Nonfactorizable QCD Effects in Higgs Boson Production via Vector Boson Fusion at $\mathcal{O}(\alpha_s^3)$

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Loops and Legs in Quantum Field Theory

Ettal, Germany, April 30th, 2022

“Factorization of Nonfactorizable”

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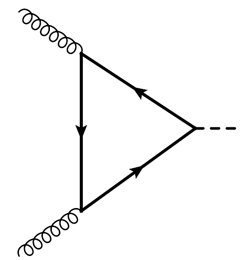
Topics discussed

- Introduction
  - *Status of QCD corrections to VBF Higgs production*
- Nonfactorizable QCD effects through $\mathcal{O}(\alpha_s^3)$
  - *Factorization of light-cone and transversal dynamics*
  - ➥ *Glauber phase noncancellation at NNLO*
  - *Decoupling of strong and electroweak dynamics*
  - ➥ *Factorization of NLO dijet cross section at N^{3}LO*
  - *Power corrections to the factorization formula*
  - *Double Higgs production*
- *Based on:*

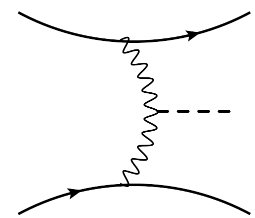
  F. Caola, A.A. Penin *to appear on arXive next week*

Higgs production at the LHC

- Gluon fusion
  - *probes Higgs coupling to quarks*
  - *dominant production channel*
  - *N^3LO QCD correction*



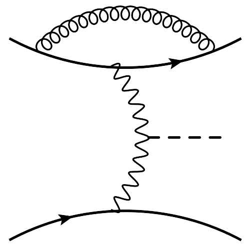
- Vector boson fusion
  - *probes Higgs coupling to electroweak bosons*
  - *separated by forward quark jets tagging*
  - *NNLO (factorizable corrections through N^3LO)*



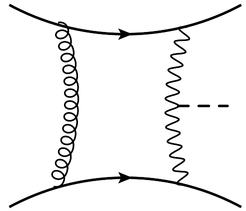
QCD corrections to VBF Higgs production

- **Factorizable**
  - *DIS-like process*
  - ➥ *“structure function approach”*

    T. Han, G. Valencia and S. Willenbrock, Phys. Rev. Lett. **69**, *3274 (1992)*
  - *known to N^3LO*



- **Nonfactorizable**
  - *starts at NNLO*
  - *real radiation numerically suppressed*
  - $1/N_c^2$ *color suppression v.s.* π^2 *Glauber phase*



T. Liu, K. Melnikov and A.A. Penin Phys. Rev. Lett. ***123***, *122002 (2019).*

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)*

- *NNNLO (factorizable, double Higgs) F. A. Dreyer and A. Karlberg,*

  Phys. Rev. D ***98****, no.11, 114016 (2018)*

- *NNLO (nonfactorizable)*

  T. Liu, K. Melnikov, A.A. Penin Phys. Rev. Lett. ***123****, 122002 (2019)*

- *NNLO (nonfactorizable, double Higgs)*

  F. A. Dreyer, A. Karlberg and L. Tancredi, JHEP ***10****, 131 (2020), erratum to appear*

Nonfactorizable corrections

- Essential for intermediate transverse jet momenta

$$M_V^2 < p_{j,\perp}^2 \ll s$$

  - *Born amplitude scales as* $1/p_{j,\perp}^4$
  - *one-loop amplitude scales as* $1/p_{j,\perp}^2$

  ↪ *qualitatively change* $p_{j,\perp}$*-dependence*

  - $p_{j,\perp}^4/M_V^4$ *enhancement* ⇨ *10% NNLO correction at* $|p_{j,\perp}| \sim 2M_V$

  ↪ *need N*^{3}*LO for uniform sub-percent precision*

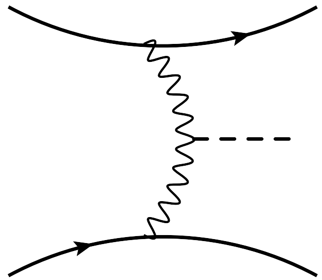
Nonfactorizable corrections

- N^{3}LO corrections
  - ✘ *brute-force calculation*
    five-point three-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*

- VBF kinematical features
  - *energetic forward quark jets*
  - *rapidity gap between Higgs and tagging jets*
- *additional kinematical condition*
  - *jet transversal momenta above EW scale*

Scales hierarchy

$$q_1(p_1) + q_2(p_2) \to q_1(p_{j_1}) + q_2(p_{j_2}) + H(p_H)$$



- VBF: $p_{j,\perp}^2/s \ll 1$ & $e^{|y_H|-|y_j|} \ll 1$
- intermediate $p_{j,\perp}$: $M_V^2/p_{j,\perp}^2 \ll 1$

Factorization of light-cone and transversal dynamics

- Expansion in $\tau = p_{j,\perp}^2/s$
  - *hard loop momentum* $k \sim \sqrt{s}$ ⇨ $\mathcal{O}(\tau)$
  - *eikonal fermion propagators*

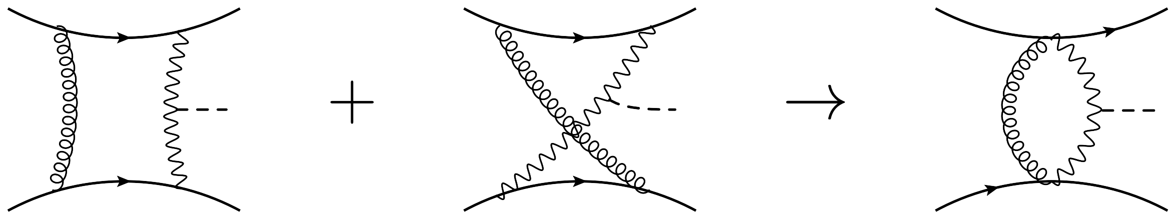
$$\frac{1}{\not p_{1,2} + \not k + i\epsilon} \to \frac{\gamma^\pm}{2k^\pm + i\epsilon} \to -i\pi\delta(k^\pm)$$

➥ *Transversal space 2D effective theory*
  - *on-shell fermions on the light-cone*
  - *Glauber gauge bosons in the transversal space*

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

H. Cheng, T. T. Wu, Phys. Rev. **186***, 1611 (1969); S. J. Chang, S. K. Ma, Phys. Rev.* **188***, 2385 (1969)*

Glauber phase



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

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

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

↪ *Glauber phase:*

$$\chi^{(1)} = \frac{1}{\pi} \int \frac{\mathrm{d}^2 k_\perp}{k_\perp^2 + \lambda^2} \frac{p_{j_1,\perp}^2 + M_V^2}{(k - p_{j_1})_\perp^2 + M_V^2} \frac{p_{j_2,\perp}^2 + M_V^2}{(k + p_{j_2})_\perp^2 + M_V^2}$$

Factorization of strong and weak dynamics

- Expansion in $x = M_V^2/p_{j,\perp}^2$ $\quad \chi^{(1)} = \sum_{n=-1}^{\infty} x^n \chi_n$
- Leading power
  - *soft weak boson* $k'_\perp \equiv k_\perp + p_{j,\perp} \sim M_V$

$$\chi_{-1} = \frac{1}{\pi}\int \frac{\mathrm{d}^2 k'_\perp}{k'^2_\perp + M_V^2}\frac{M_V^2}{(k'+p_H)^2_\perp + M_V^2} = \frac{1}{\Delta^{1/2}}\ln\left(\frac{2+\rho+\Delta^{1/2}}{2+\rho-\Delta^{1/2}}\right)$$

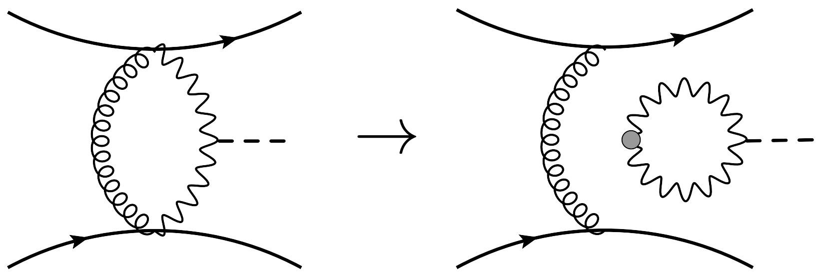
$\Delta = \rho(4+\rho)$, $\rho = p_{H,\perp}^2/M_V^2$

- Subleading power

$$\chi_0 = -\ln x + \ln\left(p_{j,\perp}^2/\lambda^2\right) + \ldots\,,$$

soft gluon IR divergent phase

Factorization of strong and weak dynamics



- Amplitude factorization

chiral dijet production $\times$ vacuum to Higgs transition

Factorization at N^3LO

$$d\sigma^{N^3LO}_{nf} = (C\tilde{\alpha}_s)^2 \frac{d\sigma^{NLO}_{jj,L}}{d\sigma^{LO}_{jj,L}} d\sigma^{LO}$$

$$C = \frac{\chi_{-1}}{x} - \ln x$$

- Leading power
  - *soft scales:* $k_{g,\perp} \sim p_{j,\perp}$ *vs* $k_{V,\perp} \sim M_V$

  ➥ χ_{-1} *factors out as* $\ln\lambda$ *QED phase*
- Subleading power (leading logs)
  - *collinear logs*
  - *RG logs*

  ➥ *same as for the dijet cross section*

How accurate is the factorization?

- Power corrections to the eikonal approximation in τ

$$-\frac{2}{3}\left(\frac{\tilde{\alpha}_s}{\pi}\right)^2 \tau \ln^3\tau\, \sigma^{\rm LO} \lesssim 0.1\,(C\tilde{\alpha}_s)^2\,\sigma^{\rm LO}$$

from leading-log subleading-power Bhabha A. Penin JHEP **04**, 156 (2020)

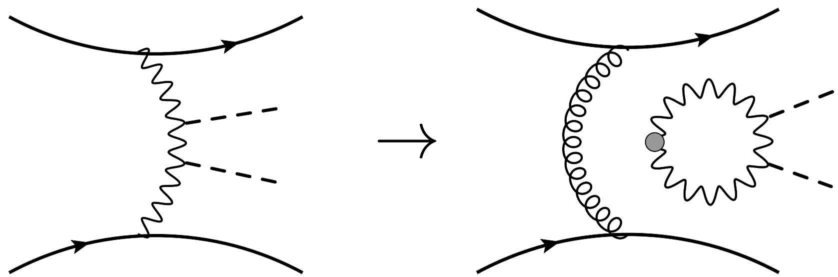
- Power corrections to dijet factorization in x

$$\left|\frac{\chi(p_H=0)}{C} - 1\right| \lesssim 0.1 \quad {\rm for} \quad x \lesssim 1.2$$

➥ *factorization works up to $x \sim 1$!*

Double Higgs production

- New: double t-channel emission



  - *electroweak factor* $\chi_{-2}(p_{H_i}, y_{H_i})/x^2$
  - *disrupts fine* $s - t$ *channel cancellation*

↪ *a few times bigger effect*

Summary

- Nonfactorizable effects in VBF Higgs production
  - *nontrivial factorization: light-cone/transversal & strong/weak*
  - *known to N^{3}LO where it matters*
  - ➥ *uniform subpercent accuracy for the cross section*

Summary

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  - *known to N^{3}LO where it matters*
  - ➥ *uniform subpercent accuracy for the cross section*

- *Physically motivated expansions uncover hidden factorization structure and solve multiscale problems at will where elliptic polylogs and other beasts give up.*