

*Higgs Hunting 2015, Orsay*

# Effects of higher dimensional operators on the Higgs' pT spectrum

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# Motivation

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## Why Effective Field Theory?

- ❖ No direct signs of New Physics
- ❖ New Physics is required (hierarchy problem, dark matter, cosmology, ... )
- ❖ New resonances may lay beyond reach of LHC
- ❖ EFT approach to BSM physics (Buchmueller, Wyler '86; Grzadkowski, Iskrzynski et al.'10):
  - ❖ consistent way to account for small deviations from SM
  - ❖ is complementary to the direct search for New Physics
  - ❖ is model independent way to parametrise New Physics

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# Motivation

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## Why Higgs pT spectrum?

- ❖ More info than just one number, as in e.g. total cross section
  - ❖ shape
  - ❖ maximum position
  - ❖ normalisation
- ❖ Enables to disentangle information, e.g. gluon Higgs coupling
- ❖ For low pT region resummation is needed
- ❖ For a scalar: production and decay factorise
- ❖ Useful for experimental analysis

# Effective Field Theory

- ❖ Full theory: light and heavy ( $M_{high} \sim \Lambda$ ) degrees of freedom:

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

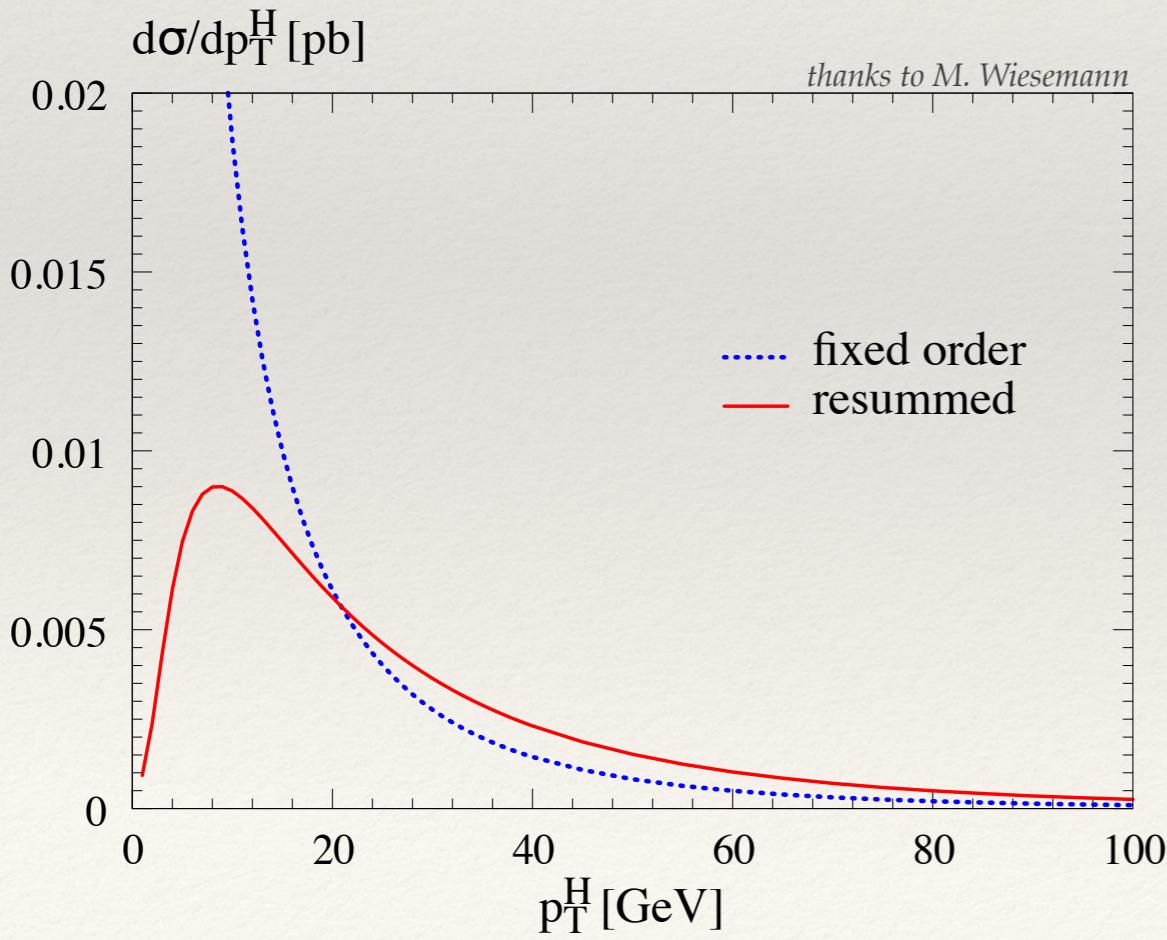
- ❖ When scale separation is big and we consider the theory at the energy scales  $\ll \Lambda$  we can integrate out the heavy degrees of freedom
- ❖ That leads to infinite ladder of new operators (expansion in  $\Lambda^{-1}$ )

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

- ❖ The new operators  $\mathcal{O}_i^{(k)}$ :
  - ❖ consist of fields from  $L_{low}$
  - ❖ are Lorentz and gauge invariant
  - ❖ have dimension  $> 4$
  - ❖ are nonrenormalizable
- ❖ Consistent way to parametrise the deviations from SM
- ❖ Bijective between model predictions and experimental measurements

# Higgs' pT spectrum

- ❖ Gluon fusion is loop process already at Leading Order
- ❖ For pT spectra parton is needed in final state to recoil against Higgs
- ❖ Fixed order pT spectra valid up to  $\sim M_H$



## Fixed order:

- ❖ LO pT spectrum known from '90 (Ellis, Hinchliffe et al.'88; Baur, Glover '90)
- ❖ NLO pT spectrum calculations in the heavy top limit (de Florian, Grazzini, Kunszt '99; Glosser, Schmidt '02; Ravindran, Smith, Van Neerven '02)
- ❖ Results on Higgs + jet at NNLO (Boughezal, Caola, et al.'13; Chen, Gehrmann, Glover, Jaquier '14)

## Resummation:

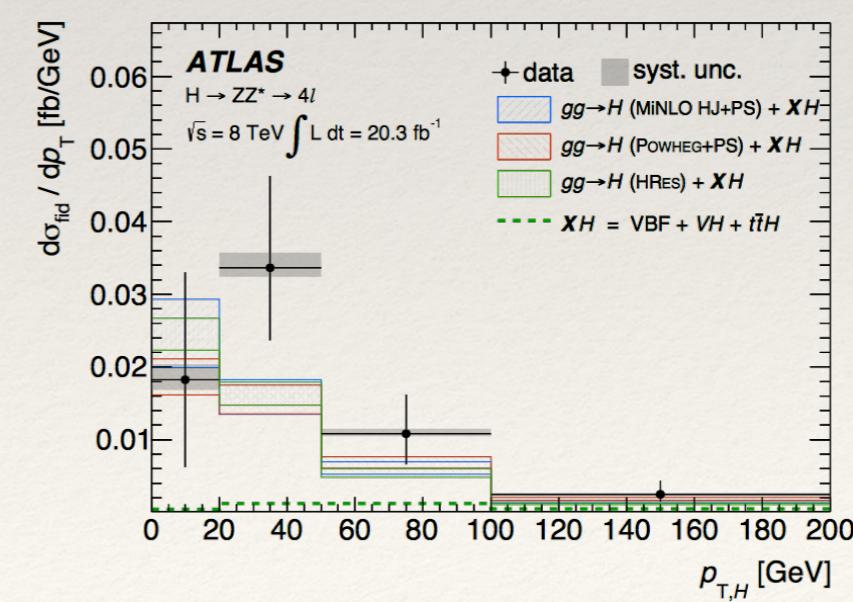
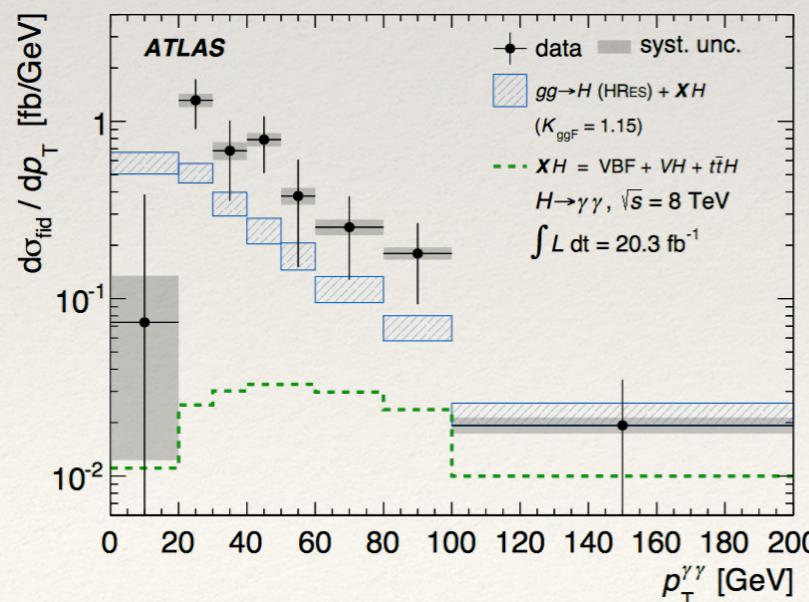
- ❖ For  $p_T \ll M_H$  the perturbative expansion is affected by large logarithms  $\sim \ln^n(\frac{m_H^2}{p_T^2})$
- ❖ These terms can be systematically resummed by working in impact parameter b-space (Collins,Soper, Sterman '85)
- ❖ Then the two (resummed and fixed order) regions needs to be matched 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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# (Very incomplete) list of BSMeff works

- ❖ Full classification of dimension 5, 6 and 7 BSMeff operators (Buchmueller, Wyler '86; Grzadkowski, Iskrzynski et al.'10, Lehman '14)
- ❖ Bounds on the Wilson coefficients from EW and Higgs observables (e.g. Riva et al.'13-'14)
- ❖ Discussion on strategy how to use BSMeff to determine if NP is weakly or strongly interacting (Contino, Ghezzi et al.'13)
- ❖ Renormalisation of dimension 6 operators at NLO (Passarino et al. '13-'15)
- ❖ Impact of dimension 6 and 8 operators on the Higgs high pT spectrum at LO (e.g. dim6: Grojeana, Salvioni et al.'13; Azatov, Paul '13, Langenegger, Spira et al.'15; dim8: Harlander, Neumann'13, Dawson, Lewis, Zeng'14)
- ❖ First data on Higgs pT spectrum from ATLAS in diphoton and four lepton channel (1407.4222,1408.3226)



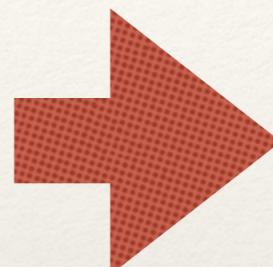
# Our approach

- Three dim 6, gauge invariant operators

$$\bar{\mathcal{O}}_1 = \frac{c_1}{\Lambda^2} |H|^2 G_{\mu\nu}^a G^{a,\mu\nu}$$

$$\bar{\mathcal{O}}_2 = \frac{c_2}{\Lambda^2} |H|^2 \bar{Q}_L H^c u_R + h.c.$$

$$\bar{\mathcal{O}}_3 = \frac{c_3}{\Lambda^2} |H|^2 \bar{Q}_L H d_R + h.c.$$



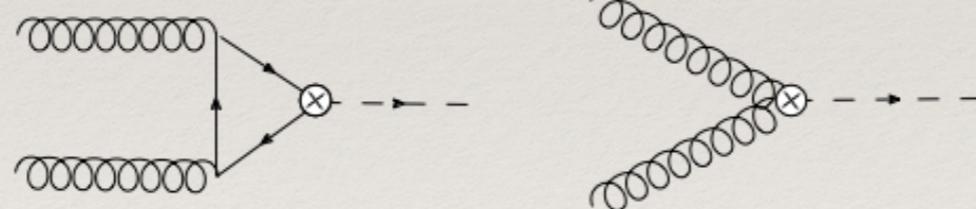
$$\frac{\alpha_s}{\pi v} c_g h G_{\mu\nu}^a G^{a,\mu\nu}$$

$$\frac{m_t}{v} c_t h \bar{t} t$$

$$\frac{m_b}{v} c_b h \bar{b} b$$

ggH coupling has same structure as heavy top limit, and following are modifications of Yukawa couplings

- Leading order contributions:



- Total cross section cannot separate these contributions:

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

- $c_t$  bounded from ttH production,  $c_b$  from bb decay channel but no easier way to put limits on  $c_g$
- Implemented in HqT and crosschecked with HIGLU and HNNLO

$d\sigma/dp_T(H)$  [pb/GeV]

ggH@LHC 13 TeV NLO+NLL

$M_h = 125$  GeV

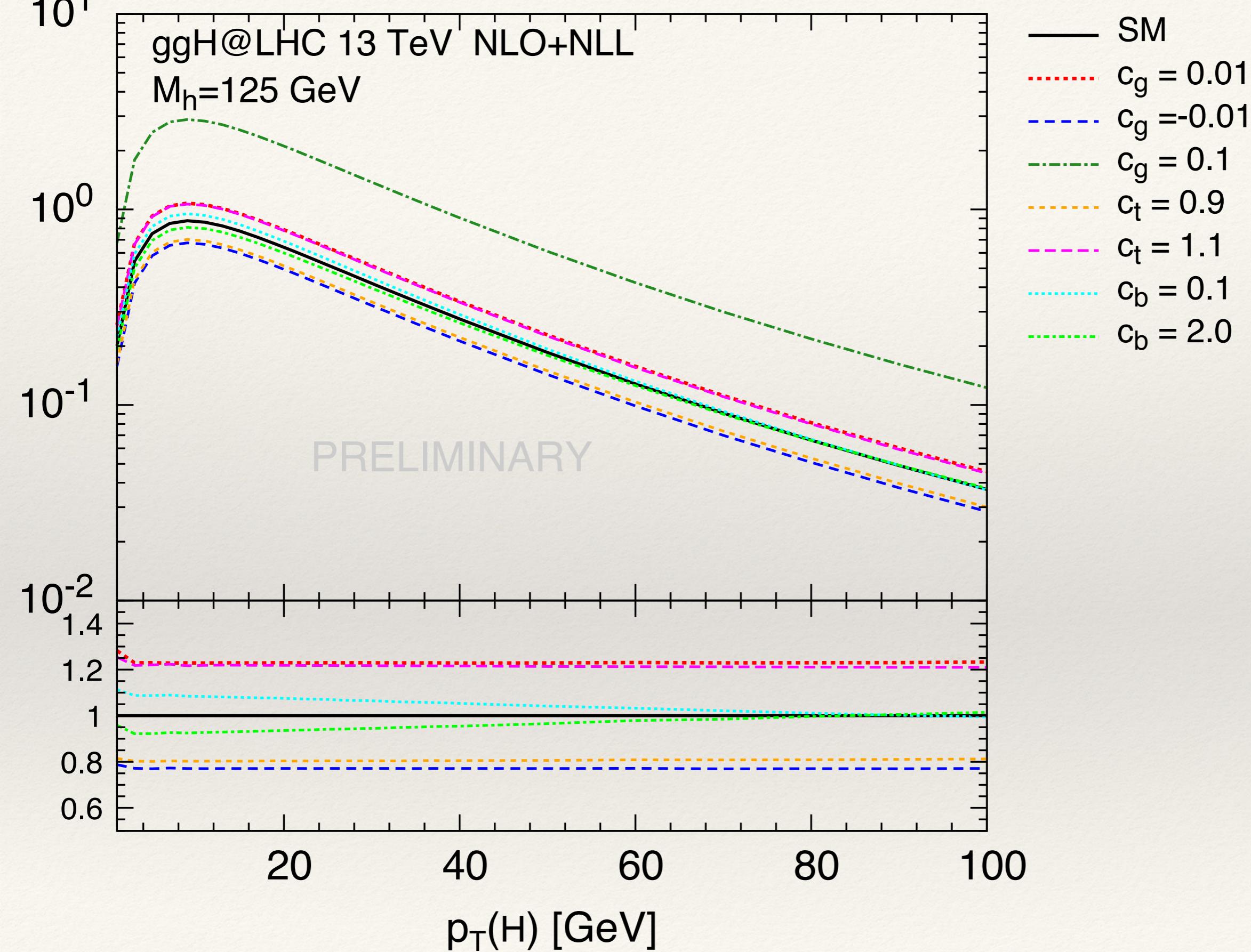
- SM
- - -  $c_g = 0.01$
- - -  $c_g = -0.01$
- - -  $c_g = 0.1$
- - -  $c_t = 0.9$
- - -  $c_t = 1.1$
- - -  $c_b = 0.1$
- - -  $c_b = 2.0$

PRELIMINARY

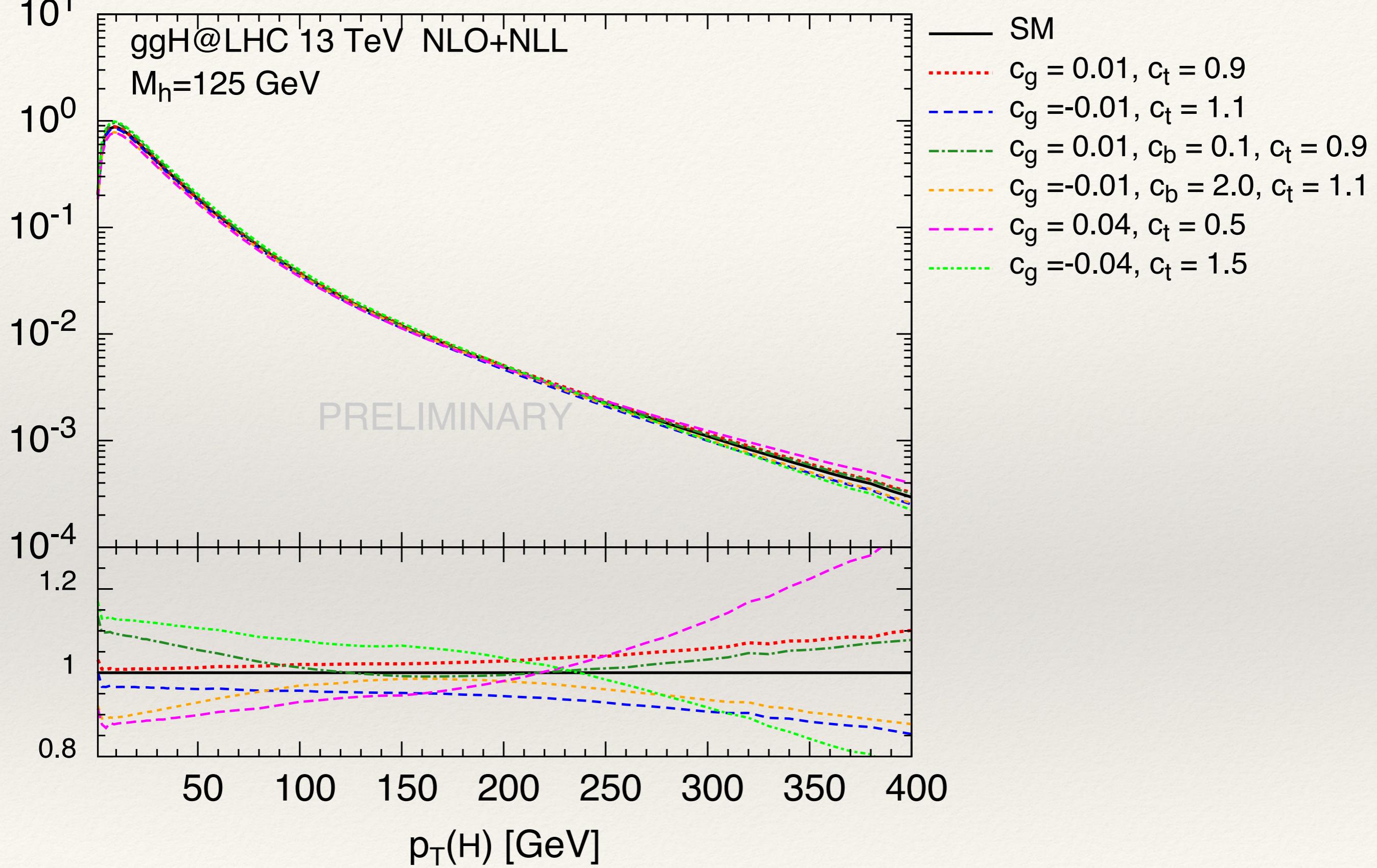
50 100 150 200 250 300 350 400

$p_T(H)$  [GeV]

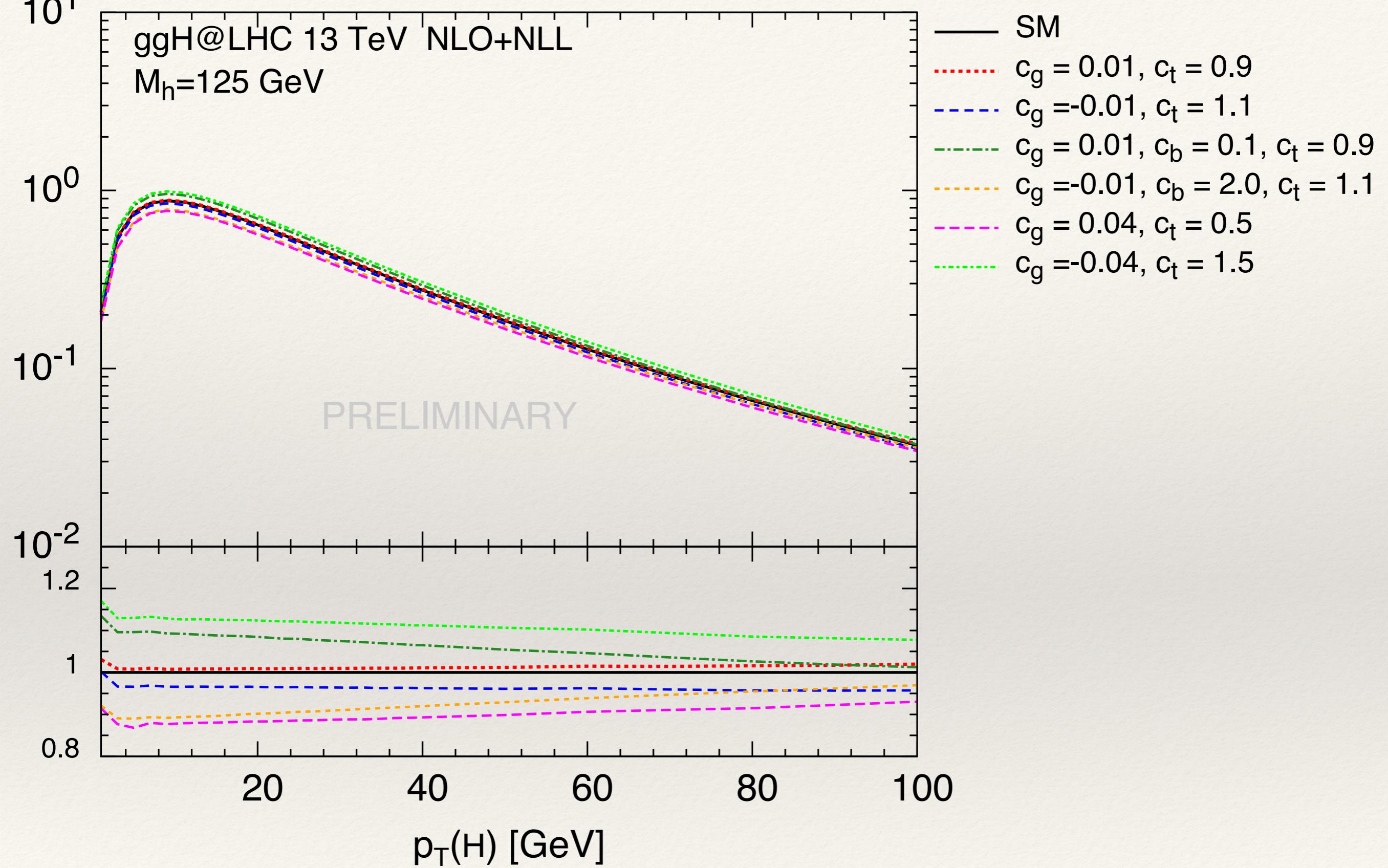
$d\sigma/dp_T(H)$  [pb/GeV]



$d\sigma/dp_T(H)$  [pb/GeV]



$d\sigma/dp_T(H)$  [pb/GeV]



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# Outlook

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- ❖ Finish new NLO implementation based on HPL and crosscheck
- ❖ Include chromomagnetic operator
- ❖ Go order higher in QCD to obtain state of the art NNLO+NNLL predictions
- ❖ Go order higher in EFT:
  - ❖ new operator basis
  - ❖ new tensor structures

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# Summary

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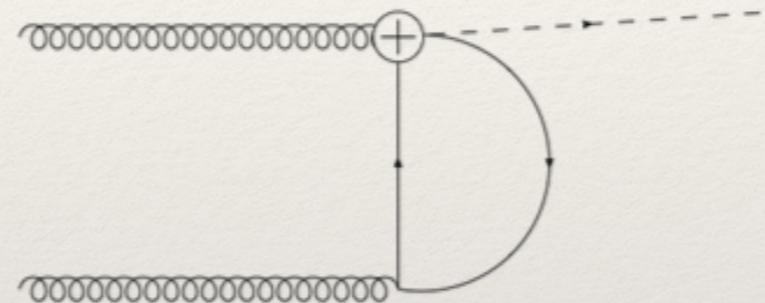
- ❖ EFT is the model independent way to consistently study the high scale BSM physics
- ❖ pT spectra are very useful to study Higgs couplings
- ❖ The pT spectra with dim 6 operators included at NLO+NLL level are available
- ❖ For first time low pT region with EFT operators is also covered
- ❖ Stay tuned for the release very soon

Back up

# Chromomagnetic operator

$$\mathcal{O}_{ChM} = \frac{c_{ChM} g_S}{m_W^2} (\bar{Q}_L H) \sigma^{\mu\nu} T^a t_R G_{\mu\nu}^a$$

The diagram relevant for  $p p \rightarrow H$



Strongly bounded by measurements of  $t\bar{t}$  in hadron colliders:

$$-1.39 \cdot 10^{-4} < \Im(c_{ChM}) < 1.21 \cdot 10^{-4}$$

$$-6.12 \cdot 10^{-3} < \Re(c_{ChM}) < 1.94 \cdot 10^{-3}$$

mixes with Yukawa-like operator at NLO

# Crosschecks:

HIGLU:

at $p_T = 300$ GeV, gg channel		
Couplings	HIGLU	Our implementation
$c_t=2; c_b=1; c_g=0$	0.1763 E-02	0.1764 E-02
$c_t=100; c_b=1; c_g=0$	4.359	4.360
$c_t=1; c_b=2; c_g=0$	0.4559 E-03	0.4561 E-03
$c_t=1; c_b=100; c_g=0$	0.2332 E-02	0.2333 E-02
$c_t=1; c_b=1; c_g=0.001$	0.4570 E-03	0.4573 E-03
$c_t=1; c_b=1; c_g=0.1$	0.2292 E-02	0.2291 E-02

HNNLO:

C1 virtual correction		
Couplings	HNNLO	Our implementation
$c_t=1; c_b=1; c_g=1.2$	8.7067	8.7067
$c_t=1; c_b=1; c_g=12$	7.6256	7.6256
$c_t=1; c_b=1; c_g=120$	7.4263	7.4263
$c_t=5; c_b=1; c_g=12$	8.2506	8.2507
$c_t=1; c_b=1; c_g=0.001$	7.6257	7.6257

$\sigma_{NLO}^{tot}(gg)$		
Couplings	HNNLO	Our implementation
SM	14.78 pb	14.78 pb
$c_t=1.1; c_b=1; c_g=0.1$	21.02 pb	21.00 pb