tX + ttX in CMS and ATLAS

Les Rencontres de Physique de la Vallée d'Aoste

Carlos Vico Villalba on behalf of the CMS and ATLAS collaborations

Grant PID2020-113341RB-I00 funded by:

1. Flavor-changing neutral currents between the top quark and the Z boson at 13 TeV
arXiv: 2301.11605

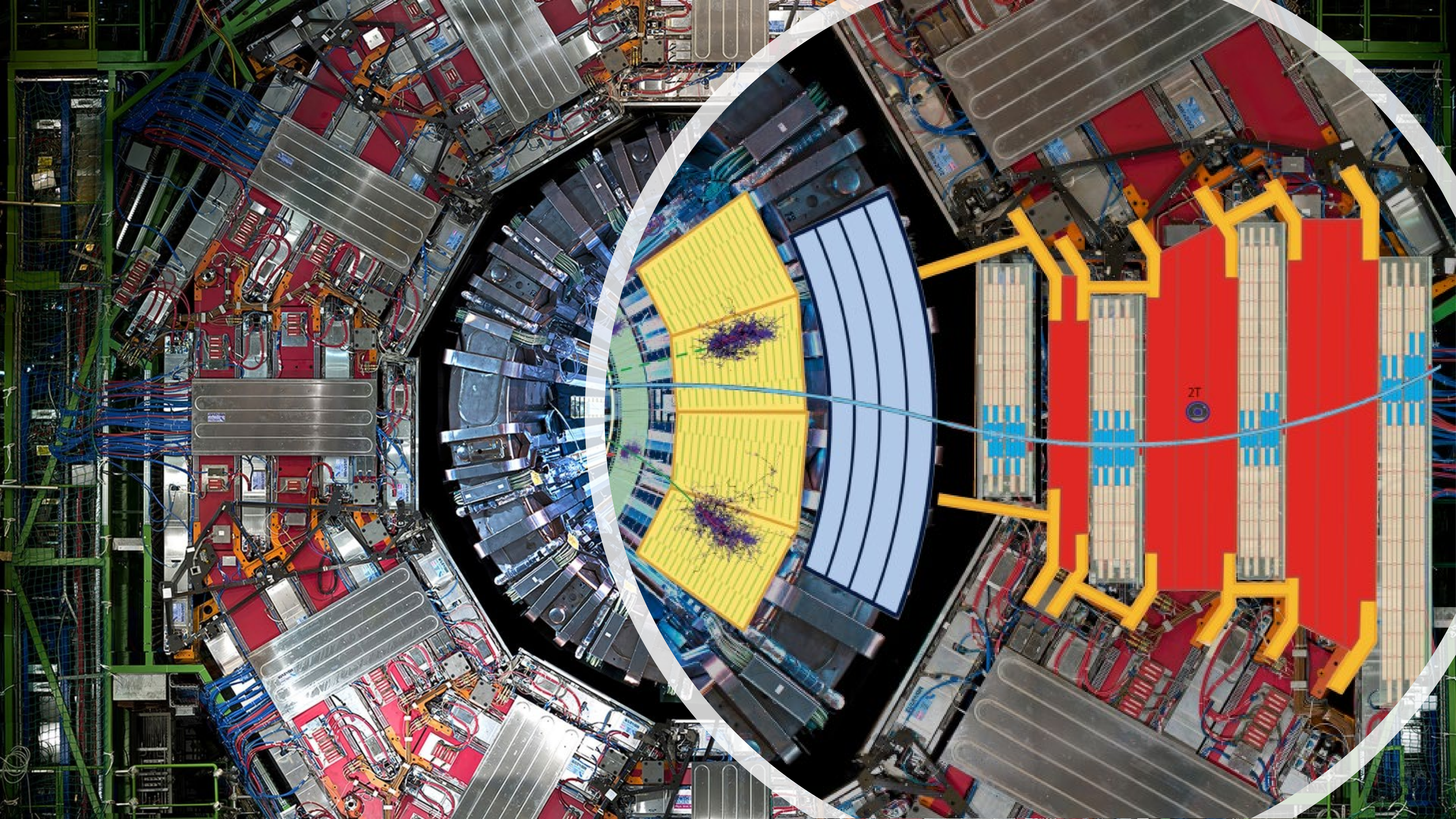
2. Inclusive $t\bar{t}W$ production at 13 TeV
arXiv: 2208.06485

3. Leptonic charge asymmetry production in $t\bar{t}W$ final states.
arXiv: 2301.04245

4. EFT searches in $t\bar{t}Z/H$ boosted topologies
arXiv: 2208.12837

5. Inclusive and differential tW production at 13 TeV
arXiv: 2208.00924

6. Observation of single-top quark production in association with a photon
arXiv:2302.01283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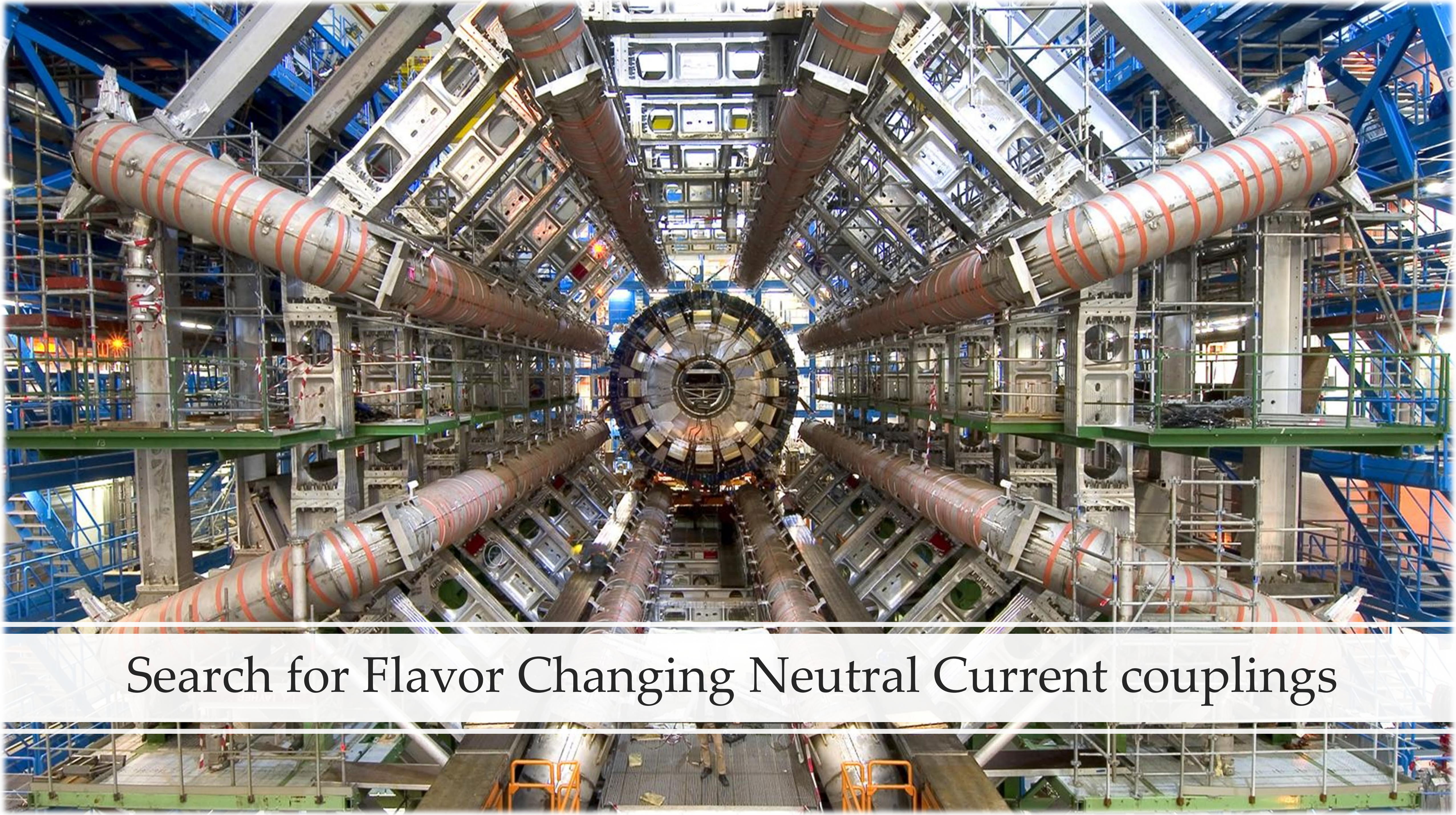


Search for Flavor Changing Neutral Current couplings

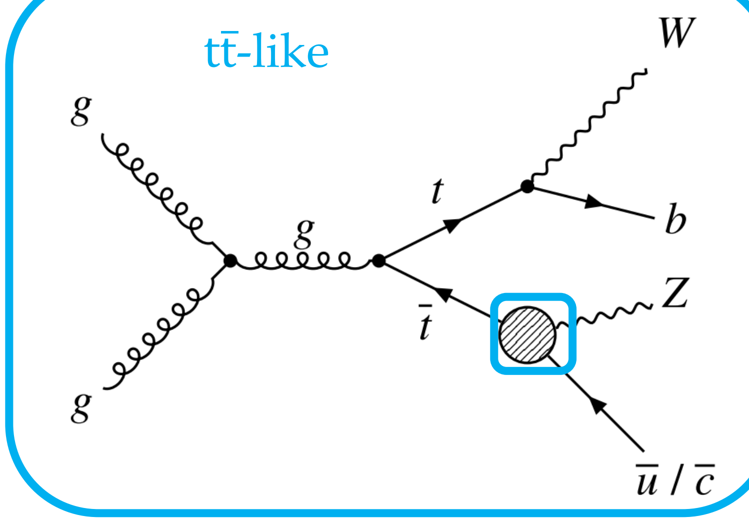
- Couplings of top quark to lighter quarks with same charge (u, c).
- These couplings can be studied as an **Effective Field Theory** (EFT).

Arxiv: 2301.11605
Submitted to PRD

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{NP}^2}\sum_k C_k O_k$$

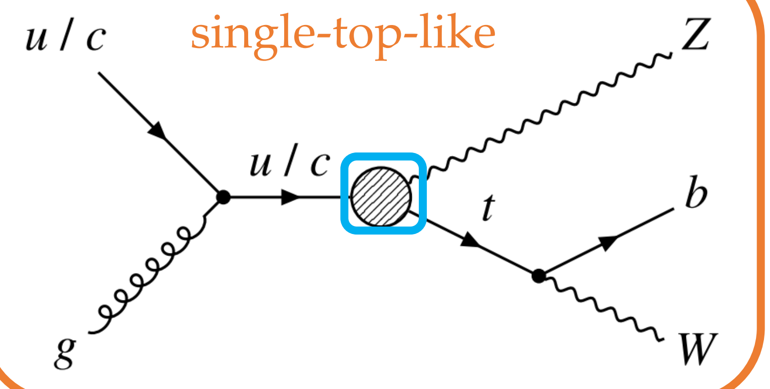
Suppressed by the scale at which new physics appear.

The strength of these couplings is given by the Wilson coefficients.



- tZq couplings for tensor operators of the extended theory are measured in tt̄-like and single-top-like topologies.

Coupling	Left Hand operator		Right Hand Operator	
tZu	$C_{uW}^{(13)}$	$C_{uB}^{(13)}$	$C_{uW}^{(31)}$	$C_{uB}^{(31)}$
tZc	$C_{uW}^{(23)}$	$C_{uB}^{(23)}$	$C_{uW}^{(32)}$	$C_{uB}^{(32)}$

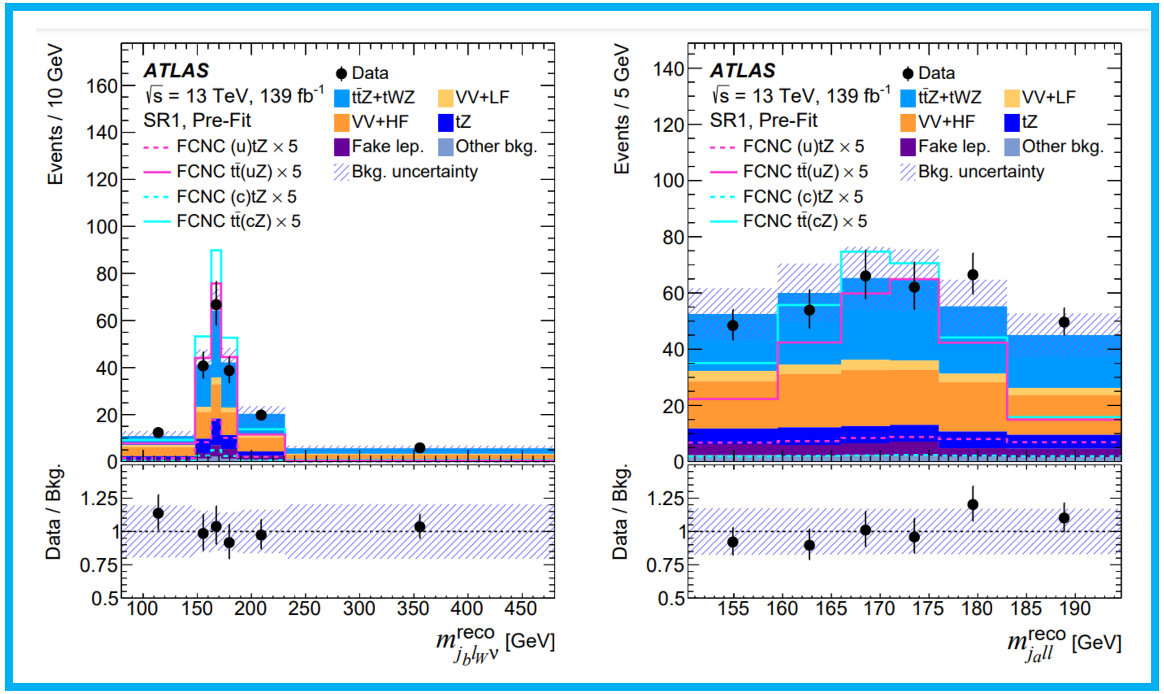


The **baseline selection** includes three final state lepton topologies, with:

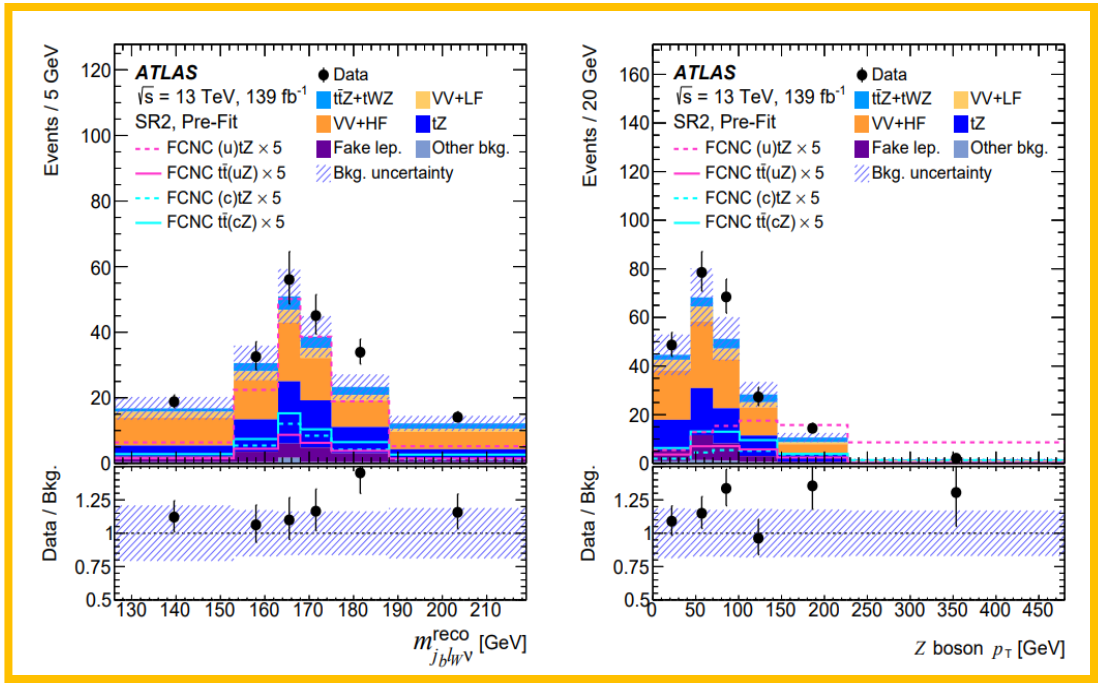
- Leptons: $p_T\ (\ell) > 27$ GeV
- OSSF pair with $|m_{\ell\ell} - m_Z| < 15$ GeV
- Overlap between regions is removed by including additional cuts on top-reconstructed kinematics

$t\bar{t}$-like	single-top-like	
SR1	SR2	
≥ 2 jets 1 b-jet –	1 jet 1 b-jet $m_T(\ell_W, \nu) > 40$ GeV	2 jets 1 b-jet $m_T(\ell_W, \nu) > 40$ GeV
$\lvert m^{reco}_{j_a\ell\ell} - m_t\rvert < 2\sigma_{t_{FCNC}}$ –	– $\lvert m^{reco}_{j_b\ell_W\nu} - m_t\rvert < 2\sigma_{t_{SM}}$	$\lvert m^{reco}_{j_a\ell\ell} - m_t\rvert > 2\sigma_{t_{FCNC}}$ $\lvert m^{reco}_{j_b\ell_W\nu} - m_t\rvert < 2\sigma_{t_{SM}}$

$t\bar{t}$-like



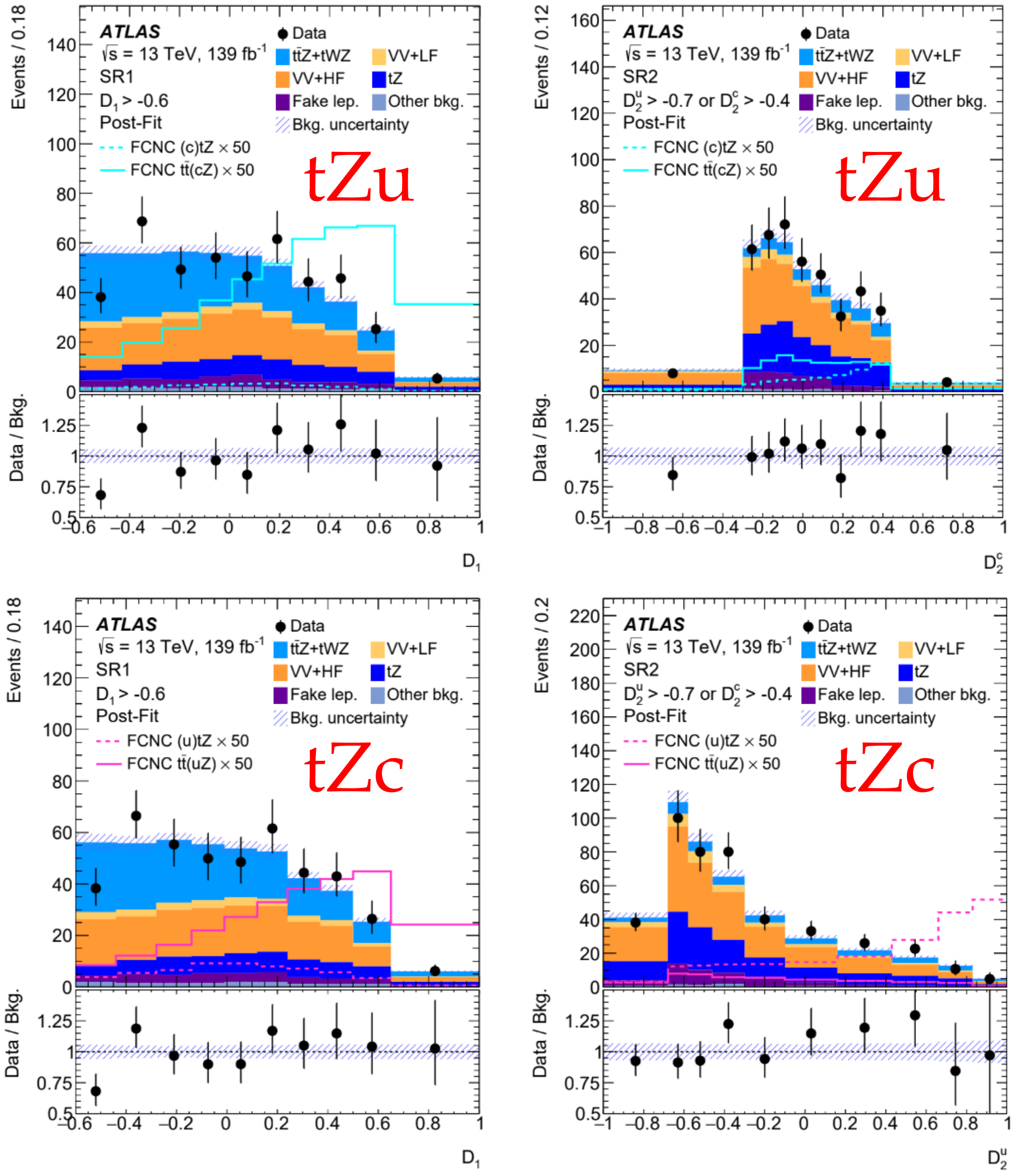
single-top-like

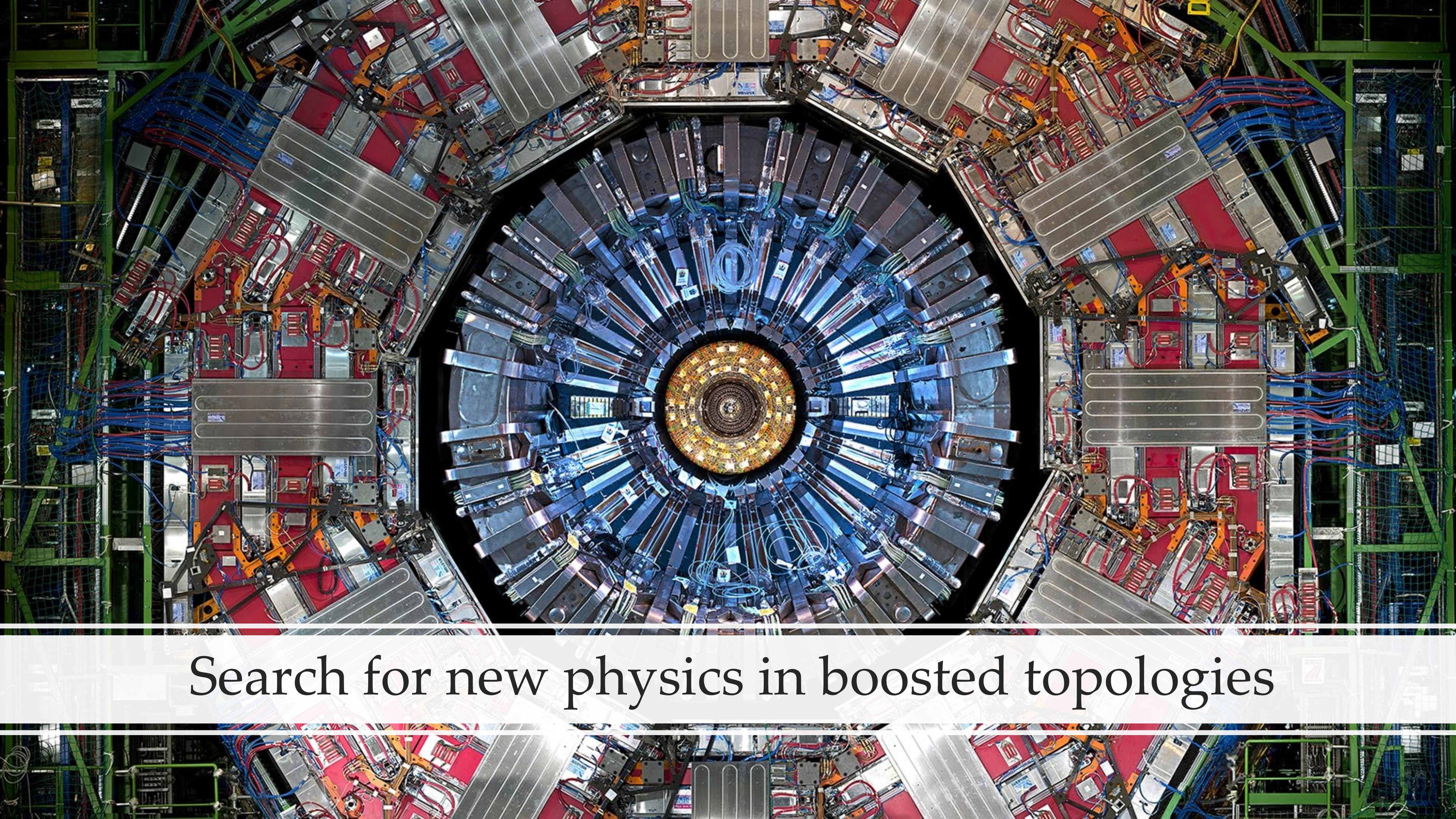


- A binned likelihood fit to the three BDT scores.

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}	$6.6\ ^{+2.9}_{-1.8} \times 10^{-5}$

- Current limits improved by a factor of 2-3 w.r.t previous ones!





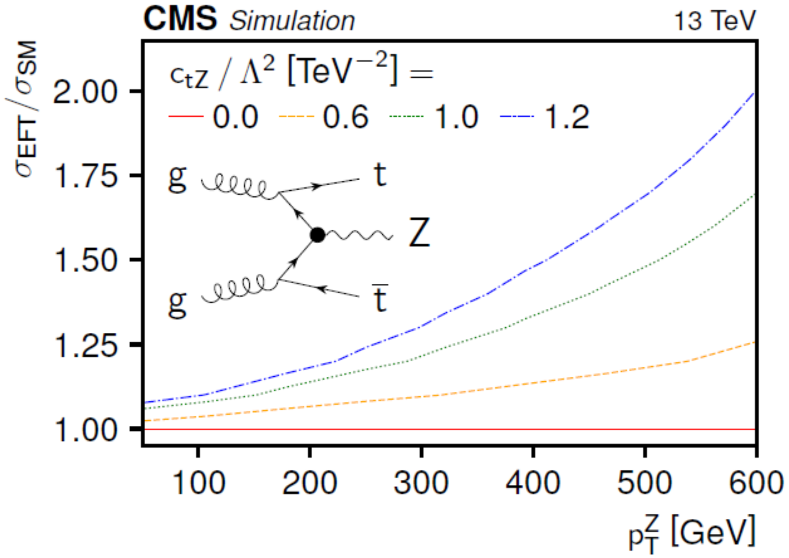
Search for new physics in boosted topologies

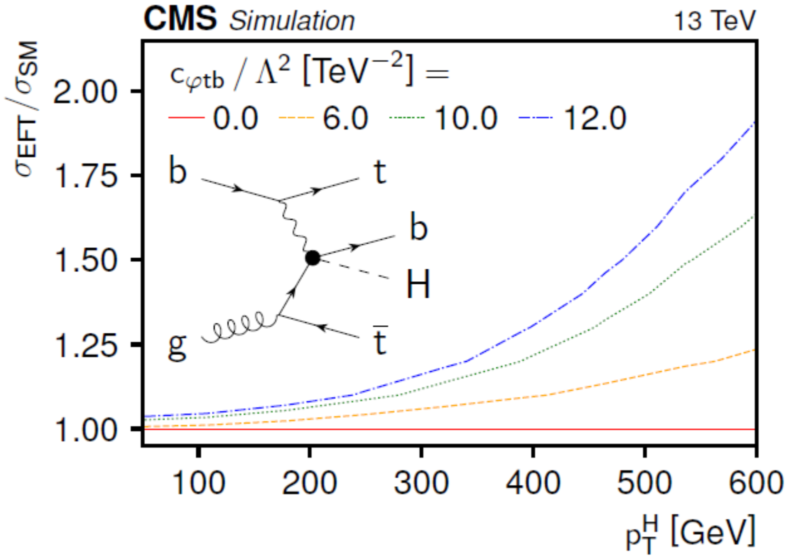
- EFT effects can be also studied in boosted topologies. A search for $t\bar{t}$ production in association with a **boosted** Z or H is presented.

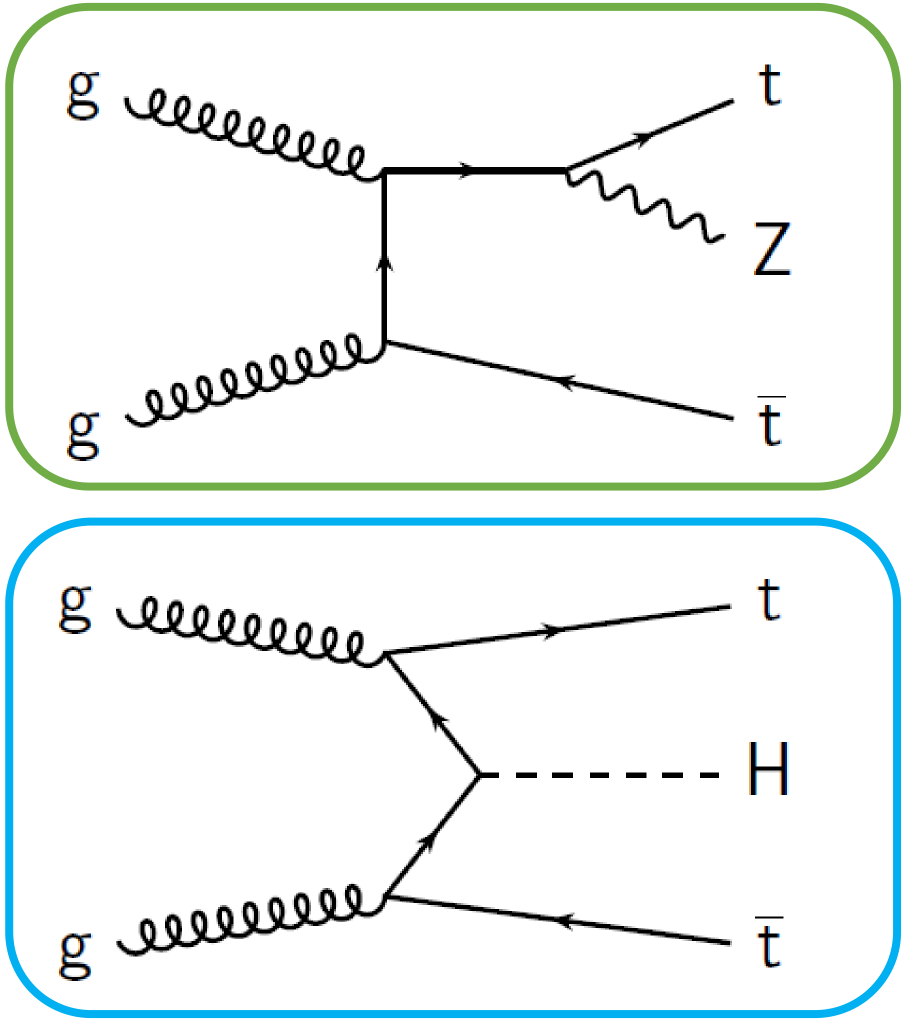
Arxiv: 2208.12837
Submitted to PRD

- Very sensitive to EFT couplings at high transverse momentum of Z/H bosons.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$



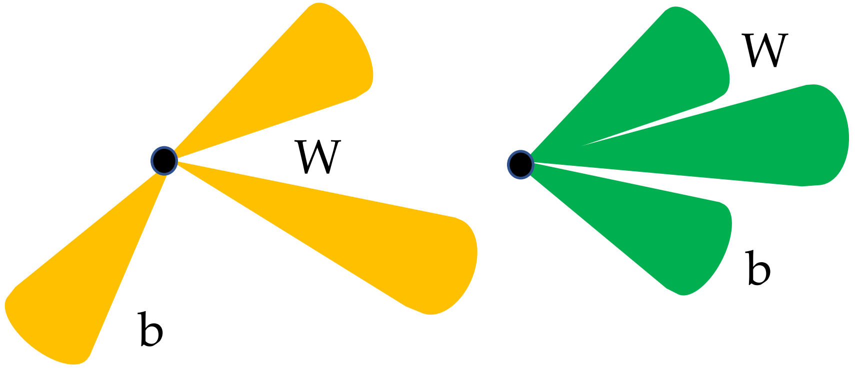




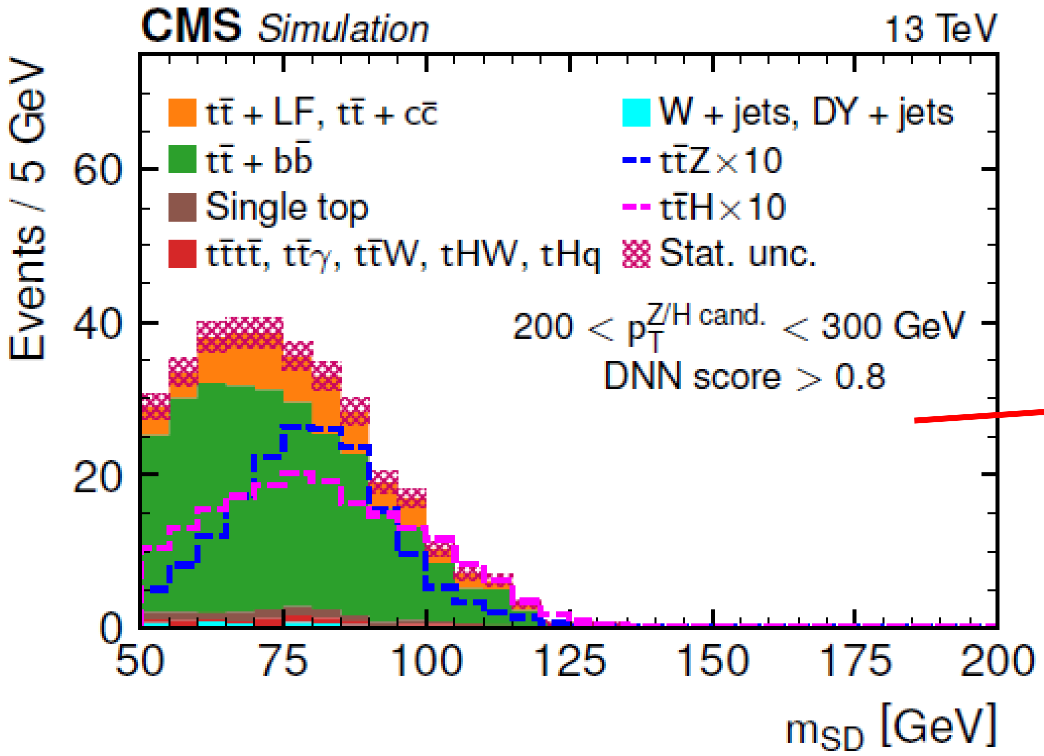
- The goal is to target single-lepton final states with Z/H→ $b\bar{b}$.
  - MVAs are used to discriminate from $t\bar{t}$+jets background.

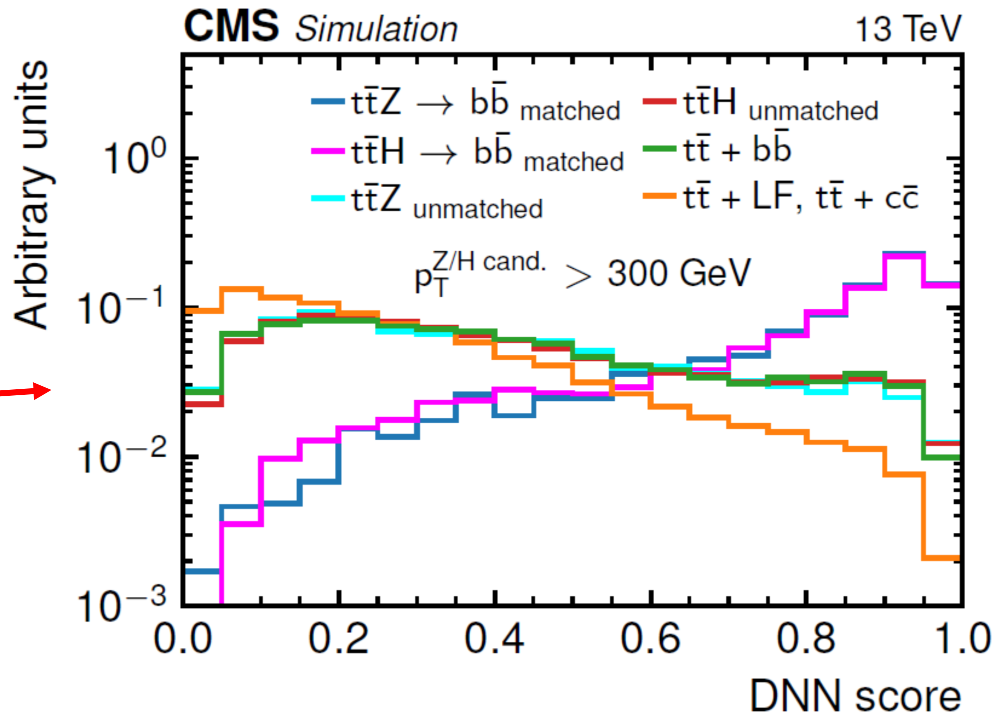
Search for new physics in boosted topologies. Analysis strategy

- Large Lorentz boost decay products will be collimated and may be reconstructed as a single "bigger" jet than resolved ones.



- The large background coming from $t\bar{t}$+jets makes it challenging to accurately reconstruct the $b\bar{b}$ pair from the bosons decay.
- MVA techniques are used in order to distinguish between $t\bar{t}Z/H \rightarrow b\bar{b}$ and $t\bar{t}+b\bar{b}$ and $t\bar{t}$+LF/$c\bar{c}$.



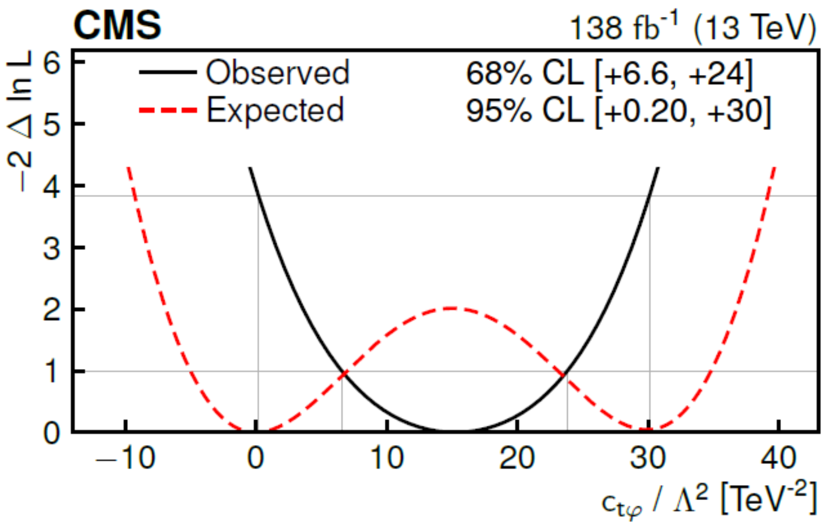


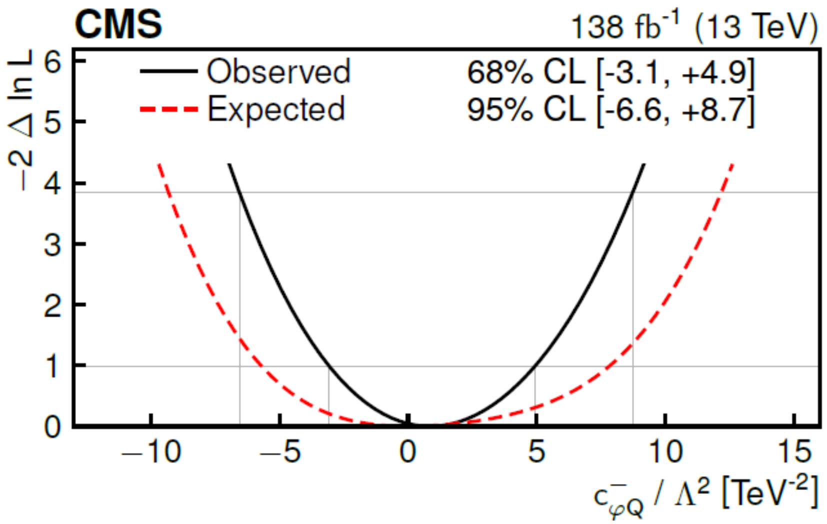
Search for new physics in boosted topologies. Results on EFT constraints

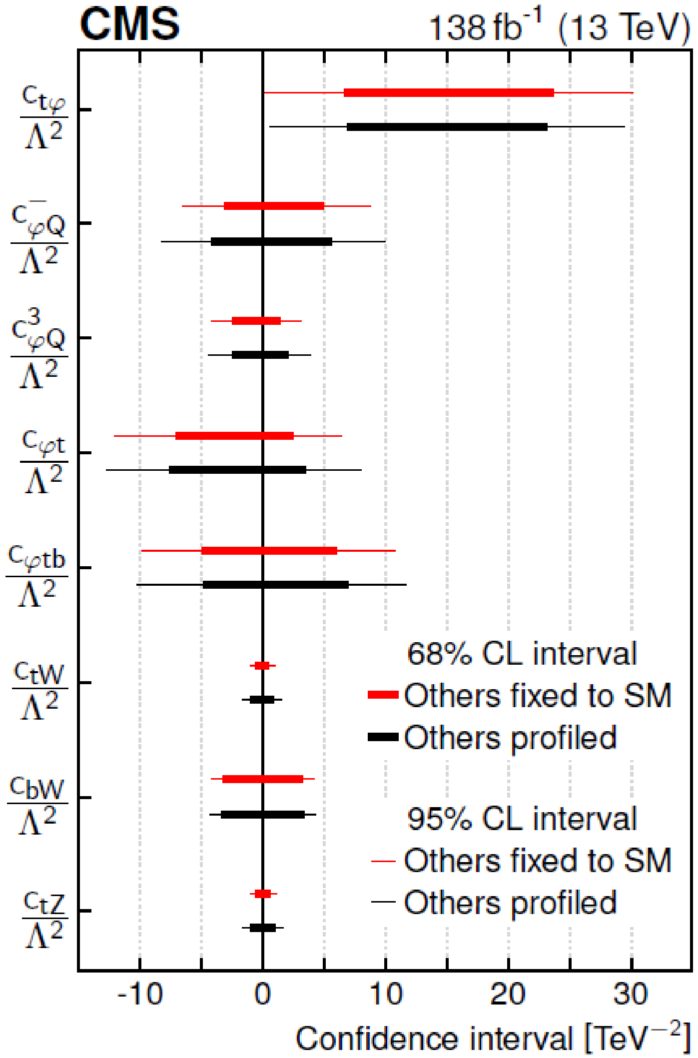
- Two likelihood fits are performed for each WC: with all other WCs profiled in the fit and with all other WCs kept fixed to SM.

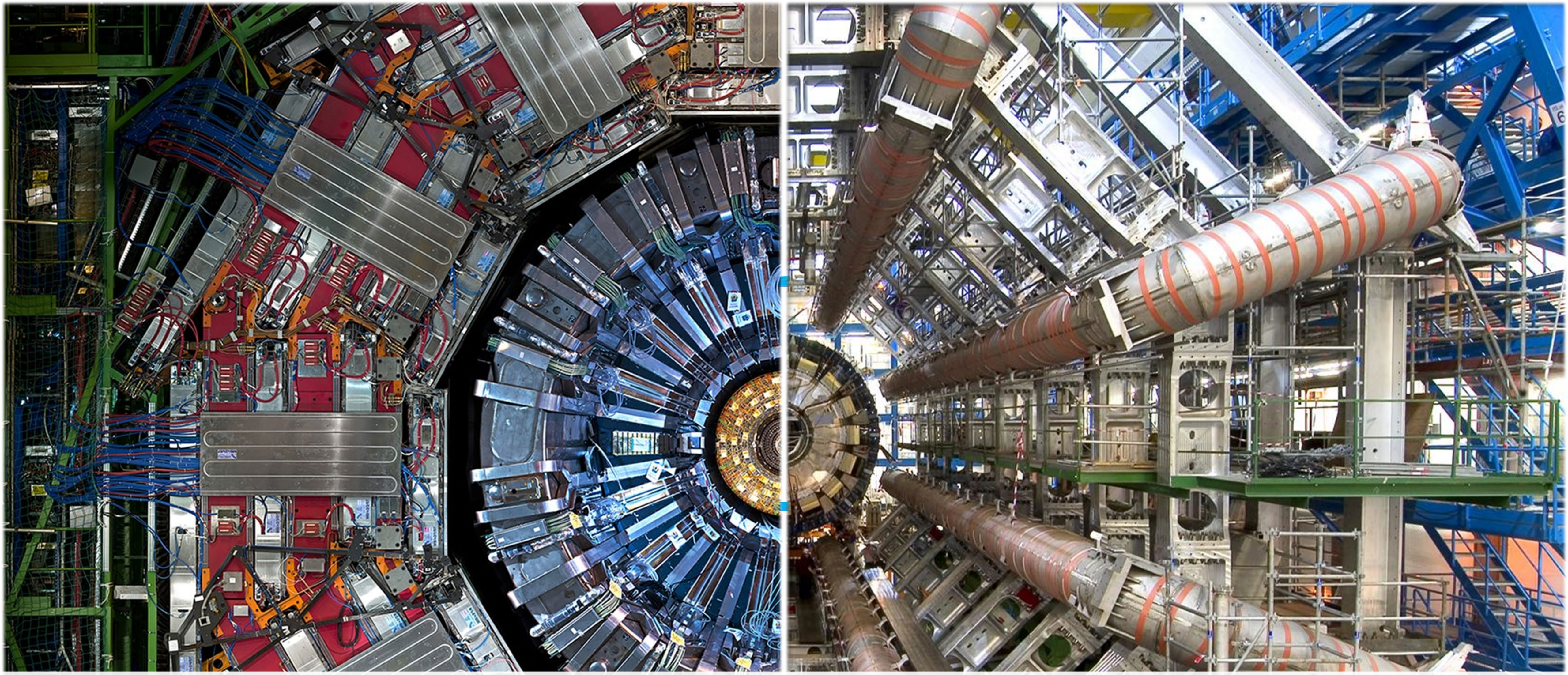
WC/Λ^2	95% CL interval [TeV^{-2}] (Others profiled)	95% CL interval [TeV^{-2}] (Others fixed to SM)
$c_{t\varphi}/\Lambda^2$	[0.56, 30]	[0.20, 30]
$c^{-}_{\varphi Q}/\Lambda^2$	[−8.3, 9.9]	[−6.6, 8.7]
$c^{3}_{\varphi Q}/\Lambda^2$	[−4.4, 3.9]	[−4.1, 3.0]
$c_{\varphi t}/\Lambda^2$	[−13, 7.9]	[−12, 6.3]
$c_{\varphi tb}/\Lambda^2$	[−10, 12]	[−9.9, 11]
c_{tW}/Λ^2	[−1.6, 1.6]	[−1.0, 0.96]
c_{bW}/Λ^2	[−4.3, 4.3]	[−4.2, 4.2]
c_{tZ}/Λ^2	[−1.7, 1.7]	[−1.0, 1.1]

Provide competitive constraints on EFT WCs in a previously **unexplored** phase space

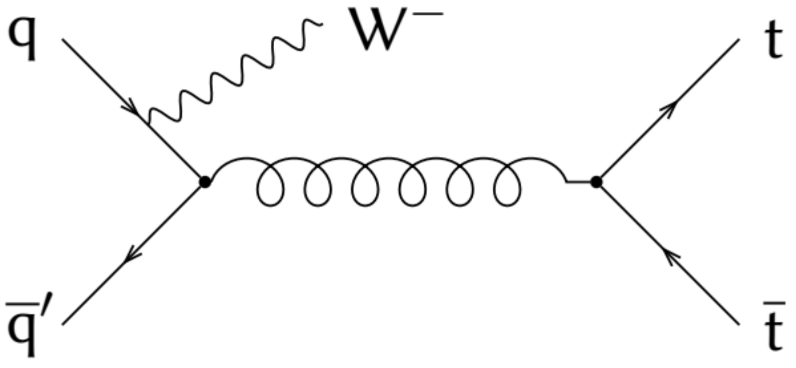








$t\bar{t}W$ measurements



Arxiv: 2208.06485

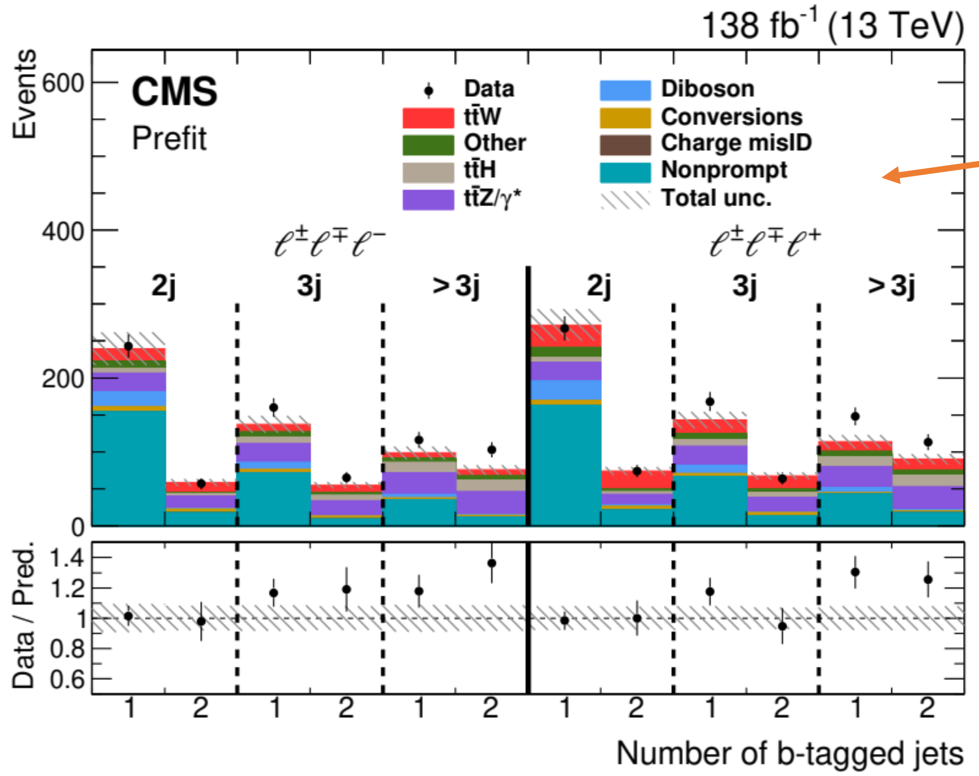
Submitted to JHEP

2ℓss strategy

- A Deep Neural Network (DNN) is used to distinguish between signal and background events.
- Lepton flavors and electric charges are used to further categorize events

3ℓ strategy

- Twelve different categories are defined in terms of jet and b tag multiplicities, as well as the charge of the 3ℓ system.
- A single observable ($m_{3\ell}$) distribution is optimized to extract tt̄W signal.

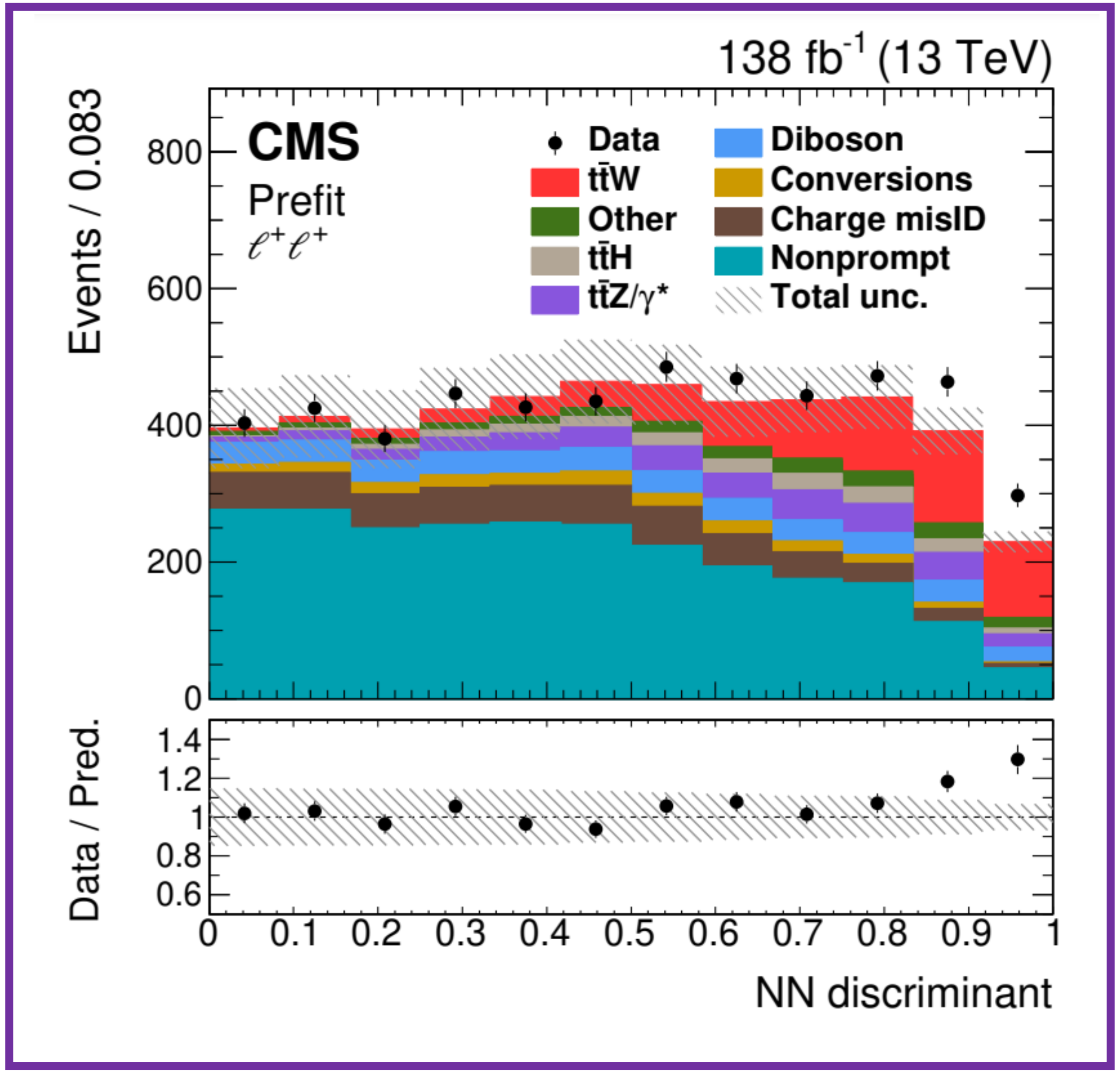


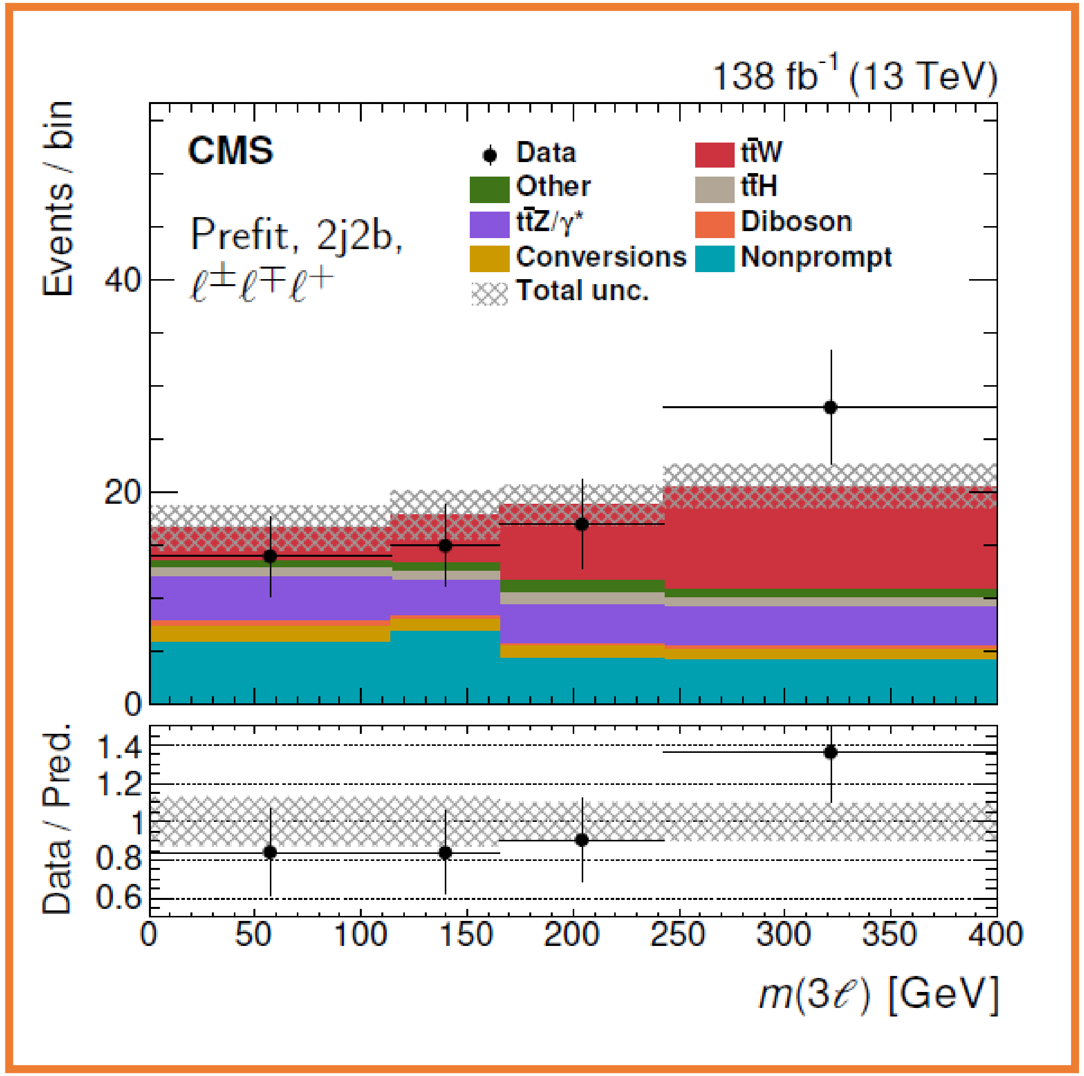
3ℓ and 4ℓ control regions

- Two extra categories targetting WZ, ZZ and tt̄Z enriched regions are defined to gain better control over these backgrounds.

Inclusive $t\bar{t}W$ cross section measurement at 13 TeV. Analysis strategy.

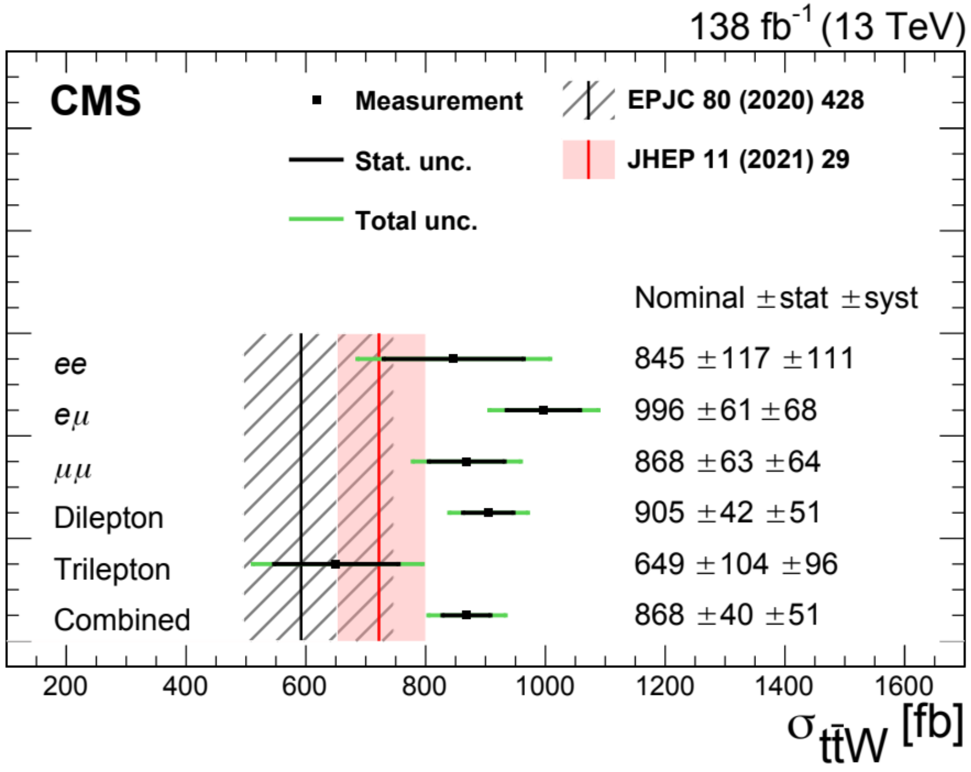
- Final $t\bar{t}W$ normalization is extracted from a **combined binned profile likelihood** fit to all $2\ell ss$ + 3ℓ + CRs distributions.





Inclusive $t\bar{t}W$ cross section measurement at 13 TeV. Results.

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
$\sigma_{t\bar{t}W+}/\sigma_{t\bar{t}W-}$	$1.61 \pm 0.15\,(\text{stat})\,^{+0.07}_{-0.05}\,(\text{syst})$	$1.94\,^{+0.37}_{-0.24}\,(\text{theo})$	$1.92\,^{+0.27}_{-0.29}\,(\text{theo})$

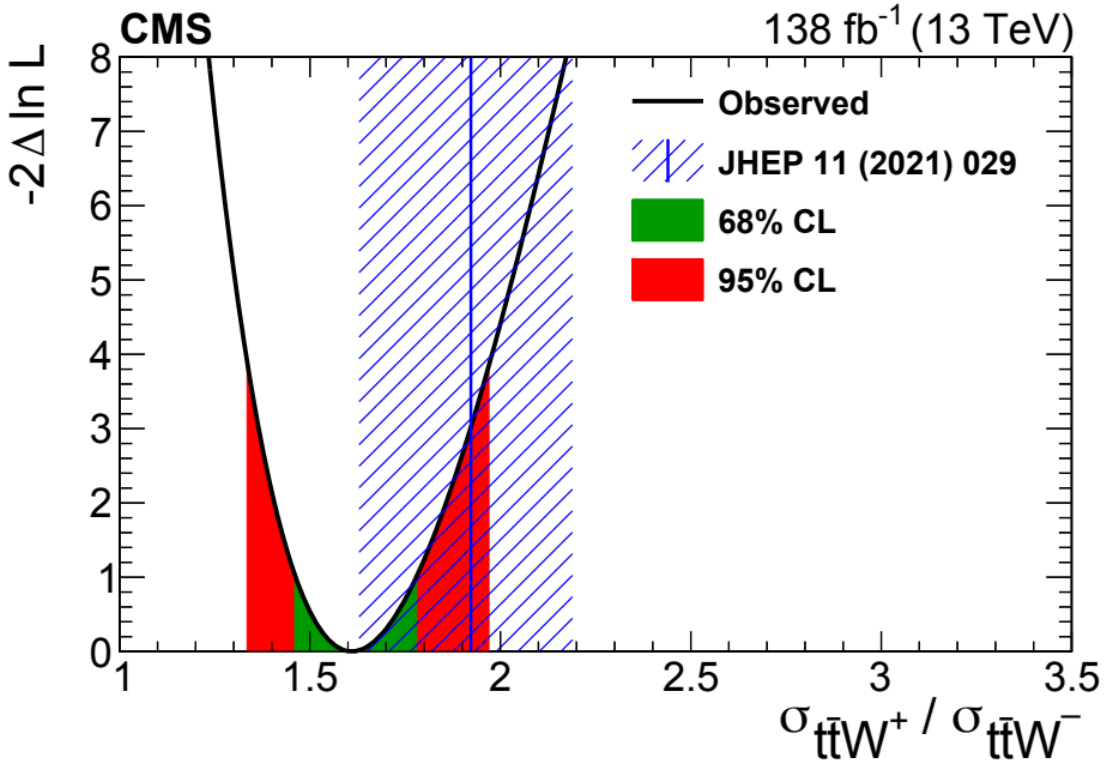


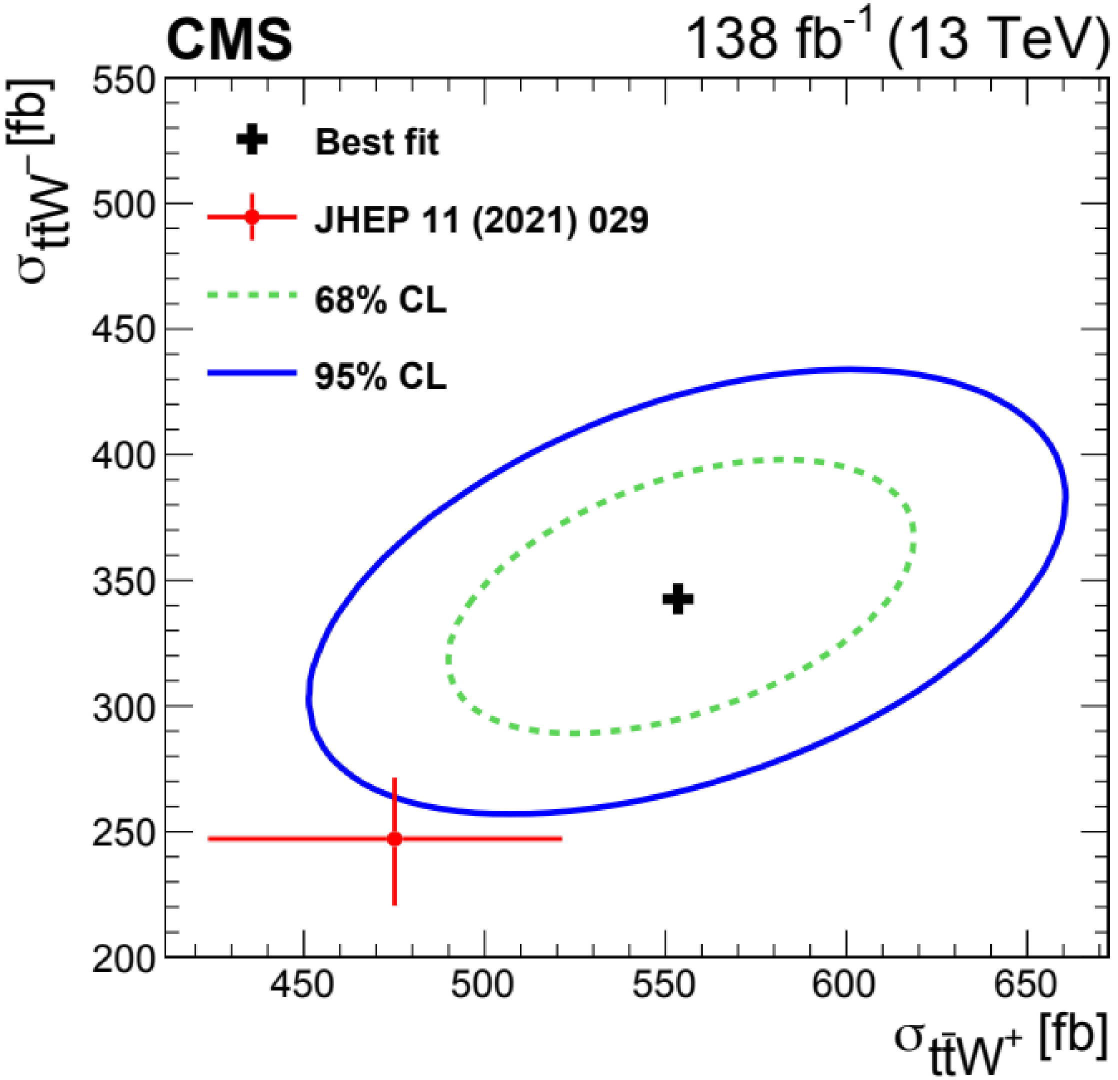
- Factor two of improvement on the systematic uncertainty with respect to 2016 measurement!

Source	Uncertainty [%]
Experimental uncertainties	
Integrated luminosity	1.9
b tagging efficiency	1.6
Trigger efficiency	1.2
Pileup reweighting	1.0
L1 inefficiency	0.7
Jet energy scale	0.6
Jet energy resolution	0.4
Lepton selection efficiency	0.4
Background uncertainties	
$t\bar{t}H$ normalization	2.6
Charge misidentification	1.6
Nonprompt leptons	1.3
VVV normalization	1.2
$t\bar{t}VV$ normalization	1.2
Conversions normalization	0.7
$t\bar{t}\gamma$ normalization	0.6
ZZ normalization	0.6
Other normalizations	0.5
$t\bar{t}Z$ normalization	0.3
WZ normalization	0.2
tZq normalization	0.2
tHq normalization	0.2
Modeling uncertainties	
$t\bar{t}W$ scale	1.8
$t\bar{t}W$ color reconnection	1.0
ISR & FSR scale for $t\bar{t}W$	0.8
$t\bar{t}\gamma$ scale	0.4
VVV scale	0.3
$t\bar{t}H$ scale	0.2
Conversions	0.2
Simulation statistical uncertainty	1.8
Total systematic uncertainty	5.8

- First steps towards a charge asymmetry measurement at CMS are also presented in 2208.06485

- Result compared to the **latest theoretical prediction** for these cross sections (provided by the authors of JHEP11(2021)029).





Charge asymmetry measurements in $t\bar{t}W$

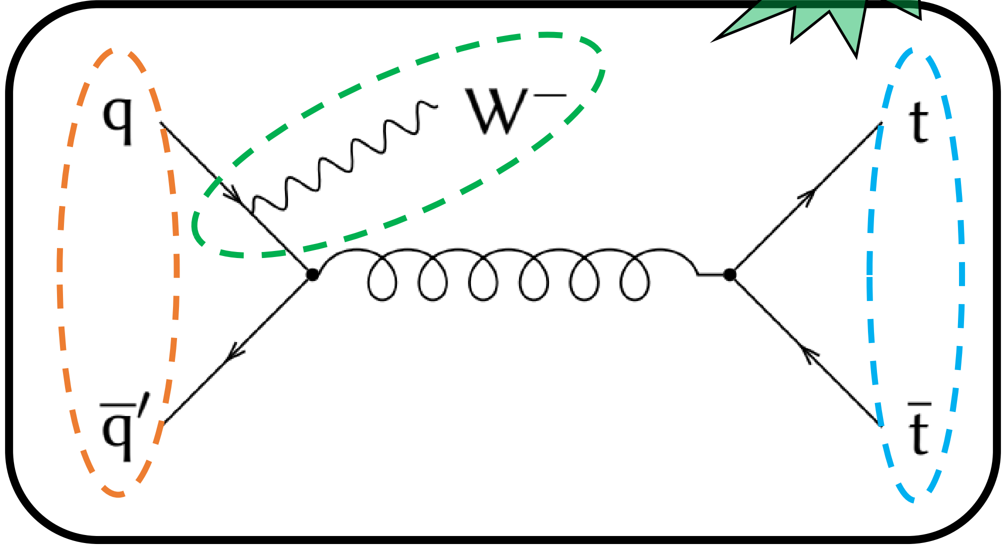
ATLAS EXPERIMENT

- $t\bar{t}W$ is the only process of the $t\bar{t}$+X family whose **QCD LO contribution** comes entirely from $q\bar{q}$ annihilation.

Arxiv: 2301.04245
Submitted to JHEP

NEW!

- This results in a sizable difference in the rapidity distribution of top quarks and top antiquarks.
  - Top (anti) quarks tend to be produced with more forward (central) rapidities than their counterparts.
  - The asymmetry is further enhanced due to polarization effects on the initial state W.



$$A_c^{\ell} = \frac{N(\Delta\eta^{\ell} > 0) - N(\Delta\eta^{\ell} < 0)}{N(\Delta\eta^{\ell} > 0) + N(\Delta\eta^{\ell} < 0)},$$

- Thus $t\bar{t}W$ provides an excellent probe for new physics in the context of EFTs, given that Dim6 operators are sensitive to these asymmetries.
- The ATLAS experiment has recently published its most recent search for charge asymmetry in $t\bar{t}W$ leptonic final states, with the full Run 2 dataset.

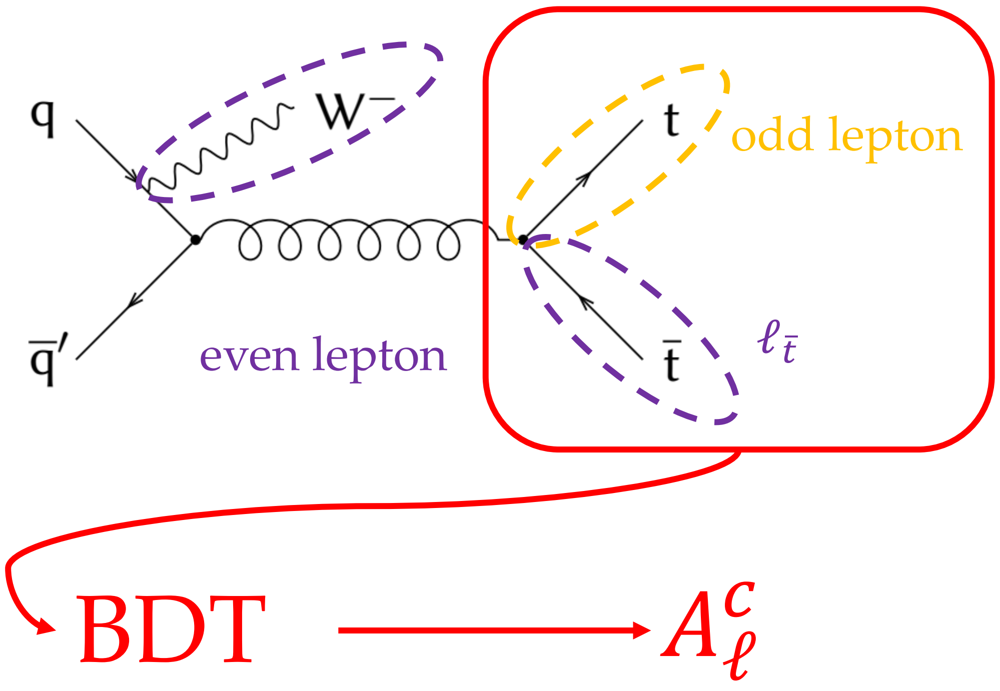
* These asymmetries can also studied in other final states:
arXiv: 2212.10552 (ATLAS $t\bar{t}\gamma$) and arXiv:2208.02751 (CMS boosted $t\bar{t}$)

Charge asymmetry measurements in $t\bar{t}W$. Analysis strategy

- Baseline selection of three leptons and at least one OSSF pair.
- Selected events are classified into four SRs that differ in n_{Jet} and $n_{\mathrm{b-tag}}$ multiplicities.
- Four additional CRs are built to control the effect of major backgrounds.

	Preselection			
N_ℓ ($\ell = e/\mu$)	= 3			
p_{T}^{ℓ} ($1^{\mathrm{st}}/2^{\mathrm{nd}}/3^{\mathrm{rd}}$)	≥ 30 GeV, ≥ 20 GeV, ≥ 15 GeV			
Sum of lepton charges	±1			
$m_{\ell\ell}^{\mathrm{OSSF}}$	≥ 30 GeV			
	Region-specific requirements			
	SR-1b-lowN_{jets}	SR-1b-highN_{jets}	SR-2b-lowN_{jets}	SR-2b-highN_{jets}
N_{jets}	[2, 3]	≥ 4	[2, 3]	≥ 4
$N_{b\text{-jets}}$	= 1	= 1	≥ 2	≥ 2
$E_{\mathrm{T}}^{\mathrm{miss}}$	≥ 50 GeV	≥ 50 GeV	–	–
$N_{Z\text{-cand.}}$	= 0			
Lepton criteria	TTT			
e/γ ambiguity-cuts	satisfy all			

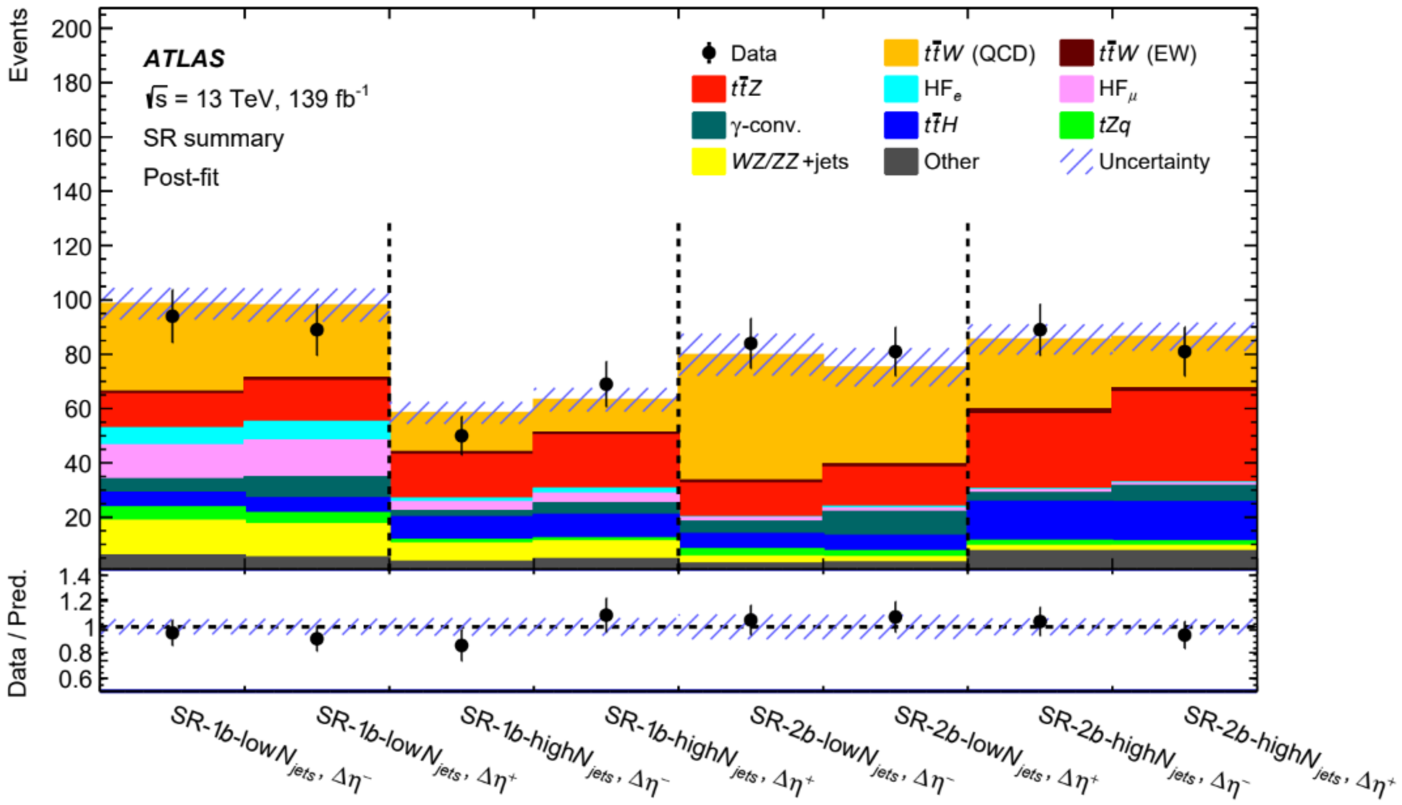
Pseudorapidity measurement



Charge asymmetry measurements in $t\bar{t}W$. Analysis strategy

- The charge asymmetry is then extracted by performing a simultaneous binned likelihood fit to the number of observed events in the SRs and some other kinematic distributions of the CRs.
- Each region is splitted into $\Delta\eta^+ = \Delta\eta^\ell > 0$ and $\Delta\eta^- = \Delta\eta^\ell < 0$.

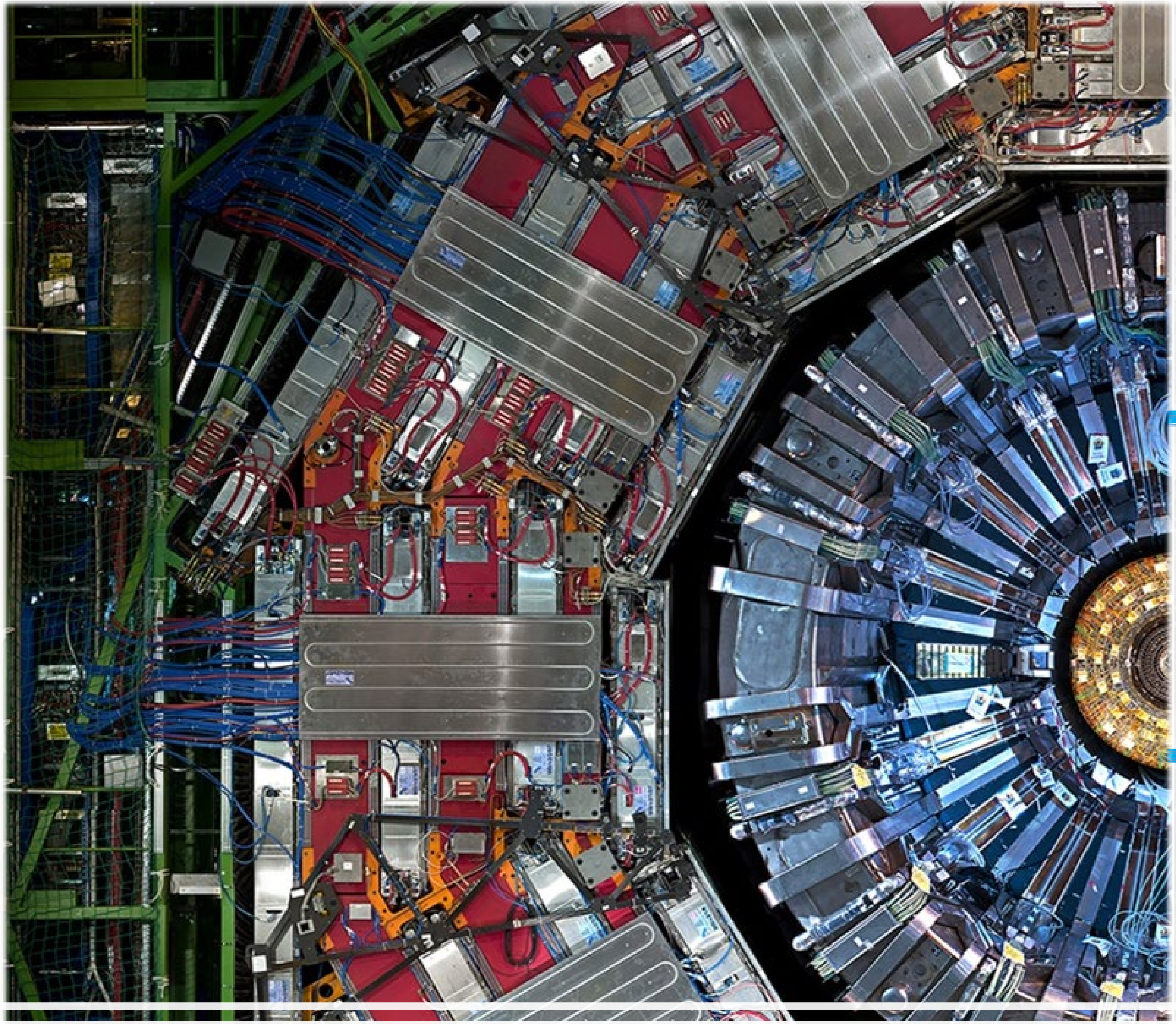
$$A_c^\ell = \frac{N(\Delta\eta_\ell^+) - N(\Delta\eta_\ell^-)}{N(\Delta\eta_\ell^+) - N(\Delta\eta_\ell^-)}$$

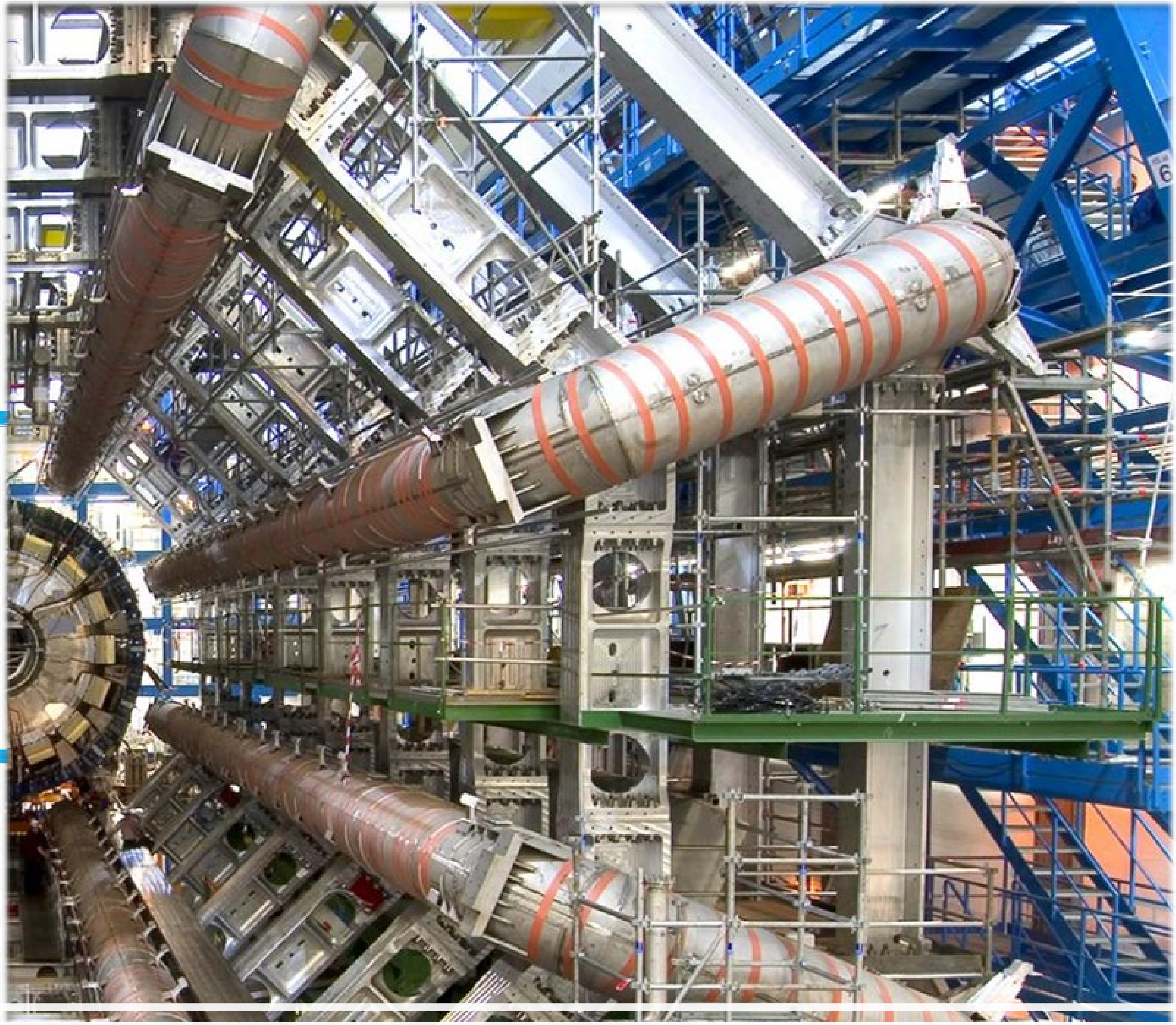


$$A_c^\ell(t\bar{t}W) = -0.123 \pm 0.136\,(\text{stat.}) \pm 0.051\,(\text{syst.})$$

Consistent with SM expectation

$$A_c^\ell(t\bar{t}W)_{\text{SM}} = -0.084\,^{+0.005}_{-0.003}\,(\text{scale}) \pm 0.006\,(\text{MC stat.})$$



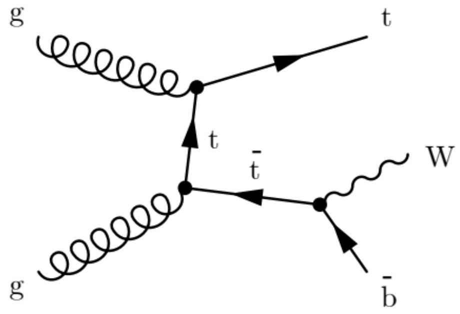


Single top production

- **the tW process** is the second most common production channel of top quarks via electroweak mechanisms (single top modes) at the LHC.

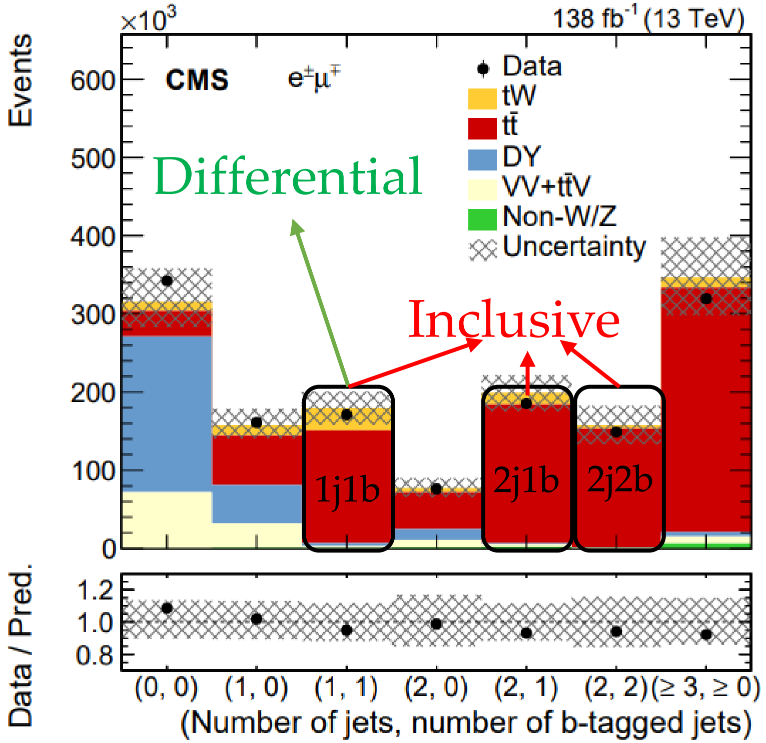
Arxiv: 2208.00924
Accepted by JHEP

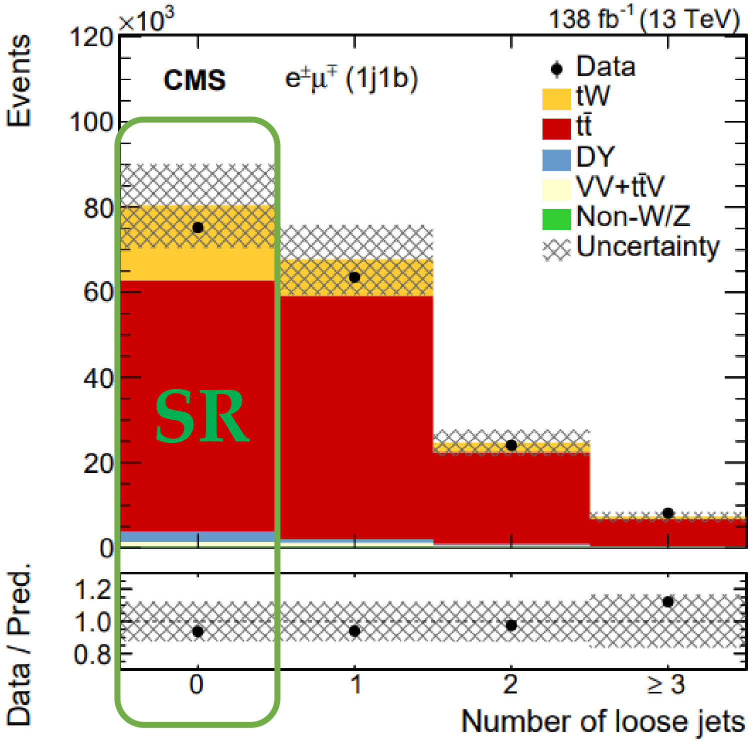
- tW (NLO) interferes with $t\bar{t}$.
  - Clearly background dominated.
  - Two methods can be used to remove the interferences: **Diagram Removal** (DR) and **Diagram Subtraction** (DS).



DR scheme is used for the nominal analysis, and the difference with respect to DS scheme is taken as an uncertainty.

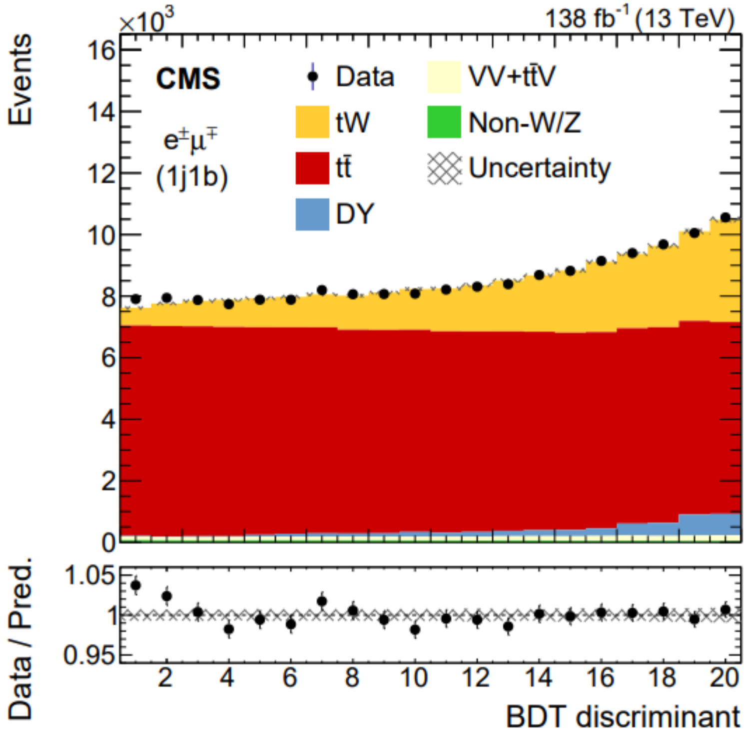
- Baseline selection:
  - Dilepton channel: $e^{\pm}\mu^{\mp}$.
  - Leading lepton $p_T > 25$ GeV
  - $m_{\ell\ell} > 20$ GeV.
  - Categorisation based on number of jets and b tags.

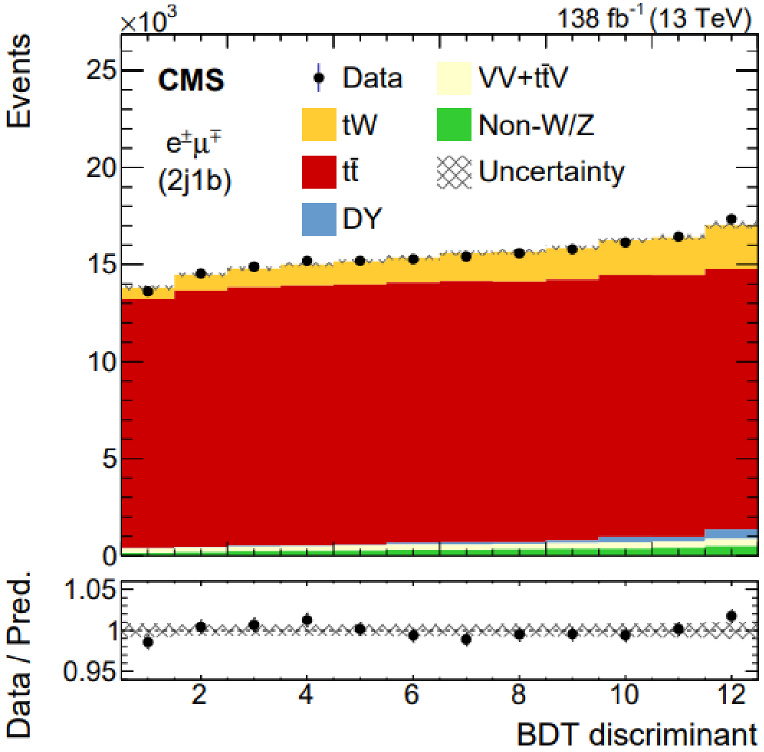


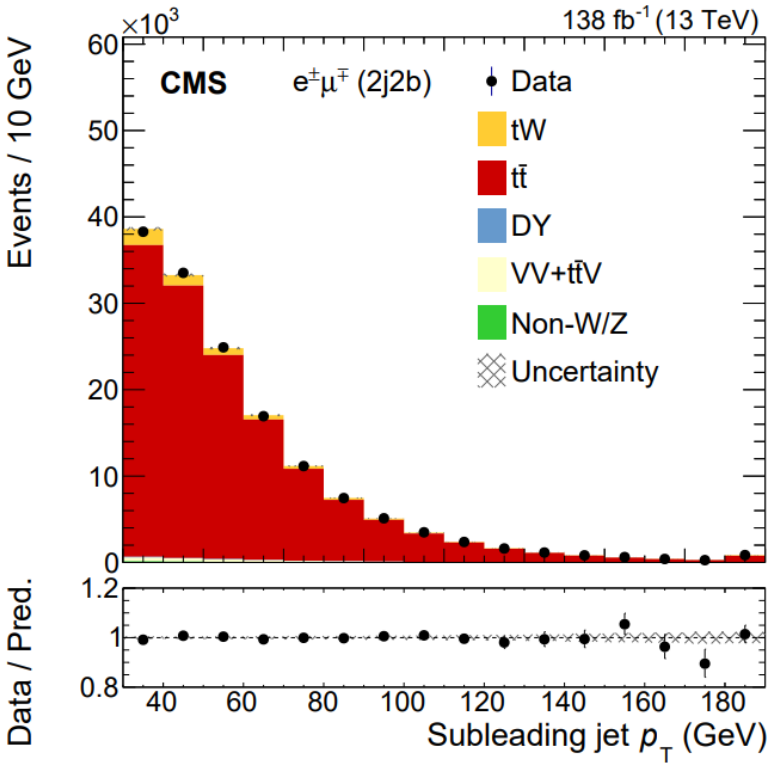


tW measurements at 13 TeV. Inclusive measurement strategy.

- A BDT is used to discriminate tW from $t\bar{t}$.
- To extract the signal, a maximum likelihood fit is performed to three distributions.







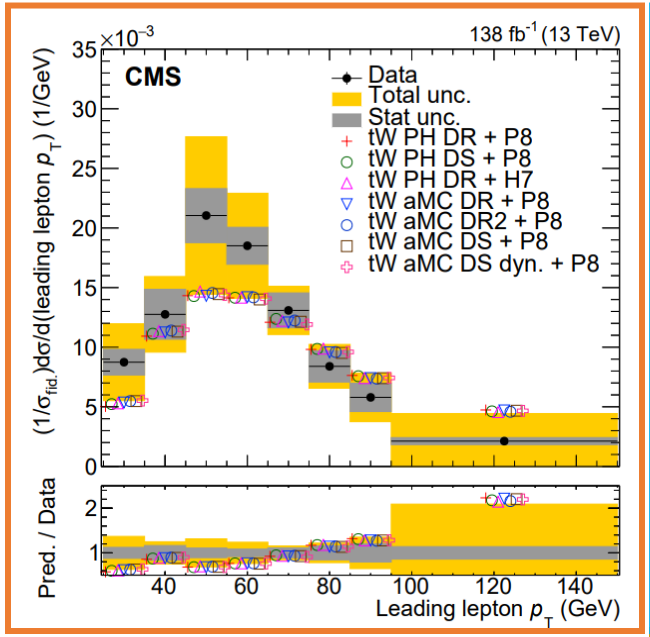
- The measured cross section is: $\sigma_{tW} = 79.2 \pm 0.8$ (stat) $\pm$ 7.1(syst) $\pm$ 1.1 (lumi) pb.
  - Compatible with SM predictions at
    - aNNLO(QCD): $\sigma_{tW}^{SM} = 71.7 \pm 1.8$ (scale) $\pm$ 3.4 (PDF) pb [PoS DIS2015 (2015) 170]
    - aN^{3}LO(QCD): $\sigma_{tW}^{SM} = 79.5 \pm 1.9$ (scale) $\pm$ 1.7 (PDF) pb [JHEP 05 (2021) 278].

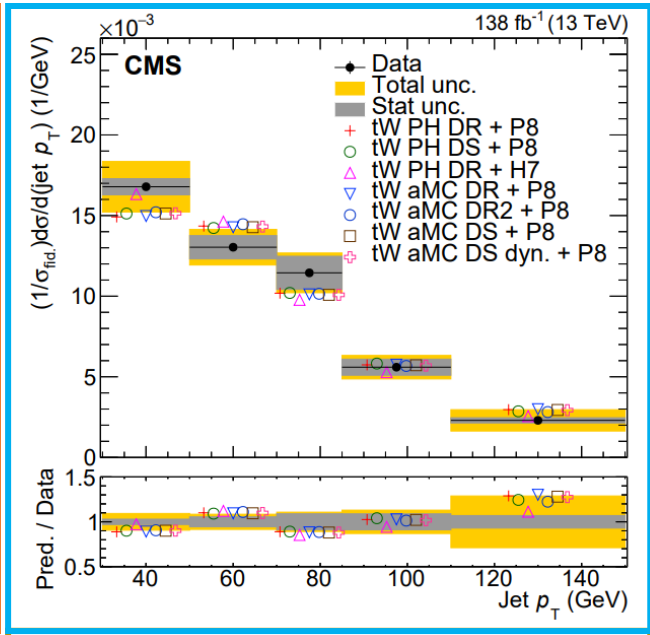
Systematically dominated

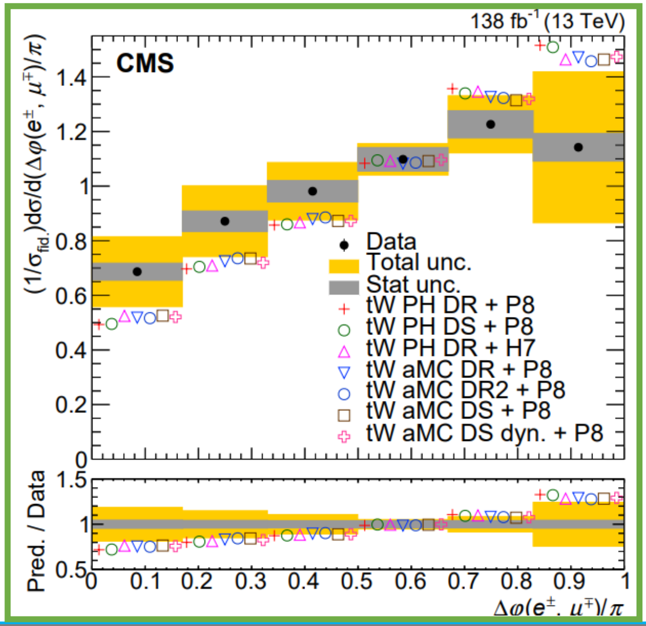
tW measurements at 13 TeV. Differential measurement strategy.

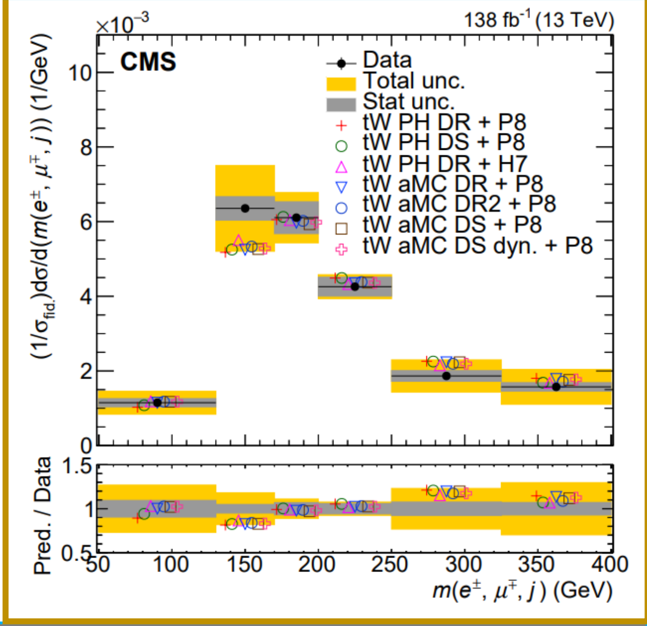
- The differential measurement is performed using 1j1b with a veto on the presence of loose b tags in the final state.

- Need to unfold detector effects so it is comparable with e.g. theoretical predictions.
- A fiducial region close to the measurement region is defined, and the signal is extracted bin by bin using maximum likelihood fits.
- Usually done for specific variables.
  - Leading lepton p_T
  - jet p_T
  - $\Delta\phi(e^{\pm},\mu^{\mp})$
  - $m(e^{\pm},\mu^{\mp})$
  - $p_Z(e^{\pm},\mu^{\mp},j)$
  - $m_T(e^{\pm},\mu^{\mp},j,\ p_T^{miss})$
- The results are normalised to the fiducial cross section
- Overall agreement between data and expectations within uncertainties
- Compatible results between the DR and DS schemes.





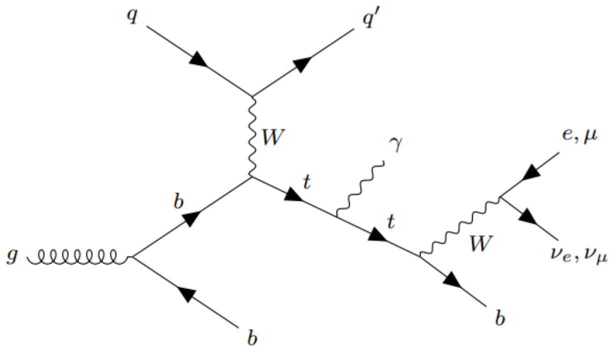




Observation of $t\gamma$ production. Introduction

- The $t\gamma q$ cross section is measured in a fiducial phase space at parton level (excluding $(t \rightarrow \ell\nu b\gamma)\gamma q$) and particle level.

Arxiv: 2302.01283
Submitted to PRL



NEW!

Measurement region

- At least one photon.
- One lepton matched to trigger.
- One tight b tag (no additional loose b tags)
- $E_T^{miss} > 30$ GeV
- Veto Z mass between lepton and photon

SR1: ≥ 1 fj

At least one forward jet.

SR2: 0 fj

NO forward jet.

Fiducial region

Parton level

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

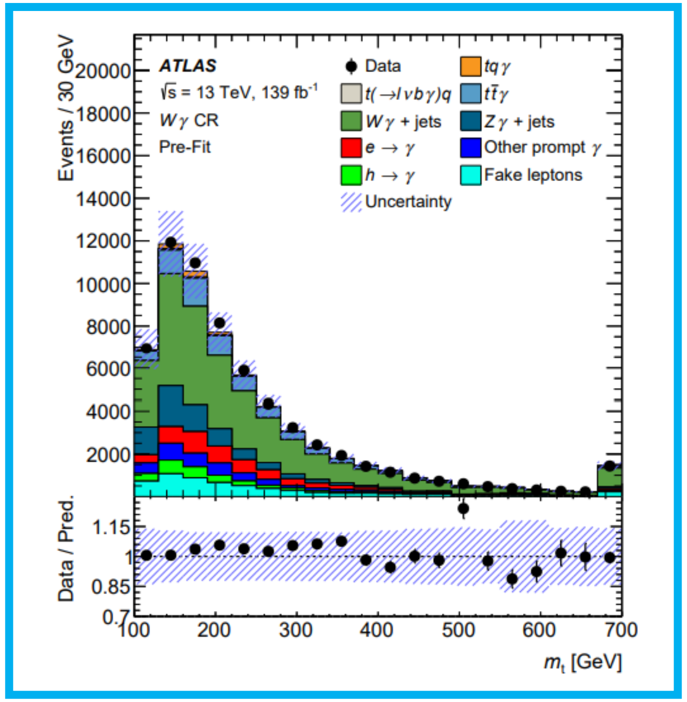
Particle level

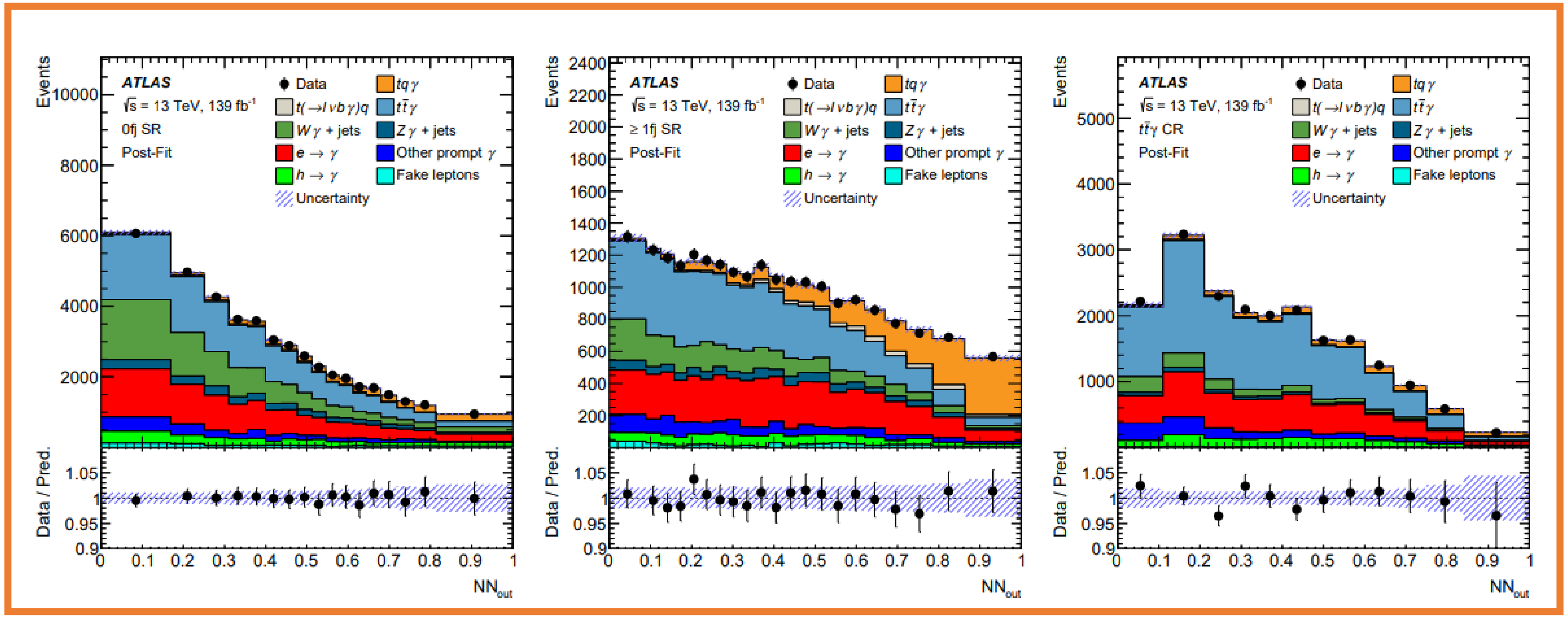
- One lepton with $p_T \geq 25$ GeV
- At least one photon with $p_T \geq 25$ GeV.
- One b with $p_T \geq 25$ GeV
- One neutrino not from a hadron decay

Observation of $t\gamma$ production. Results

- Neural networks are trained to separate signal from background.
  - Input variables: E_T^{miss}, kinematics of the photon, lepton, b tag and highest- p_T forward jet; and the mass of the reconstructed top quark.

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





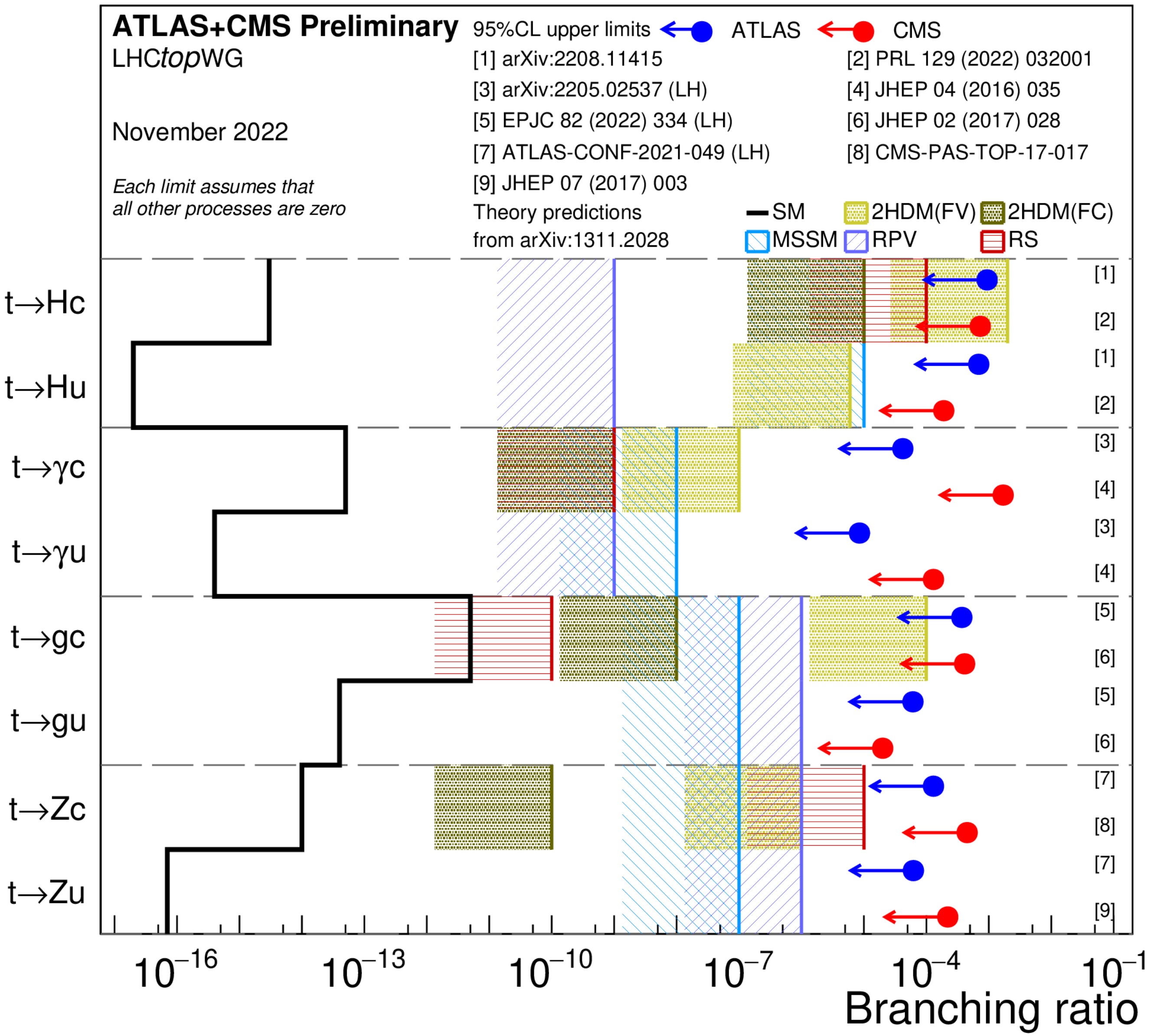
Conclusions

- In this talk we have covered some of the most recent analysis regarding **$t\bar{t}$X+tX** physics at the LHC from both ATLAS and CMS collaborations.
  - A search for FCNC couplings between the top quark and the Z boson (ATLAS).
    - Improved constraints on EFT couplings by factor 2.
  - Latest inclusive $t\bar{t}$X cross section measurement (CMS) and dedicated charge asymmetry measurement (ATLAS).
    - Agreement with the SM within 2σ. Need to improve modelling of ttW MC.
    - Charge Asymmetry. Statistically limited. In agreement with SM.
  - A search for EFT effects on boosted topologies in $t\bar{t}$Z/H (CMS).
    - Competitive constraints on EFT couplings for boosted topologies.
  - An inclusive and differential cross section measurement of the tW process (CMS).
    - Systematically dominated measurement. In agreement with SM.
  - An observation of $t\gamma$ production using the full Run2 dataset of the LHC (ATLAS)
    - Verified this process as one of the rare top-quark production processes.
- **There are many more results publicly available in** ATLAS and CMS public websites, so check them out!
- And stay tuned for future Run3 measurements!

Thank you very much for your attention (and to the organisers)

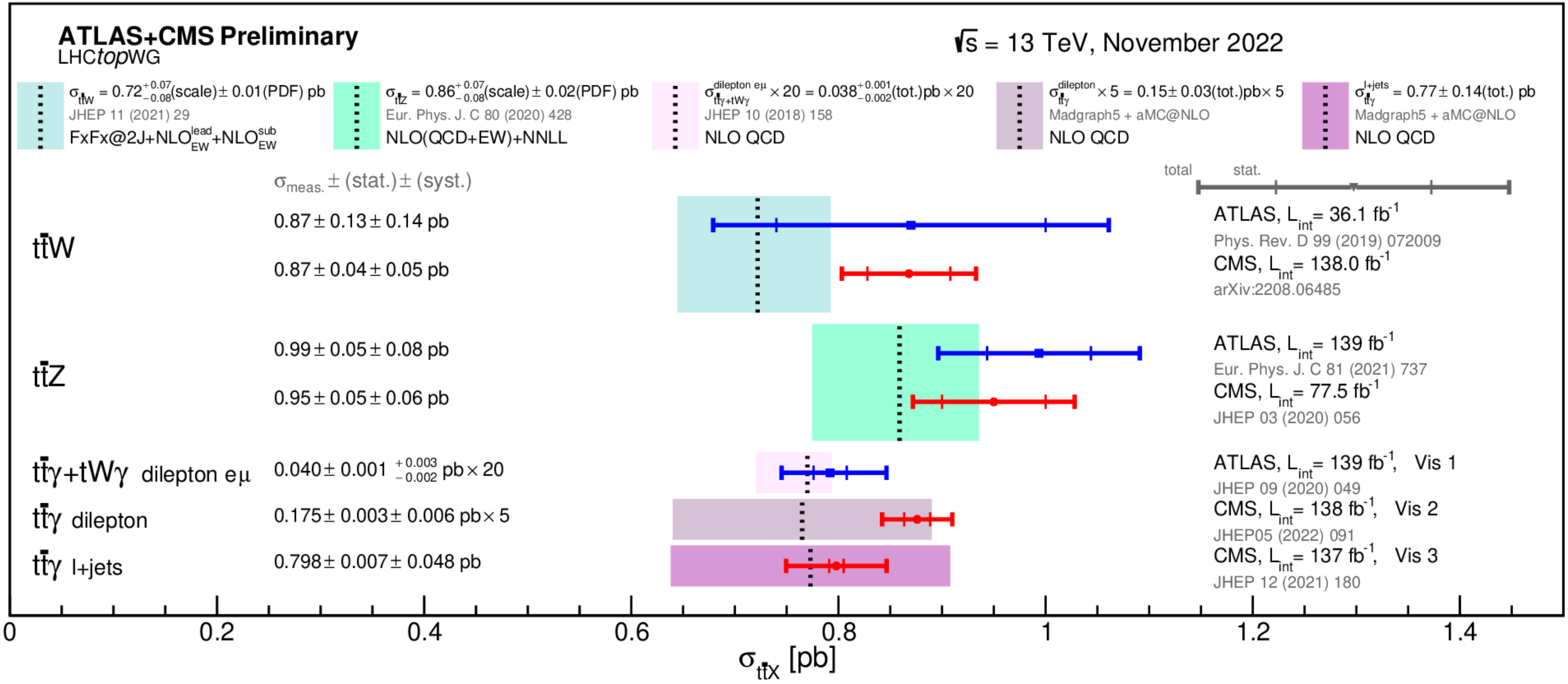
Backup

Backup



ATLAS+CMS Preliminary
LHCtopWG
November 2022
Each limit assumes that
all other processes are zero
95%CL upper limits
ATLAS
CMS
[1] arXiv:2208.11415
[2] PRL 129 (2022) 032001
[3] arXiv:2205.02537 (LH)
[4] JHEP 04 (2016) 035
[5] EPJC 82 (2022) 334 (LH)
[6] JHEP 02 (2017) 028
[7] ATLAS-CONF-2021-049 (LH)
[8] CMS-PAS-TOP-17-017
[9] JHEP 07 (2017) 003
Theory predictions
from arXiv:1311.2028
SM
2HDM(FV)
2HDM(FC)
MSSM
RPV
RS
t→Hc
t→Hu
t→γc
t→γu
t→gc
t→gu
t→Zc
t→Zu
[1]
[2]
[1]
[2]
[3]
[4]
[3]
[4]
[5]
[6]
[5]
[6]
[7]
[8]
[7]
[9]
10^{-16}
10^{-13}
10^{-10}
10^{-7}
10^{-4}
10^{-1}
Branching ratio

Backup



ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV, November 2022
σ_ttW = 0.72 +0.07 −0.08 (scale) ± 0.01(PDF) pb
JHEP 11 (2021) 29
FxFx@2J+NLO lead EW +NLO sub EW
σ_ttZ = 0.86 +0.07 −0.08 (scale) ± 0.02(PDF) pb
Eur. Phys. J. C 80 (2020) 428
NLO(QCD+EW)+NNLL
σ dilepton eμ ttγ+tWγ × 20 = 0.038 +0.001 −0.002 (tot.)pb × 20
JHEP 10 (2018) 158
NLO QCD
σ dilepton ttγ × 5 = 0.15 ± 0.03(tot.)pb × 5
Madgraph5 + aMC@NLO
NLO QCD
σ l+jets ttγ = 0.77 ± 0.14(tot.) pb
Madgraph5 + aMC@NLO
NLO QCD
σ_meas. ± (stat.) ± (syst.)
total
stat.
ttW
0.87 ± 0.13 ± 0.14 pb
0.87 ± 0.04 ± 0.05 pb
ATLAS, L_int = 36.1 fb^-1
Phys. Rev. D 99 (2019) 072009
CMS, L_int = 138.0 fb^-1
arXiv:2208.06485
ttZ
0.99 ± 0.05 ± 0.08 pb
0.95 ± 0.05 ± 0.06 pb
ATLAS, L_int = 139 fb^-1
Eur. Phys. J. C 81 (2021) 737
CMS, L_int = 77.5 fb^-1
JHEP 03 (2020) 056
ttγ+tWγ dilepton eμ
0.040 ± 0.001 +0.003 −0.002 pb × 20
ATLAS, L_int = 139 fb^-1, Vis 1
JHEP 09 (2020) 049
ttγ dilepton
0.175 ± 0.003 ± 0.006 pb × 5
CMS, L_int = 138 fb^-1, Vis 2
JHEP05 (2022) 091
ttγ l+jets
0.798 ± 0.007 ± 0.048 pb
CMS, L_int = 137 fb^-1, Vis 3
JHEP 12 (2021) 180
0
0.2
0.4
0.6
0.8
1
1.2
1.4
σ_ttX [pb]