Title: SCET for precision physics at high and low energies

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Abstract:

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FOR FUNDAMENTAL PHYSICS

SCET for precision physics at high and low energies

Thomas Becher
University of Bern

Radiative Corrections at the Intensity Frontier of Particle Physics
Perimeter Institute, June 12-14 2017

Soft-Collinear Effective Theory (SCET)

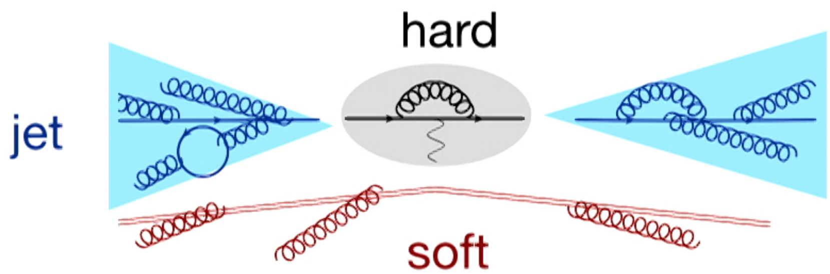
Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke, Diehl et al. 2002; ...

An effective field theory for processes with energetic particles

Hard } **high-energy**

Collinear *fields* } **low-energy part**

Soft *fields*



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

High energy?

What counts is not the energy, but the size of scale ratios, e.g.

M_J/E_J , $p_{T,J}/E_J$, M_π/M_B , $m_e/\sqrt{s}$, …

jets at LHC

$B \to \pi\, l\, \nu$

$e^- p$ scattering, Bhabha, …

Whenever scale ratios are small, effective field theory methods become relevant

- expansion in scale ratios
- resummation of logarithmically enhanced terms

Disclaimer

I have been absent from the intensity frontier for the past ten years. The same is true for most of my colleagues working on SCET: the focus was on jet physics at the LHC.

On the other hand, several topics important at the intensity frontier are currently studied

- electroweak corrections
- expansion in small masses for light, relativistic particles
- factorization of power corrections

The LHC is becoming part of the intensity frontier…

High energy?

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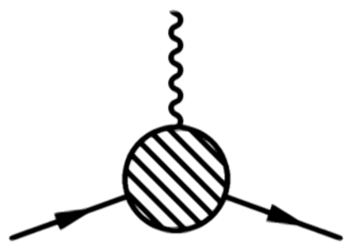
Overview

- Introduction
  - Sudakov logarithms
  - soft and collinear factorization
- Progress in SCET
  - Small m_e expansion for $e^- p$ scattering
  - Power corrections
  - Glauber (Coulomb) gluons
  - Non-global logarithms

Sudakov logarithms

Perturbative corrections to processes with energetic particles are often enhanced by logarithms.

Classic example (Sudakov '56): Dirac form-factor F_1 of electron at large momentum transfer $Q \gg m_e$.

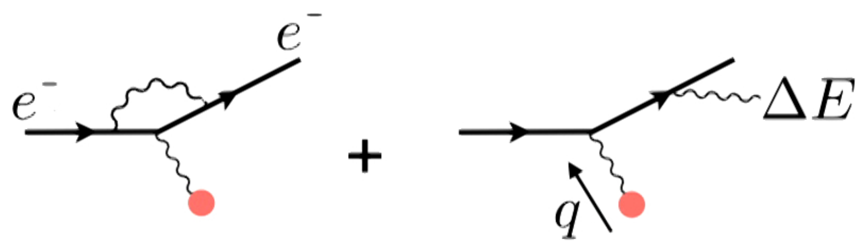


$$F_1 = S(\omega_s, m_e) \exp\left[-\frac{\alpha}{4\pi} \ln^2\left(\frac{m_e^2}{Q^2}\right)\right] + \mathcal{O}\left(\frac{m_e^2}{Q^2}\right)$$

↑ soft radiation ↑ Sudakov log ↑ power corr'n

Large logarithms degrade perturbative expansion, but can often be resummed to all orders.

Sudakov logs in $e^- p$ scattering ®



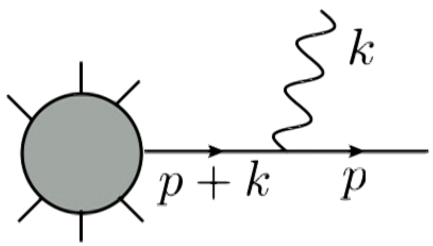
$$|F(q^2)|^2 \to |F(q^2)|^2 \left(1 - \underbrace{\frac{\alpha}{\pi} \log \frac{Q^2}{m_e^2} \log \frac{E^2}{(\Delta E)^2}}_{\approx\, 0.5} + \dots \right)$$

for $Q^2 = -q^2 \approx E^2 \approx (\mathrm{GeV})^2$ and $\Delta E \approx m_e$

Leading logarithms exponentiate and are included in experimental analyses. Subleading corrections such as $\alpha^2 L^3$ are not accounted for. ® ≡ R. Hill 1605.02613

Soft factorization

When particles with small energy and momentum are emitted, the amplitudes simplify:



$$\bar{u}(p)\not{\varepsilon}(k,\lambda)\frac{\not{p}+\not{k}+m}{(p+k)^2-m^2}\cdots$$

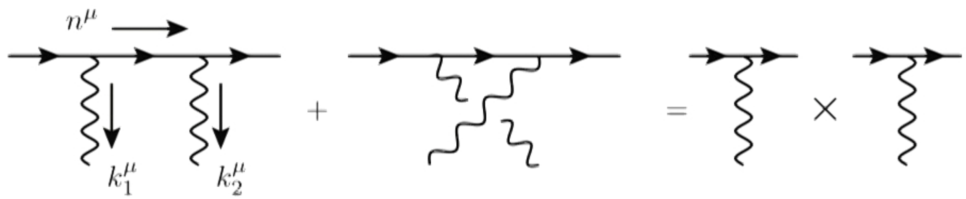
$$\approx \frac{p\cdot\varepsilon(k,\lambda)}{p\cdot k}\bar{u}(p)\ldots$$

Soft emission factors from the rest of the amplitude.

Denominator $p\cdot k = E\,\omega\,(1-\cos\theta)$ leads to logarithmic enhancements at small energy and small angle.

Exponentiation

In QED, eikonal identities



$$\frac{i}{n\cdot(k_1+k_2)}\frac{i}{n\cdot k_1}+\frac{i}{n\cdot(k_1+k_2)}\frac{i}{n\cdot k_2}=\frac{i}{n\cdot k_1}\frac{i}{n\cdot k_2}$$

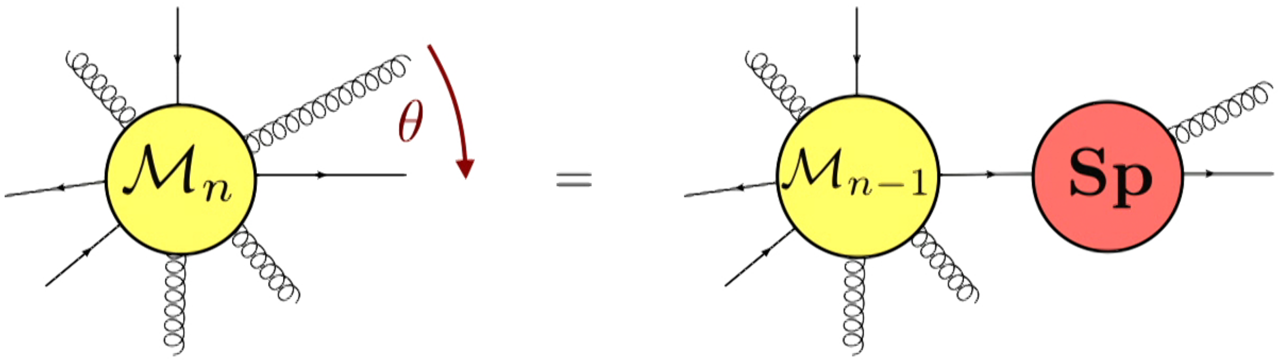
can be used to show that soft photon matrix elements exponentiate (Yennie, Frautschi, Suura '61)

In QCD, soft gluons arrange into Wilson lines

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

but matrix matrix elements nontrivial due to commutator terms

Collinear factorization



In the limit $\theta \to 0$, where the partons become collinear, the n-parton amplitude factorizes into a product of an (n-1)-parton amplitude times a splitting amplitude $\mathbf{Sp}$.

Recently tested at three loops Almelid, Duhr, Gardi, 1507.00047; Henn, Mistlberger 1608.00850

Soft-Collinear Effective Theory (SCET)

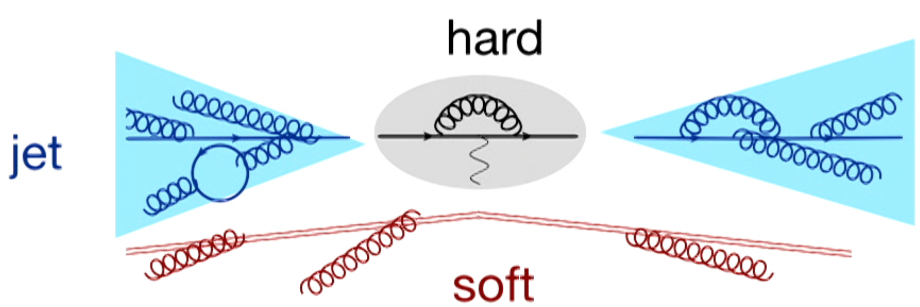
Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke, Diehl et al. 2002; ...

Factorization implemented on the operator level.

Hard } **high-energy**

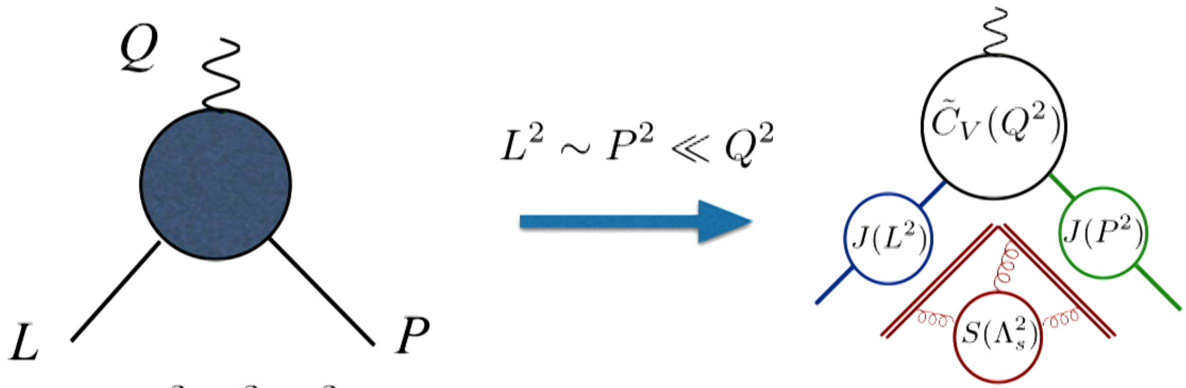
Collinear *fields*

Soft *fields* } low-energy part



Use renormalization group evolution in SCET for resummation.

Off-shell Sudakov form factor



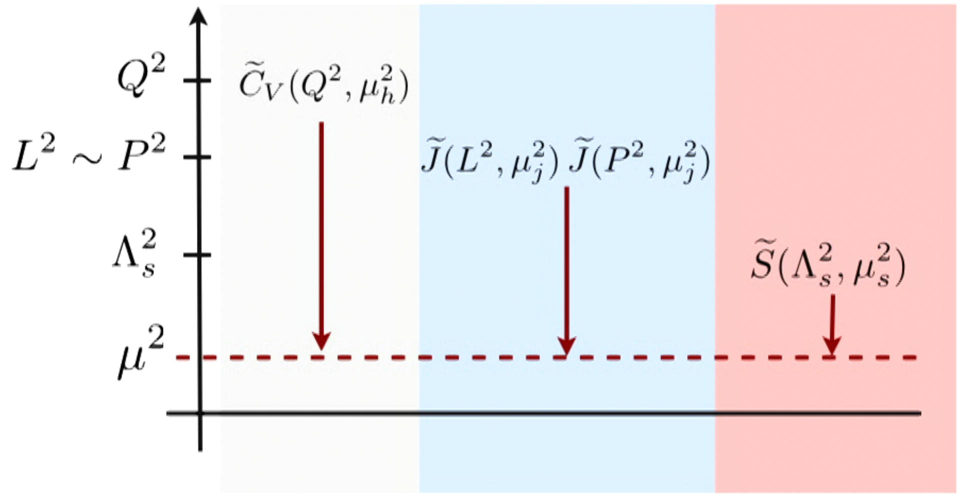
$$\Lambda_s^2 = \frac{L^2 P^2}{Q^2}$$

After factorization, each component function only depends on a single physical scale and on renormalization scale μ.

The components fulfill RG evolution equations.

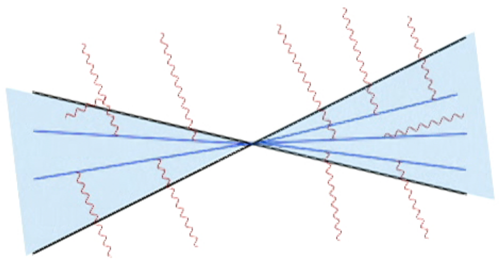
Resummation by RG evolution

Evaluate each part at its characteristic scale, evolve to common reference scale μ

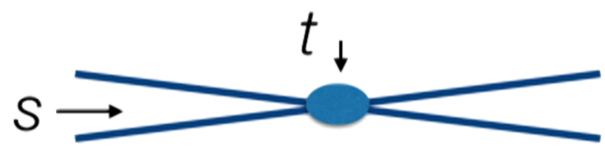


Each contribution is evaluated then at its natural scale: No large perturbative logarithms remain.

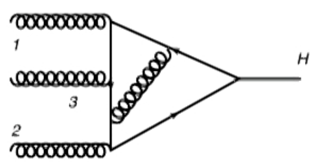
Missing factorization theorems



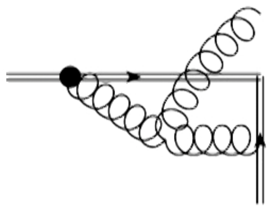
Non-global observables
(e.g. phase-space cuts, jets, …)



forward scattering, Glauber gluons
(*pp* scattering contains forward part)



Small masses
(e.g. *b*-quarks in *H* production,
EW effects at large q_{T}, ...)



Power corrections
(e.g. corrections to threshold limit,
next-to-eikonal corrections)

A lot of recent progress

Caron-Huot '15
Larkoski, Moult, Neill '15 '16
TB, Neubert, Shao, Rothen '15 +
Pecjak '16

Non-global observables
(e.g. phase-space cuts, jets, ...)

Del Duca,Falcioni, Magnea, Vernazza '14
Fleming '14,
Rothstein, Stewart '16,
Schwartz, Yan, Zhu '17

forward scattering
(*pp* scattering contains forward part)

Hoang et al. '13-'16; Melnikov, Penin '16 + Tancredi, Wever '16
Caola, Forte, Marzani, Muselli, Vita '16, Hill '16

Small masses
(e.g. EW effects at large q_T,
b-quarks in H production)

Larkoski, Neill, Stewart '14 Bonocore, Laenen, Melville, Magnea, Vernazza and White '14,'15,'16; Penin, Zerf '16; Moult, Rothen, Stewart, Tackmann and Zhu '16 Boughezal, Liu, Frank Petriello '16 Feige, Kolodrubetz, Moult, Stewart '17; Moult, Stewart and Vita '17

Power corrections
(e.g. corrections to threshold limit,
next-to-eikonal corrections)

small is beautiful

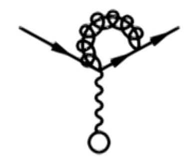
Expansion in small masses

Massive Sudakov form factor ®

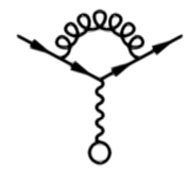
Contributions from the usual momentum regions

Hard $$F_H(\mu) = 1 + \frac{\alpha}{4\pi}\left[-\log^2\frac{Q^2}{\mu^2} + 3\log\frac{Q^2}{\mu^2} - 8 + \frac{\pi^2}{6}\right]$$

Collinear $$F_J(\mu) = 1 + \frac{\alpha}{4\pi}\left[\log^2\frac{m^2}{\mu^2} - \log\frac{m^2}{\mu^2} + 4 + \frac{\pi^2}{6}\right]$$



Soft $$F_S(\mu) = 1 + \frac{\alpha}{4\pi}\left[2\log\frac{\lambda^2}{\mu^2}\left(\log\frac{Q^2}{m^2} - 1\right)\right]$$



$$F = F_H F_J F_S$$

large log!

Resummation

Can avoid large logs in hard and collinear functions by solving RG, but

$$F_S(\mu) = 1 + \frac{\alpha}{4\pi}\left[2\log\frac{\lambda^2}{\mu^2}\left(\log\frac{Q^2}{m^2} - 1\right)\right]$$

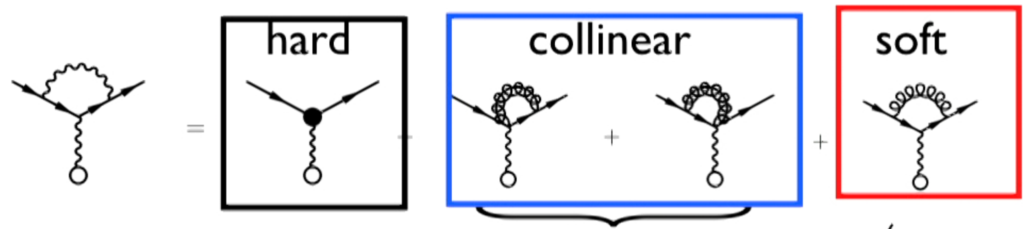
has a large log even for μ ~ λ

- rapidity log aka collinear anomaly; arises also in other contexts, e.g. p_T resummation

Chiu, Golf, Kelley, Manohar '07; TB, Neubert '10; Chiu, Jain, Neill, Rothstein '12

Not a problem because log term exponentiates!

Factorization ®



hard part

form factor for m_e=0

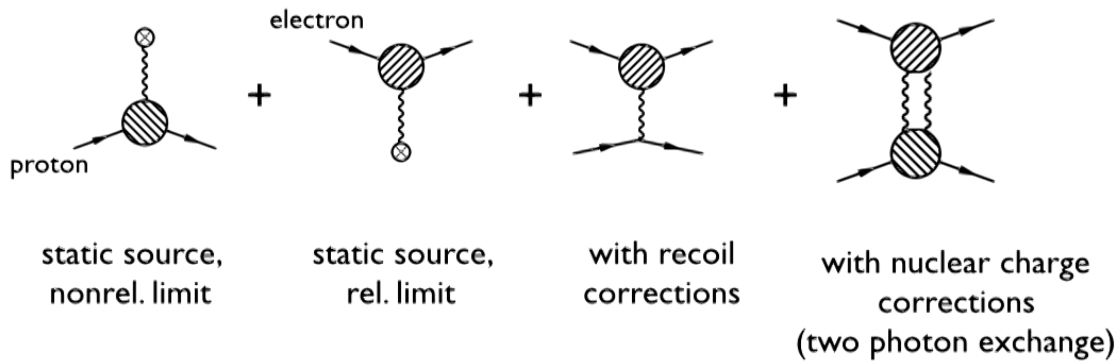
$$d\sigma \propto H\left(\frac{Q^2}{\mu^2}\right) J\left(\frac{m^2}{\mu^2}\right) R\left(\frac{m^2}{\mu^2}, \frac{p\cdot p'}{m^2}\right) S\left(\frac{\Delta E}{\mu}, \frac{p\cdot p'}{m^2}, \frac{E}{m}, \frac{E'}{m}\right)$$

[remainder function starting at 2-loop (collinear anomaly/rapidity logs)]

R. Hill 1605.0261

Have used the same factorization to obtain massive Bhabha scattering from massless result TB, Melnikov '07, confirming Penin '05.

Elements of e^-p scattering ®

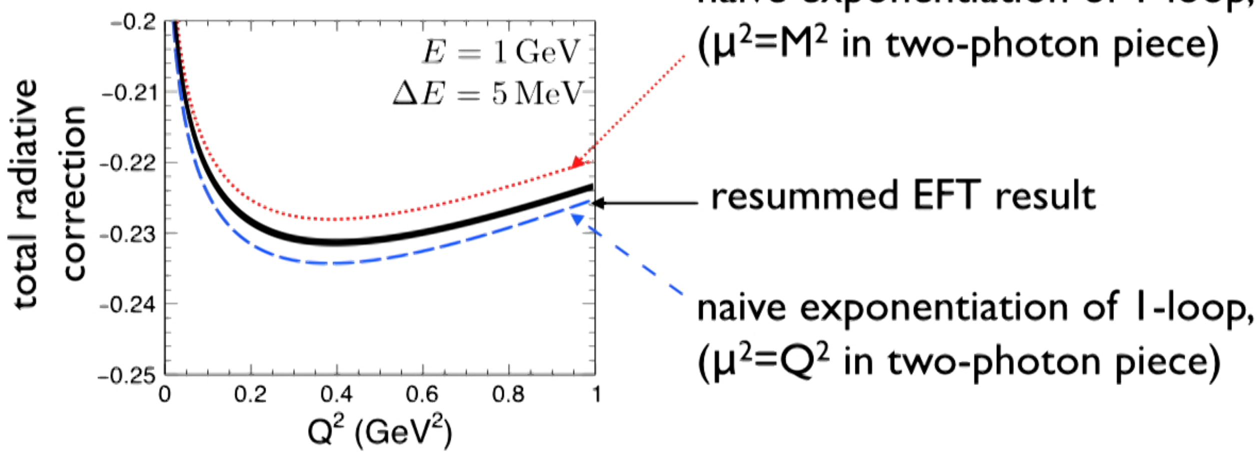


Richard has computed all perturbative ingredients at 2 loops.

Crucial point: all the hadronic structure is included in hard function *H.* EFT treatment yields clean separation of hadronic and low-*E* QED effects.

$$d\sigma \propto H\left(\frac{Q^2}{\mu^2}\right) J\left(\frac{m^2}{\mu^2}\right) R\left(\frac{m^2}{\mu^2}, \frac{p\cdot p'}{m^2}\right) S\left(\frac{\Delta E}{\mu}, \frac{p\cdot p'}{m^2}, \frac{E}{m}, \frac{E'}{m}\right)$$

Comparison to previous implementations of radiative corrections, e.g. in A1 analysis of electron-proton scattering data



- discrepancies at 0.5-1% compared to currently applied radiative correction models (cf. 0.2-0.5% systematic error budget of A1 experiment)

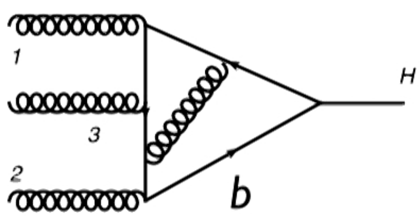
- conflicting implicit scheme choices for 1PE and 2PE

- complete analysis: account for floating normalizations, correlated shape variations when fitting together with backgrounds

Theoretical understanding of factorization and EFT formulation of small mass expansion are still lacking

- Good, gauge inv. regulator for EFT? (dim. reg. is insufficient for expanded diagrams)
- Additional momentum modes?

Even basic problems, such as the resummation for *b*-quark mass logs in total Higgs rate remain unsolved.



Melnikov, Penin '16 + Tancredi, Wever '16
Caola, Forte, Marzani, Muselli, Vita '16

Power corrections

Power suppressed contributions can be obtained in SCET by including subleading operators in Lagrangian and external currents.

Use building blocks (fields and their derivatives)

Operator	$\mathcal{B}^{\mu}_{n_i\perp}$	χ_{n_i}	$\mathcal{P}^{\mu}_{\perp}$	q_{us}	D^{μ}_{us}
Power Counting	λ	λ	λ	λ^3	λ^2
	collinear			soft	

and write down all operators compatible with symmetries (Lorentz, gauge, …).

Straightforward in principle, tedious in practice!

Power corrections

Subleading SCET Lagrangians and currents for *B*-decays were constructed very early on (Beneke, Feldmann '02; Pirjol, Stewart '02; …), but so far few phenomenological results

- factorization for power corrections to inclusive *B*-decays, tree-level results for corrections (… ; Benzke, Lee, Neubert, Paz '10)
- analysis of some power corrections in exclusive *B*-decays (…; Mantry, Pirjol, Stewart '03; …)
- but no resummations for power-suppressed observables

Recently renewed interest, thanks to precision collider physics at LHC (and String Theory!)…

Power corrections

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Helicity operators

Wilson coefficients in SCET (and other EFTs) are obtained from gauge-theory hard-scattering scattering amplitudes.

Organize operators like amplitudes; use building blocks of definite helicity Moult, Stewart, Tackmann, Waalewijn '07. Subleading operators for

- $e^+e^- \to 2$ jets Feige, Kolodrubetz, Moult, Stewart '17, goal: event shapes at subeading power;
- $gg \to H$ Moult, Stewart and Vita '17

Operators for $e^+e^- \to 2$ jets

Order	Category	Operators	# helicity configs	$\sigma_{2j}^{\mathcal{O}(\lambda^2)} \neq 0$
$\mathcal{O}(\lambda^0)$	$e\bar{e}q\bar{q}$	$O^{(0)\bar{\alpha}\beta}_{(\lambda_1;\pm)} = J^{\bar{\alpha}\beta}_{n\bar{n}\lambda_1} J_{e\pm}$	4	✓
$\mathcal{O}(\lambda)$	$e\bar{e}q\bar{q}g$	$O^{(1)a\,\bar{\alpha}\beta}_{n\bar{n}1,2\lambda_1(\lambda_2;\pm)} = \mathcal{B}^a_{n,\bar{n}\lambda_1} J^{\bar{\alpha}\beta}_{n\bar{n}\,-\lambda_1} J_{e\pm}$	8	✓
		$O^{(1)a\,\bar{\alpha}\beta}_{\bar{n}\lambda_1(\lambda_2:\pm)} = \mathcal{B}^a_{n\lambda_1} J^{\bar{\alpha}\beta}_{\bar{n}\lambda_2} J_{e\pm}$	8	✓
	$e\bar{e}ggg$	$O^{(1)abc}_{\mathcal{B}\lambda_1\lambda_2\lambda_3(\pm)} = S\,\mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{\bar{n}\lambda_2} \mathcal{B}^c_{\bar{n}\lambda_3} J_{e\pm}$	8	✓
$\mathcal{O}(\lambda^2)$	$e\bar{e}q\bar{q}Q\bar{Q}$	$O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qQ1(\lambda_1;\lambda_2:\pm)} = J^{\bar{\alpha}\beta}_{(q)n\lambda_1} J^{\bar{\gamma}\delta}_{(Q)\bar{n}\lambda_2} J_{e\pm}$	8	
		$O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qQ2(\lambda_1;\lambda_1:\pm)} = J^{\bar{\alpha}\beta}_{(q\bar{Q})n\lambda_1} J^{\bar{\gamma}\delta}_{(Q\bar{q})\bar{n}\,\lambda_1} J_{e\pm}$	4	
		$O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qQ3(\lambda_1;-\lambda_1;\pm)} = J^{\bar{\alpha}\beta}_{(q)n\bar{n}\lambda_1} J^{\bar{\gamma}\delta}_{(Q)n\bar{n}-\lambda_1} J_{e\pm}$	4	
		$O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qQ4(\lambda_1:\lambda_2;\pm)} = J^{\bar{\alpha}\beta}_{(q)\bar{n}\lambda_1} J^{\bar{\gamma}\delta}_{(Q)n\bar{n}\,\lambda_2} J_{e\pm}$	8	✓
		$O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qQ5(\lambda_1:\lambda_2;\pm)} = J^{\bar{\alpha}\beta}_{(q)\bar{n}\lambda_1} J^{\bar{\gamma}\delta}_{(Q)\bar{n}n\lambda_2} J_{e\pm}$	8	✓
	$e\bar{e}q\bar{q}q\bar{q}$	$O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qq1(\lambda_1;\lambda_2:\pm)} = J^{\bar{\alpha}\beta}_{(q)n\lambda_1} J^{\bar{\gamma}\delta}_{(q)\bar{n}\lambda_2} J_{e\pm}$	8	
		$O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qq3(\lambda_1;-\lambda_1;\pm)} = J^{\bar{\alpha}\beta}_{(q)n\bar{n}\lambda_1} J^{\bar{\gamma}\delta}_{(q)n\bar{n}-\lambda_1} J_{e\pm}$	2	
		$O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qq4(\lambda_1:\lambda_2;\pm)} = J^{\bar{\alpha}\beta}_{(q)\bar{n}\lambda_1} J^{\bar{\gamma}\delta}_{(q)n\bar{n}\,\lambda_2} J_{e\pm}$	8	✓
		$O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qq5(\lambda_1:\lambda_2;\pm)} = J^{\bar{\alpha}\beta}_{(q)\bar{n}\lambda_1} J^{\bar{\gamma}\delta}_{(q)\bar{n}n\lambda_2} J_{e\pm}$	8	✓
	$e\bar{e}q\bar{q}gg$	$O^{(2)ab\,\bar{\alpha}\beta}_{\mathcal{B}1\lambda_1\lambda_2(\lambda_3;\pm)} = S\mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{n\lambda_2} J^{\bar{\alpha}\beta}_{n\bar{n}\,\lambda_3} J_{e\pm}$	8	✓
		$O^{(2)ab\,\bar{\alpha}\beta}_{\mathcal{B}2\lambda_1\lambda_2(\lambda_3;\pm)} = S\mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{n\lambda_2} J^{\bar{\alpha}\beta}_{\bar{n}n\,\lambda_3} J_{e\pm}$	8	✓
		$O^{(2)ab\,\bar{\alpha}\beta}_{\mathcal{B}3\lambda_1\lambda_2(\lambda_3;\pm)} = \mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{\bar{n}\lambda_2} J^{\bar{\alpha}\beta}_{n\bar{n}\,\lambda_3} J_{e\pm}$	12	✓
		$O^{(2)ab\,\bar{\alpha}\beta}_{\mathcal{B}4\lambda_1\lambda_2(\lambda_3:\pm)} = \mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{\bar{n}\lambda_2} J^{\bar{\alpha}\beta}_{n\,\lambda_3} J_{e\pm}$	8	
		$O^{(2)ab\,\bar{\alpha}\beta}_{\mathcal{B}5\lambda_1\lambda_2(\lambda_3:\pm)} = \mathcal{B}^a_{\bar{n}\lambda_1} \mathcal{B}^b_{\bar{n}\lambda_2} J^{\bar{\alpha}\beta}_{n\,\lambda_3} J_{e\pm}$	4	

[1703.03411 Stewart, Moult et al.]

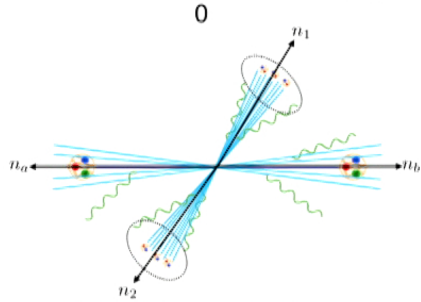
Category	Operators	# helicity configs	$\sigma_{2j}^{\mathcal{O}(\lambda^2)} \neq 0$
$e\bar{e}gggg$	$O^{(2)abcd}_{4g1\lambda_1\lambda_2\lambda_3\lambda_4(\pm)} = S\mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{n\lambda_2} \mathcal{B}^c_{\bar{n}\lambda_3} \mathcal{B}^d_{\bar{n}\lambda_4} J_{e\pm}$	6	
	$O^{(2)abcd}_{4g2\lambda_1\lambda_2\lambda_3\lambda_4(\pm)} = S\mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{\bar{n}\lambda_2} \mathcal{B}^c_{\bar{n}\lambda_3} \mathcal{B}^d_{\bar{n}\lambda_4} J_{e\pm}$	4	
$\mathcal{P}_\perp$	$O^{(2)a\,\bar{\alpha}\beta}_{\mathcal{P}2\lambda_1(\lambda_2:\pm)[\lambda_\mathcal{P}]} = \mathcal{B}^a_{n\lambda_1} \{J^{\bar{\alpha}\beta}_{\bar{n}\,\lambda_2} (\mathcal{P}_\perp^{\lambda_\mathcal{P}})^\dagger\} J_{e\pm}$	8	
	$O^{(2)a\,\bar{\alpha}\beta}_{\mathcal{P}1n,\bar{n}\lambda_1(\lambda_2;\pm)[\lambda_\mathcal{P}]} = \left[\mathcal{P}_\perp^{\lambda_\mathcal{P}} \mathcal{B}^a_{n,\bar{n}\lambda_1}\right] J^{\bar{\alpha}\beta}_{n\bar{n}\,\lambda_2} J_{e\pm}$	24	✓
	$O^{(2)abc}_{\mathcal{P}\mathcal{B}\lambda_1\lambda_2\lambda_3(\pm)[\lambda_\mathcal{P}]} = S\,\mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{\bar{n}\lambda_2} \left[\mathcal{P}_\perp^{\lambda_\mathcal{P}} \mathcal{B}^c_{\bar{n}\lambda_3}\right] J_{e\pm}$	8	
Ultrasoft	$O^{(2)a\,\bar{\alpha}\beta}_{\mathcal{B}(us(i))\lambda_1:(\lambda_2;\pm)} = \mathcal{B}^a_{us(i)\lambda_1} J^{\bar{\alpha}\beta}_{n\bar{n}\,\lambda_2} J_{e\pm}$	8	
	$O^{(2)a\,\bar{\alpha}\beta}_{\mathcal{B}(us(i))0:(\lambda_1;\pm)} = \mathcal{B}^a_{us(i)0} J^{\bar{\alpha}\beta}_{n\bar{n}\,\lambda_1} J_{e\pm}$	8	✓
	$O^{(2)\,\bar{\alpha}\beta}_{\partial(us(i))\lambda_1:(\lambda_2;\pm)} = \{\partial_{us(i)\lambda_1} J^{\bar{\alpha}\beta}_{n\bar{n}\,\lambda_2}\} J_{e\pm}$	8	
	$O^{(2)\,\bar{\alpha}\beta}_{\partial(us(i))0,\bar{0}:(\lambda_1;\pm)} = \{\partial_{us(i)0,\bar{0}} J^{\bar{\alpha}\beta}_{n\bar{n}\,\lambda_1}\} J_{e\pm}$	8	✓
	$O^{(2)abc}_{(us(i))\lambda_1:\lambda_2\lambda_3(\pm)} = \mathcal{B}^a_{us(i)\lambda_1} \mathcal{B}^b_{n\,\lambda_2} \mathcal{B}^c_{\bar{n}\,\lambda_3} J_{e\pm}$	24	
	$O^{(2)ab}_{\partial\mathcal{B}(us(i))\lambda_1:\lambda_2\lambda_3(\pm)} = \left[\partial_{us(i)\lambda_1} \mathcal{B}_{n\,\lambda_2}\right] \mathcal{B}_{\bar{n}\,\lambda_3} J_{e\pm}$	24	

from SCET17 talk by Gherardo Vita

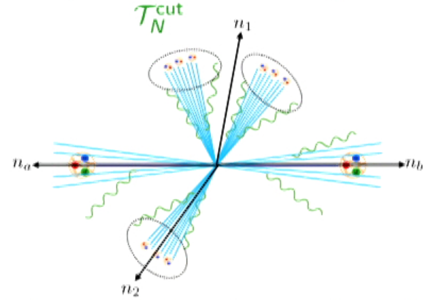
N-jettiness subtraction

SCET based slicing scheme for NNLO, based on N-jettiness event-shape Gao, Li and Zhu ‘13; Boughezal, Focke, Petriello, Liu ‘16; Gaunt, Stahlhofen, Tackmann, Walsh ’16.

$$\sigma(X) = \int_0 d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N} = \int_0^{\mathcal{T}_N^{\rm cut}} d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N} + \int_{\mathcal{T}_N^{\rm cut}} d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N}$$



NNLO calculation in singular limit



NLO calculation in resolved limit

Expand in $\tau_N^{\rm cut}$ compute in SCET

Compute with existing NLO code, e.g. MCFM

N-jettiness subtraction

- Advantage: recycles mature, existing NLO codes. Many results: H, V, H+j, V+j, $\gamma\gamma$, HZ, HW …
- Disadvantage: need to ensure independence on slicing parameter τ_N^{cut}.
    - τ_N^{cut} **must be small** to justify expansion
    - τ_N^{cut} **cannot be too small** to have stable NLO result.
- Improvement: **LL power corrections to *V* production have now been computed** Moult, Rothen, Stewart, Tackmann and Zhu '16 (using SCET), Boughezal, Liu, Frank Petriello '16 (directly in QCD)

Sudakov form factor

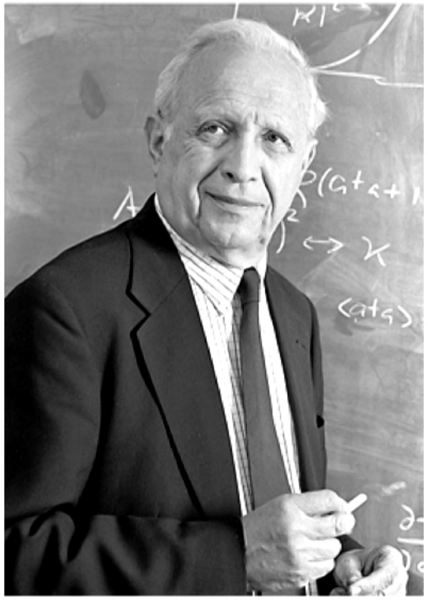
Leading logs in power correction to form-factor

$$F_1 = e^{-x} + \rho\, F_1^{(1)}(x) + \mathcal{O}(\rho^2)$$

where $x = \frac{\alpha}{4\pi} \ln^2 \rho$ and $\rho = \frac{m_e^2}{Q^2}$ Penin '14

$$F_1^{(1)} \sim -3 \, \exp\left[-x/2 + 2 \ln x\right] \quad \text{for } x \gg 1$$

First resummation for power correction! Note: at very large *x*, power correction overwhelms leading power result!

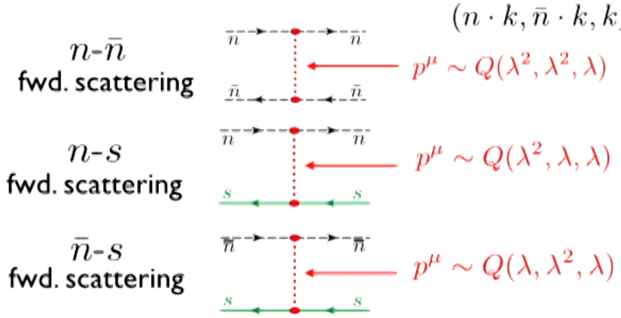


Glauber Gluons

Technical challenges

- Glauber gluons are offshell
  - $k_\mathrm{T} \gg E$, like Coulomb gluons
  - must be included as potential, not dynamical field in $\mathcal{L}_\mathrm{eff}$
- 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, …).
- Last year Rothstein and Stewart published an EFT framework for Glauber exchanges [JHEP 1608 (2016) 025 (204pp!)]

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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

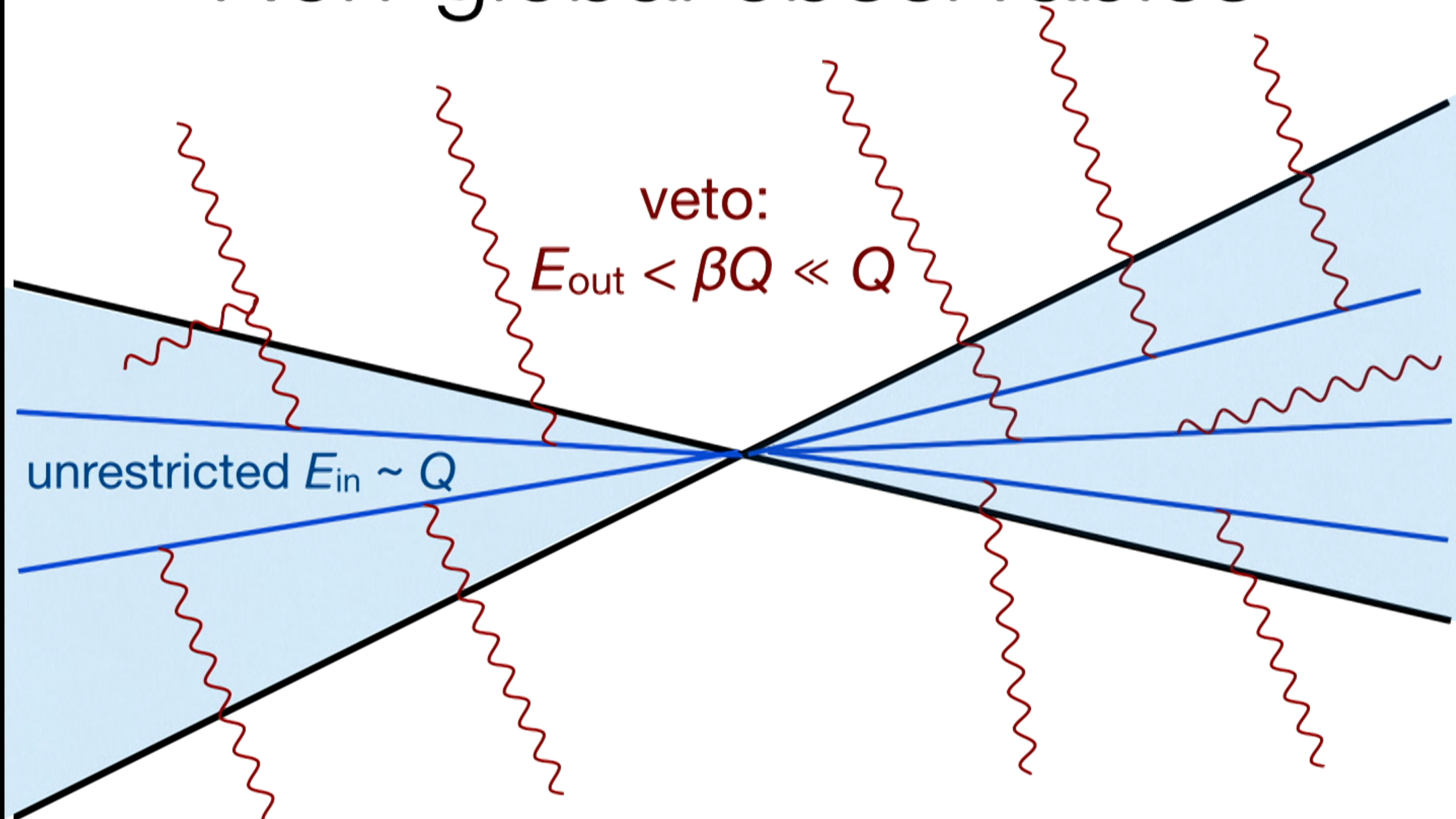
- Reggeization
- BFKL from (rapidity) renormalization group
- Lipatov vertex
- Glauber exponentiation, eikonal phase in *pp* scattering

Many more examples

- jet vetoes (includes unrestricted radiation near the beam pipe)
- gaps between jets
- jet substructure
- isolated photons (veto on radiation near photon)
- event shapes such as the light-jet mass and narrow jet broadening
- …

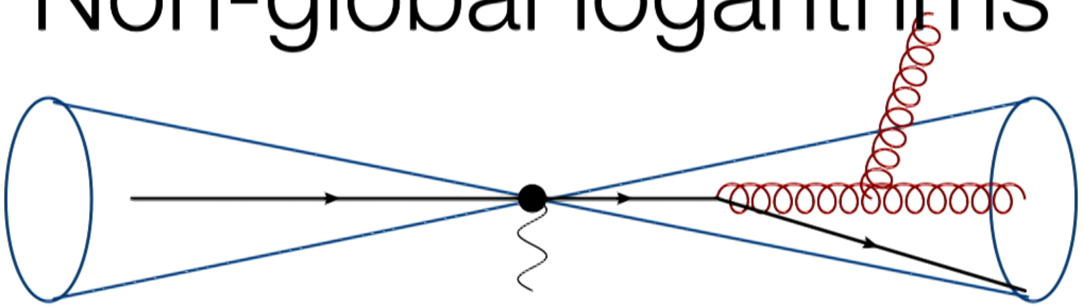
Such observables are called non-global, since they are insensitive to radiation inside certain regions of phase space.

Non-global observables



$\rightarrow$ large logs $\alpha_s^n \ln^n(E_{out} / E_{in}) \sim \alpha_s^n \ln^n(\beta)$

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

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

Banfi, Marchesini, Smye '02

$\hat{L} \sim N_c\, \alpha_s \ln \beta$

$W_{kl}^j = \frac{n_k \cdot n_l}{n_k \cdot n_j\, n_l \cdot n_j}$ dipole radiator

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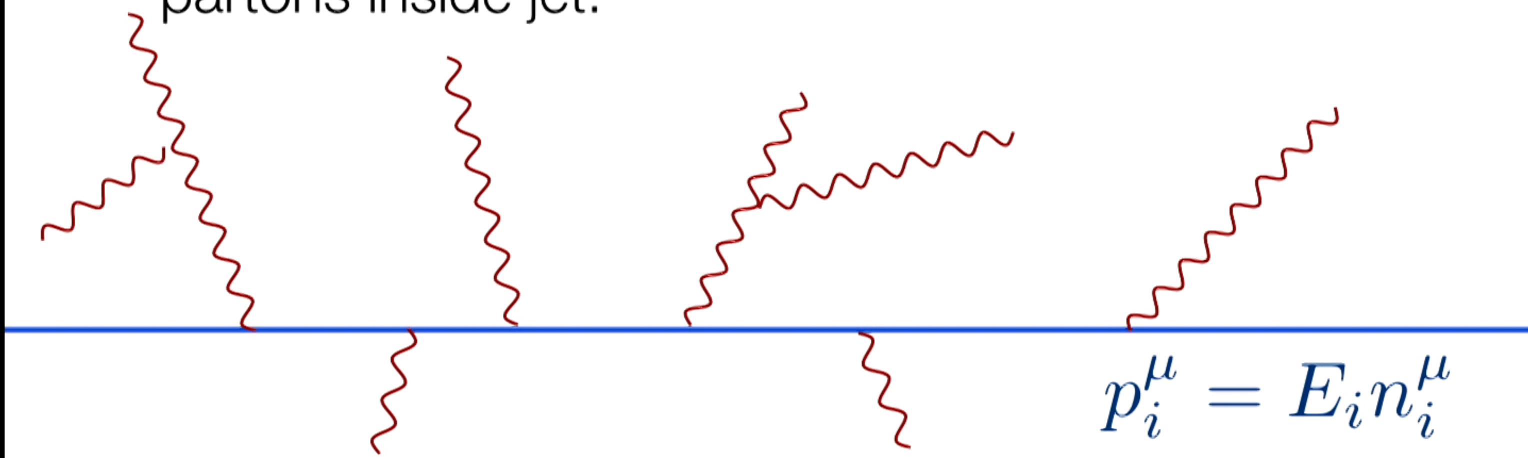
Basic physics is soft radiation off energetic partons inside jet.



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

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

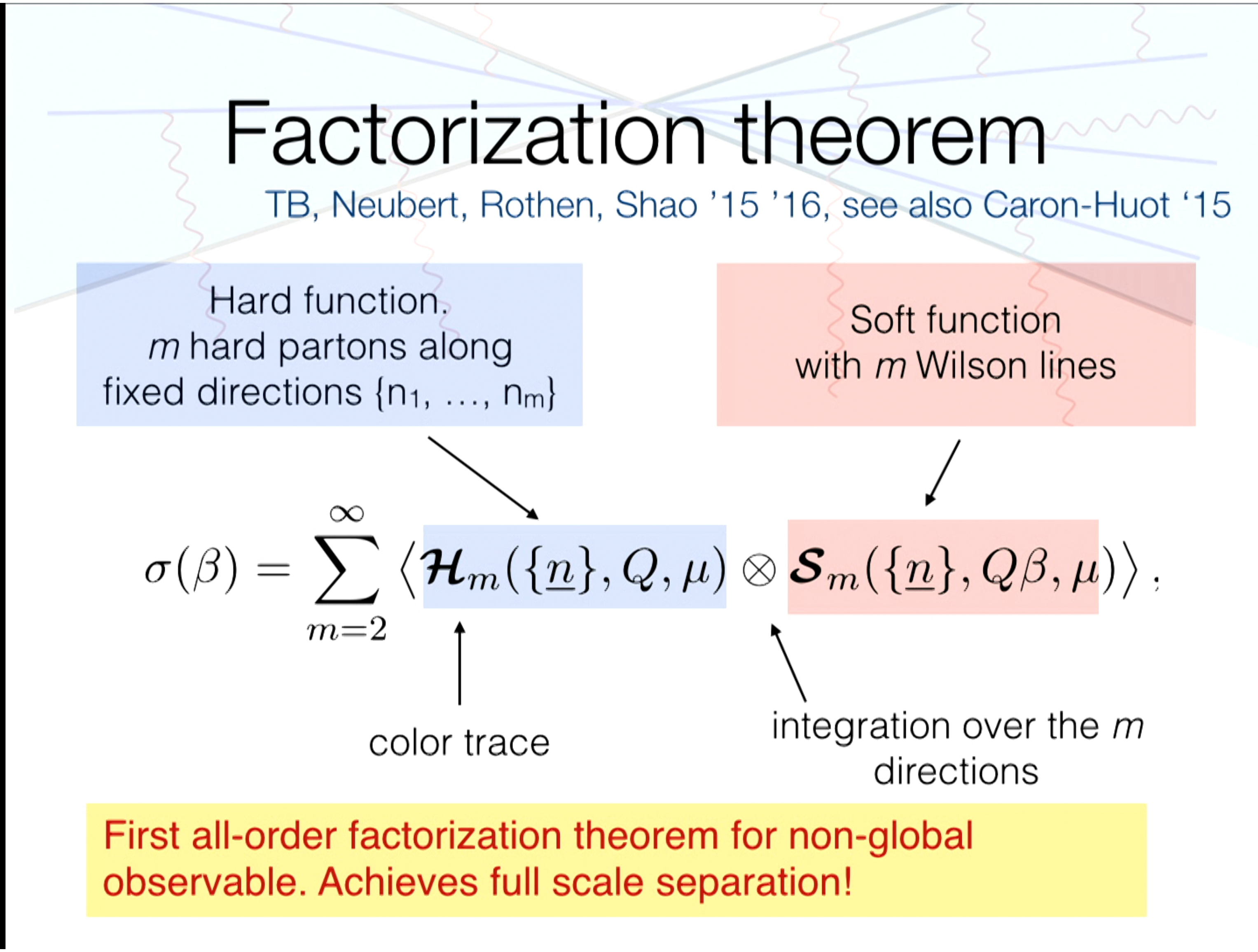
For a jet of several (nearly) collinear energetic particles, one can combine

$$\boldsymbol{S}_1(n)\,\boldsymbol{S}_2(n) = \mathbf{P}\exp\left(ig_s\int_0^\infty ds\, n\cdot A_s^a(sn)\,(\boldsymbol{T}_1^a+\boldsymbol{T}_2^a)\right)$$

into a single Wilson line with the total color charge.

For non-global observables one cannot combine the soft Wilson lines → complicated structure of logs!

- For a wide-angle jet, the energetic particles are not collinear.
- For a narrow-angle jets, we find that small-angle soft radiation plays an important role. Resolves directions of individual energetic partons!


Factorization theorem
TB, Neubert, Rothen, Shao '15 '16, see also Caron-Huot '15
Hard function.
m hard partons along
fixed directions {n1, …, nm}
Soft function
with m Wilson lines
$\sigma(\beta) = \sum_{m=2}^{\infty} \langle \mathcal{H}_m(\{\underline{n}\}, Q, \mu) \otimes \mathcal{S}_m(\{\underline{n}\}, Q\beta, \mu) \rangle$,
color trace
integration over the m
directions
First all-order factorization theorem for non-global
observable. Achieves full scale separation!

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

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

- Equivalent to parton shower equation

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

RG = Parton Shower

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- RG

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Summary

- Important theoretical progress in SCET
  - Power corrections, small masses
  - Inclusion of Glauber gluon effects
  - Resummation for non-global observables
- Many phenomenological applications
  - Higher-logs in q_T-spectra, jet vetos, jet substructure, NNLO computations …
  - … and a first few at the precision frontier, e.g. *ep* scattering