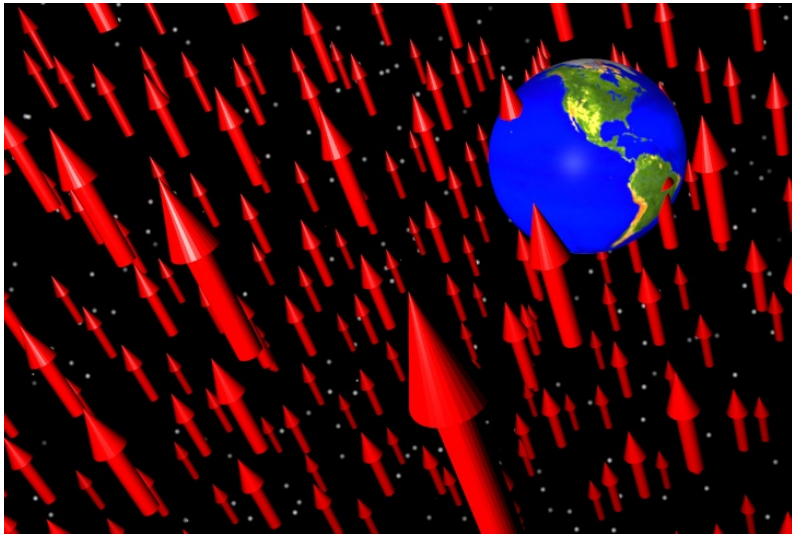
Prospects for Lorentz invariance violation searches with top quarks

Top LHC France 2022 - 10/05/2022 - IP2I Lyon



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Lorentz invariance

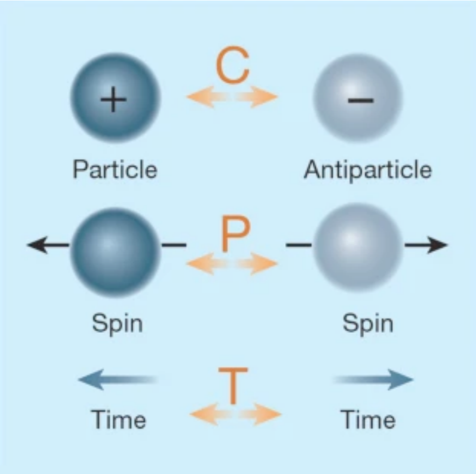
Lorentz transformation:

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

Global transformation of spacetime coordinates

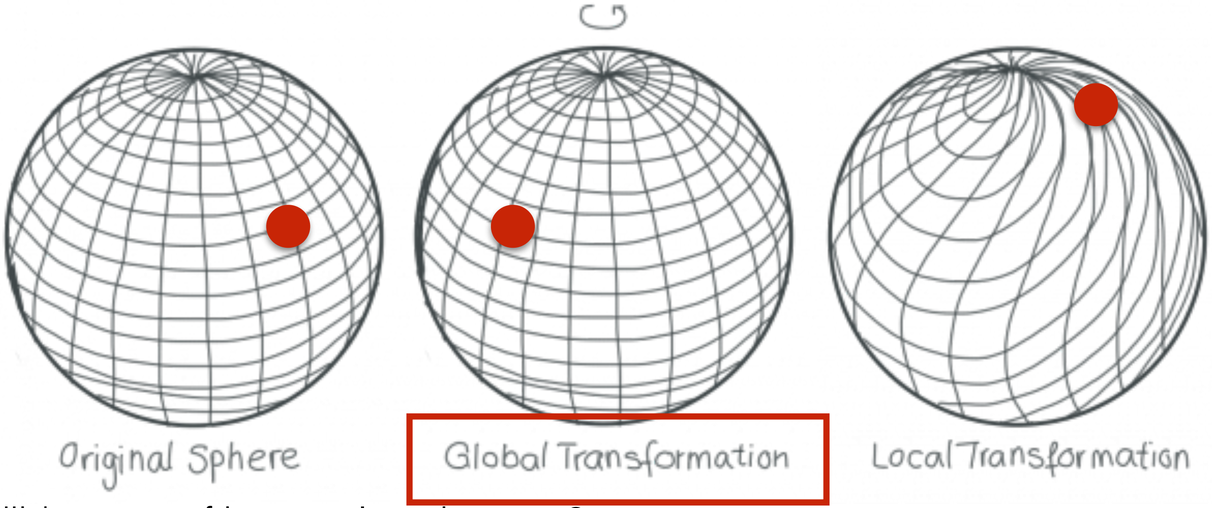
Lorentz group:

- **Rotations**
- **Lorentz boosts**
- **P** (spacial inversion) and **T** (time reversal)



C: charge conjugation, transforms particles into antiparticles
CPT theorem: a QFT a preserving Lorentz invariance must also preserve CPT symmetry.
=> CPT is intimately connected with Lorentz invariance
CPT violation implies Lorentz violation for local QFT theories *[hep-ph:0201258]*

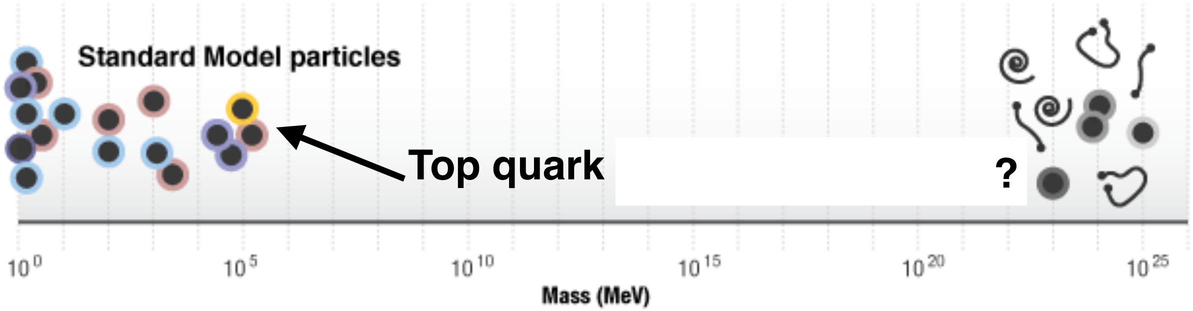
Observation shows Lorentz invariance and CPT symmetry are preserved (so far).



Standard Model Extension

Theoretical motivation:

- Models of bosonic **strings** predict spontaneous breaking of Lorentz Invariance *[PRD.39.683]*
- Lorentz Invariance is not necessarily maintained in **Loop Quantum Gravity** *[gr-qc/0205125]*
- The Quantum Gravity scale could be lower than the Planck scale, e.g. in the paradigm of large extra dimensions *[hep-ph/9803315]*
- Remnants of the breaking could be observed at lower energy scale



Standard Model Extension (SME) Effective Field Theory:

- **Add all Lorentz- and CPT-violating operators** to the SM Lagrangian *[hep-ph/9809521]*
- The Dirac sector:

$$L_{SME} = \frac{1}{2} i \bar{\psi} \Gamma^{\nu} \partial_{\nu} \psi - M \bar{\psi} \psi$$

$$\Gamma^{\nu} = \gamma^{\nu} + \boxed{c^{\mu\nu}} \gamma^{\mu} + \boxed{d^{\mu\nu}} \gamma^5 \gamma^{\mu} + e^{\nu} + i f^{\nu} \gamma^5 + \frac{1}{2} g^{\mu\nu\lambda} \sigma_{\lambda\mu}$$

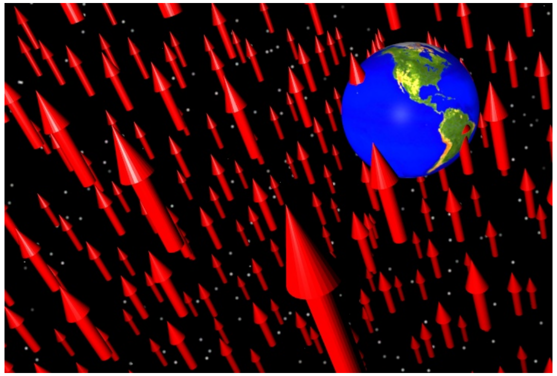
$$M = m + a_{\mu} \gamma^5 + b_{\mu} \gamma^5 \gamma^{\mu} + H_{\mu\nu} \sigma_{\mu\nu}$$

Time-dependant signal with top quarks

$$L_{SME} = \frac{1}{2} i \bar{\psi} \Gamma^{\nu} \partial_{\nu} \psi - M \bar{\psi} \psi$$

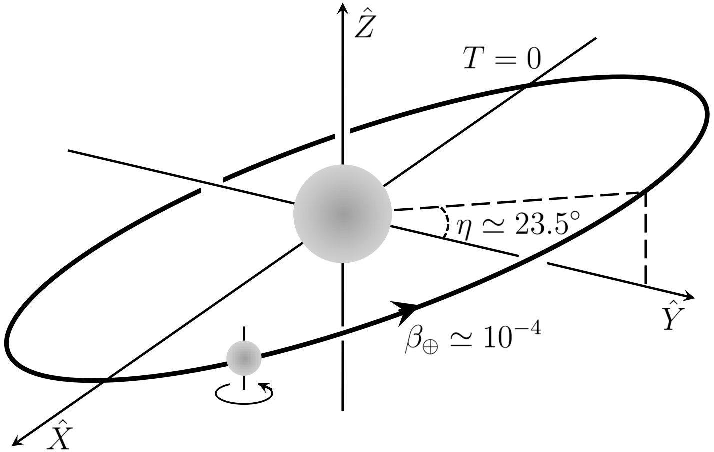
$$\Gamma^{\nu} = \gamma^{\nu} + \boxed{c^{\mu\nu}} \gamma^{\mu} + \boxed{d^{\mu\nu}} \gamma^{5} \gamma^{\mu} + e^{\nu} + i f^{\nu} \gamma^{5} + \frac{1}{2} g^{\mu\nu\lambda} \sigma_{\lambda\mu}$$

$$M = m + a_{\mu} \gamma^{5} + b_{\mu} \gamma^{5} \gamma^{\mu} + H_{\mu\nu} \sigma_{\mu\nu}$$



Particle-Lorentz violation:

- At Lagrangian level, SME coefficients are **constant matrices**, not respecting Lorentz transformations
- They indicate **preferential directions in spacetime**
- An inertial frame still needs to be defined to report any observation.
- By convention, use the **Sun-Centered frame**.

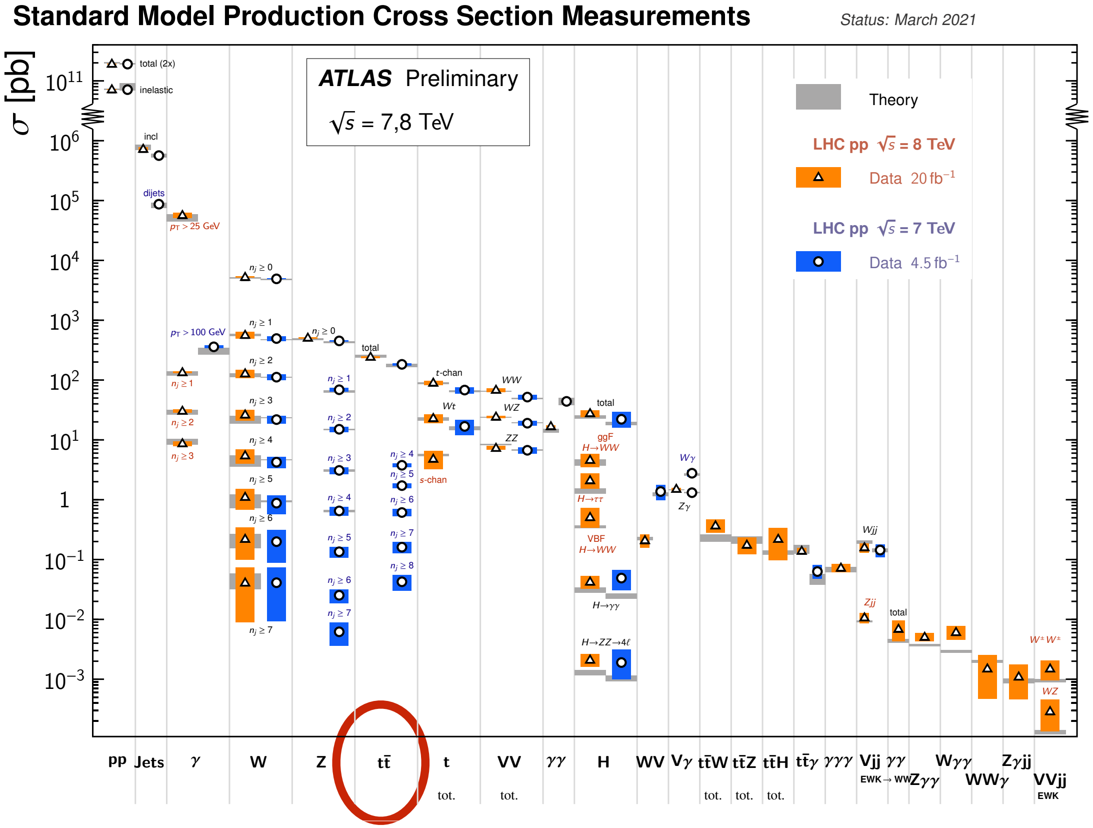


Within the Sun-centered frame:

- The laboratory (CMS) frame is rotating daily around the earth Z-axis of rotation
- The SME coefficients are constant
- Induces a **modulation of the top-antitop cross section with sidereal time**

Why searching for LIV with top quarks?

- **Only one actual measurement** performed, at **D0 Tevatron (2012)**: best direct world limits on Lorentz invariance violation at Tevatron
- The top quark is the **heaviest** known elementary particle, and the only quark which **decays before hadronizing**
- It is interesting to **test special relativity** in this poorly tested sector.
- Top quark production has **large cross section at the LHC: expect much improved precision.**



Top quark: existing bounds

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

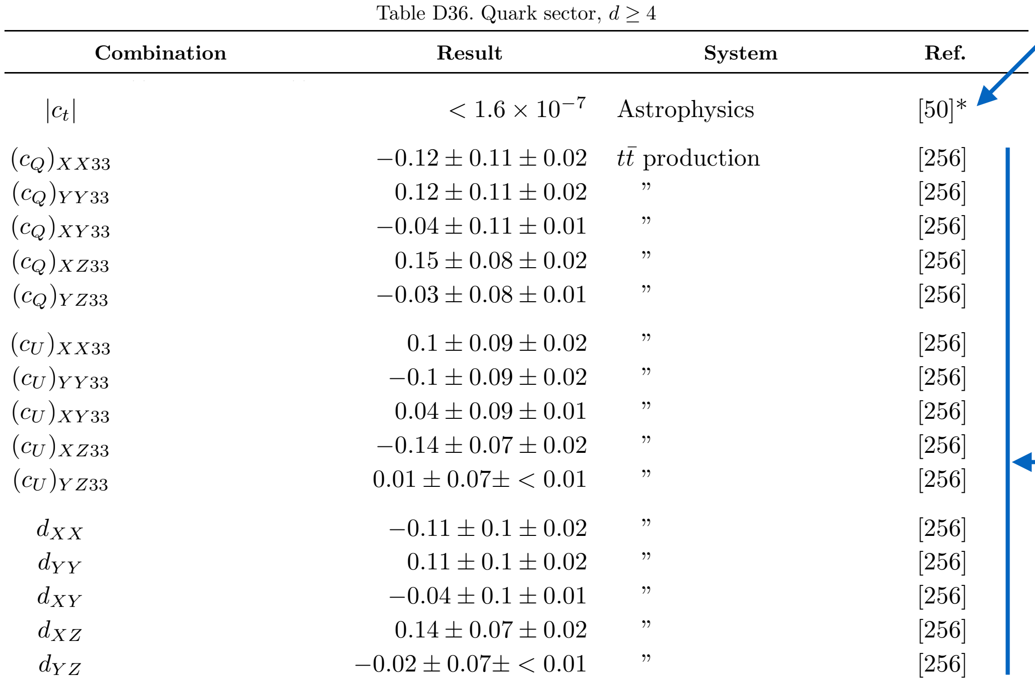
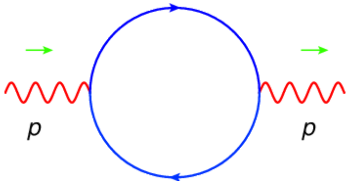


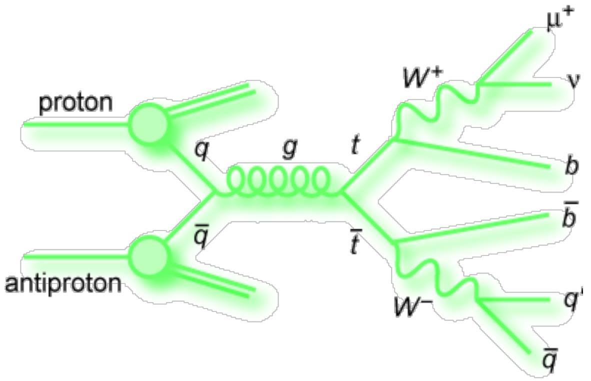
Table D36. Quark sector, $d \geq 4$

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



Direct bounds (*PRL108:261603, 2012*): measurement of top pair production at DØ (Tevatron)



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

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

Right handed charge 2/3 top singlet

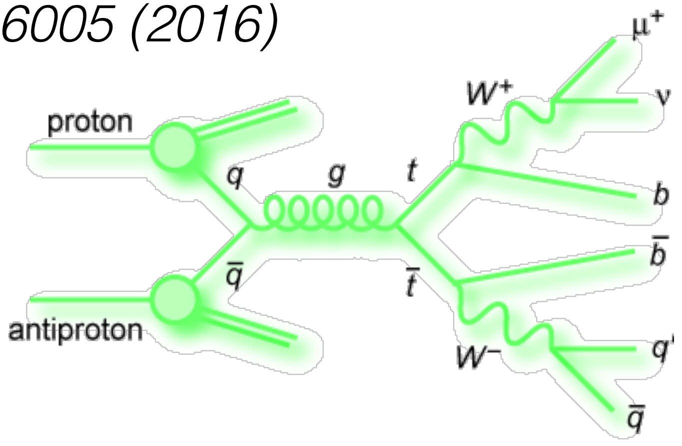
(Focus here on CPT-even coefficients)

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

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

Top pair production in the SME

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



Top quark (~173 GeV) **decays** at almost 100% to **Wb**.
Assume **narrow-width** approximation for top quarks:

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

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

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

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

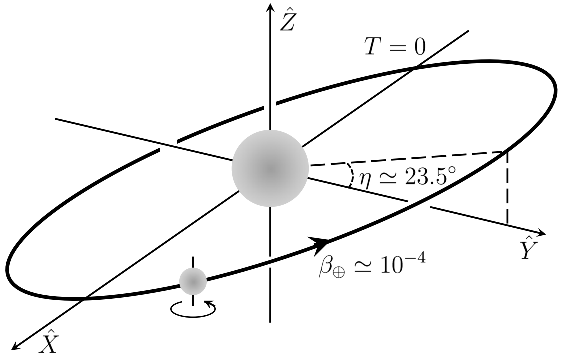
LIV change in top quark propagator

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



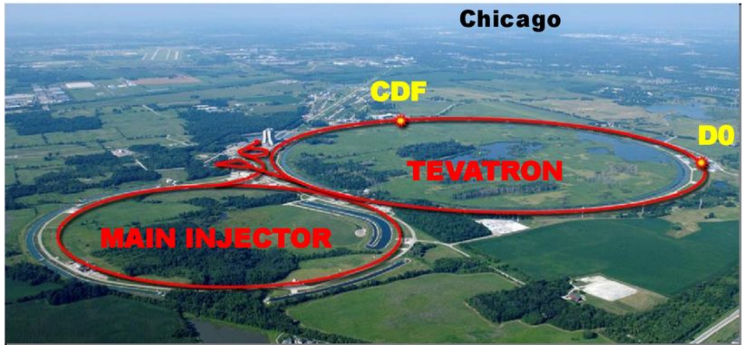
Induces a **modulation of the top-antitop cross section with sidereal time**

Selecting top pair production at DØ

D0 Collaboration, PRL108:261603, 2012

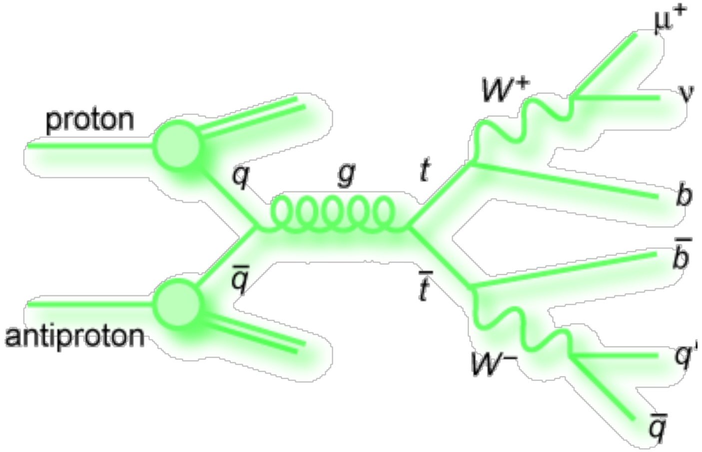
Dataset and selection

- **Dataset**: Integrated luminosity L=5.3 fb-1 of proton-antiproton collisions (2002-2009)

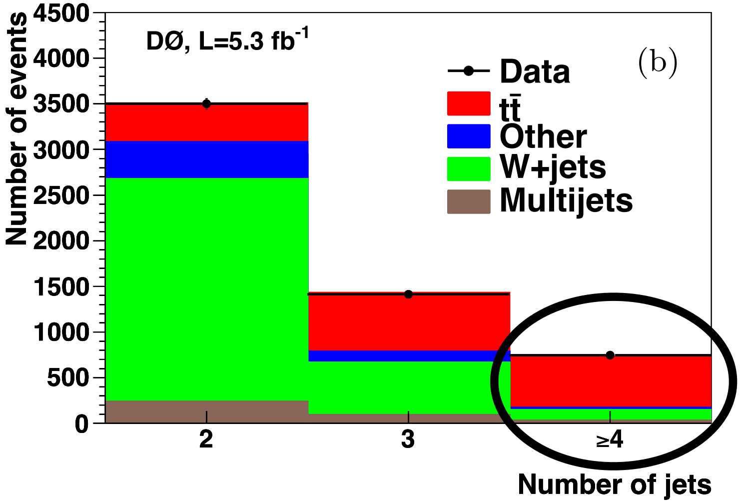


Select **semi-leptonic decays** of top pair production:

- one **electron or muon** with pT > 20 GeV and |η|<1.1 (electron) or < 2 (muon)
- **missing transverse energy** (~neutrino) mET > 20 (25) GeV
- **at least 4 jets** with pT > 20 GeV (leading: 40 GeV) and |η|<2.5,
- among which **1 b-tagged jet** (b-tagging with neural network algorithm)



Phys.Rev. D84 (2011) 012008



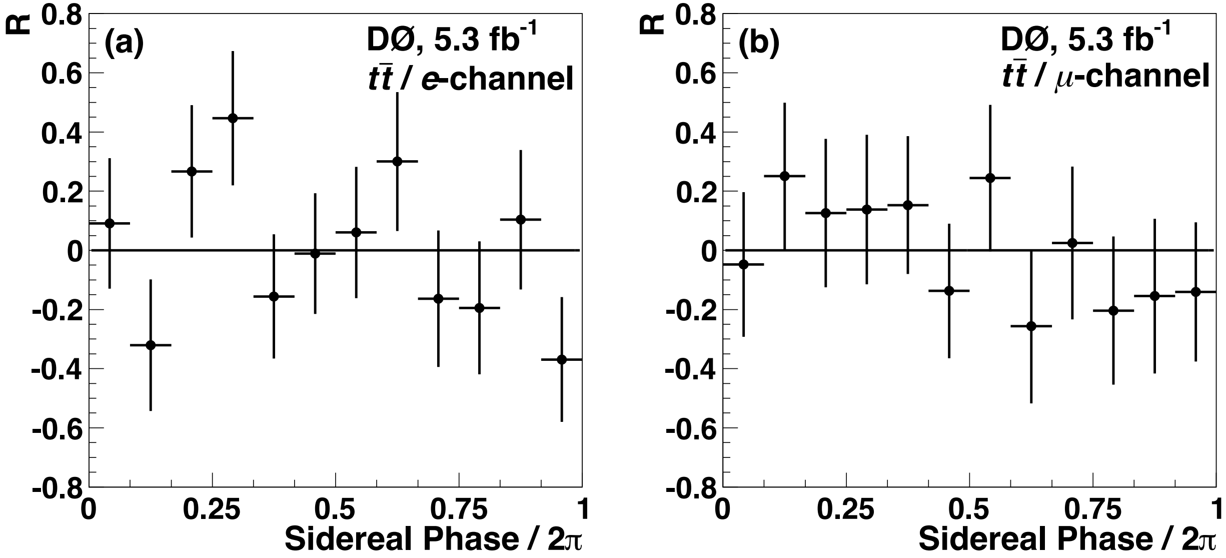
Very clean s/b~4

Searches for LIV in Top pair production at DØ

D0 Collaboration, PRL108:261603, 2012

Sidereal time analysis

- **Search for periodic variation** of the recorded number of events (bins of 2 sidereal hours)
- Correct data for varying instantaneous luminosity in the fill



f$_{\text{SME}}$:

$$\sigma(t) \approx \sigma_{\text{ave}}\left[1 + f_{\text{SME}}(t)\right]$$

f$_{\text{S}}$: average fraction of signal

$$N_i \approx N_{\text{tot}} \frac{\mathcal{L}_i}{\mathcal{L}_{\text{int}}}\left[1 + f_S f_{\text{SME}}(\phi_i)\right]$$

$$R_i \equiv \frac{1}{f_S}\left(\frac{N_i/N_{\text{tot}}}{\mathcal{L}_i/\mathcal{L}_{\text{int}}} - 1\right)$$

can be directly compared with f$_{\text{SME}}$

Search for a sinusoidal signal (fit the functional forms of f$_{\text{SME}}$ to R):

TABLE II: Forms for $f_{\text{SME}}(\phi)$ used to extract SME coefficients.

Condition	$f_{\text{SME}}(\phi)$
$C_{XX} = -C_{YY}$	$2C_{XX}\left(\frac{b_1-b_2}{2}\cos 2\phi + b_3 \sin 2\phi\right)$
$C_{XY} = C_{YX}$	$2C_{XY}\left(\frac{b_1-b_2}{2}\sin 2\phi - b_3 \cos 2\phi\right)$
$C_{XZ} = C_{ZX}$	$2C_{XZ}\left(b_4 \cos\phi + b_5 \sin\phi\right)$
$C_{YZ} = C_{ZY}$	$2C_{YZ}\left(b_4 \sin\phi - b_5 \cos\phi\right)$

DØ results

D0 Collaboration, PRL108:261603, 2012

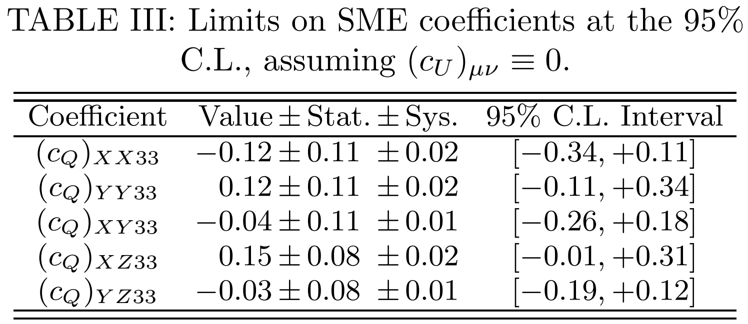


TABLE III: Limits on SME coefficients at the 95% C.L., assuming $(c_U)_{\mu\nu} \equiv 0$.

Coefficient	Value ± Stat. ± Sys.	95% C.L. Interval
$(c_Q)_{XX33}$	$-0.12 \pm 0.11 \ \pm 0.02$	$[-0.34, +0.11]$
$(c_Q)_{YY33}$	$0.12 \pm 0.11 \ \pm 0.02$	$[-0.11, +0.34]$
$(c_Q)_{XY33}$	$-0.04 \pm 0.11 \ \pm 0.01$	$[-0.26, +0.18]$
$(c_Q)_{XZ33}$	$0.15 \pm 0.08 \ \pm 0.02$	$[-0.01, +0.31]$
$(c_Q)_{YZ33}$	$-0.03 \pm 0.08 \ \pm 0.01$	$[-0.19, +0.12]$

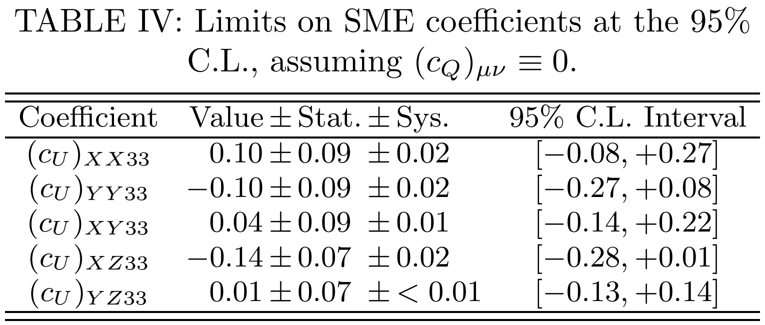


TABLE IV: Limits on SME coefficients at the 95% C.L., assuming $(c_Q)_{\mu\nu} \equiv 0$.

Coefficient	Value ± Stat. ± Sys.	95% C.L. Interval
$(c_U)_{XX33}$	$0.10 \pm 0.09 \ \pm 0.02$	$[-0.08, +0.27]$
$(c_U)_{YY33}$	$-0.10 \pm 0.09 \ \pm 0.02$	$[-0.27, +0.08]$
$(c_U)_{XY33}$	$0.04 \pm 0.09 \ \pm 0.01$	$[-0.14, +0.22]$
$(c_U)_{XZ33}$	$-0.14 \pm 0.07 \ \pm 0.02$	$[-0.28, +0.01]$
$(c_U)_{YZ33}$	$0.01 \pm 0.07 \ \pm < 0.01$	$[-0.13, +0.14]$

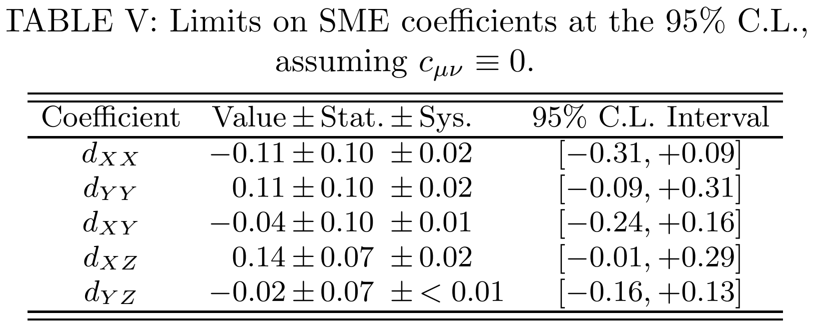


TABLE V: Limits on SME coefficients at the 95% C.L., assuming $c_{\mu\nu} \equiv 0$.

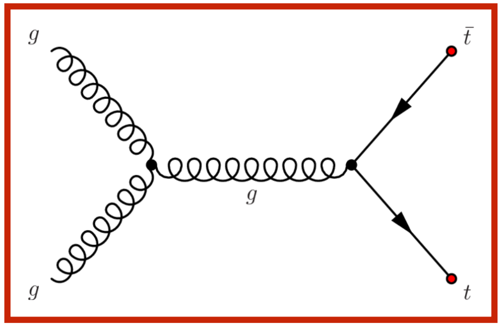
Coefficient	Value ± Stat. ± Sys.	95% C.L. Interval
d_{XX}	$-0.11 \pm 0.10 \ \pm 0.02$	$[-0.31, +0.09]$
d_{YY}	$0.11 \pm 0.10 \ \pm 0.02$	$[-0.09, +0.31]$
d_{XY}	$-0.04 \pm 0.10 \ \pm 0.01$	$[-0.24, +0.16]$
d_{XZ}	$0.14 \pm 0.07 \ \pm 0.02$	$[-0.01, +0.29]$
d_{YZ}	$-0.02 \pm 0.07 \ \pm < 0.01$	$[-0.16, +0.13]$

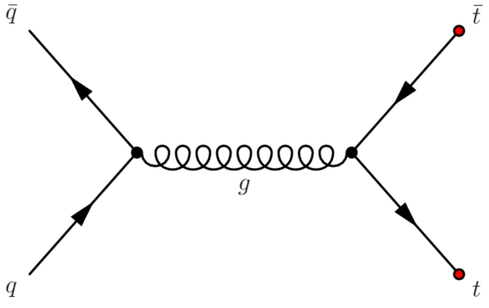
SME benchmarks:

- c_{TT} impacts inclusive cross section: no handle
- No sensitivity to c_{ZZ} (owing to earth rotation around Z-axis)
- $c_{XX}=-c_{YY}$
- $c_{XY}=c_{YX}$
- $c_{YZ}=c_{ZY}$
- $c_{XZ}=c_{ZX}$

- Measure limits on each SME coefficient assuming the other coefficients to be 0
- Each coefficient is **compatible with 0 with absolute precision of ~10%**

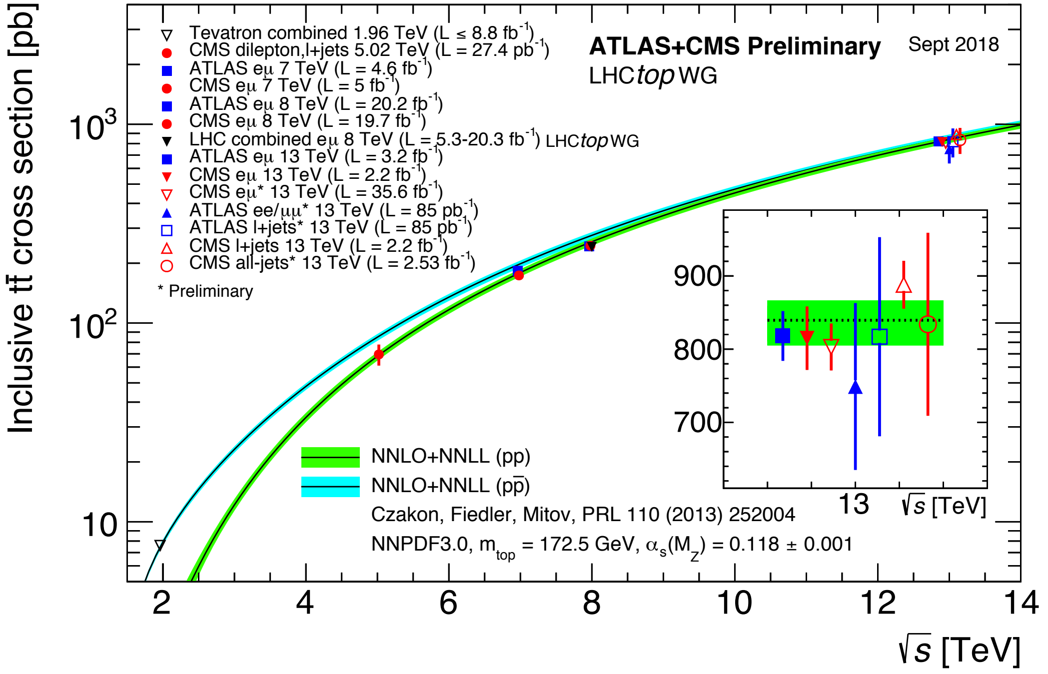
The LHC: a top quark factory





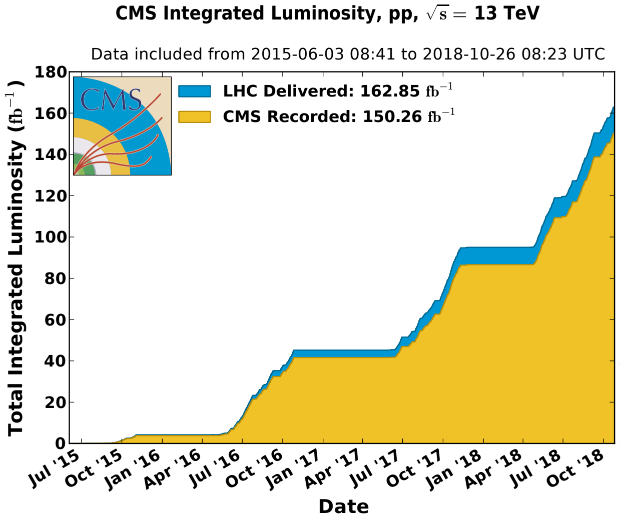
From Tevatron to LHC, x100 increase in cross section:

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



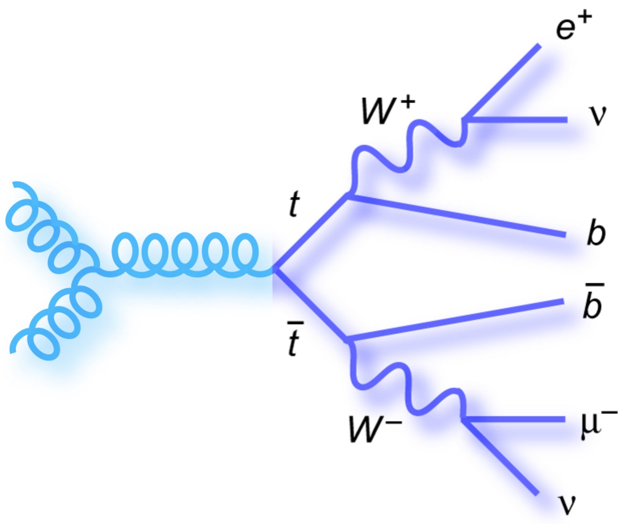
Integrated luminosity

- About 150 fb^{-1} recorded at Run 2 (2015-2018) => x30 DØ analysis



Prospects at the LHC

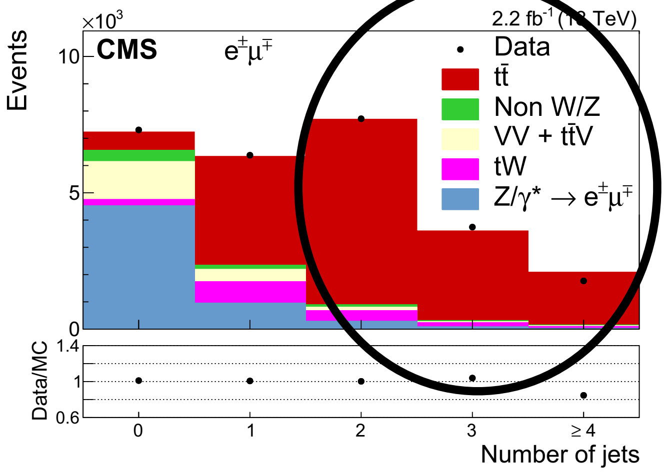
Carle, Chanon, Perriès, Eur.Phys.J.C 80 (2020) 2, 128



Prospective study:

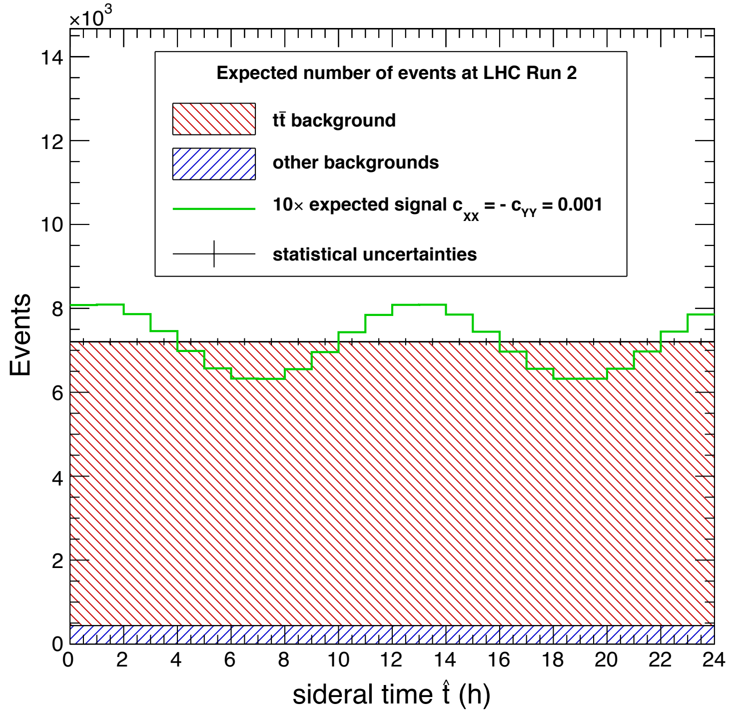
- Goal: estimate the expected precision that could be achieved at LHC Run 2 (L~150 fb-1)
- Consider dilepton eμ channel with at least 2 jets
- Generate top pair production at LO in perturbative QCD
- Normalize events to NNLO in pQCD
- Evaluate the SME time modulation with these samples
- Assume ATLAS/CMS reference frame at the LHC

Eur. Phys. J. C (2017) 77:172



very clean s/b~15

Projection at 13 TeV and Run 2 luminosity:



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 2029)
- **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}

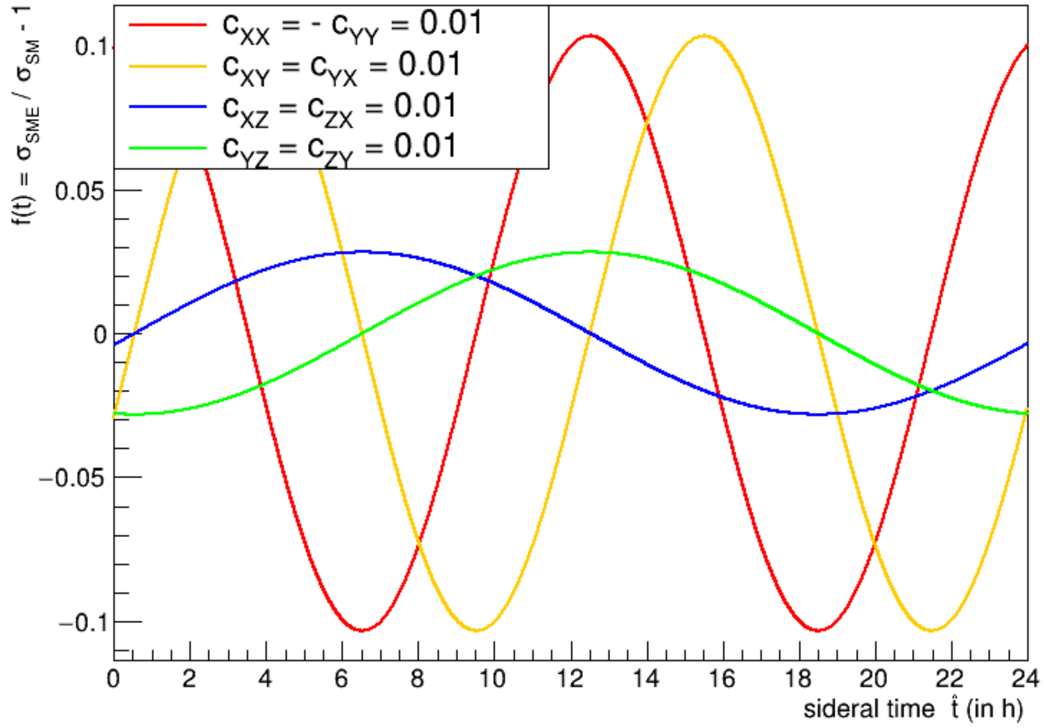
LHC Run 2: Expect 2-3 orders of magnitude improvement wrt D0 (depending on the coeff.)

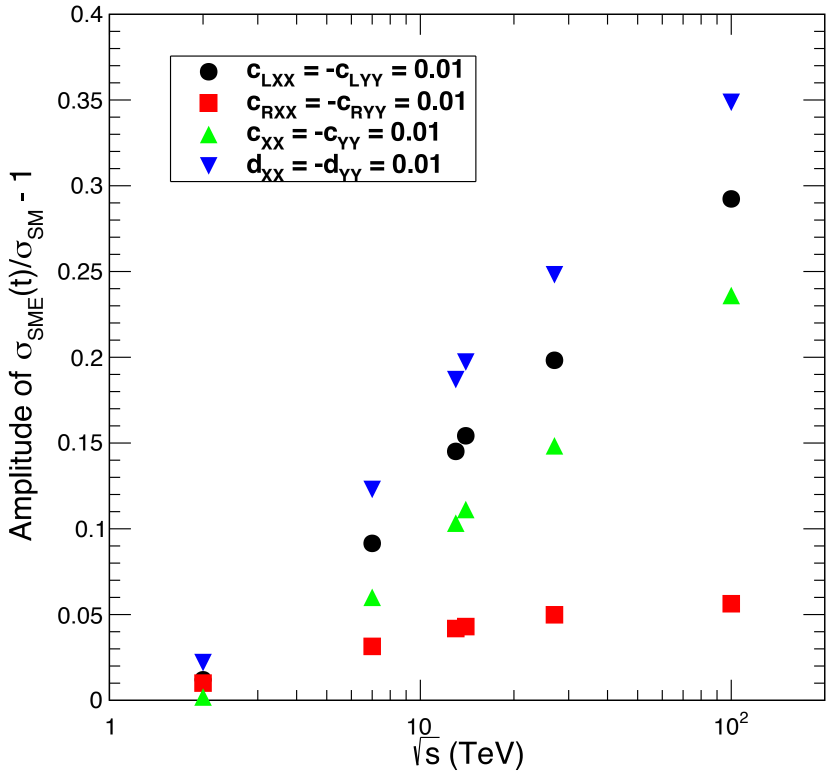
FCC: Expect 2 more orders of magnitude improvement relative to LHC Run 2

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, not pdf)

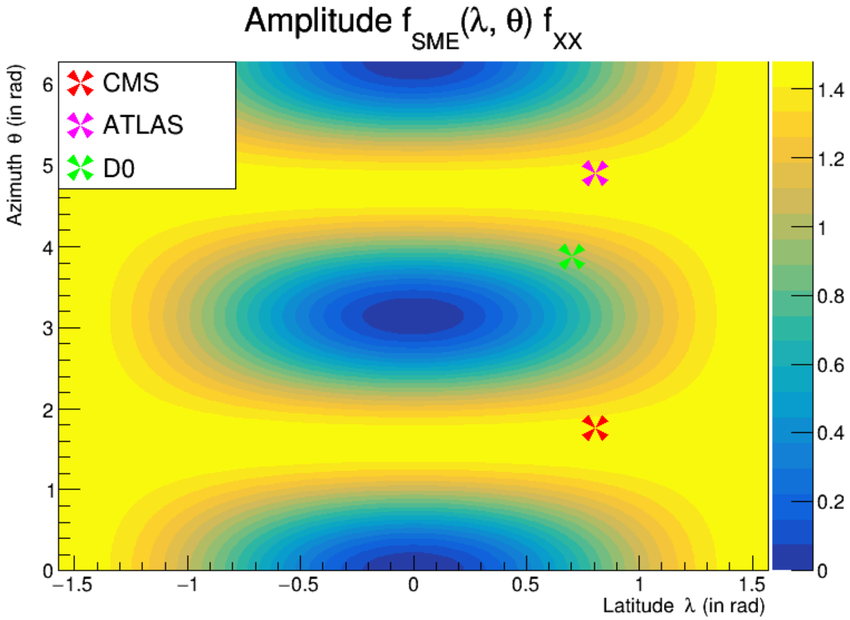




Which collider / experiment?

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)

Conclusions

Searches for Lorentz invariance in the top quark sector:

- The top sector is almost an unexplored territory for testing Lorentz invariance at high energy
- Only one direct measurement performed so far, at Tevatron
- Expect much improved results at the LHC
- Projections show an expected sensitivity that might be improved by a factor 10^2-10^3 at the LHC, and 10^5 at the FCC-hh, relative to Tevatron measurement

Back-up slides

A note on top/antitop mass difference

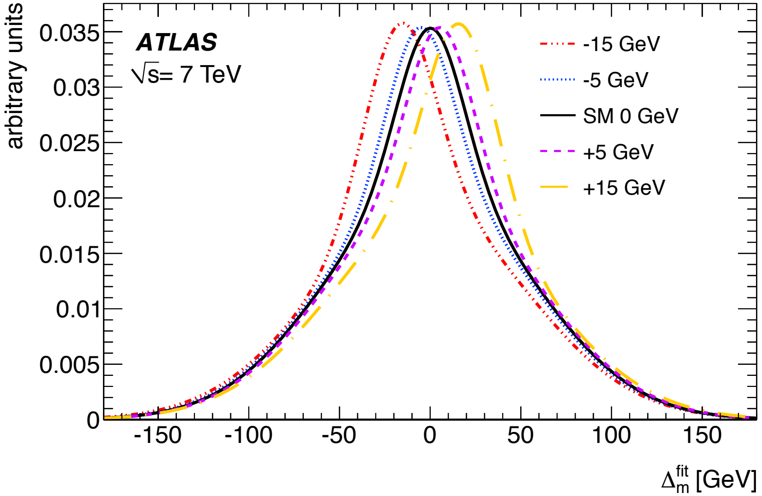
Top/Antitop mass difference

- 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



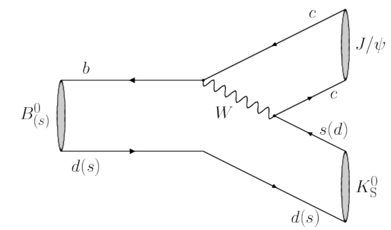
E.g. best measurement at 8 TeV (*PLB 770 (2017) 50–71*):

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

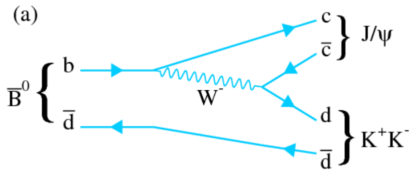
- Compatible with the SM
- This measurement has not been interpreted in the context of a given BSM model

Search for CPT violation in $B_{(s)}$ oscillations at LHCb

LHCb Collaboration, Phys. Rev. Lett. 116, 241601 (2016)



- B and Bs mesons oscillation to their antiparticle is sensitive to CP and CPT symmetry
- **Interferometry**: searching for variations of the B and Bs particle / antiparticle mass difference with sidereal time:



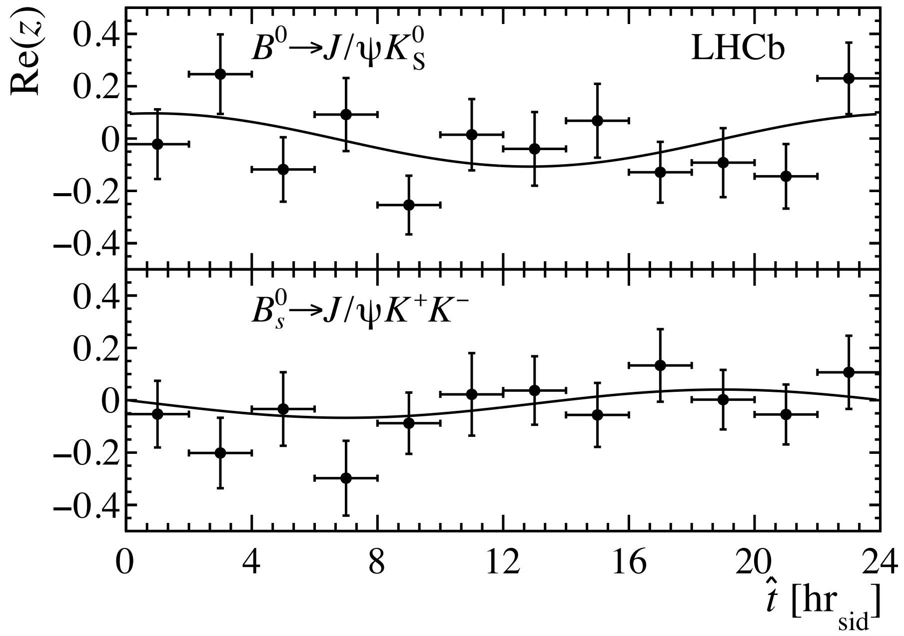
B-meson velocity

CPT-odd SME coefficient

$$z = \frac{\delta m - i\delta\Gamma/2}{\Delta m - i\Delta\Gamma/2} \qquad z \simeq \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}$$

Mass difference of mass eigenstates

Width difference of mass eigenstates



- Limits down to the 10^{-14} GeV level
- **x100 improvement in limits** relative to previous measurements