EFT in top physics

Facts, Remarks and Proposals

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Introductory remark

The facts, remarks and proposals discussed here are more general than the particular example discussed.

I will refer to *Wtb* (most studied top interaction) for definiteness. But you can imagine that the lessons to be learnt can be applied to other interactions as well.

Fact #1

Only a few among top physics measurements might qualify as *precision measurements*

$$F_0 = 0.681 \pm 0.012\ (\mathrm{stat}) \pm 0.023\ (\mathrm{syst})$$
$$F_- = 0.323 \pm 0.008\ (\mathrm{stat}) \pm 0.014\ (\mathrm{syst})$$
$$F_+ = -0.004 \pm 0.005\ (\mathrm{stat}) \pm 0.014\ (\mathrm{syst})$$

CMS

systematics dominated

while many others do not

$$\sigma_{t-\mathrm{ch}} = 83.6 \pm 2.3\ (\mathrm{stat}) \pm 7.4\ (\mathrm{syst})\ \mathrm{pb}$$
$$\sigma_t/\sigma_{\bar{t}} = 1.95 \pm 0.10\,(\mathrm{stat}) \pm 0.19\,(\mathrm{syst})$$

CMS

we are not dealing with precision physics when extracting dim6 top operator coefficients from data

Fact #2

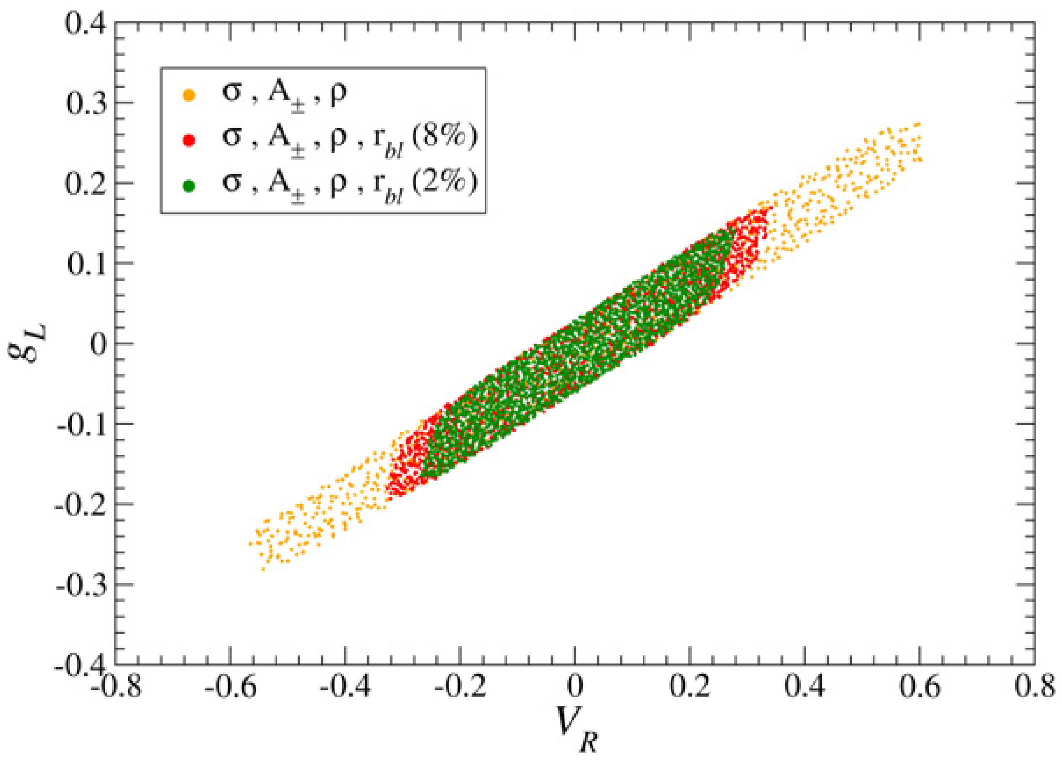
In observables there are often cancellations among anomalous contributions that further degrade the sensitivity

$$\bar{b}(p_2)\,[i\sigma^{\mu\nu}(p_1-p_2)_\nu P_L + m_t\gamma^\mu P_R]\,t(p_1) = \bar{b}(p_2)(p_1+p_2)^\mu P_L t(p_1)$$

for *t*, *b* on shell and *m*$_b$=*0*

no contribution to Γ_+ and Γ_-

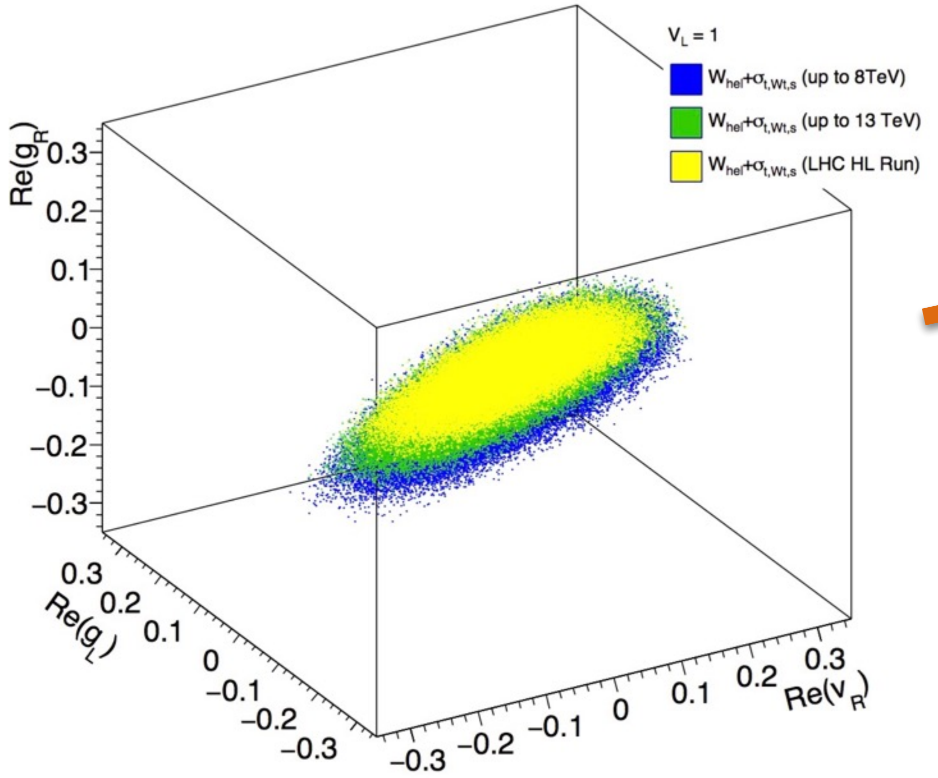
$$\left[V_R = \frac{m_t}{M_W} g_L\right] \approx \mathrm{SM}$$



JAAS 0803.3810

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

…and when all couplings are left arbitrary, limits are very loose



Birman et al. 1605.02679

$$\Lambda > 0.3 \text{ TeV}$$
$$(C = 1)$$

$$V_L = V_{tb} + C_{\phi q}^{(3,33)} \frac{v^2}{\Lambda^2} \qquad g_L = \sqrt{2} C_{dW}^{33*} \frac{v^2}{\Lambda^2}$$

$$V_R = \frac{1}{2} C_{\phi\phi}^{33*} \frac{v^2}{\Lambda^2} \qquad g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2}$$

strong temptation: ignore operators loosely constrained

as well as quadratic terms

Remark #1

Fifth Commandment of EFT: *"Thou shalt not kill quadratic terms"*

JAAS 1008.3225
JAAS et al. RMP

- often they are important, because of Facts #1 and #2
- in case they are not, they don't matter anyway

And in many cases it is <u>not</u> inconsistent to keep them while dropping dim-8

series converges

$$C_i^{(4)} \frac{E^2}{\Lambda^4} \ll C_i^{(2)} \frac{1}{\Lambda^2} \quad \Longrightarrow \quad C_i^{(4)} \lesssim C_i^{(2)}$$

meaningful Λ
[Fact #2]

$$C_i^{(2)} \gg 1 \quad \Longrightarrow \quad C_i^{(2)} \ll \left(C_i^{(2)}\right)^2$$

therefore

$$\frac{C_i^{(4)}}{\Lambda^4} \ll \left(\frac{C_i^{(2)}}{\Lambda^2}\right)^2$$

See Contino et al. 1604.06444
for an alternative argument

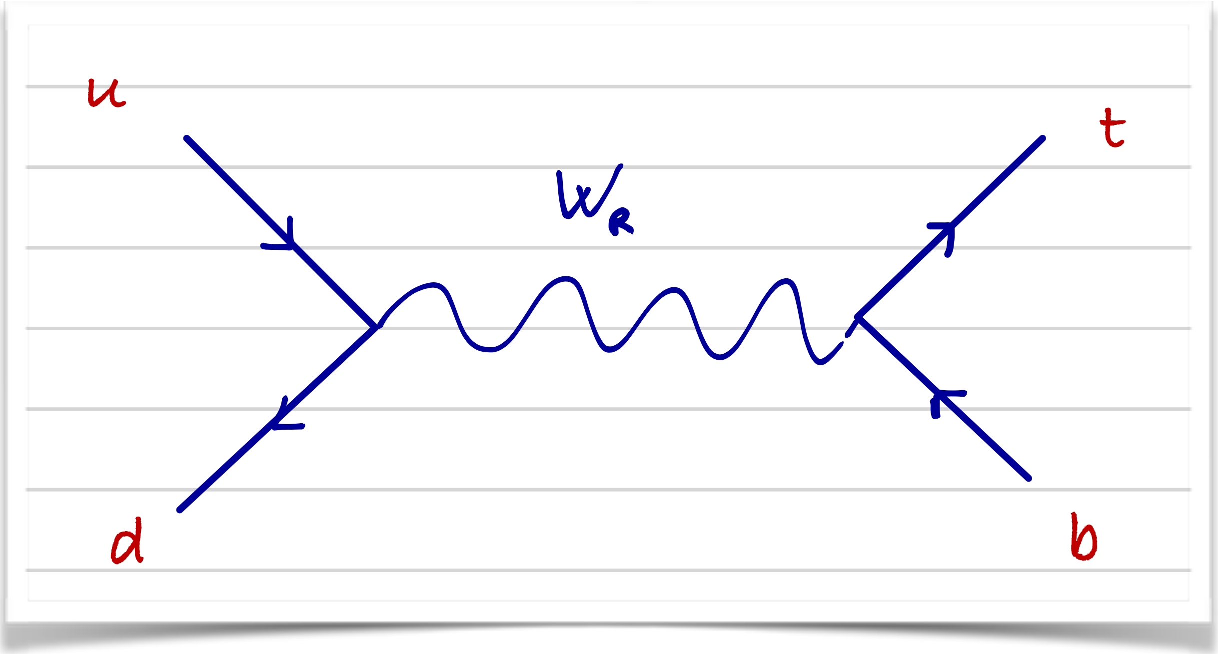
Quadratic terms are positive semidefinite and ensure that bounds on anomalous couplings exist even if measurements are insufficient or have little precision

➡ evaluating *theory uncertainty* by switching on/off quadratic terms leads to an absurd uncertainty when they dominate, which is often the case

Remark #2

Second Commandment of EFT: “*You shalt not drop operators in vain*”

JAAS 1008.3225



$$\longrightarrow \quad (\bar{d}_R\gamma^\mu u_R)(\bar{t}_R\gamma_\mu b_R)$$

New physics may only generate operators that do not interfere with SM

When possible, one should consider all contributing operators

It is not absolutely necessary, however: operators are gauge invariant

→ you lose generality but not consistency

Remark #3

EFT [in top physics] is a consistent framework to parameterise unknown heavy new physics

it is not an *extended SM*

Then, why performing global fits to C_i ?

- get precise constraints on new physics? 🙄
- identify *directions* where new physics contributions may cancel 🤔
- identify new observables more sensitive to new physics! 😊

more important than the C_i are the measurements

Fact #3

These *cancellations* are related to the fact that we have dropped operators from our list

$$\left.\begin{aligned} O^{33}_{Dd} &\supset \frac{gv}{2}\bar{b}\,p_2^{\mu} P_L t\, W^-_{\mu} \\ O^{33}_{\bar{D}d} &\supset -\frac{gv}{2}\bar{b}\,p_1^{\mu}\, P_L t\, W^-_{\mu} \end{aligned}\right\} \longrightarrow \quad O^{33}_{Dd} - O^{33}_{\bar{D}d} \supset \frac{gv}{2}\bar{b}\,(p_1 + p_2)^{\mu}\, P_L t\, W^-_{\mu}$$

does not contribute for helicity ±1

$$O^{33}_{Dd} + O^{33}_{\bar{D}d} \supset \frac{gv}{2}\bar{b}\,(p_1 - p_2)^{\mu}\, P_L t\, W^-_{\mu}$$

does not contribute for any helicity

Fact #2 ↔ we are almost insensitive to some operators

→ *"barring cancellations"* must be barred.

fine tuning is this →

Interlude: genesis of dim-6 operator list

Original list	80 operators	Buchmuller & Wyler NPB 268 621, 1986
Added missing four-fermion operator	81 operators	Artz, Einhorn, Wudka hep-ph/9405214
Removed 7: O_{qW}, O_{qB}, O_{uB}, O_{dB}, O_{lW}, O_{lB}, O_{eB}	74 operators	Grzadkowski, Hioki, Ohkuma, Wudka hep-ph/0310159
Removed 9: O_{qG}, O_{uG}, O_{dG}, O_{Du}, $O_{\bar{D}u}$, O_{Dd}, $O_{\bar{D}d}$, O_{De}, $O_{\bar{D}e}$	65 operators	JAAS 0811.3842
Removed 1 four-fermion operator	64 operators	Nomura 0911.1941
Removed 4 four-fermion operators	60 operators	JAAS 1008.3562
Removed 1 four-scalar operator	59 operators	Grzadkowski, Iszkrzynski, Misiak, Rosiek 1008.4884

Fact #4

The origin of the *insensitivity* is that

$$\bar{b}(p_2)(p_1+p_2)^\mu t(p_1)\cdot\varepsilon_\mu^\pm(p_1-p_2)^*=0$$

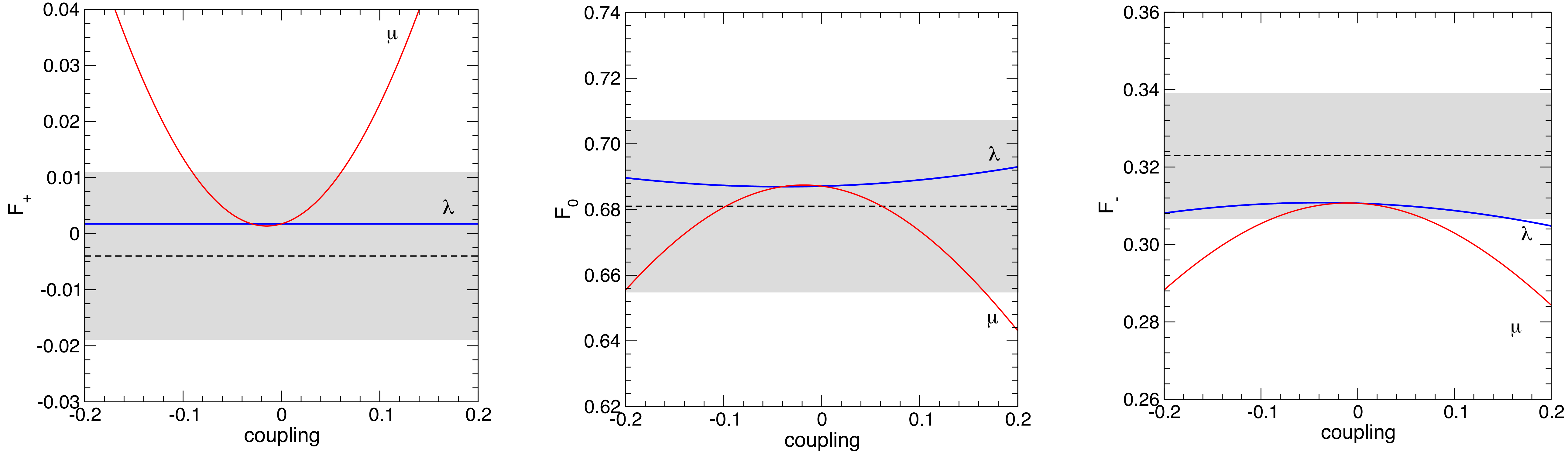
➡ $$\rho_W=\rho_W^{\mathrm{SM}}+\begin{pmatrix}0&0&0\\0&\times&0\\0&0&0\end{pmatrix}$$ 😱

Therefore, the dependence of F_+, F_- (and all W polarisations) on these operators is residual, stemming from Γ_0 in the denominator

Replacing V_R and g_L by two orthogonal combinations

$$\begin{pmatrix} \lambda \\ \mu \end{pmatrix} = \frac{1}{[m_t^2 + M_W^2]^{\frac{1}{2}}} \begin{pmatrix} m_t & M_W \\ -M_W & m_t \end{pmatrix} \begin{pmatrix} V_R \\ g_L \end{pmatrix}$$

the (in)sensitivity of helicity fractions to λ is apparent



The λ problem

But there is life beyond *W* helicity fractions!

JAAS & Bernabéu 1508.04592

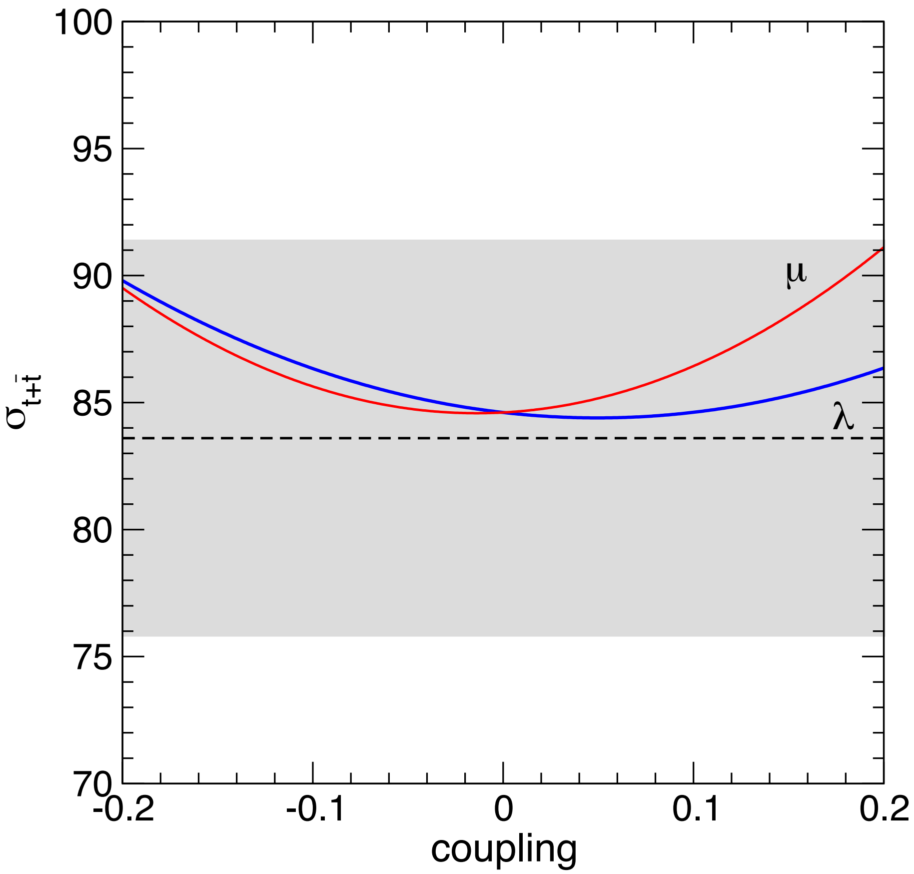
Being a spin-1 particle, the *W* boson has no less than

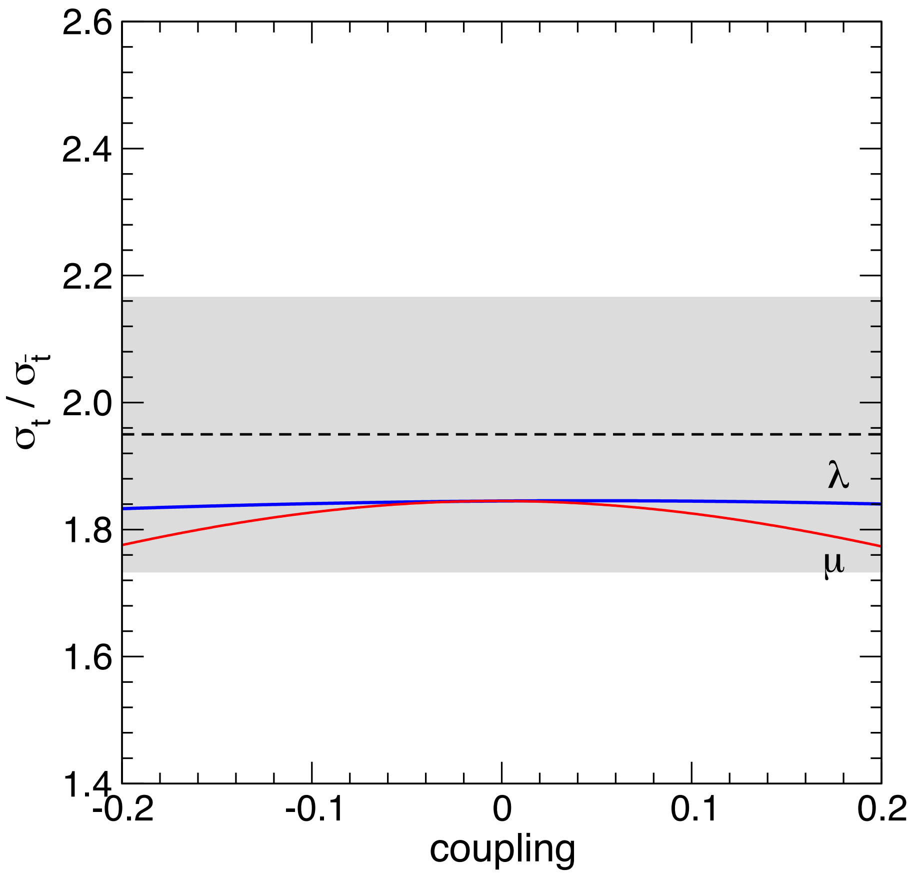
8 (eight!) polarisation observables

$$
\begin{aligned}
\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^* d\phi^*} = \frac{3}{8\pi}\Bigg\{ & \frac{1}{2}(1+\cos^2\theta^*) + \langle S_3\rangle \cos\theta^* \\
& + \left[\frac{1}{6} - \frac{1}{\sqrt{6}}\langle T_0\rangle\right]\left(1 - 3\cos^2\theta^*\right) \\
& + \langle S_1\rangle \cos\phi^* \sin\theta^* + \langle S_2\rangle \sin\phi^* \sin\theta^* \\
& - \langle A_1\rangle \cos\phi^* \sin 2\theta^* - \langle A_2\rangle \sin\phi^* \sin 2\theta^* \\
& + \langle B_1\rangle \cos 2\phi^* \sin^2\theta^* + \langle B_2\rangle \sin 2\phi^* \sin^2\theta^* \Bigg\}
\end{aligned}
$$

first measured by ATLAS

Their measurement will improve the global limits when the precision is better, but does not solve the λ problem t-channel single top cross sections depend on λ and μ but have too large uncertainties to constrain λ effectively

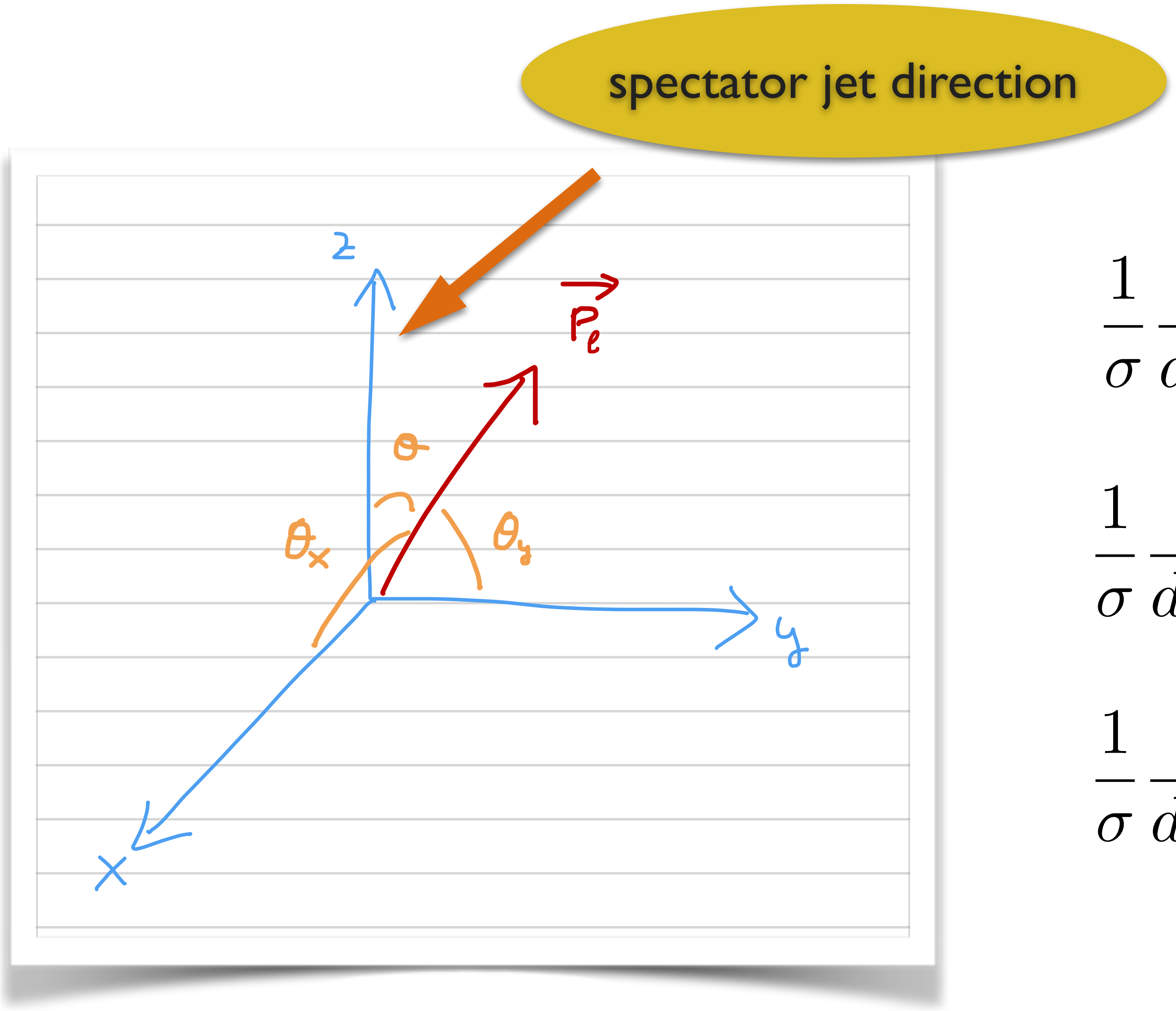




Proposal #1

More polarisation measurements and with higher precision

JAAS & Santos 1404.1585


spectator jet direction

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{1}{2}(1+\alpha P_z \cos\theta)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_x} = \frac{1}{2}(1+\alpha P_x \cos\theta_x)$$

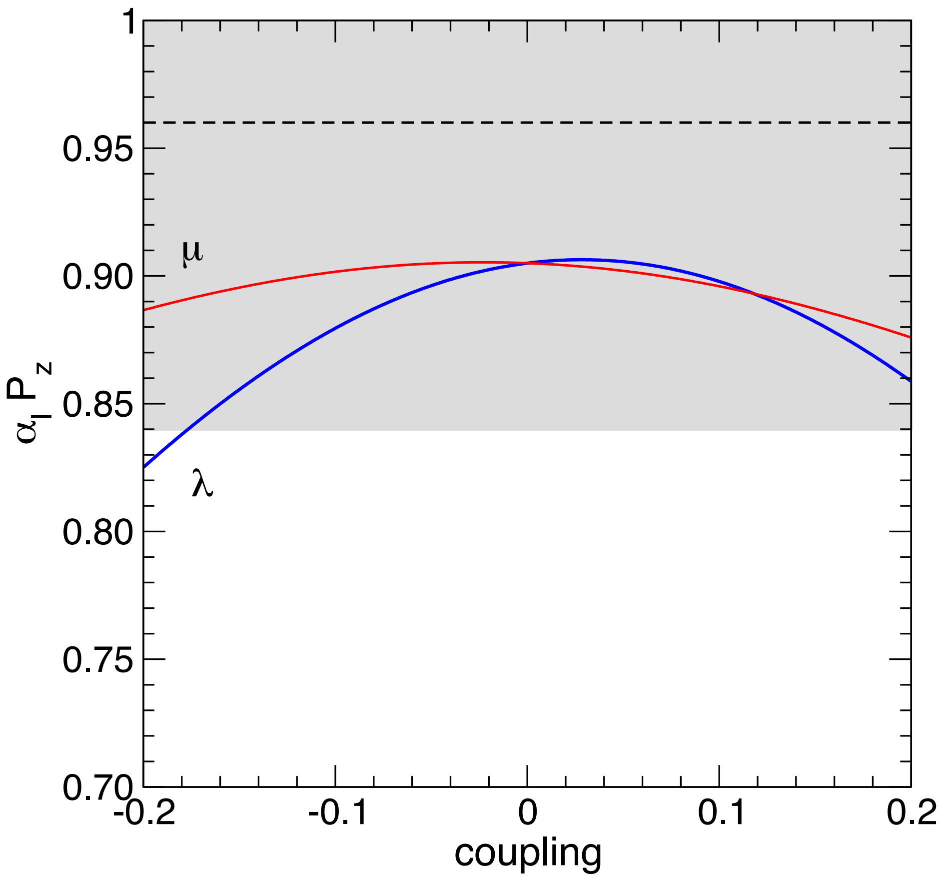
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_y} = \frac{1}{2}(1+\alpha P_y \cos\theta_y)$$

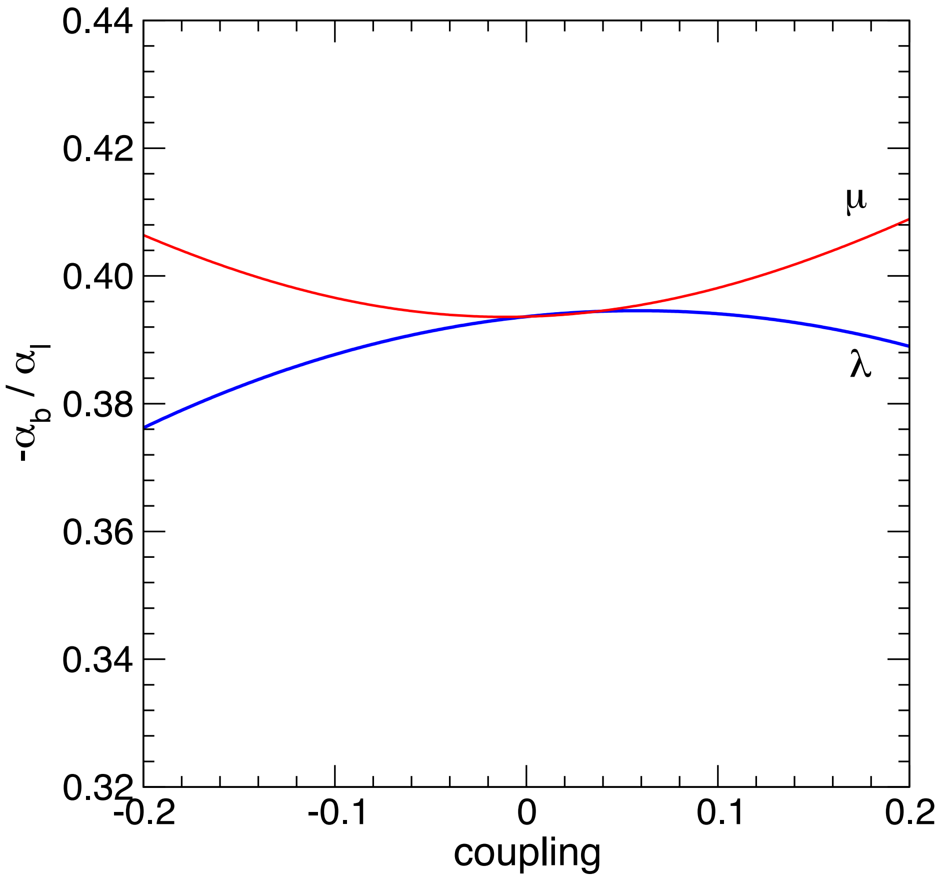
also: model-independent measurements

JAAS & Herrero-Hahn 1208.6006

$$\alpha_\ell P_z = 0.96 \pm 0.05\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst})$$

ATLAS





Improve $\alpha_l \cdot P_z$ measurement (?)

and measure P_x, P_y

Measure α_b / α_l [maybe at ILC?]

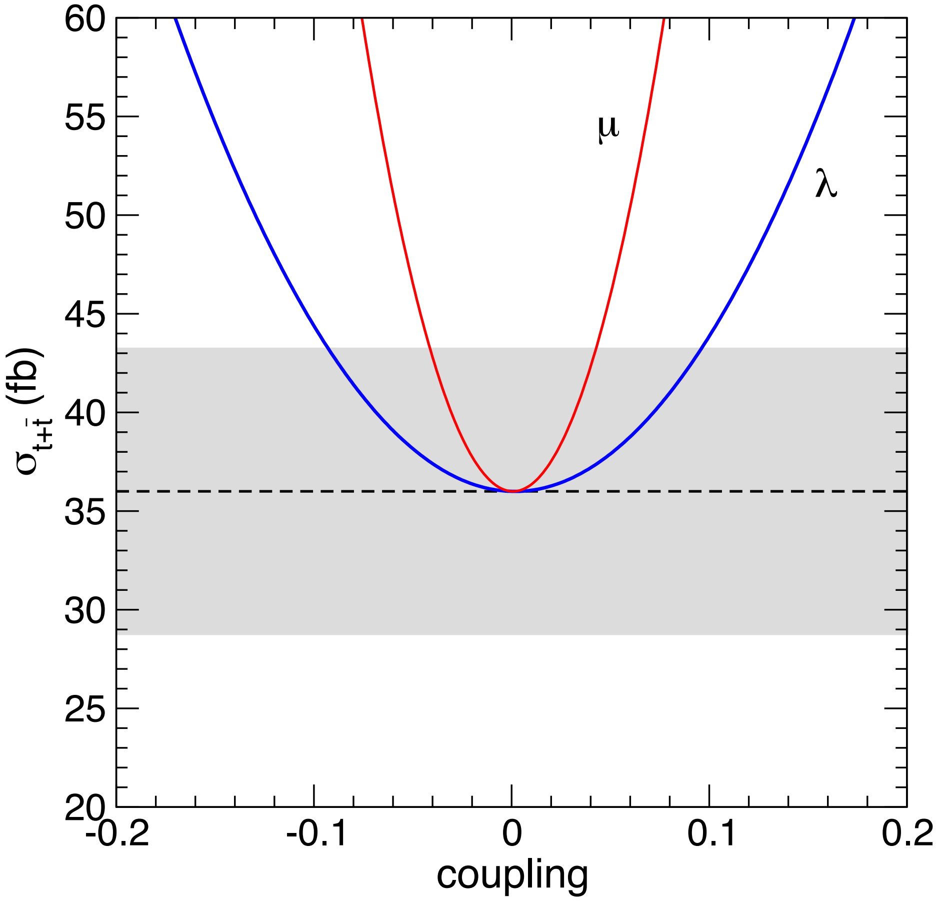
$$\alpha_b/\alpha_\ell = \ ? \pm ?$$

Proposal #2

Measurements at high *Q*, even with low precision, can be very constraining

JAAS & MLM ´14

$\sigma_{t\bar{b}+\bar{t}b}(m_{tb} > 1\ \mathrm{TeV})$



20% uncertainty

Final remarks

Besides measuring *W* helicity fractions 1205.2484, again CMS-PAS-TOP-12-015, and again CMS-PAS-TOP-12-020, and again 1308.3879, and again 1410.1154, and again CMS-PAS-TOP-14-017, and again 1605.09047,

one should consider other observables. Fortunately, new polarisation measurements are becoming available.

Many things still to be done at the pheno side [my incomplete to-do list]

- Can we possibly get limits on all 4f operators? 90 of them contribute to single top
- Global fit to top ttV operators: $O_{\varphi q}^{(1)}$, $O_{\varphi q}^{(3)}$, $O_{\varphi u}$, $O_{\varphi \varphi}$, O_{uW} , O_{dW} , $O_{uB\varphi}$, $O_{uG\varphi}$

This will trigger proposals for new measurements, stay tuned.