Perspectives from lattice QCD with exascale supercomputers

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Extended Twisted Mass Collaboration

04/03/24 - Workshop, Warsaw

Funded by the European Union

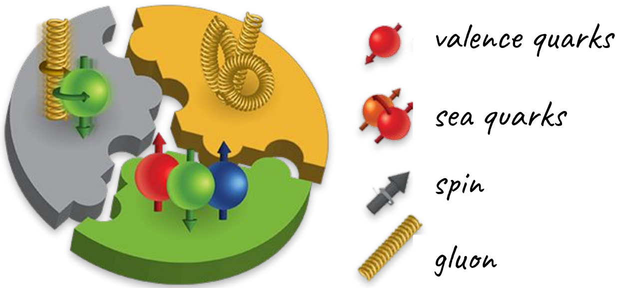
EuroHPC Joint Undertaking

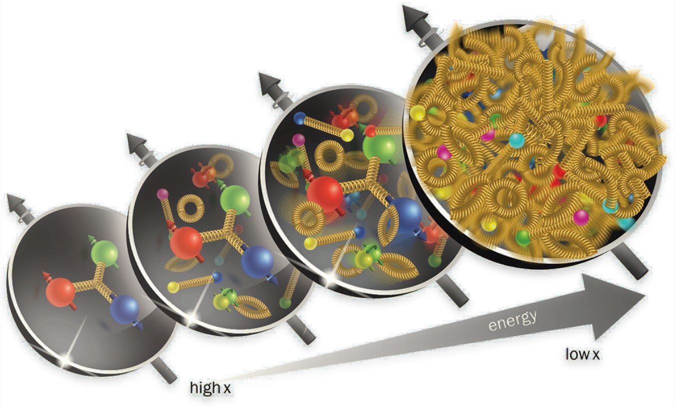
INNO4SCALE

This project has received funding from the European High-Performance Computing Joint Undertaking (JU) under grant agreement No 101118139. The JU receives support from the European Union's Horizon Europe Programme.

Overview

- State-of-the-art in Lattice QCD: A look at nucleon matrix elements
- State-of-the art in Hyperons: A brief review of the available results
- Proposal #1: Diagonal and transition matrix elements of the baryons octet
- Proposal #2: Non-leptonic two-body decays





Lattice QCD: Why? How?

Why?

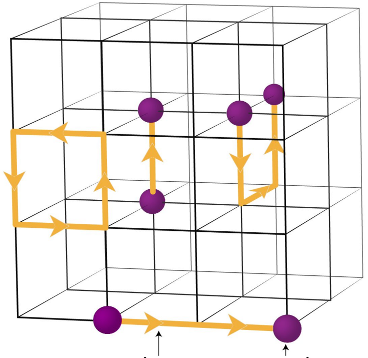
The Lattice Regularization is the only-known, ab-initio, and model-independent approach for studying a quantum field theory non-perturbatively, such as QCD at low energies

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + \sum_f \bar{\psi}_f \left(i\gamma^\mu D_\mu - m_f \right) \psi_f$$

How?

K. G. Wilson
1974

From QCD	*To Lattice QCD*
➢ Continuous space-time	➢ 4D hypercubic lattice a, V
➢ Minkowski space-time	➢ Euclidean space-time
➢ Lie algebra $A_\mu(x)$	➢ Lie group $U_\mu(x) = e^{igaA_\mu(x)}$
➢ Lagrangian $\mathcal{L}_{\text{QCD}}(g, \vec{m}_f)$	➢ Lattice action $S(a, \vec{\mu}_f)$



$$\langle \mathcal{O} \rangle_{a,V,\vec{\mu}_f} = \frac{1}{\mathcal{Z}} \int \mathrm{D}[U]^V \mathrm{D}[\psi\bar{\psi}]^{Vn_f} \mathcal{O}(U, \psi, \bar{\psi})\, e^{-S(a,\vec{\mu}_f;\, U,\psi,\bar{\psi})}$$

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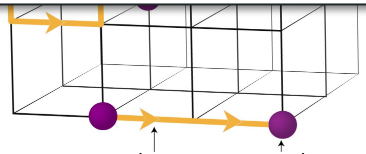
$$\langle \mathcal{O} \rangle = \lim_{\substack{\vec{\mu}_f \to \vec{m}_f \\ V \to \infty \\ a \to 0}} \langle \mathcal{O} \rangle_{a,V,\vec{\mu}_f}$$



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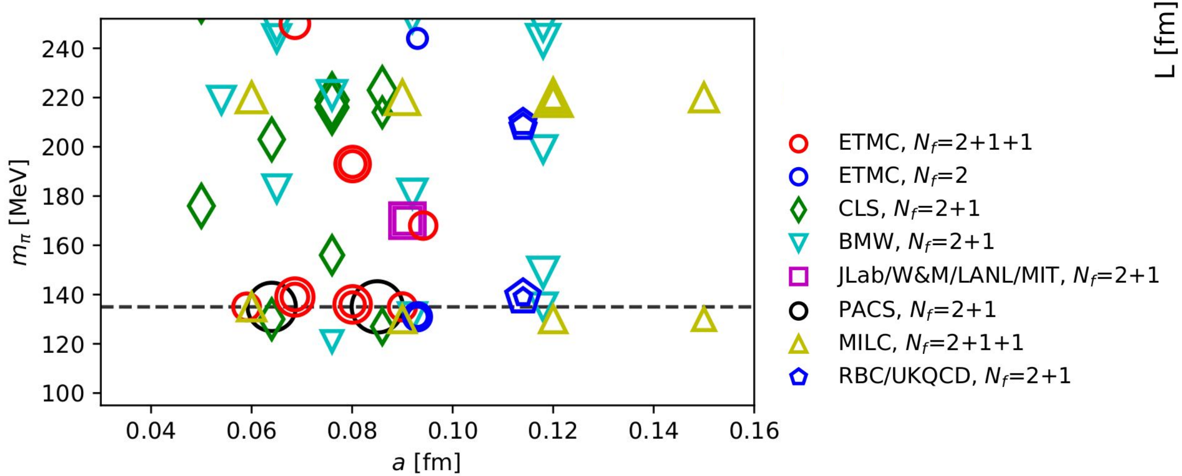
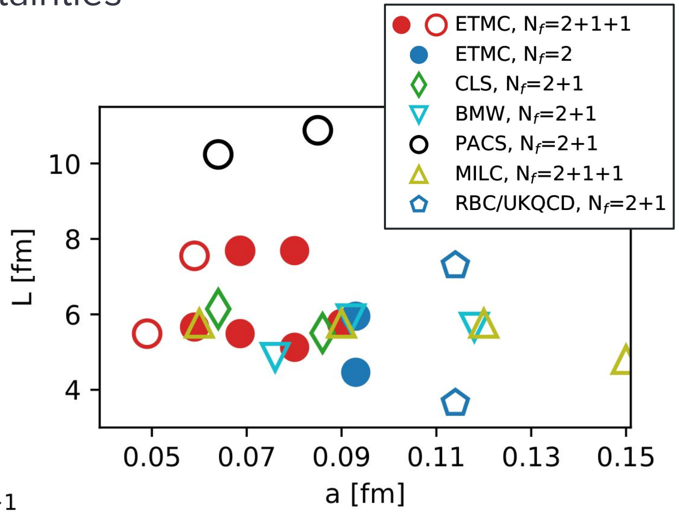
State-of-the-art in Lattice QCD

The study of nucleon matrix elements is one of the most advanced:

- Many collaborations are able to control all systematic uncertainties
  - Ensembles at physical quark masses
  - Continuum limit and infinite volume limit
  - Study of excited state contaminations





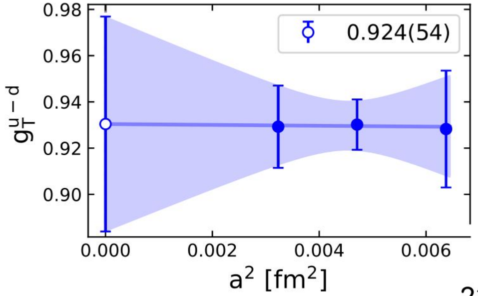
Ongoing challenge: the continuum limit

$$\langle \mathcal{O} \rangle = \lim_{\substack{\vec{\mu}_f \to \vec{m}_f \\ V \to \infty \\ a \to 0}} \langle \mathcal{O} \rangle_{a,V,\vec{\mu}_f}$$

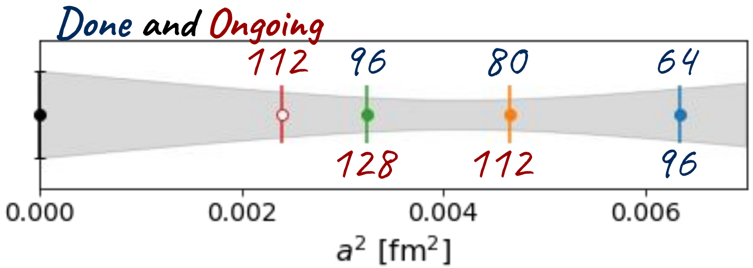
✔ $\vec{\mu}_f \to \vec{m}_f$

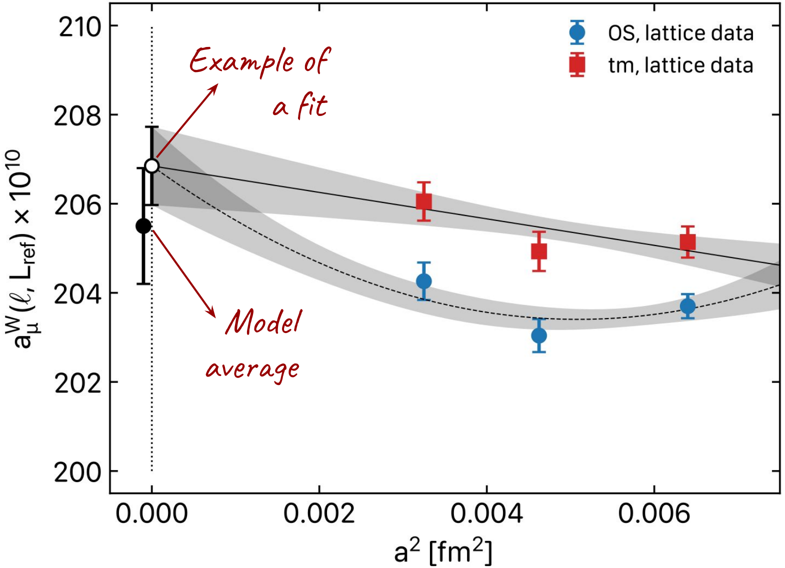
! $V \to \infty$ $t \to \infty$

$a \to 0$

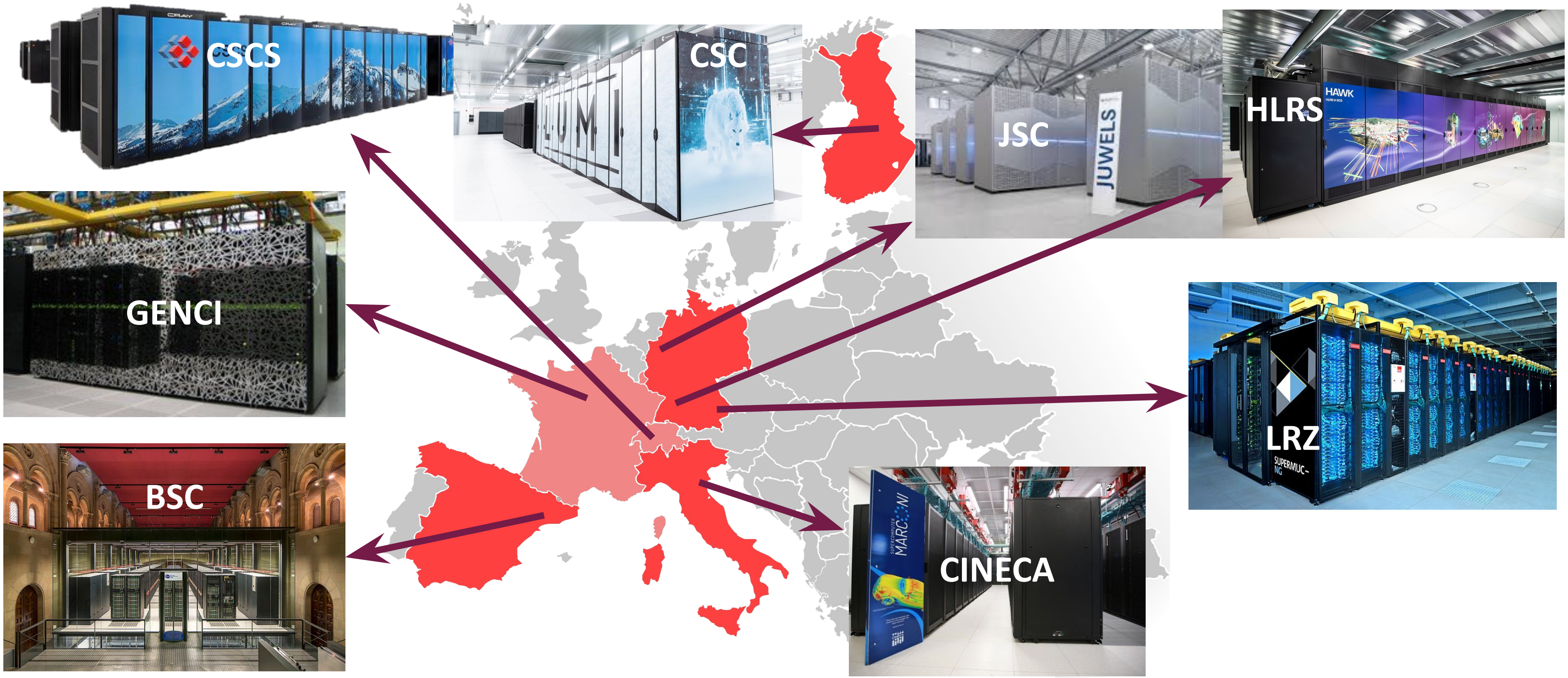


- Currently errors are dominated by the continuum extrapolation
- Ongoing new ensemble at *a=0.05 fm*
- Due to critical slowing down, it is probably the finest we can go with current algorithms!



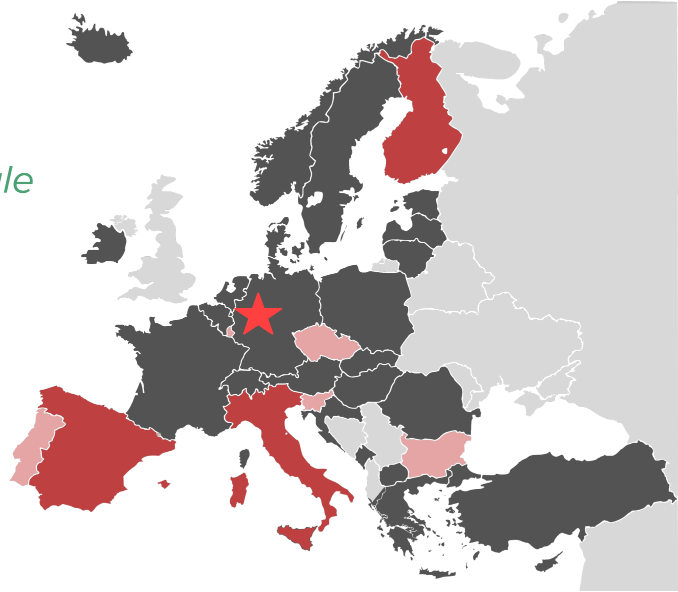


Supercomputers in Europe



EuroHPC Joint Undertaking

The European High Performance Computing Joint Undertaking (EuroHPC JU) is pooling European resources to buy and deploy top-of-the-range supercomputers and develop innovative exascale supercomputing technologies and applications.



The JU is currently supporting two main activities:

- Developing a pan-European supercomputing infrastructure:
  - **5 PetaFlop machines** in Bulgaria, Czech, Luxembourg, Slovenia, Portugal
  - **3 Pre-Exascale machines** with over 200 PetaFlops: Lumi in Finland, Leonardo in Italy and Marenostrum 5 in Spain
  - **2 Exascale machines:** JSC in Germany, TBD

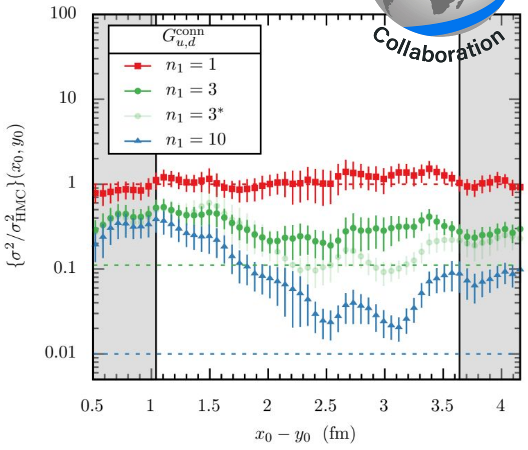
Upcoming Budget (2021 - 2033): 8 billion Euro

EuroHPC Joint Undertaking

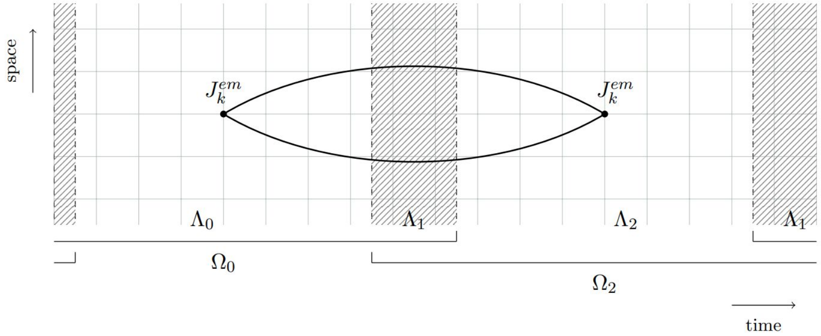
Upcoming algorithm developments

Multilevel algorithms are novel noise-reduction techniques

- M. Luscher and P. Weisz, "Locality and exponential error reduction in numerical lattice gauge theory", JHEP09 (2001), 010 [arXiv:hep-lat/0108014 [hep-lat]].
- M. Ce', L. Giusti and S. Schaefer, "Domain decomposition, multi-level integration and exponential noise reduction in lattice QCD," Phys. Rev. D 93 (2016) no.9, 094507, [arXiv:1601.04587 [hep-lat]].
- M. Dalla Brida, L. Giusti, T. Harris, and M. Pepe, "Multi-level Monte Carlo computation of the hadronic vacuum polarization contribution to (g μ -2)," Phys. Lett. B 816 (2021), 136191, [arXiv:2007.02973 [hep-lat]].



It will be critical in reaching large source-sink separation in the calculation of matrix elements and to suppress the excited state contamination, a major systemic effect!



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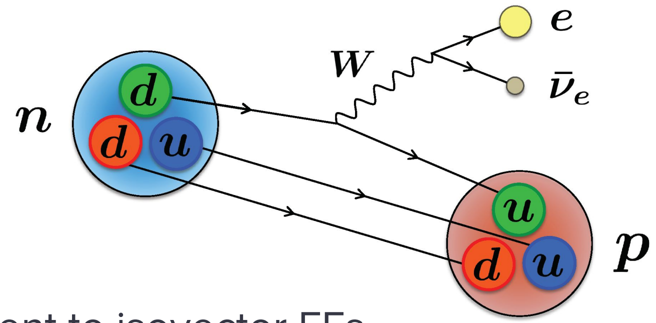
Example: the weak axial-vector matrix element

The transition matrix element of the neutron β-decay is

$$\mathcal{M}(n \to p\, e^- \bar{\nu}_e) = \frac{G_F}{\sqrt{2}} V_{ud} \sum_\mu \langle p(p')|W_\mu|n(p)\rangle\, L_\mu$$

with

$$W_\mu = V_\mu - A_\mu$$
$$V_\mu = \bar{u}\gamma_\mu d$$
$$A_\mu = \bar{u}\gamma_\mu\gamma_5 d$$

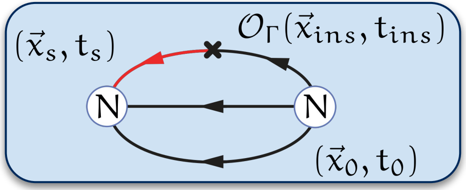


Neglecting isospin-breaking effects, transition FFs are equivalent to isovector FFs

$$\langle p(p')|A_\mu|n(p)\rangle$$
$$A_\mu = \bar{u}\gamma_\mu\gamma_5 d$$

$\Rightarrow$ $u = d$

$$\langle N(p')|A_\mu^{\text{isov}}|N(p)\rangle$$
$$A_\mu^{\text{isov}} = \bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d$$



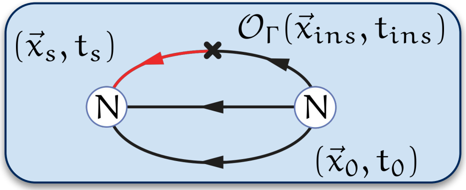
Nucleon three-point functions

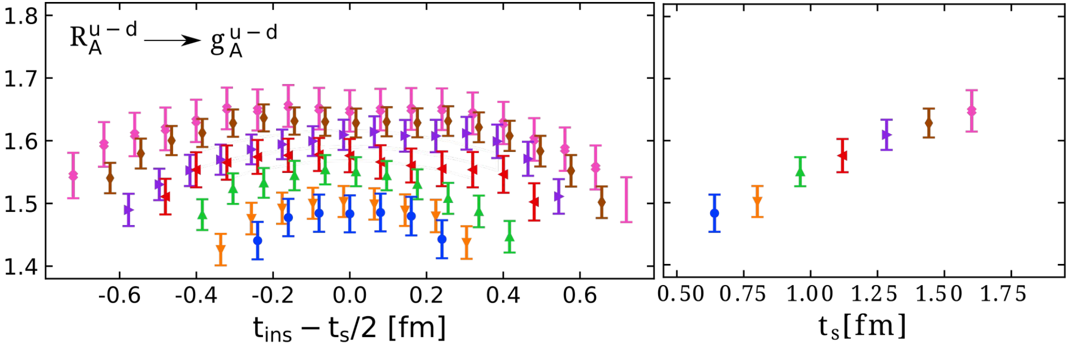
$$G_\Gamma(P;\vec{q};t_s,t_{ins}) = \sum_{\vec{x}_s,\vec{x}_{ins}} e^{-i\vec{q}\cdot\vec{x}_{ins}} P^{\alpha\beta} \langle \bar{\chi}_N^\beta(\vec{x}_s,t_s)|\mathcal{O}_\Gamma(\vec{x}_{ins},t_{ins})|\chi_N^\alpha(\vec{0},0)\rangle$$

suitable projector ↗

e.g. $\mathcal{O}_A(x) = \bar{\psi}(x)\gamma_5\gamma^\mu\psi(x)$

- Three-point functions
  - Ground state at $t_s \to \infty$, $(t_s - t_{ins}) \to \infty$
  - Error increases exponentially with t_s
  - Statistics increased to keep errors constant





×750 configurations

t_s/a	t_s[fm]	n_{src}
8	0.64	1
10	0.80	2
12	0.96	5
14	1.12	10
16	1.28	32
18	1.44	112
20	1.60	128
Nucleon 2pt		477

~30M inversions!

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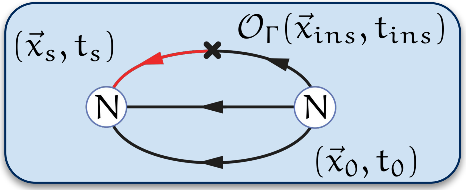
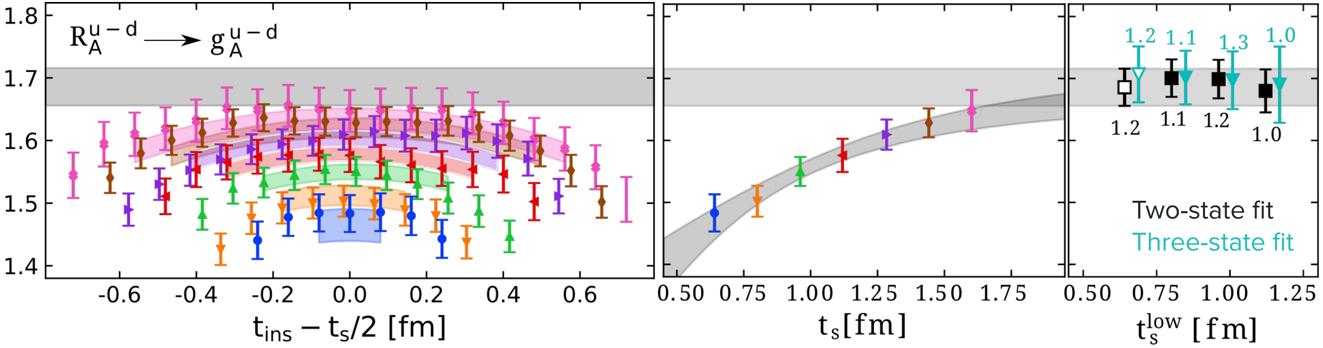
$$G_\Gamma(t_s,t_{ins}) \simeq A_{00} e^{-m_N t_s} + A_{01}\left(e^{-E_1 t_{ins}} + e^{-E_1 t_s + (E_1 - m_N) t_{ins}}\right) + A_{11} e^{-E_1 t_s}$$

$$G(t) \simeq c_0 e^{-m_N t_s} + c_1 e^{-E_1 t_s}$$

Desired matrix element: $\mathcal{M} = \dfrac{A_{00}}{c_0}$





$\times 750$ configurations

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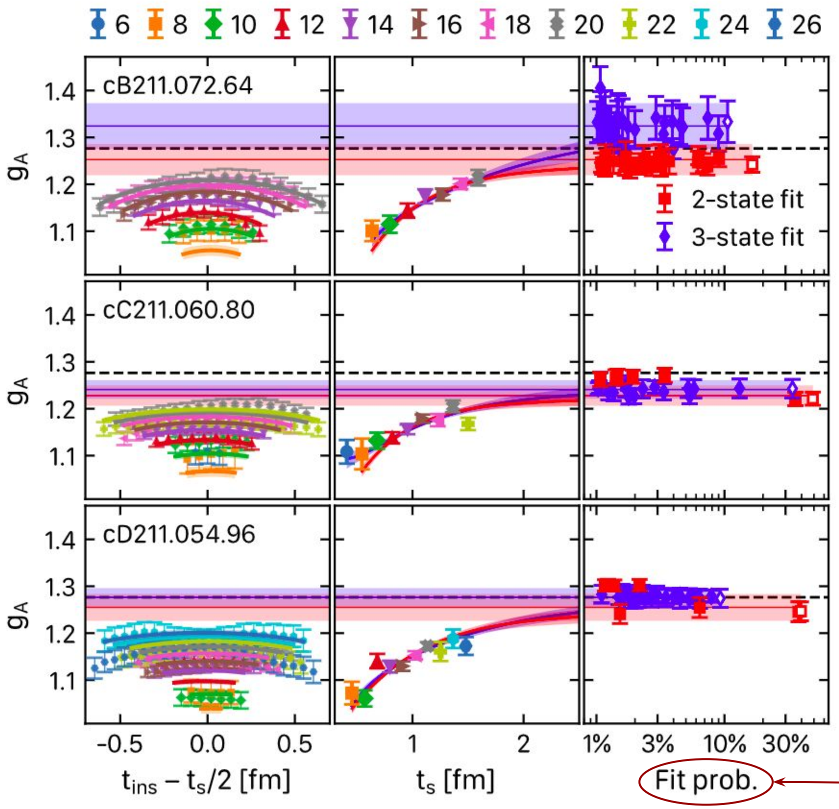
[C. Alexandrou, S. B., et al. "Nucleon axial, tensor, and scalar charges and σ-terms in lattice QCD". Phys. Rev., D102(5):054517, 2020]

The three ensembles and model averaging

Extended Twisted Mass Collaboration



Ensemble	V/a^4	β	a [fm]	m_π [MeV]	$m_\pi L$
cB211.072.64	$64^3 \times 128$	1.778	0.07957(13)	140.2(2)	3.62
cC211.060.80	$80^3 \times 160$	1.836	0.06821(13)	136.7(2)	3.78
cD211.054.96	$96^3 \times 192$	1.900	0.05692(12)	140.8(2)	3.90

cB211.072.64		
750 configurations		
t_s/a	t_s[fm]	n_{src}
8	0.64	1
10	0.80	2
12	0.96	5
14	1.12	10
16	1.28	32
18	1.44	112
20	1.60	128
Nucleon 2pt		477

cC211.060.80		
400 configurations		
t_s/a	t_s[fm]	n_{src}
6	0.41	1
8	0.55	2
10	0.69	4
12	0.82	10
14	0.96	22
16	1.10	48
18	1.24	45
20	1.37	116
22	1.51	246
Nucleon 2pt		650

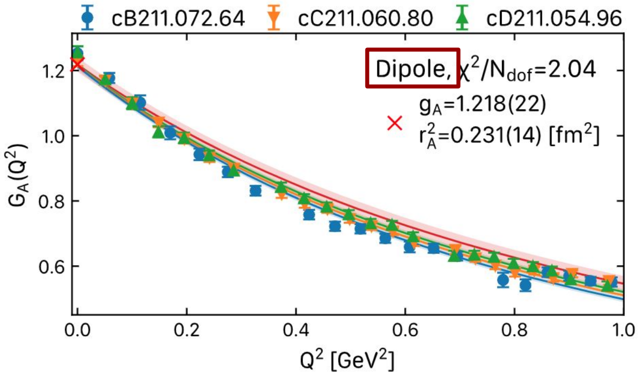
cD211.054.96		
500 configurations		
t_s/a	t_s[fm]	n_{src}
8	0.46	1
10	0.57	2
12	0.68	4
14	0.80	8
16	0.91	16
18	1.03	32
20	1.14	64
22	1.25	16
24	1.37	32
26	1.48	64
Nucleon 2pt		480

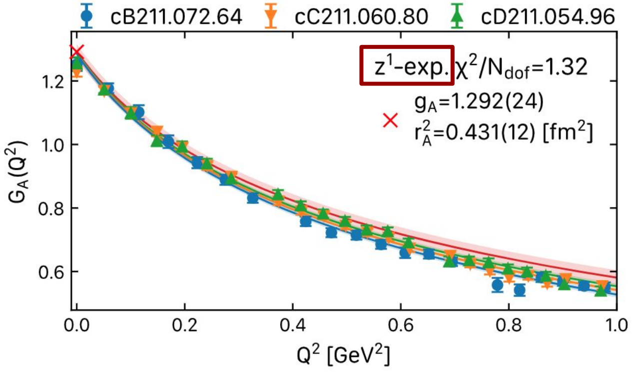
Up to 1.5fm for all ensembles

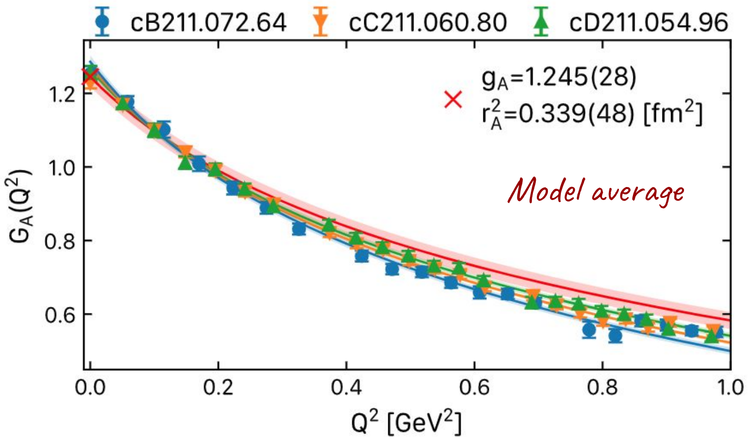
Model average over thousands of fits: $\log(w_i) = -\frac{\chi_i^2}{2} + N_{\mathrm{dof},i}$

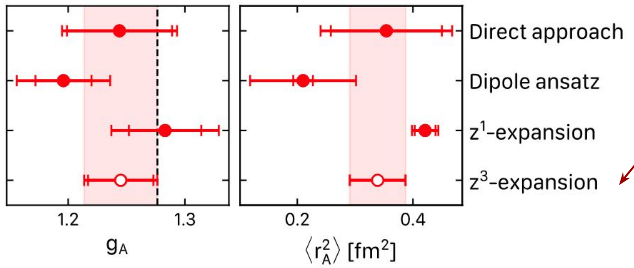
$p_i = \frac{w_i}{Z}$ with $Z = \sum_i w_i$. [E. T. Neil, J. W. Sitison, arXiv:2208.14983]

Dipole vs z-expansion



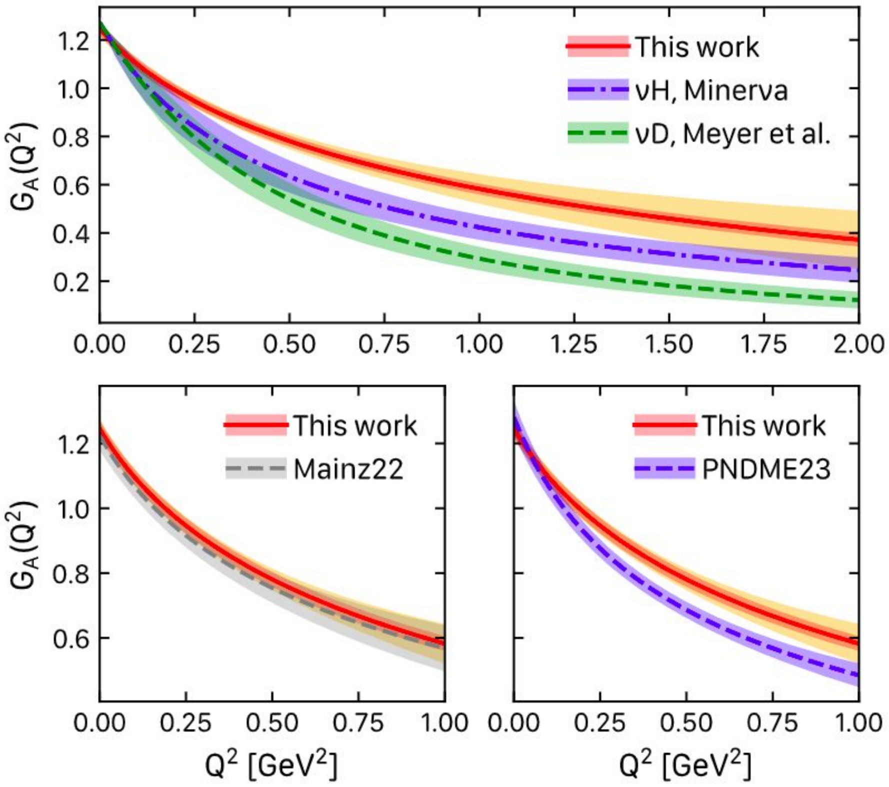




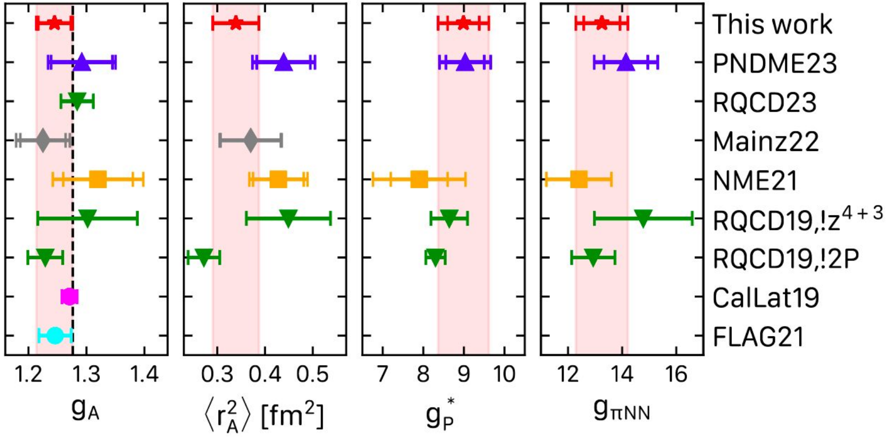


Compatible with the direct approach but smaller error because all information used

Comparison with other works

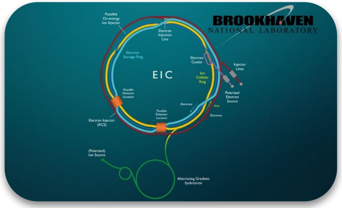


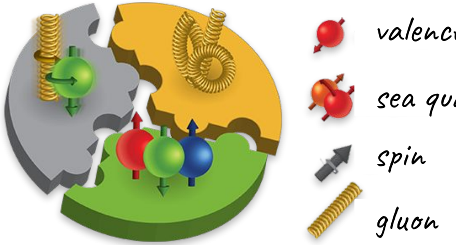
- Overall good agreement between recent lattice results and better agreement with the very recent results from Minerva

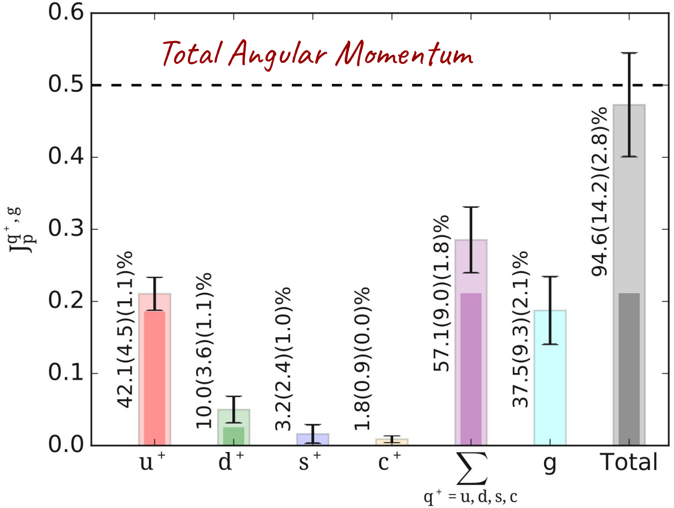


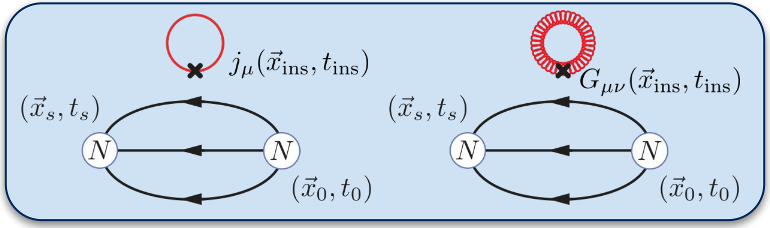
And much more…

- Electromagnetic form factors
- Transversity form factors
- Gravitational form factors
- Second and higher Mellin moments
- PDFs and GPDs via LaMET
- \+ Single flavor decomposition
- \+ Gluon contributions









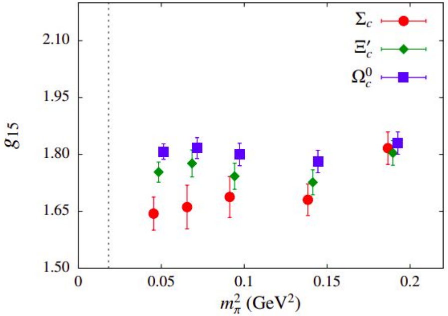
[C. Alexandrou, S. B., et al. “Complete flavor decomposition of the spin and momentum fraction of the proton using lattice QCD simulations at physical pion mass”. Phys. Rev., D101(9):094513, 2021]

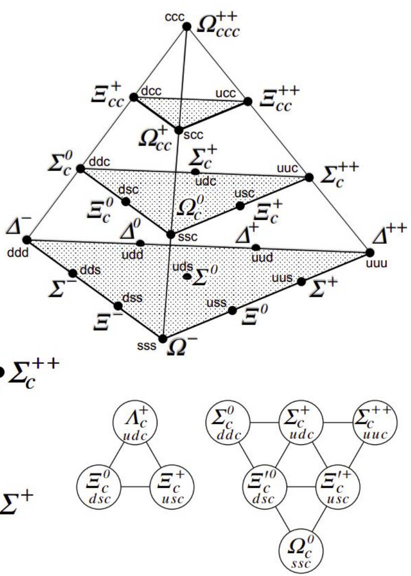
Why not more?

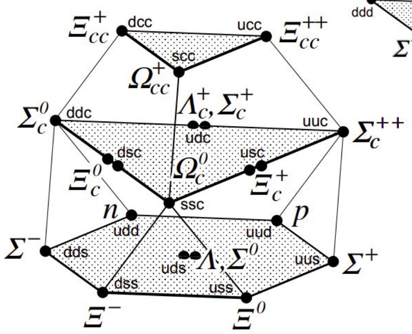
- Electromagnetic FFs
  - **N, Σ, Ξ:** P. E. Shanahan *et al.* [arXiv:1403.1965, arXiv:1401.5862]
    51 citations 61 citations
- Isovector charges
  - ★ **g_A for 40 B.:** C. Alexandrou *et al.* [arXiv:1606.01650] 25 citations
  - **g_A for Σ, Ξ:** A. Savanur, H.-W. Lin [arXiv:1901.00018] 9 citations
  - ★ **$g_{A,S,T}$ for N, Σ, Ξ:** G. Bali et al. 2023, [arXiv:2305.04717] 13 citations
- Transition form factors
  - **f_1 for ΣN, ΞΣ, Λp, ΞΛ:** P. E. Shanahan *et al.* [arXiv:1508.06923] 13 citations
  - ★ **Vector FF for ΣN, ΞΣ:** S. Sasaki [arXiv:1708.04008] 12 citations
  - ★ **V-A FF for $\Lambda_c\Lambda$:** S. Meinel [arXiv:1611.09696] 61 citations

C. Alexandrou et al. [arXiv:1606.01650]

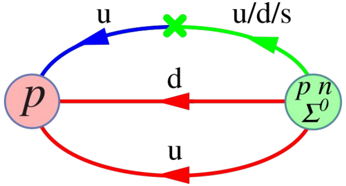
- "Axial charges of hyperons and charmed baryons using N_f=2+1+1 twisted mass fermions"
    - Isovector *u-d*, *u+d-2s* and *u+d+s-3c* axial charges of 40 baryons
    - One in a kind study:
        - Computed using fixed-insertion
        - i.e. fixed current and momentum transfer
        - Thus, got g_A for any possible baryon!

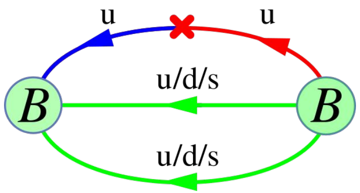






- Fixed-sink
- Fixed-insertion





- Fixed
- Free
- Sequential

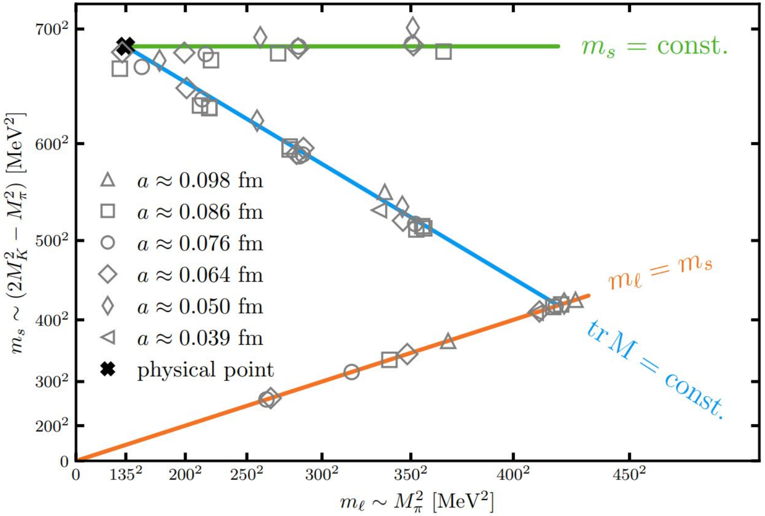
G. Bali et al. 2023, [arXiv:2305.04717]

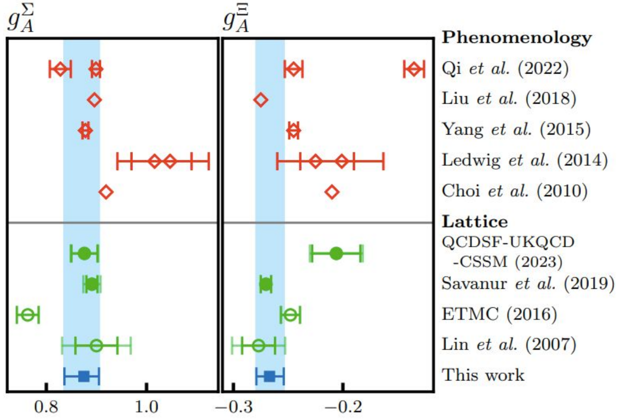
- “Octet baryon isovector charges from $N_f = 2 + 1$ lattice QCD”
  - i.e. *u-d* combination for N, Σ and Ξ
  - State-of-the-art calculation, 47 ensembles!

$$g_A^N = 1.284^{(28)}_{(27)}, \quad g_A^\Sigma = 0.875^{(30)}_{(39)}, \quad g_A^\Xi = -0.267^{(13)}_{(12)}$$

$$g_S^N = 1.11^{(14)}_{(16)}, \quad g_S^\Sigma = 3.98^{(22)}_{(24)}, \quad g_S^\Xi = 2.57^{(11)}_{(11)}$$

$$g_T^N = 0.984^{(19)}_{(29)}, \quad g_T^\Sigma = 0.798^{(15)}_{(21)}, \quad g_T^\Xi = -0.1872^{(59)}_{(41)}$$



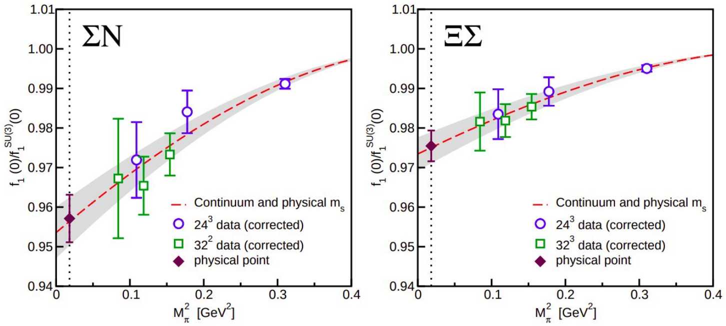


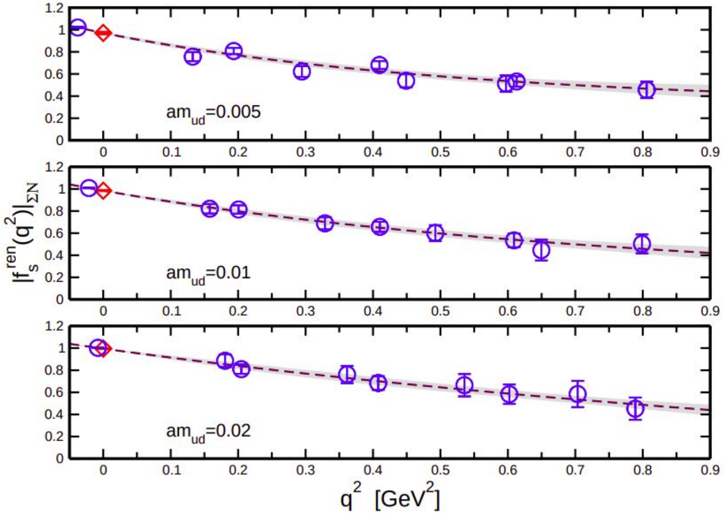
S. Sasaki [arXiv:1708.04008]

- "Continuum limit of hyperon vector coupling $f_1(0)$ from 2+1 flavor domain wall QCD"
  - One of the few studies on transition FF

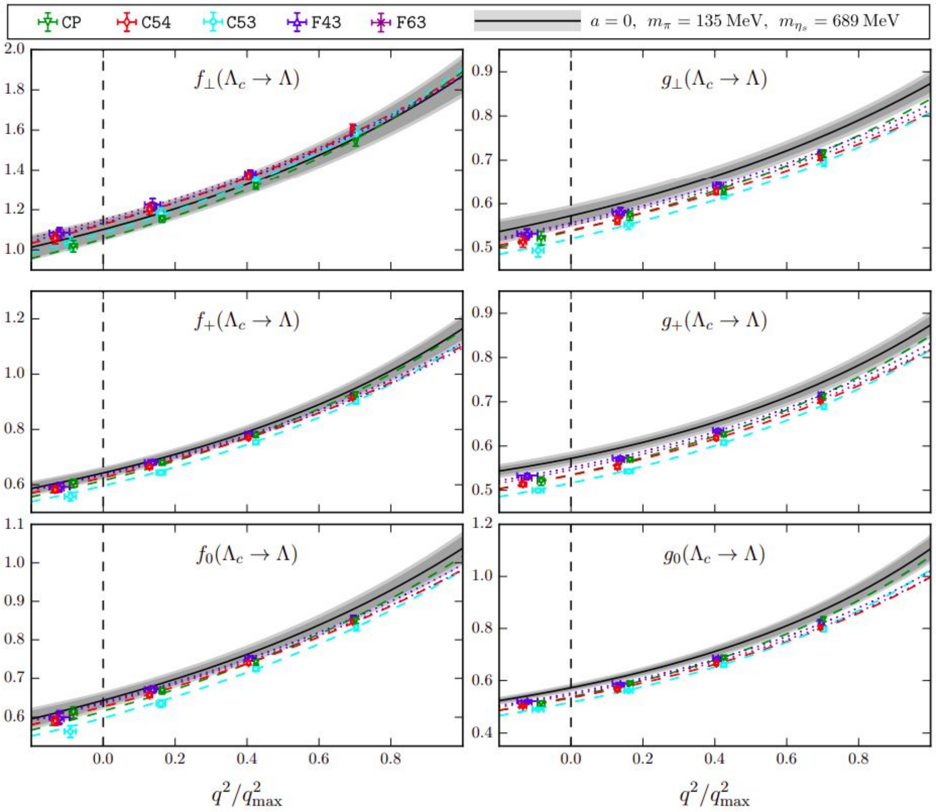
$$f_1(0) = \begin{cases} -0.9571(60)_{\rm stat}(66)_{q^2}(37)_\chi(24)_{\rm scale} & [\Sigma \to N] \\ +0.9755(39)_{\rm stat}(16)_{q^2}(21)_\chi(24)_{\rm scale} & [\Xi \to \Sigma], \end{cases}$$

$$= \begin{cases} -0.9571(99)_{\rm combined} & [\Sigma \to N] \\ +0.9755(53)_{\rm combined} & [\Xi \to \Sigma], \end{cases}$$





S. Meinel [arXiv:1611.09696]



" $\Lambda_c \to \Lambda \ell^+ \nu_\ell$ form factors and decay rates from lattice QCD with physical quark masses"

- State-of-the-art calculation
- There is actually quite few more literature on decays of Λ_c from lattice (e.g. inspire-hep)

$\Lambda_c \to N$ form factors from lattice QCD and phenomenology of $\Lambda_c \to n \ell^+ \nu_\ell$ and $\Lambda_c \to p \mu^+ \mu^-$ decays #20
Stefan Meinel (Arizona U. and RIKEN BNL) (Dec 15, 2017)
Published in: *Phys.Rev.D* 97 (2018) 3, 034511 • e-Print: 1712.05783 [hep-lat]
pdf DOI cite claim reference search 62 citations

First lattice QCD calculation of semileptonic decays of charmed-strange baryons Ξ_c * #15
Qi-An Zhang (Shanghai Jiao Tong U. and Tsung-Dao Lee Inst., Shanghai), Jun Hua (Shanghai Jiaotong U., INPAC and Tsung-Dao Lee Inst., Shanghai), Fei Huang (Shanghai Jiaotong U., INPAC and Tsung-Dao Lee Inst., Shanghai), Renbo Li (Nanjing Normal U.), Yuanyuan Li (Nanjing Normal U.) et al. (Mar 11, 2021)
Published in: *Chin.Phys.C* 46 (2022) 1, 011002 • e-Print: 2103.07064 [hep-lat]
pdf DOI cite claim reference search 37 citations

Λc→Λ*(1520) form factors from lattice QCD and improved analysis of the Λb→Λ*(1520) and Λb→Λc*(2595,2625) form factors #12
Stefan Meinel (Arizona U.), Gumaro Rendon (Brookhaven) (Jul 27, 2021)
Published in: *Phys.Rev.D* 105 (2022) 5, 054511 • e-Print: 2107.13140 [hep-lat]
pdf DOI cite claim reference search 35 citations

What else can be done?

- Given the state-of-the-art on the nucleon, much more can be done!
  - Hyperons are not harder, actually should be even simpler
  - But they do not come for free and we require proper **motivation**!

- **Proposal #1:** Extend to the baryon octet
  - Diagonal and transition matrix elements
  - Same technology as used for the nucleon

- **Proposal #2:** Non-leptonic two-body decays
  - We are currently getting experience with $\langle N|J|N\pi\rangle$
  - Where shall we start from?

Proposal #1: The Baryon octet

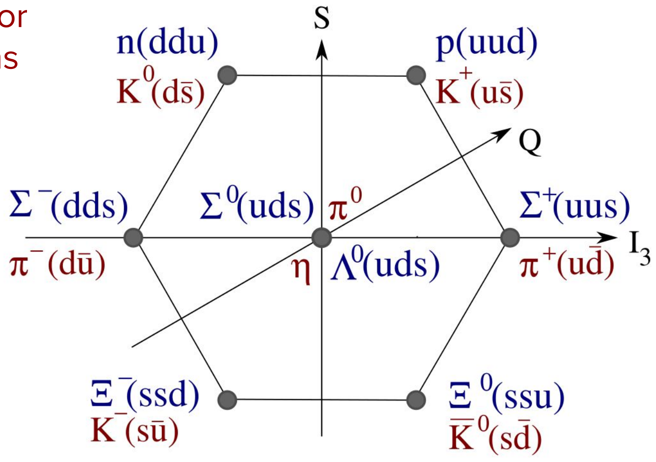
Assuming SU(2) isospin symmetry, there are 16 matrix elements non-zero

$$\mathscr{J}^{\bar{N}\pi N}, \mathscr{J}^{\bar{\Sigma}\pi\Sigma}, \mathscr{J}^{\bar{\Lambda}\pi\Sigma}, \mathscr{J}^{\bar{\Xi}\pi\Xi}, \quad \text{and} \quad \mathscr{J}^{\bar{N}K\Sigma}, \mathscr{J}^{\bar{N}K\Lambda}, \mathscr{J}^{\bar{\Lambda}K\Xi}, \mathscr{J}^{\bar{\Sigma}K\Xi},$$

$$\mathscr{J}^{\bar{N}\eta N}, \mathscr{J}^{\bar{\Sigma}\eta\Sigma}, \mathscr{J}^{\bar{\Lambda}\eta\Lambda}, \mathscr{J}^{\bar{\Xi}\eta\Xi}, \quad \text{and} \quad \mathscr{J}^{\bar{N}\eta' N}, \mathscr{J}^{\bar{\Sigma}\eta'\Sigma}, \mathscr{J}^{\bar{\Lambda}\eta'\Lambda}, \mathscr{J}^{\bar{\Xi}\eta'\Xi}.$$

Notation: current flavor labelled using mesons

Baryons (B)			Mesons (M)			Currents $\left(J^M_\Gamma\right)$
N	n	(ddu)	K	K^0	$(d\bar{s})$	$\bar{d}\Gamma s$
	p	(uud)		K^+	$(\bar{u}s)$	$\bar{u}\Gamma s$
Σ	Σ^-	(dds)	π	π^-	$(\bar{d}u)$	$\bar{d}\Gamma u$
	Σ^0	(uds)		π^0	$(u-d)$	$\bar{u}\Gamma u - \bar{d}\Gamma d$
	Σ^+	(uus)		π^+	$(\bar{u}d)$	$\bar{u}\Gamma d$
Λ	Λ^0	(uds)	η		$(u+d-2s)$	$\bar{u}\Gamma u + \bar{d}\Gamma d - 2\bar{s}\Gamma s$
			η'		$(u+d+s)$	$\bar{u}\Gamma u + \bar{d}\Gamma d + \bar{s}\Gamma s$
Ξ	Ξ^-	(ssd)	$\bar{K}$	K^-	$(\bar{s}u)$	$\bar{s}\Gamma u$
	Ξ^0	(ssu)		$\bar{K}^0$	$(\bar{s}d)$	$\bar{s}\Gamma d$



Proposal #1: The Baryon octet

- **Outcome #1:** Charges and moments
  - Comparison to available results, Ref. PDG
  - A wealth of predictions
    - Scalar charges
    - Tensor chargers
    - Second moments
    - etc…
  - Constraints to physics BSM

[Patrik Adlarson]

BESIII

$\Lambda \to p l^- \bar{\nu}_\mu$

TABLE II. SHD data for $g_1(0)/f_1(0)$ and theoretical determinations of $f_{S,T}(0)/f_1(0)$ at $\mu = 2$ GeV used in this work. The corresponding $r_{S,T}$ are shown in the last two lines.

	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^0 \to \Sigma^+$	$\Xi^- \to \Lambda$
$g_1(0)/f_1(0)$	0.718(15)	−0.340(17)	1.210(50)	0.250(50)
$f_S(0)/f_1(0)$	1.90(10)	2.80(14)	1.36(7)	2.25(11)
$f_T(0)/f_1(0)$	0.72	−0.28	1.22	0.22
r_S	1.60	4.1	0.56	3.7
r_T	5.2	1.7	7.2	1.1

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2 \mu^- \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2 e^- \bar{\nu}_e)} \qquad \frac{R^{\mu e}}{R^{\mu e}_{SM}} = 1 + r_S \epsilon_S + r_T \epsilon_T$$

$\epsilon_S = 0.003(40)$, $\epsilon_T = 0.017(34)$ at 90% CL from SLWD

Potential for $|V_{us}|$ determimation and test of BSM searches from determination of Wilson coefficients $\boldsymbol{\varepsilon}_S$ and $\boldsymbol{\varepsilon}_T$

Nice example where low-energy precision experiments with direct searches in collider experiments

PRL 114, 161802 (2015)

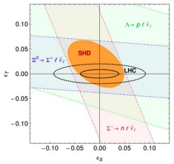


FIG. 1 (color online). 90% C.L. constraints on $\epsilon_{S,T}$ at $\mu = 2$ GeV from the measurements of $R^{\mu e}$ in different channels (dot-dashed lines) and combined (filled ellipse). LHC bounds obtained from CMS data at $\sqrt{s} = 8$ TeV (7 TeV) are represented by the black solid (dashed) ellipse.

$\sigma(pp \to e + \mathrm{MET} + X)$

Electromagnetic

Quantity	Value	
μ_Λ	-0.613(4)	μ_N
μ_{Σ^+}	2.458(10)	μ_N
μ_{Σ^-}	-1.160(25)	μ_N
μ_{Ξ^0}	-1.250(14)	μ_N
μ_{Ξ^-}	-0.6507(25)	μ_N
$\lvert\mu_{\Sigma^0 \to \Lambda^0}\rvert$	1.61(8)	μ_N
$\langle r_E^2 \rangle_{\Sigma^-}$	0.61(15)	fm

Axial-vector

$B \to B'$	g_A/f_1
$\Lambda^0 \to p$	0.718(15)
$\Sigma^- \to n$	−0.340(17)
$\Xi^0 \to \Sigma^+$	1.22(5)
$\Xi^- \to \Lambda^0$	0.25(5)

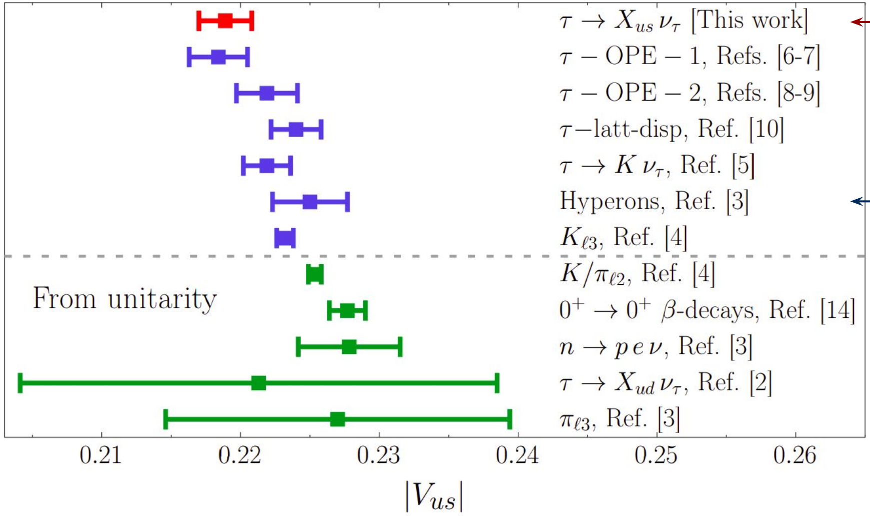
$B \to B'$	g_2/f_1
$\Xi^0 \to \Sigma^+$	−1.7(2.1)

$B \to B'$	f_2/f_1
$\Sigma^- \to n$	0.97(14)
$\Xi^0 \to \Sigma^+$	2.0(9)

Proposal #1: The Baryon octet

- **Outcome #2:** Baryonic determination of $|V_{us}|$

$$\Gamma(B \to B'\ell\nu_\ell) = \frac{G_F^2(1+\Delta_{RC})}{60\pi^3}(m_B - m_{B'})^5(1-3\delta_{BB'})|V_{us}|^2\left[\left|f_1^{\bar{B}'KB}\right|^2 + 3\left|g_A^{\bar{B}'KB}\right|^2 - 2\delta_{BB'}g_2^{\bar{B}'KB}g_A^{\bar{B}'KB} + O(\delta_{BB'}^2)\right]$$



Will be on the arXiv by next week

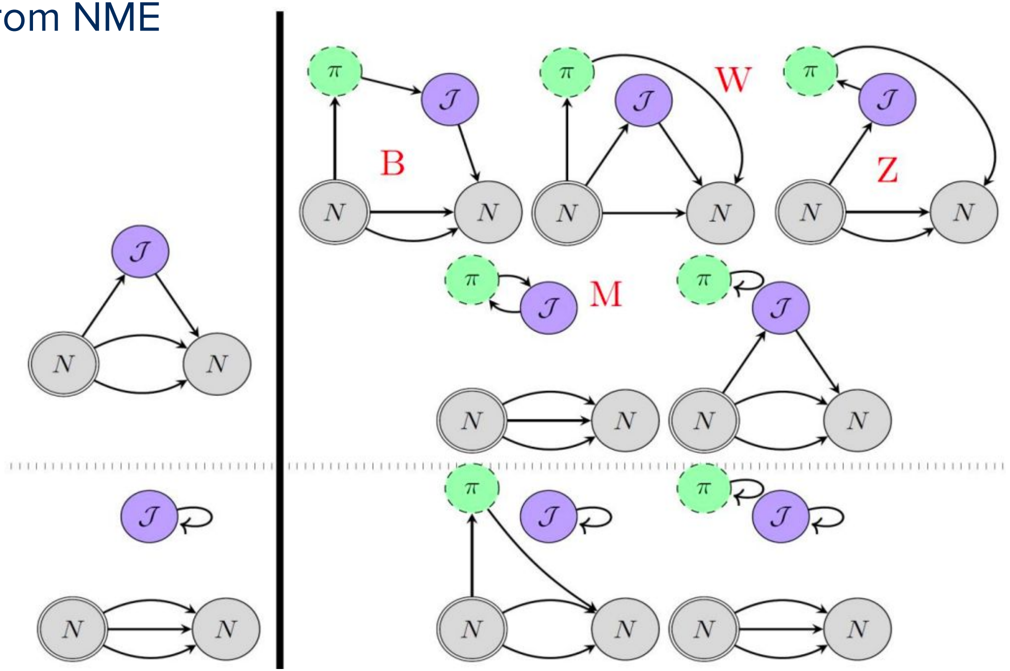
Can be improved via lattice QCD

$B \to B'$	$R^{\mu e}_{\text{exp.}}$ [20]
$\Lambda^0 \to p$	0.189(41)
$\Sigma^- \to n$	0.442(39)
$\Xi^0 \to \Sigma^+$	0.0092(14)
$\Xi^- \to \Lambda^0$	0.6(5)

$B \to B'$	$\Gamma/\Gamma(\text{total})$	Err./$\vert V_{us}\vert$
$\Lambda^0 \to p$	$8.34(14)\cdot 10^{-4}$	0.8%
$\Sigma^- \to n$	$10.17(34)\cdot 10^{-4}$	1.7%
$\Xi^0 \to \Sigma^+$	$2.52(8)\cdot 10^{-4}$	1.6%
$\Xi^- \to \Lambda^0$	$1.27(23)\cdot 10^{-4}$	9.1%
$\Xi^- \to \Sigma^0$	$0.87(17)\cdot 10^{-4}$	9.8%

Proposal #2: Non-leptonic two-body decay

- We are getting experience with $\langle N|J|N\pi\rangle$
  - Useful to remove excited states from NME
- It could be extended to
  - $\langle\Lambda|H_w|N\pi\rangle$
  - $\langle\Sigma|H_w|N\pi\rangle$
  - $\langle\Xi|H_w|\Lambda\pi\rangle$
  - ...
- Clearly very very challenging...
- ... I could not find any existing study



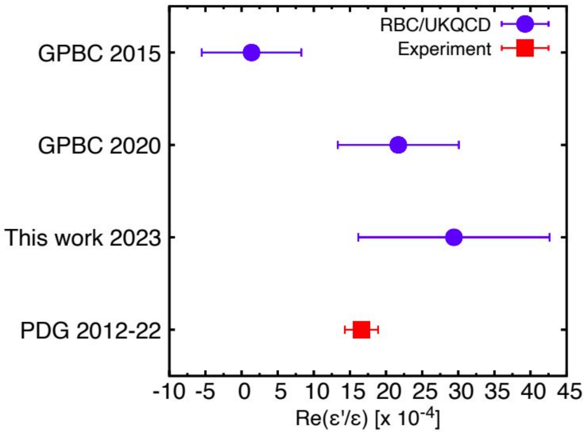
Why so difficult?

- The decay has to be on-shell, having $E_{B_1} \simeq E_{B_2P}$ to compute $\langle B_1|H_w|B_2P\rangle$
  - Achieved using a properly-sized lattice [T. Blum *et al.* arXiv:2306.06781]
  - … or G-boundary conditions [R. Abbott *et al.* arXiv:2004.09440]
  - … or twisted-boundary conditions [G. M. de Divitiis, N. Tantalo arXiv:hep-lat/0409154]

- E_{B_2P} is not a ground state
  - GEVP required

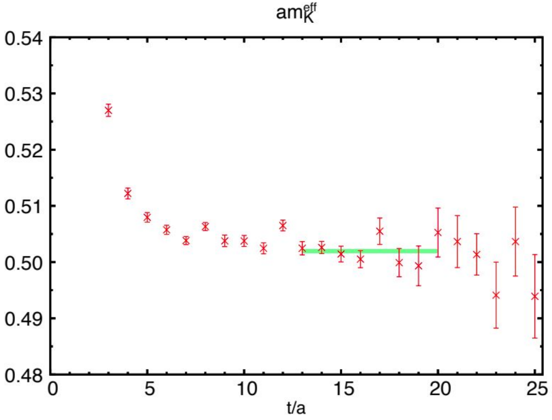
- Results available only for $K \rightarrow \pi\pi$

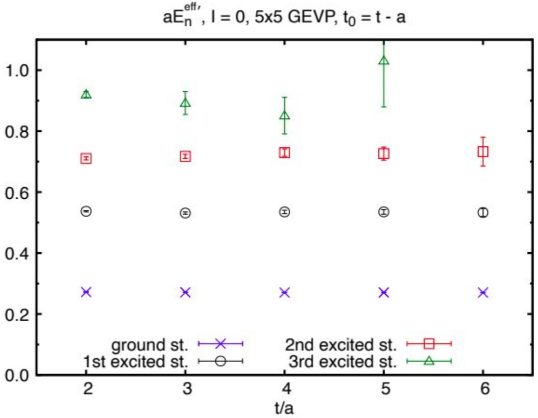
- **What is interesting & possible to look at??**



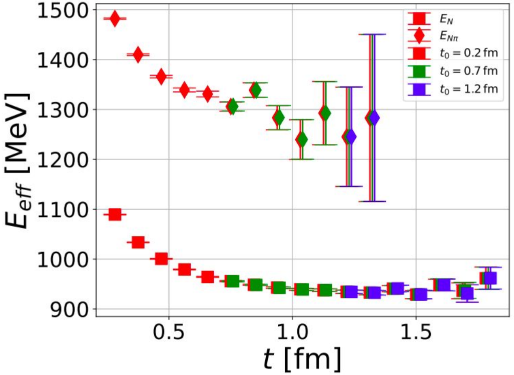
Mesonic vs baryonic case

[T. Blum *et al.* arXiv:2306.06781]



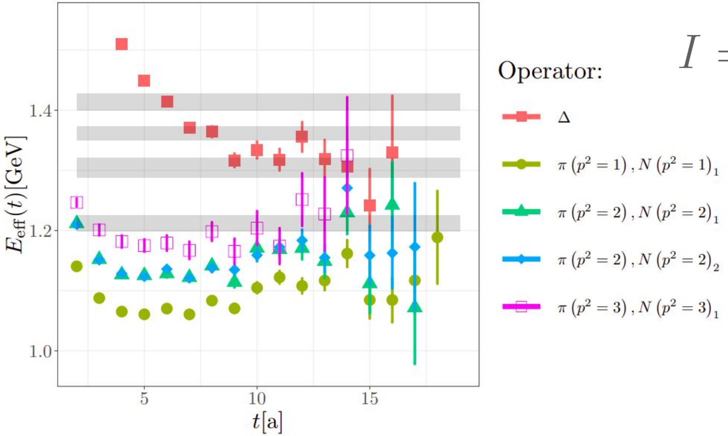


[Preliminary]



$$I = \frac{1}{2}$$

[C. Alexandrou *et al.* arXiv:2307.12846]



$$I = \frac{3}{2}$$

Thank you for your attention and the organization!

Extended Twisted Mass Collaboration

Looking forward to discussion sessions:

- Proposal #1: Diagonal and transition matrix elements of the baryons octet.
  We have the technology to provide results with controlled systematics.

- Proposal #2: Two-body decays, **where is best to start from?**

Funded by the European Union

EuroHPC Joint Undertaking

INNO4 SCALE

This project has received funding from the European High-Performance Computing Joint Undertaking (JU) under grant agreement No 101118139. The JU receives support from the European Union's Horizon Europe Programme.