Effects of higher dimensional operators on the Higgs p_T spectrum

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Motivation

Why effective operators?

- In LHC run 1 no signs of BSM physics
- Theory viewpoint: New Physics is required (hierarchy problem, dark matter, cosmology, ...)
- Possible: NP at high scales beyond reach of current experiments
- However: NP may appear indirectly as (small) deviations from the SM predictions
- Effective Field Theory approach to Beyond Standard Model Physics (BSMeff) (Buchmüller, Wyler '86; Grzadkowski, Iskrzynski '10):
  - is complementary to the direct search for New Physics (see talks by Shruti, Matìas, Michele)
  - is model independent way to parametrise New Physics (see also talk by Raquel)

Motivation

Why Higgs p_T spectrum?

- Sheds light on the Higgs coupling to gluons
- Some effect may be impossible to disentangle just by measuring total cross section
- More information than just one number:
  - shape
  - position of maximum
  - normalisation
- The resummation needed to correctly treat low p_T region
- p_T spectrum is helpful in experimental analysis
- For a scalar: production and decay factorize

Motivation

Our goal

Start from the best perturbative QCD prediction available for the p_T spectrum to incorporate BSM effects in a model independent way.

Effective Field Theory approach to Beyond Standard Model physics [1]

Effective Field Theory

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

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

- When 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

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

- The new operators $\mathcal{O}_i^{(k)}$:
    - consist of fields from $\mathcal{L}_{low}$
    - are Lorentz and gauge invariant
    - have dimension > 4
    - are nonrenormalizable

[1] see also talk by Raquel

Effective Field Theory approach to Beyond Standard Model physics

Effective Field Theory approach to Beyond Standard Model physics (BSMeff)

- As light fields all the Standard Model fields included: $\mathcal{L}_{low} = \mathcal{L}_{SM}$
- Assumes scale separation between SM and NP: complementarity to direct search approach
- No mixing between light and heavy states
- From the SM fields we construct gauge invariant operators of higher dimension
- The experimental bounds on Wilson coefficients ($\bar{c}_i^{(k)}$) after matching to full theory may be translated to constrains of model parameters
- For the some specific models one may prefer to take other $\mathcal{L}_{low}$ limits, e.g. MSSM $\rightarrow$ 2HDM, NMSSM $\rightarrow$ 2HDM+S

Current status of Higgs production at hadron colliders

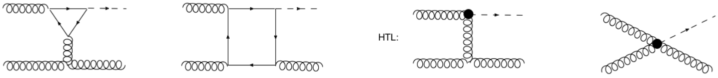
Calculations of total cross-section

- Note: Higgs production via gluon fusion is loop process at LO
- Higher orders of α_s corrections:
  - virtual: additional loop
  - real: additional parton in final state
- NLO corrections known from '90 (Ellis, Hinchliffe *et al.*'88; Baur, Glover '90; M.Spira *et al.*'91, '95; Dawson '91)
- NNLO corrections known in heavy top limit approximation (Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith, Van Neerven '03)
  - Approximate top mass effects (Marzani *et al.*'08; Harlander *et al.*'09,'10; Steinhauser *et al.*'09)
  - Inclusion of EW corrections (Aglietti *et al.*'04; Degrassi, Maltoni '04; Passarino '08)
- Recently, N^3LO calculations (Anastasiou, Duhr, Mistlberger *et al.*'13-'15)

The Higgs p_T spectrum in QCD perturbation theory

Fixed order calculations of p_T spectrum

- LO p_T spectrum is at $O(\alpha_s^3)$ (delta function at $O(\alpha_s^2)$): need parton radiation in final state to get nonzero p_T
- The contributions to LO p_T spectrum:



- p_T spectrum at fixed order valid for $p_T \gtrsim M_H$
- LO p_T spectrum known from '90 (Ellis, Hinchliffe *et al.*'88; Baur, Glover '90)
- NLO p_T spectrum calculations in the heavy top limit (de Florian, Grazzini, Kunszt '99; Glosser, Schmidt '02; Ravindran, Smith, Van Neerven '02)
  - approximate inclusion of top and bottom mass effects (Mantler, Wiesemann'12; Grazzini, Sargsyan '13)
- Results on Higgs + jet at NNLO (Boughezal, Caola, *et al.*'13; Chen, Gehrmann, Glover, Jaquier '14)

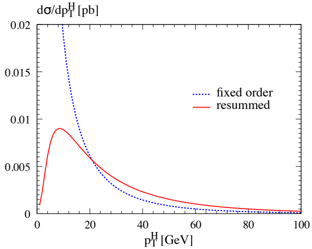
The Higgs p_T spectrum in QCD perturbation theory

Low p_T spectrum: 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 p_T (Bozzi,Catani,de Florian,Grazzini '05)

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

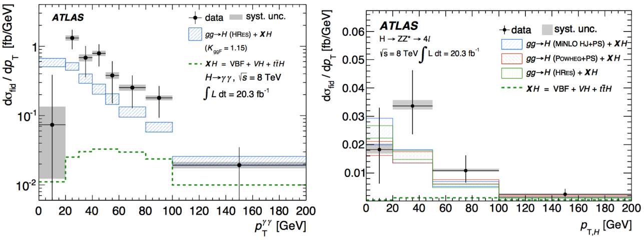
- The matched cross section satisfies the unitarity condition



from M. Wiesemann

What was done previously in BSMeff context

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



Our approach

BSM Effective Operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{\mathcal{O}}_i$$

- Three new, gauge invariant, dimension 6 operators:

$$\bar{\mathcal{O}}_1 = \frac{c_1}{\Lambda^2}|H|^2 G^a_{\mu\nu} G^{a,\mu\nu}; \bar{\mathcal{O}}_2 = \frac{c_2}{\Lambda^2}|H|^2 \bar{Q}_L H^c u_R + h.c.; \bar{\mathcal{O}}_3 = \frac{c_3}{\Lambda^2}|H|^2 \bar{Q}_L H d_R + h.c.$$

- In case of single Higgs production these may be expressed as:

$$\bar{\mathcal{O}}_1 \rightarrow \frac{\alpha_s}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu} \rightarrow \text{ggh point coupling}$$

$$\bar{\mathcal{O}}_2 \rightarrow \frac{m_t}{v} c_t h \bar{t} t \rightarrow \text{modification of top yukawa coupling}$$

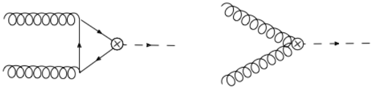
$$\bar{\mathcal{O}}_3 \rightarrow \frac{m_b}{v} c_b h \bar{b} b \rightarrow \text{modification of bottom yukawa coupling}$$

- Note: ggh coupling has same structure as the heavy top limit ($m_t \rightarrow \infty$) in SM

Our approach

BSM Effective Operators

- BSMeff Leading Order contributions:



- Note: Total cross section does not give information about cs separately:

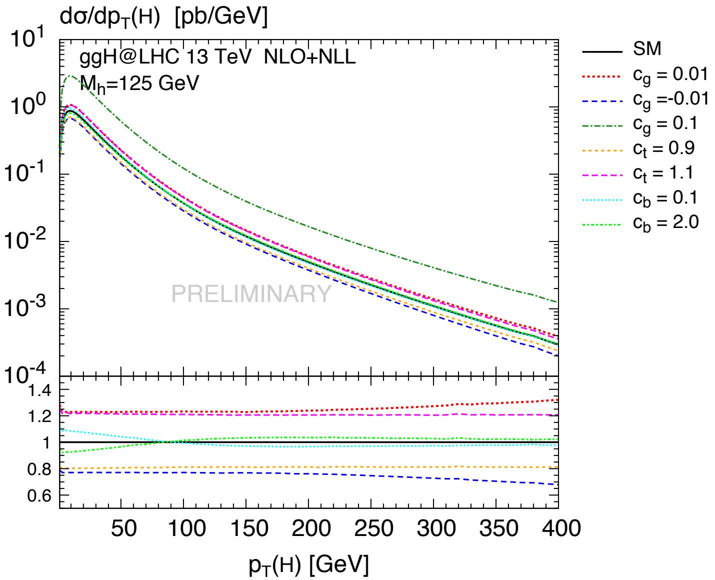
$$\sigma \approx |12c_g + c_t|^2 \sigma_{SM}$$

- c_t may be measured by tth channel, but doesn't give limit on c_g

Our implementation

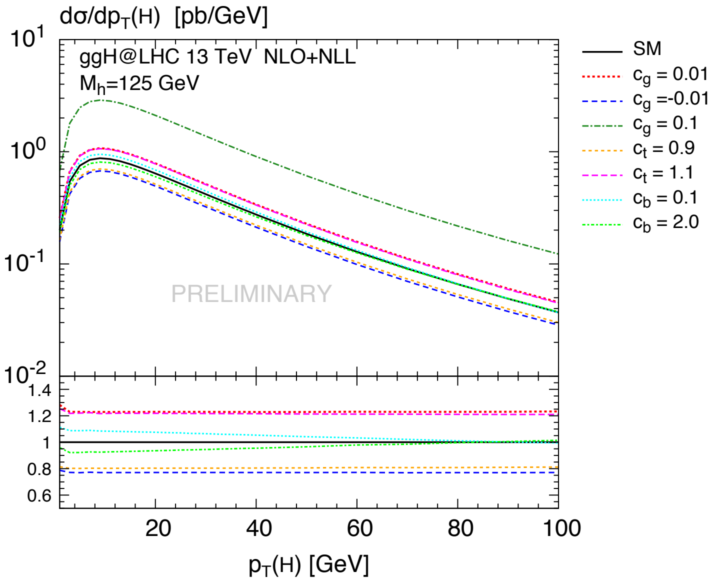
- Effective operators implemented in the HqT program up to NLO+NLL accuracy
- Cross-checked with independent implementations in HIGLU and HNNLO at fixed order

Results



dσ/dp_T(H) [pb/GeV]
ggH@LHC 13 TeV NLO+NLL
M_h=125 GeV
PRELIMINARY
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
p_T(H) [GeV]

Results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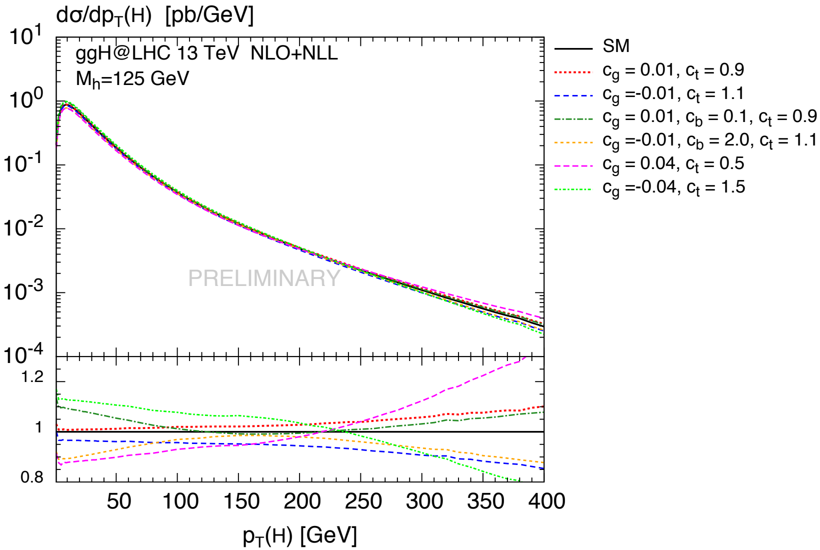
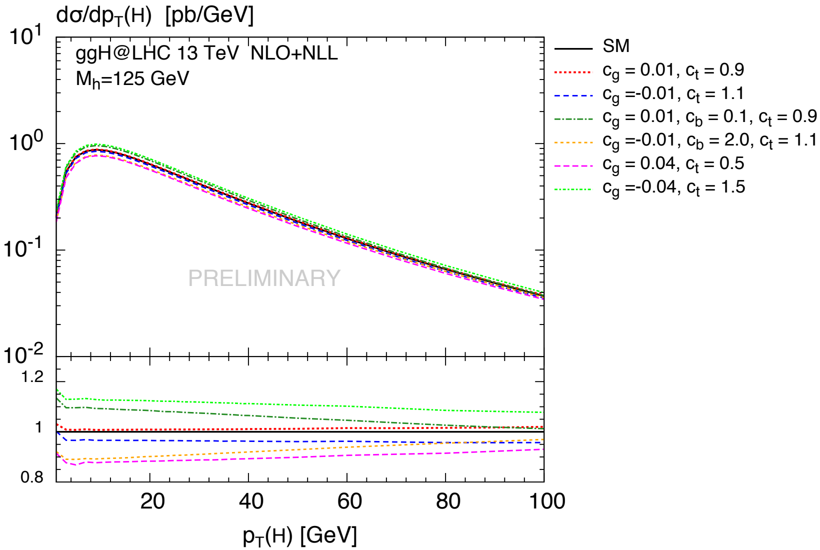
c_b = 2.0
10^1
10^0
10^-1
10^-2
1.4
1.2
1
0.8
0.6
20
40
60
80
100
p_T(H) [GeV]

Results



dσ/dp_T(H) [pb/GeV]
ggH@LHC 13 TeV NLO+NLL
M_h=125 GeV
PRELIMINARY
10^1
10^0
10^-1
10^-2
10^-3
10^-4
1.2
1
0.8
50
100
150
200
250
300
350
400
p_T(H) [GeV]
SM
c_g = 0.01, c_t = 0.9
c_g =-0.01, c_t = 1.1
c_g = 0.01, c_b = 0.1, c_t = 0.9
c_g =-0.01, c_b = 2.0, c_t = 1.1
c_g = 0.04, c_t = 0.5
c_g =-0.04, c_t = 1.5

Results


dσ/dp_T(H) [pb/GeV]
ggH@LHC 13 TeV NLO+NLL
M_h=125 GeV
PRELIMINARY
10^1
10^0
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0.8
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40
60
80
100
p_T(H) [GeV]
SM
c_g = 0.01, c_t = 0.9
c_g =-0.01, c_t = 1.1
c_g = 0.01, c_b = 0.1, c_t = 0.9
c_g =-0.01, c_b = 2.0, c_t = 1.1
c_g = 0.04, c_t = 0.5
c_g =-0.04, c_t = 1.5

Outlook

- Make our implementation bulletproof - crosschecks with other codes, compare results with existing ones
- Add higher order in QCD, i.e. NLO p_T distribution, NNLO total cross section, to obtain state of the art NNLO+NNLL calculations of p_T spectrum
- Add dimension 8 operators:
  - choice of operator basis
  - completely new operators - new tensor structures

Summary

- Effective Field Theory can be used to parametrise in model independent way the effects of high scale BSM physics
- We accomplished implementation of dimension 6 operators relevant for Higgs boson production at NLO+NLL level
- The p_T spectrum including these operators valid for whole p_T range is now available

Backup

Comparison with HIGLU and HNNLO

Comparison with 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

Comparison with HIGLU and HNNLO

Comparison with 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