Transverse momentum dependent (un)polarized gluon distributions in Higgs production

M.G. Echevarria, TK, P.J. Mulders and C. Pisano,
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Outline

- Introduction to factorization and gluon distributions (PDFs/TMDs)
- Factorization as multistep matching
  - Proper definition of TMDs
  - Evolution of gluon TMDs
  - Re-factorization in terms of PDFs
- Results for Higgs boson production at LHC
- Summary and outlook

Disclaimer: Main interest of study - to properly define gluon TMDs and derive their scale evolution. Higgs boson production is a suitable prototype process.
Collinear (PDF) factorization

- Cross section calculations based on factorization
  cross section = parton distributions × partonic cross section
  
  - example: $pp \rightarrow H + X \rightarrow \gamma\gamma + X$
  
  - At leading order
    
    \[
    \frac{d\sigma}{dx d\bar{x}} = \hat{\sigma} f_{a/A}(x; \mu) f_{b/B}(\bar{x}; \mu) + \mathcal{O}(\Lambda_{QCD}^2/Q^2)
    \]
  
  - parton distributions non-perturbative but universal, and measurable
    
    - Depend on longitudinal momentum fraction $x$
    
    - Probability of finding the parton inside the proton
  
  - partonic cross section calculable in perturbation theory
  
  - The factorization is an approximation:
    
    - Factorization formula have power suppressed corrections
TMD factorization

• Cross section calculations based on factorization
  cross section = parton distributions × partonic cross section

  • example: \( pp \rightarrow H + X \rightarrow \gamma\gamma + X \)

• Measured transverse momenta of Higgs boson

  • Sensitive to transverse momenta of the two partons
    \( \Rightarrow \) TMDs describing the partons inside the protons (instead of PDFs)

• Schematically, at leading order

\[
\frac{d\sigma}{dxd\bar{x}d^2q_T} = \hat{\sigma} \int d^2k_{aT}d^2k_{bT}\delta^{(2)}(q_T - k_{aT} - k_{bT})f_{a/A}(x, k_{aT}; \mu)f_{b/B}(\bar{x}, k_{bT}; \mu) + \mathcal{O}(q_T/Q)
\]

• Depend on momentum fraction \( x \) and transverse momenta of parton

• TMDs necessary to explain data - in particular related to spin asymmetries

• Transverse momentum spectrum of Drell-Yan process
Polarization PDFs

- There are two different types of gluon (un)polarized PDFs
  - **Unpolarized** gluon in unpolarized proton
    (sum over spin/helicities)
  - **Longitudinally** polarized gluon in longitudinally polarized proton
    (difference between aligned vs anti-aligned helicities)
- The polarized distributions describe correlations between the spins of the gluon and the proton
- Each of the two types of distributions has its own DGLAP evolution equation governing the scale evolution.
  - Splitting kernels depend on polarization
    \[ \Rightarrow \text{different for un-, longitudinally polarized gluons} \]
Polarization TMDs

- Gluon TMD correlator can be decomposed as

\[
G_{g/A}^{\mu\nu[U]}(x, k_{n\perp}) = -\frac{g_{\perp}^{\mu\nu}}{2} f_1^g(x, k_{nT}) + \frac{1}{2} \left( g_{\perp}^{\mu\nu} - \frac{2 k_{\perp}^{\mu} k_{\perp}^{\nu}}{k_{nT}^2} \right) h_{1T}^g(x, k_{nT})
\]

\[
G_{g/A}^{\mu\nu[L]}(x, k_{n\perp}) = -i \frac{\epsilon_{\perp}^{\mu\nu}}{2} \lambda g_{1L}^g(x, k_{nT}) + \frac{\epsilon_{\perp}^{k_{n\perp}\{\mu k_{\perp}^{\nu}\}}}{2k_{nT}^2} \lambda h_{1T}^g(x, k_{nT})
\]

\[
G_{g/A}^{\mu\nu[T]}(x, k_{n\perp}) = -g_{\perp}^{\mu\nu} \frac{\epsilon_{\perp}^{k_{n\perp} S_{\perp}}}{k_{nT}} f_{1T}^g(x, k_{nT}) - i\epsilon_{\perp}^{\mu\nu} \frac{k_{n\perp} \cdot S_{\perp}}{k_{nT}} g_{1T}^g(x, k_{nT})
\]

\[
+ \frac{\epsilon_{\perp}^{k_{n\perp}\{\mu k_{\perp}^{\nu}\}}}{2k_{nT}^2} h_{1T}^g(x, k_{nT}) + \frac{\epsilon_{\perp}^{s_{\perp}\{\mu k_{\perp}^{\nu}\}}}{4k_{nT}} h_{1T}^g(x, k_{nT})
\]

where the different distributions describe different types of correlations between spin of the gluon, spin of the proton and transverse momentum of the gluon.

P.J. Mulders, J. Rodrigues, 2000

- A gluon in an unpolarized proton is either unpolarized or linearly polarized
Polarization TMDs

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G_{g/A}^{\mu\nu[U]}(x, k_{n\perp}) = -\frac{g_{1}^{\mu\nu}}{2} f_{1}^{q}(x, k_{nT}) + \frac{1}{2} \left( g_{\perp}^{\mu\nu} - \frac{2 k_{n\perp}^{\mu} k_{n\perp}^{\nu}}{k_{nT}^{2}} \right) h_{1}^{q}(x, k_{nT})
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\]

\[
+ \frac{\epsilon_{\perp}^{k_{n\perp}\{\mu k_{n\perp}^{\nu}\}}}{2k_{nT}^{2}} \frac{k_{n\perp} \cdot S_{\perp}}{k_{nT}} h_{1T}^{q}(x, k_{nT}) + \frac{\epsilon_{\perp}^{k_{n\perp}\{\mu S_{\perp}^{\nu}\}} + \epsilon_{\perp}^{S_{\perp}\{\mu k_{n\perp}^{\nu}\}}}{4k_{nT}} h_{1T}^{q}(x, k_{nT})
\]

where the different distributions describe different types of correlations between spin of the gluon, spin of the proton and transverse momentum of the gluon.

P.J. Mulders, J. Rodrigues, 2000

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Wilson lines - TMDs vs PDFs

- Matrix element describing the proton need a Wilson line to be gauge invariant
  \[ f \sim \langle P | \bar{\psi} W \psi | P \rangle \]
  (true for both PDFs and TMDs)
- Wilson lines:
  \[ W_n(x) = P \exp \left[ i g \int_{-\infty}^{0} ds \, \bar{n} \cdot A_n^a(x + \bar{n}s) t^a \right] \]
  phase picked up by the gluons moving in the background field of the other hadron
- PDFs:
  - Can choose gauge where it reduces to unity
- TMDs: rich (process dependent) Wilson line structure
  \[ \Rightarrow \text{Leads for example to different sign of the Boer-Mulders function in DIS compared to DY.} \]

P. Mulders talk on Monday
TMD Higgs production

\[ h_A(P, S_A) + h_B(\bar{P}, S_B) \rightarrow H(q_T) + X \]

- Process dominated by gluon channel
  \[ gg \rightarrow H \]
  with the main contribution from the top-quark loop

- Will use the Effective Theory point of view
  - Stepwise matching at the different scales
    \[ \text{QCD}(n_f = 6) \rightarrow \text{QCD}(n_f = 5) \rightarrow \text{SCET}_{qT} \rightarrow \text{SCET}_{\Lambda_{QCD}} \]
    between different effective theories

- Previous works already addressed this process, both in pQCD and effective theory approaches:
  Neill, Rothstein, Vaidya 15; Becher, Neubert 12;
  Chiu, Jain, Neill, Rothstein 12; Mantry, Petriello 11;
  Sun, Xiao, Yuan 11; Ji, Ma, Yuan 05;
  Catani, de Florian, Grazzini, Nason 03 etc.

But do not consider well-defined gluon TMDs
Factorization theorem

\[ h_A(P, S_A) + h_B(\bar{P}, S_B) \rightarrow H(q_T) + X \]

- Different relevant scales

1. \( C_t(m_t^2/\mu^2) \)
   - SM
   - \( n_f = 6 \)

2. \( C_t(m_t^2/\mu^2) \)
   - SM
   - \( n_f = 5 \)
   - \( \tilde{G}^{\mu\nu}_{g/P}(x_A, b_T; m_H, \mu) \)
   - SCET\(_{q_T} \)

3. \( C_t(m_t^2/\mu^2) \)
   - \( C_H(m_H^2/\mu^2) \)

\[ \tilde{C}(x_A, b_T^2 \mu^2, m_H^2/\mu^2) \]
   - SCET\(_{II} \)
   - \( q_T \)
   - \( f_{g/P}(x_A; \mu) \)
   - \( \Lambda_{QCD} \)

Fig. from M. Echevarria

Factorization Theorem \( \equiv \) Multistep Matching Procedure
Step 1 \[ \text{QCD}(n_f = 6) \to \text{QCD}(n_f = 5) \to \text{SCET}_{qT} \to \text{SCET}_{\Lambda_{QCD}} \]

- Integrating out the top

- Effective Lagrangian

\[ \mathcal{L}_{\text{eff}} = C_t(m_t^2, \mu) \frac{H}{v} \frac{\alpha_s(\mu)}{12\pi} F_{\mu\nu, a} F_{\mu\nu}^a \]

Matching coefficient (known to 3-loops)

Schroder, Steinhauser, 2006; Chetyrkin, Kuhn, Sturm, 2005

- Cross section:

\[
d\sigma = \frac{1}{2s} \left( \frac{\alpha_s(\mu)}{12\pi v} \right)^2 C_t^2(m_t^2, \mu) \frac{d^3q}{(2\pi)^3 2E_q} \int d^4y \, e^{-i\mathbf{q} \cdot \mathbf{y}} \]
\[
\times \sum_X \langle P, \bar{P} | F_{\mu\nu}^a F_{\mu\nu, a}(y) | X \rangle \langle X | F_{\alpha\beta}^b F_{\alpha\beta, b}(0) | P, \bar{P} \rangle
\]
SCET crash course

• Effective theory of QCD
• Describes interactions between soft (low energy) and collinear (very energetic in one light-cone direction)
• Systematic expansion of Lagrangian in powers of small parameter $\lambda$ ($q_T/Q$)
• Separate Lagrangians for (ultra-) soft quarks gluons and (anti)collinear quarks gluons

**Assumption** SCET captures the IR physics of QCD (no Glaubers)

Holds for Higgs production

$\Rightarrow$ Matching is possible

• Useful to resum logarithms


\begin{align*}
p_n^\mu &= Q(1, \lambda^2, \lambda) & n\text{-collinear} \\
p_n^\mu &= Q(\lambda^2, 1, \lambda) & \bar{n}\text{-collinear} \\
p_{us}^\mu &= Q(\lambda^2, \lambda^2, \lambda^2) & \text{ultrasoft (SCET-I)} \\
p_s^\mu &= Q(\lambda, \lambda, \lambda) & \text{soft (SCET-II)}
\end{align*}
SCET crash course

- Effective theory of QCD
- Describes interactions between soft (low energy) and collinear (very energetic in one light-cone direction)
- Systematic expansion of Lagrangian in powers of small parameter $\lambda (q_T/Q)$
- Separate Lagrangians for (ultra-) soft quarks/gluons and (anti)collinear quarks/gluons

**Assumption** SCET captures the IR physics of QCD (no Glaubers)

Holds for Higgs production

$\Rightarrow$ Matching is possible

- Useful to resum logarithms

\[
\begin{align*}
  p_n^\mu &= Q(1, \lambda^2, \lambda) \\
  p_{\bar{n}}^\mu &= Q(\lambda^2, 1, \lambda) \\
  p_{us}^\mu &= Q(\lambda^2, \lambda^2, \lambda^2) \\
  p_s^\mu &= Q(\lambda, \lambda, \lambda)
\end{align*}
\]

n-collinear
\[\bar{n}\text{-collinear}\]
ultrasoft (SCET-I)
soft (SCET-II)

Step 2  

QCD($n_f = 6$) → QCD($n_f = 5$) → SCET$_{qT}$ → SCET$_{\Lambda_{QCD}}$

- Integrating out the Higgs mass

\[ F^{\mu\nu,a} F^a_{\mu\nu} = -2q^2 C_H(-q^2, \mu^2) g_{\mu\nu} B_{n\perp}^{\mu,a} (S_n^\dagger S_n)_{ab} B_{\overline{n}\perp}^\nu,b \]

- With the fields

\[ B_{n\perp}^\mu = i\bar{n}\alpha g_{\perp\beta}^\mu t^a (\mathcal{W}_n^\dagger)^{a\beta,b} F_n^{\alpha\beta,b} \]

and collinear and soft Wilson lines

\[ \mathcal{W}_n(x) = P \exp \left[ ig \int_{-\infty}^0 ds \bar{n} \cdot A_n^a(x + \bar{n}s)t^a \right], \quad \text{Adjoint representation} \]

\[ (t^a)^{bc} = -if^{abc} \]

\[ S_n(x) = P \exp \left[ ig \int_{-\infty}^0 ds \bar{A}^a_s(x + n s)t^a \right] \]

(phase picked up by the gluons moving in the background field of the other hadron)
Step 2  \[ \text{QCD}(n_f = 6) \to \text{QCD}(n_f = 5) \to \text{SCET}_{qT} \to \text{SCET}_{\Lambda_{QCD}} \]

- Cross section

\[
\frac{d\sigma}{dy \, d^2q_\perp} = 2\sigma_0(\mu) \, C_i^2(m_t^2, \mu) \, H(m_H, \mu) \, \frac{m_H^2}{\tau_s} \, (2\pi)^2 \int d^2b_\perp \, e^{-i b_\perp \cdot q_\perp} \\
\times J_n^{(0)\mu\nu}(x_A, b_\perp; \mu) \, J_n^{(0)\overline{\mu}\overline{\nu}}(x_B, b_\perp; \mu) \, S(b_\perp; m_H^2, \mu) + \mathcal{O}(q_T/m_H)
\]

- Collinear and soft matrix elements

\[
J_n^{(0)\mu\nu}(x_A, b_\perp; \mu) = \frac{x_A P^+}{2N_c} \int \frac{dy^-}{(2\pi)} \, e^{-i(\frac{1}{2} x_A y^- P^+)} \\
\times \sum_{X_n} \langle P | B_n^{\mu,a}(y^-, b_\perp) | X_n \rangle \langle X_n | B_n^{\overline{\nu},a}(0) | P \rangle
\]

\[
S(b_\perp; m_H^2, \mu) = \frac{1}{N_c^2 - 1} \sum_{X_s} \langle 0 | (S_n^\dagger S_\overline{n})^{ab}(b_\perp) | X_s \rangle \langle X_s | (S_n^\dagger S_\overline{n})^{ba}(0) | 0 \rangle
\]

- Individually ill-defined. They contain rapidity divergencies!
Definition of TMDs - cancellation of rapidity divergencies

To cancel rapidity divergences, split soft part and combine with the collinear/anti-collinear to defined TMDs

Collins, 2011; Echevarria, Idilbi, Scimemi, 2012
Definition of TMDs - cancellation of rapidity divergencies

- Rapidity divergencies spurious
- Collinear and Soft are ill-defined!
- Need to regulate the divergencies
  - we use the delta regulator $\Delta^\pm$

To cancel rapidity divergences, split soft part and combine with the collinear/anti-collinear to defined TMDs

\[ k_n \sim (1, \lambda^2, \lambda) \]
\[ k_{\bar{n}} \sim (\lambda^2, 1, \lambda) \]
\[ k_s \sim (\lambda, \lambda, \lambda) \]

\[ y = \frac{1}{2} \ln \left| \frac{k^+}{k^-} \right| \]

\[ k_n^2 \sim k_{\bar{n}}^2 \sim k_s^2 \sim Q^2 \lambda^2 \]
Step 2  

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

- Soft function can be separated in two pieces (to all orders)

\[ \tilde{S}(b_T; m_H^2, \mu) = \tilde{S}_-(b_T; \zeta_A, \mu; \Delta^-) \tilde{S}_+(b_T; \zeta_B, \mu; \Delta^+) \]

- Combination of soft and collinear matrix elements to form TMDs

\[
\begin{align*}
\tilde{G}^{\mu\nu}_{g/A}(x_A, b_\perp; \zeta_A, \mu^2) &= \tilde{J}^{(0)\mu\nu}_n(x_A, b_\perp; \mu^2; \Delta^+) \tilde{S}_-(b_T; \zeta_A, \mu^2; \Delta^+) \\
\tilde{G}^{\mu\nu}_{g/B}(x_B, b_\perp; \zeta_B, \mu^2) &= \tilde{J}^{(0)\mu\nu}_n(x_B, b_\perp; \mu^2; \Delta^-) \tilde{S}_+(b_T; \zeta_B, \mu^2; \Delta^-).
\end{align*}
\]

- Rapidity divergencies cancelled in the combination

- Cross section in terms of properly defined TMDs

\[
\begin{align*}
\frac{d\sigma}{dy \, d^2 q_\perp} &= 2\sigma_0(\mu) C_t^2(m_t^2, \mu) H(m_H, \mu) \frac{1}{(2\pi)^2} \int d^2 b_\perp \, e^{i(q_\perp \cdot b_\perp)} \\
&\times \tilde{G}^{\mu\nu}_{g/A}(x_A, b_\perp; \zeta_A, \mu) \tilde{G}^{\mu\nu}_{g/B}(x_B, b_\perp; \zeta_B, \mu) + \mathcal{O}(q_T/m_H)
\end{align*}
\]
Step 2

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

- Comparing the result of the full QCD(nf=5) result with the SCET result for the two TMDs gives the matching coefficient at one loop

\[
C_H(-q^2, \mu) = 1 + \frac{\alpha_s C_A}{4\pi} \left[ -\ln^2 \frac{-q^2}{\mu^2} + i0 + \frac{\pi^2}{6} \right] \quad H = C_H^2
\]

- Gives the Higgs cross section in terms of well defined TMDs

\[
\frac{d\sigma}{dy \, d^2q_\perp} = 2\sigma_0(\mu) C_t^2(m_t^2, \mu) H(m_H, \mu) \frac{1}{(2\pi)^2} \int d^2b_\perp e^{i q_\perp \cdot b_\perp} \\
\times \frac{1}{2} \left[ \tilde{f}_1^g/A(x_A, b_T; \zeta_A, \mu) \tilde{f}_1^g/B(x_B, b_T; \zeta_B, \mu) + \tilde{h}_1^\perp g/A(x_A, b_T; \zeta_A, \mu) \tilde{h}_1^\perp g/B(x_B, b_T; \zeta_B, \mu) \right] \\
+ \mathcal{O}(q_T/m_H)
\]

- The TMDs depend on two scales \( \mu \) and \( \zeta \).
- Scale invariance of cross section gives evolution of the gluon TMDs in the two scales.
Gluon TMD Evolution

- The evolution in $\mu$
  \[ \frac{d}{d\ln \mu} \ln \tilde{G}^{[pol]}_{g/A}(x_n, b_\perp, S_A; \zeta_A, \mu) \equiv \gamma_G \left( \alpha_s(\mu), \ln \frac{\zeta_A}{\mu^2} \right) \]
  and in $\zeta$
  \[ \frac{d}{d\ln \zeta_A} \ln \tilde{G}^{[pol]}_{g/A}(x_A, b_\perp, S_A; \zeta_A, \mu) = -D_g(b_T; \mu) \]

- Combined, gives us the evolution of the gluon TMDs
  \( \text{(universal evolution kernel = same for all polarizations)} \)
  \[ \tilde{G}^{[pol]}_{g/A}(x_n, b_\perp, S_A; \zeta_{A,f}, \mu_f) = \tilde{G}^{[pol]}_{g/A}(x_n, b_\perp, S_A; \zeta_A,i, \mu_i) \tilde{R}^g(b_T; \zeta_{A,i}, \mu_i, \zeta_{A,f}, \mu_f) \]

  where
  \[ \tilde{R}^g(b_T; \zeta_{A,i}, \mu_i, \zeta_{A,f}, \mu_f) = \exp \left\{ \int_{\mu_i}^{\mu_f} \frac{d\bar{\mu}}{\bar{\mu}} \gamma_G \left( \alpha_s(\bar{\mu}), \ln \frac{\zeta_{A,f}}{\bar{\mu}^2} \right) \right\} \left( \frac{\zeta_{A,f}}{\zeta_{A,i}} \right)^{-D_g(b_T; \mu_i)} \]

- Evolution contains non-perturbative piece, in $D$ at large $b$
Step 3  \( \text{QCD}(n_f = 6) \rightarrow \text{QCD}(n_f = 5) \rightarrow \text{SCET}_{qT} \rightarrow \text{SCET}_{\Lambda_{QCD}} \)

- In region where \( \Lambda_{QCD} << q_T << Q \)
- \( q_T \) gives perturbative scale inside TMDs
  - TMDs can be calculated in terms of usual PDFs

\[
\tilde{f}_{g/A}(x, b_T; \zeta, \mu) = \sum_{j=q,\bar{q},g} \tilde{C}_{g/j}^f(\bar{x}, b_T; \zeta, \mu) \otimes f_{j/A}(x/\bar{x}; \mu) + \mathcal{O}(b_T \Lambda_{QCD})
\]

\[
\tilde{h}_{g/A}(x, b_T; \zeta, \mu) = \sum_{j=q,\bar{q},g} \tilde{C}_{g/j}^h(\bar{x}, b_T; \zeta, \mu) \otimes f_{j/A}(x/\bar{x}; \mu) + \mathcal{O}(b_T \Lambda_{QCD})
\]

\[
\tilde{g}_{1L}^{g/A}(x, b_T; \zeta, \mu) = \sum_{j=q,\bar{q},g} \tilde{C}_{g\leftarrow j}^g(\bar{x}, b_T; \zeta, \mu) \otimes g_{j/A}(x/\bar{x}; \mu) + \mathcal{O}(b_T \Lambda_{QCD})
\]

- Comparing the one loop PDFs with the one loop TMDs we get the matching coefficients at one loop
- Matching coefficients spin/polarization dependent
Higgs boson cross section

\[
\frac{d\sigma}{dy \, d^2q_\perp} = 2\sigma_0(\mu) C_t^2(m_t^2, \mu) H(m_H, \mu) \frac{1}{(2\pi)^2} \int d^2b_\perp \, e^{i\mathbf{q}_\perp \cdot \mathbf{b}_\perp} \\
\times \frac{1}{2} \left[ \tilde{f}_{1g/A}^{g}(x_A, b_T; \zeta_A, \mu) \tilde{f}_{1g/B}^{g}(x_B, b_T; \zeta_B, \mu) + \tilde{h}_1^{g/A}(x_A, b_T; \zeta_A, \mu) \tilde{h}_1^{g/B}(x_B, b_T; \zeta_B, \mu) \right] \\
+ \mathcal{O}(q_T/m_H)
\]

- Evolution of gluons resums large logs
  \[\tilde{G}_{g/A}^{\text{pol}}(x_n, \mathbf{b}_\perp, S_A; \zeta_A, f, \mu_f) = \tilde{G}_{g/A}^{\text{pol}}(x_n, \mathbf{b}_\perp, S_A; \zeta_A, i, \mu_i) \tilde{R}_g(b_T; \zeta_A, i, \mu_i, \zeta_A, f, \mu_f)\]

- Build the gluon TMDs from expansion onto the PDFs (gives the perturbative tail)

- The non-perturbative input are the collinear PDFs, the large b contributions to the coefficients and the D-term.
  - Want to parametrize the non-perturbative input and test their impact on the cross section predictions
  - Will show results for two different simple parametrizations
Relative contribution of linearly-/un-polarized gluons

- Simple (multiplicative) non-perturbative model
  \[ \tilde{F}_{g/A}^{NP}(x, b_T; Q) = e^{-b_T^2(\lambda_f + \lambda_Q \ln(Q^2/Q_0^2))} \]
- At the scale of the Higgs boson, linear polarization contributes a few percent to the cross section
- At lower scales, linear polarization much larger (and dependent on non-perturbative parameters) - could be measurable in for example quarkonium production

\[ R = \frac{d\sigma_{\text{lin. pol.}}}{d\sigma_{\text{unpol.}}} \]
Higgs $p_T$ spectrum

- Simple (multiplicative) non-perturbative model
  \[ \tilde{F}_{g/A}^{NP}(x, b_T; Q) = e^{-\beta_f b_T} \]
- $q_T$ spectrum has only small dependence on the non-perturbative input
- At the current level of precision, resummed collinear result is enough
Summary

- TMDs are interesting mix of perturbative and non-perturbative physics
- We have defined **gluon TMDs** (on the light-cone), **free from rapidity divergencies**
- Derived their QCD evolution
  - Showed that it is the **same** for all gluon TMDs (all polarizations)
- Derived one-loop TMD factorization for Higgs production
- Showed results for the Higgs transverse momentum spectrum
- Studied the impact of **linearly polarized** gluons in Higgs production
  - Generically at the level of a few percent
- Non-perturbative impact on Higgs pT spectrum relatively small, justifies use of resummed collinear cross section.
- Non-perturbative parameters much larger impact at lower scales, such as quarkonia production