Complementarity of experimental and lattice QCD data on pion parton distributions

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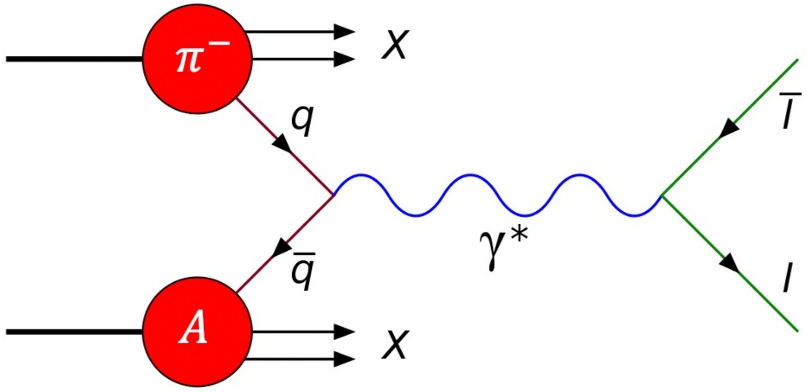
Based on a recent preprint: 2204.00543

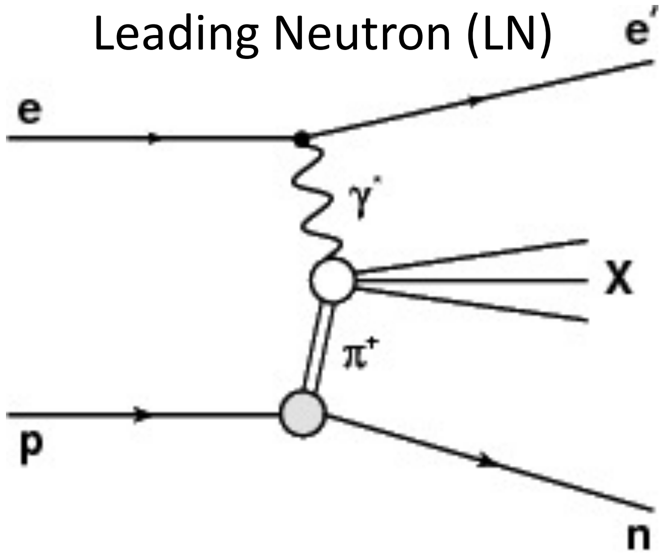
and HadStruc Collaborations

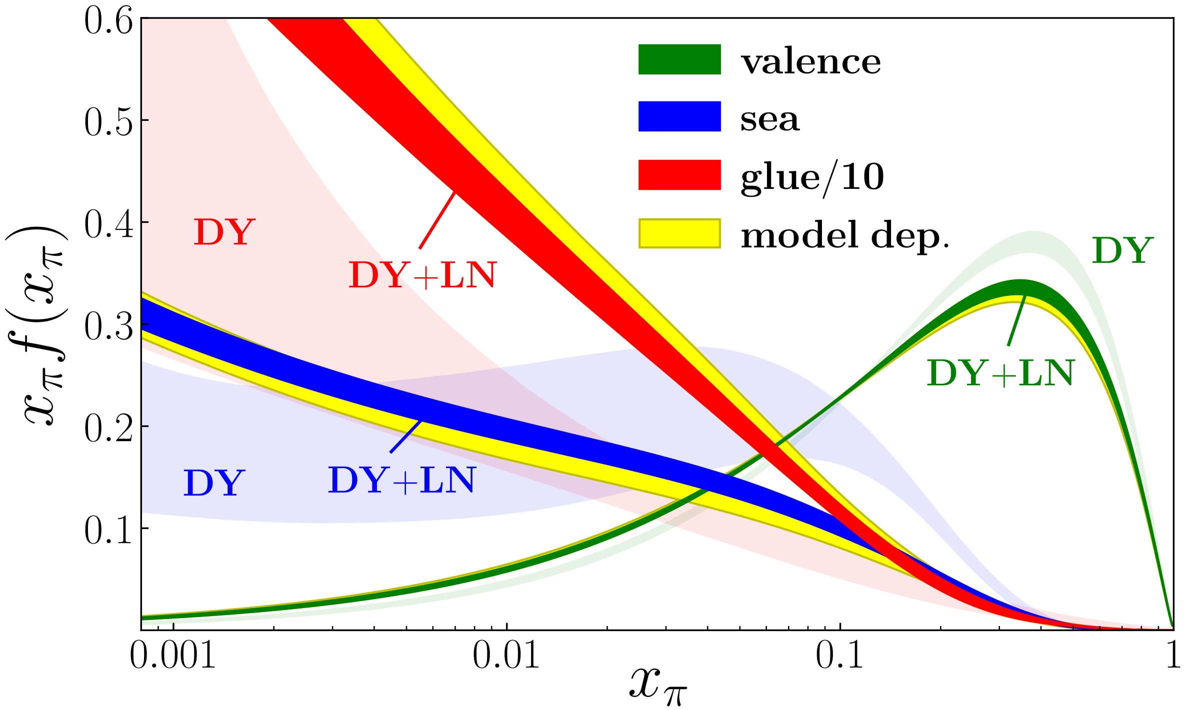
Experiments to probe pion structure

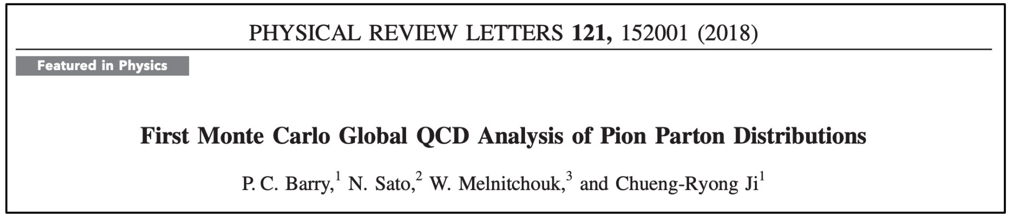
Drell-Yan (DY)



Leading Neutron (LN)







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]

Large momentum fraction behavior

- Many theoretical papers have studied the behavior of the valence quark distribution as $x \to 1$ and
- Debate whether $q_v^\pi(x \to 1) \sim (1-x)$ or $(1-x)^2$

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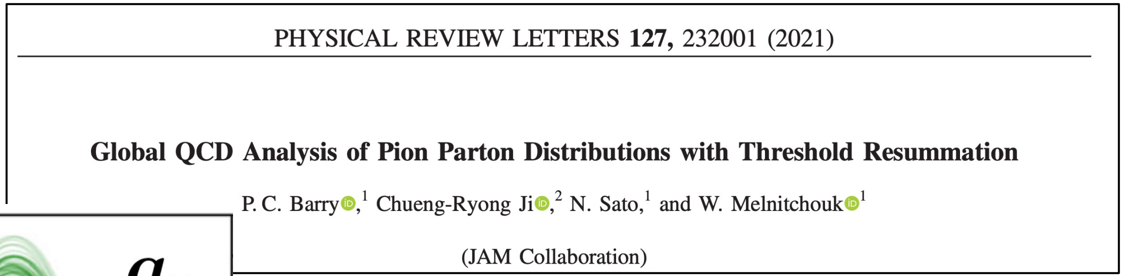
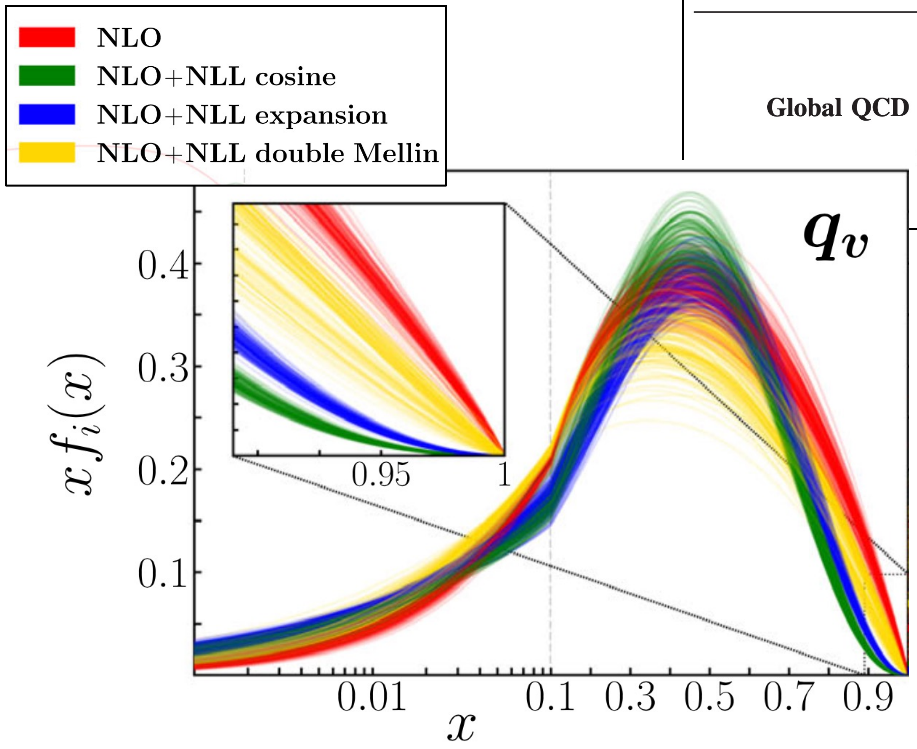
JAM analysis with threshold resummation


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

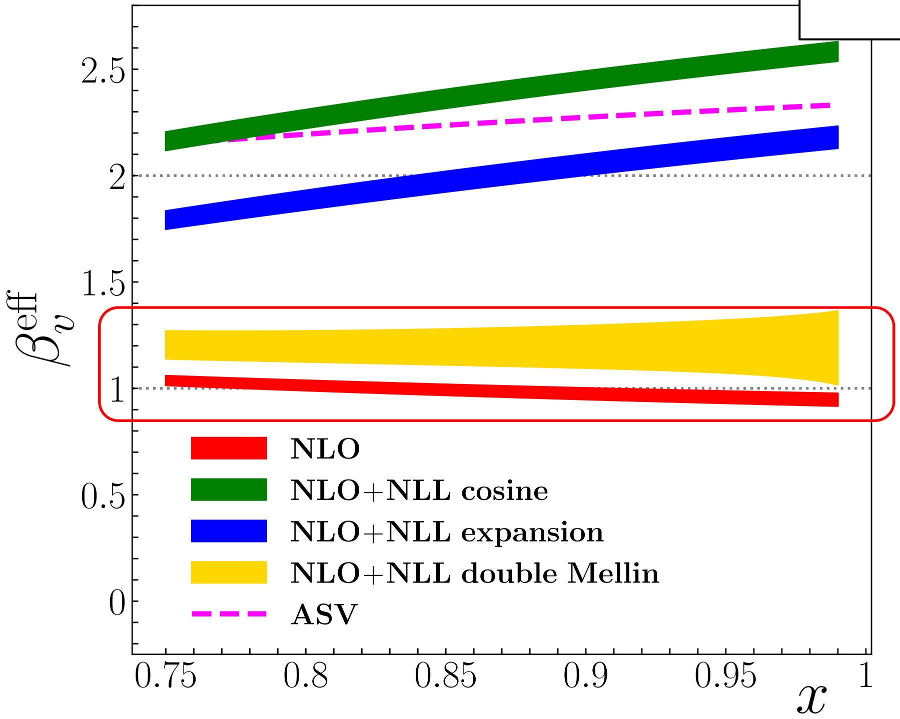
Global QCD Analysis of Pion Parton Distributions with Threshold Resummation

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

(JAM Collaboration)



$$\beta_{\text{eff}}(x,\mu) = \frac{\partial \log |q_v(x,\mu)|}{\partial \log(1-x)}$$

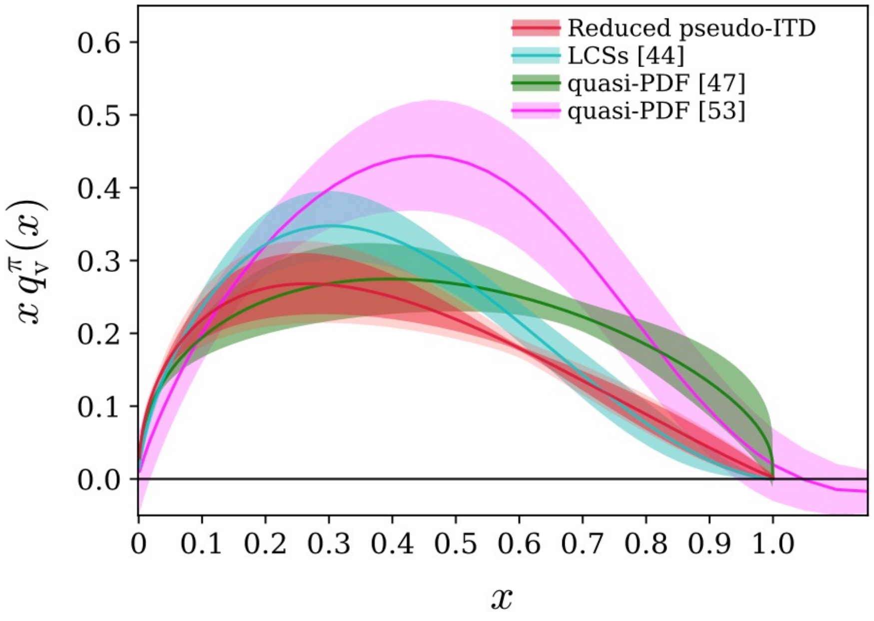


For more details, attend my talk in WG1 on Tuesday at 17:40

- Highly dependent on perturbative approach
- NLO and NLO+NLL double Mellin methods better on theoretical grounds

Lattice QCD Activity

- Simulations on the lattice have been done to investigate this structure



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Subset of pion lattice QCD analyses

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How to relate PDFs with lattice observables?

- Make use of short distance factorization and appropriate matching coefficients

$$\Sigma_{n/h}(\nu, z^2) \equiv \langle h(p)|T\{\mathcal{O}_n(z)\}|h(p)\rangle$$
$$= \sum_i f_{i/h}(x,\mu^2) \otimes \mathcal{C}_{n/i}(x\nu, z^2, \mu^2)$$
$$+\mathcal{O}(z^2\Lambda^2_{\rm QCD})$$

- Structure just like experimental cross sections – good for global analysis

Reduced Ioffe time pseudo-distribution (Rp-ITD)

- Lorentz-invariant Ioffe time pseudo-distribution:

$$\mathcal{M}(\nu, z^2) = \frac{1}{2p^0} \langle p | \bar{\psi}(0) \gamma^0 \mathcal{W}(z;0) \psi(z) | p \rangle$$

Quark and antiquark fields

Gauge link

"Ioffe time"

$$\nu = p \cdot z$$

$$z = (0,0,0,z_3)$$

Observable is the *reduced* Ioffe time pseudo-distribution (Rp-ITD)

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

Ratio cancels UV divergences

Fitting the Data and Systematic Corrections

Valence quark distribution in pion

Wilson coefficients for matching

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

Integration lower bound is 0

Other potential systematic corrections the data is not sensitive to

Systematic corrections 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

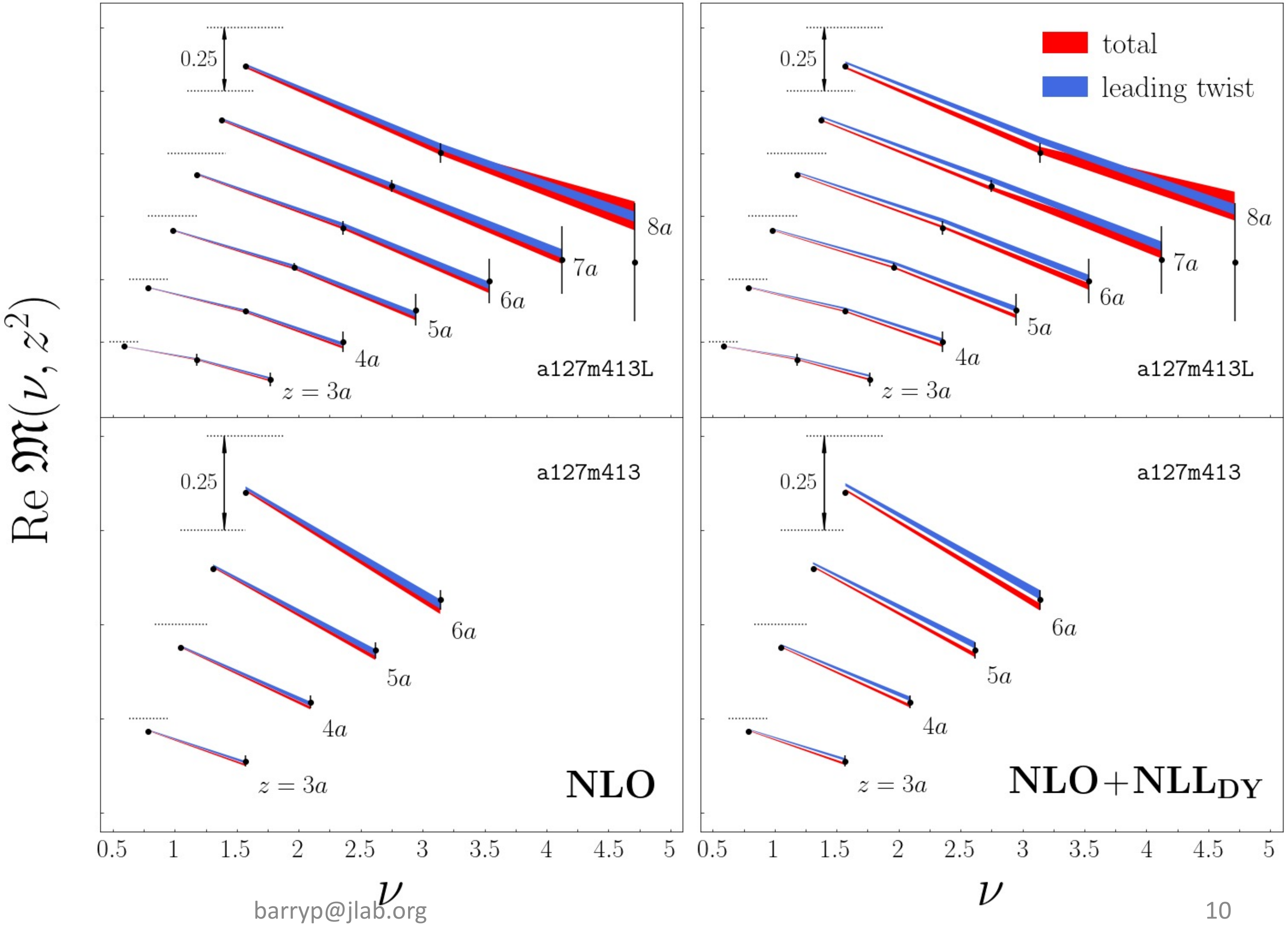
Goodness of fit

- Scenario A: experimental data alone
- Scenario B: experimental + lattice, no systematics
- Scenario C: experimental + lattice, with systematics

			Scenario A		Scenario B		**Scenario C**	
			NLO	$+\text{NLL}_{\text{DY}}$	NLO	$+\text{NLL}_{\text{DY}}$	NLO	$+\text{NLL}_{\text{DY}}$
Process	Experiment	N_{dat}	$\overline{\chi}^2$		$\overline{\chi}^2$		$\overline{\chi}^2$	
DY	E615	61	0.84	0.82	0.83	0.82	**0.84**	**0.82**
	NA10 (194 GeV)	36	0.53	0.53	0.52	0.54	**0.51**	**0.53**
	NA10 (286 GeV)	20	0.80	0.81	0.78	0.79	**0.74**	**0.81**
LN	H1	58	0.36	0.35	0.39	0.39	**0.38**	**0.37**
	ZEUS	50	1.56	1.48	1.62	1.69	**1.59**	**1.62**
Rp-ITD	a127m413L	18	–	–	1.04	1.06	**1.05**	**1.04**
	a127m413	8	–	–	1.98	2.63	**1.00**	**1.18**
Total		**251**	**0.82**	**0.80**	**0.89**	**0.92**	**0.85**	**0.86**

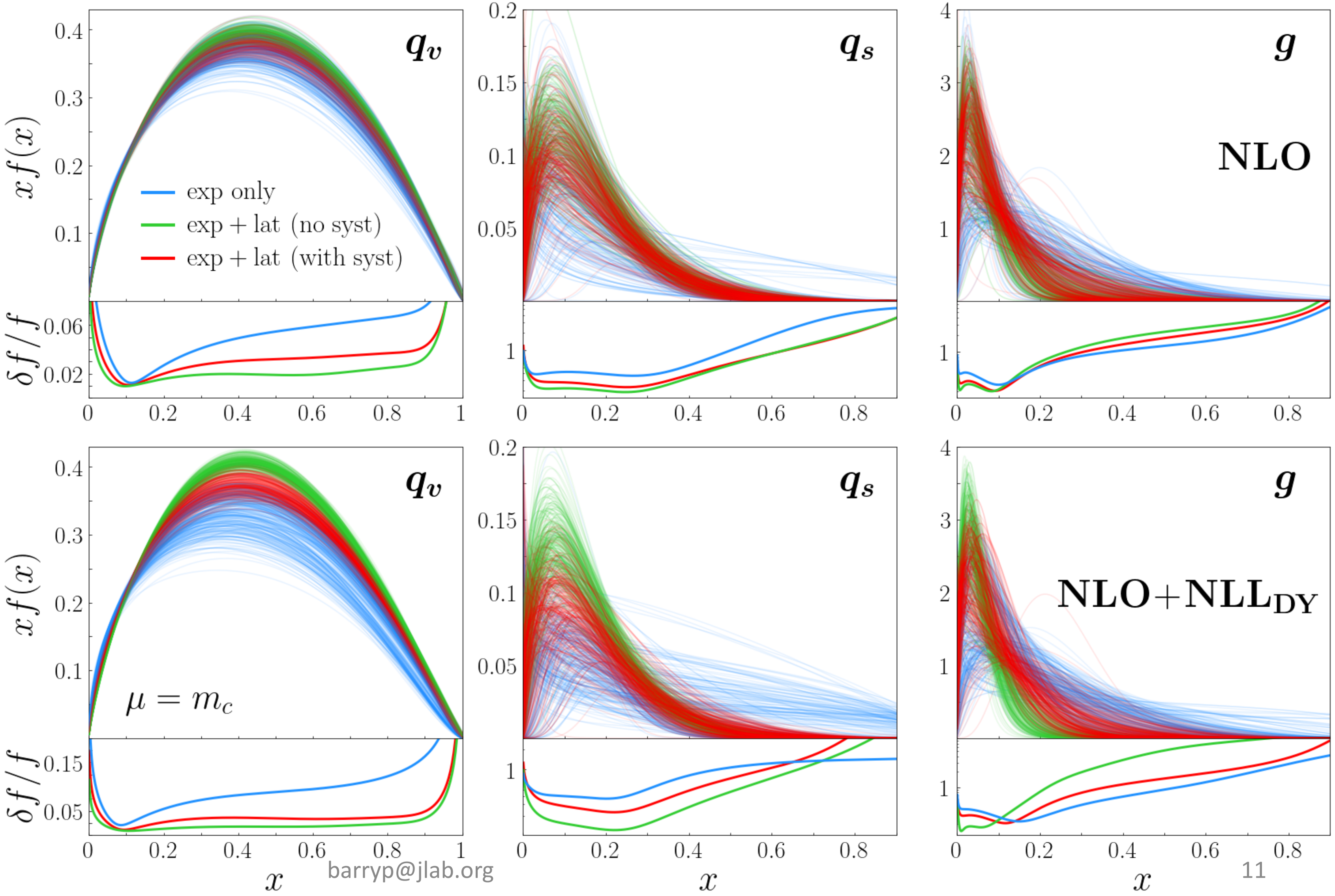
Agreement with the data

- Results from the full fit and isolating the leading twist term
- Difference between bands is the systematic correction



Resulting PDFs

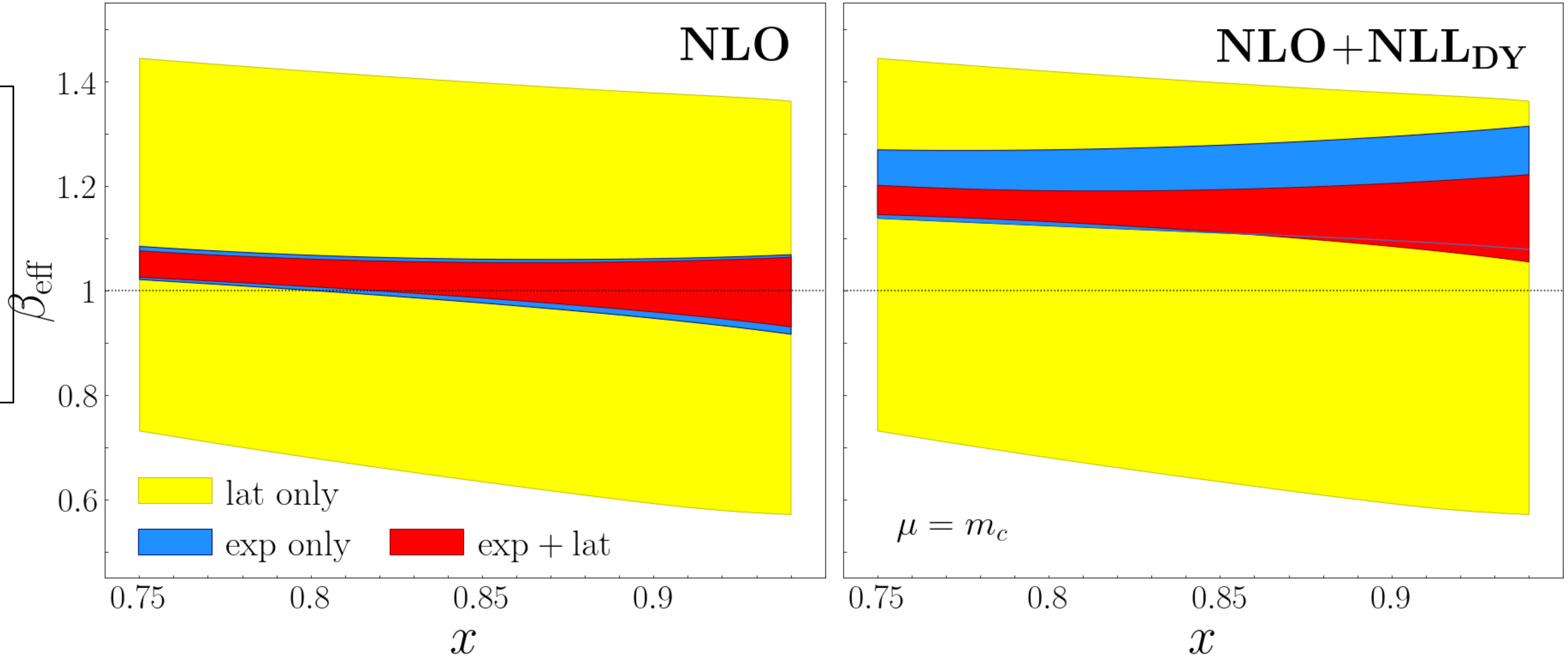
- PDFs and relative uncertainties
- Including lattice reduces uncertainties
- NLO+NLL$_{DY}$ changes a lot – unstable under new data



Effective β from $(1-x)^{\beta_{\text{eff}}}$

$$\beta_{\text{eff}}(x,\mu) = \frac{\partial \log |q_v(x,\mu)|}{\partial \log(1-x)}$$

Calculations from QCD do not predict $\beta_{\text{eff}} = 2$



Conclusions

- Including both lattice and experimental data sheds light on the pion PDF itself as well as systematics associated with the lattice
- Consistency between experimental and lattice data
- $1 \lesssim \beta_v^{\text{eff}} \lesssim 1.2$
- Performed analysis with current-current lattice QCD data – too noisy to have a sizable impact
- Extensions to non-perturbative objects that are not well constrained by experiments could aided by lattice calculations

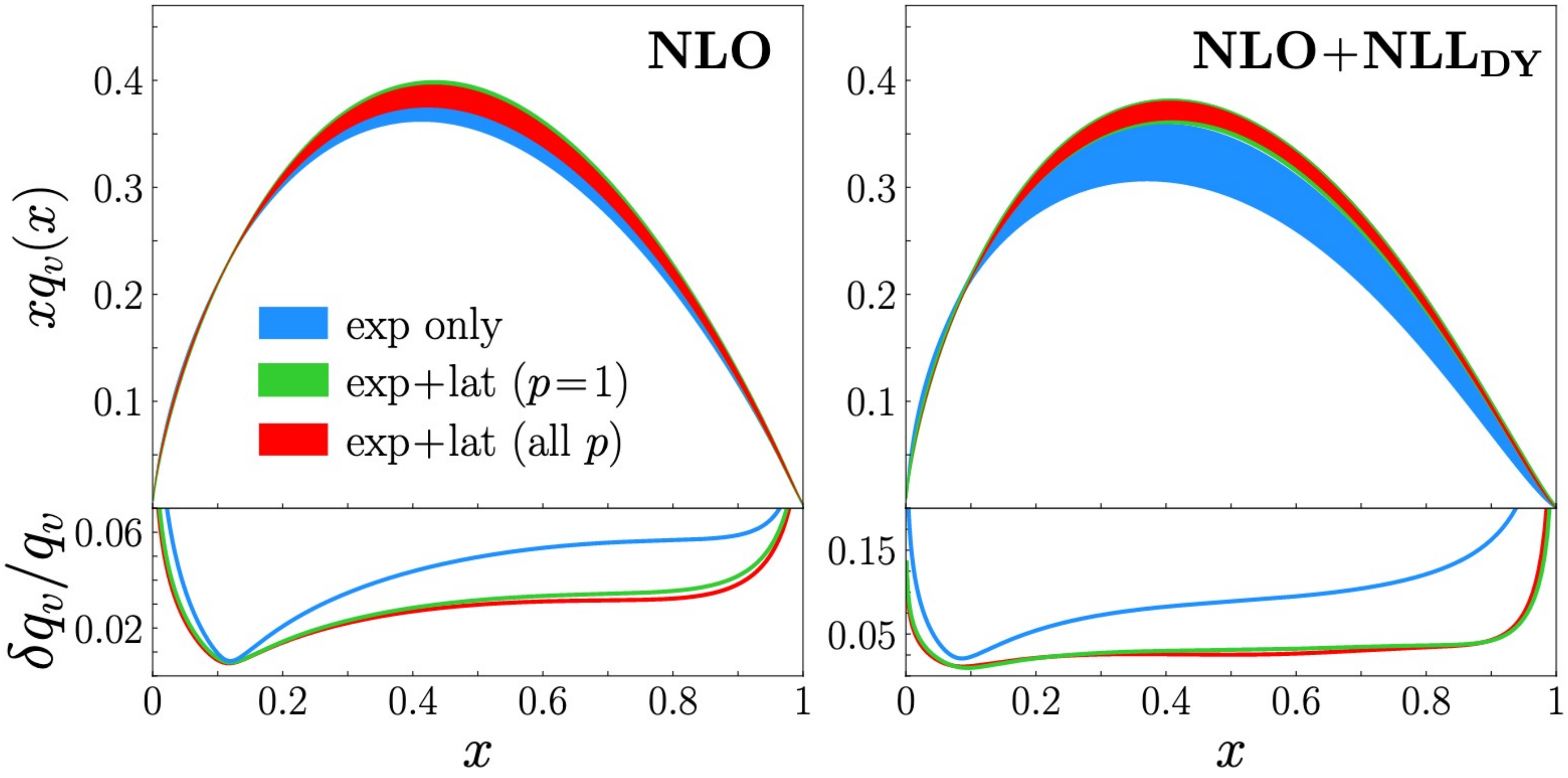
Backup Slides

Fitting only the $p = 1$ points

- Most precise points, but not large range in Ioffe time
- Through analysis containing *only* lattice data, would not be sufficient to get a large x description of PDF

Resulting low-momentum PDFs

- These momentum points do entire job!



Quantifying individual systematic corrections on the lattice

- Breaking down by the 3 systematics

$$z^2 B_1(\nu) + \frac{a}{|z|} P_1(\nu) + e^{-m_\pi (L-z)} F_1(\nu)$$

- Dominance of power or spacing corrections depends on z
- Finite volume corrections don't matter