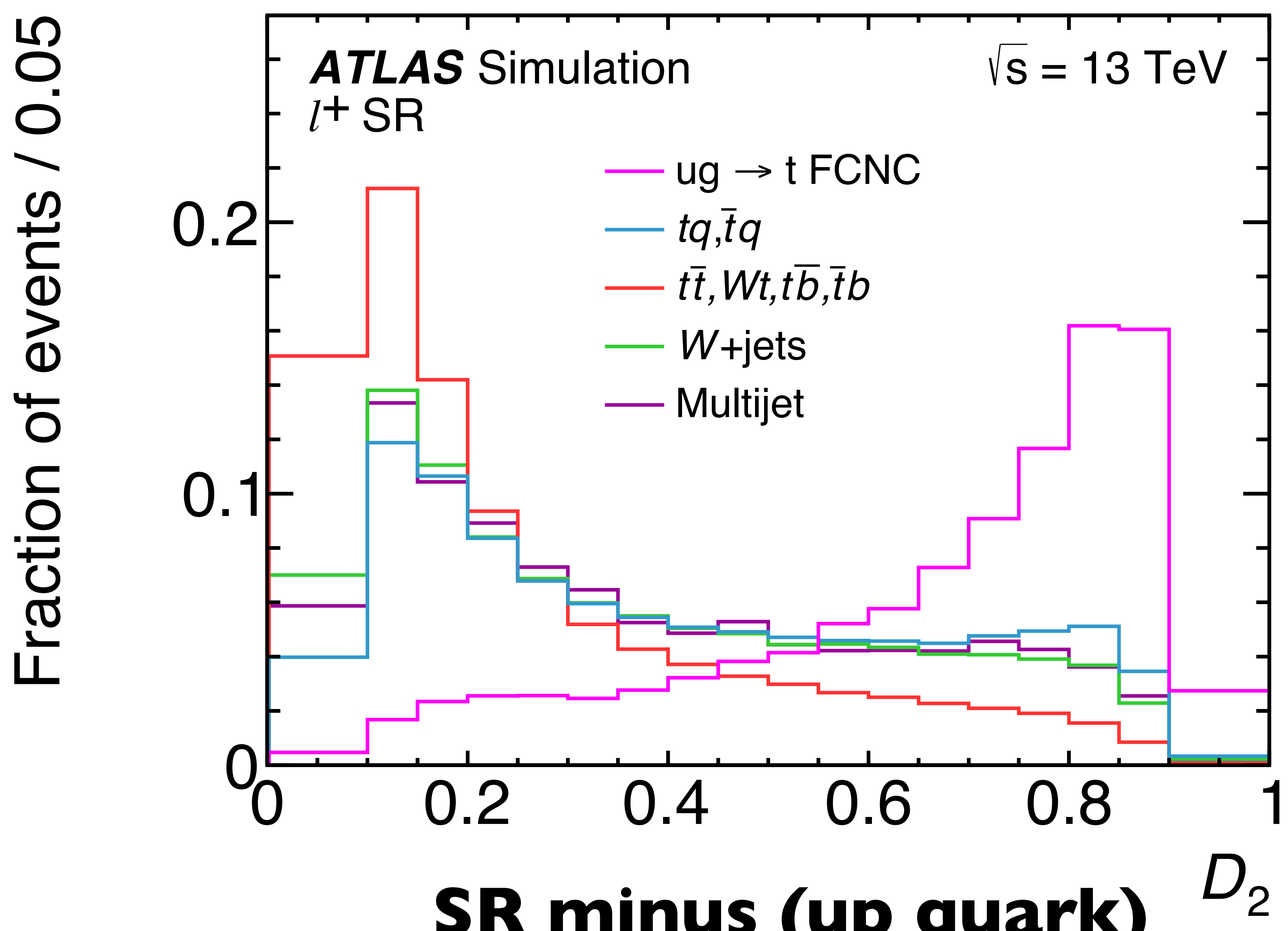
- 1 b-jet
- 1 forward jet
- intermediate NN

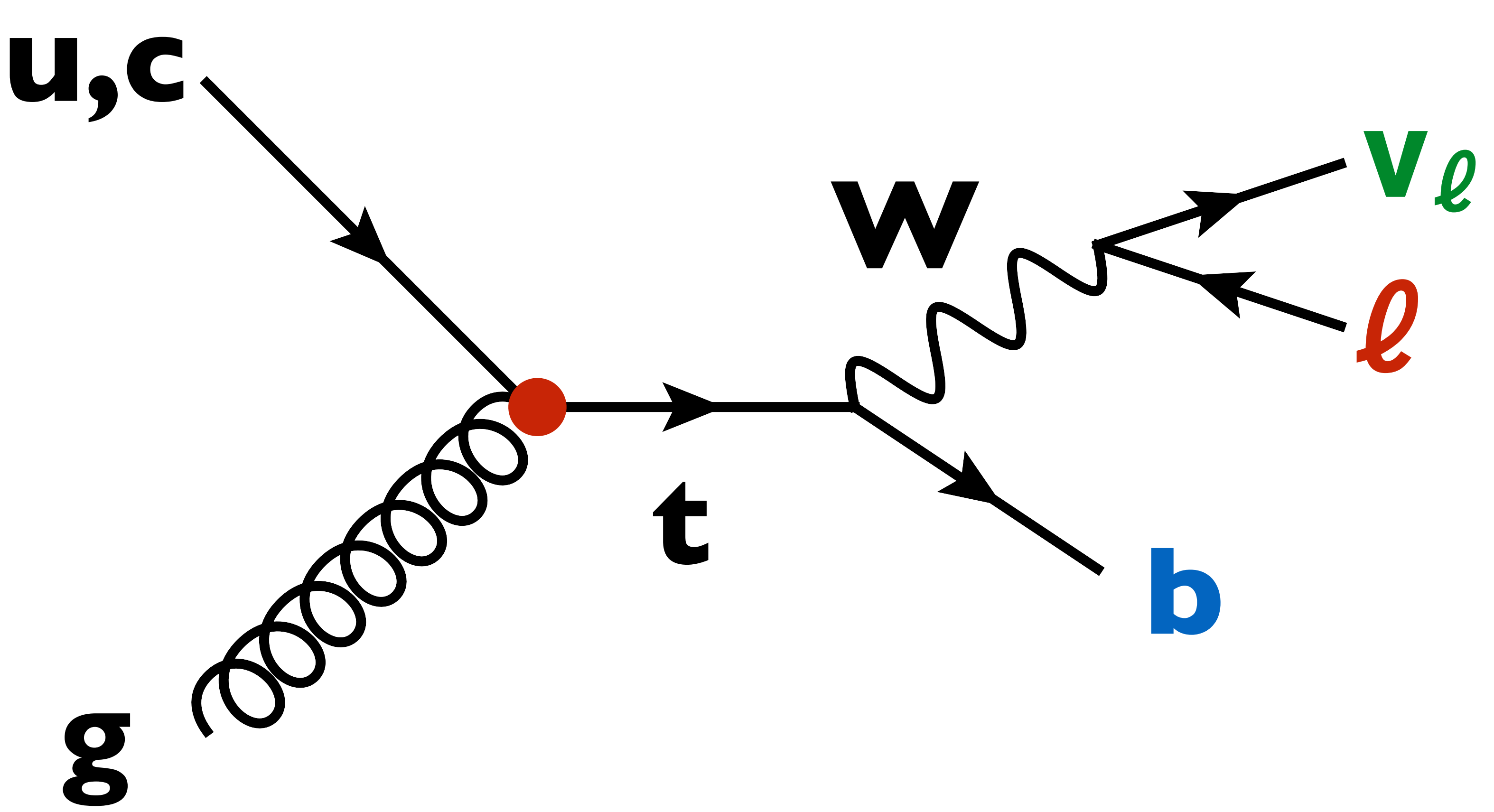


FCNC g — Neural Networks

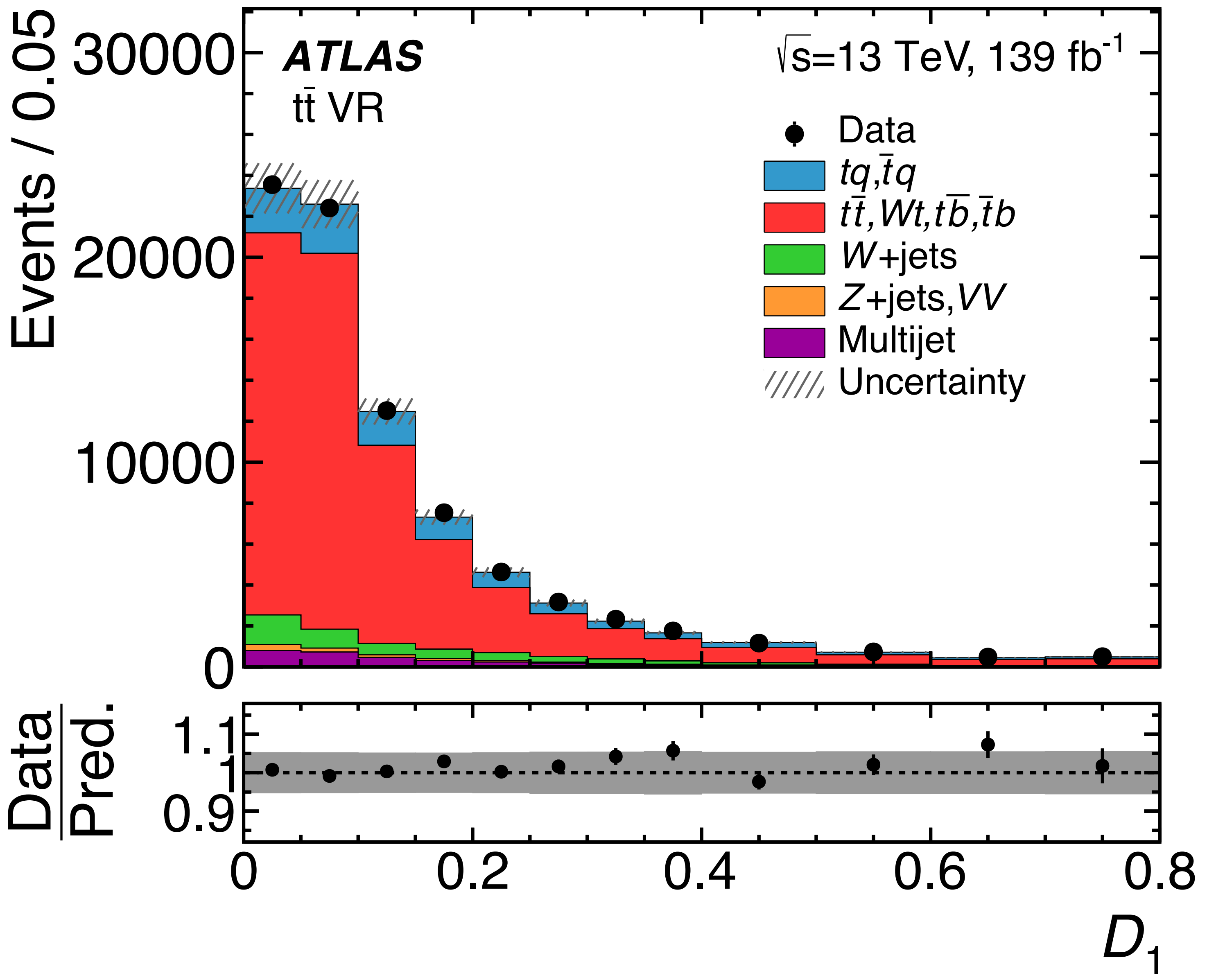
arXiv:2112.01302

- 2 NNs due to u/c PDFs
- 1 hidden layer with transformation of 12/9 input variables

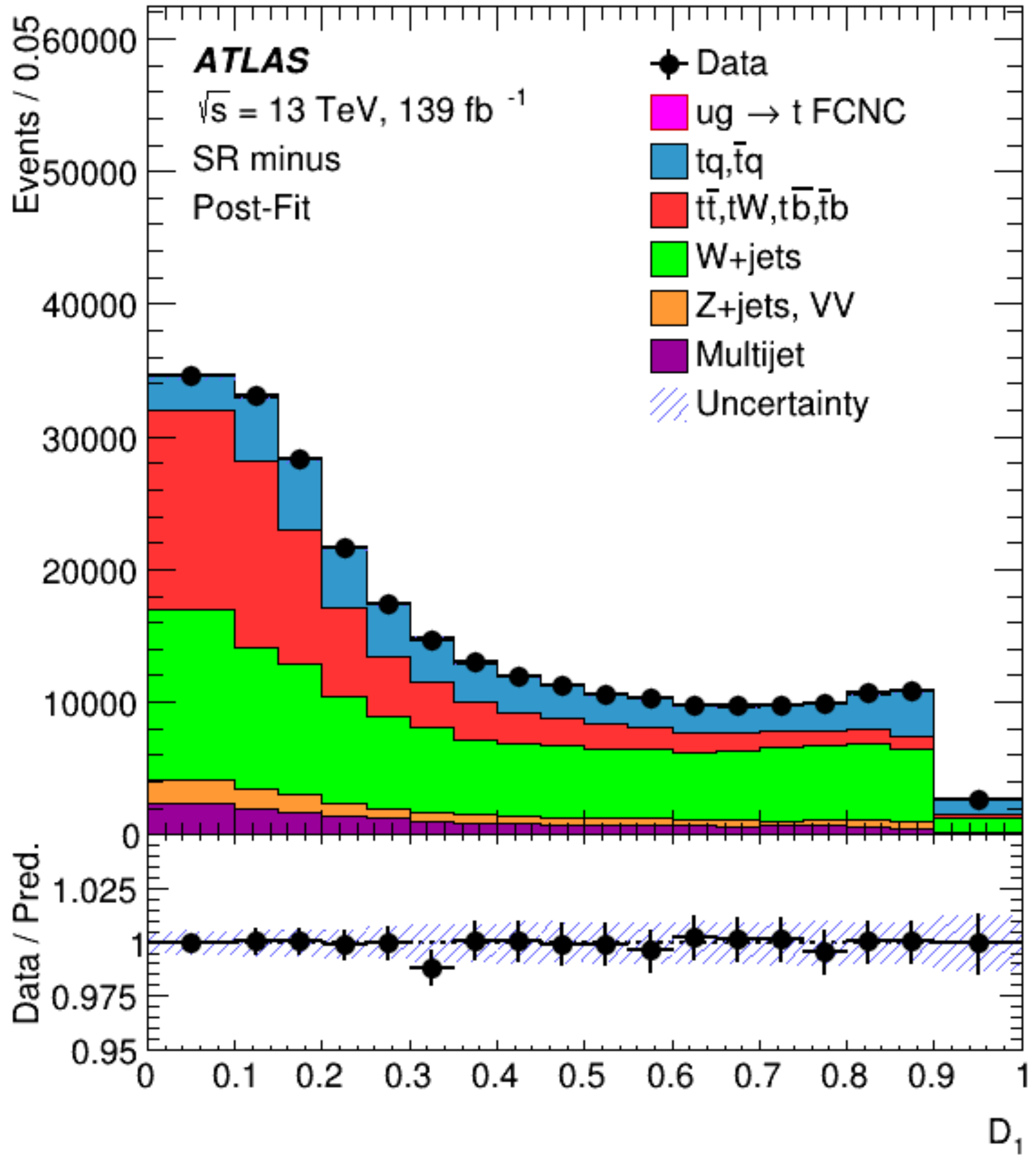




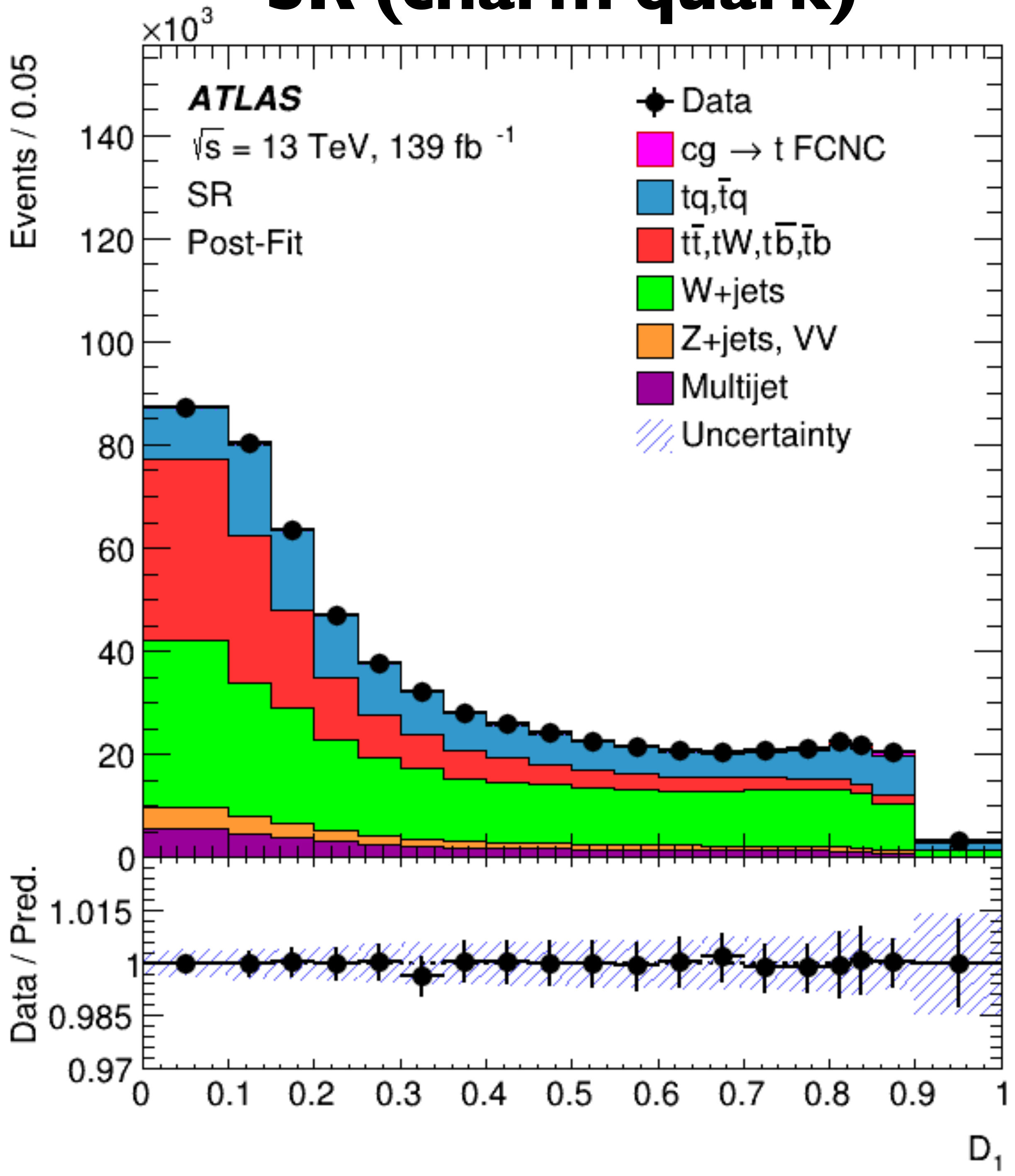
$t\bar{t}$ VR



SR minus (up quark)



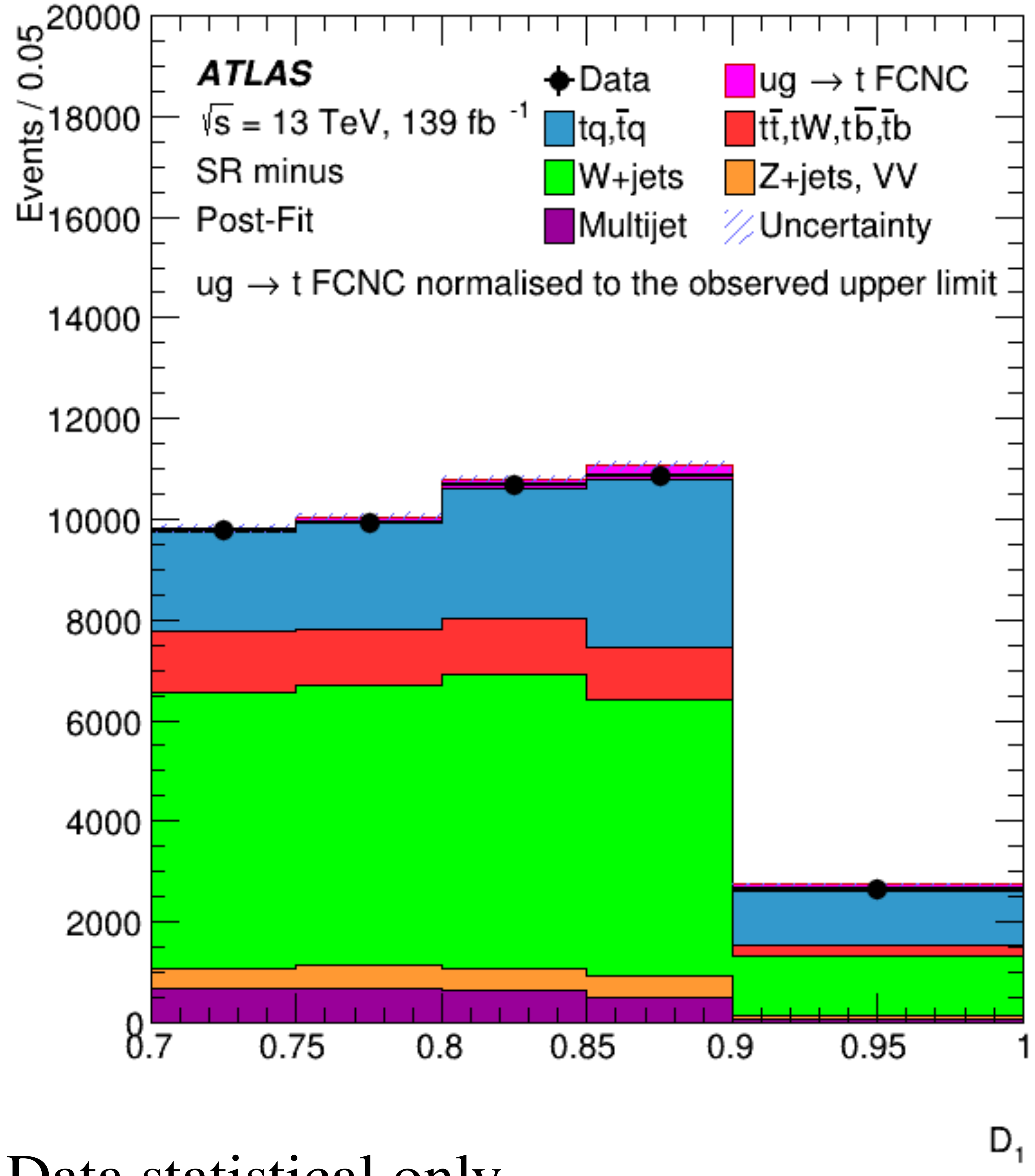
SR (charm quark)



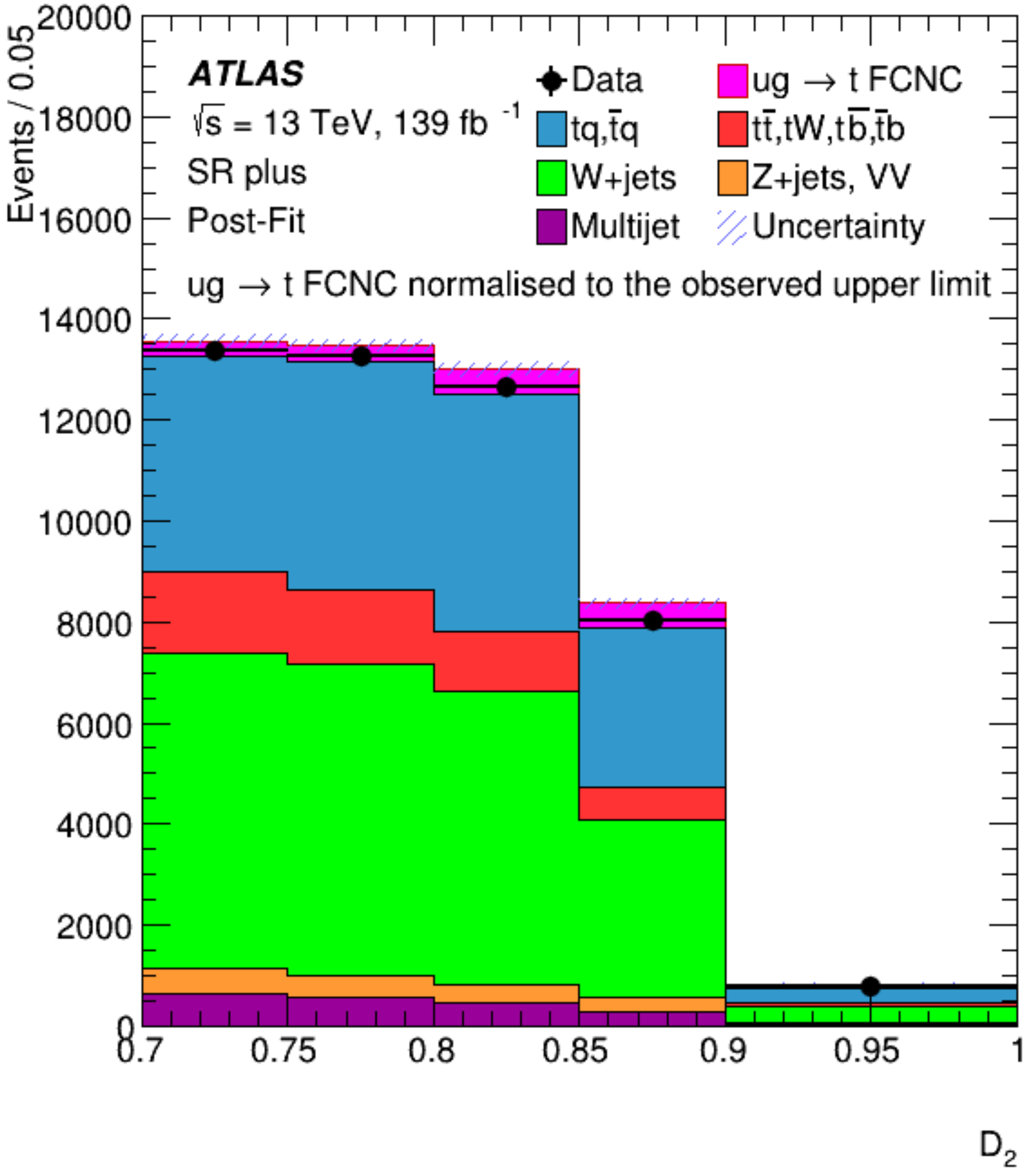
FCNC g — Results

- 95% CL limits on σ_{FCNC} interpreted as BR limits:
  BR(t→ug) < 6.1 x 10^{-5}
  BR(t→cg) < 37 x 10^{-5}
- Main systematics: bkg. modelling, jet/E_T^{miss}-related

Zoom of SR minus (up quark)



Zoom of SR plus (up quark)



$\mathcal{B}_{95}^{\text{exp}}(t \to u+g)$	$\mathcal{B}_{95}^{\text{exp}}(t \to c+g)$	
1.1×10^{-5}	2.4×10^{-5}	Data statistical only
3.1×10^{-5}	12×10^{-5}	Experimental uncertainties also
3.9×10^{-5}	18×10^{-5}	All uncertainties except MC statistical
4.9×10^{-5}	20×10^{-5}	All uncertainties

Run-1 analysis

- BR(t→ug) < 12 x 10^{-5}
- BR(t→cg) < 64 x 10^{-5}

FCNC Summary

- New FCNC searches for all elementary bosons
- Several improvements beyond luminosity scaling

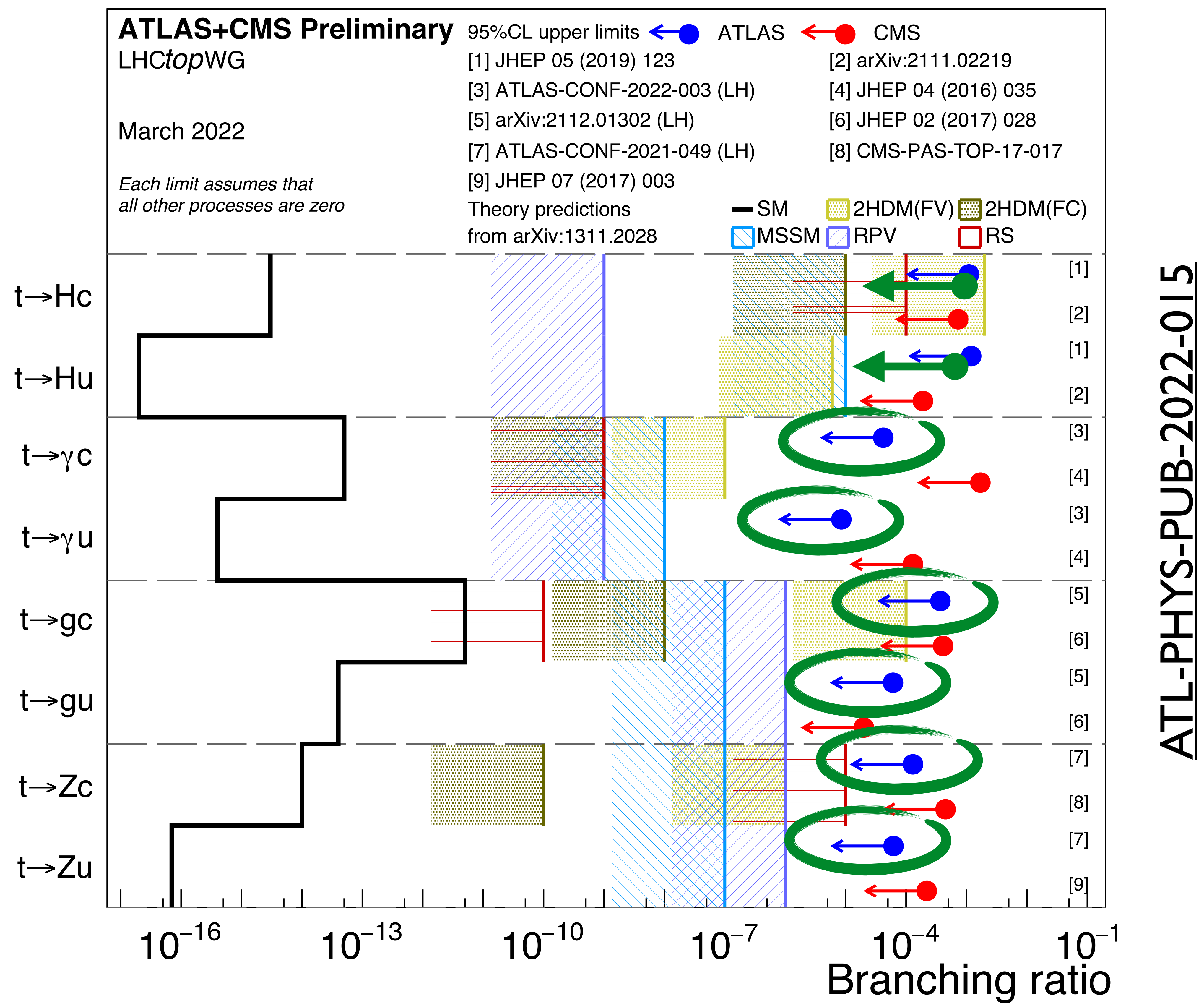
Total improvement factor

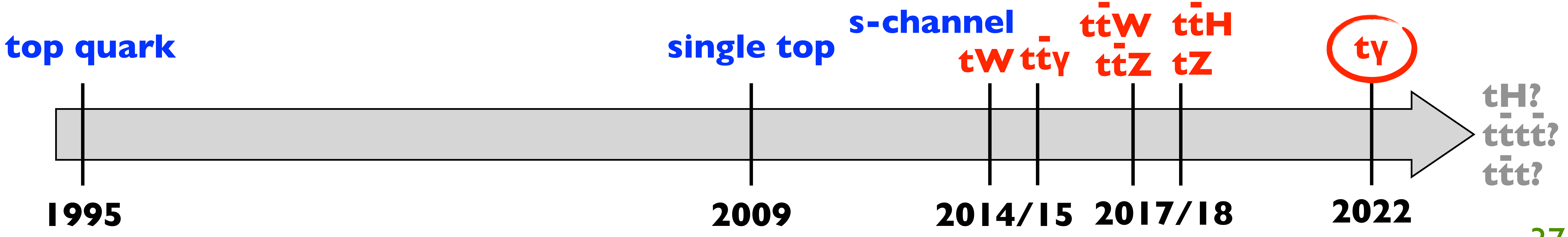
	Previous best ATLAS search	Expected Limit		Observed Limit	
		up	charm	up	charm
γ	81 fb^{-1}	~3-5	~5-6	~3-5	~4-5
Z	36 fb^{-1}	~5	~3	~3	~2
H	Combination, 36 fb^{-1}	~2	~2	~2	~1.1
	$H \rightarrow \tau\tau$, 36 fb^{-1}	~6	~4	~2	~2
g	8 TeV	~2	~3	~2	~2

Conclusions

Conclusions

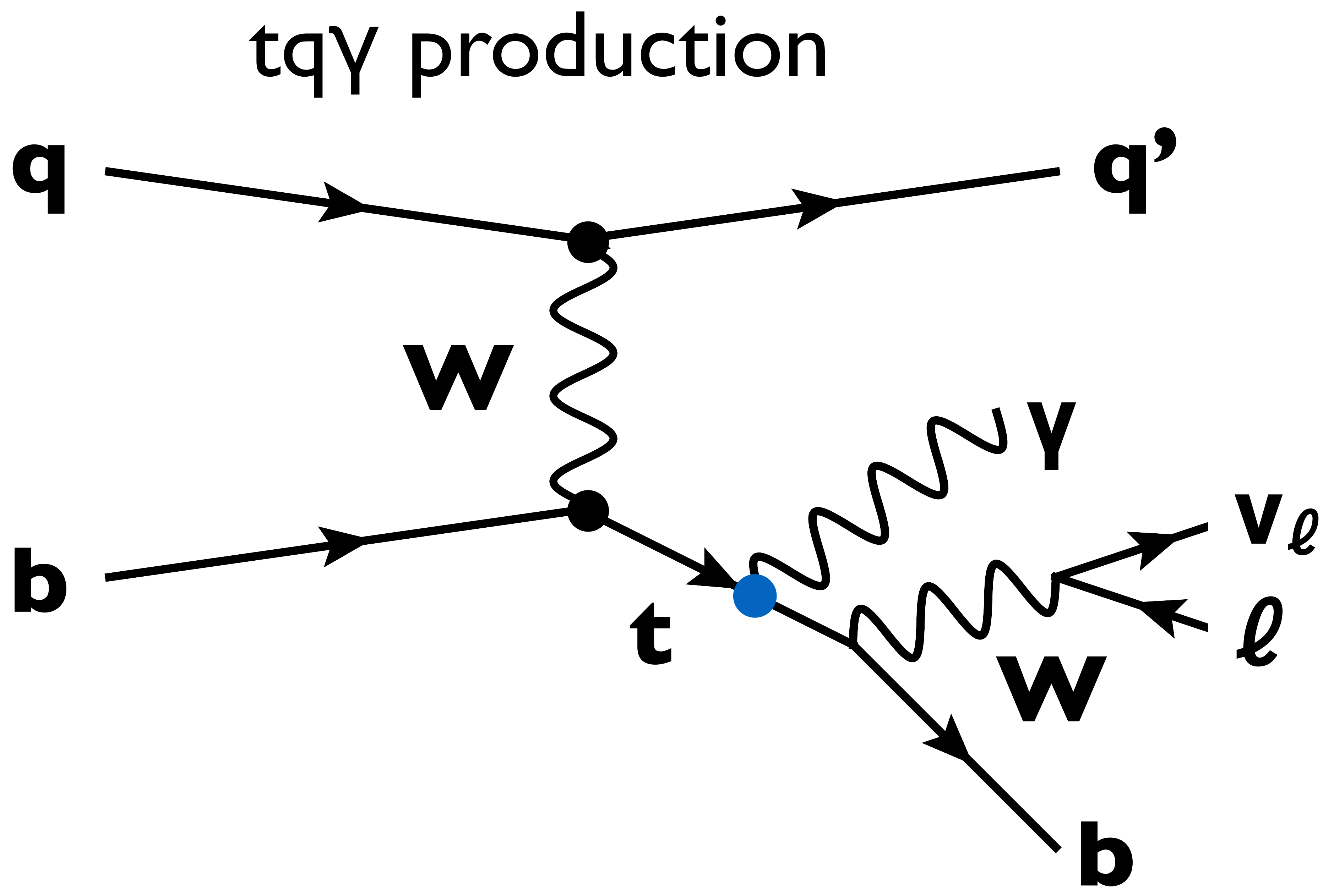
- Single-top+photon production observed (≫ 5σ)
  - 11% uncertainty on σ
- 4 new searches for top FCNC interactions
  - Improve observed limits by up to a factor ~5
- Run-2 still has more in the pocket!
- Run-3 to add more exciting opportunities!

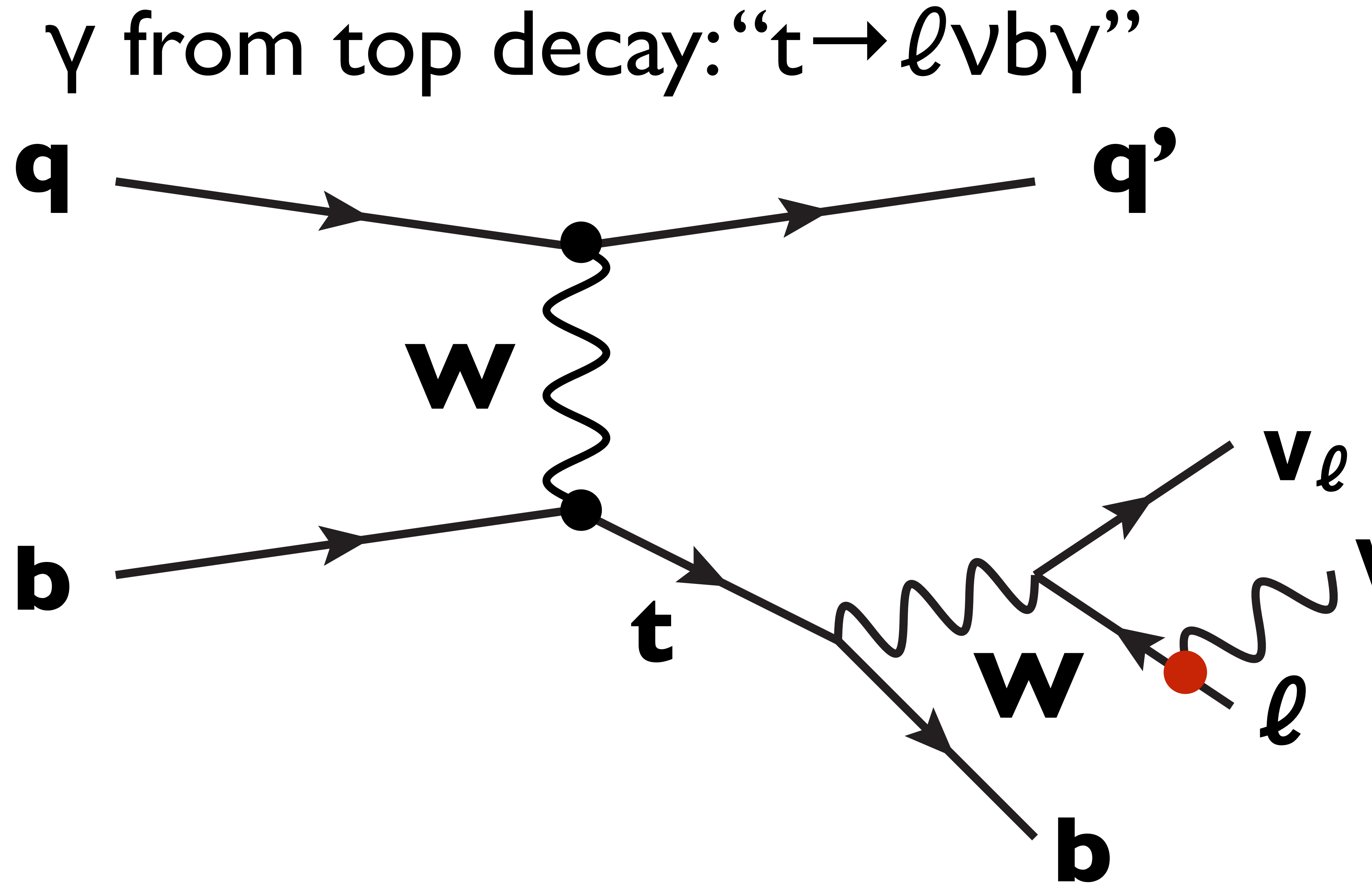




BACKUP

Sample Stitching



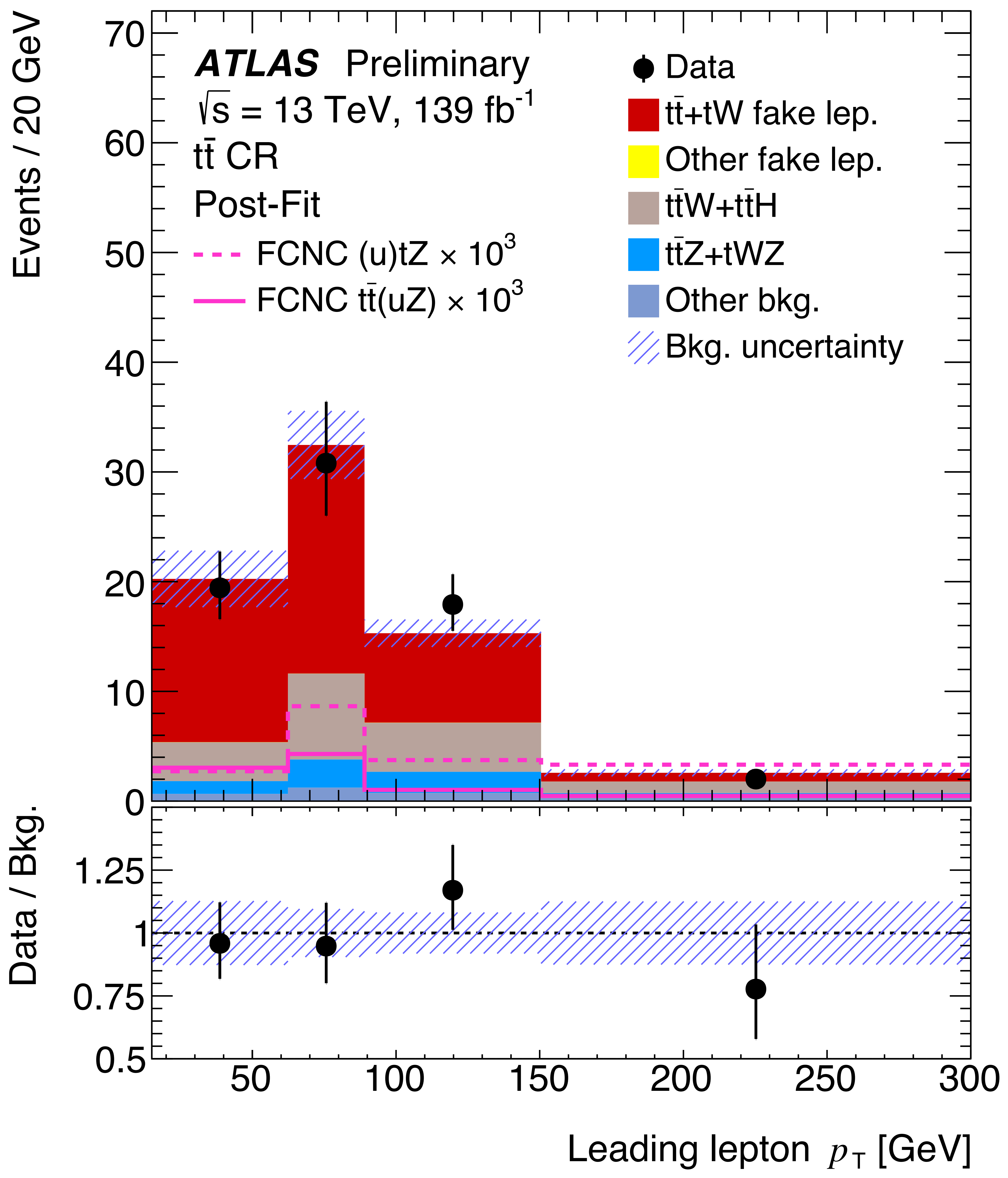


- tqγ: NLO in QCD , t→ℓνbγ: tq production at NLO in QCD with γ from PS
- Overlap removed based on particle-level criteria:

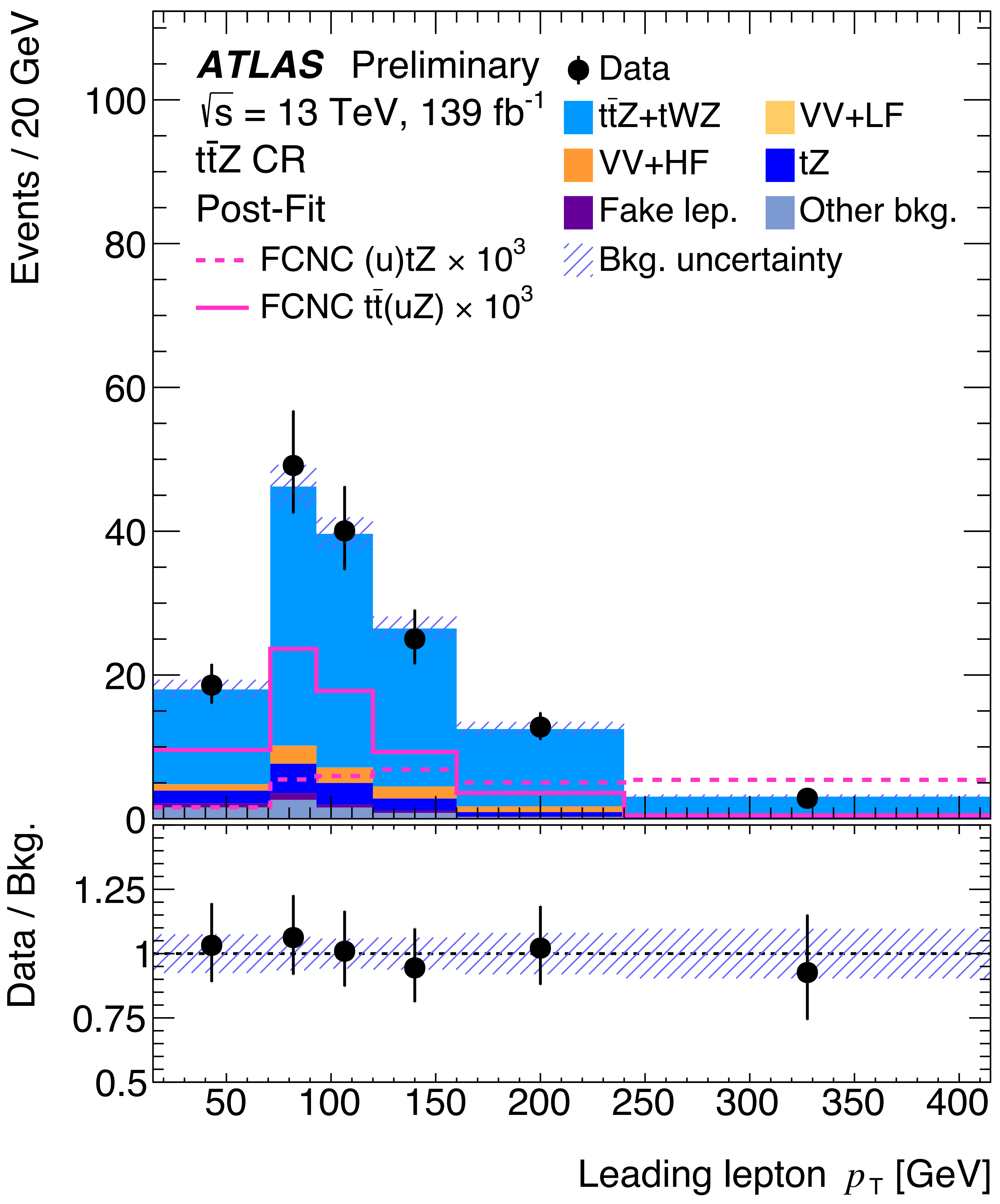
  tq events kept if $|m(\ell\nu\gamma) - m_W| < |m(\ell\nu) - m_W|$ or $|m(\ell\nu b\gamma) - m_t| < |m(\ell\nu b) - m_t|$
- Particle-level definition: 1 e/μ (25 GeV, $|\eta|<2.5$), 1 γ (20 GeV, $|\eta|<2.37$),

  1 b-jet (25 GeV, $|\eta|<2.5$), 1 ν (not from hadron), ΔR(jet,ℓ/γ) & ΔR(γ,X) requirements

FCNC Z



ATLAS Preliminary
√s = 13 TeV, 139 fb-1
tt̄ CR
Post-Fit
FCNC (u)tZ × 10^3
FCNC tt̄(uZ) × 10^3
Data
tt̄+tW fake lep.
Other fake lep.
tt̄W+tt̄H
tt̄Z+tWZ
Other bkg.
Bkg. uncertainty
Events / 20 GeV
Data / Bkg.
Leading lepton pT [GeV]



ATLAS Preliminary
√s = 13 TeV, 139 fb-1
tt̄Z CR
Post-Fit
FCNC (u)tZ × 10^3
FCNC tt̄(uZ) × 10^3
Data
tt̄Z+tWZ
VV+LF
VV+HF
tZ
Fake lep.
Other bkg.
Bkg. uncertainty
Events / 20 GeV
Data / Bkg.
Leading lepton pT [GeV]

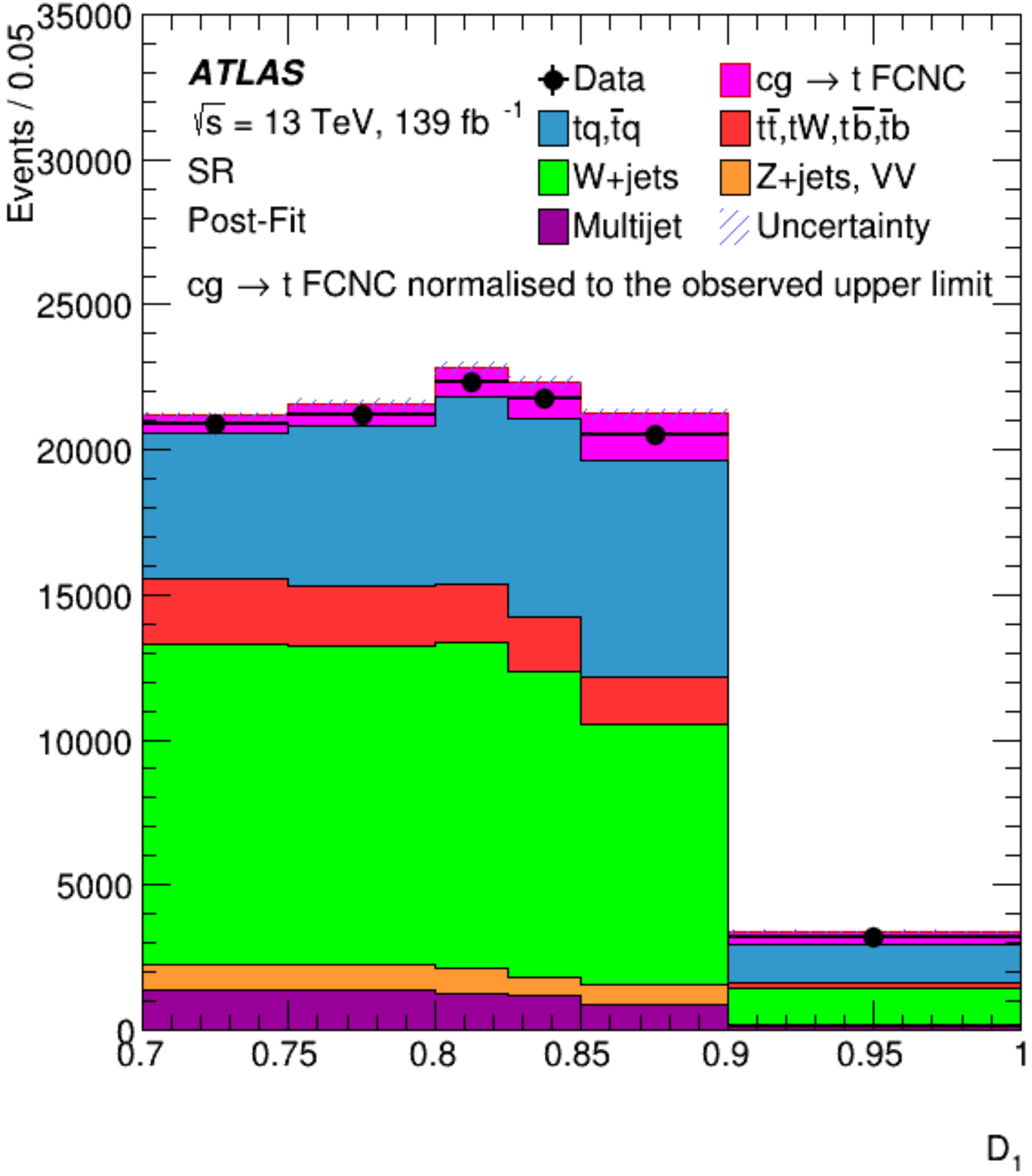
FCNC H(ττ)

Source of uncertainty	ΔB $[10^{-5}]$	
	$t \to uH$	$t \to cH$
Lepton ID	0.6	1.0
E_T^{miss}	0.7	0.8
Fake lepton modeling	0.9	1.1
JES and JER	2.4	3.2
Flavour tagging	2.7	3.7
$t\bar{t}$ modeling	2.9	4.3
Other MC modeling	2.1	2.9
Fake τ modeling	3.2	4.6
Signal modeling including Br($H \to \tau\tau$)	5.3	7.0
τ ID	3.3	4.4
Luminosity and Pileup	0.9	1.3
MC statistics	5.1	7.0
Total systematic uncertainty	11.2	15.5
Data statistical uncertainty	14.1	19.6
Total uncertainties	18	25

FCNC H(ττ)

Signal Regions	$t \to cH$ 95% CL upper limits$[10^{-3}]$ Observed (Expected)	$t \to cH$ Significance	$t \to cH$ $B[10^{-3}]$	$t \to uH$ 95% CL upper limits$[10^{-3}]$ Observed (Expected)	$t \to uH$ Significance	$t \to uH$ $B[10^{-3}]$
$t_h\tau_{\rm had}\tau_{\rm had}$-2j	$1.85(2.80^{+1.30}_{-0.78})$	$-0.96(0.78)$	$-1.03^{+1.04}_{-1.04}$	$1.10(1.65^{+0.79}_{-0.46})$	$-0.90(1.25)$	$-0.55^{+0.59}_{-0.59}$
$t_h\tau_{\rm had}\tau_{\rm had}$-3j	$1.18(1.06^{+0.50}_{-0.30})$	$0.34(1.87)$	$0.16^{+0.47}_{-0.47}$	$1.00(0.89^{+0.42}_{-0.25})$	$0.36(2.13)$	$0.14^{+0.40}_{-0.40}$
Hadronic Combination	$1.04(0.98^{+0.46}_{-0.28})$	$0.26\ (1.99)$	$0.11^{+0.43}_{-0.43}$	$0.78(0.78^{+0.37}_{-0.22})$	$0.11(2.33)$	$0.04^{+0.34}_{-0.34}$
$t_l\tau_{\rm had}$-2j	$4.86(4.32^{+1.89}_{-1.21})$	$0.40(0.48)$	$0.81^{+2.04}_{-2.04}$	$3.93(3.55^{+1.56}_{-0.99})$	$0.34(0.58)$	$0.57^{+1.66}_{-1.66}$
$t_l\tau_{\rm had}$-1j	$3.94(3.67^{+1.66}_{-1.03})$	$0.24(0.57)$	$0.40^{+1.70}_{-1.70}$	$3.10(2.87^{+1.29}_{-0.80})$	$0.24(0.73)$	$0.31^{+1.33}_{-1.33}$
$t_h\tau_{\rm lep}\tau_{\rm had}$-2j	$4.81(5.85^{+2.90}_{-1.63})$	$-0.52(0.39)$	$-1.36^{+2.56}_{-2.56}$	$2.56(3.05^{+1.38}_{-0.85})$	$-0.48(0.69)$	$-0.66^{+1.38}_{-1.38}$
$t_h\tau_{\rm lep}\tau_{\rm had}$-3j	$2.78(2.79^{+1.36}_{-0.78})$	$-0.04(0.76)$	$-0.04^{+1.26}_{-1.26}$	$2.07(2.09^{+0.94}_{-0.58})$	$-0.05(0.98)$	$-0.04^{+0.98}_{-0.98}$
$t_l\tau_{\rm had}\tau_{\rm had}$	$1.41(0.63^{+0.29}_{-0.18})$	$2.64(3.24)$	$0.74^{+0.34}_{-0.34}$	$1.01(0.45^{+0.21}_{-0.13})$	$2.64(4.08)$	$0.53^{+0.25}_{-0.25}$
Leptonic Combination	$1.29(0.59^{+0.27}_{-0.17})$	$2.59(3.34)$	$0.68^{+0.32}_{-0.32}$	$0.92(0.42^{+0.19}_{-0.12})$	$2.59(4.23)$	$0.48^{+0.23}_{-0.23}$
Combination	$0.99\ (0.50^{+0.22}_{-0.14})$	$2.34(3.69)$	$0.51^{+0.25}_{-0.25}$	$0.72\ (0.36^{+0.17}_{-0.10})$	$2.31(4.49)$	$0.37^{+0.18}_{-0.18}$

FCNC g



ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
SR
Post-Fit
Data
cg → t FCNC
tq,t̄q
tt̄,tW,tb̄,t̄b
W+jets
Z+jets, VV
Multijet
Uncertainty
cg → t FCNC normalised to the observed upper limit
Events / 0.05
35000
30000
25000
20000
15000
10000
5000
0
0.7
0.75
0.8
0.85
0.9
0.95
1
D_1