Recent Collinear Fragmentation Function Results

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CIPANP

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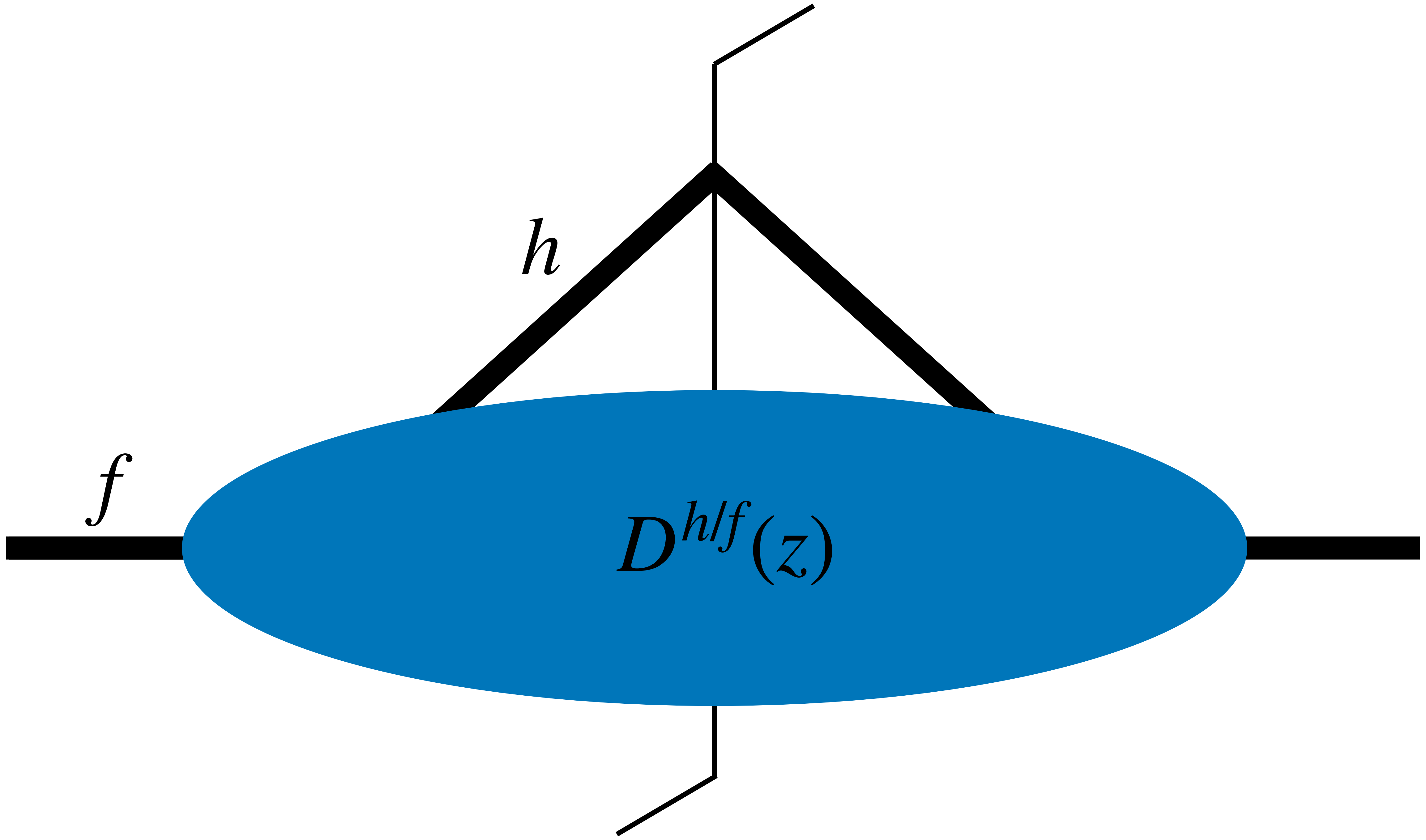
Jefferson Lab Angular Momentum Collaboration

Outline

- Fragmentation Function Overview
- Most recent Jefferson Lab Angular Momentum (JAM) Collaboration fit of Fragmentation Functions (FFs)
- Recent FF results from other groups
- Summary and Outlook

What are fragmentation functions?

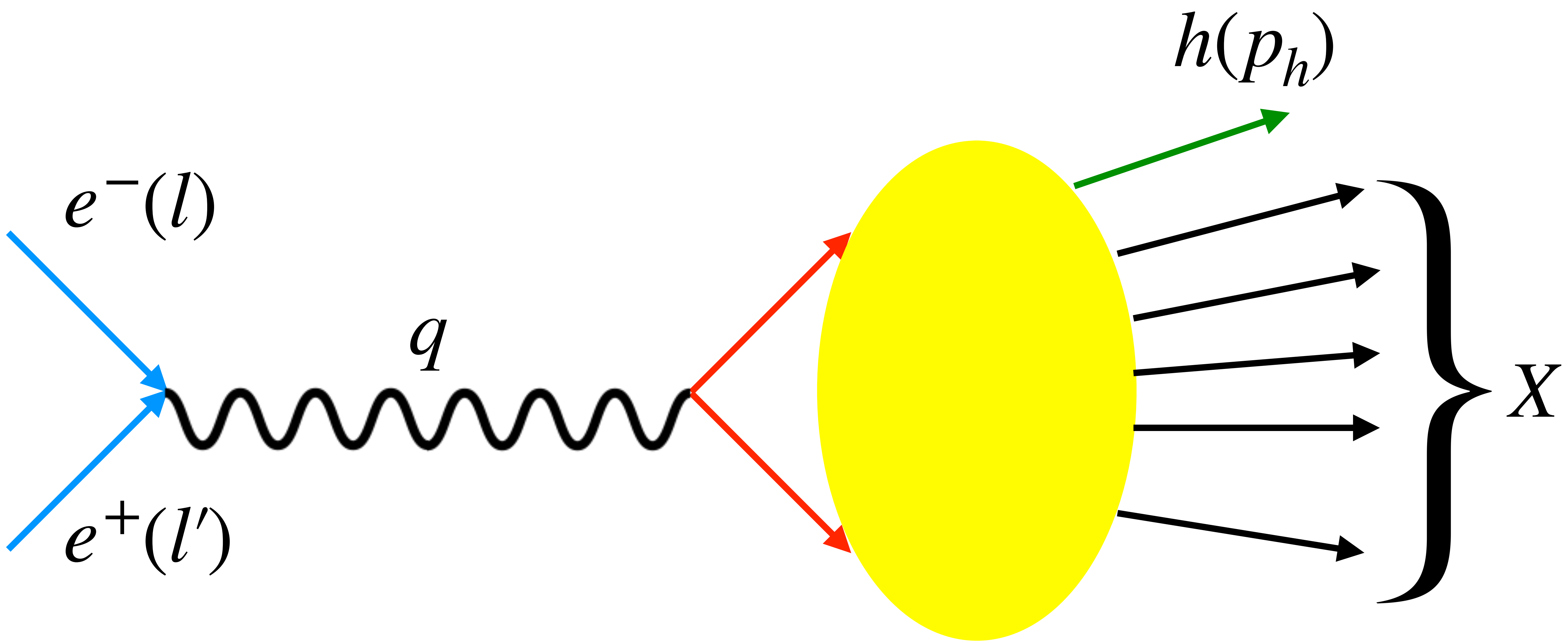
- Probability hadron has fraction z of parton's longitudinal momentum



Processes involving fragmentation functions

- Single Inclusive Electron/Positron Annihilation (SIA)

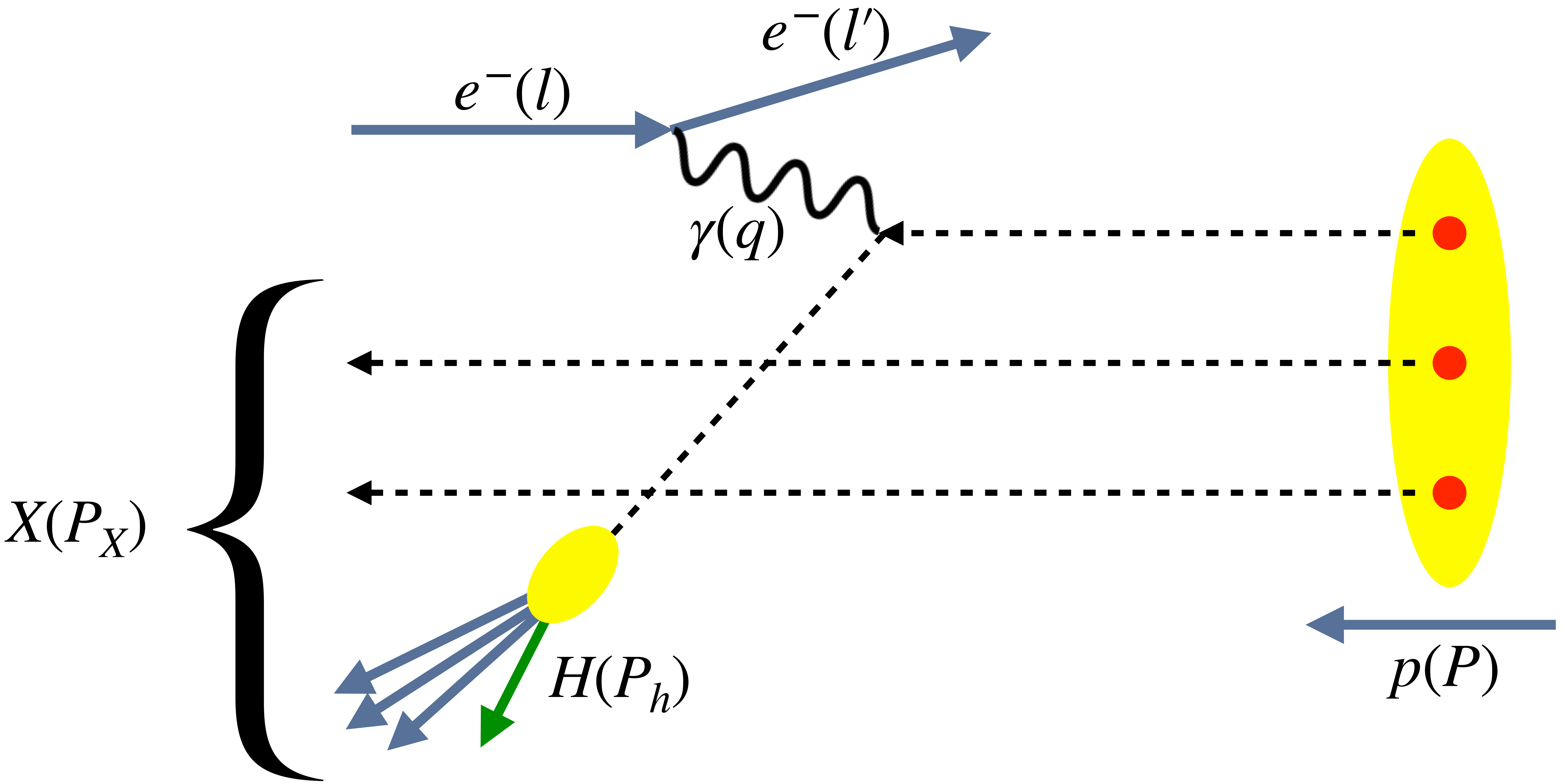
$$e^-(l) + e^+(l') \to h(p_h) + X$$



Processes involving fragmentation functions

- Semi-inclusive Deeply Inelastic Scattering (SIDIS)

$$e^-(l) + p(P) \to e^-(l') + H(P_h) + X(P_X)$$



JAM20-SIDIS

- JAM20-SIDIS:
  - Repeat of JAM19 with addition of unidentified charge hadrons
  - Simultaneously fit:
    - Unpolarized PDFs
    - Unpolarized FFs
      - Charged pion, kaon, and unidentified hadron

JAM Methodology

- Multi-Step Monte Carlo approach utilizing Bayesian Inference
- Bayesian Inference:
    - Baye's Theorem:

$$\mathscr{P}(\mathbf{a}\,|\,\text{data}) \sim \mathscr{L}(\mathbf{a},\text{data})\pi(\mathbf{a})$$

    - Likelihood Function:

$$\mathscr{L}(\mathbf{a},\text{data}) = \exp\left(-\frac{1}{2}\chi^2(\mathbf{a},\text{data})\right)$$

JAM Methodology

- Chi squared:

$$\chi^2(\mathbf{a}, \text{data}) = \sum_{i,e} \left[\left(\frac{d_{i,e} - \sum_k r_e^k \beta_{i,e}^k - T_{i,e}/N_e}{\alpha_{i,e}} \right)^2 + \sum_k \left(r_e^k\right)^2 + \left(\frac{1 - N_e}{\delta N_e} \right)^2 \right]$$

- Least squares fit
    - Minimum Chi squared
    - Maximum Likelihood

JAM Methodology

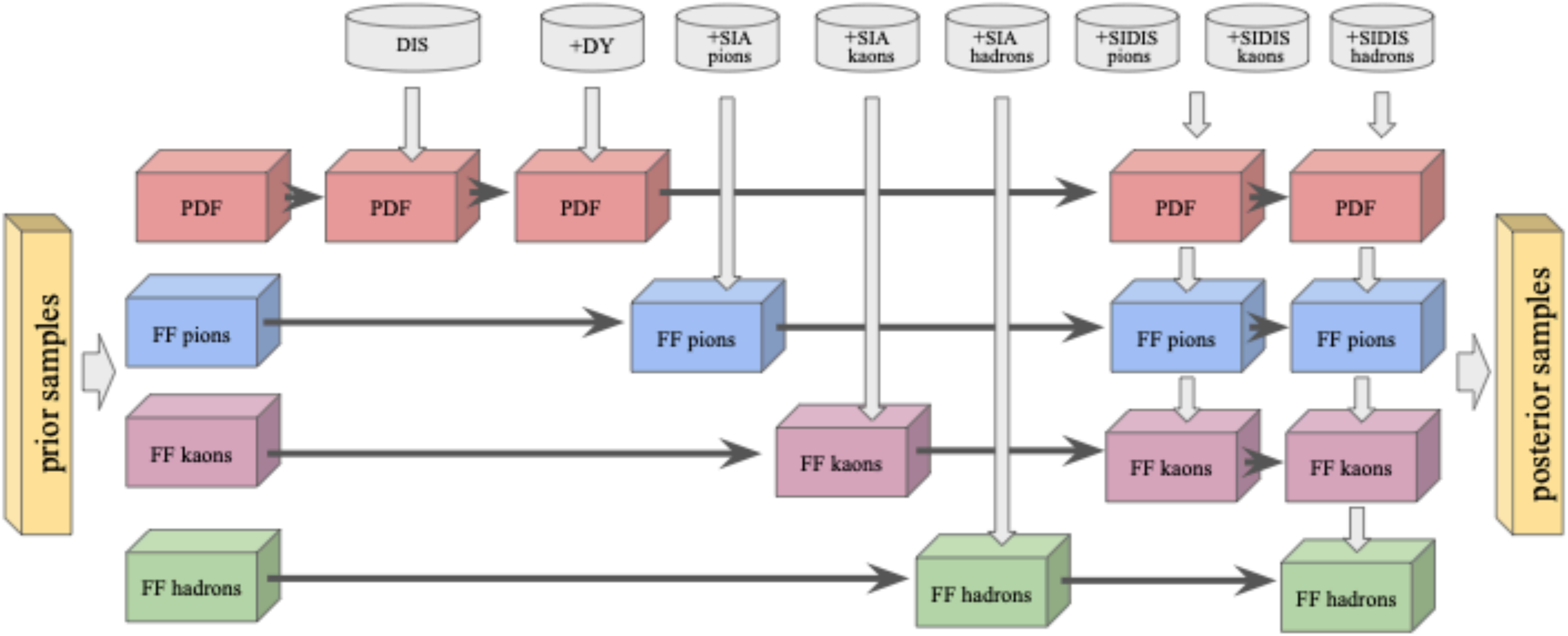
- Monte Carlo approach:
  - Expectation value and variance of an observable:

$$E[\mathcal{O}] = \int d\mathbf{a}\mathcal{P}(\mathbf{a}\,|\,\text{data})\mathcal{O}(\mathbf{a}) \qquad V[\mathcal{O}] = \int d\mathbf{a}\mathcal{P}(\mathbf{a}\,|\,\text{data})\big(\mathcal{O}(\mathbf{a}) - E[\mathcal{O}]\big)\big)^2$$

  - Approximate using a finite number of replicas:

$$E[\mathcal{O}] = \frac{1}{n}\sum_{k=1}^{n}\mathcal{O}(\mathbf{a}_k) \qquad V[\mathcal{O}] = \frac{1}{n}\sum_{k=1}^{n}\big(\mathcal{O}(\mathbf{a}_k) - E[\mathcal{O}]\big)\big)^2$$

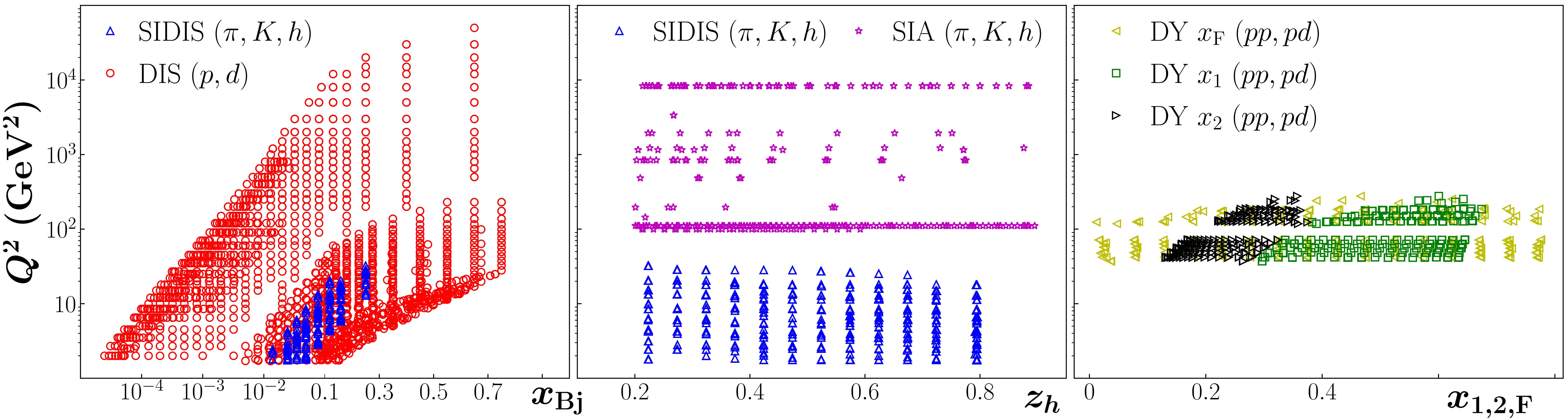
Multi-Step Process



Observables

- Utilize NLO in calculation of observables
- Data Sets:
  - Inclusive Deep Inelastic Scattering (DIS)
    - BCDMS, NMC, SLAC, HERA
  - Semi-Inclusive DIS (SIDIS)
    - COMPASS
  - Single-Inclusive e+/e- Annihilation (SIA)
    - TASSO, TPC, TOPAZ, BELLE, BABAR, ARGUS, DELPHI, ALEPH, OPAL, SLD
  - Drell-Yan Scattering (DY)
    - E866

Kinematic Coverage



Parametrization

- Functional Form:

$$T\left(z;\boldsymbol{a}\right)=M\frac{z^{\alpha}\left(1-z\right)^{\beta}\left(1+\gamma\sqrt{z}+\delta z\right)}{\int_0^1 \mathrm{d}z z^{\alpha+1}\left(1-z\right)^{\beta}\left(1+\gamma\sqrt{z}+\delta z\right)}$$

- Unidentified Charged Hadron FF:

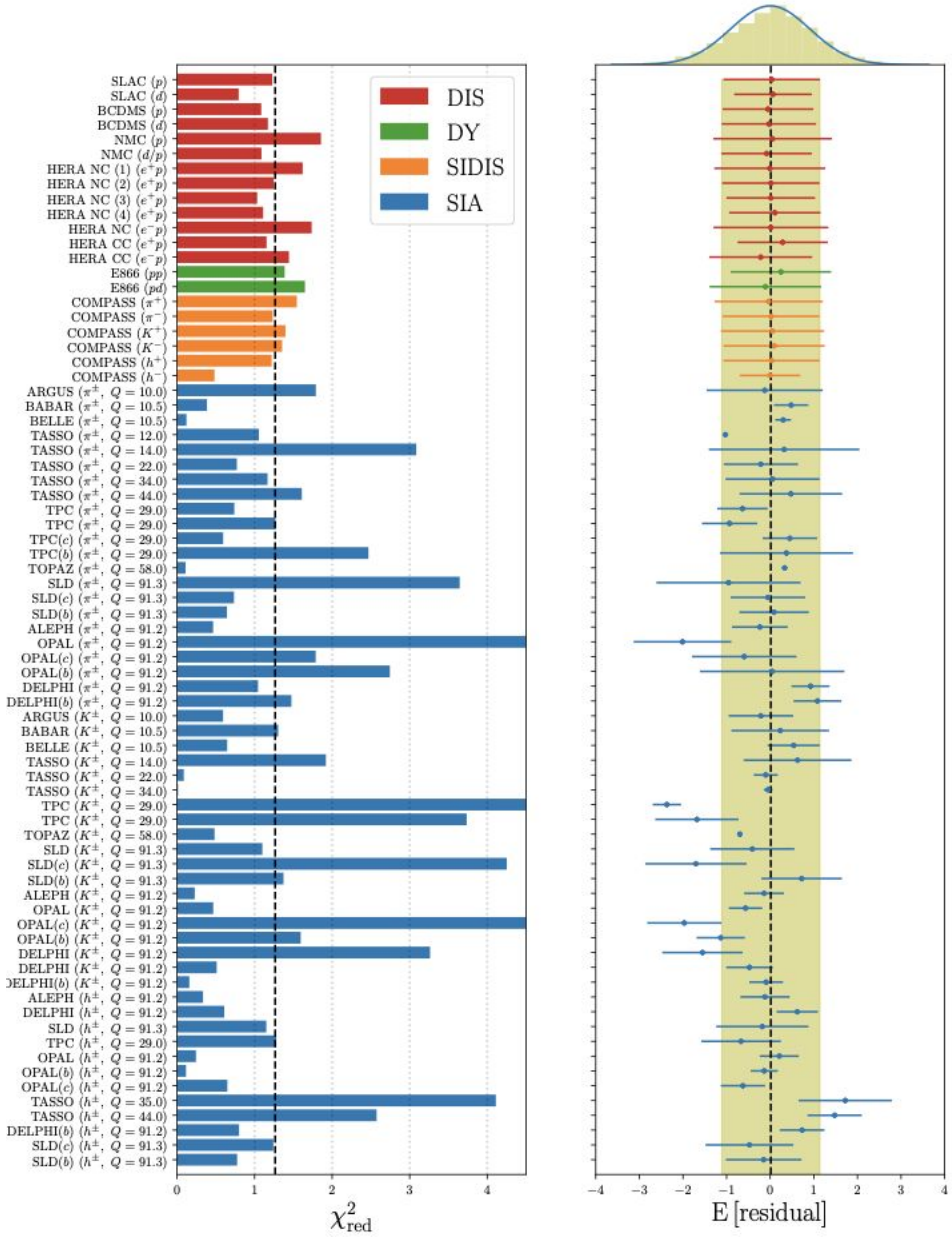
$$D_i^{h^+}=D_i^{\pi^+}+D_i^{K^+}+D_i^{res^+}$$

χ^2 Results

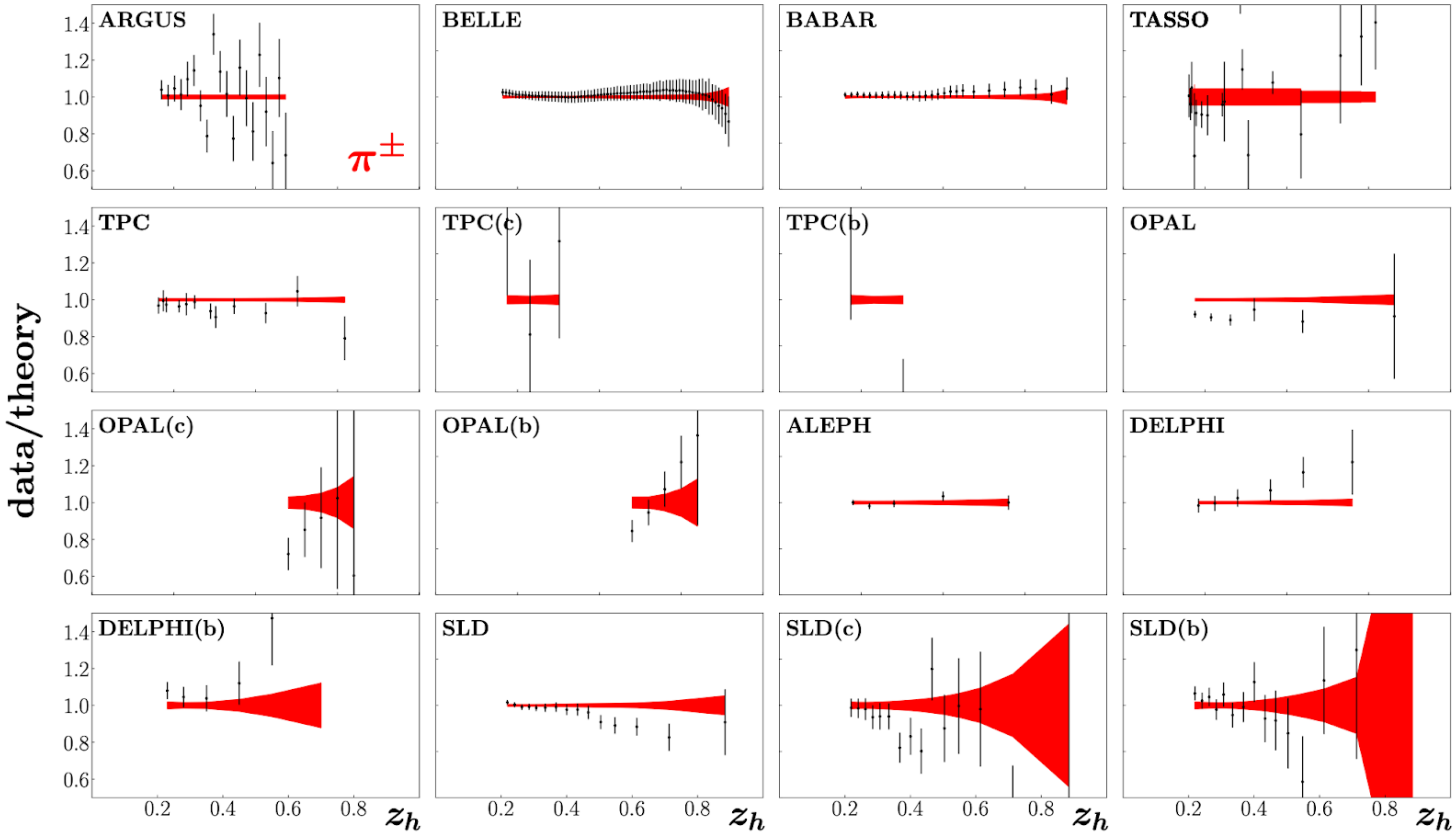
reaction		χ^2_{red}	N_{dat}
DIS		1.29	2680
DY		1.52	250
SIDIS	$\pi^\pm$	1.39	498
	$K^\pm$	1.38	494
	$h^\pm$	0.85	498
SIA	$\pi^\pm$	1.09	231
	$K^\pm$	1.37	213
	$h^\pm$	1.15	120
total		1.26	4984

$$\chi^2_{\mathrm{red}} = \frac{1}{N}\sum_{i,e}\frac{1}{\alpha^2_{i,e}}\left(d_{i,e} - \mathrm{E}\left[\sum_k r^k_e \beta^k_{i,e} + T_{i,e}/N_e\right]\right)^2$$

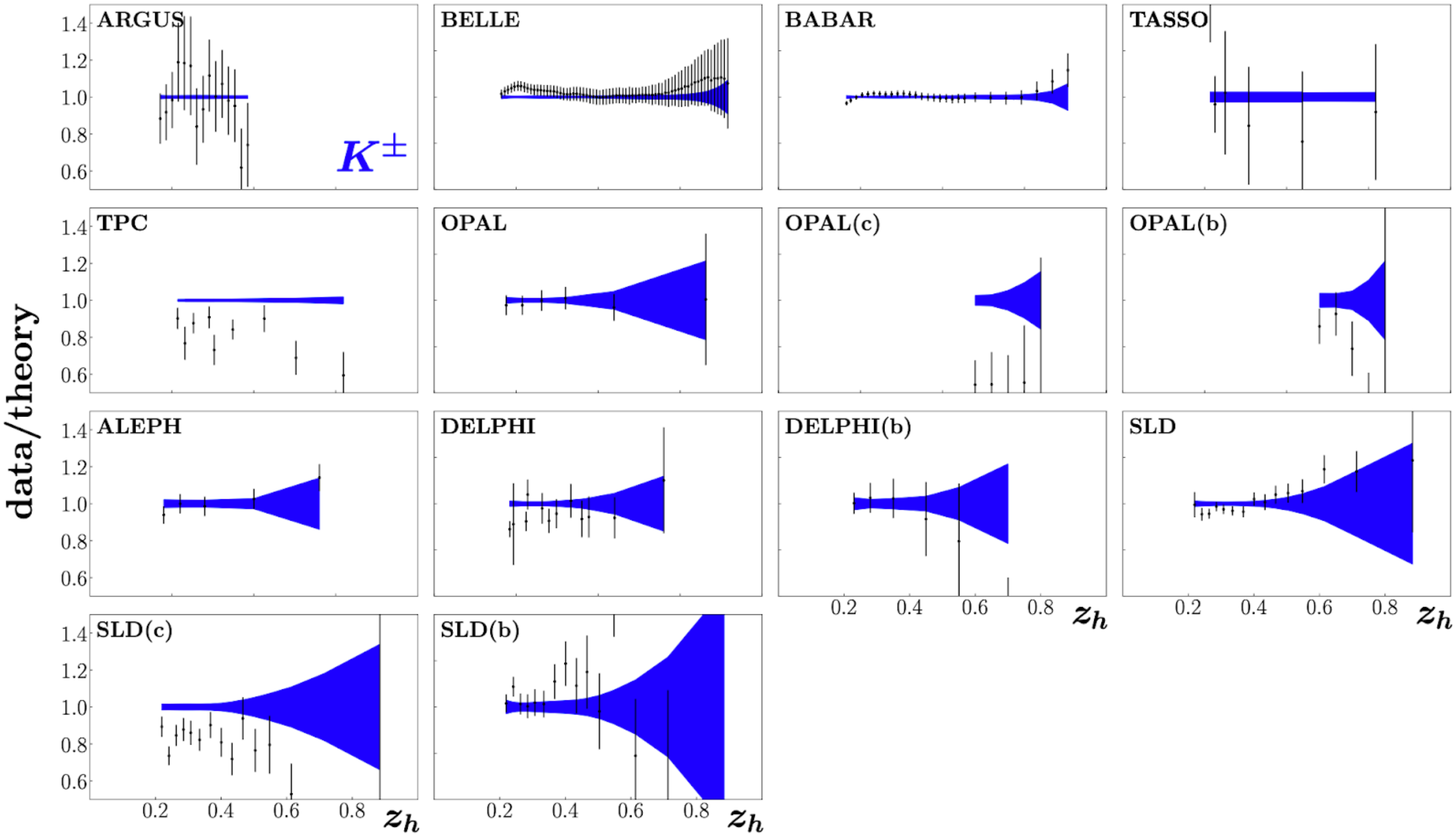
$$\mathrm{residual}\,(e,i) = \frac{1}{\alpha_{i,e}}\left(d_{i,e} - \mathrm{E}\left[\sum_k r^k_e \beta^k_{i,e} + T_{i,e}/N_e\right]\right)$$



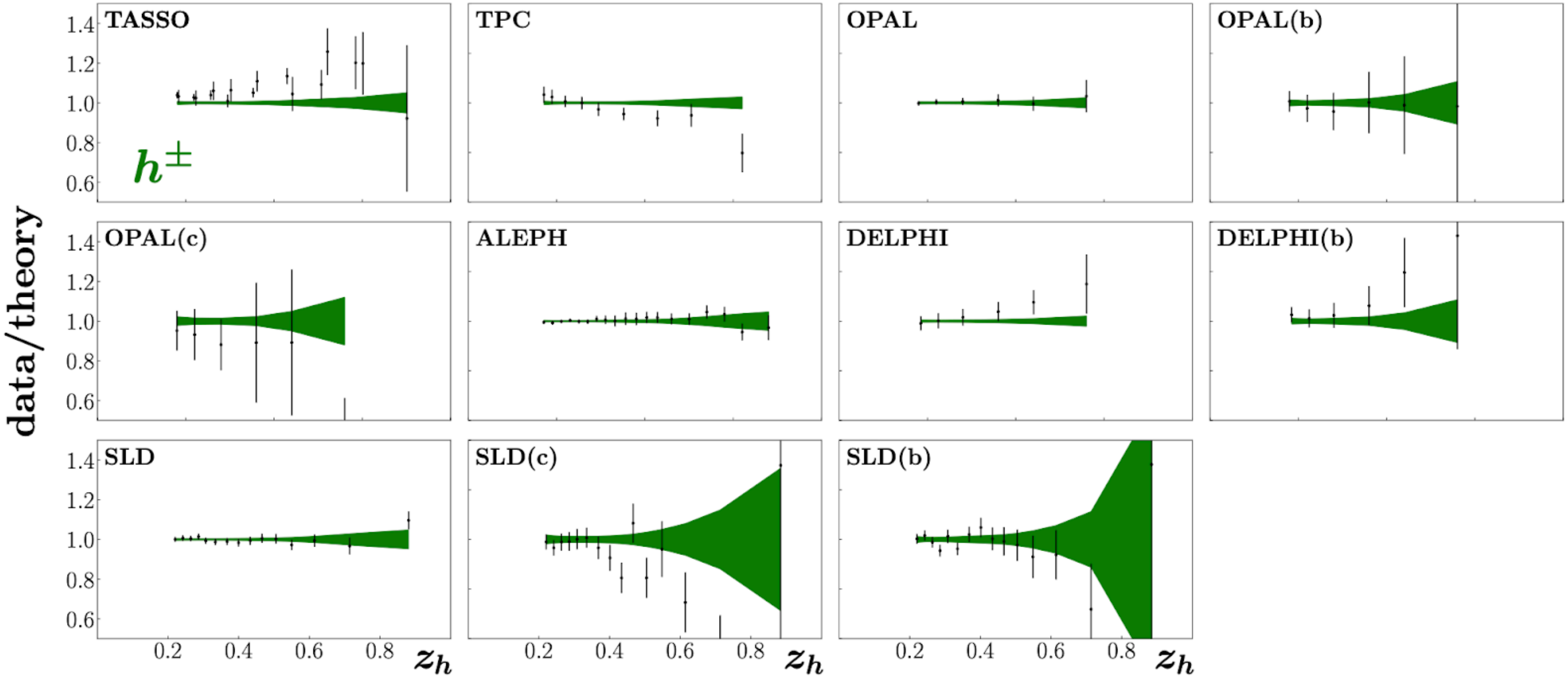
SIA Data over theory comparison: pions



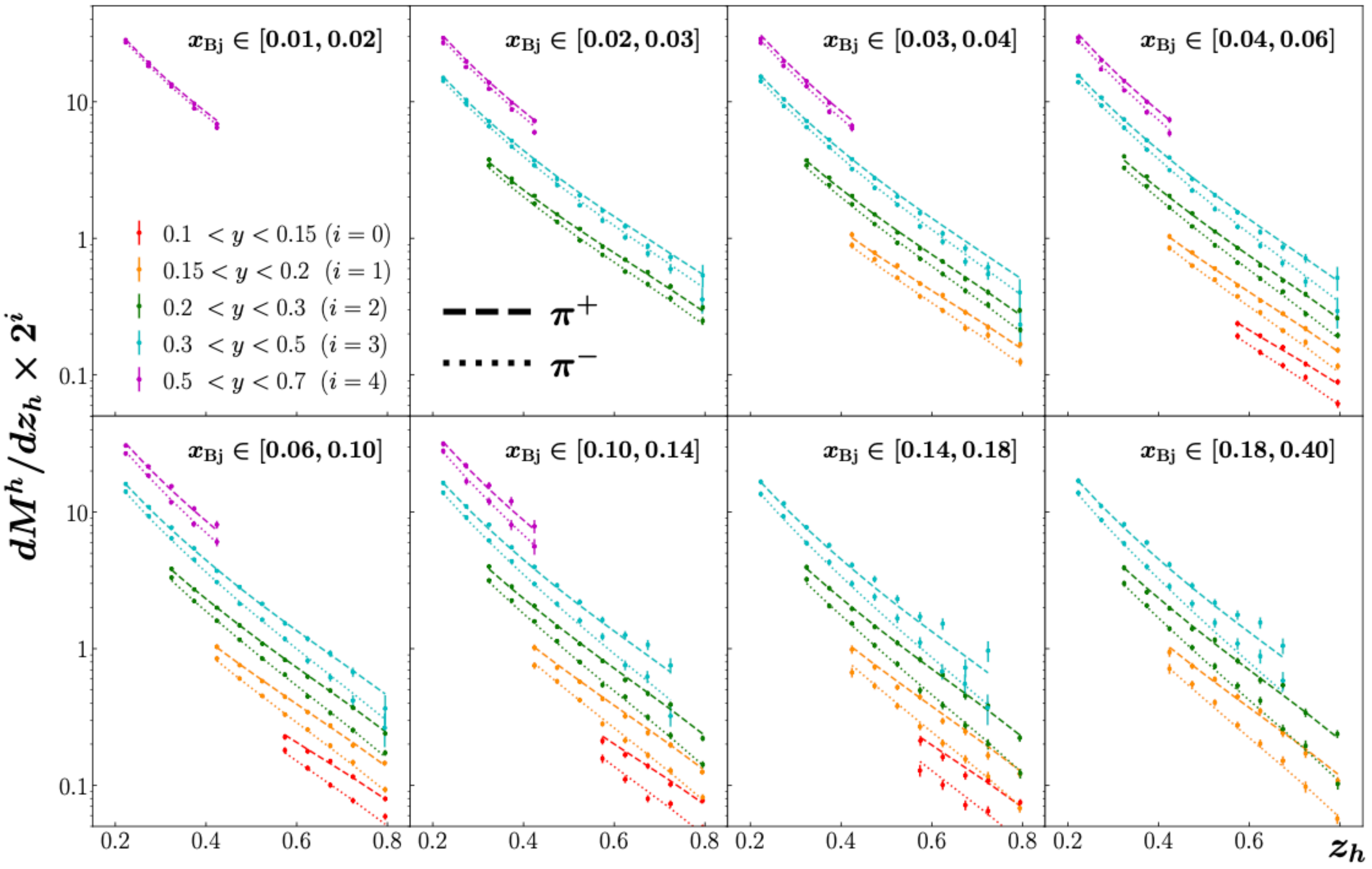
SIA Data over theory comparison: kaons



SIA Data over theory comparison: hadrons



SIDIS Data and theory comparison: pions



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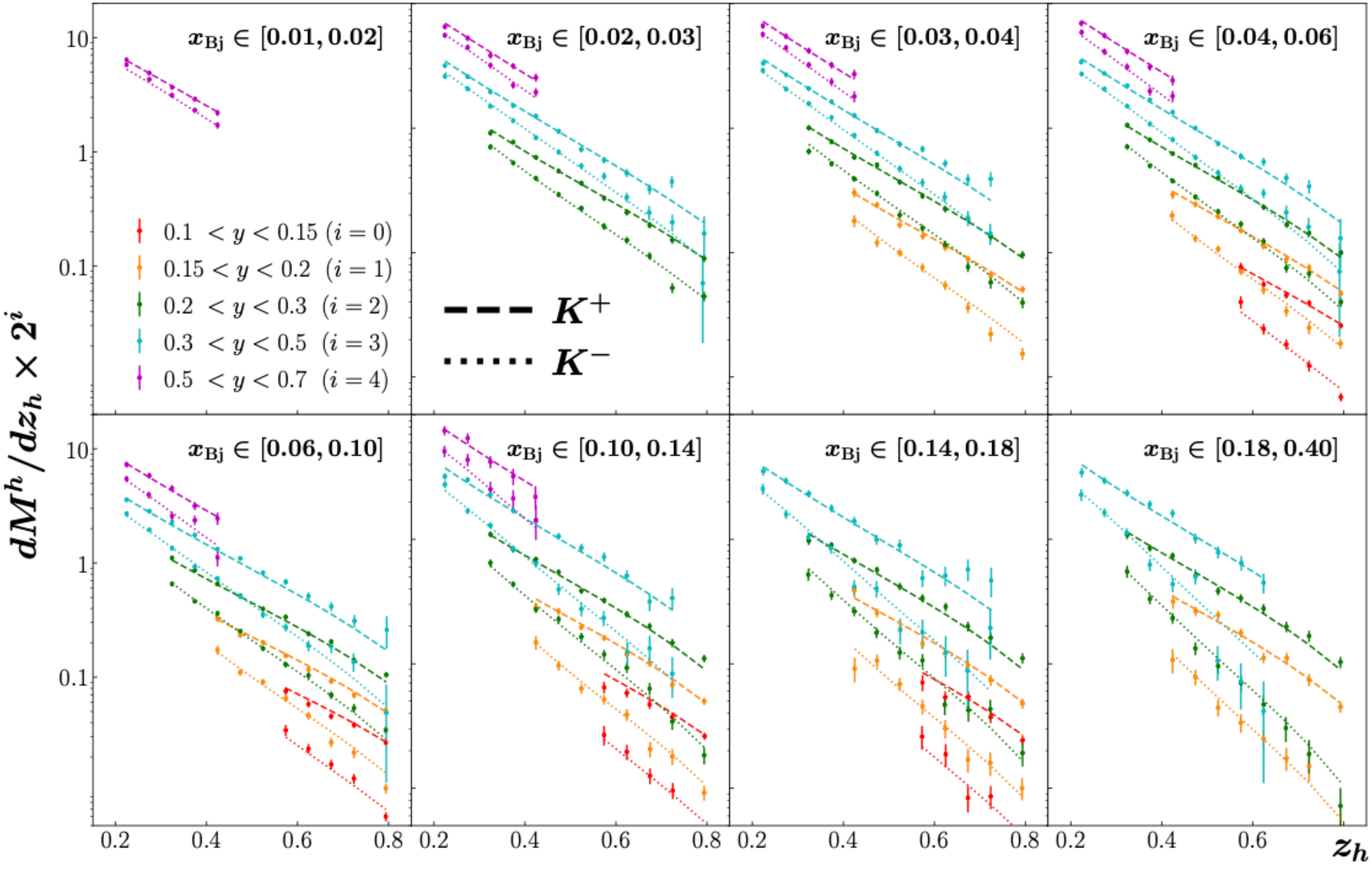

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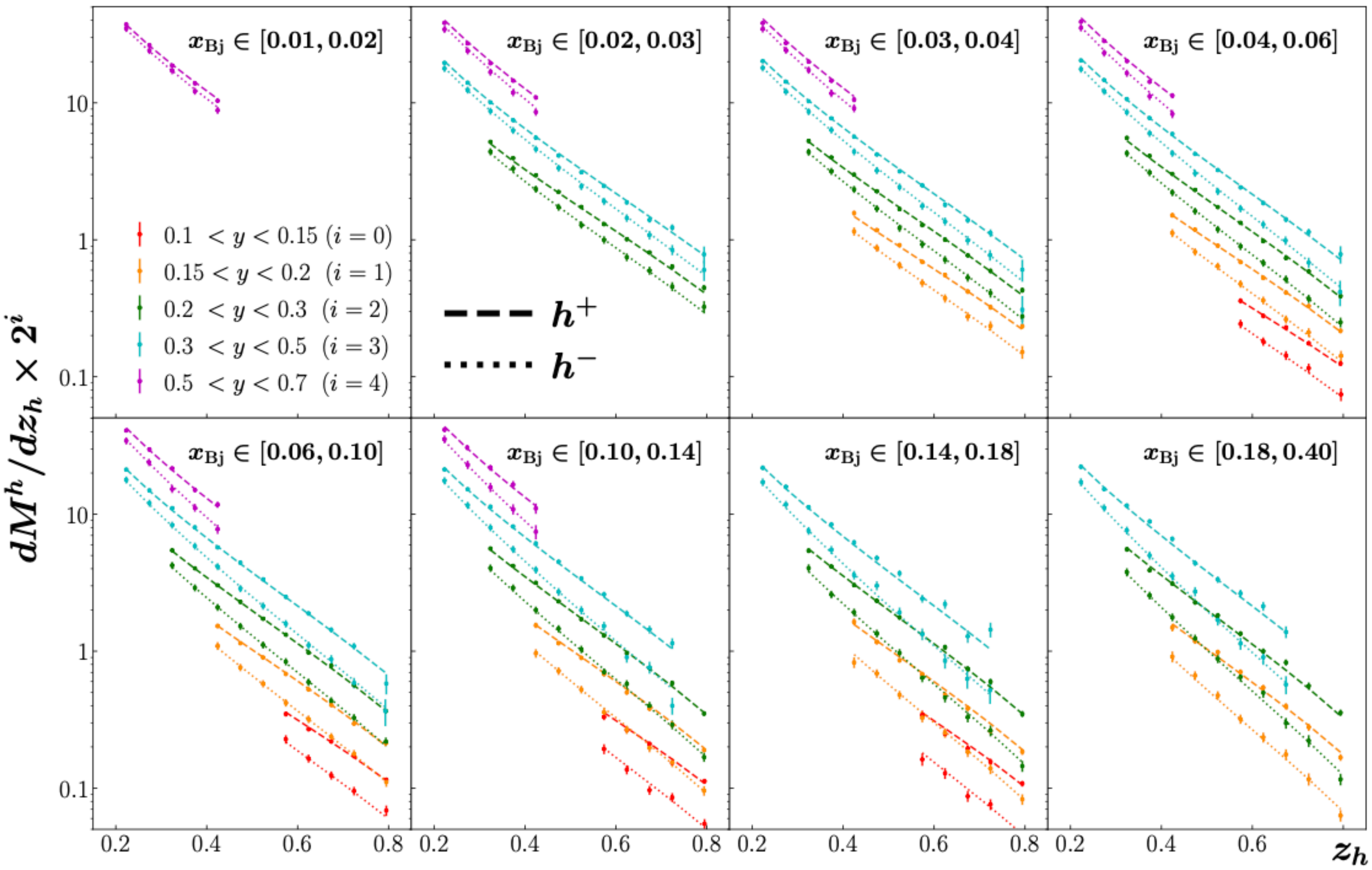
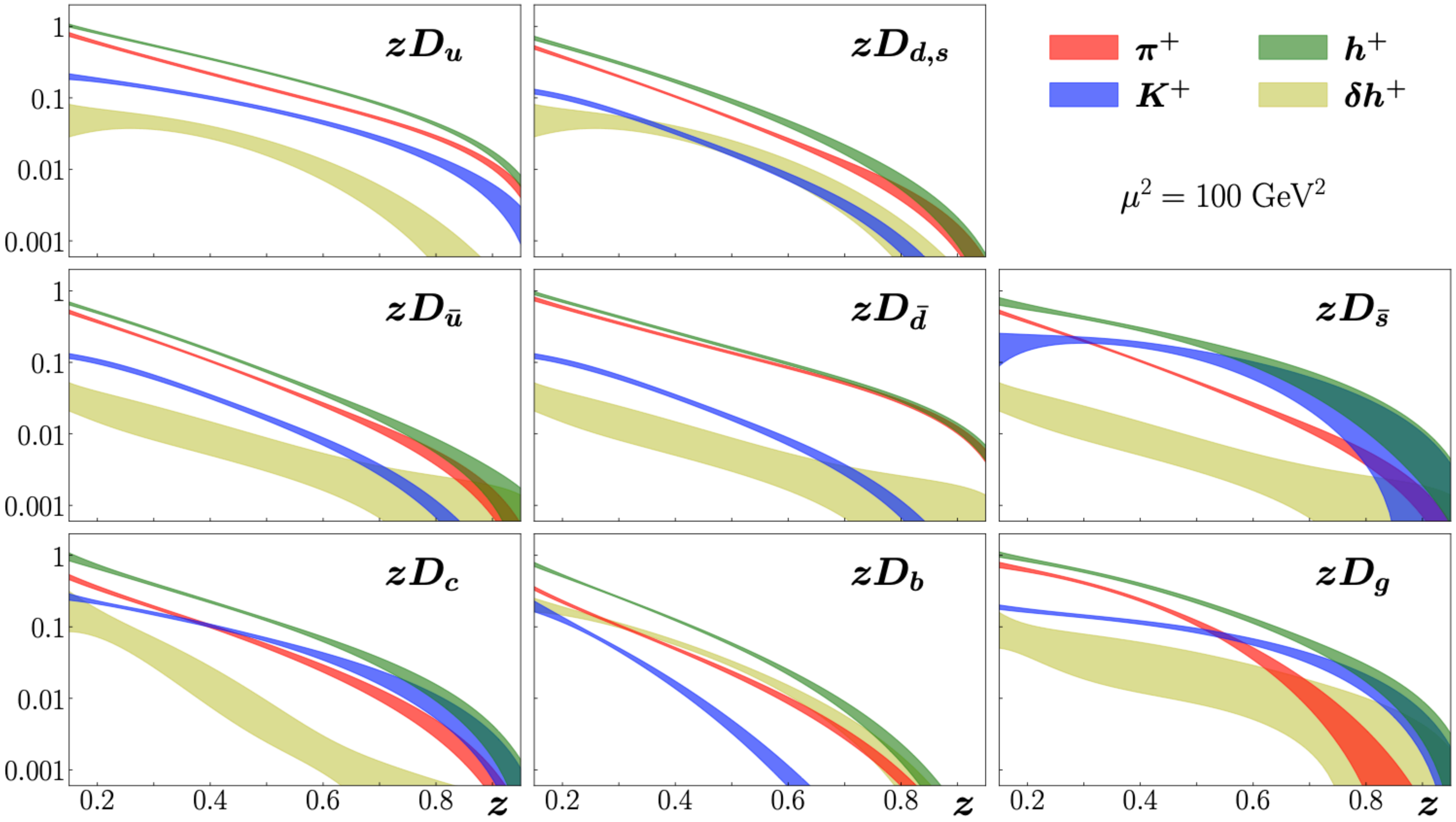
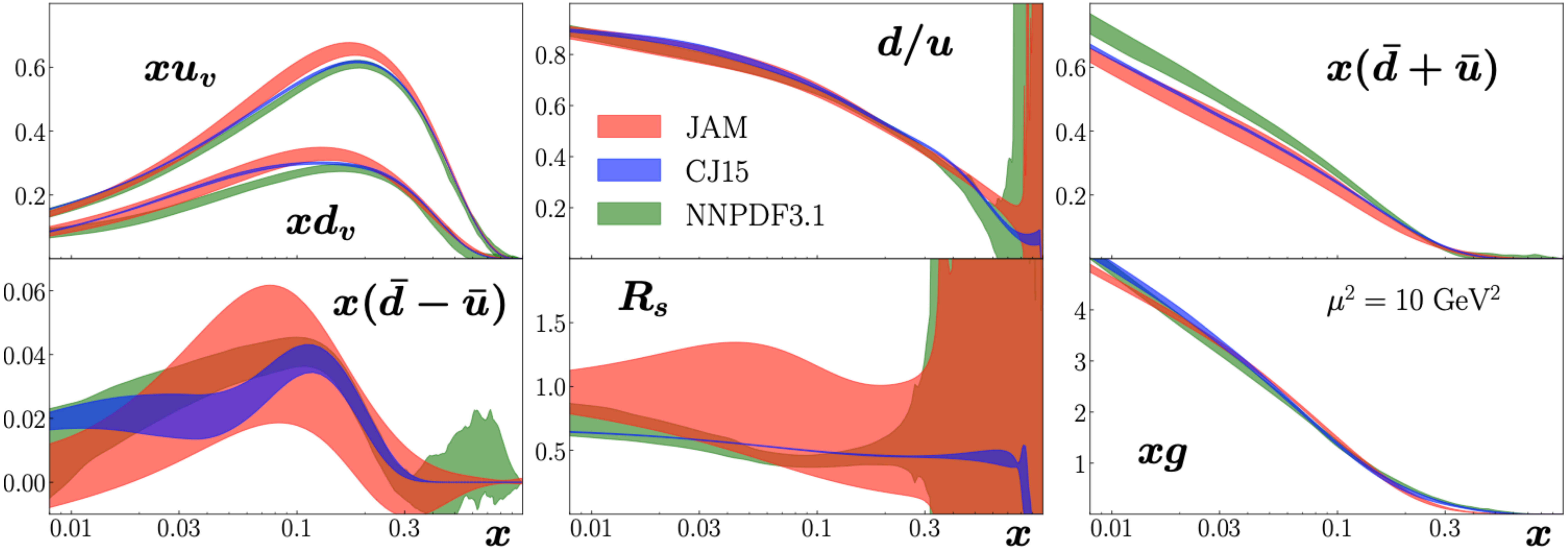


FF Results



zD_u
$zD_{d,s}$
$zD_{\bar{u}}$
$zD_{\bar{d}}$
$zD_{\bar{s}}$
zD_c
zD_b
zD_g
π^+
K^+
h^+
δh^+
$\mu^2 = 100$ GeV^2
1
0.1
0.01
0.001
0.2
0.4
0.6
0.8
z

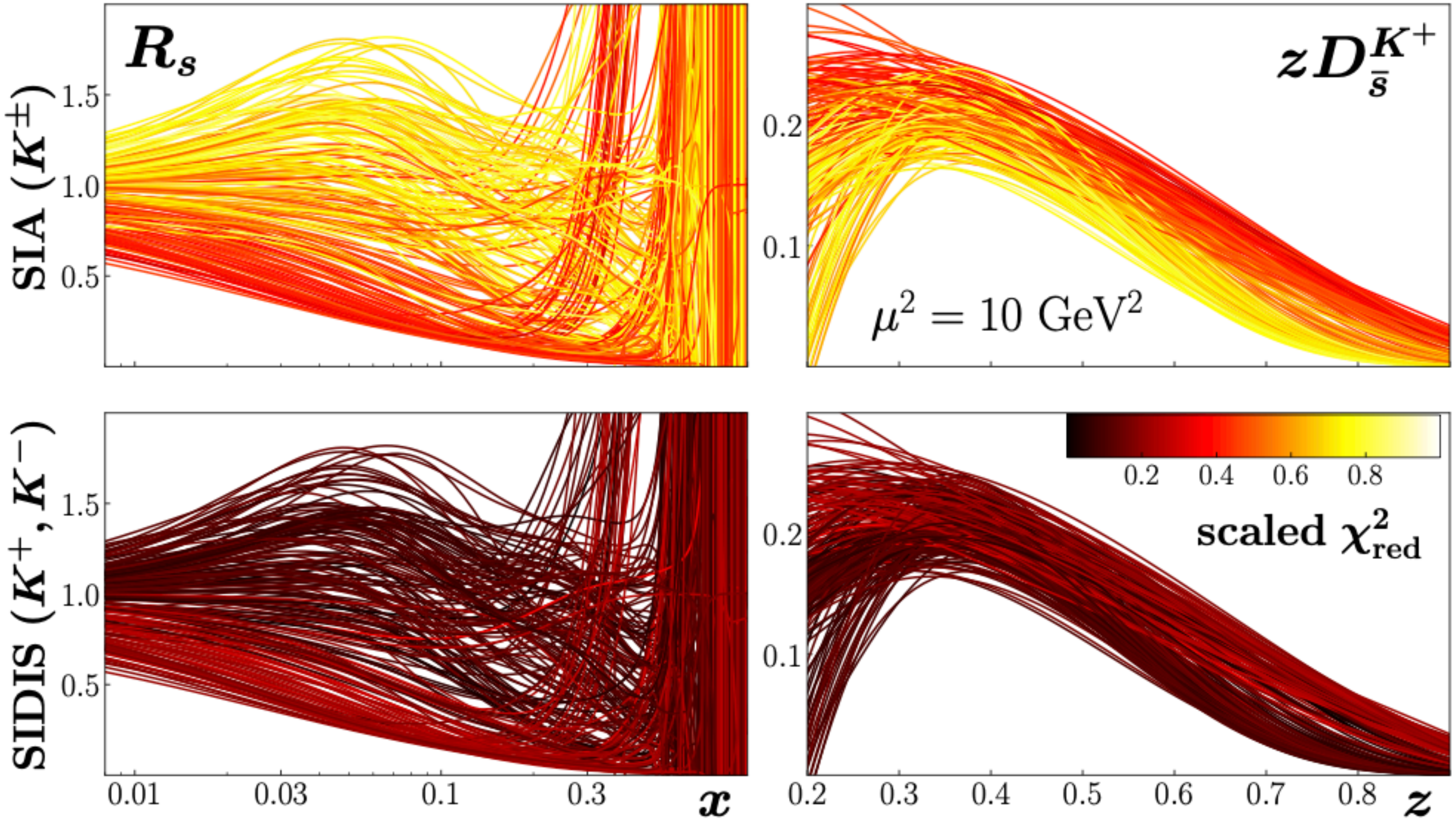
PDF Results



xu_v
xd_v
d/u
JAM
CJ15
NNPDF3.1
$x(\bar{d}+\bar{u})$
$x(\bar{d}-\bar{u})$
R_s
$\mu^2 = 10$ GeV^2
xg
0.01
0.03
0.1
0.3
x

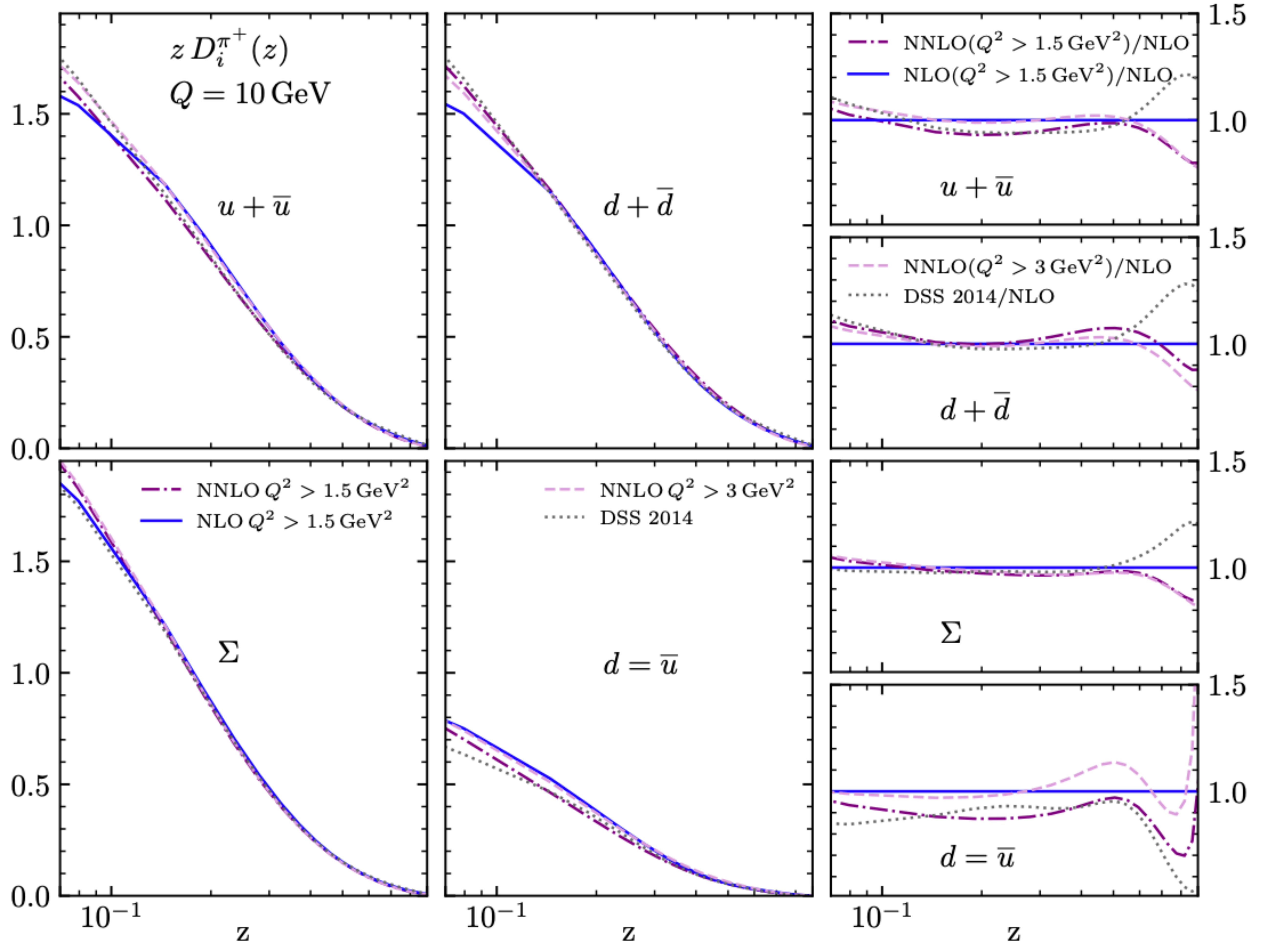
Strange PDF suppression

- Best fits to kaon SIA data favor smaller strange PDFs
- Consistent with JAM19 findings



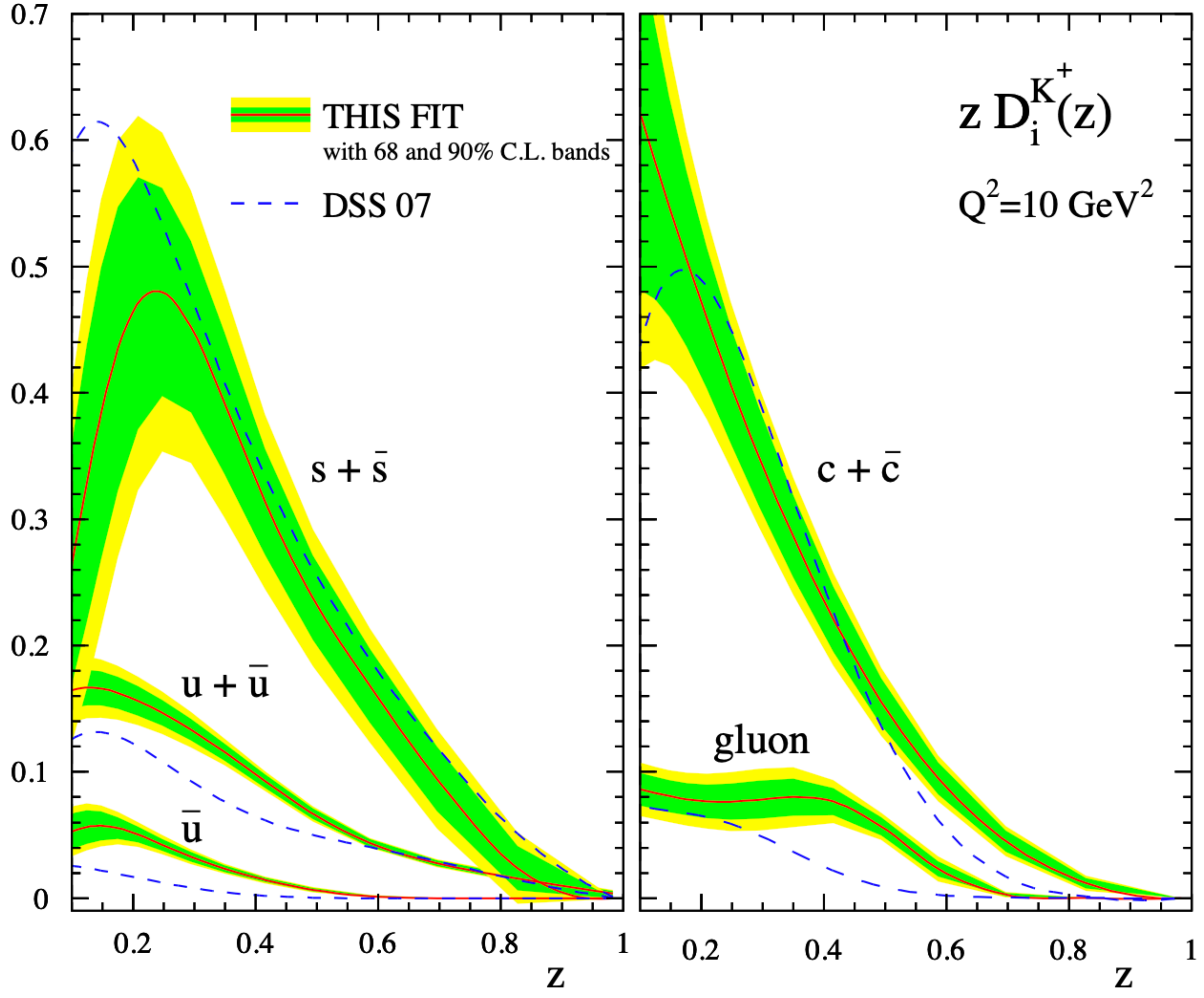
DSS FFs

- DSS: de Florean, Sassot, and Stratmann
    - Utilize single fits
- Pion results:
    - Borsa, et. al., Phys.Rev.Lett. 129 (2022)
    - NNLO fit to SIA and SIDIS data
    - For SIDIS, use NNPDF4.0 for the PDF contribution
        - Ball, et. al. Eur.Phys.J.C 82 (2022)



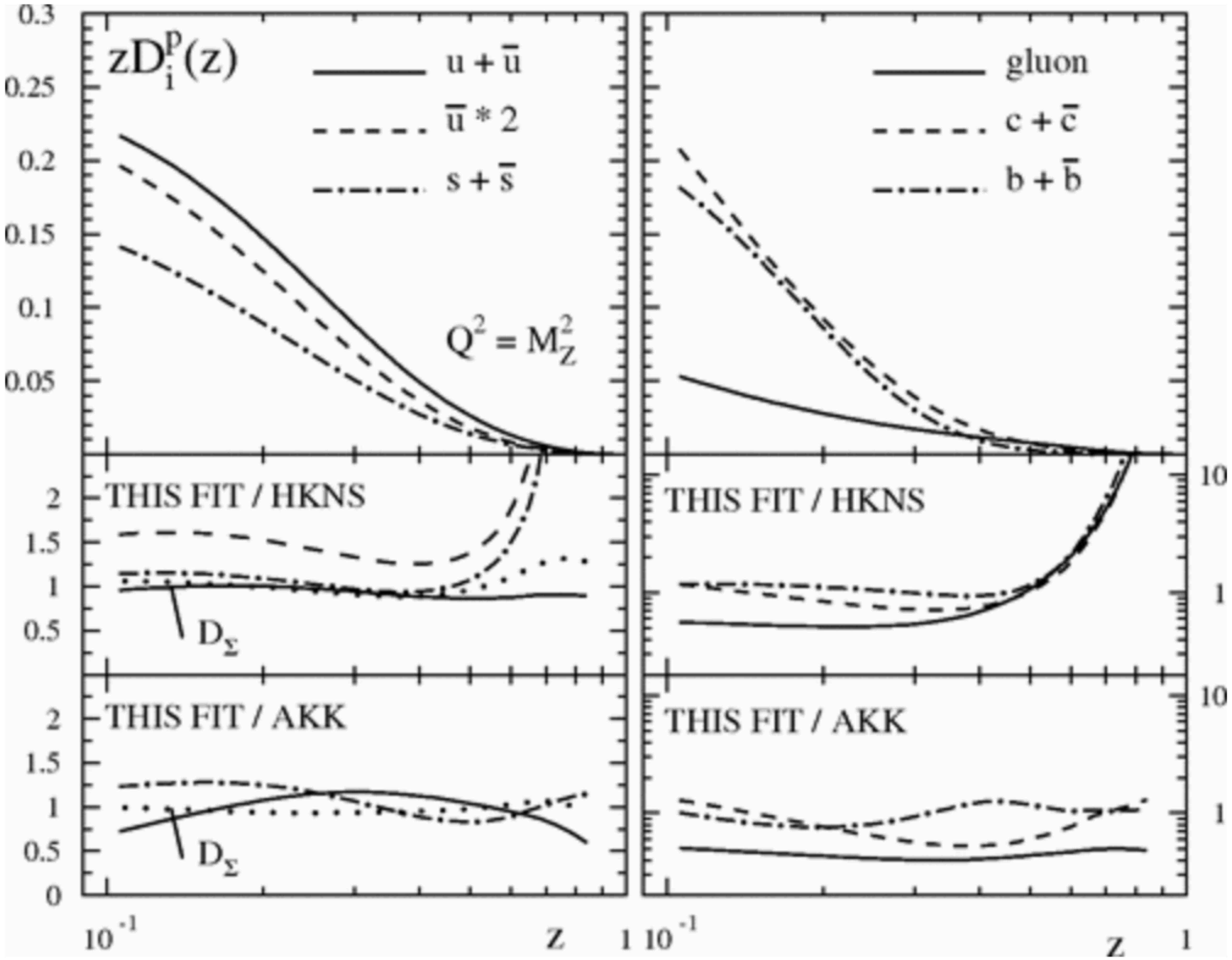
DSS FFs

- Kaon results:
  - Hernandez-Pinto, et. al., J.Phys.Conf.Ser. 912 (2017)
  - NLO fit to SIA, SIDIS, and PP data
  - For SIDIS, used MMHT 2014 for the PDF contribution
    - Harland-Lang, et. al. Eur.Phys.J.C 75 (2015)



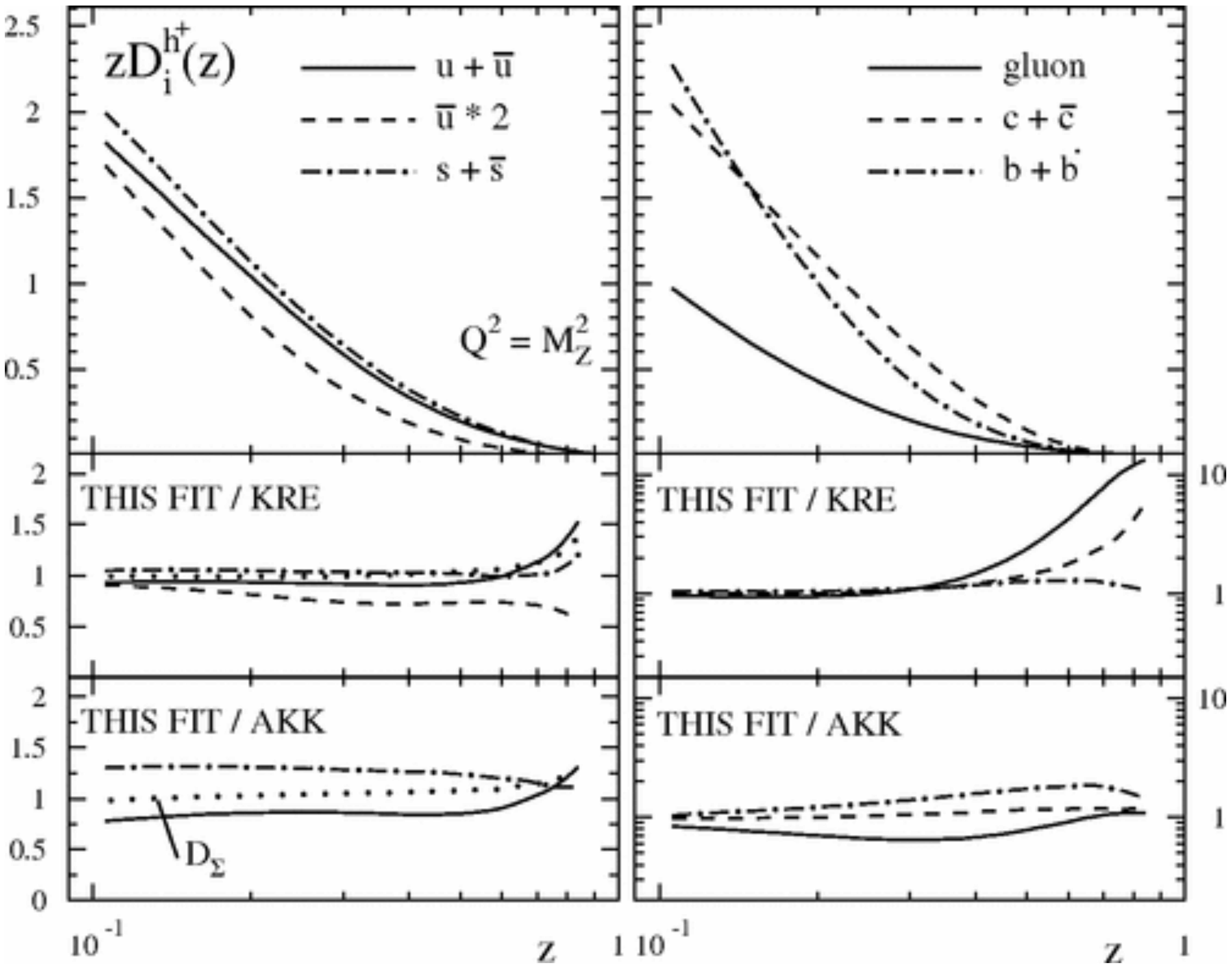
DSS FFs

- Proton results:
  - de Florian, et. al., Phys.Rev.D 76 (2007)
  - NLO fit to SIA and PP data



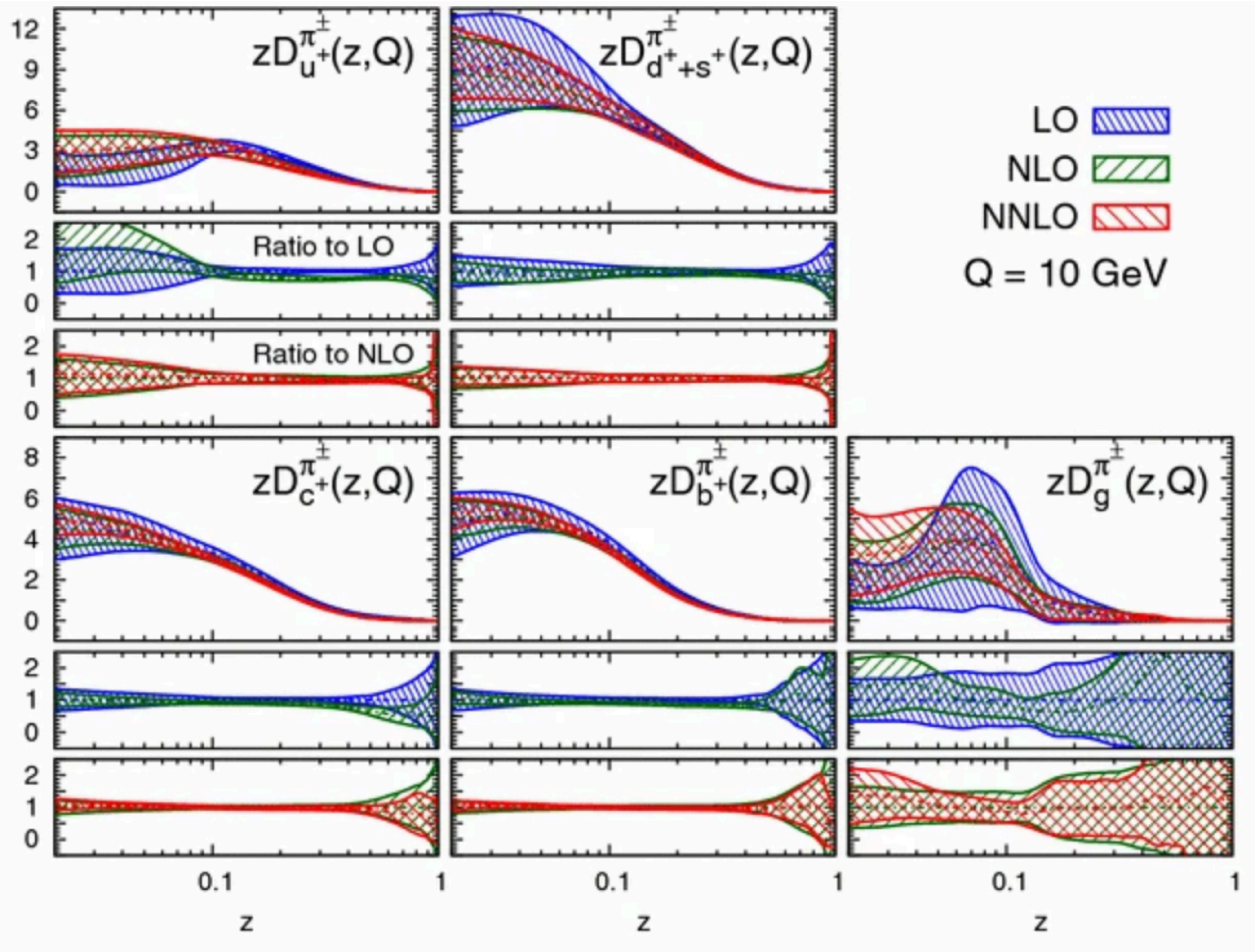
DSS FFs

- Unidentified hadron results:
  - de Florian, et. al., Phys.Rev.D 76 (2007)
  - NLO fit to SIA and PP data



NNFF

- Fragmentation functions from the NNPDF group
    - Monte Carlo approach using a neural network
- Pion results:
    - Bertone, et. al., Eur.Phys.J.C 77 (2017)
    - Up to NNLO fit to SIA data



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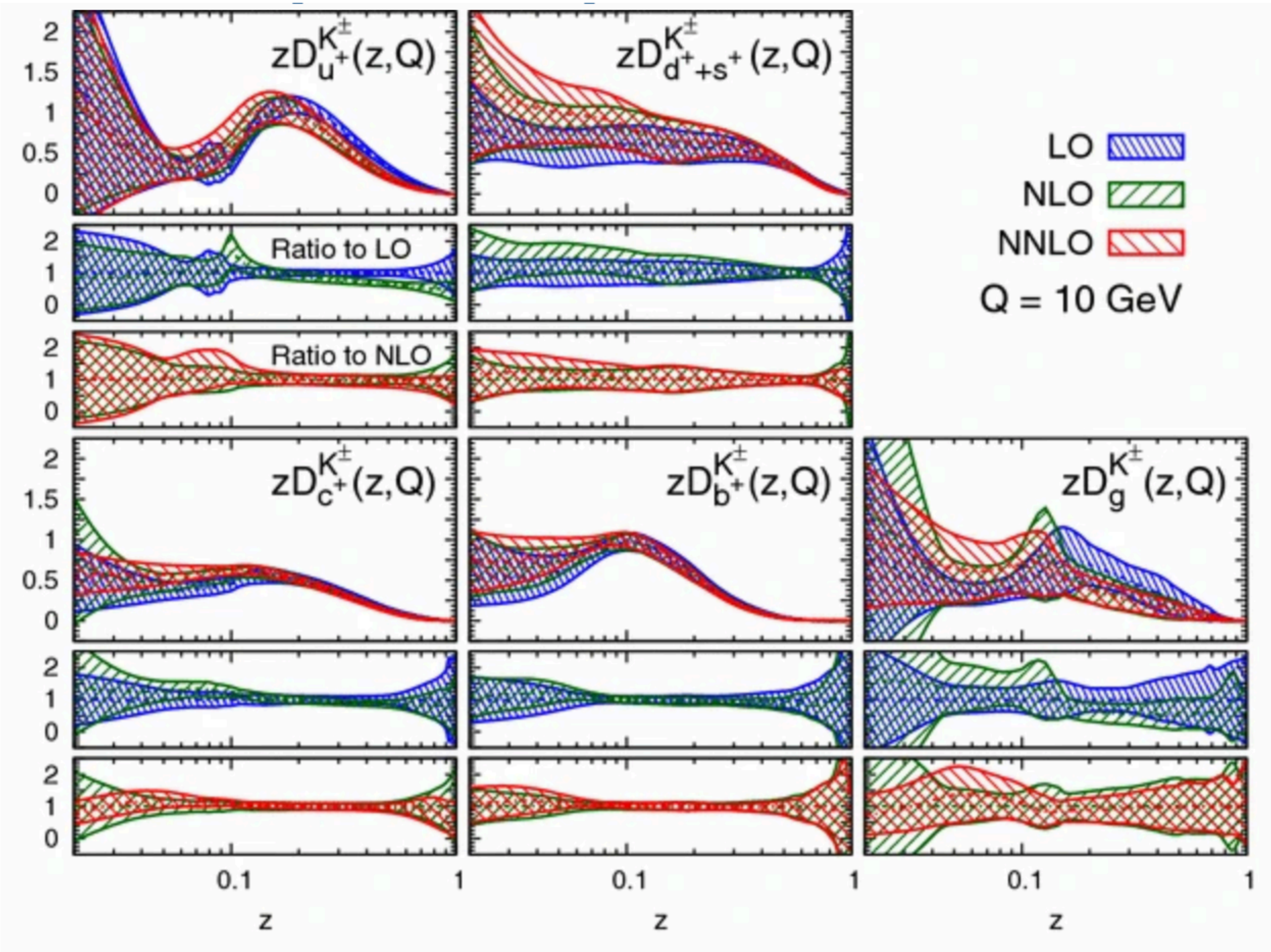

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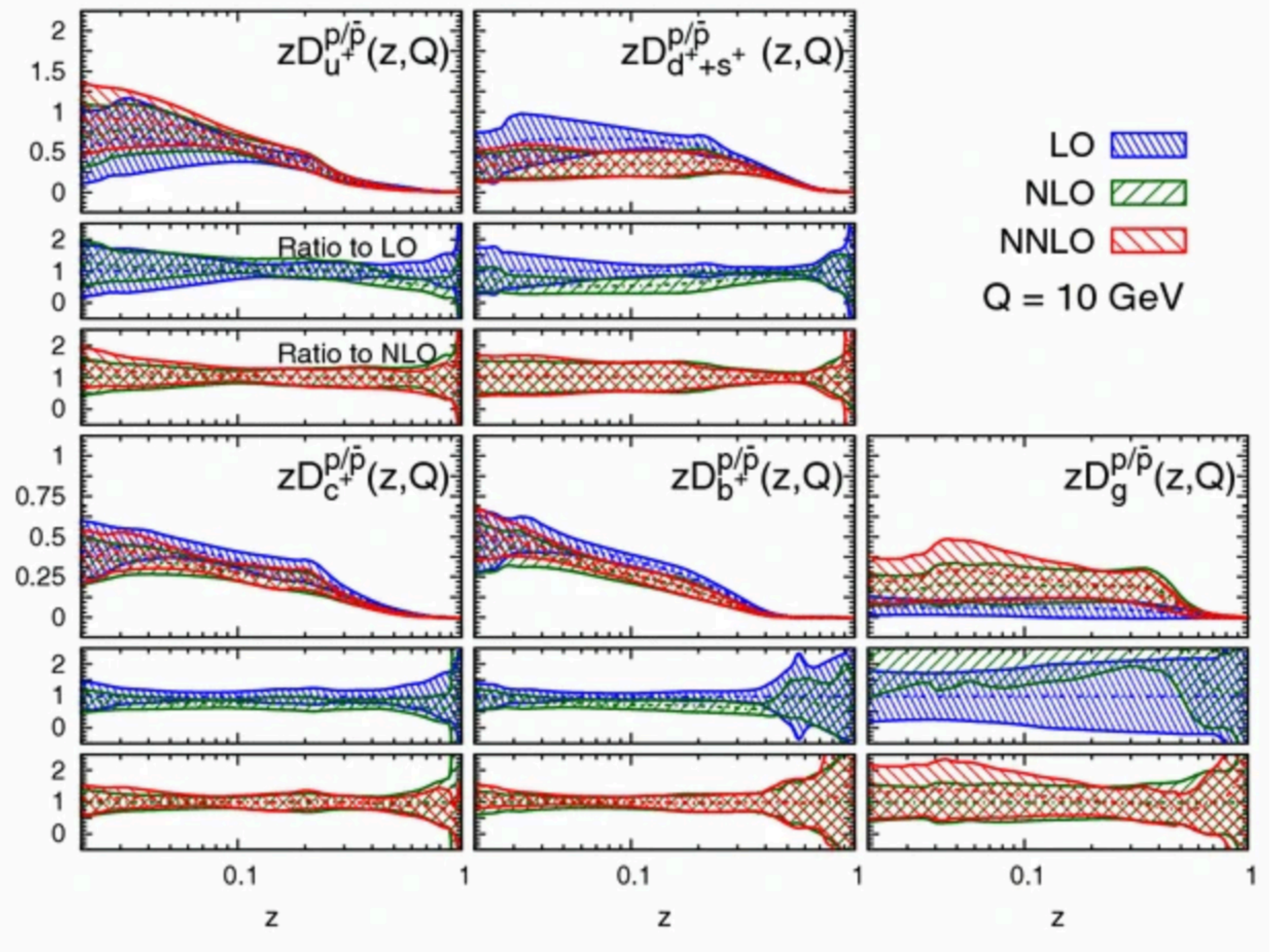
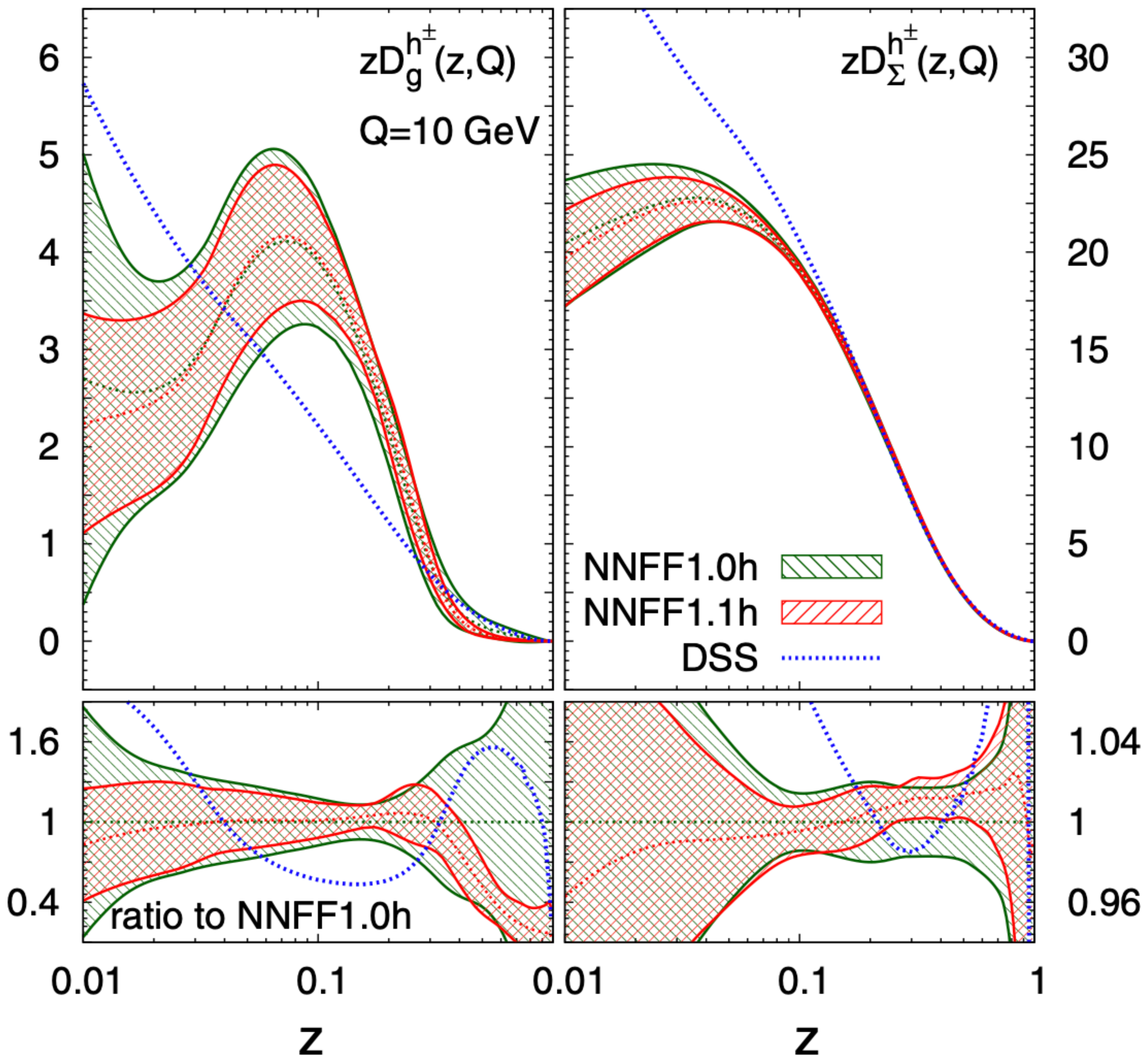


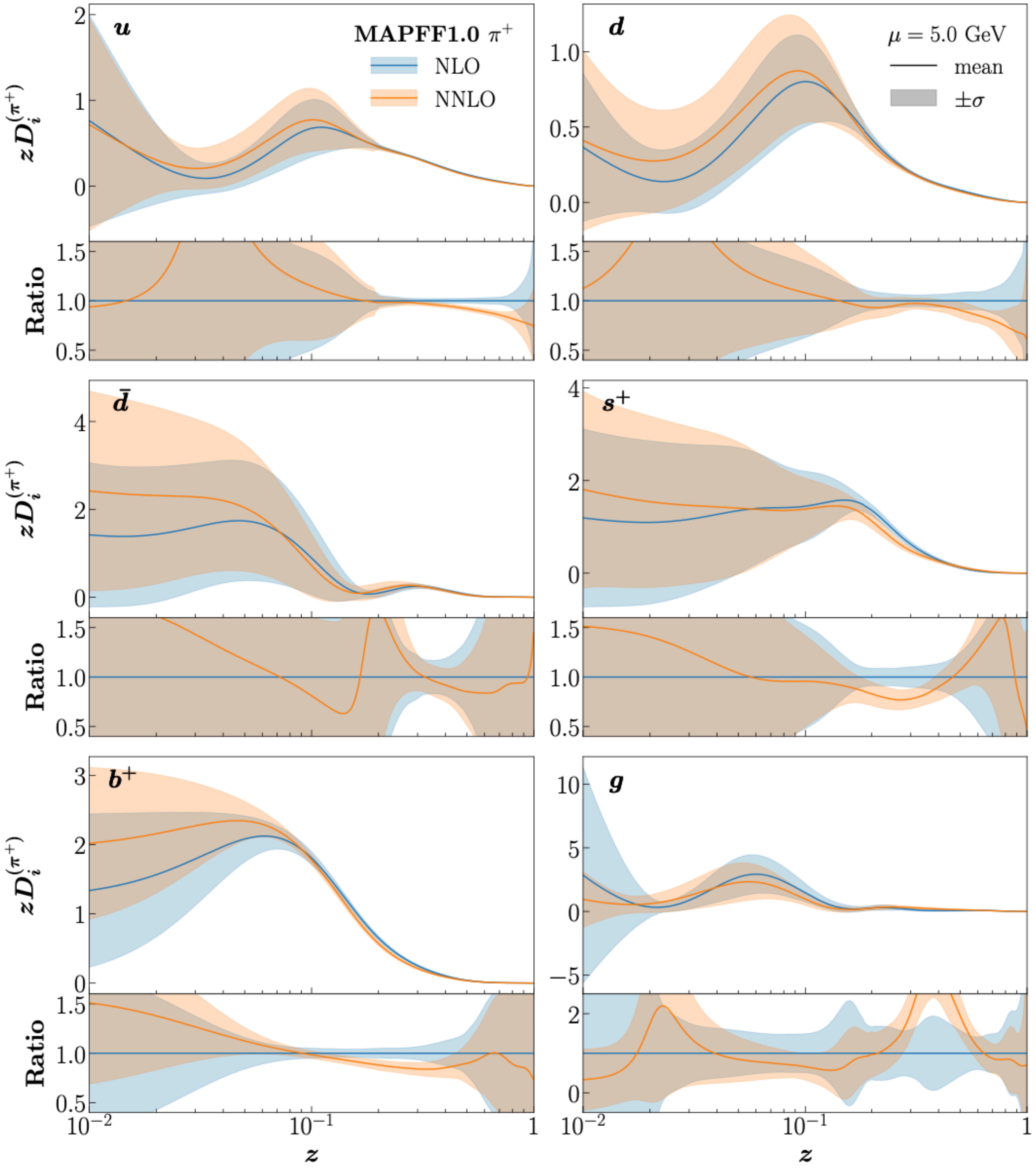
NNFF

- Unidentified hadron results:
  - Bertone, et. al., Eur.Phys.J.C 78 (2018)
  - Up to NLO fit to SIA and PP data



MAP FFs

- Multi-dimensional Analyses of Partonic (MAP) distributions collaboration
  - Monte Carlo approach using a neural network
- Pion results:
  - Khalek, et. al., arXiv:2204.10331
  - NNLO fit to SIA and SIDIS data
  - For SIDIS, use NNPDF3.1 for the PDF contribution
    - Ball, et. al. Eur.Phys.J.C 77 (2017)



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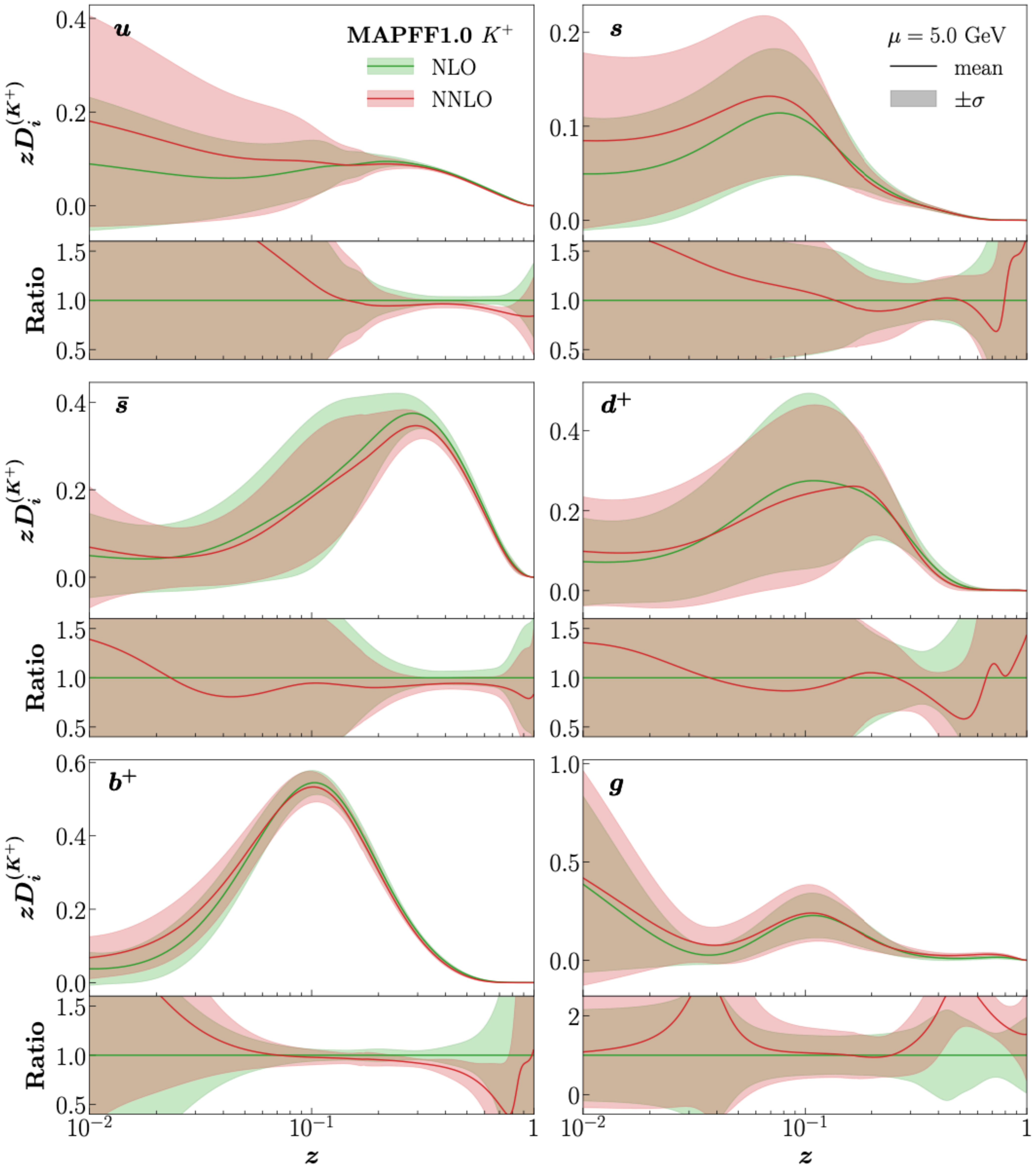

Summary and Outlook

- Summary:
  - Most recent JAM results for FFs:
    - Simultaneous fit of PDFs and pion, kaon, and unidentified hadron FFs
  - Highlighted FF results from DSS and the NNPDF and MAP collaborations
- Outlook:
  - Working towards fitting collinear and transverse momentum dependent functions simultaneously.