Non-global logarithms in jet and isolation cone cross sections

DingYu Shao
CERN

SCET Workshop, 19-22 March 2018, Amsterdam

Balsiger, Becher, DYS 1803.07045

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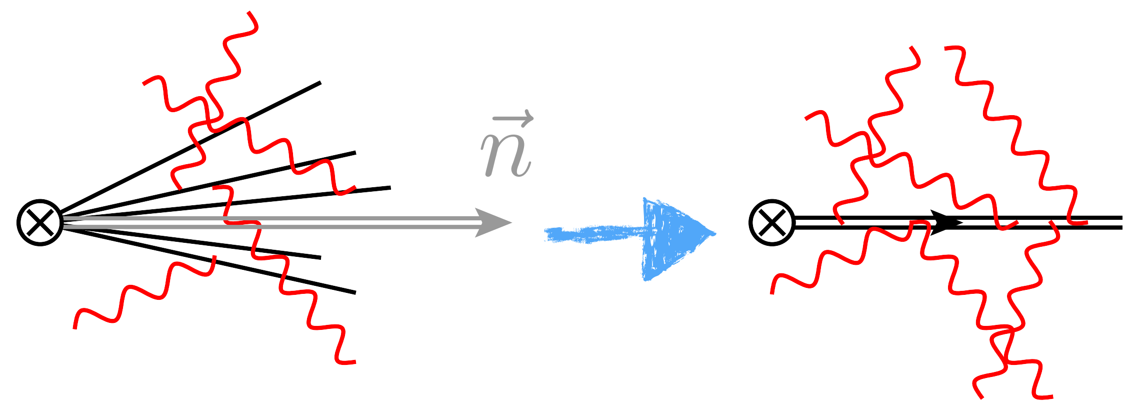
A brief review

- Non-global observables: soft radiations resolve the colors and directions of individual energetic partons.

$$\sum_i Q_i \frac{p_i \cdot \epsilon(k)}{p_i \cdot k} \sim Q_{\text{tot}} \frac{n \cdot \epsilon}{n \cdot k}$$



- Dasgupta-Salam angular dipole shower

$$\mathcal{S}(\alpha_s L) \simeq \exp\left(-C_F C_A \frac{\pi^2}{3}\left(\frac{1+(at)^2}{1+(bt)^c}\right)t^2\right)$$

$a = 0.85\, C_A, \qquad b = 0.86\, C_A$

$c = 1.33$

(Dasgupta & Salam 2001)

- 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 2002)

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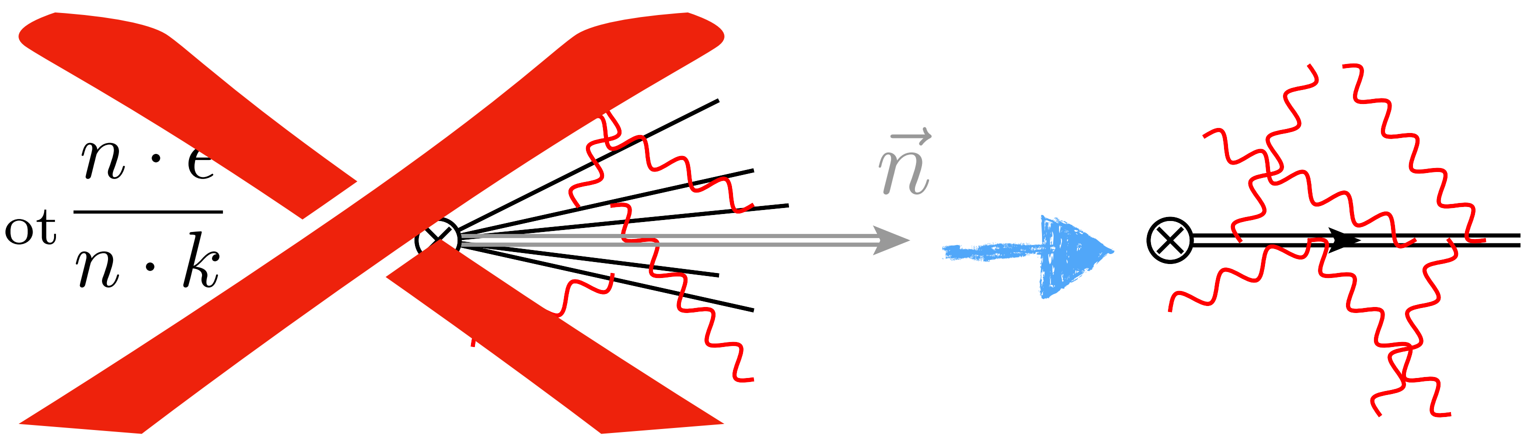

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(Banfi, Marchesini & Smye 2002)

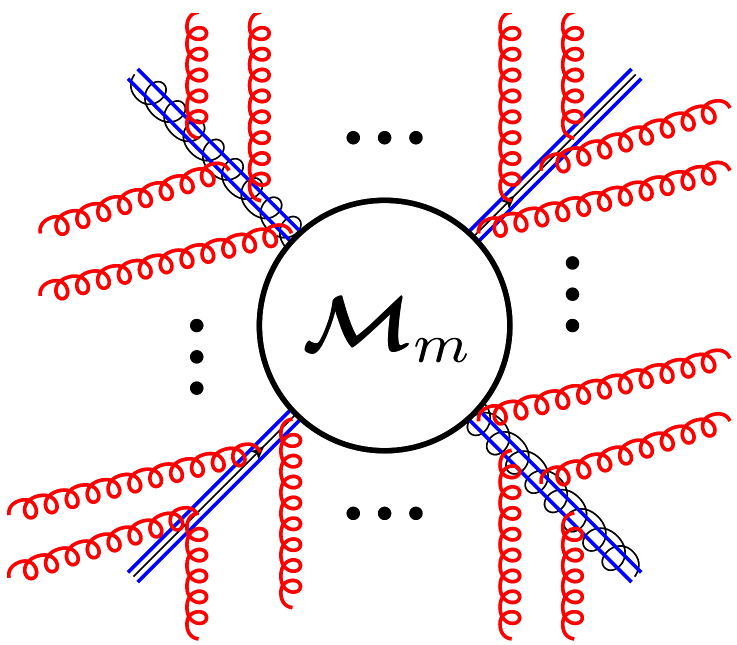
Some recent progress

- Color density matrix Caron-Huot ’15
- Dressed gluon expansion Larkoski, Moult & Neill ’15 ’16
- Multi-Wilson-line structure in SCET Becher, Neubert, Rothen & DYS ’15 ’16
    - For a wide-angle jet, the energetic particles are not collinear.
    - For a narrow-angle jets, small-angle soft radiation plays an important role. Resolves directions of individual energetic partons!
- 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

Factorization

Becher, Neubert, Rothen & DYS ’15 ’16

- The operator for the emission from an amplitude with m hard partons



hard scattering amplitude with m particles (vector in color space)

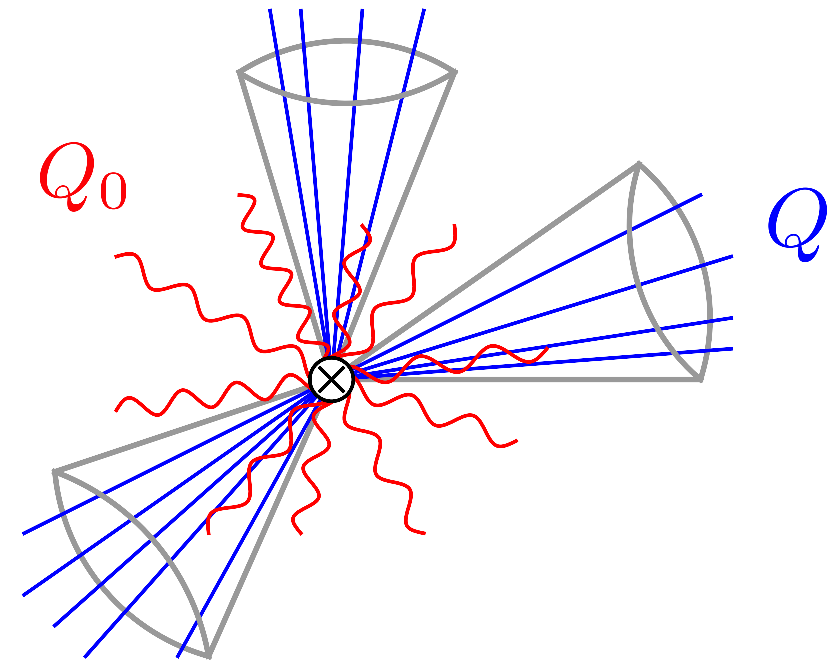
$$\boldsymbol{S}_1(n_1)\,\boldsymbol{S}_2(n_2)\,\ldots\,\boldsymbol{S}_m(n_m)\,|\mathcal{M}_m(\{\underline{p}\})\rangle$$

soft Wilson lines along the directions of the energetic particles (color matrices)

$$\boldsymbol{S}_i(n_i) = \mathbf{P}\exp\left(ig_s\int_0^\infty ds\, n_i\cdot A_s^a(sn_i)\,\boldsymbol{T}_i^a\right)$$

Factorization and resummation for jet cross section

- For k jets process at lepton collider



$$d\sigma(Q,Q_0) = \sum_{m=k}^{\infty} \big\langle \boldsymbol{\mathcal{H}}_m(\{\underline{n}\},Q,\mu) \otimes \boldsymbol{\mathcal{S}}_m(\{\underline{n}\},Q_0,\mu) \big\rangle$$

Hard function

$$\boldsymbol{\mathcal{H}}_m(\{\underline{n}\},Q,\mu) = \frac{1}{2Q^2} \sum_{\text{spins}} \prod_{i=1}^{m} \int \frac{dE_i\, E_i^{d-3}}{(2\pi)^{d-2}} \, |\mathcal{M}_m(\{\underline{p}\})\rangle\langle\mathcal{M}_m(\{\underline{p}\})| \, (2\pi)^d \, \delta\Big(Q - \sum_{i=1}^{m} E_i\Big) \, \delta^{(d-1)}(\vec{p}_{\text{tot}}) \, \Theta_{\text{in}}\big(\{\underline{p}\}\big)$$

(similar to the density matrix in Soper-Nagi parton shower)

- Resummation

$$d\sigma(Q,Q_0) = \sum_{l=k,\, m\geq l}^{\infty} \big\langle \boldsymbol{\mathcal{H}}_l(\{\underline{n}\},Q,\mu_h) \otimes \boldsymbol{U}_{lm}(\{\underline{n}\},\mu_s,\mu_h) \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m(\{\underline{n}\},Q_0,\mu_s) \big\rangle$$

- Infinite operators are mixed under RG evolution —> Analytical methods fail

LL resummation

- LL resummation formula

$$d\sigma_{\rm LL}(Q,Q_0) = \sum_{m=k}^{\infty} \big\langle \boldsymbol{\mathcal{H}}_k(\{\underline{n}\},Q,\mu_h) \otimes \boldsymbol{U}_{km}(\{\underline{n}\},\mu_s,\mu_h)\,\hat{\otimes}\,\mathbf{1}\big\rangle$$

One-loop anomalies dimension

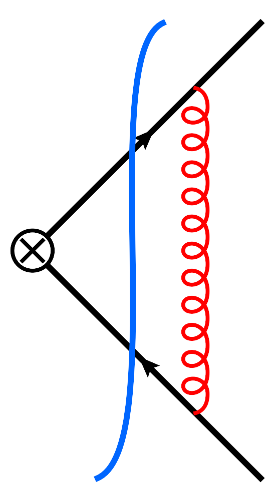
$$\boldsymbol{\Gamma}^{(1)} = \begin{pmatrix} \boldsymbol{V}_k & \boldsymbol{R}_k & 0 & 0 & \dots \\ 0 & \boldsymbol{V}_{k+1} & \boldsymbol{R}_{k+1} & 0 & \dots \\ 0 & 0 & \boldsymbol{V}_{k+2} & \boldsymbol{R}_{k+2} & \dots \\ 0 & 0 & 0 & \boldsymbol{V}_{k+3} & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\boldsymbol{V}_m = 2\sum_{(ij)} (\boldsymbol{T}_{i,L}\cdot\boldsymbol{T}_{j,L} + \boldsymbol{T}_{i,R}\cdot\boldsymbol{T}_{j,R}) \int \frac{d\Omega(n_l)}{4\pi} W_{ij}^l - 2\,i\pi \sum_{(ij)} (\boldsymbol{T}_{i,L}\cdot\boldsymbol{T}_{j,L} - \boldsymbol{T}_{i,R}\cdot\boldsymbol{T}_{j,R})\,\Pi_{ij},$$

$$\boldsymbol{R}_m = -4\sum_{(ij)} \boldsymbol{T}_{i,L}\cdot\boldsymbol{T}_{j,R}\, W_{ij}^{m+1}\,\Theta_{\rm in}(n_{m+1})\,.$$

$$W_{ij}^l = \frac{n_i\cdot n_j}{n_i\cdot n_l\, n_j\cdot n_l}$$

- Imaginary part of V_m from cutting two eikonal propagators
  - Nonzero for both incoming or outgoing
  - Cancel out at e^+e^- or ep colliders, but induce super-leading logs at pp colliders. Forshaw, Keates & Marzani '09



RG evolution ≡ parton shower

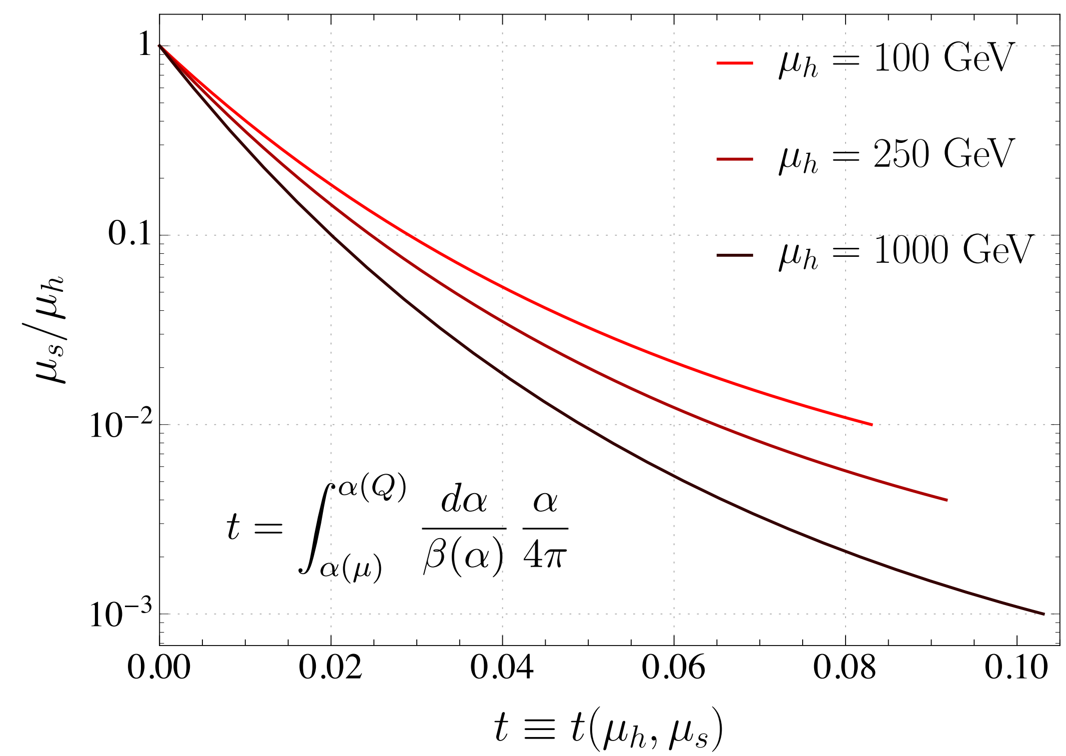
$$d\sigma_{\rm LL}(Q,Q_0) = \left\langle \boldsymbol{\mathcal{H}}_k(t) + \int \frac{d\Omega_1}{4\pi} \boldsymbol{\mathcal{H}}_{k+1}(t) + \int \frac{d\Omega_1}{4\pi} \int \frac{d\Omega_2}{4\pi} \boldsymbol{\mathcal{H}}_{k+2}(t) + \dots \right\rangle$$

$$\boldsymbol{\mathcal{H}}_k(t) = \boldsymbol{\mathcal{H}}_k(0)\, e^{t\boldsymbol{V}_k}$$

$$\boldsymbol{\mathcal{H}}_{k+1}(t) = \int_0^t dt'\, \boldsymbol{\mathcal{H}}_k(t')\, \boldsymbol{R}_k\, e^{(t-t')\boldsymbol{V}_{k+1}}$$

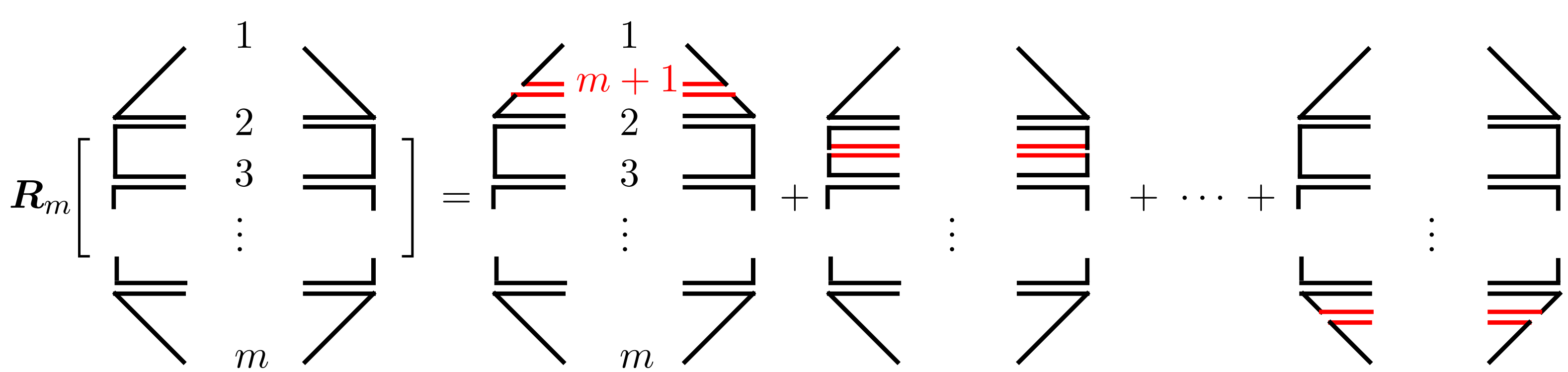
$$\boldsymbol{\mathcal{H}}_{k+2}(t) = \int_0^t dt'\, \boldsymbol{\mathcal{H}}_{k+1}(t')\, \boldsymbol{R}_{k+1}\, e^{(t-t')\boldsymbol{V}_{k+2}}$$

$$\boldsymbol{\mathcal{H}}_{k+3}(t) = \dots$$



In large Nc limit:

$$\boldsymbol{T}_i \cdot \boldsymbol{T}_j \to -\frac{N_c}{2} \delta_{i,j\pm1}\, \boldsymbol{1}$$



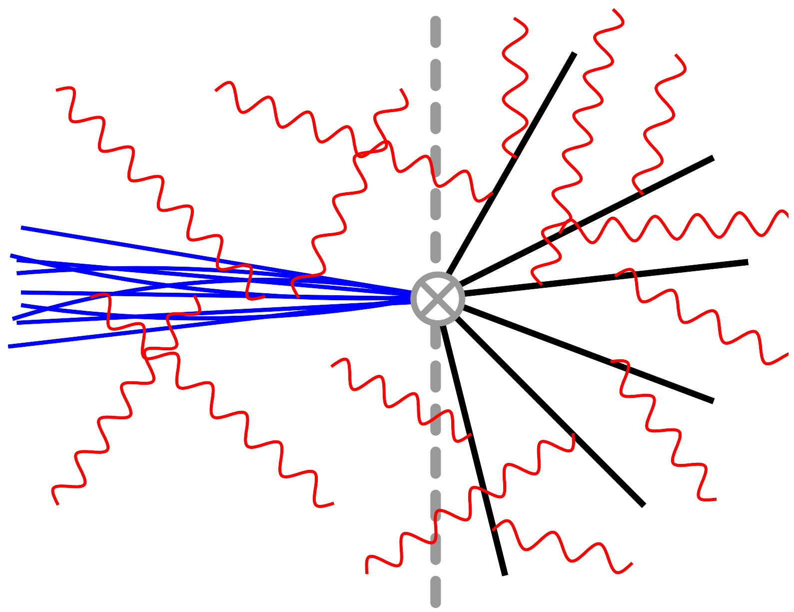
We re-derive Dasgupta-Salam angular dipole shower!!!

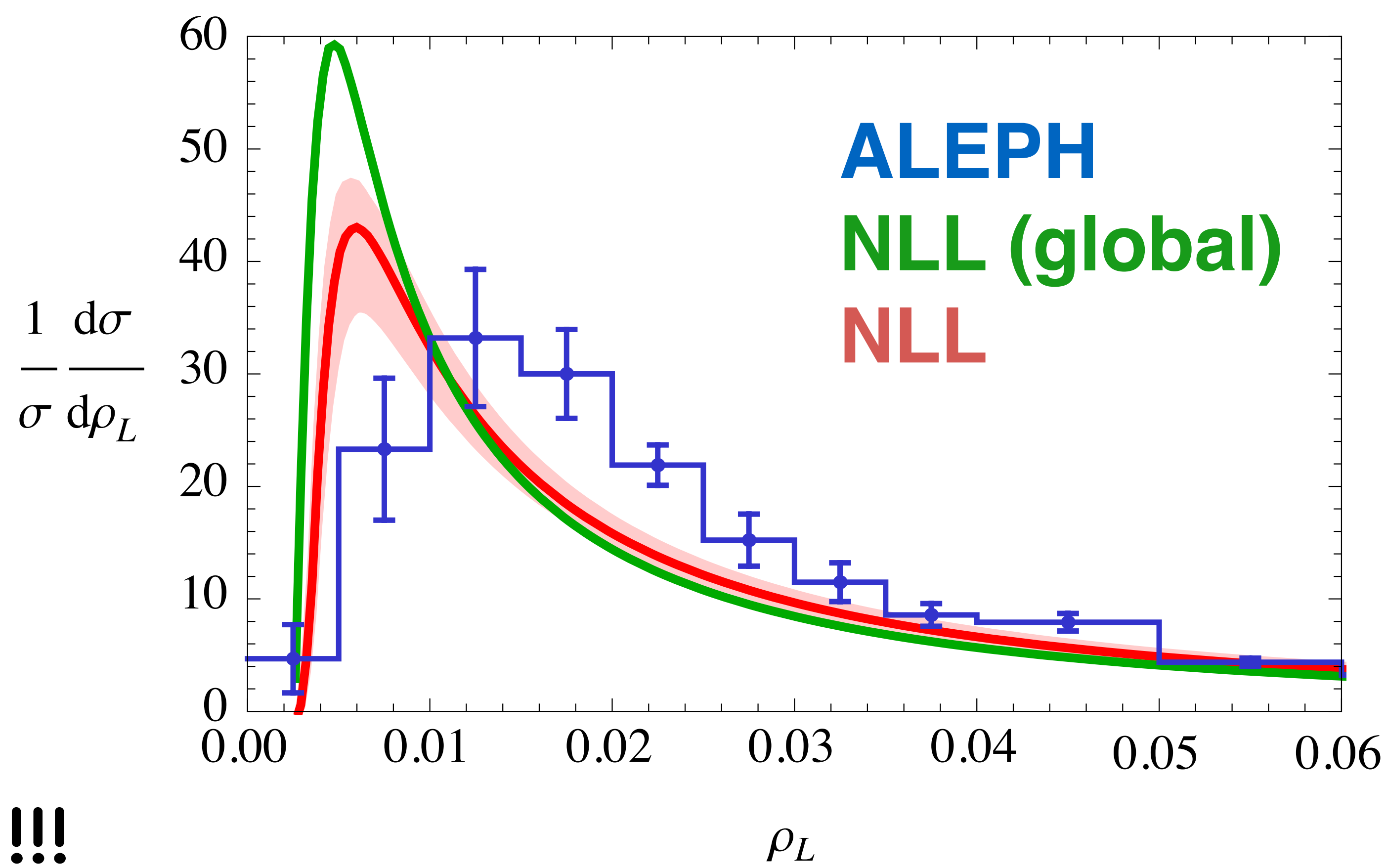
SCET$_{\rm I}$: Light jet mass

Dasgupta & Salam '01; Becher, Pacjek & DYS '16

$$\frac{d\sigma}{dM_L^2} = \sum_{i=q,\bar{q},g} \int_0^\infty d\omega_L \, J_i(M_L^2 - Q\,\omega_L) \sum_{m=1}^{\infty} \langle \boldsymbol{\mathcal{H}}_m^i(\{\underline{n}\},Q) \otimes \boldsymbol{\mathcal{S}}_m(\{\underline{n}\},\omega_L) \rangle$$

$$M_L \ll M_R \sim Q$$





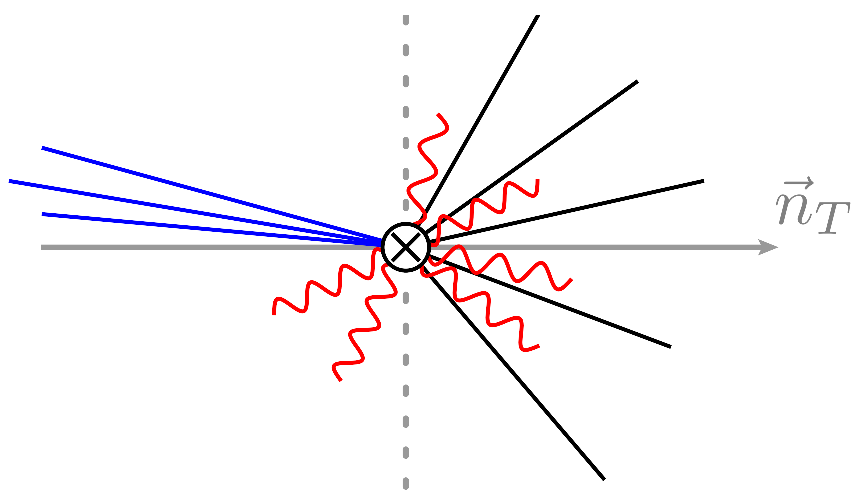
- Sizeable NGL corrections !!!
- Finite Nc correction is small Hatta & Ueda, '13
- Non-perturbative corrections not only linear shift

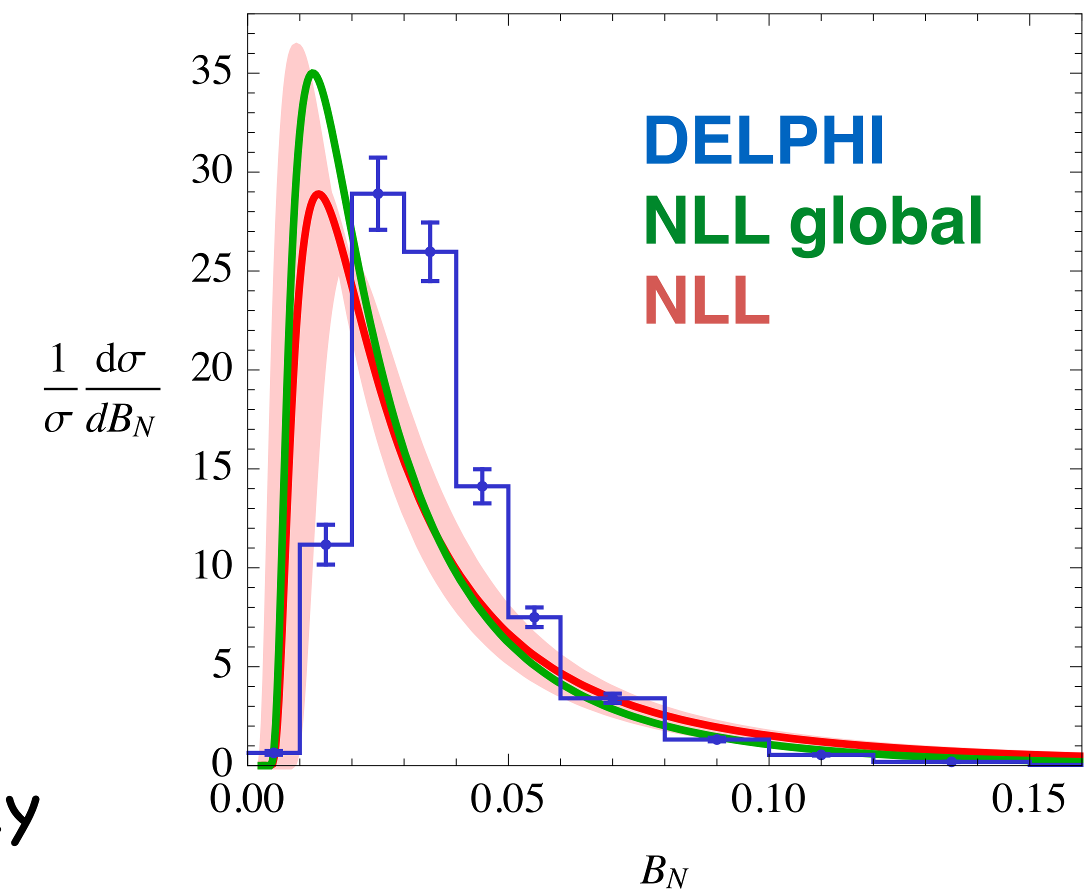
SCET$_{\rm II}$: Narrow broadening

Becher, Rahn & DYS '17

$$\frac{d\sigma}{db_L} = \sum_{f=q,\bar{q},g} \int db_L^s \int d^{d-2}p_L^\perp \, \mathcal{J}_f(b_L - b_L^s, p_L^\perp) \sum_{m=1}^{\infty} \langle \boldsymbol{\mathcal{H}}_m^f(\{\underline{n}\}, Q) \otimes \boldsymbol{\mathcal{S}}_m(\{\underline{n}\}, b_L^s, -p_L^\perp)\rangle$$

$$b_L \ll b_R \sim Q$$





- **In SCET$_{\rm II}$ NP corrections to the anomaly coefficients are dominant.** (Becher & Bell '13)

$$B_N \to B_N - \frac{\mathcal{A}}{2} \ln \frac{1}{B_N}$$

$\mathcal{A} \approx 0.3$ extracted from thrust which implies shifts of $\Delta B_N \approx 0.007$ near peak

Collinear limit and NGLs

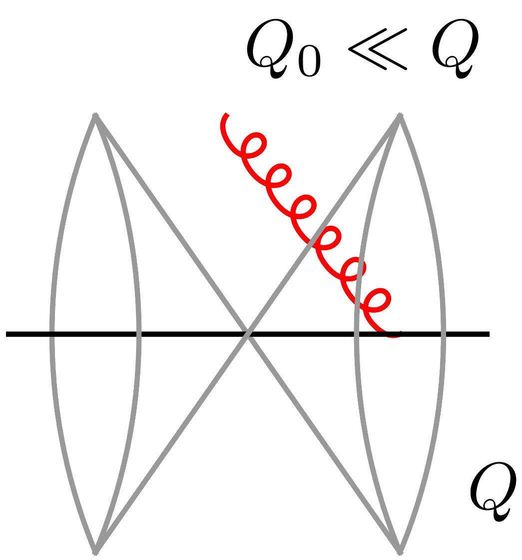
- Dijet cross section with a gap
  - Soft radiations from two Wilson lines (global)

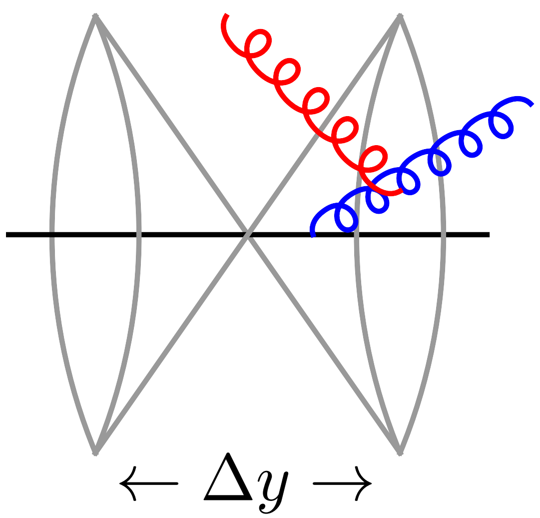
$$\frac{\sigma_{\rm GL}^{\rm LL}}{\sigma_0} = \exp\left[-8\, C_F \Delta y\, t\right]$$

  - Leading NGLs at two-loops

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

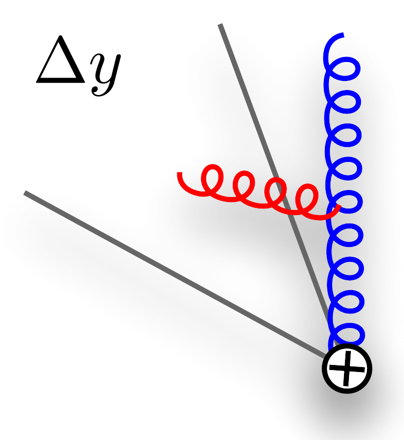
  - Large gap limit: $\Delta y \to \infty$
    - GL resummation at the LHC See Makris's talk
    - NGL: coft mode, jet radius resummation Becher, Neubert, Rothen & DYS `15; Chien, Hornig, Lee `15
  - Narrow gap limit: $\Delta y \to 0$
    - Collinear enhanced power corrections



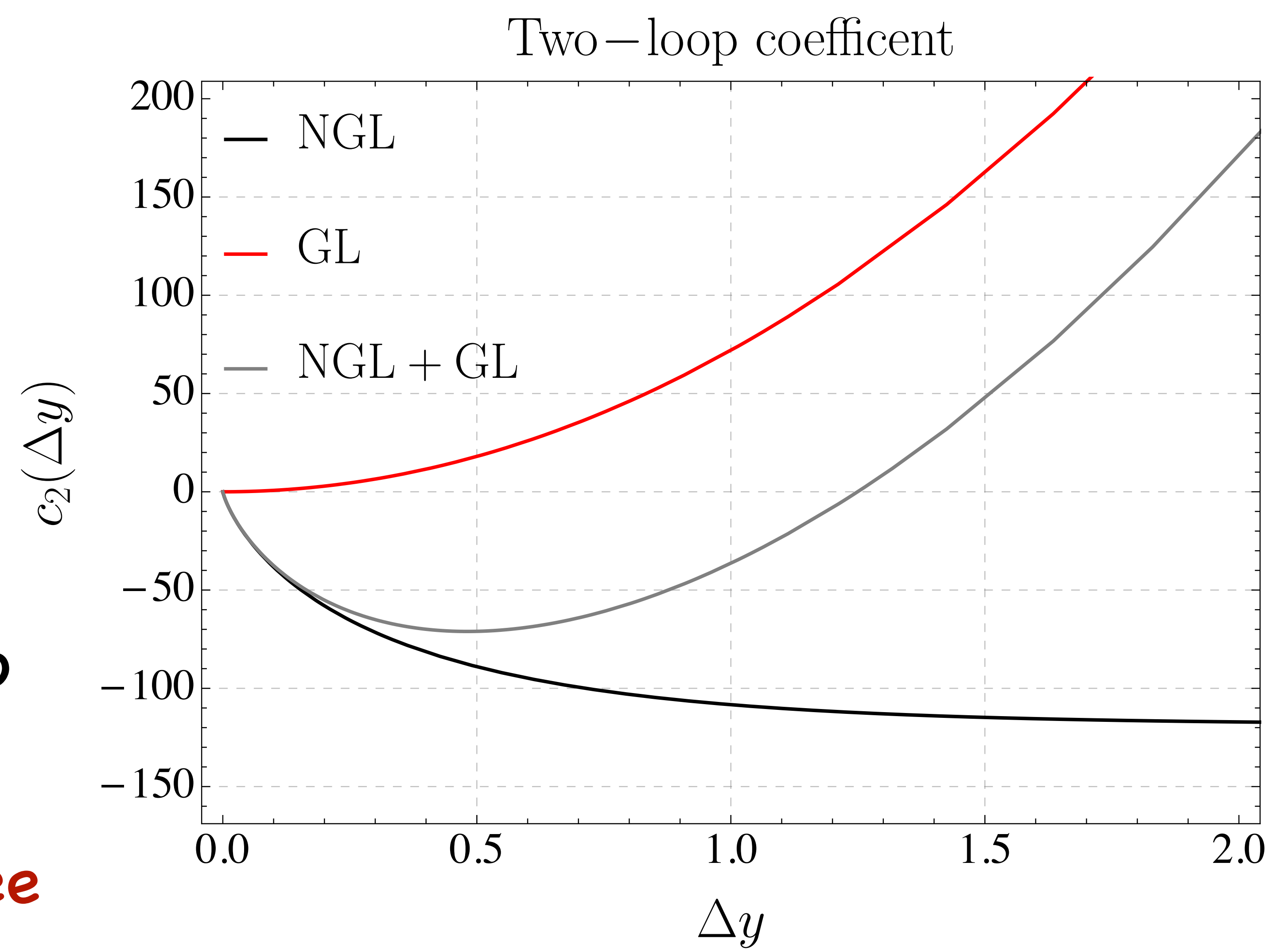


Leading log at two loop

- In narrow gap limit: $$\frac{\sigma_{\rm NGL}^{\rm LL}}{\sigma_0} = 4\, C_F C_A \Big[8\,\Delta y\big(\ln(2\Delta y) - 1\big) - 4\,\Delta y^2 + \dots\Big] t^2$$
- Collinear enhancement from boundary region (Hatta, et.al. '17)



- Power correction, interesting to study in SCET framework
- An example: photon isolation (see latter)



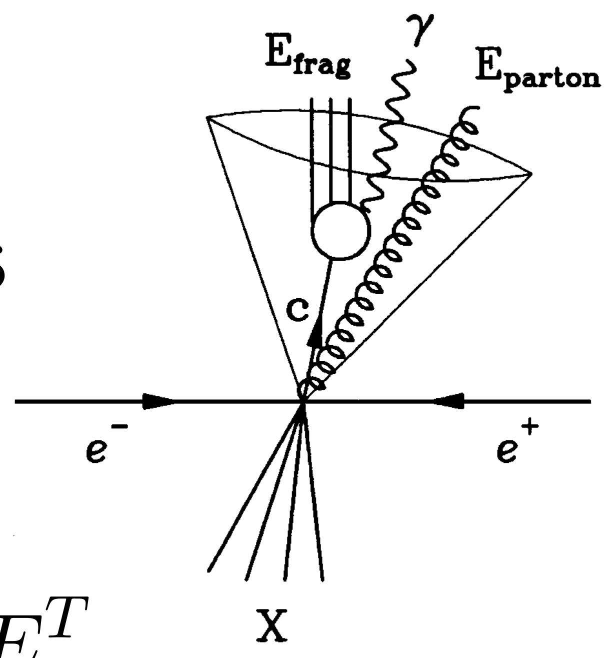
Automated resummation for Non-global observables

(Balsiger, Becher, DYS, 1803.07045)

$$d\sigma_{\rm LL}(Q,Q_0) = \sum_{m=k}^{\infty} \big\langle \boldsymbol{\mathcal{H}}_k(\{\underline{n}\},Q,\mu_h) \otimes \boldsymbol{U}_{km}(\{\underline{n}\},\mu_s,\mu_h)\,\hat{\otimes}\,\boldsymbol{1}\big\rangle$$

- 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

Isolated photon production



- Experiments use isolation cone to reduce photon from hard scattering from photons due to hadron decays such as $\pi^0 \to \gamma\gamma$.

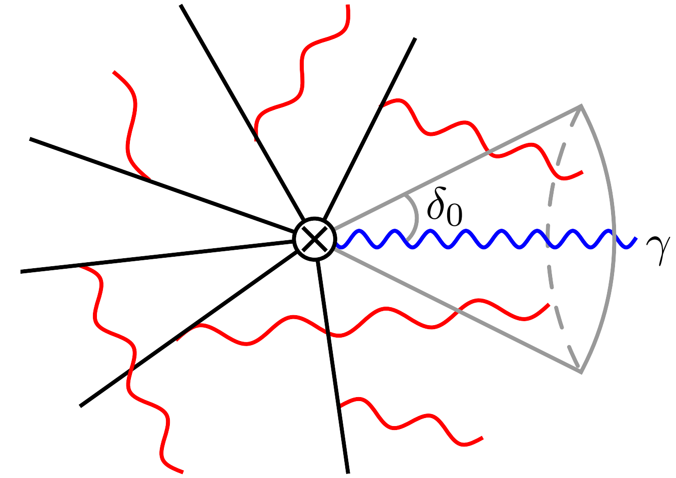
- ATLAS '16 imposes $E^T_{\text{iso}} = 4.8\,\text{GeV} + 0.0042\,E^T_\gamma$ on hadronic energy inside cone.

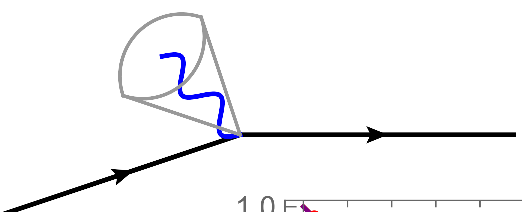
- Large logs of $\epsilon_\gamma = E^T_\gamma / E^T_{\text{iso}}$

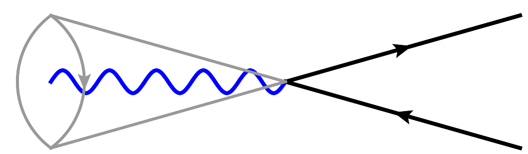
- GLs: $(\alpha_s R^2 \ln \epsilon_\gamma)^n$ NGLs: $R^2 \times \alpha_s^n \ln^n \epsilon_\gamma \ln^{n-1} R$

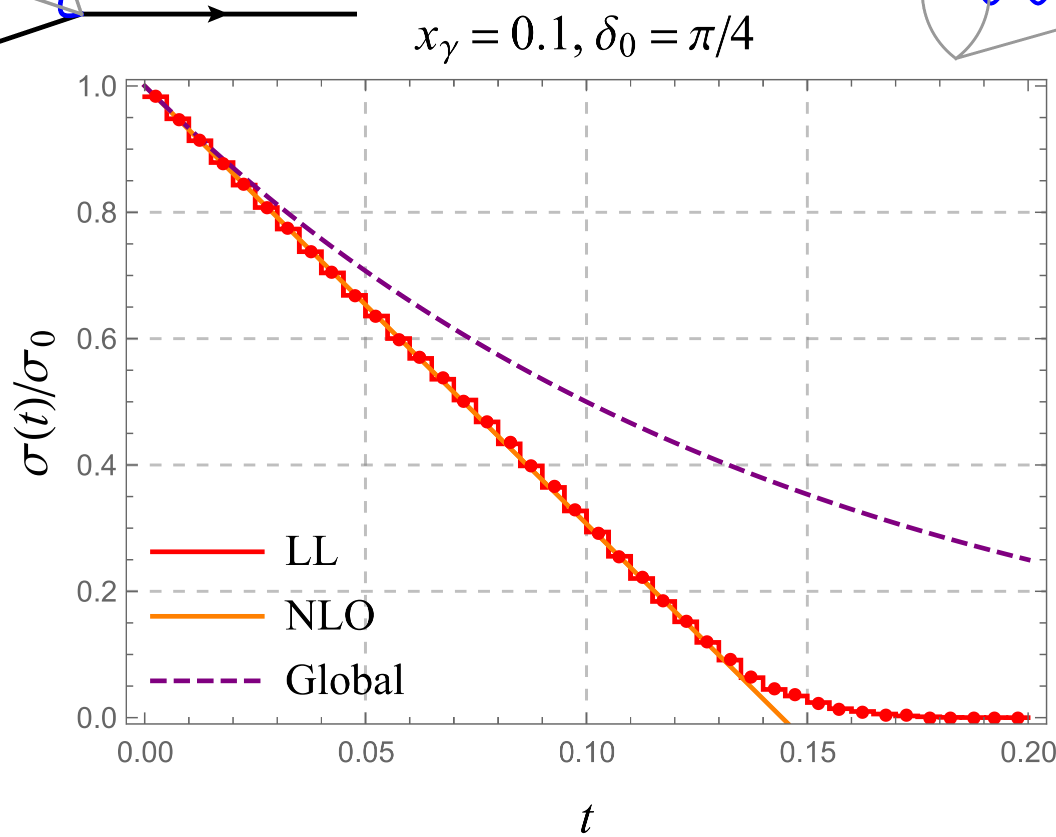
Effect of isolation cut at lepton collider

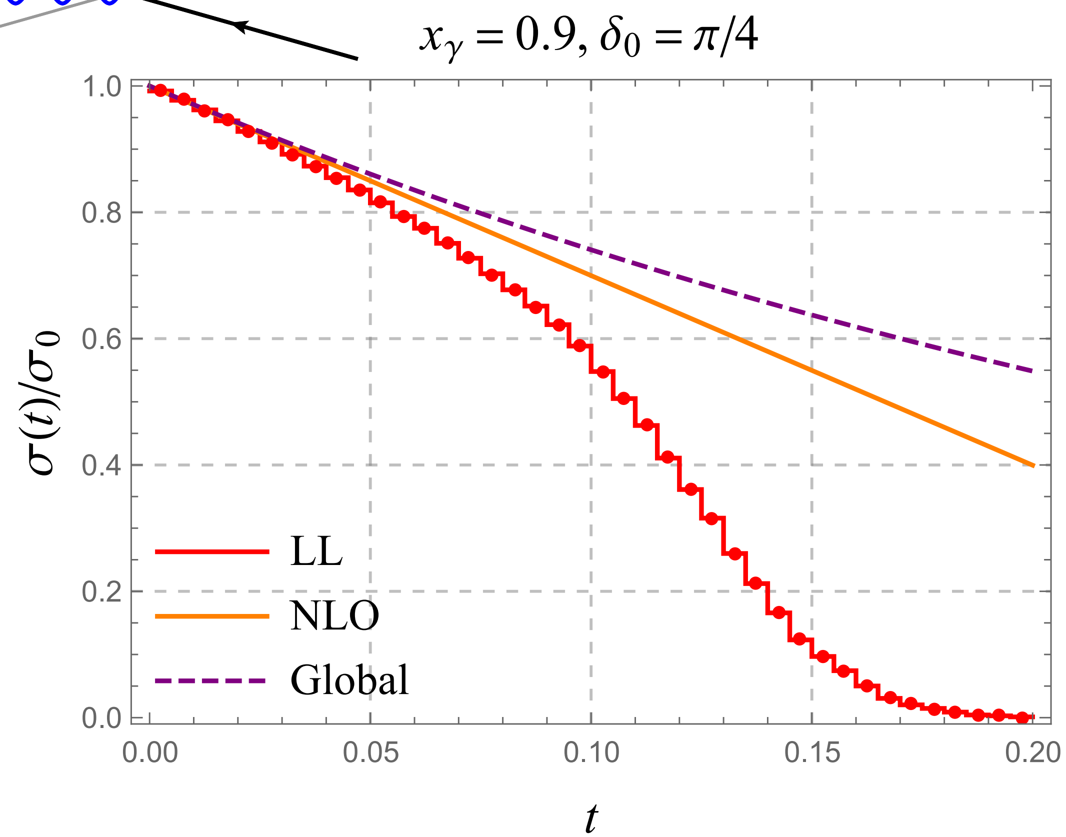
$$\frac{\mathrm{d}\sigma(\epsilon_\gamma, \delta_0)}{\mathrm{d}E_\gamma} = \sum_{m=2}^{\infty} \langle \boldsymbol{\mathcal{H}}_{\gamma+m}\left(\{\underline{n}\}, E_\gamma, Q, \delta_0\right) \otimes \boldsymbol{\mathcal{S}}_m\left(\{\underline{n}\}, \epsilon_\gamma\, E_\gamma, \delta_0\right)\rangle$$





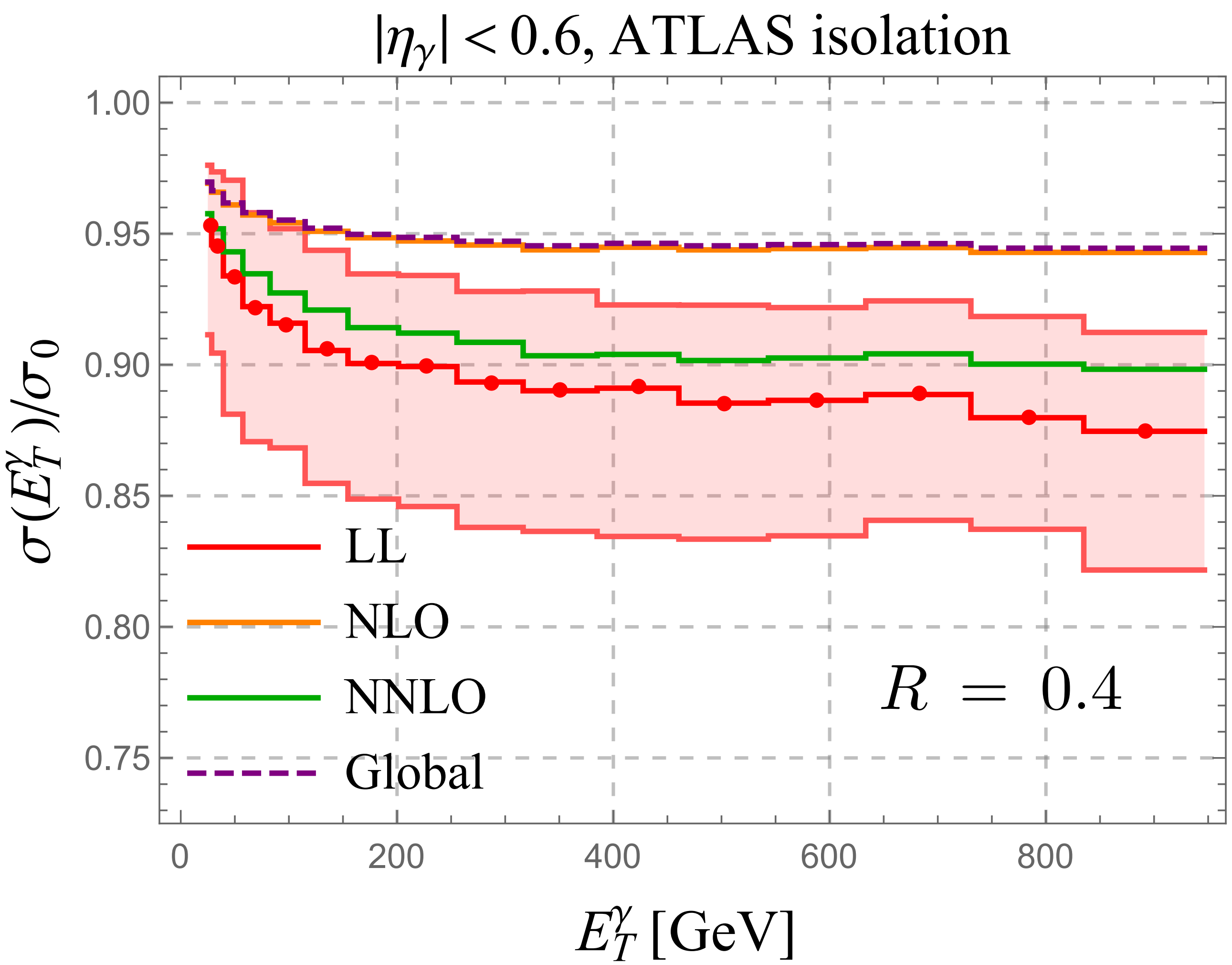






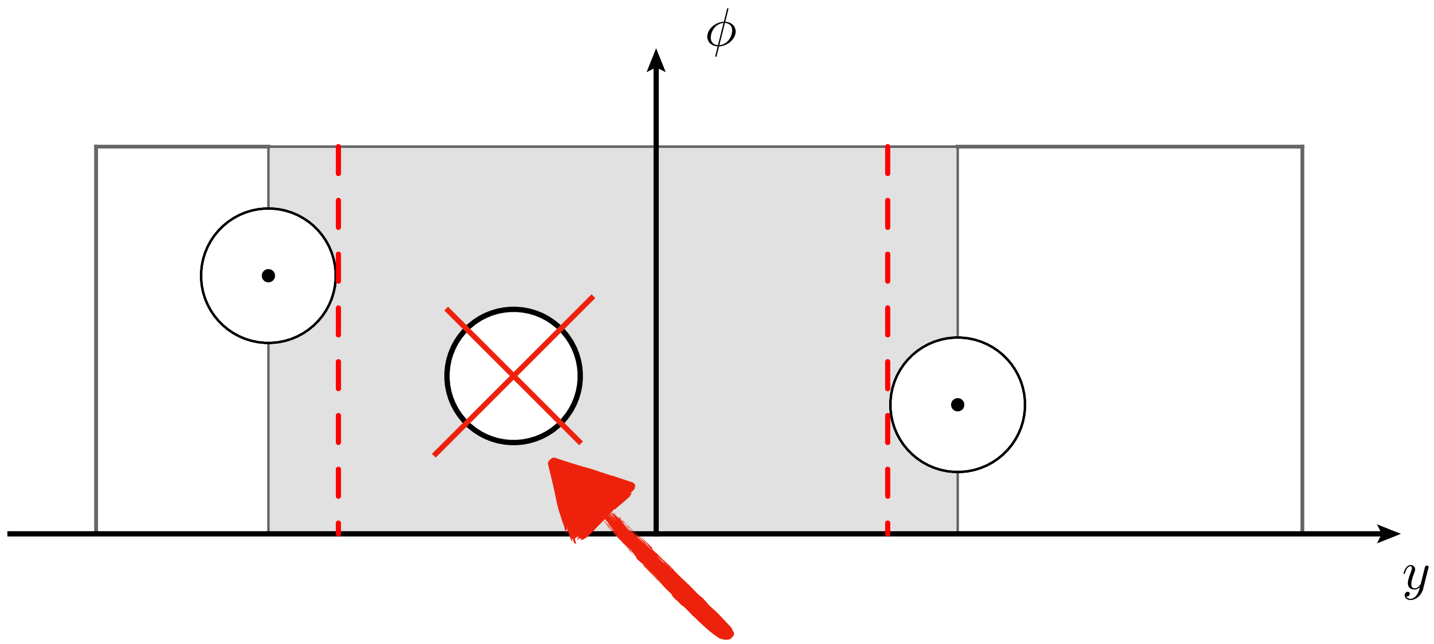
Sizable NGLs corrections

Effects on γ isolation at LHC



- NLO: ~5% reduction, NNLO ~10%, resummed ~ 12%
- NGL dominates over global contribution: naive exponentiation (dashed) not appropriate!

Gap fraction at the LHC



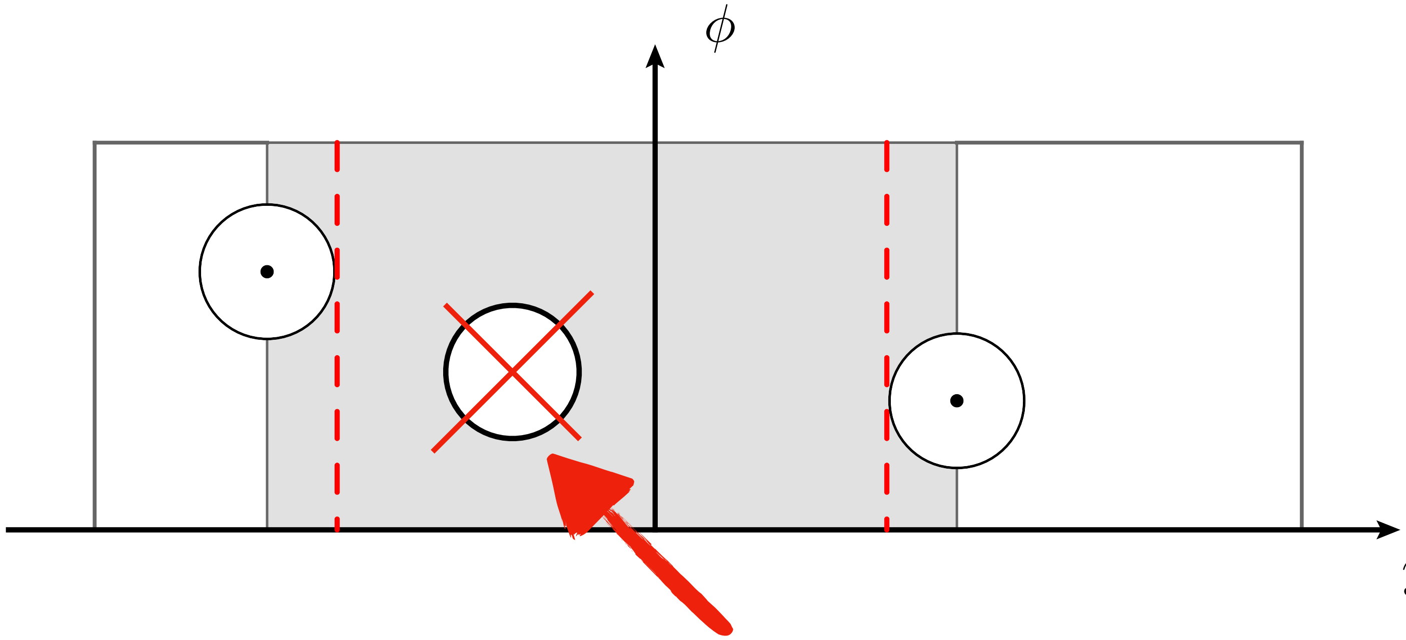
$$R(\bar{p}_T, Q_0) = \frac{\sigma_{2-\mathrm{jet}}(\bar{p}_T, Q_0)}{\sigma_{2-\mathrm{jet}}(\bar{p}_T, Q_0 = \bar{p}_T)}$$

$$\bar{p}_T = \frac{1}{2}\left(p_{T,\,\mathrm{jet1}} + p_{T,\,\mathrm{jet2}}\right)$$

veto events with $p_{T,\,\mathrm{jet3}} > Q_0$

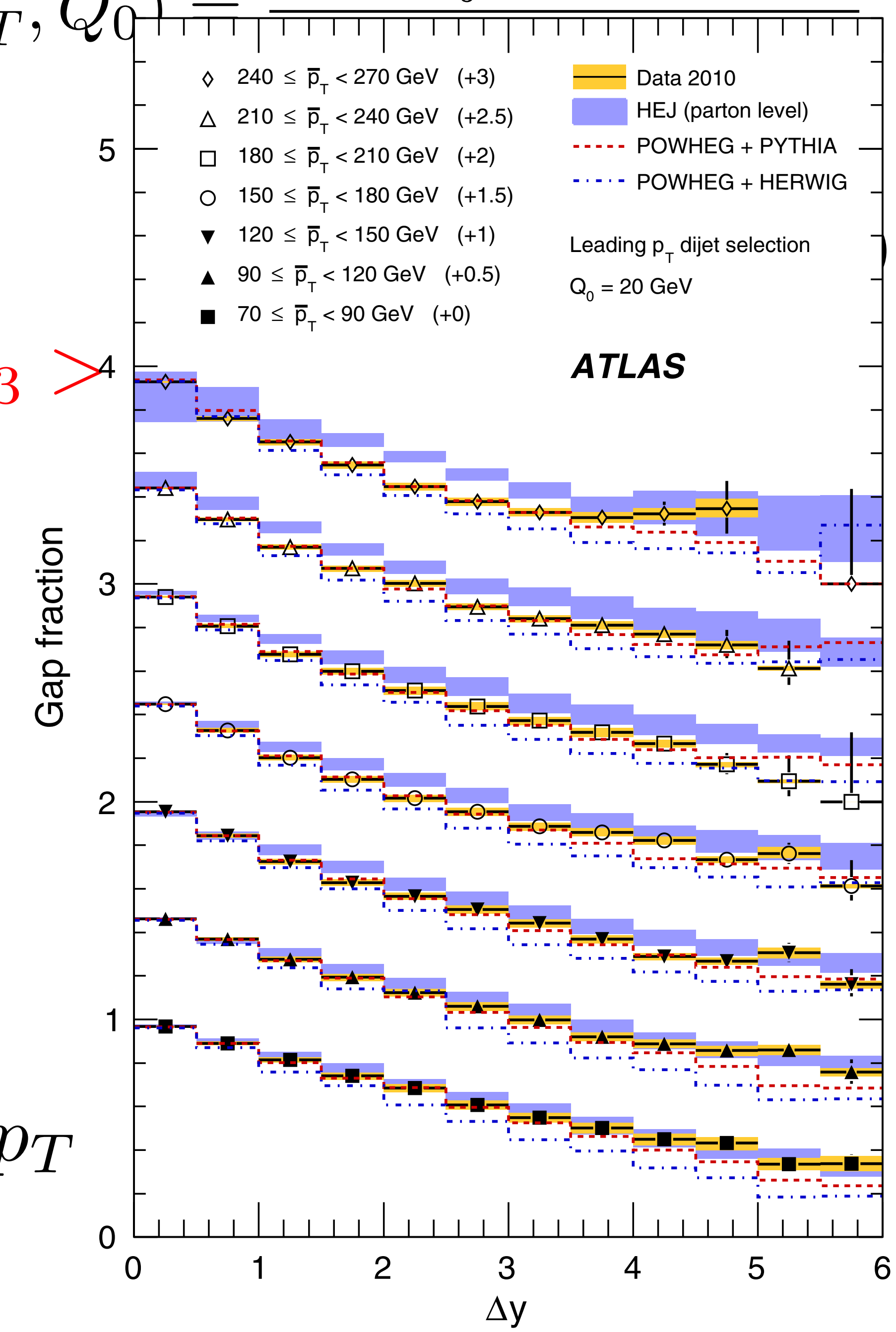
- BFKL evolution at large gap
- soft wide angle gluon resummation at small Q_0
- ATLAS '11 '14 observes data and Monte Carlo predictions is not totally satisfactory
  - fixed-order calculations matched with parton shower tend to be below data at large Δy
  - HEJ (BFKL logs) overestimates the data at large p_T

Gap fraction at the LHC



veto events with $p_{T,\,\mathrm{jet3}} >$

$R(\bar{p}_T, Q_0) = \frac{\sigma_{2-\mathrm{jet}}(\bar{p}_T, Q_0)}{\quad}$



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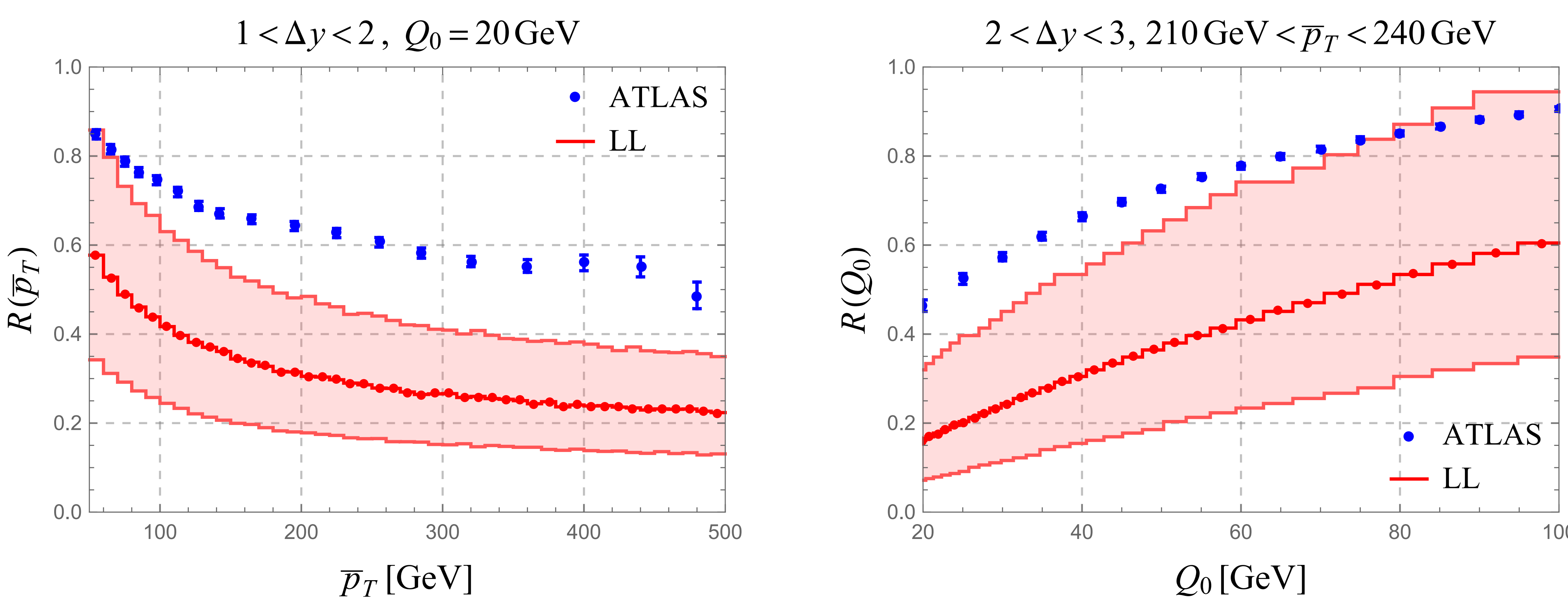
Resummation

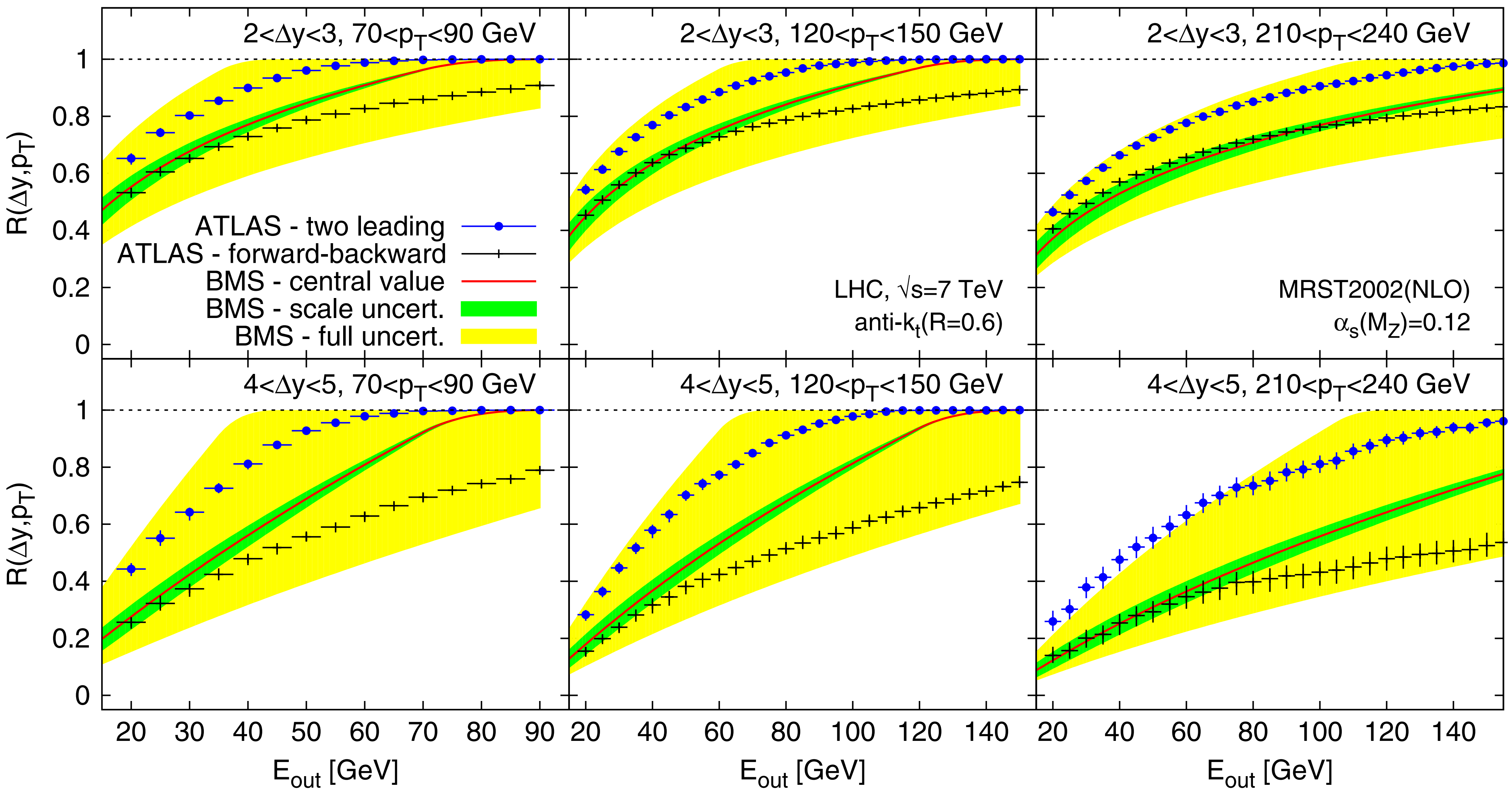
- Factorization formula to all order is unknown due to glauber gluons
- In LL and large Nc limit

$$\frac{d\sigma(Q_0)}{d\Delta y\, d\overline{p}_T} = \sum_{a,b=q,\bar{q},g} \int dx_1 dx_2 f_a(x_1,\mu_f) f_b(x_2,\mu_f) H_2^{ab}(\hat{s},\Delta y,\overline{p}_T,\mu_h) \langle U_{2m}(\mu_s,\mu_h) \hat{\otimes} 1 \rangle$$

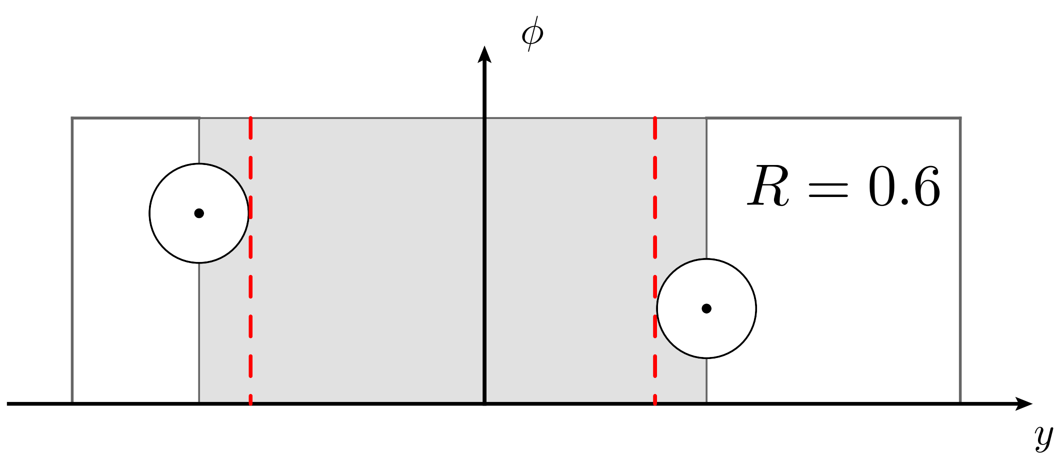
- scale setting $\mu_f = \mu_h = \overline{p}_T$ and $\mu_s = Q_0$
- focus on central jets, small gap & no collinear logs



$\mu_f, \mu_h \in [\overline{p}_T/2, 2\,\overline{p}_T]$
$\mu_s \in [Q_0/2, 2Q_0]$



Hatta et. al. '13



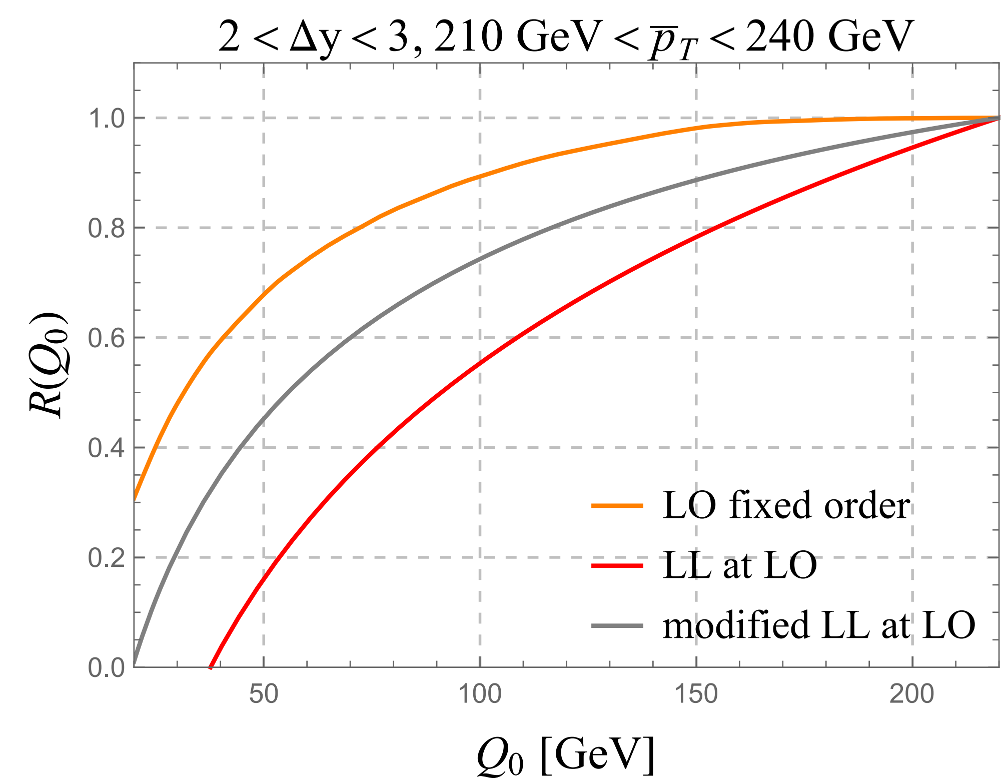
- Our results are consistent with theirs
- Their method are based on BMS eq
- They use rectanglar veto region instead of exact one

How to improve resummation predictions

- Hadronizaiton and underline events
  - Gap energy defined at jet level, reduce NP corrections
- Sub-leading color
  - Super-Leading Log
  - start at α_s^4 , estimated to be small Forshaw, Keates & Marzani '09
- Power corrections
  - one power correction from soft expansion of momentum conservation

$$R(\overline{p}_T, Q_0) = 1 - \frac{1}{\sigma^{\rm LO}_{2-\rm jet}(\overline{p}_T)} \int_{Q_0}^{\overline{p}_T} dQ_0' \frac{d\sigma^{\rm LO}_{3-\rm jet}(\overline{p}_T, Q_0')}{dQ_0'}$$

$$\hat{s} = (p_{J_1} + p_{J_1})^2 \longrightarrow \hat{s} = (p_{J_1} + p_{J_1} + k_s)^2$$



- Higher log terms
  - Collinear log resummation
  - NLL (jet algorithm dependence)

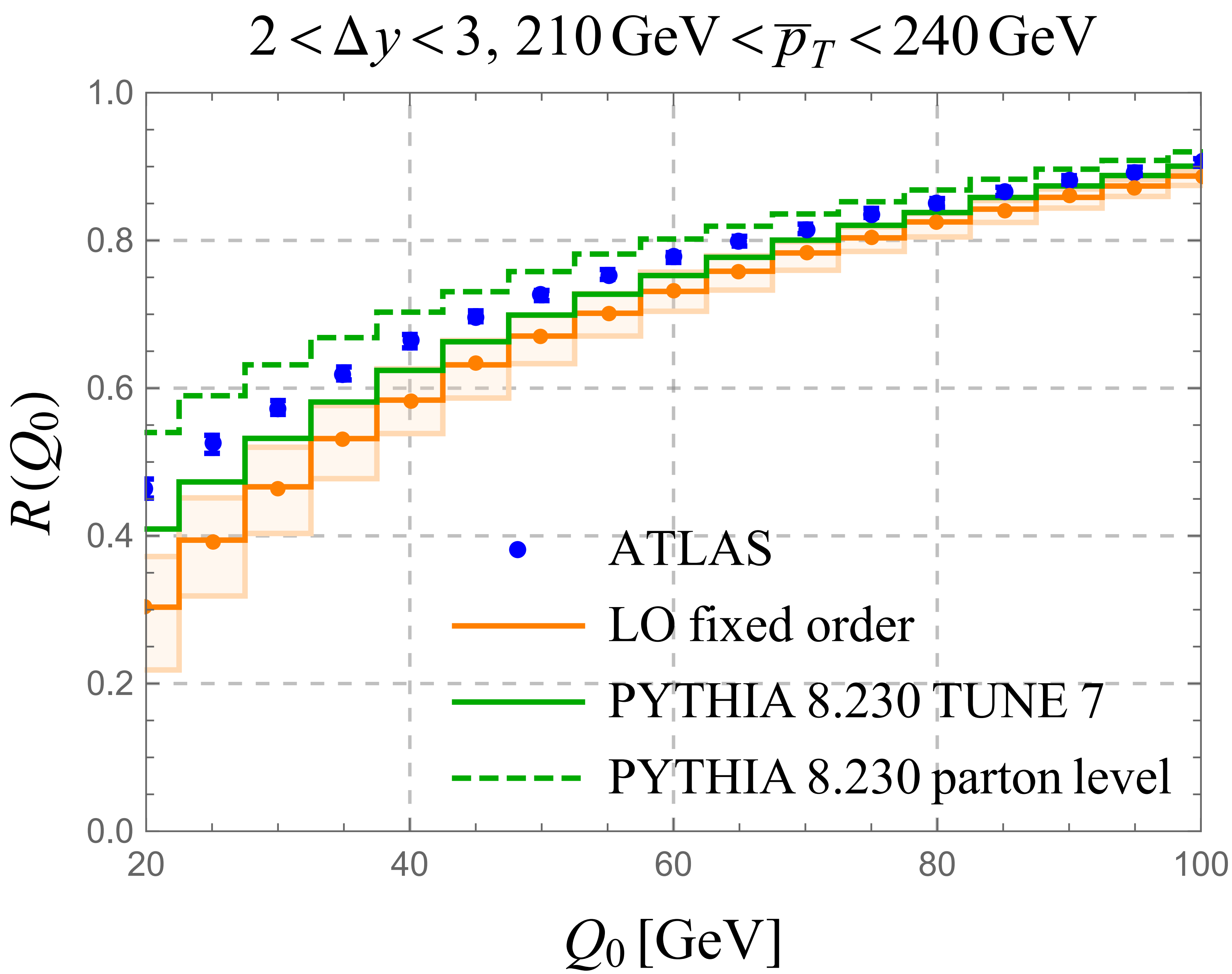
Conclusion and outlook

- For non-global observables, we obtained a parton shower from effective field theory
  - first-principles derivation of shower, based on RG evolution
  - flexible implementation of shower using MG5_aMC@NLO
  - To resum NLLs, one should include higher-order corrections to the anomalous dimension matrix and matching coefficients
  - when the veto region is small, NGLs are enhanced due to dependence on the size of the veto region
- (Finite N_c) + Glauber + non-global = super-leading log
  - interesting to understand in EFT framework Rothstein & Stewart '16

Thank you

Backup Slides

Fixed order and MC results



Dasgupta-Salam shower from EFT

$$
\begin{aligned}
-\frac{1}{\sigma_0}\frac{d}{dt}\sigma_{\text{veto}} = &\int_\Omega \mathbf{3}_{\text{out}} \left[V_2\, e^{-tV_2}\right] \frac{R^3_{12}}{V_2} \\
&+ \int_\Omega \mathbf{4}_{\text{out}} \mathbf{3}_{\text{in}} \int_0^t dt' \left[V_2\, e^{-t'V_2}\right] \frac{R^3_{12}}{V_2} \left[V_3\, e^{-(t-t')V_3}\right] \frac{R^4_{132}}{V_3} \\
&+ \int_\Omega \mathbf{5}_{\text{out}}\, \mathbf{4}_{\text{in}}\, \mathbf{3}_{\text{in}} \int_0^t dt' \int_0^{t'} dt'' \left[V_2\, e^{-t''V_2}\right] \frac{R^3_{12}}{V_2} \left[V_3\, e^{-(t'-t'')V_3}\right] \frac{R^4_{13}}{V_{13}} \\
&\qquad \times \left\{ \frac{V_{13}}{V_3} \left[V_4^{(1)}\, e^{-(t-t')V_4^{(1)}}\right] \frac{R^5_{1432}}{V_4^{(1)}} + \frac{V_{32}}{V_3} \left[V_4^{(2)}\, e^{-(t-t')V_4^{(2)}}\right] \frac{R^5_{1342}}{V_4^{(2)}} \right\} \\
&+ \cdots\,,
\end{aligned}
\tag{B.12}
$$