Factorization of the Drell-Yan q_T spectrum with massive quarks

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based on arXiv:1703.09702

in collaboration with Piotr Pietrulewicz, Anne Spiering and Frank J. Tackmann

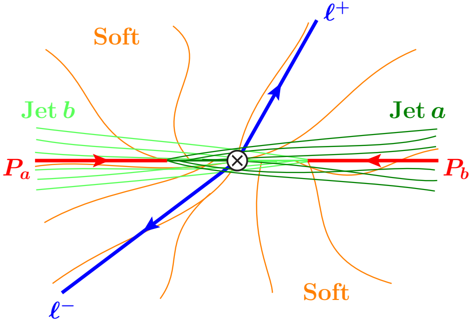
29th Rencontres de Blois
30 May 2017

universität wien

$\int dk \prod$ Doktoratskolleg Particles and Interactions

Motivation

- p_T spectrum of Z-boson measured
  with high precision
- NNLL′ analyses available
- no systematic theoretical description of
  b-quark mass effects yet
  can be relevant in m_W measurements
- discrepancies between MC and
  experiment in low p_T region



from: I.W.Stewart,F.J.Tackmann,W.J.Waalewijn, *Phys. Rev.* **D81** (2010) 094035

goal: systematic treatment of quark mass effects at NNLL′ accuracy
for transverse momentum spectrum of the Z-boson

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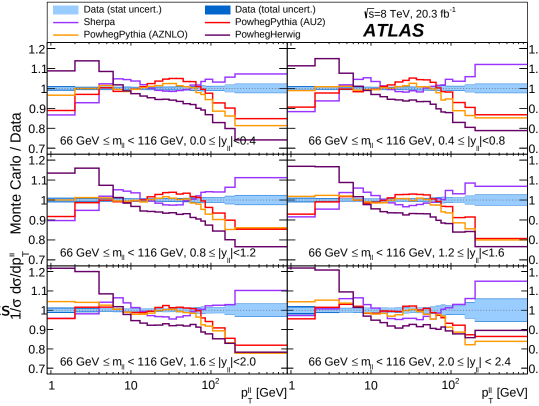
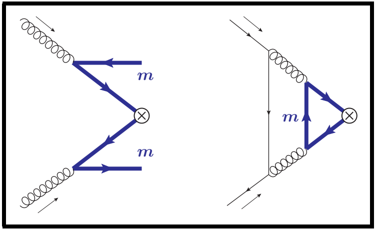


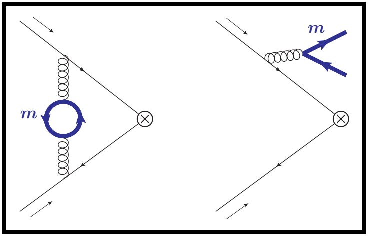
[ATLAS Collaboration (2015)]

goal: systematic treatment of quark mass effects at NNLL′ accuracy
for transverse momentum spectrum of the Z-boson

Massive Quarks in DY

primary and secondary massive quarks.



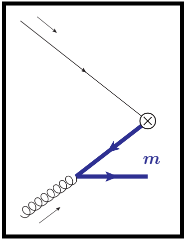


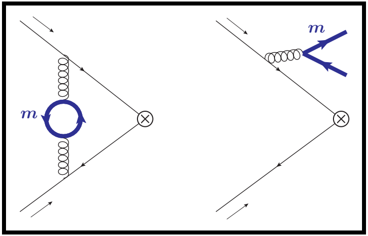
- primay: massive quarks go into hard interaction
- secondary: massive quark corrections to light quark induced processes
- both start at $\mathcal{O}\left(\alpha_s^2\right)$, relevant for NNLL′ resummation
- different hierarchies between p_T and m possible:

  $m \ll p_T$ $\qquad$ $p_T \sim m$ $\qquad$ $p_T \ll m$

Massive Quarks in W production

primary and secondary massive quarks.





- secondary massive quark effects the same as for Z production
- primary charm quarks already contribute at $\mathcal{O}(\alpha_s)$
- primary bottom quarks CKM suppressed

Massive Quarks in W production

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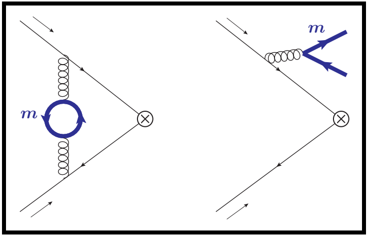

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W boson mass measurements

- experimentalists rely on ratio of W and Z boson spectrum

$$\left[\frac{\mathrm{d}\sigma^W}{\mathrm{d}q_T}\right]_{\text{prediction}} = \left[\frac{\mathrm{d}\sigma^W}{\mathrm{d}q_T} \times \left(\frac{\mathrm{d}\sigma^Z}{\mathrm{d}q_T}\right)^{-1}\right]_{\text{theory}} \times \left[\frac{\mathrm{d}\sigma^Z}{\mathrm{d}q_T}\right]_{\text{measured}}$$

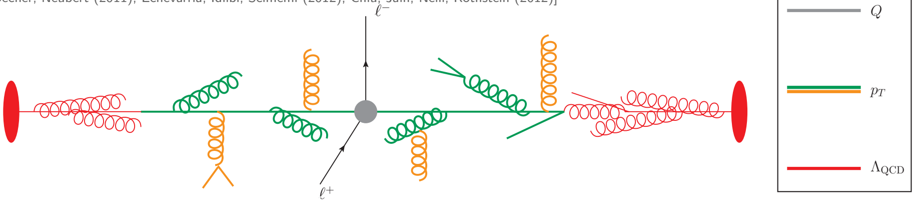
- Z boson spectrum measured with very high accuracy

- many things cancel to large extent in the ratio

- every difference between Z and W production can become relevant

Massless Factorization for p_T-spectrum in DY

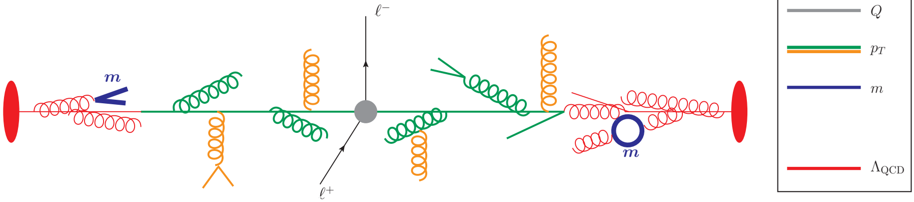
[Collins, Soper, Sterman (1985)]
[Becher, Neubert (2011); Echevarria, Idilbi, Scimemi (2012); Chiu, Jain, Neill, Rothstein (2012)]



$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T} = \sum_{i\in\{q\}} H_i^{(n_f)}(Q) \times \Big[\sum_{j\in\{q,g\}} \mathcal{I}_{ij}^{(n_f)}(p_T, x) \otimes f_j^{(n_f)}(x) \Big]^2 \otimes_\perp S^{(n_f)}(p_T) + \mathcal{O}\Big(\frac{p_T}{Q}, \frac{\Lambda_{\mathrm{QCD}}^2}{p_T^2}\Big)$$

- H: hard function, scale Q
- $\mathcal{I}$: beam function, scale p_T
- S: soft function, scale p_T
- f: PDF, scale Λ_{QCD}

Factorization for $m \ll p_T$



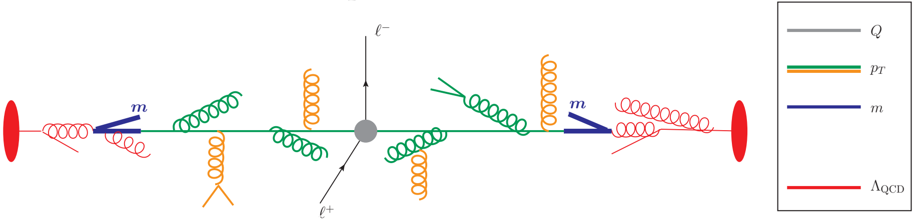
$$\frac{d\sigma}{dp_T} = \sum_{i\in\{q,Q\}} H_i^{(5)}(Q) \times \Big[\sum_{j\in\{q,Q,g\}} \mathcal{I}_{ij}^{(5)}(p_T, x) \otimes f_j^{(5)}(x) \Big]^2 \otimes_\perp S^{(5)}(p_T)$$

Power Corrections: $\mathcal{O}\Big(\frac{m^2}{p_T^2}\Big)$

- matching: $f_j^{(5)}(x) = \sum_k \mathcal{M}_{jk}(x,m) \otimes f_k^{(4)}(x)$
- secondary $\mathcal{M}_{qq}$ and primary $\mathcal{M}_{Qg}$ heavy quarks

  [M. Buza, Y. Matinounine, J. Smith, W. van. Neerven (1998)]
- hard, beam and soft functions with 5 massless flavors

Factorization for $m \ll p_T$



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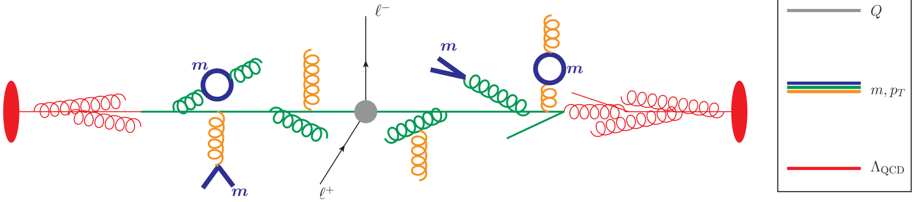
Factorization for $p_T \sim m$



$$\frac{d\sigma_{\rm sec}}{dp_T} = \sum_{i\in\{q\}} H_i^{(5)}(Q) \times \Big[\sum_{j\in\{q,g\}} \mathcal{I}_{ij}^{(5)}(p_T, x, m) \otimes f_j^{(4)}(x)\Big]^2 \otimes_\perp S^{(5)}(p_T, m)$$

Power Corrections: $\mathcal{O}\Big(\frac{m^2}{Q^2}\Big)$

- secondary massive quarks in beam function $\mathcal{I}_{qq}$ and soft function S

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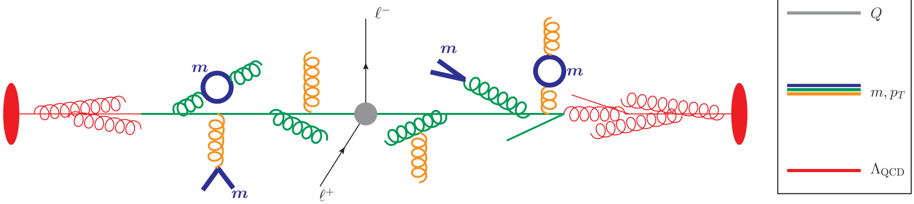

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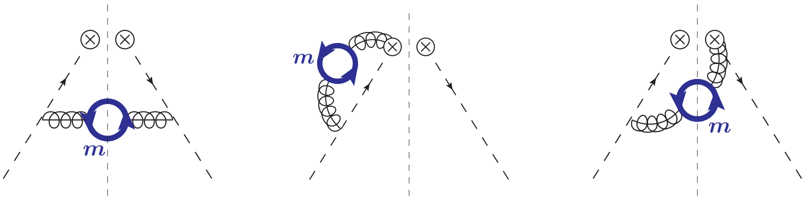

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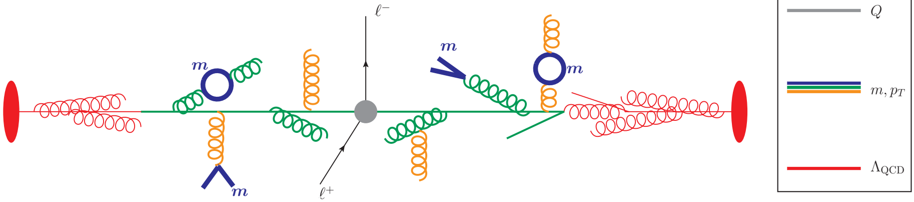

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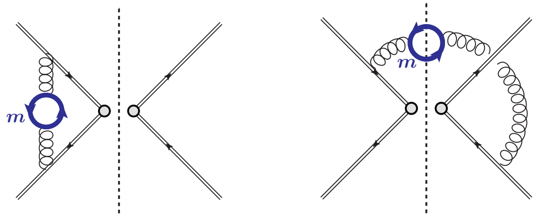

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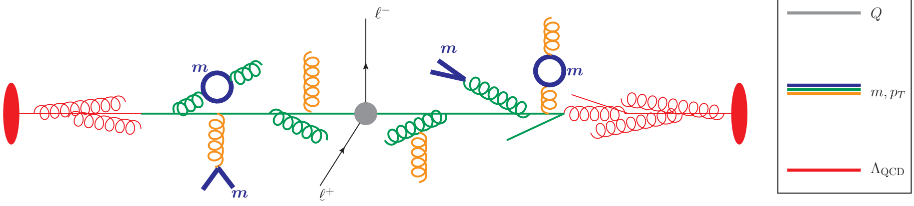

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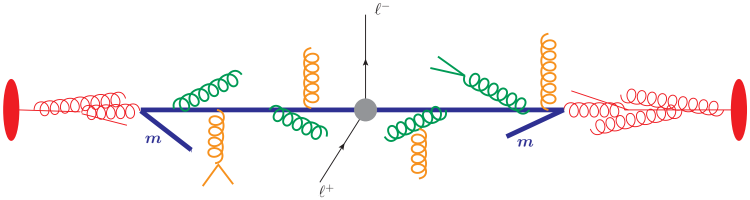

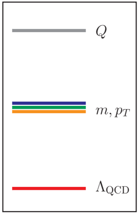

$$\frac{d\sigma_{\rm prim}}{dp_T} = H_Q^{(5)}(Q) \times \Big[\sum_{j\in\{q,g\}} \mathcal{I}_{Qj}^{(5)}(p_T, x, m) \otimes f_j^{(4)}(x)\Big]^2 \otimes_\perp S^{(5)}(p_T, m)$$

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- secondary massive quarks in beam function $\mathcal{I}_{qq}$ and soft function S
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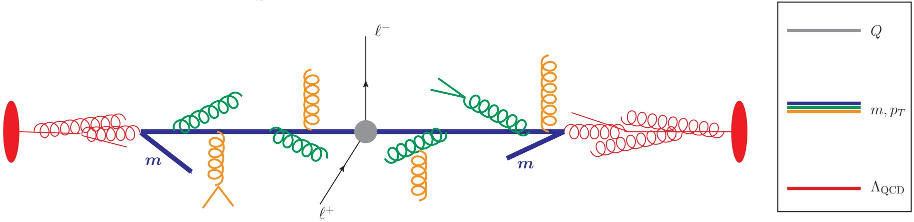
Factorization for $p_T \sim m$



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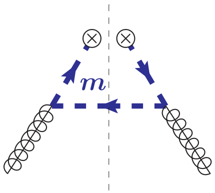

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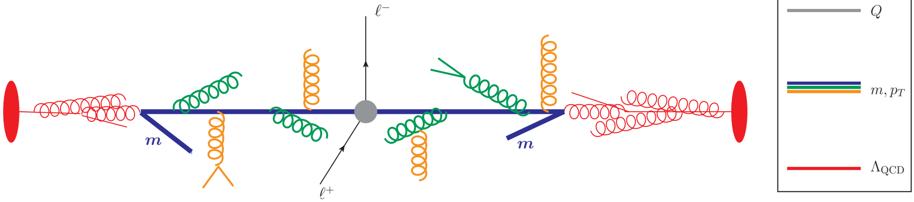

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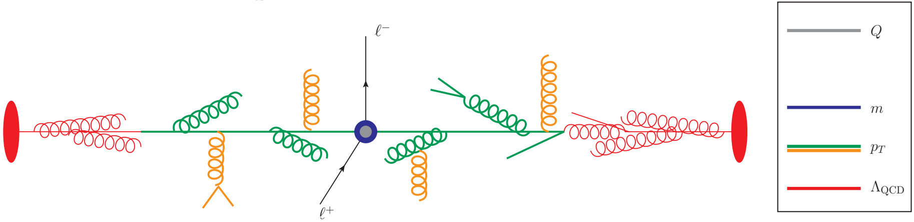
- PDF with 4 and hard function with 5 massless flavors

Factorization for $p_T \ll m$

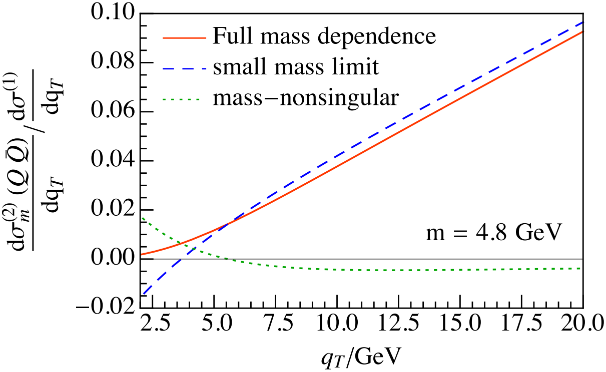


$$\frac{d\sigma}{dp_T} = \sum_{i\in\{q\}} H_i^{(5)}(Q) \times H_m(m) \times \Big[\sum_{j\in\{q,g\}} \mathcal{I}_{ij}^{(4)}(p_T,x) \otimes f_j^{(4)}(x) \Big]^2 \otimes_\perp S^{(4)}(p_T)$$

Power Corrections: $\mathcal{O}\Big(\frac{p_T^2}{m^2}, \frac{m^2}{Q^2}\Big)$

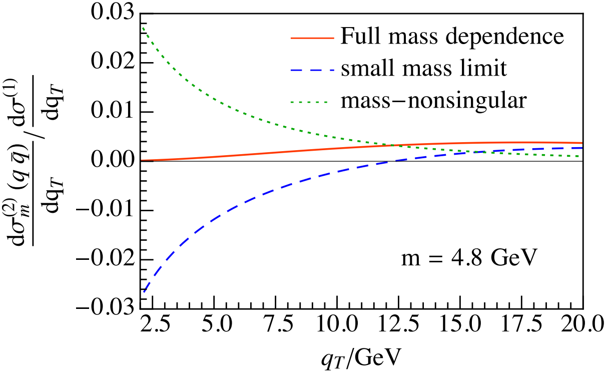
- mass mode matching function H_m from integrating out the heavy flavor from the current
  [S. Gritschacher, A. Hoang, I. Jemos , V. Mateu, P. Pietrulewicz (2014)]
- beam function, soft function, PDF with 4 massless flavors,
  hard function with 5 massless flavors

Mass Effects - Primary



- $\mathcal{O}(\alpha_s^2)$ contributions from primary massive quarks at fixed order, normalized to the LO spectrum
- $E_{\rm cm} = 13\,\mathrm{TeV}$, $m_b = 4.8\,\mathrm{GeV}$, $Q = m_Z$, $Y = 0$, MSTW NLO PDFs

Mass Effects - Secondary



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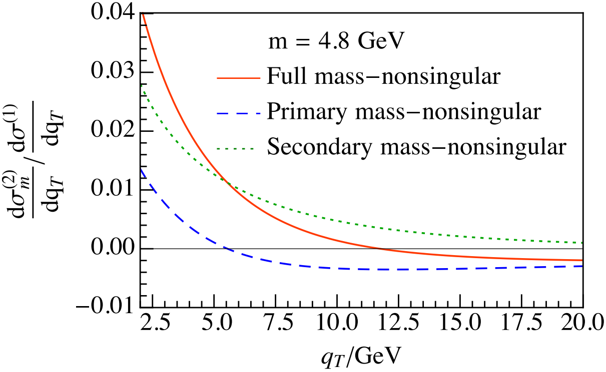
Mass Effects



- $\mathcal{O}(\alpha_s^2)$ quark mass corrections to the Z-boson p_T-spectrum at fixed order, normalized to the LO spectrum
- $E_{\rm cm} = 13\,\text{TeV}$, $m_b = 4.8\,\text{GeV}$, $Q = m_Z$, $Y = 0$, MSTW NLO PDFs

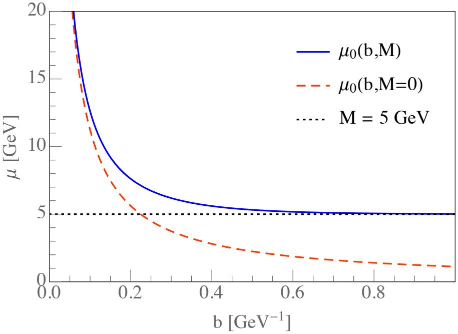
Rapidity Logs from Massive Flavors

- secondary massive quarks lead to mass dependent rapidity anomalous dimension $\tilde{\gamma}_\nu(b, m, \mu)$ (here in b space)

$$\tilde{\gamma}_\nu(b, m, \mu) \overset{b\to 0}{\longrightarrow} = \Big(\frac{\alpha_s(\mu)}{4\pi}\Big)^2 C_F T_F \Big(\frac{16}{3} L_b^2 + \frac{160}{9} L_b + \frac{224}{27}\Big) \qquad L_b = \ln\Big(\frac{b^2\mu^2 e^{2\gamma_E}}{4}\Big)$$

$$\tilde{\gamma}_\nu(b, m, \mu) \overset{b\to \infty}{\longrightarrow} = \Big(\frac{\alpha_s(\mu)}{4\pi}\Big)^2 C_F T_F \Big(-\frac{16}{3} L_m^2 - \frac{160}{9} L_m - \frac{224}{27}\Big) \qquad L_m = \ln\frac{m^2}{\mu^2}$$

- large logarithms in $\tilde{\gamma}_\nu$ can be avoided e.g. by b space setting of μ



$$\mu_0(b, m) \overset{b\to 0}{\longrightarrow} \frac{2e^{-\gamma_E}}{b}$$

$$\mu_0(b, m) \overset{b\to \infty}{\longrightarrow} m$$

$\Rightarrow$ mass introduces IR cutoff

$\Rightarrow$ no non-pert. regime for $b \to \infty$

Summary

- achieved resummation of all mass-related logarithms for p_T-spectrum in Drell-Yan at NNLL$'$
- calculated one-loop primary and two-loop secondary massive quark corrections to beam and soft functions
- with these ingredients also NNLL$'$ resummation for bottom mass effects in W production (for charm only NNLL)
- mass effects estimated to be at percent level

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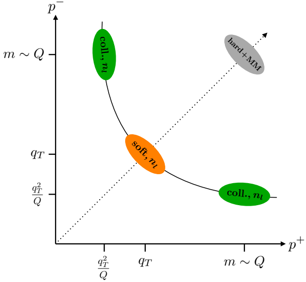
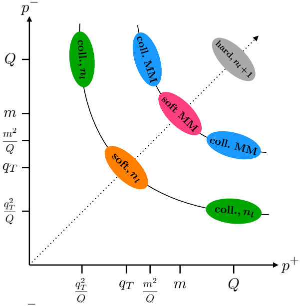
Thank you for your attention

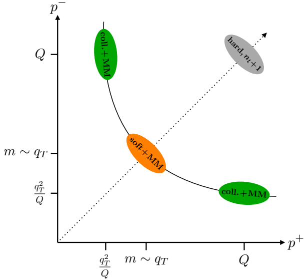
Modes



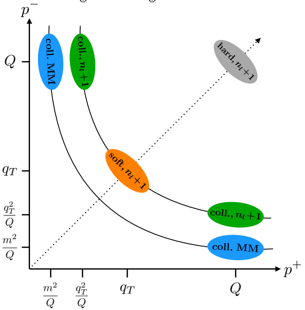
p^-
$m \sim Q$
q_T
$\frac{q_T^2}{Q}$
coll., n_l
hard+MM
soft, n_l
coll., n_l
p^+
$\frac{q_T^2}{Q}$
q_T
$m \sim Q$



p^-
Q
m
$\frac{m^2}{Q}$
q_T
$\frac{q_T^2}{Q}$
coll., n_l
coll. MM
hard, n_l+1
soft MM
coll. MM
soft, n_l
coll., n_l
p^+
$\frac{q_T^2}{Q}$
q_T
$\frac{m^2}{Q}$
m
Q

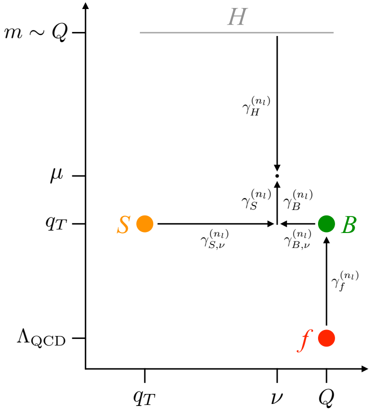


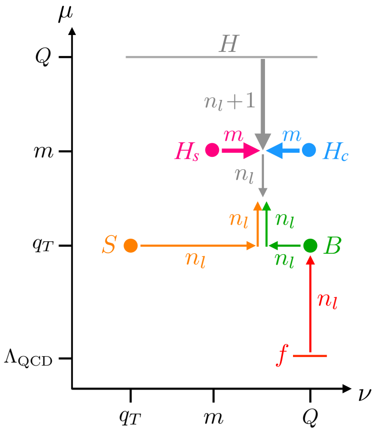
p^-
Q
$m \sim q_T$
$\frac{q_T^2}{Q}$
coll.+MM
hard, n_l+1
soft+MM
coll.+MM
p^+
$\frac{q_T^2}{Q}$
$m \sim q_T$
Q



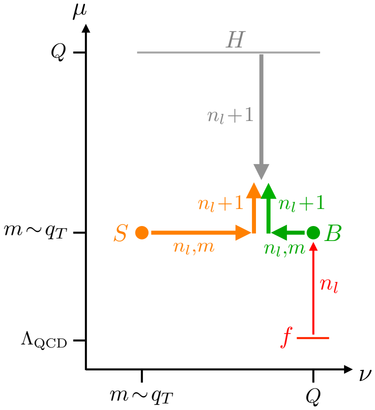
p^-
Q
q_T
$\frac{q_T^2}{Q}$
$\frac{m^2}{Q}$
coll. MM
coll., n_l+1
hard, n_l+1
soft, n_l+1
coll., n_l+1
coll. MM
p^+
$\frac{m^2}{Q}$
$\frac{q_T^2}{Q}$
q_T
Q

Evolution 1

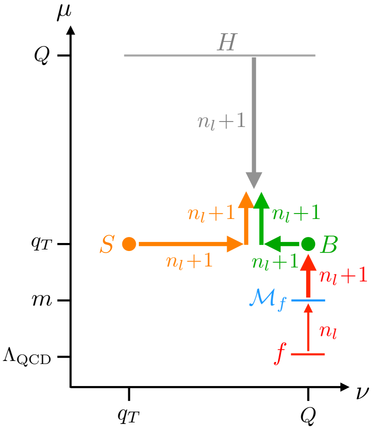

H
m ∼ Q
μ
q_T
Λ_{QCD}
$\gamma_H^{(n_l)}$
$\gamma_S^{(n_l)}$
$\gamma_B^{(n_l)}$
S
B
$\gamma_{S,\nu}^{(n_l)}$
$\gamma_{B,\nu}^{(n_l)}$
$\gamma_f^{(n_l)}$
f
q_T
ν
Q


μ
H
Q
n_l+1
m
H_s
m
m
H_c
n_l
n_l
n_l
q_T
S
B
n_l
n_l
n_l
Λ_{QCD}
f
q_T
m
Q
ν

Evolution 2



μ
Q
H
$n_l{+}1$
$n_l{+}1$
$n_l{+}1$
$m \sim q_T$
S
B
n_l,m
n_l,m
n_l
$\Lambda_{\rm QCD}$
f
ν
$m \sim q_T$
Q



μ
Q
H
$n_l{+}1$
$n_l{+}1$
$n_l{+}1$
q_T
S
B
$n_l{+}1$
$n_l{+}1$
$n_l{+}1$
m
$\mathcal{M}_f$
n_l
$\Lambda_{\rm QCD}$
f
ν
q_T
Q