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Soft-Collinear Effective Field Theory

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Soft-Collinear Effective Theory (SCET)

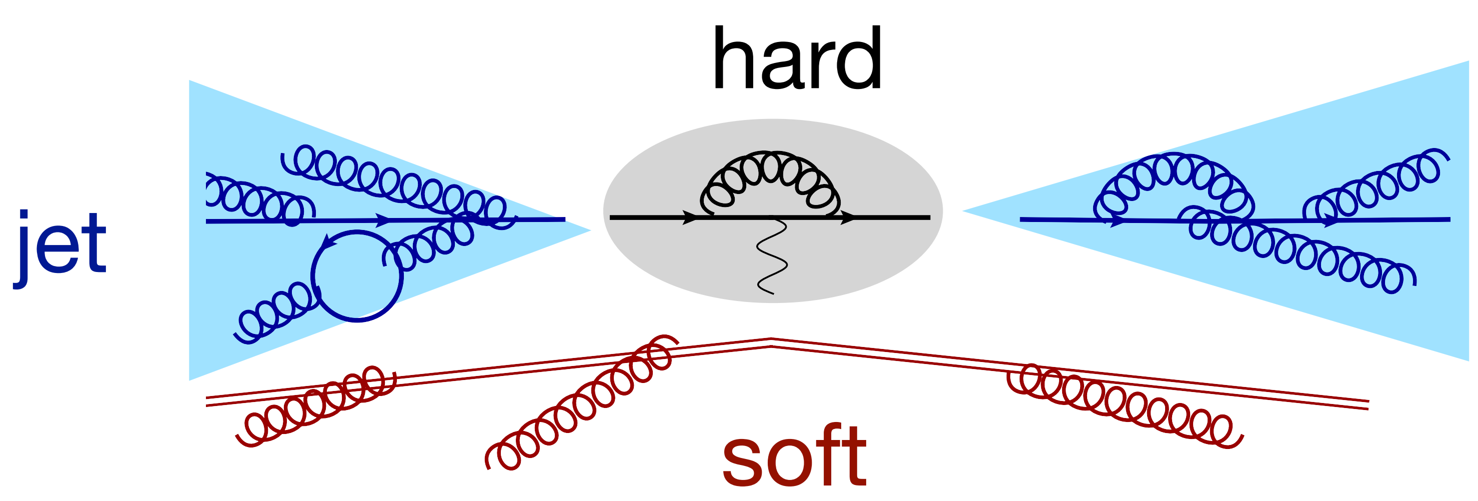
Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke, Diehl et al. 2002; ...

An effective field theory for processes with energetic particles

Hard } **high-energy**

Collinear *fields*

Soft *fields* } **low-energy part**



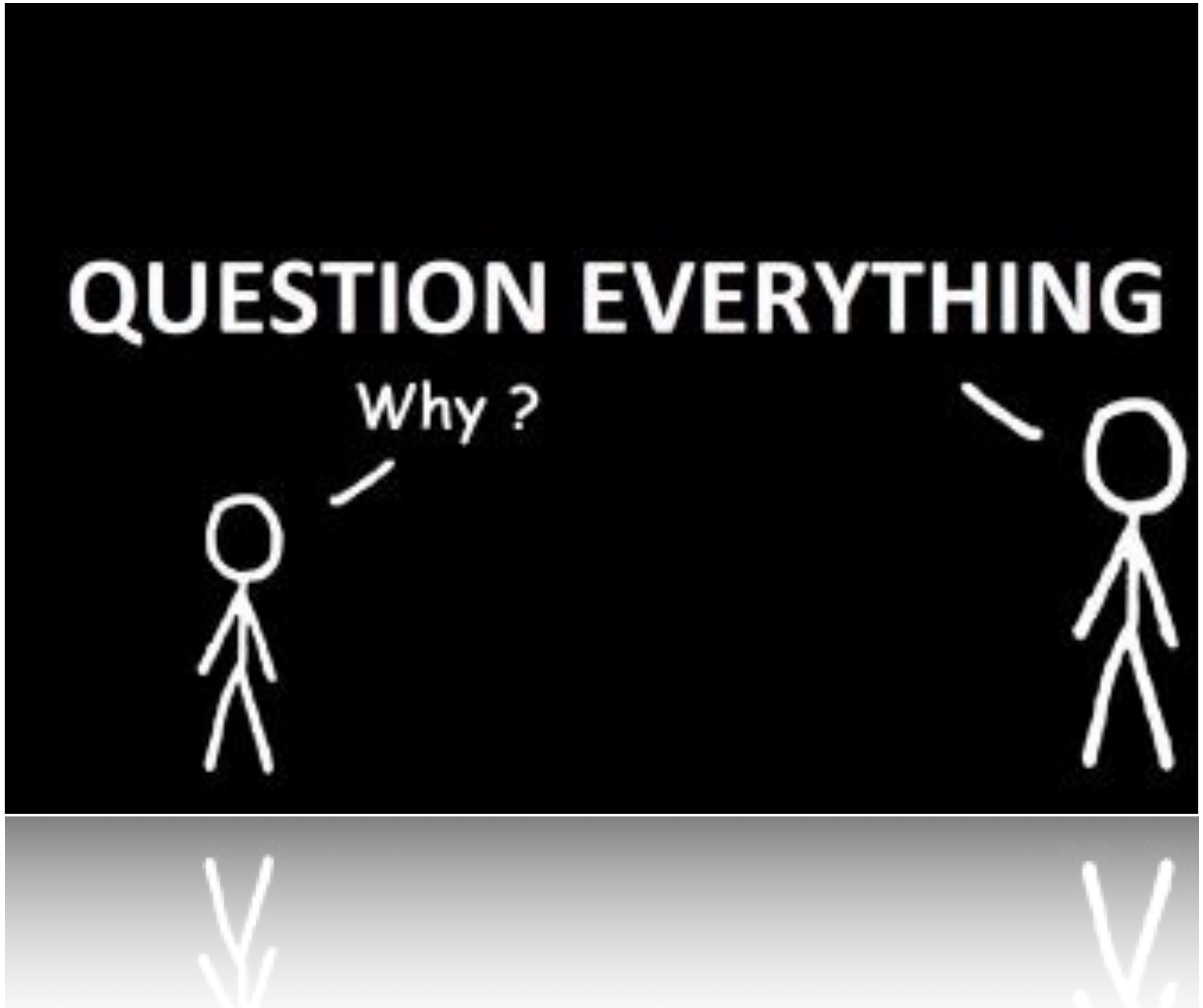
Allows one to analyze factorization of cross sections and perform resummations of large Sudakov logarithms.

Disclaimer

- $O(70)$ papers over the past year
  - SCET is now a standard method to perform resummations
- To be semi-coherent I will focus on a small number of them
  - for more on Higgs, see talk by Lorena Rothen
- Among other things, I will leave out all results concerning
  - QED
  - heavy-ion physics
  - B-physics → talk by Roman Zwicky

Overview

- Philosophical considerations
    - Logs, SCET and QCD
- Theoretical progress
    - Glauber gluons
    - Non-global logarithms
- Applications
    - N^3LL for q_T, NNLL for m_J, m_t^{MC} , ...



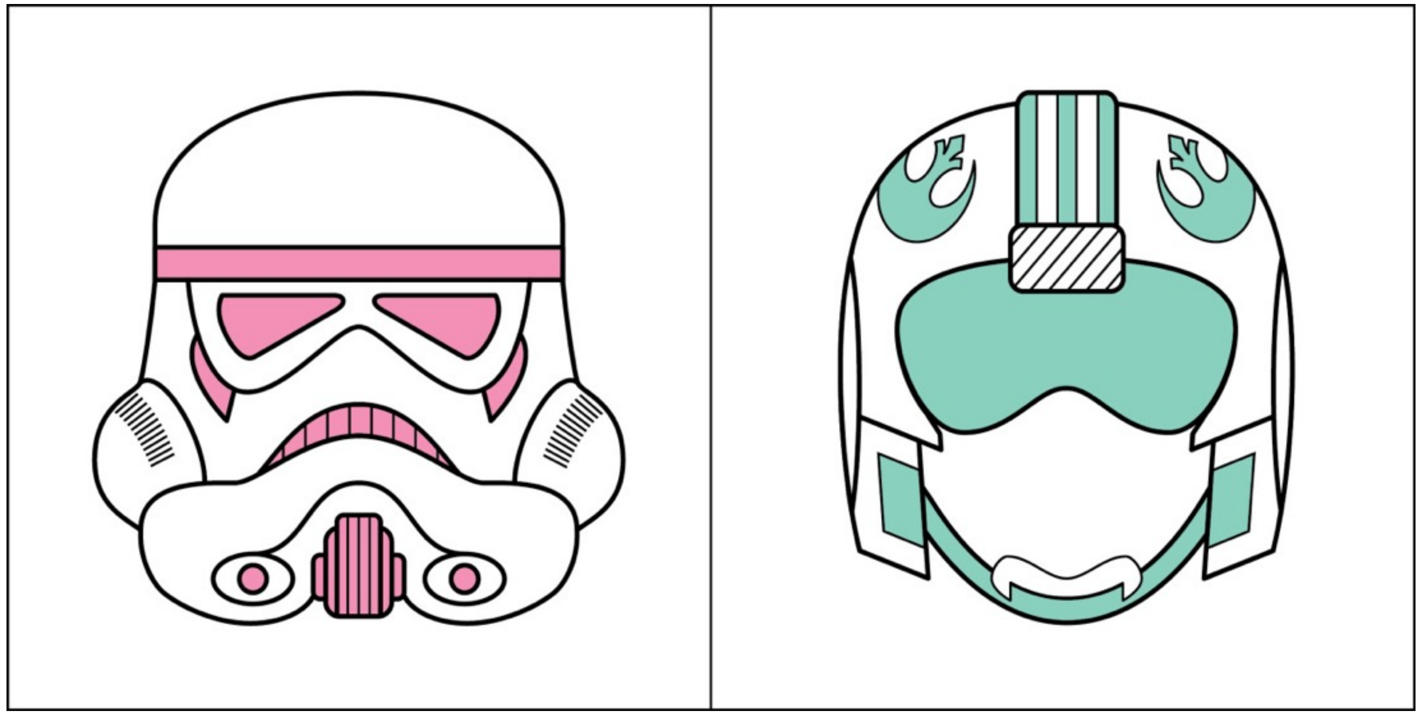
Philosophical considerations

There is an rich and interesting interplay of soft and collinear physics

- threshold logarithms
- rapidity logarithms
- non-global logarithms
- super-leading logarithms
- small-x logarithms
- Reggeization

$\rightarrow$ SCET is a framework of EFTs

However, at the end of the day …

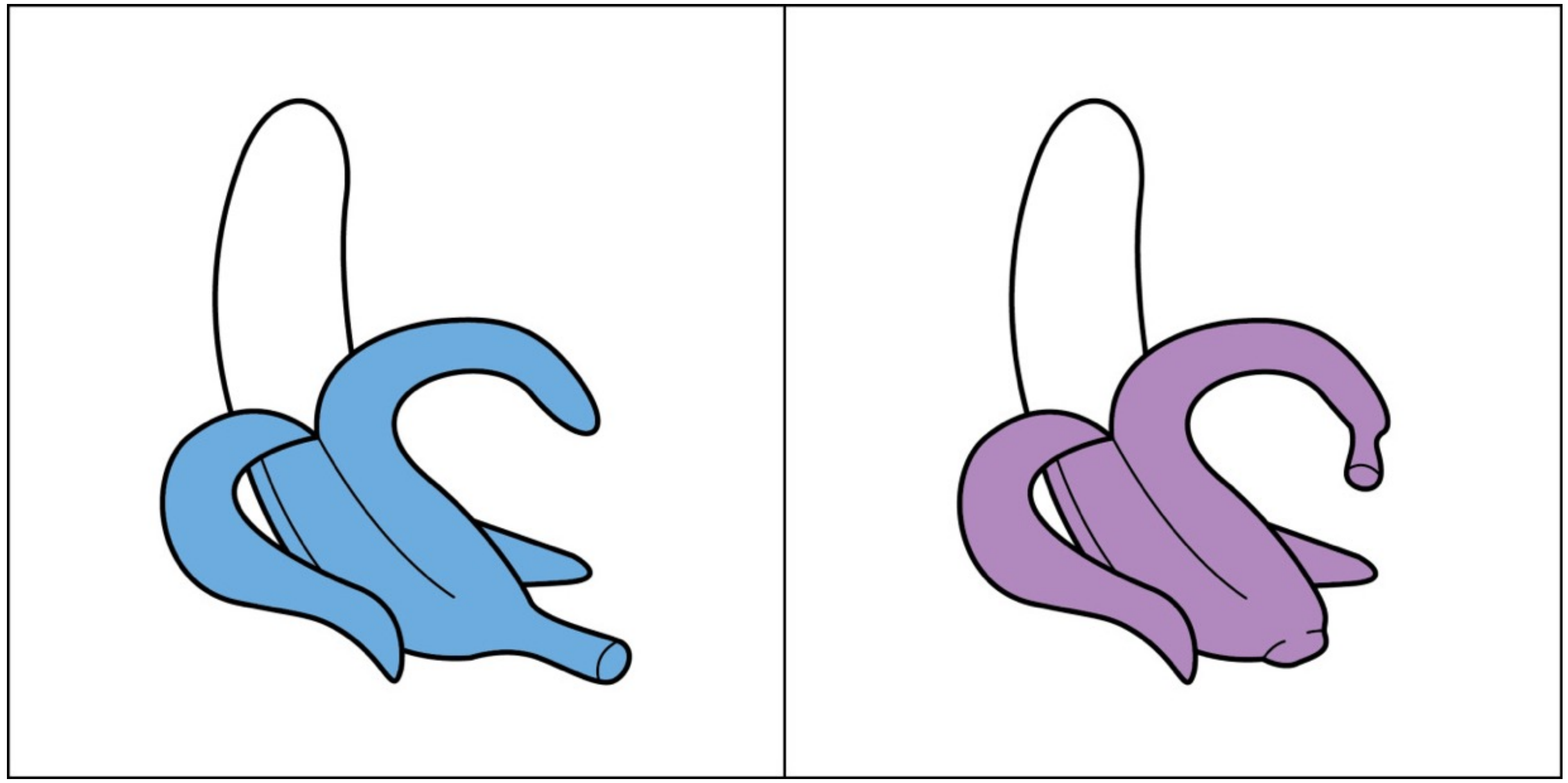


source: http://2kindsofpeople.tumblr.com

…there are only two kinds of logarithms:

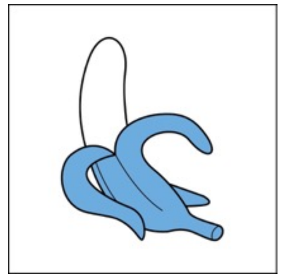
1. the ones we know how to resum
2. those we don't know *yet*

The logarithms in perturbative cross sections are independent of the method used to resum them.

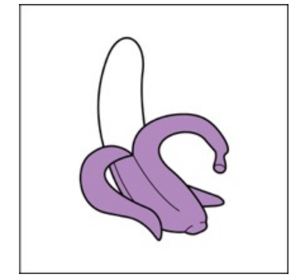


Two general approaches to resummation:

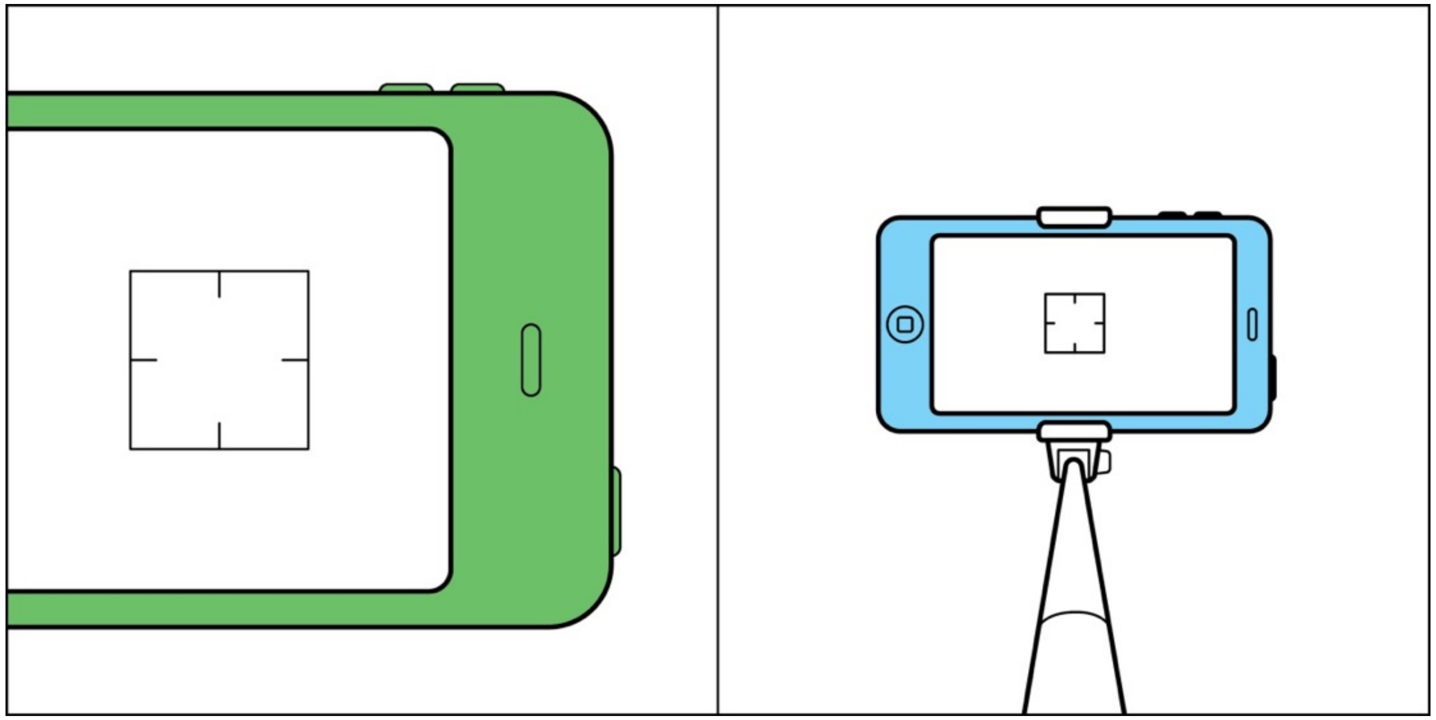
1. Top down: approximations of all-order factorization theorems. CSS, SCET, …
2. Bottom up: corrections to coherent branching. PS, CAESAR, ARES, …



versus



- Top down (CSS, SCET, …)
  - All-order structure manifest: immediately clear how to increase accuracy
  - Observable specific (but same structure for many)
- Bottom up (PS, CAESAR, ARES, …)
  - Simplifications at a given accuracy (e.g. LL and NLL structure much simpler than full fact. theorem)
  - Lends itself to automation and MC implementation
  - Higher-log resummation also for cases where factorization theorem is not available

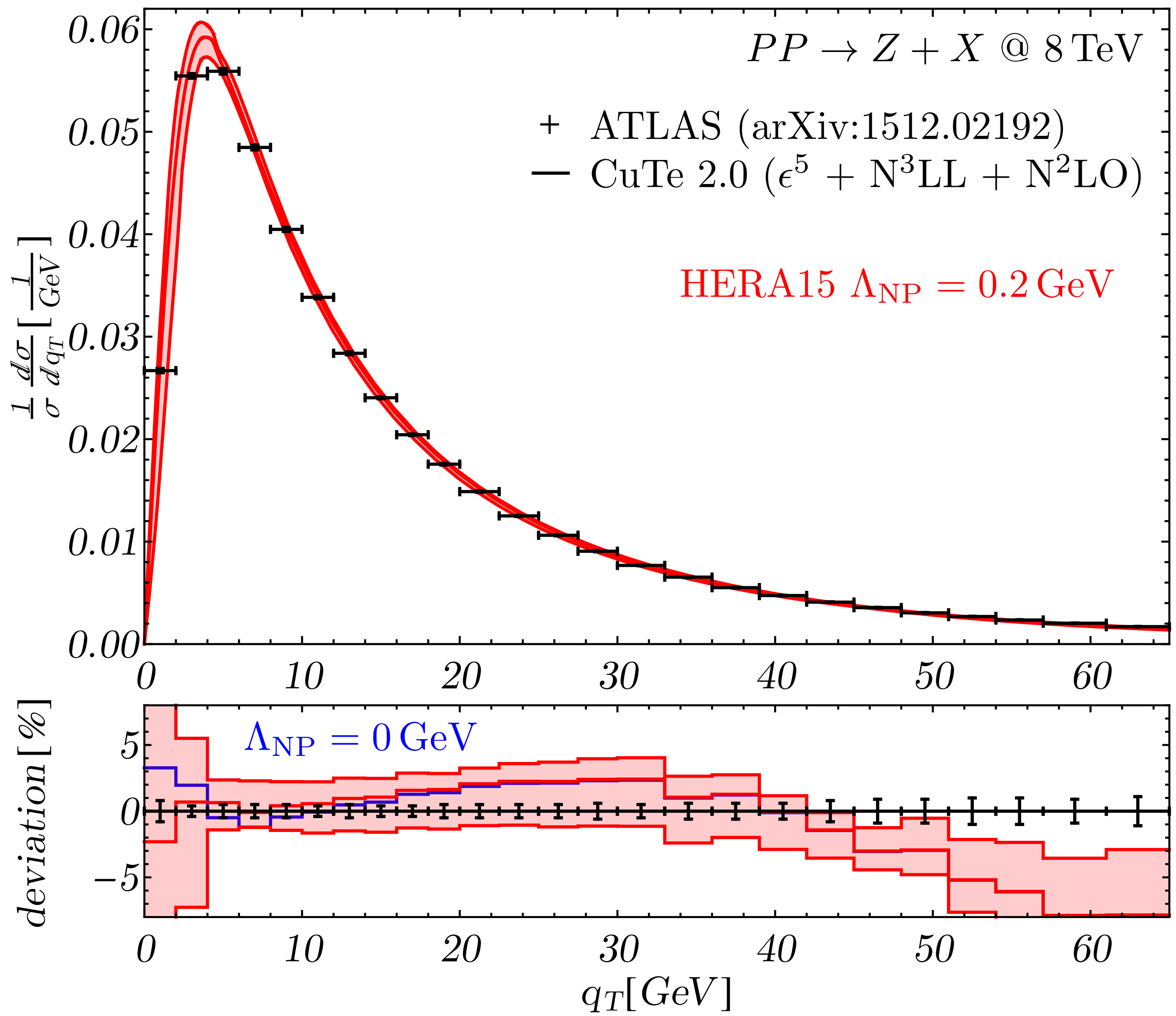


Two kinds of logarithms:

1. large ones
2. others

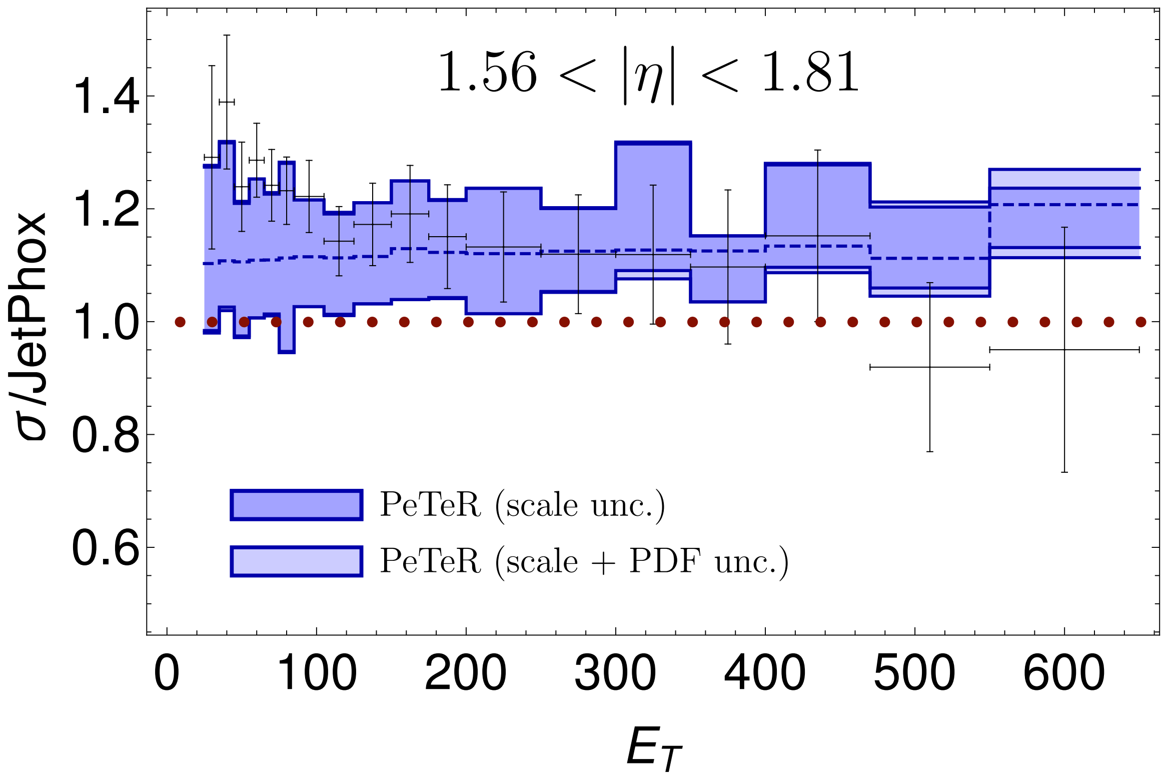
Large logs: e.g. q_T resummation

CuTe 2.0 TB, Lübbert, Neubert, Wilhelm



Cannot use fixed-order computation in peak region.

Not so large logs: threshold resummation



$pp \longrightarrow \gamma + j$

ATLAS '16
Schwartz '16

PeTeR (TB, Bell, Marti, Lorentzen) result contains NLO from Jetphox plus

- full NNLO virtual effects
- approximate NNLO real emissions
- + EW effects TB, Garcia i Tormo

Inclusive cross section. Fixed order is applicable. Should eventually upgrade to full NNLO!

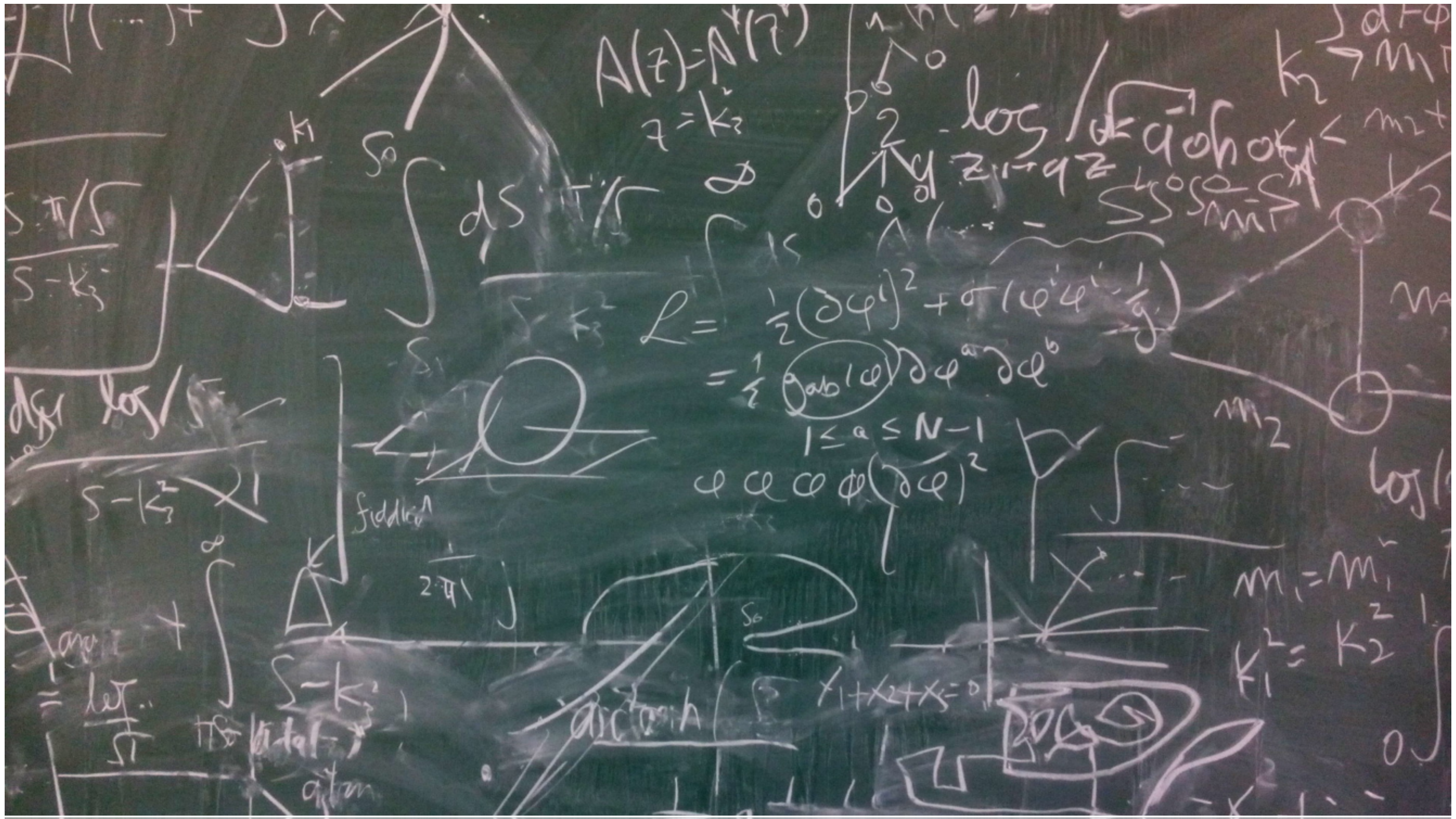
Two applications of SCET et al.

1. resummation
2. expansion around soft and collinear limit

Expansion simplifies cross section and its computation

- Approximate higher-order computations:
  - threshold resummation
  - NNLO and N^3LO Higgs cross section first computed in an expansion around soft limit
- Slicing and subtraction schemes

Useful applications even when logs are not large!



Theoretical progress

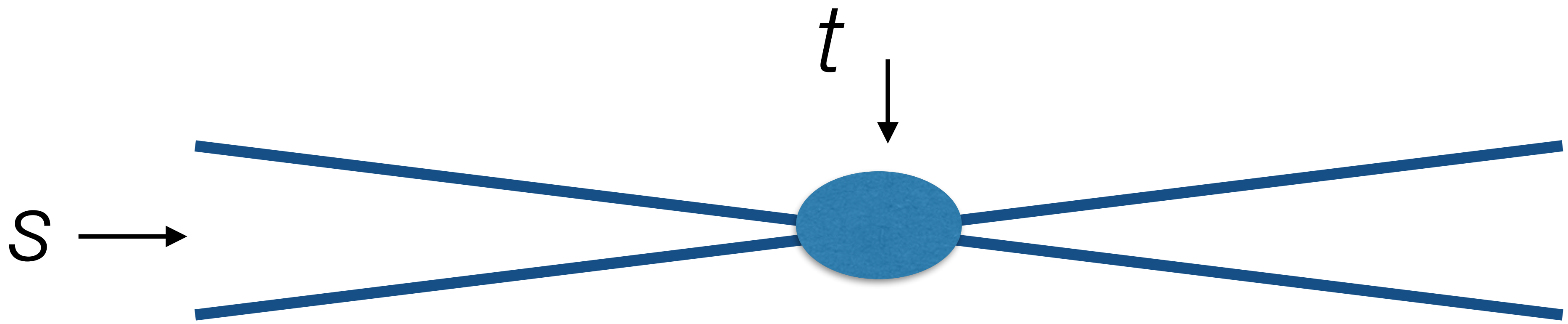
Theoretical progress

For the past few years, the most important open issues in SCET (and also in direct resummation) were

1. Forward scattering, Glauber gluons, factorization violation in hadronic collisions
2. Resummation for non-global observables

A lot of progress in both areas during the past year! Effective field theories to analyze both kinematical situations are now available.

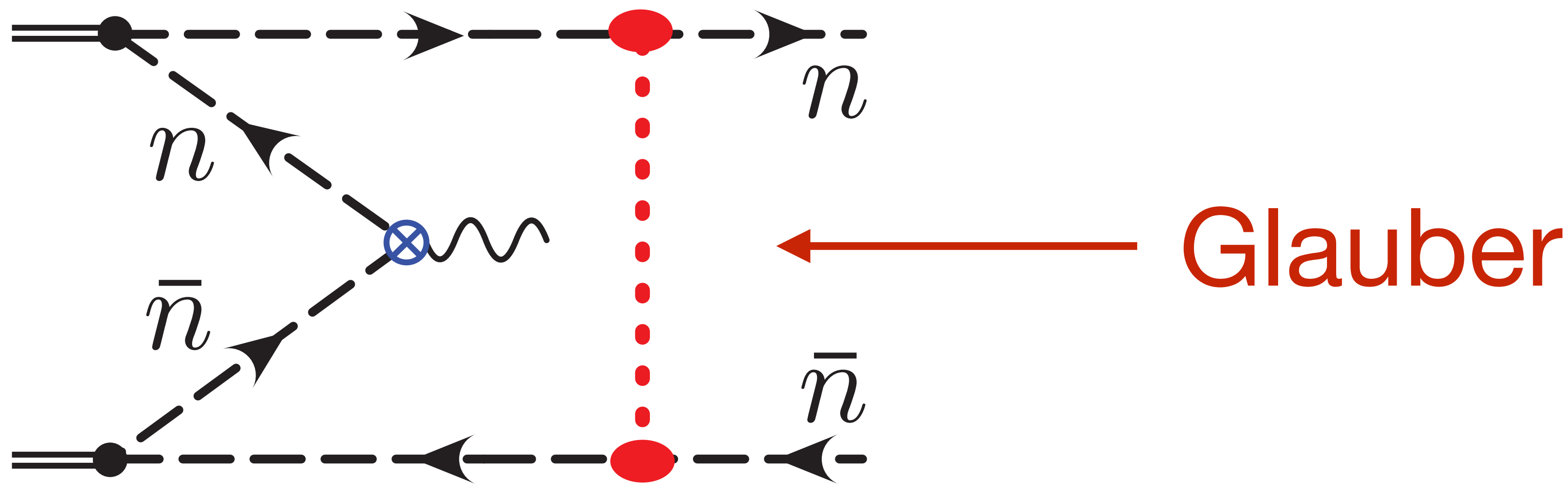
Forward scattering



For $s \to \infty$ there are large logarithms $\alpha_s^n \ln^n(s/-t)$

- Reggeization, BFKL, Glauber gluons, …

Not the same situation as in ordinary SCET, which considers large momentum transfers and small invariant masses.



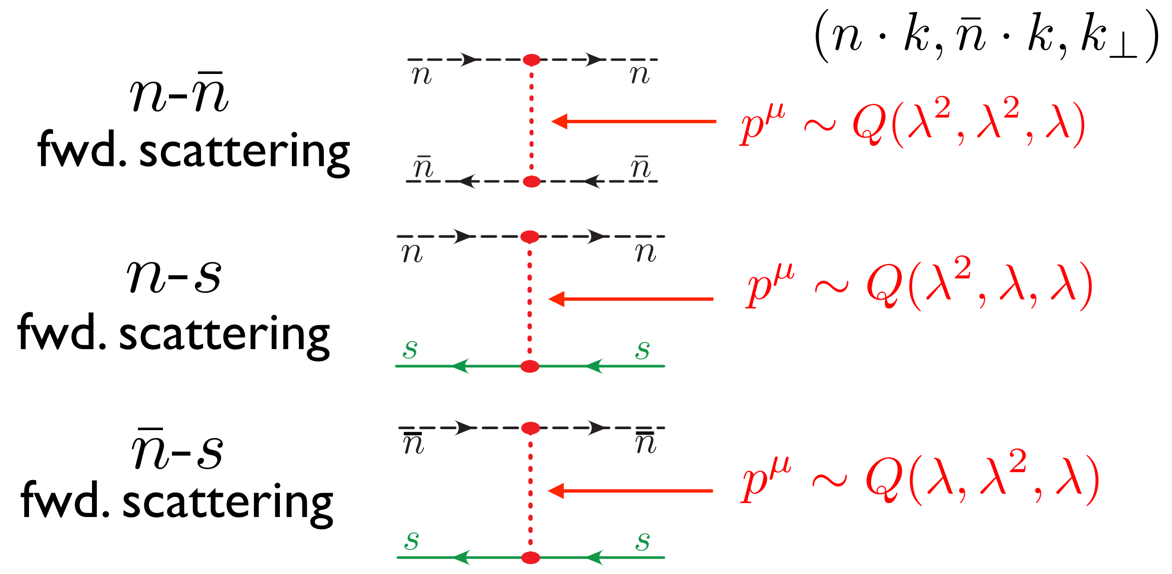
All proton collisions include forward component (proton remnants). EFT for *pp* collisions must describe forward scattering.

- EFT should include Glauber-gluons.
- Absence of factorization-violation due to Glauber gluons is important element of factorization proof for Drell-Yan process.

Technical challenges

- Glauber gluons are offshell
  - $k_T \gg E$, like Coulomb gluons
  - must be included as potential, not dynamical field in $\mathcal{L}_{\rm eff}$
- Glauber region is not well defined without additional rapidity regulator (on top of dim.reg.)
  - separation among soft, collinear and Glauber gluons scheme dependent

Glauber exchanges



- Exploratory studies by several groups (Liu et al., Idilbi et al, Bauer et al. Donoghue et al., Fleming, …).
- This year Rothstein and Stewart published an EFT framework for Glauber exchanges [JHEP 1608 (2016) 025 (204pp!)]

Full Leading Power Glauber Lagrangian:

Rothstein and Stewart '16

$$\mathcal{L}_G^{\mathrm{II}(0)} = \sum_{n,\bar{n}} \sum_{i,j=q,g} \mathcal{O}_n^{iB} \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_s^{BC} \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_{\bar{n}}^{jC} + \sum_{n} \sum_{i,j=q,g} \mathcal{O}_n^{iB} \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_s^{j_n B}$$

sum pairwise on all collinears

Glauber potential

sum on all collinears

- Interactions with more sectors is given by T-products
- No Wilson coefficient ie. no new structures at loop level.

$$\mathcal{O}_n^{qB} = \overline{\chi}_n T^B \frac{\bar{n}\!\!\!/}{2} \chi_n \qquad \mathcal{O}_n^{gB} = \frac{i}{2} f^{BCD} \mathcal{B}_{n\perp\mu}^C \frac{\bar{n}}{2} \cdot (\mathcal{P}+\mathcal{P}^\dagger) \mathcal{B}_{n\perp}^{D\mu}$$

$$\mathcal{O}_{\bar{n}}^{qB} = \overline{\chi}_{\bar{n}} T^B \frac{n\!\!\!/}{2} \chi_{\bar{n}} \qquad \mathcal{O}_{\bar{n}}^{gB} = \frac{i}{2} f^{BCD} \mathcal{B}_{\bar{n}\perp\mu}^C \frac{n}{2} \cdot (\mathcal{P}+\mathcal{P}^\dagger) \mathcal{B}_{\bar{n}\perp}^{D\mu}$$

$$\mathcal{O}_s^{BC} = 8\pi\alpha_s \Big\{ \mathcal{P}_\perp^\mu \mathcal{S}_n^T \mathcal{S}_{\bar{n}} \mathcal{P}_{\perp\mu} - \mathcal{P}_\mu^\perp g \widetilde{\mathcal{B}}_{S\perp}^{n\mu} \mathcal{S}_n^T \mathcal{S}_{\bar{n}} - \mathcal{S}_n^T \mathcal{S}_{\bar{n}} g \widetilde{\mathcal{B}}_{S\perp}^{\bar{n}\mu} \mathcal{P}_\mu^\perp - g \widetilde{\mathcal{B}}_{S\perp}^{n\mu} \mathcal{S}_n^T \mathcal{S}_{\bar{n}} g \widetilde{\mathcal{B}}_{S\perp\mu}^{\bar{n}} - \frac{n_\mu \bar{n}_\nu}{2} \mathcal{S}_n^T i g \widetilde{G}_s^{\mu\nu} \mathcal{S}_{\bar{n}} \Big\}^{BC}$$

$$\mathcal{O}_s^{q_n B} = 8\pi\alpha_s \left(\bar{\psi}_S^n T^B \frac{\bar{n}\!\!\!/}{2} \psi_S^n \right) \qquad \mathcal{O}_s^{g_n B} = 8\pi\alpha_s \left(\frac{i}{2} f^{BCD} \mathcal{B}_{S\perp\mu}^{nC} \frac{\bar{n}}{2} \cdot (\mathcal{P}+\mathcal{P}^\dagger) \mathcal{B}_{S\perp}^{nD\mu} \right)$$

$$\mathcal{O}_s^{q_{\bar{n}} B} = 8\pi\alpha_s \left(\bar{\psi}_S^{\bar{n}} T^B \frac{n\!\!\!/}{2} \psi_S^{\bar{n}} \right) \qquad \mathcal{O}_s^{g_{\bar{n}} B} = 8\pi\alpha_s \left(\frac{i}{2} f^{BCD} \mathcal{B}_{S\perp\mu}^{\bar{n}C} \frac{n}{2} \cdot (\mathcal{P}+\mathcal{P}^\dagger) \mathcal{B}_{S\perp}^{\bar{n}D\mu} \right)$$

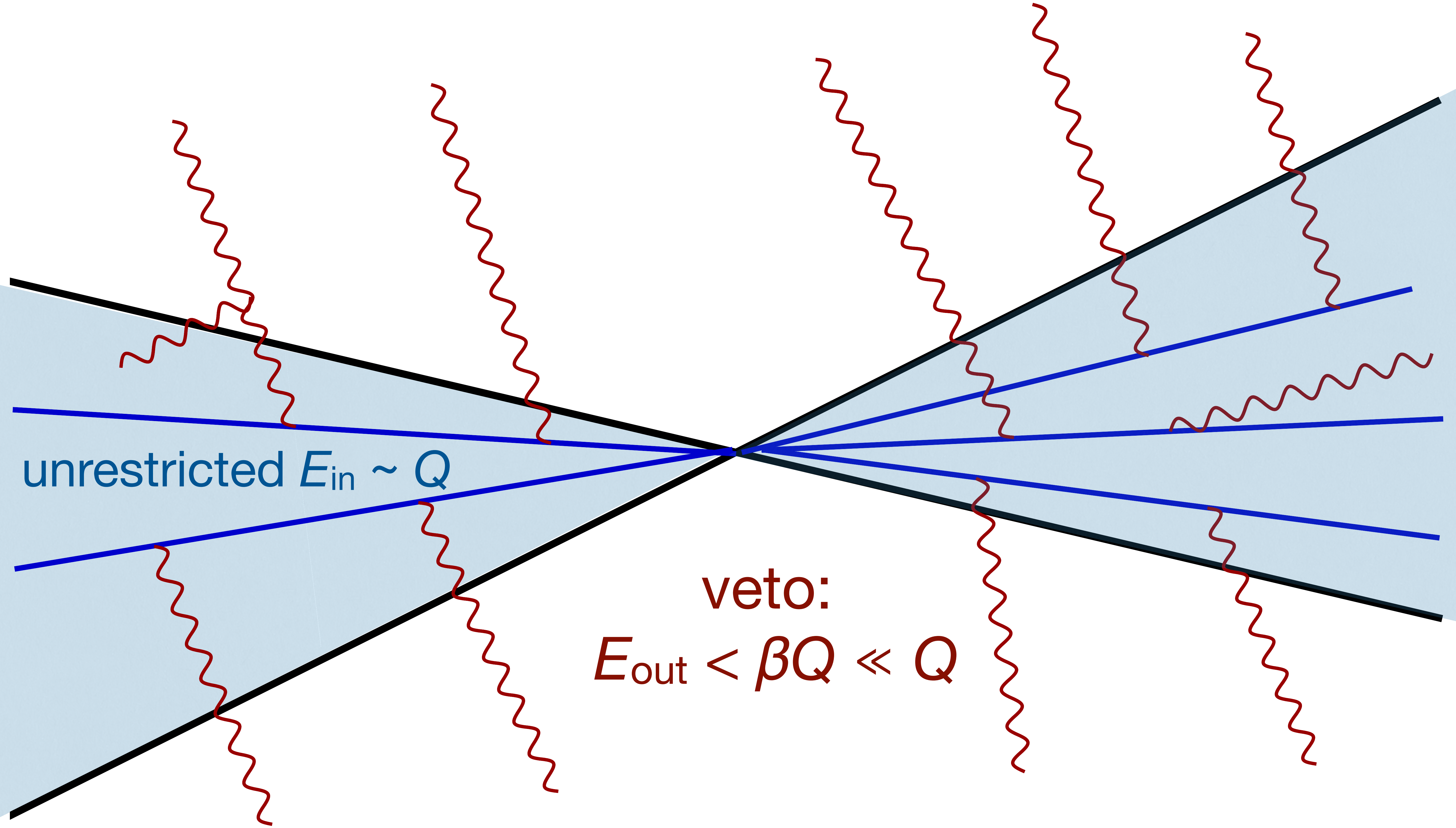
(slide from a talk by I. Stewart)

First applications

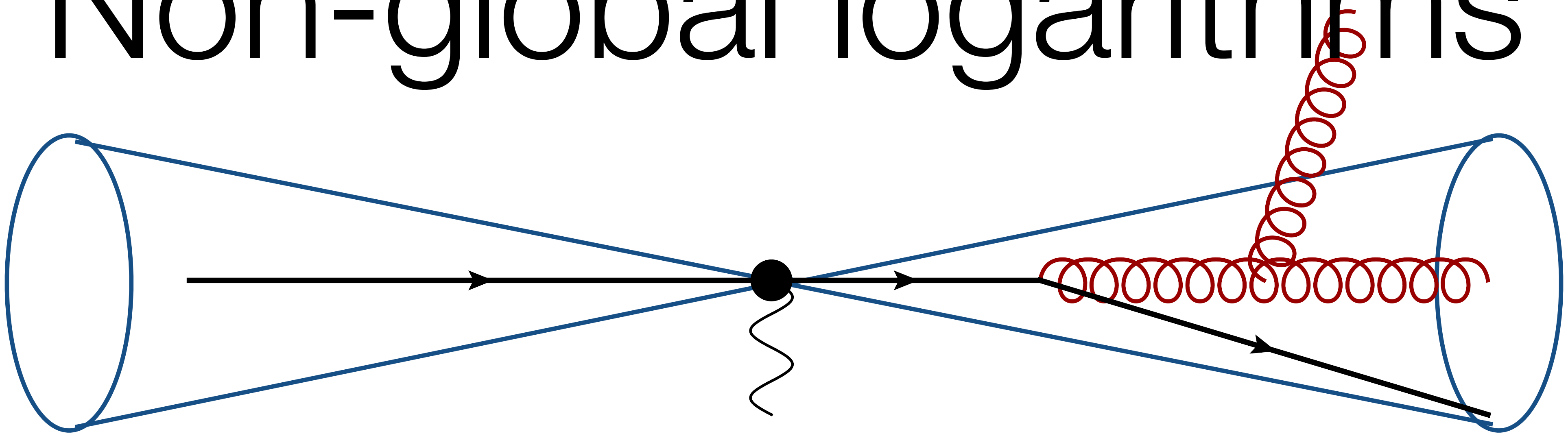
Rothstein and Stewart '16 mostly focus on the construction of $\mathcal{L}_{\text{eff}}$, but have used their framework to reproduce some classic results in this area

- Reggeization
- BFKL from (rapidity) renormalization group
- Lipatov vertex
- Glauber exponentiation, eikonal phase in *pp* scattering

Non-global observables



Non-global logarithms



Large logarithms $\alpha_s^n \ln^m(\beta)$ in non-global observables do not exponentiate Dasgupta and Salam '02.

Leading logarithms at large N_c can be obtained from non-linear integral equation

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

Banfi, Marchesini, Smye '02

Many examples of non-global observables

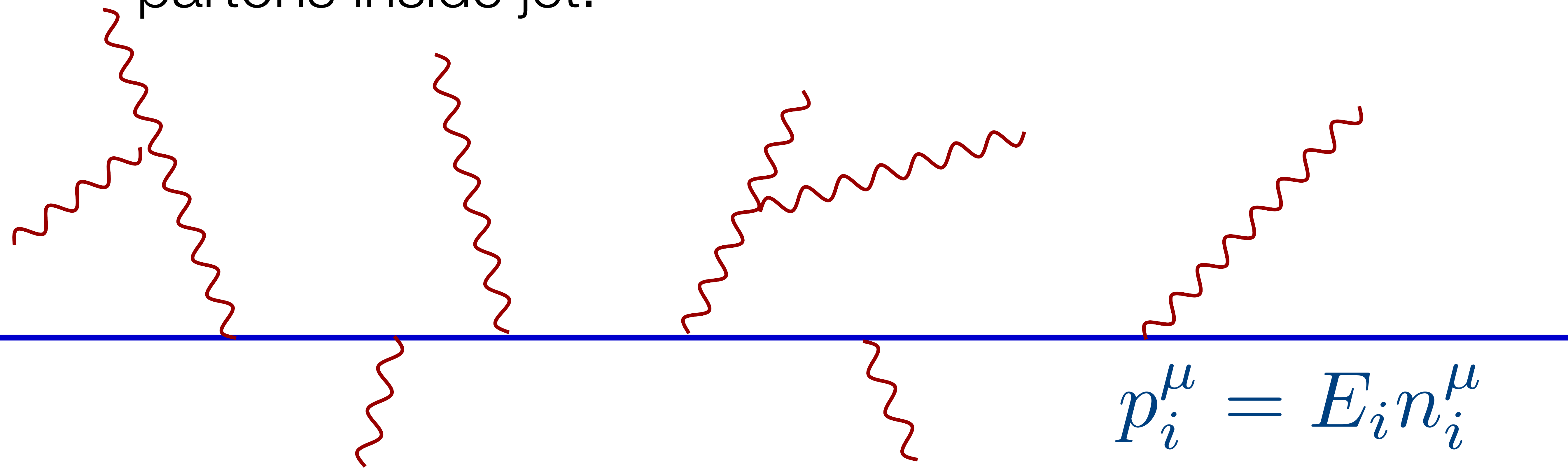
- Exclusive jet cross sections
- Jet vetoes, gaps between jets
- jet substructure
- Event shapes such as the light-jet mass and narrow jet broadening

Resummation of realistic observables, needs to address non-global logarithms! Should either

- resum or
- eliminate / reduce

these logarithms.

Basic physics is soft radiation off energetic partons inside jet.



Wilson line along direction of each hard parton inside the jet.

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

Soft emissions in process with m energetic particles are obtained from the matrix elements of the operator

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

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

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

For a jet of several (nearly) collinear energetic particles, their soft radiation is described by a single Wilson line with the total color charge.

- For non-global observables one cannot combine Wilson lines

Factorization theorem

TB, Neubert, Rothen, Shao ’15 ’16

see also Caron-Huot ‘15

Hard function.
m hard partons along
fixed directions $\{n_1, \ldots, n_m\}$

Soft function
with *m* Wilson lines

$$\sigma(\beta) = \sum_{m=2}^{\infty} \big\langle \boldsymbol{\mathcal{H}}_m(\{\underline{n}\}, Q, \mu) \otimes \boldsymbol{\mathcal{S}}_m(\{\underline{n}\}, Q\beta, \mu) \big\rangle \,;$$

color trace

integration over the *m* directions

Comments

- Infinitely many operators $\mathcal{S}_\mathrm{m}$, mix under RG
- Also for narrow-cone jets, the same type of structure is relevant TB, Neubert, Rothen, Shao ’15 ’16; Chien, Hornig, Lee ‘15

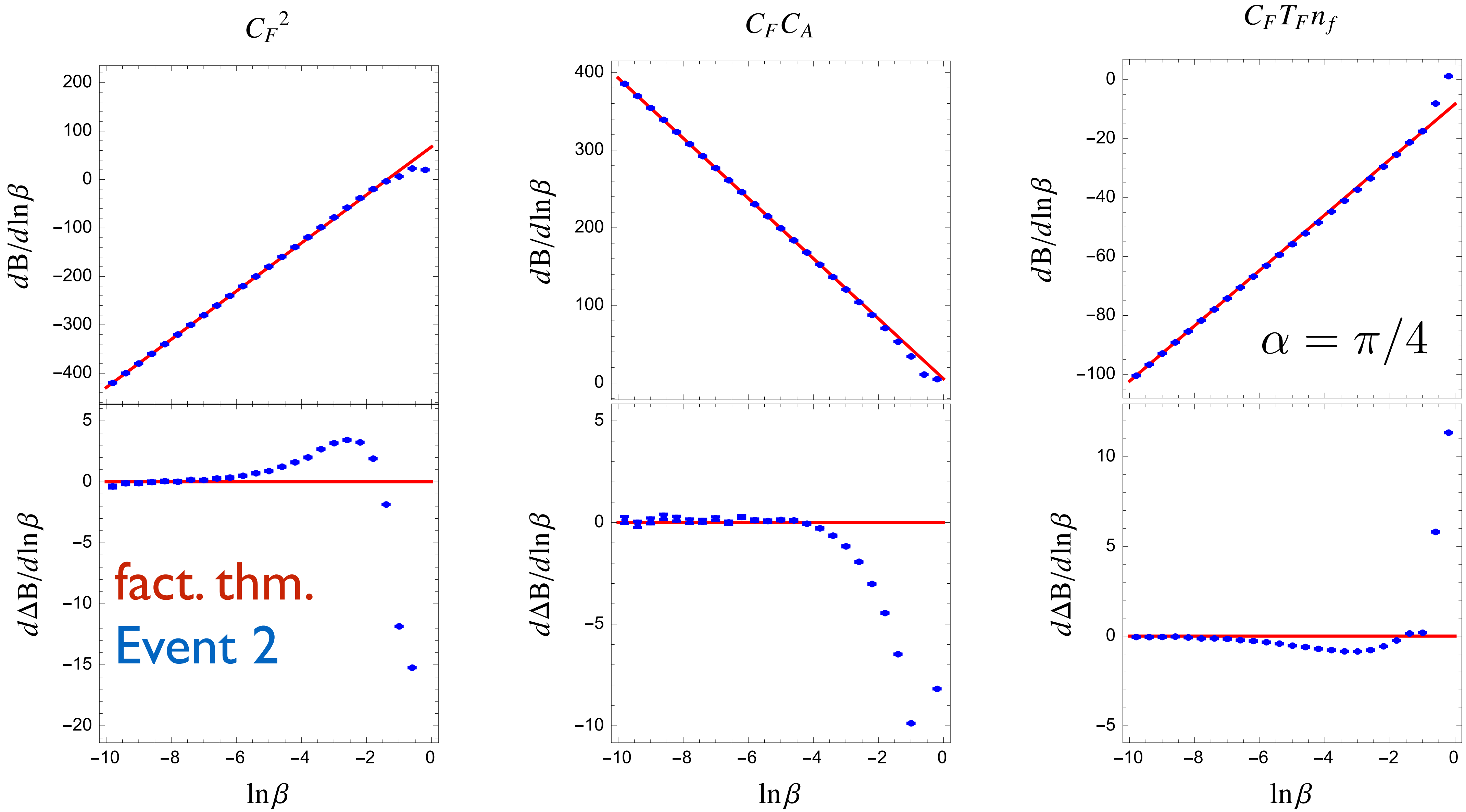
$$\boldsymbol{\mathcal{H}}_m \otimes \boldsymbol{\mathcal{S}}_m \longrightarrow \boldsymbol{\mathcal{J}}_m \otimes \boldsymbol{\mathcal{U}}_m$$

collinear

“coft”
soft+collinear

- **Check:** Have computed all ingredients for cone cross section at NNLO. Obtain full logarithmic structure at this order.

Numerical check against Event 2



- Works: agreement for small β.
- Perform same check also for narrow jets.

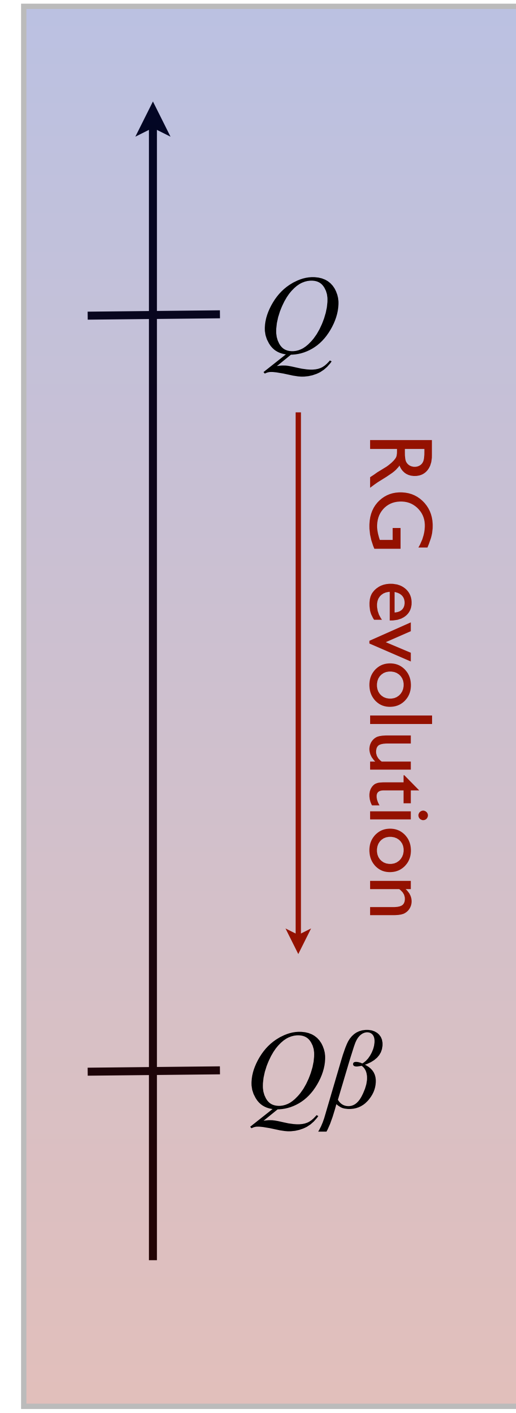
Resummation by RG evolution

Wilson coefficients fulfill renormalization group (RG) equations

$$\frac{d}{d\ln\mu}\boldsymbol{\mathcal{H}}_m(Q,\mu) = -\sum_{l=2}^{m}\boldsymbol{\mathcal{H}}_l(Q,\mu)\,\boldsymbol{\Gamma}^H_{lm}(Q,\mu)$$

1. Compute $\mathcal{H}_\mathrm{m}$ at a characteristic high scale $\mu_h \sim Q$
2. Evolve $\mathcal{H}_\mathrm{m}$ to the scale of low energy physics $\mu_l \sim Q\beta$

Avoids large logarithms ${\alpha_s}^n \ln^n(\beta)$ of scale ratios which can spoil convergence of perturbation theory.



RG = Parton Shower

- Ingredients for LL

$$\boldsymbol{\mathcal{H}}_2(\mu = Q) = \sigma_0$$
$$\boldsymbol{\mathcal{H}}_m(\mu = Q) = 0 \text{ for } m > 2$$
$$\boldsymbol{\mathcal{S}}_m(\mu = \beta Q) = 1$$

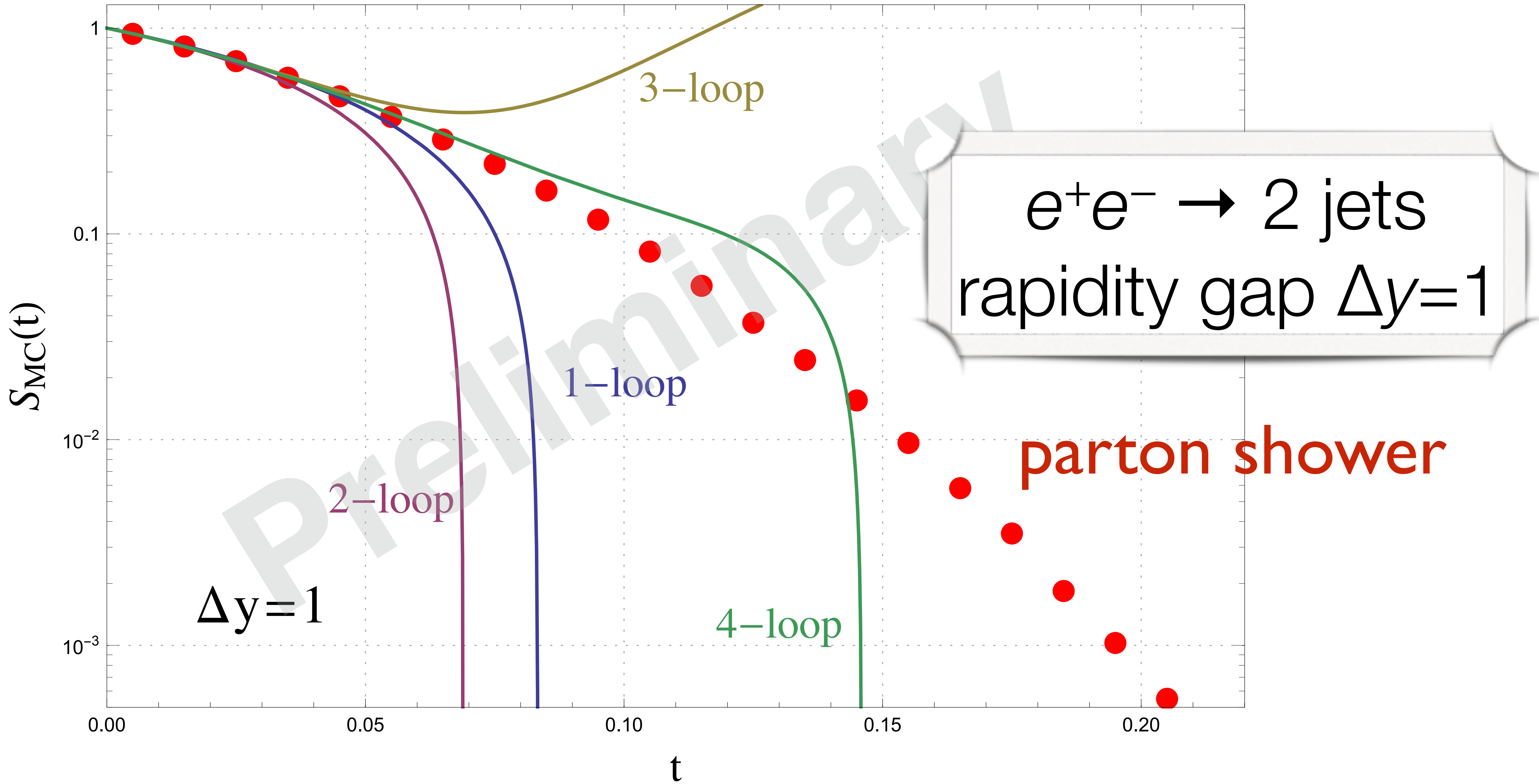
$$\boldsymbol{\Gamma}^{(1)} = \begin{pmatrix} \boldsymbol{V}_2 & \boldsymbol{R}_2 & 0 & 0 & \dots \\ 0 & \boldsymbol{V}_3 & \boldsymbol{R}_3 & 0 & \dots \\ 0 & 0 & \boldsymbol{V}_4 & \boldsymbol{R}_4 & \dots \\ 0 & 0 & 0 & \boldsymbol{V}_5 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- RG

$$\frac{d}{dt}\boldsymbol{\mathcal{H}}_m(t) = \boldsymbol{\mathcal{H}}_m(t)\boldsymbol{V}_m + \boldsymbol{\mathcal{H}}_{m-1}(t)\boldsymbol{R}_{m-1}\,. \qquad t = \int_{\alpha(\mu)}^{\alpha(Q)} \frac{d\alpha}{\beta(\alpha)}\,\frac{\alpha}{4\pi}$$

- Solution is parton shower equation

$$\boldsymbol{\mathcal{H}}_m(t) = \boldsymbol{\mathcal{H}}_m(t_1)e^{(t-t_1)V_n} + \int_{t_1}^{t} dt'\boldsymbol{\mathcal{H}}_{m-1}(t')\boldsymbol{R}_{m-1}e^{(t-t')\boldsymbol{V}_n}$$



- Equivalent to the dipole shower used by Dasgupta and Salam '02.
- For higher-log accuracy we will need to include corrections to $\mathcal{H}_m$, $\mathcal{S}_m$, $\boldsymbol{\Gamma}_{mn}$ into the shower.

NGLs: Status and Outlook

- Have applied formalism to hemisphere soft function and light-jet mass
  - factorization theorems have same general structure as the ones for jet cross sections

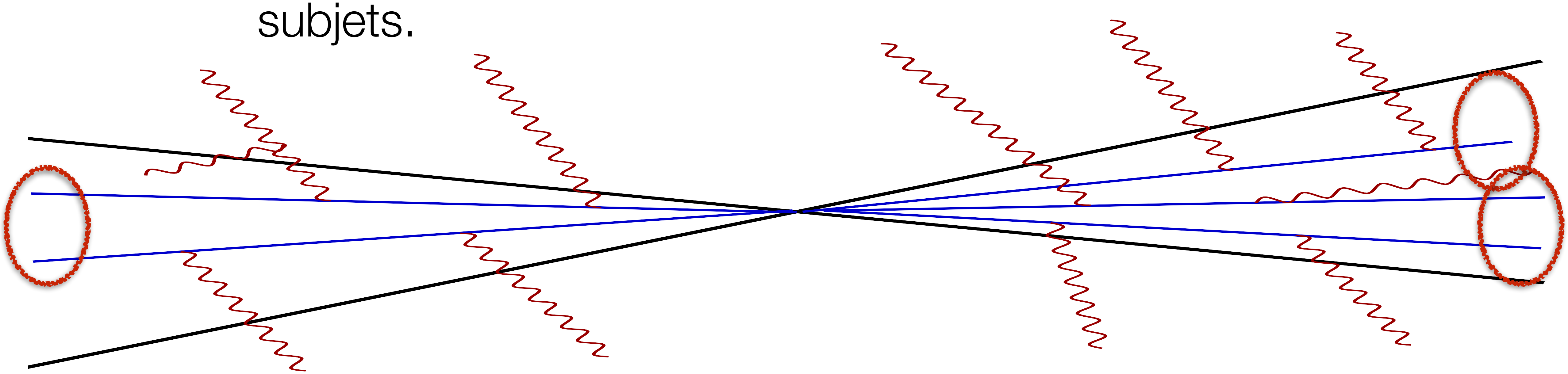
TB, Pecjak, Shao, in preparation

- Are developing MC formalism for higher-log resummation
- Applications …
- Interplay with Glauber gluons? Superleading logs?

Alternative: ``Globalization”

Alternative approach to observables with NGLs based on resummation for substructure. Larkoski, Moult, Neill ‘15

- Divide jet cross section into contributions from *n* sub-jets. Idea is to lower the hard scale in the NGLs by resolving the subjets.



- Resum global logarithms in subjet observables: ``Dressed gluons”.
- At leading-log level, this maps into iterative solution of BMS equation (talk by Ian Moult at LHC-ESI workshop)

Recent SCET Applications

q_T resummation at N^{3}LL

Unknown ingredients at achieve N^{3}LL accuracy

1. Four-loop Γ_{cusp}
2. Three-loop anomaly d_3 *aka* rapidity anomalous dimension γ_r, directly related to B_3 of CSS.

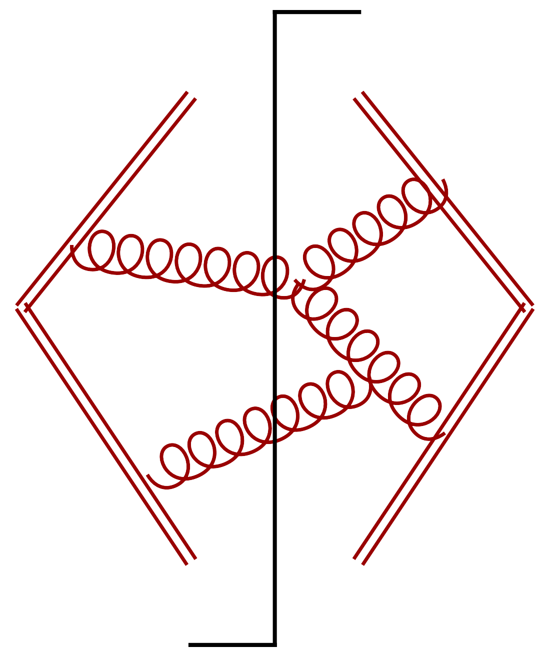
$$\frac{d\sigma}{dq_T dy} = \overset{\Gamma_{\text{cusp}}}{H(M^2,\mu)} \frac{1}{4\pi} \int d^2 x_\perp e^{-iq_\perp \cdot x_\perp} \left(\frac{x_T^2 M^2}{b_0^2}\right)^{-F_{q\bar{q}}(x_T^2,\mu)}$$
$$\times \sum_q e_q^2 \left[B_{q/N_1}\left(z_1, x_T^2, \mu\right) B_{\bar{q}/N_2}\left(z_2, x_T^2, \mu\right) + (q \leftrightarrow \bar{q})\right]$$

Catani, Grazzini et al. ‘12

Gehrmann, Luebbert, Yang ’12 ‘14

Computation of γ_r / d_3 / B_3

Easiest to extract coefficient from a three-loop soft function



Same matrix element as H production near threshold Anastasiou et al., Li et al. '14, but constraint on $p_{X,T}$ instead of E_X.

- $p_{X,T}$ function needs additional regulator

Computation of γ_r / d_3 / B_3

- Interesting to consider *double* differential soft function in E_X and $p_{X,T}$. Li, Neill, Zhu ‘16
  - E_X regularizes rapidity divergences
  - intriguing relations among threshold and q_T soft functions
- Li and Zhu ’16 have computed three-loop double differential soft function
  - make general ansatz, fix coefficients using Taylor expansion

Full three-loop double differential soft function in QCD

$$-\frac{8}{3} C_A^2 C_F \left(H_{1,1}[x] - \frac{H_{1,1}[x]}{x}\right) + \frac{8}{3} C_A C_F n_f \left(H_{1,1}[x] - \frac{H_{1,1}[x]}{x}\right) +$$

Cancel in N=1 SYM

$$C_F^2 n_f \left(-\frac{110}{3} H_{0,1}[x] + 32\,\text{Zeta}[3]\,H_{0,1}[x] - 8 H_{0,0,1}[x] + 8 H_{0,1,1}[x]\right) +$$

$$C_F n_f^2 \left(\frac{400}{81} H_{0,1}[x] + \frac{160}{27} H_{0,0,1}[x] - \frac{160}{27} H_{0,1,1}[x] + \frac{32}{9} H_{0,0,0,1}[x] - \frac{32}{9} H_{0,0,1,1}[x] + \frac{32}{9} H_{0,1,1,1}[x]\right) +$$

$$\begin{aligned} C_A C_F n_f \Big(&-\frac{7988}{81} H_{0,1}[x] + \frac{160}{9} \zeta_2 H_{0,1}[x] - \frac{2312}{27} H_{0,0,1}[x] + \frac{16}{3} \zeta_2 H_{0,0,1}[x] + \\ &\frac{2312}{27} H_{0,1,1}[x] - 16 \zeta_2 H_{0,1,1}[x] - \frac{64}{3} H_{0,0,0,1}[x] + \frac{224}{3} H_{0,0,1,1}[x] + \frac{160}{9} H_{0,1,0,1}[x] - \\ &\frac{32}{9} H_{0,1,1,1}[x] + \frac{80}{3} H_{0,0,0,0,1}[x] + \frac{64}{3} H_{0,0,0,1,1}[x] + 16 H_{0,0,1,0,1}[x] - \frac{64}{3} H_{0,0,1,1,1}[x] + \\ &\frac{16}{3} H_{0,1,0,0,1}[x] - \frac{64}{3} H_{0,1,0,1,1}[x] - \frac{16}{3} H_{0,1,1,0,1}[x] - 64 H_{0,1,1,1,1}[x]\Big) + \end{aligned}$$

$$\begin{aligned} C_A^2 C_F \Big(&\frac{30\,790}{81} H_{0,1}[x] - \frac{1072}{9} \zeta_2 H_{0,1}[x] + 120 \zeta_4 H_{0,1}[x] - 176\,\text{Zeta}[3]\,H_{0,1}[x] + \frac{7120}{27} H_{0,0,1}[x] - \\ &\frac{88}{3} \zeta_2 H_{0,0,1}[x] - \frac{7120}{27} H_{0,1,1}[x] + 88 \zeta_2 H_{0,1,1}[x] - \frac{104}{9} H_{0,0,0,1}[x] + 16 \zeta_2 H_{0,0,0,1}[x] - \\ &\frac{3112}{9} H_{0,0,1,1}[x] + 64 \zeta_2 H_{0,0,1,1}[x] - \frac{1072}{9} H_{0,1,0,1}[x] + 48 \zeta_2 H_{0,1,0,1}[x] - \frac{392}{3} H_{0,1,1,1}[x] + \\ &96 \zeta_2 H_{0,1,1,1}[x] - \frac{440}{3} H_{0,0,0,0,1}[x] - \frac{352}{3} H_{0,0,0,1,1}[x] - 88 H_{0,0,1,0,1}[x] + \frac{352}{3} H_{0,0,1,1,1}[x] - \\ &\frac{88}{3} H_{0,1,0,0,1}[x] + \frac{352}{3} H_{0,1,0,1,1}[x] + \frac{88}{3} H_{0,1,1,0,1}[x] + 352 H_{0,1,1,1,1}[x] + 48 H_{0,0,0,0,0,1}[x] + \\ &128 H_{0,0,0,0,1,1}[x] + 72 H_{0,0,0,1,0,1}[x] + 224 H_{0,0,0,1,1,1}[x] + 40 H_{0,0,1,0,0,1}[x] + 144 H_{0,0,1,0,1,1}[x] + \\ &80 H_{0,0,1,1,0,1}[x] + 256 H_{0,0,1,1,1,1}[x] + 24 H_{0,1,0,0,0,1}[x] + 80 H_{0,1,0,0,1,1}[x] + 56 H_{0,1,0,1,0,1}[x] + \\ &160 H_{0,1,0,1,1,1}[x] + 16 H_{0,1,1,0,0,1}[x] + 96 H_{0,1,1,0,1,1}[x] + 64 H_{0,1,1,1,0,1}[x] + 192 H_{0,1,1,1,1,1}[x]\Big) \end{aligned}$$

Full three-loop double differential soft function in QCD

$$-\frac{8}{3} C_A^2 C_F \left(H_{1,1}[x] - \frac{H_{1,1}[x]}{x}\right) + \frac{8}{3} C_A C_F n_f \left(H_{1,1}[x] - \frac{H_{1,1}[x]}{x}\right) +$$

Cancel in N=1 SYM

$C_F^2 n_f \Big(-\frac{110}{3} H_{0,1}[x$

$C_F n_f^2 \Big(\frac{400}{81} H_{0,1}[x]$

$C_A C_F n_f \Big(-\frac{7988}{81} H_0$

$\frac{2312}{27} H_{0,1,1}[x]$

$\frac{32}{9} H_{0,1,1,1}[x]$

$\frac{16}{3} H_{0,1,0,0,1}[x$

$C_A^2 C_F \Big(\frac{30\,790}{81} H_{0,1}$

$\frac{88}{3} \zeta_2 H_{0,0,1}[x]$

$\frac{3112}{9} H_{0,0,1,1}[x$

$96\, \zeta_2 H_{0,1,1,1}[x$

$\frac{88}{3} H_{0,1,0,0,1}[x$

$128\, H_{0,0,0,0,1,1}$

3-loop coefficient Li and Zhu '16

$$\gamma_0^r = 0$$

$$\gamma_1^r = C_a C_A \left(28\zeta_3 - \frac{808}{27}\right) + \frac{112 C_a n_f}{27}$$

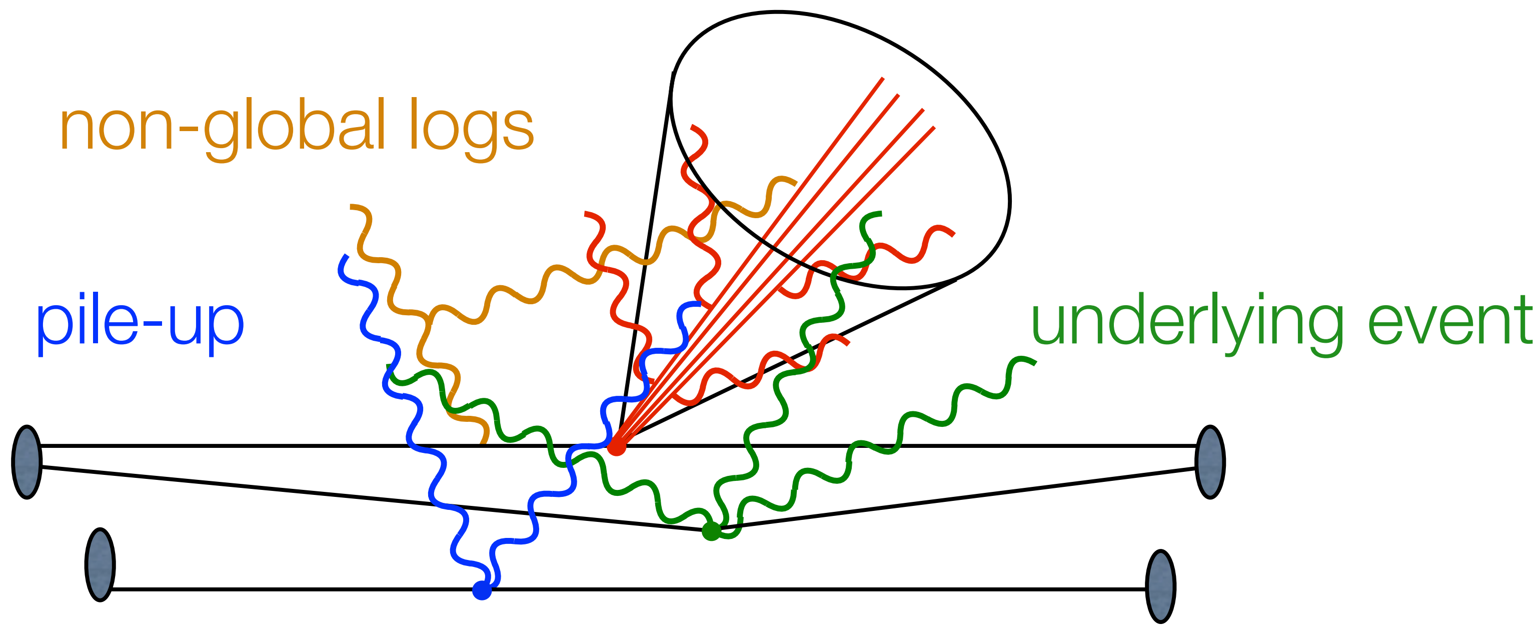
$$\gamma_2^r = C_a C_A^2 \left(-\frac{176}{3}\zeta_3\zeta_2 + \frac{6392\zeta_2}{81} + \frac{12328\zeta_3}{27} + \frac{154\zeta_4}{3} - 192\zeta_5 - \frac{297029}{729}\right) + C_a C_A n_f \left(-\frac{824\zeta_2}{81} - \frac{904\zeta_3}{27} + \frac{20\zeta_4}{3} + \frac{62626}{729}\right) + C_a n_f^2 \left(-\frac{32\zeta_3}{9} - \frac{1856}{729}\right) + C_a C_F N_f \left(-\frac{304\zeta_3}{9} - 16\zeta_4 + \frac{1711}{27}\right)$$

$80\, H_{0,0,1,1,0,1}[x] + 256\, H_{0,0,1,1,1,1}[x] + 24\, H_{0,1,0,0,0,1}[x] + 80\, H_{0,1,0,0,1,1}[x] + 56\, H_{0,1,0,1,0,1}[x] +$

$160\, H_{0,1,0,1,1,1}[x] + 16\, H_{0,1,1,0,0,1}[x] + 96\, H_{0,1,1,0,1,1}[x] + 64\, H_{0,1,1,1,0,1}[x] + 192\, H_{0,1,1,1,1,1}[x] \Big)$

Jet substructure: m_J in $pp \to Z + j$

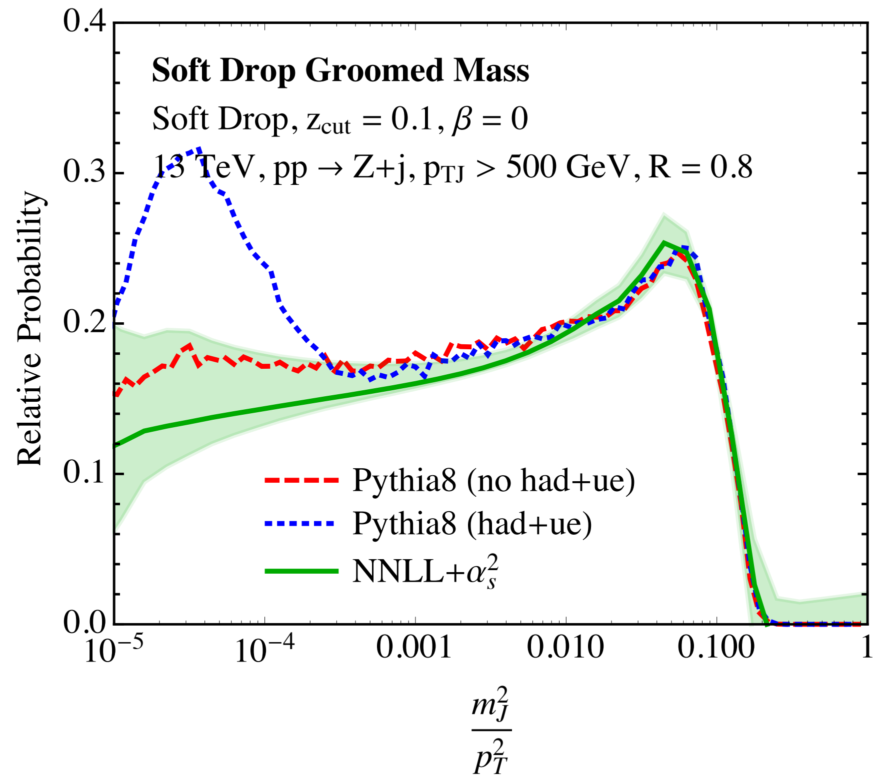
Challenges and contaminations

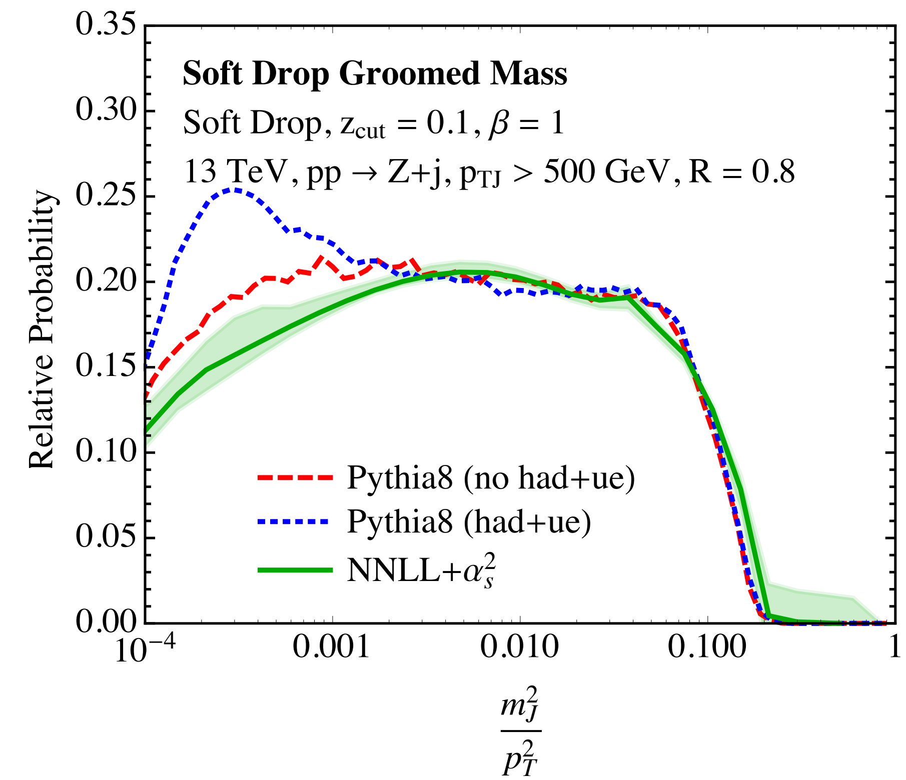


- Grooming can mitigate these problems
- mMDT also eliminates NGLs in m_J
- Analytical NLL Dasgupta, Fregoso, Marzani, Salam '13, Larkoski, Marzani, Soyez,Thaler '14

NNLL + $O(\alpha_s^2)$ for jet mass

Frye, Larkoski, Schwartz, Yan'16





Based on factorization

$$m_J^2 \ll z_{\text{cut}} p_{TJ}^2 \ll p_{TJ}^2$$

$$\frac{d\sigma^{\text{resum}}}{dm_J^2} = \sum_{k=q,\bar{q},g} D_k(p_T, z_{\text{cut}}, R) S_{C,k}(z_{\text{cut}} m_J^2) \otimes J_k(m_J^2)$$

sum over jet flavor

includes pdfs, emissions that were groomed away, out-of-jet radiation,...

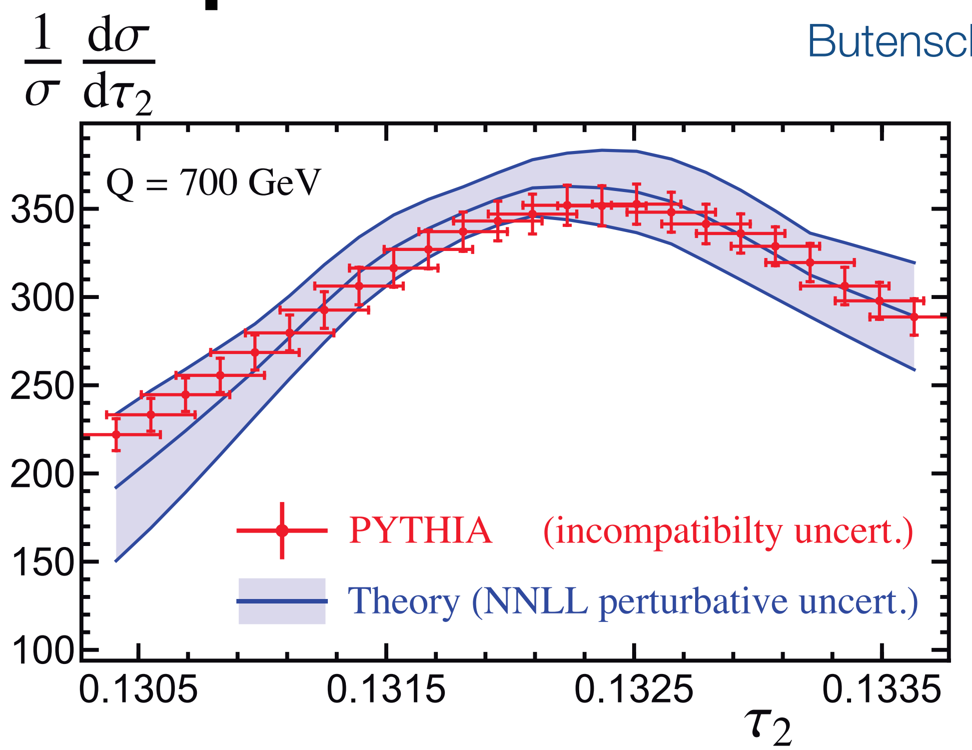
collinear-soft radiation

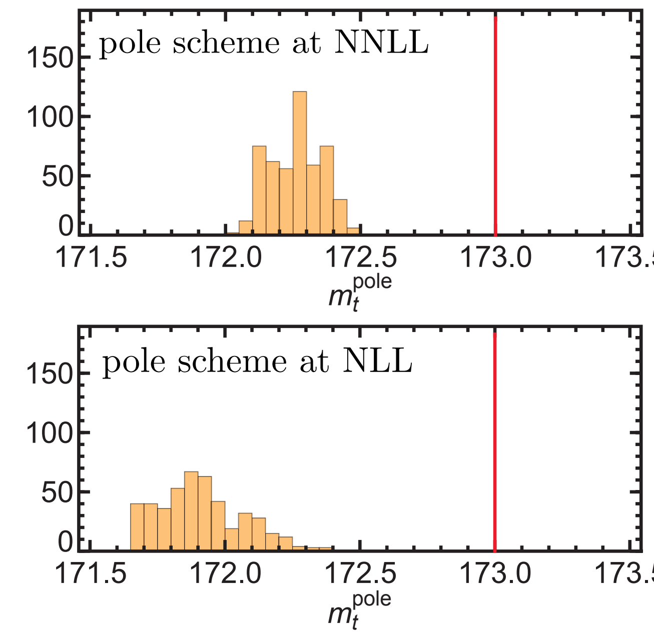
hard collinear radiation

15

Top mass in Pythia?

Butenschoen, Dehnadi, Hoang, Mateu, Preisser and Stewart ‘16





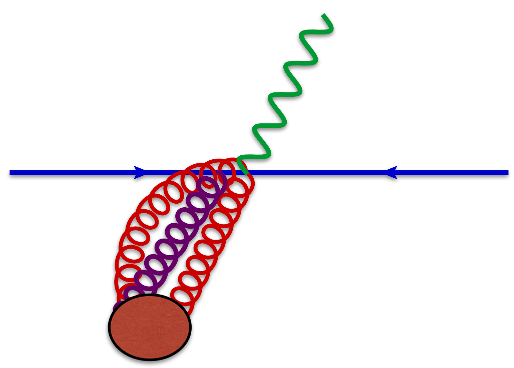
Butenschoen et al. compute NNLL resummed result for thrust event shape in $e^+e^- \to t\bar{t}$

- Exclusive observable, sensitive to m_t
- Compare to MC predictions at different Q and relate Pythia parameter m_t^{MC} to m_t^{pole}
- Universality? Initial state effects at hadron colliders?

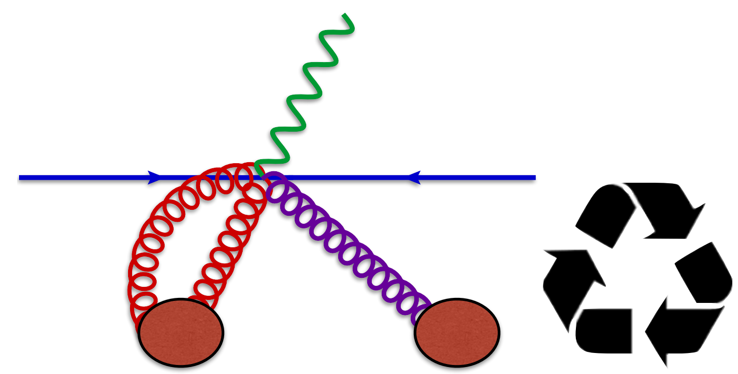
N-jettiness subtraction

Boughezal, Liu, Petreillo 15, Gaunt, Stahlhofen, Tackmann Walsh 15

q_T or τ_N



Two-loop graphs
Soft and collinear
emissions: factorization



NLO

Use event shape τ_N to separate out most singular region of NNLO computations

- Use SCET to compute σ in singular region
- Use existing NLO code away from end-point.

Extension of q_T subtraction Catani, Grazzini '07 to processes with jets in the final state.

N-jettiness subtraction

- Advantage: can use existing NLO codes to obtain NNLO results
  - Already an impressive list of applications H, Z, W, W+j, H+j, Z+j, HZ, HW, $\gamma\gamma$, …
  - MCFM 8 includes NNLO for color neutral final states Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello and Williams ‘16
- Challenge: independence of slicing parameter q_T or τ_N. Parameter needs to be small, but numerical problems if too small.

Automated resummation

- Automated computations of 2-loop soft functions Bell, Rahn and Talbert ‘15
- NNLL for jet veto cross sections, TB, Frederix, Neubert and Rothen ‘15
- NLL for $pp \rightarrow 2$ jets Farhi, Feige, Freytsis and Schwartz ’15
- NNLL soft-gluon resummations for arbitrary distributions. *ttH*, Broggio, Ferroglia, Pecjak, Signer and Yang ‘15. *ttW*, Broggio, Ferroglia, Ossola and Pecjak ’16
- GENEVA results for Drell-Yan process → talk by Christian Bauer

Note: NNLL resummations use automated one-loop computations of hard functions as input.

Jet radius logarithms

A lot of work during the past year

- Inclusive jet cross section Chien, Kang, Ringer and Vitev ’16; Idilbi, Kim ’16; Dai, Kim, Leibovich ‘16
    - based on jet fragmentation function
- Exclusive jet cross sections Chien, Hornig, Lee ’15, Kolodrubetz, Hornig, Makris and Mehen ’16 Pietrulewicz, Stewart, Tackmann and Waalewijn ‘16
    - non-global logarithms are not resummed

Summary

- Important theoretical progress in SCET
  - Inclusion of Glauber gluon effects
  - Resummation for non-global observables
- Many phenomenological applications
  - Higher-logs in q_T-spectra, jet vetos, jet substructure, …
- Efforts to extend higher-log resummation to more observables
  - Automation, factorization for generic scale hierarchies, multi-differential cross sections, …