k_t-factorization in a variable-flavor-number scheme: heavy-hadron production

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in collaboration with

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REF25

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High-energy or k_t factorization

Initially designed to resum large $\log(1/x)$ terms.

Seminal papers: Collins, Ellis: *Nucl. Phys. B 360 (1991) 3-30*; Catani, Ciafaloni, Hautmann: *Phys. Lett. B242 (1990) 97, Nucl. Phys. B 366(1991) 135, Nucl.Phys. b427 (1994) 475*

$$\frac{d\sigma}{dx_1 dx_2 d^2 p_t} = \int^{k^2_{max}} d^2k_{1t} d^2k_{2t} F_i(x_1, k^2_{1t}; \mu^2) F_j(x_2, k^2_{2t}; \mu^2) \hat{\sigma}_{ij}(k^2_{1t}, k^2_{2t}; \mu^2)$$

$\hat{\sigma}$ is an **off-shell cross section**. The **unintegrated PDFs**, $F(x, k_t^2; \mu^2)$, are related to collinear PDFs by

$$f_i(x;\mu) = \int_0^{\mu^2} F_i(x, k_t^2; \mu^2) dk_t^2$$

$F_i(x, k_t^2; \mu^2)$ obey the BFKL equation.

I use the event generator KaTie for $d\sigma$.

Schemes and HF production

Fixed-flavor-number scheme

Proton made of gluon+light quarks

$\sigma = \mathrm{PDF}^{FFNS}_{\mathrm{order}} \otimes \hat{\sigma}^{FFNS}_{\mathrm{order}}$

Dominant process: $gg \to Q\bar{Q}$

Variable-flavor-number scheme

gluon+light quarks+heavy quarks

$\sigma = \mathrm{PDF}^{VFNS}_{\mathrm{order}} \otimes \hat{\sigma}^{VFNS}_{\mathrm{order}}$

Dominant processes: $gQ \to gQ$ (for $p_t >$ a few GeV).

- Typical calculations use $\hat{\sigma}^{FFNS}_{\mathrm{LO}}$ with $\mathrm{PDF}^{VFNS}_{\mathrm{LO,\ NLO}}$.
- Expect better results with a VFNS at LHC energies (where you can reach $P_t \gtrsim 5m_Q$).

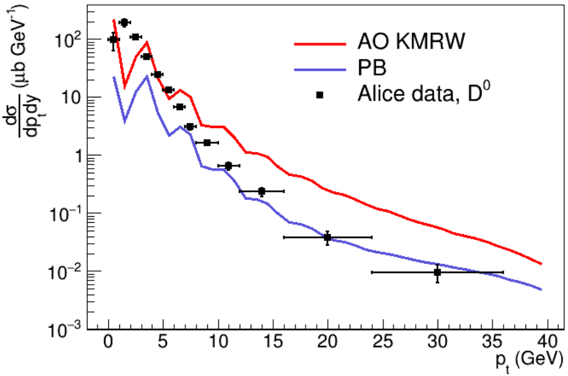
Goal

Implementation of HEF within a variable-flavor-number scheme (VFNS):

- Bring HEF closer in rigor to collinear factorization.
- Most of modern PDFs extracted in a VFNS.

Issue:

- KMRW UPDFs + KaTie + VFNS overestimates data.
- No publication found specifying which value is used for k_{max}.



k_t factorization in a Yukawa theory

Inspired by "Basics of factorization in a scalar Yukawa field theory", *Aslan, Gamberg, Gonzalez-Hernandez, Rainaldi, Rogers*.

$$\mathscr{L} = \sum_j \frac{i}{2}\left[\overline{\psi}_j \gamma^\mu \partial_\mu \psi_j - (\partial_\mu \overline{\psi}_j)\gamma^\mu \psi_j\right] - M_j \overline{\psi}_j \psi_j + \frac{1}{2}(\partial\phi)^2 - \frac{m_s^2}{2}\phi^2$$
$$- \lambda\left(\overline{\psi}_1 \psi_2 \phi + \overline{\psi}_2 \psi_1 \phi\right)$$

The structure functions can be computed exactly = w/o factorization (but still in perturbation theory).

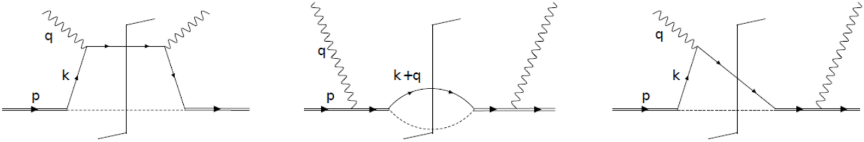
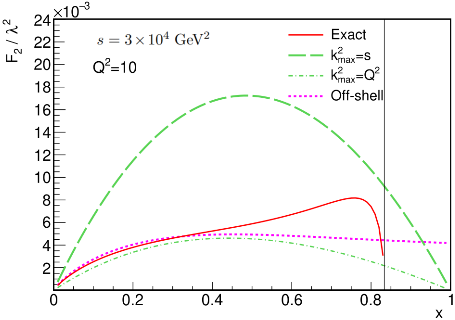


Figure 1. Order $\mathcal{O}(\lambda^2)$ diagrams for the DIS on a quark target in the Yukawa theory.

k_t factorization in a Yukawa theory

Guiot, Hameren: JHEP 04 (2024) 085

Compute the KMRW UPDFs in the Yukawa theory.



$k^2_{max} \sim s$ overshoots the exact result.

$k^2_{max} \sim Q^2$ is also justified by theoretical considerations.

Parton-Branching UPDFs: rapidly decreasing when $k_t > Q$:
$k^2_{max} \to \infty$ is fine.

Implementation of the VFNS *Guiot, Hameren: Phys.Rev.D 104 (2021)*

- All partonic channels included, in particular the dominant $Qg \to Qg$ contribution.
- UPDFs obtained from CT14 PDFs following the KMRW formalism, but with $k_{max} \sim Q$.
- Peterson's fragmentation functions:

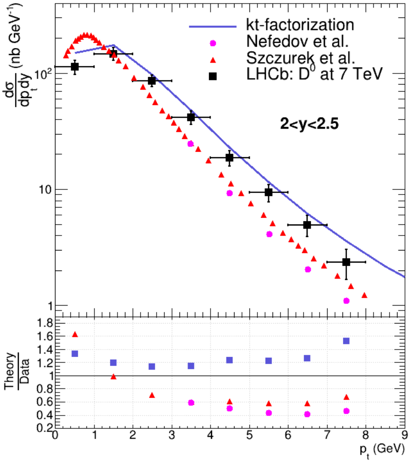
$$D_{Q \to H_Q}(z) \propto f(Q \to H_Q) \frac{1}{z\left(1 - \frac{1}{z} - \frac{\varepsilon_i}{1-z}\right)^2}$$

  Fixed scale $\to$ partial implementation.
  Cacciari's fragmentation fractions.
  Standard value $\varepsilon_c = 0.05$ and $\varepsilon_b = 0.01$.

- Standard factorization scale $\mu_i \simeq m_t$.

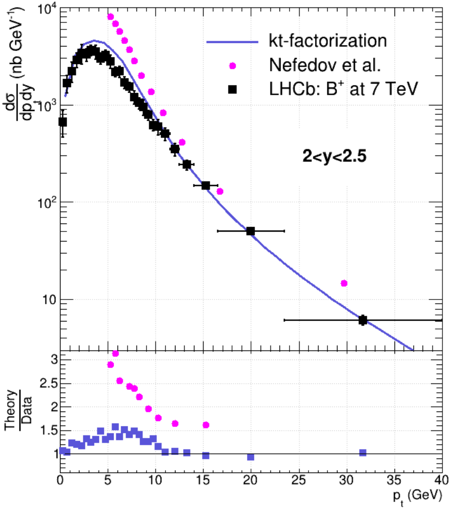
Results: D mesons

Improved agreement between theory and data.



Nefedov et al.: *Phys. Rev. D 91 (2015) 5, 054009*
Szczurek et al.: *Phys. Rev. D 87 (2013) 094022*

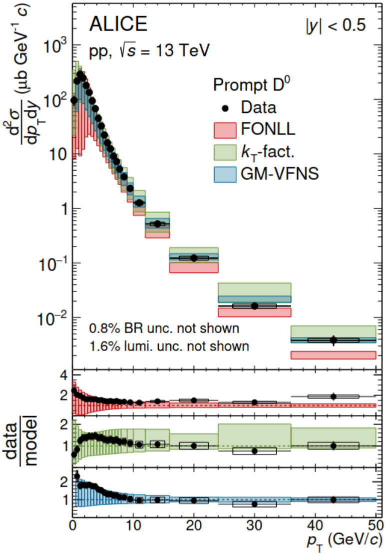
Results: B mesons



Nefedov et al.: *Int. J. Mod. Phys. A 30 (2015) 04n05, 1550023*

Fewer theoretical results are available for B mesons.

Prediction for D-meson production at 13 TeV



More plots in: Alice Collaboration, *JHEP 12 (2023) 086.*

Scale dependence of FFs

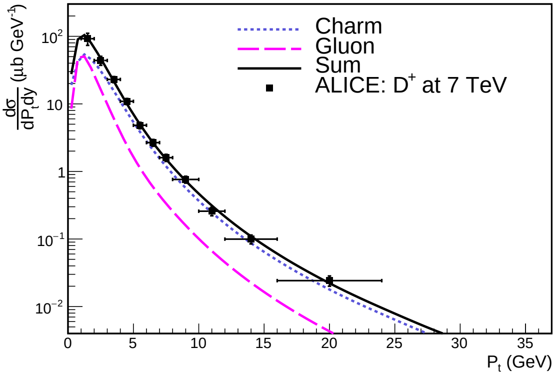
Barattini, Dib, Guiot: JHEP 05 (2025) 115

- Contributions: $D_{Q\to H_Q}(z;\mu)$ and $D_{g\to H_Q}(z;\mu)$.
- Evolution with QCDNUM.
- Initial conditions: $D_{g\to H_Q}(z;\mu_0) = 0$ and $D_{Q\to H_Q}(z;\mu_0)$ with Peterson parametrization

$$\frac{d\sigma(pp\to H_Q+X)}{dYd^2P_t}(Y,P_t) = \sum_j \int_{z_{\mathsf{min}}}^1 \frac{dz}{z^2} D_{j\to H_Q}(z;\mu_f) \times \frac{d\sigma(pp\to j+X)}{dyd^2p_t}\left(y,\frac{P_t}{z};\mu_f\right)$$

$$\frac{d\sigma(pp\to j+X)}{dyd^2p_t} = \sum_{a,b} F_a(\mu_i^2)\otimes F_b(\mu_i^2)\otimes \hat{\sigma}_{ab\to j+X}(\mu_i,\mu_f)$$

Results: D^+ meson



$D_{g \to D}$ improves the agreement between theory and data at small P_t.

Results: B meson

At small P_t the results are sensitive to the choice of factorization scales.

Default scheme:

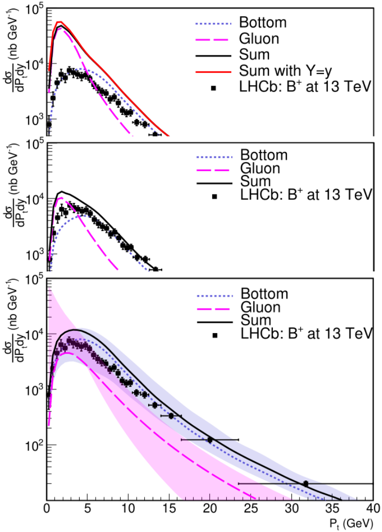
$$\mu_i = \sqrt{p_t^2 + m_Q^2},\ \mu_f = \sqrt{P_t^2 + M^2}$$

BKKSS scheme:

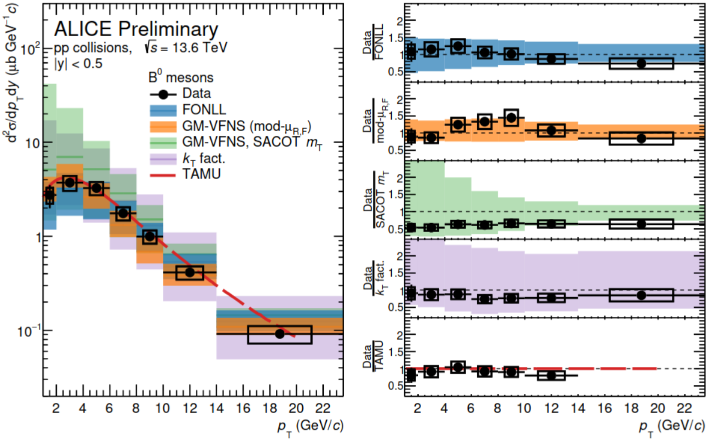
$$\mu_i = 0.49\sqrt{p_t^2 + 4m_Q^2},$$
$$\mu_f = 0.49\sqrt{P_t^2 + 4M^2}$$

SACOT-m_T scheme:

Default scheme, but p_t replaced by m_t in the partonic X-section for e.g. $gg \to gg$



Prediction for B-meson production at 13.6 TeV

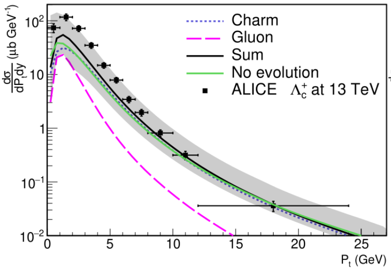


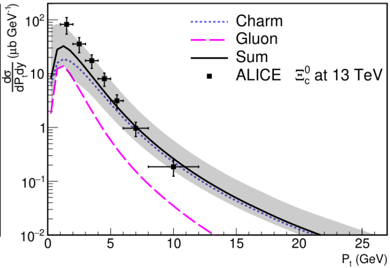
k_t-factorization: SACOT-m_T scheme.

Heavy-baryon production

Peterson FF with $\varepsilon_c = 0.001$ (same as for B mesons):

$$f(c \to \Lambda_c^+) = 0.1 \text{ and } f(c \to \Xi_c^0) = f(c \to \Lambda_c^+)\frac{f(c\to\Xi_c^0)_{\text{ALICE}}}{f(c\to\Lambda_c^+)_{\text{ALICE}}}$$



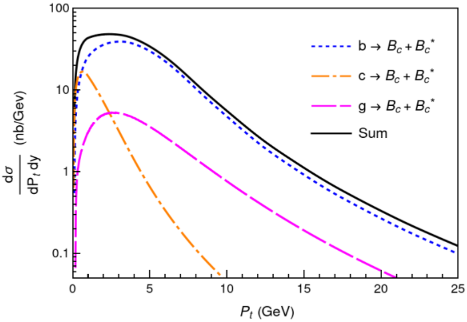


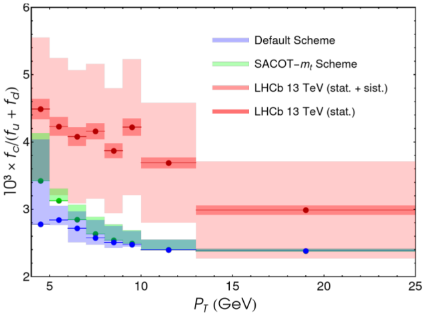
Usual underestimation of small-P_t data by theory (even at NLO).

B_c production

Only fragmentation contribution included. Missing higher-power mechanisms explains the deficit at low P_t

Leading order FF with color-singlet LDME.





Summary

- Complete implementation of the HEF within a VFNS.
- Successful predictions for ALICE measurements of D and B mesons.
- Results for heavy baryons in agreement with collinear calculations.
- A single choice of factorization scales describes the whole dataset (we prefer SACOT-m_T). The B-meson cross section is sensitive to this choice at small P_t.
- The $D_{g\to H_Q}(z;\mu)$ FF helps at small P_t.

Thanks for your attention!