Collinear Distributions from Universal QCD Analyses

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With JAM members: N. Sato, C. Andrés, and W. Melnitchouk

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Global QCD Analyses

- Method to obtain reliable information of nonperturbative dynamics associated with hadron structure and hadronization

Factorization → separation of short and long distance physics in pQCD expressions of experimental observables, e.g.

Unpolarized deep inelastic scattering (DIS) observable

$\ell + (p, d) \to \ell' + X$

$$d\sigma(x, Q^2) \simeq \sum_f \int_x^1 \frac{d\xi}{\xi} f\left(\frac{x}{\xi}, Q^2\right) d\hat{\sigma}_f(\xi, Q^2)$$

Parton distribution function (PDF)

Hard scattering cross section

- Collinear factorization → distributions depend on the fraction of longitudinal momentum carried by partons

- Nonperturbative distributions typically determined empirically

→ Objects are parameterized: $xf(x) = Nx^a(1-x)^b(1+c\sqrt{x}+dx)$

→ Parameters are optimized (typically by chi-squared minimization):

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

Global QCD Analyses

- Different nonperturbative distributions related between experimental observables
  - → Unpolarized (Polarized) PDFs: describe nucleon's momentum (spin) structure
  - → Fragmentation functions (FFs) D_f : describe parton-to-hadron fragmentation

PDF-dependent Reactions	FF-dependent Reactions
NC+CC DIS	electron-positron annihilation
proton-proton semi-inclusive DIS →	semi-inclusive observables – measurement of final state particles

- Polarization asymmetries – ratios of spin-dependent to spin-averaged cross sections

Polarized semi-inclusive DIS observable

$\ell + (p, d) \rightarrow \ell' + h + X$

$$A_1^h \sim \frac{g_1^h}{F_1^h} \sim \frac{\sum_{f,f'} \Delta f \otimes \Delta C_{ff'} \otimes D_{f'}^h}{\sum_{f,f'} f \otimes C_{ff'} \otimes D_{f'}^h}$$

- Global analyses typically fit one distribution of interest – other functions fixed to previous extractions

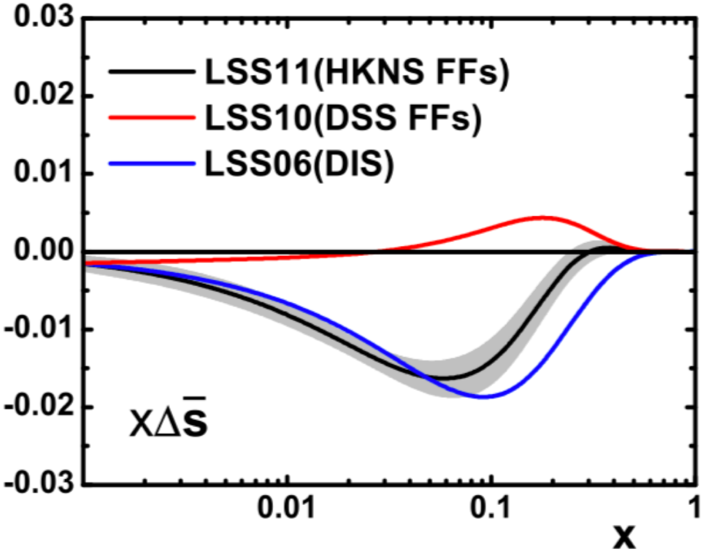
Universal QCD Analyses

- Simultaneous extractions of PDFs + FFs – crucial to obtain reliable information about proton structure

  → FFs not as well constrained – different FF shapes can lead to different solutions for unpolarized/polarized PDFs

E. Leader et al. Phys.Rev. D84 014002 (2011)

Impact of FF parameterizations on the extraction of the polarized strange distribution



DSS FFs → positive strange at $x \sim 0.1$

HKNS FFs → negative strange polarization

- Need modern statistical and machine learning tools to properly study correlations between PDFs and FFs

JAM Collaboration Efforts

- Recent efforts by the JAM collaboration:

→ JAM15: Iterative Monte Carlo Analysis of spin PDFs (DIS only) – studies impact of high precision Jefferson Lab data on proton spin structure N. Sato *et. al.* Phys. Rev. D93 074005 (2016)

→ JAM16: First Monte Carlo analysis of FFs (SIA only) – preformed to obtain reliable determination of FFs and their uncertainties

N. Sato *et. al.* Phys. Rev. D94 114004 (2016)

		JAM15	JAM16	JAM17	JAM19
Process	DIS	☑	☒	☑	☑
	SIA	☒	☑	☑	☑
	SIDIS	☒	☒	☑	☑
	DY	☒	☒	☒	☑
Function	f	☒	☒	☒	☑
	Δf	☑	☒	☑	☒
	D_f^h	☒	☑	☑	☑

→ JAM17: First combined Monte Carlo analysis of polarized DIS, polarized SIDIS, and SIA data – studies impact of SIDIS on sea quark helicity distributions

JE, N. Sato, W. Melnitchouk PRL 119 132001 (2017)

→ JAM19: Simultaneous extraction of unpolarized PDFs and FFs (in progress)

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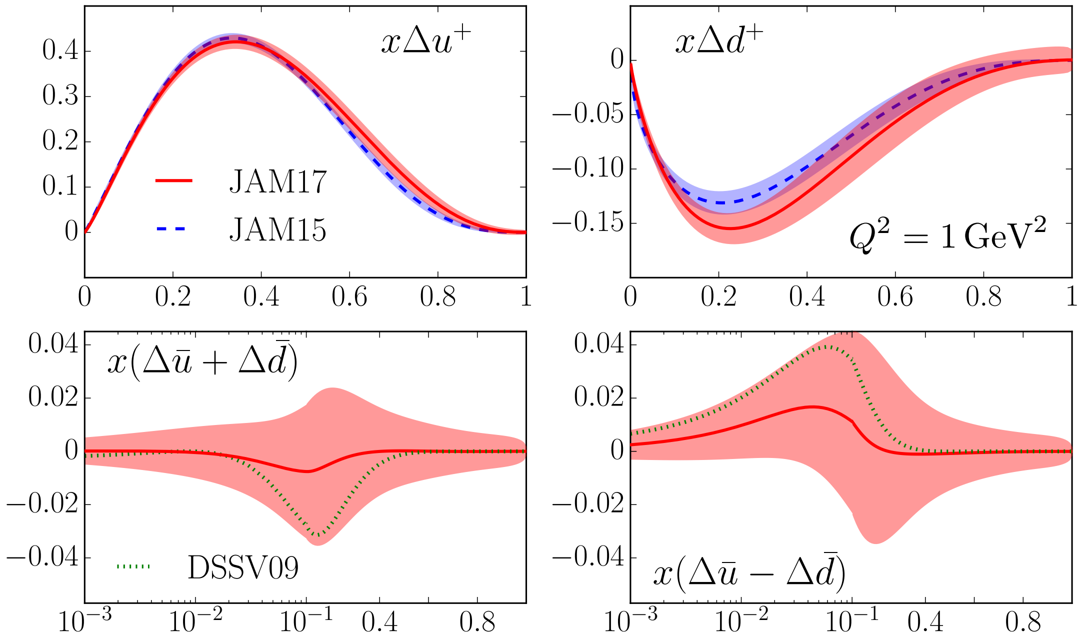
JAM17 Polarized PDF Distributions



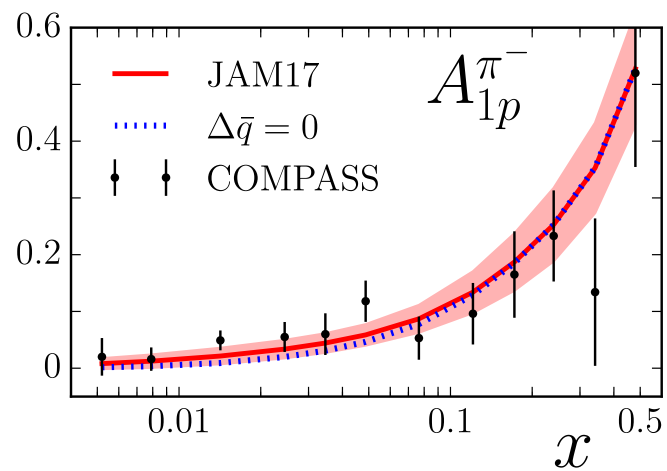
JE, N. Sato, W. Melnitchouk PRL 119 132001 (2017)

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

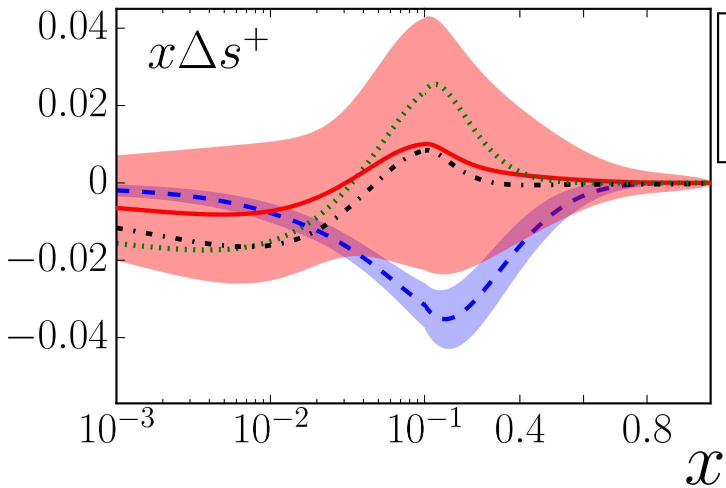
→ Anti-correlation with Δs^+, which is less negative than JAM15 at $x \sim 0.2$

- 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 – Resolution of the Strange Polarization

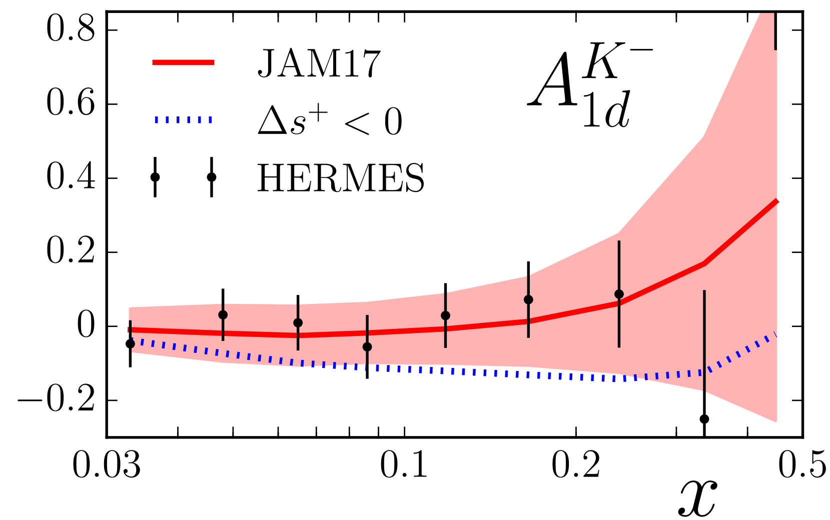


JE, N. Sato, W. Melnitchouk PRL 119 132001 (2017)

- Δs^+ distribution consistent with zero, slightly positive in intermediate x range
- Primarily influenced by HERMES K^- data from deuterium target

Why does DIS+SU(3) give large negative Δs^+?

- Low x DIS deuterium data from COMPASS prefers small negative Δs^+
- Negative polarization shifted to intermediate region to satisfy SU(3) constraint
- Large-x shape parameter for Δs^+ typically fixed to values ~6-10, producing a peak at x~0.1

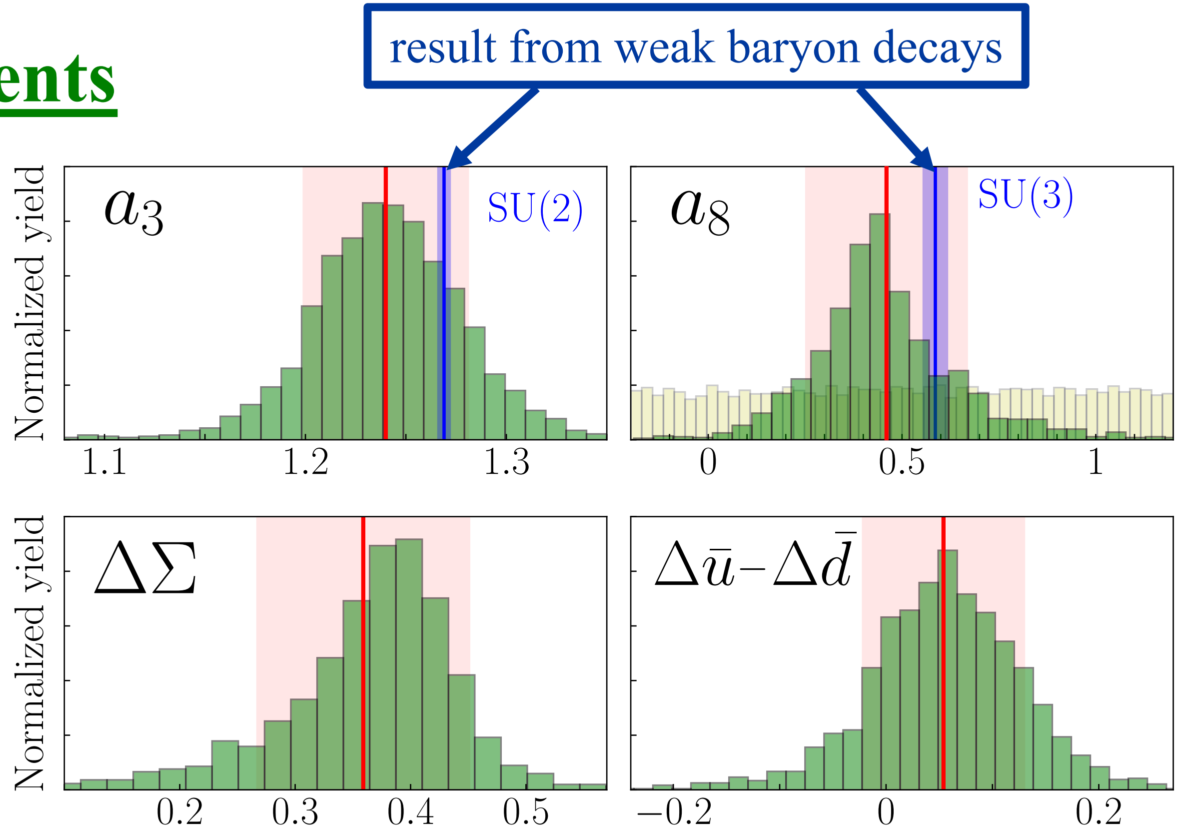


JAM17 – Moments

$$a_3 \equiv \int_0^1 dx\,(\Delta u^+ - \Delta d^+)$$

$$a_8 \equiv \int_0^1 dx\,(\Delta u^+ + \Delta d^+ - 2\Delta s^+)$$

$$\Delta\Sigma \equiv \int_0^1 dx\,(\Delta u^+ + \Delta d^+ + \Delta s^+)$$



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

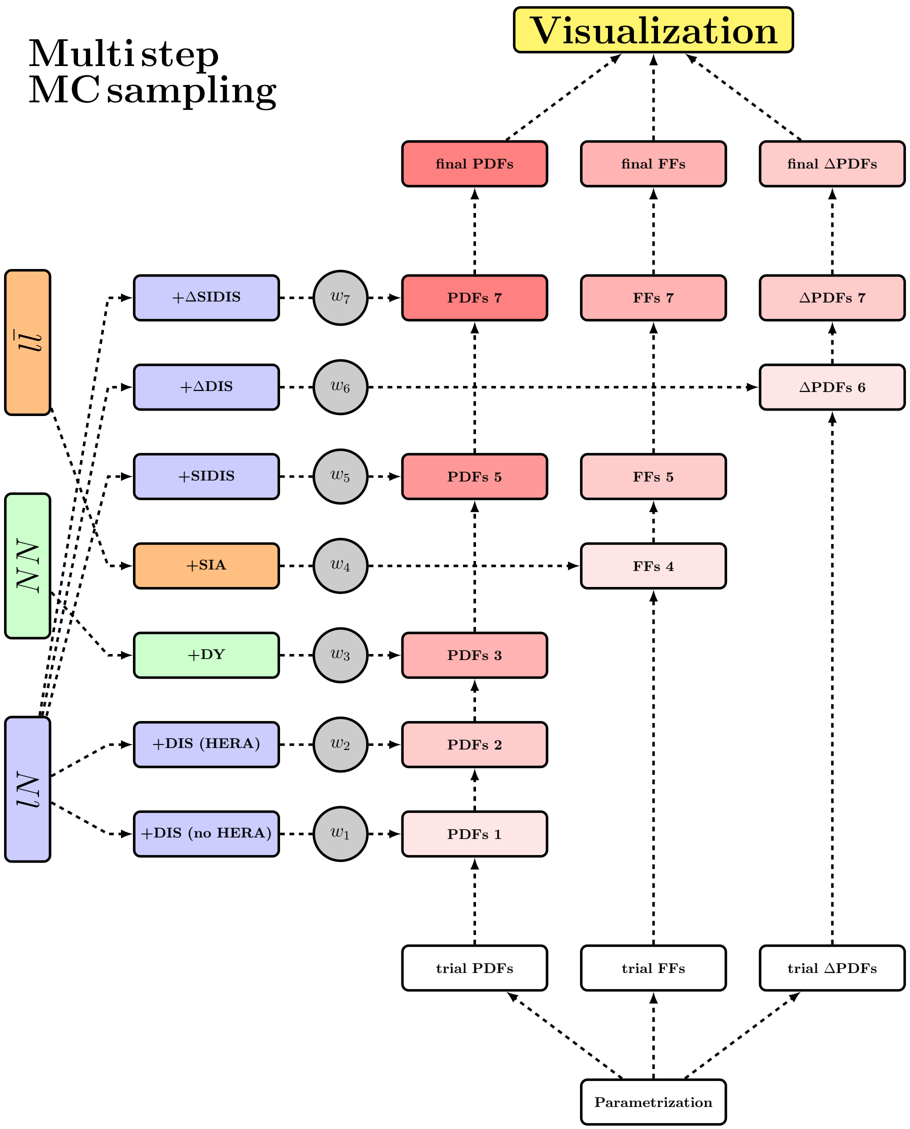
$$a_8 = 0.46 \pm 0.21$$ ~20% SU(3) breaking ± ~20%; large uncertainty

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

$$\Delta s^+ = -0.03 \pm 0.09$$

JAM19 Analysis (Preliminary)

- Simultaneous unpolarized PDF + FF fit → multi-step process



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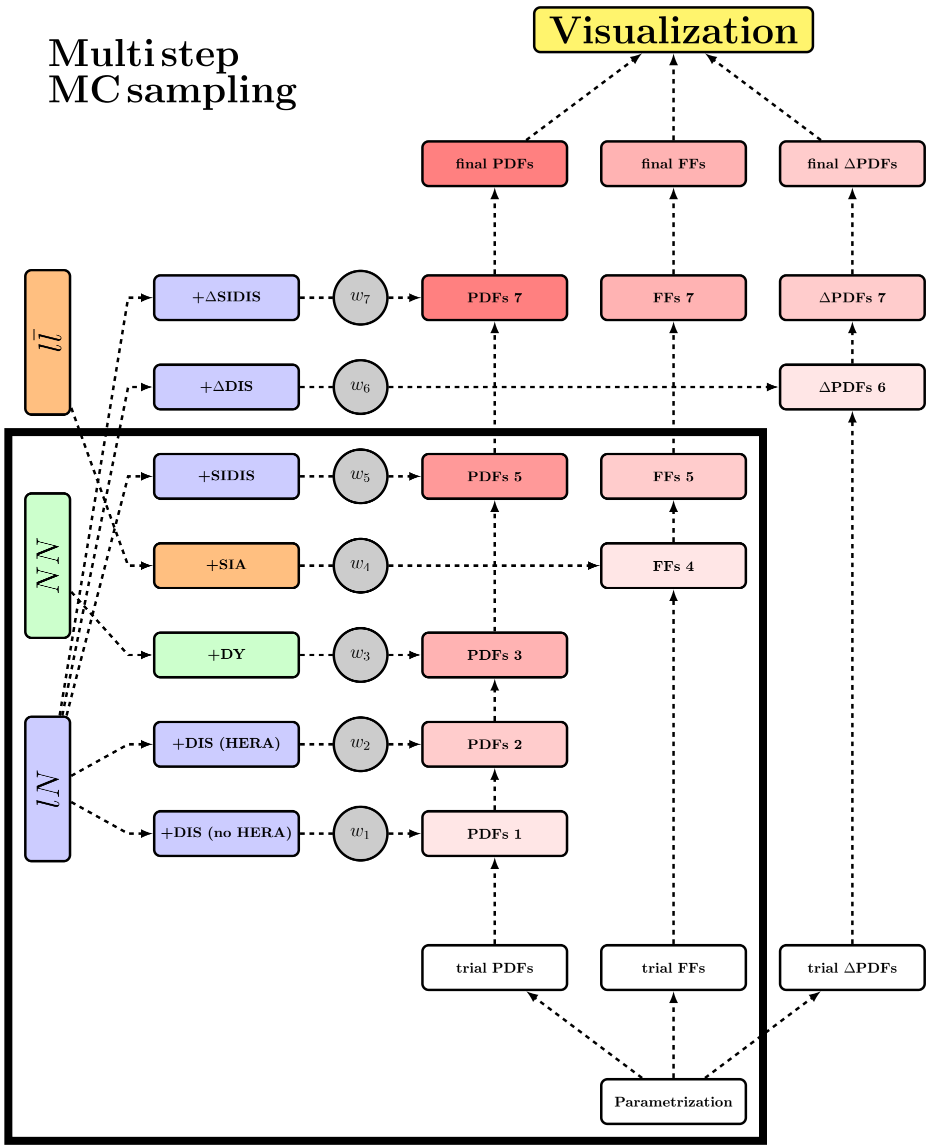
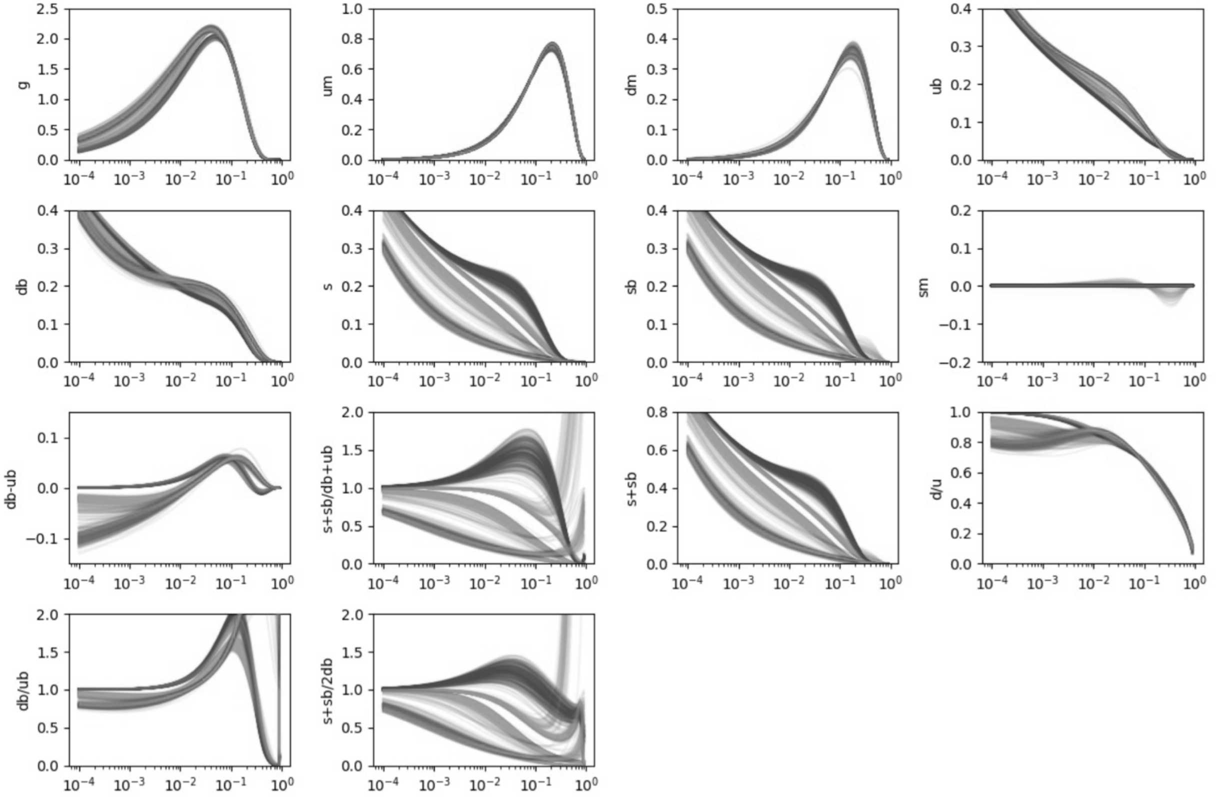


JAM19

JAM19 Analysis (Preliminary)

- Isolating solutions → k-means clustering algorithm



DIS + DY + SIA + SIDIS

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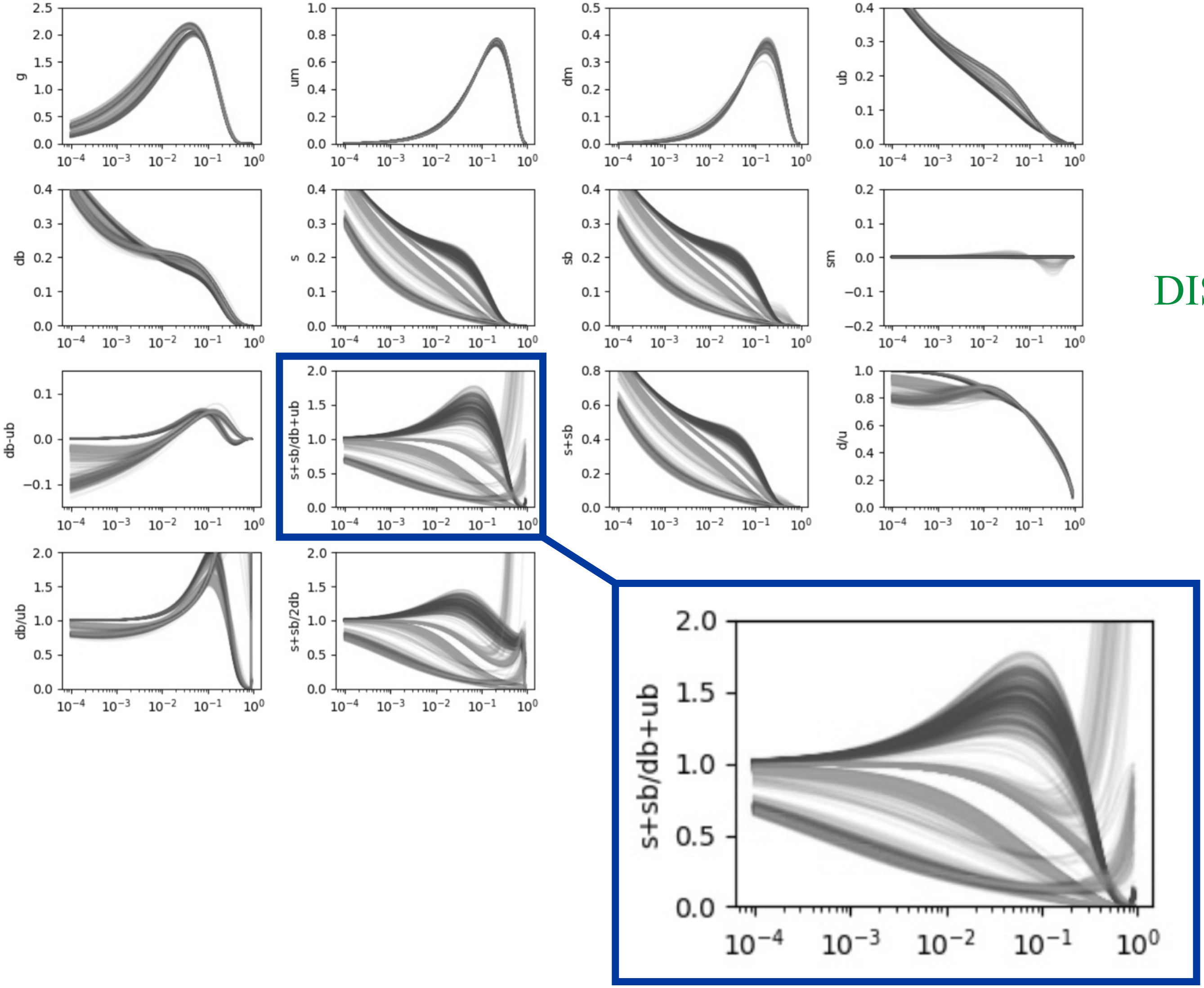

DIS + DY + SIA + SIDIS

$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

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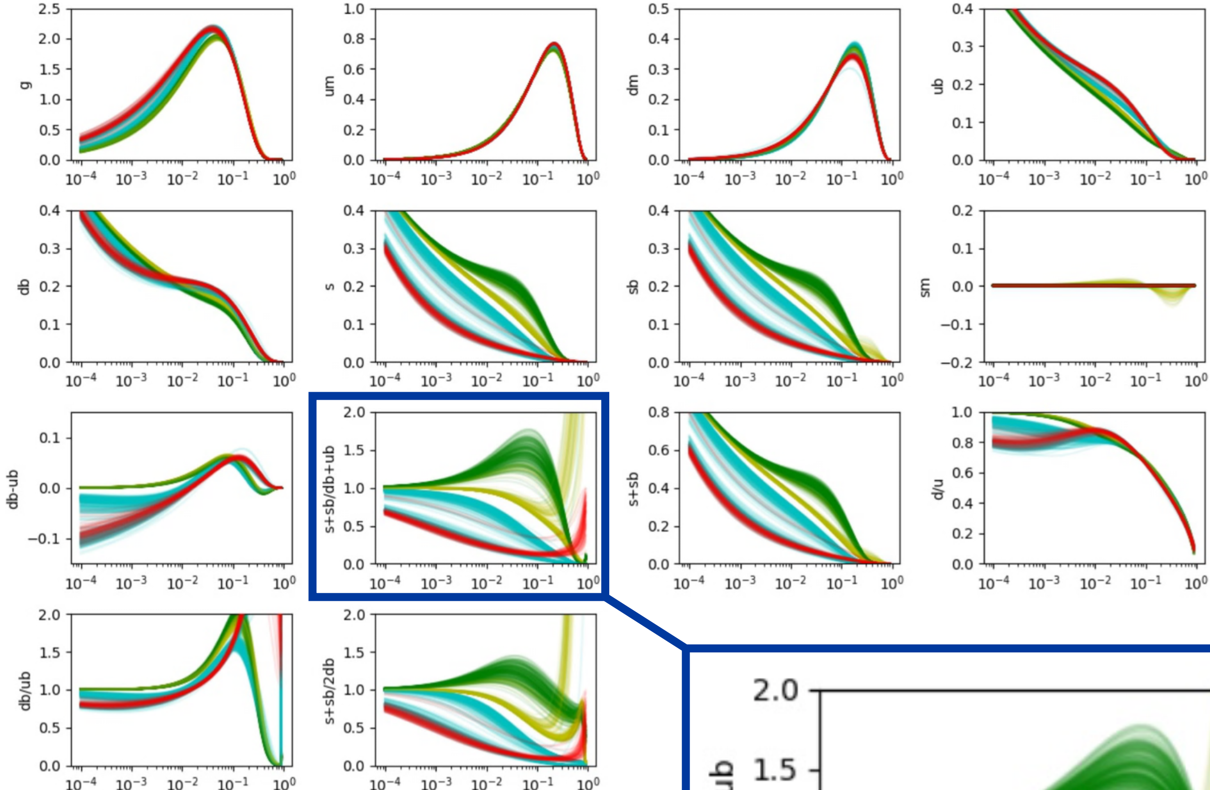

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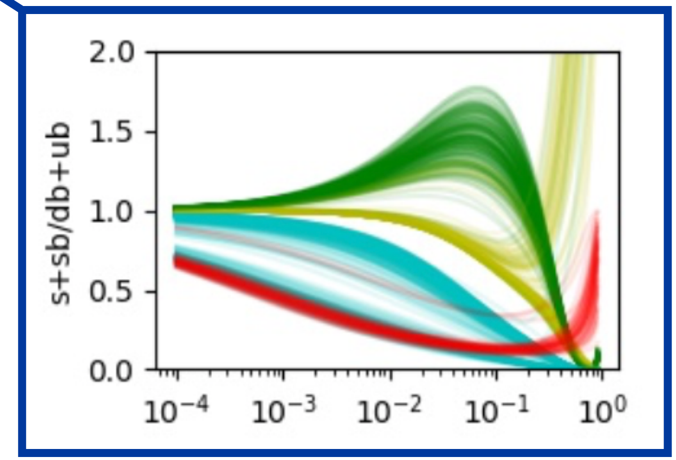

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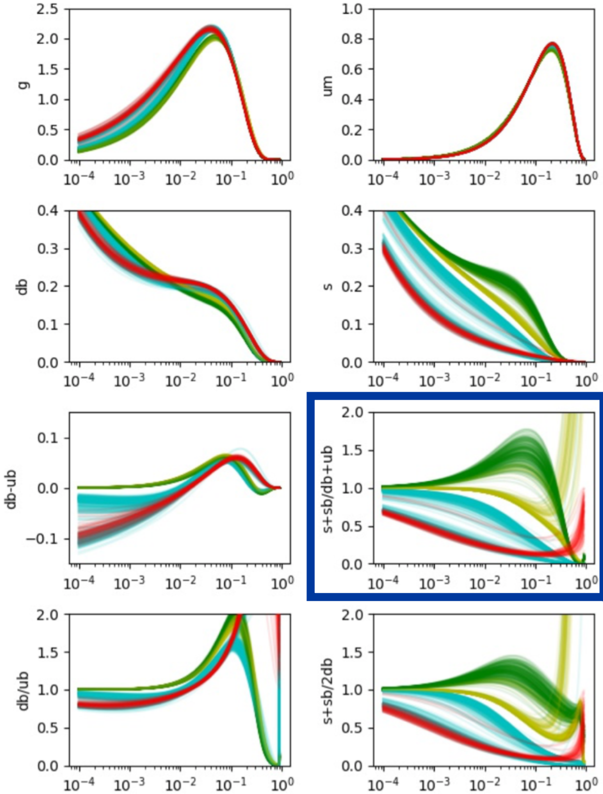
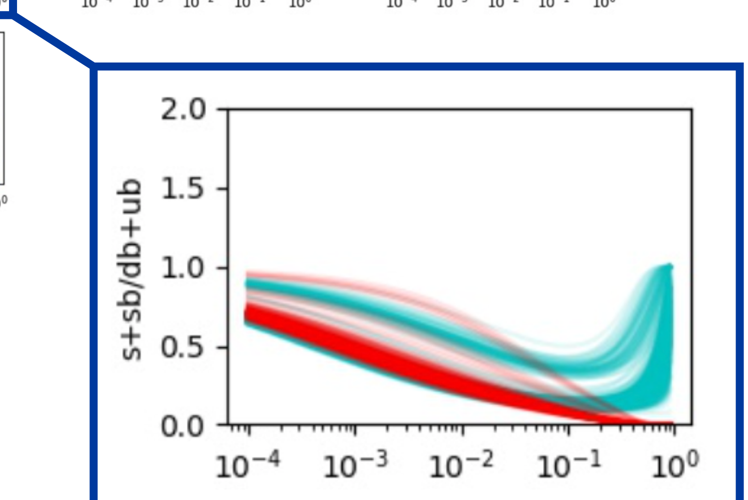


DIS + DY + SIA + SIDIS

Classify with respect to chi-squared values and perform fits with initial flat sampling around best cluster



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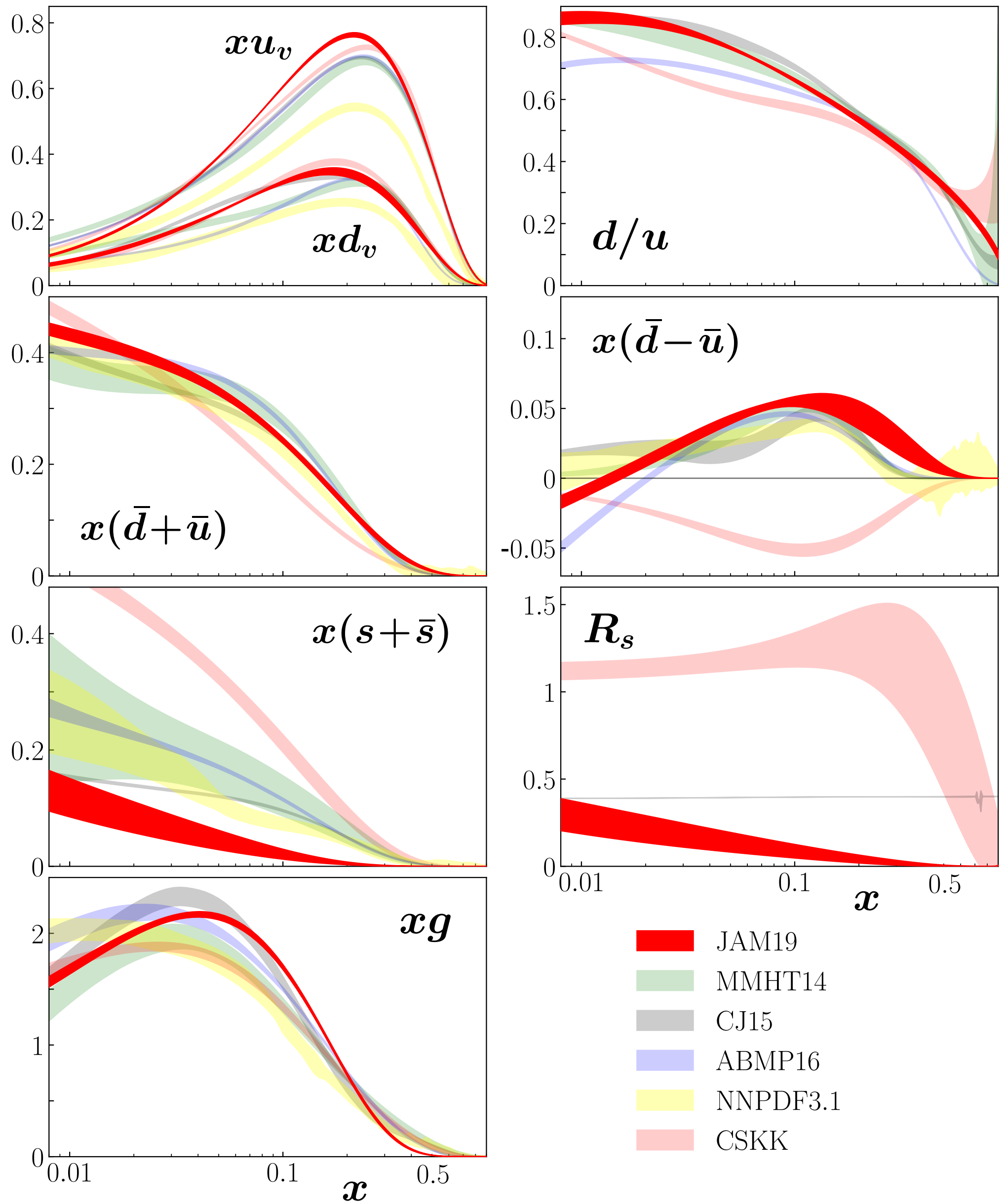
JAM19 Unpolarized PDFs (Preliminary)

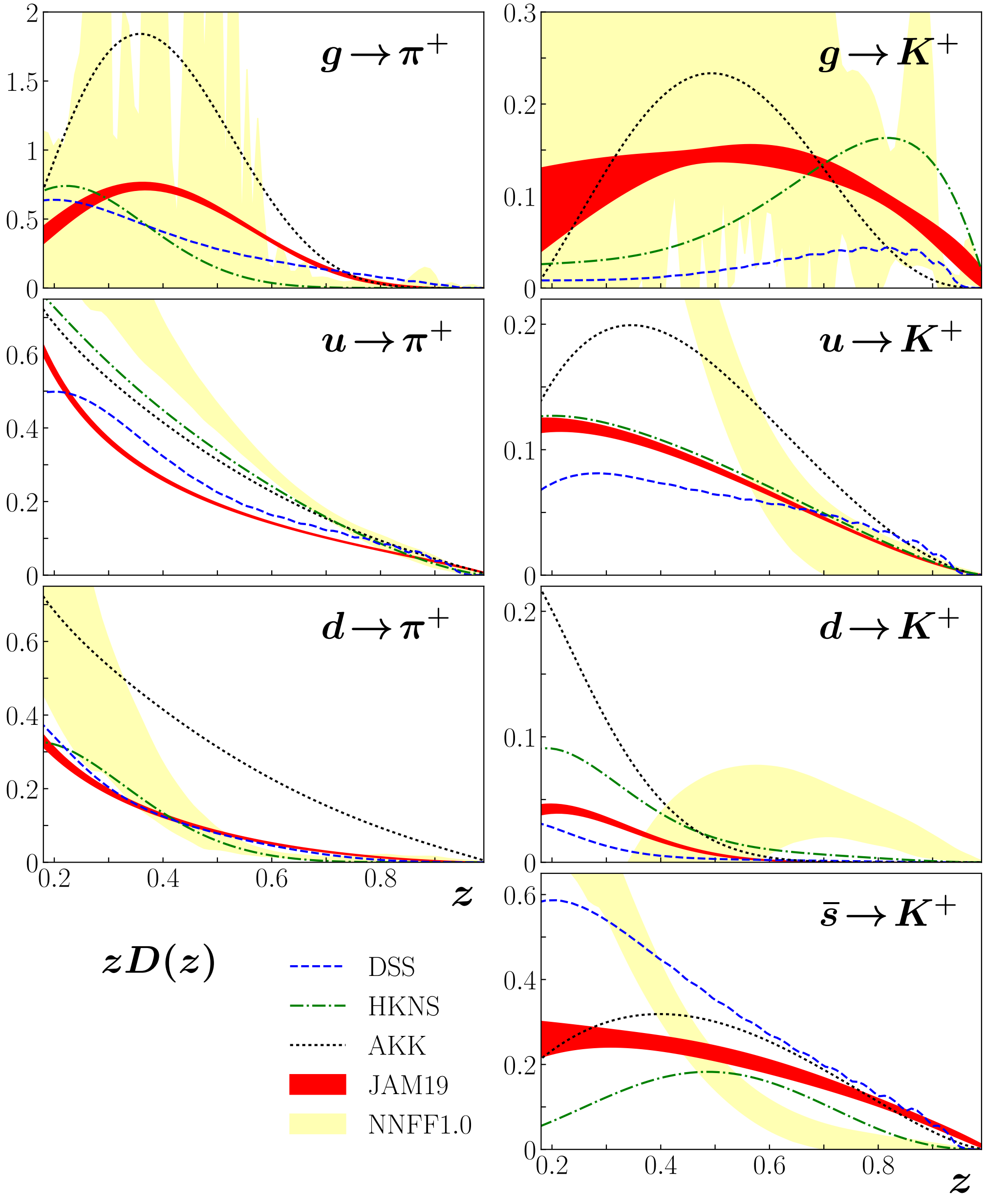


Consistency with previous analyses

Sea asymmetry from E866 measurements

Strong strange suppression!

JAM19 FFs (Preliminary)

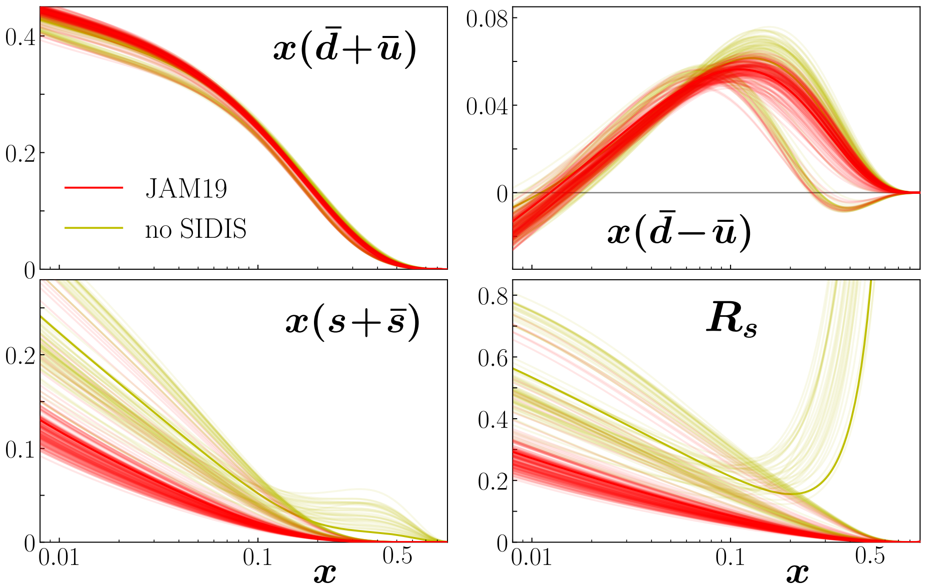


Constraints on gluon distributions at low Q

Consistent with unfavored < favored expectations

Large s → K distribution at large z

JAM19 Impact of SIDIS (Preliminary)

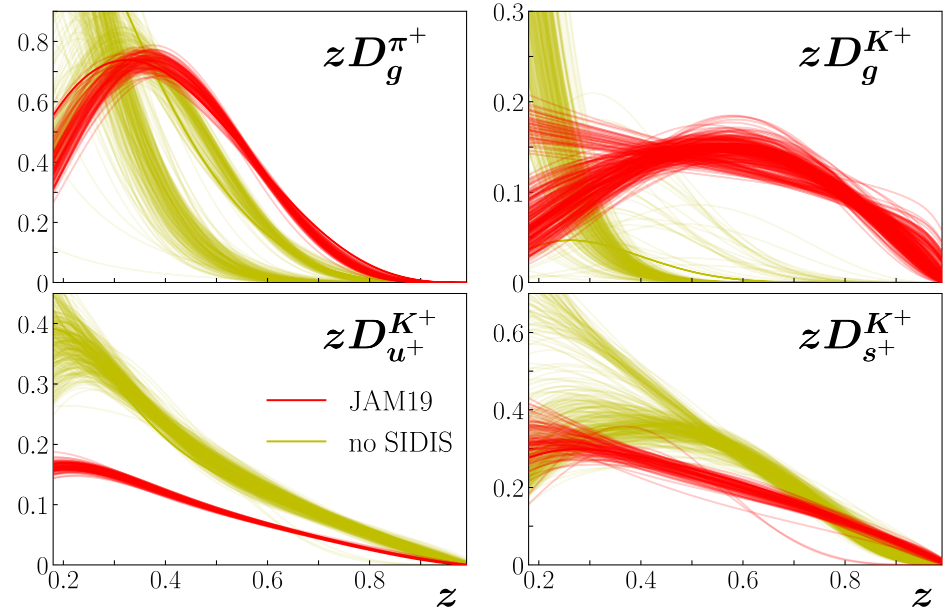


Preference for larger sea asymmetry solution at medium to large x

Strange suppression driven by SIDIS data!

SIDIS constraints on gluon FF distributions

Significant impact on favored fragmentation



Fitting Strategies

- Simultaenous PDF+FF extractions require robust fitting methodologies

  → Single least-squares fits with Hessian error estimation is impractical

- Monte Carlo methods provide more reliable PDF/FF uncertainties

  → Many least-squares fits with parameter sampling + Gaussian smearing (JAM, NNPDF, …)

  → Nested Sampling (JAM – arXiv:1804.01965, arXiv:1710.09858)

  → Markov Chain Monte Carlo (MCMC) or Hybrid Monte Carlo (HMC) – M. Mangin-Brinet & Y. Gabin Gbedo

- Shifting towards modern data science techniques in PDF/FF analyses:

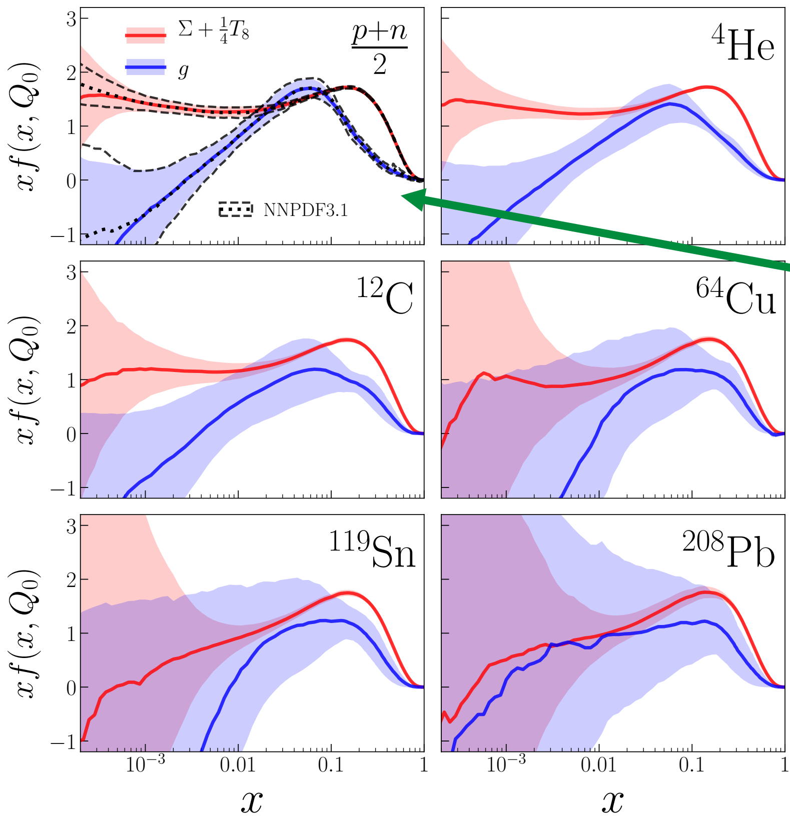
  → ML tools (scikit-learn, etc.) for training, clustering, outlier detection

  → ML libraries (PyTorch,TensorFlow,etc) for model building and training

"Simultaneous" Nuclear PDF Fit

R. Abdul Khalek, JE, J. Rojo
arXiv:1904.00018

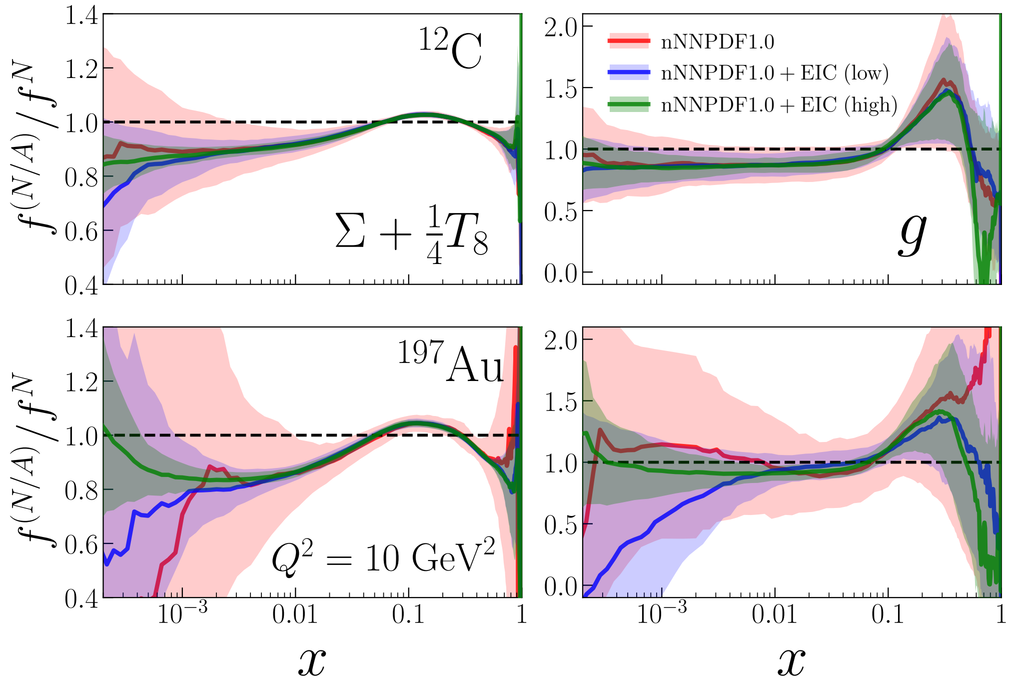
- First PDF fit using TensorFlow -- machine learning library developed by Google AI team



$$\chi^2 \equiv \sum_{i,j=1}^{N_{\rm dat}} \left(R_i^{(\rm exp)} - R_i^{(\rm th)}(\{f_m\})\right) ({\rm cov}_{t_0})^{-1}_{ij} \left(R_j^{(\rm exp)} - R_j^{(\rm th)}(\{f_m\})\right)$$

$$+ \lambda \sum_{m=g,\Sigma,T_8} \sum_{l=1}^{N_x} \left(f_m(x_l, Q_0, A) - f_m^{(p+n)/2}(x_l, Q_0)\right)^2$$

Replicating proton PDFs at A=1



Studied impact of EIC pseudodata

Summary and Outlook

- Monte Carlo and machine learning methods are important for robust extractions of non-perturbative functions and their uncertainties

  → Necessary for future global and universal QCD studies that contain large data sets and have many fit parameters

- New approaches being developed:

  → Simultaneous extractions of PDFs and FFs

  → Implementation of modern machine learning tools

- Current JAM universal analyses

  → Impact of polarized SIDIS on strange polarization (JAM17)

  → Impact of unpolarized SIDIS on strange PDF (JAM19)

- Future JAM studies

  → Inclusion of jet, W+c, and other unpolarized pp collision observables

  → Including polarized observables in simultaneous unpolarized+polarized PDF + FF analysis