

Resonance-aware MC@NLO

QCD+EW-matched parton showers

Based on 2607.06059 with L. Flower and M. Schönherr
and 26xx.xxxxx with M. Schönherr

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Overview

- ① Mc@NLO QCD+EW
- ② Resonance-aware matching
- ③ Results
- ④ Summary and outlook

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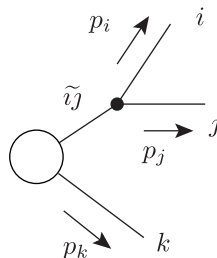
Dipole showers

Shower generating functional:

$$\mathcal{F}_n(t_n; O) = \Delta_n(t_n, t_c) O(\Phi_n) + \int_{t_c}^{t_n} d\Phi_1 K_n(\Phi_1) \Delta_n(t_n, t_{n+1}) \mathcal{F}_{n+1}(t_{n+1}; O)$$

In a dipole shower, splitting kernel $K_{ij,k} = \frac{D_{ij,k}}{B_n}$ describes splitting

$$\tilde{i}j + \tilde{k} \rightarrow i + j + k$$



QCD vs QED dipole showers

$$D_{ij,k} = \begin{cases} -\frac{1}{2p_i p_j} \frac{\mathbf{T}_{\tilde{k}} \mathbf{T}_{\tilde{i}j}}{\mathbf{T}_{\tilde{i}j}^2} \mathbf{V}_{ij,k} \otimes B_n & \text{for QCD } \text{Catani, Seymour } \text{hep-ph/9605323} \\ -\frac{1}{2p_i p_j} \frac{Q_{\tilde{k}} Q_{\tilde{i}j}}{Q_{\tilde{i}j}^2} \mathbf{V}_{ij,k} \otimes B_n & \text{for QED } \text{Schönherr } 1712.07975 \end{cases}$$

- $\mathbf{V}_{ij,k}$ is a spin-dependent splitting function. For collinear splittings, it is independent of spectator k

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- For QCD, we use the large N_c limit to replace the colour matrices with the constraint that we only use colour-connected spectators

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$$D_{ij,k} = \begin{cases} \frac{1}{2p_i p_j} \frac{1}{N_{\text{spec}}} \mathbf{V}_{ij,k} \otimes B_n & \text{for QCD } \text{Catani, Seymour hep-ph/9605323} \\ -\frac{1}{2p_i p_j} \frac{Q_k Q_{\tilde{i}j}}{Q_{\tilde{i}j}^2} \mathbf{V}_{ij,k} \otimes B_n & \text{for QED } \text{Schönherr 1712.07975} \end{cases}$$

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QCD vs QED dipole showers

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- For matching, we include all spin- and colour-correlations

Mc@NLO matching

- Hard emissions are generated by the real matrix element (H events)
- Soft emissions are generated by the shower (S events)

$$\langle O \rangle = \int d\Phi_n \overbrace{\bar{B}_n \otimes \bar{\mathcal{F}}_n(t_n; O)}^{\text{S event}} + \int d\Phi_{n+1} \overbrace{[R_{n+1} - D_n] \mathcal{F}_{n+1}(t_{n+1}; O)}^{\text{H event}}$$

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$$\bar{B}_n = B_n + V_n + \int d\Phi_1 D_n$$

$$\bar{\mathcal{F}}_n(t_n; O) = \bar{\Delta}_n(t_n, t_c) O(\Phi_n) + \int_{t_c}^{t_n} d\Phi_1 \bar{\Delta}_n(t_n, t_{n+1}) \frac{D_n}{B_n} \mathcal{F}_{n+1}(t_{n+1}; O)$$

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Everything up to this point also applies to Mc@NLO EW. See L. Flower's talk for further details.

H events

$$\langle O \rangle = \int d\Phi_n \bar{B}_n \otimes \bar{\mathcal{F}}_n(t_n; O) + \int d\Phi_{n+1} [R_{n+1} - D_n] \mathcal{F}_{n+1}(t_{n+1}; O)$$

H events

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$$\begin{aligned} \langle O^\gamma \rangle &= \int d\Phi_{n+1} \left\{ R_n^{\text{QED}} + \left[\frac{\bar{B}_n}{B_n} \bar{\Delta}_n(t_n, t_{n+1}) - 1 \right] D_n^{\text{QED}} \right\} O^\gamma(\Phi_{n+1}) + \dots \\ &= \int d\Phi_{n+1} R_n^{\text{QED}} + \mathcal{O}(\alpha\alpha_s, \alpha^2) \end{aligned}$$

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Formally, $\bar{\Delta}_n = 1 - \mathcal{O}(\alpha_s, \alpha)$ but in practice $\bar{\Delta}_n \ll 1$ so we see very large, negative $\mathcal{O}(\alpha\alpha_s)$ corrections to photonic observables.

H events

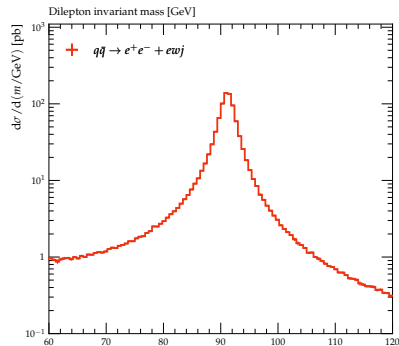
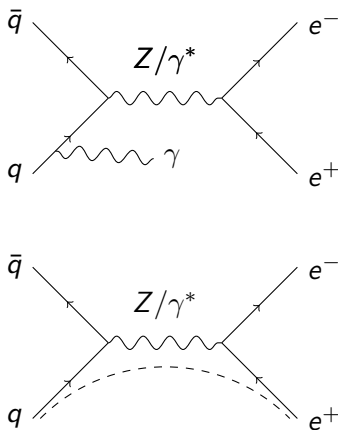
$$\langle O \rangle = \int d\Phi_n \bar{B}_n \otimes \bar{\mathcal{F}}_n(t_n; O) + \int d\Phi_{n+1} [R_{n+1} - D_n] \Delta_n(t_n, t_{n+1}) \mathcal{F}_{n+1}(t_{n+1}; O)$$

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The extra Sudakov suppresses large higher order artefacts at the cost of changing the inclusive cross section by higher terms.

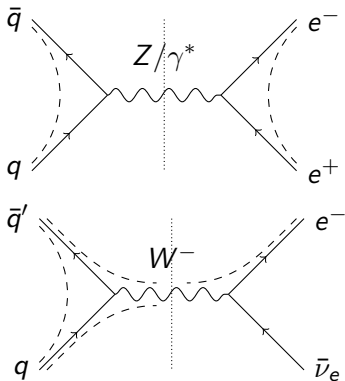
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Resonance-aware subtraction: motivation



The standard parton shower formulation assumes that the underlying Born changes very little. This is not the case near a resonance!

Resonance-aware dipoles



- For hard photon emissions, we factorise the process into production and decay.
- A charged resonance can act as an emitter or spectator, with modified splitting functions.
- Soft photons can't resolve the resonance so we return to standard dipoles, with threshold $t = t_{\text{res}} \sim \Gamma^2$.

Flower, JR, Schönherr 2607.06059

Recovering limits

$$D_{ij,k} = -\frac{1}{2p_i p_j} \frac{Q_{\tilde{ij}} Q_{\tilde{k}}}{Q_{\tilde{ij}}^2} \mathbf{V}_{ij,k} \otimes B_n$$

Collinear limit $p_i \rightarrow z p_{\tilde{ij}}, p_j \rightarrow (1-z) p_{\tilde{ij}}$:

$$\sum_{k \neq i,j} D_{ij,k} \rightarrow \frac{4\pi\alpha}{p_i p_j} \mathbf{P}_{\tilde{ij},i}(z) \otimes B_n$$

where $\mathbf{P}_{\tilde{ij},i}(z)$ are the (spin dependent) Altarelli-Parisi splitting functions.

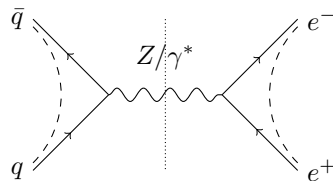
Soft limit $p_j \rightarrow 0$:

$$D_{ij,k} + D_{kj,i} \rightarrow -4\pi\alpha \frac{Q_{\tilde{ij}} Q_{\tilde{k}}}{Q_{\tilde{ij}}^2} \left(\frac{p_i^\mu}{p_i p_j} - \frac{p_k^\mu}{p_k p_j} \right)^2 B_n$$

Recovering limits: neutral resonance

- In the collinear limit, the only dependence on the spectator is from the charge correlator $Q_{ij,k}^2 = \frac{Q_{ij} Q_k}{Q_{ij}^2}$
- In this limit, the resonance-spanning dipoles exactly cancel pairwise so we always recover the correct sum

$$- \sum_{\substack{\tilde{k} \neq \tilde{ij} \\ \text{no IF/FI}}} Q_{\tilde{ij}} Q_{\tilde{k}} = - \sum_{\tilde{k} \neq \tilde{ij}} Q_{\tilde{ij}} Q_{\tilde{k}} = Q_{\tilde{ij}}^2$$

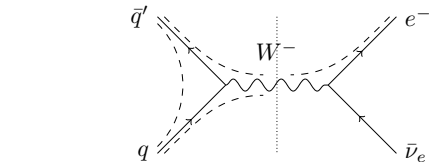


- In the soft limit, we use our standard subtraction so the correct limit is guaranteed

Recovering limits: charged resonance

- We never choose the resonance as an emitter, only a spectator, because the collinear limit $j \parallel k$ is not enhanced due to the large mass $m_k^2 \sim t_n$.
- The collinear limit $j \parallel i$ is therefore guaranteed by charge conservation similarly to the neutral case:

$$Q_{W^-} = Q_{e^-} + Q_{\bar{\nu}} = Q_q + Q_{\bar{q}'}$$



- For the soft limit, however, we must modify our splitting functions to include the entire squared eikonal associated with the resonance, rather than sharing it between $D_{ij,k}$ and $D_{kj,i}$.

Resonance-aware clustering

- To attach the parton shower to an H-event, we need to find the scale of the real emission to be the shower starting scale.
- The most likely shower history is given by choosing the splitting $\tilde{ij} \tilde{k} \rightarrow i j k$ that gives the maximum dipole

$$D_{ij,k} = -\frac{C_{ij,k}}{2p_i p_j} \mathbf{v}_{ij,k} \otimes B_n.$$

- Using the exact B_n is expensive so we usually assume it's the same for all dipoles.
- For resonant processes, we instead approximate it as a Breit-Wigner function

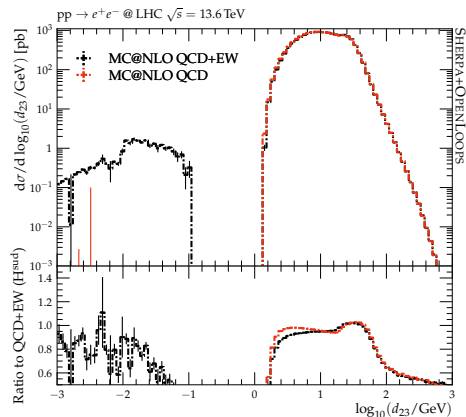
$$B_n \propto \frac{1}{(q^2 - m^2)^2 + m^2 \Gamma^2}$$

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MC@NLO QCD+EW: validation

MC@NLO QCD+EW matched to interleaved QCD+QED shower

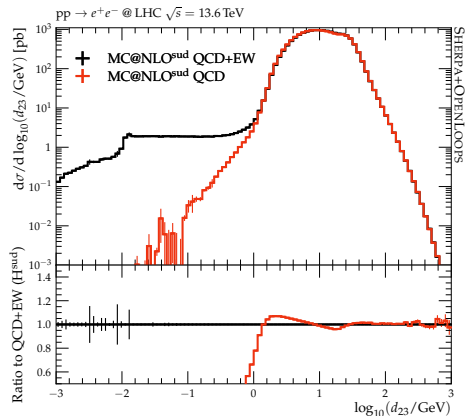
- IS shower cutoffs
 $t_c^{\text{IS,QCD}} = t_c^{\text{IS,QED}} = 3 \text{ GeV}^2$
- FS shower cutoffs
 $t_c^{\text{FS,QCD}} = 1 \text{ GeV}^2$
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MC@NLO QCD+EW: validation

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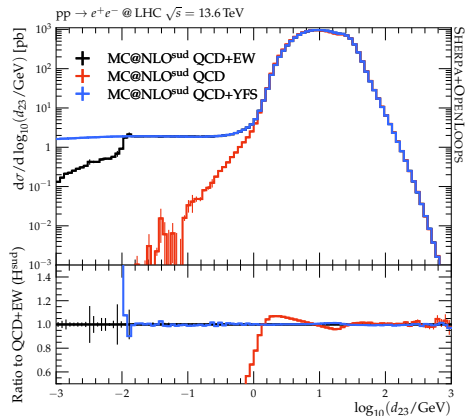
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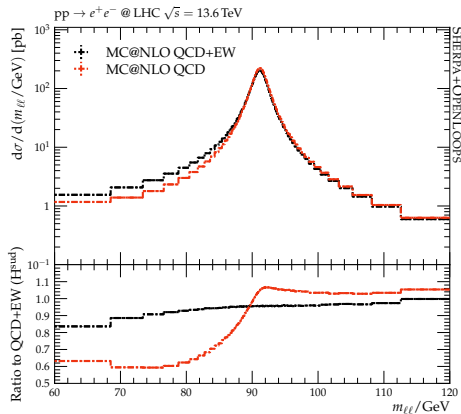
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- YFS resummation generates unordered FS soft photon radiation.
(See J. Paltrinieri's talk)



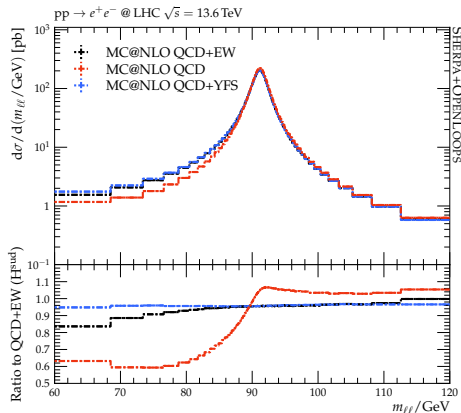
Yennie, Frautschi, Suura 1961

MC@NLO QCD+EW: validation



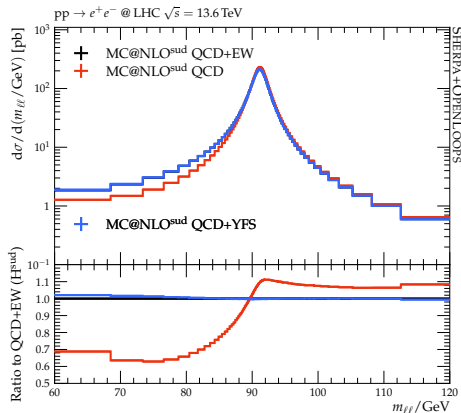
- $\mathcal{O}(1)$ QED corrections

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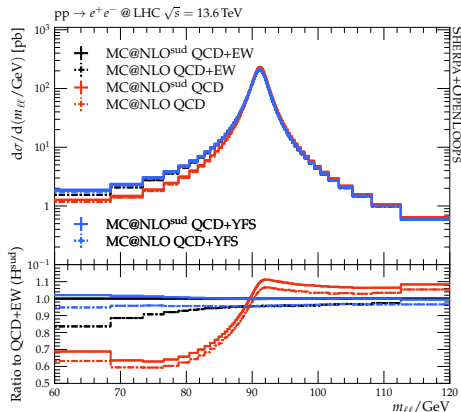
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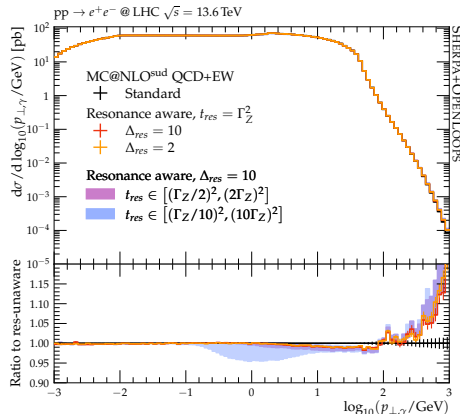
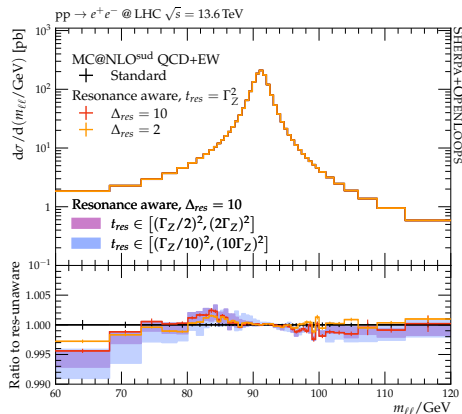
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- Sudakov needed for MC@NLO QCD+EW to agree with YFS

MC@NLO QCD+EW: validation



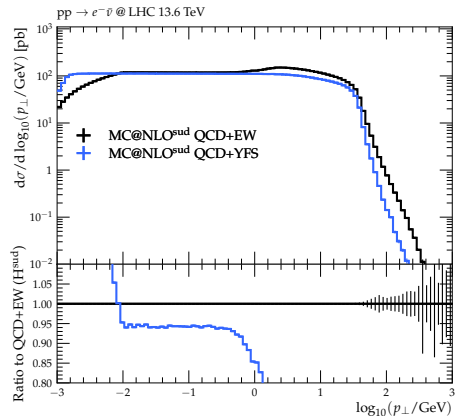
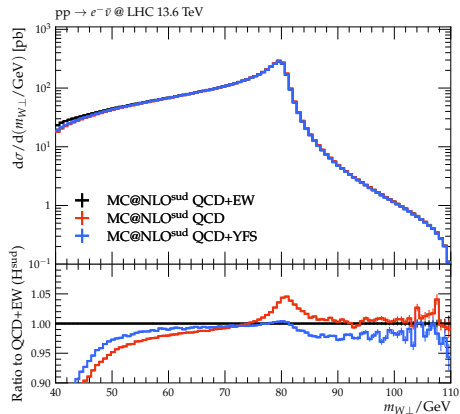
- $\mathcal{O}(1)$ QED corrections
- Sudakov needed for MC@NLO QCD+EW to agree with YFS
- As before, the extra Sudakov suppresses an unphysical effect

Resonance-aware MC@NLO: neutral resonance

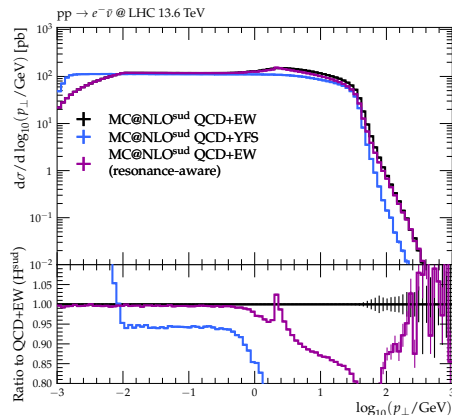
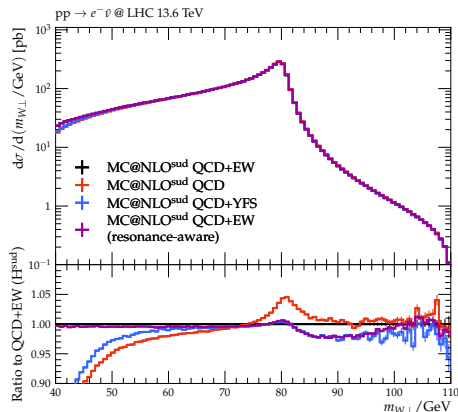


The resonance-aware treatment corrects a per mille distortion of the Z mass distribution.

Resonance-aware MC@NLO: charged resonance



Resonance-aware MC@NLO: charged resonance



Transverse mass of a W resonance sees much smaller QED corrections but the effect of resonance-aware matching is now $\mathcal{O}(1\%)$.

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Summary and outlook

- ✓ Automated Mc@NLO QCD+EW matching to QCD+QED parton shower
- ✓ Resonance-aware Mc@NLO matching in place for $q\bar{q} \rightarrow e^+e^-$ and $q\bar{q}' \rightarrow e^-\bar{\nu}_e$

Next:

- Automate resonance identification and the construction of resonance-aware dipoles (partially complete)
- Apply to processes with multiple resonances

Summary and outlook

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Next:

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- Apply to processes with multiple resonances

Thank you!

Backup slides: QED spectator selection

- Unlike in QCD, the QED charge correlator can take either sign which can lead to many negative weighted events and degrade the significance of the sample
- We can avoid this by restricting our choice of spectators in the shower
- Need $-\sum_{\tilde{k} \neq \tilde{ij}} Q_{\tilde{ij}} Q_{\tilde{k}} = Q_{\tilde{ij}}^2 \implies$ choose $Q_{\tilde{k}} = -Q_{\tilde{ij}}$
- Each splitter is assigned a single *opposite sign same flavour* (OSSF) spectator
- Phase space considerations mean that we should assign pairs that were produced together We estimate these by minimising dipole mass. [Flower, Schönherr 2603.05585](#)
- Anything left over is grouped together

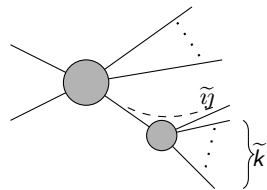
Backup slides: Charged resonance splitting functions

$$V_{FI}^{\text{res}} = \frac{-1}{2p_i p_j} \left[\frac{2}{1 - z(1 - y)} \left(1 + \frac{2m_i^2}{m_k^2} \right) - 1 - z - \frac{m_i^2}{p_i p_j} \right]$$

$$- \frac{Q^2}{m_k^4} \frac{4}{(1 - z(1 - y))^2}$$

$$y = \frac{p_i p_j}{p_i p_j + p_j p_k + p_i p_k}, \quad z = \frac{p_i p_k}{p_i p_k + p_j p_k}$$

$$Q^2 = (p_i + p_j + p_k)^2$$



Basso et al 1507.04676

Soft (splitter), Hard collinear (splitter), Soft (spectator)

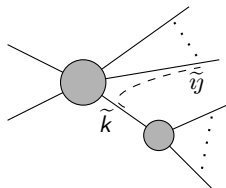
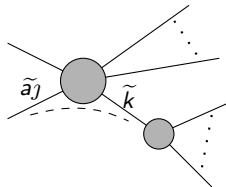
Backup slides: Charged resonance splitting functions

$$V_{IF}^{\text{res}} = \frac{-1}{2p_i p_a x} \left[\frac{2x}{1-x+\tilde{z}} + 1 - x + \frac{\tilde{z}}{1-x} \left(\frac{2(1-\tilde{z})}{1-x+\tilde{z}} - \frac{2m_k^2}{m_k^2 - Q^2} \frac{x}{1-x} \right) \right]$$

$$x = \frac{p_a p_j + p_a p_k - p_j p_k}{p_a p_j + p_a p_k}, \quad u = \frac{p_a p_j}{p_a p_j + p_a p_k}$$

$$V_{FF}^{\text{res}} = \frac{1}{2p_i p_j} \left[\frac{2}{1-z(1-y)} \left(1 + \frac{y}{(1-z)(1-y)} \right) - \left(1 + z + \frac{m_i^2}{p_i p_j} \right) \right. \\ \left. - \left(\frac{y}{(1-z)(1-y)} \right)^2 \frac{m_k^2}{p_i p_j} \right]$$

$$y = \frac{p_i p_j}{p_i p_j + p_j p_k + p_i p_k}, \quad z = \frac{p_i p_k}{p_i p_k + p_j p_k}$$



Soft (splitter), Hard collinear (splitter), Soft (spectator)