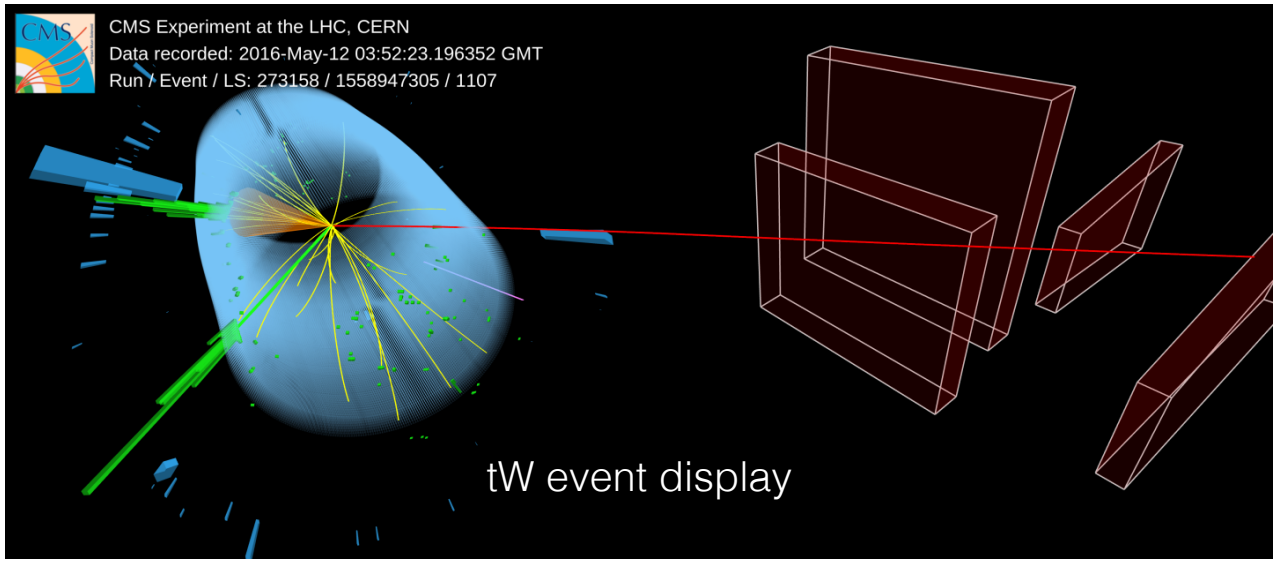
Searches for BSM and FCNC with top quarks at CMS

LHCP2023 - 25/05/2023



Nicolas Chanon - IP2I Lyon, CNRS/IN2P3 (France)
On behalf of the CMS Collaboration

Introduction

- **Extensions of the SM** thought to solve hierarchy problem, provide dark matter candidates, etc.
- Many of the BSM models are assigning a special role to the **top quark**, because of its large mass and Yukawa coupling close to 1
- This talk shows CMS results in top quark final states covering a **wide range of BSM models,** made public since previous LHCP edition

1) FCNC:
e.g. 2HDM, SUSY
TOP-21-013

3) W' boson:
e.g. L-R symmetric models, SUSY, UED
B2G-20-012

4) Excited quarks:
e.g. composite models
B2G-21-005

2) Φ (pseudo)scalar:
e.g. NMSSM
EXO-21-018

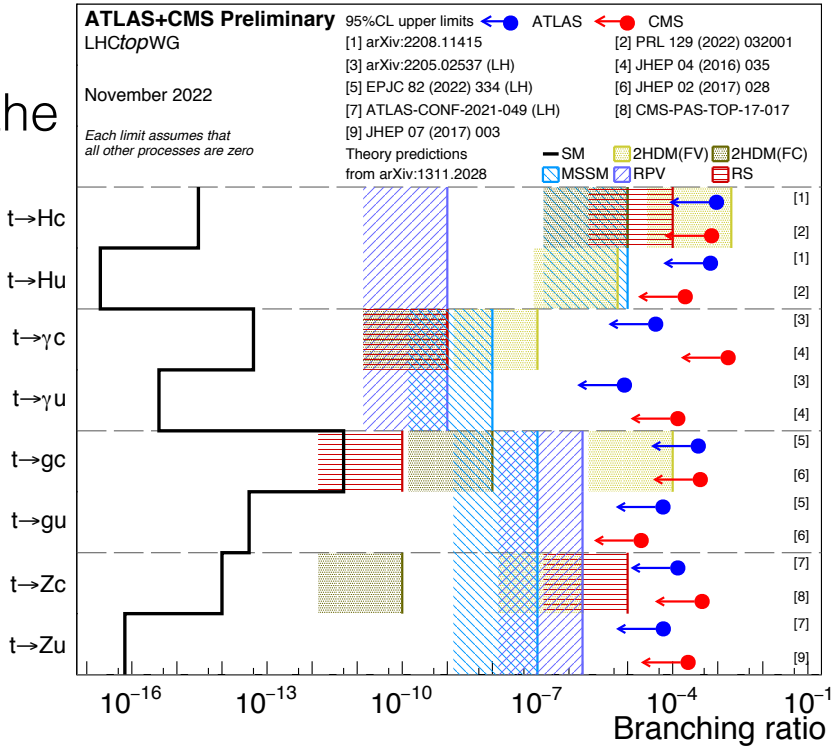
New for LHCP

5) Violation of Lorentz invariance:
e.g. string theory, LQG
TOP-22-007

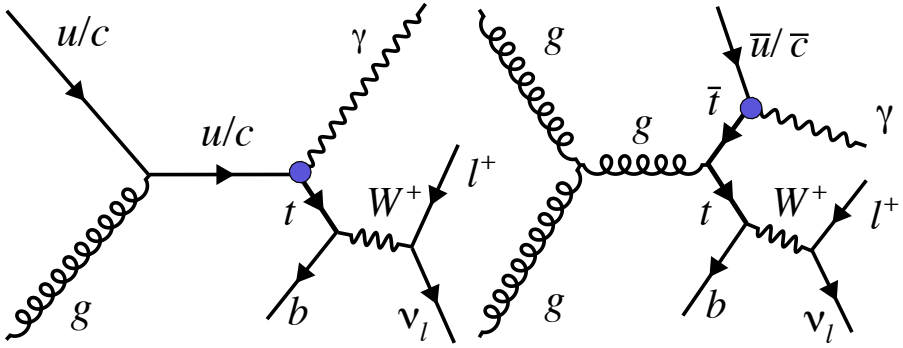
Searches for tqγ (q=u,c) FCNC coupling

CMS-PAS-TOP-21-013

- SM tγq (q=u,c) couplings via loops: suppressed by the GIM mechanism, any observed signal = discovery
- Limits on FCNC approaching BSM expectations



Single lepton channel: 1 e (μ) with p_T>35 (30) GeV



ST region

exactly 1 jet, required to be b-tagged (deepCSV)

TT region

≥2 jets, among which exactly 1 b-jet

+**Control regions**: **ttγ** (≥2 jets, 2 b-jets), **Wγ** (≥1 jet, 0 b-jet, high mlγ), **Zγ** (≥1 jet, 0 b-jet, low mlγ)

- **Photon: p_T>30 GeV** in the ECAL barrel, away from leptons
- p_T^{mis} > 30 GeV
- Electron channel only: veto 80<|$m_{eγ}$-m_Z|<100 GeV

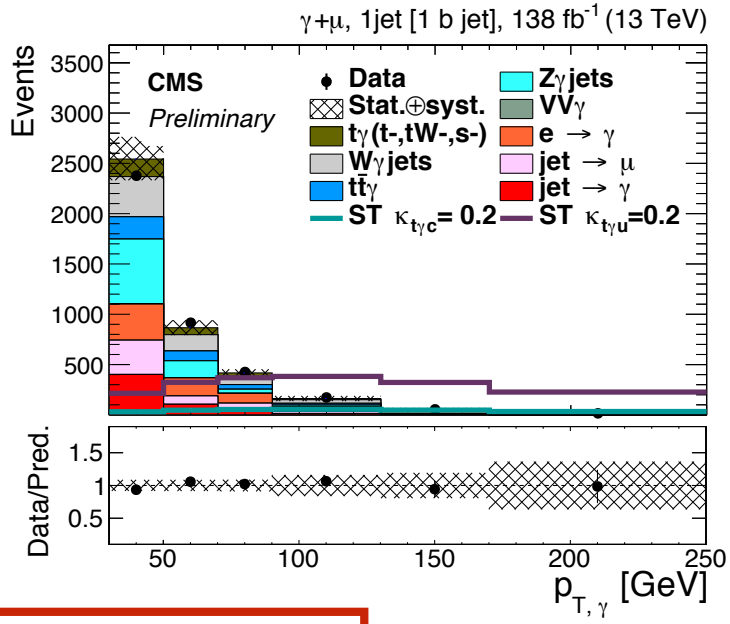
Searches for tqγ (q=u,c) FCNC coupling

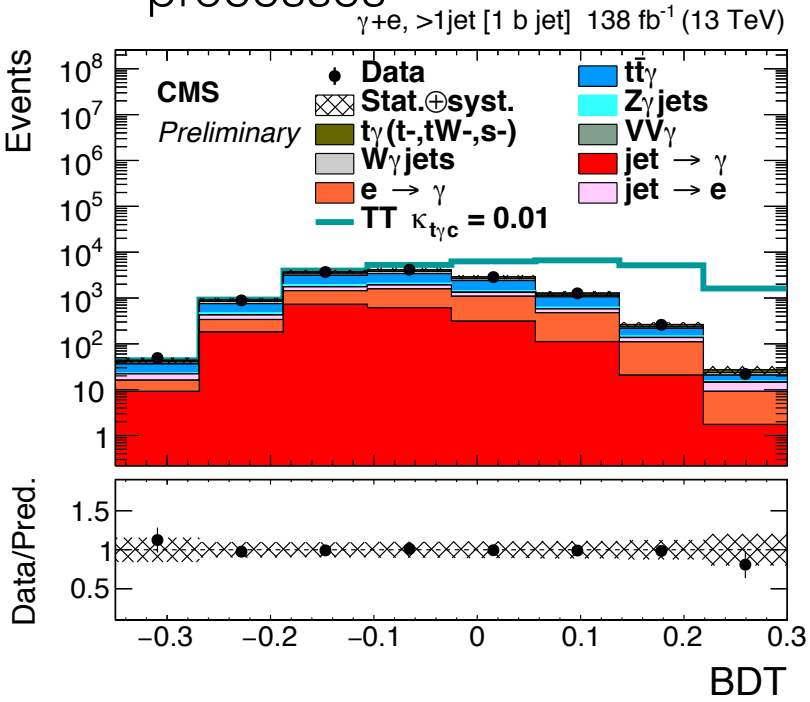
CMS-PAS-TOP-21-013

- **Jets faking photons**: from data with ABCD method, using charged hadron isolation and cluster shape
- **Jets faking leptons**: from data by extrapolating from region with relaxed isolation
- **Electrons misidentified as photons**: from Z events with $|m_{e\gamma}-m_Z|<10$ GeV

Discriminant: BDT

- inputs variables: kinematics
- lepton charge for tuγ
- FCNC against ttγ, Wγ, diboson processes





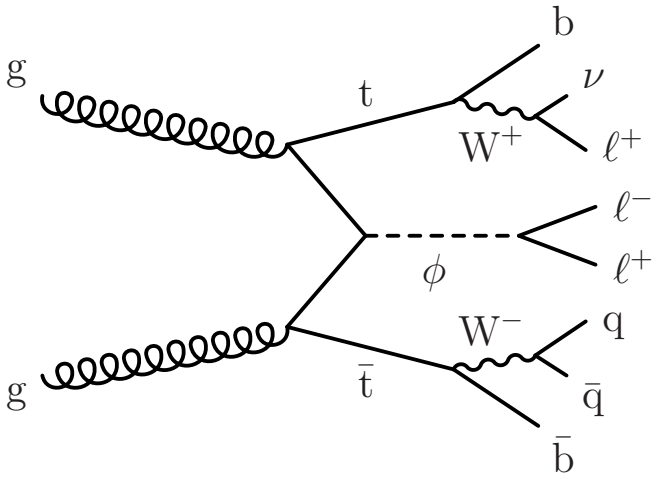
Combined	Obs. limit	Exp. limit	$\pm1\sigma$ (exp. limit)	$\pm2\sigma$ (exp. limit)
$\kappa_{tu\gamma}$	6.2×10^{-3}	6.9×10^{-3}	$(5.9-8.4)\times10^{-3}$	$(5.1-10.1)\times10^{-3}$
$\kappa_{tc\gamma}$	7.7×10^{-3}	7.8×10^{-3}	$(6.7-9.7)\times10^{-3}$	$(5.7-11.5)\times10^{-3}$
$\mathcal{B}(t\to u+\gamma)$	0.95×10^{-5}	1.20×10^{-5}	$(0.89-1.78)\times10^{-5}$	$(0.64-2.57)\times10^{-5}$
$\mathcal{B}(t\to c+\gamma)$	1.51×10^{-5}	1.54×10^{-5}	$(1.13-2.37)\times10^{-5}$	$(0.81-3.32)\times10^{-5}$

(FCNC signal NLO normalization)

Best limits on t→cγ

Search for $t\bar{t}$+(pseudo)scalar boson

CMS-PAS-EXO-21-018



- Consider scalar or pseudo-scalar Φ (effective coupling), narrow-width assumption
- Searches in ttbar+Φ mode motivated if Φ has Yukawa-like couplings
- Probing the region $10<m_{\Phi}<350$ GeV

ttbar+Φ multi lepton final state:

- target 3 or 4 leptons + (b) jets
- Electrons/muons with at least p_T > 10 GeV, tau p_T>20 GeV
- Jets p_T>30 GeV, b-jets identified with deepCSV
- Exclude Z region: $75<m_{\Phi}<108$ GeV for e/μ (large background from Z production)

13 signal regions:

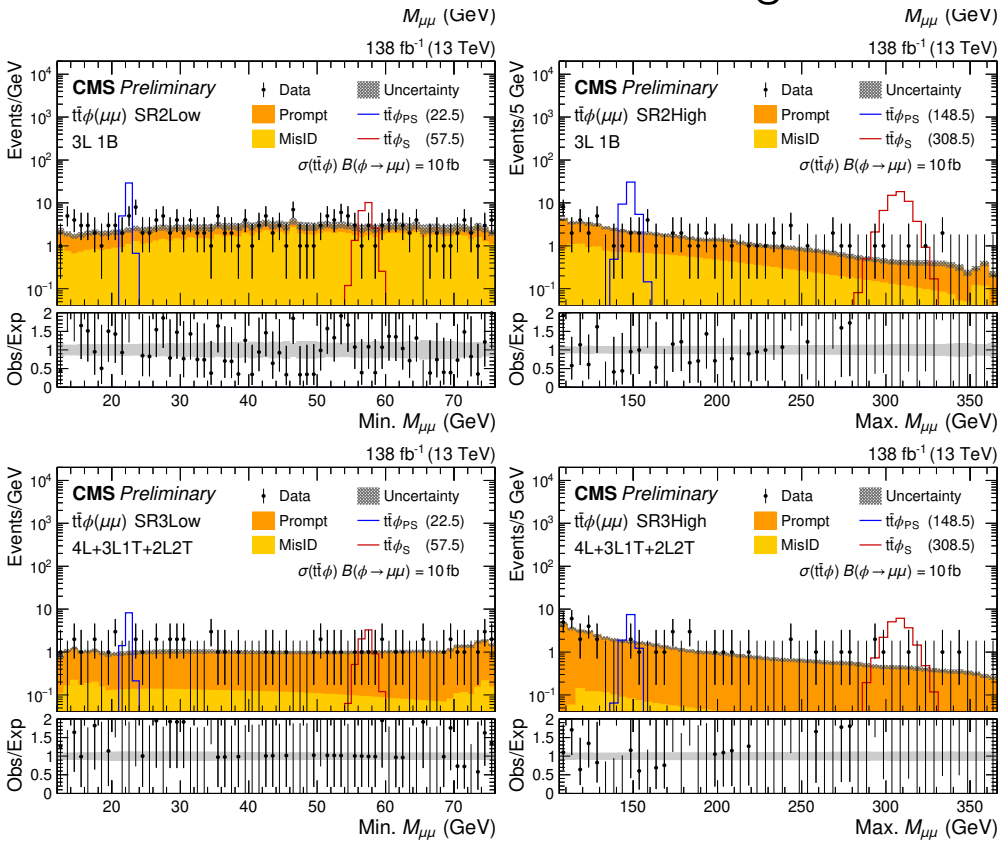
- Use 1L2T, 1L3T, 2L1T, 2L2T, 3L, 3L1T, 4L channels (L= e,μ; T=τ_h)
- Selection on S_T (scalar sum pT of leptons, jets, p_T^{mis}), minimum lepton p_T, invariant mass of all leptons
- Minimum number of jets and b-jets,

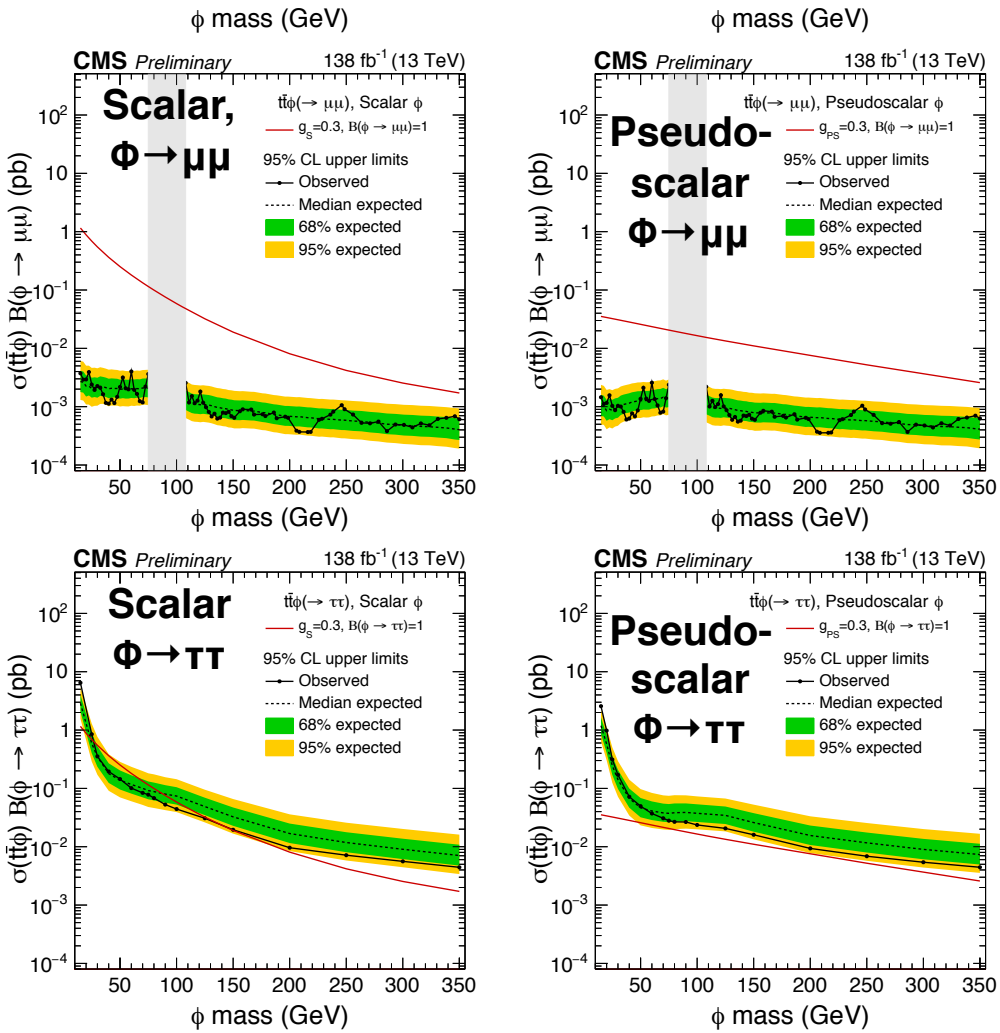
Control regions: ttZ, dibosons, e/μ/τ_h misid.

Search for tt+(pseudo)scalar boson

CMS-PAS-EXO-21-018

Dilepton mass distributions in the SR used to extract the signal:



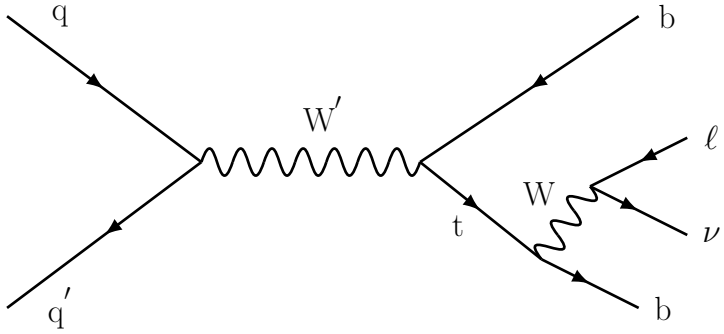


- Low mass: best results from Φ→μμ
- First limits in this mass range for ttΦ,Φ→ττ
- Improvement wrt EXO-19-002: x2-3 at m_Φ<50 GeV
- This analysis also set limits on WΦ, ZΦ

Search for W'→tb in leptonic final states

CMS-PAS-B2G-20-012

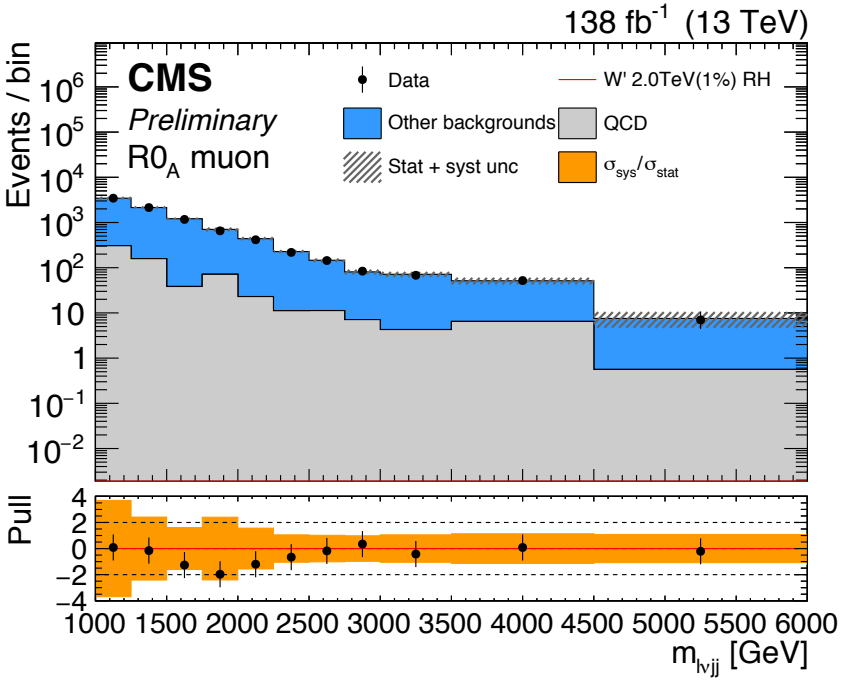
- This search: **2<$m_{W'}$<6 TeV** (previous $m_{W'}$<3 TeV)
- Coupling to left-handed, right-handed, or equal left/ right coupling to fermions
- **Scenarios for the W' width**: 1,10,20,30%
- W_L' Interference with SM s-channel included



Single lepton channel: e (μ) p_T>50 (55) GeV

- **Backgrounds**: W+jets, QCD, ttbar, single top
- ≥2 ak8 jets with p_T>170 GeV, and p_T^{mis} >120 GeV to reduce QCD
- ≥2 ak4 jets with p_T>300,150 GeV for reconstructing the final state; b-jets identified with DeepJet tagger.
- **Top quarks and W' reconstruction** assuming W nominal mass constraint
- **Categories**: 0, 1 (from top or W') or ≥2 b jets
- **Background estimated with ABCD method** using $m_{ak8,W'}$ vs m_{top}

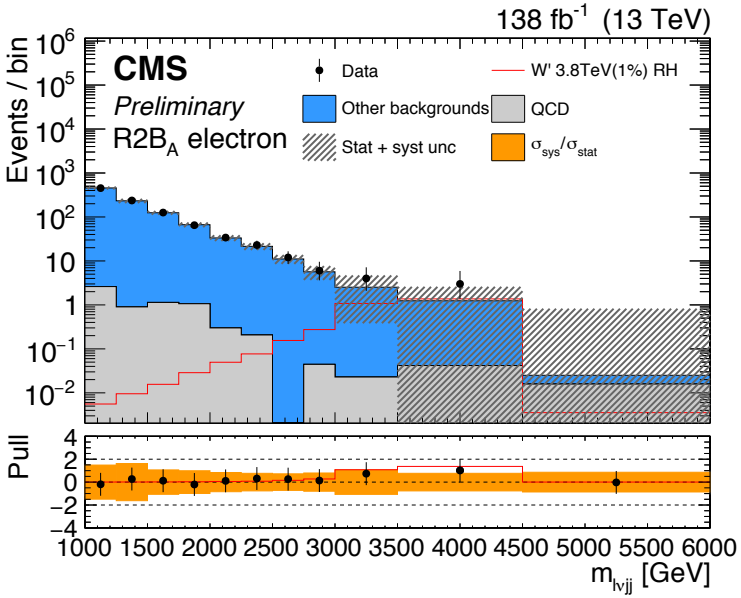
Control region: 0 b-jet

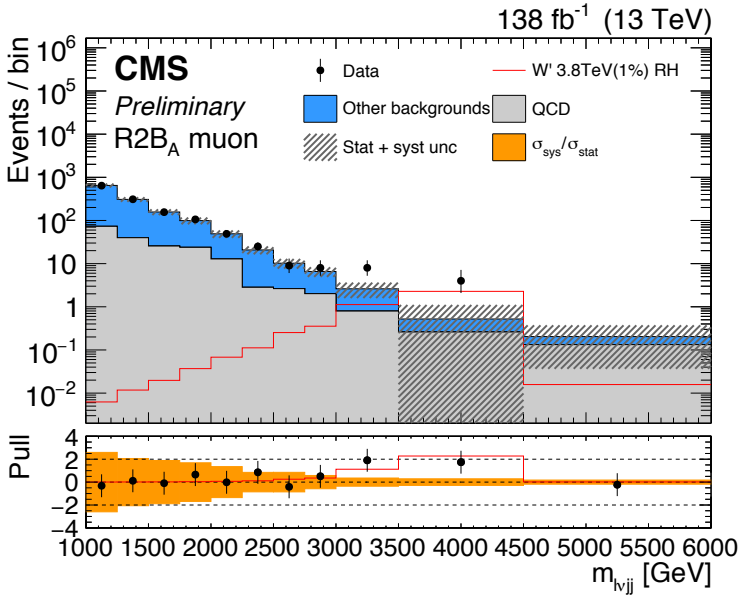


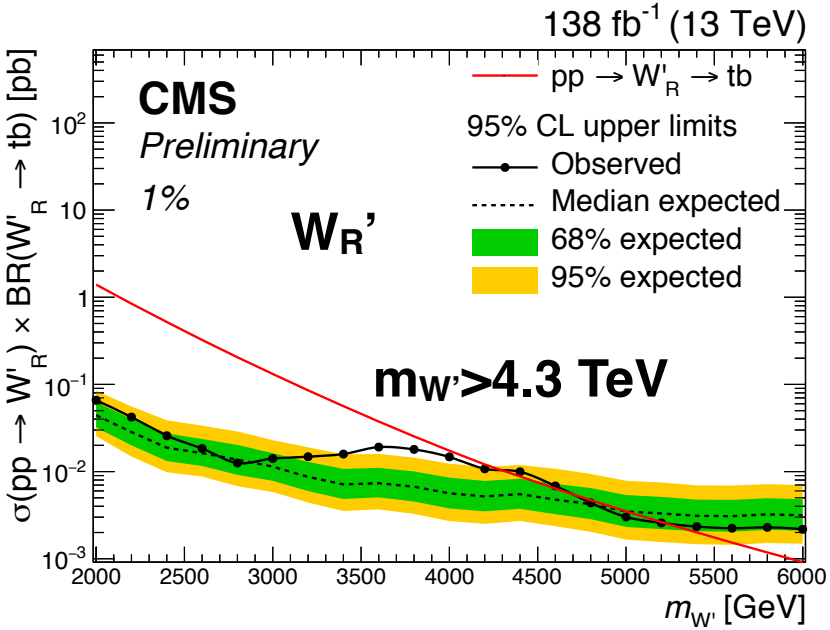
Search for W'→tb in leptonic final states

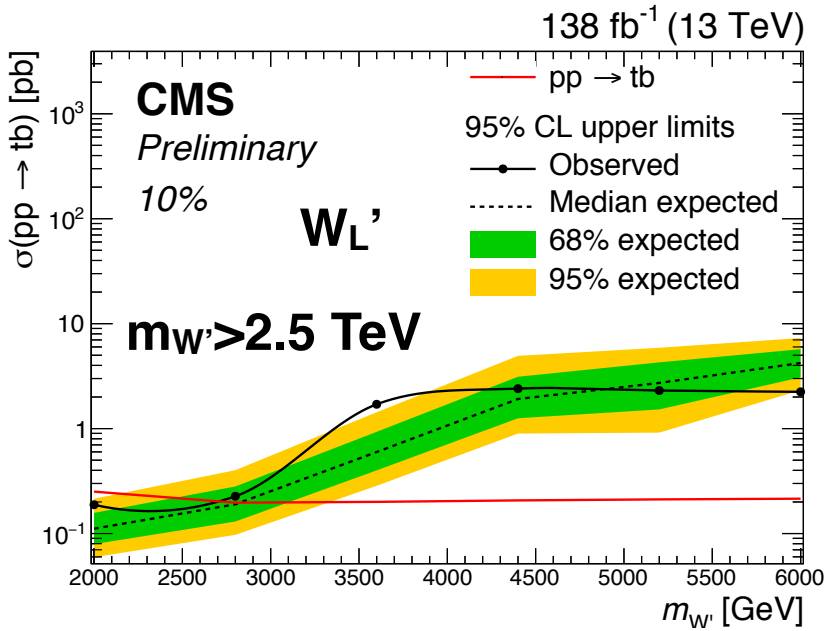
CMS-PAS-B2G-20-012

- Discriminant: **invariant mass of lνjj** system
- Limits with 1% width $m_{W'} > \sim 4$ TeV, 10% width $m_{W'} > \sim 2.5$ TeV
- **RH signal 3.8 TeV, width 1%: 2.6σ local excess** (2.0σ global)





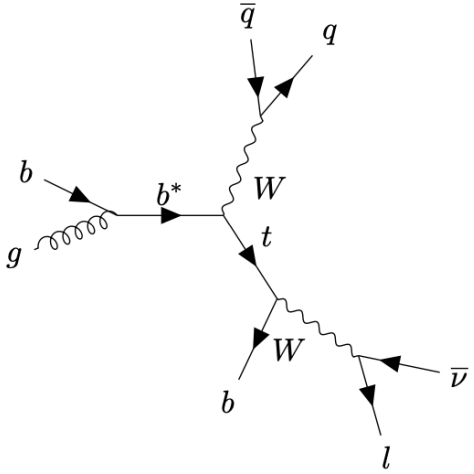




Search for heavy tW resonances

CMS-PAS-B2G-21-005

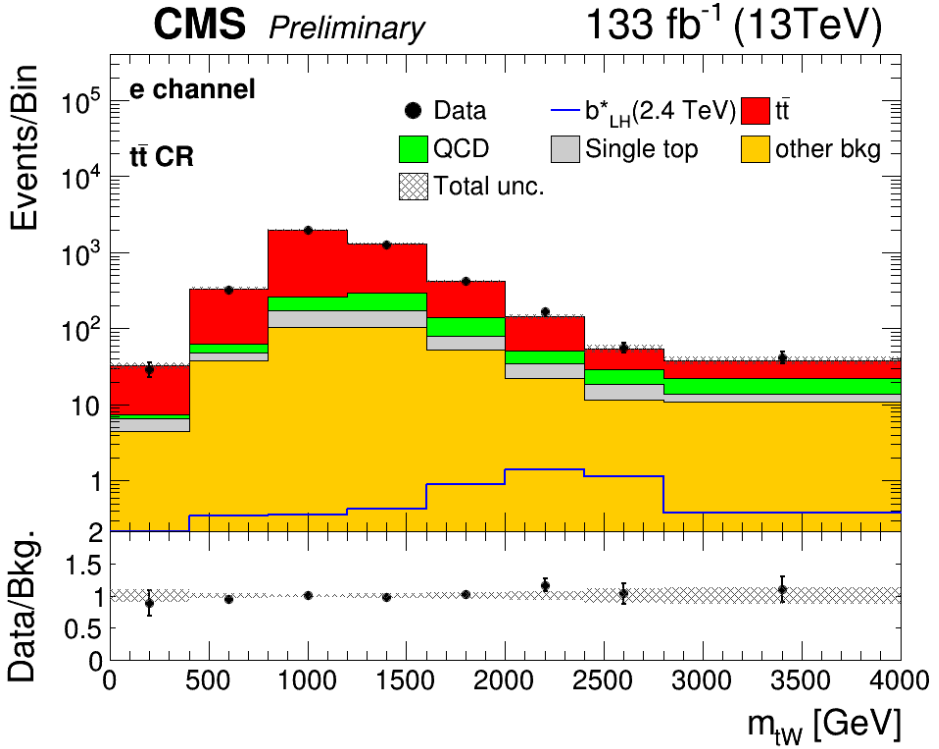
- **Signal b*** left-handed, right-handed, vector-like
- **Lepton+jets final state** targeting t→W(lν)+b, associated W→qq'



- **Top reconstruction**: non-isolated lepton with p_T>53 GeV, at least 1 ak4 b-jet (DeepJet), use nominal m_W constraint with p_T^{mis}
- **W reconstruction**: Large radius ak8 jet, N-subjettiness, soft-drop mass

Main backgrounds:
- ttbar (simulation normalised from CR),
- QCD multijets (estimated from data with likelihood-based ABCD method)

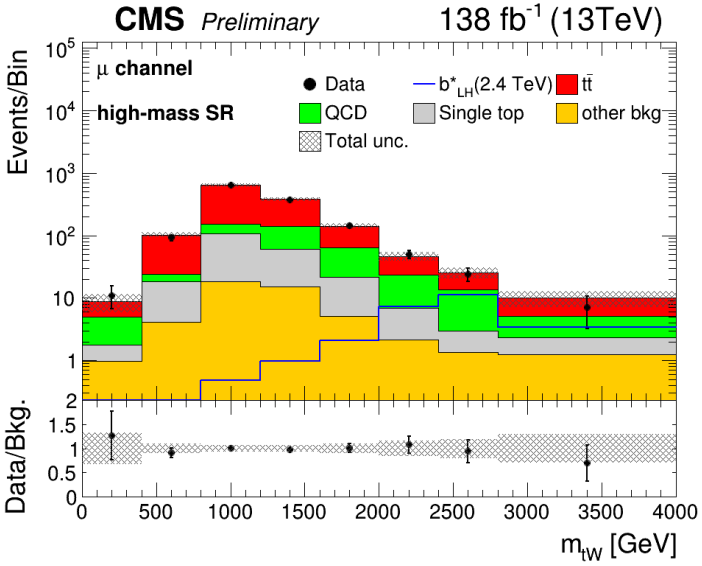
Categories:
- low- and high-mass SR (depending on p_T^{mis} and m_{TW} criteria),
- ttbar CR (top-tagging)

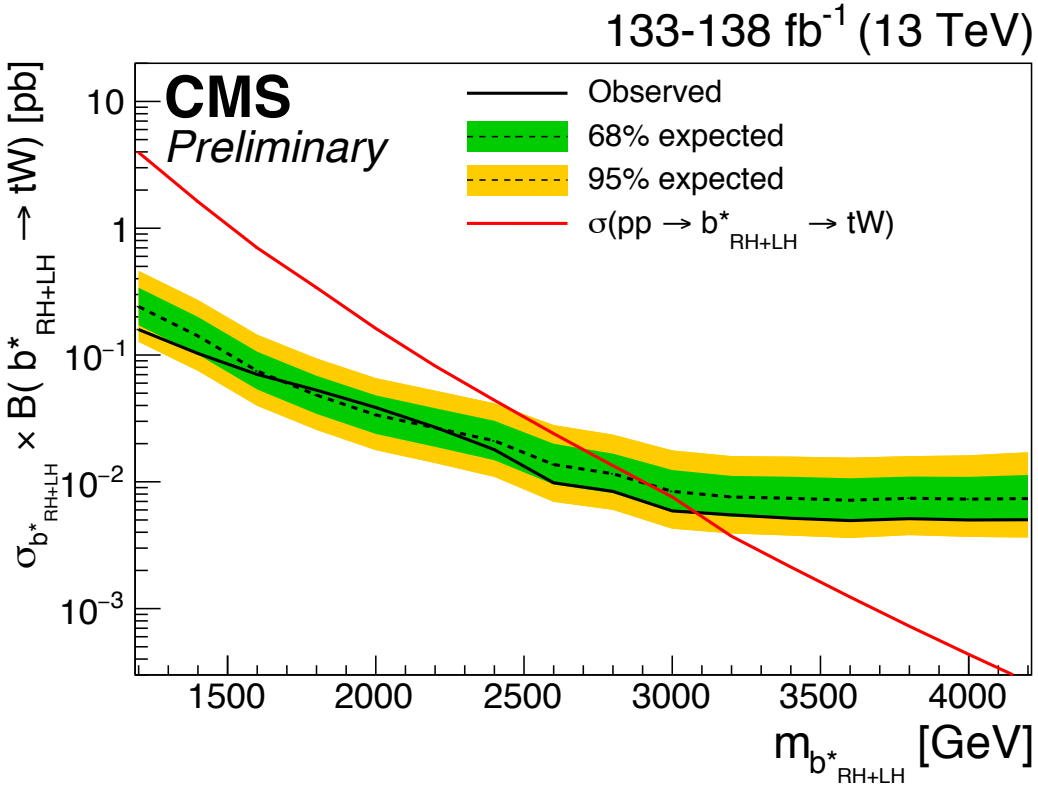


Search for heavy tW resonances

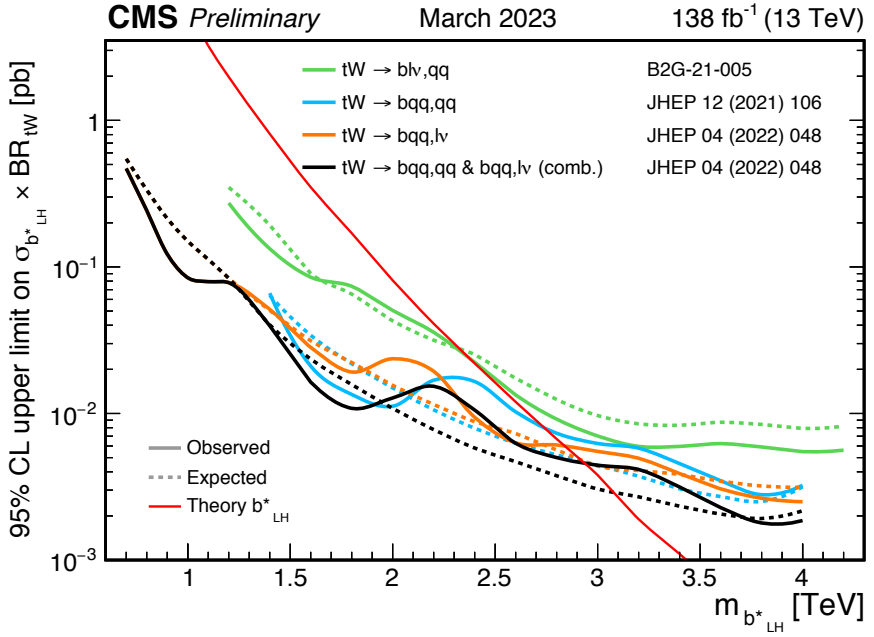
CMS-PAS-B2G-21-005

- Discriminant: **invariant mass of tW system**
- **Main uncertainties**: jet energy resolution, W tagging
- Limits: $m_{b^*} > 2.4$ (LH), 2.8 (RH), 3.1 (LH+RH) TeV





Summary for tW resonances:



Searches for violation of Lorentz invariance with $t\bar{t}$

CMS-PAS-TOP-22-007

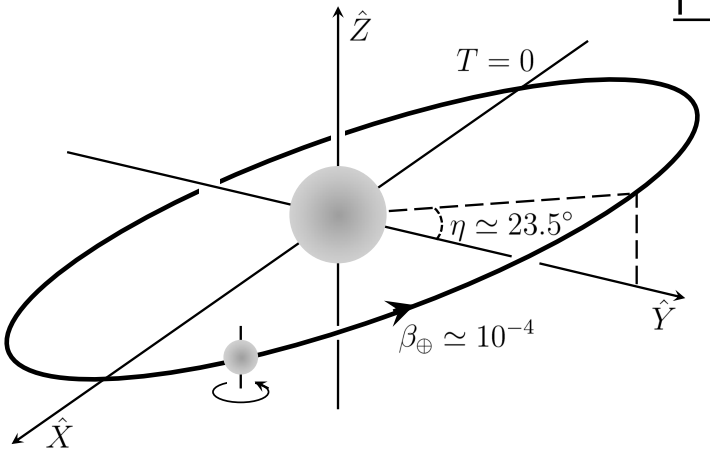
New for LHCP

Lorentz transformation:

$$x^\mu \mapsto x'^\mu = \Lambda^\mu_{\ \nu} x^\nu$$

- Rotations

- Lorentz boosts



Lorentz-violating Standard Model Extension (SME):

- Motivated by String theory or Loop quantum gravity
- Add all **Lorentz-violating operators** to the SM Lagrangian
- Tested in many sectors, but only once with top quarks (D0, PRL 108 (2012) 261603))

$$L_{\text{SME}} = \frac{1}{2} i\bar{\psi}(\gamma^\nu + c^{\mu\nu}\gamma_\mu + d^{\mu\nu}\gamma_5\gamma_\mu)\overleftrightarrow{\partial_\nu}\psi - m_t\bar{\psi}\psi$$

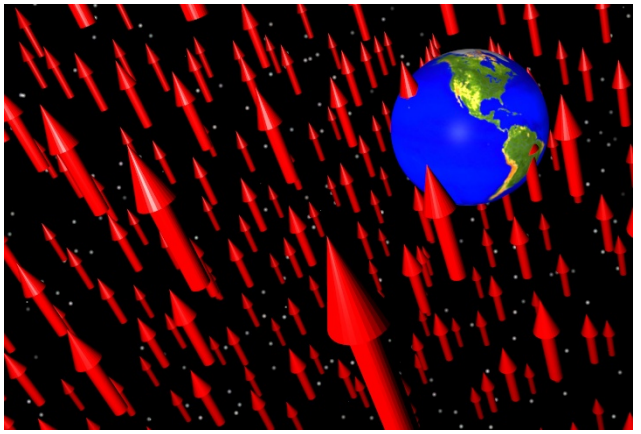
- SME coefficients: constant matrices (Lorentz-violating)
- Indicate **preferential directions in spacetime**

Report the measurement in the **Sun-centered frame**:

- CMS frame is rotating daily around the earth Z-axis,

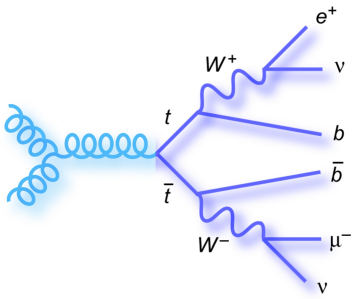
=> modulation of the top-antitop cross section with sidereal time

Rotation period of the earth lasts ~23h 56min 4s (UTC time ~UNIX time), or 24h, 86400 s (sidereal time)

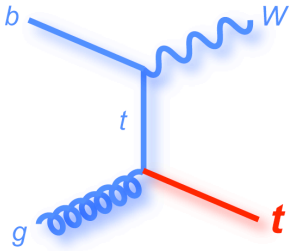


Searches for violation of Lorentz invariance with $t\bar{t}$

CMS-PAS-TOP-22-007



ttbar signal

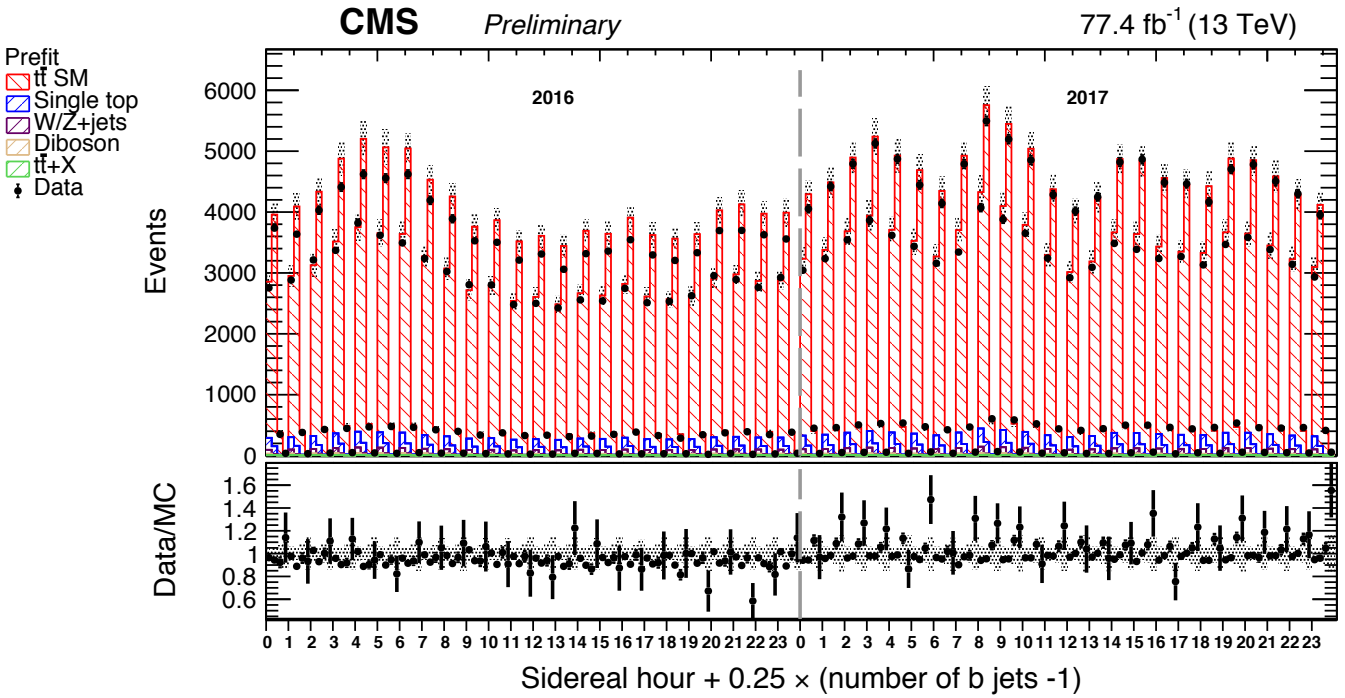


main background: single top tW

Selection:

- Dilepton final state: **eμ**
- Leading lepton pT>25 GeV, subheading pT>20 GeV
- **≥ 2 jets** with pT>30 GeV and $|\eta| < 2.4$
- Among which **≥ 1 b jet** (deepCSV tagger)

Discriminant observable: **number of b jets** (good separation between ttbar and tW), **in bins of sidereal time**



Dedicated MC corrections in bins of sidereal time:

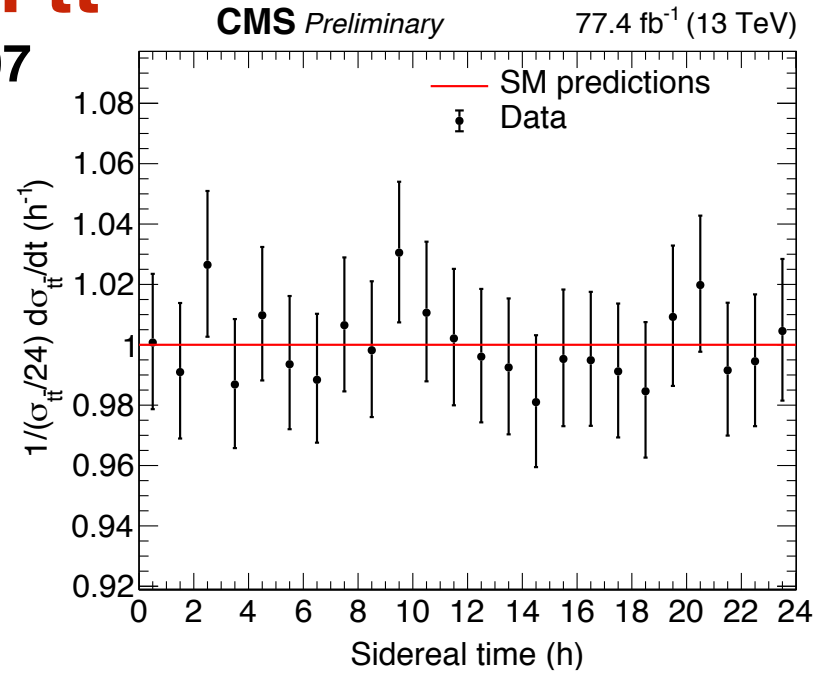
- Integrated luminosity,
- Pileup distribution,
- Trigger efficiencies
- Other corrections are treated independently of sidereal time bin

Searches for violation of Lorentz invariance with $t\bar{t}$

CMS-PAS-TOP-22-007

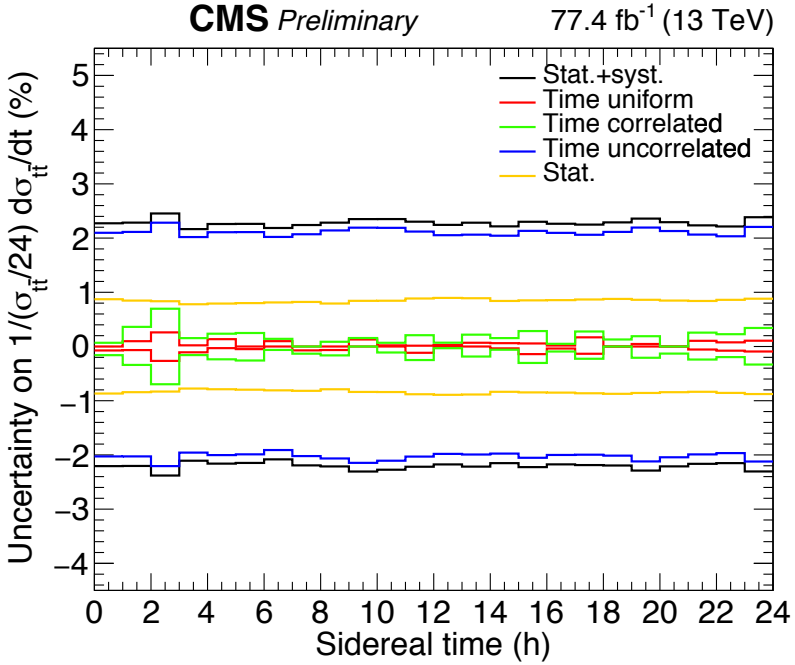
Direct fit of normalised differential ttbar cross section

- Uncertainty is around 2.2% in each time bin
- Statistical uncertainty accounts for ~0.9%



Treatment of the systematics with sidereal time:

- Uncertainty in pileup, luminosity stability and linearity, trigger: evaluated as a function of sidereal time, treated as **correlated: subdominant**
- Other experimental systematics treated as **uncorrelated,** to let the fit find their impact on each time bin in data: **dominant**
- SM theory, background norm, other luminosity uncertainties treated as **uniform**: **cancel** almost completely in the ratio

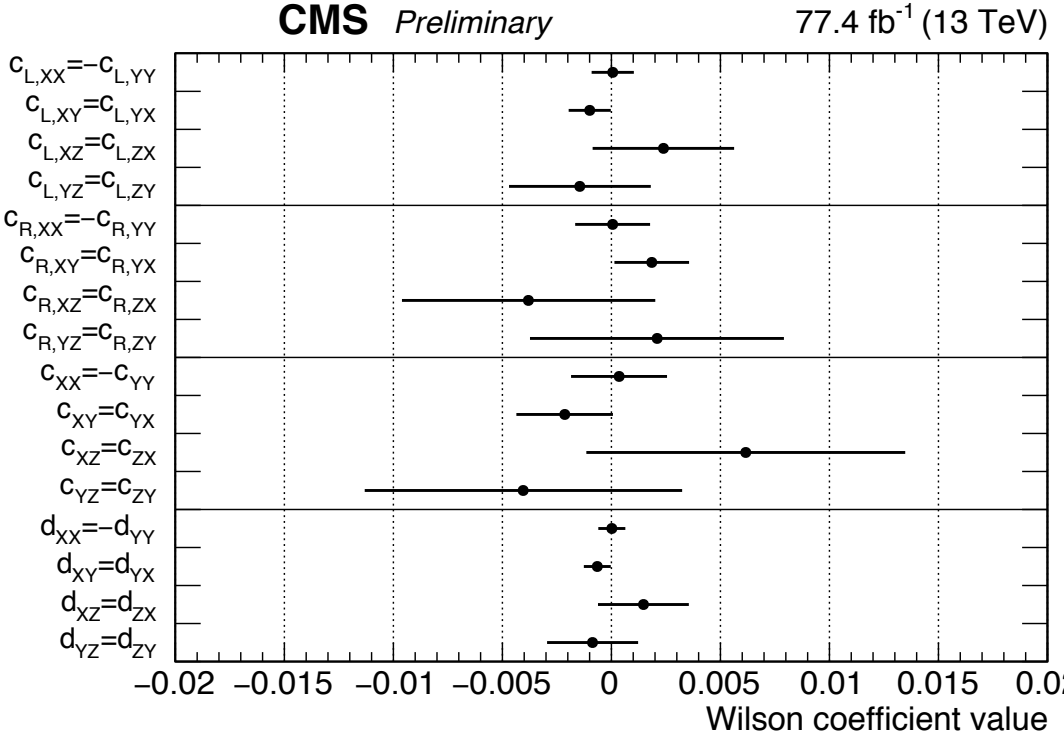


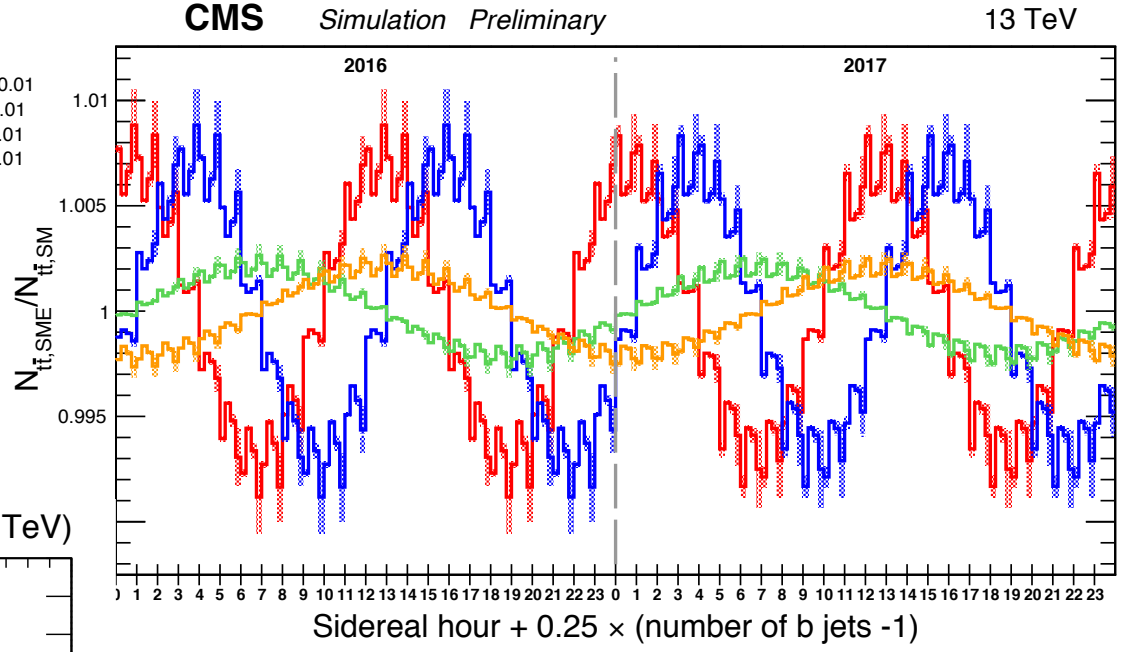
Searches for violation of Lorentz invariance with $t\bar{t}$

CMS-PAS-TOP-22-007

SME signal model (evaluated at LO):

- Time modulation calculated in bins of sidereal time and number of b jets
- 4 directions tested: XX, XY, XZ, YZ
- 4 families of coefficients: c, d, c_L, c_R





- No significant deviation
- **Improved precision by a factor ~100 relative to D0**
- Special relativity tested at the 0.1-0.8% level with top quarks at the LHC

Conclusions and perspectives

Presented a variety of recent BSM searches using top quarks at CMS:

Searches for tqγ (q=u,c) FCNC coupling:

- Results at the 10^{-5} level in BR, best limits on tcγ coupling

Searches for ttbar+Φ in multilepton final states:

- Large improvement at low mass in ttΦ,Φ→ee/μμ, first such search for ttΦ,Φ→ττ

Searches for W'→tb in leptonic final states:

- Extend range of search from 3 to 6 TeV, limits with 1% W' width result in $m_{W'}$> ~4 TeV

Search for heavy tW resonances in t→W(lν)+b, associated W→qq':

- Complementary to other final states

Searches for violation of Lorentz invariance with ttbar:

- First measurement at the LHC, improve by a factor 100 relative to D0
- Workshop in Belgrade on Monday: https://indico.cern.ch/event/1261662/

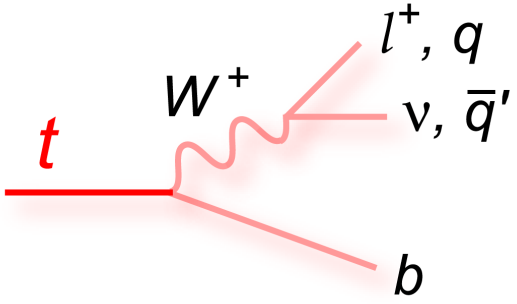
Perspectives:

- Moving to 13.6 TeV should allow to probe higher mass regime
- Opens the door to more final states and new scenarios to be tested in the future

Thanks for your attention

Back-up slides

Top quark decay



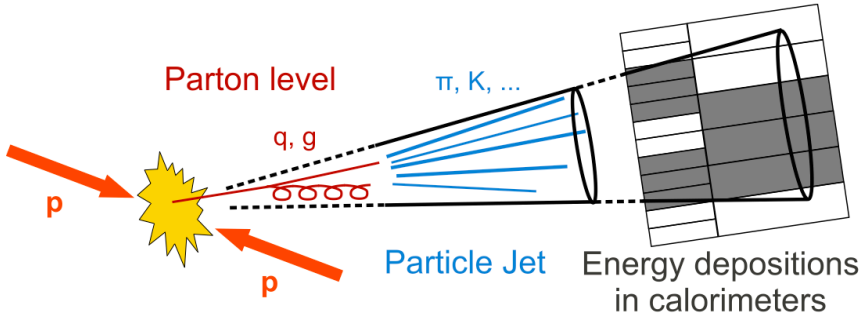
CKM matrix

	d	s	b
u			
c			
t			

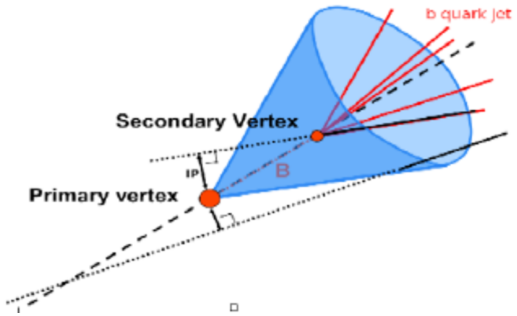
Top quark decay

- The top quark undergoes electroweak decay to Wb before hadronizing
- W decays via W→lν or W→qq', leading to to b + leptons or jets signatures

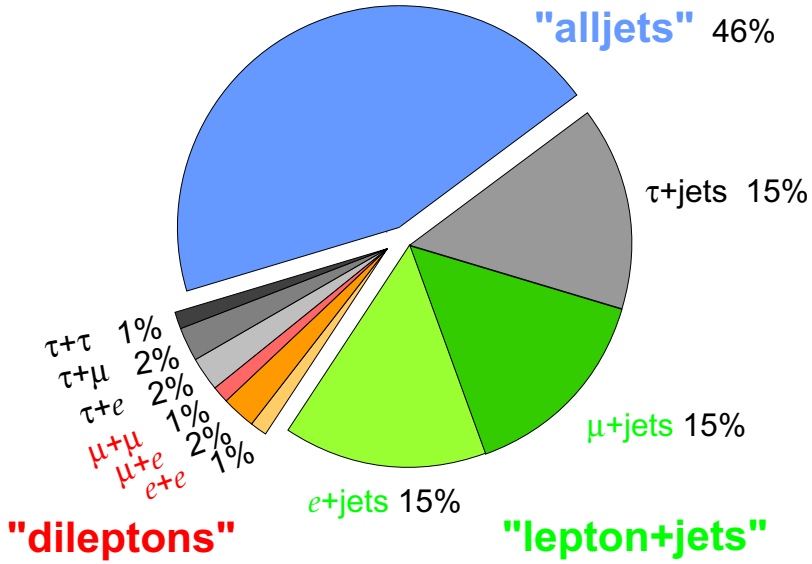
Jet



B-jet



Top Pair Branching Fractions



Searches for tqγ (q=u,c) FCNC coupling

CMS-PAS-TOP-21-013

Combined	Obs. limit	Exp. limit	$\pm1\sigma$ (exp. limit)	$\pm2\sigma$ (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}	$(1.13 - 2.37) \times 10^{-5}$	$(0.81 - 3.32) \times 10^{-5}$

(FCNC signal NLO normalization)

Best limits on t→cγ

Limits from ATLAS [2205.02537]:

$\mathcal{B}(t \to u + \gamma) < 0.85 \times 10^{-5}$ (LH) , $\mathcal{B}(t \to u + \gamma) < 1.2 \times 10^{-5}$ (RH),

$\mathcal{B}(t \to c + \gamma) < 4.2 \times 10^{-5}$ (LH) , $\mathcal{B}(t \to c + \gamma) < 4.5 \times 10^{-5}$ (RH),

ST FCNC TT FCNC

sigma [pb] = (96.87 + 136.7) * (k_{tuγ}) ^2

sigma [pb] = (14.15 + 136.7) * (k_{tcγ})^2

CMS analysis is sensitive to both ST and TT contribution

Search for $t\bar{t}$+(pseudo)scalar boson

Signal regions

CMS-PAS-EXO-19-002

Label	$N_{leptons}$	N_{OSSF}	M_{OSSF}	N_b	Variable and range (GeV)		Number of bins		
					S_T (GeV)		0–400	400–800	>800
3L(ee/$\mu\mu$) 0B	3	1	off-Z	0	M^{20}_{OSSF}	[12, 77]	13	13	5
					M^{300}_{OSSF}	[106, 356]	10	10	10
3L(ee/$\mu\mu$) 1B	3	1	off-Z	$\geq$1	M^{20}_{OSSF}	[12, 77]	13	13	5
					M^{300}_{OSSF}	[106, 356]	10	10	10
					S_T (GeV)		0–400	>400	
4L(ee/$\mu\mu$) 0B	$\geq$4	$\geq$1	off-Z	0	M^{20}_{OSSF}	[12, 77]	3	2	
					M^{300}_{OSSF}	[106, 356]	3	2	
					S_T inclusive				
4L(ee/$\mu\mu$) 1B	$\geq$4	$\geq$1	off-Z	$\geq$1	M^{20}_{OSSF}	[12, 77]	3		
					M^{300}_{OSSF}	[106, 356]	3		

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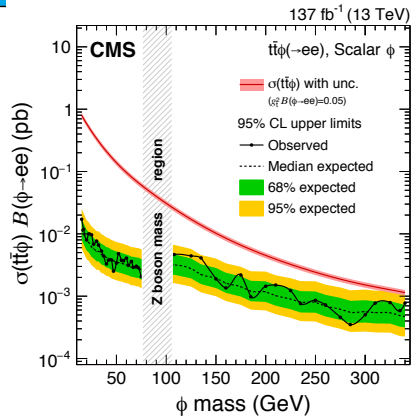
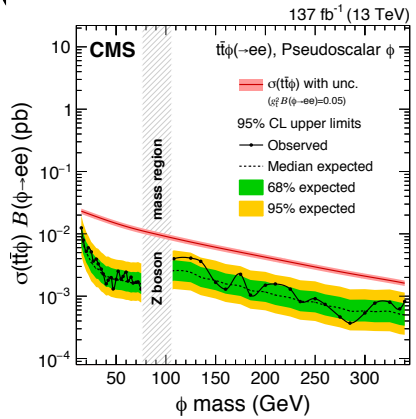
Label	Channels	Q_ℓ	OSSFn	M_{OSSF}	N_b	S_T	p_T^3	M_ℓ	Dilepton mass
Wϕ(ee/$\mu\mu$) SR1Low	3L(eeμ/e$\mu\mu$)	1	1	OffZ	0	–	–	$< 76,\ > 106$	M_{ee} / $M_{\mu\mu}$
Wϕ(ee/$\mu\mu$) SR2Low	3L(eee/$\mu\mu\mu$)	1	1	OffZ	0	–	–	$< 76,\ > 106$	M^{min}_{ee} / $M^{min}_{\mu\mu}$
Wϕ(ee/$\mu\mu$) SR1High	3L(eeμ/e$\mu\mu$)	1	1	OffZ	0	> 200	> 15	> 150	M_{ee} / $M_{\mu\mu}$
Wϕ(ee/$\mu\mu$) SR2High	3L(eee/$\mu\mu\mu$)	1	1	OffZ	0	> 200	> 15	> 150	M^{max}_{ee} / $M^{max}_{\mu\mu}$
Zϕ(ee/$\mu\mu$) SRLow	4L+3L1T+2L2T	0	≥ 1	Not double-OnZ	0	–	–	–	M^{min}_{ee} / $M^{min}_{\mu\mu}$
Zϕ(ee/$\mu\mu$) SRHigh	4L+3L1T+2L2T	0	≥ 1	Not double-OnZ	0	> 200	–	> 150	M^{max}_{ee} / $M^{max}_{\mu\mu}$
$t\bar{t}\phi$(ee/$\mu\mu$) SR1Low	3L(eeμ/e$\mu\mu$)	1	1	OffZ	≥ 1	> 350	–	> 100	M_{ee} / $M_{\mu\mu}$
$t\bar{t}\phi$(ee/$\mu\mu$) SR2Low	3L(eee/$\mu\mu\mu$)	1	1	OffZ	≥ 1	> 350	–	> 100	M^{min}_{ee} / $M^{min}_{\mu\mu}$
$t\bar{t}\phi$(ee/$\mu\mu$) SR1High	3L(eeμ/e$\mu\mu$)	1	1	OffZ	≥ 1	> 400	> 15	> 100	M_{ee} / $M_{\mu\mu}$
$t\bar{t}\phi$(ee/$\mu\mu$) SR2High	3L(eee/$\mu\mu\mu$)	1	1	OffZ	≥ 1	> 400	> 15	> 100	M^{max}_{ee} / $M^{max}_{\mu\mu}$
$t\bar{t}\phi$(ee/$\mu\mu$) SR3Low	4L+3L1T+2L2T	0	≥ 1	OffZ	–	> 350	–	–	M^{min}_{ee} / $M^{min}_{\mu\mu}$
$t\bar{t}\phi$(ee/$\mu\mu$) SR3High	4L+3L1T+2L2T	0	≥ 1	OffZ	–	> 400	–	–	M^{max}_{ee} / $M^{max}_{\mu\mu}$

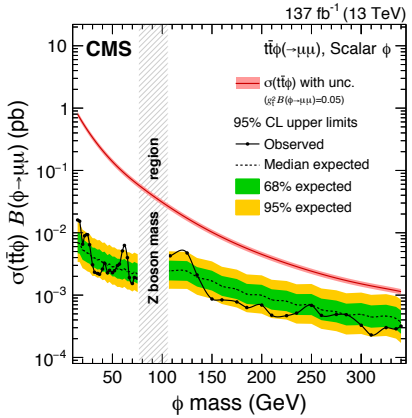
Label	Channels	Q_ℓ	OSSFn	M_{OSSF}	N_b	S_T	N_j	p_T^3	M_ℓ	Dilepton mass
W$\phi(\tau\tau)$ SR1	3L	1	0	–	0	> 200	–	> 15	> 150	$M^{min}_{e\mu}$
W$\phi(\tau\tau)$ SR2	2L1T+1L2T	1	0	–	0	> 200	–	> 30	> 150	$M^{min}_{\ell\tau}$
W$\phi(\tau\tau)$ SR3	1L2T	1	1	–	0	> 200	–	> 30	> 150	$M^{min}_{\tau\tau}$
Z$\phi(\tau\tau)$ SR1	4L+2L2T	0	1	–	0	> 200	–	–	–	$M^{min}_{e\mu}$
Z$\phi(\tau\tau)$ SR2	3L1T	0	1	–	0	> 200	–	–	–	$M^{min}_{\ell\tau}$
Z$\phi(\tau\tau)$ SR2	2L2T	0	0	–	0	> 200	–	–	–	$M^{min}_{\ell\tau}$
Z$\phi(\tau\tau)$ SR3	2L2T	0	2	–	0	> 200	–	–	–	$M^{min}_{\tau\tau}$
$t\bar{t}\phi(\tau\tau)$ SR1	3L	1	0	–	0	> 400	> 1	> 15	> 100	$M^{min}_{e\mu}$
$t\bar{t}\phi(\tau\tau)$ SR2	2L1T+1L2T	1	0	–	0	> 400	> 1	> 30	> 100	$M^{min}_{\ell\tau}$
$t\bar{t}\phi(\tau\tau)$ SR3	1L2T	1	1	–	0	> 400	> 1	> 30	> 100	$M^{min}_{\tau\tau}$
$t\bar{t}\phi(\tau\tau)$ SR4	3L	1	1	OffZ	> 0	> 400	> 1	> 15	> 100	$M^{min}_{e\mu}$
$t\bar{t}\phi(\tau\tau)$ SR4	3L	1	0	–	> 0	> 400	> 1	> 15	> 100	$M^{min}_{e\mu}$
$t\bar{t}\phi(\tau\tau)$ SR5	2L1T+1L2T	1	0	–	> 0	> 400	> 1	> 30	> 100	$M^{min}_{\ell\tau}$
$t\bar{t}\phi(\tau\tau)$ SR6	1L2T	1	1	–	> 0	> 400	> 1	> 30	> 100	$M^{min}_{\tau\tau}$
$t\bar{t}\phi(\tau\tau)$ SR7	3L1T	0	1	OffZ	–	> 400	–	–	–	$M^{min}_{\ell\tau/\tau\tau}$
$t\bar{t}\phi(\tau\tau)$ SR7	3L1T	0	0	–	–	> 400	–	–	–	$M^{min}_{\ell\tau/\tau\tau}$
$t\bar{t}\phi(\tau\tau)$ SR7	2L2T	0	2	OffZ	–	> 400	–	–	–	$M^{min}_{\ell\tau/\tau\tau}$
$t\bar{t}\phi(\tau\tau)$ SR7	2L2T	0	< 2	–	–	> 400	–	–	–	$M^{min}_{\ell\tau/\tau\tau}$
$t\bar{t}\phi(\tau\tau)$ SR7	1L3T	0	1	–	–	> 400	–	–	–	$M^{min}_{\ell\tau/\tau\tau}$

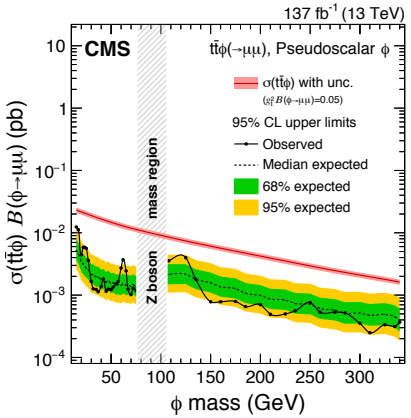
Search for $t\bar{t}$+(pseudo)scalar boson

CMS-PAS-EXO-19-002 (JHEP 03 (2020) 051)

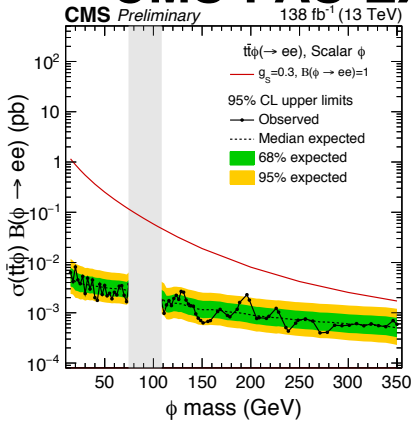


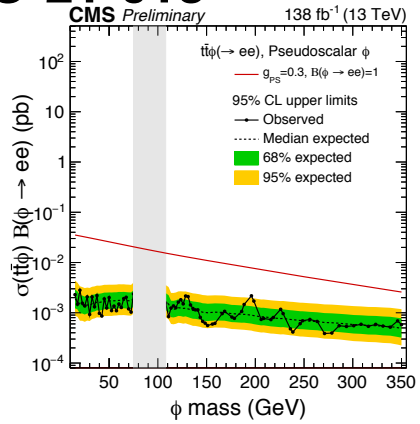


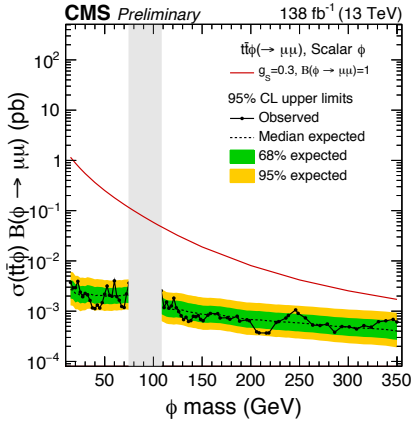


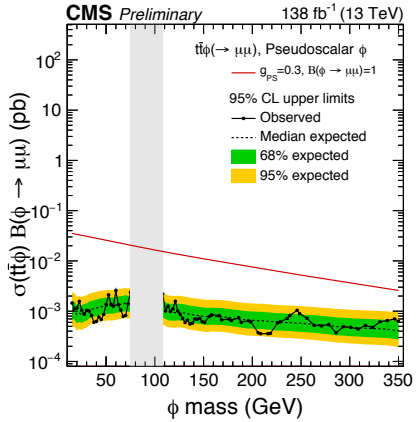


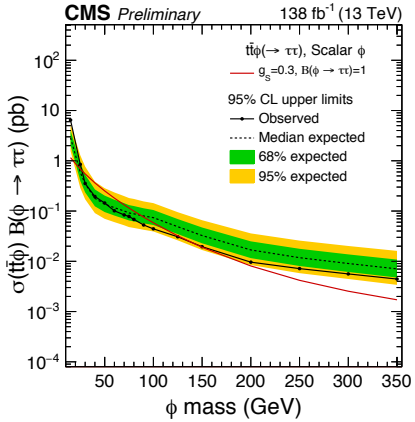
CMS-PAS-EXO-21-018

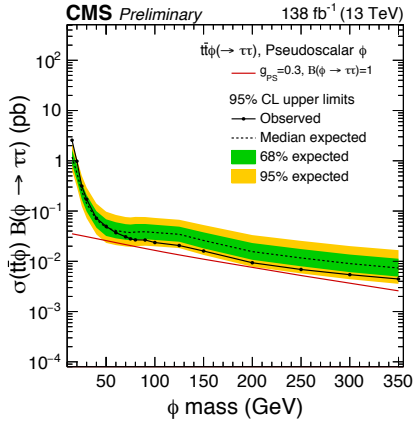








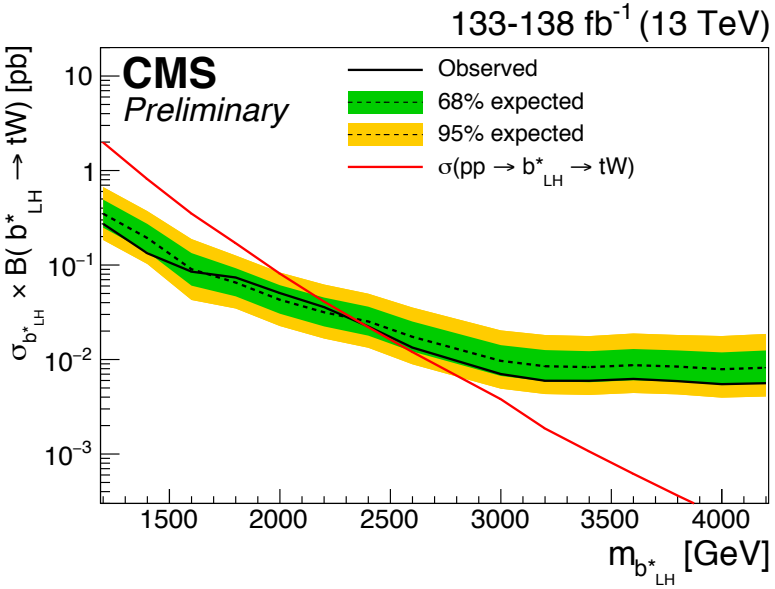


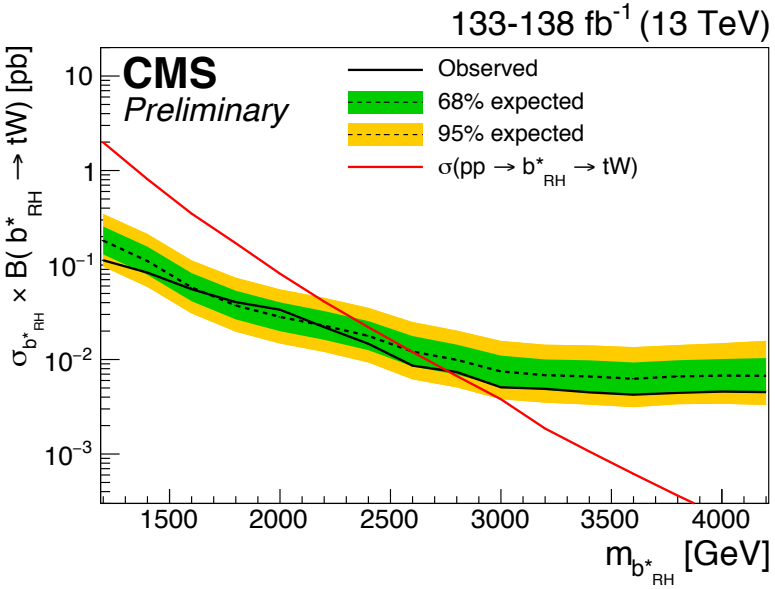


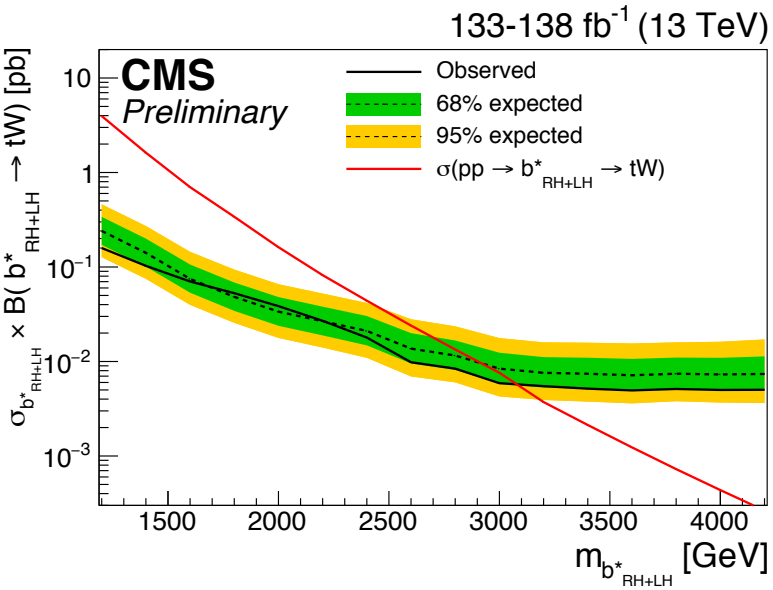
Improvement at low mass by a factor 2-3:
narrower bin widths in mass spectra and
improved event selection/categorization criteria

Search for heavy tW resonances

CMS-PAS-B2G-21-005



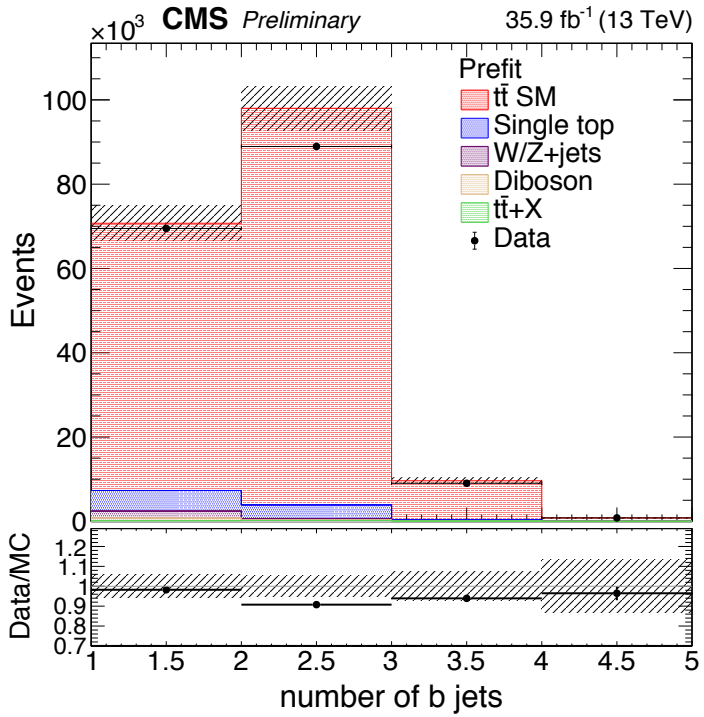


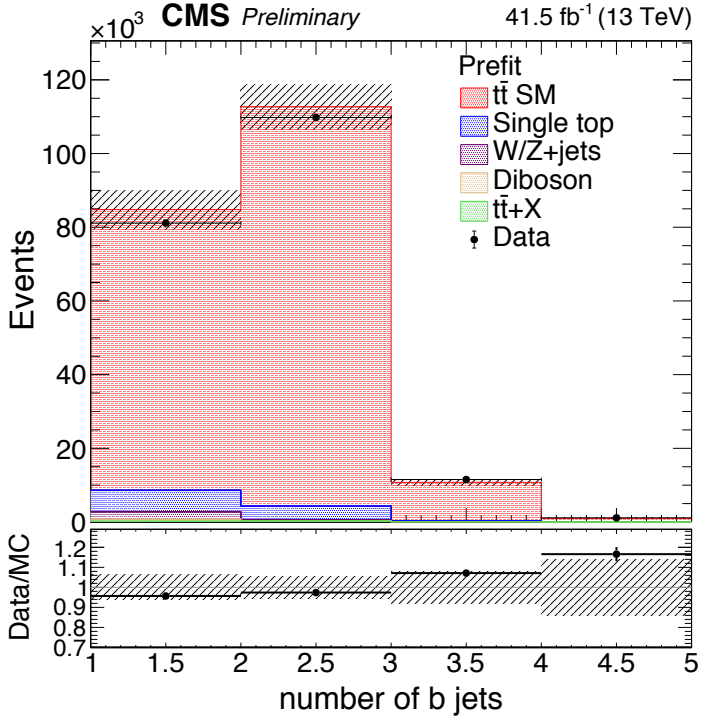


Searches for violation of Lorentz invariance with $t\bar{t}$

CMS-PAS-TOP-22-007

Process	2016	2017
$t\bar{t}$ SM	167641	195871
$t\bar{t}$+X	456	544
Single top	8375	9888
Dibosons	692	651
W/Z+jets	2084	2321
Total background	11607	13404
Total MC	179247	209277
Data	168282	203584





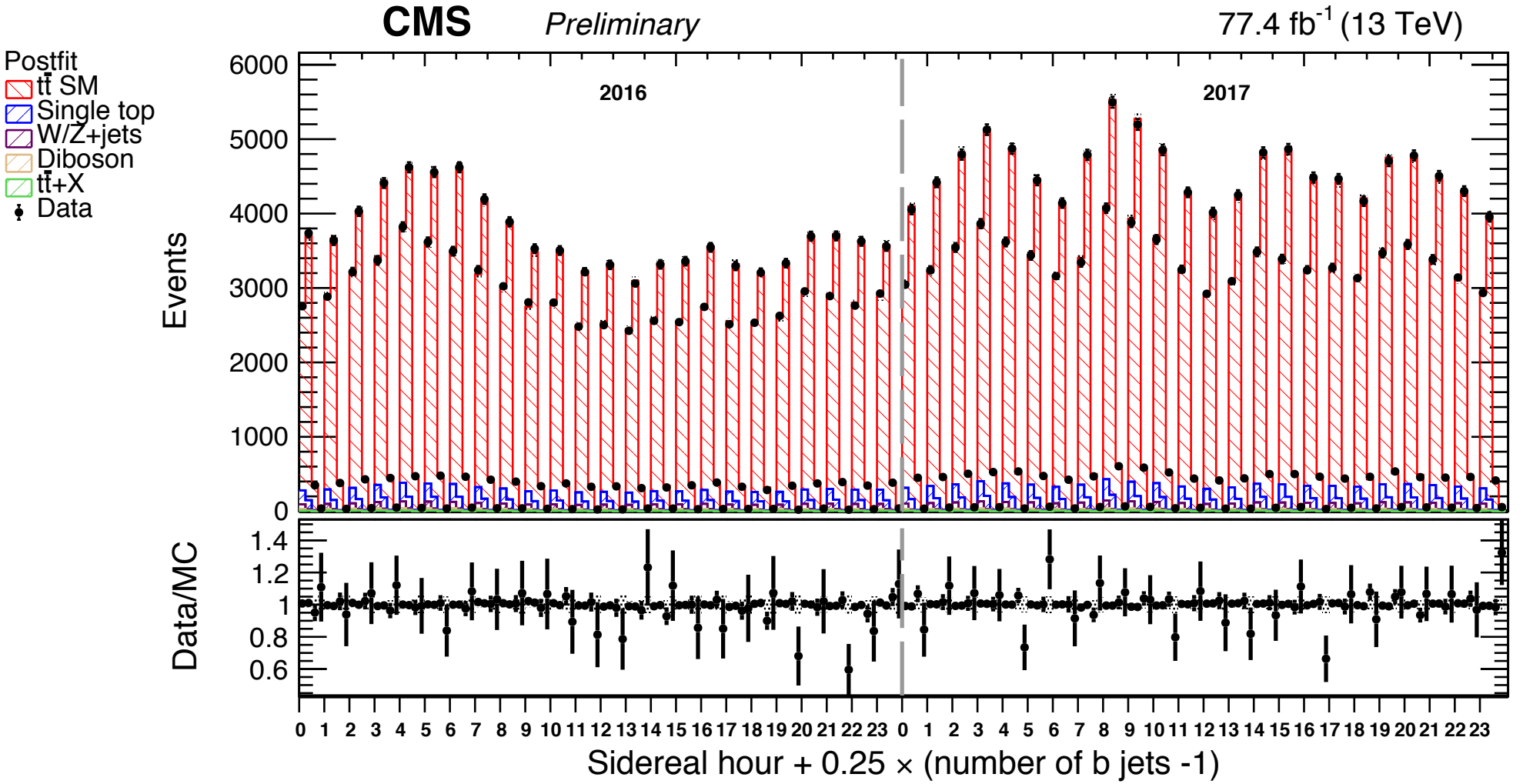
Searches for violation of Lorentz invariance with $t\bar{t}$

CMS-PAS-TOP-22-007

Systematic uncertainty source	Correlation 2016–2017	Correlation time bins	Magnitude
Flat luminosity, year-to-year correlated part	100%	100%	0.6% (2016), 0.9% (2017)
Flat luminosity, year-to-year uncorrelated part	0%	100%	0.9% (2016), 1.4% (2017)
Time-dependent luminosity stability	0%	100%	0.2% (2016), 0.4% (2017)
Time-dependent luminosity linearity	0%	100%	0.2% (2016), 0.4% (2017)
Time-dependent pileup reweighting	100%	100%	0.3–5%
Time-dependent trigger efficiency, syst. component	0%	100%	0.5–1%
Time-dependent trigger efficiency, stat. component	0%	0%	0.5%
L1 ECAL prefiring	100%	0%	0.5%
Electron reconstruction	100%	0%	0.4%
Electron identification	100%	0%	1.2–2.2%
Muon identification, syst. component	100%	0%	0.3%
Muon identification, stat. component	0%	0%	0.5%
Muon isolation, syst. component	100%	0%	<0.1%
Muon isolation, stat. component	0%	0%	0.2%
Phase-space extrapolation of lepton isolation	100%	100%	0.5–1%
Jet energy scale, year-to-year correlated part	100%	0%	0.8%
Jet energy scale, year-to-year uncorrelated part	0%	0%	1.4%
Parton flavor impact on jet energy scale	100%	100%	1.1%
b tagging	0%	0%	2–4%
Matrix element scale	100%	100%	0.3–6%
PDF+α_S	100%	100%	0.1–0.4%
Initial- & final-state radiation scale	100%	100%	1–5%
Top quark p_T	100%	100%	0.5–2.5%
Matrix element-parton shower matching	100%	100%	0.7%
Underlying event tune	100%	100%	0.2%
Color reconnection	100%	100%	0.3%
Top quark mass	100%	100%	0.5–3%
Single top quark cross section	100%	100%	30%
$t\bar{t}$+X cross section	100%	100%	20%
Diboson cross section	100%	100%	30%
W/Z+jets cross section	100%	100%	30%
$t\bar{t}$ cross section *	100%	100%	4%
Single top quark time modulation *	100%	100%	2%
MC statistical uncertainty	0%	100%	0.1–1%

Searches for violation of Lorentz invariance with $t\bar{t}$

CMS-PAS-TOP-22-007



Searches for violation of Lorentz invariance with $t\bar{t}$

CMS-PAS-TOP-22-007

Wilson coefficient	SM expected Others fixed to SM (10^{-3} units)	Data Others fixed to SM (10^{-3} units)	SM expected Others floating (10^{-3} units)	Data Others floating (10^{-3} units)
$c_{L,XX} = -c_{L,YY}$	[−0.97; 0.97]	[−0.91; 1.03]	[−0.97; 0.97]	[−0.91; 1.03]
$c_{L,XY} = c_{L,YX}$	[−0.97; 0.97]	[−1.94; −0.01]	[−0.97; 0.97]	[−1.96; −0.03]
$c_{L,XZ} = c_{L,ZX}$	[−3.25; 3.25]	[−0.91; 5.58]	[−3.25; 3.25]	[−0.86; 5.63]
$c_{L,YZ} = c_{L,ZY}$	[−3.26; 3.26]	[−4.66; 1.83]	[−3.27; 3.27]	[−4.7; 1.81]
$c_{R,XX} = -c_{R,YY}$	[−1.71; 1.71]	[−1.65; 1.79]	[−1.71; 1.71]	[−1.66; 1.77]
$c_{R,XY} = c_{R,YX}$	[−1.72; 1.72]	[0.11; 3.53]	[−1.72; 1.72]	[0.14; 3.56]
$c_{R,XZ} = c_{R,ZX}$	[−5.81; 5.82]	[−9.52; 2.1]	[−5.82; 5.82]	[−9.61; 2.01]
$c_{R,YZ} = c_{R,ZY}$	[−5.84; 5.84]	[−3.79; 7.86]	[−5.84; 5.84]	[−3.74; 7.91]
$c_{XX} = -c_{YY}$	[−2.19; 2.19]	[−1.78; 2.62]	[−2.19; 2.19]	[−1.85; 2.55]
$c_{XY} = c_{YX}$	[−2.19; 2.19]	[−4.27; 0.15]	[−2.19; 2.19]	[−4.36; 0.07]
$c_{XZ} = c_{ZX}$	[−7.25; 7.25]	[−1.35; 13.27]	[−7.26; 7.25]	[−1.15; 13.48]
$c_{YZ} = c_{ZY}$	[−7.29; 7.29]	[−11.16; 3.35]	[−7.29; 7.29]	[−11.31; 3.24]
$d_{XX} = -d_{YY}$	[−0.62; 0.62]	[−0.6; 0.64]	[−0.62; 0.62]	[−0.6; 0.64]
$d_{XY} = d_{YX}$	[−0.62; 0.62]	[−1.25; −0.02]	[−0.62; 0.62]	[−1.27; −0.03]
$d_{XZ} = d_{ZX}$	[−2.09; 2.09]	[−0.65; 3.52]	[−2.09; 2.09]	[−0.62; 3.55]
$d_{YZ} = d_{ZY}$	[−2.1; 2.1]	[−2.93; 1.24]	[−2.1; 2.1]	[−2.95; 1.23]

Searches for violation of Lorentz invariance with $t\bar{t}$

CMS-PAS-TOP-22-007