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Top Quark Properties

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DFG Deutsche Forschungsgemeinschaft

Introduction

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What do we mean by "*top quark properties*"?

Person A: Mass, Width

Person B: Gauge and Yukawa couplings

Person C: Cross section, A_{C}, W helicity fractions

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At the level of the SM Lagrangian, it is a well-defined question:

$$\mathcal{L}_{\text{top}}^{\text{SM}} = \bar{t}\,\mathrm{i}\left(\not{\partial} + \frac{\mathrm{i}e}{c_w} Y \not{B} - \frac{\mathrm{i}e}{s_w} I^a \not{W}^a - \mathrm{i} g_s T^c \not{G}^c\right) t \; - m_t \,\bar{t}\, t$$

Everything is determined by: $\alpha, s_w, \alpha_s, m_t$ (+SM symmetries).

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These are not observables but free parameters of the theory, fixed by some measurement.

$$\mathcal{O}^{\text{nature}}_{\text{measured}} = \mathcal{O}^{\text{theory}}_{\text{predicted}}(\alpha) \xrightarrow[\text{theory} \approx \text{nature}]{\text{solve}} \alpha$$

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Everything is determined by: $\alpha, s_w, \alpha_s, m_t$ (+SM symmetries).

Once the parameters are reliably fixed, we try to *test the theory*, i.e. try to *falsify* the model, i.e. *find New Physics*:

$$\mathcal{O}^{\rm nature}_{\rm measured} = \mathcal{O}^{\rm theory}_{\rm predicted}(\alpha) \quad \xleftarrow[\text{theory} \approx \text{nature?}]{\text{test}} \quad \alpha$$

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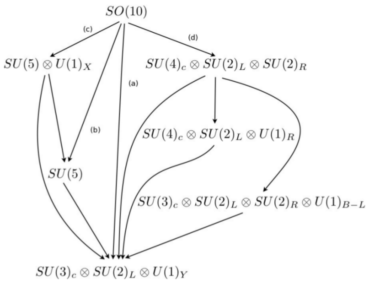
Everything is determined by: $\alpha, s_w, \alpha_s, m_t$ (+SM symmetries).

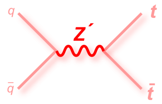
→ We have to probe observables that are sensitive to physics beyond the SM

→ We need high precision to reliably identify small deviations

How to search for New Physics?

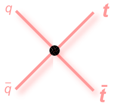


Strategy I: Explicit model building and testing the predictions



Introduce a new $\mathcal{L}_{\mathrm{BSM}}$ such that $\mathcal{L}_{\mathrm{BSM}} \to \mathcal{L}_{\mathrm{SM}}$ in some limit

Strategy II: Model-independent Effective Field Theory (EFT)

$\frac{1}{\Lambda^2} \times$ 

Extend the SM such that $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{c_i}{\Lambda^2}\,\mathcal{O}_i^{\mathrm{dim6}} + \ldots,$ fit to data yields constraint on $\frac{c_i}{\Lambda^2}$

$\mathcal{L}^{\mathrm{dim6}}$ is the most general expression that respects all symmetries of the SM

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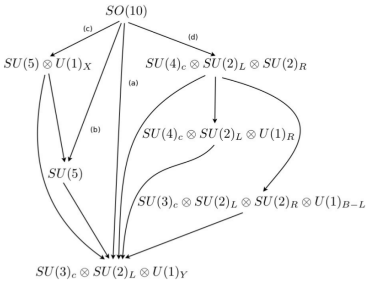

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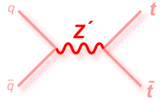

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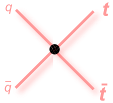
$\frac{1}{\Lambda^2} \times$ 

Extend the SM such that $\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_i}{\Lambda^2} \mathcal{O}_i^{\rm dim6} + \ldots$, fit to data yields constraint on $\frac{c_i}{\Lambda^2}$

$\mathcal{L}^{\rm dim6}$ is the most general expression that respects all symmetries of the SM

SM-EFT:

Assumptions:

- New Physics is heavy
- New Physics does not break $\mathrm{SU(2)_L xU(1)}$ at $E \leq \Lambda$

Consequences:

→ Effects from dim6 dominate over dim8, ...

→ Relations between anomalous couplings of SM fields

Example:

Add new dim6 Lagrangian term

$$\mathcal{O}_{\phi q1}^{\mathrm{dim6}} = \underbrace{\mathrm{i}(\phi^\dagger D_\mu \phi)(\bar{U}_\mathrm{L}\gamma^\mu U_\mathrm{L})}_{\text{SU(2)xU(1) invariant}}$$

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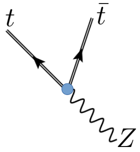
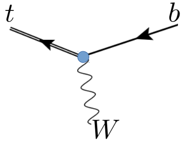
Yields modified coupling for $t\bar{t}Z$ and tbW



$$= \frac{\mathrm{i}e}{2s_w c_w}\gamma^\mu \left\{ \left(1 + \frac{c_{\phi q1}}{\Lambda^2}\right) P_\mathrm{L} + P_\mathrm{R} - 2s_w^2 Q_t \right\}$$



$$= \frac{\mathrm{i}e}{\sqrt{2}s_w}\gamma^\mu P_\mathrm{L}\left(1 + \frac{c_{\phi q1}}{\Lambda^2}\right)$$

Cross section contribution:

$$\sigma_\mathrm{BSM} = \sigma_\mathrm{SM} + \frac{v^2}{\Lambda^2}\,\sigma_\mathrm{EFT} + \frac{v^4}{\Lambda^4}\,\sigma_{\mathrm{EFT}^2}$$

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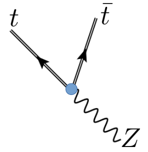

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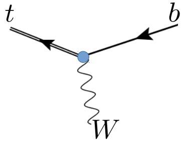

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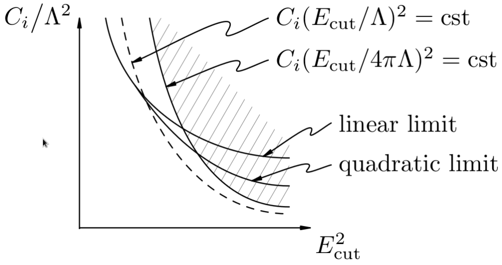
SM-EFT interference

squared dim6 EFT term



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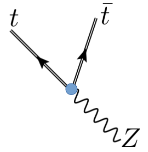

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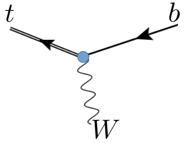

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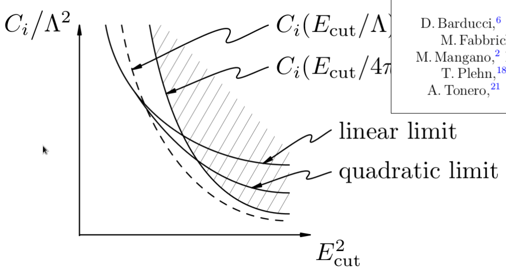

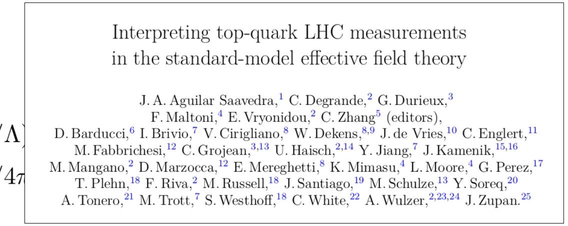

Interpreting top-quark LHC measurements in the standard-model effective field theory

J. A. Aguilar Saavedra,[1] C. Degrande,[2] G. Durieux,[3] F. Maltoni,[4] E. Vryonidou,[2] C. Zhang[5] (editors), D. Barducci,[6] I. Brivio,[7] V. Cirigliano,[8] W. Dekens,[8,9] J. de Vries,[10] C. Englert,[11] M. Fabbrichesi,[12] C. Grojean,[3,13] U. Haisch,[2,14] Y. Jiang,[7] J. Kamenik,[15,16] M. Mangano,[2] D. Marzocca,[12] E. Mereghetti,[8] K. Mimasu,[4] L. Moore,[4] G. Perez,[17] T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20] A. Tonero,[21] M. Trott,[7] S. Westhoff,[18] C. White,[22] A. Wulzer,[2,23,24] J. Zupan.[25]

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$$\mathcal{O}_{uW}^{\text{dim6}} = (\bar{U}_{\text{L}}\sigma^{\mu\nu}\tau^a t_{\text{R}})\tilde{\phi}W^a_{\mu\nu}$$

SU(2)xU(1) invariant

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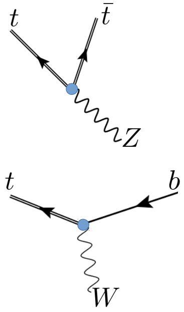

$$= \Gamma^Z_{\text{SM}} + \text{i}\frac{\sigma^{\mu\nu}}{m_t}(g^Z_{\text{L}}P_{\text{L}} + g^Z_{\text{R}}P_{\text{R}})\boldsymbol{q}_\mu\varepsilon^Z_\nu$$

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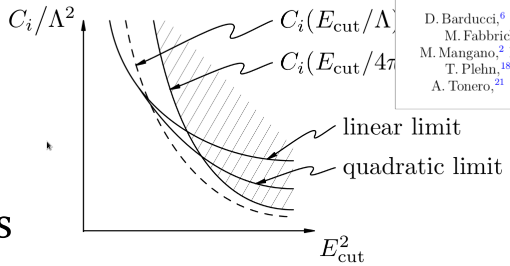
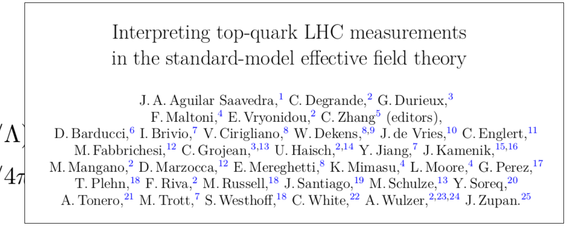
energy dependence leads to violation of unitarity

Require: $E \ll \Lambda$

$\rightarrow$ Limit energy range of the analysis





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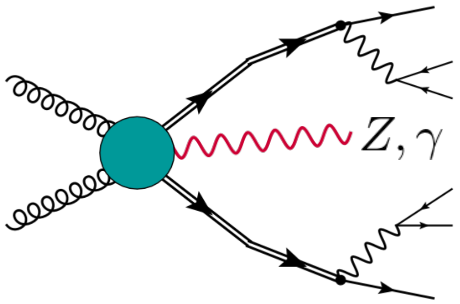
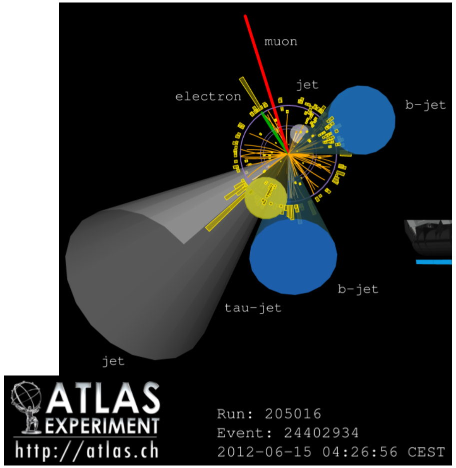
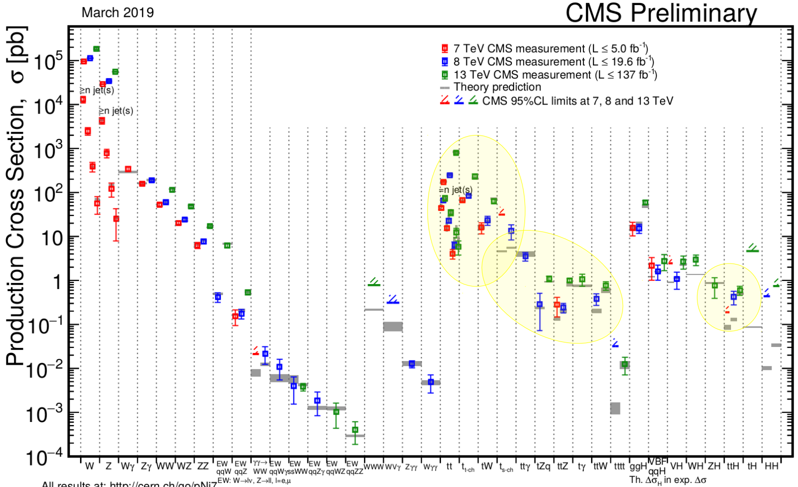
Anatomy of Top Quark Production at the LHC



Features:

- Very complex final state (often up to 8 particles)
- Sufficiently large cross sections
- Small backgrounds & clean signature (if $W \longrightarrow$ leptons)
- Meaningful separation into production and decay dynamics
- Sensitivity to New Physics





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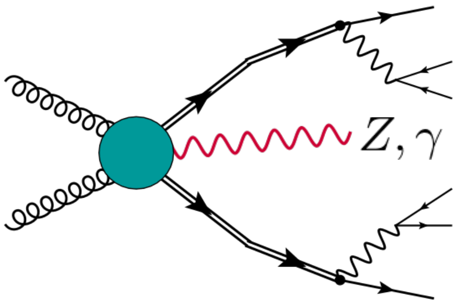

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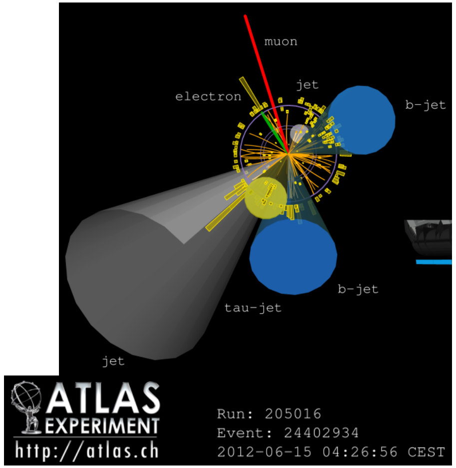
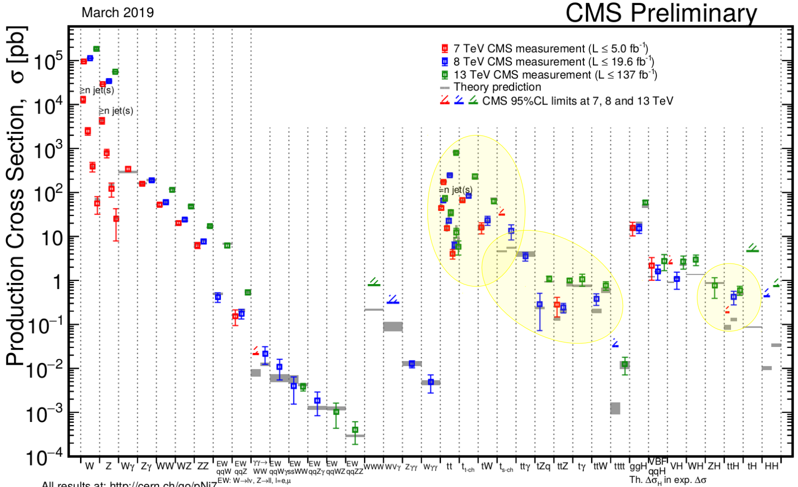


Special property: $\Lambda_{\text{QCD}} \ll \Gamma_t \ll m_t$

- No hadronic bound states
- Spin information is transferred to decay products

- Production and decay are separated by large time scale
- Top quarks like to go on-shell before they decay



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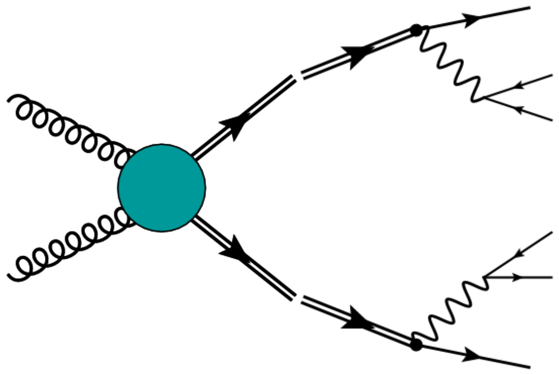

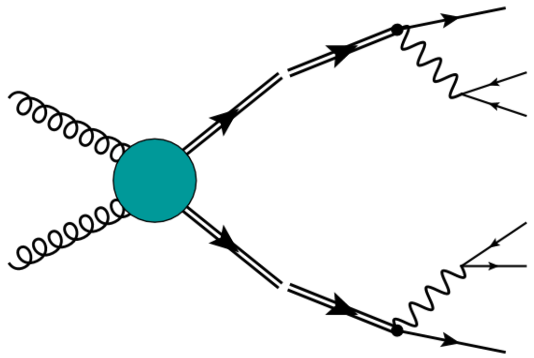

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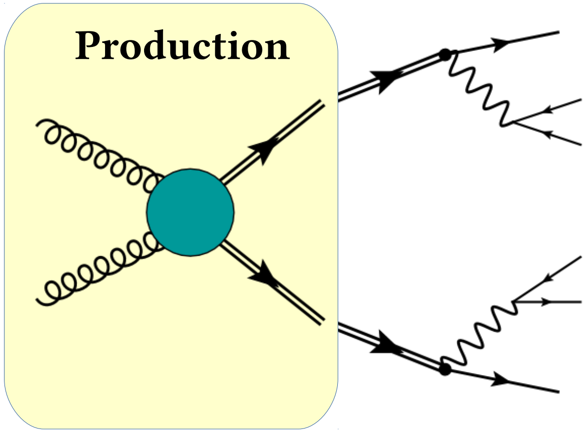

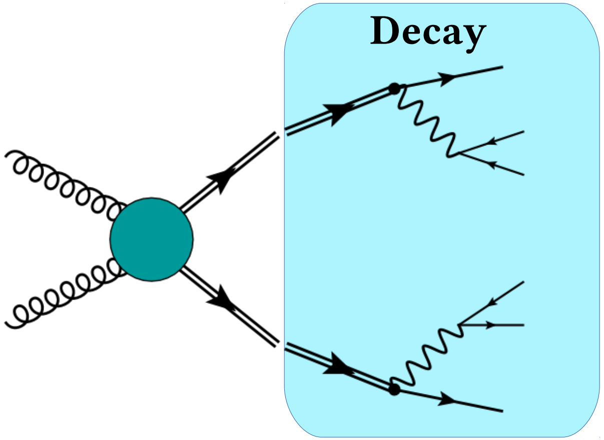

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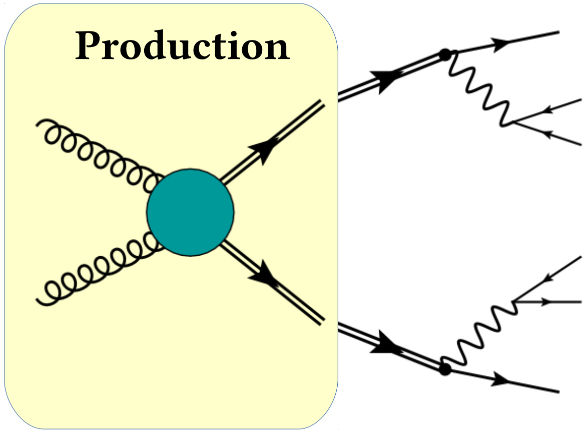
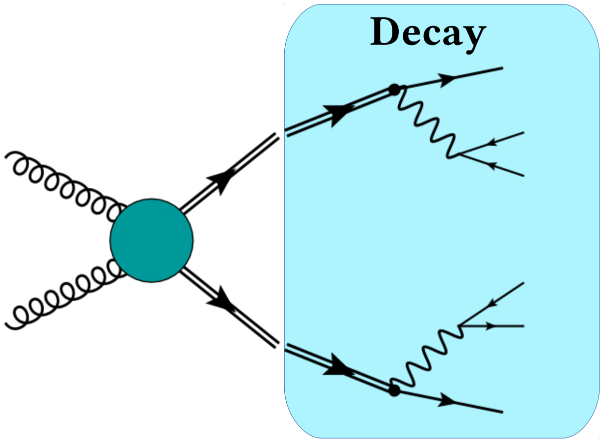


Sensitivity to
QCD dynamics



Sensitivity to
EW physics

$$
\begin{aligned}
\mathcal{O}_{Qq}^{(8,3)} &= (\bar{Q}_L\gamma_\mu T^a\tau^i Q_L)(\bar{q}_L\gamma^\mu T^a\tau^i q_L)\\
\mathcal{O}_{Qq}^{(8,1)} &= (\bar{Q}_L\gamma_\mu T^a Q_L)(\bar{q}_L\gamma^\mu T^a q_L)\\
\mathcal{O}_{td}^{(8)} &= (\bar{t}_R\gamma_\mu T^a t_R)(\bar{d}_R\gamma^\mu T^a d_R)\\
\mathcal{O}_{tu}^{(8)} &= (\bar{t}_R\gamma_\mu T^a t_R)(\bar{u}_R\gamma^\mu T^a u_R)\\
\mathcal{O}_{tq}^{(8)} &= (\bar{t}_R\gamma_\mu T^a t_R)(\bar{q}_L\gamma^\mu T^a q_L)\\
\mathcal{O}_{Qd}^{(8)} &= (\bar{Q}_L\gamma_\mu T^a Q_L)(\bar{d}_R\gamma^\mu T^a d_R)\\
\mathcal{O}_{Qu}^{(8)} &= (\bar{Q}_L\gamma_\mu T^a Q_L)(\bar{u}_R\gamma^\mu T^a u_R)\\
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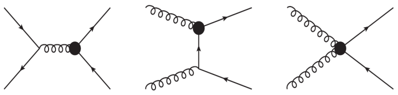
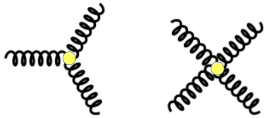
\end{aligned}
$$

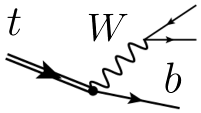


$$O_{tG} = y_t g_s\,(\bar{Q}\sigma^{\mu\nu}T^A t)\,\tilde{\phi}G^A_{\mu\nu}$$



$$c_G\mathcal{O}_G = \frac{g_s\,c_G}{\Lambda^2}\,f_{abc}G^\rho_{a\nu}G^\nu_{b\lambda}G^\lambda_{c\rho}$$

$\longrightarrow$ see [Krauss, Kuttimalai, Plehn] (2016)



$$
\begin{aligned}
C_{\phi q}^{(3,33)} &= \mathrm{i}\,(\phi^\dagger\tau^a D_\mu\phi)\,(\bar{t}_\mathrm{L}\gamma^\mu\tau_a t_\mathrm{L}),\\
\mathcal{O}_{\phi\phi}^{33} &= \mathrm{i}(\tilde{\phi}^\dagger D_\mu\phi)(\bar{u}_R\gamma^\mu d_R)\\
\mathcal{O}_{uW}^{33} &= (\bar{q}_\mathrm{L}\sigma^{\mu\nu}\tau^I t_\mathrm{R})\,\tilde{H}W^I_{\mu\nu},\\
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\mathcal{O}_{uB\phi}^{33} &= (\bar{q}_\mathrm{L}\sigma^{\mu\nu} t_\mathrm{R})\,\tilde{H}B_{\mu\nu},
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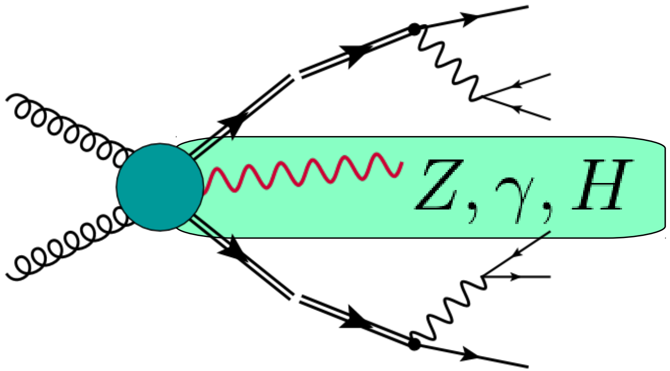
$$

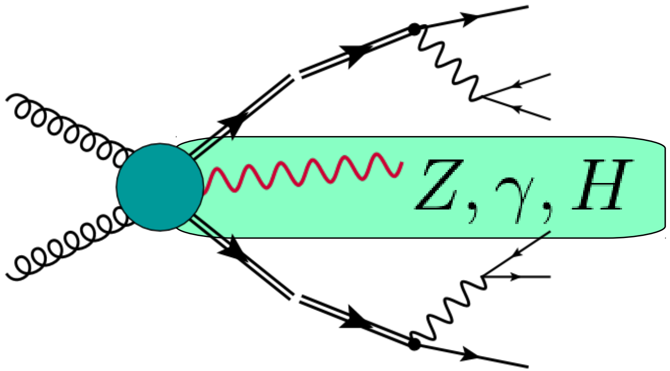
Anatomy of Top Quark Production at the LHC



Associated production:

Sensitivity to couplings of neutral gauge bosons and the Higgs Boson

Anatomy of Top Quark Production at the LHC



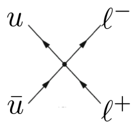
Associated production:

Sensitivity to couplings of neutral gauge bosons and the Higgs Boson

$$C_{u\phi}^{33} = (\tilde{\phi}^\dagger \phi)(\bar{q}_L u_R)$$
$$C_{\phi q}^{(3,33)} = \mathrm{i}\,(\phi^\dagger \tau^a D_\mu \phi)\,(\bar{t}_\mathrm{L}\gamma^\mu \tau_a t_\mathrm{L}),$$
$$C_{\phi q}^{(1,33)} = \mathrm{i}\,(\phi^\dagger D_\mu \phi)\,(\bar{t}_\mathrm{L}\gamma^\mu t_\mathrm{L}),$$
$$C_{\phi u}^{33} = \mathrm{i}\,(\phi^\dagger D_\mu \phi)\,(\bar{t}_\mathrm{R}\gamma^\mu t_\mathrm{R}).$$

$$\mathcal{O}_{uW}^{33} = (\bar{q}_\mathrm{L}\sigma^{\mu\nu}\tau^I t_\mathrm{R})\,\tilde{H} W_{\mu\nu}^I,$$
$$\mathcal{O}_{dW}^{33} = (\bar{q}_\mathrm{L}\sigma^{\mu\nu}\tau^I b_\mathrm{R})\,H W_{\mu\nu}^I,$$
$$\mathcal{O}_{uB\phi}^{33} = (\bar{q}_\mathrm{L}\sigma^{\mu\nu} t_\mathrm{R})\,\tilde{H} B_{\mu\nu},$$

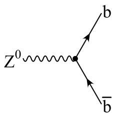
- Allows to probe a large range of new couplings
- Electroweak top quark couplings are not very well constrained
- Tevatron never produced *ttbar+X* final states
- Relations from EW precision observables



$$O_{lq}^1 \equiv \bar{l}\gamma_\mu l \quad \bar{q}\gamma^\mu q,$$
$$O_{lu} \equiv \bar{l}\gamma_\mu l \quad \bar{u}\gamma^\mu u,$$
$$O_{eq} \equiv \bar{e}\gamma^\mu e \quad \bar{q}\gamma_\mu q,$$
$$O_{eu} \equiv \bar{e}\gamma_\mu e \quad \bar{u}\gamma^\mu u,$$

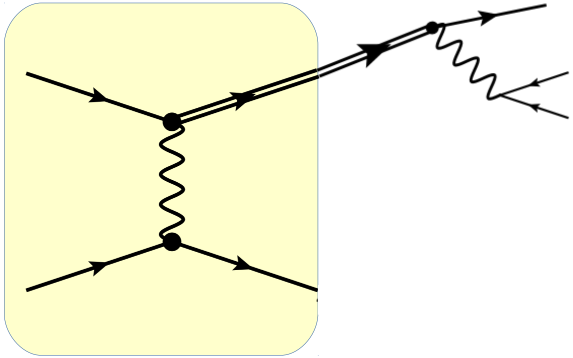
$$O_{lequ}^1 \equiv \bar{l}e \;\; \varepsilon \;\; \bar{q}u,$$
$$O_{lequ}^3 \equiv \bar{l}\sigma_{\mu\nu} e \;\; \varepsilon \;\; \bar{q}\sigma^{\mu\nu} u$$
$$O_{lq}^3 \equiv \bar{l}\gamma_\mu \tau^I l \quad \bar{q}\gamma^\mu \tau^I q,$$

$$\delta\varepsilon_1 = \frac{3m_t^2 G_\mathrm{F}}{2\sqrt{2}\pi^2}\,\mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} + C_{\phi u}^{33} + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right]\left(\frac{v^2}{\Lambda^2}\right)\log\left(\frac{\Lambda^2}{m_t^2}\right)$$
$$\delta\varepsilon_b = -\frac{m_t^2 G_\mathrm{F}}{2\sqrt{2}\pi^2}\,\mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} + \frac{1}{4}C_{\phi u}^{33}\right]\left(\frac{v^2}{\Lambda^2}\right)\log\left(\frac{\Lambda^2}{m_t^2}\right).$$



$$C_{\phi q}^{(3,33)} \approx -C_{\phi q}^{(1,33)}$$

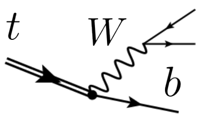
Anatomy of Top Quark Production at the LHC



Single top quark production:

Only mentioned briefly for brevity

Excellent sensitivity to tbW coupling and top quark mass



$$C_{\phi q}^{(3,33)} = \mathrm{i}\,(\phi^\dagger \tau^a D_\mu \phi)\,(\bar{t}_\mathrm{L}\gamma^\mu \tau_a t_\mathrm{L}),$$
$$\mathcal{O}_{\phi\phi}^{33} = \mathrm{i}(\tilde{\phi}^\dagger D_\mu \phi)(\bar{u}_R \gamma^\mu d_R)$$
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$$\mathcal{O}_{dW}^{33} = (\bar{q}_\mathrm{L}\sigma^{\mu\nu}\tau^I b_\mathrm{R})\,HW_{\mu\nu}^I,$$
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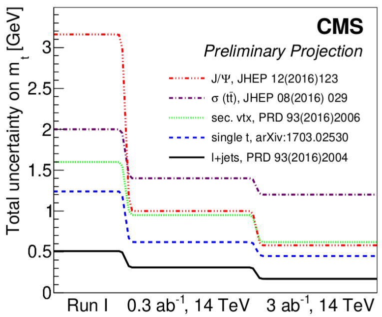


The big picture

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

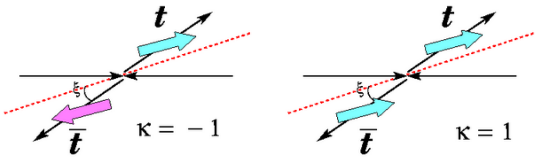
$$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\,\gamma^{\mu}t\,A_{\mu} - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{m_t}(d_V^{\gamma} + id_A^{\gamma}\gamma_5)\,t\,A_{\mu}\,.$$

$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W}\bar{t}\,\gamma^{\mu}\left(X_{tt}^{L}P_L + X_{tt}^{R}P_R - 2s_W^2 Q_t\right)t\,Z_{\mu} - \frac{g}{2c_W}\bar{t}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_Z}(d_V^{Z} + id_A^{Z}\gamma_5)\,t\,Z_{\mu}\,,$$

Spin Correlations

Spin Correlations

Top quarks produced at the LHC are unpolarized.



However, the relative polarization of top and anti-top is correlated.

[Barger,Ohnemus,Philips] (1988)

$$C_{\rm LO}^{\rm SM} = \frac{\#\left(\uparrow\uparrow + \downarrow\downarrow\right) - \#\left(\uparrow\downarrow + \downarrow\uparrow\right)}{\#\text{total}} = \begin{cases} -46\% \text{ at Tevatron,} \\ +31\% \text{ at LHC.} \end{cases}$$

(quantization axis = direction of flight)

Spin Correlations

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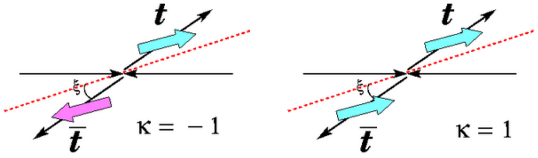

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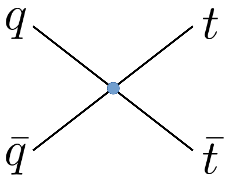
$$C^{\mathrm{SM}}_{\mathrm{LO}} = \frac{\#\,(\uparrow\uparrow + \downarrow\downarrow) - \#\,(\uparrow\downarrow + \downarrow\uparrow)}{\#\mathrm{total}} = \begin{cases} -46\% \text{ at Tevatron,} \\ +31\% \text{ at LHC.} \end{cases}$$

(quantization axis = direction of flight)

Interesting quantity because very sensitive to New Physics:

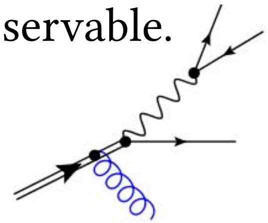


$$\mathcal{L}_{\mathrm{BSM}} = \frac{g_s^2}{2m_t^2}\,\hat{c}_{VV}\,\left(\bar{q}\gamma^\mu t^a q\right)\left(\bar{t}\gamma_\mu t^a t\right) + \frac{g_s^2}{4m_t^2}\,\hat{c}_1\left\{\left(\bar{q}\gamma^\mu \sigma_3 t^a q\right)\left(\bar{t}\gamma_\mu t^a t\right) + \left(\bar{q}\gamma^\mu\gamma^5\sigma_3 t^a q\right)\left(\bar{t}\gamma_\mu t^a t\right)\right\}$$

$$C^{\mathrm{BSM}}_{\mathrm{LO}} = \begin{cases} -89\% & c_{VV} \\ +18\% & c_1 \end{cases}$$

[Bernreuther,Heisler,Si] (2015)

Spin Correlations



In the early days (Tevatron run-II) it was questionable whether spin correl. are observable.

Non-perturbative effects and radiative top quark decays wash out the correlation.

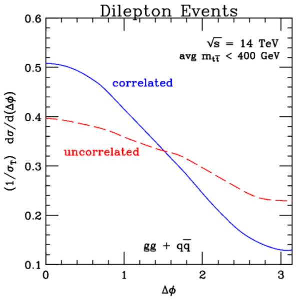
Thanks to $\Lambda_{\rm QCD} \ll \Gamma_t \ll m_t$, the non pert. dilution is small. No collinear enhancement.

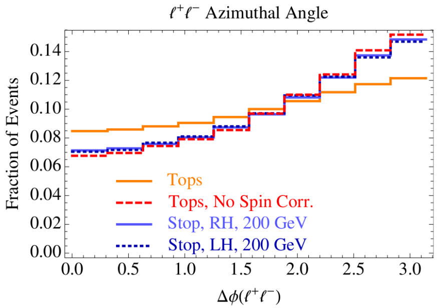
$\longrightarrow$ Spin correlations first observed by DZero (2011) in $\Delta\phi_{\ell\ell}$ distribution using MEM methods.

[Melnikov, M.S.] (2011)

Important: (*V-A*) interaction in decay transfers spin information to decay products
Top quark spin correlation is imprinted in lepton angular distribution

[Mahlon] (2010)





[Han,Katz,Krohn,Reece] (2012)

Spin Correlations

State-of-the-art:

NNLO QCD for top quark production + decay (NWA)

Higher order corrections to spin correlations in top quark pair production at the LHC

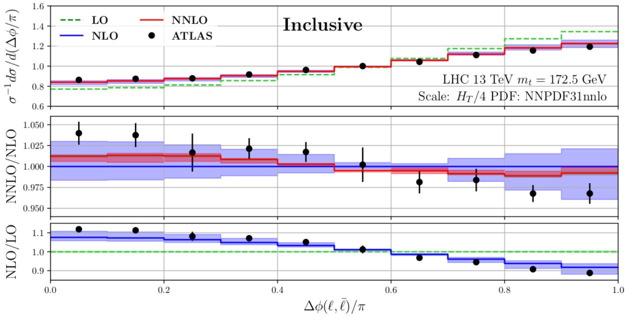
Arnd Behring
Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany and Institute for Theoretical Particle Physics, KIT, Karlsruhe, Germany

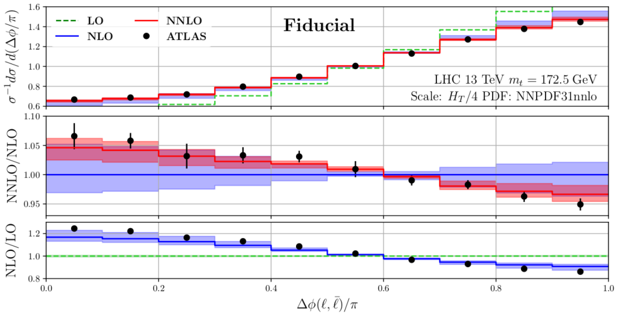
Michał Czakon
Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany

Alexander Mitov, Andrew S. Papanastasiou, and Rene Poncelet
Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK
(Dated: January 17, 2019)

→ see also talk by Rene Poncelet

$$d\sigma^{\mathrm{LO}} = d\sigma^{\mathrm{LO\times LO}},$$
$$d\sigma^{\mathrm{NLO}} = d\sigma^{\mathrm{NLO\times LO}} + d\sigma^{\mathrm{LO\times NLO}} - \frac{2\Gamma_t^{(1)}}{\Gamma_t^{(0)}} d\sigma^{\mathrm{LO}}, \quad (1)$$
$$d\sigma^{\mathrm{NNLO}} = d\sigma^{\mathrm{NNLO\times LO}} + d\sigma^{\mathrm{LO\times NNLO}} + d\sigma^{\mathrm{NLO\times NLO}} - \frac{2\Gamma_t^{(1)}}{\Gamma_t^{(0)}} d\sigma^{\mathrm{NLO}} - \frac{\left(\Gamma_t^{(1)}\right)^2 + 2\Gamma_t^{(0)}\Gamma_t^{(2)}}{\left(\Gamma_t^{(0)}\right)^2} d\sigma^{\mathrm{LO}}.$$





Exp. data from ATLAS-CONF-2018-027
13 TEV, 36 fb-1

Quote: “*In our view the most plausible explanation for this discrepancy lies in the extrapolation of the fiducial measurement to the full phase space.*”

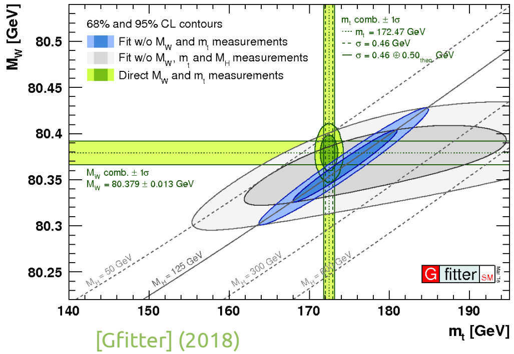
Sensible since extrapolation does not use NNLO QCD simulation.

Top Quark Mass

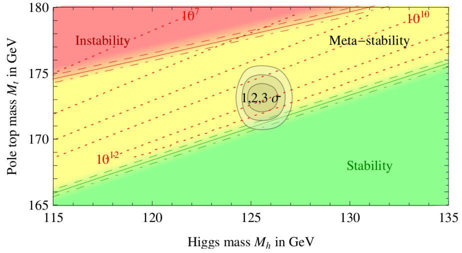
Top Quark Mass

This is a very broad field. Therefore *just the basics*:

- m_t is an important parameter of the SM: consistency checks, vacuum stability
- m_t is a parameter of the Lagrangian $\longrightarrow \mathcal{O}^{\text{nature}}_{\text{measured}} = \mathcal{O}^{\text{N}^\times\text{LOtheory}}_{\text{predicted}}(m_t, \text{ren. scheme})$
- Typical mass definitions: Pole mass, MSbar mass, MSR mass

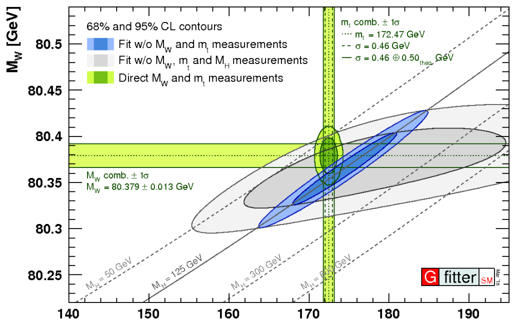


[Gfitter] (2018)



[Degrassi,Di Vita,Elias-Miro,Espinosa,Giudice,Isidori,Strumia] (2012)

Top Quark Mass



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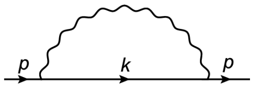
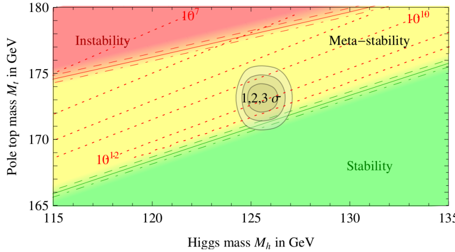


- Since MC generators are involved in the extraction of m_t, the term "*MC mass*" appeared

  Strictly speaking: not a well-defined mass. No relation between $\mathcal{O}^{\text{nature}}_{\text{measured}}, \mathcal{O}^{\text{theory}}_{\text{predicted}}$.

  Arguments have been presented that MC mass should be numerically close to pole mass

see e.g. [Beneke], [Hoang], [Mangano], [Nason]



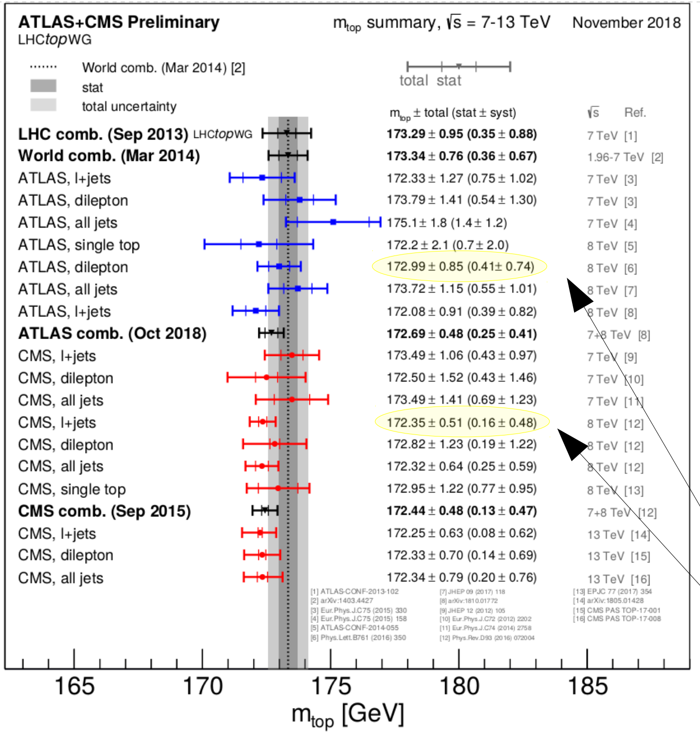
[Degrassi,Di Vita,Elias-Miro,Espinosa,Giudice,Isidori,Strumia] (2012)

$\longrightarrow$ MC mass is a slippery notion. It would be better to discuss sources of uncertainties.

$\longrightarrow$ Monte Carlo modeling cannot be avoided completely, but should be reduced to a minimum in favor of first principle calculations.

Top Quark Mass

State-of-the-art:



At this level of precision:
Spin correlated top quark production+decay needs to be accounted for. Unfolding/simulation of stable top quarks is no longer justified.

single measurements with
smallest systematics

Top Quark Mass

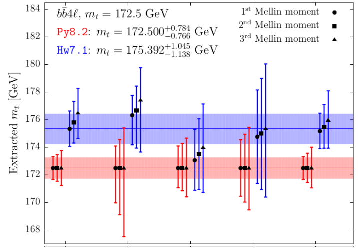
State-of-the-art:

- NLO QCD
- Top quark decays
- Off-shell effects
- Advanced understanding of PS uncert.

A Theoretical Study of Top-Mass Measurements at the LHC Using NLO+PS Generators of Increasing Accuracy

(Jan 2018)

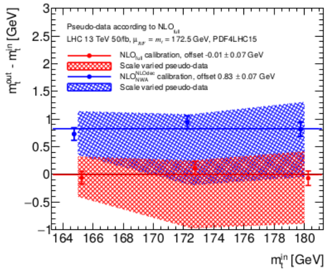
Silvia Ferrario Ravasio,[a] Tomáš Ježo,[b] Paolo Nason,[c] Carlo Oleari[a]



NLO and off-shell effects in top quark mass determinations

(Sep 2017)

Gudrun Heinrich,[a] Andreas Maier,[b] Richard Nisius,[a] Johannes Schlenk,[c] Markus Schulze,[d] Ludovic Scyboz,[a] Jan Winter [e]

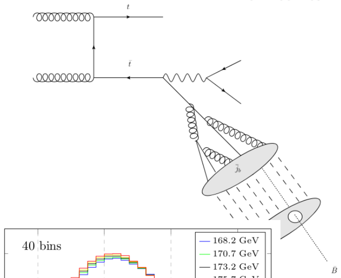


Fragmentation uncertainties in hadronic observables for top-quark mass measurements

Gennaro Corcella [a], Roberto Franceschini [b], Doojin Kim [c,*]

[a] INFN, Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati (RM), Italy
[b] Dipartimento di Matematica e Fisica, Universitá degli Studi Roma Tre and INFN, sezione di Roma Tre, I-00146 Rome, Italy
[c] Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland

Received 22 December 2017; received in revised form 19 February 2018; accepted 20 February 2018
Available online 27 February 2018
Editor: Tommy Ohlsson

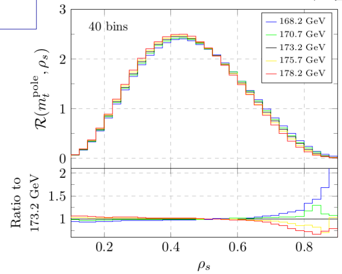


Journal of High Energy Physics
March 2018, 2018:169 | Cite as

Top quark mass studies with $t\bar{t}j$ at the LHC

Authors Authors and affiliations

G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Schulze, M. Worek



New Physics in Single Top

New Physics in Single Top

Eur. Phys. J. C (2018) 78:919
https://doi.org/10.1140/epjc/s10052-018-6399-3
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Theoretical Physics

Effective operators in *t*-channel single top production and decay

M. de Beurs[1], **E. Laenen**[1,2,3], **M. Vreeswijk**[1], **E. Vryonidou**[1,4,a]

[1] Nikhef, Science Park 105, Amsterdam, The Netherlands
[2] ITFA, University of Amsterdam, Science Park 904, Amsterdam, The Netherlands
[3] ITF, Utrecht University, Leuvenlaan 4, Utrecht, The Netherlands
[4] CERN Theory Division, 1211 Geneva 23, Switzerland

$$\mathcal{L}_{Wtb}^{\mathrm{SM}} = -\sum_{f=d,s,b}^{3} \frac{gV_{tf}}{\sqrt{2}}\, \bar{q}_f(x)\gamma^\mu P_L t(x)\, W_\mu(x) + \mathrm{h.\,c.}$$

$$\begin{aligned}
O_{\varphi Q}^{(3)} &= i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu^I \varphi\right) (\bar{Q}\gamma^\mu \tau^I Q) \\
O_{tW} &= y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W_{\mu\nu}^I \\
O_{qQ,rs}^{(3)} &= \left(\bar{q}_r \gamma^\mu \tau^I q_s\right) \left(\bar{Q}\gamma_\mu \tau^I Q\right)
\end{aligned}$$

simultaneously affect production and decay

New Physics in Single Top

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THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Theoretical Physics

Effective operators in t-channel single top production and decay

M. de Beurs[1], E. Laenen[1,2,3], M. Vreeswijk[1], E. Vryonidou[1,4,a]
[1] Nikhef, Science Park 105, Amsterdam, The Netherlands
[2] ITFA, University of Amsterdam, Science Park 904, Amsterdam, The Netherlands
[3] ITF, Utrecht University, Leuvenlaan 4, Utrecht, The Netherlands
[4] CERN Theory Division, 1211 Geneva 23, Switzerland

$$\mathcal{L}^{\rm SM}_{Wtb} = -\sum_{f=d,s,b}^{3} \frac{gV_{tf}}{\sqrt{2}}\, \bar{q}_f(x)\gamma^\mu P_L t(x)\, W_\mu(x) + \text{h. c.}$$

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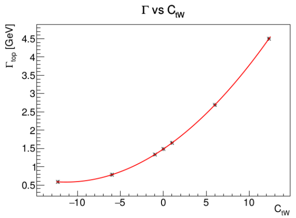
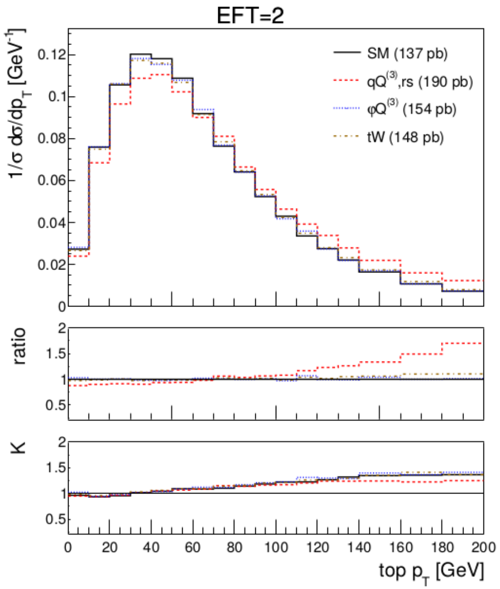
} simultaneously affect production and decay

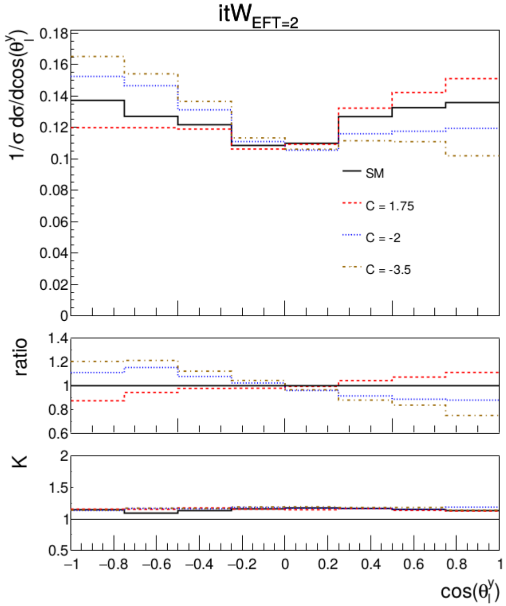
→ First time consistent treatment at NLO QCD

e.g. top quark width changes:

$$\Gamma_{\rm top}(C_{tW}) = \Gamma_{\rm SM} + \frac{1\text{TeV}^2}{\Lambda^2} C_{tW}\,\Gamma_{tW} + \frac{1\text{TeV}^4}{\Lambda^4} C_{tW}^2\,\Gamma_{tW,tW}$$







Note: SM NNLO QCD calculations for production x decay are available see e.g. [Berger, Gao, Yuan, Zhu] (2017)

Towards Global Analyses

Towards Global Analyses

A Monte Carlo global analysis of the Standard Model Effective Field Theory: the top quark sector

Nathan P. Hartland,[1,2] Fabio Maltoni,[3,4] Emanuele R. Nocera,[2,5] Juan Rojo,[1,2] Emma Slade,[6] Eleni Vryonidou,[7] and Cen Zhang[8]

Basic Idea: Use all available top quark measurements and allow for most general NP parametrization. Then do a simultaneous fit to all degrees of freedom.

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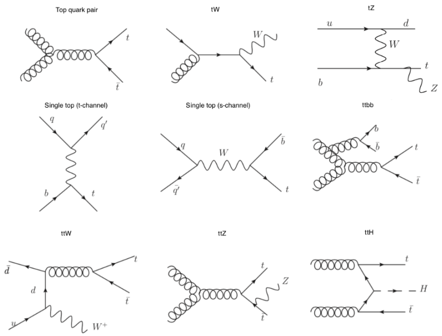
Basic Idea: Use all available top quark measurements and allow for most general NP parametrization. Then do a simultaneous fit to all degrees of freedom.

Class	Notation	Degree of Freedom	Operator Definition
$QQQQ$	OQQ1	c^1_{QQ}	$2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$
	OQQ8	c^8_{QQ}	$8C^{3(3333)}_{qq}$
	OQt1	c^1_{Qt}	$C^{1(3333)}_{qu}$
	OQt8	c^8_{Qt}	$C^{8(3333)}_{qu}$
	OQb1	c^1_{Qb}	$C^{1(3333)}_{qd}$
	OQb8	c^8_{Qb}	$C^{8(3333)}_{qd}$
	Ott1	c^1_{tt}	$C^{(3333)}_{uu}$
	Otb1	c^1_{tb}	$C^{1(3333)}_{ud}$
	Otb8	c^8_{tb}	$C^{8(3333)}_{ud}$
	OQtQb1	c^1_{QtQb}	$C^{1(3333)}_{quqd}$
	OQtQb8	c^8_{QtQb}	$C^{8(3333)}_{quqd}$
$QQqq$	O81qq	$c^{1,8}_{Qq}$	$C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$
	O11qq	$c^{1,1}_{Qq}$	$C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$
	O83qq	$c^{3,8}_{Qq}$	$C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$
	O13qq	$c^{3,1}_{Qq}$	$C^{3(ii33)}_{qq} + \frac{1}{6}(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq})$
	O8qt	c^8_{tq}	$C^{8(ii33)}_{qu}$
	O1qt	c^1_{tq}	$C^{1(ii33)}_{qu}$
	O8ut	c^8_{tu}	$2C^{(i33i)}_{uu}$
	O1ut	c^1_{tu}	$C^{(ii33)}_{uu} + \frac{1}{3}C^{(i33i)}_{uu}$
	O8qu	c^8_{Qu}	$C^{8(33ii)}_{qu}$
	O1qu	c^1_{Qu}	$C^{1(33ii)}_{qu}$
	O8dt	c^8_{td}	$C^{8(33ii)}_{ud}$
	O1dt	c^1_{td}	$C^{1(33ii)}_{ud}$
	O8qd	c^8_{Qd}	$C^{8(33ii)}_{qd}$
	O1qd	c^1_{Qd}	$C^{1(33ii)}_{qd}$



$QQ+V,G,\varphi$	OtG	c_{tG}	$\mathrm{Re}\{C^{(33)}_{uG}\}$
	OtW	c_{tW}	$\mathrm{Re}\{C^{(33)}_{uW}\}$
	ObW	c_{bW}	$\mathrm{Re}\{C^{(33)}_{dW}\}$
	OtZ	c_{tZ}	$\mathrm{Re}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$
	Off	$c_{\varphi tb}$	$\mathrm{Re}\{C^{(33)}_{\varphi ud}\}$
	Ofq3	$c^3_{\varphi Q}$	$C^{3(33)}_{\varphi q}$
	OpQM	$c^-_{\varphi Q}$	$C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$
	Opt	$c_{\varphi t}$	$C^{(33)}_{\varphi u}$
	Otp	$c_{t\varphi}$	$\mathrm{Re}\{C^{(33)}_{u\varphi}\}$

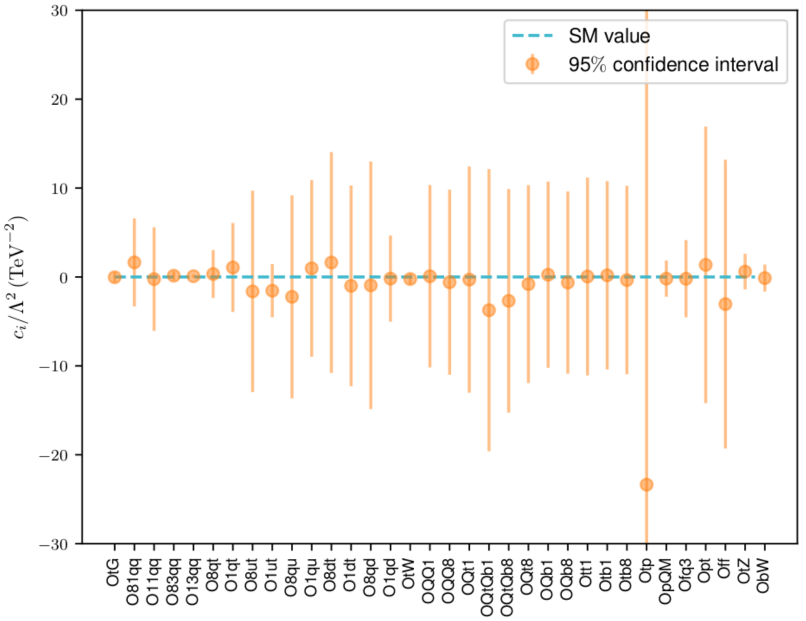
34 operators, 30 different measurements form 10 processes

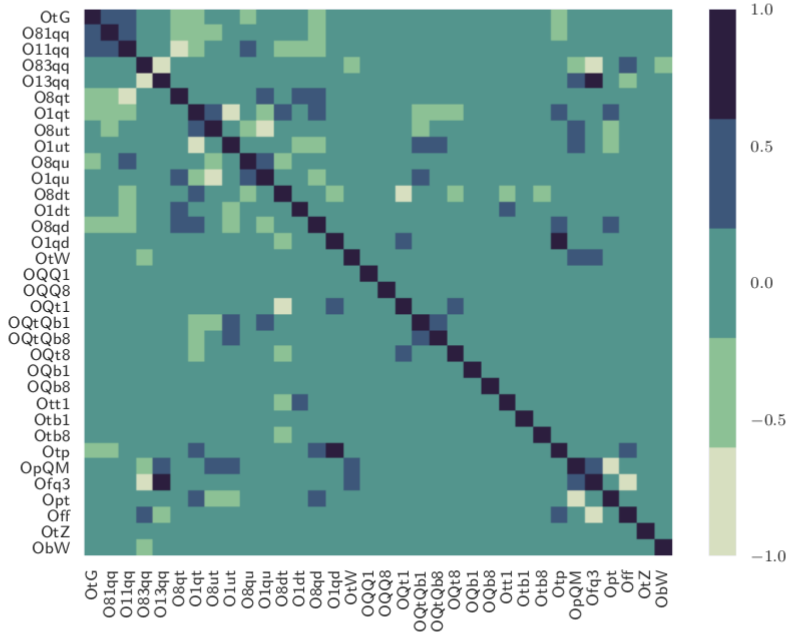
Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ $(\mathcal{O}(\Lambda^{-4}))$								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1									✓
OQb8									✓
Ott1								✓	
Otb1									✓
Otb8									✓
OQtQb1									(✓)
OQtQb8									(✓)
O81qq	✓				✓	✓	✓	✓	✓
O11qq	[✓]				[✓]	[✓]	[✓]	✓	✓
O83qq	✓	[✓]		[✓]	✓	✓	✓	✓	✓
O13qq	[✓]	✓		✓	[✓]	[✓]	[✓]	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	[✓]				[✓]	[✓]	[✓]	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	[✓]					[✓]	[✓]	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	[✓]					[✓]	[✓]	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	[✓]					[✓]	[✓]	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	[✓]					[✓]	[✓]	✓	✓
OtG	✓		✓		✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)	(✓)					
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓					
OpQM				✓		✓			
Opt				✓		✓			
Otp							✓		

Towards Global Analyses

Main ingredient: Generation of MC replicas (N=1000), similar to PDF fits

Results:

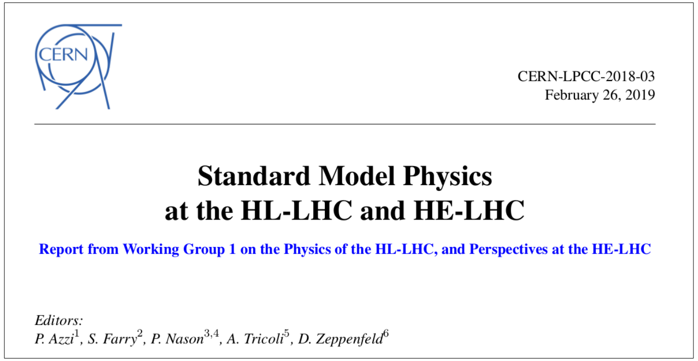




→ see talk by Emma Slade

Community Effort: HL-LHC and HE-LHC

Community Effort: LHC-HL & LHC-HE Working Groups


CERN-LPCC-2018-03
February 26, 2019

Standard Model Physics
at the HL-LHC and HE-LHC

Report from Working Group 1 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

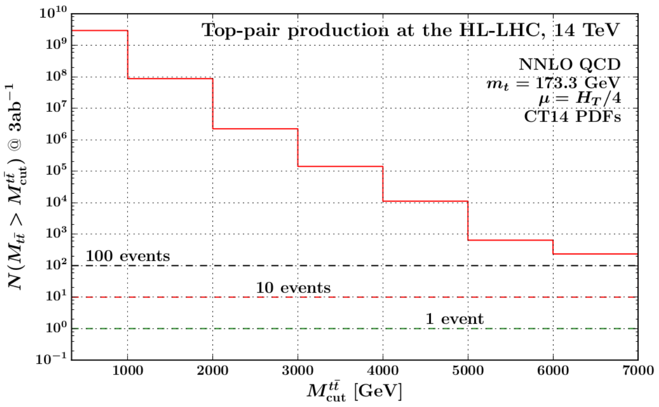
Editors:
P. Azzi[1], S. Farry[2], P. Nason[3,4], A. Tricoli[5], D. Zeppenfeld[6]

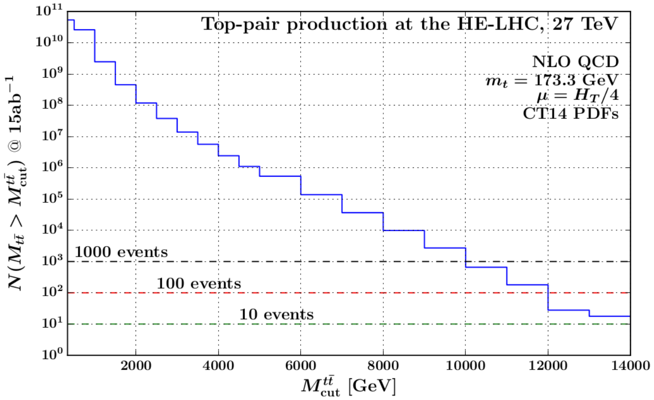
A large compendium of studies for

- HL-LHC: 14 TeV, 3000 fb^{-1}
- HE-LHC: 27 TeV, 15 000 fb^{-1}

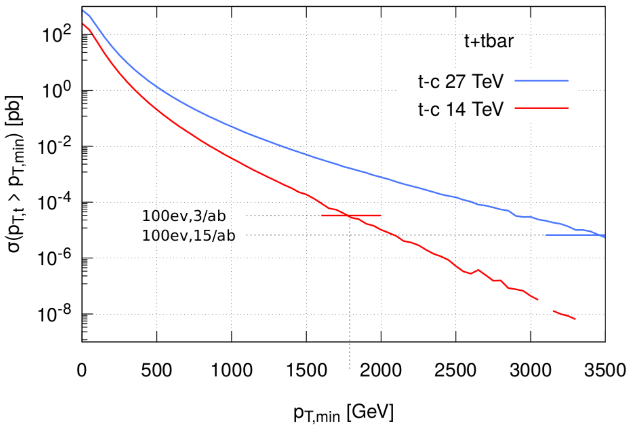
A few selections: …

Top quark pair production



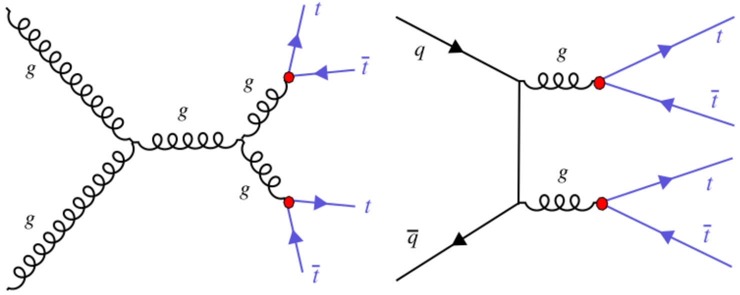


Single top production



Community Effort: LHC-HL & LHC-HE Working Groups

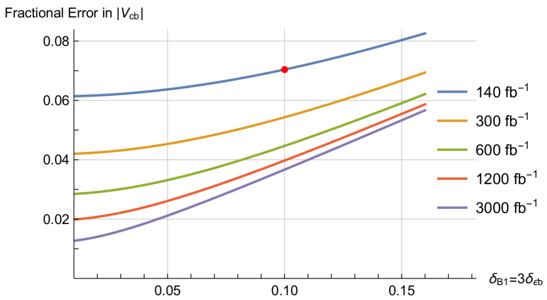
Four top production



HL-LHC	Basic
$\bar{t}t\bar{t}t_H$	577.22
$\bar{t}t\bar{t}t_{g/Z/\gamma}$	5006.34
$\bar{t}t\bar{t}t_{\text{int}}$	-764.67
$\bar{t}t$	2.5×10^8
$\bar{t}tW^+$	32670
$\bar{t}tW^-$	16758
$\bar{t}tZ$	24516
$W^\pm W^\pm jj$	4187.7

HE-LHC	Basic
$\bar{t}t\bar{t}t_H$	15174.4
$\bar{t}t\bar{t}t_{g/Z/\gamma}$	148898.
$\bar{t}t\bar{t}t_{\text{int}}$	-20141.9
$\bar{t}t$	3.3×10^7
$\bar{t}tW^+$	1.3×10^6
$\bar{t}tW^-$	7.6×10^5
$\bar{t}tZ$	3.9×10^6
$W^\pm W^\pm jj$	888700

Vcb extraction



Quote: "*To date, |Vcb | has always been measured in B decays, i.e. at an energy scale mb , far below the weak scale, and it is currently known to an uncertainty of about 2%.*

Rare decays

$\mathcal{B}$ limit at 95%C.L.	3 ab^{-1}, 14 TeV	15ab^{-1}, 27 TeV	Ref.
$t \to gu$	3.8×10^{-6}	5.6×10^{-7}	[731]
$t \to gc$	32.1×10^{-6}	19.1×10^{-7}	[731]
$t \to Zq$	$2.4 - 5.8 \times 10^{-5}$		[743]
$t \to \gamma u$	8.6×10^{-6}		[734]
$t \to \gamma c$	7.4×10^{-5}		[734]
$t \to Hq$	10^{-4}		[743]

SUMMARY

- Studying top quark properties is a way of searching for physics beyond the SM
- The top quark system is an ideal place because it yields sensitivity to a large variety of possible New Physics interactions
- Assuming SU(2)xU(1) symmetry holds, certain top quark interactions are related
- I presented a selection of state-of-the-art on:
  - Spin correlations
  - Top quark mass
  - Single top and Top pair associated production
- General trend in theory: Modeling is replaced by first principle calculations
  This is what is required for reliably interpreting the data

Thanks for your attention!