Pushing Higgs Effective Theory over the Edge

based on 1602.05202

Anke Biekötter, Johann Brehmer, Tilman Plehn

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Johann Brehmer, Ayres Freitas, David Lopez-Val, Tilman Plehn
[1510.03443]

EFT cannot describe LHC Higgs physics

- EFT: reproducible and model independent parametrization
- B and L conservation $\rightarrow$ D6 is lowest dimension to describe NP
- $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \text{D8} + \cdots$
- LHC accuracy $\sim$ $10\ \%$
- scenarios with $\Lambda \gg E$ not measurable at the LHC
- D8 not sufficiently suppressed

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EFT can describe LHC Higgs physics

➜ answer some remaining questions

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D6 can describe LHC Higgs physics

➜ answer some remaining questions

Outline

D6 description

- To square or not to square?
- Higgs-strahlung and WBF
- Which observable to study for WBF?

A simplified model

- Can a scalar be a vector?

D6 description - to square or not to square?

$$|\mathcal{M}_{4+6}|^2 = |\mathcal{M}_4|^2 + 2\,\mathsf{Re}\mathcal{M}_4^*\mathcal{M}_6 \overset{?}{+} |\mathcal{M}_6|^2$$

D6 description - to square or not to square?

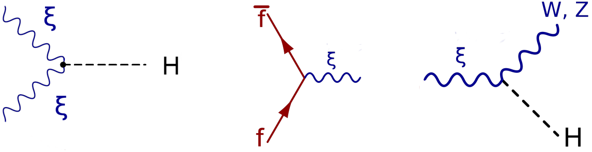
$$|\mathcal{M}_{4+6}|^2 = |\mathcal{M}_4|^2 + 2\,\mathsf{Re}\mathcal{M}_4^*\mathcal{M}_6 \overset{?}{+} |\mathcal{M}_6|^2$$

Preferable to include $\mathrm{D6}^2$ when neglecting D8?

Study for vector triplet model

Vector triplet model

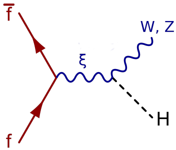
- new $\mathrm{SU}(2)_L$ triplet
- mixing of the new heavy states with the weak gauge bosons
- three new heavy states $\xi^0,\ \xi^\pm$



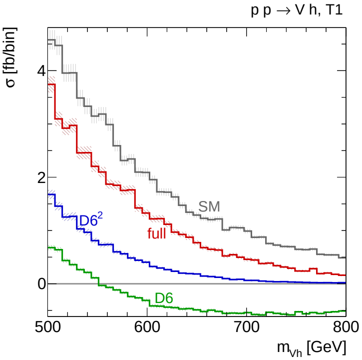
describe interactions using D6 operators such as

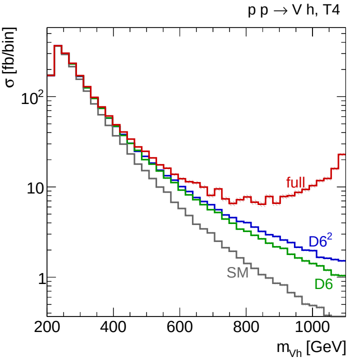
$$\mathcal{O}_W = \frac{ig}{2}(D^\mu\phi^\dagger)\sigma^k(D^\nu\phi)\ W^k_{\mu\nu}$$

Higgs-strahlung

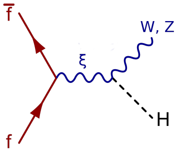


- study distribution of m_{Vh} ($p_{T,V}$)
- two benchmarks (destructive/constructive) with $m_\xi = 1200$ GeV





Higgs-strahlung



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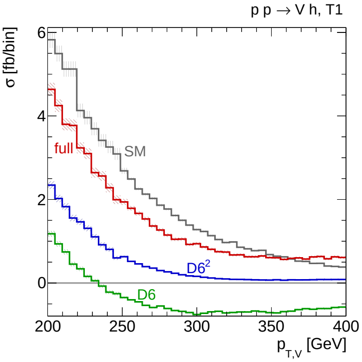
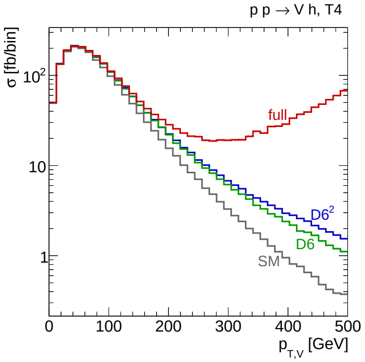
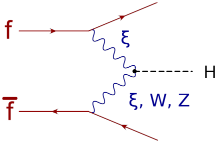


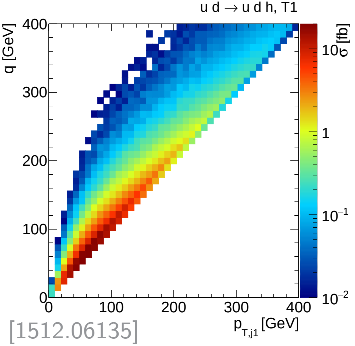


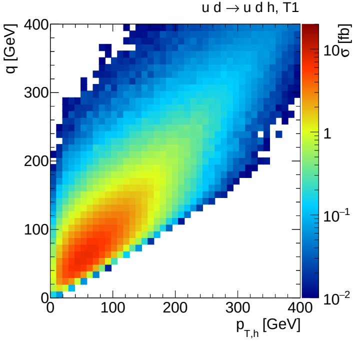
WBF - momentum transfer



- study parton-level process $ud \to udh$
- momentum transfer q

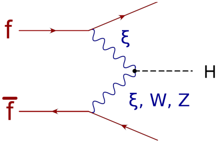
$$q = \begin{cases} \max\left(\sqrt{|(p_{u'} - p_d)^2|},\ \sqrt{|(p_{d'} - p_u)^2|}\right) & W\text{-like PS points} \\ \max\left(\sqrt{|(p_{u'} - p_u)^2|},\ \sqrt{|(p_{d'} - p_d)^2|}\right) & Z\text{-like PS points} \end{cases}$$



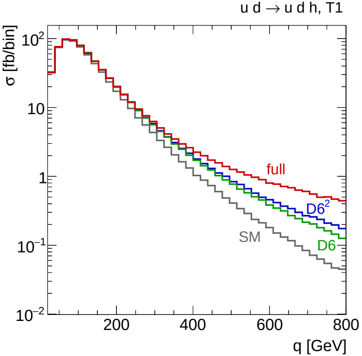


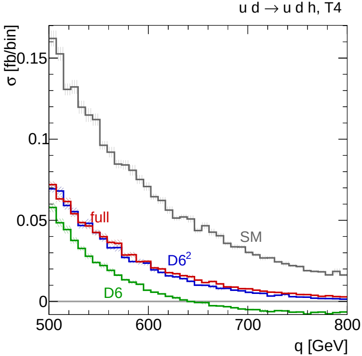
[1512.06135]

WBF - parton level



- study momentum transfer q (p_{T,j_1})
- two benchmarks (constructive/destructive) with $m_\xi = 1200$ GeV





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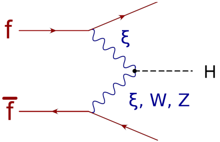

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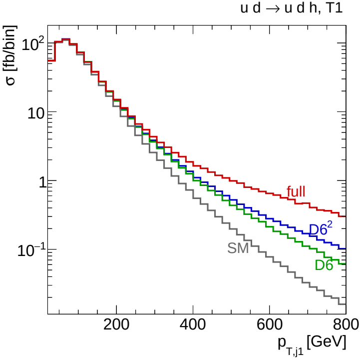
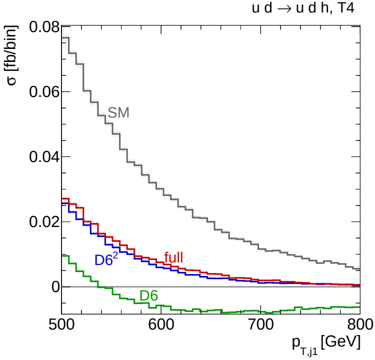




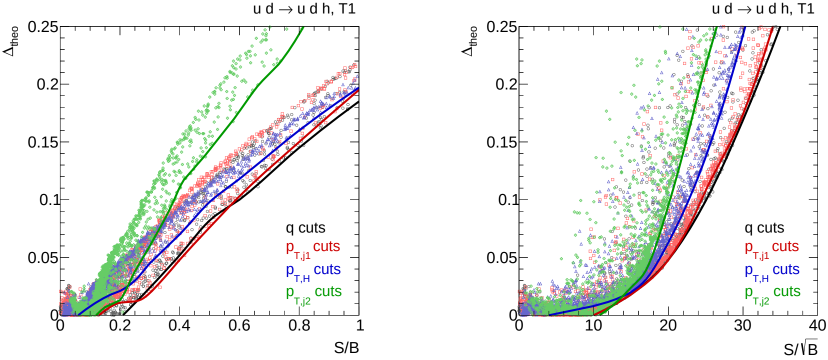
WBF - Which observable to study?

Compare deviations from the full model

$$\Delta_{\text{theo}}(x_{\text{min,max}}) = \left| \frac{\sigma_{\text{D6}} - \sigma_{\text{full}}}{\sigma_{\text{full}}} \right| \;,\; x \in \{q,\, p_{T,j_1},\, p_{T,j_2},\, p_{T,h}\}$$

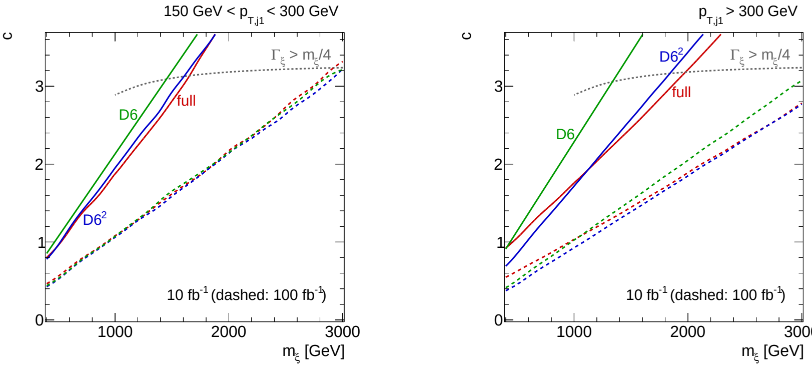
to statistics-driven and systematics-driven significances

$$\frac{S}{B}(x_{\text{min,max}}) = \left| \frac{\sigma_{\text{full}} - \sigma_{\text{SM}}}{\sigma_{\text{SM}}} \right| \qquad \text{and} \qquad \frac{S}{\sqrt{B}}(x_{\text{min,max}}) = \sqrt{L}\left| \frac{\sigma_{\text{full}} - \sigma_{\text{SM}}}{\sqrt{\sigma_{\text{SM}}}} \right|$$



WBF - comparison of expected exclusion limits

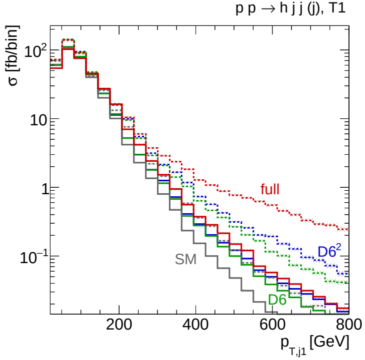
- choose universal coupling rescaling c
- m_ξ mass of the new heavy vector



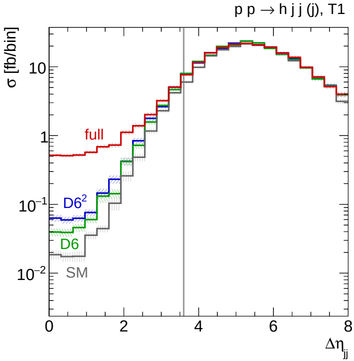
WBF - getting realistic

- hadron level analysis $pp \to h\, jj\, (+j)$
- using PYTHIA6 and FastJet
- apply WBF cuts

$$p_{T,j} > 20 \text{ GeV}\,, \qquad m_{jj} > 500 \text{ GeV}\,, \qquad \Delta\eta_{jj} \ > \ 3.6$$



dotted: WBF diagrams only, without $\Delta\eta_{jj}$ cut



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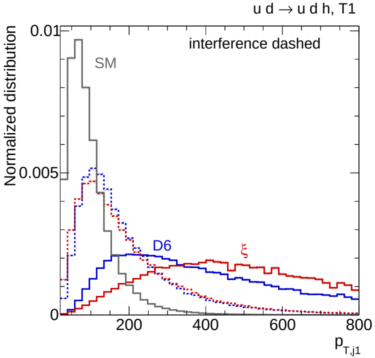
A simplified model - Can a scalar be a vector?

Improved description of kinematics in a simplified model?

Vector triplet model already quite simple

simpler approach ➜ (pseudo) scalar

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S}{2} S^2 + \sum_{\text{fermions}} g_F \, S \overline{F} \gamma_5 F + g_S \, S^2 \phi^\dagger \phi \, .$$



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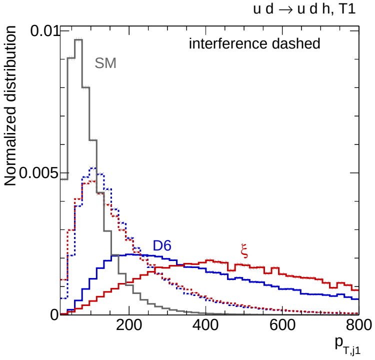
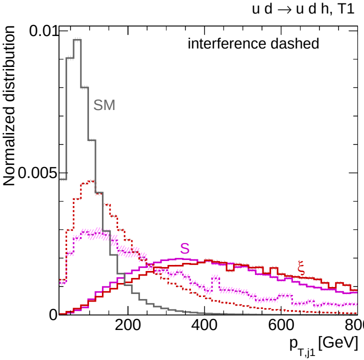
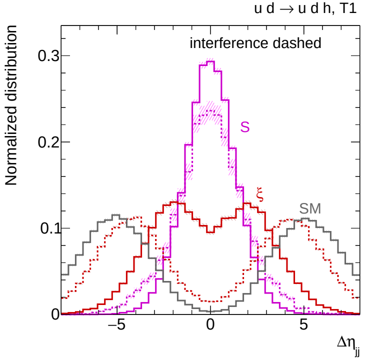




Goldstone boson equivalence theorem



$$|\mathcal{M}(qq \to q'\, q'\, h)|^2 \propto \frac{g_F^4 \;\, t_1\, t_2}{(t_1 - m_S^2)^2 \; (t_2 - m_S^2)^2} \xrightarrow{m_S \to 0} \frac{\text{const}}{t_1\, t_2}$$

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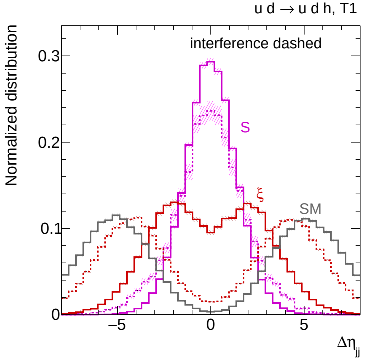

No collinear divergence after PS integration

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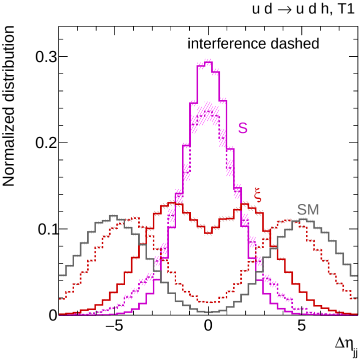

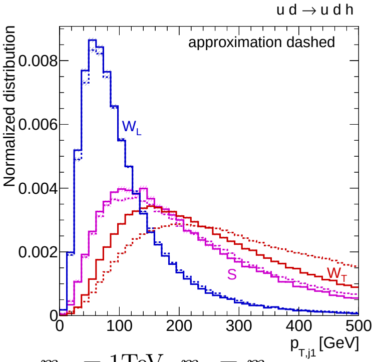

$m_H = 1\mathrm{TeV},\ m_S = m_W$

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Conclusions

- Including $D6^2$ terms improves agreement with full model and avoids negative cross sections
- WBF: the leading tagging jet's $p_{T,j1}$ is especially suited for new physics searches
- scalar simplified model: improved modelling of m_{VH} and p_{T,j_1} distributions at the cost of larger deviations in the dominant interference terms
- scalar simplified model fails badly for description of $\Delta\eta_{jj}$

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D6 description of LHC Higgs physics works

Conclusions

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- scalar simplified model fails badly for description of $\Delta\eta_{jj}$

D6 description of LHC Higgs physics works even better when including D6^2

Thank you for your attention!

Vector triplet model

[1510.03443], [1211.2229], [1406.7320], [1506.03631]

$$\mathcal{L} \supset -\frac{1}{4}\,\tilde{V}^a_{\mu\nu}\,\tilde{V}^{\mu\nu\,a} + \frac{M^2_{\tilde{V}}}{2}\,\tilde{V}^a_\mu\,\tilde{V}^{\mu\,a} + i\,\frac{g_V}{2}\,c_H\,\tilde{V}^a_\mu\left[\phi^\dagger\sigma^a \overleftrightarrow{D}^\mu\,\phi\right]$$
$$+\frac{g_w^2}{2g_V}\,\tilde{V}^a_\mu \sum_{\text{fermions}} c_F\,\overline{F}_L\,\gamma^\mu\,\sigma^a\,F_L + \frac{g_V}{2}\,c_{VVV}\,\epsilon_{abc}\,\tilde{V}^a_\mu\,\tilde{V}^b_\nu\,D^{[\mu}\,\tilde{V}^{\nu]\,c}$$
$$+\,g_V^2\,c_{VVHH}\,\tilde{V}^a_\mu\,\tilde{V}^{\mu a}\,(\phi^\dagger\,\phi) - \frac{g_w}{2}\,c_{VVW}\,\epsilon_{abc}\,W^{\mu\nu}\,\tilde{V}^b_\mu\,\tilde{V}^c_\nu$$

Benchmark	Triplet model					
	M_V	g_V	c_H	c_F	c_{VVHH}	m_ξ
T1	591	3.0	-0.47	-5.0	2.0	1200
T4	1246	3.0	-0.50	3.0	-0.2	1200

D6 operators

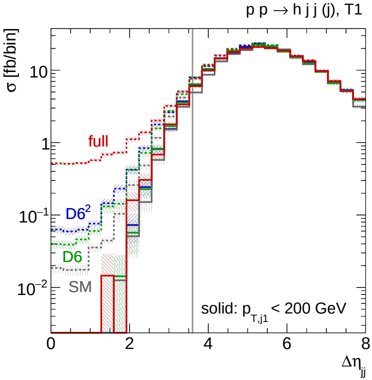
HISZ basis	
$\mathcal{O}_{\phi 1} = (D_\mu \phi)^\dagger \, (\phi \, \phi^\dagger) \, (D^\mu \phi)$	$\mathcal{O}_{\phi 2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \, \partial_\mu (\phi^\dagger \phi)$
$\mathcal{O}_{\phi 3} = \frac{1}{3} (\phi^\dagger \, \phi)^3$	
$\mathcal{O}_{GG} = (\phi^\dagger \, \phi) \, G^A_{\mu\nu} \, G^{\mu\nu \, A}$	$\mathcal{O}_{BW} = -\frac{g \, g'}{4} (\phi^\dagger \sigma^k \phi) \, B_{\mu\nu} \, W^{\mu\nu \, k}$
$\mathcal{O}_{BB} = -\frac{g'^2}{4} (\phi^\dagger \, \phi) \, B_{\mu\nu} \, B^{\mu\nu}$	$\mathcal{O}_{WW} = -\frac{g^2}{4} (\phi^\dagger \, \phi) \, W^k_{\mu\nu} \, W^{\mu\nu \, k}$
$\mathcal{O}_B = \frac{ig}{2} (D^\mu \phi^\dagger)(D^\nu \phi) \, B_{\mu\nu}$	$\mathcal{O}_W = \frac{ig}{2} (D^\mu \phi^\dagger) \sigma^k (D^\nu \phi) \, W^k_{\mu\nu}$

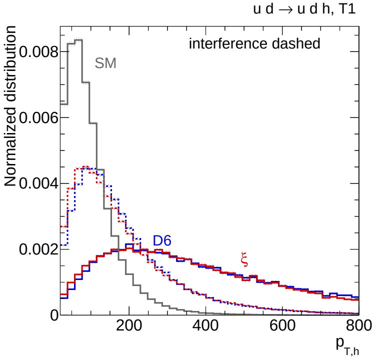
Table : Bosonic CP-conserving Higgs operators in the HISZ basis.

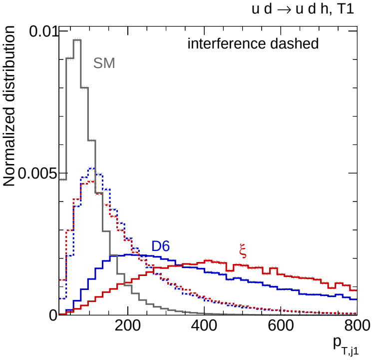
Wilson coefficients

$$
\begin{aligned}
f_{\phi 2} &= \frac{3}{4}\left(-2\, c_F\, g^2 + c_H\, g_V^2\right)\,, & f_{WW} &= c_F\, c_H \\
f_{\phi 3} &= -3\lambda\left(-2\, c_F\, g^2 + c_H\, g_V^2\right)\,, & f_{BW} &= c_F\, c_H \equiv f_{WW} \\
f_{f\phi} &= -\frac{1}{4}\, y_f\, c_H\left(-2\, c_F\, g^2 + c_H\, g_V^2\right)\,, & f_W &= -2\, c_F\, c_H\,.
\end{aligned}
$$

Only WBF diagrams, $\Delta\eta_{jj}$




u d → u d h, T1
interference dashed
SM
D6
ξ
Normalized distribution
0.008
0.006
0.004
0.002
0
200
400
600
800
p_{T,h}


u d → u d h, T1
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Normalized distribution
0.01
0.005
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200
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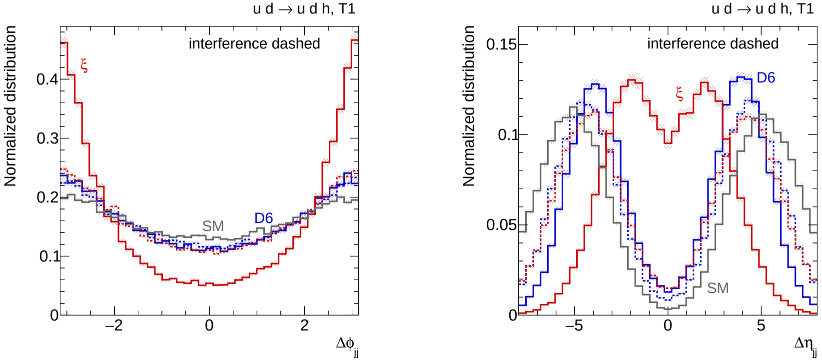
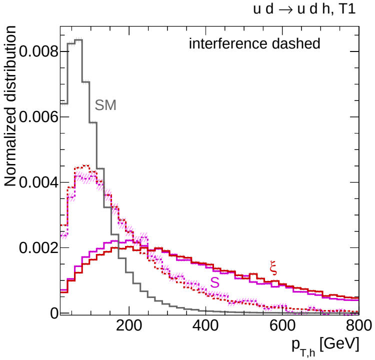
800
p_{T,j1}


u d → u d h, T1
interference dashed
Normalized distribution
ξ
SM
D6
0
0.1
0.2
0.3
0.4
−2
0
2
Δφ_jj
u d → u d h, T1
interference dashed
Normalized distribution
D6
ξ
SM
0
0.05
0.1
0.15
−5
0
5
Δη_jj


u d → u d h, T1
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Normalized distribution
0.008
0.006
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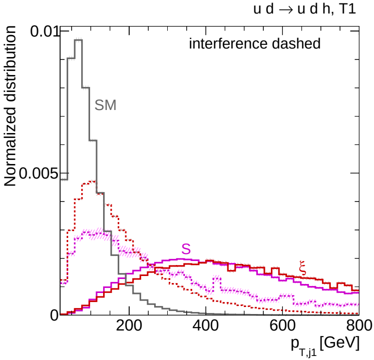
SM
S
ξ
200
400
600
800
$p_{T,h}$ [GeV]


u d → u d h, T1
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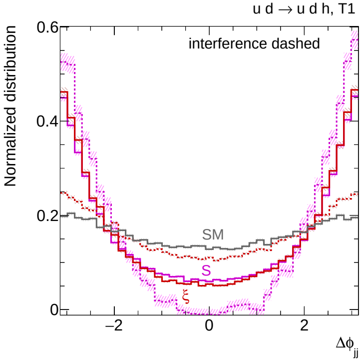
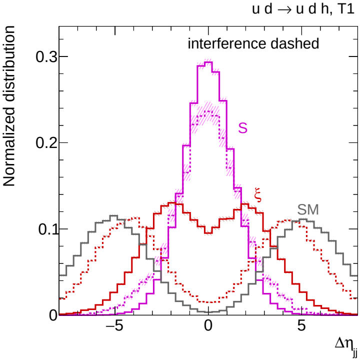
$p_{T,j1}$ [GeV]


u d → u d h, T1
interference dashed
Normalized distribution
0.6
0.4
0.2
0
SM
S
ξ
−2
0
2
$\Delta\phi_{jj}$


u d → u d h, T1
interference dashed
Normalized distribution
0.3
0.2
0.1
0
S
ξ
SM
−5
0
5
$\Delta\eta_{jj}$

Scalar splitting function

13

$$|\mathcal{M}(q \to q' S)|^2 = g_F^2 \, \frac{x^2 \, m_q^2}{1-x} + g_F^2 \, \frac{p_T^2}{1-x} + \mathcal{O}\left(\frac{m_q^2 p_T^2}{E^2}, \frac{m_q^4}{E^2}, \frac{p_T^4}{E^2} \right)$$

$$\sigma(qX \to q' \, Y) = \int \mathrm{d}x \, \mathrm{d}p_T \, F_S(x, p_T) \, \sigma(SX \to \, Y)$$

with the splitting function

$$F_S(x, p_T) = \frac{g_F^2}{16\pi^2} \, x \, \frac{p_T^3}{\left(m_S^2(1-x) + p_T^2\right)^2}$$

$$F_T(x, p_T) = \frac{g^2}{16\pi^2} \, \frac{1 + (1-x)^2}{x} \, \frac{p_T^3}{\left(m_W^2(1-x) + p_T^2\right)^2}$$

$$F_L(x, p_T) = \frac{g^2}{16\pi^2} \, \frac{(1-x)^2}{x} \, \frac{2 m_W^2 \, p_T}{\left(m_W^2(1-x) + p_T^2\right)^2}$$

[9712400], [S. Dawson (1985)], [G. L. Kane, W. W. Repko, W. B. Rolnick (1684)], [0706.0536], [1202.1904]