Higgs Boson Distributions from Effective Field Theory

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Outline

- Introductory Remarks
- Collins-Soper-Sterman Approach
- Effective field theory Approach

- Factorization and resummation formula:

\[
\frac{d^2 \sigma}{dp_T^2 dY} \sim H \otimes G^{ij} \otimes f_i \otimes f_j
\]

- Numerical Results and Comparison with Data for Z-production
- Conclusions
The Higgs boson is the last missing piece of the SM.

Search strategy complicated by decay properties:

- Typically there are three search regions:
  - (i) $90 \, \text{GeV} < M_H < 130 \, \text{GeV}$,
  - (ii) $130 \, \text{GeV} < M_H < 2 \cdot M_{Z^0}$,
  - (iii) $2 \cdot M_{Z^0} < M_H < 800 \, \text{GeV}$.

Search strategies vary in different mass regions.
Higgs Search at the LHC

- For the Higgs mass range:
  \[ 130 \text{ GeV} < m_h < 180 \text{ GeV} \]
- Higgs search channel:
  \[ gg \rightarrow h \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}. \]
- Large backgrounds from:
  \[ pp \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow \ell^+\nu\ell^-\bar{\nu} + \text{jets} \]
- Background elimination requires jet vetoes:
  \[ \text{veto events with jets of } p_T > 20 \text{ GeV} \]

<table>
<thead>
<tr>
<th>LHC 14 TeV</th>
<th>Accepted event fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>reaction ( pp \rightarrow X )</td>
<td>( \sigma \times BR^2 ) [pb]</td>
</tr>
<tr>
<td>( pp \rightarrow H \rightarrow W^+W^- \ (m_H = 170 \text{ GeV}) )</td>
<td>1.24</td>
</tr>
<tr>
<td>( pp \rightarrow W^+W^- )</td>
<td>7.4</td>
</tr>
<tr>
<td>( pp \rightarrow t\bar{t} \ (m_t = 175 \text{ GeV}) )</td>
<td>62.0</td>
</tr>
<tr>
<td>( pp \rightarrow Wtb \ (m_t = 175 \text{ GeV}) )</td>
<td>( \approx 6 )</td>
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Jet Veto enhances signal to background ratio

(Dittmar, Dreiner)
Higgs low $p_T$ Restriction

$pp \rightarrow h + X$

• We restrict the transverse momentum of the Higgs:

\[ m_h \gg p_T \gg \Lambda_{QCD} \]

• Such $p_T$ restrictions can be studied for any color neutral particle. We use Higgs production as an illustrative example.
LHC is a complicated environment!

- Proton structure
- soft, collinear radiation
- underlying events
- hadronization
- hard interactions
- multiple scale physics

• How do we make sense of this environment?

Factorization!
Factorization

\[ d\sigma = \sum_{i,j} d\sigma_{ij}^{\text{part}} \otimes f_i(\xi_a) \otimes f_j(\xi_b) \]

- Separates perturbative and non-perturbative scales.
- Turns perturbative calculations into a predictive framework in the complicated collider environment.
- Factorization is not obvious and often difficult to prove. Few theorems exist for hadron colliders.
Resummation

- Fully inclusive Drell-Yan:

\[ d\sigma = \sum_{i,j} d\sigma_{ij}^{\text{part}} \otimes f_i(\xi_a) \otimes f_j(\xi_b) \]

Lives at the hard scale. Live at non-perturbative scale.

- Large logarithms of hard and non-perturbative scales arise. Resummation needed.

- Resummation done by evaluating PDFs at the hard scale after renormalization group running (DGLAP).
In the presence of final state restrictions:

\[ d\sigma = \sum_{i,j} d\sigma_{ij}^{\text{part}} \otimes f_i(\xi_a) \otimes f_j(\xi_b) \]

- Multiple disparate scales involved.
- Live at non-perturbative scale.
- Additional resummation needed.

The low transverse momentum distribution in Drell-Yan is such an example.
Why do logs arise from final state restrictions?

- Recall fully inclusive electron-positron annihilation.

- Incomplete cancellation of IR divergences in presence of final state restrictions gives rise to large logarithms of restricted kinematic variable.

Infrared Safety!
Low pT Region

• The schematic perturbative series for the pT distribution for $pp \rightarrow h + X$

$$\frac{1}{\sigma} \frac{d\sigma}{dp_T^2} \simeq \frac{1}{p_T^2} \left[ A_1 \alpha_s \ln \frac{M^2}{p_T^2} + A_2 \alpha_s^2 \ln^3 \frac{M^2}{p_T^2} + \ldots + A_n \alpha_s^n \ln^{2n-1} \frac{M^2}{p_T^2} + \ldots \right]$$

Large Logarithms spoil perturbative convergence

• Resummation of large logarithms required.

• Resummation has been studied in great detail in the Collins-Soper-Sterman formalism.

(Davies, Stirling; Arnold, Kauffman; Berger, Qiu; Ellis, Veseli, Ross, Webber; Ladinsky, Yuan; Fai, Zhang; Catani, Emilio, Trentadue; Hinchliffe, Novae; Florian, Grazzini, ....)
Collins-Soper-Sterman Formalism
CSS Formalism

\[ A(P_A) + B(P_B) \rightarrow C(Q) + X, \quad C = \gamma^*, W^\pm, Z, h \]

- The transverse momentum distribution in the CSS formalism is schematically given by:

\[
\frac{d\sigma_{AB\rightarrow CX}}{dQ^2 \ dy \ dQ_T^2} = \frac{d\sigma^{(\text{resum})}_{AB\rightarrow CX}}{dQ^2 \ dy \ dQ_T^2} + \frac{d\sigma^{(Y)}_{AB\rightarrow CX}}{dQ^2 \ dy \ dQ_T^2}
\]

- Most singular contribution

- Soft or collinear pT emission

- Back to Back hard jets
CSS Formalism

Focus of this talk

\[
\frac{d\sigma_{AB\rightarrow CX}}{dQ^2 \, dy \, dQ^2_T} = \frac{d\sigma^{(\text{resum})}_{AB\rightarrow CX}}{dQ^2 \, dy \, dQ^2_T} + \frac{d\sigma^{(Y)}_{AB\rightarrow CX}}{dQ^2 \, dy \, dQ^2_T}
\]

- Singular as at least \(Q_T^{-2}\) as \(Q_T \rightarrow 0\)

- Important in region of small \(Q_T\).

- Treated with resummation.

- Less Singular terms.

- Important in region of large \(Q_T\).
CSS Formalism

- The CSS resummation formula takes the form:

\[
\frac{d^2\sigma}{dp_T\,dY} = \sigma_0 \int \frac{d^2b_\perp}{(2\pi)^2} e^{-i\vec{p}_T\cdot\vec{b}_\perp} \sum_{a,b} \left[ C_a \otimes f_{a/P} \right] (x_A, b_0/b_\perp) \left[ C_b \otimes f_{b/P} \right] (x_B, b_0/b_\perp)
\]

\[
\times \exp \left\{ \int_{b_0^2/b_\perp^2}^{\hat{Q}^2} \frac{d\mu^2}{\mu^2} \left[ \ln \frac{\hat{Q}^2}{\mu^2} A(\alpha_s(\mu^2)) + B(\alpha_s(\mu^2)) \right] \right\} \cdot \text{Sudakov Factor}
\]

Coefficients with well defined perturbative expansions
The CSS resummation formula takes the form:

\[
\frac{d^2 \sigma}{dp_T \, dY} = \sigma_0 \int \frac{d^2 b_\perp}{(2\pi)^2} e^{-i \vec{p}_T \cdot \vec{b}_\perp} \sum_{a,b} \left[ C_a \otimes f_a/P \right] (x_A, b_0/b_\perp) \left[ C_b \otimes f_b/P \right] (x_B, b_0/b_\perp) \\
\times \exp \left\{ \int_{b_0^2/b_\perp^2} \frac{d\mu^2}{\mu^2} \left[ \ln \frac{\hat{Q}^2}{\mu^2} A(\alpha_s(\mu^2)) + B(\alpha_s(\mu^2)) \right] \right\}.
\]

PDF

Perturbatively calculable

Sudakov Factor

Coefficients with well defined perturbative expansions

Landau Pole
CSS Formalism

\[
\frac{d^2 \sigma}{dp_T dY} = \sigma_0 \int \frac{d^2 b_\perp}{(2\pi)^2} e^{-ip_T \cdot \vec{b}_\perp} \sum_{a,b} [C_a \otimes f_{a/P}](x_A, b_0/b_\perp) [C_b \otimes f_{b/P}](x_B, b_0/b_\perp) \\
\times \exp \left\{ \int_{\hat{Q}_0^2 / \mu_0^2}^{\hat{Q}_2^2 / \mu_2^2} \frac{d\mu^2}{\mu^2} \left[ \ln \frac{\hat{Q}^2}{\mu^2} A(\alpha_s(\mu^2)) + B(\alpha_s(\mu^2)) \right] \right\}.
\]

- Landau pole appears for ANY pT.
## CSS Formalism

\[
\frac{d^2 \sigma}{dp_T \, dY} = \sigma_0 \int \frac{d^2 b_\perp}{(2\pi)^2} e^{-i\vec{p}_T \cdot \vec{b}_\perp} \sum_{a,b} \left[ C_a \otimes f_{a/P} (x_A, b_0/b_\perp) \right] \left[ C_b \otimes f_{b/P} (x_B, b_0/b_\perp) \right] \times \exp \left\{ \int_0^{\hat{Q}^2} \frac{d\mu^2}{\mu^2} \left[ \ln \frac{\hat{Q}^2}{\mu^2} A(\alpha_s(\mu^2)) + B(\alpha_s(\mu^2)) \right] \right\}.
\]

- **Landau pole** appears for ANY pT.
- **Landau pole** must be treated with a **model dependent prescription**.

(Collins, Soper, Sterma; Kulesza, Laenen, Vogelsang; Qiu, Zhang,...)
CSS Formalism

\[ \frac{d^2 \sigma}{dp_T dY} = \sigma_0 \int \frac{d^2 b_\perp}{(2\pi)^2} e^{-i\vec{p}_T \cdot \vec{b}_\perp} \sum_{a,b} \left[ C_a \otimes f_{a/P} \right] (x_A, b_0/b_\perp) \left[ C_b \otimes f_{b/P} \right] (x_B, b_0/b_\perp) \]

\[ \times \exp \left\{ \int_{\hat{Q}^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[ \ln \frac{\hat{Q}^2}{\mu^2} A(\alpha_s(\mu^2)) + B(\alpha_s(\mu^2)) \right] \right\} . \]

- Landau pole appears for ANY pT.
- Landau pole must be treated with a model dependent prescription.
- Obtaining a smooth transition from low to high pT is typically plagued with problems due to prescription dependence of resummed result.

(Collins, Soper, Sterma; Kulesza, Laenen, Vogelsang; Qiu, Zhang,...)
EFT Approach
EFT framework

• The low transverse momentum distribution is affected by physics at the scales:

\[ m_h \gg p_T \gg \Lambda_{QCD} \]

• Hierarchy of scales suggests EFT approach with well defined power counting.

• The most singular pT emissions recoiling against the Higgs are soft and collinear emissions whose dynamics may be addressed in Soft-Collinear Effective Theory (SCET).
EFT framework

\[ \text{QCD}(n_f = 6) \rightarrow \text{QCD}(n_f = 5) \rightarrow \text{SCET}_{pT} \rightarrow \text{SCET}_{\Lambda_{QCD}} \]

Top quark integrated out.

Matched onto SCET.

Soft-collinear factorization.

Matching onto PDFs.
EFT framework

\[ \text{QCD}(n_f = 6) \rightarrow \text{QCD}(n_f = 5) \rightarrow \text{SCET}_{p_T} \rightarrow \text{SCET}_{\Lambda_{QCD}} \]

Top quark integrated out.

Matched onto SCET.

Soft-collinear factorization.

Matching onto PDFs.

Newly defined objects describing soft and collinear pT emissions
SCET Factorization Formula

- Factorization formula derived in SCET in schematic form:

\[
\frac{d^2 \sigma}{dp_T^2 dY} \sim H \otimes G^{ij} \otimes f_i \otimes f_j
\]

- Hard function.
- Transverse momentum function.
- PDFs.
- Sums logs of $m_h/p_T$
- Evaluated at $p_T$ scale.
- RG evolved to $p_T$ scale

- All objects are field theoretically defined.
- Large logarithms are summed via RG equations in EFTs.
- Formulation is free of Landau poles.
Integrating out the top

- Leading term in the Higgs effective interaction with Gluons:

\[
\mathcal{L}_{m_t} = C_{GGh} \frac{h}{V} G^\alpha_{\mu\nu} G^{\alpha}_{\mu\nu}, \quad C_{GGh} = \frac{\alpha_s}{12\pi} \left\{ 1 + \frac{11}{4} \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2) \right\}
\]

Two loop result for Wilson coefficient.

(Chetyrkin, Kniehl, Kuhn, Schroder, Steinhauser, Sturm)
Matching onto SCET

• Matching equation:

\[ O_{QCD} = \int d\omega_1 \int d\omega_2 \ C(\omega_1, \omega_2) \ O(\omega_1, \omega_2) \]

• Effective SCET operator:

\[ O(\omega_1, \omega_2) = g_{\mu\nu} h \ T \{ \text{Tr} \left[ S_n (g B_{n\perp}^\mu) \omega_1 S_n^\dagger S_{\bar{n}} (g B_{\bar{n}\perp}^\nu) \omega_2 S_{\bar{n}}^\dagger \right] \} \]

Soft and Collinear emissions build into Wilson lines determined by soft and collinear gauge invariance of SCET.
• **SCET differential cross-section:**

\[
\frac{d^2\sigma}{du\,dt} = \frac{1}{2Q^2} \left[ \frac{1}{4} \right] \int \frac{d^2 p_{h\perp}}{(2\pi)^2} \int \frac{dn\cdot p_h d\vec{n}\cdot p_h}{(2\pi)^2} (2\pi)^2 \theta(n\cdot p_h + \vec{n}\cdot p_h) \delta(n\cdot p_h p_h - \vec{p}_{h\perp} - m_h^2) \\
\times \delta(u - (p_2 - p_h)^2) \delta(t - (p_1 - p_h)^2) \sum_{\text{initial pols.}} \sum_X |C(\omega_1, \omega_2) \otimes \langle h_{X_n X_{\bar{n}} X_s} | O(\omega_1, \omega_2) | pp \rangle|^2 \\
\times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - P_{X_n} - P_{X_{\bar{n}}} - P_{X_s} - p_h),
\]

• **Schematic form of SCET cross-section:**

\[
\frac{d^2\sigma}{dp_T^2 dY} \sim \int PS |C \otimes \langle O \rangle|^2
\]

Phase space integrals. \hspace{1cm} Hard matching coefficient. \hspace{1cm} SCET matrix element.

Factorize using soft-collinear decoupling
Factorization in SCET

\[ \frac{d^2 \sigma}{dp_T^2 dY} \sim \int PS \left| C \otimes \langle O \rangle \right|^2 \]

Factorize cross-section using soft-collinear decoupling in SCET

\[ \frac{d^2 \sigma}{dp_T^2 dY} \sim H \otimes B_n \otimes \bar{B}_n \otimes S \]

Hard matching coefficient squared

Decoupled collinear and soft functions
Factorization in SCET

\[
\frac{d^2\sigma}{dp_T^2dY} \sim H \otimes B_n \otimes B_{\bar{n}} \otimes S
\]

Hard function
Impact-parameter Beam Functions (iBFs)
Soft function

Physics of hard scale. Sums logs of mh/pT.
Describes collinear pT emissions
Describes soft pT emissions
Factorization in SCET

- Factorization formula in full detail:

\[
\frac{d^2 \sigma}{du \, dt} = \frac{(2\pi)^2}{(N_c^2 - 1)^2 \lambda_2} \int dp_h^+ dp_h^- \int d^2 k_{h\perp} \int d^2 b_{\perp} \frac{e^{-i k_{h\perp} \cdot b_{\perp}}}{(2\pi)^2} \delta \left[ u - m_h^2 + Q p_h^- \right] \delta \left[ t - m_h^2 + Q p_h^+ \right] \delta \left[ p_h^+ p_h^- - k_{h\perp}^2 - m_h^2 \right] \int d\omega_1 d\omega_2 |C(\omega_1, \omega_2, \mu)|^2 \\
\times \int dk_n^+ dk_{-n}^- B_{n}^{\alpha \beta}(\omega_1, k_n^+, b_{\perp}, \mu) B_{\bar{n}\alpha \beta}(\omega_2, k_{-n}^-, b_{\perp}, \mu) S(\omega_1 - p_h^- - k_{-n}^-, \omega_2 - p_h^+ - k_n^+, b_{\perp}, \mu)
\]

- iBFs and soft functions field theoretically defined as the Fourier transform of:

\[
J_n^{\alpha \beta}(\omega_1, x^-, x_{\perp}, \mu) = \sum_{\text{initial pols.}} \langle p_1 | [g B_{1n\perp \beta}^A(x^-, x_{\perp}) \delta(\vec{P} - \omega_1) g B_{1n\perp \alpha}^A(0)] | p_1 \rangle
\]

\[
J_{\bar{n}}^{\alpha \beta}(\omega_1, y^+, y_{\perp}, \mu) = \sum_{\text{initial pols.}} \langle p_2 | [g B_{1n\perp \beta}^A(y^+, y_{\perp}) \delta(\vec{P} - \omega_2) g B_{1n\perp \alpha}^A(0)] | p_2 \rangle
\]

\[
S(\zeta, \mu) = \langle 0 | \bar{T} \left[ \text{Tr} \left( S_{\bar{n}} T^D S_{\bar{n}}^\dagger S_n T^C S_n^\dagger \right)(\zeta) \right] T \left[ \text{Tr} \left( S_n T^C S_n^\dagger S_{\bar{n}} T^D S_{\bar{n}}^\dagger \right)(0) \right] | 0 \rangle.
\]
Factorization in SCET

We are here

\[ \frac{d^2 \sigma}{dp_T^2 dY} \sim H \otimes \tilde{B}_n \otimes \tilde{B}_{\bar{n}} \otimes S^{-1} \]

iBFs are proton matrix elements and sensitive to the non-perturbative scale

- The iBFs are matched onto PDFs to separate the perturbative and non-perturbative scales:

\[ \tilde{B}_n = I_{n,i} \otimes f_i, \quad \tilde{B}_{\bar{n}} = I_{\bar{n},j} \otimes f_j \]
• iBF is matched onto the PDF with matching coefficient defined as:

\[ \tilde{B}_{\alpha\beta}^n(z, t^n, b_\perp, \mu) = -\frac{1}{z} \sum_{i=g,q,\bar{q}} \int_0^1 \frac{dz'}{z'} \mathcal{I}^{\alpha\beta}_{n;i,g,i} \left( \frac{z}{z'}, t^n, b_\perp, \mu \right) f_{i/P}(z', \mu) \]

• The PDF is known to be scaleless and defined as:

\[ f_{g/P}(z, \mu) = \frac{-z\bar{n} \cdot p_1}{2} \sum_{\text{spins}} \langle p_1 | \left[ \text{Tr} \left\{ B^\mu_\perp(0) \delta(\vec{P} - z\bar{n} \cdot p_1) B^\mu_\perp(0) \right\} \right] | p_1 \rangle. \]

• The matching coefficient is given by:

\[ \mathcal{I}^{\beta\alpha}_{n;g,i} \left( \frac{z}{z'}, t^n, b_\perp, \mu \right) = -z \left[ \tilde{B}_{\alpha\beta}^n \left( \frac{z}{z'}, z't^n, b_\perp, \mu \right) \right] \text{finite part in dim-reg} \]
Factorization in SCET

\[ \frac{d^2 \sigma}{dp_T^2 dY} \sim H \otimes \tilde{B}_n \otimes \tilde{B}_{\bar{n}} \otimes S^{-1} \]

- After matching the iBFs to the PDFs we get:

\[ \frac{d^2 \sigma}{dp_T^2 dY} \sim H \otimes [I_n,i \otimes f_i] \otimes [I_{\bar{n}},j \otimes f_j] \otimes S^{-1} \]

- Group the perturbative pT scale functions into transverse momentum dependent function(TMF):

\[ \frac{d^2 \sigma}{dp_T^2 dY} \sim H \otimes [I_n \otimes I_{\bar{n}} \otimes S^{-1}] \otimes f_i \otimes f_j \]

We are here

Hard function Transverse momentum dependent function(TMF) PDFs
Factorization Formula

- Factorization formula in full detail:

\[
\frac{d^2 \sigma}{dp_T^2 \, dY} = \frac{\pi^2}{4(N_c^2 - 1)^2 Q^2} \int_0^1 \frac{dx_1}{x_1} \int_0^1 \frac{dx_2}{x_2} \int_0^1 \frac{dx_1'}{x_1'} \int_0^1 \frac{dx_2'}{x_2'} \times H(x_1, x_2, \mu_Q; \mu_T) G^{ij}(x_1, x_1', x_2, x_2', p_T, Y, \mu_T) f_{i/P}(x_1', \mu_T) f_{j/P}(x_2', \mu_T)
\]

Hard function. Transverse momentum function. PDFs.

- The transverse momentum function is a convolution of the iBF matching coefficients and the soft function:

\[
G^{ij}(x_1, x_1', x_2, x_2', p_T, Y, \mu_T) = \int dt^+_n \int dt^-_n \int \frac{d^2 b_\perp}{(2\pi)^2} J_0(|\vec{b}_\perp|p_T)
\times \mathcal{I}^{\beta\alpha}_{n:g,i}(\frac{x_1}{x_1'}, \frac{t^+_n}{t^-_n}, b_\perp, \mu_T) \mathcal{I}^{\beta\alpha}_{n:g,j}(\frac{x_2}{x_2'}, \frac{t^-_n}{t^+_n}, b_\perp, \mu_T)
\times S^{-1}(x_1 Q - e^Y \sqrt{p_T^2 + m_h^2 - \frac{t^-_n}{Q}}, x_2 Q - e^{-Y} \sqrt{p_T^2 + m_h^2 - \frac{t^+_n}{Q}}, b_\perp, \mu_T)
\]
Fixed order and Matching Calculations
One loop Matching onto SCET

\[ O_{QCD} = \int d\omega_1 \int d\omega_2 \, C(\omega_1, \omega_2) \, O(\omega_1, \omega_2) \]

\[ C(\vec{n} \cdot \hat{p}_1 \vec{n} \cdot \hat{p}_2, \mu) = \frac{c \vec{n} \cdot \hat{p}_1 \vec{n} \cdot \hat{p}_2}{v} \left\{ 1 + \frac{\alpha_s}{4\pi} C_A \left[ \frac{11}{2} + \frac{\pi^2}{6} - \ln^2 \left( -\frac{\vec{n} \cdot \hat{p}_1 \vec{n} \cdot \hat{p}_2}{\mu^2} \right) \right] \right\} \]

(Ahrens, Becher, Neubert, Yang; Harlander)
iBFs

- Definition of the iBF:

\[
\tilde{B}^{\alpha\beta}_{n}(x_1, t_1^+, b_\perp, \mu) = \int \frac{db^-}{4\pi} e^{i \frac{t_1^+ b^-}{Q}} \sum_{\text{initial pols. } X_n} \langle p_1 | [g B^A_{1n\perp\beta}(b^-, b_\perp) | X_n \rangle \\
\times \langle X_n | \delta(\bar{P} - x_1 \bar{n} \cdot p_1) g B^A_{1n\perp\alpha}(0) | p_1 \rangle,\]

One loop graphs
Soft function

• Soft function definition:

\[ S(z) = \langle 0 | \text{Tr} \left( \bar{T} \{ S_n T^D S_n^\dagger S_n T^C S_n^\dagger \} \right) (z) \text{Tr} \left( T \{ S_n T^C S_n^\dagger S_n T^D S_n^\dagger \} \right) (0) | 0 \rangle \]
Running
Running

- Factorization formula:

\[
\frac{d^2\sigma}{dp_T^2 dY} \sim H \otimes G^{ij} \otimes f_i \otimes f_j
\]

- Schematic picture of running:

\[ H \]

SCET Running

\[ G^{ij} \]

DGLAP Running

\[ f_i, f_j \]

\[ \Lambda_{QCD} \]

\[ \mu_Q \sim m_h \]

\[ \mu_T \sim p_T \]
Running

• Factorization formula:

\[ \frac{d^2 \sigma}{dp_T^2 dY} \sim H \otimes G^{ij} \otimes f_i \otimes f_j \]

• Schematic picture of running:

\[ \Lambda_{QCD} \]

All objects evaluated at \( p_T \) scale. No Landau pole!

\[ \mu_Q \sim m_h \]

\[ \mu_T \sim p_T \]

SCET Running

DGLAP Running
Limit of very small $p_T$

- We derived a factorization formula in the limit:

$$m_h \gg p_T \gg \Lambda_{QCD}$$

- For smaller values of $p_T$, one can introduce a non-perturbative model for the transverse momentum function:

$$\frac{d^2\sigma}{dp_T^2dY} \sim H \otimes G^{ij} \otimes f_i \otimes f_j$$

Hard function.

Transverse momentum function.

Can make non-perturbative model

Field theoretically defined object

PDFs.

Scale dependence and running known
Numerical Results
(Preliminary: To appear soon)
• Prediction for Higgs boson $p_T$ distribution.
Z-production: Comparison with Data

Preliminary

- Excellent agreement with data.
- The result is free of any ‘prescriptions’ and derived entirely in QFT.
Conclusions

• Derived factorization formula for the Higgs/Drell-Yan transverse momentum distribution in an EFT approach:

\[
\frac{d^2\sigma}{dp_T^2 dY} \sim H \otimes G^{ij} \otimes f_i \otimes f_j
\]

• Resummation via RG equations in EFTs.

• Formulation is free of Landau poles and prescription independent.

• Limit of very small pT described by an additional field theoretically defined non-perturbative pT dependent function.

• Formalism applies to the pT distribution of any other color neutral particles