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:

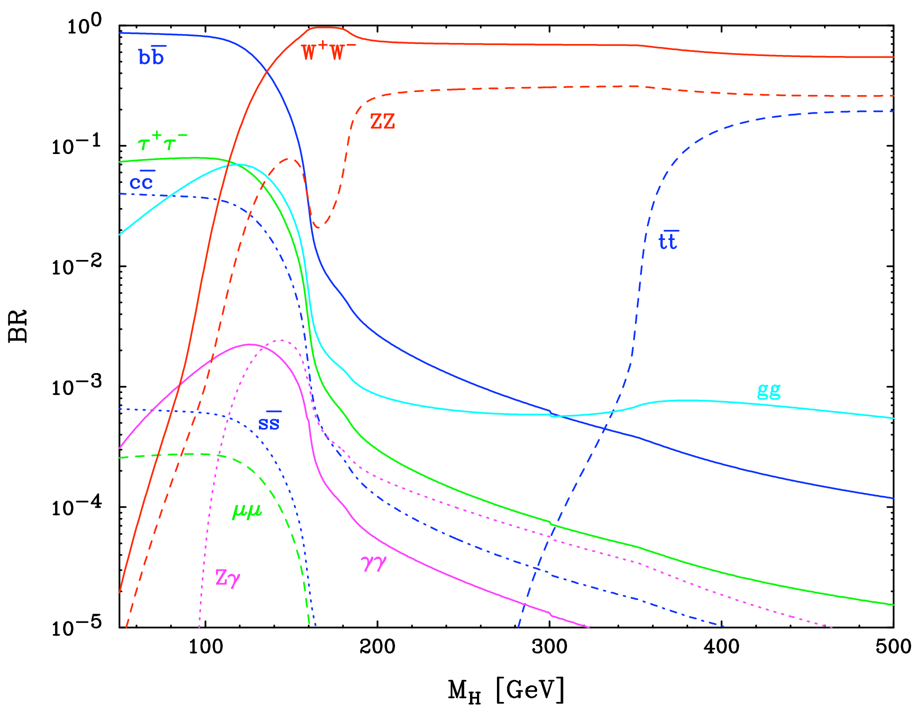
$$\frac{d^2\sigma}{dp_T^2 dY} \sim H \otimes \mathcal{G}^{ij} \otimes f_i \otimes f_j$$

- Numerical Results and Comparison with Data for Z-production
- Conclusions

Higgs Boson Searches

- The Higgs boson is the last missing piece of the SM.

- Search strategy complicated by decay properties:

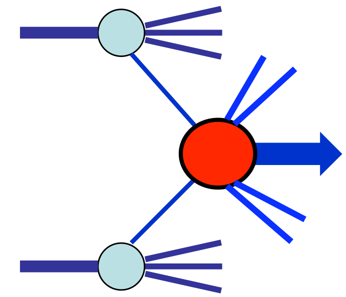


- Typically there are three search regions:

$$
\begin{array}{llclcl}
(i) & 90\text{GeV} & < & M_H & < & 130\ \text{GeV}, \\
(ii) & 130\text{GeV} & < & M_H & < & 2 \cdot M_{Z^0}, \\
(iii) & 2 \cdot M_{Z^0} & < & M_H & < & 800\ \text{GeV}.
\end{array}
$$

- 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:

$$gg \to h \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$$

- Large backgrounds from:

$$pp \to t\bar{t} \to bW^+\bar{b}W^- \to \ell^+\nu\ell^-\bar{\nu} + \text{jets}$$

- Background elimination requires jet vetoes:

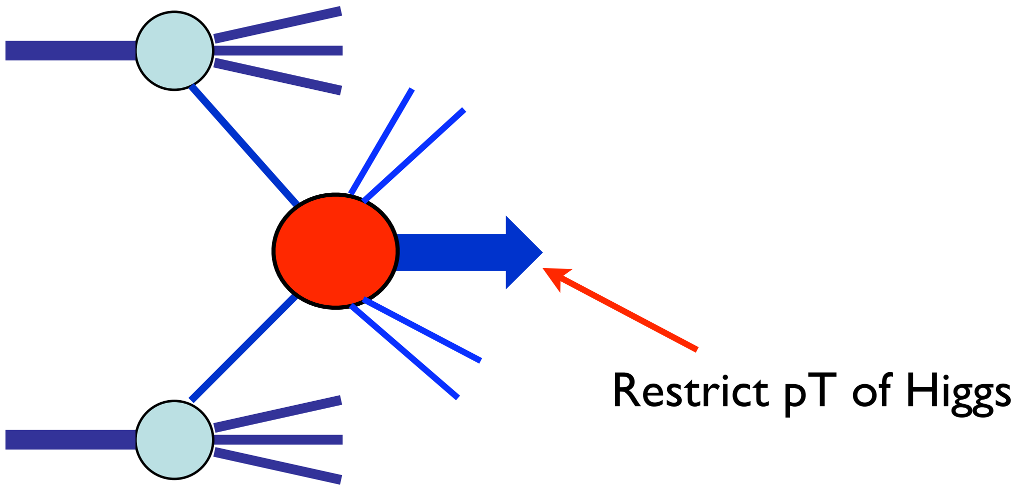
veto events with jets of $p_T > 20$ GeV

Jet Veto enhances signal to background ratio

(Dittmar, Dreiner)

LHC 14 TeV		Accepted event fraction		
reaction $pp \to X$	$\sigma \times BR^2$ [pb]	cut 1-3	cut 4-6	cut 7
$pp \to H \to W^+W^-$ ($m_H = 170$ GeV)	1.24	0.21	0.18	0.080
$pp \to W^+W^-$	7.4	0.14	0.055	0.039
$pp \to t\bar{t}$ ($m_t = 175$ GeV)	62.0	0.17	0.070	0.001
$pp \to Wtb$ ($m_t = 175$ GeV)	≈6	0.17	0.092	0.013

Higgs low pT Restriction



$$pp \to h + X$$

- We restrict the transverse momentum of the Higgs:

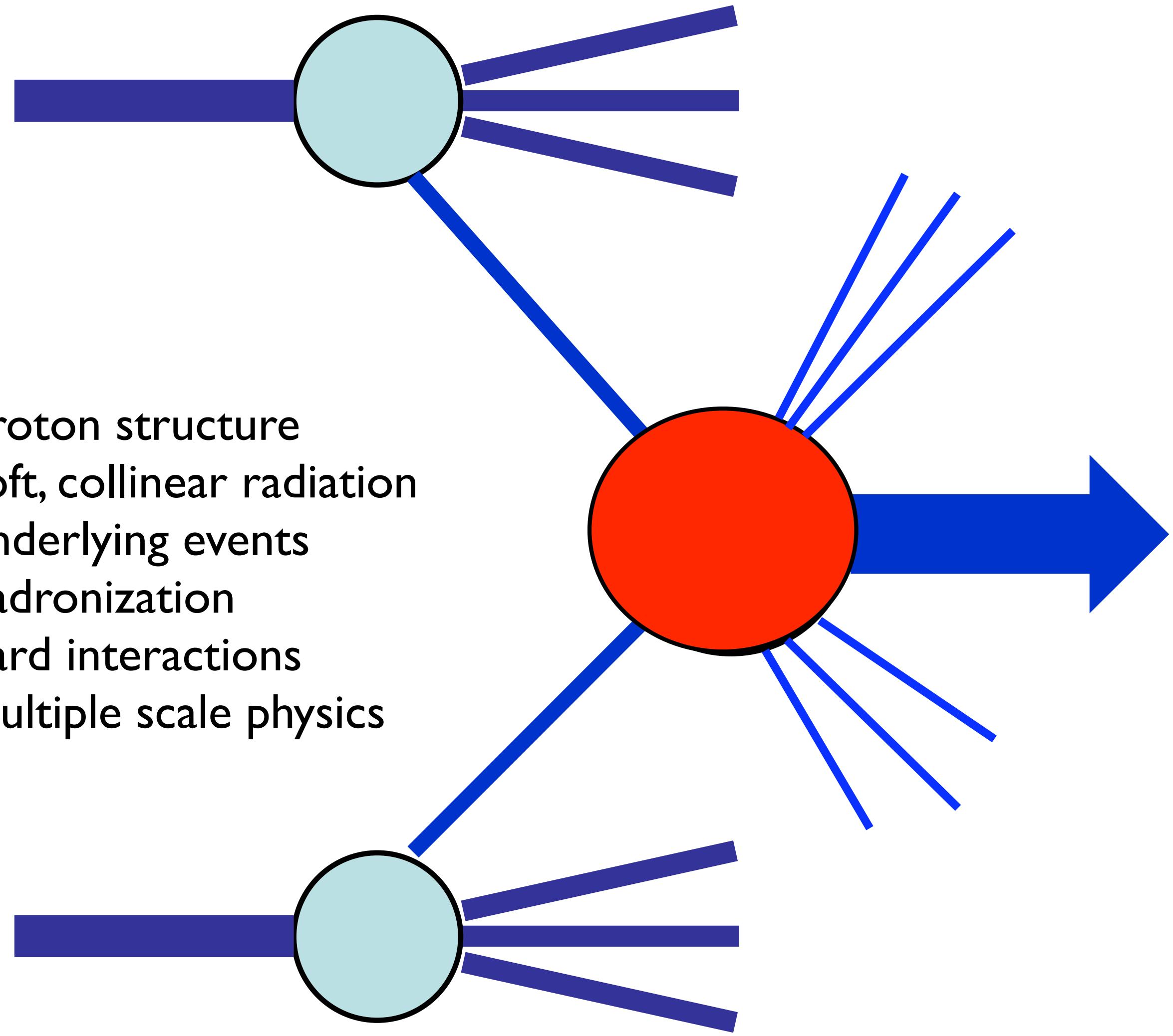
$$m_h \gg p_T \gg \Lambda_{QCD}$$

- Such pT restrictions can be studied for any color neutral particle. We use Higgs production as an illustrative example.

Factorization

LHC is a complicated environment!

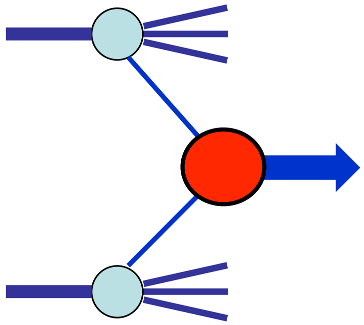
-Proton structure
-soft, collinear radiation
-underlying events
-hadronization
-hard interactions
-multiple scale physics



- How do we make sense of this environment?

Factorization!

Factorization



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

Calculable in pQCD.

Extracted from data

- 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.

RG evolve to hard 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).

Resummation

- 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.

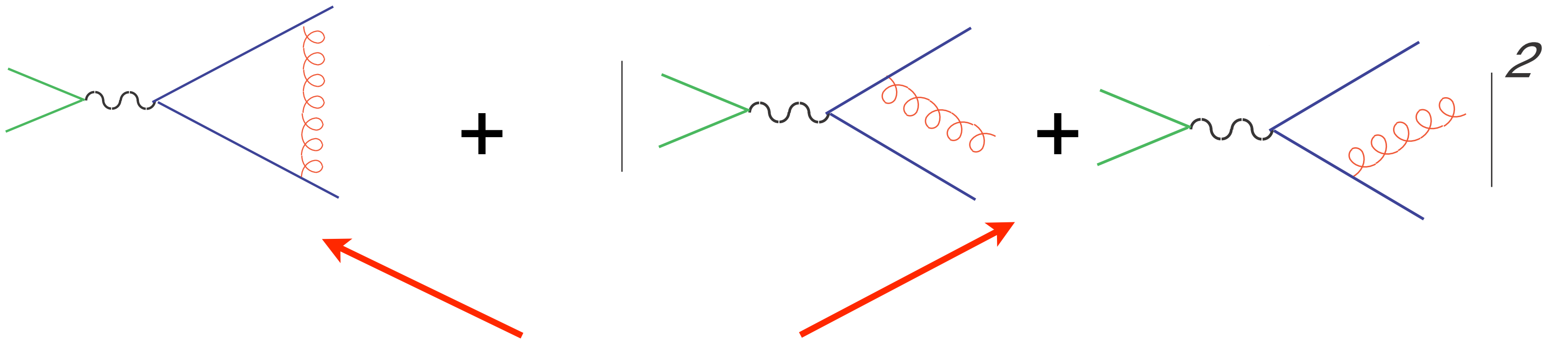
Live at non-perturbative scale.

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.



Cancellation of infrared divergences between virtual and real graphs. → Infrared Safety!

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

Low pT Region

- The schematic perturbative series for the pT distribution for $pp \longrightarrow h + X$

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

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, ...)

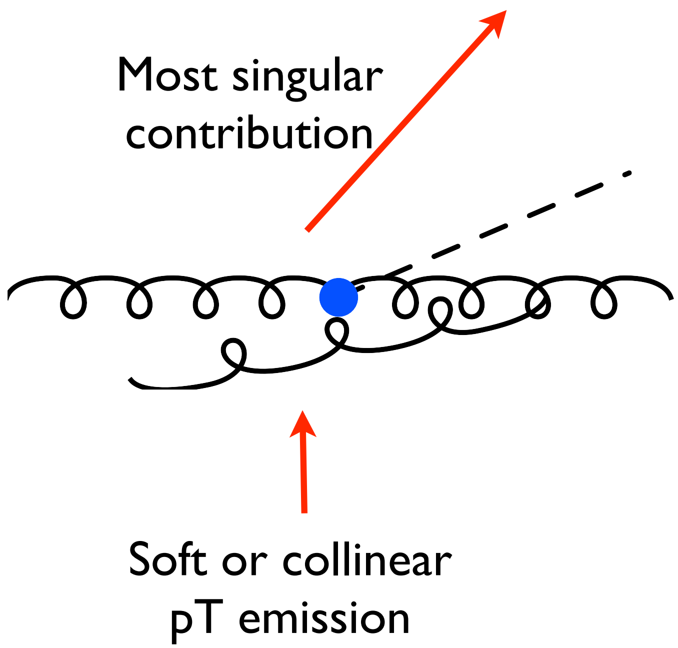
Collins-Soper-Sterman Formalism

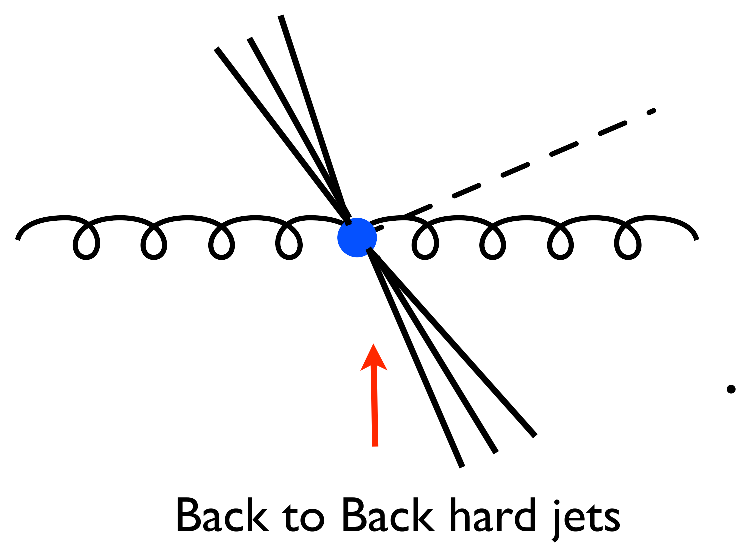
CSS Formalism

$$A(P_A) + B(P_B) \to C(Q) + X, \qquad C = \gamma^*, W^\pm, Z, h$$

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

$$\frac{d\sigma_{AB\to CX}}{dQ^2\,dy\,dQ_T^2} = \frac{d\sigma^{(\mathrm{resum})}_{AB\to CX}}{dQ^2\,dy\,dQ_T^2} + \frac{d\sigma^{(\mathrm{Y})}_{AB\to CX}}{dQ^2\,dy\,dQ_T^2}$$





CSS Formalism

Focus of this talk

$$\frac{d\sigma_{AB\to CX}}{dQ^2\,dy\,dQ_T^2} = \frac{d\sigma^{(\mathrm{resum})}_{AB\to CX}}{dQ^2\,dy\,dQ_T^2} + \frac{d\sigma^{(\mathrm{Y})}_{AB\to CX}}{dQ^2\,dy\,dQ_T^2}$$

- Singular as at least Q_T^{-2} as $Q_T \to 0$
- 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:

Perturbatively calculable

PDF

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

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

Sudakov Factor

Coefficients with well defined perturbative expansions

CSS Formalism

- The CSS resummation formula takes the form:

PDF

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Sudakov Factor

Coefficients with well defined perturbative expansions

Landau Pole

CSS Formalism

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Landau Pole

- Landau pole appears for ANY pT.

CSS Formalism

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Landau Pole

- 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

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- Landau pole must be treated with a model dependent prescription.

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

- Obtaining a smooth transition from low to high pT is typically plagued with problems due to prescription dependence of resummed result.

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

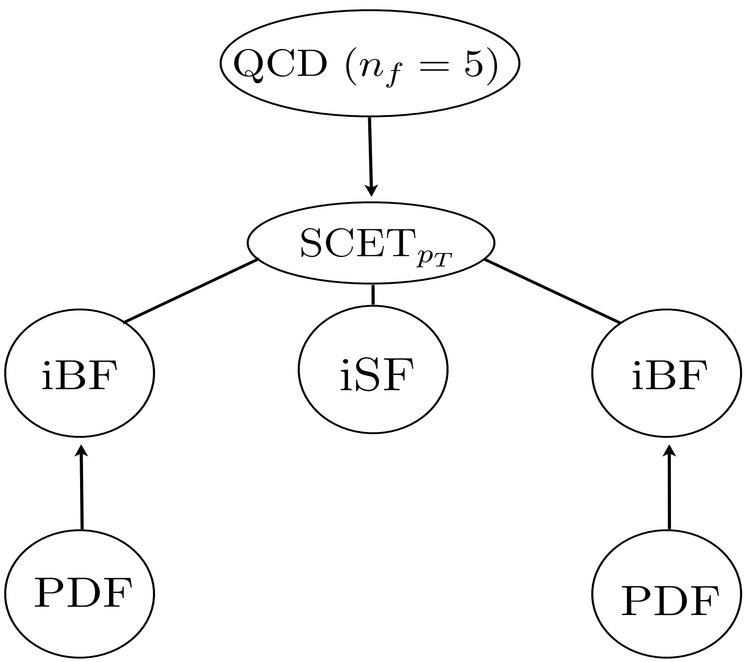
$$\mathrm{QCD}(n_f = 6) \to \mathrm{QCD}(n_f = 5) \to \mathrm{SCET}_{p_T} \to \mathrm{SCET}_{\Lambda_{QCD}}$$

Top quark integrated out.

Matched onto SCET.

Soft-collinear factorization.

Matching onto PDFs.



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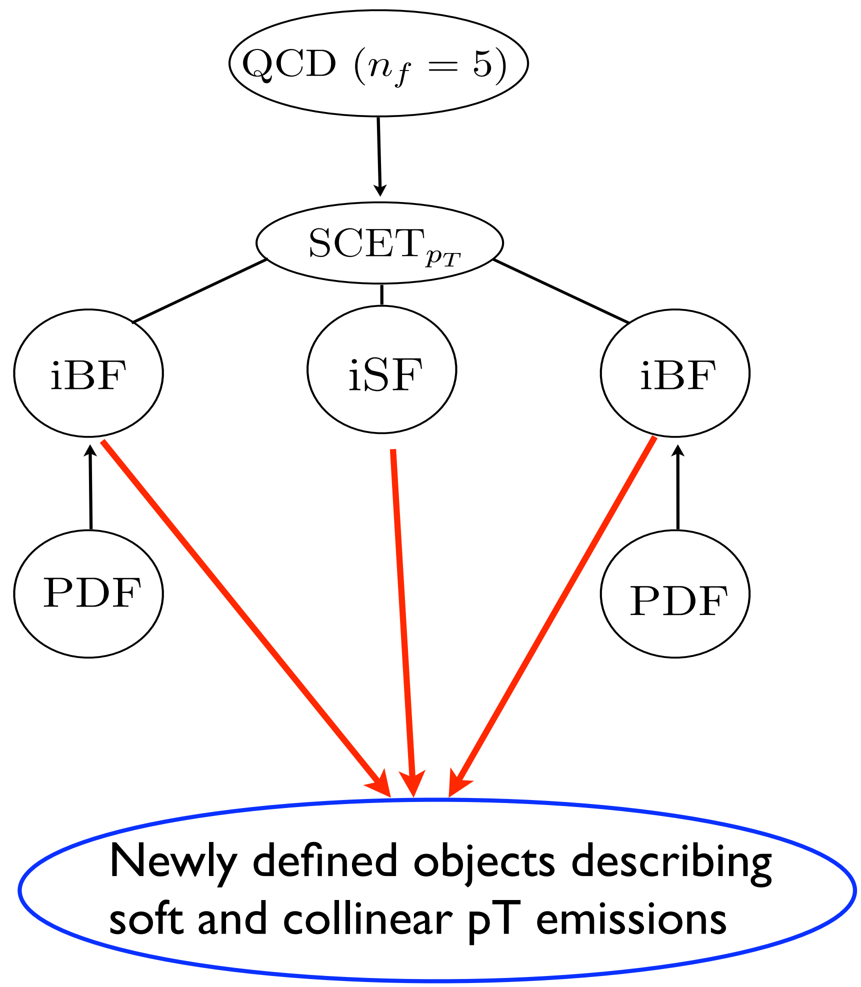


SCET Factorization Formula

- Factorization formula derived in SCET in schematic form:

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

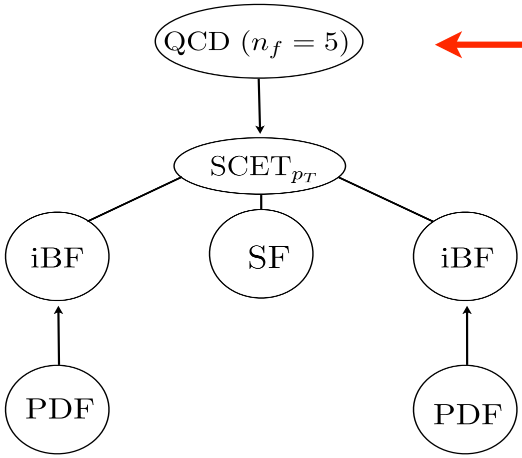
Hard function. → Sums logs of m_h/p_T

Transverse momentum function. → Evaluated at pT scale.

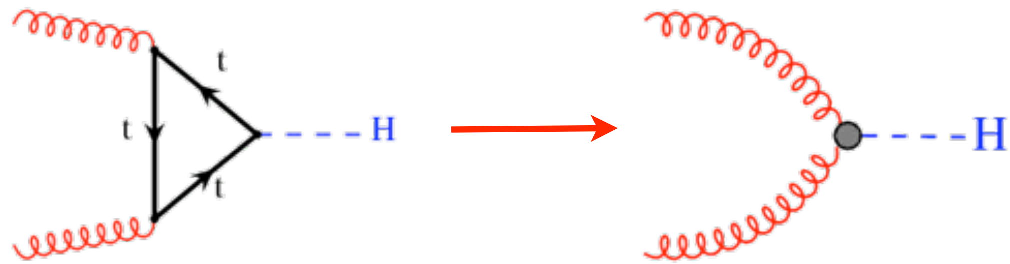
PDFs. → RG evolved to pT scale

- 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



We are here



- Leading term in the Higgs effective interaction with Gluons:

$$\mathcal{L}_{m_t} = C_{GGh}\,\frac{h}{v}\,G^a_{\mu\,\nu}\,G^{\mu\,\nu}_a \quad , \qquad C_{GGh} = \frac{\alpha_s}{12\pi}\left\{1 + \frac{11}{4}\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right\}$$

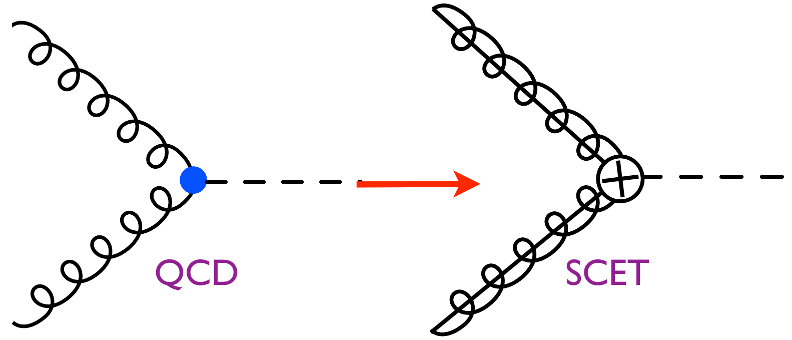
Two loop result for
Wilson coefficient.

(Chetyrkin, Kniehl, Kuhn, Schroder, Steinhauser, Sturm)

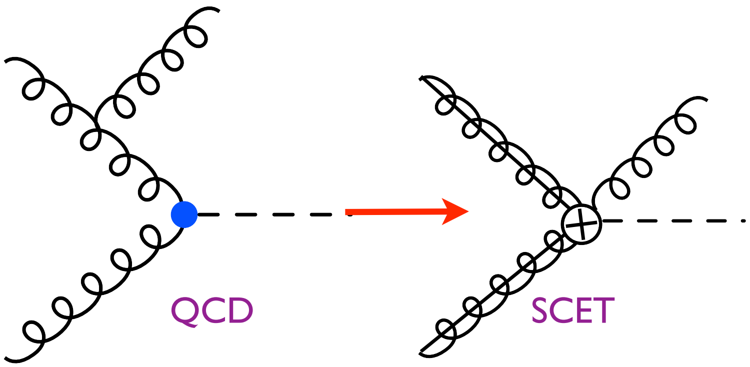
Matching onto SCET

- Matching equation:

$$O_{QCD} = \int d\omega_1 \int d\omega_2 \, C(\omega_1, \omega_2) \, \mathcal{O}(\omega_1, \omega_2)$$

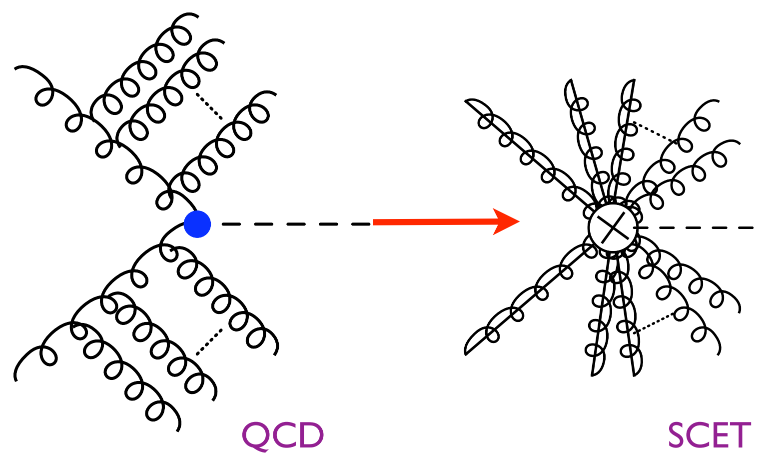


Tree level matching



Matching real emission graphs

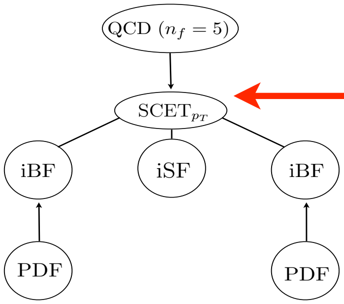
Soft and Collinear emissions build into Wilson lines determined by soft and collinear gauge invariance of SCET.



- Effective SCET operator:

$$\mathcal{O}(\omega_1, \omega_2) = g_{\mu\nu} h \, T\{\mathrm{Tr}\Big[S_n (gB^{\mu}_{n\perp})_{\omega_1} S_n^{\dagger} S_{\bar{n}} (gB^{\nu}_{\bar{n}\perp})_{\omega_2} S_{\bar{n}}^{\dagger}\Big]\}$$

SCET Cross-Section



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- SCET differential cross-section:

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

- Schematic form of SCET cross-section:

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

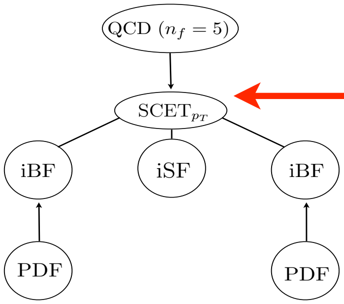
Phase space integrals.

Hard matching coefficient.

SCET matrix element.

Factorize using soft-collinear decoupling

Factorization in SCET



We are here

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

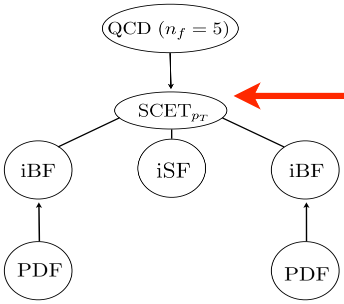
Factorize cross-section
using soft-collinear
decoupling in SCET

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

Hard matching
coefficient
squared

Decoupled
collinear and
soft functions

Factorization in SCET



We are here

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

Hard function

Impact-parameter Beam Functions (iBFs)

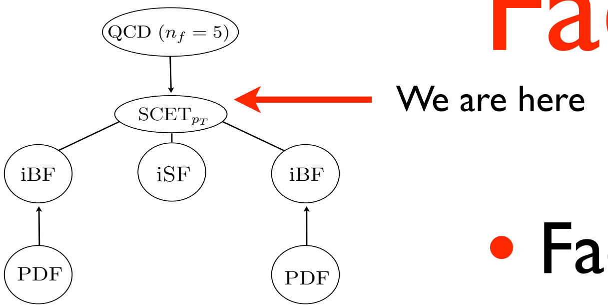
Soft function

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:

Hard

$$
\begin{aligned}
\frac{d^2\sigma}{du\,dt} = {} & \frac{(2\pi)}{(N_c^2-1)^2 8Q^2} \int dp_h^+ dp_h^- \int d^2k_h^\perp \int \frac{d^2b_\perp}{(2\pi)^2} e^{-i\vec{k}_h^\perp\cdot\vec{b}_\perp} \\
& \times \delta\left[u - m_h^2 + Qp_h^-\right] \delta\left[t - m_h^2 + Qp_h^+\right] \delta\left[p_h^+ p_h^- - \vec{k}_{h\perp}^2 - m_h^2\right] \int d\omega_1 d\omega_2 |C(\omega_1,\omega_2,\mu)|^2 \\
& \times \int dk_n^+ dk_{\bar{n}}^- B_n^{\alpha\beta}(\omega_1, k_n^+, b_\perp, \mu) B_{\bar{n}\alpha\beta}(\omega_2, k_{\bar{n}}^-, b_\perp, \mu) S(\omega_1 - p_h^- - k_{\bar{n}}^-, \omega_2 - p_h^+ - k_n^+, b_\perp, \mu)
\end{aligned}
$$

n-collinear iBF

bn-collinear iBF

Soft

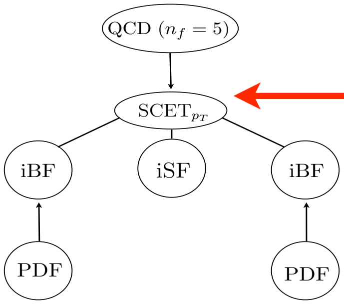
- iBFs and soft functions field theoretically defined as the fourier transform of:

$$
J_n^{\alpha\beta}(\omega_1, x^-, x_\perp, \mu) = \sum_{\text{initial pols.}} \langle p_1 | \left[gB^A_{1n\perp\beta}(x^-, x_\perp)\delta(\bar{\mathcal{P}} - \omega_1) gB^A_{1n\perp\alpha}(0) \right] | p_1 \rangle
$$

$$
J_{\bar{n}}^{\alpha\beta}(\omega_1, y^+, y_\perp, \mu) = \sum_{\text{initial pols.}} \langle p_2 | \left[gB^A_{1n\perp\beta}(y^+, y_\perp)\delta(\bar{\mathcal{P}} - \omega_2) gB^A_{1n\perp\alpha}(0) \right] | p_2 \rangle
$$

$$
S(z,\mu) = \langle 0 | \bar{T} \left[\mathrm{Tr}\left(S_{\bar{n}} T^D S_{\bar{n}}^\dagger S_n T^C S_n^\dagger \right)(z) \right] T \left[\mathrm{Tr}\left(S_n T^C S_n^\dagger S_{\bar{n}} T^D S_{\bar{n}}^\dagger \right)(0) \right] | 0 \rangle
$$

Factorization in SCET



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

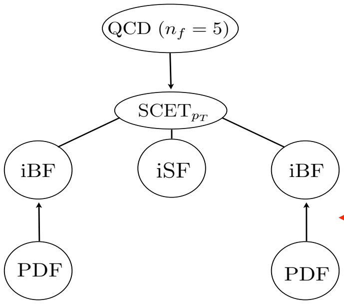
iBFs are proton matrix elements
and sensitive to the
non-perturbative scale

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

$$\tilde{B}_n = \mathcal{I}_{n,i} \otimes f_i, \qquad \tilde{B}_{\bar{n}} = \mathcal{I}_{\bar{n},j} \otimes f_j$$

iBF   Matching coefficient   PDF

iBFs to PDFs



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- iBF is matched onto the PDF with matching coefficient defined as:

$$\tilde{B}_n^{\alpha\beta}(z, t_n^+, b_\perp, \mu) = -\frac{1}{z} \sum_{i=g,q,\bar{q}} \int_z^1 \frac{dz'}{z'} \mathcal{I}_{n;g,i}^{\alpha\beta}\left(\frac{z}{z'}, t_n^+, b_\perp, \mu\right) f_{i/P}(z', \mu)$$

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

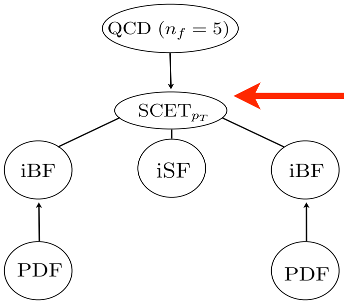
Scaleless

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

- The matching coefficient is given by:

$$\mathcal{I}_{n;g,i}^{\beta\alpha}\left(\frac{z}{z'}, t_n^+, b_\perp, \mu\right) = -z \left[\tilde{B}_n^{\alpha\beta}\left(\frac{z}{z'}, z' t_n^+, b_\perp, \mu\right) \right]_{\text{finite part in dim-reg}}$$

Factorization in SCET



We are here

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

- After matching the iBFs to the PDFs we get:

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

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

$$\frac{d^2\sigma}{dp_T^2 dY} \sim H \otimes [\mathcal{I}_n \otimes \mathcal{I}_{\bar{n}} \otimes S^{-1}] \otimes f_i \otimes f_j$$

$\mathcal{G}^{ij}$

Hard function

Transverse momentum dependent function(TMF)

PDFs

Factorization Formula

- Factorization formula in full detail:

$$\frac{d^2\sigma}{d\mathrm{p}_T^2\, dY} = \frac{\pi^2}{4(N_c^2-1)^2Q^2}\int_0^1 \frac{dx_1}{x_1}\int_0^1 \frac{dx_2}{x_2}\int_{x_1}^1 \frac{dx_1'}{x_1'}\int_{x_2}^1 \frac{dx_2'}{x_2'}$$

$$\times \underbrace{H(x_1,x_2,\mu_Q;\mu_T)}_{\text{Hard function.}}\underbrace{\mathcal{G}^{ij}(x_1,x_1',x_2,x_2',p_T,Y,\mu_T)}_{\text{Transverse momentum function.}}\underbrace{f_{i/P}(x_1',\mu_T)f_{j/P}(x_2',\mu_T)}_{\text{PDFs.}}$$

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

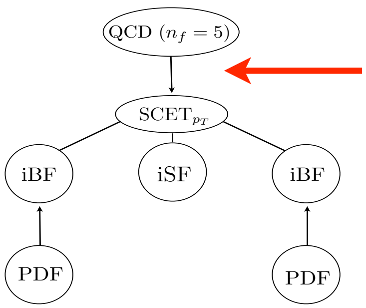
$$\mathcal{G}^{ij}(x_1,x_1',x_2,x_2',p_T,Y,\mu_T) = \int dt_n^+ \int dt_{\bar{n}}^- \int \frac{d^2b_\perp}{(2\pi)^2} J_0(|\vec{b}_\perp|p_T)$$

$$\times \mathcal{I}_{n;g,i}^{\beta\alpha}\Big(\frac{x_1}{x_1'},t_n^+,b_\perp,\mu_T\Big)\mathcal{I}_{\bar{n};g,j}^{\beta\alpha}\Big(\frac{x_2}{x_2'},t_{\bar{n}}^-,b_\perp,\mu_T\Big)$$

$$\times \mathcal{S}^{-1}\Big(x_1Q - e^{Y}\sqrt{\mathrm{p}_T^2+m_h^2}-\frac{t_{\bar{n}}^-}{Q}, x_2Q - e^{-Y}\sqrt{\mathrm{p}_T^2+m_h^2}-\frac{t_n^+}{Q}, b_\perp,\mu_T\Big)$$

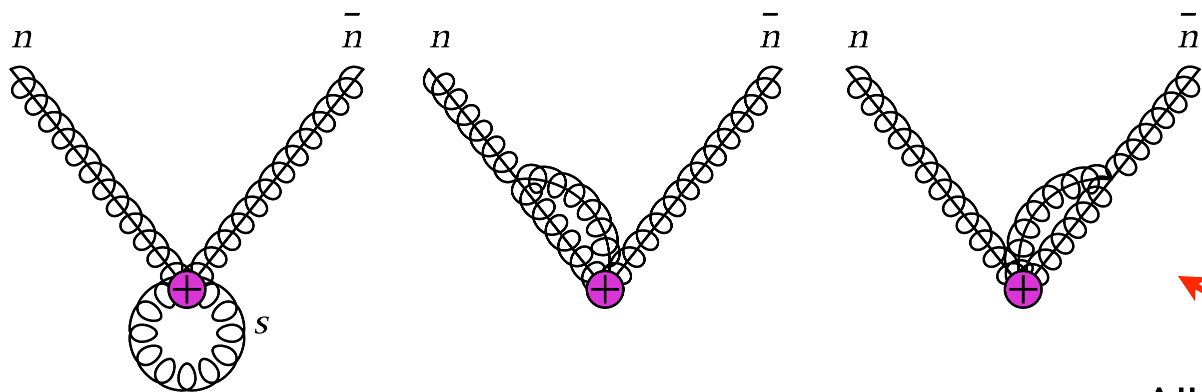
Fixed order and Matching Calculations

One loop Matching onto SCET



We are here

$$O_{QCD} = \int d\omega_1 \int d\omega_2\, C(\omega_1, \omega_2)\, \mathcal{O}(\omega_1, \omega_2)$$



One loop SCET graphs

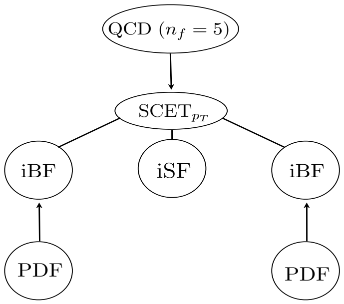
All graphs scaless and vanish in dimensional regularization.

- Wilson Coefficient obtained from finite part in dimensional regularization of the QCD result for gg->h. At one loop we have:

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

(Ahrens, Becher, Neubert, Yang; Harlander)

iBFs

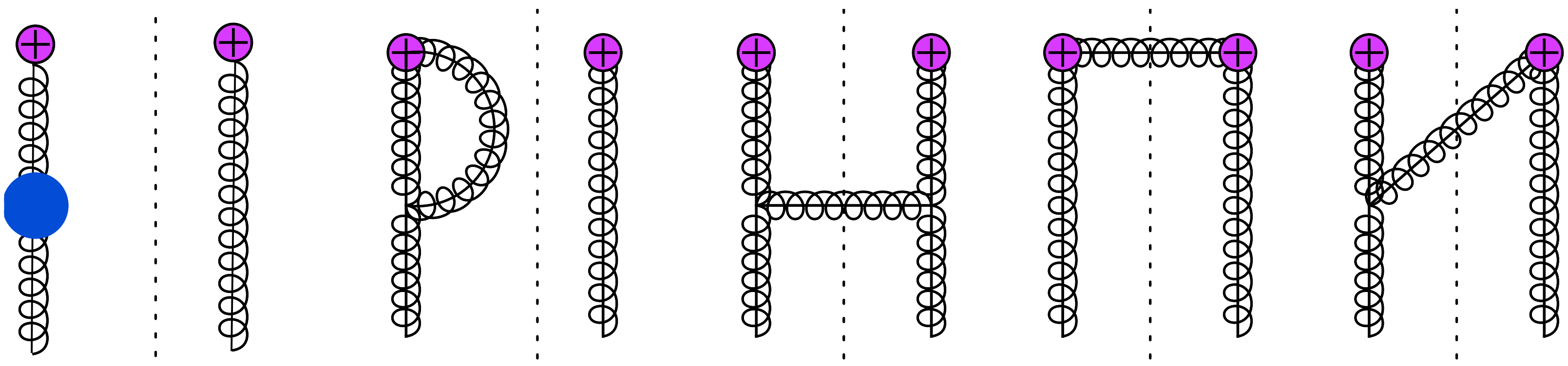


We are here

- Definition of the iBF:

$$
\tilde{B}_n^{\alpha\beta}(x_1, t_n^+, b_\perp, \mu) \;=\; \int \frac{db^-}{4\pi} e^{\frac{i}{2}\frac{t_n^+ b^-}{Q}} \sum_{\text{initial pols.}} \sum_{X_n} \langle p_1 | \left[g B^A_{1n\perp\beta}(b^-, b_\perp) | X_n \rangle \right.
$$

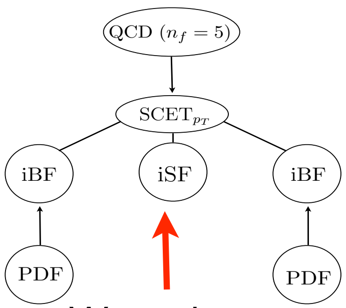
$$
\times \; \left. \langle X_n | \delta(\bar{\mathcal{P}} - x_1 \bar{n}\cdot p_1) g B^A_{1n\perp\alpha}(0) \right] | p_1 \rangle ,
$$



$+ \quad c.c$

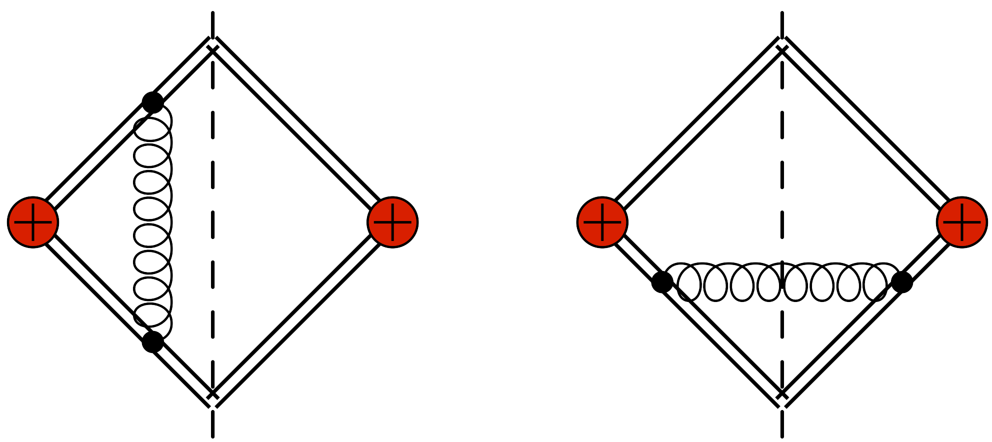
One loop graphs

Soft function



- Soft function definition:

$$S(z) \;=\; \langle 0|\mathrm{Tr}\Big(\bar{T}\{S_{\bar{n}}T^D S_{\bar{n}}^\dagger S_n T^C S_n^\dagger\}\Big)(z)\,\mathrm{Tr}\Big(T\{S_n T^C S_n^\dagger S_{\bar{n}} T^D S_{\bar{n}}^\dagger\}\Big)(0)|0\rangle$$



One loop graphs

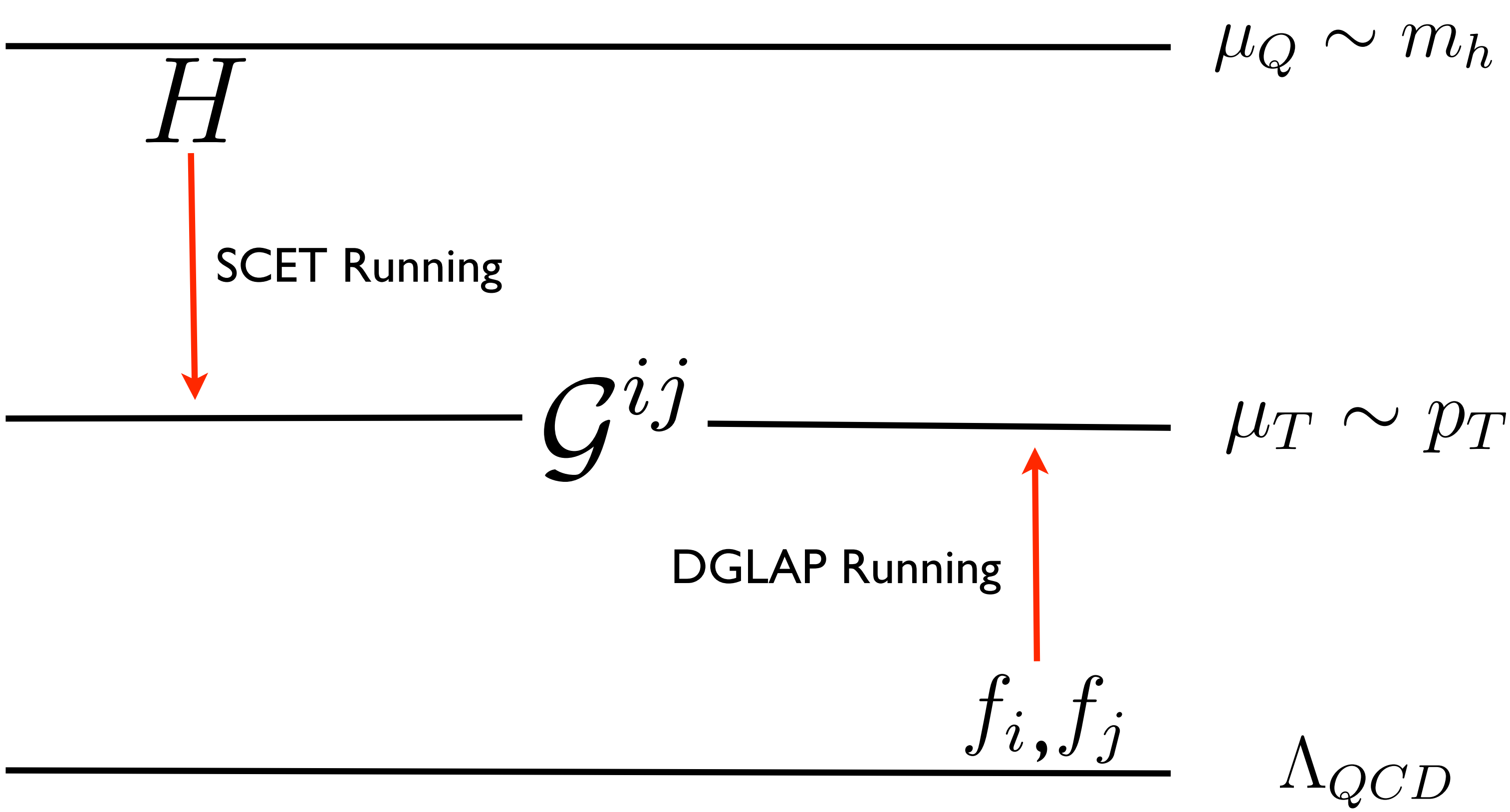
Running

Running

- Factorization formula:

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

- Schematic picture of running:



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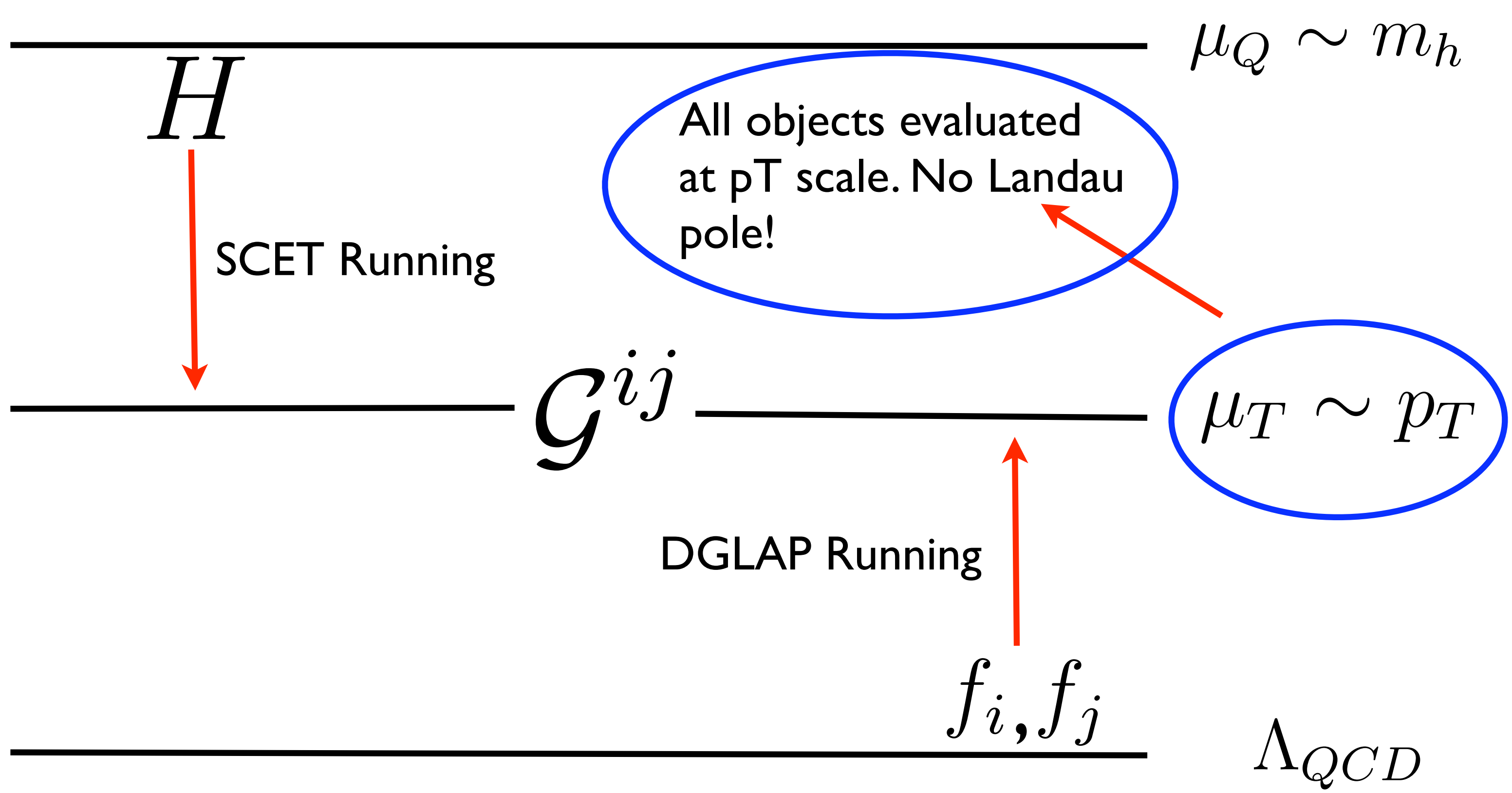

Limit of very small pT

- We derived a factorization formula in the limit:

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

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

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

Hard function.

Transverse momentum function.

PDFs.

Can make non-perturbative model

Field theoretically defined object

Scale dependence and running known

Numerical Results

(Preliminary: To appear soon)

Higgs pT Distribution

Preliminary

- Prediction for Higgs boson pT 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:

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

- 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