All order nonfactorizable jet veto effects in Higgs boson production

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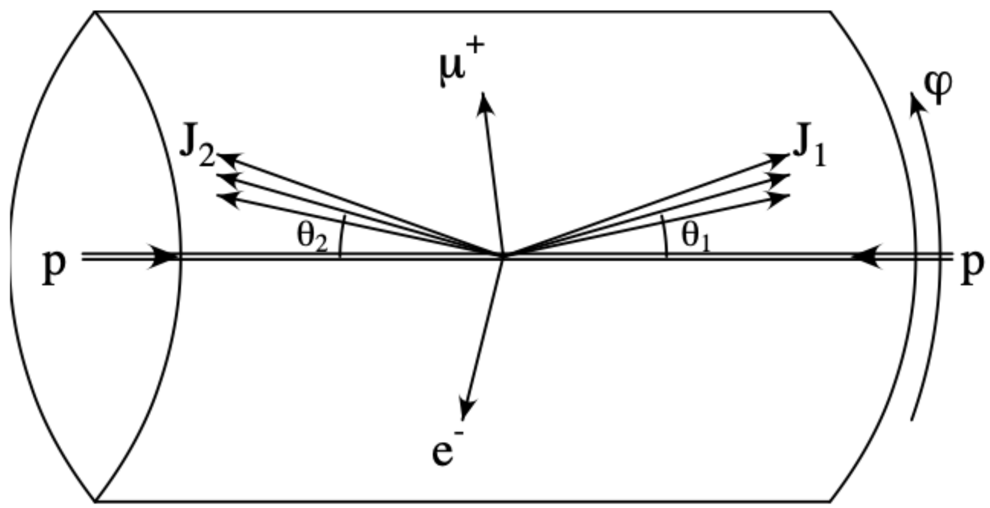
Based on arXiv:2107.01212 with Thomas Becher and Matthias Neubert

Higgs potential and BSM opportunity **Nanjing University (online)** **Aug 28 2017**

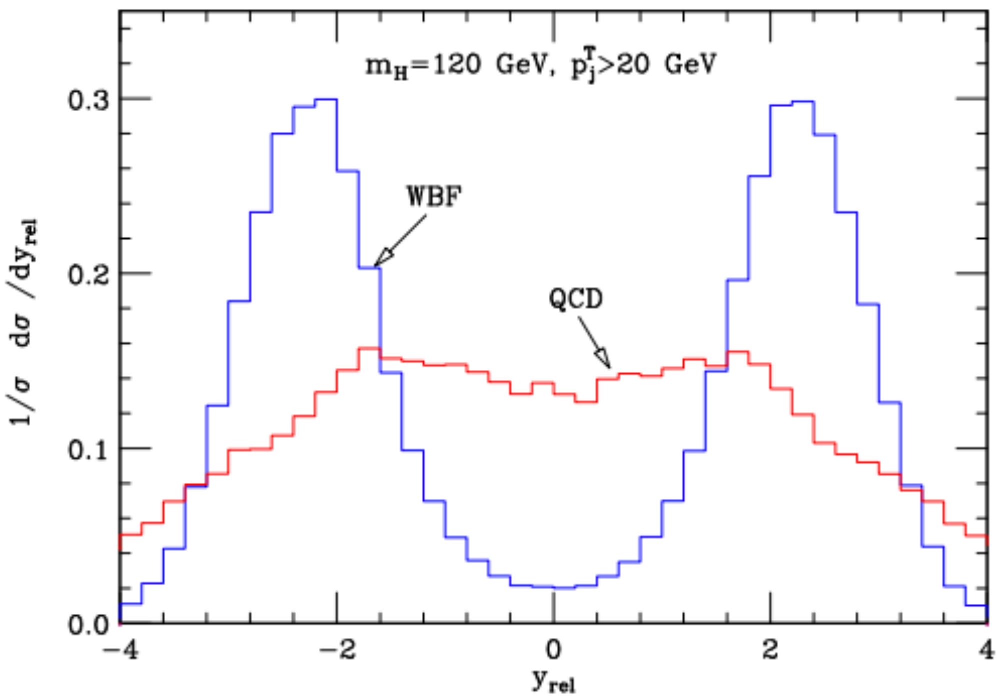
Central jet veto in Higgs production via VBF



VBF signature:

- **Energetic jets in the forward and backward directions**
- **Large rapidity separation and large invariant mass of two tagged jets**
- **Little radiation in the central-rapidity region**

- **Major QCD backgrounds: t-channel color octet exchange**
- **Central jet veto can suppresses QCD background**
- **Central jet veto: no extra jets between tagging jets**



Del Duca, Frizzo, Maltoni '05

Jet veto & QCD resummation

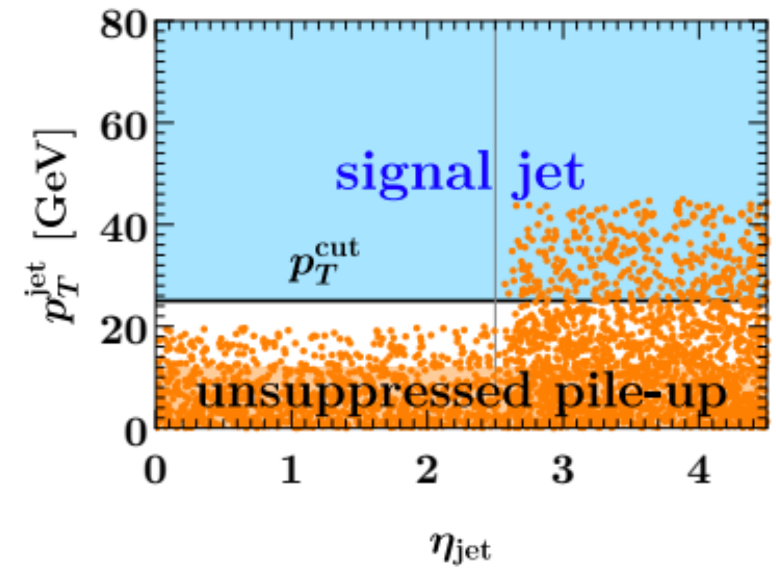
- **Due to existence of a small scale p_T^{veto}, the fixed order calculations are unreliable**
- **QCD resummation is necessary, the large log should be resumed to all order**
- **Standard jet veto resummation for gg->H processes**
  - **Rapidity cut independent**

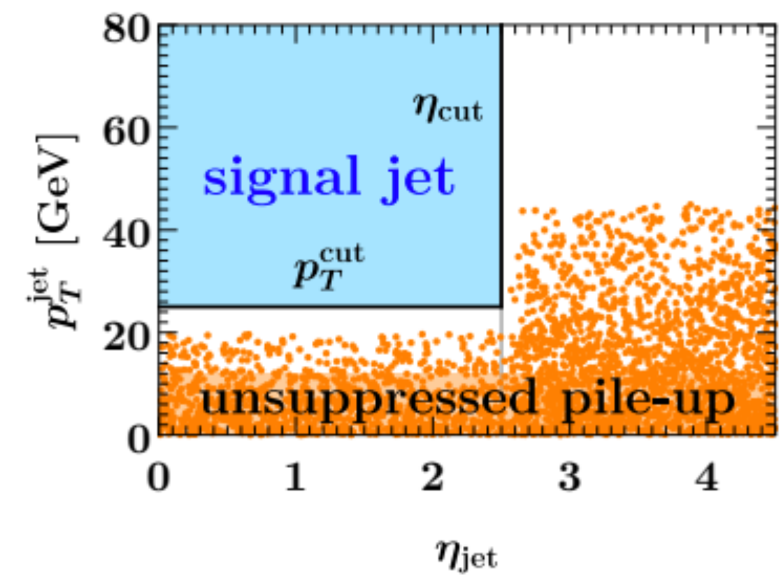
    Banfi, Monni, Salam, Zanderighi ’12;

    Becher, Neubert, Rothen ’12, ’13;

    Stewart, Tackmann, Walsh, Zuberi ’12, ’13
  - **Rapidity cut dependent**

    Michel, Pietrulewicz, Tackmann ’18
  - **Nonfactorizable jet veto in VBF: Superleading Logs**
    - **Four-loop** Forshaw, Kyrieleis, Seymour ’06
    - **Five-loop** Keates, Seymour ‘09
    - **All-order** Becher, Neubert, DYS ‘21





Courtesy of Johannes Michel

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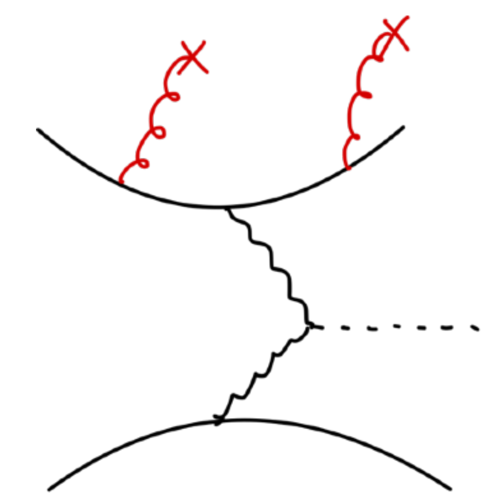

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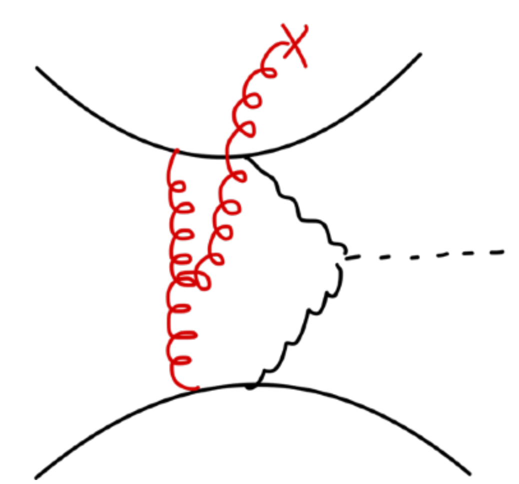
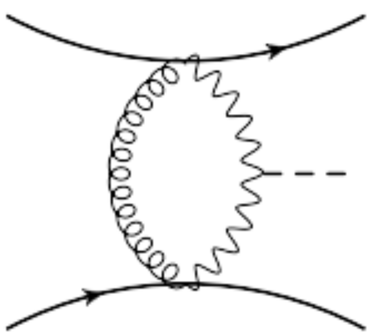
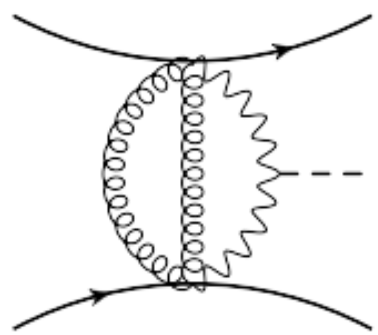


Nonfactorizable QCD effects in Higgs production via VBF

Liu, Melnikov, Penin '19





$$\mathcal{M}^{(2)} = -\frac{\tilde{\alpha}_s^2}{2!}\chi^{(2)}(\boldsymbol{q}_3, \boldsymbol{q}_4)\mathcal{M}^{(0)}$$

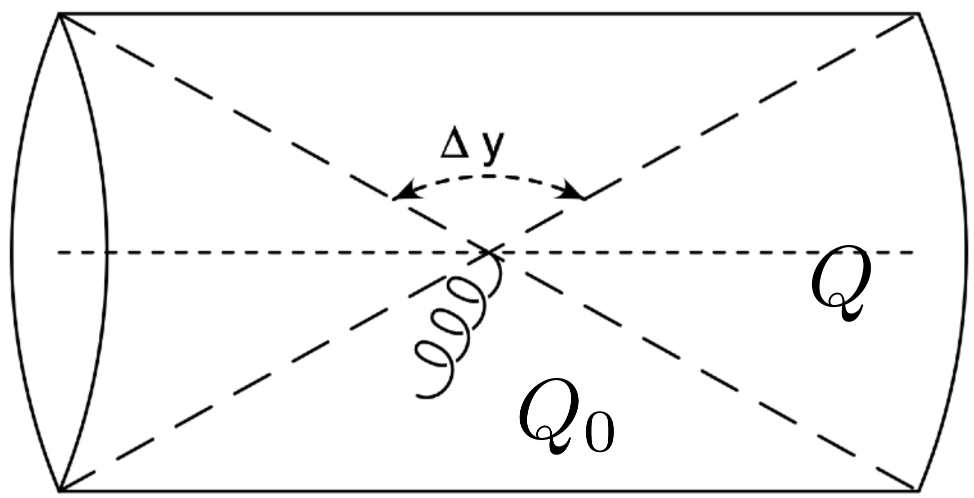
with $\chi^{(2)}(\boldsymbol{q}_3, \boldsymbol{q}_4) = \frac{1}{\pi^2}\int \left(\prod_{i=1}^{2} \frac{\mathrm{d}^2\boldsymbol{k}_i}{\boldsymbol{k}_i^2 + \lambda^2}\right)$

$$\times \frac{\boldsymbol{q}_3^2 + M_V^2}{(\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{q}_3)^2 + M_V^2} \frac{\boldsymbol{q}_4^2 + M_V^2}{(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{q}_4)^2 + M_V^2}$$

nonfactorizable correction: $\Delta_{\mathrm{NF}} = \frac{\sigma_{\mathrm{VBF}}^{\mathrm{NNLO,NF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{LO}}} \times 100\% = -0.39\%$

- **the nonfactorizable correction is comparable to the NNNLO QCD factorizable corrections**
- **appear for the first time at NNLO, scale dependence is large**

Central jet veto at the LHC

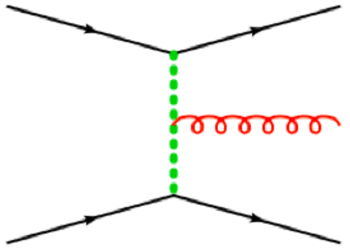


leading logs:

$$e^+e^-, ep: \quad \alpha_s^n \ln^n\left(\frac{Q}{Q_0}\right)$$

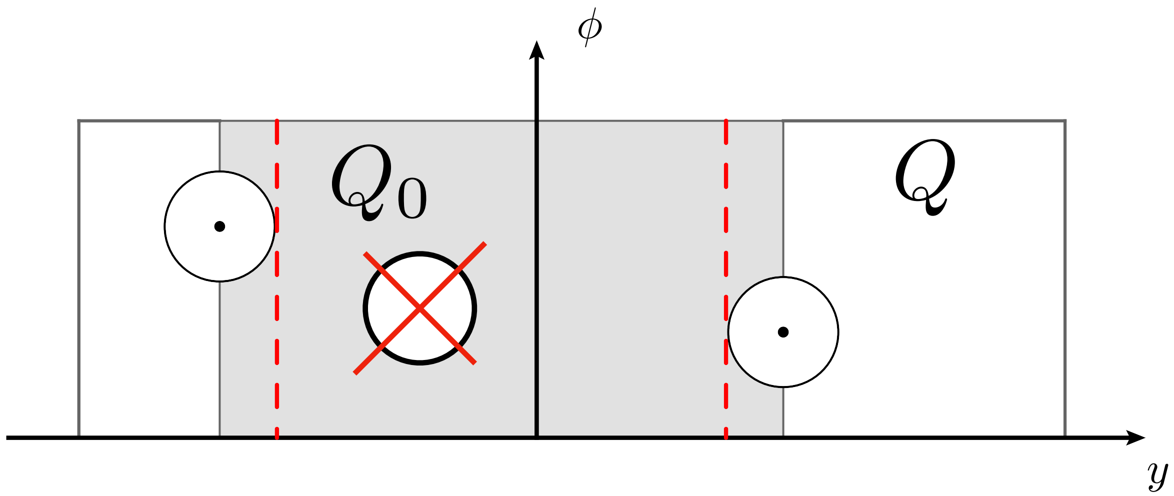
$$pp: \qquad \cdots \qquad + \alpha_s^3 (i\pi)^2 \ln^3\left(\frac{Q}{Q_0}\right) \times \alpha_s^n \ln^{2n}\left(\frac{Q}{Q_0}\right)$$

- Such events was originally suggested on the basis of color flow considerations in QCD Bjorken ’93
- Global Logs resummation is first done by Oderda & Sterman ’98
- Forshaw, Kyrieleis, Seymour ’06 have analyzed the effect of Glauber phases in non-global observables directly in QCD
  - Non-zero contributions starting at 3 loops
  - Collinear logarithms starting at 4 loops: Super-leading logs



wide angle soft gluon emission developing a sensitivity to emission at small angles

Central jet veto at the LHC



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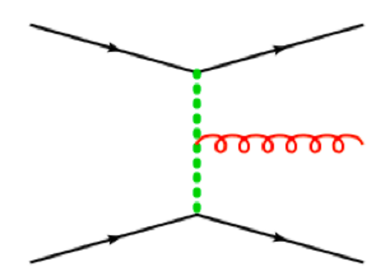
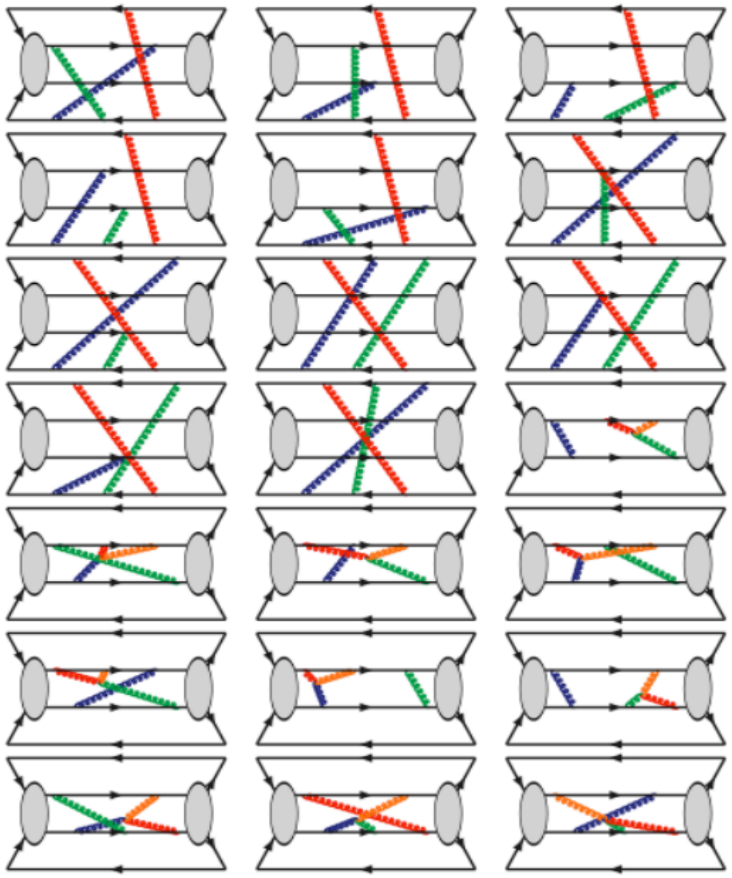


wide angle soft gluon emission developing a sensitivity to emission at small angles

Fixed order calculation

- Gluons are added in all possible ways to trace diagrams and colour factors calculated using COLOUR
- Diagrams are then cut in all ways consistent with strong ordering
- At fourth order there are 10,529 diagrams and 1,746,272 after cutting.
- SLL terms are confirmed at fourth order and computed for the first time at 5^{th} order



Keates and Seymour
arXiv:0902.0477 [hep-ph]

Simone Marzani's slide

Factorization for gap between jets in e+e-

(Becher, Neubert, Rothen, **DYS**, ’15 PRL, ’16 JHEP; Caron-Huot ’15 JHEP)

Hard function
m hard partons along
fixed directions {n_1, …, n_m}
$\mathcal{H}_m \propto |\mathcal{M}_m\rangle\langle\mathcal{M}_m|$

Soft function
squared amplitude
with *m* Wilson lines

Color Trace **Hard scale** **Soft scale**

$$\sigma(Q, Q_\Omega) \sim \sum_{m=2}^{\infty} \prod_{i=1}^{m} \int \frac{d\Omega(\vec{n}_i)}{4\pi} \mathrm{Tr}_c \left[\mathcal{H}_m(\{\vec{n}_1, \cdots, \vec{n}_m\}, Q, \mu) \mathcal{S}_m(\{\vec{n}_1, \cdots, \vec{n}_m\}, Q_\Omega, \mu)\right]$$

# of jet not fixed

Integrate the angles for hard partons

One-loop anomalous dimension:

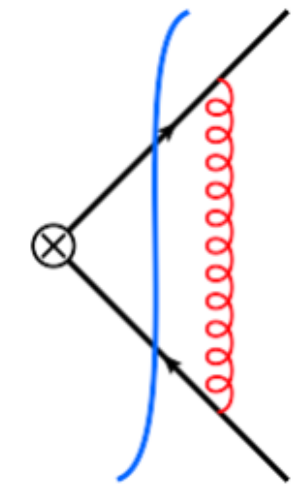
$$\Gamma^{(1)} = \begin{pmatrix} \boldsymbol{V}_2 & \boldsymbol{R}_2 & 0 & 0 & \dots \\ 0 & \boldsymbol{V}_3 & \boldsymbol{R}_3 & 0 & \dots \\ 0 & 0 & \boldsymbol{V}_4 & \boldsymbol{R}_4 & \dots \\ 0 & 0 & 0 & \boldsymbol{V}_5 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\boldsymbol{V}_m = -2 \sum_{(ij)} \int \frac{d\Omega(n_k)}{4\pi} \left(\boldsymbol{T}_{i,L} \cdot \boldsymbol{T}_{j,L} + \boldsymbol{T}_{i,R} \cdot \boldsymbol{T}_{j,R}\right) W_{ij}^{k} \left[\Theta_{\text{in}}^{n\bar{n}}(k) + \Theta_{\text{out}}^{n\bar{n}}(k)\right]$$

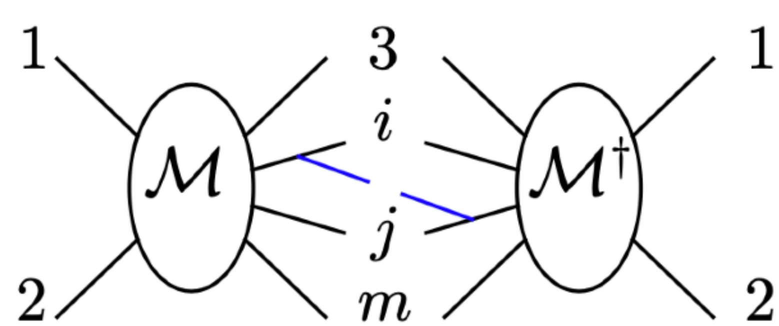
$$+ 2 i\pi \sum_{(ij)} \left(\boldsymbol{T}_{i,L} \cdot \boldsymbol{T}_{j,L} - \boldsymbol{T}_{i,R} \cdot \boldsymbol{T}_{j,R}\right) \Pi_{ij},$$

$$\boldsymbol{R}_m = 4 \sum_{(ij)} \boldsymbol{T}_{i,L} \cdot \boldsymbol{T}_{j,R} \, W_{ij}^{m+1} \, \Theta_{\text{in}}(n_{m+1}) \, .$$

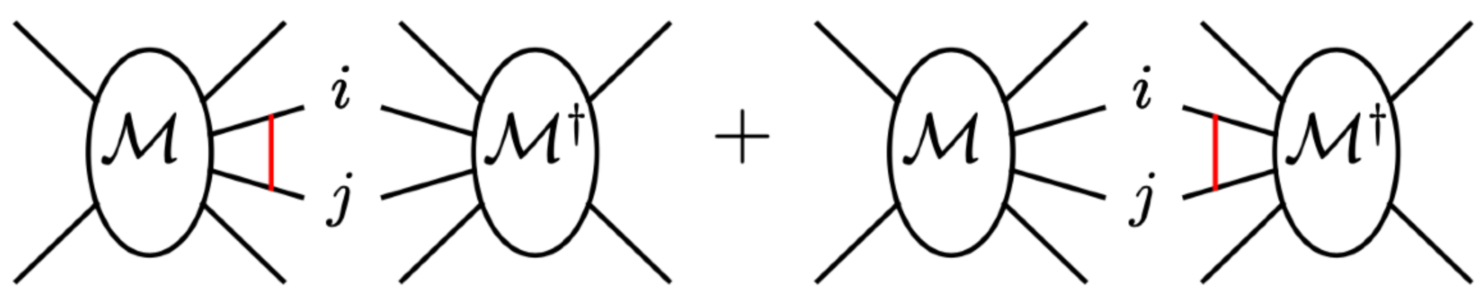
$\Pi_{ij} = 1$ **if both incoming or outgoing**



$$\boldsymbol{\mathcal{H}}_m \, \boldsymbol{R}_m = \sum_{(ij)}$$



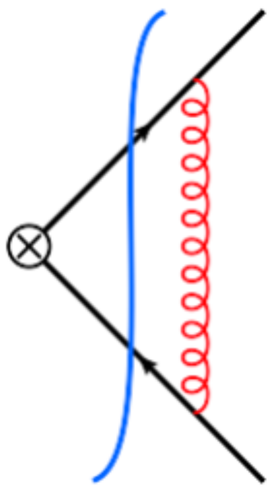
$$\boldsymbol{\mathcal{H}}_m \, \boldsymbol{V}_m = \sum_{(ij)}$$



One-loop anomalous dimension:

$$\boldsymbol{V}_m = -2\sum_{(ij)}\int\frac{d\Omega(n_k)}{4\pi}\left(\boldsymbol{T}_{i,L}\cdot\boldsymbol{T}_{j,L}+\boldsymbol{T}_{i,R}\cdot\boldsymbol{T}_{j,R}\right)W_{ij}^k\left[\Theta_{\rm in}^{n\bar{n}}(k)+\Theta_{\rm out}^{n\bar{n}}(k)\right]$$
$$+\,2\,i\pi\sum_{(ij)}\left(\boldsymbol{T}_{i,L}\cdot\boldsymbol{T}_{j,L}-\boldsymbol{T}_{i,R}\cdot\boldsymbol{T}_{j,R}\right)\Pi_{ij}\,,$$
$$\boldsymbol{R}_m = 4\sum_{(ij)}\boldsymbol{T}_{i,L}\cdot\boldsymbol{T}_{j,R}\,W_{ij}^{m+1}\,\Theta_{\rm in}(n_{m+1})\,.$$

$\Pi_{ij}=1$ **if both incoming or outgoing**



Imaginary part of the anomalous dimension:

For e+e-:

$$\sum_{i\neq j}\mathbf{T}_i\cdot\mathbf{T}_j = -\sum_i\mathbf{T}_i^2 = -\sum_i C_i$$

For pp:

$$\sum_{(ij)}\boldsymbol{T}_i\cdot\boldsymbol{T}_j\,\Pi_{ij} = 2\,\boldsymbol{T}_1\cdot\boldsymbol{T}_2+\sum_{i=3}^m\boldsymbol{T}_i\cdot\left(-\boldsymbol{T}_1-\boldsymbol{T}_2-\boldsymbol{T}_i\right)$$
$$= 2\,\boldsymbol{T}_1\cdot\boldsymbol{T}_2+(\boldsymbol{T}_1+\boldsymbol{T}_2)\cdot(\boldsymbol{T}_1+\boldsymbol{T}_2)-\sum_{i=3}^m C_i^2$$
$$= \boxed{4\,\boldsymbol{T}_1\cdot\boldsymbol{T}_2}+C_1^2+C_2^2-\sum_{i=3}^m C_i^2$$

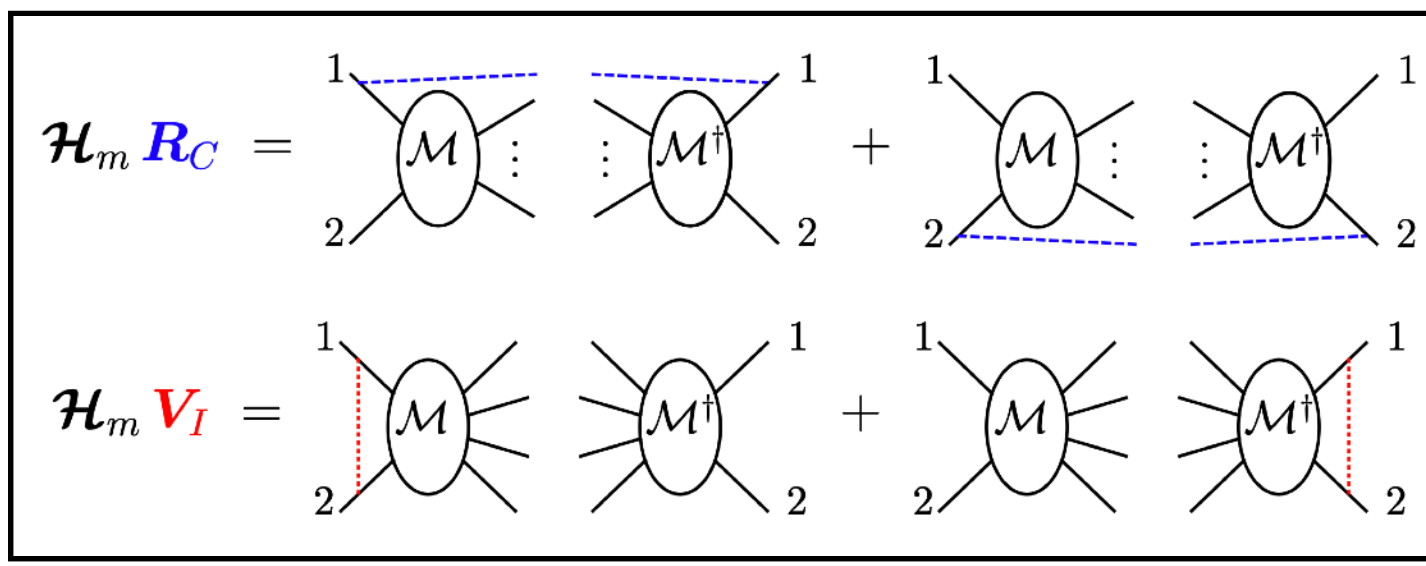
Non trivial

Extracting the collinear singularities: $\overline{W}_{ij}^{k} = \frac{n_i \cdot n_j}{n_i \cdot n_k \, n_j \cdot n_k} - \frac{\delta(n_k - n_i)}{n_i \cdot n_k} - \frac{\delta(n_k - n_j)}{n_j \cdot n_k}$

$$\begin{aligned}
\boldsymbol{V}_m &= 2 \sum_{(ij)} \left(\boldsymbol{T}_{i,L} \cdot \boldsymbol{T}_{j,L} + \boldsymbol{T}_{i,R} \cdot \boldsymbol{T}_{j,R} \right) \left\{ -\ln \frac{\mu^2}{Q^2} + \int \frac{d\Omega(n_k)}{4\pi} \overline{W}_{ij}^{k} \right\} \\
&\quad - 2\, i\pi \sum_{(ij)} \left(\boldsymbol{T}_{i,L} \cdot \boldsymbol{T}_{j,L} - \boldsymbol{T}_{i,R} \cdot \boldsymbol{T}_{j,R} \right) \Pi_{ij} , \\
\boldsymbol{R}_m &= 4 \sum_{(ij)} \boldsymbol{T}_{i,L} \cdot \boldsymbol{T}_{j,R} \left\{ \frac{1}{2} \Big[\delta(n_k - n_i) + \delta(n_k - n_j) \Big] \ln \frac{\mu^2}{Q^2} - \overline{W}_{ij}^{m+1} \, \Theta_{\text{in}}(n_{m+1}) \right\}
\end{aligned}$$

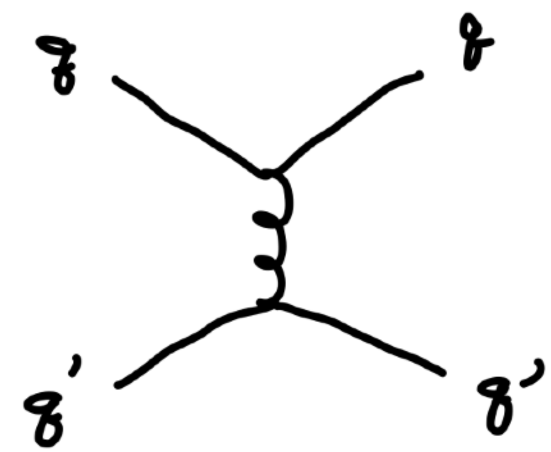
The one-loop anomalous dimension is

$$\begin{aligned}
\boldsymbol{V}_m &= \overline{\boldsymbol{V}}_m + \boldsymbol{V}^I + \sum_{i=1}^{m} \boldsymbol{V}_i^C \, \ln \frac{\mu^2}{Q^2} , \\
\boldsymbol{R}_m &= \overline{\boldsymbol{R}}_m + \sum_{i=1}^{m} \boldsymbol{R}_i^C \, \ln \frac{\mu^2}{Q^2} ,
\end{aligned}$$



Super-leading logs from RG evolution

(Becher, Neubert, **DYS**, ’21)



Consider the processes $q_1\, q_2' \to q_3\, q_4'$

LO hard function: $\mathcal{H}_4 = t^a_{\alpha_3\alpha_1} t^a_{\alpha_4\alpha_2} t^b_{\beta_1\beta_3} t^b_{\beta_2\beta_4} \sigma_0$

Expand the expansion kernel (Becher, Neubert, Rothen, DYS ’16 PRL)

$$\begin{aligned}\boldsymbol{\mathcal{H}}_4\, \boldsymbol{U}(\mu_s,\mu_h) &= \boldsymbol{\mathcal{H}}_4\, \mathbf{P}\exp\left[\int_{\mu_s}^{\mu_h} \frac{d\mu}{\mu}\, \boldsymbol{\Gamma}^H(Q,\mu)\right] \\ &= \boldsymbol{\mathcal{H}}_4 + \int_{\mu_s}^{\mu_h} \frac{d\mu}{\mu}\, \boldsymbol{\mathcal{H}}_4\, \boldsymbol{\Gamma}^H(Q,\mu) + \int_{\mu_s}^{\mu_h} \frac{d\mu}{\mu} \int_{\mu}^{\mu_h} \frac{d\mu'}{\mu'} \boldsymbol{\mathcal{H}}_4\, \boldsymbol{\Gamma}^H(Q,\mu')\, \boldsymbol{\Gamma}^H(Q,\mu)\end{aligned}$$

The first non-zero contribution of has factor arises at 3-loop order

$$S^{(3)} = \langle \boldsymbol{\mathcal{H}}_4 \boldsymbol{V}^I \boldsymbol{V}^I (\overline{\boldsymbol{V}}_4 + \overline{\boldsymbol{R}}_4)\rangle \left(\frac{\alpha_s}{4\pi}\right)^3 \frac{1}{3!} \ln^3\left(\frac{Q}{\mu}\right) = -\left(\frac{\alpha_s}{4\pi}\right)^3 \frac{16\, C_F}{3}\, \pi^2 L_Q^3\, J_1\, \sigma_0$$

$$J_1 = 2\Delta Y\, \mathrm{sign}(\eta_J)$$

Super-leading logs at 4-loop order:

$$S_0^{(4)} = \left\langle \boldsymbol{\mathcal{H}}_4 \boldsymbol{V}^I \left[\sum_{i=1}^{4} \boldsymbol{V}_i^L \boldsymbol{V}^I (\overline{\boldsymbol{V}}_4 + \overline{\boldsymbol{R}}_4) + \sum_{i=1}^{4} \boldsymbol{R}_i^L \boldsymbol{V}^I (\overline{\boldsymbol{V}}_5 + \overline{\boldsymbol{R}}_5)\right]\right\rangle \left(\frac{\alpha_s}{4\pi}\right)^4 \frac{(-2)}{5!} \ln^5\left(\frac{Q}{\mu}\right)$$

All-order results of super-leading logs

(Becher, Neubert, **DYS** '21)

Owen's T function

$$f_1(w) = \frac{\sqrt{\pi}}{2w}\int_0^{\sqrt{\frac{w}{2}}} \frac{dz}{z^2}\left[\mathrm{erf}\,(z) - \frac{e^{-2z^2}}{i}\mathrm{erf}(iz)\right]$$

hypergeometric function

$$f_\delta(w) = \frac{1}{3}\,{}_2F_2\left(1,1;2,\frac{5}{2};-w\right)$$

error function

$$f_2(w) = \frac{1}{w} - \frac{\sqrt{\pi}}{2w^{3/2}}\,\mathrm{erf}(\sqrt{w})$$

$$\omega \sim \alpha_s L^2$$

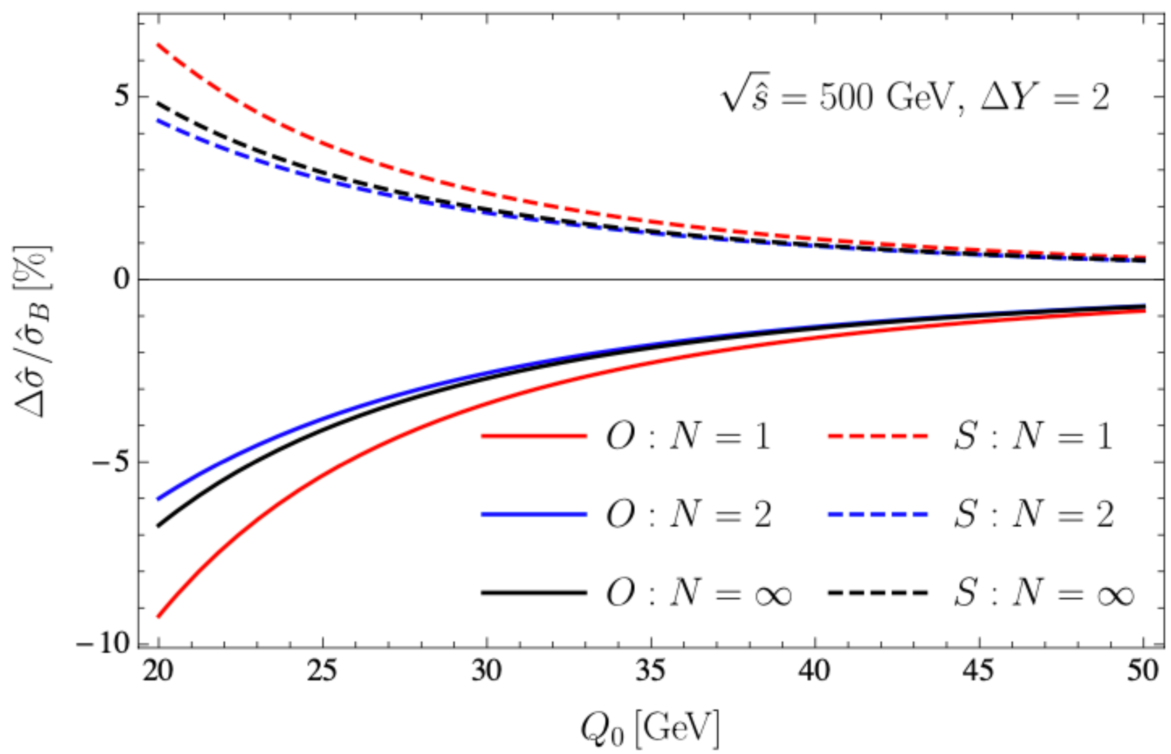
$$S_O = \left(\frac{\alpha_s}{\pi}\right)^3 \pi^2 \ln^3\frac{Q}{\mu_s}\frac{1}{N_c}\left[N_c^2\left(4f_1(w) - 2f_\delta(w)\right] - 4f_2(\omega) + 2f_\delta(w)\right)\Delta Y\,\sigma_0$$

Sudakov suppression of the superleading logarithms is weaker than the one present for global observables

Global logs ⟶ $e^{-\omega}$

Superleading logs $\xrightarrow{\omega\to\infty}$ $\frac{1}{\omega}$

Numerical results



Red: Four loop Blue: Five loop Black: all order

Summary

- **If the radiation in a high-energy scattering process is restricted by experimental cuts, higher-order terms in the perturbative series are enhanced by large logarithms**
- **The simple structure of these emissions often makes it possible to resum the logarithmic terms to all orders, either analytically or using parton-shower methods.**
- **For exclusive jet cross sections at hadron colliders where a veto on radiation is imposed only in certain regions, even the LLs have a complicated structure**
- **We derive the all-order structure of SLLs for generic 2 → N scattering processes at hadron colliders and resum them in closed form**
- **Our findings indicate that SLLs could have an appreciable effect on precision observables, in particular in Higgs production via VBF**

Thank you