Global Fitting Paradigms

Synergy Between Lattice And Phenomenology?

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

QCD Real–Time Dynamics and Inverse Problems

Date: Monday, October 19, 2020 - 8:20am to Thursday, October 22, 2020 - 12:30pm

Krzysztof Cichy

Adam Mickiewicz University

Research: Partonic distributions from Lattice QCD

Nobuo Sato

Jefferson Lab Theory Center

Research: QCD Global analysis (JAM) on hadron structure and hadronization

Panel Discussion

What we are going to discuss?

Global analysis (NS)

> What is a QCD global analysis?

> The **Bayesian inference** in a nutshell

> Why **lattice + experimental** data?

Synergy between lattice and pheno (KC)

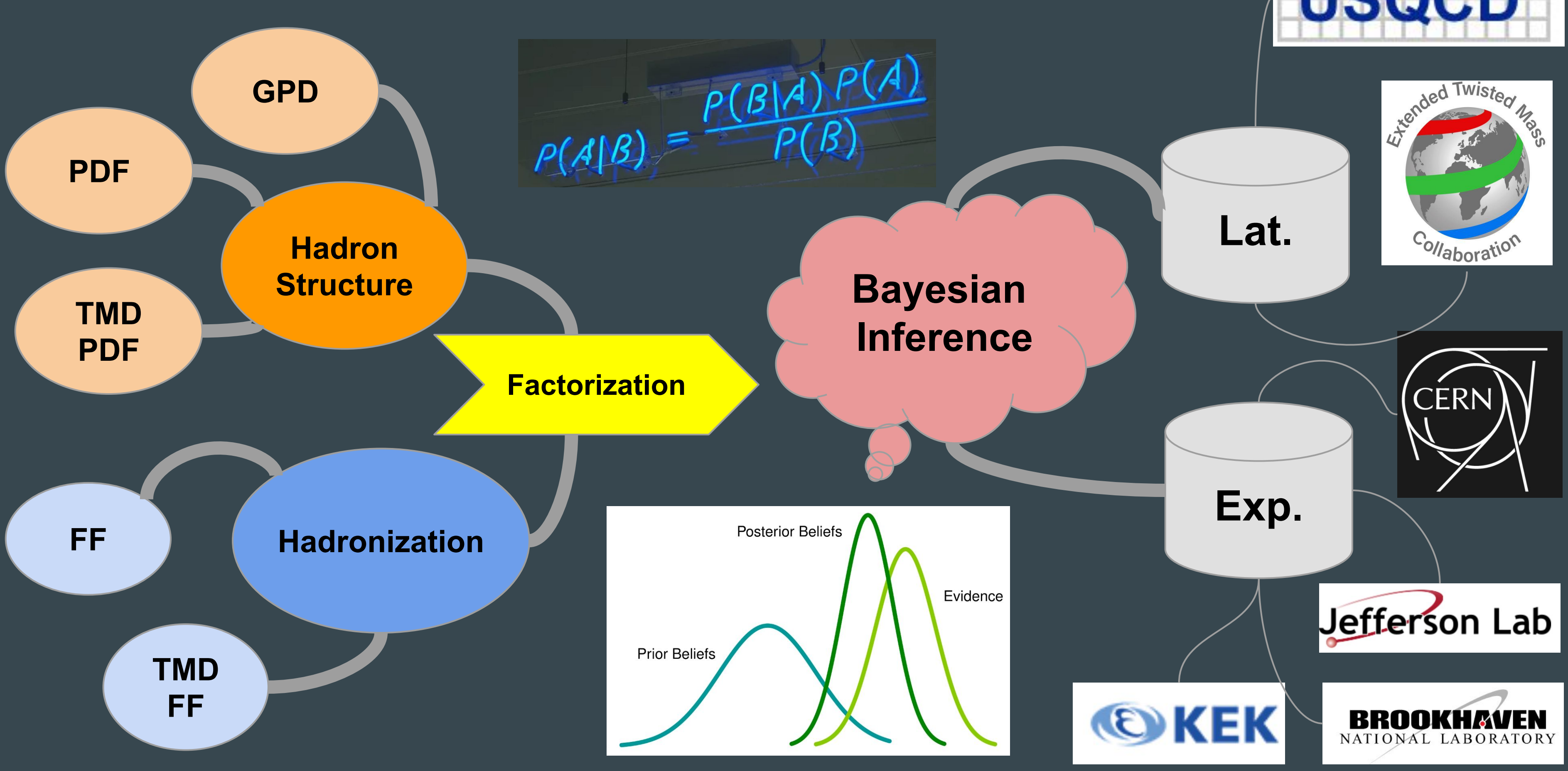
> LQCD: exploratory vs. precision studies

> Lattice approaches to partonic functions

> Some state-of-the-art lattice results

> Synergy: open problems/challenges

What is (the future of) QCD global analysis?



The Bayesian inference

$$f_i(\xi, \mu_0^2) = N_i \xi^{a_i} (1-\xi)^{b_i} (1 + ...)$$

$$d_i(\zeta, \mu_0^2) = N_i \zeta^{a_i} (1-\zeta)^{b_i} (1 + ...)$$

$$\mathbf{a} = (N_i, a_i, b_i, ...)$$

$$\mathrm{d}\sigma_{\mathrm{DIS}} = \sum_i H_i^{\mathrm{DIS}} \otimes f_i$$

$$\mathrm{d}\sigma_{\mathrm{DY}} = \sum_{ij} H_{ij}^{\mathrm{DY}} \otimes f_i \otimes f_j$$

$$\mathrm{d}\sigma_{\mathrm{SIA}} = \sum_i H_i^{\mathrm{SIA}} \otimes d_i$$

$$\mathrm{d}\sigma_{\mathrm{SIDIS}} = \sum_{ij} H_{ij}^{\mathrm{SIDIS}} \otimes f_i \otimes d_j$$

Posterior distribution

Prior distribution

$$\rho(\mathbf{a}|\mathrm{data}) \sim \mathcal{L}(\mathbf{a}, \mathrm{data}) \pi(\mathbf{a})$$

Likelihood

$$\mathrm{E}[f_i(\xi, \mu^2)] = \int \mathrm{d}^n\mathbf{a}\, \rho(\mathbf{a}|\mathrm{data}) f_i(\xi, \mu^2; \mathbf{a})$$

$$\mathrm{V}[f_i(\xi, \mu^2)] = \int \mathrm{d}^n\mathbf{a}\, \rho(\mathbf{a}|\mathrm{data}) \left[f_i(\xi, \mu^2; \mathbf{a}) - \mathrm{E}[f_i(\xi, \mu^2)]\right]^2$$

The Bayesian inference

$$\mathcal{L}(\boldsymbol{a}, \text{data}) = \exp\left[-\frac{1}{2}\chi^2(\boldsymbol{a}, \text{data})\right]$$

$$\chi^2(\boldsymbol{a}, \text{data}) = \sum_{e,i} \left(\frac{d_{e,i} - \sum_k r_{e,k}\beta_{e,k,i} - t_{e,i}(\boldsymbol{a})/N_e}{\alpha_i} \right)^2$$

$$+ \sum_k r_{e,k}^2 + \left(\frac{1 - N_e}{\delta N_e} \right)^2$$

Combined measurement and QCD analysis of the inclusive $e^{\pm}p$ scattering cross sections at HERA

Source	Data Samples
H1 E'_e	δ_1 H1 NC [4] — δ_1 H1 NC HY [5] — δ_1 H1 NC [3] — δ_1 H1 NC [5]
H1 E_h	δ_2 H1 CC [3] — δ_2 H1 CC [5] — δ_2 H1 CC [4] — δ_3 H1 NC [4]
	δ_3 H1 NC HY [5] — δ_3 H1 NC [3] — δ_3 H1 NC [5]
H1 γp asymmetry	δ_6 H1 NC HY [5] — δ_6 H1 NC [5]
H1 γp background	δ_4 H1 CC [3] — δ_4 H1 CC [5] — δ_4 H1 CC [4] — δ_5 H1 NC [4]
	δ_5 H1 NC HY [5] — δ_5 H1 NC [3] — δ_5 H1 NC [5]
H1 θ_e	δ_2 H1 NC [4] — δ_2 H1 NC HY [5] — δ_2 H1 NC [5]
H1 CC cuts	δ_1 H1 CC [5] — δ_1 H1 CC [4]
H1 LAr Noise	δ_3 H1 CC [3] — δ_3 H1 CC [5] — δ_3 H1 CC [4] — δ_4 H1 NC [4]
	δ_4 H1 NC HY [5] — δ_4 H1 NC [3] — δ_4 H1 NC [5]
H1 Lumi 94 – 97	δ_5 H1 CC [3] — δ_6 H1 NC [3]
H1 Lumi 98 – 99	δ_5 H1 CC [4] — δ_6 H1 NC [4] — δ_7 H1 NC HY [5]
H1 Lumi 99 – 00	δ_5 H1 CC [5] — δ_7 H1 NC [5]
ZEUS E'_e	δ_1 ZEUS NC [11] — δ_1 ZEUS NC [13]
ZEUS E_h a	δ_1 ZEUS CC [12] — δ_1 ZEUS CC [14]
ZEUS E_h b	δ_2 ZEUS CC [12] — δ_2 ZEUS CC [14]
ZEUS E_h in BCAL	δ_2 ZEUS CC [10] — δ_6 ZEUS NC [9]
ZEUS E_h in FCAL	δ_1 ZEUS CC [10] — δ_5 ZEUS NC [9]
ZEUS δ cut	δ_8 ZEUS BPC [6] — δ_1 ZEUS BPT [7]
ZEUS γp background	δ_2 ZEUS NC [11] — δ_2 ZEUS NC [13]
ZEUS γp background	δ_9 ZEUS BPC [6] — δ_{14} ZEUS BPT [7] — δ_8 ZEUS SVX [8]
ZEUS y_h cut	δ_3 ZEUS BPC [6] — δ_2 ZEUS BPT [7]
ZEUS BPC linearity	δ_5 ZEUS BPC [6] — δ_9 ZEUS BPT [7]
ZEUS BPC shower	δ_4 ZEUS BPC [6] — δ_3 ZEUS BPT [7]
ZEUS CAL energy	δ_2 ZEUS BPC [6] — δ_{12} ZEUS BPT [7] — δ_9 ZEUS SVX [8]
ZEUS Cuts_1	δ_3 ZEUS NC [11] — δ_3 ZEUS NC [13]
ZEUS Cuts_2	δ_4 ZEUS NC [11] — δ_4 ZEUS NC [13]
ZEUS HFS model	δ_3 ZEUS CC [10] — δ_3 ZEUS CC [12] — δ_6 ZEUS NC [11]
	δ_6 ZEUS NC [13] — δ_3 ZEUS CC [14]
ZEUS Lumi 94 – 97	δ_4 ZEUS CC [10] — δ_{11} ZEUS NC [9]
ZEUS Lumi 98 – 99	δ_4 ZEUS CC [12] — δ_7 ZEUS NC [11]
ZEUS Lumi 99 – 00	δ_9 ZEUS NC [13] — δ_4 ZEUS CC [14]

Table 5. List of systematic sources that are correlated across the data samples. The type of the systematic uncertainty is given in the "source" column. The labels δ_i denote the sources according to the sequential ordering in the list of the correlated systematic uncertainties of the corresponding publication. An overall 0.5% normalisation uncertainty, common to all data sets, is not included in this list.

The Bayesian inference

$$\rho(\mathbf{a}|\text{data}) \sim \mathcal{L}(\mathbf{a}, \text{data})\pi(\mathbf{a})$$

$$\mathrm{E}[f_i(\xi, \mu^2)] = \int d^n\mathbf{a}\ \rho(\mathbf{a}|\text{data}) f_i(\xi, \mu^2; \mathbf{a})$$

$$\mathrm{V}[f_i(\xi, \mu^2)] = \int d^n\mathbf{a}\ \rho(\mathbf{a}|\text{data}) \left[f_i(\xi, \mu^2; \mathbf{a}) - \mathrm{E}[f_i(\xi, \mu^2)]\right]^2$$

Maximum Likelihood

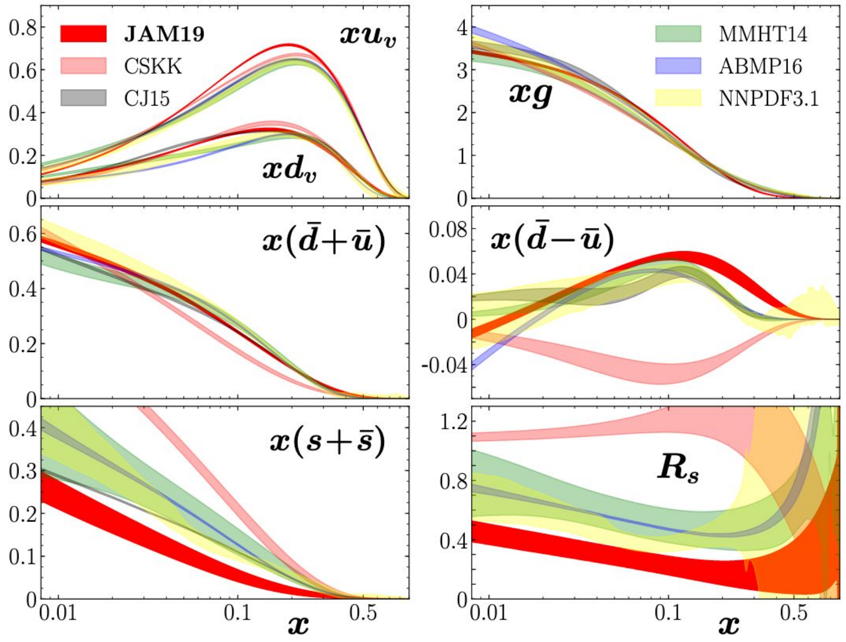
$$\mathrm{E}[f_i(\xi)] = f_i(\xi; \mathbf{a}_0)$$

$$\mathrm{V}[f_i(\xi)] = \text{Hessian, Lagrange}$$

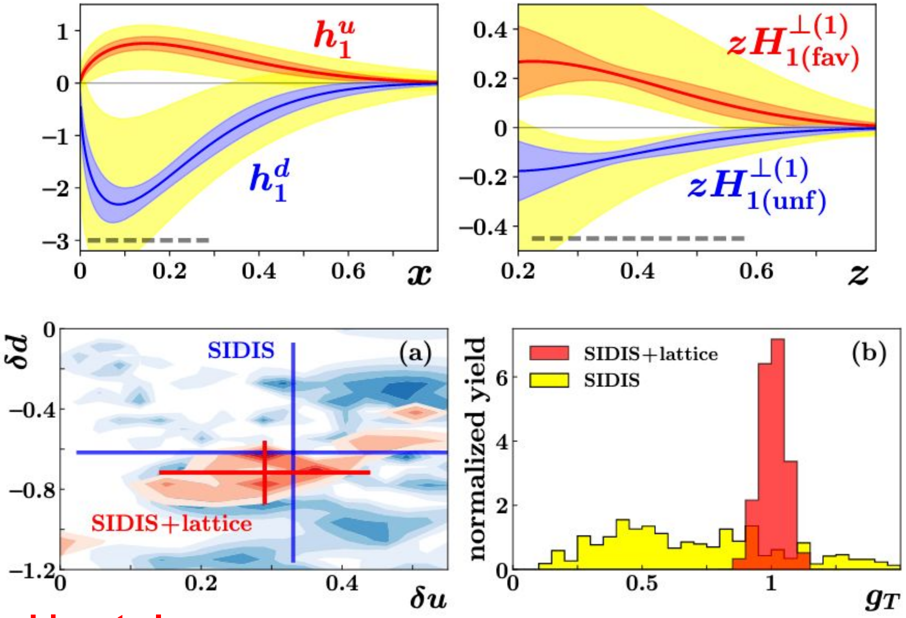
MC methods

$$\mathrm{E}[f_i(\xi)] = \frac{1}{N}\sum_k f_i(\xi; \mathbf{a}_k)$$

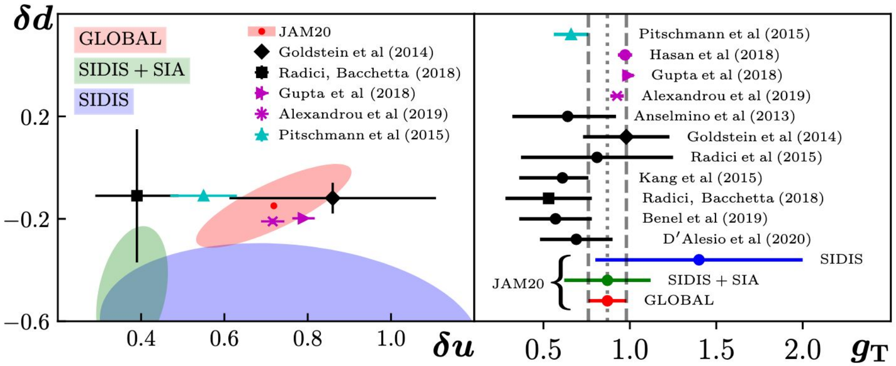
$$\mathrm{V}[f_i(\xi)] = \frac{1}{N}\sum_k [f_i(\xi; \mathbf{a}_k) - \mathrm{E}[f_i(\xi)]]^2$$



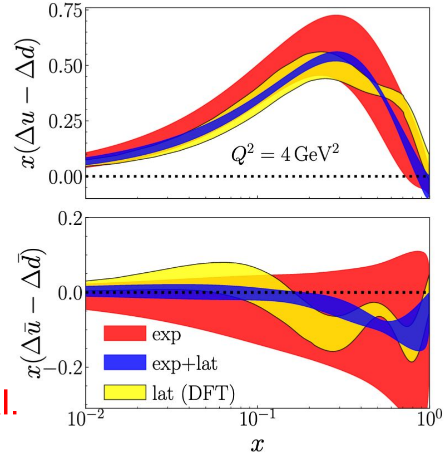
Why lattice and experimental data?



Lin, et al.



Cammarota et al.



Bringewatt et al.

Complementarity

Experiment

> Huge **amount of data** to access hadron structure and hadronization

> Provides the **testing platform** for universality and QCD predictions

> **Requires to separate** reaction dependent parts from intrinsic properties

Lattice

> Provides constraints on hadron structures **not accessible** experimentally

> Universality of factorization **can be tested** within combined lattice observables and experimental data

> **Direct access** to intrinsic properties of hadron structure that can be compared with infrared structures from experiments

Challenges

Uncertainty quantification

> Modeling the likelihood function -> treatment of systematic uncerties

> Confidence levels in the presence of incompatible data

> Bayesian posterior sampling on **large dimensional space** ~ O(100)

JLab 12 and EIC + (Lattice)

> New era of high luminosity experiments -> enormous amount of data

>New ideas emerging using **machine learning** models