HEJ: The Path to NLL

Subleading Processes in W+Jets

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Durham University

17th MCnet Meeting

CERN, April 2018

Science & Technology Facilities Council

MCnet

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High Energy Jets

- A Partonic Monte Carlo Generator which aims to describe **high multiplicity events**.

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- Provides perturbative predictions at LL accuracy ($\log(\hat{s})$) with **resummation of hard corrections to all orders**.
- Hard corrections are α_s suppressed but phase space enhanced in the **large invariant mass limit**.
- but we need a formalism...

Multi Regge Kinematic (MRK) Limit

The MRK Limit:

large $\hat{s}$; small P_T ; **strongly ordered jet rapidities (y_j):**

$$y_1 \lll y_2 \lll ... \lll y_i \lll .. \lll y_{n-1} \lll y_n$$

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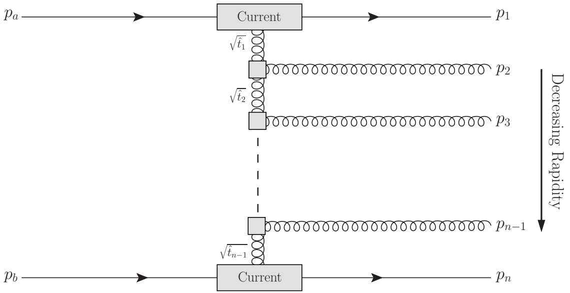
Some nice relations:

$$\begin{aligned}\hat{s}^2 &\sim -\hat{u}^2 \to large \\ \hat{t}_i &\sim -p^2_{\perp j_i} \sim -p^2_{\perp} \\ \log\left(\frac{\hat{s}_{ij}}{\hat{t}_{ij}}\right) &\approx |y_j - y_i|\end{aligned}$$

FKL Contributions

FKL configurations are the leading contributions in the MRK limit.

- $(2 \to n)$ amplitudes with strong rapidity ordering in final state



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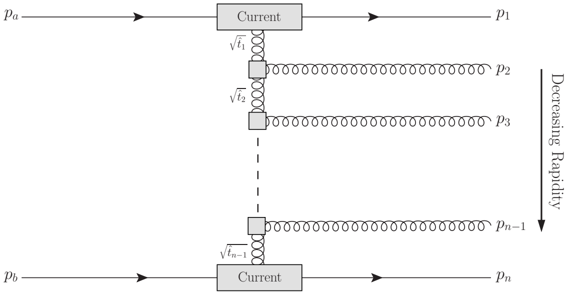

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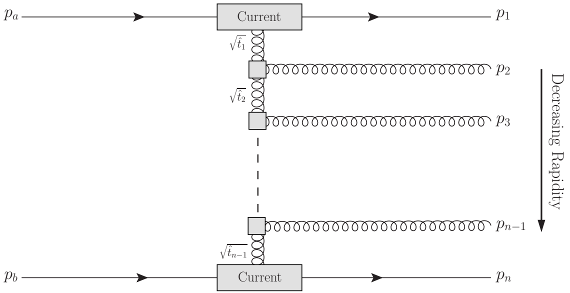

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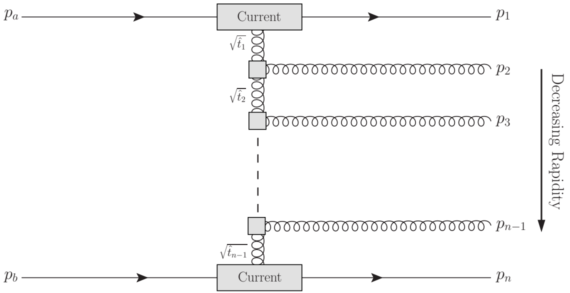

Resum via effective **Lipatov Vertices** and the **Lipatov Ansatz**.

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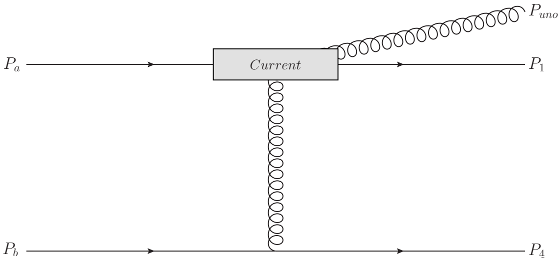
Unordered Contributions

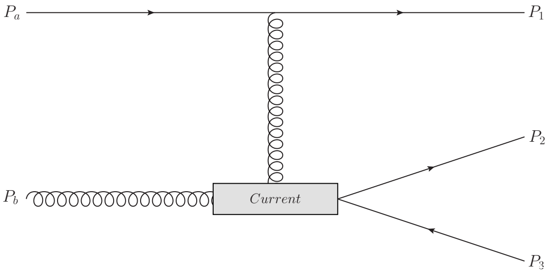


A gluon outside of FKL rapidity ordering is known as an **Unordered emission**.

In HEJ this is modelled as a modified current. Where we now allow that $y_{uno} \sim y_1$ and $y_1 >> y_2$. (QMRK Limit)

$$\mathcal{M}^{\text{uno}}_{qQ\to gqQ} \sim \frac{j^{\mu}_{\text{uno}}(p_a, p_1, p_{uno}) j_{\mu}(p_b, p_2)}{\hat{t}}$$

Extremal $q\bar{q}$



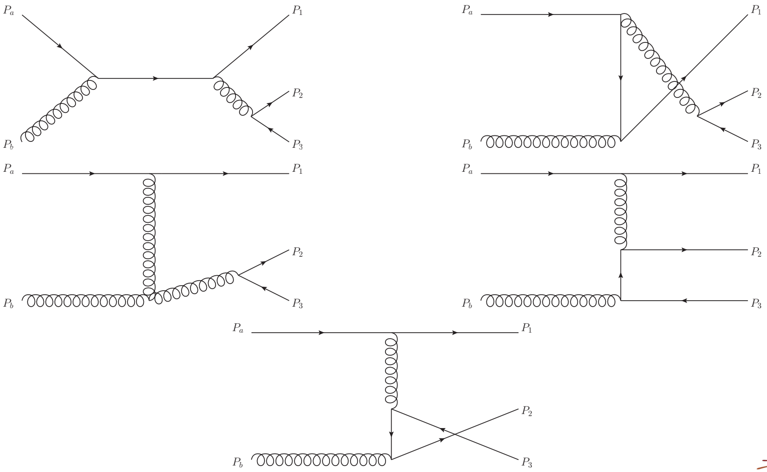
The **Extremal qq̄** case is an incoming gluon splitting to $q\bar{q}$.

In HEJ use a a modified current (related by crossing symmetry to Uno case) in the scattering.

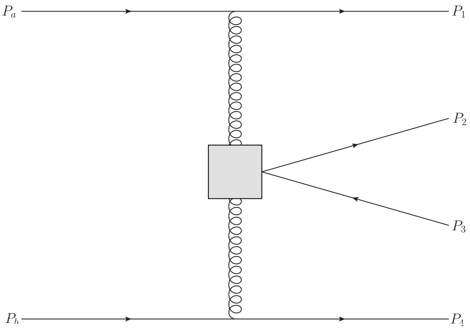
$$\mathcal{M}^{q\bar{q}}_{qg\to qQQ} \sim \frac{j^{\mu}_{q\bar{q}}(p_b, p_2, p_3) j_{\mu}(p_a, p_1)}{\hat{t}}$$

There are **5 possible diagrams** which contribute.

Extremal $q\bar{q}$: Possibilities



Central $q\bar{q}$

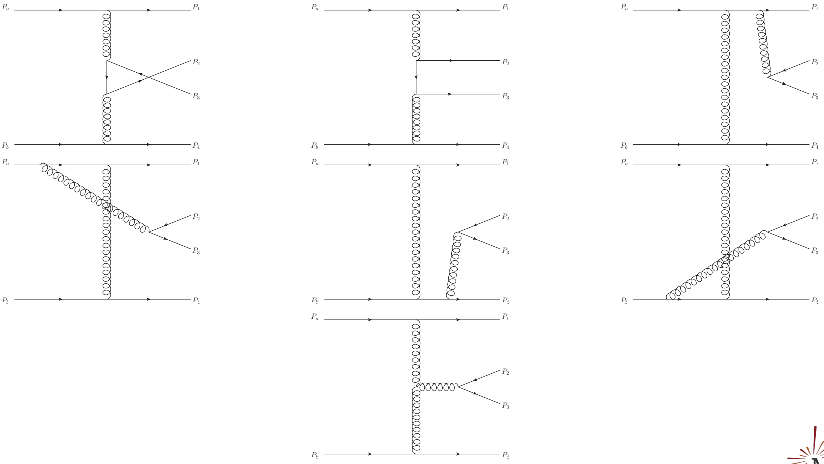


In the case a **Central q$\bar{\text{q}}$** pair is produced, we use an effective vertex which fits the form:

$$\mathcal{M}_{qq\to qQ\overline{Q}q} \sim \frac{\langle 1|\mu|a\rangle\, X^{\mu\nu}\, \langle 4|\nu|b\rangle}{\hat{t}_1\,\hat{t}_3}$$

There are **7 possible diagrams** which contribute.

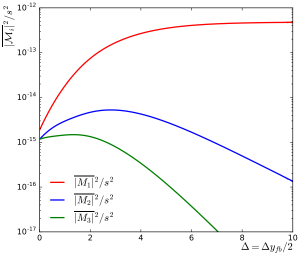
Central $q\bar{q}$

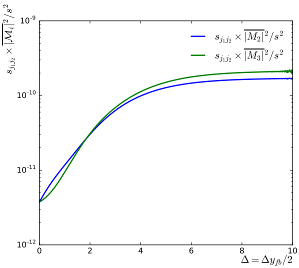


Scaling of the Matrix Elements

Higgs+3j: $qQ \to qgHQ$

FKL Ordering | Unordered | Unordered





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FKL Ordering

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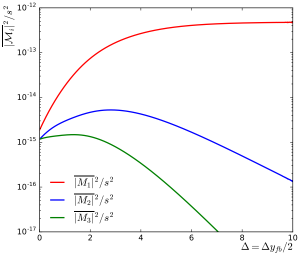
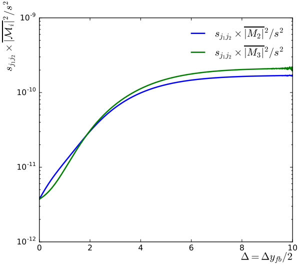


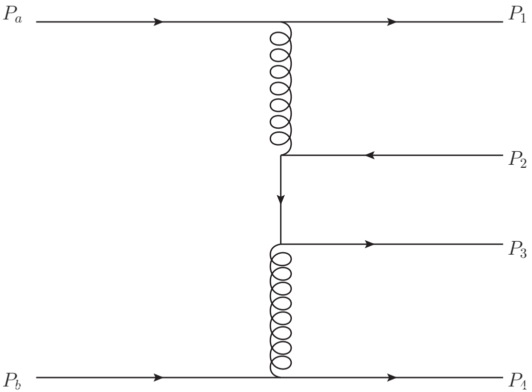


In MRK:

$$|\mathcal{M}| \sim (\hat{s}_{j_i j_j})^{spin}$$

Swapping propagator (gluon $\to$ quark) suppresses ME by $(\hat{s}_{j_i j_j})^{1/2}$.

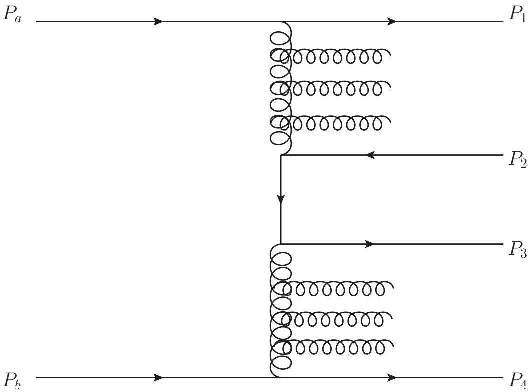
Reducing Dependence on Matching



By Matching

α_s^4

Reducing Dependence on Matching



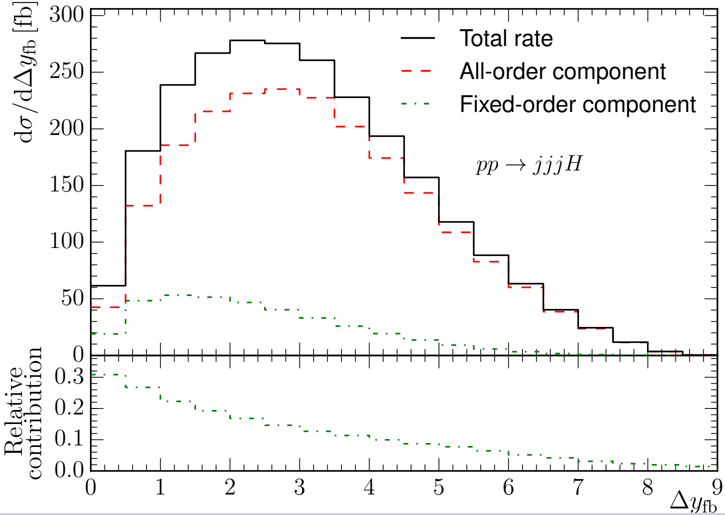
By Matching

α_s^4

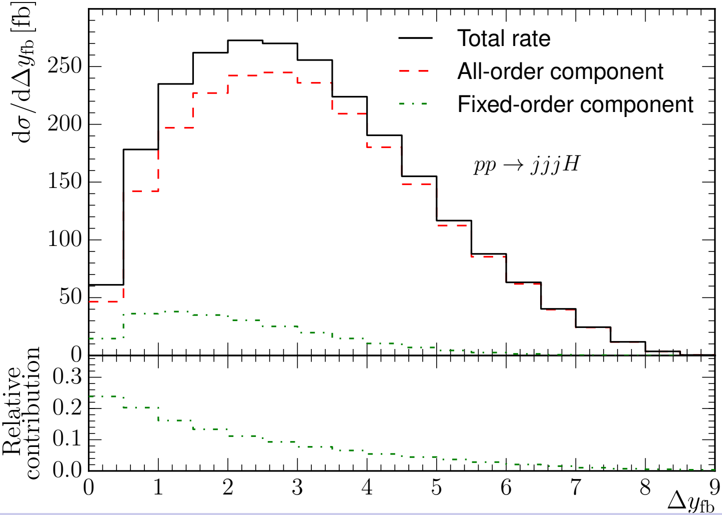
Add Resummation

$(\alpha_s \Delta_y)^N$

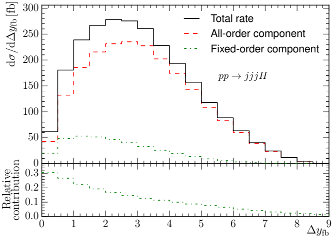
Leading Log Only

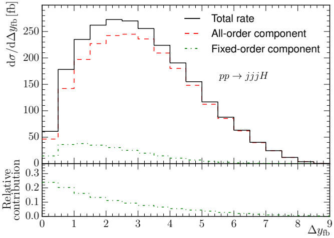


Leading Log Including Unordered

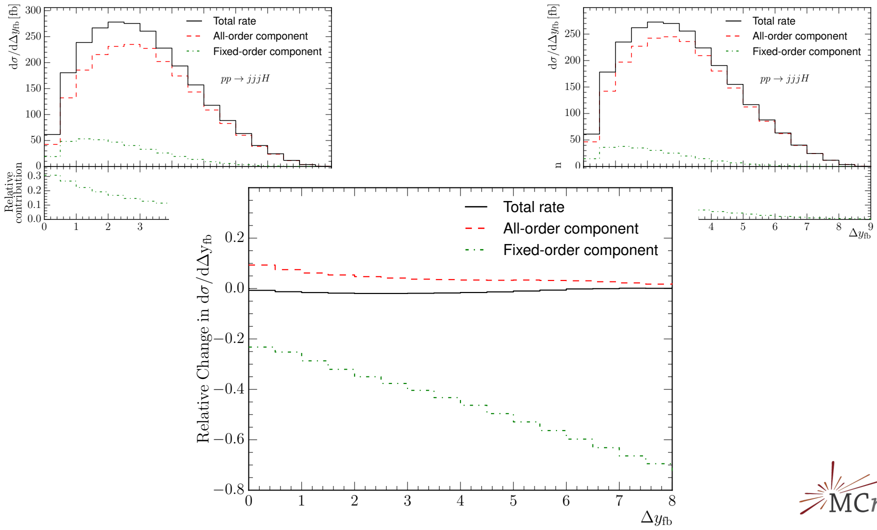


Change due to Unordered





Change due to Unordered



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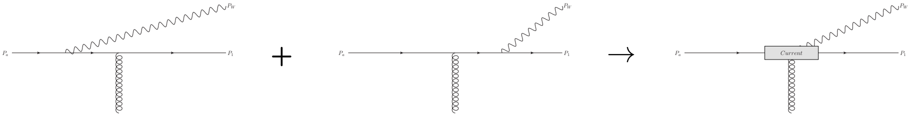
W+Jets at LL

In HEJ, W+Jets are usually calculated differently from Pure Jets by the use of a **modified current**.



With the addition of the $q\bar{q}$ pairs we have additional places from which a W-Boson can be emitted.

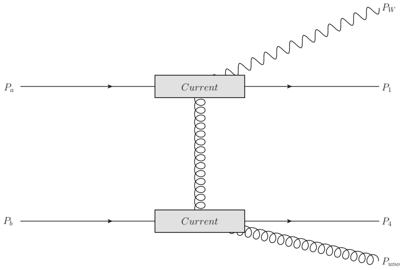
W+Jets at NLL: Unordered

Complications to Unordered

W+Jets at NLL: Unordered

Complications to Unordered

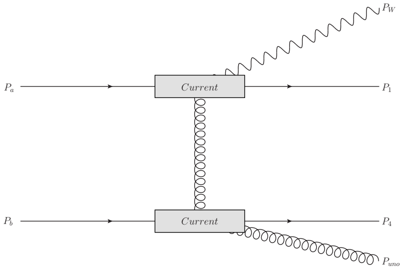
No New Objects



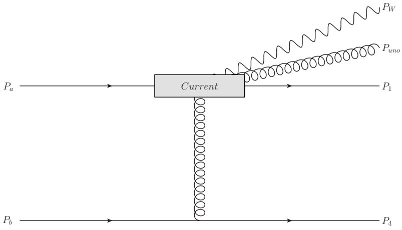
W+Jets at NLL: Unordered

Complications to Unordered

No New Objects



New Objects Required



W+Jets at NLL: $q\bar{q}$

Complications to $\mathbf{q\bar{q}}$

W+Jets at NLL: $q\bar{q}$

Complications to $q\bar{q}$

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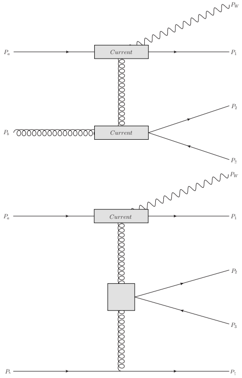

W+Jets at NLL: $q\bar{q}$

Complications to $q\bar{q}$

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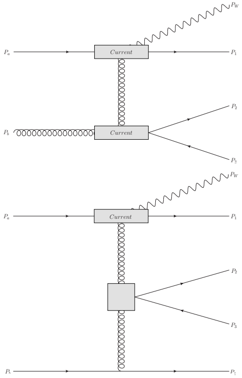

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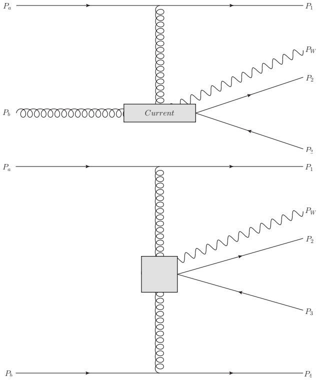

W+Jets at NLL: Extremal $q\bar{q}$

Consider Process: $qg \rightarrow qQ\overline{Q}W$

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Consider Process: $qg \to qQ\overline{Q}W$

AIM:

Factorise the t channel exchanges and the current scattering, resulting in a new effective current at either end of the FKL chain.

W+Jets at NLL: Extremal $q\bar{q}$

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AIM:

Factorise the t channel exchanges and the current scattering, resulting in a new effective current at either end of the FKL chain.

Need to find an amplitude for the process $qg \to qQ\overline{Q}W$ of the form:

$$\mathcal{M}_{qg\to qQ\overline{Q}W} \sim \frac{\langle 1|\mu|a\rangle\, Q_W^{\mu\nu\rho}\,(p_2, p_w, p_3, p_b)\,\varepsilon_\nu(p_b)\varepsilon^*_\rho(p_w)}{\hat{t}_1}$$

Where $Q_W^{\mu\nu\rho}$ is this effective current.

W+Jets at NLL: Central $q\bar{q}$

Consider Process: $qq \rightarrow qQ\overline{Q}Wq$

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Consider Process: $qq \rightarrow qQ\overline{Q}Wq$

AIM:

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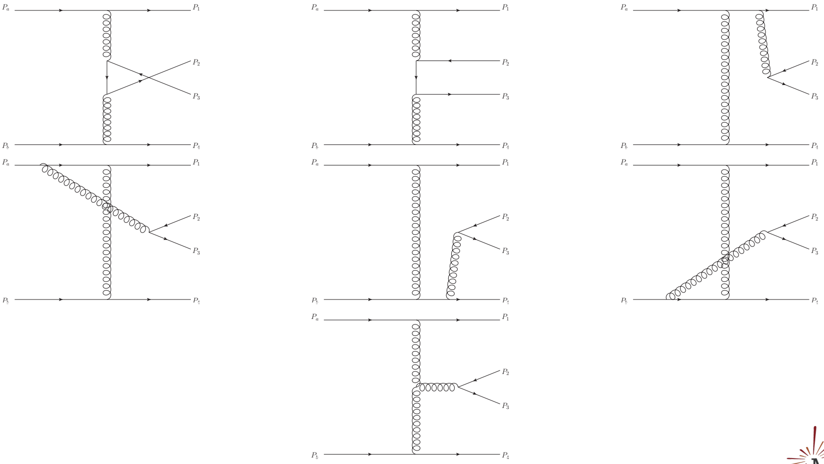
We therefore search for an expression of the form:

$$\mathcal{M}_{qq\rightarrow qQ\bar{Q}qW} \sim \frac{\langle 1|\mu|a\rangle \, X_W^{\mu\nu} \, \langle 4|\nu|b\rangle}{\hat{t}_1 \, \hat{t}_3}$$

Central $q\bar{q}$



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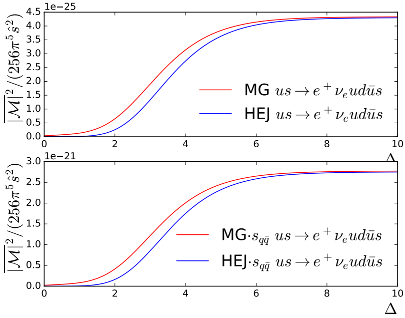
Matrix Element Comparison

$q\bar{q}$ at fixed Δ_y



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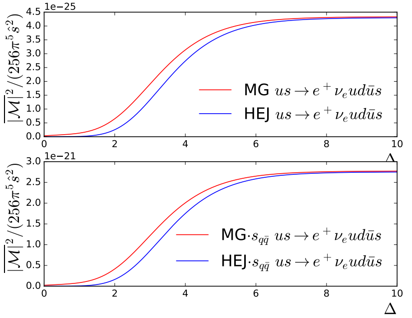
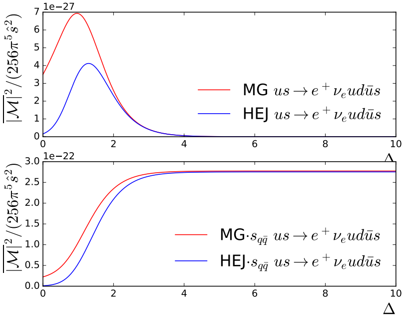


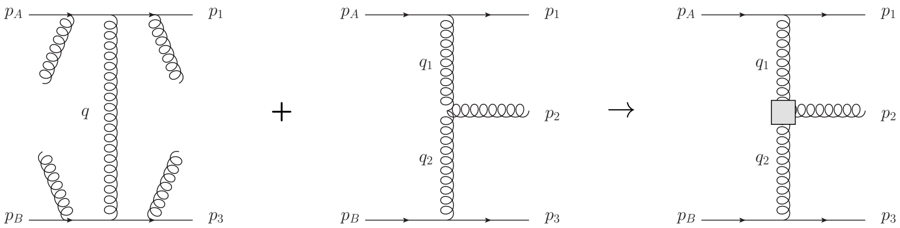
$q\bar{q}$ at increasing Δ_y



Conclusions

- Processes moved from FO Matching to Resummation
- Verification process underway
- Next steps for NLL:
  - Virtual Corrections
  - Remove need for the contributions to be hard enough to form jets

Lipatov Vertices



$$
\begin{aligned}
V^\rho(q_1, q_2) = &- (q_1 + q_2)^\rho \\
&+ \frac{p_A^\rho}{2}\left(\frac{q_1^2}{p_2 \cdot p_A} + \frac{p_2 \cdot p_B}{p_A \cdot p_B} + \frac{p_2 \cdot p_3}{p_A \cdot p_3}\right) + p_A \leftrightarrow p_1 \\
&- \frac{p_B^\rho}{2}\left(\frac{q_2^2}{p_2 \cdot p_B} + \frac{p_2 \cdot p_A}{p_B \cdot p_A} + \frac{p_2 \cdot p_1}{p_B \cdot p_1}\right) - p_B \leftrightarrow p_3 .
\end{aligned}
$$

Virtual Corrections

Lipatov Ansatz

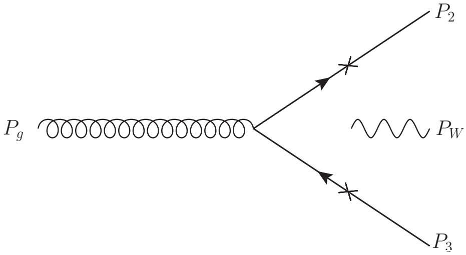
One can obtain the virtual corrections in the MRK limit with the Lipatov Ansatz, which is the following substitution within the analytic expression for the amplitudes:

$$\frac{1}{t_i} \rightarrow \frac{1}{t_i} \exp[\hat{\alpha}(q_i)(y_{i-1} - y_i)]$$

where

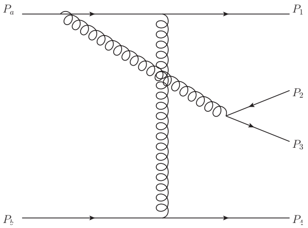
$$\hat{\alpha} = -g^2 C_A \frac{\Gamma(1-\varepsilon)}{(4\pi)^{2+\varepsilon}} \frac{2}{\varepsilon} \left(\frac{q^2}{\mu^2} \right)^{\varepsilon}$$

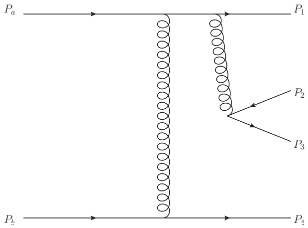
Building Blocks



$$J_V^\mu(p_2, p_A, p_B, p_3) = \left(\frac{\bar{u}_2 \gamma^\nu (\not{p}_2 + \not{p}_A + \not{p}_B) \gamma^\mu u_3}{s_{2AB}} + \frac{\bar{u}_2 \gamma^\mu (\not{p}_3 - \not{p}_A - \not{p}_B) \gamma^\nu u_3}{s_{3AB}} \right) [\bar{u}_A \gamma_\nu u_B]$$

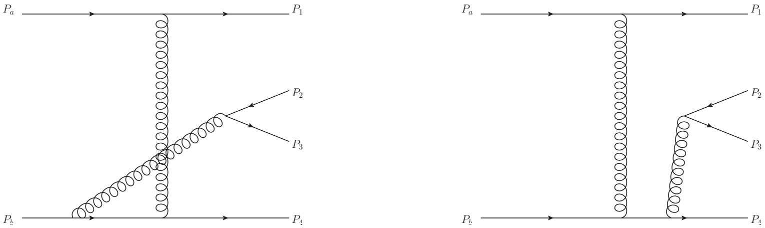
1a Contribution





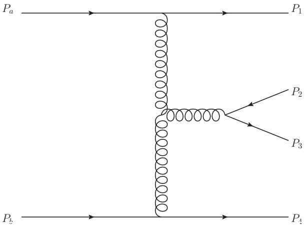
$$X_{1a}^{\mu\nu} = \frac{g^{\mu\nu} C_1 g_w g_s^4}{2\sqrt{2} s_{23AB} (s_{123AB})} (p_1^{\rho}) J_{V\rho}$$

4b Contribution



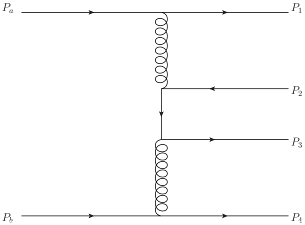
$$X_{4b}^{\mu\nu} = \frac{-g^{\mu\nu} C_1 g_w g_s^4}{2\sqrt{2} s_{23AB} (s_{234AB})} (p_4^\rho) J_{V\rho}$$

3 Gluon Contribution



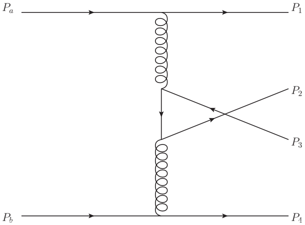
$$X_{3g}^{\mu\nu} = \frac{g_W g_s^2 \, T^{geg'} \, T_{23}^e}{2\sqrt{2}\,\hat{t}_1 s_{23AB}\,\hat{t}_3}\Big[(q_1)^\mu \, \eta^{\nu\rho} + (q_3)^\nu \, \eta^{\mu\rho} - (q_1 + q_3)^\rho \, \eta^{\mu\nu} \Big] J_{V\rho}(p_a, p_A, p_B, p_1)$$

Uncrossed Contributions



$$X^{\mu\nu}_{\text{uncross}} = \frac{\langle A|\sigma|B\rangle}{(p_A+p_B)^2}\bar{u}_2\left[\frac{\gamma^\sigma(\not{p}_2+\not{p}_A+\not{p}_B)\gamma^\nu(\not{p}_3+\not{p}_4-\not{p}_b)\gamma^\mu}{(s_{2AB})(t_{int_2})}+\right.$$
$$\frac{\gamma^\nu(\not{p}_a-\not{p}_1-\not{p}_2)\gamma^\sigma(\not{p}_3+\not{p}_4-\not{p}_b)\gamma^\mu}{(t_{int_1})(t_{int_2})}+$$
$$\left.\frac{\gamma^\nu(\not{p}_a-\not{p}_1-\not{p}_2)\gamma^\mu(\not{p}_3+\not{p}_A+\not{p}_B)\gamma^\sigma}{(t_{int_1})(s_{3AB})}\right]u_3$$

Crossed Contributions



$$X^{\mu\nu}_{cross} = \frac{\langle A|\sigma|B\rangle}{(p_A+p_B)^2}\bar{u}_2\left[\frac{\gamma^\sigma(\not{p}_2+\not{p}_A+\not{p}_B)\gamma^\nu(\not{p}_a-\not{p}_1-\not{p}_3)\gamma^\mu}{(s_{2AB})(t_{int_3})} + \frac{\gamma^\nu(\not{p}_2-\not{p}_4-\not{p}_b)\gamma^\sigma(\not{p}_a-\not{p}_1-\not{p}_3)\gamma^\mu}{(t_{int_3})(t_{int_4})} + \frac{\gamma^\nu(\not{p}_2+\not{p}_4-\not{p}_b)\gamma^\mu(\not{p}_3+\not{p}_A+\not{p}_B)\gamma^\sigma}{(t_{int_4})(s_{3AB})}\right]u_3$$