Higgs EFT and kinematic distributions

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RWTH Aachen

based on 1602.05202
(with Johann Brehmer and Tilman Plehn)

Higgs Hunting in Paris, September 1, 2016

Higgs effective field theory

- New physics at $\Lambda \gg E_{\mathsf{LHC}} \sim v$? [Grzadkowski et al 1008.4884; ...]

$$\mathcal{L}_{\mathsf{EFT}} = \mathcal{L}_{\mathsf{SM}} + \underbrace{\sum_i^{59} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)}}_{} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

$$\text{e.g. } \mathcal{O}_{WW} = -\frac{g^2}{4}(\phi^\dagger \phi)\, W^a_{\mu\nu}\, W^{\mu\nu\, a}, \quad \mathcal{O}_W = \frac{ig}{2}(D^\mu \phi)^\dagger\, \sigma^k (D^\nu \phi) W^k_{\mu\nu}$$

- Framework for indirect searches at the electroweak scale
- reproducible and (mostly) model independent

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

EFT cannot describe LHC Higgs physics

- LHC accuracy $\sim\ 10\ \%$ translates to new physics reach of:

$$\left|\frac{\sigma \times \mathsf{BR}}{(\sigma \times \mathsf{BR})_{\mathsf{SM}}} - 1\right| = \frac{g^2 m_h^2}{\Lambda^2} \gtrsim 10\% \quad \Leftrightarrow \quad \Lambda < \frac{g\, m_h}{\sqrt{10\%}} \approx 400\ \mathrm{GeV}$$

- scenarios with $\Lambda \gg E$ not measurable at the LHC
- D8 not sufficiently suppressed

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

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 dimension-6 amplitudes?
- Vector triplet model
- Higgs-strahlung and WBF
- Which observable to study for WBF?

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?

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

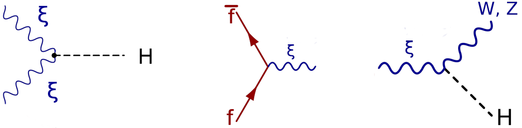
Preferable to include D6^2 when neglecting D8?

Study for vector triplet model

NOT a consistent EFT $\rightarrow$ **practical** question

Vector triplet model

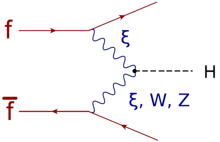
Full model	D6 approximation
$$\mathcal{L} \supset -\frac{1}{4} V^a_{\mu\nu} V^{\mu\nu\, a} + \frac{M_V^2}{2} V^a_\mu V^{\mu\, a} + i\,\frac{g_V}{2} c_H V^a_\mu \left[\phi^\dagger \sigma^a \overleftrightarrow{D}^\mu \phi\right] + \frac{g_w^2}{2g_V} V^a_\mu \sum_{\text{fermions}} c_F \overline{F}_L \gamma^\mu \sigma^a F_L + g_V^2\, c_{VVHH} V^a_\mu V^{\mu a} (\phi^\dagger \phi)$$	$$\mathcal{O}_{WW} = -\frac{g^2}{4} (\phi^\dagger \phi) W^a_{\mu\nu} W^{\mu\nu\, a}$$ $$\mathcal{O}_W = \frac{ig}{2} (D^\mu \phi)^\dagger \sigma^k (D^\nu \phi) W^k_{\mu\nu}$$ $$\Lambda = m_\xi$$



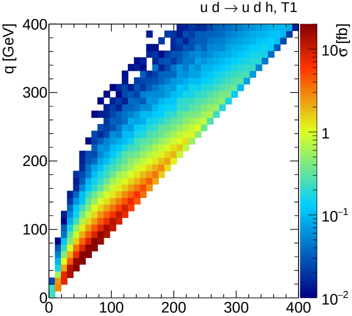
new ξ resonance - modification of Higgs couplings

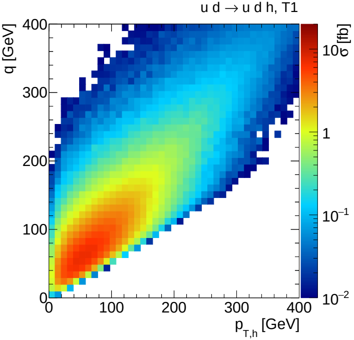
[1510.03443; 1211.2229; 1406.7320; 1506.03631]

WBF - momentum transfer



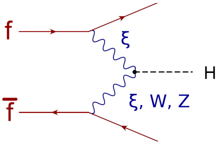
- study parton-level process $ud \to u'd'h$
- momentum transfer q





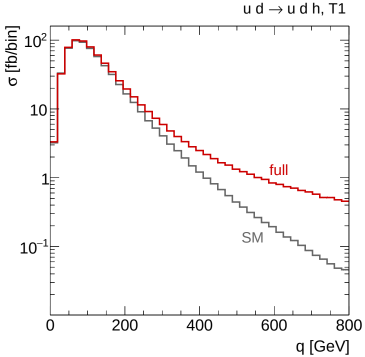
[1512.06135]

WBF - parton level



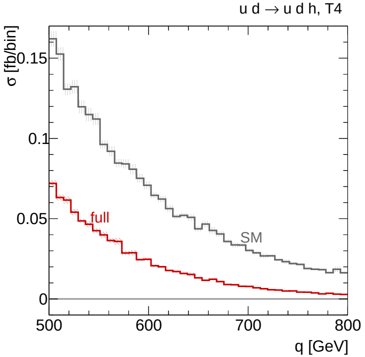
- study momentum transfer q (p_{T,j_1})
- two benchmarks with $m_\xi = 1200$ GeV

constructive



$g_V = 3$, $c_H = -0.47$, $c_F = -5$, $c_{VVHH} = 2$

destructive



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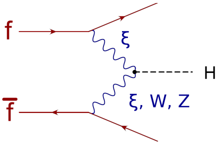

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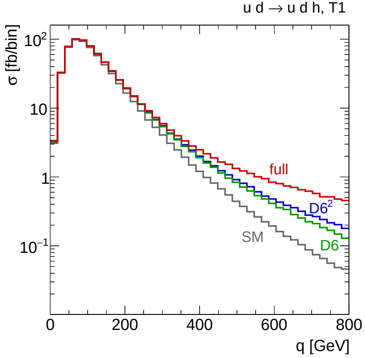

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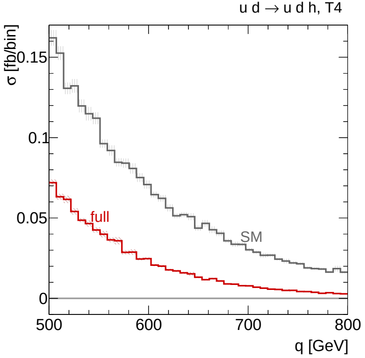

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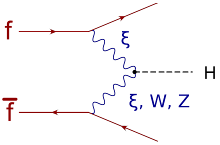

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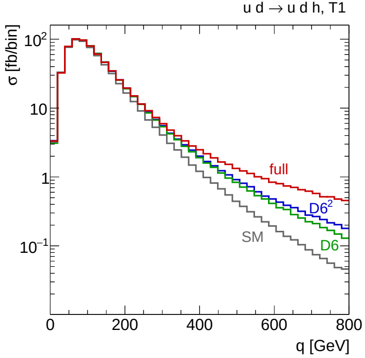

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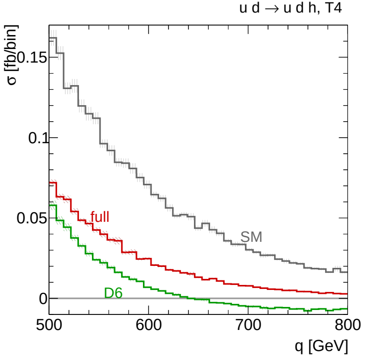

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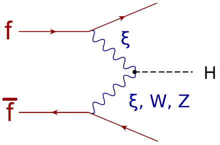

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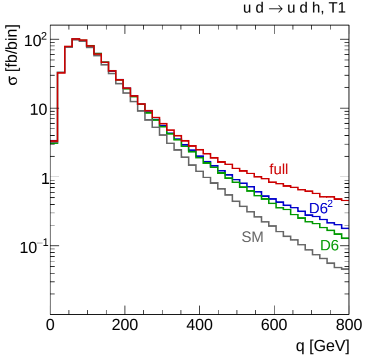

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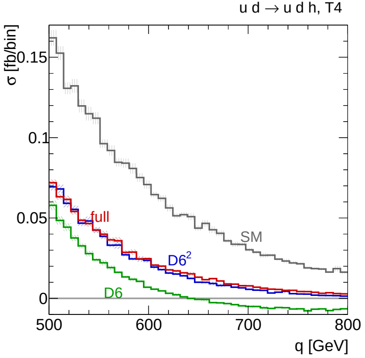

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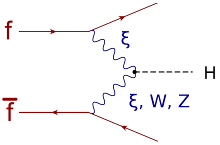

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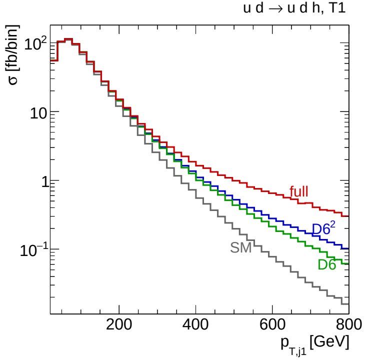

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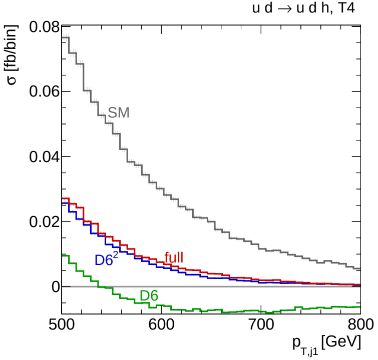

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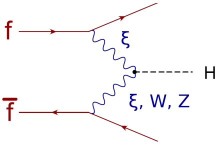

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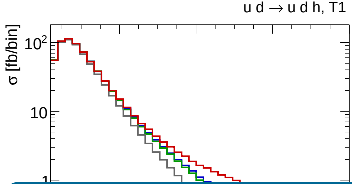

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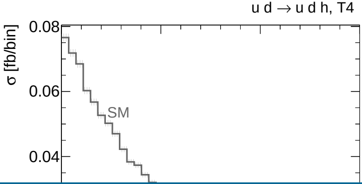

Reality check

- ☐ Valid for larger parameter range?
- ☐ Valid for full, hadron level process?

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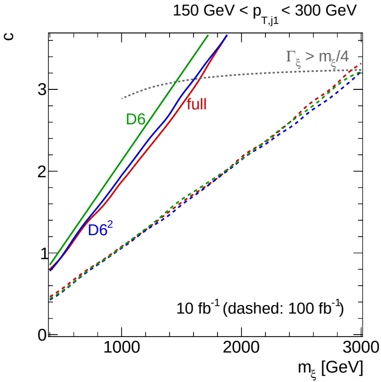
WBF - Comparison of expected exclusion limits

- choose universal coupling rescaling c

  $g_V = 1\,, \quad c_H = c\,, \quad c_F = \frac{g_V^2}{2g^2}\,c\,, \quad c_{HHVV} = c^2$

- m_ξ mass of the new heavy vector



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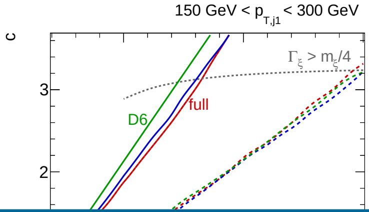

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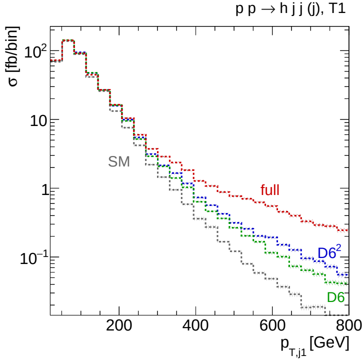
WBF - getting realistic

- 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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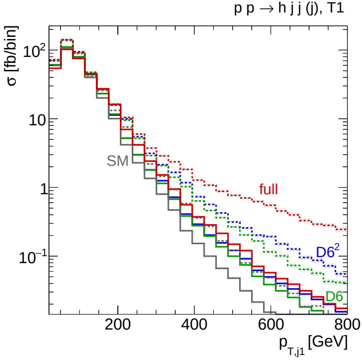

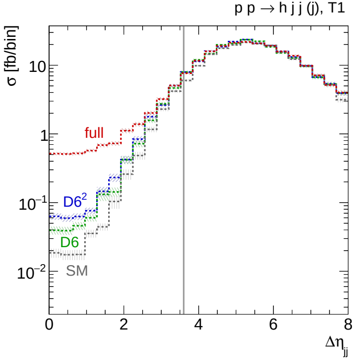

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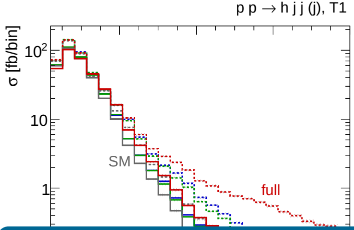

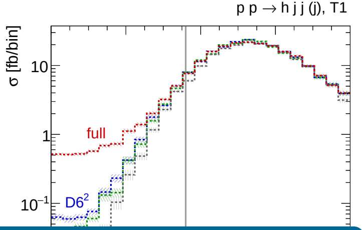

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Conclusions

- Including $\mathrm{D6}^2$ terms improves agreement with full model and avoids negative cross sections
- Leading tagging jet p_T highly correlated with momentum transfer q for WBF
- Results survive in a realistic environment

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Thank you for your attention!
Any questions?

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

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

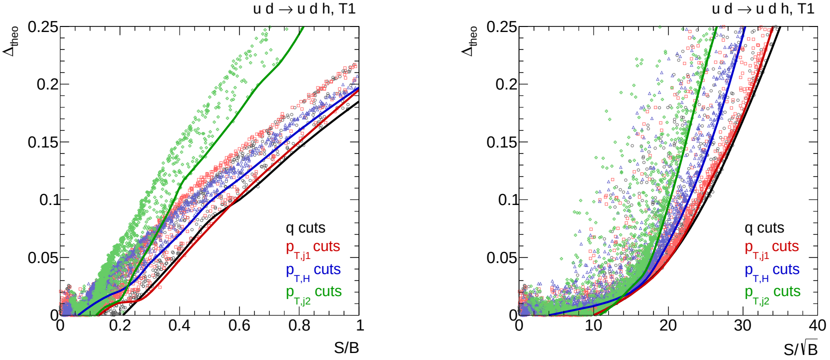
WBF - Which observable to study?

Compare deviations from the full model

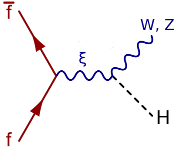
$$\Delta_{\text{theo}}(x_{\text{min,max}}) = \left| \frac{\sigma_{\text{D6}} - \sigma_{\text{full}}}{\sigma_{\text{full}}} \right| , \; x \in \{q,\, p_{T,j_1},\, p_{T,j_2},\, p_{T,h}\}$$

to statistics-driven and systematics-driven significances

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

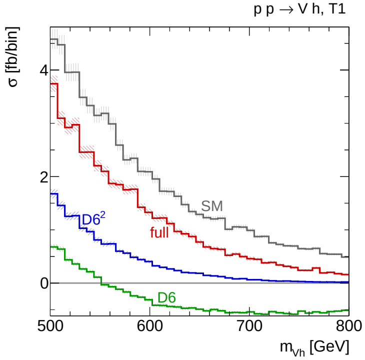


Higgs-strahlung



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

destructive



$g_V = 3,\ c_H = -0.47,\ c_F = -5,\ c_{VVHH} = 2$

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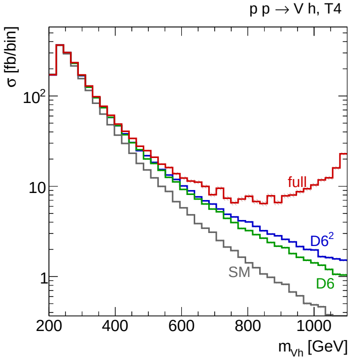

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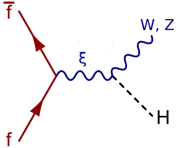
Higgs-strahlung



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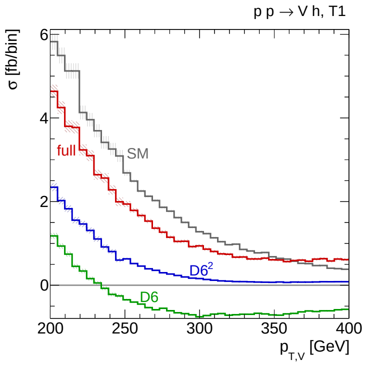

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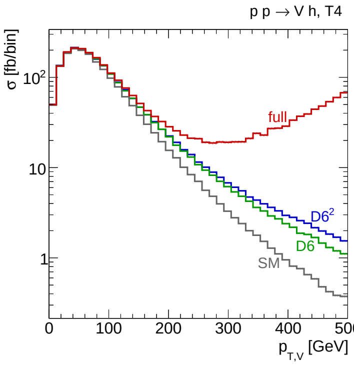

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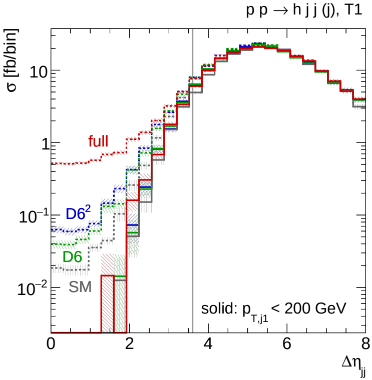
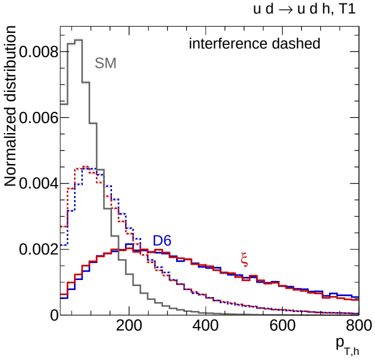
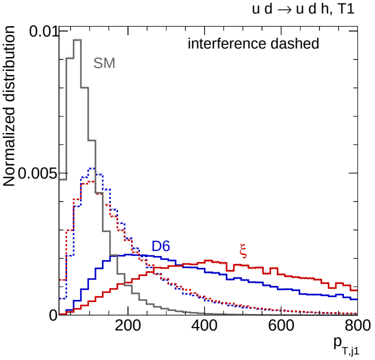
Only WBF diagrams, $\Delta\eta_{jj}$




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
interference dashed
SM
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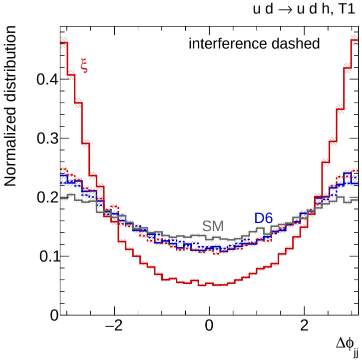
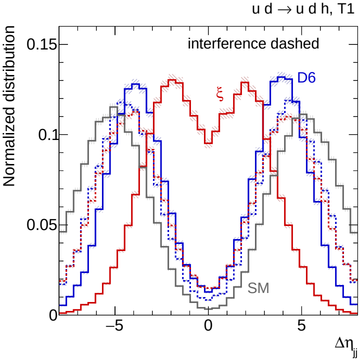
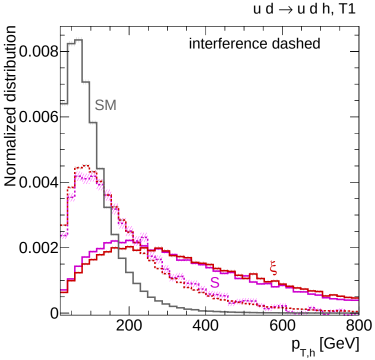
ξ
Normalized distribution
0.01
0.005
0
200
400
600
800
p_{T,j1}

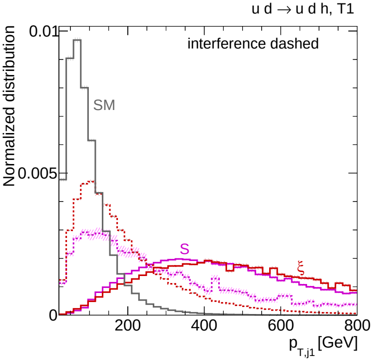


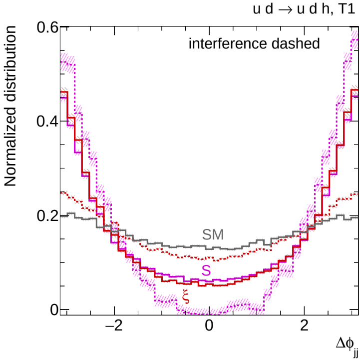
u d → u d h, T1
interference dashed
Normalized distribution
ξ
SM
D6
0.4
0.3
0.2
0.1
0
−2
0
2
Δφ_jj

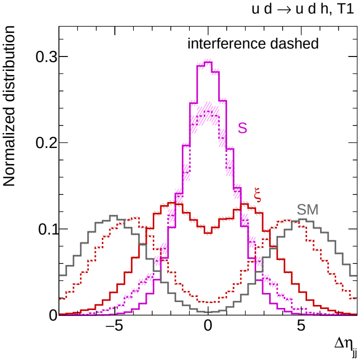


u d → u d h, T1
interference dashed
Normalized distribution
D6
ξ
SM
0.15
0.1
0.05
0
−5
0
5
Δη_jj


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


u d → u d h, T1
interference dashed
Normalized distribution
0.01
0.005
0
SM
S
ξ
200
400
600
800
p_{T,j1} [GeV]


u d → u d h, T1
interference dashed
Normalized distribution
SM
S
ξ
0.6
0.4
0.2
0
−2
0
2
Δφjj


u d → u d h, T1
interference dashed
Normalized distribution
S
ξ
SM
0.3
0.2
0.1
0
−5
0
5
Δηjj

Scalar splitting function

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

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

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]