Recent highlights of top-quark property measurements from CMS

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on behalf of the CMS Collaboration

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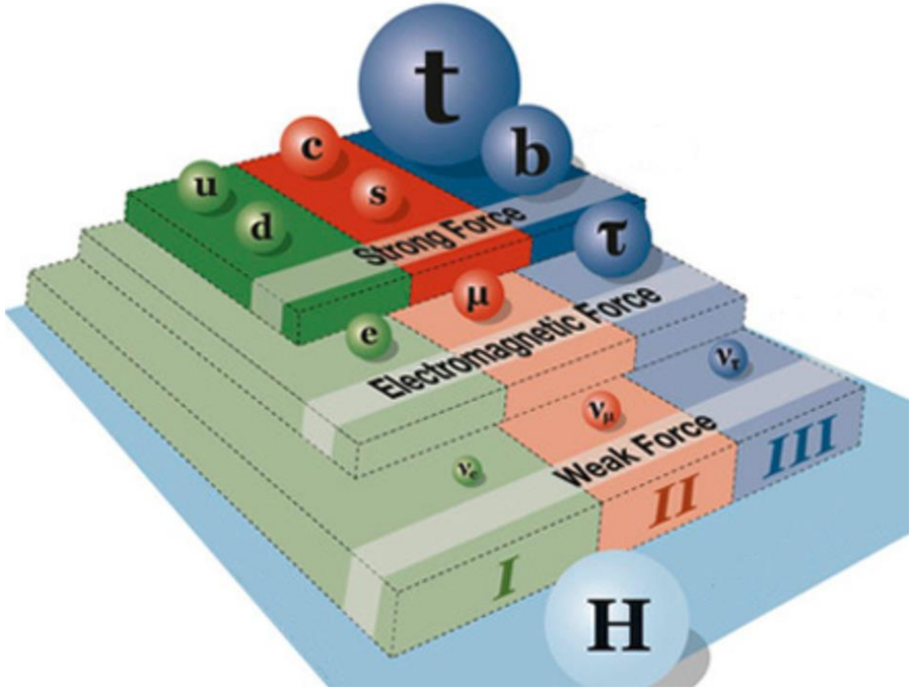
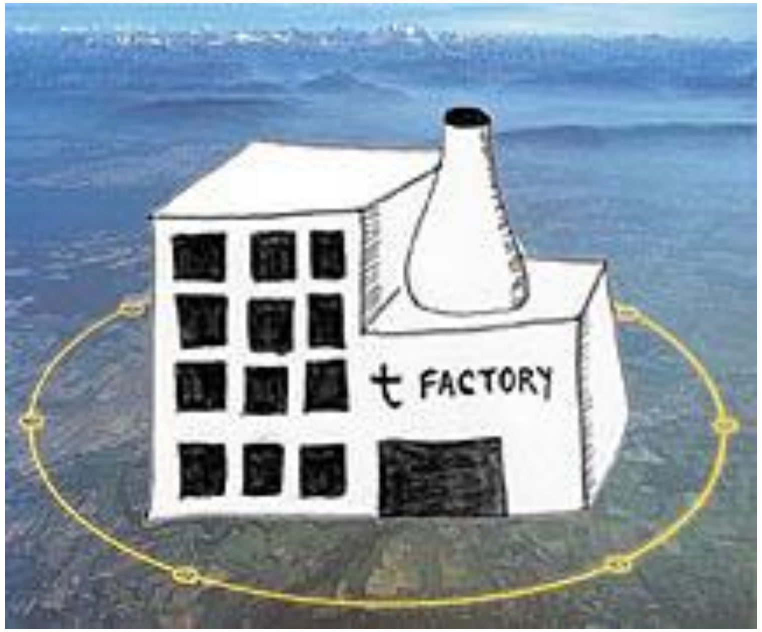
Top Quark Physics

- Top quark is the heaviest fundamental particle discovered thus far: m_t = 173.34 +/- 0.76 GeV
- Unique: [arxiv:1403.4427]

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$

- LHC is a top quark factory (**<u>100m+</u>** thus far)

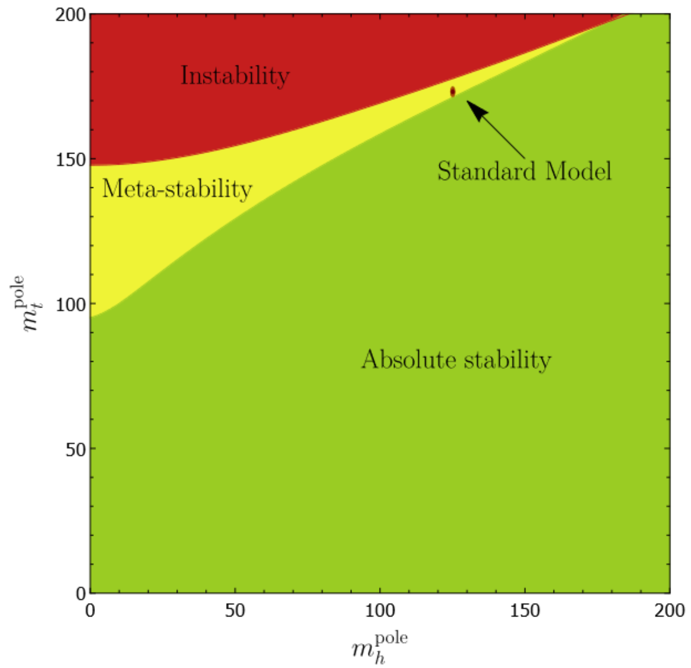




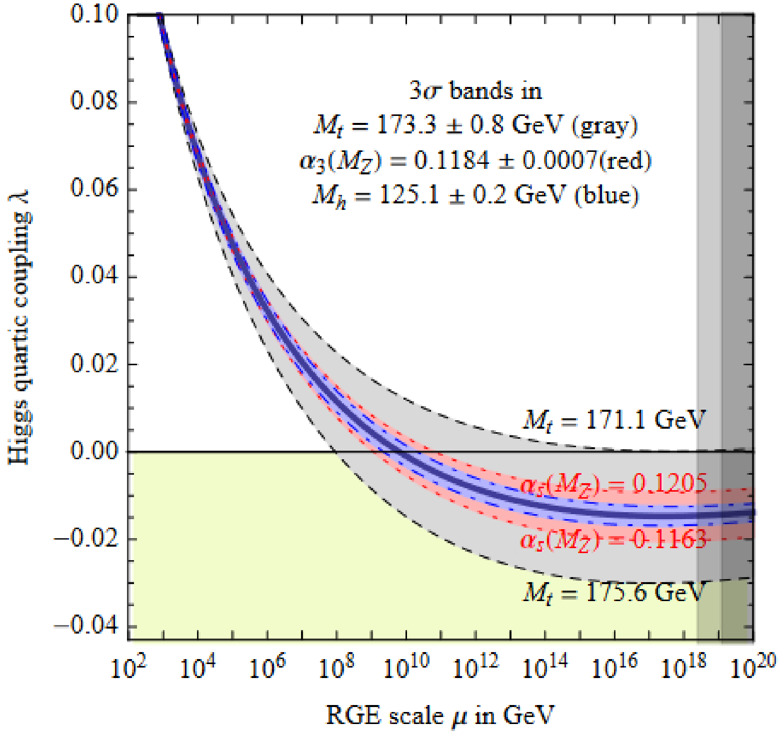
arXiv:2402.08713

Run I Top Quark Mass Combination - Motivation

- **Top quark mass** is a fundamental parameter of the Standard Model
- Precision of **top quark mass** dictates our ability to predict (and sometimes measure) phenomena



Phys. Rev. D **97**, 056006 (2018)



J. High Energ. Phys. **2013**, 89 (2013)

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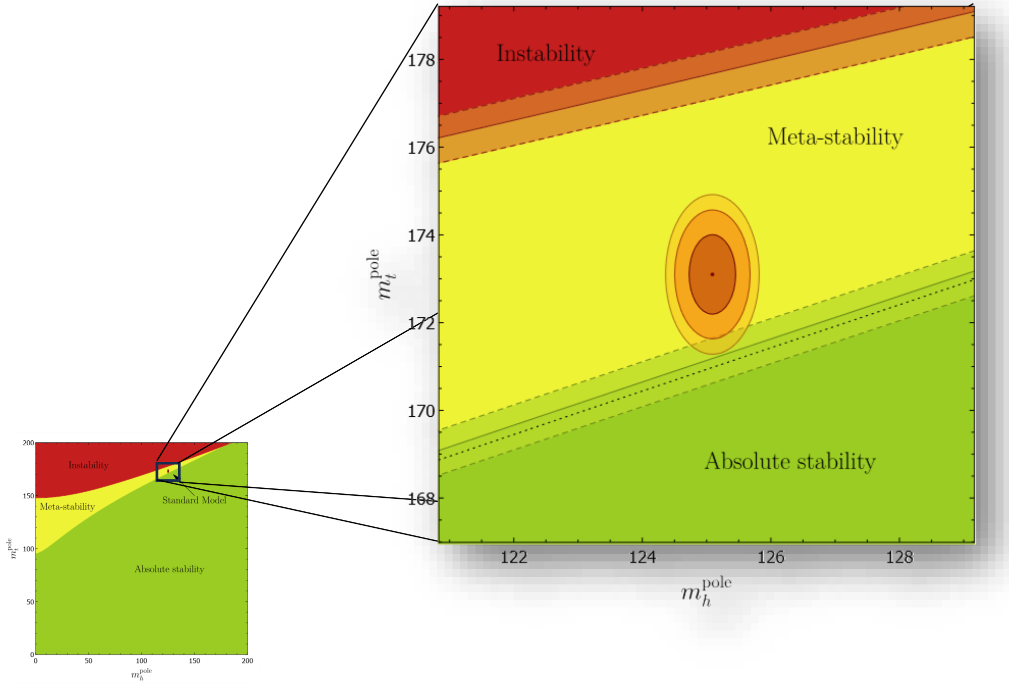

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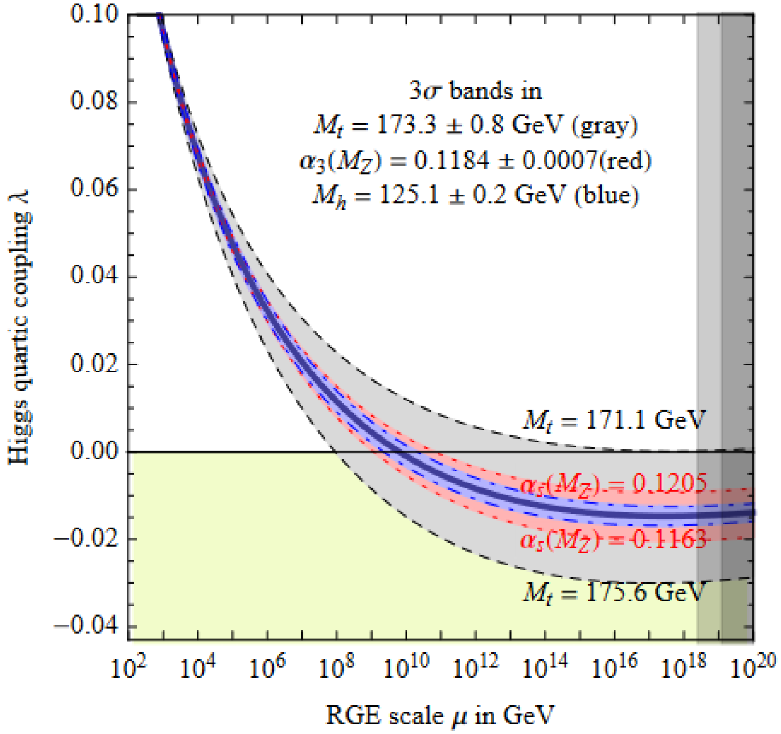
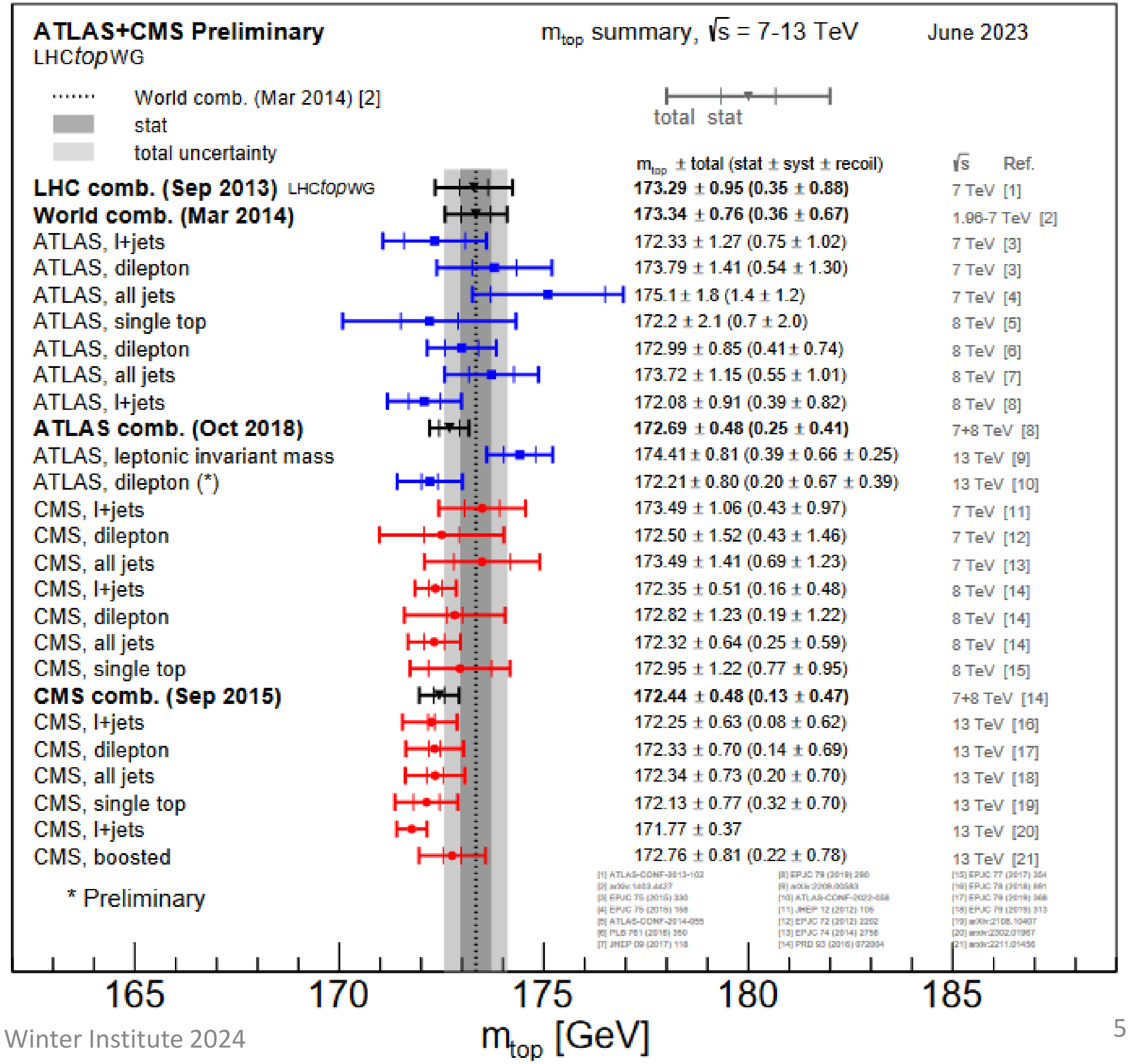


J. High Energ. Phys. **2013**, 89 (2013) [arXiv:2402.08713](https://arxiv.org/abs/2402.08713)

Run I Top Quark Mass Combination – Motivation ctd.

- ~10 years since last LHC combination
  - Preliminary for world combination
  - Didn’t include most precise 8 TeV measurements
- ATLAS and CMS combinations both agree



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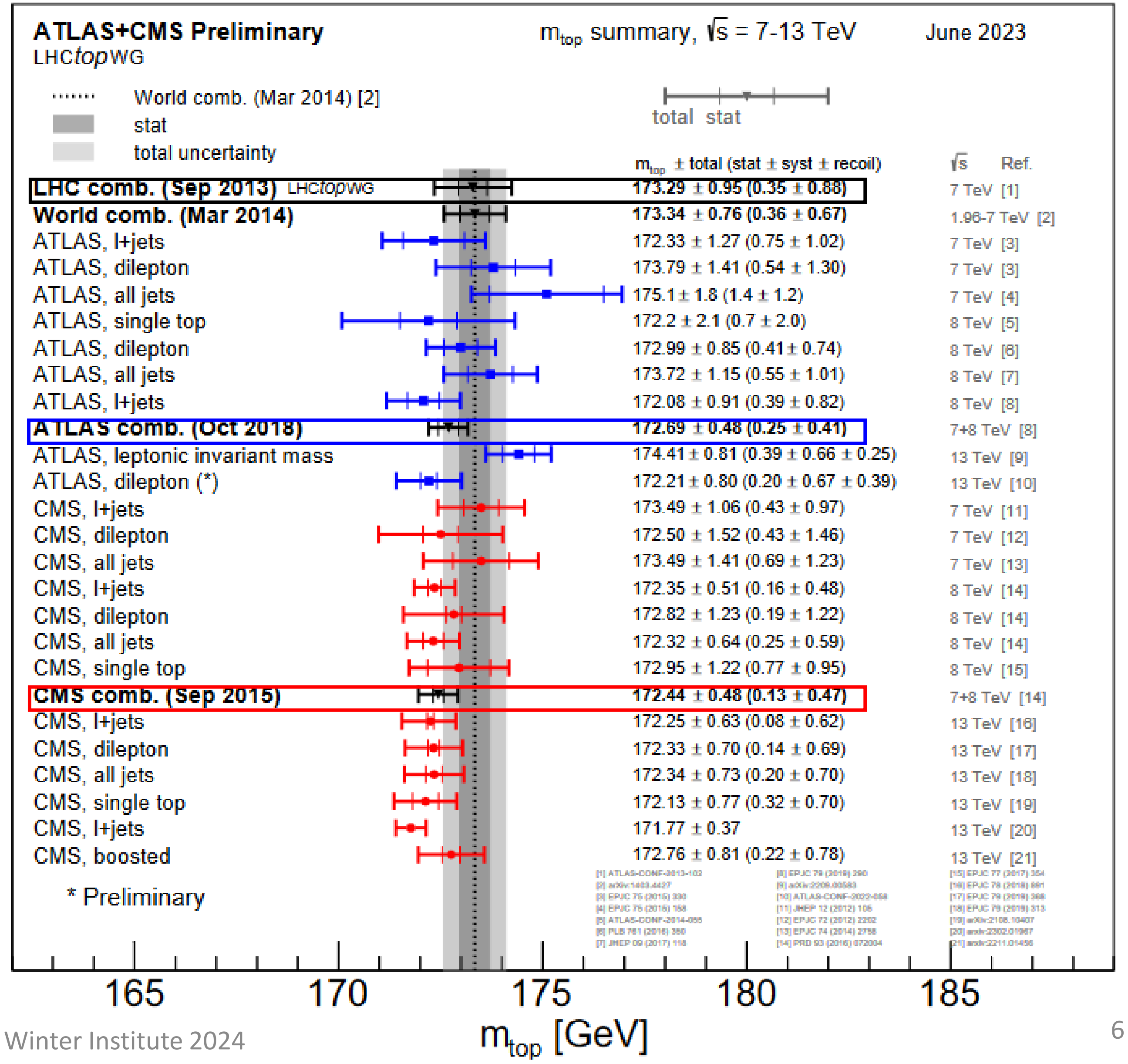
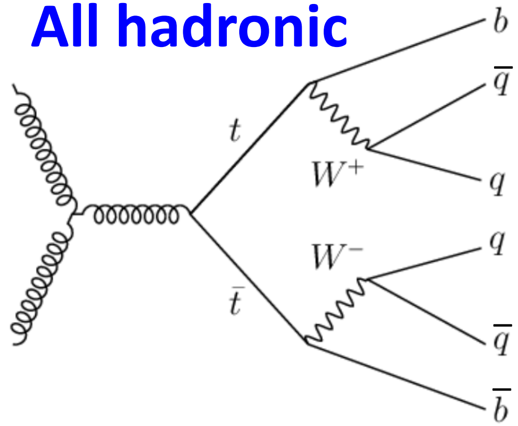


Run I Top Quark Mass Combination – Input Measurements

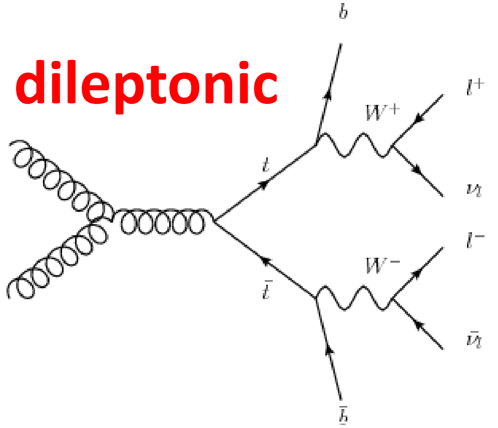
Red = CMS Blue = ATLAS

	7 TeV	8 TeV
dilepton	Eur. Phys. J. C **75** (2015) 330 Eur. Phys. J. C **72** (2012) 2202	Phys. Lett. B **761** (2016) 350 Phys. Rev. D **96** (2017) 032002
lepton+jets	Eur. Phys. J. C **75** (2015) 330 JHEP **12** (2012) 105	Eur. Phys. J. C **79** (2019) 290 Phys. Rev. D **93** (2016) 072004
All hadronic	Eur. Phys. J. C **75** (2015) 158 Eur. Phys. J. C **74** (2014) 2758	JHEP **09** (2017) 118 Phys. Rev. D **93** (2016) 072004
Single top	-	Eur. Phys. J. C **77** (2017) 354
Secondary Vertex	-	Phys. Rev. D **93** (2016) 092006
J/ψ	-	JHEP **12** (2016) 123

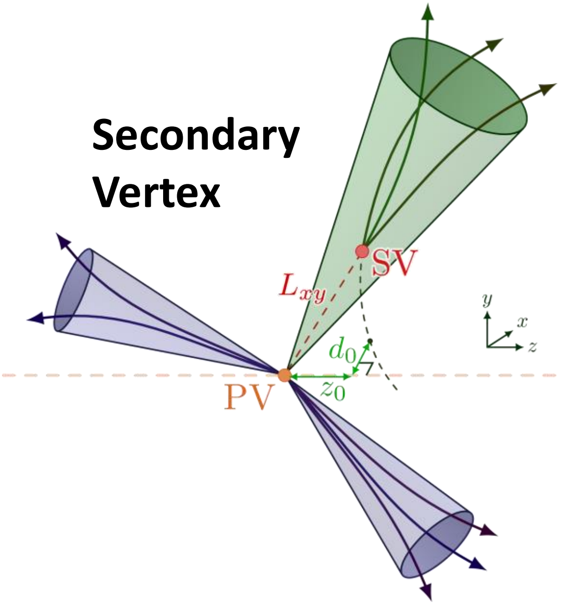
All hadronic



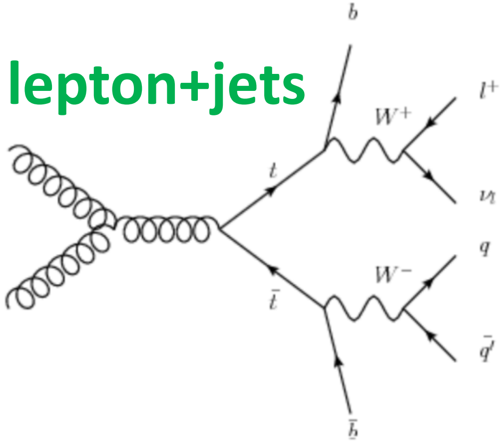
dileptonic

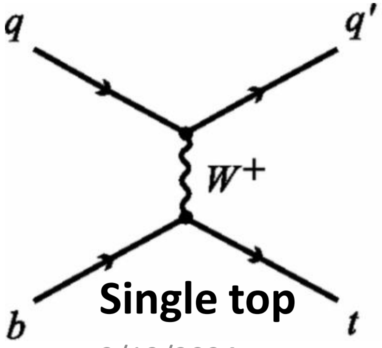


Secondary Vertex

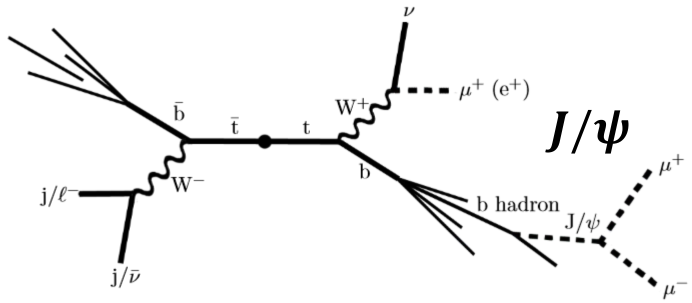


lepton+jets





Single top



J/ψ

arXiv:2402.08713

Run I Top Quark Mass Combination – Method & Correlations

[SoftwareX 11 (2020) 100468] [Nucl. Instrum. Meth. A 270 (1988) 110]

- **B**est **L**inear **U**nbiased **E**stimated – **BLUE**
  $$\boldsymbol{m_t} = \sum_i \boldsymbol{w_i m_t^i} \text{ where } \sum_i w_i = 1$$
- Correlations between channels within an experiment are determined
- Correlations between experiments are assessed:
  - **Uncorrelated: $\rho = 0$**
  - **Partially Correlated: $\rho = 0.5$**
  - **Strongly Correlated: $\rho = 0.85$**
- Covariance matrices are summed

Uncertainty category	ρ	Scan range	$\Delta m_t/2$ [MeV]	$\Delta\sigma_{m_t}/2$ [MeV]
LHC JES 1	0	—	—	—
LHC JES 2	0	[−0.25, +0.25]	8	7
LHC JES 3	0.5	[+0.25, +0.75]	1	<1
LHC b-JES	0.85	[+0.5, +1]	26	5
LHC g-JES	0.85	[+0.5, +1]	2	<1
LHC l-JES	0	[−0.25, +0.25]	1	<1
CMS JES 1	—	—	—	—
JER	0	[−0.25, +0.25]	5	1
Leptons	0	[−0.25, +0.25]	2	2
b tagging	0.5	[+0.25, +0.75]	1	1
p_T^{miss}	0	[−0.25, +0.25]	<1	<1
Pileup	0.85	[+0.5, +1]	2	<1
Trigger	0	[−0.25, +0.25]	<1	<1
ME generator	0.5	[+0.25, +0.75]	<1	4
LHC radiation	0.5	[+0.25, +0.75]	7	1
LHC hadronization	0.5	[+0.25, +0.75]	1	<1
CMS B hadron BR	—	—	—	—
Color reconnection	0.5	[+0.25, +0.75]	3	1
Underlying event	0.5	[+0.25, +0.75]	1	<1
PDF	0.85	[+0.5, +1]	1	<1
Top quark p_T	—	—	—	—
Background (data)	0	[−0.25, +0.25]	8	2
Background (MC)	0.85	[+0.5, +1]	2	<1
Method	0	—	—	—
Other	0	—	—	—

Run I Top Quark Mass Combination – Correlations

ATLAS+CMS $\sqrt{s}$ = 7,8 TeV

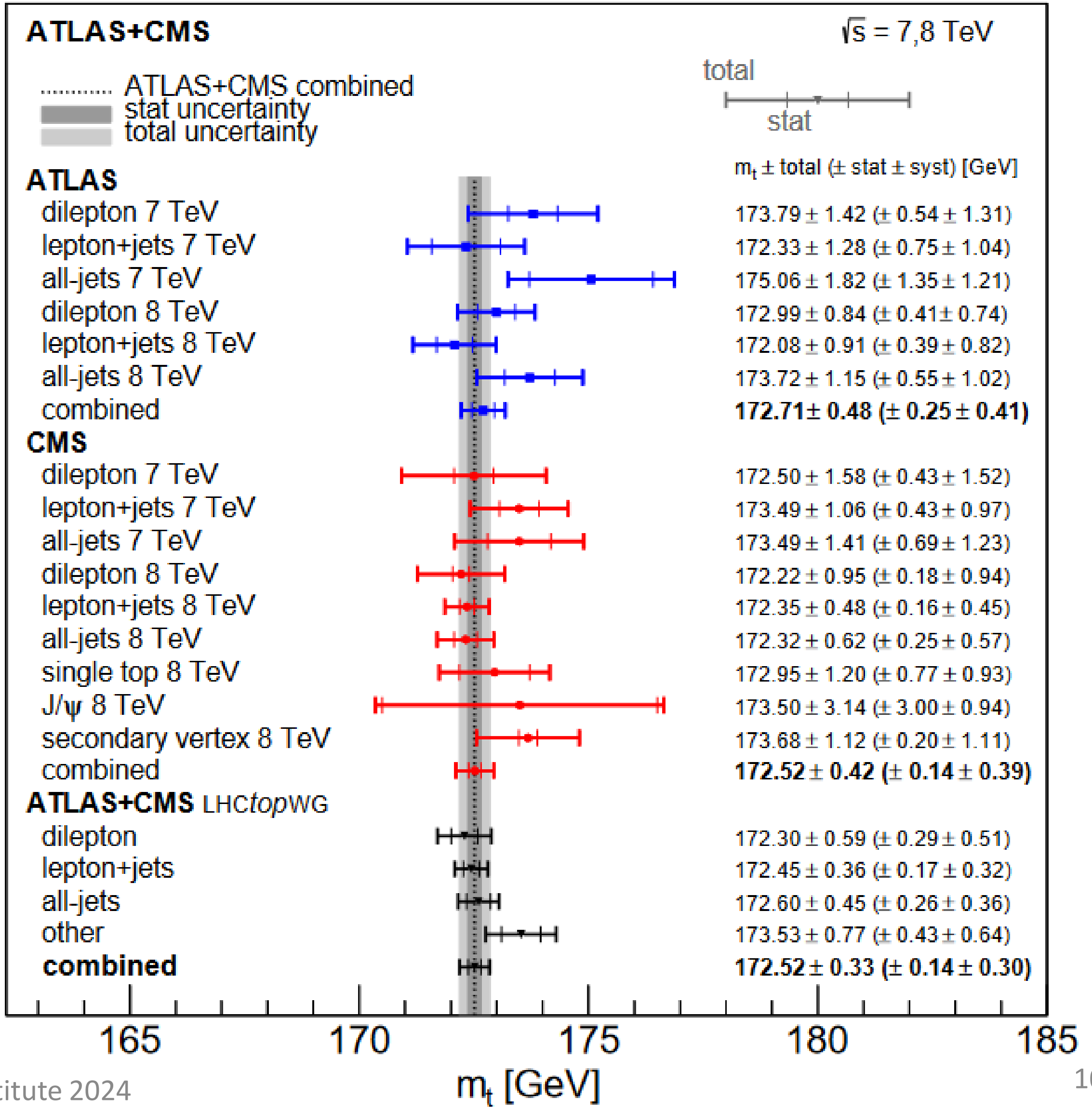
	ATLAS dil 7 TeV	ATLAS lj 7 TeV	ATLAS aj 7 TeV	ATLAS dil 8 TeV	ATLAS lj 8 TeV	ATLAS aj 8 TeV	CMS dil 7 TeV	CMS lj 7 TeV	CMS aj 7 TeV	CMS dil 8 TeV	CMS lj 8 TeV	CMS aj 8 TeV	CMS t 8 TeV	CMS J/Ψ 8 TeV	CMS vtx 8 TeV
ATLAS dil 7 TeV	1.00	-0.07	0.42	0.51	0.06	0.07	0.13	0.22	0.11	0.18	0.23	0.13	0.10	-0.06	-0.15
ATLAS lj 7 TeV	-0.07	1.00	-0.01	0.00	-0.07	-0.02	0.09	0.08	0.03	0.08	0.04	0.01	0.10	0.02	-0.04
ATLAS aj 7 TeV	0.42	-0.01	1.00	0.29	-0.06	0.00	0.11	0.19	0.11	0.13	0.21	0.16	0.09	-0.01	-0.04
ATLAS dil 8 TeV	0.51	0.00	0.29	1.00	-0.18	0.31	0.09	0.16	0.08	0.12	0.16	0.10	0.07	-0.04	-0.10
ATLAS lj 8 TeV	0.06	-0.07	-0.06	-0.18	1.00	-0.03	0.02	-0.00	-0.00	-0.04	0.05	-0.03	0.03	-0.01	0.00
ATLAS aj 8 TeV	0.07	-0.02	0.00	0.31	-0.03	1.00	0.10	0.11	0.06	-0.01	0.14	0.08	0.07	0.01	0.10
CMS dil 7 TeV	0.13	0.09	0.11	0.09	0.02	0.10	1.00	0.31	0.57	0.31	0.46	0.36	0.26	0.08	0.13
CMS lj 7 TeV	0.22	0.08	0.19	0.16	-0.00	0.11	0.31	1.00	0.53	0.10	0.41	0.45	0.29	-0.03	0.03
CMS aj 7 TeV	0.11	0.03	0.11	0.08	-0.00	0.06	0.57	0.53	1.00	0.12	0.34	0.35	0.21	-0.03	0.07
CMS dil 8 TeV	0.18	0.08	0.13	0.12	-0.04	-0.01	0.31	0.10	0.12	1.00	0.23	0.07	0.09	-0.04	-0.16
CMS lj 8 TeV	0.23	0.04	0.21	0.16	0.05	0.14	0.46	0.41	0.34	0.23	1.00	0.70	0.48	0.06	0.15
CMS aj 8 TeV	0.13	0.01	0.16	0.10	-0.03	0.08	0.36	0.45	0.35	0.07	0.70	1.00	0.47	0.05	0.22
CMS t 8 TeV	0.10	0.10	0.09	0.07	0.03	0.07	0.26	0.29	0.21	0.09	0.48	0.47	1.00	-0.01	0.08
CMS J/Ψ 8 TeV	-0.06	0.02	-0.01	-0.04	-0.01	0.01	0.08	-0.03	-0.03	-0.04	0.06	0.05	-0.01	1.00	0.12
CMS vtx 8 TeV	-0.15	-0.04	-0.04	-0.10	0.00	0.10	0.13	0.03	0.07	-0.16	0.15	0.22	0.08	0.12	1.00

[arXiv:2402.08713](https://arxiv.org/abs/2402.08713)

Run I Top Quark Mass Combination – Results

- Most precise determination of the **top quark mass** to date – 0.2% relative uncertainty!
- Dominated by systematic uncertainties
  - JES, b-tagging, and $t\bar{t}$ modeling are dominant

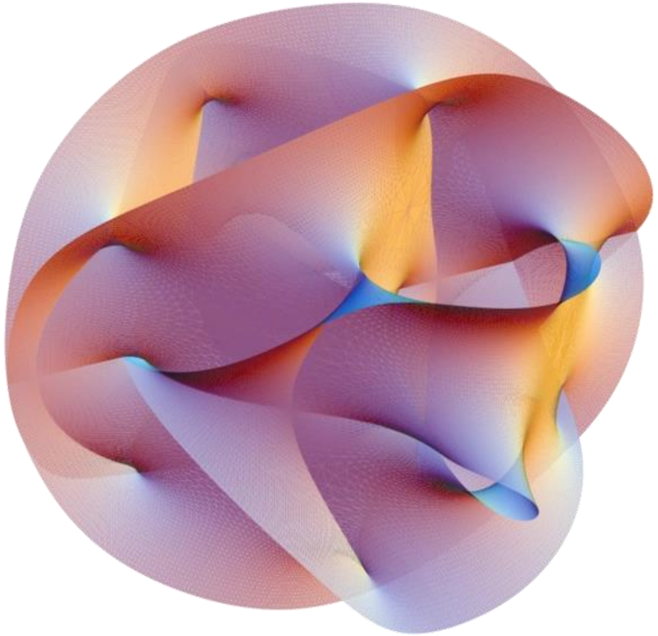
$$m_{top} = 172.52 \pm 0.14(stat) \pm 0.30(syst)\ \text{GeV}$$

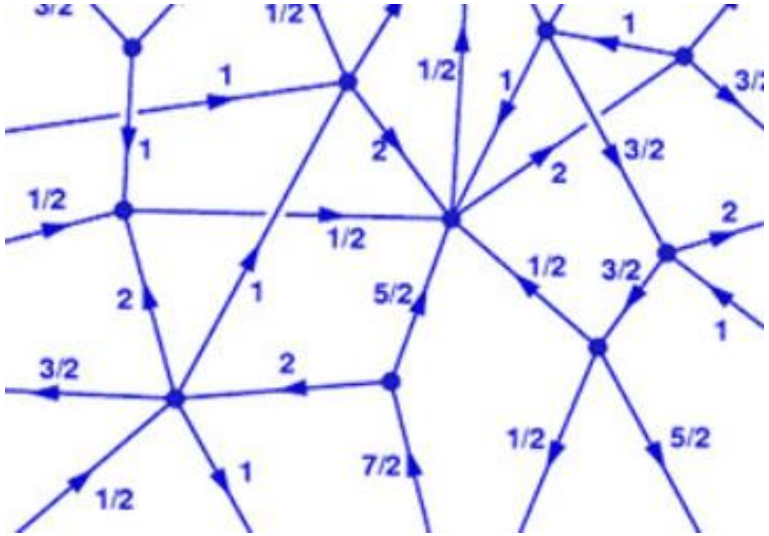


CMS-TOP-22-007

Search for Violation of Lorentz Invariance - Motivation

- The Standard Model is **Lorentz invariant**
- **Lorentz violation** can emerge in string theory & loop quantum gravity @$\sim M_{PL}$
- Searches via neutral meson mixing: KLOE, KTeV, FOCUS, BaBar, and LHCb
- 1st search with $t\bar{t}$ @Tevatron $p\bar{p}$ collider: D0 [Phys. Rev. Lett. 108 (2012) 261603]
- New search with **CMS**!



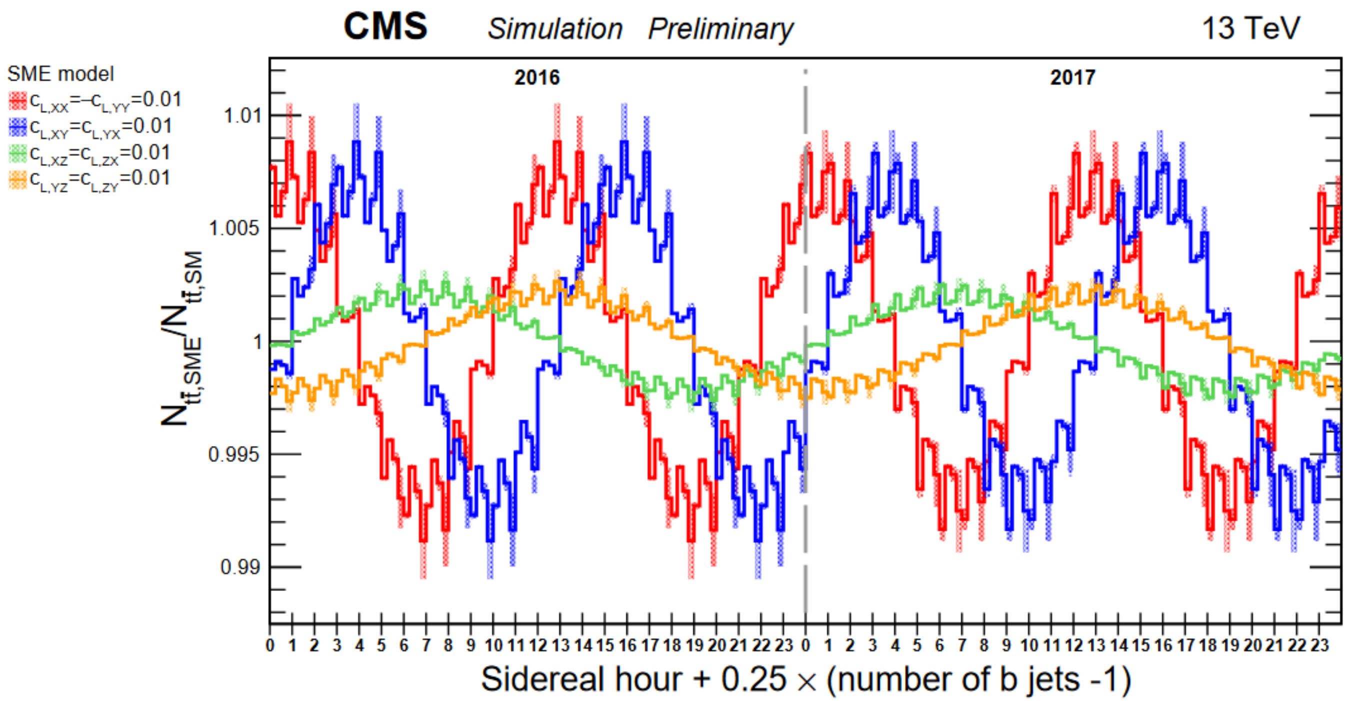


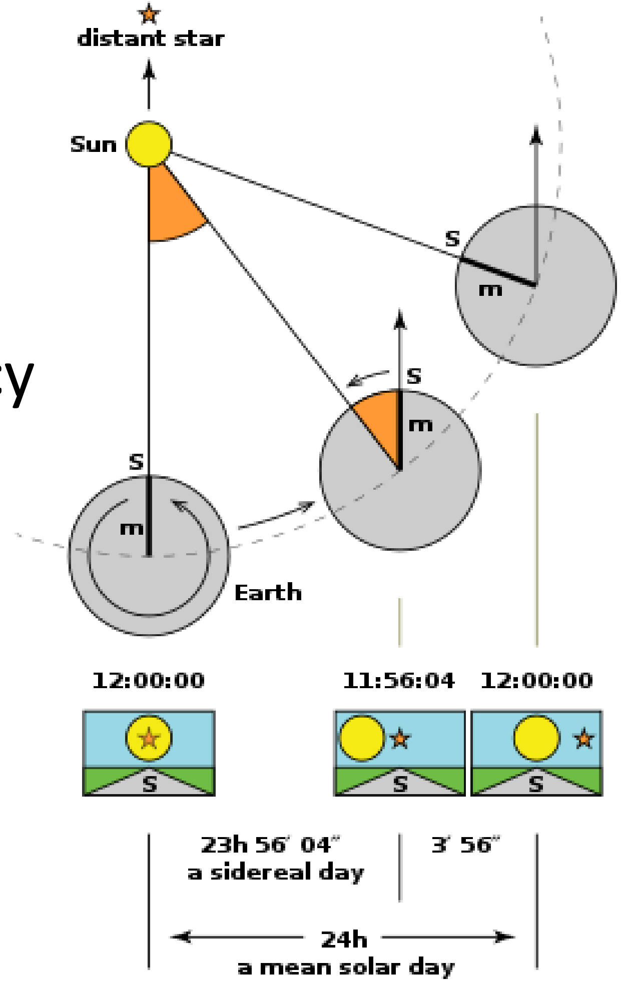
Search for Violation of Lorentz Invariance - Method

- **Lorentz Violation** in SME model given by:

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

- Average direction of top quarks change w/ sidereal time → Wilson coefficients $c^{\mu\nu}$ and $d^{\mu\nu}$ encode sidereal dependency



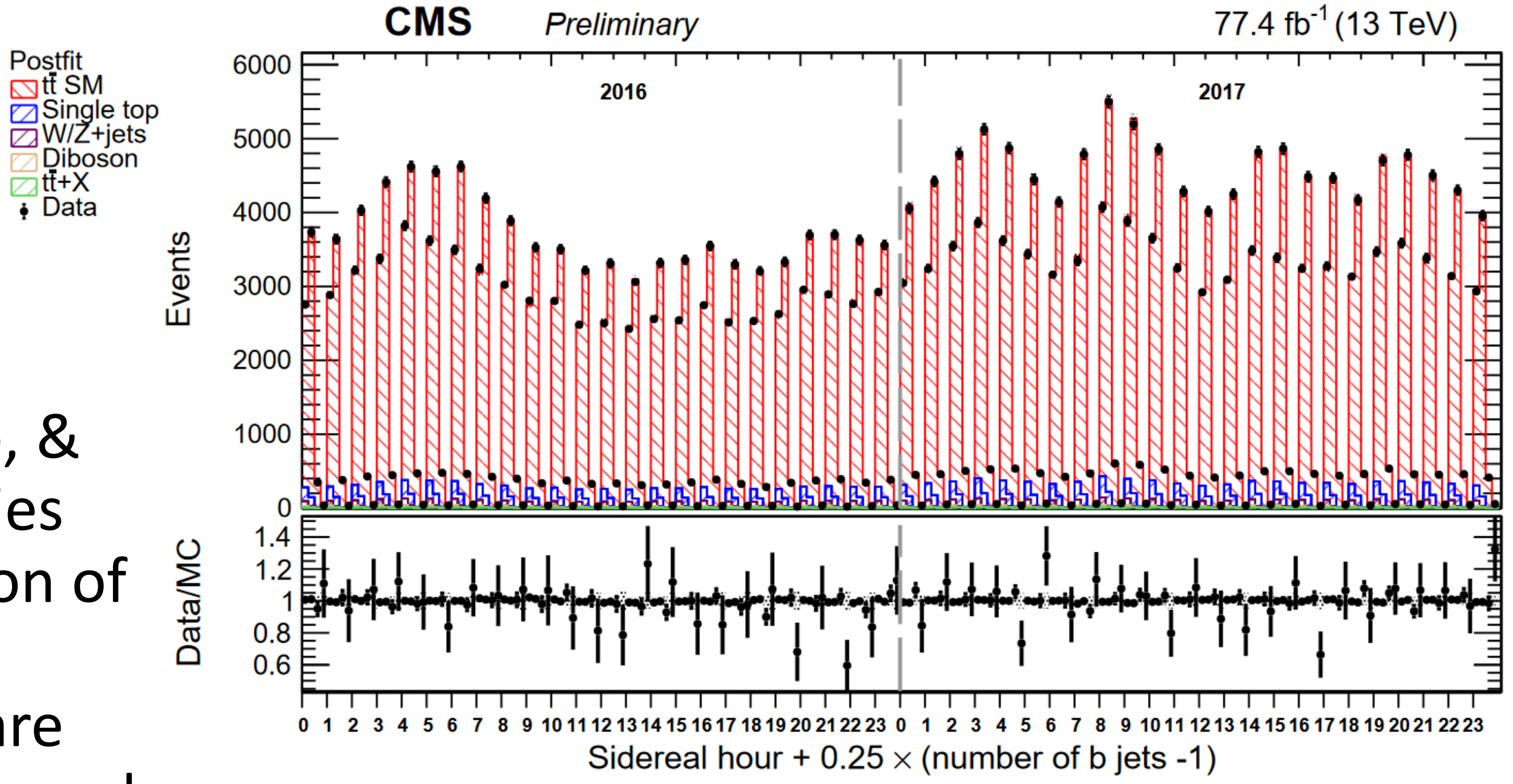


$$\Omega_{\text{sidereal}} t_{\text{sidereal}} = \Omega_{\text{UTC}}(t_{\text{UNIX}} - t_0) + \phi_{\text{UNIX}} + \phi_{\text{longitude}}$$

CMS-TOP-22-007

Search for Violation of Lorentz Invariance – Method ctd.

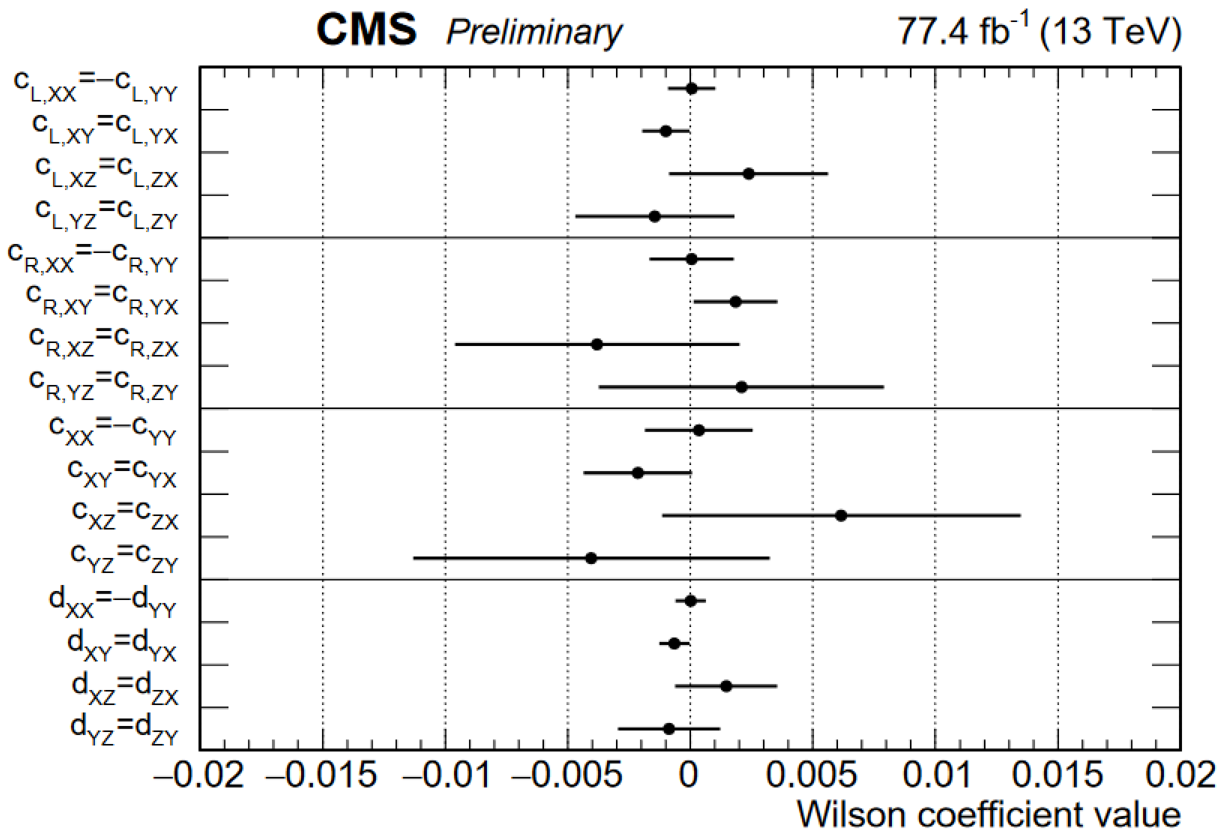
- Measured the $t\bar{t}$ cross section differentially in $t_{sidereal} \otimes N_{bjets}$ w/ $\boldsymbol{e\mu}$ events from 2016+2017
- Luminosity unc., pileup, & lepton trigger efficiencies determined as a function of sidereal time
- Added nuisances that are uncorrelated across sidereal bins to account for unknown sidereal dependence



CMS-TOP-22-007

Search for Violation of Lorentz Invariance - Results

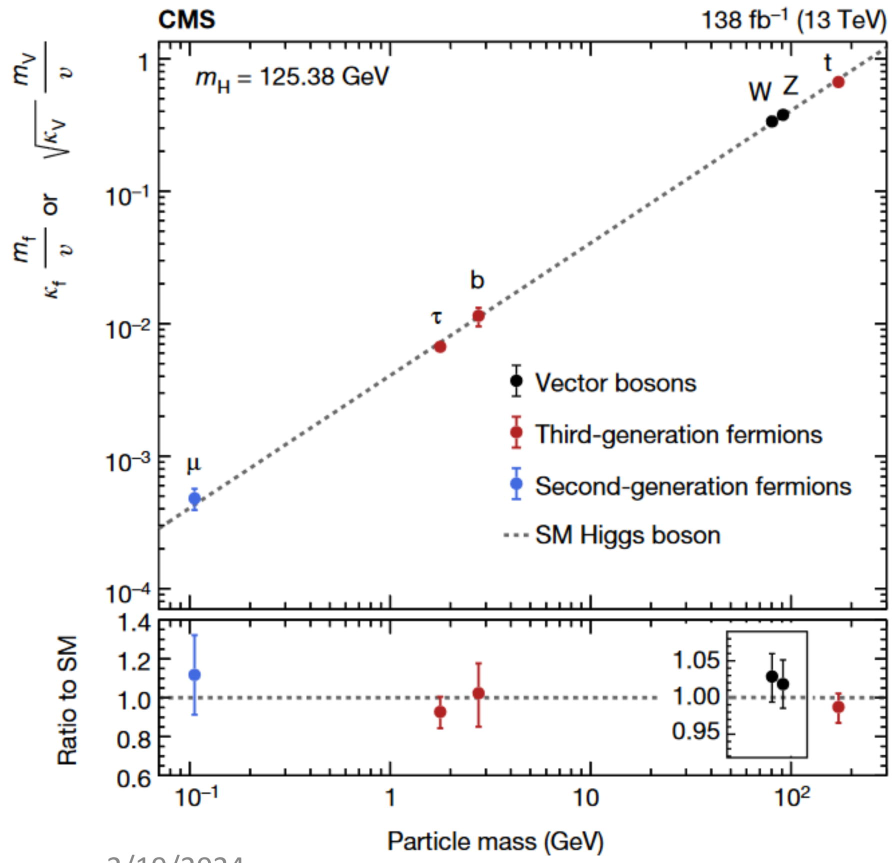
- 10x increase in precision of **Lorentz Violation** top quark Wilson coefficient constraints compared to D0 [Phys. Rev. Lett. **108** (2012) 261603]
- Checked both fitting coefficients individually and together with no sizeable differences due to small correlations between coefficients
- No significant deviation from 0 observed

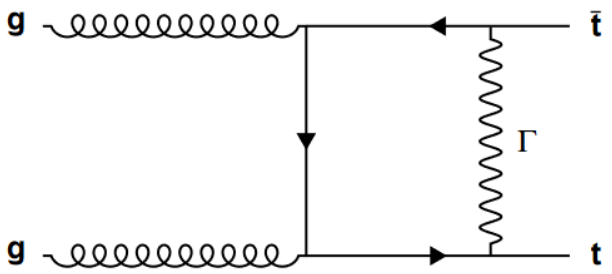


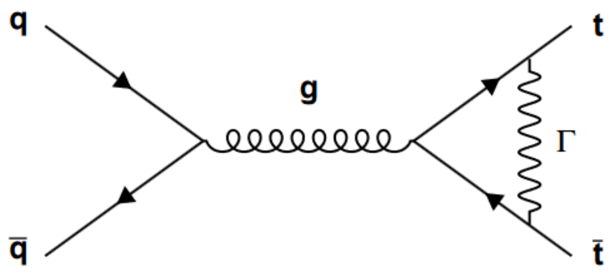
Phys. Rev. D **102**, 092013

Measurement of the top quark Yukawa coupling - Motivation

- Important goal for **LHC** is to characterize new Higgs boson and its couplings
- Top quark **Yukawa coupling** is curiously close to unity
- Can be measured directly through ttH
- Indirectly through electroweak contributions to $t\bar{t}$ cross section







Phys. Rev. D **102**, 092013

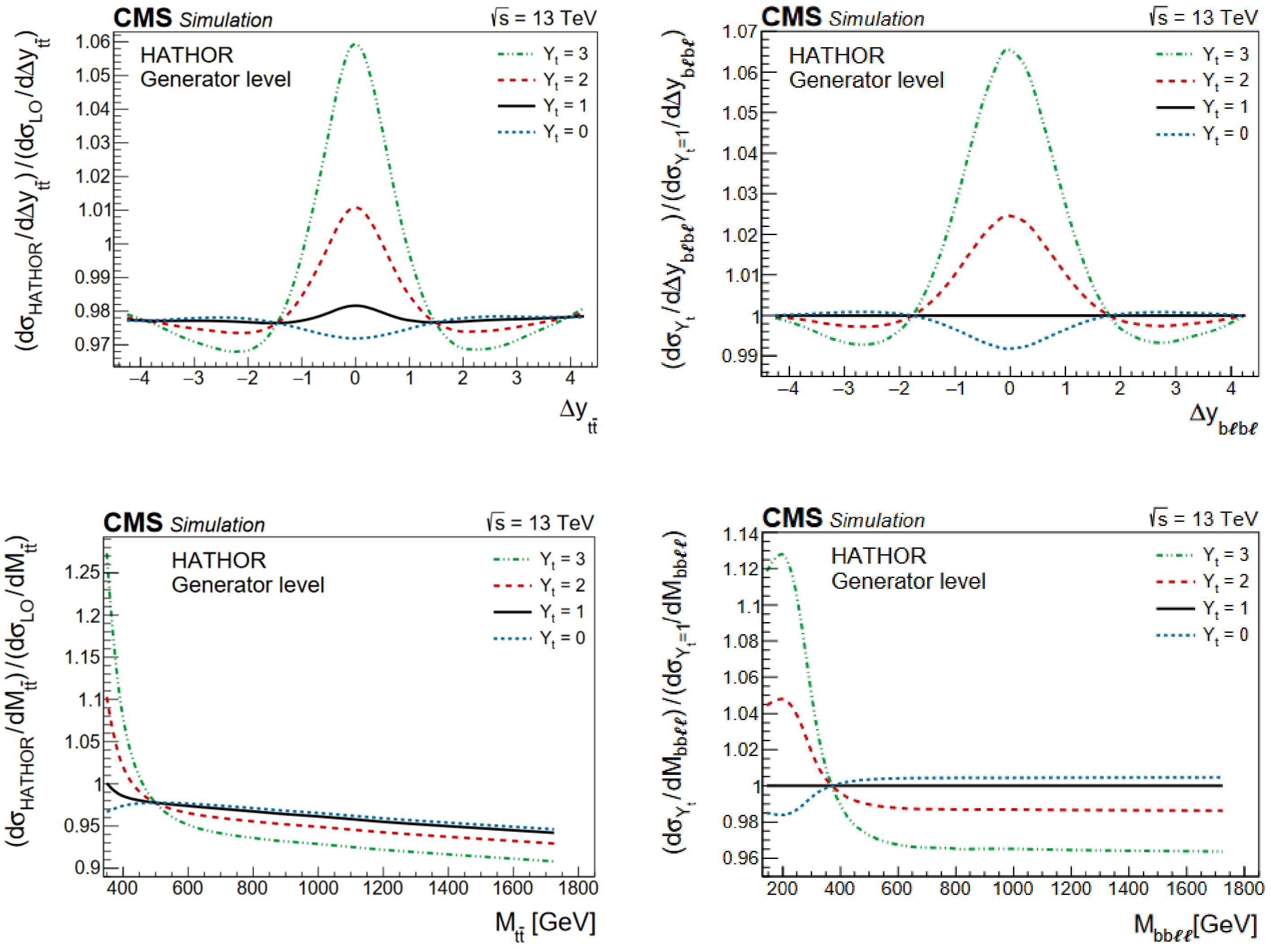
Measurement of the top quark Yukawa coupling - Method

- Used dileptonic decays and full Run II dataset
- Profile likelihood fit in double differential distribution:

$$\mathrm{M}_{\mathrm{b\bar{b}}\ell\bar{\ell}} \otimes \Delta y_{\mathrm{b\bar{b}}\ell\bar{\ell}}$$

  - $\mathrm{M}_{\mathrm{b\bar{b}}\ell\bar{\ell}} = M\left(b + \bar{b} + \ell + \bar{\ell}\right)$
  - $\Delta y_{\mathrm{b\bar{b}}\ell\bar{\ell}} = |y(b + \bar{\ell}) - y(\bar{b} + \ell)|$
  - Removes necessity for top quark reconstruction which is difficult in dileptonic decays

$$\mathcal{L}_{\mathrm{bin}} = \mathrm{Poisson}\left[n_{\mathrm{obs}}^{\mathrm{bin}} \middle| s^{\mathrm{bin}}(\{\theta_i\})\, R_{\mathrm{EW}}^{\mathrm{bin}}(Y_t, \phi) + b^{\mathrm{bin}}(\{\theta_i\})\right]$$



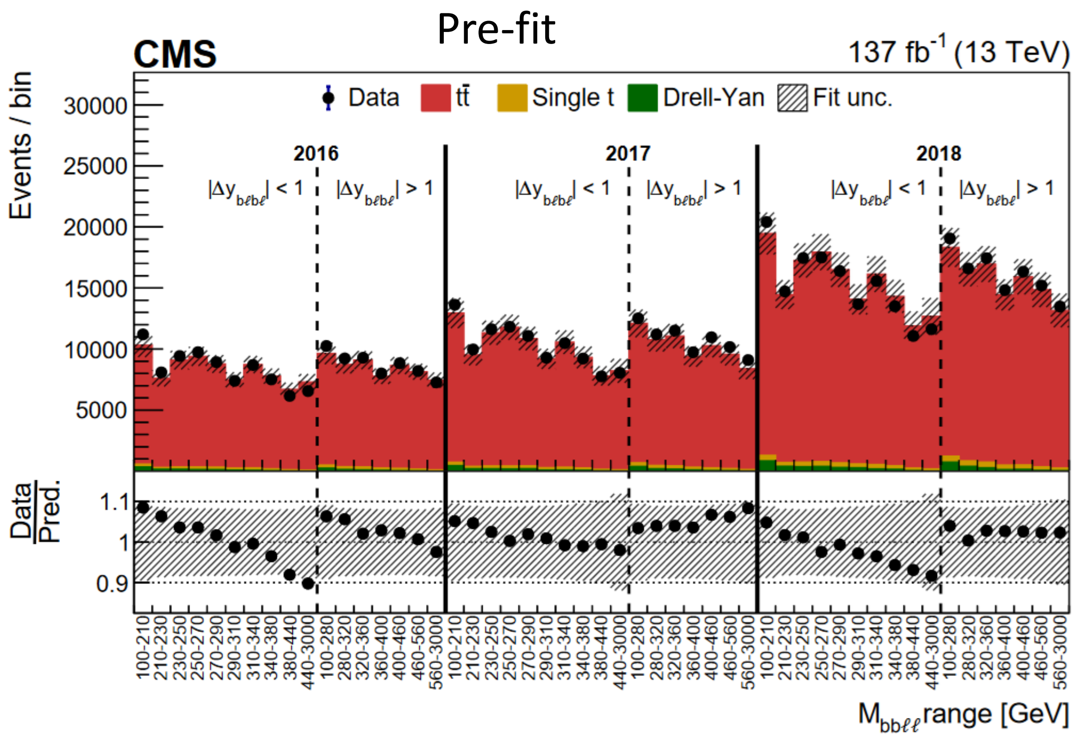
Measurement of the top quark Yukawa coupling - Method

- $Y_t = \frac{g_t}{g_t^{SM}}, \; g_t = \frac{\sqrt{2} m_t}{\nu}$
- **Yukawa coupling** and nuisance for electroweak corrections change signal event yields

$$R_{\mathrm{EW}}^{\mathrm{bin}}(Y_t, \phi) = [1 + \delta_{\mathrm{EW}}^{\mathrm{bin}}(Y_t)]\,[1 + \delta_{\mathrm{QCD}}^{\mathrm{bin}} \delta_{\mathrm{EW}}^{\mathrm{bin}}(Y_t)]^{\phi}$$

- Unc. for electroweak correction is difference between additive and multiplicative approach

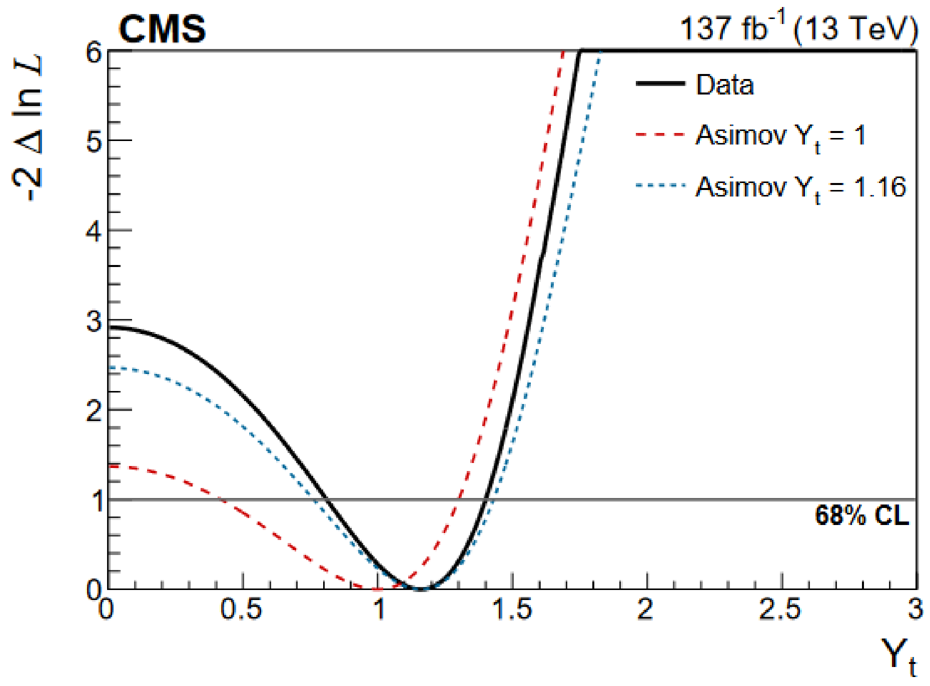
$$\delta_{\mathrm{EW}}^{\mathrm{bin}} = \frac{n_{\mathrm{HATHOR}}^{\mathrm{bin}} - n_{\mathrm{LO\,QCD}}^{\mathrm{bin}}}{n_{\mathrm{LO\,QCD}}^{\mathrm{bin}}}, \quad \delta_{\mathrm{QCD}}^{\mathrm{bin}} = \frac{n_{\mathrm{POWHEG}}^{\mathrm{bin}} - n_{\mathrm{LO\,QCD}}^{\mathrm{bin}}}{n_{\mathrm{POWHEG}}^{\mathrm{bin}}}$$



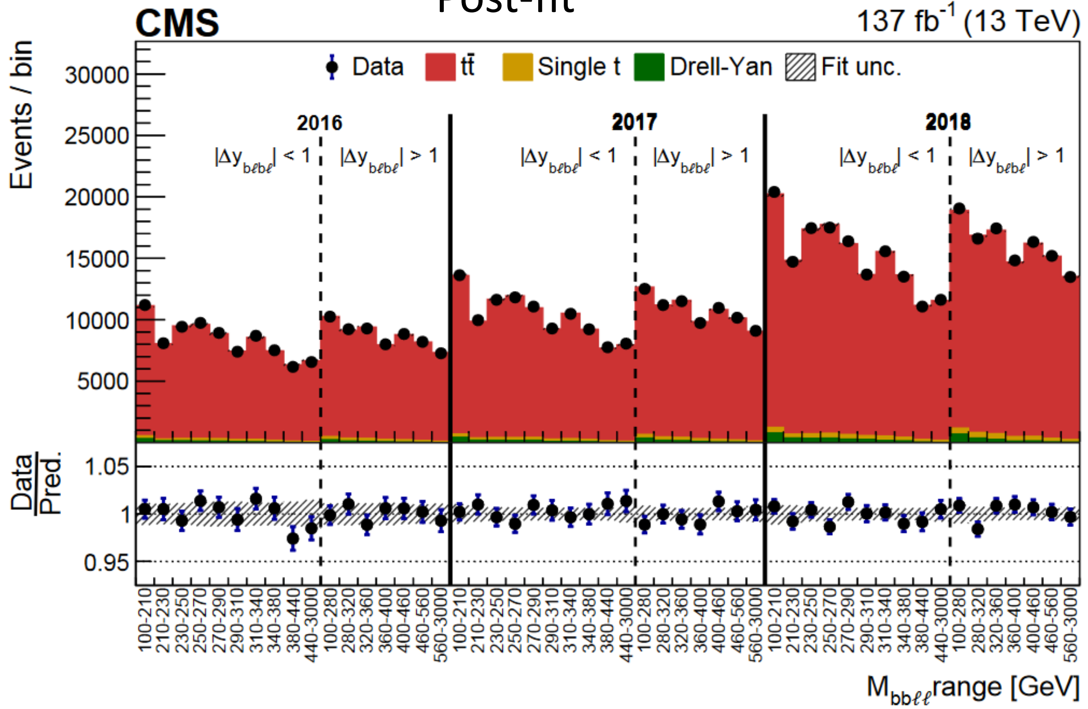
Phys. Rev. D **102**, 092013

Measurement of the top quark Yukawa coupling - Result

- $Y_t = 1.16^{+0.24}_{-0.35}$
- Measurement of top quark Yukawa coupling independent of assumptions on other Yukawa couplings



Post-fit



Summary

- Lots of exciting new results from **CMS**
- Most precise **top quark mass measurement** from **CMS**+**ATLAS** combination
  - Lots of work performed in determining the correlations between experiments
- 1st search for **Lorentz violation** in top quark pairs produced from proton-proton collider
- Indirect and independent top quark **Yukawa coupling** measurement consistent with SM
  - Electroweak corrections crucial for correct modeling of $t\bar{t}$ threshold region

Thanks!

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Correlations for LIV

- Statistical unc. in corrections are uncorrelated across years
- Modeling systematics are correlated (sidereal time-independent)

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%

Profile Maximum Likelihood fit

$$\mathrm{L} = \prod_{c \in channels} \prod_{b \in bins_c} Pois(n_{cb} | \nu_{cb}(\mathrm{H}, \mathrm{X})) \prod_{\chi \in \mathbf{X}} p_\chi(a_\chi | \chi)$$

- Channels are statistically independent “channels”. Can be decay topology for example (ee vs. eμ vs. $\mu\mu$)
- $\eta_i \in \mathrm{H}$ are unconstrained nuisance parameters meaning they have no prior
  - Signal strength modifier is typically an unconstrained nuisance
  - D is also unconstrained in our fit and we freeze signal strength modifier
- $\chi_i \in \mathrm{X}$ are constrained nuisance parameters meaning we know/can estimate their prior probability distribution
  - a_χ are parameters/inputs for the prior
  - All of our priors are either log normal or shape-based