2026.07.28 *The 1st Conference on Strong-Interaction Spin Physics*

Intrinsic quark spin in octet baryons from 2+1 flavour LQCD at the physical point

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Context

- ◆ Chapter 1: Background
- ◆ Chapter 2: Excited-State Contaminations on LQCD
- ◆ Chapter 3: Numerical result
- ◆ Chapter 4: Summary

Context

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1. Background: The Origin of Proton Spin

Quark model

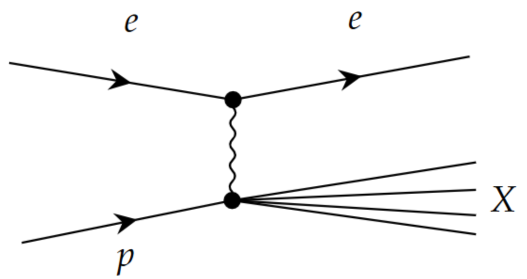
1980s

- Proton spin comes from sum of quarks.

$$S_p = \sum_q S_q = \frac{1}{2}\Sigma.$$

Proton spin crisis

$$\mathrm{DIS}: e + p \to e + X$$



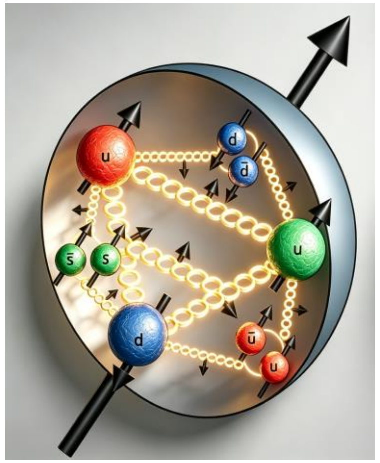
- 1989: $\frac{1}{2}\Sigma = 12(17)\% S_p$

EMC, PLB ***206****,364(1988)*

- Now: $\frac{1}{2}\Sigma \sim 30\% S_p$

Rept.Prog.Phys. ***82*** *(2019) 076201*

Spin Sum rules



- **Jaffe-Manohar:**

$$\frac{\hbar}{2} = \frac{1}{2}\Sigma + \Delta G + \ell_q + \ell_g$$

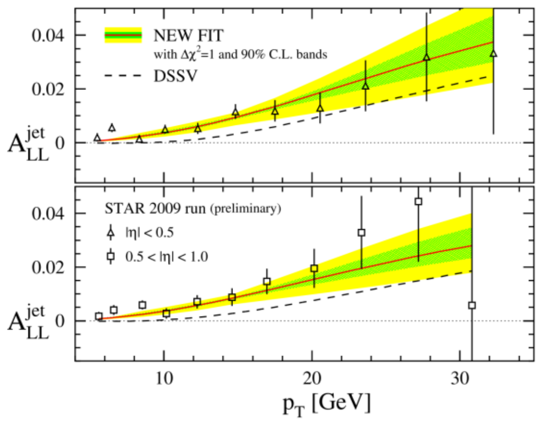
R.L. Jaffe et.al, NPB ***337*** *(1990) 509-546*

- **Ji's sum rule:**

$$\frac{\hbar}{2} = \frac{1}{2}\Sigma + L_q + J_g$$

X.D. Ji, PRL ***78****, 610(1997)*

Constrain Gluon Spin



$$p + p \to \mathrm{jet} + X$$

$$\int_{0.05}^{1} \mathrm{d}x \Delta g(x) = 0.20(7)$$

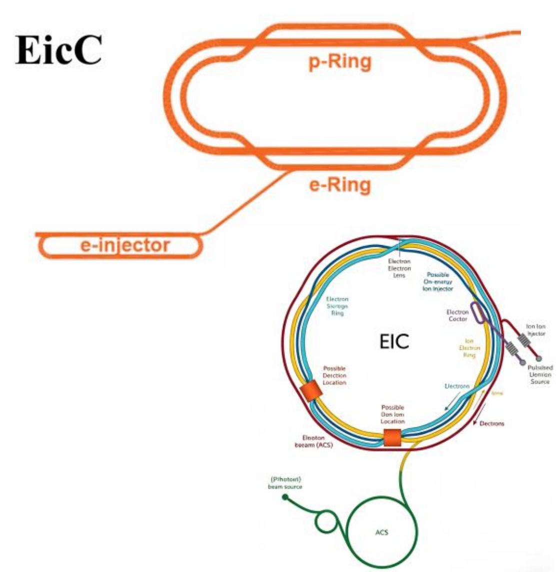
D.D. Florian,et.al, PRL ***113****, 012001 (2014)*

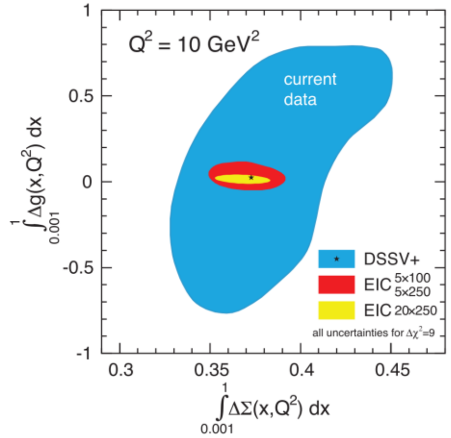
STAR*, PRL* ***115****, 092002 (2015)*

1. Background: The Origin of Proton Spin

- **EIC physics in the future:** precision on the total quark/gluon helicity contributions to the **proton spin**

$$\mathrm{DIS}: \vec{e} + \vec{p} \to \vec{e} + X$$





*NPA **1026** (2022) 122447*
Front. Phys. 16, 64701 (2021)

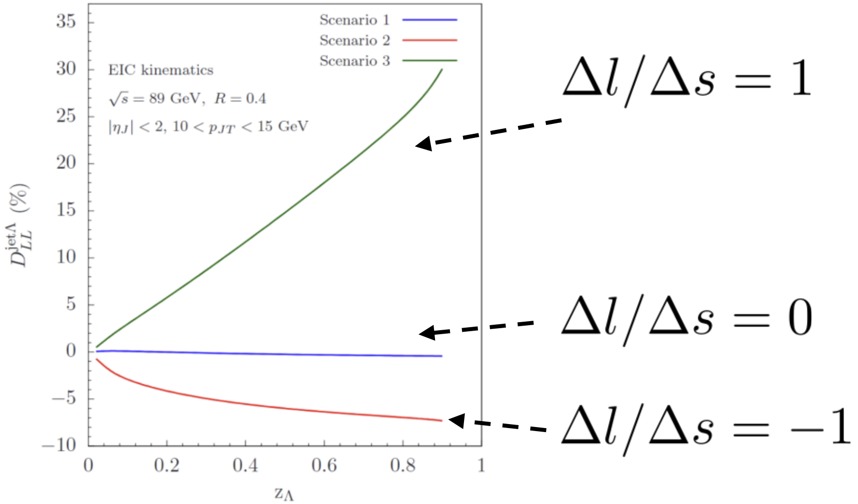
Higher precision for proton

- **Λ spin in EIC:**

$$\vec{p} + \vec{e} \to \mathrm{jet}(\Lambda) + X$$

Λ polarization asymmetry:

$$D_{LL}^{\mathrm{jet}\Lambda} = \frac{d\Delta\sigma^{\vec{p}p\to(\mathrm{jet}\vec{\Lambda}X)}}{dp_{JT}d\eta_J dZ_\Lambda} \Big/ \frac{d\sigma^{pp\to(\mathrm{jet}\Lambda X)}}{dp_{JT}d\eta_J dZ_\Lambda}.$$



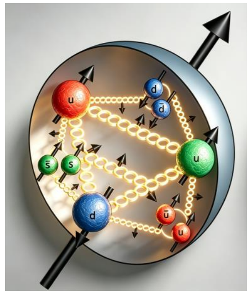
*Z. B. Kang, PLB **809**, 135756(2020)*

More baryons under study

1. Background: The Origin of Proton Spin

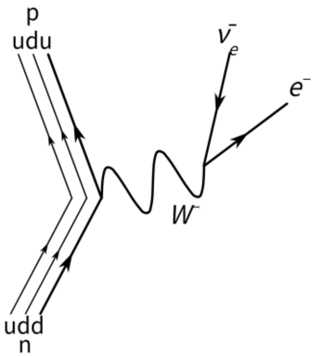
➢ Hadron matrix elements contain rich information about the hadronic structure;

- **Proton spin puzzle**

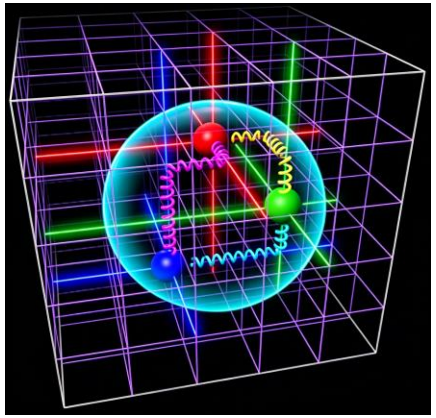


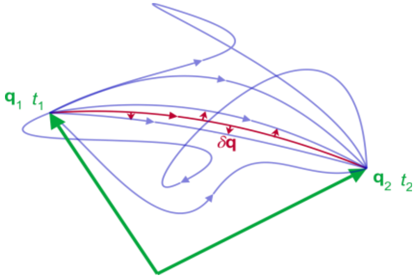
EMC, PLB 206,364(1988)
X.D. Ji, PRL 78, 610(1997)

- **Neutron beta decay**



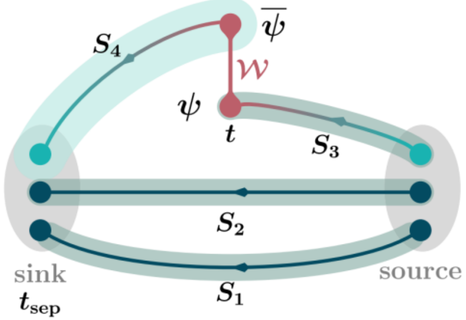
B. Markisch; et.al; PRL. 122, 242501 (2019)
CalLAT, Nature 558, 91(2018);





Lattice QCD

- **Parton Structure (PDFs)**



X.D. Ji, PRL 110, 262002(2013)
LPC, PRL 131.261901(2023)

✓ **Lattice QCD** provides **a first-principle, non-perturbative** description of the strong interaction.

K. G. Wilson, PRD. 10, 8 (1974);

Context

◆ Chapter 1: Background

◆ **Chapter 2: Excited-State Contaminations on LQCD**

◆ Chapter 3: Numerical result

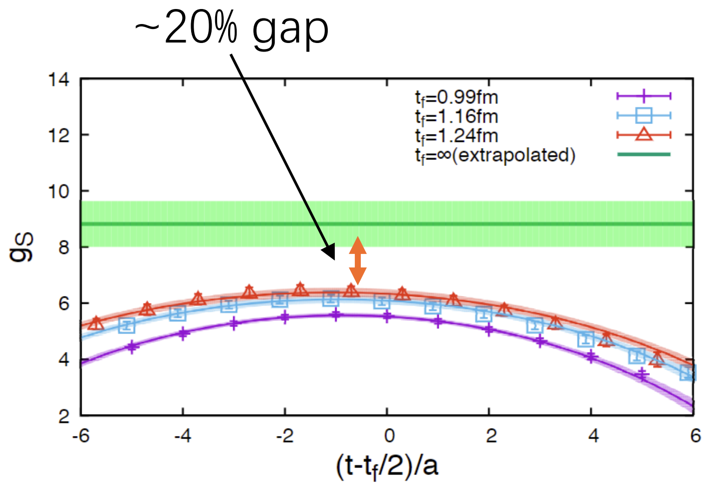
◆ Chapter 4: Summary

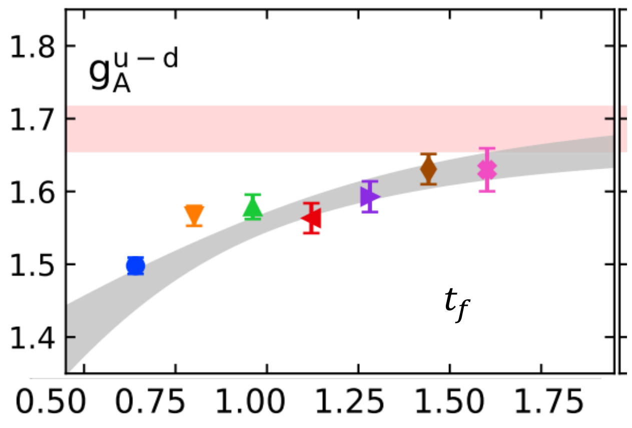
2. Excited-State Contaminations in LQCD

1. **Imaginary-time evolution** presents a serious challenge to the **signal-to-noise ratio**;

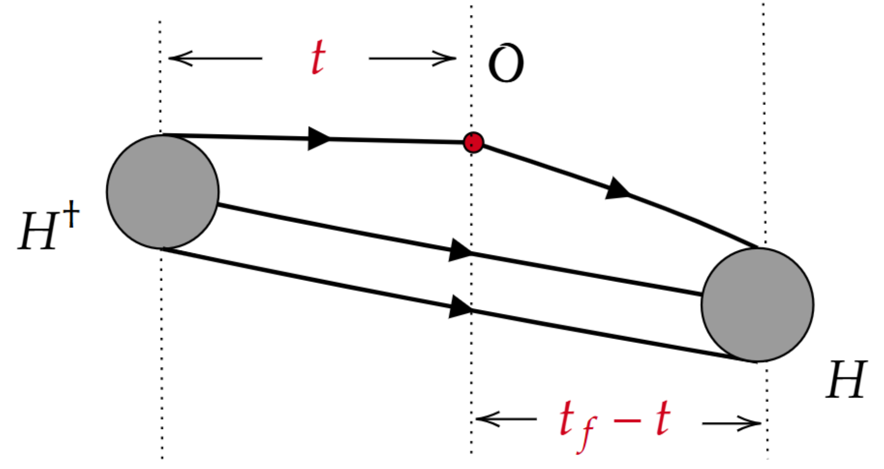
2. The **excited-state contamination** of the baryon matrix elements is serious, which will introduce systematic errors；

$$\langle H(t_f)\mathcal{O}(t)H^\dagger(t=0)\rangle = \exp(-E_0 t_f)\left(\langle 0|\mathcal{O}|0\rangle + \sum_{i>0}\langle i|\mathcal{O}|i\rangle e^{-\Delta_i t_f} + \sum_{i\neq 0; j\neq 0}\langle i|\mathcal{O}|j\rangle(e^{-\Delta_i(t_f-t)-\Delta_j t} + e^{-\Delta_j(t_f-t)-\Delta_i t})\right)$$





*Y.B. Yang, et al, PRD **94**(2016)5, 054503*
*ETMC, PRD **102**(2020)5, 054517*



➢ Signal-to-noise ratio decays exponentially with t_f;

2. Excited-State Contaminations in LQCD

➢ ChPT guides the very low-lying excited-states contamination (<300 MeV) from $N\pi$ and $N\pi\pi$ in 3-pts:

- $N\pi$ ESC in N 2-pt and 3-pt(nucleon charge)

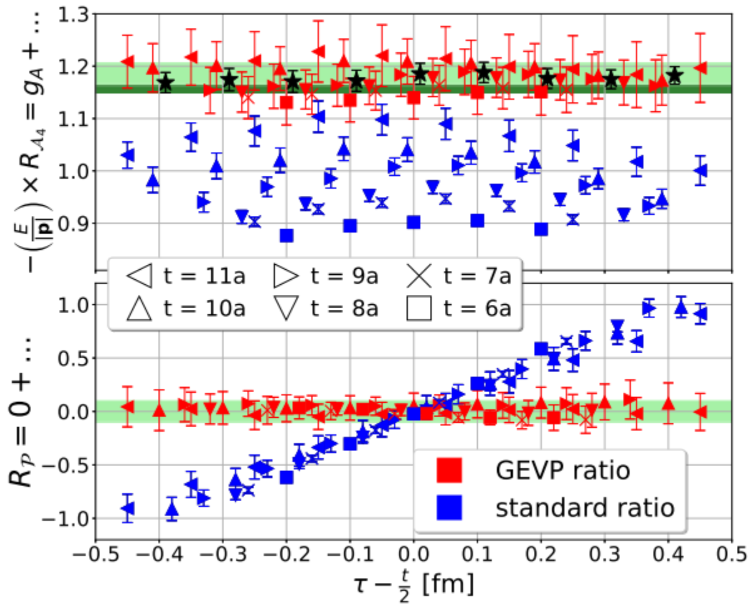
  B. Tiburzi, PRD 91 (2015) 094510

- $N\pi$ ESC in N 3-pt with $J^\mu = \bar{q}\gamma_5 q$ can be very large;

  O. Bär, PRD 100 (2019) 5, 054507

- $N\pi$ and $N\pi\pi$ in N 3-pts with $J^\mu = \bar{q}\ I\ q$ can be very large;

  R. Gupta, et al. PRD 99 (2019) 5, 054506



$\langle \mathcal{N} | \bar{q}\gamma^5 q(Q^2) | \mathcal{N} \rangle$ $\langle \mathcal{N} | \bar{q}\gamma^5\gamma^4 q(Q^2) | \mathcal{N} \rangle$

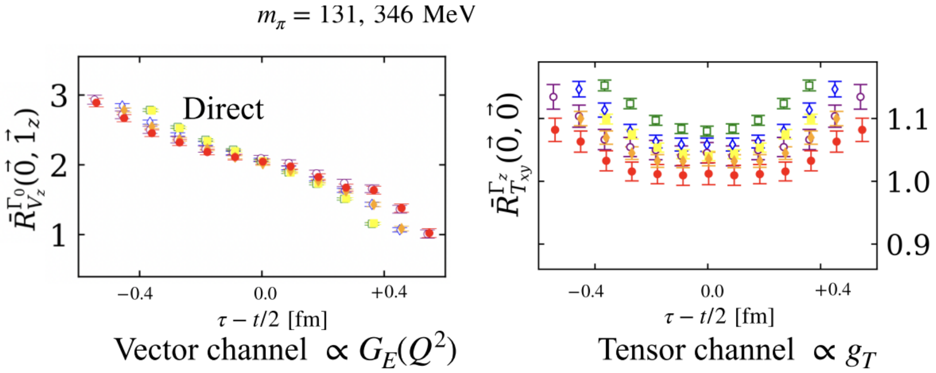
L. Barca, PRD 112(2025) 9, L091503

✓ After GEVP with $N\pi$, the convergence behaviors have been improved significantly for axial vector and pseudoscalar matrix element in LQCD;

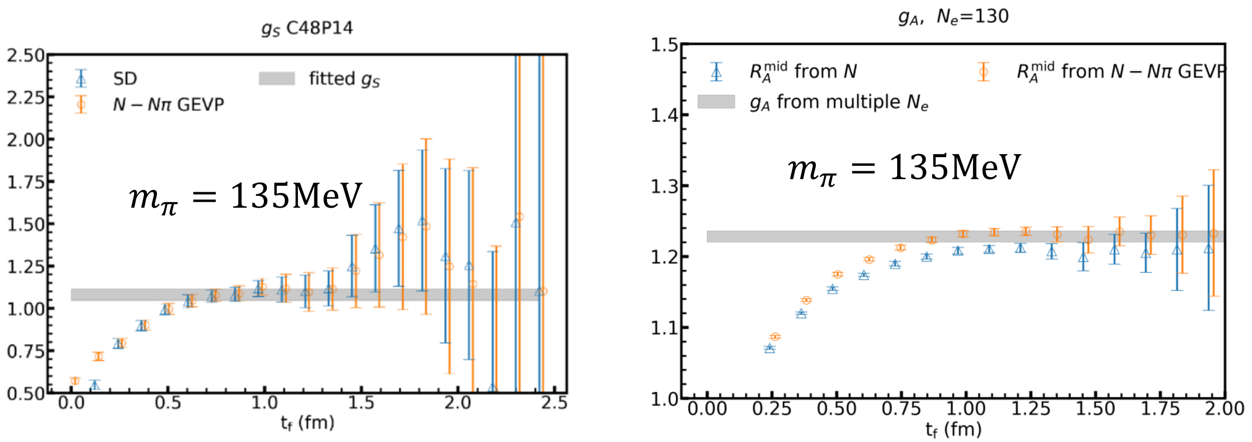
◆ ***$N\pi$* is not general !!!**

2. Current enhanced Excited-State contaminations

- $N\pi$ states **is not import** for nucleon charge at rest framework;



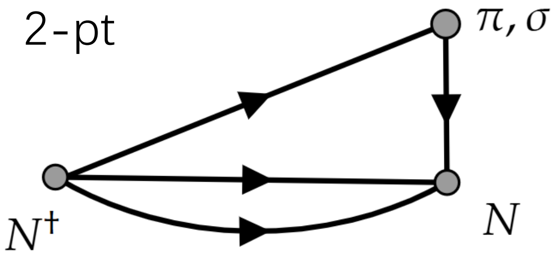
ETMC, *PRD 110 (2024) 9, 094514*



CLQCD, *arXiv:2511.02326*

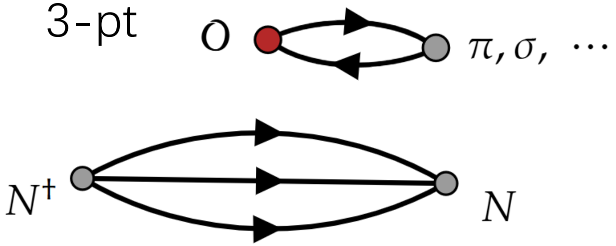
- **Current enhanced Excited-State contamination**; *Lorenzo Barcal, PRD 112 (2025) 9, L091503*

2-pt



$$< \mathcal{N}|\mathcal{N}\pi, \mathcal{N}\sigma \cdots > \sim 1/V$$

3-pt



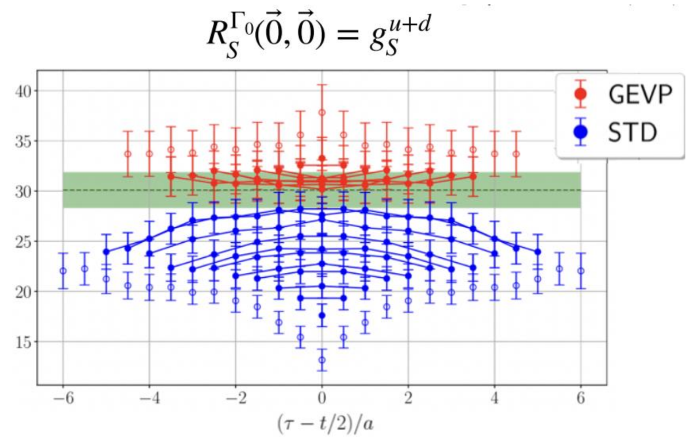
if $\langle \mathcal{O}|\pi,\sigma,\cdots > \neq 0$

$$< \mathcal{N}|\mathcal{O}|\mathcal{N}\pi, \mathcal{N}\sigma \cdots > \sim V$$

- After volume enhancement, nucleon matrix elements get O(1) excited state contamination;

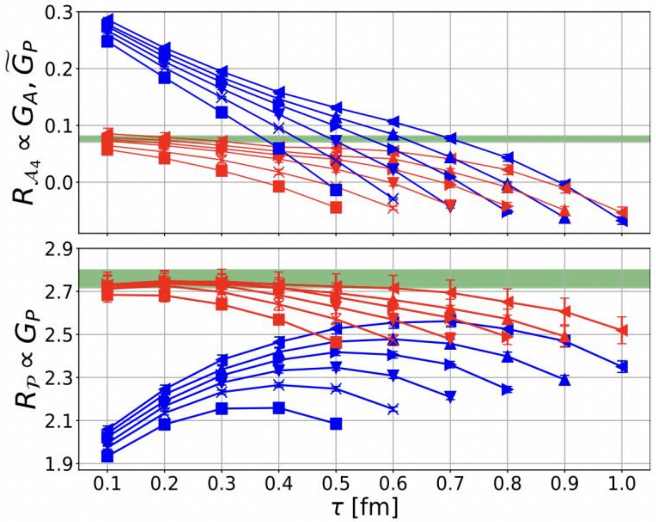
2. Current enhanced Excited-State contaminations

g_s v.s. $N\sigma$



Lorenzo Barcal, PRD 111 (2025) 3, L031505

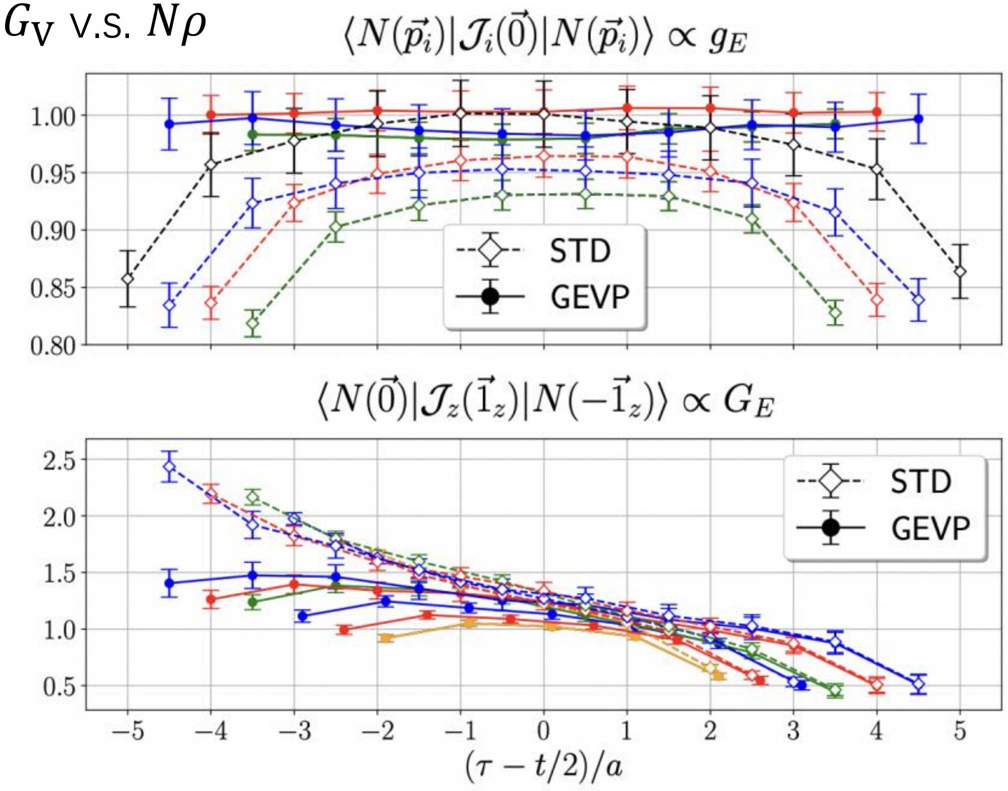
G_p v.s. $N\pi$



Lorenzo Barcal, PRD 107 (2023) 5, L051505

✓ GEVP removes leading order excited contaminations;

G_V v.s. $N\rho$



Lorenzo Barcal, PRD 112 (2025) 9, L091503

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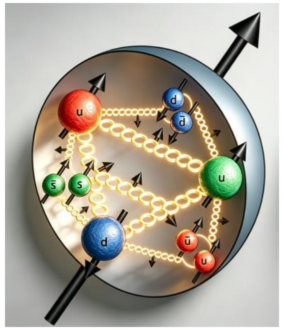
3. Application on nucleon matrix element: GEVP



- Proton spin puzzle

$$\frac{\hbar}{2} = \frac{1}{2}\sum_q \Delta q + L_q + J_g$$

*X.D. Ji, PRL **78**, 610(1997)*

➢ Quark spin can be extracted from the local matrix element g_A^{u+d+s};

✓ Major excited-state contamination comes from $\mathcal{N}f_1$ scattering state for g_A^{u+d+s};

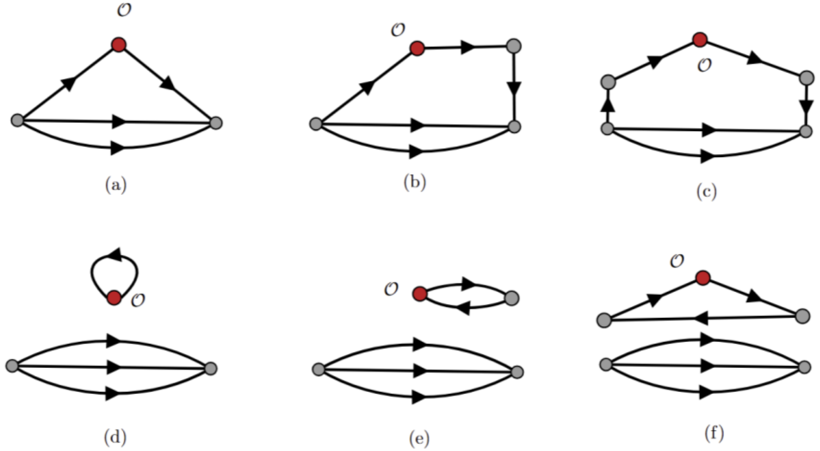
$\boxed{f_1(1285) \text{ width 23MeV}}$

$$\mathcal{N} = P^+ u(uC\gamma^5 d)$$

$$f_1 = \frac{1}{\sqrt{3}}(\bar{u}\gamma_5\gamma^i u + \bar{d}\gamma_5\gamma^i d + \bar{s}\gamma_5\gamma^i s)$$

$$f_1' = \frac{1}{\sqrt{6}}(\bar{u}\gamma_5\gamma^i u + \bar{d}\gamma_5\gamma^i d - 2\bar{s}\gamma_5\gamma^i s)$$

3x3 GEVP based on the operator basis $(\mathcal{N}, \mathcal{N}f_1, \mathcal{N}f'_1)$



✓ The s-wave scattering of nucleons and $f_1(1^+)$ mesons can couple to the nucleon $(1/2^+)$ representation.

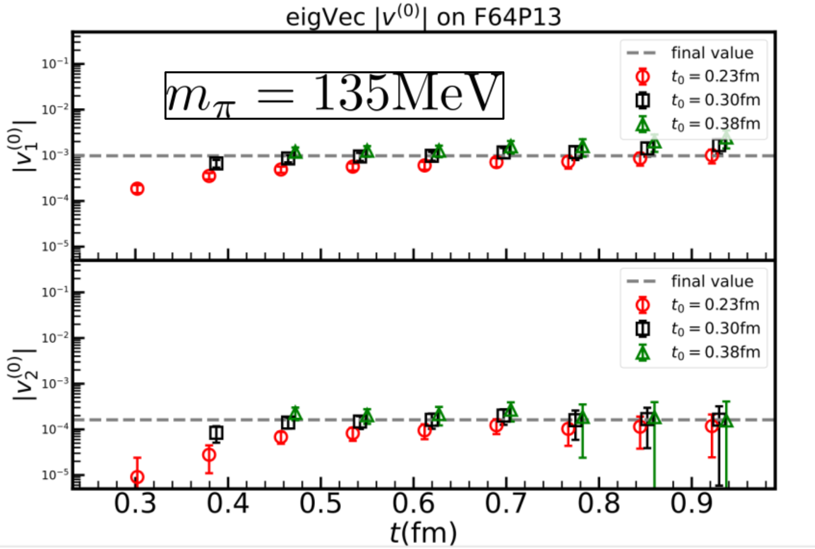
✓ The Full GEVP analysis need $\mathcal{O}(1000)$ Wick Construction;

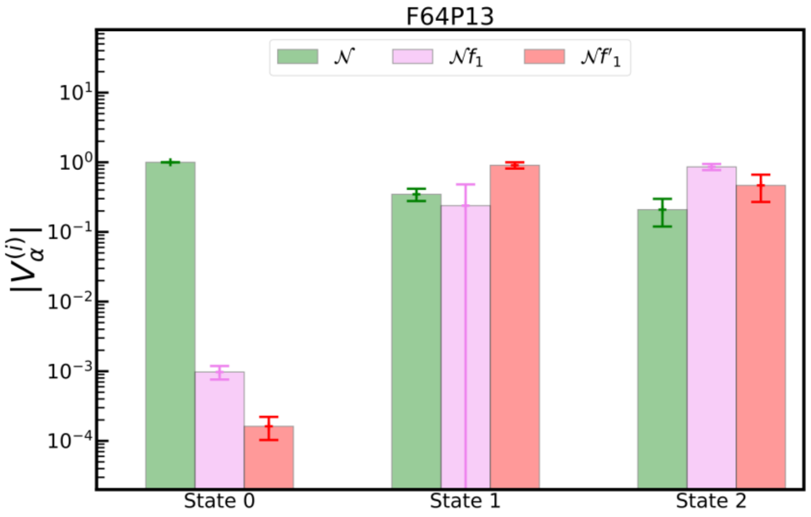
✓ "Blending" method realizes all-to-all propagator.

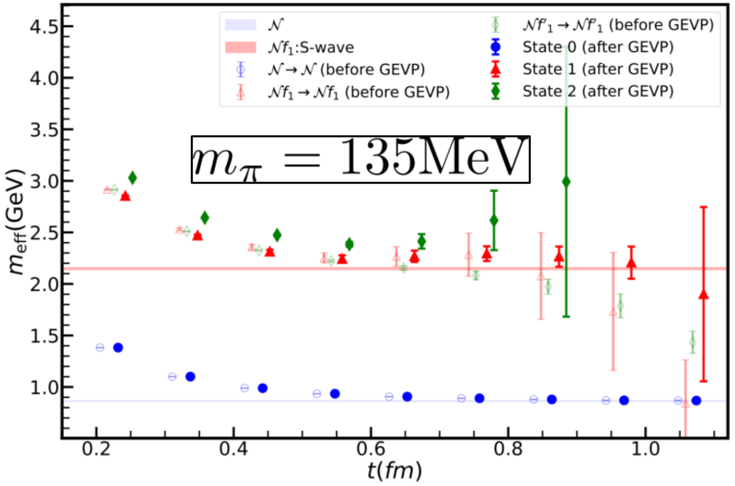
Z.C. Hu [CLQCD] arXiv: 2505.01719

3. Application on nucleon matrix element: GEVP

$$C_{2,\alpha\beta}(t)V^n_\beta(t,t_0) = \lambda^n(t,t_0)C_{2,\alpha\beta}(t_0)V^n_\beta(t,t_0),$$





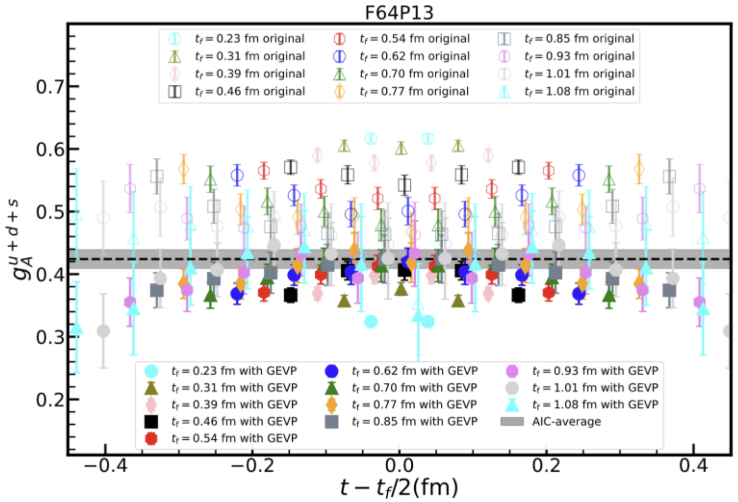


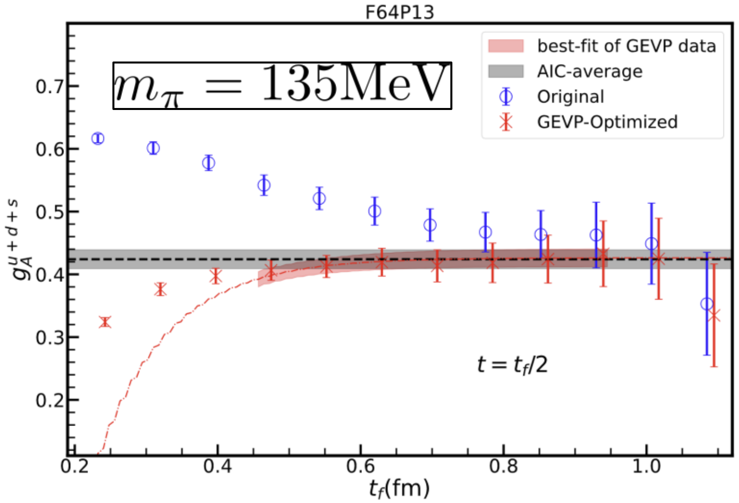
- ✓ GEVP vector can be uniquely determined by solving the GEVP equation and by the imaginary-time evolution;
- ✓ After applying the GEVP, a state with an energy near the no-interaction Nf_1 threshold is obtained;

- ✓ Applying GEVP to 3-p function, Convergent behaviors are largely improved after GEVP;

$$C_{3,\alpha\beta}(t_f,t) \equiv \langle X_\alpha(t_f) A_\Sigma(t) X_\beta^\dagger(0)\rangle,$$

$$\tilde{C}_{3,00}(t_f,t) \equiv V_\alpha^0(t,t_0)\, C_{3,\alpha\beta}(t_f,t)\, V_\beta^0(t,t_0),$$





- ✓ Even though the overlap is only about 0.1%, it plays a very effective role in the 3-p process;

- ✓ The result with AIC on fit windows is $g_A^{u+d+s}(a = 0.077\text{fm}) = 0.417(17),$ achieveing world leading precision at physical point directly.

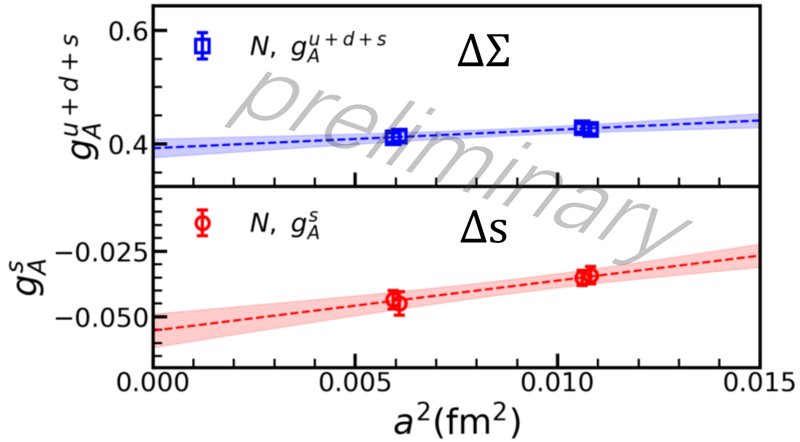
	Ensemble	L	T	a(fm)	m_π	n_{cfg}	g_A^s	g_A^{u+d+s}	Inversion	Inv.to 4% g_A^{u+d+s}
PNDME	a09m310	64	96	0.09	138	847	-0.047(27)	–	8.8 M	–
ETM17	cA2.09.48	48	96	0.09	135	2136	-0.021(5)	0.402(35)	7.2 M	34.1 M
ETM19	cB211.072.64	64	128	0.08	139	750	-0.046(7)	0.382(31)	1.37 M	5.63 M
This Work	F64P13	64	128	0.078	134	46	-0.0409(37)	0.416(17)	0.39 M	0.39 M

3. Quark spin at continue limit

➢ Continuum extrapolation based 4 ensembles($a \to 0$)

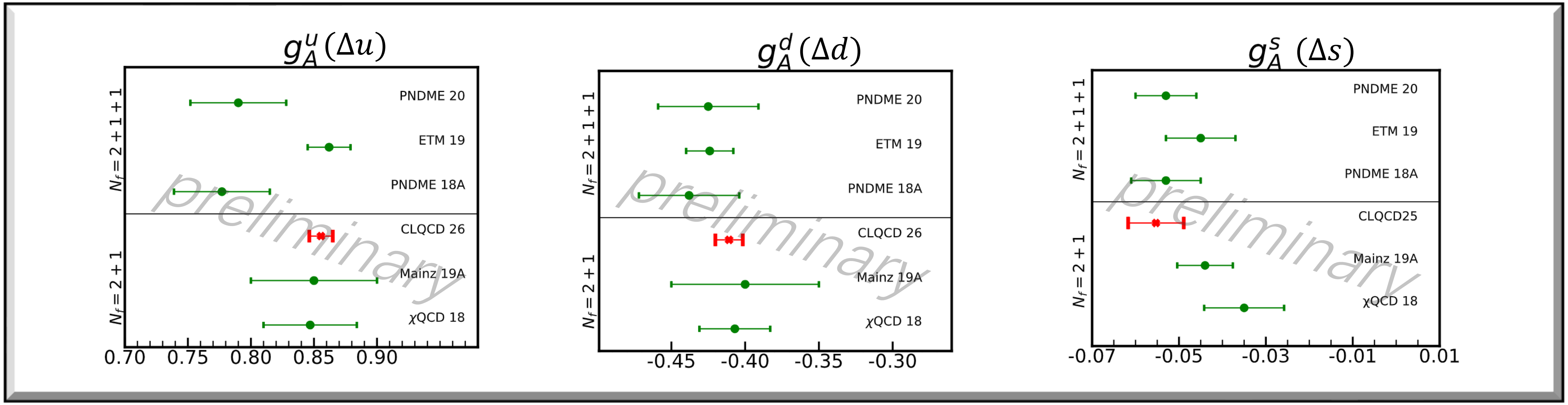
	a [fm]	$L^3 \times T$	m_π [MeV]	$m_\pi L$	$N_{\rm cfg}$
C32P29	0.105	$32^3 \times 64$	292.4(1.1)	5.01	160
C48P13	0.105	$48^3 \times 96$	135.5(1.6)	3.47	53
F48P30	0.077	$48^3 \times 96$	303.4(0.9)	5.72	40
F64P13	0.077	$64^3 \times 128$	134.1(1.5)	3.37	43

$$g_A(a, m_\pi) = g_A^{\rm phys} + c_1(m_\pi^2 - m_{\pi,{\rm phys}}^2) + c_2 a^2.$$



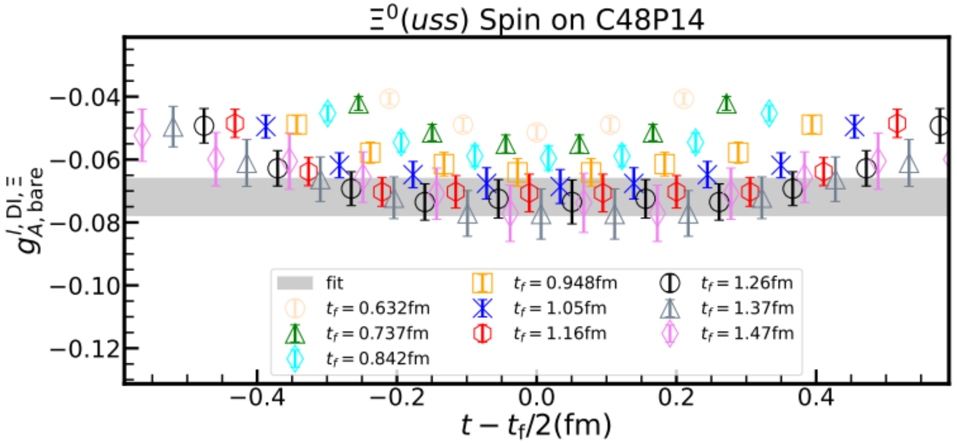
$$\frac{1}{2}\Delta\Sigma = 39(2)\%\ S_p$$

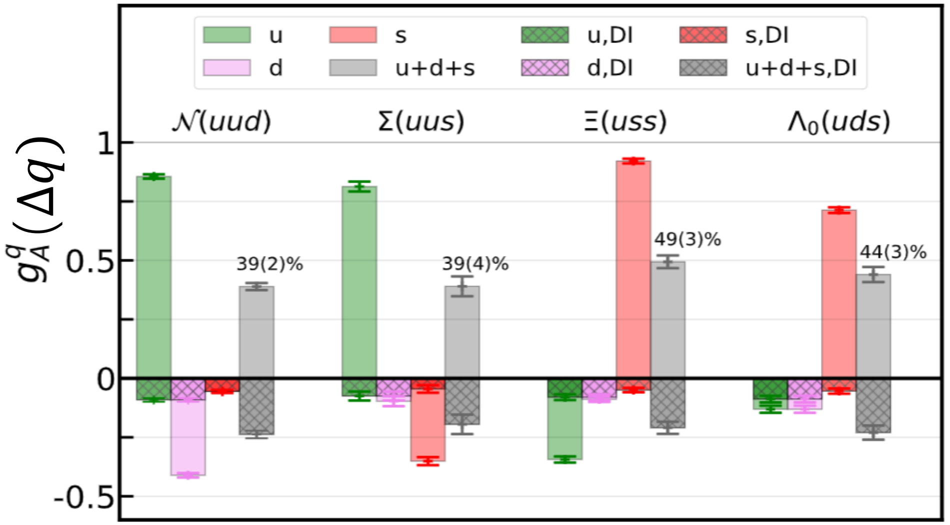
$$\frac{1}{2}\Delta s = -5.5(6)\%\ S_p$$



3. Quark spin on Octet baryons

✓ For the first time, the quark spin of the hyperon was obtained at the physical point;





◆ The contribution of the sea quarks is significantly non-zero;

1. $\mathcal{N}(uud)$ with $\Delta s = -5.53(64)\%S_P$;

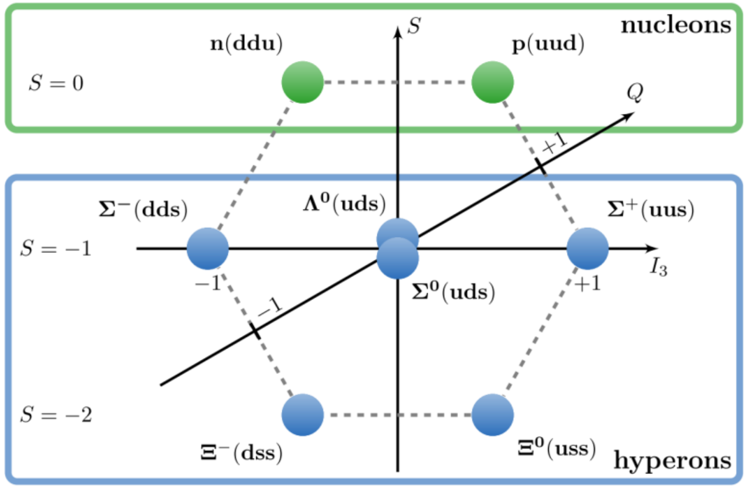
2. $\Sigma^+(uus)$ with $\Delta d = -10(2)\%\ S_\Sigma$;

3. $\Xi^0(uss)$ with $\Delta d = -9(1)\%S_\Xi$;

◆ $\Delta u, \Delta d$ on Λ_0 are significantly non-zero too;

$$\Delta u = \Delta d = -13(2)\%S_{\Lambda_0}$$

3. Quark spin in octet baryons and SU(3)-flavour symmetry



$SU(3)_f$ symmetry →

- Isospin vector:

$$g_{A,p}^{u-d} + g_{A,\Xi^0}^{u-d} - g_{A,\Sigma^+}^{u-d} = 0;$$

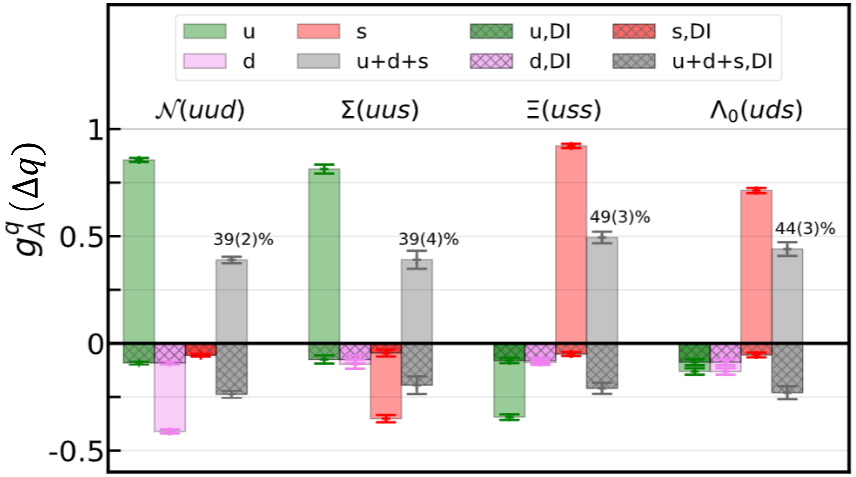
- Flavour singlet:

$$g_{A,N}^{u+d+s} = g_{A,\Xi}^{u+d+s} = g_{A,\Sigma}^{u+d+s} = g_{A,\Lambda}^{u+d+s};$$

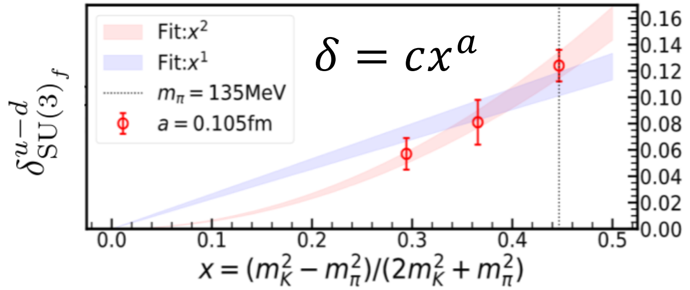
➢ Quark Spin could be extrapolated to Hyperon From nucleon data based in $SU(3)_f$ symmetry

Baryon	ΔU	ΔD	ΔS
p	0.83 ± 0.03	-0.43 ± 0.03	-0.10 ± 0.03
n	-0.43 ± 0.03	0.83 ± 0.03	-0.10 ± 0.03
Σ^+	0.83 ± 0.03	-0.10 ± 0.03	-0.43 ± 0.03
Σ^-	-0.10 ± 0.03	0.83 ± 0.03	-0.43 ± 0.03
Ξ^o	-0.43 ± 0.03	-0.10 ± 0.03	0.83 ± 0.03
Ξ^-	-0.10 ± 0.03	-0.43 ± 0.03	0.83 ± 0.03
Σ^o	0.37 ± 0.03	0.37 ± 0.03	-0.43 ± 0.03
Λ	-0.17 ± 0.03	-0.17 ± 0.03	0.63 ± 0.03

*D. Ashery; et.al; PLB **469**,263-269 (1999)*



➢ $(m_s - m_l)$ drives the breaking of $SU(3)_f$ symmetry;



$$\delta_{SU(3)}^{u-d} = \frac{g_{A(u-d)}^{\mathcal{N}} - g_{A(u-d)}^{\Sigma^+} + g_{A(u-d)}^{\Xi^0}}{g_A^{\exp}} = 11(1)\%$$

$$\delta_{SU(3)}^{u+d+s} = \frac{g_{A,\Xi}^{u+d+s} - g_{A,\mathcal{N}}^{u+d+s}}{\left(g_{A,\Xi}^{u+d+s} + g_{A,\mathcal{N}}^{u+d+s}\right)/2} = 24(7)\%,$$

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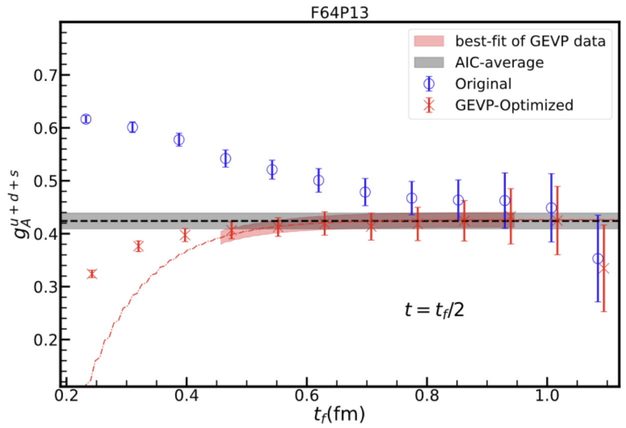
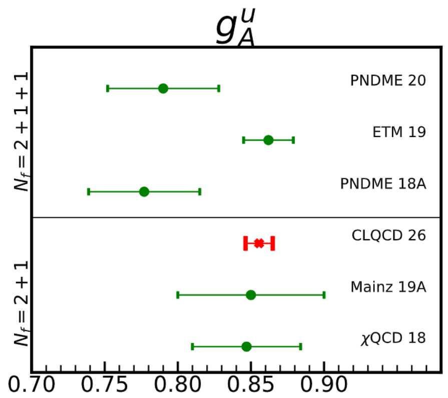
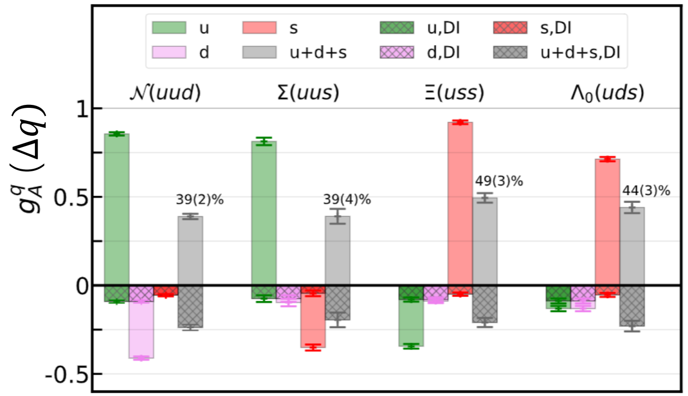
4. Summary

1. We completed GEVP-analysis based on nucleon and f_1 scattering state to improve convergence behaviors of 3-pt effectively based on the idea of "<u>Current enhanced excited state contaminations</u>";





2. We achieve world leading precision of quark spin ΔΣ based on the "Blending" method and the GEVP analysis.



3. We obtained the quark spin on octet baryons systematically;

Thank you!