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PARTON SHOWERS BEYOND LEADING ORDER: A FACTORIZATION APPROACH

1. Motivation: parton showers vs. fixed-order calculations

2. Subtractive methods and factorization

3. An example from ep collisions

4. Conclusions

TWO APPROACHES TO THE MC SIMULATION OF MULTI-JET FINAL STATES:

- parton model to generate simplest final state - additional jets by showering

- compute in perturbative QCD at NLO (or NNLO, ...) with bare partons as jets - add model for partons → jets

CAN WE COMBINE THEM?

Note:

- Many "nonleading effects" already included: exact multiparton kinematics; angular ordering; ...
- Treatments of NLO corrections to hard scattering: see Seymour (1995); André - Sjöstrand (1998); ...

|| BUT AS YET NO SYSTEMATIC METHOD FOR GOING BEYOND LEADING LOGS ||

Are subtraction procedures useful?

Friberg - Sjöstrand, hep-ph/9906316

Cross section in a parton shower MC event generator:

$$\sigma[W] = \sum_{\substack{\text{final} \\ \text{states } X}} \underset{\substack{\uparrow \\ \text{weight} \\ \text{function}}}{W(X)} \quad \underset{\substack{\uparrow \\ \text{parton} \\ \text{shower}}}{PS} \otimes \underset{\substack{\uparrow \\ \text{hard} \\ \text{scattering}}}{H}$$

- Standard MC: H is taken to the LO
- NLO-improved MC:

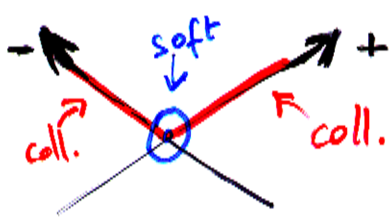
$$PS \otimes \Big[\underbrace{H^{(LO)}}_{\text{LO events}} + \underbrace{\alpha_s \Big(H^{(NLO)} - PS_I(1) \otimes H^{(LO)} - PS_F(1) \otimes H^{(LO)} \Big)}_{\text{NLO correction events}} \Big]$$

Example (simple): $\gamma^* g \to q\bar{q}$ in DIS

Collins, hep-ph/0001040

- $PS_I(1)$ term only
- no soft gluons

General NLO processes:



overlapping soft and collinear regions

QUESTION: COLLINEAR REGIONS ACCURATELY TAKEN INTO ACCOUNT BY SUBTRACTION TERMS. SOFT REGION?

- IN STANDARD MC's:

  SOFT SINGULARITIES HANDLED BY IR CUT-OFF

  $\Rightarrow$ EFFECTIVE KERNELS $P \cdot \Theta \equiv P_{\text{cut-off}}$ IN SUDAKOV FORM F.'s

- IDEA OF THIS WORK:

  CONSTRUCT FACTORIZATION $\Rightarrow$ FULLY SUBTRACTED, PURELY UV $\hat{H}_{NLO}$

  FOR THIS, NEED DECOMPOSITION

$$H^{(NLO)} = \sum_{\substack{\text{regions } R = \\ = \{\text{soft, coll., UV}\}}} A_H(R) + \text{nonleading power}$$

uniformly over the whole of the phase space

- each piece equipped with counterterms (instead of phase space splitting: cf., e.g., Corcella-Seymour (1998))

NOTE:

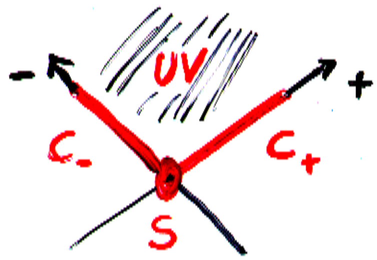
- Local techniques to isolate IR contributions ? (Binoth-Heinrich, hep-ph/0004013)

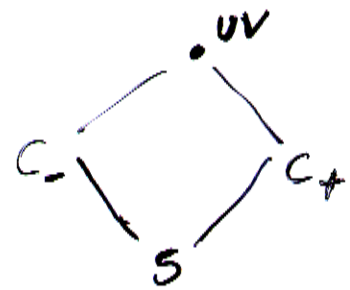
- For IR safe quantities, subtractions devised by Catani-Seymour, Frixione-Kunszt-Signer

$\Rightarrow$ BUT DIFFERENT ORGANIZATION NEEDED FOR MC's (IR <u>UN</u>SAFE!)

Method of Collins + FH, PLB 472 (2000):

- INSPIRED TO RENORMALIZATION METHODS:





(4-dim)

(1-dim)

(0-dim)

- start with "smaller" regions
- construct approximation valid in that region
- subtract divergences from "larger" regions

- ENFORCES GAUGE INVARIANCE BY USE OF WILSON-LINE OPERATORS

$$V(n) \approx P \exp\left(ig \int A(nz) \cdot n \, dz\right)$$

direction n of the Wilson line $\approx$ cut-off parameter

INTERPRETATION IN TERMS OF MC's:

UV term $\rightarrow$ subtracted NLO hard-scattering function

collinear terms $\rightarrow$ evolution kernels in the showering

soft term $\rightarrow$ can be eliminated by suitable choice of Wilson-line directions

Example: $\gamma^* q \to q g$ in DIS

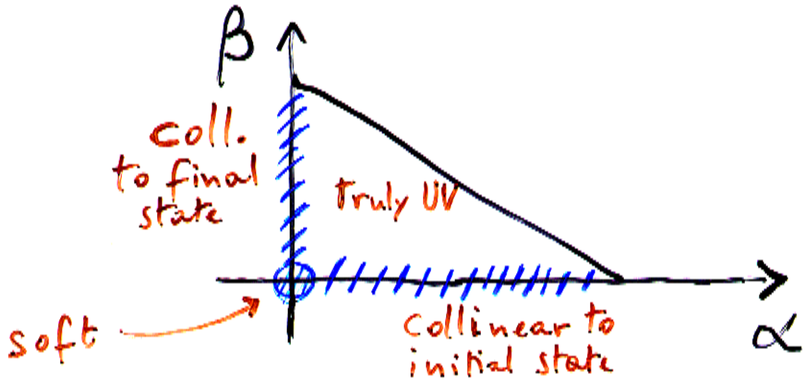
$$K = \left(\alpha\, x P^+,\ \beta \frac{Q^2}{2xP^+},\ \hat{\vartheta} k_\perp\right)$$

$$\Sigma[\varphi] = \int_0^\infty d\alpha \int_0^\infty d\beta \int_0^{2\pi} \frac{d\vartheta}{2\pi}\, J(x;\alpha,\beta)\, \varphi(x,Q^2;\alpha,\beta,\vartheta)\, M(\alpha,\beta)$$

jacobian

contains weight function + showering

hard scattering



$$M(\alpha,\beta) = (1-\beta)^2\, \frac{1+(1+\alpha-\beta)^2}{\alpha\beta(1+\alpha-\beta)} + 2 + 6\, \frac{(1-\beta)^2}{1+\alpha-\beta}$$

APPLYING THE WILSON-LINE DECOMPOSITION WITH DIRECTIONS u (IN.-STATE), u' (FIN.-STATE) YIELDS ($u^-/u^+ \equiv \eta$, $u'^+/u'^- \equiv \eta'$)

$\Rightarrow$ soft term: $$M_S(\alpha,\beta) = \frac{2}{\alpha\beta} - \frac{2}{(\alpha+\eta'\beta)\beta} - \frac{2}{\alpha(\beta+\eta\alpha)}$$

pure soft approximation to M

collinear subtractions

Soft region:

$$M_S(\alpha,\beta) = \frac{2}{\alpha\beta} - \frac{2}{(\alpha+\eta'\beta)\beta} - \frac{2}{\alpha(\beta+\eta\alpha)}$$

Collinear regions:

$$M_I(\alpha,\beta) = \frac{1}{\beta}\,\frac{1+(1+\alpha)^2}{\alpha(1+\alpha)} - \frac{2}{\alpha\beta} + \frac{2}{(\alpha+\eta'\beta)\beta}$$

$$M_F(\alpha,\beta) = \frac{1}{\alpha}\,\frac{1+(1-\beta)^2}{\beta}(1-\beta) - \frac{2}{\alpha\beta} + \frac{2}{\alpha(\beta+\eta\alpha)}$$

Fully subtracted matrix element:

$$M_{(\text{subtr.})}(\alpha,\beta) = M - M_S - M_I - M_F$$

$$= \beta + \frac{\alpha}{(1+\alpha)(1+\alpha-\beta)} + 6\frac{(1-\beta)^2}{(1+\alpha-\beta)}$$

- finite in all of the IR regions
- independent of η, η'

Collins + FH hep-ph/0009286

THIS STRUCTURE IS GENERAL. CAN WE REORGANIZE IT IN A WAY THAT IS SUITED FOR A PARTON SHOWER ALGORITHM?

$\Rightarrow$ CHOOSE η, η' SO THAT $M_S = 0$,

$$\begin{cases} M_I^{(MC)} = \dfrac{1}{\beta}\,\dfrac{1+(1+\alpha)^2}{\alpha(1+\alpha)} - \dfrac{1}{\alpha}\,\dfrac{2}{\alpha+\beta} \\[2ex] M_F^{(MC)} = \dfrac{1}{\alpha}\,\dfrac{1+(1-\beta)^2}{\beta}(1-\beta) - \dfrac{1}{\beta}\,\dfrac{2}{\alpha+\beta} \end{cases}$$

First piece: standard Sudakov kernel

Second piece: counterterm

NOTE: effective cut-offs in initial-state and final-state showers are not independent!

CONCLUSIONS

- ONGOING EFFORT TO RECAST FACTORIZATION IN FORM USEFUL FOR MC's.

- FORMULATION IN TERMS OF
  - SUBTRACTED MATRIX ELEMENTS
  - MODIFIED KERNELS $P_{\text{cut-off}} \rightarrow P - \text{counterterm}$

  ↑ more work needed to derive full algorithms

- GAUGE INVARIANCE INJECTED THROUGH WILSON LINES
  $\rightarrow$ EXACT $k_\perp$ KINEMATICS

  ↑ work needed on evolution equations in n

- ALLOW WEIGHTED EVENTS $\rightarrow$ NEGATIVE WEIGHTS NOT FATAL

  ↑ develop methods to reduce their number