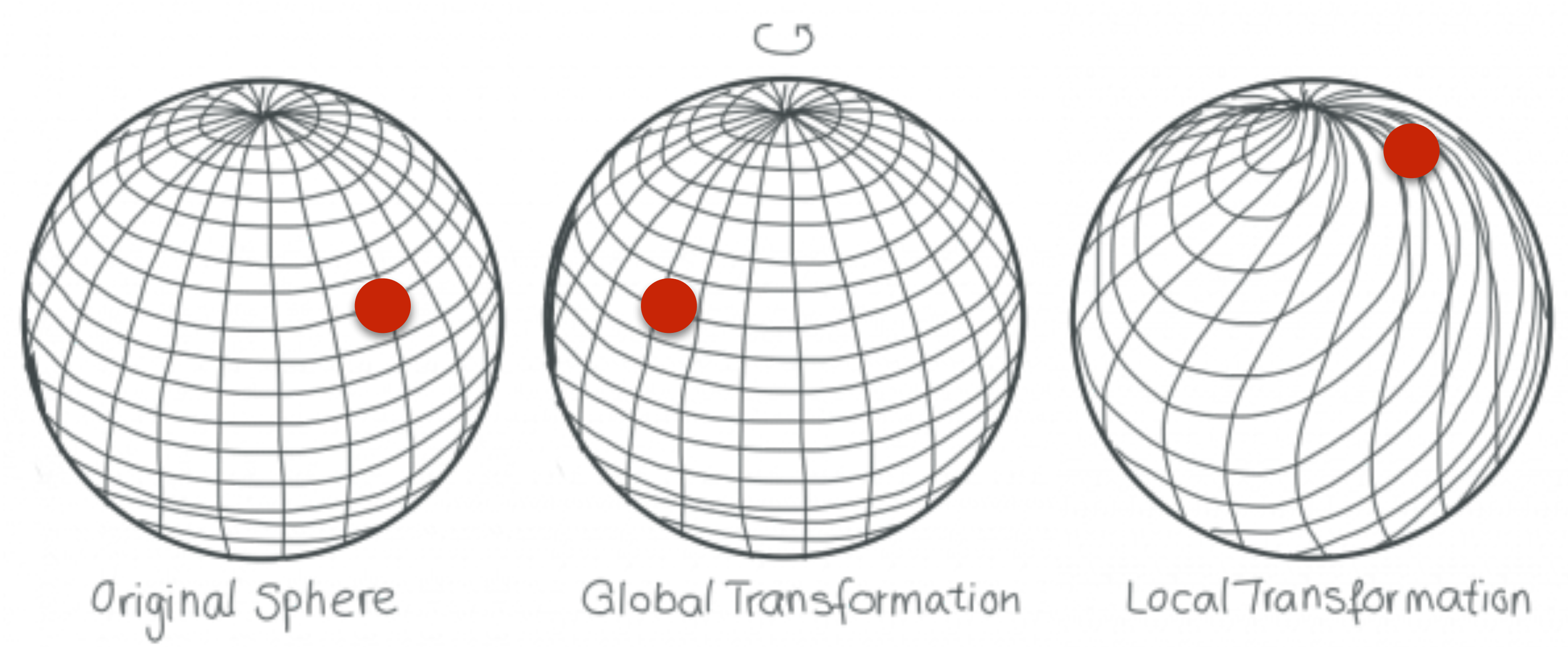
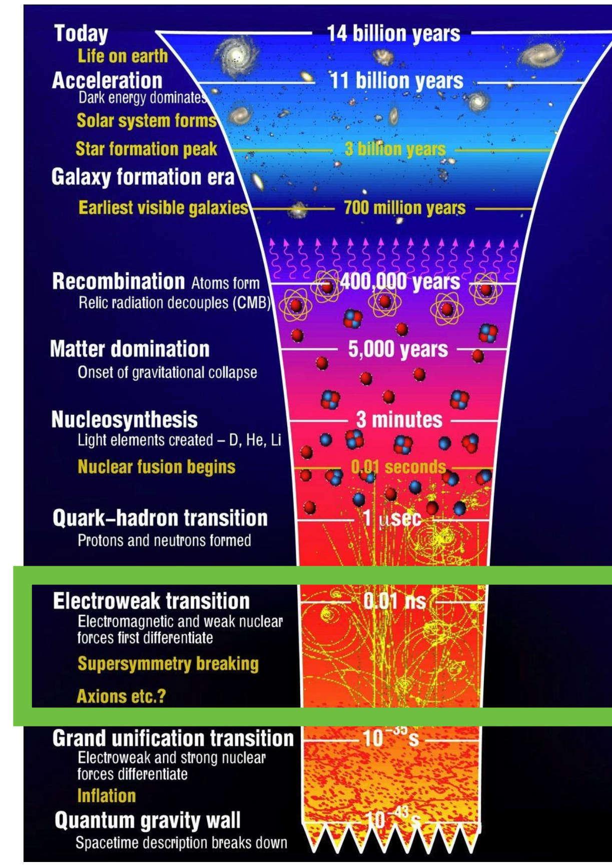
Probing global symmetries with top quark and Higgs boson at CMS

DISCRETE conference, Ljubljana - 04/12/2024



Nicolas Chanon for the CMS Collaboration,
IP2I Lyon CNRS/IN2P3

Lorentz, CPT, CP and baryogenesis



Standard model electroweak baryogenesis:

$$\eta_{SM} = (n_b - n_{\bar{b}})/n_\gamma \approx 10^{-27}$$

Observation:

$$\eta = (n_b - n_{\bar{b}})/n_\gamma \approx 6 \times 10^{-10}$$

Beyond SM electroweak baryogenesis:
- Additional scalars may ensure 1st order electroweak phase transition
- A new source of CP violation is required

CPT baryogenesis:
- CPT violation
- Induces baryon number violation at thermal equilibrium

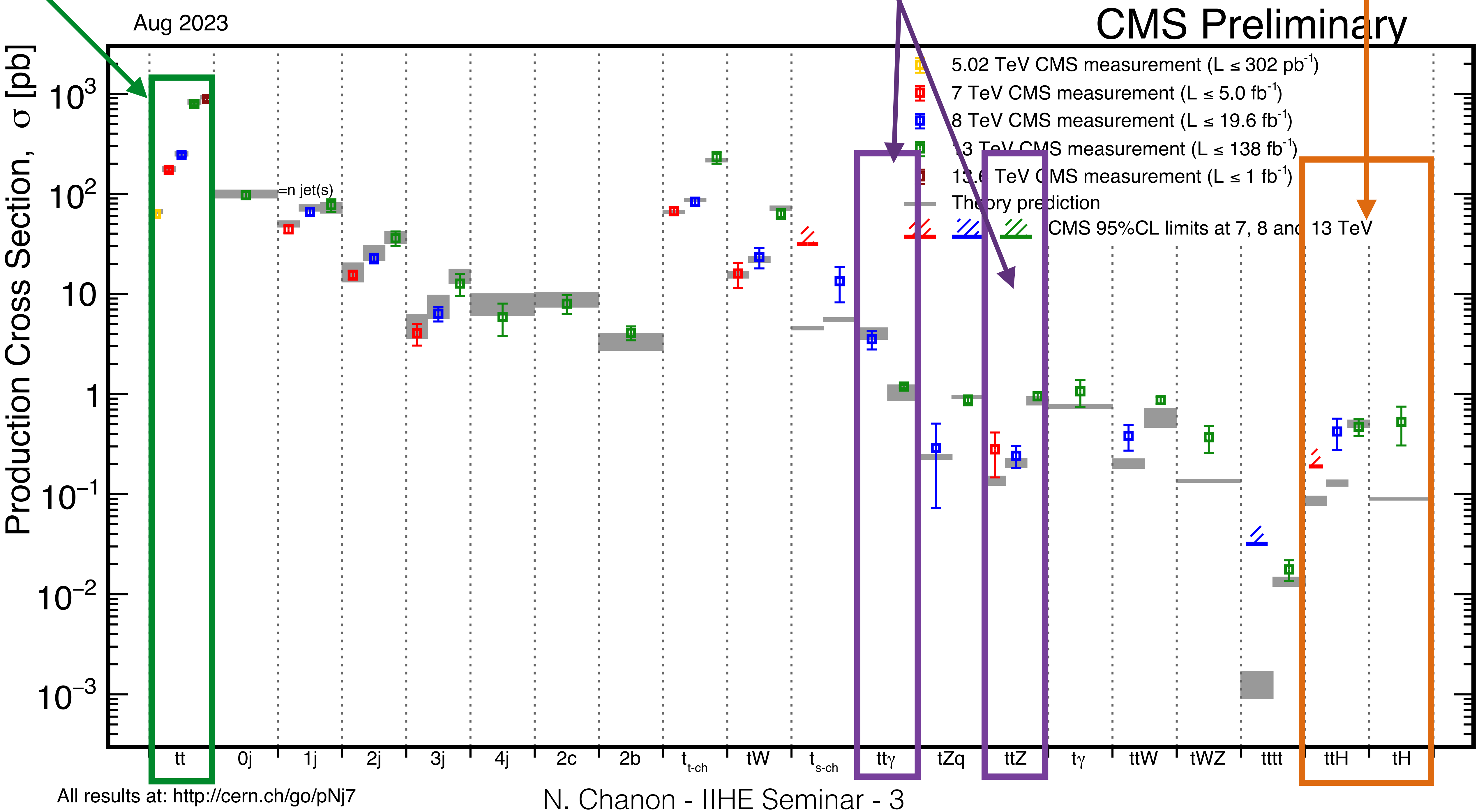
CPT theorem: a QFT a preserving Lorentz invariance must also preserve CPT symmetry.
CPT violation implies Lorentz violation for local QFT theories [Greenberg 2002]

top and Higgs in searches for…

- **CPT** asymmetry with ttbar
- Violation of **Lorentz invariance** with ttbar
- **CP violation** in top-gluon coupling

CP violation in **top-Z/γ** coupling

CP violation in **top-Higgs** coupling

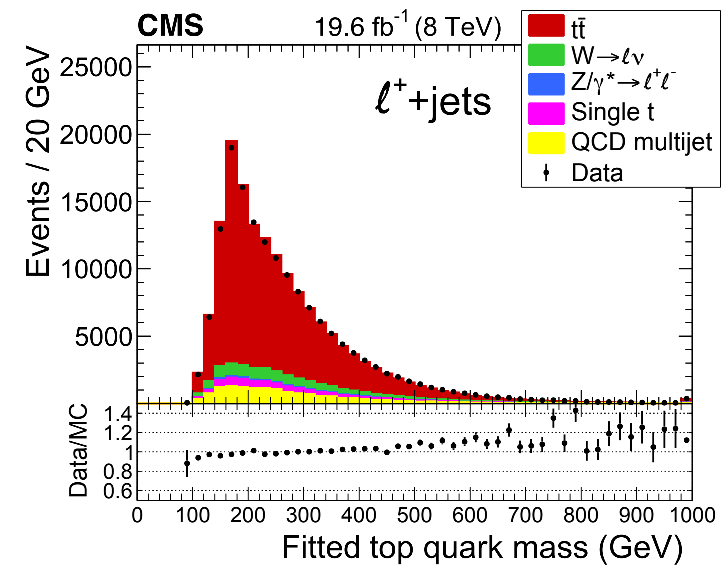


CPT from top/antitop mass difference

PLB 770 (2017) 50–71, arXiv:2403.01313

top/antitop mass difference

- Difference of nominal top quark masses is not allowed within local quantum field theories

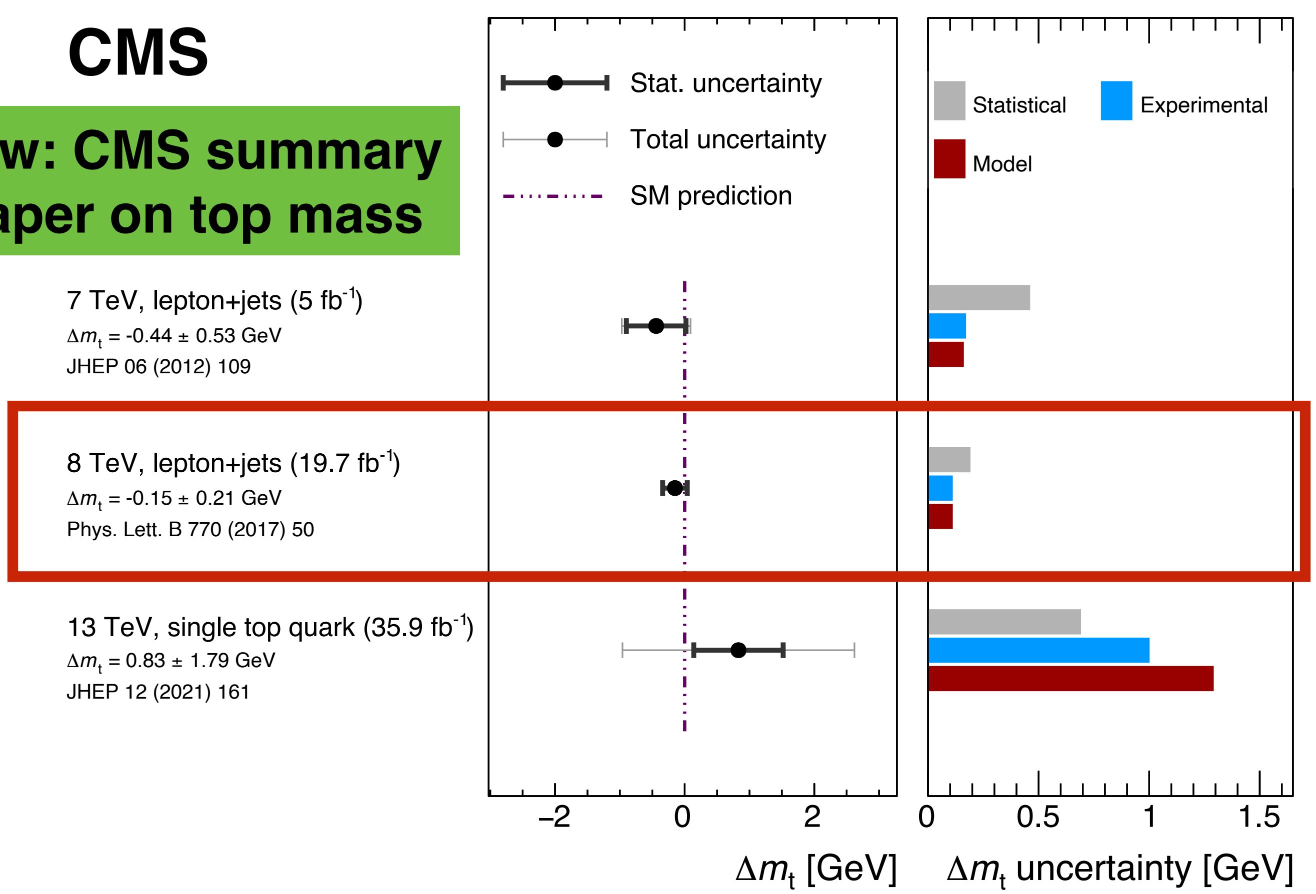


Experimental method, CMS at 8 TeV

- ttbar production in lepton/antilepton+jets decay channels
- top/antitop reconstruction with a kinematic fit
- Many systematics cancel out in the difference

Source	Uncertainty in Δm_t (MeV)
Jet energy scale	7 ± **16**
Jet energy resolution	7 ± **11**
b vs. $\bar{b}$ jet response	**51** ± 1
Signal fraction	**27** ± 2
Background charge asymmetry	**11.9** ± 0.1
Background composition	**28** ± 1
Pileup	**9.1** ± 0.3
b tagging efficiency	**24** ± 7
b vs. $\bar{b}$ tagging efficiency	**11** ± 7
Method calibration	3 ± **53**
Parton distribution functions	**9** ± 3
Total	91

New: CMS summary paper on top mass



- Compatible with the SM $\Delta m_t = -0.15 \pm 0.19\,(\text{stat}) \pm 0.09\,(\text{syst})$ GeV
- **Interpretation** of this measurement: PRL 133, 221601 (2024), talk N. Sherrill on Tuesday

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

Physics briefing

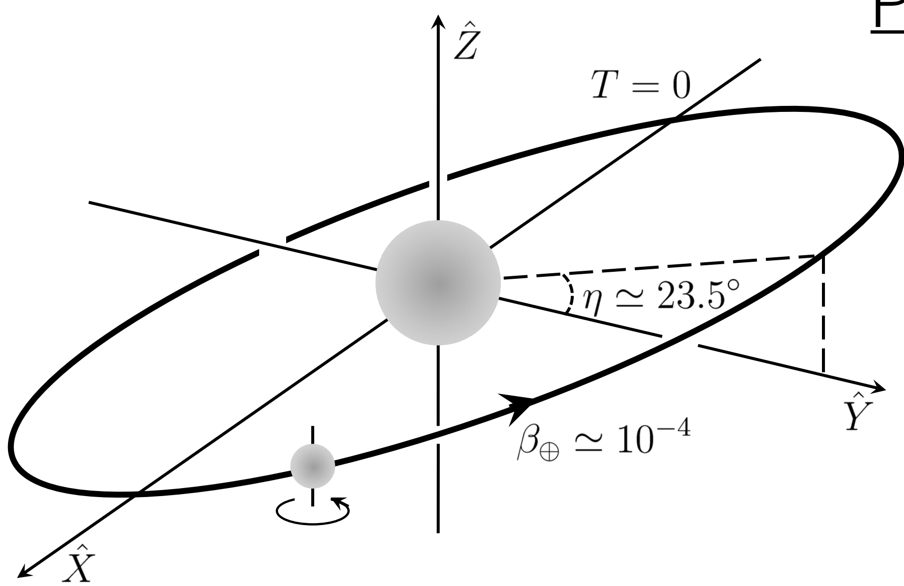
PLB 857 (2024) 138979

Paper just published

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))

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

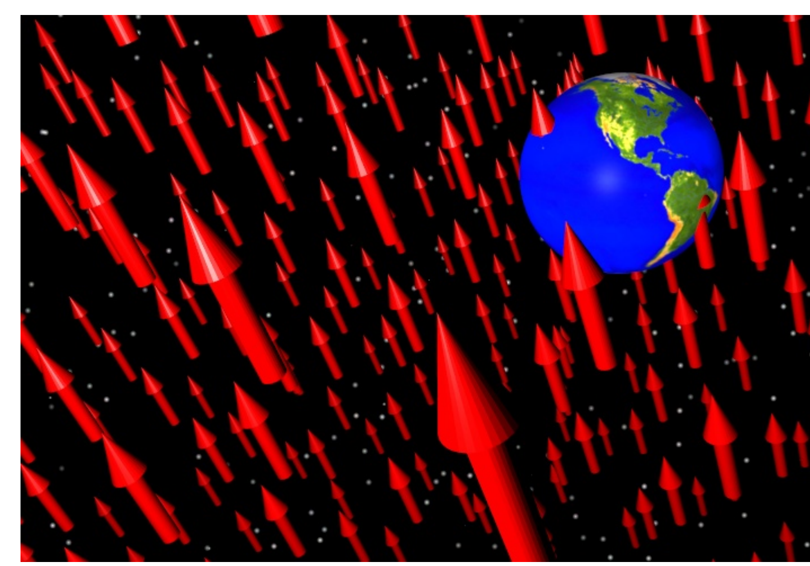
- SME coefficients: constant matrices (Lorentz-violating)
- Indicate **preferential directions in spacetime**

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

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

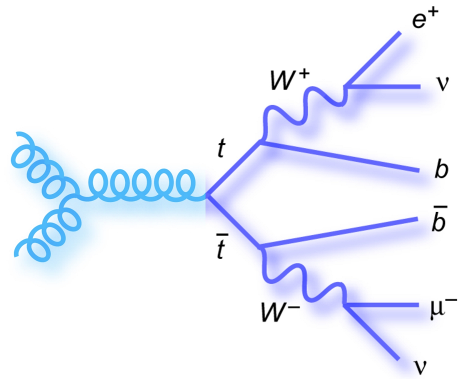
=> modulation of the top-antitop cross section with sidereal time

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

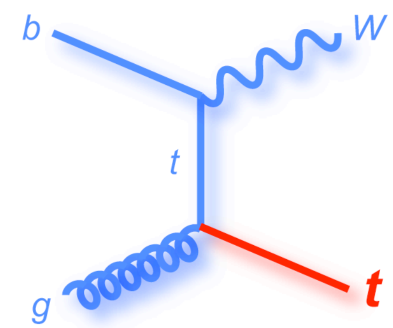


Searches for violation of Lorentz invariance with $t\bar{t}$

PLB 857 (2024) 138979



ttbar signal



main background: single top tW

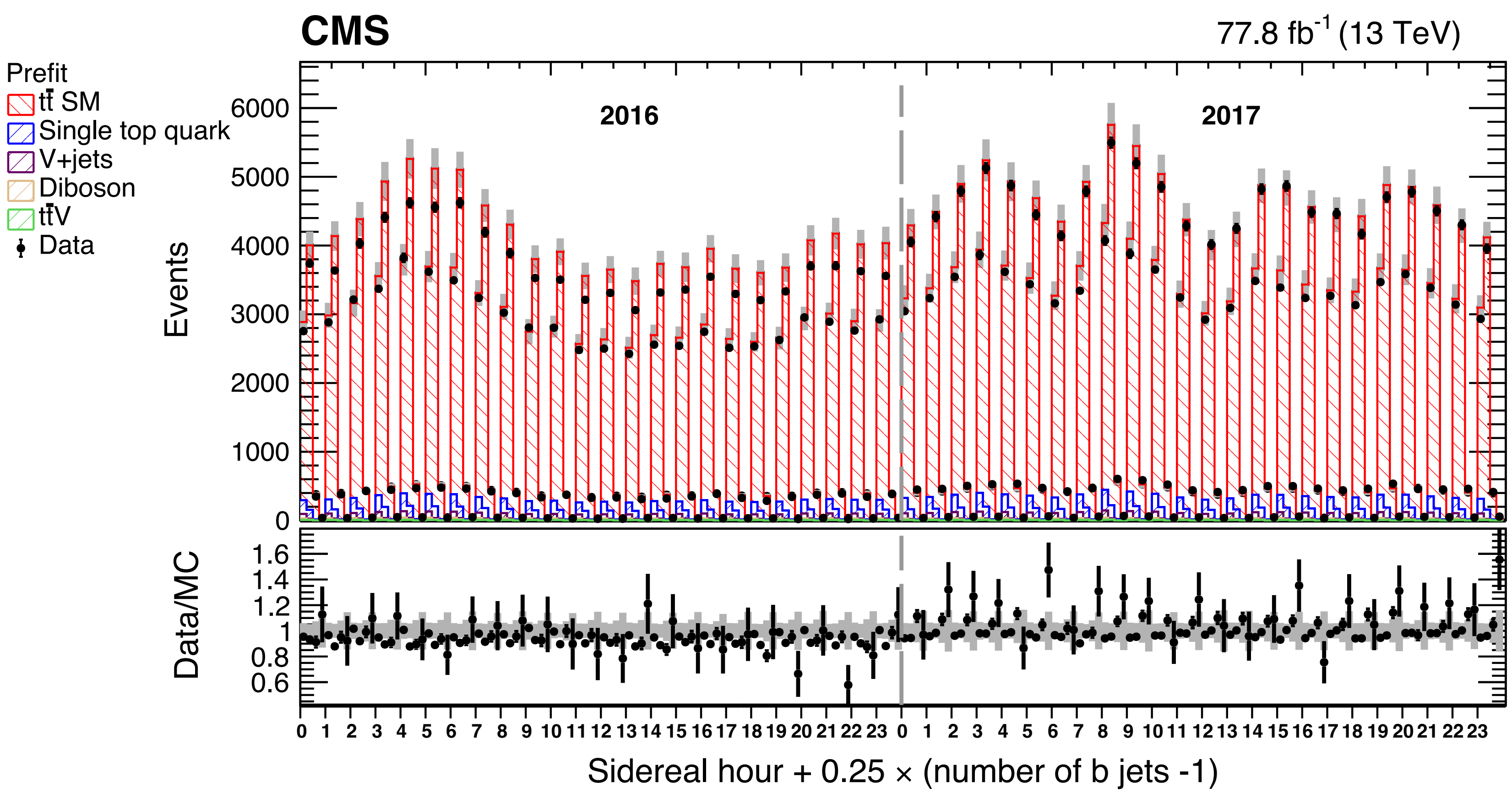
Selection:

- Dilepton final state: **eμ**
- Leading lepton pT>25 GeV, subheading pT>20 GeV
- **≥ 2 jets** with pT>30 GeV and |η| < 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**

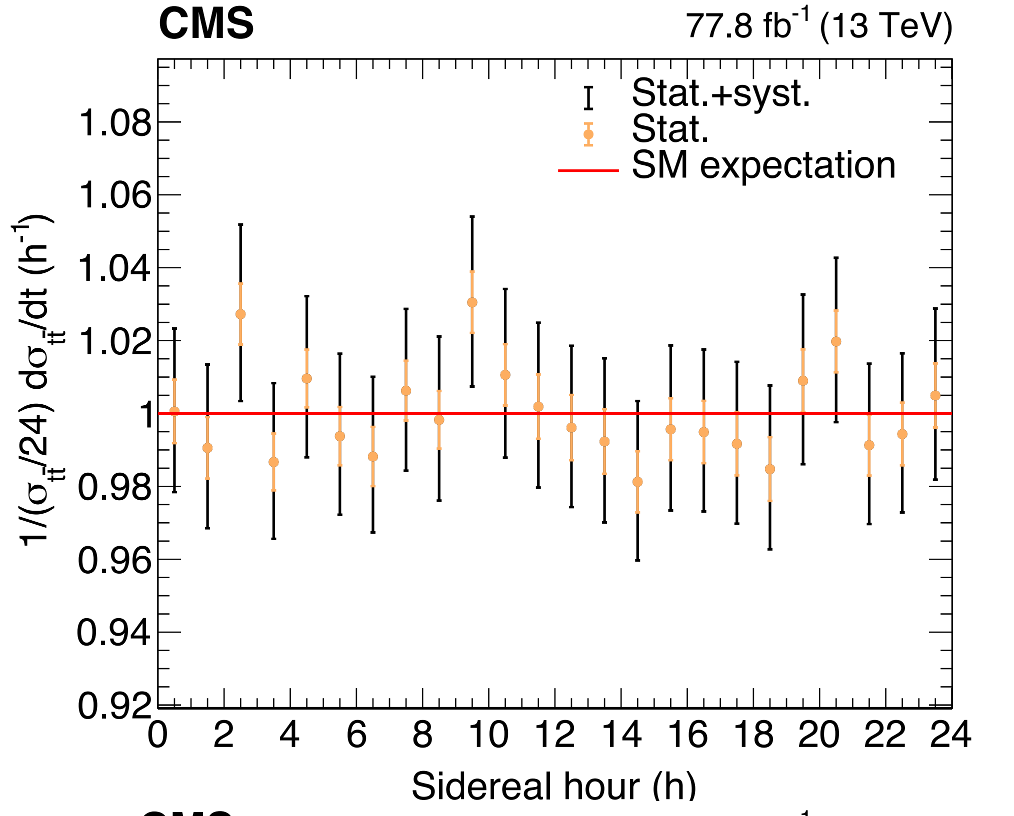
Dedicated MC corrections in bins of sidereal time:

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



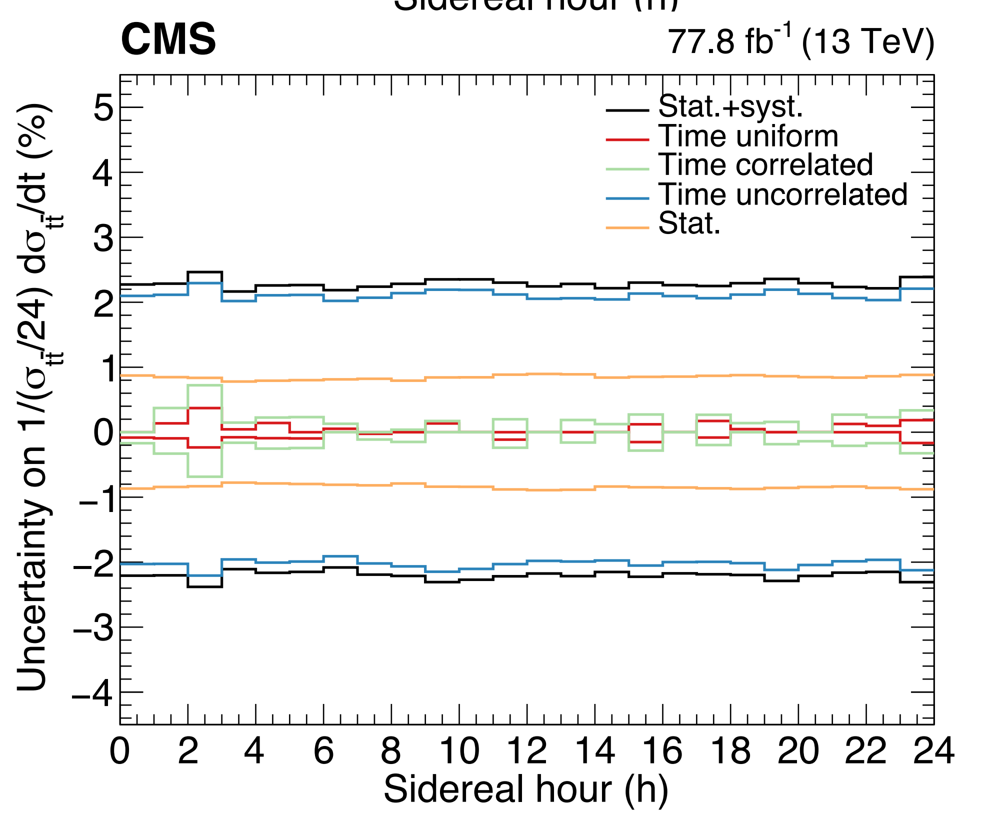
Searches for violation of Lorentz invariance with $t\bar{t}$

PLB 857 (2024) 138979



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:

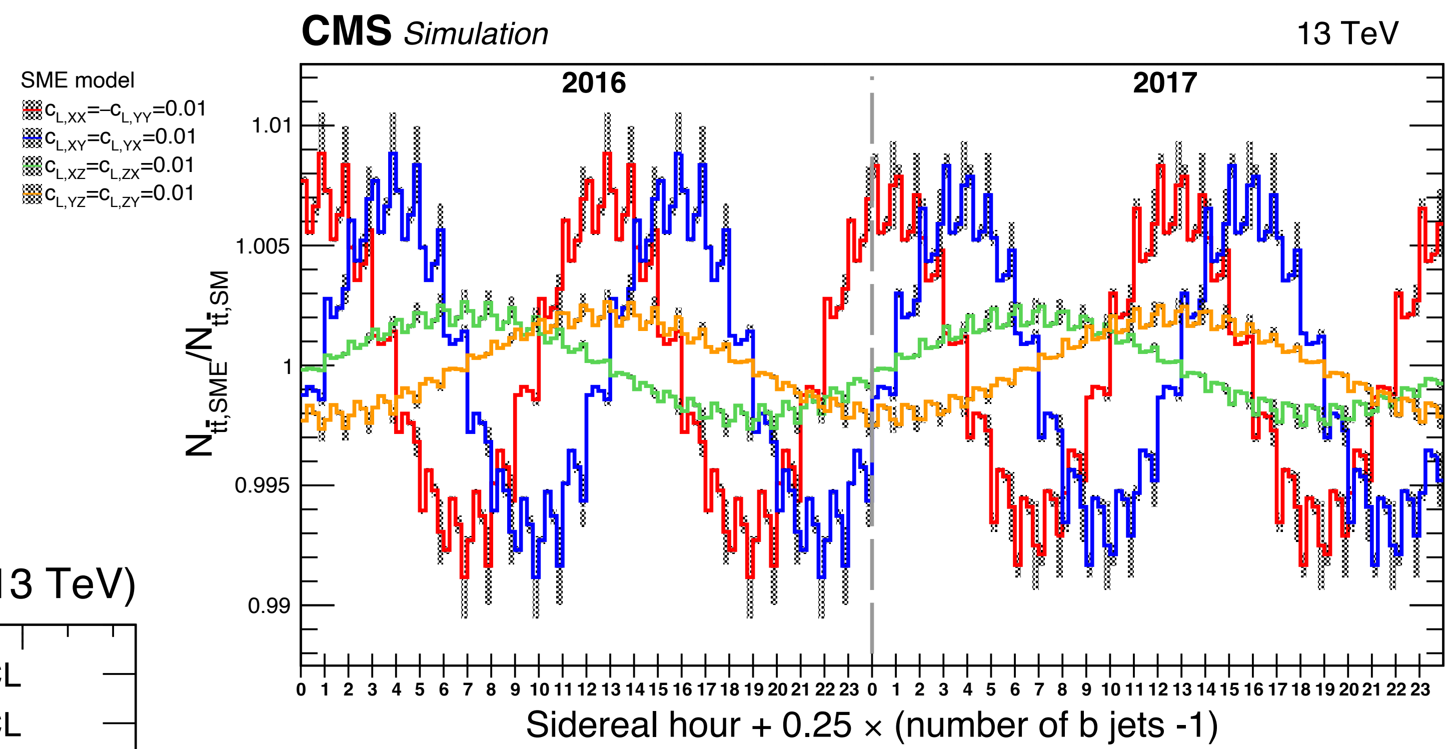
- Uncertainty in pileup, luminosity stability and linearity, trigger: evaluated as a function of sidereal time, treated as **correlated: subdominant**
- Other experimental systematics treated as **uncorrelated,** to let the fit find their impact on each time bin in data: **dominant**
- SM theory, background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

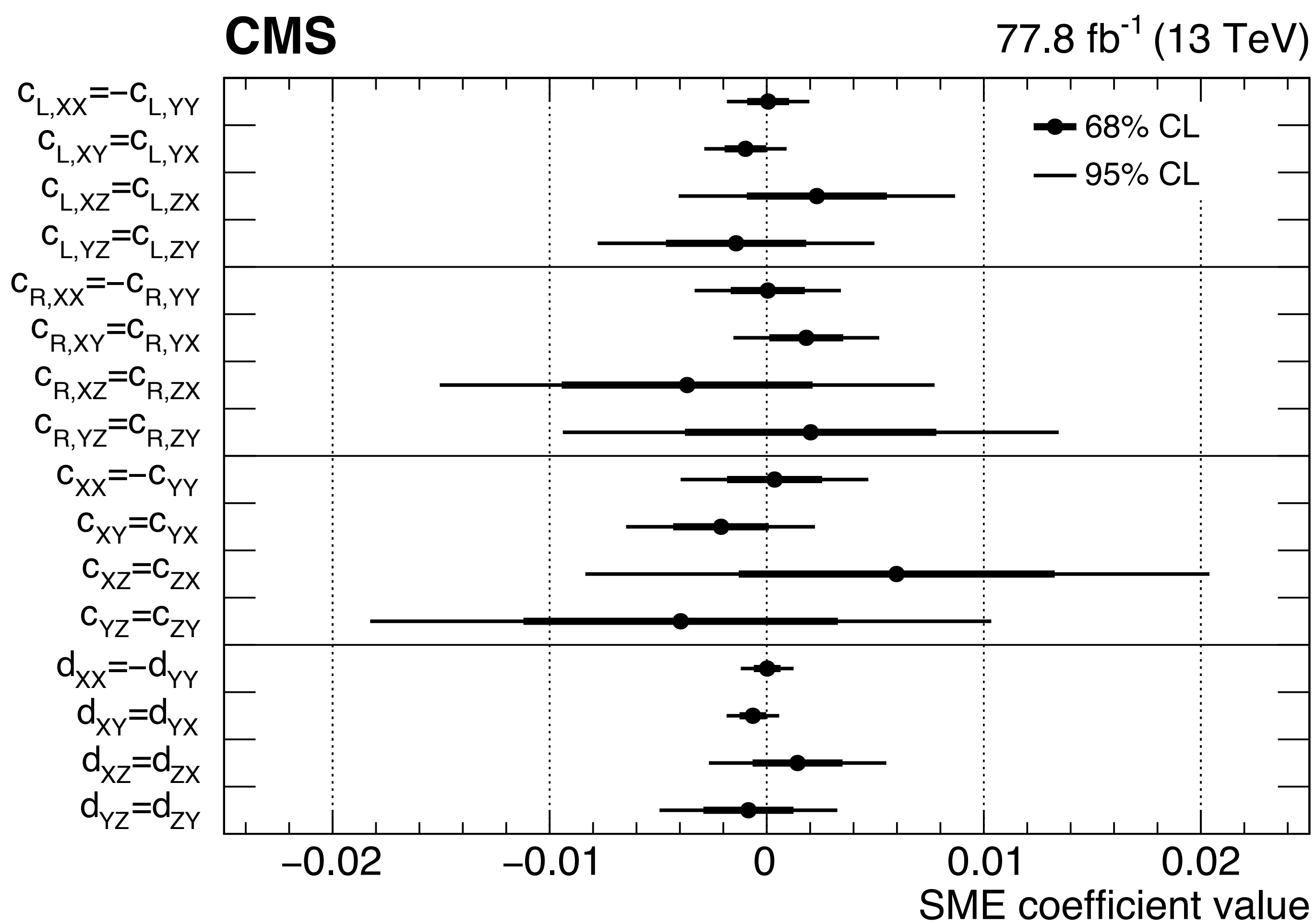
Searches for violation of Lorentz invariance with $t\bar{t}$

PLB 857 (2024) 138979

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



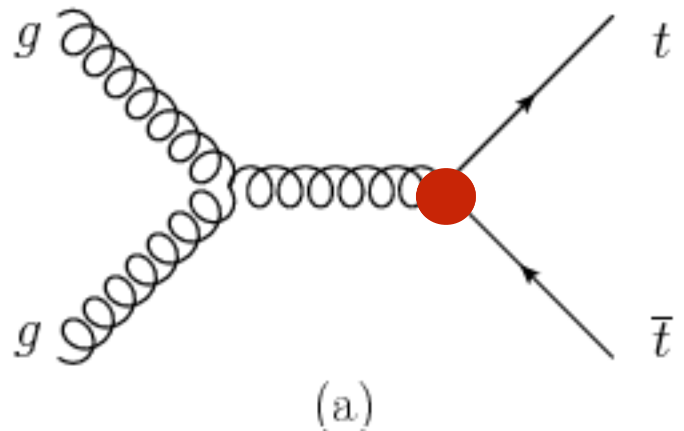


- No significant deviation
- **Improved precision by up to a factor ~100 relative to D0**
- Spacetime isotropy of special relativity tested at the 0.1-0.8% level with top quarks at the LHC

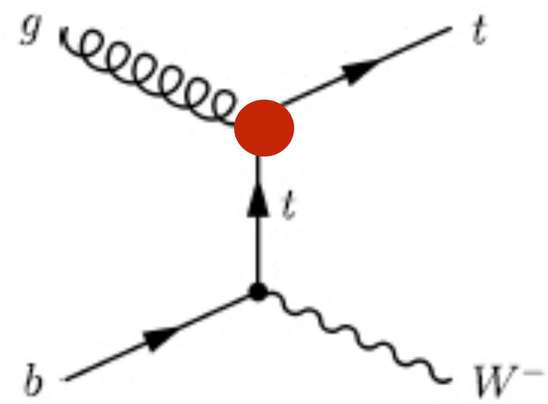
CP violation in top-gluon coupling

PRD 100, 072002 (2019)

ttbar production:



single top tW-channel:



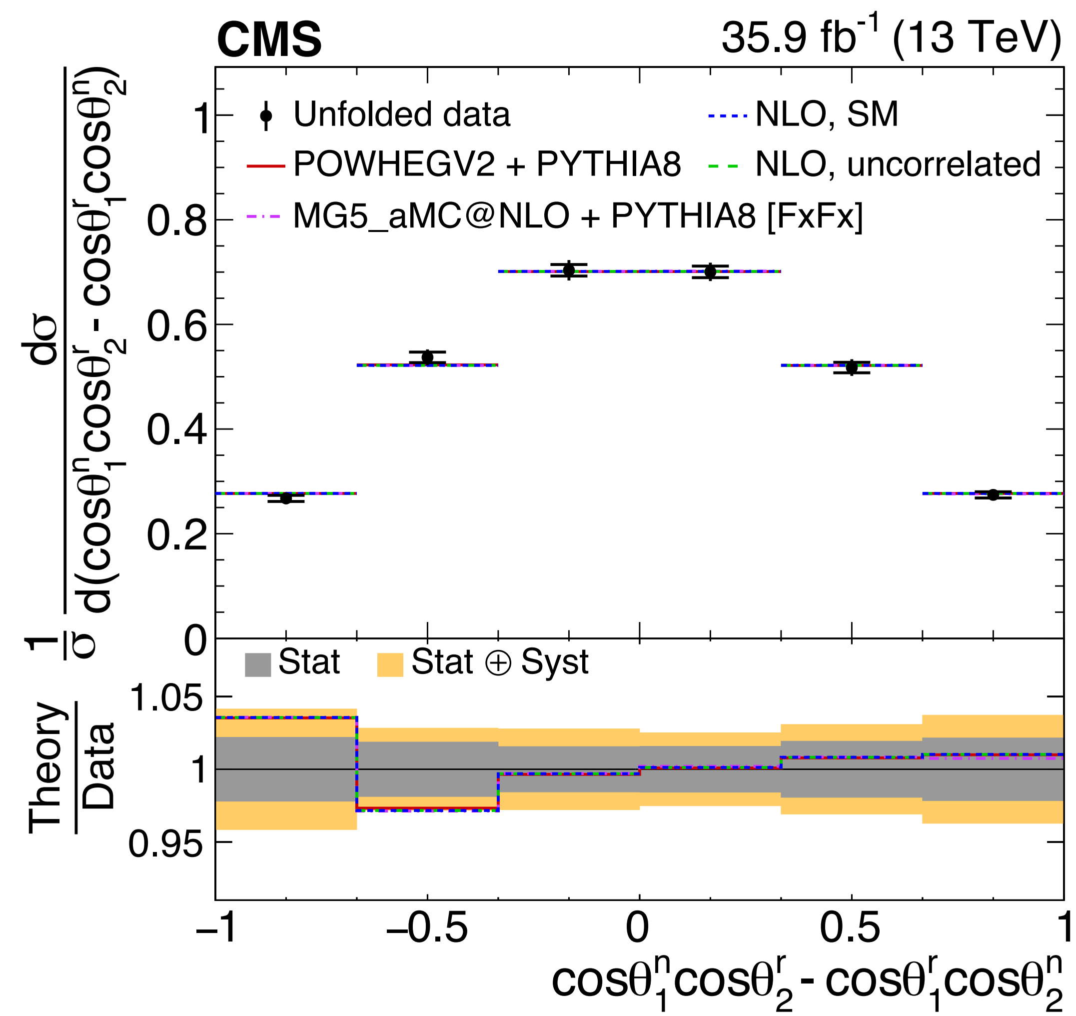
Imaginary part: top **chromo electric** dipole moment, CP violating

$$\frac{C_{uG}}{\Lambda^2}(\bar{q}\sigma^{\mu\nu}T^A u)\tilde{\varphi}G^A_{\mu\nu}$$

Method:

- Employ ttbar dilepton dataset
- Measure angular distributions sensitive to top quark polarisation and CP-odd spin correlation observables
- Extract top-gluon coupling from a simultaneous fit of several distributions

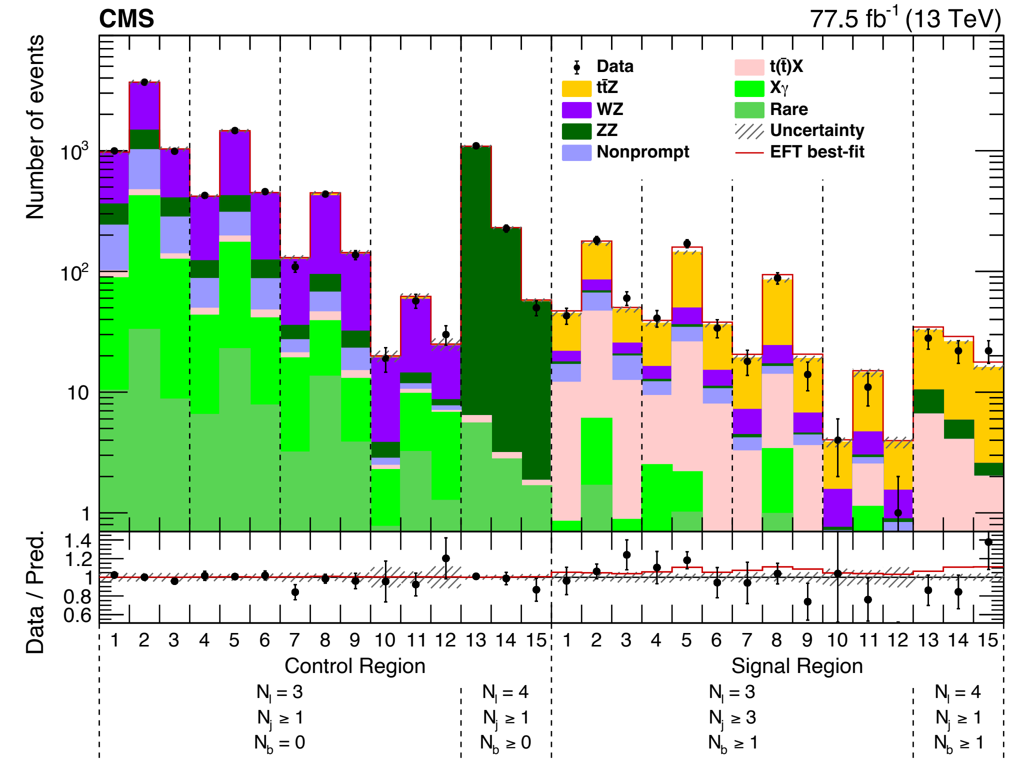
constraint at 95% CL of $-0.33 < C^I_{tG}/\Lambda^2 < 0.20\,\mathrm{TeV}^{-2}$



- CP-odd triple product asymmetry (JHEP 06 (2023) 081, JHEP 07 (2023) 023): similar sensitivity to the top quark chromoelectric moment

CP violation in top-Z/γ coupling

JHEP 03 (2020) 056, JHEP 12 (2021) 180, JHEP 05 (2022) 091



Measurement of CP-violating Im(ctZ) in ttZ (3l/4l) and ttγ (dilepton, lepton+jet)

ttZ: fit of Z boson pT x cosθ* distribution

ttγ: fit of the photon pT distribution

Before EW symmetry breaking:

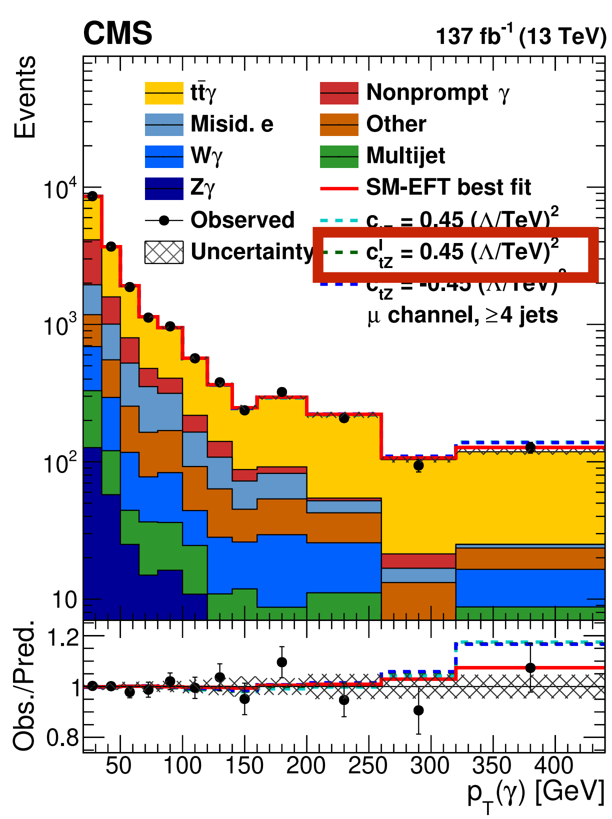
$$O_{tB} = \frac{c_{tB}}{\Lambda^2}(\bar{q}\sigma^{\mu\nu}t)\widetilde{\phi}B_{\mu\nu}$$

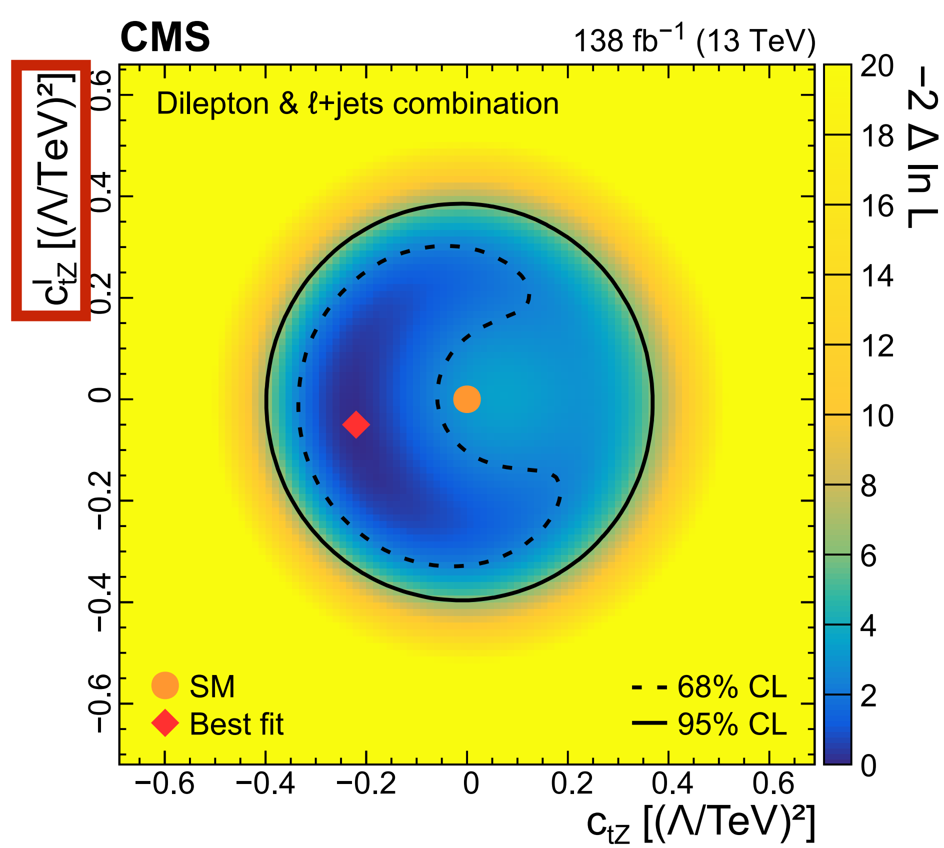
$$O_{tW} = \frac{c_{tW}}{\Lambda^2}(\bar{q}\sigma^{\mu\nu}\tau^I t)\widetilde{\phi}W^I_{\mu\nu}$$

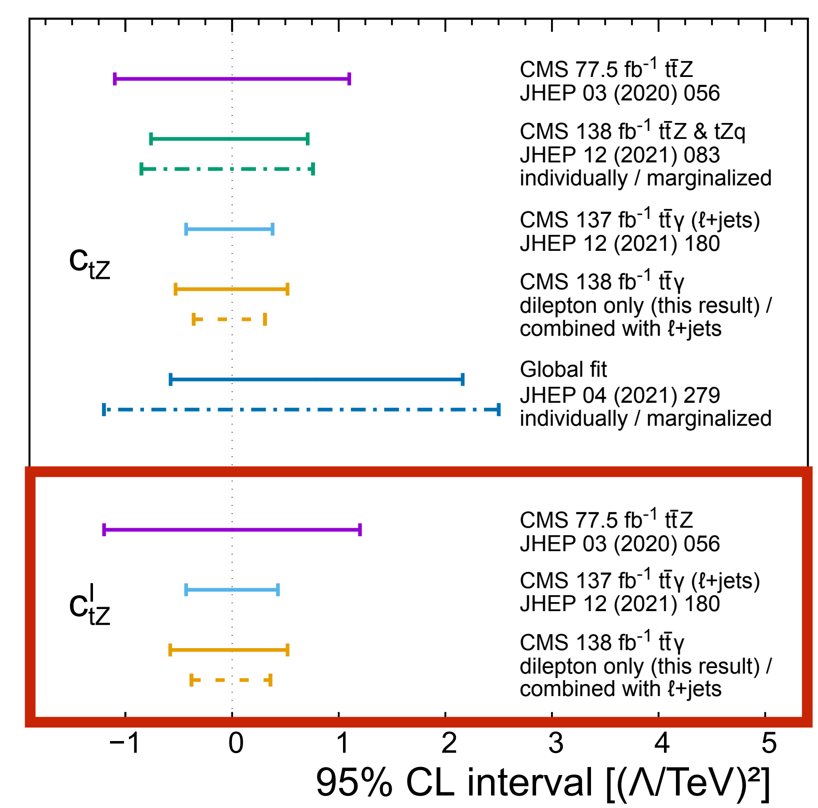
Im(ctZ) measured with photons assuming (ctW, ctZ) basis

$$c_{t\gamma} = cos\theta_W c_{tB} + sin\theta_W c_{tW}$$

$$c_{tZ} = -sin\theta_W c_{tB} + cos\theta_W c_{tW}$$

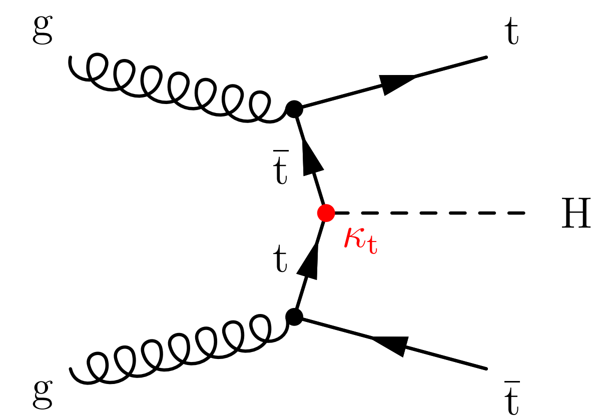






CP violation in top-Higgs coupling (γγ)

PRL 125, 061801 (2020)



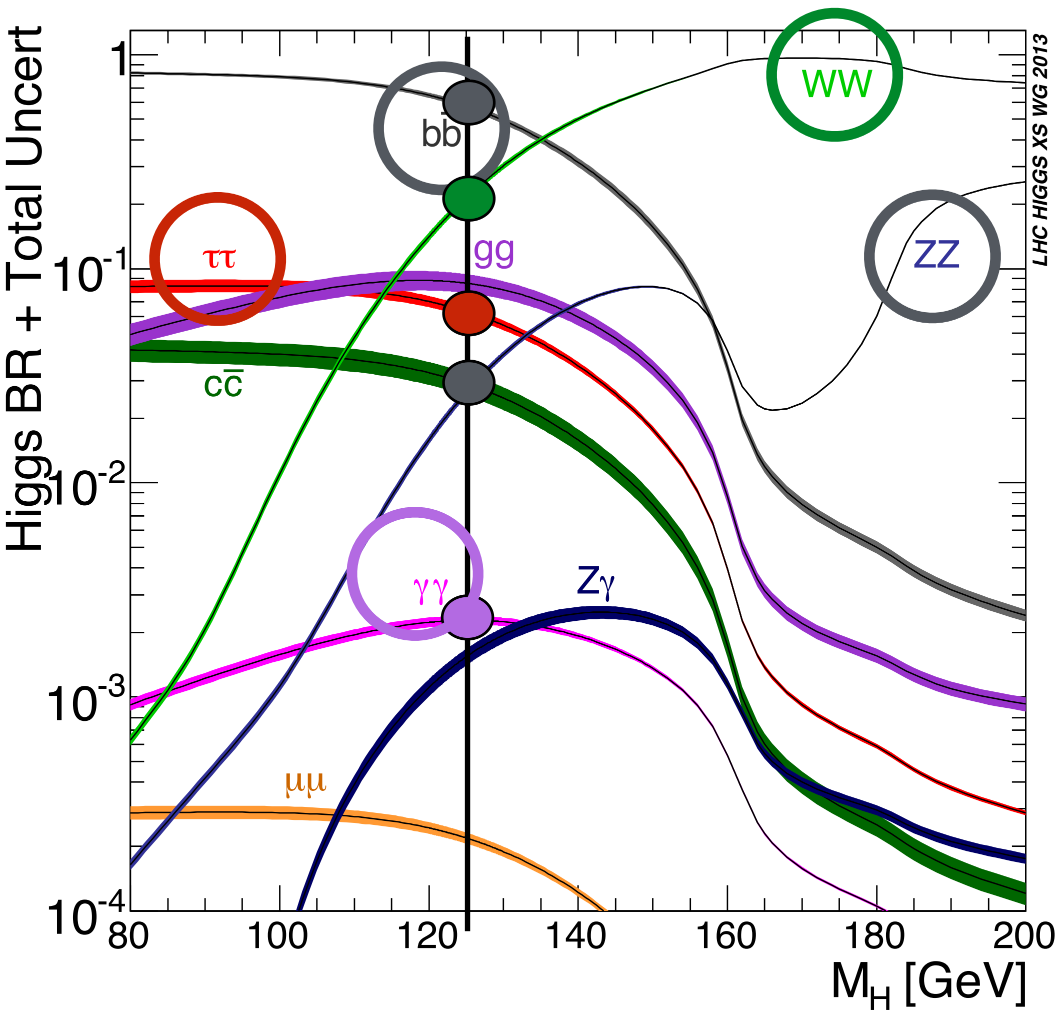
Electroweak baryogegesis with **CP-violation in top Yukawa** coupling can reproduce **observed baryon density** in the Universe (see for instance arXiv:1512.08922)

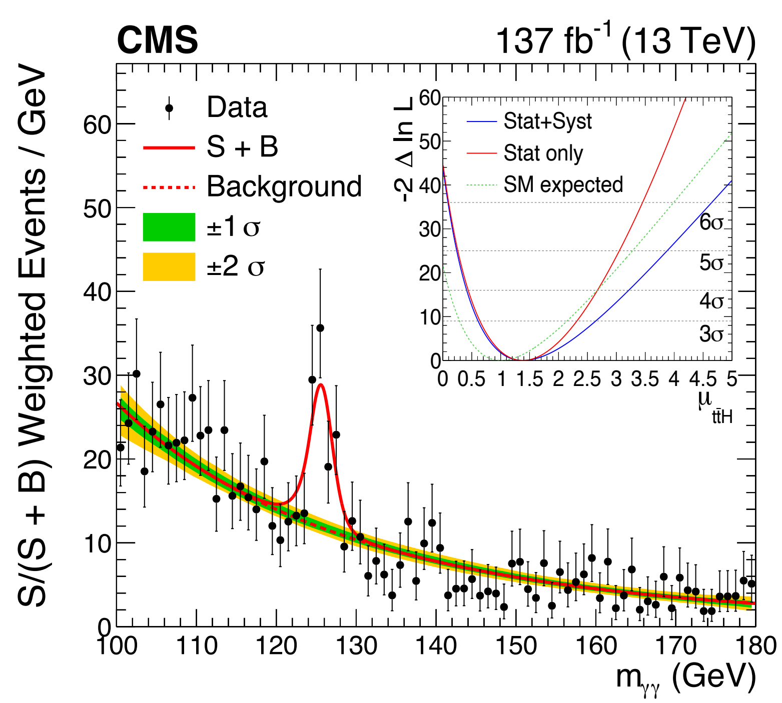
$$\mathcal{L}(Hf\bar{f}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + \mathrm{i}\,\tilde{\kappa}_f\gamma_5\right)\psi_f\,H$$

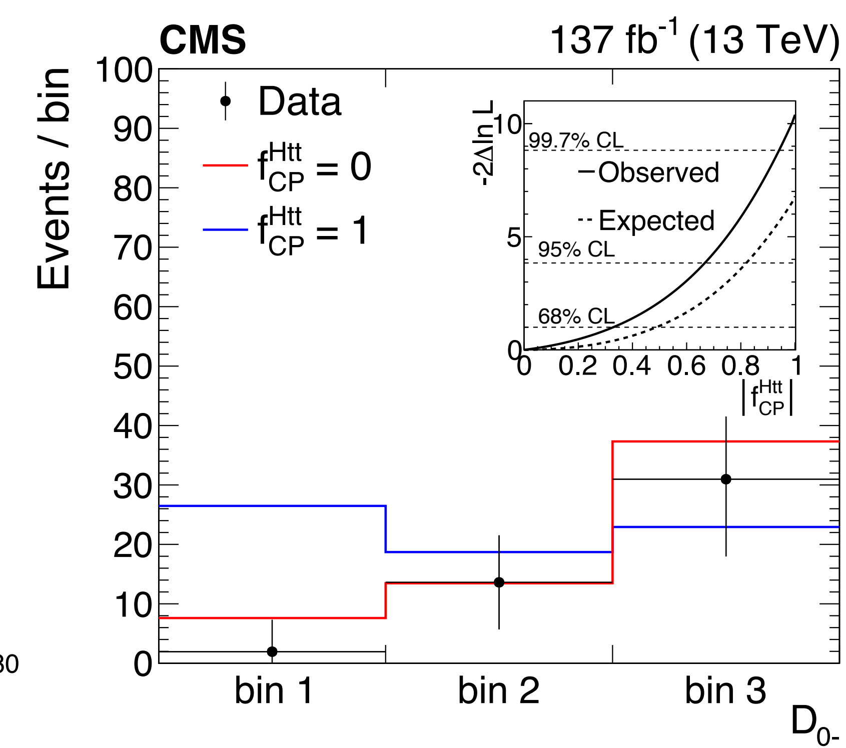
ttH: Direct (tree level) **probe of top-Higgs coupling**

ttH,H→γγ: BDT in several ttH and tH categories, and a dedicated discriminant for CP violation

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$

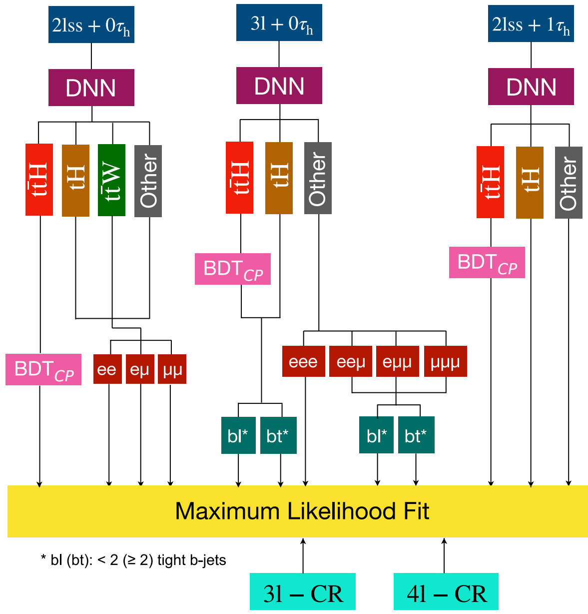






CP violation in top-Higgs coupling (WW/ττ)

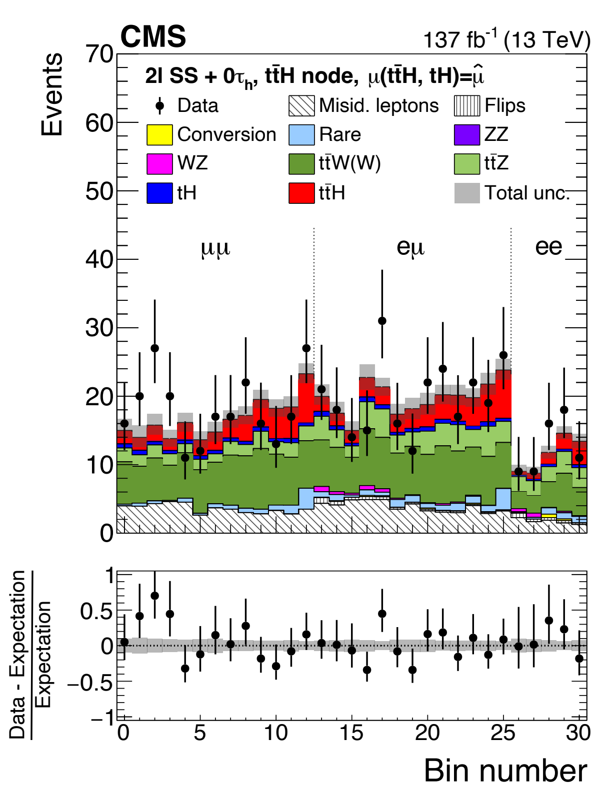
JHEP 07 (2023) 092



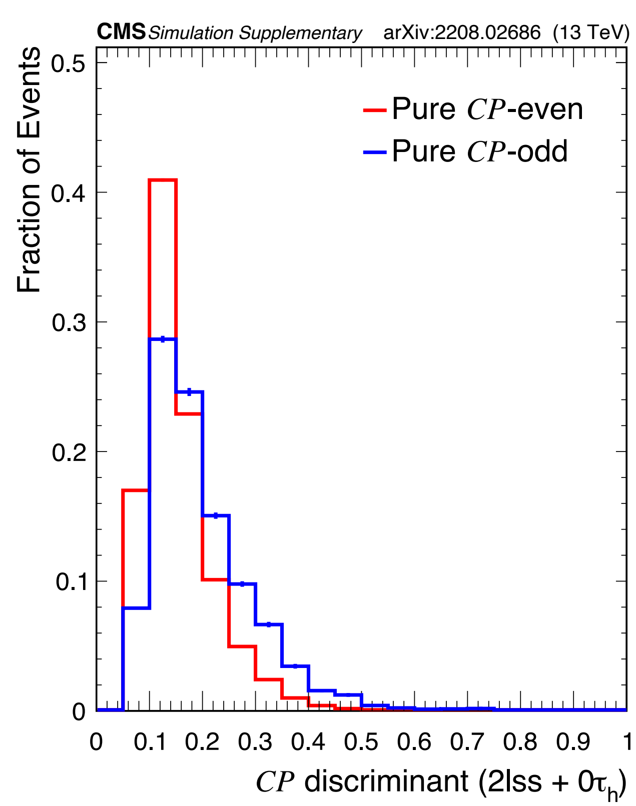
ttH,H→WW/ττ (multilepton channel):

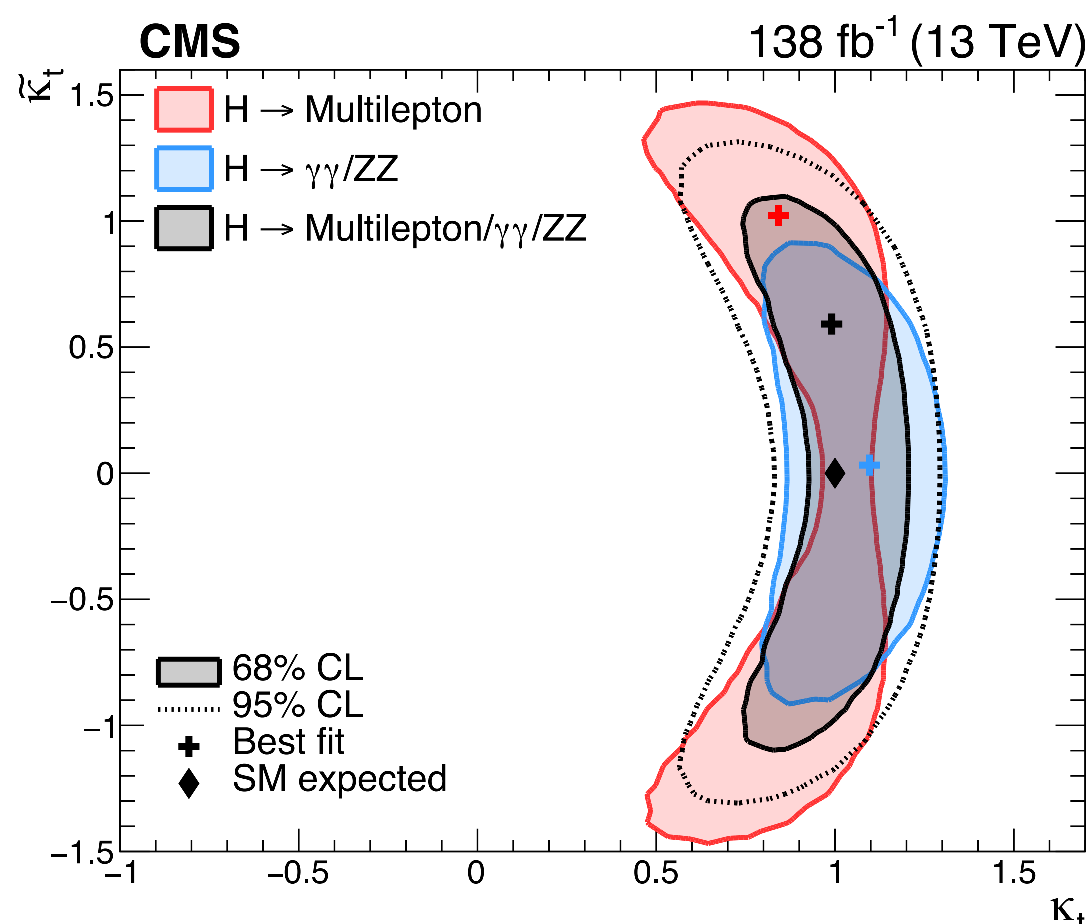
- Best expected sensitivity, wrt other channels
- 2 leptons of same sign (2ℓss), 3ℓ, 2ℓss+1τ_h (hadronic tau)
- Jets faking leptons, charge mis-assignment: from data
- Signal extraction with **DNN against SM background**, and **BDT targeting CP-violation**

DNN for ttH extraction



BDT for CP-violation





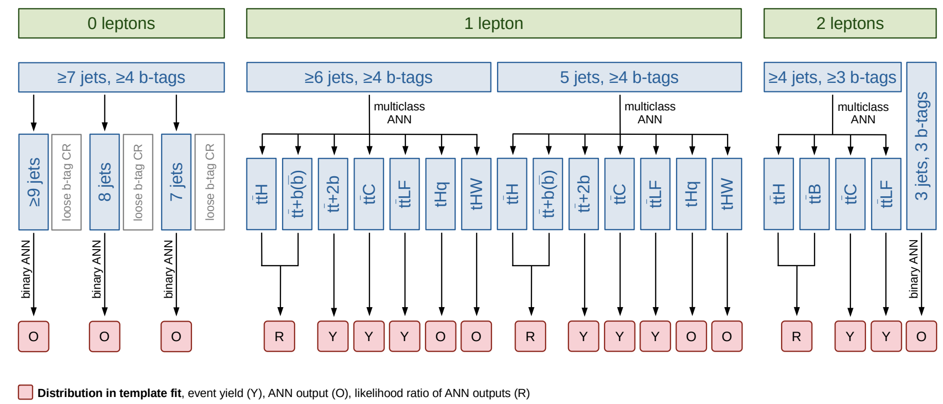
CP violation in top-Higgs coupling (bb)

arXiv:2407.10896 submitted to JHEP

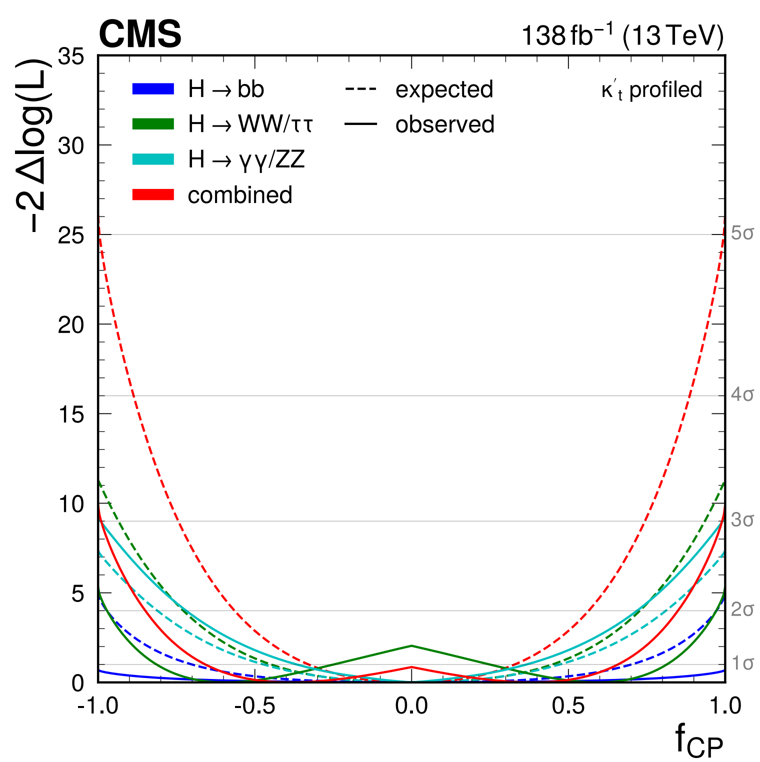
New: ttH,H→bb paper with combination

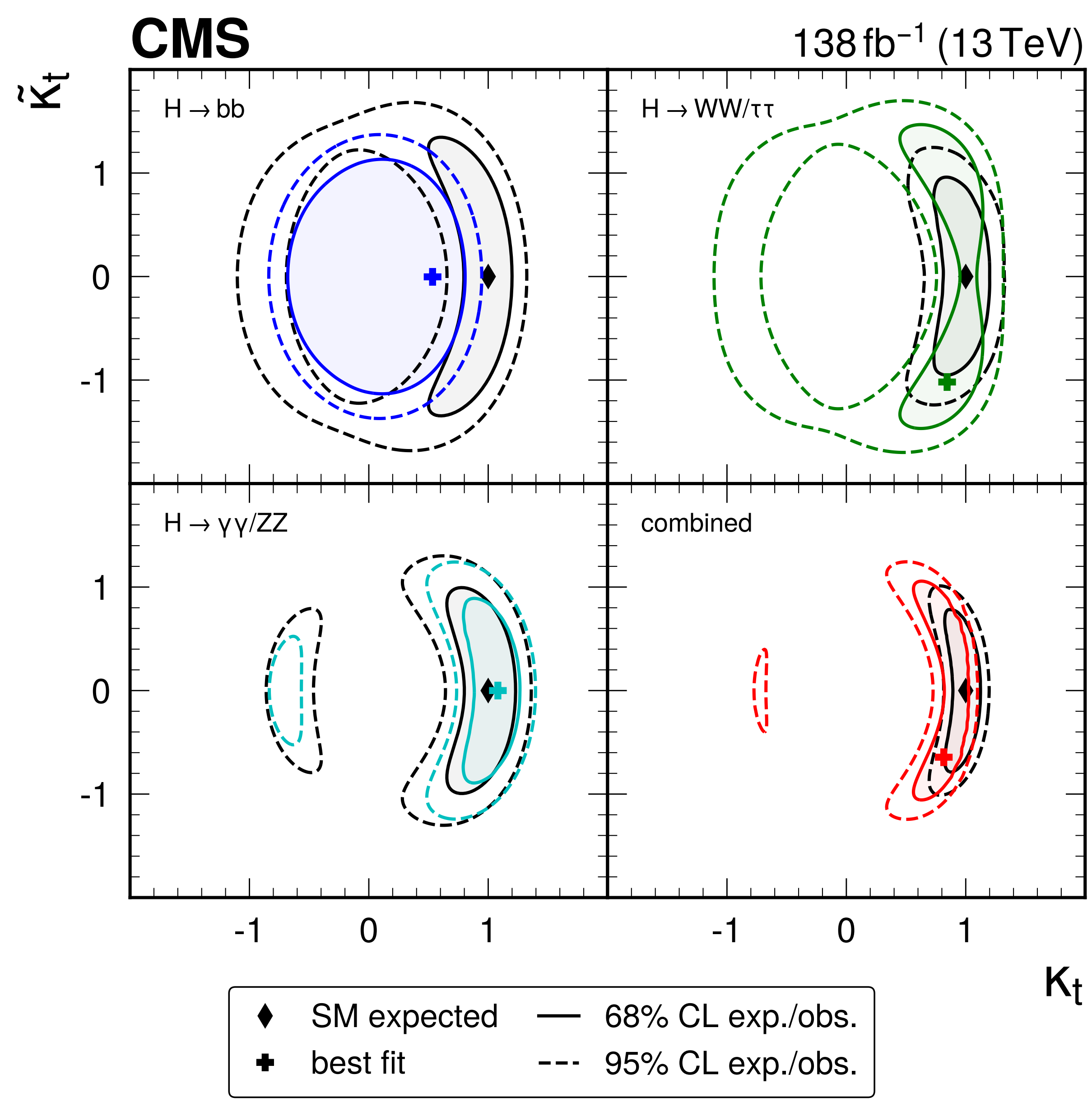
- Measuring signal strength below SM expectation:

$$\mu_{t\bar{t}H} = 0.33 \pm 0.26$$



- **ttH,H→bb** channel improves slightly the expected sensitivity to CP-violation
- However the measured low signal strength weakens the observed sensitivity to CP-violation





Conclusions and perspectives

Search for CPT asymmetry with top quarks

- Most precise top/antitop mass difference, precision 0.21 GeV, at CMS with 8 TeV
- Would be interesting to perform again at 13 TeV with ttbar

Search for violation of Lorentz invariance with top quarks

- First search for violation of Lorentz invariance with ttbar at the LHC, with the SME
- Measured differential normalised cross section with sidereal time
- Spacetime anisotropy: special relativity tested at the 0.1-0.8% level with top quarks

Search for CP violation in top quark-vector boson coupling:

- **top-gluon:** from spin correlation or CP-odd triple products: precision of 0.2-0.3 TeV^{-2}
    - N.B.: Spin correlation used for top quark quantum entanglement (arXiv:2409.11067)
- **top-Z/γ**: large improvements in sensitivity arise from ttγ final state, precision ~0.4 TeV^{-2}

Search for CP violation in top quark-Higgs boson coupling:

- Combination of ttH final states: H→γγ,ZZ,WW/ττ,bb
- Exclude an observed (expected) CP fraction of >0.85 (0.6) at 95% CL
- Expected sensitivity improved with H→bb, however measured signal strength is low, thus the observed sensitivity is degraded

Back-up slides

Top quark sector in the SME

Berger, Kostelecký, Liu, Phys. Rev. D 93, 036005 (2016)

LIV lagrangian related to top quark:

Third generation left-handed quark doublet

Gauge covariant derivative

$$\mathcal{L}^{\mathrm{CPT}+} \supset \tfrac{1}{2} i (c_Q)_{\mu\nu AB} \overline{Q}_A \gamma^\mu \overleftrightarrow{D}^\nu Q_B + \tfrac{1}{2} i (c_U)_{\mu\nu AB} \overline{U}_A \gamma^\mu \overleftrightarrow{D}^\nu U_B - \tfrac{1}{2} (H_U)_{\mu\nu AB} \overline{Q}_A \phi^c \sigma^{\mu\nu} U_B + \mathrm{h.c.},$$

Right handed charge 2/3 top singlet

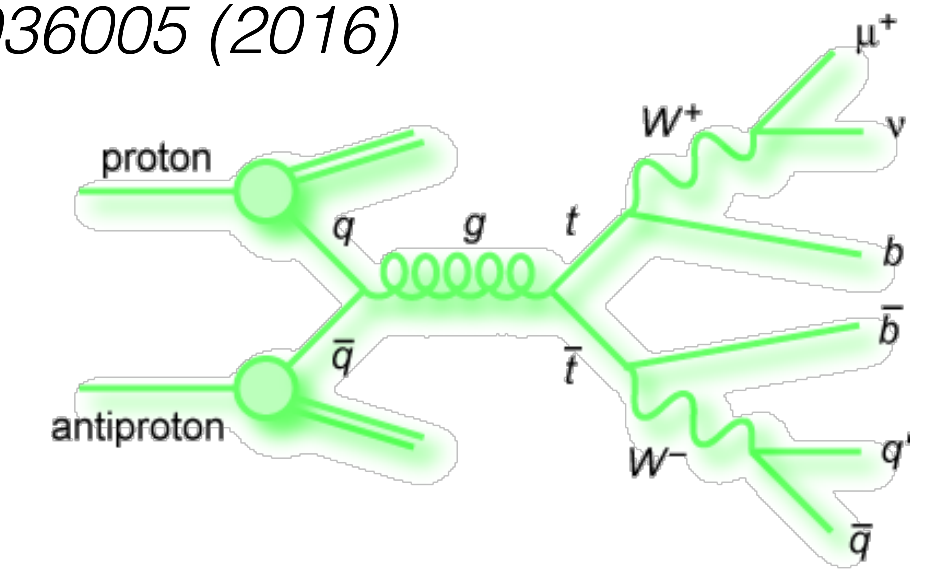
(Focus here on CPT-even coefficients)

- SME coefficients $\mathbf{c_{\mu\nu}}$ are **violating particle Lorentz invariance**
- $c_{\mu\nu}$ trace is Lorentz-invariant, and its antisymmetric part can be absorbed elsewhere in the Lagrangian: consider $\mathbf{c_{\mu\nu}}$ **as symmetric and traceless**

Define: $$c_{\mu\nu} = \tfrac{1}{2}[(c_L)_{\mu\nu} + (c_R)_{\mu\nu}], \quad d_{\mu\nu} = \tfrac{1}{2}[(c_L)_{\mu\nu} - (c_R)_{\mu\nu}]$$

Top pair production in the Lorentz-violating SME

Berger, Kostelecký, Liu, Phys. Rev. D 93, 036005 (2016)



Assume **narrow-width** approximation for top quarks:

SM LIV

$$|\mathcal{M}|^2_{\mathrm{SME}} = PF\bar{F} + (\delta P)F\bar{F} + P(\delta F)\bar{F} + PF(\delta\bar{F})$$

SME weight: $$w = \frac{|\mathcal{M}_{SME}|^2}{|\mathcal{M}_{SM}|^2}$$

$$w(t) = 1 + f(t)$$

LIV change in top quark propagator

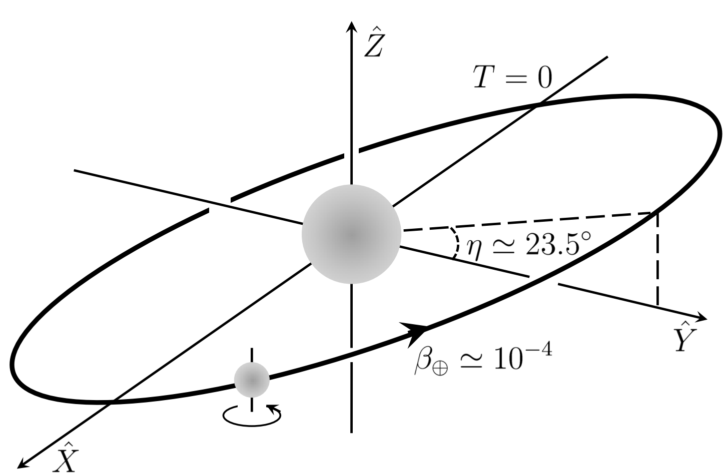
LIV change in top production via top-gluon vertex

$$f(t) = ((c_L)_{\mu\nu} + (c_R)_{\mu\nu}) R^\mu_\alpha(t) R^\nu_\beta(t) \left(\frac{\delta_p P}{P} + \frac{\delta_v P}{P}\right)^{\alpha\beta}$$
$$+ (c_L)_{\mu\nu} R^\mu_\alpha(t) R^\nu_\beta(t) \left(\frac{\delta F}{F} + \frac{\delta\bar{F}}{\bar{F}}\right)^{\alpha\beta}$$

SME coefficients

Rotation matrices to relate sun-centered frame and laboratory frame

LIV change in top and antitop decay width



Induces a **modulation of the top-antitop cross section with sidereal time**

Lorentz-violation with top quarks: previous bounds

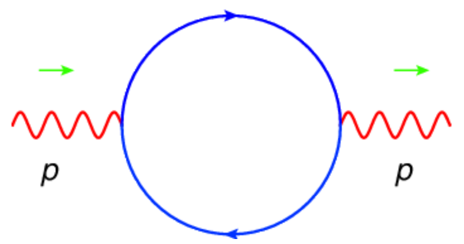
Rev.Mod.Phys. 83: 11 (2011)

- Lorentz-violation **tested in many sectors**,
- Before CMS-PAS-TOP-22-007: **only one actual measurement** with top quarks at collider: **precision O(10%)**

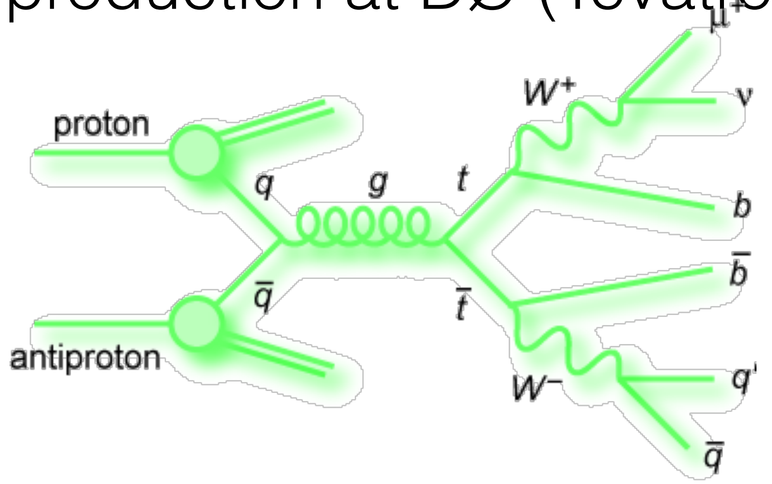
Table D36. Quark sector, $d \geq 4$

Combination	Result	System	Ref.
$\lvert c_t \rvert$	$< 1.6 \times 10^{-7}$	Astrophysics	[50]*
$(c_Q)_{XX33}$	$-0.12 \pm 0.11 \pm 0.02$	$t\bar{t}$ production	[256]
$(c_Q)_{YY33}$	$0.12 \pm 0.11 \pm 0.02$	"	[256]
$(c_Q)_{XY33}$	$-0.04 \pm 0.11 \pm 0.01$	"	[256]
$(c_Q)_{XZ33}$	$0.15 \pm 0.08 \pm 0.02$	"	[256]
$(c_Q)_{YZ33}$	$-0.03 \pm 0.08 \pm 0.01$	"	[256]
$(c_U)_{XX33}$	$0.1 \pm 0.09 \pm 0.02$	"	[256]
$(c_U)_{YY33}$	$-0.1 \pm 0.09 \pm 0.02$	"	[256]
$(c_U)_{XY33}$	$0.04 \pm 0.09 \pm 0.01$	"	[256]
$(c_U)_{XZ33}$	$-0.14 \pm 0.07 \pm 0.02$	"	[256]
$(c_U)_{YZ33}$	$0.01 \pm 0.07 \pm < 0.01$	"	[256]
d_{XX}	$-0.11 \pm 0.1 \pm 0.02$	"	[256]
d_{YY}	$0.11 \pm 0.1 \pm 0.02$	"	[256]
d_{XY}	$-0.04 \pm 0.1 \pm 0.01$	"	[256]
d_{XZ}	$0.14 \pm 0.07 \pm 0.02$	"	[256]
d_{YZ}	$-0.02 \pm 0.07 \pm < 0.01$	"	[256]

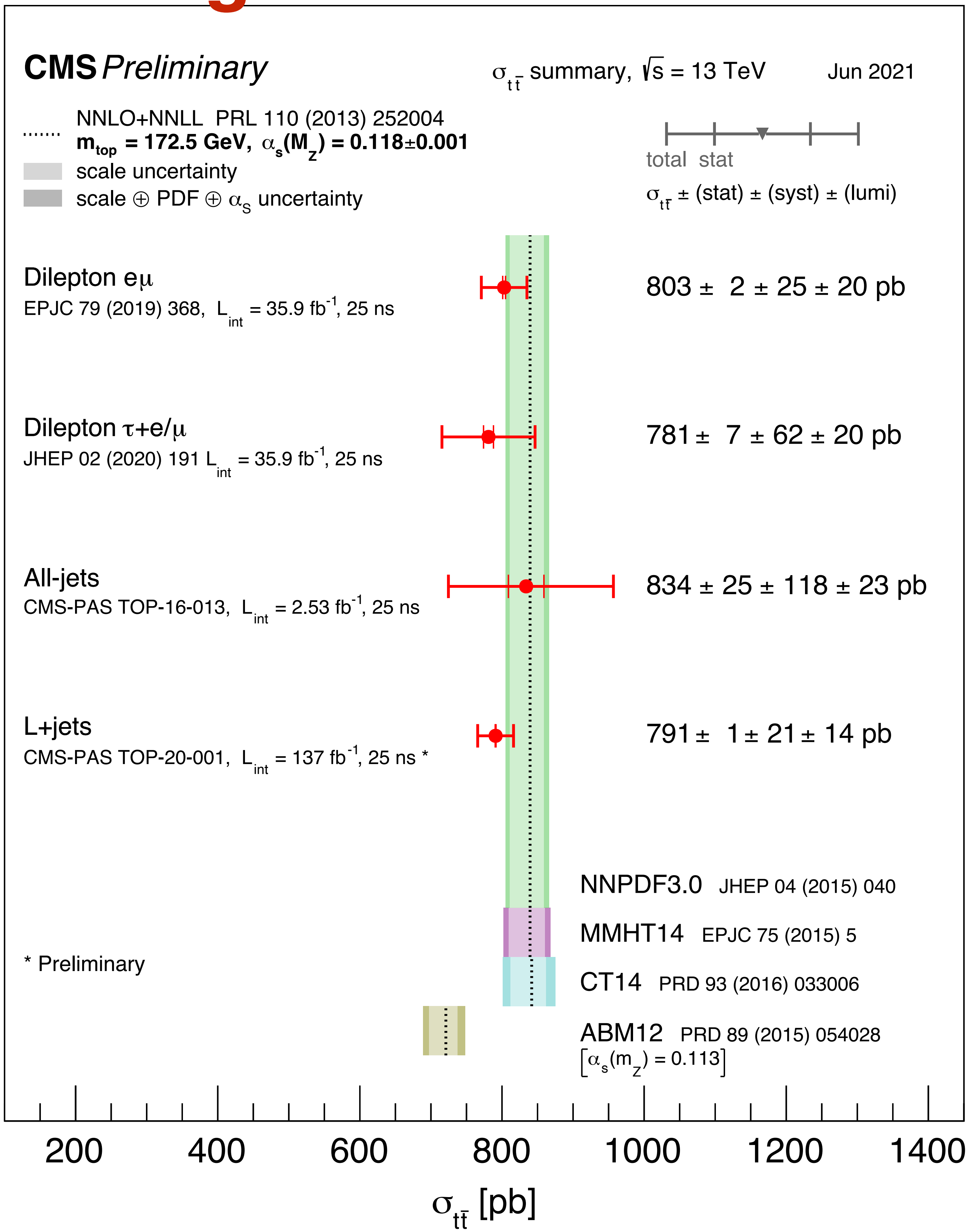
Indirect, isotrope, bound (*Phys. Rev. D 97, 125016(2018)*): from top-quark loop correction to photon propagator, using astrophysics photons



Direct, directional, bounds (*PRL 108:261603, 2012*): measurement of top pair production at DØ (Tevatron)



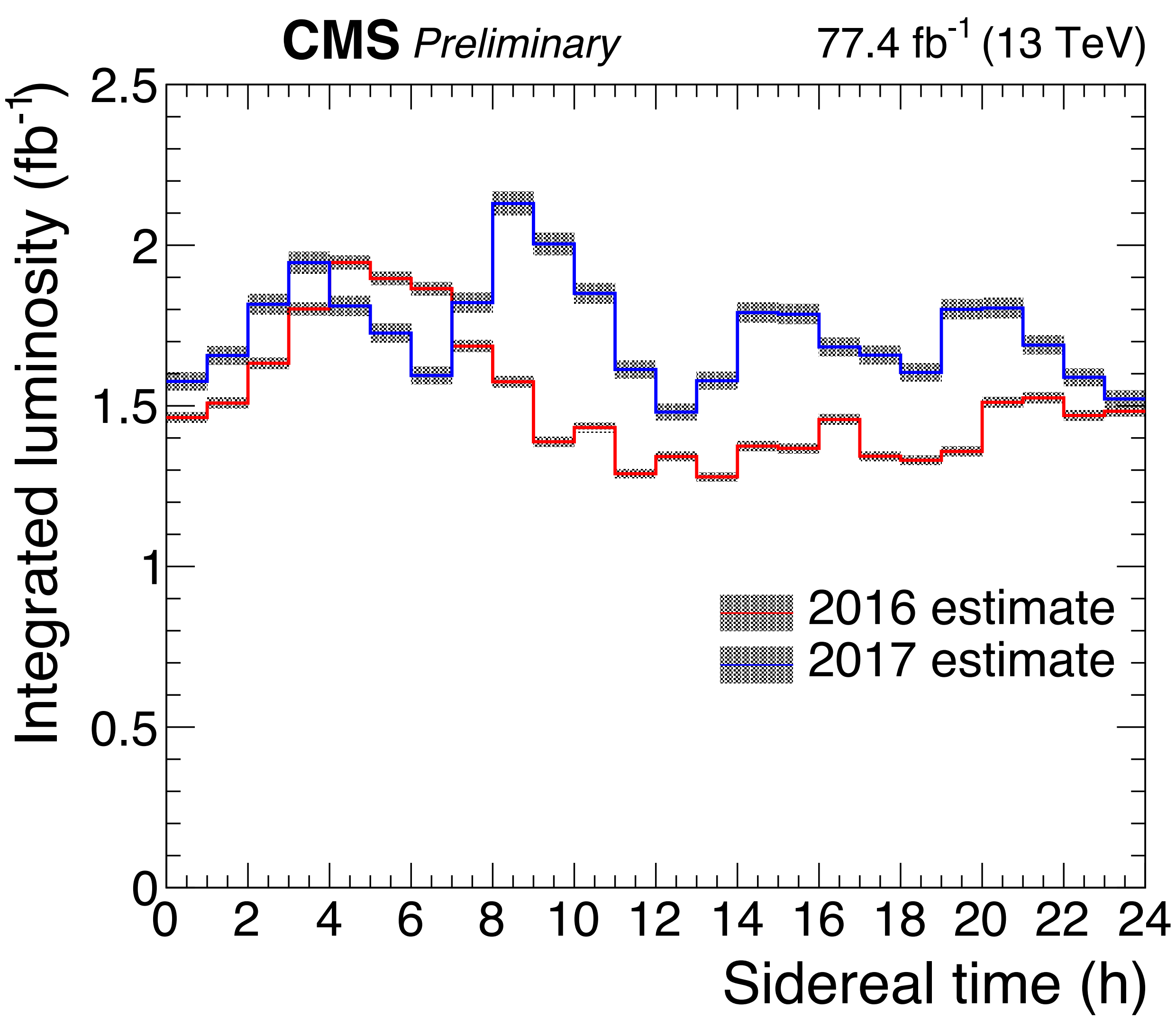
Signal strength in other ttbar analyses

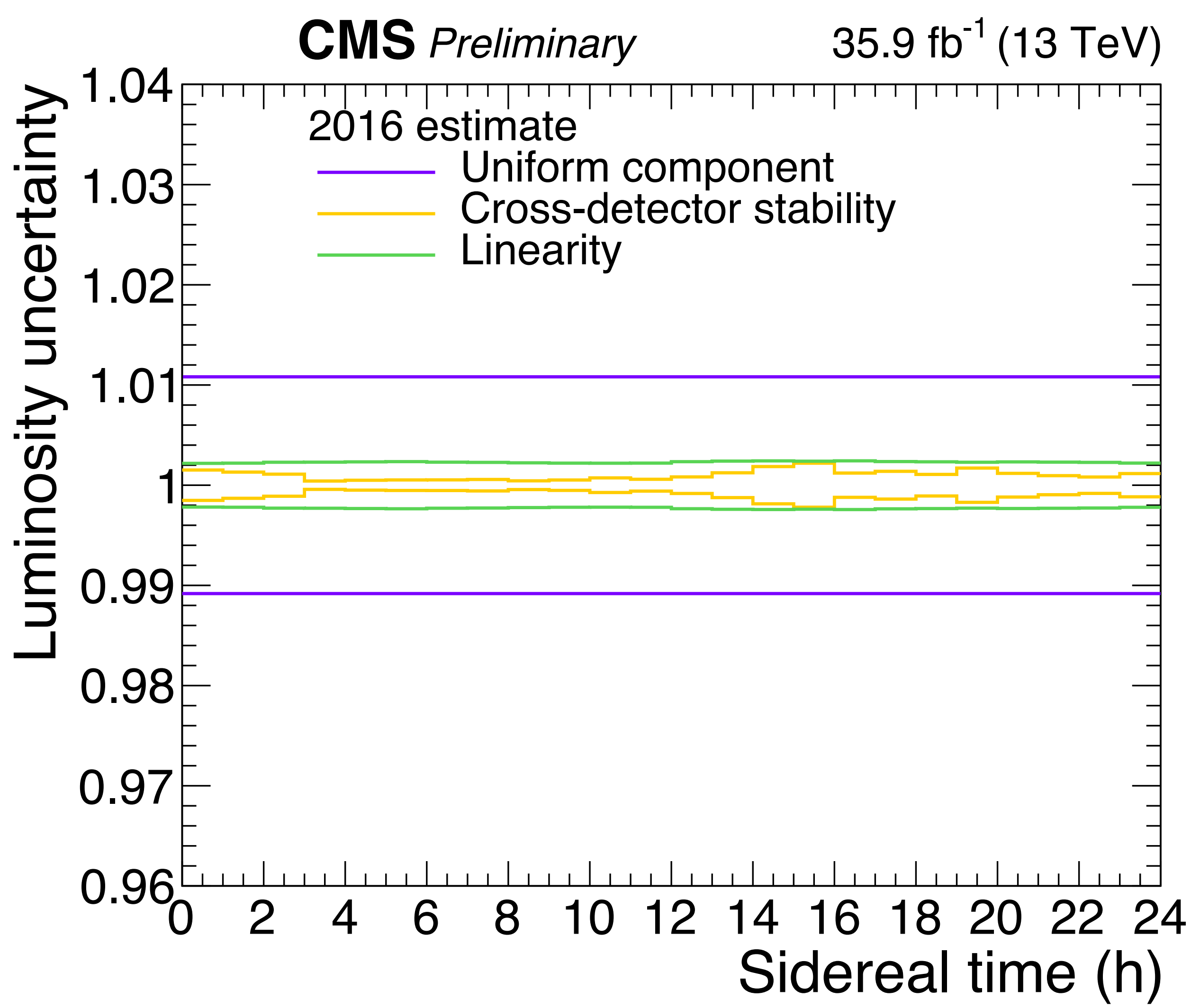


Integrated luminosity with sidereal time

Integrated luminosity:

- **Integrated luminosity can vary** up to 20% per sidereal time bin
- Scale simulation yield for each sidereal time bin
- **Re-estimate luminosity uncertainties** as a function of time: cross-detector stability, luminometer linearity response

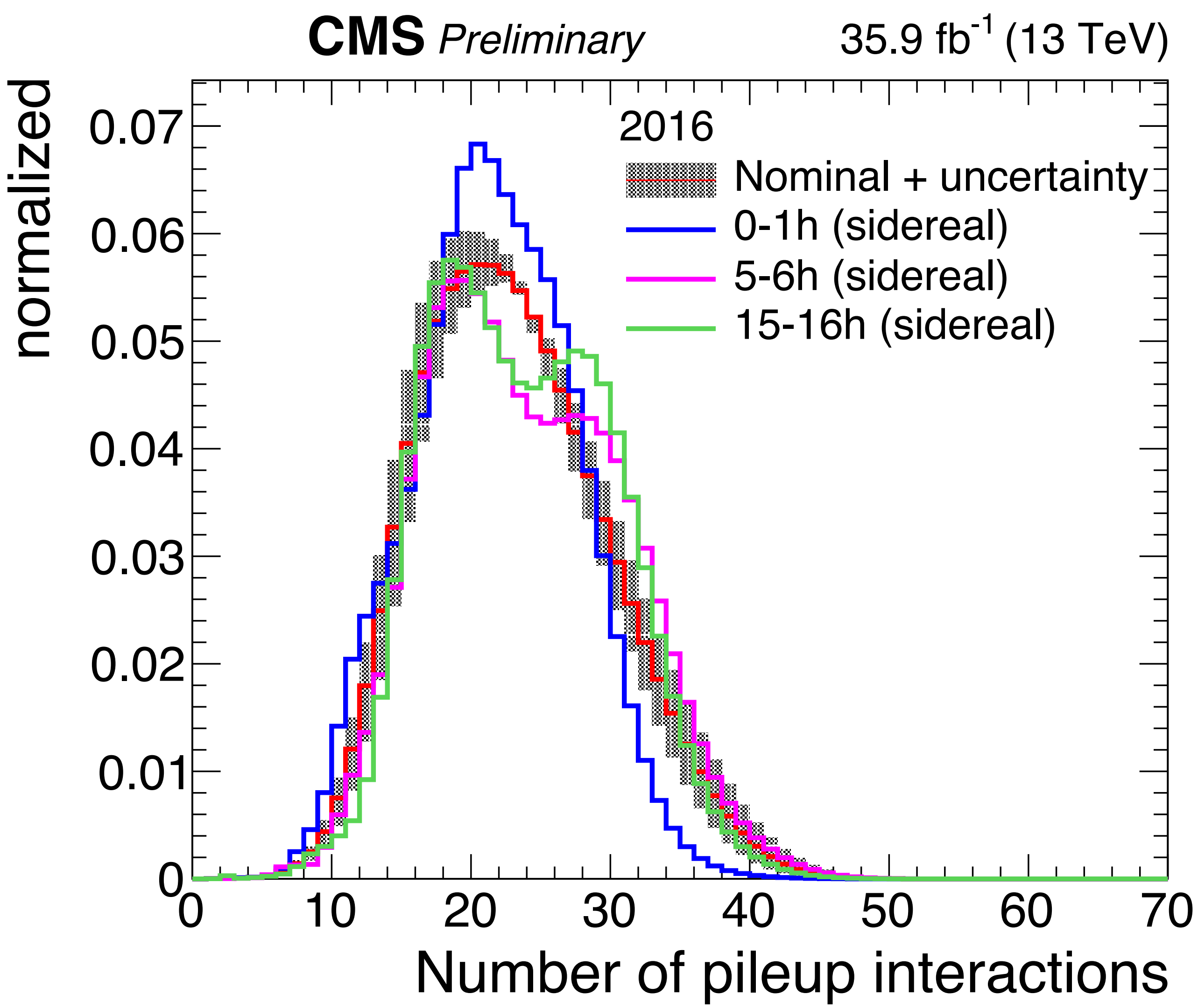


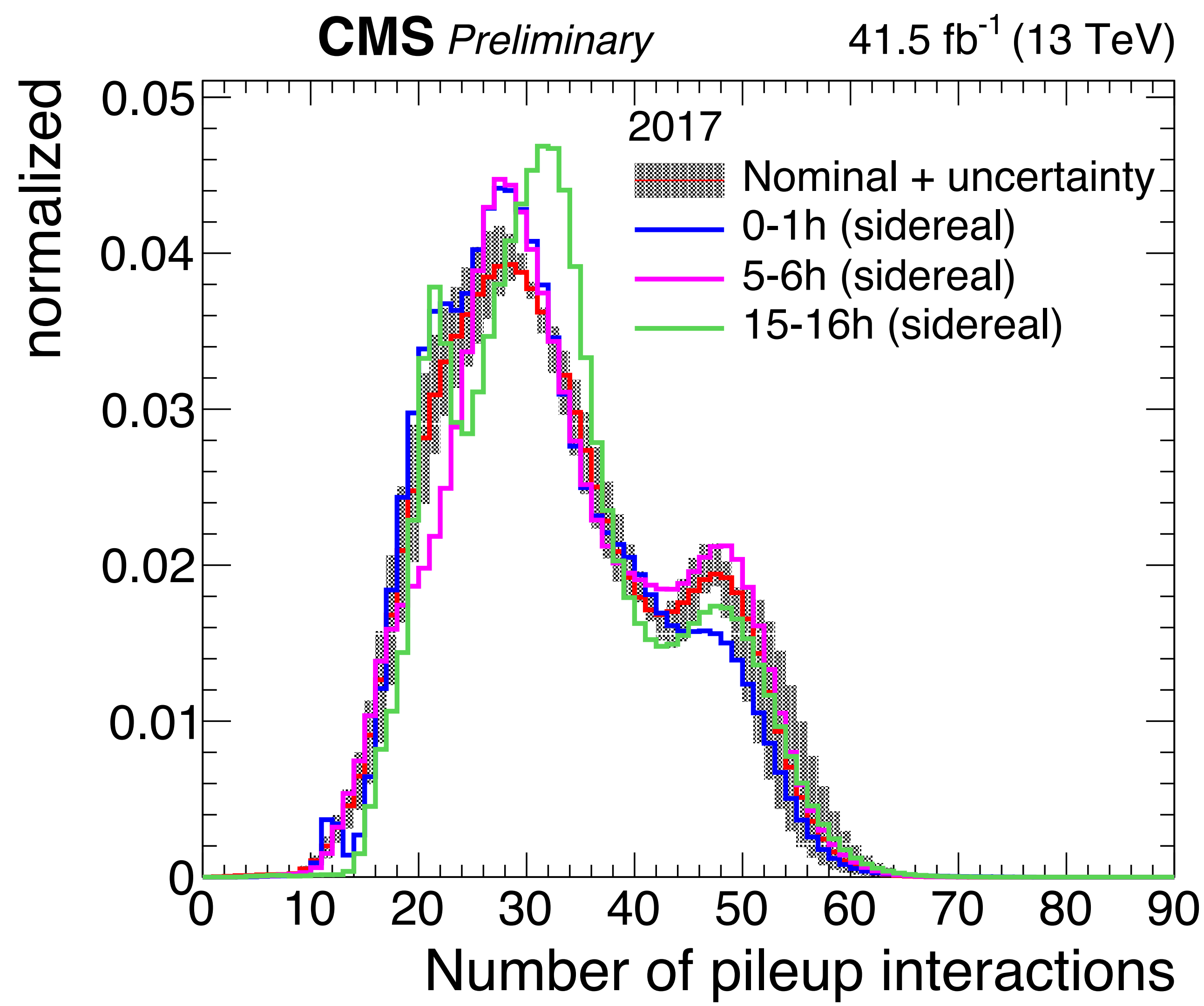


Pileup with sidereal time

Pileup distribution:

- Nominal **pileup profile and associated uncertainty** (from the cross section for minimum bias events) does not cover for the pileup profile in time bins
- **For each sidereal time bin: reweight pileup distribution** and assign corresponding uncertainty

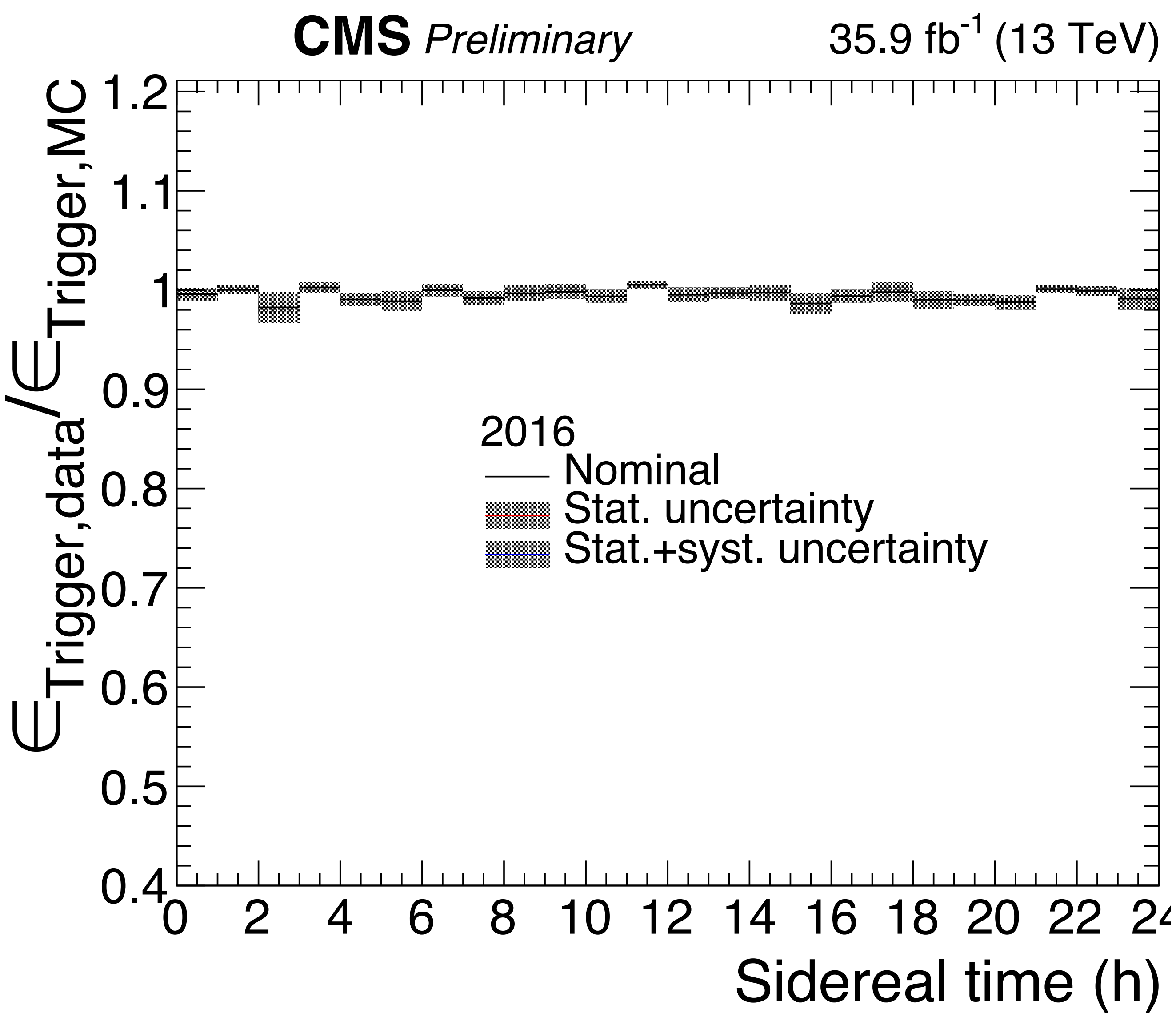


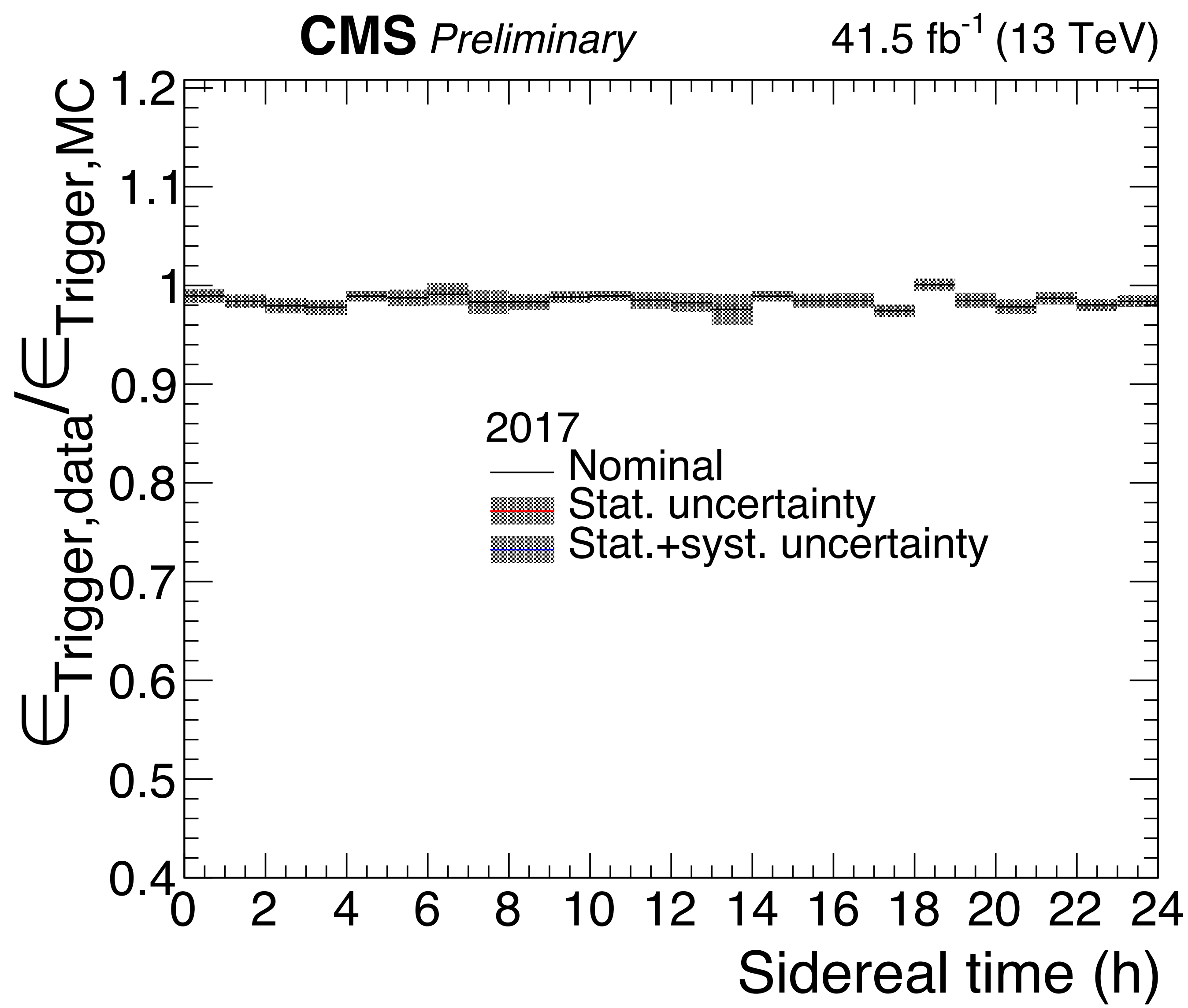


Trigger efficiency with sidereal time

Data/simulation differences in dilepton trigger efficiencies:

- Estimated using p_T^{mis} trigger in events with ≥1 b jet
- **Uncertainties** estimated from partitions of the data: uncertainty arising from the number of jets, and run era dependency





Uncertainties and their correlation

Re-estimated as a function of sidereal time: correlated in sidereal time

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%

Experimental syst. for which dependency in sidereal time is unknown: uncorrelated in sidereal time

Systematic uncertainty source	Correlation 2016–2017	Correlation time bins	Magnitude
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%

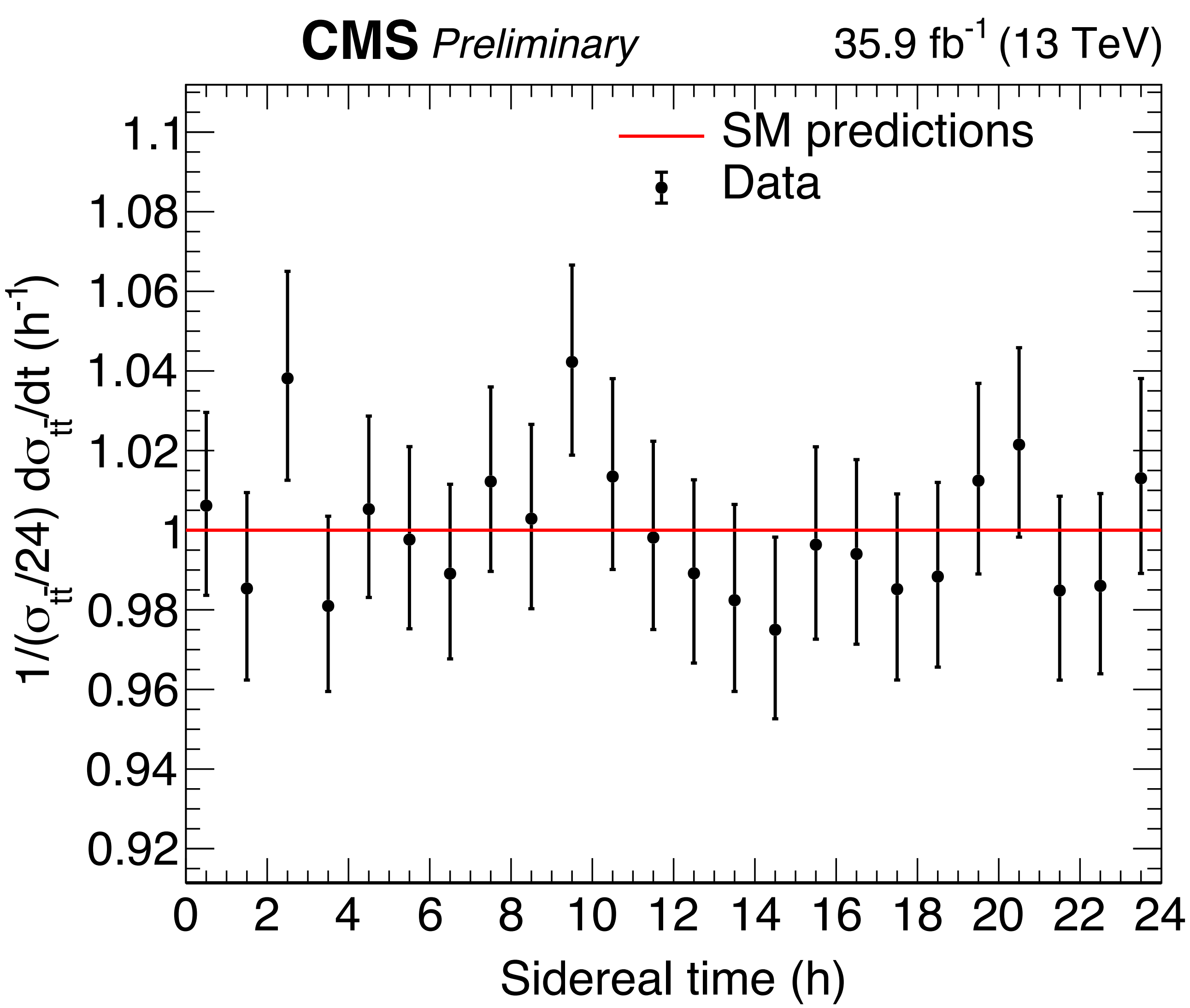
SM theory and background normalisation uncertainties: uniform (and correlated) in sidereal time

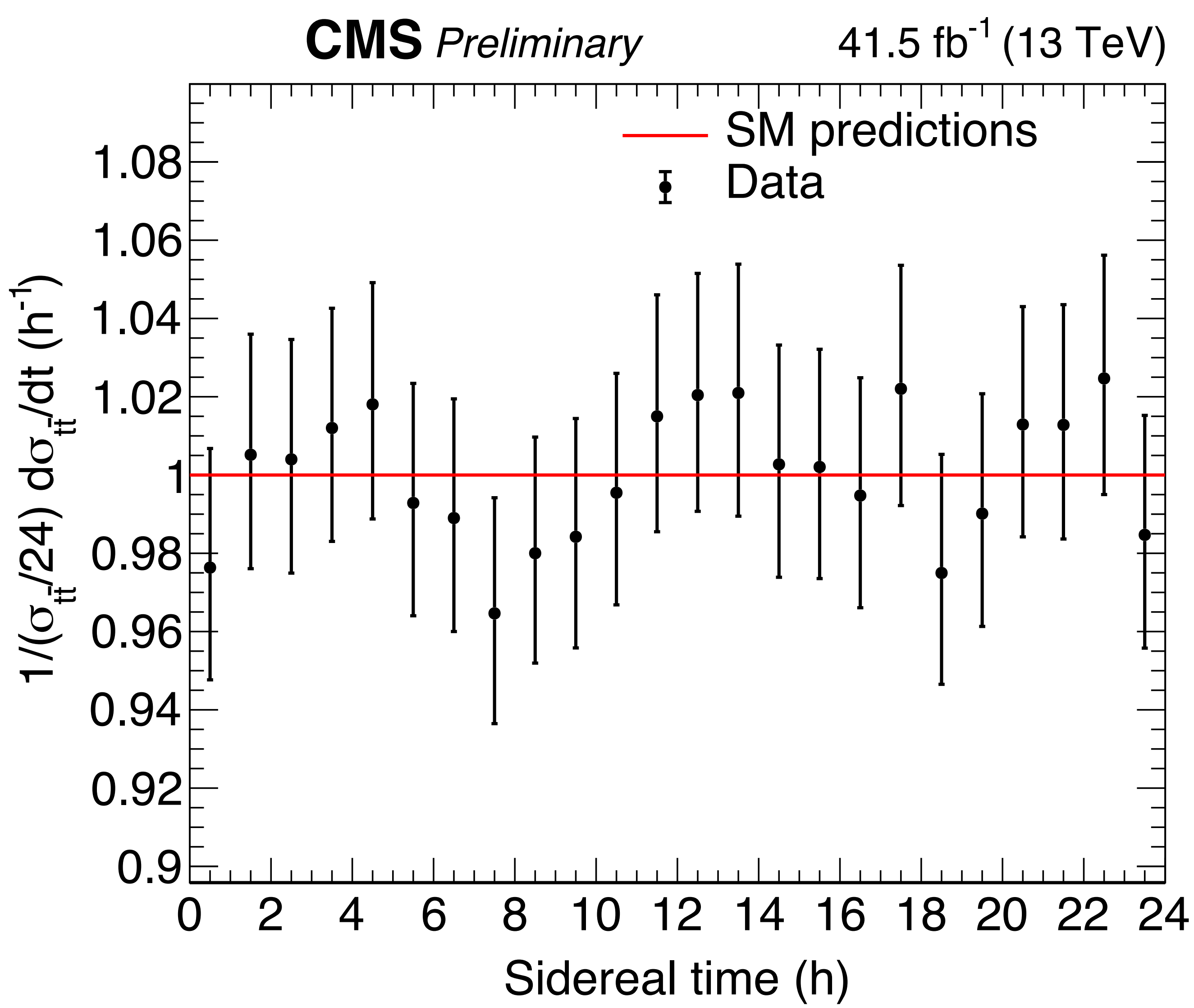
Systematic uncertainty source	Correlation 2016–2017	Correlation time bins	Magnitude
Matrix element scale	100%	100%	0.3–6%
PDF+α_S	100%	100%	0.1–0.4%
Initial- & final-state radiation scale	100%	100%	1–5%
Top quark p_T	100%	100%	0.5–2.5%
Matrix element-parton shower matching	100%	100%	0.7%
Underlying event 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 stat.: correlated in sidereal time

Systematic uncertainty source	Correlation 2016–2017	Correlation time bins	Magnitude
MC statistical uncertainty	0%	100%	0.1–1%

Differential fit in 2016 and 2017



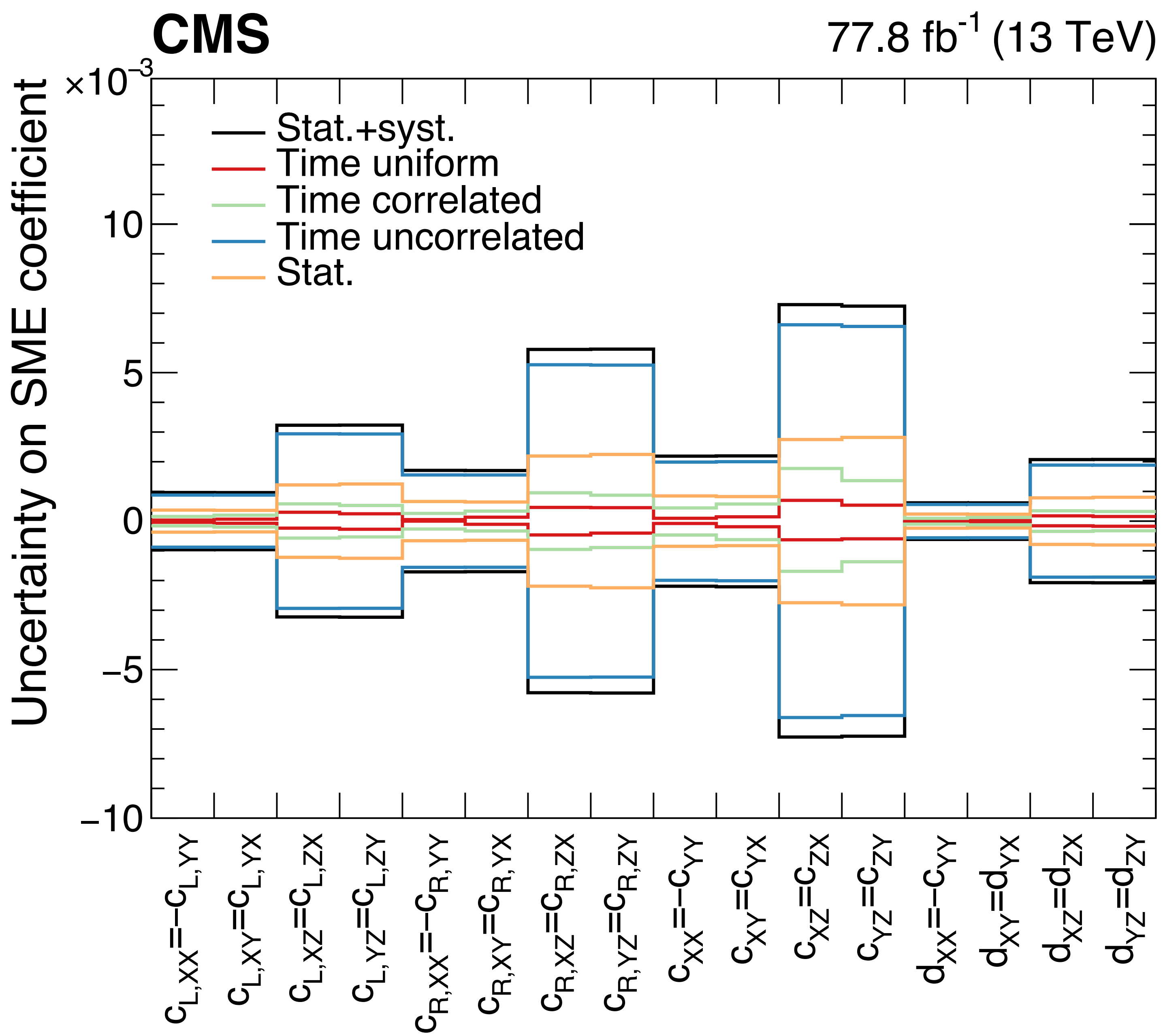


Comparison with SM expectations

- Alternative fit: Fit of each Wilson **individually, others set to SM**
- Correlation between coefficients of different directions is 0-4%

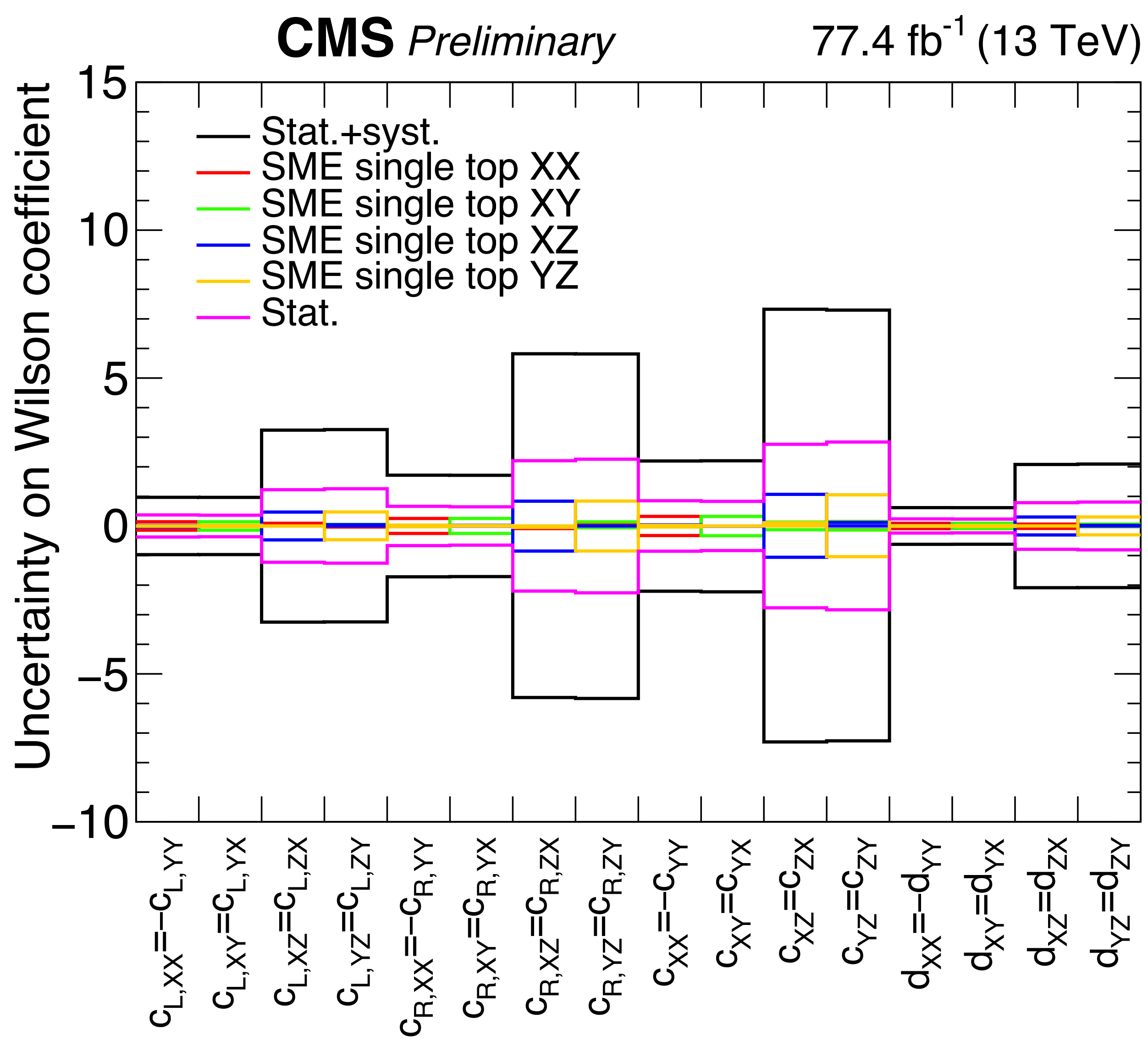
SME coefficient	Others fixed to SM		Others floating	
(10^{-3} unit)	Expected	Observed	Expected	Observed
$c_{L,XX} = -c_{L,YY}$	$[-0.96; 0.96]$	$[-0.9; 1.03]$	$[-0.96; 0.96]$	$[-0.9; 1.03]$
$c_{L,XY} = c_{L,YX}$	$[-0.97; 0.97]$	$[-1.92; 0.0]$	$[-0.97; 0.97]$	$[-1.94; -0.02]$
$c_{L,XZ} = c_{L,ZX}$	$[-3.23; 3.23]$	$[-0.97; 5.49]$	$[-3.23; 3.23]$	$[-0.92; 5.54]$
$c_{L,YZ} = c_{L,ZY}$	$[-3.24; 3.24]$	$[-4.61; 1.85]$	$[-3.24; 3.24]$	$[-4.64; 1.82]$
$c_{R,XX} = -c_{R,YY}$	$[-1.7; 1.7]$	$[-1.65; 1.77]$	$[-1.7; 1.7]$	$[-1.66; 1.76]$
$c_{R,XY} = c_{R,YX}$	$[-1.71; 1.71]$	$[0.09; 3.5]$	$[-1.71; 1.71]$	$[0.12; 3.52]$
$c_{R,XZ} = c_{R,ZX}$	$[-5.78; 5.78]$	$[-9.36; 2.2]$	$[-5.78; 5.78]$	$[-9.45; 2.11]$
$c_{R,YZ} = c_{R,ZY}$	$[-5.8; 5.8]$	$[-3.82; 7.76]$	$[-5.8; 5.8]$	$[-3.77; 7.82]$
$c_{XX} = -c_{YY}$	$[-2.17; 2.17]$	$[-1.76; 2.62]$	$[-2.17; 2.17]$	$[-1.83; 2.55]$
$c_{XY} = c_{YX}$	$[-2.18; 2.18]$	$[-4.23; 0.17]$	$[-2.18; 2.18]$	$[-4.31; 0.09]$
$c_{XZ} = c_{ZX}$	$[-7.21; 7.21]$	$[-1.49; 13.07]$	$[-7.21; 7.21]$	$[-1.29; 13.27]$
$c_{YZ} = c_{ZY}$	$[-7.24; 7.24]$	$[-11.05; 3.38]$	$[-7.24; 7.24]$	$[-11.21; 3.28]$
$d_{XX} = -d_{YY}$	$[-0.61; 0.61]$	$[-0.6; 0.63]$	$[-0.61; 0.61]$	$[-0.59; 0.64]$
$d_{XY} = d_{YX}$	$[-0.62; 0.62]$	$[-1.24; -0.01]$	$[-0.62; 0.62]$	$[-1.25; -0.02]$
$d_{XZ} = d_{ZX}$	$[-2.07; 2.07]$	$[-0.68; 3.46]$	$[-2.08; 2.07]$	$[-0.65; 3.49]$
$d_{YZ} = d_{ZY}$	$[-2.08; 2.08]$	$[-2.9; 1.25]$	$[-2.08; 2.08]$	$[-2.92; 1.23]$

Uncertainty in SME fits



Uncertainty for single top in the SME

- Formula for **single top** production in presence of non-null c or d **SME coefficients are not known**
- Evaluate an uncertainty arising from top quark decay in the SME, using single top processes
- Small impact on the total uncertainty



Translating UNIX to sidereal time

UTC time (~UNIX time): rotation period of the earth lasts ~23h 56min 4s (UTC)
Sidereal time: rotation period of the earth is defined as 24h, 86400 s (sidereal)

Angular velocity of earth's rotation around its axis in *sidereal* time: $\sim 2\pi/86400\ \mathrm{s}^{-1}$

Angular velocity of earth's rotation around its axis in *UTC* time: $2\pi/86164\ \mathrm{s}^{-1}$

Jan 1st 2016 in UNIX time

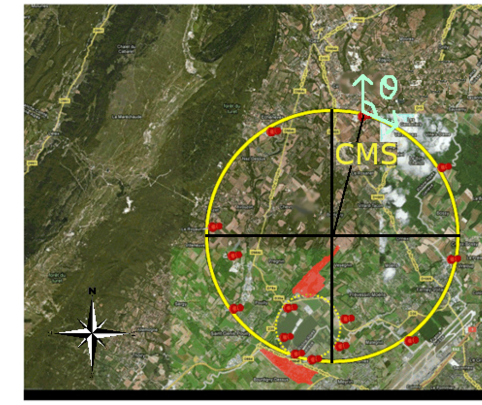
Effective longitude of the beam at CMS P5 relative to Greenwich meridian, in rad

$$\Omega_{\mathrm{sidereal}} t_{\mathrm{sidereal}} = \Omega_{\mathrm{UTC}} * (t_{\mathrm{UNIX}} - t_0) + \phi_{\mathrm{UNIX}} + \phi_{\mathrm{longitude}}$$

Timestamp of the lumisection in UNIX time (seconds since 1st Jan 1970)

Phase between J2000 (reference in Sun-centered frame) and Unix epoch

SME rotation matrices



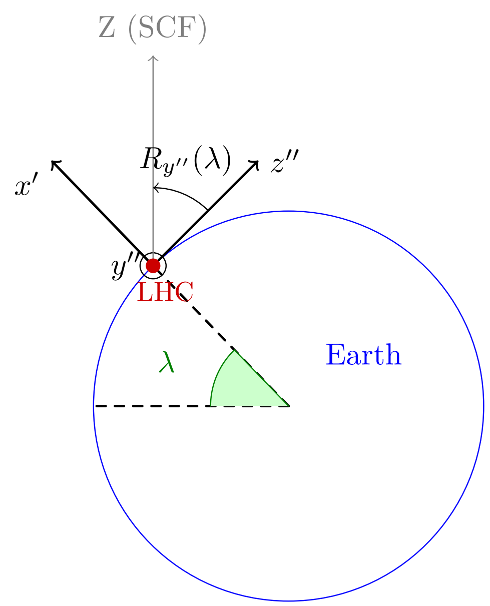
$$R(\lambda,\theta,\alpha) = R_Z(\Omega t)\cdot R_{y''}(\lambda)\cdot R_{x'}\Big(-(\pi-\theta)\Big)\cdot R_z\left(\frac{\pi}{2}\right)\cdot R_x(\alpha)$$

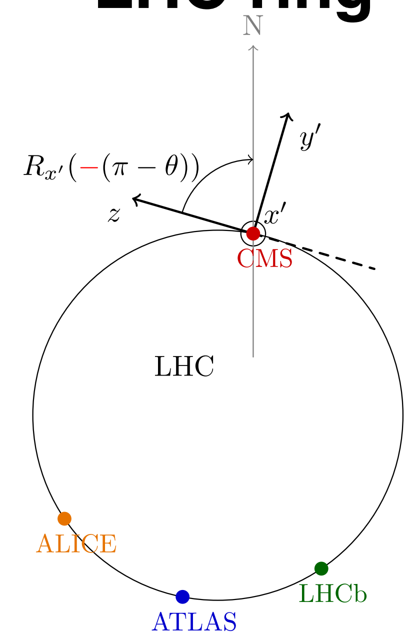
Rotation of the earth around its axis

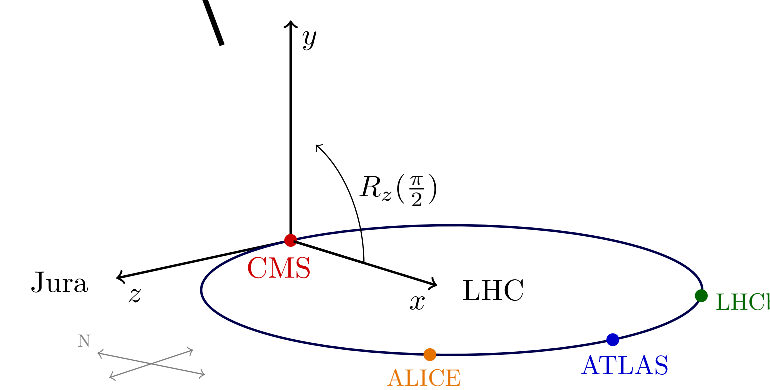
Latitude

azimuth in LHC ring

Tilt of LHC plane relative to the surface

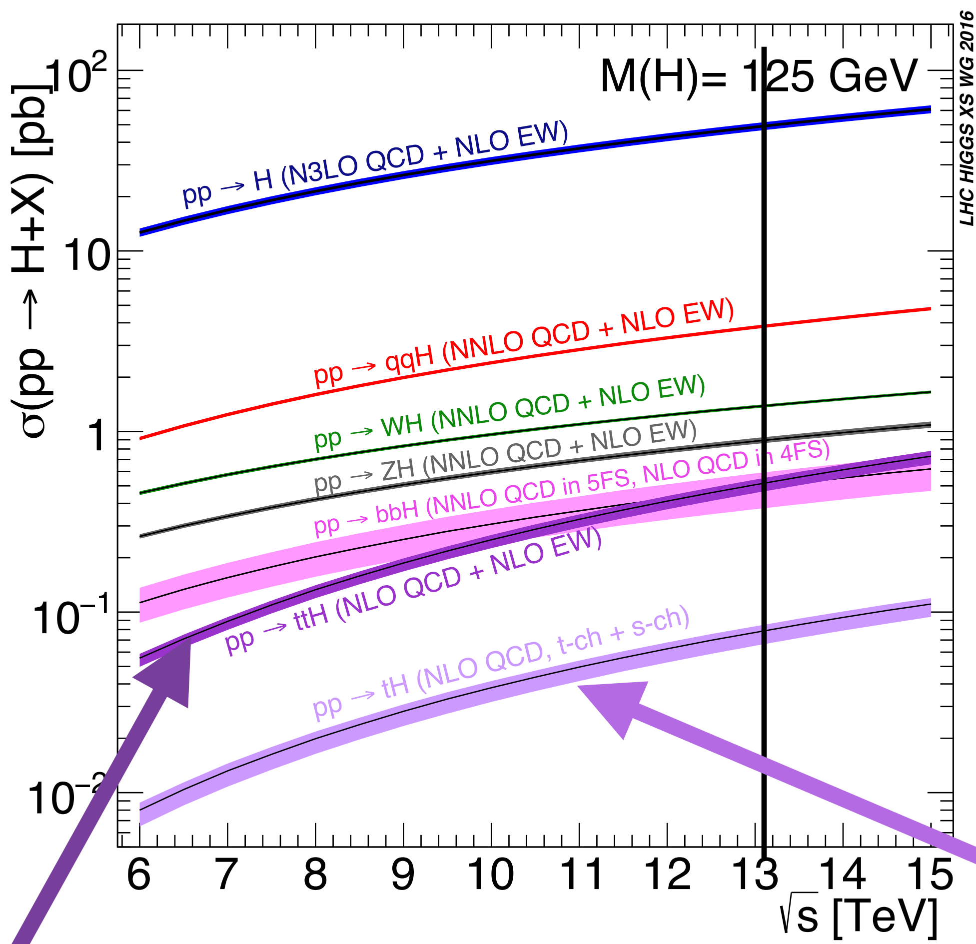


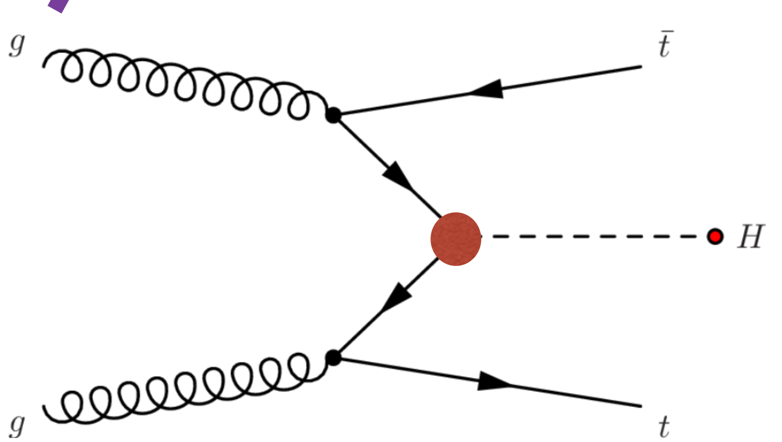




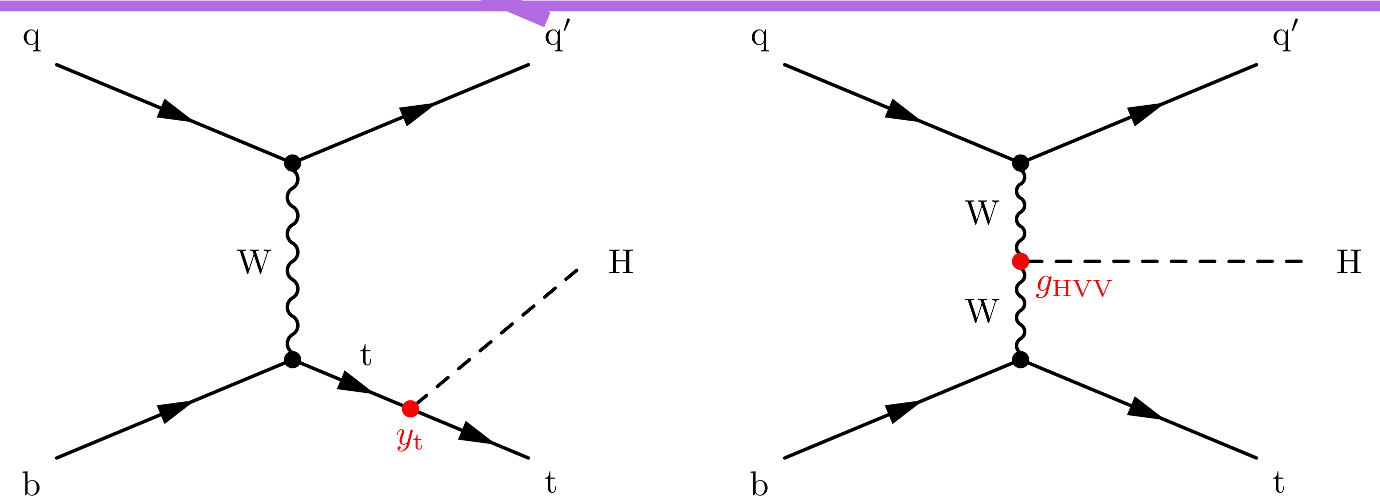
$$R(\lambda,\theta,\alpha,t) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \sin(\Omega t)c_\theta - \cos(\Omega t)s_\theta s_\lambda & \cos(\Omega t)(-s_\alpha c_\theta s_\lambda - c_\alpha c_\lambda) - \sin(\Omega t)s_\alpha s_\theta & \cos(\Omega t)(s_\alpha c_\lambda - c_\alpha c_\theta s_\lambda) - \sin(\Omega t)c_\alpha s_\theta \\ 0 & -\sin(\Omega t)s_\theta s_\lambda - \cos(\Omega t)c_\theta & \sin(\Omega t)(-s_\alpha c_\theta s_\lambda - c_\alpha c_\lambda) + \cos(\Omega t)s_\alpha s_\theta & \sin(\Omega t)(s_\alpha c_\lambda - c_\alpha c_\theta s_\lambda) + \cos(\Omega t)c_\alpha s_\theta \\ 0 & -s_\theta c_\lambda & c_\alpha s_\lambda - s_\alpha c_\theta c_\lambda & -s_\alpha s_\lambda - c_\alpha c_\theta c_\lambda \end{pmatrix}$$

top+Higgs processes





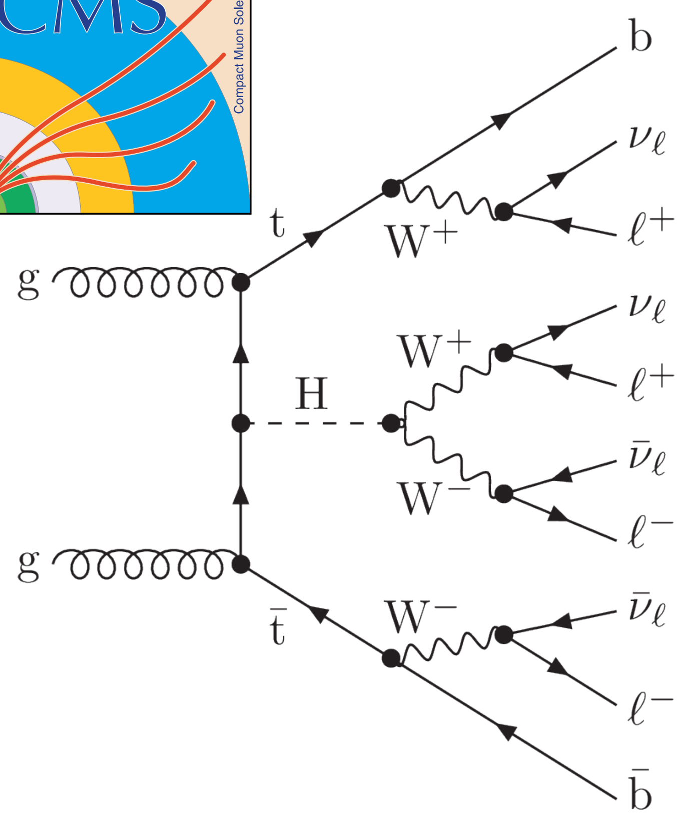
ttH: Direct (tree level) **probe of top-Higgs coupling**



tHq: Direct (tree level) **probe of top-Higgs coupling + sign of the coupling** through interference

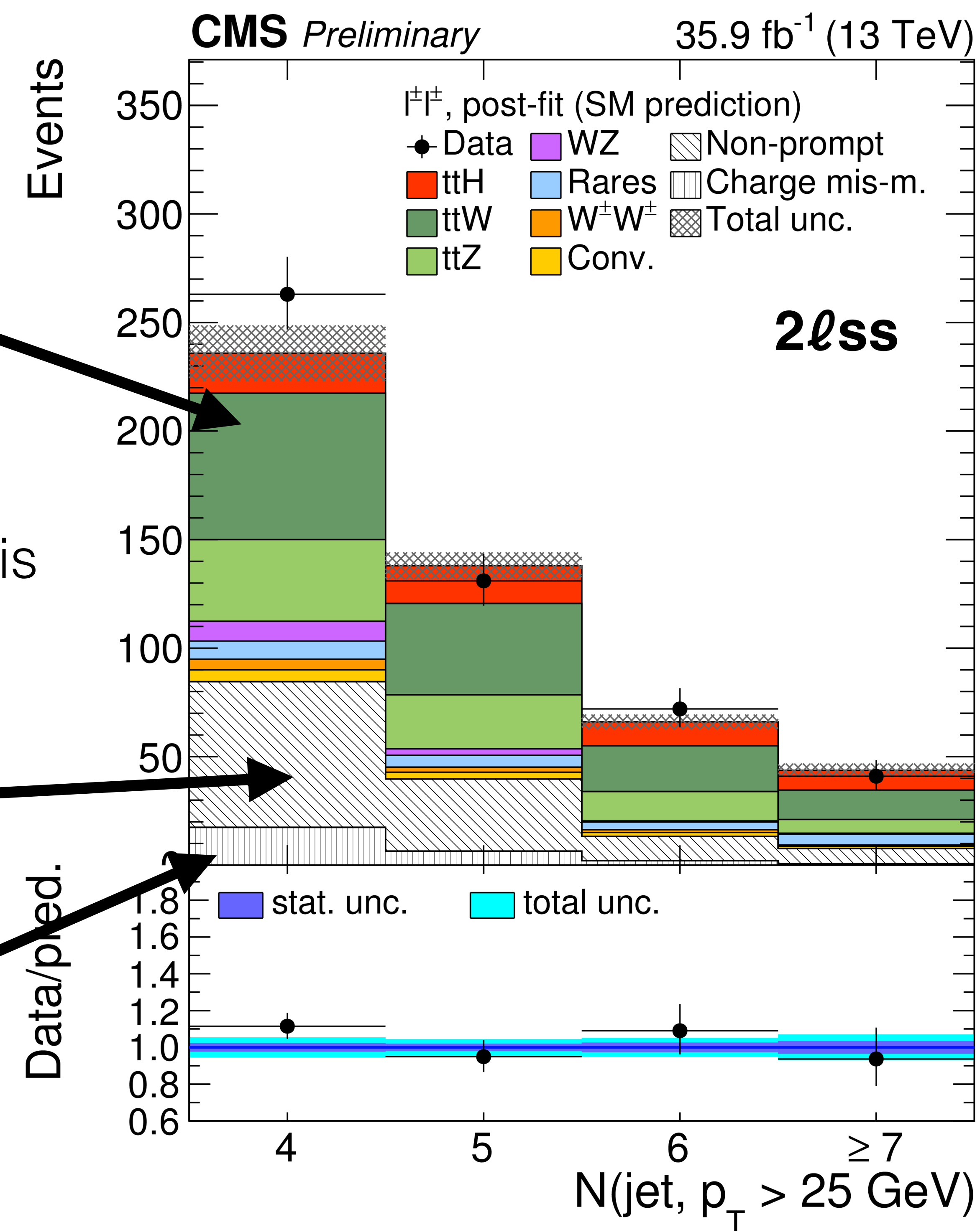
$t\bar{t}$H multilepton

Eur. Phys. J. C 81 (2021) 378



Most sensitive event categories: 2 leptons of same sign (2ℓss), 3ℓ, 2ℓss+1τ_h (hadronic tau), 1ℓ+2τ_h

Irreducible: tt+W/Z/γ*
- from Monte Carlo,
- O(10%) uncertainty

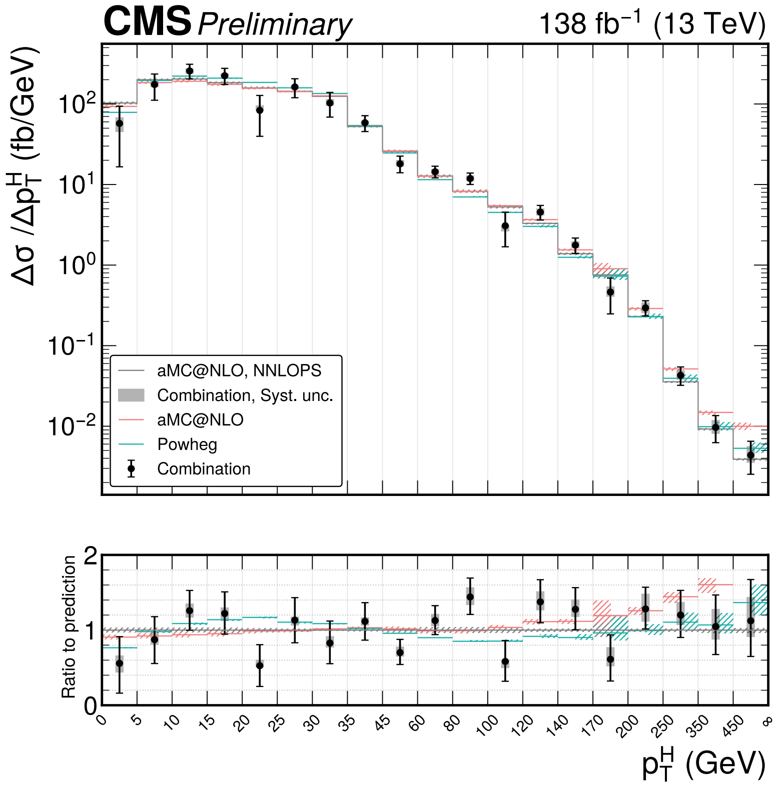


Reducible: mainly tt+jets,
- Lepton identification optimised for this analysis
- measured in data,
- O(30%) uncertainty

- **Jets faking leptons:** fake rate computed from jets control region with loosened identification
- **Charge mis-assignment** (2ℓss only)**:** flip rate from Z→$\ell^\pm\ell^\pm$ data

CP violation from Higgs differential

CMS-PAS-23-013 **New public note**



Combination and interpretation of differential Higgs => Im(cbH), Im(ceH), Im(cbW)

Class	Operator	Wilson coefficient
$\mathcal{L}_6^{(1)} - X^3$	$\varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	c_W
$\mathcal{L}_6^{(3)} - H^4D^2$	$(D^\mu H^\dagger H)(H^\dagger D_\mu H)$	c_{HD}
	$(H^\dagger H)\Box(H^\dagger H)$	$c_{H\Box}$
$\mathcal{L}_6^{(4)} - X^2H^2$	$H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$	c_{HG}
	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	c_{HB}
	$H^\dagger H W^i_{\mu\nu} W^{i\mu\nu}$	c_{HW}
	$H^\dagger \sigma^i H W^i_{\mu\nu} B^{i\mu\nu}$	c_{HWB}
$\mathcal{L}_6^{(5)} - \psi^2H^3$	$(H^\dagger H)(\bar{Q}Hb)$	$\mathrm{Re}(c_{bH})$ $\mathrm{Im}(c_{bH})$
	$(H^\dagger H)(\bar{Q}\tilde{H}t)$	$\mathrm{Re}(c_{tH})$
	$(H^\dagger H)(\bar{l}_p e_r H)$	$\mathrm{Re}(c_{eH})$ $\mathrm{Im}(c_{eH})$
	$(H^\dagger H)(\bar{q} Y_u^\dagger u \tilde{H})$	$\mathrm{Re}(c_{uH})$
$\mathcal{L}_6^{(6)} - \psi^2XH$	$(\bar{Q}\sigma^{\mu\nu} T^a t)\tilde{H} G^a_{\mu\nu}$	$\mathrm{Re}(c_{tG})$
	$(\bar{Q}\sigma^{\mu\nu} b) H B_{\mu\nu}$	$\mathrm{Re}(c_{bB})$
	$(\bar{Q}\sigma^{\mu\nu} t) H B_{\mu\nu}$	$\mathrm{Re}(c_{tB})$
	$(\bar{Q}\sigma^{\mu\nu} b)\sigma^i H W^i_{\mu\nu}$	$\mathrm{Re}(c_{bW})$ $\mathrm{Im}(c_{bW})$
	$(\bar{Q}\sigma^{\mu\nu} t)\sigma^i \tilde{H} W^i_{\mu\nu}$	$\mathrm{Re}(c_{tW})$
$\mathcal{L}_6^{(7)} - \psi^2H^2D$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	$c_{Hl}^{(1)}$
	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p \sigma^i \gamma^\mu l_r)$	$c_{Hl}^{(3)}$
	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$c_{Hq}^{(1)}$
	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p \sigma^i \gamma^\mu q_r)$	$c_{Hq}^{(3)}$
	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}_p \gamma^\mu Q_r)$	$c_{HQ}^{(1)}$
	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{Q}_p \sigma^i \gamma^\mu Q_r)$	$c_{HQ}^{(3)}$
	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	c_{Hu}
	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	c_{Hd}
	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	c_{He}
	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	c_{Hb}
	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	c_{Ht}
$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	c'_{ll}