$g_A$

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Current Status - $g_A$

- $N_f = 2+1+1$
  - PNDME ’18 (Preliminary)
  - CalLat ’17B (Preliminary)
  - CalLat ’17A
  - PNDME ’16

- $N_f = 2+1$
  - LHPC ’14
  - LHPC ’10
  - RBC/UKQCD ’08
  - Lin/Orginos ’07

- $N_f = 2$
  - Mainz ’17
  - ETMC ’17
  - ETMC ’15
  - RQCD ’14
  - QCDSF/UKQCD ’14
  - Mainz ’12

- Expt
  - PDG 1.2723(23)
• Lattice
  – TMF, $N_f=2$
  – $a = 0.094$ fm
  – $m_\pi = 130$ MeV
  – $m_\pi L = 3.0$

• Measurement/Analysis
  – APE-smearred links
  – Fixed-sink method
  – *Plateau method* at $t_{sep} = 1.31$ fm
    (compared with Two-state fit)
  – NPR
  – Single lattice spacing at physical pion mass
Mainz ’17 (arXiv:1705.06186)

• Lattices
  – CLS, $N_f=2$
  – $a = 0.050, 0.063$ and 0.079 fm
  – $m_\pi = 190 – 473$ MeV, $m_\pi L \gtrsim 4$

• Measurement/Analysis
  – APE-smeared links
  – Fixed-sink method
  – O(a)-improved axial current
  – *Two-state fit* with assumption of the Nππ dominant excited-state (compared with summation method)
  – NPR
  – No $a$-dependence, central value from linear fit in $m_\pi^2$ for $m_\pi < 330$ MeV
• Lattices
  – DWF-on-HISQ, $N_f=2+1+1$
  – $a = 0.09, 0.12$ and $0.15$ fm
  – $m_{\pi} = 130 - 400$ MeV

• Measurement/Analysis
  – Gradient-flowed links
  – Feynman-Hellmann-inspired current-at-all-timeslices method
  – Summation method + two-state fit
  – $g_A/g_V$ with $Z_A/Z_V = 1$, $Z_V g_V = 1$
  – $(a, m_{\pi}, L)$ extrapolation:
    
    $$ g_A = g_0 - \epsilon_\pi^2 \left[ (g_0 + 2 g_0^3) \ln \epsilon_\pi^2 - c_2 \right] + g_0 c_3 \epsilon_\pi^3 
    + a_2 \epsilon_a^2 + c_4 \epsilon_\pi^4 + b_4 \epsilon_a^2 \epsilon_\pi^2 + a_4 \epsilon_a^4 
    + (8/3) \epsilon_\pi^2 \left[ g_0^3 F_1(m_{\pi} L) + g_0 F_3(m_{\pi} L) \right] $$

CalLat ’17 (EPJ WoC 175, 01008, 2018)
• **Lattices**
  – Clover-on-HISQ, $N_f = 2+1+1$
  – $a = 0.06, 0.09, 0.12$ and $0.15$ fm
  – $m_\pi = 130 - 320$ MeV

• **Measurement/Analysis**
  – HYP-smeared links
  – Fixed-sink-method
  – 3-state fit for excited state
  – NPR
  – $(a, m_\pi, L)$ extrapolation:
    
    \[
    g_A = c_1 + c_2 a \\
    + c_3 m_\pi^2 + c_3' m_\pi^2 \ln \left( \frac{m_\pi}{m_\rho} \right)^2 \\
    + c_4 m_\pi^2 e^{-m_\pi L}
    \]

[Graph showing trend of $g_A$ with $a$]
$g_A$ Comparison between CalLat and PNDME

**PDG**
1.272(02)

**CalLat ’17B**
1.285(17) [+0.8σ]

**PNDME ’18**
1.213(33) [-1.8σ]

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LHPC ’14
LHPC ’10
RBC/UKQCD ’08
Lin/Orginos ’07
Mainz ’17
ETMC ’17
ETMC ’15
RQCD ’14
QCDSF/UKQCD ’14
Mainz ’12

**CalLat ’17B (Preliminary)**

**PNDME ’18 (Preliminary)**

**CalLat ’17A**

**PNDME ’16**

**Mainz ’17**

**ETMC ’15**

**Lin/Orginos ’07**

**RBC/UKQCD ’08**

**LHPC ’14**

**LHPC ’10**

**PNDME ’18 (Preliminary)**

**PDG 1.2723(23)**
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<tr>
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<th>PNDME</th>
<th>CalLat</th>
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<td>Sequential source position in $C_{3pt}$</td>
<td>At sink</td>
<td>At current (at all $t$)</td>
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<td>All $\vec{p}$ &amp; $\gamma$, single $t_{sep}$</td>
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<td>Excited State</td>
<td>three-state fit</td>
<td>Summation method + two-state fit</td>
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<td>$t_{sep} = 0.9 - 1.5$ fm</td>
<td>$t_{sep} = 0.5 - 1.5$ fm</td>
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<td>Renormalization</td>
<td>NPR</td>
<td>$Z_A/Z_V = 1$</td>
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<td>Leading ($a, m_\pi$)</td>
<td>$a, m_\pi^2$</td>
<td>$(a/w_0)^2, (m_\pi/F_\pi)^2$</td>
</tr>
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</table>
**Fixed-sink method**

- Fixed sink timeslice, momentum, projection
- Sequential prop from sink
- Any operator insertions with any momenta can be obtained by contraction
- Need sequential prop for each $t_{sep}$

**Current-at-all-timeslices**

- Current inserted at all lattice space-time
- Sequential prop from current insertion
- Any sink timeslices obtained by contraction
- Need sequential propagator calculation for each current $(A, V)$ and momentum
Excited States - PNDME

- 3-state fit with \( t_{sep} \approx 0.9 - 1.5 \text{ fm} \)
- Data at \( t_{sep} = 14a \) are noisy
Excited States - CalLat

- Remove excited states by 2-point difference in summation method:

\[
g_{A,V}^{\text{eff}}(t_{\text{sep}}) = \frac{N_{3\text{pt}}(t_{\text{sep}} + 1)}{C_{2\text{pt}}(t_{\text{sep}} + 1)} - \frac{N_{3\text{pt}}(t_{\text{sep}})}{C_{2\text{pt}}(t_{\text{sep}})}
\]

Usual summation method:

\[
\sum_{t=1}^{t_{\text{sep}}-1} \frac{C_{3\text{pt}}(t_{\text{sep}}, t)}{C_{2\text{pt}}(t_{\text{sep}})} = \text{Const} + t_{\text{sep}}g_A + \cdots
\]

- Remove remaining excited state by two-state fit to \(g_{A,V}^{\text{eff}}\) with

\[t_{\text{sep}} \approx 0.5 - 1.5 \text{ fm}\]
Continuum extrapolation - CalLat

- Upward trend in $\alpha^2$
- $g_A = 1.285(17)$
Continuum extrapolation - PNDME

- Downward trend in $a$
- $g_A = 1.213(33)$
- Largely driven by $a \sim 0.06$ fm points
- Without $a \sim 0.06$ fm, $g_A = 1.238(49)$
Flavor-diagonal $g_A^u$, $g_A^d$, and $g_A^s$

- Proton spin decomposition
  \[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta G \]
  \[ \Delta \Sigma = g_A^u + g_A^d + g_A^s + \cdots \]

- Need evaluation of quark-line connected & disconnected diagrams
Current Status - $g_A^s$

- Experiments Lattice QCD
  - PNDME ’18 (Preliminary)
  - ETMC ’17
  - χQCD ’16
  - CMMS/QCDSF/UKQCD ’15
  - Engelhardt ’12
  - QCDSF ’12

- Global Fit (Lattice PDF ’17)
  - JAM17
  - JAM15
  - NNPDFpol1.1
  - DSSV08

Current Status - $g_A^u$ and $g_A^d$

Lattice QCD
- ETMC '17
- JAM17
- JAM15
- NNPDFpol1.1
- DSSV08

Experiments
- Global Fit (Lattice PDF '17)
- JAM17
- JAM15
- NNPDFpol1.1
- DSSV08

Disconnected contribution: PNDME

\[ g_{\text{disc}} \]

\[ g_{\text{disc}}^s \]

\[ a \text{ (fm)} \]

\[ M_{\pi}^2 \text{ (GeV}^2) \]
Conclusion

• $g_A$: CalLat provides most precise lattice QCD estimate based on fits with small $t_{sep}$ and exact $Z_A/Z_V = 1$

• Difference between PNDME and CalLat comes mostly from difference in $a$-extrapolation with results at $a \sim 0.06$ fm

• $g^u,d_A$: PNDME show a significant dependence on $a$ and $m_\pi$. The larger negative disconnected contribution reduces the contribution of quarks to the proton spin:

\[ \frac{1}{2} \Sigma = 0.201(18) \text{ [ETMC ’17]} \]
\[ \frac{1}{2} \Sigma = 0.144(17) \text{ [PNDME ’18 (preliminary)]} \]