

x-dependent Baryon Light-cone DA from Lattice QCD

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In collaboration with: Haoyang Bai (IHEP), Jun Hua (SCNU), Wei Wang (SJTU), Jia-Lu Zhang(SJTU)
(Lattice Parton Collaboration)

Oct. 10 @ LaMET 2025

01 Why baryon LCDA ?
Exclusive process; Lattice QCD; LaMET

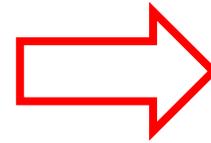
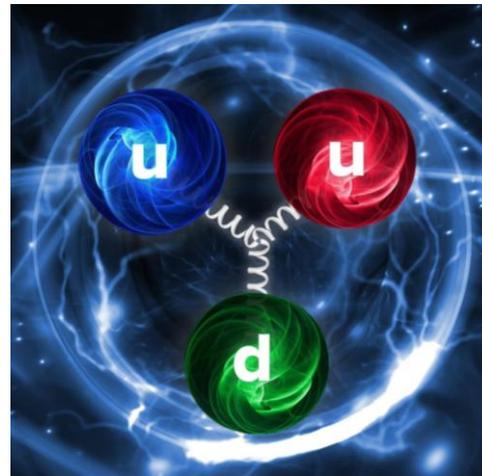
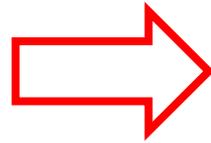
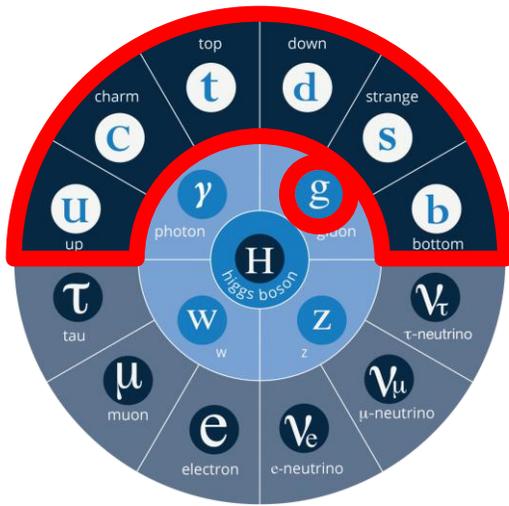
02 How to calculate baryon LCDA ?
Definition; Quasi-DA; Operators; Symmetries

03 Recent Progresses
Lattice setup; Renormalization; Matching

04 Summary & Outlook
Other Strategies; Planning in future

Why Baryon ?

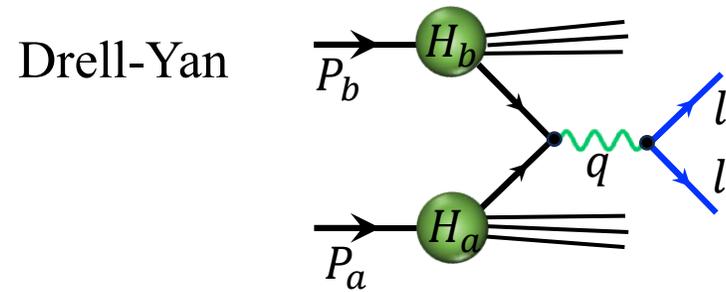
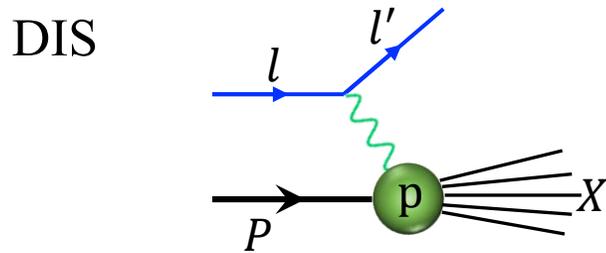
Baryon — cornerstone particles



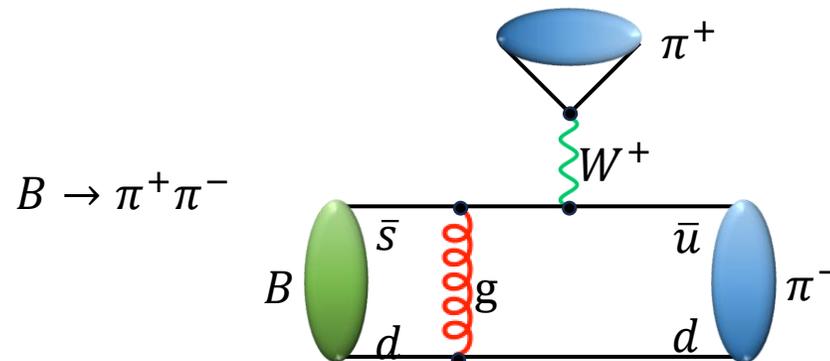
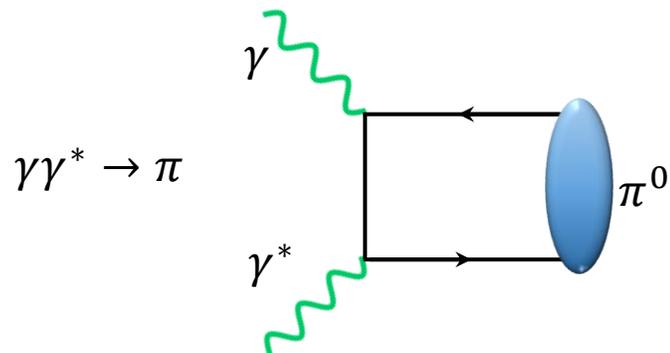
- Matter genesis in the Universe
- Tools to probe micro world
- Astronomy & Cosmology
-

Why LCDA ?

- Probe internal structure of nucleons in **Inclusive processes**
- **PDFs**



- Obtain richer QCD dynamical information in **Exclusive processes**
- **LCDAs**



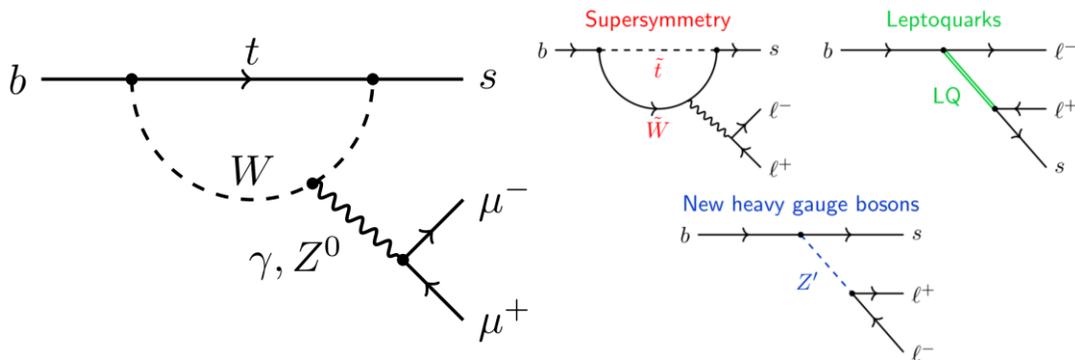
Why Baryon LCDA ?

Establish CPV in Baryon Decays

- 2025, first observation of direct CPV in Baryon:

$$\underline{\Lambda_b^0} \rightarrow p$$

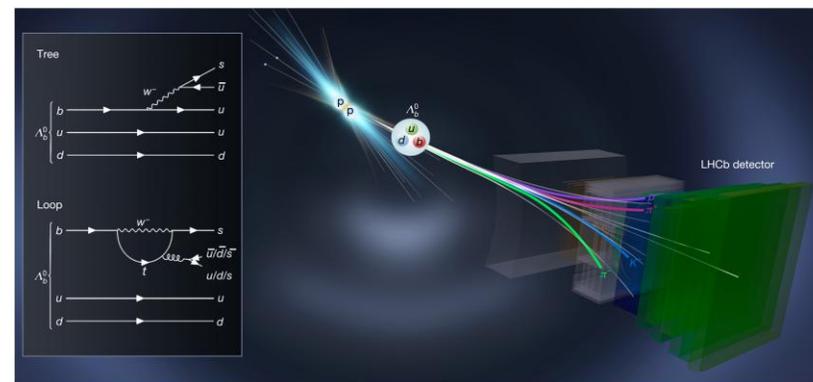
Searching New Physics beyond SM



Observation of charge-parity symmetry breaking in baryon decays

LHCb Collaboration

[Nature](#) 643, 1223–1228 (2025) | [Cite this article](#)



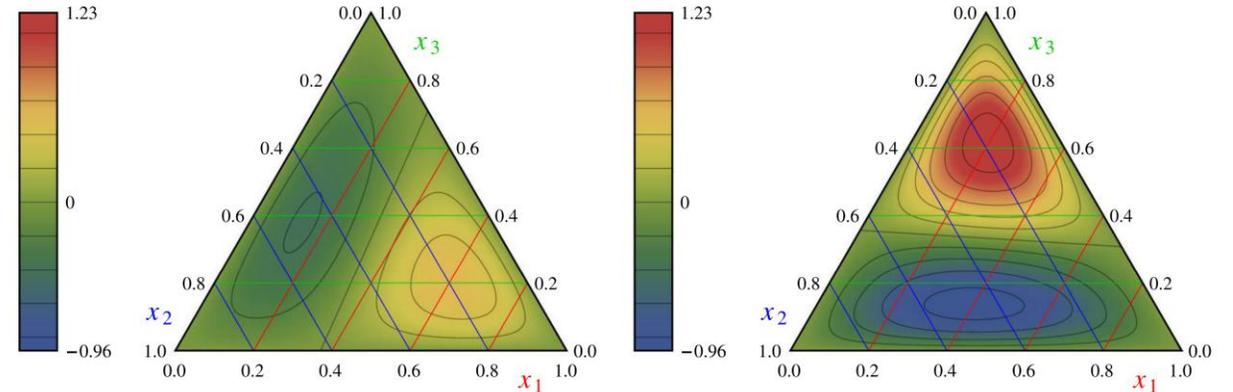
- b-baryon decays are highly sensitive to NP;
- Leading power FF can factorize out **LCDA**s

*LHCb, Nature (2025);
J.J.Han, et.al. PRL 134, 221801 (2025)
W.Wang PLB 708 (2012)*

How to study LCDA ?

Research methods: (1983 - now)

- **Asymptotic form**
Chernyak, Zhitnitsky, 1983;
- **QCD Sum Rules**
King, Sachrajda, 1987;
Stefanis, Bergmann, 1993;
Braun, et al, 2000, 2006;
- **Models parametrization**
Bell, et al, 2013;

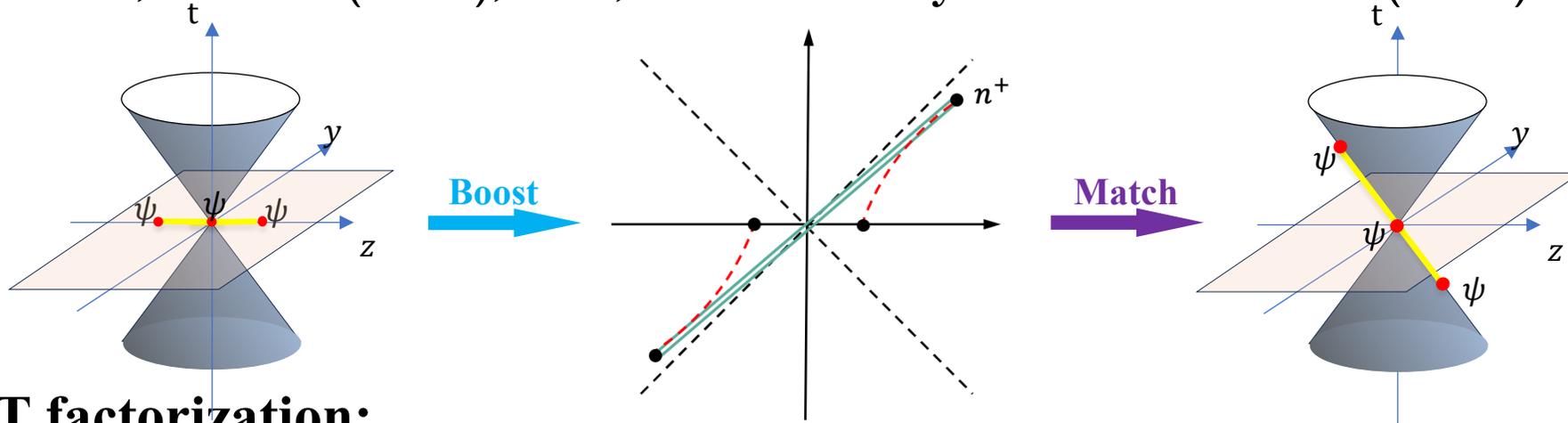


- **Moments from Lattice QCD**
QCDSF, 2008, 2009;
RQCD, 2016, 2019, 2025;
- **x-dependence from Lattice QCD**
LPC, PRD 111, 034510 (2025);
LPC, arXiv: 2508.08971;

How to study LCDA ?

Large-momentum Effective Theory

X.Ji, PRL 110, 262002 (2013); X.Ji, Sci.China Phys.Mech.Astron. 57 (2014)



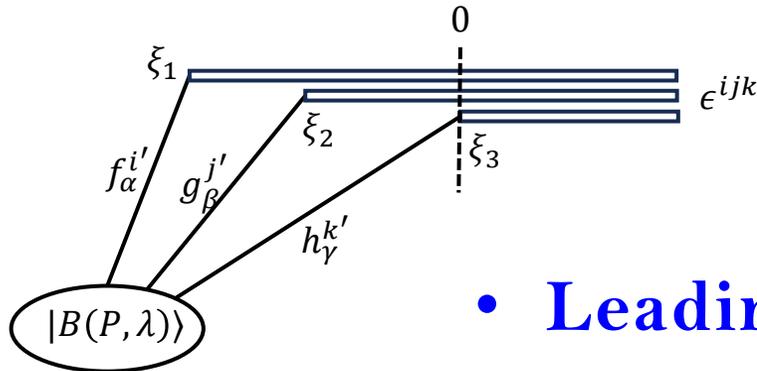
LaMET factorization:

$$\begin{aligned}
 & \text{LCDA} \\
 \phi(x_1, x_2; \mu) &= \int dy_1 dy_2 \mathcal{C}(x_1, x_2; y_1, y_2; P^z, \mu) \tilde{\phi}(y_1, y_2; P^z, \mu) \\
 & + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{(x_1 P^z)^2}, \frac{\Lambda_{\text{QCD}}^2}{(x_2 P^z)^2}, \frac{\Lambda_{\text{QCD}}^2}{((1-x_1-x_2)P^z)^2}\right)
 \end{aligned}$$

Higher power correction

- Operator definition in coordinate space:

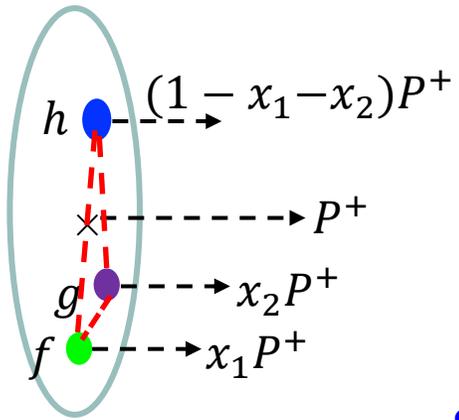
$$H_{\alpha\beta\gamma}(\xi_1, \xi_2, \xi_3) = \epsilon^{ijk} \langle 0 | f_{\alpha}^{i'}(\xi_1 n) W^{i'i}(\xi_1 n, \xi_0 n) \times g_{\beta}^{j'}(\xi_2 n) W^{j'j}(\xi_2 n, \xi_0 n) \times h_{\gamma}^{k'}(\xi_3 n) W^{k'k}(\xi_3 n, \xi_0 n) | B(P, \lambda) \rangle$$



- Leading twist for octet baryon:

$$\begin{aligned} & \langle 0 | f_{\alpha}(\xi_1 n) g_{\beta}(\xi_2 n) h_{\gamma}(\xi_3 n) | B(P, \lambda) \rangle \\ &= \frac{1}{4} f_V \left[(\not{P} C)_{\alpha\beta} (\gamma_5 u_B)_{\gamma} \Phi_V(\xi_i n \cdot P) + (\not{P} \gamma_5 C)_{\alpha\beta} (u_B)_{\gamma} \Phi_A(\xi_i n \cdot P) \right] \\ &+ \frac{1}{4} f_T (i\sigma_{\mu\nu} P^{\nu} C)_{\alpha\beta} (\gamma^{\mu} \gamma_5 u_B)_{\gamma} \Phi_T(\xi_i n \cdot P) \end{aligned}$$

Octet	n	p	Λ
fgh	ddu	uud	uds



- **Definition of baryon LCDA:**

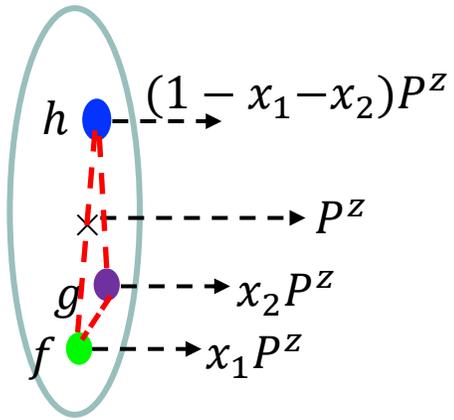
$$\phi(x_1, x_2, \mu) = \int \frac{P^+ d\xi_1^-}{2\pi} \frac{P^+ d\xi_2^-}{2\pi} e^{i(x_1 \xi_1^- + x_2 \xi_2^-) P^+} \Phi(\xi_1, \xi_2, \mu)$$

- **Leading twist for octet baryon LCDA**

$$-f_V \Phi_V(\xi_i n \cdot P) P^+ \gamma_5 u_B = \langle 0 | f^T(\xi_1 n) (C \not{n}) g(\xi_2 n) h(0) | B \rangle$$

PRD 111, 034510 (2025) — Λ : $f_V \Phi_A(\xi_i n \cdot P) P^+ u_B = \langle 0 | f^T(\xi_1 n) (C \gamma_5 \not{n}) g(\xi_2 n) h(0) | B \rangle$

$$2f_T \Phi_T(\xi_i n \cdot P) P^+ \gamma_5 u_B = \langle 0 | f^T(\xi_1 n) (iC \sigma_{\mu\nu} n^\nu) g(\xi_2 n) \gamma^\mu h(0) | B \rangle$$



- **Definition of baryon quasi-DA:**

$$\tilde{\phi}(x_1, x_2, \mu) = \int \frac{P^z dz_1}{2\pi} \frac{P^z dz_2}{2\pi} e^{-i(x_1 z_1 + x_2 z_2) P^z} \tilde{\Phi}(z_1, z_2, \mu)$$

- **Matrix elements of quasi-DA:**

$$-f_V \tilde{\Phi}_V(z_i, P^z) P^\nu \gamma_5 u_B = \langle 0 | f^T(z_1) (C \gamma^\nu) g(z_2) h(0) | B \rangle$$

PRD 111, 034510 (2025) — Λ :
$$f_V \tilde{\Phi}_A(z_i, P^z) P^\nu u_B = \langle 0 | f^T(z_1) (C \gamma_5 \gamma^\nu) g(z_2) h(0) | B \rangle$$

$$2f_T \tilde{\Phi}_T(z_i, P^z) P^\nu \gamma_5 u_B = \langle 0 | f^T(z_1) \left(\frac{1}{2} C [\gamma^\nu, \gamma^\mu] \right) g(z_2) \gamma^\mu h(0) | B \rangle$$

Nonlocal 2-point function related to baryon quasi-DA:

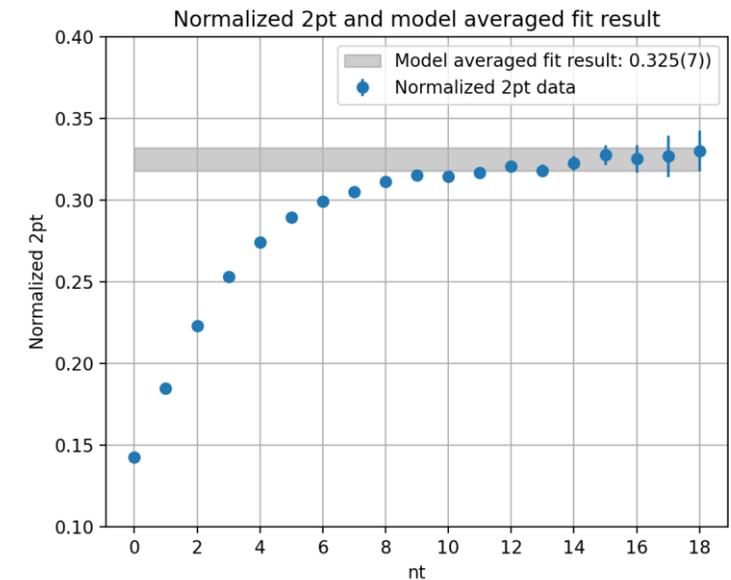
$$C_2(z_1, z_2; t, P^z) = \int d^3x e^{-i\vec{x}\cdot\vec{P}} \langle 0 | \mathcal{O}_{\text{Sink}}^{\gamma'}(\vec{x}, t; z_1, z_2) \overline{\mathcal{O}}_{\text{Src}}^{\gamma}(0, 0; 0, 0) T_{\gamma'\gamma} | 0 \rangle$$

- **Extract & norm quasi-DA from 2-point function**

$$\frac{C_2(z_1, z_2; P^z, t)}{C_2(0, 0; P^z, t)} \xrightarrow{t \rightarrow \infty} \frac{\tilde{\Phi}(z_1, z_2; P^z)}{\tilde{\Phi}(0, 0; P^z)}$$

$$C_2^{\text{Norm}}(z_1, z_2; P^z, t) = \underbrace{\tilde{\Phi}(z_1, z_2; P^z)}_{\text{ground-state}} \left(1 + \underbrace{\Delta A(z_1, z_2; P^z)}_{\text{excited-states}} e^{-\Delta E t} \right)$$

~10³ points!



Nonlocal 2-point function related to baryon quasi-DA:

$$C_2(z_1, z_2; t, P^z) = \int d^3x e^{-i\vec{x}\cdot\vec{P}} \langle 0 | \underbrace{\mathcal{O}_{\text{Sink}}^{\gamma'}(\vec{x}, t; z_1, z_2)}_{\text{Determined by DA}} \underbrace{\overline{\mathcal{O}}_{\text{Src}}^\gamma(0, 0; 0, 0)}_{\text{Up to choice?}} \underbrace{T_{\gamma'\gamma}}_{\text{Up to choice?}} | 0 \rangle$$

- **Interpolators and projection operators**

- Sink-side Interpolators

$$\mathcal{O}_{\text{Sink},V} = f^T(z_1)(C\gamma^t)g(z_2) h(0)$$

$$\mathcal{O}_{\text{Sink},A} = f^T(z_1)(C\gamma_5\gamma^t)g(z_2) h(0)$$

$$\mathcal{O}_{\text{Sink},T} = f^T(z_1)(C[\gamma^t, \gamma^y]/2)g(z_2) \gamma_y h(0)$$

- Projector ?

$$T = I, \gamma^t, \gamma^z$$

- Source-side Interpolators ?

$$\mathcal{O}_{\text{Src}}^P = (u^T C\gamma_5 d)u$$

$$\mathcal{O}_{\text{Src}}^\Lambda = \frac{1}{\sqrt{6}} \left(2(u^T C\gamma_5 d)s + (u^T C\gamma_5 s)d + (s^T C\gamma_5 d)u \right)$$

Improvement from interpolator: Kinematically-enhancement

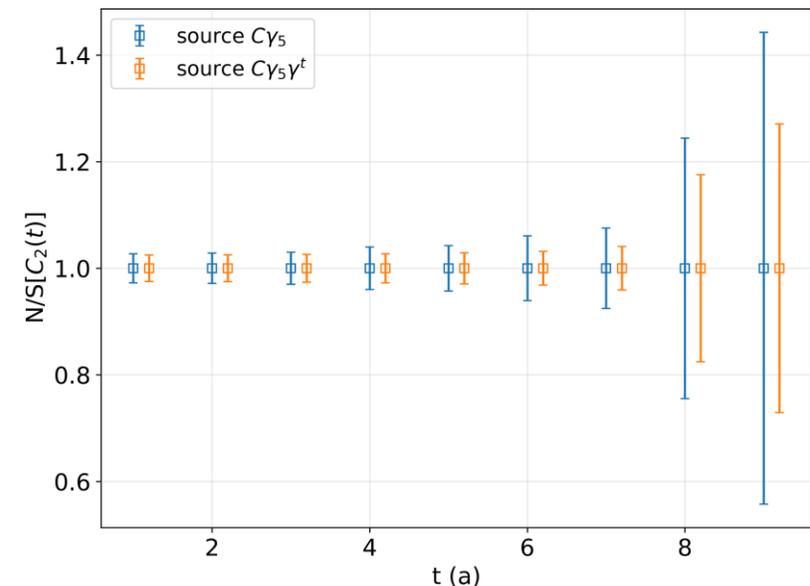
□ Standard interpolator: $N_{\gamma_5} = \epsilon^{ijk} (f_i^T C \gamma_5 g_j) h_k$ for a static baryon states

$$\langle 0 | N_{\gamma_5} | N(P) \rangle = \lambda u(P)$$

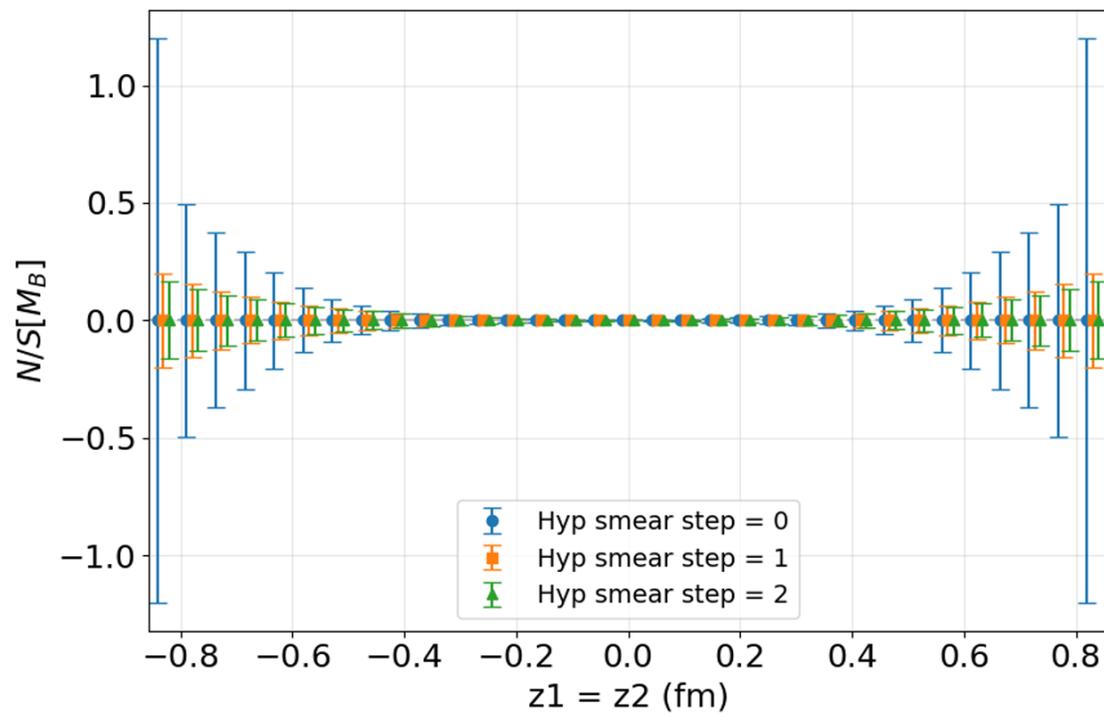
□ Enhanced interpolator: $N_{\gamma_5 \gamma_\mu} = \epsilon^{ijk} (f_i^T C \gamma_5 \gamma_\mu g_j) h_k$ better overlap with boosted states

$$\langle 0 | N_{\gamma_5 \gamma_\mu} | N(P) \rangle = \alpha P_\mu u(P) + \beta \gamma_\mu u(P)$$

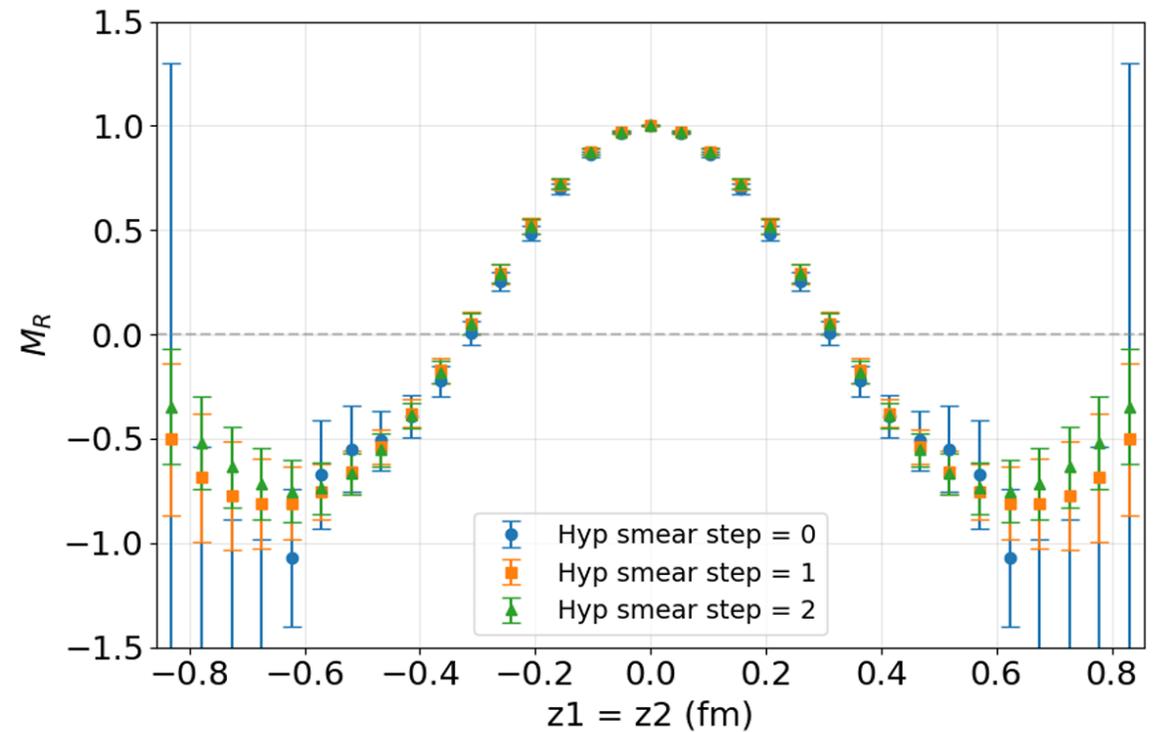
⇒ $\text{SNR}(C_{2\text{pt}}(t \rightarrow \infty)) \propto \frac{P_\mu}{M_0} e^{-E't}$



Improvement from gauge link: HYP smearing



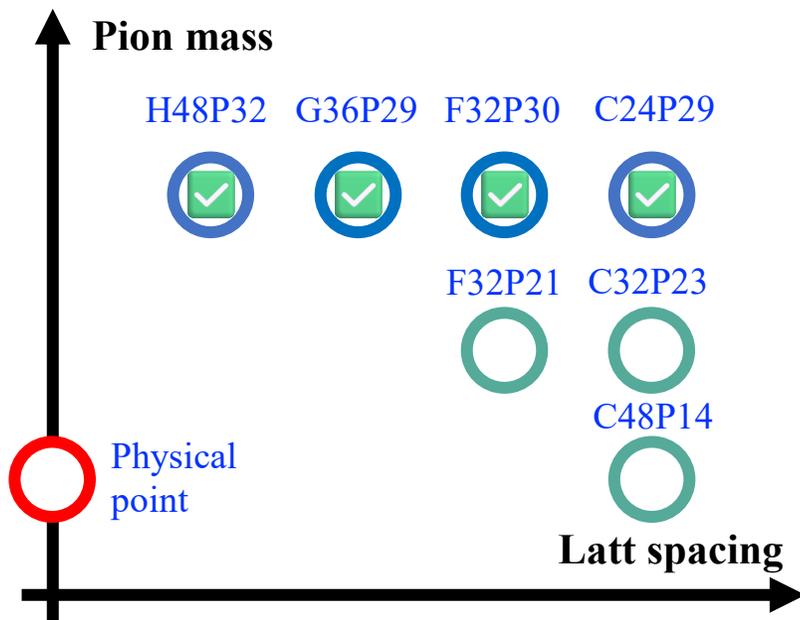
NtS of bare quasi-DA



Ratio scheme quasi-DA

CLQCD Ensembles

- 4 lattice spacings for $a \rightarrow 0$ limit & renormalization
- multi momentums for $P_z \rightarrow \infty$ limit
- More pion masses to **physical mass** limit

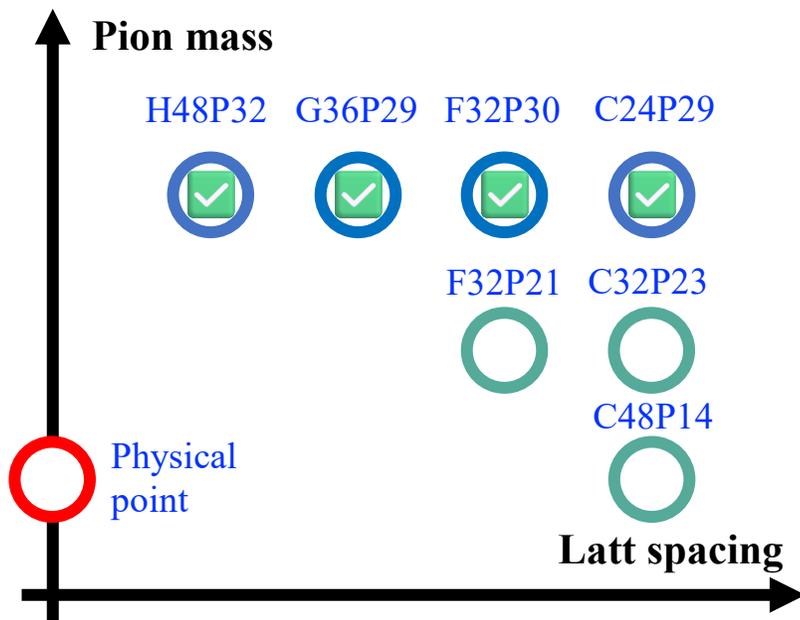


Ensemble	Lattice spacing	π mass	measurements	P^z
C24P29	0.1052 fm	292 MeV	864 *4 *9	1.96, 2.45, 2.94 GeV
F32P30	0.0775 fm	300 MeV	777 *4 *8	2.00, 2.50, 3.00 GeV
H48P32	0.0520 fm	317 MeV	550 *6*9	2.01, 2.52, 3.02 GeV
G36P29	0.0689 fm	297 MeV	656 *6*8	1.99, 2.48, 2.98 GeV

Other ensembles with different pion masses

CLQCD Ensembles

- 4 lattice spacings for $a \rightarrow 0$ limit & renormalization
- multi momentums for $P_z \rightarrow \infty$ limit
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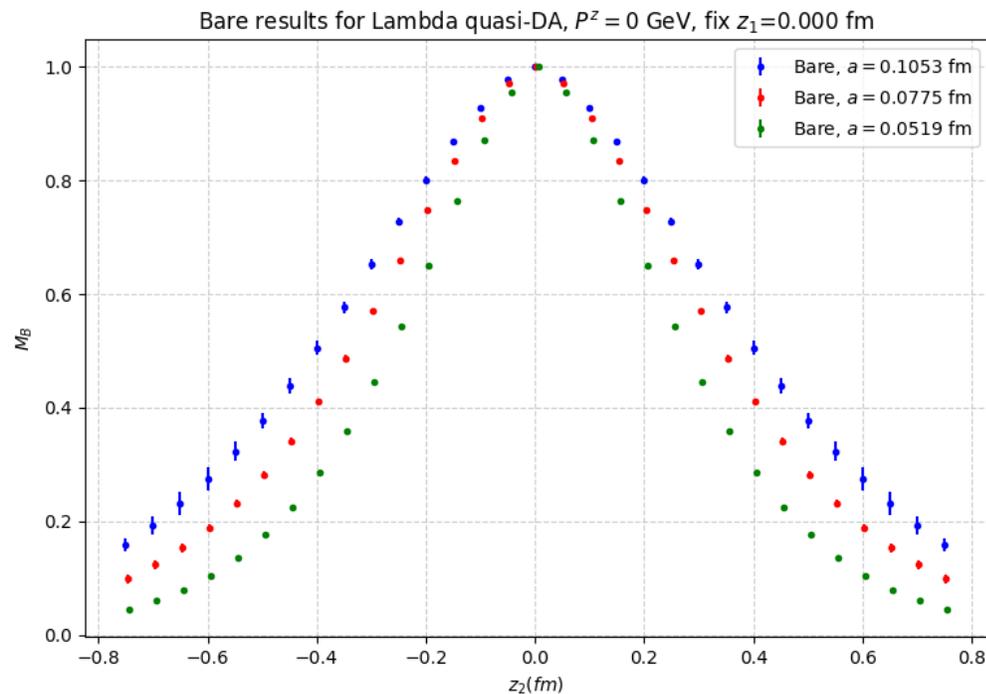
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Other ensembles with different pion masses

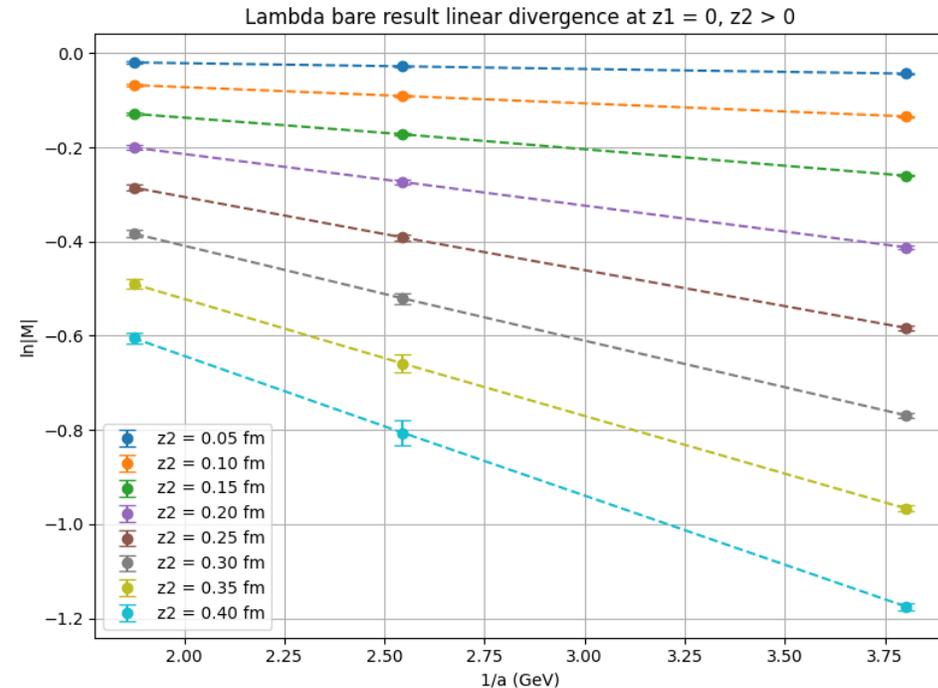
z-dependence of normed bare quasi-DA on different lattice spacing

Lambda A term

$P^Z=0$ GeV



log scale



Bare quasi-DA results: Linear divergence

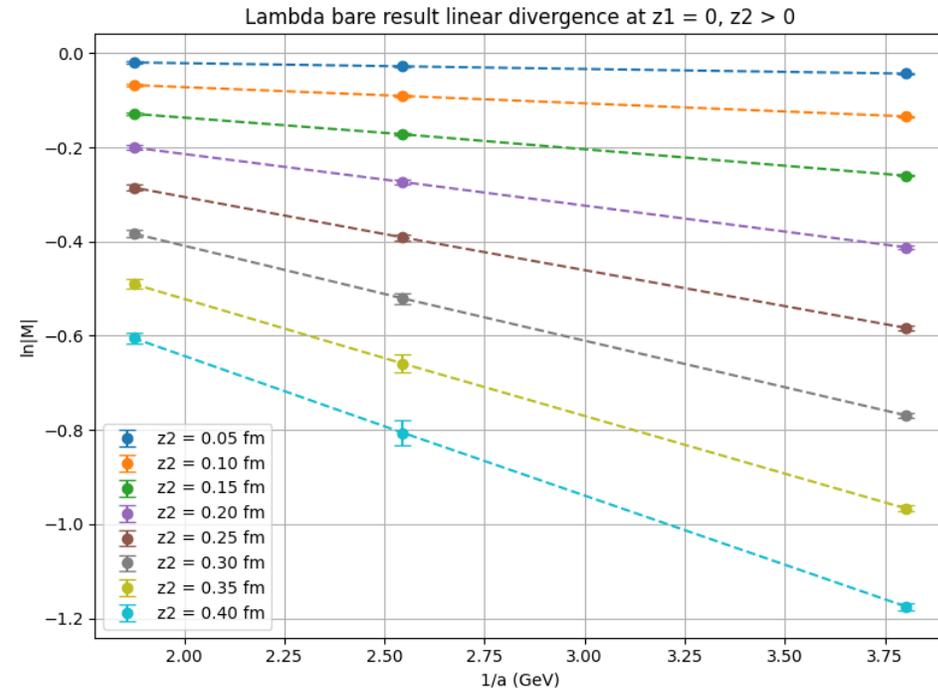
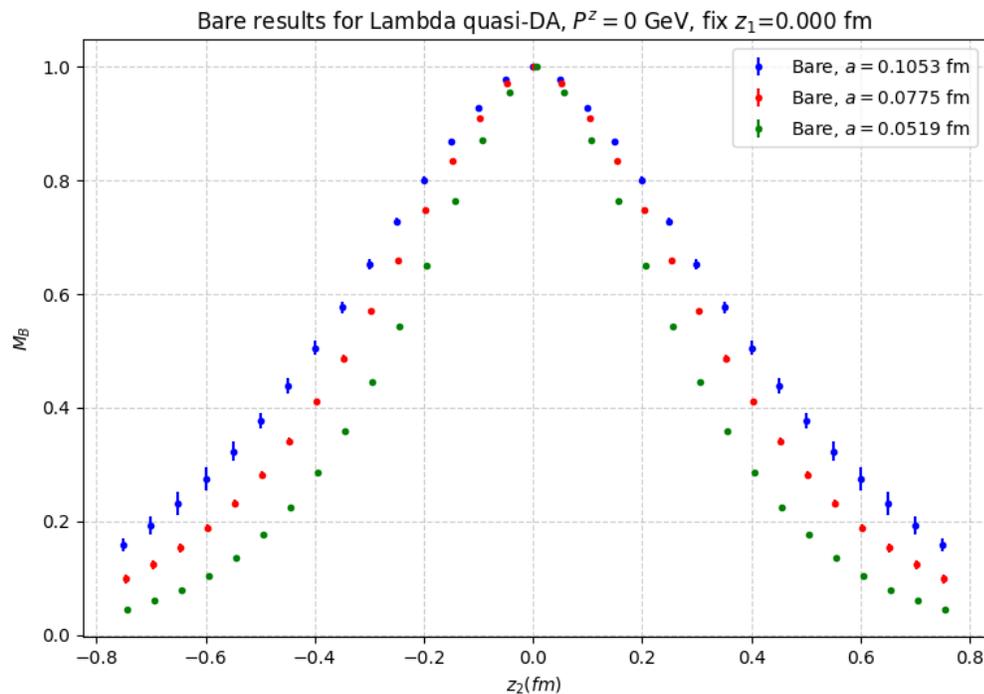
Linear divergence of Normed Bare quasi-DA

$$\tilde{z} = \begin{cases} |z_1 - z_2| & z_1 z_2 < 0 \\ \max(z_1, z_2) & z_1 z_2 \geq 0 \end{cases}$$

$$M(z_1, z_2; P^z, a) \propto \exp \left[\left(\frac{k}{a \ln(a \Lambda_{\text{QCD}})} + m_0 \right) \tilde{z} \right] m(z_1, z_2, P^z)$$

$P^z = 0 \text{ GeV}$

log scale



Bare quasi-DA results: Linear divergence

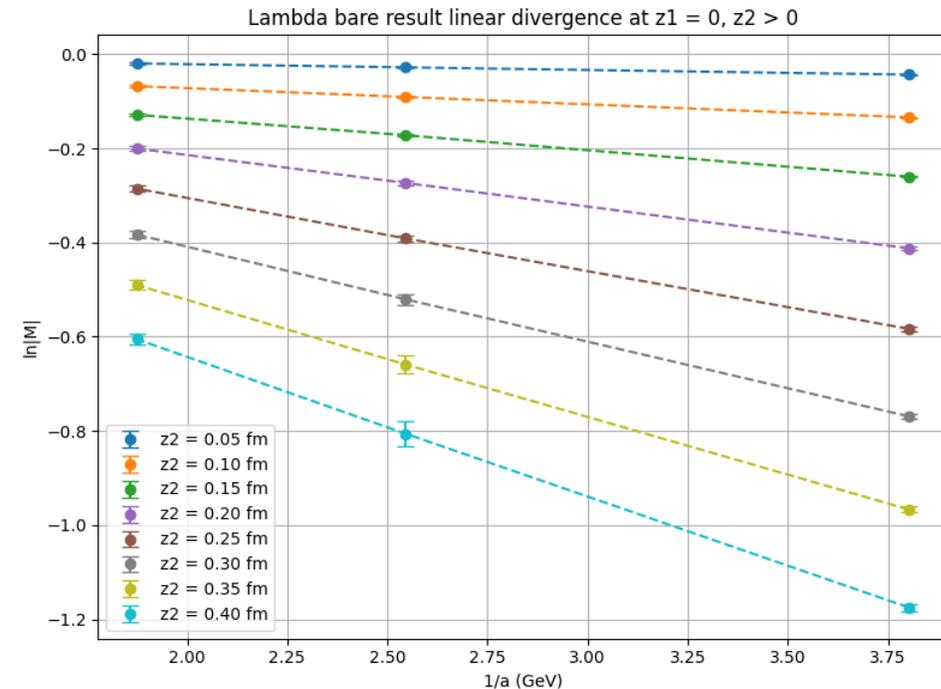
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Linear divergence of Normed Bare quasi-DA

$$\tilde{z} = \begin{cases} |z_1 - z_2| & z_1 z_2 < 0 \\ \max(z_1, z_2) & z_1 z_2 \geq 0 \end{cases}$$

$$M(z_1, z_2; P^z, a) \propto \exp \left[\left(\frac{k}{a \ln(a \Lambda_{\text{QCD}})} + m_0 \right) \tilde{z} \right] m(z_1, z_2, P^z)$$

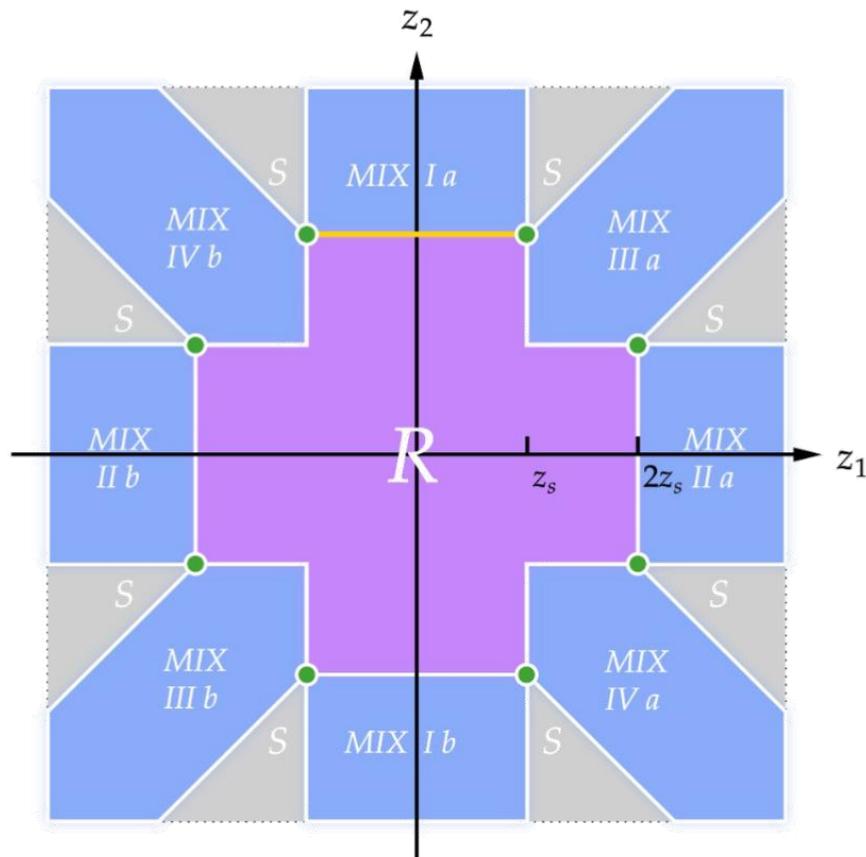
log scale



**We need proper scheme
to eliminate the linear divergences !**

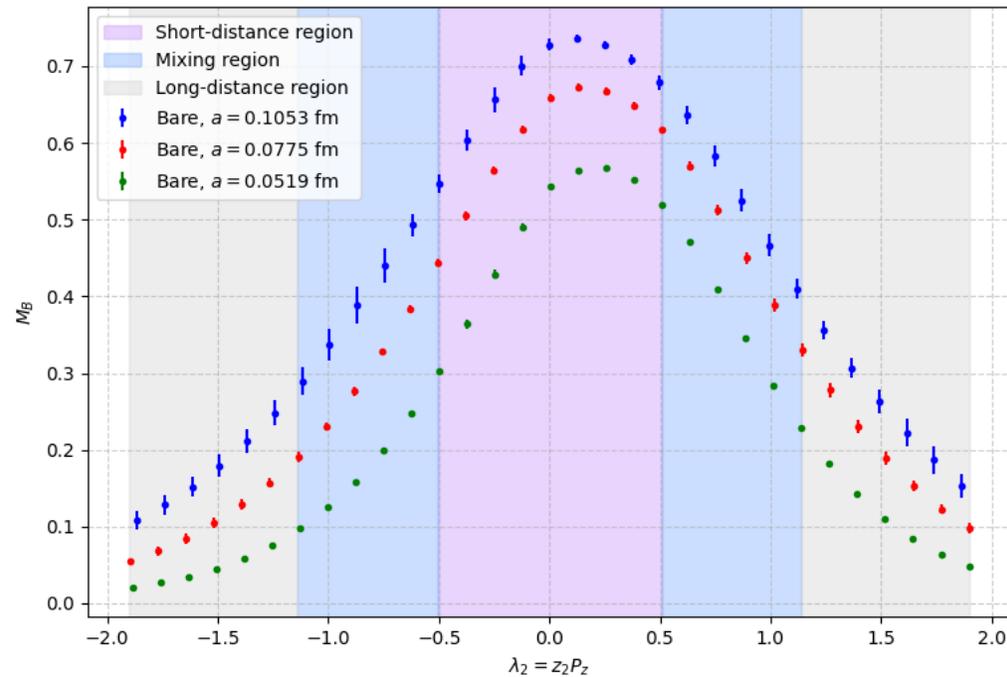
2D renormalization in Hybrid Renormalization

—— Best choice for all z regions & LaMET matching

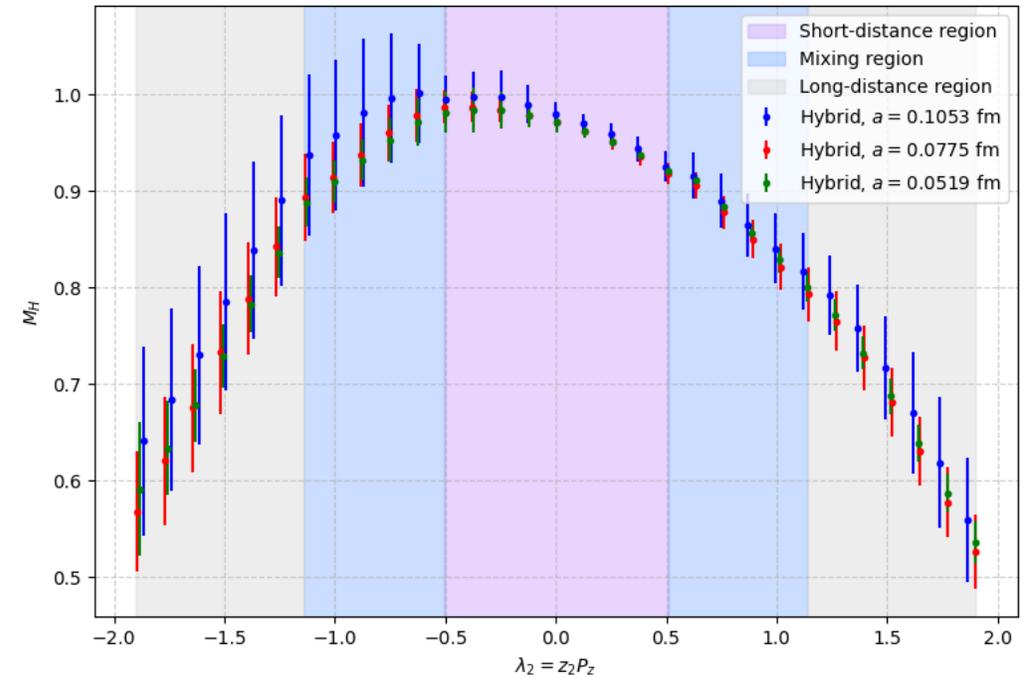


- Very complicated in applying to **Baryon DAs!**
 - Details in **LPC, arXiv: 2508.08971**
 - Also see Haoyang Bai's talk

Bare Matrix Element

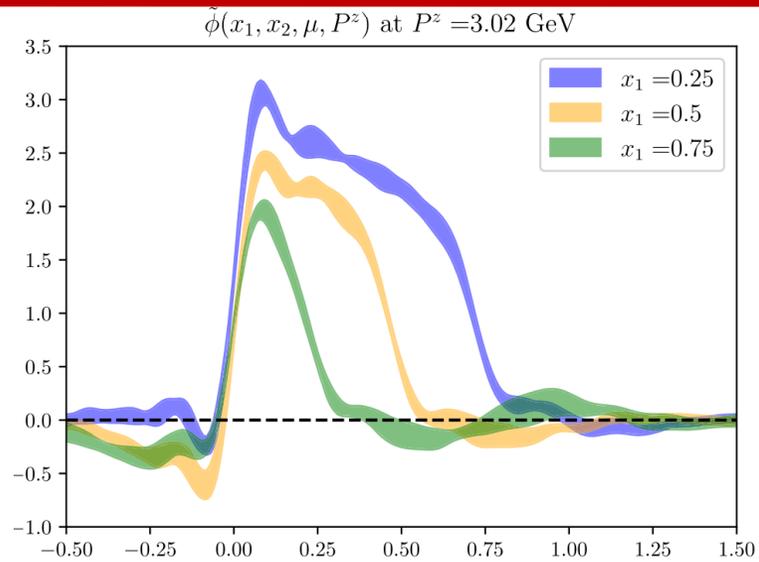


Hybrid Renormalization result

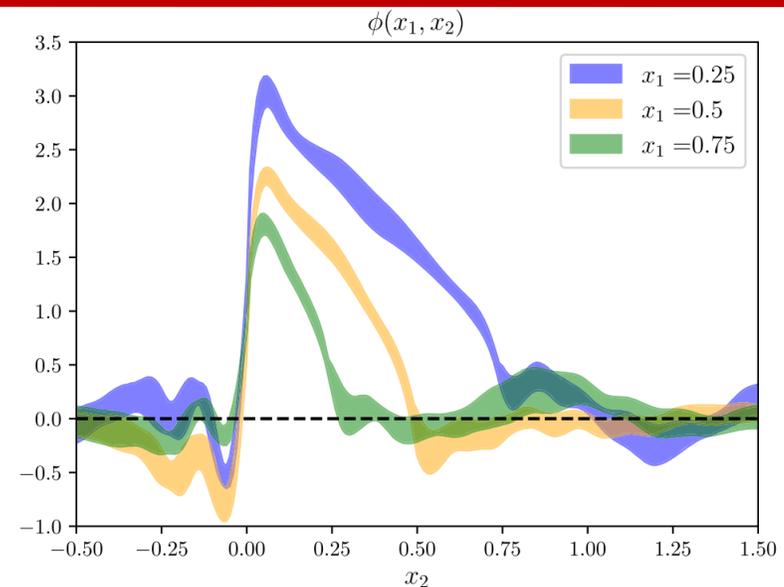


- Satisfying elimination of linear divergence
- Well defined at short, long & mixing regions
- Smooth between different regions

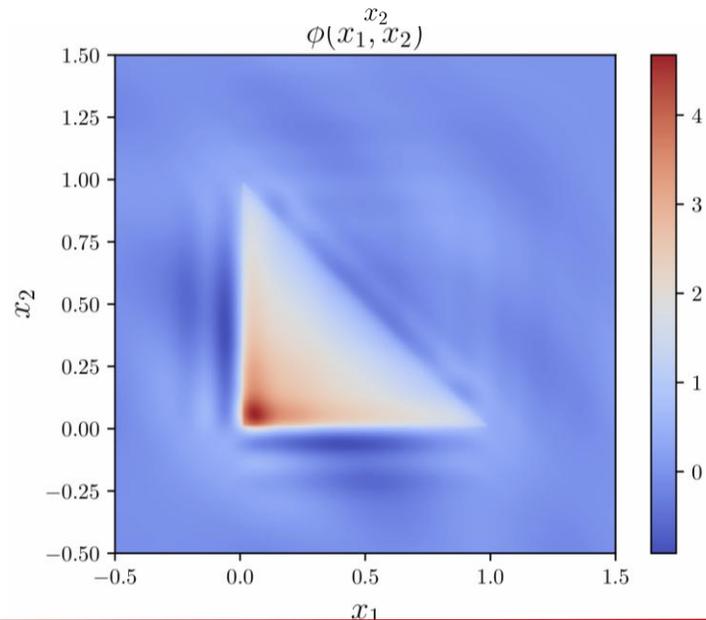
Renormalization & Matching



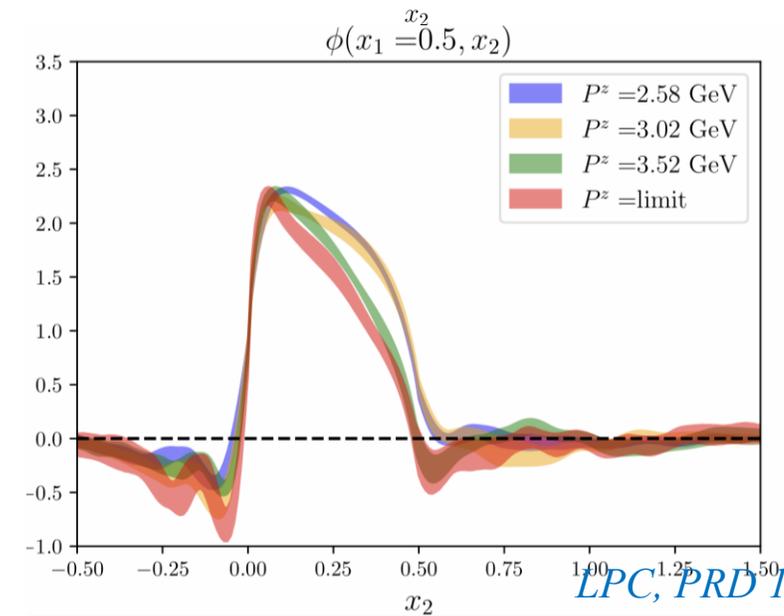
Matching



Large P^z
limit



LCDA



- We have done:
 - ❑ *LPC, PRD 111, 034510*, validated the concept of lattice calculation of baryon LCDA from LaMET
 - ❑ *arXiv: 2508.08971*, successfully adopted the Hybrid renormalization on baryon matrix element
- We now proceeding:
 - ❑ Continuum & physical mass limit
 - ❑ Methods for limited FT, inverse & matching schemes
 - ❑ More potential strategies to enhance & optimize
 - ❑ **gradient flow,**
- Please stay tuned our results for **all leading twists LCDAs of Proton and Lambda !**

Thanks for attention!

Backup

Why Baryon LCDA ?

FFs in *ep* elastic scattering

Nonlocal 2-point function related to baryon quasi-DA:

$$C_2(z_1, z_2; t, P^z) = \int d^3x e^{-i\vec{x}\cdot\vec{P}} \langle 0 | \underbrace{\mathcal{O}_{\text{Sink}}^{\gamma'}(\vec{x}, t; z_1, z_2)}_{\text{green}} \underbrace{\overline{\mathcal{O}}_{\text{Src}}^\gamma(0, 0; 0, 0)}_{\text{blue}} \underbrace{T_{\gamma'\gamma}}_{\text{red}} | 0 \rangle$$

- **Extract & normalize quasi-DA from 2-point function**

$$C_2(z_1, z_2; P^z, t) = \sum_k \langle 0 | \mathcal{O}_{\text{Sink}}^{\gamma'}(z_1, z_2; t) | B(P^z)_k \rangle \langle B(P^z)_k | \overline{\mathcal{O}}_{\text{Src}}^\gamma(0, 0; t) | 0 \rangle T_{\gamma'\gamma}$$

$$\stackrel{t \rightarrow \infty}{\sim} \tilde{\Phi}(z_1, z_2; P^z) \tilde{\Phi}^*(0, 0; P^z) |f_\Lambda|^2 \left[u_\Lambda(P^z) u_\Lambda^\dagger(P^z) \right]^{\gamma'\gamma} T_{\gamma'\gamma}$$

$$\Rightarrow \frac{C_2(z_1, z_2; P^z, t)}{C_2(0, 0; P^z, t)} = f(t) \frac{\tilde{\Phi}(z_1, z_2; P^z) \tilde{\Phi}^*(0, 0; P^z)}{\tilde{\Phi}(0, 0; P^z) \tilde{\Phi}^*(0, 0; P^z)} \cdots \xrightarrow{t \rightarrow \infty} \frac{\tilde{\Phi}(z_1, z_2; P^z)}{\tilde{\Phi}(0, 0; P^z)}$$

CLQCD Ensembles

- 4 lattice spacings for $a \rightarrow 0$ limit & renormalization
- 4 momentums for $P_z \rightarrow \infty$ limit

Ensemble	Volume	Lattice spacing	π mass	measurements	P^z
C24P29	$24^3 \times 72$	0.1052 fm	292.3 MeV	864 *4src *9it0	1.96, 2.45, 2.94, 3.43 GeV
F32P30	$32^3 \times 96$	0.0775 fm	300.4 MeV	777 *4src *8it0	2.00, 2.50, 3.00, 3.49 GeV
G36P29	$36^3 \times 108$	0.0689 fm	297.2 MeV	656 *6src *9it0	2.01, 2.52, 3.02, 3.52 GeV
H48P32	$48^3 \times 144$	0.0520 fm	316.6 MeV	550 *6src *8it0	1.99, 2.48, 2.98, 3.48 GeV

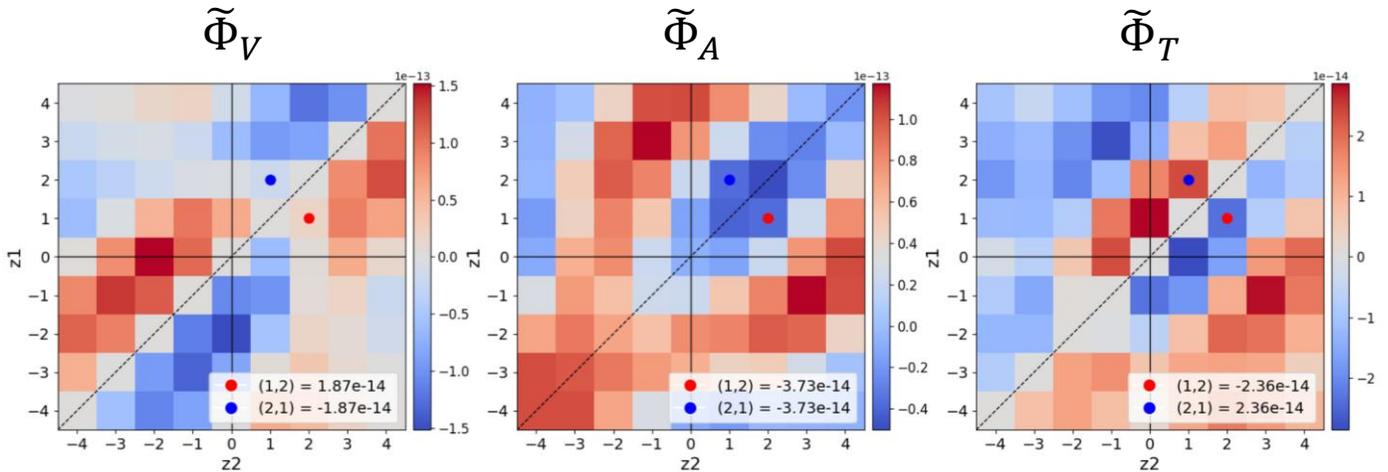
Symmetries of quasi-DA

□ isospin symmetry for “u, d” quarks (on a single configuration);

symmetry of z_1, z_2 exchanging:

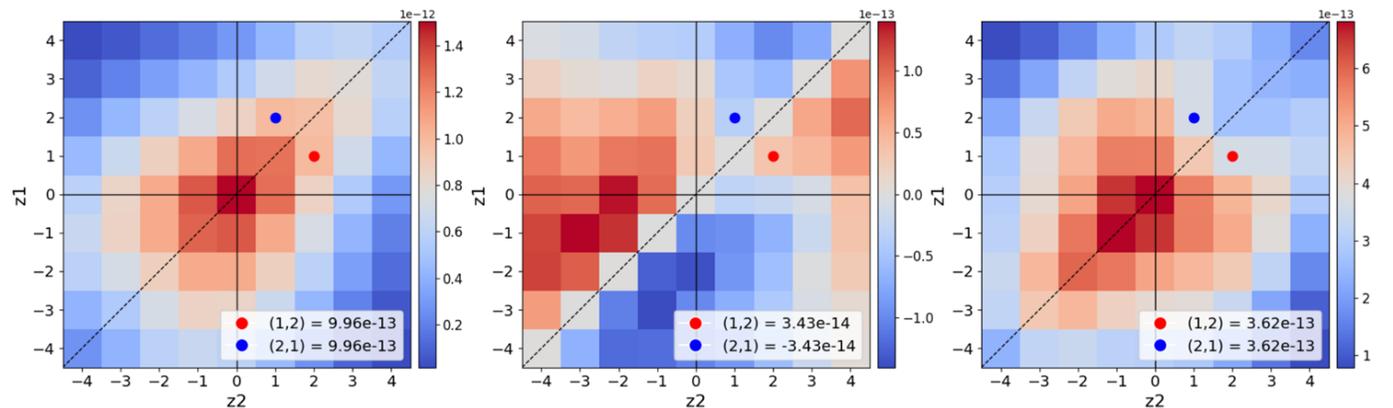
$$\begin{aligned}
 V^\Lambda(x_2, x_1, x_3) &= -V^\Lambda(x_1, x_2, x_3), \\
 A^\Lambda(x_2, x_1, x_3) &= +A^\Lambda(x_1, x_2, x_3), \\
 T^\Lambda(x_2, x_1, x_3) &= -T^\Lambda(x_1, x_2, x_3).
 \end{aligned}$$

Lambda



$$\begin{aligned}
 V^{B \neq \Lambda}(x_2, x_1, x_3) &= +V^B(x_1, x_2, x_3), \\
 A^{B \neq \Lambda}(x_2, x_1, x_3) &= -A^B(x_1, x_2, x_3), \\
 T^{B \neq \Lambda}(x_2, x_1, x_3) &= +T^B(x_1, x_2, x_3),
 \end{aligned}$$

Proton



Symmetries of quasi-DA

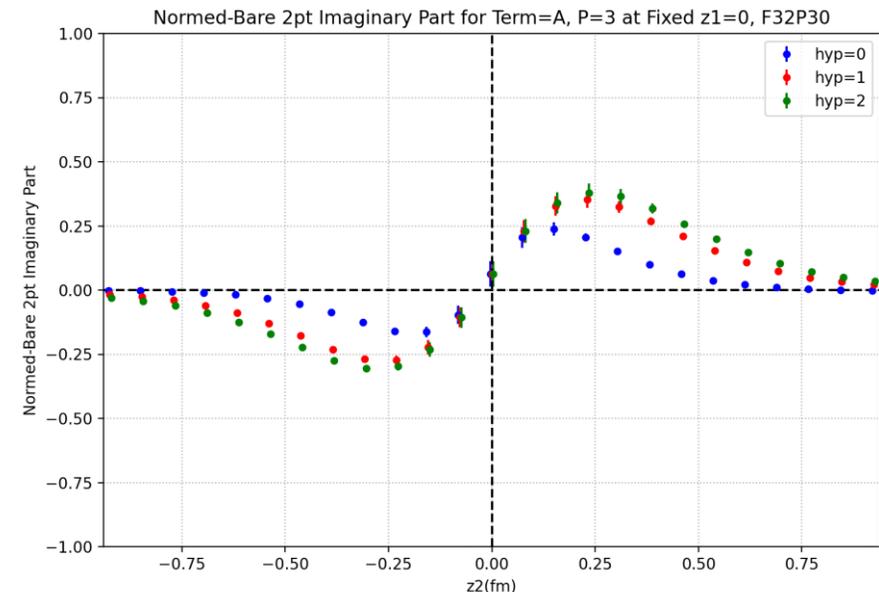
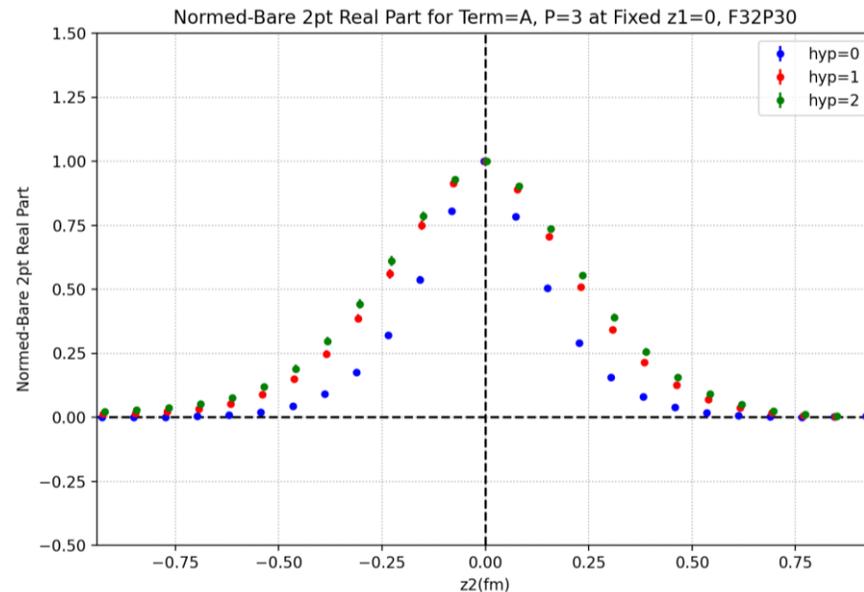
- spatial parity symmetry (at statistical level);

$$\tilde{\Phi}(z_1, z_2, \mu) = \int_0^1 dx_1 \int_0^1 dx_2 e^{i(x_1 z_1 + x_2 z_2) P^z} \times \tilde{\phi}(x_1, x_2, \mu) \quad \text{Pure real}$$

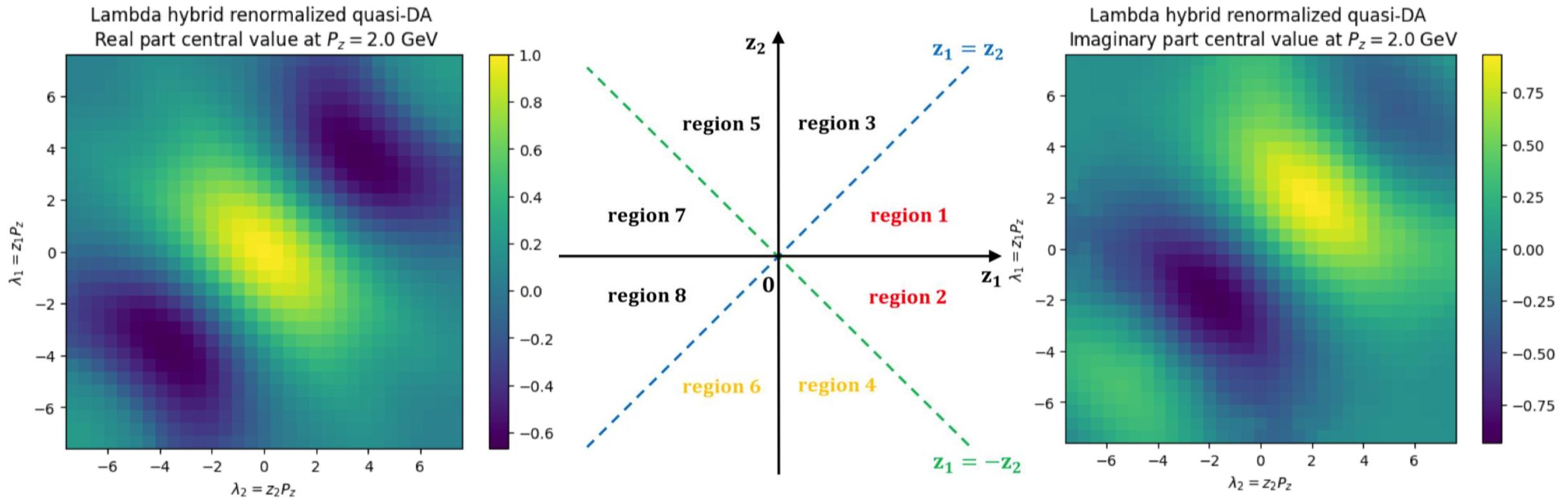
the reality in momentum space $\tilde{\Phi}(x_1, x_2)$ leads to: $\tilde{\Phi}(z_1, z_2) = \tilde{\Phi}^*(-z_1, -z_2)$

$$\text{Re } \tilde{\Phi}(-z_1, -z_2) = \text{Re } \tilde{\Phi}(z_1, z_2)$$

$$\text{Im } \tilde{\Phi}(-z_1, -z_2) = -\text{Im } \tilde{\Phi}(z_1, z_2)$$



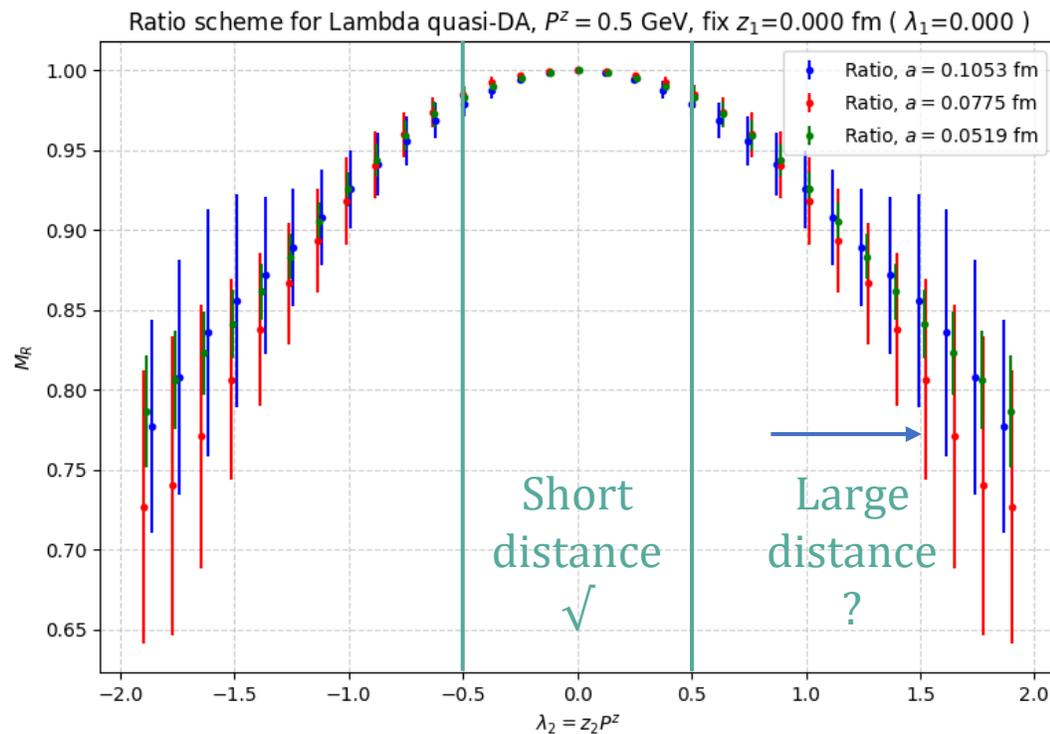
Symmetries of quasi-DA



Ratio renormalization scheme

$$\tilde{\psi}^{\text{ratio}}(z_1, z_2, P^Z) = \frac{\tilde{\psi}^{\text{bare}}(z_1, z_2, P^Z)}{\tilde{\psi}^{\text{bare}}(z_1, z_2, P^Z = 0)}$$

Lambda A term $P^Z = 0.5 \text{ GeV}$



Uncontrollable IR structures
on large z region !

Step-1 (in all regions with linear div.)

$$\ln M(z_1, z_2; P_z = 0; a) = \frac{\underline{k}}{a \ln(a\Lambda_{\text{QCD}})} \tilde{z} + \underline{g(z_1, z_2)} + \underline{f(z_1, z_2)} a^2 + \frac{\gamma_0}{b_0} \ln \frac{\ln(1/a\Lambda_{\text{QCD}})}{\ln(\mu/\Lambda_{\overline{\text{MS}}})} + \ln \left[1 + \frac{d}{\ln(a\Lambda_{\text{QCD}})} \right]$$

Step-2 (in perturbative region)

$$g(z_1, z_2) - \ln Z_{\overline{\text{MS}}}(z_1, z_2; \mu, \Lambda_{\overline{\text{MS}}}) = \underline{m_0} \tilde{z} + \underline{b_0}$$

$$Z_{\overline{\text{MS}}}(z_1, z_2; \mu, \Lambda_{\overline{\text{MS}}}) = 1 + \frac{\alpha_s C_F}{2\pi} \left[\frac{7}{8} \ln \frac{z_1^2 \mu^2 e^{2\gamma_E}}{4} + \frac{7}{8} \ln \frac{z_2^2 \mu^2 e^{2\gamma_E}}{4} + \frac{3}{4} \ln \frac{(z_1 - z_2)^2 \mu^2 e^{2\gamma_E}}{4} + 4 \right]$$

Renormalization factor

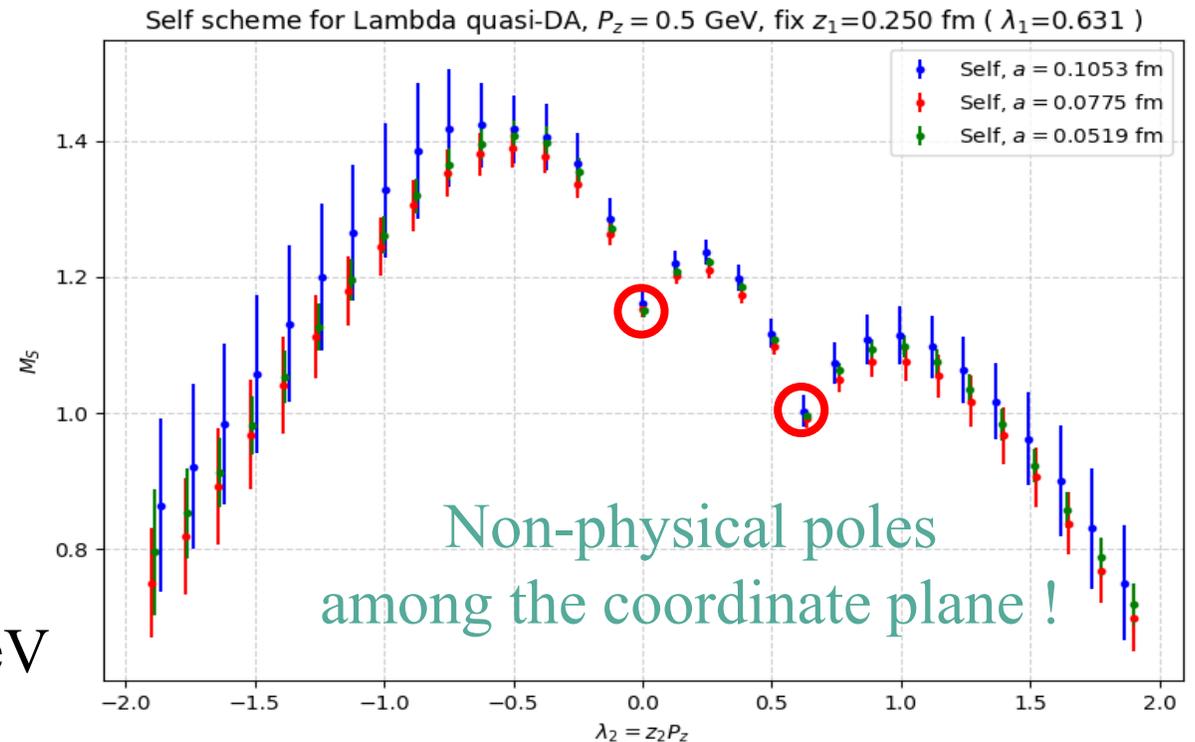
$$Z_R(z_1, z_2; a) = \exp \left[\frac{k}{a \ln(a\Lambda_{\text{QCD}})} \tilde{z} + m_0 \tilde{z} + f(z_1, z_2) a^2 + \frac{\gamma_0}{b_0} \ln \frac{\ln(1/a\Lambda_{\text{QCD}})}{\ln(\mu/\Lambda_{\overline{\text{MS}}})} + \ln \left[1 + \frac{d}{\ln(a\Lambda_{\text{QCD}})} \right] \right]$$

Renormalized 0 & large-momentum matrix element

$$M_R(z_1, z_2; P_z = 0) = \exp \left(g(z_1, z_2) - m_0 \tilde{z} - b_0 \right)$$

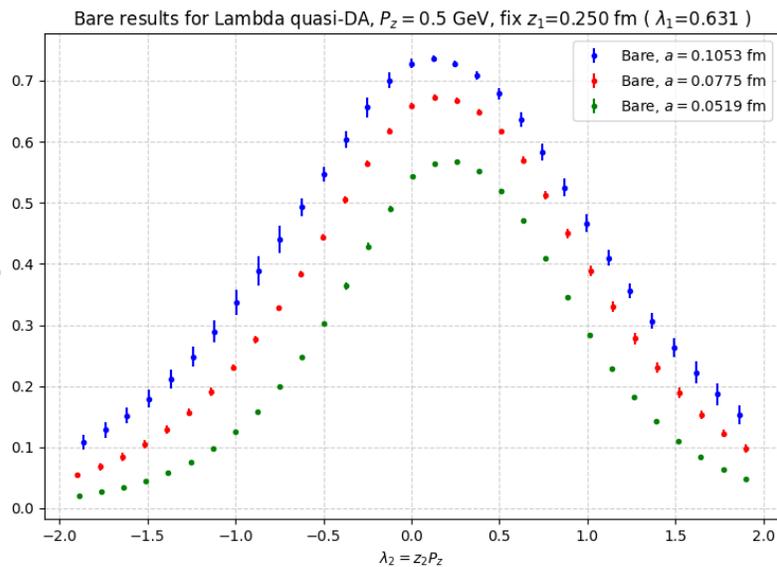
$$M_R(z_1, z_2; P_z) = \frac{M(z_1, z_2; P_z; a)}{Z_R(z_1, z_2; a)}$$

$P^Z=0.5 \text{ GeV}$



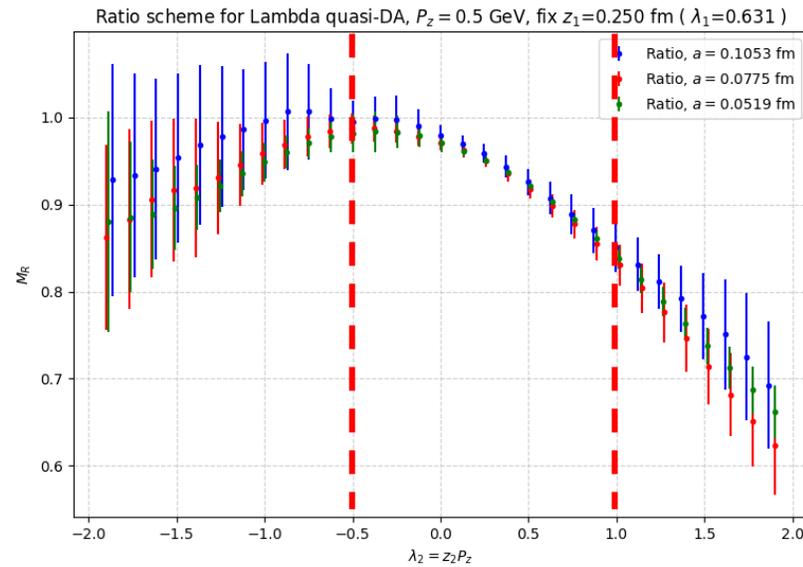
Bare Matrix Element

$$M(z_1, z_2; P_z; a)$$



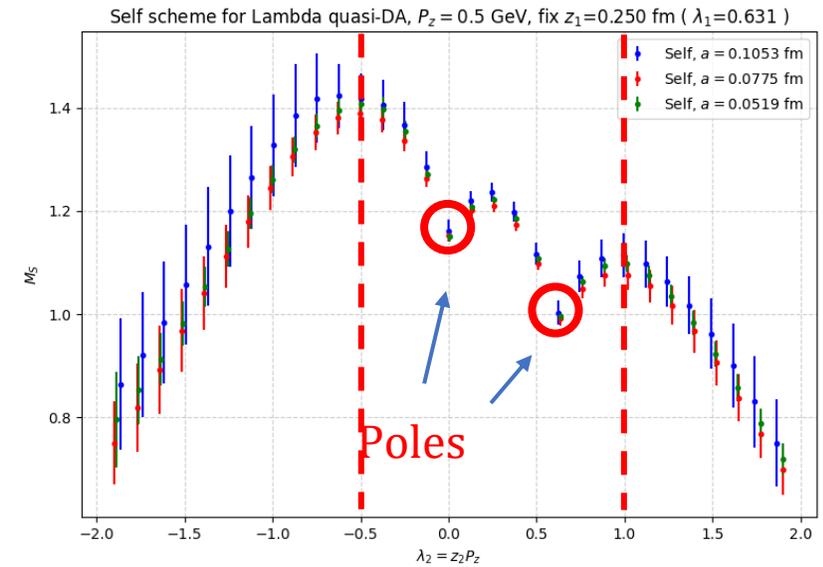
Ratio scheme

$$\frac{M(z_1, z_2; P_z; a)}{M(z_1, z_2; 0; a)}$$

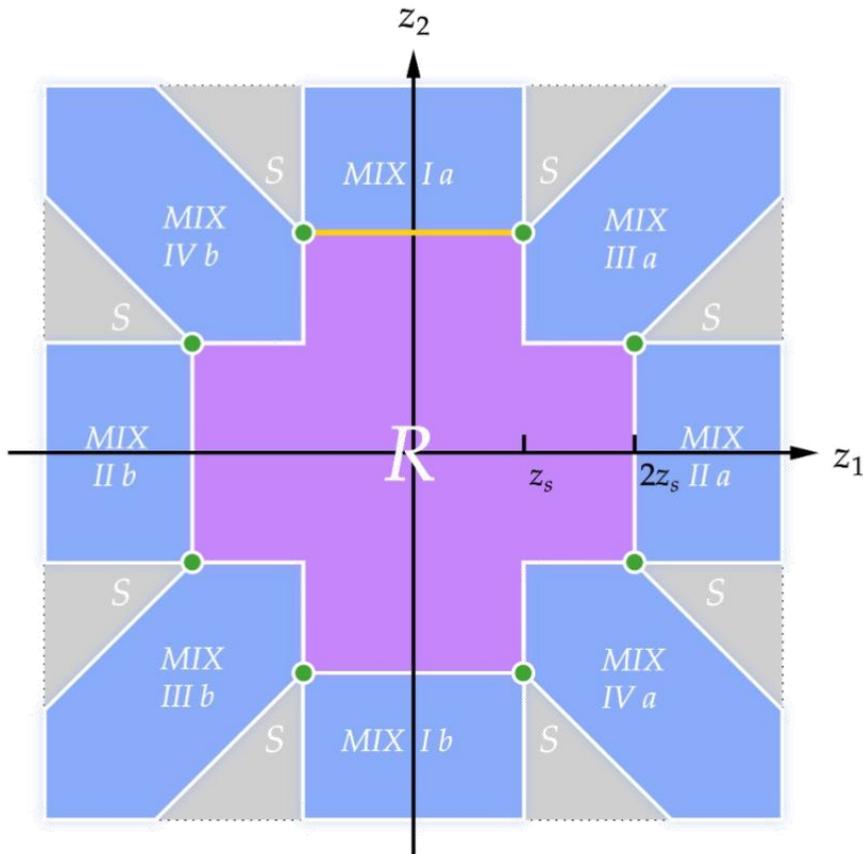


Self scheme

$$\frac{M(z_1, z_2; P_z; a)}{Z_R(z_1, z_2; a)}$$



2D renormalization in Hybrid scheme



- 1) Short-distance region

$$\frac{\hat{M}_{\overline{\text{MS}}}(z_1, z_2, 0, P^z, \mu)}{\hat{M}_{\overline{\text{MS}}}(z_1, z_2, 0, 0, \mu)}$$

- 2) Long-distance region

$$\frac{\hat{M}_{\overline{\text{MS}}}(z_1, z_2, 0, P^z, \mu)}{\hat{M}_{\overline{\text{MS}}}(\text{sign}(z_1)z_s, \text{sign}(z_2)2z_s, 0, 0, \mu)}$$

- 3) Mixing regions

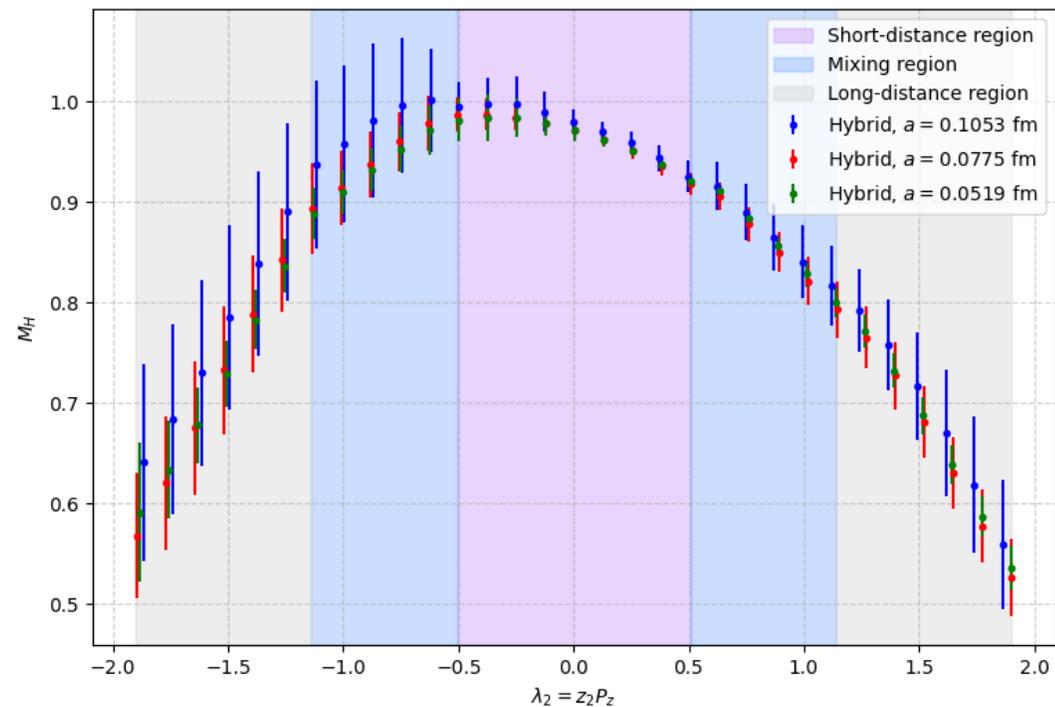
$$\frac{\hat{M}_{\overline{\text{MS}}}(z_1, z_2, 0, P^z, \mu)}{\hat{M}_{\overline{\text{MS}}}(z_1, \text{sign}(z_2)2z_s, 0, 0, \mu)} \cdot \theta(z_s - |z_1|)\theta(|z_2| - 2z_s)$$

Hybrid Renormalization results

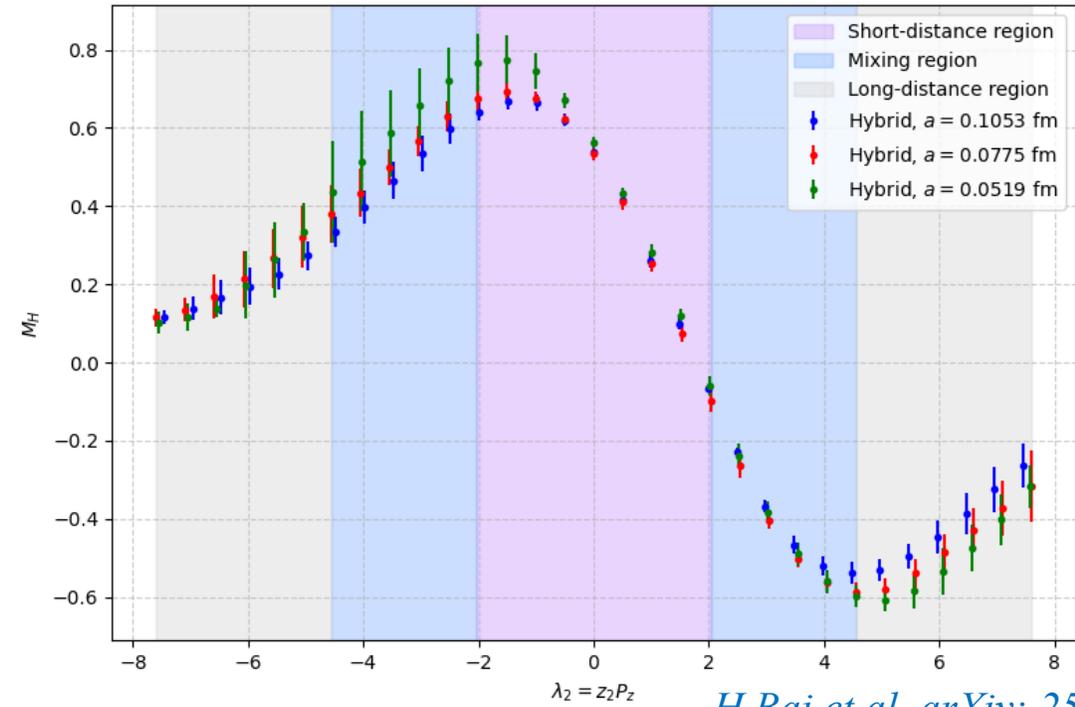
z-dependence of Hybrid renormalized quasi-DA on different lattice spacing

Lambda A term $z_1=0.250$ fm

$P^Z=0.5$ GeV

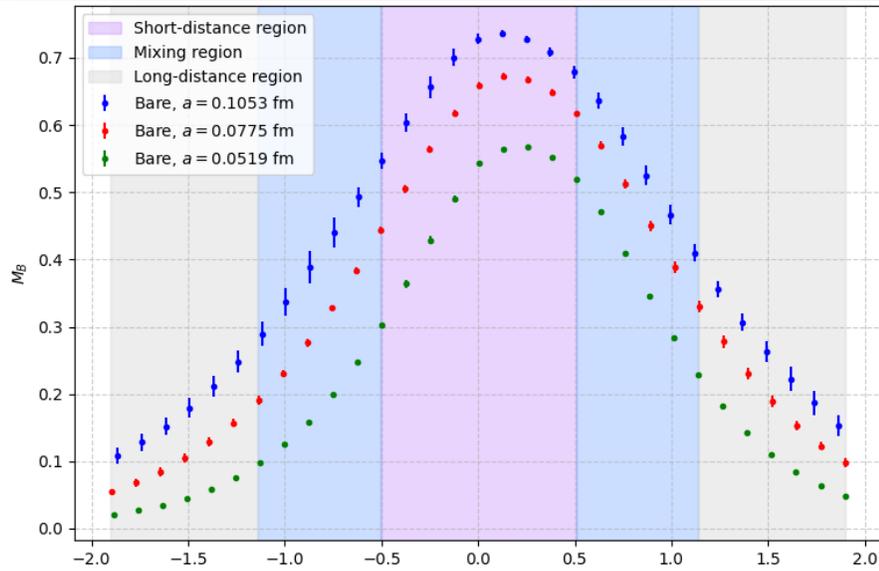


$P^Z=2.0$ GeV

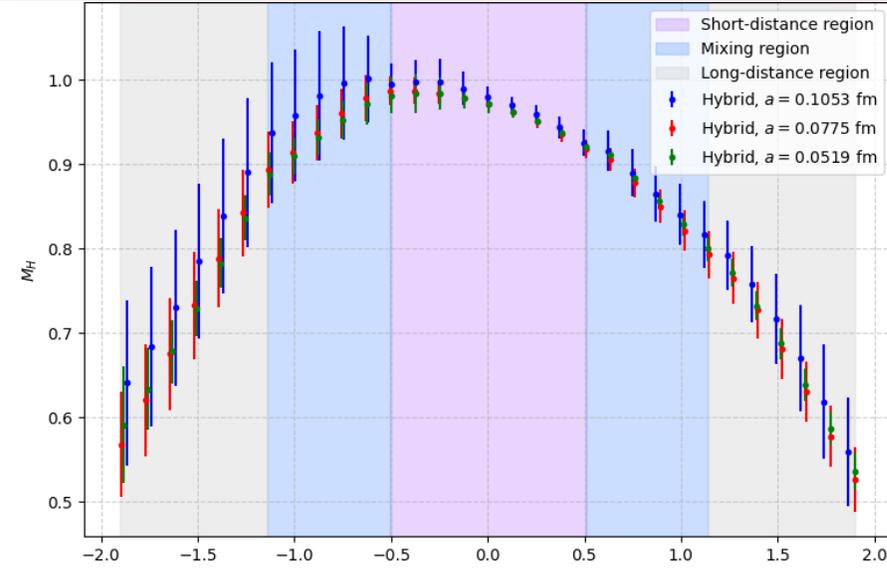
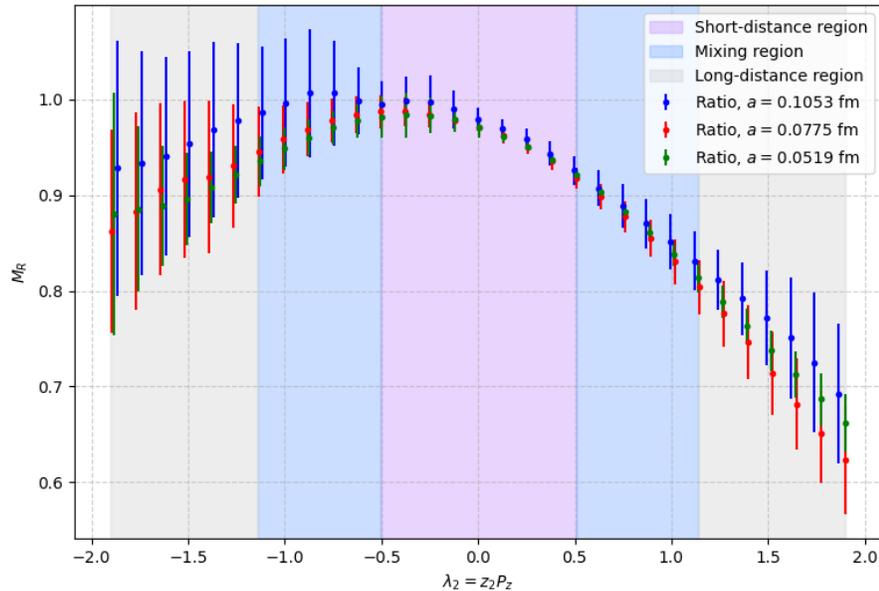


Hybrid Renormalization

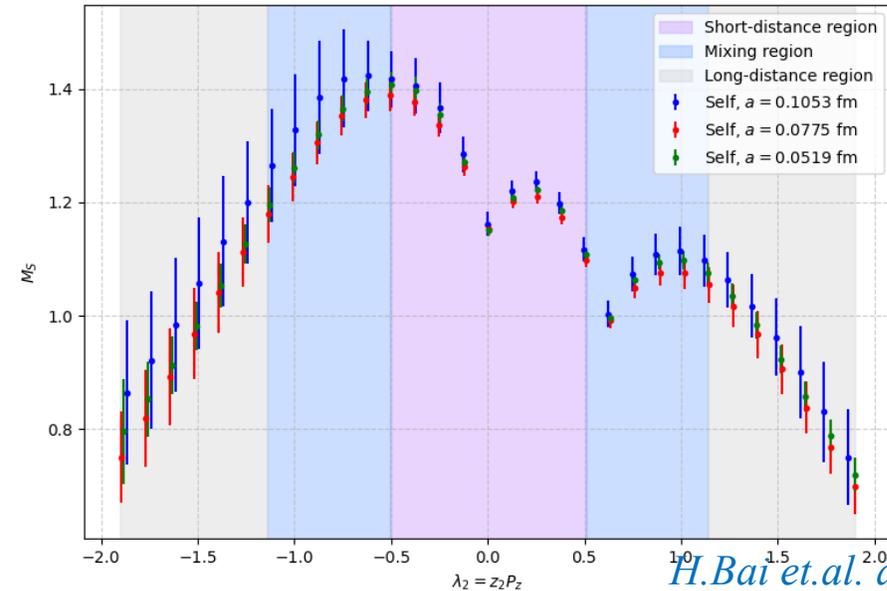
**Bare
Matrix
Element**



**Ratio scheme
result**



**Hybrid scheme
result**



**Self scheme
result**

2 Lattice methods for LCDA

Operator Product Expansion (OPE)

the local moments are consistent between light-cone coordinate and Euclidean space

- Focus on several lowest moments
- Inverse problem from moments to LCDA

Light baryon:

QCDSF, 2008, 2009;

RQCD, 2016, 2019, 2025

Large momentum effective theory (LaMET)

the light-cone correlator relates to an equal-time correlator with a large momentum boost

- x-dependent LCDA directly
- Power correction at both endpoints

Light baryon:

LPC PRD 111, 034510 (2025)