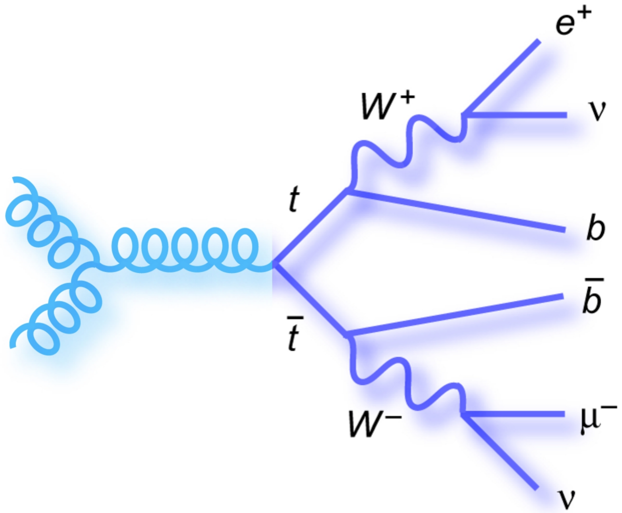
Searches for violation of Lorentz invariance with $t\bar{t}$ dilepton final state at CMS

Top LHC France - 09/04/2024



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

CMS-PAS-TOP-22-007

- Document: http://cds.cern.ch/record/2859658?ln=en

- Supplementary plots available at: https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP-22-007/index.html

Available on the CERN CDS information server **CMS PAS TOP-22-007**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-top@cern.ch 2023/05/23

Searches for violation of Lorentz invariance in $t\bar{t}$ production using dilepton events in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration

Abstract

Violation of Lorentz invariance is searched for using top quark pair ($t\bar{t}$) production in proton-proton collisions at the LHC, at a center-of-mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$. Events containing one electron and one muon collected with the CMS detector are analyzed in a data sample corresponding to an integrated luminosity of $77.4\,\mathrm{fb}^{-1}$. A measurement of the differential normalized cross section for $t\bar{t}$ production as a function of sidereal time is performed. Potential violation of Lorentz invariance is introduced as an extension of the standard model (SM), with an effective field theory predicting the modulation of the $t\bar{t}$ cross section with sidereal time. Bounds on Lorentz-violating couplings are extracted, and found to be compatible with Lorentz invariance with an absolute precision of $0.1-0.8\%$. This search can also be interpreted as a precision test of special relativity with top quarks, improving precision by two orders of magnitude over a previous such measurement.

$t\bar{t}$ cross section under Lorentz-violation

Lorentz transformation:

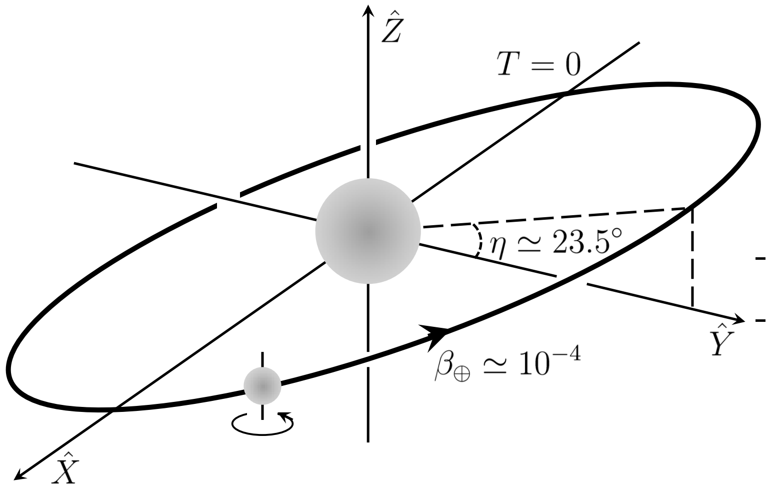
$$x^\mu \mapsto x'^\mu = \Lambda^\mu_{\ \nu} x^\nu$$

- 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



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

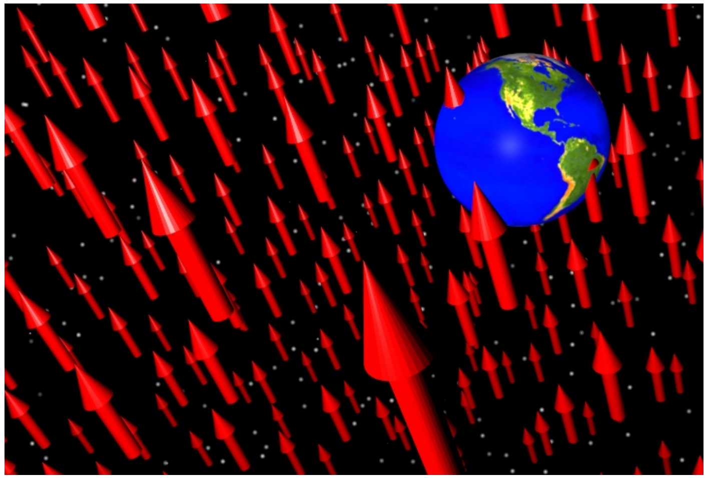
- SME coefficients: constant matrices (Lorentz-violating)
- Indicate **preferential directions in spacetime**

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)



Lorentz-violation with top quarks: previous bounds

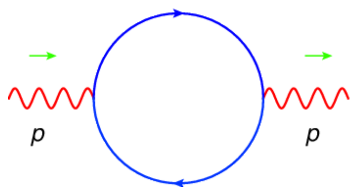
Rev.Mod.Phys. 83: 11 (2011)

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

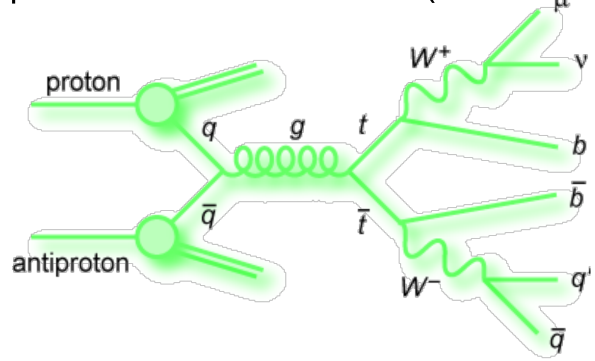
Table D36. Quark sector, $d \geq 4$

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

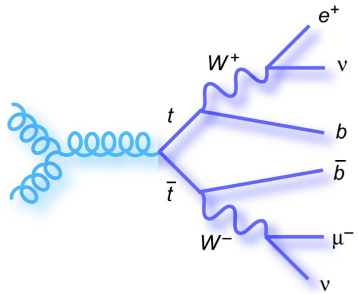


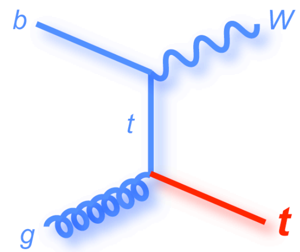
Direct, directional, bounds (*PRL 108:261603, 2012*): measurement of top pair production at DØ (Tevatron)



Analysis strategy

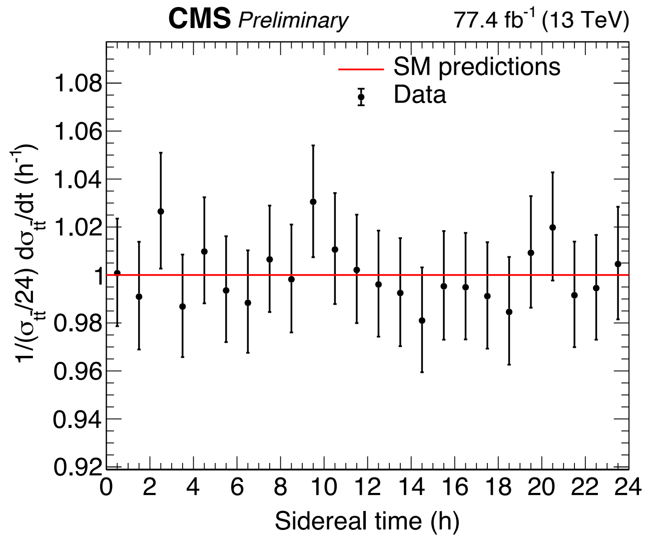
1) Discriminate between $t\bar{t}$ and SM backgrounds

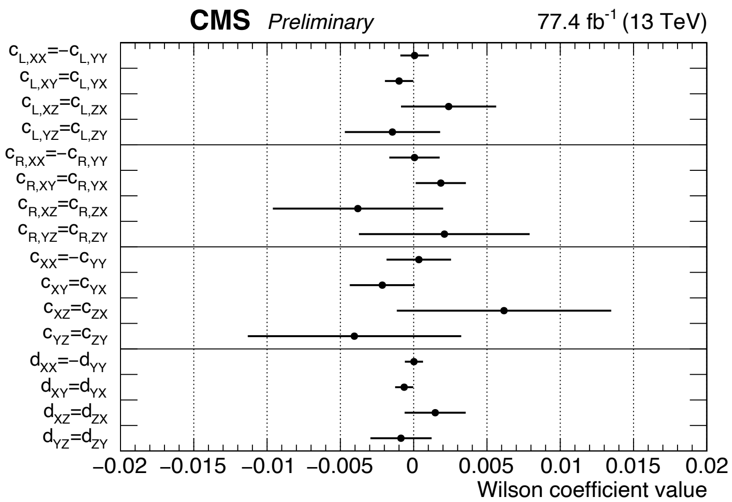




2) Evaluate relevant **corrections and systematic uncertainties as a function of sidereal time**

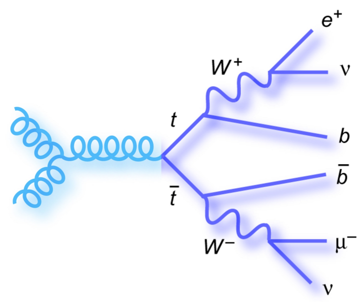
3) Measure **normalized differential cross section** with sidereal time



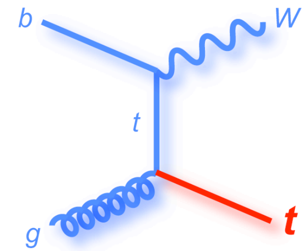


4) Extract Lorentz-violating SME coefficients

Employing $t\bar{t}$ dilepton final state



ttbar signal



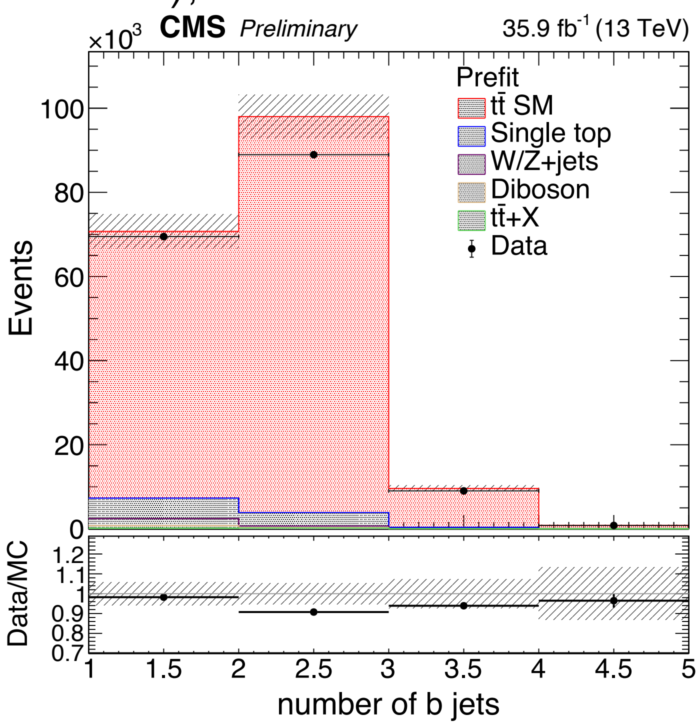
main background: single top tW

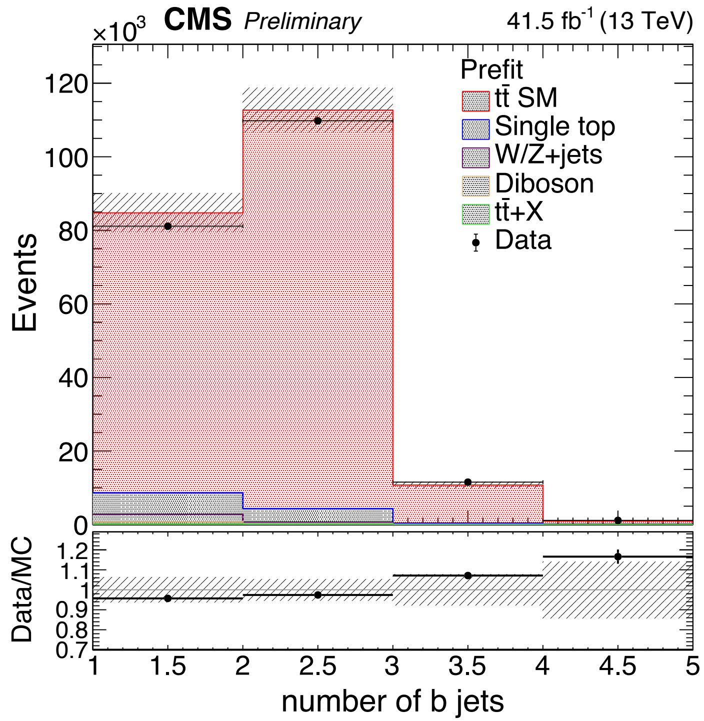
Selection:

- Dilepton final state: **eμ** (dilepton + single lepton triggers)
- Leading lepton p_T>25 GeV, subheading p_T>20 GeV
- **≥ 2 jets** with p_T>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),

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

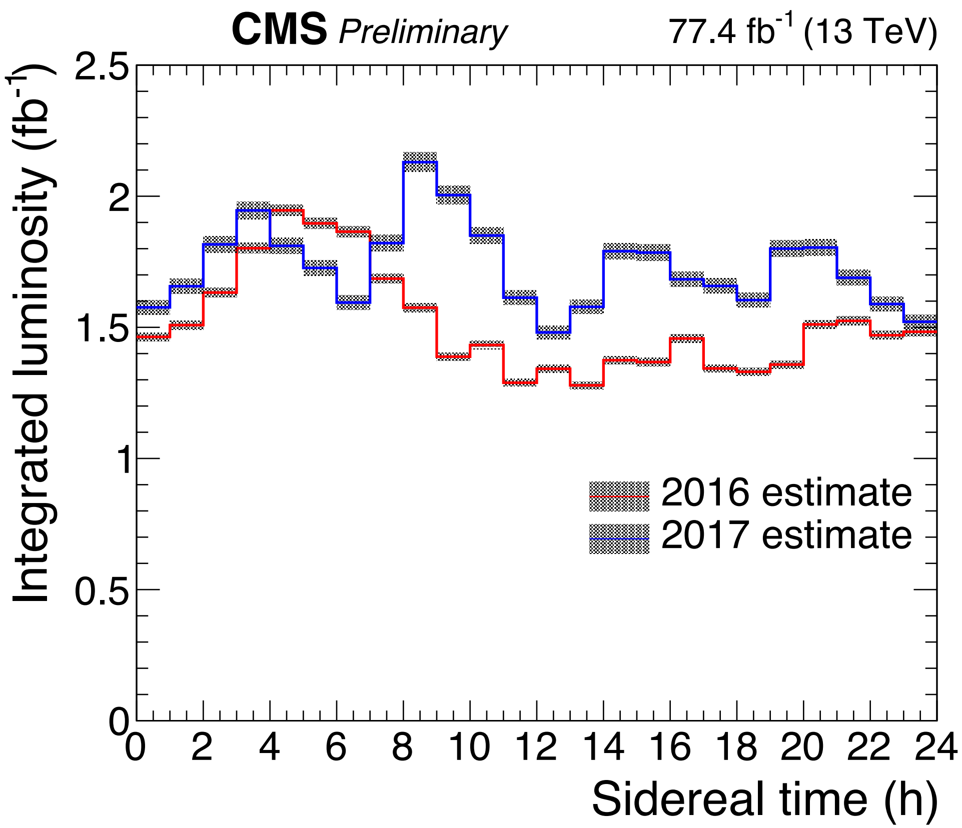


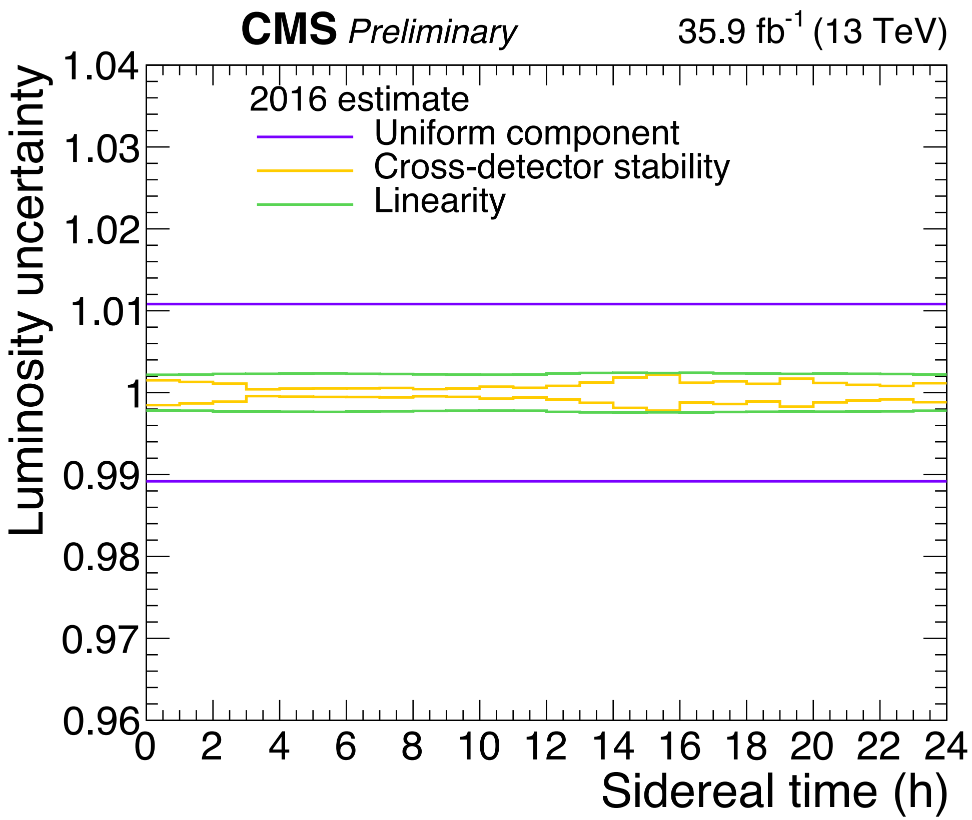


Integrated luminosity with sidereal time

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

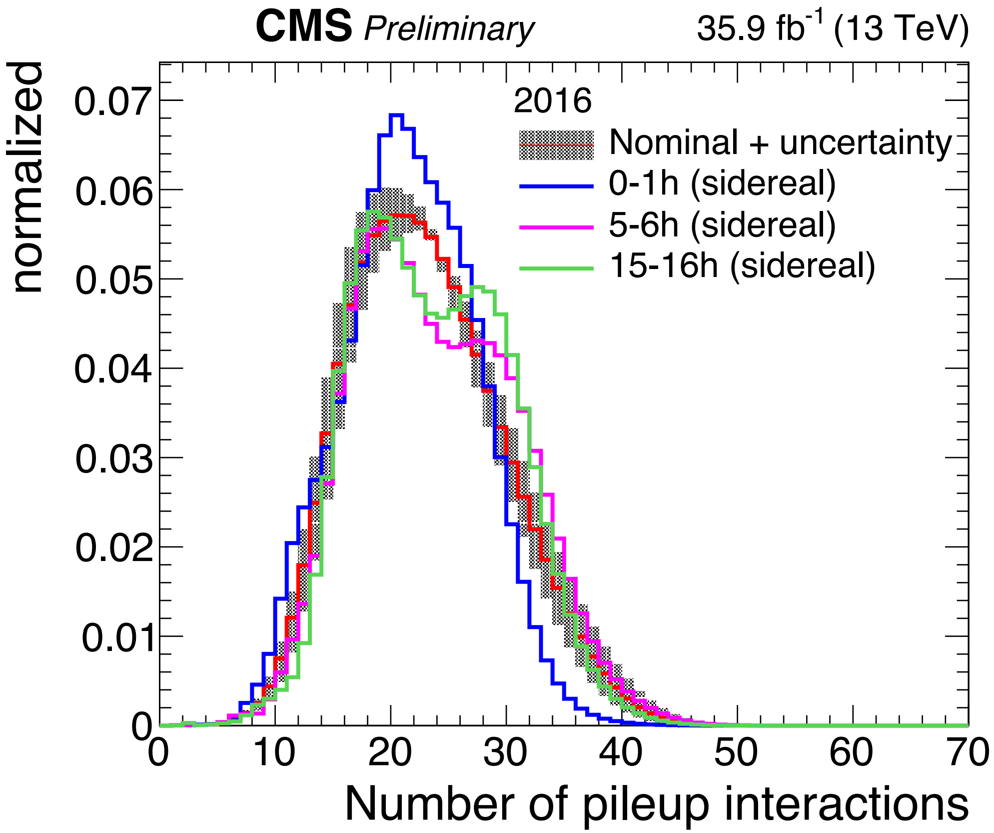


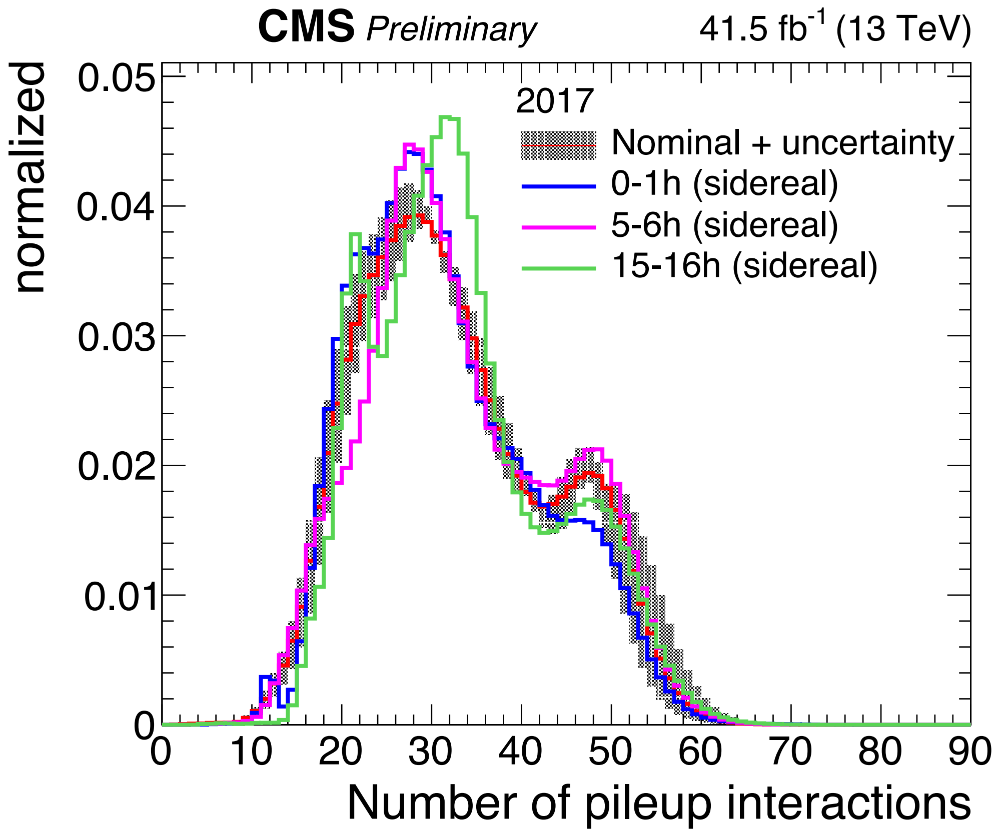


Pileup with sidereal time

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

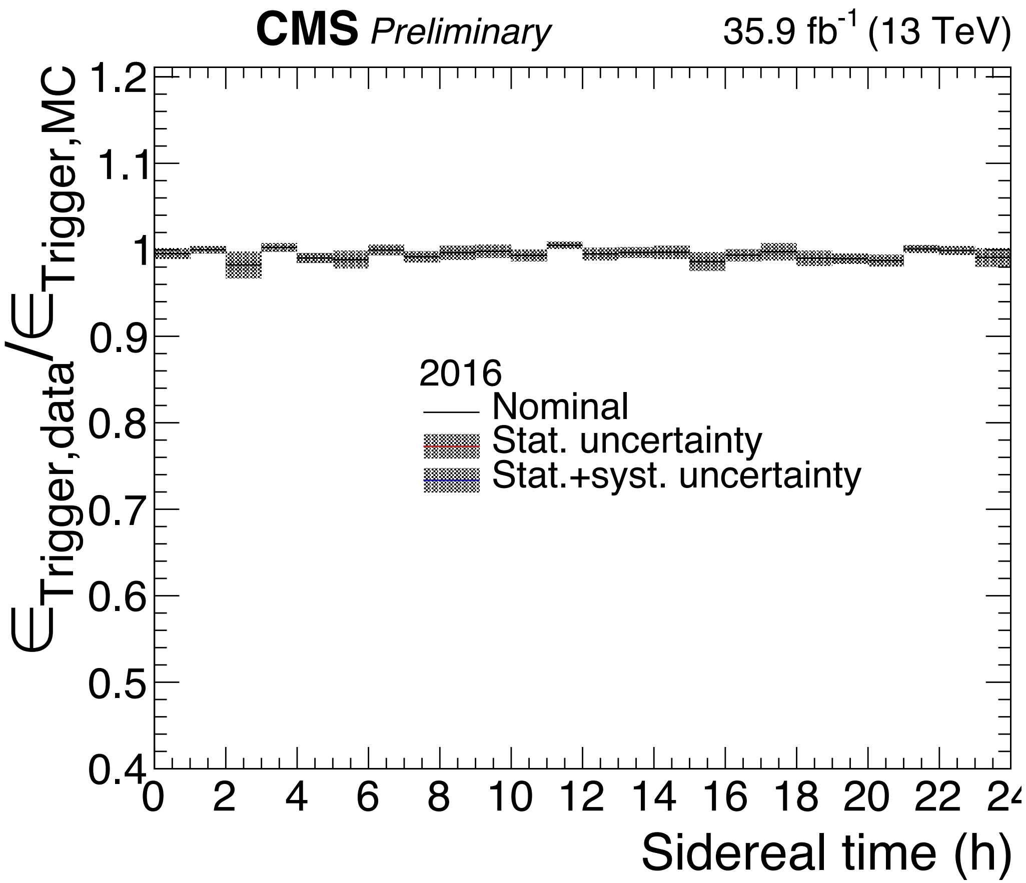


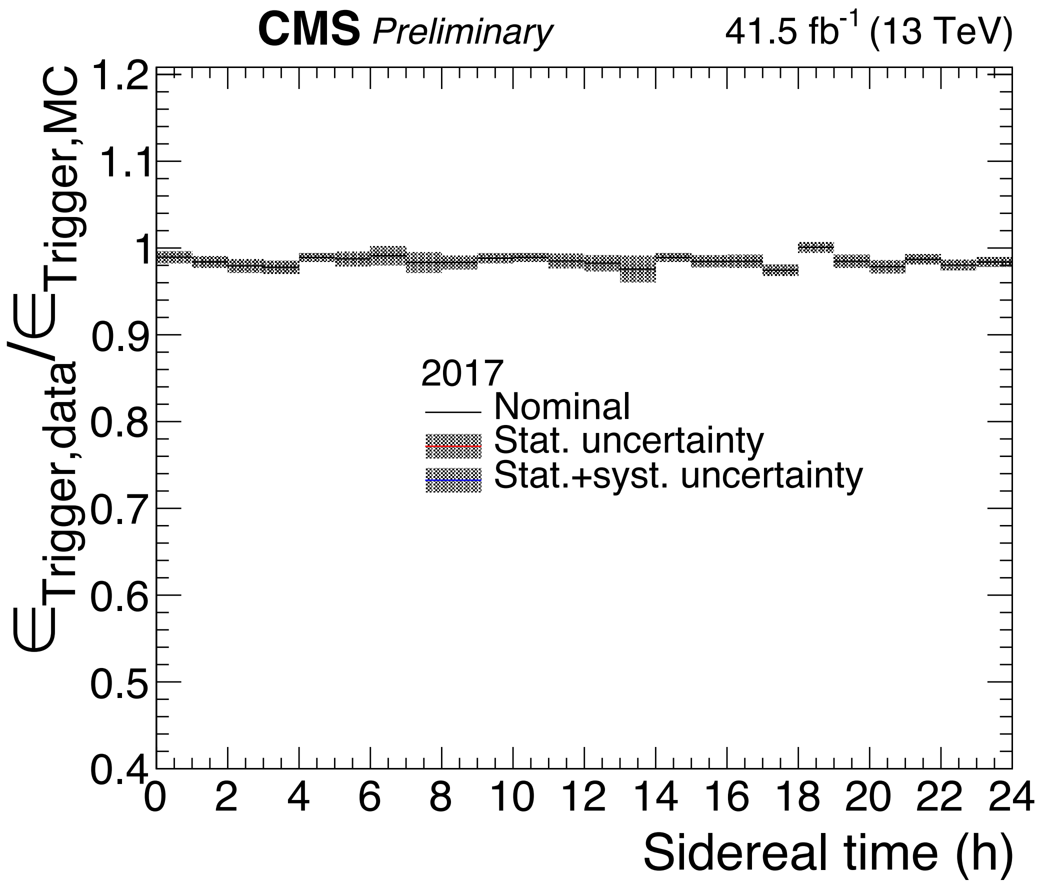


Trigger efficiency with sidereal time

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





Fitting the normalized differential XS

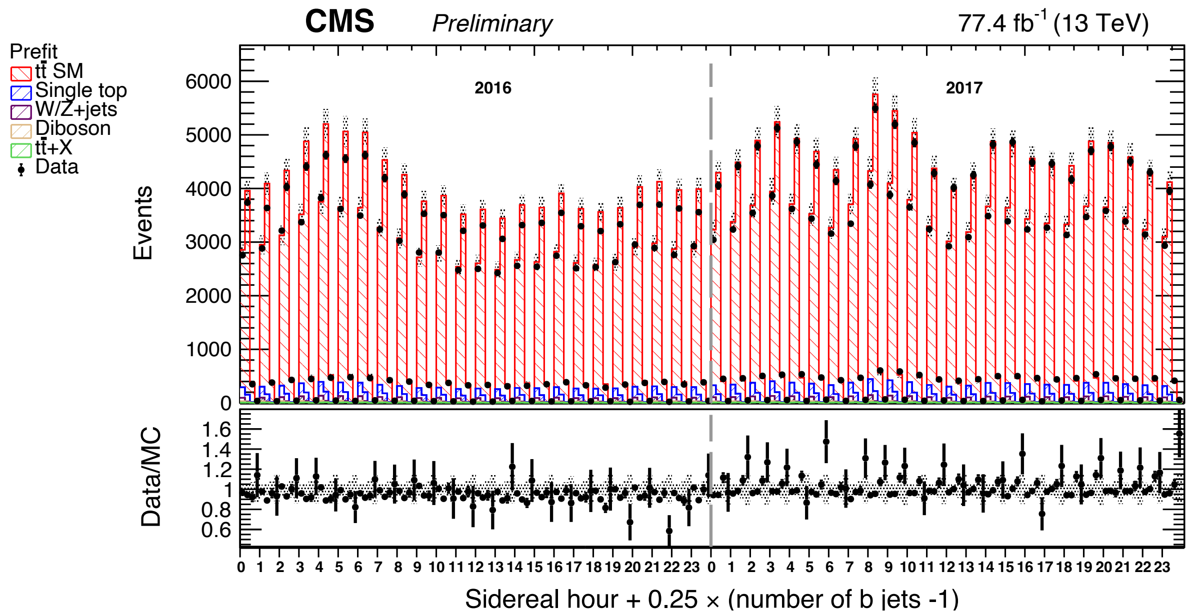
Reminder: Integrated lumi, pileup and trigger corrections depend on time

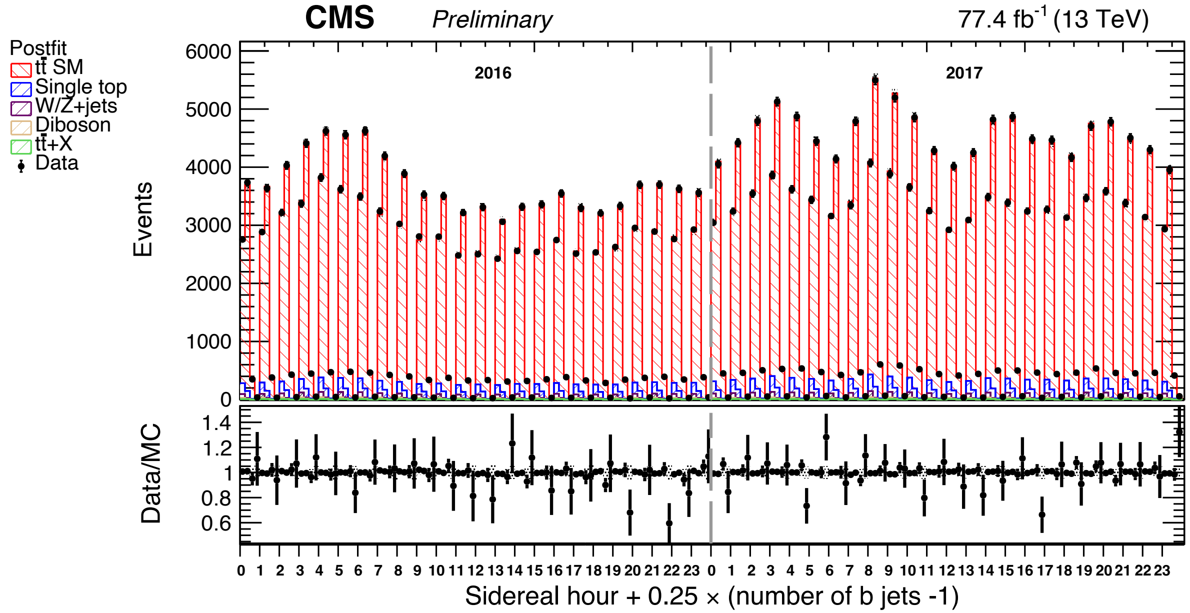
Fit method

- Profile likelihood method using the LHC test-statistic
- Fit of 24 parameters of interest (POIs): 23 fractions + the average signal strength

- Reconstructed and particle-level sidereal time are identical: diagonal response matrix
- Under the SM hypothesis, same expected prediction in each bin

- The normalised differential cross section reduces to:
  $\boldsymbol{\sigma_i/\sigma_{avg} = \mu_i/\mu_{avg}}$ (which are the POIs)





Uncertainties and their correlation

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

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

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

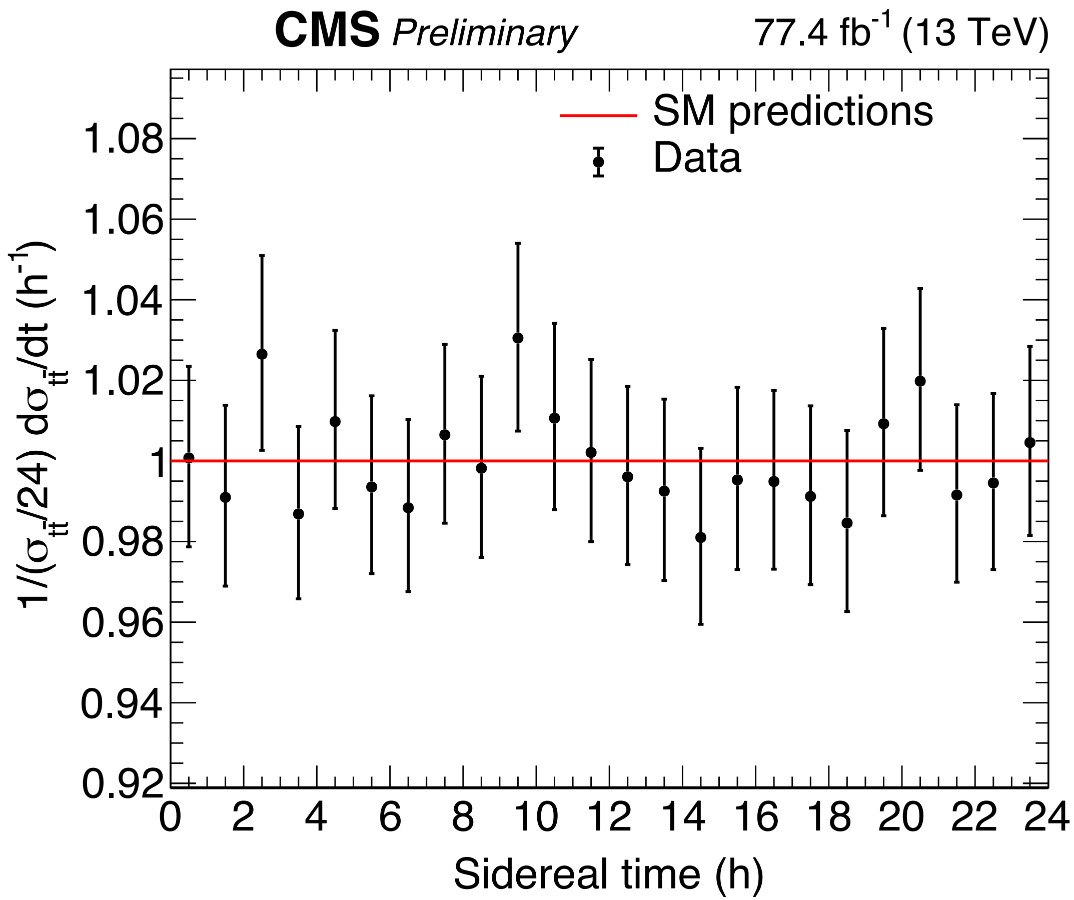
MC stat.: correlated in sidereal time

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%
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%

Normalized differential XS: result

Direct fit of normalised differential ttbar cross section

- Uncertainty is around 2.2% in each time bin
- Statistical uncertainty accounts for ~0.9%
- **Goodness-of-fit** (saturated model): p-value=**0.92**



Uncertainty breakdown

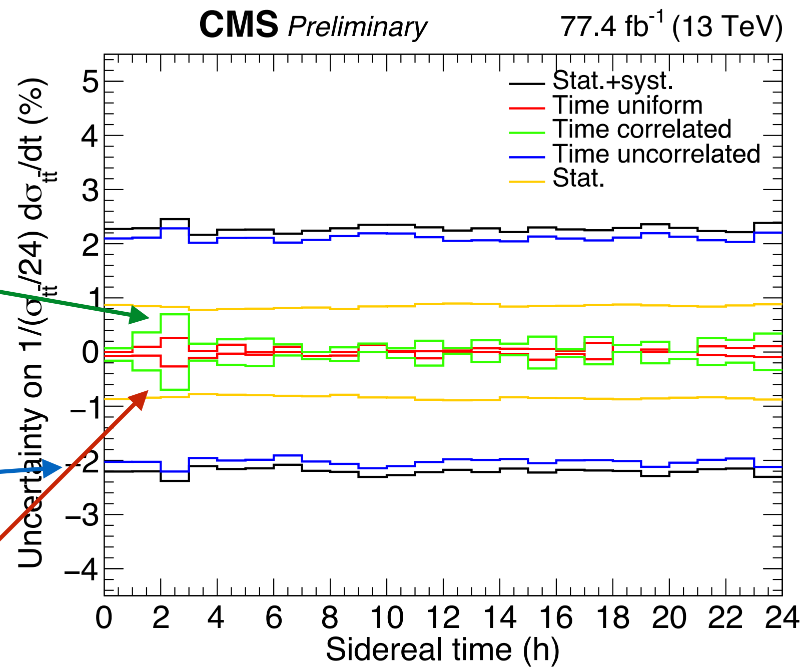
Uncertainty breakdown bin by bin: in each sidereal time bin, freeze groups of uncertainties in the fit and calculate the resulting uncertainty by subtracting to the total in quadrature.

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**

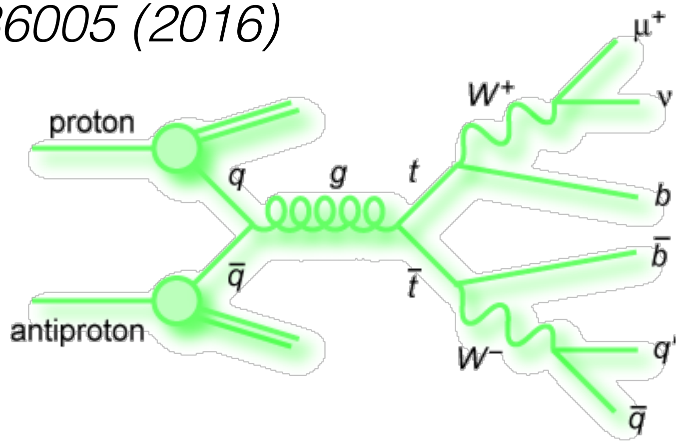
- Other experimental systematics treated as **uncorrelated,** to let the fit find their impact on each time bin in data: **dominant**

- SM theory, background norm, other luminosity uncertainties treated as **uniform**: **cancel** almost completely in the ratio
- Cancellation of uncertainties is imperfect because of remaining correlations



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

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

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

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

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

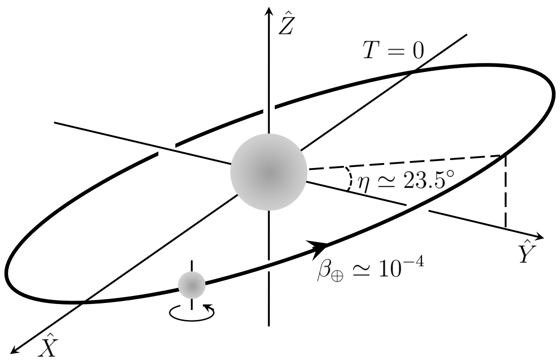
LIV change in top quark propagator

LIV change in top production via top-gluon vertex

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**

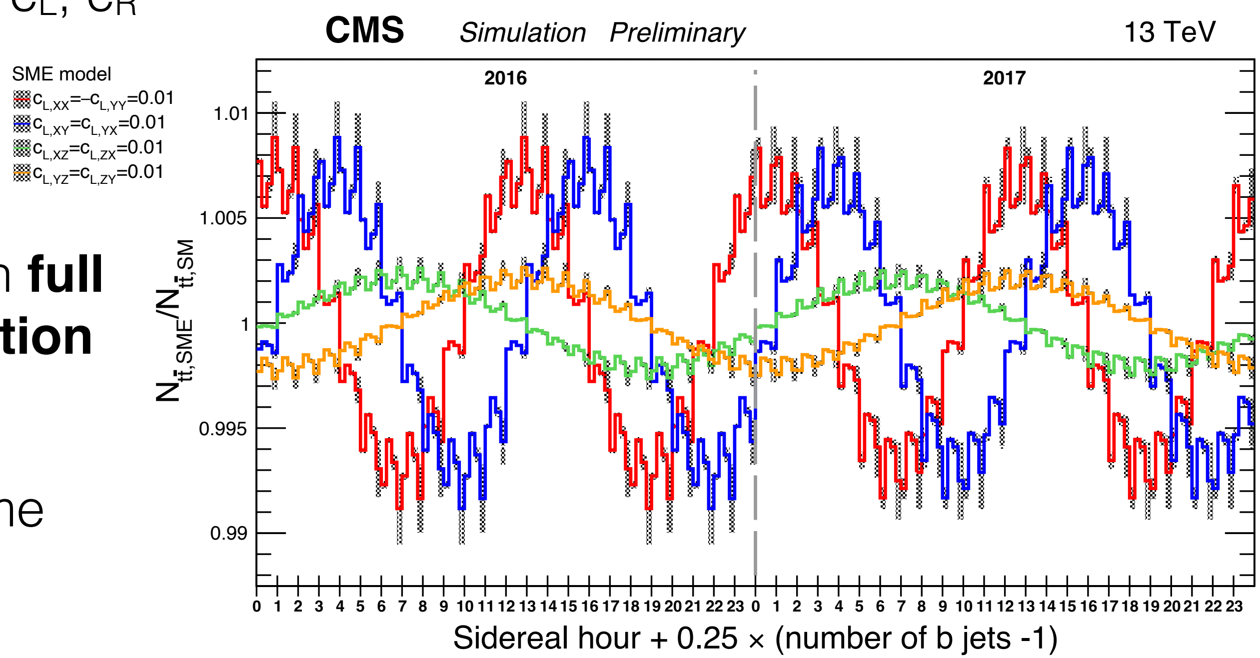
Lorentz-violating signal model (SME)

- Computation of the **time modulation using exact LO kinematics** *[Berger, Kostelecký, Liu, Phys. Rev. D 93, 036005 (2016)].*
- Includes SM + SM/SME interference term: linear in the new physics coefficients

SME signal model (evaluated at LO):
- Not sensitive to Z and T direction.
- Use similar benchmarks as Tevatron
- 4 directions tested: XX, XY, XZ, YZ
- 4 families of coefficients: c, d, c_L, c_R

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

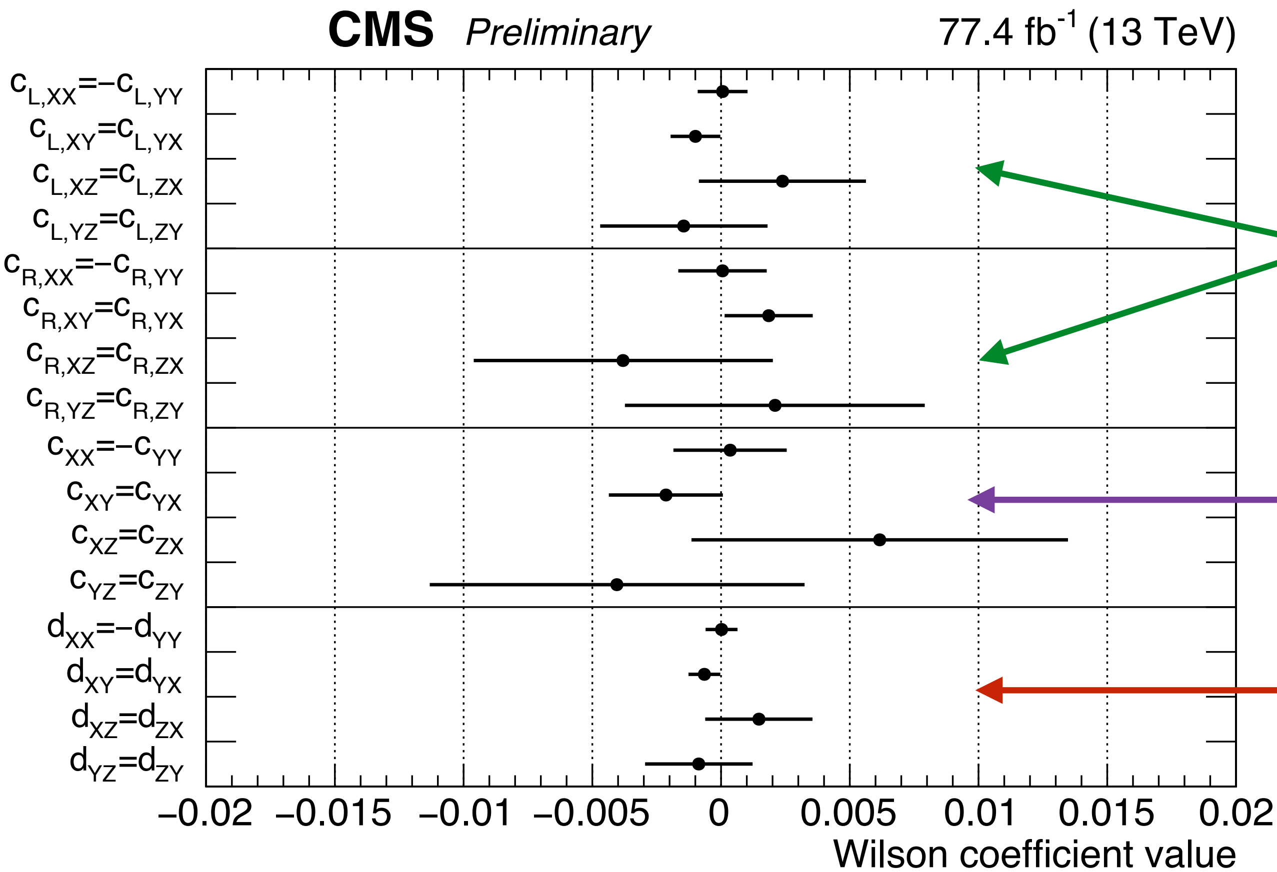
- Use Madgraph LO + Pythia, with **full detector simulation, and selection** at reco level
- Calculated in bins of sidereal time and number of b jets



Bounds on the SME coefficients

Fit of each **coefficient** individually**, while coefficients corresponding to the three other directions in a family** (cL, cR, c, d) **are left floating** in the fit

- Goodness-of-fit p-value is 0.98
- Correlation between coefficients of different directions is 0-4%



- **cL, cR coefficients:** Improved precision by a factor ~20-50 relative to D0

- **c coefficients:** measured for the first time

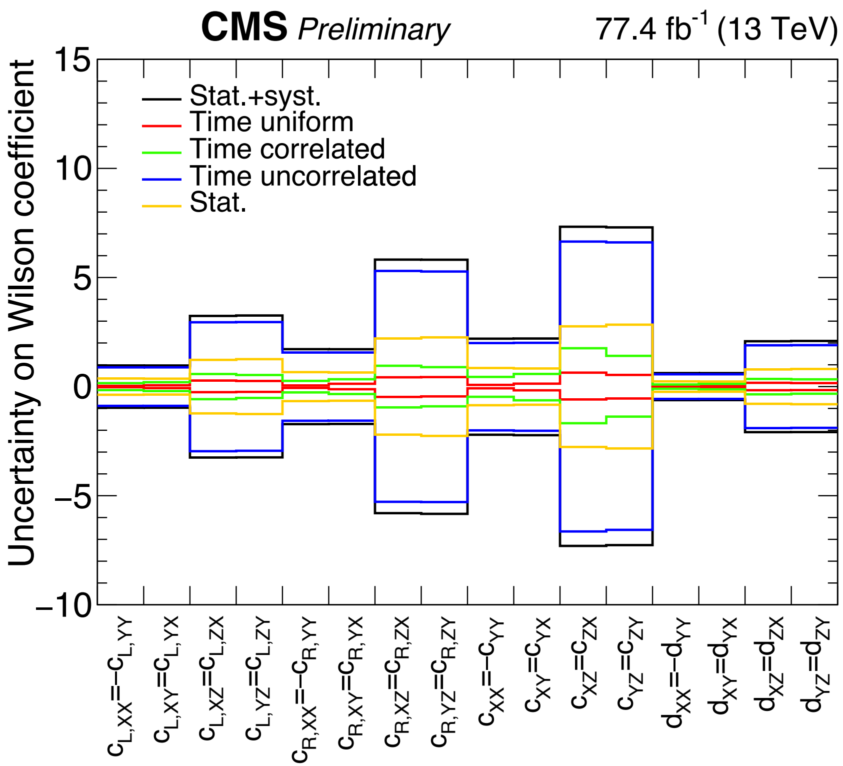
- **d coefficients:** Improved precision by a factor up to ~100 relative to D0

- No significant deviation from the SM
- **Special relativity tested with precision 0.1-0.8% using top quarks at the LHC**

Uncertainty breakdown

Similar conclusions as in the differential fit

- Largest uncertainty is the **time-uncorraleted component:** most exp. syst. have an individual uncertainty per sidereal time bin
- **Statistical uncertainty** is about 1/3 of total stat+syst uncertainty
- **Time-correlated** uncertainties follow. It includes an **uncertainty on single top** process in the **SME**.
- Usual **time-uniform systematics** have small impact



Conclusions and perspectives

Summary PAS TOP-22-007:

- Performed the **first search** for violation of **Lorentz** invariance with **ttbar at the LHC,** within the context of the **SME**
- Measured **differential normalised cross section with sidereal time**
- **Measured SME coefficients** in XX, XY, XZ, YZ directions for cL, cR, c, d families
- **Improvement by a factor up to 100** on the SME coefficients
- Special relativity tested at **0.1-0.8% precision level** with top quarks at the LHC

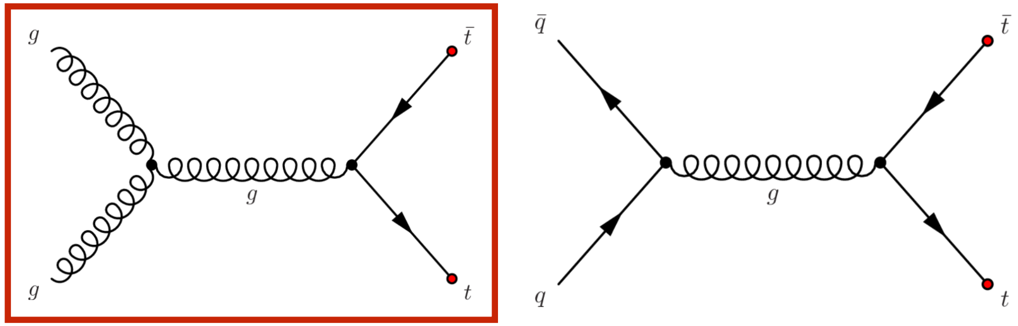
Perspectives:

- Statistical uncertainty: **factor of 5-10** improvement expected at the **HL-LHC**, and a **factor 100** at the **FCC-hh** *[Carle, Chanon, Perriès, Eur.Phys.J.C 80 (2020) 2, 128]*

Thanks for your attention

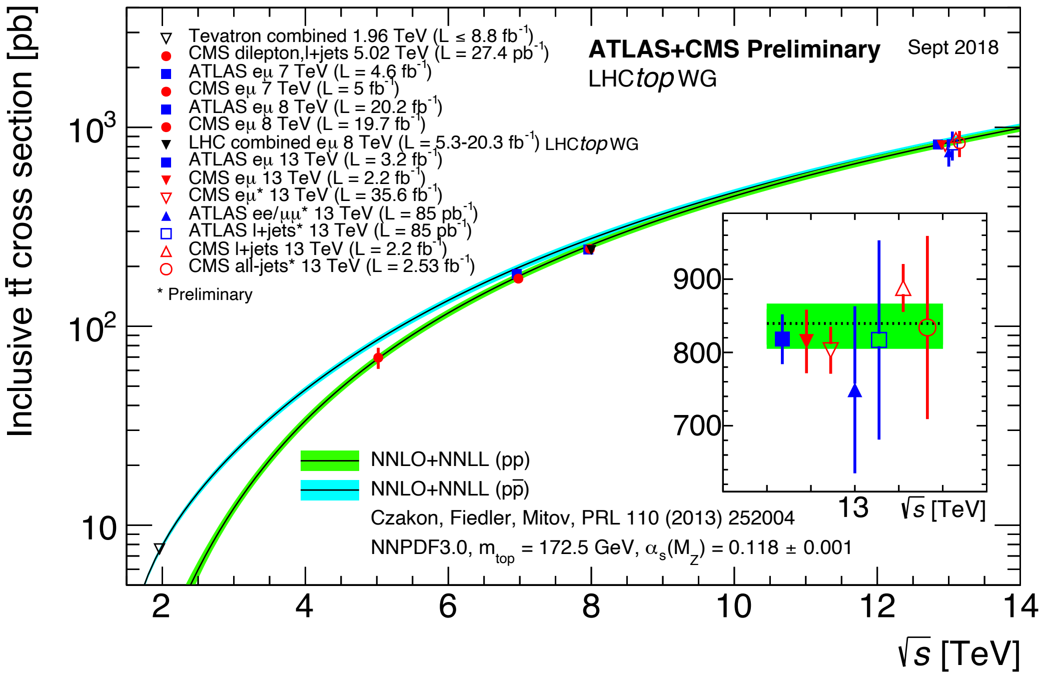
Back-up slides

The LHC: a top quark factory



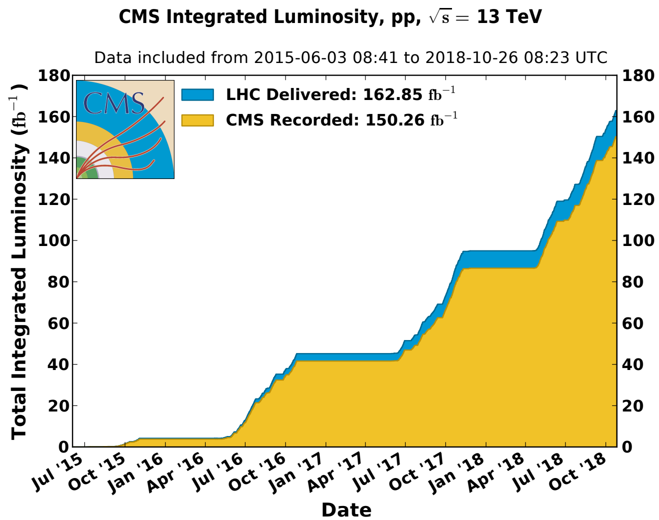
From Tevatron to LHC, x100 increase in cross section:

- Gluon fusion mechanism is now dominant,
- Higher gluon parton density function in the proton at the LHC
- Higher center-of-mass energy

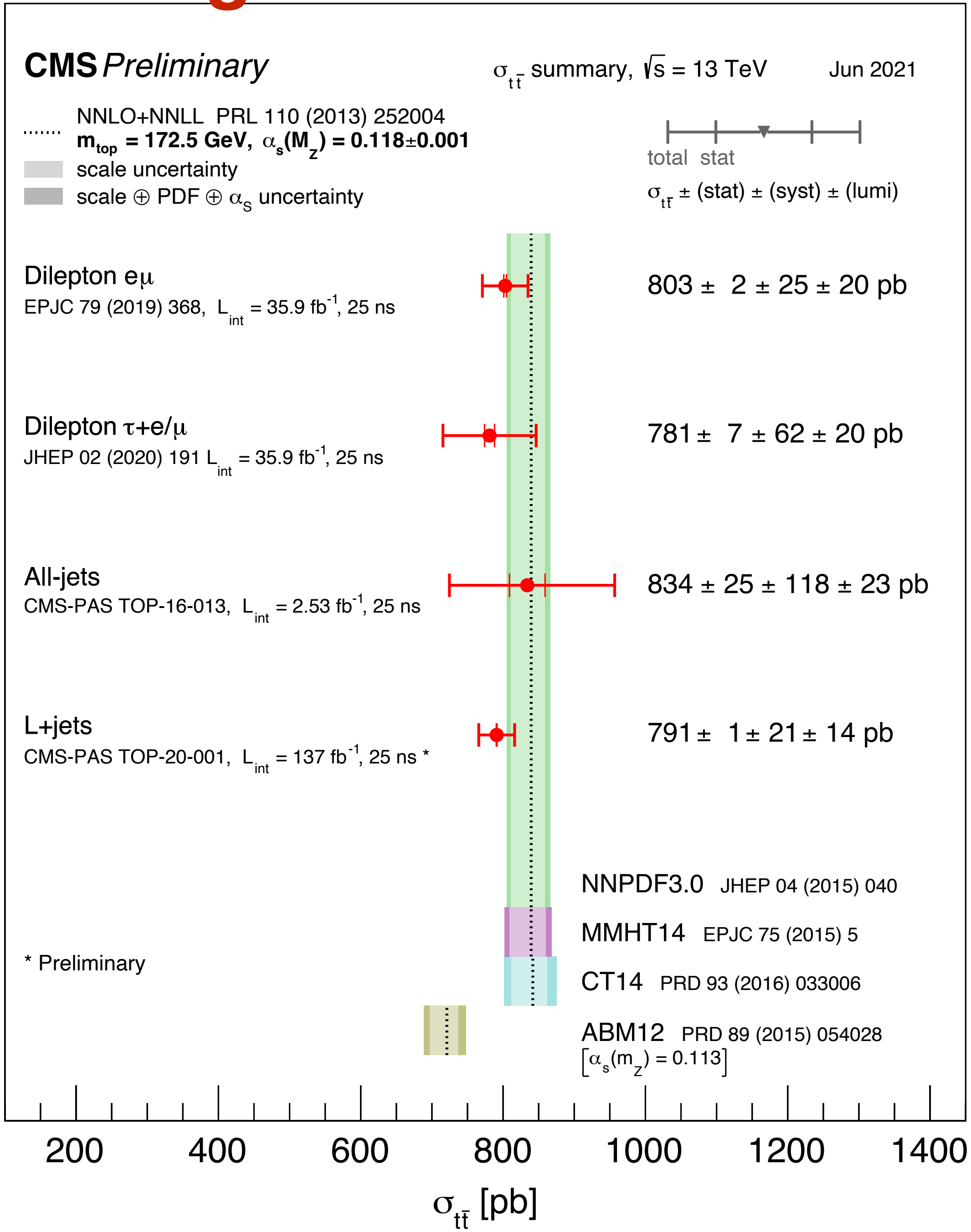


Integrated luminosity

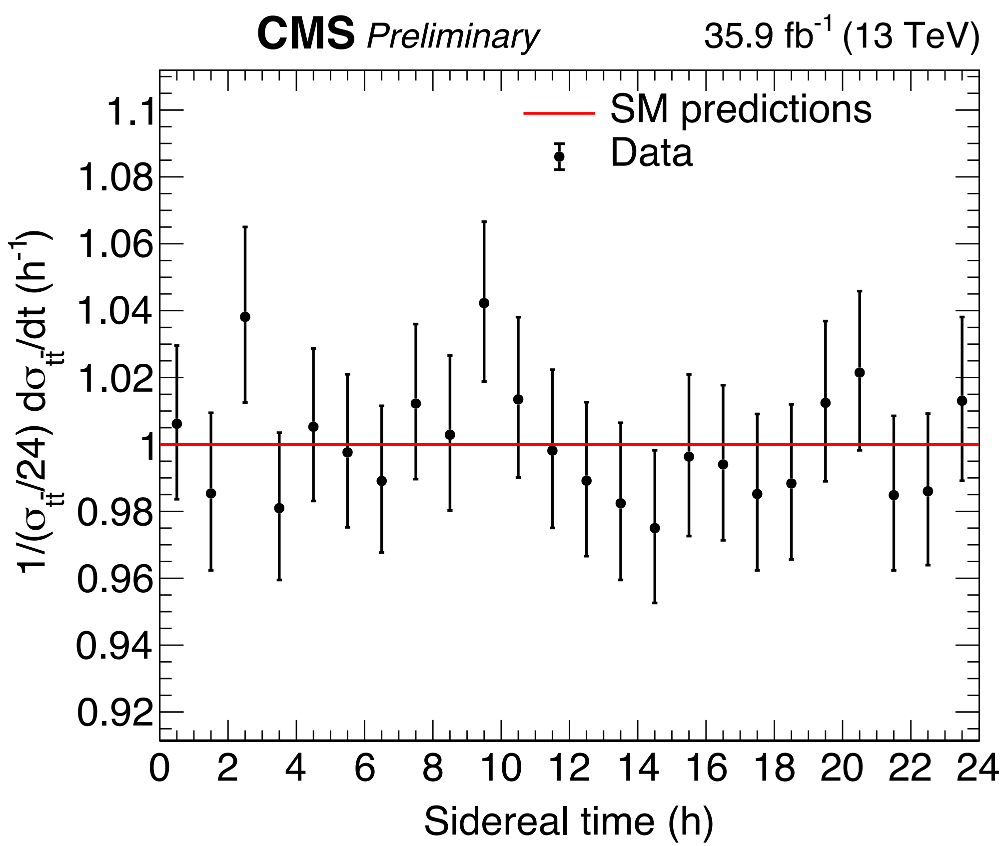
- 5 fb^{-1} at DØ analysis, 77 fb^{-1} in this analysis

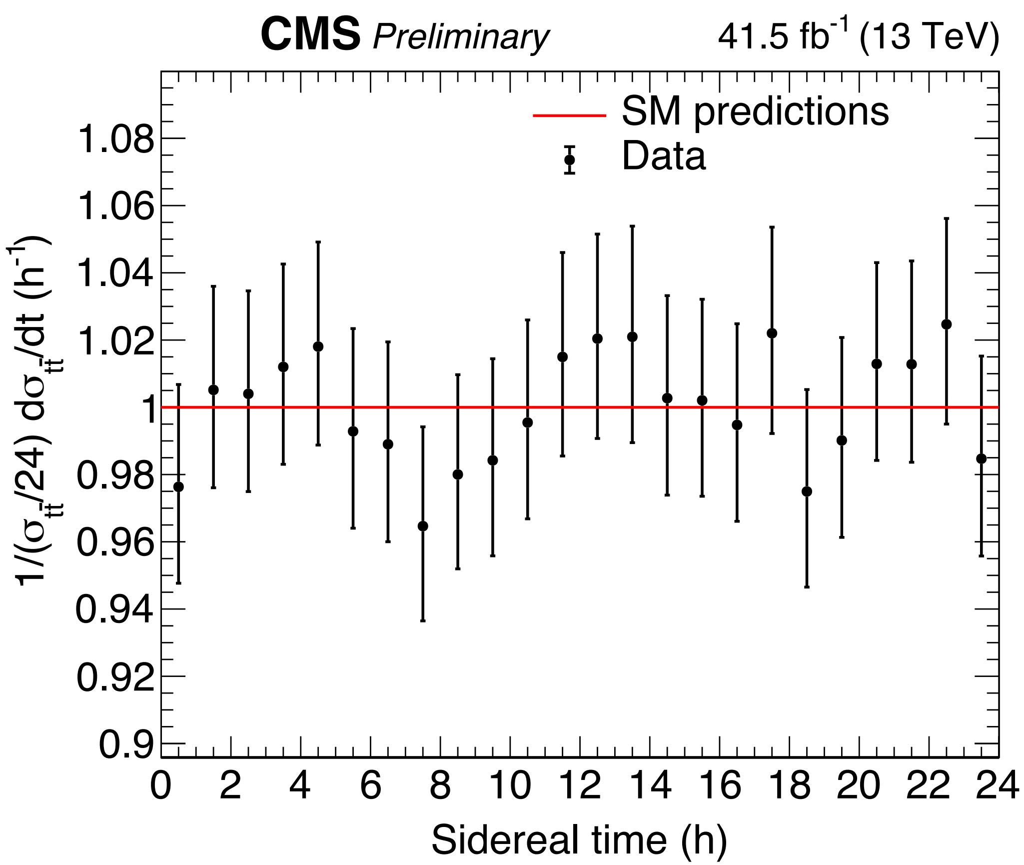


Signal strength in other ttbar analyses



Differential fit in 2016 and 2017





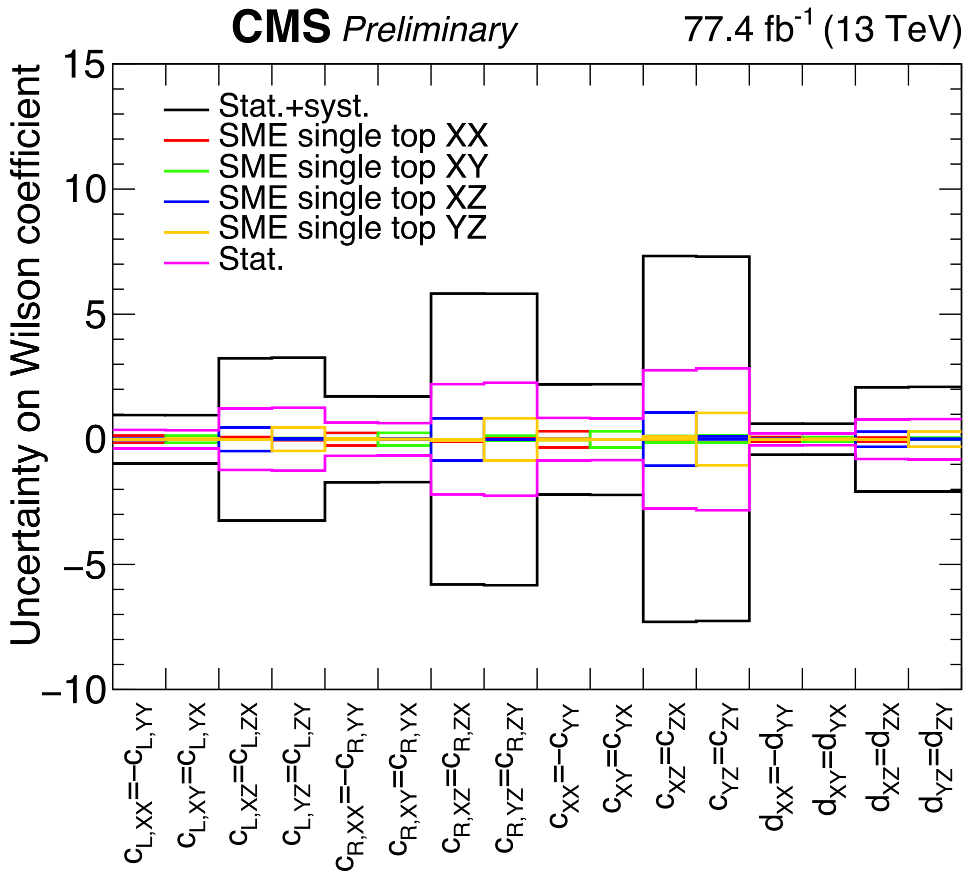
Comparison with SM expectations

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

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

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: ~2π/86400 s^{-1}

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

Jan 1st 2016 in UNIX time

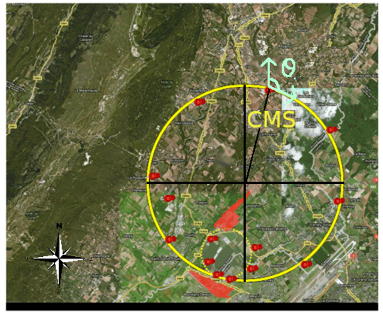
Effective longitude of the beam at CMS P5 relative to Greenwich meridian, in rad

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

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



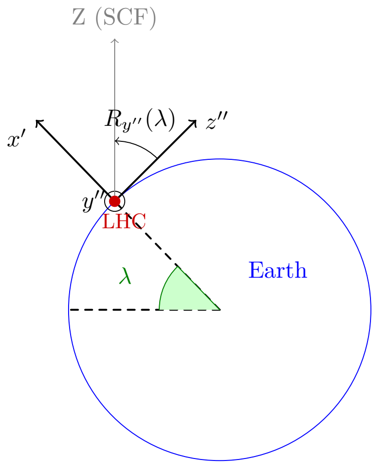
$$R(\lambda,\theta,\alpha) = R_Z(\Omega t)\cdot R_{y''}(\lambda)\cdot R_{x'}\Big(-(\pi-\theta)\Big)\cdot R_z\left(\frac{\pi}{2}\right)\cdot R_x(\alpha)$$

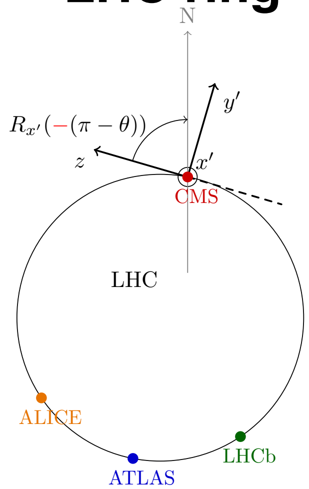
Rotation of the earth around its axis

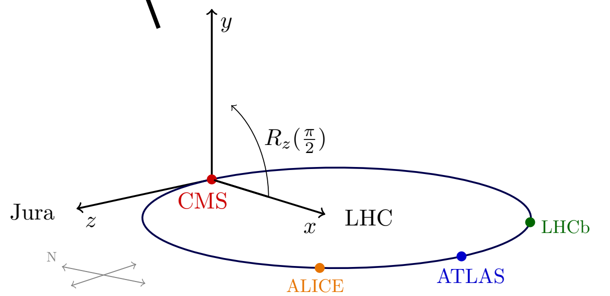
Latitude

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 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

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

Right handed charge 2/3 top singlet

(Focus here on CPT-even coefficients)

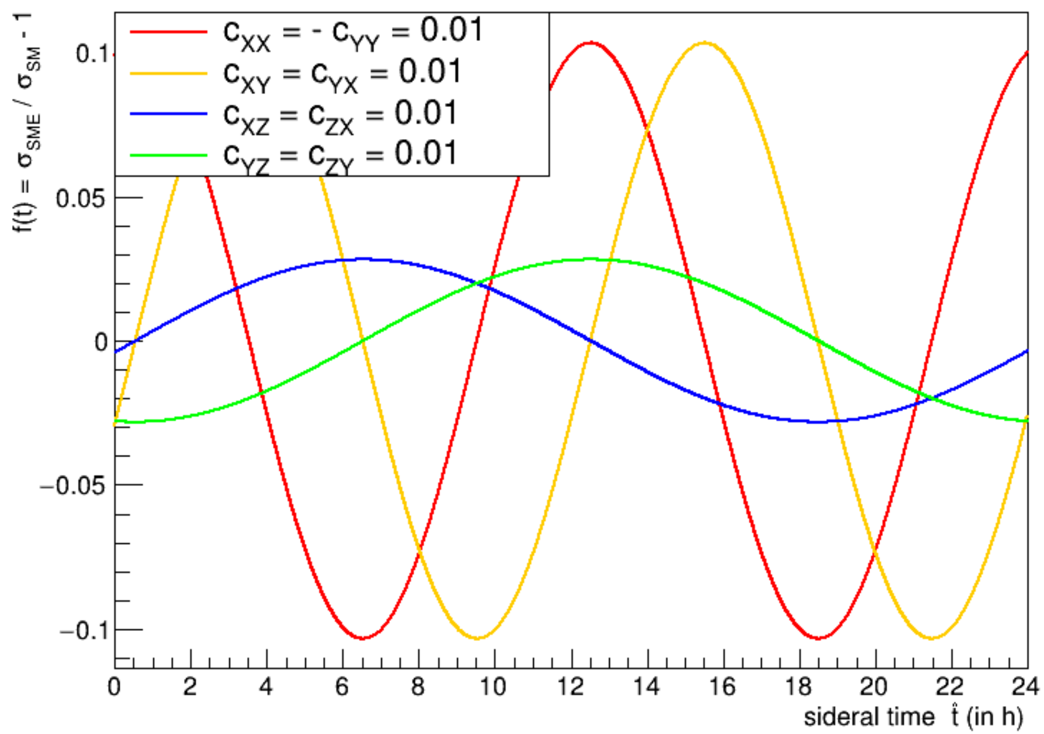
- SME coefficients $\mathbf{c_{\mu\nu}}$ are **violating particle Lorentz invariance**
- $c_{\mu\nu}$ trace is Lorentz-invariant, and its antisymmetric part can be absorbed elsewhere in the Lagrangian: consider $\mathbf{c_{\mu\nu}}$ **as symmetric and traceless**

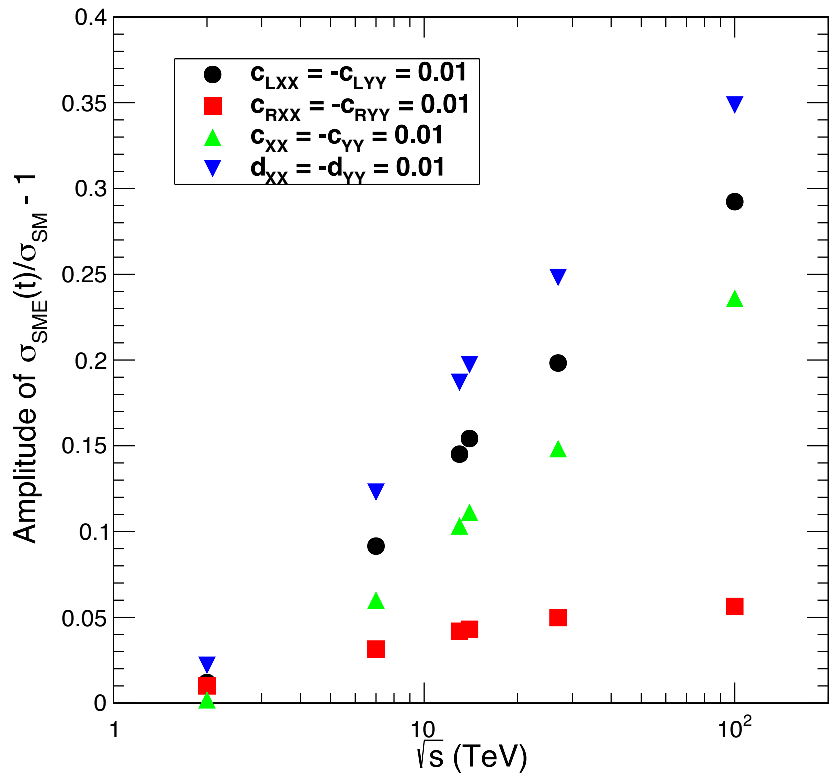
Define: $$c_{\mu\nu} = \tfrac{1}{2}[(c_L)_{\mu\nu} + (c_R)_{\mu\nu}], \quad d_{\mu\nu} = \tfrac{1}{2}[(c_L)_{\mu\nu} - (c_R)_{\mu\nu}]$$

Higher center-of-mass energies

Carle, Chanon, Perriès, Eur.Phys.J.C 80 (2020) 2, 128

- Compare f(t) in p-p collisions at several center-of-mass energy (assuming CMS reference frame), and for several benchmark coefficients
- The amplitude of f(t) increases with the energy (comes mostly from the matrix element)





Expected sensitivity at the LHC and future colliders

Carle, Chanon, Perriès, Eur.Phys.J.C 80 (2020) 2, 128

Benchmarks:

- **D0:** Recomputed expected sensitivity for 5.3 fb-1 of p-pbar collisions at 1.96 TeV
- **LHC Run 2**: Expected sensitivity for 150 fb-1 of p-p collisions at 13 TeV
- **HL-LHC:** 3 ab-1 of p-p collisions at 14 TeV (expected to start data taking in 2027)
- **HE-LHC:** 15 ab-1 of p-p collisions at 27 TeV (option for after HL-LHC, replacing LHC magnets in the same tunnel)
- **FCC-hh:** 15 ab-1 of p-p collisions at 100 TeV (option for after HL-LHC, new magnets and new 100km tunnel)

Expected precision on the top-quark SME coefficients:

	DØ	LHC (Run 2)	HL-LHC	HE-LHC	FCC
$\Delta c_{LXX}, \Delta c_{LXY}$	1×10^{-1}	7×10^{-4}	2×10^{-4}	2×10^{-5}	5×10^{-6}
$\Delta c_{LXZ}, \Delta c_{LYZ}$	8×10^{-2}	3×10^{-3}	5×10^{-4}	9×10^{-5}	2×10^{-5}
$\Delta c_{RXX}, \Delta c_{RXY}$	9×10^{-2}	3×10^{-3}	5×10^{-4}	8×10^{-5}	5×10^{-5}
$\Delta c_{RXZ}, \Delta c_{RYZ}$	7×10^{-2}	1×10^{-2}	2×10^{-3}	4×10^{-4}	8×10^{-5}
$\Delta c_{XX}, \Delta c_{XY}$	7×10^{-1}	1×10^{-3}	2×10^{-4}	3×10^{-5}	9×10^{-6}
$\Delta c_{XZ}, \Delta c_{YZ}$	6×10^{-1}	4×10^{-3}	7×10^{-4}	1×10^{-4}	3×10^{-5}
$\Delta d_{XX}, \Delta d_{XY}$	1×10^{-1}	6×10^{-4}	1×10^{-4}	2×10^{-5}	8×10^{-6}
$\Delta d_{XZ}, \Delta d_{YZ}$	7×10^{-2}	2×10^{-3}	4×10^{-4}	8×10^{-5}	2×10^{-5}

LHC Run 2: Expect 2-3 orders of magnitude improvement wrt D0 (depending on the coeff.)

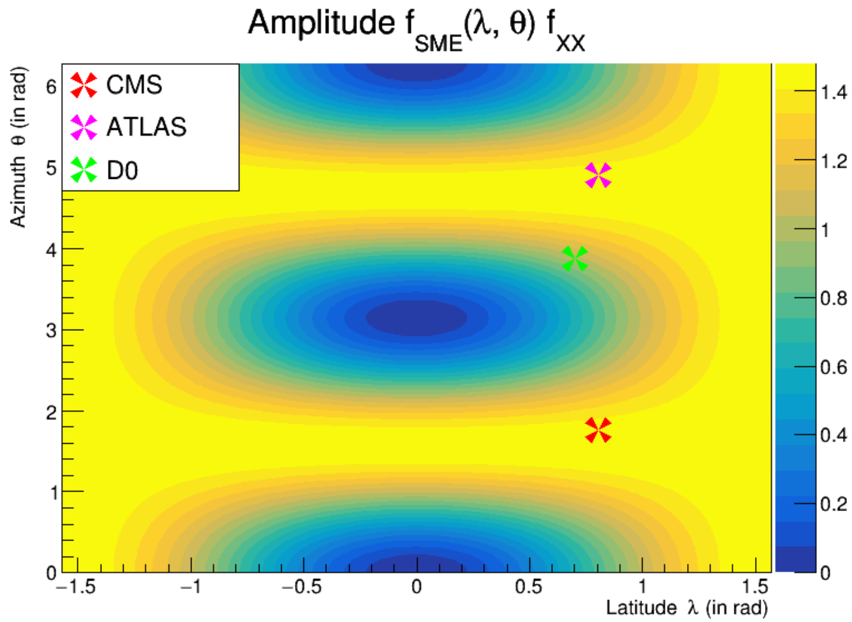
FCC: Expect 2 more orders of magnitude improvement relative to LHC Run 2

Which collider / experiment?

Carle, Chanon, Perriès, arXiv:1909.01990

Comparison LHC / Tevatron (assuming same center-of-mass energy):

- D0 less sensitive than ATLAS/CMS to cXX or cXY scenario
- D0 more sensitive than ATLAS/CMS to cXZ or cYZ scenario



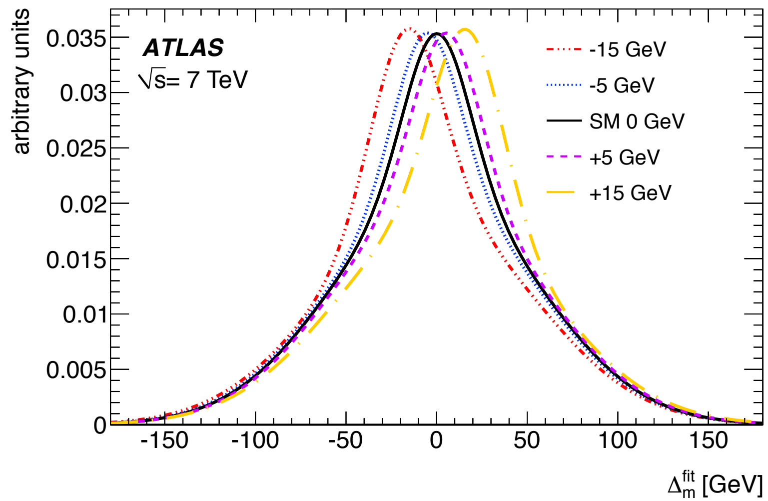
- **Equivalent sensitivity at ATLAS or CMS** (opposite azimuth in the LHC ring)

A note on top/antitop mass difference

Top/Antitop mass difference

- Particle/antiparticle mass difference is not allowed to elementary particles within local quantum field theories, such as the SME
- Can be allowed in non-local theories with CPT breaking

PLB 728 (2014) 363–379



Experimental method

- Kinematic fit used to reconstruct the top mass in lepton+jets or dilepton decay channels
- Can measure top / antitop mass in separated dataset and combine statistically
- Or can measure simultaneously top and antitop masses

CMS 8 TeV (*PLB 770 (2017) 50–71*):

$$\Delta m_t = -0.15 \pm 0.19\,(\text{stat}) \pm 0.09\,(\text{syst})\ \text{GeV}$$

- Compatible with the SM
- This measurement has not been interpreted in the context of a given BSM model