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

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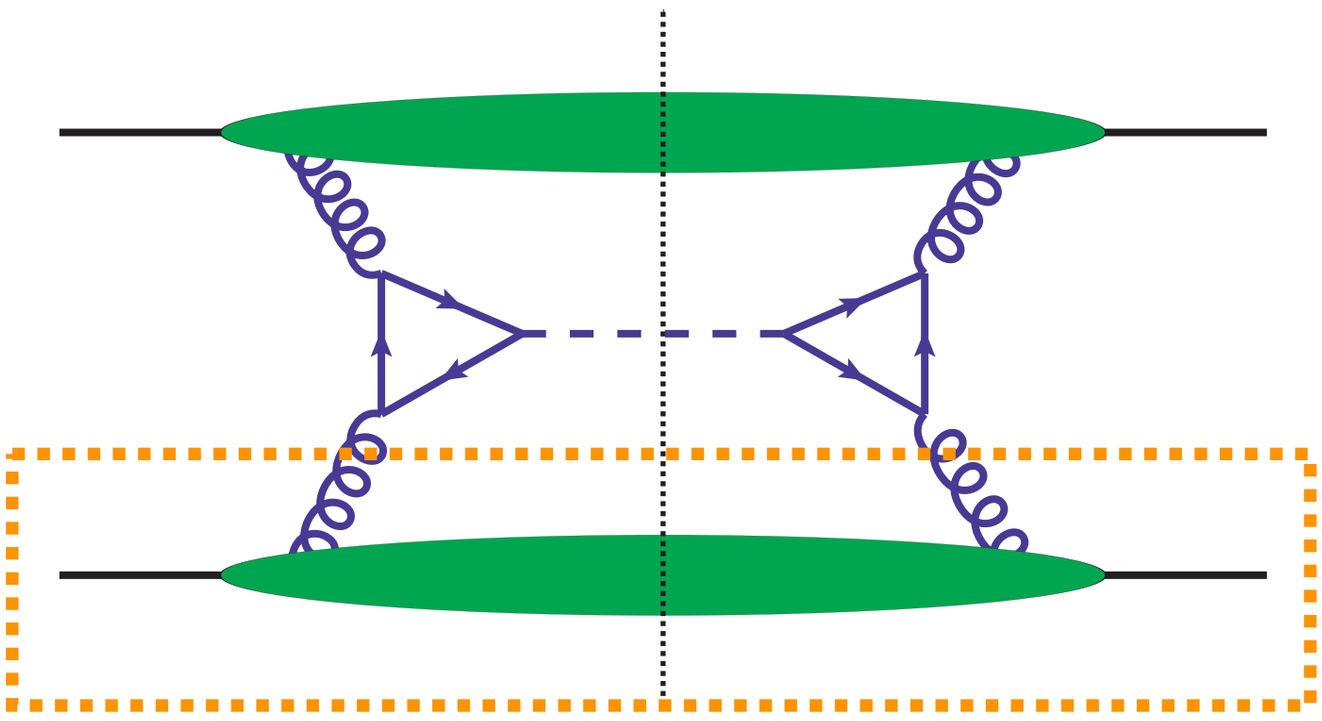
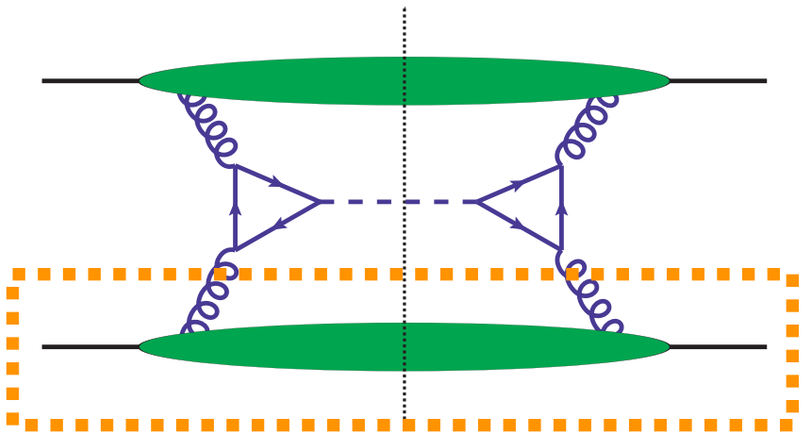


M.G. Echevarria, TK, P.J. Mulders and C. Pisano,
arXiv:1502.05354

DIS2015 - Dallas, April 30, 2015

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

$$\text{cross section} = \text{parton distributions} \times \text{partonic cross section}$$

  - example: $pp \to H + X \to \gamma\gamma + X$
  - 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

$$\text{cross section} = \text{parton distributions} \times \text{partonic cross section}$$

  - example: $pp \to H + X \to \gamma\gamma + X$
- 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

$$\frac{d\sigma}{dx d\bar{x} d^2\boldsymbol{q}_T} = \hat{\sigma} \int d^2\boldsymbol{k}_{aT} d^2\boldsymbol{k}_{bT} \delta^{(2)}(\boldsymbol{q}_T - \boldsymbol{k}_{aT} - \boldsymbol{k}_{bT}) f_{a/A}(x, \boldsymbol{k}_{aT}; \mu) f_{b/B}(\bar{x}, \boldsymbol{k}_{bT}; \mu) + \mathcal{O}(q_T/Q)$$

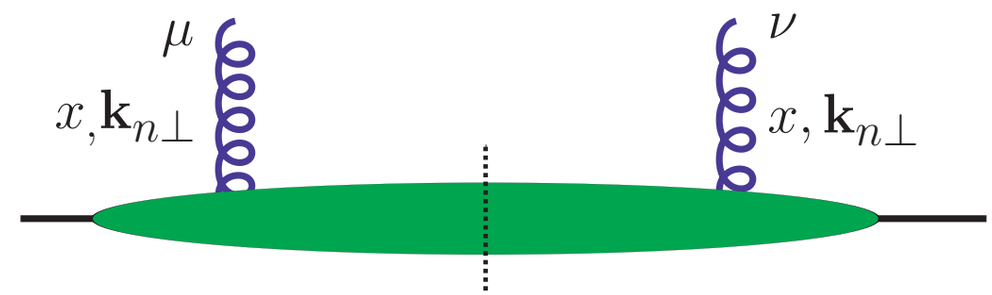
  - Depend on momentum fraction x and transverse momenta of parton
  - TMDs necessary to explain data - in particular related to spin asymmetries
  - Transverse momentum spectrum of Drell-Yan process

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

    $\Rightarrow$ different for un-, longitudinally polarized gluons

Polarization TMDs



- Gluon TMD correlator can be decomposed as

$$G^{\mu\nu[U]}_{g/A}(x, \boldsymbol{k}_{n\perp}) = -\frac{g^{\mu\nu}_{\perp}}{2} f^{g}_{1}(x, k_{nT}) + \frac{1}{2}\left(g^{\mu\nu}_{\perp} - \frac{2k^{\mu}_{n\perp}k^{\nu}_{n\perp}}{k^{2}_{nT}}\right) h^{\perp g}_{1}(x, k_{nT})$$

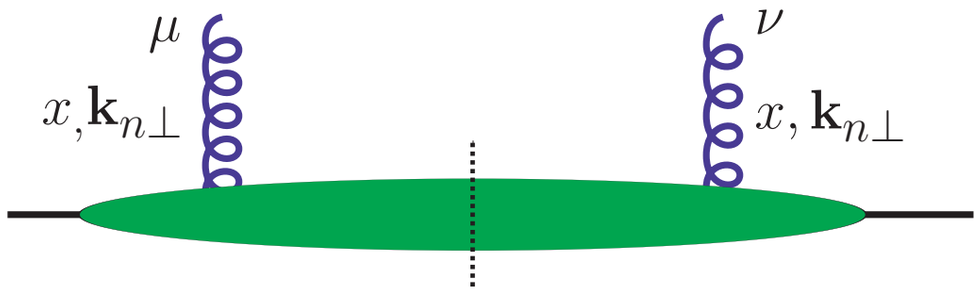
$$G^{\mu\nu[L]}_{g/A}(x, \boldsymbol{k}_{n\perp}) = -i\frac{\epsilon^{\mu\nu}_{\perp}}{2}\lambda\, g^{g}_{1L}(x, k_{nT}) + \frac{\epsilon^{k_{n\perp}\{\mu}_{\perp} k^{\nu\}}_{n\perp}}{2k^{2}_{nT}}\lambda\, h^{\perp g}_{1L}(x, k_{nT})$$

$$G^{\mu\nu[T]}_{g/A}(x, \boldsymbol{k}_{n\perp}) = -g^{\mu\nu}_{\perp}\frac{\epsilon^{k_{n\perp}S_{\perp}}_{\perp}}{k_{nT}} f^{\perp g}_{1T}(x, k_{nT}) - i\epsilon^{\mu\nu}_{\perp}\frac{\boldsymbol{k}_{n\perp}\cdot\boldsymbol{S}_{\perp}}{k_{nT}} g^{g}_{1T}(x, k_{nT})$$
$$+\frac{\epsilon^{k_{n\perp}\{\mu}_{\perp} k^{\nu\}}_{n\perp}}{2k^{2}_{nT}}\frac{\boldsymbol{k}_{n\perp}\cdot\boldsymbol{S}_{\perp}}{k_{nT}} h^{\perp g}_{1T}(x, k_{nT}) + \frac{\epsilon^{k_{n\perp}\{\mu}_{\perp} S^{\nu\}}_{\perp} + \epsilon^{S_{\perp}\{\mu}_{\perp} k^{\nu\}}_{n\perp}}{4k_{nT}} h^{g}_{1T}(x, k_{nT})$$

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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$$+\frac{\epsilon^{k_{n\perp}\{\mu}_{\perp} k^{\nu\}}_{n\perp}}{2k^{2}_{nT}}\frac{\boldsymbol{k}_{n\perp}\cdot\boldsymbol{S}_{\perp}}{k_{nT}} h^{\perp g}_{1T}(x, k_{nT}) + \frac{\epsilon^{k_{n\perp}\{\mu}_{\perp} S^{\nu\}}_{\perp} + \epsilon^{S_{\perp}\{\mu}_{\perp} k^{\nu\}}_{n\perp}}{4k_{nT}} h^{g}_{1T}(x, k_{nT})$$

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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:

$$W_n(x) = P \exp\left[ig \int_{-\infty}^{0} ds\, \bar{n} \cdot A_n^a(x + \bar{n}s) t^a\right]$$

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

  $\Rightarrow$ Leads for example to different sign of the Boer-Mulders function in DIS compared to DY.

P. Mulders talk on Monday

TMD Higgs production

$$h_A(P, S_A) + h_B(\bar{P}, S_B) \to H(q_T) + X$$

- Process dominated by gluon channel

  $$gg \to H$$

  with the main contribution from the top-quark loop
- Will use the Effective Theory point of view
  - Stepwise matching at the different scales

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

    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 <u>well-defined</u> gluon TMDs

Factorization theorem

$$h_A(P, S_A) + h_B(\bar{P}, S_B) \to H(q_T) + X$$

- Different relevant scales

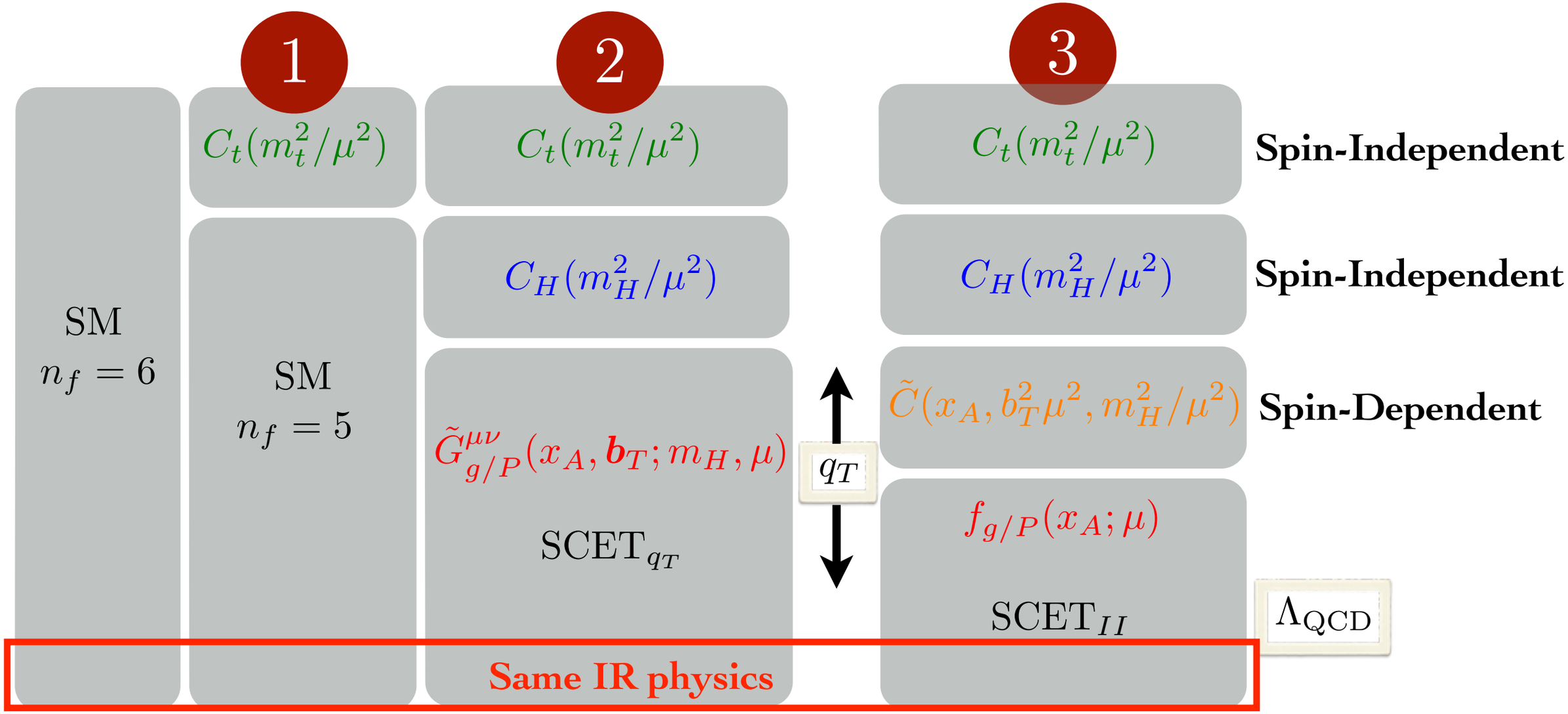
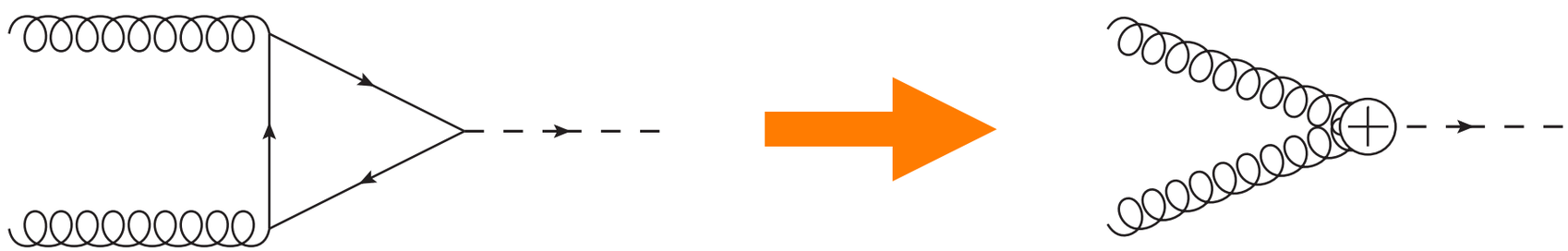


Fig. from M. Echevarria

Factorization Theorem = Multistep Matching Procedure

Step 1 $\mathrm{QCD}(n_f = 6) \to \mathrm{QCD}(n_f = 5) \to \mathrm{SCET}_{q_T} \to \mathrm{SCET}_{\Lambda_{QCD}}$

- Integrating out the top



- Effective Lagrangian

Matching coefficient (known to 3-loops)

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

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

- Cross section:

$$d\sigma = \frac{1}{2s}\left(\frac{\alpha_s(\mu)}{12\pi v}\right)^2 C_t^2(m_t^2, \mu)\frac{d^3q}{(2\pi)^3 2E_q}\int d^4y\, e^{-iq\cdot y}$$
$$\times \sum_X \langle P, \bar{P}|\, F^a_{\mu\nu}F^{\mu\nu,a}(y)\, |X\rangle\, \langle X|\, F^b_{\alpha\beta}F^{\alpha\beta,b}(0)\, |P, \bar{P}\rangle$$

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 λ (q_T/Q)
- Separate Lagrangians for (ultra-) soft quarks/gluons and (anti)collinear quarks/gluons

Bauer, Fleming, Pirjol, Stewart, 2001; BPS, 2002;
Beneke, Chapovsky, Diehl, Feldmann, 2002;

- <u>Assumption</u> SCET captures the IR physics of QCD (no Glaubers)

  Holds for Higgs production

  $\Rightarrow$ Matching is possible
- Useful to resum logarithms

$$\boxed{\begin{aligned} p_n^\mu &= Q(1,\lambda^2,\lambda) \\ p_{\bar{n}}^\mu &= Q(\lambda^2,1,\lambda) \\ p_{us}^\mu &= Q(\lambda^2,\lambda^2,\lambda^2) \\ p_s^\mu &= Q(\lambda,\lambda,\lambda) \end{aligned}}$$

n-collinear

$\bar{n}$ -collinear

ultrasoft (SCET-I)

soft (SCET-II)

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Step 2 $\mathrm{QCD}(n_f = 6) \to \mathrm{QCD}(n_f = 5) \to \mathrm{SCET}_{q_T} \to \mathrm{SCET}_{\Lambda_{QCD}}$

- Integrating out the Higgs mass

$$F^{\mu\nu,a}\, F^a_{\mu\nu} = -2q^2 C_H(-q^2,\mu^2)\, g^\perp_{\mu\nu} \mathcal{B}^{\mu,a}_{n\perp} \left(\mathcal{S}^\dagger_n \mathcal{S}_{\bar{n}}\right)^{ab} \mathcal{B}^{\nu,b}_{\bar{n}\perp}$$

Matching coefficient (known to 3-loops)

- With the fields

$$\mathcal{B}^\mu_{n\perp} = i\bar{n}_\alpha g^\mu_{\perp\beta} t^a (\mathcal{W}^\dagger_n)^{ab} F^{\alpha\beta,b}_n$$

Baikov et. al., 2009; Lee et. al, 2010; Gehrmann et. al, 2010

and collinear and soft Wilson lines

$$\mathcal{W}_n(x) = P\exp\left[ig\int_{-\infty}^0 ds\, \bar{n}\cdot A^a_n(x+\bar{n}s)t^a\right],$$

$$\mathcal{S}_n(x) = P\exp\left[ig\int_{-\infty}^0 ds\, n\cdot A^a_s(x+ns)t^a\right]$$

Adjoint representation $(t^a)^{bc} = -if^{abc}$

(phase picked up by the gluons moving in the background field of the other hadron)

Step 2 $\quad \mathrm{QCD}(n_f = 6) \to \mathrm{QCD}(n_f = 5) \to \mathrm{SCET}_{q_T} \to \mathrm{SCET}_{\Lambda_{QCD}}$

- Cross section

$$\frac{d\sigma}{dy\, d^2 q_\perp} = 2\sigma_0(\mu)\, C_t^2(m_t^2, \mu) H(m_H, \mu)\, \frac{m_H^2}{\tau s}\, (2\pi)^2 \int d^2 b_\perp e^{-i\boldsymbol{b}_\perp \boldsymbol{q}_\perp}$$
$$\times\, J_n^{(0)\mu\nu}(x_A, \boldsymbol{b}_\perp; \mu)\, J^{(0)}_{\bar{n}\,\mu\nu}(x_B, \boldsymbol{b}_\perp; \mu)\, S(\boldsymbol{b}_\perp; m_H^2, \mu) + \mathcal{O}(q_T/m_H)$$

$$H(m_H, \mu) = C_H^2$$

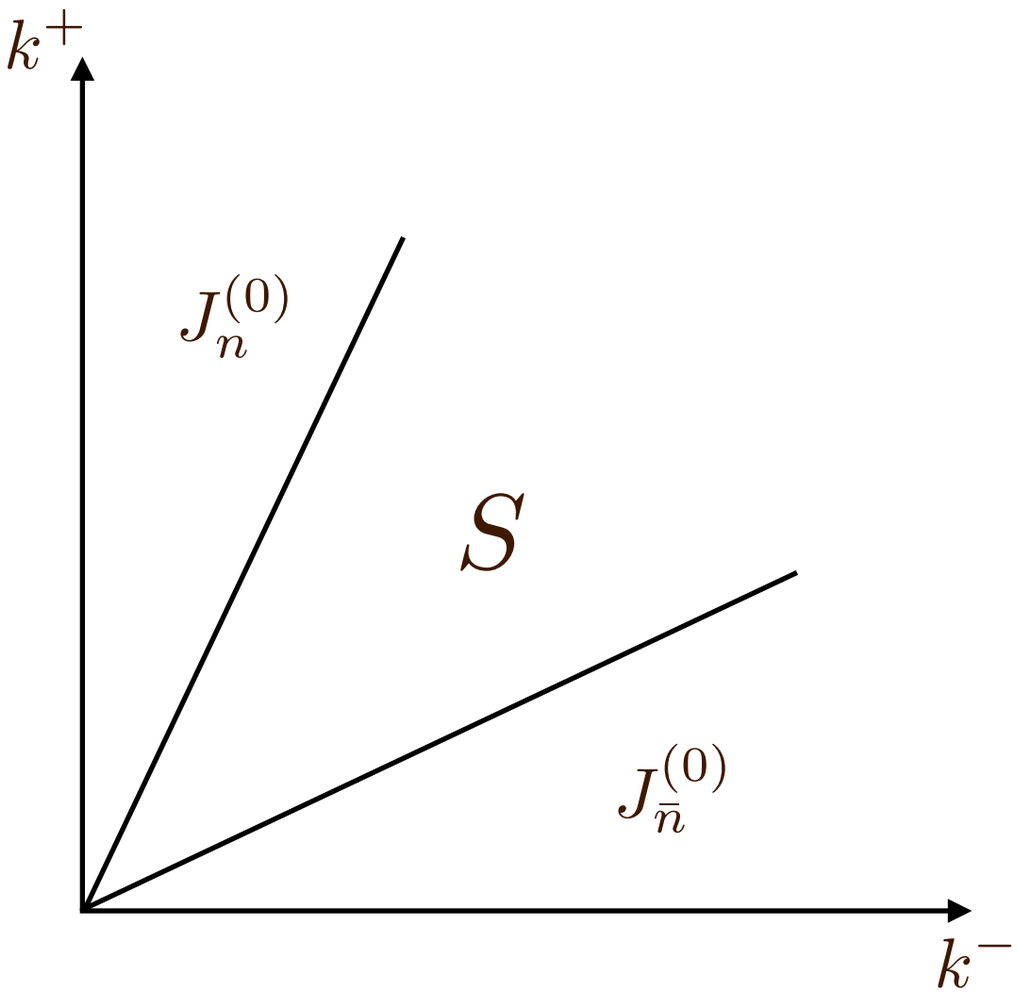
- Collinear and soft matrix elements

$$J_n^{(0)\mu\nu}(x_A, \boldsymbol{b}_\perp; \mu) = \frac{x_A P^+}{2N_c} \int \frac{dy^-}{(2\pi)}\, e^{-i\left(\frac{1}{2} x_A y^- P^+\right)}$$
$$\times \sum_{X_n} \langle P|\, \mathcal{B}_{n\perp}^{\mu,a}(y^-, \boldsymbol{b}_\perp)\, |X_n\rangle\, \langle X_n|\, \mathcal{B}_{n\perp}^{\nu,a}(0)\, |P\rangle$$

$$S(\boldsymbol{b}_\perp; m_H^2, \mu) = \frac{1}{N_c^2 - 1} \sum_{X_s} \langle 0|\, \left(\mathcal{S}_n^\dagger \mathcal{S}_{\bar{n}}\right)^{ab}(\boldsymbol{b}_\perp)\, |X_s\rangle\, \langle X_s|\, \left(\mathcal{S}_{\bar{n}}^\dagger \mathcal{S}_n\right)^{ba}(0)\, |0\rangle$$

- Individually ill-defined. They contain rapidity divergencies!

Definition of TMDs - cancellation of rapidity divergencies



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

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

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

$$k_n^2 \sim k_{\bar{n}}^2 \sim k_s^2 \sim Q^2\lambda^2$$

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

Collins, 2011; Echevarria, Idilbi, Scimemi, 2012

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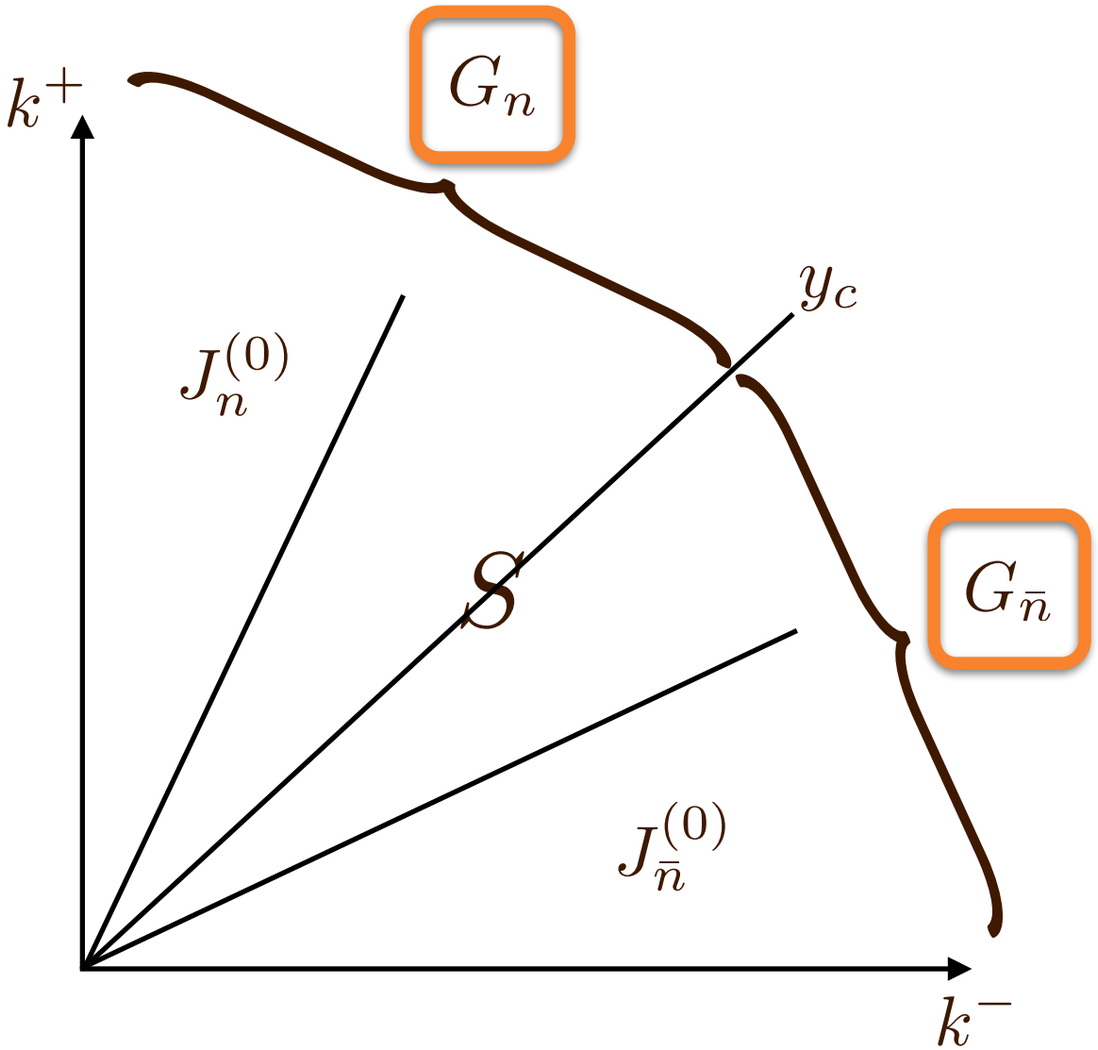

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Step 2 $\mathrm{QCD}(n_f = 6) \to \mathrm{QCD}(n_f = 5) \to \mathrm{SCET}_{q_T} \to \mathrm{SCET}_{\Lambda_{QCD}}$

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

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

- Combination of soft and collinear matrix elements to form TMDs

$$\tilde{G}^{\mu\nu}_{g/A}(x_A, \boldsymbol{b}_\perp; \zeta_A, \mu^2) = \tilde{J}^{(0)\mu\nu}_n(x_A, \boldsymbol{b}_\perp; \mu^2; \Delta^+)\, \tilde{S}_-(b_T; \zeta_A, \mu^2; \Delta^+)\,,$$
$$\tilde{G}^{\mu\nu}_{g/B}(x_B, \boldsymbol{b}_\perp; \zeta_B, \mu^2) = \tilde{J}^{(0)\mu\nu}_{\bar{n}}(x_B, \boldsymbol{b}_\perp; \mu^2; \Delta^-)\, \tilde{S}_+(b_T; \zeta_B, \mu^2; \Delta^-)\,.$$

  - Rapidity divergencies cancelled in the combination

- Cross section in terms of properly defined TMDs

$$\frac{d\sigma}{dy\, d^2 q_\perp} = 2\sigma_0(\mu)\, C_t^2(m_t^2, \mu) H(m_H, \mu)\, \frac{1}{(2\pi)^2} \int d^2 b_\perp\, e^{i\boldsymbol{q}_\perp \cdot \boldsymbol{b}_\perp}$$
$$\times\, \tilde{G}^{\mu\nu}_{g/A}(x_A, \boldsymbol{b}_\perp; \zeta_A, \mu)\, \tilde{G}_{g/B\,\mu\nu}(x_B, \boldsymbol{b}_\perp; \zeta_B, \mu) + \mathcal{O}(q_T/m_H)$$

Step 2 $\mathrm{QCD}(n_f = 6) \to \mathrm{QCD}(n_f = 5) \to \mathrm{SCET}_{q_T} \to \mathrm{SCET}_{\Lambda_{QCD}}$

- 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

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

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

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

- The TMDs depend on two scales μ and ζ.
- Scale invariance of cross section gives evolution of the gluon TMDs in the two scales

Gluon TMD Evolution

- The evolution in μ

$$\frac{d}{d\ln\mu}\ln\tilde{G}^{[pol]}_{g/A}(x_n, \boldsymbol{b}_\perp, S_A; \zeta_A, \mu) \equiv \gamma_G\left(\alpha_s(\mu), \ln\frac{\zeta_A}{\mu^2}\right)$$

and in ζ

$$\frac{d}{d\ln\zeta_A}\ln\tilde{G}^{[pol]}_{g/A}(x_A, \boldsymbol{b}_\perp, S_A; \zeta_A, \mu) = -D_g(b_T; \mu)$$

- Combined, gives us the evolution of the gluon TMDs

(universal evolution kernel = same for all polarizations)

$$\tilde{G}^{[pol]}_{g/A}(x_n, \boldsymbol{b}_\perp, S_A; \zeta_{A,f}, \mu_f) = \tilde{G}^{[pol]}_{g/A}(x_n, \boldsymbol{b}_\perp, S_A; \zeta_{A,i}, \mu_i)\, \tilde{R}^g\left(b_T; \zeta_{A,i}, \mu_i, \zeta_{A,f}, \mu_f\right)$$

where

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

- Evolution contains non-perturbative piece, in D at large b

Step 3 $\mathrm{QCD}(n_f = 6) \to \mathrm{QCD}(n_f = 5) \to \mathrm{SCET}_{q_T} \to \mathrm{SCET}_{\Lambda_{QCD}}$

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

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

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

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

- 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

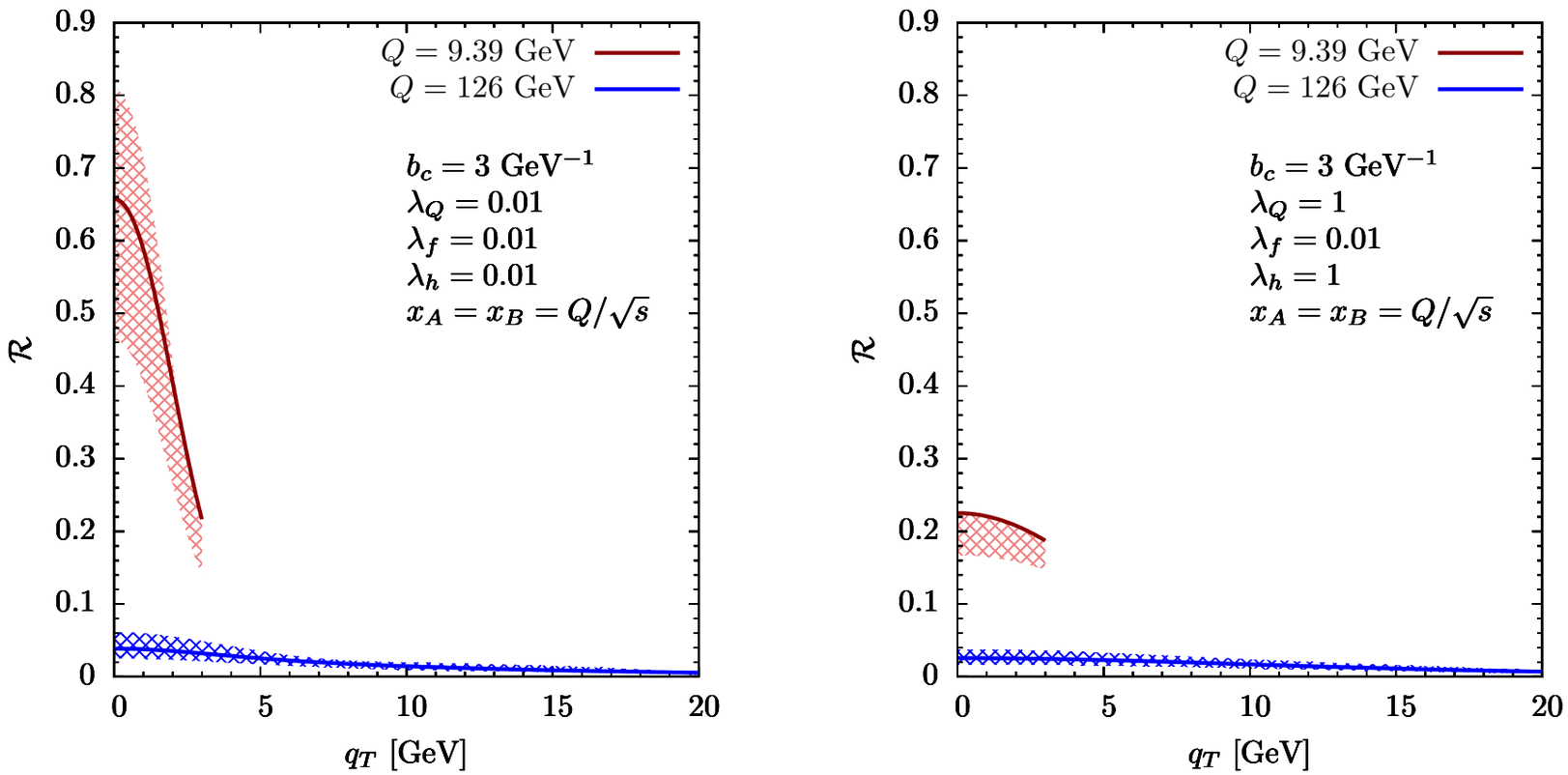
$$\frac{d\sigma}{dy\, d^2q_\perp} = 2\sigma_0(\mu)\, C_t^2(m_t^2,\mu) H(m_H,\mu)\, \frac{1}{(2\pi)^2} \int d^2b_\perp\, e^{i\boldsymbol{q}_\perp\cdot\boldsymbol{b}_\perp}$$
$$\times \frac{1}{2}\left[\tilde{f}_1^{g/A}(x_A,b_T;\zeta_A,\mu)\, \tilde{f}_1^{g/B}(x_B,b_T;\zeta_B,\mu) + \tilde{h}_1^{\perp\,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

- Evolution of gluons resums large logs

$$\tilde{G}_{g/A}^{[pol]}(x_n,\boldsymbol{b}_\perp,S_A;\zeta_{A,f},\mu_f) = \tilde{G}_{g/A}^{[pol]}(x_n,\boldsymbol{b}_\perp,S_A;\zeta_{A,i},\mu_i)\, \tilde{R}^g\,(b_T;\zeta_{A,i},\mu_i,\zeta_{A,f},\mu_f)$$

- 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



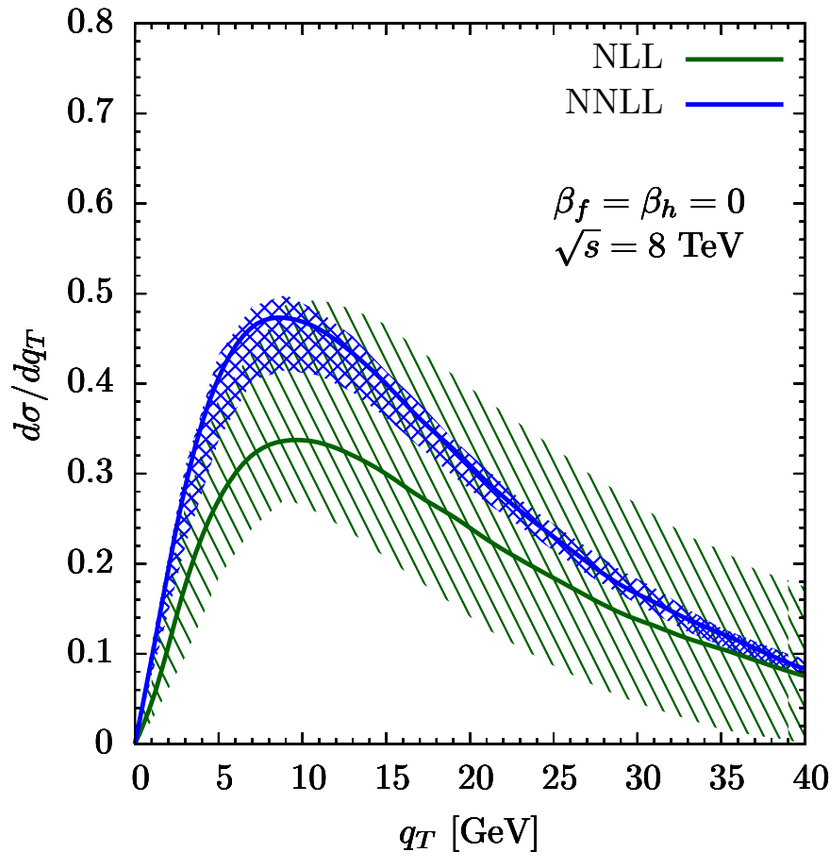
$$R = \frac{d\sigma_{\text{lin. pol.}}}{d\sigma_{\text{unpol.}}}$$

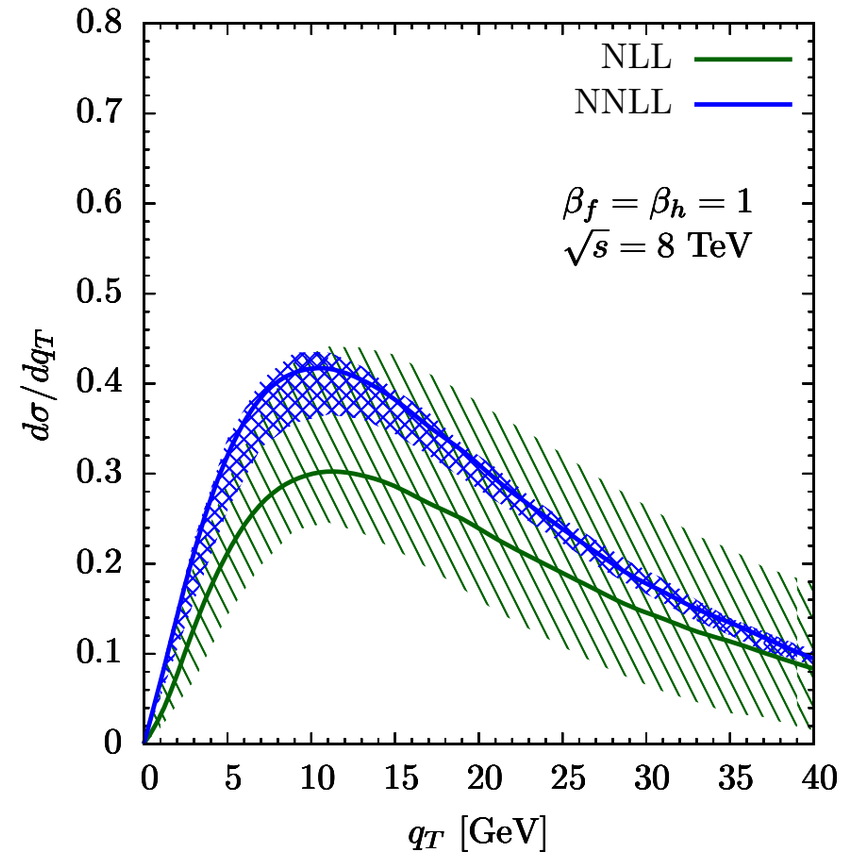
- Simple (multiplicative) non-perturbative model

$$\tilde{F}^{\text{NP}}_{g/A}(x, b_T; Q) = e^{-b_T^2(\lambda_f + \lambda_Q \ln(Q^2/Q_0^2))}$$

- At the scale of the Higgs boson, linear polarization contributes a few precent 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

Higgs pT spectrum





- Simple (multiplicative) non-perturbative model

$$\tilde{F}^{\rm NP}_{g/A}(x, b_T; Q) = e^{-\beta_f b_T}$$

- qT 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