Kt-factorization calculations for D and B meson production using a variable-flavor-number scheme

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kt-factorization

Seminal papers: Collins and Ellis, *Nucl. Phys. B 360 (1991) 3-30*; Catani, Ciafaloni, Hautmann, *Nucl. Phys. B 366(1991) 135-188*; Gribov, Levin, Ryskin, *Phys.Rep. 100 (1983) 1.*

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

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

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

- In these papers, $F_i(x_1, k_{1t}^2; \mu^2) = G(x_1, k_{1t}^2; \mu^2)$. It obeys the Balitsky-Fadin-Kuraev-Lipatov equation
- The goal was the resummation of large $\log(1/x)$.
- Transverse-momentum-dependent (TMD) formalism.

kt-factorization and Heavy-quark production

0-flavor number scheme

$\sigma(gg \to Q\bar{Q})$

Unintegrated gluon densities extracted from data

H. Jung and collaborators did some work with this scheme

Correct but not accurate

mixed scheme

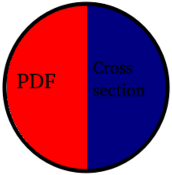
$\sigma(gg \to Q\bar{Q})$

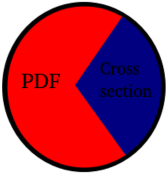
Unintegrated parton densities built from modern (VFNS) collinear PDFs

Incorrect (the main focus of this talk)

Ex: *Phys. Rev. D 87 (2013) 094022*, 127 citations

Schemes?





Fixed-flavor-number scheme

Proton made of gluon+light quarks

$\sigma = \text{PDF}_{LO}^{FFNS} \otimes \hat{\sigma}_{LO}^{FFNS}$

Main process: $gg \to Q\bar{Q}$ (flavor creation)

Variable-flavor-number scheme

gluon+light quarks+heavy quarks

$\sigma = \text{PDF}_{LO}^{VFNS} \otimes \hat{\sigma}_{LO}^{VFNS}$

Main processes: $gg \to Q\bar{Q}$ and $gQ \to gQ$ (flavor excitation)

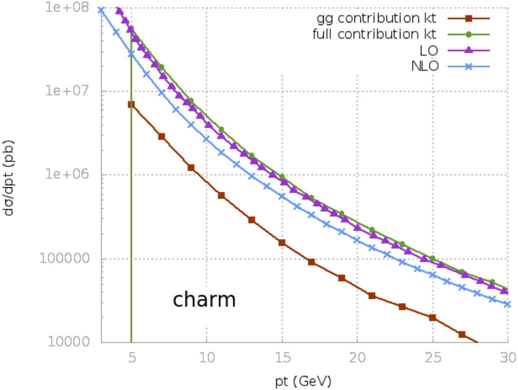
$$\hat{\sigma}_{LO}^{VFNS} \simeq 4\hat{\sigma}_{LO}^{FFNS} \Rightarrow \text{PDF}_{LO}^{VFNS} \simeq \text{PDF}_{LO}^{FFNS}/4.$$

"Mixed scheme": $\sigma = \text{PDF}_{LO}^{VFNS} \otimes \hat{\sigma}_{LO}^{FFNS}$ too small by a factor ~ 4.

Expected: strong underestimation of the cross section

Several groups use (have used) this “mixed scheme”.

Include only the gg contribution but they build their uPDFs from VFNS collinear PDFs.



My (old) results obtained with the PB uPDFs and the event generator KaTie. **Main contribution:** $cg \to cg$, *Phys.Rev.D99 no.7, 074006*

Published "mixed scheme" calculations describe data (approximately)... How?

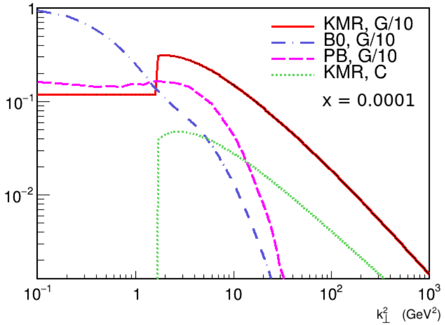
Some studies include an effective large K factor:

1. Too large factorization scale $\mu_F^2 > \hat{s}$, $g(x,\mu_F) \to 2g(x,\mu_F)$.
2. **Too large k_t tail (for $k_t > \mu$). This is the case for KMR uPDFs** (with the angular-ordering cut-off).

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

$F_i(x,k_t^2;\mu^2)$ **unconstrained** for $k_t^2 > \mu^2 \sim p_t^2$.

Cutting $k_t^2 > \mu^2$ of the AO KMR uPDFs reduces the result by a factor of 4, *B. Guiot, Phys.Rev.D 99 (2019) 7, 074006*.



$\mu^2 = 10$ GeV^2

A convincing prediction (?)

Mesage of *Phys.Rev.D 99 (2019) 7, 074006* (april): The AO KMR uPDFs are too large and compensate the wrong mixed scheme. Replaced by the PB uPDFs, the groups using this method will underestimate data by a factor of 4.

Phys. Rev. D 100, 054001 (2019) (september): "The use of the KMR uPDF leads to a good description of the existing charm (D-meson) data already at the leading-order. On the other hand, a new Parton-Branching (PB) uPDF strongly underestimates the same experimental data. A direct inclusion of the higher-orders ..."

Proposed solution:

$$\mathrm{PDF}^{VFNS} \otimes \hat{\sigma}_{LO}^{FFNS} \to \mathrm{PDF}^{VFNS} \otimes \hat{\sigma}_{NLO}^{FFNS}$$

The authors of *Phys. Rev. D 100, 054001 (2019)* have their results shown in ALICE papers.

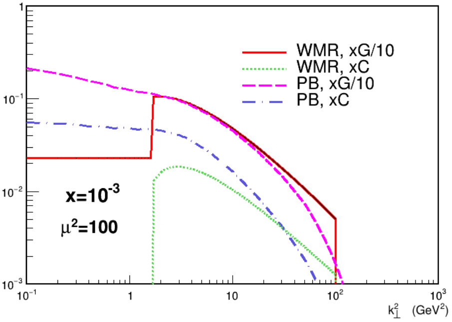
kt-factorization calculations using a VFNS

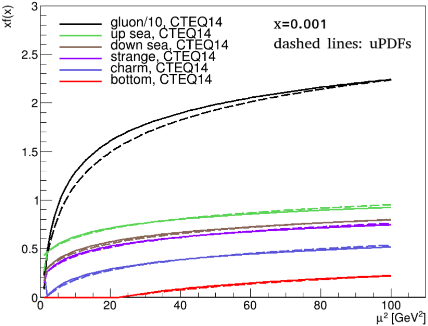
$$\sigma = \text{uPDF}_{LO}^{VFNS} \otimes \hat{\sigma}_{LO}^{VFNS}$$

- Never done before!
- At high energies, VFNS more efficient than the FFNS because the H.Q. PDFs resum large $\ln(p_t/m_Q)$.
- Off-shell cross section computed with the event generator KaTie, *A. Van Hameren, arXiv:1611.00680*.

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

- VFNS uPDFs: strong ordering (SO) Watt-Martin-Ryskin (WMR) prescription, *Eur. Phys. J. C 31(2003) 73*.
- We used the leading-order CT14 PDFs.
- In the SO prescription, $F(x,k_t;\mu^2) = 0$ if $k_t > \mu$. This is the main difference with the AO prescription.





D meson production

Processes:

Flavor excitation: $cg \to cg$, $qc \to qc$
Flavor creation : $gg \to c\bar{c}$, $q\bar{q} \to c\bar{c}$

Mass: Not a free parameter. For consistency choose the value used by CTEQ, $m_c = 1.3$ GeV.

Fragmentation:

$$\frac{d\sigma}{dyd^2p_{t,D}} \approx \int_0^1 \frac{dz}{z^2} D_{c\to D}(z) \frac{d\sigma(ab \to c+X)}{dyd^2p_{t,c}},$$

with $p_{t,c} = p_{t,D}/z$. We used the Peterson model for $D_{c\to D}(z)$ with $\varepsilon_c = 0.05$.

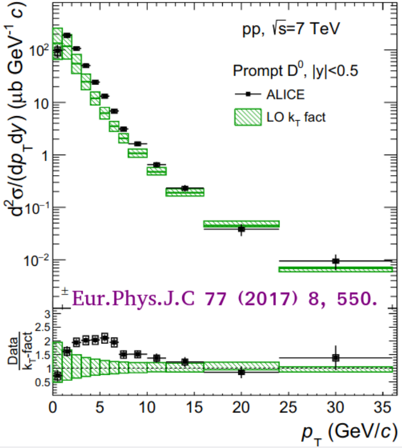
Fragmentation fractions:

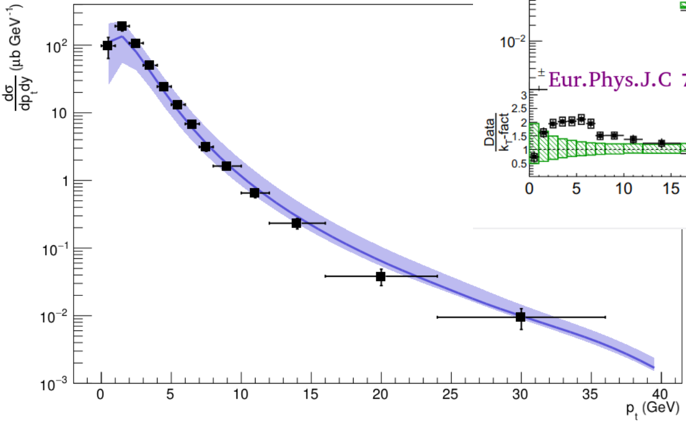
$f(c \to D^0)$	$f(c \to D^+)$	$f(c \to D^{*+})$	$f(c \to D_s^+)$
0.588	0.234	0.234	0.116

Factorization scale: $\mu = \frac{1}{2}(m_{t,1} + m_{t,2})$, $m_t = \sqrt{p_t^2 + m_c^2}$.

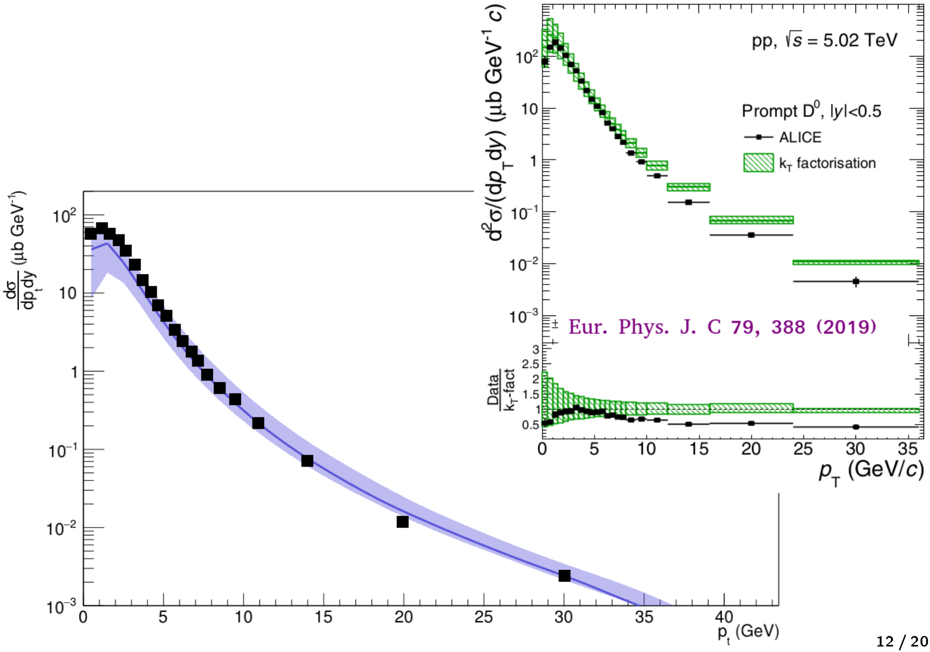
D meson production at 7 TeV

- Green: "mixed scheme" calculations. We used the same frag. function with the same parameter.
- Better result due to the consistent use of a VFNS.



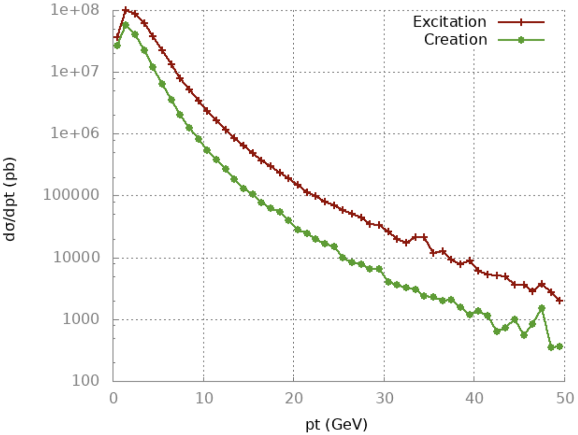


D meson production at 5 TeV



Contributions to the D meson cross section

- "Mixed scheme" with PB uPDFs underestimates the cross section by a factor of ~ 4.
- Compensating this factor by any mechanism would hardly work because the $gg \to Q\bar{Q}$ process does not have the correct shape.



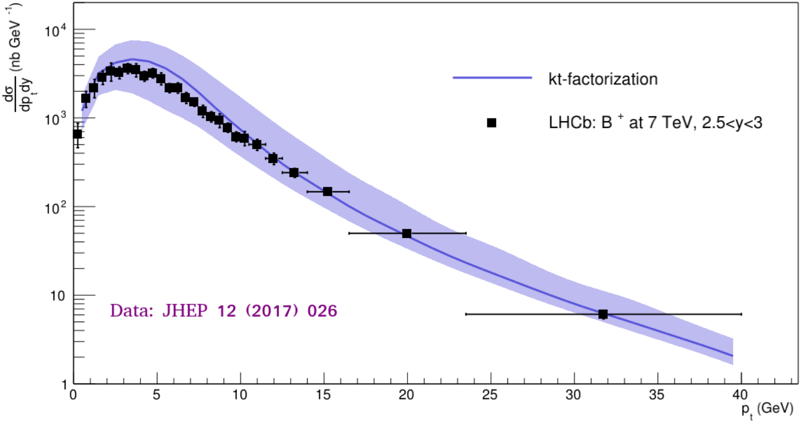
B meson production, 7 TeV

Mass: $m_B = 1.75$ GeV (used for CT14 PDFs).

Fragmentation: Peterson model with $\varepsilon_b = 0.01$.

Fragmentation fractions: 0.403

Surprisingly (?), I didn't find modern kt-factorization calculations for B mesons.

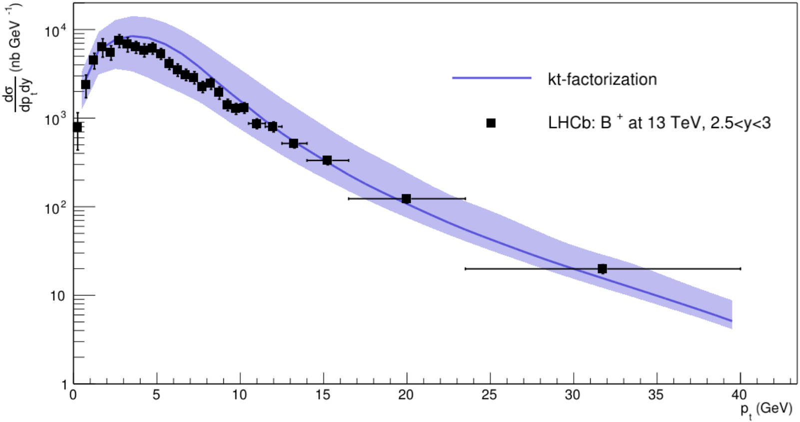


B meson production at 13 TeV

Mass: $m_B = 1.75$ GeV.

Fragmentation: Peterson model with $\varepsilon_b = 0.01$.

Fragmentation fractions: 0.403



LHCb data: *JHEP 12 (2017) 026*

Conclusion

- At high energy, VFN schemes should be prefered.
- Our VFNS kt-factorization calculations provide a good description of ALICE and LHCb data from 5 to 13 TeV.
- Works better than available results, obtained either in a FFNS or in an (incorrect) “mixed scheme”.

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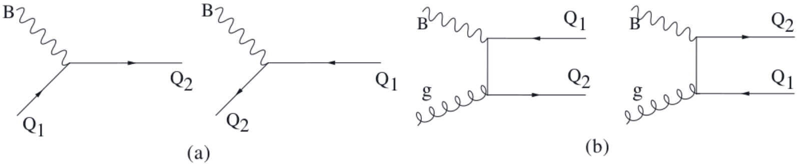
Future work: Consistent implementation of the $2 \to 1 + 2 \to 2$ contributions.

Treatment of $2 \to 1 + 2 \to 2$ processes

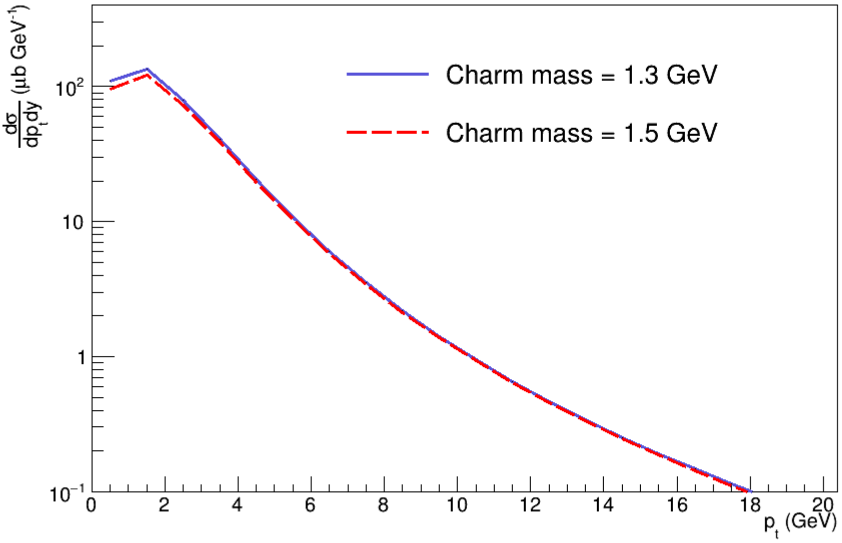
- In principle, for full consistency we should include the true lowest order.
- Just follow the lines of the ACOT paper.



$$\sigma = \sigma^{LO} + \sigma^{NLO} + \text{subtraction term}$$

- We can expect that the subtraction term cancels completely the $2 \to 1$ contribution.

Mass uncertainty



Contributions to the B meson cross section