

# NLO VERTEX FOR A FORWARD JET PLUS A RAPIDITY GAP AT HIGH ENERGIES

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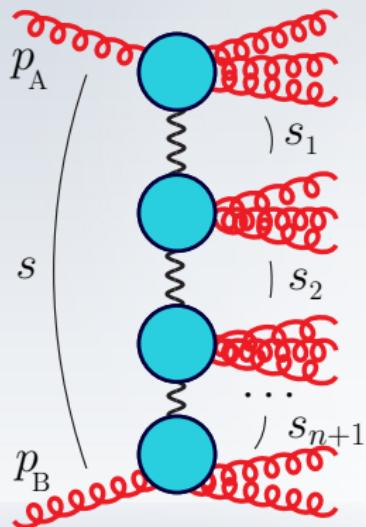
# Dijets with Rapidity Separation as a Probe of BFKL Pomeron

# From Quasi-Multi-Regge Factorization to Perturbative Diffraction

In multi-Regge limit, amplitudes factorize into effective vertices connected through reggeon exchange

[Fadin, Kuraev & Lipatov '75,76,77]

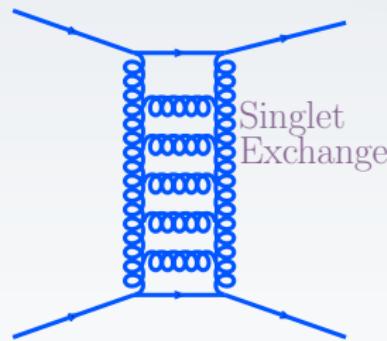
[Lipatov'76; Balitsky & Lipatov '78]



Clusters strongly ordered in rapidity

$$y_0 \gg y_1 \gg \dots \gg y_{n+1}, \quad y_i = \frac{1}{2} \ln \frac{k_i^+}{k_i^-}$$

- Using  $s$ -channel unitarity, one can obtain elastic amplitude via pomeron exchange [Solution to BFKL Equation]

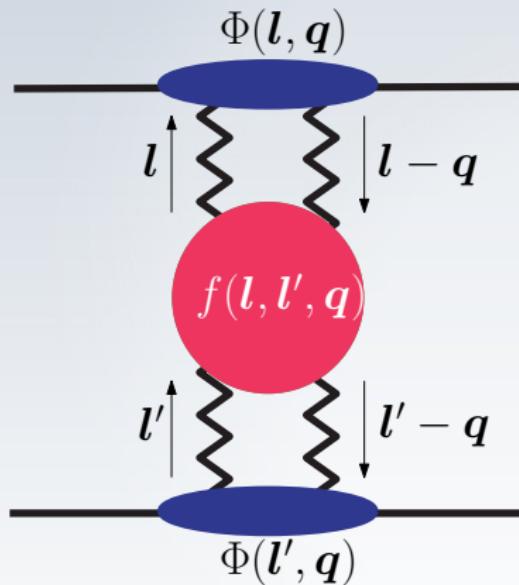


Pomeron  $\sim$  Bound State of two Reggeons

- Singlet exchange  $\Rightarrow$  Rapidity Gap  $\Rightarrow$  Diffraction

Describable *a priori* within  $p$ QCD for high momentum transfers

# From Quasi-Multi-Regge Factorization to Perturbative Diffraction



- Diffraction processes allow to study **non-forward** BFKL Green's function ( $\sim$  pomeron slope)

**Forward-Backward Jets with Rapidity Gap very well suited to study BFKL**

[Mueller & Tang '92]

- High- $p_T$  of tagged jets ensures application of pQCD
- Large rapidity gap enhances BFKL resummation

Amplitudes are convolutions of universal BFKL  
Green's function and impact factors

# BFKL Observables at NLO

- BFKL Green's function known at NLO, both in forward [Fadin & Lipatov '98; Ciafaloni & Camici '98; Kotikov & Lipatov '00] and non-forward [Fadin & Fiore '05; Fadin, Fiore & Papa '12] cases

- NLO corrections are rather large, although stabilized through collinear resummation [Salam '98; Ciafaloni, Colferai, Salam & Stašto '02,'03,'04]

Also a number of impact factors known at NLO:

- Colliding partons [Fadin, Fiore, Kotsky & Papa '00]
- Forward jet production [Bartels, Colferai & Vacca '02,'03; Caporale *et al.*'12]
- Forward vector meson production [Ivanov, Kotsky & Papa '04]
- $\gamma^* \rightarrow \gamma^*$  transition [Bartels *et al.* '02,'03; Balitsky & Chirilli '11,'13]

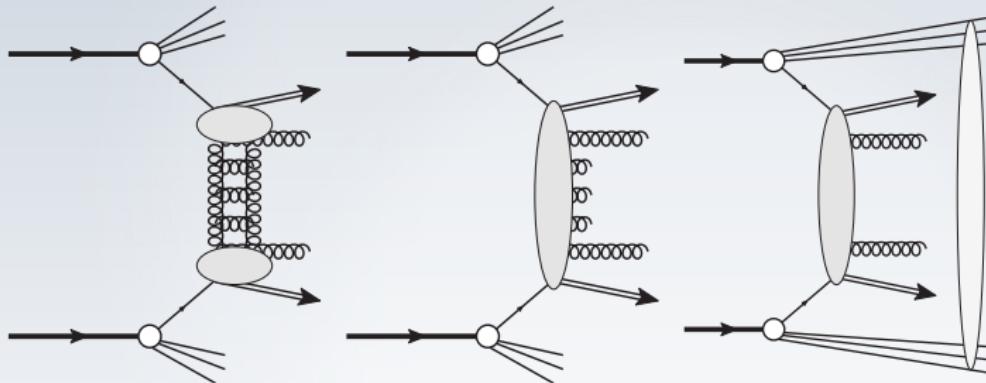
(However, none of them proves non-forward BFKL!)

In general,

- NLO corrections turn out to be **also large** for cross-sections (see, e.g. [Colferai, Schwennsen, Szymanowski & Wallon'02,'03,'04])
- **Uncertainties** in renormalization, factorization and reggeization scales **reduced**
- **Realistic jets** (containing more than one parton)

# The Mueller-Tang Cross-Section

*Gap is never empty...  $\Rightarrow$  Need to introduce resolution scale  $E_{\text{gap}}$*



**Singlet**

( $\alpha_s$  suppressed)

**Octet**

(Sudakov suppressed)

**Residual Interaction**

(from soft rescattering)

RAPIDITY GAP  
SURVIVAL PROBABILITY

# The Challenge of Dijets with Rapidity Gap

- The high- $p_T$  of the tagged jets ensures one can control the pomeron-proton coupling **perturbatively**

*In this respect, is the Mueller-Tang prescription for Green's function valid?* [Mueller & Tang '92; Bartels *et al.* '95]

- The **exclusive** character of the observable may preclude applicability of **collinear factorization**

# Lipatov's Effective Action for Quasi-Multi-Regge Kinematics

# The High-Energy Effective Action

[Lipatov'91; Kirschner, Lipatov & Szymanowski'93,'94]  
 [Lipatov'95,'97]

- Effective action provides powerful tool for computing amplitudes in QMR kinematics
- Implements nontrivially rapidity factorization in a gauge-invariant way

$$S_{\text{eff}} = S_{\text{QCD}} + S_{\text{ind}};$$

$$\begin{aligned} S_{\text{ind}} = \int d^4x \text{Tr} & \left[ (W_+[v(x)] - \mathcal{A}_+(x)) \partial_\perp^2 \mathcal{A}_-(x) \right] \\ & + \int d^4x \text{Tr} \left[ (W_-[v(x)] - \mathcal{A}_-(x)) \partial_\perp^2 \mathcal{A}_+(x) \right]; \end{aligned}$$

$$W_\pm[v] = v_\pm \frac{1}{D_\pm} \partial_\pm = v_\pm - g v_\pm \frac{1}{\partial_\pm} v_\pm + \dots$$

$\mathcal{A}_\pm$ : reggeons,     $v_\mu$ : gluons

## Kinematical Constraints

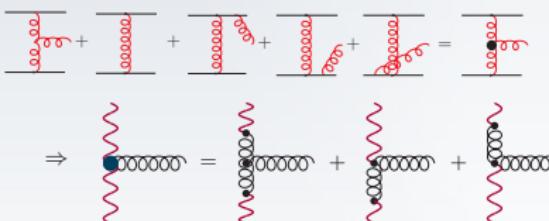
$$\partial_\pm \mathcal{A}_\mp(x) = 0, \quad \sum_{i=0}^r k_i^\pm = 0$$

Reggeon fields **invariant** under  
*local* gauge transformations

# The High-Energy Effective Action

- Infinite number of new induced vertices (perturbative expansion of Wilson line) needed to reconcile gauge invariance and high-energy factorization

GENERIC VERTEX = PROJECTION + INDUCED VERTEX



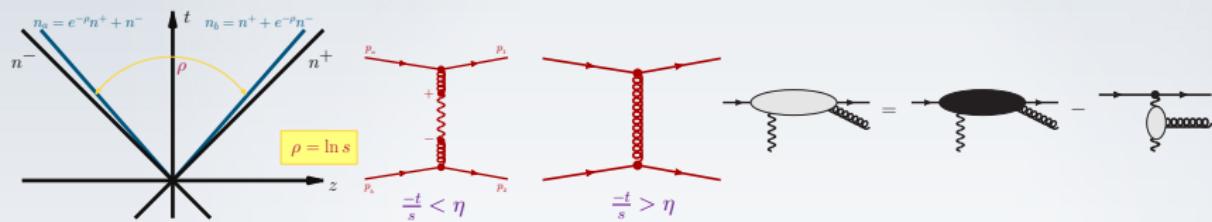
$$S_{\text{eff}} = S_{\text{QCD}} + S_{\text{ind}}$$

[Antonov, Cherednikov, Kuraev & Lipatov'05]

$$\begin{aligned} & \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} = \Delta_{a_0 c}^{\nu_0 -} = -i \mathbf{q}^2 \delta^{a_0 c} (n^-)^{\nu_0}, \\ & \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} = g \mathbf{q}^2 f^{a_0 a_1 c} \frac{1}{k_0^-} (n^-)^{\nu_0} (n^-)^{\nu_1}, \\ & \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} = \Delta_{a_0 a_1 a_2 c}^{\nu_0 \nu_1 \nu_2 -} = ig^2 \mathbf{q}^2 \left( \frac{f^{a_2 a_1 a} f^{a_0 a c}}{k_2^- k_0^-} \right. \\ & \quad \left. + \frac{f^{a_2 a_0 a} f^{a_1 a c}}{k_2^- k_1^-} \right) (n^-)^{\nu_0} (n^-)^{\nu_1} (n^-)^{\nu_2}, \\ & \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} = \frac{i}{2 \mathbf{q}^2}. \end{aligned}$$

# Lipatov's Action Beyond Tree Level

- When dealing with loops, it is needed to regularize new rapidity divergences and avoid overcounting of diagrams
- This can be achieved in a manifestly gauge-invariant way [Hentschinski & Sabio Vera '11; Chachamis, Hentschinski, JDM & Sabio Vera '13]



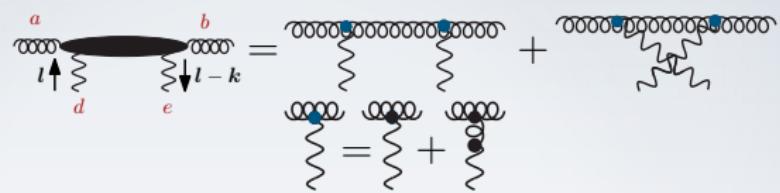
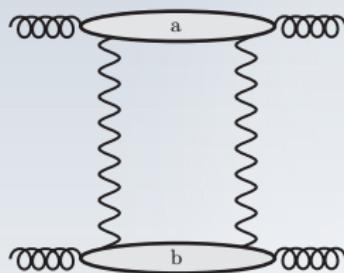
- This procedure has already been checked successfully for 1-loop corrections to forward jet vertex [Hentschinski & Sabio Vera '11; Chachamis, Hentschinski, JDM & Sabio Vera '13] and 2-loop gluon Regge trajectory [Chachamis, Hentschinski, JDM & Sabio Vera '12, '13]

# NLO Mueller-Tang Vertex

# The Leading-Order Cross-Section

Impact factors determined from parton (quark/gluon)-pomeron coupling

Pomeron  $\sim$  Two Reggeons in color singlet



- Rapidity factorization suggests including integral over light-cone component of loop momentum in impact factors

$$i\mathcal{M}_{g_a g_b \rightarrow g_1 g_2}^{(0)} = \int \frac{d^{2+2\epsilon} \mathbf{l}}{(2\pi)^{2+2\epsilon}} \phi_{gg,a} \phi_{gg,b} \frac{1}{\mathbf{l}^2 (\mathbf{k} - \mathbf{l})^2},$$

$$i\phi_{gg,a} = \int \frac{dl^-}{8\pi} i\tilde{\mathcal{M}}_{gr^* r^* \rightarrow g}^{abde} P^{de}, \quad P^{de} = \frac{\delta^{de}}{\sqrt{N_c^2 - 1}}$$

# The Leading-Order Cross-Section

$$\frac{d\hat{\sigma}_{ij}}{d^2\mathbf{k}} = \int \frac{d^2\mathbf{l}_1 d^2\mathbf{l}'_1}{\pi} \frac{d^2\mathbf{l}_2 d^2\mathbf{l}'_2}{\pi} h_{i,a}^{(0)} h_{j,b}^{(0)} G\left(\mathbf{l}_1, \mathbf{l}'_1, \mathbf{k}, \frac{s}{s_0}\right) G\left(\mathbf{l}_2, \mathbf{l}'_2, \mathbf{k}, \frac{s}{s_0}\right),$$

$$h_q^{(0)} = C_f^2 h^{(0)}, \quad h_g^{(0)} = C_a^2 (1 + \epsilon) h^{(0)}; \quad h^{(0)} = \frac{\alpha_{s,\epsilon}^2 2^\epsilon}{\mu^{4\epsilon} \Gamma^2(1 - \epsilon)(N_c^2 - 1)}$$

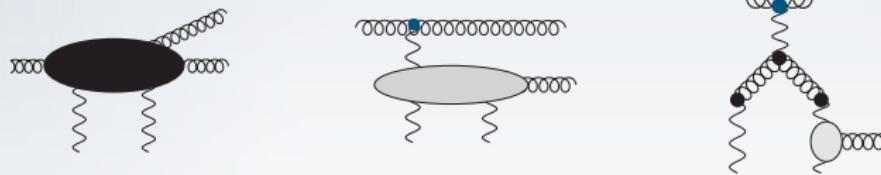
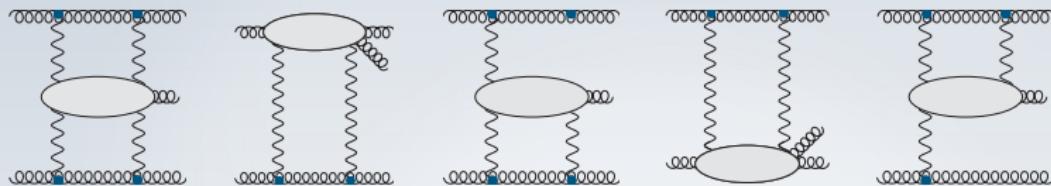
*G* is the non-forward BFKL Green's function

- We expect that, for  $s \rightarrow \infty$ , Green's function avoids singularities in transverse momentum integral as it occurs at LO

[Motyka, Martin & Ryskin '02]

# Types of NLO Corrections

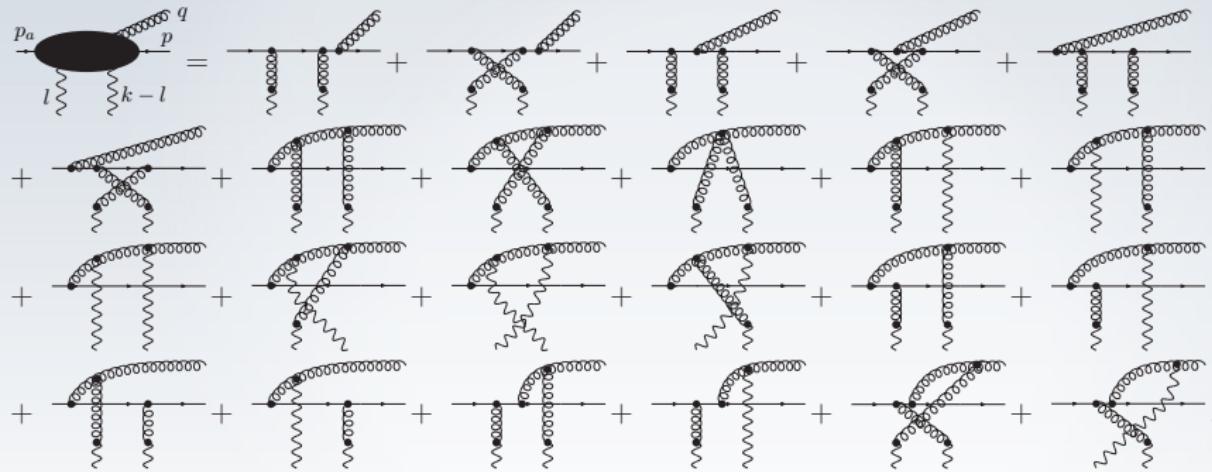
- Virtual corrections already computed in [Fadin, Fiore, Kotisky & Papa '00]



$$\lim_{s_{qg} \rightarrow \infty} \text{Diagram with black oval} = \text{Diagram with grey oval}$$

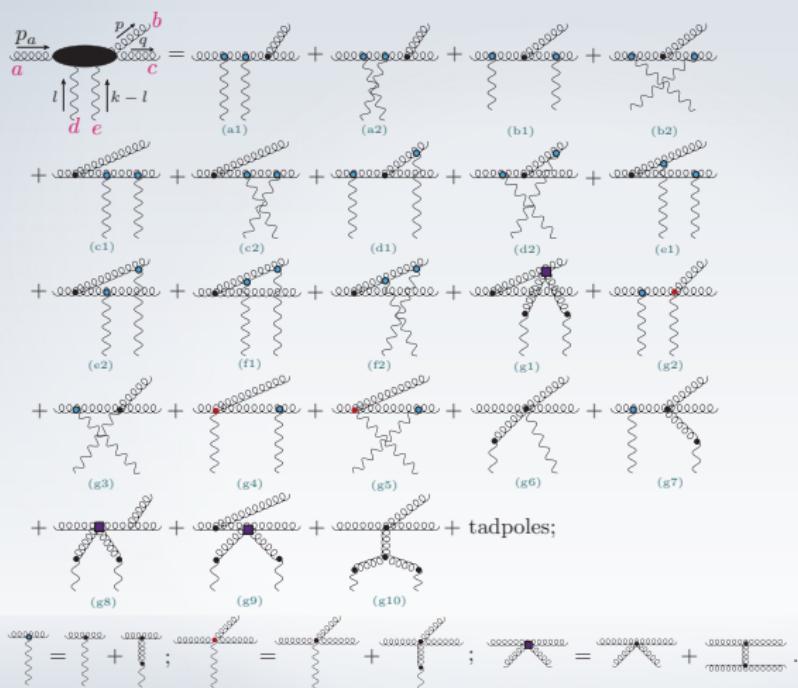
# Diagrams for Quasielastic Corrections

$$q(\bar{q}) \rightarrow q(\bar{q})g$$



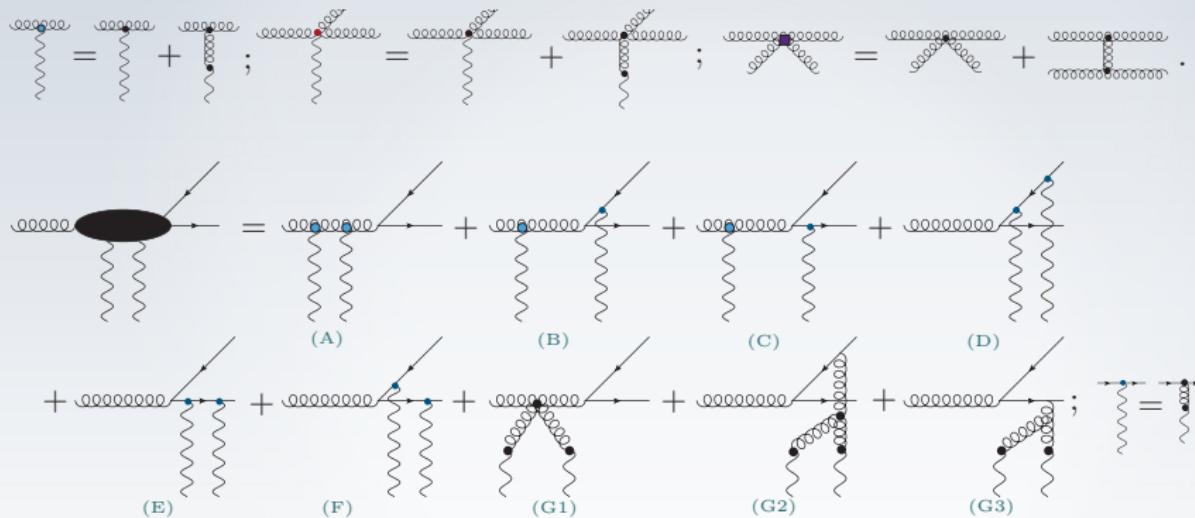
# Diagrams for Quasielastic Corrections

$g \rightarrow gg$



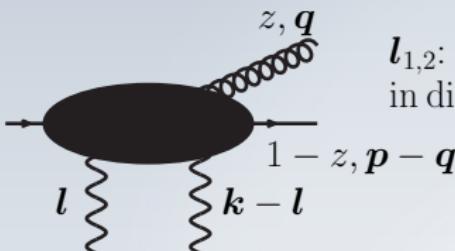
# Diagrams for Quasielastic Corrections

$g \rightarrow q\bar{q}$



+ crossing counterparts of diagrams (A)-(F);

# Differential Partonic Impact Factor



$\mathbf{l}_{1,2}$ : transverse momenta of pomeron loop  
in direct and complex conjugate amplitude

$$h_{r,ij}^{(1)} d\Gamma^{(2)} = \frac{h^{(0)}(1+\epsilon)}{\mu^{2\epsilon}\Gamma(1-\epsilon)} \frac{\alpha_{s,\epsilon}}{2\pi} P_{ij}(z, \epsilon)$$

$$\left[ A_{ij}^{(1)} \frac{\Delta}{\Delta^2} - A_{ij}^{(2)} \frac{\mathbf{q}}{\mathbf{q}^2} - A_{ij}^{(3)} \frac{\mathbf{p}}{\mathbf{p}^2} - \frac{1}{2} A_{ij}^{(4)} \left( \frac{\mathbf{q}-\mathbf{l}_1}{(\mathbf{q}-\mathbf{l}_1)^2} + \frac{\mathbf{l}_1-\mathbf{p}}{(\mathbf{l}_1-\mathbf{p})^2} \right) \right] \cdot \left[ \{\mathbf{l}_1 \leftrightarrow \mathbf{l}_2\} \right] d\Gamma^{(2)},$$

$$ij = gq, gg, qg$$

$$P_{gq}(z, \epsilon) = C_f \frac{1 + (1-z)^2 + \epsilon z^2}{z} \quad P_{gg}(z, \epsilon) = 2C_a \frac{(1-z(1-z))^2}{z(1-z)} \quad P_{qg}(z, \epsilon) = \frac{1}{2} \left( 1 - \frac{2z(1-z)}{1+\epsilon} \right)$$

$$A_{gq}^{(k)} = \frac{1}{1+\epsilon} (C_f, C_f, C_a, C_a) \quad A_{gg}^{(k)} = \frac{1}{2!} (C_a, C_a, C_a, C_a) \quad A_{qg}^{(k)} = (C_a, C_f, C_f, 2(C_f - C_a))$$

$$d\Gamma^{(2)} = dz d^{2+2\epsilon} \mathbf{q} / \pi^{1+\epsilon}$$

$$\Delta = \mathbf{q} - z\mathbf{k}$$

# Including the Jet Function

- Collinear and infrared singularities manifest as poles in dimensional regularization parameter  $\epsilon$
- In order to define an infrared and collinear safe NLO cross section, we need to convolute the partonic cross section with a jet function  $S_J$ :

$$\frac{d\hat{\sigma}_J}{dJ_1 dJ_2 d^2 \mathbf{k}} = d\hat{\sigma} \otimes S_{J_1} S_{J_2}, \quad dJ_i = d^{2+2\epsilon} \mathbf{k}_{J_i} dy_{J_i}, \quad i = 1, 2.$$

- ★ At LO, jet = parton:  $S_J^{(2)}(\mathbf{p}, x) = x \delta\left(x - \frac{|\mathbf{k}_J| e^{y_J}}{\sqrt{s}}\right) \delta^{2+2\epsilon}(\mathbf{p} - \mathbf{k}_J)$
- ★ At NLO, collinear and IR safe definition of jet function must satisfy

$$S_J^{(3)}(\mathbf{p}, \mathbf{q}, zx, x) \xrightarrow{\mathbf{p} \rightarrow 0} S_J^{(2)}(\mathbf{k}, zx); \quad S_J^{(3)}(\mathbf{p}, \mathbf{q}, zx, x) \xrightarrow[z \rightarrow \frac{\mathbf{p}}{1-z}]{} S_J^{(2)}(\mathbf{k}, x).$$

# Final Result for NLO Jet Vertex

- After renormalization of the coupling and parton densities (UV and collinear counterterms) and including virtual corrections, finite jet vertex in  $d = 4$
- To see explicitly the cancellation, we isolate the poles with a phase slicing parameter  $\lambda^2 \rightarrow 0$ 
  - ★ Remanent dependence of jet vertex on  $\lambda$  satisfies  $\frac{d}{d\lambda} \frac{d\hat{V}^{(1)}}{dJ} \rightarrow 0$  for  $\lambda^2 \ll k^2$
- Within collinear factorization

$$\begin{aligned} \frac{d\sigma_{J,H_1H_2}}{dJ_1 dJ_2 d^2k} = & \frac{1}{\pi^2} \int dl_1 dl'_1 dl_2 dl'_2 \frac{dV(l_1, l_2, k, p_{J,1}, y_1, s_0)}{dJ_1} \\ & \times G\left(l_1, l'_1, k, \frac{\hat{s}}{s_0}\right) G\left(l_2, l'_2, k, \frac{\hat{s}}{s_0}\right) \frac{dV(l'_1, l'_2, k, p_{J,2}, y_2, s_0)}{dJ_2}, \end{aligned}$$

# Final Result for NLO Jet Vertex

$$\begin{aligned}
 \frac{dV}{dJ} = \sum_{j=\{q,\bar{q},g\}} \int_{x_0}^1 dx f_{j/H}(x, \mu_F^2) \left( \frac{d\hat{V}_j^{(0)}}{dJ} + \frac{d\hat{V}_j^{(1)}}{dJ} \right), \quad x_0 = \frac{-t}{M_{x,\max}^2 - t} \\
 \frac{d\hat{V}_j^{(0)}}{dJ} = \frac{\alpha_s^2 C_j^2}{N_c^2 - 1} S_J^{(2)}(\mathbf{k}, x), \quad C_{q,\bar{q}} = C_f, \quad C_g = C_a \\
 \frac{d\hat{V}_j^{(1)}}{dJ} = \left( \frac{d\hat{V}_{j,v}^{(1)}}{dJ} + \frac{d\hat{V}_{j,r}^{(1)}}{dJ} + \frac{d\hat{V}_{j,\text{UV ct.}}^{(1)}}{dJ} + \frac{d\hat{V}_{j,\text{col. ct.}}^{(1)}}{dJ} \right), \\
 \frac{d\hat{V}_{j,v}^{(1)}}{dJ} = h_{v,j} S_J^{(2)}(\mathbf{k}, x), \\
 \frac{d\hat{V}_{j,r}^{(1)}}{dJ} = \int d\Gamma^{(2)} \sum_i h_{r,ij}^{(1)} S_J^{(3)}(\mathbf{p}, \mathbf{q}, zx, x).
 \end{aligned}$$

# Final Result for NLO Jet Vertex

$$\alpha_s = \alpha_s(\mu^2), \quad \phi_i = \arccos \frac{\mathbf{l}_i \cdot (\mathbf{k} - \mathbf{l}_i)}{|\mathbf{l}_i| |\mathbf{k} - \mathbf{l}_i|},$$

$$P_0(z) = C_a \left[ \frac{2(1-z)}{z} + z(1-z) \right], \quad P_1(z) = C_a \left[ \frac{2z}{[1-z]_+} + z(1-z) \right], \quad P_{qq}^{(0)}(z) = C_f \left( \frac{1+z^2}{1-z} \right)_+,$$

$$P_{qg}^{(0)}(z) = \frac{z^2 + (1-z)^2}{2} \quad P_{gq}^{(0)}(z) = C_f \frac{1 + (1-z)^2}{z}, \quad P_{gg}^{(0)}(z) = P_0(z) + P_1(z) + \frac{\beta_0}{2} \delta(1-z),$$

$$J_1(\mathbf{q}, \mathbf{k}, \mathbf{l}_i, z) = \frac{1}{4} \left[ 2 \frac{\mathbf{k}^2}{\mathbf{p}^2} \left( \frac{(1-z)^2}{\Delta^2} - \frac{1}{\mathbf{q}^2} \right) - \left( \frac{(\mathbf{l}_i - z\mathbf{k})^2}{\Delta^2(\mathbf{q} - \mathbf{l}_i)^2} - \frac{\mathbf{l}_i^2}{\mathbf{q}^2(\mathbf{q} - \mathbf{l}_i)^2} \right) - \left( \frac{(\mathbf{l}_i - (1-z)\mathbf{k})^2}{\Delta^2(\mathbf{p} - \mathbf{l}_i)^2} - \frac{(\mathbf{l}_i - \mathbf{k})^2}{\mathbf{q}^2(\mathbf{p} - \mathbf{l}_i)^2} \right) \right],$$

$$J_2(\mathbf{q}, \mathbf{k}, \mathbf{l}_1, \mathbf{l}_2) = \frac{1}{4} \left[ \frac{\mathbf{l}_1^2}{\mathbf{p}^2(\mathbf{p} - \mathbf{l}_1)^2} + \frac{(\mathbf{k} - \mathbf{l}_1)^2}{\mathbf{p}^2(\mathbf{q} - \mathbf{l}_1)^2} + \frac{\mathbf{l}_2^2}{\mathbf{p}^2(\mathbf{p} - \mathbf{l}_2)^2} + \frac{(\mathbf{k} - \mathbf{l}_2)^2}{\mathbf{p}^2(\mathbf{q} - \mathbf{l}_2)^2} \right. \\ \left. - \frac{1}{2} \left( \frac{(\mathbf{l}_1 - \mathbf{l}_2)^2}{(\mathbf{q} - \mathbf{l}_1)^2(\mathbf{q} - \mathbf{l}_2)^2} + \frac{(\mathbf{k} - \mathbf{l}_1 - \mathbf{l}_2)^2}{(\mathbf{p} - \mathbf{l}_1)^2(\mathbf{q} - \mathbf{l}_2)^2} + \frac{(\mathbf{k} - \mathbf{l}_1 - \mathbf{l}_2)^2}{(\mathbf{q} - \mathbf{l}_1)^2(\mathbf{p} - \mathbf{l}_2)^2} + \frac{(\mathbf{l}_1 - \mathbf{l}_2)^2}{(\mathbf{p} - \mathbf{l}_1)^2(\mathbf{p} - \mathbf{l}_2)^2} \right) \right],$$

# Final Result for NLO Jet Vertex

$$\frac{d\hat{V}_q^{(1)}(x, \mathbf{k}, \mathbf{l}_1, \mathbf{l}_2; x_J, \mathbf{k}_J; M_{X,\max}, s_0)}{dJ} = v^{(0)} \frac{\alpha_s}{2\pi} (Q_1 + Q_2 + Q_3)$$

$$\begin{aligned} Q_1 &= S_J^{(2)}(\mathbf{k}, x) C_f^2 \left[ -\frac{\beta_0}{4} \left\{ \left[ \ln \left( \frac{\mathbf{l}_1^2}{\mu^2} \right) + \ln \left( \frac{(\mathbf{l}_1 - \mathbf{k})^2}{\mu^2} \right) + \{1 \leftrightarrow 2\} \right] - \frac{20}{3} \right\} - 4C_f \right. \\ &\quad \left. + \frac{C_a}{2} \left( \left\{ \frac{3}{2k^2} \left[ \mathbf{l}_1^2 \ln \left( \frac{(\mathbf{l}_1 - \mathbf{k})^2}{\mathbf{l}_1^2} \right) + (\mathbf{l}_1 - \mathbf{k})^2 \cdot \ln \left( \frac{\mathbf{l}_1^2}{(\mathbf{l}_1 - \mathbf{k})^2} \right) - 4|\mathbf{l}_1||\mathbf{l}_1 - \mathbf{k}| \phi_1 \sin \phi_1 \right] - \frac{3}{2} \left[ \ln \left( \frac{\mathbf{l}_1^2}{k^2} \right) \right. \right. \right. \\ &\quad \left. \left. \left. + \ln \left( \frac{(\mathbf{l}_1 - \mathbf{k})^2}{k^2} \right) \right] - \ln \left( \frac{\mathbf{l}_1^2}{k^2} \right) \ln \left( \frac{(\mathbf{l}_1 - \mathbf{k})^2}{s_0} \right) - \ln \left( \frac{(\mathbf{l}_1 - \mathbf{k})^2}{k^2} \right) \cdot \ln \left( \frac{\mathbf{l}_1^2}{s_0} \right) - 2\phi_1^2 + \{1 \leftrightarrow 2\} \right\} + 2\pi^2 + \frac{14}{3} \right) \right], \\ Q_2 &= \int_{z_0}^1 dz S_J^{(2)}(\mathbf{k}, zx) \left[ \ln \frac{\lambda^2}{\mu_F^2} \left( C_f^2 P_{qq}^{(0)}(z) + C_a^2 P_{gq}^{(0)}(z) \right) + C_f (1-z) \left( C_f^2 - \frac{2}{z} C_a^2 \right) + 2C_f (1+z^2) \left( \frac{\ln(1-z)}{1-z} \right)_+ \right], \\ Q_3 &= \int_0^1 dz \int \frac{d^2 q}{\pi} \left[ \Theta \left( \hat{M}_{X,\max}^2 - \frac{(\mathbf{p} - z\mathbf{k})^2}{z(1-z)} \right) S_J^{(3)}(\mathbf{p}, \mathbf{q}, (1-z)x, x) C_f^2 P_{qq}^{(0)}(z) \Theta \left( \frac{|\mathbf{q}|}{1-z} - \lambda^2 \right) \frac{\mathbf{k}^2}{\mathbf{q}^2(\mathbf{p} - z\mathbf{k})^2} \right. \\ &\quad \left. + \Theta \left( \hat{M}_{X,\max}^2 - \frac{\Delta^2}{z(1-z)} \right) S_J^{(3)}(\mathbf{p}, \mathbf{q}, zx, x) P_{gq}^{(0)}(z) \left\{ C_f C_a [J_1(\mathbf{q}, \mathbf{k}, \mathbf{l}_1) + J_1(\mathbf{q}, \mathbf{k}, \mathbf{l}_2)] + C_a^2 J_2(\mathbf{q}, \mathbf{k}, \mathbf{l}_1, \mathbf{l}_2) \Theta(\mathbf{p}^2 - \lambda^2) \right\} \right]. \end{aligned}$$

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$$\begin{aligned}
 G_1 = & C_a^2 S_J^{(2)}(\mathbf{k}, x) \left[ C_a \left( \pi^2 - \frac{5}{6} \right) - \beta_0 \left( \ln \frac{\lambda^2}{\mu^2} - \frac{4}{3} \right) + \left( \frac{\beta_0}{4} + \frac{11C_a}{12} + \frac{n_f}{6C_a^2} \right) \left( \ln \frac{\mathbf{k}^4}{\mathbf{l}_1^2(\mathbf{k}-\mathbf{l}_1^2)} + \ln \frac{\mathbf{k}^4}{\mathbf{l}_2^2(\mathbf{k}-\mathbf{l}_2)^2} \right) \right. \\
 & + \frac{1}{2} \left\{ C_a \left( \ln^2 \frac{\mathbf{l}_1^2}{(\mathbf{k}-\mathbf{l}_1)^2} + \ln \frac{\mathbf{k}^2}{\mathbf{l}_1^2} \ln \frac{\mathbf{l}_1^2}{s_0} + \ln \frac{\mathbf{k}^2}{(\mathbf{k}-\mathbf{l}_1)^2} \ln \frac{(\mathbf{k}-\mathbf{l}_1)^2}{s_0} \right) - \left( \frac{n_f}{3C_a^2} + \frac{11C_a}{6} \right) \frac{\mathbf{l}_1^2 - (\mathbf{k}-\mathbf{l}_1)^2}{\mathbf{k}^2} \ln \frac{\mathbf{l}_1^2}{(\mathbf{k}-\mathbf{l}_1)^2} \right. \\
 & - 2 \left( \frac{n_f}{C_a^2} + 4C_a \right) \frac{(\mathbf{l}_1^2(\mathbf{k}-\mathbf{l}_1)^2)^{\frac{1}{2}}}{\mathbf{k}^2} \phi_1 \sin \phi_1 + \frac{1}{3} \left( C_a + \frac{n_f}{C_a^2} \right) \left[ 16 \frac{(\mathbf{l}_1^2(\mathbf{k}-\mathbf{l}_1)^2)^{\frac{3}{2}}}{(\mathbf{k}^2)^3} \phi_1 \sin^3 \phi_1 \right. \\
 & - 4 \frac{\mathbf{l}_1^2(\mathbf{k}-\mathbf{l}_1)^2}{(\mathbf{k}^2)^2} \left( 2 - \frac{\mathbf{l}_1^2 - (\mathbf{k}-\mathbf{l}_1)^2}{\mathbf{k}^2} \ln \frac{\mathbf{l}_1^2}{(\mathbf{k}-\mathbf{l}_1)^2} \right) \sin^2 \phi_1 + \frac{(\mathbf{l}_1^2(\mathbf{k}-\mathbf{l}_1)^2)^{\frac{1}{2}}}{(\mathbf{k}^2)^2} \cos \phi_1 \\
 & \left. \left. \left( 4\mathbf{k}^2 - 12(\mathbf{l}_1^2(\mathbf{k}-\mathbf{l}_1)^2)^{\frac{1}{2}} \phi_1 \sin \phi_1 - (\mathbf{l}_1^2 - (\mathbf{k}-\mathbf{l}_1)^2) \ln \frac{\mathbf{l}_1^2}{(\mathbf{k}-\mathbf{l}_1)^2} \right) \right] - 2C_a \phi_1^2 + \{ \mathbf{l}_1 \leftrightarrow \mathbf{l}_2, \phi_1 \leftrightarrow \phi_2 \} \right\} \Bigg]
 \end{aligned}$$

$$\begin{aligned}
 G_2 = & \int_{z_0}^1 dz S_J^{(2)}(\mathbf{k}, zx) \left\{ 2n_f P_{qg}^{(0)}(z) \left( C_f^2 \ln \frac{\lambda^2}{\mu_F^2} + C_a^2 \ln(1-z) \right) \right. \\
 & + C_a^2 P_{gg}^{(0)}(z) \ln \frac{\lambda^2}{\mu_F^2} + C_f^2 n_f + 2C_a^3 z \left( (1-z) \ln(1-z) + 2 \left[ \frac{\ln(1-z)}{1-z} \right]_+ \right)
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$$\begin{aligned}
G_3 = & \int_0^1 dz \int \frac{d^2 \mathbf{q}}{\pi} \left\{ n_f P_{qg}^{(0)}(z) \left[ C_a^2 \Theta \left( \hat{M}_{X,\max}^2 - \frac{z \mathbf{p}^2}{(1-z)} \right) S_J^{(3)}(\mathbf{k} - z\mathbf{q}, z\mathbf{q}, zx, x) \right. \right. \\
& \left[ \Theta(\mathbf{p}^2 - \lambda^2) \mathbf{k}^2 + \frac{\mathbf{k}^2}{(\mathbf{p}^2 + \mathbf{q}^2)\mathbf{p}^2} + \frac{\mathbf{k}^2}{(\mathbf{p}^2 + \mathbf{q}^2)\mathbf{q}^2} \right] - \Theta \left( \hat{M}_{X,\max}^2 - \frac{\Delta^2}{z(1-z)} \right) S_J^{(3)}(\mathbf{p}, \mathbf{q}, zx, x) \left( C_a^2 \frac{\mathbf{k}^2}{(\mathbf{p}^2 + \mathbf{q}^2)\mathbf{q}^2} - 2C_f^2 \frac{\mathbf{k}^2 \Theta(\mathbf{q}^2 - \lambda^2)}{(\mathbf{p}^2 + \mathbf{q}^2)\mathbf{q}^2} \right) \Big] \\
& + P_1(z) \Theta \left( \hat{M}_{X,\max}^2 - \frac{(\mathbf{p} - z\mathbf{k})^2}{z(1-z)} \right) S_J^{(3)}(\mathbf{p}, \mathbf{q}, (1-z)x, x) \frac{(1-z)^2 \mathbf{k}^2}{(1-z)^2 (\mathbf{p} - z\mathbf{k})^2 + \mathbf{q}^2} \left[ \Theta \left( \frac{|\mathbf{q}|}{1-z} - \lambda \right) \frac{1}{\mathbf{q}^2} \right. \\
& + \Theta \left( \frac{|\mathbf{p} - z\mathbf{k}|}{1-z} - \lambda \right) \frac{1}{(\mathbf{p} - z\mathbf{k})^2} + \Theta \left( \hat{M}_{X,\max}^2 - \frac{\Delta^2}{z(1-z)} \right) S_J^{(3)}(\mathbf{p}, \mathbf{q}, zx, x) \left[ \frac{n_f}{C_a^2} P_{qg}^{(0)} \left( J_2(\mathbf{q}, \mathbf{k}, \mathbf{l}_1, \mathbf{l}_2) - \frac{\mathbf{k}^2}{\mathbf{p}^2(\mathbf{q}^2 + \mathbf{p}^2)} \right) \right. \\
& \left. \left. - n_f P_{qg}^{(0)} \left( J_1(\mathbf{q}, \mathbf{k}, \mathbf{l}_1, z) + J_1(\mathbf{q}, \mathbf{k}, \mathbf{l}_2, z) \right) + P_0(z) \left( J_1(\mathbf{q}, \mathbf{k}, \mathbf{l}_1) + J_1(\mathbf{q}, \mathbf{k}, \mathbf{l}_2) + J_2(\mathbf{q}, \mathbf{k}, \mathbf{l}_1, \mathbf{l}_2) \Theta(\mathbf{p}^2 - \lambda^2) \right) \right] \right\}.
\end{aligned}$$

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  - ★ Finite result for jet vertex within collinear factorization

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