University of Science and
Technology of Mazandaran

First determination of D*-meson fragmentation functions and their uncertainties at next-to-next-to-leading order

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Outline

- Fragmentation functions (FFs)
- QCD factorization theorem

- Analysis strategy:
  - The data sets
  - Fit settings
  - χ^2 Minimizations and FFs uncertainties

- Numerical results for the global analysis of $D^{*\pm}$ FFs
- Fit quality
- Summary and Conclusions

Fragmentation functions

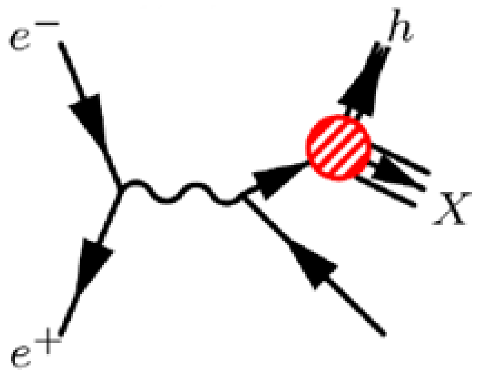
- Fragmentation functions describe the non-perturbative part of hard-scattering processes and along with the PDFs of initial hadrons (in hadron-hadron collision) and parton-level differential cross sections are three necessary ingredients to obtain theoretical predictions for hadroproduction cross sections.

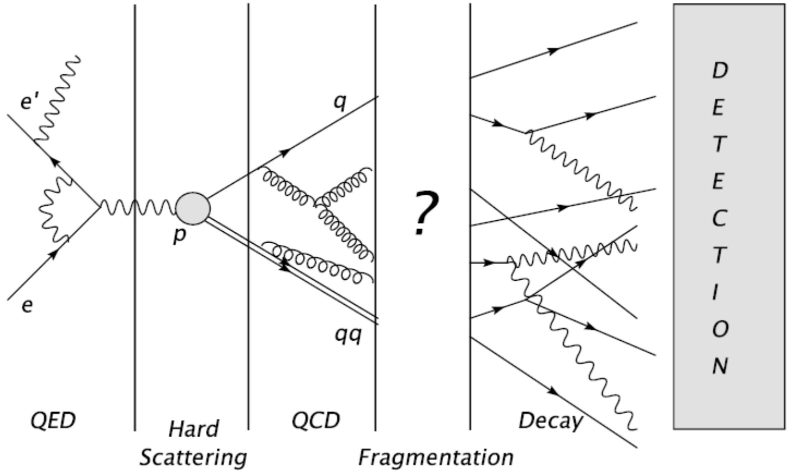
- The process-independent FFs, $D_i^H(z, \mu_F^2)$, describe the probability for a parton i at the factorization scale μ_F to fragment into a hadron H carrying away a fraction z of its momentum.

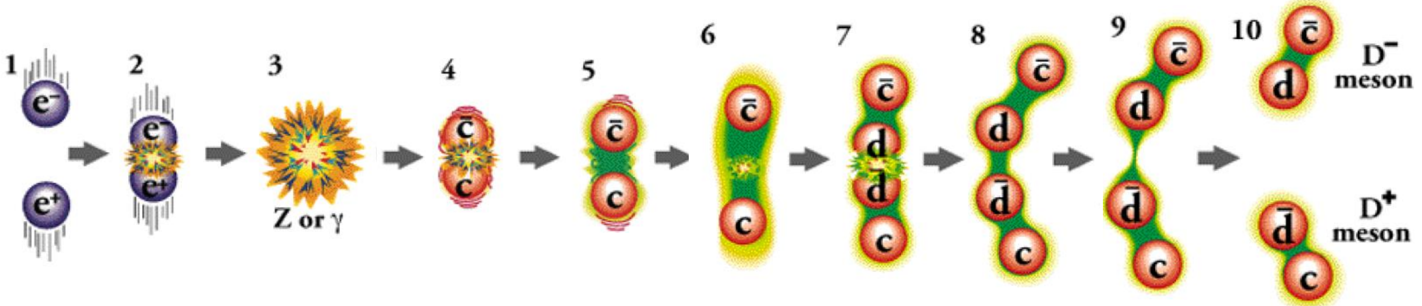
- The scaling violations of FFs are subject to the perturbatively computable DGLAP evolution equations.

- The optimal way to determine the $D^{*\pm}$ FFs is to fit them to the experimental date extracted from the single-inclusive $e^{-}e^{+}$ annihilation processes.

$$e^+e^- \to (\gamma, Z) \to D^* + X$$

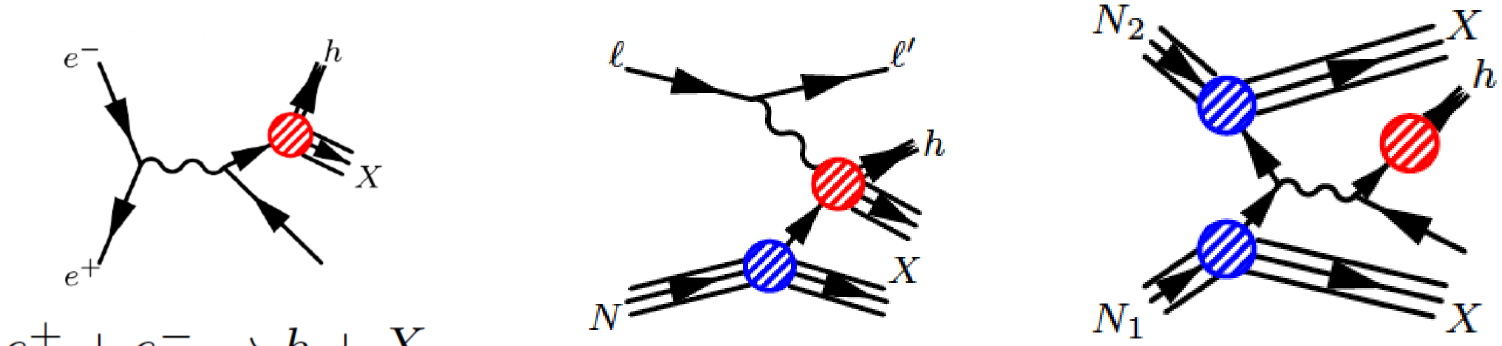






QCD factorization theorem

- According to the factorization theorem, the differential cross section of process can be written as a convolutions of perturbatively calculable partonic cross sections with the FFs,



$e^+ + e^- \to h + X$
single-inclusive annihilation (SIA)

$\ell + N \to \ell' + h + X$
semi-inclusive deep-inelastic scattering (SIDIS)

$N_1 + N_2 \to h + X$
high-p_T hadron production in proton-proton collisions (PP)

$$
\begin{aligned}
\sigma^{e^+e^-\to hX} &= \hat{\sigma} \otimes FF\,, \\
\sigma^{\ell N\to \ell hX} &= \hat{\sigma} \otimes PDF \otimes FF\,, \\
\sigma^{pp\to hX} &= \hat{\sigma} \otimes PDF \otimes PDF \otimes FF
\end{aligned}
$$

- For the $D^{*\pm}$ production in annihilations, the factorization theorem reads

$$\frac{1}{\sigma_{\mathrm{tot}}}\frac{d}{dx_D}\sigma(e^+e^- \to D^*X) = \sum_i \int_{x_D}^{1} \frac{dx_i}{x_i} D_i^{D^*}\left(\frac{x_D}{x_i}, \mu_F\right) \frac{1}{\sigma_{\mathrm{tot}}}\frac{d\sigma_i}{dx_i}(x_i, \mu_R, \mu_F)$$

$D^{*\pm}$-meson FFs

Perturbatively calculable partonic cross sections

- The total cross section up to NNLO for e^+e^- annihilation into hadrons

$$\sigma_{\mathrm{tot}} = \frac{4\pi\alpha^2(Q)}{Q^2}\left(\sum_i^{n_f} \tilde{e}_i^2(Q)\right) \times \left(1 + \alpha_s K_{\mathrm{QCD}}^{(1)} + \alpha_s^2 K_{\mathrm{QCD}}^{(2)} + \cdots\right)$$

APFEL

- APFEL is a public PDF evolution library with QED corrections.
- APFEL evolution features:
  - Up to NNLO in QCD and LO in QED.
  - The time-like evolution for fragmentation functions in x-space.
  - FFNS and VFNS solution in *x*-space.
- The DIS module: Computation of DIS observables, Up to order α_s^2 (when possible), Heavy quark schemes: FONLL, FFNS and ZM-VFNS.

APFEL

http://apfel.hepforge.org

Available $D^{*\pm}$ FFs analysis

- SKM18: Maryam Soleymaninia, Hamzeh Khanpour, S. Mohammad Moosavi Nejad, First determination of $D^{*\pm}$-meson fragmentation functions and their uncertainties at next-to-next-to-leading order, Phys. Rev. D **97** (2018) no.7, 074014.

  SIA data sets (ALEPH and OPAL), ZM-VFNS, NLO and NNLO accuracy

- AKSRV17: Daniele P. Anderle, Tom Kaufmann, Marco Stratmann, Felix Ringer, Ivan Vitev, Using hadron-in-jet data in a global analysis of D^{*} fragmentation functions, Phys.Rev. D96 (2017) no.3, 034028.

  SIA data sets + hadron-hadron + jet fragmentaion in pp scattering, ZM-VFNS, NLO accuracy

- KKKS08: T. Kneesch, B.A. Kniehl, G. Kramer, I. Schienbein, Charmed-meson fragmentation functions with finite-mass corrections, Nucl.Phys. B799 (2008) 34-59.

  SIA data sets (ALEPH, OPAL, CLEO and Belle), GM-VFNS, NLO accuracy

Analysis strategy and results

Phys. Rev. D **97**, no. 7, 074014 (2018)
arXiv:1711.11344 [hep-ph]]

The data sets

- Most of experimental data for $D^{*\pm}$ in e^+e^--annihilation is reported by ALEPH, OPAL, CLEO and Belle Collaborations.
- We use the c-tagged and b-tagged SIA cross sections from ALEPH and OPAL Collaborations.

ALEPH: Eur. Phys. J. C 16, 597 (2000). OPAL: Eur. Phys. J. C 1, 439 (1998).

Collaboration	Data properties	$\sqrt{s}$ GeV	Data points	$\mathcal{N}_i$	χ^2(NLO)
ALEPH	Inclusive	91.2	17	0.999 006	24.59
	b-tagged	91.2	15	1.001 04	18.73
OPAL	Inclusive	91.2	9	0.999 305	2.02
	b-tagged	91.2	9	0.999 672	8.01
	c-tagged	91.2	9	1.002 758	17.39
TOTAL:			59		70.74
(χ^2/d.o.f)					1.31

Collaboration	Data properties	$\sqrt{s}$ GeV	Data points	$\mathcal{N}_i$	χ^2(NNLO)
ALEPH	Inclusive	91.2	17	0.998 900	24.51
	b-tagged	91.2	15	1.000 990	17.99
OPAL	Inclusive	91.2	9	0.999 099	1.92
	b-tagged	91.2	9	0.999 700	7.61
	c-tagged	91.2	9	1.002 699	16.94
TOTAL:			59		68.97
(χ^2/d.o.f)					1.27

Fit settings

- We parametrize the z distributions of the $c(\bar{c})$ and $b(\bar{b})$ quark FFs at their starting scales $\mu_0^2 = 18.5\ GeV^2$ as,

$$D_i^{D^{*\pm}}(z, \mu_0^2) = N_i z^{-(1+\alpha_i^2)} (1-z)^{\beta_i} e^{-\alpha_i^2/z}$$

- The FFs of gluon and light quarks are set to zero, i.e.

$$D_i^{D^{*\pm}}(z, \mu_0^2) = 0, \qquad i = u, \bar{u}, d, \bar{d}, s, \bar{s}, g$$

- According to the parton structure of D^{*-}, the FFs of D^{*-} can be obtained as

$$D_q^{D^{*-}}(z, \mu^2) = D_{\bar{q}}^{D^{*+}}(z, \mu^2) \qquad D_g^{D^{*-}}(z, \mu^2) = D_g^{D^{*+}}(z, \mu^2)$$

χ^2 Minimizations and FFs uncertainties

- In our analysis, the total χ^2 is calculated in comparison with the experimental data for $D^{*\pm}$ production in e^+e^- annihilation:

$$\chi_n^2(\{\eta_i\}) = \left(\frac{1-\mathcal{N}_n}{\Delta\mathcal{N}_n}\right)^2 + \sum_{k=1}^{N_n^{\text{data}}} \left(\frac{(\mathcal{N}_n \mathcal{O}_k^{\text{data}} - T_k^{\text{theory}}(\{\eta_i\})}{\mathcal{N}_n \delta D_k^{\text{data}}}\right)^2$$

- The *Hessian method* gives the uncertainties of a given observable $\mathcal{O}$:

$$[\Delta\mathcal{O}_i]^2 = \Delta\chi^2 \sum_{j,k} \left(\frac{\partial\mathcal{O}_i(\eta)}{\partial\eta_j}\right)_{\hat{\eta}} C_{j,k} \left(\frac{\partial\mathcal{O}_i(\eta)}{\partial\eta_k}\right)_{\hat{\eta}}$$

- The Hessian matrix is accessible by running the CERN program library MINUIT

F. James, Report No. CERN-D-506.

Numerical results for the global analysis of $D^{*\pm}$ FFs

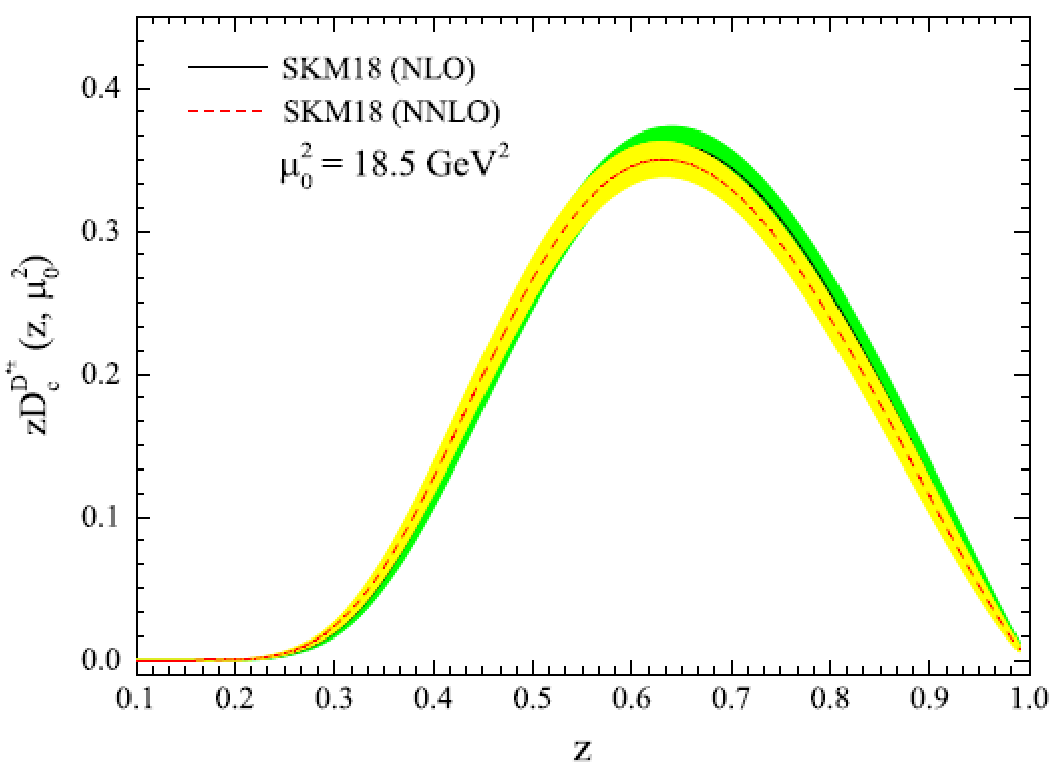
NLO

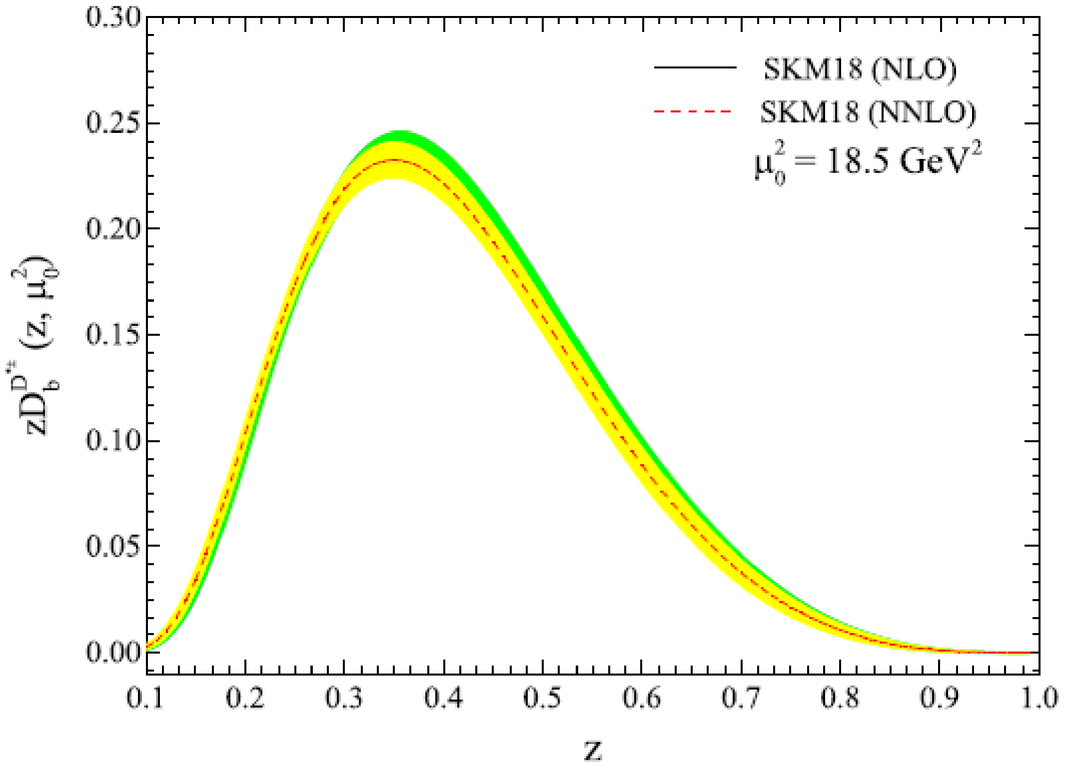
Flavor i	N_i	α_i	β_i
$c, \bar{c}$	67.031^*	1.908 ± 0.0194	1.133 ± 0.070
$b, \bar{b}$	5.742 ± 1.574	0.994 ± 0.0385	3.249 ± 0.279

NNLO

Flavor i	N_i	α_i	β_i
$c, \bar{c}$	53.896^*	1.854 ± 0.0191	1.170 ± 0.069
$b, \bar{b}$	5.127 ± 1.351	0.967 ± 0.0372	3.248 ± 0.274

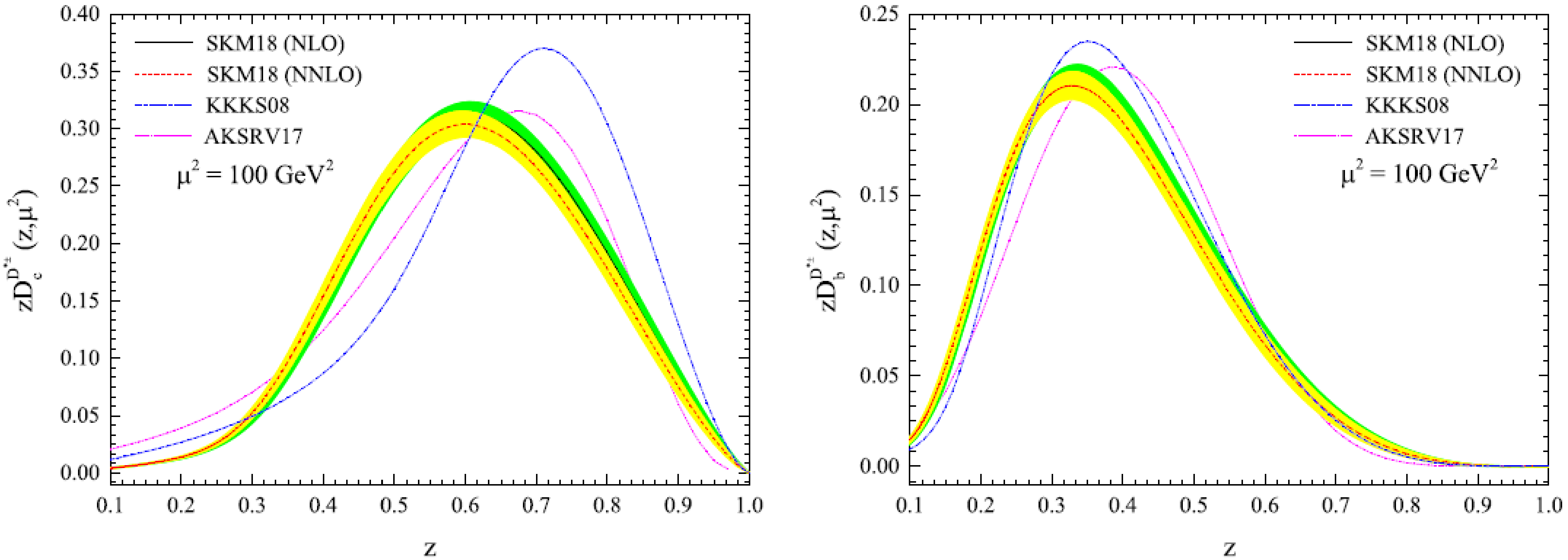
D*-meson FFs at NLO and NNLO





SKM18 fragmentation densities and their uncertainties (shaded bands) are shown at the initial scale $\mu_0^2 = 18.5\ GeV^2$ for c and b both at NLO (solid lines) and NNLO (dashed lines).

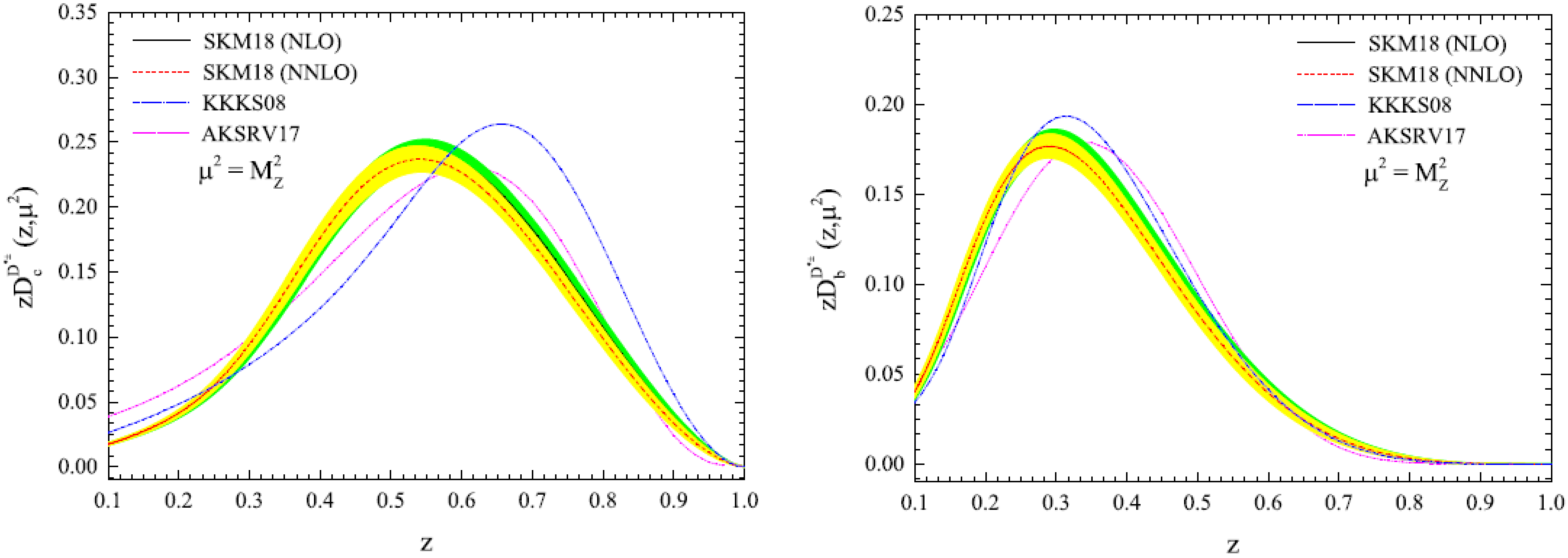
Comparison with other QCD analyses



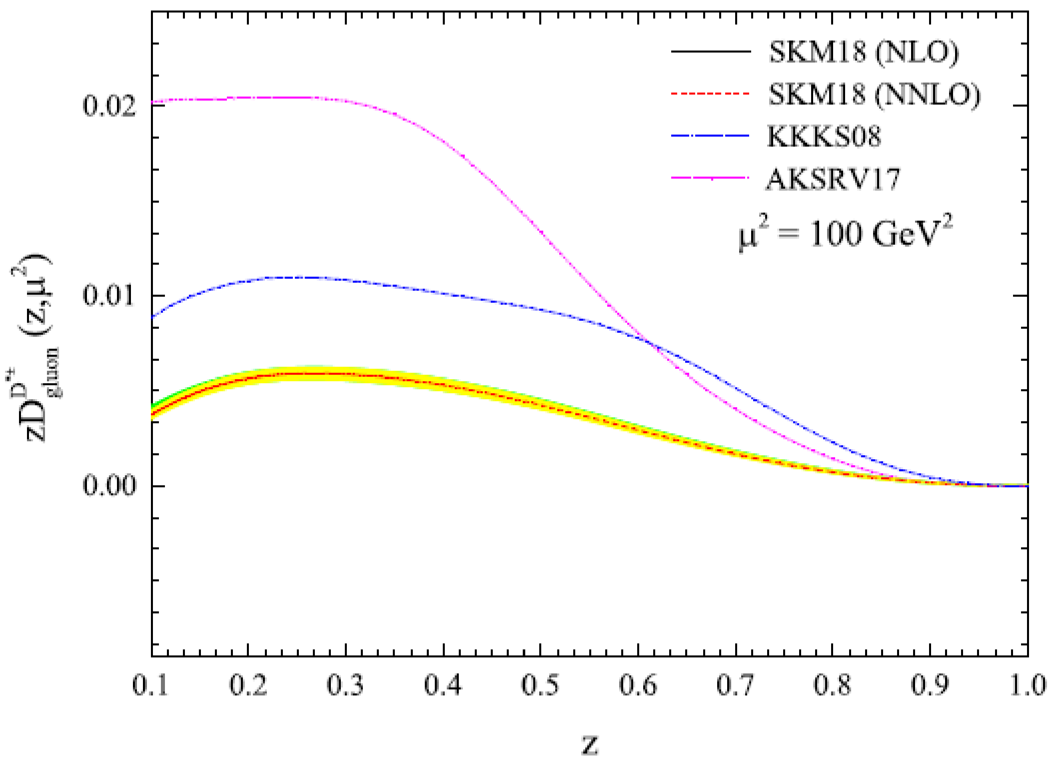
Fragmentation densities and their uncertainties (shaded bands) are shown $\mu^2 = 100\ GeV^2$ for c and b both at NLO (solid lines) and NNLO (dashed lines). Our results are also compared with the KKKS08 (dot-dashed lines) and the AKSRV17 (short dashed lines) results at NLO.

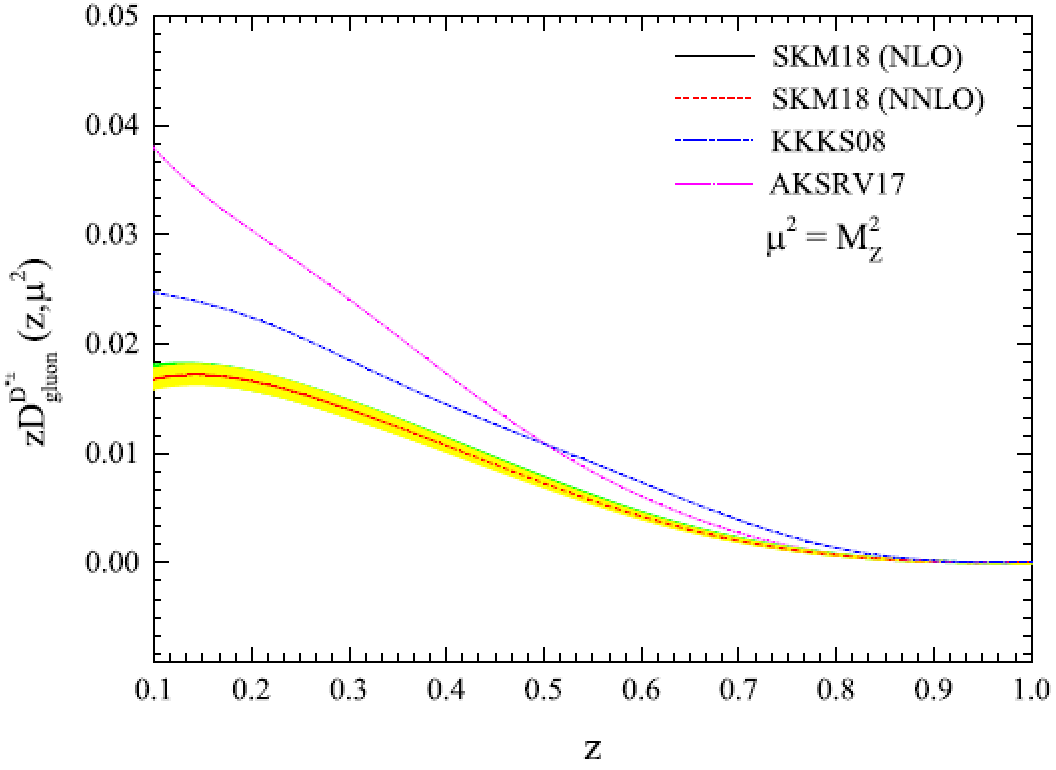
D. P. Anderle, T. Kaufmann, M. Stratmann, F. Ringer, and I. Vitev, Phys. Rev. D 96, 034028 (2017).

T. Kneesch, B. A. Kniehl, G. Kramer, and I. Schienbein, Nucl. Phys. B799, 34 (2008).



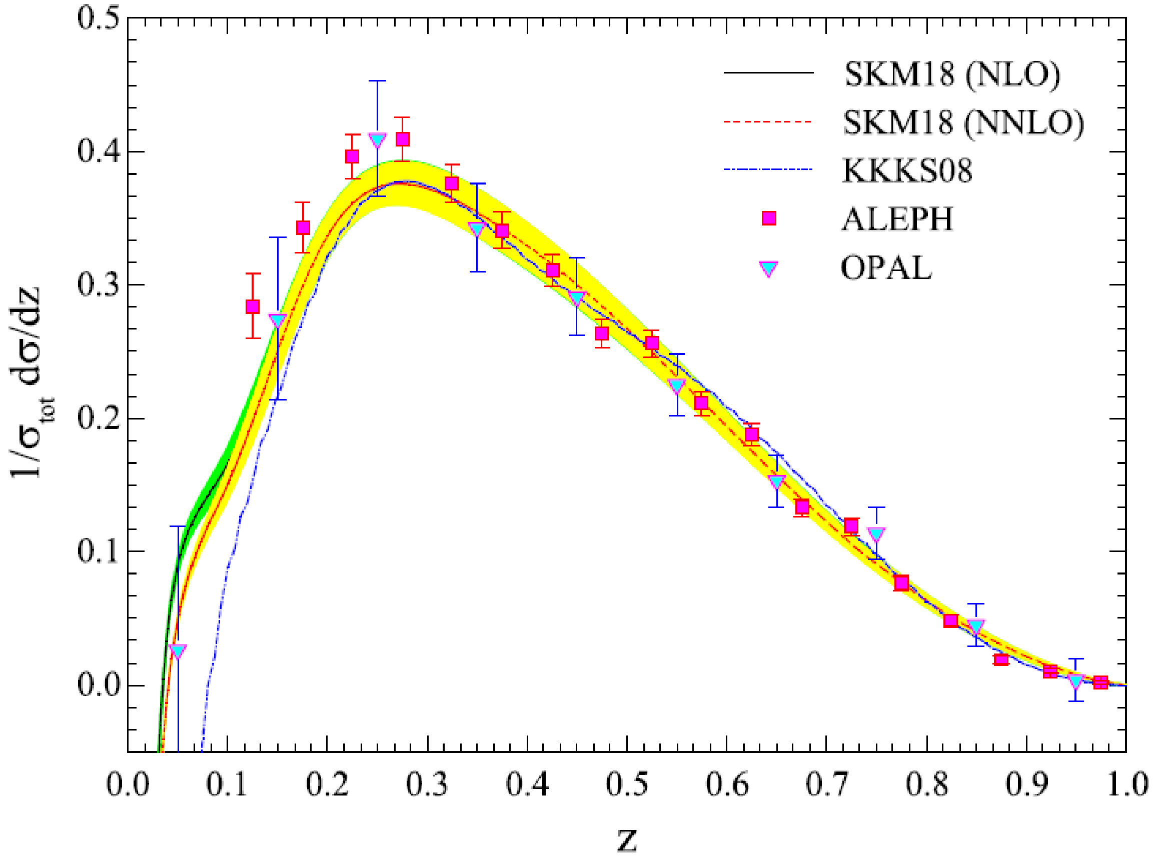
Fragmentation densities and their uncertainties (shaded bands) are shown $\mu^2 = M_Z^2$ for c and b both at NLO (solid lines) and NNLO (dashed lines).



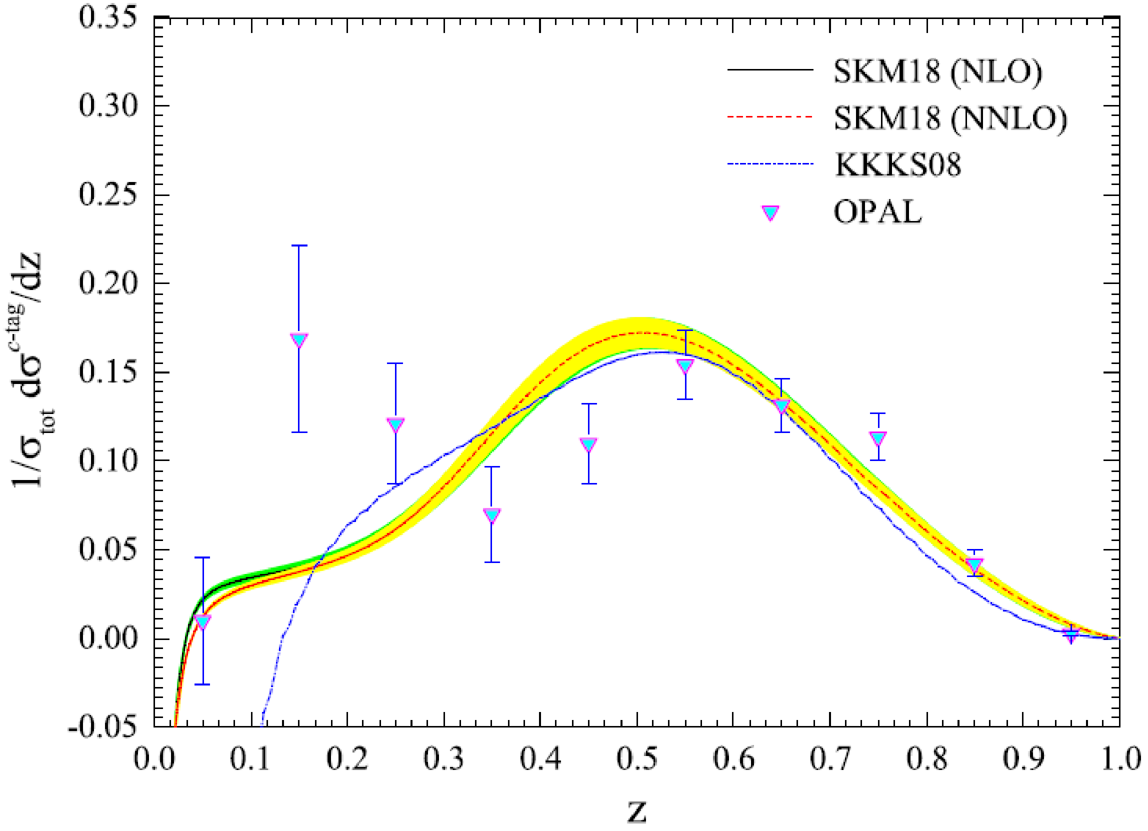


Fragmentation densities and their uncertainties (shaded bands) are shown $\mu^2 = 100\ GeV^2$ and M_Z^2 for the gluon densities both at NLO (solid lines) and NNLO (dashed lines).

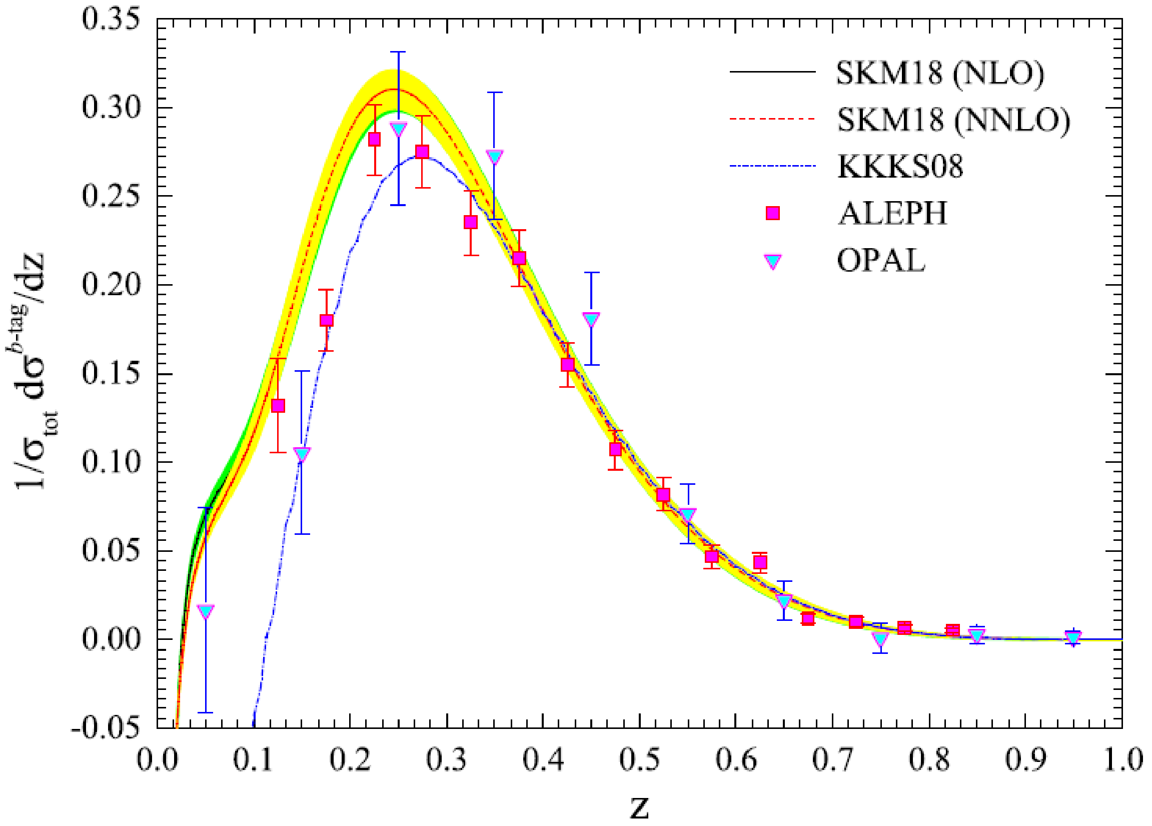
Fit quality



Our NLO (solid line) and NNLO (dashed line) results for the normalized total cross sections of $D^{*\pm}$-production compared with the KKKS08 ones (dot-dashed line) at the scale $Q = M_Z$.

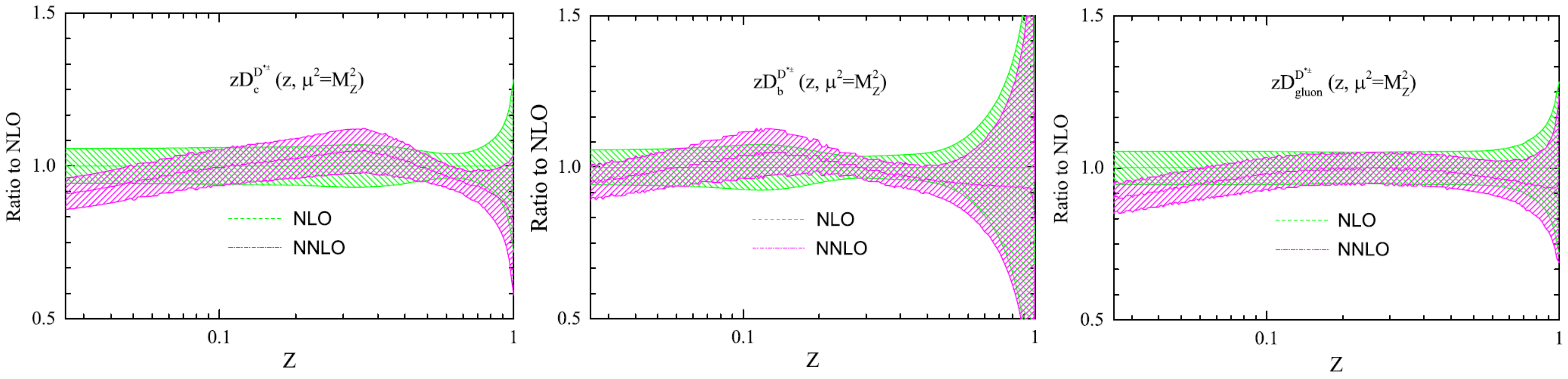


Our NLO (solid line) and NNLO (dashed line) results for the normalized charm-tagged cross sections of $D^{*\pm}$-production compared with the KKKS08 ones (dot-dashed line) at the scale $Q = M_Z$.



Our NLO (solid line) and NNLO (dashed line) results for the normalized bottom-tagged cross sections of $D^{*\pm}$-production compared with the KKKS08 ones (dot-dashed line) at the scale $Q = M_Z$.

Uncertainties: NLO vs NNLO



The experimental uncertainties for the $D^{*\pm}$-meson FFs and SIA cross sections are similar in size both for the NLO and NNLO approximations.

Summary and Conclusion

- We have determined the non-perturbative FFs of partons into the $D^{*\pm}$-meson at NLO perturbative QCD and, for the first time, at NNLO one from global analyses of single inclusive electron-positron annihilation.
- Our analyses are based on the ZM-VFN scheme in which all quarks are treated as massless partons.
- We applied all SIA experimental data as much as possible including most of the data from ALEPH and OPAL Collaborations.
- We considered the NNLO accuracy in our global fit using the public APFEL code.
- We found that the experimental uncertainties for the $D^{*\pm}$-meson FFs and SIA cross sections are similar in size both for the NLO and NNLO approximations.


Thank you