Physics at LHC, Vienna, Austria, 13-17 July 2004

Resummed Higgs Boson Transverse Momentum Distribution at the LHC

Anna Kulesza

Institut für Theoretische Teilchenphysik
Universität Karlsruhe

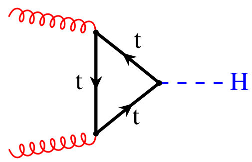
based on work in collaboration with

G. Sterman and W. Vogelsang,

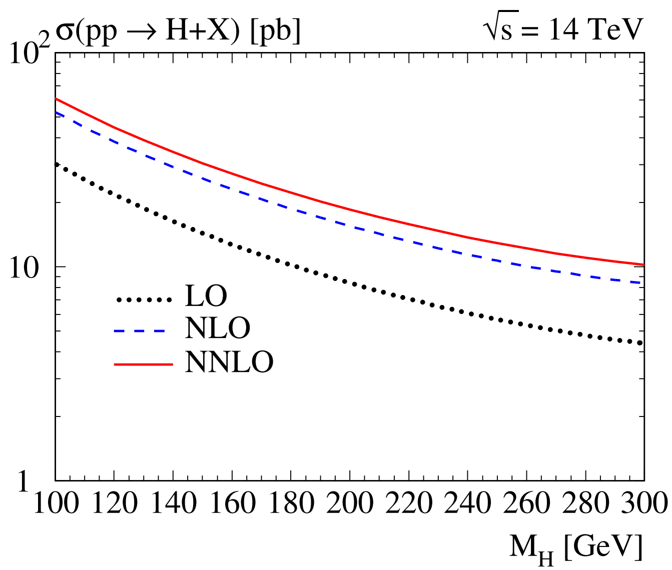
Phys.Rev. D69 (2004) 014012 & Phys.Rev. D66 (2002) 014011

1. Introduction

* Light Higgs at the LHC – main production mechanism is gluon-gluon fusion $gg \to HX$
* LO cross section $O(\alpha_s^2)$ mediated via a heavy quark loop (SM: only top loop relevant)



for $m_H \leq 2m_t$ Higgs-gluon interaction described using effective Lagrangian $\to$ effective ggH vertex



[from R. Harlander et al. PRL88 (2002) 201801]

– NLO QCD corrections to the total cross section large $\sim$70% [Dawson'91] [Djouadi, Spira, Zerwas'91] [Spira, Djouadi, Graudenz, Zerwas'95]

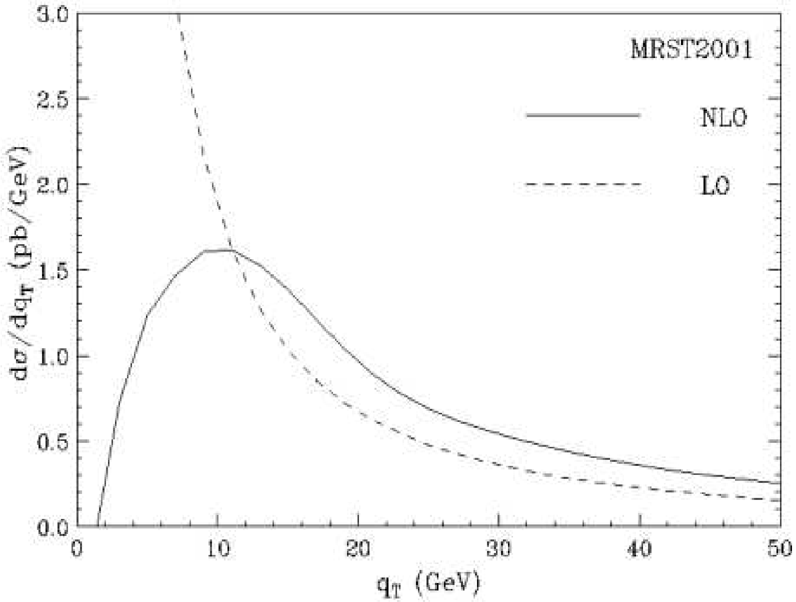
– NNLO QCD corrections also substantial $\sim$30% [Harlander, Kilgore'02] [Anastasiou, Melnikov'02]

– Dominant part of these contributions comes from soft & virtual gluon contributions [Catani, de Florian, Grazzini'01] [Harlander, Kilgore'01]

Introduction

Search and analysis strategies for the Higgs boson at the LHC rely on precise knowledge of production characteristics

$\rightarrow$ transverse momentum (Q_T) distribution



[from M. Grazzini, talk at Loops and Legs'04]

Fixed-order perturbation theory not applicable in the $Q_T \ll M_H$ region:

LO & NLO distributions diverge as $Q_T \rightarrow 0$

(LO Q_T distribution corresponds to Higgs recoiling against one parton $\rightarrow$ $O(\alpha_s^3)$)

* Small Q_T regime related to soft and collinear gluon emission

Introduction

Processes with two hadrons in the initial state – predictions based on perturbative calculations and factorization theorems

$$\sigma = \sum_q \int dx_1 dx_2 f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2) \hat{\sigma}_{q\bar{q}\to l^+l^-}$$

Collinear factorization: separation of short–distance IR-safe $\sigma_{q\bar{q}\to l^+l^-}$ and long–distance universal parton distribution functions f_q

However , for short-distance quantities which are not inclusive enough, perturbation theory may not be applicable in certain kinematic regions (most often near phase-space boundary)

- real gluon emission suppressed ($\Rightarrow$ soft & collinear gluons), virtual emission always allowed
- Real and virtual corrections cancellation leaves large logarithmic terms at each order in perturbation theory

Introduction

Classes of logarithmic corrections related to soft gluon emission:

- Explicit corrections e.g. recoil (transverse momentum distributions)

$$leading: \qquad \alpha_s^N \frac{\ln^{2N-1}\left(Q^2/Q_T^2\right)}{Q_T^2}$$

- Implicit corrections e.g. threshold (hadronic collisions at threshold) $\rightarrow$ integrated over

$$leading: \qquad \alpha_s^N \frac{\ln^{2N-1}(1-z)}{1-z}$$

inelasticity variable z, measures distance from the threshold, here $z = Q^2/\hat{s}$

$\Rightarrow$ large logarithmic corrections close to the phase space edge, in the limit

$z \rightarrow 1$ (threshold) and $Q_T \rightarrow 0$ (recoil)

2. Resummation

Reorganization of the standard perturbative expansion in α_s by selecting and summing classes of logarithmic terms to all orders

$$\hat{\sigma} \sim \hat{\sigma}_0 \left[T_1(\alpha_s L^2) + \alpha_s L T_2(\alpha_s L^2) + \alpha_s^2 L^2 T_3(\alpha_s L^2) + \ldots \right]$$

where e.g. T_1 (first 'Tower' of logarithms) collects terms of the form $\alpha_s^N \ln^{2N-1}(\ldots)$

Resummed cross sections exponentiate

$\Rightarrow$ In general, resummation follows from (re)factorization

(factorization $\Rightarrow$ evolution eq. $\Rightarrow$ exponentiation)

* dynamical factorization (process independent)
  – in the soft limit gluon emission factorizes [*Ermolaev, Fadin '81*] [*Bassetto, Ciafaloni, Marchesini '83*]
* phase-space factorization (process dependent, often performed in a conjugate space)

Resummation

Resummed cross sections exist for both:

→ recoil resummation (in Fourier conjugate to Q_T, b space) [Collins, Soper '83] [Collins, Soper, Sterman '85]

$$\delta\left(\mathbf{Q_T} - \sum_i \mathbf{k_T^i}\right) = \frac{1}{2\pi^2}\int d^2b e^{i\mathbf{b}(\mathbf{Q_T}-\sum_i \mathbf{k_T^i})} \qquad \ln(Q/Q_T) \leftrightarrow \ln(Qb)$$

→ threshold resummation (in Mellin N space) [Sterman '87] [Catani, Trentadue'89]

$$\delta\left(1 - z - \sum_i z_i\right) = \frac{1}{2\pi i}\int_C dN e^{-N(1-z-\sum_i z_i)} \qquad \ln(1-z) \leftrightarrow \ln N$$

and are of the form

$$\hat{\sigma} = \hat{\sigma}_0 \int_{\text{inv}} \mathcal{C} \exp(\mathcal{S})$$

where

$$\mathcal{S} = L f_1(\alpha_s L) + f_2(\alpha_s L) + \alpha_s f_3(\alpha_s L) + \ldots$$

$$\qquad LL \qquad NLL \qquad NNLL \qquad \ldots$$

$L = \ln(bQ), \ln(N)$ $\qquad$ $\mathcal{C}$ contains finite contributions

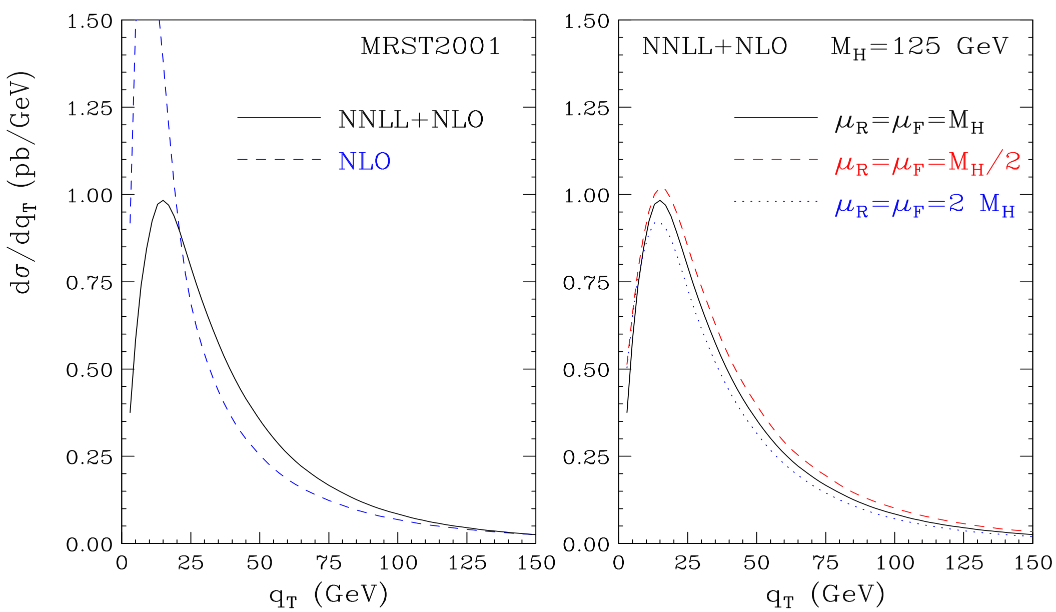
All singular dependence on L exponentiates

Resummation for Higgs production

Transverse momentum resummation

Many recent applications & developments of the "standard" Collins-Soper-Sterman (b-space) formalism [*Bozzi, Catani, de Florian, Grazzini '03*] [*AK, Stirling '03*] [*Berger, Qiu '02*] [*Balazs, Yuan '00*]

Comparison (also with PYTHIA and HERWIG predictions) can be found in the latest Les Houches workshop proceedings (hep-ph/0403052)



[*from Bozzi et al. PLB564 (2003) 65*]

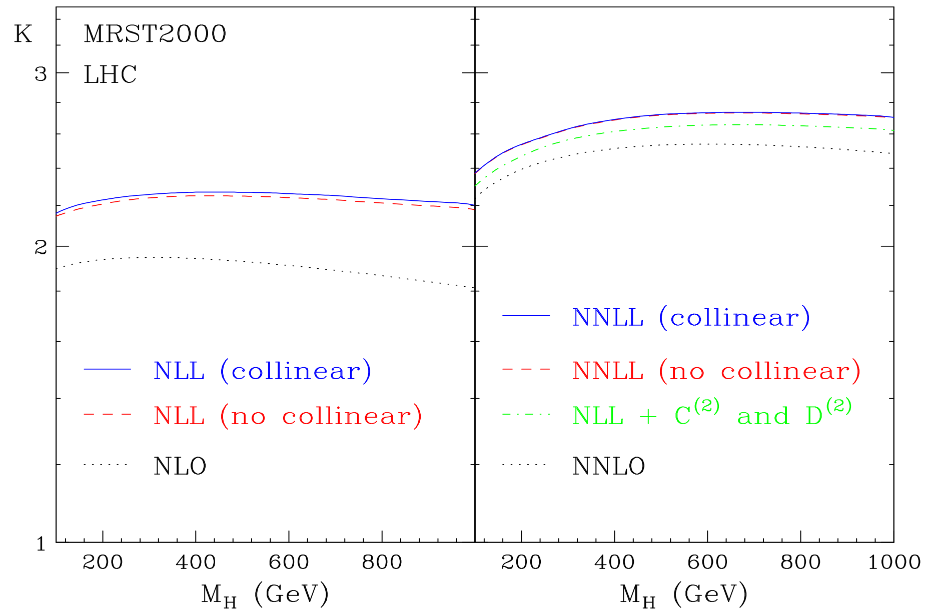
→ NNLL matched to NLO at high Q_T

→ unitarity constraint imposed such that the total cross section recovered after integration over Q_T

Resummation for Higgs production

Threshold resummation

[*Catani, de Florian, Grazzini, Nason '02*]



- better convergence to fixed order at NNLL $\Rightarrow$ 6-9% wrt. NNLO (13-20% at NLL)
- dominant subleading collinear terms taken into account
- colour charge C_A for gluons $\rightarrow$ increased sensitivity to Sudakov logarithms
- gluon induced processes sensitive to radiation at low x

3. Joint resummation

Joint resummation: combined resummation of threshold and recoil corrections [Laenen, Sterman, Vogelsang '00]
$\Rightarrow$ refactorization of short- and long-distance physics at fixed transverse momentum and energy

$$\frac{d\sigma^{\rm res}}{dQ^2\,dQ_T^2} = \sum_a \sigma_a^{(0)} \int_{C_N} \frac{dN}{2\pi i} \tau^{-N} \int \frac{d^2b}{(2\pi)^2} e^{i\vec{Q}_T\cdot\vec{b}}\, \mathcal{C}_a(Q,b,N,\mu,\mu_F)\, \exp\left[\mathcal{S}^{\rm PT}_{a\bar a}(N,b,Q,\mu)\right]\, \mathcal{C}_{\bar a}(Q,b,N,\mu,\mu_F)$$

where $\mathcal{S}^{\rm PT}_{a\bar a}$ summarizes QCD dynamics in the transverse momentum range $Q/\chi \le k_T \le Q$ and up to NLL accuracy in N and b [AK, Sterman, Vogelsang '02]

$$\mathcal{S}^{\rm PT}_{a\bar a}(N,b,Q,\mu) = -\int_{Q^2/\chi^2}^{Q^2} \frac{dk_T^2}{k_T^2}\left[A_a(\alpha_s(k_T))\ln\left(\frac{Q^2}{k_T^2}\right) + B_a(\alpha_s(k_T))\right]$$

$$A(\alpha_S) = \sum_{i=1}^{\infty}\left(\frac{\alpha_S}{2\pi}\right)^i A^{(i)}, \qquad B(\alpha_S) = \sum_{i=1}^{\infty}\left(\frac{\alpha_S}{2\pi}\right)^i B^{(i)}$$

$$\mathcal{C}_a(Q,b,N,\mu,\mu_F) = \sum_{j,k} C_{a/j}(N,\alpha_s(\mu))\,\mathcal{E}_{jk}(N,Q/\chi,\mu_F)\,f_k(N,\mu_F), \qquad C(\alpha_S) = \sum_{i=1}^{\infty}\left(\frac{\alpha_S}{2\pi}\right)^i C^{(i)}$$

$\mathcal{E}$ - evolution matrix from μ_F to Q/χ at LO $\mathcal{E} = \exp\left(\frac{\gamma_N^0}{2\pi}\int_{\mu_F^2}^{Q^2/\chi^2}\frac{dk_T^2}{k_T^2}\alpha_s(k_T^2)\right)$

Joint resummation

$\Rightarrow$ sums threshold and recoil corrections to NLL accuracy

$\Rightarrow$ recovers threshold and recoil resummation formalisms up to NLL in the appropriate limits,

$N \to \infty$ (at fixed b)

Threshold $\to$ $$\sigma(N) \sim \sum_q \exp\left\{2\int_{Q^2/\bar{N}^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} A(\alpha_s(\bar{\mu}^2)) \ln\left(\frac{\bar{\mu}\bar{N}}{Q}\right)\right\} f_q^N(Q) f_{\bar{q}}^N(Q),$$

$b \to \infty$ (at fixed N)

Recoil $\to$ $$\sigma(b) \sim \sum_q \exp\left\{-\int_{Q^2/\bar{b}^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\left[\ln\left(\frac{Q^2}{\bar{\mu}^2}\right) A(\alpha_S(\bar{\mu}^2)) + B(\alpha_S(\bar{\mu}^2))\right]\right\} f_q^N(Q/\bar{b}) f_{\bar{q}}^N(Q/\bar{b})$$
$$\to \sum_q \exp\left\{2\int_{Q^2/\bar{b}^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} A(\alpha_s(\bar{\mu}^2)) \ln\left(\frac{\bar{\mu}\bar{N}}{Q}\right)\right\} f_q^N(Q) f_{\bar{q}}^N(Q)$$

χ is chosen to be

$$\chi(\bar{N}, \bar{b}) = \bar{b} + \frac{\bar{N}}{1 + \eta \bar{b}/\bar{N}}\,; \qquad \bar{N} \equiv N e^{\gamma_E}\,; \qquad \bar{b} \equiv bQe^{\gamma_E}/2\,; \qquad \eta = \text{const}.$$

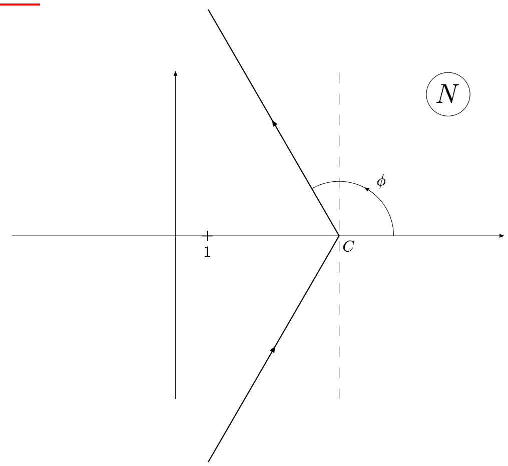
$\Rightarrow$ includes the leading $\alpha_s^N \ln^{2N-1} N/N$ collinear non-soft terms to all orders

Joint resummation: transforms

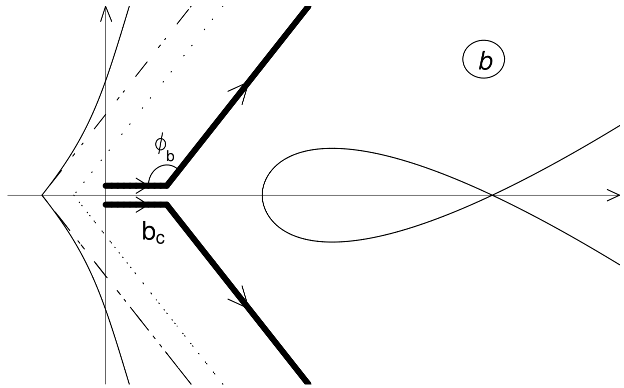
* Inverse $\bar{N}$ and b transforms – integrals along contours in $(\bar{N}, b)$ complex space

* Regularization of running coupling singularity – 'Minimal Prescription' [*Catani et al.'96*]

N contour:



b contour:



Landau pole:

$$\beta = \frac{1}{2} \quad \Rightarrow \quad \chi(\bar{N}, \bar{b}) = \exp[1/(2b_0\alpha_s(\mu))] \equiv \rho_L$$

$$rightmost\ pdf\ singularity < C < \rho_L$$

$$\chi(\bar{N}, \bar{b}) = \bar{b} + \frac{\bar{N}}{1 + \frac{\bar{b}}{4\bar{N}}} = \exp[1/(2b_0\alpha_s(\mu))] \equiv \rho_L$$

$\rightarrow \chi = 0 \Rightarrow \bar{b} = -2\bar{N}$

$\rightarrow 1 + \frac{\bar{b}}{4\bar{N}} = 0 \Rightarrow \bar{b} = -4\bar{N}$

* unambigous definition of resummed perturbation theory without introducing any additional dimensional scales

* functional form of non-perturbative corrections implied

Joint resummation for Higgs production

In a specific resummation scheme [Catani, de Florian, Grazzini '00]

$$\frac{d\sigma^{\rm res}}{dQ^2\,dQ_T^2} = \pi\tau\sigma_0^H\delta(Q^2-M_H^2)H(\alpha_s(Q^2))\int_{C_N}\frac{dN}{2\pi i}\tau^{-N}\int\frac{d^2b}{(2\pi)^2}e^{i\vec{Q}_T\cdot\vec{b}}$$
$$\times\quad \mathcal{C}_{g/A}(Q,b,N,\mu,\mu_F)\,\exp\left[S_{gg}^{\rm PT}(N,b,Q,\mu)\right]\,\mathcal{C}_{g/B}(Q,b,N,\mu,\mu_F)$$

where H collects the effect of hard virtual corrections

$$H(\alpha_s) = 1+\frac{\alpha_s}{2\pi}\left(2\pi^2+11\right)$$

and [Kodaira, Trentadue '82] [Catani, D'Emilio, Trentadue '88] [de Florian, Grazzini '00]

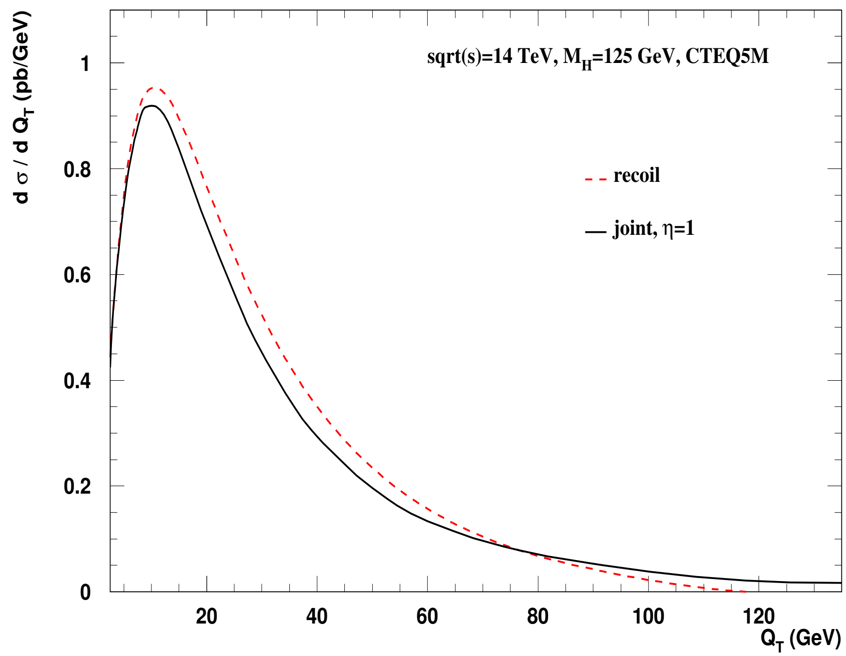
$$C_{g/g}^{(1)}(N,\alpha_s) = 1+\frac{\alpha_s}{4\pi}\pi^2\,,\qquad C_{g/q}^{(1)}(N,\alpha_s) = \frac{\alpha_s}{2\pi}C_F\frac{1}{N+1} = C_{g/\bar{q}}(N,\alpha_s)\,,$$

$$A_g^{(1)} = C_A\,,\qquad B_g^{(1)} = -\frac{1}{6}(11C_A-4T_RN_F)\,,\qquad A_g^{(2)} = \frac{C_A}{2}\left[C_A\left(\frac{67}{18}-\frac{\pi^2}{6}\right)-\frac{10}{9}T_RN_F\right]\,,$$
$$B_g^{(2)} = C_A^2\left(-\frac{4}{3}+\frac{11}{36}\pi^2-\frac{3}{2}\zeta_3\right)+\frac{1}{2}C_FT_RN_F+C_AN_FT_R\left(\frac{2}{3}-\frac{\pi^2}{9}\right).$$

In principle, joint resummation valid only up to NLL (formal extension to NNLL – work in progress)

Contribution from NNLL terms with $B^{(2)}$, $C^{(1)}$ and H numerically significant — but easy to include

Joint resummation *[AK, Sterman, Vogelsang '04]*



→ NLL with the NNLL coefficients $B^{(2)}$, $C^{(1)}$ and H included

→ matched to LO Q_T distribution

→ $\mu = \mu_F = Q = m_H$

→ non-perturbative term $-gb^2$ added to the exponent, $g = 1.67\mathrm{GeV}^2$.

- joint resummation comparable with recoil resummation in the low Q_T region
- relatively low influence of threshold effects at low Q_T; applicability of recoil approach confirmed
- integrated distribution contains non-leading contributions beyond threshold resummation
  → associated with $small-x$ terms from parton evolution and decreasing the distribution

4. Conclusions

Resumation:

- recoil and threshold resummation methods well established
- results for Higgs production at the LHC available; many new developments

Joint resummation:

- successfully sums threshold and recoil corrections to next–to–leading log accuracy
- recovers threshold and recoil resummation formalisms in the appropriate limits
- provides result for Higgs Q_T distribution confirming applicability of recoil resummation at low Q_T
- shows corrections due to threshold effects small at low Q_T