Global analysis of parton densities and fragmentation functions

Carlota Andrés

Jefferson Lab

2018 JLab Users Group Meeting

Newport News, Virginia,

June 18-20, 2018

Jefferson Lab Angular Momentum Collaboration

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Why JAM?

JAM: Jefferson Lab Angular Momentum Collaboration

- To study the quark and gluon structure of the nucleon by performing global fits of both spin-dependent (ΔPDFs) and unpolarized parton distribution functions (**PDFs**)

How?

- Analyzing the impact of JLab in a rigorous way
- JLab DIS data: large x_b, low-intermediate Q^2 and W^2
- Framework: (NLO) collinear factorization

  Higher twist (HT) and Target Mass Corrections (TMC) needed at large x_b

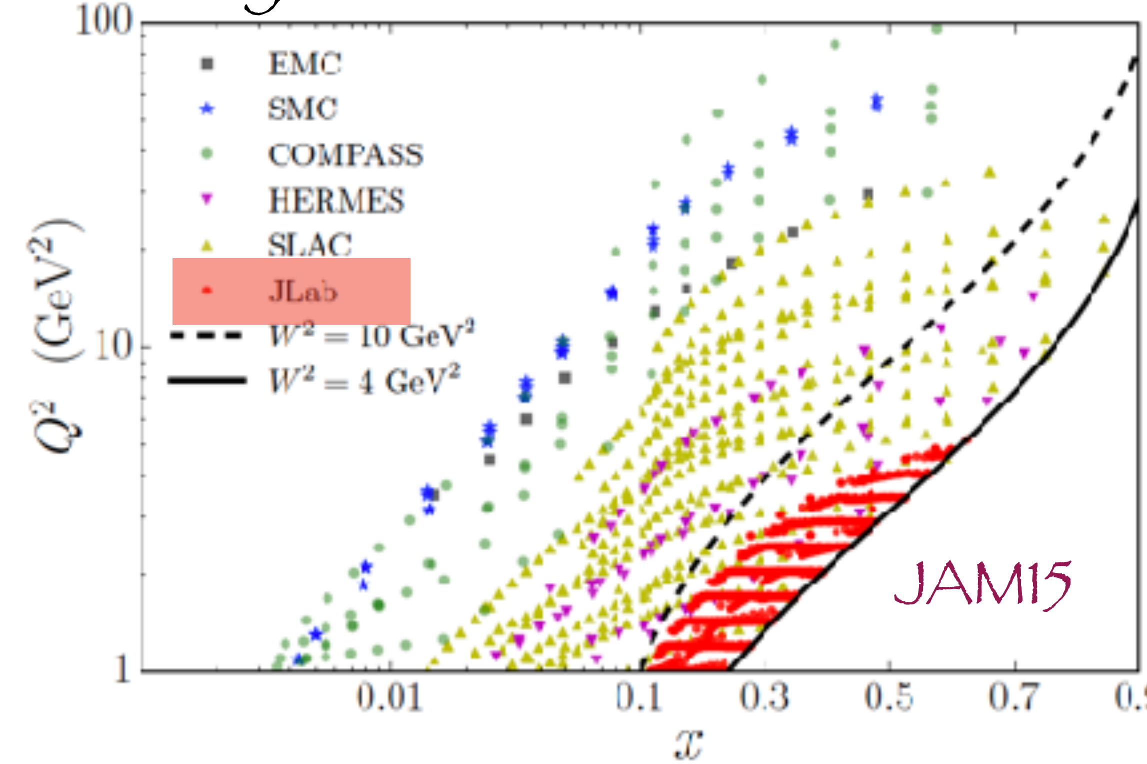
Evolution of JAM

Iterative MC fitting technique

		JAM15	JAM16	JAM17	JAM18
Process	DIS	☑	☒	☑	☑
	SIA	☒	☑	☑	☑
	SIDIS	☒	☒	☑	☑
	DY	☒	☒	☒	☑
Function	f	☒	☒	☒	☑
	Δf	☑	☒	☑	☑
	D_f^h	☒	☑	☑	☑

JAM15

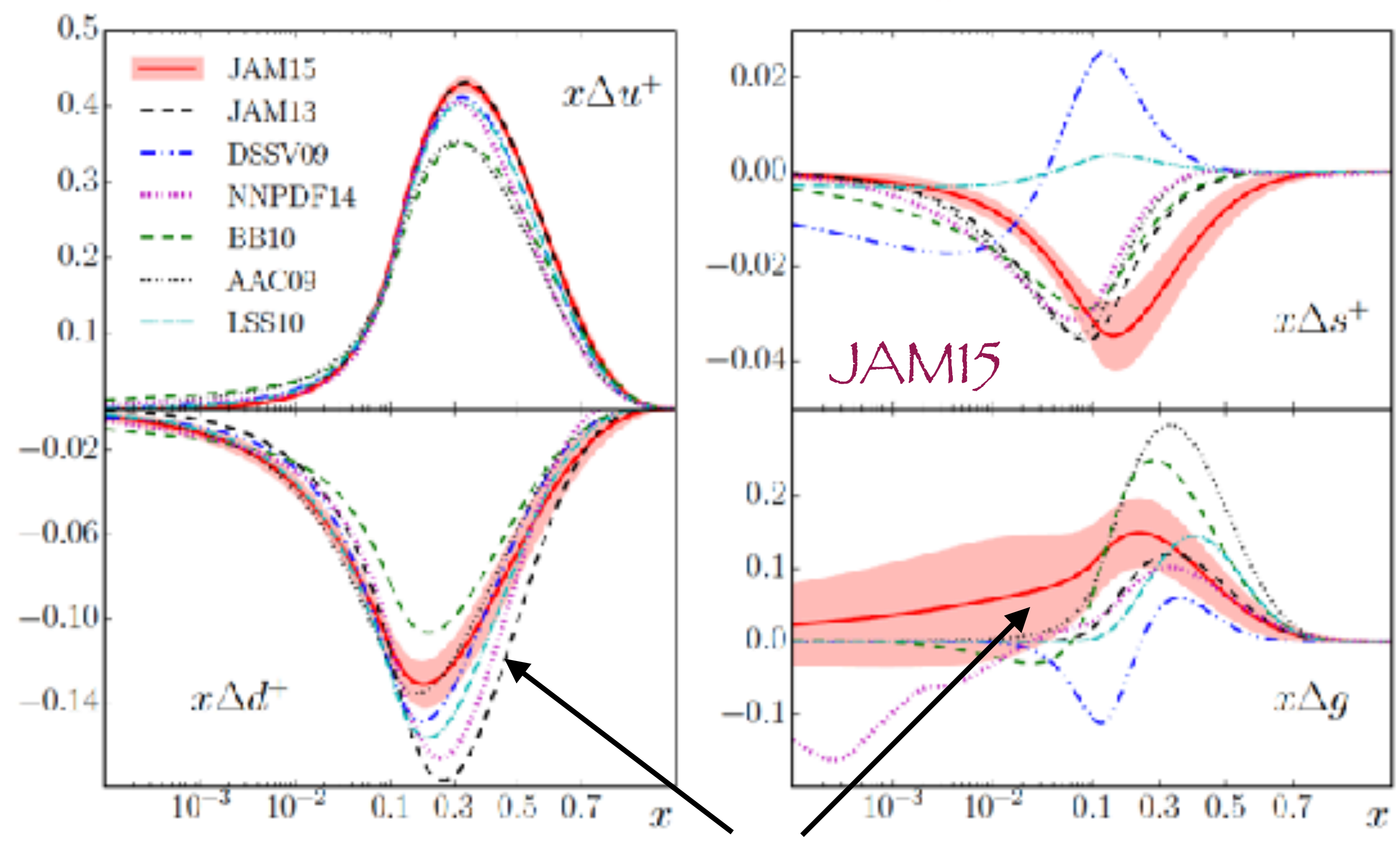
IMC analysis + all available JLab data



Uses CJ12 NLO unpolarized PDFs

- Δu^+ and Δd^+ consistent with previous analysis
- Δs^+ slightly harder

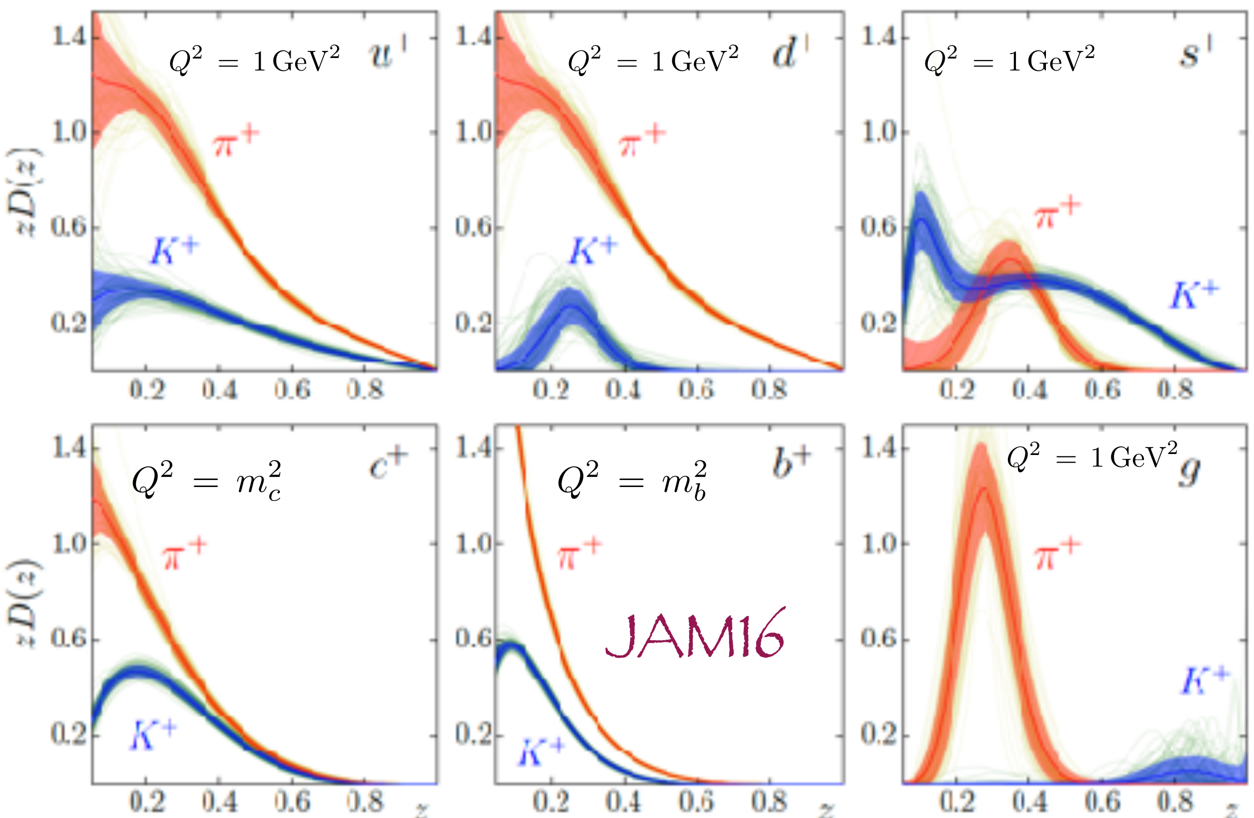
Sato, Melnitchouk, Kuhn, Ethier, Accardi
Phys. Rev. D 93, 074005 (2016)



Impact of JLab data

JAM16

- First IMC analysis of FFs
- Only SIA included



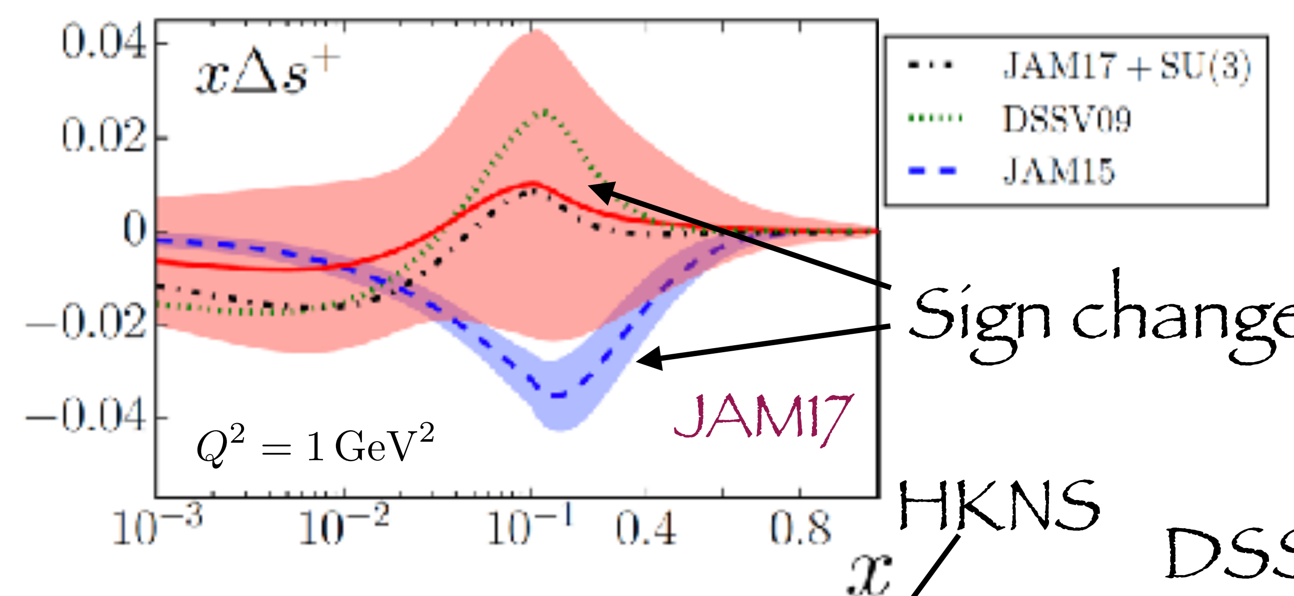
Sato,Ethier,Melnitchouk, Hirai, Kumano and Accardi

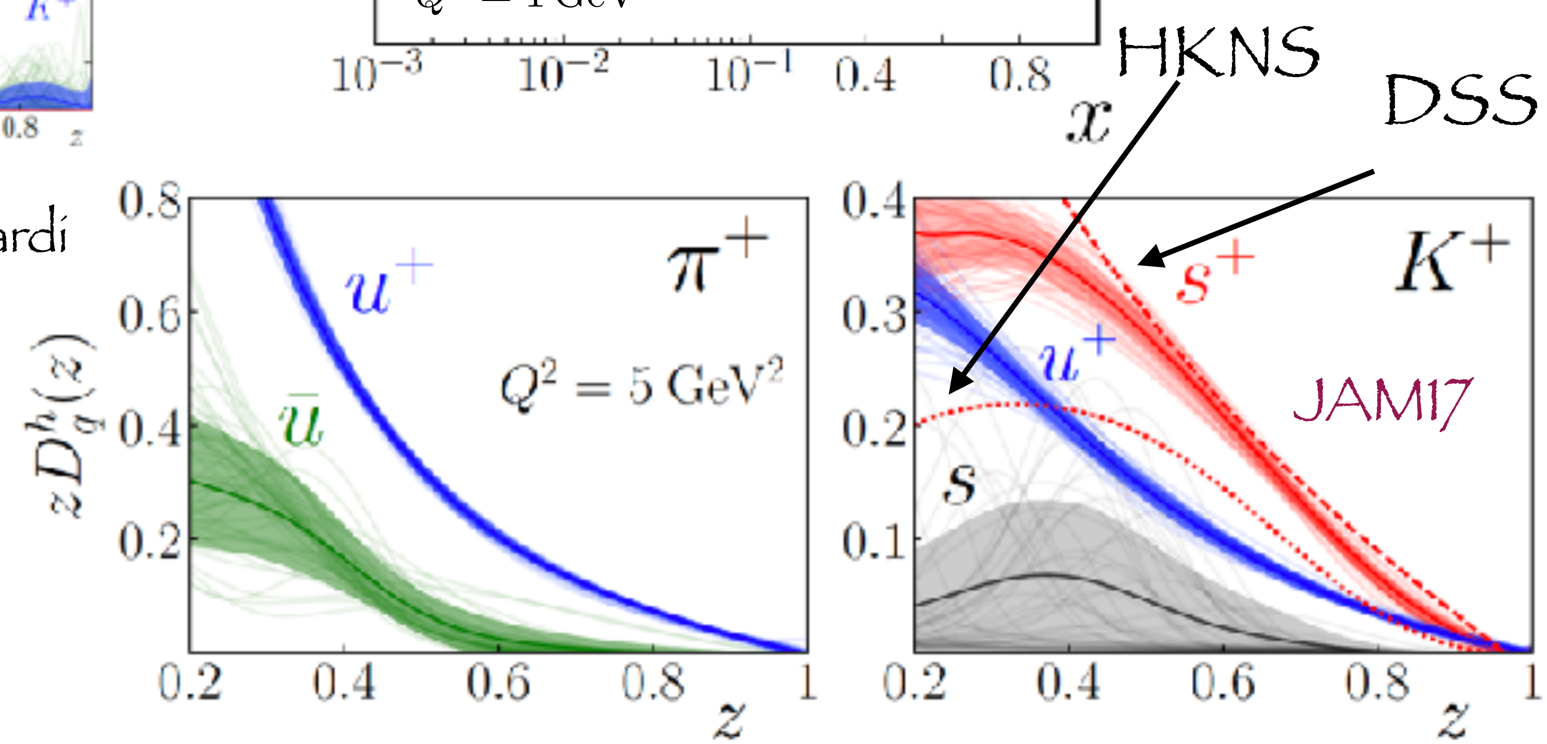
Phys. Rev. D 94, 114004 (2016)

JAM17 FFs better agreement with other analysis

JAM17

- First (simultaneous) MC analysis of polarized PDFs and FFs
- Polarized SIDIS, polarized DIS and SIA included





 Ethier, Sato, Melnitchouk: Phys. Rev. Lett. 119, 132001 (2017)

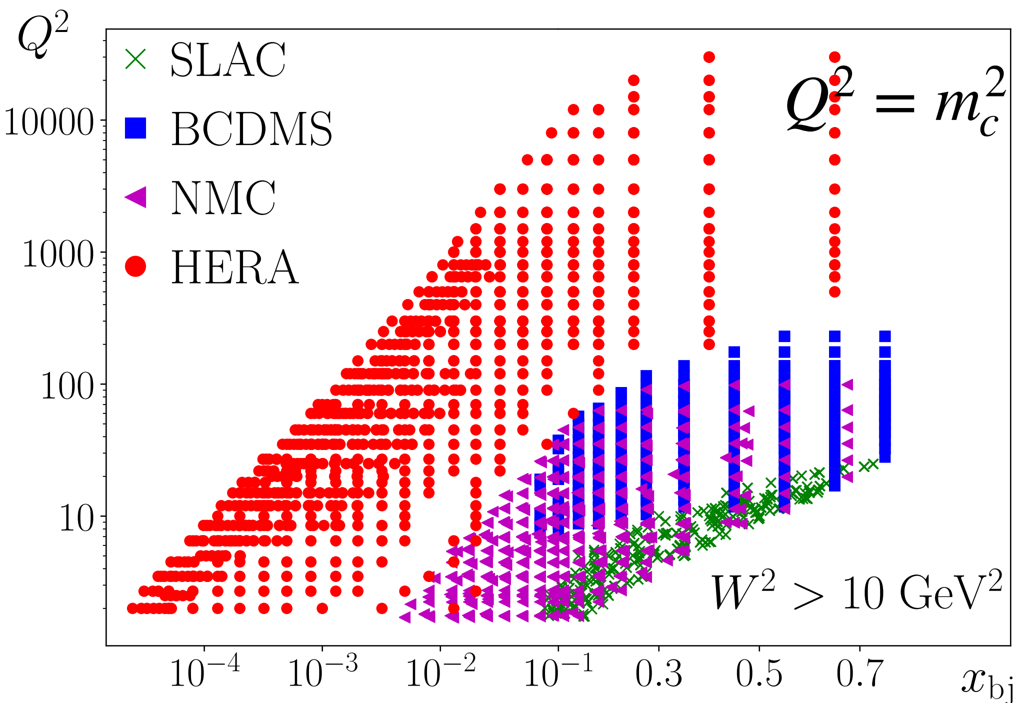
JAM18

Motivation

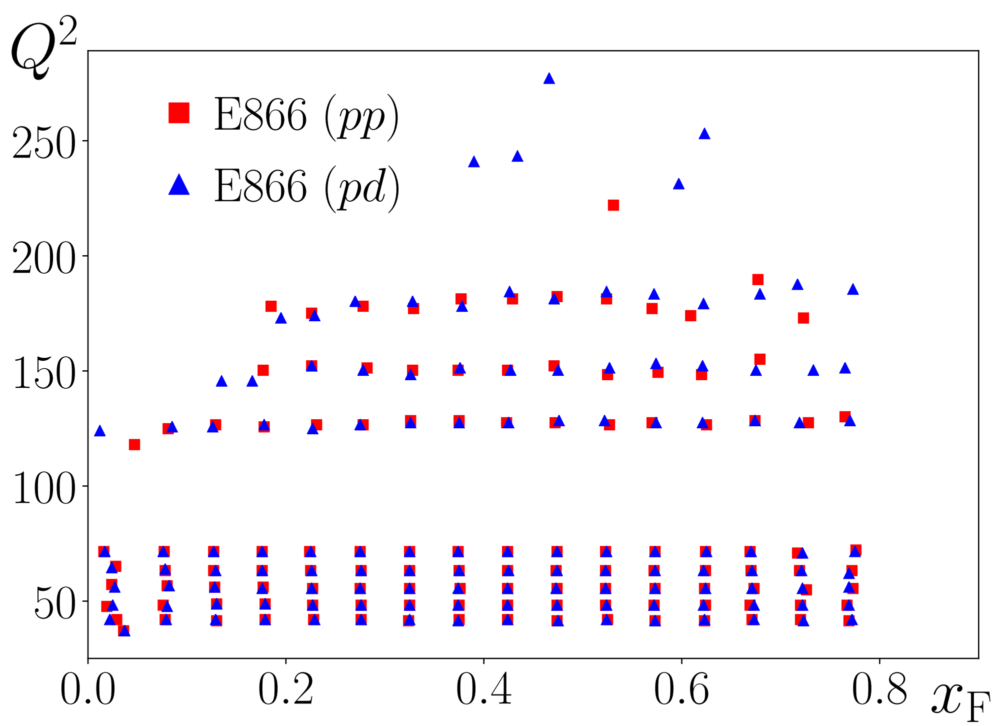
- Knowing the limits in x and Q^2 of collinear factorization
- Testing the universality of PDFs ,FFs…
- All the data must be studied using the same theoretical framework
- First step: (first) combined analysis of unpolarized PDFs and FFs

Setup: JAM18 data

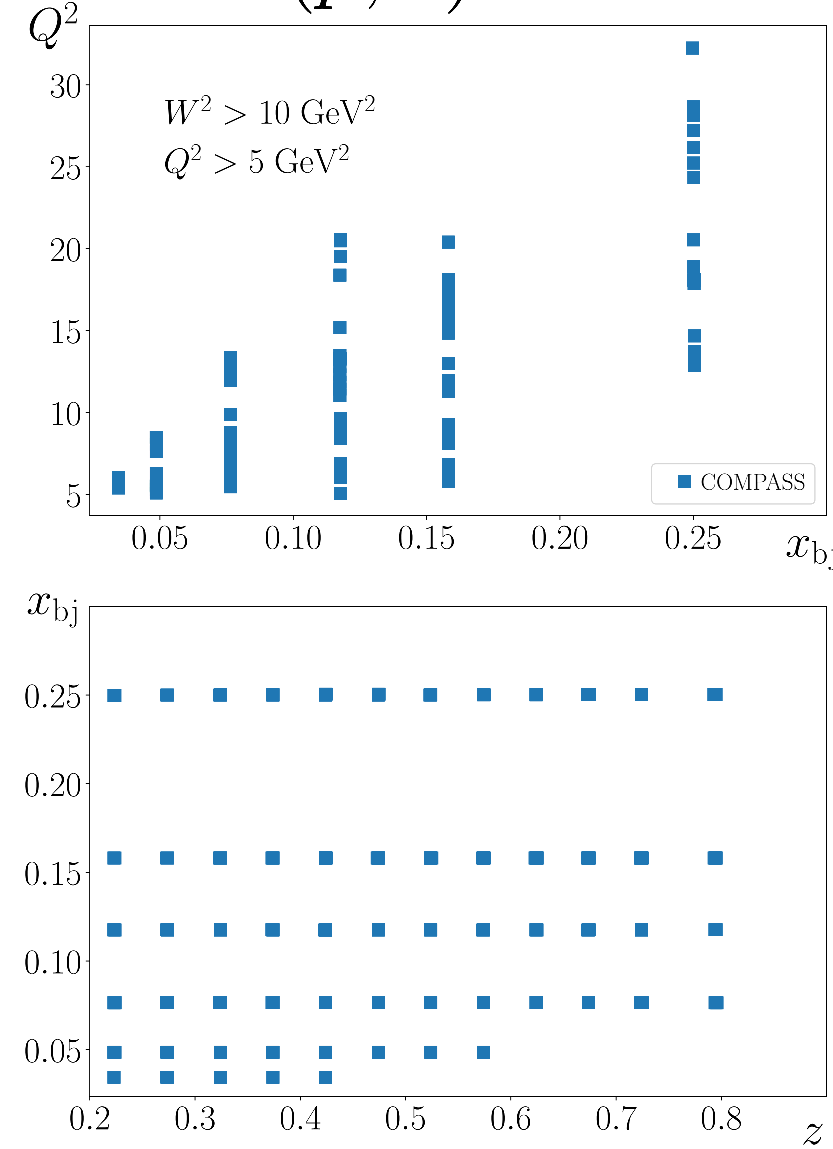
DIS : $l + (p,d) \to l' + X$



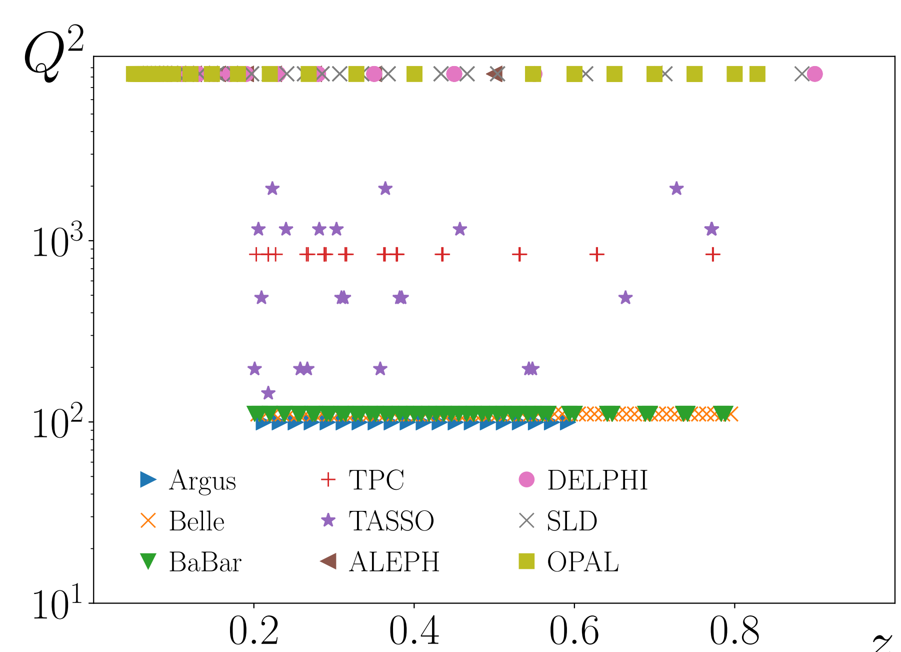
DY : $p + (p,d) \to l\bar{l} + X$



SIDIS : $l + (p,d) \to l' + h + X$



SIA : $e^+ + e^- \to h + X$



Setup: theory

- All observables computed at NLO in pQCD
- DGLAP truncated evolution at order α_s in Mellin space
- DIS cross sections computed at leading twist
- Nuclear smearing for deuterium DIS
- Heavy quark treatment : ZM-VFN
- Fitting methodology:
    - IMC based on Bayesian statistics
    - Future: Nested sampling

Why IMC?

$$\chi^2 = \sum_{e}^{N_{exp}} \sum_{i}^{N_{data}} \frac{(D_i^e - T_i)^2}{(\sigma_i^e)^2}$$

- Typical PDF parametrization:

$$x\Delta f(x) = N x^a (1-x)^b (1 + c\sqrt{x} + dx)$$ → Multiple local minima!

- Perform single χ^2 fit:

Parameters difficult to constrain

Hessian method for uncertainties → Introduces tolerance criteria

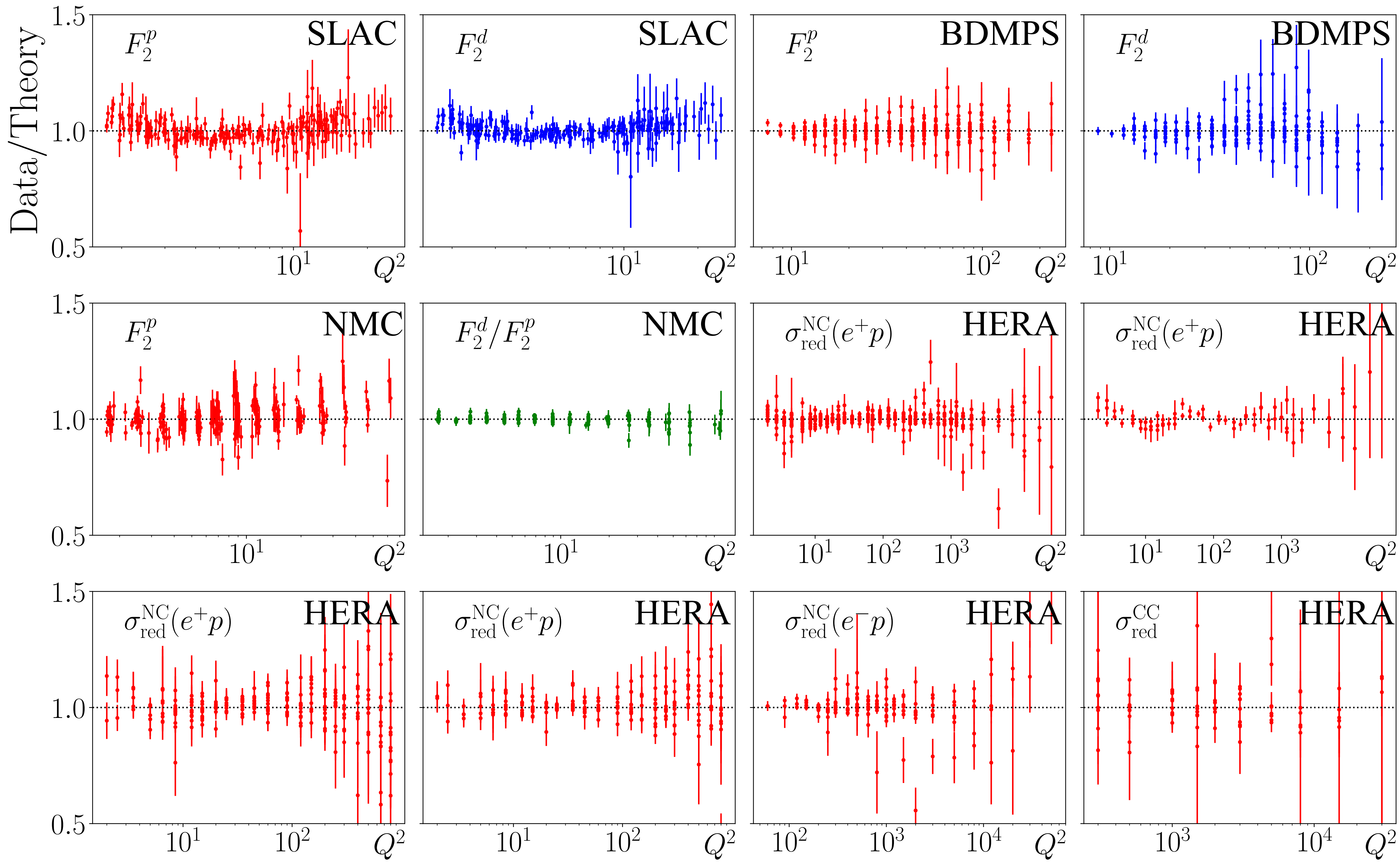
Unsuitable for simultaneous analysis of collinear distributions

- Monte Carlo methods:
  - Allows efficient exploration of the parameter space
  - Uncertainties directly obtained from MC replicas

JAM18 currently uses an IMC based on a Bayesian approach

Data vs. theory: DIS

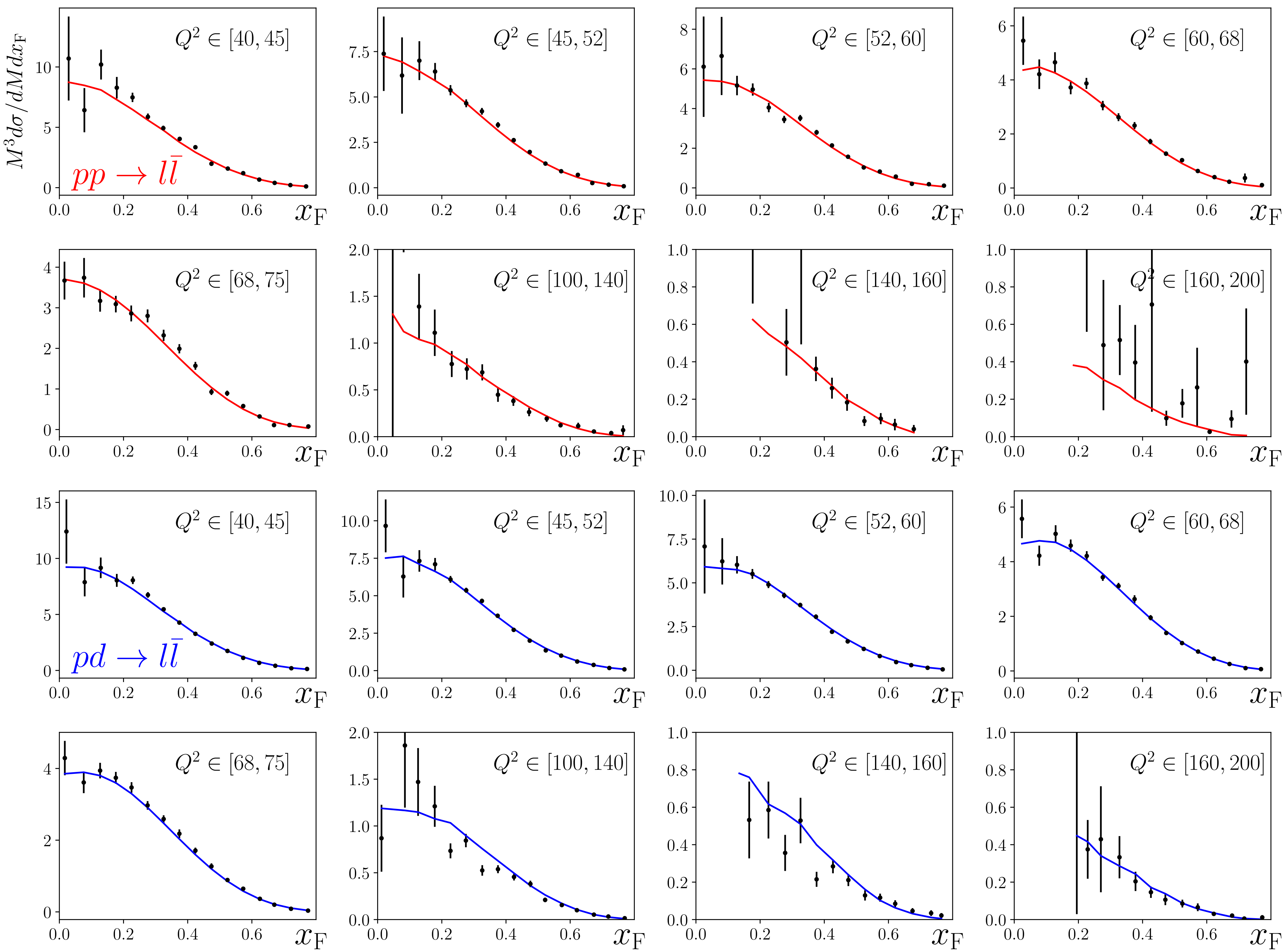
$$\text{DIS}: l + (p, d) \to l' + X$$



Data vs. theory: DY

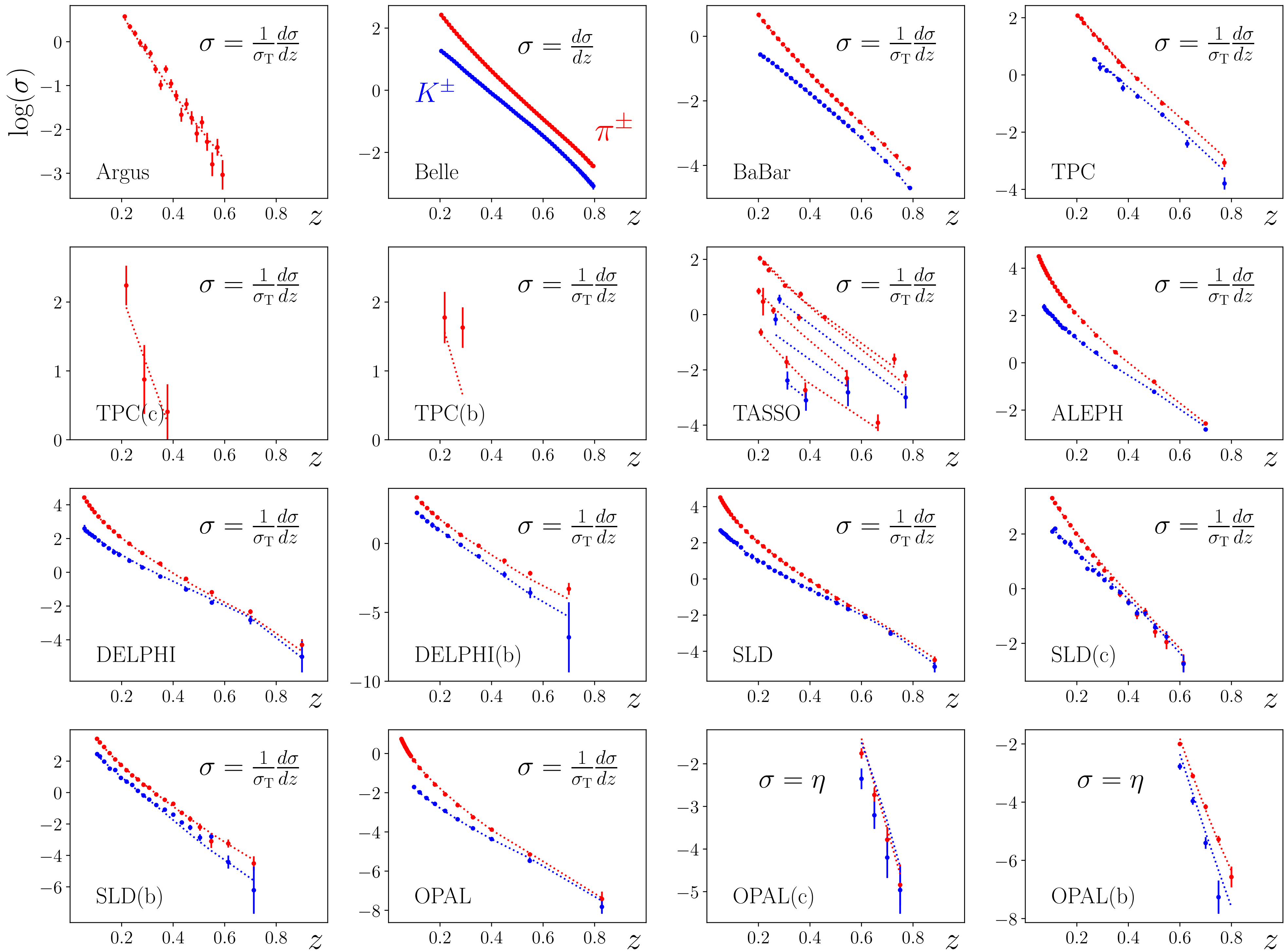
E866

$$\text{DY} : p + (p, d) \to l\bar{l} + X$$



Data vs. theory: SIA

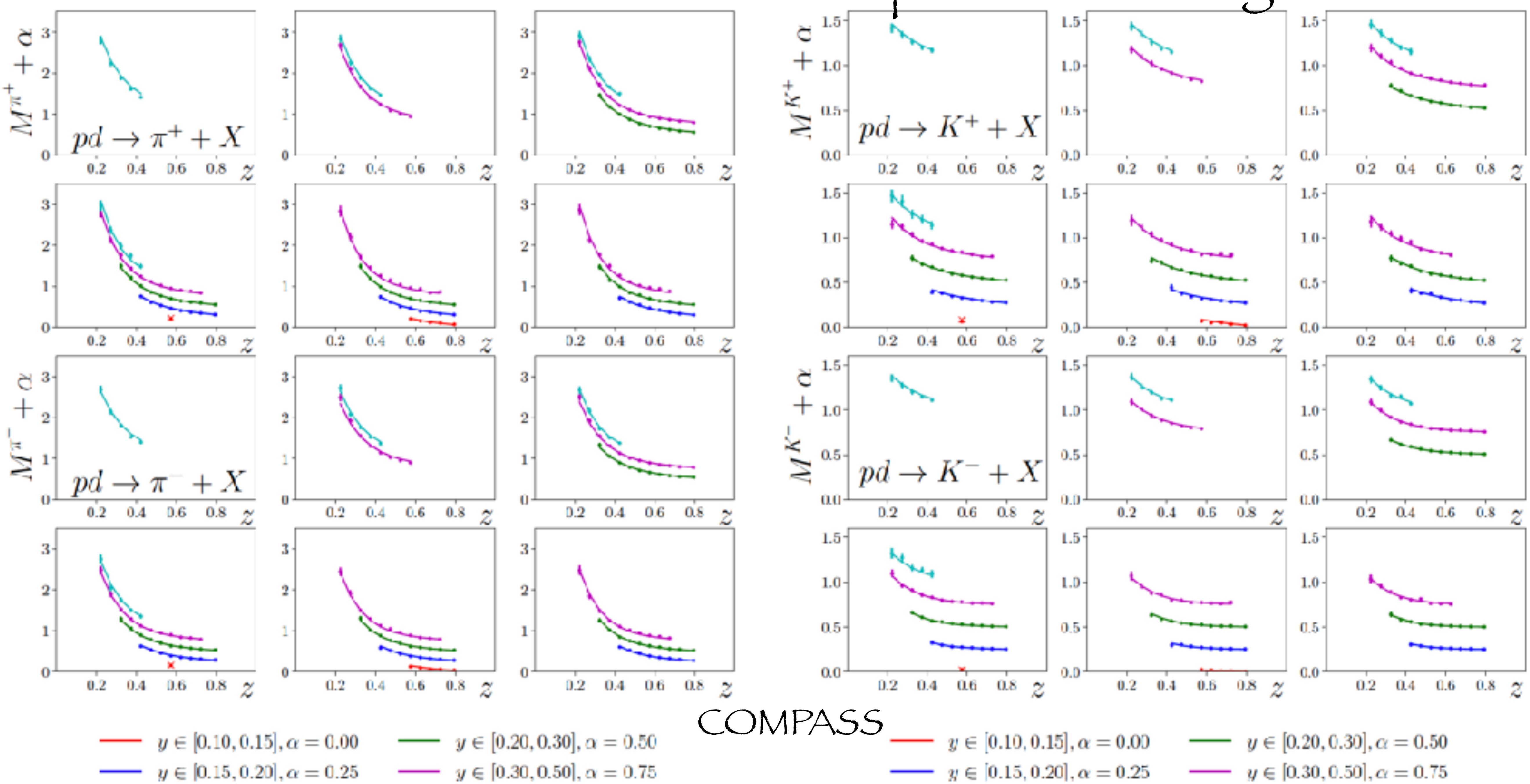
$$\mathrm{SIA} : e^+ + e^- \to h + X$$



Data vs. theory: SIDIS

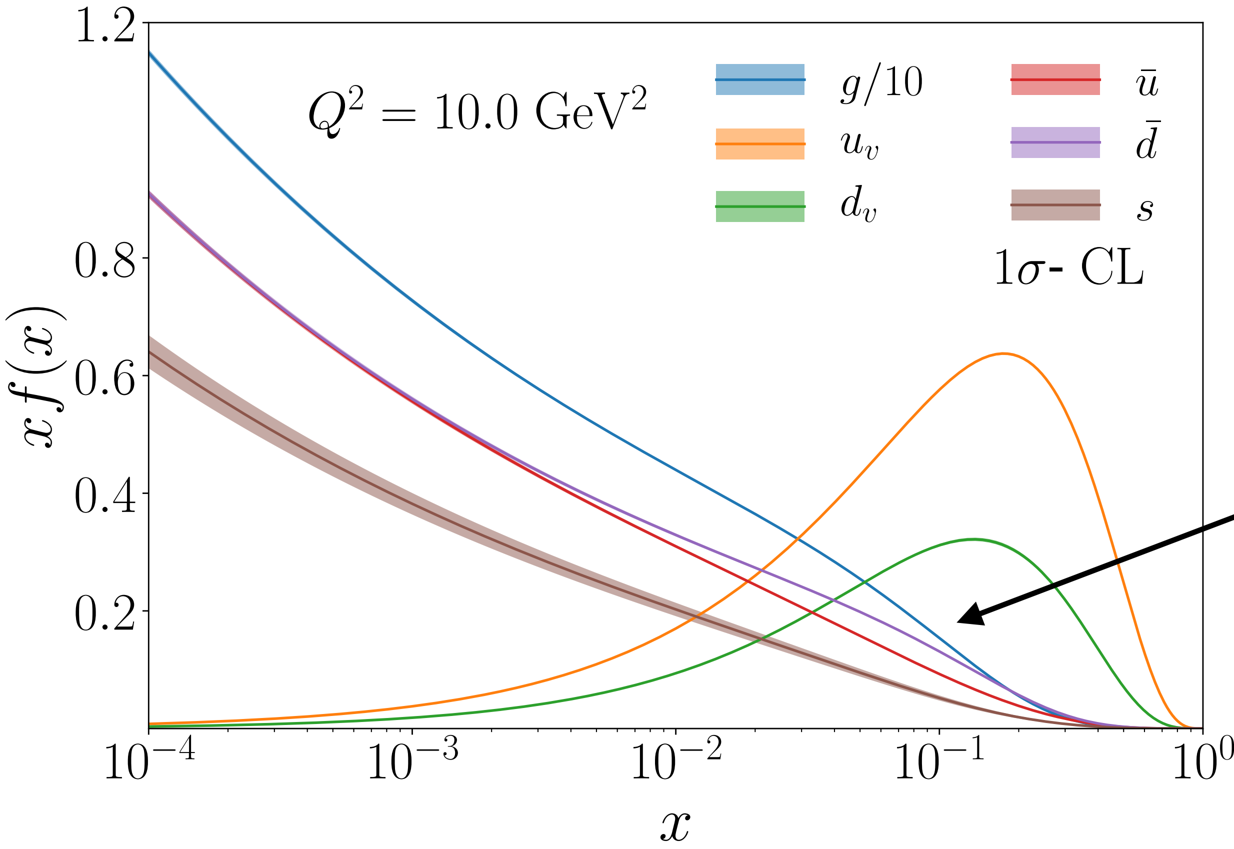
SIDIS : $l + p/d \to l' + h + X$

First time SIDIS data are included in unpolarized PDFs global fit!



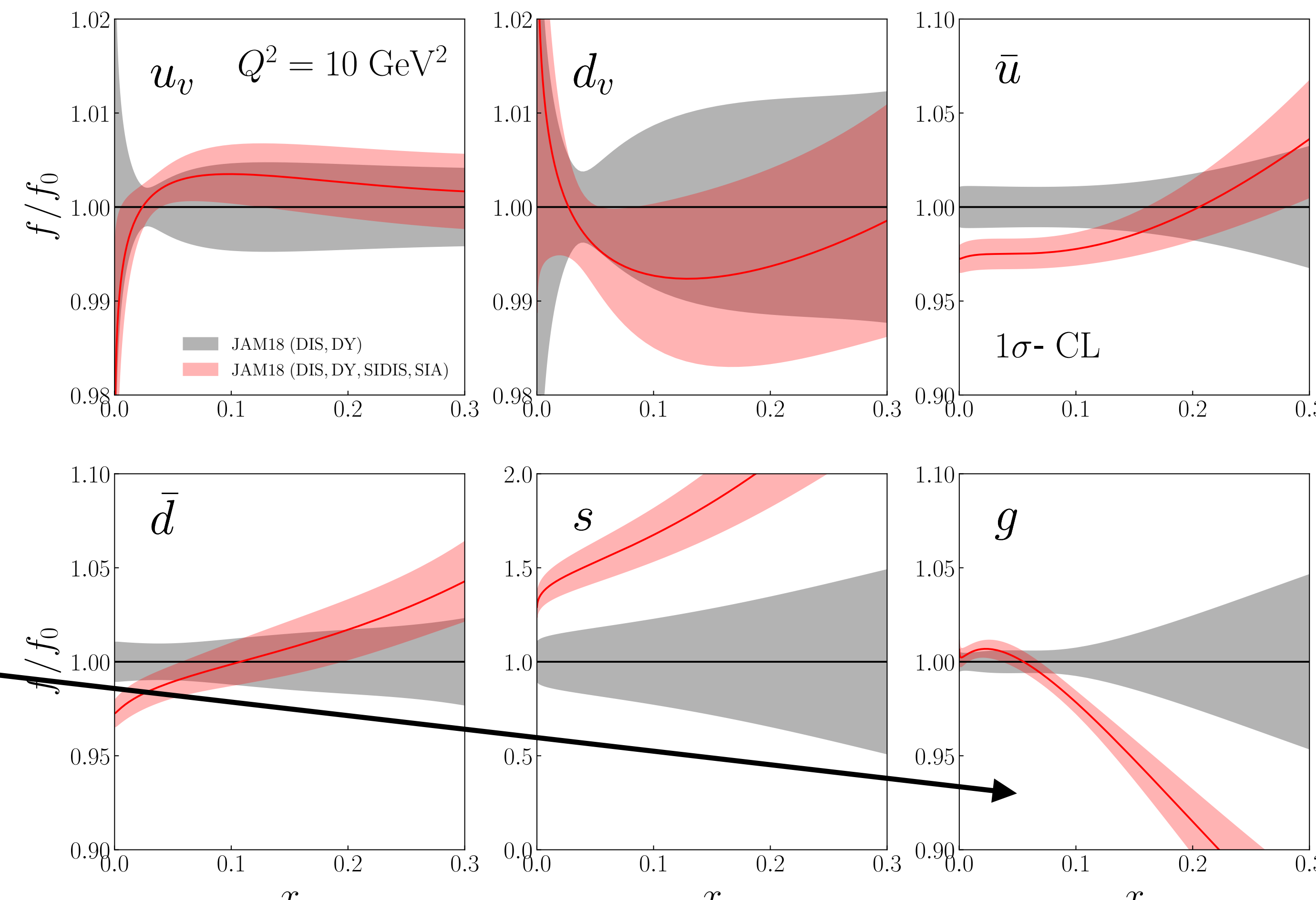
Difficult to fit low Q^2 data $\to$ only $Q^2 > 5$ GeV^2 data included

Unpolarized PDFs (preliminary)



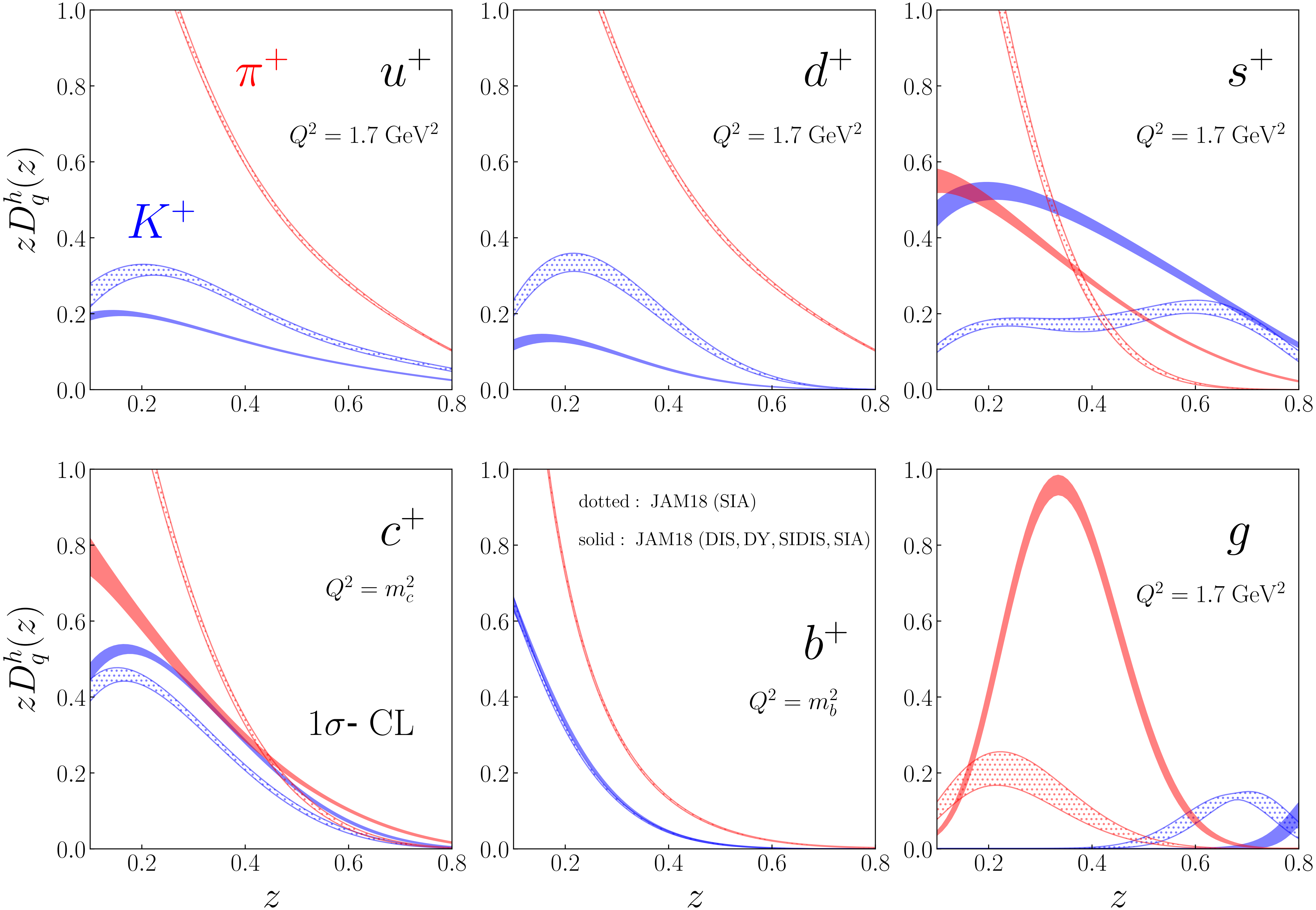
SIDIS supports the strange suppression

$\bar{u}-\bar{d}$ asymmetry at large x



The gluon distribution changes significantly with the inclusion of SIDIS

FFs (preliminary)



SIDIS data has large effect on flavor decomposition of FFs

Summary

- MC statistical methods are important for a robust extraction of non-perturbative collinear distributions

  → Crucial for future Global TMDs, GPDs analysis

- First (preliminary) MC fit of PDFs and FFs using DIS, SIDIS and SIA data

- Strange PDF constrained by SIDIS data

- Significant effect of SIDIS data on flavor decomposition of FFs

- Difficulties in incorporating low $Q^2 < 5\,\mathrm{GeV}^2$ SIDIS data

Outlook

- Impact pf SIDIS data on s vs. $\bar{s}$
- Introduce the HQ treatment: ACOT (GM-VFNS) ✓
- Use F_2^c and F_2^b HERA data GM-VFNS required!
- Likelihood sampling methods: Nested sampling ✓
- Inclusion of polarized DIS and SIDIS and extract

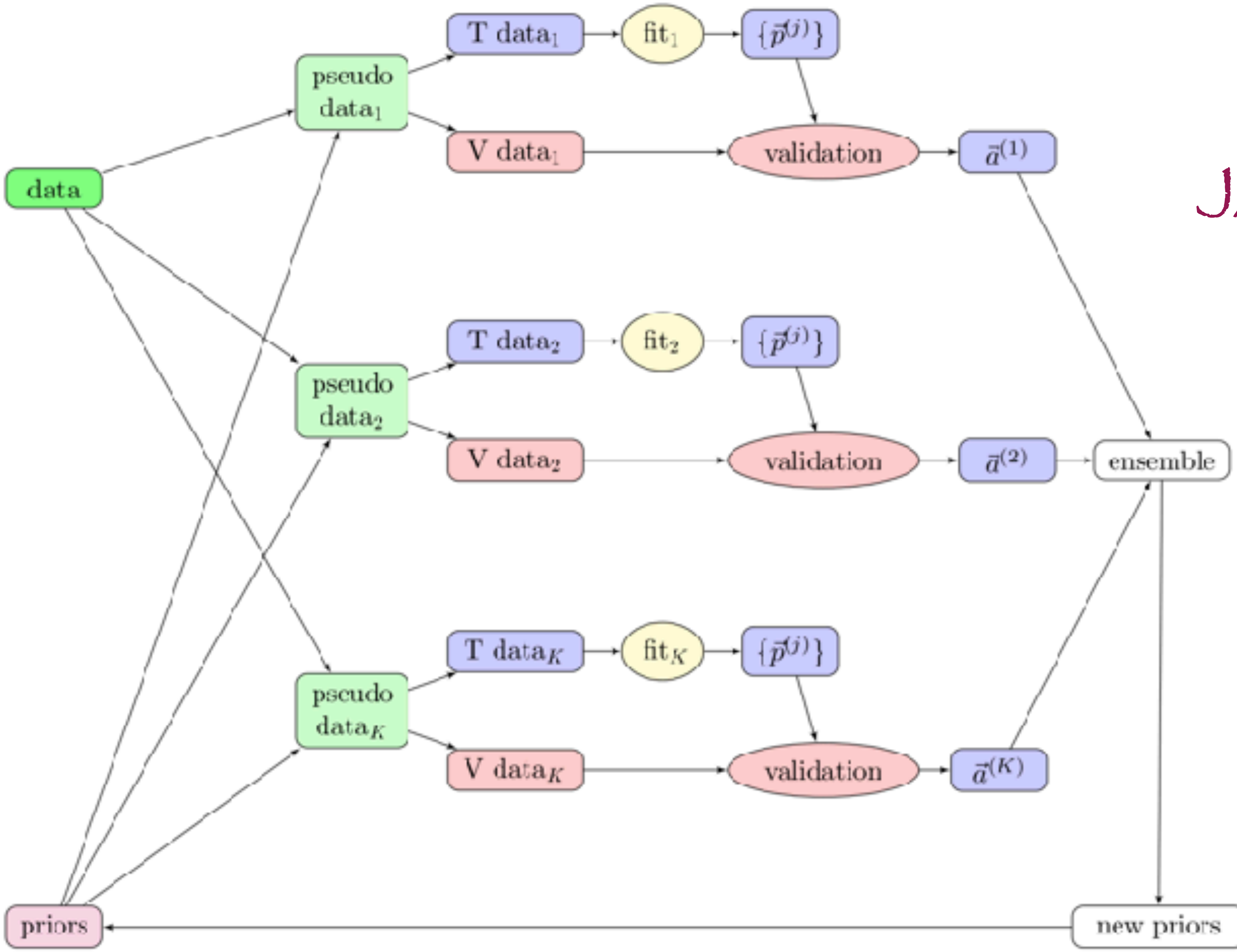
$$\text{PDFs, FFs, and } \Delta\text{PDFs}$$

→ Simultaneous extraction of all non-perturbative input

→ Strict test of universality

Backup

Iterative Monte Carlo (IMC)

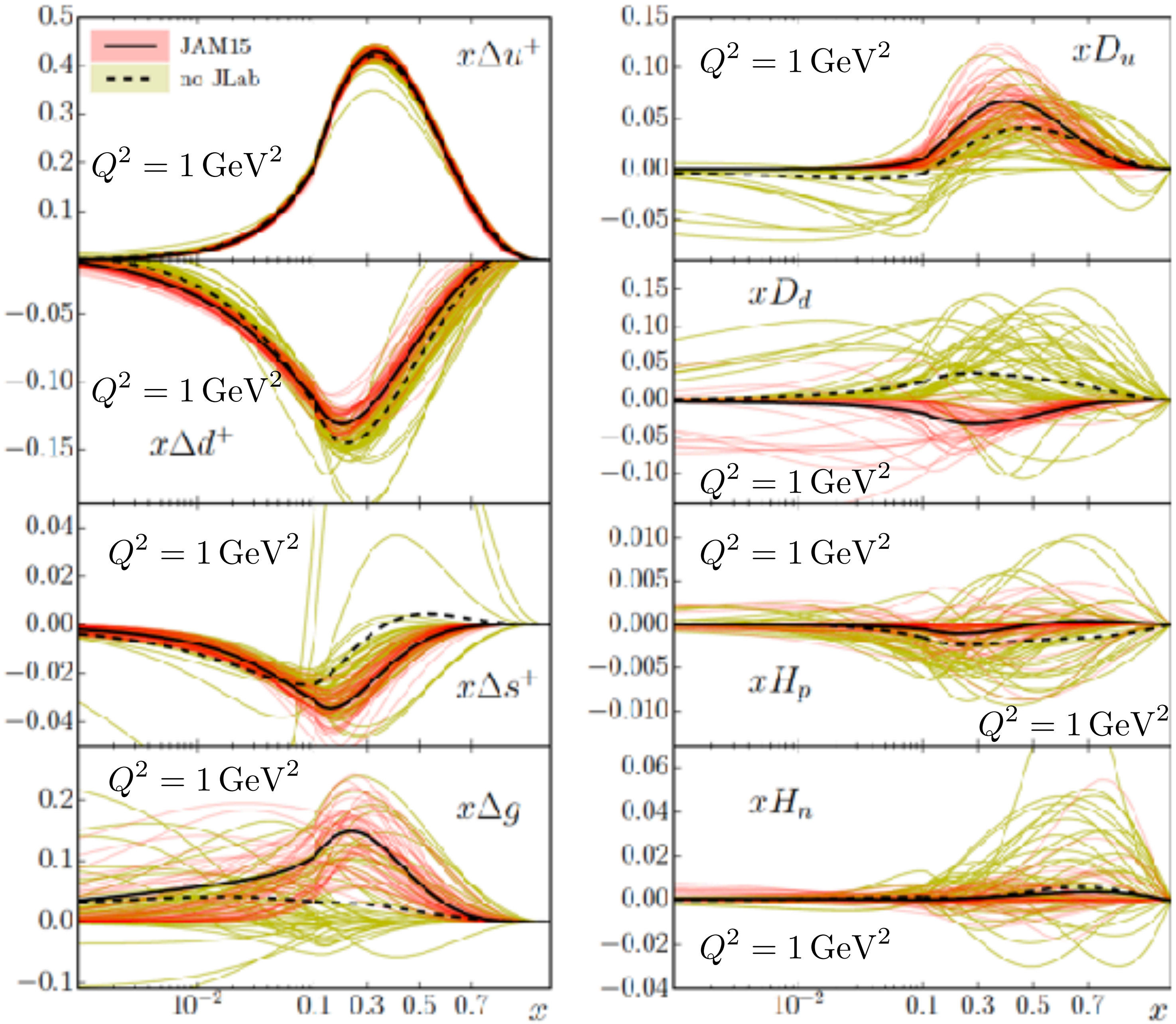


JAM15

FIG. 1. Schematic illustration of the workflow for the iterative Monte Carlo fitting method. In the first stage, K pseudodata sets are generated, each of which is partitioned into training (T) and validation (V) subsets. For each pseudodata set, the training set is fitted and the parameters $\{\vec{p}^{(j)}\}$ across all the minimization stages j are stored. The cross-validation procedure selects a single set of best-fit parameters $\vec{a}^{(l)}$ from $\{\vec{p}^{(j)}\}$ for each pseudodata set l, and the collection of $\{\vec{a}^{(l)}; l = 1, \ldots, K\}$ is then used as the priors for the next iteration.

JAM15

Impact of JLab data



$$g_1(x,Q^2) = g_1^{\mathrm{LT+TMC}}(\Delta u^+, \Delta d^+, \Delta g, ...) + g_1^{\mathrm{T3+TMC}}(D_u, D_d) + g_1^{\mathrm{T4}}(H_{p,n})$$

$$g_2(x,Q^2) = g_2^{\mathrm{LT+TMC}}(\Delta u^+, \Delta d^+, \Delta g, ...) + g_2^{\mathrm{T3+TMC}}(D_u, D_d)$$

Δu^+ Δd^+ :reduction of the uncertainties

Δd^+ less negative due to Jlab data

↓

Harder Δs^+

Δs^+ positive

Δg big uncertainty

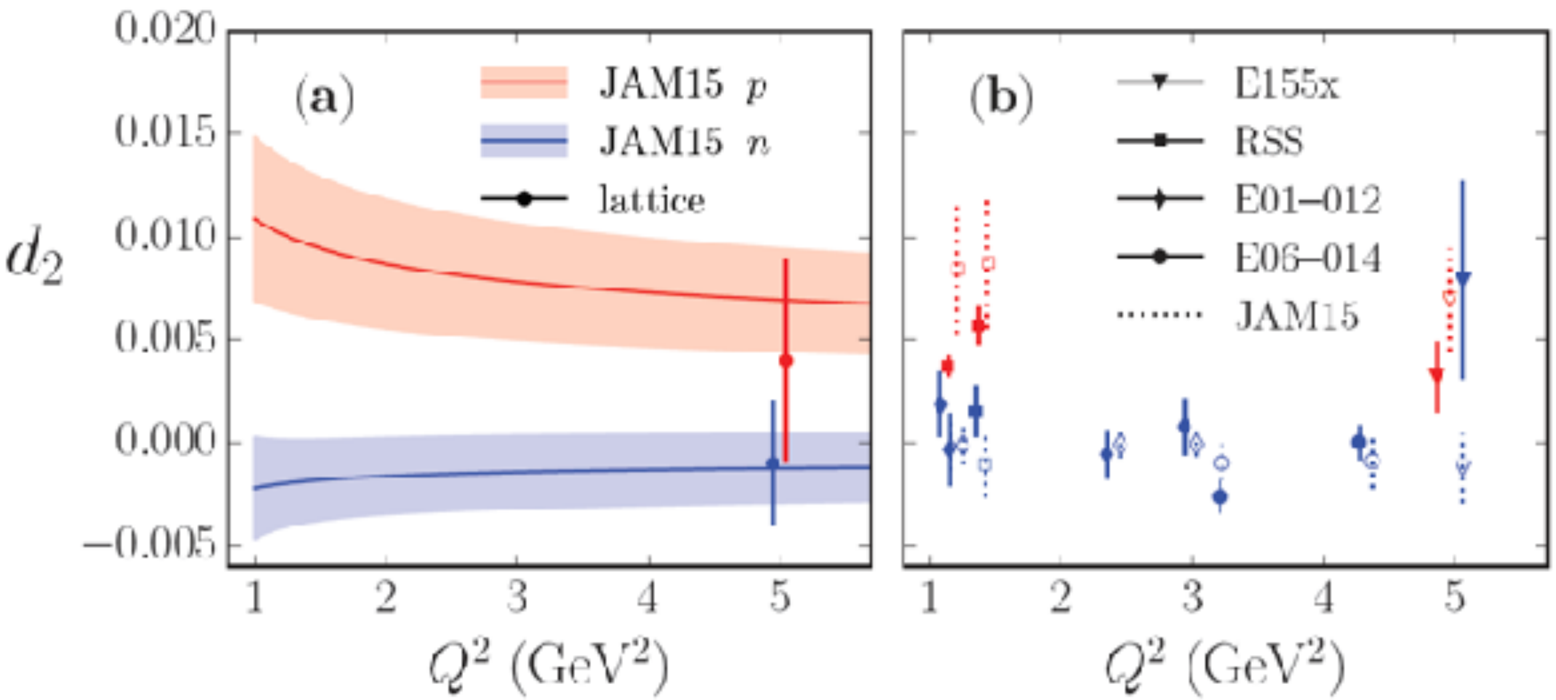
Δg positive

Flavor decomposition of twist-3 distributions

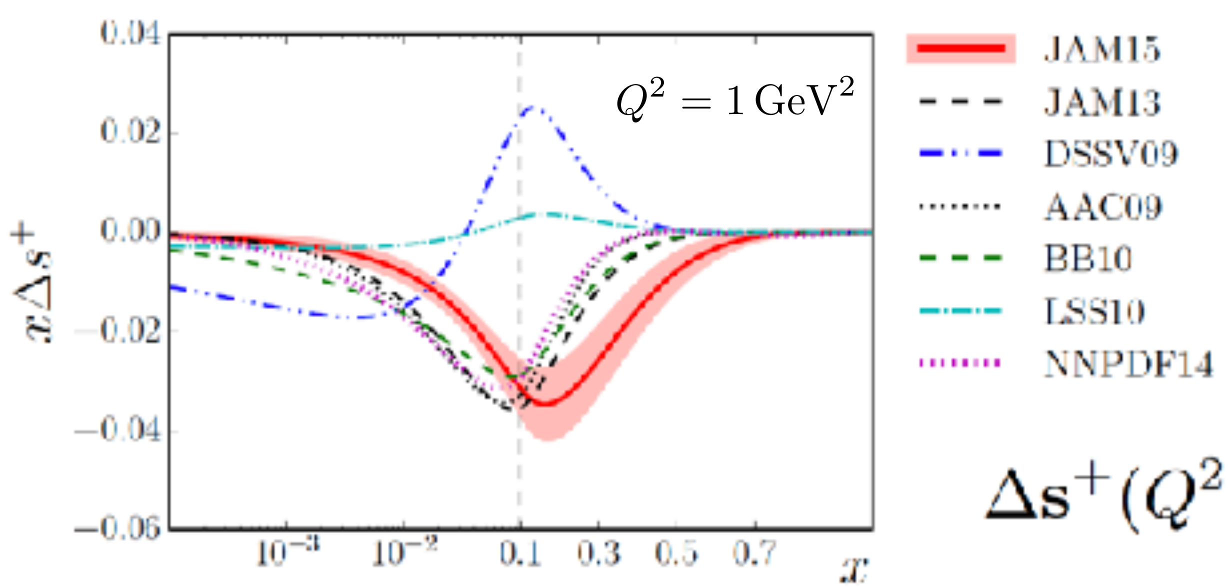
Twist-4 functions compatible with 0

JAM15

$$d_2(Q^2) = \int_0^1 dx x^2 \left(2g_1(x,Q^2) + 3g_2(x,Q^2)\right)$$



d_2-moment agrees with experimental data

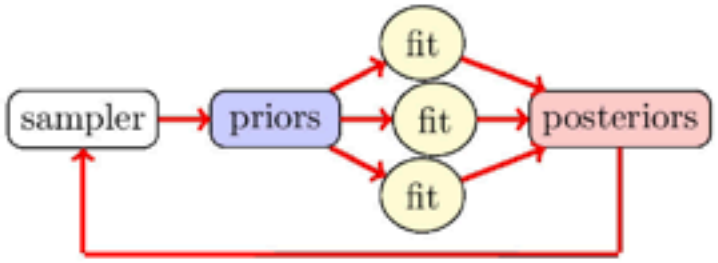


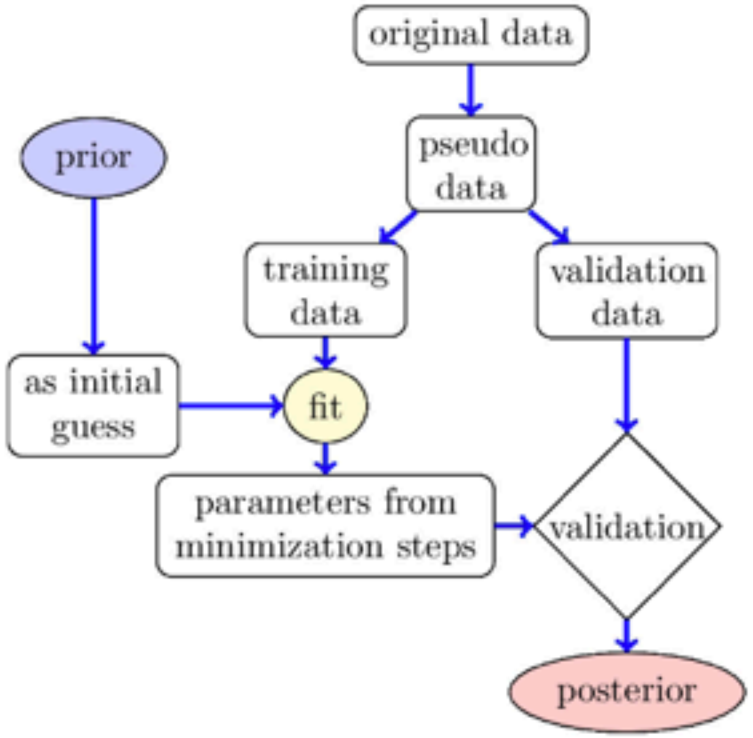
$$\Delta s^+(Q^2) = \int_0^1 dx \Delta s^+(x,Q^2)$$

JAM15: $\Delta s^+ = -0.1 \pm 0.01$ DSSV09: $\Delta s^+ = -0.11$ $Q^2 = 1\,\mathrm{GeV}^2$

Iterative Monte Carlo (IMC)

JAM16



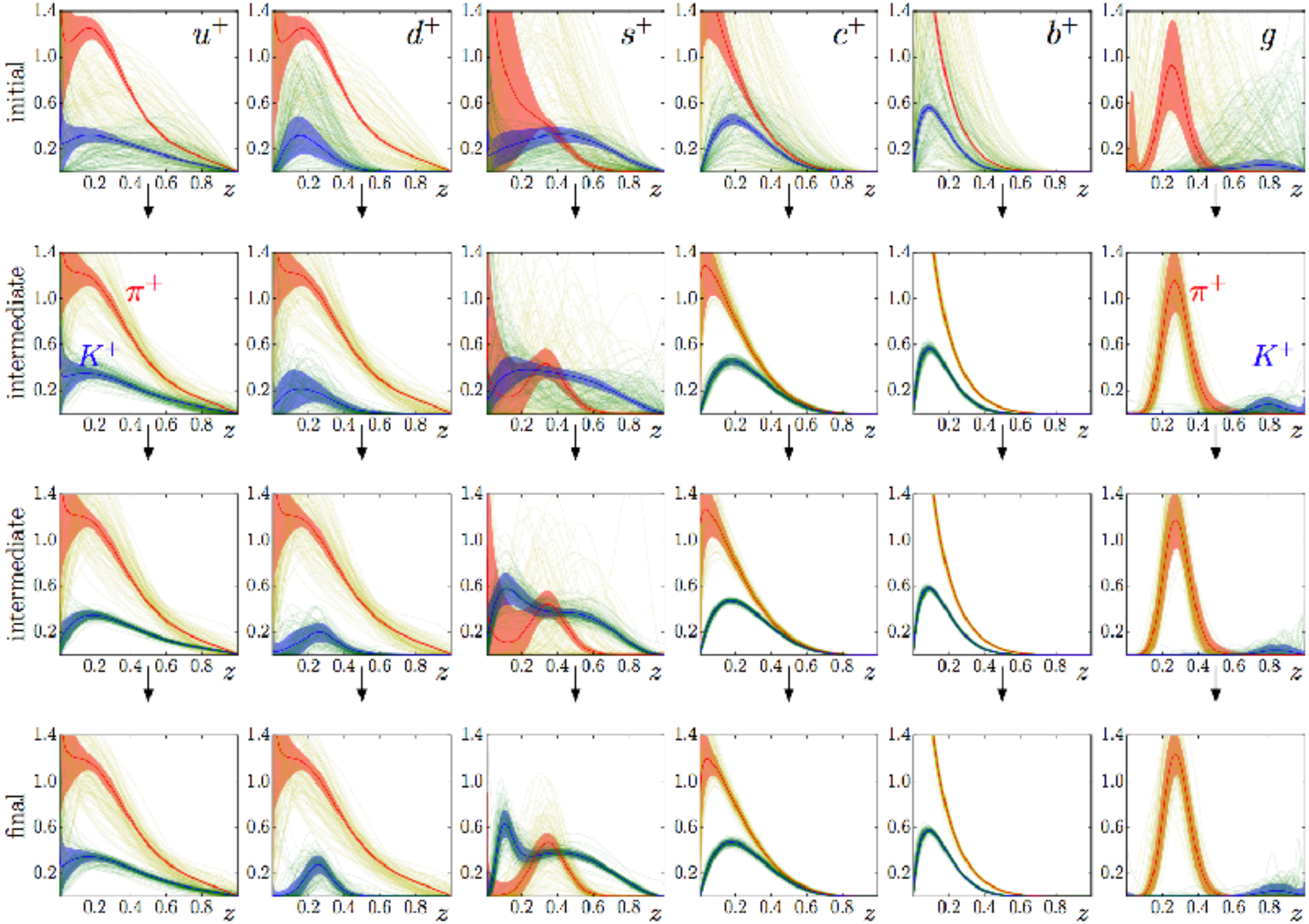


- → Samples wide region of parameter space
- → Data is partitioned for cross-validation – training set is fitted via chi-square minimization
- → Posteriors used to construct sampler (multi-dimensional Guassian, kernel density estimation, etc) – where parameters are chosen for the next iteration
- → Procedure iterated until converged

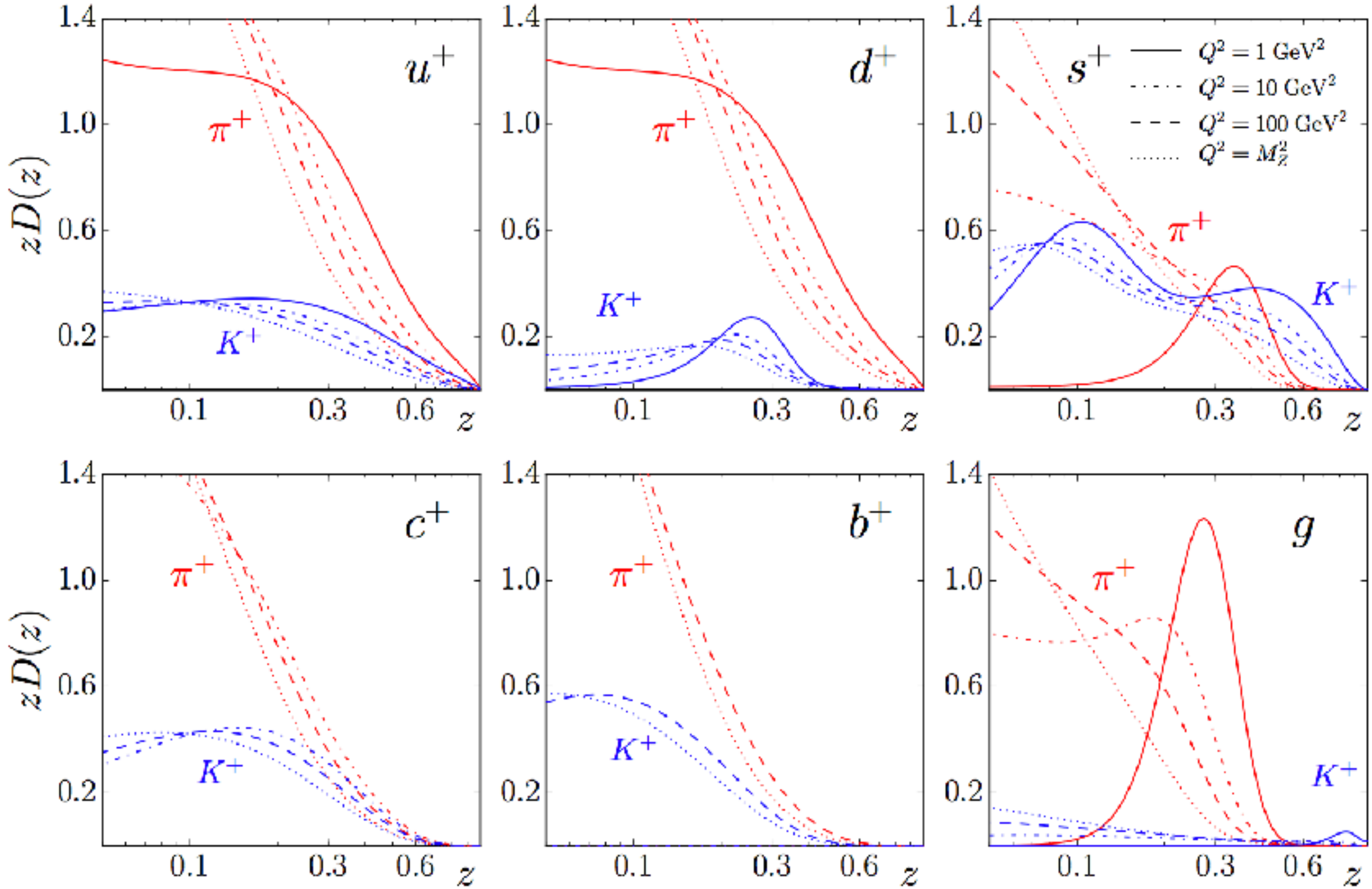
$$\mathrm{E}[\mathcal{O}] = \frac{1}{n}\sum_{k=1}^{n}\mathcal{O}(\boldsymbol{a}_k)$$

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

JAM16: iterative convergence

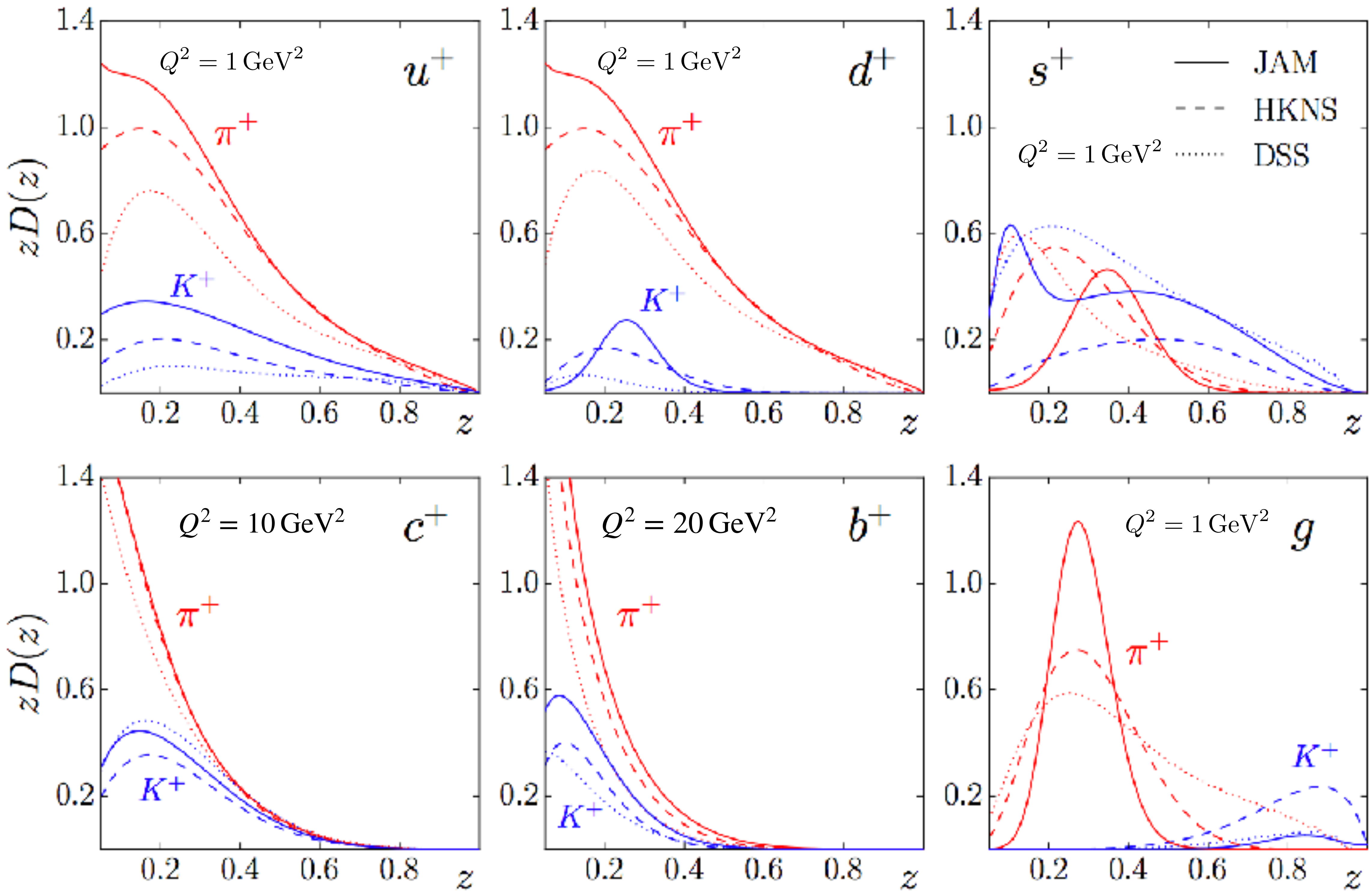


JAM16: FFs evolution

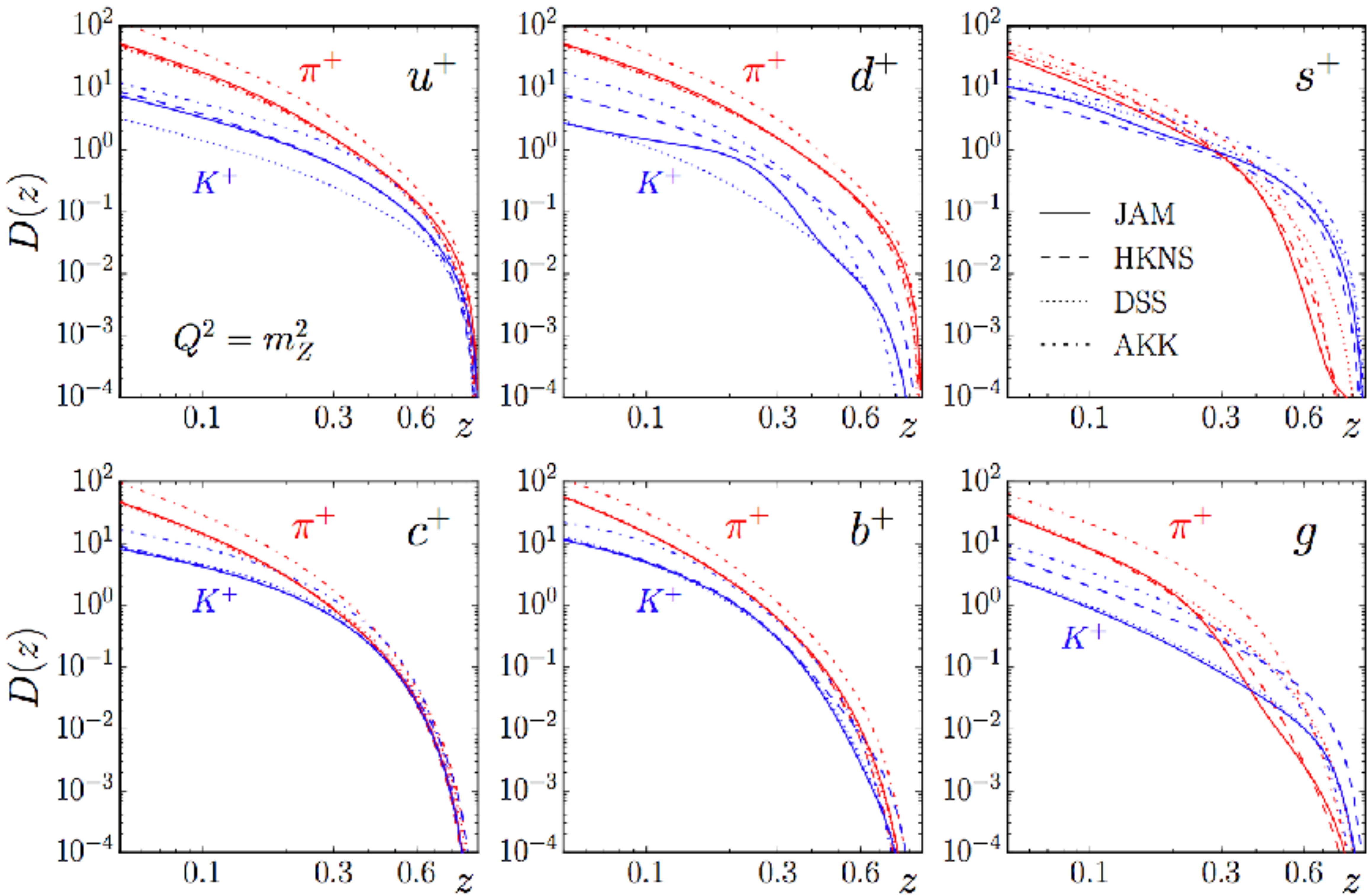


The gluon peak disappears

JAM16: comparison



JAM16: comparison II



JAM17: motivation

Spin sum rule

$$\Delta\Sigma(Q^2) = \int_0^1 dx\,\left(\Delta u^+(x,Q^2) + \Delta d^+(x,Q^2) + \Delta s^+(x,Q^2)\right)$$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\Delta G(Q^2) = \int_0^1 dx \Delta g(x,Q^2)$$

$$\Delta\Sigma(Q^2_{\mathrm{EMC}}) \sim 0.1$$

- First moment of polarized structure function g_1:

$$\int_0^1 dx g_1^p(x,Q^2) = \frac{1}{36}\left[8\Delta\Sigma + 3g_A + a_8\right]\left(1 - \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right) + \mathcal{O}(\frac{1}{Q^2})$$

→ DIS requires assumptions about triplet and octet axial charges to extract $\Delta\Sigma$

- Assuming exact $SU(2)_f$ and $SU(3)_f$ values from weak baryon decays

$$\int dx\,\left(\Delta u^+ - \Delta d^+\right) = g_A \sim 1.269 \qquad \int dx\,\left(\Delta u^+ + \Delta d^+ - 2\Delta s^+\right) = a_8 \sim 0.586$$

$$\Delta\Sigma_{[10^{-3},0.8]} \sim 0.3$$

Released in JAM17

Parameterizations and Chi-square

Euler Beta function

Template function: $\mathrm{T}(x;\boldsymbol{a}) = \dfrac{M\,x^{a}(1-x)^{b}(1+c\sqrt{x})}{B(n+a,1+b)+cB(n+\frac{1}{2}+a,1+b)}$

- PDFs: n = 1 $\Delta q^{+}, \Delta\bar{q}, \Delta g = \mathrm{T}(x;\boldsymbol{a})$
- FFs: n = 2, c = 0 Favored: $D^{h}_{q^{+}} = \mathrm{T}(z;\boldsymbol{a}) + \mathrm{T}(z;\boldsymbol{a}')$

  Unfavored: $D^{h}_{q^{+},g} = \mathrm{T}(z;\boldsymbol{a})$

Isospin →

Pions:

$$D_{\bar{u}}^{\pi^{+}} = D_{d}^{\pi^{+}} = \mathrm{T}(z;\boldsymbol{a})$$

$$D_{s}^{\pi^{+}} = D_{\bar{s}}^{\pi^{+}} = \frac{1}{2}D_{s^{+}}^{\pi^{+}}$$

Kaons:

$$D_{\bar{u}}^{K^{+}} = D_{d}^{K^{+}} = \frac{1}{2}D_{d^{+}}^{K^{+}}$$

$$D_{s}^{K^{+}} = \mathrm{T}(z;\boldsymbol{a})$$

- Chi-squared definition:

Penalty term

$$\chi^{2}(\boldsymbol{a}) = \sum_{e}\left[\sum_{i}\left(\frac{\mathcal{D}_{i}^{(e)}N_{i}^{(e)} - T_{i}^{(e)}(\boldsymbol{a})}{\alpha_{i}^{(e)}N_{i}^{(e)}}\right)^{2} + \sum_{k}\left(r_{k}^{(e)}\right)^{2}\right] + \sum_{\ell}\left(\frac{a^{(\ell)} - \mu^{(\ell)}}{\sigma^{(\ell)}}\right)^{2}$$

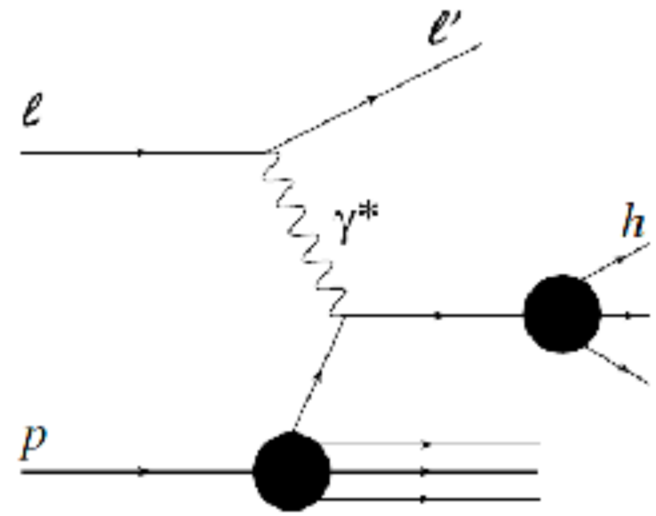
syst + stat (quad.)

Normalization
(Correlated uncertainties)

Nuisance parameters

Polarized SIDIS

Proton Spin Structure from SIDIS



- Measured via longitudinal double spin asymmetries

$$A_1^h(x,z,Q^2) = \frac{g_1^h(x,z,Q^2)}{F_1^h(x,z,Q^2)}$$

- Polarized structure function at NLO defined in terms of 2-D convolution

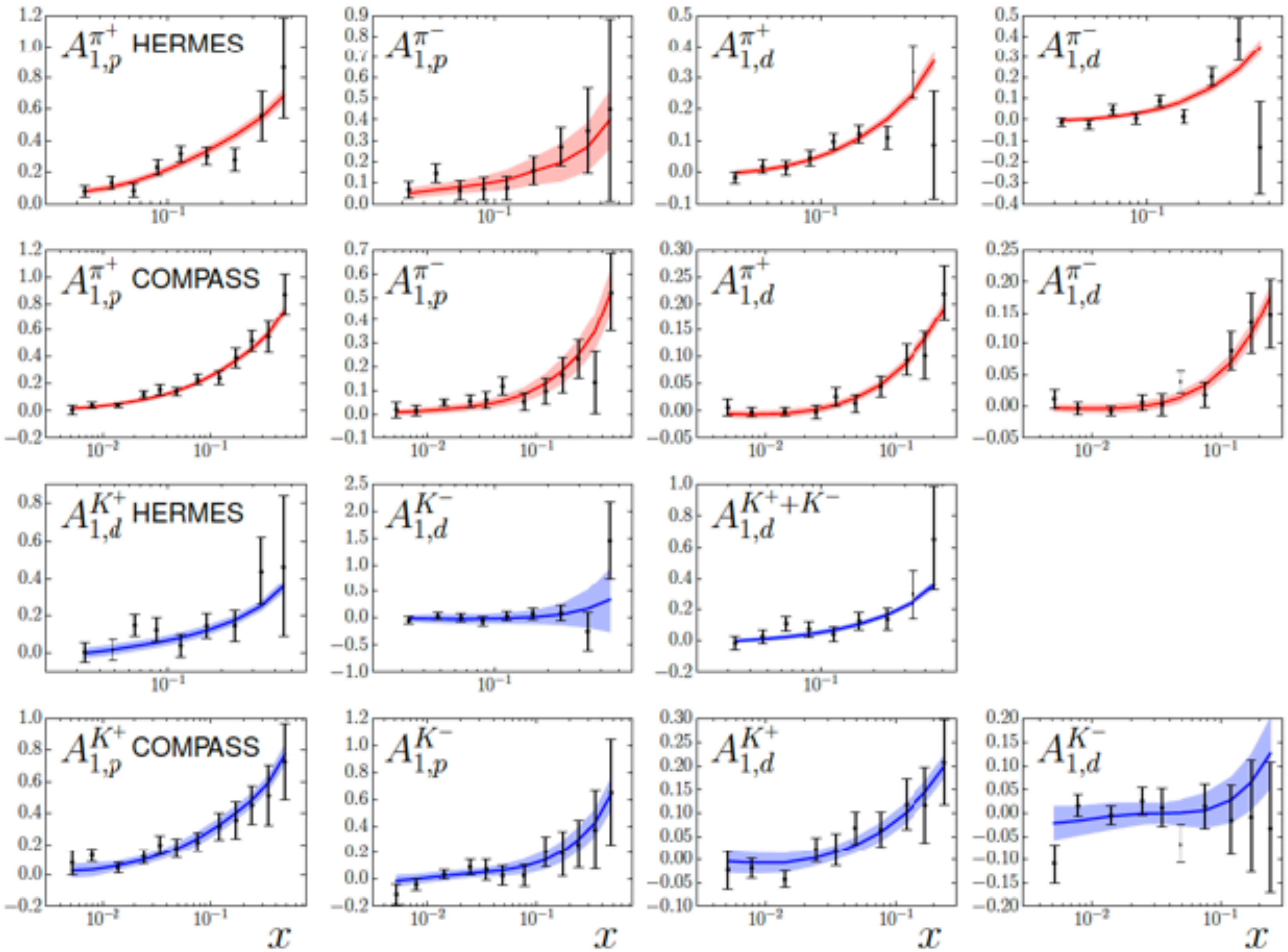
$$g_1^h(x,z,Q^2) = \frac{1}{2}\sum_q e_q^2 \Big\{ \Delta q(x,Q^2) D_q^h(z,Q^2) + \frac{\alpha_s(Q^2)}{2\pi} \times \Big(\Delta q \otimes \Delta C_{qq} \otimes D_q^h + \Delta q \otimes \Delta C_{gq} \otimes D_g^h + \Delta g \otimes \Delta C_{qg} \otimes D_q^h \Big) \Big\}$$

- To include SIDIS observables in the JAM global analyses, fragmentation functions (FFs) must be known

→ Choice of FF parameterizations available (HKNS & DSS) differed significantly in kaon sector – strongly impacts Δs^+ extraction

JAM decided to use Monte Carlo procedure to extract FFs from SIA

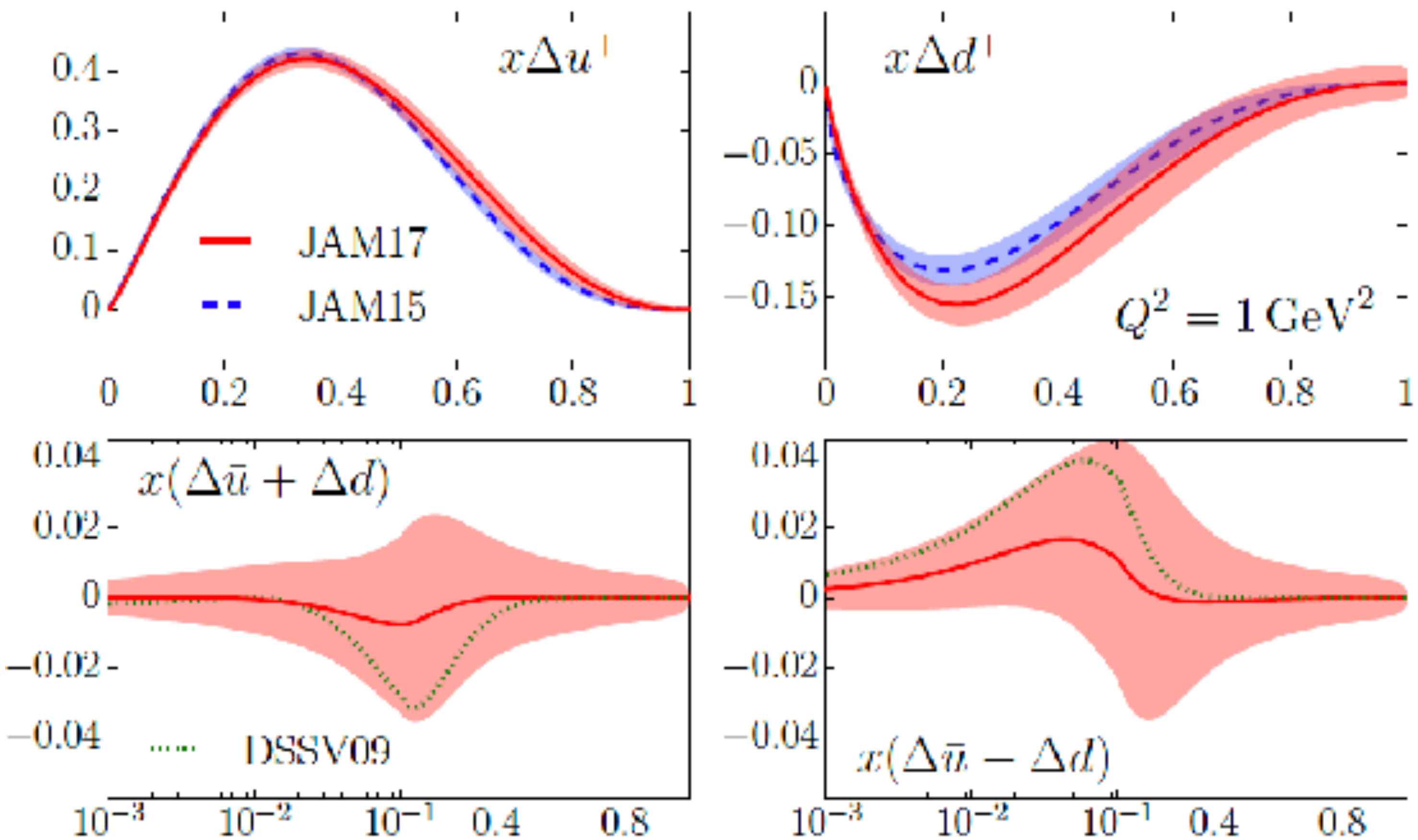
JAM17: Data vs. Theory



$$A_1^h = \frac{g_1^h}{F_1^h}$$

process	target	$N_{\rm dat}$	^{2}
DIS	$p, d, {}^3$He	854	854.8
SIA $(\pi^\pm, K^\pm)$		850	997.1
SIDIS $(\pi^\pm)$			
HERMES	d	18	28.1
HERMES	p	18	14.2
COMPASS	d	20	8.0
COMPASS	p	24	18.2
SIDIS $(K^\pm)$			
HERMES	d	27	18.3
COMPASS	d	20	18.7
COMPASS	p	24	12.3
Total:		**1855**	**1969.7**

JAM17: Polarized PDFs

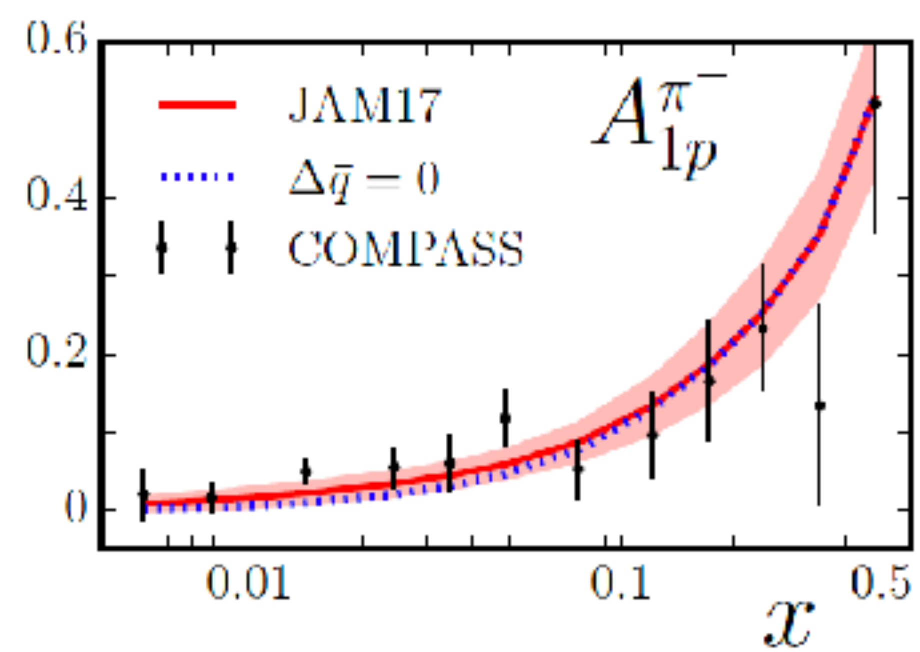


- Δu^+ consistent with previous analysis
- Δd^+ slightly larger in magnitude

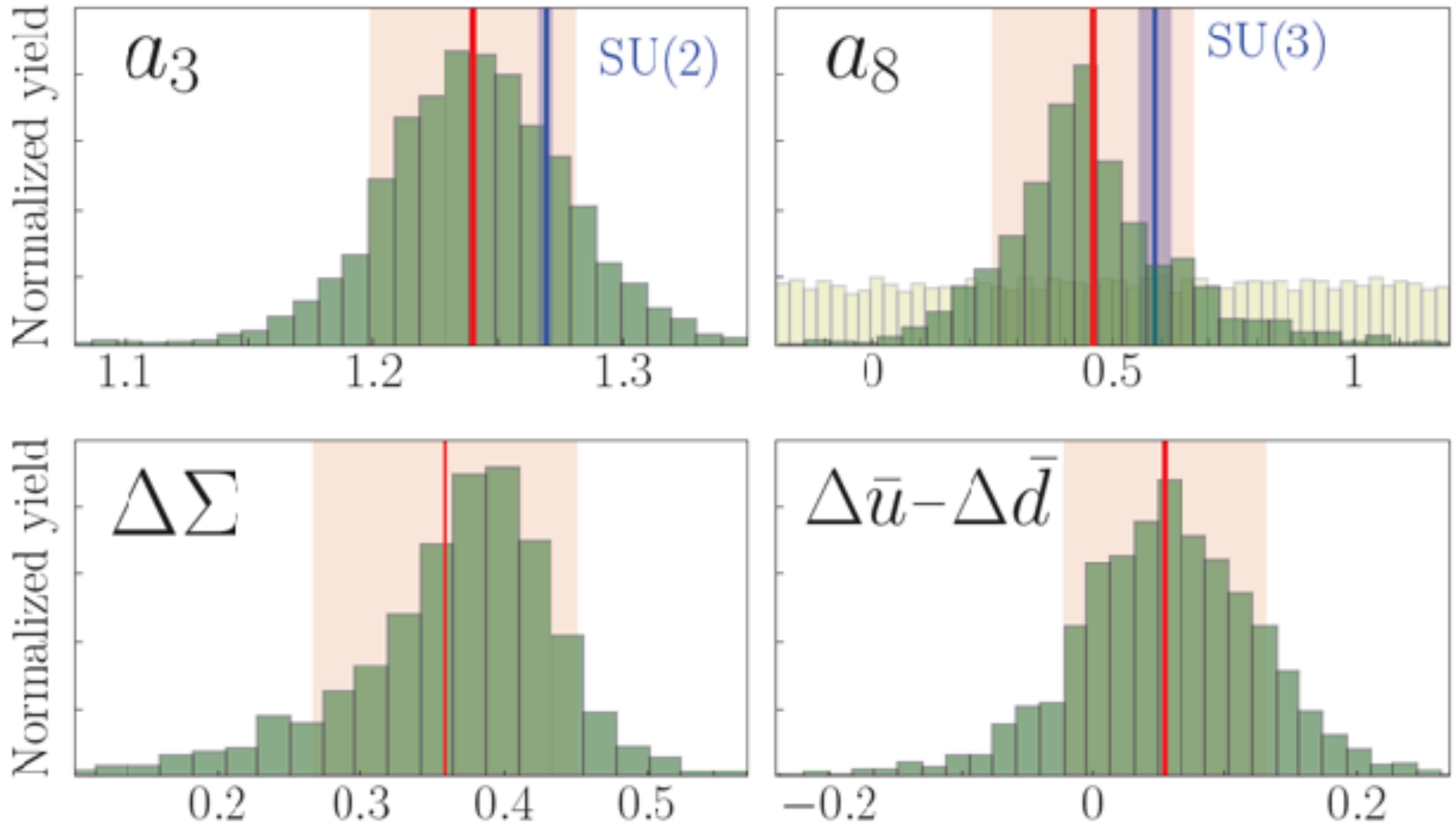
  → Anti-correlation with Δs^+, which is less negative than JAM15 at $x \sim 0.2$

- Isoscalar sea distribution consistent with zero
- Isovector sea slightly prefers positive shape at low x

  → Non-zero asymmetry given by small contributions from SIDIS asymmetries



JAM17: Lowest moments



$$g_A = 1.24 \pm 0.04$$ Confirmation of SU(2) symmetry to ~2%

$$a_8 = 0.46 \pm 0.21$$ ~20% SU(3) breaking ± ~20%; large uncertainty

- Need better determination of Δs^+ moment to reduce a_8 uncertainty!

$$\Delta \mathbf{s}^+ = -0.03 \pm 0.09$$

$$\Delta\Sigma = 0.36 \pm 0.09$$

JAM18: Parametrization

Parametrization $\rightarrow$ generic template functions

$$T(\xi;\boldsymbol{a}) = N\frac{\xi^a(1-\xi)^b(1+c\sqrt{\xi}+d\xi)}{B(2+a,b+1)+cB(5/2+a,b+1)+dB(3+a,b+1)}$$

For PDFs 13 parameters

- g, u_v, d_v, $\bar{u}$, $\bar{d}$, $s=\bar{s}$
- momentum sum rules and quark number sum rule

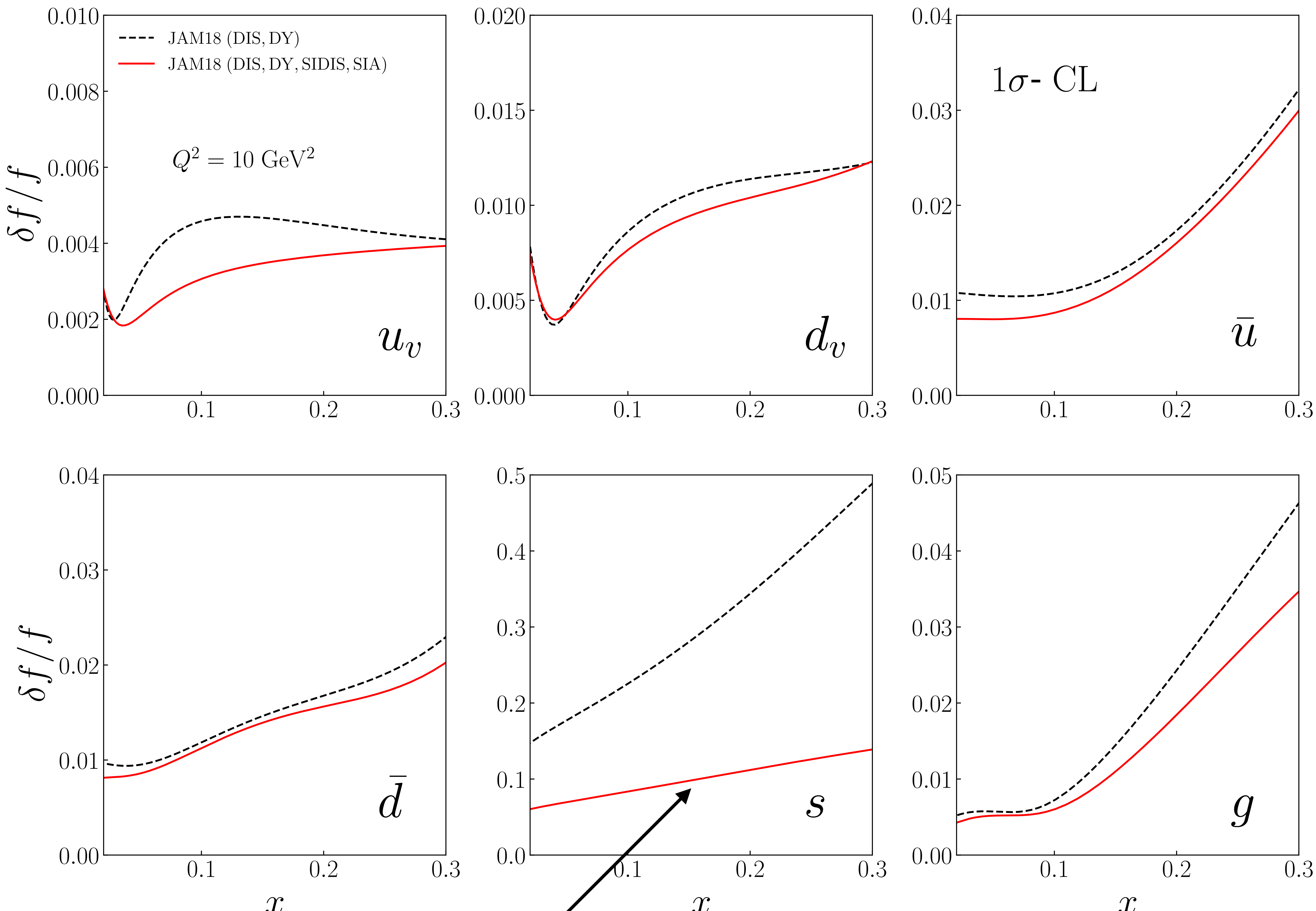
For FFs π^+ 16 parameters

- g, u(fav.), d (ufav.), c, b
- $u=\bar{d}$, $d=\bar{u}=s=\bar{s}$

For FFs K^+ 15 parameters

- g, u (fav.), d (unf.), $\bar{s}$ (fav.), c, b
- $d=\bar{d}=\bar{u}=s$

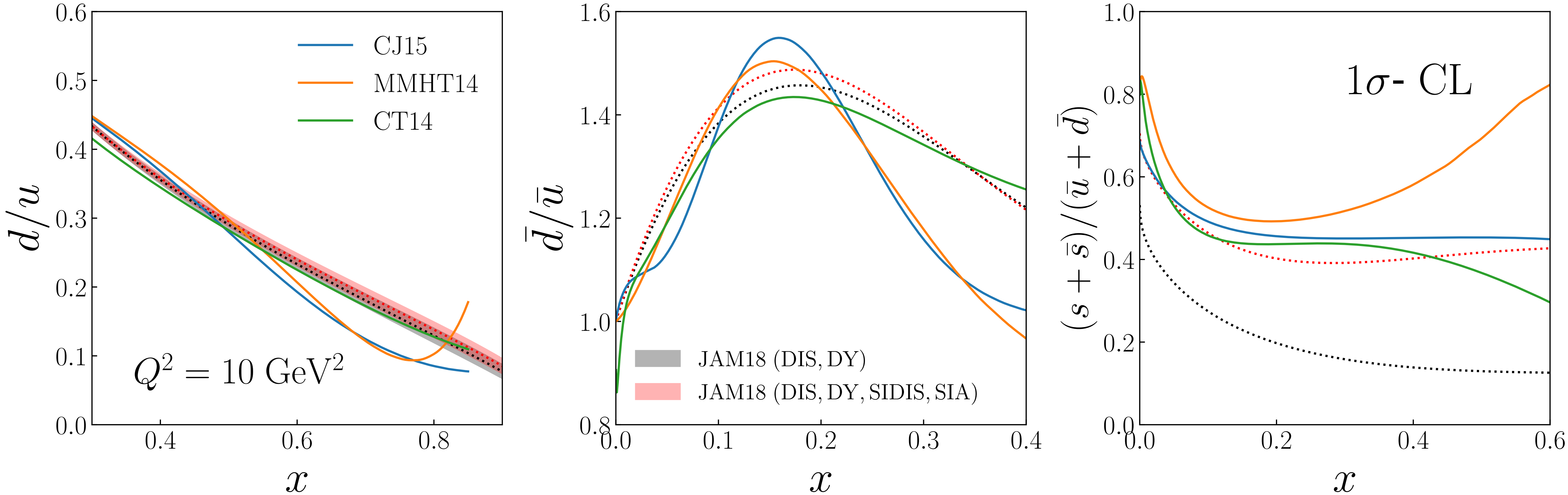
Unpolarized PDFs (JAM18)



Decrease of strange uncertainties due to K SIDIS data

Unpolarized PDFs (JAM18)

Sea distributions



Next steps

- Using F_2^c and F_2^b data? GM-VFNS required!

HERA data: arXiv:1804.01019 [hep-ex]

52 points $\sigma_{red}^{c\bar{c}}$: $3 \cdot 10^{-5} < x < 0.05 \quad \text{and} \quad 2.5\,\text{GeV}^2 < Q^2 < 2000\,\text{GeV}^2$

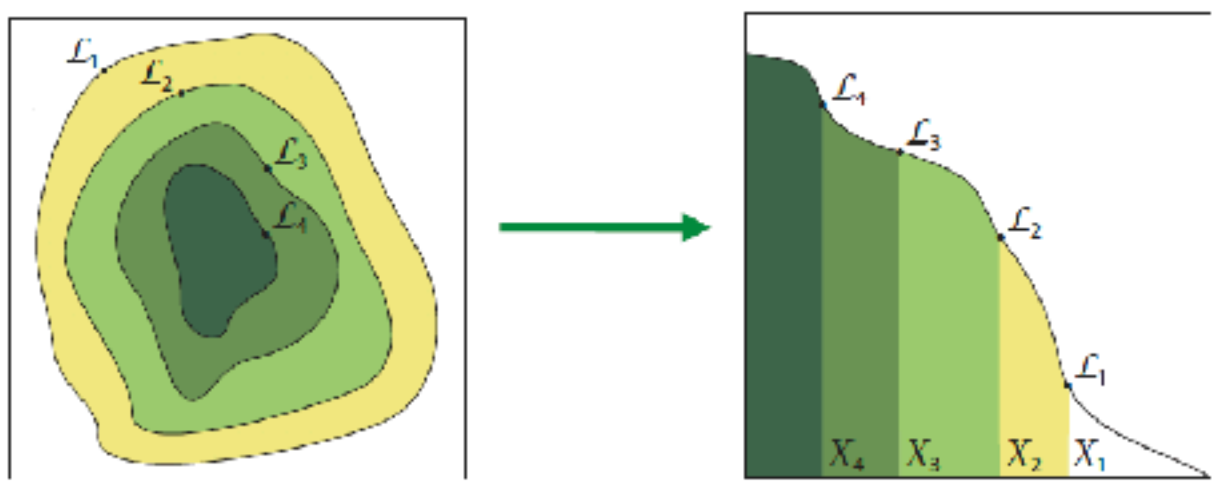
27 points $\sigma_{red}^{b\bar{b}}$: $1.3 \cdot 10^{-4} < x < 0.05 \quad \text{and} \quad 2.5\,\text{GeV}^2 < Q^2 < 2000\,\text{GeV}^2$

Methodology Shift: Nested Sampling

- Statistical mapping of multidimensional integral to 1-D

$$Z = \int d^n a \mathcal{L}(data|\vec{a})\pi(\vec{a}) = \int_0^1 dX \mathcal{L}(X)$$

where the *prior volume* $dX = \pi(\vec{a})d^n a$



$$Z_i \sim \sum_i \mathcal{L}_i w_i$$

where $w_i = \frac{1}{2}(X_{i-1} - X_{i}$

Feroz et al. arXiv:1306.2144 [astro-ph]

- Algorithm:

→ Initialize $X_0 = 1$, $L = 0$ and choose N active points $X_1, X_2, \ldots, X_N$ from prior

→ For each iteration, sample new point and remove lowest L_i, replacing with point such that L is monotonically increasing

→ Repeat until entire parameter space has been explored