Top Quark Physics Prospectives

Romain Madar (CNRS/IN2P3/LPC) on behalf of many contributors

IN2P3 Prospectives - Particle Physics (GT01)

IP2I Lyon – 12/03/2020

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French contributions and references

HL-LHC

Contribution sur la physique du quark top pour les prospectives IN2P3

Jeremy Andrea[1], Samuel Calvet[2], Sabine Crépé-Renaudin[3], Frédéric Déliot *[4], Benjamin Fuks[5], et Romain Madar[2]

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Linear e^+e^- collider

Physics opportunities at a future linear e^+e^- collider

Contribution du Comité Collisionneur Linéaire à l'atelier GT01 des prospectives IN2P3

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Main references:

- Standard Model Physics at HL-LHC and HE-LHC - arXiv:1902.04070 (chap 6)
- Physics at the HL-LHC and HE-LHC - arXiv:1902.10229 (chap 2)
- ILC Technical Design Report (volume 2) - arXiv:1306.6352 (chap 5)
- Top-Quark Physics at CLIC - arXiv:1807.02441
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Caution: this talk is necessarily incomplete *and* biased.

Place of top quark physics

2-folded general motivations

1. top quark *is* special, through its mass: **why?**
2. top quark processes is limiting for many measurements/searches

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- Q_t, m_t, Γ_t, ...
- QCD coupling: $gt\bar{t}$ (*e.g.* spin correlation, strong diplole moments)
- electro-weak couplings: $Wt\bar{b}$, $Zt\bar{t}$, $\gamma t\bar{t}$ (*e.g.* EDM, FCNCs)
- Higgs coupling y_t (*e.g.* vacuum stability)

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2. Top quark physics as a limiting factor (for other *and* itself!)

- not so well controlled effects (*e.g.* color reconnections)
- extreme kinematic regions (rare processes/searches, 'top tagging')
- production with other particles: (heavy) quarks, γ, W, Z, H or t

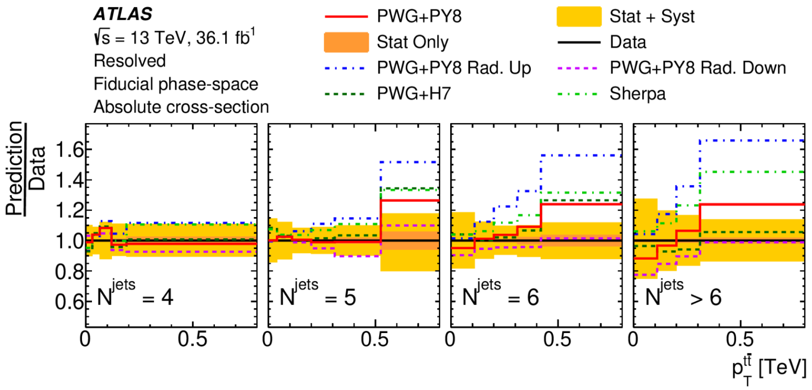
Content

1. Precision measurements
2. Rare processes
3. Effective Fields Theory
4. Conclusions

Precision measurements

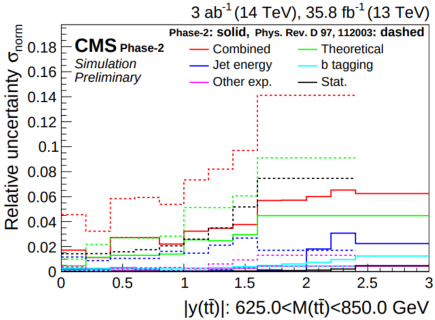
Differential cross-section $pp \to t\bar{t}$

Why do we need to improve these measurements?



Differential cross-section $pp \to t\bar{t}$

Add-on values from HL-LHC: extended phase-space & better precision



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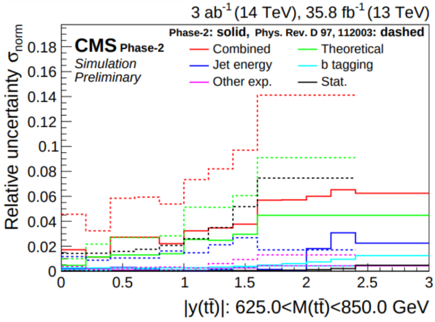

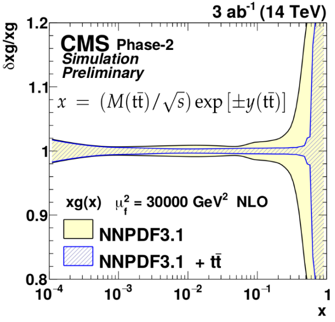

Impact: improved gluon distribution in the proton $(0.002 \le x_g \le 0.5)$

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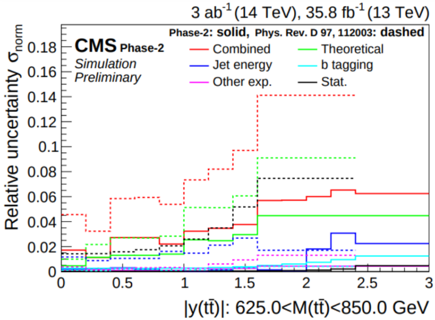

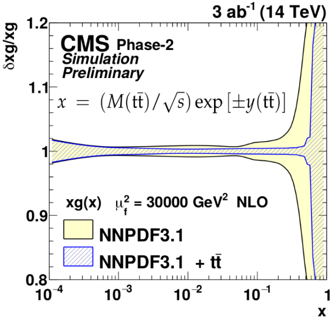

Impact: improved gluon distribution in the proton ($0.002 \leq x_g \leq 0.5$)

Limiting uncertainties: theory (production/decay modelling), jet energy scale

Assumed theory unc.: twice better than the current ones (!)

Top quark mass

Importance of the top quark mass

- consistency of the SM through the relation between (m_W, m_t, m_H)
- relation between y_t and m_t, as a probe of the Yukawa Higgs sector
- *tricky quark mass concept*: several top quark mass definitions
  - m_{MC}: simulation parameter driving events kinematics
  - m_{pole}: in *principle* well defined; in *practice* ambiguious due to long-range QCD effects
  - $m_{\overline{\mathrm{MS}}}$: running renormalized mass, well defined

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Current measurements

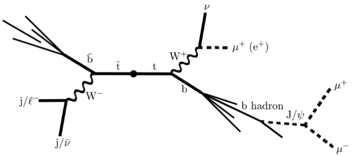
- m_{MC}: $\Delta m \sim 500\,\mathrm{MeV}$ syst. limited ($t\bar{t}$ modelling, jet energy scale)
- m_{pole}: $\Delta m \sim 1.2\,\mathrm{GeV}$ syst. limited ($t\bar{t}$ modelling, jet energy scale)
- main existing approaches (ranked by precision)
  - **kinematic-based** most accurate. Reducing jet energy scale systematics constraining both light jet and b-jet scales (multi-dimensionnal fit $\rightarrow$ statistically limited)
  - $\mathbf{J/\psi \rightarrow \mu\mu}$ approach with $m(\mu\mu\ell)$ (limited by stat. - low BR - and b-fragmentation)
  - $\mathbf{d\sigma_{t\bar{t}}(m_t)}$ **SM dependence** compared to the observed $\mathrm{d}\sigma_{t\bar{t}}$: well defined mass

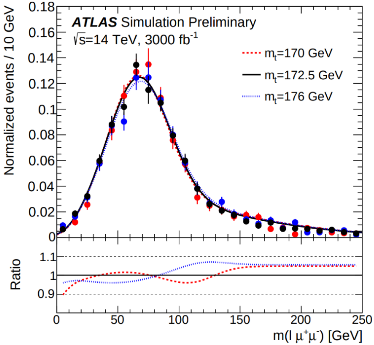
Top quark mass future

How to better measure this fundamental SM parameter?

- improving existing measurements
  - simply stat limited - *e.g.* J/ψ,
  - technics requiring large stat - *e.g.* 3D fit of (JES, b-JES, m_t)
- new independent measurements sensitive to different syst - *e.g.* $gg \to \gamma\gamma$ with a bump at $2m_t$
- e^-e^+ colliders: potential of $\Delta m_t \sim 50\,\text{MeV}$ with $\sigma_{t\bar{t}}(\sqrt{s})$ - if $\sqrt{s} > 2m_t$ threshold; Well defined m_t (different scheme than LHC)

Top quark mass future: HL-LHC examples

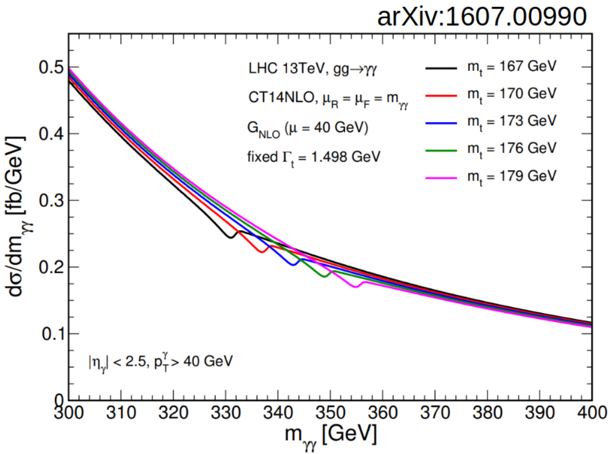




ATL-PHYS-PUB-2018-042

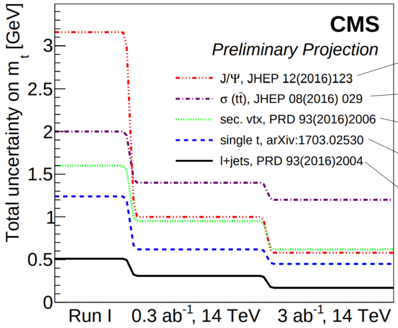
Source of uncertainty	$\sigma(m_{\text{top}})$ [GeV]
Statistical uncertainty	0.14
Method uncertainty	0.11
Signal modelling uncertainties	
$t\bar{t}$ NLO modelling	0.06
$t\bar{t}$ PS and hadronisation	0.05
$t\bar{t}$ b-production	0.24
$t\bar{t}$ b-fragmentation	0.11
Initial- and final-state radiation	0.04
Underlying event	0.02
Colour reconnection	0.02
Background modelling uncertainties	0.10
Experimental uncertainties	
Jet energy scale (JES)	0.31
b-jet energy scale (b-JES)	0.06
Jet energy resolution (JER)	0.13
Jet vertex fraction	0.02
Electrons	0.03
Muons	0.09
Pile-up	0.04
Total Systematic uncertainty	0.48
Total	0.50

Top quark mass future: HL-LHC examples



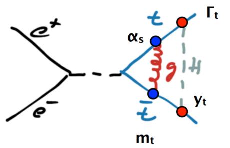
future studies. Another example is given in the work of Ref. [695], where it is argued that a glitch in the dilepton spectrum should be visible for a dilepton invariant mass near twice the top mass. This effect is due to the diphoton production subprocess $gg \to \gamma\gamma$ mediated by a top loop. The projected statistical error for the mass determination using this method is of 2-3 GeV for the High Luminosity LHC, and

Top quark mass future: HL-LHC overview



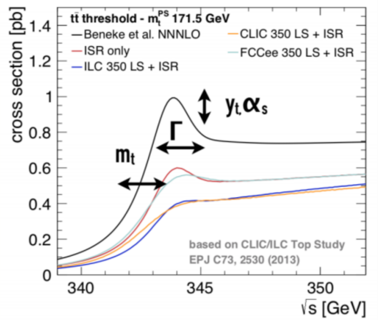
- based on b-hardon dilepton decay. Final state with 3l → bkg free sample!
- Global observable with a theoretically well-defined pole/MS mass (not the "MC mass")
- based on secondary vertex properties (reduced impact from JES)
- EW production → less QCD-related uncertainties (e.g. color reconnection)
- Direct top mass reconstruction with *in situ* constrain of (b) jet energy scales

Top quark mass future: e^+e^- colliders



Observable: $\sigma_{t\bar{t}}$ as function of $\sqrt{s}$ depends on

- m_t ("1S scheme" based on hypothetical Υ_t meson)
- Γ_t, y_t and α_s
- EW production: smaller modelling unc.



arXiv:1611.04492, "Top Quark Physics at FCC" (2018)

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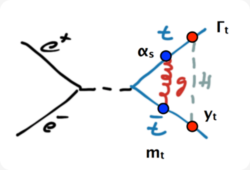

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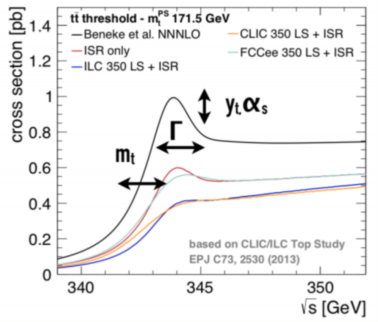

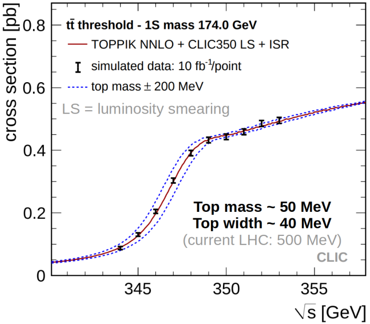

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Precision measurements: concluding remarks

Rare processes

Rare processes: what and why

- $t\bar{t}$: 832 pb

QCD production discussed earlier

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QCD production discussed earlier

- t-channel: 217 pb
- tW: 72 pb
- s-channel: 10 pb

EW production, probe Wtb vertex (V_{tb}, dipoles), PDFs, but also m_t – arXiv:1710.10699

Proton-proton cross-sections at $\sqrt{s} = 13$ TeV

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- $t\bar{t}W$: 0.6 pb
- $t\bar{t}\gamma$: $\sim$ 0.5 pb
- $t\bar{t}H$: 0.6 pb
- $t\gamma q$: 0.6 pb
- tZq: 0.6 pb

Few 100's fb: rare processes. Low couplings and/or high mass final-state. probes $Zt\bar{t}$, $\gamma t\bar{t}$, FCNC, ... first observation of tZq: 2018

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- $t\bar{t}tX$: 1.6 fb

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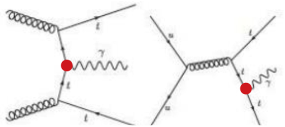
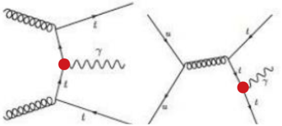


ATL-PHYS-PUB-2018-049

Measurements of top-quark properties play an important role in testing the Standard Model (SM) and its possible extensions. Studies of the production and kinematic properties of a top-quark pair ($t\bar{t}$) in association with a photon ($t\bar{t}\gamma$) probe the $t\gamma$ electroweak coupling. For instance, deviations in the transverse momentum (p_{T}) spectrum of the photon from the SM prediction could point to new physics through anomalous dipole moments of the top quark [1–3]. A precision measurement of the $t\bar{t}\gamma$ production cross-section could effectively constrain some of the Wilson coefficients in top-quark effective field theories [4]. Furthermore, differential distributions of photon production in $t\bar{t}$ events can provide insight on the $t\bar{t}$ production mechanism, in particular about the $t\bar{t}$ spin correlation and the production charge asymmetry [5].

$t\bar{t}\gamma$ production - LHC



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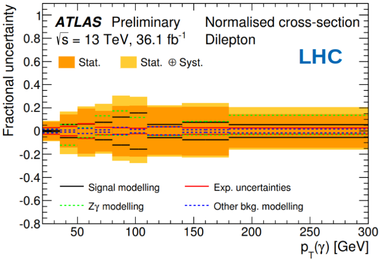

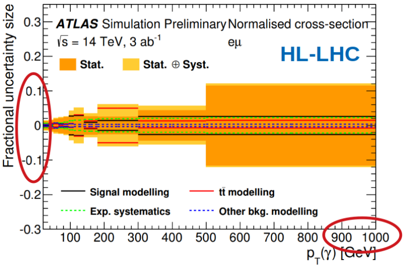

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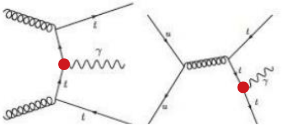

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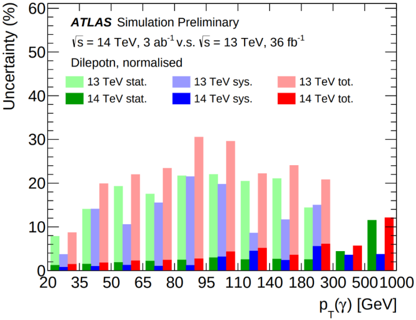
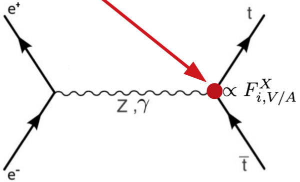


Source	e+jets	μ+jets	ee	$e\mu$	$\mu\mu$
$t\bar{t}\gamma$ PY8 vs H7	1.0%	1.0%	1.0%	1.0%	1.0%
$t\bar{t}$ ISR/FSR	3.1%	3.4%	1.1%	1.1%	1.0%
$t\bar{t}$ MG5 vs Sherpa	1.0%	1.0%	0.4%	0.4%	0.4%
$W\gamma$ norm.	1.6%	2.7%			
$Z\gamma$ norm.	1.7%	0.7%	2.8%	<0.1%	4.7%
$Z\gamma$ QCD scale			1.7%	<0.1%	2.8%
Single top norm.	1.1%	1.3%	0.9%	0.3%	0.6%
Diboson norm.	<0.1%	<0.1%	0.1%		0.1%
Fake-lep norm.	3.0%	0.5%			
e-fake norm. 1	1.5%	1.5%			
e-fake norm. 2	0.7%	0.8%			
JES NP 1	2.2%	2.2%	1.2%	1.0%	1.2%
JES Rho topo.	1.1%	1.1%	1.2%	1.0%	1.2%
Photon eff.	1.1%	1.1%	1.2%	1.0%	1.2%
Pile-up	2.2%	2.2%	2.3%	2.0%	2.4%
Luminosity	1.1%	1.1%	1.2%	1.0%	1.2%
Total systematics	6.6%	6.2%	4.9%	3.3%	6.7%

Anomalous (CP-conserving) EW dipoles

$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5\widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5\widetilde{F}_{2A}^X(k^2)\right)\right\}$$

Z, gamma   Z, gamma   electro-weak anomal moment



$t\bar{t}\gamma$ production - e^+e^- colliders

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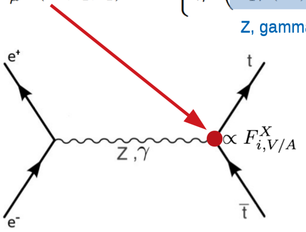
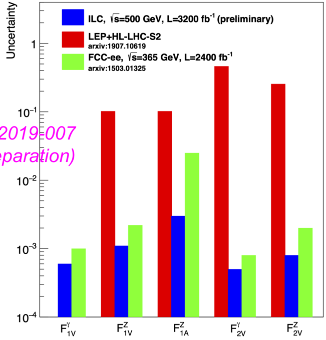
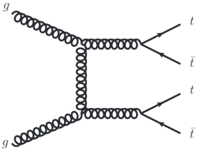


ILD-Note-2019-007
(under preparation)



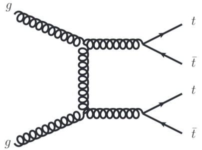
$t\bar{t}t\bar{t}$ production



ATL-PHYS-PUB-2018-047

In the Standard Model (SM) the production of four top quarks ($t\bar{t}t\bar{t}$) is a very rare process with an expected cross-section of $\sigma(pp \to t\bar{t}t\bar{t}) = 15.83^{+18\%}_{-21\%}$ fb at 14 TeV [1]. This process has not been observed. Many theories beyond the SM predict an enhancement of the $t\bar{t}t\bar{t}$ cross-section; examples include gluino pair production in supersymmetric models [2], pair production of scalar gluons [3, 4], and production of a heavy pseudoscalar or scalar boson in association with a $t\bar{t}$ pair in Type II two-Higgs-doublet models (2HDM) [5, 6]. In the context of Effective Field Theories, the $t\bar{t}t\bar{t}$ cross-section uniquely constrains the four-top-quark effective operators [7].

$t\bar{t}t\bar{t}$ production



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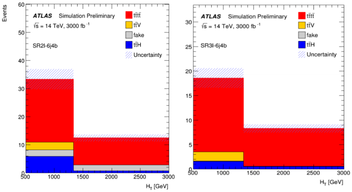
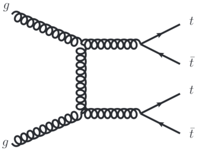
Simple strategy:
4 SRs based on (Nlep, Nj, Nb) and exploit H_T

7 Conclusion

Projections for the measurement of the SM four-top-quark production cross-section in final states containing two same-charge leptons or at least three leptons, at least five jets and at least two b-jets at $\sqrt{s}$ = 14 TeV were performed in the context of the High-Luminosity LHC with 3000 fb^{-1} of proton-proton collisions with the ATLAS experiment. An uncertainty on the $t\bar{t}t\bar{t}$ cross-section of 11% is expected with the precision being dominated by the statistical uncertainty. This corresponds to a significance to observe this yet-unmeasured signal well above 5 standard deviations. The current theoretical uncertainty on the computation of the four-top-quark production cross-section is roughly twice larger than the experimental projected uncertainty.



$t\bar{t}t\bar{t}$ production



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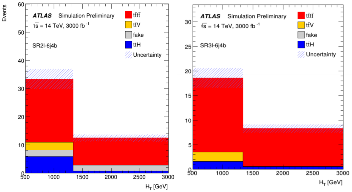
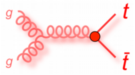
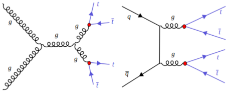


Comment: lepton colliders will not be sensitive to this process. Key element of the HL-LHC physics program!

Anomalous strong dipoles

$$\mathcal{L} = \mathcal{L}_{\mathrm{QCD}} + \frac{g_s}{m_t}\,\bar{t}\sigma^{\mu\nu}(d_V + \mathrm{i}\,d_A\gamma_5)\frac{\lambda_a}{2}\,t\,G^a_{\mu\nu}$$





Constraining top-gluon interaction with $t\bar{t}t\bar{t}$ and $t\bar{t}$

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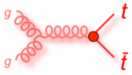

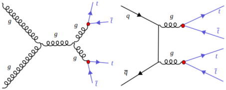

Four-top constraints

Coupling	HL-LHC, 14 TeV, 3 ab^{-1}	HE-LHC, 27 TeV, 15 ab^{-1}
d_V^g	[-0.084, 0.009]	[-0.063, 0.001]
d_A^g	[-0.030, 0.030]	[-0.011, 0.011]

(1) Four-top and $t\bar{t}$ complementary with at (HL-)LHC
(2) FCC-pp reaches a precision better by o(5)

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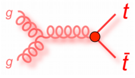

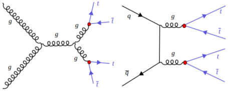

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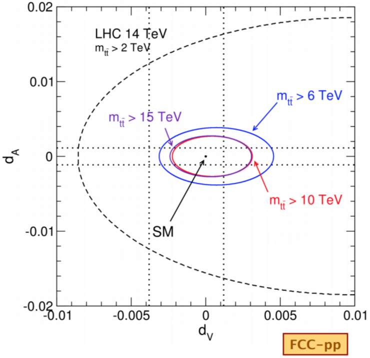
arXiv:1412.6654

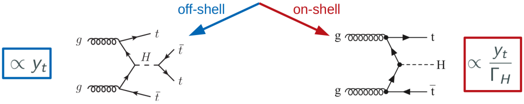


Angular observables: spin correlation in $t\bar{t}$ sensitive to strong dipoles
→ CMS (13 TeV, 139 fb^{-1}): $-0.014 < d_V < 0.004$ PRD **100** 072002 (2019)

$t\bar{t}t\bar{t}$ production: resonant physics

Probing the Higgs sector – arXiv:1602.01934

$$\mathcal{M}_H(q) \propto \frac{y_t}{(q^2 - m_H^2) + i m_H \Gamma_H}$$



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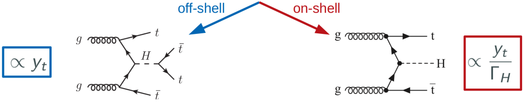

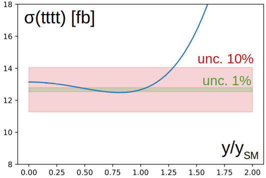

$$\sigma_{t\bar{t}t\bar{t}}(y_t)\,[\text{fb}] = 13.14 - 2.01 \left(\frac{y_t}{y_t^{\text{SM}}}\right)^2 + 1.52 \left(\frac{y_t}{y_t^{\text{SM}}}\right)^4$$

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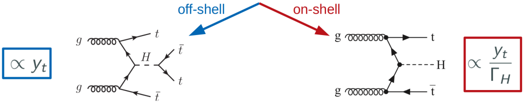

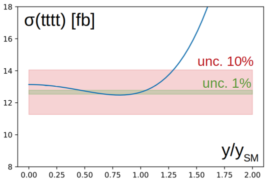

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Probing new sector: a new vector boson interacting only with the top quark *cannot be produced otherwise* than in resonant $t\bar{t}t\bar{t}$ process.

Rare processes: concluding remarks

Effective Fields Theory

EFT - how to parametrize our ignorance

Motivations

- agnostic approach: precision measurement $\leftrightarrow$ what NP could be
- correlations across channels and observables over the full SM
- **combination only** fully exploits EFT power (*e.g.* arXiv:1901.05965)
- few individual constraints already discussed (*e.g.* anomalous dipoles)

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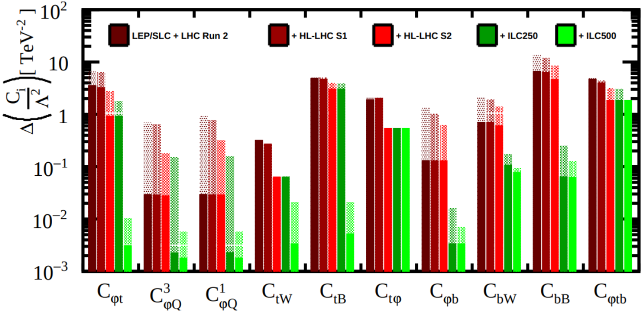
EW couplings only - arXiv:1907.10619



Conclusions

Summary and conclusion

The top quark is one the key element of the SM

Current state of the art

- impressive precision reached in some areas (*e.g.* $\Delta m_t \sim 0.5\%$)
- certain top-related effects: limiting searches/measurements
- main bottleneck: modelling and associated uncertainties

Summary and conclusion

The top quark is one the key element of the SM

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- impressive precision reached in some areas (*e.g.* $\Delta m_t \sim 0.5\%$)
- certain top-related effects: limiting searches/measurements
- main bottleneck: modelling and associated uncertainties

Future of top quark physics

- improve precision on fundamental parameters (m_t, y_t, ...)
- reveal only-partially explored phenomena (*e.g.* $t\bar{t}t\bar{t}$)

→ HL-LHC: improve precision and enlarge accessible phase-space

→ e^+e^- colliders (above $2m_t$ threshold): reach another level of precision

Strong and broad expertise in the french community

Backup Slides

Existing ATLAS/CMS projections at HL-LHC

arXiv:1902.10229

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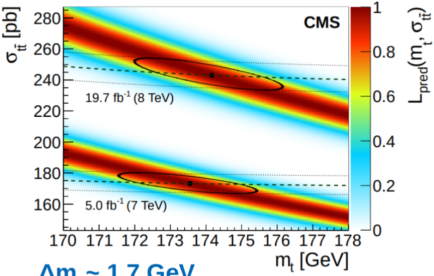
Top quark pole mass: examples

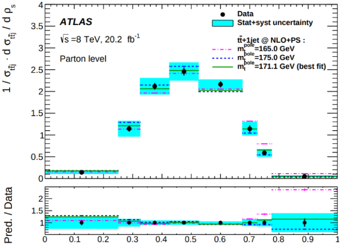
Pole mass accessed only 'indirectly' (first time in 2011 - arXiv:1104.2887)

- inclusive $pp \to t\bar{t}$ cross-section
- differential $pp \to t\bar{t} + 1\,\text{jet}$ cross-section *v.s.* $m_{t\bar{t}j}^{-1}$

JHEP 08 (2016) 029 | **JHEP 11 (2019) 150**



$\Delta m_t \sim 1.7$ GeV

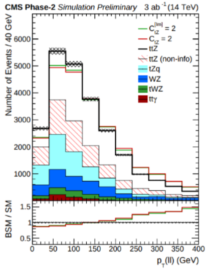


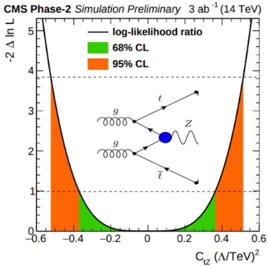
$\Delta m_t \sim 1.2$ GeV

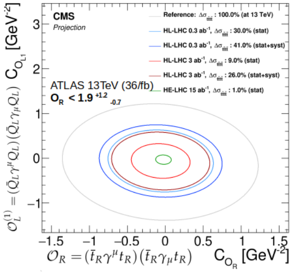
$$\rho_s = \frac{2m_0}{m_{t\bar{t}+1\text{-jet}}}$$

Limiting uncertainties: shower/hadronization & colour reconnection, energy scale of (b-) jets

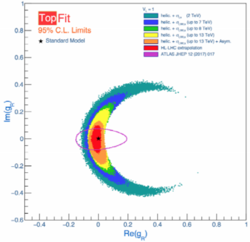
EFT: C_{Zt}, C_{tt}, Wtb interaction



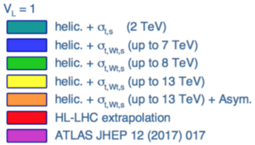




arXiv:1811.02492



$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\, t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)\, t\, W_{\mu}^{-} + \text{h.c.}\ (1)$$



HL-LHC → reduce by a factor 2 allowed ranges wrt LHC

Anomalous QED/QCD dipoles: formalism

Gordon decomposition of spin-1/2 current

$$\bar{u}(\bar{p})\gamma^{\mu}u(p) = \bar{u}(\bar{p})\left[\frac{(p+\bar{p})^{\mu}}{2m} + i\sigma^{\mu\nu}\frac{(p-\bar{p})_{\nu}}{2m}\right]u(p)$$

EM form factor definitions describe generalized γee vertex ($q \equiv p - \bar{p}$)

- $F_1(q)$: charge - or Dirac - form factor $\rightarrow$ effective charge 'distribution'
- $F_2(q)$: magnetic - or Pauli - form factor $\rightarrow$ $F_2(0)$ contains corrections to $(g-2)$
- only anomalous magnetic dipole here, no electric dipole (cf. next slide)

$$\begin{aligned}\Gamma^{\mu}(p,\bar{p}) &\equiv \gamma^{\mu}F_1(q) + \sigma^{\mu\nu}\frac{(p-\bar{p})_{\nu}}{2m}F_2(q) \\ &\equiv \frac{(p+\bar{p})^{\mu}}{2m}F_1(q) + i\sigma^{\mu\nu}\frac{(p-\bar{p})_{\nu}}{2m}\{F_1(q)+F_2(q)\}\end{aligned}$$

Dipoles as addionnal interaction terms present at tree level (not generated *via* loops)

$$g_{\mathrm{QED}}\,\bar{\psi}\left[\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{\psi}}(d_V^{\mathrm{QED}} + i d_A^{\mathrm{QED}}\gamma^5)\right]\psi\,A_{\mu} + g_{\mathrm{QCD}}\,\bar{\psi}\lambda_a\left[\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{\psi}}(d_V^{\mathrm{QCD}} + i d_A^{\mathrm{QCD}}\gamma^5)\right]\psi\,G_{\mu}^{a}$$

Electromagnatic form factors: the full picture

Complete review: arXiv:0402058

EM form factors allowed by the EM gauge invariance

- $F_1(q)$: charge - or Dirac - form factor $\rightarrow$ effective charge 'distribution'
  $\rightarrow Q_e \equiv eF_1(0)$
- $F_2(q)$: magnetic - or Pauli - form factor $\rightarrow$ $F_2(0)$ contains corrections to $(g-2)$
  $\rightarrow \frac{1}{2m}(F_1(0)+F_2(0)) \equiv \mu$ and $H_{\rm int} \propto \mu\,\vec{\sigma}\cdot\vec{B}$
- $F_3(q)$: electric dipole moment (never observed, violate time-reversal symmetry)
  $\rightarrow -\frac{1}{2m}F_3(0) \equiv d$ and $H_{\rm int} \propto -d\,\vec{\sigma}\cdot\vec{E}$
- $F_4(q)$: anapole moment (never observed, violate time-reversal symmetry)
  $\rightarrow H_{\rm int} \propto F_4(0)\,\vec{\sigma}\cdot\left[\nabla\times\vec{B}-\frac{\partial\vec{E}}{\partial t}\right]$

General expression of the electromagnetic current

$$\begin{aligned}\Gamma^\mu(p,\bar{p}) \quad &\equiv \quad F_1(q)\,\gamma^\mu + F_2(q)\,\sigma^{\mu\nu}\frac{q_\nu}{2m} \\ &+ \quad F_3(q)\,i\epsilon^{\mu\nu\alpha\beta}\sigma_{\alpha\beta}\frac{q_\nu}{4m} + F_4(q)\,\frac{1}{2m}\left(q^\mu - \frac{q^2}{2m}\gamma^\mu\right)\gamma^5\end{aligned}$$

Magnetic-like dipole

- loop-induced: $F_1 + F_2$; $F_2 \equiv$ anomalous component on top of $\bar{\psi}\gamma^\mu\psi$
- tree-level: $\frac{i\sigma^{\mu\nu}q_\nu}{m_\psi}d_V$ term - vectorial component of the current

Electric-like dipole (CP-violating term)

- loop-induced: F_3
- tree-level: $\frac{i\sigma^{\mu\nu}q_\nu}{m_\psi}id_A\gamma^5$ term - axial component of the current

(Questions to me: for the last, one needs to check that $\sigma^{\mu\nu}\gamma^5 \propto \epsilon^{\mu\nu\alpha\beta}\sigma_{\alpha\beta}$ to be consitent with previous slides). Is that a problem to have q_μ in the lagrangian? Why this is CP-violating?)

General comments

- these formulations work for both electro-weak and strong interactions
- tree-level terms are dim-6 operators: EFT or loop-induced in BSM theories