Non-factorizable QCD Effects in Higgs Boson Production via Vector Boson Fusion

Alexander Penin

University of Alberta

RADCOR 2019

Avignon, France, September 9th, 2019

How to Compute Two-Loop Five-Point Massive Amplitudes by Hand

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Topics discussed

- Introduction
  - *Status of QCD corrections to VBF Higgs production*
- Nonfactorizable NNLO QCD Corrections
  - *Transverse momentum expansion*
  - *Decoupling of light-cone and transversal dynamics*
  - *Two-loop result*
  - *Glauber phase noncancellation*
  - *Numerical estimates*

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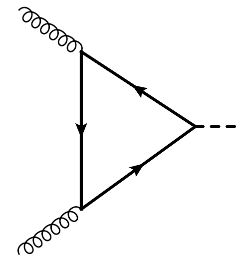
  - *Two-loop result*
  - *Glauber phase noncancellation*
  - *Numerical estimates*
- *Based on:*

T. Liu, K. Melnikov, A.A. Penin
e-Print arXiv:1906.10899 [hep-ph]
Phys.Rev.Lett. (2019)

Higgs production at the LHC

- Gluon fusion
  - *probes Higgs coupling to quarks*
  - *dominant production channel*
  - *NNNLO QCD correction*

    (no high-$p_\perp$ and b-quark contributions)



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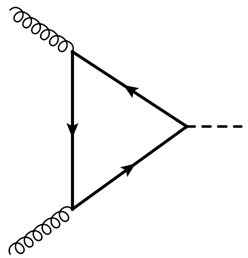
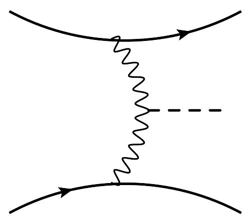


- Vector boson fusion
  - *probes Higgs coupling to electroweak bosons*
  - *separated by forward quark jets tagging*
  - *NLO+*

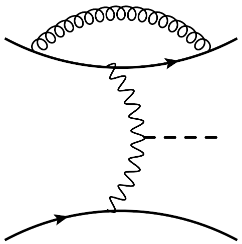
  (NNLO QCD nonfactorizable corrections are missing)



QCD corrections to VBF Higgs production

- Factorizable
  - *DIS-like process*
  - *"structure function approach"*

    T. Han, G. Valencia and S. Willenbrock, Phys. Rev. Lett. **69***, 3274 (1992)*
  - *known to NNLO*



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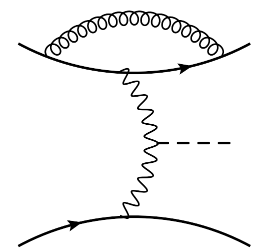
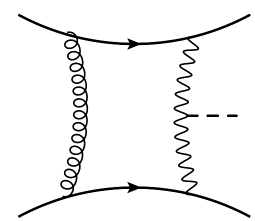


- **Nonfactorizable** (neglect t-u interference)
  - *starts at NNLO*
  - $1/N_c^2$ *color suppression*
  - *real radiation numerically suppressed*



Status of perturbative QCD analysis

- *NLO differential*

  T. Figy, C. Oleari and D. Zeppenfeld,
  Phys. Rev. D **68**, *073005 (2003)*

- *NNLO total (factorizable)*

  P. Bolzoni, F. Maltoni, S. O. Moch and M. Zaro,
  Phys. Rev. Lett. **105**, *011801 (2010)*

- *NNLO differential (factorizable)*

  M. Cacciari, F. A. Dreyer, A. Karlberg, G. P. Salam, G. Zanderighi,
  Phys. Rev. Lett. **115**, *082002 (2015);*

  J. Cruz-Martinez, T. Gehrmann, E. W. N. Glover and A. Huss,
  Phys. Lett. B **781**, *672 (2018)*

- *NNNLO differential (factorizable)*

  F. A. Dreyer and A. Karlberg,
  Phys. Rev. Lett. **117**, *072001 (2016)*

Nonfactorizable NNLO corrections

- Bottleneck: two-loop virtual corrections

Nonfactorizable NNLO corrections

- Bottleneck: two-loop virtual corrections

➥ *two options:*

- *brute-force calculation*

  five-point two-loop function with two masses M_V, M_H

- *asymptotic expansion*

  study the process kinematics ⇨ *find a small parameter* ⇨ *expand* ⇨ *get an effective theory description*

Nonfactorizable NNLO corrections

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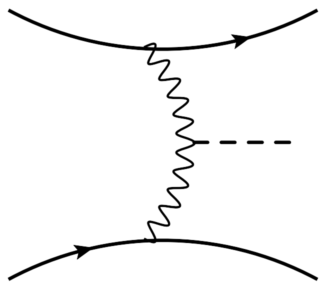
- VBF kinematical features
  - *energetic forward quark jets*
  - *rapidity gap between Higgs and tagging jets*

➥ *Regge limit*

Expansion: Born amplitude

$$q(p_1^+) + q'(p_2^-) \to q(p_3) + q'(p_4) + H(p_H)$$



vector boson momenta $\quad q_3 = p_3 - p_1, \qquad q_4 = p_4 - p_2$

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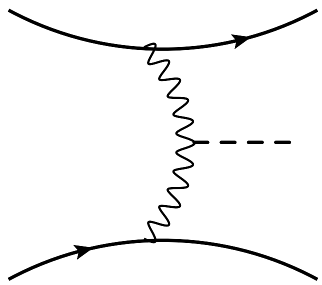

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- *Scale hierarchy:*

$$(p_\perp^2, M_{V,H}^2)/s \sim 0.03$$

$$e^{|y_H|-|y_j|} \sim 0.05$$

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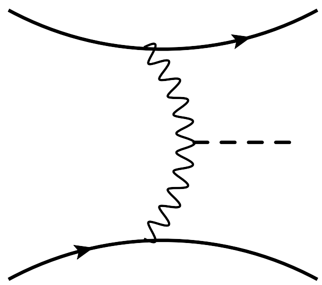

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- Leading power approximation:
  - Glauber vector bosons $\quad q_i^2 \approx q_{i\perp}^2$
  - light-cone gauge currents $\quad j^\mu \approx j^\pm$

Expansion: one-loop amplitude

- no NLO *(color conservation)*
- *one-loop* $\times$ *one-loop* at NNLO
- gluons in color singlet state
  - ➥ *effective abelian coupling*

$$\tilde{\alpha}_s = \left(\frac{N_c^2-1}{4N_c^2}\right)^{1/2} \alpha_s$$

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- *Abelian gauge theory in Regge limit*

Landau school (V. Sudakov, V. Gribov, L. Lipatov, V. Gorshkov, G. Frolov)

H. Cheng and T. T. Wu, Phys. Rev. **186**, *1611 (1969)*

S. J. Chang and S. K. Ma, Phys. Rev. **188**, *2385 (1969)*

Leading power approximation in Regge limit

- Hard loop momentum $k \sim \sqrt{s}$
  - ➥ *subleading power* $\mathcal{O}(p_\perp^4/s^2)$
- Leading power $k \ll \sqrt{s}$
  - ➥ *eikonal fermion propagatrors* $\frac{1}{\not{p}_{1,2}+\not{k}+i\epsilon} \to \frac{\gamma^\pm}{2k^\pm+i\epsilon}$
- Sum over permutations $\frac{1}{2k^\pm+i\epsilon} - c.c. = -i\pi\delta(k^\pm)$

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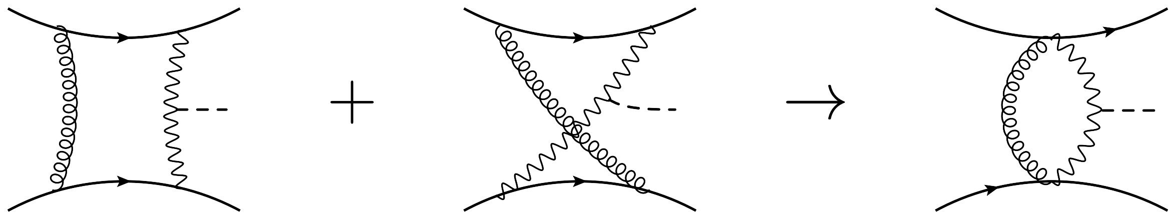
- Sum over permutations $\frac{1}{2k^\pm + i\epsilon} - c.c. = -i\pi\delta(k^\pm)$
- *Decoupling of light-cone and transversal dynamics*
  - *on-shell fermions on the light-cone*
  - *Glauber gauge bosons in the transversal space*

Transversal space 2d effective theory



- One-loop leading-power amplitude *(purely imaginary)*

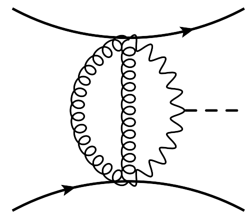
$$\mathcal{M}^{(1)} = i\tilde{\alpha}_s \chi^{(1)} \mathcal{M}^{(0)}$$

$$\chi^{(1)} = \frac{1}{\pi} \int \frac{\mathrm{d}^2\boldsymbol{k}}{\boldsymbol{k}^2 + \lambda^2} \times \frac{\boldsymbol{q}_3^2 + M_V^2}{(\boldsymbol{k} - \boldsymbol{q}_3)^2 + M_V^2} \frac{\boldsymbol{q}_4^2 + M_V^2}{(\boldsymbol{k} + \boldsymbol{q}_4)^2 + M_V^2},$$

- Infrared divergence: $\chi^{(1)} = -\ln\left(\frac{\lambda^2}{M_V^2}\right) + f^{(1)}(\boldsymbol{q}_3, \boldsymbol{q}_4, M_V^2)$

↪ *Glauber phase:* $e^{-i\tilde{\alpha}_s \ln \lambda^2}$

Two-loop amplitude



- Two-loop leading-power amplitude

$$\mathcal{M}^{(2)} = -\frac{\tilde{\alpha}_s^2}{2!}\chi^{(2)}\mathcal{M}^{(0)}$$

- Infrared divergence structure

$$\chi^{(2)} = \ln^2\left(\frac{\lambda^2}{M_V^2}\right) - 2\ln\left(\frac{\lambda^2}{M_V^2}\right) f^{(1)}(\boldsymbol{q}_3, \boldsymbol{q}_4, M_V^2) + f^{(2)}(\boldsymbol{q}_3, \boldsymbol{q}_4, M_V^2)$$

  - $f^{(i)}$ *are finite one-dimensional integrals*

NNLO cross section

- Nonfactorizable correction

$$\mathrm{d}\sigma_{\rm nf}^{\rm NNLO} = \left(\frac{N_c^2-1}{4N_c^2}\right)\alpha_s^2\,\chi_{\rm nf}\,\mathrm{d}\sigma^{\rm LO}$$

$$\chi_{\rm nf} = \left[\chi^{(1)}\right]^2 - \chi^{(2)} = \left[f^{(1)}\right]^2 - f^{(2)}$$

- Uncancelled part of Glauber phase enhanced by π^2

  ➥ nonfactorizable NNLO/factorizable NNLO $\sim \frac{\pi^2}{N_c^2}$

Explicit result

$$f^{(1)} = \int_0^1 \mathrm{d}x \frac{\Delta_3\Delta_4}{r_{12}^2}\left[\ln\left(\frac{r_{12}^2}{r_2 M_V^2}\right) + \frac{r_1 - r_2}{r_2}\right],$$

$$f^{(2)} = \int_0^1 \mathrm{d}x \frac{\Delta_3\Delta_4}{r_{12}^2}\left[\left(\ln\left(\frac{r_{12}^2}{r_2 M_V^2}\right) + \frac{r_1 - r_2}{r_2}\right)^2 - \ln^2\left(\frac{r_{12}}{r_2}\right) - \frac{2r_{12}}{r_2}\ln\left(\frac{r_{12}}{r_2}\right) - 2\,\mathrm{Li}_2\left(\frac{r_1}{r_{12}}\right) - \left(\frac{r_1 - r_2}{r_2}\right)^2 + \frac{\pi^2}{3}\right]$$

$$r_1 = \boldsymbol{q}_3^2\, x + \boldsymbol{q}_4^2\,(1-x) - \boldsymbol{q}_H^2\, x(1-x)\,,$$

$$r_2 = \boldsymbol{q}_H^2\, x(1-x) + M_V^2\,,$$

$$r_{12} = r_1 + r_2\,,$$

$$\Delta_i = \boldsymbol{q}_i^2 + M_V^2$$

$$\boldsymbol{q}_H = \boldsymbol{q}_3 + \boldsymbol{q}_4$$

Limits

- **Forward production**

$$\lim_{q_{3,4}\to 0} \chi_{\rm nf} = 1 - \frac{\pi^2}{3}$$

➥ -1% *correction to the cross section*

- **Forward Higgs production** ($x = M_V^2/\boldsymbol{q}_3^2$)

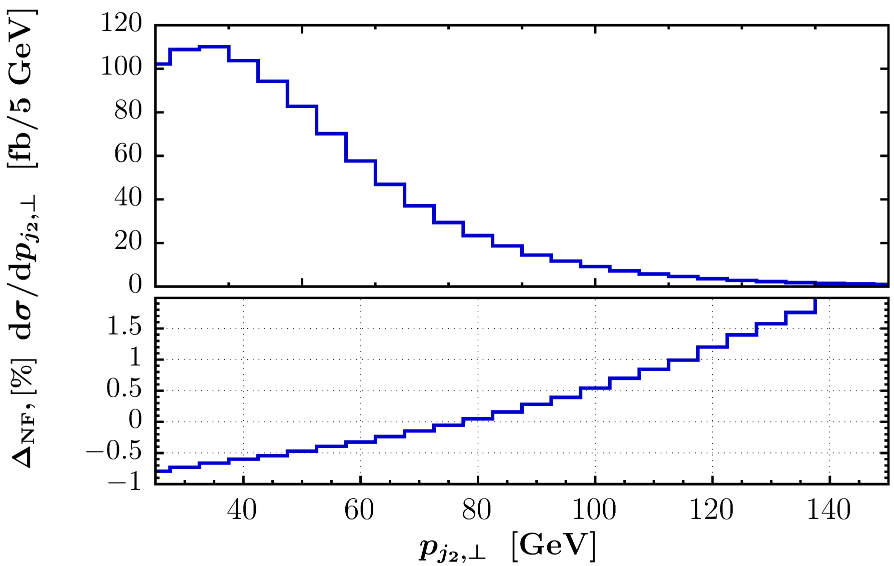
$$\lim_{q_H\to 0} \chi_{\rm nf} = \ln^2\left(\frac{1+x}{x}\right) + 2\,{\rm Li}_2\left(\frac{1}{1+x}\right) - \frac{\pi^2}{3} + 2\,\frac{1+x}{x}\ln\left(\frac{1+x}{x}\right) + \left(\frac{1-x}{x}\right)^2$$

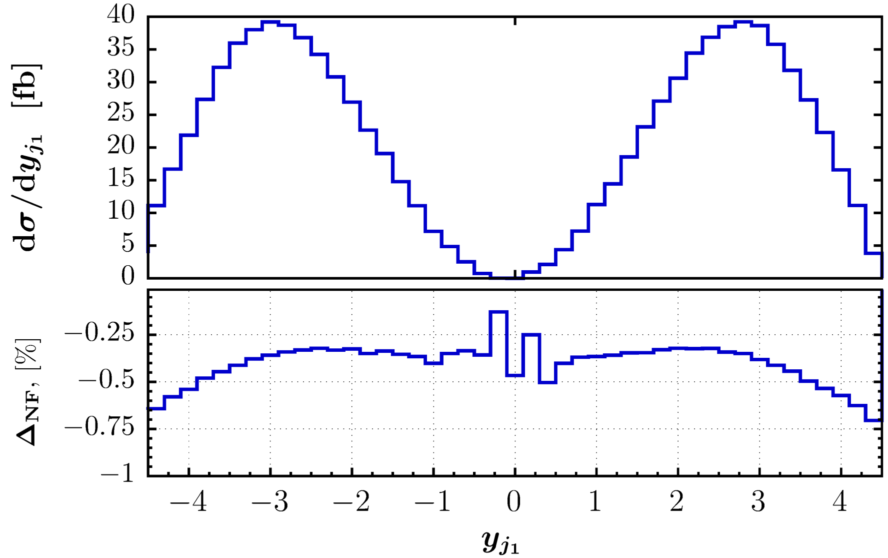
➥ *large positive correction for small* x

- **Forward jet production**

$$\lim_{q_3\to 0} \chi_{\rm nf} = \ln^2\left(\frac{1+x}{x}\right) + 2\,{\rm Li}_2\left(\frac{1}{1+x}\right) - \frac{\pi^2}{3}\,.$$

Numerics: Jets





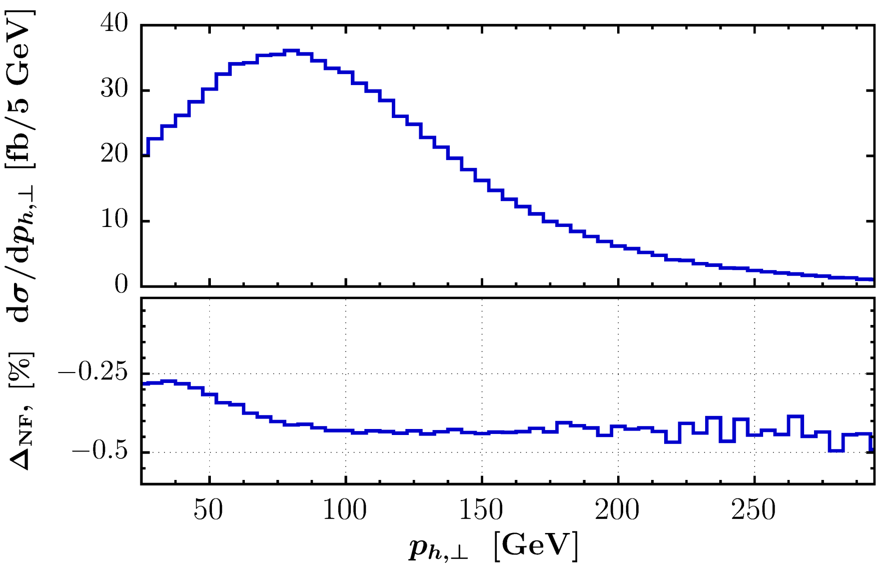
transverse momentum distribution

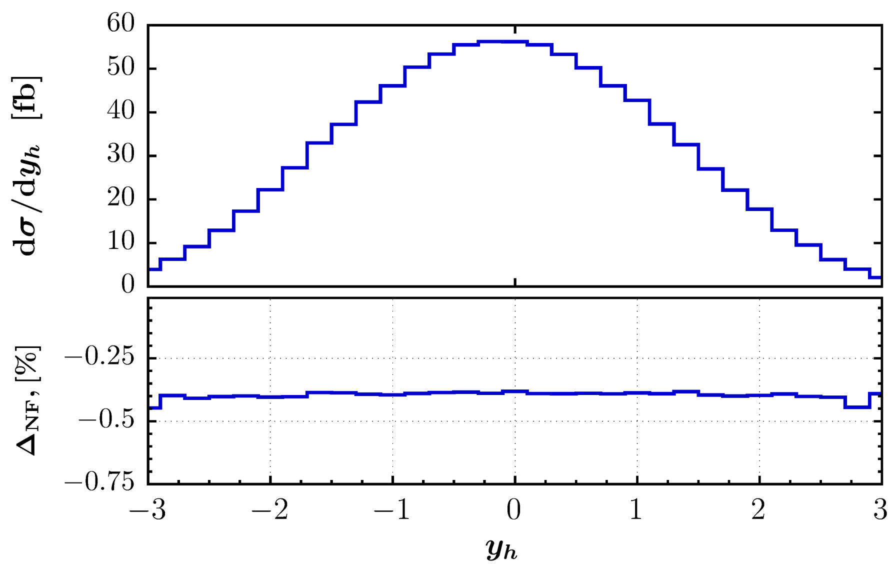
(2nd jet)

rapidity distribution

(1st jet)

Numerics: Higgs





transverse momentum distribution

rapidity distribution

Factorizable vs nonfactorizable corrections

	NNLO fact.	NNLO nonfact.	NNNLO fact.
$\sigma^{\text{VBF cuts}}$	-4%	-0.5%	permill
$\mathrm{d}\sigma/\mathrm{d}p_{j_2,\perp}$	-6%	+1.5%	permill

$p_{j_2,\perp} \sim 140$ GeV

Summary

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- Nonfactorizable NNLO QCD corrections to VBF Higgs production
  - *Glauber phase enhancement vs color suppression:* $\pi^2/N_c^2 \sim 1$
  - *a percent scale, transverse momentum dependence*
  - *comparable to factorizable counterpart*

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  - *Glauber phase enhancement vs color suppression:* $\pi^2/N_c^2 \sim 1$
  - *a percent scale, transverse momentum dependence*
  - *comparable to factorizable counterpart*
- *In coming era of elliptic polylogs and numerical unitarity, physically motivated expansions still fly high, solve challenging problems and uncover nontrivial dynamics.*