Modeling BSM effects on the Higgs transverse-momentum spectrum in an EFT approach

Agnieszka Ilnicka

based on JHEP03(2017)115 [1612.00283], [1705.05143], *work in progress*,
in collaboration with:
M.Grazzini, M.Spira, M.Wiesemann

Why BSM via Effective Field Theory?
Why Higgs pT spectrum?

Theory consistent

Model independent

Allows for systematic improvements from theoretical side

Well suited to parametrise small deviations from SM

Why BSM via Effective Field Theory?

Why Higgs pT spectrum?

Complementary to direct searches

Can be used to store what LHC measured

Proved to work in flavour physics

Can link many measurements

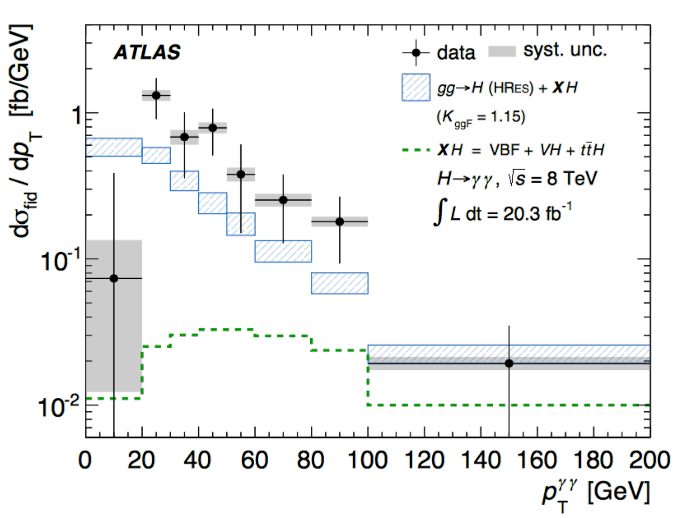
More information than single number:
Shape
Normalisation
Maximum position

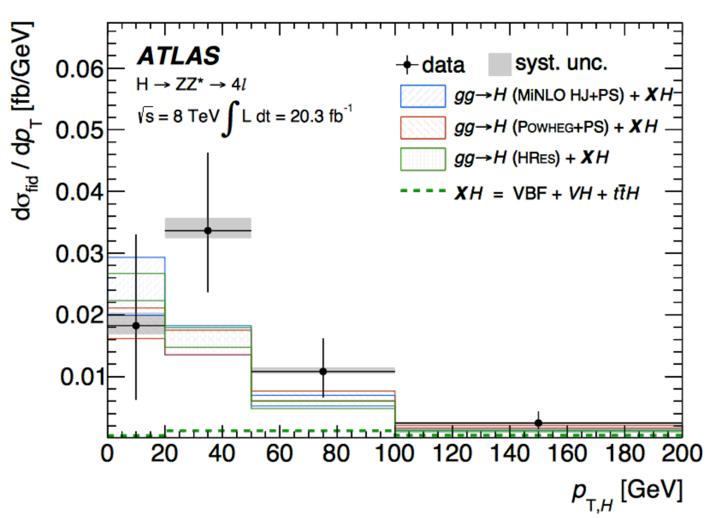
Enable to disentangle properties hidden in total rates: eg. Higgs-gluon coupling

For the scalar particle production and decay factorise

Why BSM via Effective Field Theory?
Why Higgs pT spectrum?

First data from ATLAS & CMS available

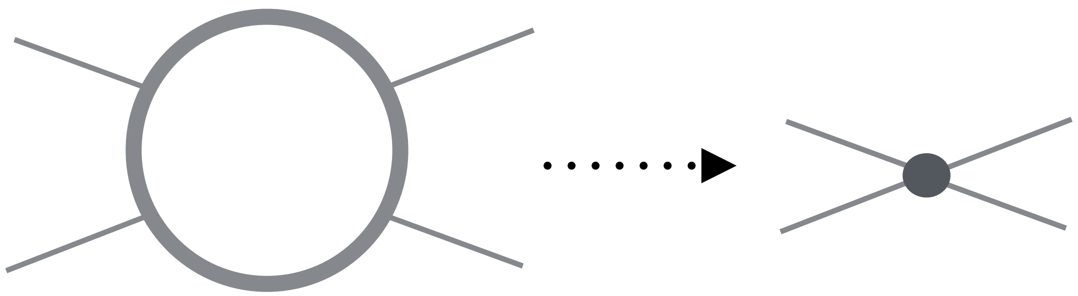




Should be significantly improved in Run 2 and HL

What is Effective Field Theory?

Top-down:



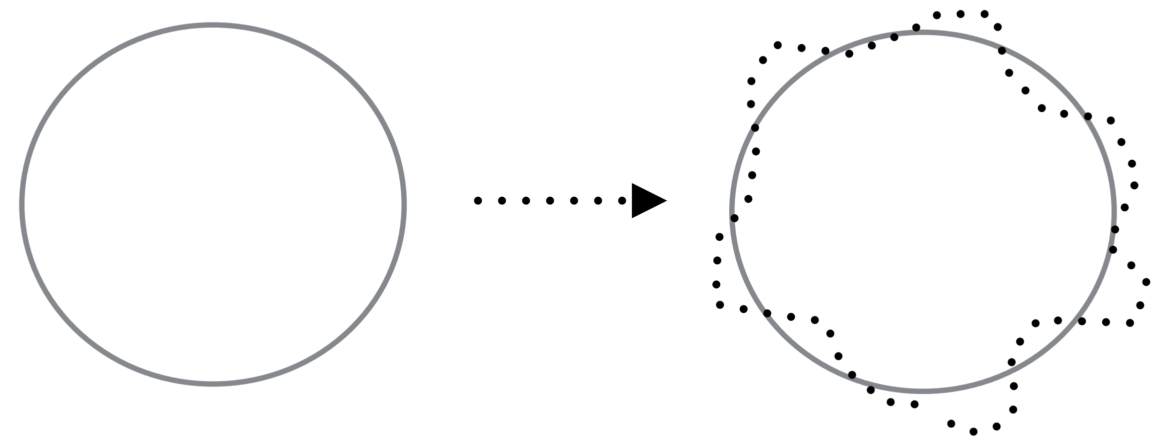
From UV complete model heavy degrees of freedom are integrated out.

$$\mathcal{L} = \mathcal{L}_{low} + \mathcal{L}_{high} + \mathcal{L}^{int}$$

As a consequence an infinite ladder of new operators build from light fields will appear.

$$\mathcal{L} = \mathcal{L}_{low}^{(4)} + \sum_{k=4}^{\infty} \sum_{i} \frac{\bar{c}_i^{(k)}}{\Lambda^{(k-4)}} \mathcal{O}_i^{(k)}$$

Bottom-up:



We take the renormalizable theory (e.g. SM).
From its fields we build the operators of higher dimensions obeying the Lorentz and gauge invariance to account for the small deviations from the theory.

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c^{(5)}}{\Lambda} \mathcal{O}^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \ldots$$

What is Effective Field Theory?

Dimension 5, 6, 7, … operators:

Weinberg ‘80
Buchmuller et al ‘86
Grzadkowski ‘10
Lehman ‘14

Different basis of dim 6:

Contino et al ‘13
Falkowski et al ’15

2HDMEFT:

Crivellin et al ’16

Radiative corrections and renormalisation:

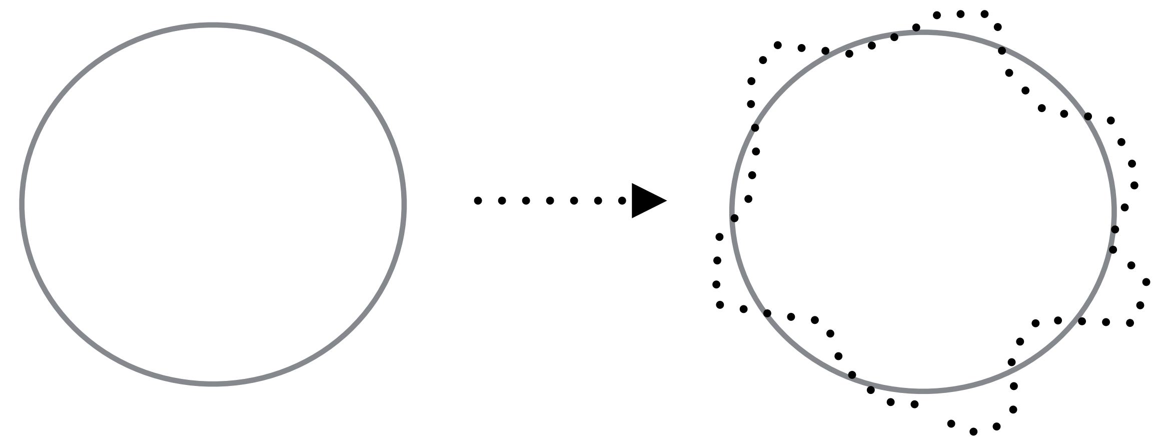
Passarino et al ’12-16
Jenkins et al ’13-‘14

How to use it in LHC:

HXSWG Yellow Report 4:
Section 2 (and 3.1)

Inclusion in the observables,
Fits to the available data…

Bottom-up:



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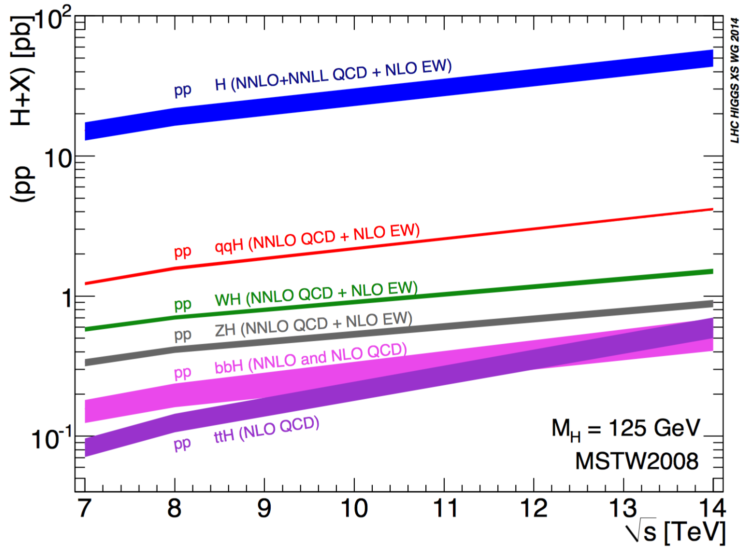
Nonrenormalisable but renormalisable order by order

How to get Higgs boson in LHC?

Gluon fusion is the most efficient Higgs boson production channel at the LHC

Due to the dominance of gluon pdf



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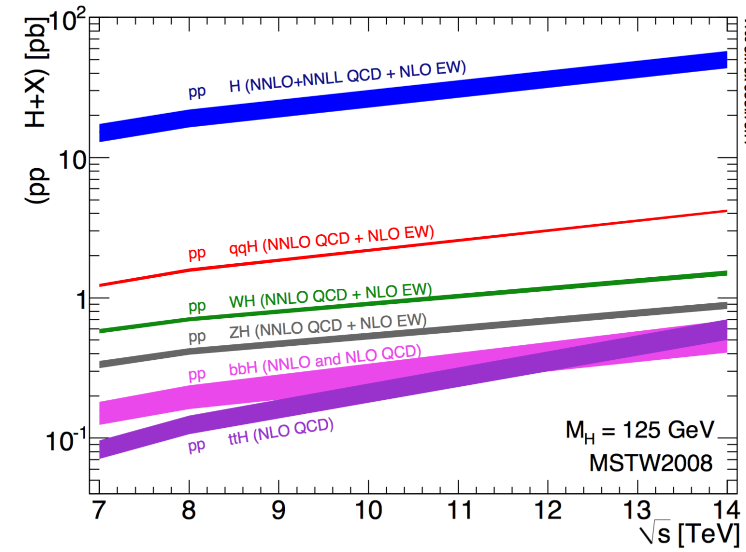

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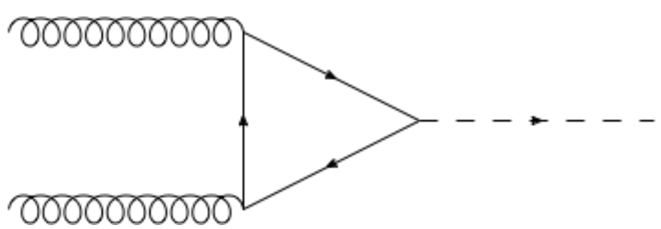

Even though it is loop induced process

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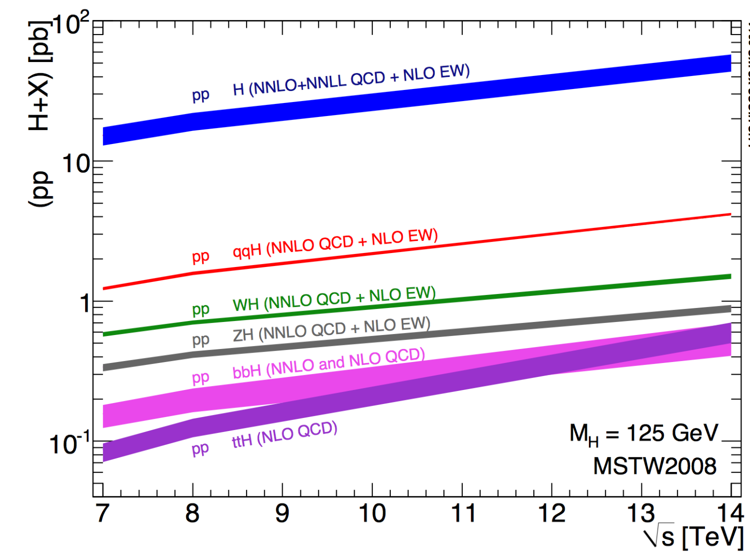

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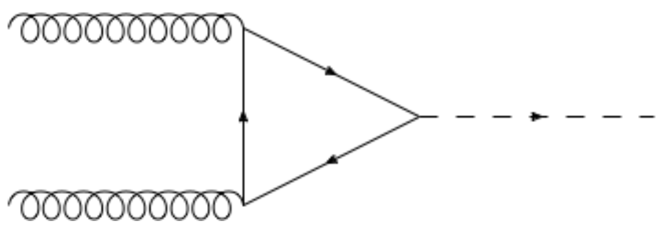
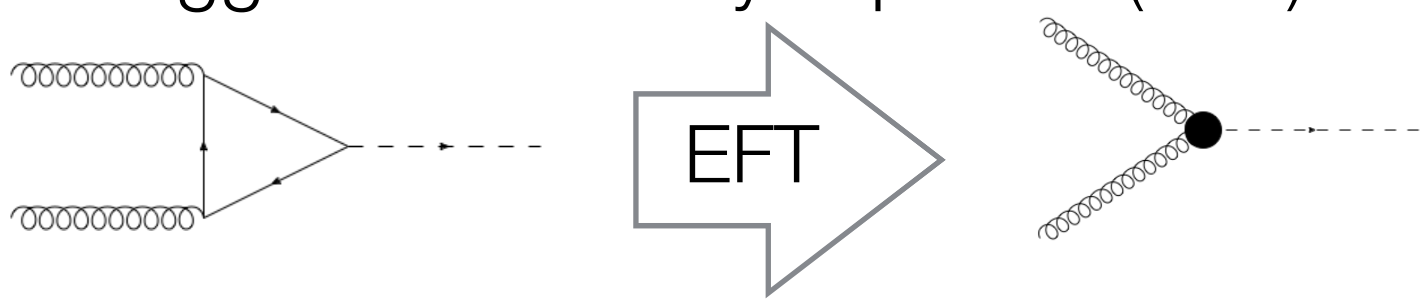


Even though it is loop induced process

Top mass > Higgs mass: Heavy Top Limit (HTL) useful approximation:

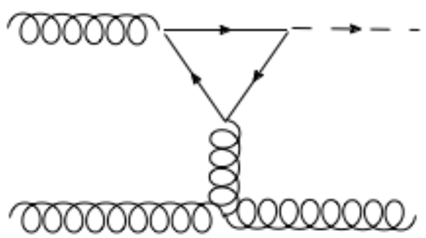


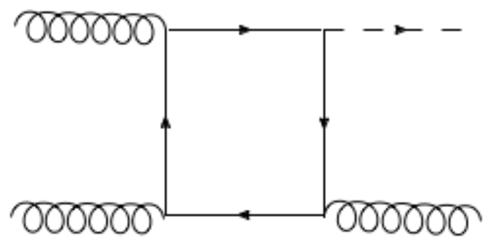
Known up to NLO QCD
Ellis, Hinchliffe et al.'88; Baur, Glover '90; Spira et al.'91, '95; Dawson '91, Anastasiou et al.'09
and NLO EW corrections
Aglietti et al.'04; Degrassi, Maltoni '04; Passarino et al '08

Known up to N3LO QCD
Anastasiou, Duhr, Mistlberger et al.'13-'15
and NNLO QCD
Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith, Van Neerven '03
and N3LL treshold resummation
de Florian, Grazzini '12; Bonvini, Marziani '14; Schmidt, Spira '15
with approximate top mass effects
Marzani et al.'08; Harlander et al.'09,'10; Steinhauser et al.'09

Why and how we care about Higgs pT?

We need additional parton to recoil Higgs





HTL:

LO known:

Ellis, Hinchliffe et al.'88; Baur, Glover '90

NLO first partial results:

Bonciani et al.'16

NNLO results:

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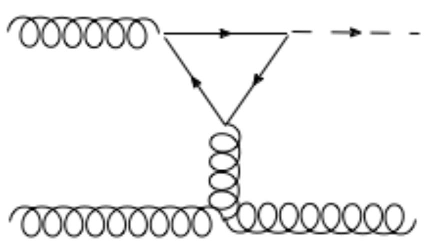

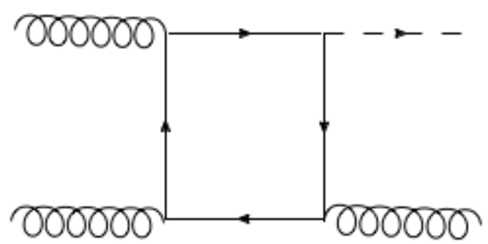

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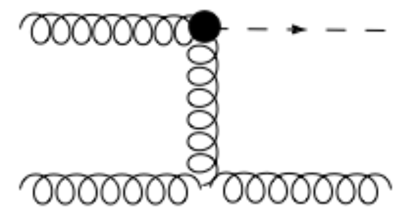

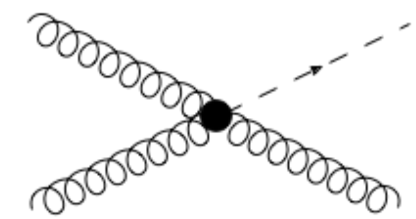

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"New Physics sits in the tails of distributions"

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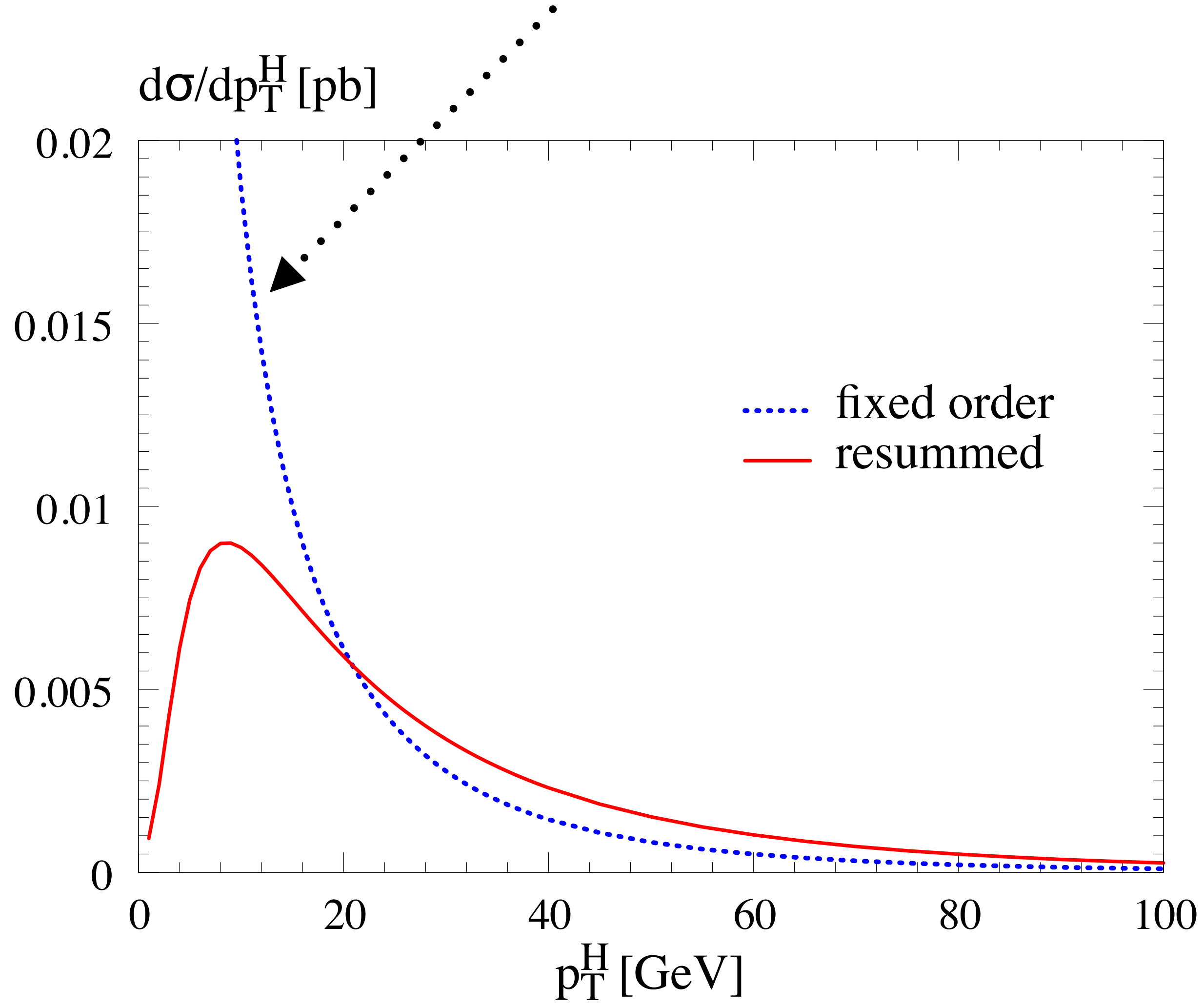
"New Physics sits in the tails of distributions"

but there is a problem at low pT…

Problems at low pT? Resummation!

Singular behaviour at pT<mH



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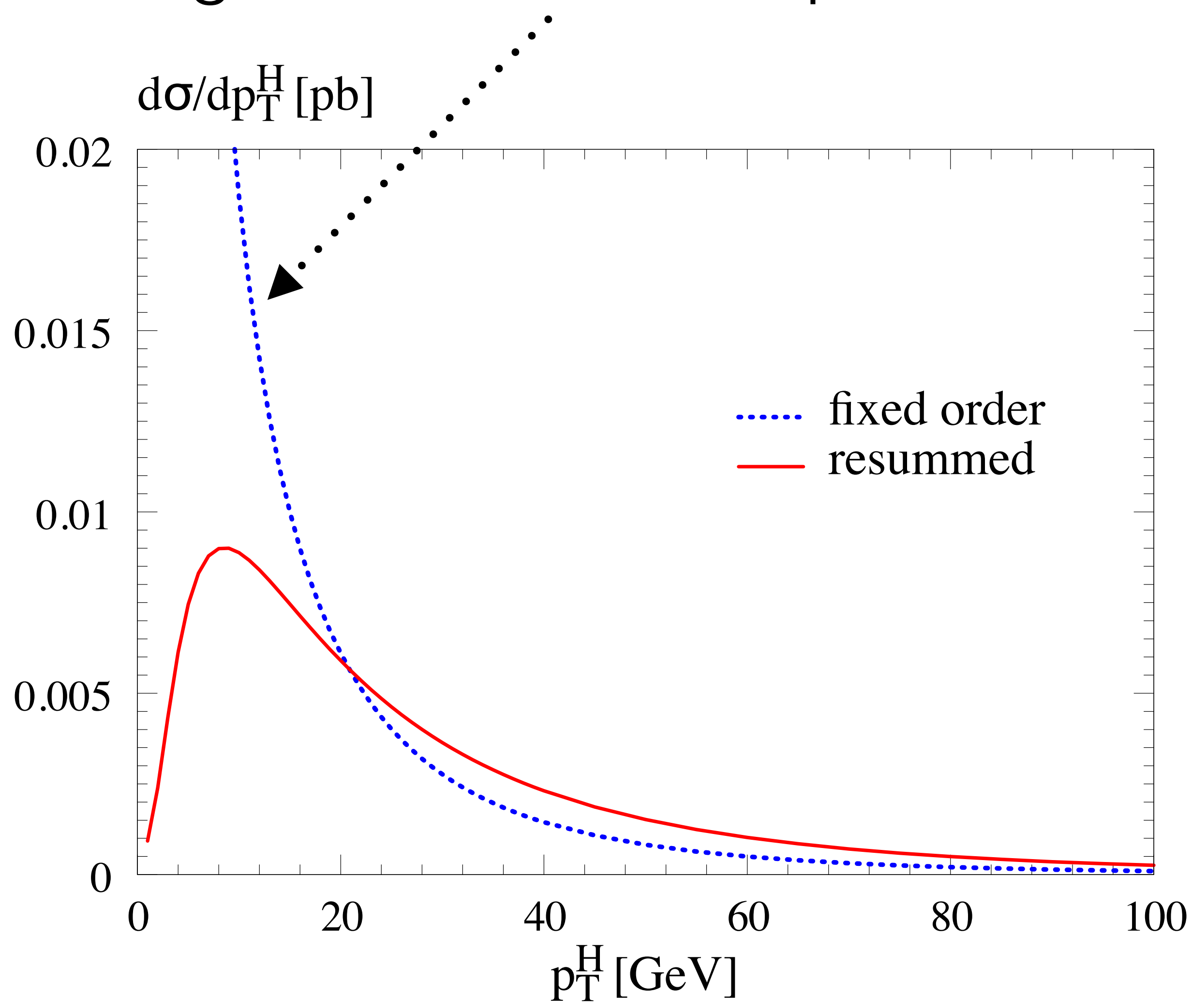

Technically, the perturbative expansion is affected by large logarithms of a form $ln^n(\frac{m_H^2}{p_T^2})$

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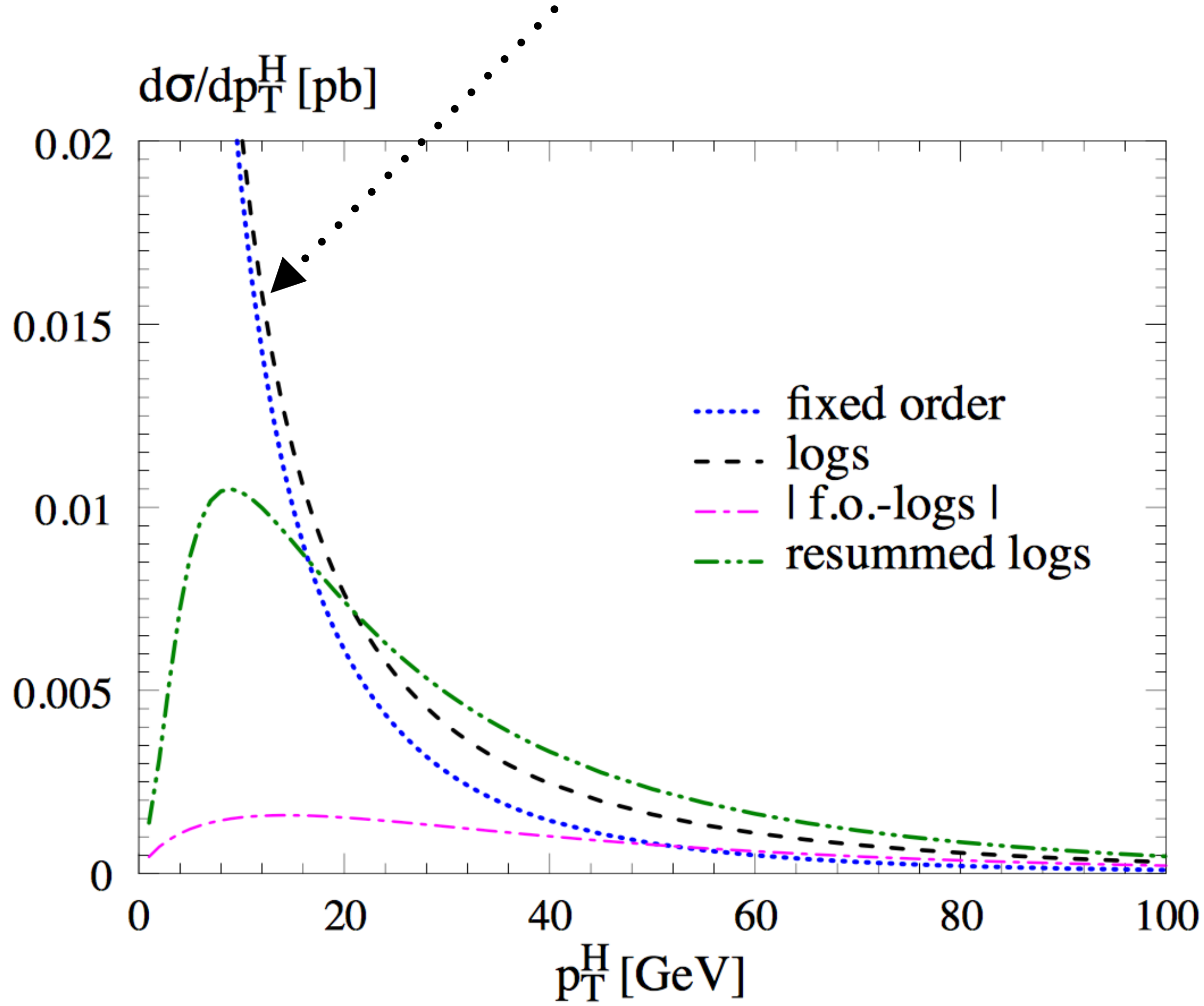

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They can be systematically resummed working in the impact parameter *b* space to all orders

Collins, Soper,Sterman '85

Then the resummed and fixed order spectra need to be properly matched at intermediate pT

Bozzi, Catani, de Florian, Grazzini '05

$$\left[\frac{d\sigma}{dp_T^2}\right]_{f.o.+a.o.} = \left[\frac{d\sigma}{dp_T^2}\right]_{f.o.} - \left[\frac{d\sigma^{(res)}}{dp_T^2}\right]_{f.o.} + \left[\frac{d\sigma^{(res)}}{dp_T^2}\right]_{.a.o.}$$

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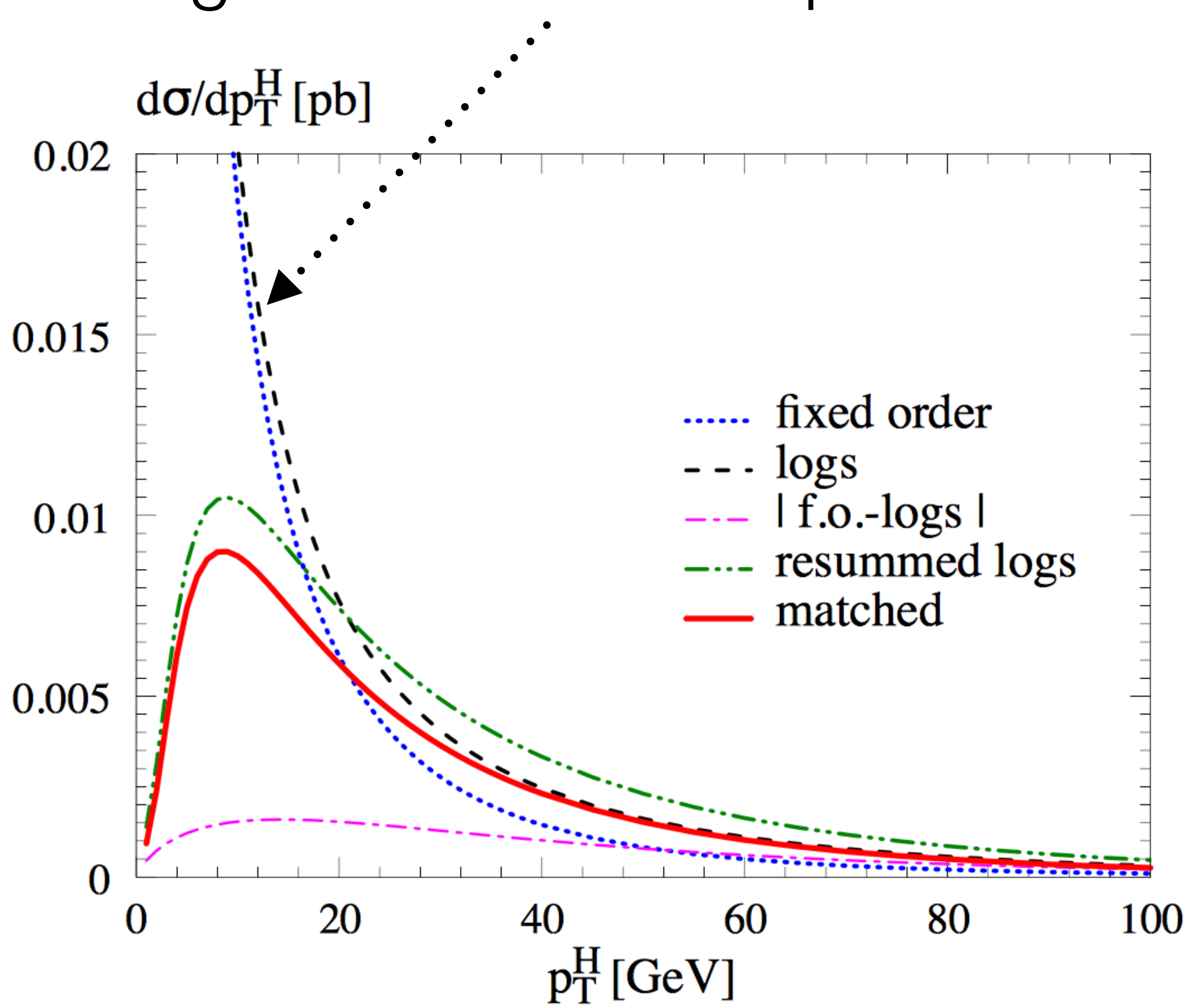

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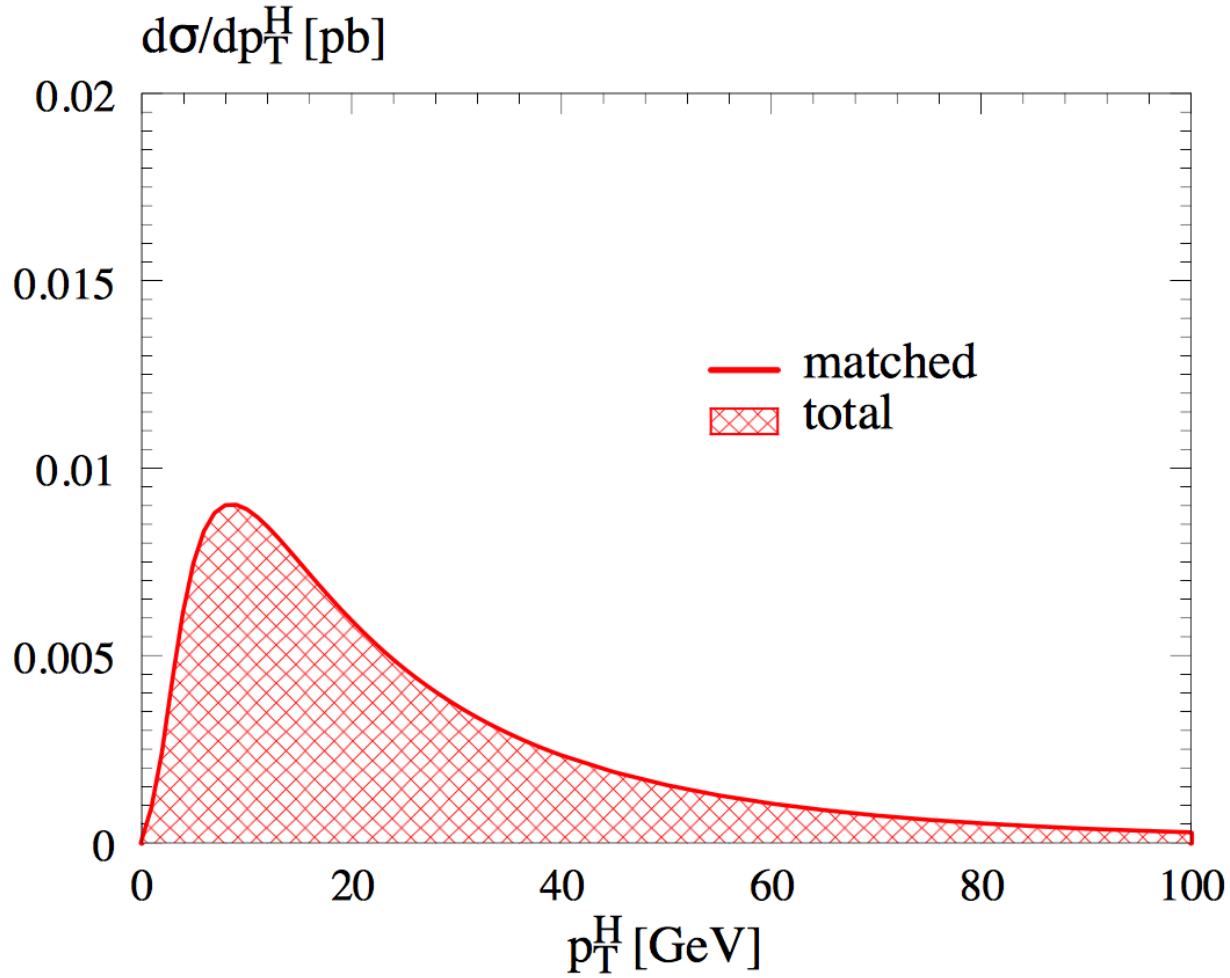

The matched spectrum satisfies the unitarity condition:
area below graph corresponds to the total cross section

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Our setup for Higgs production and pT spectrum including EFT effects

Our SMEFT operators

$$\mathcal{O}_1 = |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}$$
$$\mathcal{O}_2 = |H|^2 \bar{Q}_L H^c u_R + h.c.$$
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$$\frac{\alpha_S}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu}$$

← as HTL in SM

$$\frac{m_t}{v} c_t h \bar{t} t$$
$$\frac{m_b}{v} c_b h \bar{b} b$$

← modified top/bottom Yukawa coupling

$$c_{tg} \frac{g_S m_t}{2v^3} (v+h) G^a_{\mu\nu} (\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c)$$

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c_t can be bounded from the *tth* production

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c_b can be bounded from the h->bb decay (and *bbh* production)

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c_{tg} can be bounded from the *tt* production

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Easiest to bound from the Higgs pT spectrum

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⇒

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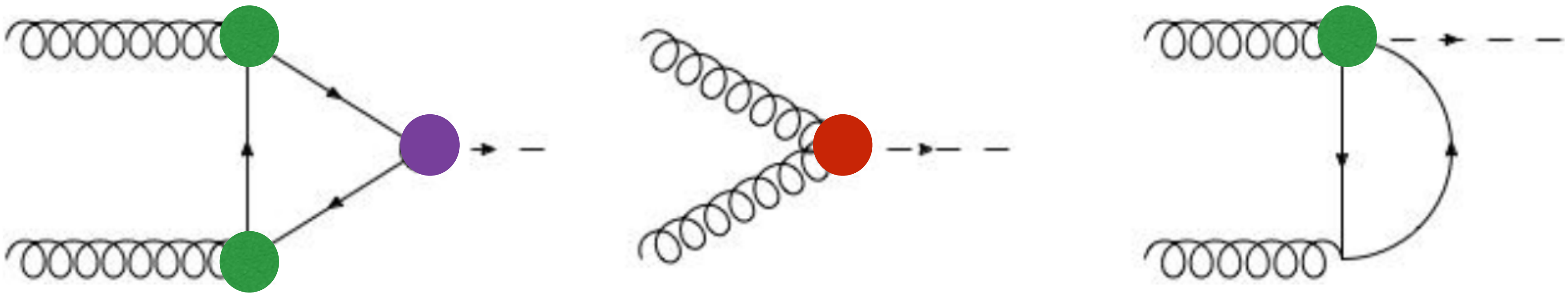
Previous studies including dimension 6 and dimension 8 operators

Grojean, Salvioni et al.'13;
Azatov, Paul '13,
Langenegger, Spira et al.'15
Maltoni, Vryonidou, Zhang '16

Harlander, Neumann'13,
Dawson, Lewis, Zeng'14

- (mostly) did not include chromomagnetic operator
- (mostly) only valid for high pT - no resummation included

Higgs production at LO



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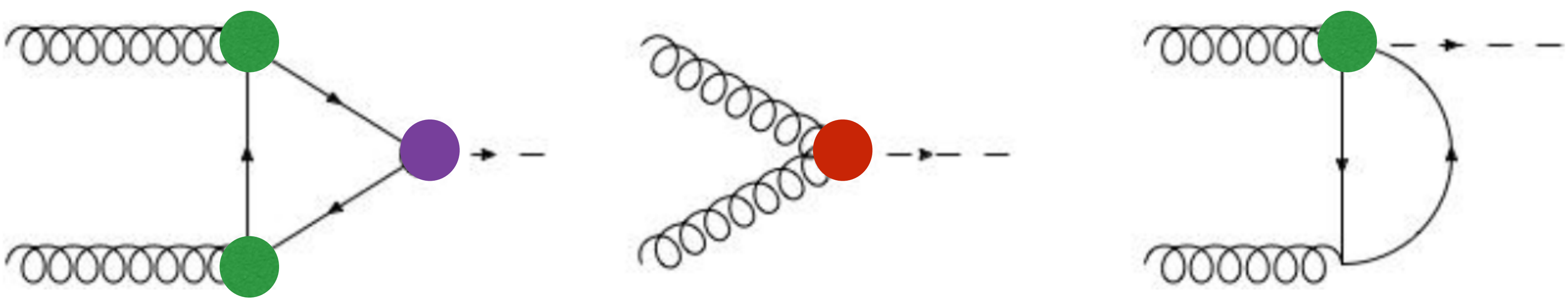
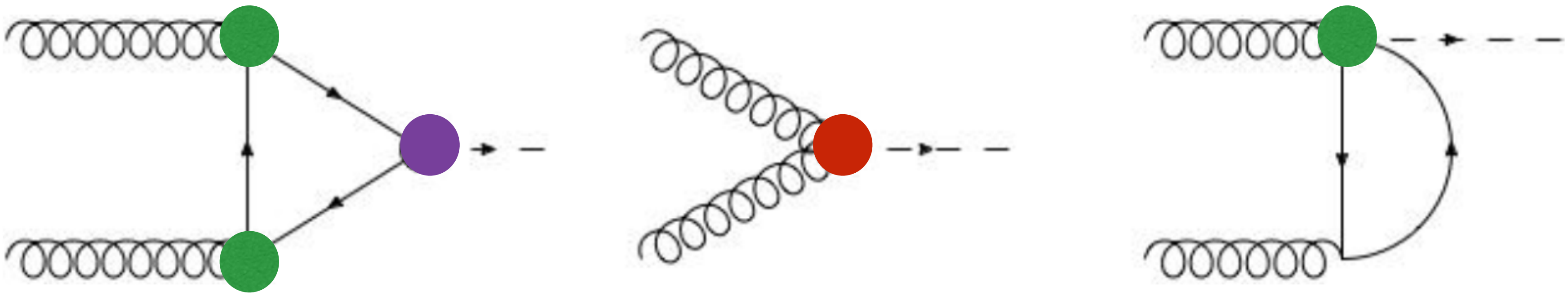


$$\mathcal{M}\left(g(p_1)+g(p_2)\to H\right)=i\frac{\alpha_S}{3\pi v}\epsilon_{1\mu}\epsilon_{2\nu}\left[p_1^{\nu}p_2^{\mu}-(p_1p_2)g^{\mu\nu}\right]F(\tau)$$

$$F(\tau)=c_t F_1(\tau)+c_g(\mu_R)F_2(\tau)+Re(c_{tg})\frac{m_t^2}{v^2}F_3(\tau)$$

Higgs production at LO



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$$F(\tau)=c_t F_1(\tau)+c_g(\mu_R)F_2(\tau)+Re(c_{tg})\frac{m_t^2}{v^2}F_3(\tau)$$

$$F_1(\tau)=\frac{3}{2}\tau\left[1+(1-\tau)f(\tau)\right],$$

$$F_2(\tau)=12,$$

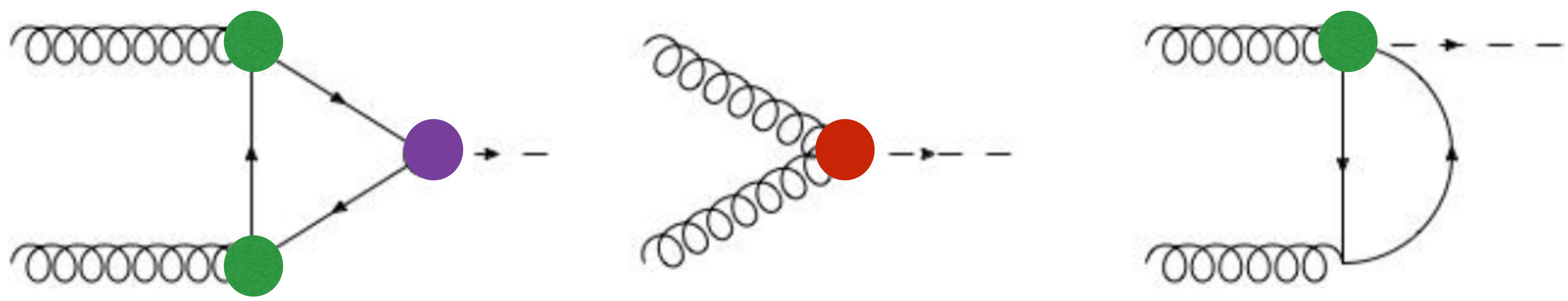
$$F_3(\tau)=3\left(1-\tau f(\tau)-2g(\tau)+2\ln\frac{\mu_R^2}{m_t^2}\right)$$

$$g(\tau)=\begin{cases}\sqrt{\tau-1}\arcsin\frac{1}{\sqrt{\tau}} & \tau\geq 1\\ \sqrt{1-\tau}\left[\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}-i\pi\right] & \tau<1\end{cases}$$

$$f(\tau)=\begin{cases}\arcsin^2\frac{1}{\sqrt{\tau}} & \tau\geq 1\\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}-i\pi\right]^2 & \tau<1\end{cases}$$

HTL: $F_1(\tau)\to 1,\qquad F_2(\tau)\to 12,\qquad F_3(\tau)\to 6\left(\ln\frac{\mu_R^2}{m_t^2}-1\right)$

Higgs production at LO



$$\mathcal{M}\left(g(p_1)+g(p_2)\to H\right) = i\frac{\alpha_S}{3\pi v}\epsilon_{1\mu}\epsilon_{2\nu}\left[p_1^\nu p_2^\mu - (p_1p_2)g^{\mu\nu}\right]F(\tau)$$

$$F(\tau) = c_t F_1(\tau) + c_g(\mu_R)F_2(\tau) + Re(c_{tg})\frac{m_t^2}{v^2}F_3(\tau)$$

Calculations published with contradictory results
Choudhury et al ’12
Degrande et al ’12

$$F_1(\tau) = \frac{3}{2}\tau\left[1+(1-\tau)f(\tau)\right],$$

$$F_2(\tau) = 12,$$

$$F_3(\tau) = 3\left(1-\tau f(\tau) - 2g(\tau) + 2\ln\frac{\mu_R^2}{m_t^2}\right)$$

Formally higher order of yt

$$g(\tau) = \begin{cases} \sqrt{\tau-1}\arcsin\frac{1}{\sqrt{\tau}} & \tau\geq 1 \\ \sqrt{1-\tau}\left[\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right] & \tau<1 \end{cases}$$

$$f(\tau) = \begin{cases} \arcsin^2\frac{1}{\sqrt{\tau}} & \tau\geq 1 \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau<1 \end{cases}$$

HTL: $F_1(\tau)\to 1,\qquad F_2(\tau)\to 12,\qquad F_3(\tau)\to 6\left(\ln\frac{\mu_R^2}{m_t^2}-1\right)$

Higgs transverse momentum spectrum

Based on the *HqT* program, cross-checked for f.o. part with *HNNLO* and *HIGLU* programs

We included three of SMEFT operators:

- top Yukawa modification
- bottom Yukawa modification
- *ggh* point-like coupling

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The values used for eff. coupling were inspired by currently available fits

Dumont et al '13
Falkowski '15
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Highest known with full top mass dependence

Calculations performed on the NLL+NLO level of accuracy

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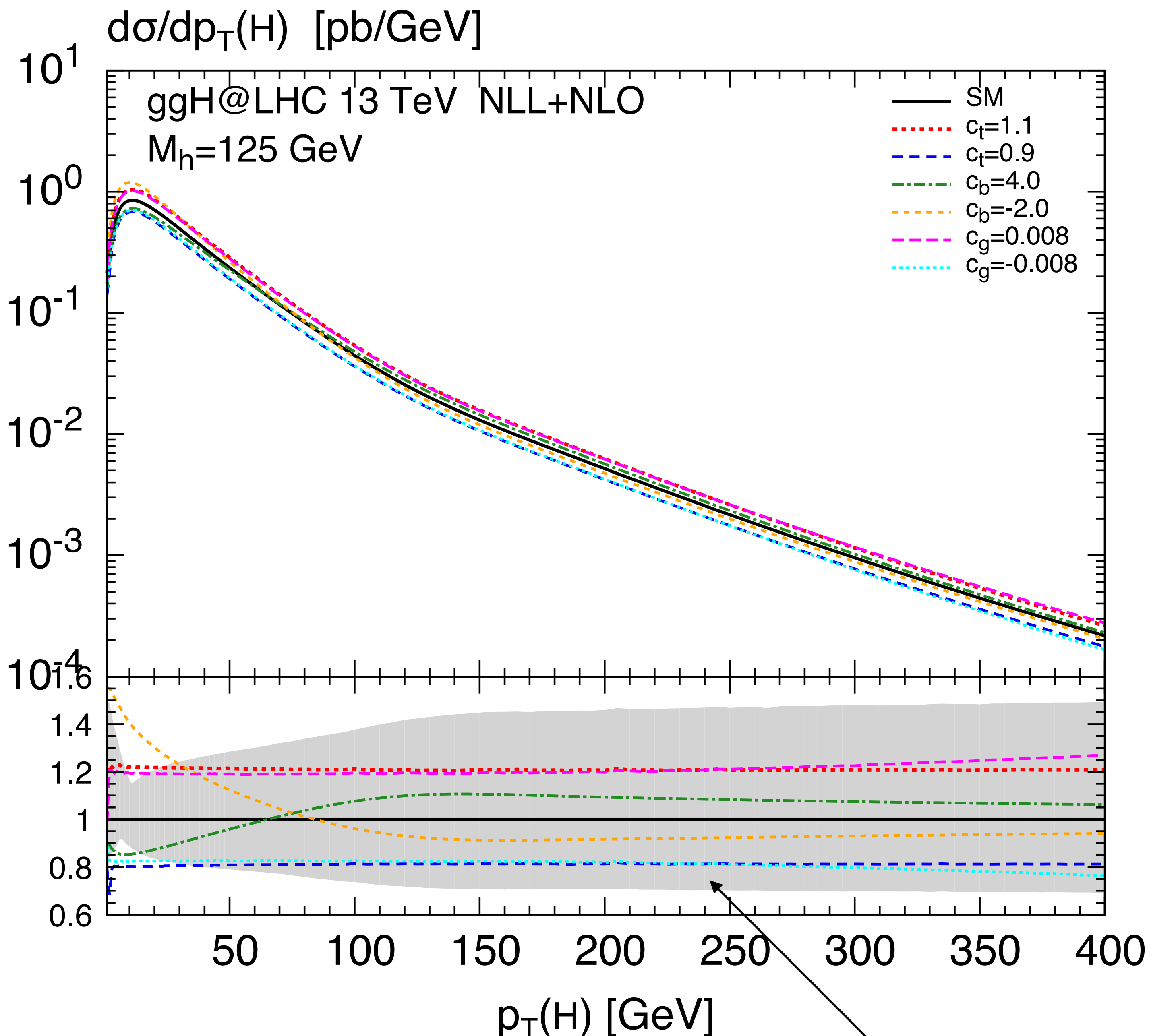
Renormalisation and factorisation scales: $\mu_R = \mu_F = \mu_0 = \sqrt{p_T^2 + m_H^2}/2$

Three scales of resummation: $Q_t = m_H/2 \;\; Q_b = 4\,m_b \;\; Q_{\rm int} = \sqrt{Q_t\,Q_b}$

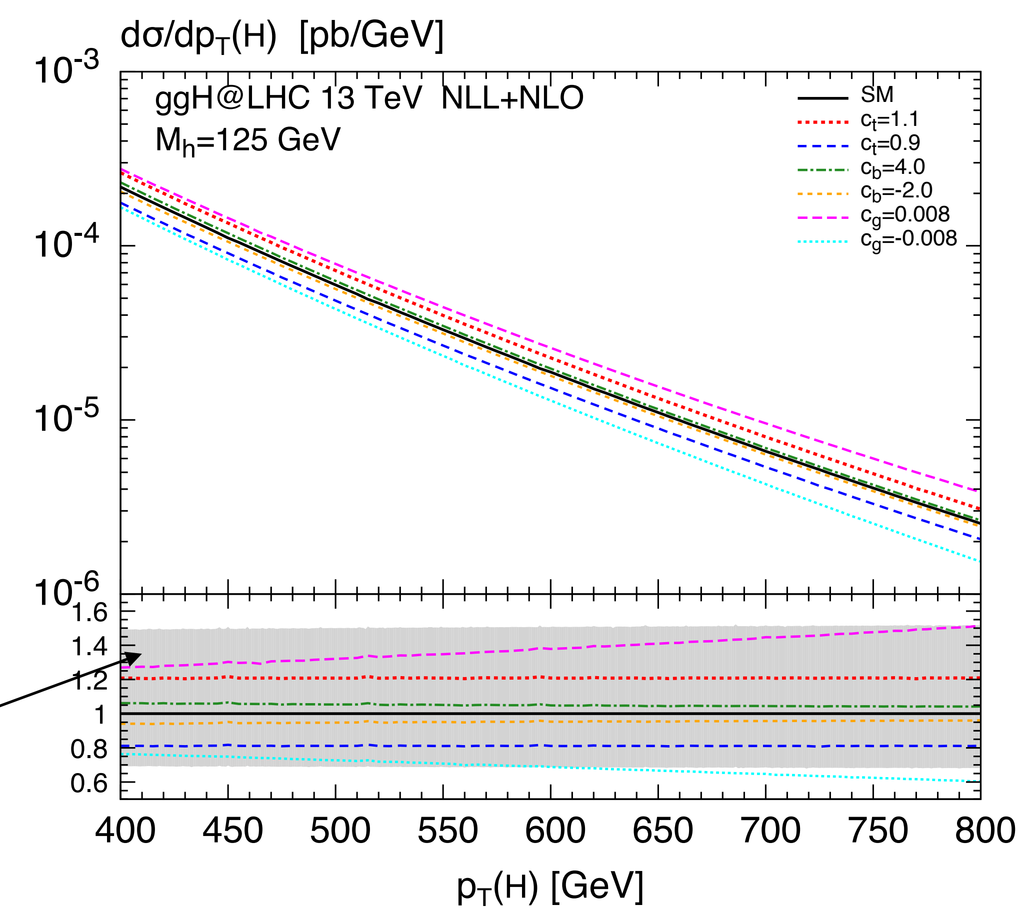
in line with Grazzini, Sargsyan '13
Harlander et al '14

Parton distribution functions: NLO set from PDF4LHC2015

Separate contributions of dim 6 operators

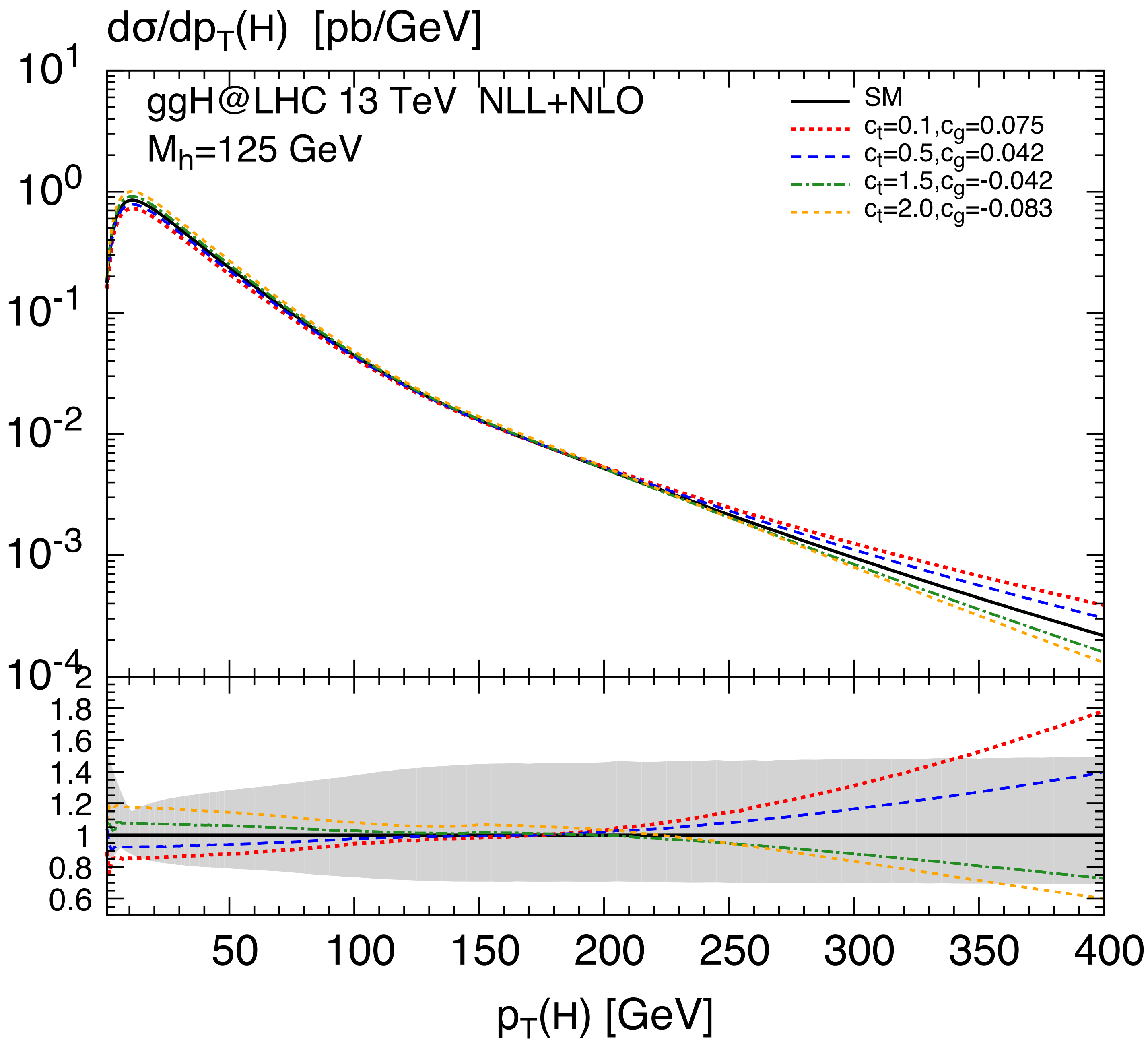


- **Kept within 20% from SM total cross section**
- Not exceeding (much) the SM uncertainty
- Effects in different regions of the spectrum



SM scale variation

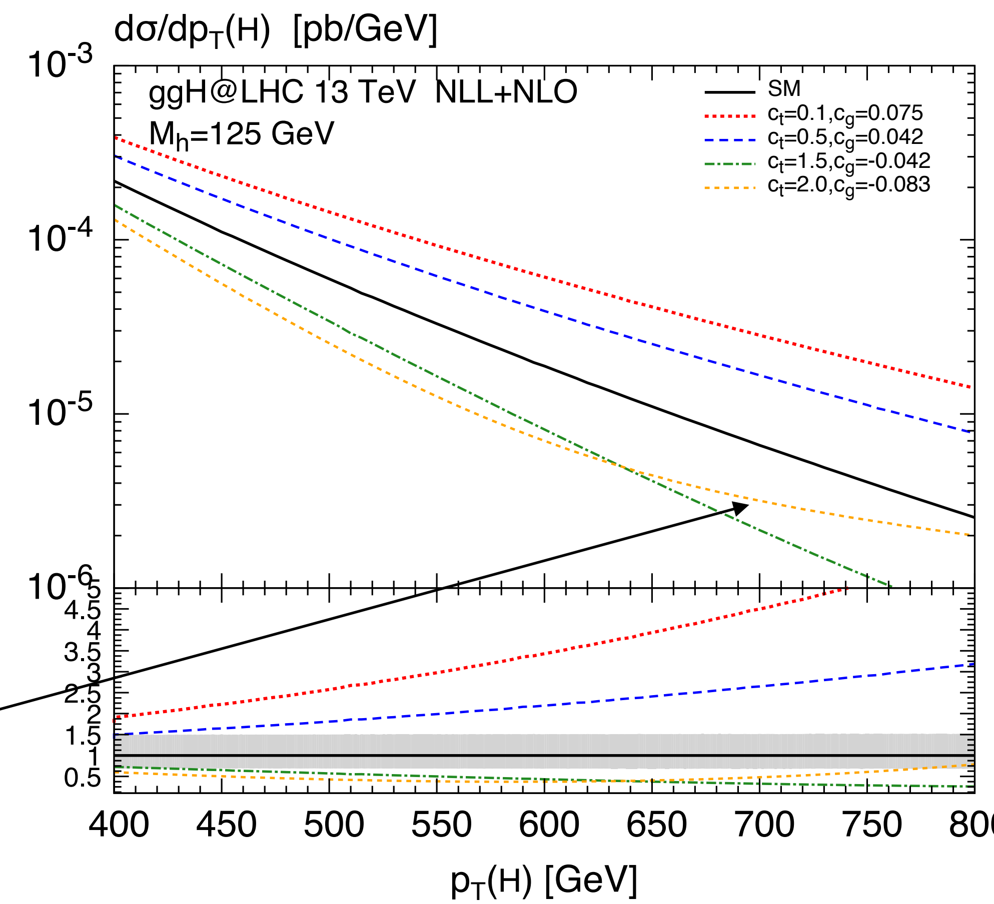
Mixed contributions of ct and cg



- More dramatic shape effects with same total rate

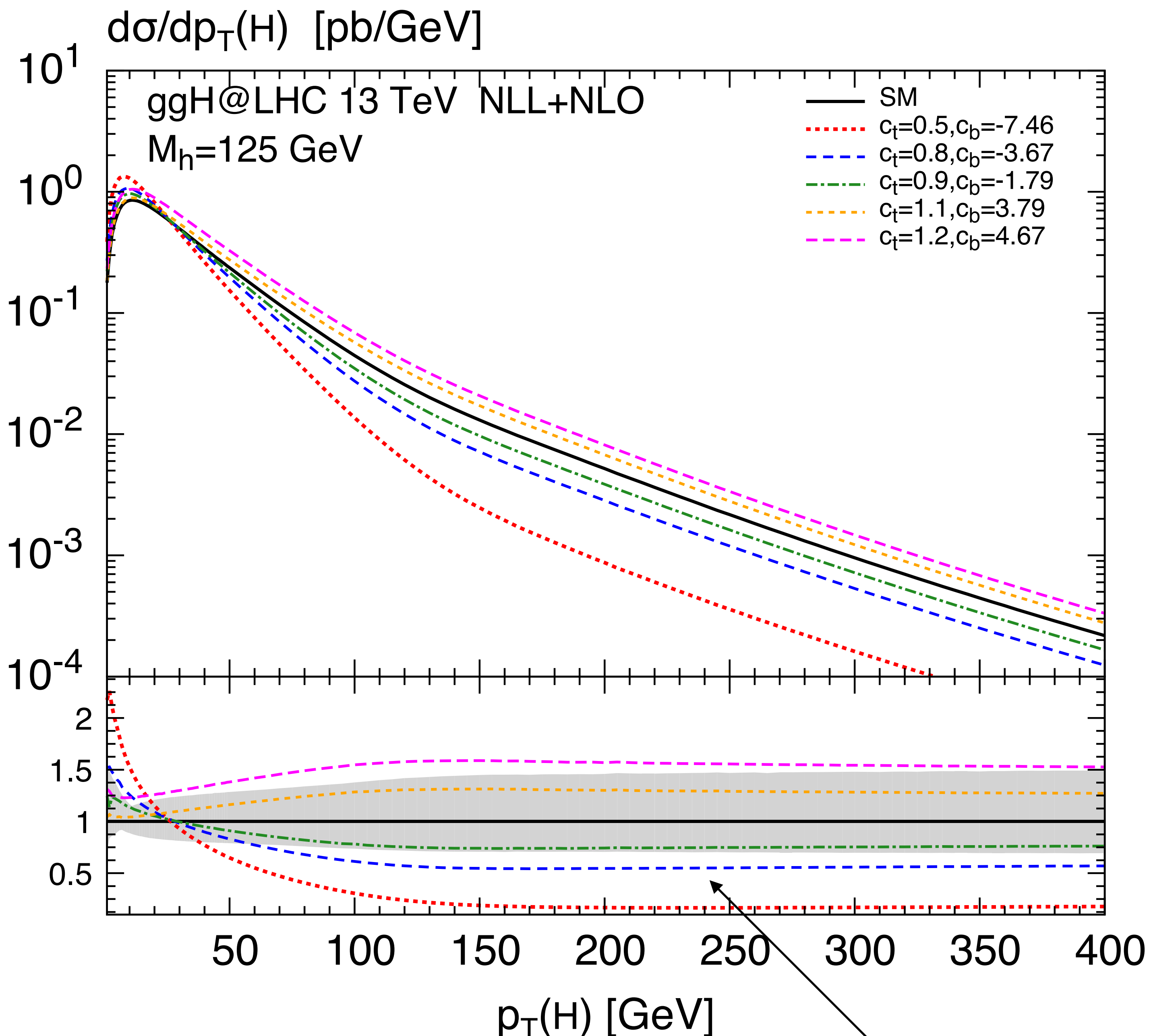
$$\sigma \approx |12c_g + c_t|^2 \sigma_{SM}$$

- At high pT clearly visible effect of point-like coupling

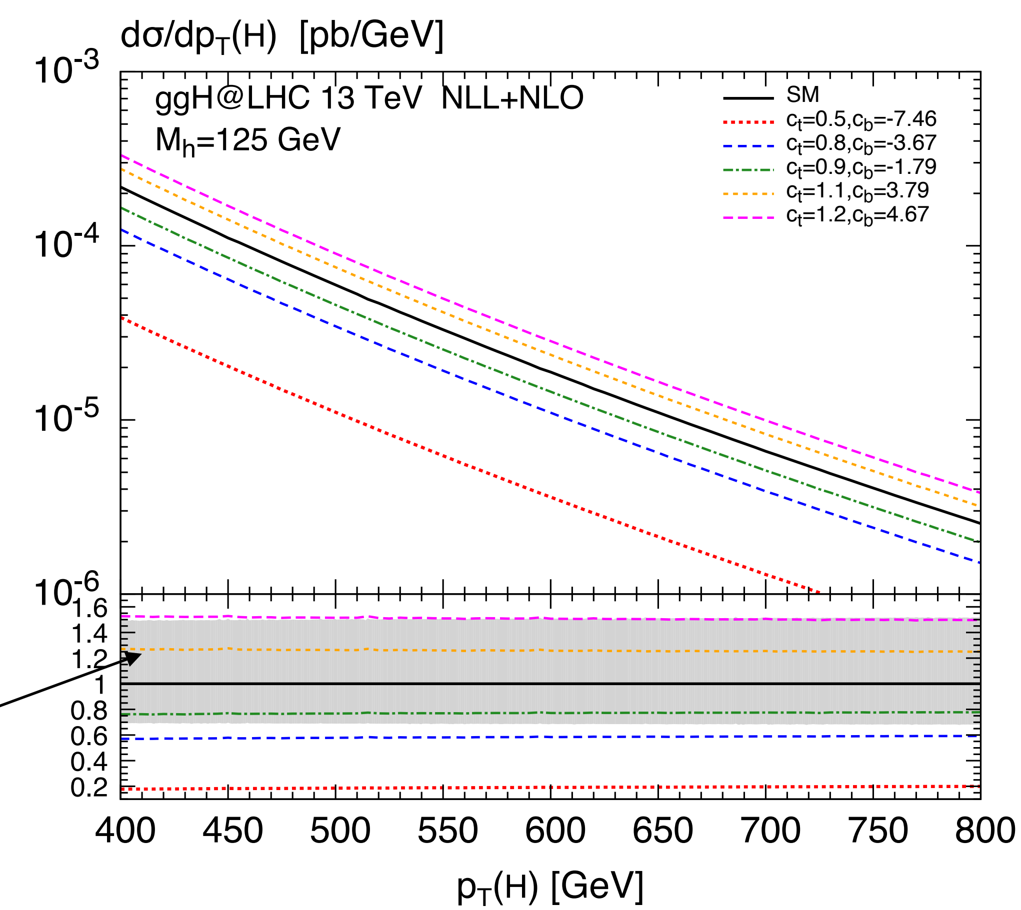


effect caused by dominance of cg2

Mixed contributions of ct and cb

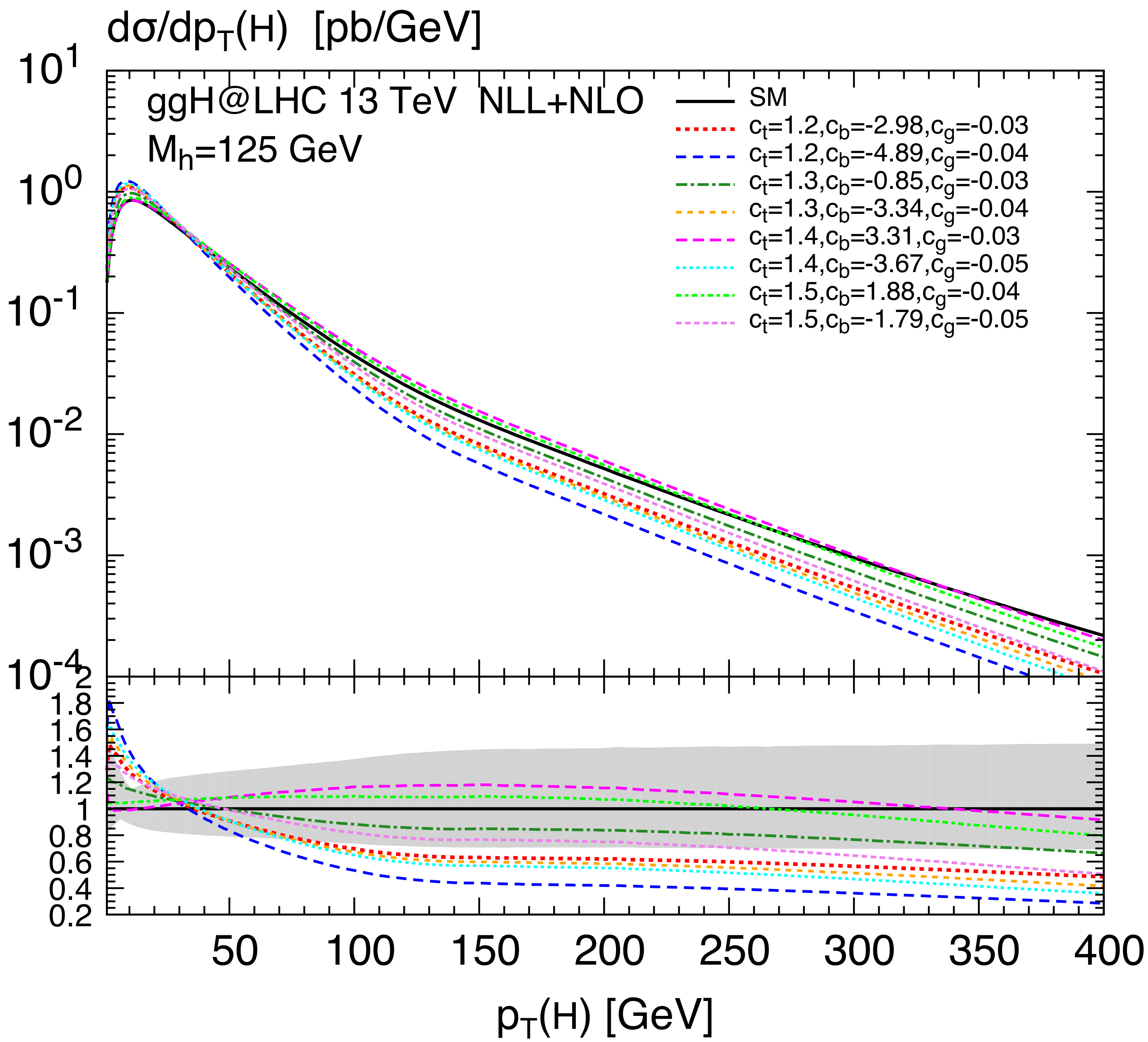


- For ct >1 hard to balance with real cb
- At low pT clearly visible effect of modification of bottom Yukawa
- For pT>150 GeV governed by the ct modification

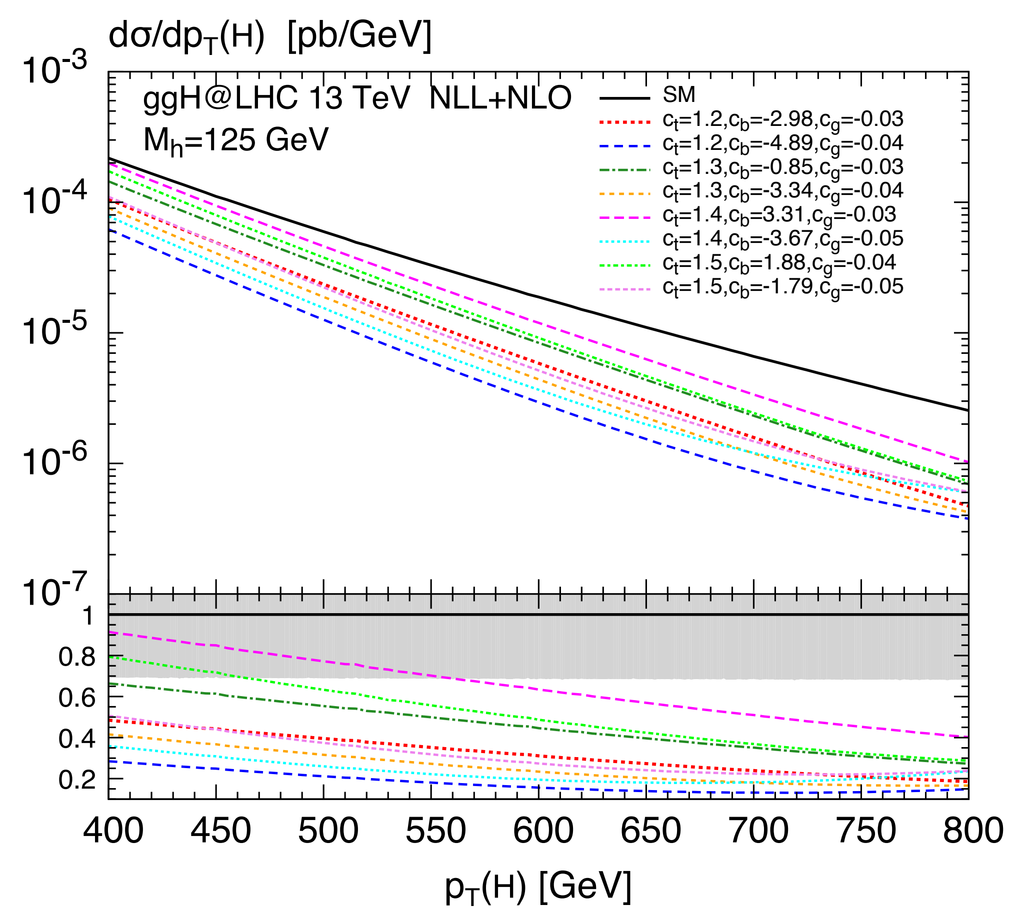


No shape distortion compared to SM
top loop dominance

Mixed contributions of all three operators



- Scenario with top Yukawa enhanced, inspired by the higher than SM rate of ttH in first CMS and ATLAS results
- Leads to the softer spectrum
- Combination of all previous effects



Higgs pT spectrum at NNLL+NNLO

The best available SM prediction at NNLL+NNLO including mass effects obtained with *HRes.*

D. de Florian, G. Ferrera, et al. '12;
M. Grazzini, H. Sargsyan '13

No full top mass dependence known!

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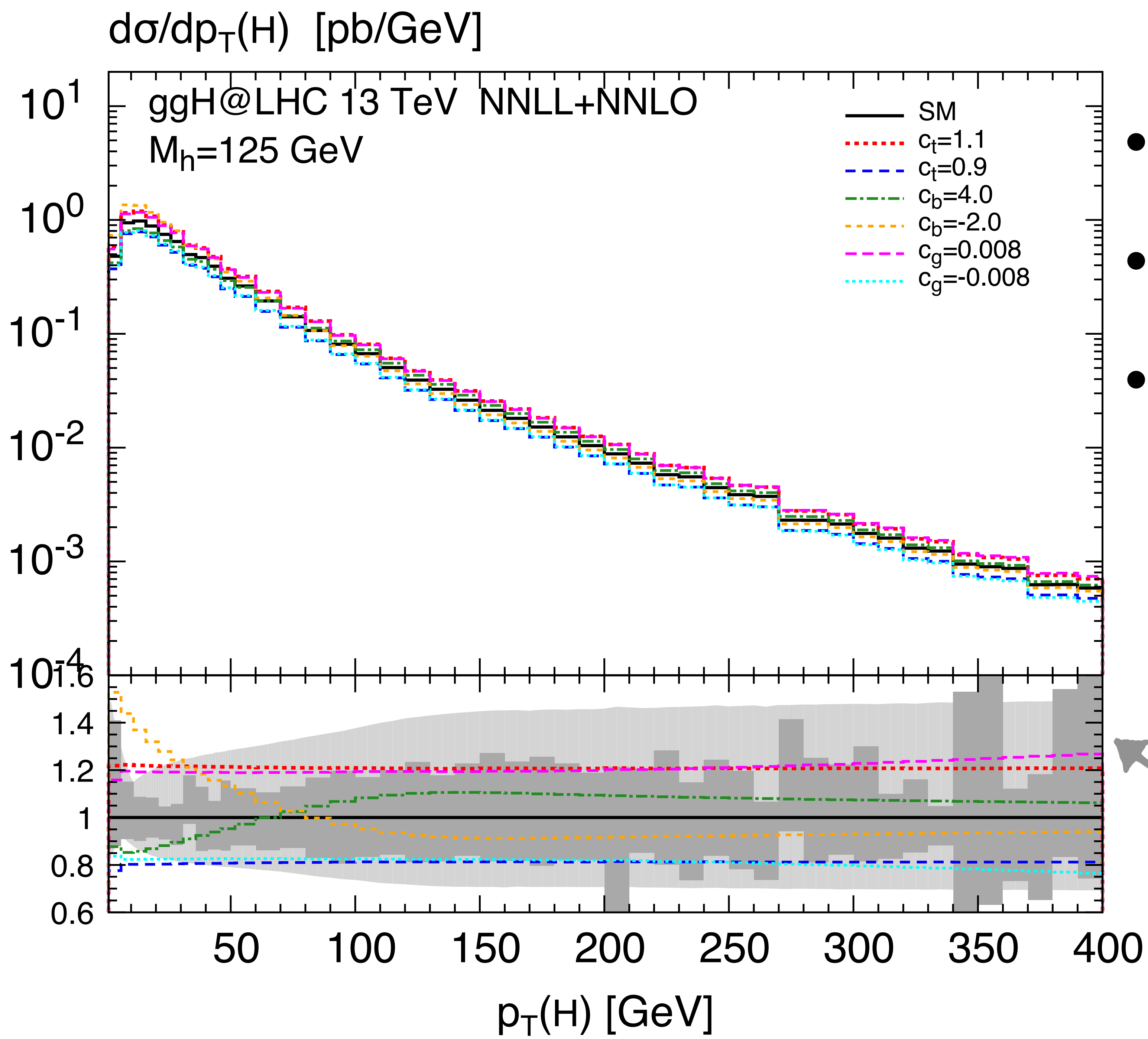
No full top mass dependence known!

Having the best SM prediction we apply on top the SMEFT effects, factorised from the NLO predictions:

$$\left(\frac{d\sigma}{dp_t}\right)^{SMEFT}_{NNLL+NNLO}(p_T) = \frac{\left(\frac{d\sigma}{dp_t}\right)^{SMEFT}_{NLL+NLO}(p_T)}{\left(\frac{d\sigma}{dp_t}\right)^{SM}_{NLL+NLO}(p_T)} \cdot \left(\frac{d\sigma}{dp_t}\right)^{SM}_{NNLL+NNLO}(p_T)$$

- Input kept as similar as possible (pdfs, scales, masses)
- HqT analytic while HRes numeric
- Different binning

Higgs pT spectrum at NNLL+NNLO
Separate contributions of dim 6 operators

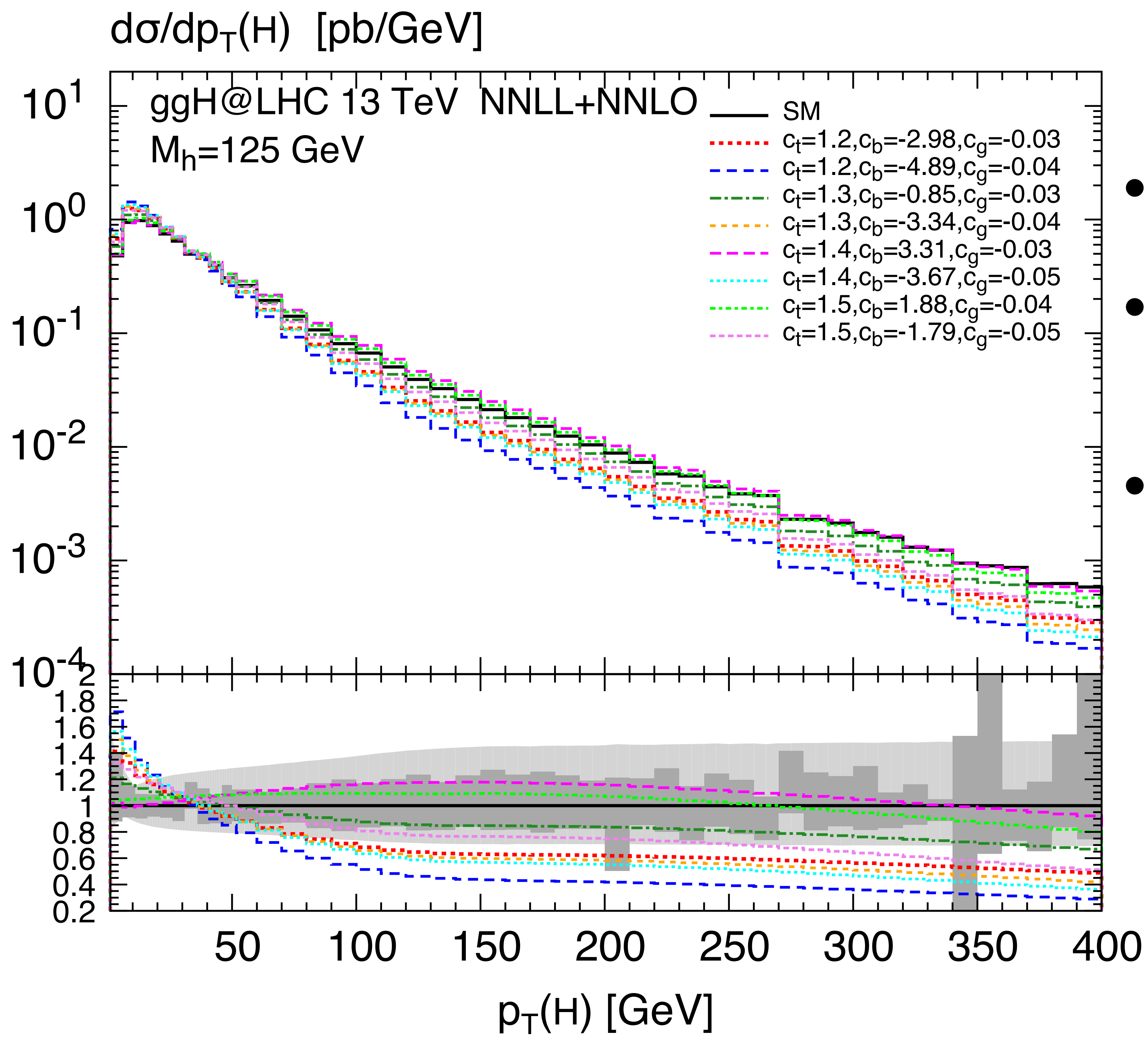


- Noticeable improvement of scale variation at low pT
- BSM effects exceeding the SM uncertainty
- At high pT problems due to the statistics (*HRes* numerical)

The SM scale variation:

- light grey NLL+NLO
- dark grey NNLL+NNLO

Higgs pT spectrum at NNLL+NNLO
Mixed contributions of all three operators

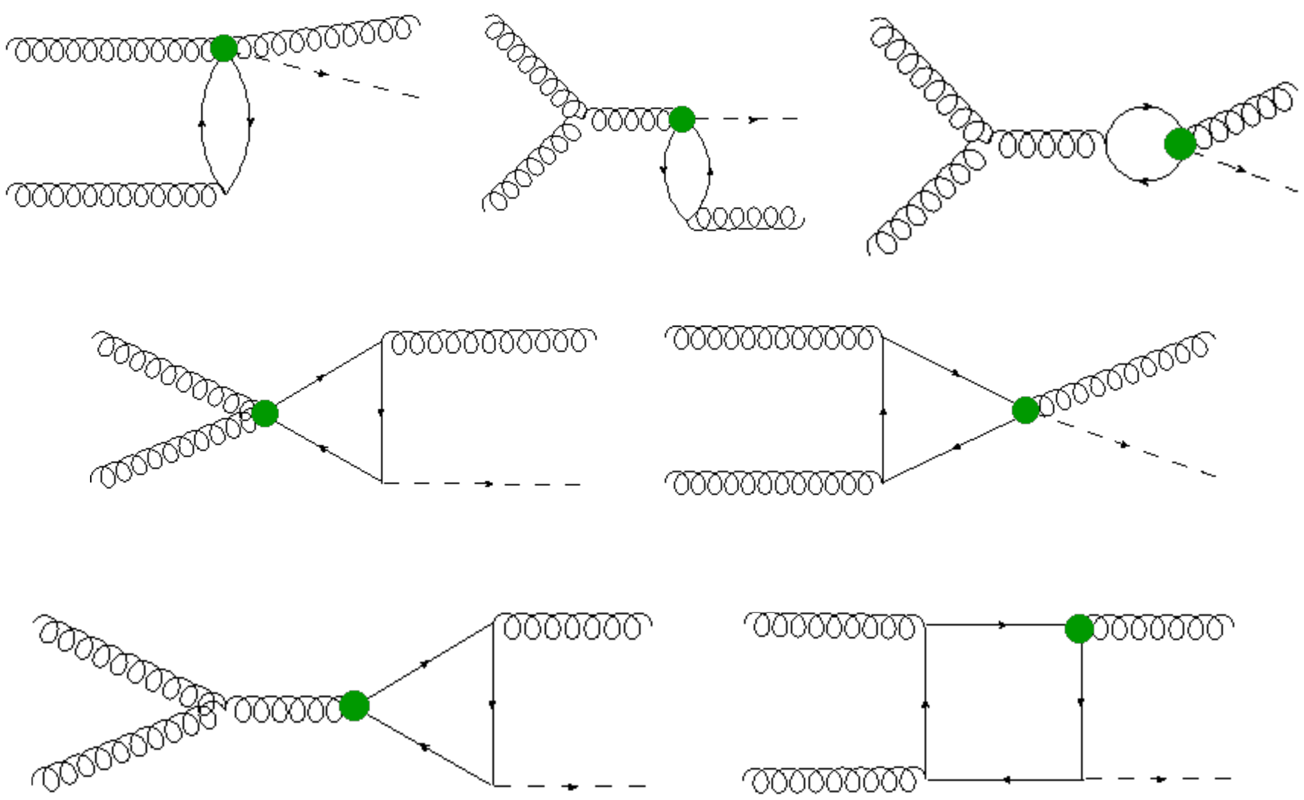


- Can be redone for all the previous operators combinations
- With smaller SM scale uncertainty the sensitivity on the BSM effects is higher
- Full top mass dependence at NNLO would be appreciated

Outlook

Calculate the NLO with the chromomagnetic operator to include also in the transverse momentum spectrum

- 39 diagrams a priori for gggh case
- different tensor structure of operator than the SM
- work in progress



Summary

Bottom-up Effective Field Theory for Standard Model (SMEFT) is a model independent framework to study high scale BSM physics and also to store LHC precision measurements

Measurement of the Higgs transverse momentum spectrum would be useful in determining its properties

We studied the impact of a set of relevant SMEFT operators on the Higgs production and its pT spectrum

The effect of different operators is manifested in different regions of the spectrum: cg at high and cb at low pT

Calculations are available on NNLL+NNLO level, i.e. current state-of-the-art SM accuracy and allowing access to low pT region

Thank you for the attention!

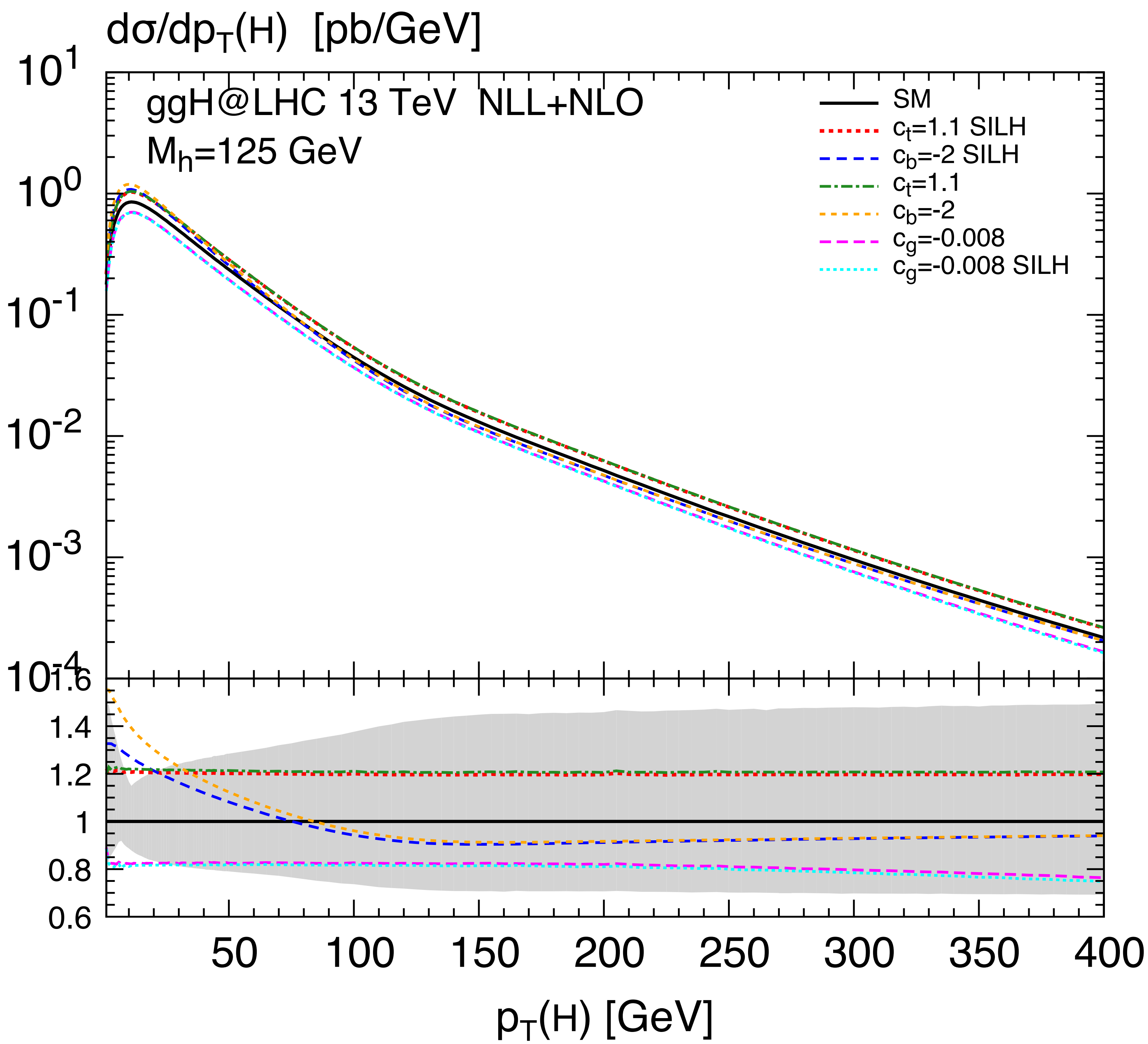
Back up

Importance of squared terms

$$\mathcal{A} = \mathcal{A}_{\text{SM}} + \mathcal{A}_{\text{dim6}} + \mathcal{A}_{\text{dim8}} + ...$$

$$|\mathcal{A}|^2 = |\mathcal{A}_{\text{SM}}|^2 + |\mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim6}}| + |\mathcal{A}_{\text{dim6}}|^2 + |\mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim8}}| + ...$$

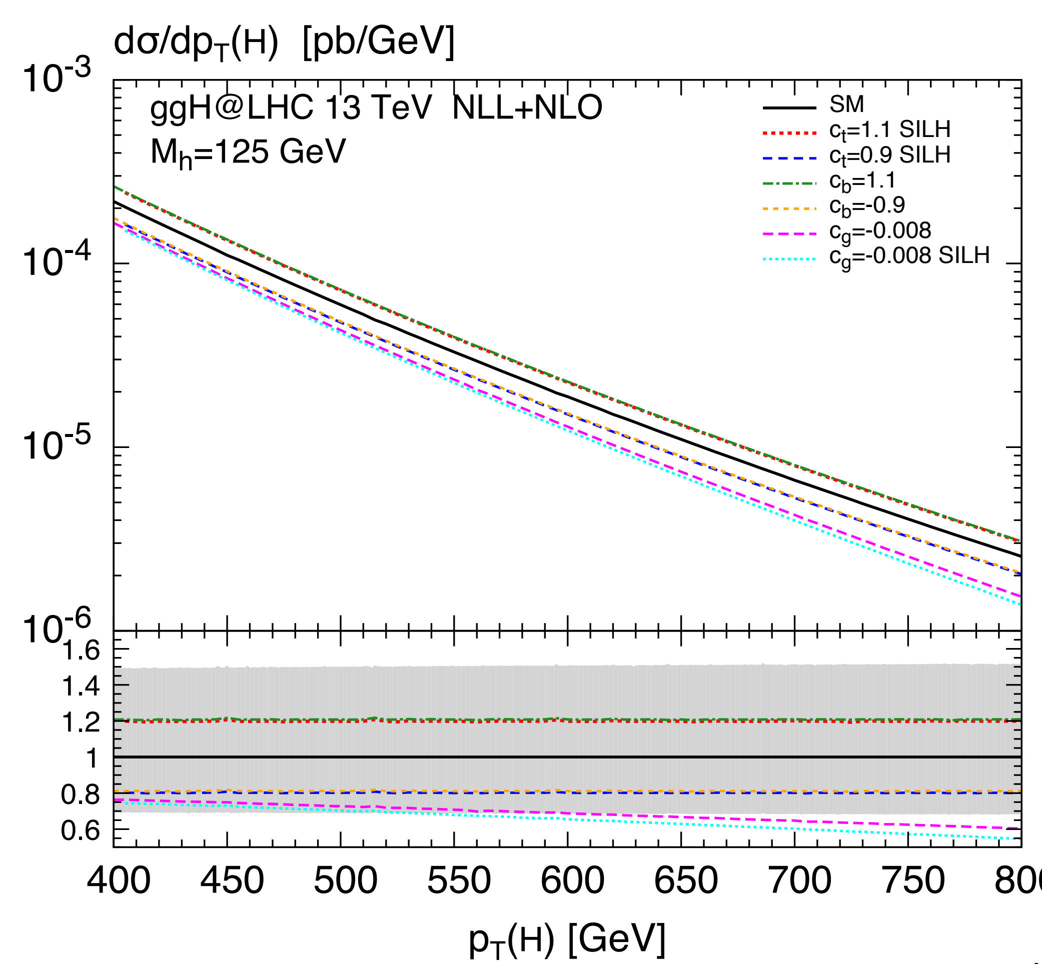
Importance of squared terms



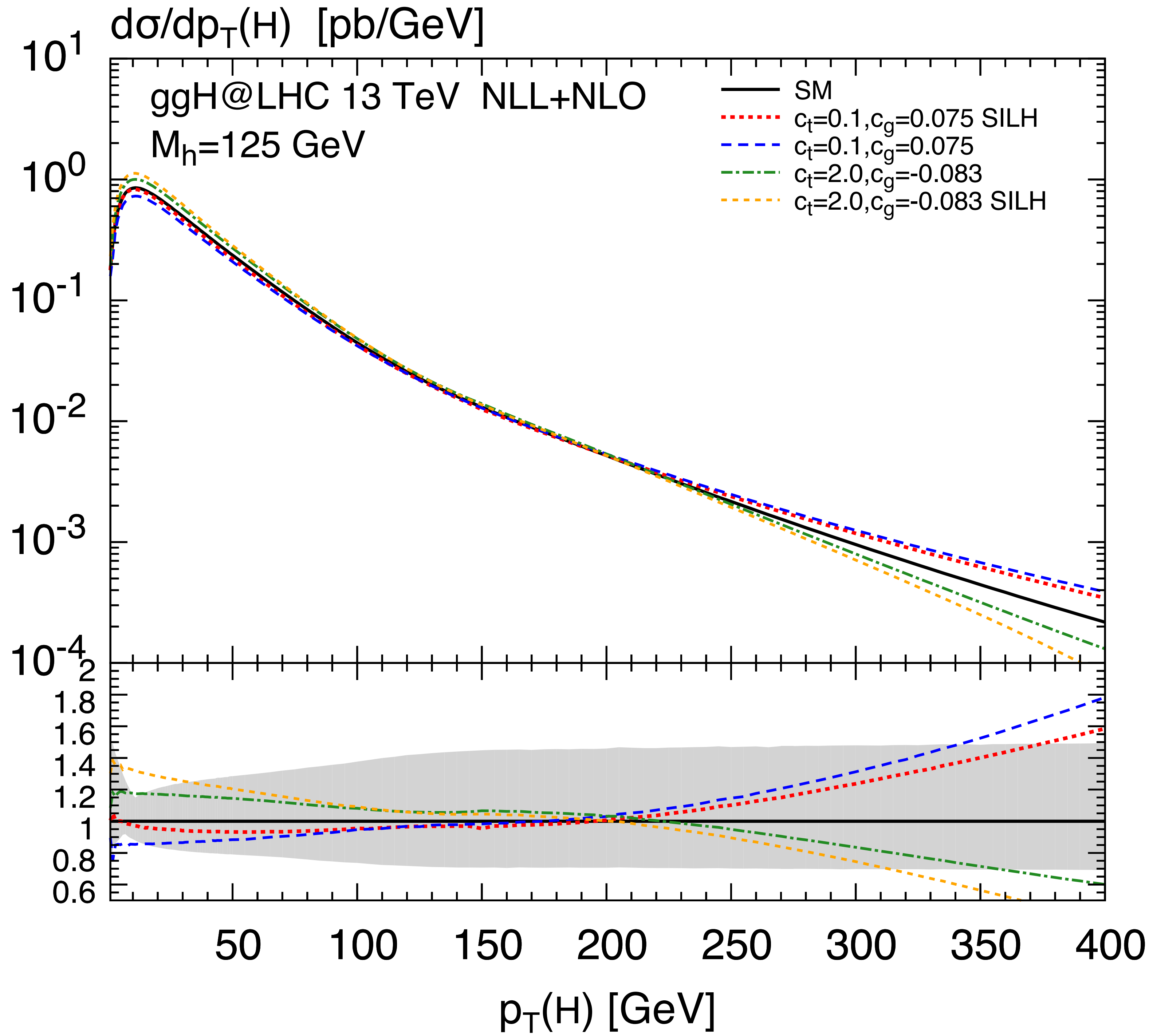
Separate contributions of operators

Our program can run in two modes (switch in input):

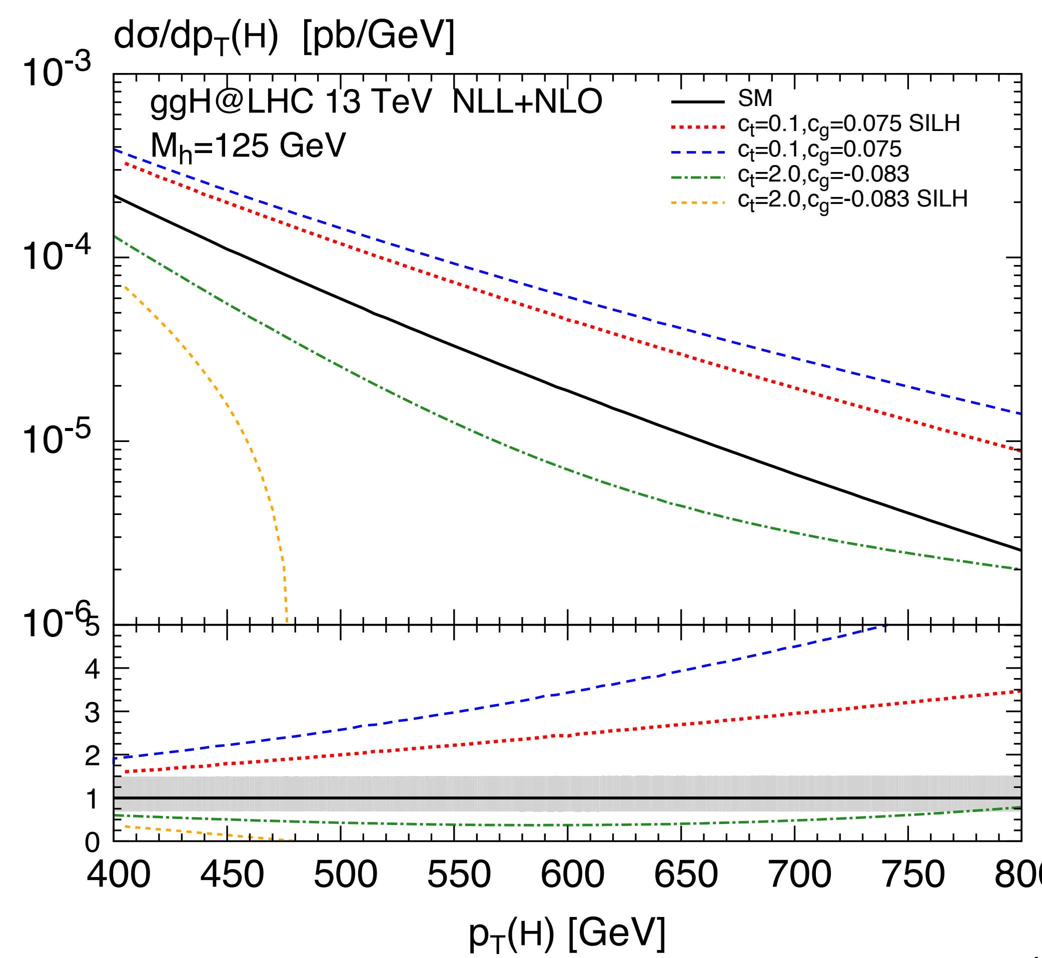
- including squared SMEFT contributions
- including just SMEFT-SM interference



Importance of squared terms



The difference between two approaches grows with the values of Wilson coefficients



Mixed ct-cg contribution:
the extreme case!