Precision determination of the Wtb coupling in single top production

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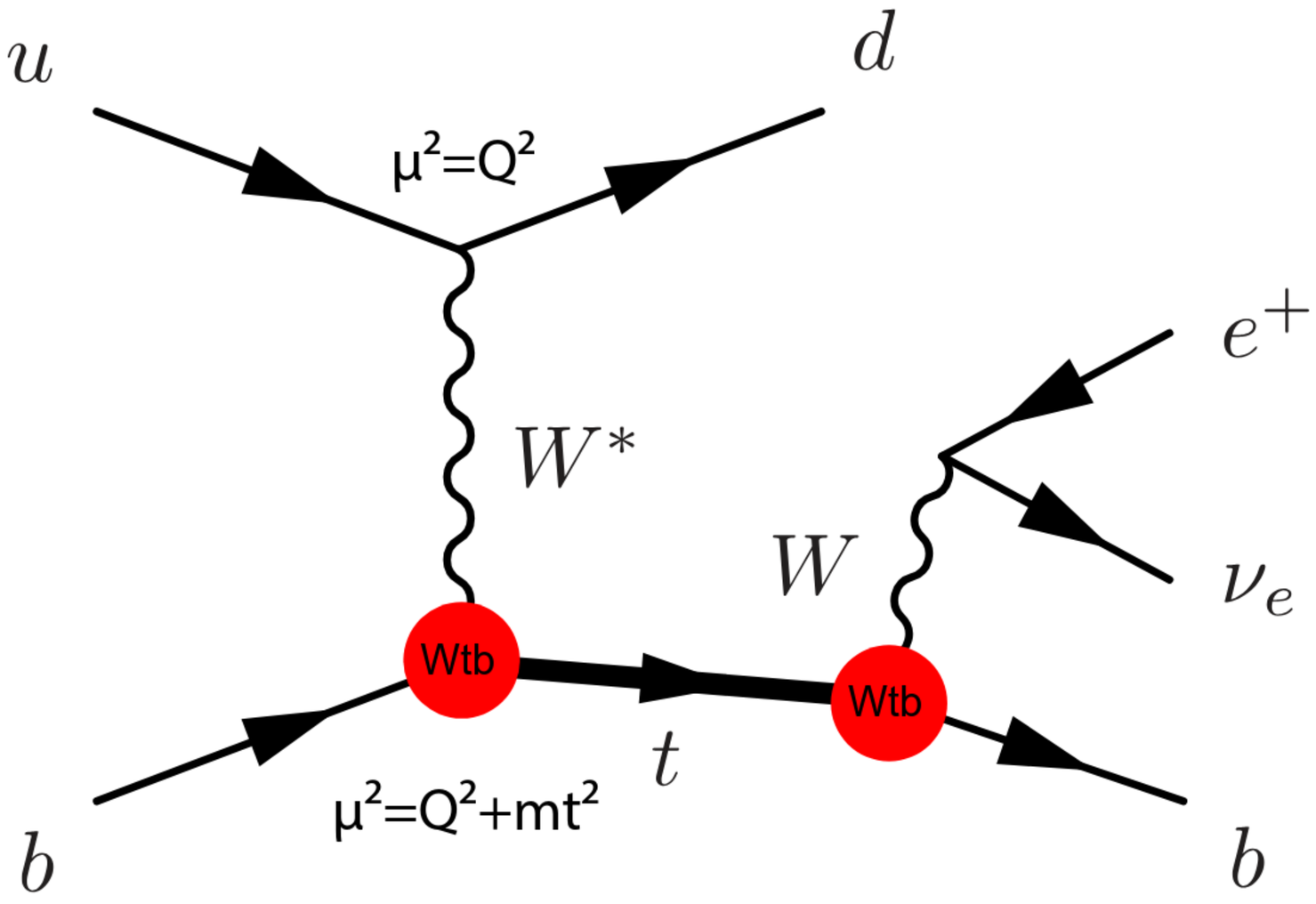
Single top: the t-channel



Easy motivation

ATLAS anomalous couplings: 1702.08309

- SM NLO events: POWHEG BOX, 4f scheme, stable top, CT10 PDFs, scale choice A
- LO protos, CTEQ6 PDFs, scale choice B

CMS anomalous couplings: 1610.03545

- CompHEP LO generator
- "matching to simulate effective NLO approach"
- LO codes for everything else

What constitutes a theoretical precision determination?

Standard model precision calculations!

- fixed order (NLO, NNLO), resummation and parton shower
- Yes.. even at NLO it is not trivial..
  ... 4-flavor scheme, 5-flavor scheme, on-shell top, stable top, off-shell top, non-resonant contributions ...

A tiny and incomplete list of some recent results:

(partial) NNLO: Brucherseifer, Caola, Melnikov '14 (stable top); Berger, Gao, Yuan, Zhu '16 '17 (on-shell but with decay), IBP reduction for full result: Assadolimani, Kant, Tausk, Uwer '14; NNLL threshold resummation: Kidonakis '12

NLO 4/5-flavor, on-shell (in MCFM): Campbell, Ellis, Tramontano '04; Campbell, Frederix, Frixione, Maltoni, Tramontano '09; Campbell, Ellis '12; (in POWHEG and aMC@NLO): Frederix, Re, Torrielli '12; NLO off-shell + non-resonant + parton shower: Prestel, Torrielli, Papanastasiou, Frederix, Frixione, Hirschi, Maltoni '13 '16; NLO with analytic transverse momentum dependent resummation: Cao, Sun, Bin Yan, C.P. Yuan, F. Yuan '18

NNLO is even more difficult

Inclusive NNLO to NLO corrections are about 1-2%.

" We found a difference of ~1% on the NNLO cross sections"

Berger, Gao, Yuan, Zhu '16

What else do we need?

(Standard model) Effective Field Theory (SMEFT) precision calculations!

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_k \sum_i \frac{C_{i,k}}{\Lambda^k} \mathcal{O}_{i,k}$$

- Using the effective field theory framework allows us to better quantify deviations and constrain concrete models.

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

Buchmueller, Wyler '86; Gradkowski, Iskrzynski, Misiak, Rosiek '10

Single top in the Standard Model EFT

Equally lots of work, beginning with anomalous couplings..

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

EFT correspondence:

$$\delta V_L = \left(C_{\phi q}^{(3)*} + \frac{g}{2}\text{Re}\,C_{qW}\right)\frac{v^2}{\Lambda^2}\,, \quad \delta g_L = \sqrt{2}C_{dW}^{*}\frac{v^2}{\Lambda^2}\,,$$
$$\delta V_R = \frac{1}{2}C_{\phi\phi}^{*}\frac{v^2}{\Lambda^2}\,, \quad \delta g_R = \sqrt{2}C_{uW}\frac{v^2}{\Lambda^2}$$

- *LO EFT, anomalous couplings: Aguilar-Saavedra '08 '09; Bach, Ohl '12*
- *Analysis and fit to observables, specific model interpretation: Cao, Bin Yan, Yu, Zhang '15*
- *further work, up to including NLO EFT effects: Zhang, Willenbrock '11; Franzosi, Zhang '15; Zhang '14 '16*
- *connection to flavor physics and low energy precision measurements: Alioli, Cirigliano, Dekens, Vries, Mereghetti '17*

NLO SMEFT corrections have been shown to be important

Most recent progress

partial NLO SMEFT calculation with limited set of operators

Beurs, Laenen, Vreeswijk, Vryonidou, '18

- MadGraph5_aMC@NLO framework, off-shell top, +PS
- PS: "resonant aware matching": tuning parameter to reproduce on-shell result
- shown at LO that tj with MadSpin, Wbj with MadSpin and $bl\nu j$ agree at few percent level for angular correlations
- Operators corresponding to V_L, g_R and 4q (all left-handed)

Beyond NLO SMEFT

SMEFT, NLO QCD, $1/\Lambda^2$: four relevant operators

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

Why should we care about $1/\Lambda^4$?

$$|\mathcal{A}|^2 = \left| A_{\text{SM}} + \frac{A^{1\text{ ins.}}_{\text{dim. 6}}}{\Lambda^2} + \frac{A^{2\text{ ins.}}_{\text{dim. 6}}}{\Lambda^4} + \frac{A^{1\text{ ins.}}_{\text{dim. 8}}}{\Lambda^4} \right|^2$$

Why should we go beyond SMEFT: EFT without SM symmetries?

Our setup

Unified framework for t-channel Single Top analyses

- t-channel Single Top in MCFM at NLO ⇒ easy and hackable
- Full decay chain, off-shell top in the complex mass scheme: no approximations in decays
- "Analytical" and compact amplitudes ⇒ numerically fast
- Want to compare with data as closely as possible: DDIS scales

Our setup

Era of precision physics:
Go beyond CompHEP, Protos, MG5_aMC@NLO + MadSpin setups

1. strict SMEFT mode: $1/\Lambda^2$ (done)
2. extended EFT mode: partial $1/\Lambda^4$ terms (TODO)

shipping with pre-packaged analysis framework, b-tagging

Last slide

- Single top **incredibly** active field. **The** process to study the Wtb coupling. Consistency test of PDFs.
- Lots of room for precision improvements:
  - full NNLO calculation and check of currently disagreeing results
  - NLO (SM)EFT: off-shell, full decay spin correlations, analytic, fast, easy to use and hackable implementation in MCFM
  - consistent SMEFT mode ($1/\Lambda^2$), extended mode: partial $1/\Lambda^4$
- Establish contact with experimentalists so NLO EFT improvements get actually used! ✓$?!$