Resummation effects in photon isolation

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Isolated photon production

- Experiments use isolation to reduce photon from hard scattering from photons due to hadron decays.
- Experimentalists choose \( \sum_{\text{had} \in C(R)} E_{\text{had}}^T \leq \epsilon_\gamma E_\gamma^T \)
- E.g. ATLAS ’16 imposes \( E_{\text{iso}}^T = 4.8 \text{ GeV} + 0.0042 E_\gamma^T \) on hadronic energy inside cone.
- Smooth isolation Frixione ’98 \( E_{\text{iso}}(r) = \epsilon_\gamma E_\gamma \left( \frac{1 - \cos r}{1 - \cos R} \right)^n \lim_{r \to 0} E_{\text{iso}}(r) \to 0 \)
  - collinear safe; no fragmentation process
  - can’t be implemented in experiments
- Soft-drop isolation Hall & Thaler ’18
  - democratic criteria; equivalent to smooth isolation at LO
New scales introduced by isolation

\[ p_T^\gamma \]
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\[ R p_T^\gamma \]
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\[ \epsilon_\gamma p_T^\gamma \]
Resummation effects in isolation

- **Small cone radius** $R \ll 1$

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<th>Direct contribution</th>
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- **Log(R) spoils perturbative convergence**

- **This log comes from mismatching between inside and outside radiation**

- **LL resummation has been studied by** Catani & et. al. ‘13

  - Higher-order effects are moderate for $R \sim 0.4$
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Resummation effects in isolation

- Tight isolation cut $\epsilon_\gamma \ll 1$
- Large logs $\ln \epsilon_\gamma$ from soft gluon radiation inside cone
- Fragmentation process are power suppressed
- At the NLO log term is $\alpha_s R^2 \ln \epsilon_\gamma$ Gordon & Vogelsang ‘94
- NLO results show no significant infrared sensitivity. Catani & et. al. ‘02

destabilize the numerical convergence of the perturbative expansion. Nonetheless, owing to the presence of higher powers of $\ln \varepsilon_h$ at higher perturbative orders, the actual sensitivity of the cross section to very low values of $\varepsilon_h$ is probably underestimated in the present NLO calculation.

- **Non-global observables:** more complicated logarithmic terms will appear beyond NLO

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$$R^2 \times \alpha_s^n \ln^n \epsilon_\gamma \ln^{n-1} R$$
Non–global observables
(Dasgupta & Salam ’01 ’02)

Observables which are insensitive to emissions into certain regions of phase space involve additional NGLs not captured by usual exponentiation formula.

Non–global logs:

\[(\frac{\alpha_s}{2\pi})^2 C_F C_A \left[ -\frac{2\pi^2}{3} + 4 \text{Li}_2 (e^{-2\Delta \eta}) \right] \ln^2 \frac{Q_\Omega}{Q}\]

- **Dasgupta–Salam shower**

\[S(\alpha_s L) \simeq \exp \left( -C_F C_A \frac{\pi^2}{3} \left( \frac{1 + (at)^2}{1 + (bt)^c} \right) t^2 \right) \]
\[a = 0.85 C_A, \quad b = 0.86 C_A, \quad c = 1.33\]

- **Banfi–Marchesini–Smye equation**

\[\partial_{\hat{L}} G_{kl}(\hat{L}) = \int \frac{d\Omega(n_j)}{4\pi} W_{kl}^j \left[ \Theta_{\text{in}}^{n\bar{n}}(j) G_{kj}(\hat{L}) G_{jl}(\hat{L}) - G_{kl}(\hat{L}) \right]\]

(Banfi, Marchesini & Smye ’02)
Some recent progress

- **Dressed gluon expansion** Larkoski, Moult & Neill ’15 ’16
- **Multi-Wilson-line theory in SCET** Becher, Neubert, Rothen & DYS ’15 ’16
- **Color density matrix** Caron-Huot ’15
- **Collinear logs improved BMS eq** Hatta, Iancu, Mueller, & Triantafyllopoulos ’17
- **Soft (Glauber) gluon evolution at amplitude level, finite Nc** Martínez, Angelis, Forshaw, Plätzer & Seymour ’18
- **Reduced density matrix** Neill & Vaidya ‘18
where corresponding matrix elements are given by It follows from the discussion in the previous section that, an expression which is suitable for evolving the hard functions (see explicitly in the following that the same pattern contin have observed this cancellation at the one-loop level in the

The anomalous dimensions leading logarithmic accuracy, so that the soft functions re

Infinite operators are mixed under RG evolution (not limited to Leading Log or Leading color)

Operator definition for different ingredients

Separates contributions from hard and soft scale

Analytical method fails; RG evolution = parton shower

Infinite operators are mixed under RG evolution

LL evolution is equivalent to Dasgupta-Salam shower

\[ \sigma(\beta, \delta) = \sum_{l=2}^{\infty} \langle \mathcal{H}_l(\{n\}, Q, \delta, \mu_h) \otimes \sum_{m \geq l} U^S_{lm}(\{n\}, \delta, \mu_s, \mu_h) \hat{\otimes} S_m(\{n\}, Q\beta, \delta, \mu_s) \rangle \]

\[ \sigma_{LL}(\delta, \beta) = \sigma_0 \langle S_2(\{n, \bar{n}\}, Q\beta, \delta, \mu_h) \rangle = \sigma_0 \sum_{m=2}^{\infty} \langle U^S_{2m}(\{n\}, \delta, \mu_s, \mu_h) \hat{\otimes} 1 \rangle \]
Some applications

Energy flow & gap fraction

Light-jet mass

Hemisphere soft function

Narrow broadening

Photon isolation

Becher, Neubert, Rothen, DYS '15 '16
Becher, Pecjak, DYS '16
Becher, Rahn, DYS '17
Balsiger, Becher, DYS, ’18
Collinear limit and NGLs

- E.g. Inter-jet energy flow @ e^+e^- colliders
  - Soft radiations from two Wilson lines (global)
    \[
    \frac{\sigma_{GL}^{LL}}{\sigma_0} = \exp[-8 C_F \Delta y t]
    \]
    \[
    t = \int_{\alpha(Q_0)}^{\alpha(Q)} \frac{d\alpha}{\beta(\alpha)} \frac{\alpha}{4\pi}
    \]
  - Leading NGLs at two-loops
    \[
    \frac{\sigma_{NGL}^{LL}}{\sigma_0} = 4 C_F C_A \left[ -\frac{2\pi^2}{3} + 4 \text{Li}_2(e^{-2\Delta y}) \right] t^2
    \]
  - Narrow gap limit: \( \Delta y \to 0 \)
    \[
    \frac{\sigma_{NGL}^{LL}}{\sigma_0} = 4 C_F C_A \left[ 8 \Delta y (\ln(2\Delta y) - 1) - 4 \Delta y^2 + \ldots \right] t^2
    \]

- Collinear enhancement from boundary region (Hatta, Iancu, Mueller, Triantafyllopoulos '17)
Collinear limit and NGLs

- E.g.
- S
- L
- N

- Collinear enhancement from boundary region (Hatta, Iancu, Mueller, Triantafyllopoulos ’17)
Effect of isolation cut at lepton collider

\[
\frac{d\sigma(\epsilon_\gamma, \delta_0)}{dE_\gamma} = \sum_{m=2}^{\infty} \langle \mathcal{H}_{\gamma+m}(\{n\}, E_\gamma, Q, \delta_0) \otimes \mathcal{S}_m(\{n\}, \epsilon_\gamma E_\gamma, \delta_0) \rangle
\]

For any angle \(x_\gamma = 0.1, \delta_0 = \pi/4\) and \(x_\gamma = 0.9, \delta_0 = \pi/4\), the cross section is shown in the plots. The logarithms we want to study become large in the limit of large \(t\) and the area tends to be small. If we substitute \(\epsilon_\gamma = 0\), this cancels each other out and for photon isolation results displayed in Figure 4.1, the predictions using \(\epsilon_\gamma = 0\) have the same size logarithms as a fixed-cone computation with \(\epsilon_\gamma = 0.05\). Together with radiation collinear to the photon, this smooth-cone isolation can cancel each other out and for photon isolation results displayed in Figure 4.1.

Sizable NGLs corrections
Automated resummation for Non-global observables

(Balsiger, Becher, DYS, 1803.07045)

- Use Madgraph5_aMC@NLO generator
  - event file with directions and large-$N_c$ color connections of hard partons
  - provides lowest multiplicity hard function for given process
- Run our shower on each event to generate additional partons and write result back into event file
- Analyze events, according to cuts on hard partons, obtain resummed cross section with hard cuts and veto scale
Resummation effects in $\gamma$ isolation at LHC

- **Ratio** for $pp \rightarrow \gamma + X$ between with and without isolation
- **NLO**: $\sim 5\%$ reduction, **NNLO** $\sim 10\%$, **resummed** $\sim 12\%$
- **NGL dominates over global contribution**: naive exponentiation (dashed)
Conclusion

- Isolation cross sections are non-global observables, which involve large NGLs in tight isolation cut limit
  - Since isolation area is small, GLs are suppressed and NGLs are enhanced due to boundary collinear radiations
- For non-global observables, we obtained a parton shower from effective field theory
  - Flexible implementation of shower using MG5_aMC@NLO
  - LL results suffer from large scale uncertainties
- Joint resummation for cone radius and isolation cut is on progress

Thank you!!!
Backup
Figure 1. The relation between shower time $t$, hard scale $\mu_h$ and soft scale $\mu_s$. We stop the lines in the plot when $\mu_s$ reaches 1 GeV.

At leading logarithmic accuracy, we only need these functions at leading power in $\mu_s$. The soft functions then become trivial $S_m = 1$ and all higher-multiplicity hard functions are suppressed, $H_m \ll \mu_s H_k$. The cross section thus simplifies to

$$d_{\text{LL}}(Q, Q_0) = \frac{1}{X_m} \prod_{k=1}^{m} H_k \left( \{n\}, Q, \mu_h \right) \prod_{k=1}^{m} U_{km} \left( \{n\}, \mu_s, \mu_h \right) \hat{\prod}_{k=1}^{m} \left( \mu_s \right).$$

(2.8)

where the evolution factor can be evaluated with the leading-order expression for the anomalous dimension $H$. We note that the Born-level cross section is given by

$$d_0(Q, Q_0) = \prod_{k=1}^{m} H_k \left( \{n\}, Q, \mu_h \right).$$

(2.9)

This demonstrates that the starting point of the evolution is the tree-level cross section, as we have indicated earlier. The additional piece of information needed is the color structure since the evolution changes the colors. The paper [32] has modified the MadGraph code in such a way that it provides the full color information. We will focus on the large-$N_c$ limit below and use the color information which MadGraph provides for showering its tree-level events. We will come back to this point later.

It is convenient to rewrite the exponent of the evolution matrix (2.6) at leading order in RG-improved perturbation theory in the form

$$Z_{\mu_h} \mu_s d\mu = Z_{\mu_h} \left( \mu_h \right) Z_{\mu_s} \left( \mu_s \right) d\mu.$$

(2.10)

Using the one-loop anomalous-dimension matrix yields leading logarithmic accuracy in the evolution. The prefactor $t = \frac{1}{2} \ln \left( \frac{\mu_s}{\mu_h} \right) = \frac{\mu_s}{4 \pi} \ln \mu_h \mu_s + O(\mu_s^2)$ (2.11)
Standard cone and smooth cone

- In the soft limit one-loop smooth cone results can be obtained from standard cone using

\[
\ln \frac{\epsilon_\gamma E_\gamma}{\mu} \rightarrow \ln \frac{\epsilon_\gamma e^{-n} E_\gamma}{\mu}.
\]

- Smooth cone with \( \epsilon_\gamma = 0.1 \) and \( n = 2 \) is correspond fixed cone with \( \epsilon_\gamma = 0.01 \)