Usefulness of EFT for Boosted Higgs Production

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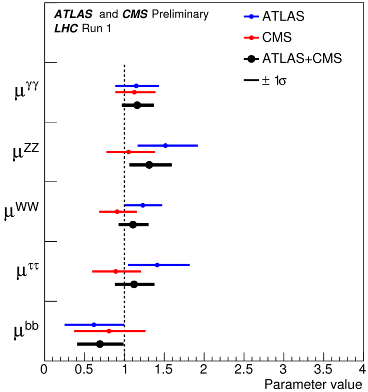
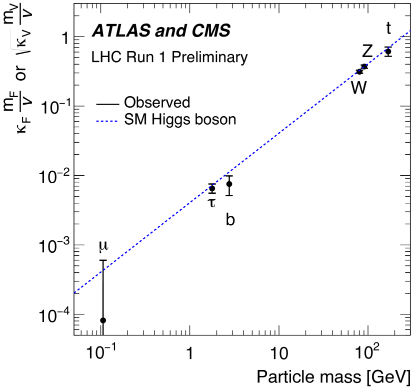
Dawson, IL, Zeng PRD90 (2014) 093007; PRD91 (2015) 074012

November 5, 2015
HEFT 2015
University of Chicago

Remarkably Standard Model Like

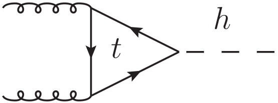


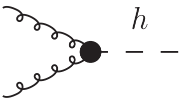


ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002

However, a degeneracy in single Higgs production (as we heard about yesterday.)

Single Higgs Production





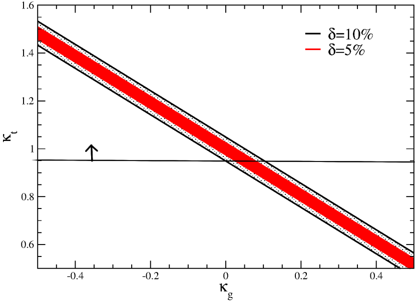
- Assume new heavy physics.
  - Parameterize new heavy particle via effective operator between gluons and Higgs.
- New physics can also shift the top Yukawa coupling.

$$\mathcal{L} = -\kappa_t \left(\frac{m_t}{v}\right) \bar{t} t h + \kappa_g \left(\frac{\alpha_s}{12\pi v}\right) G^{A,\mu\nu} G^A_{\mu\nu} h$$

- Degeneracy in single Higgs production rate via gluon fusion.
  - Can alter top Yukawa and add new particles at same time.

Single Higgs Production

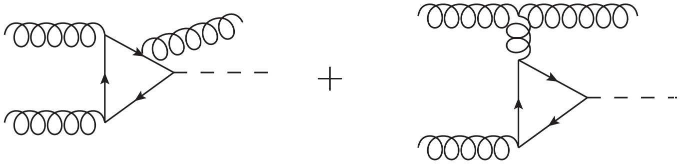
gg → h rate within δ of SM predicition



$$\mathcal{L} = -\kappa_t \left(\frac{m_t}{v}\right) \bar{t}th + \kappa_g \left(\frac{\alpha_s}{12\pi v}\right) G^{A,\mu\nu} G^A_{\mu\nu} h$$

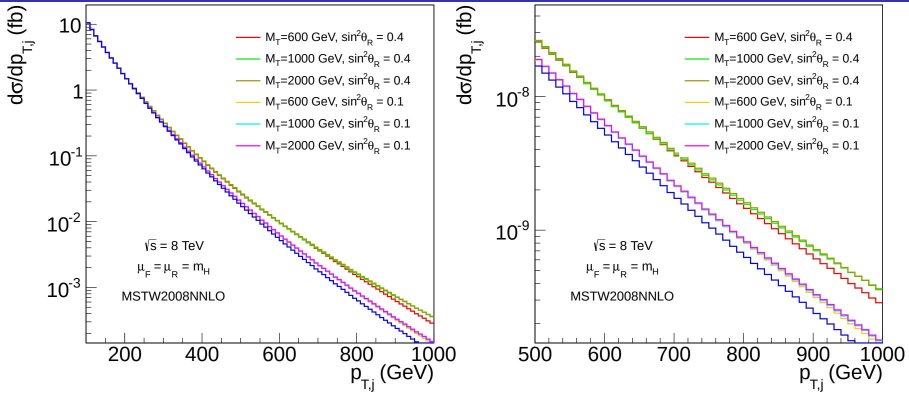
- Degeneracy in Higgs production rate: $\kappa_t + \kappa_g = 1$ reproduces SM Higgs production rate.
- Need to break degeneracy.
  - Measure tth and/or th
  - Exploit different energy scalings between the SM and new physics contributions to the loop.

Higgs Plus Jet



- Look at p_T distribution of Higgs.
  - Since NP and top quark distributions have different scales, could hopefully resolve difference between top quark Yukawa scalings and new physics in loops.
  - Pass over $p_T \sim m_{NP}$, will resolve loops from new physics.
- Much work trying to study this possibility. Grojean *et al* JHEP (2014) 1405:022; Azatov, Paul JHEP (2014) 1401:014; Buschmann *et al* PRD90 (2014) 013010; Buschmann *et all* JHEP 1502 (2015) 038; Schlaffer *et al* EPJ C74 2014 3120; Banfi, Martin, Sanz JHEP (2014) 1408:053

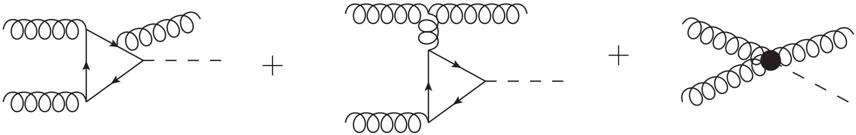
Higgs Plus Jet with Top Partner



Banfi, Martin, Sanz. JHEP 1408 (2014) 053

- Standard Model: Blue
- For $p_T < m_T$, see overall deviation insensitive to absolute scale of new physics.
- For $p_T \gtrsim m_T$, deviation changes.
- With current top partner limits approaching 1 TeV, suggests using an EFT.

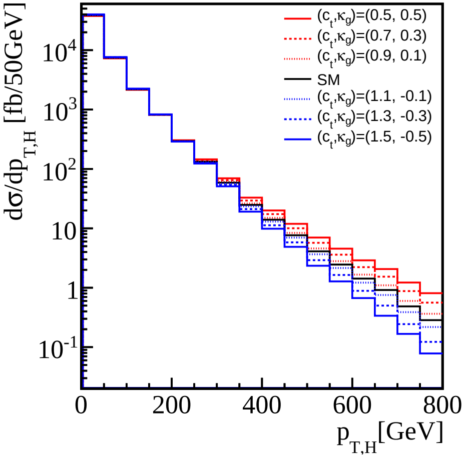
Higgs Plus Jet EFT



- EFT and SM contributions scale different with energy.
- Simple to keep single Higgs rate SM-like: $\kappa_t + \kappa_g = 1$.
- Allows more model independent approach: don't have to assume what new colored physics is giving new operator.

$$\mathcal{L} = -\kappa_t \left(\frac{m_t}{v}\right) \bar{t}tH + \kappa_g \left(\frac{\alpha_s}{12\pi v}\right) G^{A,\mu\nu} G^A_{\mu\nu} H$$

Higgs Plus Jet EFT

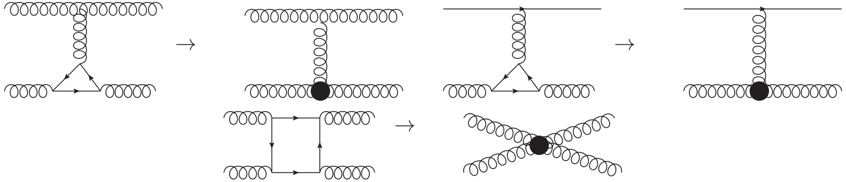


Schlaffer *et al*, Eur.Phys.J C74 (2014) 10, 3120

- Impose $\kappa_t + \kappa_g = 1$.
- Can see deviation in tail.
- Some questions:
  - How well is the SM predicted?
  - For new physics, is it important to add higher dimensional operators?

$$\mathcal{L} = -\kappa_t \left(\frac{m_t}{v}\right) \bar{t}tH + \kappa_g \left(\frac{\alpha_s}{12\pi v}\right) G^{A,\mu\nu} G^A_{\mu\nu} H$$

Effectiveness of EFT



- Previous results calculated using a Dimension-5 operator.

$$hG^A_{\mu\nu}G^{A,\mu\nu}$$

- Coefficient calculated by taking exact loop and expanding in $1/m^2$ and keeping LO in the expansion.
- How well does this EFT work?
  - Can calculate higher order, dimension-7 operators using next order in expansion for parton-Higgs interactions.
- Rest of talk:
  - Give overview of the dimension-7 operator basis.
  - First present results in the SM, including NLO QCD effects.
  - Quantify how well it works for the new physics (how large are the Wilson coefficients.)

Dimension 7 Operators

- Have Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + (\kappa_t - 1)\left(-\frac{m_t}{v}\right)\bar{t}th + \mathcal{L}_5 + \mathcal{L}_7$$

- Dimension 5 operator:

$$\mathcal{L}_5 \equiv \hat{C}_1 O_1 = \hat{C}_1 G^A_{\mu\nu} G^{\mu\nu,A} h$$

- Four independent Dimension-7 operators relevant for Higgs production (see also Harlander, Neumann PRD88 (2013) 074015; Neill 0908.1573, 0911.2707):

$$\mathcal{L}_7 = \sum_{i=2,3,4,5} \hat{C}_i O_i$$

$$O_2 = D_\sigma G^A_{\mu\nu} D^\sigma G^{\mu\nu,A} h \qquad O_3 = f_{ABC} G^{A,\mu}_\nu G^{B,\nu}_\sigma G^{C,\sigma}_\mu h$$

$$O_4 = g_s^2 h \sum_{i,j=1}^{n_{lf}} \overline{\psi}_i \gamma_\mu T^A \psi_i \overline{\psi}_j \gamma^\mu T^A \psi_j \qquad O_5 = g_s h \sum_{i,j=1}^{n_{lf}} G^A_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^A \psi_i$$

- On-shell Higgs boson can be used to simplify basis.

Dimension 7 Operators

- Using Jacobi identities and on-shell Higgs, can eliminate one operator.

$$m_h^2 O_1 = -2O_2 + 4g_s O_3 + 4O_5$$

- Finally, choose basis O_1, O_3, O_4, O_5, and the effective Lagrangian is

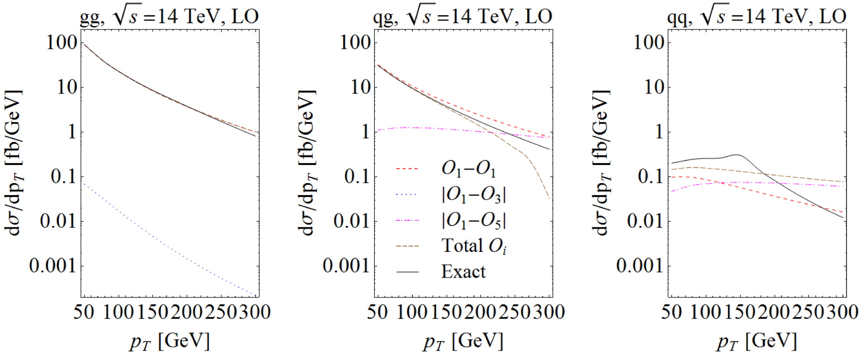
$$\mathcal{L}_{eff} = C_1 O_1 + (C_3 O_3 + C_4 O_4 + C_5 O_5)$$

$$O_1 = G^A_{\mu\nu} G^{\mu\nu,A} h \qquad O_3 = f_{ABC} G^{A,\mu}_{\nu} G^{B,\nu}_{\sigma} G^{C,\sigma}_{\mu} h$$

$$O_4 = g_s^2 h \sum_{i,j=1}^{n_{lf}} \overline{\psi}_i \gamma_\mu T^A \psi_i \overline{\psi}_j \gamma^\mu T^A \psi_j \qquad O_5 = g_s h \sum_{i,j=1}^{n_{lf}} G^A_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^A \psi_i$$

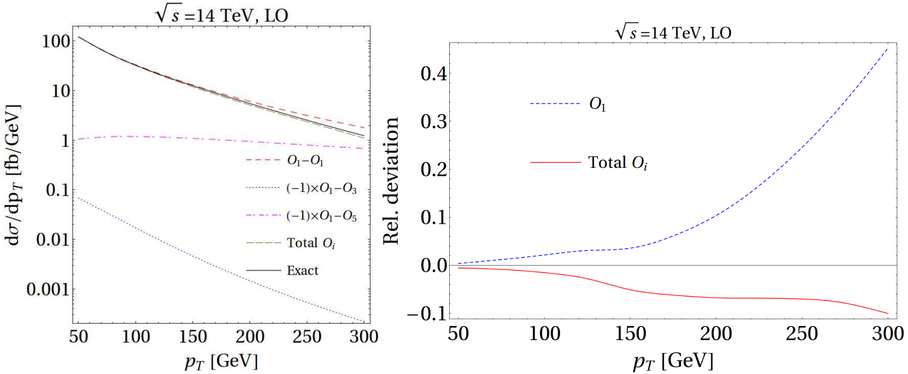
- O_1 only operator that contributes to LO gluon fusion Higgs production.
- O_3 and O_5 begin contributing at Higgs+jet.
- Since O_4 involves 4 light fermions, contributes to Higgs+jet starting at NLO.

LO Relative Contributions-SM Case



- O_5 only contributes to $qg \to qh$: $O_5 = g_s h \sum_{i,j=1}^{n_{lf}} G^A_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^A \psi_i$
- O_3 only contributes to $gg \to gh$: $O_3 = f_{ABC} G_\nu^{A,\mu} G_\sigma^{B,\nu} G_\mu^{C,\sigma} h$
- qg production important in tail, O_5 more important to total distribution.
- EFT does not work well for qq, but subleading effect.

LO Relative Contributions

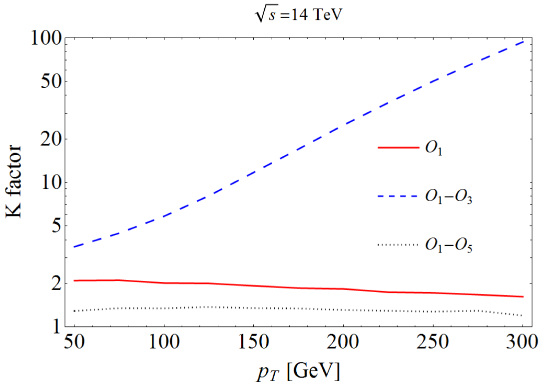


- O_3 makes little difference: $O_3 = f_{ABC} G_\nu^{A,\mu} G_\sigma^{B,\nu} G_\mu^{C,\sigma} h$
- O_5 important in tail of distribution: $O_5 = g_s h \sum_{i,j=1}^{n_{lf}} G_{\mu\nu}^A D^\mu \overline{\psi}_i \gamma^\nu T^A \psi_i$
- RHS: Relative deviation from exact result.

Higher order corrections

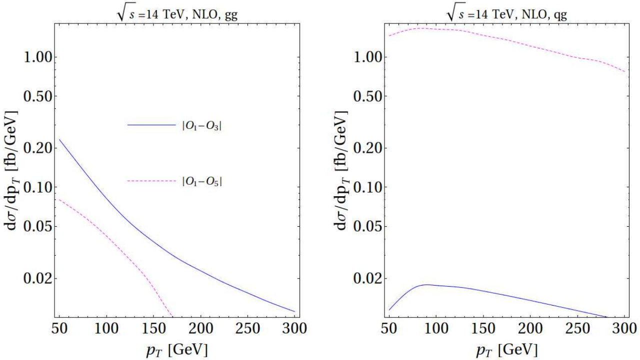
- Higher order corrections have been calculated with dimension-5 operator.
  - Used for SM Higgs production at NNLO Harlander, Kilgore, PRL88 (2002) 201801; Ravindran, Smith, van Neerven, NPB665 (2003) 325; Anastasiou, Melnikov NPB646 (2002) 220
  - Used for SM Higgs p_T distribution Anastasiou, Melnikov, Petriello NPB724 (2005) 197; Catani, Grazzini PRL98 (2007) 222002; Ravindran, Smith, van Neerven, NPB634 (2002) 247
  - SM Higgs production to N^3LO Anastasiou, Duhr, Dulat, Herzong, Mistlberger PRL114 (2015) 212001
  - Higgs+jet at NNLO Boughezal, Caola, Melnikov, Petriello, Schulze, PRL115 (2015) 082003, JHEP 1306 (2013) 072
- New operators could make a difference in QCD corrections.
  - Different operators have different structures.
- Next order in $1/m_t^2$ has been calculated numerically Harlander, Neumann, Ozeren, Wiesemann JHEP 1208 (2012) 139
- We use EFT language, can find equations for virtual corrections with arbitrary Wilson coefficients in Dawson, IL, Zeng, PRD90 (2014), 034016

SM K-factor by Operator



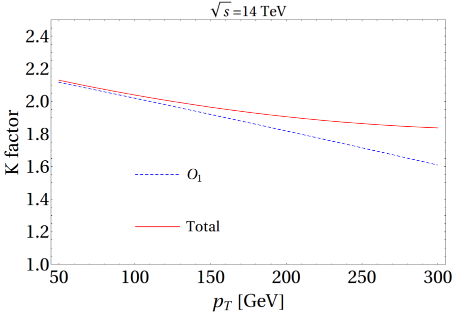
- $O_5 = g_s h \sum_{i,j=1}^{n_{lf}} G^A_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^A \psi_i$
- $O_3 = f_{ABC} G^{A,\mu}_\nu G^{B,\nu}_\sigma G^{C,\sigma}_\mu h$
- Increasing K-factor for O_3, but small overall rate.

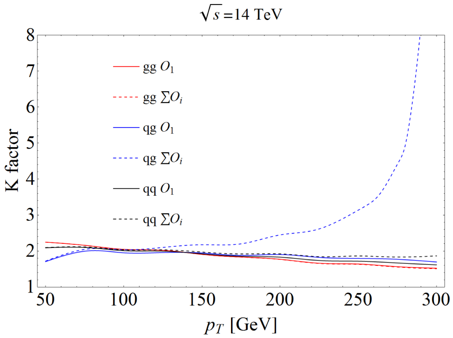
SM NLO by channel



- Operators matched onto SM.
- O_5 now makes subdominant contribution to gg initial state.
  - $O_5 = g_s h \sum_{i,j=1}^{n_{lf}} G^A_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^A \psi_i$
- O_3 now makes subdominant contribution to qg initial state.
  - $O_3 = f_{ABC} G^{A,\mu}_\nu G^{B,\nu}_\sigma G^{C,\sigma}_\mu h$

K-factors

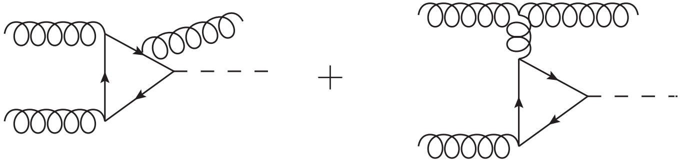




- New operators effect K-factor for $p_T \gtrsim 150$ GeV.
- K-factor for qg initial state separates from other initial states for $p_T \gtrsim 150$ GeV.

NEW PHYSICS

New Physics



- Consider two models:
  - Singlet top partner:

$$\mathcal{L} = -\left\{\cos^2\theta_L \frac{m_t}{v}\bar{t}_L t_R h + \sin^2\theta_L \frac{M_T}{v}\bar{T}_L T_R h + \frac{M_T}{2v}\sin(2\theta_L)\bar{t}_L T_R h + \frac{m_t}{2v}\sin(2\theta_L)\bar{T}_L t_R H + H.c.\right\}$$

  - Colored scalar:

$$V = V_{SM}(H) + m_i^2 \phi_i^\dagger \phi_i + \frac{C_h}{v}\phi_i^\dagger \phi_i H^\dagger H - \lambda_4 (\phi_i^\dagger \phi_t)^2$$

- Work at LO in QCD.
  - Keep SM top quark loops exactly.
  - Integrate out heavy new physics loops and match onto dimension-5 and 7 operators.

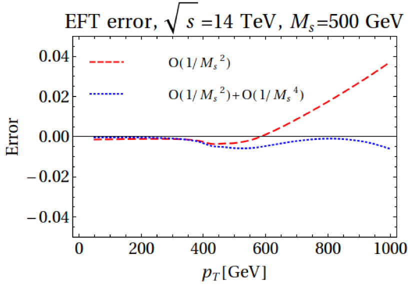
New Physics

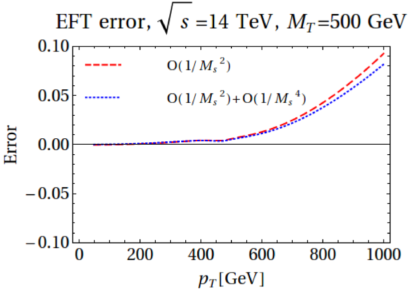
- Besides Standard Model, can check validity of EFT in New physics.
  - Matched singlet top partner and colored scalar models onto Dim-7 EFT.

	Dirac Fermion	$SU(3)$ Triplet Scalar	$SU(3)$ Octet Scalar
$C_1(\Lambda)$	$\frac{\alpha_s\kappa_F}{12\pi v}\left[1+\frac{7m_h^2}{120m_F^2}\right]$	$-\frac{\alpha_s}{96\pi M_S^2}C_h\left[1+\frac{2m_h^2}{15M_S^2}\right]$	$-\frac{\alpha_s}{16\pi M_S^2}C_h\left[1+\frac{2m_h^2}{15M_S^2}\right]$
$C_3(\Lambda)$	$-\frac{g_s\alpha_s\kappa_F}{360\pi v m_F^2}$	$-\frac{g_s\alpha_s}{1440M_S^4}C_h$	$-\frac{g_s\alpha_s}{240M_S^4}C_h$
$C_5(\Lambda)$	$\frac{11\kappa_F\alpha_s}{360\pi v m_F^2}$	$-\frac{\alpha_s}{360\pi M_S^4}C_h$	$-\frac{\alpha_s}{60\pi M_S^4}C_h$

- $\kappa_F = \sin^2\theta_L$, θ_L is left-handed mixing angle between top and top partner.
- $C_h = 3m_Z$ is the scalar-scalar-Higgs boson triple coupling.

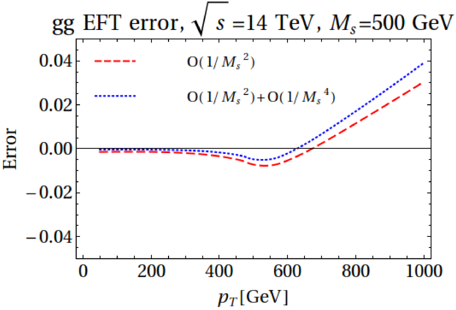
Triplet Scalar and Top Partner Results

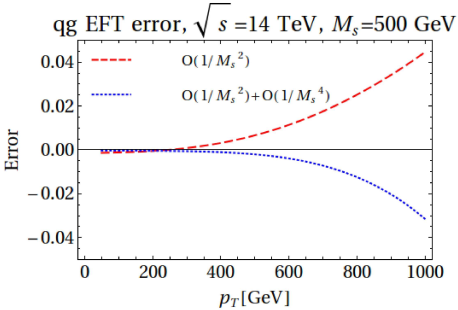




- EFT error is relative deviation from exact LO QCD calculation.
- Dimension 5 works well for $p_T \lesssim$ new physics scale..
- Results within a few percent of exact result.
- Standard Model top quark contribution included exactly.
- Parameters:
  - Triple scalar couplings $C_h = 3m_Z$
  - Heavy top-partner mixing: $\sin\theta_L = 0.26$

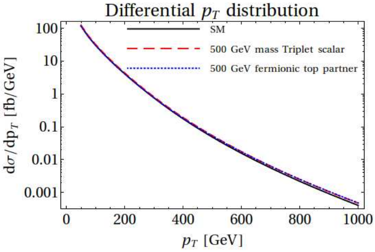
Triplet Scalar By Channel

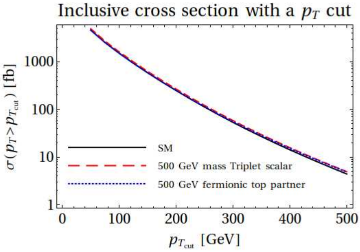




- *gg* channel
  - Dimension 7 operators make mild difference.
  - Help convergence for $p_T \lesssim M_S$.
- *qg* channel
  - Dimension 7 operators, help convergence.

Distributions



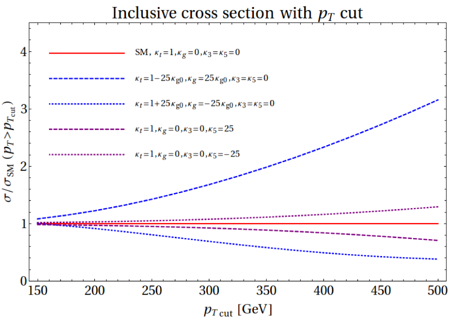


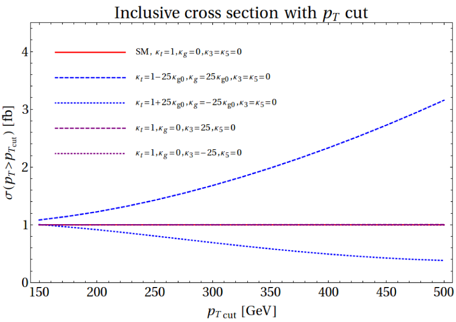
- New physics makes little contribution to the differential or inclusive distribution.
- Inclusive distribution defined as:

$$\sigma(p_T > p_{T\,cut}) = \int_{p_{T\,cut}}^{\infty} dp_T \frac{d\sigma}{dp_T}$$

- How big of a new physics effect is needed to make appreciable difference?

Rescaling Operators





- Red: SM
- Blue: Scaling of top yukawa, O_1
- Violet: Scaling of O_5

- Red: SM
- Blue: Scaling of top yukawa, O_1
- Violet: Scaling of O_3

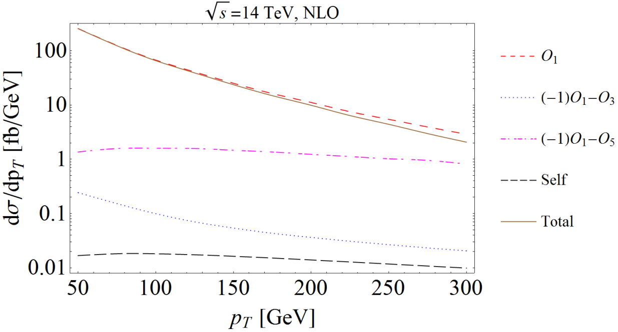
- Scale operators by factor of 25 w.r.t. 500 GeV scalar triplet.
- Difficult to get large effects.
- $O_1 = G^A_{\mu\nu} G^{A,\mu\nu} h$, $O_5 = g_s h \sum_{i,j=1}^{n_{lf}} G^A_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^A \psi_i$, $O_3 = f_{ABC} G^{A,\mu}_\nu G^{B,\nu}_\sigma G^{C,\sigma}_\mu h$

Conclusions

- Investigated how higher order operators effect Higgs+jet production.
- Standard Model:
  - Dimension-7 operators start becoming important for $p_T \gtrsim 150$ GeV.
  - Main effect came from O_5 which effects qg initial state.
  - Reproduces exact LO p_T distribution within 10% for $p_T \lesssim 300$ GeV
  - At NLO, dimension-7 operators effect K-factor by a few to 10 percent for $p_T \gtrsim 150$ GeV.
    - Mainly because of K-factor for qg channel.
- New physics:
  - Investigated singlet top partner and color triplet scalar extensions of SM, specifically how important dimension-7 operators are to the rate.
  - Dimension-7 operators made little difference to p_T distribution for p_T below heavy particle's mass.
  - To make considerable contribution to p_T distributions need very large rescaling of dimension-7 operators.

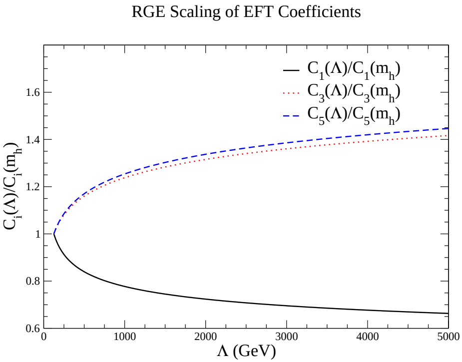
EXTRA SLIDES

SM NLO by Operator



- $O_5 = g_s h \sum_{i,j=1}^{n_{lf}} G^A_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^A \psi_i$
- $O_3 = f_{ABC} G^{A,\mu}_\nu G^{B,\nu}_\sigma G^{C,\sigma}_\mu h$
- Dimension-7 operators start being important around $p_T \gtrsim m_t$.

NLO Running of Wilson Coefficients



Effect of Running on p_T distribution

- Taken from Englert, Spannowsky PLB740 (2014)
- Only consider running and effect of O_1.
- New physics scale set to 14 TeV.
- For each event, Wilson coefficient evaluated at scale $\sqrt{\hat{s}}$.
- Makes little difference.