

Effective Field Theory for Higgs properties parametrisation: the transverse momentum spectrum case

Agnieszka Ilnicka

based on JHEP03(2017)115 [1612.00283], *work in progress*,

in collaboration with:

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ETH zürich



University of
Zurich^{UZH}

PAUL SCHERRER INSTITUT

PSI



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

Proved to work in flavour physics

Can be used to store what LHC measured

Can link many measurements

More information than single number:

Shape

Normalisation

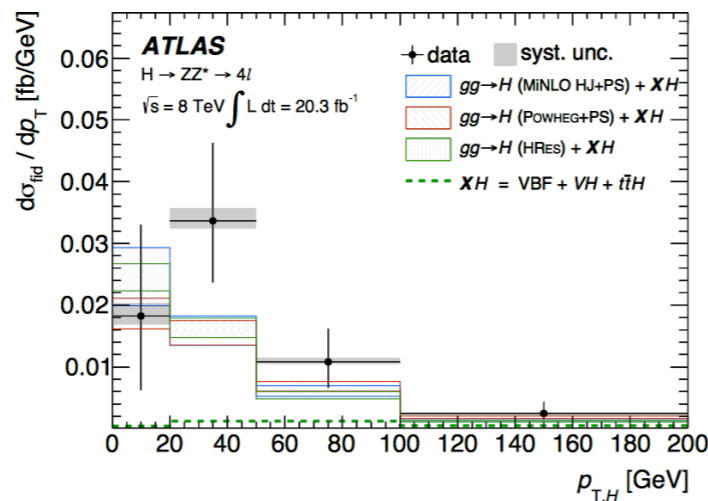
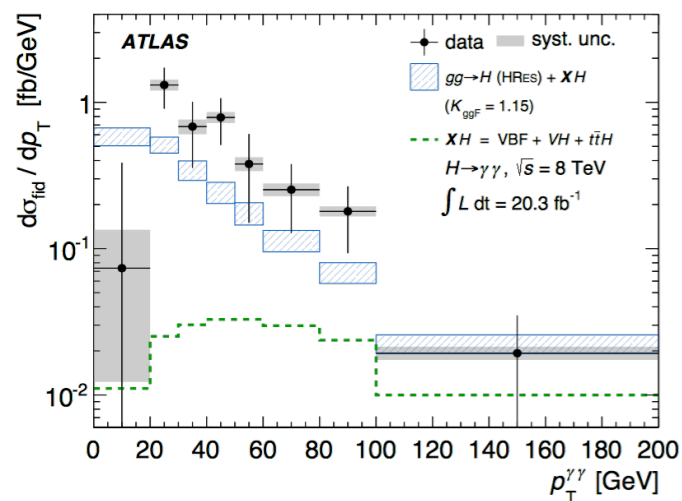
Maximum position

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

For the scalar particle
production and decay
factorise

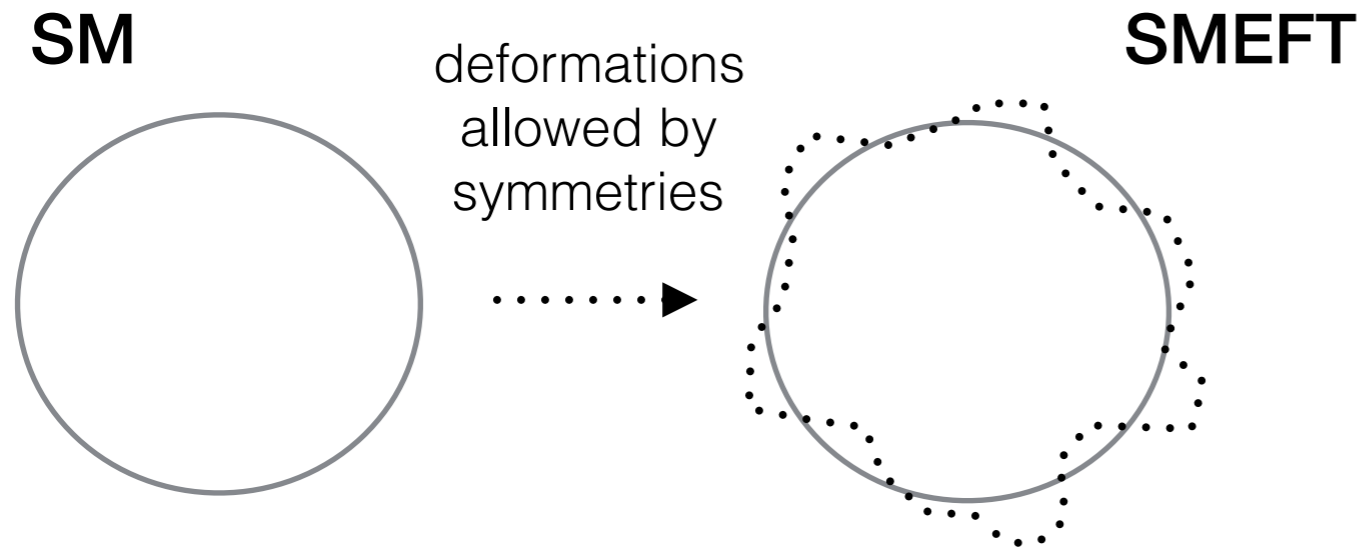
Why BSM via Effective Field Theory? Why Higgs pT spectrum?

First data from ATLAS & CMS
available



Should be significantly
improved in Run 2 and HL

What is Bottom-up Effective Field Theory?



Take the renormalizable theory (e.g. SM).

From its fields build the operators of higher dimensions obeying the Lorentz and gauge invariance to account for small deviations from the theory.

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

Nonrenormalisable but renormalisable order by order

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

2HDM EFT:

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:

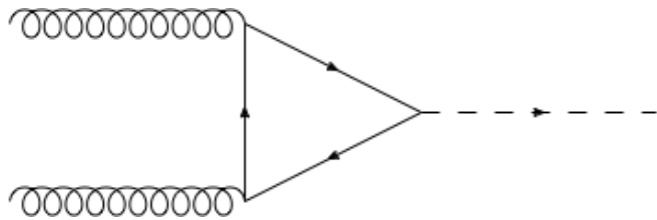
Section 2 (and 3.1)

Inclusion in the observables, Fits to the available data...

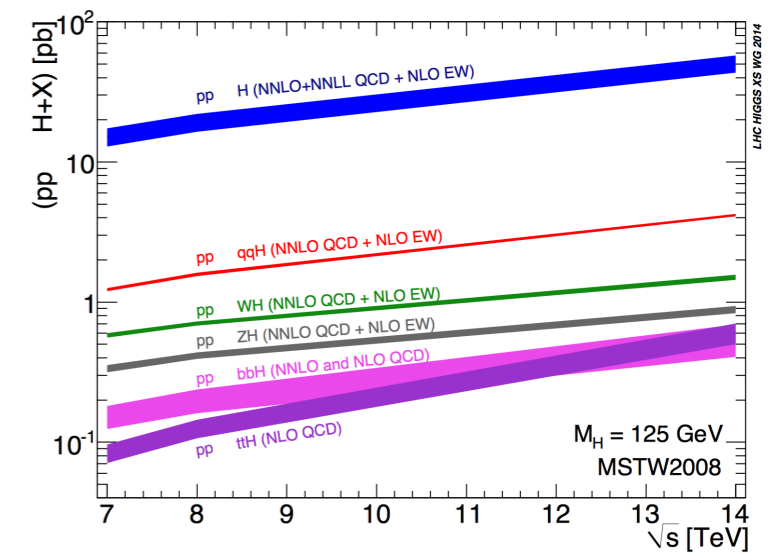
How to get the Higgs boson at the LHC?

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

Due to the dominance of gluon pdf



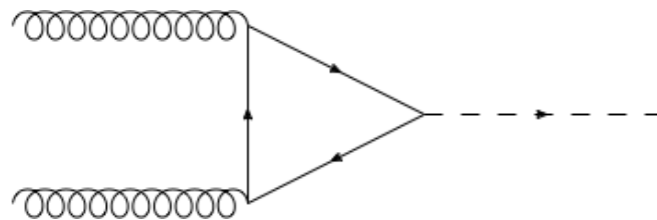
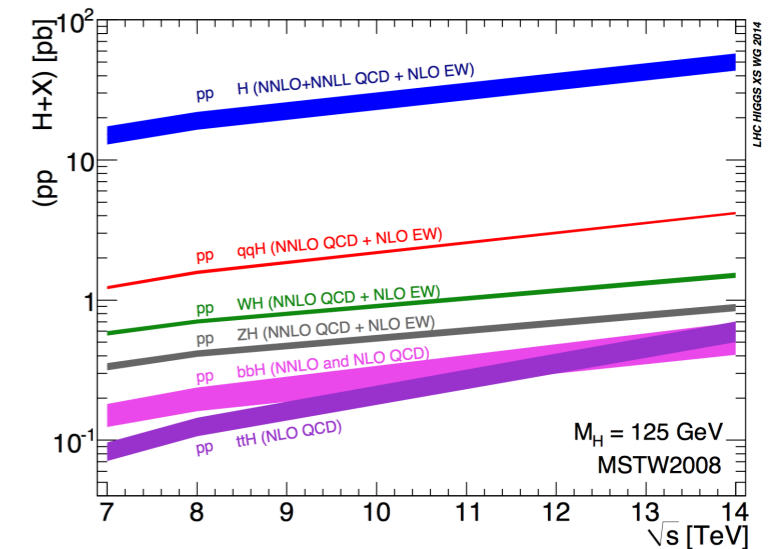
Even though it is loop induced process



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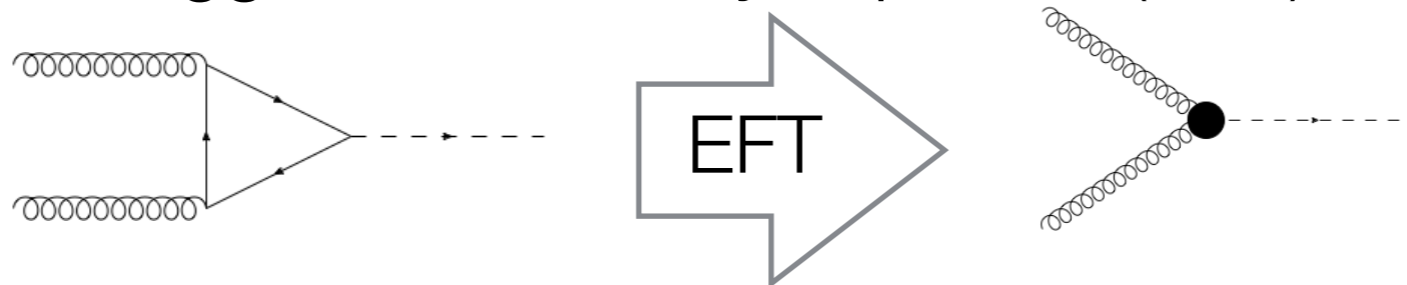
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Top mass > Higgs mass: Heavy Top Limit (HTL) useful approximation:



Known up to NLO QCD

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

Spira et al.'91, '95; Anastasiou et al.'09

and NLO EW corrections

Aglietti et al.'04; Degrossi, Maltoni '04;

Passarino et al '08

NNLO QCD

Harlander, Kilgore '02; Anastasiou, Melnikov '02;

Ravindran, Smith, Van Neerven '03

and with N3LL resummation

de Florian, Grazzini '12; Bonvini, Marziani '14; Schmidt, Spira '15

with approximate top mass effects

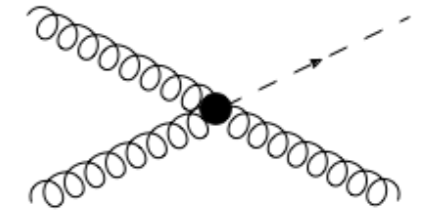
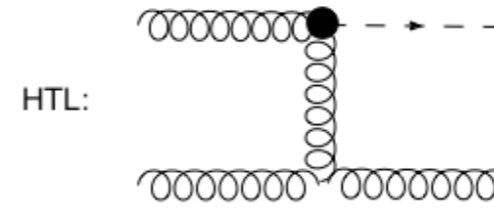
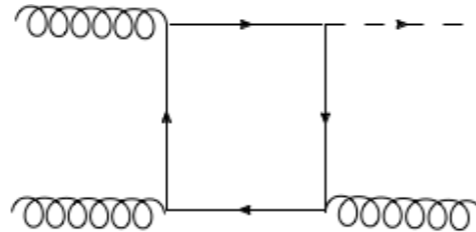
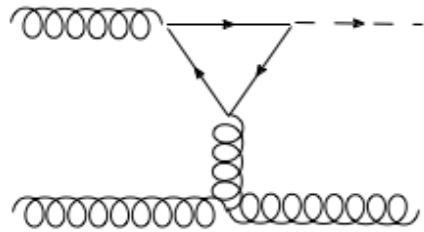
Marzani et al.'08; Harlander et al.'09,'10; Steinhauser et al.'09

N3LO QCD

Anastasiou, Duhr, Mistlberger et al.'13-'15

Why and how we care about Higgs p_T ?

We need an additional parton to recoil against the Higgs



LO known:

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

NLO first partial results:

Bonciani et al.'16

NNLO results:

Boughezal, Caola, et al.'13-'15; Boughezal, Focke et al.'15;
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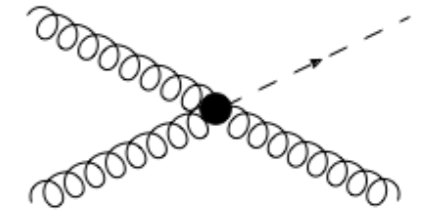
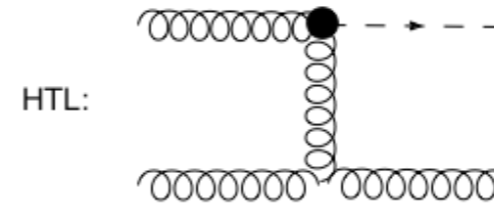
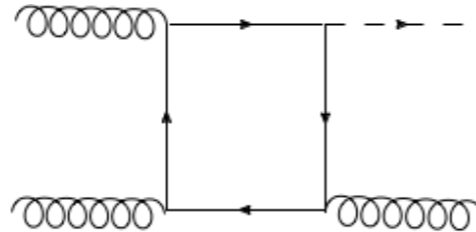
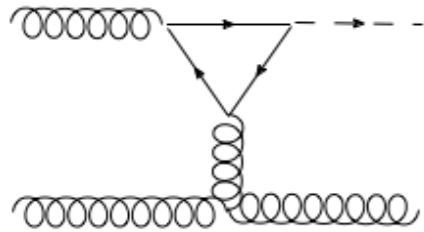
de Florian, Grazzini, Kunszt '99; Glosser, Schmidt '02;
Ravindran, Smith, Van Neerven '02

with approximate top mass effects:

Neumann et al.'12-'14; Grazzini, Sargsyan '13;
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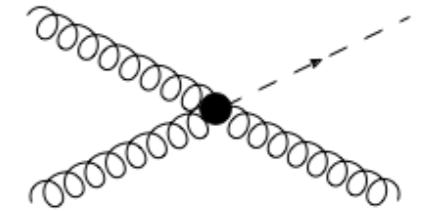
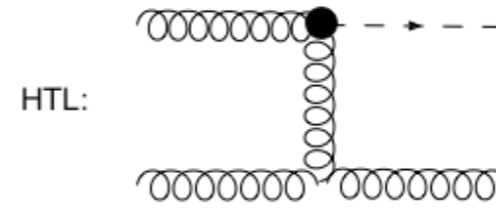
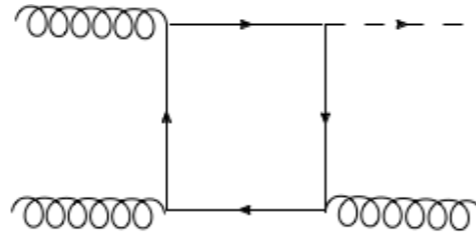
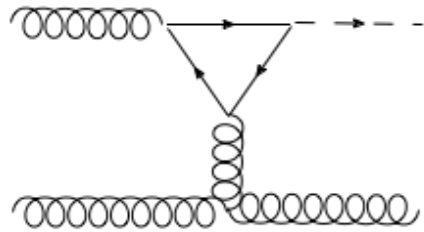
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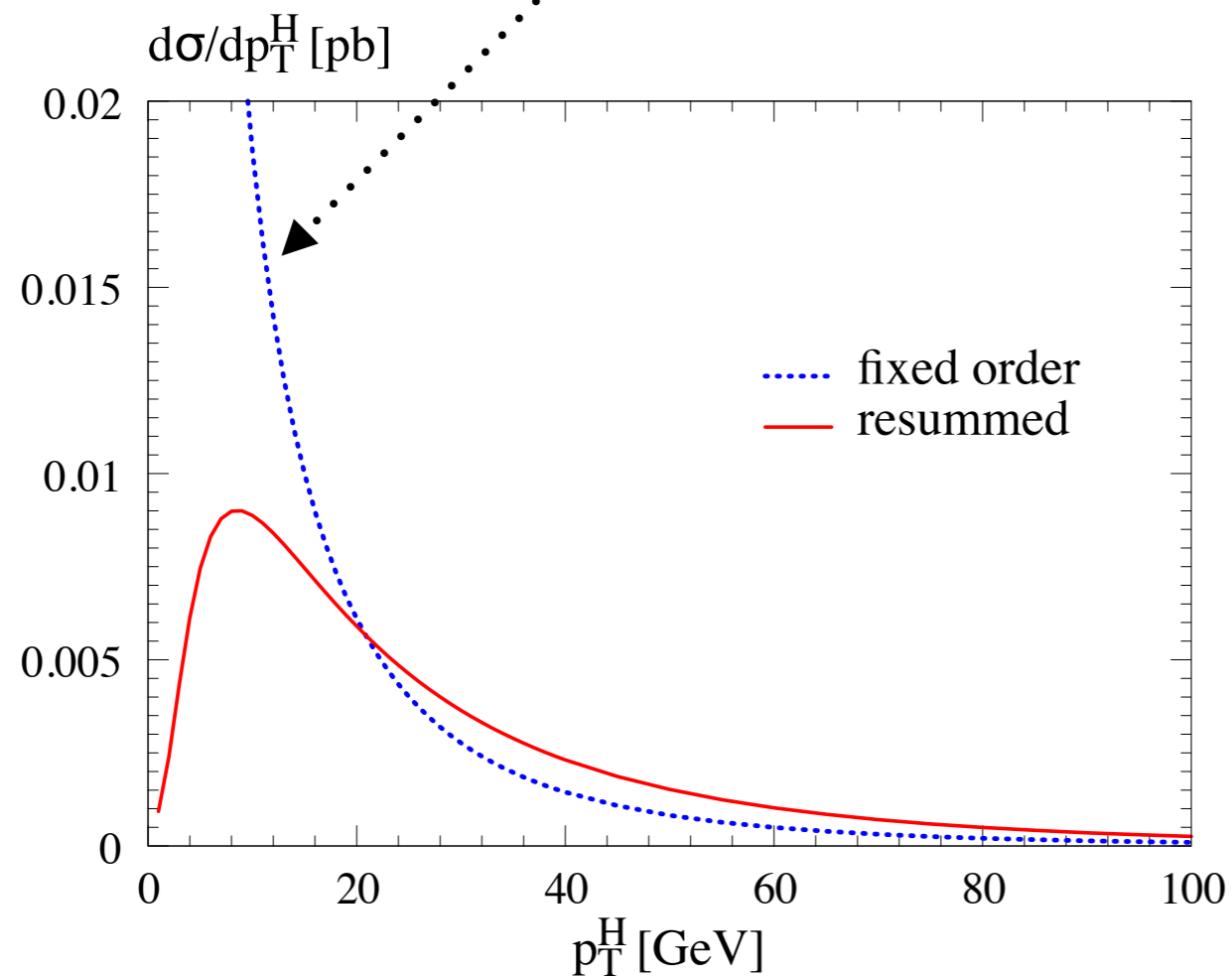
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“New Physics sits in the tails of distributions”

but there is a problem at low p_T ...

Problems at low p_T ? Resummation!

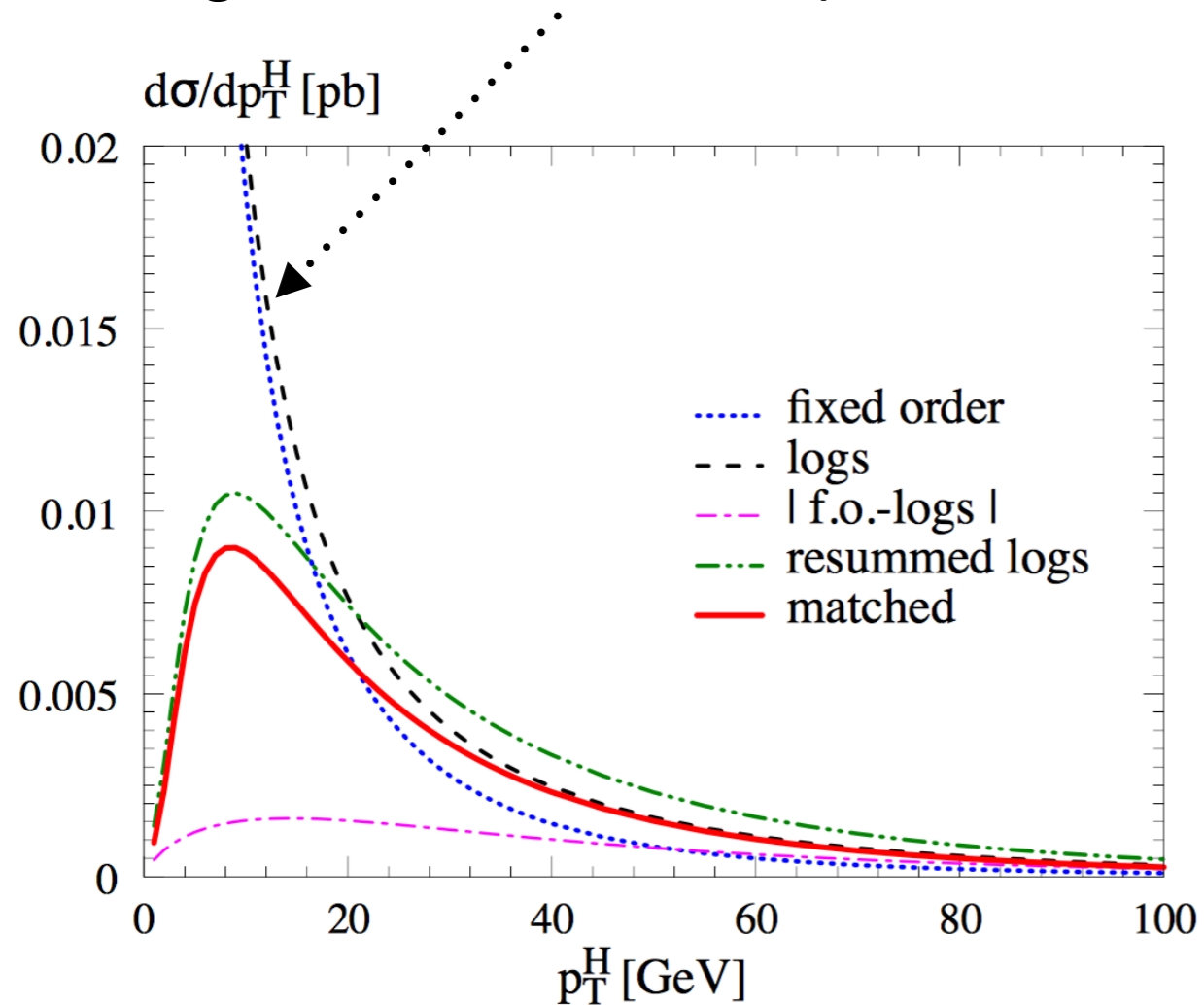
Singular behaviour at $p_T < m_H$



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

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

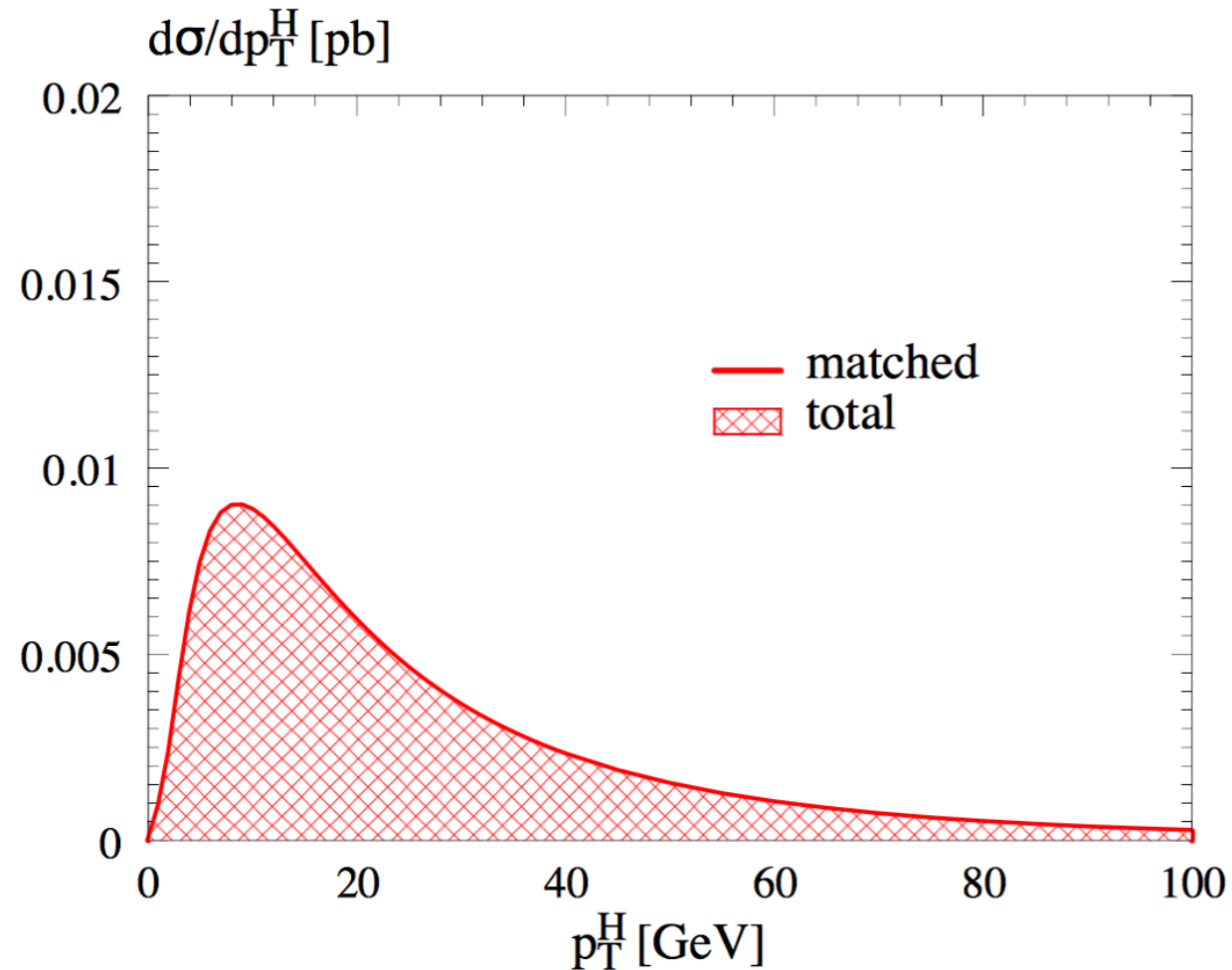
Collins, Soper, Sterman '85

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

Bozzi, Catani, de Florian, Grazzini '05

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

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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

$$\mathcal{O}_1 = |H|^2 G_{\mu\nu}^a G^{a,\mu\nu}$$

$$\mathcal{O}_2 = |H|^2 \bar{Q}_L H^c u_R + h.c.$$

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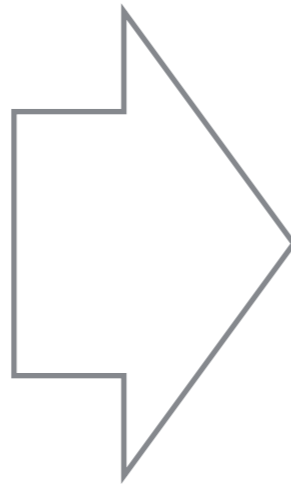
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$$\frac{\alpha_S}{\pi v} c_g h G_{\mu\nu}^a G^{a,\mu\nu} \leftarrow \dots \text{ as HTL in SM}$$

$$\frac{m_t}{v} c_t h \bar{t} t \leftarrow \dots \text{ modified top/bottom}$$

$$\frac{m_b}{v} c_b h \bar{b} b \leftarrow \dots \text{ Yukawa coupling}$$

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

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can be bounded from $h \rightarrow b\bar{b}$ decay (and $b\bar{b}h$ production)

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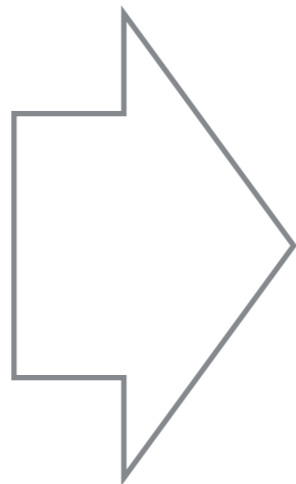
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Easiest to bound from the Higgs pT spectrum

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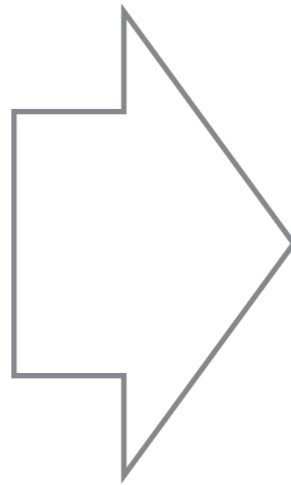
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Previous studies including dimension 6 and dimension 8 operators

Grojean, Salvioni et al.'13;

Azatov, Paul '13,

Langenegger, Spira et al.'15

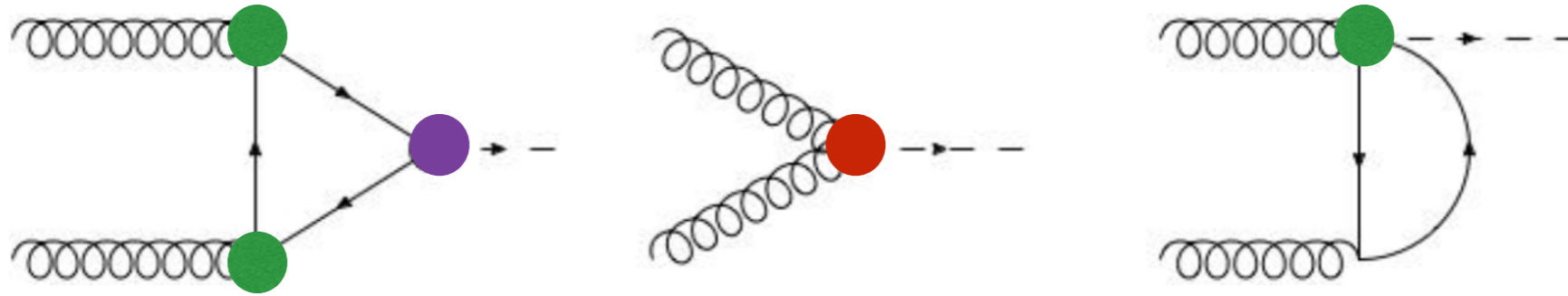
Maltoni, Vryonidou, Zhang '16

Harlander, Neumann'13,

Dawson, Lewis, Zeng'14

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

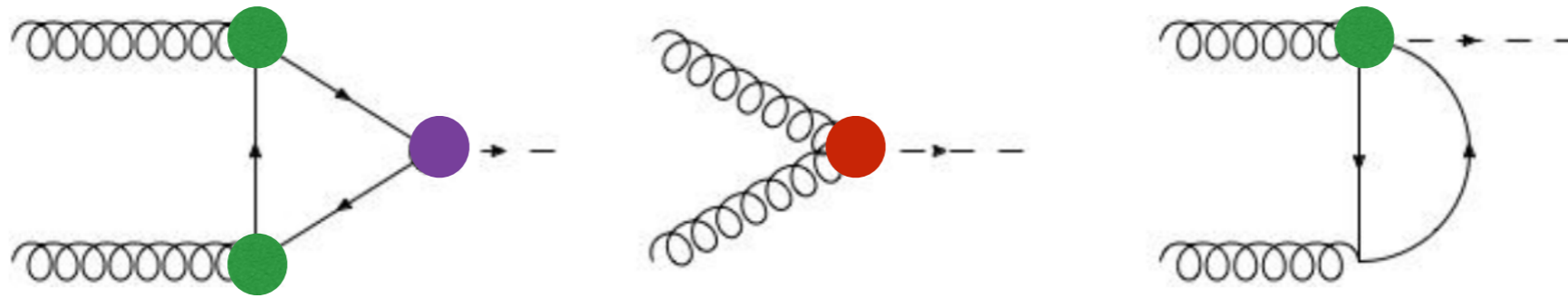
Higgs production at LO



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

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

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Calculations published with contradictory results

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

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

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

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

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

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

Formally higher order of γ_t

Choudhury et al '12
Degrande et al '12

Higgs transverse momentum spectrum

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

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We included three of SMEFT operators:

- top Yukawa modification
- bottom Yukawa modification ◀..... Can re-use the SM calculations
- *ggh* point-like coupling

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Calculations performed at the **NLL+NLO** level of accuracy

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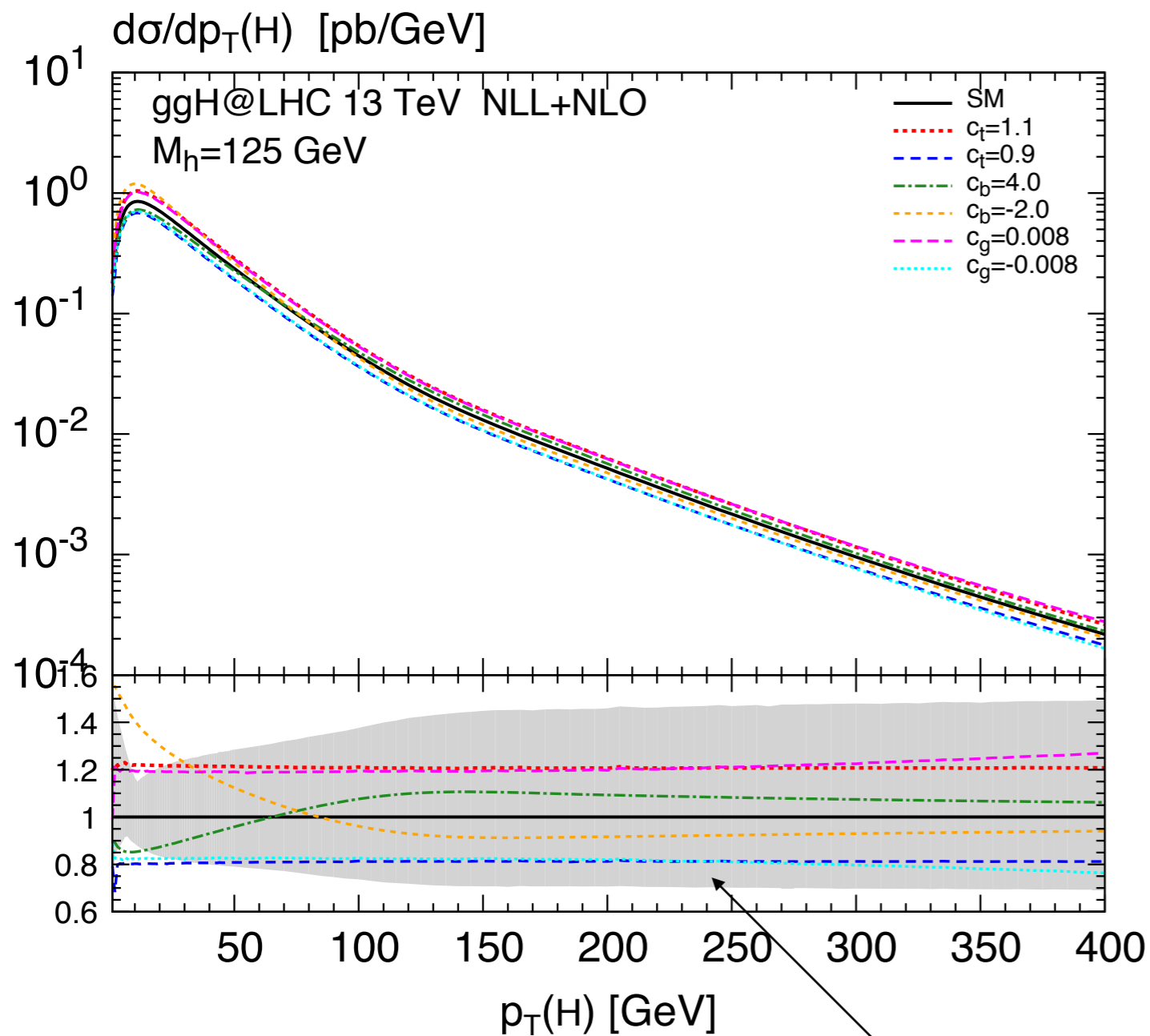
Renormalisation and factorisation scales: $\mu_R = \mu_F = \mu_0 = \sqrt{p_T^2 + m_H^2}/2$

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

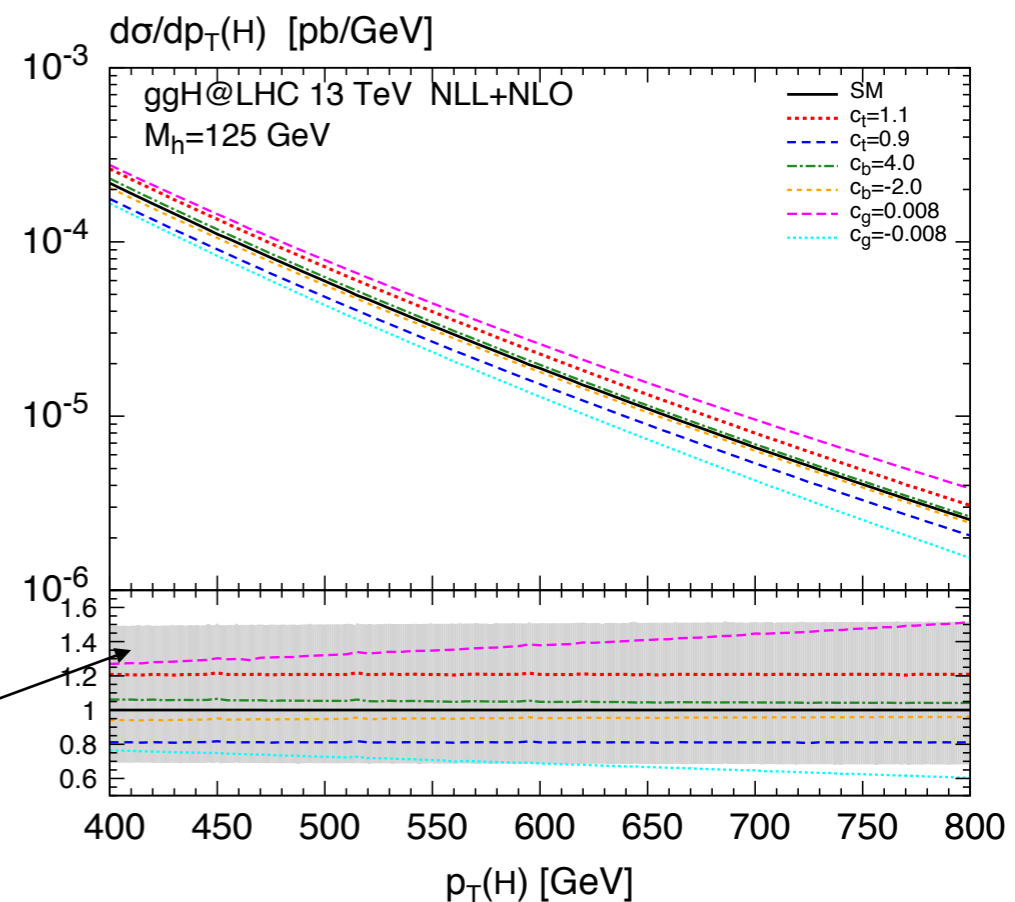
Parton distribution functions: NLO set from PDF4LHC2015

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

Separate contributions of dim 6 operators

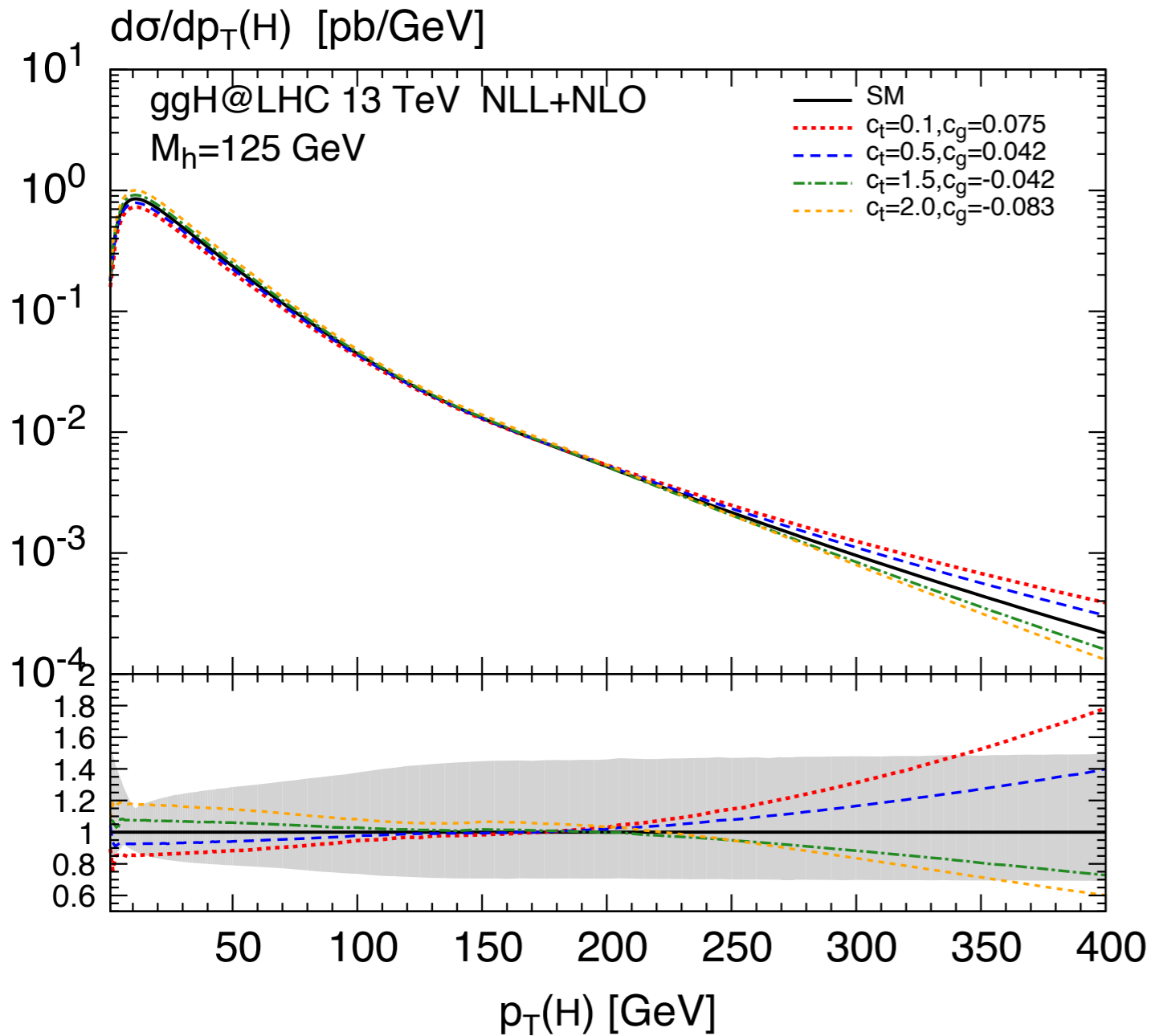


- Kept within 20% from SM total cross section
- Not exceeding (much) the SM uncertainty
- Effects in different regions of the spectrum



SM scale variation

Mixed contributions of c_t and c_g

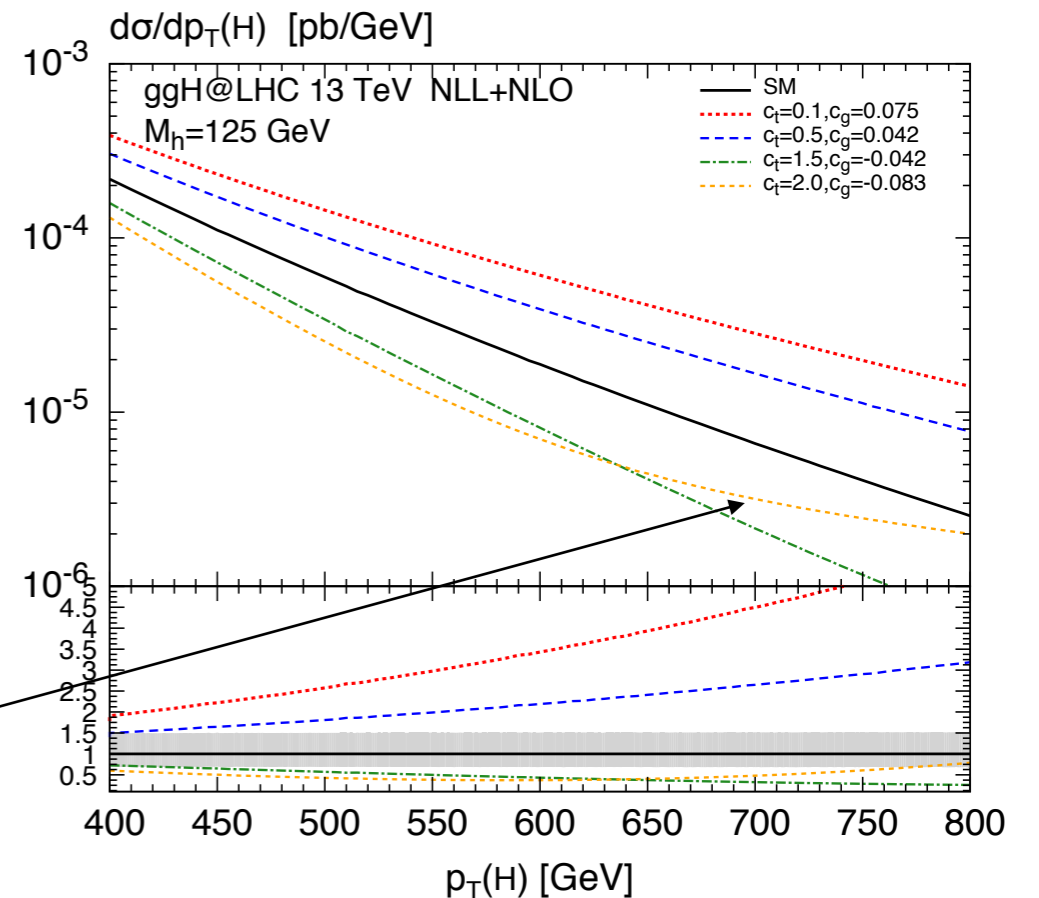


- More dramatic shape effects with same total rate

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

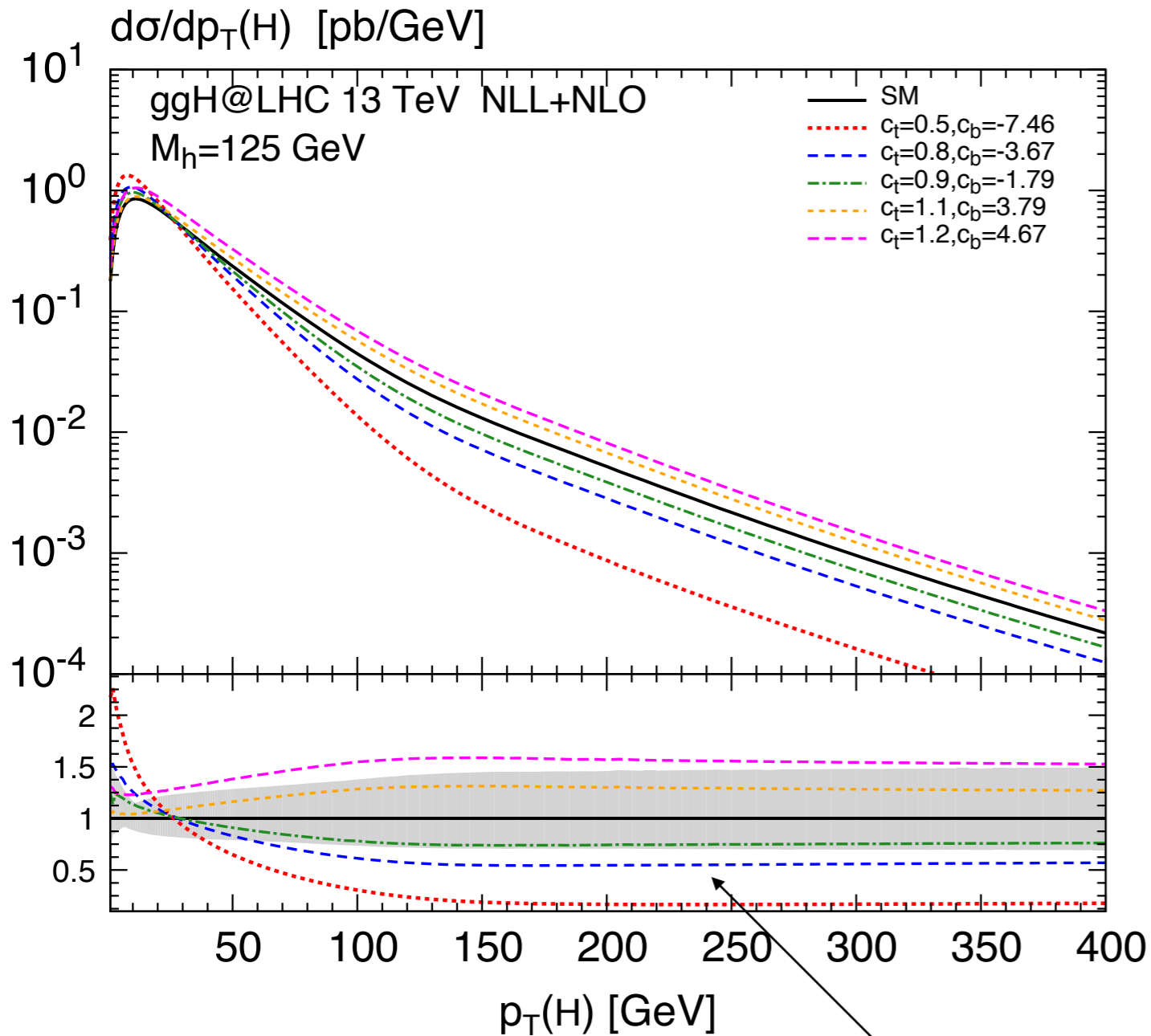
- At high p_T clearly visible effect of point-like coupling

effect caused by dominance of c_g^2

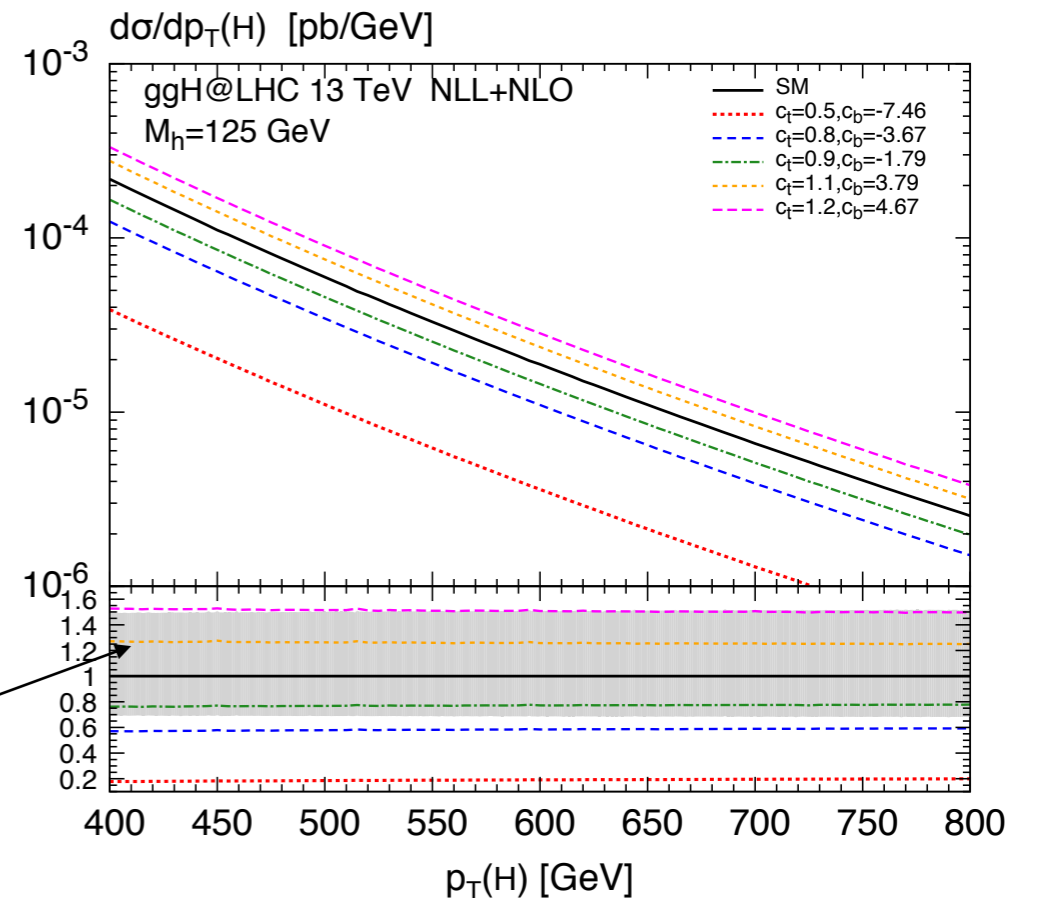


Mixed contributions of ct and cb

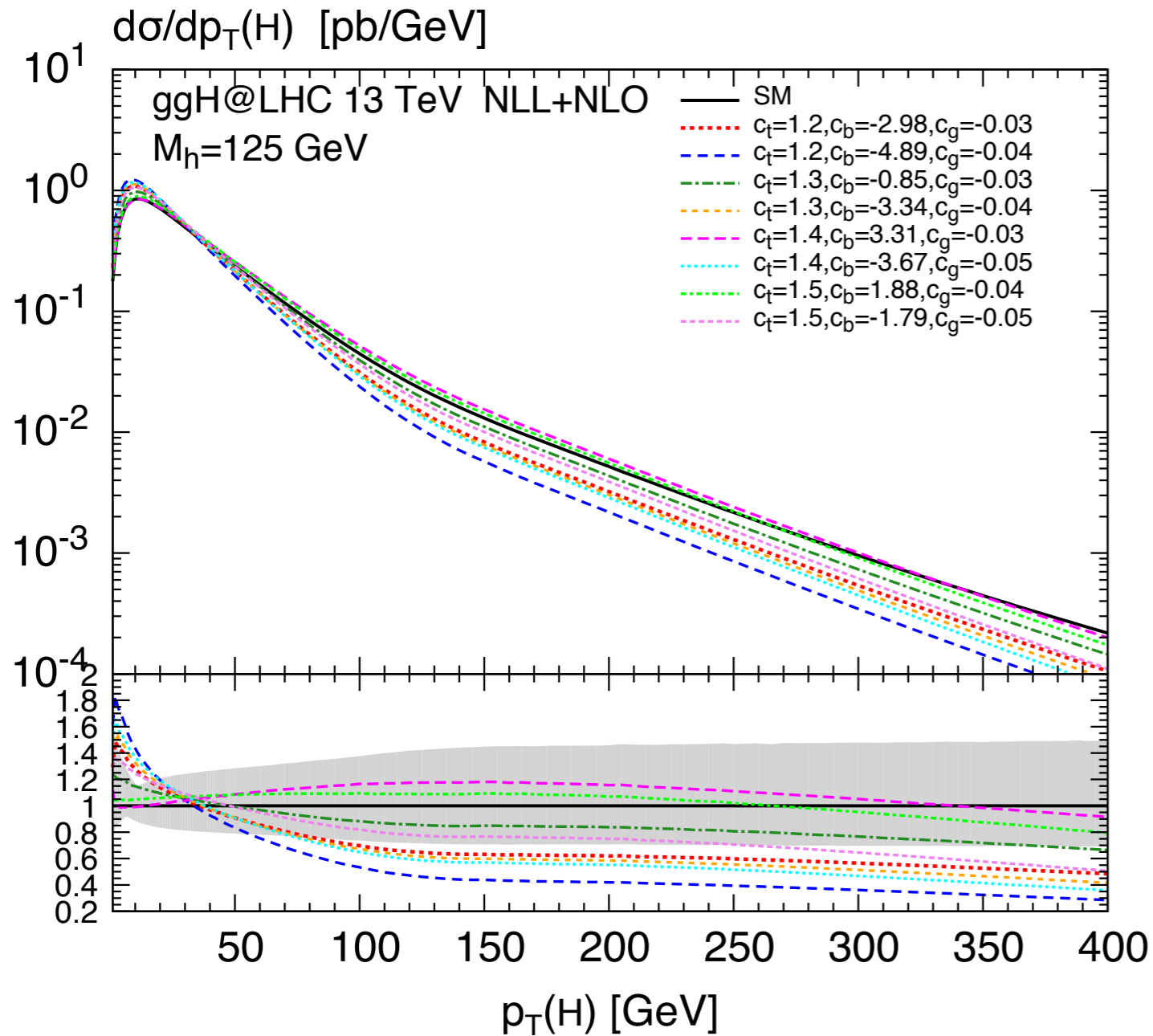
- For $ct > 1$ hard to balance with real cb
- At low p_T clearly visible effect of modification of bottom Yukawa
- For $p_T > 150$ GeV governed by the ct modification



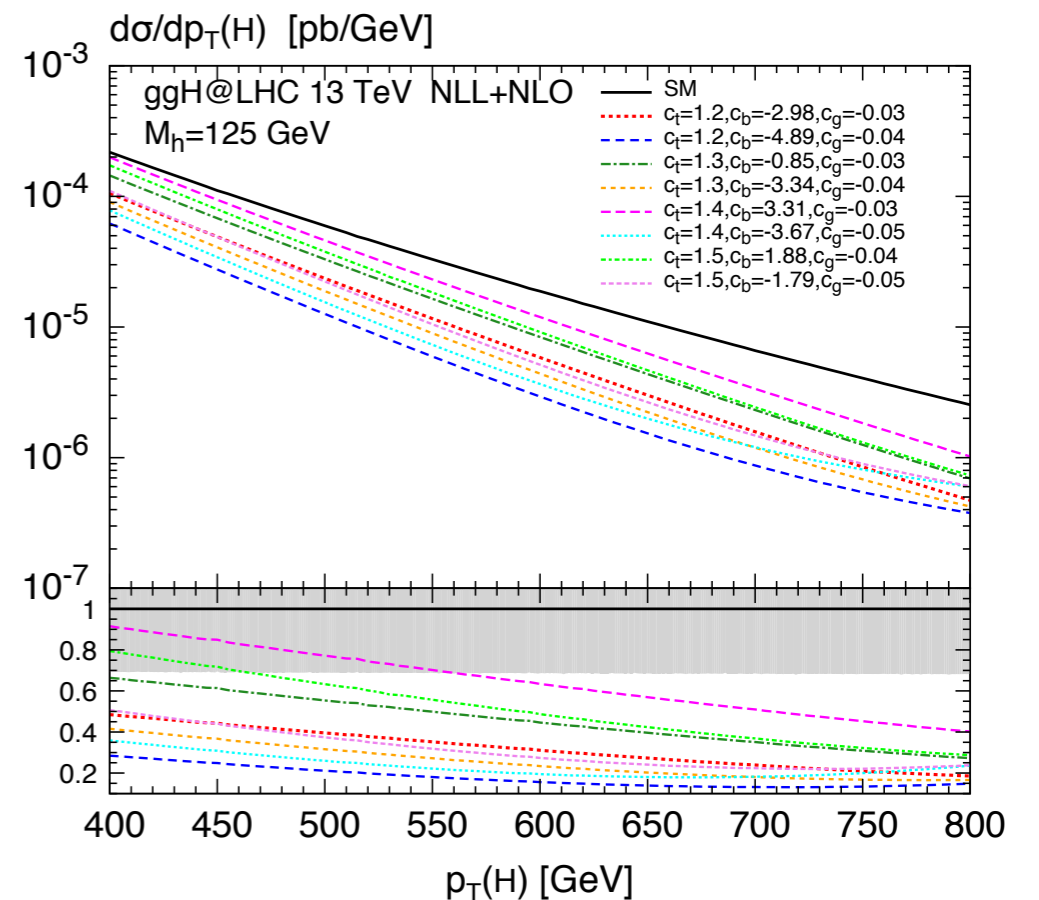
No shape distortion compared to SM
 top loop dominance



Mixed contributions of all three operators



- Scenario with enhanced top Yukawa, inspired by the higher than SM rate of $t\bar{t}H$ in first CMS and ATLAS results
- Leads to the softer spectrum
- Combination of all previous effects



Higgs p_T spectrum at NNLL+NNLO

NEW

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:

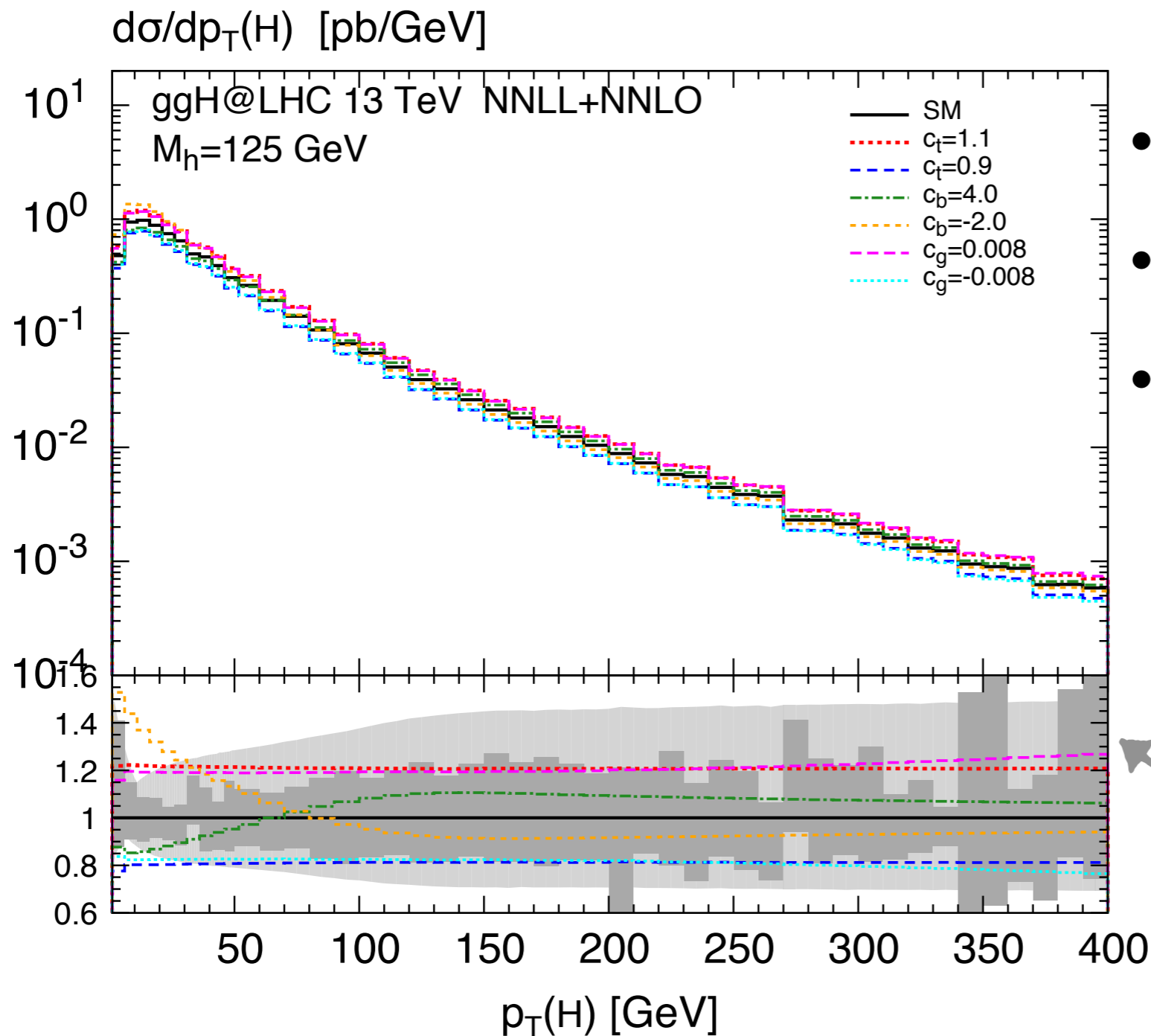
$$\left(\frac{d\sigma}{dp_t}\right)_{NNLL+NNLO}^{SMEFT}(p_T) = \frac{\left(\frac{d\sigma}{dp_t}\right)_{NLL+NLO}^{SMEFT}(p_T)}{\left(\frac{d\sigma}{dp_t}\right)_{NLL+NLO}^{SM}(p_T)} \cdot \left(\frac{d\sigma}{dp_t}\right)_{NNLL+NNLO}^{SM}(p_T)$$

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

NEW

Higgs p_T spectrum at NNLL+NNLO

Separate contributions of dim 6 operators



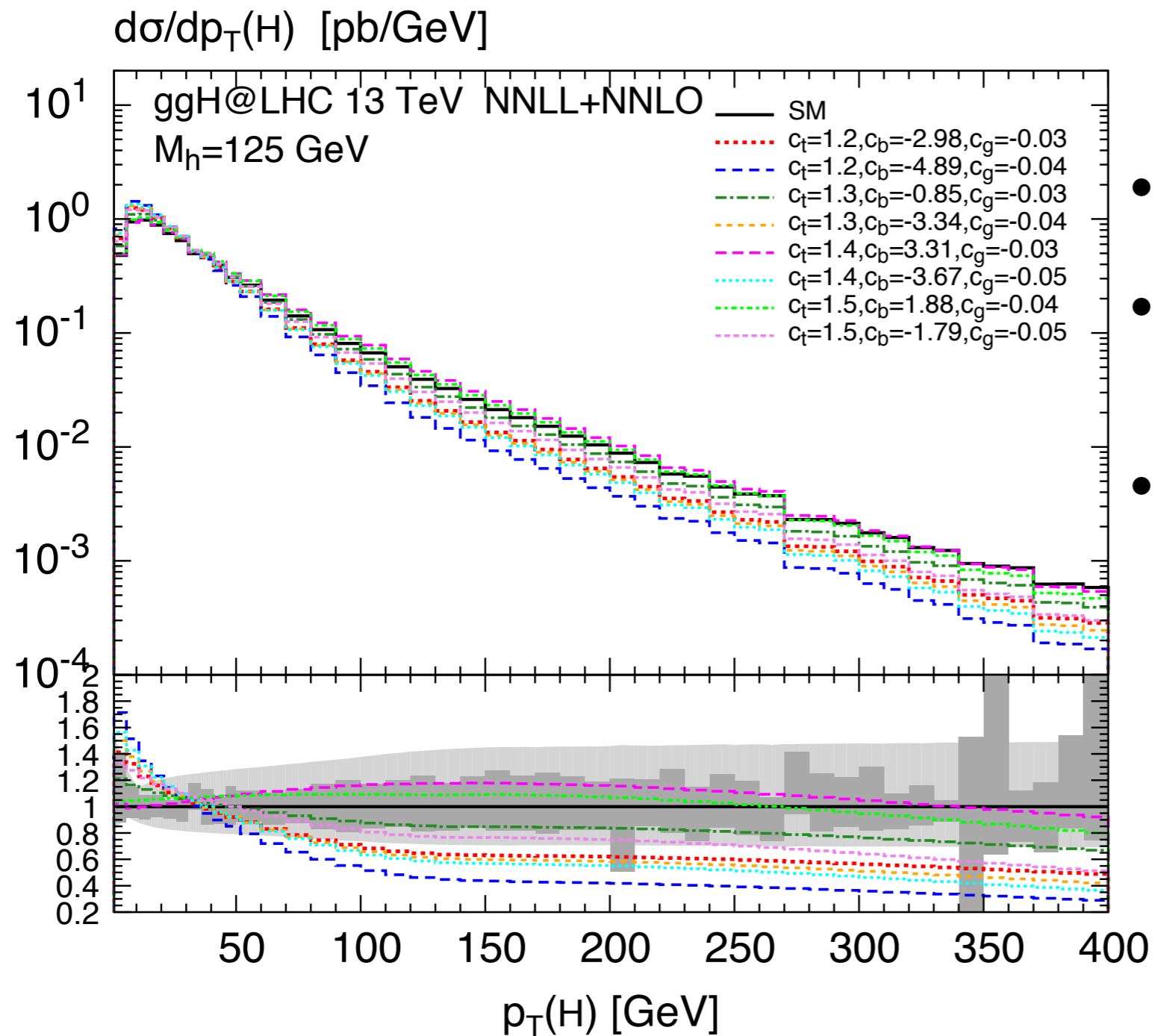
- Noticeable improvement of scale variation at low p_T
- BSM effects exceeding the SM uncertainty
- At high p_T problems due to the statistics (*HRes* numerical)

- The SM scale variation:
- light grey NLL+NLO
 - dark grey NNLL+NNLO

NEW

Higgs p_T spectrum at NNLL+NNLO

Mixed contributions of all three operators



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

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 Higgs production and its p_T spectrum

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

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

Thank you for the attention!

Back-up

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 in the SM
- work in progress...

