What R we doing with the HL LHC?

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ATLAS

LIP

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POCH

Main Topics in this Talk

- Global Fits of Data
- More on Top couplings: Top-Higgs Yukawa Couplings

....a change in analysis strategy to improve performance, required?

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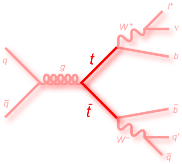
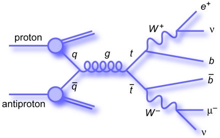
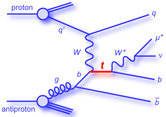
Main objective: extend the studies already performed at the LHC on top quark Anomalous Couplings/EFT in $t \rightarrow Wb$ decays to HL-LHC/HE-LHC

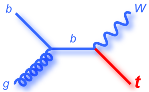
Several processes under study to probe the *Wtb* vertex[1]:

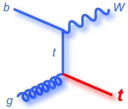
- Top quark pair production ($t\bar{t}$)
  - (i) semileptonic channel
  - (ii) dileptonic decays
- single top quark physics
  - (i) *t*-channel (single lepton)
  - (ii) *Wt*-channel (dileptonic decay)
- EFT/anomalous couplings studied associated to the *Wtb* vertex





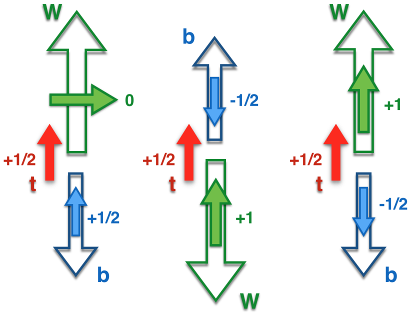






[1] JHEP**1206**(2012)088, EPJC**77**(2017)264, JHEP**04**(2017)124, JHEP**04**(2016)023, JHEP**12**(2017)017, PLB**717**(2012)330, PRD**90**(2014)112006, PLB**716**(2012)142, PLB**756**(2016)228, EPJC**77**(2017)531, JHEP**01**(2016)064, JHEP**04**(2017)086, JHEP**01**(2018)63, EPJC**78**(2018)186

☞ Observable(s): angular distribution(s) $\cos\theta^*_\ell$ $[F_0, F_L, F_R]$



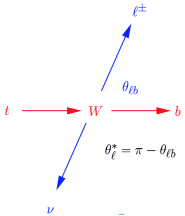
F_0 — W Longitudinal fraction

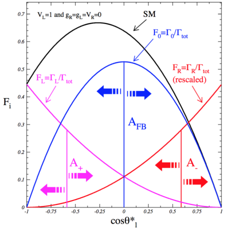
F_L — W Left-Handed fraction

F_R — W Right-Handed fraction

$$F_0^{\rm SM} = 0.687 \pm 0.005$$
$$F_L^{\rm SM} = 0.311 \pm 0.005$$
$$F_R^{\rm SM} = 0.0017 \pm 0.0001$$

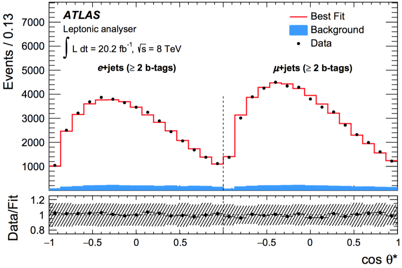
@ NNLO QCD calculation, PRD**81**(2010)111503
($F_0 + F_L + F_R = 1$)



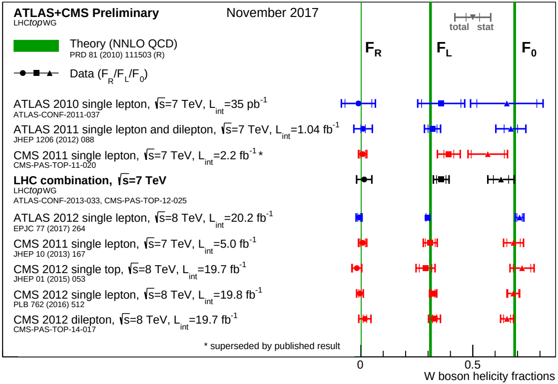


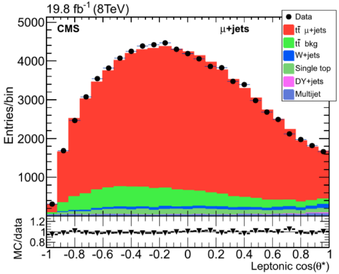
$$\frac{1}{N}\frac{dN}{d\cos\theta^*_\ell} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*_\ell}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\theta^*_\ell}{2}\right)^2 + F_R\left(\frac{1+\cos\theta^*_\ell}{2}\right)^2\right]$$

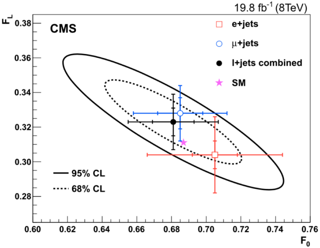
EPJC**77**(2017)264



Summary of W-boson helicity meas. @ LHC







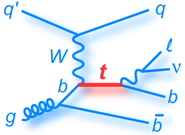
$\Delta F_0 / F_0 \sim$2.7% (3.7$\times$ theo. unc.)

$\Delta F_L / F_L \sim$5% (3.1$\times$ theo. unc.)

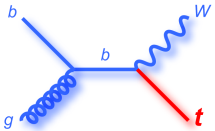
F_R=-0.008$\pm$0.014

Single top quark production

- Processes currently under study:

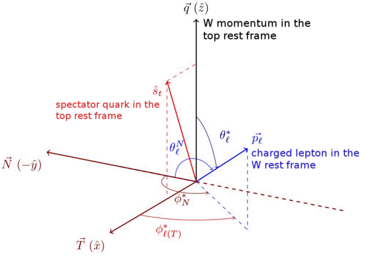


t-channel



(*Wt*-prod.)

☞ Observables: 2D angular distributions in *t*-channel production as a function of 6 spin observabels $< S_{1,2,3} >$, $< T_0 >$, $< A_{1,2} >$ [PRD **93** (2016) 011301]



1) Double-differential distribution:

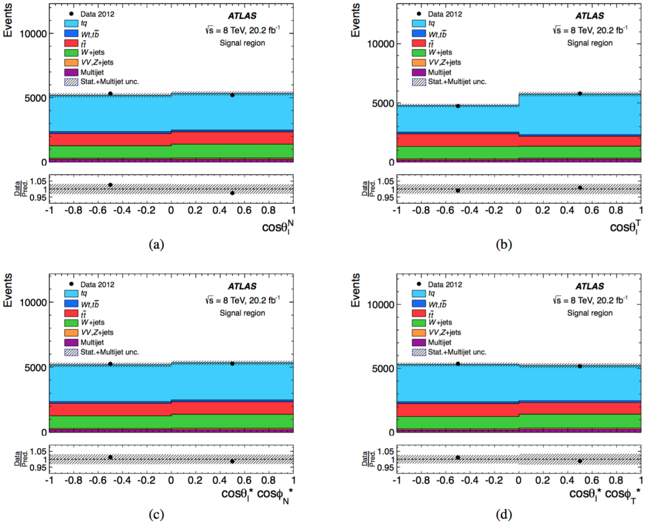
$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}(\cos\theta_\ell^*)\mathrm{d}\phi_\ell^*} = \frac{3}{8\pi}\Bigg\{\frac{2}{3} + \frac{1}{\sqrt{6}}\langle T_0\rangle\left(3\cos^2\theta_\ell^* - 1\right) + \langle S_3\rangle\cos\theta_\ell^*$$
$$+ \langle S_1\rangle\cos\phi_\ell^*\sin\theta_\ell^* + \langle S_2\rangle\sin\phi_\ell^*\sin\theta_\ell^*$$
$$- \langle A_1\rangle\cos\phi_\ell^*\sin 2\theta_\ell^* - \langle A_2\rangle\sin\phi_\ell^*\sin 2\theta_\ell^*\Bigg\}.$$

2) A_{FB} and A_{EC} Asymmetries:

$$A_{\mathrm{FB}} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

$$A_{\mathrm{EC}} = \frac{N(|\cos\theta| > \frac{1}{2}) - N(|\cos\theta| < \frac{1}{2})}{\ldots}$$

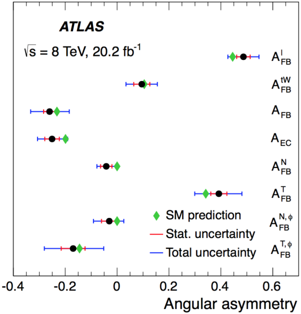
- Angular observables distributions in signal region [JHEP**04**(2017)124]:

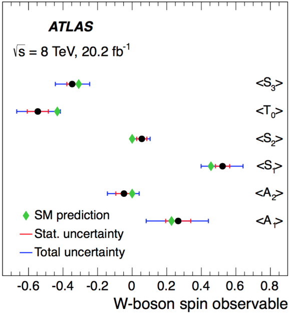


- Asymmetries with associated angular distributions [JHEP**04**(2017)124]:

Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P(F_R+F_L)$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_R-F_L)$	−0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}(1-3F_0)$	−0.20
A_{FB}^{T}	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
A_{FB}^{N}	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{FB}^{T,\phi}$	$\cos\theta_\ell^*\cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{FB}^{N,\phi}$	$\cos\theta_\ell^*\cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

$$A_{FB}^{\ell} = 0.49 \pm 0.03\ (\text{stat.}) \pm 0.05\ (\text{syst.}) = 0.49 \pm 0.06\,,$$
$$A_{FB}^{tW} = 0.10 \pm 0.03\ (\text{stat.}) \pm 0.05\ (\text{syst.}) = 0.10 \pm 0.06\,,$$
$$A_{FB} = -0.26 \pm 0.02\ (\text{stat.}) \pm 0.07\ (\text{syst.}) = -0.26 \pm 0.08\,,$$
$$A_{EC} = -0.25 \pm 0.03\ (\text{stat.}) \pm 0.05\ (\text{syst.}) = -0.25 \pm 0.06\,,$$
$$A_{FB}^{T} = 0.39 \pm 0.03\ (\text{stat.}) \pm 0.09\ (\text{syst.}) = 0.39 \pm 0.09\,,$$
$$A_{FB}^{N,\phi} = -0.03 \pm 0.03\ (\text{stat.}) \pm 0.05\ (\text{syst.}) = -0.03 \pm 0.06\,,$$
$$A_{FB}^{T,\phi} = -0.17 \pm 0.05\ (\text{stat.})^{+0.11}_{-0.10}\ (\text{syst.}) = -0.17^{+0.12}_{-0.11}\,.$$





Spin Measurements:

$< S_3 >= -0.35 \pm 0.10$

$< T_0 >= -0.55 \pm 0.13$

$< S_2 >= +0.06 \pm 0.05$

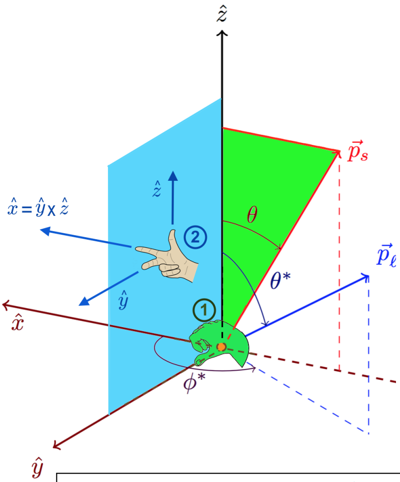
$< S_1 >= +0.52 \pm 0.12$

$< A_2 >= -0.05 \pm 0.10$

$< A_1 >= +0.27\ ^{+0.17}_{-0.19}$

Single top quark production

- Triple-differential (3D) decay rates of polarised top quarks
  - ☞ define specific coordinate system (in t centre-of-mass):



1) System Definition (in t-system):

$$\hat{z} = \hat{p}^*_W = \vec{p}^{\,*}_W / |\vec{p}^{\,*}_W|, \quad \vec{p}^{\,*}_s = \text{spectator quark mom.}$$

$$\hat{y} = \hat{p}^*_s \times \hat{p}^*_W, \qquad \hat{x} = \hat{y} \times \hat{p}^*_W$$

2) Triple-differential distribution:

$$\begin{aligned}
\varrho(\theta,\theta^*,\phi^*;P) = \frac{1}{N}\frac{\mathrm{d}^3N}{\mathrm{d}(\cos\theta)\mathrm{d}\Omega^*} &= \frac{1}{8\pi}\left\{\frac{3}{4}\left|A_{1,\frac{1}{2}}\right|^2(1+P\cos\theta)(1+\cos\theta^*)^2\right.\\
&+ \frac{3}{4}\left|A_{-1,-\frac{1}{2}}\right|^2(1-P\cos\theta)(1-\cos\theta^*)^2\\
&+ \frac{3}{2}\left(\left|A_{0,\frac{1}{2}}\right|^2(1-P\cos\theta)+\left|A_{0,-\frac{1}{2}}\right|^2(1+P\cos\theta)\right)\sin^2\theta^*\\
&- \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right]\\
&\left.- \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1-\cos\theta^*)\,\mathrm{Re}\left[e^{-i\phi^*}A_{-1,-\frac{1}{2}}A^*_{0,-\frac{1}{2}}\right]\right\}\\
&= \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m}M^m_{k,l}(\theta,\theta^*,\phi^*)\,,
\end{aligned}$$

A_{λ_W,λ_b} = helicity amplitudes $\qquad M^m_{k,l}(\theta,\theta^*,\phi^*) = \sqrt{2\pi}\,Y^m_k(\theta,0)\,Y^m_l(\theta^*,\phi^*)$

Results Interpreted in Terms of Anomalous Couplings (V_R, g_L, g_R) ☞ **next slide**

Anomalous couplings/EFT parameters in global fits

General Wtb vertex

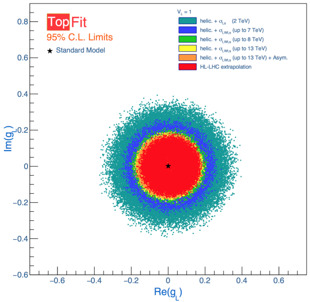
Eur.Phys.J. C50 (2007) 519-533

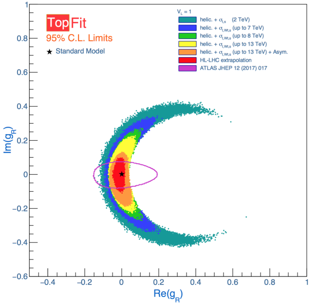
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)t\,W_{\mu}^{-}$$

vector (V_{R}) and tensor like couplings (g_{L}, g_{R}) zero @ tree level in SM

☞ EFT parameters: anomalous couplings described by effective operators $\mathcal{O}_{uW}$,$\mathcal{O}_{dW}$, $\mathcal{O}_{\phi q}^{(3)}$ and $\mathcal{O}_{\phi ud}$ i.e., constraints on anomalous couplings equivalent to constraints on EFT parameters (a more integrating framework) [arXiv:1802.07237]

PRD 97 (2018) 1, 013007 (TopFit), arXiv:1811.02492





Fits Using:

σ, W_{hel}, A_{FB} @ 7,8,13 TeV

Main Topics in this Talk

- Global Fits of Data
- More on Top couplings:
  Top-Higgs Yukawa Couplings

....a change in analysis strategy
to improve performance,
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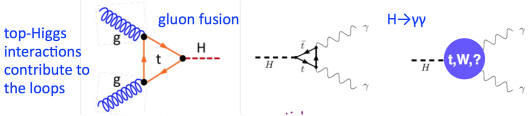
Top-Higgs Yukawa Couplings

☞ all about top quark-Higgs Couplings!

- the top quark has the biggest coupling to the Higgs SM boson ($Y_t \sim 1.$)
- precision measurements of top quark Yukawa couplings are really important
- .....as well as deviations !!!
- need also to understand the nature of the coupling ($h = H, A$)
- indirect constraints are important (involve several contributions)



☞ probing CP-even(a) -odd(d) nature of couplings in $t\bar{t}H$,

$$L_{hf\bar{f}} \sim [a_f + ib_f\gamma_5] \sim [cos(\alpha) + isin(\alpha)\gamma_5]$$

PRL **76**, 24 (1996)
J.F.Gunion, Xiao-Gang He

$$a_1, a_2, b_1, b_2, b_3...b_4 = \frac{p_t^z p_{\bar{t}}^z}{|p_t||p_{\bar{t}}|}$$

PRD **92**, 1 (2015)
F.Boudjema, R.M.Godbole, D.Guadagnoli, K.A.Mohan

$$\Delta\phi^{t\bar{t}}(l+, l-),\ \beta_{b\bar{b}}\Delta\theta^{lh}(l+, l-)$$

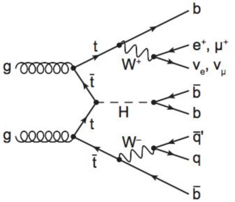
$$\beta \equiv \mathrm{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})\right)$$

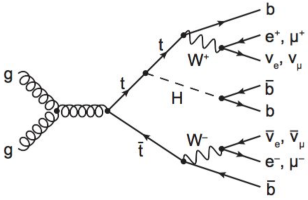
$$\cos(\Delta\theta^{\ell h}(\ell^+, \ell^-)) = \frac{(\vec{p}_h \times \vec{p}_{\ell^+}) \cdot (\vec{p}_h \times \vec{p}_{\ell^-})}{|\vec{p}_h \times \vec{p}_{\ell^+}||\vec{p}_h \times \vec{p}_{\ell^-}|}$$

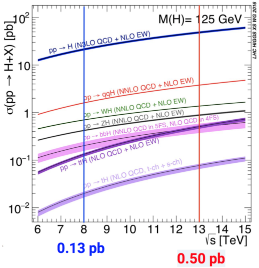
- need to understand $t\bar{t}H$ production and decay

arXiv:1611.00049v2, A.Broggio,A.Ferroglia,B.D.Pecjak,L.L.Yang

Top-Higgs Yukawa Couplings







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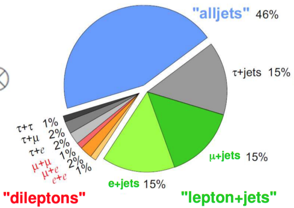
Top pair Branching Fractions



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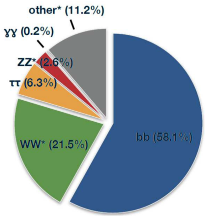
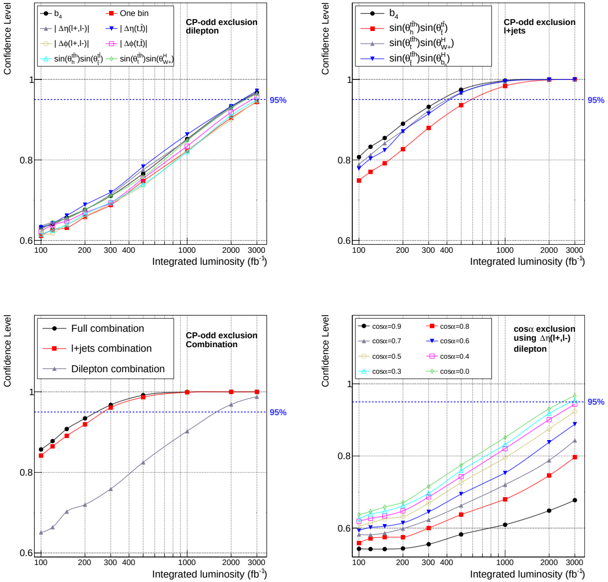
Higgs Branching Fractions



Top-Higgs Yukawa Couplings



Conclusions

Global Fits to Data (contribution to the HL-LHC):

1) several analysis under way ($t\bar{t}$, t-channel and Wt-channel)
2) full kinematical reconstruction
3) angular distributions identified in several signal regions
4) fit the Standard Model and extract EFT wilson coefficients
5) need to go global

Top-Higgs Yukawa Couplings (contribution to the HL-LHC):

1) many new angular observables available
2) sensitivity of the semileptonic final state better (factor 5) then dileptonic
3) combination allow probing top quark Yukawa coupling in the fermionic sector