Asymptotic expansions for highly boosted Higgs production through the loop-tree duality

Judith Plenter

in collaboration with Germán Rodrigo

Instituto de Física Corpuscular - Universitat de València/CSIC

27th September 2018

1st Workshop on High Energy Theory and Gender

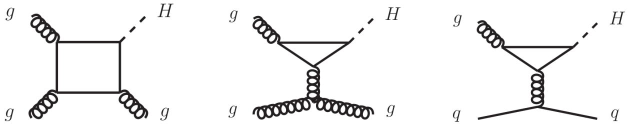
highly-boosted Higgs boson production

- effective point-like ggH-coupling not ruled out [Grojean et al. '14]

$$\frac{m_t}{v}\bar{t}tH \rightarrow -\kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{\mu\nu,a} H + \kappa_t \frac{m_t}{v}\bar{t}tH$$

- need to consider Higgs + jet production at p_T sufficiently high for resolving the top loop in order to disentangle possible BSM effects

LO result known for decades



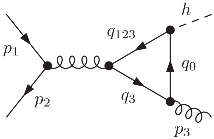
[Ellis et al. '87]
[Baur, Glover '89]

NLO
- fix Higgs-top mass ratio, numerical integration [Jones, Kerner, Luisoni '18]
- integration-by-parts identities + expansion in $\frac{m_H^2}{4m_t^2}$, $\frac{m_t^2}{s}$ [Lindert et al. '18]

goal: obtain independent NLO result using new regularization technique: loop-tree duality (LTD) [Catani et al. '08]

$q\bar{q} \to Hg$ amplitude

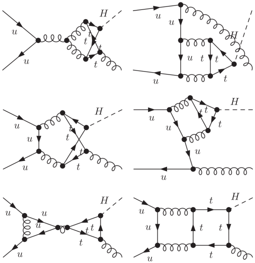
- **LO amplitude**: $\mathcal{M}_{\text{LO}} \sim$
  $\varepsilon^*_\mu(p_3)\ \bar{v}(p_2)\gamma_\nu u(p_1)\ F_{12}\left(g^{\mu\nu} - \frac{p_{12}^\mu p_3^\nu}{p_3 \cdot p_{12}}\right)$



- straight-forward with dim. reg.: solutions for master integrals available

$$F_{12} = \int_\ell \frac{N\left(\ell \cdot p_3,\ \ell \cdot p_{12},\ \ell^2,\ s,\ m_H^2\right)}{[\ell^2 - m_t^2 + i0][(\ell + p_3)^2 - m_t^2 + i0][(\ell + p_{123})^2 - m_t^2 + i0]}$$

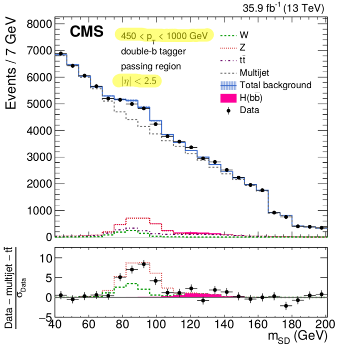
- while at LO only one kinematic variable s,
  NLO amplitude depends on: s, t



$$\mathcal{M}_{\text{NLO}} \sim\ F_{12}^{(1)}\left(g^{\mu\nu} - \frac{p_{12}^\mu p_3^\nu}{p_3 \cdot p_{12}}\right) + \bar{F}_{12}^{(1)}\left(g^{\mu\nu} - \frac{\bar{p}_{12}^\mu p_3^\nu}{p_3 \cdot \bar{p}_{12}}\right)$$

$\Rightarrow$ four scales + two loops: simplification through asymptotic expansion necessary

Asymptotic expansions in the high-p_T limit



[CMS '17]

- high-p_T distribution measurement by CMS
- express p_T and pseudorapidity η through Mandelstam variables:

$$p_T = \frac{u\ t}{s} \qquad \tanh\eta = \frac{t-u}{s-m_H^2}$$

- hierarchy used in literature:

$$m_H^2 \ll m_t^2 \ll |s| \sim |t| \sim |u|$$

[Lindert et al. '18]

- a simple expansion in $s, t, u \propto p_T^2$ might not suffice at NLO

- first: **study expansions for the LO amplitude**
  - Expansion by Regions. How to identify needed regions? [Beneke, Smirnov '98]
  - general problem for expanding: integrand depends on four-momenta

  $\Rightarrow$ will see: obtain integrands depending only on euclidean loop three-momenta when using the loop-tree duality

Loop-tree duality theorem (LTD)

Cauchy residue theorem: $\int_{\ell_0} \to \sum$ residues

LTD theorem

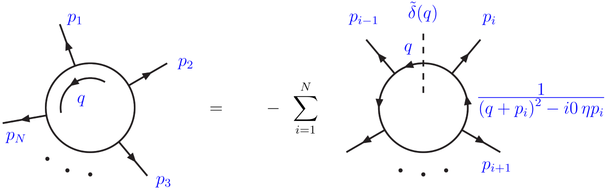
[Catani et al. '08]

$$\int_\ell N(\ell) \prod_i G_F(q_i) = -\sum_i \int_\ell N(\ell)\ \tilde{\delta}(q_i) \prod_{j\neq i} G_D(q_i; q_j),$$

$$\tilde{\delta}(q_i) = 2\pi i\ \theta(q_{i,0})\ \delta(q_i^2 - m_t^2)$$

dual propagator:

$$G_D(q_i; q_j) = \frac{1}{q_j^2 - m_j^2 - i0\eta \cdot (q_j - q_i)}$$

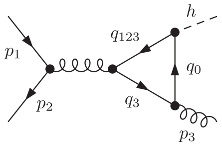


- local cancellation of soft/collinear divergences (FDU) $\Rightarrow$ calc. in $d = 4$
- succesful applications to:
  - physical cross-section for $\gamma^* \to q\bar{q}(g)$ [Sborlini et al. '16]
  - extended to massive particles [Sborlini, Driencourt-Mangin, Rodrigo '16]
  - amplitude for $gg \to H$ and $H \to \gamma\gamma$ [Driencourt-Mangin, Rodrigo, Sborlini '17]

application of LTD on $q\bar{q} \to Hg$

- test applicability: need to extend usage of LTD to further processes
- asymptotic expansions (needed in the NLO calculation) expected to be easier in a phase-space integral

$$F_{12} \overset{LTD}{=} -\int_\ell \Bigg[\frac{\tilde{\delta}(q_0)\, N(q_0)}{(2p_3 \cdot q_0 - i0)\,(2p_{123} \cdot q_0 + m_H^2 + i0)} + \frac{\tilde{\delta}(q_3)\, N(q_3 - p_3)}{(-2p_3 \cdot q_3 + i0)\,(2p_{12} \cdot q_3 + s + i0)} + \frac{\tilde{\delta}(q_{123})\, N(-p_{123} + q_{123})}{(-2p_{12} \cdot q_{123} + s - i0)\,(-2p_{123} \cdot q_{123} + m_H^2 - i0)} \Bigg]$$



note: integrand now only depends on loop three-momenta

expand dual propagators:

- $\frac{\tilde{\delta}(\ell)}{\pm m_H^2 - 2h\cdot\ell} = -\frac{\tilde{\delta}(\ell)}{2h\cdot\ell} \sum_{n=0}^{\infty} (-1)^n \left(\mp \frac{m_H^2}{2h\cdot\ell}\right)^n$
- in cmf: $\tilde{\delta}(\ell)\ p_{12} \cdot \ell = -\tilde{\delta}(\ell)\ \sqrt{s\,(m_t^2 + \boldsymbol{\ell}^2)}$

$\Rightarrow$ need to separate the integral into two parts with distinct expansions. However: complexity reduced

Conclusion

- large-p_T Higgs production necessary to exclude point-like ggH coupling
- NLO calculation needs properly defined asymptotic expansion of the integrand
- loop-tree duality allows to rewrite a loop integral in terms of a sum of phase-space integrals over the cut amplitude

$\Rightarrow$ the resulting expression can be expanded more straight-forwardly

Outlook:

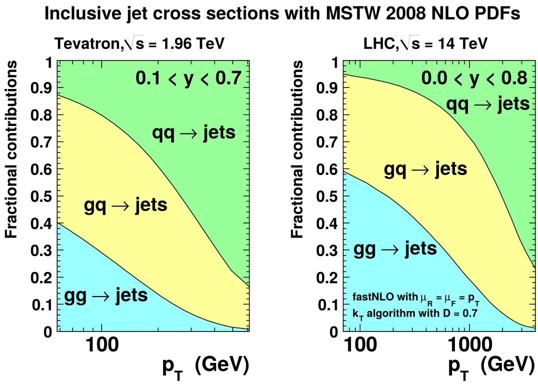
- reproduce LO result for $\bar{q}q \to Hg$ both using
  - dimensional regularization + expansion by regions and
  - LTD + direct expansions
- repeat for the other two LO contributions to large-p_T Higgs production: $gg \to Hg$ and $qg \to qH$
- extend to the NLO amplitude, will include local UV renormalization of the amplitude

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 713673. Judith Plenter has received financial support through the "la Caixa" INPhINIT Fellowship Grant for Doctoral studies at Spanish Research Centres of Excellence, "la Caixa" Banking Foundation, Barcelona, Spain.

backup slides

initial state for jet production

for jets with large p_T ($\leftrightarrow$ Higgs with large p_T) the likelyhood of having a gluon-gluon initial state decreases:



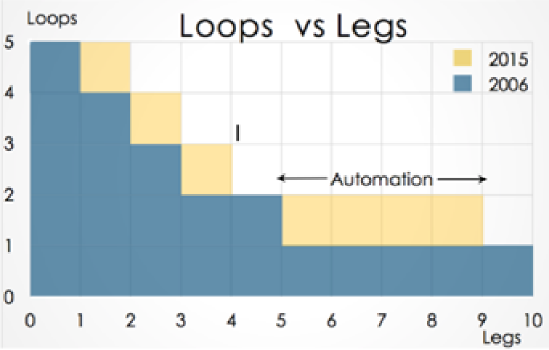
[taken from: Salam, Bautzen lectures, '09]

dimensional regularization result for F_{12}

$$
\begin{aligned}
F_{12} = \ & c_1 \mathrm{B}_0\big(m_H^2, m_t^2, m_t^2\big) + c_2 \bigg(\mathrm{B}_0\left(s, m_t^2, m_t^2\right) - \mathrm{B}_0\left(m_H^2, m_t^2, m_t^2\right) \bigg) \\
& + c_3 \mathrm{C}_0\left(0, s, m_H^2, m_t^2, m_t^2, m_t^2\right) \\
= \ & \frac{1}{32\pi^2} \Bigg[\left(1 - \frac{4m_t^2}{t+u}\right) \left(\log^2\left(\frac{\sqrt{s\left(s - 4m_t^2\right)} + 2m_t^2 - s}{2m_t^2} \right) \right. \\
& \left. - \ \log^2\left(\frac{\sqrt{m_H^2\left(m_H^2 - 4m_t^2\right)} + 2m_t^2 - m_H^2}{2m_t^2} \right) \right) \\
& + \frac{4s}{t+u} \left(\sqrt{1 - 4\frac{m_t^2}{m_H^2}} \log\left(\frac{\sqrt{m_H^4 - 4m_H^2 m_t^2} + 2m_t^2 - m_H^2}{2m_t^2} \right) \right. \\
& \left. - \sqrt{1 - 4\frac{m_t^2}{s}} \log\left(\frac{\sqrt{s^2 - 4sm_t^2} + 2m_t^2 - s}{2m_t^2} \right) \right) + 4 \Bigg]
\end{aligned}
$$

difficulty of multi-loop or multi-leg calculations

amplitudes that contain up to one mass scale:



Mandelstam variables

$$s = m_H^2 - \frac{2p_\mathrm{T}^2}{\tanh^2\eta - 1}\left(1 + \sqrt{1 + \frac{m_H^2}{p_\mathrm{T}^2}(1 - \tanh^2\eta)}\right)$$

$$t = \frac{p_\mathrm{T}^2}{\tanh\eta - 1}\left(1 + \sqrt{1 + \frac{m_H^2}{p_\mathrm{T}^2}(1 - \tanh^2\eta)}\right)$$

$$u = -\frac{p_\mathrm{T}^2}{\tanh\eta + 1}\left(1 + \sqrt{1 + \frac{m_H^2}{p_\mathrm{T}^2}(1 - \tanh^2\eta)}\right)$$

expansion by regions of $q\bar{q} \to Hg$

expansion by regions

- Divide space of loop momentum into various regions and expand the integrand into a Taylor series w.r.t. the parameters considered small there.
- Integrate expanded integrand *over the whole integration domain* of the loop momenta.
- Set to zero any scaleless integral. [Beneke, Smirnov '98]

- 'region': $\ell \sim m$ instead of $0 \leq \ell \leq \Lambda$.
- let's try for one of the integrals needed for $\bar{q}q \to Hg$ at LO:

$$\int_\ell \frac{1}{(\ell^2 - m_t^2 + i0)\,(\ell^2 + 2\ell \cdot p_{12} + 2\ell \cdot p_3 + m_H^2 - m_t^2 + i0)}$$

- How many regions? At least $\ell \sim m$ (soft) and $\ell \sim p_\mathrm{T}$ (hard)
  - How about $\ell \sim \frac{m}{p_\mathrm{T}}$ (ultrasoft)? Or $\ell_0 \sim \frac{m}{p_\mathrm{T}}, |\boldsymbol{\ell}| \sim m$ (potential)?
  - How to treat the scalar products?