Global QCD Analysis of Pion Parton Distributions Including Lattice QCD Data

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Jefferson Lab
Exploring the Nature of Matter

Jefferson Lab Angular Momentum Collaboration

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Overarching themes

1. Can the lattice QCD data provide constraints on PDFs beyond current experimental data?
2. What systematic effects are intrinsic to the lattice and how do we quantify them?
3. The complementarity of experimental and lattice QCD data.

Motivation

- QCD allows us to study the structure of hadrons in terms of partons (quarks, antiquarks, and gluons)
- Use factorization theorems to separate hard partonic physics out of soft, non-perturbative objects to quantify structure

Complicated inverse problem

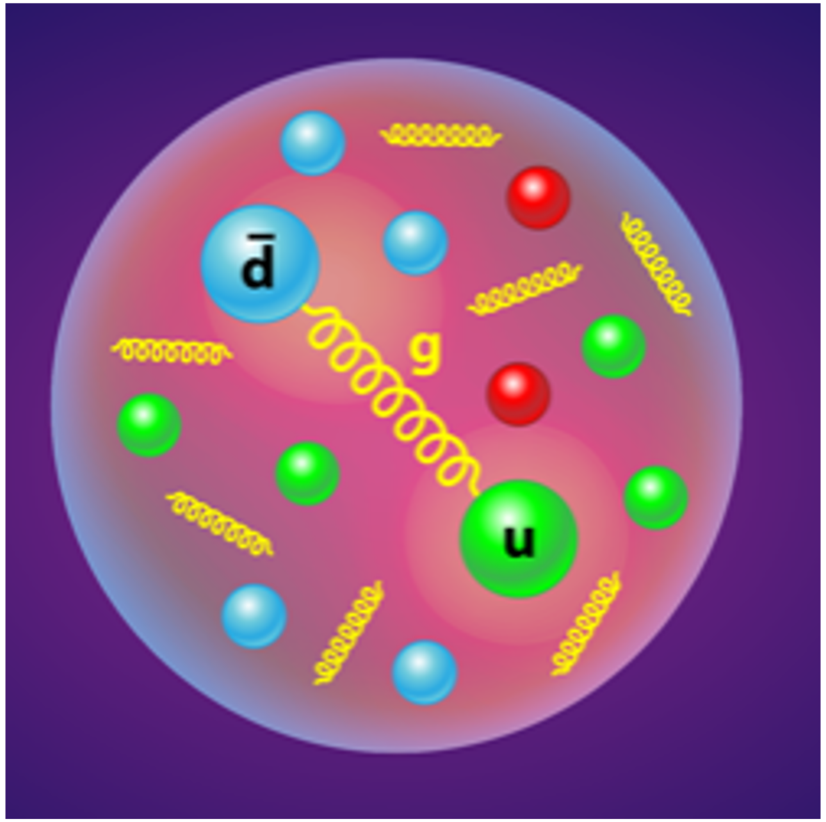
- Factorization theorems involve convolutions of hard perturbatively calculable physics and non-perturbative objects

$$\frac{d\sigma}{d\Omega} \propto \mathcal{H} \otimes f = \int_x^1 \frac{d\xi}{\xi} \mathcal{H}(\xi) f\left(\frac{x}{\xi}\right)$$

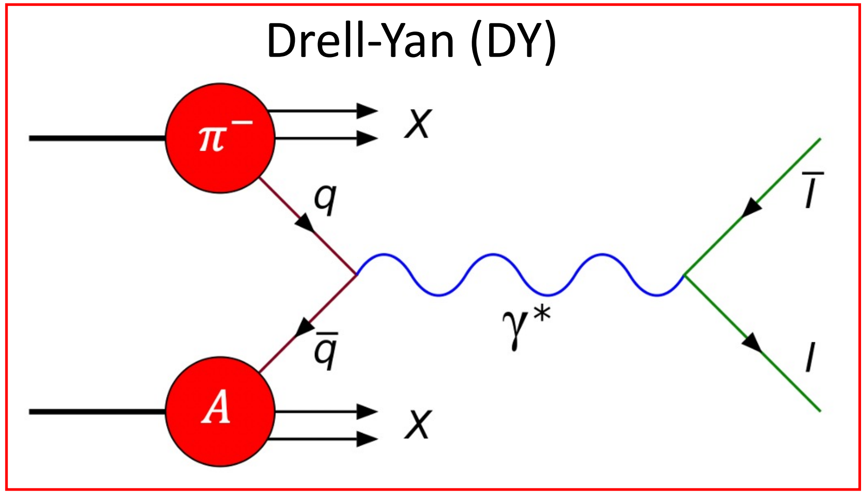
- Parametrize the non-perturbative objects and perform global fit
- “Good lattice cross sections” also follow this convolution structure

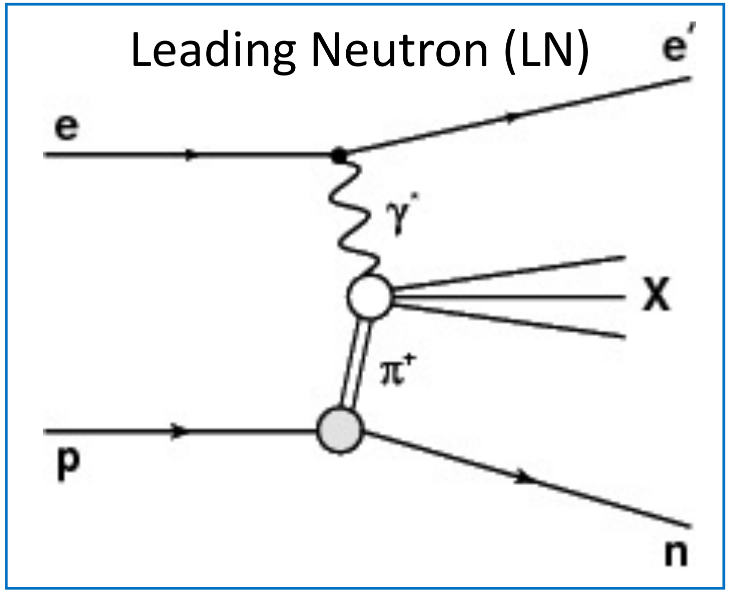
Pions

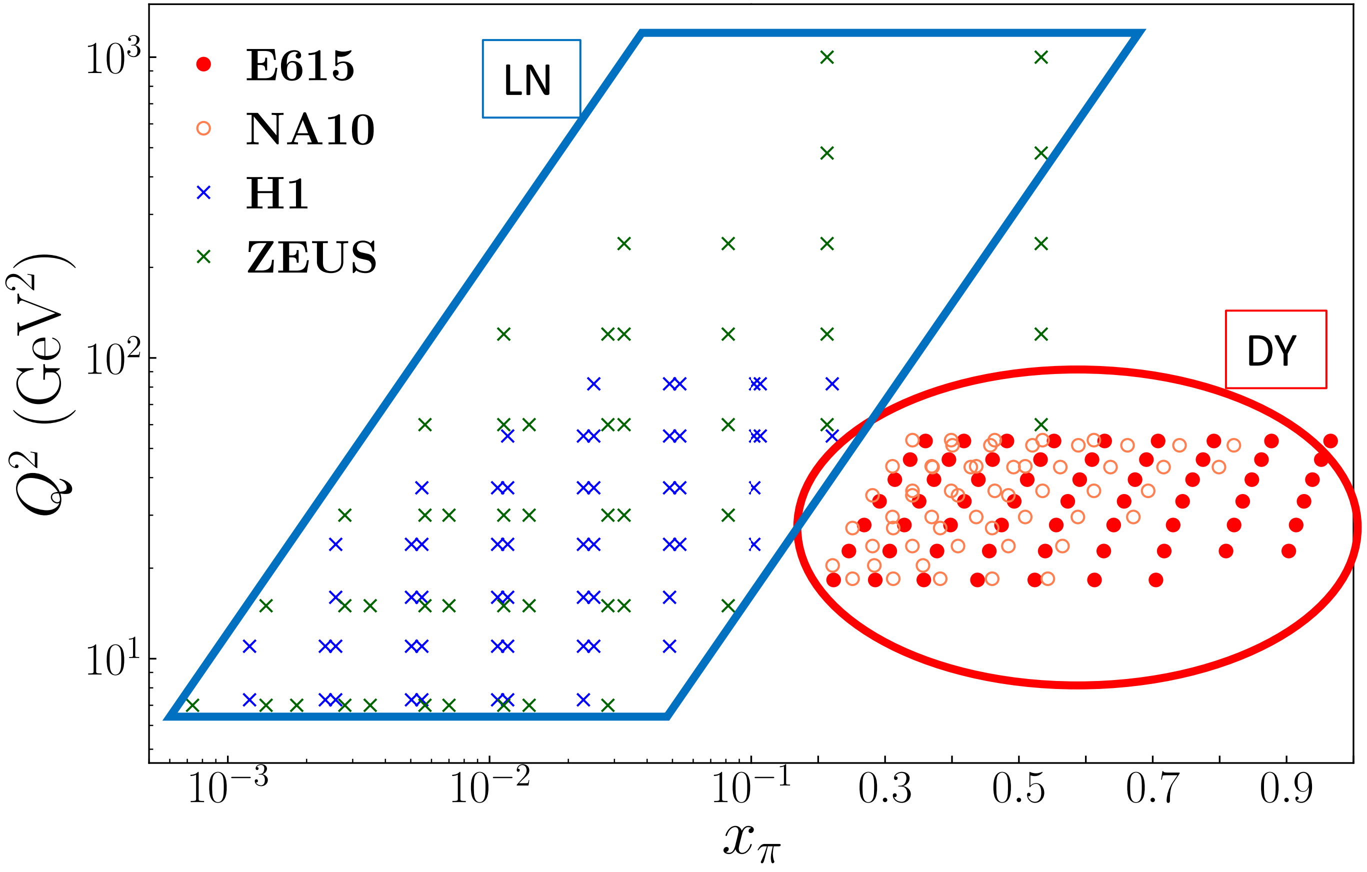
- Pion is the Goldstone boson associated with spontaneous symmetry breaking of chiral $SU(2)_L \times SU(2)_R$ symmetry
- Lightest hadron
- Made up of q and $\bar{q}$ constituents



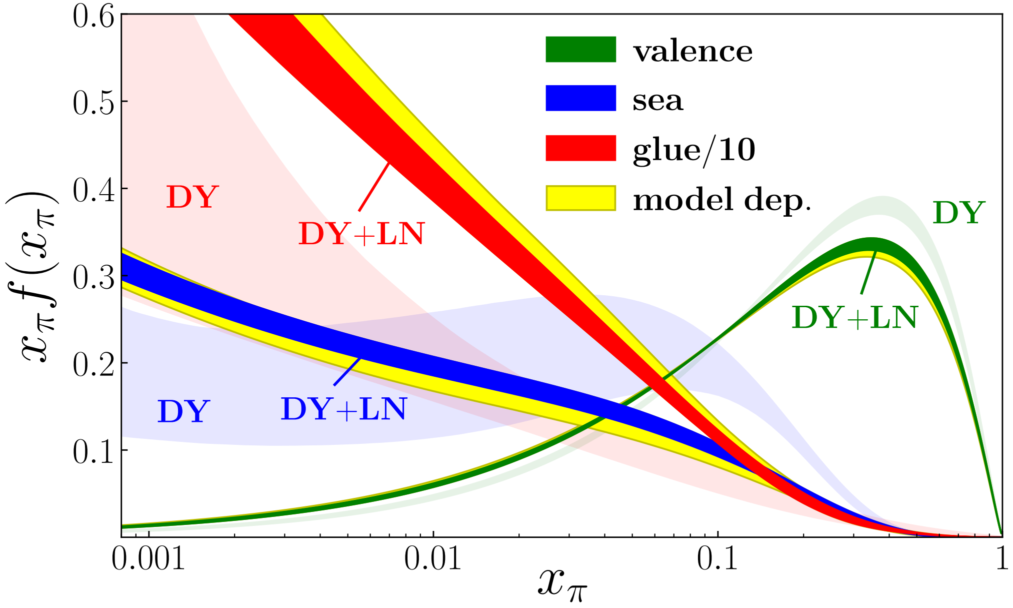
Experiments to probe pion structure







Global analyses to experimental data

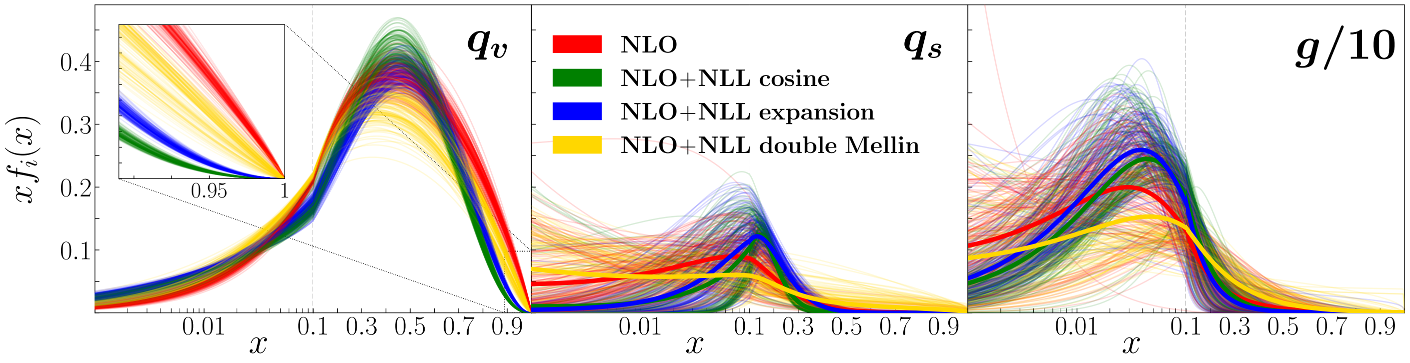


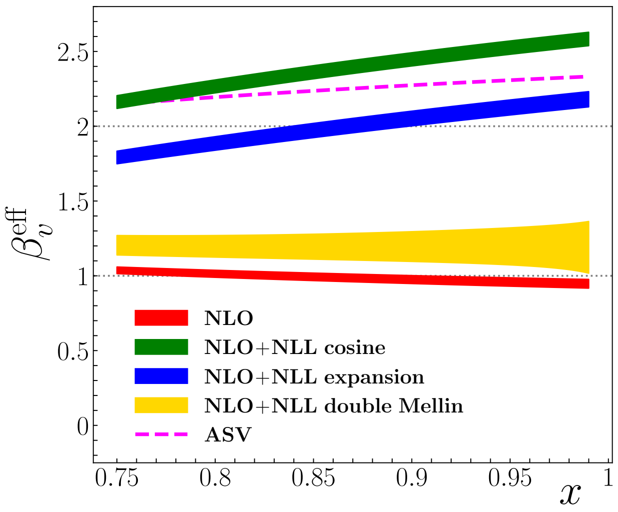
PHYSICAL REVIEW LETTERS **121,** 152001 (2018)

Featured in Physics

First Monte Carlo Global QCD Analysis of Pion Parton Distributions

P. C. Barry,[1] N. Sato,[2] W. Melnitchouk,[3] and Chueng-Ryong Ji[1]





PHYSICAL REVIEW LETTERS **127,** 232001 (2021)

Global QCD Analysis of Pion Parton Distributions with Threshold Resummation

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Lattice QCD observables

- Lattice calculation gives the **reduced** pseudo Ioffe time distribution

$$\mathfrak{M}(\nu, z^2) = \frac{\mathcal{M}(\nu, z^2)}{\mathcal{M}(0, z^2)}$$

"Ioffe time"

$$\boxed{\nu = p \cdot z}$$

- The UV divergences arising from choosing the spacelike z cancel from taking the ratio at the rest frame $p_z = 0$

B. Joó, et al., Phys. Rev. D **100**, 114512 (2019).

Fitting the Data and Systematic Effects

$$\mathrm{Re}[\mathfrak{M}(\nu, z^2)] = \int_0^1 dx\, q_v(x, \mu_{\mathrm{lat}})\, \mathcal{C}^{\mathrm{Rp-ITD}}\left(x\nu, z^2, \mu_{\mathrm{lat}}\right) + z^2 B_1(\nu) + \frac{a}{|z|} P_1(\nu) + e^{-m_\pi (L-z)} F_1(\nu) + \ldots,$$

Valence quark distribution in pion

Wilson coefficients for matching

Systematic Effects to parametrize

- $z^2 B_1(\nu)$: power corrections
- $\frac{a}{|z|} P_1(\nu)$: lattice spacing errors
- $e^{-m_\pi(L-z)} F_1(\nu)$: finite volume corrections

Other potential systematic corrections the data is not sensitive to

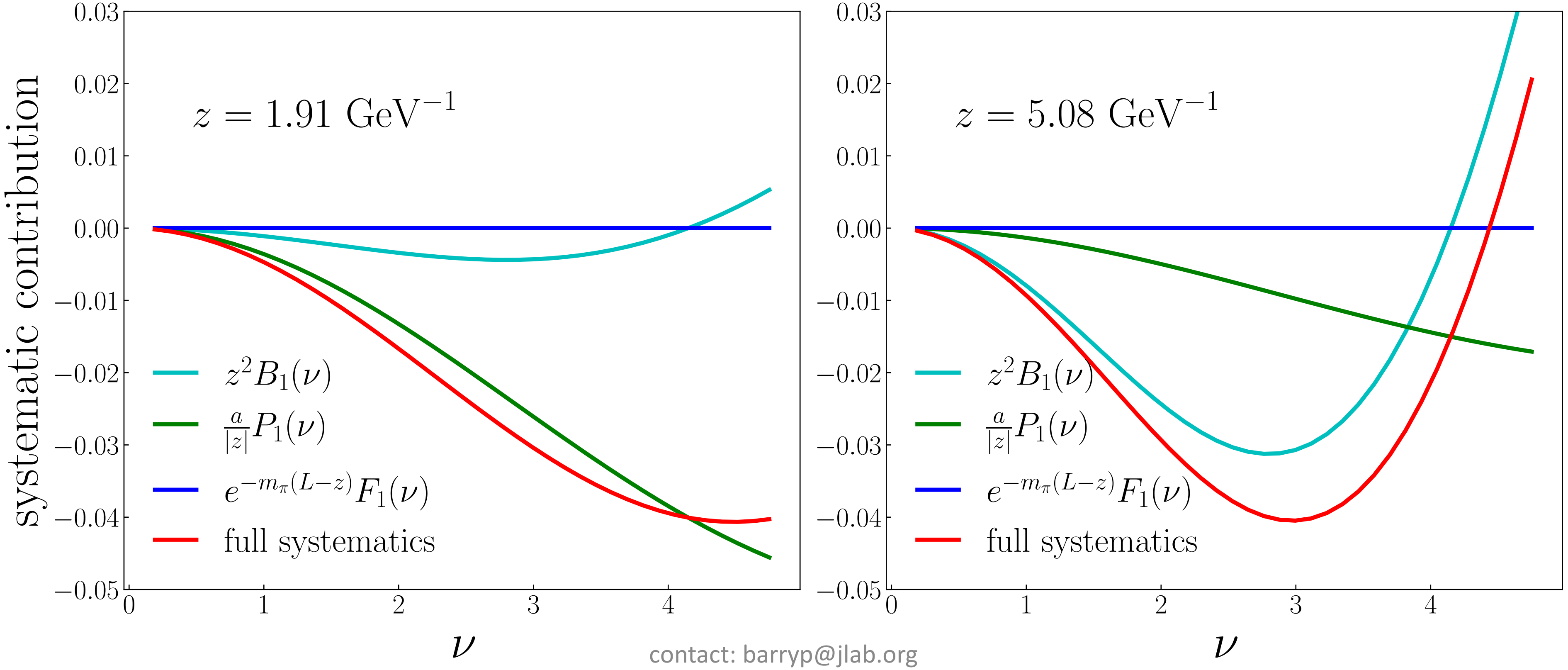
Resulting χ^2_{red}

- Scenario A: only experimental data
- Scenario B: include lattice data without fitting systematic effects
- Scenario C: Include systematics

		Scenario A		Scenario B		Scenario C	
Process	Experiment	N_{dat}	χ^2_{red}	N_{dat}	χ^2_{red}	N_{dat}	χ^2_{red}
DY	E615	61	0.82	61	0.82	61	0.82
	NA10 (194 GeV)	36	0.53	36	0.54	36	0.55
	NA10 (286 GeV)	20	0.81	20	0.79	20	0.88
LN	H1	58	0.35	58	0.39	58	0.37
	ZEUS	50	1.48	50	1.69	50	1.61
Rp-ITD	a127m415L	–	–	18	1.06	18	1.07
	a127m415	–	–	8	2.63	8	1.50
Total		**225**	**0.80**	**251**	**0.92**	**251**	**0.88**

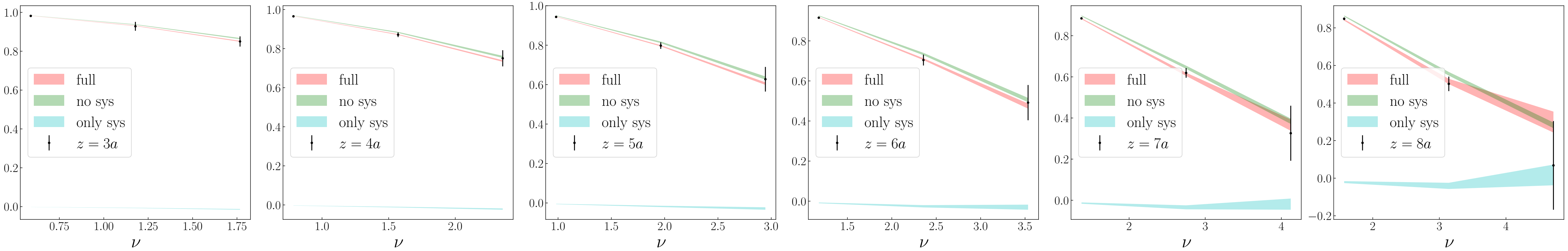
Systematic Effects

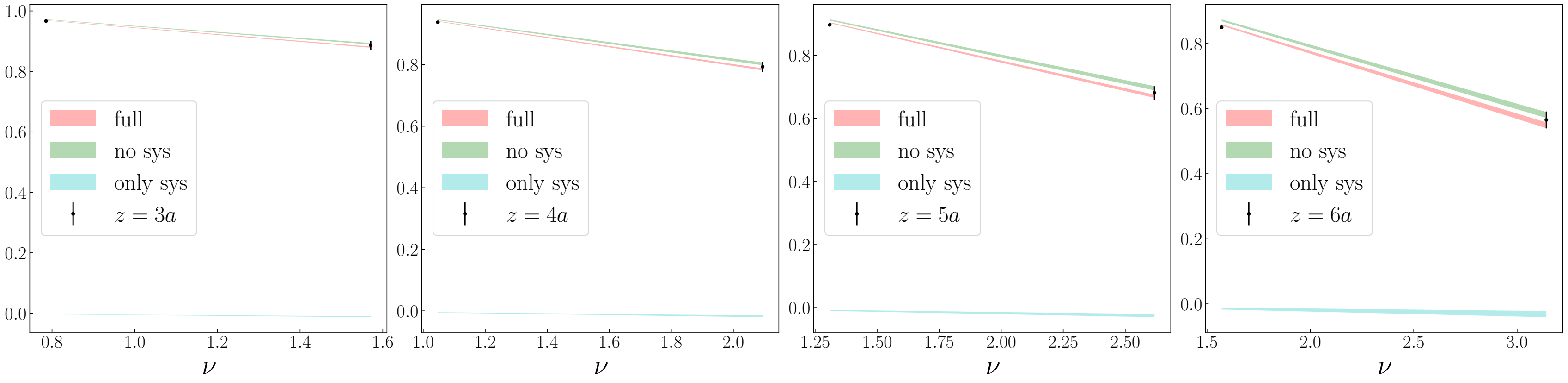
- Red curve shows the total sum of systematic corrections to the leading power terms



Fits to the data

Larger lattice volume





Smaller lattice volume

- Systematic effects shown in blue, are very small at low momentum and Ioffe time, ν

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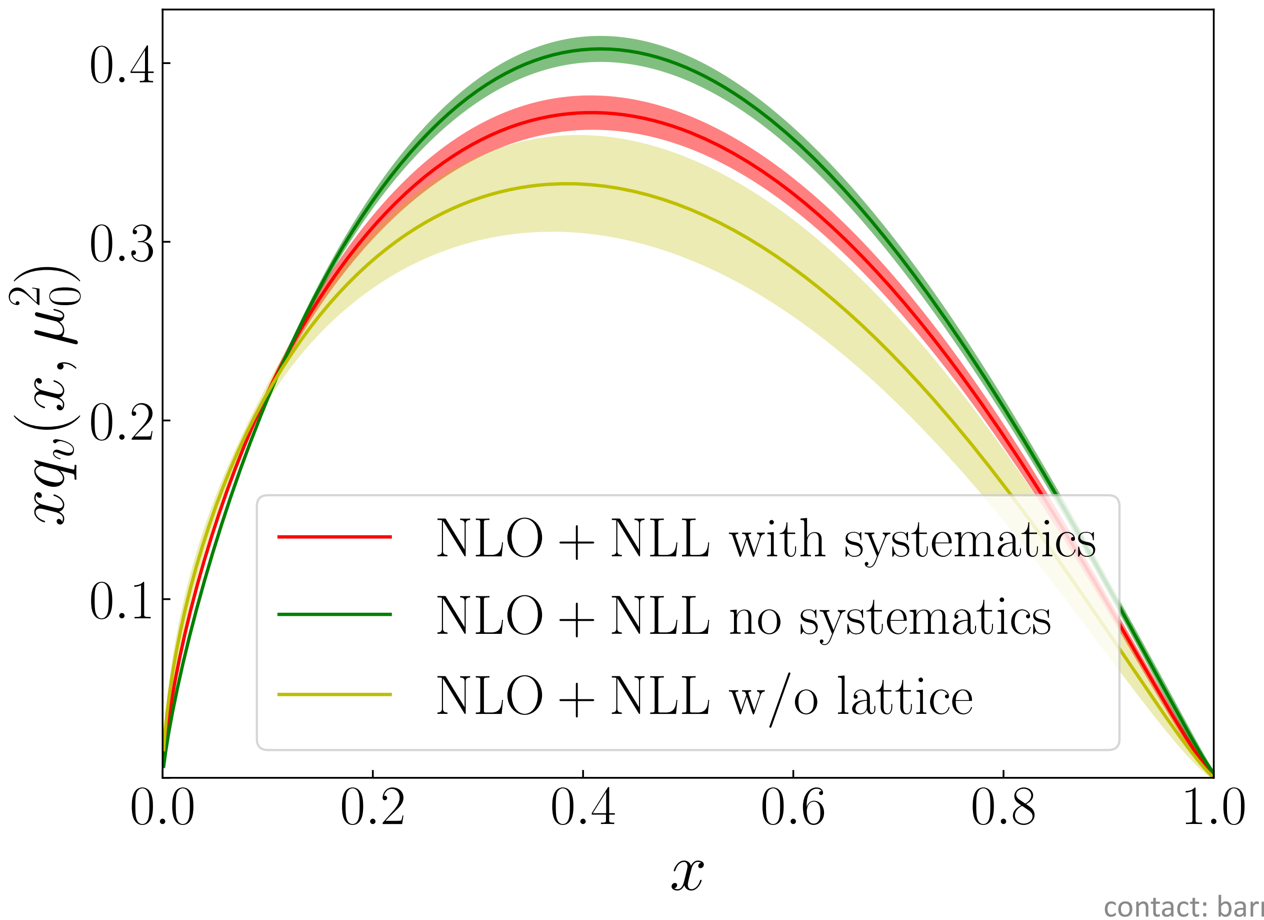
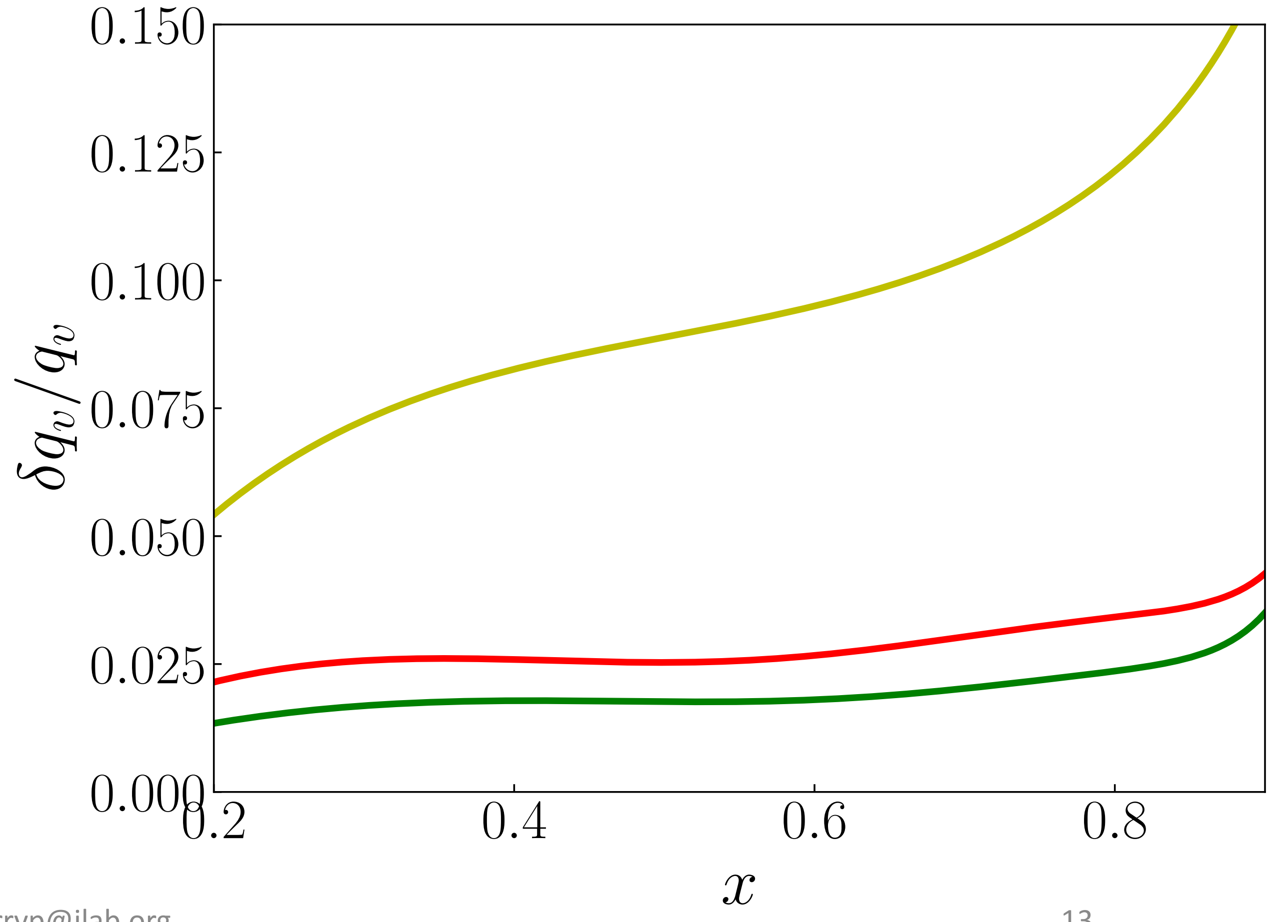
Effect on q_v^π

- Sizeable effect even when including systematics





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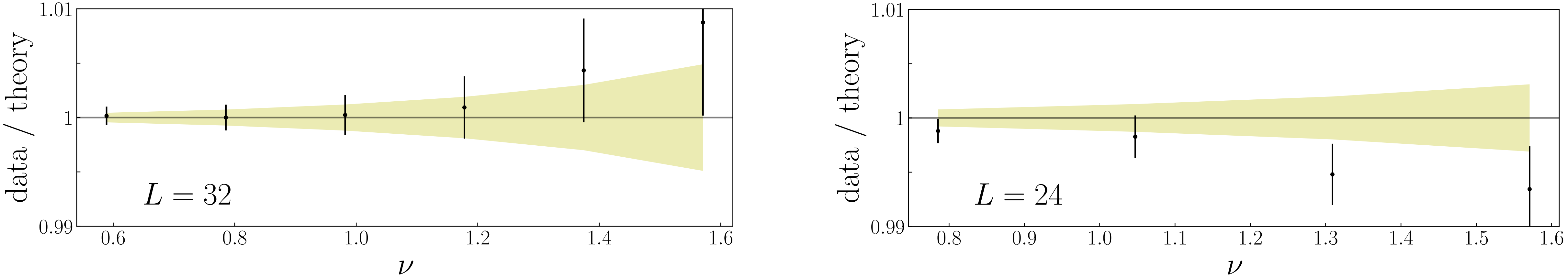
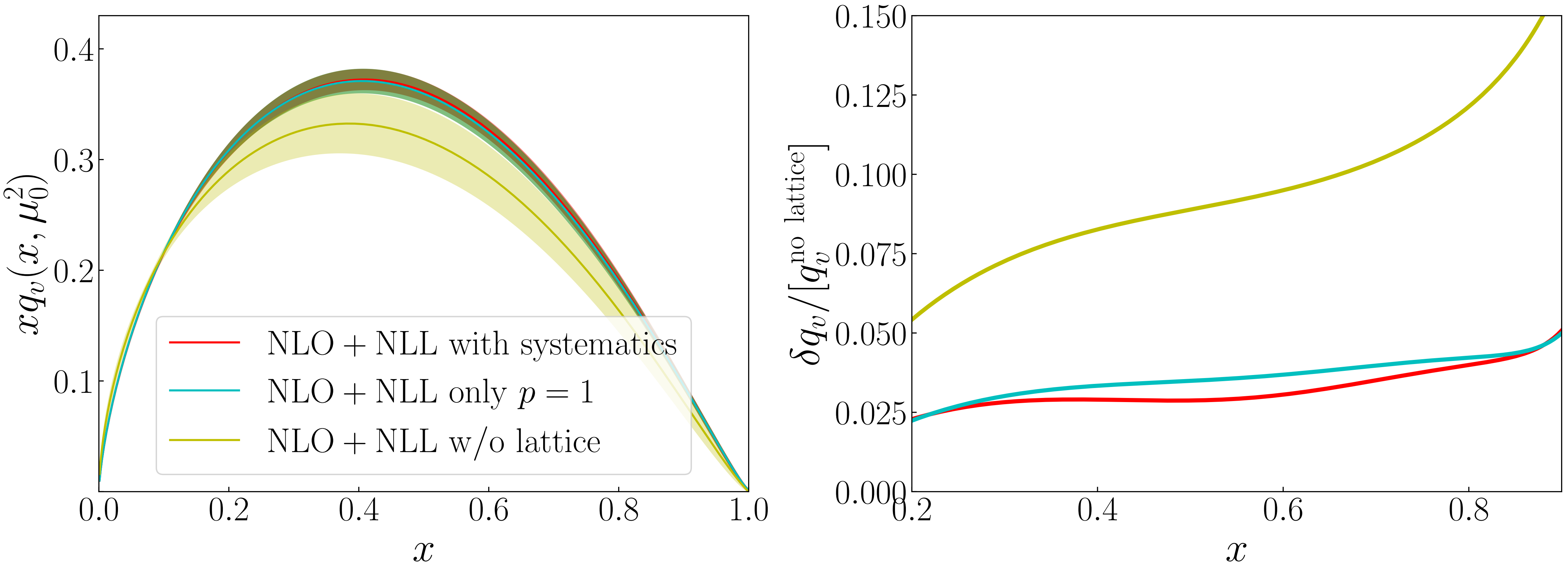
Fitting smallest momentum

- The $p = 1$ points are the most precise, and removing larger momentum can be constructive



Fitting smallest momentum

- These points provide biggest constraints



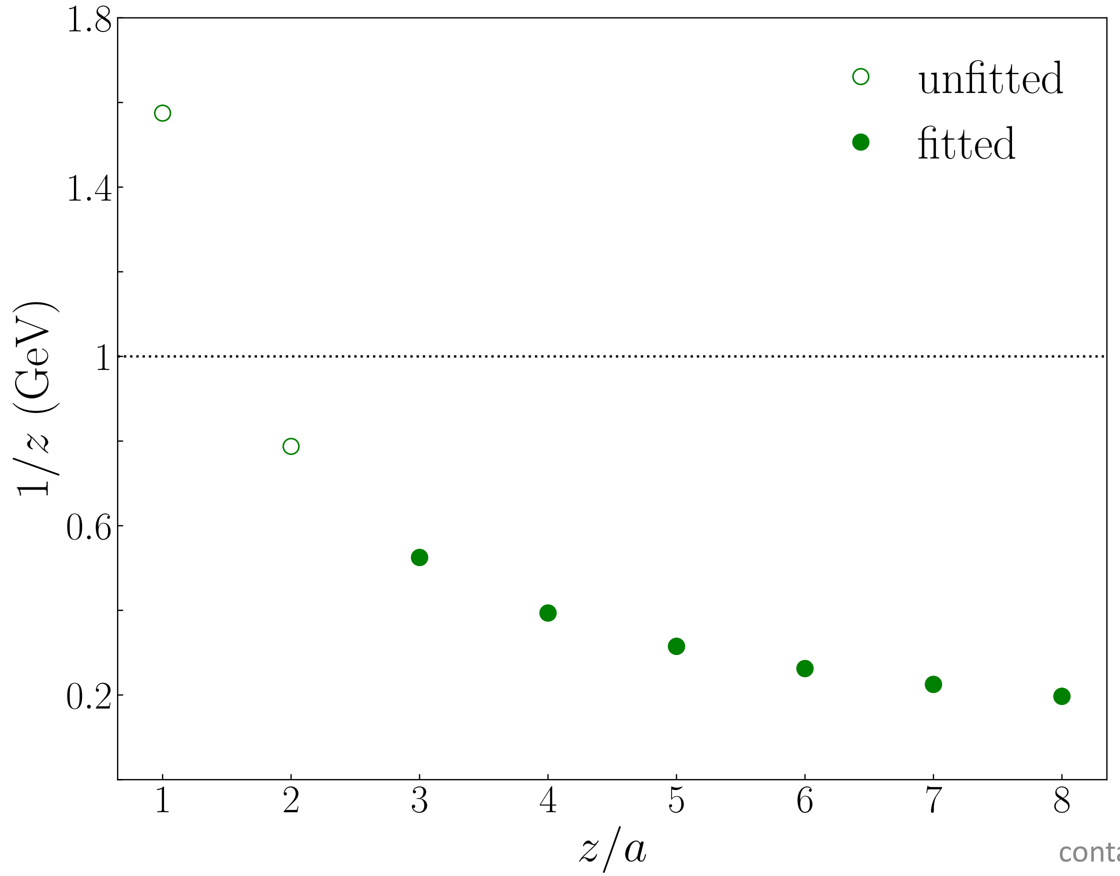
Summary

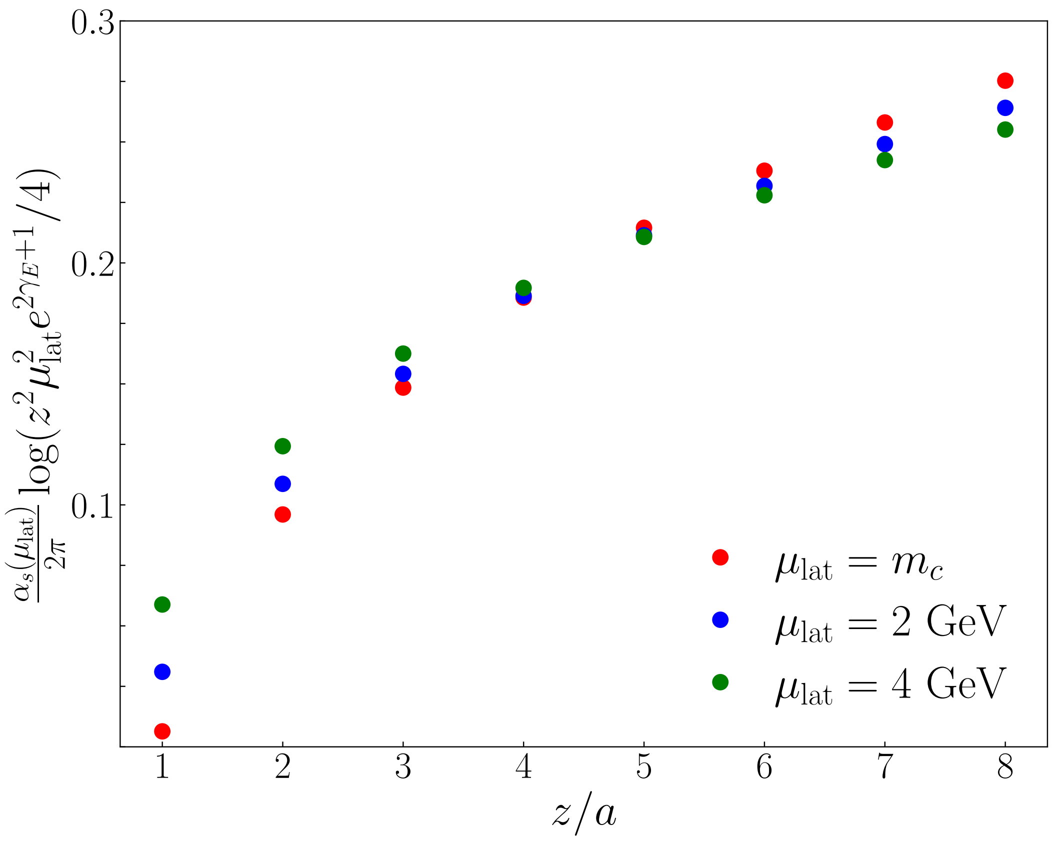
- Lattice QCD data are consistent with experimental data *and* constrain the valence quark distribution by 50-80% depending on x
- Systematic effects on the lattice have been rigorously quantified with the help of experimental data
- Focusing on data with smallest momentum will be instructive to the large-x regions of the valence quark distribution
- Final results for current-current correlator analysis coming soon
- This global analysis prefers $\beta_v^{\mathrm{eff}} \sim 1$

Backup

Scale setting

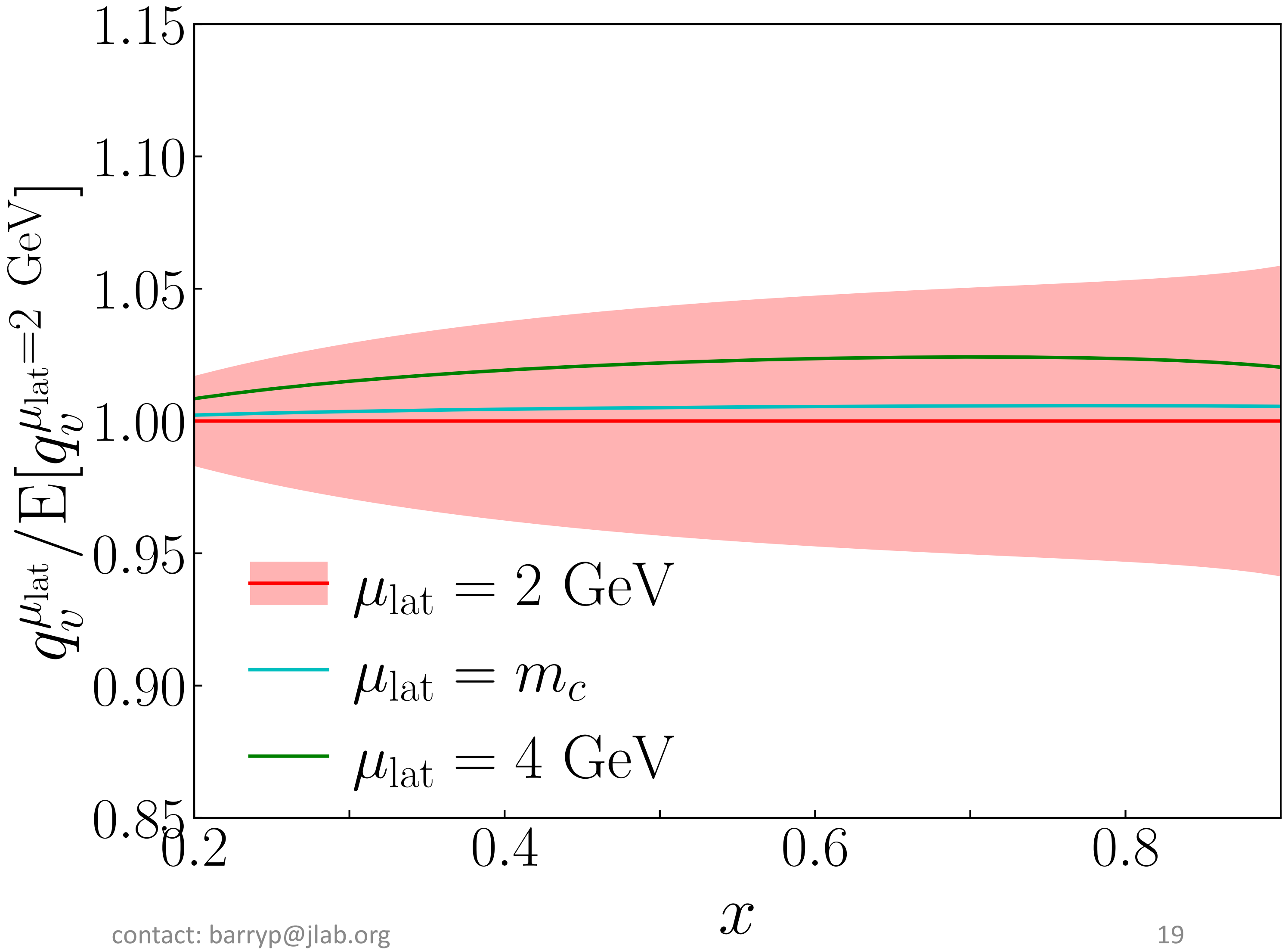
- $1/z$ is not quite perturbative, but fixing a scale doesn't spoil perturbation





Varying scale

- Choosing a scale $\mu = m_c$ or $\mu = 4\text{GeV}$ agrees with the case when $\mu = 2\text{GeV}$



Comparing with NLO

- Region from expt+lattice fits where NLO and NLO+NLL agree shows where lattice constrains the PDF in x