Precision determination of the Wtb coupling in single top production

Tobias Neumann, Illinois Tech/Fermilab

with Zack Sullivan, Illinois Tech

August 30th, 2018
Single top: the $t$-channel

$\mu^2 = Q^2$

$W^*$

$W$

$b$

$e^+$

$\nu_e$

$u$

$d$

$\mu^2 = Q^2 + mt^2$

$W_{tb}$

$W_{tb}$
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.
Single top in the Standard Model EFT

Equally lots of work, beginning with anomalous couplings..

\[ \mathcal{L}_{\text{WW}} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- + \text{h.c.} \]

\[
-\frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{m_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.}
\]

**EFT correspondence:**

\[ \delta V_L = \left( C_{\phi^0}^{(3)} + \frac{3}{2} \text{Re} C_{\phi^0 W} \right) \frac{v^2}{\Lambda^2}, \quad \delta q_L = \sqrt{2} C_{W} \frac{v^2}{\Lambda^2} \]

\[ \delta V_R = \frac{1}{2} C_{\phi^0} \frac{v^2}{\Lambda^2}, \quad \delta q_R = \sqrt{2} C_{W} \frac{v^2}{\Lambda^2} \]

- **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 $blvj$ 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

$$\mathcal{L}_{tbW} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^{\mu}(V_L P_L + V_R P_R) t W^-_{\mu} + \text{h.c.}$$

$$-\frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_{\nu}}{m_W} (g_L P_L + g_R P_R) t W^-_{\mu} + \text{h.c.}$$

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

$$|A|^2 = |A_{SM} + \frac{A_1 \text{ins. dim. 6}}{\Lambda^2} + \frac{A_2 \text{ins. dim. 6}}{\Lambda^4} + \frac{A_1 \text{ins. dim. 8}}{\Lambda^4}|^2$$

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
• 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! ✓ ?!