$p_T$-dependent semi-inclusive scattering in QCD

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In some sense, all processes used to determine the partonic structure of hadrons are “semi inclusive” and involve high-$p_T$ final states.

Today: discuss a few pQCD aspects relevant to processes “sensitive to OAM”

Outline:

- Introduction
- Single-scale processes
- Two-scale processes
Introduction
Reactions with measured $p_T$ play crucial role in QCD:

- Probes of nucleon structure
- Involved in most of today’s Hadron Collider physics (“New Physics”)
- Test our understanding of QCD at high energies, and our ability to do “first-principles” computations

Cornerstones: factorization & asymptotic freedom
Distinguish:

<table>
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<th>Processes with single measured hard scale $p_T$</th>
<th>Two-scale problems: small measured $q_T$ and hard scale $Q$</th>
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<td>• Examples:</td>
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<td>( pp \rightarrow \pi X \quad \gamma p \rightarrow \pi X )</td>
<td>“TMD-SIDIS”, Higgs-$q_T$</td>
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<td>• Collinear factorization</td>
<td>• For simplest observables: TMD factorization</td>
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<td>• Typically, fixed-order hard scattering (NLO, ...)</td>
<td>• Perturbation theory: double-logs</td>
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<td>• “DGLAP” evolution = resummation of logs</td>
<td>( \alpha_s^k \log^2 k (q_T/Q) )</td>
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<tr>
<td>( \alpha_s^k \log^k (p_T/Q_0) ) to all orders</td>
<td>• TMD evolution = resummation of these logs</td>
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Examples:

- Examples:
  - “TMD-SIDIS”, Higgs-$q_T$
  - For simplest observables: TMD factorization
  - Perturbation theory: double-logs
    \( \alpha_s^k \log^2 k (q_T/Q) \)
  - TMD evolution = resummation of these logs
Connections between the two:

- $q_T$ - integrated (weighted) cross sections revert to single-scale problem

- this typically involves formal relations such as

$$T_F(x, x) = - \int \frac{d^2 \vec{k}_\perp}{2\pi} \frac{\vec{k}_\perp^2}{M^2} \left( f_{1T}^\perp(x, k_\perp) \right)_{\text{DIS}}$$

( “sign puzzle” Kang, Qiu, WV, Yuan – see Kang’s talk )
\[ \frac{d\sigma}{dq_\perp} \]

\[ q_\perp \ll Q: \text{TMD fact.} \]

\[ \Lambda_{QCD} \ll q_\perp \ll Q: \text{same physics} \]

\[ q_\perp \sim Q: \text{coll.fact.} \]

- Likewise:
Single-scale processes
Factorized cross section: e.g. Drell-Yan

\[ Q^4 \frac{d\sigma}{dQ^2} = \sum_{ab} \int dxa dx_b f_a(x_a, \mu) f_b(x_b, \mu) \omega_{ab} \left( z = \frac{Q^2}{\hat{s}}, \alpha_s(\mu), \frac{Q}{\mu} \right) + \ldots \]

- \( f_{a,b} \) parton distributions: non-pert., but universal
- \( \omega_{ab} \) partonic cross sections: process-dep., but pQCD
  \[ \omega_{ab} = \omega_{ab}^{(LO)} + \frac{\alpha_s}{2\pi} \omega_{ab}^{(NLO)} + \ldots \]
- \( \mu \sim Q \) factorization / renormalization scale

Numerous applications: \( f(x), \Delta f(x), T_F(x, x') \), \ldots
LO:

\[ z = \frac{Q^2}{\hat{s}} \]

\[ \omega_{q\bar{q}}^{(LO)} \propto \delta(1 - z) \]
• **NLO correction:**

\[ z \to 1 : \]

\[ \omega_{qq}^{(NLO)} \propto \alpha_s \left( \frac{\log(1-z)}{1-z} \right) + \ldots \]

• **higher orders:**

\[ \omega_{qq}^{(N^kLO)} \propto \alpha_s^k \left( \frac{\log^{2k-1}(1-z)}{1-z} \right) + \ldots \]

“threshold logarithms”

• for \( z \to 1 \) real radiation inhibited

• (so, not really a “single-scale” problem)
• logs emphasized by parton distributions:

\[ d\sigma \sim \int_\tau^1 \frac{dz}{z} \mathcal{L}_{q\bar{q}} \left( \frac{\tau}{z} \right) \omega_{q\bar{q}}(z) \quad \tau = \frac{Q^2}{S} \]

\[ z = 1 \text{ relevant, in particular as } \tau \to 1 \]

• logs more relevant at lower hadronic energies
Large logs can be resummed to all orders

Catani, Trentadue; Sterman; ...

- factorization of matrix elements in soft limit
- and of phase space when integral transform is taken:

\[
\delta \left( 1 - z - \sum_{i=1}^{n} z_i \right) = \frac{1}{2\pi i} \int_{C} dN \, e^{N(1-z-\sum_{i=1}^{n} z_i)}
\]

\[
\tilde{\omega}_{q\bar{q}}^{(\text{res})}(N) \propto \exp \left[ 2 \int_{0}^{1} dy \, y^{N-1} \int_{\mu^2}^{Q^2(1-y)^2} \frac{d{k}_2^2}{k^2_2} \, A_q(\alpha_s(k^2_2)) + \ldots \right]
\]

\[
A_q(\alpha_s) = C_F \left\{ \frac{\alpha_s}{\pi} + \left( \frac{\alpha_s}{\pi} \right)^2 \left[ \frac{C_A}{2} \left( \frac{67}{18} - \zeta(2) \right) - \frac{5}{9} T_R n_f \right] + \ldots \right\}
\]

- logs enhance cross section!
LL :
\[ \tilde{\omega}^{(\text{res})}_{q\bar{q}}(N) \propto \exp \left[ + \frac{2C_F}{\pi} \alpha_s \ln^2 N + \ldots \right] \]

to NLL :
\[ \tilde{\omega}^{(\text{res})}_{q\bar{q}}(N) \propto \exp \left\{ 2 \ln \bar{N} \ h^{(1)}(\lambda) + 2h^{(2)} \left( \lambda, \frac{Q^2}{\mu^2} \right) \right\} \]

\[ \lambda = \alpha_s(\mu^2) b_0 \ \text{log}(N e^{\gamma_E}) \]

\[ h^{(1)}(\lambda) = \frac{A_q^{(1)}}{2\pi b_0 \lambda} \left[ 2\lambda + (1 - 2\lambda) \ln(1 - 2\lambda) \right] \]

\[ h^{(2)} = \ldots \]
Note,

\[ \int_0^1 d\tau \, \tau^{N-1} \frac{d\sigma}{dQ^2} \propto \sum_{ab} \left( \int_0^1 dx_a \, x_a^N \, f_a \right) \left( \int_0^1 dx_b \, x_b^N \, f_b \right) \tilde{\omega}_{ab}(N) \]

Inverse transform:

\[ \sigma^{\text{res}} = \frac{1}{2\pi i} \int_{C-i\infty}^{C+i\infty} dN \, \tau^{-N} \tilde{\sigma}^{\text{res}}(N) \]

"Minimal prescription"

Catani, Mangano, Nason, Trentadue
Drell-Yan process in $\pi N$ scattering

M. Aicher, A. Schäfer, WV
• Drell-Yan process has been main source of information on pion structure:

\[ d\sigma = \sum_{ab} \int dx_a \int dx_b f_a^\pi(x_a, \mu) f_b(x_b, \mu) d\hat{\sigma}_{ab}(x_a P_a, x_b P_b, Q, \alpha_s(\mu), \mu) \]

• Kinematics such that data mostly probe valence region: ~200 GeV pion beam on fixed target
LO extraction of $u_\nu$ from E615 data: $\sqrt{S} = 21.75$ GeV

\[ \sim (1 - x)^2 \]

QCD counting rules
Farrar, Jackson; Berger, Brodsky; Yuan Blankenbecler, Gunion, Nason
Dyson-Schwinger
Hecht et al.
\[ \sqrt{S} = 19 \text{ GeV} \]

(Compass kinematics)

Aicher, Schäfer, WV
(earlier studies: Shimizu, Sterman, WV, Yokoya)
\[ x\nu^\pi(x, Q_0^2) = N_x x^\alpha (1 - x)^\beta (1 + \gamma x^\delta) \]

<table>
<thead>
<tr>
<th>Fit</th>
<th>(2\langle x\nu^\pi \rangle)</th>
<th>(\alpha)</th>
<th>(\beta)</th>
<th>(\gamma)</th>
<th>(K)</th>
<th>(\chi^2) (no. of points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.55</td>
<td>0.15 ± 0.04</td>
<td>1.75 ± 0.04</td>
<td>89.4</td>
<td>0.999 ± 0.011</td>
<td>82.8 (70)</td>
</tr>
<tr>
<td>2</td>
<td>0.60</td>
<td>0.44 ± 0.07</td>
<td>1.93 ± 0.03</td>
<td>25.5</td>
<td>0.968 ± 0.011</td>
<td>80.9 (70)</td>
</tr>
<tr>
<td>3</td>
<td>0.65</td>
<td>0.70 ± 0.07</td>
<td>2.03 ± 0.06</td>
<td>13.8</td>
<td>0.919 ± 0.009</td>
<td>80.1 (70)</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
<td>1.06 ± 0.05</td>
<td>2.12 ± 0.06</td>
<td>6.7</td>
<td>0.868 ± 0.009</td>
<td>81.0 (70)</td>
</tr>
</tbody>
</table>

\[ Q = 4 \text{ GeV} \]

\[ \sim (1 - x)^{2.34} \]
E615
$\sqrt{t} = 0.335$

$\frac{d^2\sigma}{d\sqrt{t}dx_F}$ (nb/nucleon)

$\frac{d^2\sigma}{d\sqrt{t}dx_F}$ (nb/nucleon)

$\Delta_\mu$

$\mu = Q/2$

$\mu = 2Q$

$\sqrt{t} = 0.289$
Hadron production
\[ p_T, \eta \quad \quad x_T = \frac{2p_T}{\sqrt{S}} \]

\[ \frac{d\sigma}{dp_T d\eta} = \int_{x_a^0}^1 dx_a \int_{x_b^0}^1 dx_b \int_{z_c^0}^1 dz_c \ f_a(x_a) f_b(x_b) \frac{d\hat{\sigma}_{ab \rightarrow c}}{dp_T d\eta} D_c(z_c) \]

\[ x_a^0 = \frac{x_T e^\eta}{2 - x_T e^{-\eta}} \quad \quad x_b^0 = \frac{x_a x_T e^{-\eta}}{2x_a - x_T e^\eta} \]

\[ z_c^0 = \frac{2p_T}{\sqrt{\hat{s}}} \cosh \left( \eta - \frac{1}{2} \ln \frac{x_a}{x_b} \right) \]
Partonic variables: 
\[ \hat{x}_T = \frac{2p_T}{z_c \sqrt{\hat{s}}} \quad \hat{\eta} = \eta - \frac{1}{2} \ln \frac{x_a}{x_b} \]

\[ \frac{d\sigma}{dp_T d\eta} = \int_{x_a}^{1} dx_a \int_{x_b}^{1} dx_b \int_{z_c}^{1} dz_c \ f_a(x_a) f_b(x_b) \ \frac{d\hat{\sigma}_{ab \to c}(\hat{x}_T, \hat{\eta})}{dp_T d\eta} \ D_c(z_c) \]

\[ \{ \text{mass}^2 \} = s_4 \]

\[ s_4 = \hat{s} \left( 1 - \hat{x}_T \cosh \hat{\eta} \right) \]
LO:

\[ d\hat{\sigma}_{ab\rightarrow c}^{(\text{LO})} \propto \delta \left( \frac{s_4}{\hat{s}} \right) \]

NLO:

\[ d\hat{\sigma}_{ab\rightarrow c}^{(\text{NLO})} \propto \alpha_s \left( \frac{\log(s_4/\hat{s})}{s_4/\hat{s}} \right) + \ldots \]

yet higher orders:

\[ d\hat{\sigma}_{ab\rightarrow c}^{(\text{N}^k\text{LO})} \propto \alpha_s^k \left( \frac{\log^{2k-1}(s_4/\hat{s})}{s_4/\hat{s}} \right) + \ldots \]
Resummation is more complicated now:

- color structure of hard scattering
- cross section does not simplify under Mellin-moments
\[ \int_0^1 \frac{ds_4}{s} \left( 1 - \frac{s_4}{s} \right)^N \frac{d \sigma_{ab\rightarrow c}^{\text{resum}}(\hat{x}_T, \hat{\eta})}{dp_T d\eta} = \Delta_a^N \Delta_b^N \Delta_c^N J_{\text{recoil}}^N \]

Kidonakis, Oderda, Sterman
Bonciani, Catani, Mangano, Nason
Banfi, Salam, Zanderighi
Dokshitzer, Marchesini

\[ \sum_{IK} [H_{IK}^{ab\rightarrow cd} S_{KI}^{ab\rightarrow cd}] (\hat{\eta}, N) \]
\[ \int \frac{d\sigma}{dp_T d\eta} \]

\[ = \int_{x_T^2}^1 dx_a \int_{x_T^2/x_a}^1 dx_b \int_{x_T/\sqrt{x_a x_b}}^1 dz_c \ f_a(x_a) f_b(x_b) \left( \frac{d\hat{\sigma}_{ab\to c}}{dp_T} \right) \frac{x_T}{z_c \sqrt{x_a x_b}} D_c(z_c) \]

\[ \rightarrow \text{used in studies until recently} \]

de Florian, WV, ...

\[ \sigma_{\text{resum}}(\eta \in \exp) \approx \sigma_{\text{resum}}(\text{all } \eta) \]

\[ \times \frac{\sigma_{\text{NLO}}(\eta \in \exp)}{\sigma_{\text{NLO}}(\text{all } \eta)} \]
WA70

\[ pp \rightarrow \pi^0 + X \]

\[ E^* d^3 \sigma/dp^3 \ (\text{pb/GeV}^2) \]

- \( \mu = 1 \)
- \( \mu = 2 \)

NLL
NLO
MRST2002
KKP

WA70 \( \sqrt{s} = 22.9 \text{ GeV} \) \( |\eta| < 0.05 \)

(effects at RHIC more modest)
COMPASS

\[
\frac{1}{2\pi p_T} \frac{d\sigma}{dp_T}
\]

-NLO pQCD curves by W. Vogelsang (DSS FF, CTEQ6M5)

- \( \mu = p_T/2 \)
- \( \mu = p_T \)
- \( \mu = 2p_T \)

COMPASS - 30% of 2004
\( \mu^+ + d \to \mu'^+ + h^+ + X \)

\( \sqrt{s} = 17.4 \text{ GeV} \)
\( Q^2 < 0.1 \text{ (GeV/c)}^2, -0.1 < \eta < 1.7 \)

- systematic uncertainty
- statistical uncertainty
- additional 10% normalization uncertainty

\[
\frac{1}{(2\pi p_T)} d\sigma/dp_T \text{ (pb (GeV/c)}^2)
\]

-0.1 < \( \eta < 1.7 \)

\( Q^2_{\text{max}} = 0.1 \text{ GeV}^2 \)

COMPASS: \( S = (17.4 \text{ GeV})^2 \)
\[
\frac{d\sigma}{dp_T d\eta} = \int_{x_a^0}^1 dx_a f_a(x_a) \int_{x_b^0}^1 dx_b f_b(x_b) \int_{z_c^0}^1 dz_c \frac{d\hat{\sigma}_{ab \to c}(\hat{x}_T, \hat{\eta})}{dp_T d\eta} D_c(z_c)
\]

\[
z_c^0 = \frac{2p_T}{\sqrt{s}} \cosh(\hat{\eta}) = z_c \hat{x}_T \cosh(\hat{\eta})
\]

- factorizes under Mellin-moments!
- technique allows to do resummation at fixed rapidity
$\overline{\psi} \ E706 \ pBe \rightarrow \pi^0 \pi^0 X \quad s^{1/2} = 38.8 \text{ GeV}$
(with E711 cuts)
• should be very relevant for single-spin asymmetries in $pp \rightarrow \pi X$

[Graphs and figures related to single-spin asymmetries and corresponding data points are shown.]

Used to extract TF:

Qiu, Sterman
Kouvaris et al.
Kanazawa, Koike
Kang, Prokudin
STAR

$p+p \rightarrow \pi^0 + X \quad \sqrt{s}=200 \text{ GeV}$

$E d^3\sigma/d^3p$ (µb c³/GeV²)

$\pi^0$ mesons
- $3.7<\eta<4.15$
- $3.4<\eta<4.0$
- $3.05<\eta<3.45$

$\langle \eta \rangle = 4.00$
$\langle \eta \rangle = 3.3$
$\langle \eta \rangle = 3.8$

NLO pQCD calc.
- KKP FF
- Kretzer FF

$p+p \rightarrow \pi^0 + X \quad \sqrt{s}=52.8 \text{ GeV}$

$\theta = 5^\circ$
$\theta = 10^\circ$
$\theta = 53^\circ$

Bourrely, Soffer
• expect large corrections at high-$x_F$

• cf. NLO calculation of Drell-Yan single-spin asymm.

\[
\frac{d\langle q_\perp \Delta \sigma(S_\perp) \rangle}{dQ^2} = \sigma_0 \frac{\alpha_s}{2\pi} \int \frac{dx}{x} \frac{dx'}{x'} T_F(x, x; \mu^2) \bar{q}(x'; \mu^2) \left[ 8C_F \left( \frac{\ln(1 - z)}{1 - z} \right)_+ + \ldots \right]
\]

• affect phenomenological extraction of $T_F$?
Two-scale processes
well-known feature: emergence of Sudakov logarithms

\[ \alpha_s^k \log^{2k-1} \left( \frac{Q^2}{q_T^2} \right) \frac{q_T^2}{Q^2} + \ldots \]
• these logs are related (although not identical) to the threshold logs

• all-order resummation for “ordinary” cross section understood for long time

\[ \delta^2 \left( \vec{q}_T + \sum_i \vec{k}_{T_i} \right) = \frac{1}{(2\pi)^2} \int d^2b \ e^{-i\vec{b} \cdot (\vec{q}_T + \sum_i \vec{k}_{T_i})} \]

\[ \log^{2k-1} \left( \frac{Q^2}{q_T^2} \right) \frac{q_T^2}{Q^2} \leftrightarrow \log^{2k} (bQ) \]

\[ \hat{\sigma}^{(\text{resum})}(b) \propto \exp \left[ 2 \int_0^{Q^2} \frac{dk_{\perp}^2}{k_{\perp}^2} \left( J_0(bk_{\perp}) - 1 \right) \right] \left\{ A_q(\alpha_s(k_{\perp}^2)) \log \frac{Q^2}{k_{\perp}^2} + \ldots \right\} \]

(Sudakov exponent)

• logs suppress cross section!
• great strides forward recently on resummation formalism for single-spin observables

Kang, Xiao, Yuan
Aybat, Collins, Qiu, Rogers

• Kang, Xiao, Yuan: use full NLO calculation of \( d\sigma / dq_T \)
(in b-space)

\[
\sigma_{UT}(b) \sim \frac{\alpha_s}{2\pi} \left( -i b \frac{\alpha}{2} \right) \left\{ \left[ -\frac{1}{\epsilon} + \ln \frac{4}{b^2 \mu^2} e^{-2\gamma_E} \right] (\mathcal{P}_{q/g} \otimes \bar{q}(z_2')) + \mathcal{P}_{qg \rightarrow qg} \otimes T_F(z_1') \right\} \\
+ C_F (1 - \xi_2) \delta(1 - \xi_1) \\
+ \left( -\frac{1}{2N_c} \right) (1 - \xi_1) \delta(1 - \xi_2) + \delta(1 - \xi_1) \delta(1 - \xi_2) \\
\times \left[ -\ln^2 \left( \frac{Q^2 b^2}{4} e^{2\gamma_E - \frac{3}{2}} \right) - \frac{23}{4} + \pi^2 \right] \}
\]
• **Aybat, Collins, Qiu, Rogers:**
  organize in terms of simple parton-model TMD-like formula

\[
\frac{d\sigma}{dq_{\perp}^2} \sim \sigma_0 \int d^2 k_{\perp,1} \int d^2 k_{\perp,2} \, \bar{F}(x_1, k_{\perp,1}, Q) \, F(x_2, k_{\perp,2}, Q) \, \delta^{(2)}(k_{\perp,1} + k_{\perp,2} - q_{\perp})
\]

• find (at large $Q$)

\[
\tilde{F}_{1T}^{\perp f}(x, b_T; \mu, \zeta_F) = \sum_j \frac{M_p b_T}{2} \int_{x}^{1} \frac{d\hat{x}_1}{\hat{x}_1} \frac{d\hat{x}_2}{\hat{x}_2} \tilde{C}_f_{/j}^{Sivers}(\hat{x}_1, \hat{x}_2, b_*, \mu_b^2, \mu_b, g(\mu_b)) \, T_{F/j/P}(\hat{x}_1, \hat{x}_2, \mu_b)
\]

\[
\sim \text{Sudakov}
\]

\[
\times \exp \left\{ \ln \frac{\sqrt{\zeta_F}}{\mu_b} \tilde{K}(b_*; \mu_b) + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[ \gamma_F(g(\mu'); 1) - \ln \frac{\sqrt{\zeta_F}}{\mu'} \gamma_K(g(\mu')) \right] \right\}
\]

\[
\times \exp \left\{ -g_{Sivers}^{f/p}(x, b_T) - g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{Q_0} \right\}
\]

non-perturbative piece

• represents “evolution” of TMDs
Reason for non-perturbative piece:

\[ \hat{\sigma}^{(\text{resum})}(b) \propto \exp \left[ \frac{2C_F}{\pi} \int_0^{Q^2} \frac{dk^2_{\perp}}{k^2_{\perp}} \left( J_0(bk_{\perp}) - 1 \right) \left\{ \alpha_s(k^2_{\perp}) \log \frac{Q^2}{k^2_{\perp}} + \ldots \right\} \right] \]

Logarithms are contained in

\[ \exp \left[ - \frac{2C_F}{\pi} \int_{1/b^2}^{Q^2} \frac{dk^2_{\perp}}{k^2_{\perp}} \left\{ \alpha_s(k^2_{\perp}) \log \frac{Q^2}{k^2_{\perp}} + \ldots \right\} \right] \]

→ needs prescription for dealing with large-\( b \)

\[ \int d^2b \ e^{-i\vec{b} \cdot \vec{q}_T} \ldots \]

e.g. \( b^* \equiv \frac{b}{\sqrt{1 + b^2/b^2_{\text{max}}}} \) or

\[ \begin{array}{c}
\end{array} \]
Contribution from very low $k_\perp$

\[
\exp \left[ -b^2 \frac{C_F}{\pi} \int dk_\perp^2 \alpha_s(k_\perp^2) \log \left( \frac{Q}{k_\perp} \right) \right]
\]

\[
= g_1 + g_2 \log \left( \frac{Q}{Q_0} \right)
\]

- suggests Gaussian non-pert. contribution with logarithmic Q dependence
- expected to be universal (unpol. <-> Sivers)
- “global” fits
  Davies, Webber, Stirling; Landry et al., Ladinsky, Yuan; Qiu, Zhang; Konychev, Nadolsky
- values of $g_1, g_2$ depend on treatment of large-b region!
Evolution of Sivers fcts. (Gaussian)

Aybat, Collins, Qiu, Rogers

- cf. unpolarized TMD
  Aybat, Rogers

- evolution for Sivers more sensitive to large b
Interesting “follow-up”:

- we know there is no TMD factorization for general QCD hard scattering

- gauge links in parton distributions “know” about full hard process

- what does this imply for perturbative resummation?

Bomhof, Mulders, Pijlman; Collins, Qiu; Mulders, Rogers
• at some order, breakdown of “standard” formula should occur

• recent study of collinear singularities at high orders

Space-like (vs. time-like) collinear limits in QCD: is factorization violated?

Stefano Catani (a), Daniel de Florian (b)(c) and Germán Rodrigo (d)

usually,

\[ \hat{\sigma}^{(0)} \sim P_{qq} \otimes \hat{\sigma}^{(0)} \]
Conclusions:

- numerous applications of QCD resummation to hadronic scattering:
  Threshold-resum. / qT-resum. → “joint” resummation?
  Laenen, Sterman, WV

- many are relevant for the processes we use to determine nucleon structure

- great recent progress, in particular in TMD area