# GF HJJJ Production at the LHC

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in collaboration with M.Kubocz | 04/07/2014
THEORY DIVISION

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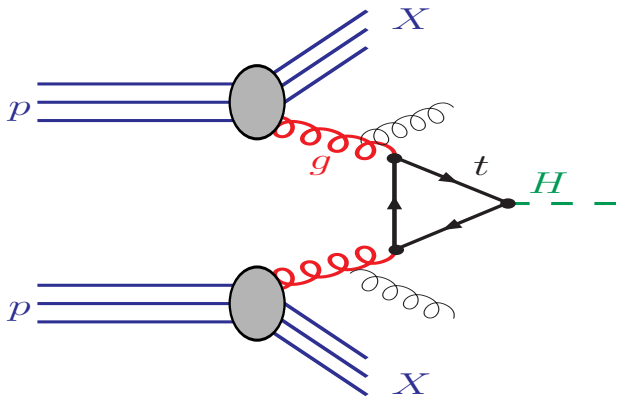
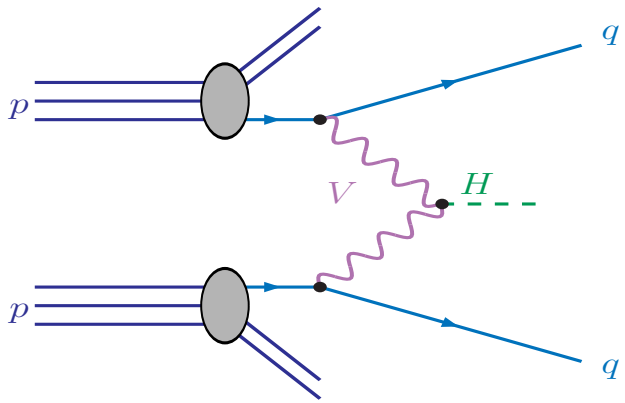
# Higgs + 2(3) jet Production at LHC




GF H+2J:

- Background to WBF
- Sensitive to: CP-structure and coupling of fermions
- NLO known within Effective Theory [Campbell,Ellis,Zanderighi hep-ph/0608194]
- LO known for the full Theory [Del Duca et al.hep-ph/0105129;FC,Kubocz,Zeppenfeld 1011.3819]

GF H+3J:

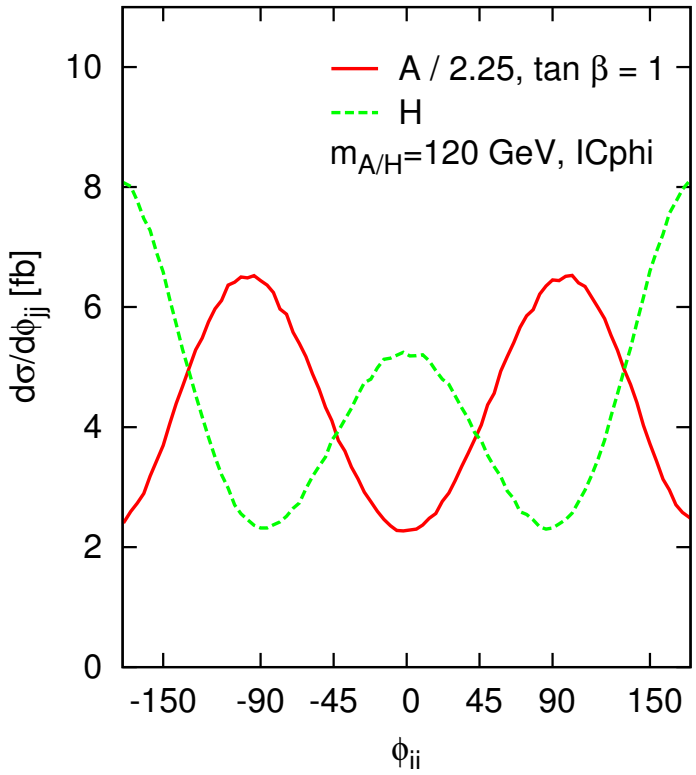
- Background to WBF process[1] (CJV strategies known at NLO)

[1] [Figy,Hankele,Zeppenfeld 0710.5621; FC,Figy,Platzer,Sjodahl 1308.2932]

- NLO corrections known within Effective Theory [Cullen et al. 1307.4737]
- Here: LO corrections for the full Theory [FC,Kubocz 1306.1830; 1402.1154]
- Soft radiation: Distort CP-sensitive distributions?

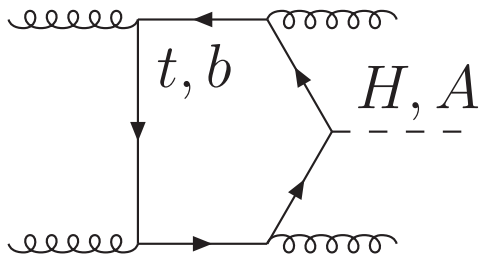
# GF Higgs + 2 jet Production at LHC

- sensitive to the $\mathcal{CP}$-structure $\rightarrow$ azimuthal angle correlation




$$\phi_{jj} = \phi_F - \phi_B$$

$$\mathcal{L}_{\text{Yukawa}} = y_q\,\overline{q}\,q\,H + \mathrm{i}\tilde{y}_q\overline{q}\gamma_5\,q\,A$$

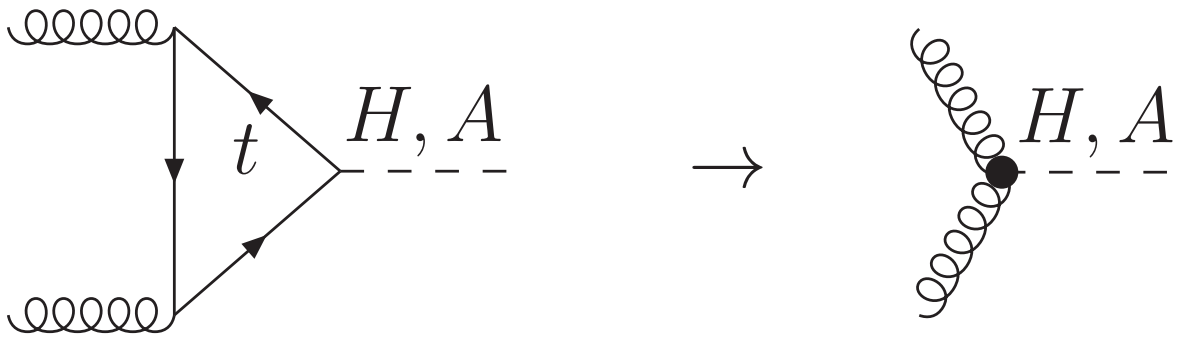



"LO": one loop $2 \rightarrow 3$ process of $\mathcal{O}(\alpha_s^4)$

$$Y_q = \frac{m_q}{v}$$

- bottom-quark: suppressed
- top-quark: effective theory

# Effective Lagrangian




$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{H^0gg} + \mathcal{L}_{A^0gg} = \frac{1}{v}\frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a,\mu\nu} H + \frac{1}{v}\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} A$$

- Validity: $m_{\text{Higgs}} < m_t$ and $p_T^j < m_t$
- If used correcty $\rightarrow$ powerful tool
- bottom loops: Not described (Important in BSM)

# CP-Violating Higgs: $\Phi$ available in VBFNLO

$\Phi = H \cos\alpha + A \sin\alpha$

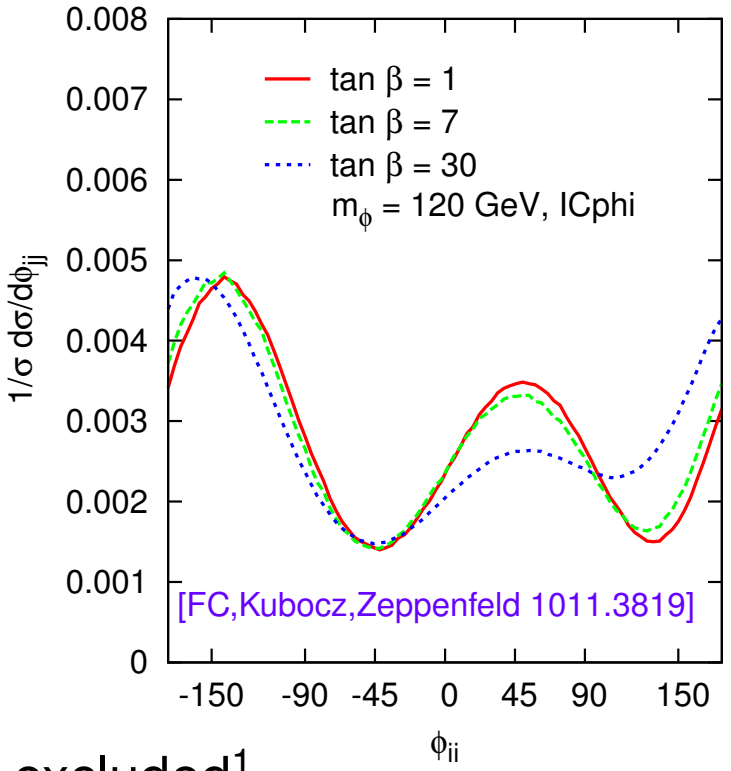
Min: $\tan\Delta\phi_{jj} = -\frac{2y_t}{3\tilde{y}_t}\cot\alpha$

- $\frac{y_q}{\tilde{y}_q} = \frac{3}{2}$ and $\alpha = 45°$

Min: $\Delta\phi_{jj} = -45°$

Type II HDM(MSSM): $\tilde{y}_b = -\frac{m_b}{v}\tan\beta$

$\rightarrow$ distortion for large $\tan\beta$



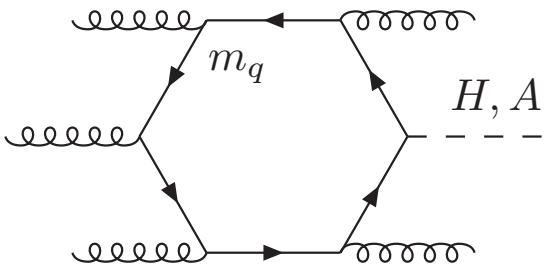

- For 50 $fb^{-1}$ and $\tilde{y}_q = y_q^{SM} \rightarrow \alpha > 40°$ excluded[1]

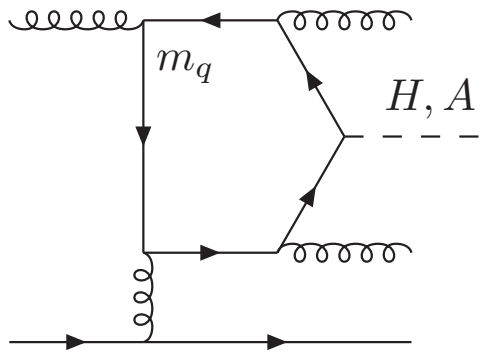
[1] [Dolan,Harris,Jankowiak,Spannowsky 1406.3322]

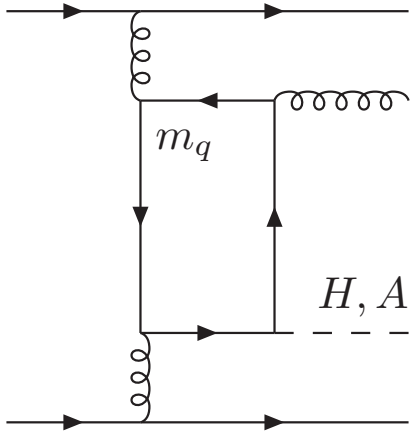
- Additional soft radiation?
- HJJJ:First step to an improved NLO HJJ prediction.

# Higgs + 3 jet production [FC,Kubocz 1306.1830; 1402.1154]

Subprocesses: a) $gg \to ggg\Phi$ b) $gq \to qgg\Phi$ c) $qq \to qqg\Phi$

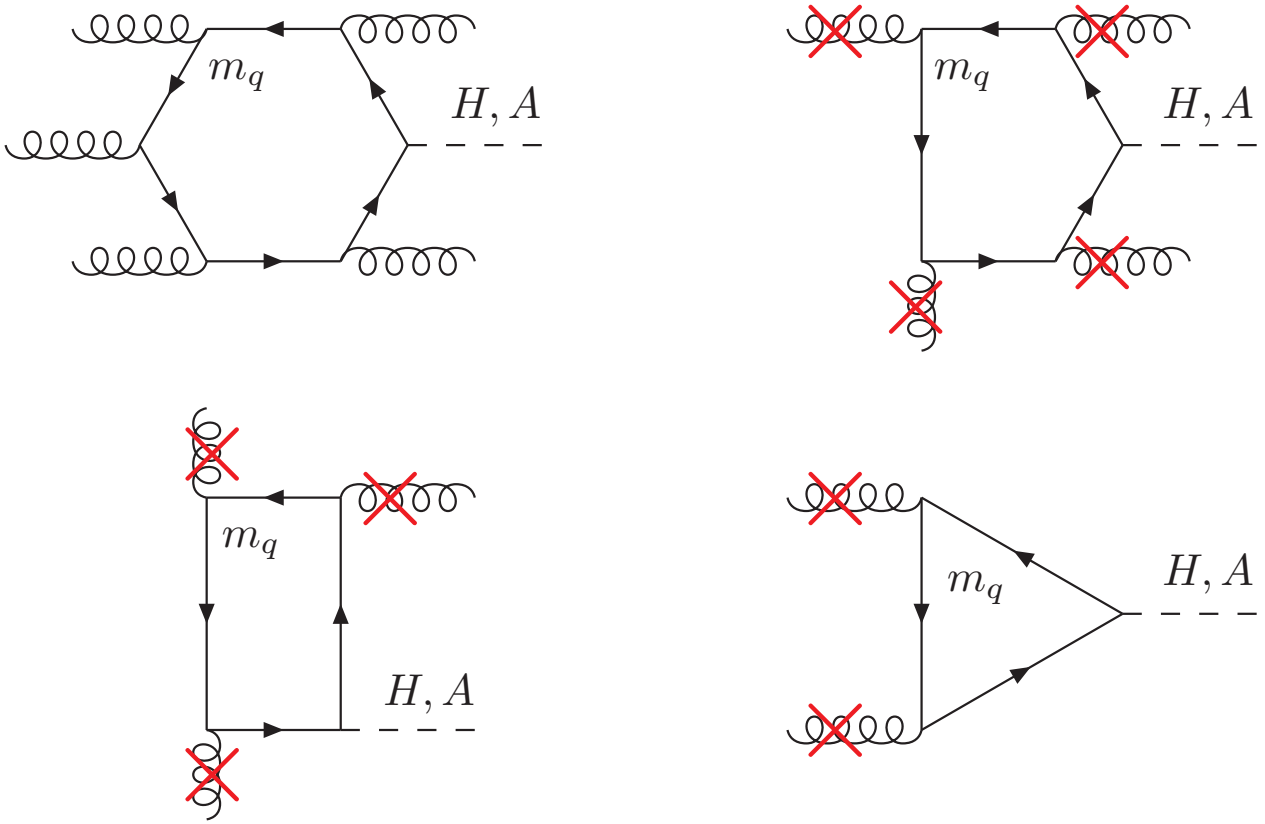


# Higgs + 3 jet production [FC,Kubocz 1306.1830; 1402.1154]

Subprocesses: a) $gg \to ggg\Phi$




[FC 1105.0920]

1560 diagrams. GGFLO: Highly stable results despite Hexagons

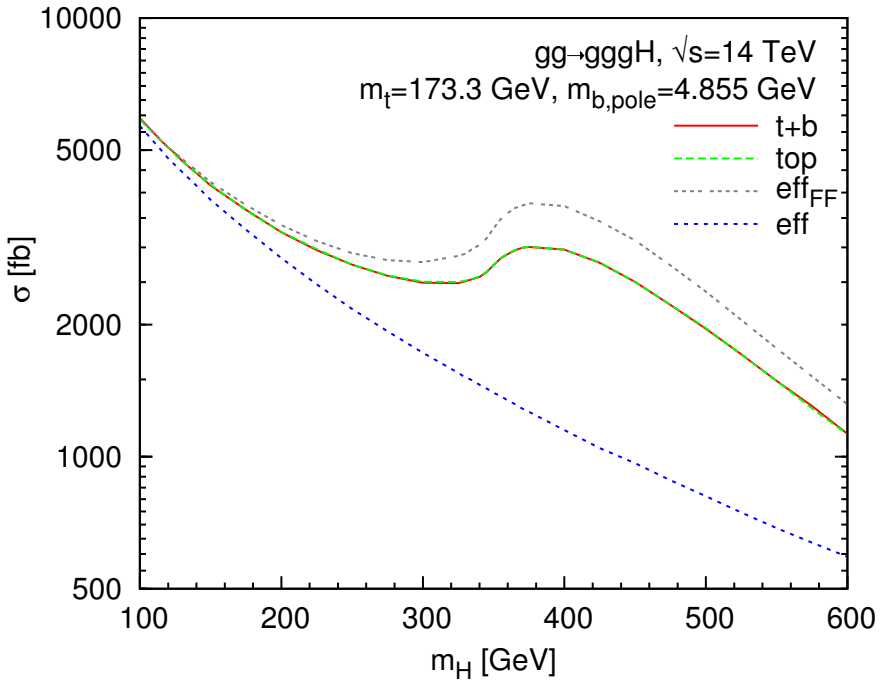
# Phenomenology

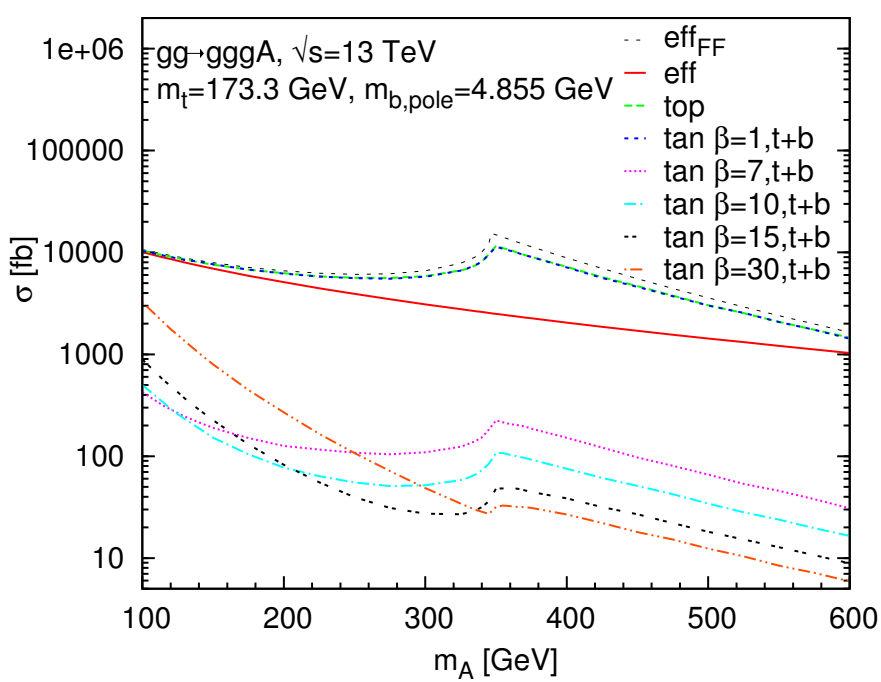
Cuts: kT-clustering, $p_{T_j} > 20\text{GeV}$, $|y_j| < 4.5$, $R_{jj} > 0.6$

ICPhiCuts: $p_{T_j} > 30\text{GeV}$, $\Delta y_{j_1 j_2} > 3$

running bottom mass $m_b(m_{\text{Higgs}})$

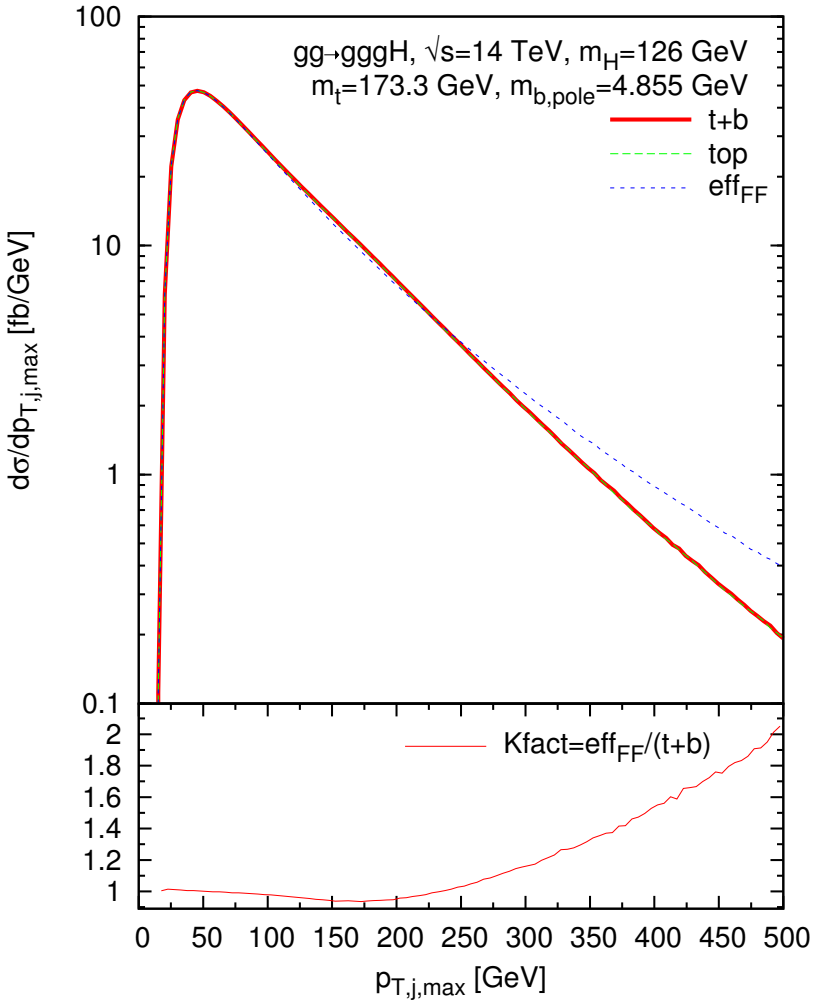
Scales: $\mu_F = (p_{T1}\ p_{T2}\ p_{T3})^{1/3}$ $\alpha_s^5(\mu_R) = \alpha_s(p_{T1})\alpha_s(p_{T2})\alpha_s(p_{T3})\alpha_s^2(m_\Phi)$

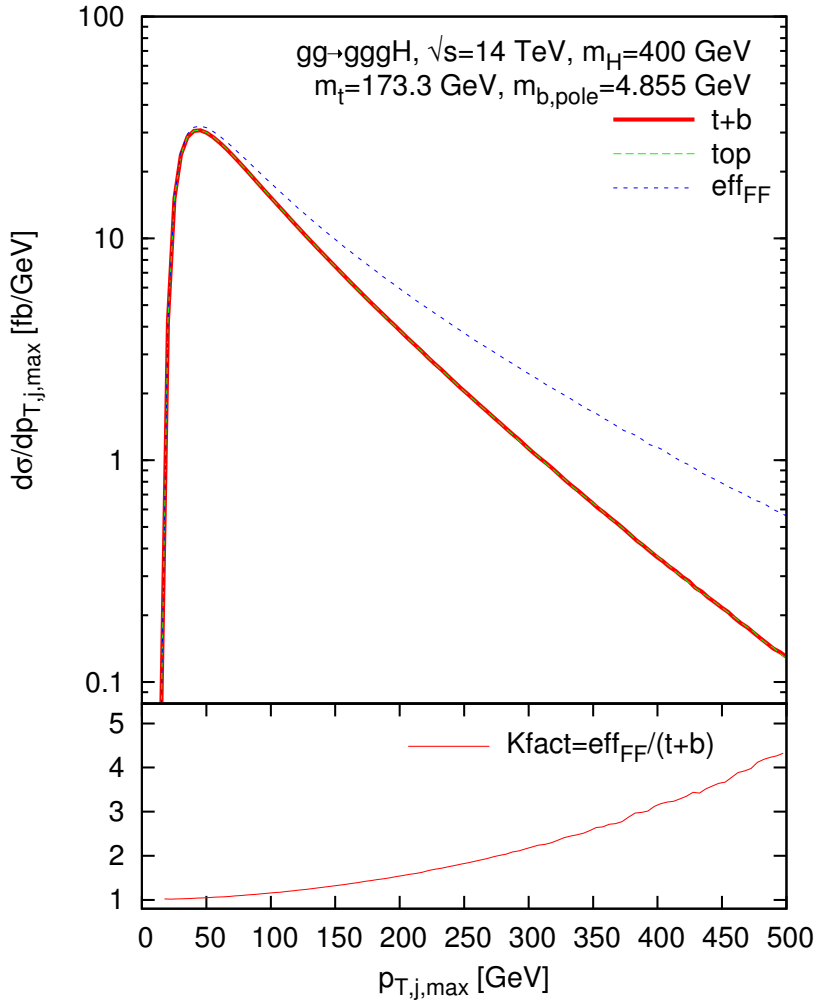



FF: Form factor from full-mass dependence of $\Phi \to gg$(*Triangles*)

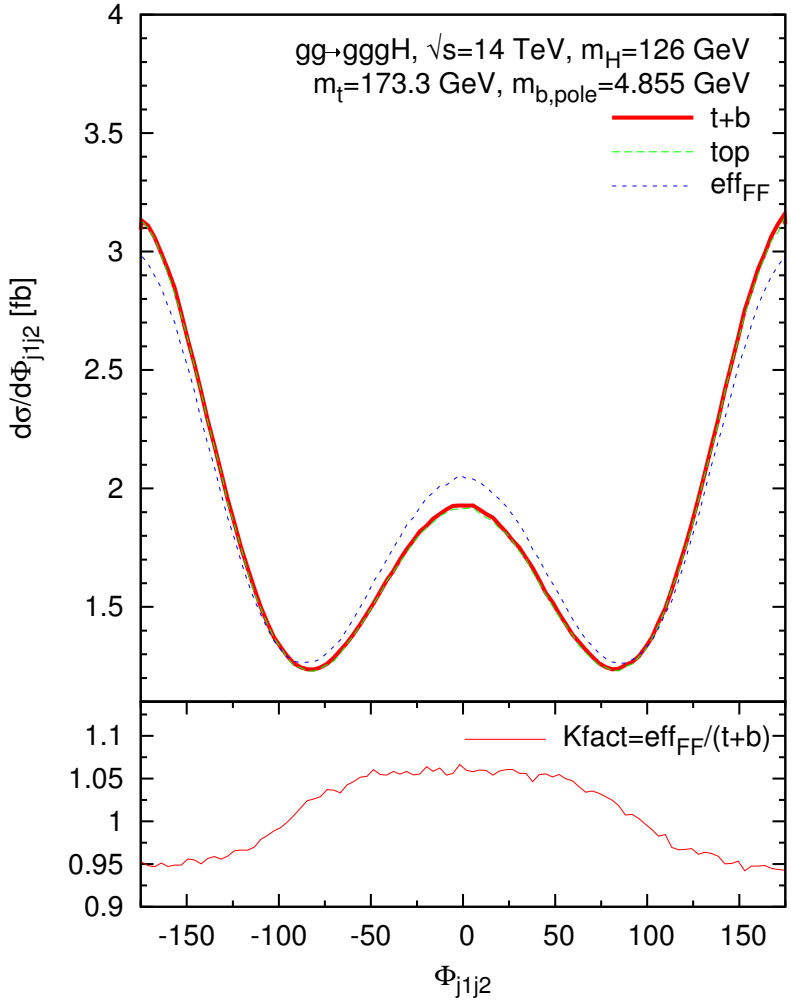
# CP-even Higgs: $p_T$

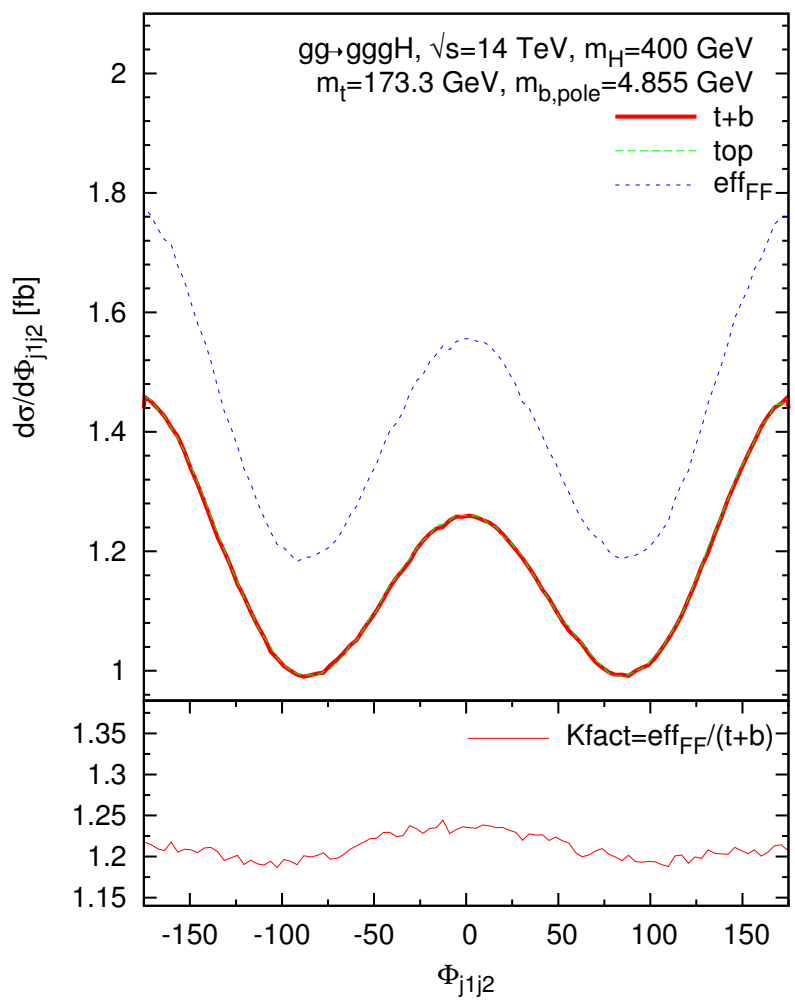



- Light Higgs: $m_{\text{Higgs}} < m_t$ and $p_T^j < m_t$

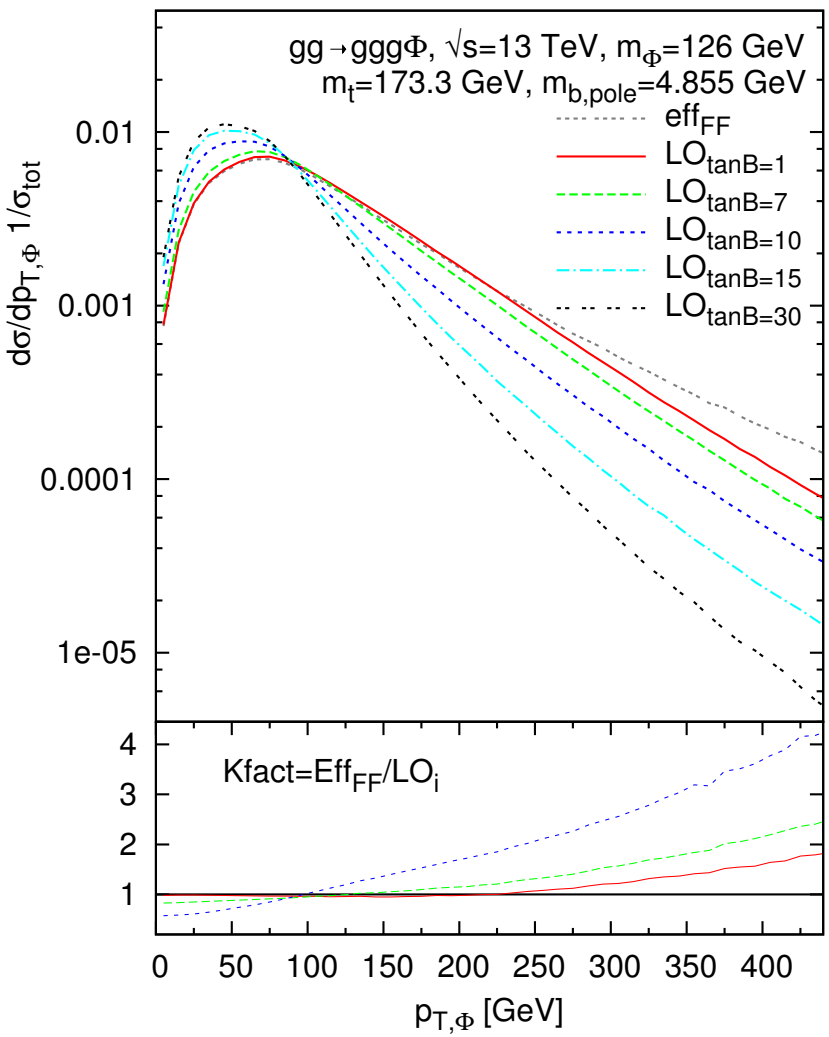
# CP-even Higgs: Azimuthal angle correlations

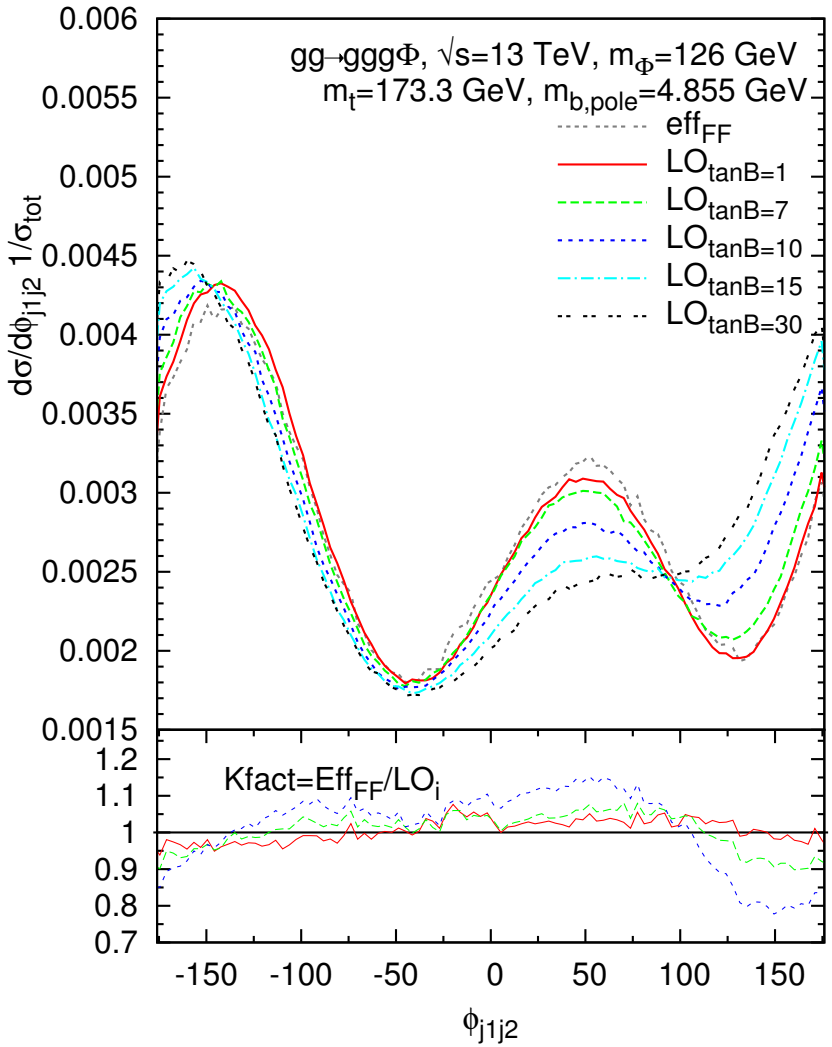



- Wrong normalization for $m_{\text{Higgs}} > m_t$
- Soft radiation: Does not alter the distributions

# CP-violating Φ




- Bottom corrections important for large tan $\beta$

# Conclusions

GF *HJJ*(J):

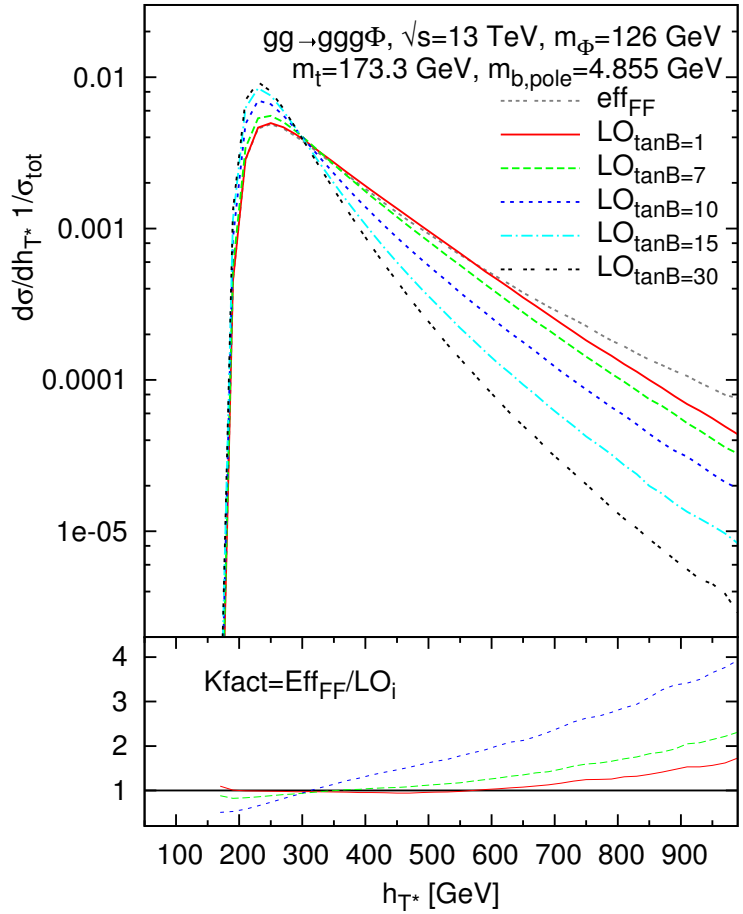
- Access to CP-mixing angle and coupling to fermions
- Bottom-loop corrections might distort distributions
- Effective theory: $m_H < m_{top}$ and $p_T^j < m_{\text{top}}$
  - No restriction on $m_{jj}$. Important for WBF studies.
- Additional soft radiation does not alter sensitive CP-distributions

**GGFLO & VBFNLO**

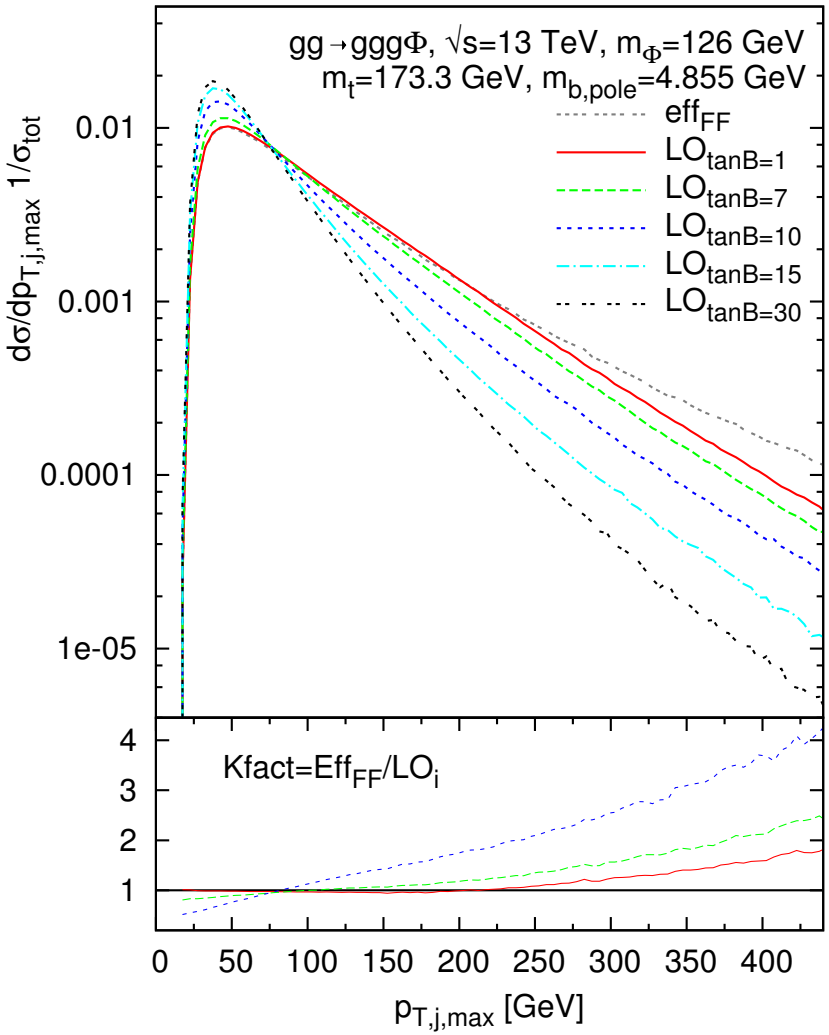
http://www.itp.kit.edu/∼vbfnloweb/wiki/doku.php

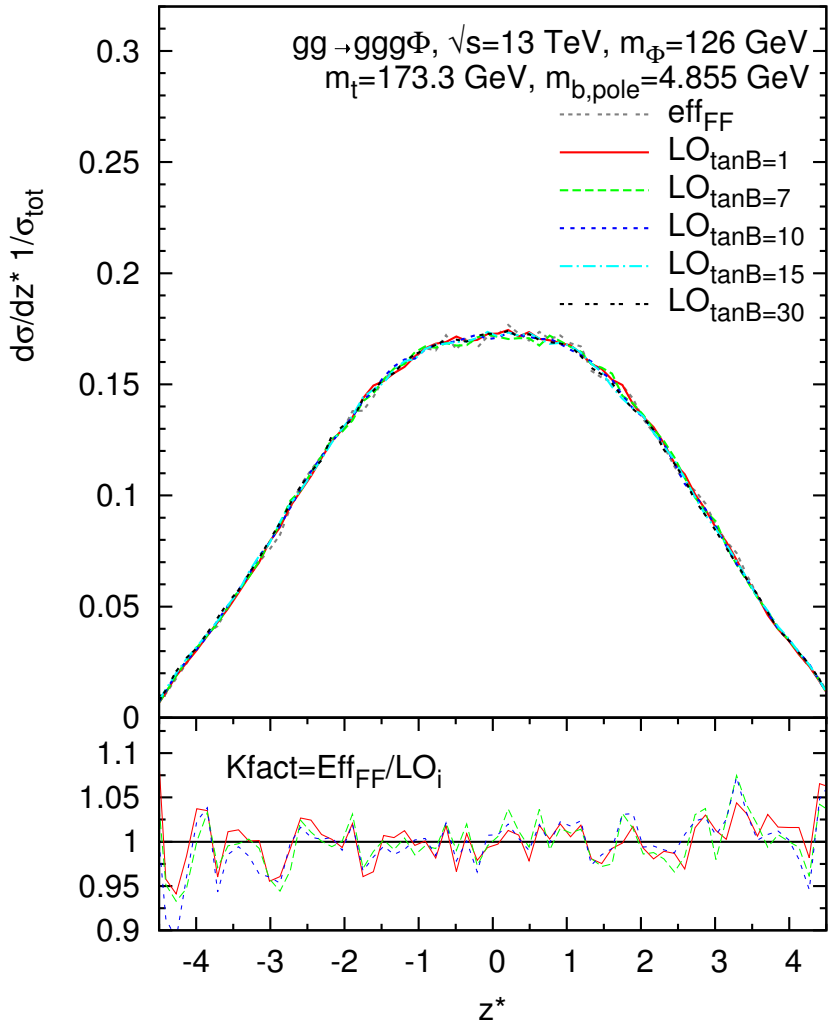
THANK YOU FOR YOUR ATTENTION

# $H_T$


gg→gggΦ, √s=13 TeV, m_Φ=126 GeV
m_t=173.3 GeV, m_b,pole=4.855 GeV
eff_FF
LO_tanB=1
LO_tanB=7
LO_tanB=10
LO_tanB=15
LO_tanB=30
dσ/dh_T* 1/σ_tot
0.01
0.001
0.0001
1e-05
Kfact=Eff_FF/LO_i
4
3
2
1
100 200 300 400 500 600 700 800 900
h_T* [GeV]

# CP-violating Φ



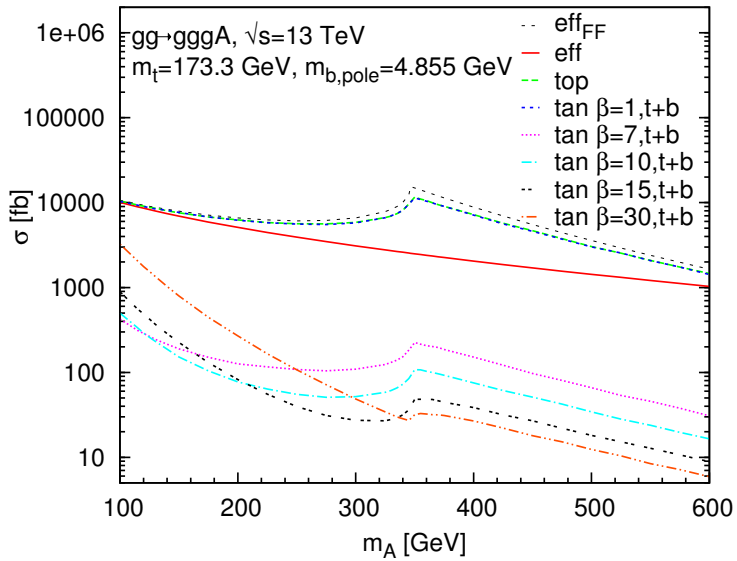
- Higgs-doublets $\Phi_1$ and $\Phi_2$:
  - **model I** : $\Phi_2$ couples to up- and down-type fermions as in SM
    $\Phi_1$ is decoupled from fermions
- Higgs couplings in **model II**:

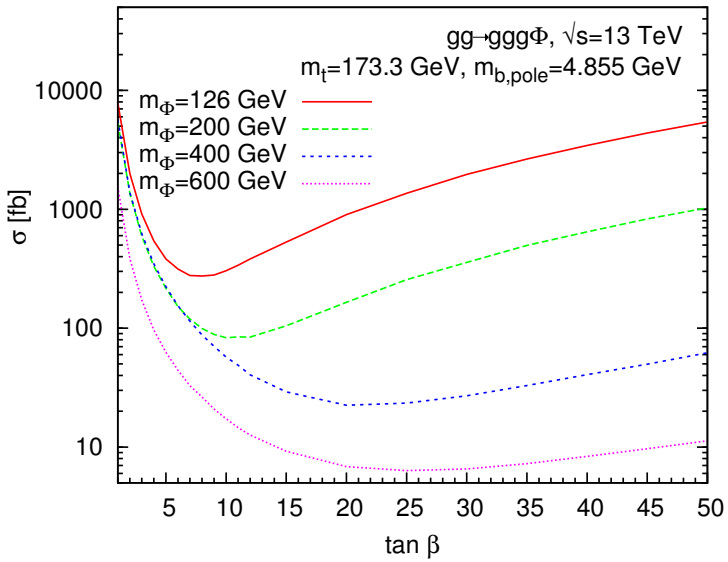
| Higgs-Boson | up-type-Quarks | down-type-Quarks |
|---|---|---|
| $H^0$ | $-\mathrm{i}\,\frac{m_u}{v}\,\frac{\sin\alpha}{\sin\beta}$ | $-\mathrm{i}\,\frac{m_d}{v}\,\frac{\cos\alpha}{\cos\beta}$ |
| $h^0$ | $-\mathrm{i}\,\frac{m_u}{v}\,\frac{\cos\alpha}{\sin\beta}$ | $-\mathrm{i}\,\frac{m_d}{v}\,\frac{\sin\alpha}{\cos\beta}$ |
| $A^0$ | $-\frac{m_u}{v}\cot\beta\,\gamma_5$ | $-\frac{m_d}{v}\tan\beta\,\gamma_5$ |

- important free parameters

$$\tan\beta = \frac{v_2}{v_1};\quad \sin\beta = \frac{v_2}{v};\quad \cos\beta = \frac{v_1}{v};\quad \alpha;\, m^2_{H^\pm},\, m^2_{A^0},\, m^2_{H^0,h^0}$$

$$v^2 = v_1^2 + v_2^2 = \left(\sqrt{2}G_F\right)^{-1/2} = (246\ \mathrm{GeV})^2 \;\rightarrow\; \text{is fixed by } m_W$$


gg→gggA, √s=13 TeV
m_t=173.3 GeV, m_b,pole=4.855 GeV
eff_FF
eff
top
tan β=1,t+b
tan β=7,t+b
tan β=10,t+b
tan β=15,t+b
tan β=30,t+b
σ [fb]
m_A [GeV]
1e+06
100000
10000
1000
100
10
100
200
300
400
500
600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σ [fb]
tan β
10000
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