Top cross-section measurements and rare $t\bar{t}X$ processes

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26 May 2022
LHCP 2023 Belgrade

Introduction

- Heaviest particle in Standard Model
- Produced in copious numbers at LHC!
  - $t\bar{t}$ production: ~120M events @10 Hz for $\sqrt{s} = 13$ TeV
- Allows for precise tests of SM
- Interesting properties (interacts strongly with Higgs sector, …)

Also see talks by Thomas Stevenson, Massimiliano Grazzini, James Howarth, Ashley Parker, Adrian Salas, & Nicolas Chanon!

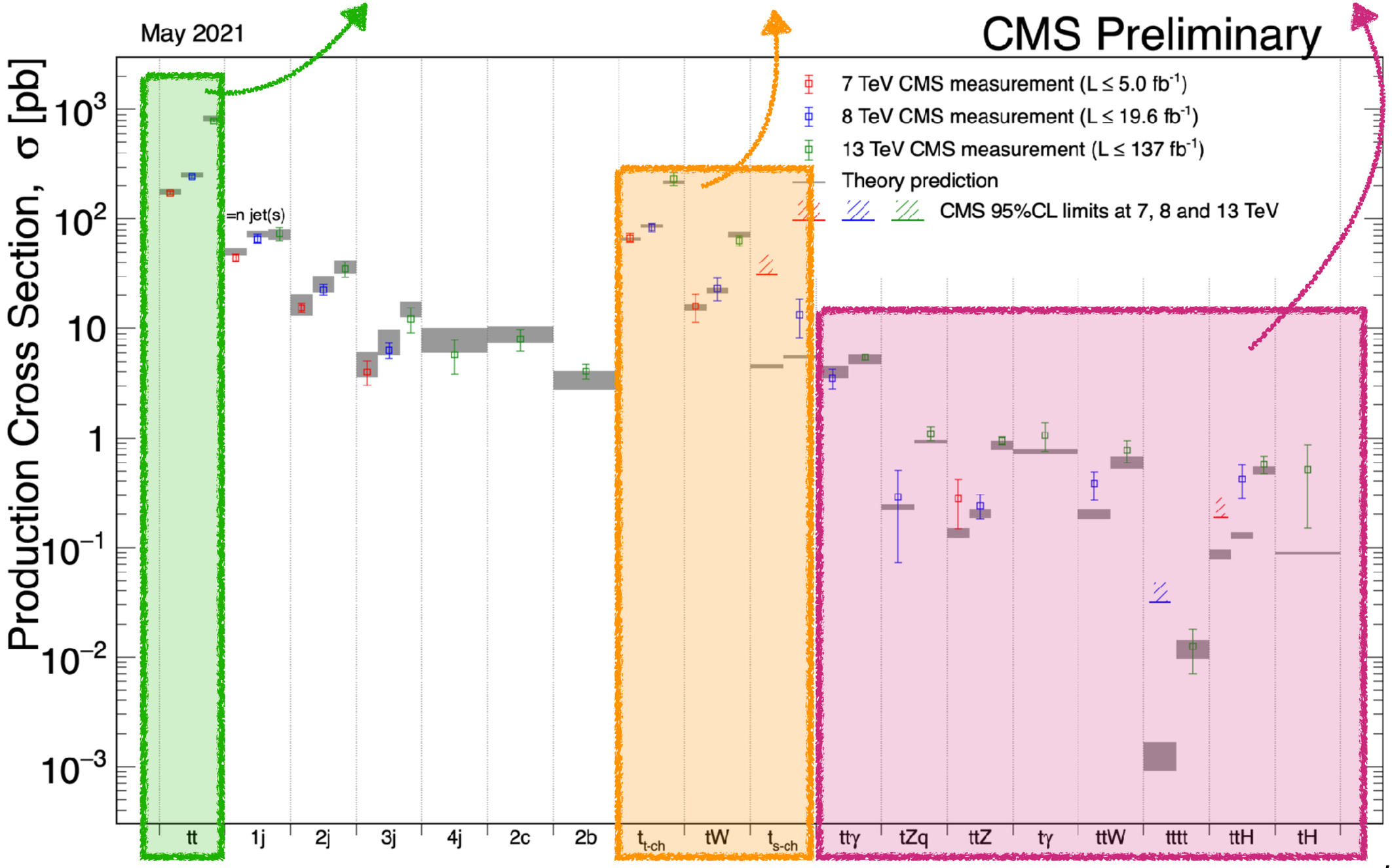
This talk highlights a few of the latest ATLAS & CMS top cross section and $t\bar{t}$X measurements

Overview

1) pair production
main production process, sensitive

2) single-top production
good EWK probe

3) associated production
rare tests of SM



xsec summary plot

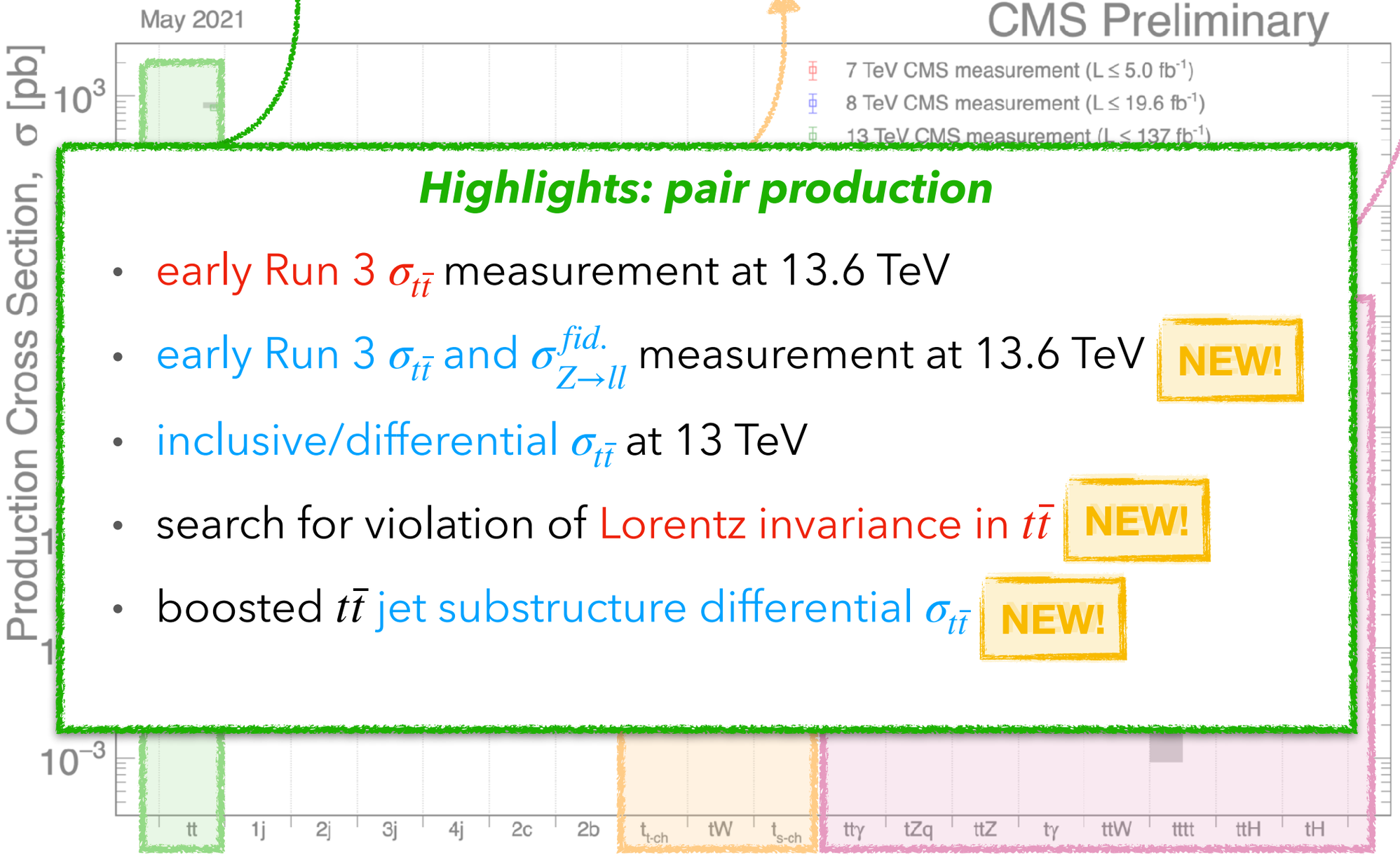
$t\bar{t}$ production

Also see talks by Mohammed Faraj, Kathryn Coldham, Federica Colombina, & Carmen Diez Pardos!

1) pair production

2) production

production



Highlights: pair production

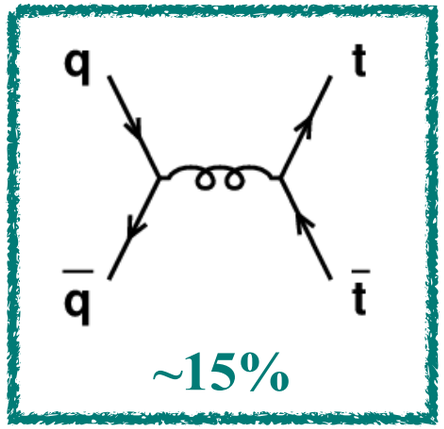
- early Run 3 $\sigma_{t\bar{t}}$ measurement at 13.6 TeV
- early Run 3 $\sigma_{t\bar{t}}$ and $\sigma^{fid.}_{Z\to ll}$ measurement at 13.6 TeV **NEW!**
- inclusive/differential $\sigma_{t\bar{t}}$ at 13 TeV
- search for violation of Lorentz invariance in $t\bar{t}$ **NEW!**
- boosted $t\bar{t}$ jet substructure differential $\sigma_{t\bar{t}}$ **NEW!**

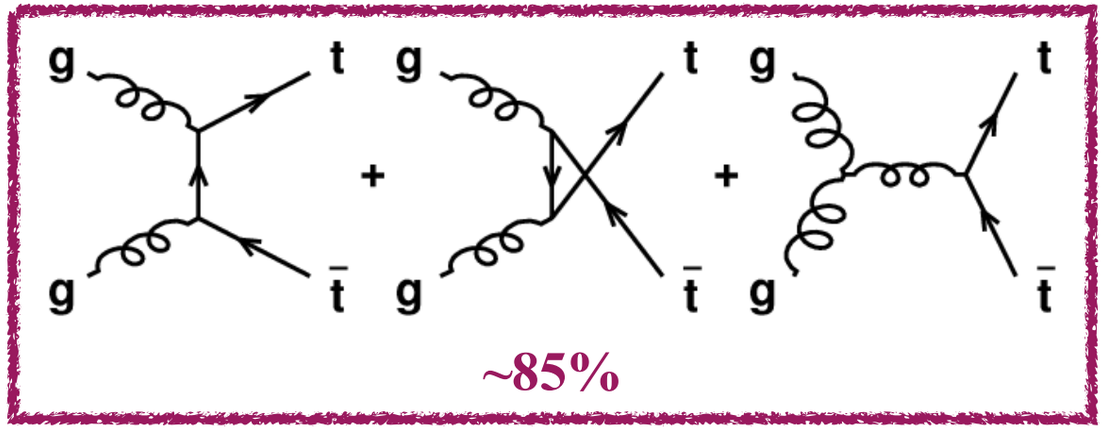
$t\bar{t}$ production

$\sqrt{s}$	$\sigma_{t\bar{t}}$ (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%)

(LHCPhysics)

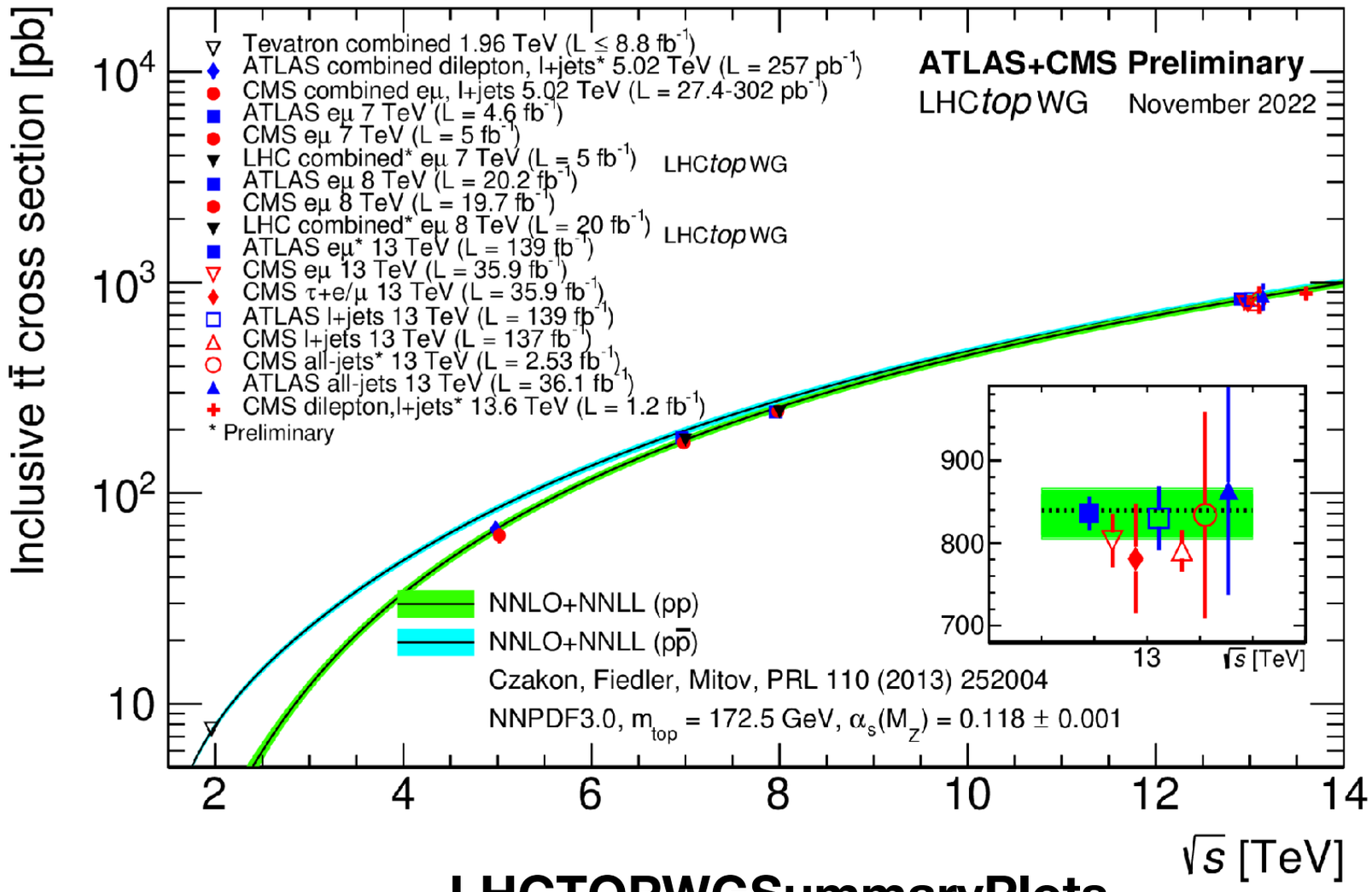
- Dominant production mode at LHC
- → Allows for precise probes of SM!





(pp@13 TeV)

Top-pair production cross-section summary



LHCTOPWGSummaryPlots

inclusive $t\bar{t}$ production NEW!

CMS-TOP-22-012

ATLAS-CONF-2023-006

CMS-TOP-22-012

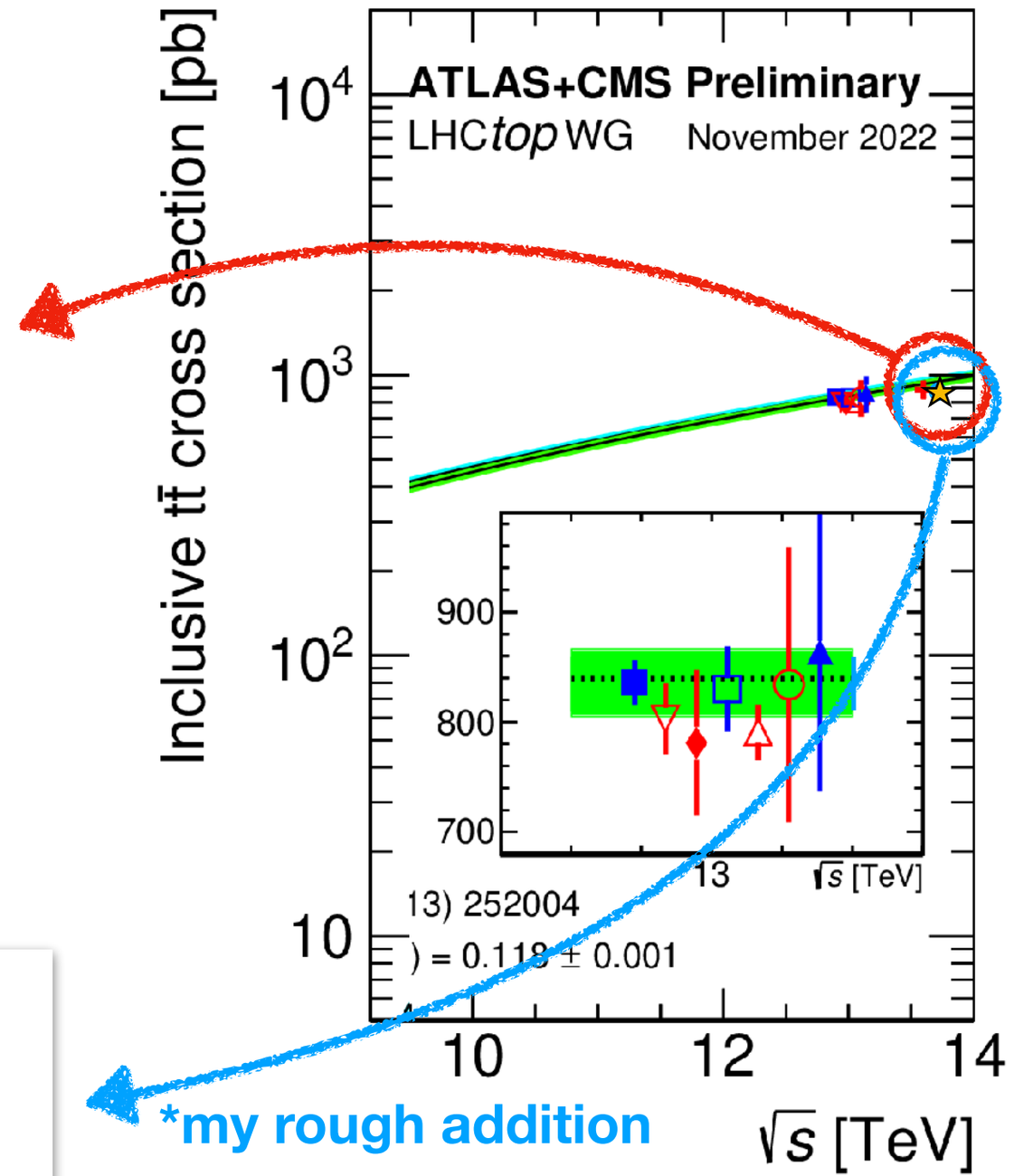
- Summer 2022 inclusive $\sigma_{t\bar{t}}$
- 1 or 2 leps (e/μ) +jets
- First early Run 3 results @ 13.6 TeV!

$$\sigma(pp \to t\bar{t}) = 882 \pm 23\ (\text{stat+syst}) \pm 20\ (\text{lumi})\ \text{pb}$$

ATLAS-CONF-2023-006

- 2022 inclusive $\sigma_{t\bar{t}}$ & fiducial σ_Z
- OS $e\mu$ + b-jets
- First early Run 3 results @ 13.6 TeV!

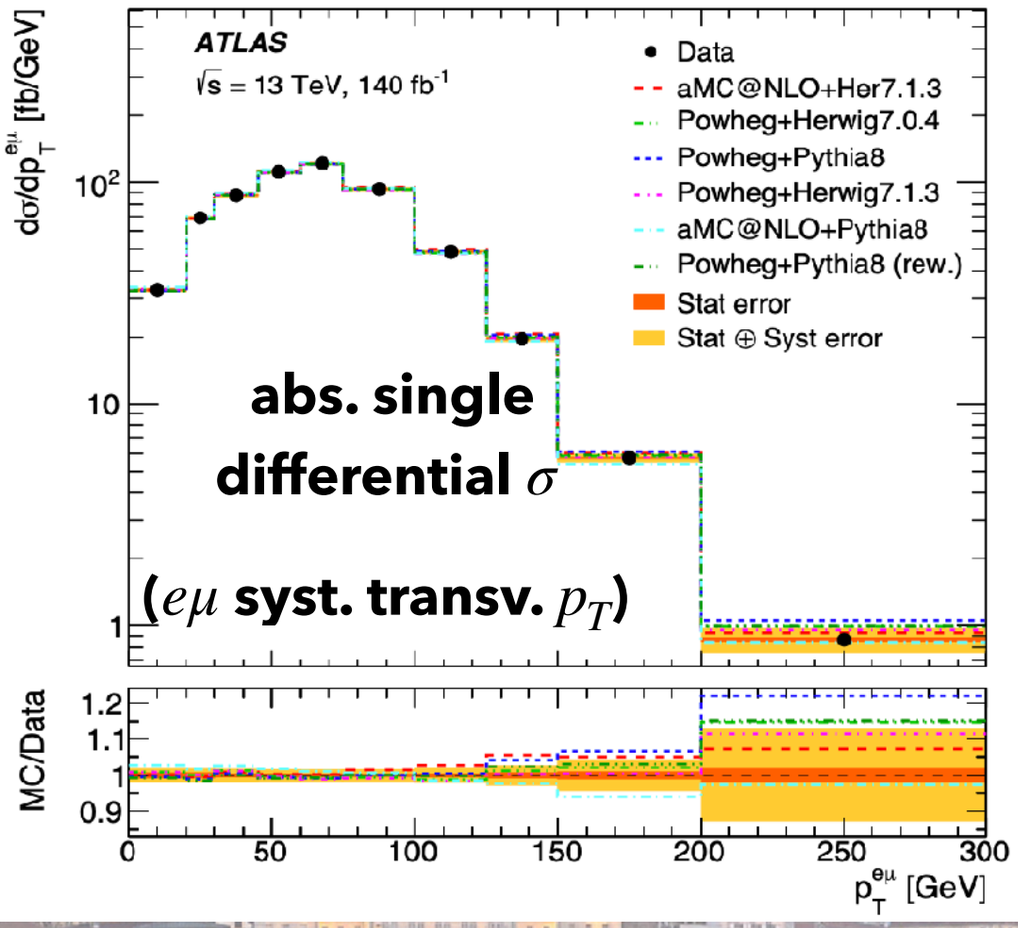
$$\sigma(pp \to t\bar{t}) = 859 \pm 4\ (\text{stat}) \pm 22\ (\text{syst}) \pm 19\ (\text{lumi})\ \text{pb}$$
$$\sigma(pp \to Z_{ll}^{fid.}) = 751 \pm 0.3\ (\text{stat}) \pm 15(\text{syst}) \pm 17\ (\text{lumi})\ \text{pb}$$
$$R_{t\bar{t}/Z} = 1.144 \pm 0.006\ (\text{stat}) \pm 0.022\ (\text{syst}) \pm 0.003\ (\text{lumi})$$

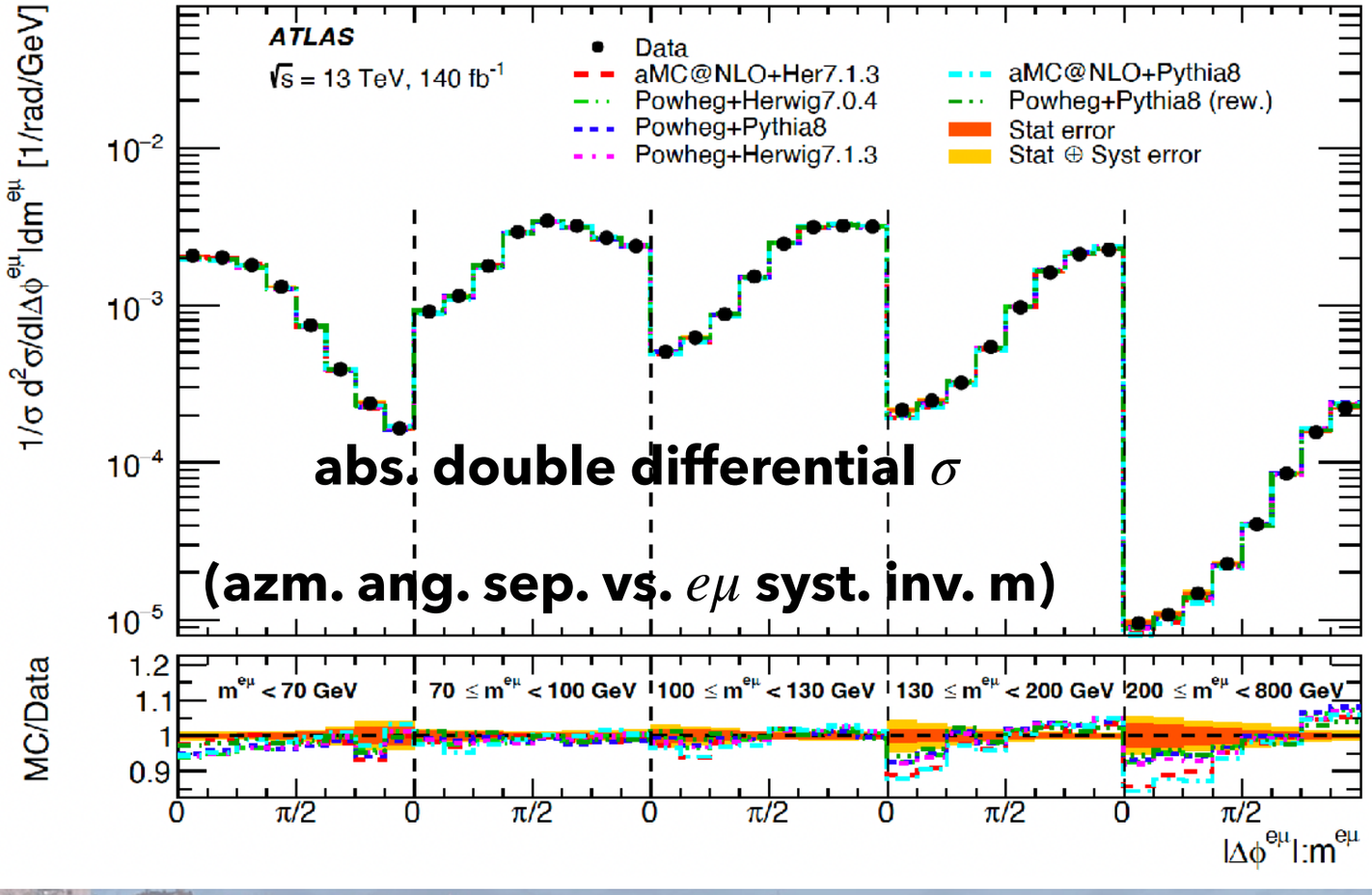


inclusive & differential $t\bar{t}$

- Inclusive & single/double differential $\sigma_{t\bar{t}}$ ($e\mu$ final state)
- Inclusive: Most precise inclusive $\sigma_{t\bar{t}}$ @ 13 TeV! → impressive systematics (0.8% lumi!)
- Differential: Kinematic dists. of 8 variables → good agreement with predictions except tails, improved MC needed (NNLO/EW corrections, threshold effects)

$$\sigma(pp \to t\bar{t}) = 829 \pm 1\,(\text{stat}) \pm 13\,(\text{syst}) \pm 8\,(\text{lumi}) \pm 2\,(\text{beam})\ \text{pb}$$





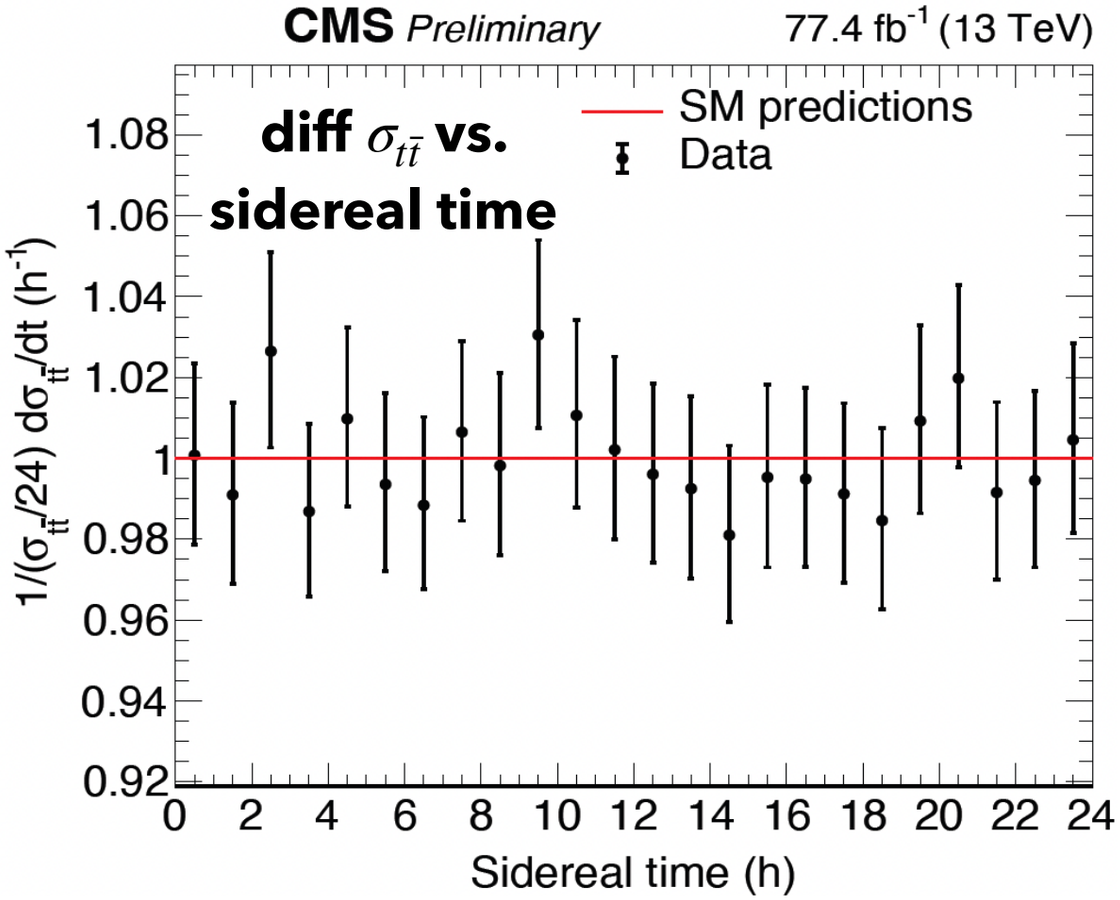
$t\bar{t}$ measurements NEW!

CMS PAS TOP-22-007

ATLAS-CONF-2023-027-22

search for violation of Lorentz invariance in $t\bar{t}$ (CMS PAS TOP-22-007)

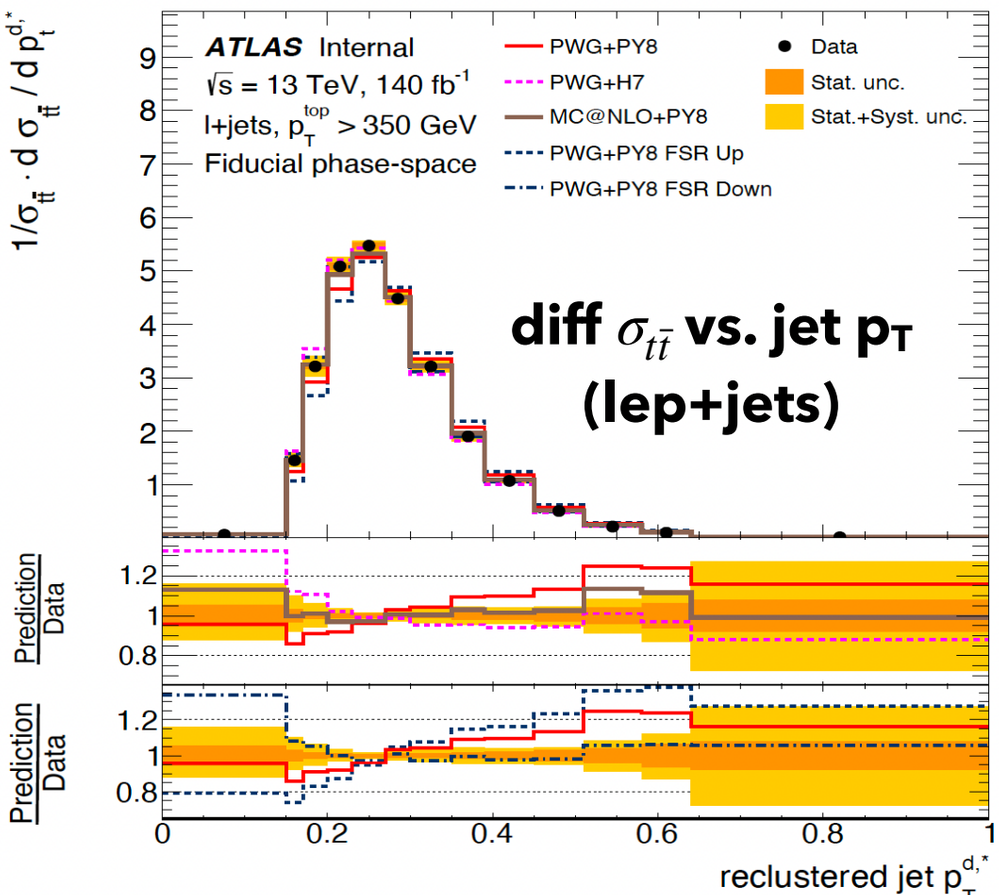
- dilepton ($e\mu$) final state (2016+17)
- diff $\sigma_{t\bar{t}}$ as function of sidereal time in EFT framework



See talk by Nicolas Chanon!

boosted $t\bar{t}$ differential jet substructure measurement (ATLAS-CONF-2023-027)

- lep+jets & all-had final states (Run II)
- single/double diff $\sigma_{t\bar{t}}$ for 8 vars related to charged jet compontents



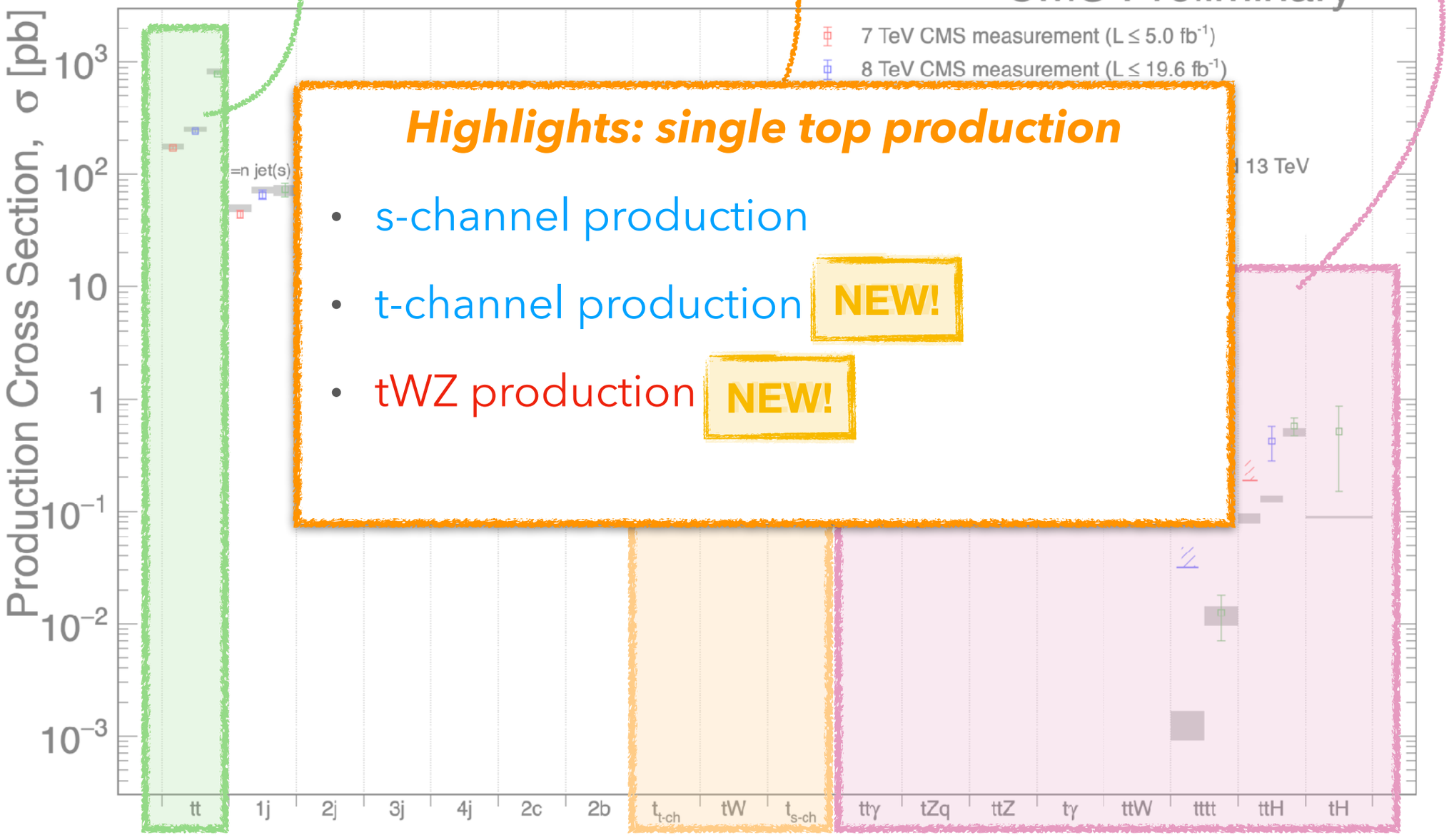
See talk by Mohammed Faraj!

single top production

1) pair production

2) single-top production

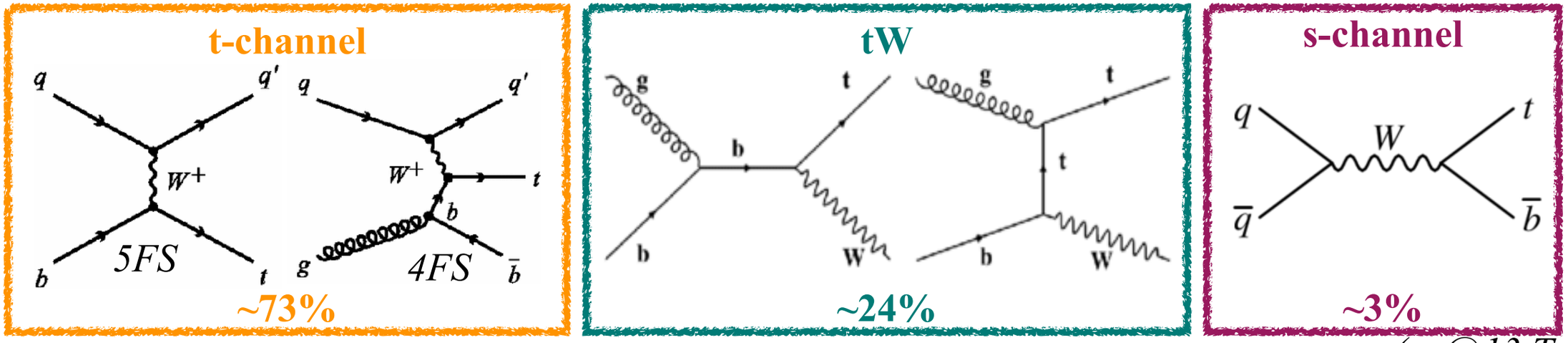
3) associated production



Highlights: single top production

- s-channel production
- t-channel production **NEW!**
- tWZ production **NEW!**

single top production

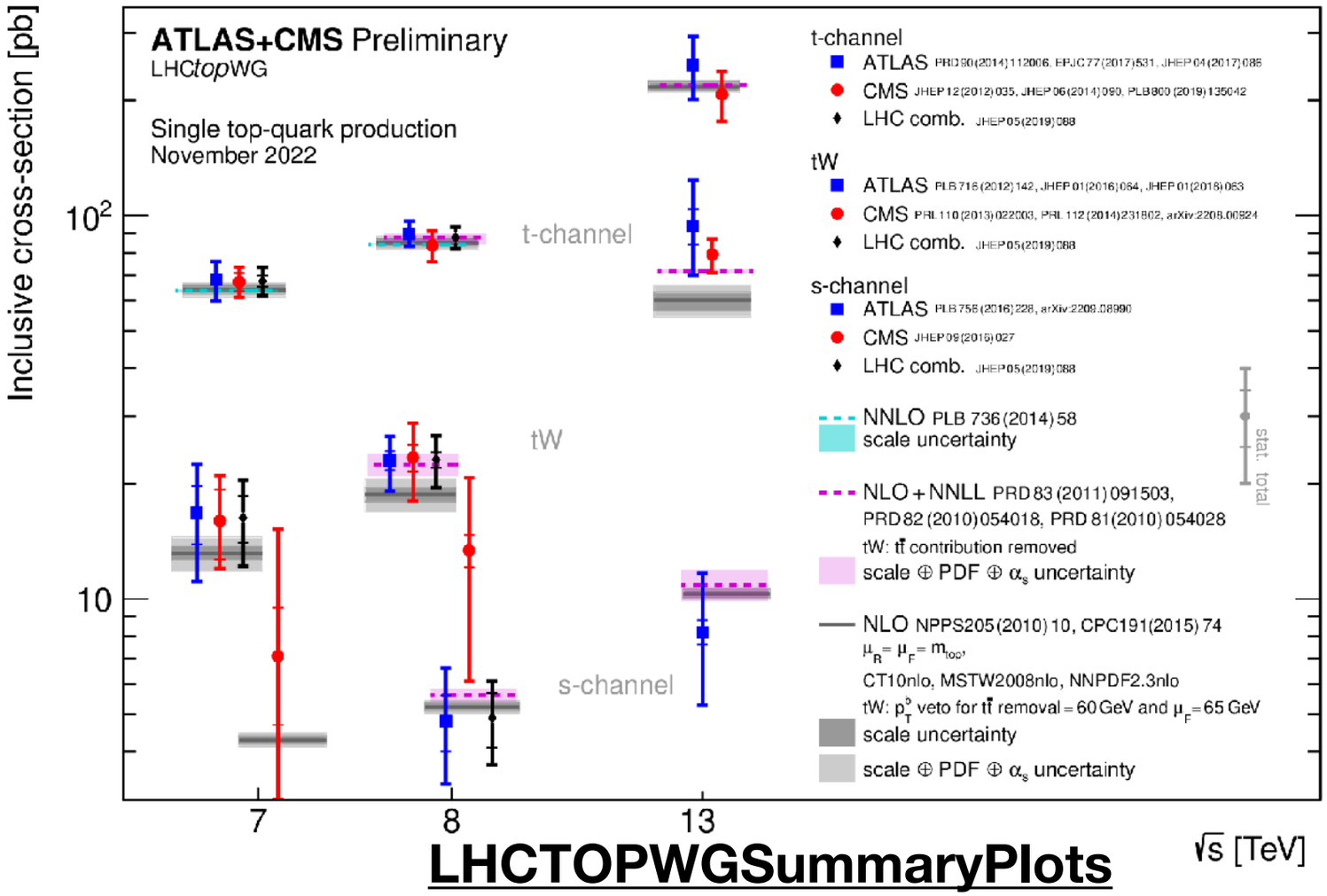


(pp@13 TeV)

σ (pb)	√s = 13 TeV
t-channel (NNLO)	$214.2^{+4.1}_{-2.6}$
tW (NNLO)	$79.3^{+2.9}_{-2.8}$
s-channel (NLO)	$10.32^{+0.40}_{-0.36}$

(LHCPhysics)

- t-channel →"golden channel" sensitive to FCNC
- tW observed at LHC, good probe of BSM couplings
- s-channel very challenging!

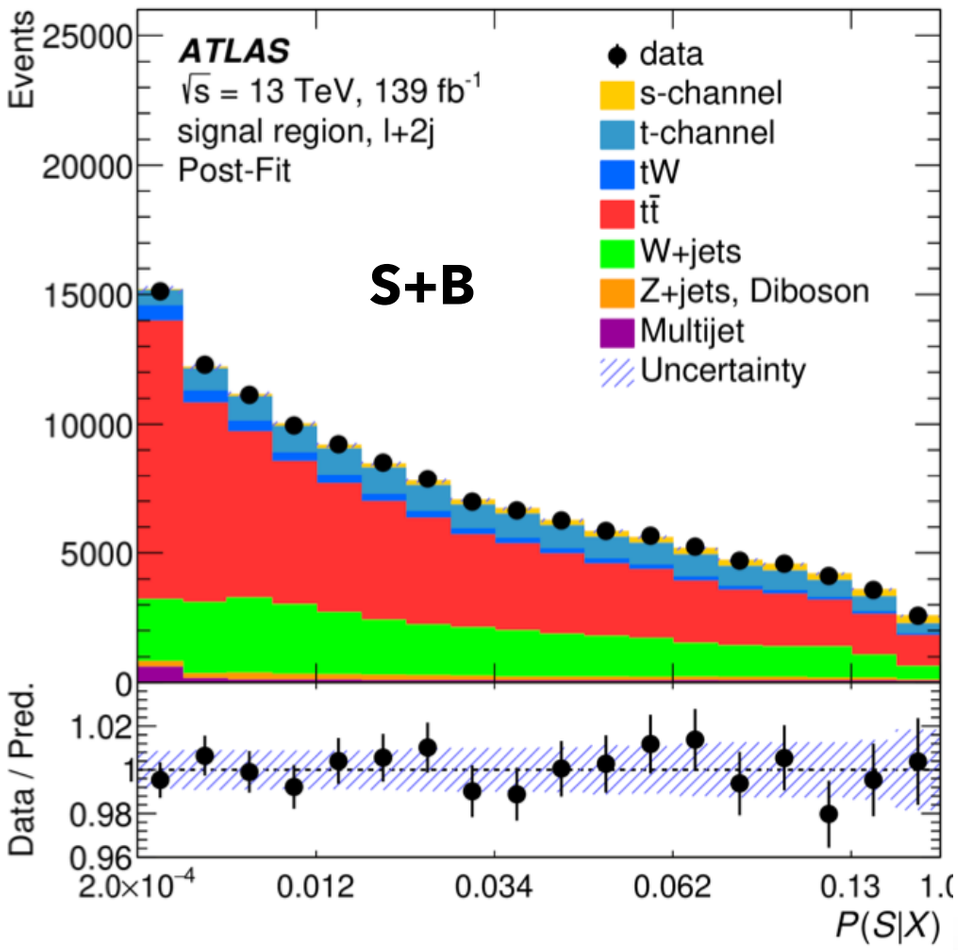


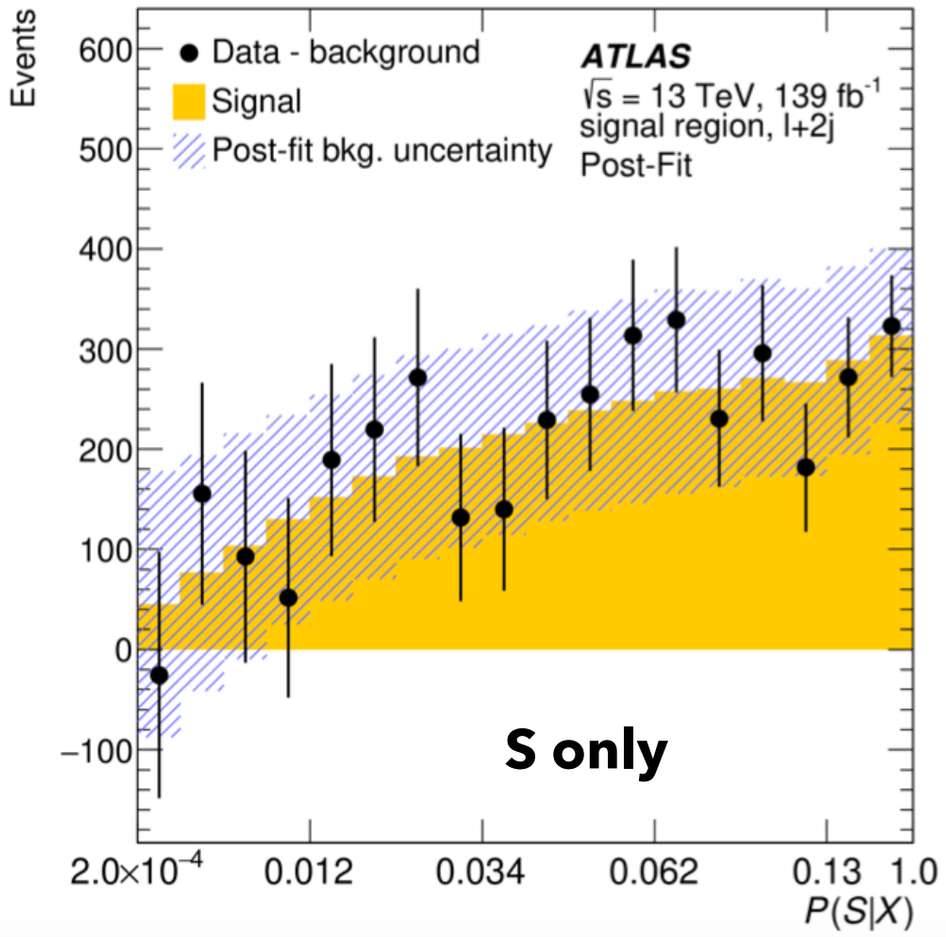
LHCTOPWGSummaryPlots

arXiv:2209.08990

s-channel production

- 1-lep final state
- CRs for major $t\bar{t}$ & $W+jets$ bkgs
- Data-driven QCD bkg.





- Matrix-element method to derive signal probablility per event P(S|X)
- First evidence of s-channel production @ 13 TeV!
- obs (exp) significance : 3.3 (3.9) s.d.

$$\sigma_{s-channel} = 8.2 \pm 0.6\ (\text{stat})^{+3.5}_{-2.9}\ (\text{syst})\ \text{pb}$$

t-channel production NEW!

- Production of single tops/antitops via t-channel exchange of virtual W
- 1-lep final state @13 TeV
- NN-based sig vs. bkg discrimination
- Include EFT interpretations, CKM result
- Good agreement with SM predictions

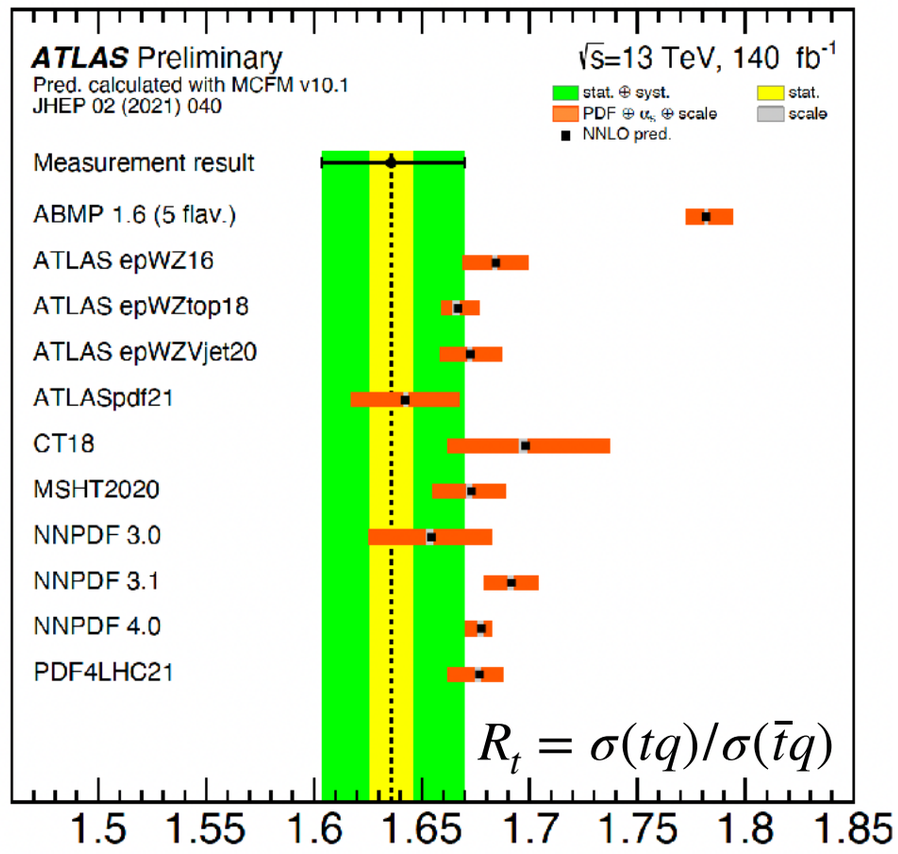
$$\sigma(tq + \bar{t}q) = 221 \pm 13 \text{ pb}$$
$$R_t = \sigma(tq)/\sigma(\bar{t}q) = 1.636^{+0.036}_{-0.034}$$

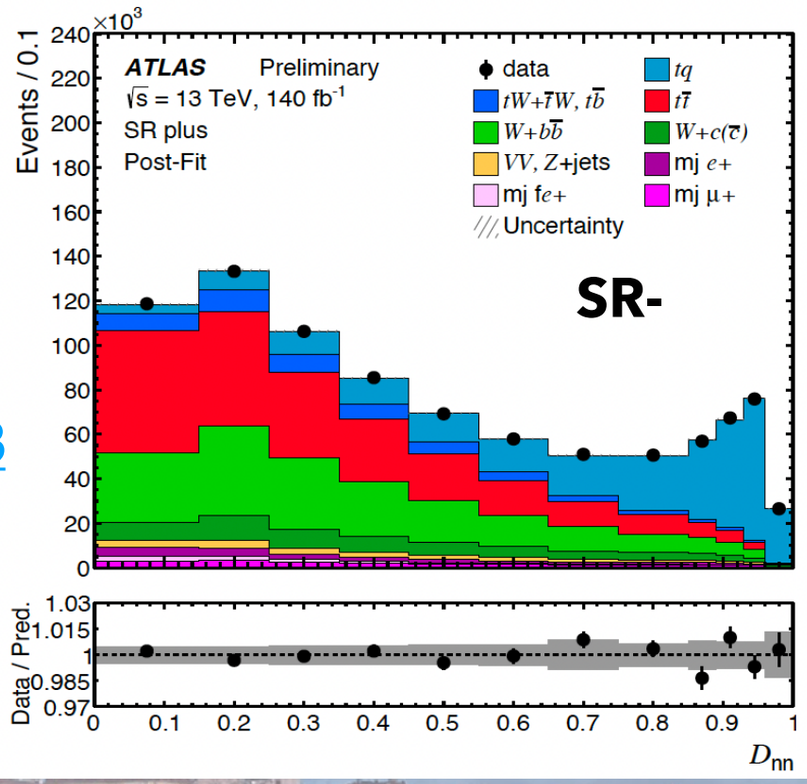
Also new 5 TeV result!!

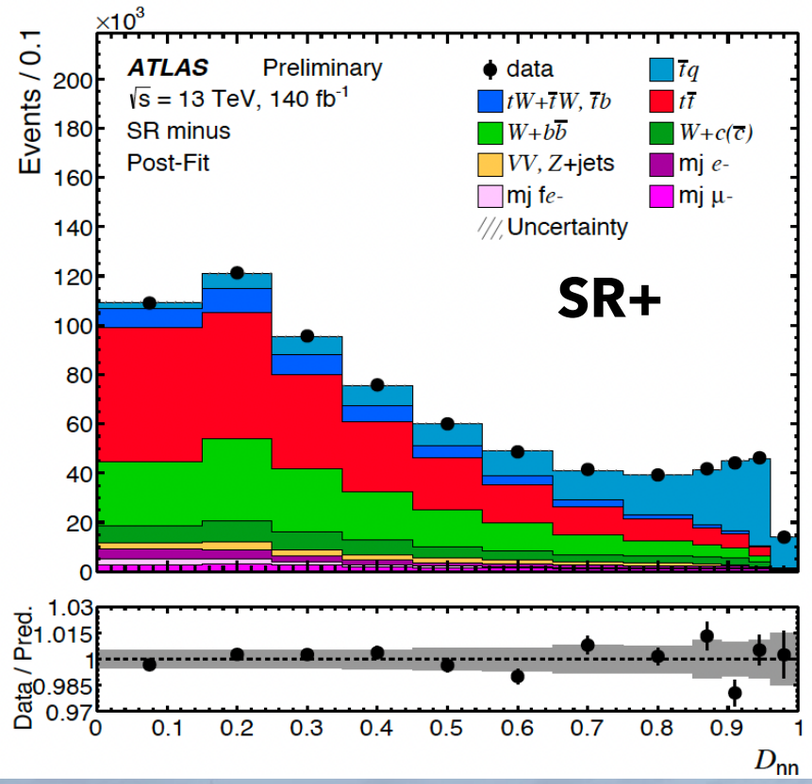
ATLAS-COM-CONF-2023-026

See talk by Mohammed Faraj!

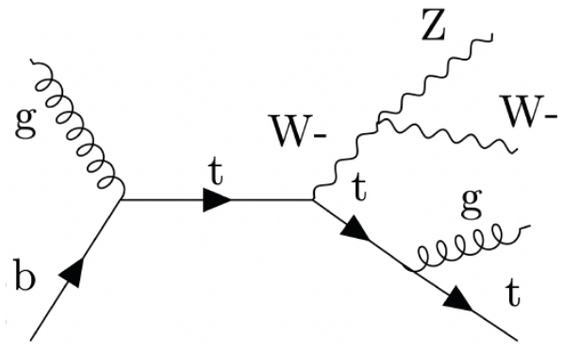
ATLAS-COM-CONF-2023-026







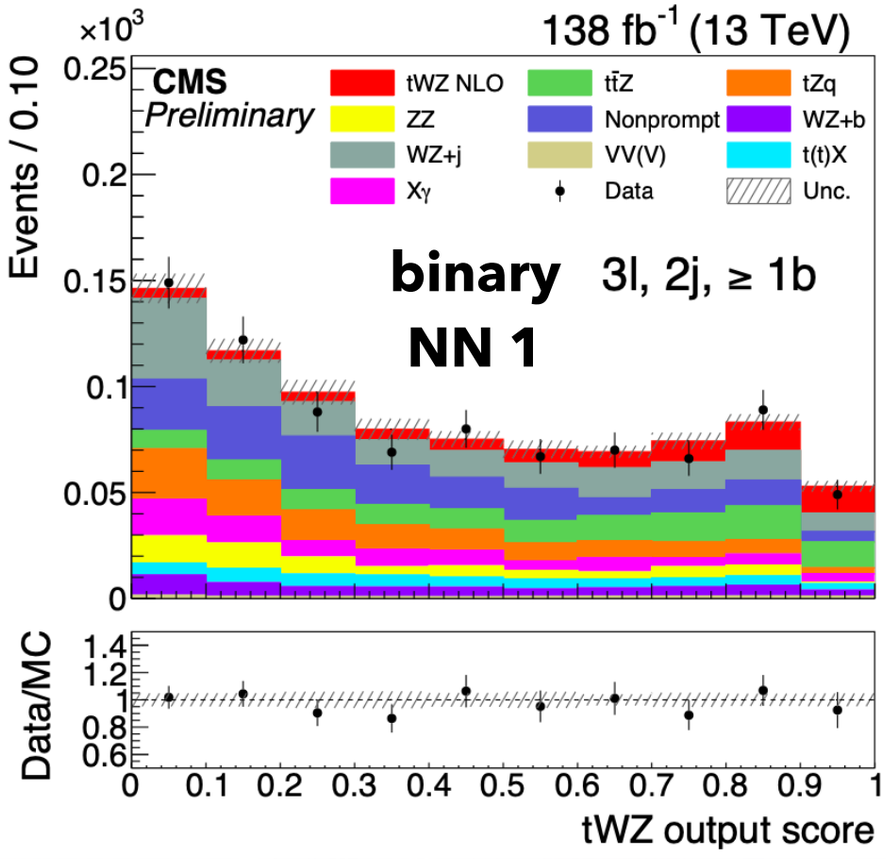
tWZ production NEW!

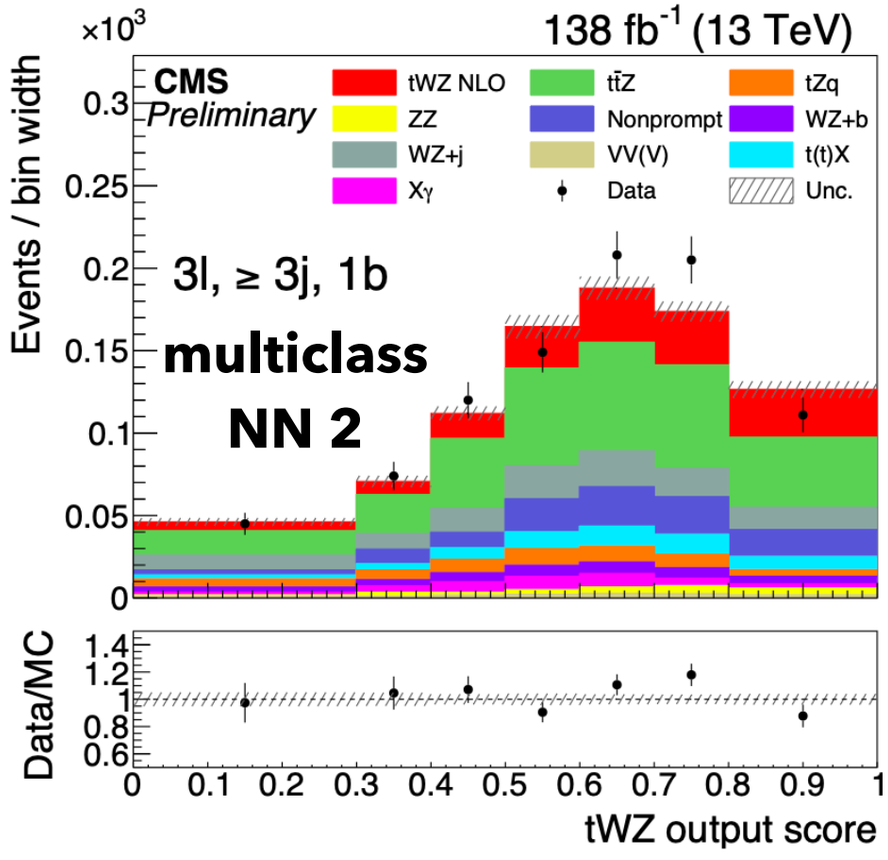


CMS-TOP-22-008

- Very rare (σ_{tWZ}~136 fb)
- New physics potential via modified interactions, good probe of EFT
- First ever tWZ search (multi lep final state)
- Use binary and multiclass NNs for sig. vs. bkg. (tWZ, ttZ, other)
- Reached evidence of tWZ production
  - obs (exp) significance : 3.5 (1.4) s.d.

$$\sigma_{tWZ} = 0.37 \pm 0.05\ (\text{stat}) \pm 0.10\ (\text{syst})\ \text{pb}$$





associated production

Also see talks by Johnny Raine & Stergios Kazakos!

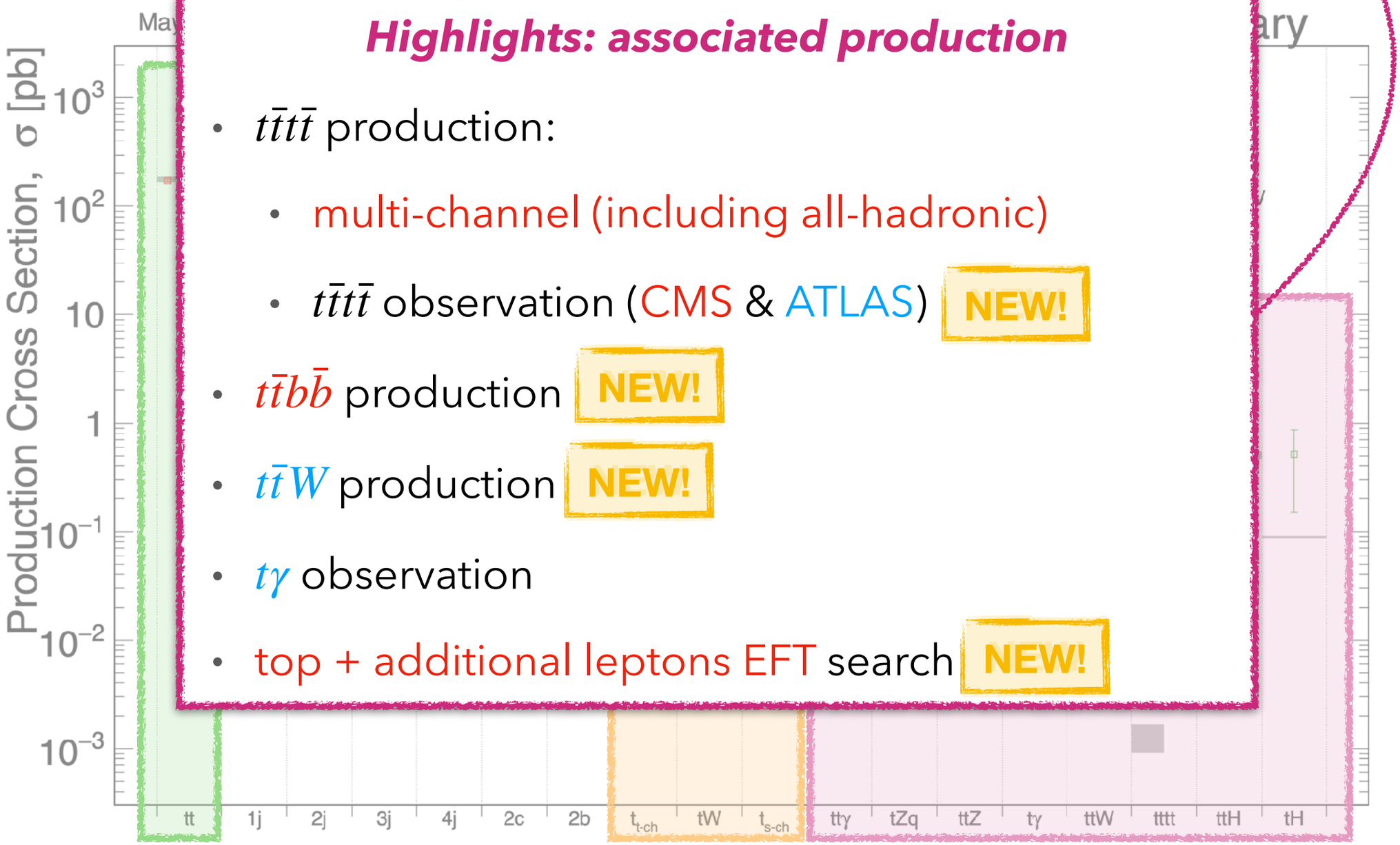
1) pair production

2) single-top production

3) associated production

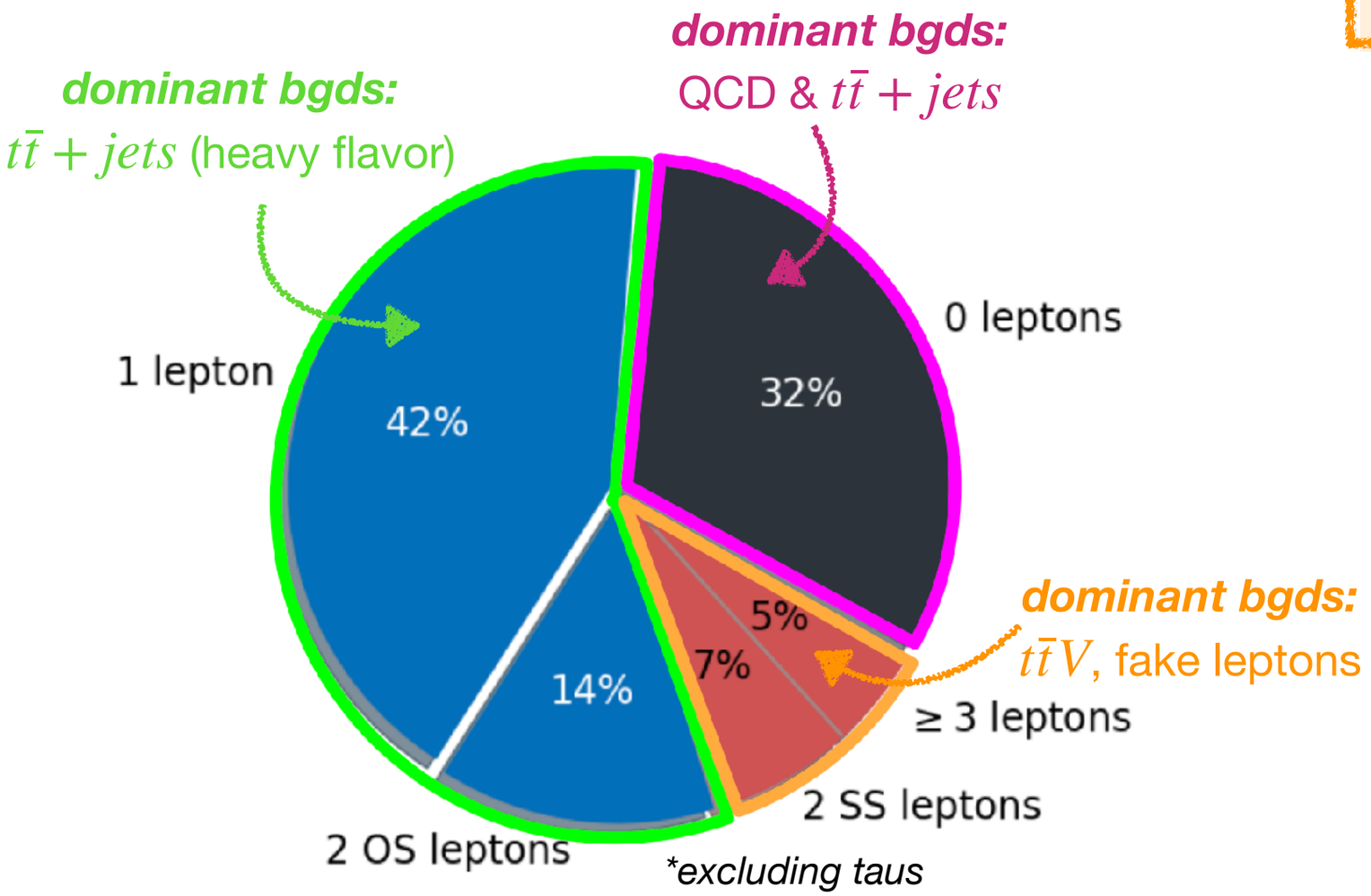
Highlights: associated production

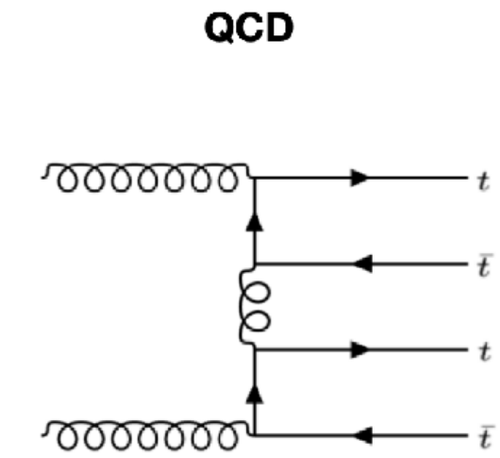
- $t\bar{t}t\bar{t}$ production:
  - multi-channel (including all-hadronic)
  - $t\bar{t}t\bar{t}$ observation (CMS & ATLAS) **NEW!**
- $t\bar{t}b\bar{b}$ production **NEW!**
- $t\bar{t}W$ production **NEW!**
- $t\gamma$ observation
- top + additional leptons EFT search **NEW!**



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

Also see talks by Hesham El Faham & Laura Valero!





- $\sigma_{t\bar{t}t\bar{t}} = 13.4^{+1.0}_{-1.8}$ fb (NLO (QCD + EW) + NLL @13TeV) [1]
  - $\sigma_{t\bar{t}t\bar{t}} = 12$ fb (NLO (QCD + EW) @13TeV) [2]
- Sensitive to Yukawa & EFT couplings
- Enhancement of $\sigma_{t\bar{t}t\bar{t}}$ predicted by BSM

[1] arXiv:2212.03259

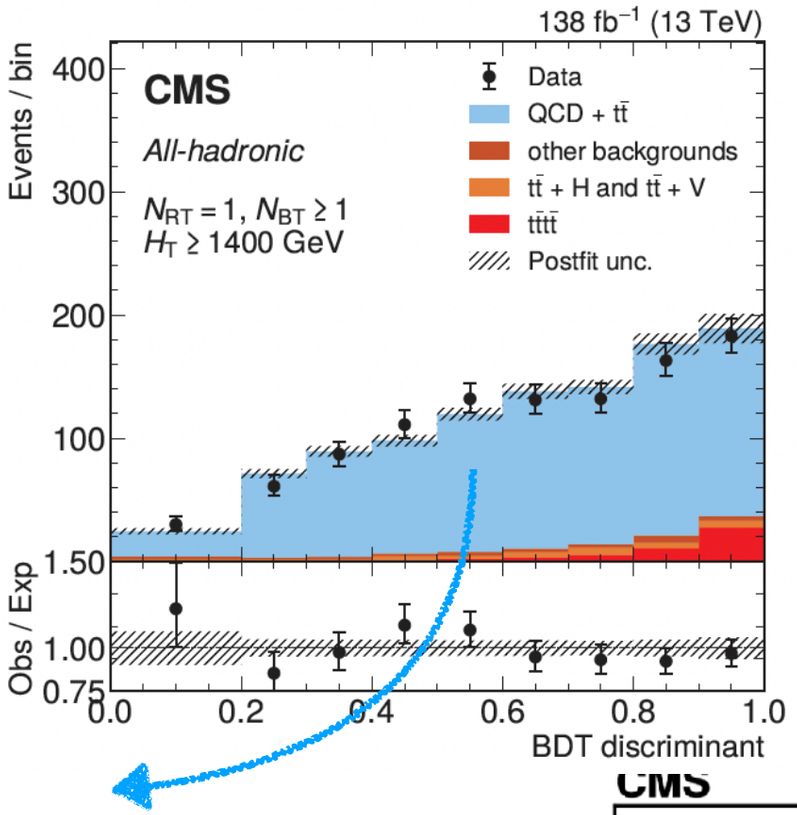
[2] arXiv:1711.02116

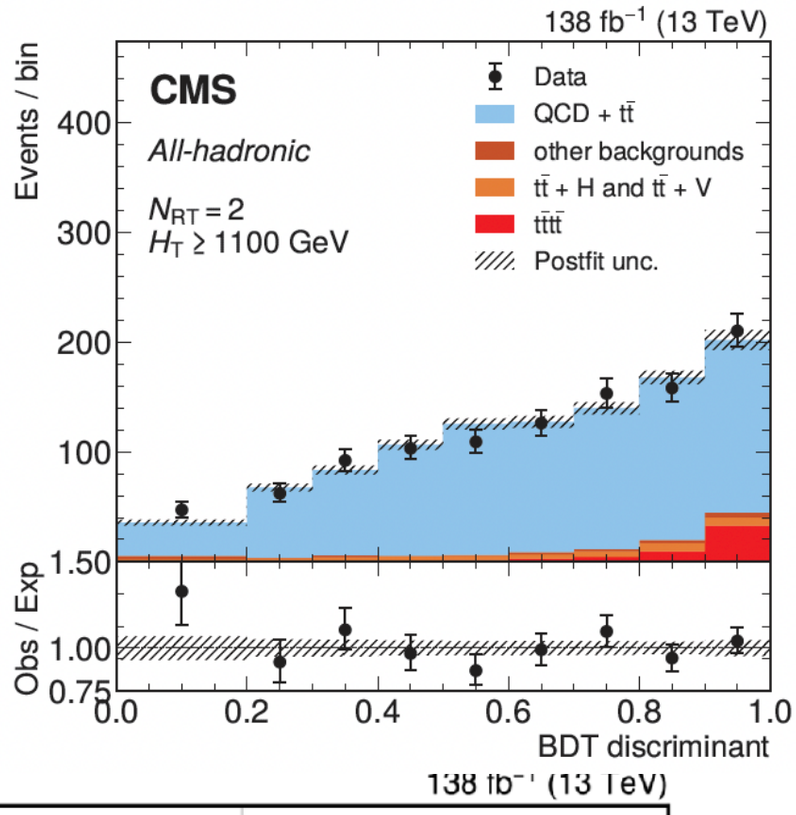
$t\bar{t}t\bar{t}$ evidence

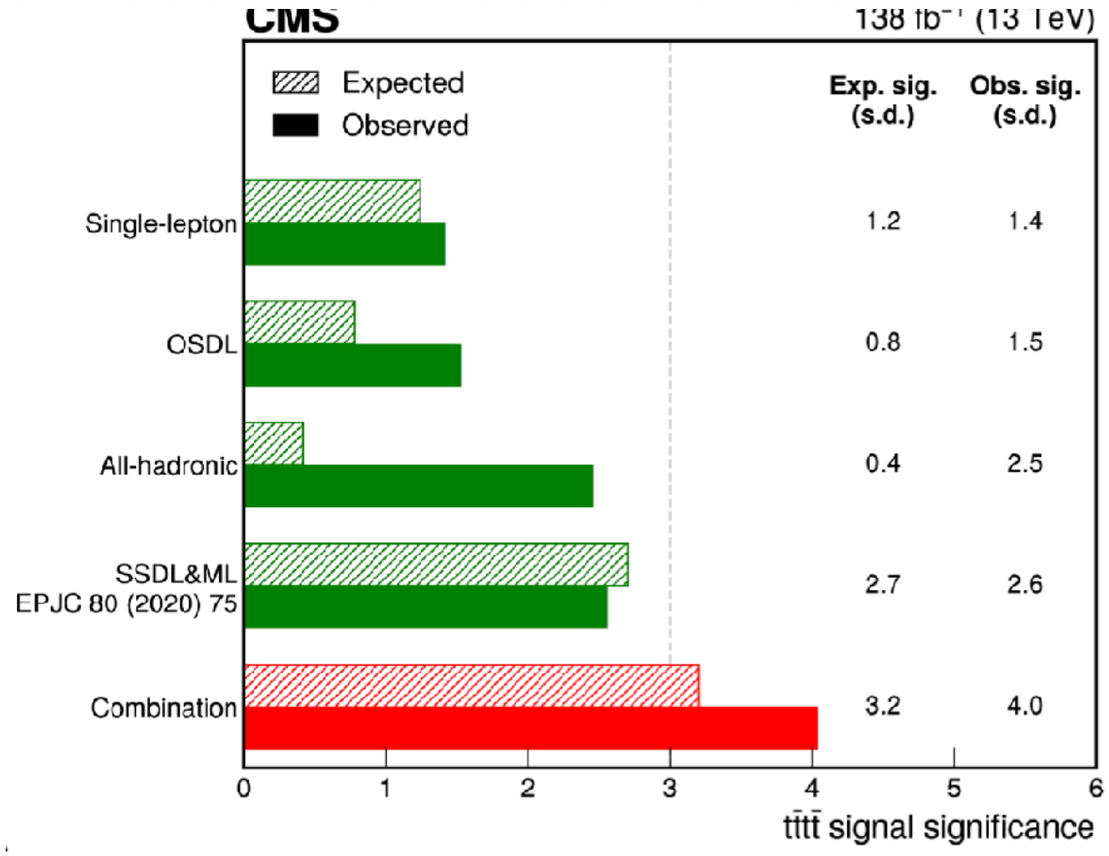
CMS-TOP-21-005

- **1lep, OS 2-lep, all-hadronic** combination
- First inclusion of all-hadronic channel!
  - difficult due to large QCD bkgs
  - normalizing flow NN used to predict QCD & $t\bar{t}$ + *jets* from data in CRs
- obs (exp) significance : 4.0 (3.2) s.d.
  → first evidence of $t\bar{t}t\bar{t}$

$$\sigma(pp \to t\bar{t}t\bar{t}) = 17 \pm 4\,(\text{stat}) \pm 3\,(\text{syst})\ \text{fb}$$



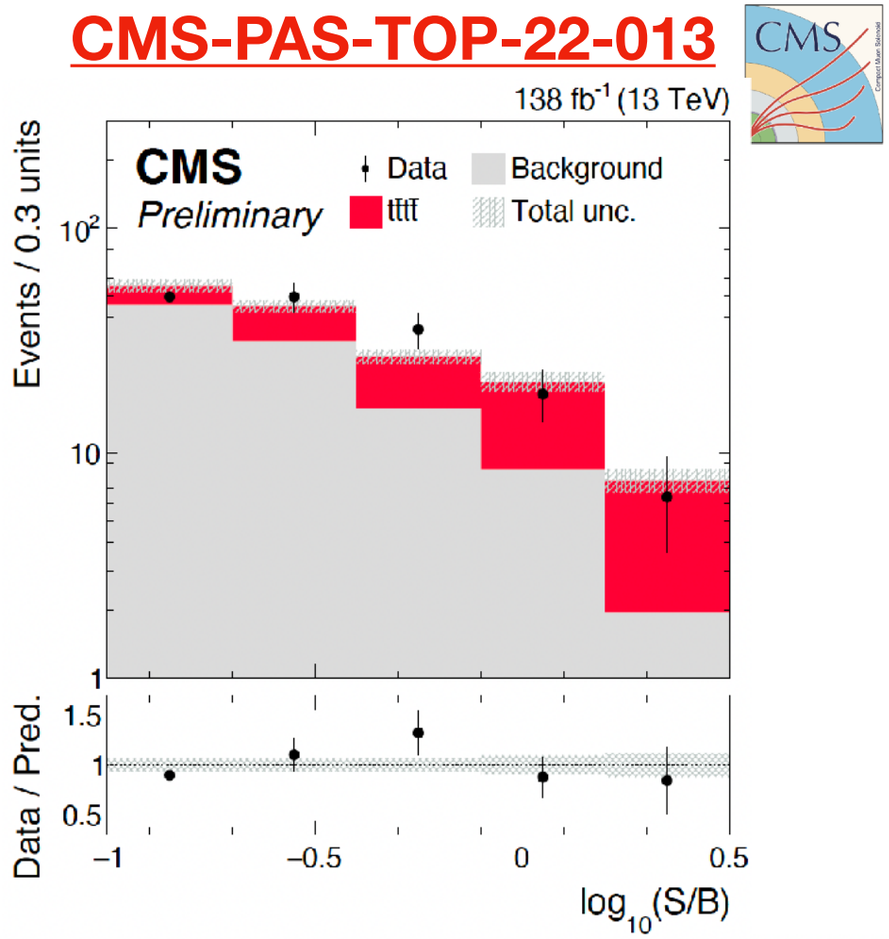


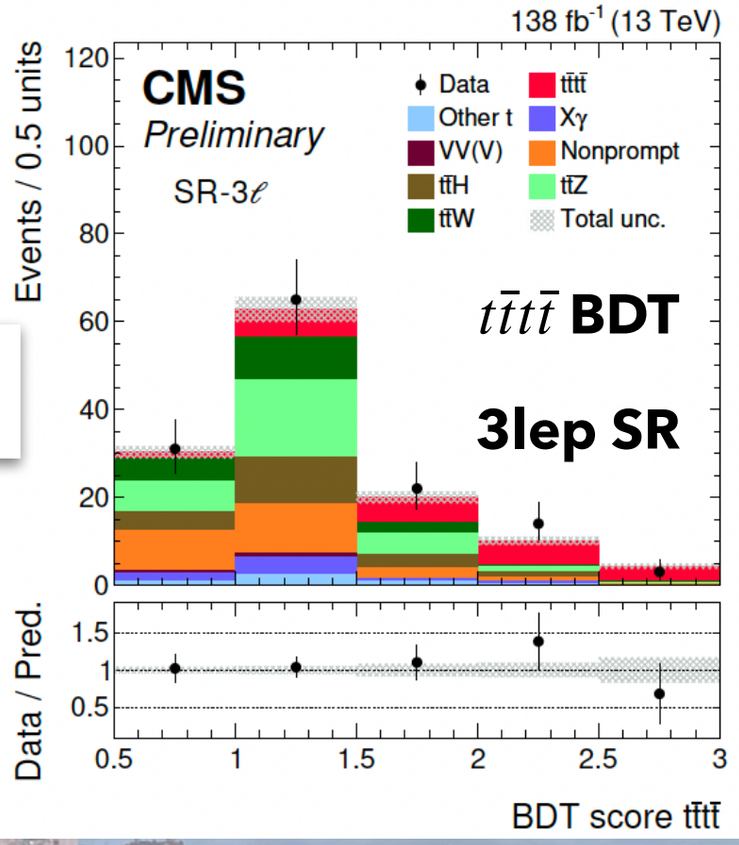


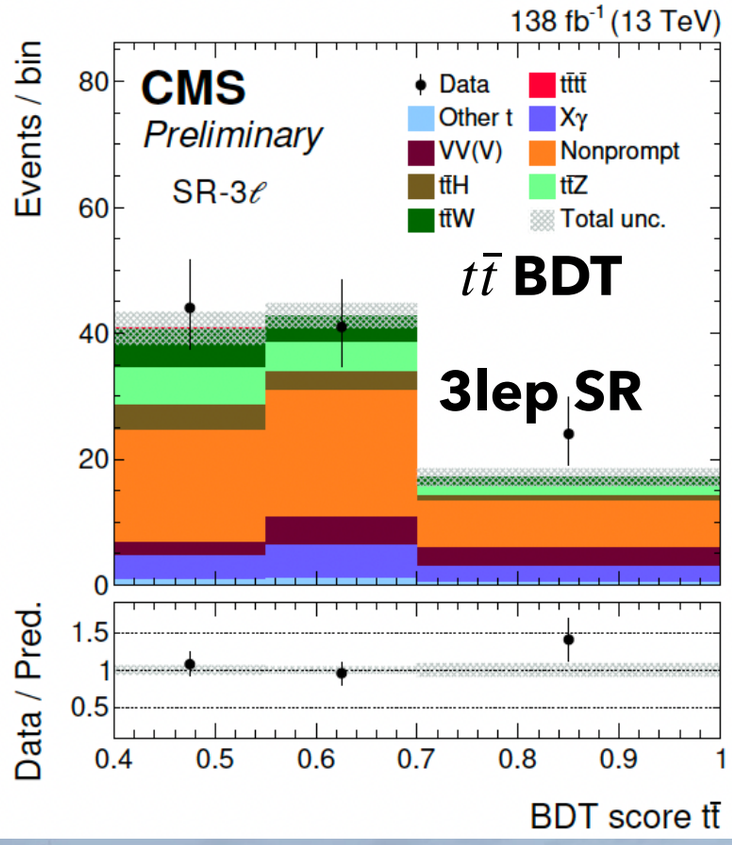
$t\bar{t}t\bar{t}$ observation - CMS NEW!

- New **2+ lep SS** result with legacy reprocessing of Run 2
- Key improvements:
  - BDT lep Id. → looser event sel.
  - Improved b-jet tags
  - Separate multi-class BDTs per SS 2lep, 3lep & 4lep channels ($t\bar{t}t\bar{t}$, $t\bar{t}V$ or $t\bar{t}$ like)
- obs (exp) significance : 5.5 (4.9) s.d.

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}t\bar{t}}) = 17.9\,^{+3.7}_{-3.5}\,(\mathrm{stat})\,^{+2.4}_{-2.1}\,(\mathrm{syst})\,\mathrm{fb}$$



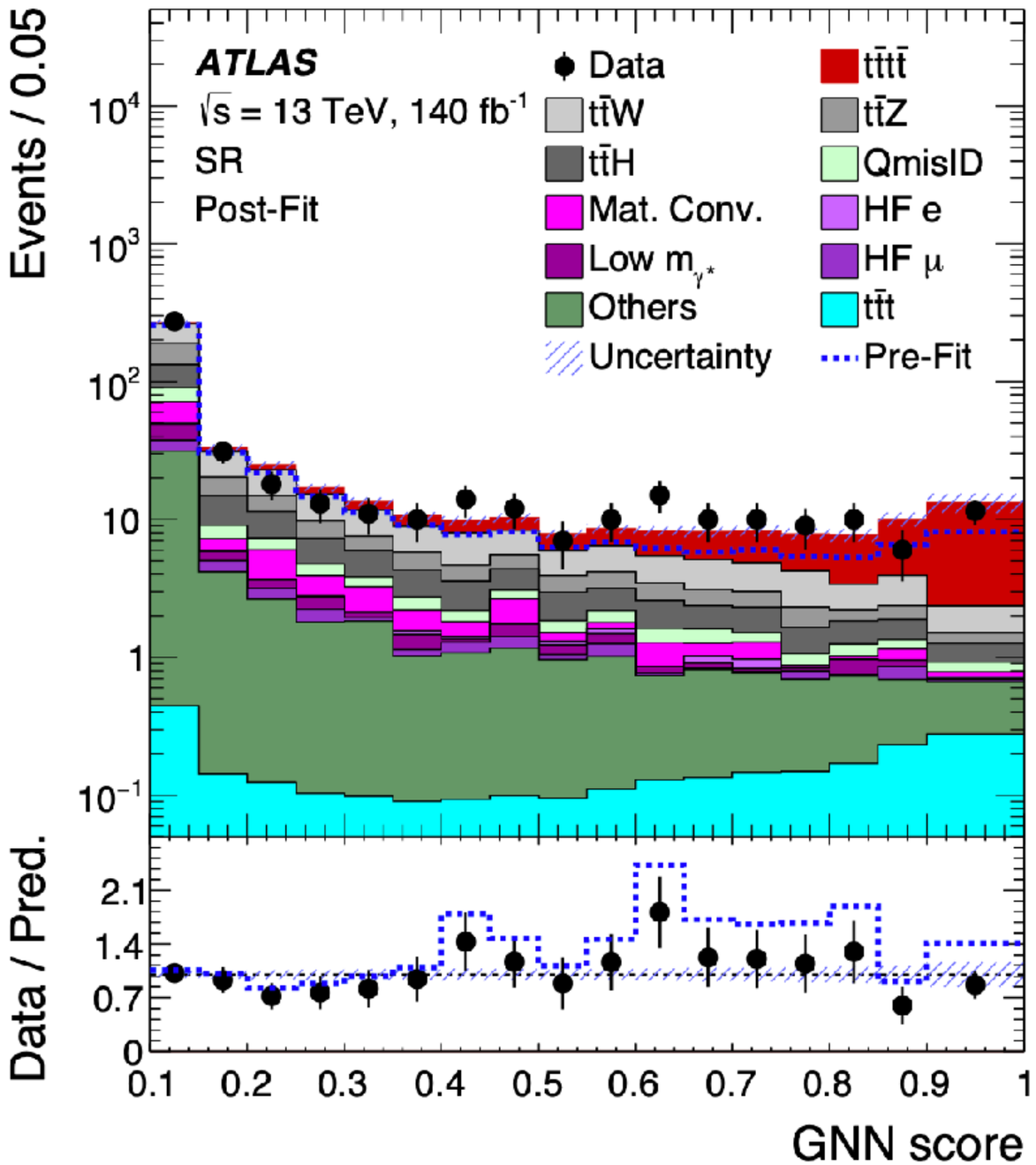




$t\bar{t}t\bar{t}$ observation - ATLAS NEW!

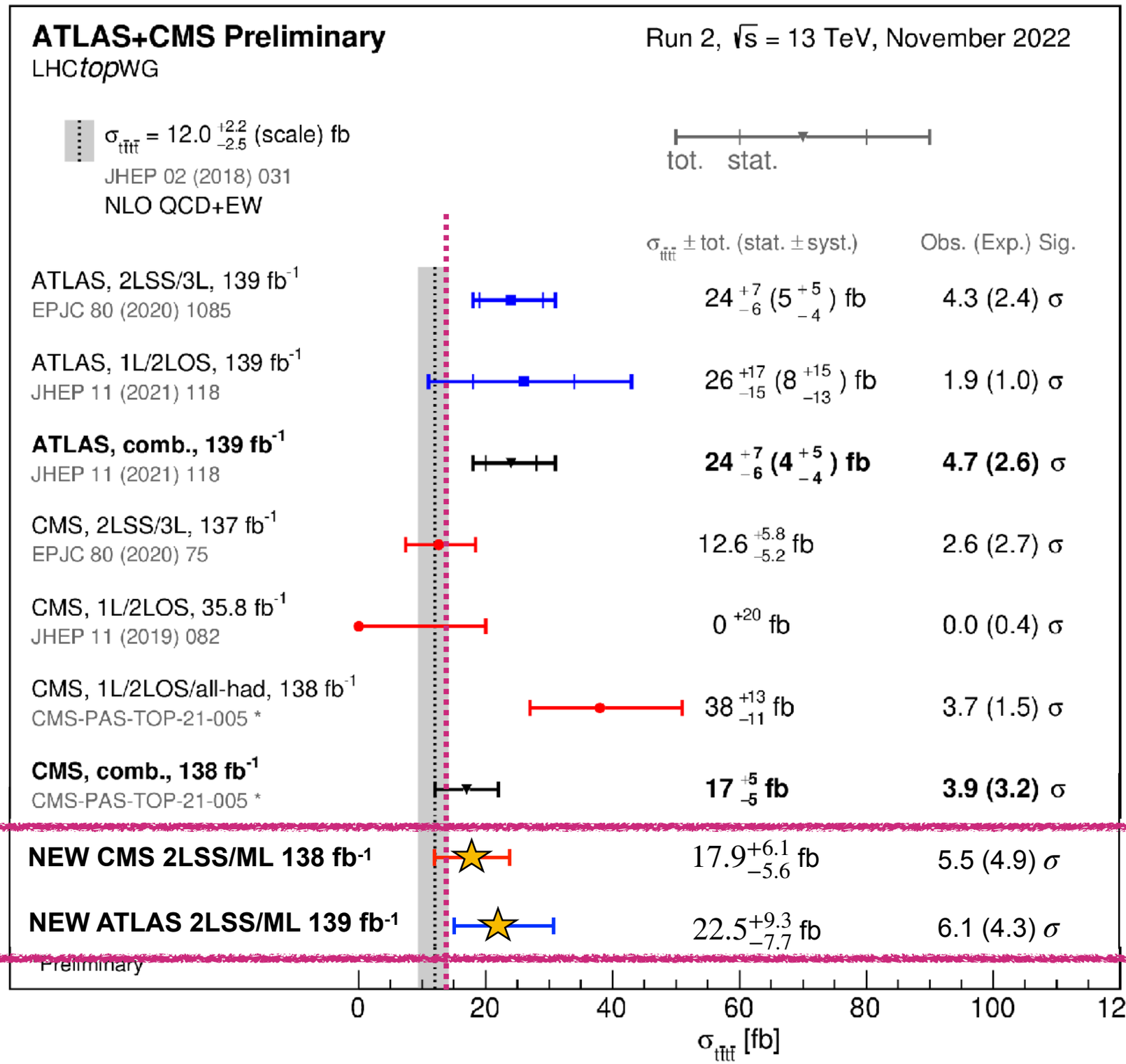
arXiv:2303.15061

- New **2+ lep SS** result with legacy reprocessing of Run 2
- Key improvements:
  - looser event selection
  - Improved b-jet tags, improved systs.
  - data-driven $t\bar{t}W + jets$, improved $t\bar{t}t$
  - GNN-based sig vs. bkg discrimination
- Also extract limits on $t\bar{t}t$, top-H Yukawa coupling, EFT interpretations
- observed (expected) significance : 6.1 (4.3) s.d.



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

$t\bar{t}t\bar{t}$ production - summary

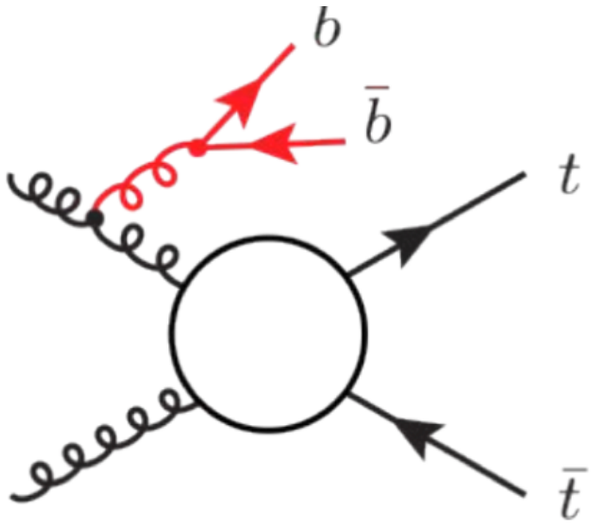


my rough addition…

NEW!

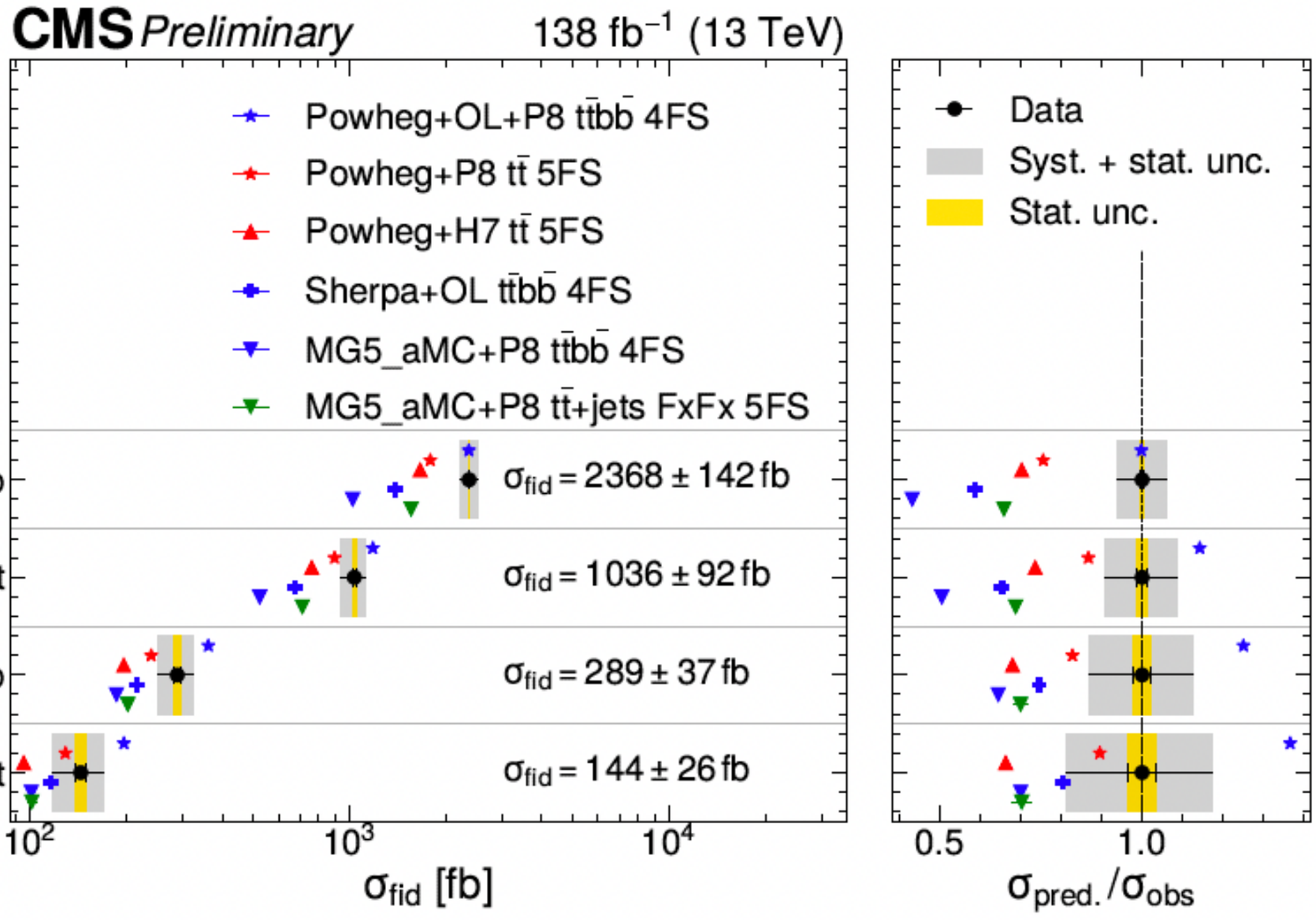
$t\bar{t}b\bar{b}$ production (inclusive) NEW!

CMS-PAS-TOP-22-009



- Rare SM process, irreducible $t\bar{t}H$ & $t\bar{t}t\bar{t}$ backgrounds
- lep+jets final state (e or μ, 5+ jets)
- Inclusive and differential (4 fiducial regions)
- Most precise inclusive ttbb results so far
- Inclusive σ higher than theor. preds (consistent with previous measurements)

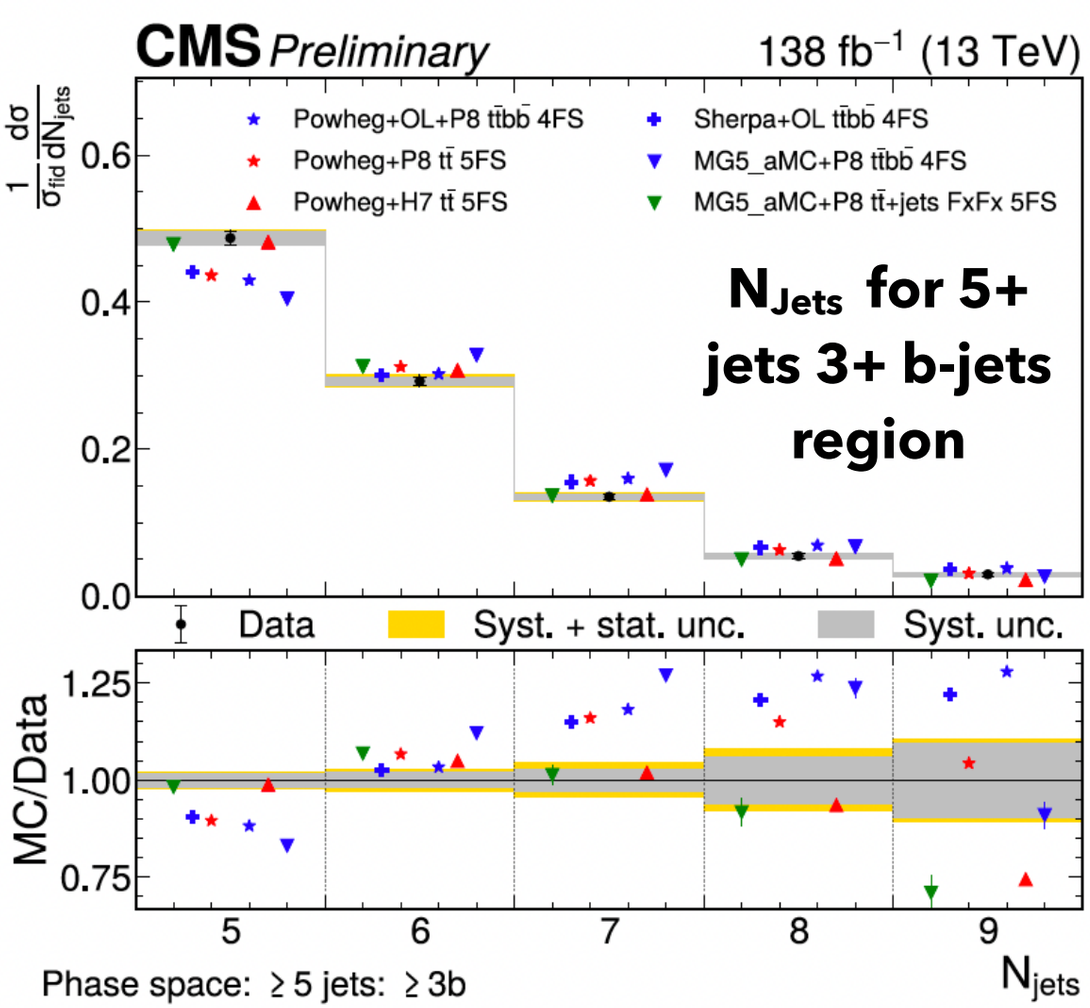
Inclusive σs for phase spaces vs. sim preds.

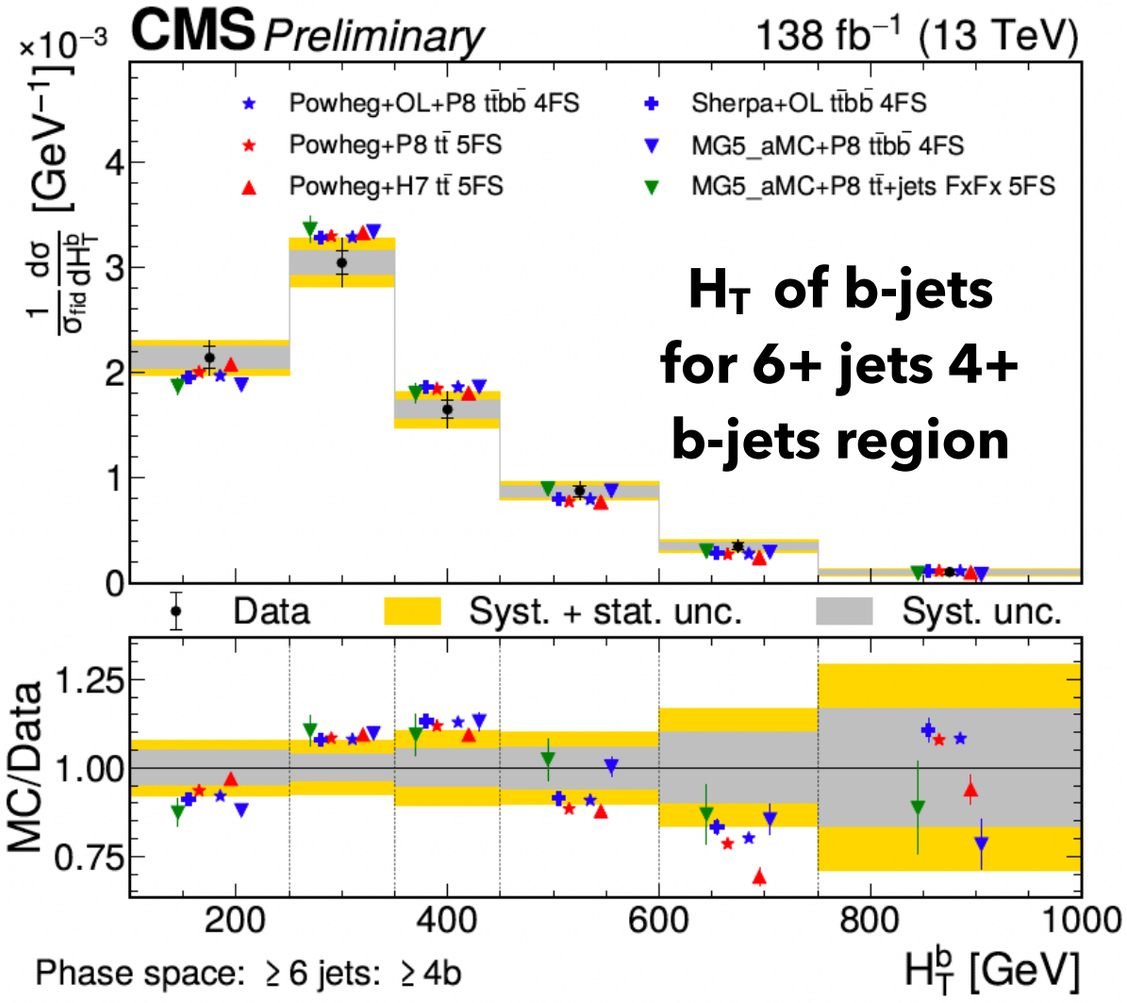


$t\bar{t}b\bar{b}$ production (differential) NEW!

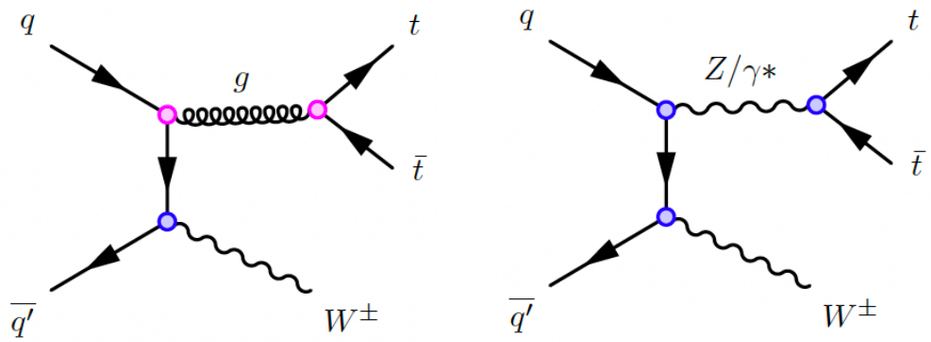
CMS-PAS-TOP-22-009

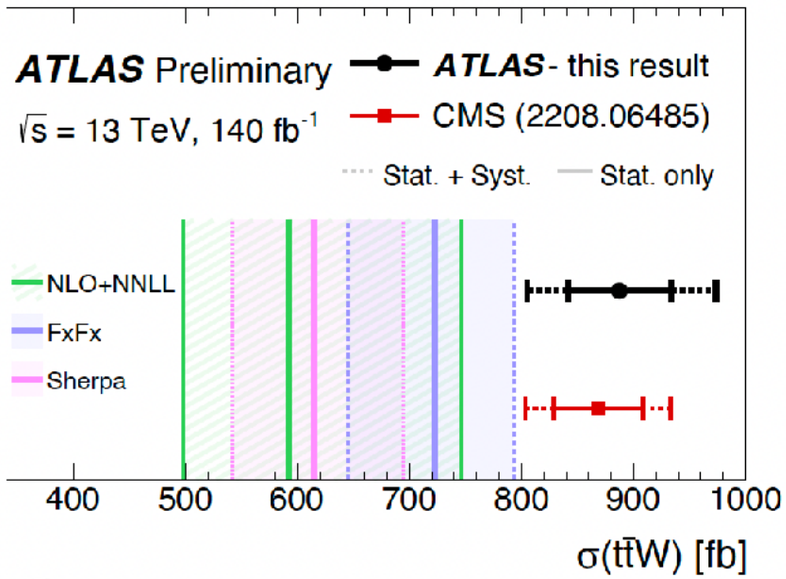
- lep+jets final state (e or μ, 5+ jets)
- Inclusive and differential (4 fiducial regions)
- Normalized differential σs: measured for 37 observables
- Varying compatibility with theoretical predictions

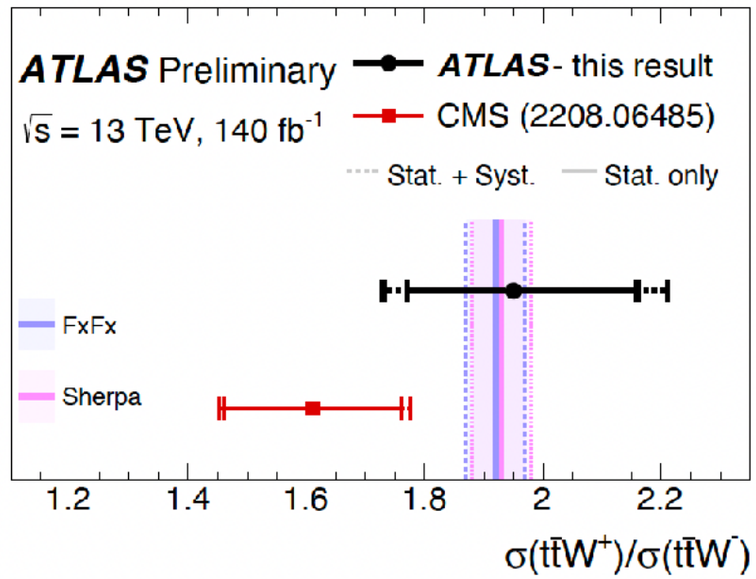




$t\bar{t}W$ production (inclusive) NEW! ATLAS-CONF-2023-019

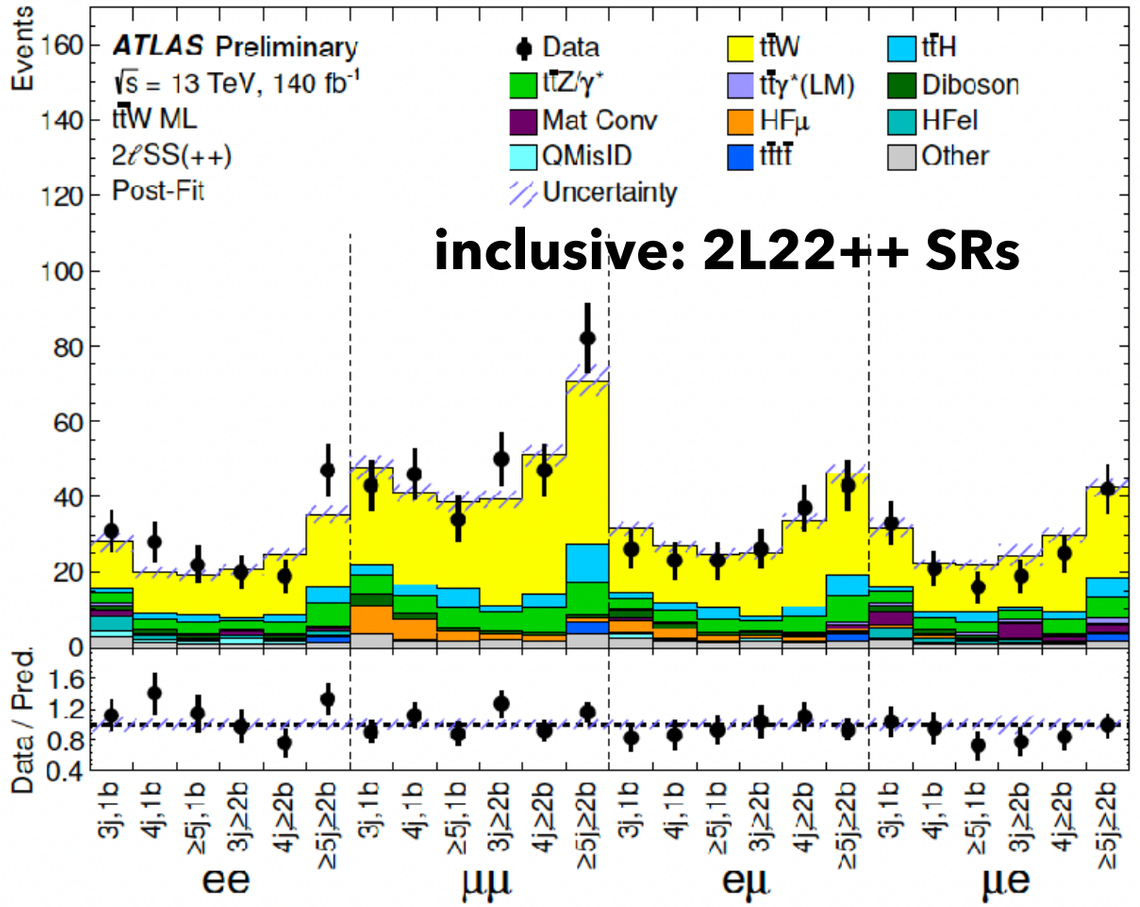






- $\sigma_{tt\bar{W}} = 722^{+70}_{-78}$ (scale) ± 7 (PDF) fb (NLO (QCD + EW) @13TeV) ←NNLO needed!
- SS and multi-lep final states
- Inclusive and differential
- Robust MC modeling + uncertainties
- Inclusive σ higher than theor. preds (consistent with previous measurements)

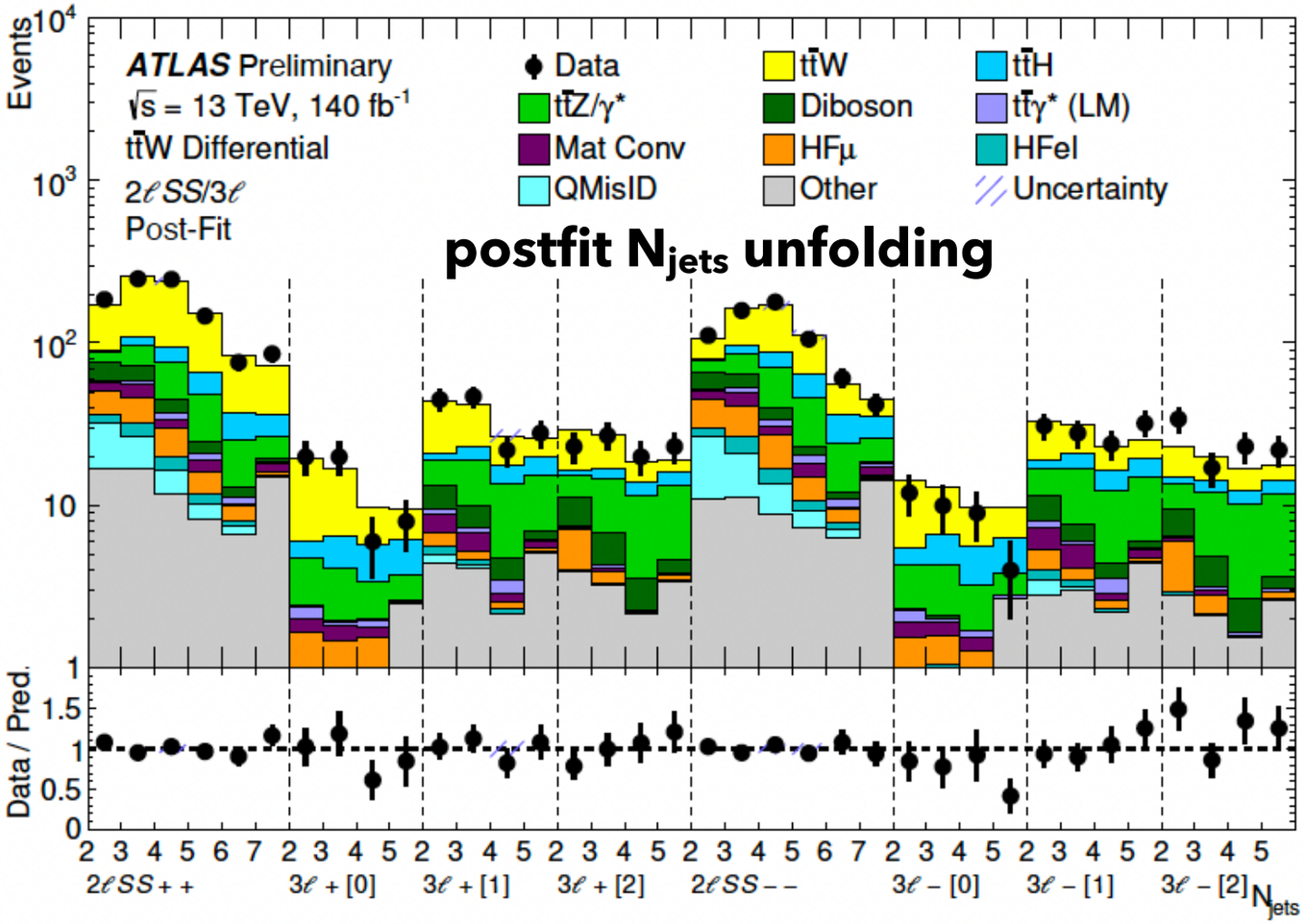
$$\sigma(pp \to t\bar{t}W) = 890 \pm 50\,(\text{stat}) \pm 70\,(\text{syst})\ \text{fb}$$

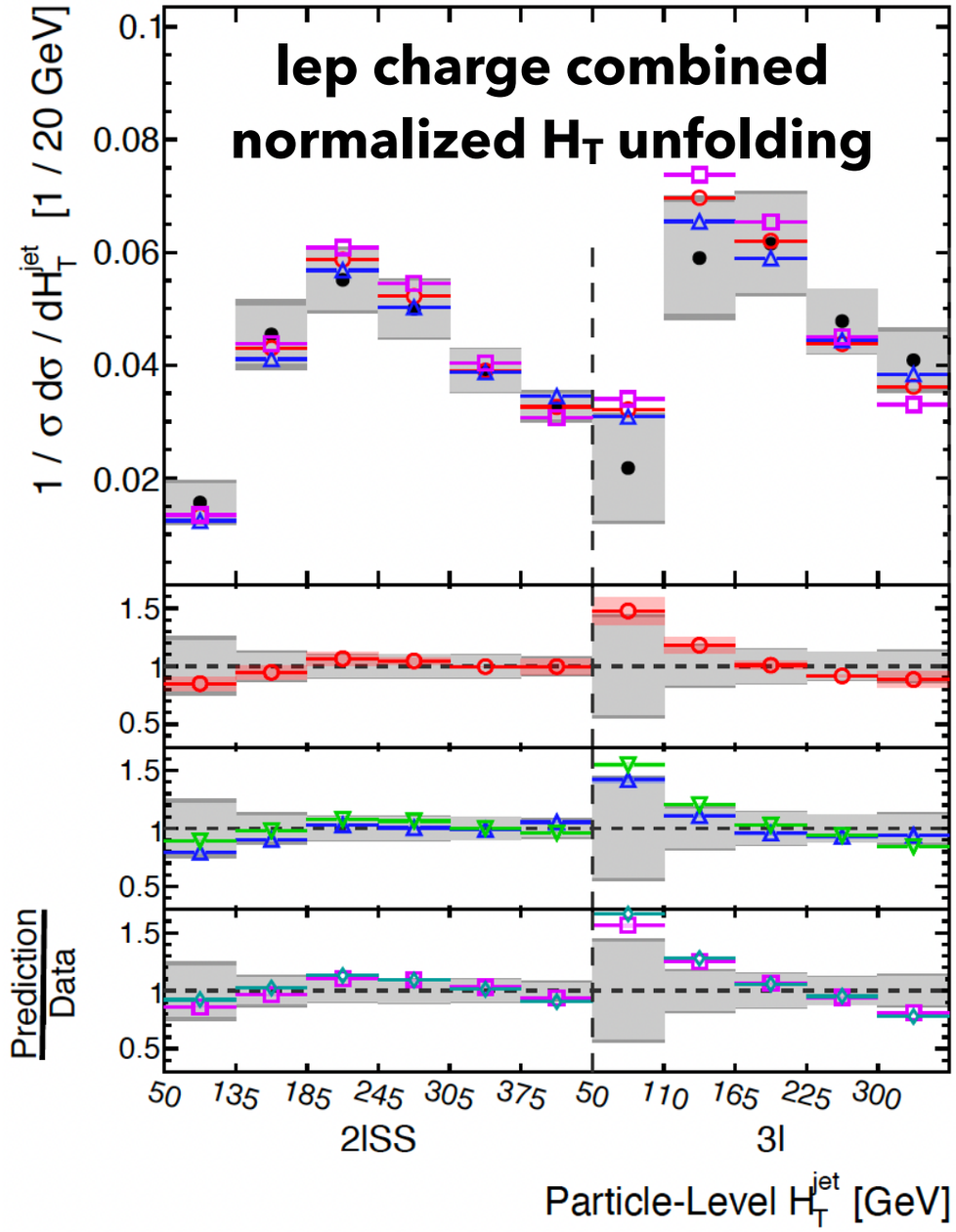


ATLAS-CONF-2023-019

$t\bar{t}W$ production (differential) NEW!

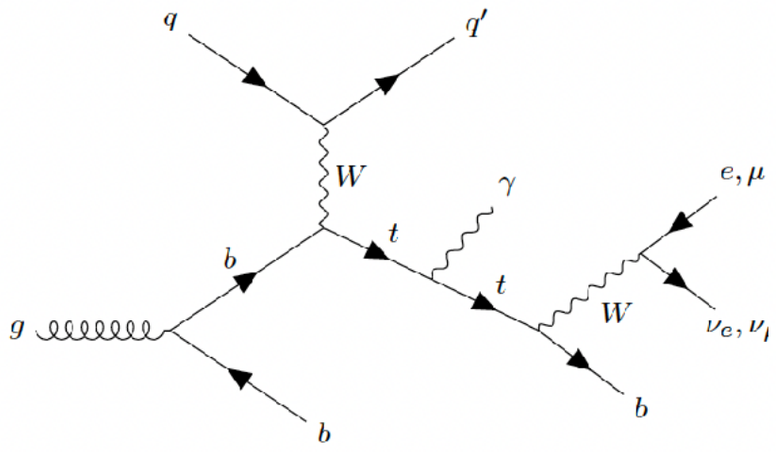
- SS and multi-lep final states
- Normalized differential σs: measured for 7 observables
- First differential measurement!
- Generally consistent with SM



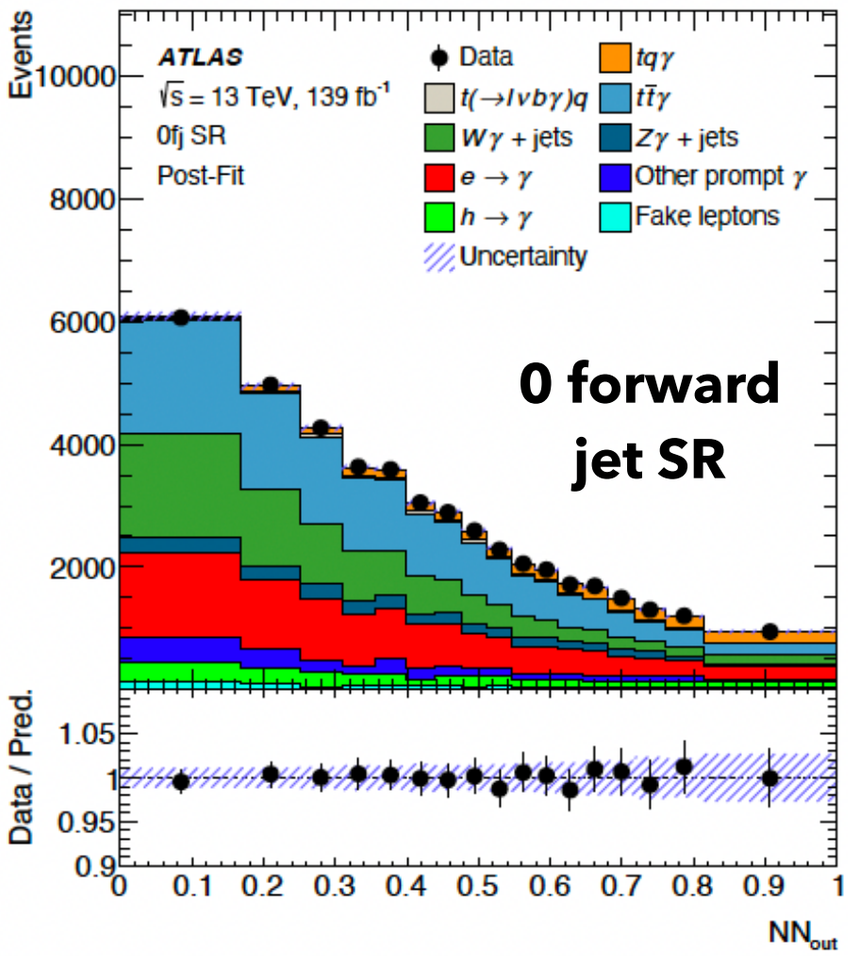


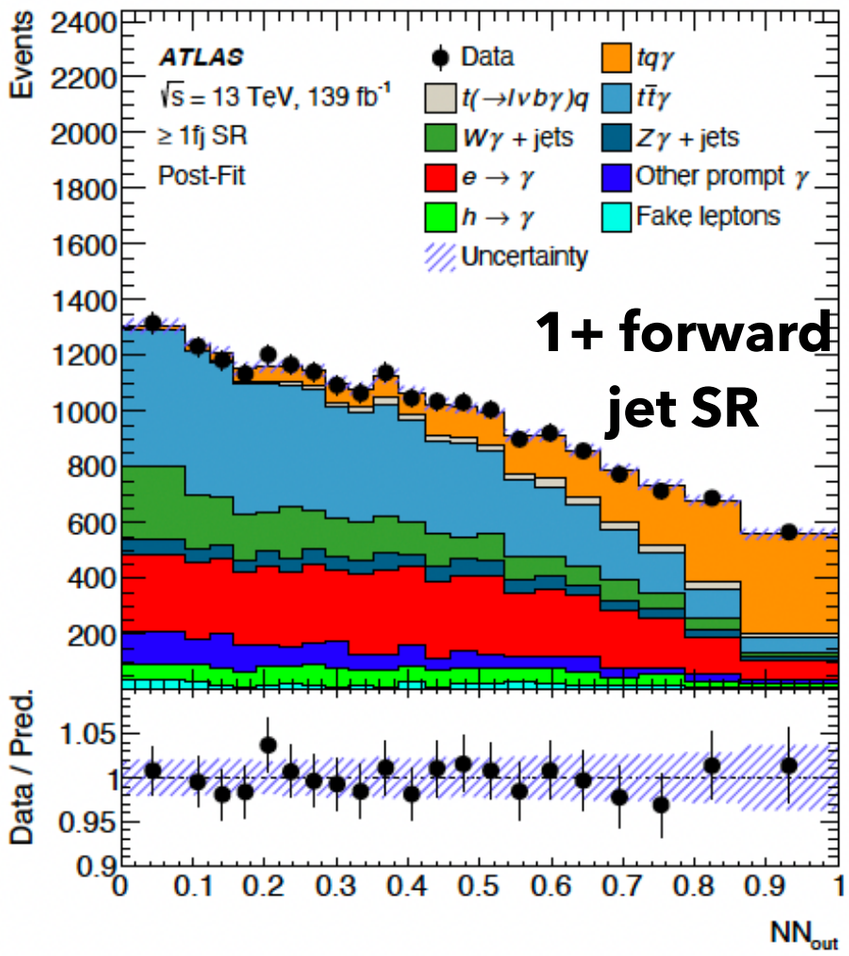
arXiv:2302.01283

$t\gamma$ observation



- Final state: 1 lep, 1 γ, +jets
- 2 SRs w/ forward jets
- NNs to separate sig from bkg
- Previously 4.4 s.d. evidence (CMS 35.9 fb^{-1} @ 13TeV)
- First observation!
- obs (exp) significance : 9.3 (6.8) s.d. 139 fb^{-1} @ 13 TeV



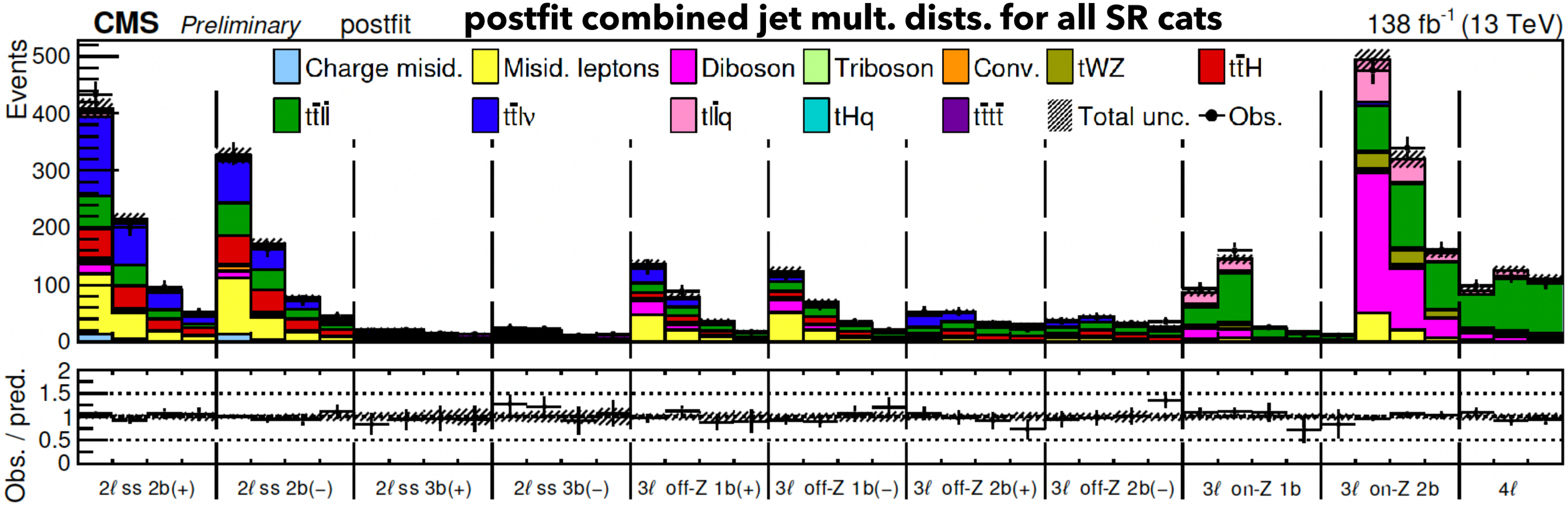


$\sigma_{tq\gamma} \times \mathcal{B}(t \to b\ell\nu)$	Meas. fid. cross section (fb)	SM prediction (fb)
Parton level	$688 \pm 23\ (\text{stat})\ ^{+75}_{-71}\ (\text{syst})$	515^{+36}_{-42}
Particle level	$303 \pm 9\ (\text{stat})\ ^{+33}_{-32}\ (\text{syst})$	217^{+27}_{-15}

top+leptons EFT search NEW!

CMS-TOP-22-006

- Potential new physics parametrized vs. 26 6-dim EFT operators
- Run II data categorized by lep/jet/b-jet multiplicities, total lep charge
- Fit to kinematic vars. (leading leps/jets transv. p_T, on-shell Z p_T)
- No significant deviation from SM predictions



Also see talks by Davide Valsecchi & Eleonora Rossi!

Conclusion

ATLAS, CMS, and LHC top results

- Highlighted latest ATLAS & CMS top cross section and $t\bar{t}X$ measurements that showcase tops as key tool for probing limits of SM
- Several new measurements and observations beyond expectations because of improved analysis strategies and techniques
  - First Run 3 results!
  - First evidence of tWZ!
  - First $t\bar{t}t\bar{t}$ observation!
  - New $t\bar{t}b\bar{b}$, $t\bar{t}W$, top EFT, & single top t-channel measurements!
- Generally good agreement with SM with some excesses ($t\bar{t}t\bar{t}$, $t\bar{t}W$, tWZ…)
  - NNLO calculations & improved MC needed
- Look forward to further exploration in Run 3/HL-LHC!

BACKUP

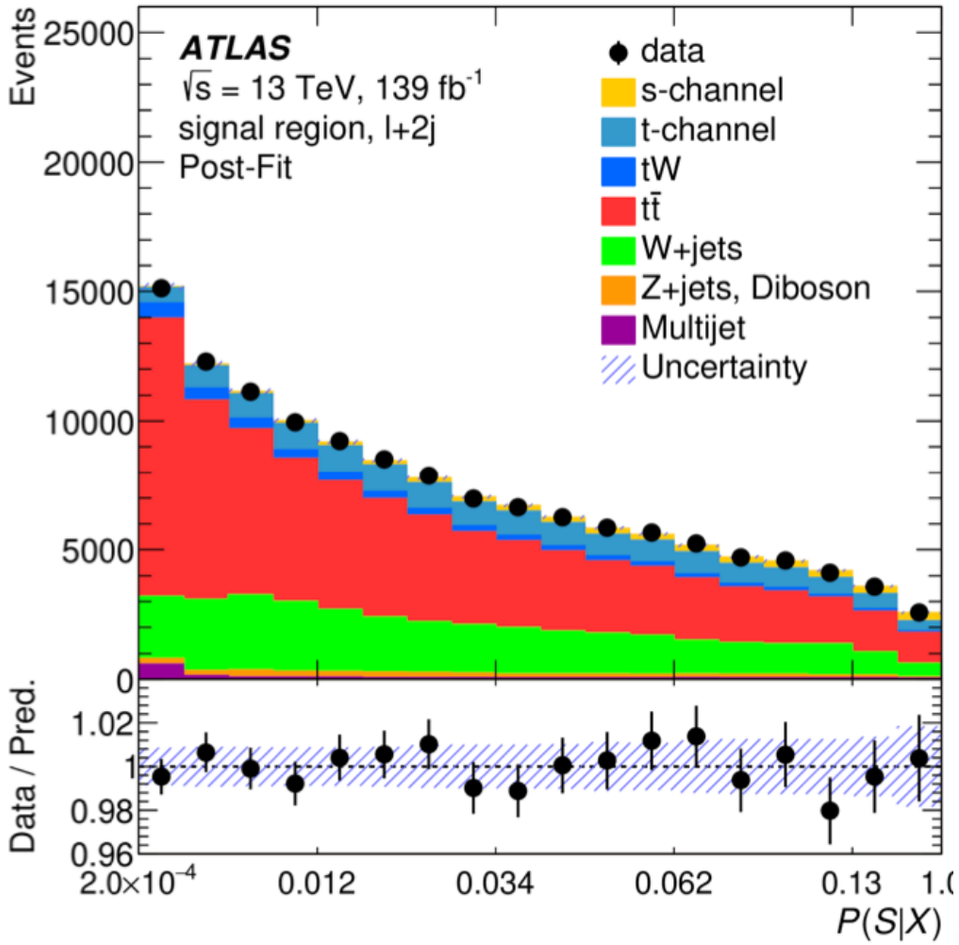
inclusive & differential $t\bar{t}$

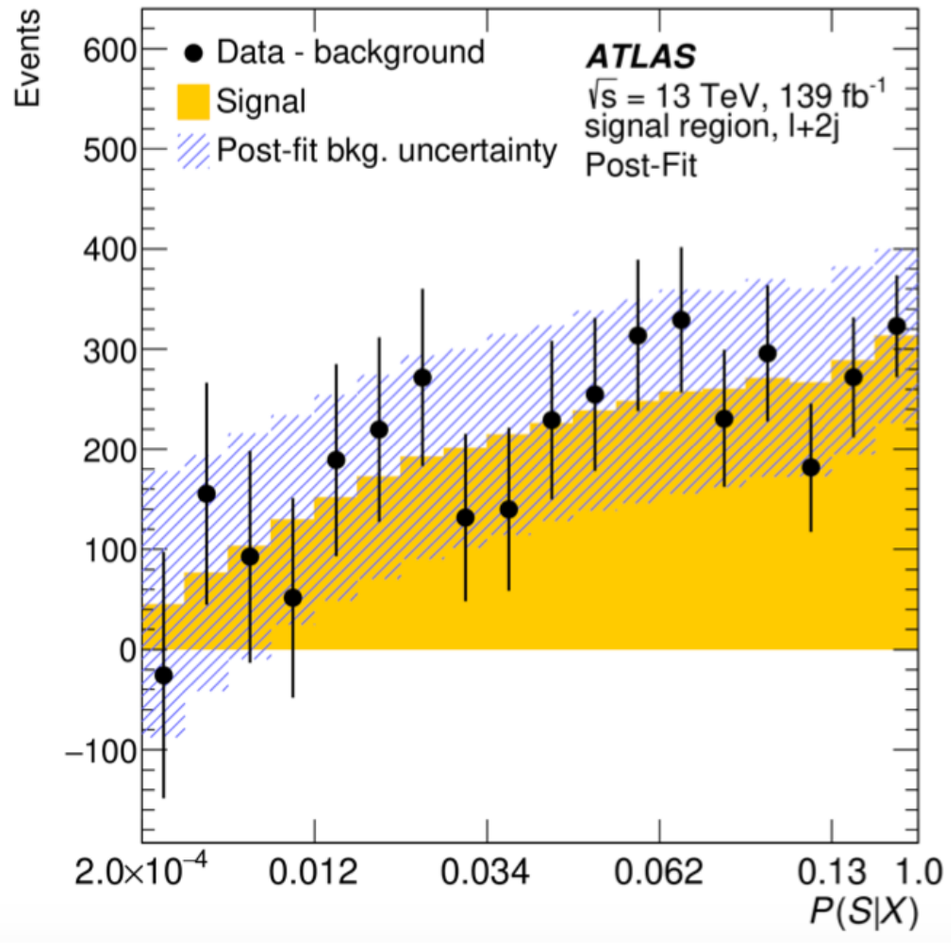
TOPQ-2018-26

- p_{T}^{ℓ}, the single-lepton transverse momentum[1] ($\ell = e$ or μ);
- $|\eta^{\ell}|$, the single-lepton pseudorapidity;
- $m^{e\mu}$, the $e\mu$ system invariant mass;
- $p_{\mathrm{T}}^{e\mu}$, the $e\mu$ system transverse momentum;
- $|y^{e\mu}|$, the $e\mu$ system rapidity;
- $E^{e} + E^{\mu}$, the sum of lepton energies;
- $p_{\mathrm{T}}^{e} + p_{\mathrm{T}}^{\mu}$, the scalar sum of lepton transverse momenta;
- $|\Delta\phi^{e\mu}|$, the azimuthal angular separation of the leptons.

arXiv:2209.08990

s-channel production

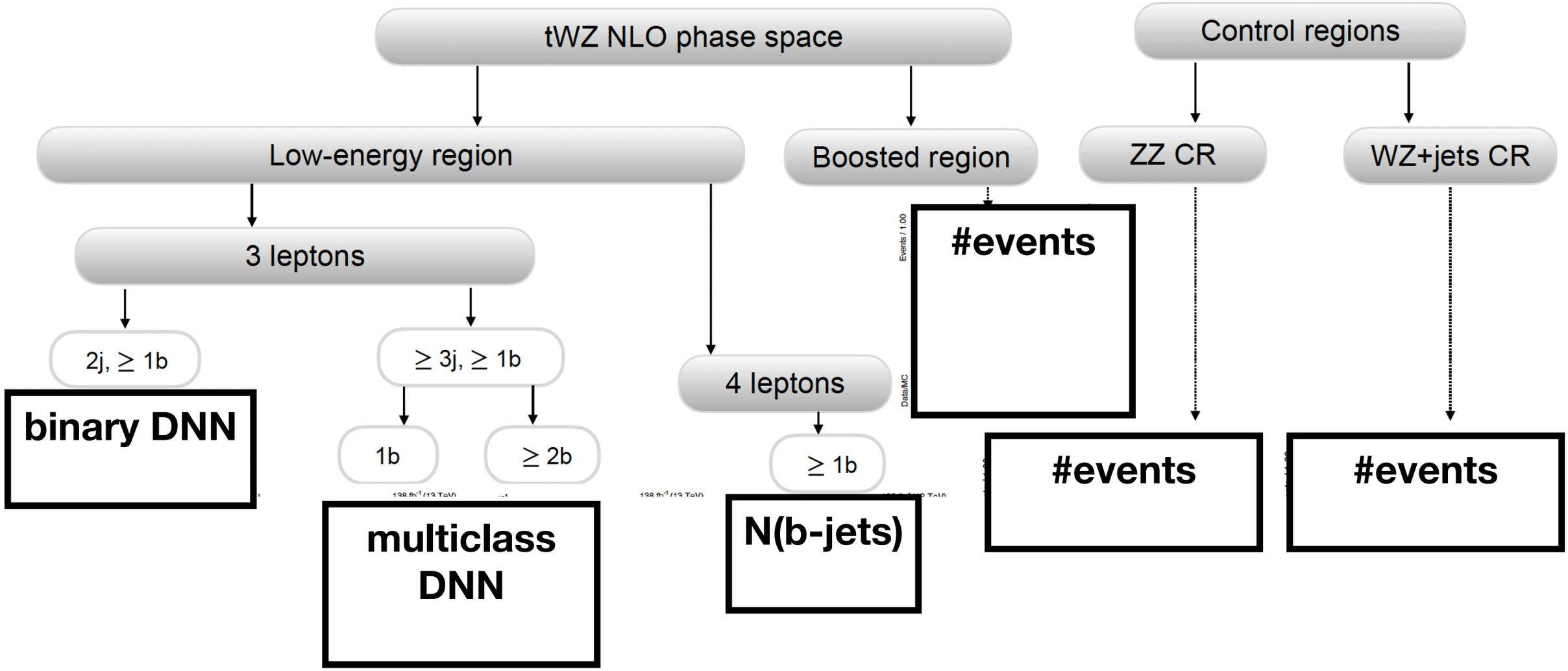




- **the right-hand plot is data minus all background**
- **different error bars in the left and the right plot come from the background subtraction and correlations of uncertainties**

tWZ production NEW!

Templates used in the maximum likelihood fit

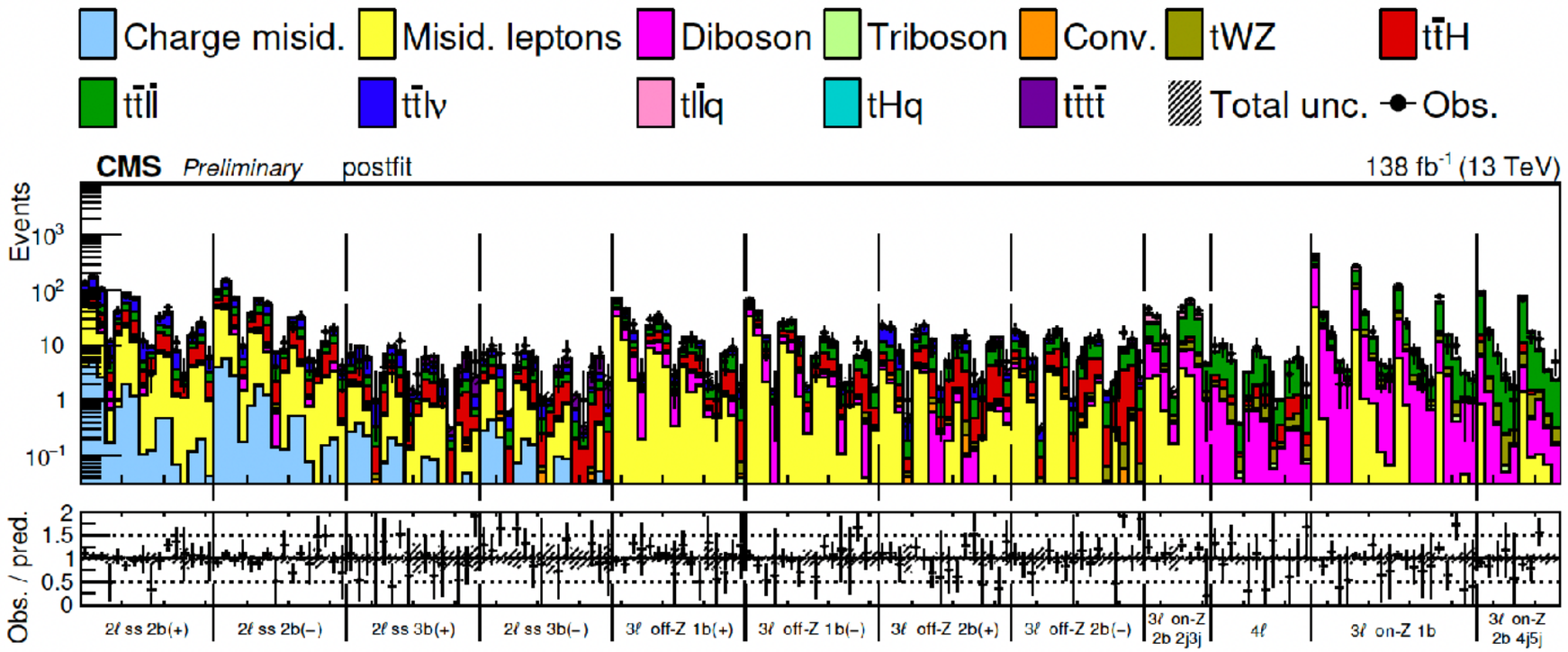


top+leptons EFT search

CMS-TOP-22-006

Table 1: List of WCs included in this analysis. The definitions of the WCs and the definitions of the corresponding operators can be found in Table 1 of Ref. [18]. Note that in order to allow MADGRAPH5_aMC@NLO to properly handle the emission of gluons from the vertices involving the c_{tG} WC, an extra factor of the strong coupling is applied to the c_{tG} coefficients.

Operator category	WCs
Two heavy quarks	$c_{t\varphi}$, $c^{-}_{\varphi Q}$, $c^{3}_{\varphi Q}$, $c_{\varphi t}$, $c_{\varphi tb}$, c_{tW}, c_{tZ}, c_{bW}, c_{tG}
Two heavy quarks two leptons	$c^{3(\ell)}_{Q\ell}$, $c^{-(\ell)}_{Q\ell}$, $c^{(\ell)}_{Qe}$, $c^{(\ell)}_{t\ell}$, $c^{(\ell)}_{te}$, $c^{S(\ell)}_{t}$, $c^{T(\ell)}_{t}$
Two light quarks two heavy quarks	c^{31}_{Qq}, c^{38}_{Qq}, c^{11}_{Qq}, c^{18}_{Qq}, c^{1}_{tq}, c^{8}_{tq}
Four heavy quarks	c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}



top+leptons EFT search

CMS-TOP-22-006

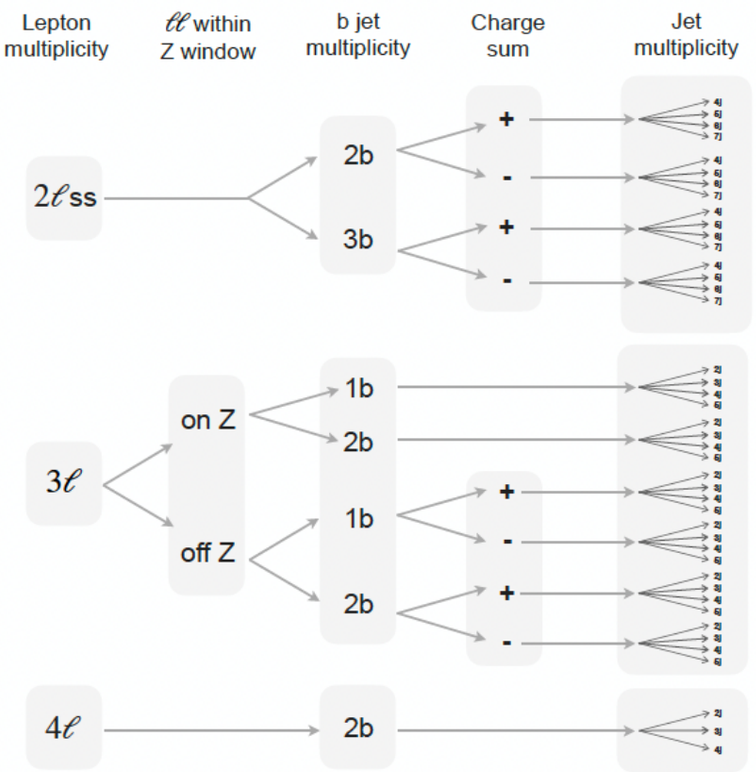
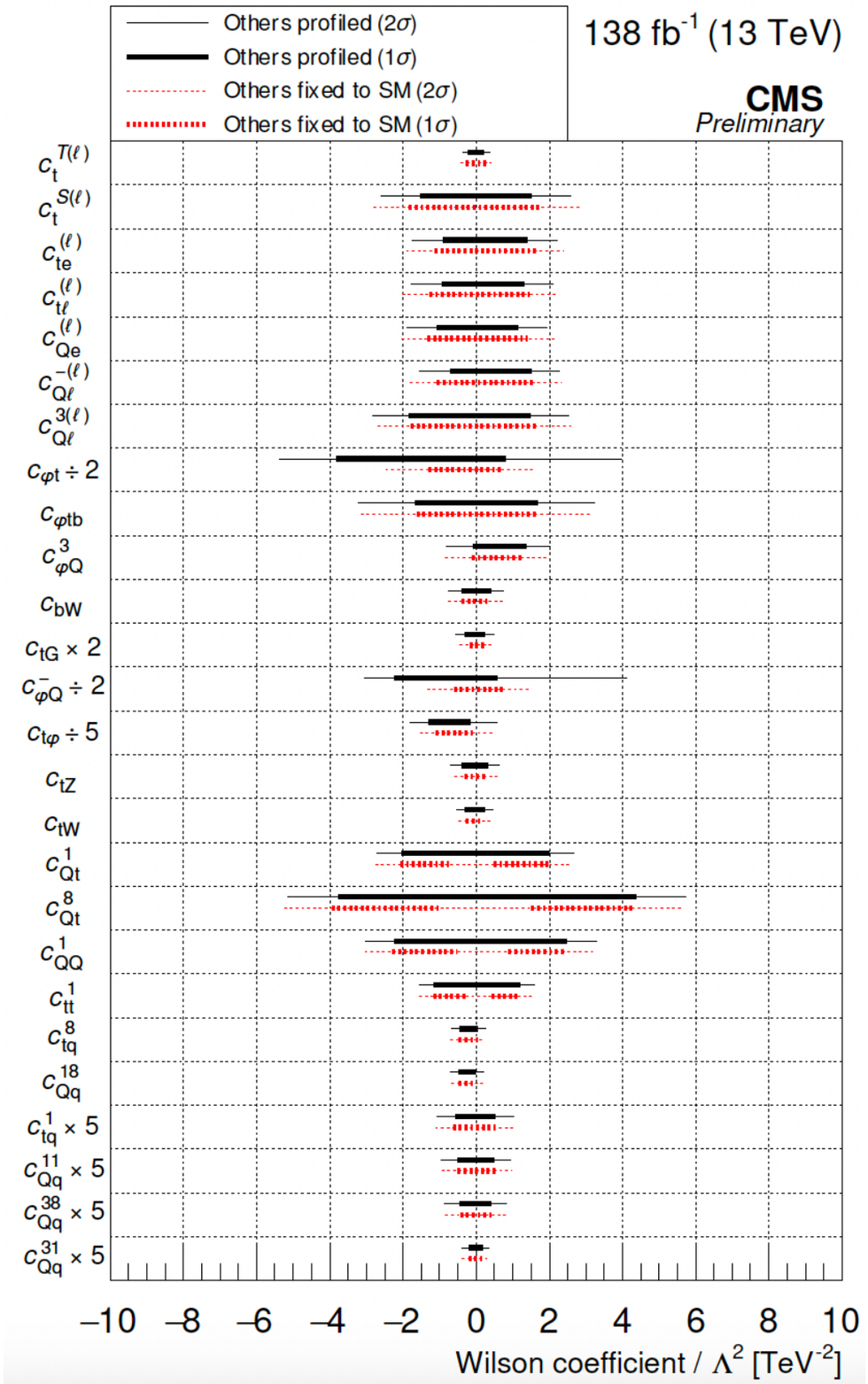


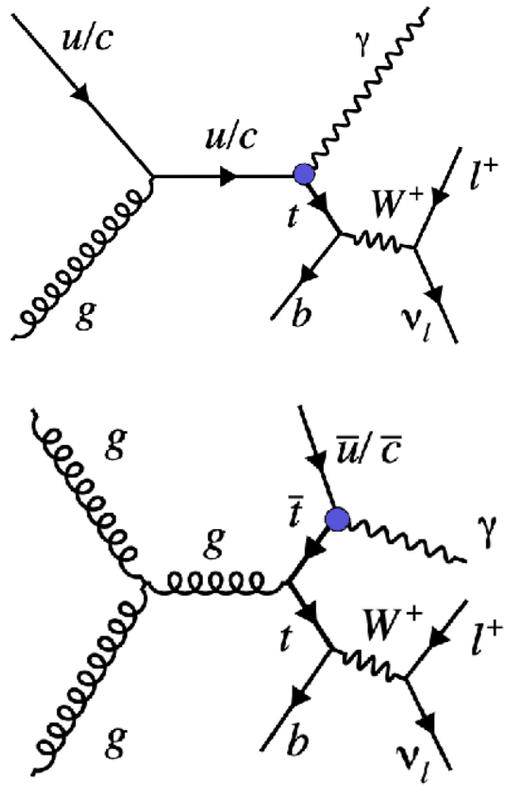
Figure 1: Summary of the event selection categorization. The details for the selection requirements are described in Sections 5.1, 5.2, and 5.3.



Additional Analyses

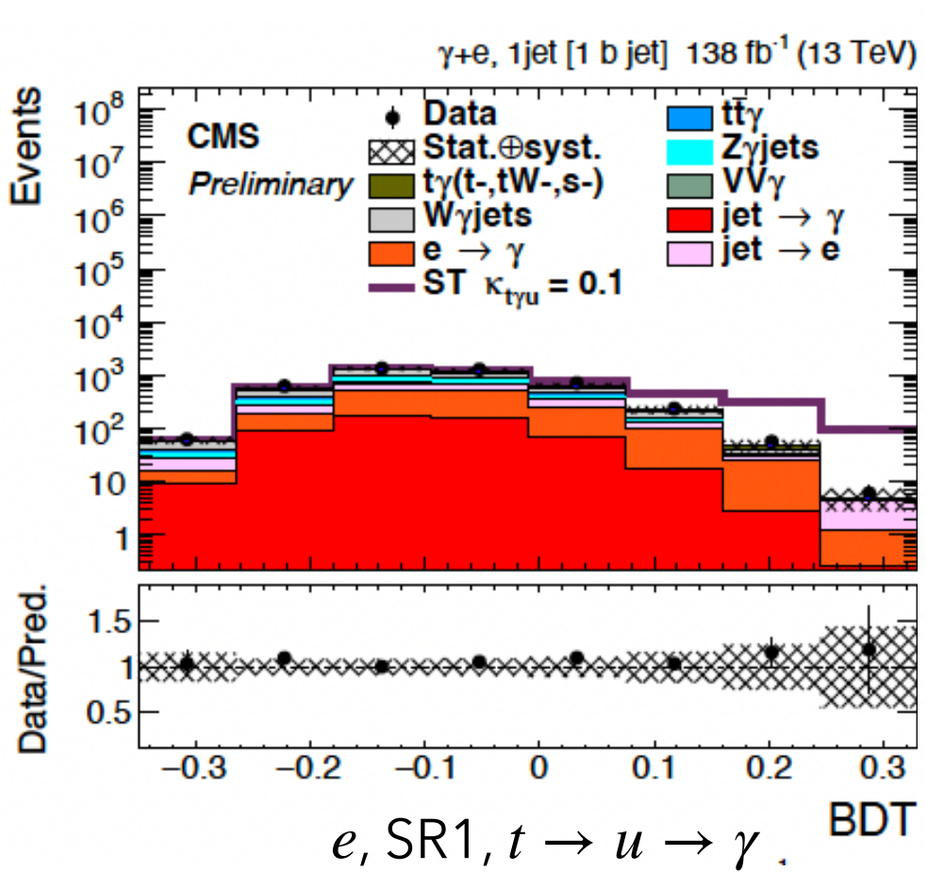
FCNC in $t\gamma$

- Search for FCNC top interactions in assoc. with $\gamma + jets$
- Final states with 1 lep 1 γ, +jets
- BDTs to separate sig vs. bkg
- Obs (exp) upper limits set on FCNC coupling strengths ($\kappa_{tq\gamma}$) & branching fractions of top quark decays

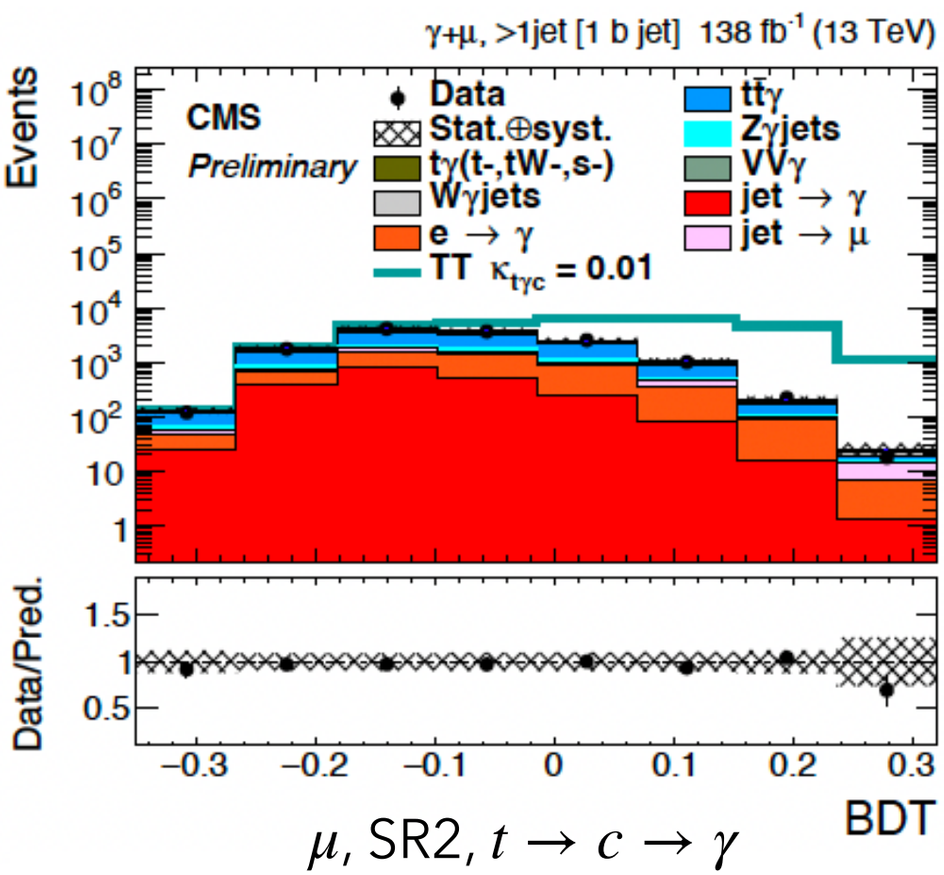


CMS-PAS-TOP-21-013

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}



e, SR1, $t \to u \to \gamma$

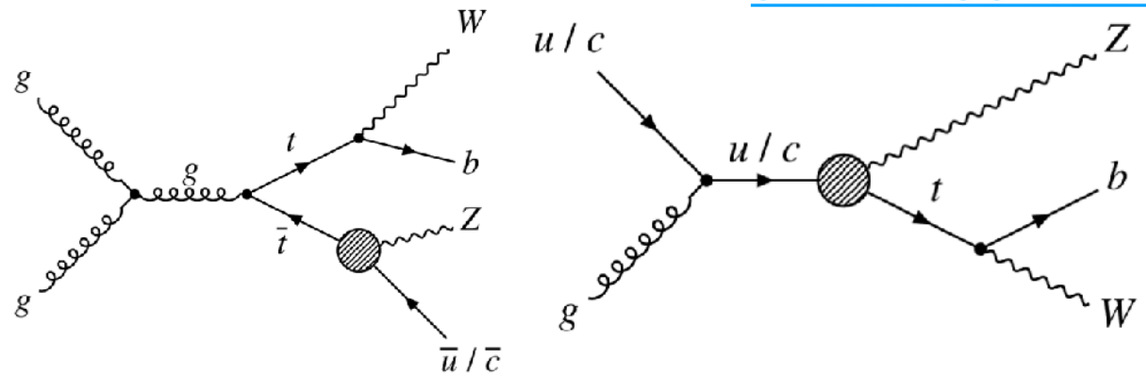


μ, SR2, $t \to c \to \gamma$

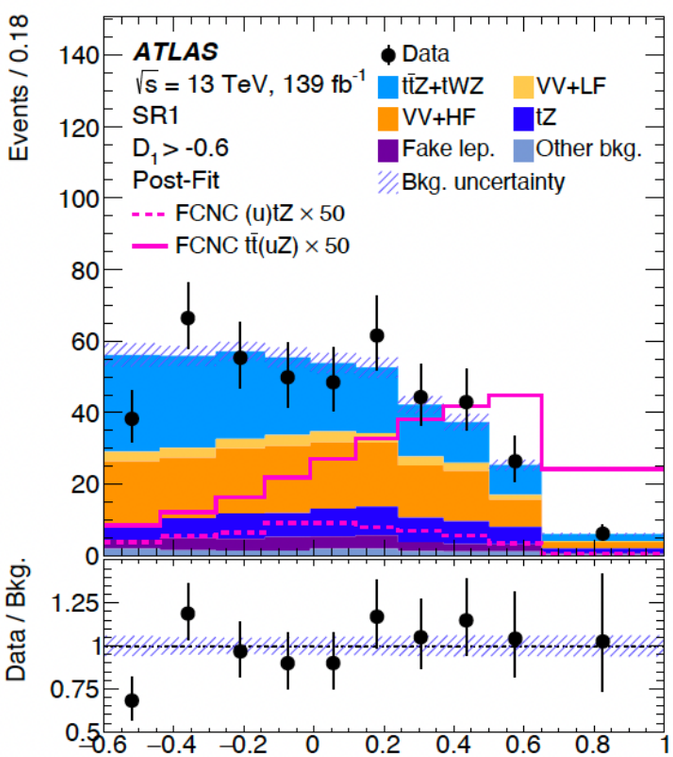
FCNC in tZ

- Search for FCNC top interactions in assoc. with Z
- Final states with 1 or 2 tops, 3 leps, 1 b-jet, MET
- BDTs to separate sig from bkg
- Obs (exp) upper limits set on FCNC coupling strengths & branching fractions of top quark decays

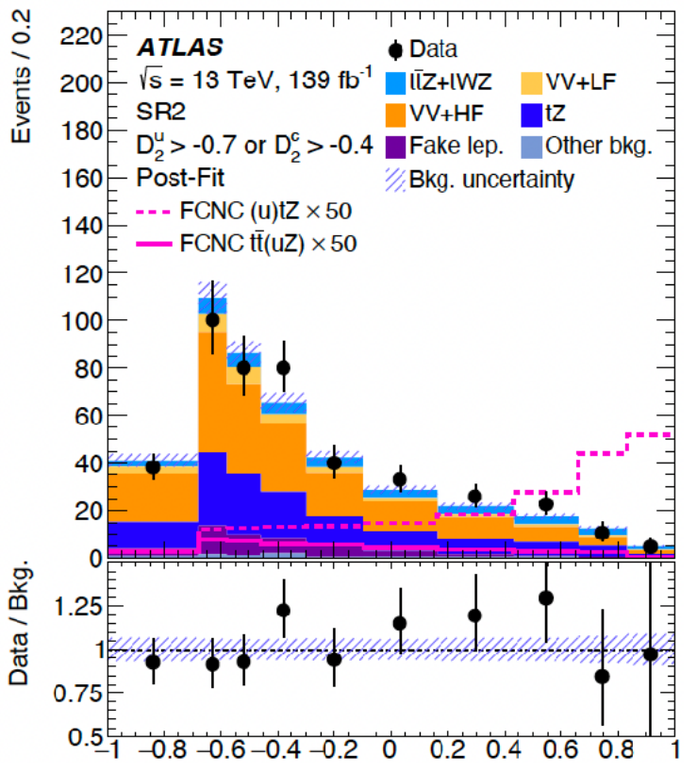
arXiv:2301.11605



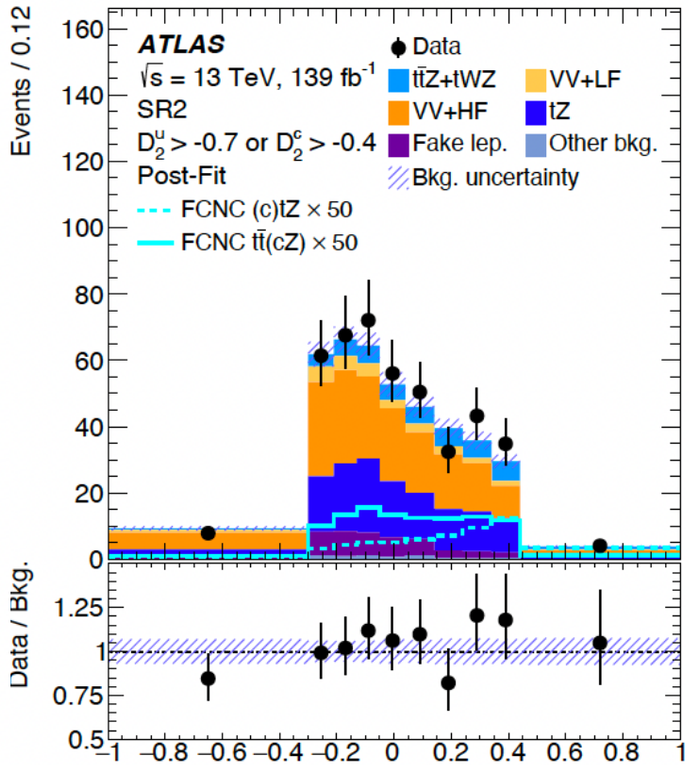
Observable	Vertex	Coupling	Observed	Expected
	SRs+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3}\times10^{-5}$
$\mathcal{B}(t \to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



BDT 1, $t \to Z \to u/c$ D_1



BDT 2, $t \to Z \to u$ D_2^u

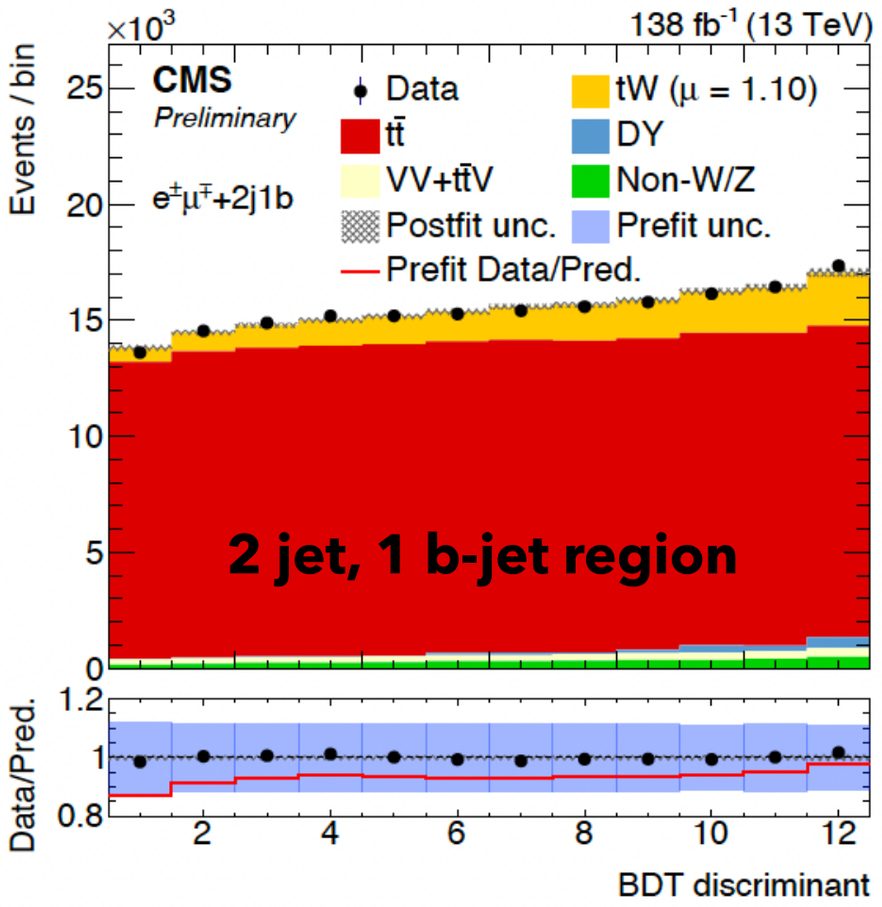


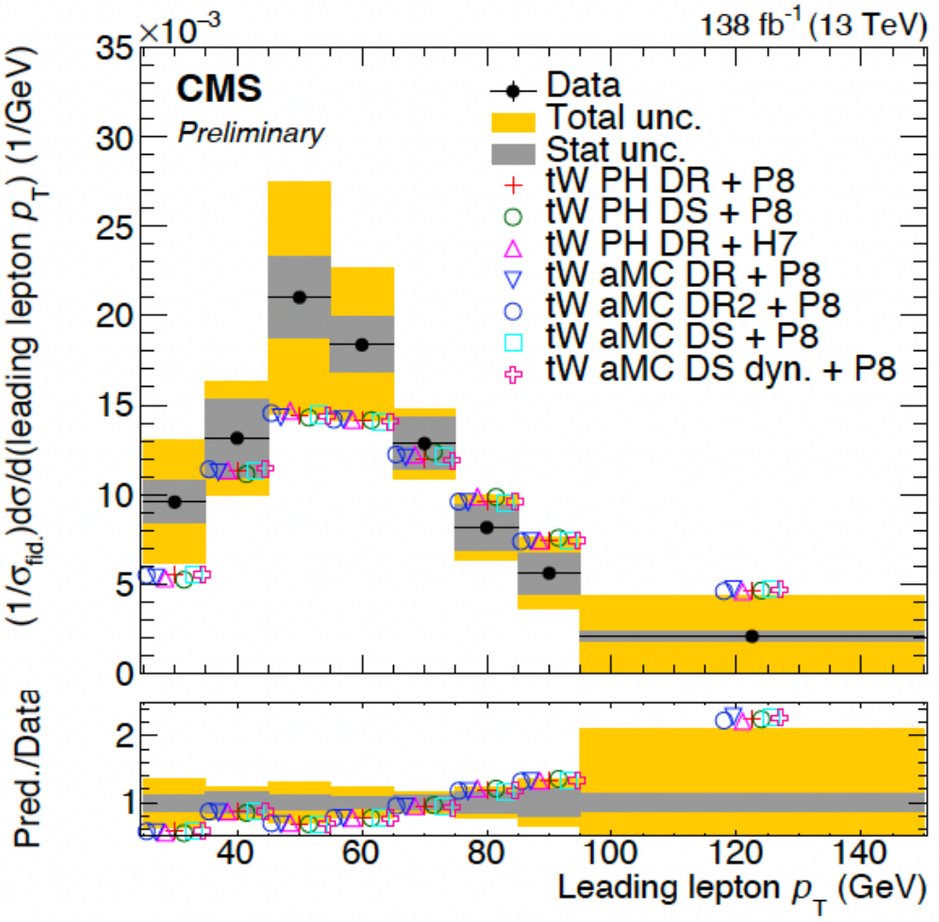
BDT 2, $t \to Z \to c$ D_2^c

single top tW production

CMS-PAS-TOP-21-010

- 1-lepton final state (e or μ)
- inclusive and differential
- max likelihood fit to BDTs & subleading jet pT in 1 & 2 jet/ b-jet regions.





- Study differential distributions of 6 kinematic variables
- Consistent with SM predictions

$$\sigma_{tW} = 79.2 \pm 0.8\ (\text{stat})^{+7.0}_{-7.2}\ (\text{syst}) \pm 1.1\ (\text{lumi})\ \text{pb}$$