valance PDF of pion from lattice QCD:

radial excitation, improved matching, physical mass, chiral quarks

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based on: 2007.06590 2101.11632 2102.01101 preliminary

- significant contributions of gluons (trace-anomaly) to proton mass, even in the chiral limit

- contribution of gluons (trace-anomaly) to pion mass ?

$$m_q \to 0 \ : -\langle T_{\mu\mu} \rangle = \langle H_m \rangle + \langle H_a \rangle = M_\pi \to 0$$

a puzzling dichotomy !!

understanding the role of gluons in hadron mass generation will remain incomplete without explaining the *absence* of pions mass *where are the gluons? … valance quark PDF of pion*

different for different models/fits

$$q_v^\pi(x) = Ax^\alpha(1-x)^\beta\left[1 + \text{sub leading}\right]$$

data: Fermilab E615 Phys. Rev. D39, 92 (1989)

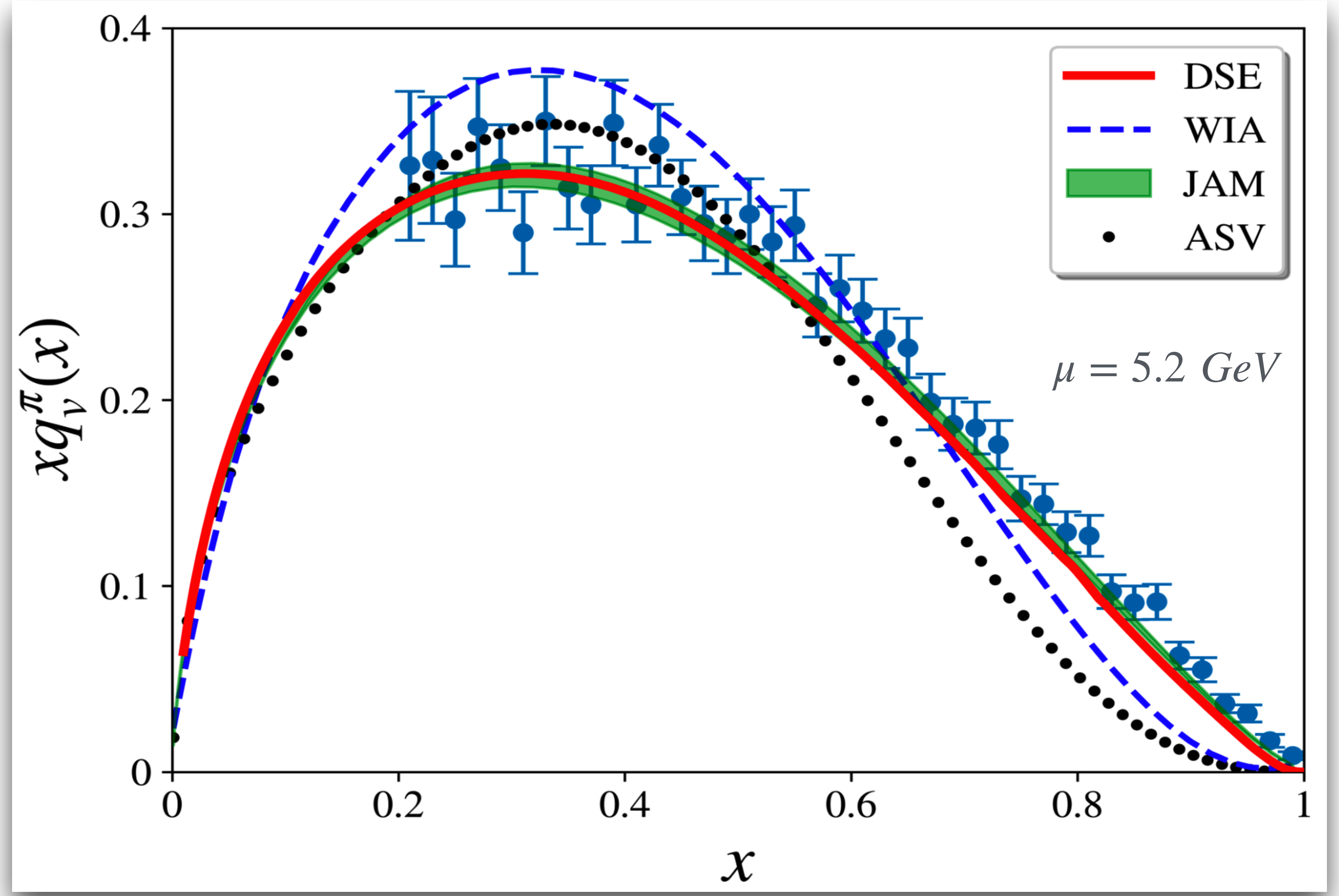
pQCD: $b \simeq 2$ dominated by one-gluon exchange
Berger, Brodsky: Phys. Rev. Lett. 42, 940

JAM: $b \simeq 1$ Phys. Rev. Lett. 121, 152001 (2018)

ASV: $b \simeq 2$ NLL threshold resummation
Phys. Rev. Lett. 105, 252003 (2010)

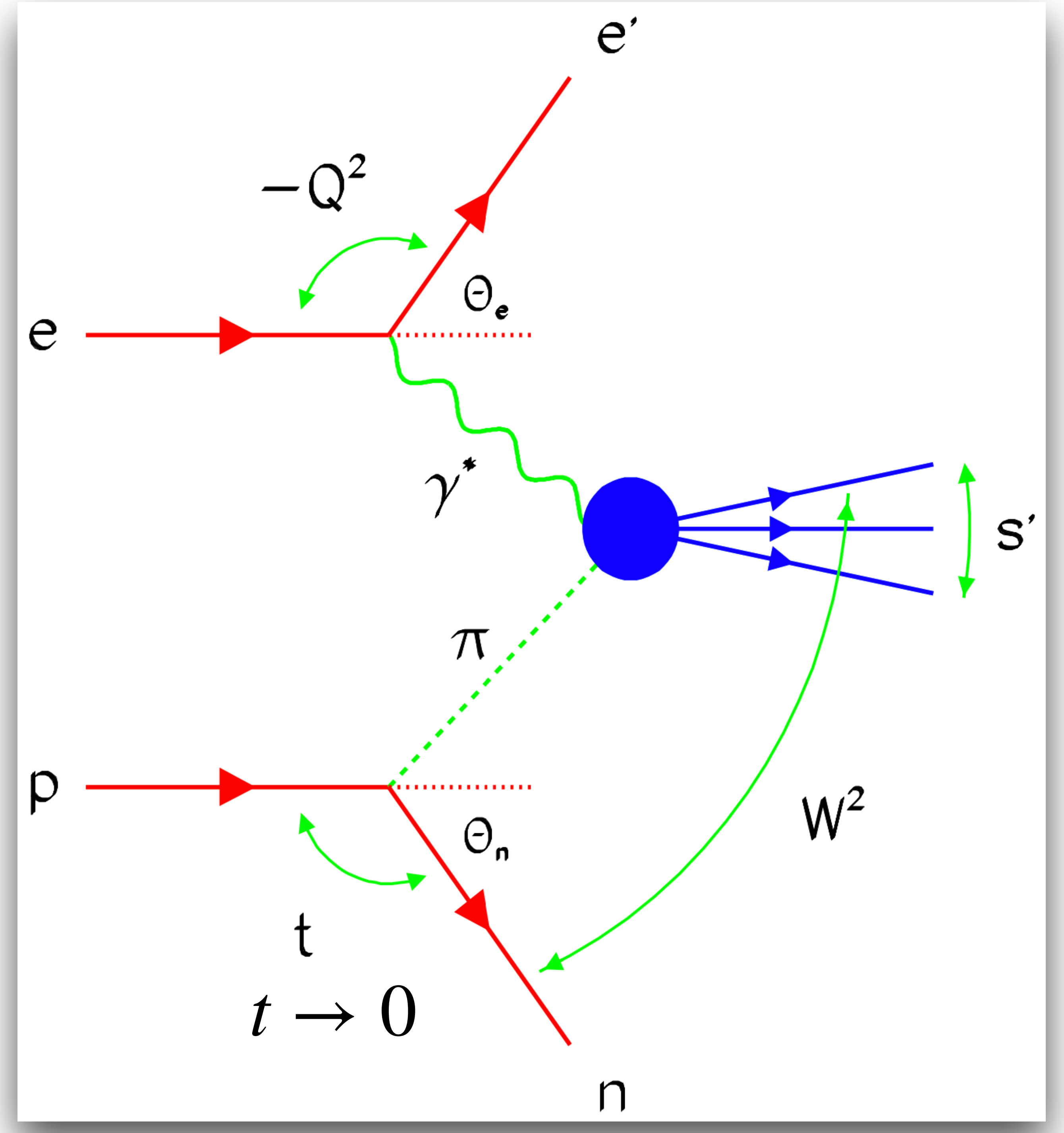
WIA: $b \simeq 2$ DSE, rainbow-ladder truncation
Nguyen et al: Phys. Rev. C83, 062201 (2011)

DSE: $b \simeq 2$ another DSE w/ different quark dressing, different contributions of gluons
Phys. Rev. Lett. 124, 042002 (2020)



Bednar, Cloet, Tandy: Phys. Rev. Lett. 124, 042002 (2020)

Sullivan process w/ off-shell pion

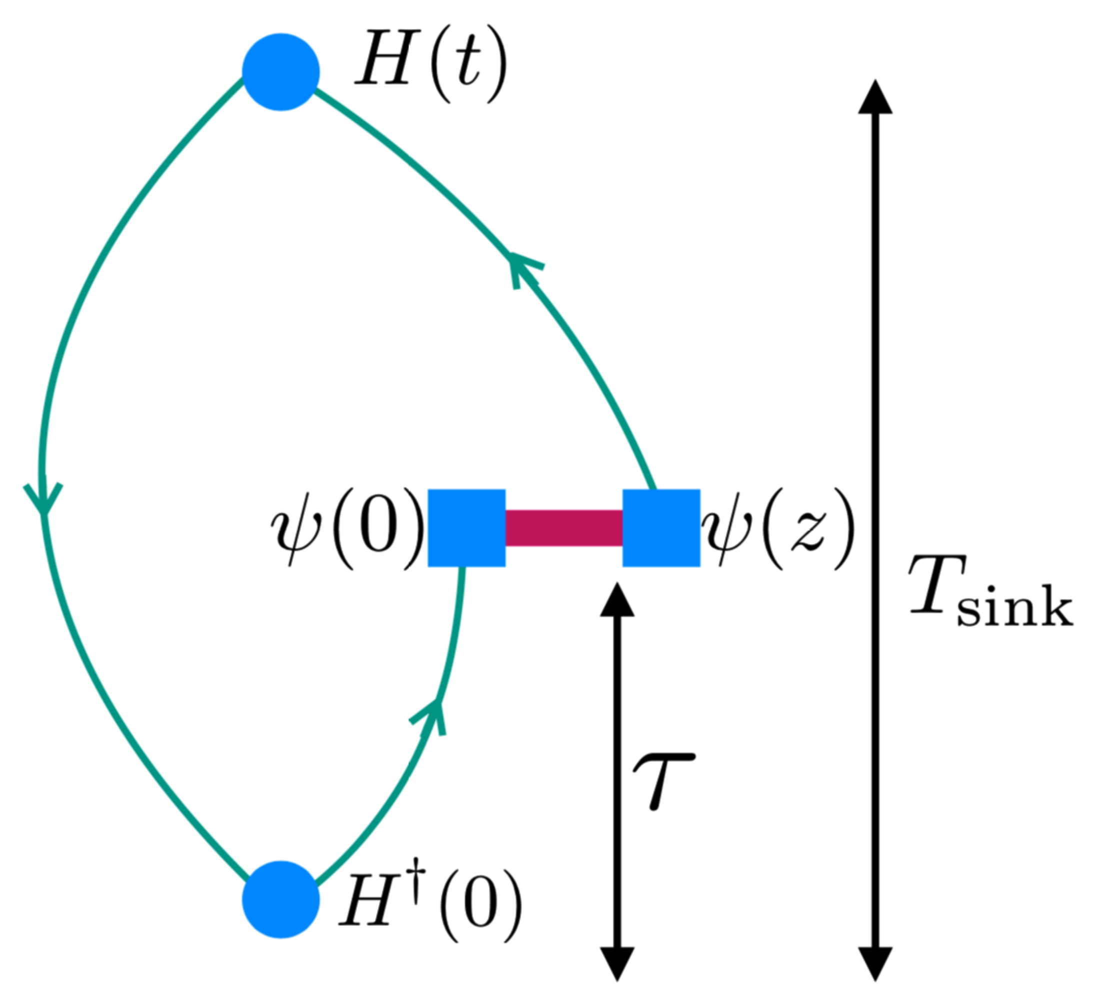


whitepaper: Eur. Phys. J. A55,190 (2019)

Pion and Kaon Structure at the Electron-Ion Collider

abstract

1 GeV mass-scale that characterizes atomic nuclei appear; why does it have the observed value; and, enigmatically, why are the composite Nambu-Goldstone (NG) bosons in quantum chromodynamics (QCD) abnormally light in comparison? In this perspective, we provide an analysis of the mass budget of the pion and proton in QCD; discuss the special role of the kaon, which lies near the boundary between dominance of strong and Higgs mass-generation mechanisms; and explain the need for a coherent effort in QCD phenomenology and continuum calculations, in exa-scale computing as provided by lattice QCD, and in experiments to make progress in understanding the origins of hadron masses and the distribution of that mass within them. We compare the unique capabilities foreseen at the electron-ion collider (EIC) with those at the hadron-electron ring accelerator (HERA), the



- bare matrix element:

$$Q_b(z,p_z) = \langle H(p_z,0)\,|\,\overline{\psi}(0,\tau)\gamma_0 W(0,z)\psi(z,\tau)\,|\,H(p_z,T_{\mathrm{sink}})\rangle$$

equal-time, non-local operator within boosted hadron

$W(0,z)$: Wilson line from *0* to *z*

- renormalization group invariant ratio

$$\mathscr{M}(z,p_z,p_z^0) = \frac{Q_b(z,p_z)}{Q_b(z,p_z^0)}$$

$p_z^0 = 0$ Radyushkin: Phys. Rev. D96, 034025 (2017)

$p_z^0 > 0$ BNL et. al.: Phys. Rev. D102, 074504 (2020)

- leading twist factorization in momentum space

X. Ji: Phys. Rev. Lett. 110, 262002 (2013)

Yong Zhao's talk

- leading twist factorization in coordinate space

short distance expansion

Radyushkin: Phys. Rev. D96, 034025 (2017)
Phys. Lett. B781, 433 (2018)

Karpie, Orginos, Zafeiropoulos: JHEP 11, 178 (2018)

BNL et.al.: Phys. Rev. D102, 074504 (2020)

$$\mathcal{M}(z, p_z, p_z^0) = \frac{\sum_{n=0}^{\infty} \frac{(-izp_z)^n}{n!} c_n(z^2\mu^2) \langle x^n \rangle (\mu)}{\sum_{n=0}^{\infty} \frac{(-izp_z^0)^n}{n!} c_n(z^2\mu^2) \langle x^n \rangle (\mu)} + \mathcal{O}\left(z^2 m_h^2, z^2 \Lambda_{\text{QCD}}\right)$$

coefficient function　　PDF moments　　target mass, higher twist

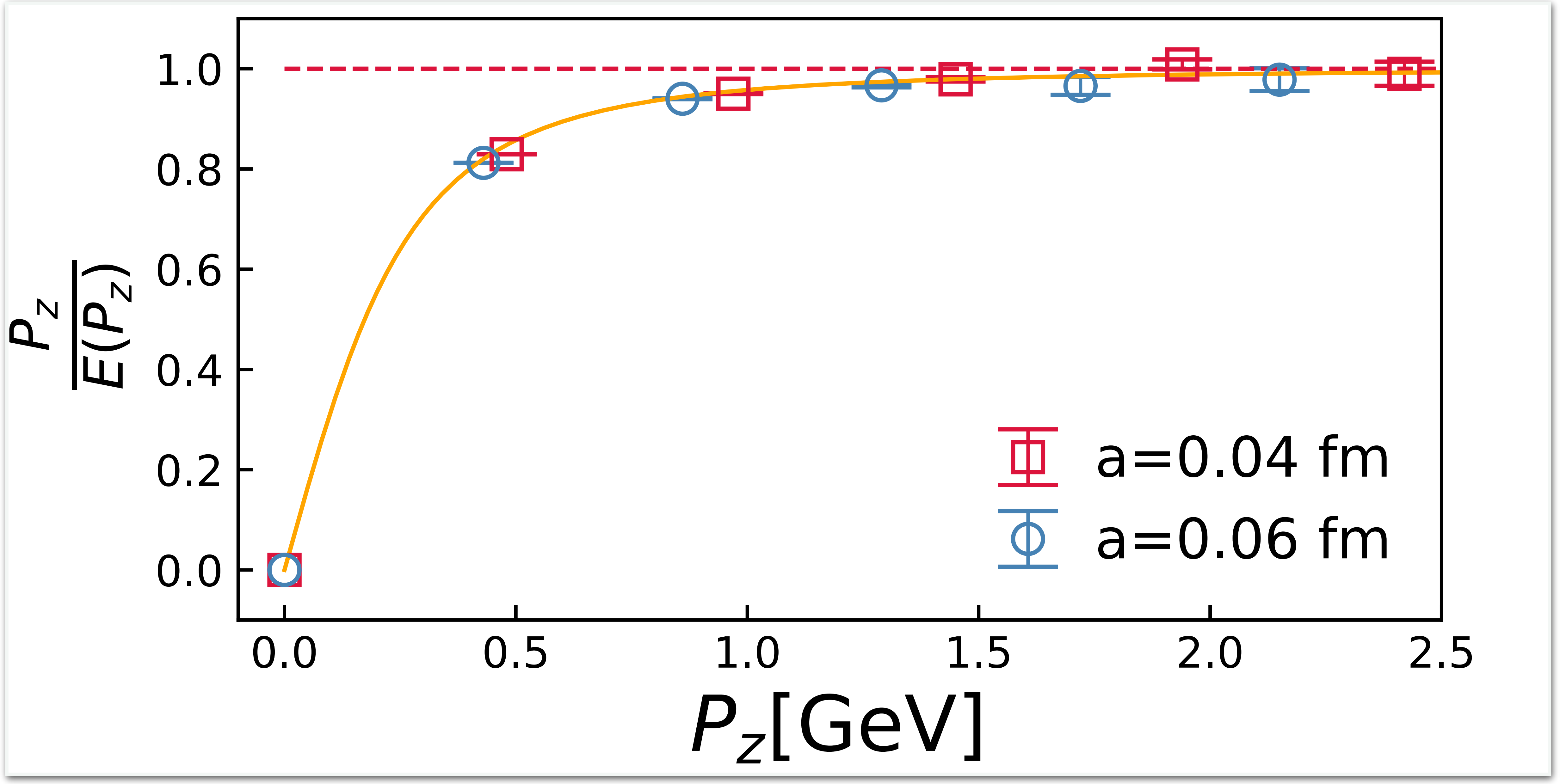
$$\langle x^n \rangle = \int_{-1}^{1} dx x^n f(x, \mu)$$

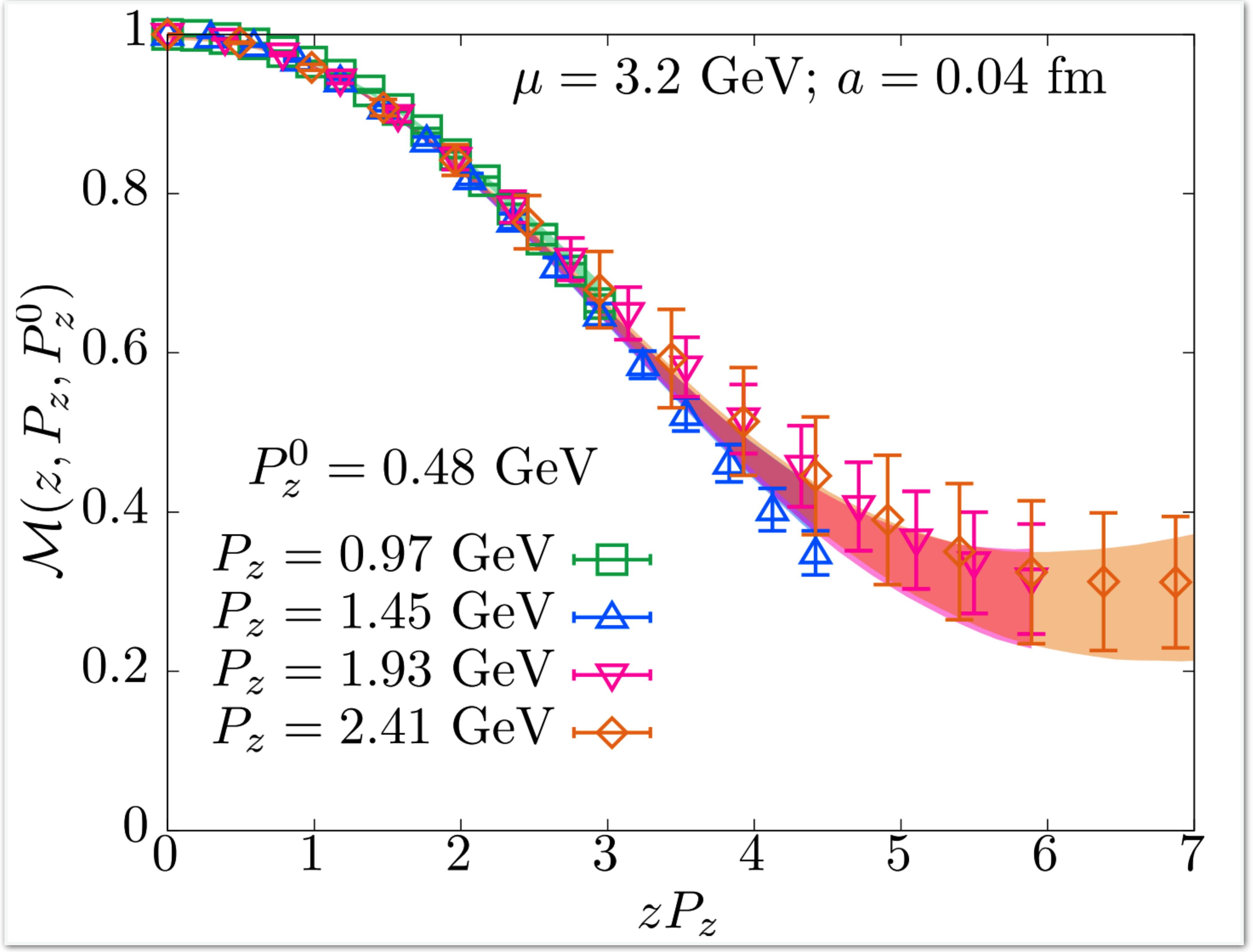
NLO: Izubuchi et. al.: Phys. Rev. D 98, 056004 (2018)
NNLO: Li, Ma, Qiu: 2006.12370
NLO+NLL: BNL-ANL: 2102.01101

valance PDF of pion …

BNL: Phys. Rev. D102, 094513 (2020)

$m_\pi = 300$ MeV

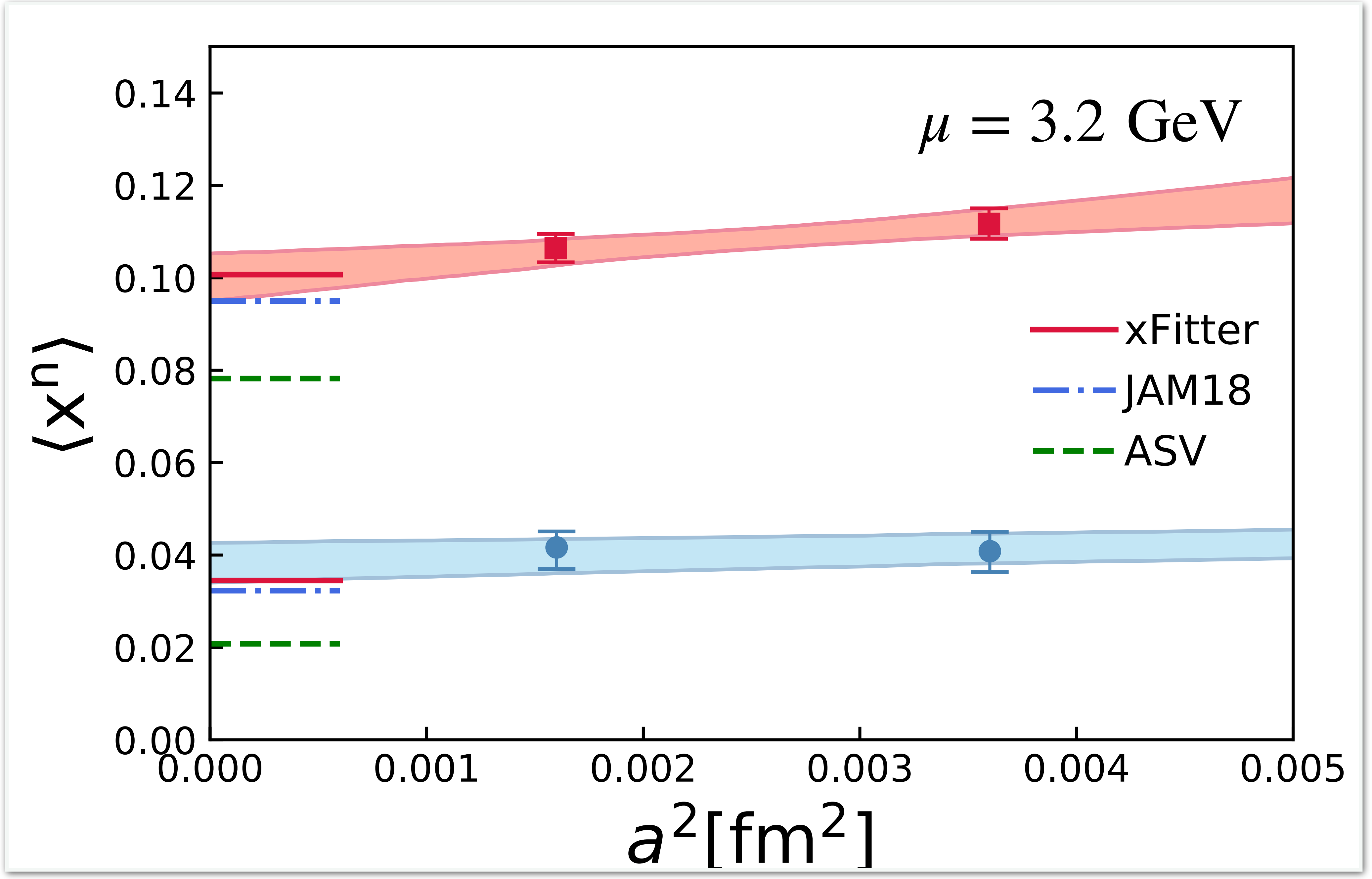




valance quarks: Wilson-Clover

sea quarks: 2+1 flavor HISQ, $m_\pi^{sea} \simeq 160$ MeV, $m_K^{sea} \simeq 500$ MeV

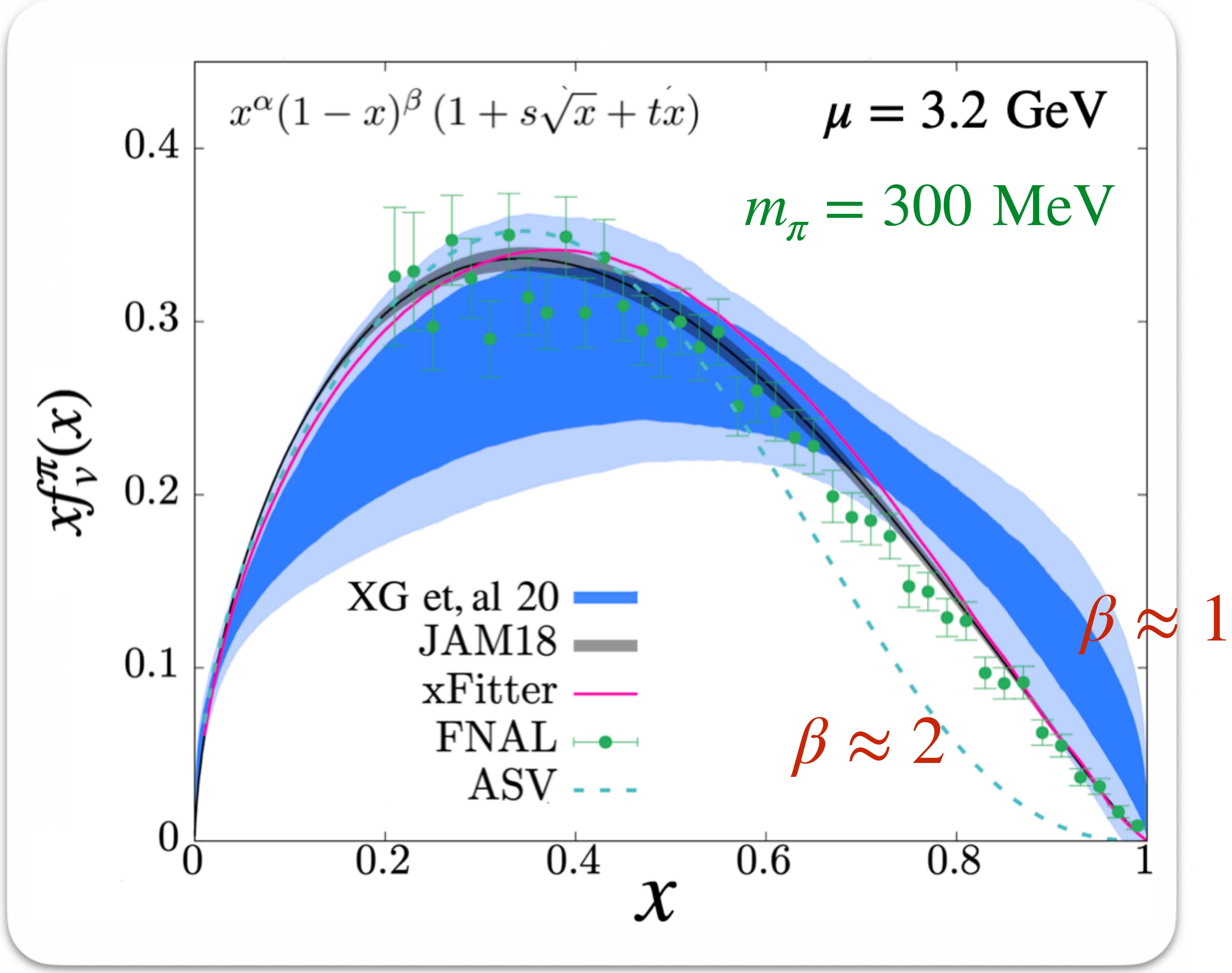
model-independent moments



BNL: Phys. Rev. D102, 094513 (2020)

model-dependent fit:

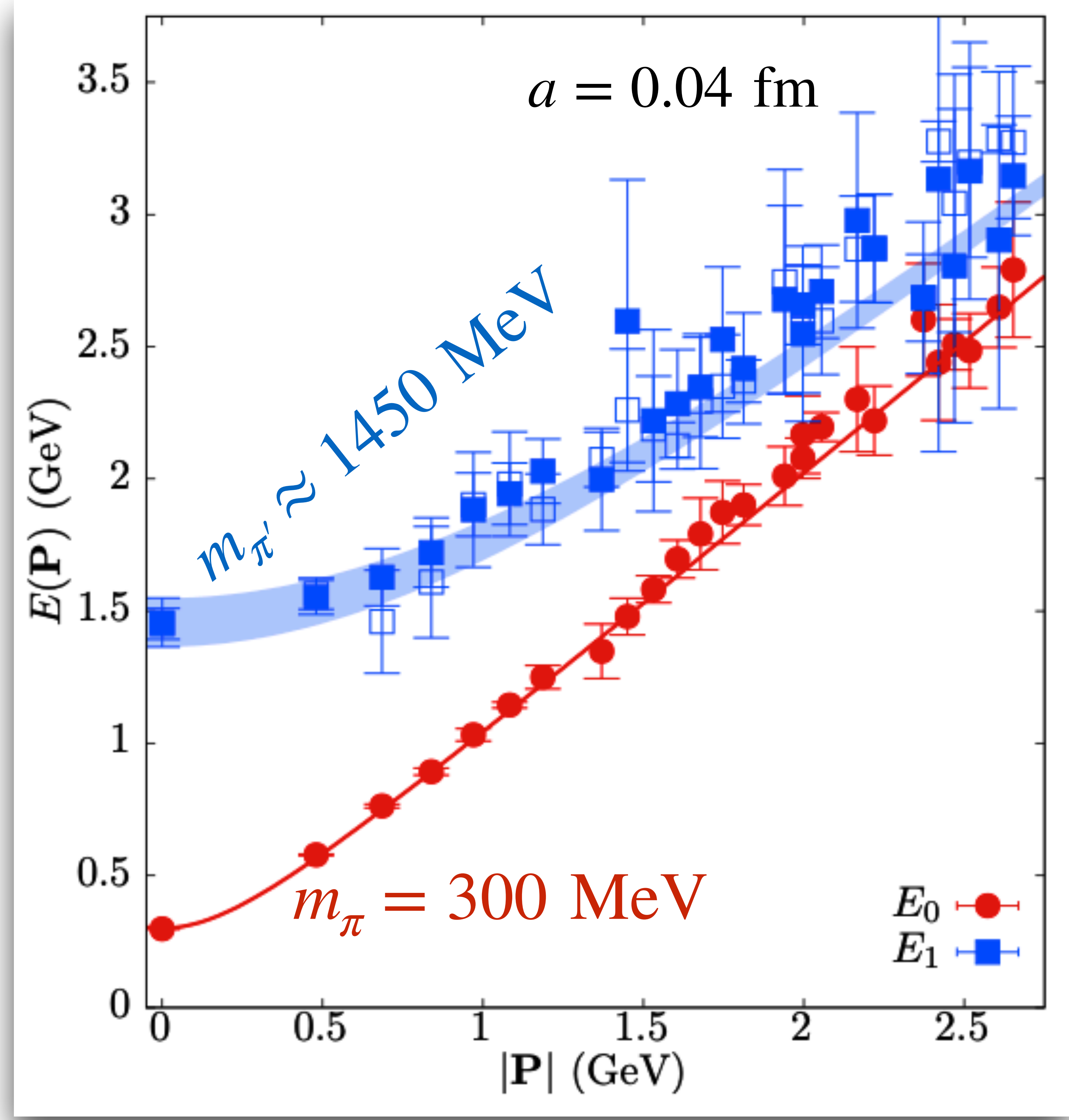
$$f_v^\pi(x) = Ax^\alpha(1-x)^\beta(1+s\sqrt{x}+tx)$$

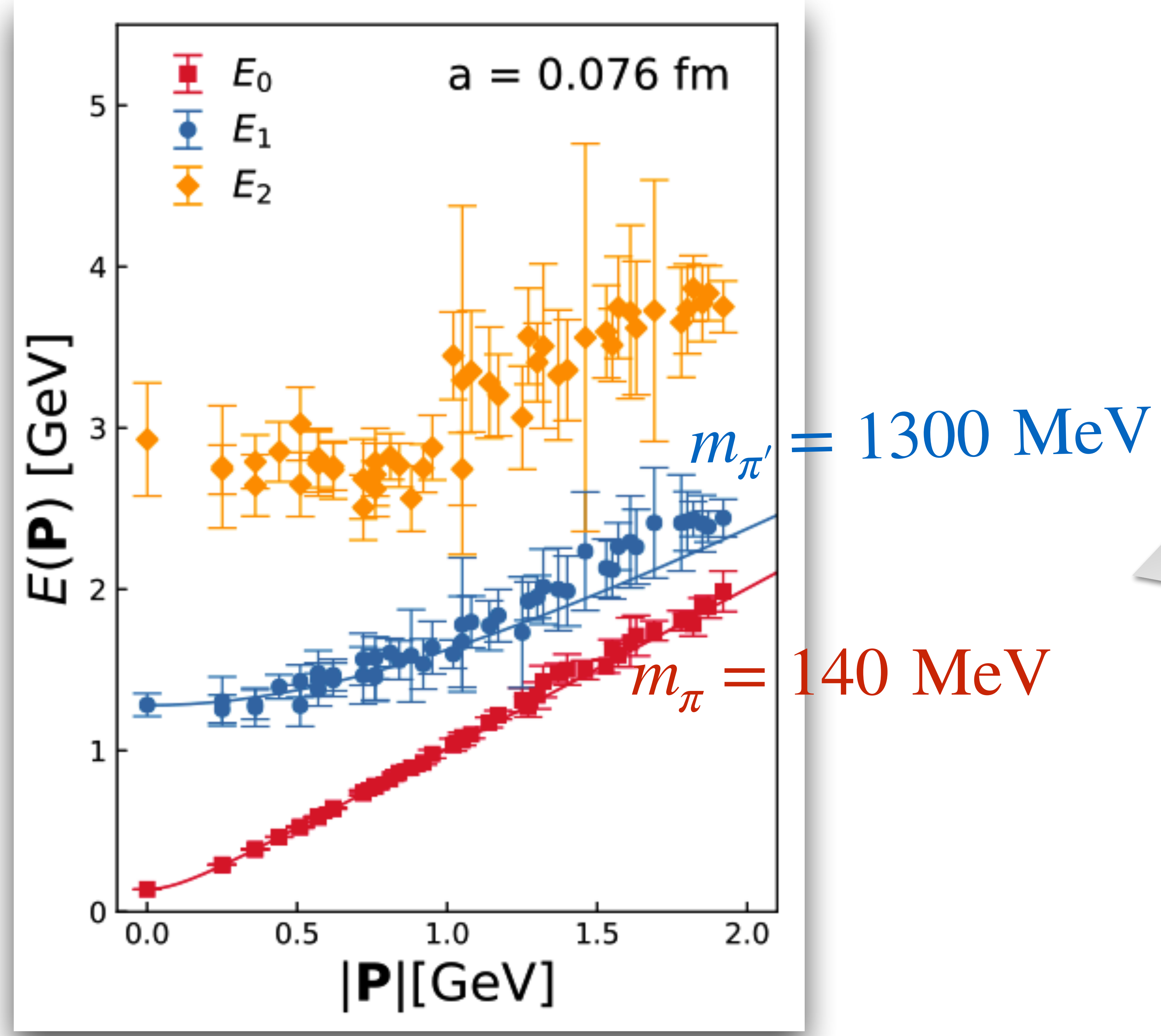


radial excitation: valance PDF

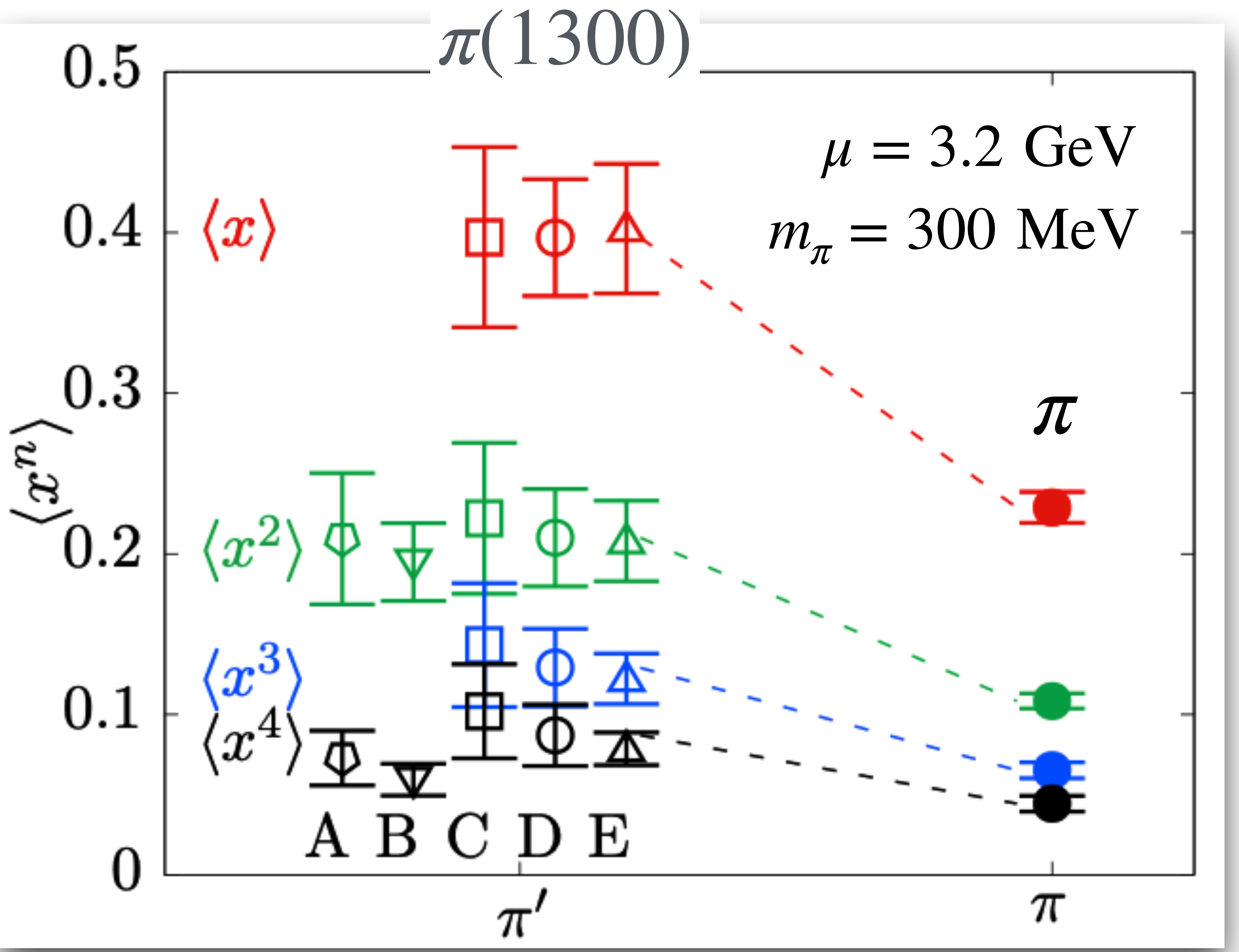
$\pi(1300)$

BNL: 2101.11632

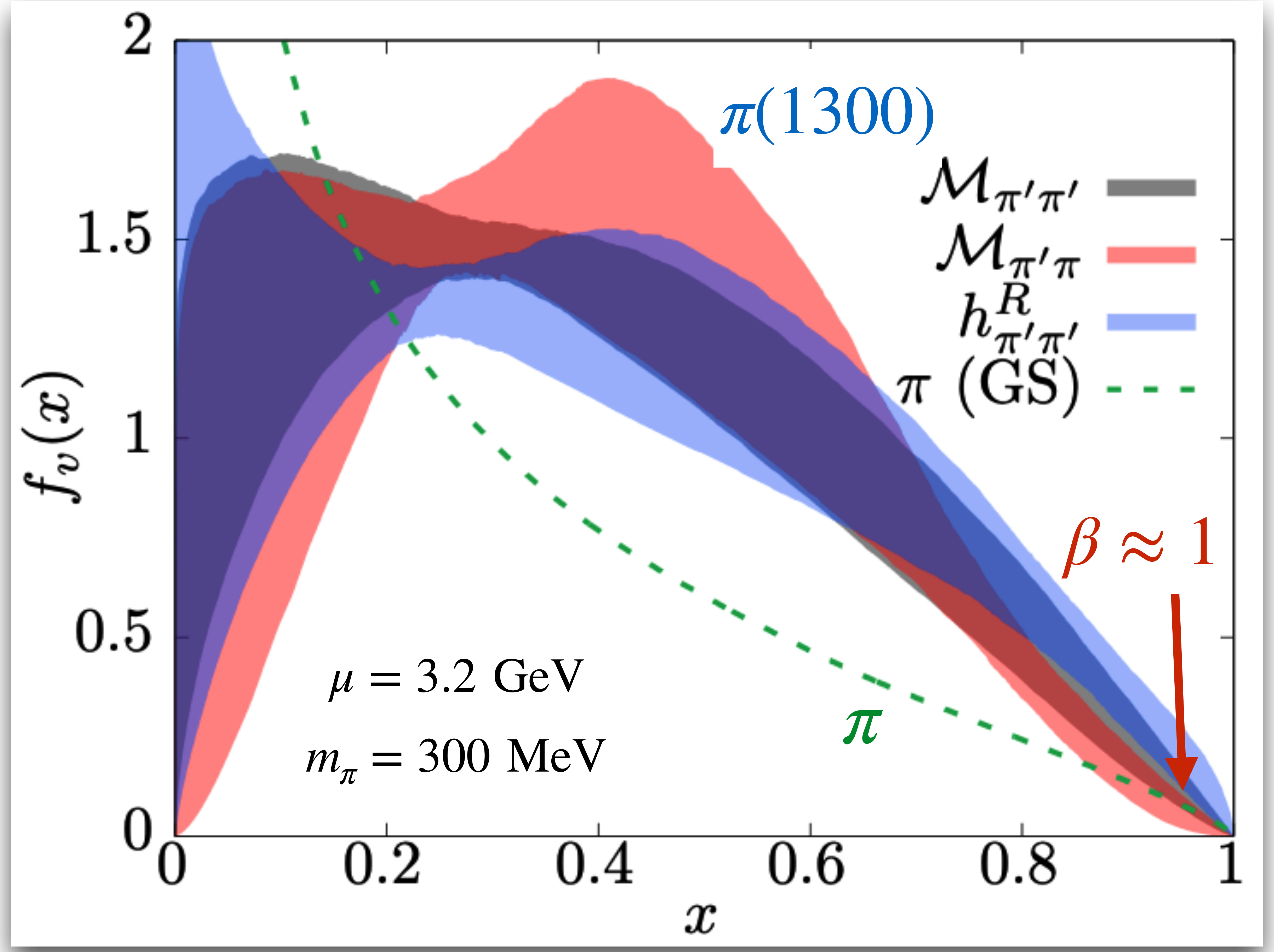




BNL-ANL: 2102.06047



moments



model fit: $f_v^\pi(x) = Ax^\alpha(1-x)^\beta$

improved matching: threshold resummation

BNL - ANL - K. Lee: 2102.01101

Melin space:

$$\lim_{N\to\infty} C_N^{\mathrm{NLO}} = \frac{\alpha_s(\mu)C_F}{2\pi}\Big[2\ln N'\ln(z_0^2\mu^2) - 2\ln^2 N' + 2\ln N' - \frac{\pi^2}{3}\Big]$$

resum: $\alpha_s \ln^2 N'$ and $\alpha_s \ln N'$

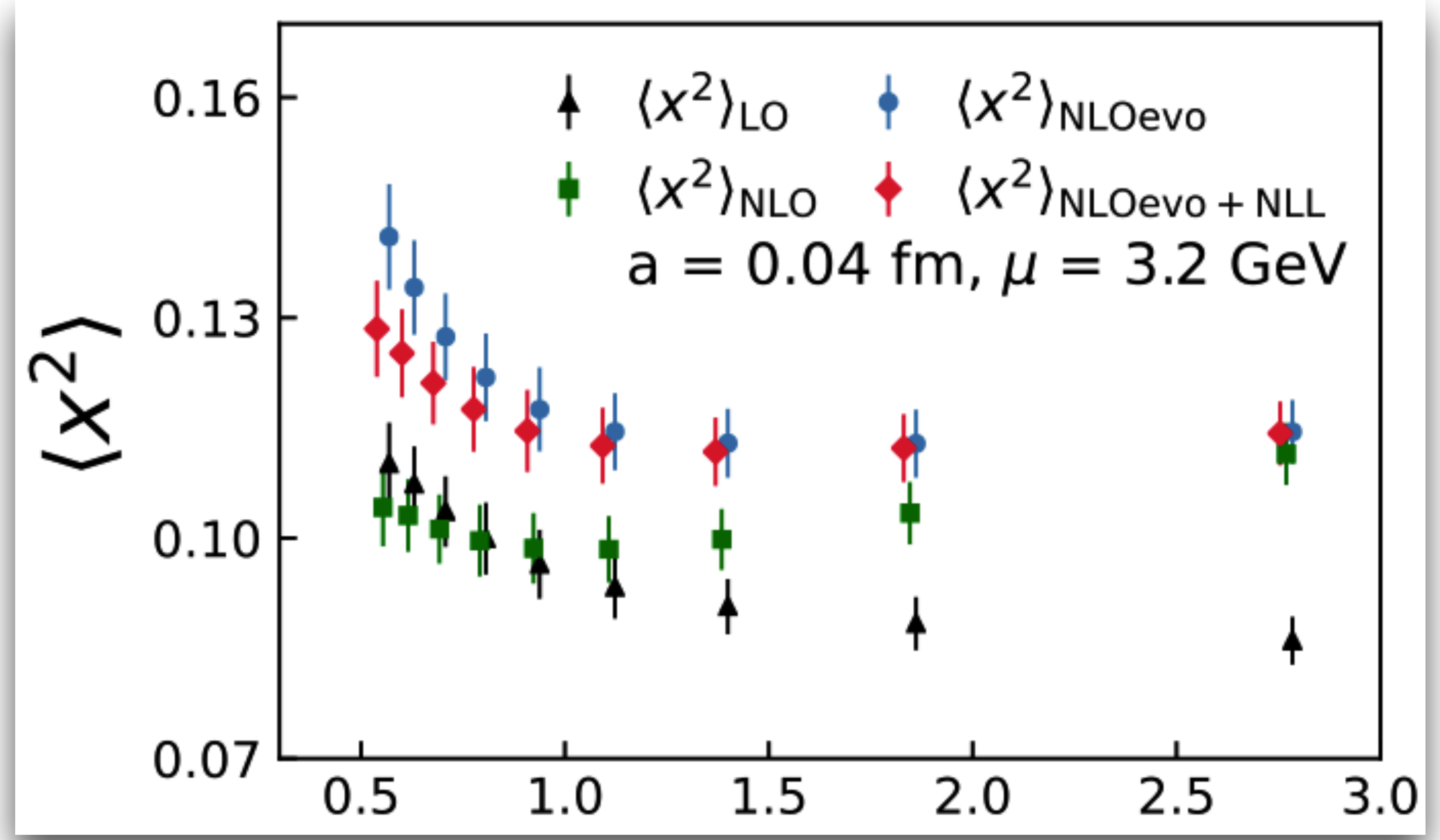
$$C_n(z^2\mu^2) = 1 + \frac{\alpha_s(\mu)C_F}{2\pi}[(\frac{3+2n}{2+3n+n^2} + 2H_n)\ln(z_0^2\mu^2) + \dots] + \dots$$

'evo': resum DGLAP logs

$$\Big[\frac{\partial}{\partial \ln \mu^2} + \beta(\alpha_s(\mu))\frac{\partial}{\partial \alpha_s} - \gamma_n\Big] C_n^{evo} = 0$$

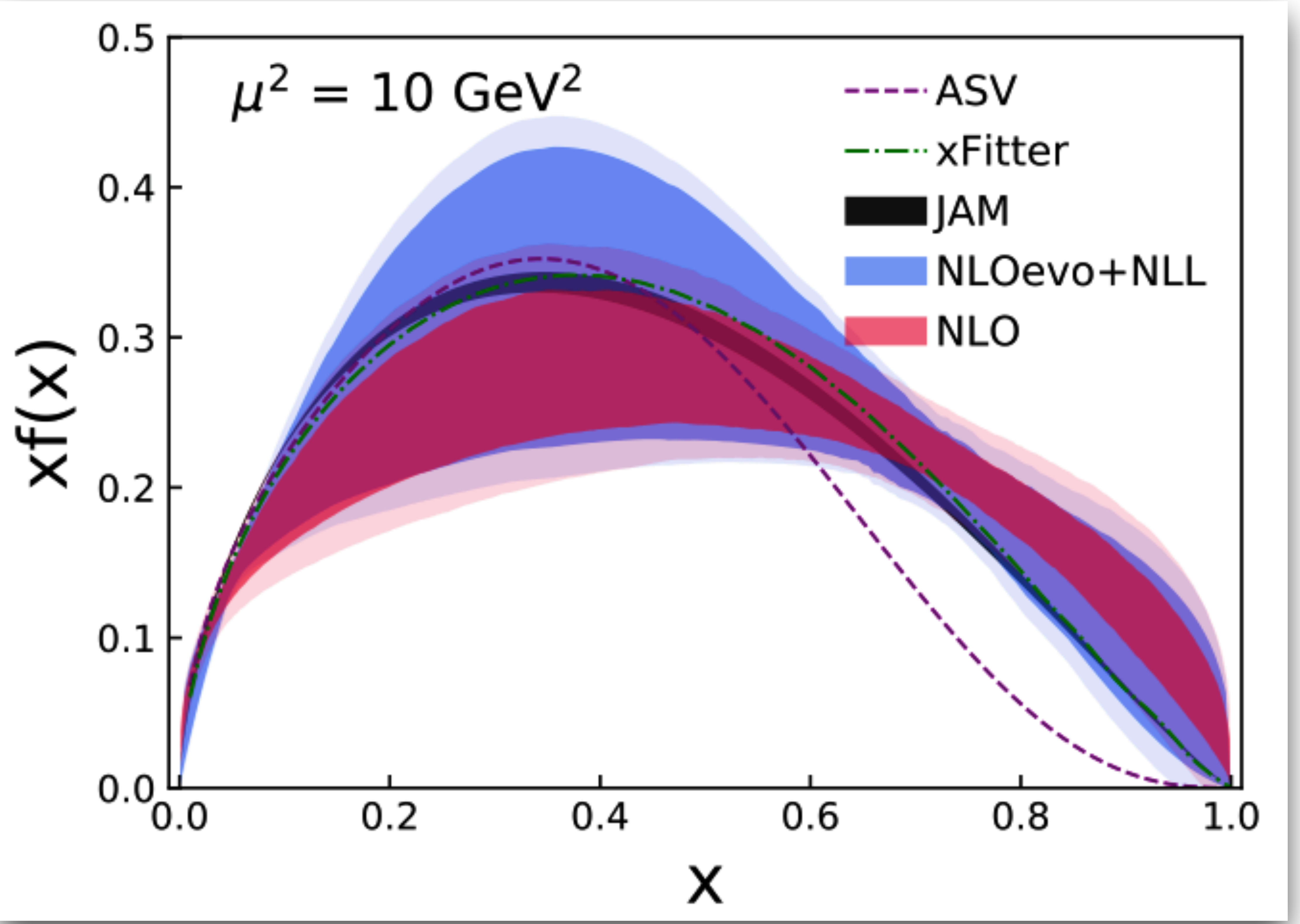
$$z_0^2 = z^2 e^{2\gamma_E}/4$$

BNL - ANL - K. Lee: 2102.01101



$1/z_0\ [GeV]$

$z_0^2 = z^2 e^{2\gamma_E}/4$

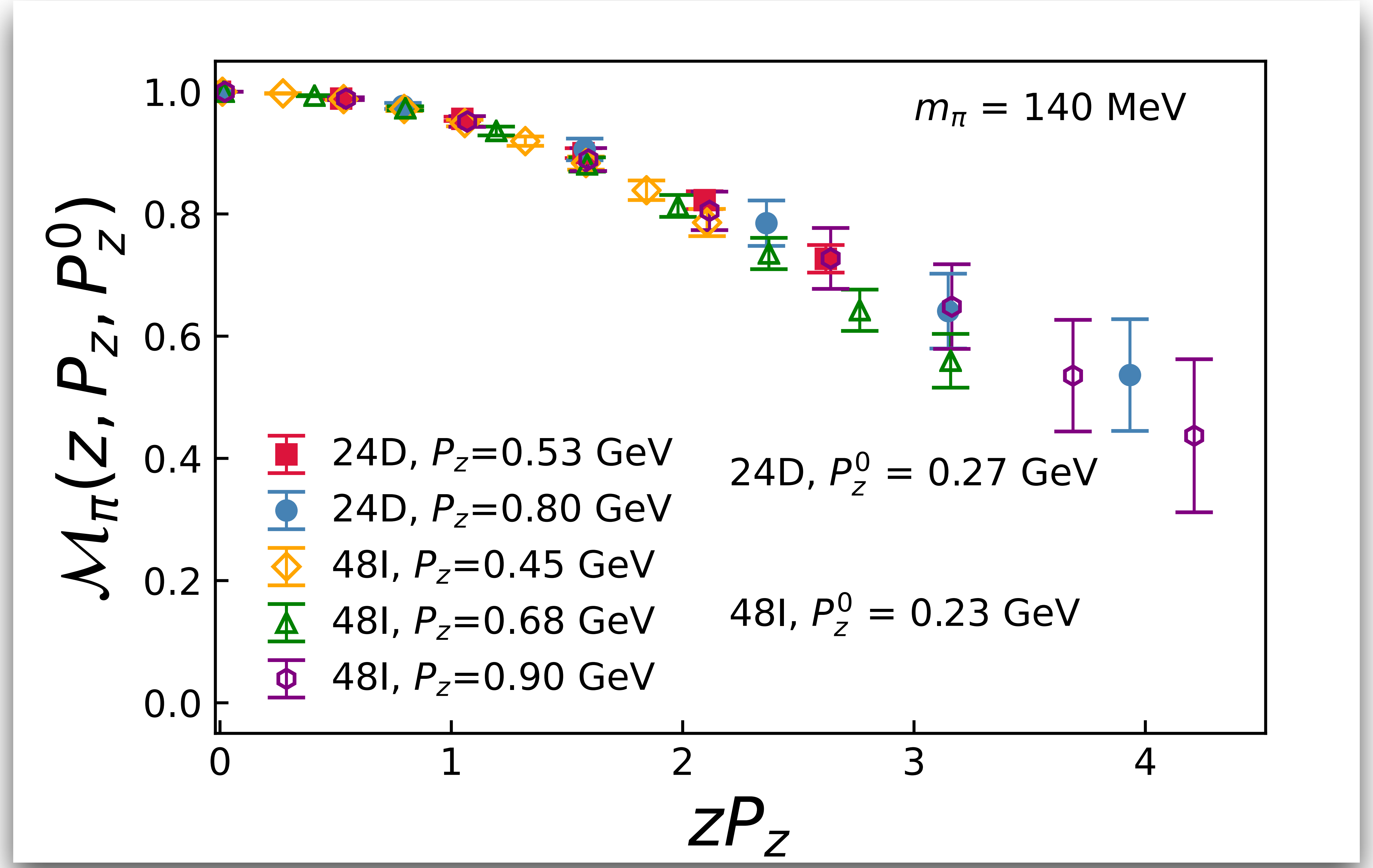


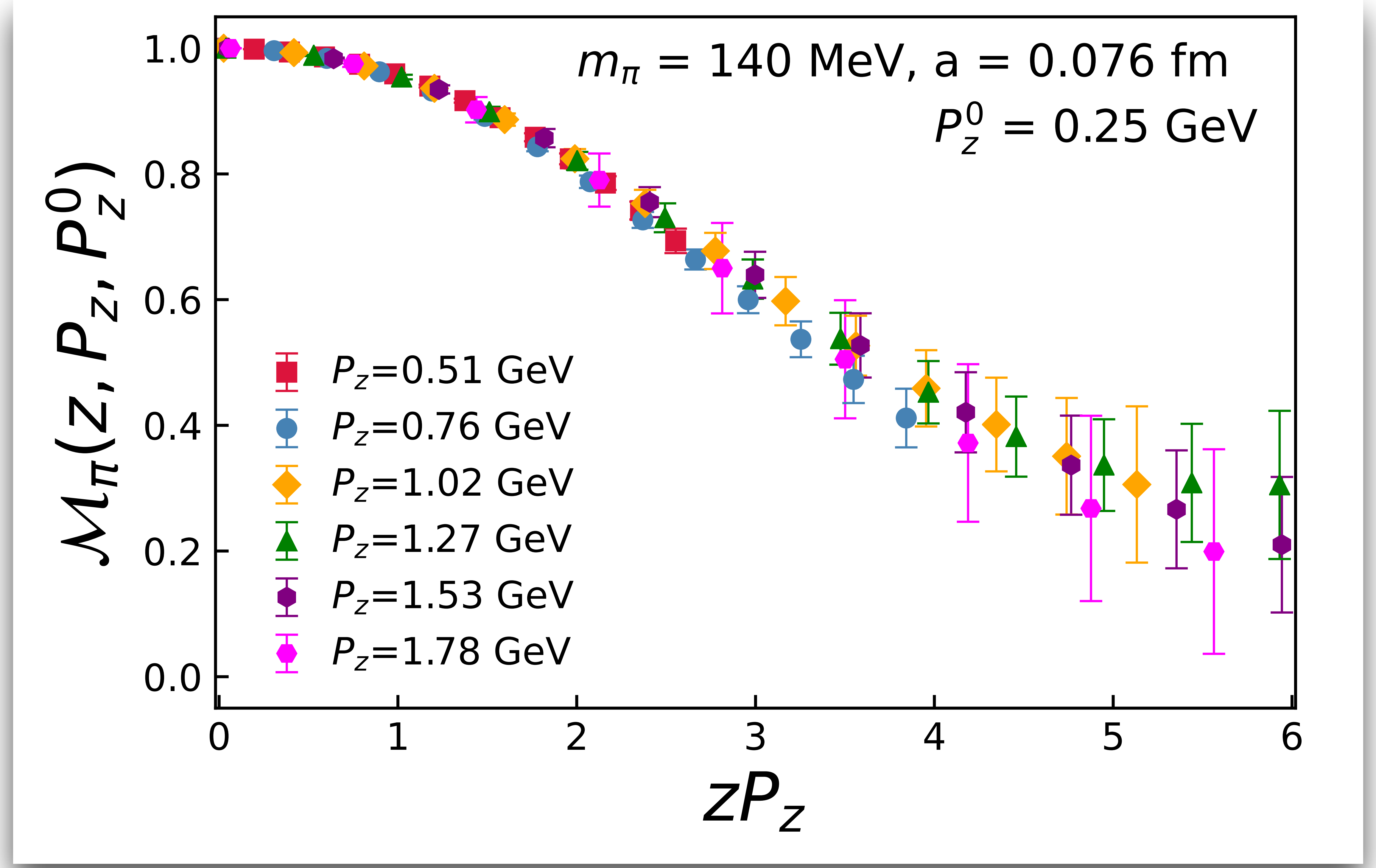
physical mass and chiral quarks …

BNL-ANL: preliminary

unitary chiral domain wall fermion (DWF)

$m_\pi = 140$ MeV





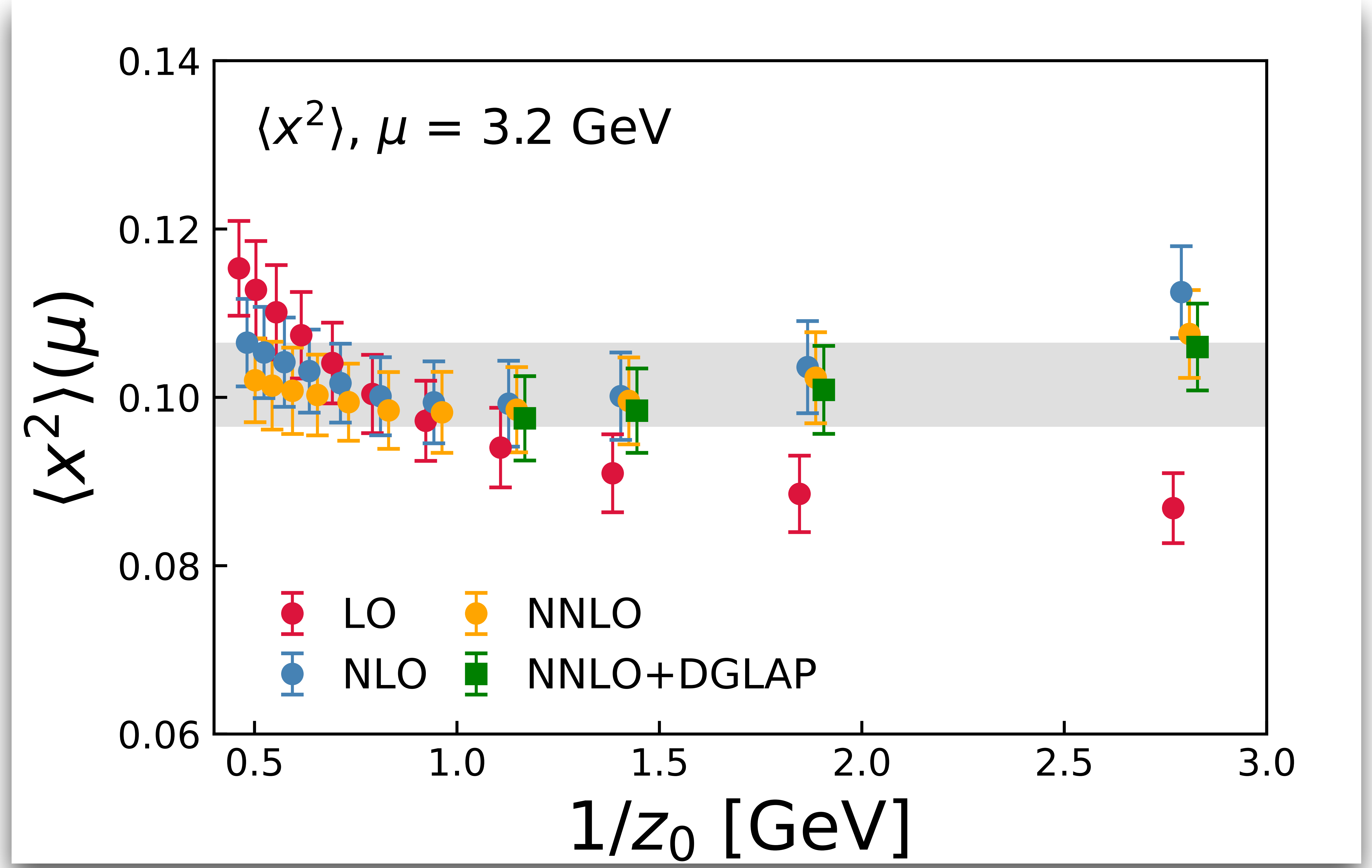
$a = 0.11,\ 0.19$ fm $\quad P_z < 1$ GeV

$P_z \leq 1.8$ GeV

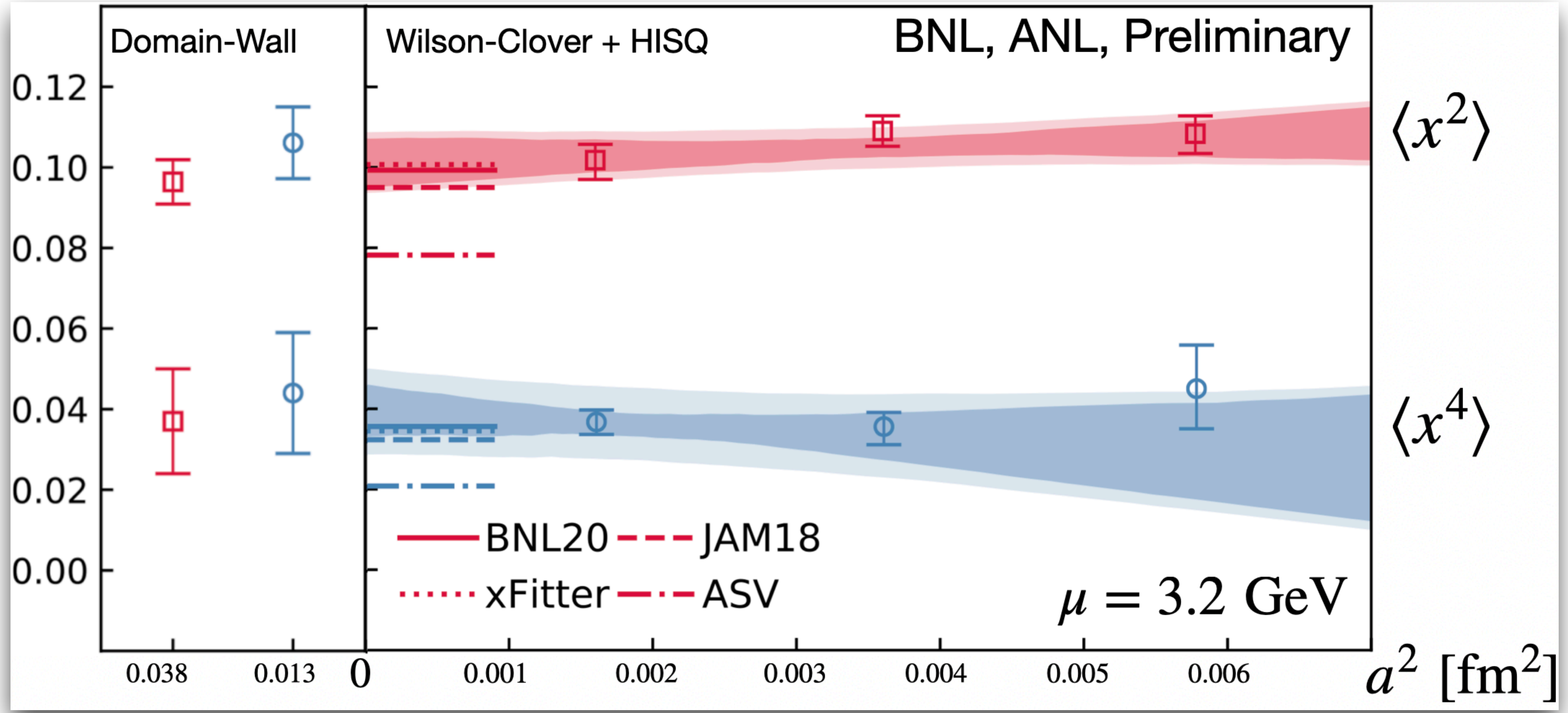
Wilson-Clover + HISQ

… *with NNLO matching*

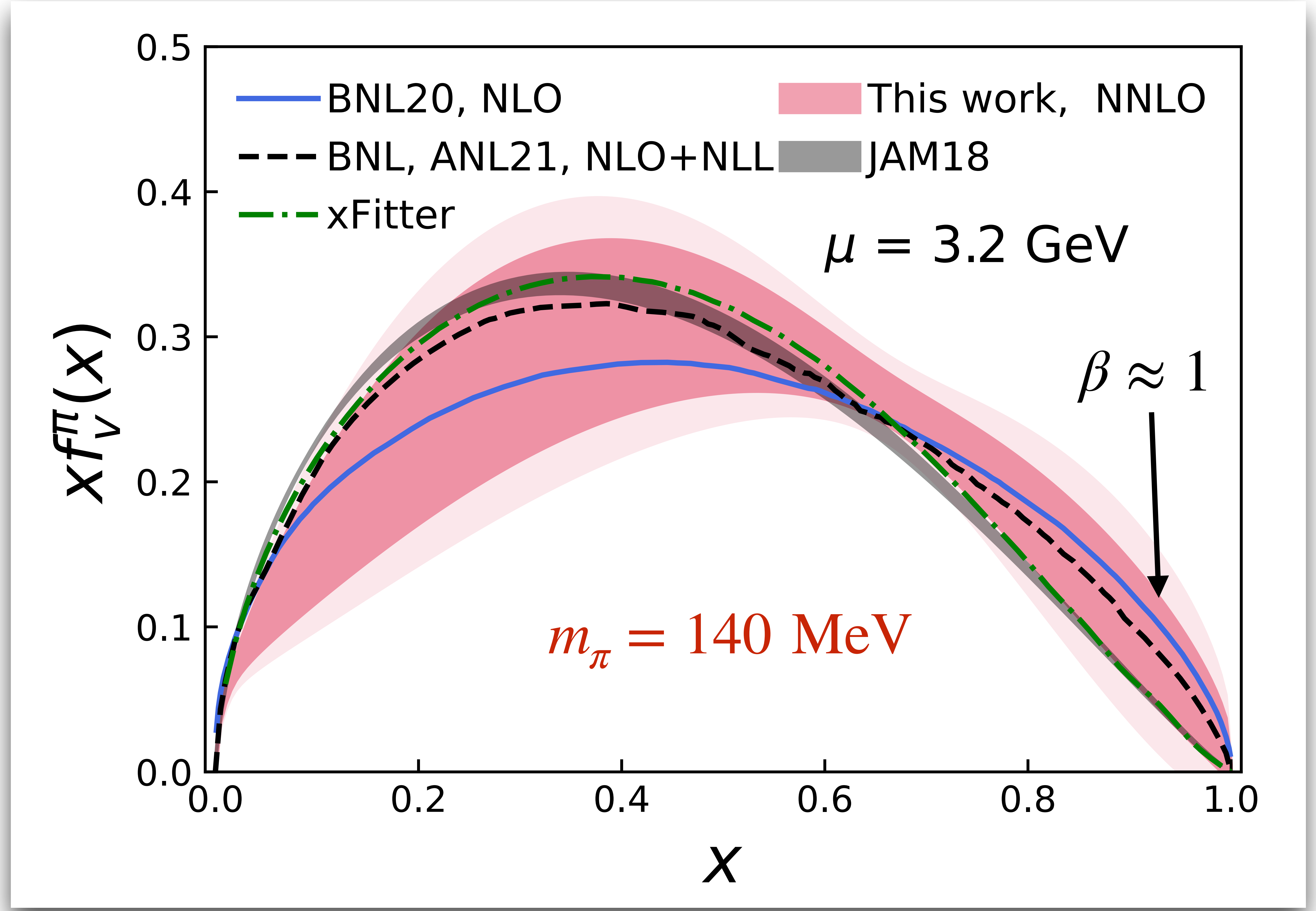
BNL-ANL: preliminary



model-independent moments
NNLO matching, physical mass, chiral quarks



- pion mass dependence is very mild
- good agreement between DWF and Wilson-Clover + HISQ

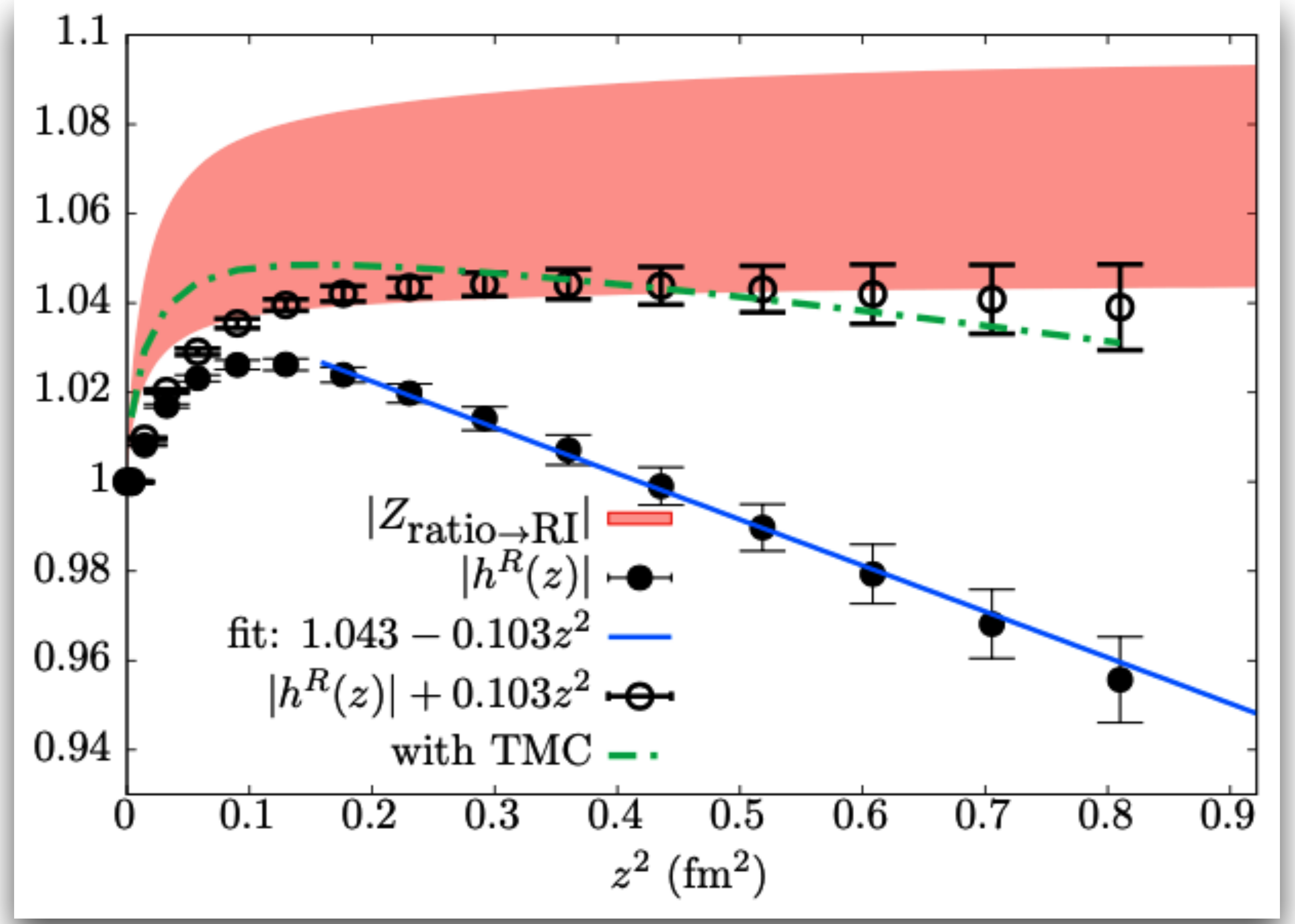


model fit: $f_v^\pi(x) = Ax^\alpha(1-x)^\beta(1+s\sqrt{x}+tx)$

back up …

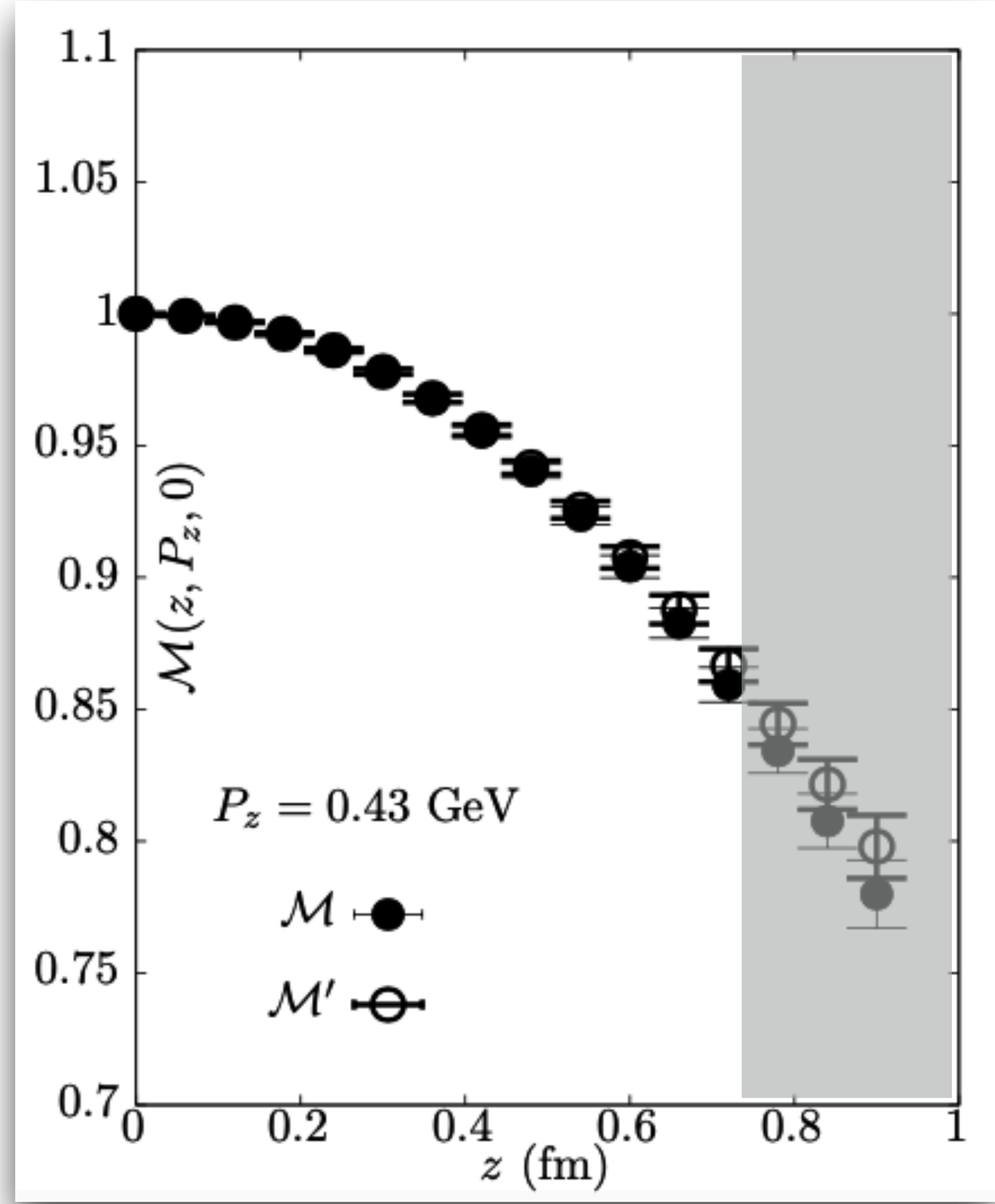
assessing higher twist corrections

RI-MOM renormalized



$$Q(z, p_z = 0; p_z^R = 1.29\ GeV, p_\perp^R = 2.98\ GeV)$$

ratio scheme



$$\mathcal{M}(z, p_z = 0.43\ GeV, p_z^0 = 0)$$