$t\bar{t} + X$ and $t(\bar{t}) + X$ measurements in ATLAS and CMS

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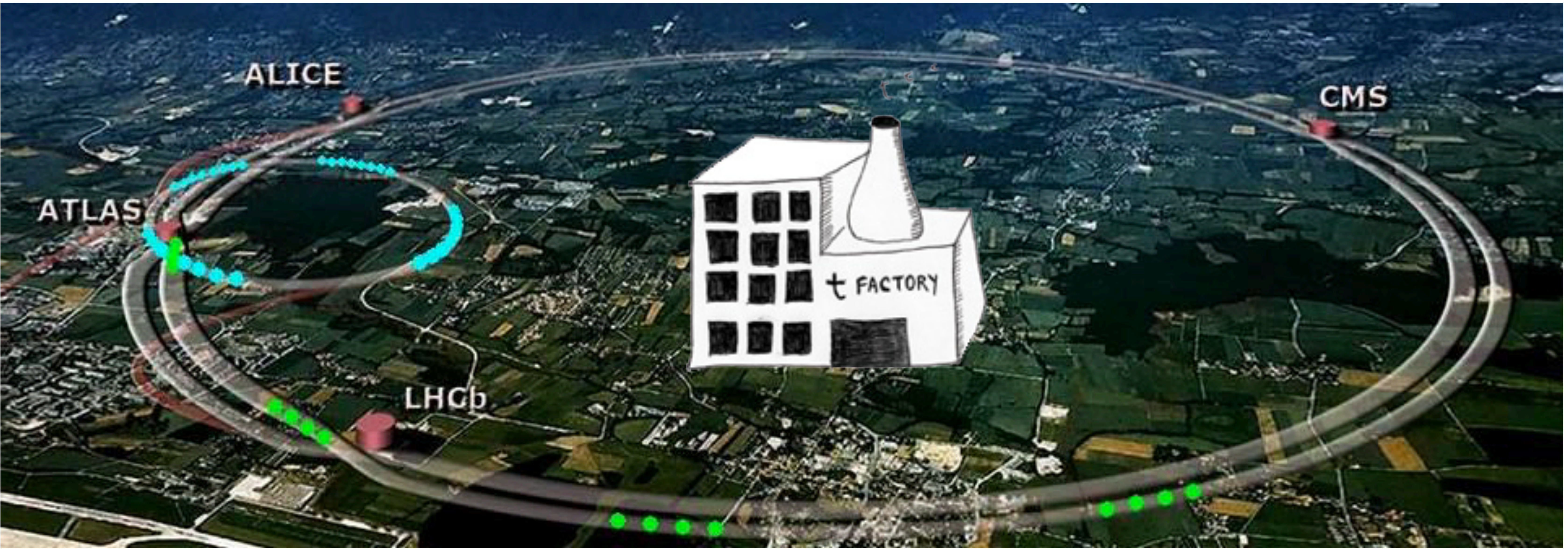
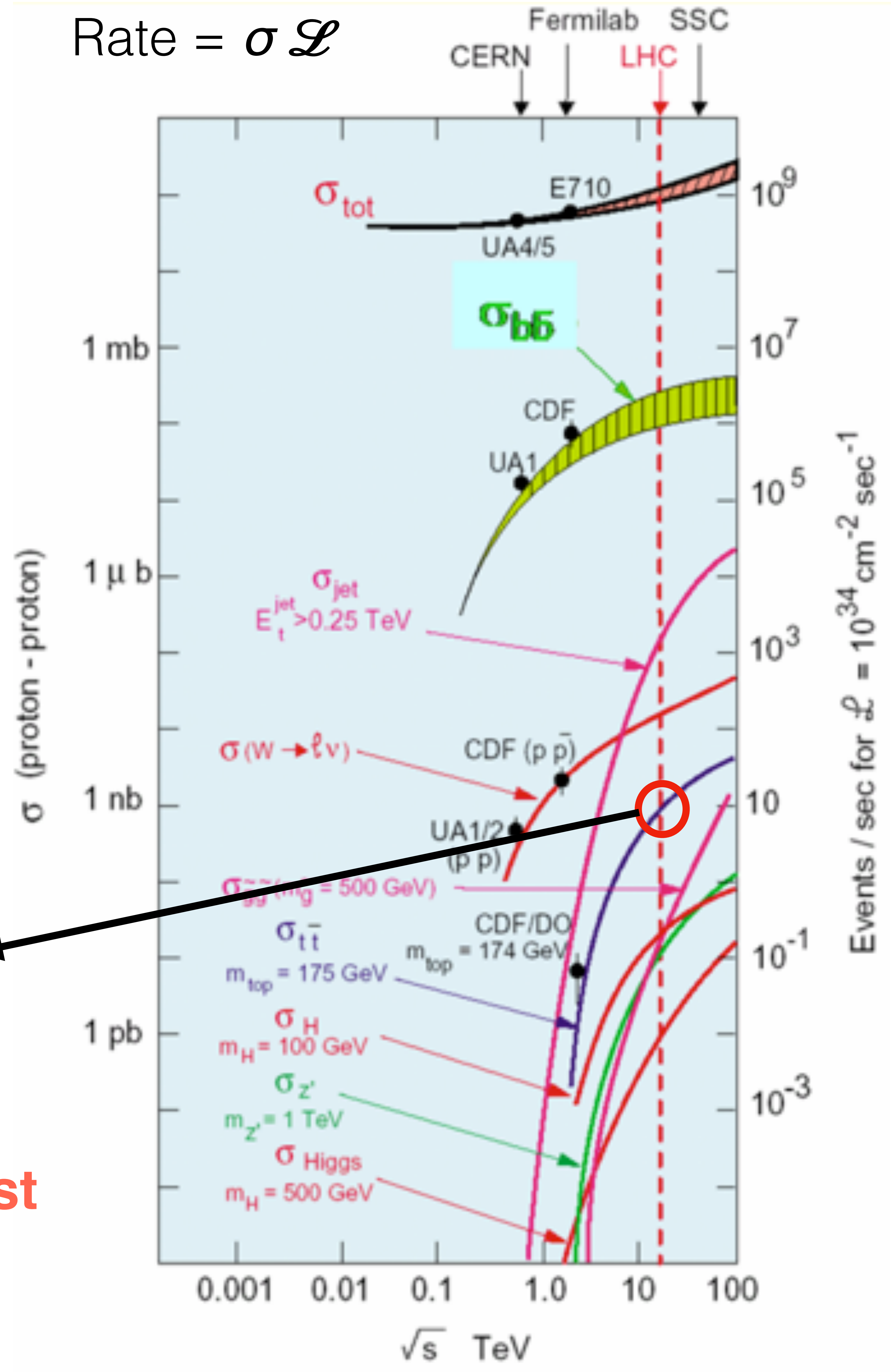
Moriond EW Session, 18-25 March, 2023

LHC - The *top quark* Factory

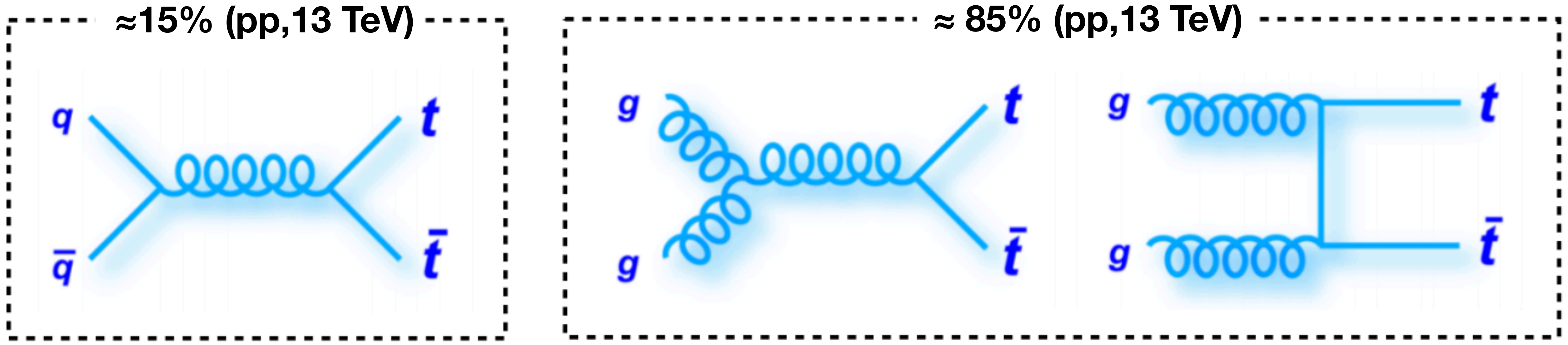




- Top quarks are produced in abundance at the LHC
- Dominant production modes:
  - ➢ $t\bar{t}$ production: ~120M events @10 Hz for $\sqrt{s} = 13$ TeV
  - ➢ Single $t(\bar{t})$ production ~ 40M events @1 Hz for $\sqrt{s} = 13$ TeV

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

$t\bar{t}$ production: inclusive



√s	$\sigma_{t\bar{t}}$ (NNLO + NNLL)
13 TeV	$833.9^{+29.4}_{-36.6}$ pb (4.4%)
13.6 TeV	$923.6^{+32.1}_{-40.4}$ pb (4.4%)

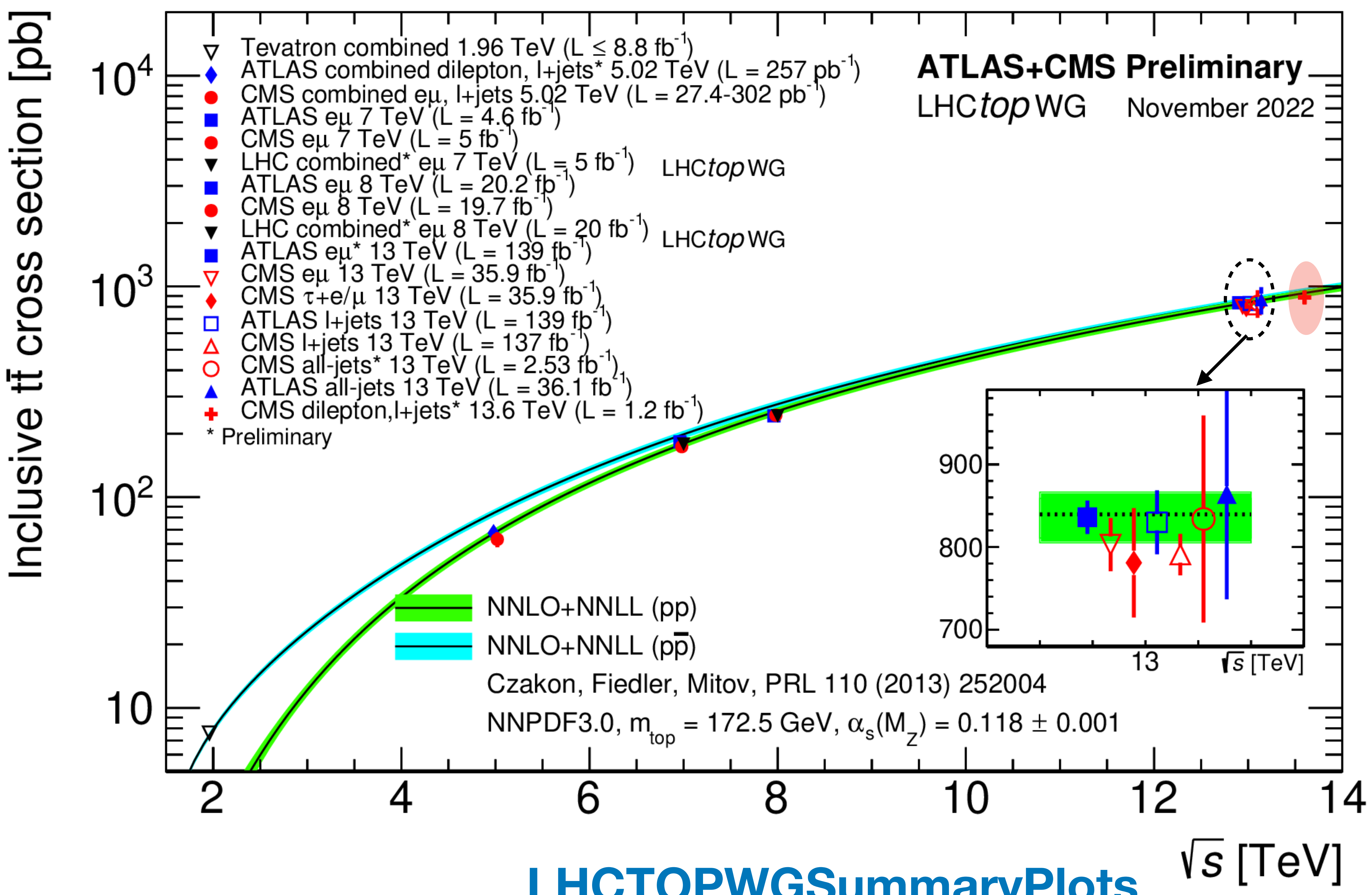
- Theo. unc. due to variations in μ_R & μ_F scales, PDF + α_S Ref.
- Most precise inclusive $\sigma_{t\bar{t}}$ at 13 TeV (TOPQ-2018-26) measured in the $e\mu$ final state

$$\sigma_{t\bar{t}} = 829 \pm 1 \text{ (stat)} \pm 13 \text{ (syst)} \pm 8 \text{ (lumi)} \pm 2 \text{ (beam) pb (1.8\%)}$$

- Dominant systematics:
  - ➢ Luminosity (0.93%)
  - ➢ top p_T reweighting (0.58%)
  - ➢ *tW* bkg. cross-section (0.52%)
  - ➢ *In situ* electron isolation (0.51%)
  - ➢ PDF (0.43%)

Covered in Joscha's talk

- $\sigma_{t\bar{t}} = 882 \pm 23 \text{ (stat + syst)} \pm 20 \text{ (lumi) pb @ 13.6 TeV}$
  → **first results with early Run3 data (CMS-TOP-22-012)**

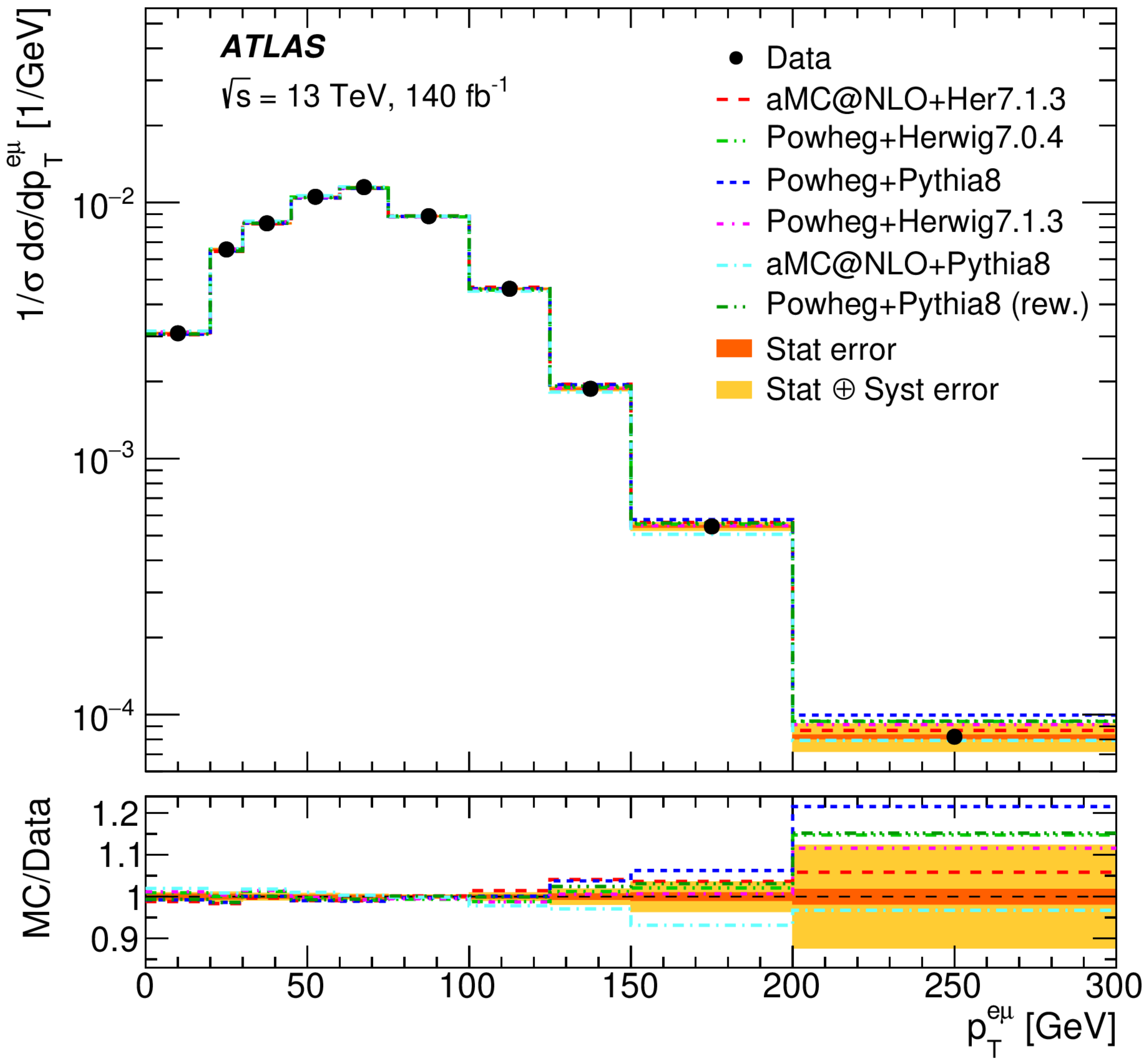


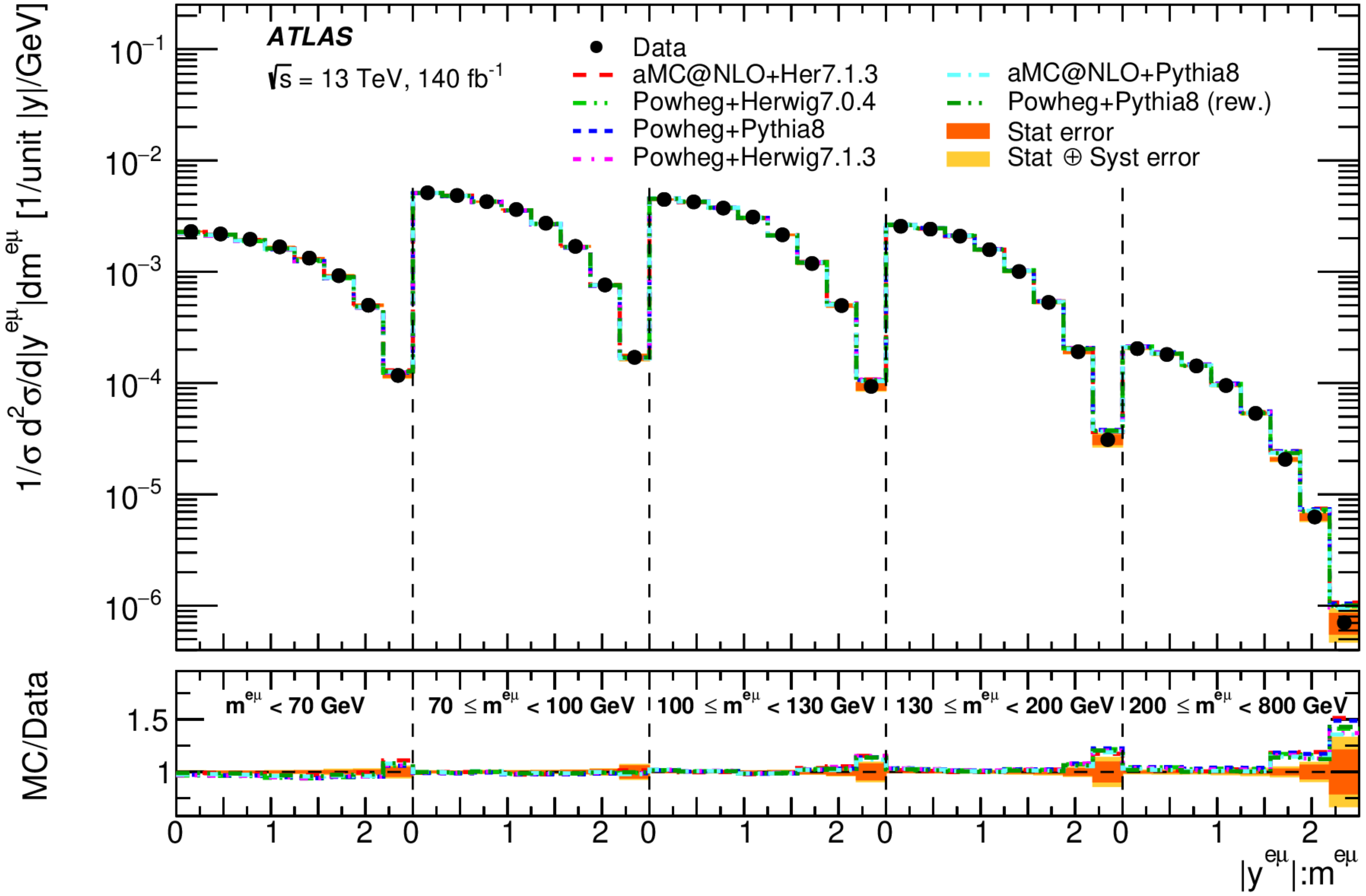
LHCTOPWGSummaryPlots

$t\bar{t}$ production: differential

- Single and double differential cross section measurements in the $e\mu$ final state
- 8 leptonic kinematic variables studied : $p_T^{\ell}, |\eta_\ell|, m_{e\mu}, p_T^{e\mu}, |y^{e\mu}|, E^e + E^\mu, p_T^e + p_T^\mu, \Delta\phi^{e\mu}$
- Data compared to various predictions
  → Good agreement observed except for the tails

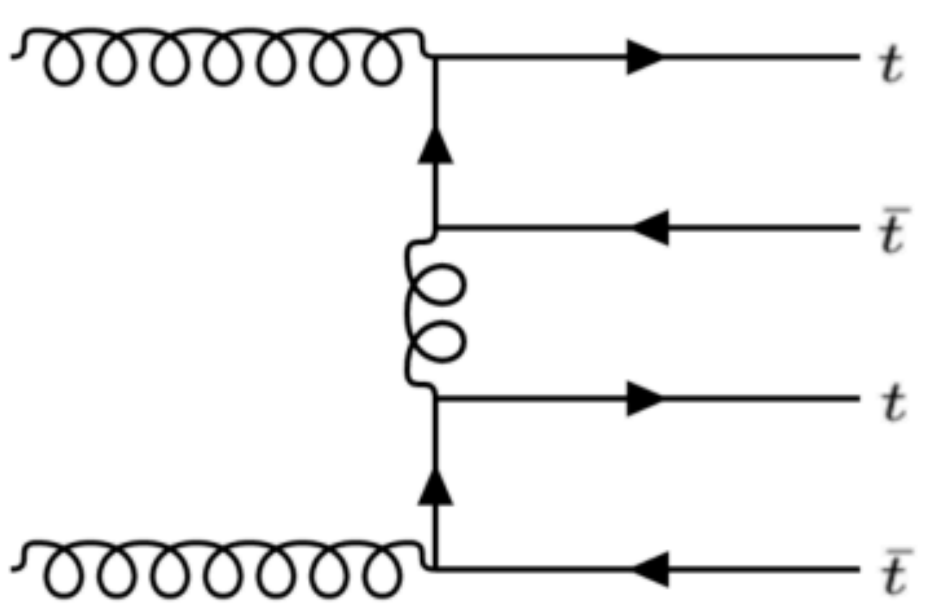
TOPQ-2018-26



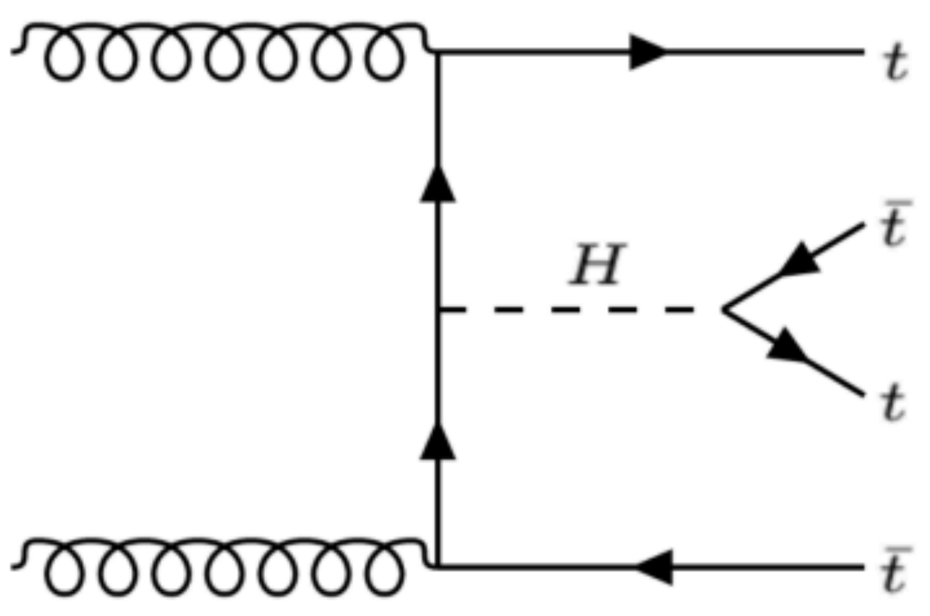


$t\bar{t}t\bar{t}$ production

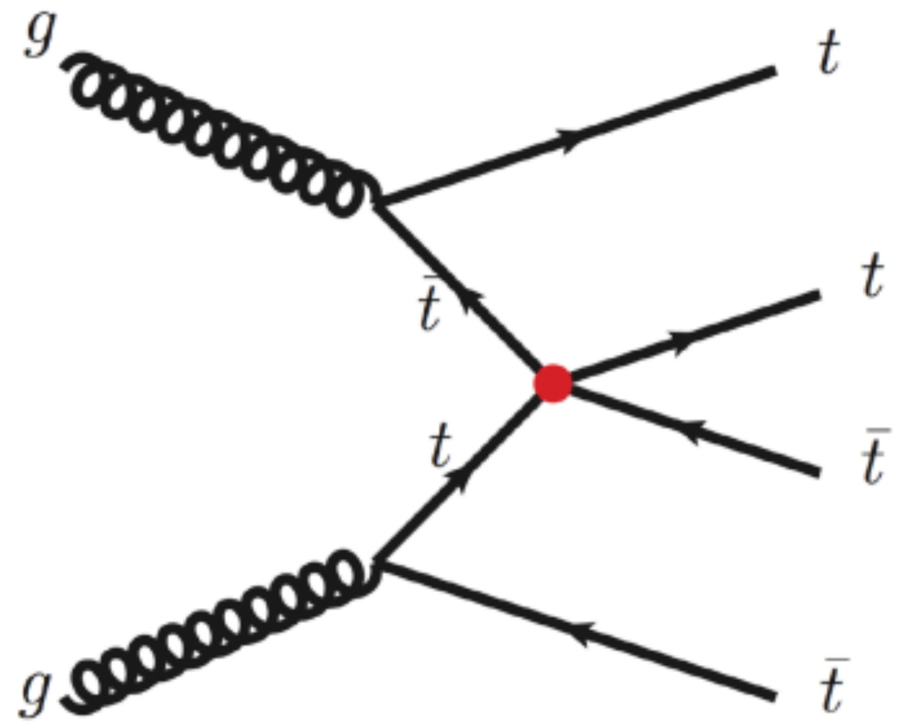
QCD



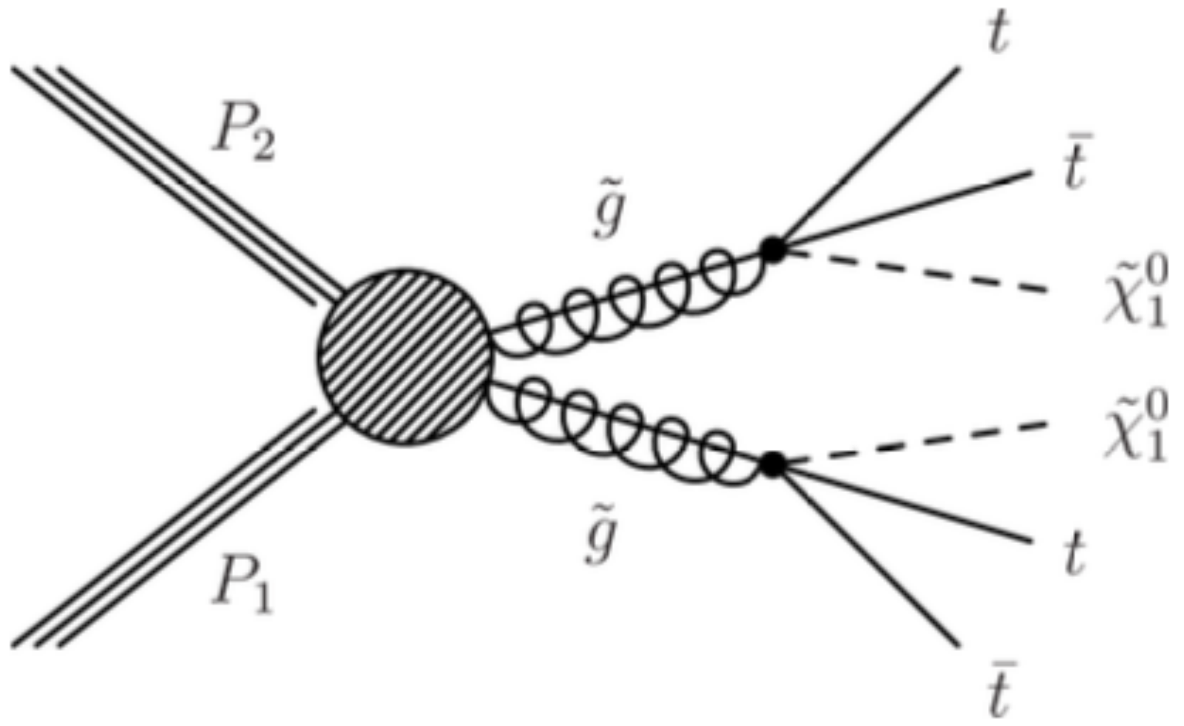
EWK



EFT four-fermion coupling

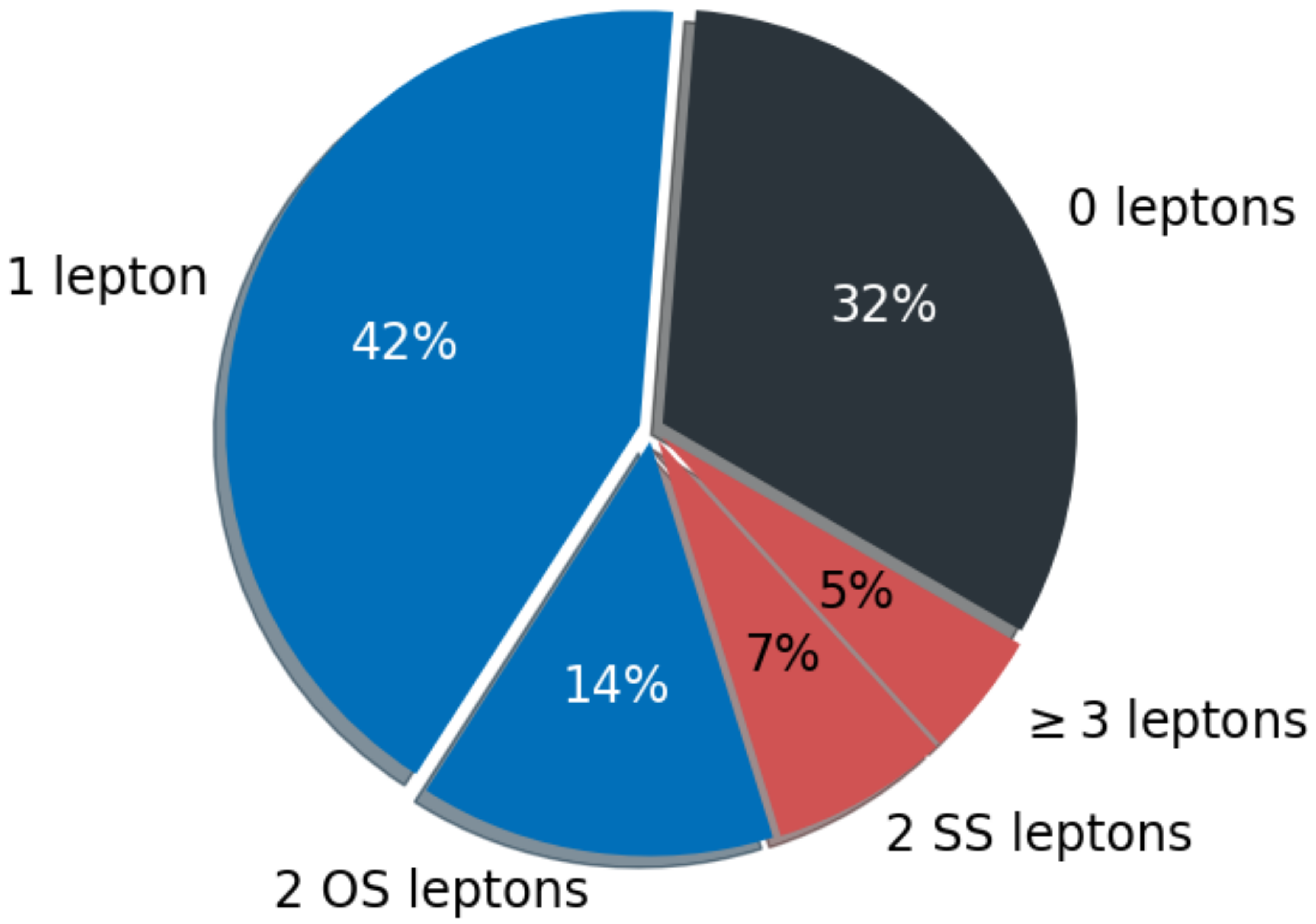


SUSY



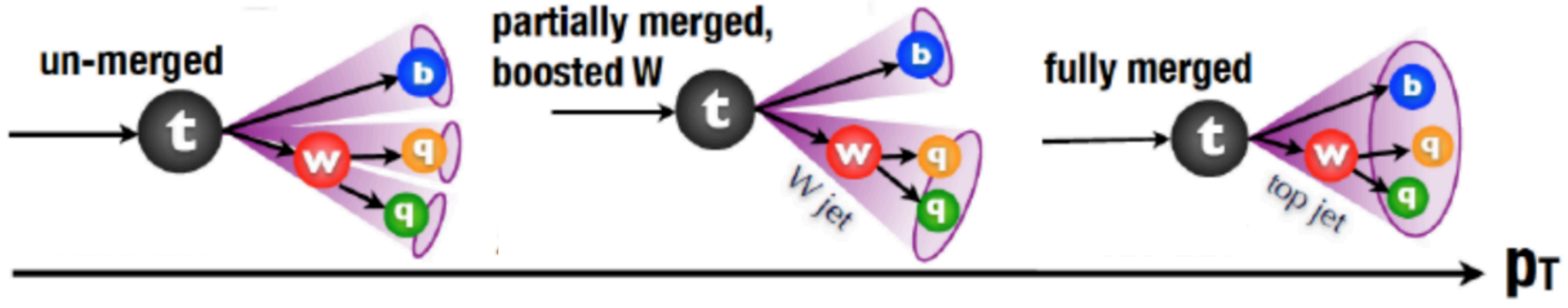
- NLO (QCD + EW) + NLL prediction: $\sigma_{t\bar{t}t\bar{t}} = 13.4^{+1.0}_{-1.8}\,\mathrm{fb}$ arXiv:2212.03259
- MVA techniques to extract signal in all final states

1ℓ or 2ℓOS	SSML : 2ℓSS or $\geq 3\ell$
Dominant bkg : $t\bar{t}$ + heavy flavor	Dominant bkg : $t\bar{t}V$
Negligible non-prompt ℓ	Significant non-prompt ℓ
limits on EFT couplings	limits on yukawa coupling



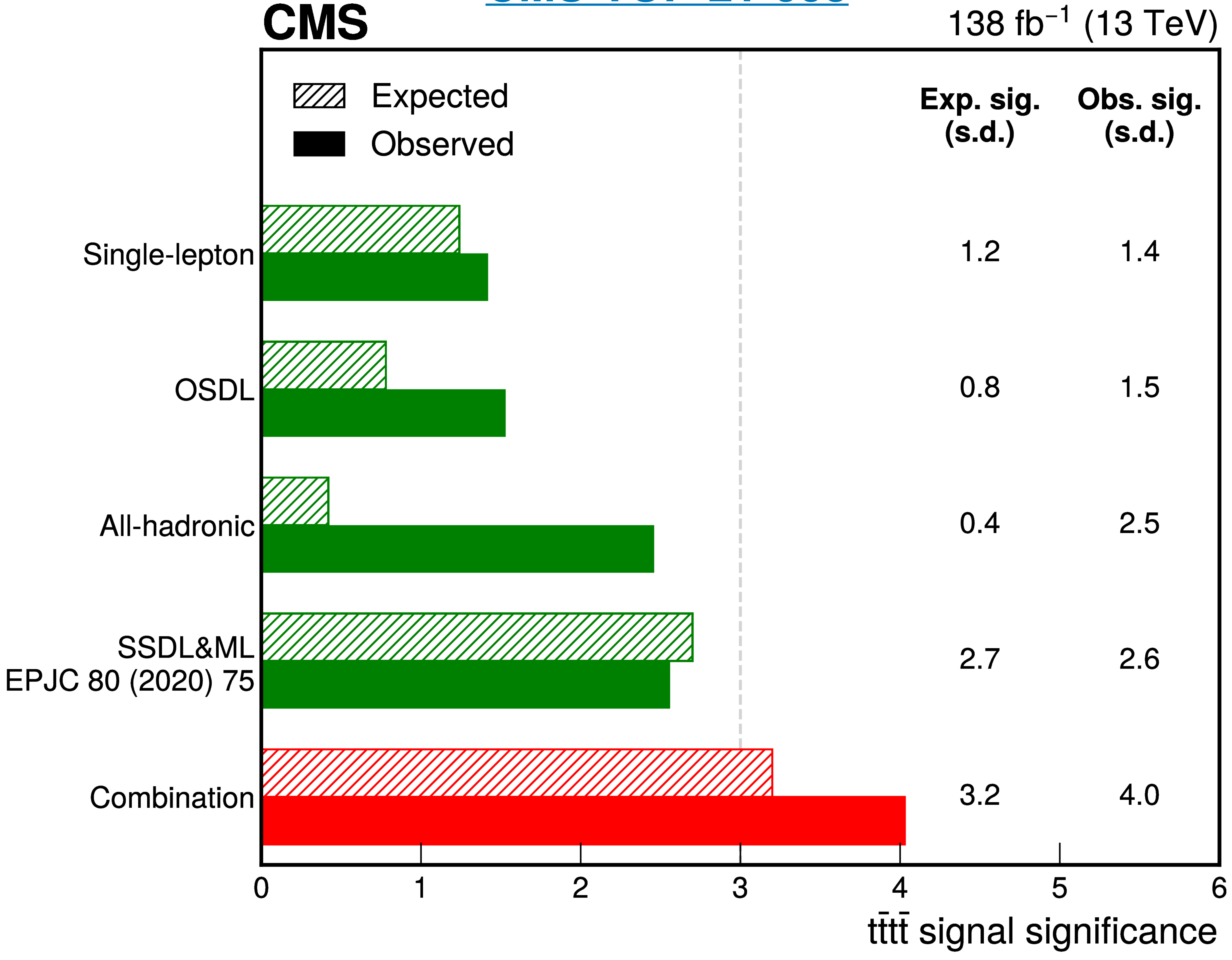
$t\bar{t}t\bar{t}$: all hadronic

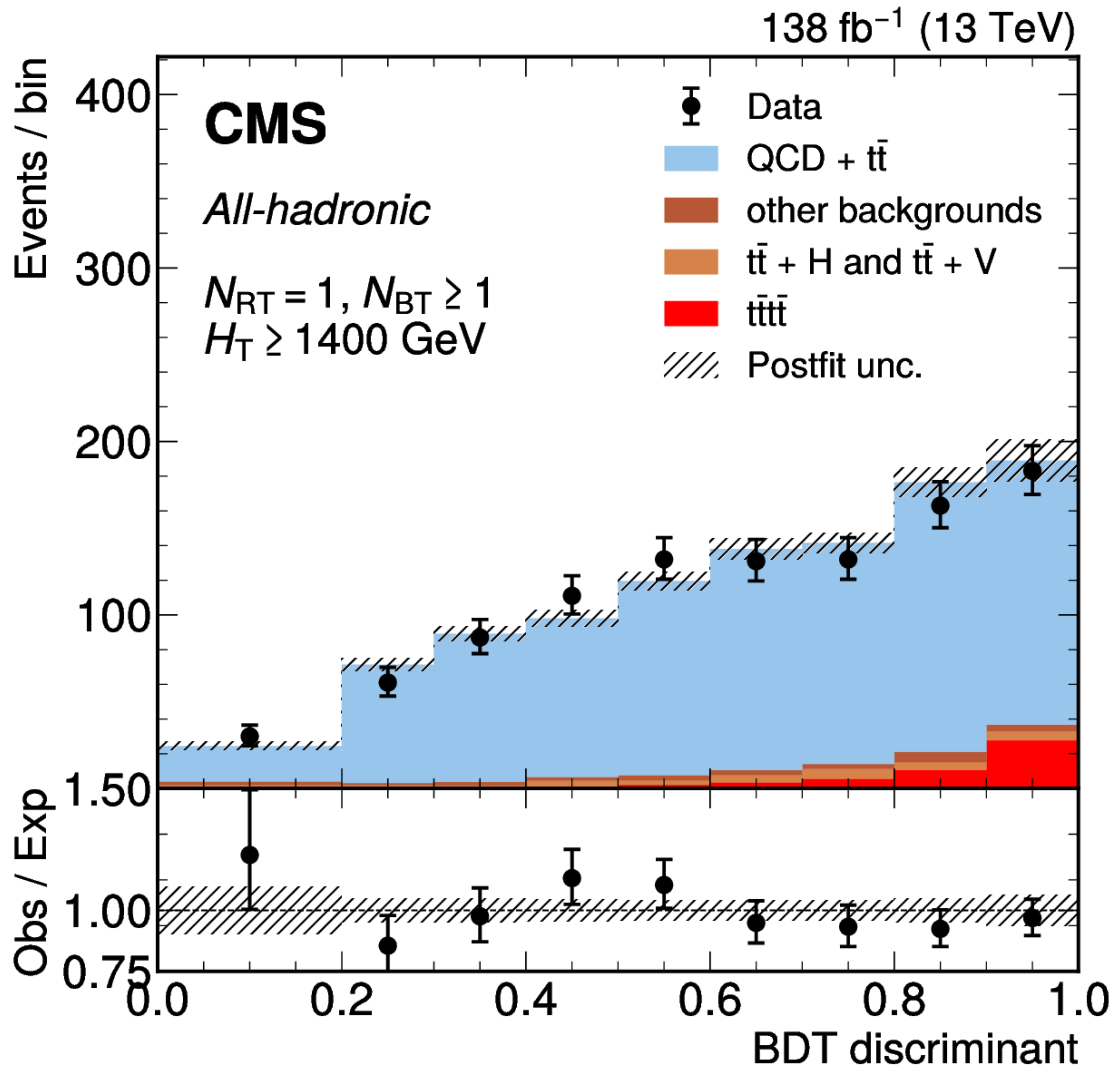
- ***First** time **all had.** channel used in 4-top searches!*
- SR divided based on resolved / boosted top candidates and H_T
- Data-driven estimation of QCD multijet and $t\bar{t}$ + jets bkgs. from CRs with different jet and b-tag multiplicities

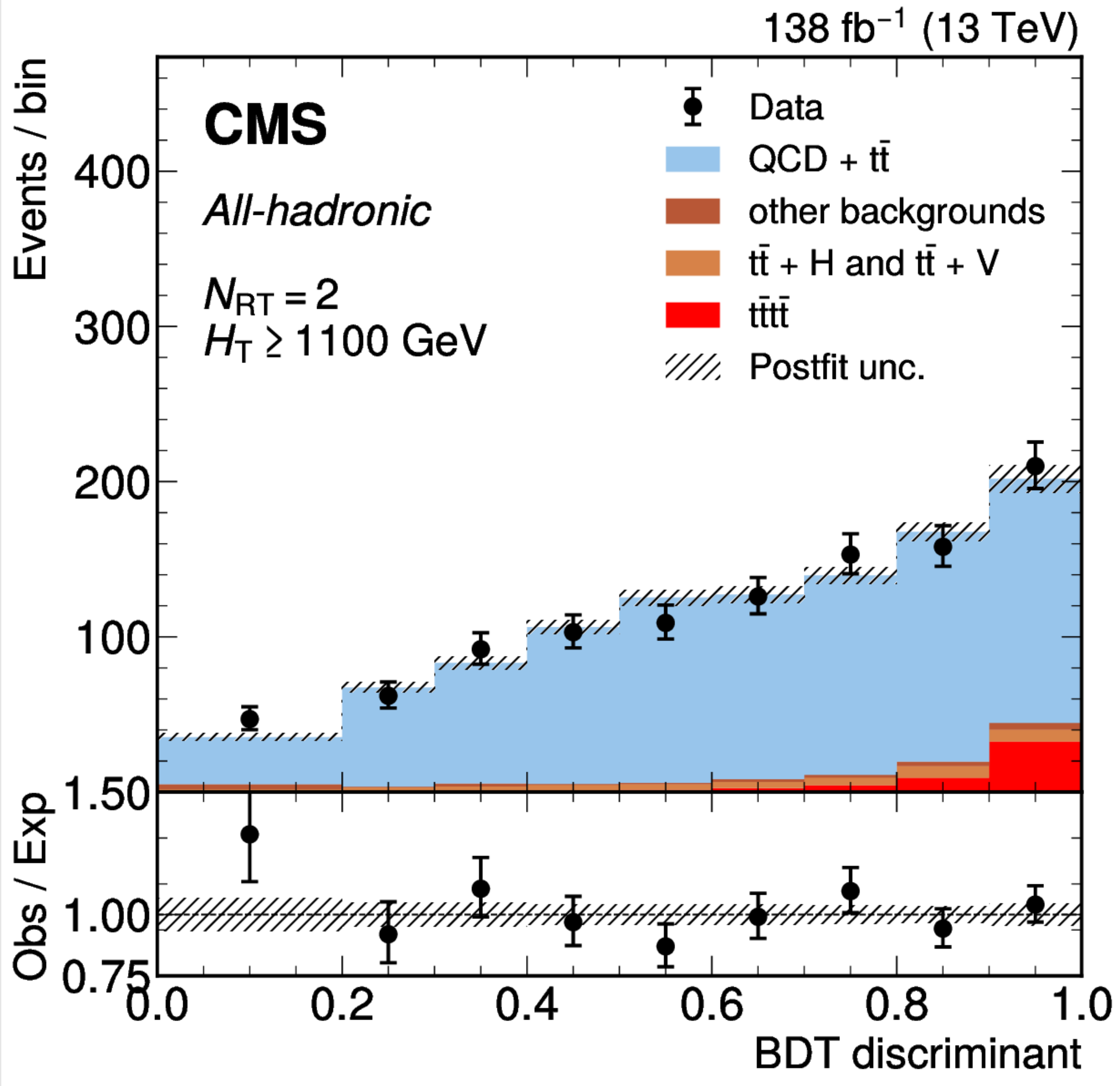


- Combination with results from other final states
  - ☞ $\sigma_{t\bar{t}t\bar{t}} = 17 \pm 4\ (\text{stat})\ \pm 3\ (\text{syst})\ \text{fb}$
  - ☞ **Observed** (**Expected**) significance : **4.0** (**3.2**) s.d.
  - ☞ **First *evidence* of 4tops production !!**

CMS-TOP-21-005





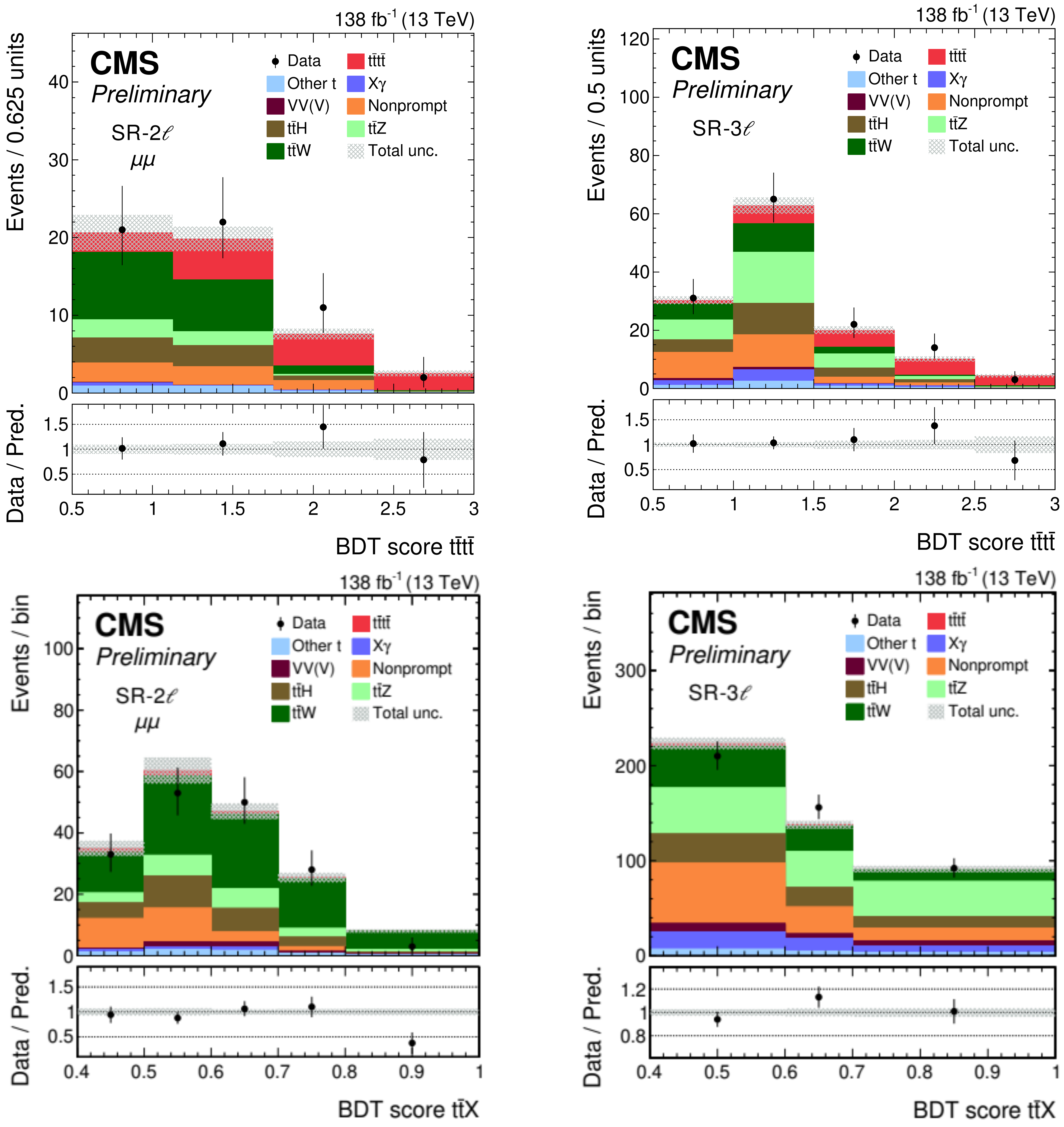


$t\bar{t}t\bar{t}$: SSML

New

CMS-PAS-TOP-22-013

- **New result** with *legacy reprocessing of Run2 data*
  - ☞ *MVA-based lepton Id.* to reject *fake lepton bkg.*
  - ☞ *DeepJet* over *DeepCSV* for *b-jet identification performance*
- Veto events with OSSF lepton pair within m_Z window to reject $t\bar{t}Z$ and multi-boson bkgs.
- Several event categories based on jet and b-tag multiplicities and H_T for better bkg. estimates
- Multi-classification using separate BDTs in the $2\ell SS$ and 3ℓ & 4ℓ channels
  - ☞ $t\bar{t}t\bar{t}-$like,
  - ☞ $t\bar{t}X-$like
  - ☞ $t\bar{t}-$like



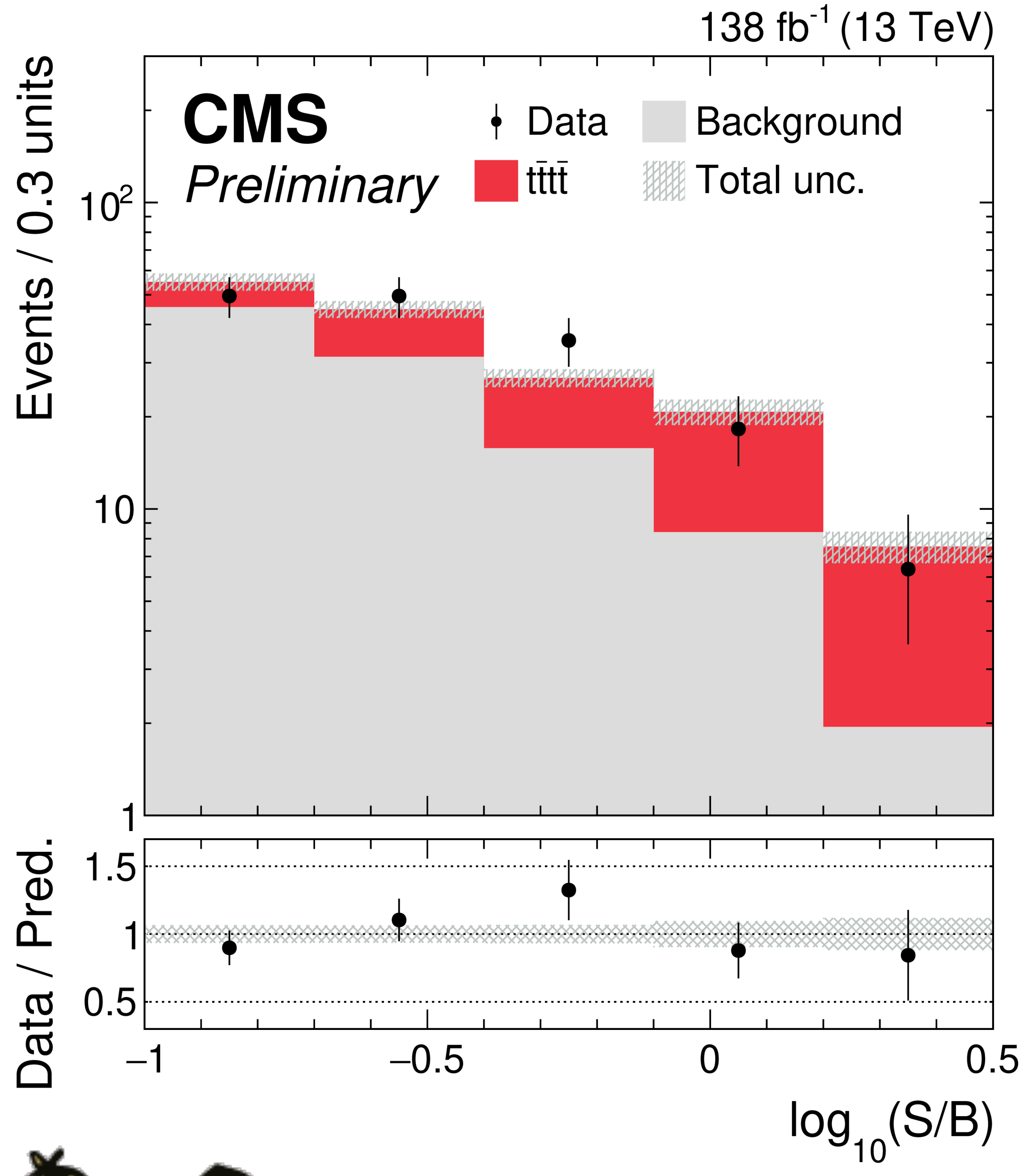
Observation of $t\bar{t}t\bar{t}$: SSML

$$\sigma(pp \to t\bar{t}t\bar{t}) = 17.9\,^{+3.7}_{-3.5}\,(\text{stat})\,^{+2.4}_{-2.1}\,(\text{syst})\,\text{fb},$$
$$\sigma(pp \to t\bar{t}W) = 997 \pm 58\,(\text{stat})\,^{+79}_{-72}\,(\text{syst})\,\text{fb},$$
$$\sigma(pp \to t\bar{t}Z) = 1134\,^{+52}_{-43}\,(\text{stat}) \pm 86\,(\text{syst})\,\text{fb}$$

- Measurement is limited by stat. unc.
- <u>Dominant syst :</u>
  ☞ $t\bar{t}X$ + bb, $t\bar{t}W$ + jj bkg. contribution, b-tagging calibration, $t\bar{t}t\bar{t}$ simulation model etc.

New

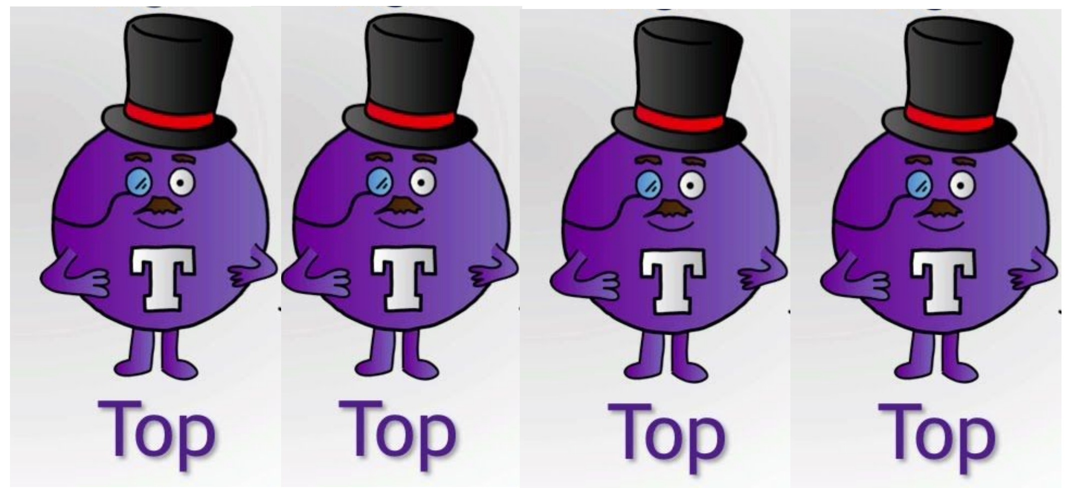
CMS-PAS-TOP-22-013



Channel	Obs. (exp.) significance	$\sigma(pp \to t\bar{t}t\bar{t})$
2ℓ	4.1 (4.1) s.d.	$17.6\,^{+4.7}_{-4.3}\,(\text{stat})\,^{+2.8}_{-2.7}\,(\text{syst})$ fb
3ℓ	3.5 (3.0) s.d.	$19.4\,^{+7.1}_{-6.4}\,(\text{stat})\,^{+2.9}_{-2.3}\,(\text{syst})$ fb
4ℓ	0.0 (0.8) s.d.	—
Combined	5.5 (4.9) s.d.	$17.9\,^{+3.7}_{-3.5}\,(\text{stat})\,^{+2.4}_{-2.1}\,(\text{syst})$ fb

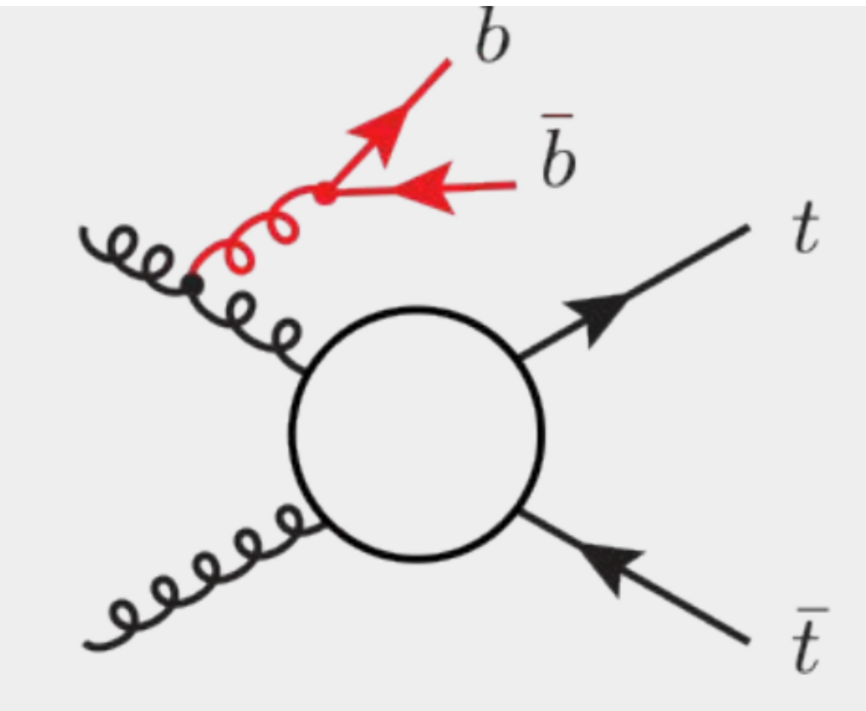
Observation !!

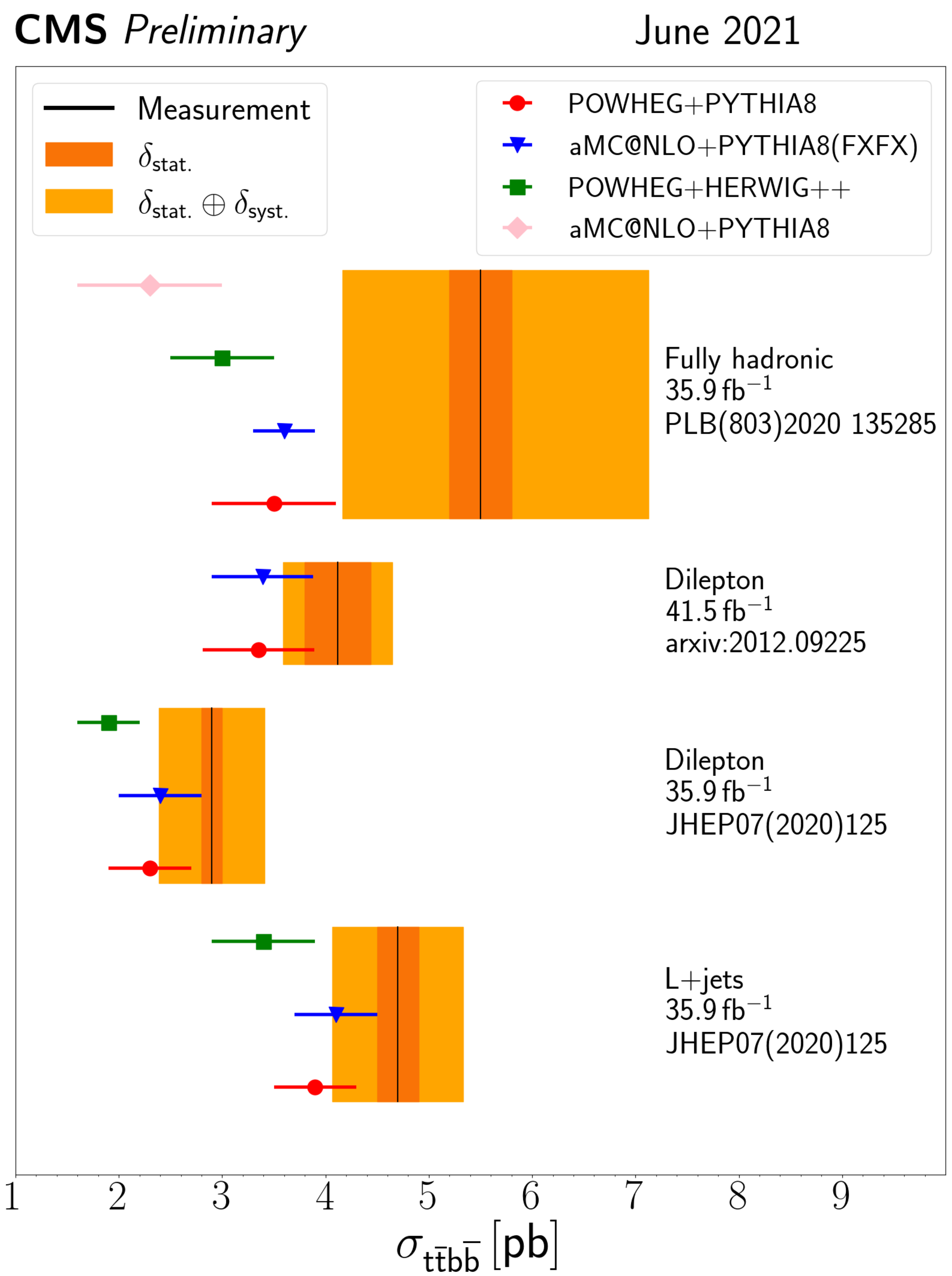
LHC Seminar from CMS on Tuesday, March 28



$t\bar{t}b\bar{b}$ production

- Irreducible bkg. to
  - ➢ $t\bar{t}H(b\bar{b})$
  - ➢ $t\bar{t}t\bar{t}$ (1ℓ and 2ℓOS final states)
- Multi-scale process
  - ➢ m_t ~ 172 GeV (*large*); m_b ~ 4 GeV (*non-negligible*)
  - ➢ challenging to model in simulation
- Different modeling approaches
  - ➢ $t\bar{t}b\bar{b}$ ME@NLO (additional b-jets from matrix element)
  - ➢ $t\bar{t}$ ME@NLO (additional b-jets from parton shower)
  - ➢ 4 vs 5-flavor schemes (massive vs. massless b-quarks in the initial state)
- Previous measurements reported higher cross sections than state-of-the-art predictions



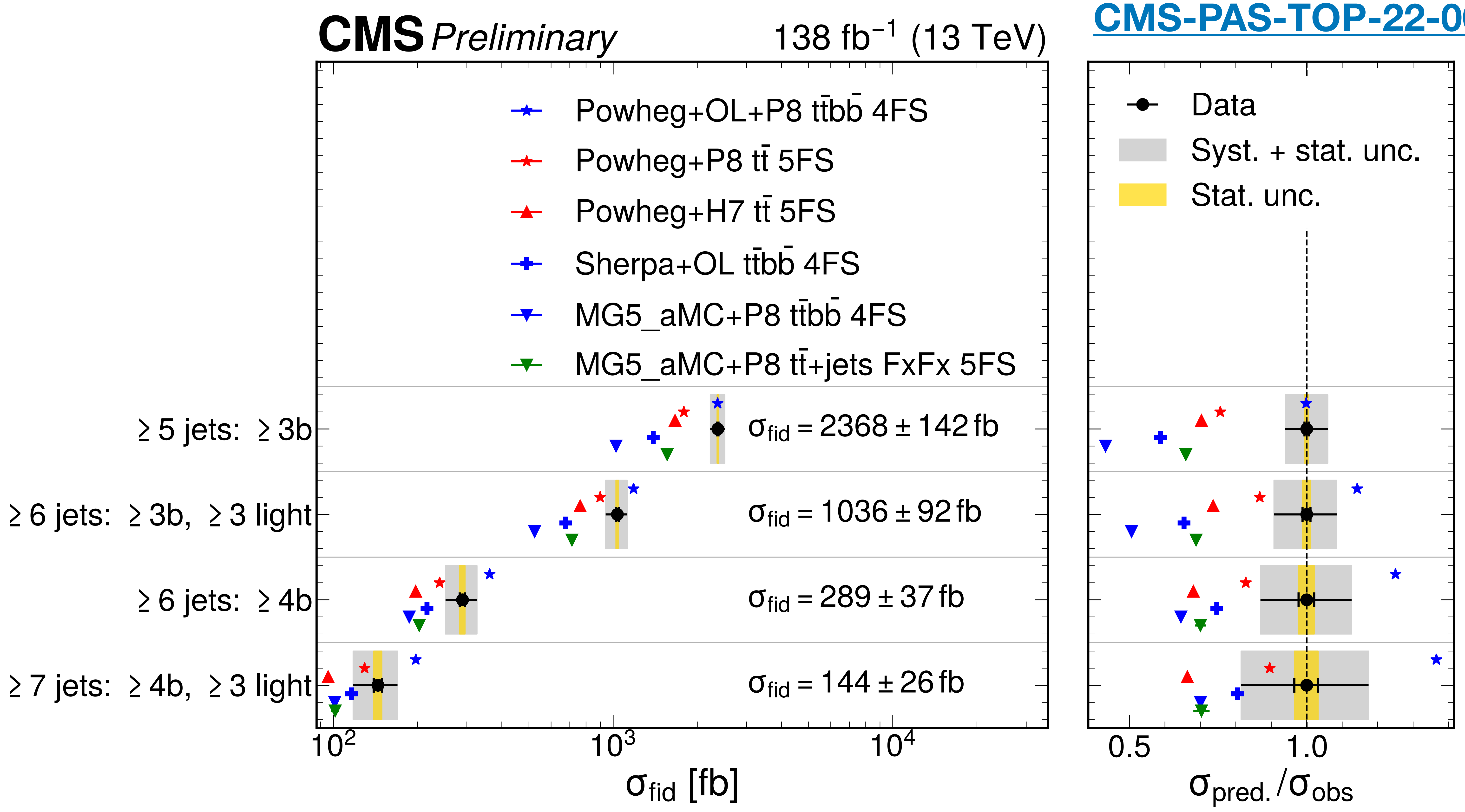


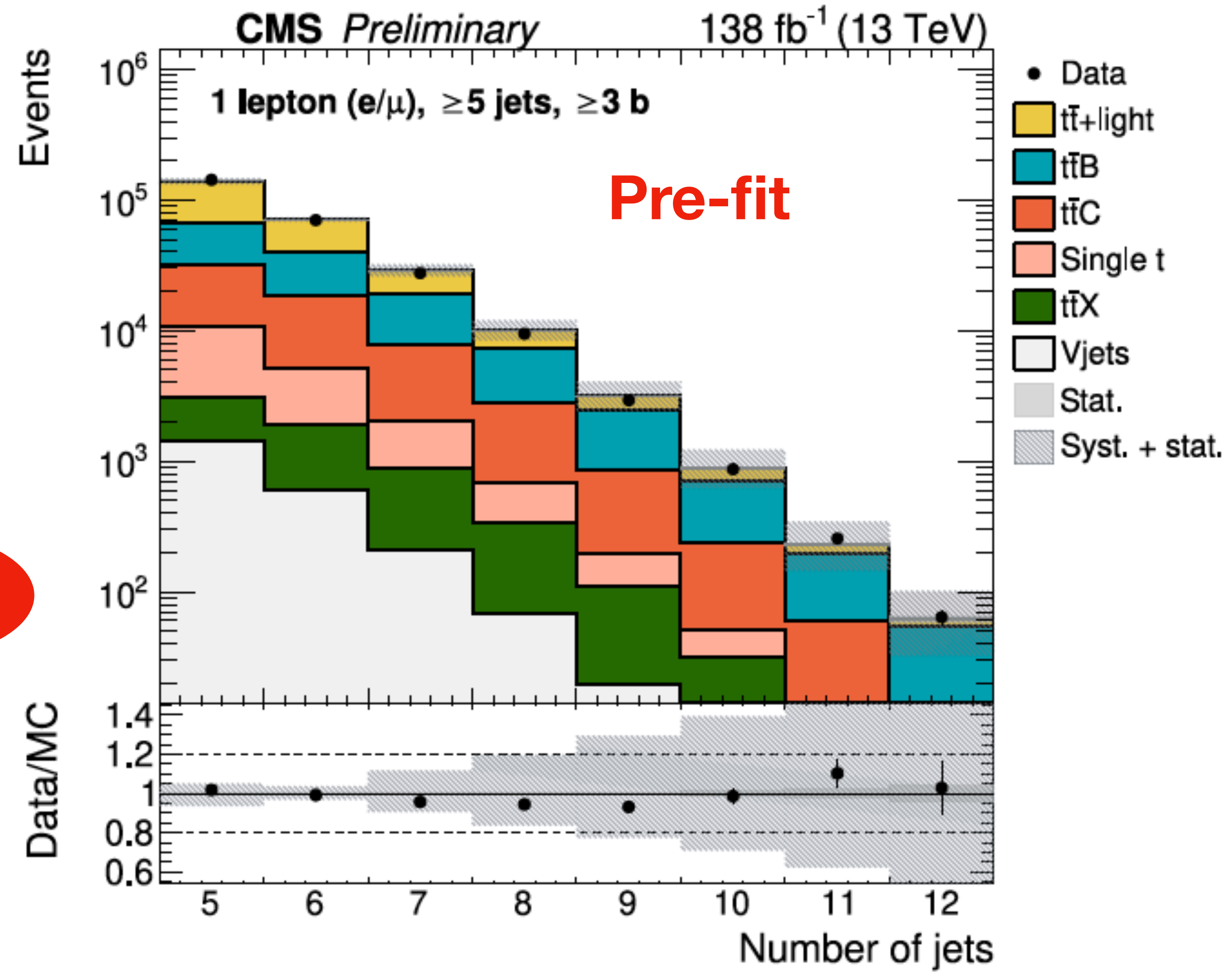
$t\bar{t}b\bar{b}$ production

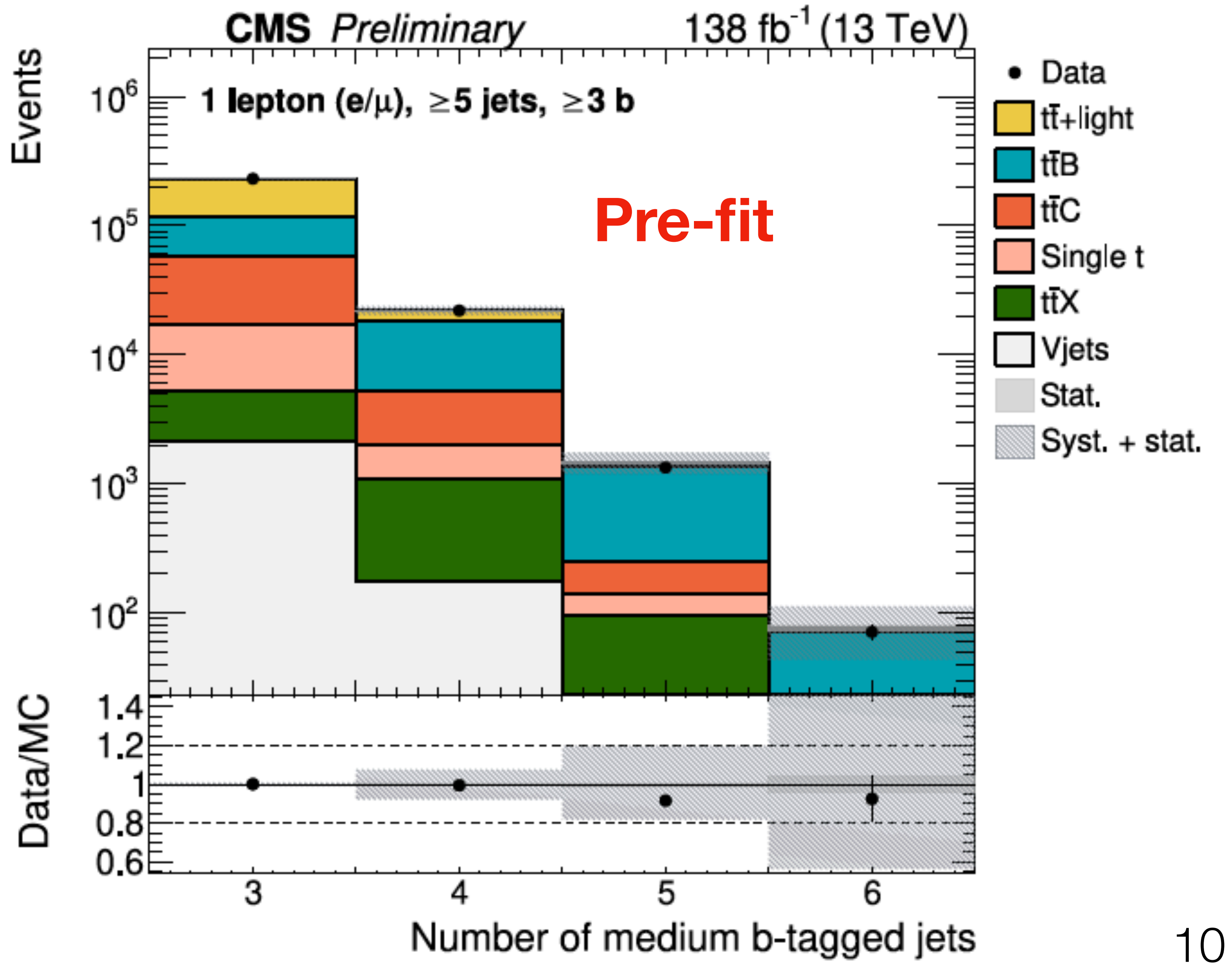
- New CMS measurement in $\ell +$ jets final state: $\geqslant 5$j, $\geqslant 3$b
- Fiducial and differential cross sections compared with various predictions
- Dominant syst. : μ_R scale, ISR/FSR model, b-tagging, jet energy scale etc.

New

CMS-PAS-TOP-22-009





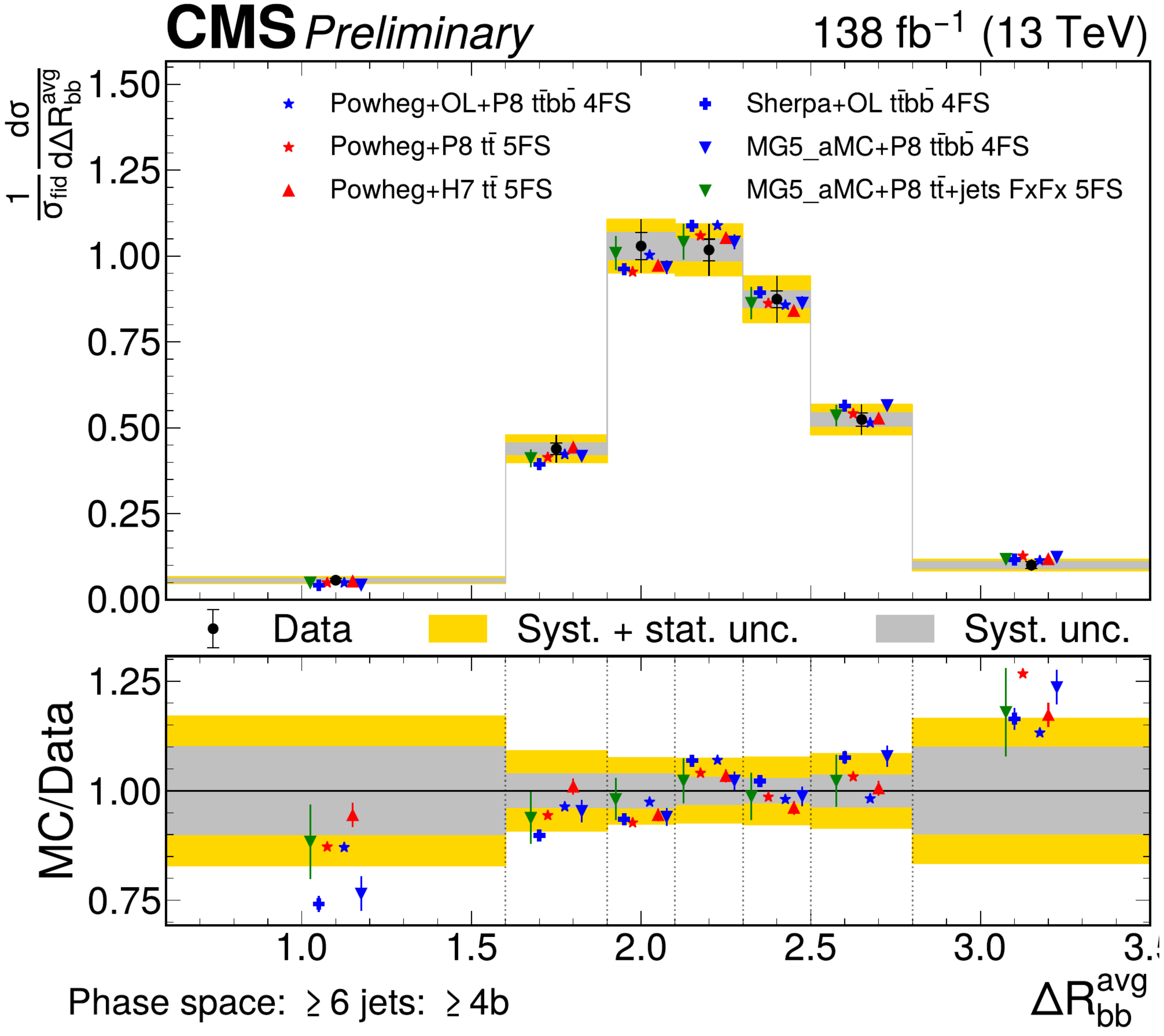


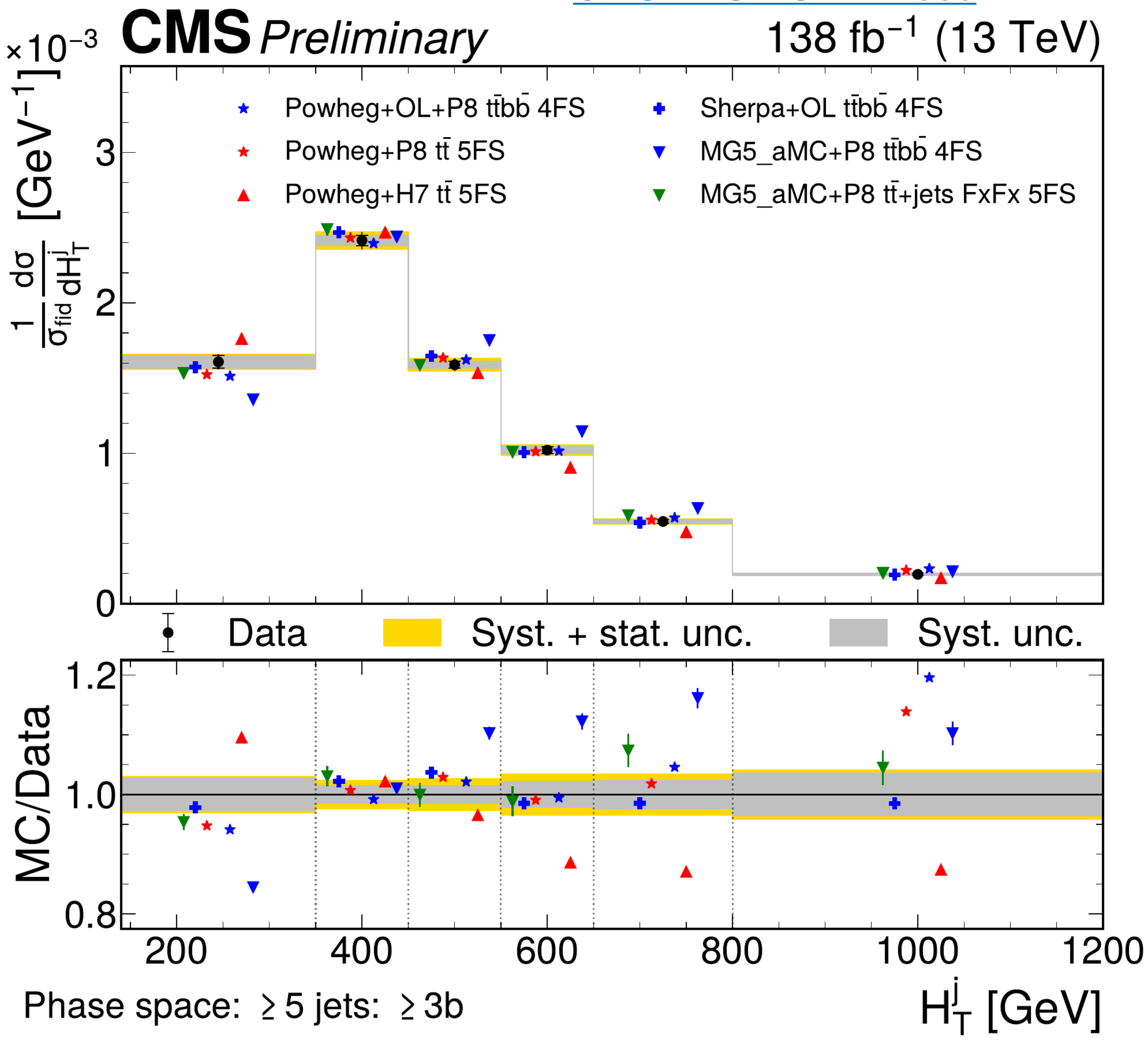
$t\bar{t}b\bar{b}$ production

Differential measurements performed using *maximum likelihood based unfolding technique*

New

CMS-PAS-TOP-22-009

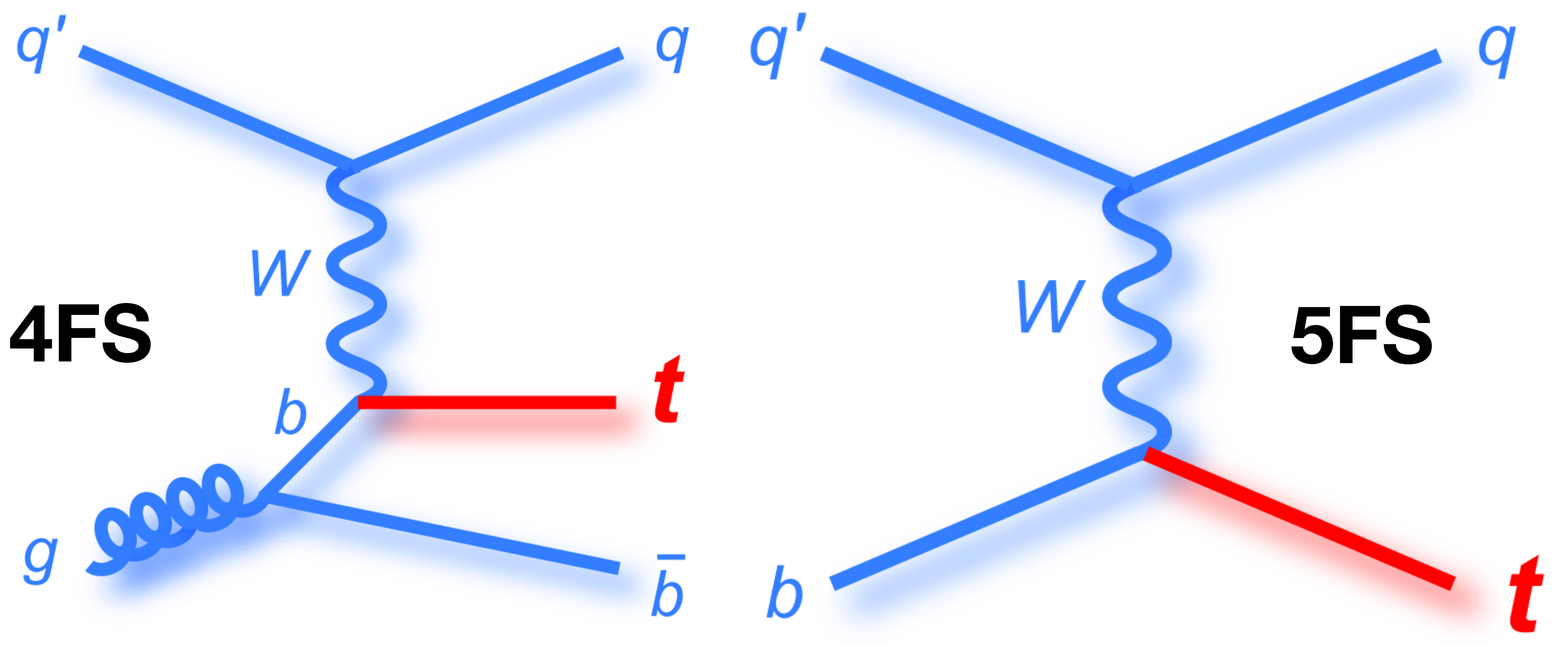




Single $t(\bar{t})$ production

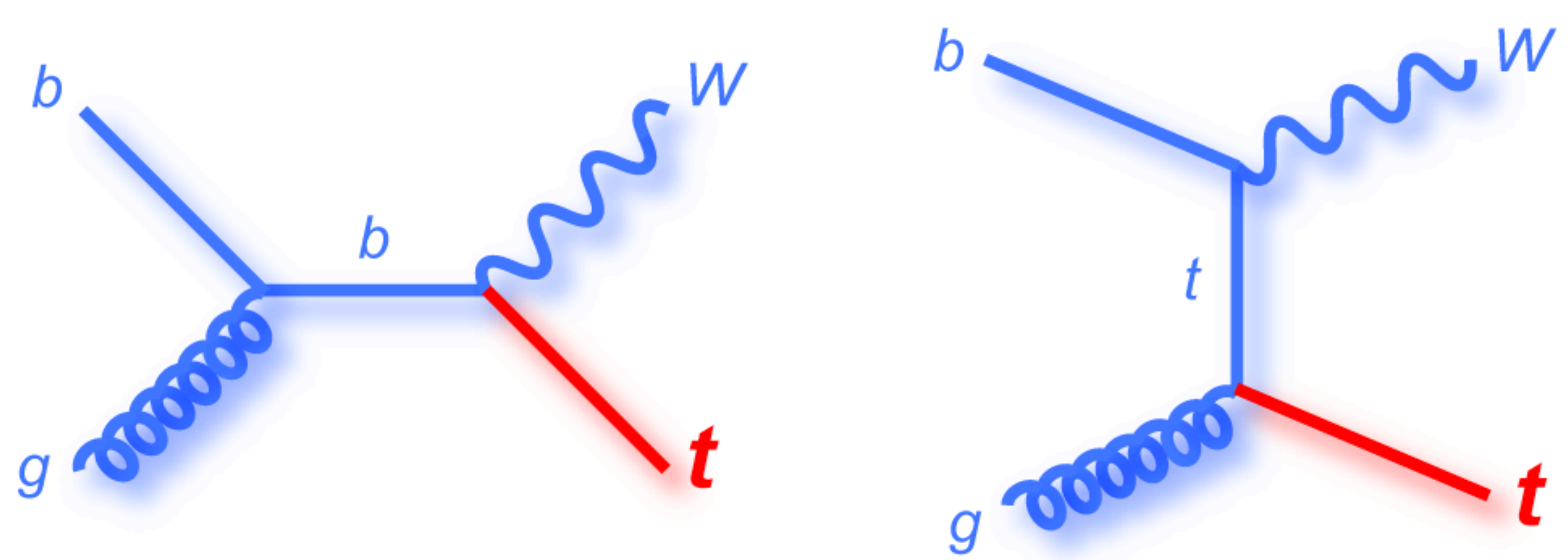
t-channel (~ 73% at LHC)

Golden Channel, sensitive to FCNC



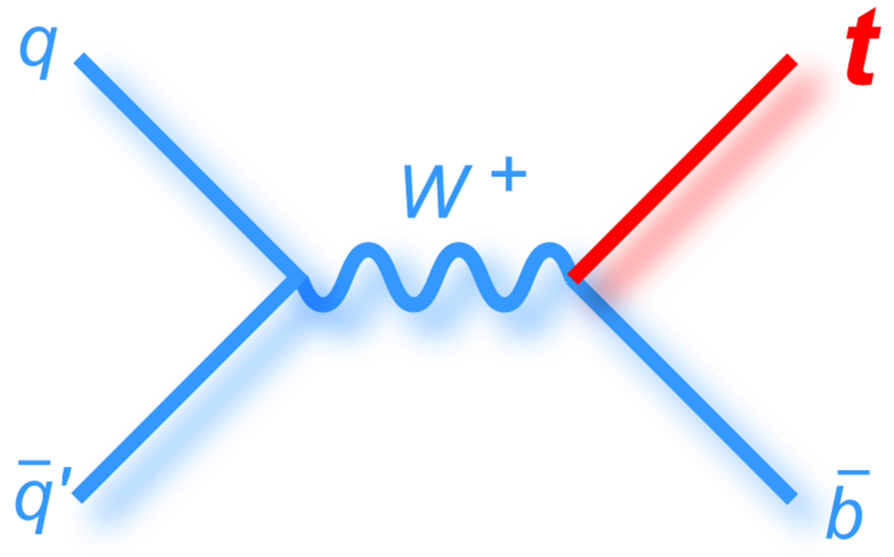
tW (~ 24% at LHC)

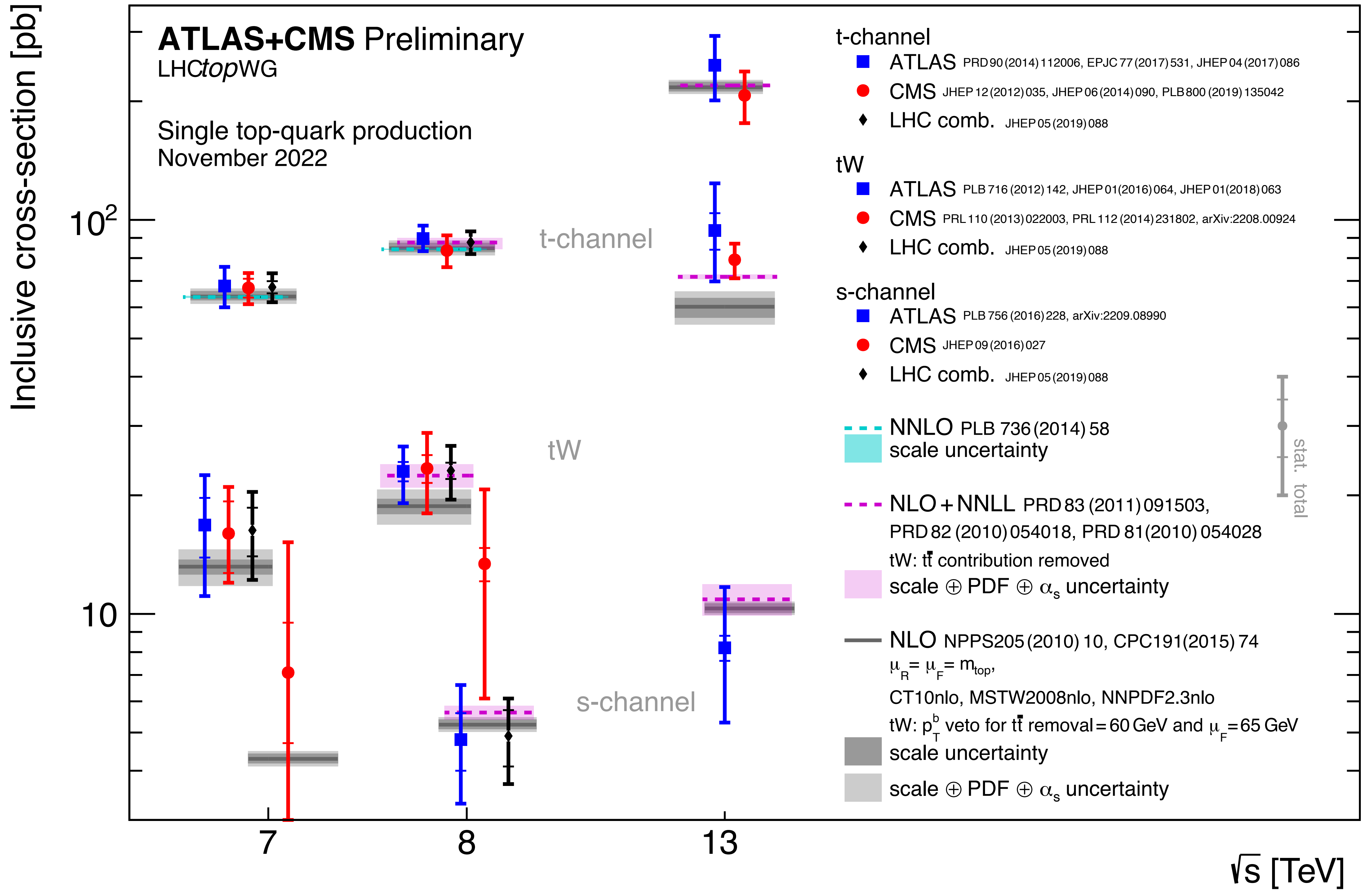
Observed at LHC, sensitive to BSM couplings



s-channel (~ 3% at LHC)

Challenging at LHC





LHCTOPWGSummaryPlots

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

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

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

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

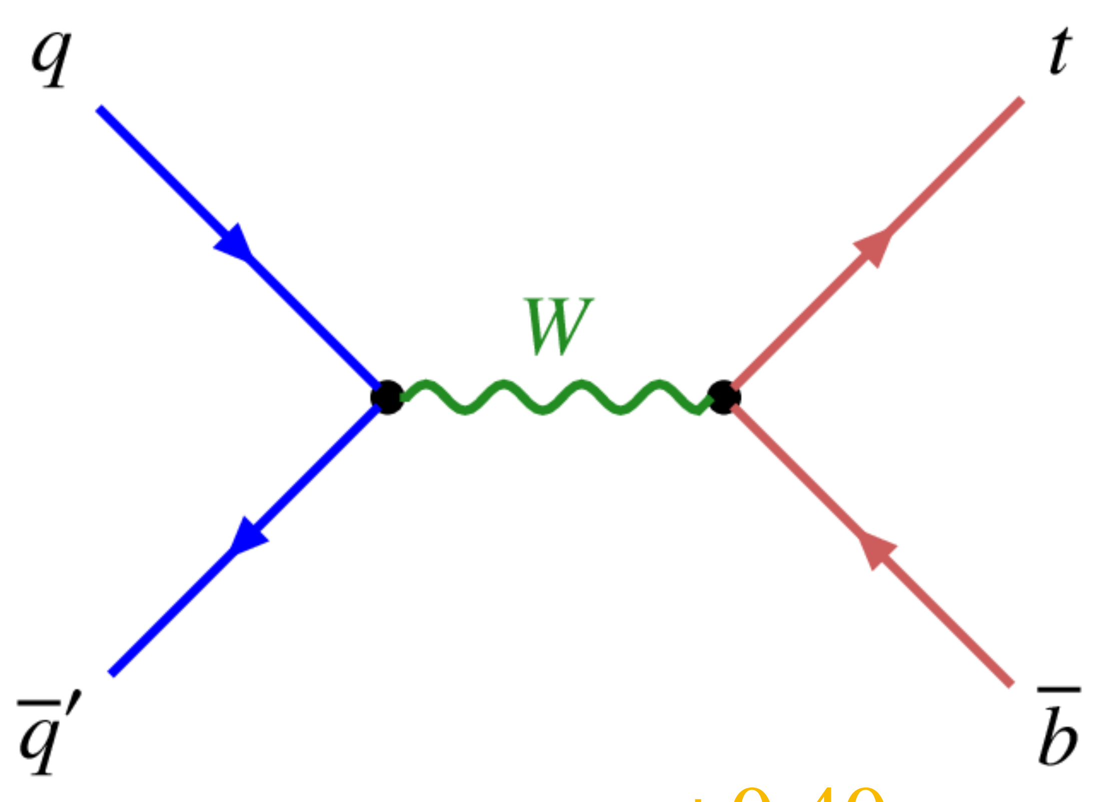
CMS-TOP-17-011

Evidence of s-ch. production

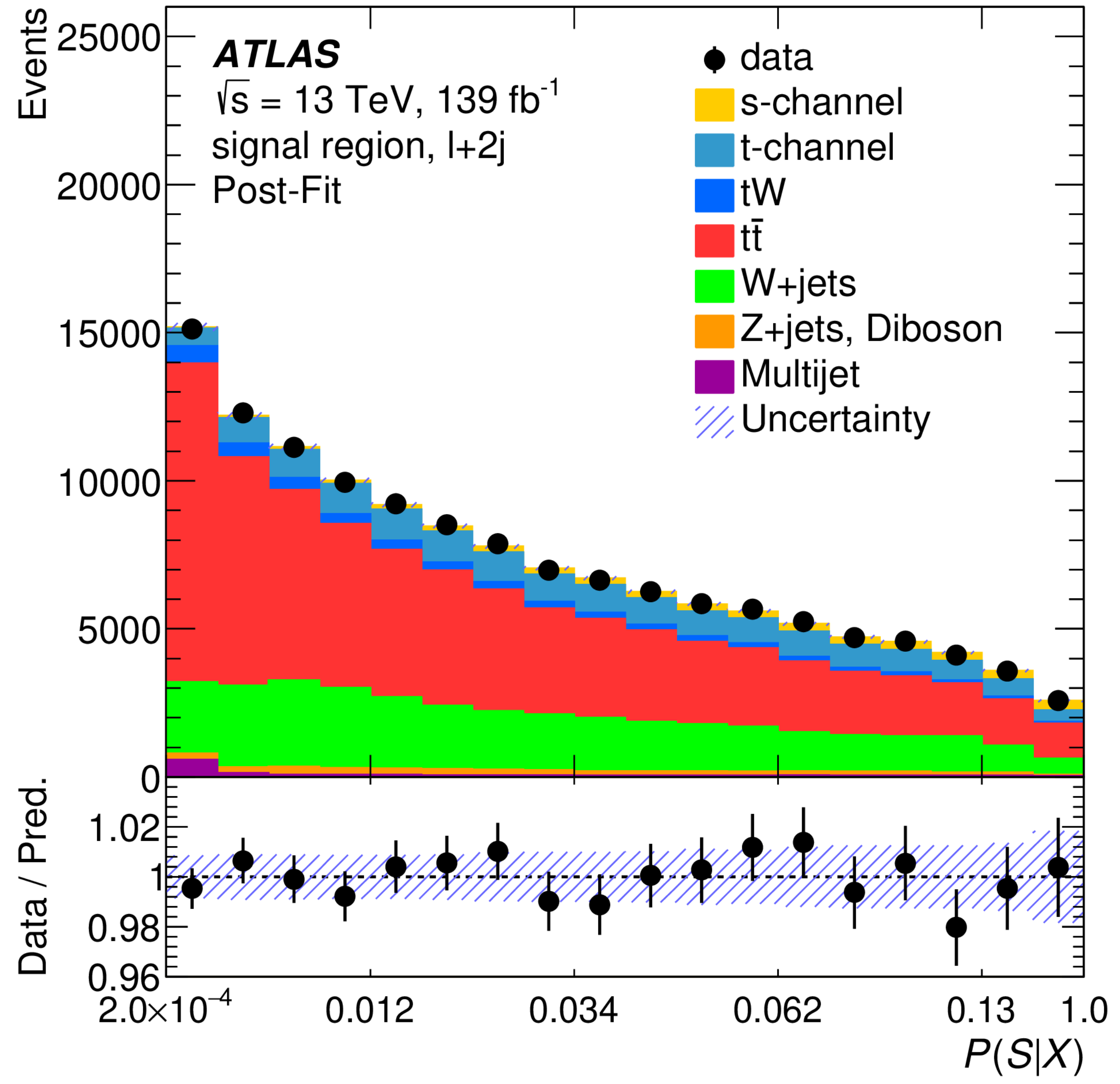
arXiv:2209.08990

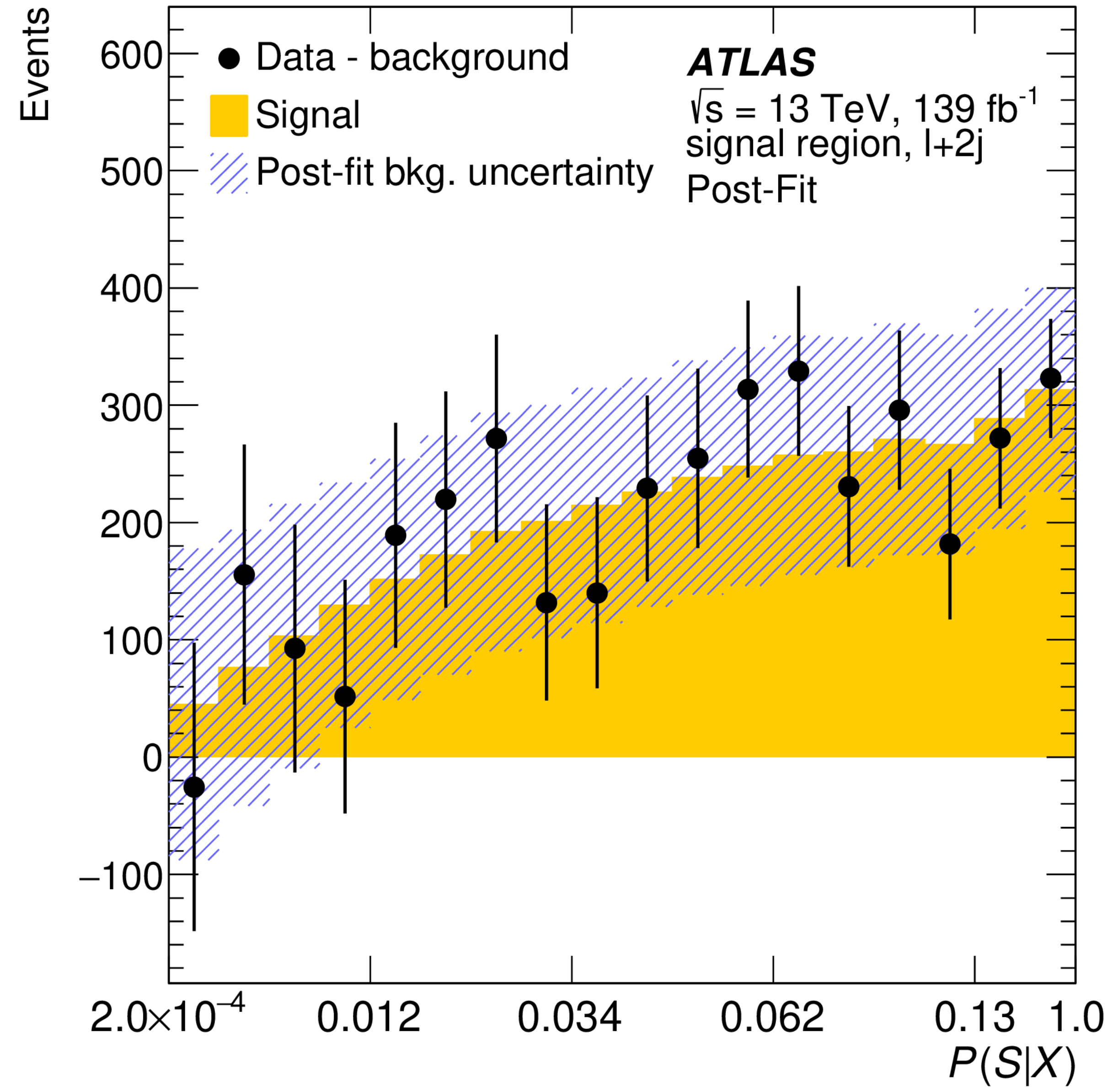
- Measurement in $1\ell +$ jets final state

SR	W + jets CR	$t\bar{t}$ CR
2 jets	2 jets	≥ 3 jets
2 tight b	1 tight b, 1 loose b	≥ 2 tight b



$\sigma_{SM} = 10.32^{+0.40}_{-0.32}$ pb

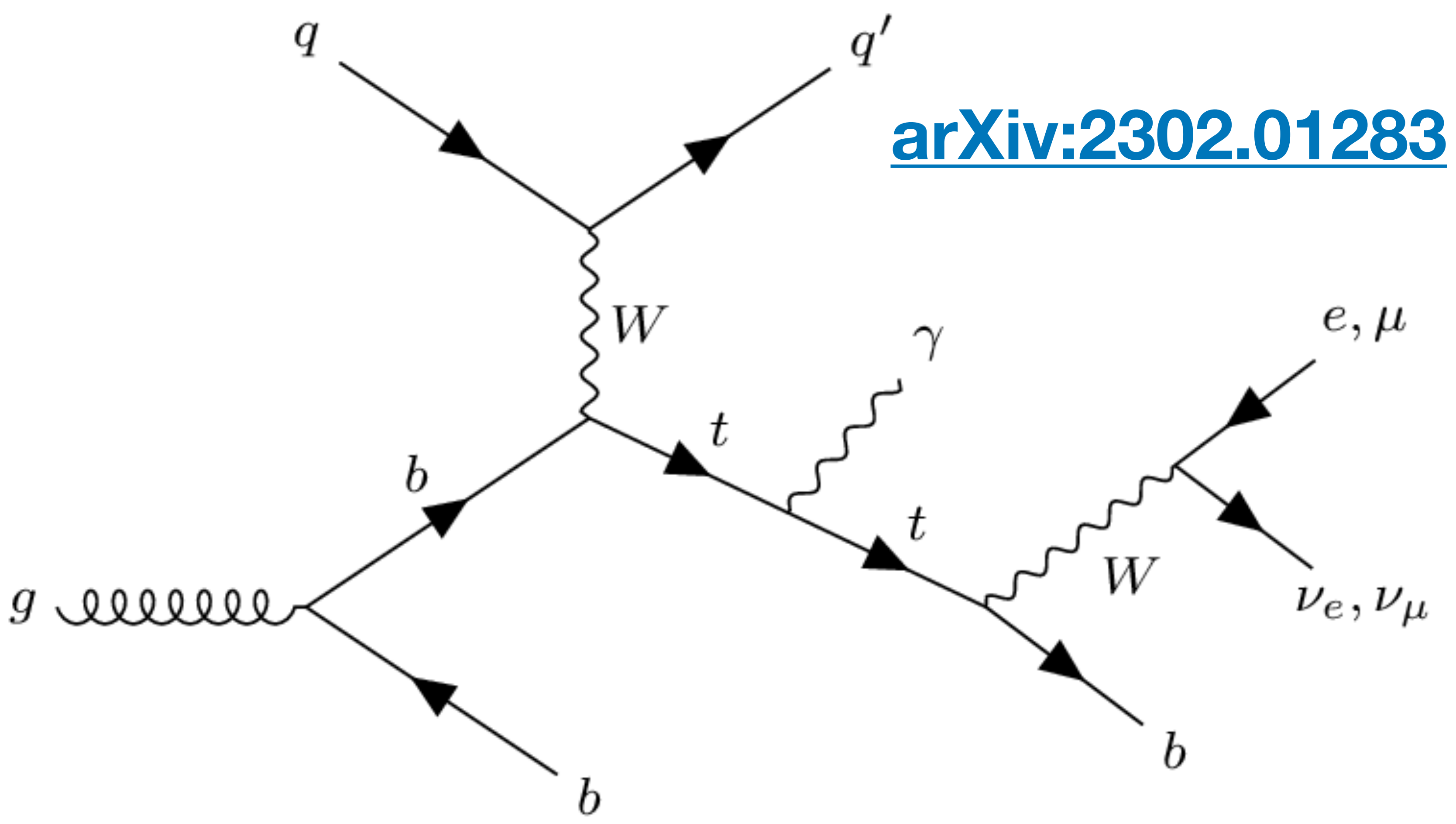




- Data-driven QCD multijet bkg. estimation using $m_T^W(E_T^{miss})$ for $\mu(e)$
- Matrix-element-method to derive *signal probability* per event : ***P(S|X)***
- $\sigma_{s-\mathrm{ch.}} = 8.2 \pm 0.6\ (\mathrm{stat})\ ^{+3.4}_{-2.8}\ (\mathrm{syst})\ \mathrm{pb} = 8.2^{+3.5}_{-2.9}\ \mathrm{pb}$
- **Observed** (**Expected**) signal significance over bkg.-only hypothesis : **3.3** (**3.9**) s.d.
- Dominant unc. sources: $t\bar{t}$ norm., signal and $t\bar{t}$ simulation model, jet energy scale, jet energy resolution etc.

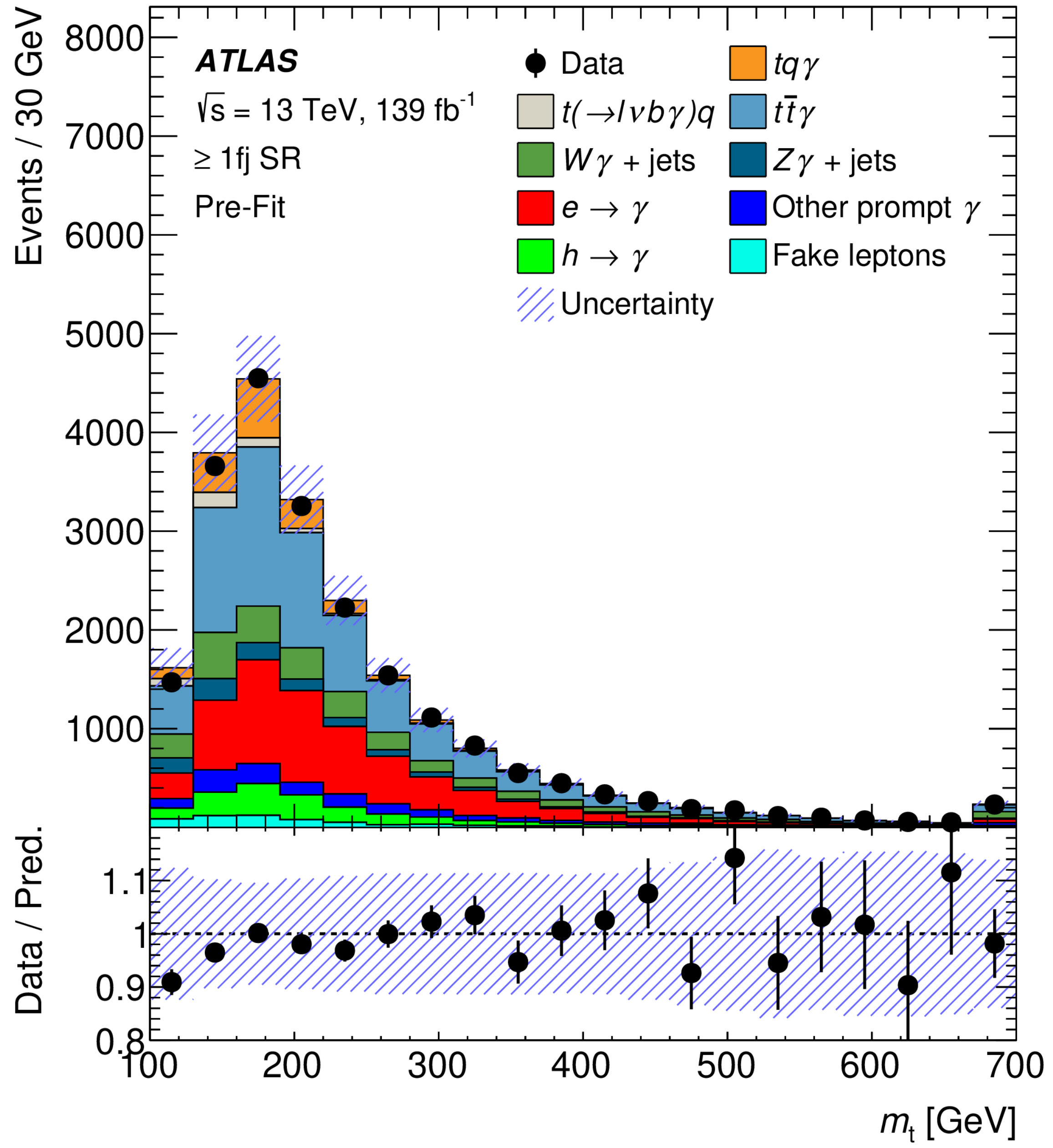
Observation of $tq\gamma$ production

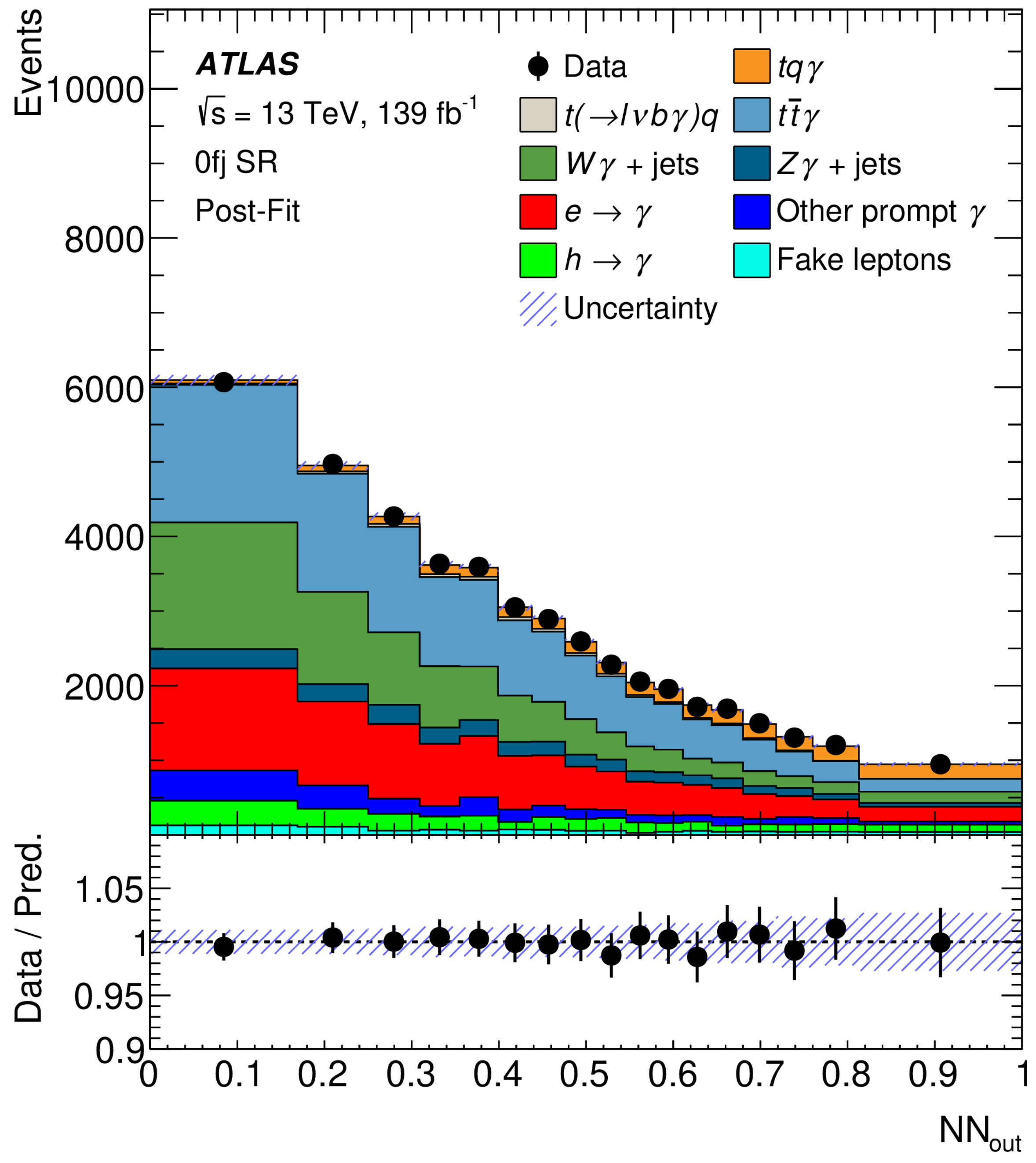
- 1ℓ, 1 tight b-tag, $\geqslant 1\gamma$ in the final state
- Veto events with $m_{\ell\gamma}$ close to m_Z
- SR1: 0 forw. jet and SR2: $\geqslant 1$ forw. jet
- NN discr. in SRs to separate signal from bkgs.

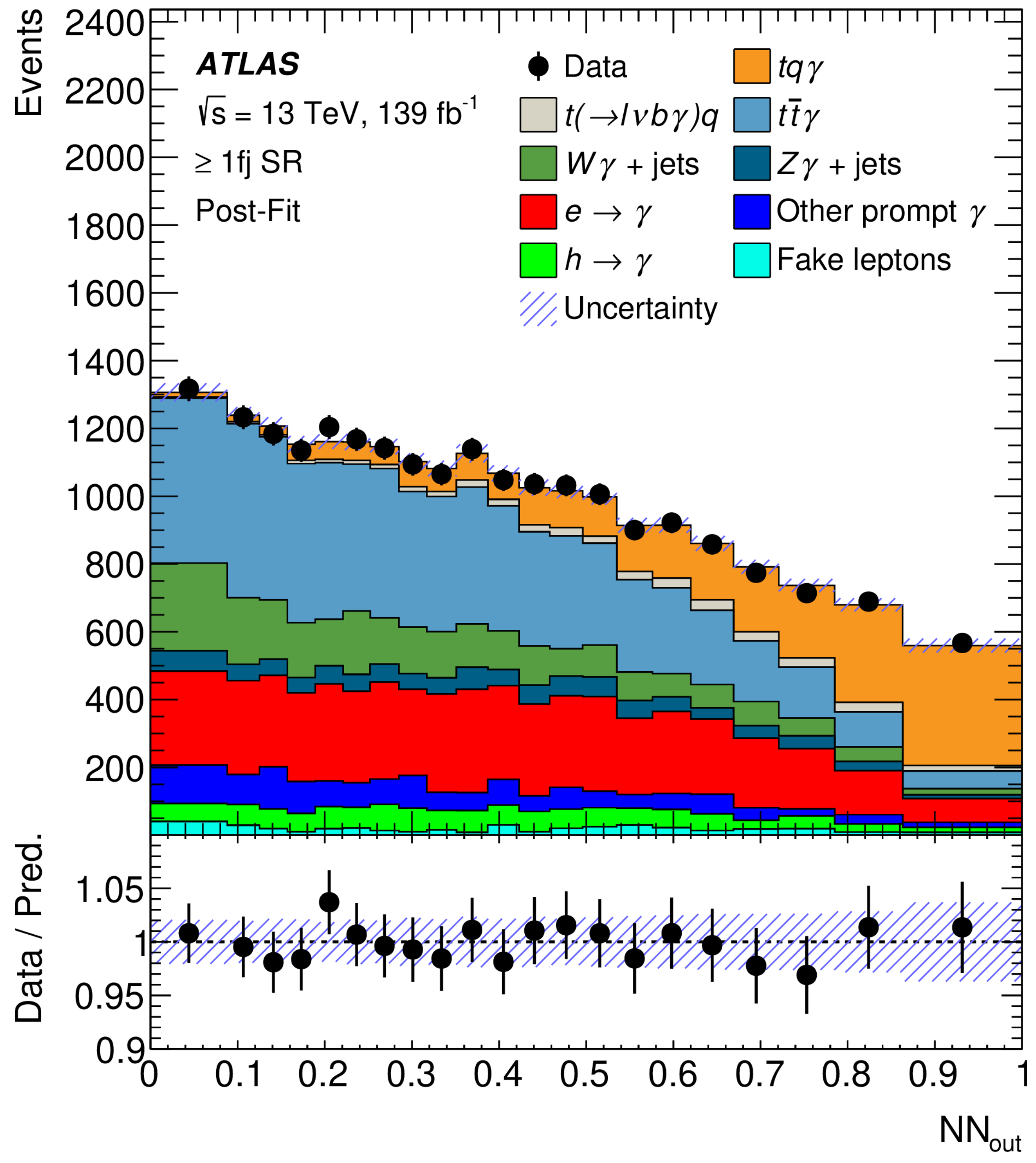


arXiv:2302.01283

$\sigma_{tq\gamma} \times \mathscr{B}(t \to b\ell\nu)$	Meas. fid. cross section (fb)	SM prediction (fb)
Parton level	688 ± 23 (stat) $^{+75}_{-71}$ (syst)	515^{+36}_{-42}
Particle level	303 ± 9 (stat) $^{+33}_{-32}$ (syst)	217^{+27}_{-15}





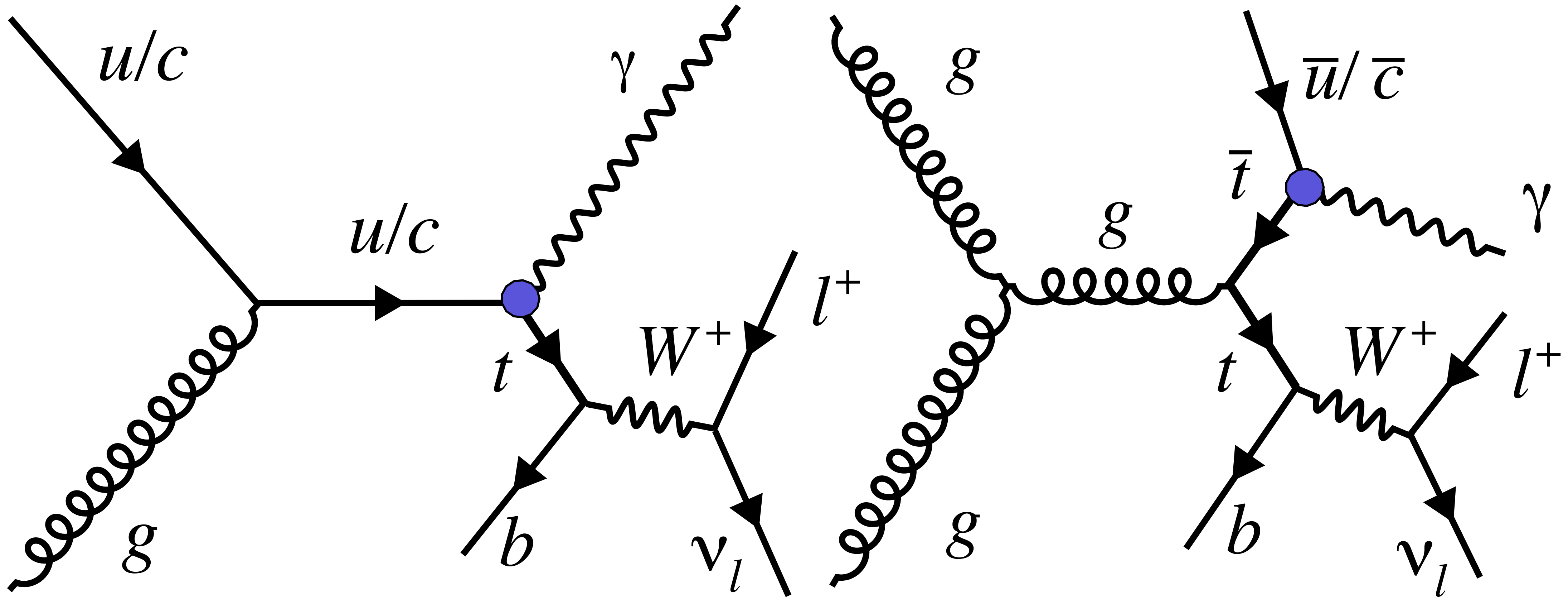


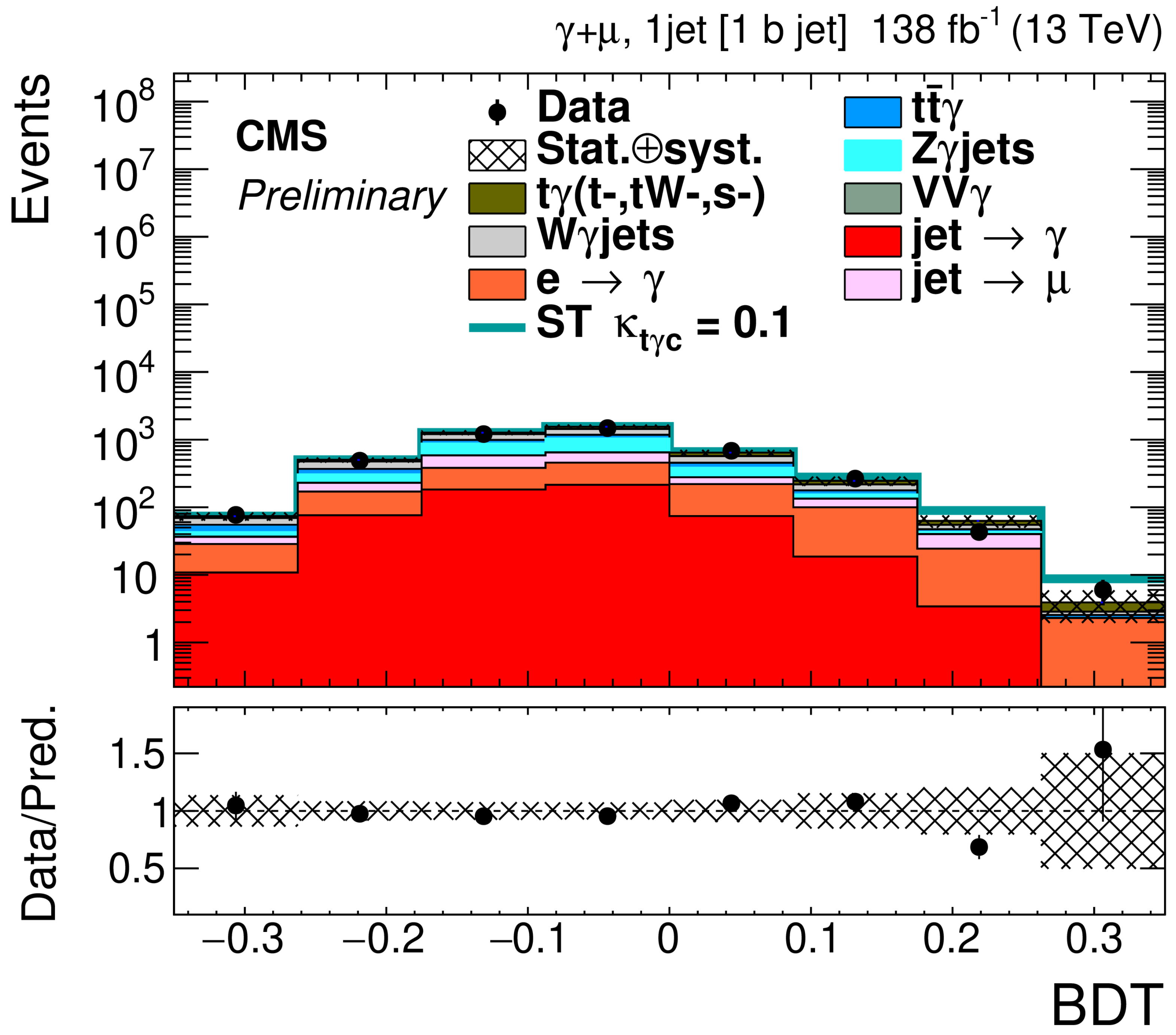
- **Observed** (**Expected**) significance of the $tq\gamma$ signal is: **9.3** (**6.8**) s.d.
- Evidence @ **4.4 s.d.** with partial ($35.9\ fb^{-1}$) Run2 data reported earlier by CMS ([CMS-TOP-17-016](CMS-TOP-17-016))

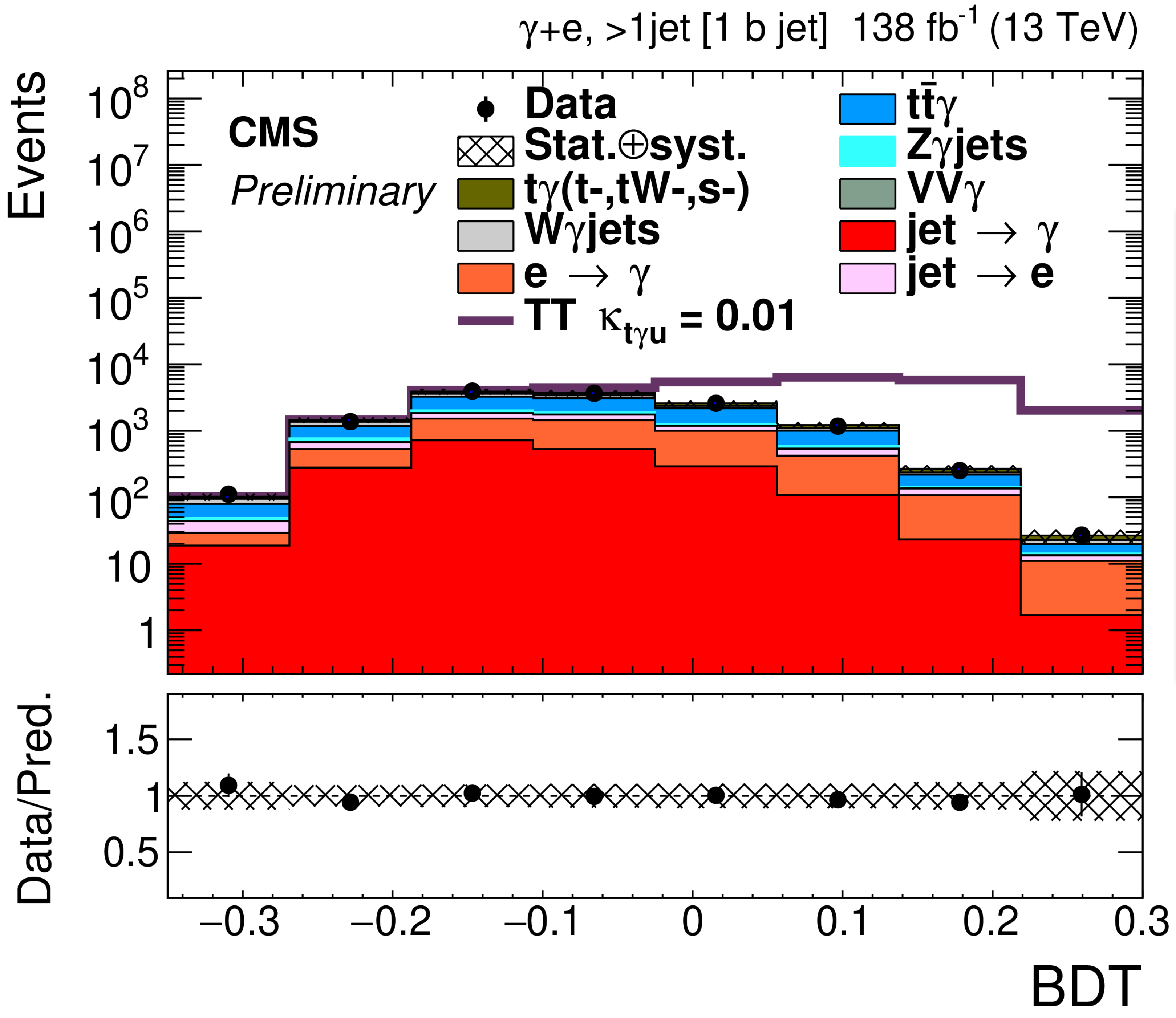
FCNC in $t\gamma$

[New] CMS-PAS-TOP-21-013

- 1ℓ, $\geqslant 1\gamma$ (in barrel), & $\geqslant 1j$ in the final state
- Veto events with $|m_{e\gamma} - m_Z| < 10$ GeV
- SR1: 1j1b and SR2: $> 1j$, 1b
- BDTs to separate FCNC signal from SM bkgs.
- *Upper Limits @95% CL* extracted for $\kappa_{tq\gamma}$ and $\mathscr{B}(t \to q + \gamma)$







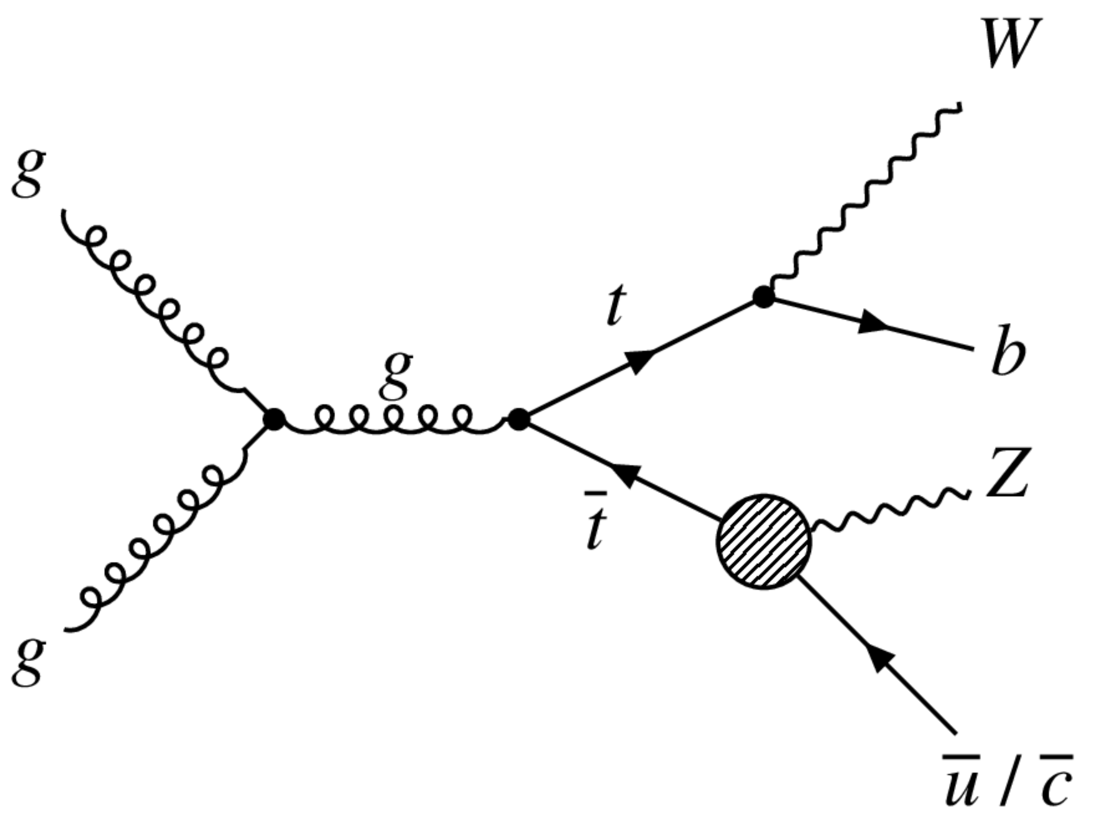
Combined	Obs. limit	Exp. limit
$\kappa_{tu\gamma}$	6.2×10^{-3}	6.9×10^{-3}
$\kappa_{tc\gamma}$	7.7×10^{-3}	7.8×10^{-3}
$\mathcal{B}(t \to u + \gamma)$	0.95×10^{-5}	1.20×10^{-5}
$\mathcal{B}(t \to c + \gamma)$	1.51×10^{-5}	1.54×10^{-5}

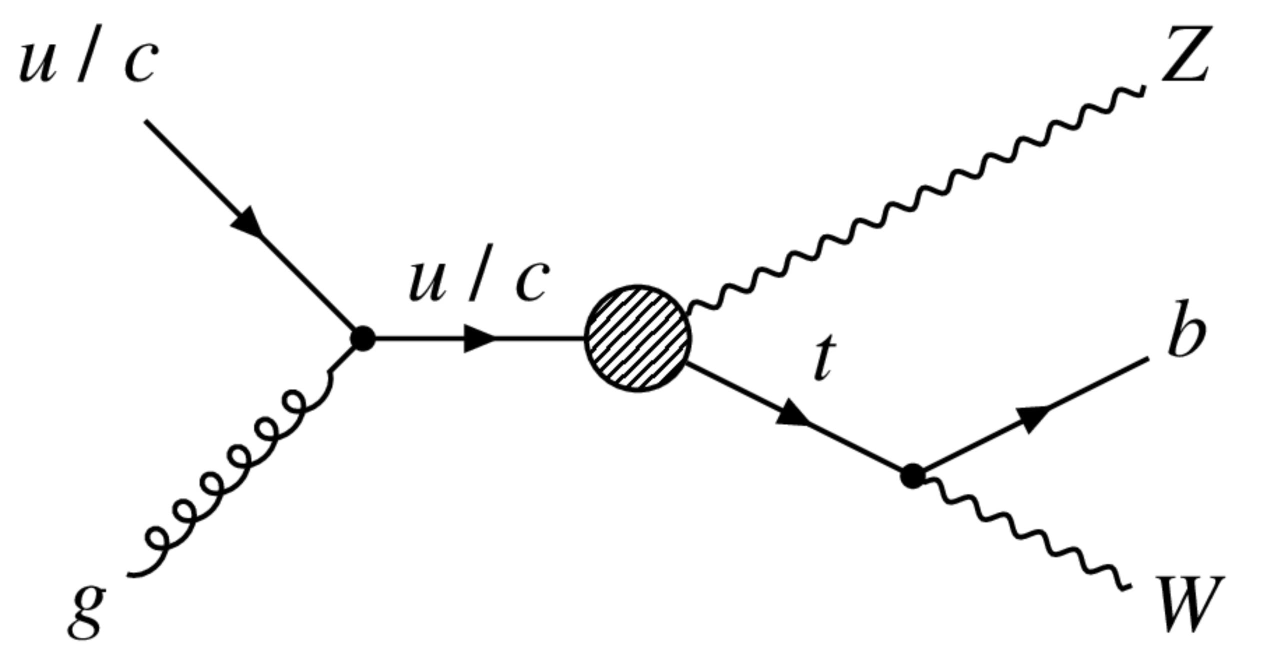
FCNC in tZ

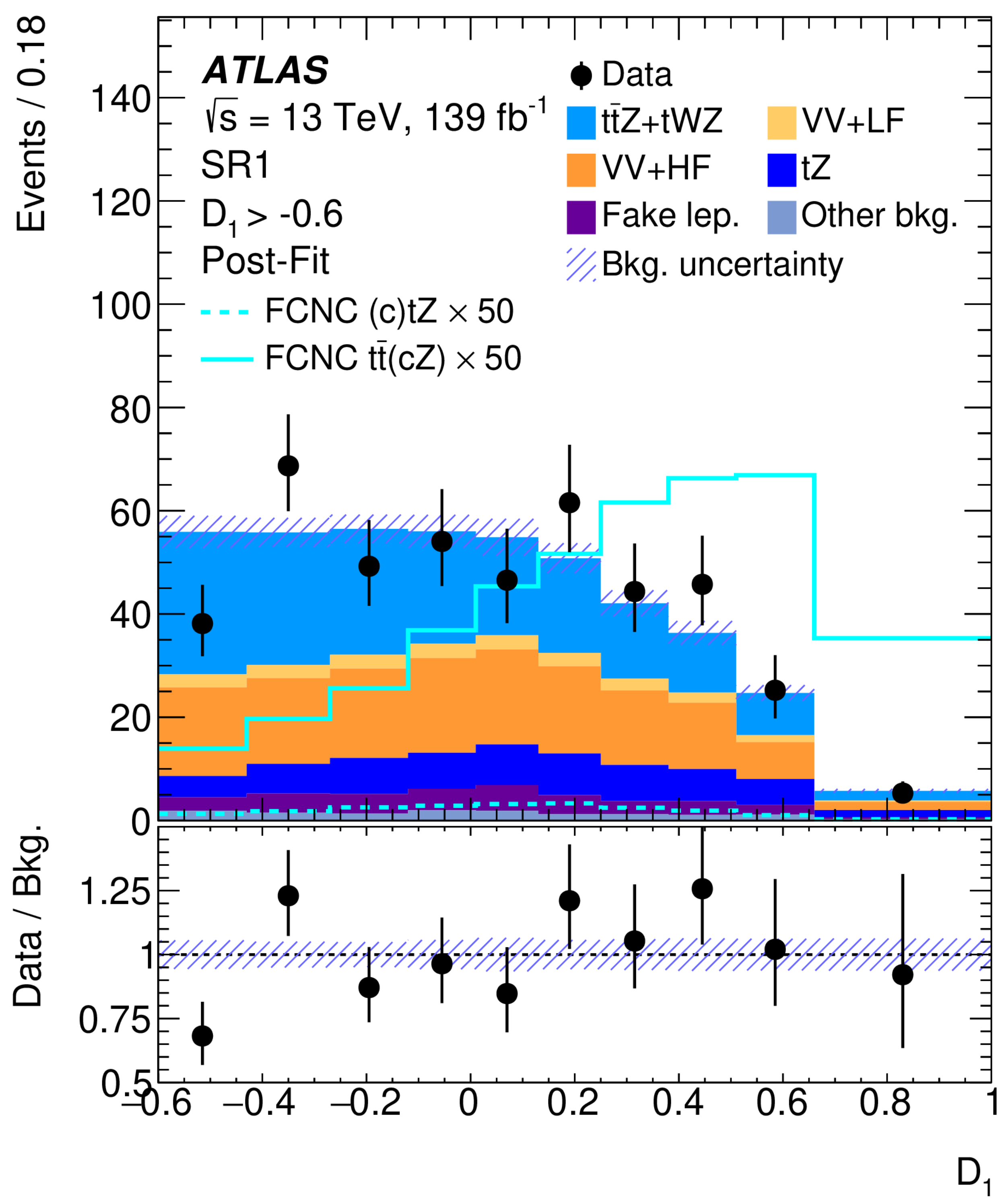
[arXiv:2301.11605](https://arxiv.org/abs/2301.11605)

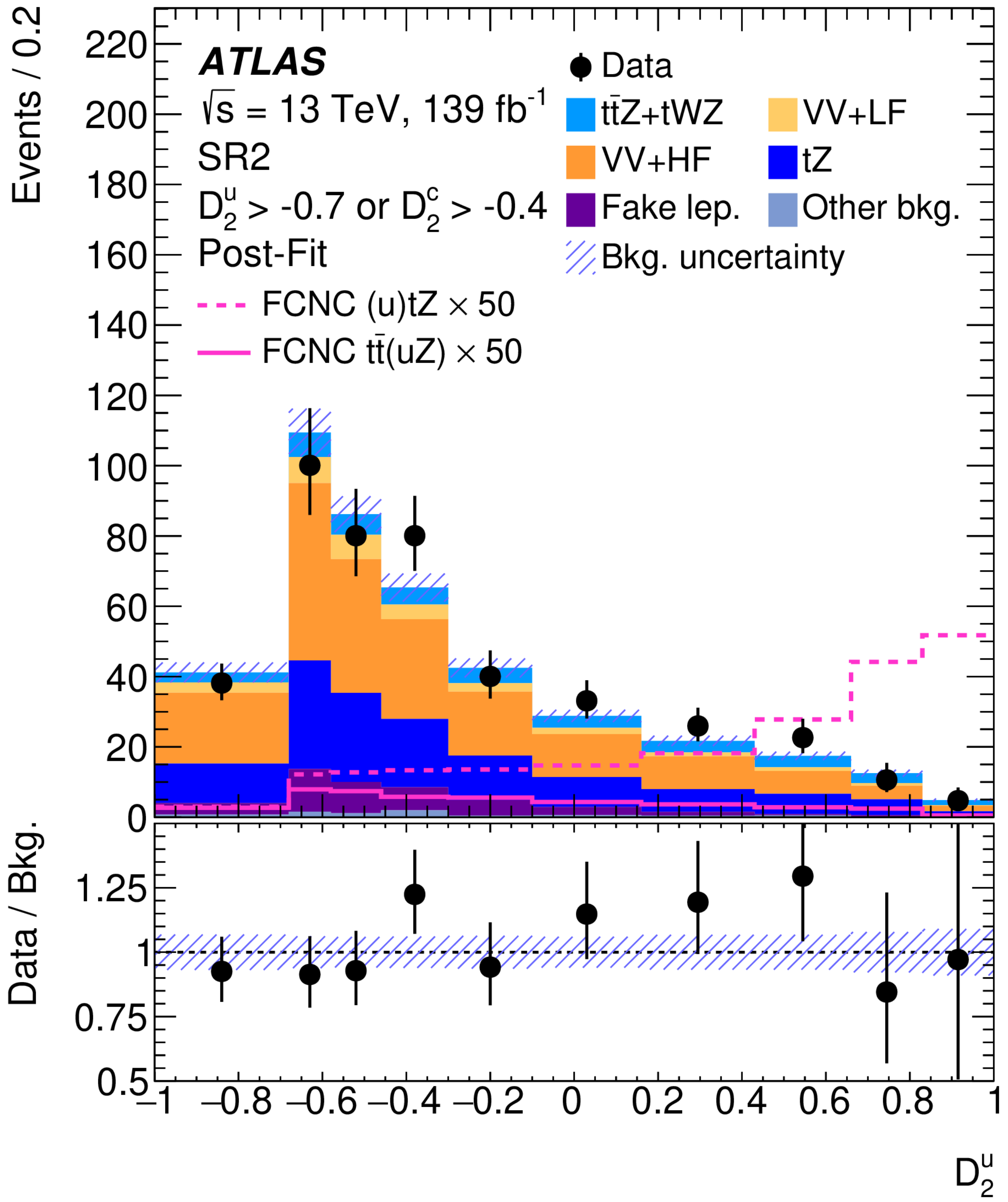
- $\geqslant 3\ell$ with exactly 1 OSSF pair in the final state
- OSSF lepton pair with $|m_{\ell\ell} - m_Z| < 15$ GeV
- SR1($t\bar{t}$ -like): $\geqslant$ 2j1b & SR2 (Single t-like): 1j1b + 2j1b
- *Kinematic event reconstruction* based on the signal topology
- Dominant bkgs : $t\bar{t}$*-dilepton* and $t\bar{t}V$
- BDTs to separate FCNC signal from SM bkgs.
- *Upper limits* are extracted *@95% CL* for $\mathcal{B}(t \to Zq)$

Observable	Vertex	Coupling	Observed	Expected
	SRs+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	RH	12×10^{-5}	$10\,^{+4}_{-3}\times10^{-5}$









Summary

- LHC ≡ Top quark factory
  ⇒ precision lab for studying top quark production & properties

  ⇒ portal to new physics beyond SM

- Most measurements agree with SM prediction within uncertainties
  ⇒ several measurements out-perform predictions in precision

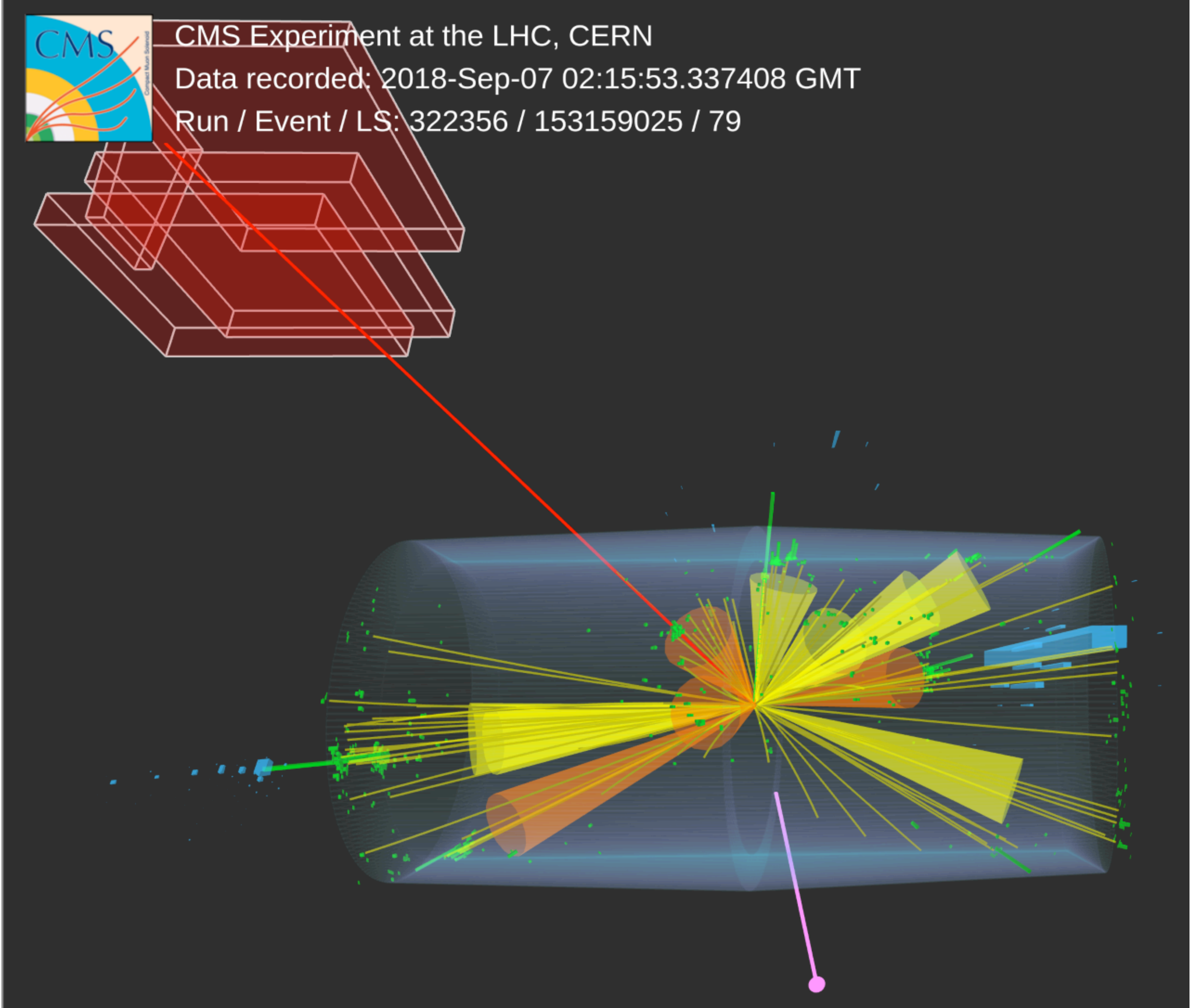
- Differential and fiducial measurements are key inputs for better MC modeling in future

- Observation or evidence of several rare top quarks processes during Run2
  ⇒ waiting to be fully exploited during Run3 and High Luminosity- LHC

- Stringent limits on FCNC couplings are placed with Run2 data

- More information : ATLAS Top Public Results, CMS Top Public Results, LHC Top WG

- More TOP results today by Michele, Sergio, and Jack



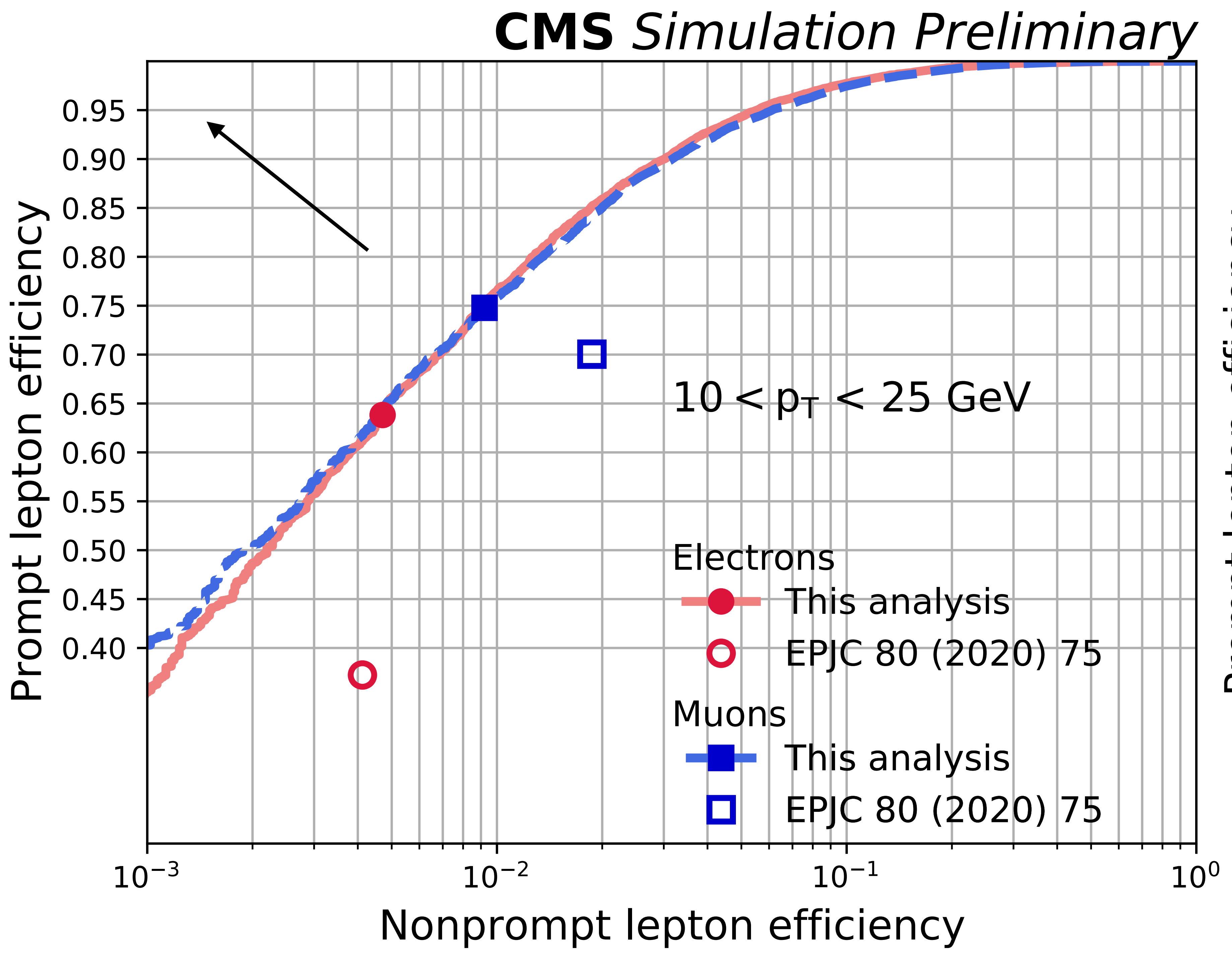
Thank you for your attention !!

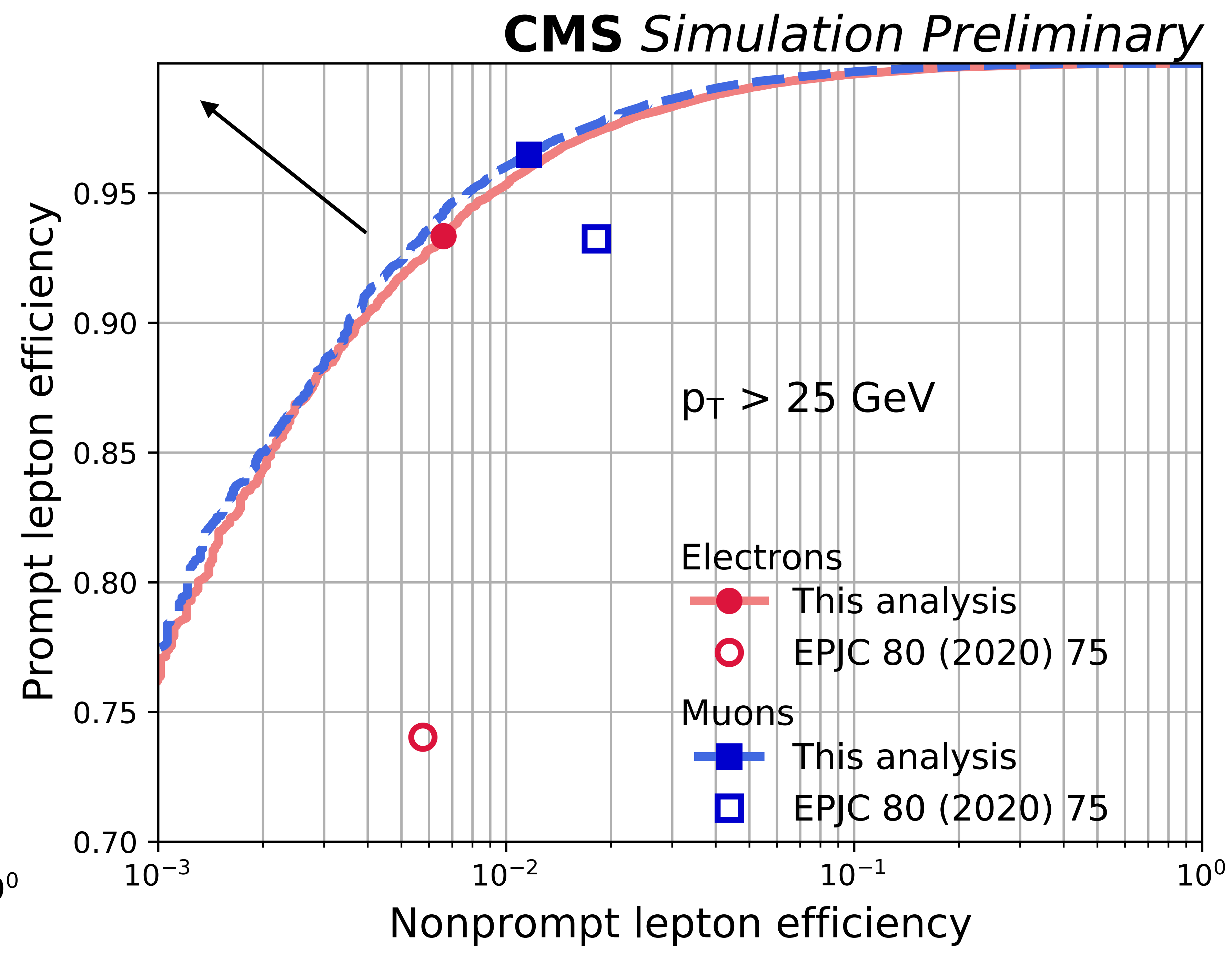
Back - up

Observation of $t\bar{t}t\bar{t}$: SSML

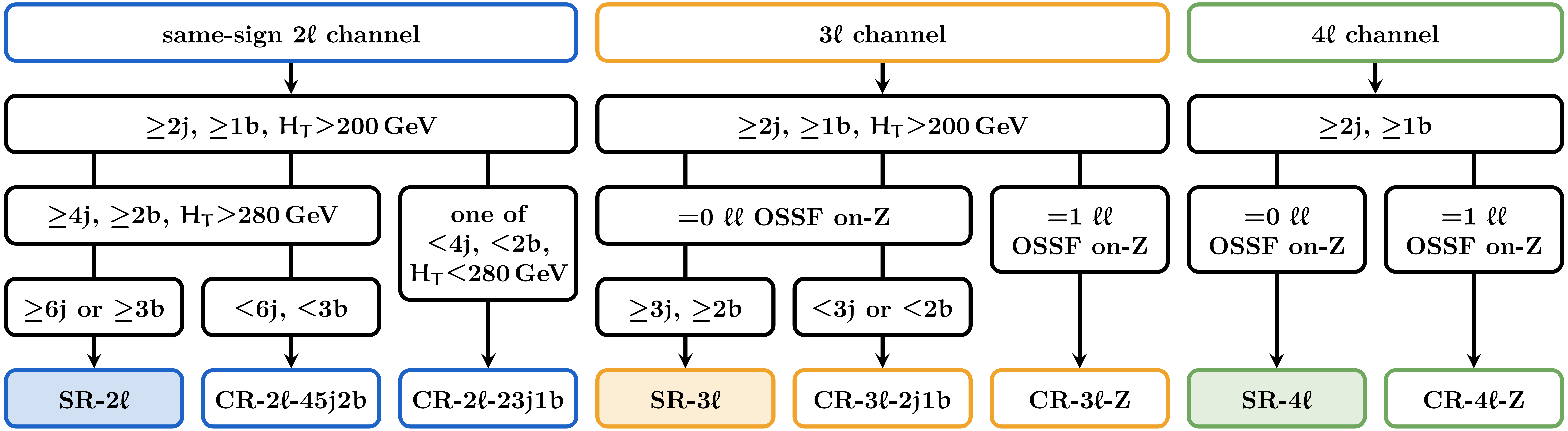
New

CMS-PAS-TOP-22-013

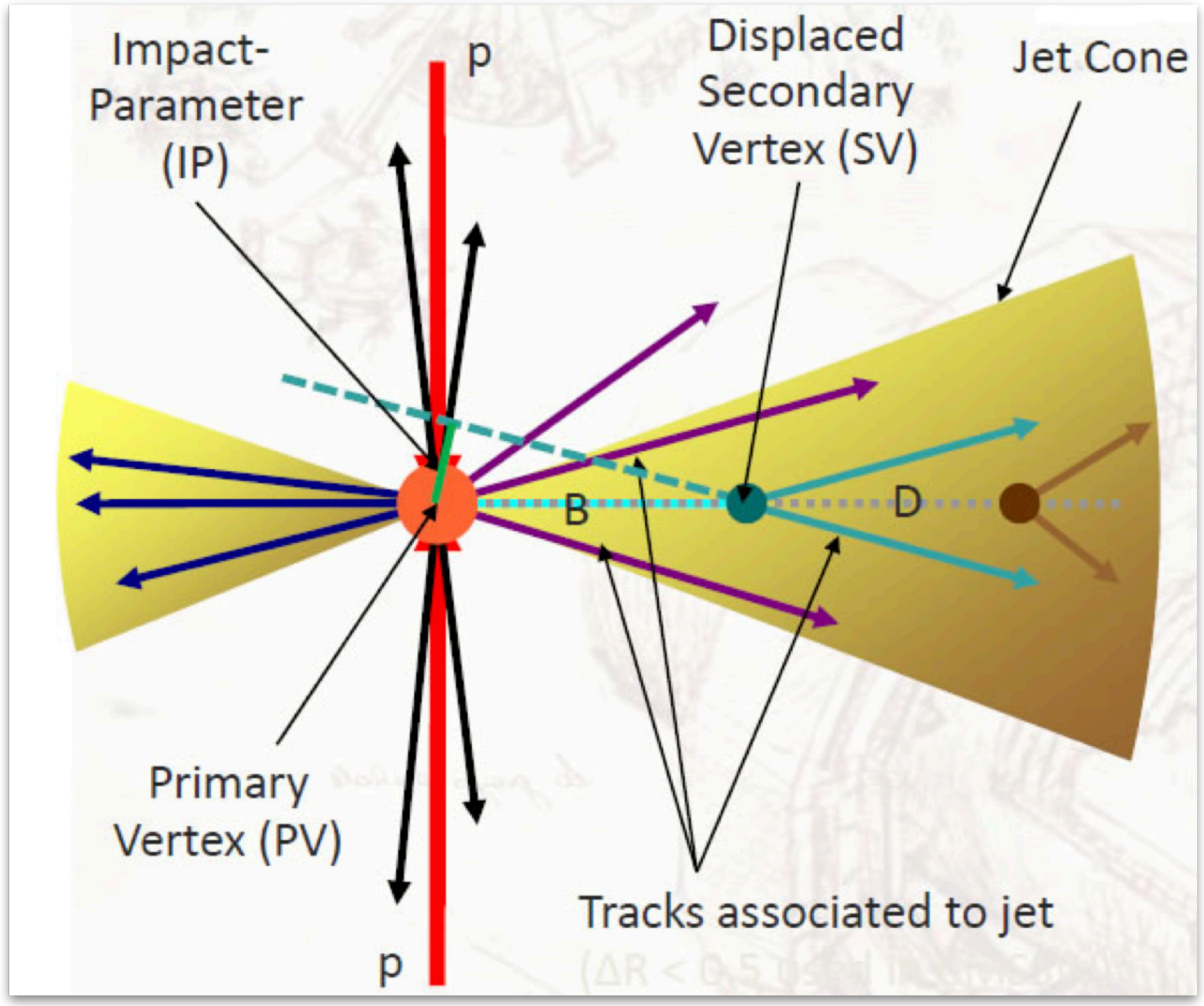




$t\bar{t}t\bar{t}$ pred	$13.4^{+1.0}_{-1.8}$ fb
$t\bar{t}t\bar{t}$ meas	$17.9^{+3.7}_{-3.5}$ (stat) $^{+2.4}_{-2.1}$ (syst) fb
$t\bar{t}W$ pred	722 ± 74 fb
$t\bar{t}W$ meas	997 ± 58 (stat) $^{+79}_{-72}$ (syst) fb
$t\bar{t}Z$ pred	859 ± 80 fb
$t\bar{t}Z$ meas	1134^{+52}_{-43} (stat) ± 86 (syst) fb



b-tagging in CMS



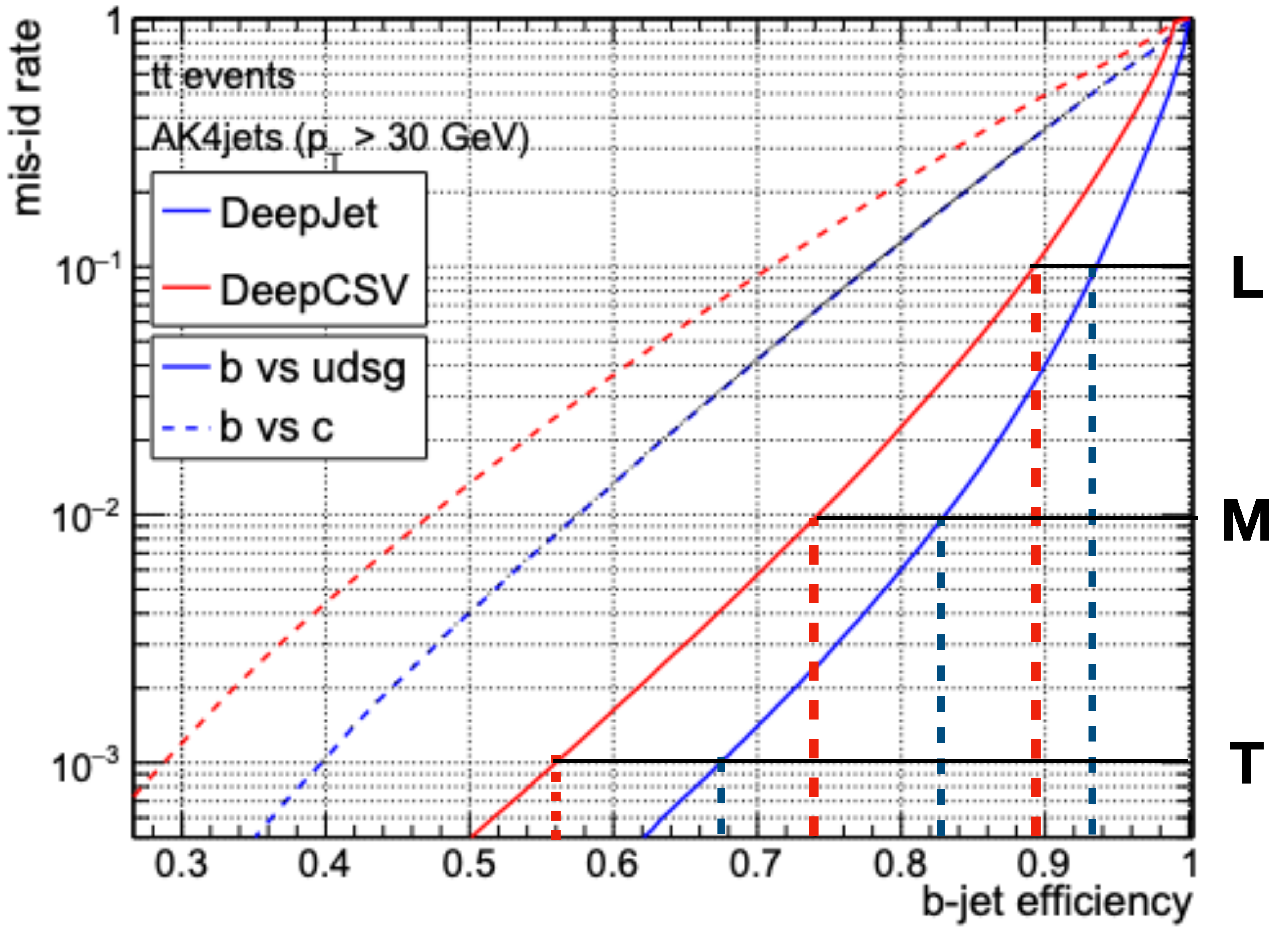
Typical features of heavy flavor jets:

- Contain SVs due to b(c)-hadron decays
- High track multiplicity
- Tracks with high impact parameter (IP) relative to PV
- Presence of soft leptons inside jets $\mathscr{B}(\mathrm{b} \to \mu X) \approx 20\,\%$

Tagging typically relies on:

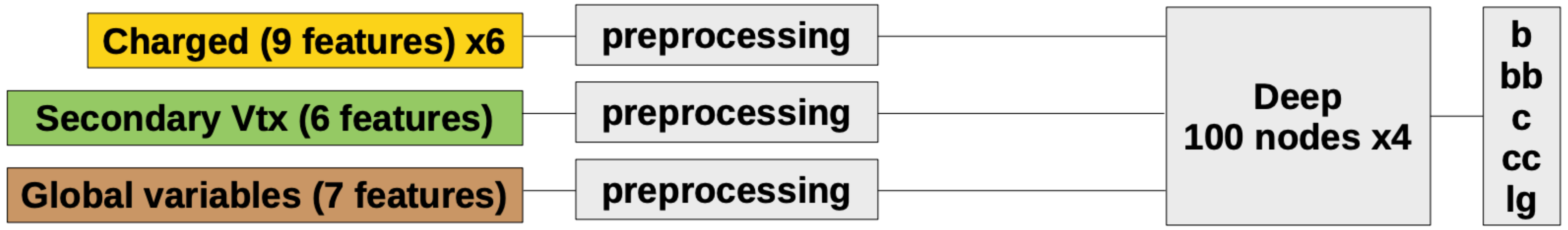
- Track info. : IP2D, IP3D, track multiplicity etc.
- SV info. : m_{SV} , SV flight distance etc.
- Charged and neutral hadron and soft lepton candidate info.
- Some combination of the above : NN

JINST 15 (2020) P12012



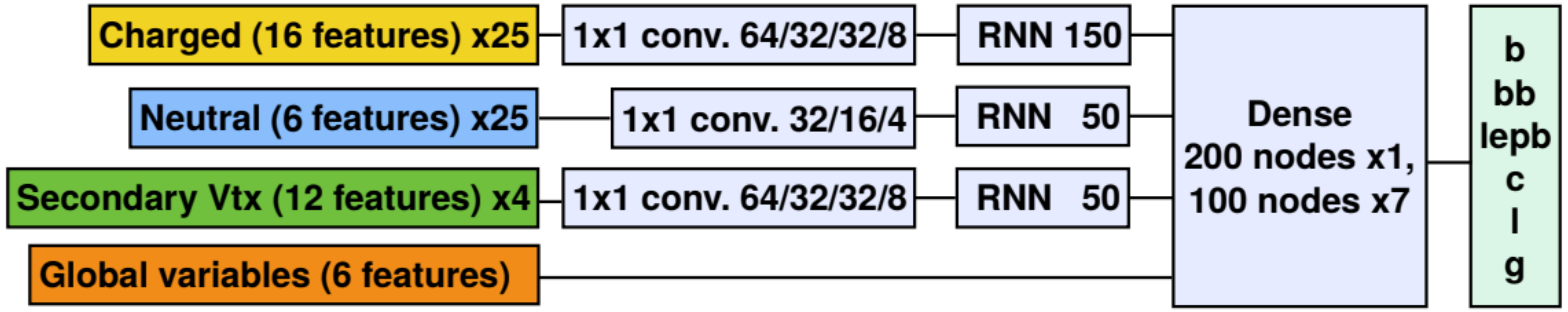
DeepCSV

More tracks
More nodes
More hidden layers (deeper)
JINST 13 (2018) P05011



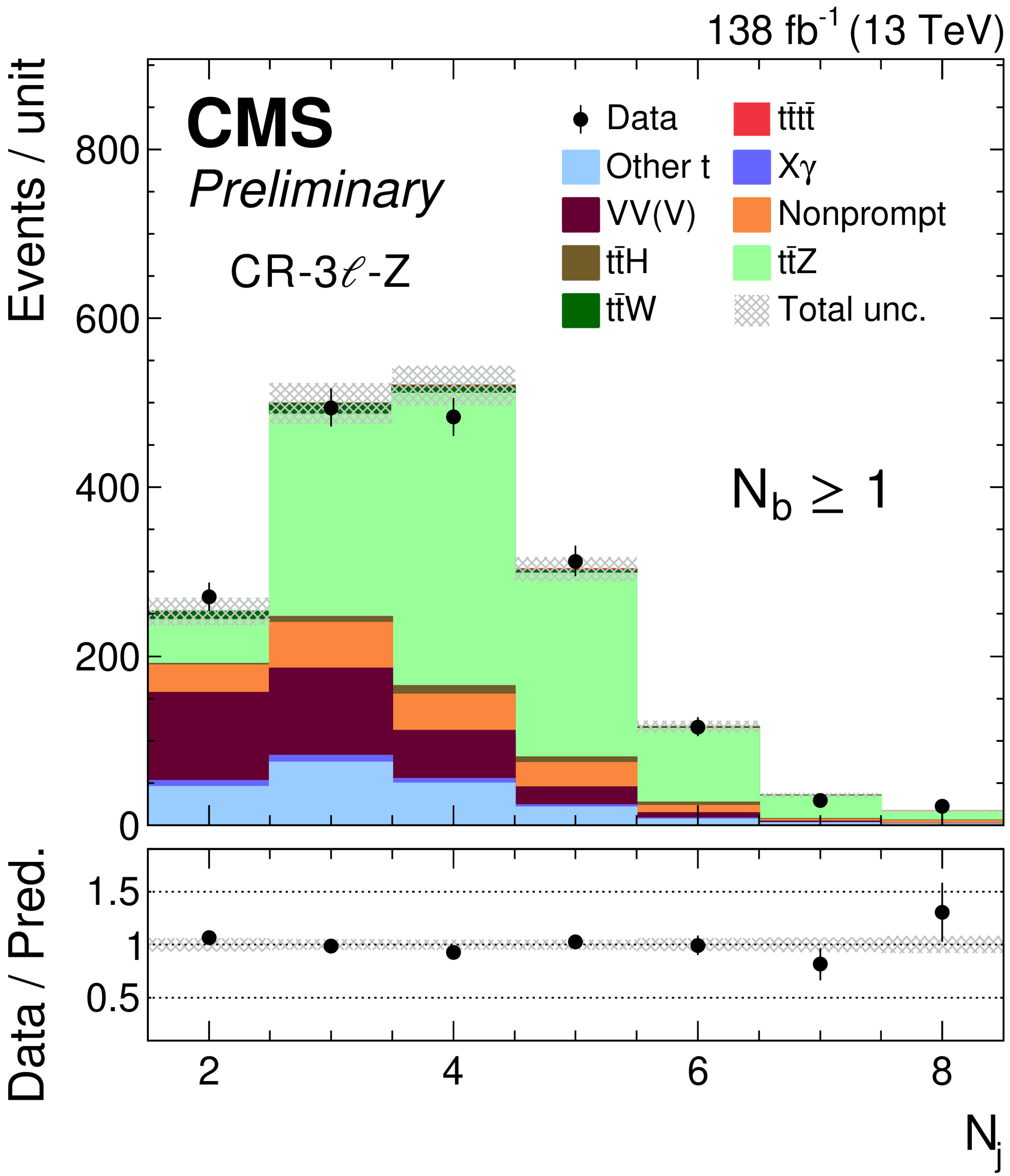
DeepJet

JINST 15 (2020) P12012

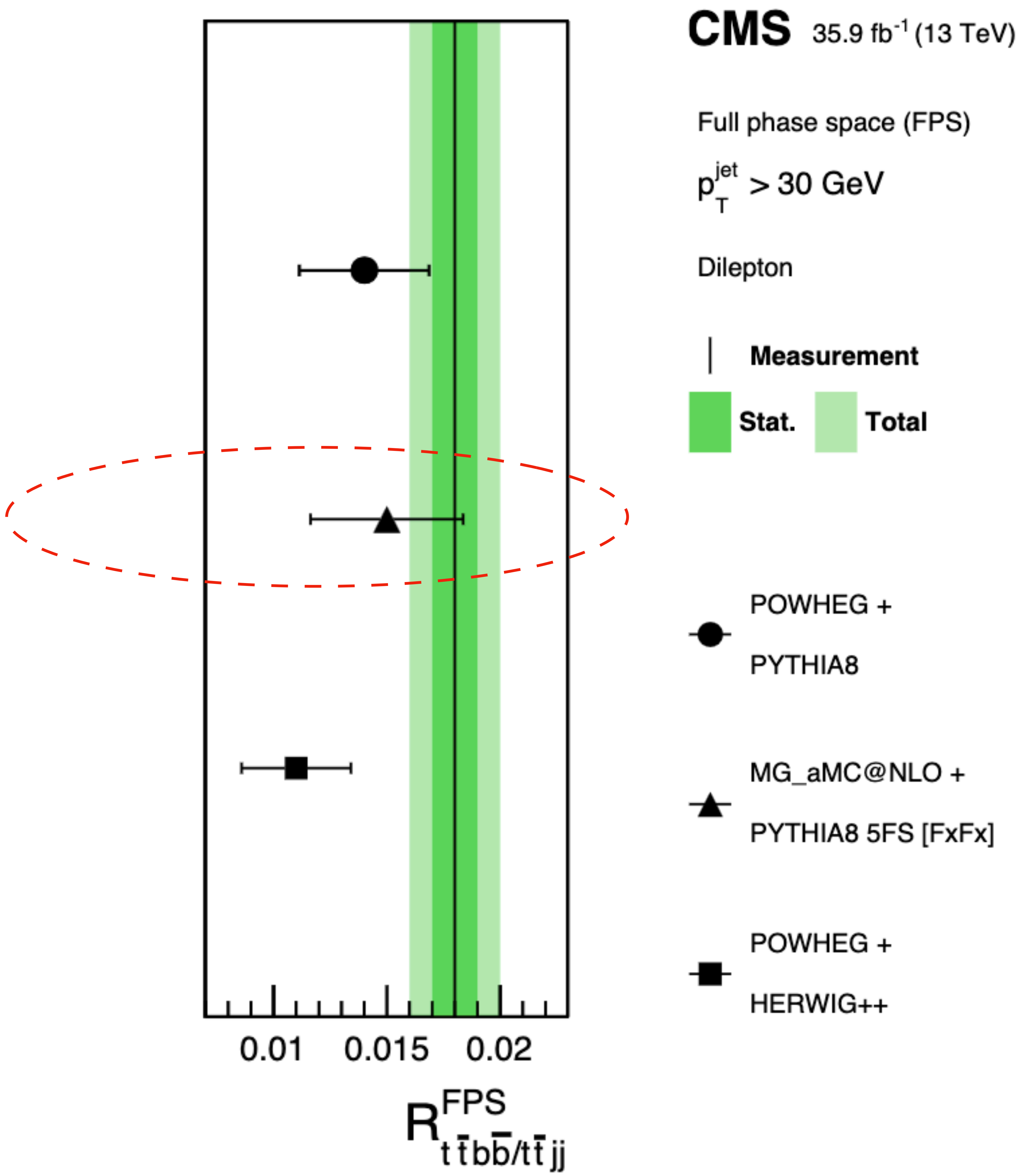


$t\bar{t}t\bar{t}$: SSML

[CMS-PAS-TOP-22-013](CMS-PAS-TOP-22-013)

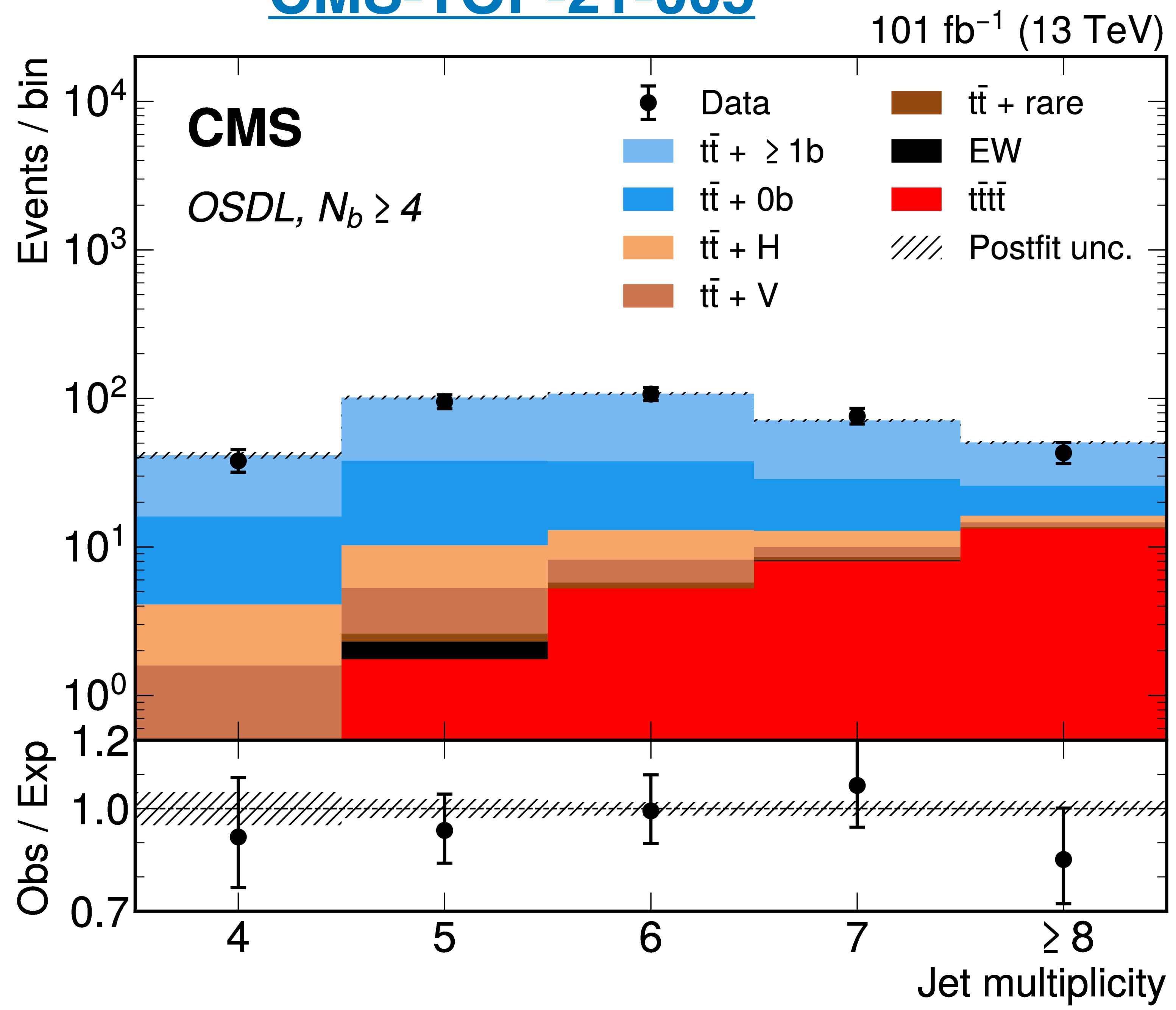


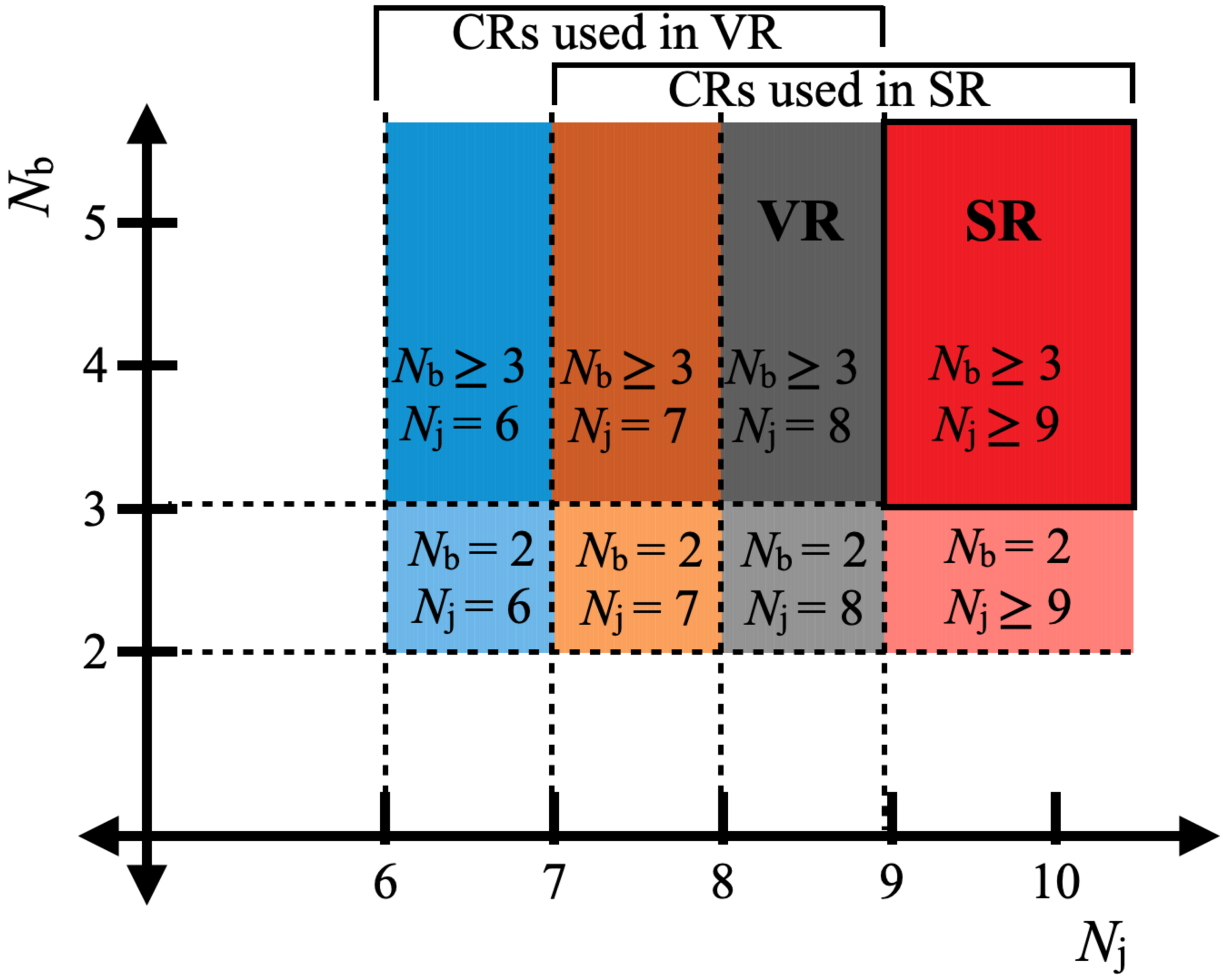
JHEP 07 (2020) 125

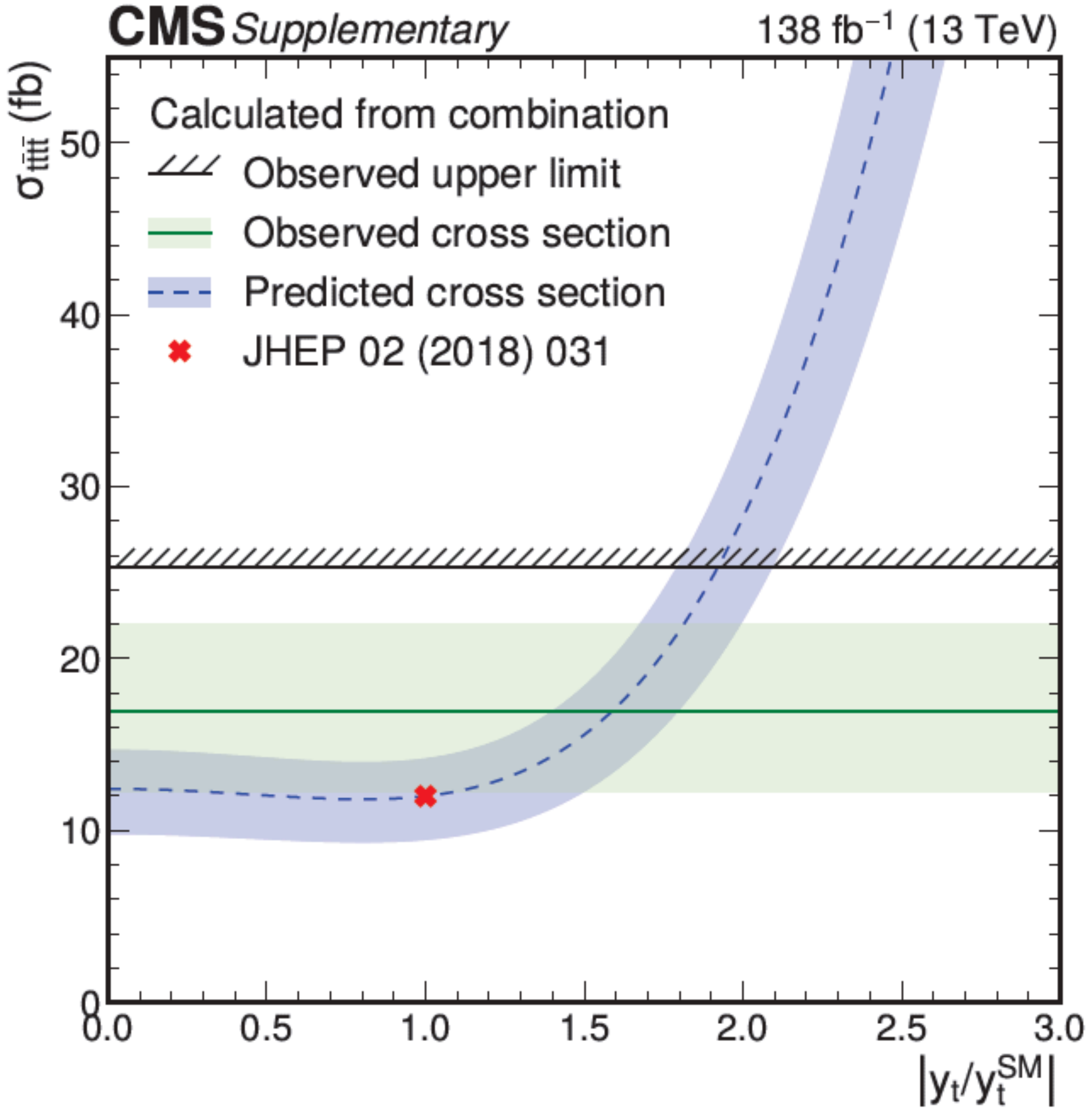


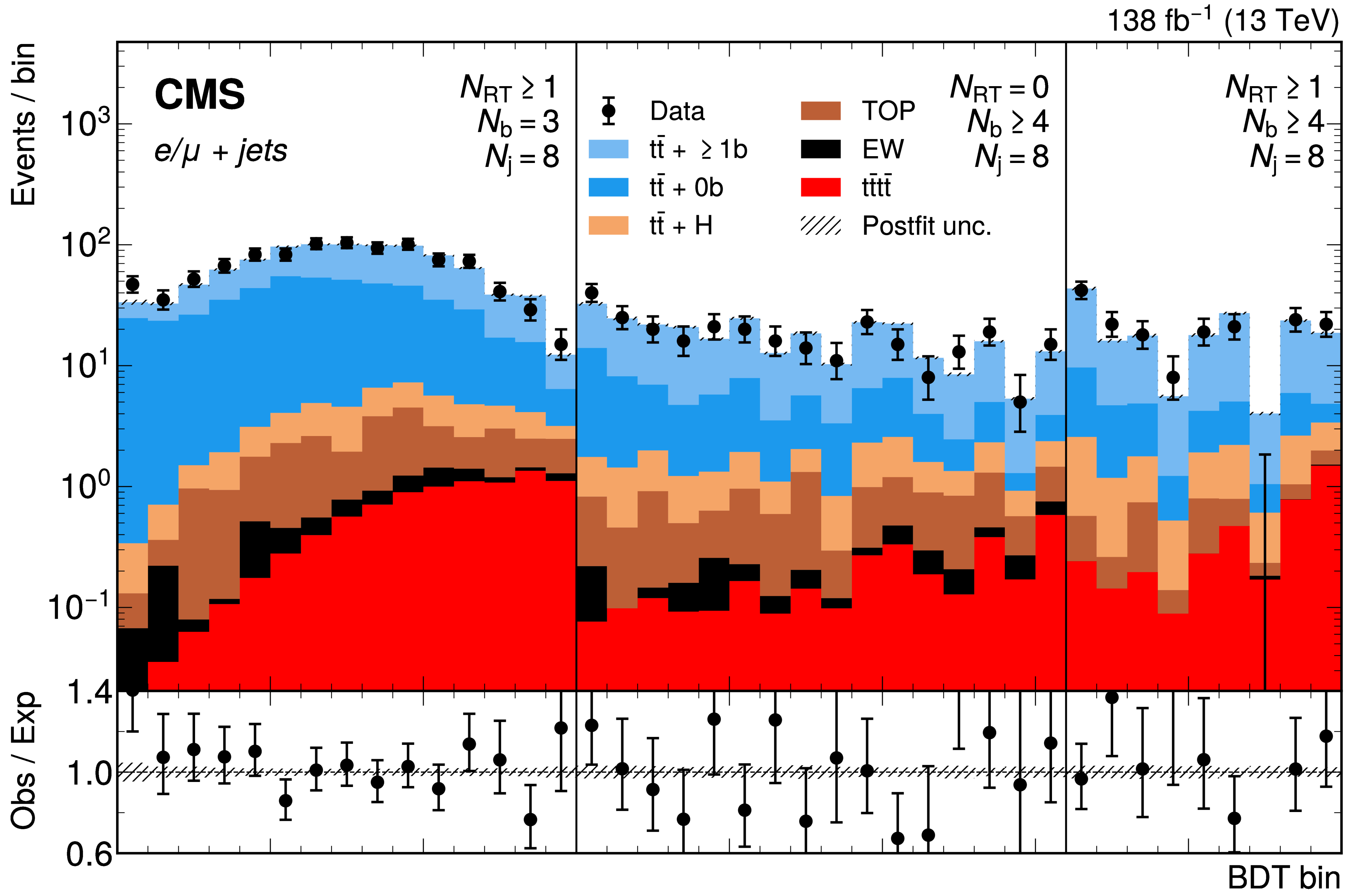
$t\bar{t}t\bar{t}$ combination

CMS-TOP-21-005



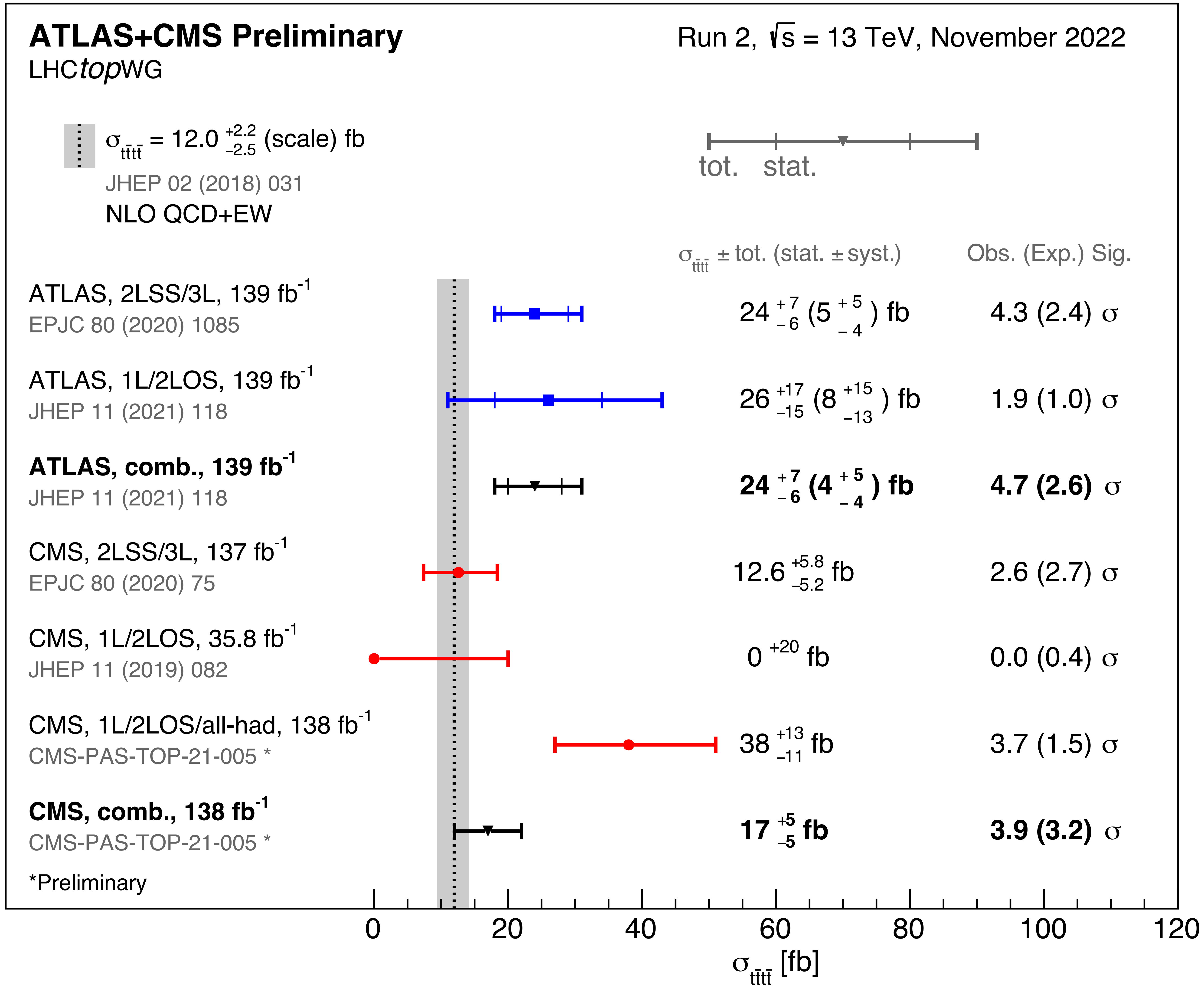






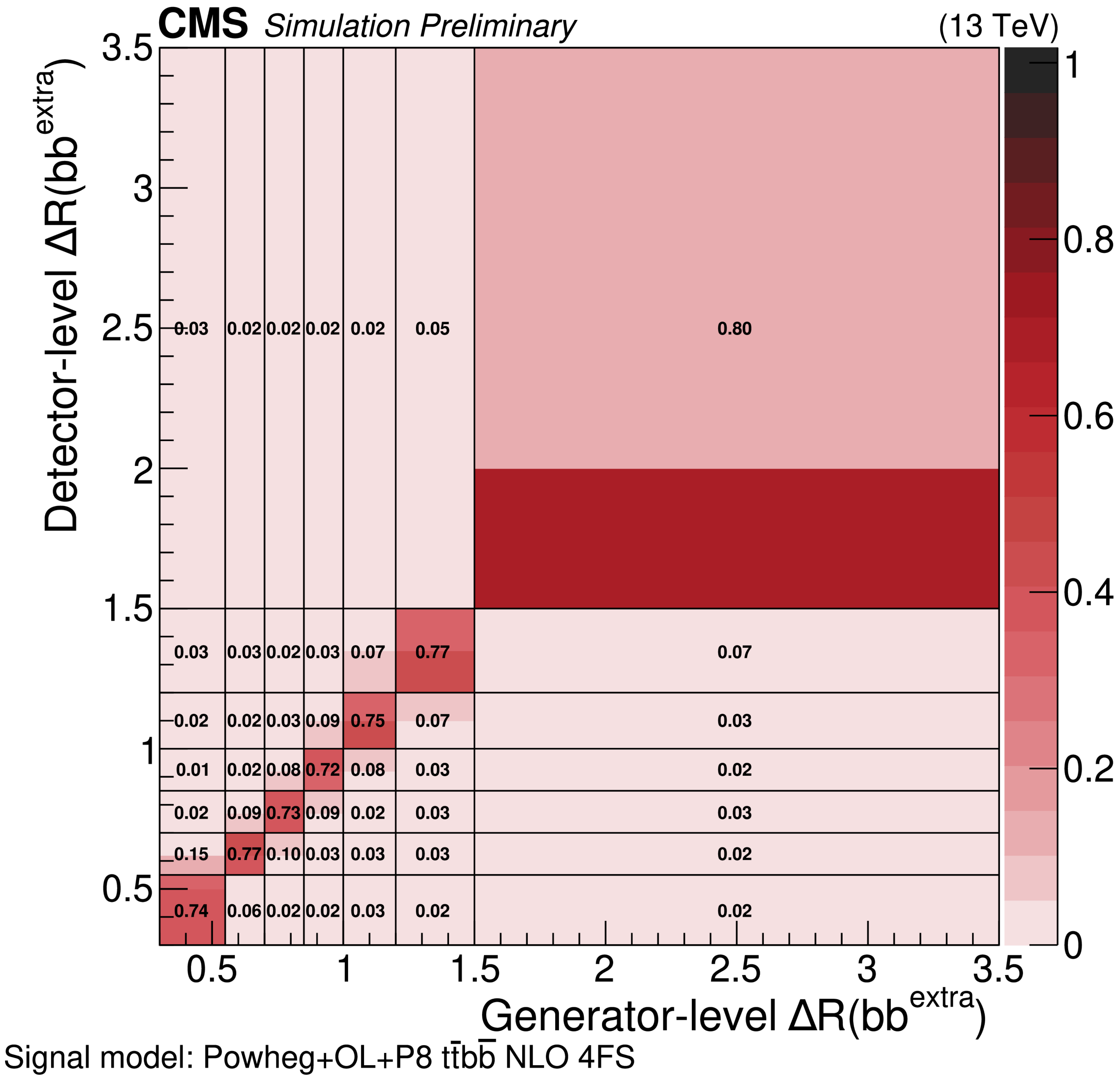
Analysis	Signal strength (μ)	(stat.)	(syst.)	Cross section (fb)	(stat.)	(syst.)	Significance (s.d.) Exp.	Obs.
OSDL (2017+2018)	2.8	± 1.0	$^{+1.9}_{-1.2}$	33	± 12	$^{+15}_{-14}$	0.6	1.8
Single-lepton	1.2	$^{+0.7}_{-0.6}$	± 0.6	15	± 8	$^{+10}_{-7}$	1.2	1.4
All-hadronic	5.8	± 1.4	± 2.0	70	± 17	$^{+25}_{-23}$	0.4	2.5
Combination of above	2.5	± 0.5	± 0.5	36	± 7	$^{+10}_{-8}$	1.5	3.9
SSDL&ML (2016–2018) [21]	1.0	± 0.4	$^{+0.3}_{-0.2}$	13	$^{+5}_{-4}$	± 3	2.7	2.6
OSDL (2016) [22]	−0.2	$^{+1.7}_{-1.5}$	± 1.5	−2	$^{+20}_{-18}$	± 18	0.4	0
Full combination	1.4	± 0.3	± 0.2	17	± 4	± 3	3.2	4.0

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



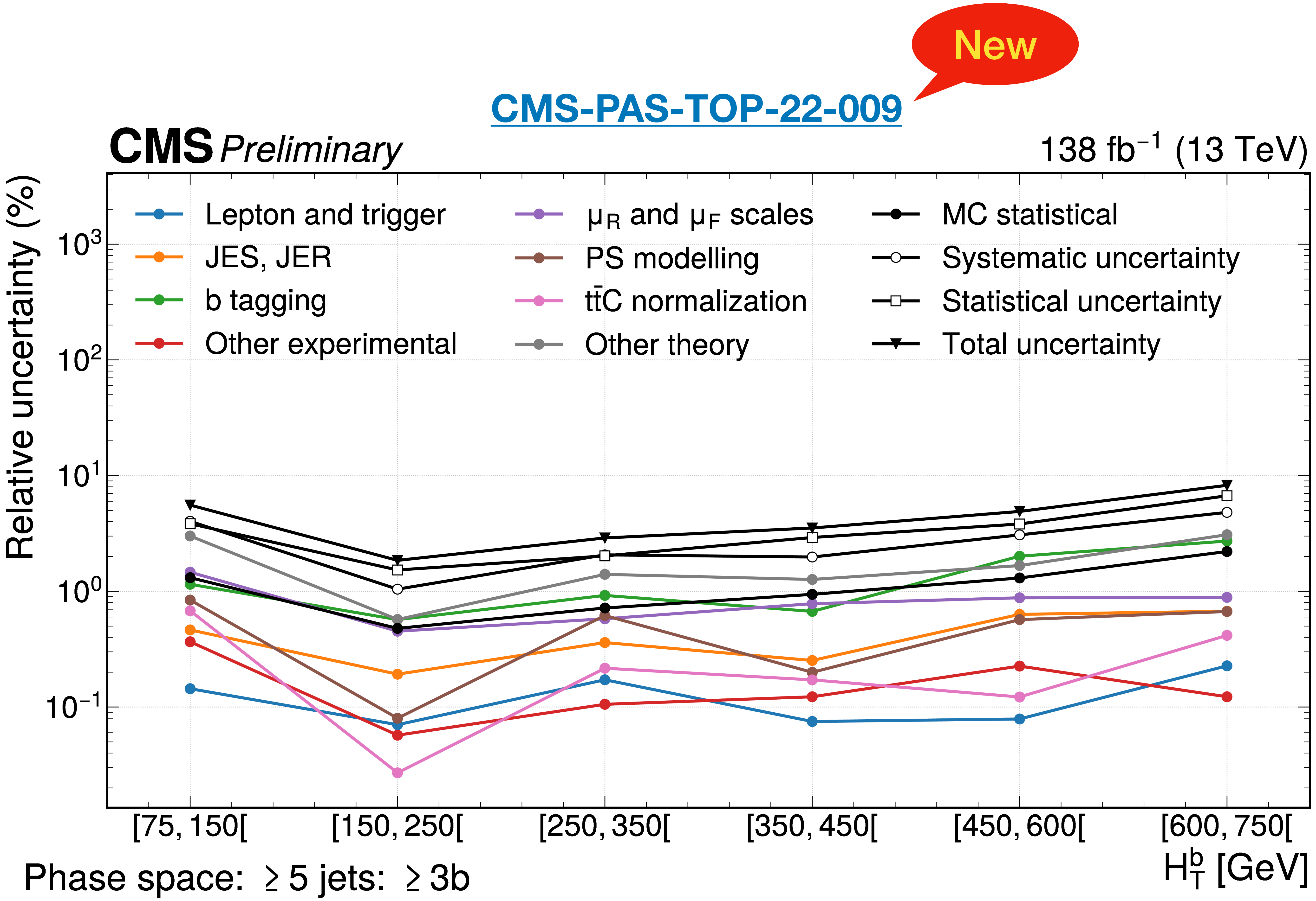
LHCTOPWGSummaryPlots

$t\bar{t}b\bar{b}$ production



Response Matrix

CMS-PAS-TOP-22-009

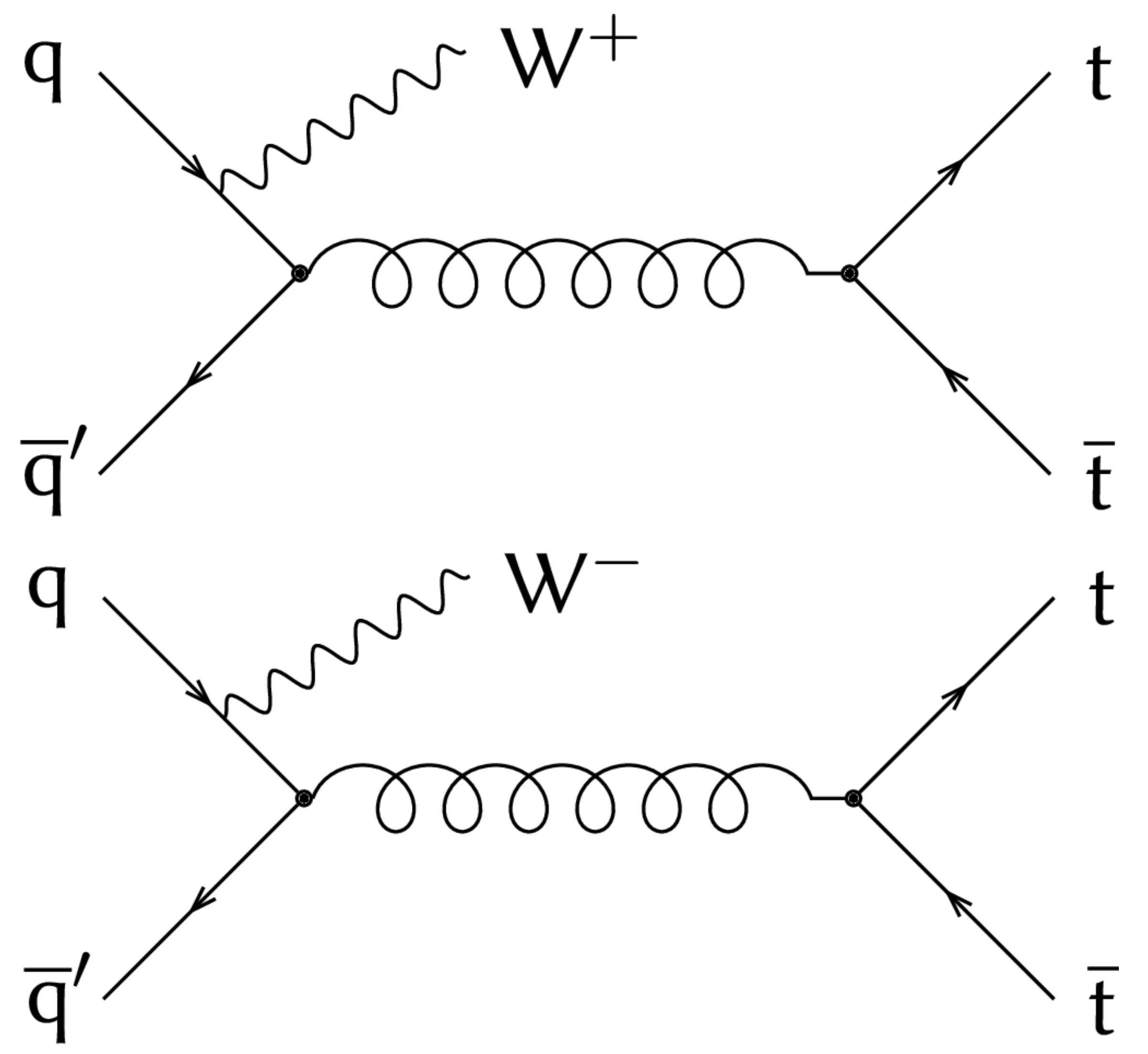


Uncertainties in diff. measurements

$t\bar{t}W$ production

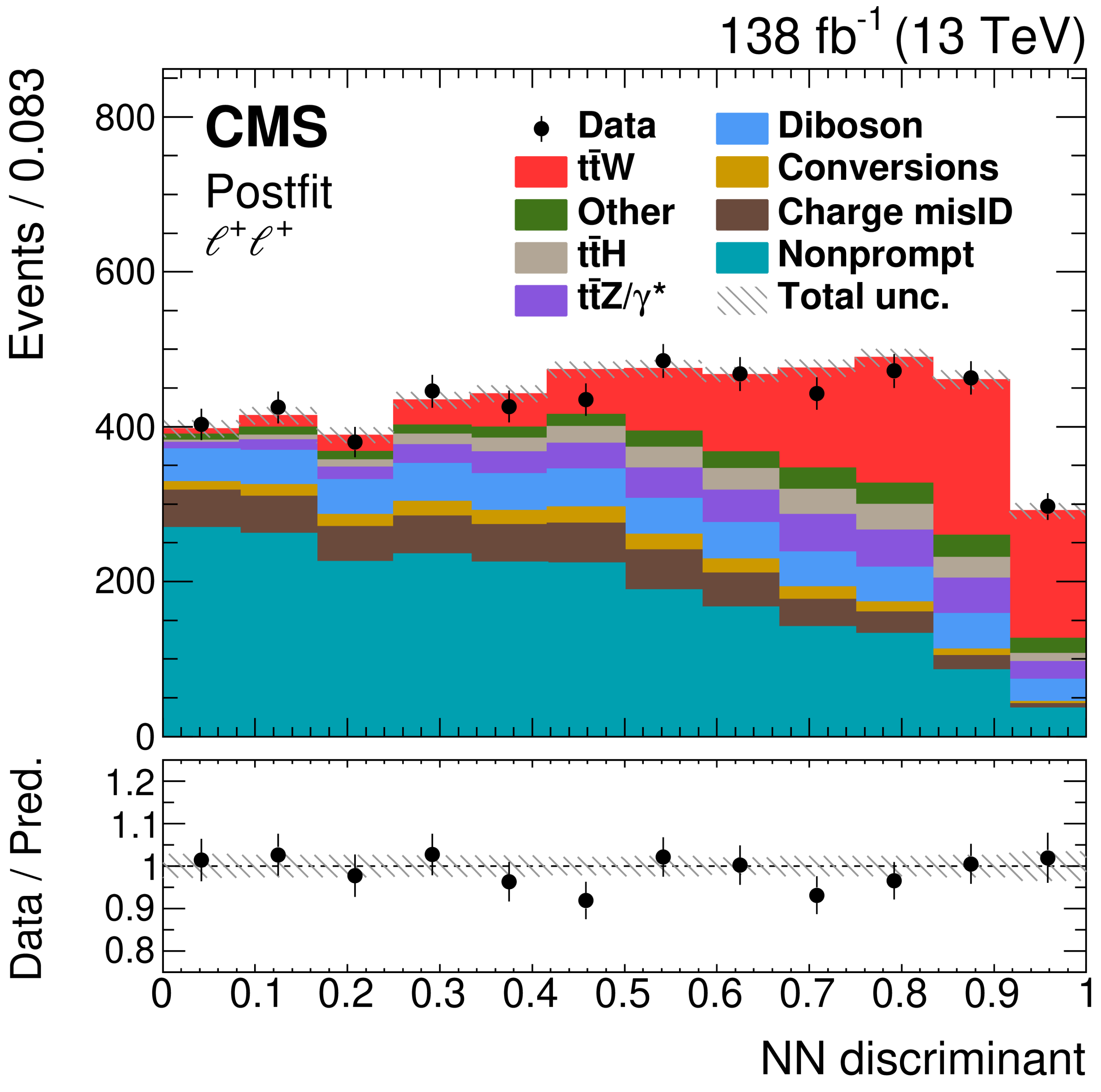
- SR consists of $2\ell SS$ and 3ℓ final state

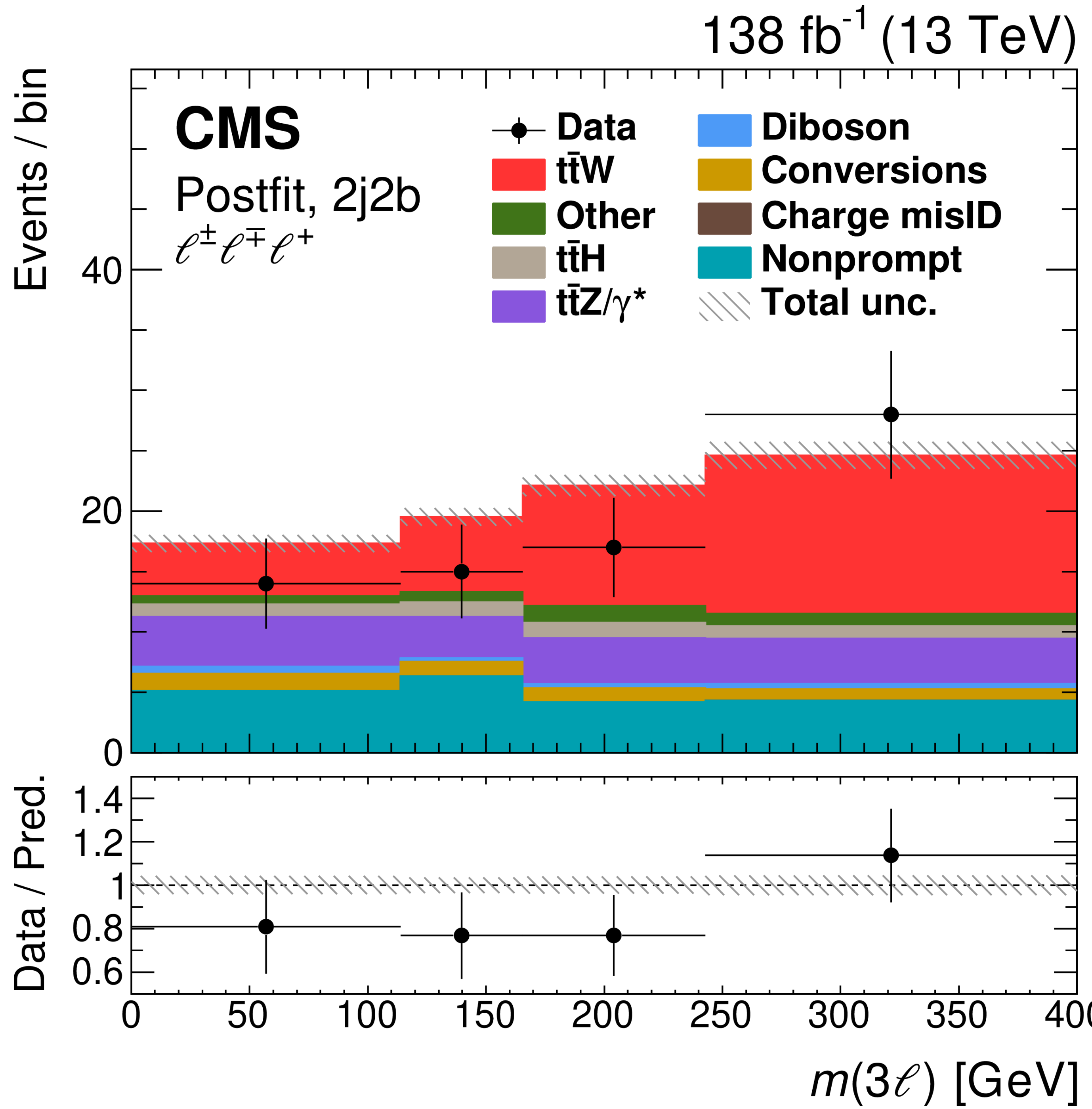
2ℓSS	**3ℓ**
Event categories based on ℓ flavor & charge	12 event categories based on jet and b-tag multiplicities & charge of the 3ℓ system
DNN discr. for signal vs bkg. separation	Signal extraction using $m(3\ell)$ observable



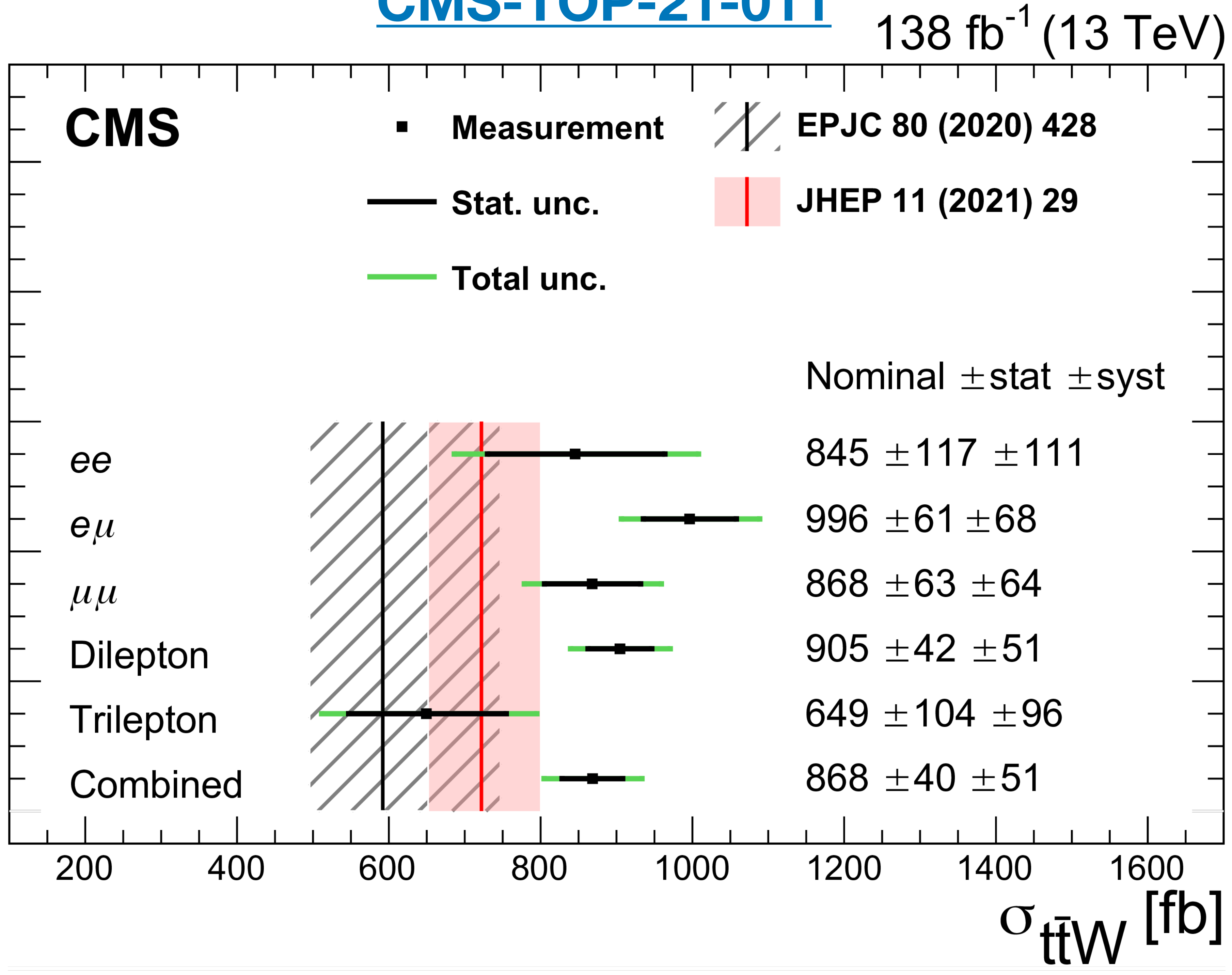
- Additional CRs defined with 3ℓ or 4ℓ events to control WZ and $t\bar{t}Z$ bkgs.

- Final $t\bar{t}W$ normalization extracted by profile likelihood fit in $2\ell SS$ + 3ℓ + CRs





CMS-TOP-21-011



$t\bar{t}W$ production

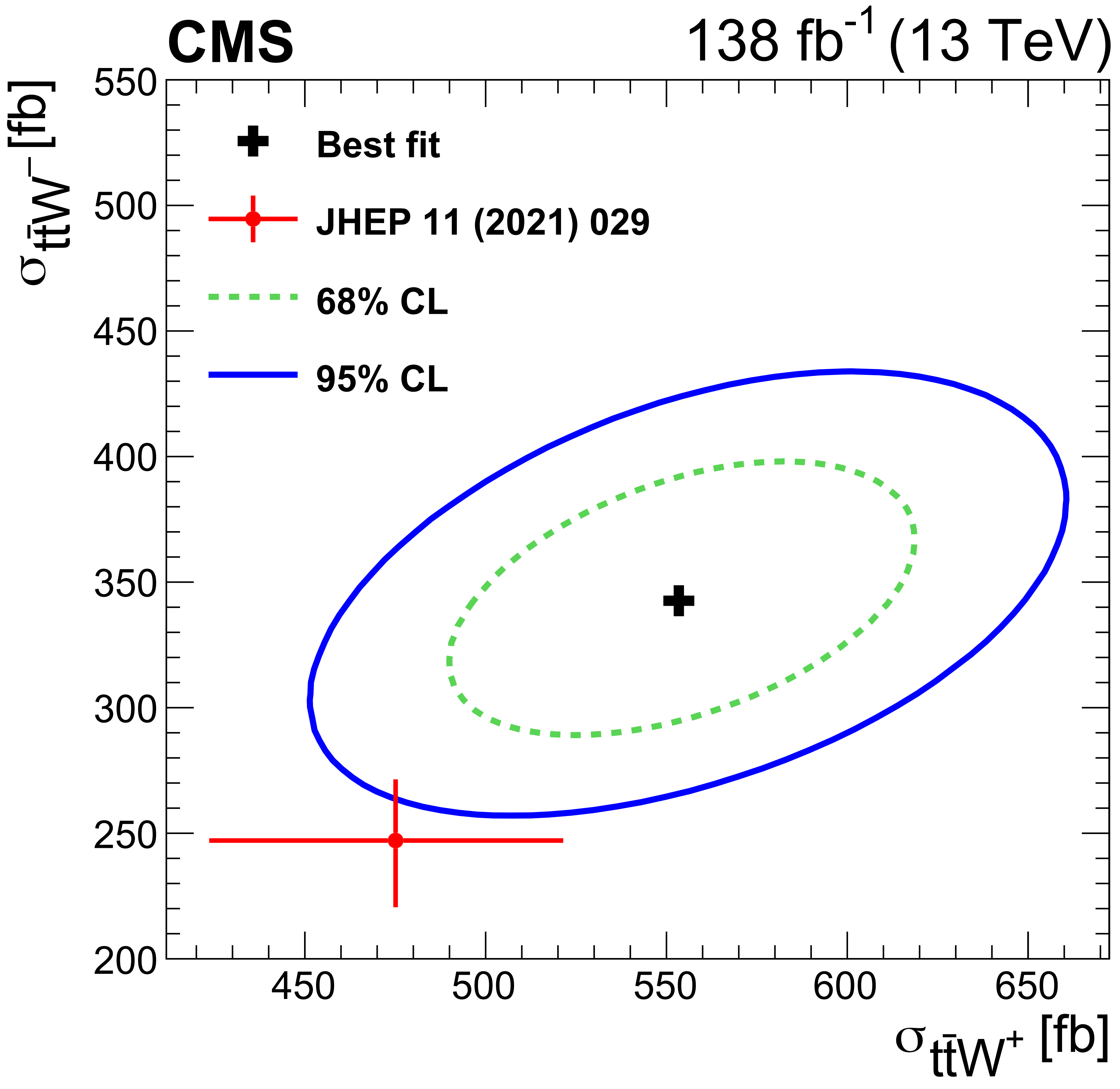
Observable	Measurement	SM prediction NLO + NNLL	SM prediction NLO + FxFx
$\sigma_{t\bar{t}W}$	$868 \pm 40\,(\text{stat}) \pm 51\,(\text{syst})$ fb	$592\,^{+155}_{-97}\,(\text{theo})$ fb	$722\,^{+71}_{-78}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W^+}$	$553 \pm 30\,(\text{stat}) \pm 30\,(\text{syst})$ fb	$384\,^{+53}_{-33}\,(\text{theo})$ fb	$475\,^{+46}_{-52}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W^-}$	$343 \pm 26\,(\text{stat}) \pm 25\,(\text{syst})$ fb	$198\,^{+26}_{-17}\,(\text{theo})$ fb	$247\,^{+24}_{-27}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W^+} / \sigma_{t\bar{t}W^-}$	$1.61 \pm 0.15\,(\text{stat})\,^{+0.07}_{-0.05}\,(\text{syst})$	$1.94\,^{+0.37}_{-0.24}\,(\text{theo})$	$1.92\,^{+0.27}_{-0.29}\,(\text{theo})$

Factor of 2 improvement on systematic uncertainty w.r.t earlier measurement @ 13 TeV with only 2016 data !!!

Dominant systematics:

- $t\bar{t}H$ normalization (2.6%)
- Luminosity(1.9%)
- $t\bar{t}W$ ME scale (1.8 %)
- b tagging efficiency (1.6 %)

CMS-TOP-21-011



Inclusive and differential $t\bar{t}\gamma$: 2ℓ

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

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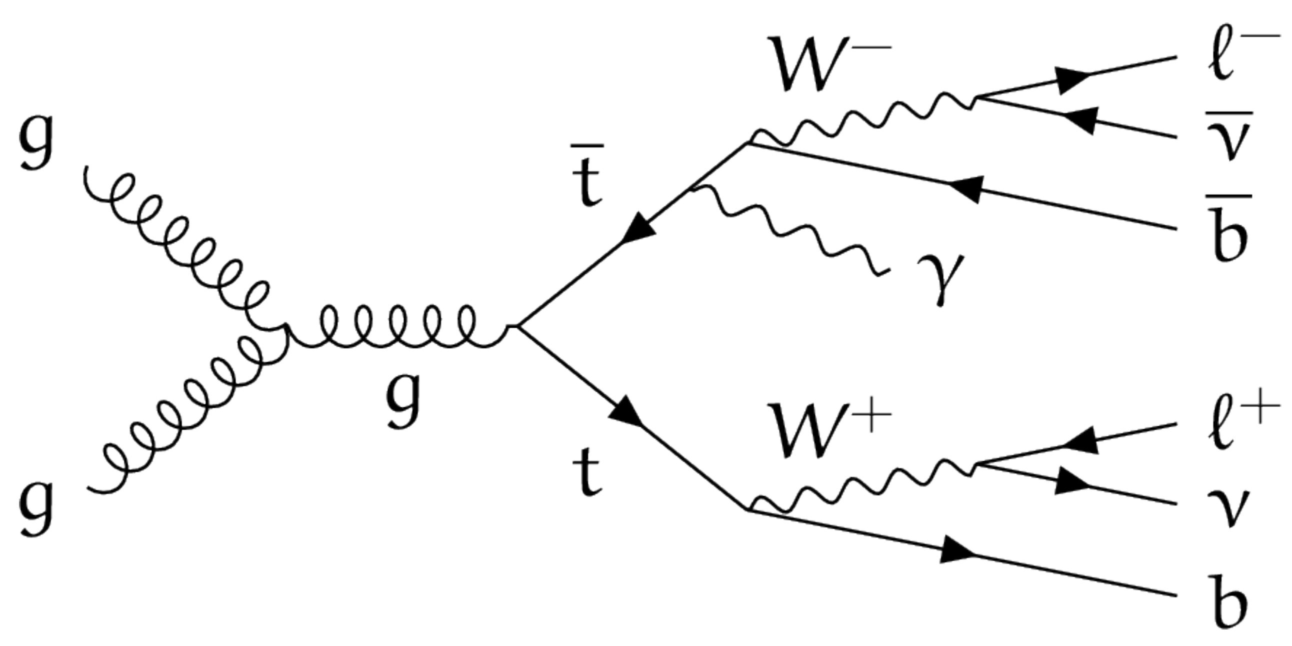
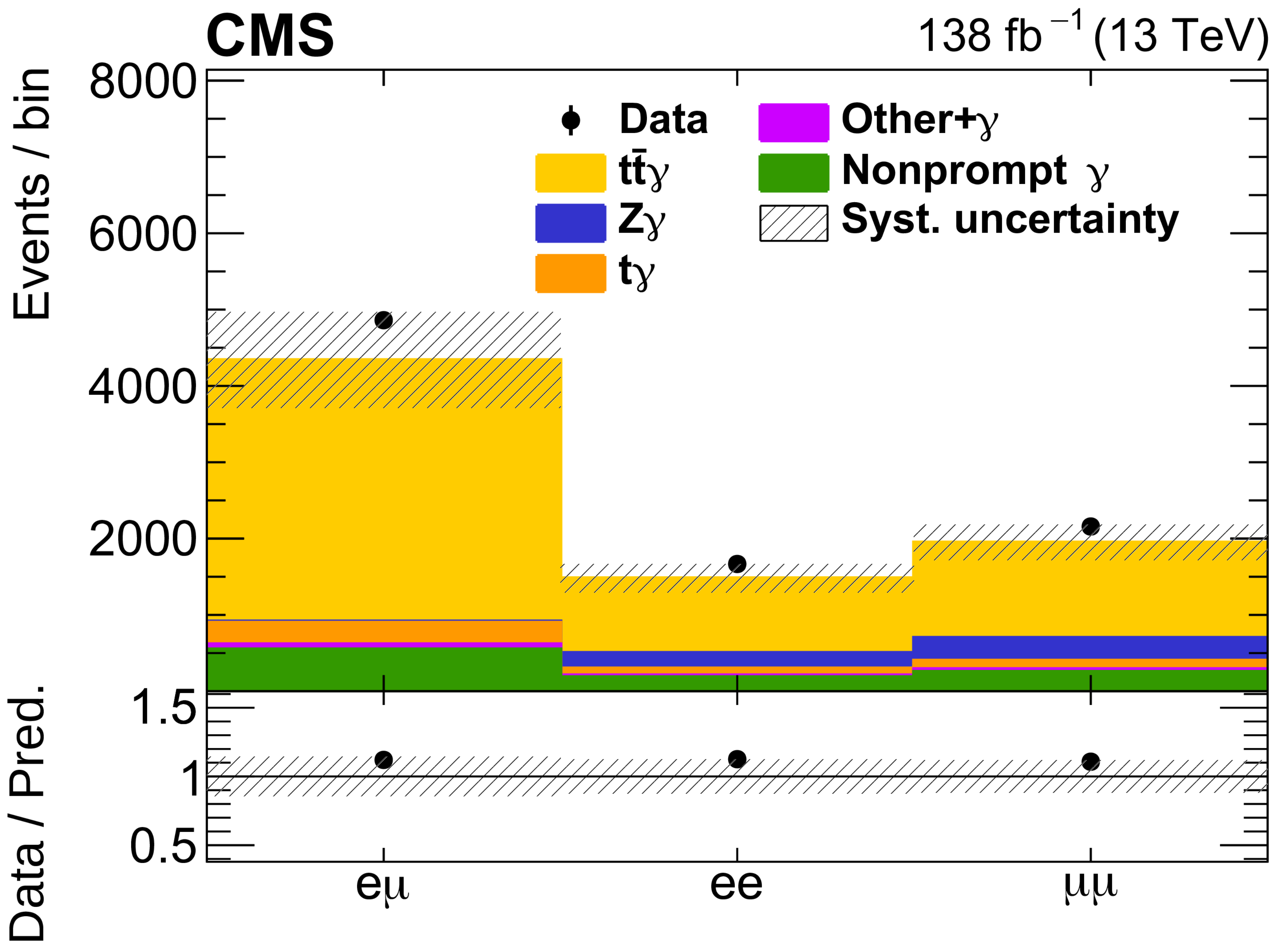
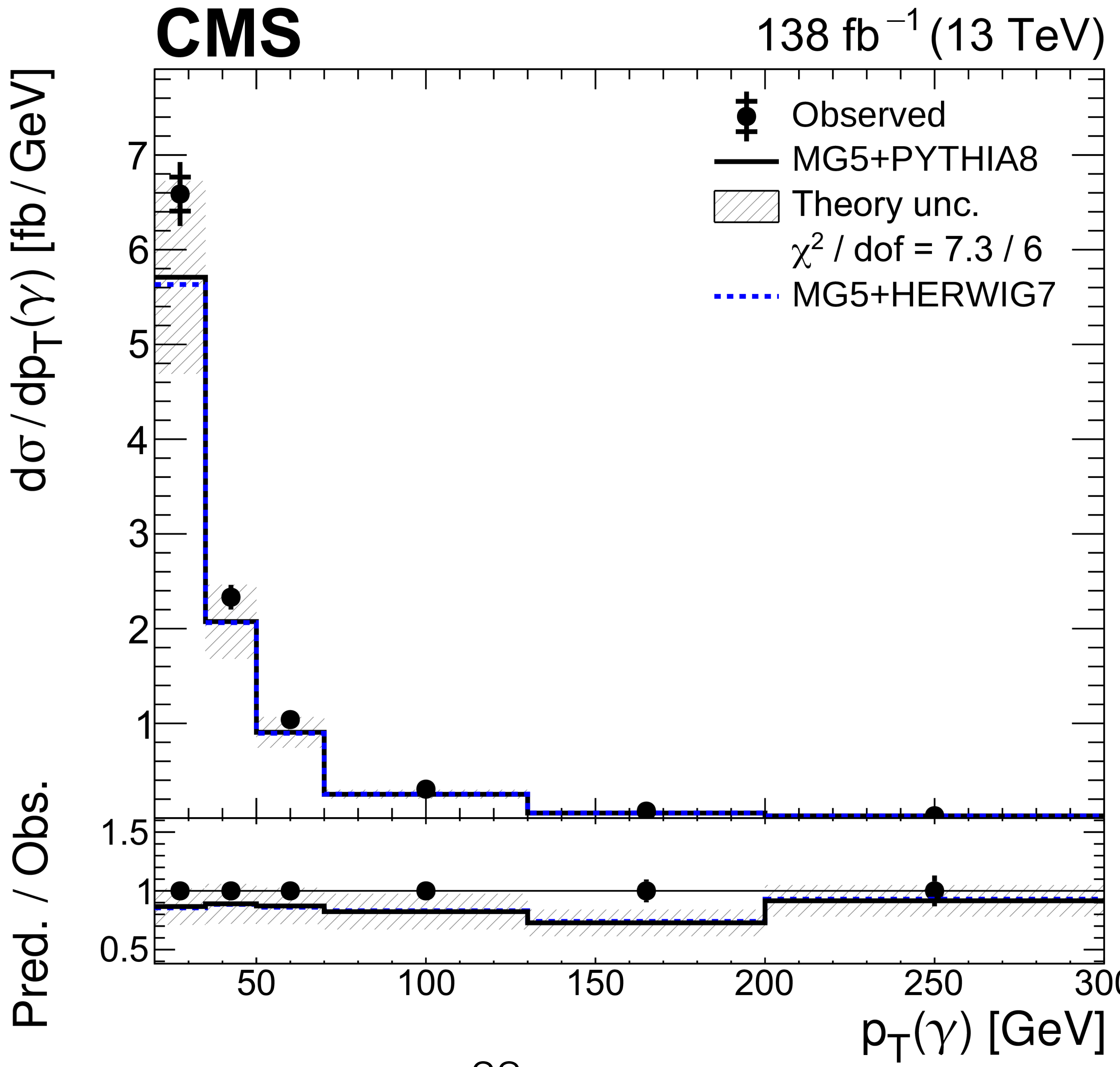
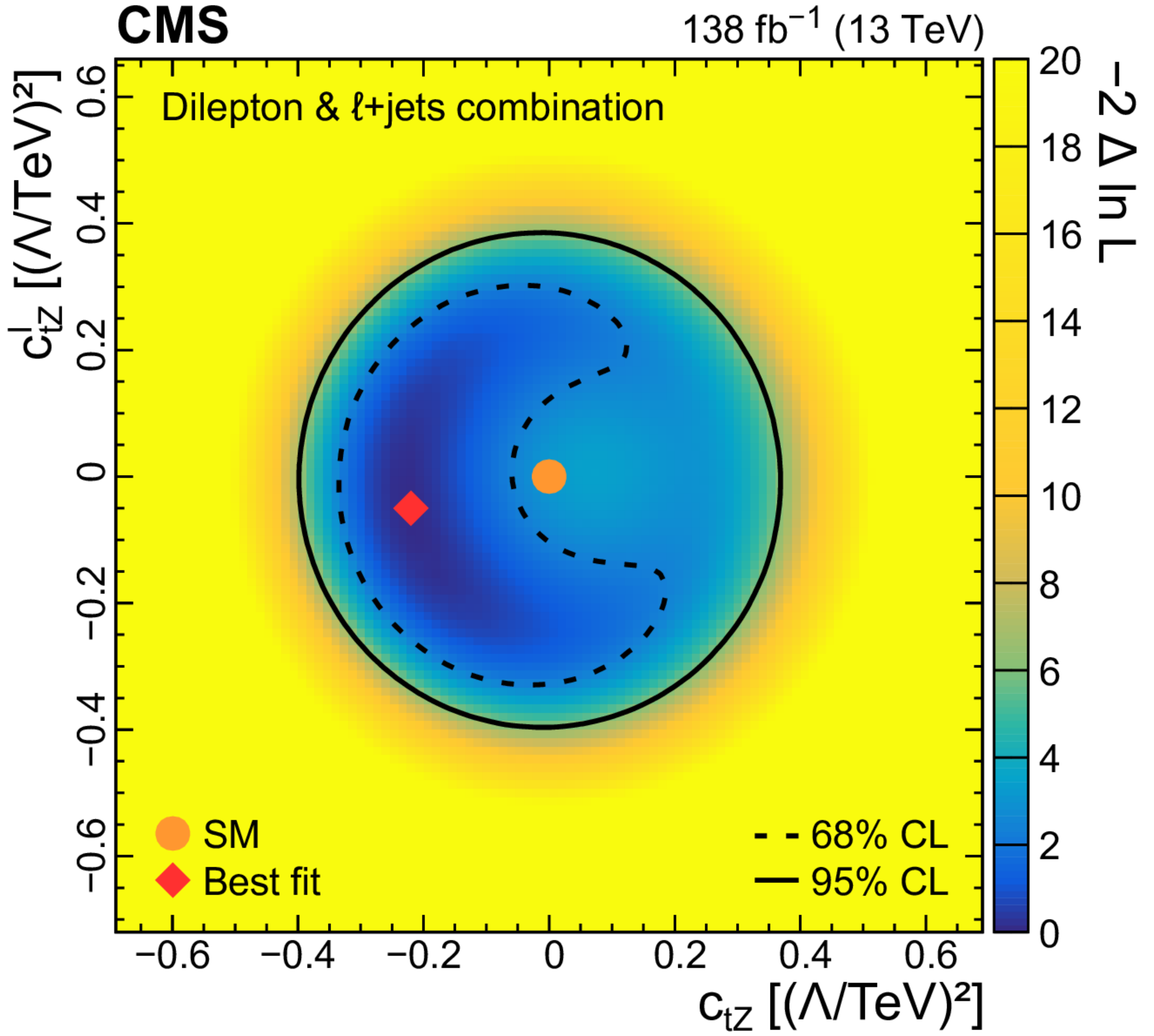
- Exactly 1γ, exactly 1 OS ℓ pair, $\geqslant 1$ b-tagged jet in the final state
  ➛ Bkgs.: Non-prompt γ (data-driven), Zγ (from Z peak), others from simulation
- Measured: $\sigma_{t\bar{t}\gamma} = 175.2 \pm 2.5(\text{stat}) \pm 6.3(\text{syst})$ fb (4%)
  ➛ Dominant sources: Luminosity, signal model, bkg. normalization



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







Inclusive and differential $t\bar{t}\gamma$: ℓ + jets

- NLO Prediction: $\sigma_{t\bar{t}\gamma} = 773 \pm 135\,\text{fb}$ $\left[p_T(\gamma) > 20\ \text{GeV}\ \&\ |\eta(\gamma)| < 1.442\right]$
- Final state consists of exactly 1 γ, exactly 1 ℓ, ≥ 3 jets, ≥ 1 b-tagged jet
- Measured inclusive cross section: $\sigma_{t\bar{t}\gamma} = 798 \pm 7\ (\text{stat})\ \pm 48\ (\text{syst})\ \text{fb}$
- Differential measurements used to extract limits on EFT coupling C_{tZ}

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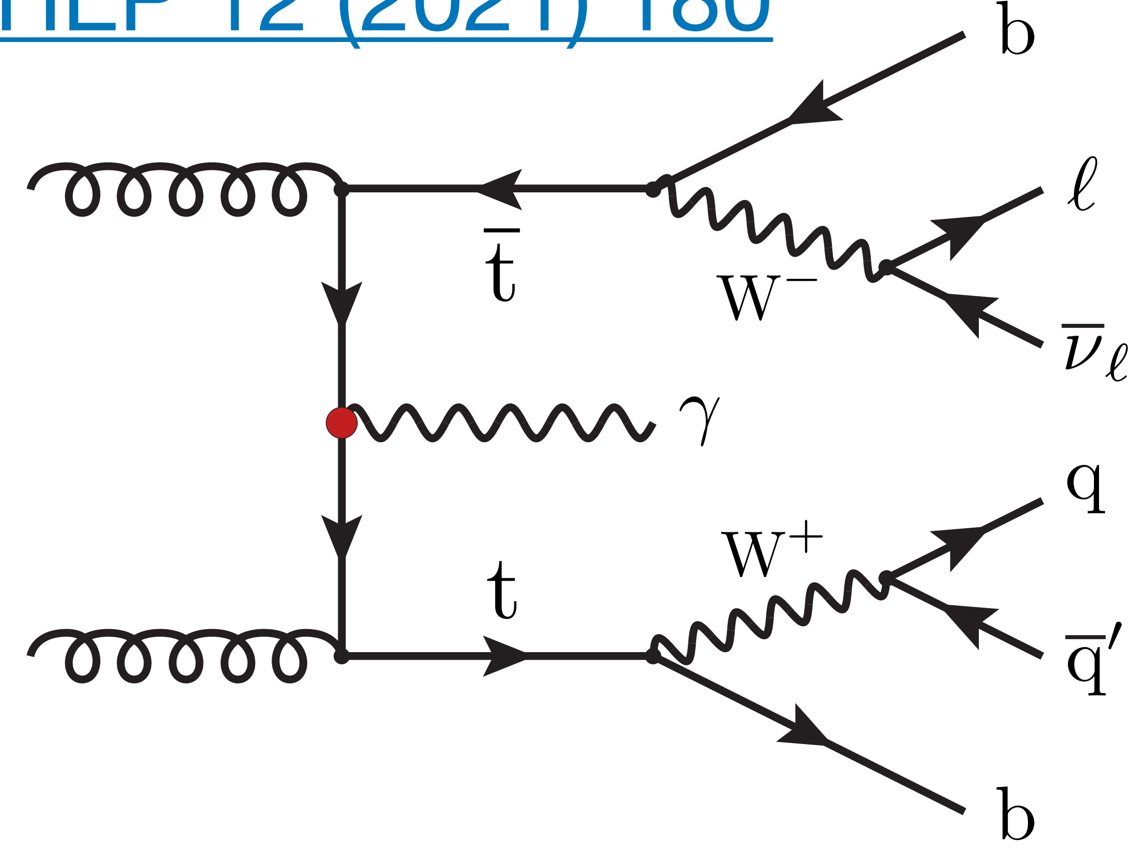
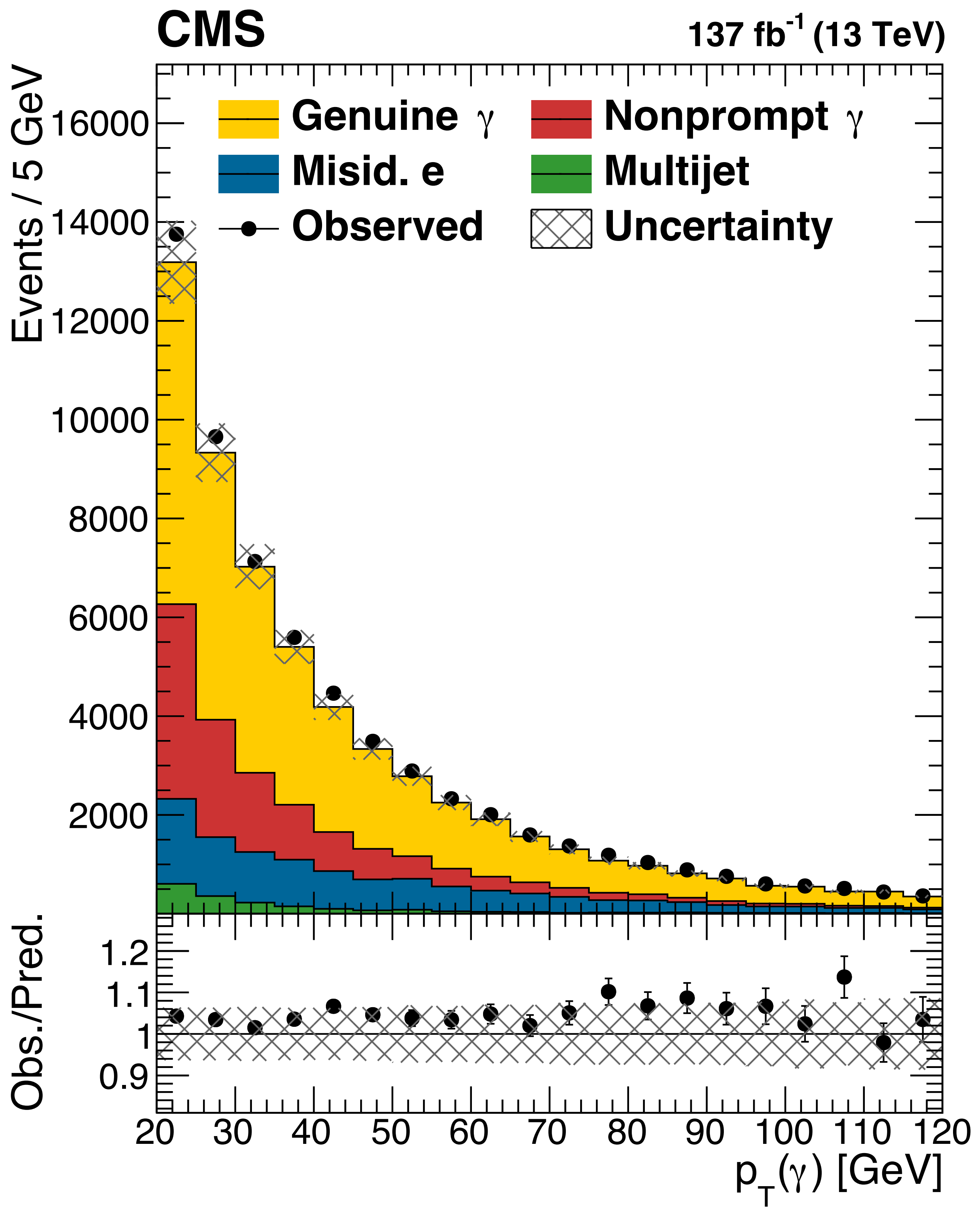
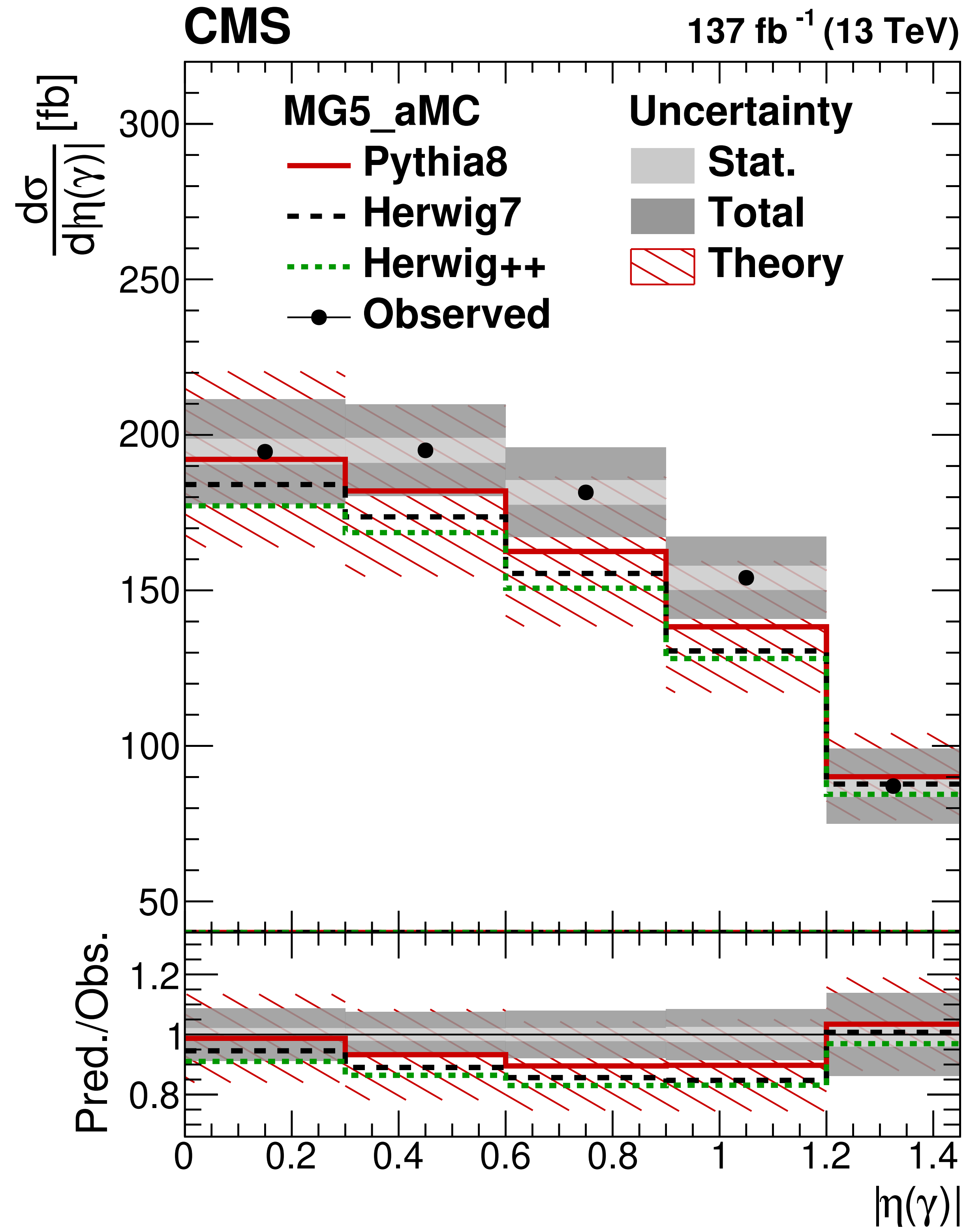
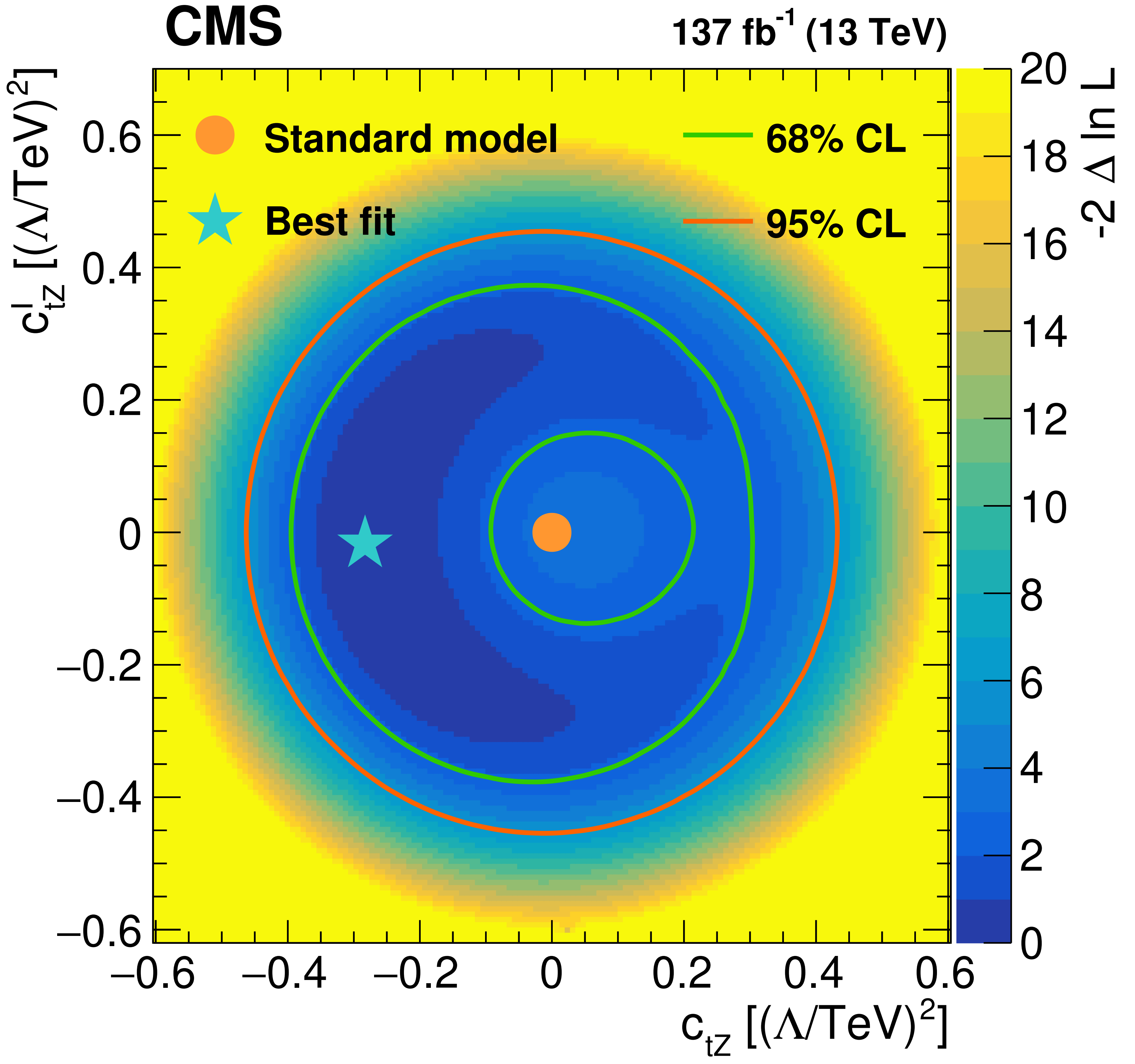
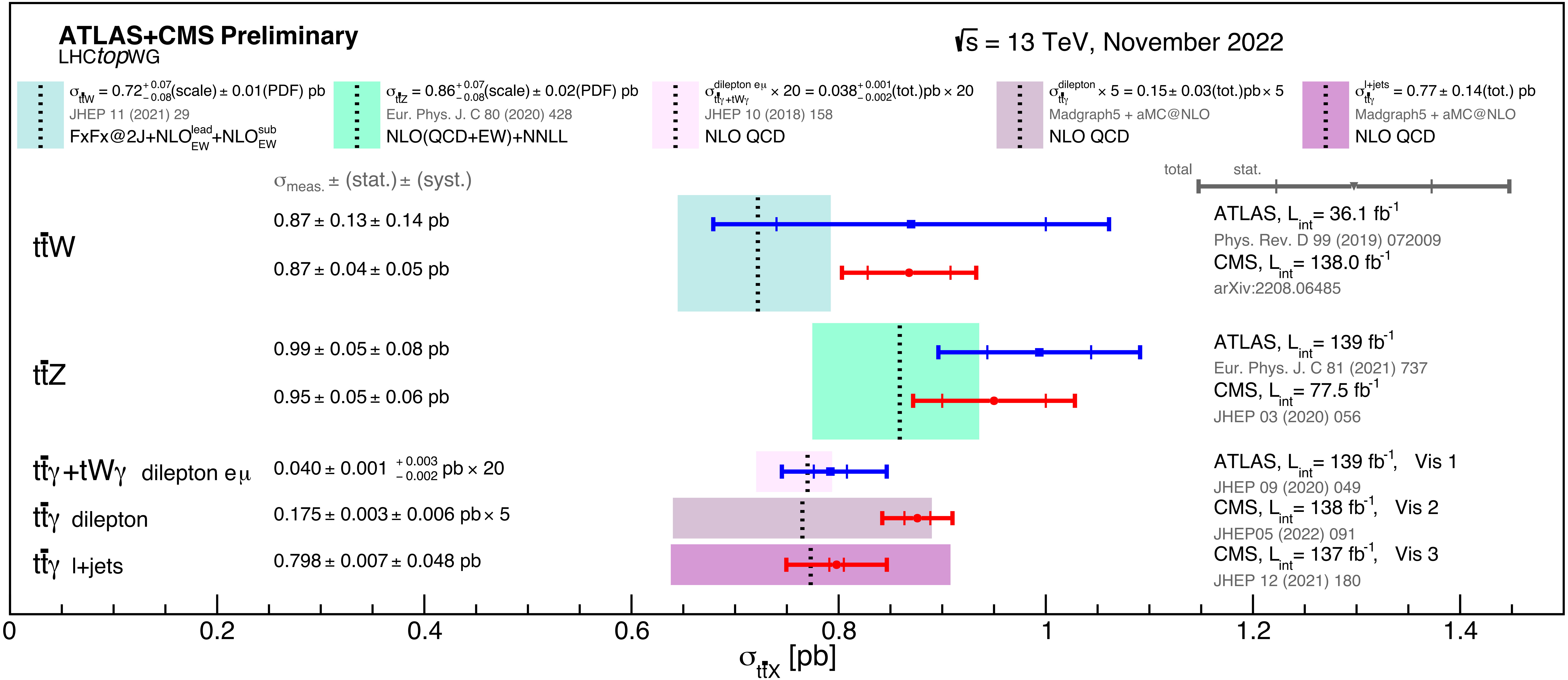








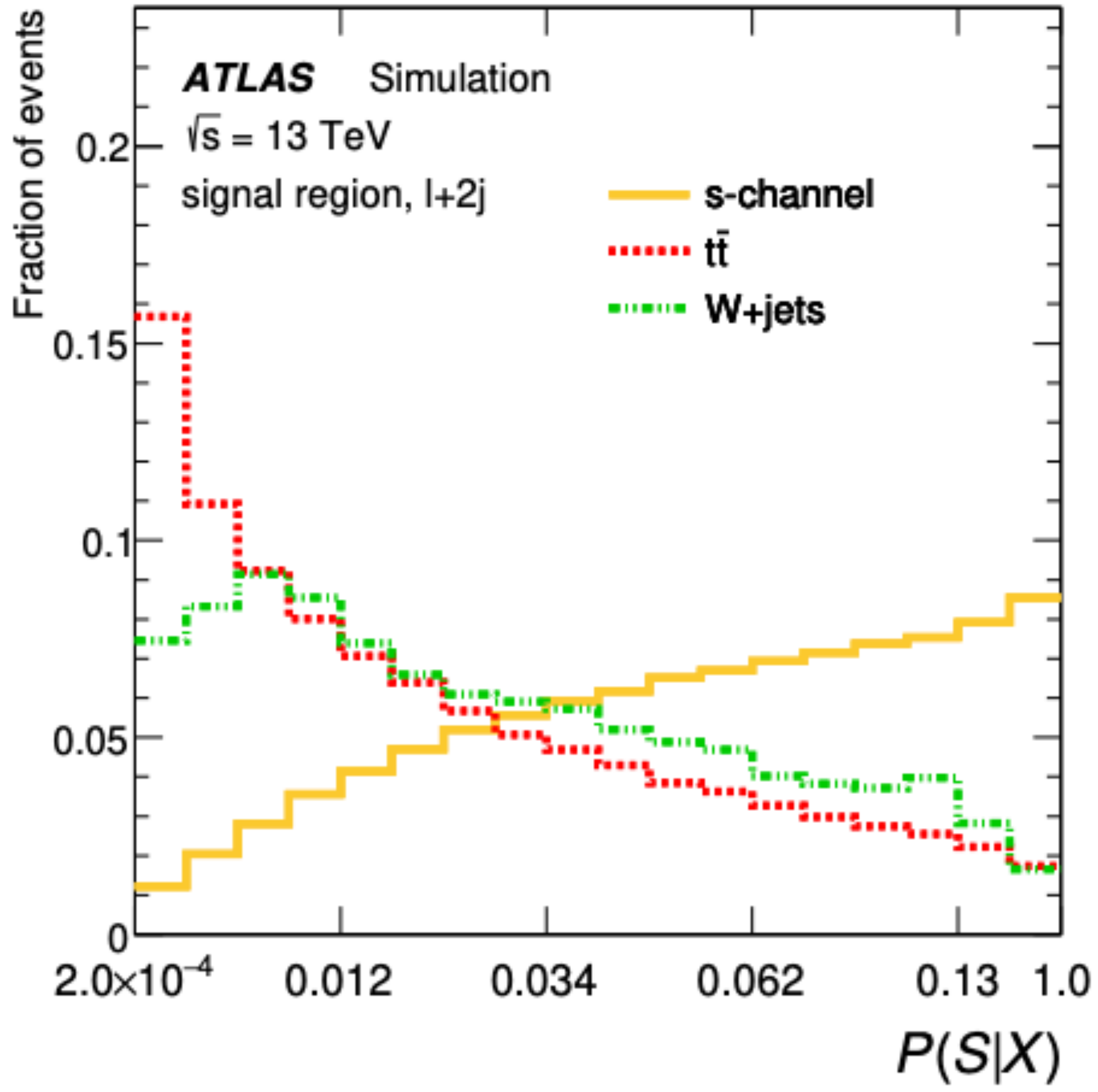
Summary of $t\bar{t}V$ measurements



LHCTOPWGSummaryPlots arXiv:2209.08990

$$\mathcal{P}(X \mid H_{\text{proc}}) = \int \mathrm{d}\Phi \, \frac{1}{\sigma_{H_{\text{proc}}}} \frac{\mathrm{d}\sigma_{H_{\text{proc}}}}{\mathrm{d}\Phi} T_{H_{\text{proc}}}(X \mid \Phi) \, .$$

$$P(S \mid X) = \frac{\sum_i P(S_i)\, \mathcal{P}(X \mid S_i)}{\sum_i P(S_i)\, \mathcal{P}(X \mid S_i) + \sum_j P(B_j)\, \mathcal{P}(X \mid B_j)}$$



Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ normalisation	+24/−17
$t\bar{t}$ shape modelling	+18/−15
PS & had.	+12/−10
ME/PS matching	+10/−8
h_{damp}	< 1
s-channel modelling	+18/−8
PS & had.	+18/−8
ISR/FSR	+3/−1
Jet energy resolution	+18/−12
Jet energy scale	+18/−13
MC statistics	+13/−11
Flavour tagging	+12/−10
$W+$jets normalisation	+11/−8
PDFs	+10/−9
$t\bar{t}$	+10/−9
s-channel	±1
t-channel	±1
tW	±1
t-channel modelling	±6
PS & had.	±5
ISR/FSR	±4
$W+$jets $\mu_{\text{r}}/\mu_{\text{f}}$ shape	+6/−5
Normalisation of other processes	+6/−5
Pile-up	+5/−3
Luminosity	+4/−3
tW modelling	+1/−2
PS & had.	±1
$t\bar{t}$ overlap	±1
ISR/FSR	±1
Missing transverse momentum	±1
Multijet shape modelling	±1
Other detector sources	±1
Systematic uncertainties	+42/−34
Statistical uncertainty	±8
Total	+42/−35

Observation of $tq\gamma$ production

arXiv:2302.01283

Fiducial region

Parton level

- At least one photon with $p_T \geq 20$ GeV Frixione isolated with $\Delta R < 0.2$.

Particle level

- One lepton with $p_T \geq 25$ GeV
- At least one photon with $p_T \geq 25$ GeV.
- One b with $p_T \geq 25$ GeV
- One neutrino not from a hadron decay

Parton-level

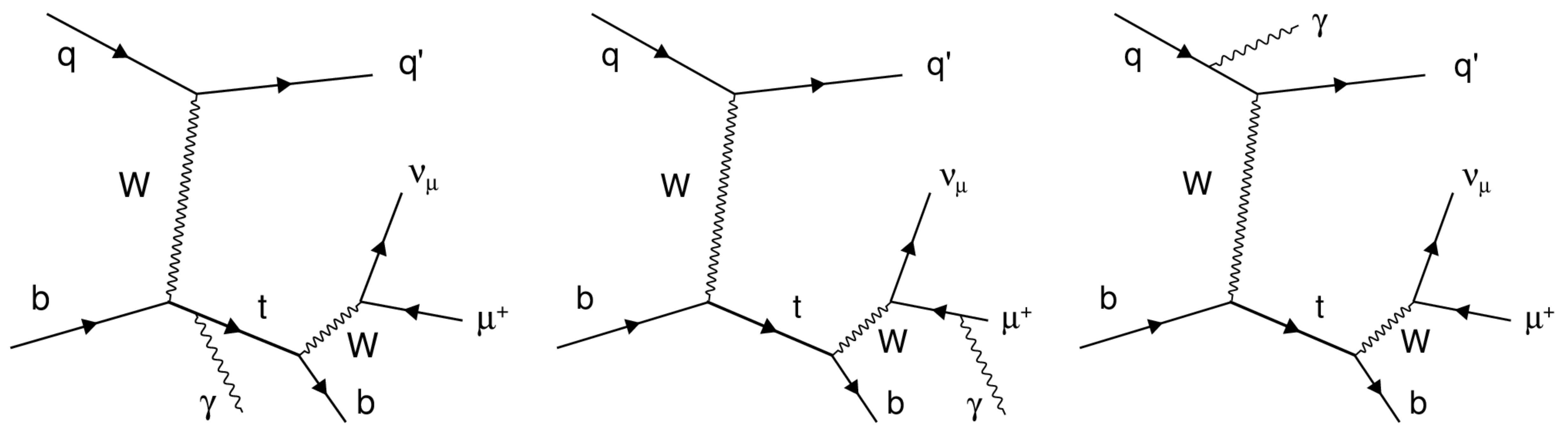
Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modeling	±5.5%
Background MC statistics	±3.5%
$tq\gamma$ MC statistics	±3.3%
$t\bar{t}$ modeling	±2.4%
$tq\gamma$ modeling	±2.0%
$t\,(\rightarrow \ell\nu b\gamma)\,q$ modeling	±1.9%
Additional background uncertainties	±1.9%
$t\,(\rightarrow \ell\nu b\gamma)\,q$ MC statistics	±0.3%
$h \rightarrow \gamma$ photon fakes	±2.0%
Lepton fakes	±1.9%
$e \rightarrow \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.2%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.6%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.9%
Total systematic uncertainty	±10.6%

Particle-level

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modeling	±5.5%
Background MC statistics	±3.6%
$t\,(\rightarrow \ell\nu b\gamma)\,q$ modeling	±3.3%
$tq\gamma$ MC statistics	±3.0%
$t\bar{t}$ modeling	±2.3%
$tq\gamma$ modeling	±2.3%
Additional background uncertainties	±2.0%
$t\,(\rightarrow \ell\nu b\gamma)\,q$ MC statistics	±0.3%
Lepton fakes	±2.2%
$h \rightarrow \gamma$ photon fakes	±2.1%
$e \rightarrow \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.3%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.5%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.7%
Total systematic uncertainty	±10.7%

Evidence for $tq\gamma$ (CMS-TOP-17-016)

- $1\mu, 1\gamma$, & 2j1b in the final state
- $\Delta R(X, \gamma) > 0.5$, where $X = \mu$ or jets
  - ➛ Removes overlap b/w single top + "soft" γ (PS) & single top + "hard" γ (ME)

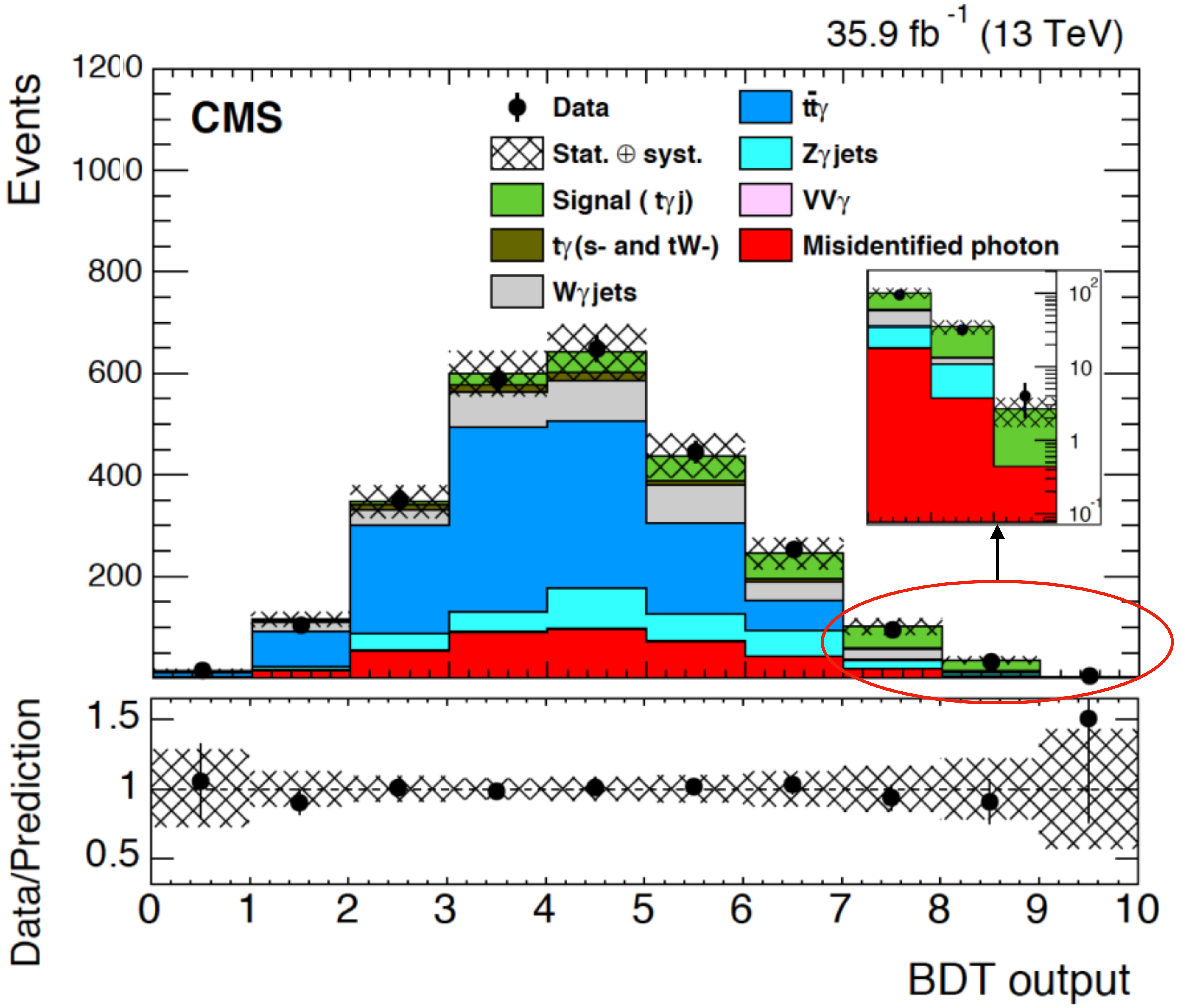


- Fake γ bkg. estimated from SB data ➛ loose *Id.* and inversion of *Iso.* / *shower shape* criteria
- Maximum likelihood fit to BDT discriminant to extract signal

$$\sigma^{\text{Fid.}}(pp \to t\gamma j)\mathscr{B}(t \to \mu\nu b) = 115 \pm 17(\text{stat}) \pm 30(\text{syst})\ \text{fb}$$

$$\sigma^{\text{Fid.}}_{\text{SM}} = 81 \pm 4\ \text{fb}$$

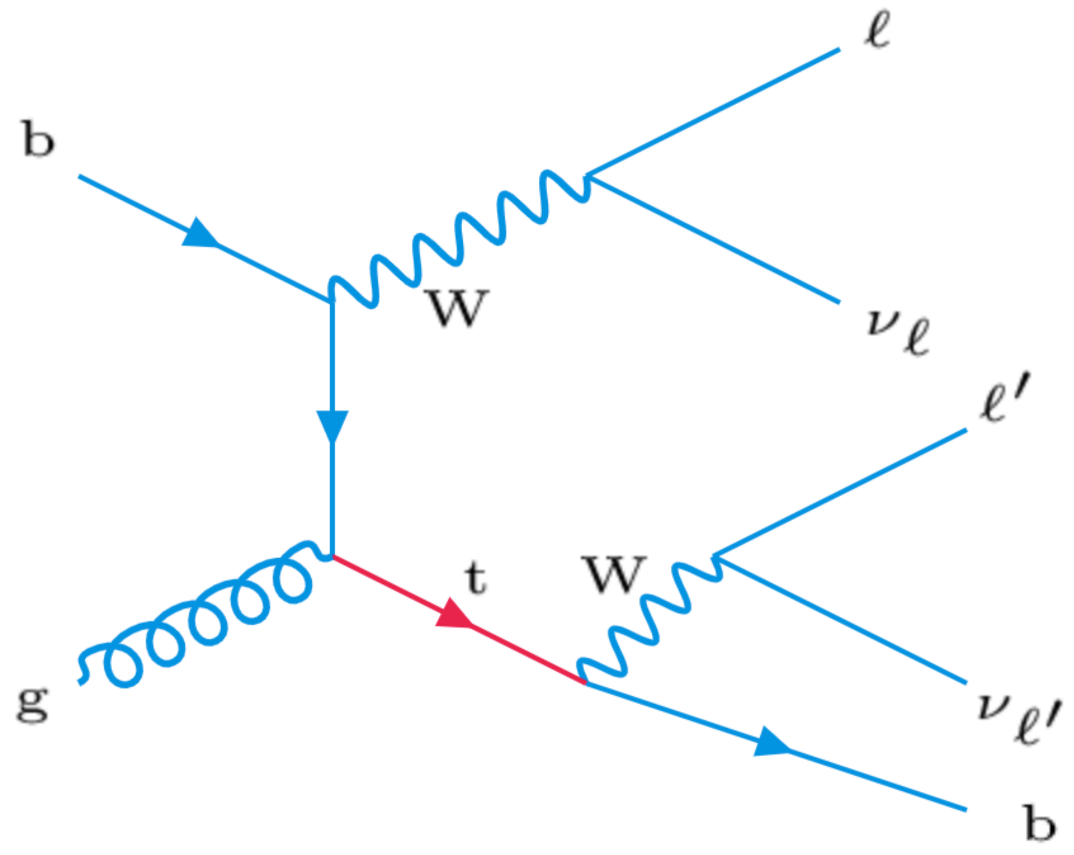
- Observed (Expected) significance of 4.4 (3.0) s.d
- Dominant Uncertainties:
  - ➛ Jet energy scale ~ 12%
  - ➛ Signal modeling ~ 9%
  - ➛ Estimation of Zγ+jets Bkg. ~ 8%
  - ➛ b-tag/mistag ~ 7%

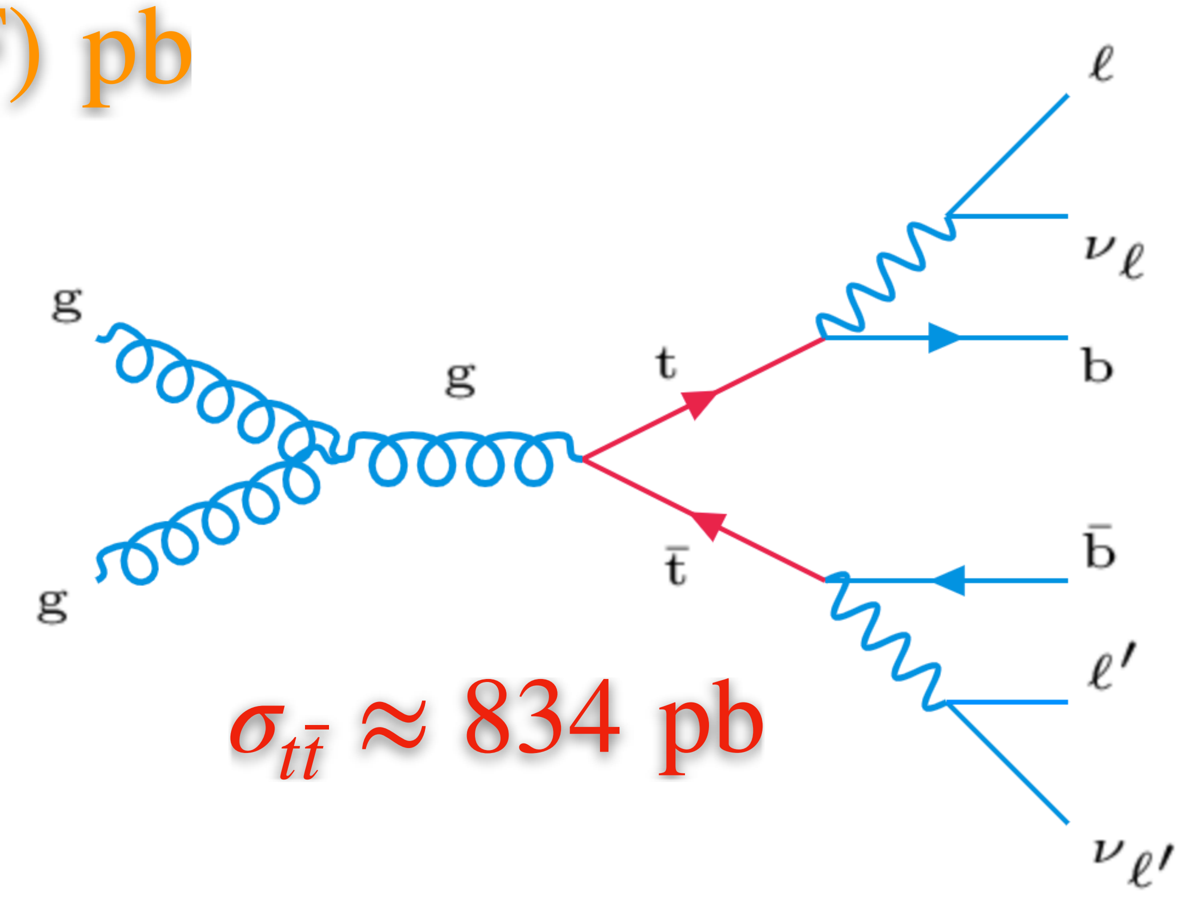


tW production

- tW @NLO has large interference with $t\bar{t}$
- Two schemes to tackle this in MC
  - ☞ Remove $t\bar{t}$ diagrams from ME → Diagram Removal (DR)
  - ☞ Local subtraction term added to ME to cancel resonant $t\bar{t}$ contribution → Diagram Subtraction (DS)
- Diff. b/w DR (nominal) and DS (alternative) schemes as signal modeling uncertainty

$\sigma_{tW}^{\text{N3LO}} = 79.5 \pm 1.9\ (\text{scale}) \pm 1.7\ (\text{PDF})\ \text{pb}$

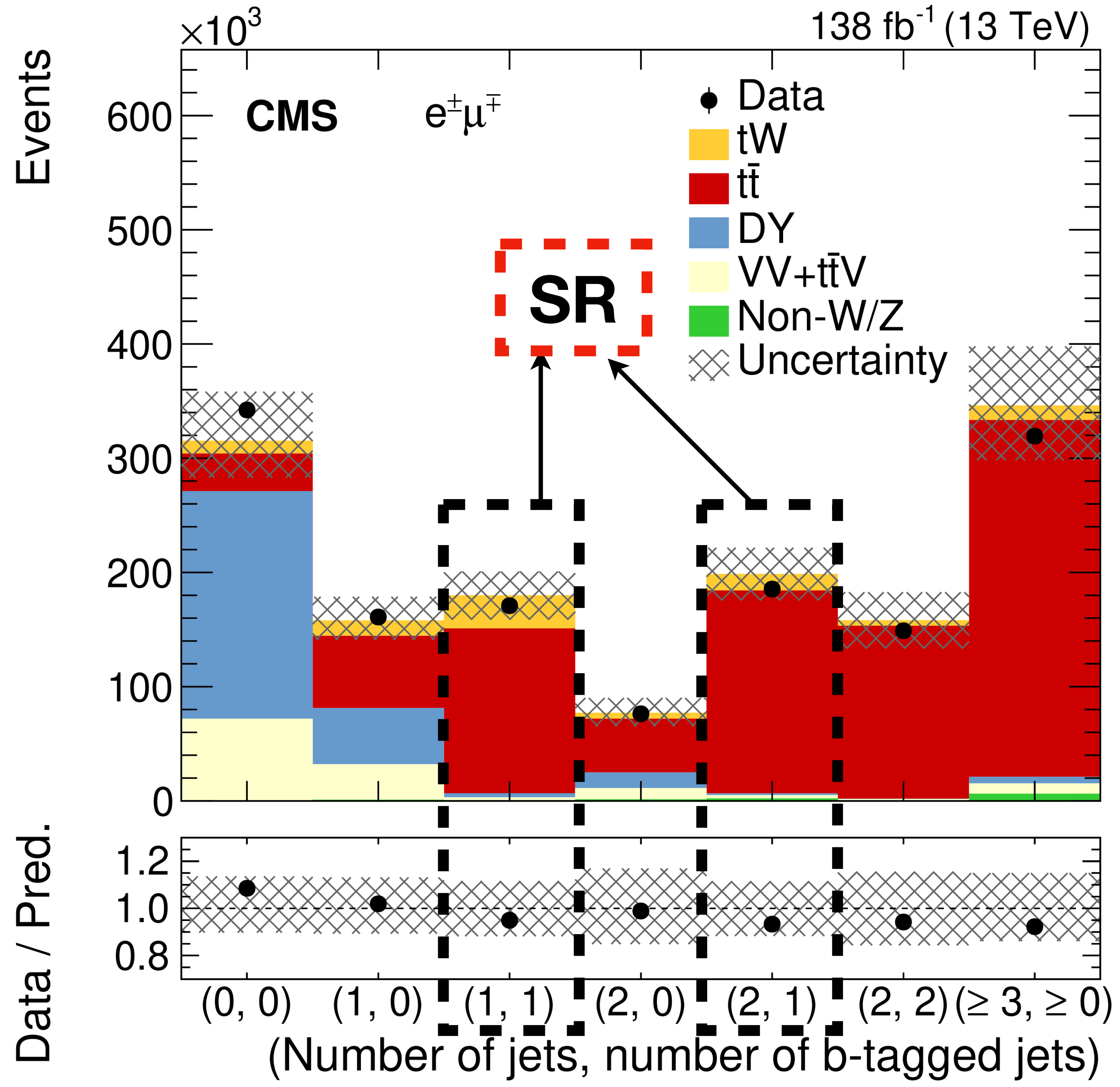


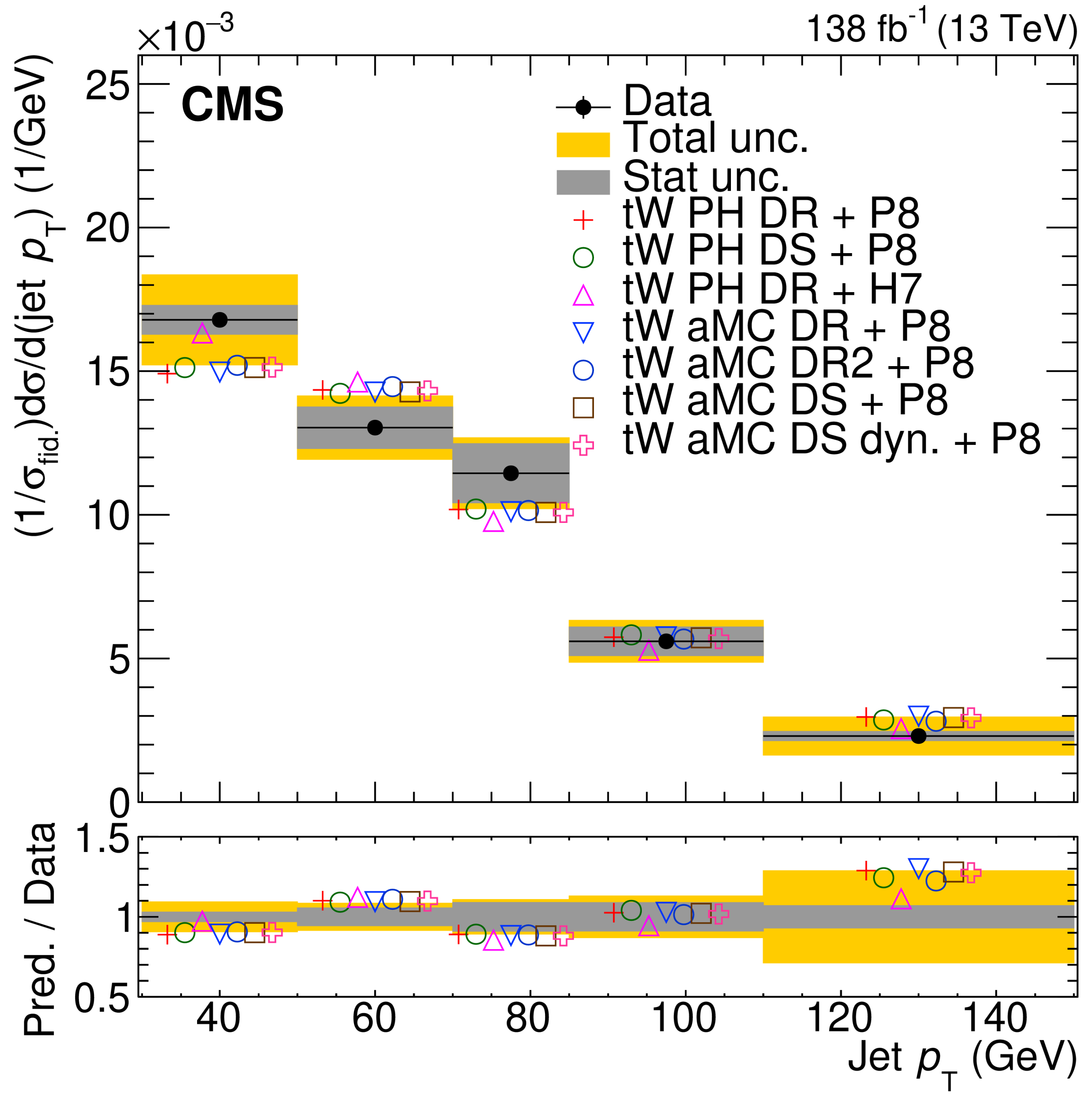


$\sigma_{t\bar{t}} \approx 834\ \text{pb}$

CMS-TOP-21-010

- BDTs to separate tW signal from $t\bar{t}$
  → ML fit to BDTs in 1j1b and 2j1b to extract signal
- $\sigma_{tW}^{\text{meas.}} = 79.2 \pm 0.8\ (\text{stat}) \pm 7.1\ (\text{syst}) \pm 1.1\ (\text{lumi})\ \text{pb}$
- Dominant sources: JES, non-W/Z bkg. rate, μ_R & μ_F scales of tW signal
- Diff. cross section measured against various kinematic variables → Good agreement b/w data and various predictions





arXiv:2301.11605

Observable	Vertex	Coupling	Observed	Expected
	SRs+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	RH	12×10^{-5}	$10\,^{+4}_{-3} \times 10^{-5}$
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20\,^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19\,^{+0.04}_{-0.03}$
	SR1+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	9.7×10^{-5}	$8.6\,^{+3.6}_{-2.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.5×10^{-5}	$8.2\,^{+3.4}_{-2.3} \times 10^{-5}$
	SR2+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	7.8×10^{-5}	$6.1\,^{+2.7}_{-1.7} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.0×10^{-5}	$6.6\,^{+2.9}_{-1.8} \times 10^{-5}$

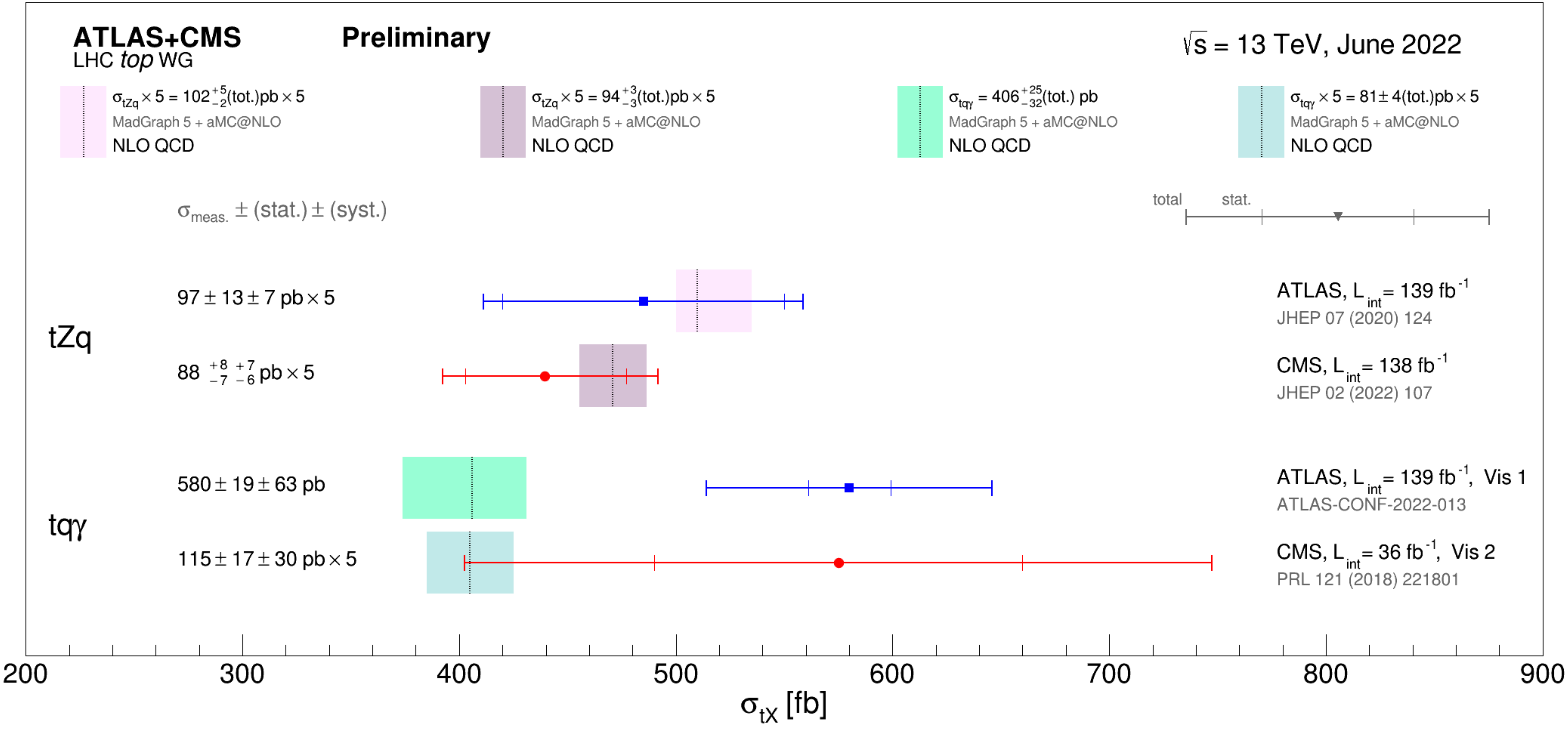
FCNC in $t\gamma$

New

CMS-PAS-TOP-21-013

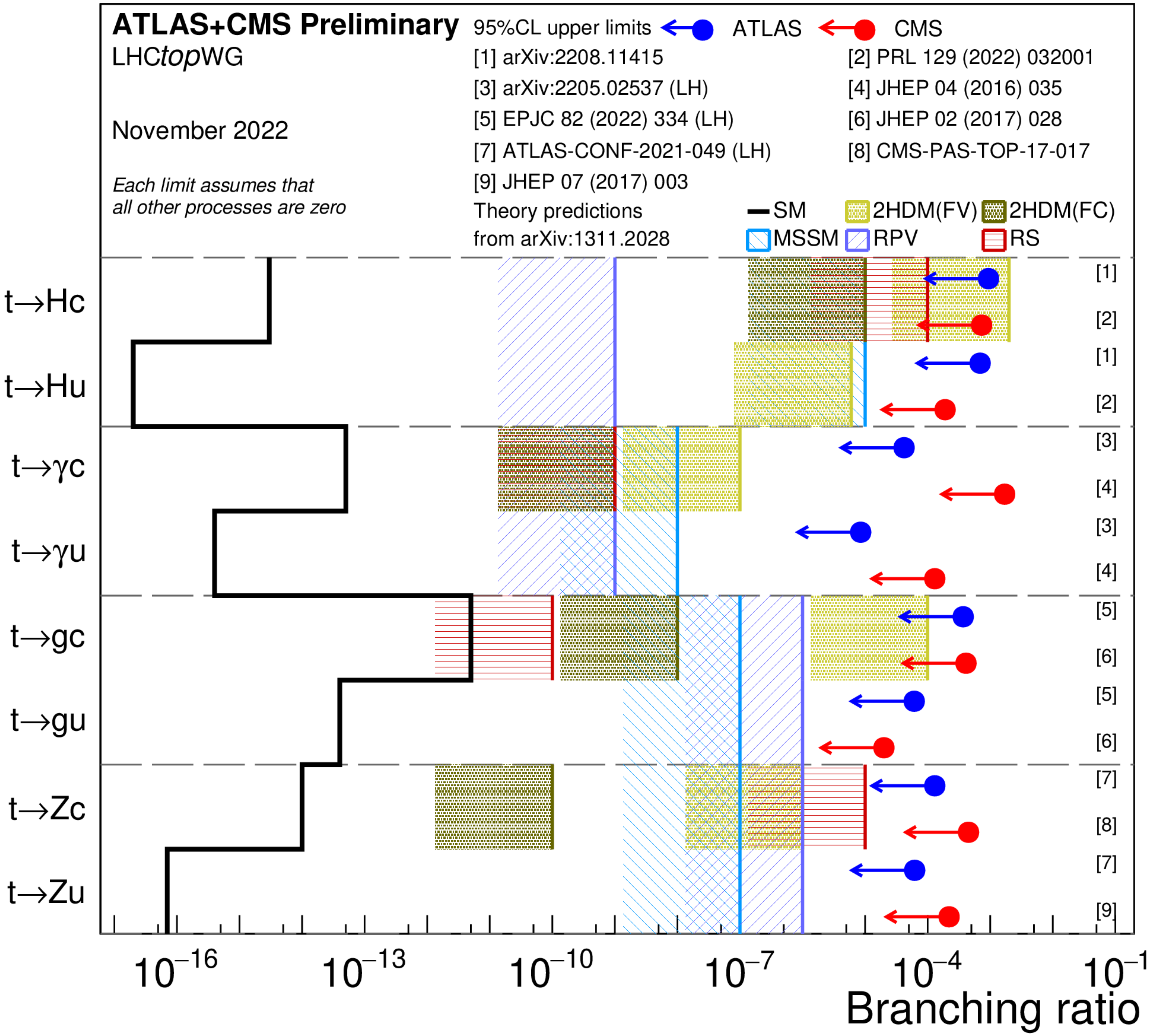
Combined	Obs. limit	Exp. limit	$\pm 1\sigma$ (exp. limit)	$\pm 2\sigma$ (exp. limit)
$\kappa_{tu\gamma}$	6.2×10^{-3}	6.9×10^{-3}	$(5.9 - 8.4) \times 10^{-3}$	$(5.1 - 10.1) \times 10^{-3}$
$\kappa_{tc\gamma}$	7.7×10^{-3}	7.8×10^{-3}	$(6.7 - 9.7) \times 10^{-3}$	$(5.7 - 11.5) \times 10^{-3}$
$\mathcal{B}(t \to u + \gamma)$	0.95×10^{-5}	1.20×10^{-5}	$(0.89 - 1.78) \times 10^{-5}$	$(0.64 - 2.57) \times 10^{-5}$
$\mathcal{B}(t \to c + \gamma)$	1.51×10^{-5}	1.54×10^{-5}	$(1.13 - 2.37) \times 10^{-5}$	$(0.81 - 3.32) \times 10^{-5}$

Summary of tX measurements



LHCTOPWGSummaryPlots

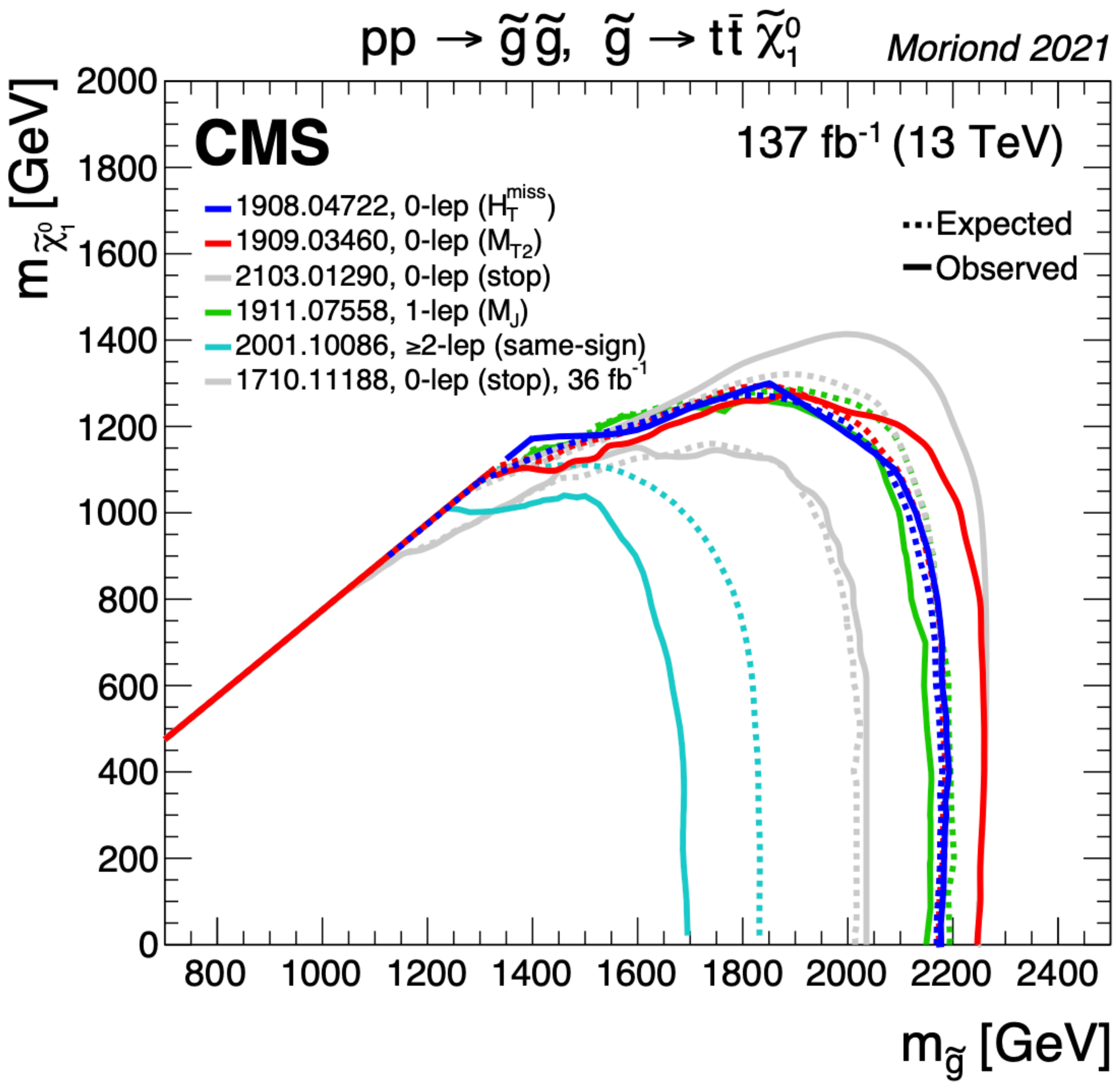
Summary of FCNC measurements



LHCTOPWGSummaryPlots

Limits @ *95% CL* from $\tilde{g}\tilde{g}$ production

CMS-SUSY-Summary-Plots



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