

Complete leading-twist baryon LCDAs from lattice QCD

张沐华

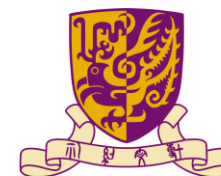
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第六届中国格点量子色动力学研讨会

CUHK-Shenzhen, Shenzhen • 8–11 October 2026

arXiv:2606.29597 • arXiv:2606.30387



香港中文大學(深圳)
The Chinese University of Hong Kong, Shenzhen

Why baryon LCDAs ?

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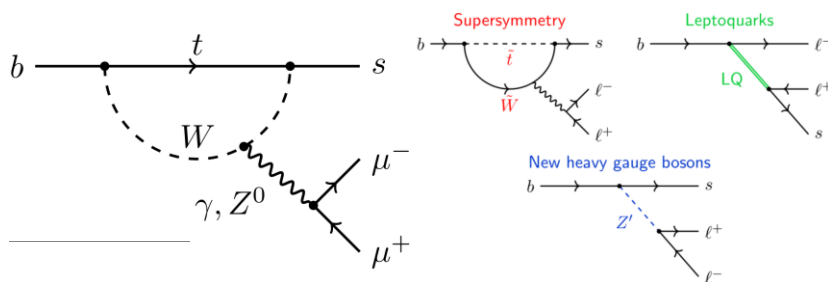
Baryon Weak Decays

Establish CPV in baryonic decays

- First observation of CPV in Baryon:

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

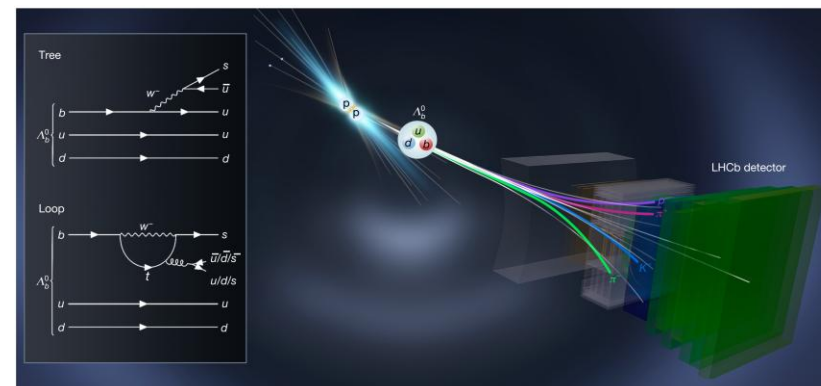
New Physics beyond SM



Observation of charge–parity symmetry breaking in baryon decays

[LHCb Collaboration](#)

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



Multi-dimensional structure

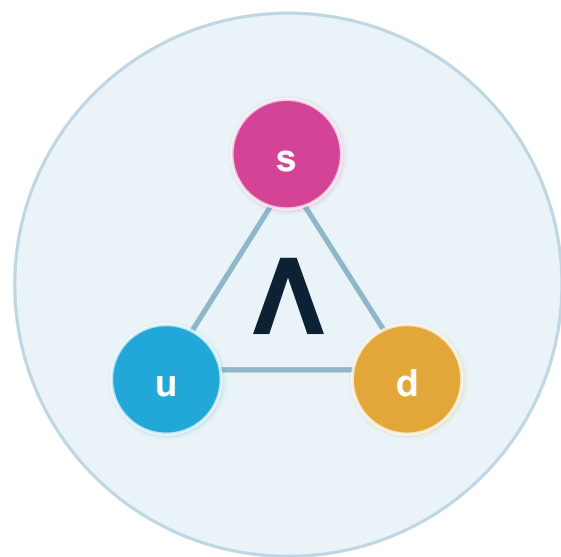
Baryon form factors,
Electric dipole moment,

.....

Why baryon LCDAs ?

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Λ : lightest strange baryon



1956



Λ
polarization
and
discrete
symmetry

2019



Quantum
entangle-
ment of
 $\Lambda\bar{\Lambda}$ pair

2025



CPV and
precise
time-like
form-factor

2025–26



Hyperon
EDM from
BESIII

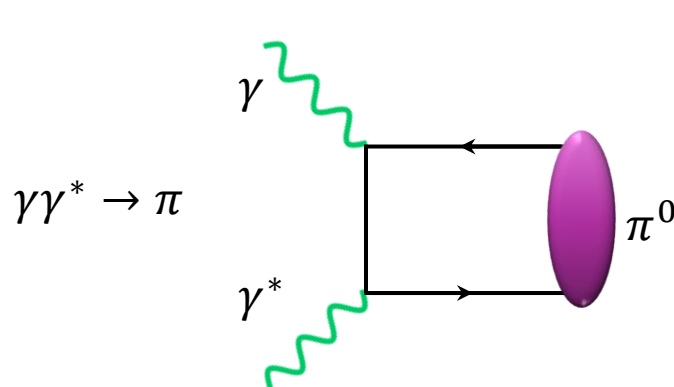
Precise experiments require **complete multi-dimensional hyperon structure** with controlled uncertainty

Why baryon LCDAs ?

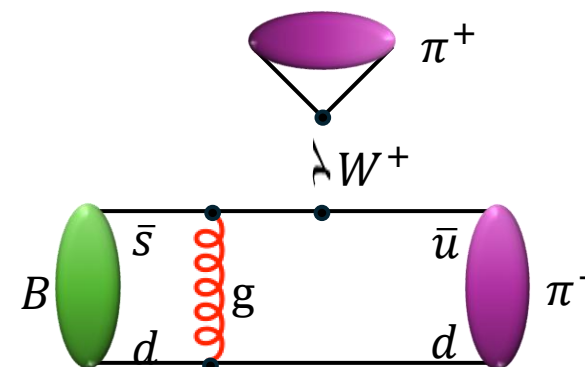
4

Key non-perturbative input for observables

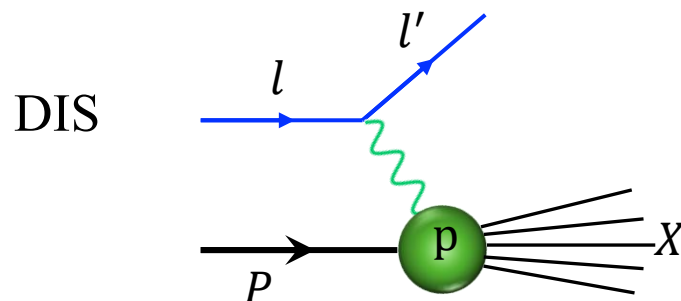
- **LCDAs**: QCD dynamical information in **Exclusive processes**



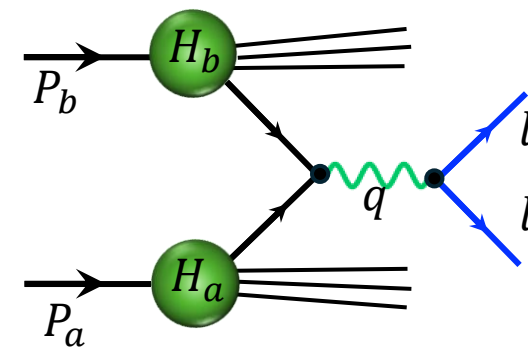
$B \rightarrow \pi^+\pi^-$



- **PDFs**: internal structure of hadrons in **Inclusive processes**



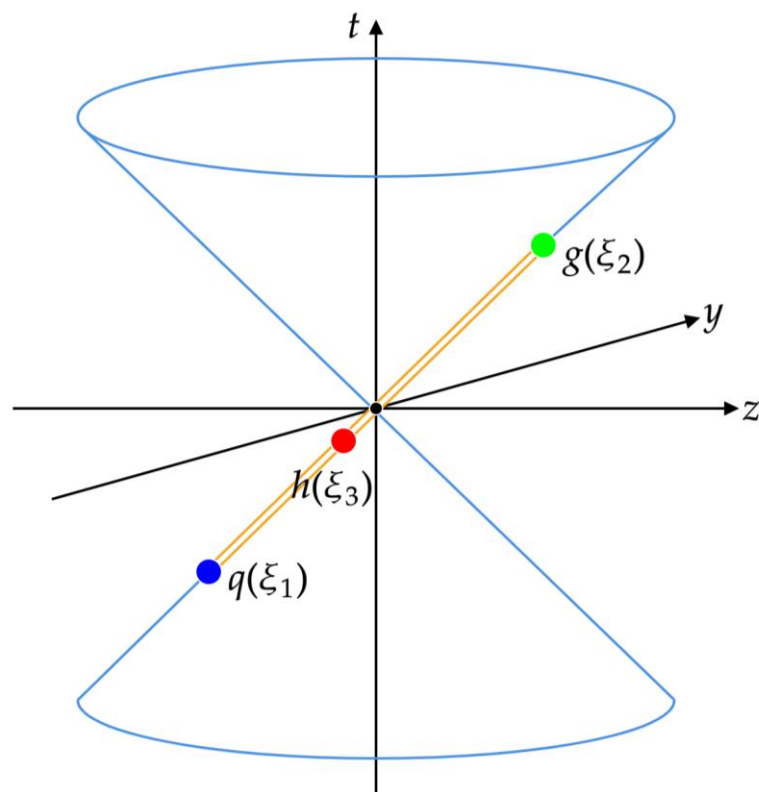
Drell-Yan



How to access baryon LCDAs ?

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Operator definition of baryon LCDAs:



Coordinate space:

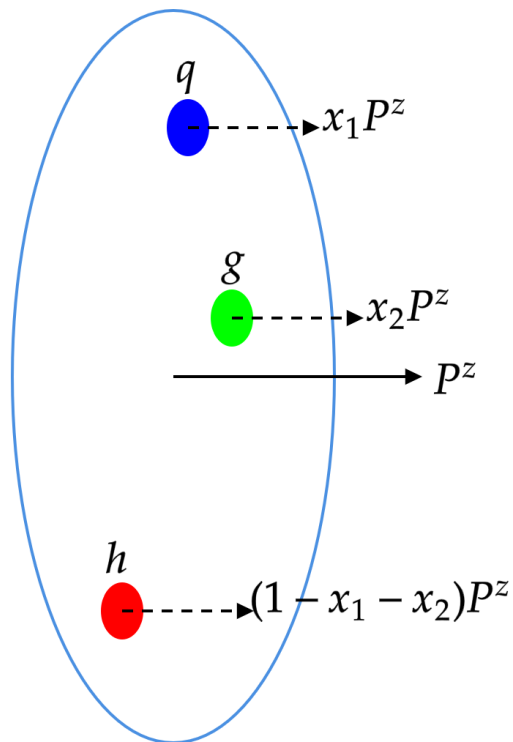
$$\begin{aligned} & \epsilon^{ijk} \langle 0 | q_{\alpha}^{i'}(\xi_1 n) U_{i' i}(\xi_1 n, \xi_0 n) \\ & \quad \times g_{\beta}^{j'}(\xi_2 n) U_{j' j}(\xi_2 n, \xi_0 n) \\ & \quad \times h_{\gamma}^{k'}(\xi_3 n) U_{k' k}(\xi_3 n, \xi_0 n) | B(P) \rangle^R \end{aligned}$$

light-cone separated quarks

How to access baryon LCDAs ?

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Operator definition of baryon LCDAs:



**hadron momentum
distribute among quarks**

Momentum space:

$$\phi_B^X(x_1, x_2; \mu) = (n \cdot P)^2 \int \frac{d\xi_1}{2\pi} \frac{d\xi_2}{2\pi} e^{i(x_1 \xi_1 + x_2 \xi_2) n \cdot P} \\ \times \epsilon^{ijk} \langle 0 | q_{\alpha}^{i'}(\xi_1 n) U_{i' i}(\xi_1 n, \xi_0 n) \\ \times g_{\beta}^{j'}(\xi_2 n) U_{j' j}(\xi_2 n, \xi_0 n) \\ \times h_{\gamma}^{k'}(\xi_3 n) U_{k' k}(\xi_3 n, \xi_0 n) | B(P) \rangle^R$$

Two independent momentum fractions: x_1, x_2

How to access baryon LCDAs ?

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Leading twist for octet baryon:

$$\begin{aligned} & \langle 0 | f_\alpha(\xi_1 n) g_\beta(\xi_2 n) h_\gamma(\xi_3 n) | B(P) \rangle^R \\ &= \frac{1}{4} f_B \left[(\not{P} C)_{\alpha\beta} (\gamma^5 u_B)_\gamma \underline{\Phi_B^V} + (\not{P} \gamma^5 C)_{\alpha\beta} (u_B)_\gamma \underline{\Phi_B^A} \right] + \frac{1}{4} f_B^T (\mathrm{i} \sigma_{\mu\nu} P^\nu C)_{\alpha\beta} (\gamma^\mu \gamma^5 u_B)_\gamma \underline{\Phi_B^T} \end{aligned}$$

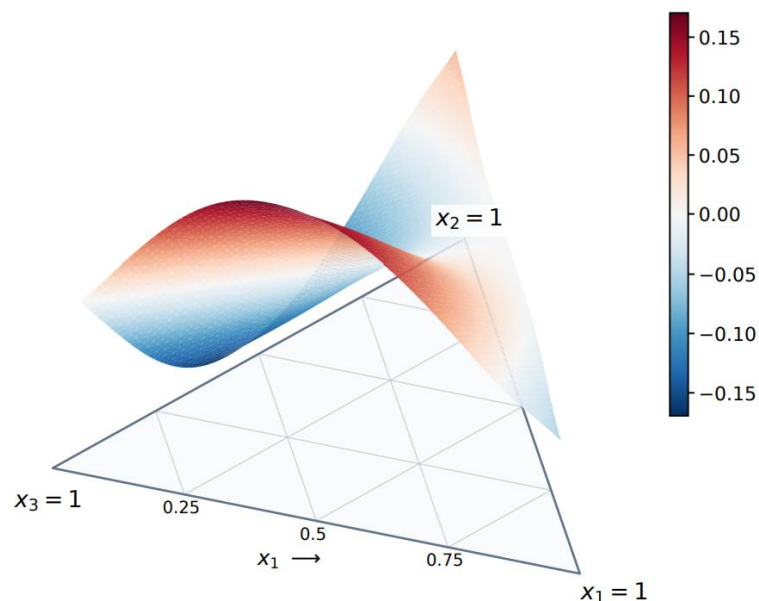
How to access baryon LCDAs ?

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Leading twist for octet baryon:

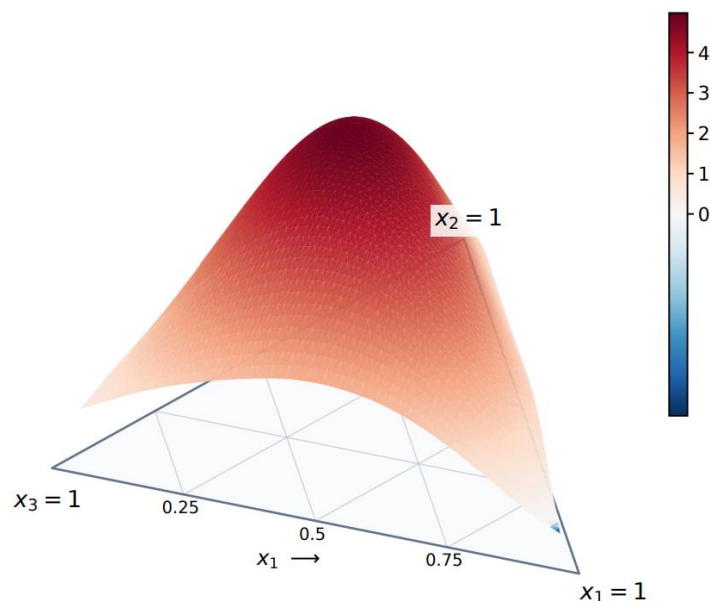
$$\begin{aligned} & \langle 0 | f_\alpha(\xi_1 n) g_\beta(\xi_2 n) h_\gamma(\xi_3 n) | B(P) \rangle^R \\ &= \frac{1}{4} f_B \left[(\not{P} C)_{\alpha\beta} (\gamma^5 u_B)_\gamma \Phi_B^V + (\not{P} \gamma^5 C)_{\alpha\beta} (u_B)_\gamma \Phi_B^A \right] + \frac{1}{4} f_B^T (\mathrm{i} \sigma_{\mu\nu} P^\nu C)_{\alpha\beta} (\gamma^\mu \gamma^5 u_B)_\gamma \Phi_B^T \end{aligned}$$

Λ LCDA: V



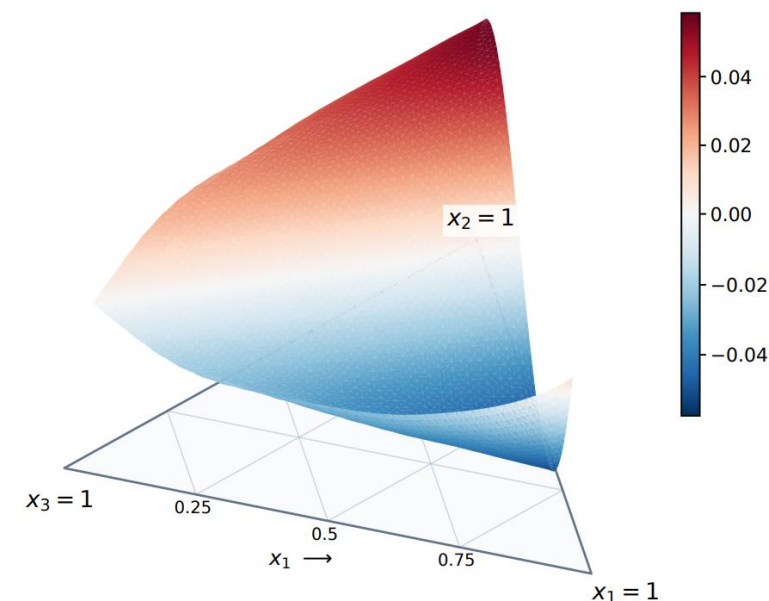
antisymmetric

Λ LCDA: A



symmetric

Λ LCDA: T



antisymmetric

Research history: (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;

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only lowest moments

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only lowest moments

- x -dependent LCDAs from Lattice QCD



Companion article

**Formalism ·
Renormalization ·
Extrapolation · Matching**

(LPC) arXiv:2606.30387



Letter

**Complete physical V, A, T
+ phenomenology**

(LPC) arXiv:2606.29597

How to access baryon LCDAs ?

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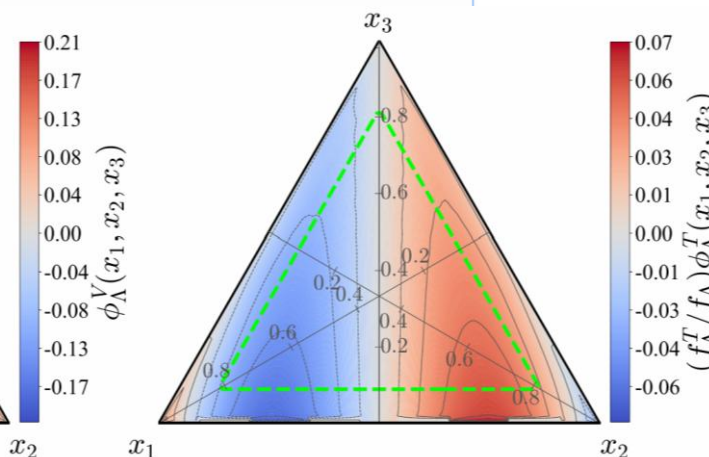
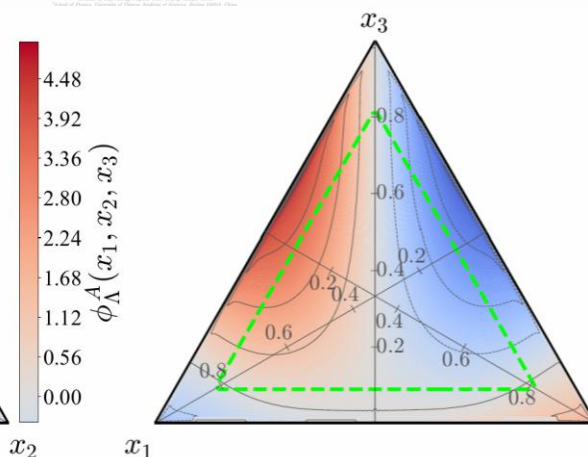
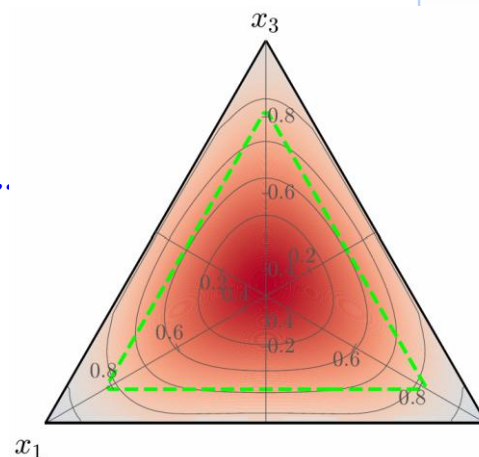
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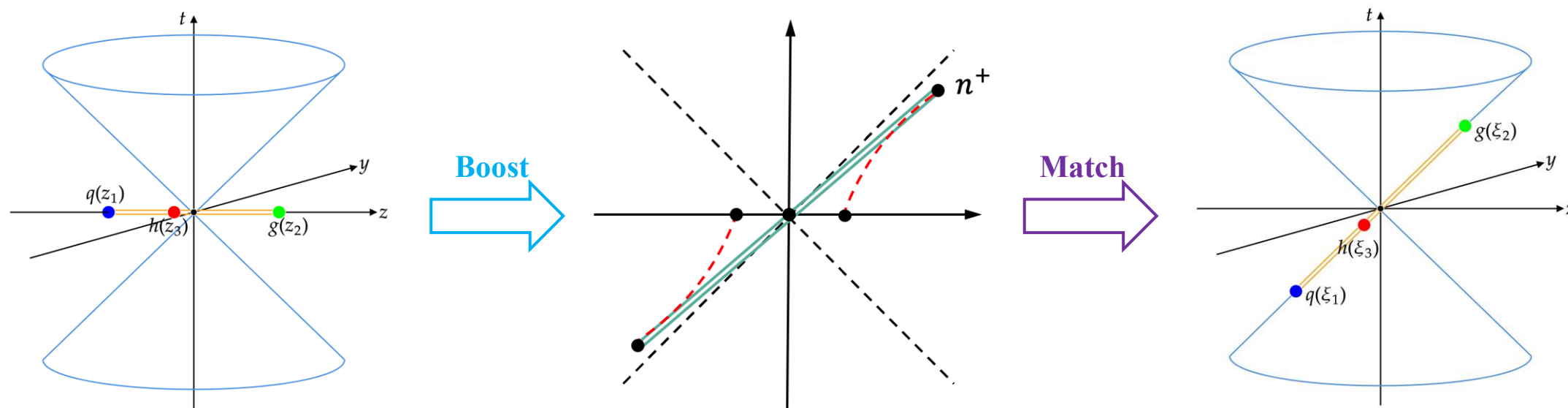
Companion article

LPC, arXiv:2606.29597;

Complete physical V, A, T
+ phenomenology

Full shape, all structures!

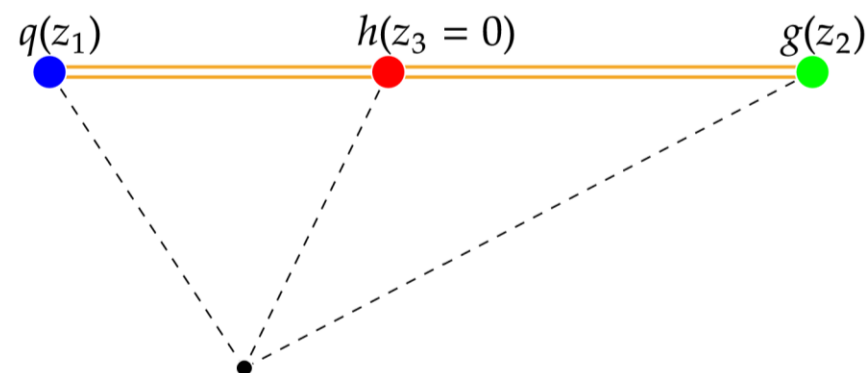
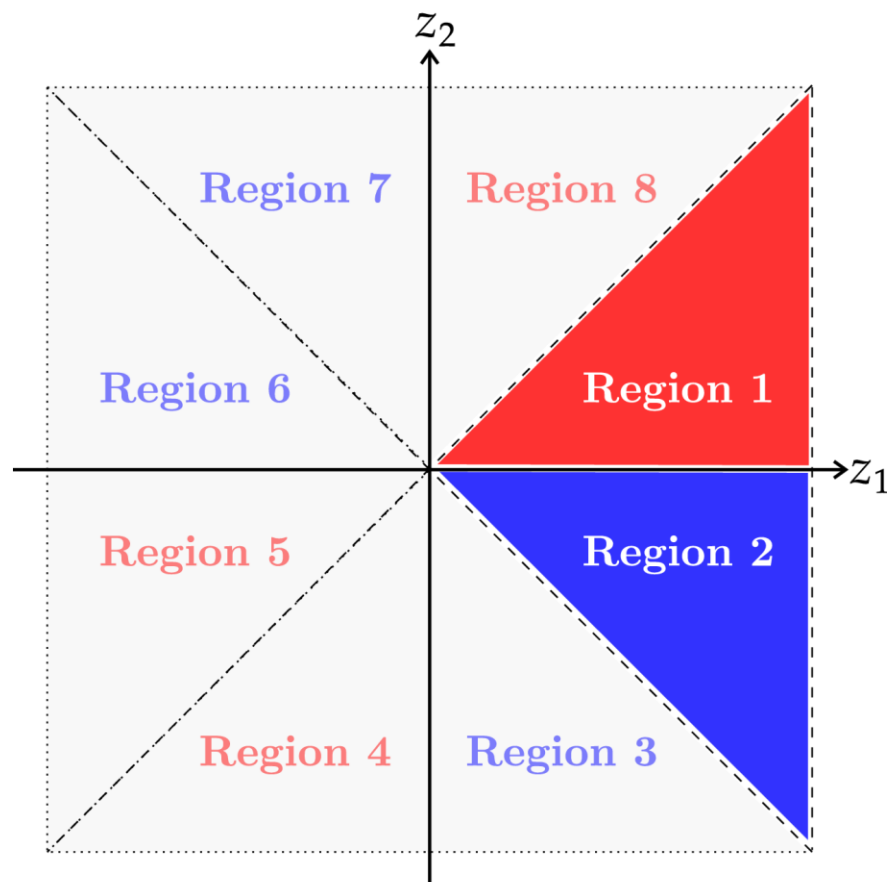
(LPC) arXiv:2006.29597



LaMET expansion:

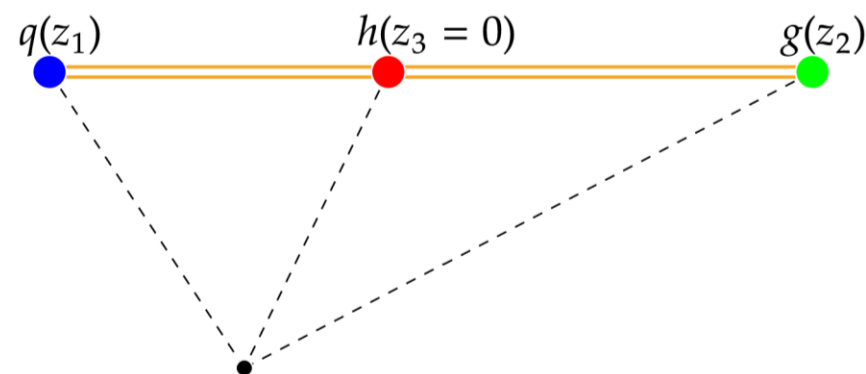
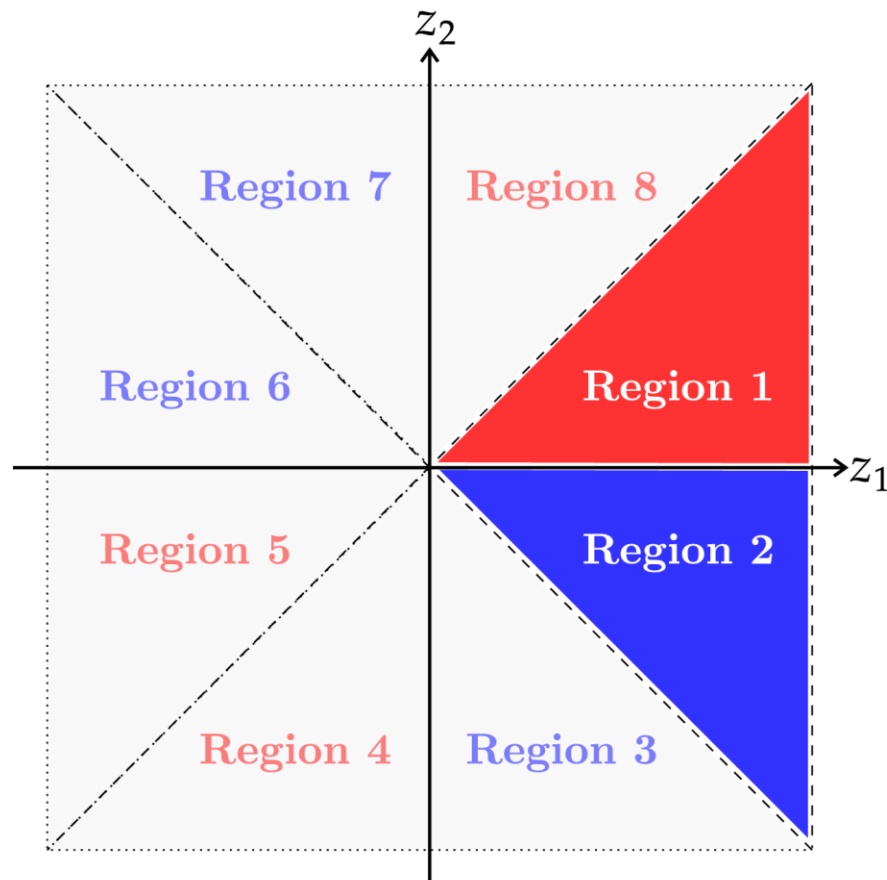
$$\begin{aligned}
 \phi(x_1, x_2; \mu) = & \int dy_1 dy_2 \overset{\text{LCDA}}{\mathcal{C}}(x_1, x_2; y_1, y_2; P^z, \mu) \overset{\text{Matching kernel}}{\tilde{\phi}}(y_1, y_2; P^z, \mu) \overset{\text{quasi-DA}}{\tilde{\phi}}(y_1, y_2; P^z, \mu) \\
 & + \mathcal{O} \left(\frac{\Lambda_{\text{QCD}}^2}{(x_1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

Genuinely 2-dimensional distribution



- ❑ 2-dimensional distributions;
- ❑ 3-quark operator with 2 Wilson-lines;
- ❑ Multi leading twist structures **V**, **A**, and **T**

Genuinely 2-dimensional distribution

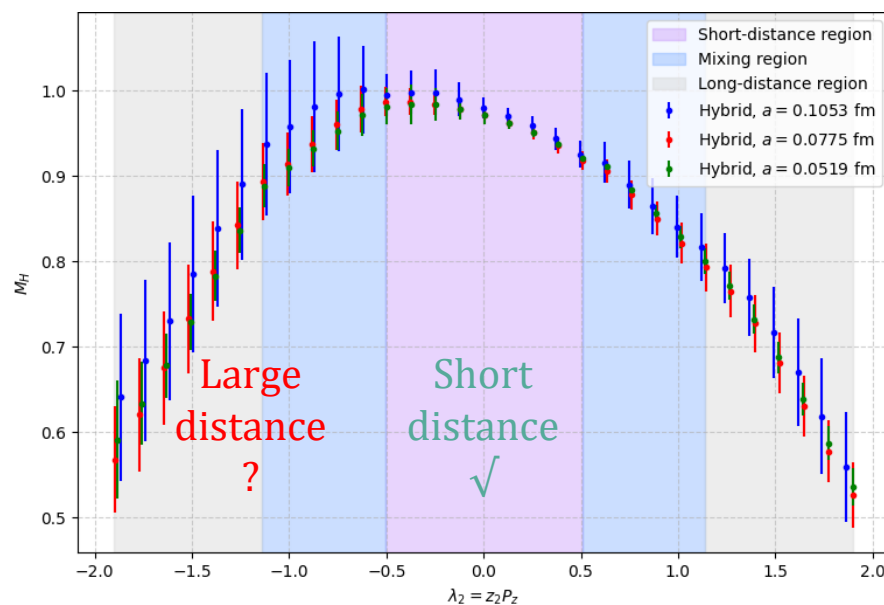


- ❑ 2-dimensional distributions;
- ❑ 3-quark operator with 2 Wilson-lines;
- ❑ Multi leading twist structures **V**, **A**, and **T**

Central challenge !

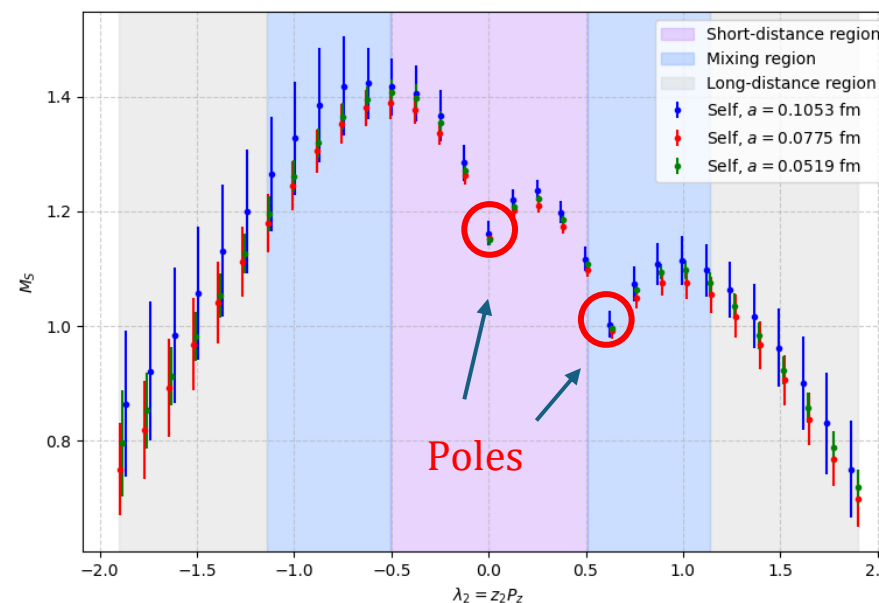
Hybrid Renormalization:

adopt different schemes in different regions



- **Ratio:**

cancel divergences at short distance

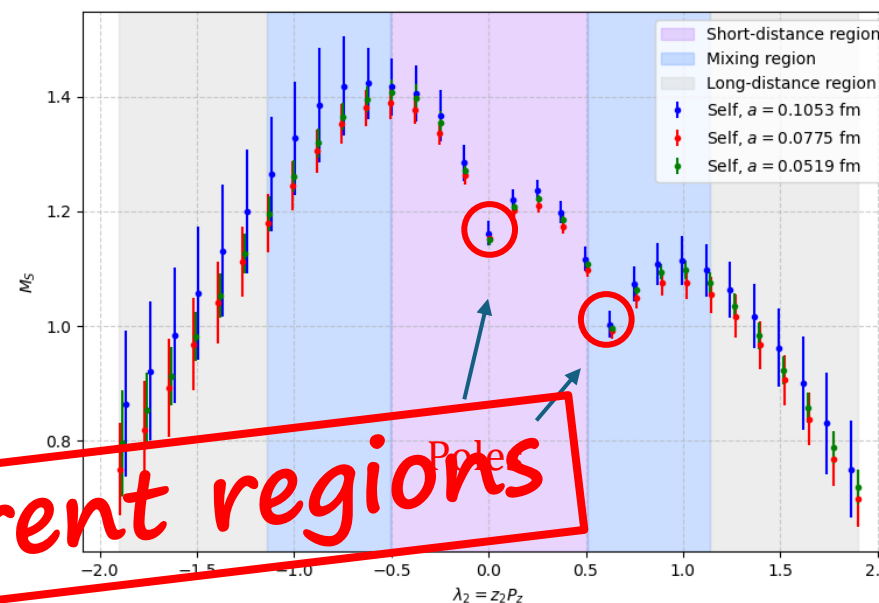
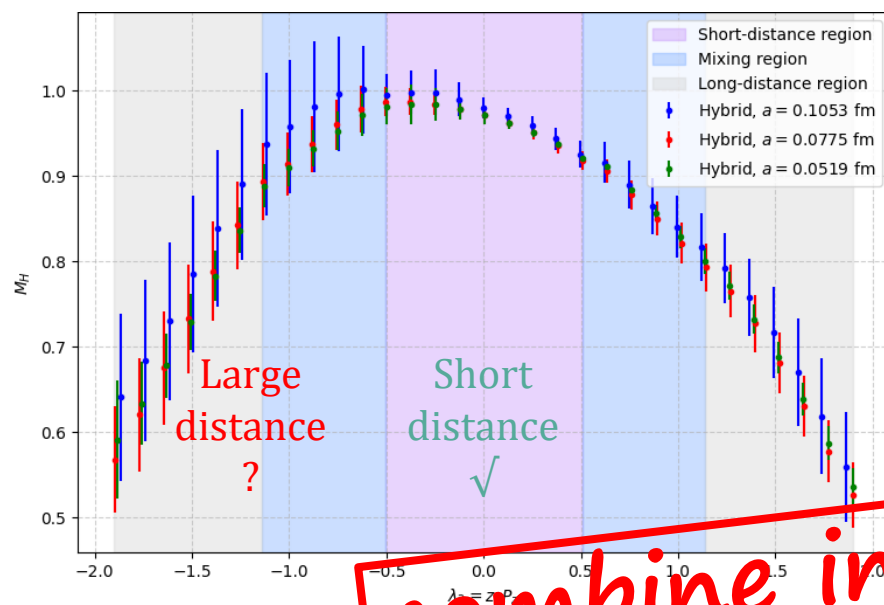


- **Self-Renormalization:**

control long-distance behavior

Hybrid Renormalization:

adopt different schemes in different regions



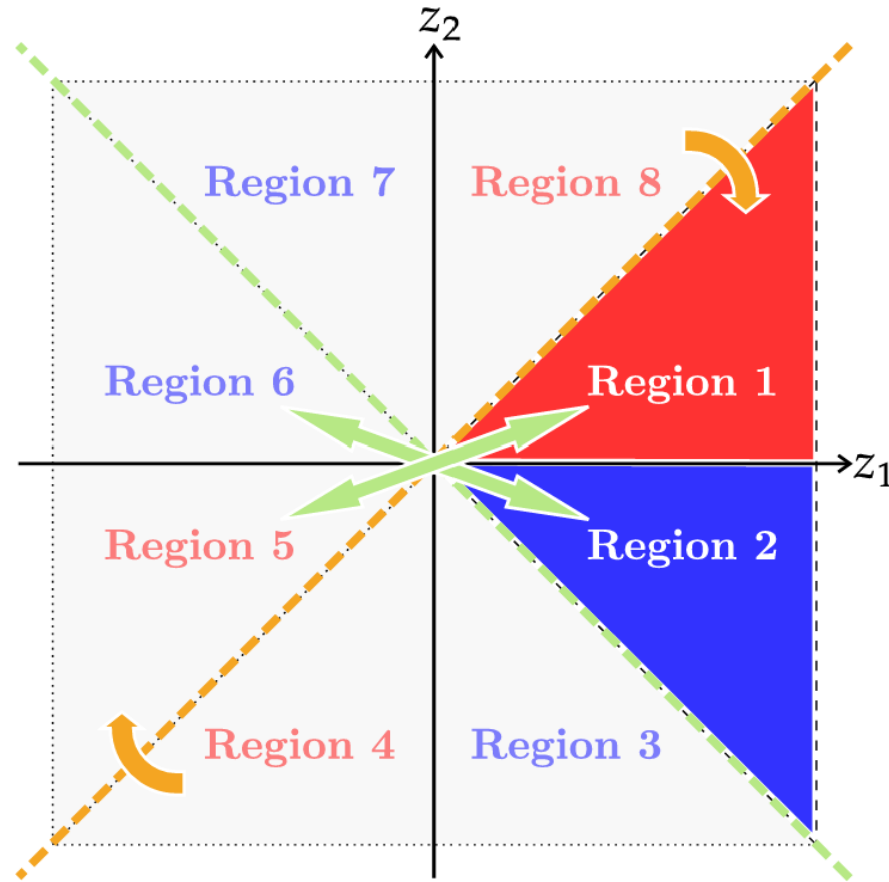
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- **Self-Renormalization:**

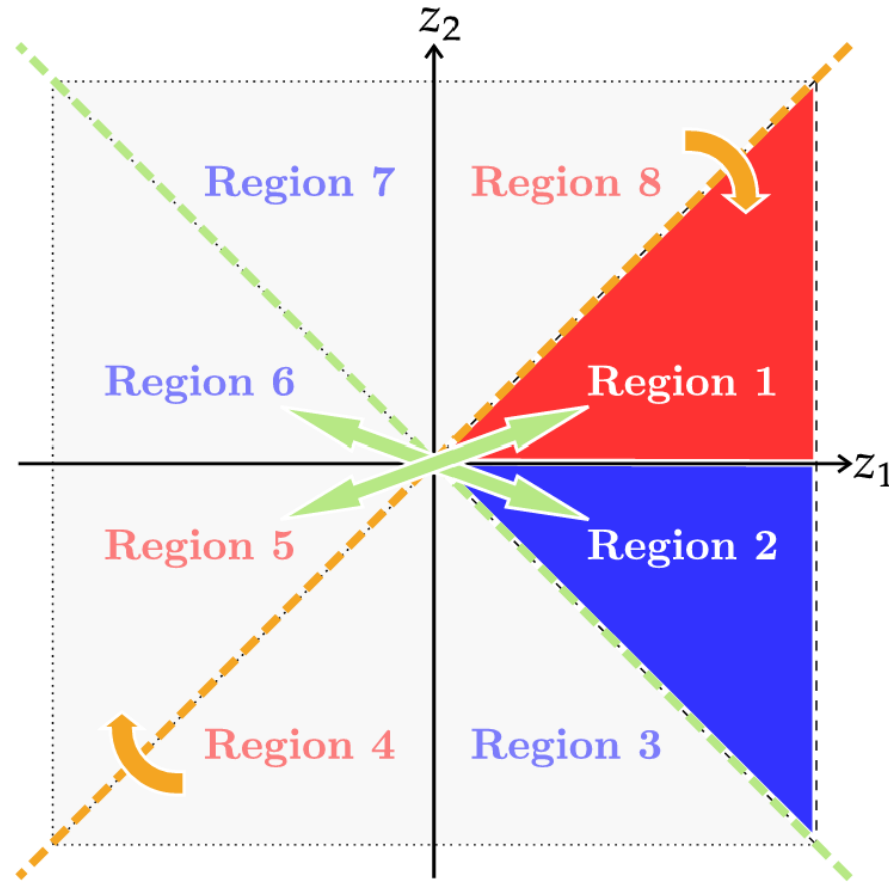
control long-distance behavior

2-Dimensional Hybrid Scheme

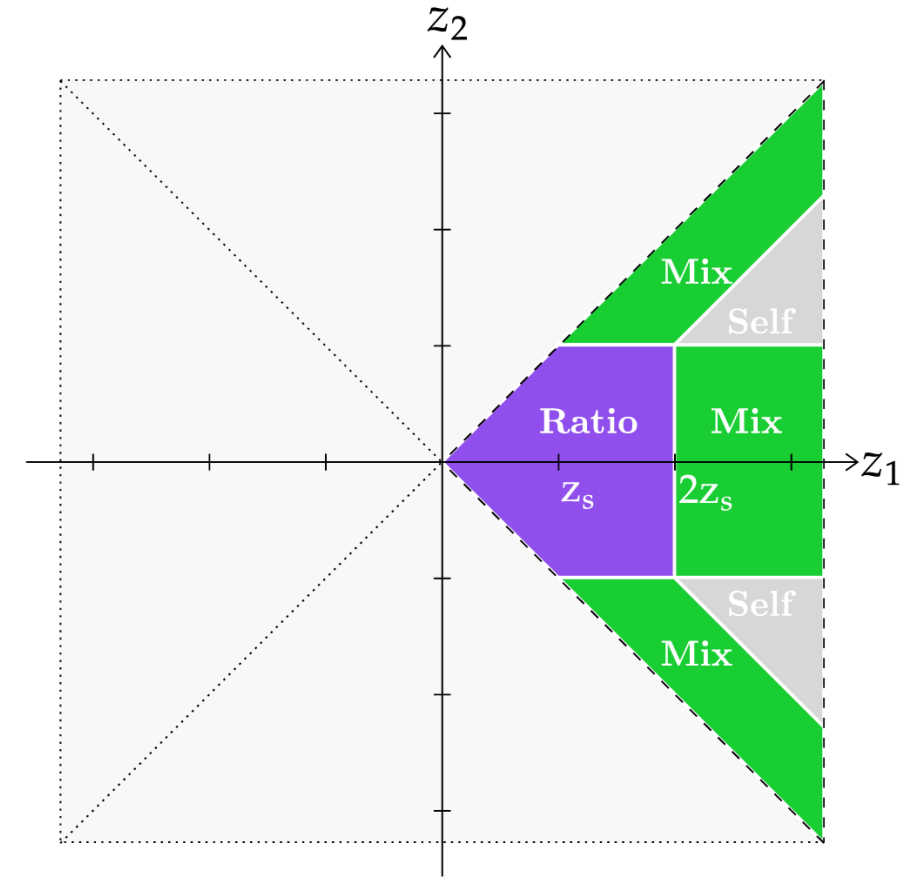


region partition by
short-long distances:
 $|z_1|, |z_2|, |z_1 - z_2|$

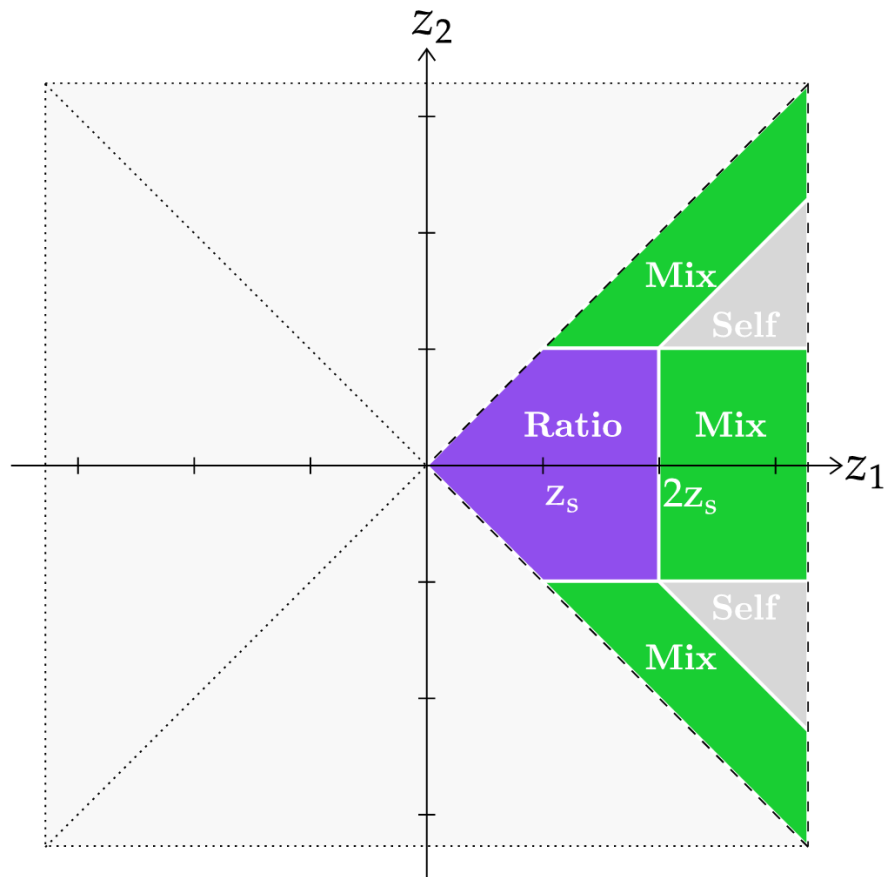
2-Dimensional Hybrid Scheme



region partition by
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2-Dimensional Hybrid Scheme



- 1) Short-distance regions: Ratio

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

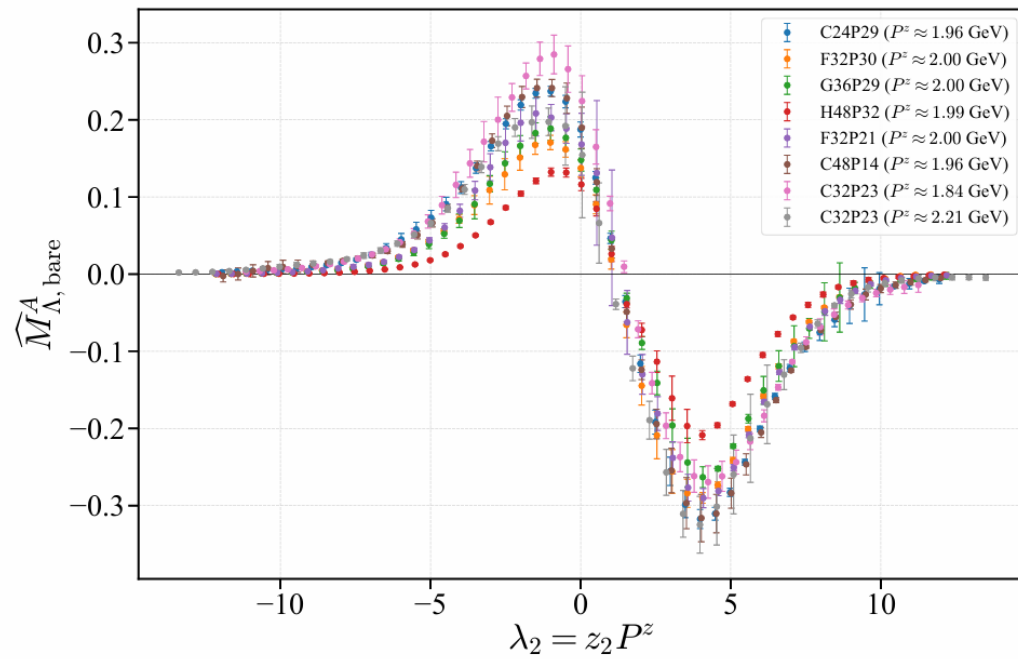
- 2) Long-distance regions: Self-renormalization

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

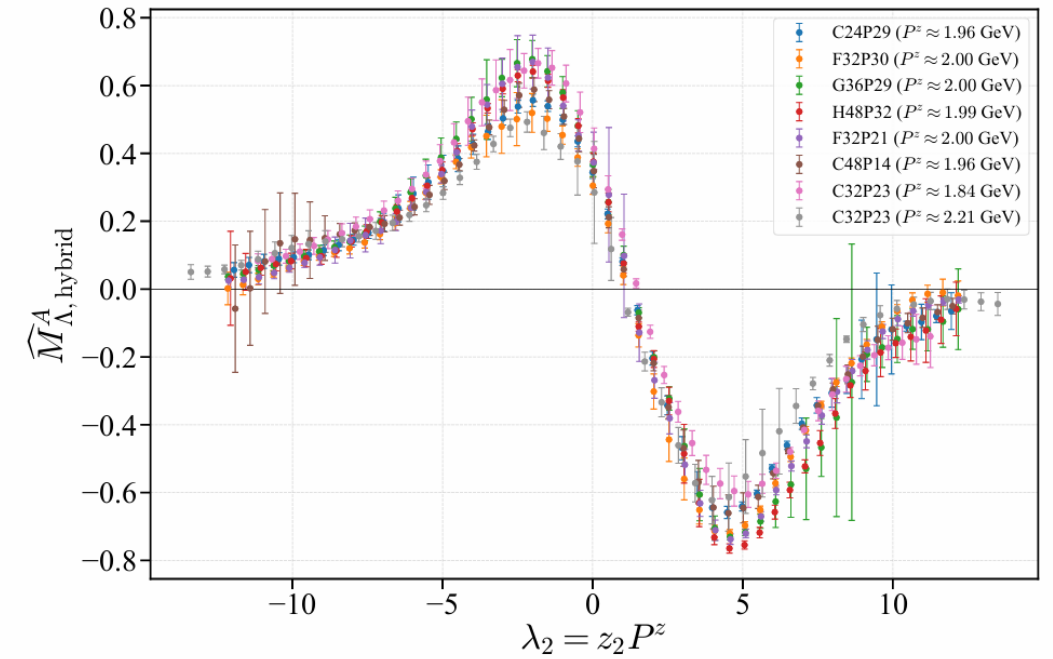
- 3) **Mixing regions**

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

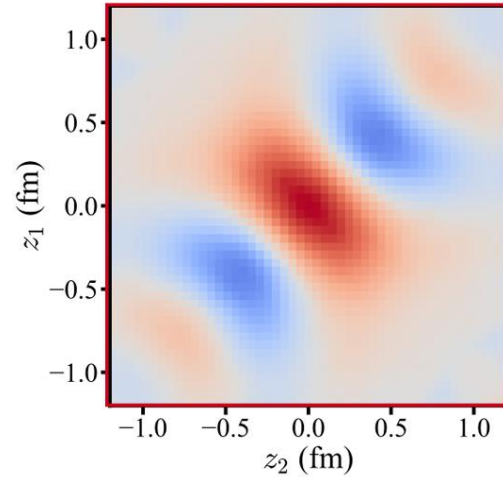
Bare Matrix Element



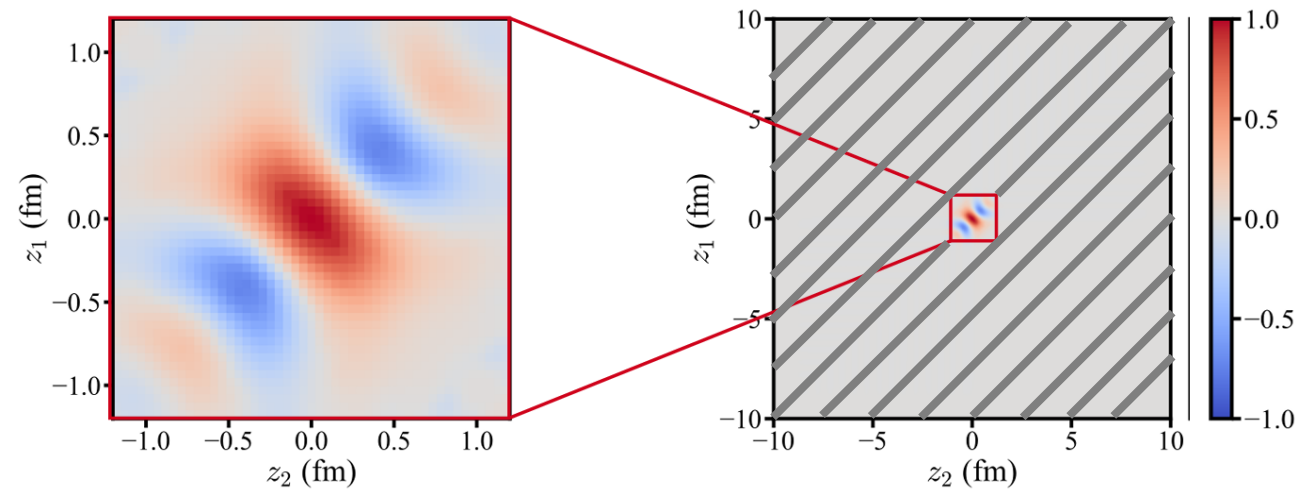
Hybrid Renormalized result



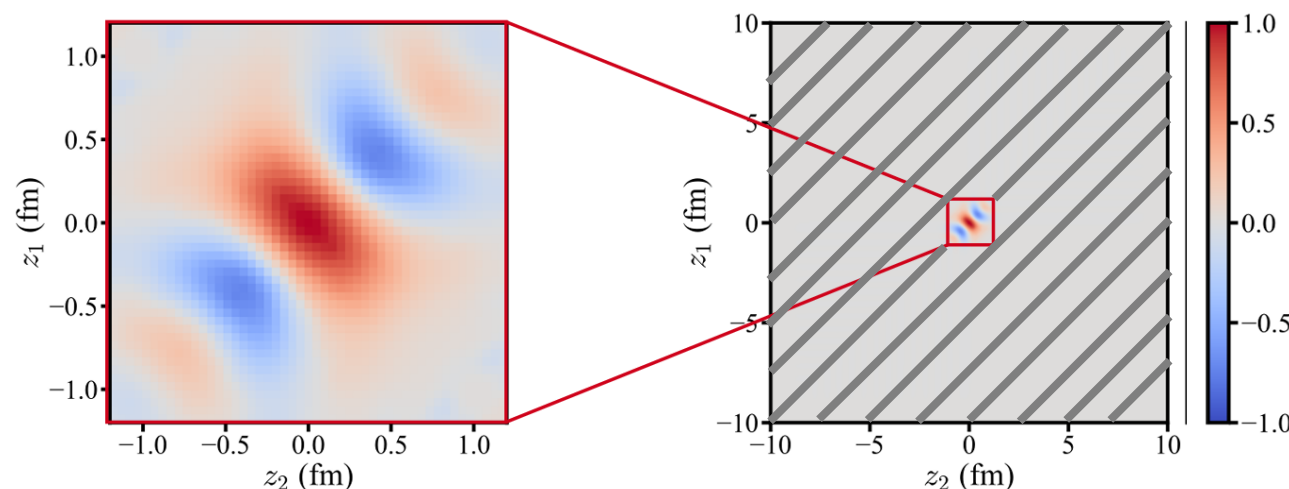
Asymptotic expansion: long region data for FT



Asymptotic expansion: long region data for FT



Asymptotic expansion: long region data for FT



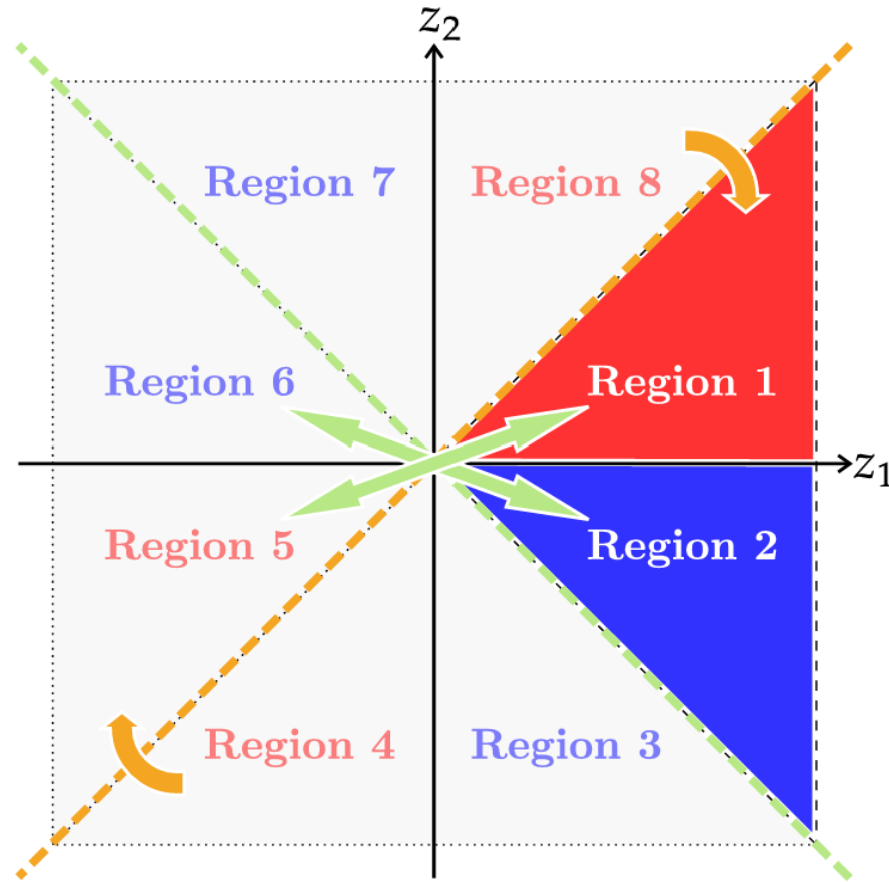
Expand Euclidean Correlators in large Euclidean separation $|z|$:

$$\tilde{h}(z, P^z) = \sum_{\Lambda^{JP}} e^{-\Lambda^{JP}|z|} \times \left[\left(\mathcal{H}_1 e^{-izP^z} + \mathcal{H}_2 \right) + \left(\mathcal{H}'_1 e^{-izP^z} + \mathcal{H}'_2 \right) \frac{1}{|z|} + \dots \right],$$

LA NLA

X. Ji, Y. Liu, Y. Su, arXiv:2601.12189

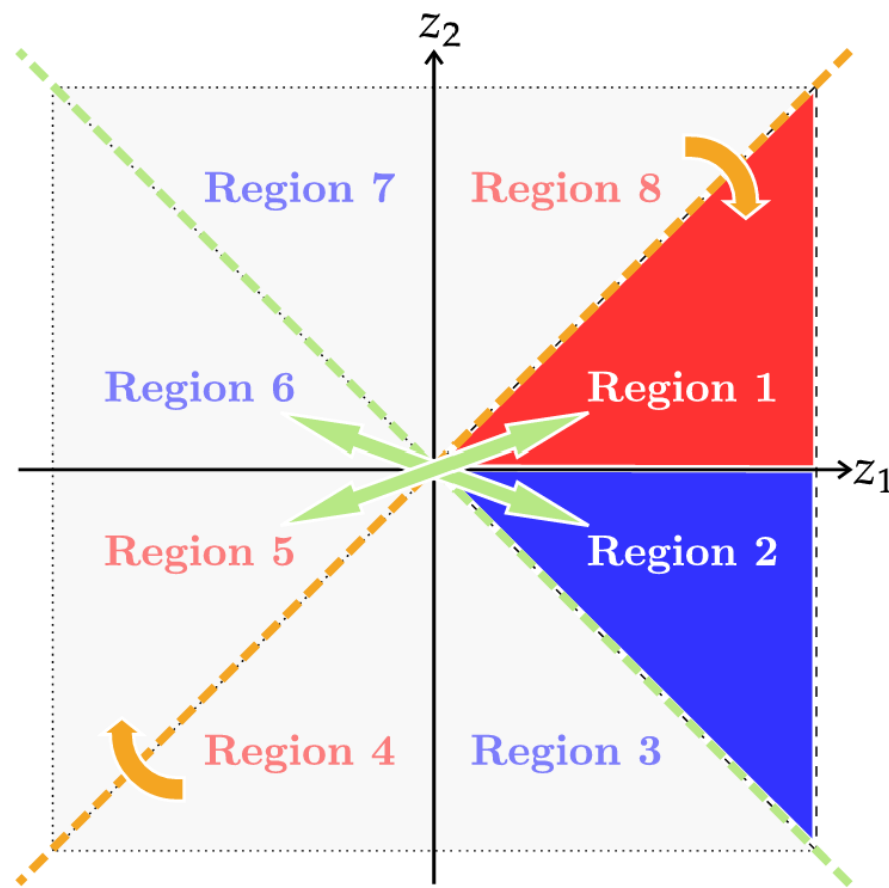
Generalize to baryon-DA case:



3 relevant distances:

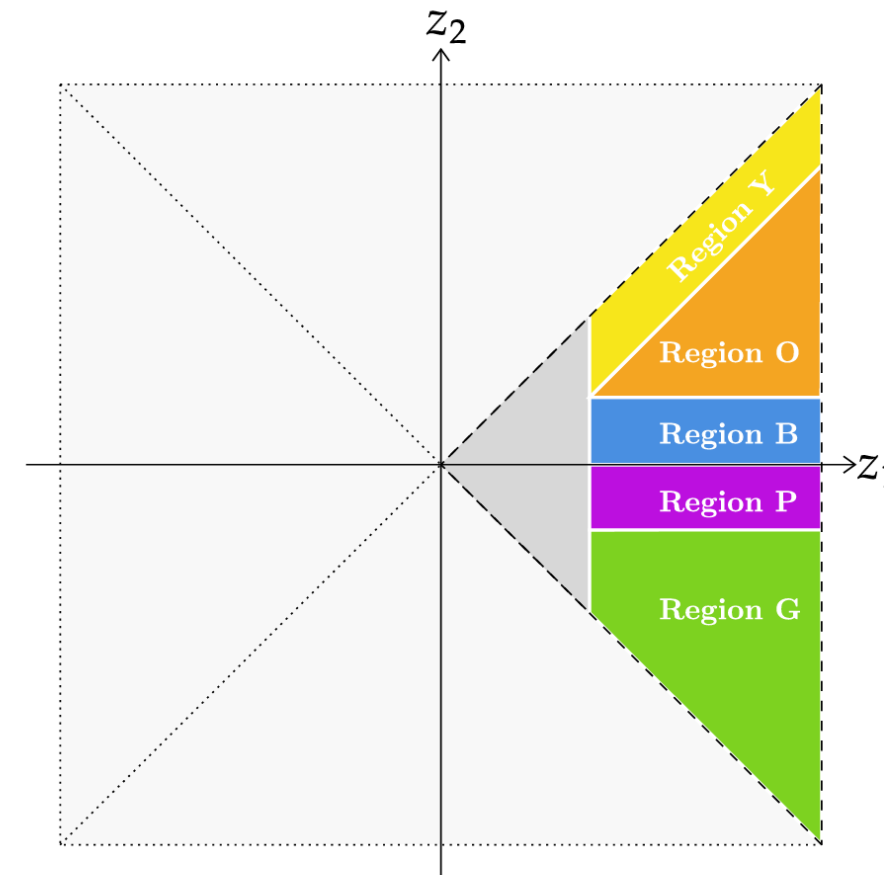
$$|z_1|, |z_2|, |z_1 - z_2|$$

Generalize to baryon-DA case:



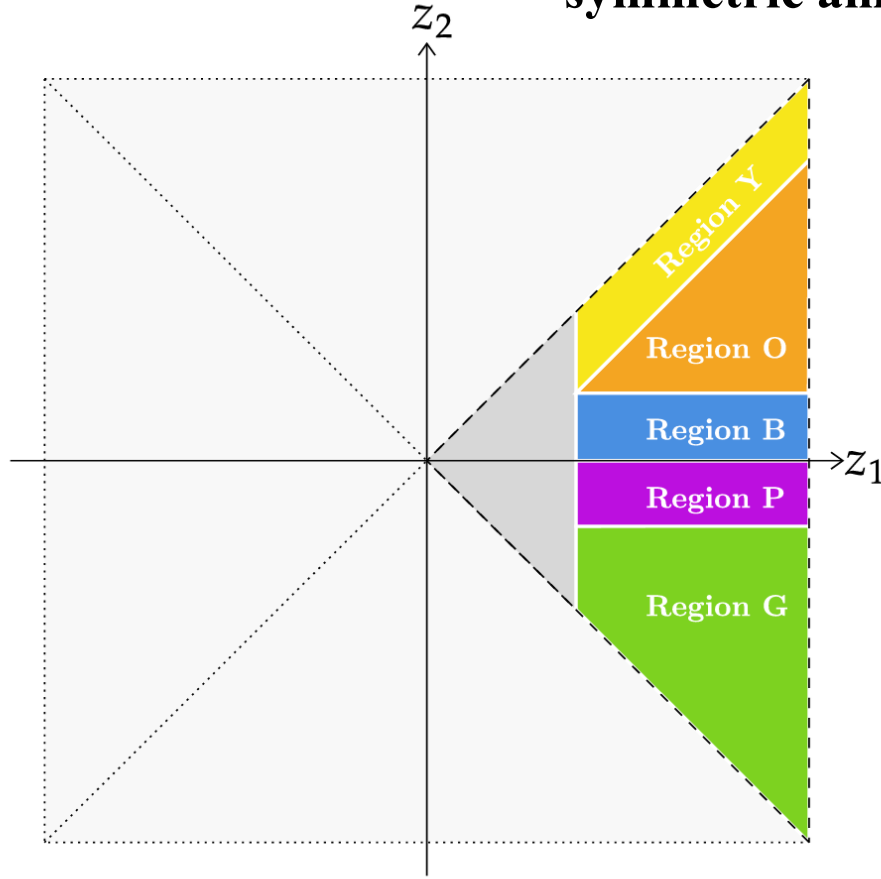
3 relevant distances:

$$|z_1|, |z_2|, |z_1 - z_2|$$



for Lambda A:

symmetric amplitude with good signal quality



- **Region G:** $z_1 z_2 < 0$, $|z_1| \rightarrow \infty$, $|z_2| \rightarrow \infty$ and $|z_1 - z_2| \rightarrow \infty$

$$\tilde{A}^{\text{NLA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_1|} e^{-\Lambda_0 - |z_2|} \left[G_A(i\hat{z}_1, i\hat{z}_2, P^z) + G'_A(i\hat{z}_1, i\hat{z}_2, P^z) \frac{1}{|z|} \right] ; \quad ($$

- **Region P:** $z_1 z_2 < 0$, $|z_1| \rightarrow \infty$, $|z_1 - z_2| \rightarrow \infty$ while $|z_2|$ kept finite

$$\tilde{A}^{\text{NLA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_2|} e^{iz_1 P^z} \left[P_{A,1}(iz_1, i\hat{z}_2, P^z) + P'_{A,1}(iz_1, i\hat{z}_2, P^z) \frac{1}{|z|} \right] + e^{-\Lambda_0 - |z_2|} \left[P_{A,2}(iz_1, i\hat{z}_2, P^z) + P'_{A,2}(iz_1, i\hat{z}_2, P^z) \frac{1}{|z|} \right] ; \quad ($$

- **Region B:** $z_1 z_2 > 0$, $|z_1| \rightarrow \infty$, $|z_1 - z_2| \rightarrow \infty$ while $|z_2|$ kept finite

$$\tilde{A}^{\text{NLA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_2 - z_1|} e^{iz_1 P^z} \left[B_{A,1}(-iz_1, i\hat{z}_2, P^z) + B'_{A,1}(-iz_1, i\hat{z}_2, P^z) \frac{1}{|z|} \right] + e^{-\Lambda_0 - |z_2 - z_1|} \left[B_{A,2}(-iz_1, i\hat{z}_2, P^z) + B'_{A,2}(-iz_1, i\hat{z}_2, P^z) \frac{1}{|z|} \right] ; \quad ($$

- **Region O:** $z_1 z_2 > 0$, $|z_1| \rightarrow \infty$, $|z_2| \rightarrow \infty$ and $|z_1 - z_2| \rightarrow \infty$

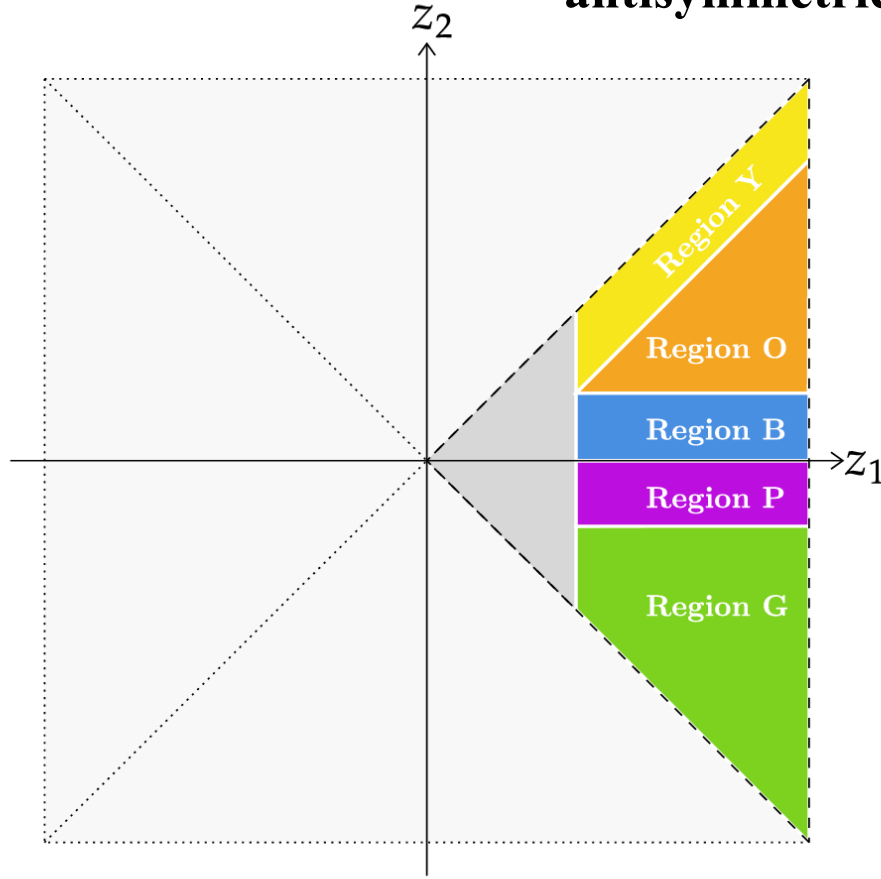
$$\tilde{A}^{\text{NLA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_1|} e^{-\Lambda_0 - |z_2 - z_1|} e^{iz_1 P^z} \left[O_A(i\hat{z}_1, i\hat{z}_2, P^z) + O'_A(i\hat{z}_1, i\hat{z}_2, P^z) \frac{1}{|z|} \right] ; \quad ($$

- **Region Y:** $z_1 z_2 > 0$, $|z_1| \rightarrow \infty$, $|z_2| \rightarrow \infty$ while $|z_1 - z_2|$ kept finite

$$\tilde{A}^{\text{NLA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_1|} e^{iz_2 P^z} \left[Y_{A,1}(i\hat{z}_1, i(z_2 - z_1), P^z) + Y'_{A,1}(i\hat{z}_1, i(z_2 - z_1), P^z) \frac{1}{|z|} \right] + e^{-\Lambda_0 - |z_1|} e^{iz_1 P^z} \left[Y_{A,2}(i\hat{z}_1, i(z_2 - z_1), P^z) + Y'_{A,2}(i\hat{z}_1, i(z_2 - z_1), P^z) \frac{1}{|z|} \right] ; \quad ($$

for Lambda V/T:

antisymmetric amplitudes with poor signal qualities



- **Region G:** $z_1 z_2 < 0$, $|z_1| \rightarrow \infty$, $|z_2| \rightarrow \infty$ and $|z_1 - z_2| \rightarrow \infty$

$$\tilde{V}^{\text{LA}}/\tilde{T}^{\text{LA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_1|} e^{-\Lambda_0 + |z_2|} G_{V/T}(i\hat{z}_1, i\hat{z}_2, P^z) - e^{-\Lambda_0 + |z_1|} e^{-\Lambda_0 - |z_2|} G_{V/T}^*(i\hat{z}_1, i\hat{z}_2, P^z) ;$$

- **Region P:** $z_1 z_2 < 0$, $|z_1| \rightarrow \infty$, $|z_1 - z_2| \rightarrow \infty$ while $|z_2|$ kept finite

$$\tilde{V}^{\text{LA}}/\tilde{T}^{\text{LA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_2|} e^{iz_1 P^z} P_{V/T,1}(iz_1, i\hat{z}_2, P^z) + e^{-\Lambda_0 - |z_2|} P_{V/T,2}(iz_1, i\hat{z}_2, P^z) ;$$

- **Region B:** $z_1 z_2 > 0$, $|z_1| \rightarrow \infty$, $|z_1 - z_2| \rightarrow \infty$ while $|z_2|$ kept finite

$$\tilde{V}^{\text{LA}}/\tilde{T}^{\text{LA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_2 - z_1|} e^{iz_1 P^z} B_{V/T,1}(-iz_1, i\hat{z}_2, P^z) + e^{-\Lambda_0 - |z_2 - z_1|} B_{V/T,2}(-iz_1, i\hat{z}_2, P^z) ;$$

- **Region O:** $z_1 z_2 > 0$, $|z_1| \rightarrow \infty$, $|z_2| \rightarrow \infty$ and $|z_1 - z_2| \rightarrow \infty$

$$\tilde{V}^{\text{LA}}/\tilde{T}^{\text{LA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_1|} e^{-\Lambda_0 - |z_2 - z_1|} e^{iz_1 P^z} O_{V/T}(i\hat{z}_1, i\hat{z}_2, P^z) ;$$

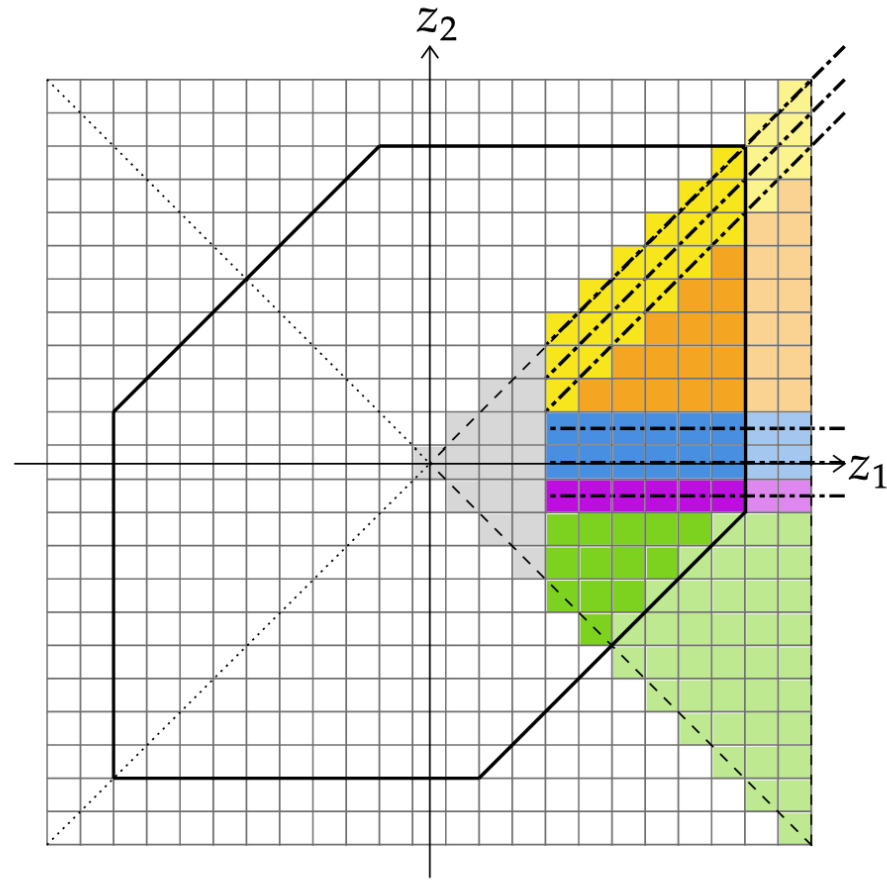
- **Region Y:** $z_1 z_2 > 0$, $|z_1| \rightarrow \infty$, $|z_2| \rightarrow \infty$ while $|z_1 - z_2|$ kept finite

$$\tilde{V}^{\text{LA}}/\tilde{T}^{\text{LA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_1|} e^{iz_2 P^z} Y_{V/T,1}(i\hat{z}_1, i(z_2 - z_1), P^z) + e^{-\Lambda_0 - |z_1|} e^{iz_1 P^z} Y_{V/T,2}(i\hat{z}_1, i(z_2 - z_1), P^z) ;$$

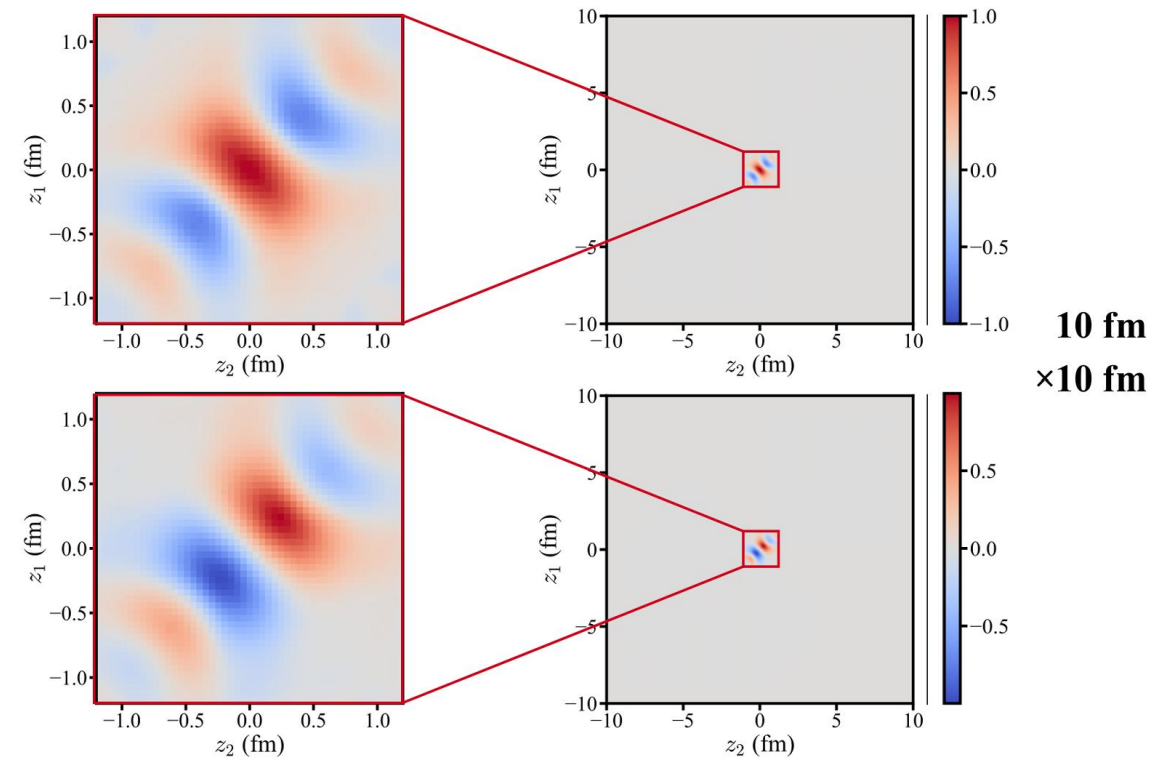
Formalism: Large-distance Extrapolation

29

Enlarge the data region sufficient for 2-dimensional FT:



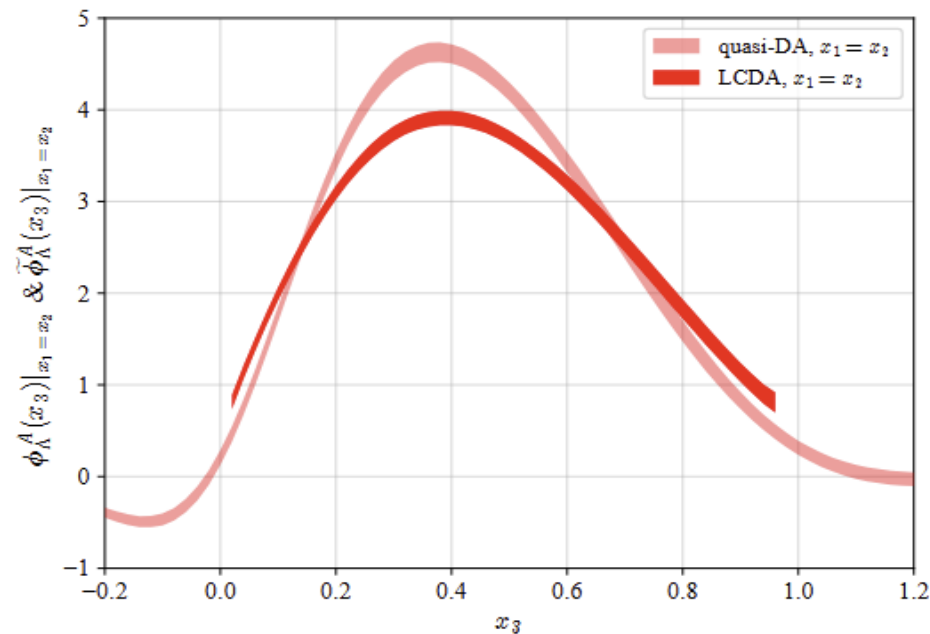
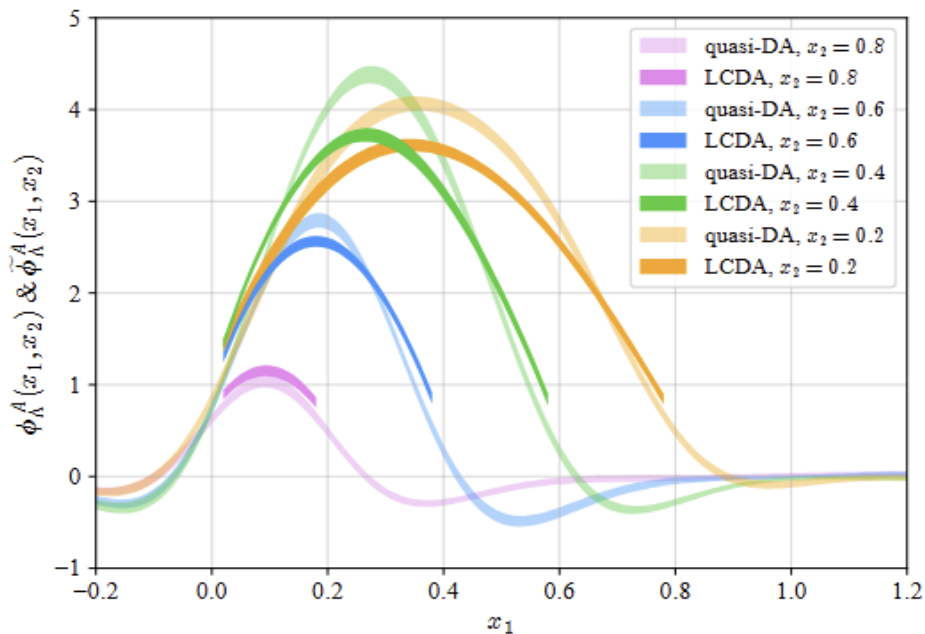
1.2 fm
× 1.2 fm



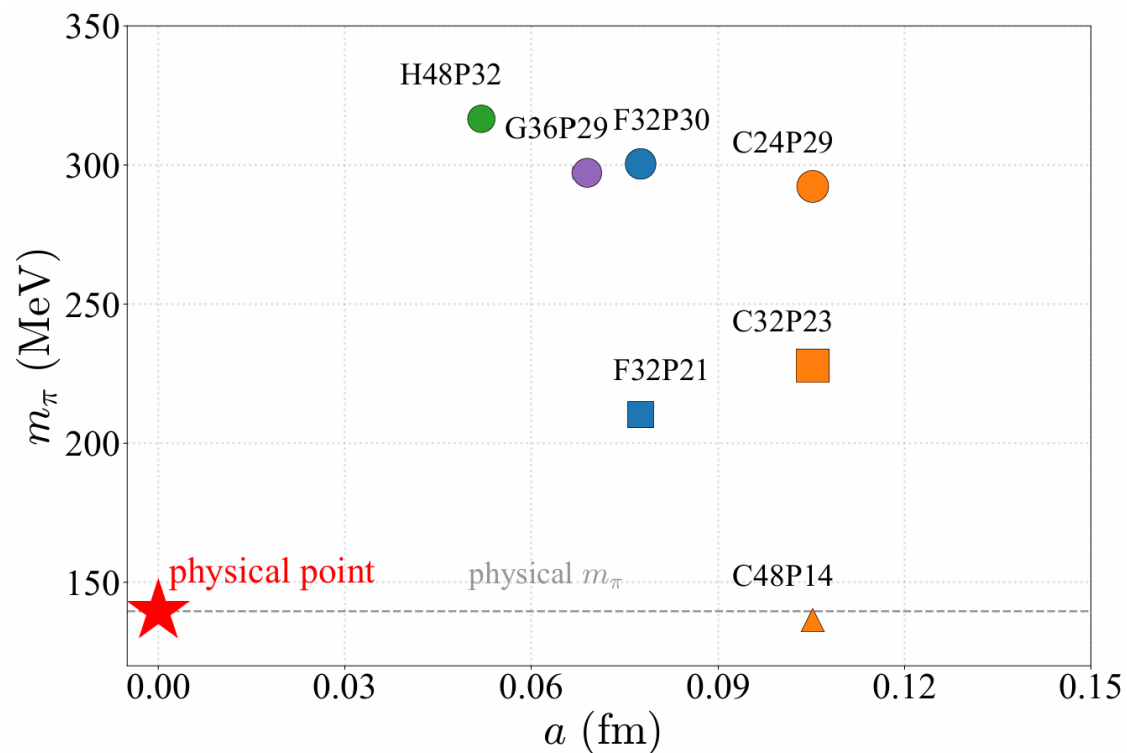
10 fm
× 10 fm

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

$$\mathcal{C}^{(1)}(x_1, x_2; y_1, y_2; P_B^z, \mu) = \left[\overline{\text{MS}} \text{ kernel } \mathcal{C}_{\text{MS}}^{(1)}(x_1, x_2; y_1, y_2; P_B^z, \mu) + \text{hybrid counter-term } \delta \mathcal{C}_H^{(1)}(x_1, x_2; y_1, y_2; P_B^z, \mu) \right]_{\oplus}.$$



- **3 a** : 0.052–0.105 fm;
- **4 m_π** : 136–317 MeV;
- **P^Z** : up to 3 GeV



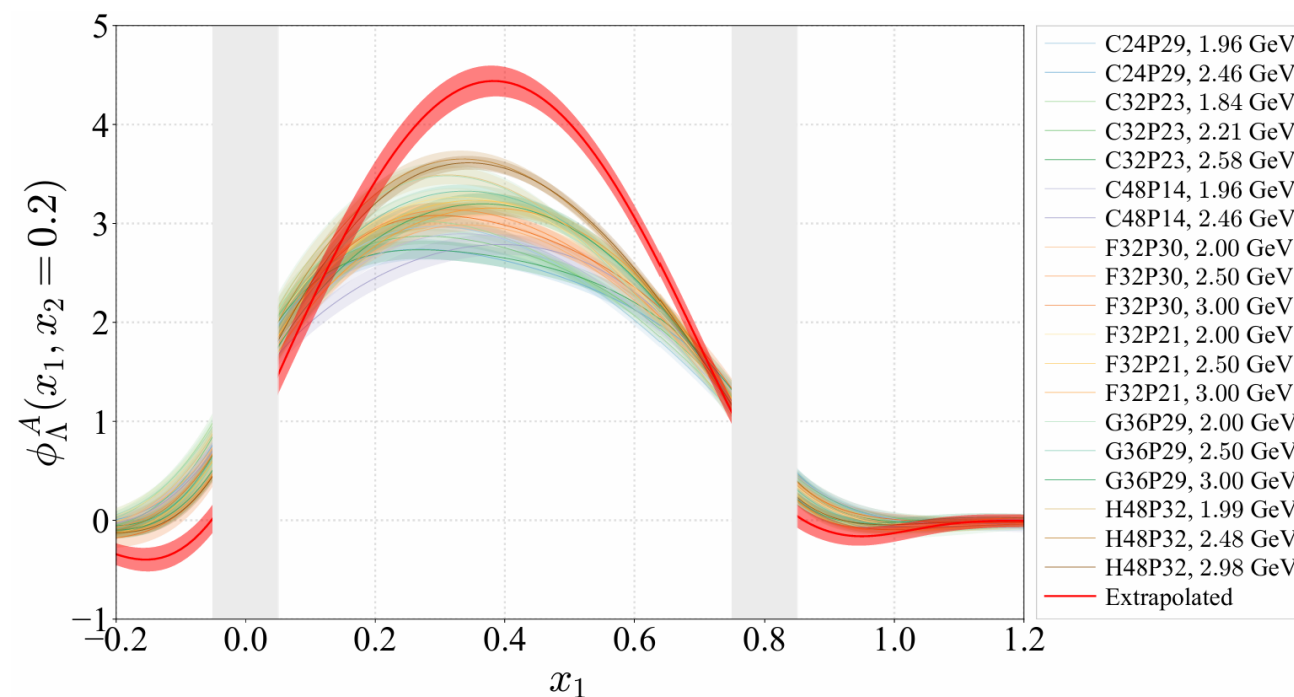
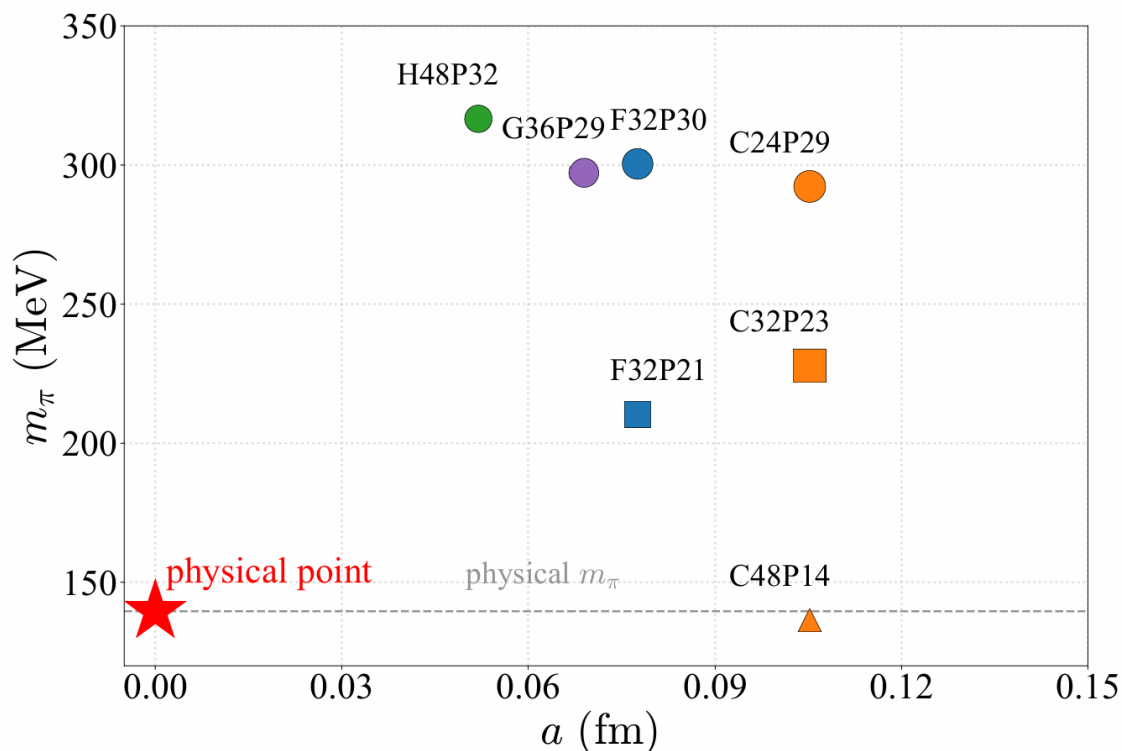
power corrections m_π -dependence

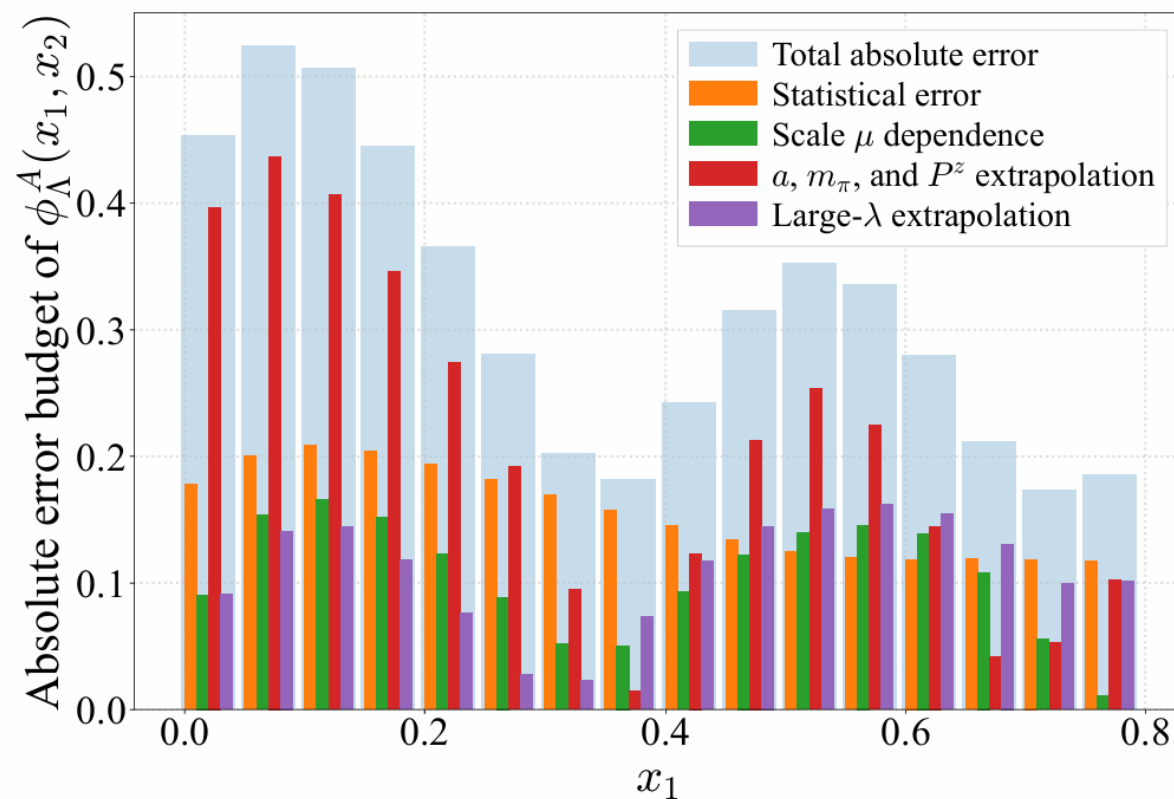
- **3 a** : 0.052–0.105 fm;
- **4 m_π** : 136–317 MeV;
- **P^z** : up to 3 GeV

$$\phi(x_1, x_2)|_{a, m_\pi, P^z} = \phi_{\text{phys}}(x_1, x_2) + \frac{A}{(P^z)^2} + (m_\pi^2 - m_{\pi, \text{phys}}^2) B$$

+ $a^2 [C_1 + C_2 (P^z)^2]$ discretization effects:

- P^z -independent, and
- P^z -dependent $a^2 (P^z)^2$





- **Scale variation**

$$\mu = \mu_R = \mu_F$$

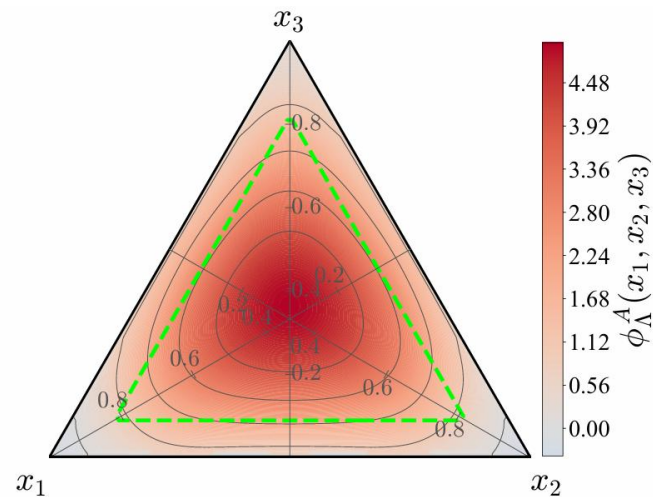
- **Large- λ extrapolation**

NLA / LA ansaetze

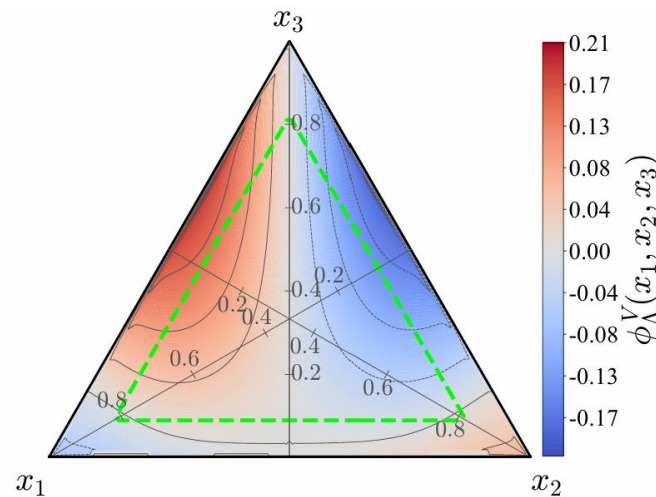
- **Physical-limit extrapolation**

Combine / Sequential strategies

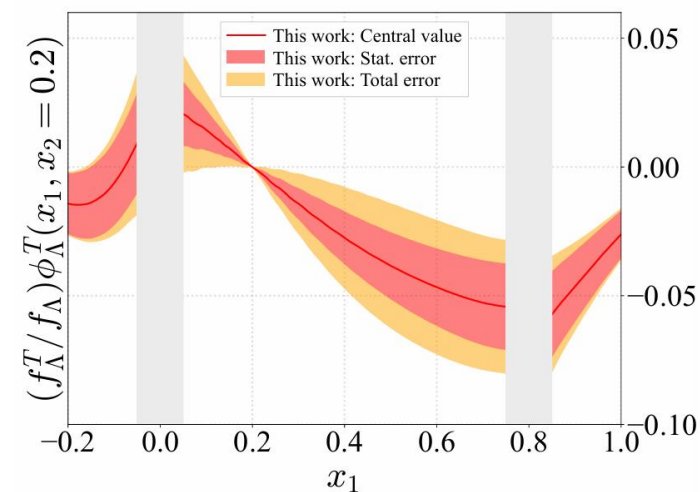
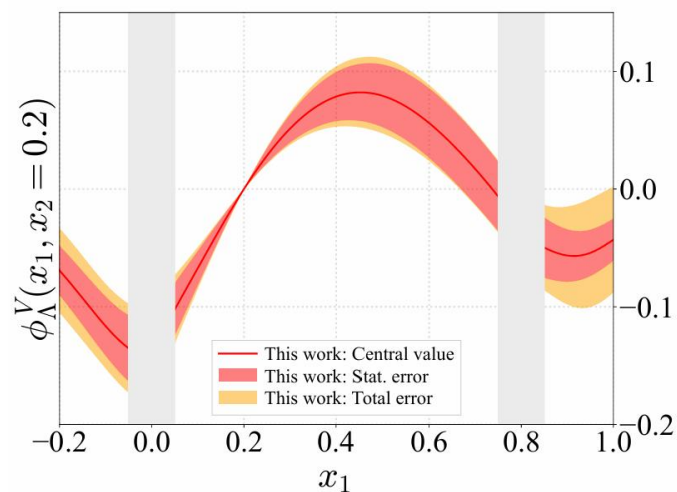
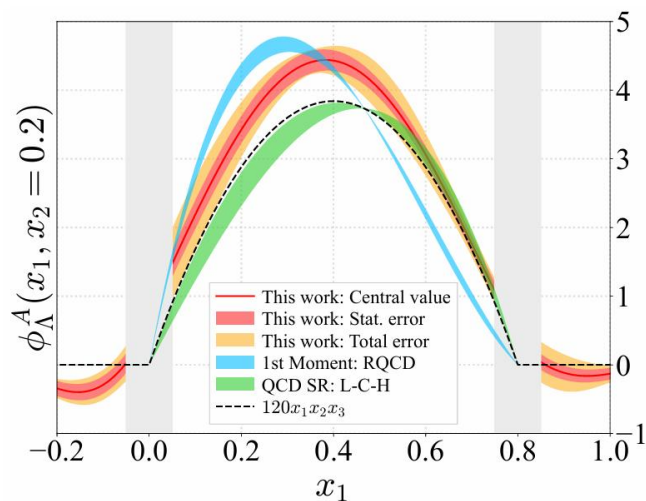
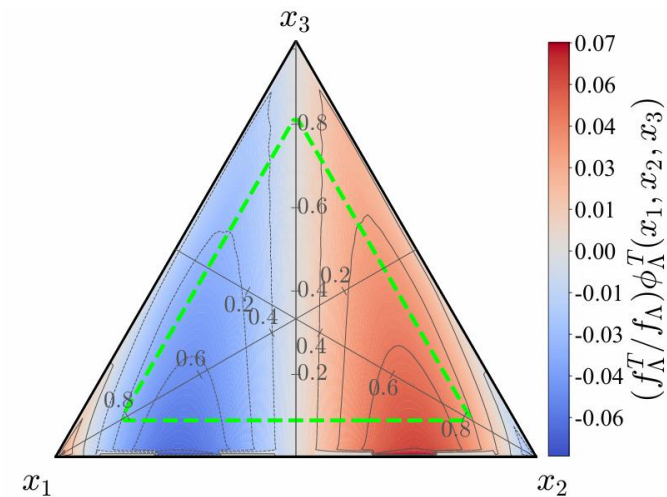
A · symmetric



V · antisymmetric



T · antisymmetric



First complete 2D lattice-QCD determination !

Parameterization form

$$F_{\Lambda}(x_{123}) = 120x_1x_2x_3 \left[\eta_{\Lambda,0} + \sum_{n=1}^3 \sum_{m=0}^n \eta_{\Lambda,nm} \mathcal{P}_{nm}(x_{123}) + \cdots \right] ,$$

$$\mathcal{P}_{00}(x_{123}) = 1 ,$$

$$\mathcal{P}_{10}(x_{123}) = 21x_1 - 21x_3 ,$$

$$\mathcal{P}_{11}(x_{123}) = 7x_1 - 14x_2 + 7x_3 ,$$

$$\mathcal{P}_{20}(x_{123}) = \frac{189x_1^2 - 189x_1x_2 - 378x_1x_3 + 126x_2^2 - 189x_2x_3 + 189x_3^2}{10} ,$$

$$\mathcal{P}_{21}(x_{123}) = \frac{63x_1^2 - 189x_1x_2 + 189x_2x_3 - 63x_3^2}{2} ,$$

$$\mathcal{P}_{22}(x_{123}) = \frac{9x_1^2 + 81x_1x_2 - 108x_1x_3 - 54x_2^2 + 81x_2x_3 + 9x_3^2}{5} ,$$

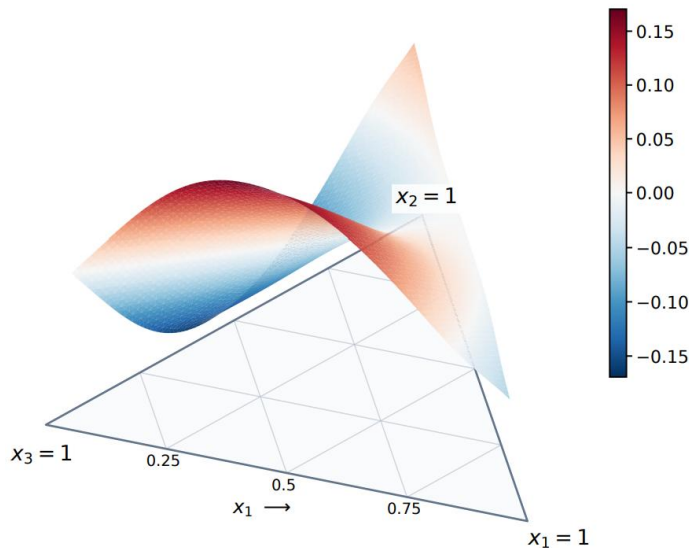
Parameterization form

$$F_{\Lambda}(x_{123}) = 120x_1x_2x_3 \left[\eta_{\Lambda,0} + \sum_{n=1}^3 \sum_{m=0}^n \eta_{\Lambda,nm} \mathcal{P}_{nm}(x_{123}) + \cdots \right],$$

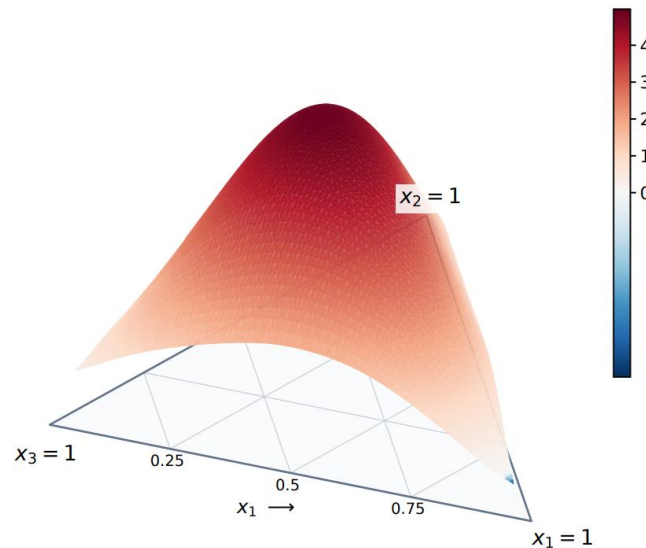
TABLE IV. Fit results for A_{Λ} and V_{Λ} parameters at varying truncation orders, with the fitted region $x_{1,2,3} \geq 0.1$.

Order	χ^2/dof	$\phi_{\Lambda,0}$	$\phi_{\Lambda,10}$	$\phi_{\Lambda,11}$	$\phi_{\Lambda,20}$	$\phi_{\Lambda,21}$	$\phi_{\Lambda,22}$	$\phi_{\Lambda,30}$	$\phi_{\Lambda,31}$	$\phi_{\Lambda,32}$	$\phi_{\Lambda,33}$
1	1.026	1.1242(19)	0.0366(11)	0.00493(36)	—	—	—	—	—	—	—
2	0.126	1.1161(26)	0.0343(12)	0.00543(40)	0.0012(14)	-0.0267(18)	-0.0087(14)	—	—	—	—
3*	0.047	1.1215(29)	0.0375(23)	0.00565(77)	-0.0005(16)	-0.0215(20)	-0.0055(16)	0.29(11)	0.007(12)	0.062(13)	0.171(17)

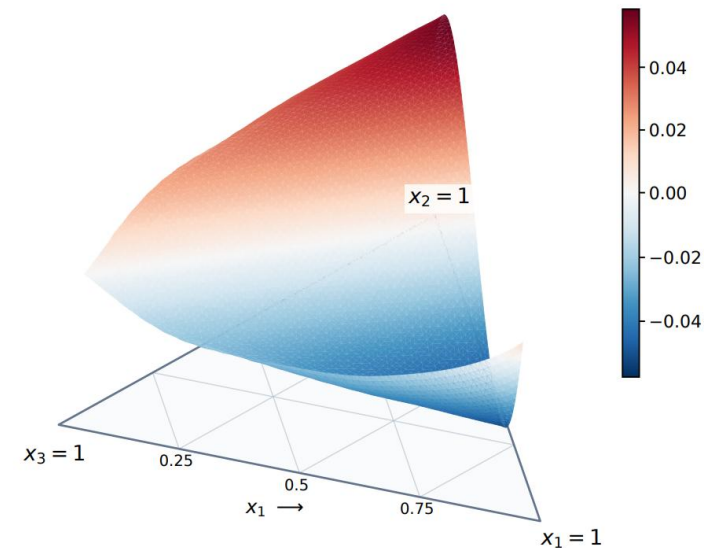
Λ LCDA: V



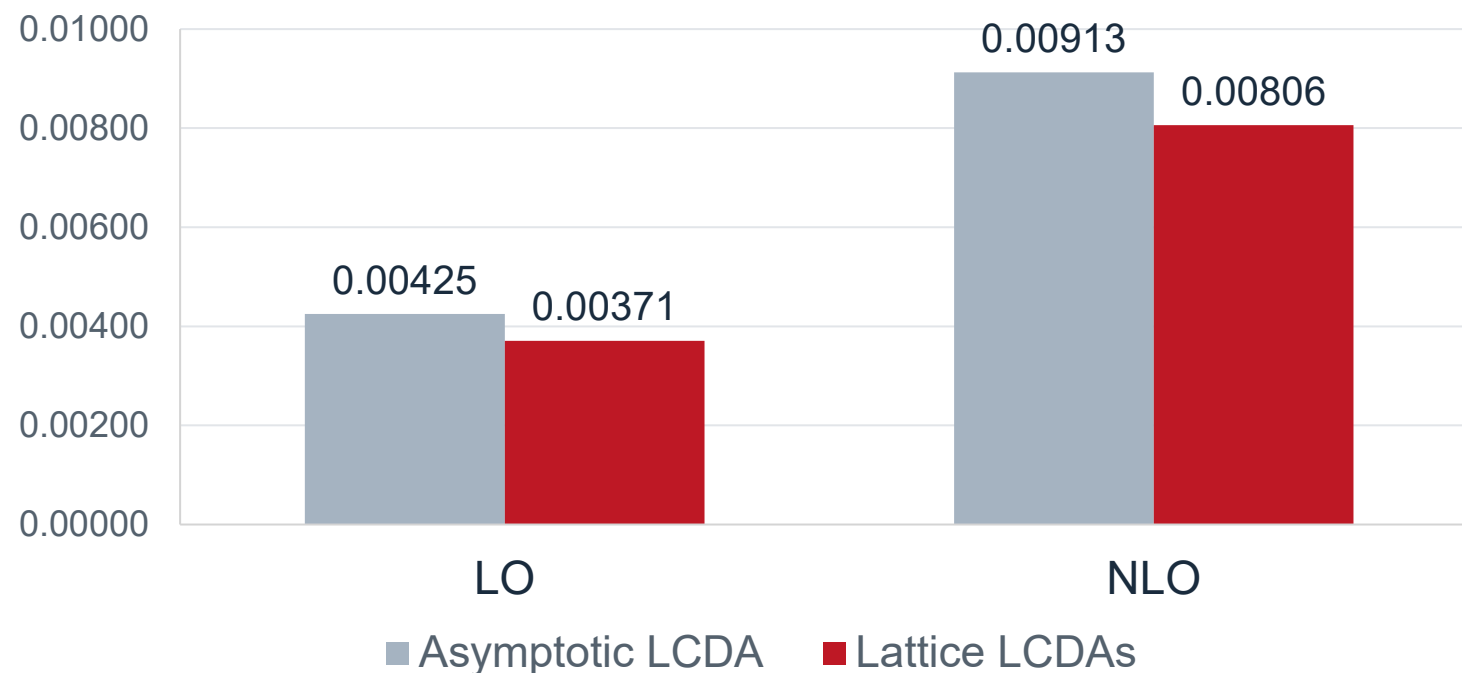
Λ LCDA: A



Λ LCDA: T



Λ Dirac form factor F_1 at $Q^2 = 20 \text{ GeV}^2$



-12.7%

LO relative shift

-11.7%

NLO relative shift

Thank Long-Bin Chen and Feng Feng for providing the code of NLO Λ electromagnetic form factor

■ [arXiv:2606.30387](#): Article to establish the **framework** for multi-dimensional distributions

- 2-dimensional prescriptions for baryonic operators;
- 7 ensembles** to physical-limit;
- Quantified analysis uncertainties;



■ [arXiv:2606.29597](#): Letter to report the first complete numerical results for Λ LCDAs

- Complete **3 leading-twist** Λ amplitudes A, V and T;
- Full **2-dimensional functions** of momentum fractions;
- Visible effect in high- Q^2 exclusive observable;



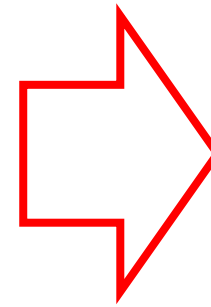
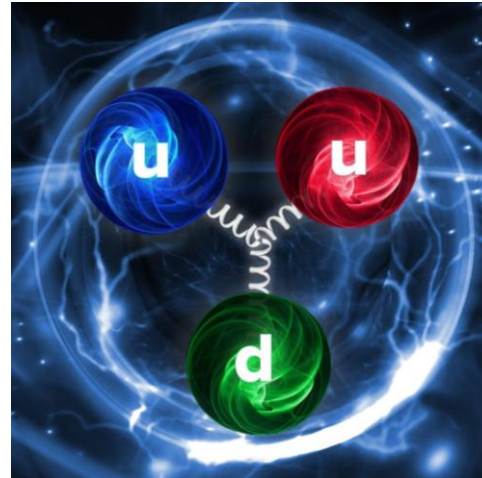
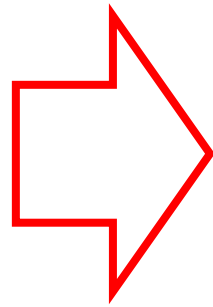
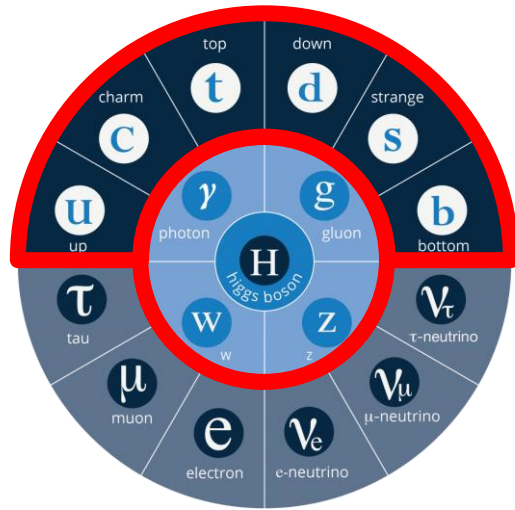
**Thanks for
your attention!**

Back Up

Why baryons ?

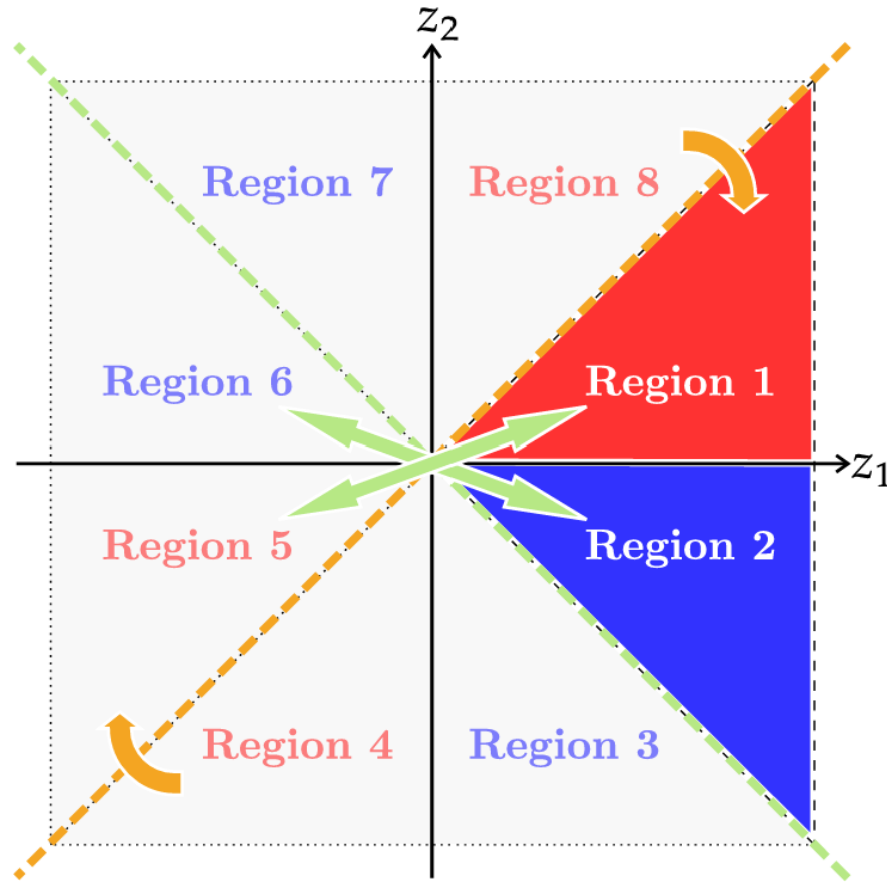
40

Baryon — cornerstone particles



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

Genuinely 2-dimensional distribution



- Exchange symmetry of $x_1 \leftrightarrow x_2$

for Lambda:

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

other octets:

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

- Hermiticity condition

$$\text{Re } \tilde{\phi}_B^X(x_1, x_2) = \tilde{\phi}_B^X(x_1, x_2) ,$$

$$\text{Im } \tilde{\phi}_B^X(x_1, x_2) = 0 ,$$

$$\Rightarrow \tilde{\Phi}_B^X(-z_1, -z_2) = \left[\tilde{\Phi}_B^X(z_1, z_2) \right]^* ,$$

Research history: (1983 - now)

- **Asymptotic form**

Chernyak, Zhitnitsky, 1983;

- **QCD Sum Rules**

King, Sachrajda, 1987;

Stefanis, Bergmann, 1993;

Braun, et al, 2000, 2006;

- **Models parametrization**

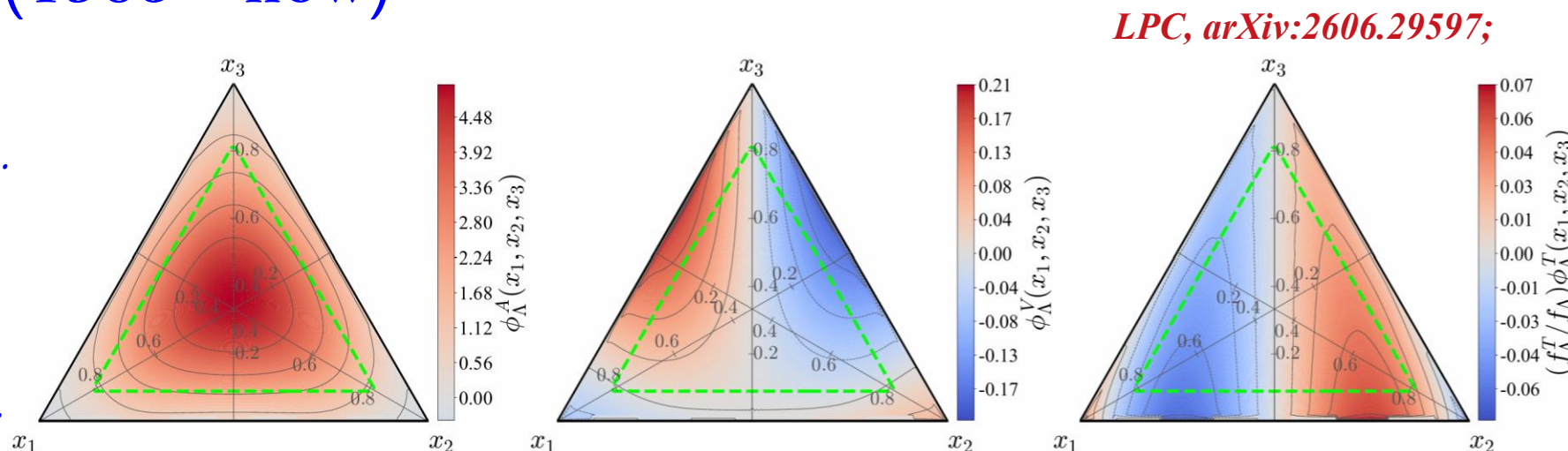
Bell, et al, 2013;

- **Moments from Lattice QCD**

QCDSF, 2008, 2009;

RQCD, 2016, 2019, 2025;

only lowest moments



- **x -dependent LCDAs from Lattice QCD**

LPC, PRD 111, 034510 (2025);

LPC, PRD 112, 114515 (2025);

LPC, arXiv:2606.30387;

Baryon Light-Cone Distribution Amplitudes from Lattice QCD: Formalism, Renormalization, Extrapolation, and Matching

LPC, arXiv:2606.29597;

Complete Access to Leading-Twist Λ -Baryon Light-Cone Distribution Amplitudes from Lattice QCD

Full shape, all structures!

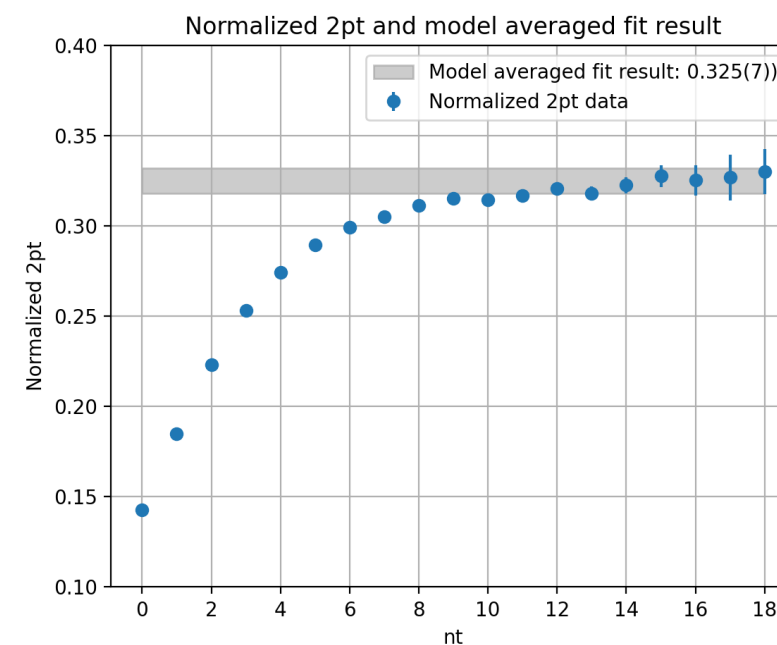
Nonlocal 2-point function related to baryon quasi-DAs:

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

- Extract ground-state quasi-DA from 2-state fit

$$\frac{C_{2\text{pt}}(\tau, P^z; z_1, z_2)}{C_{2\text{pt}}(\tau, P^z; 0, 0)} = \underbrace{\widehat{M}(z_1, z_2; P^z)}_{\text{ground-state matrix element}} \left[1 + \underbrace{\Delta C_1(z_1, z_2; P^z) e^{-\Delta E_1(z_1, z_2; P^z)\tau}}_{\text{excited-states contribution}} \right]$$

LPC, PRD 112, 114515 (2025);



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

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

- **Interpolators and projection operators**

- Sink-side Interpolators

$$\mathcal{O}^{\text{snk}, A}(z_1, z_2) = q^T(z_1) (C\gamma^5\gamma^t) g(z_2) h(x) ,$$

$$\mathcal{O}^{\text{snk}, V}(z_1, z_2) = q^T(z_1) (C\gamma^t) g(z_2) \gamma^5 h(x) ,$$

$$\mathcal{O}^{\text{snk}, T}(z_1, z_2) = q^T(z_1) (\tfrac{1}{2} C[\gamma^t, \gamma^{x,y}]) g(z_2) \gamma^5 \gamma_{x,y} h(x) .$$

- Projector

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

?

- Source-side Interpolators

$$\mathcal{O}_{\Lambda}^{\text{src}} = \frac{2u^T(C\gamma^5)ds + u^T(C\gamma^5)sd + s^T(C\gamma^5)du}{\sqrt{6}} ,$$

$$\mathcal{O}_{\text{p}}^{\text{src}} = u^T(C\gamma^5)du .$$

?

Improvement from interpolator: Kinematically-enhancement

□ Traditional interpolator: $N_{\gamma_5} = \epsilon^{ijk} (f_i^T C \gamma_5 g_j) h_k$

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

for static baryon states

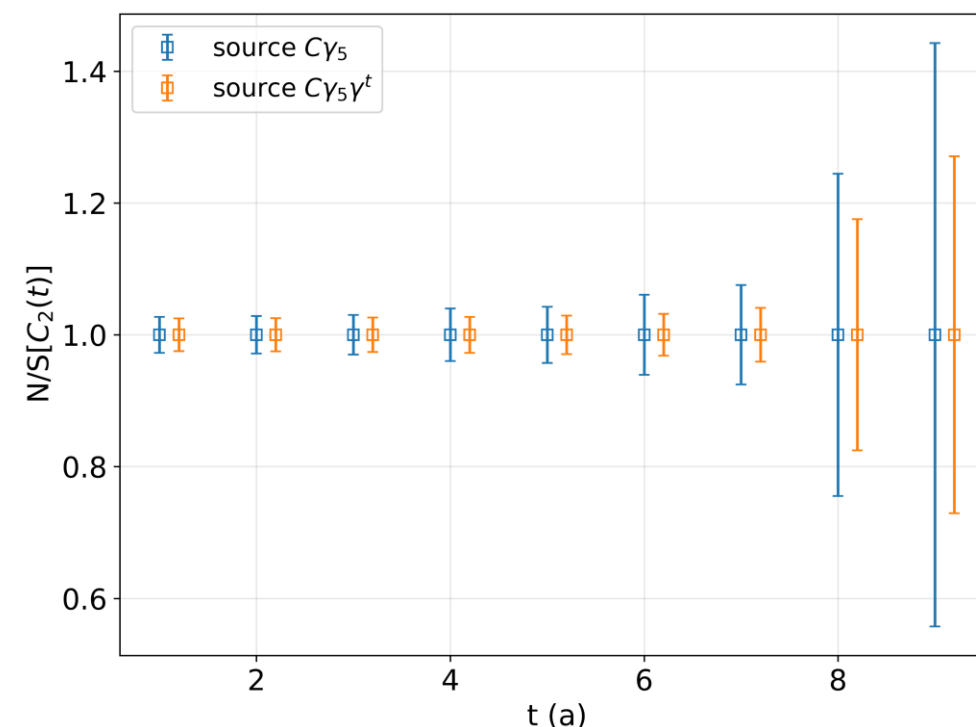
□ Enhanced interpolator: $N_{\gamma_5 \gamma_\mu} = \epsilon^{ijk} (f_i^T C \gamma_5 \gamma_\mu g_j) h_k$

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

better overlap with boosted states

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

LPC, PRD 112, 114515 (2025);



Improvement from projector

□ Traditional parity projector

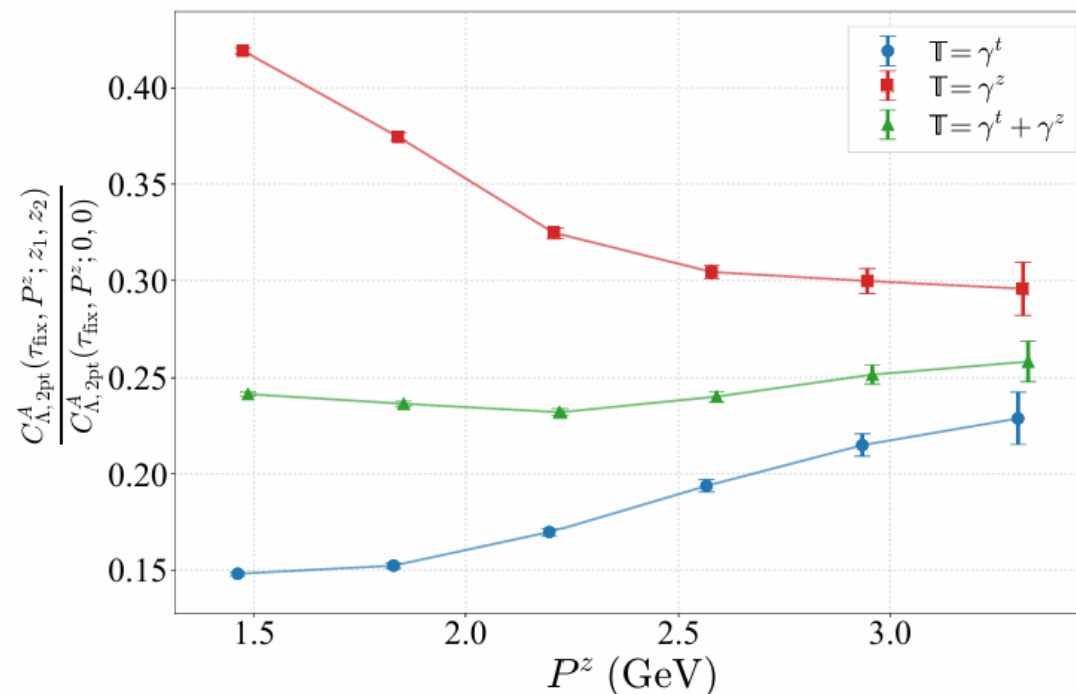
$$\mathbb{T}_{\text{parity}} = \frac{1 + \gamma^t}{2}$$

Parity is *not* a good quantum number when boosted !

□ consider spinor structure $\text{tr} [u_B(n \cdot P) \not{n} u_B(n \cdot P)]$

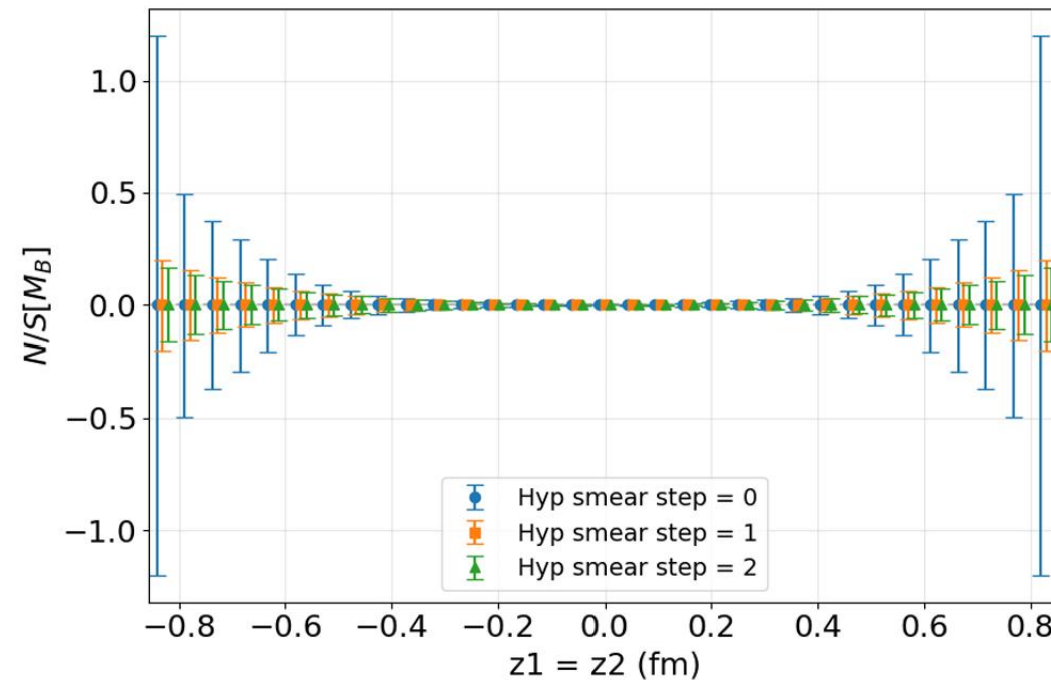
$$\mathbb{T} = \not{n} = \gamma^t + \gamma^z$$

- for leading-twist contribution;
- suppress sub-leading powers



Other improvement strategies

- for gauge link: **HYP smearing**

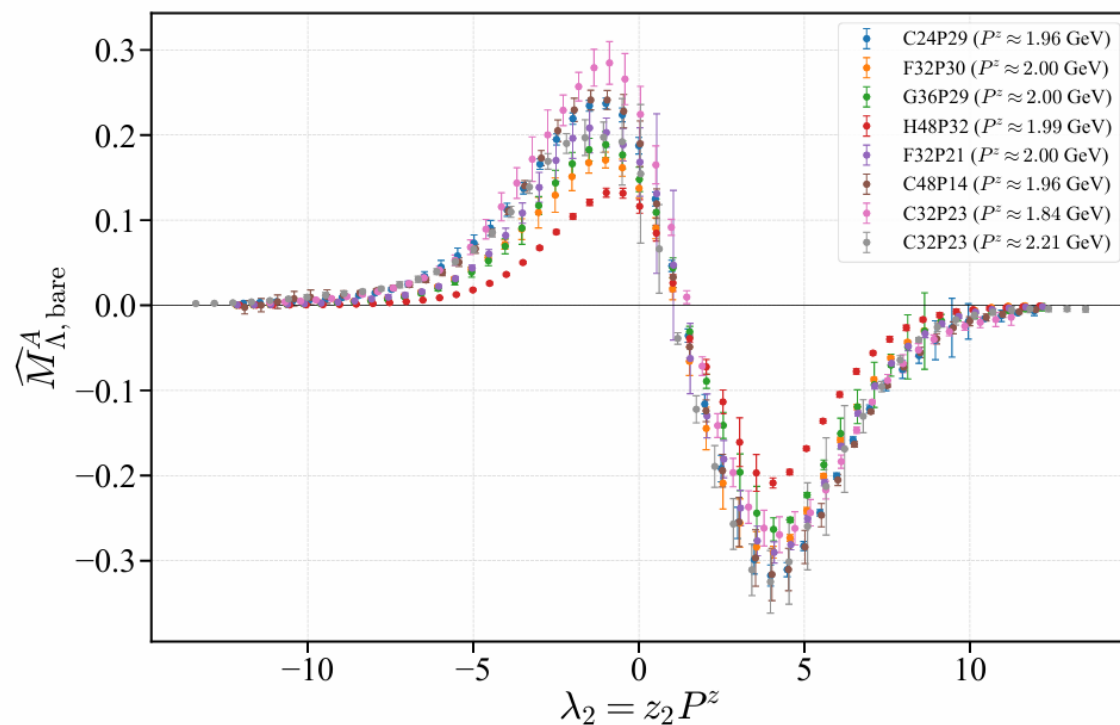


- for propagator: **momentum smearing**

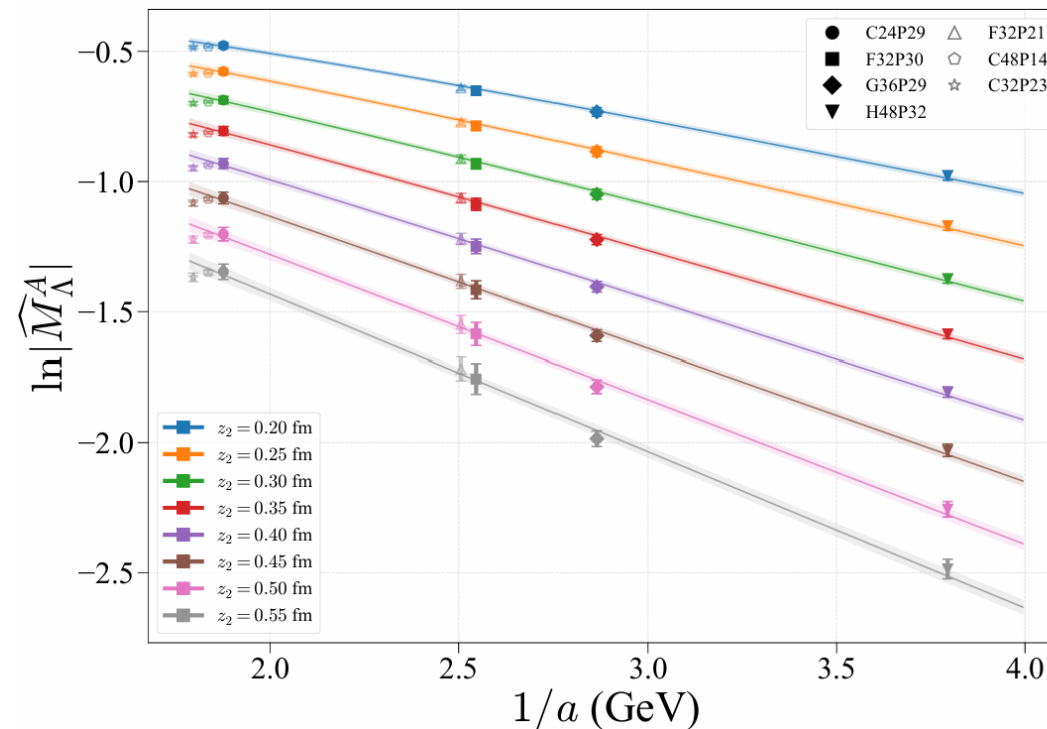
Linear divergences in Bare quasi-DAs

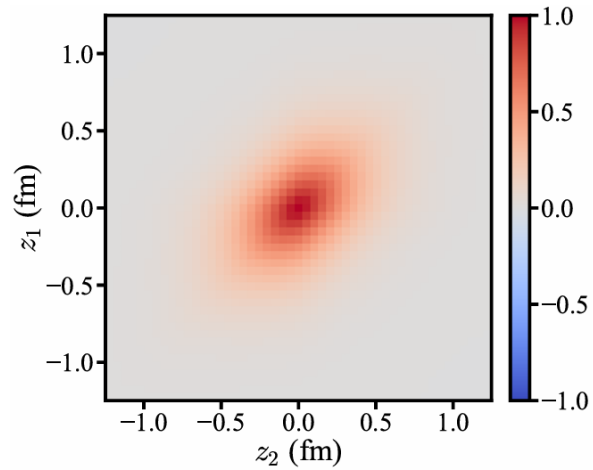
$$M(z_1, z_2; P^z, a) \propto \exp \left[\left(\frac{k}{a \ln(a \Lambda_{\text{QCD}})} + m_0 \right) \tilde{z} \right] m(z_1, z_2, P^z)$$

bare matrix elements



$\log M$ v.s. $1/a$



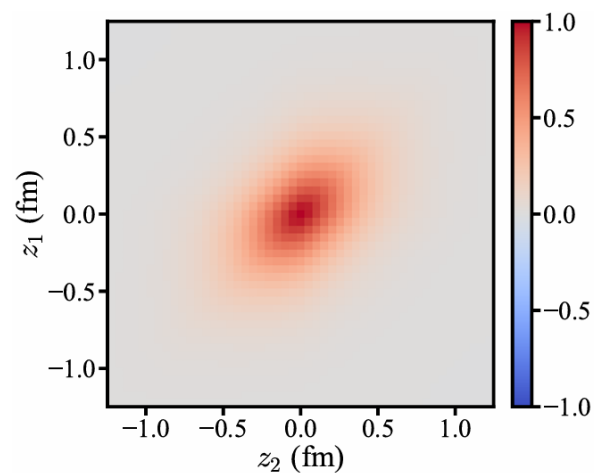


(a) Λ -baryon A

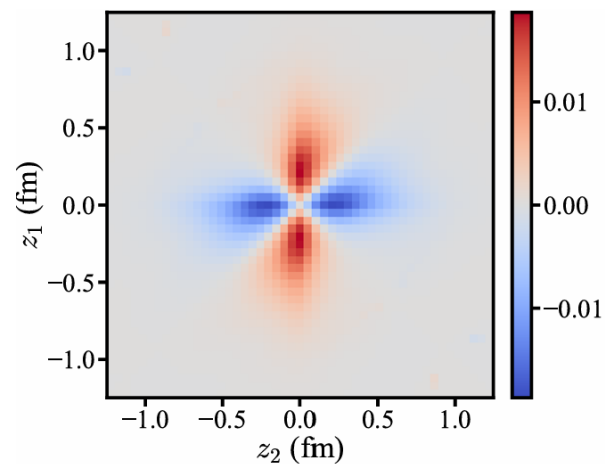
*LPC, PRD 112, 114515 (2025)
for symmetric amplitude*

Hybrid Renormalization

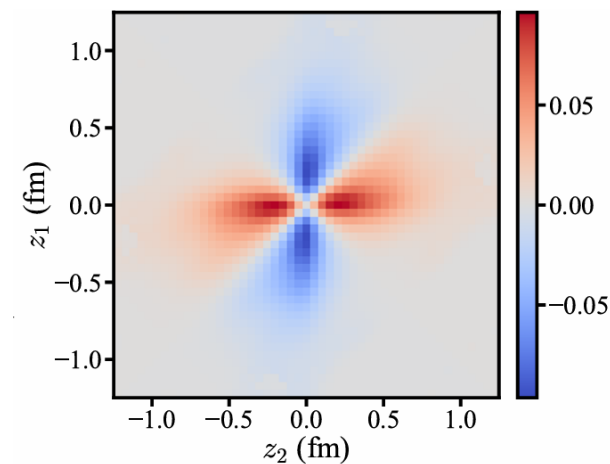
50



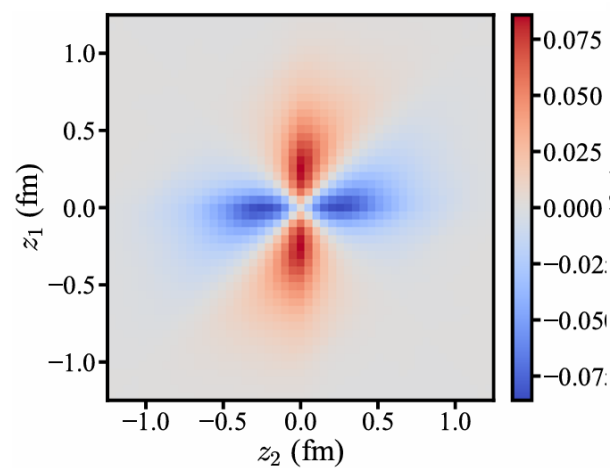
(a) Λ -baryon A



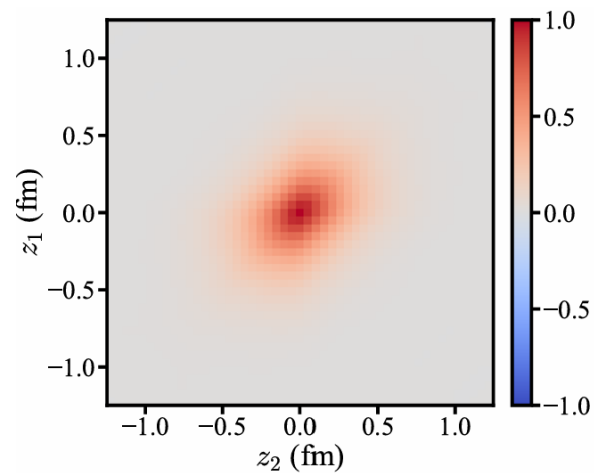
(b) Λ -baryon V



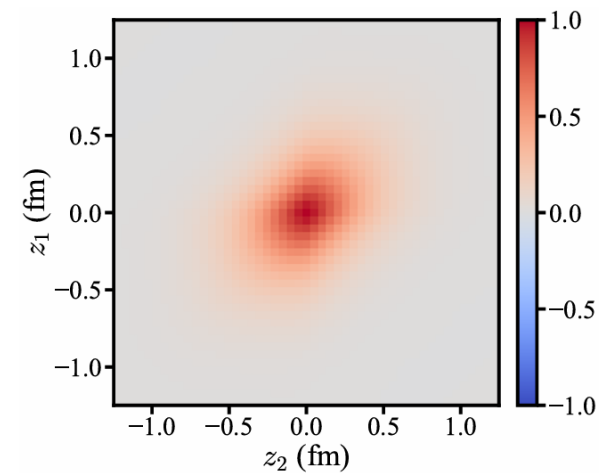
(c) Λ -baryon T



(d) proton A



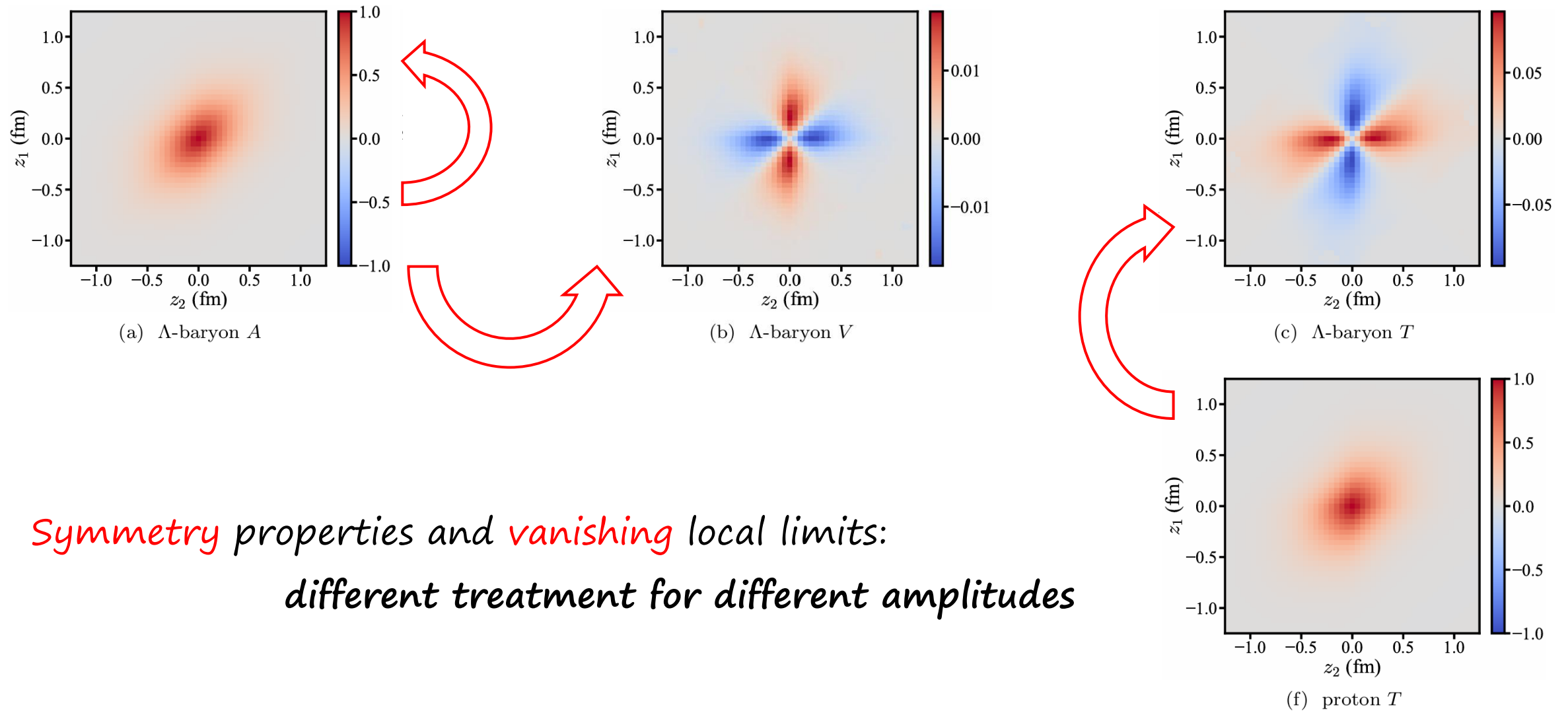
(e) proton V

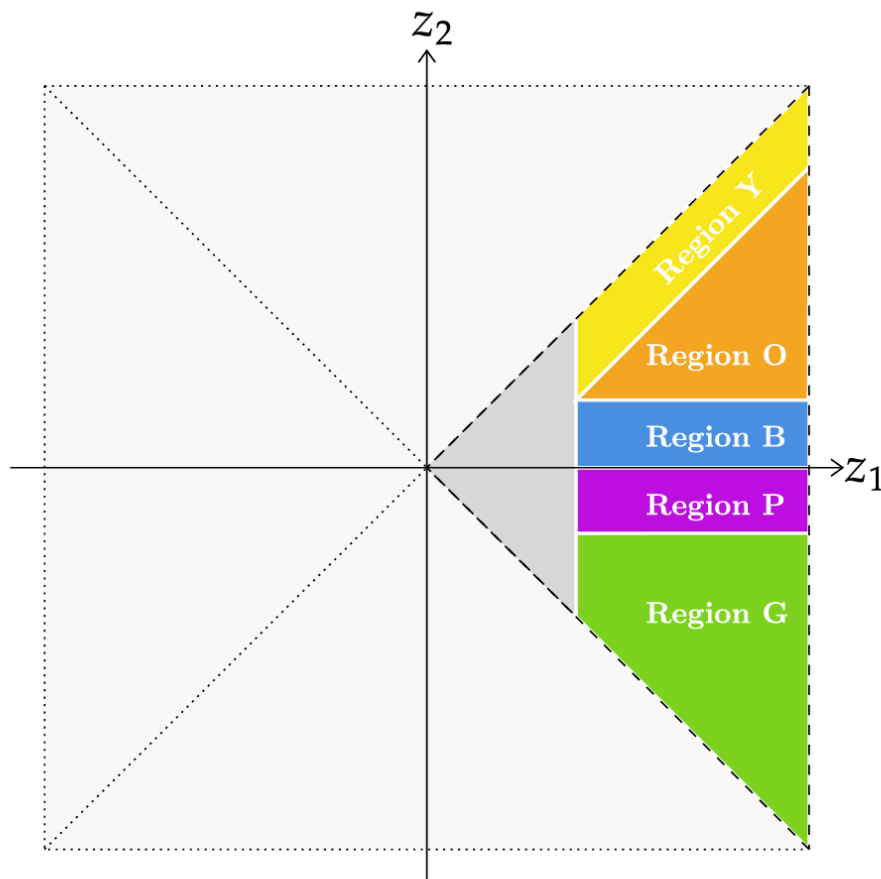


(f) proton T

Hybrid Renormalization

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- for Lambda A:

symmetric amplitude with good signal quality

$$\tilde{A}^{\text{NLA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_1|} e^{-\Lambda_0 - |z_2|} \left[G_A(i\hat{z}_1, i\hat{z}_2, P^z) + G'_A(i\hat{z}_1, i\hat{z}_2, P^z) \frac{1}{|z|} \right] ;$$

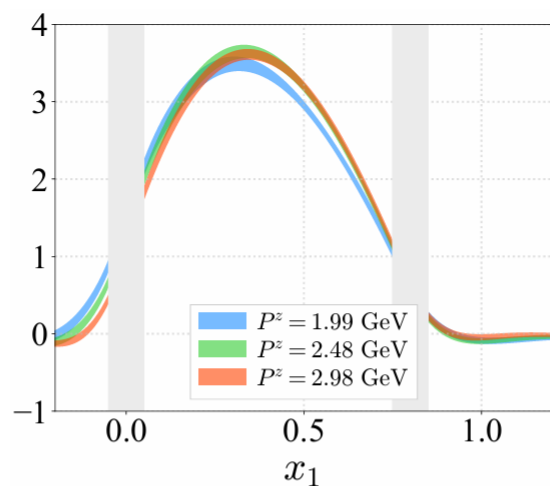
NLA ansaetze

- for Lambda V / T:

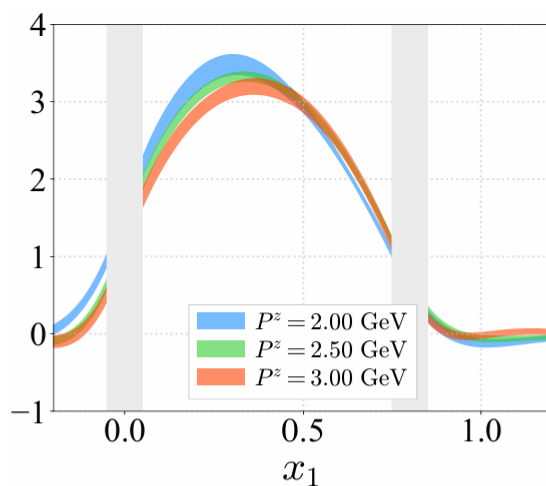
antisymmetric amplitudes with poor signal qualities

$$\tilde{V}^{\text{LA}} / \tilde{T}^{\text{LA}}(z_1, z_2, P^z) = e^{-\Lambda_0 - |z_1|} e^{-\Lambda_0 + |z_2|} G_{V/T}(i\hat{z}_1, i\hat{z}_2, P^z)$$

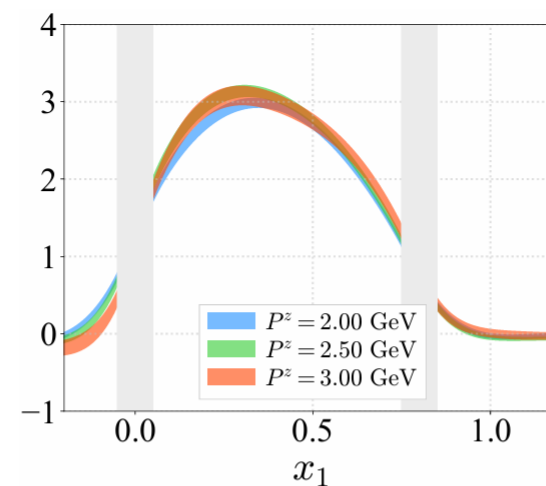
LA ansaetze



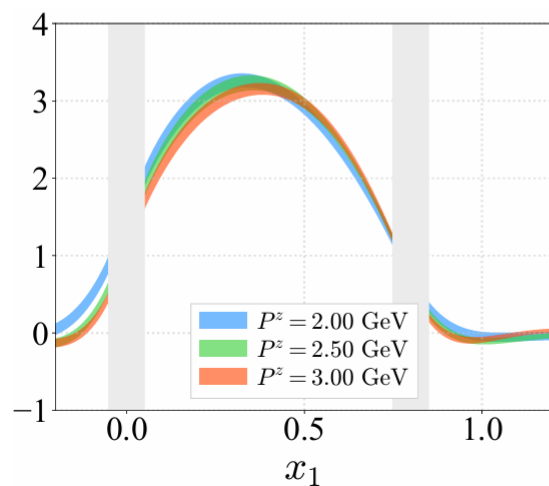
(a) H48P32



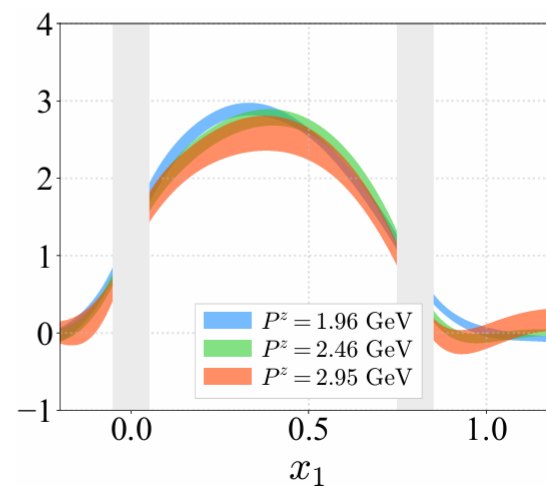
(b) G36P29



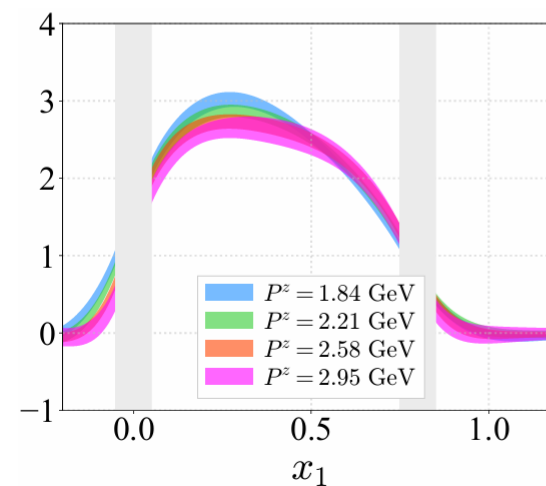
(c) F32P30



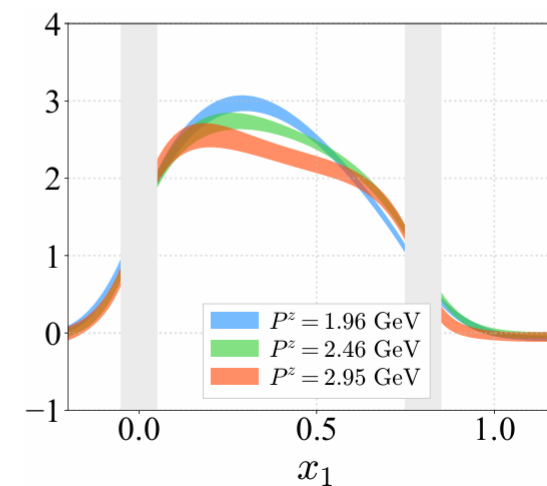
(d) F32P21



(e) C48P14



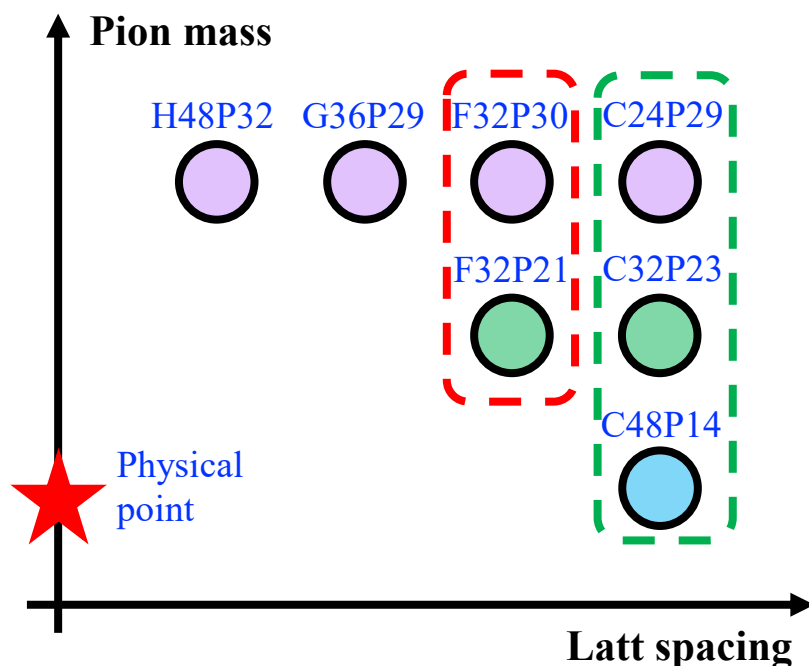
(f) C32P23



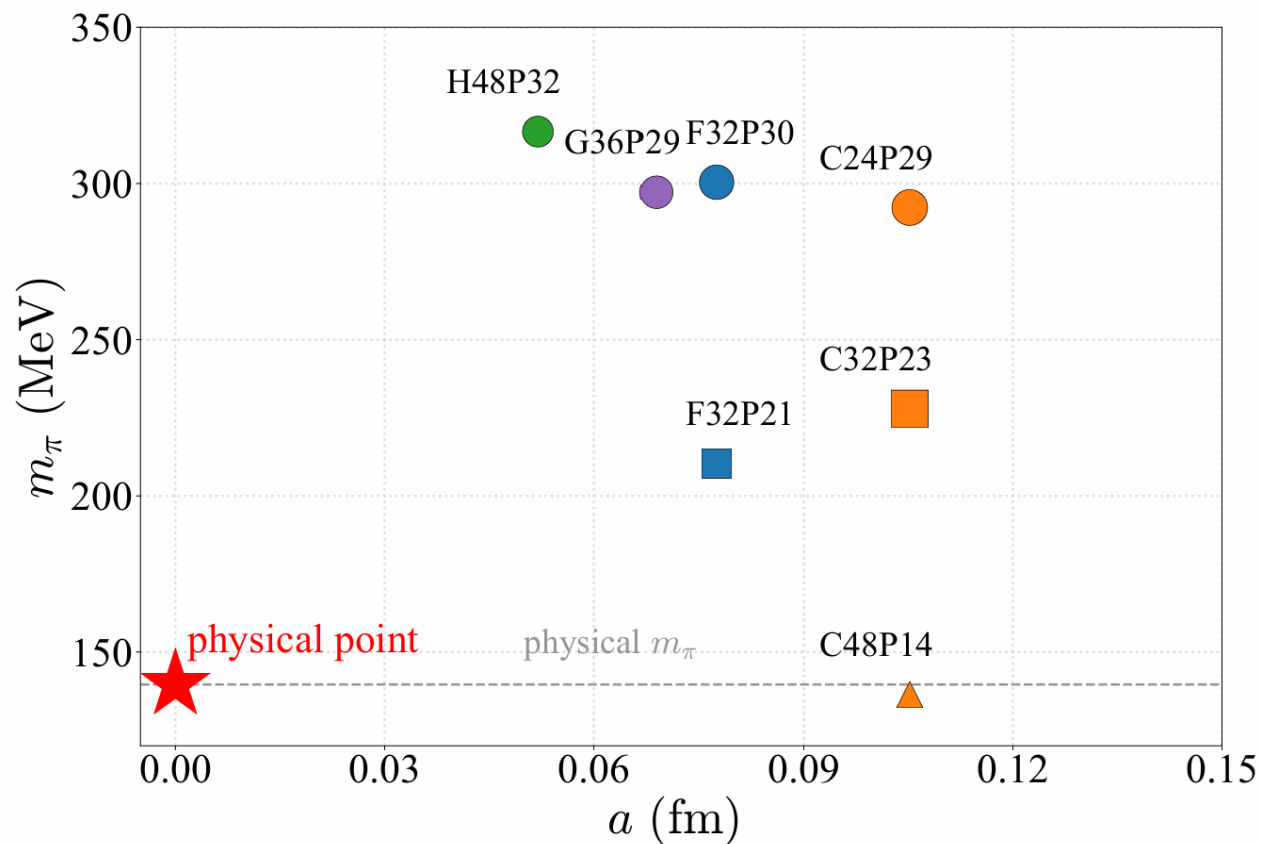
(g) C24P29

CLQCD Ensembles

- 4 lattice spacings for *continuum* limit
- 3 pion masses for *physical mass* limit
- multi momenta for $P_z \rightarrow \infty$ limit



Ensemble	Lattice spacing	π mass	measurements	P_z / GeV
C24P29	0.105 fm	292 MeV	864 *4 src *9 nt	0, 1.96, 2.45, 2.94
C32P23	0.105 fm	228 MeV	954 *4 src *8 nt	0, 1.84, 2.21, 2.57, 2.94
C48P14	0.105 fm	136 MeV	302 *4 src *16 nt	0, 1.96, 2.45, 2.94
F32P30	0.078 fm	300 MeV	777 *4 src *8 nt	0, 2.00, 2.49, 2.99
F32P21	0.078 fm	210 MeV	459 *4 src *16 nt	0, 2.00, 2.49, 2.99
G36P29	0.069 fm	297 MeV	656 *6 src *8 nt	0, 2.00, 2.50, 3.00
H48P32	0.052 fm	317 MeV	550 *6 src *9 nt	0, 1.98, 2.48, 2.98



$$\phi(x_1, x_2)|_{a, m_\pi, P^z} = \phi_{\text{phys}}(x_1, x_2)$$

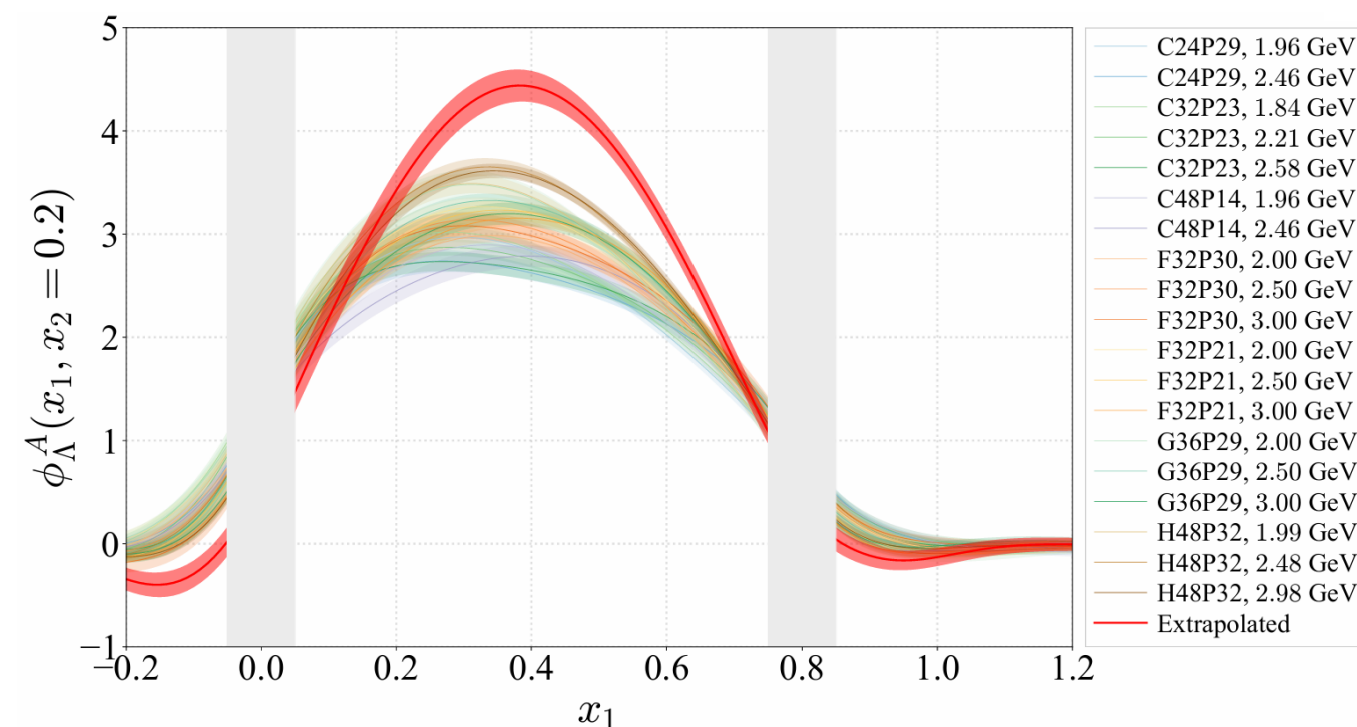
$$+ \frac{A(x_1, x_2)}{(P^z)^2} \quad \text{LaMET power corrections}$$

$$+ (m_\pi^2 - m_{\pi, \text{phys}}^2) B(x_1, x_2) \quad m_\pi\text{-dependence}$$

$$+ a^2 [C_1(x_1, x_2) + C_2(x_1, x_2)(P^z)^2] ,$$

discretization effects, including:

- P^z -independent artifacts, and
- P^z -dependent artifacts $a^2(P^z)^2$



$$\phi(x_1, x_2)|_{a, m_\pi, P^z} = \phi_{\text{phys}}(x_1, x_2)$$

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