First simultaneous extraction of spin PDFs and FFs from a global QCD analysis [arXiv:1705.05889 PRL 119 132001]

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The Flavor Structure of Nucleon Sea
October 3rd, 2017

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JAM

Proton spin structure from DIS

- Measured via longitudinal and transverse spin asymmetries

$$A_{\parallel} = \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} = D\left(A_1 + \eta A_2\right) \qquad A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\uparrow\Leftarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\uparrow\Leftarrow}} = d\left(A_2 + \zeta A_1\right)$$

→ Virtual photoproduction asymmetries: $A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1}$ $A_2 = \gamma \frac{(g_1 + g_2)}{F_1}$ $\gamma^2 = \frac{4M^2x^2}{Q^2}$

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- First moment of polarized structure function g_1:

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

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

"Plus" helicity distributions: $\Delta q^+ = \Delta q + \Delta \bar{q}$

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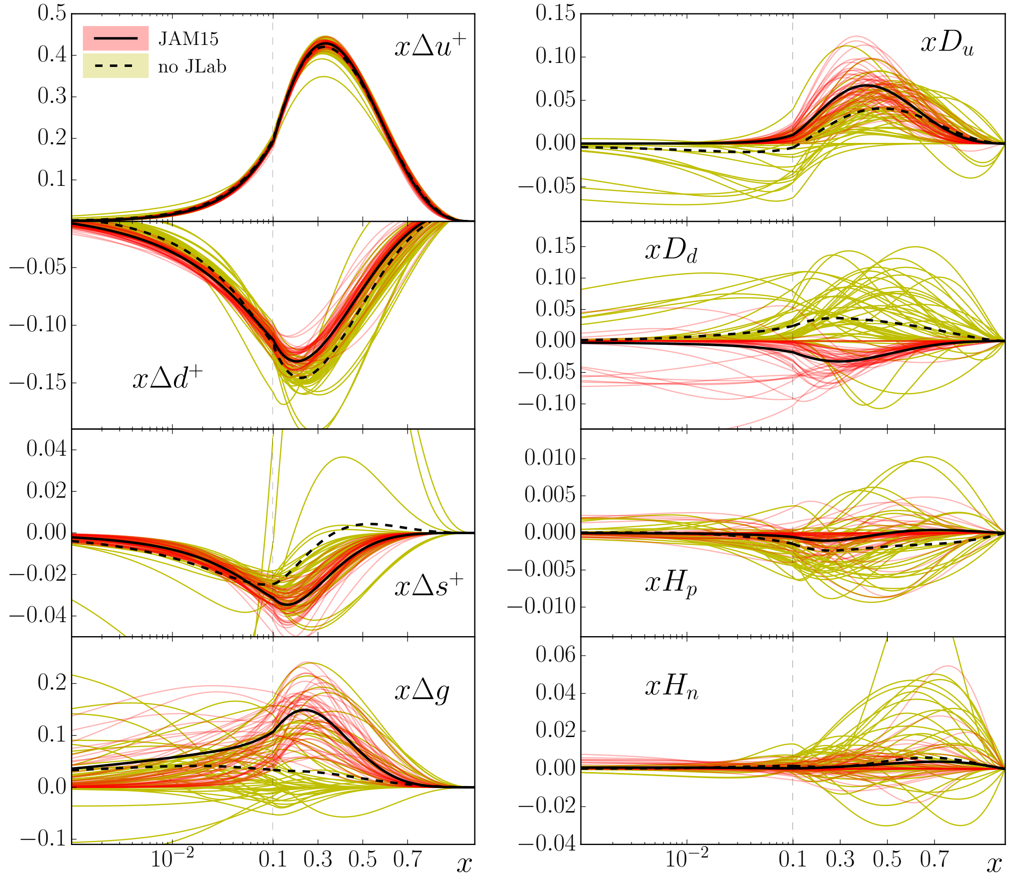
→ DIS requires assumptions about triplet and octet axial charges

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

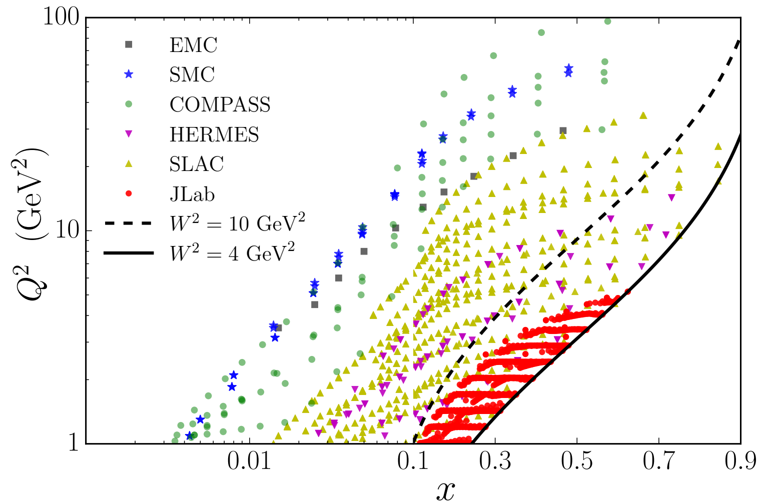
$$\int dx\left(\Delta u^+ - \Delta d^+\right) = g_A \sim 1.269 \qquad \int dx\left(\Delta u^+ + \Delta d^+ - 2\Delta s^+\right) = a_8 \sim 0.586$$

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

JAM15 Analysis – Impact of JLab Data



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



- Low-Q^2 / Low-W^2 cuts
- Systematic treatment of higher twist corrections – based on formalism from J. Blümlein

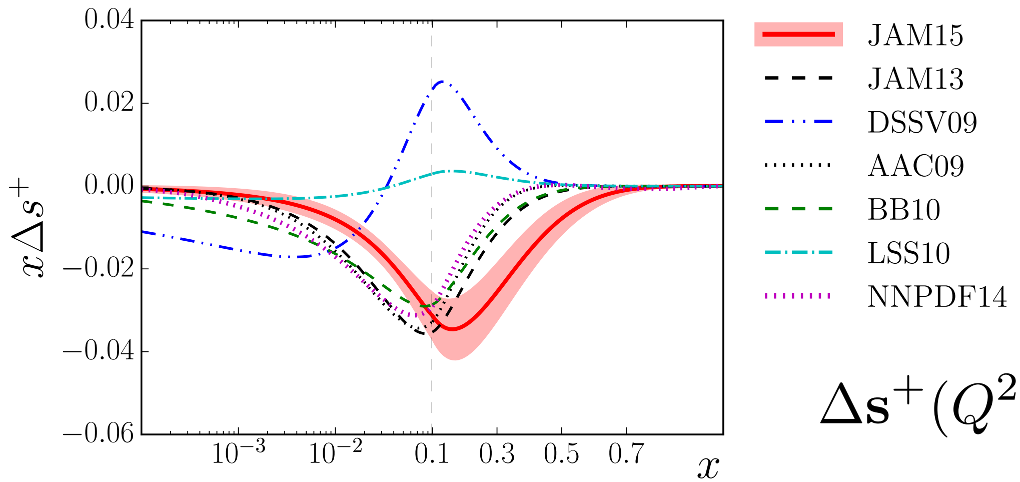
J. Blümlein and A. Tkabladze
Nucl. Phys. B553, 427 (1999)

$$\Delta\Sigma_{[0.001,0.8]} = 0.31 \pm 0.03$$

Strange polarization

- How much does the strange quark contribute to the proton spin?

  → Global QCD analyses indicate non-zero strange polarization – violation of Ellis-Jaffe sum rule



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

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

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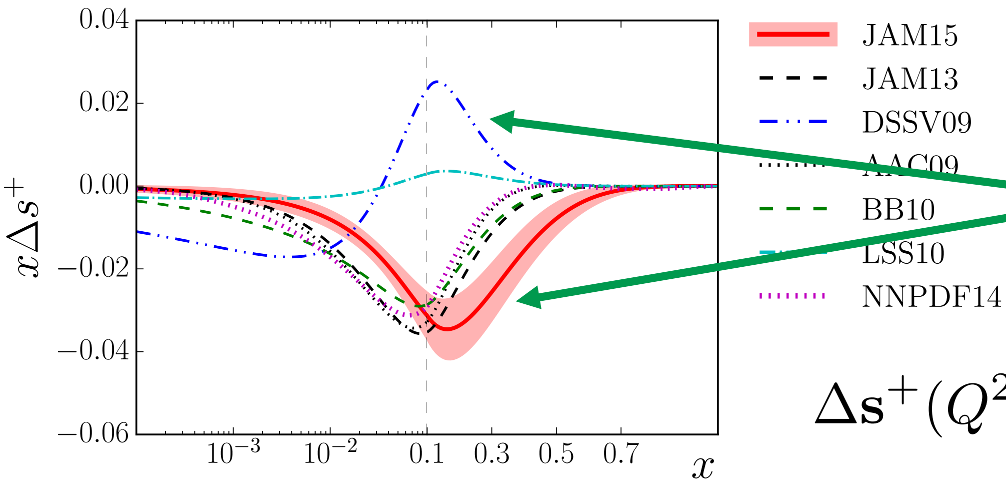

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Extracted under SU(3) constraint

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- Assuming ~20% $SU(3)_f$ symmetry breaking in value of a_8

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

C. Aidala et. al. Rev. Mod. Phys. 85 655 (2013)

- How does semi-inclusive DIS affect the shape of Δs+?

  → More general: what can SIDIS tell us about sea quark contributions?

Semi-inclusive DIS

- SIDIS observables require information on FFs → contains information about quark to hadron fragmentation.

$$d\sigma^{SIDIS} = \sum_f \int d\xi d\zeta\, \Delta f(\xi) D_f(\zeta) d\hat{\sigma}$$

- Which SIDIS observable is most sensitive to strange PDF?

→ Kaon valence structure contains strange flavor $K^+(u\bar{s})$ $K^-(u\bar{s})$

- From proton target:

$$d\sigma^{K^+} \sim 4\Delta u D_u^{K^+} + \Delta\bar{s} D_{\bar{s}}^{K^+}$$

$$d\sigma^{K^-} \sim 4\Delta\bar{u} D_{\bar{u}}^{K^-} + \Delta s D_s^{K^-} + 4\Delta u D_u^{K^-}$$

- From deuteron target:

$$d\sigma^{K^+} \sim 4(\Delta u + \Delta d) D_u^{K^+} + 2\Delta\bar{s} D_{\bar{s}}^{K^+}$$

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Dominate terms in intermediate to large-*x* region

Low-x sensitivity

- From deuteron target:

$$d\sigma^{K^+} \sim 4(\Delta u + \Delta d) D_u^{K^+} + 2\Delta\bar{s} D_{\bar{s}}^{K^+}$$

$$d\sigma^{K^-} \sim 4(\Delta\bar{u} + \Delta\bar{d}) D_{\bar{u}}^{K^-} + 2\Delta s D_s^{K^-} + 4(\Delta u + \Delta d) D_u^{K^-}$$

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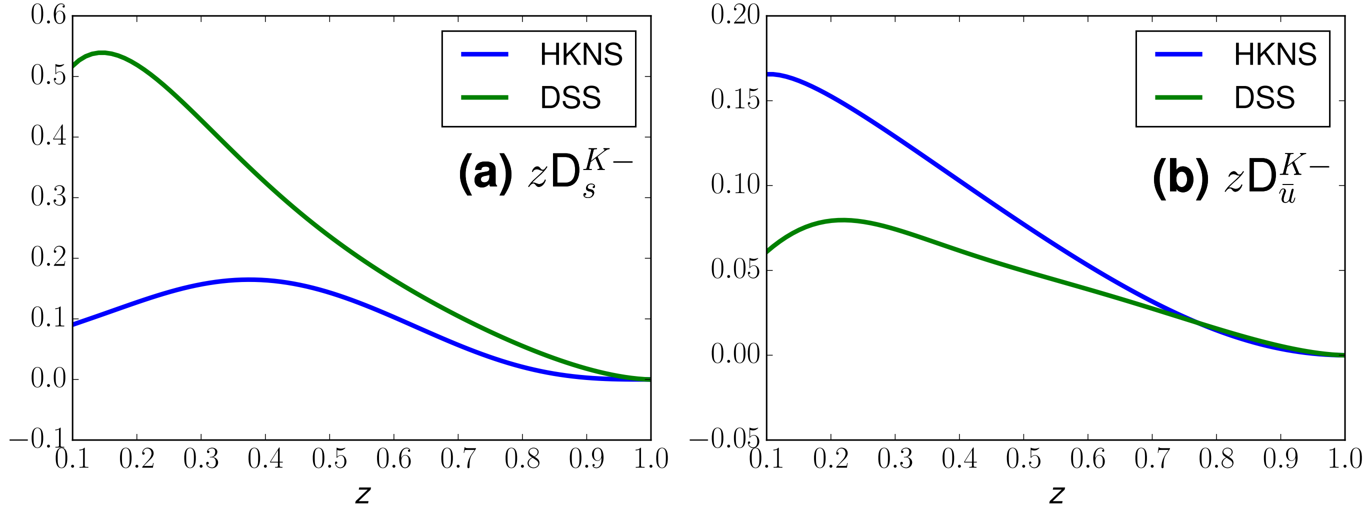
Fragmentation Functions

- SIDIS observables require information on FFs → contains information about quark to hadron fragmentation.

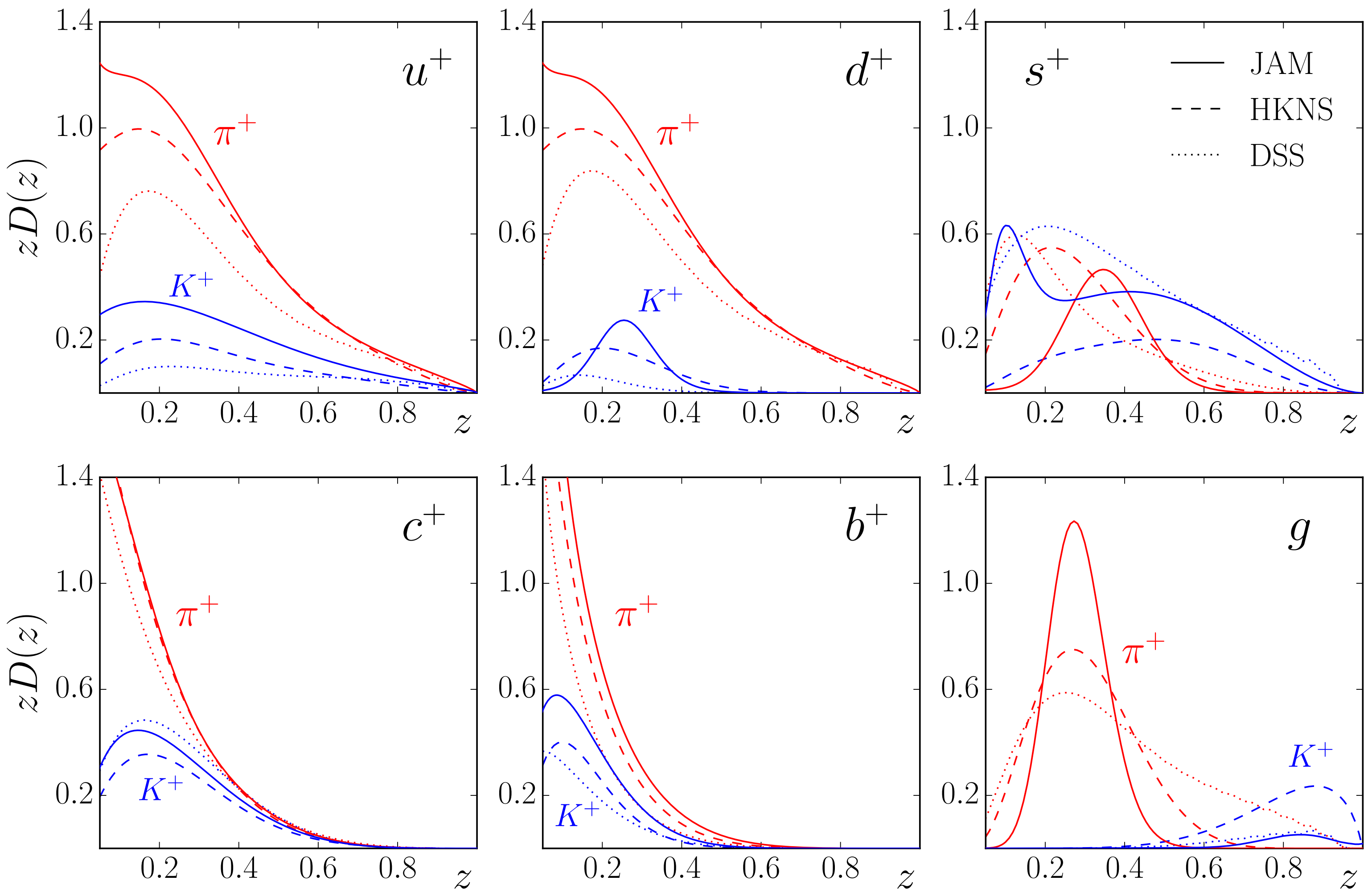
$$d\sigma^{SIDIS} = \sum_f \int d\xi d\zeta\, \Delta f(\xi) D_f(\zeta) d\hat{\sigma}$$

→ Choice of kaon FF parameterization influences shape of strange polarization density in SIDIS analysis (*Leader et. al.*)



→ Recent JAM analysis extracted FFs from single-inclusive e^+e^- annihilation using the iterative Monte Carlo technique (arXiv:1609:00899)

JAM16 Analysis – SIA analysis



- Closer agreement with DSS analysis for $s^+ \rightarrow K^+$ distribution

JAM17 Combined Analysis

- We perform the first ever combined Monte Carlo analysis of polarized DIS, polarized SIDIS, and SIA data (at NLO)

$$d\sigma^{DIS} = \sum_f \int d\xi\, \Delta f(\xi) d\hat{\sigma} \qquad d\sigma^{SIA} = \sum_f \int d\zeta\, D_f(\zeta) d\hat{\sigma}$$

$$d\sigma^{SIDIS} = \sum_f \int d\xi d\zeta\, \Delta f(\xi) D_f(\zeta) d\hat{\sigma}$$

- Spin PDFs and FFs are fitted simultaneously
- SU(2) and SU(3) constraints used in DIS only analyses are released

$$\int_0^1 dx\,(\Delta u^+ - \Delta d^+) \stackrel{?}{=} g_A$$

→ Direct test of QCD

$$\int_0^1 dx\,(\Delta u^+ + \Delta d^+ - 2\Delta s^+) \stackrel{?}{=} a_8$$

→ Combined DIS+SIDIS can determine values for g_A and a_8

Fitting Methods

- Start with functional form for PDFs and FFs, e.g.

$$xf(x) = Nx^a(1-x)^b(1+c\sqrt{x}+dx)$$

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

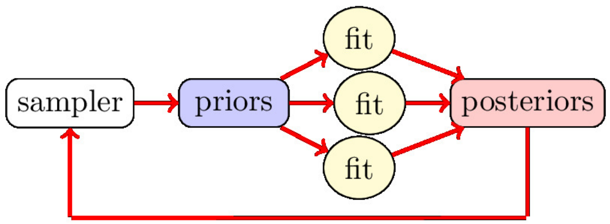
- Single χ^2 fit of parameters
  - → Typically fix parameters that are difficult to constrain
  - → Uncertainties determined by Hessian or Lagrange multiplier methods
    - → Introduces tolerance criteria

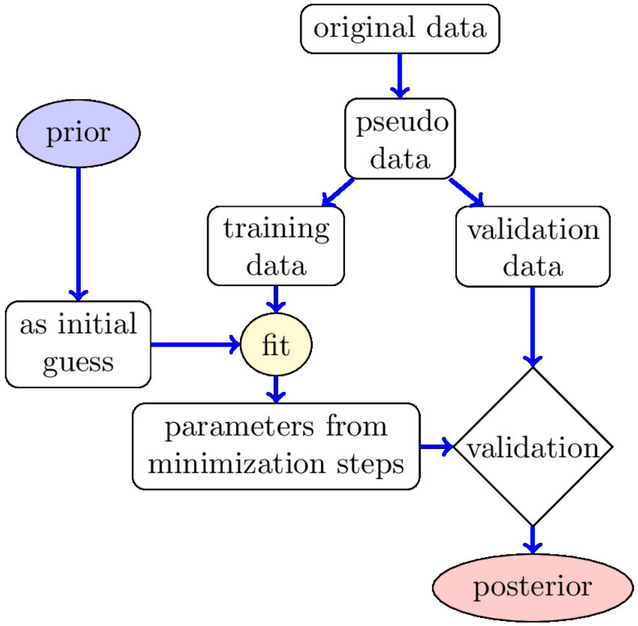
However, χ^2 is a highly non-linear function of the fit parameters…there can be many local minima!

- Monte Carlo methods (neural network, Markov chain, nested sampling, etc.)
  - → Allows exploration of the parameter/chi-squared landscape
  - → Uncertainties determined directly from Monte Carlo sample

- JAM17 uses iterative Monte Carlo procedure for combined PDF/FF analysis

Iterative Monte Carlo (IMC) Fitting Methodology





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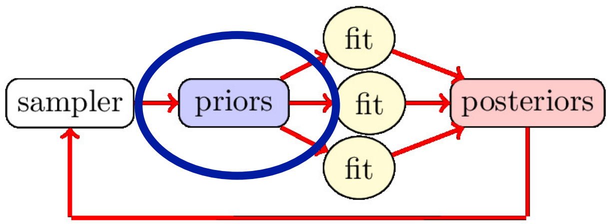

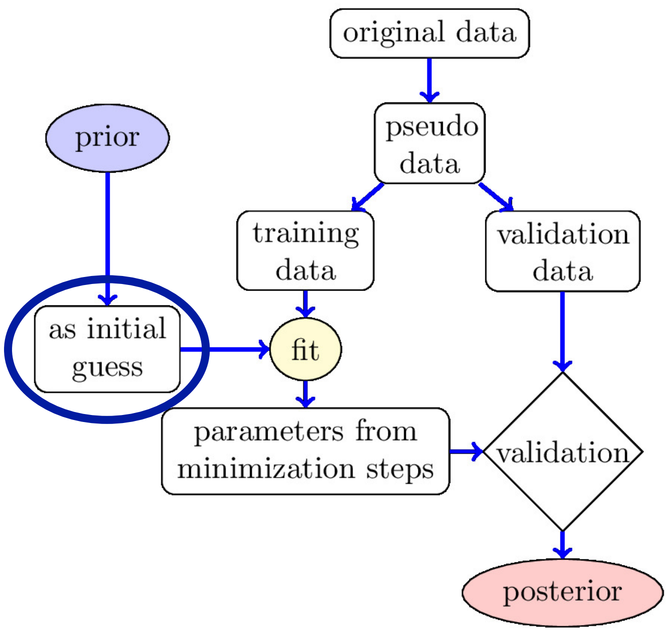

Initial iteration: flat sample priors

→ Set of parameters used as initial guess for least-squares fits

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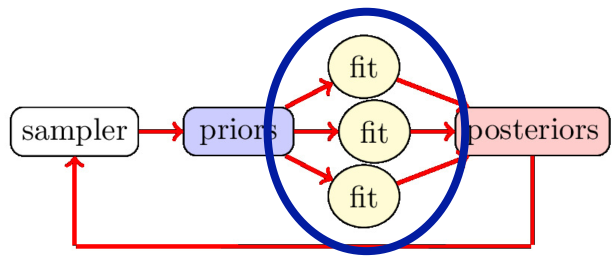
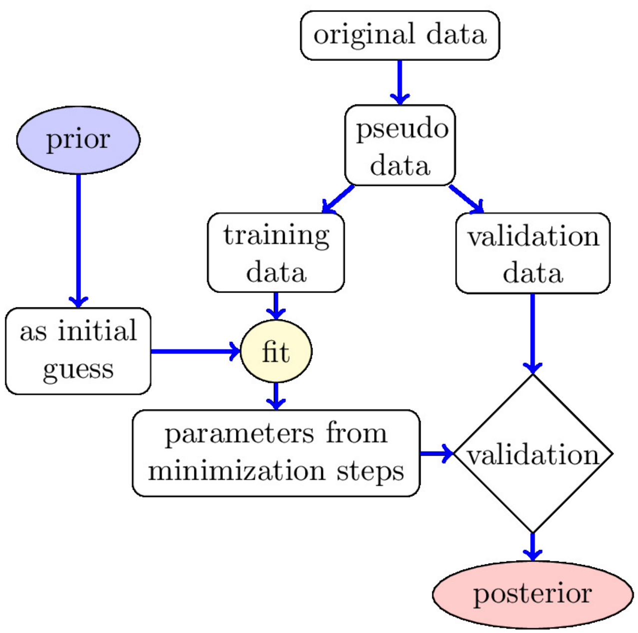


Perform thousands of fits



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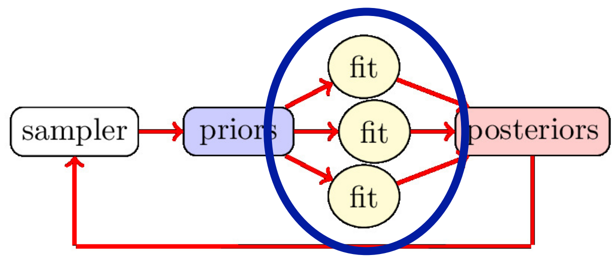
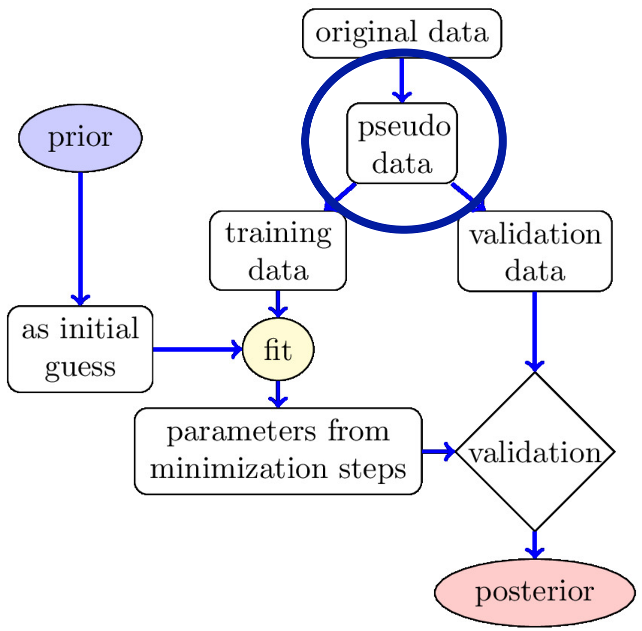
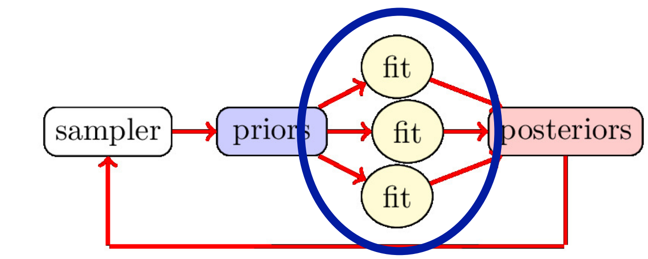


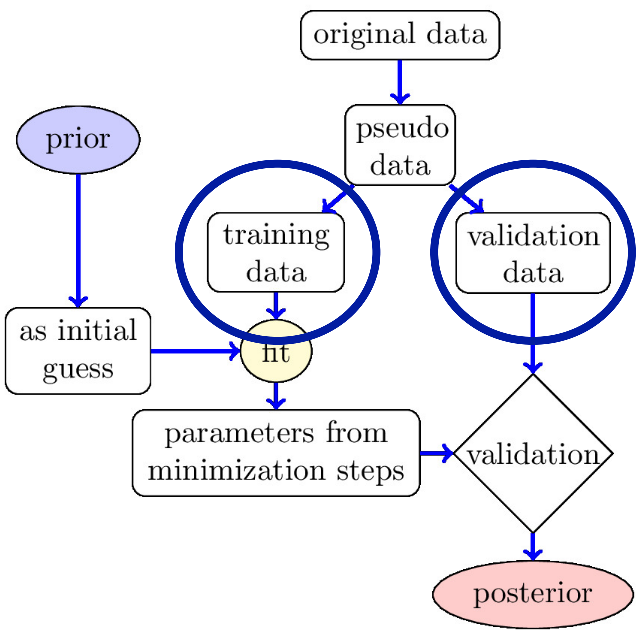


Perform thousands of fits

→ Pseudo-data constructed by bootstrap method

Iterative Monte Carlo (IMC) Fitting Methodology



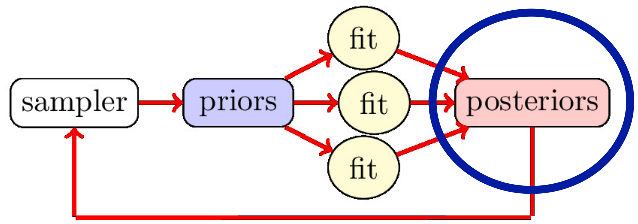


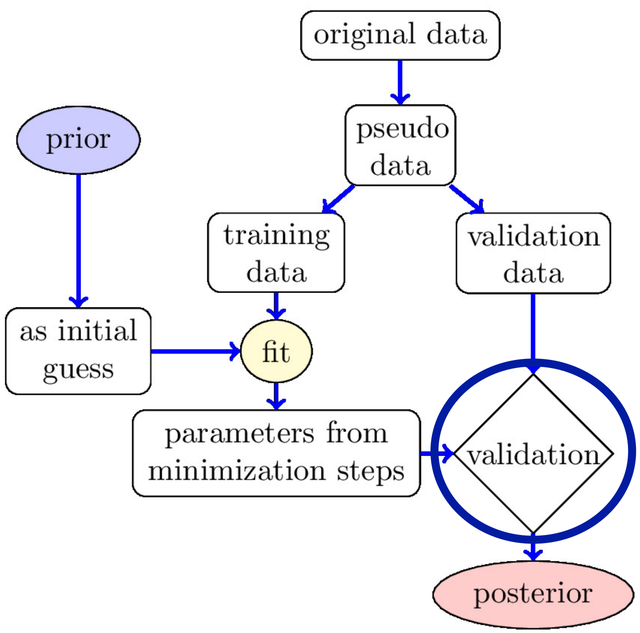
Perform thousands of fits

→ Pseudo-data constructed by bootstrap method

→ Data is partitioned for cross-validation – training set is fitted via chi-square minimization

Iterative Monte Carlo (IMC) Fitting Methodology

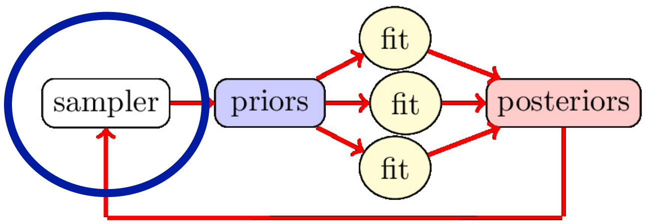


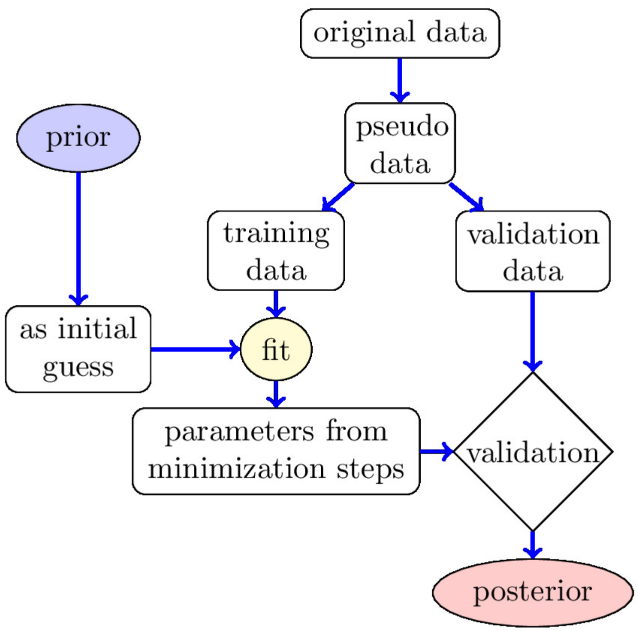


Obtain a set of posteriors

→ Set of parameters that minimize validation chi-square are chosen as posteriors

Iterative Monte Carlo (IMC) Fitting Methodology





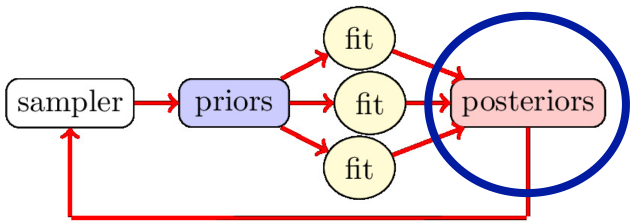
Posteriors are sent through a sampler

→ Kernel density estimation (KDE): estimates the multi-dimensional probability density function of the parameters

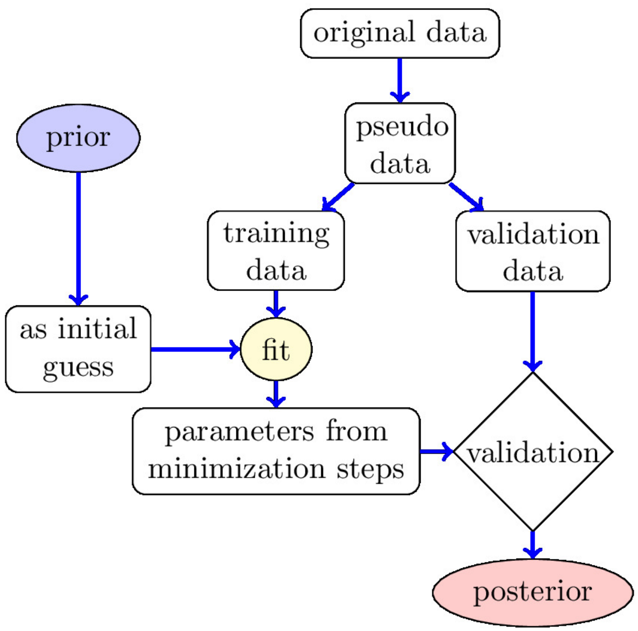
→ A sample of parameters is chosen from the KDE and used as starting priors for the next iteration

→ Iterated until distributions are converged

Iterative Monte Carlo (IMC) Fitting Methodology



Obtain final set of parameters

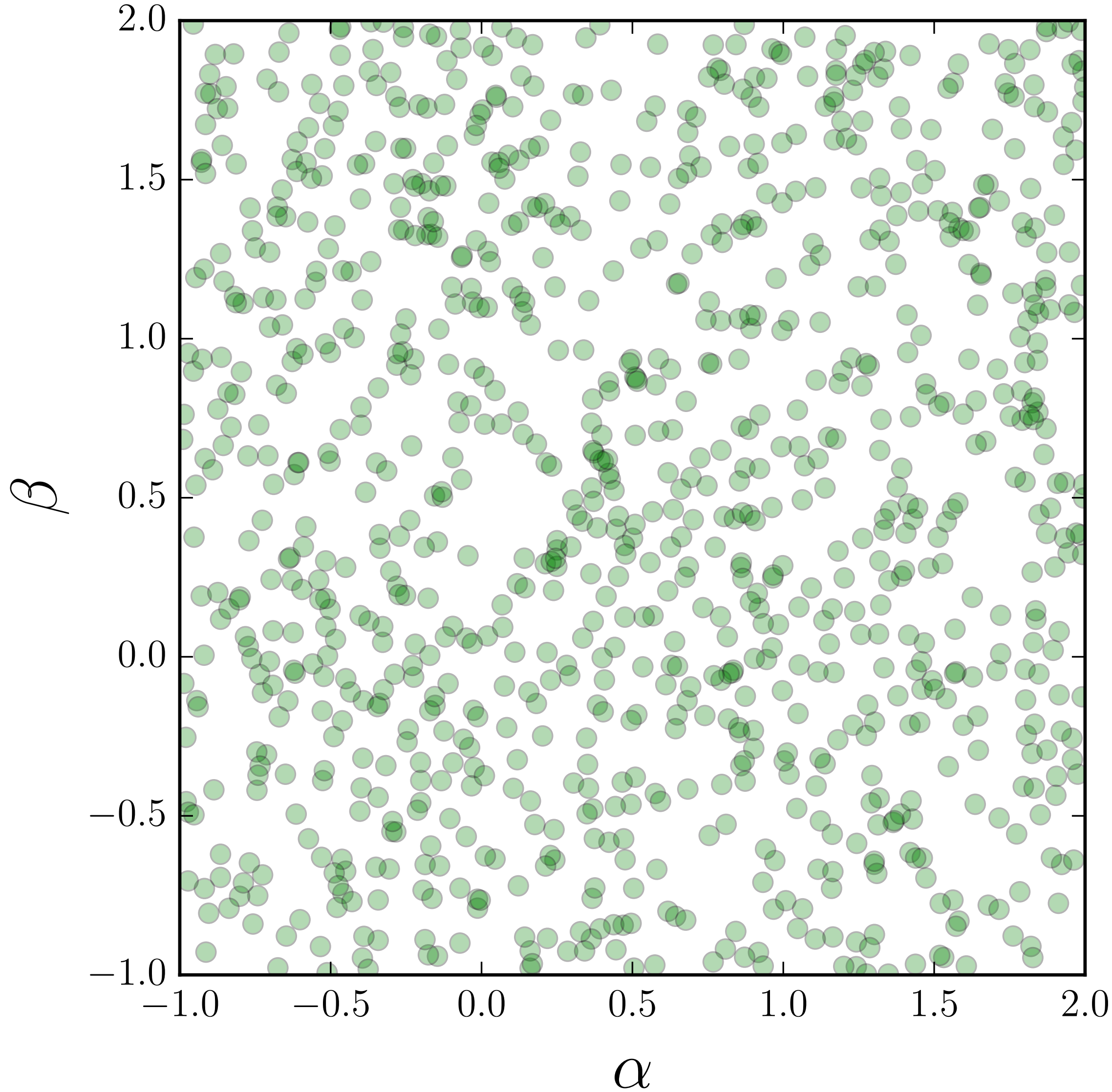


→ Compute mean and standard deviation of observables

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

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

IMC Methodology

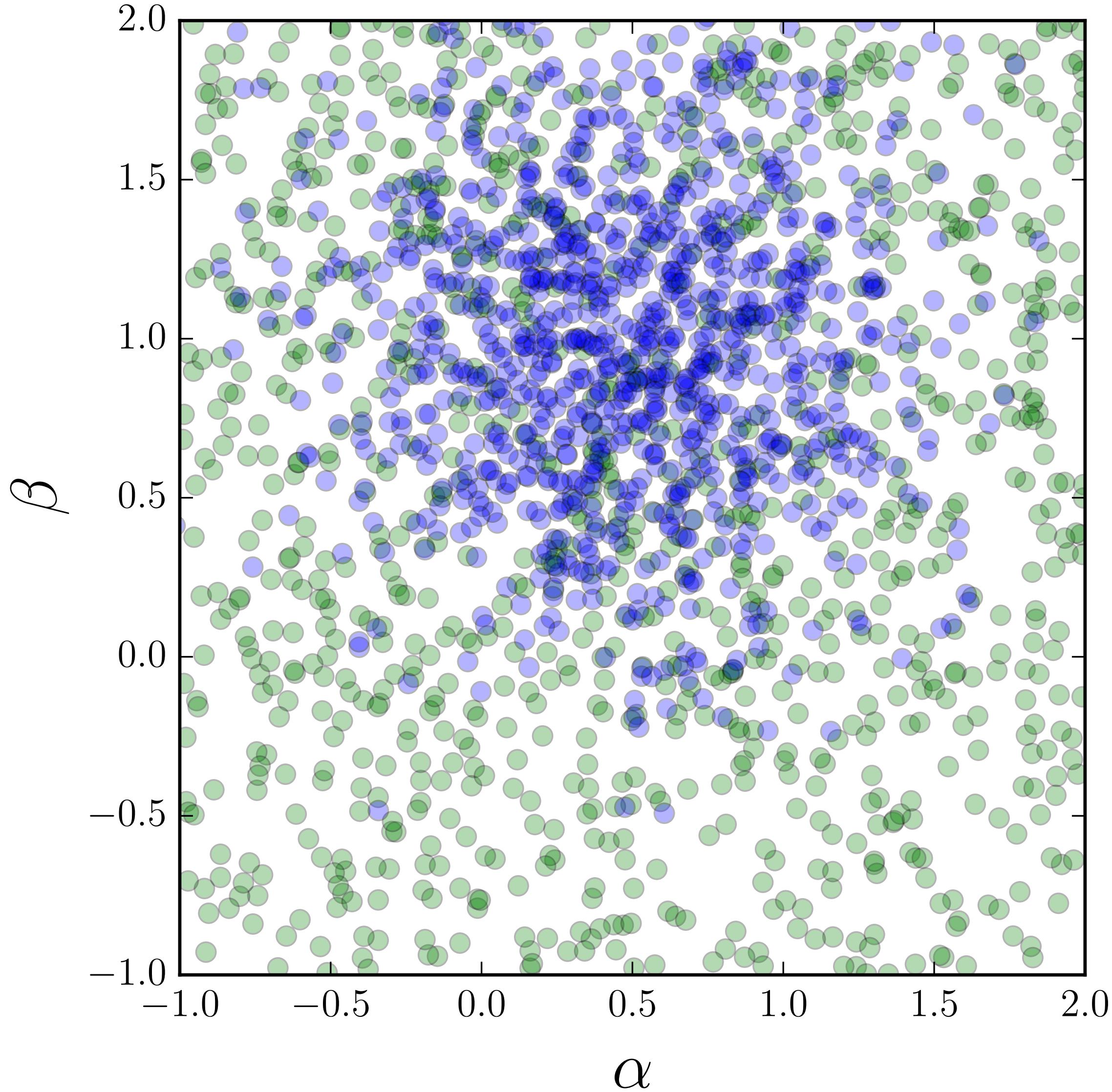


Toy Model

- Flat sampling of initial priors

$$\{\alpha, \beta\}$$

IMC Methodology



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- Initial set of fits → posteriors

$$\{\alpha, \beta\} \rightarrow \{\alpha, \beta\}$$

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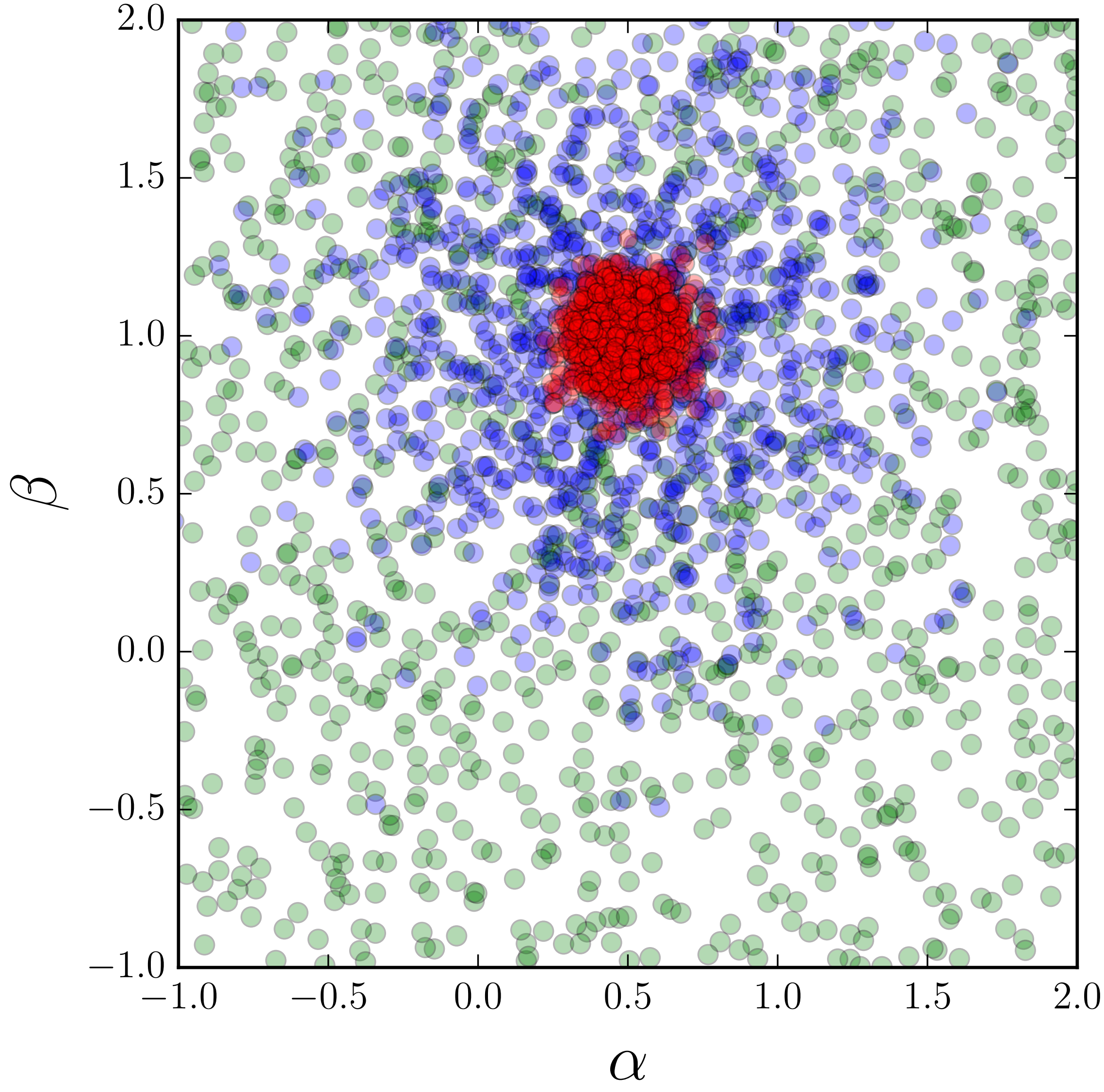

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- Posteriors → priors for first iteration → new posteriors

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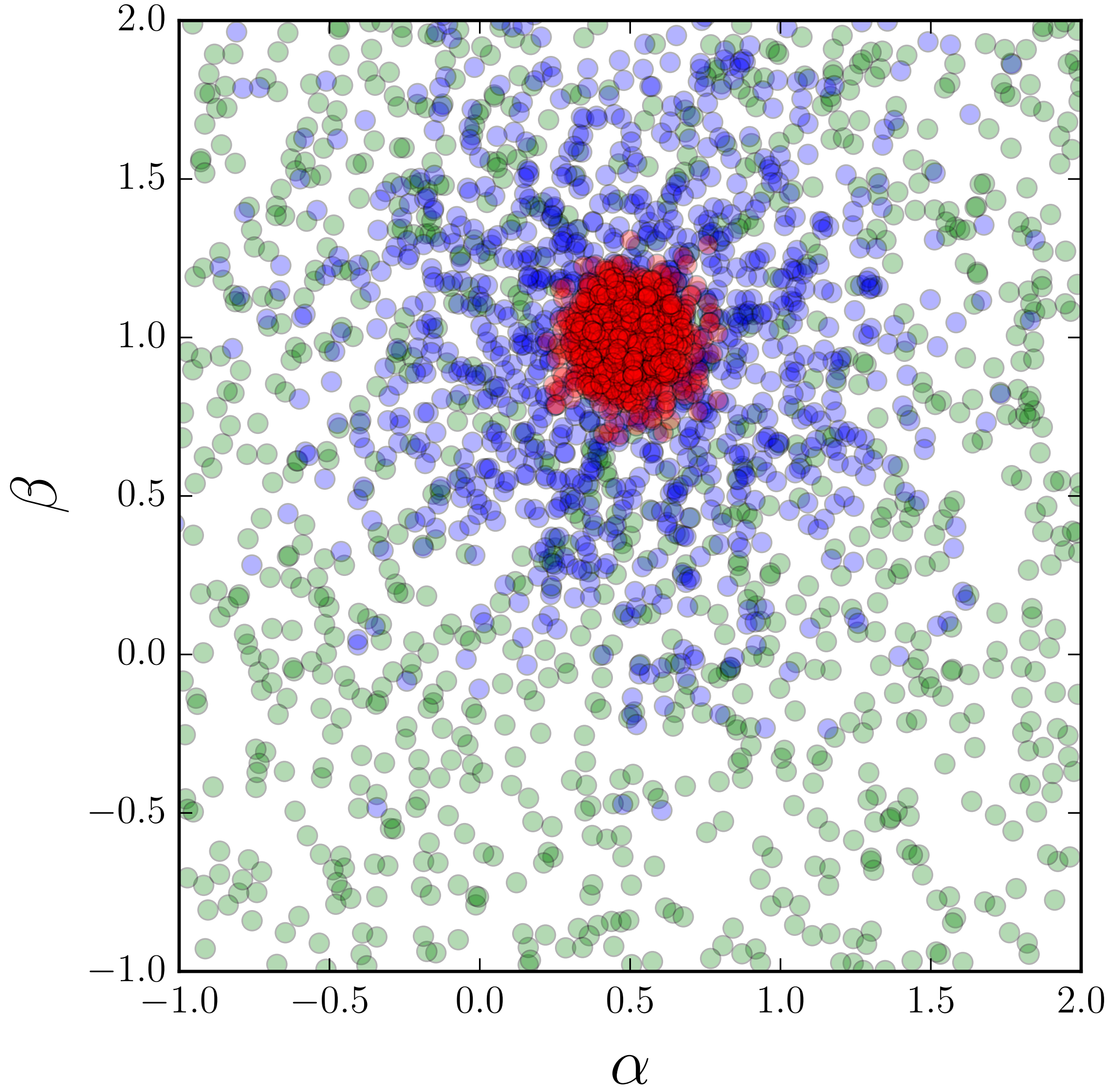
IMC Methodology



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- Repeat until convergence…

Parameterizations and Chi-square

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

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

Pions:

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

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

Kaons:

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

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

- Chi-squared definition:

$$\chi^{2}(\boldsymbol{a}) = \sum_{e}\left[\sum_{i}\left(\frac{\mathcal{D}^{(e)}_{i}N^{(e)}_{i} - T^{(e)}_{i}(\boldsymbol{a})}{\alpha^{(e)}_{i}N^{(e)}_{i}}\right)^{2} + \sum_{k}\left(r^{(e)}_{k}\right)^{2}\right] + \sum_{\ell}\left(\frac{a^{(\ell)}-\mu^{(\ell)}}{\sigma^{(\ell)}}\right)^{2}$$

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Penalty for fitting normalizations

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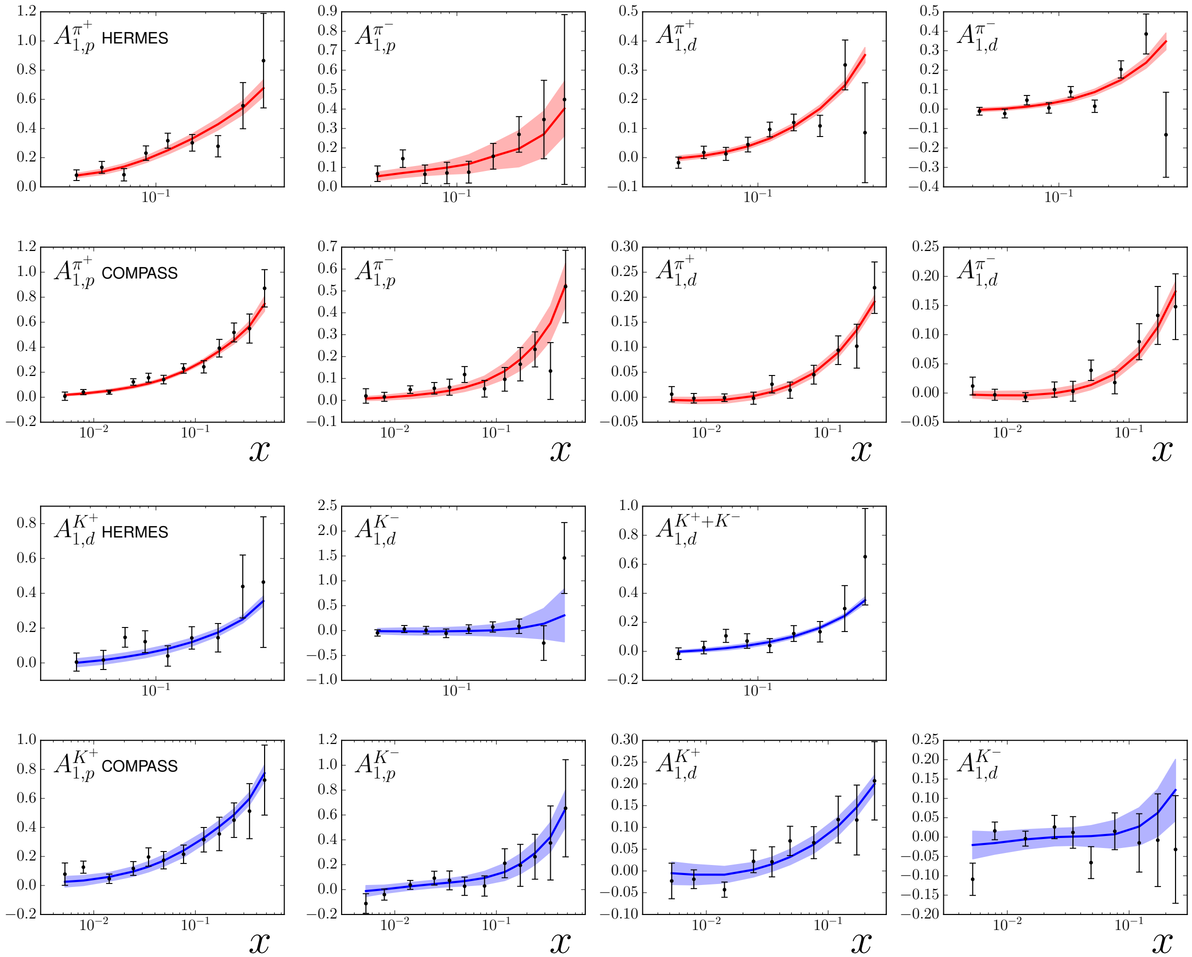
$$D^{K^+}_{s} = \mathrm{T}(z;\boldsymbol{a})$$

- Chi-squared definition:

$$\chi^2(\boldsymbol{a}) = \sum_e \left[\sum_i \left(\frac{\mathcal{D}^{(e)}_i N^{(e)}_i - T^{(e)}_i(\boldsymbol{a})}{\alpha^{(e)}_i N^{(e)}_i}\right)^2 + \sum_k \left(r^{(e)}_k\right)^2\right] + \sum_\ell \left(\frac{a^{(\ell)} - \mu^{(\ell)}}{\sigma^{(\ell)}}\right)^2$$

Modified likelihood to include prior information

Data vs Theory – SIDIS

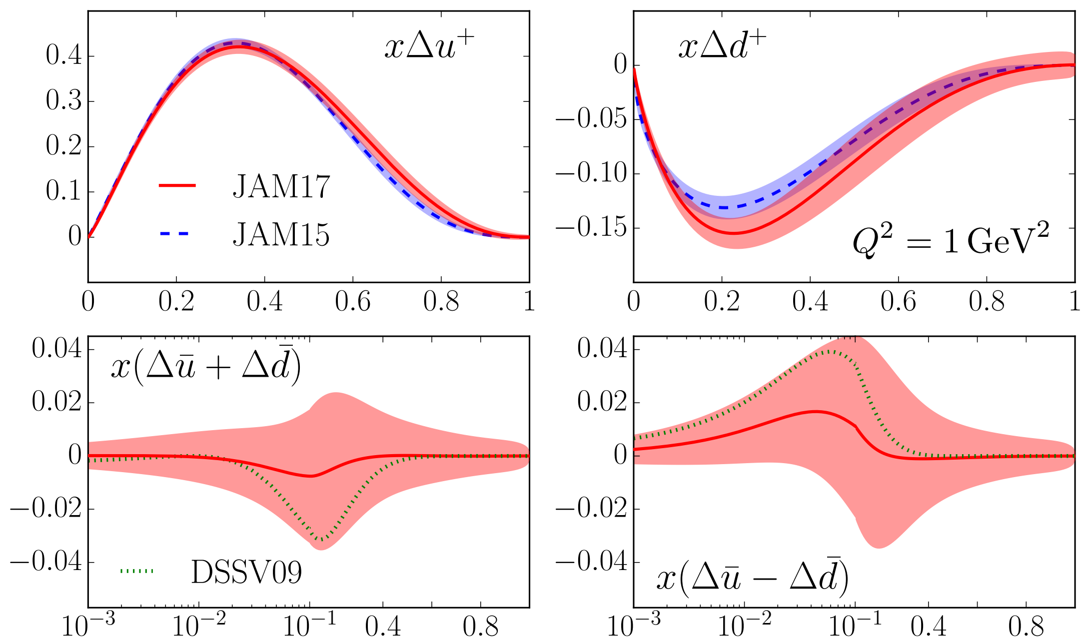


$$A_1^h = \frac{g_1^h}{F_1^h}$$

process	target	$N_{\rm dat}$	χ^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**

Good agreement overall with all data!

Polarized PDF Distributions

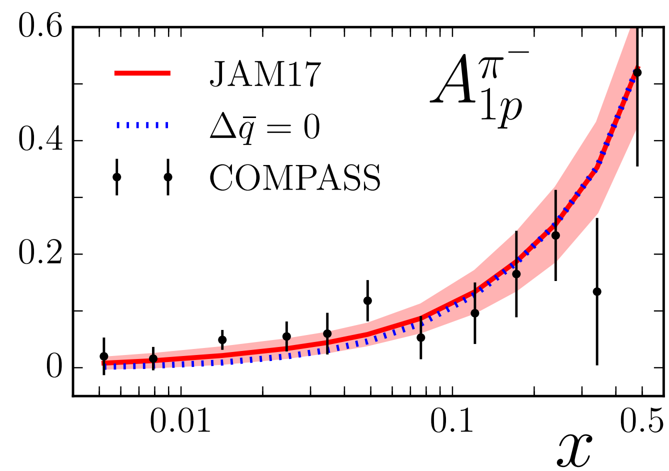


- Δu+ consistent with previous analysis
- Δd+ slightly larger in magnitude

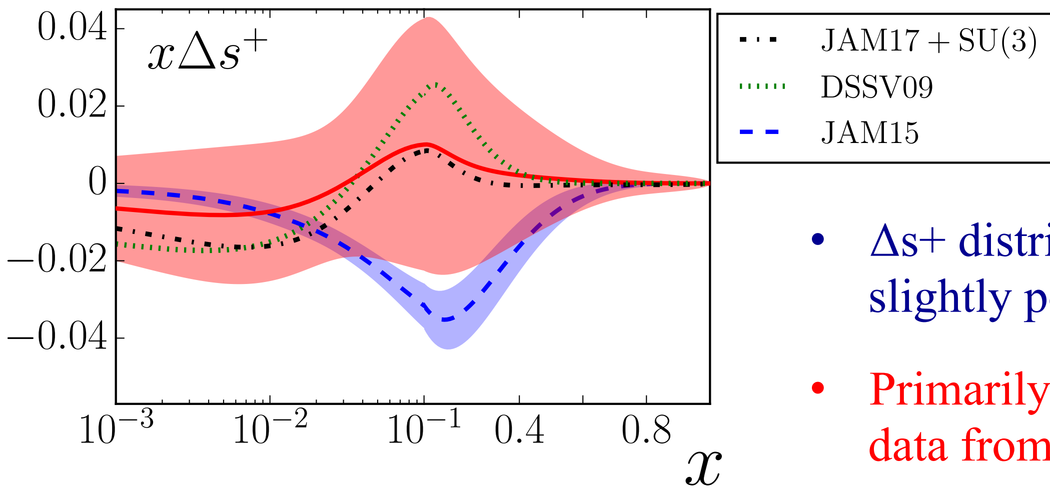
→ Anti-correlation with Δs+, which is less negative than JAM15 at *x* ~ 0.2

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

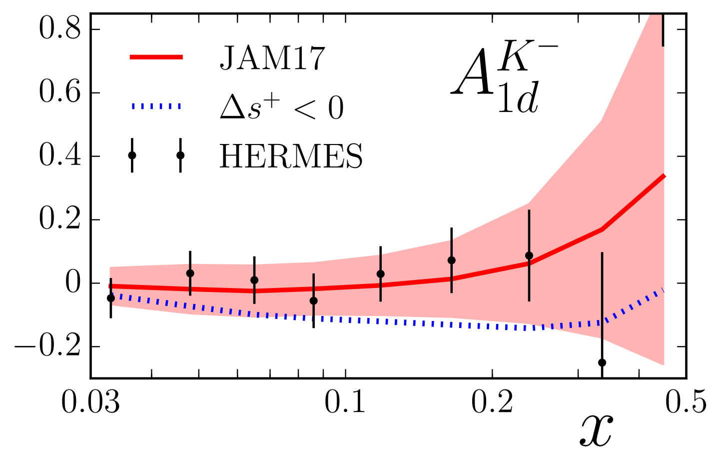
→ Non-zero asymmetry given by small contributions from SIDIS asymmetries



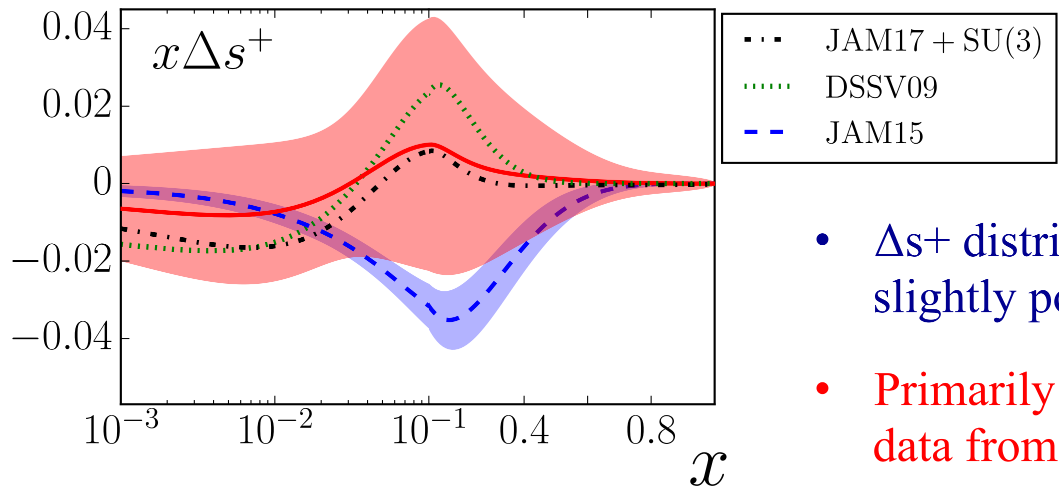
Strange polarization



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



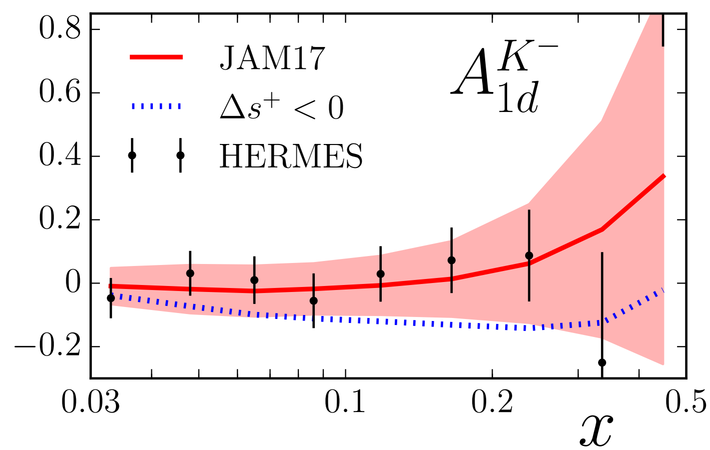
Strange polarization



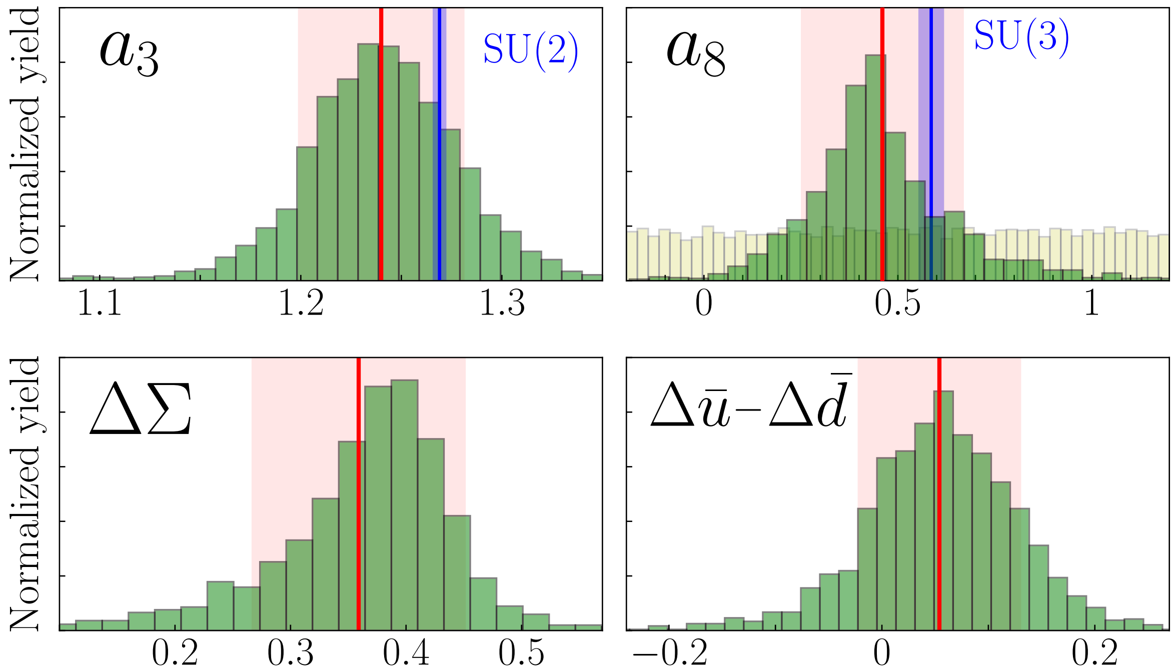
- Δs+ distribution consistent with zero, slightly positive in intermediate *x* range
- Primarily influenced by HERMES K$^-$ data from deuterium target

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

- Low *x* DIS deuterium data from COMPASS prefers small negative Δs$^+$
- Needs to be more negative in intermediate region to satisfy SU(3) constraint
- b parameter for Δs+ typically fixed to values ~6-10, producing a peak at x~0.1



Moments



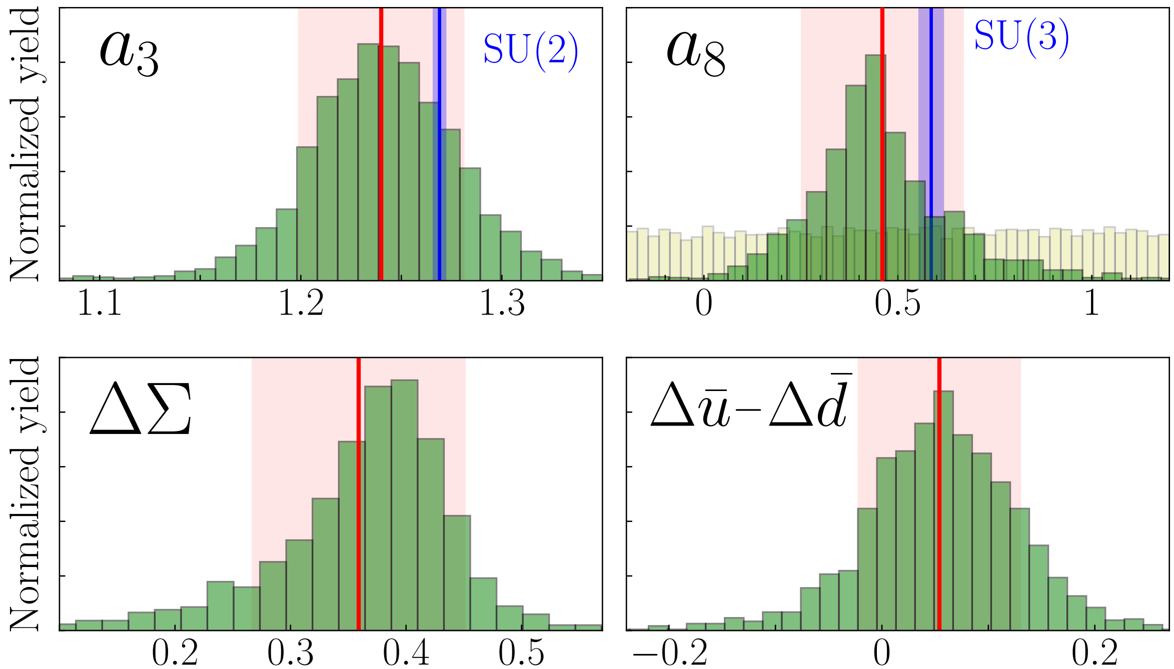
$$g_A = 1.24 \pm 0.04$$ Confirmation of SU(2) symmetry to ~2%

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

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

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

Moments



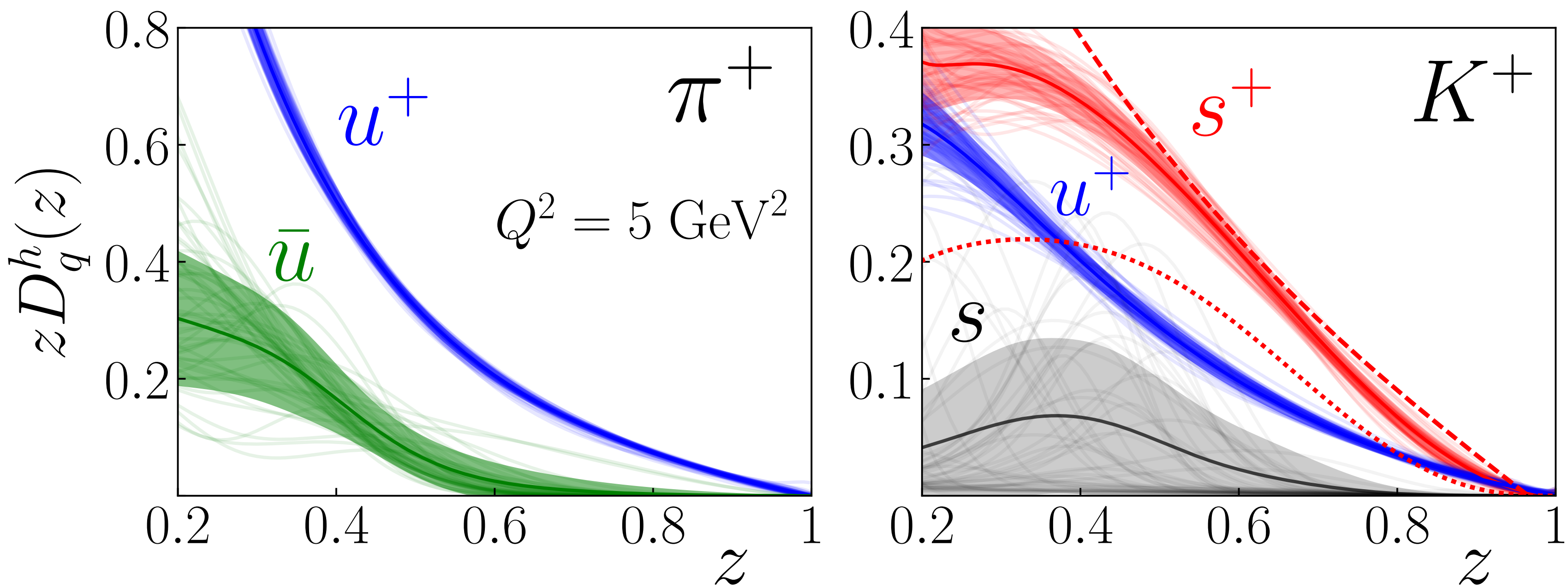
$$\Delta\Sigma = 0.36 \pm 0.09$$

Slightly larger central value than previous analyses, but consistent within uncertainty

Preference for slightly positive sea asymmetry; not very well constrained by SIDIS

$$\Delta\bar{u} - \Delta\bar{d} = 0.05 \pm 0.08$$

Fragmentation Functions



- Little change in 'plus' distributions from JAM16

  → s^+ to K^+ FF marginally smaller at low-z compared to JAM16

- Better agreement with DSS's strange FF (dashed red line) in intermediate z region than HKNS (dotted red line)
- Uncertainty for unfavored ū to π distribution smaller than s to K

  → Due to lower precision kaon production data

Summary and Outlook

- Analysis suggests the resolution of the "strange polarization puzzle"

  → Shape of Δs^+ in DIS+SU(3) analyses is artificial (caused by SU(3) constraint + large-x shape parameter)

- Data sensitive to Δs^+ distribution give result consistent with zero with large uncertainties

  → Need higher precision polarized SIDIS kaon data

- Difficult to determine a_8 with DIS+SIDIS, but results confirm SU(2) symmetry to ~2%

- QCD observables yet to be implemented:
  - *W* asymmetries for constraints on up and down sea polarization
  - Unpolarized SIDIS and single-inclusive *pp* collision for FFs

- JAM is working towards a universal fit of quark helicity distributions $q^{\uparrow}, q^{\downarrow}$
  - Global analyses of combined unpolarized and polarized data