Simultaneous Monte Carlo analysis of parton densities and fragmentation functions

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Introduction

- Significant tension between large transverse momentum data and Fixed Order (FO) predictions using existing collinear Parton Distribution Functions (PDFs) and Fragmentation Functions (FFs)
- Resolving this tension is crucial for the study of Transverse Momentum Dependent (TMD) PDFs and FFs and Generalized PDFs (GPDs).
- To facilitate exploring the reasons for this tension in SIDIS, performed a new fit using Jefferson Lab Angular Momentum Collaboration (JAM) methodology:
    - Multi-Step Monte Carlo fit utilizing Bayesian Inference
    - Simultaneously fit PDFs and charged pion, kaon, and unidentified hadron FFs.
        - First such fit involving charged hadrons

Theory

$$\frac{\mathrm{d}\sigma_{\mathrm{DIS}}}{\mathrm{d}Q^2\mathrm{d}x_{\mathrm{Bj}}} = \sum_{i\,\in\,\mathrm{flavors}} \mathcal{H}_i^{\mathrm{DIS}} \otimes f_i\,, \qquad \text{inclusive DIS}$$

$$\frac{\mathrm{d}\sigma_{\mathrm{SIDIS}}}{\mathrm{d}Q^2\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}z_h} = \sum_{ij\,\in\,\mathrm{flavors}} \mathcal{H}_{ij}^{\mathrm{SIDIS}} \otimes f_i \otimes D_j^h\,, \qquad \text{semi-inclusive DIS}$$

$$\frac{\mathrm{d}\sigma_{\mathrm{DY}}}{\mathrm{d}Q^2\mathrm{d}x_{\mathrm{F}}} = \sum_{ij\,\in\,\mathrm{flavors}} \mathcal{H}_{ij}^{\mathrm{DY}} \otimes f_i \otimes f_j\,, \qquad \text{Drell-Yan lepton-pair production}$$

$$\frac{\mathrm{d}\sigma_{\mathrm{SIA}}}{\mathrm{d}Q^2\mathrm{d}z_h} = \sum_{j\,\in\,\mathrm{flavors}} \mathcal{H}_j^{\mathrm{SIA}} \otimes D_j^h\,, \qquad \text{semi-inclusive annihilation}$$

- Using NLO perturbative calculations

JAM fit

- Simultaneously fit PDFs and charged pion, kaon, and unidentified hadron FFs
  - Functional form:

$$T(x; \boldsymbol{a}) = \mathcal{M} \frac{x^{\alpha}(1-x)^{\beta}(1+\gamma\sqrt{x}+\delta x)}{\int_0^1 dx\, x^{\alpha+1}(1-x)^{\beta}(1+\gamma\sqrt{x}+\delta x)}$$

  - Unidentified charged hadron fragmentation function:

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

  - Total: Fitting 24 functions, 129 parameters

JAM fit

- Multi-Step Monte Carlo fit utilizing Bayesian Inference:

$$\mathcal{P}(\boldsymbol{a}|\text{data}) \sim \mathcal{L}(\boldsymbol{a}, \text{data})\,\pi(\boldsymbol{a}) \qquad \mathcal{L}(\boldsymbol{a}, \text{data}) = \exp\left(-\frac{1}{2}\chi^2(\boldsymbol{a}, \text{data})\right)$$

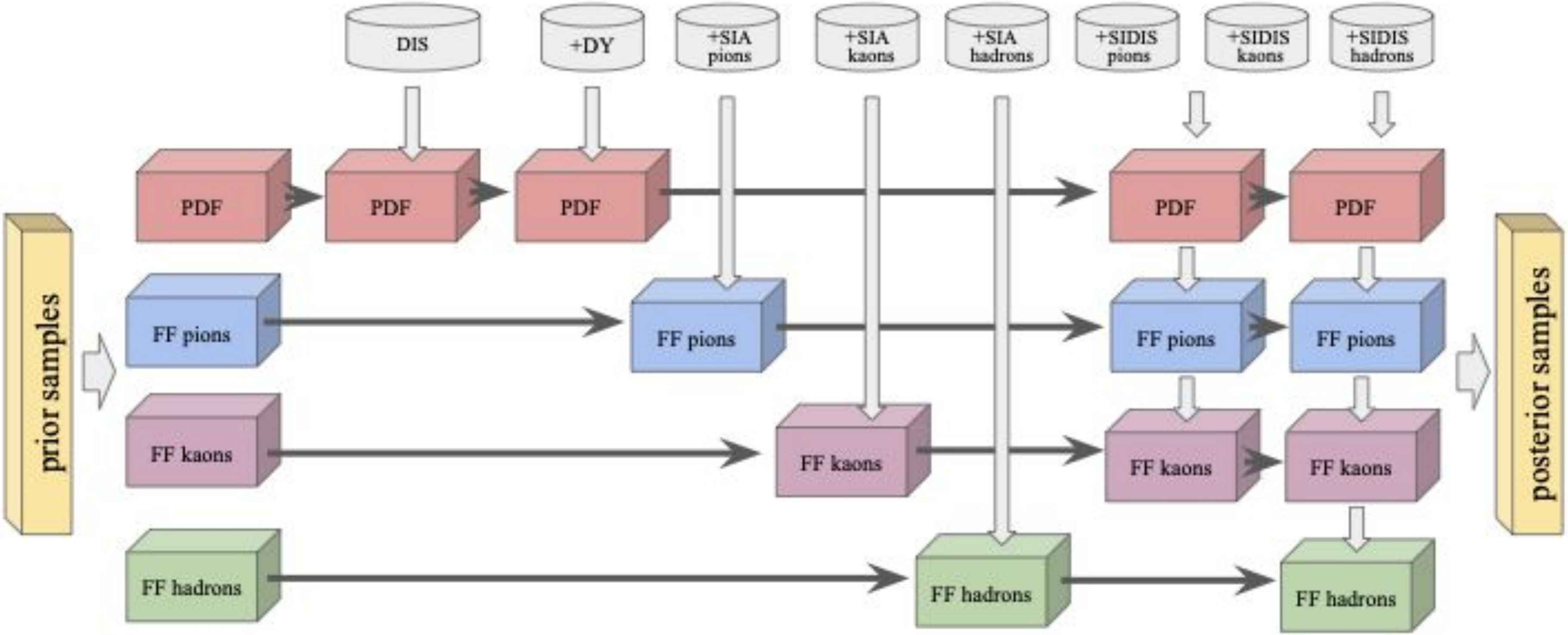
$$\chi^2(\boldsymbol{a}) = \sum_{i,e}\left(\frac{d_{i,e} - \sum_k r_e^k \beta_{i,e}^k - T_{i,e}(\boldsymbol{a})/N_e}{\alpha_{i,e}}\right)^2 + \sum_k \left(r_e^k\right)^2 + \left(\frac{1-N_e}{\delta N_e}\right)^2$$

$$\mathrm{E}[\mathcal{O}] = \int \mathrm{d}^d\boldsymbol{a}\,\mathcal{P}(\boldsymbol{a}|\text{data})\,\mathcal{O}(\boldsymbol{a}), \qquad \mathrm{E}[\mathcal{O}] = \frac{1}{n}\sum_{k=1}^{n}\mathcal{O}(\boldsymbol{a}_k),$$

$$\mathrm{V}[\mathcal{O}] = \int \mathrm{d}^d\boldsymbol{a}\,\mathcal{P}(\boldsymbol{a}|\text{data})\left(\mathcal{O}(\boldsymbol{a}) - \mathrm{E}[\mathcal{O}]\right)^2 \qquad \mathrm{V}[\mathcal{O}] = \frac{1}{n}\sum_{k=1}^{n}\left(\mathcal{O}(\boldsymbol{a}_k) - \mathrm{E}[\mathcal{O}]\right)^2$$

- Use least squares to obtain maximum likelihood (minimum chi squared) for each replica.

Multi-step process



Data sets

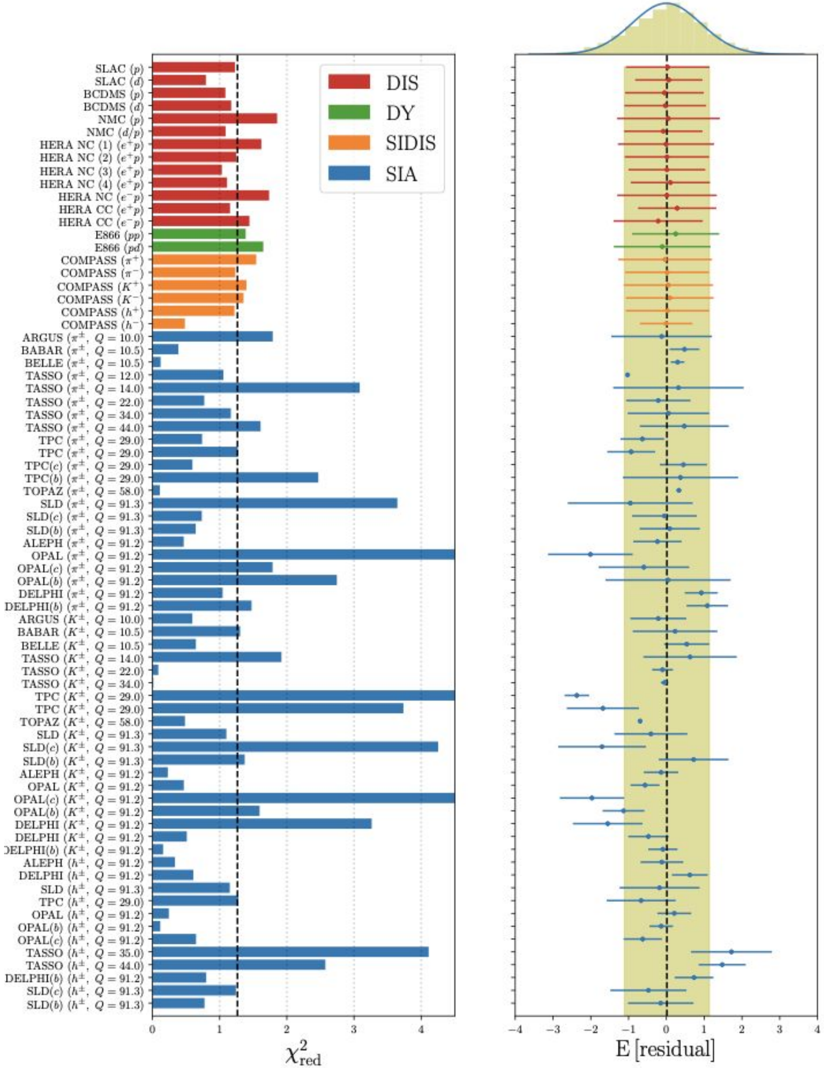
- Data Sets:
  - Inclusive Deep Inelastic Scattering (DIS)
    - BCDMS, NMC, SLAC, HERA
  - Semi-Inclusive DIS (SIDIS)
    - COMPASS
  - Single-Inclusive e+/e- Annihilation (SIA)
    - TASSO, TPC, TOPAZ, BELLE, BABAR, ARGUS, DELPHI, ALEPH, OPAL, SLD
  - Drell-Yan Scattering (DY)
    - E866

χ^2_{red}

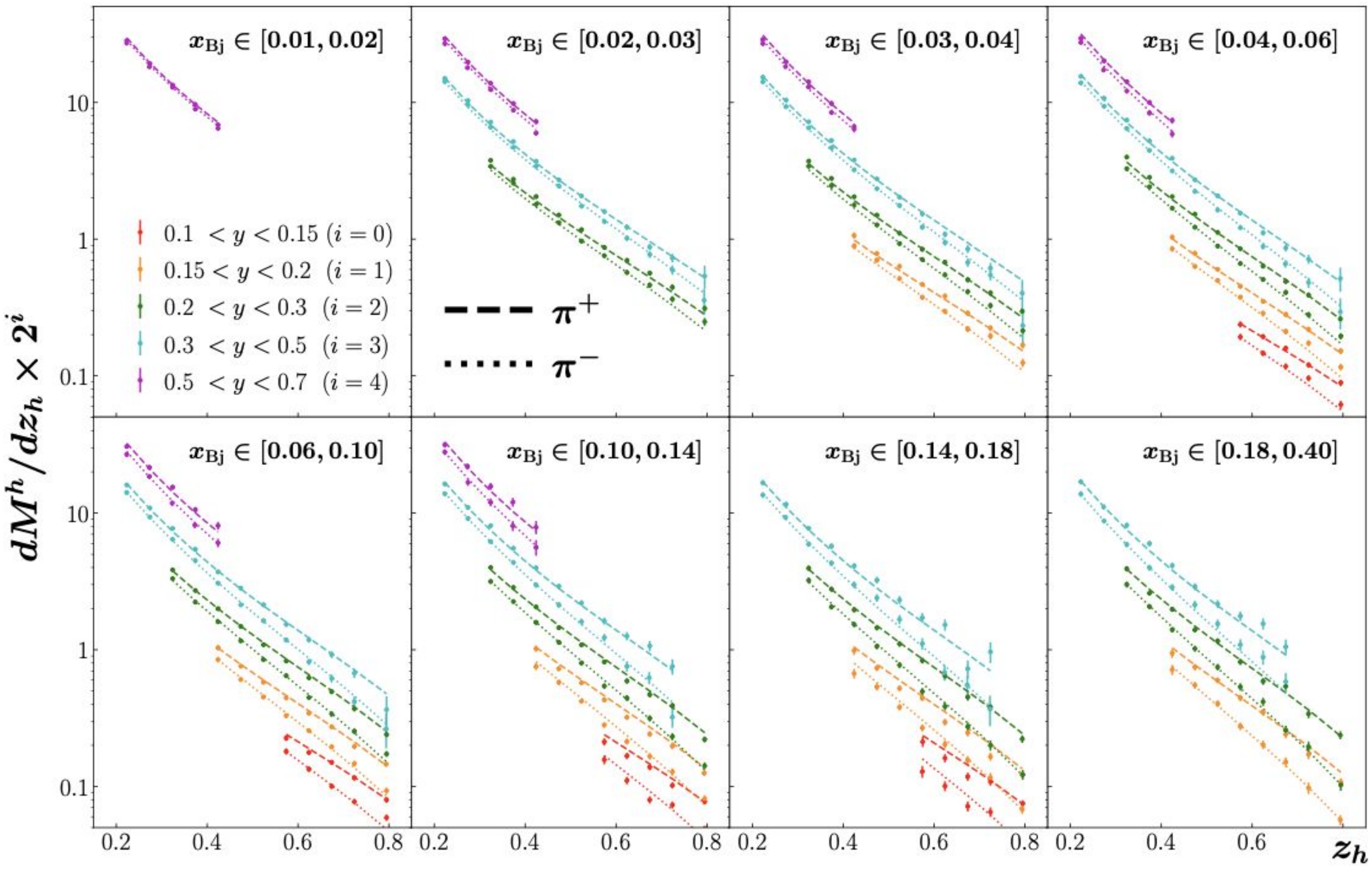
reaction		χ^2_{red}	N_{dat}
DIS		1.29	2680
DY		1.52	250
SIDIS	$\pi^\pm$	1.39	498
	$K^\pm$	1.38	494
	$h^\pm$	0.85	498
SIA	$\pi^\pm$	1.09	231
	$K^\pm$	1.37	213
	$h^\pm$	1.15	120
total		1.26	4984

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

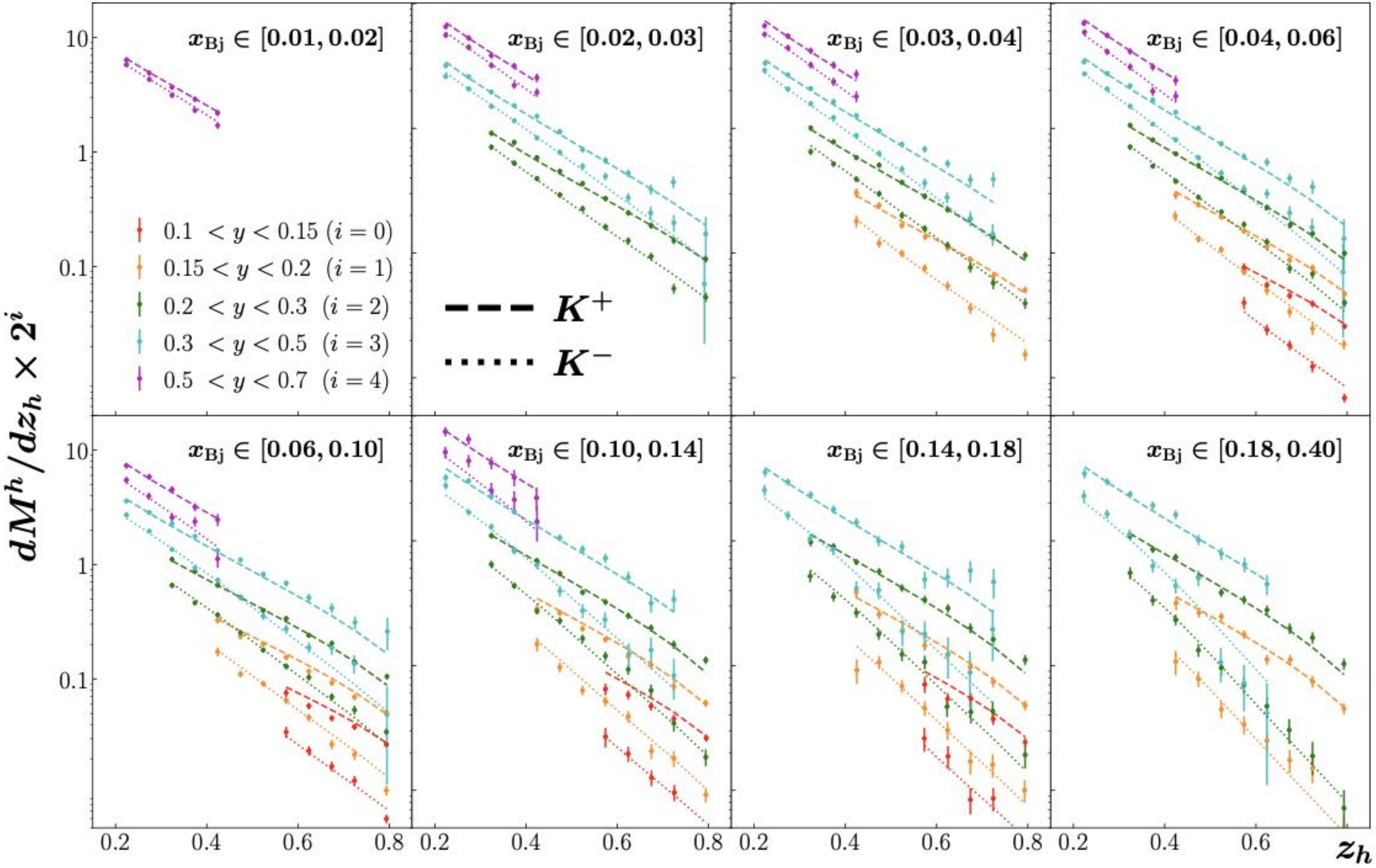
$$\text{residual}\,(e,i) = \frac{1}{\alpha_{i,e}}\left(d_{i,e} - \text{E}\Big[\sum_k r^k_e \beta^k_{i,e} + T_{i,e}/N_e\Big]\right)$$



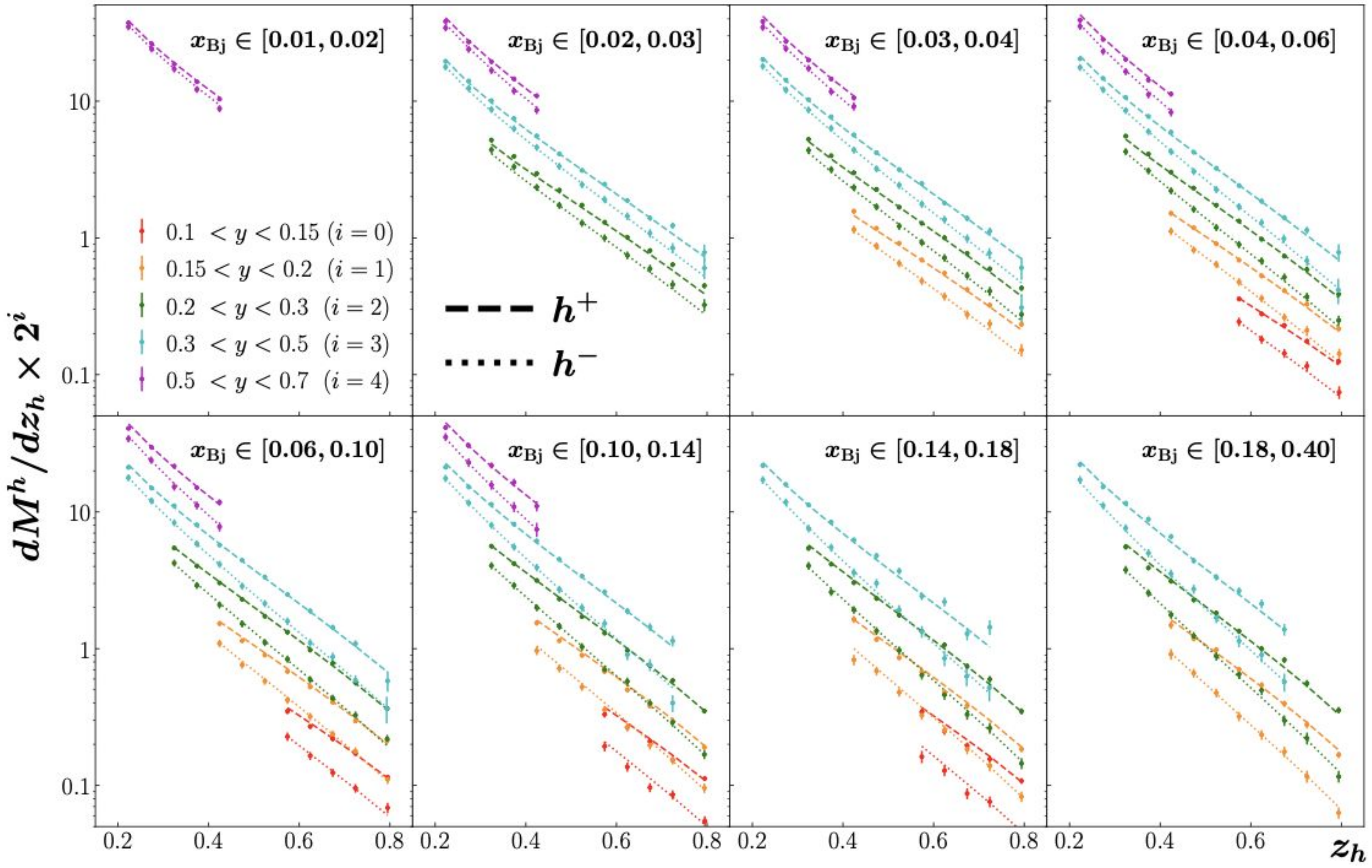
SIDIS Data and theory comparison: pions



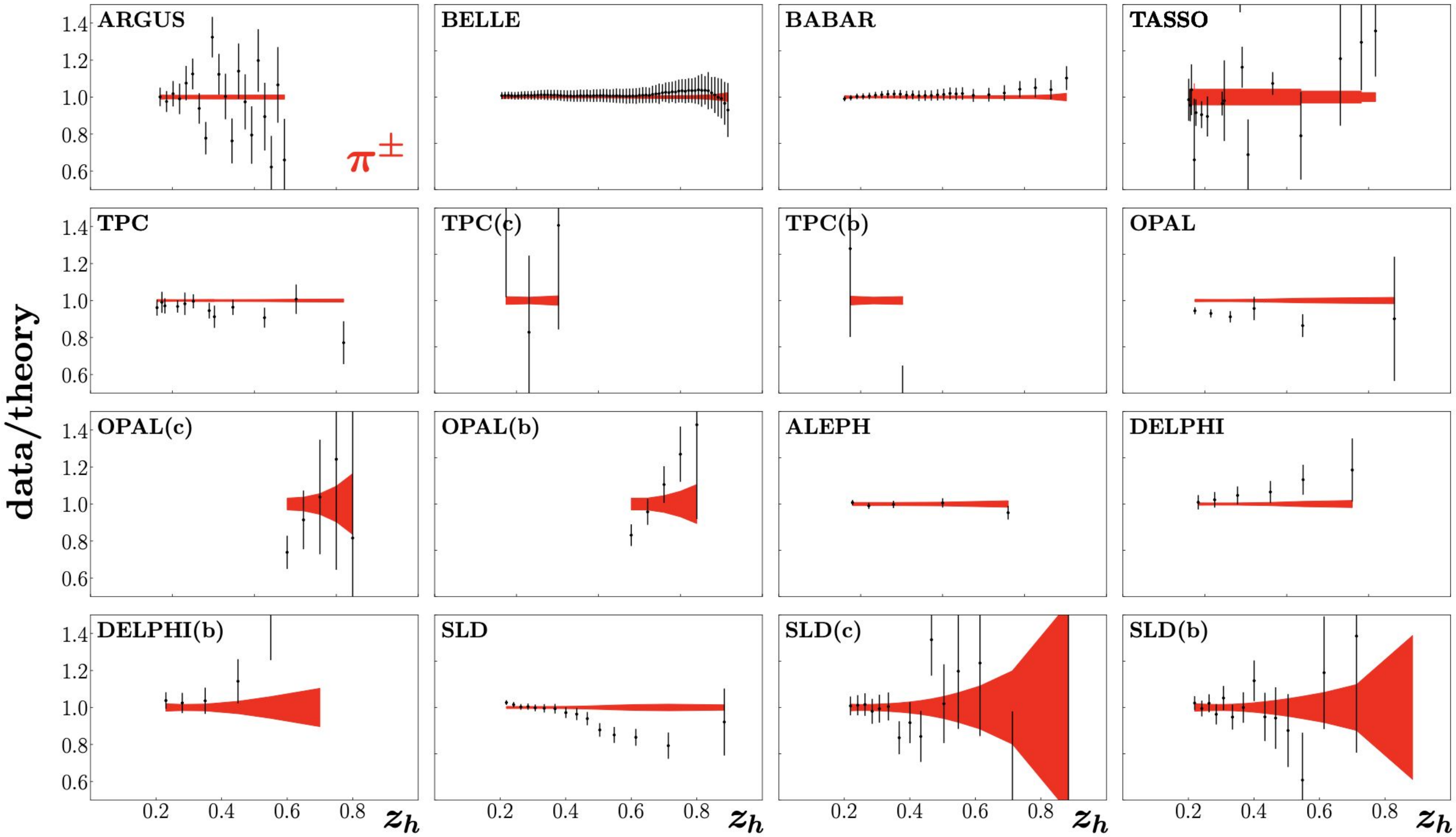
SIDIS Data and theory comparison: kaons



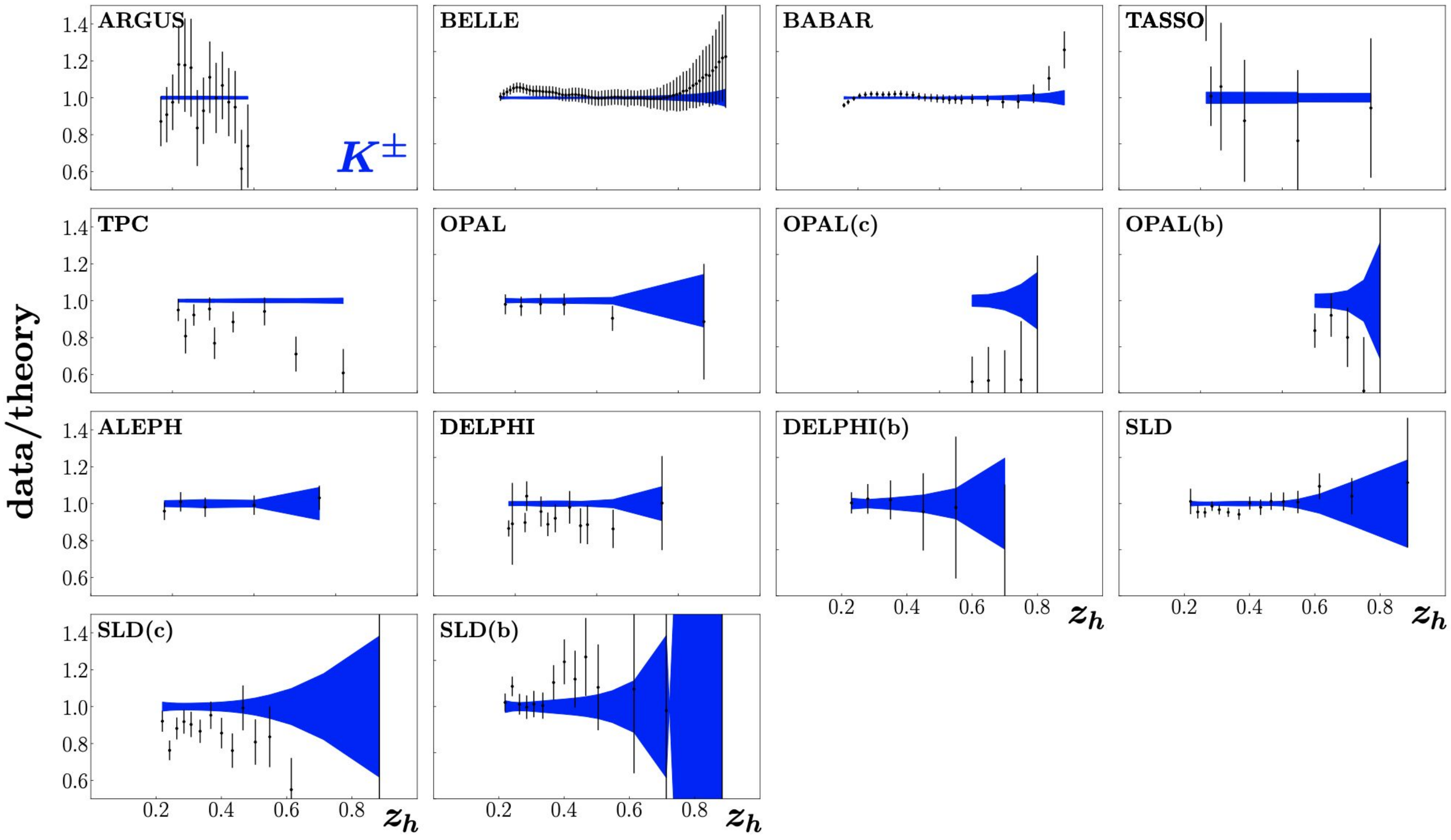
SIDIS Data and theory comparison: hadrons



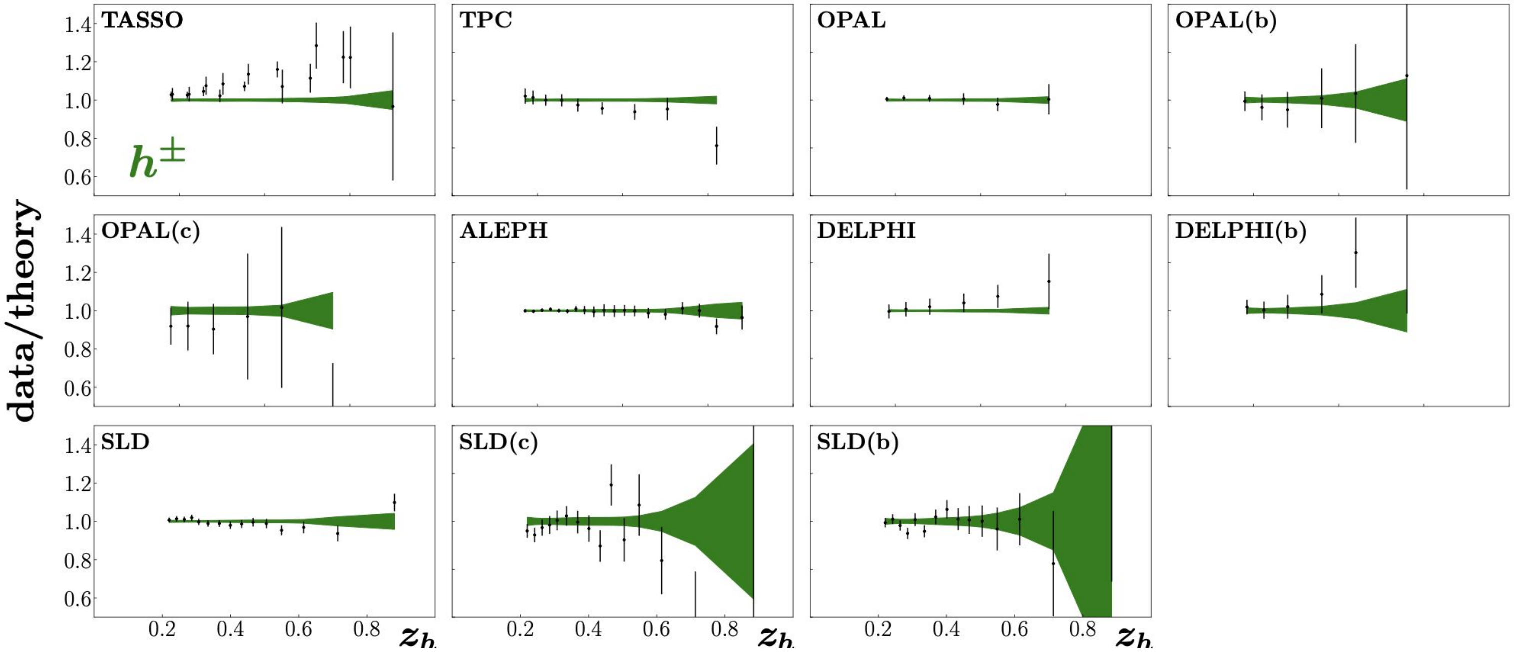
SIA Data over theory comparison: pions



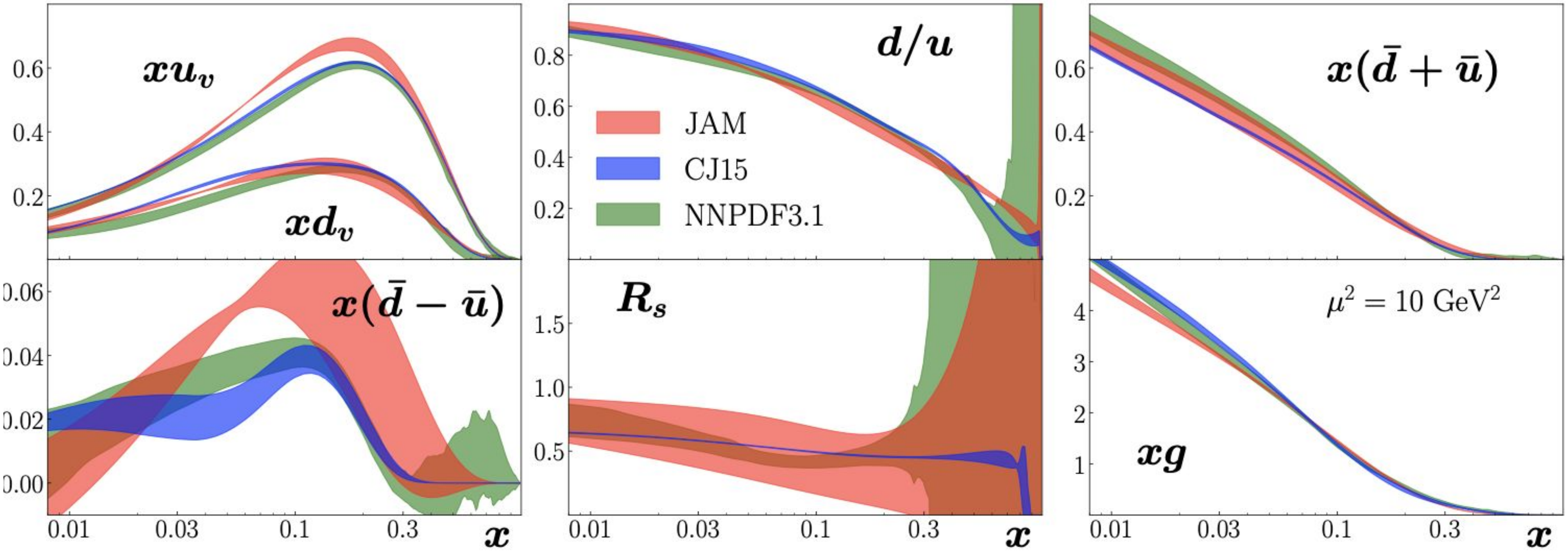
SIA Data over theory comparison: kaons



SIA Data over theory comparison: hadrons

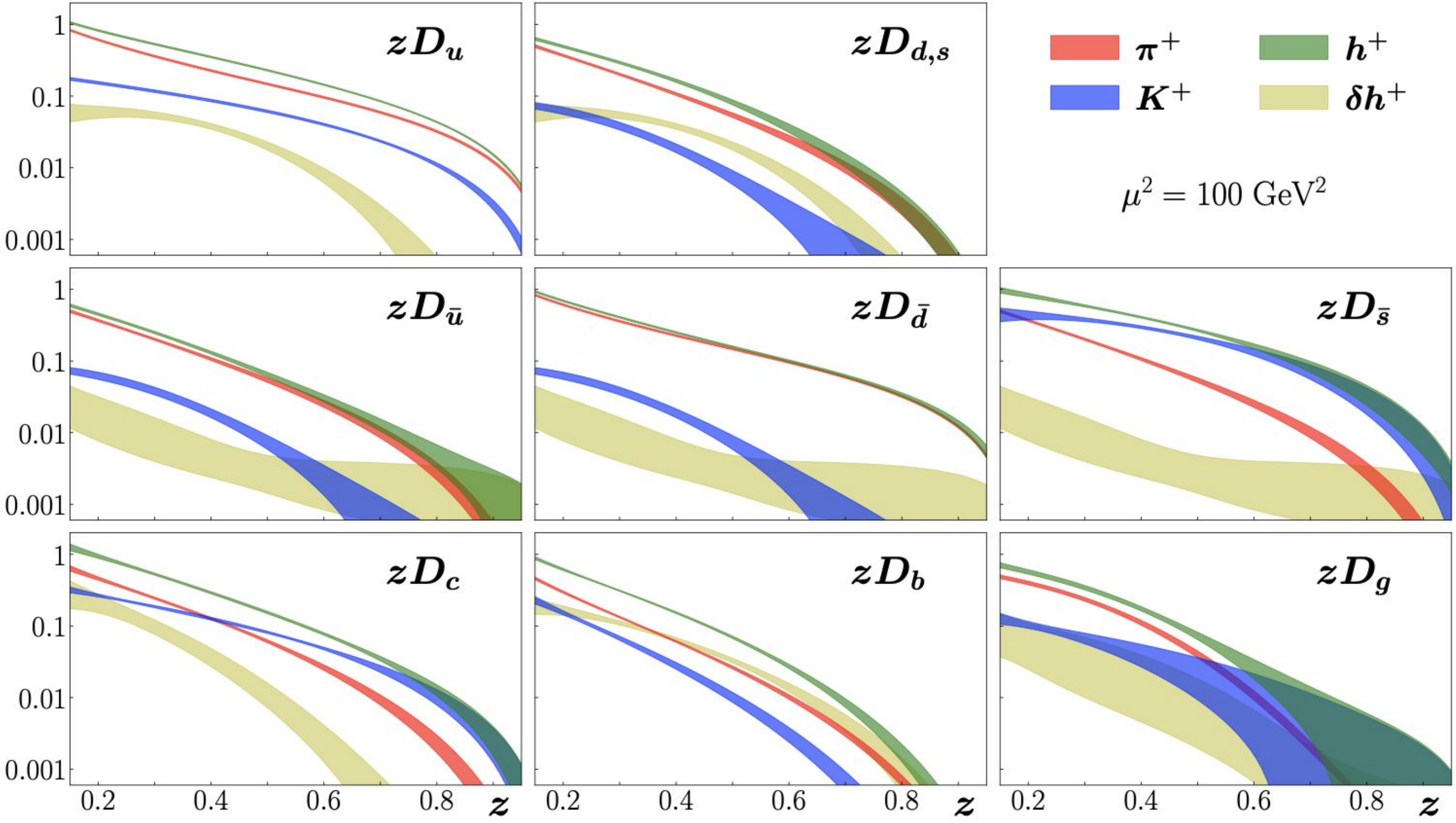


PDFs



xu_v
xd_v
d/u
JAM
CJ15
NNPDF3.1
$x(\bar{d}+\bar{u})$
$x(\bar{d}-\bar{u})$
R_s
xg
$\mu^2 = 10$ GeV^2
0.6
0.4
0.2
0.8
0.06
0.04
0.02
0.00
1.5
1.0
0.5
4
3
2
1
0.01
0.03
0.1
0.3
x

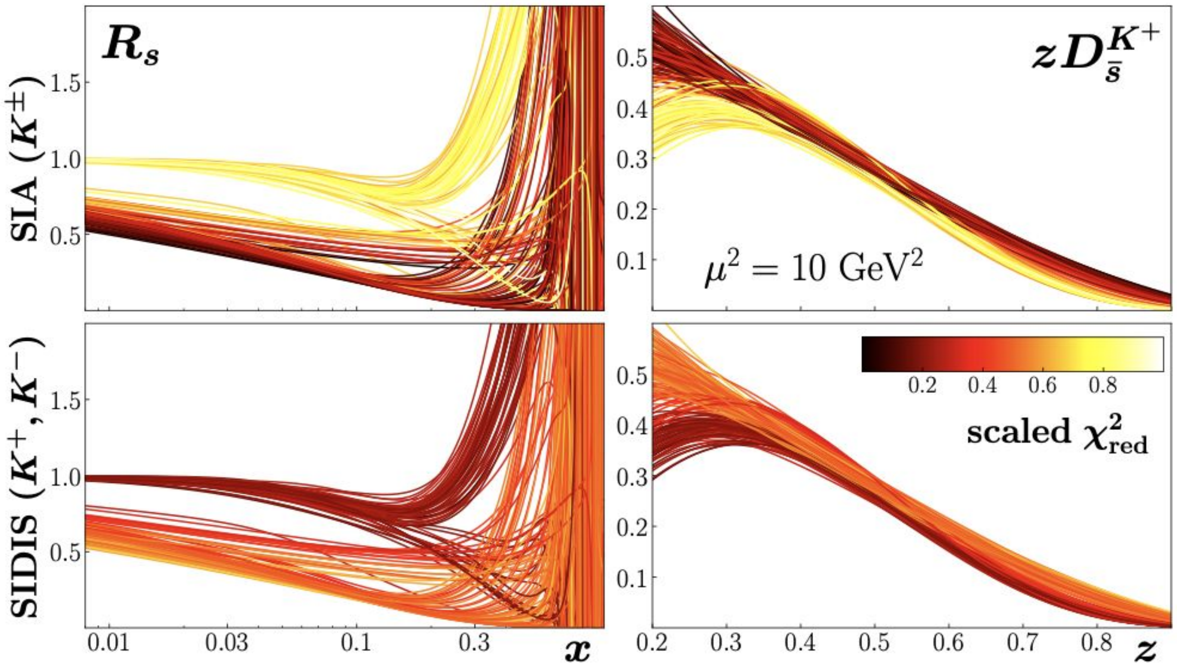
FFs



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

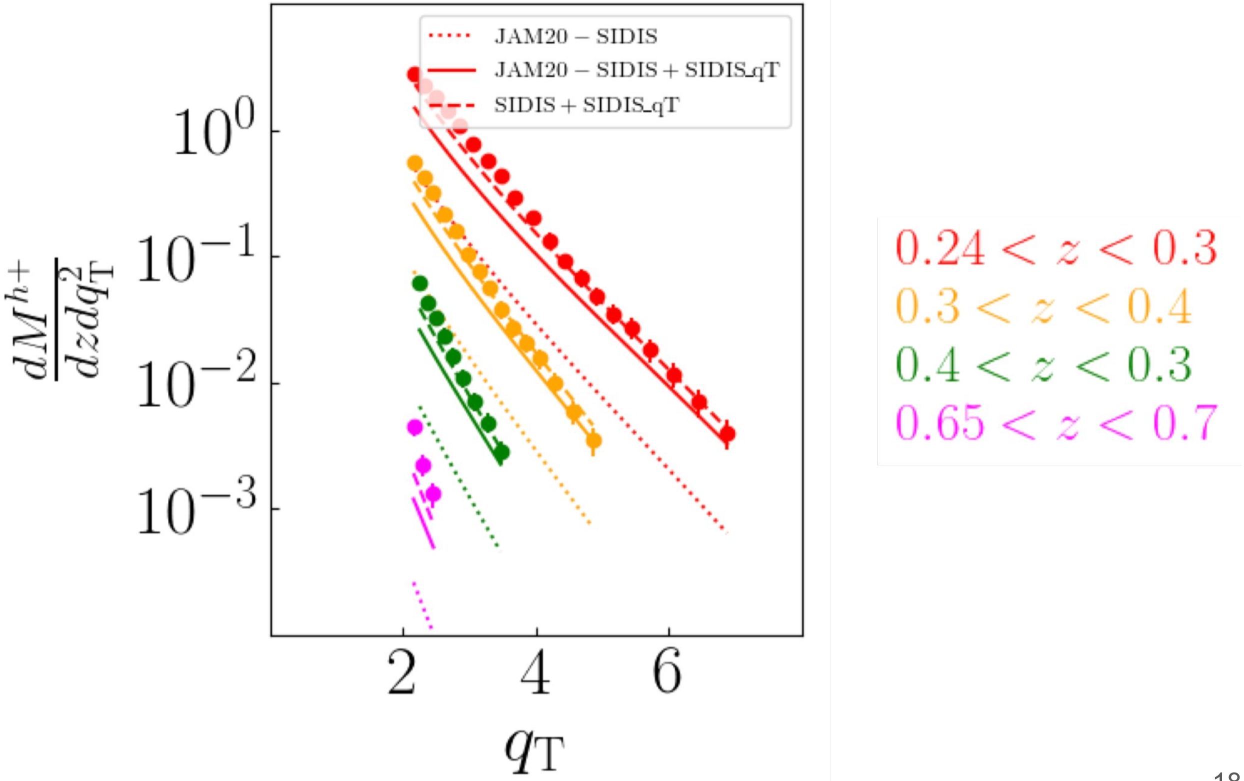
Strange PDF suppression

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



Transverse momentum dependent SIDIS predictions

- FO predictions for large transverse momentum SIDIS
- Discrepancy between FO predictions and data can be reduced significantly by including the transverse momentum dependent data in the fit.



Conclusions

- Successfully performed simultaneous global extraction of PDFs and pion, kaon, and hadron FFs.
- Observed similar strange PDF suppression as was observed in JAM19.
- Comparison of FO predictions using these results to COMPASS transverse momentum dependent data shows there is still a large discrepancy
  - This discrepancy is reduced when transverse momentum dependent data is included in the fit.