Resummation effects in photon isolation

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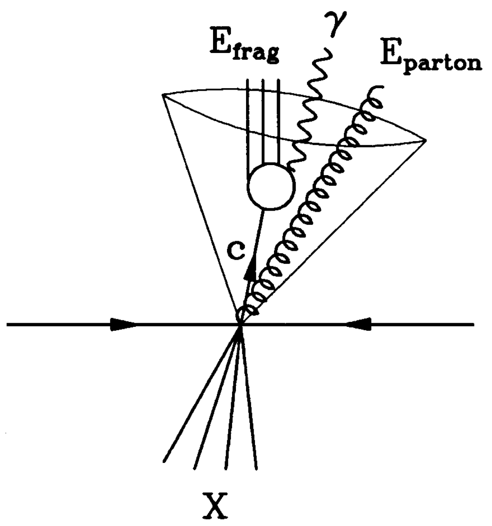
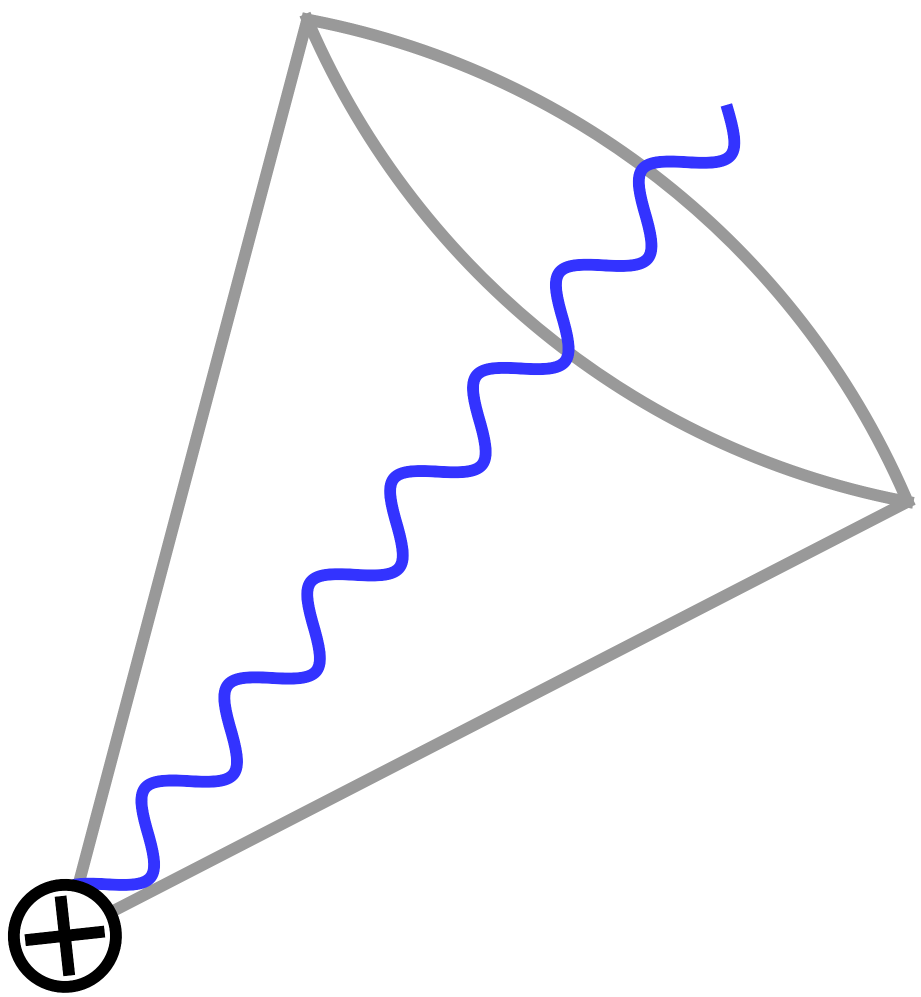
Isolated photon production



- Experiments use isolation to reduce photon from hard scattering from photons due to hadron decays.
- Experimentalists choose $\sum_{\mathrm{had}\in\mathcal{C}(R)} E_T^{\mathrm{had}} \leq \epsilon_\gamma E_\gamma^T$
    - E.g. ATLAS '16 imposes $E_{\mathrm{iso}}^T = 4.8\,\mathrm{GeV} + 0.0042\,E_\gamma^T$ on hadronic energy inside cone.
- Smooth isolation Frixione '98 $E_{\mathrm{iso}}(r) = \epsilon_\gamma E_\gamma \left(\frac{1-\cos r}{1-\cos R}\right)^n$ $\lim_{r\to 0} E_{\mathrm{iso}}(r) \to 0$
    - 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^γ

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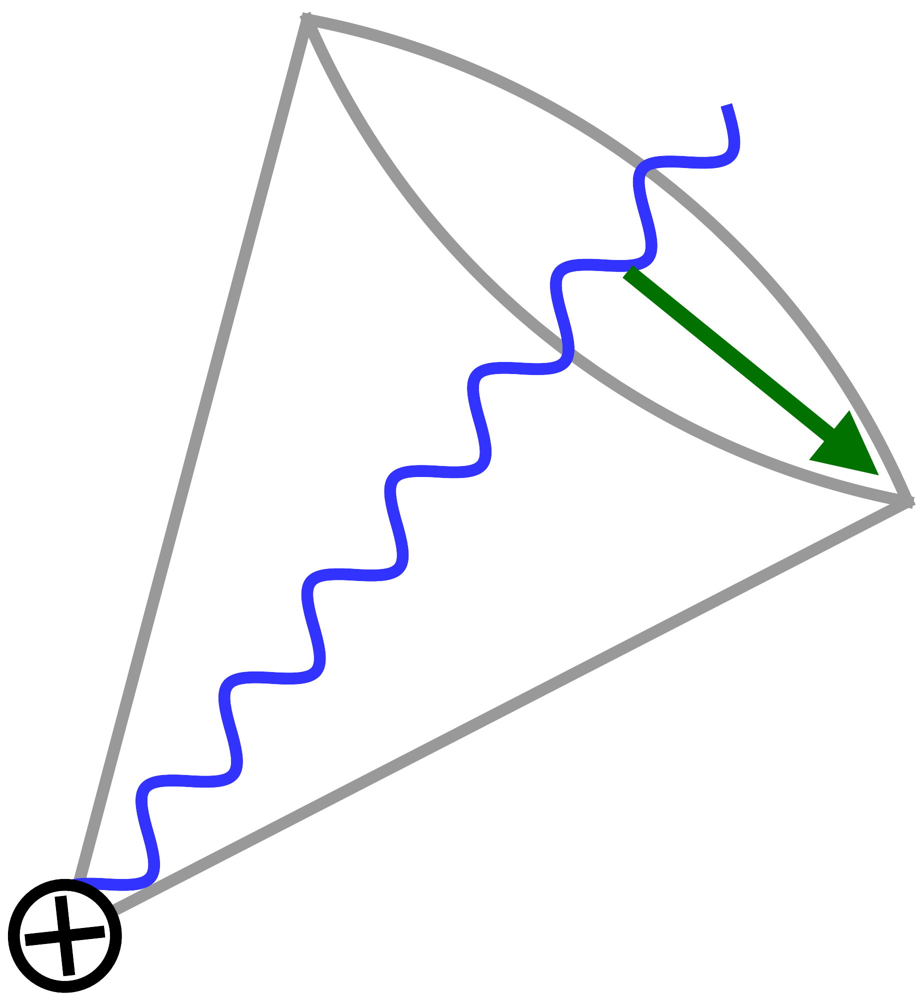

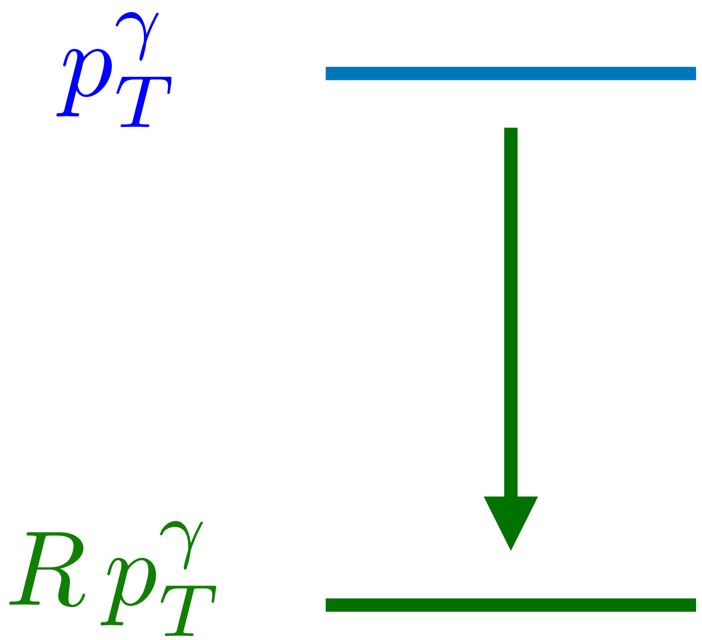

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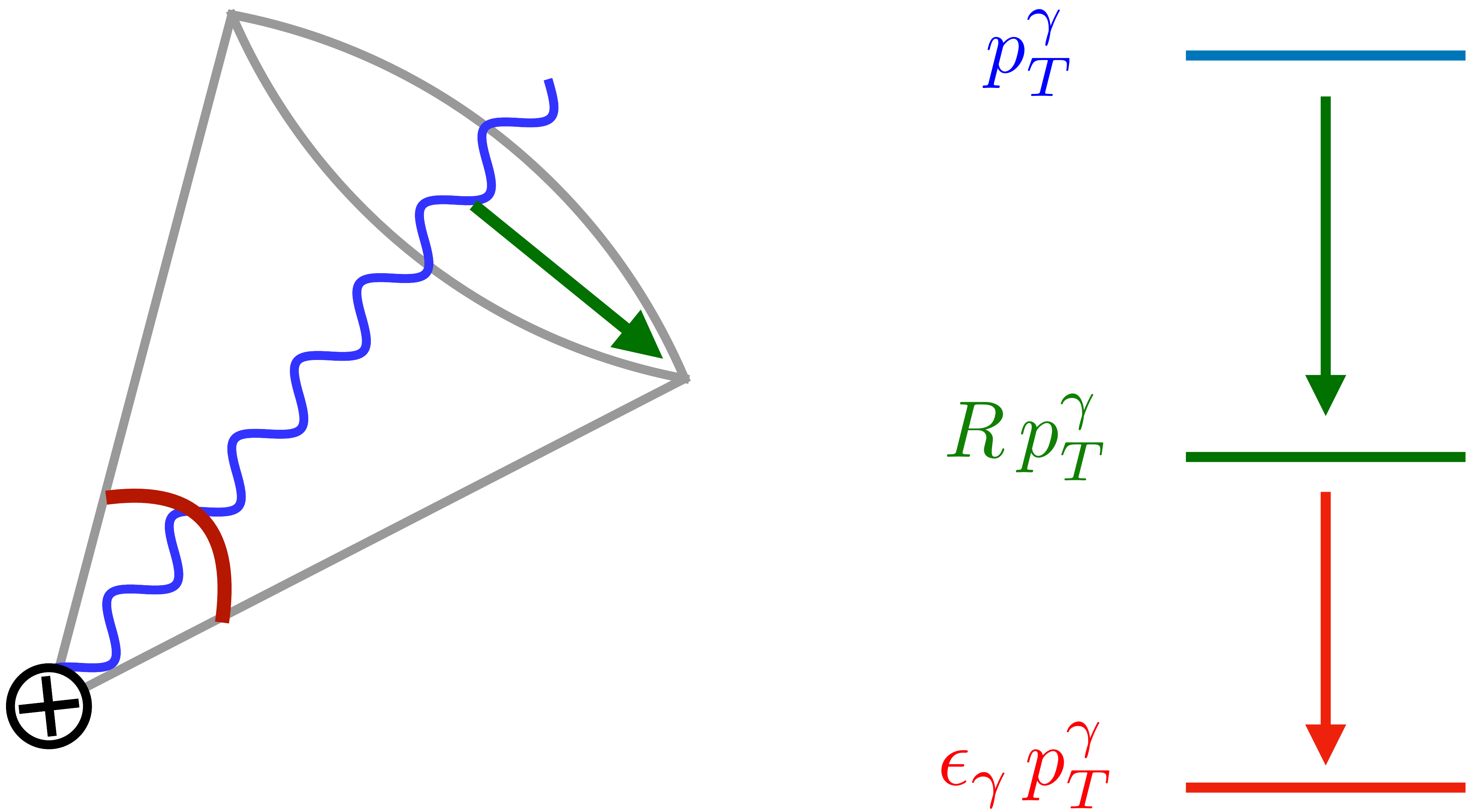

Resummation effects in isolation

- Small cone radius $R \ll 1$

Catani & et. al. '02

Isolation radius	Direct contribution		Fragmentation contribution		Total
R	Born	NLO	Born	NLO	NLO
1.0	1764.6	3318.4	265.0	446.7	3765.1
0.7	1764.6	3603.0	265.0	495.0	4098.0
0.4	1764.6	3968.9	265.0	555.6	4524.5
0.1	1764.6	4758.2	265.0	678.9	5431.1
Without isolation	1764.6	3341.1	1724.3	1876.8	5217.9

- NLO results are unphysical as $R = 0.1$!!!
- 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 ε_h is probably underestimated in the present NLO calculation.

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

$$R^2 \times \alpha_s^n \ln^n \epsilon_\gamma \ln^{n-1} R$$

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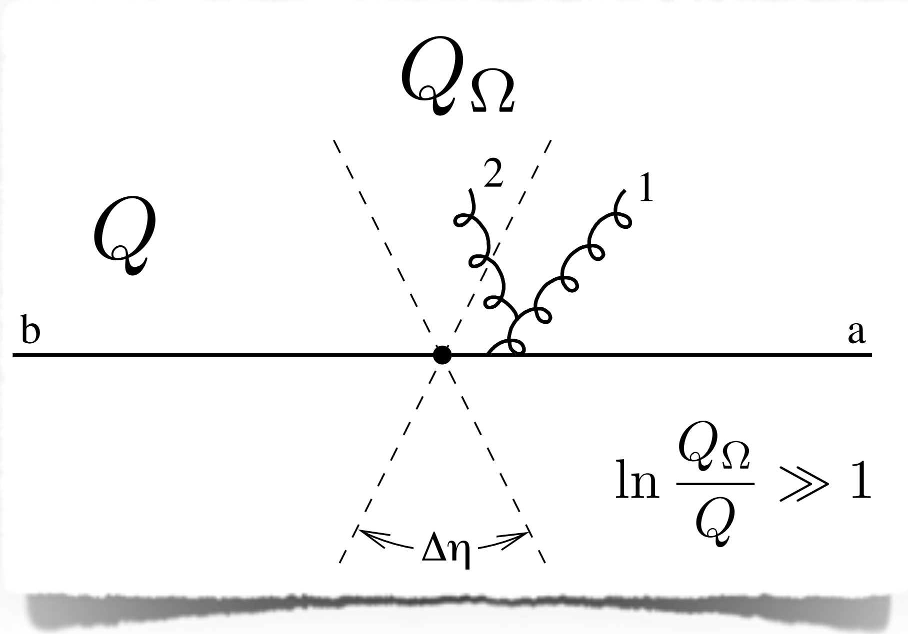
- Non-global observables: more complicated logarithmic terms will appear beyond NLO

$$R^2 \times \alpha_s^n \ln^n \epsilon_\gamma \ln^{n-1} R$$

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:

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

- Dasgupta-Salam shower

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

- Banfi-Marchesini-Smye eqation

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

(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

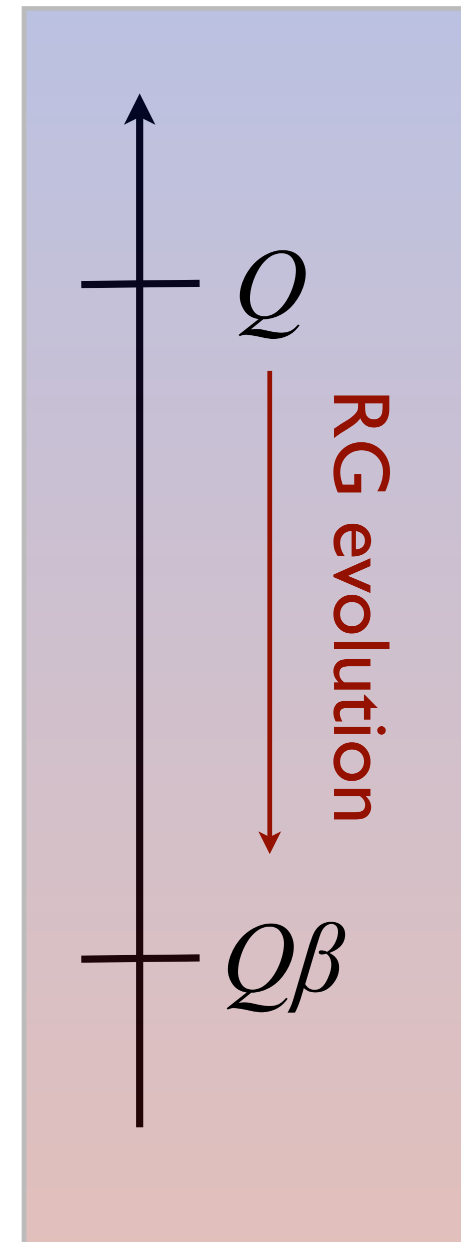
Resummation in multi-Wilson-line theory

Becher, Neubert, Rothen & DYS '15 '16

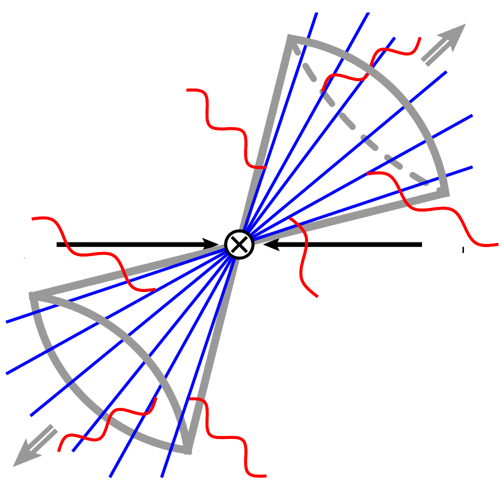
$$\sigma(\beta,\delta) = \sum_{l=2}^{\infty} \left\langle \boldsymbol{\mathcal{H}}_l(\{\underline{n}\},Q,\delta,\mu_h) \otimes \sum_{m\geq l} \boldsymbol{U}^S_{lm}(\{\underline{n}\},\delta,\mu_s,\mu_h) \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m(\{\underline{n}\},Q\beta,\delta,\mu_s) \right\rangle$$

- Separates contributions from hard and soft scale
- Operator definition for different ingredients
- Not limited to Leading Log or Leading color
- Infinite operators are mixed under RG evolution
  - Analytical method fails; RG evolution = parton shower
- LL evolution is equivalent to Dasgupta-Salam shower

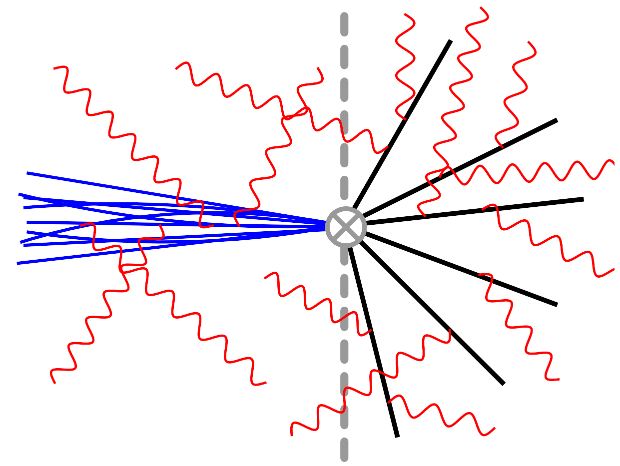
$$\sigma_{\rm LL}(\delta,\beta) = \sigma_0 \left\langle \boldsymbol{\mathcal{S}}_2(\{n,\bar{n}\},Q\beta,\delta,\mu_h) \right\rangle = \sigma_0 \sum_{m=2}^{\infty} \left\langle \boldsymbol{U}^S_{2m}(\{\underline{n}\},\delta,\mu_s,\mu_h) \,\hat{\otimes}\, \mathbf{1} \right\rangle$$



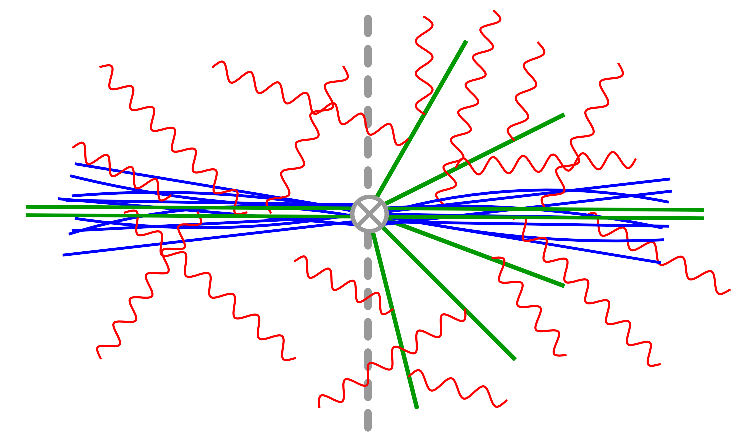
Some applications



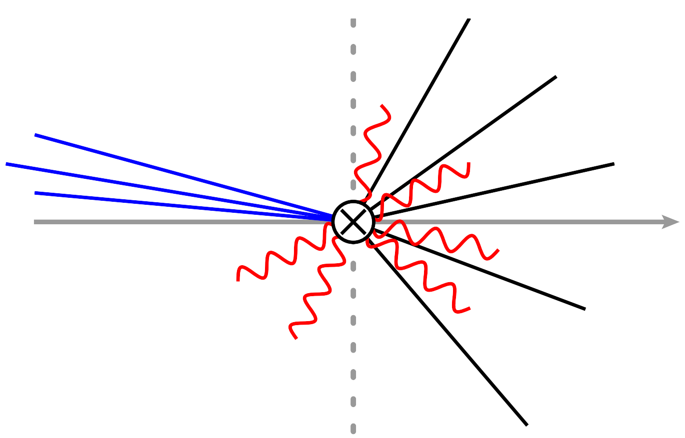
Energy flow &
gap fraction



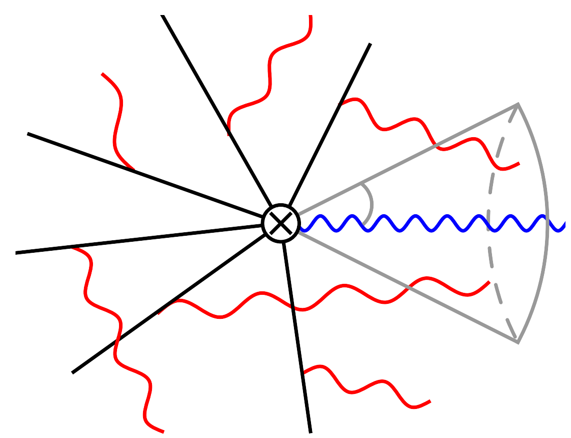
Light-jet mass



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)

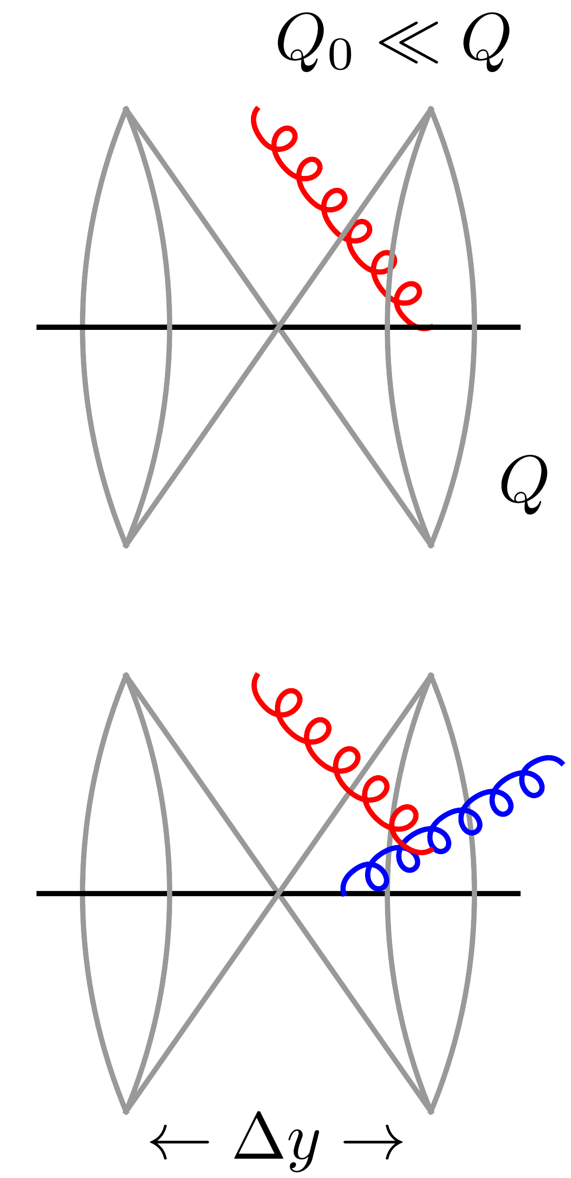
$$\frac{\sigma^{\rm LL}_{\rm GL}}{\sigma_0} = \exp\left[-8\, C_F \Delta y\, t\right] \qquad t = \int_{\alpha(Q_0)}^{\alpha(Q)} \frac{d\alpha}{\beta(\alpha)} \frac{\alpha}{4\pi}$$

  - Leading NGLs at two-loops

$$\frac{\sigma^{\rm LL}_{\rm NGL}}{\sigma_0} = 4\, C_F C_A \left[-\frac{2\pi^2}{3} + 4\, {\rm Li}_2\left(e^{-2\Delta y}\right)\right] t^2$$

  - Narrow gap limit: $\Delta y \to 0$

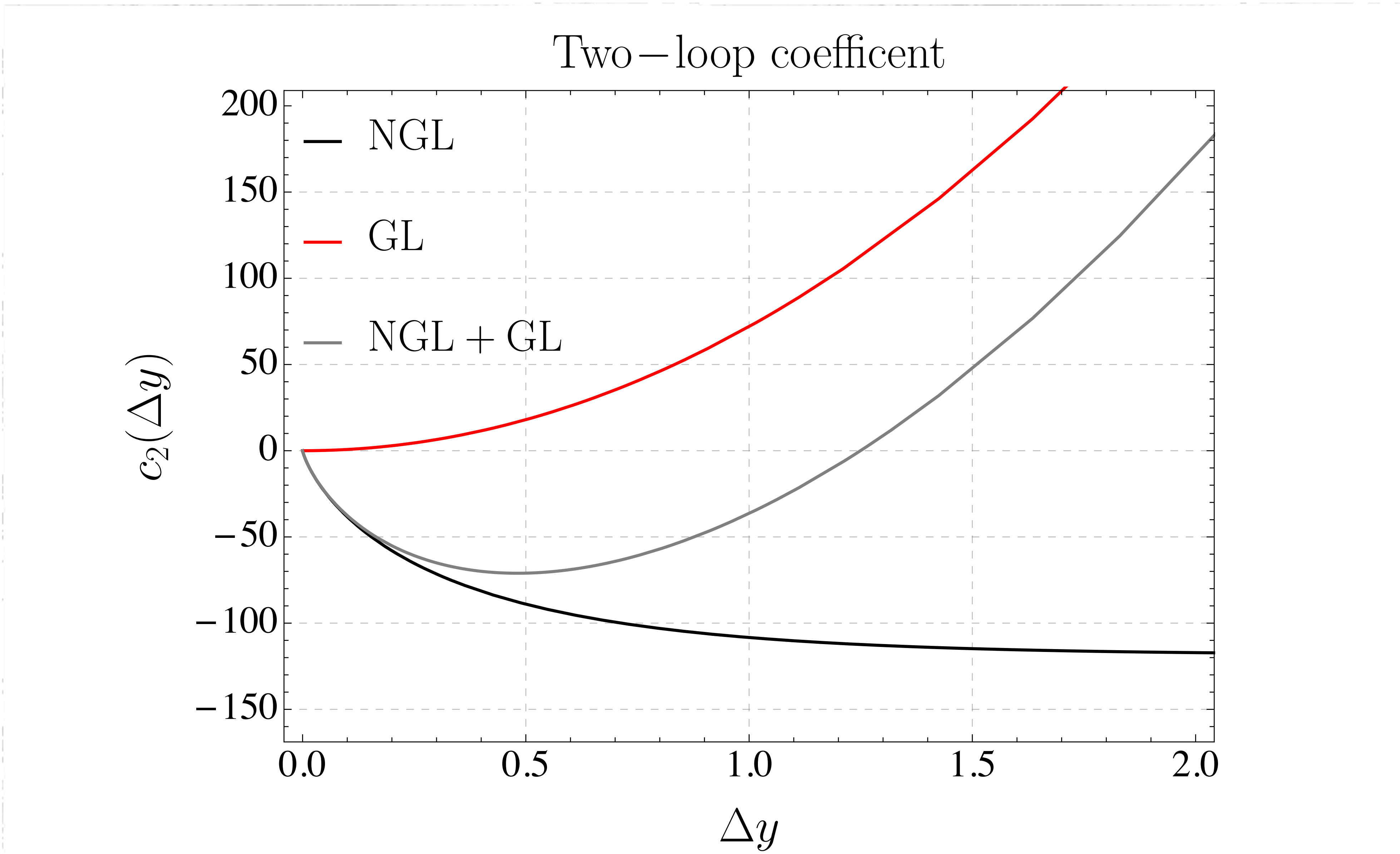
$$\frac{\sigma^{\rm LL}_{\rm NGL}}{\sigma_0} = 4\, C_F C_A \Big[8\, \Delta y\big(\ln(2\Delta y) - 1\big) - 4\, \Delta y^2 + \ldots\Big] t^2$$

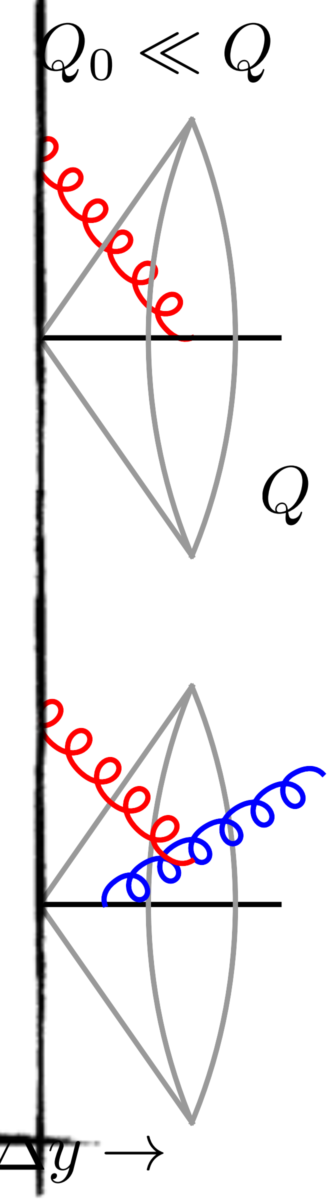


- Collinear enhancement from boundary region (Hatta, Iancu, Mueller, Triantafyllopoulos '17)

Collinear limit and NGLs

- E.g.
  - S
  - L
  - N





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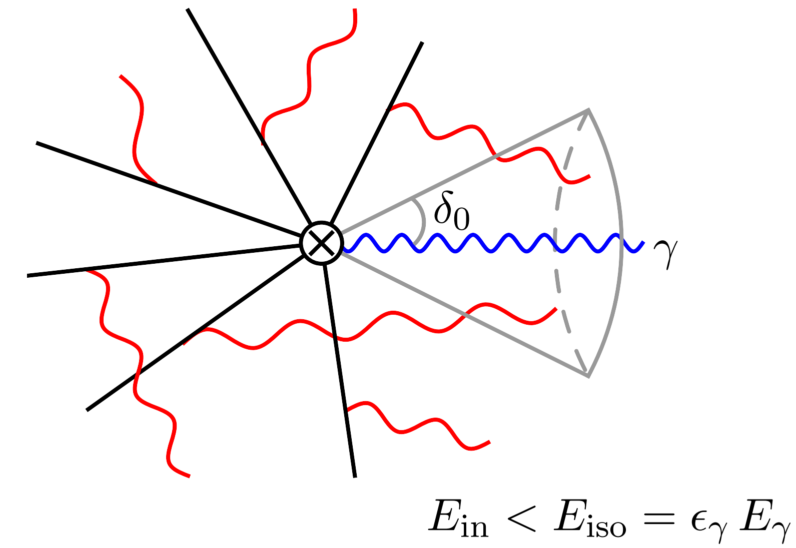
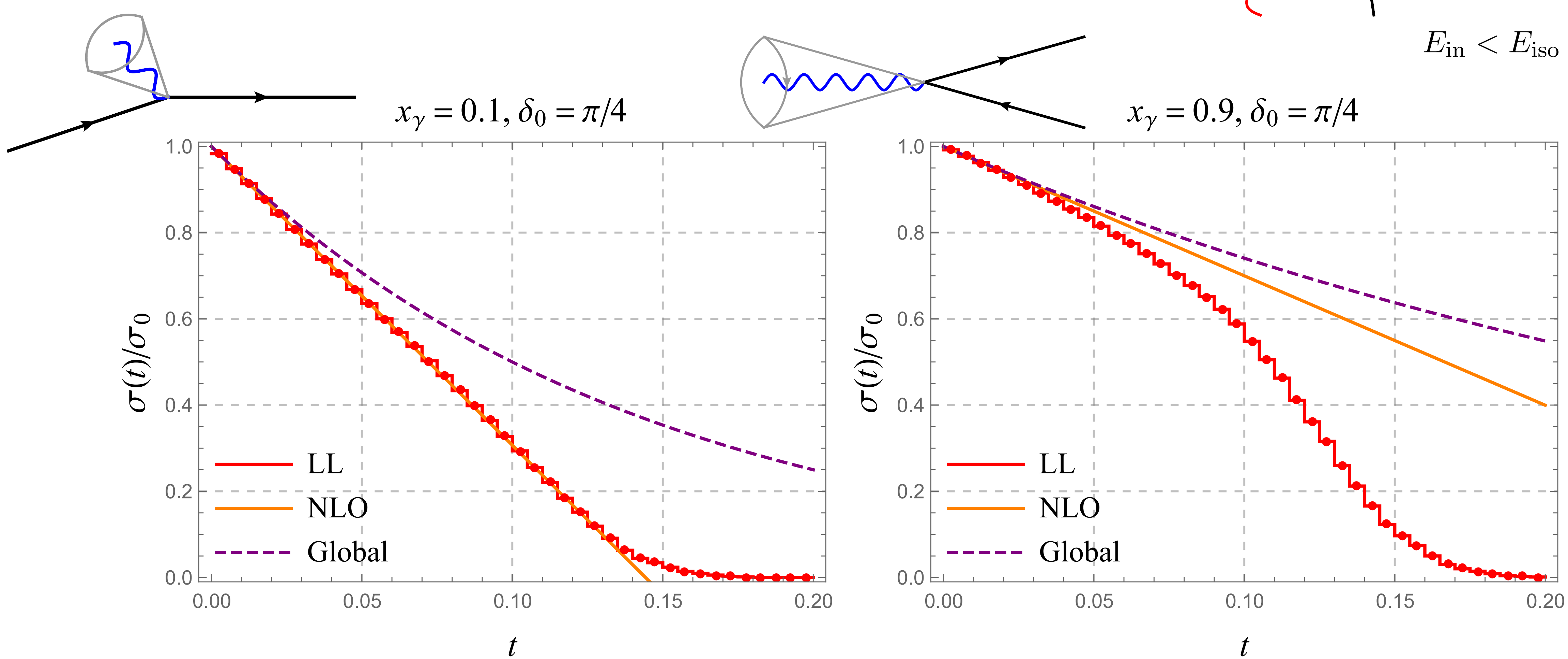
Effect of isolation cut at lepton collider

$$\frac{\mathrm{d}\sigma(\epsilon_\gamma,\delta_0)}{\mathrm{d}E_\gamma} = \sum_{m=2}^{\infty} \langle \boldsymbol{\mathcal{H}}_{\gamma+m}\left(\{\underline{n}\}, E_\gamma, Q, \delta_0\right) \otimes \boldsymbol{\mathcal{S}}_m\left(\{\underline{n}\}, \epsilon_\gamma\, E_\gamma, \delta_0\right)\rangle$$





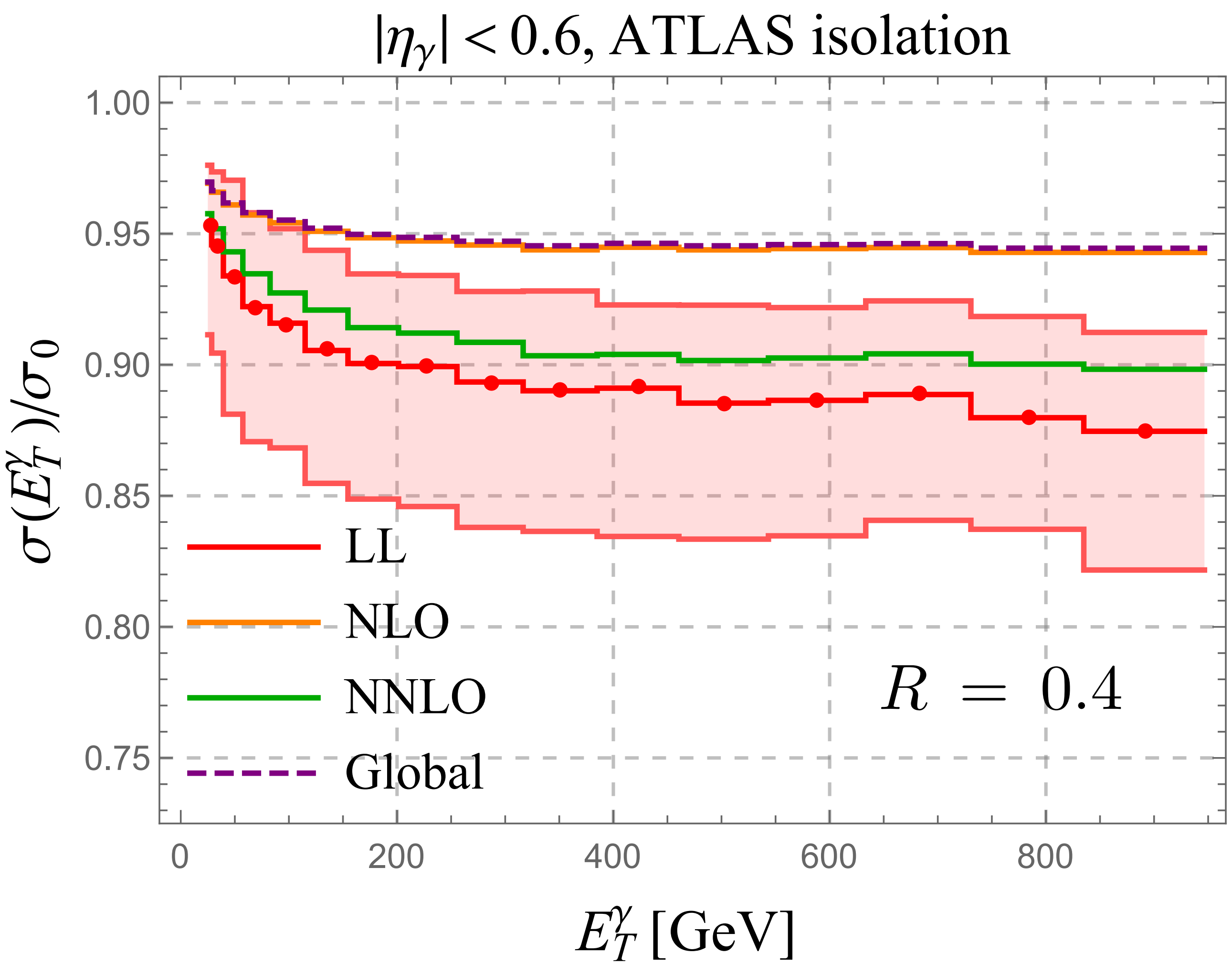
Sizable NGLs corrections

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 γ isolation at LHC



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

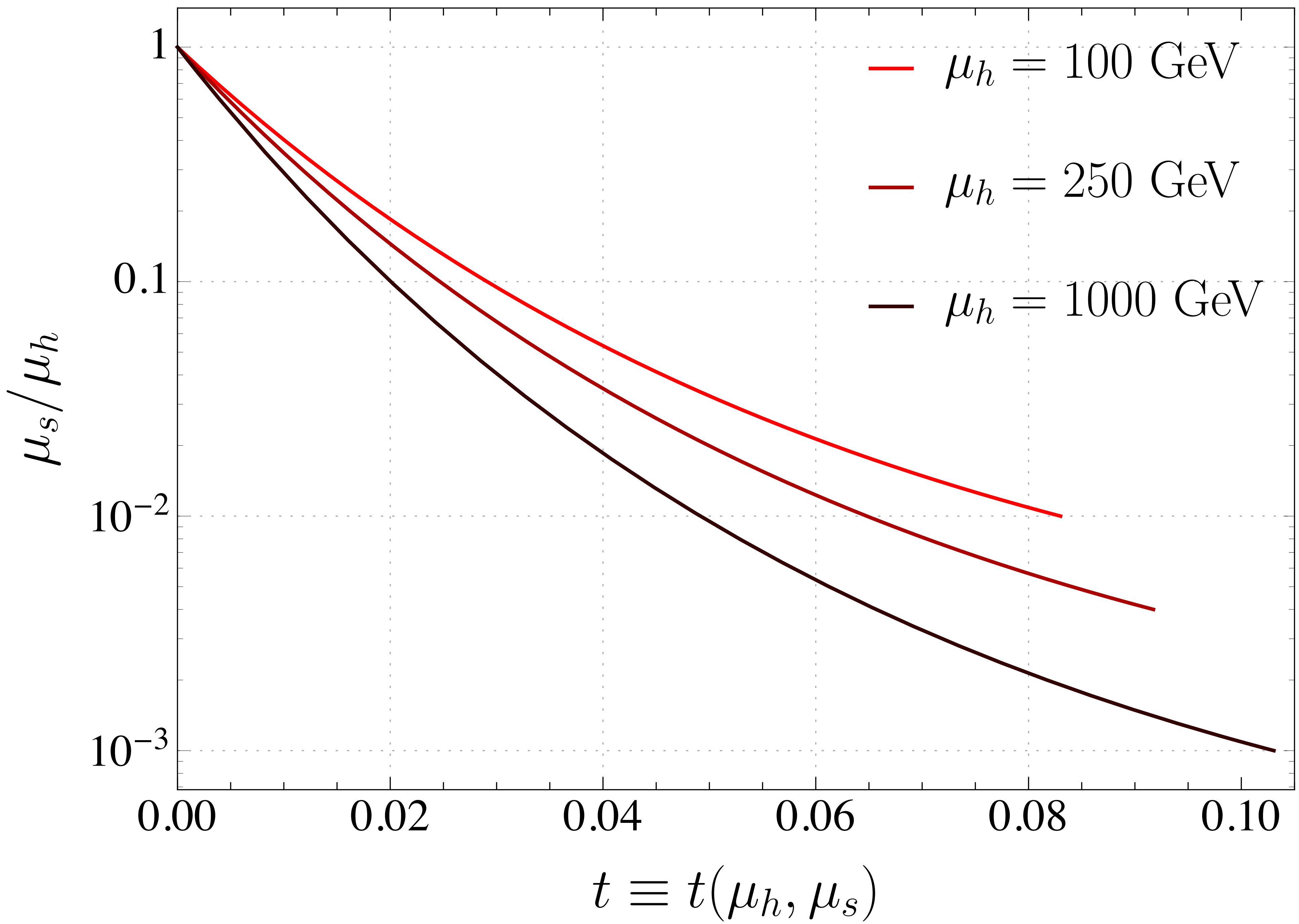
Conclusion

- 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
  - Momentum conservation? Non-perturbative corrections? Higher-order logs?. . .
- Joint resummation for cone radius and isolation cut is on progress

Thank you!!!

Backup

Shower time and scale



Standard cone and smooth cone

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

$$\ln \frac{\epsilon_\gamma E_\gamma}{\mu} \quad \longrightarrow \quad \ln \frac{\epsilon_\gamma e^{-n} E_\gamma}{\mu}\,.$$

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