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Octet baryon magnetic moments at next-to-next-to-leading order in covariant chiral perturbation theory

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OUTLINE

1. INTRODUCTION
2. FORMALISM
3. RESULTS
4. CONCLUSION

1 INTRODUCTION

Magnetic moment of particles

- **Spin magnetic moment**

$$\mu = g\frac{e}{2m}S$$

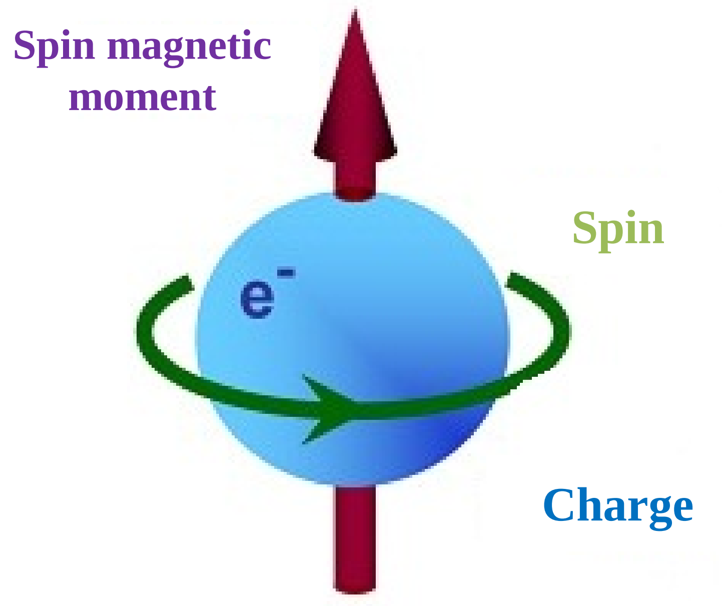
- **Nucleon magnetic moments**

$$\mu_p = \frac{e}{2m_N} \quad \mu_n = 0$$

- **Anomalous magnetic moment**

$$\mu_p = 2.793\frac{e}{2m_N}$$

$$\mu_n = -1.193\frac{e}{2m_N}$$



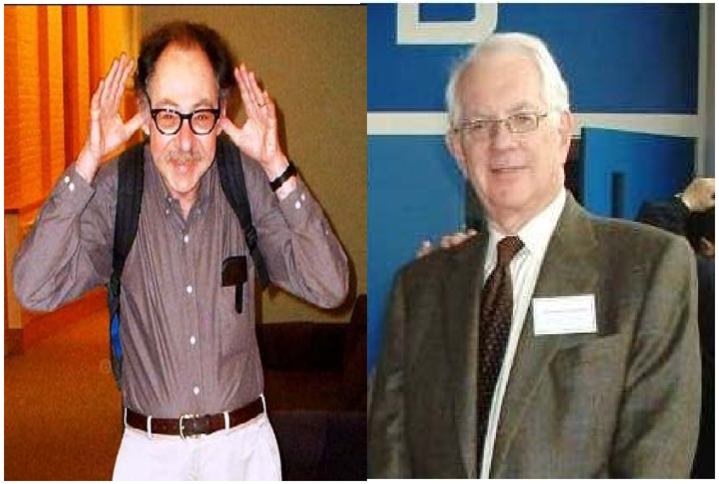
g/2=1.001159652193（10）

- **Radiative correction (electron and muon)**
- **Internal structure (proton and neutron)**

Coleman-Glashow Formula

SU(3) Symmetry

Sheldon Lee Glashow



Sidney Coleman

$$\mu(\Sigma^+) = \mu(p)$$
$$\mu(\Lambda) = \frac{1}{2}\mu(n)$$
$$\mu(\Xi^0) = \mu(n)$$
$$\mu(\Xi^-) = \mu(\Sigma^-) = -[\mu(p) + \mu(n)]$$
$$\mu(\Sigma^0) = -\frac{1}{2}\mu(n)$$

Coleman, Sidney R. et al. Phys.Rev.Lett. 6 423 (1961)

A Leading order calculation in Chiral Perturbation Theory(ChPT)

Coleman-Glashow Formula

SU(3) Symmetry

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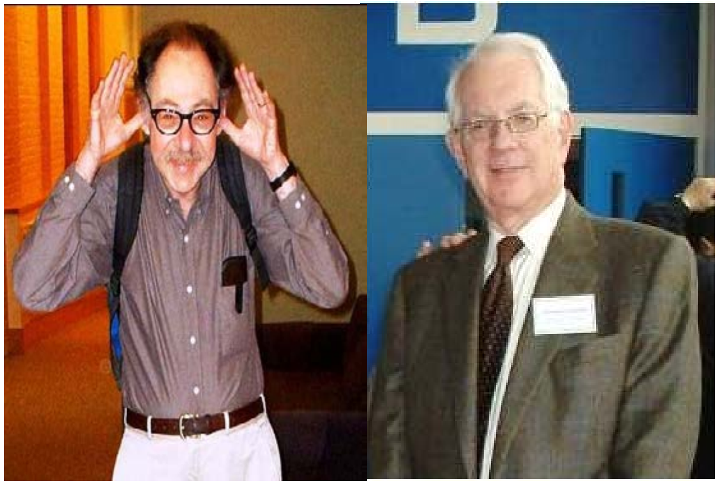

Sidney Coleman

$$2.46 = 2.793$$

$$-0.61 = -0.596$$

$$-1.25 = -1.193$$

$$-0.65 = -1.16 = -0.8$$

$$? = 0.596$$

Coleman, Sidney R. et al. Phys.Rev.Lett. 6 423 (1961)

A Leading order calculation in
Chiral Perturbation Theory(ChPT)

Coleman-Glashow Formula

SU(3) Symmetry

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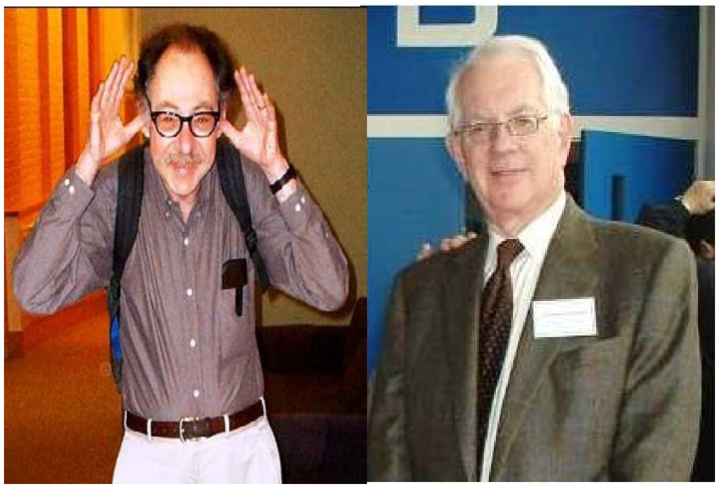


Sidney Coleman

$$2.46 = 2.793$$

These relations are consistent with experiment data

$$? = 0.596$$

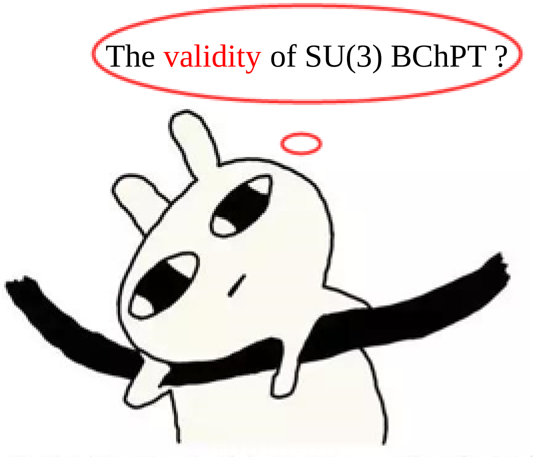
Coleman, Sidney R. et al. Phys.Rev.Lett. 6 423 (1961)

A Leading order calculation in
Chiral Perturbation Theory(ChPT)

Loop correction

SU(3) symmetry breaking

1. D. G. Caldi and H. Pagels, Phys. Rev. D 10, 3739 (1974).
2. J. Gasser and H. Leutwyler, Nucl. Phys. B250, 465 (1985).
3. J. Gasser, M. E. Sainio, and A. Svarc, Nucl. Phys. B307, 779 (1988).
4. E. E. Jenkins, M. E. Luke, A.V. Manohar, and M. J. Savage, Phys. Lett. B 302, 482 (1993); 388, 866 (1996).
5. S. Scherer, Adv. Nucl. Phys. 27, 277 (2003).
6. …………



□ The contribution of NLO turns to worsen the results

Theoretical calculation

Nonrelativistic

$M_K/\Lambda_{QCD} = 0.5$

- Heavy Baryon chiral perturbation theory
- Up to NNLO
- Bad convergence at NLO
- Excellent convergence at NNLO

$$\begin{aligned}
\mu_p &= +4.48(1 - 0.49 + 0.11) = +2.79,\\
\mu_n &= -2.47(1 - 0.34 + 0.12) = -1.91,\\
\mu_{\Sigma^+} &= +4.48(1 - 0.62 + 0.17) = +2.46,\\
\mu_{\Sigma^-} &= -2.01(1 - 0.31 - 0.11) = -1.16,\\
\mu_{\Sigma^0} &= +1.24(1 - 0.87 + 0.40) = +0.65,\\
\mu_{\Lambda} &= -1.24(1 - 0.87 + 0.37) = -0.61,\\
\mu_{\Xi^0} &= -2.47(1 - 0.89 + 0.40) = -1.25,\\
\mu_{\Xi^-} &= -2.01(1 - 0.64 - 0.03) = -0.65,\\
\mu_{\Lambda\Sigma^0} &= +2.14(1 - 0.53 + 0.19) = +1.40.
\end{aligned}$$

U. G. Meissner and S. Steininger, Nucl. Phys. B499, 349 (1997).

Relativistic

- Extended On Mass Shell ChPT
- Up to NLO
- Nice convergence properties

$$\begin{aligned}
\mu_p &= +3.47(1 - 0.257) = +2.58,\\
\mu_n &= -2.55(1 - 0.175) = -2.10,\\
\mu_{\Sigma^+} &= +3.47(1 - 0.300) = +2.43,\\
\mu_{\Sigma^-} &= -0.93(1 + 0.187) = -1.16,\\
\mu_{\Sigma^0} &= +1.27(1 - 0.482) = +0.66,\\
\mu_{\Lambda} &= -1.27(1 - 0.482) = -0.66,\\
\mu_{\Xi^0} &= -2.55(1 - 0.501) = -1.27,\\
\mu_{\Xi^-} &= -0.93(1 + 0.025) = -0.95,\\
\mu_{\Lambda\Sigma^0} &= +2.21(1 - 0.284) = +1.58.
\end{aligned}$$

L.S. ,Geng et al. Phys.Rev.Lett. 101 222002 (2008).

Theoretical calculation

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U. G. Meissner and S. Steininger, Nucl. Phys. B499, 349 (1997).

Relativistic

- Extended On Mass Shell ChPT
- Up to NLO
- Nice convergence properties

Coincidence?

$$
\begin{aligned}
\mu_p &= +3.47(1-0.257) = +2.58,\\
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\end{aligned}
$$

L.S. ,Geng et al. Phys.Rev.Lett. 101 222002 (2008).

2 FORMALISM

Baryon magnetic moments

Definition

Magnetic moments are defined through electromagnetic current

$$\langle \bar{B} | J_\mu | B \rangle = \bar{u}(p_f) \left[\gamma_\mu F_1^B(t) + \frac{i\sigma_{\mu\nu} q^\nu}{2m_B} F_2^B(t) \right] u(p_i).$$

t=0

Magnetic moments= Anomalous magnetic moments + Charge

Steps

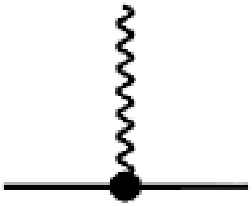
1. **Calculate all Feynman diagrams** $\mu = \mu^{(2)} + \mu^{(3)} + \mu^{(4)} + \cdots\cdots$
2. **Extract the $F_2^B(0)$**
3. **Fit LECS**

Feynman diagrams and Lagrangians

Leading order

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

$$\mathcal{L}_{MB}^{(2)} = \frac{b_6^D}{8m}\langle \bar{B}\sigma^{\mu\nu}\left\{F_{\mu\nu}^+, B\right\}\rangle + \frac{b_6^F}{8m}\langle \bar{B}\sigma^{\mu\nu}\left[F_{\mu\nu}^+, B\right]\rangle,$$



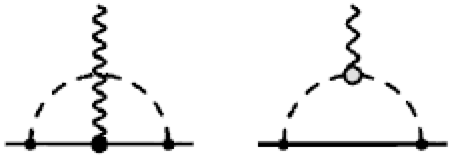
(a)

Next to leading order

$$\mathcal{L}_B^{(1)} = \langle \bar{B} i\gamma^\mu D_\mu B\rangle,$$

$$\mathcal{L}_{MB}^{(1)} = \frac{D}{2}\langle \bar{B}\gamma^\mu\gamma^5\left\{u_\mu, B\right\}\rangle + \frac{F}{2}\langle \bar{B}\gamma^\mu\gamma^5\left[u_\mu, B\right]\rangle,$$

$$\mathcal{L}_M^{(2)} = \frac{F_0^2}{4}\langle u_\mu u^\mu + \chi^+\rangle,$$

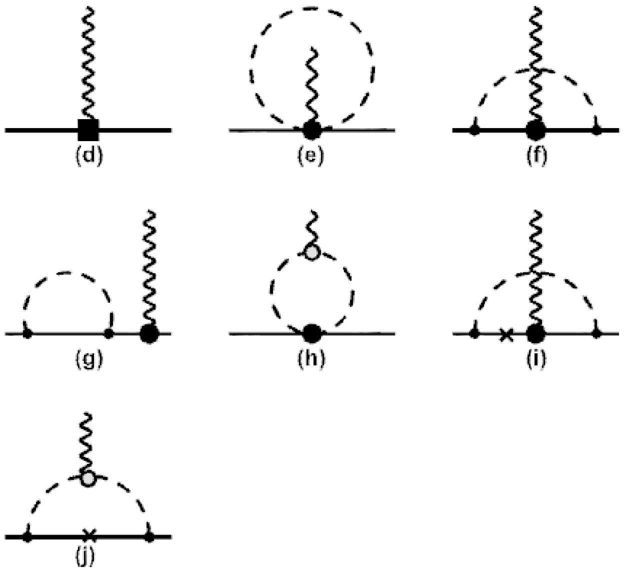


(b) (c)

Feynman diagrams and Lagrangians

Next to next to leading order

$$\mathcal{L}_{MB}^{(4)} = +\frac{b_6^{D'}}{8m}\langle\chi^+\rangle\langle\bar{B}\sigma^{\mu\nu}\{F_{\mu\nu}^+, B\}\rangle + \frac{b_6^{F'}}{8m}\langle\chi^+\rangle\langle\bar{B}\sigma^{\mu\nu}[F_{\mu\nu}^+, B]\rangle$$
$$+\frac{\alpha_1}{8m}\langle\bar{B}\sigma^{\mu\nu}\left[\left[F_{\mu\nu}^+, B\right], \chi^+\right]\rangle + \frac{\alpha_2}{8m}\langle\bar{B}\sigma^{\mu\nu}\left\{\left[F_{\mu\nu}^+, B\right], \chi^+\right\}\rangle$$
$$+\frac{\alpha_3}{8m}\langle\bar{B}\sigma^{\mu\nu}\left[\left\{F_{\mu\nu}^+, B\right\}, \chi^+\right]\rangle + \frac{\alpha_2}{8m}\langle\bar{B}\sigma^{\mu\nu}\left\{\left\{F_{\mu\nu}^+, B\right\}, \chi^+\right\}\rangle$$
$$+\frac{\beta_1}{8m}\langle\bar{B}\sigma^{\mu\nu}B\rangle\langle\chi^+F_{\mu\nu}^+\rangle.$$



$$\mathcal{L}_{MB}^{(2')} = \frac{i}{2}\left\{b_9\langle\bar{B}\sigma^{\mu\nu}u_\mu\rangle\langle u_\nu B\rangle + b_{10,11}\langle\bar{B}\sigma^{\mu\nu}\left(\left[u_\mu, u_\nu\right], B\right)_\pm\rangle\right\}$$

$$\mathcal{L}_{MB}^{(2'')} = b_D\langle\bar{B}\{\chi^+, B\}\rangle + b_F\langle\bar{B}[\chi^+, B]\rangle.$$

Fit LECS

Problem

- **9 LECs**

  $b_6^D, b_6^F, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \beta_1, b_6^{D'}, b_6^{F'}$

- **7 experiment data**

  $p, n, \Lambda, \Sigma^-, \Sigma^+, \Sigma^0, \Xi^-, \Xi^0$

9>7 ⟶ Cannot fit directly！！！

Solution 1

Absorb $b_6^{D\prime}$ and $b_6^{F\prime}$

$$\mathcal{L}_{MB}^{(2)} = \frac{b_6^D}{8m}\langle \bar{B}\sigma^{\mu\nu}\{F_{\mu\nu}^+, B\}\rangle + \frac{b_6^F}{8m}\langle \bar{B}\sigma^{\mu\nu}[F_{\mu\nu}^+, B]\rangle,$$

$$\mathcal{L}_{MB}^{(4)} = +\frac{b_6^{D\prime}}{8m}\langle\chi^+\rangle\langle \bar{B}\sigma^{\mu\nu}\{F_{\mu\nu}^+, B\}\rangle + \frac{b_6^{F\prime}}{8m}\langle\chi^+\rangle\langle \bar{B}\sigma^{\mu\nu}[F_{\mu\nu}^+, B]\rangle$$

$$\Rightarrow \quad b_6^{D,F} \to b_6^{D,F} + \langle\chi^+\rangle b_6^{D',F'}$$

U. G. Meissner and S. Steininger, Nucl. Phys. B499, 349 (1997).

Fit LECS

Solution 2

Constrain b_6^D and b_6^F according to the convergence properties

Start point

- **The success of BChPT**
  - **Baryon mass and sigma terms**
    PRD82:074504,2010 ;PLB766-325, 2017
  - **$N-N$ interaction**
    arXiv:1611.08475
  - **$\pi-N$ scattering**
    PRC83:055205, 2011
  - ……

Assumption

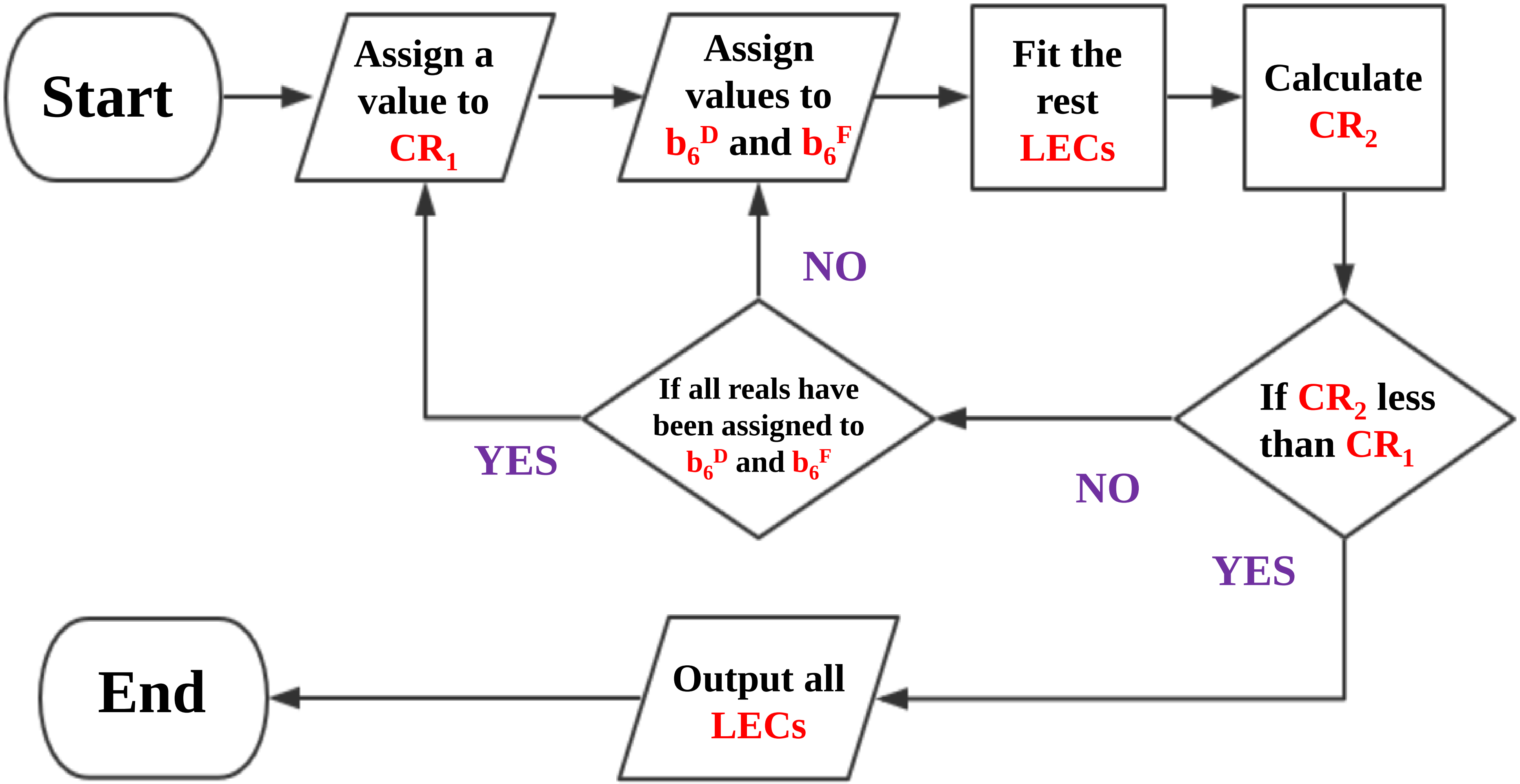
- **BChPT should present good convergence properties**

Fit LECS

Solution 2

Convergence rate

$$\mathrm{CR} = \max(\mu_B^{(3)}/\mu_B^{(2)}, \mu_B^{(4)}/\mu_B^{(3)})$$



Fit LECS

Solution 3

Fit to the lattice QCD data

- **At physical point**
  - **7 data**
- **Large pion mass**
  - **Lots of data**

Fit to exp+LQCD !

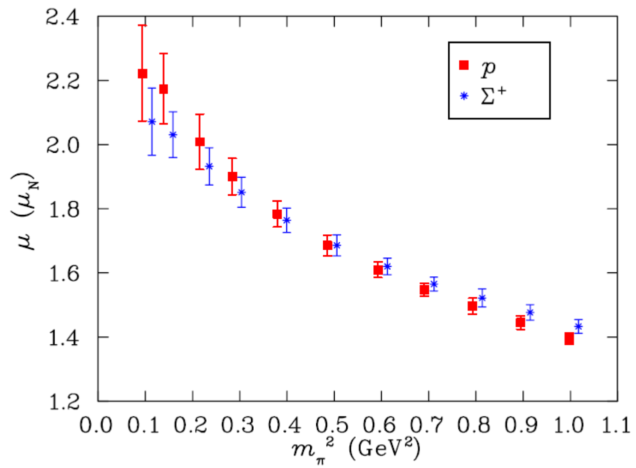


FIG. 26: Magnetic moments of the proton and Σ^+. The Σ^+ moments are offset to the right for clarity.

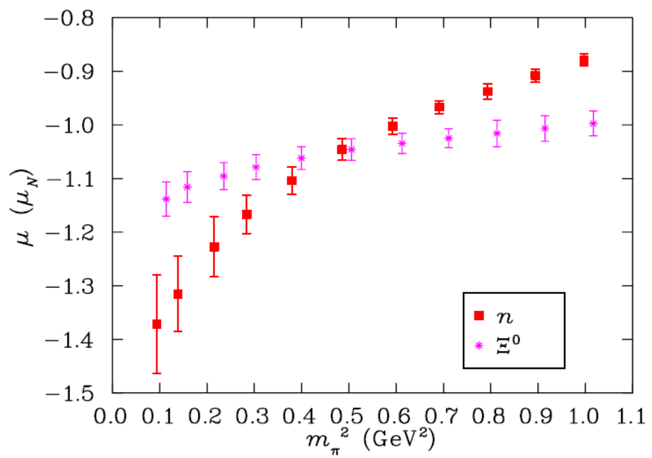


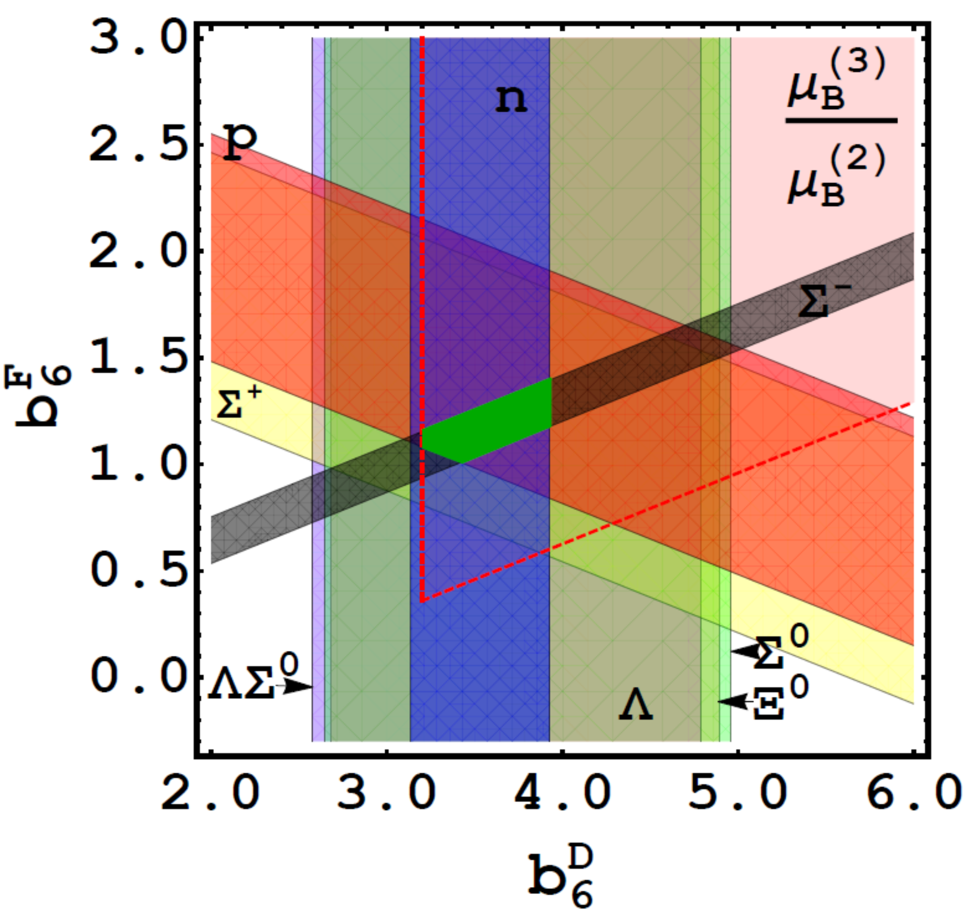
FIG. 27: Magnetic moments of the neutron and Ξ^0. Ξ^0 moments are offset to the right for clarity.

- **Phys. Rev. D 74,093005 (2006)**

3

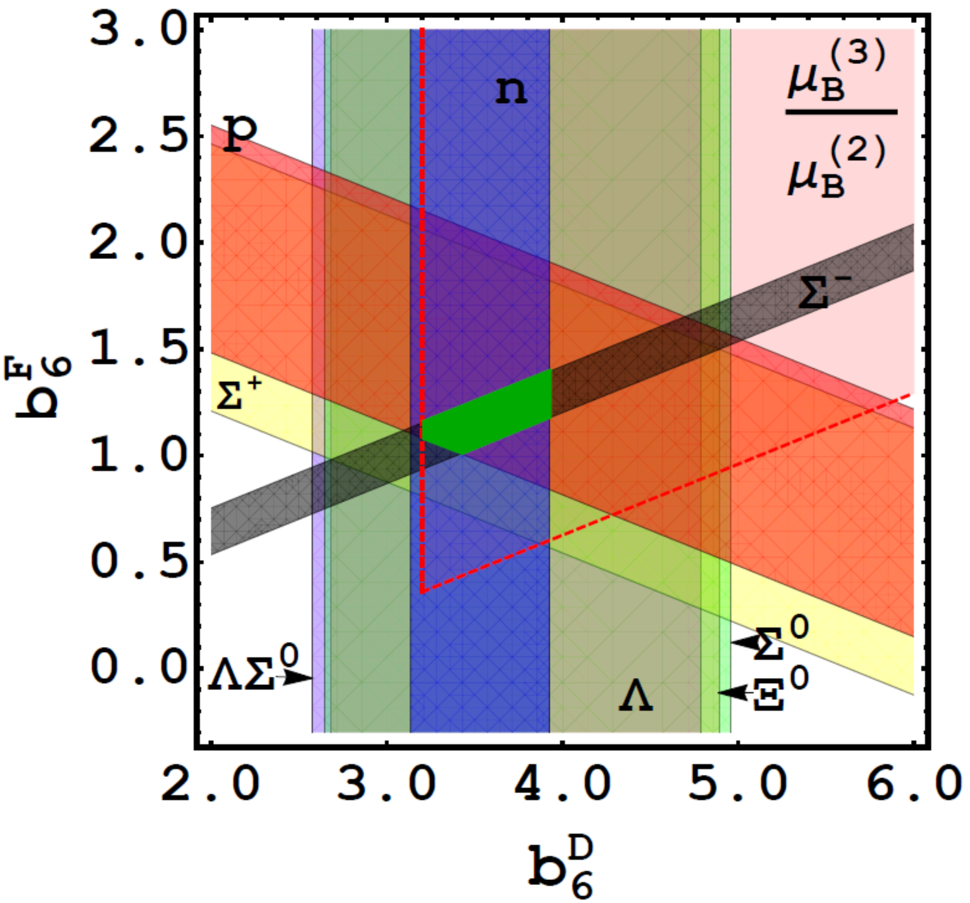
RESULTS

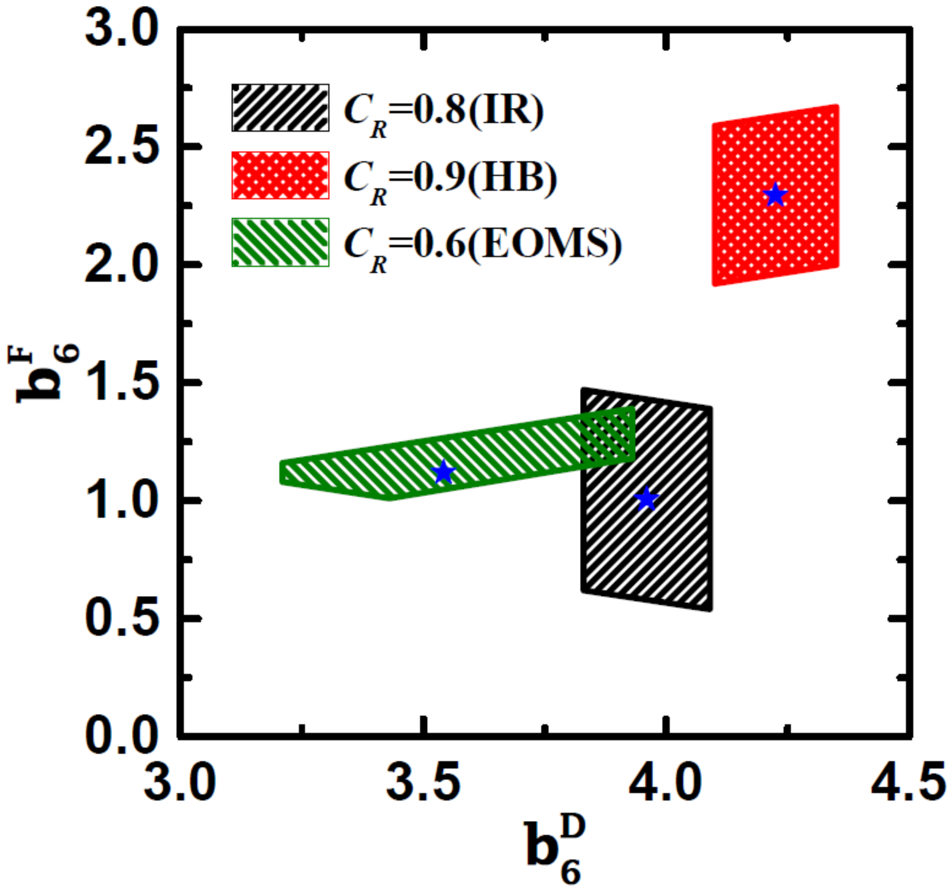
Constrain the values of b_6^D and b_6^F



$\mathrm{CR} = \max(\mu_B^{(3)}/\mu_B^{(2)}, \mu_B^{(4)}/\mu_B^{(3)})$ **CR=0.6**

Constrain the values of b_6^D and b_6^F





$\mathrm{CR} = \max(\mu_B^{(3)}/\mu_B^{(2)}, \mu_B^{(4)}/\mu_B^{(3)})$ **CR=0.6**

Convergence properties of different BChPT

TABLE I. Contributions of different chiral orders of the HB, IR, and EOMS schemes up to $\mathcal{O}(p^4)$.

Baryons	EOMS		IR		HB	
	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$
P	−0.27	−0.38	−0.16	0.01	−0.44	−0.07
N	−0.19	0.02	−0.17	0.61	−0.18	0.74
Λ	−0.52	−0.08	−0.73	−0.27	−0.83	−0.32
Σ^-	0.18	−0.04	2.58	−0.73	−0.30	0.30
Σ^+	−0.31	−0.15	−0.05	4.20	−0.61	−0.22
Σ^0	−0.52	−0.13	−0.73	−0.31	−0.83	−0.35
Ξ^-	0.03	−12.88	3.10	−1.02	−0.74	−0.12
Ξ^0	−0.54	−0.13	−0.77	−0.32	−0.87	−0.36
$\Lambda\Sigma^0$	−0.31	0.27	−0.38	−0.11	−0.43	0.46

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P	−0.27	−0.38	−0.16	0.01	−0.44	−0.07
N	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ξ^-	0.03	−12.88	3.10	−1.02	−0.74	−0.12
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EOMS ChPT presents the best convergence properties!

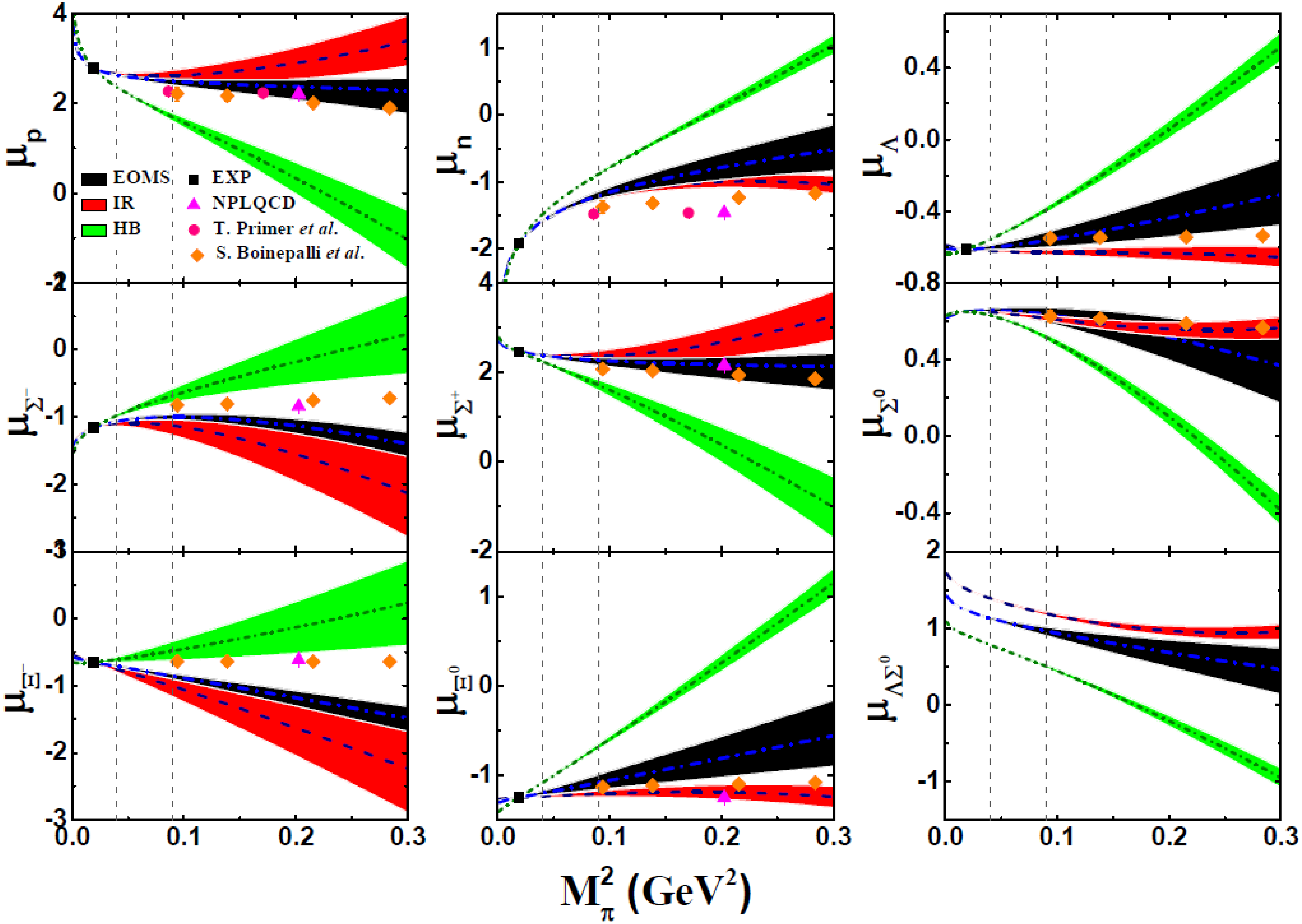
Check the reliability of the LECS

- **9 LECS**

  $b_6^D, b_6^F, b_6^{D\prime}, b_6^{F\prime}, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \beta_1$

- **Are these LECS reliable?**
  - ✓ **Two model independent theory**
    - **Chiral perturbation theory**
    - **Lattice QCD**
  - ✓ **ChPT and Lattice QCD can verify each other**

Pion mass dependence



Chi-square between the ChPT results and LQCD

Chiral schemes	Chi-square		
	S.Boinepalli et al.[1]	NPLQCD[2]	T. Primer et al.[3]
IR	12.01	2.48	0.69
HB	43.45	12.49	4.64
EOMS	3.66	1.11	0.5

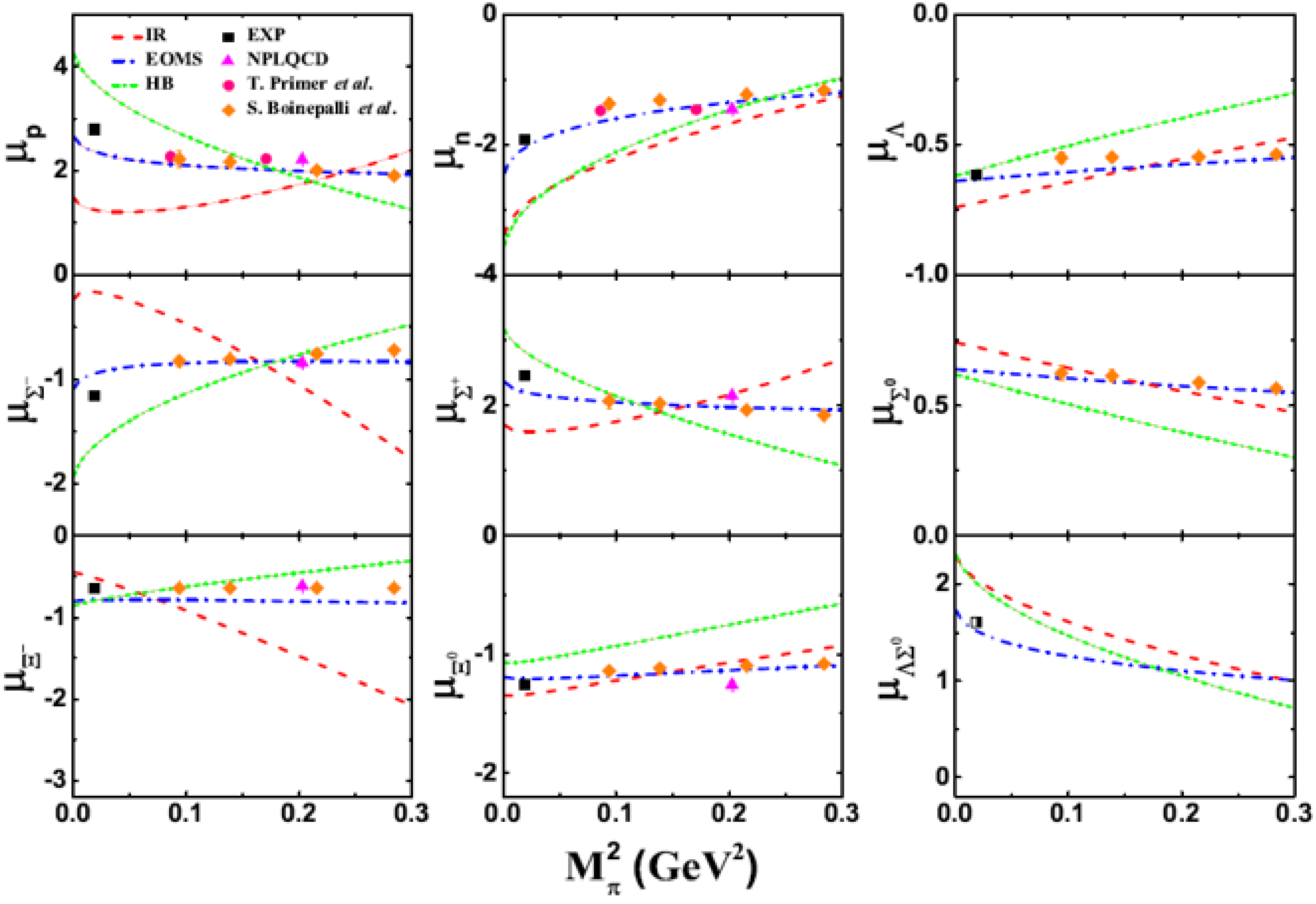
[1] Phys. Rev. D 74,093005 (2006)
[2] Phys. Rev. D 89, 034508 (2014)
[3] Phys.Rev. D 95, 114513 (2017)

Fit to the lattice QCD data

At NLO

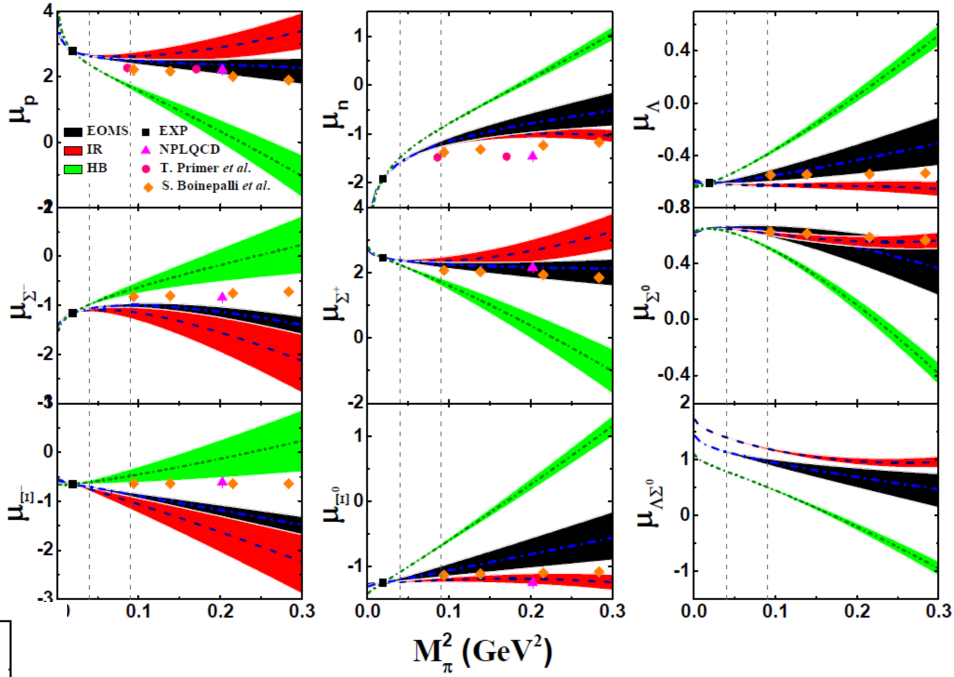
Chiral schemes		EOMS	IR	HB
Fit exp	b_6^D	3.83	4.82	4.73
	b_6^F	1.20	-0.03	2.49
	Chi-square (exp+lattice)	1.42	28.16	12.21
Fit exp +lattice QCD	b_6^D	3.73	5.07	5.29
	b_6^F	1.00	-0.92	2.95
	Chi-square (exp+lattice)	0.64	13.18	5.75

Pion mass dependence at NLO



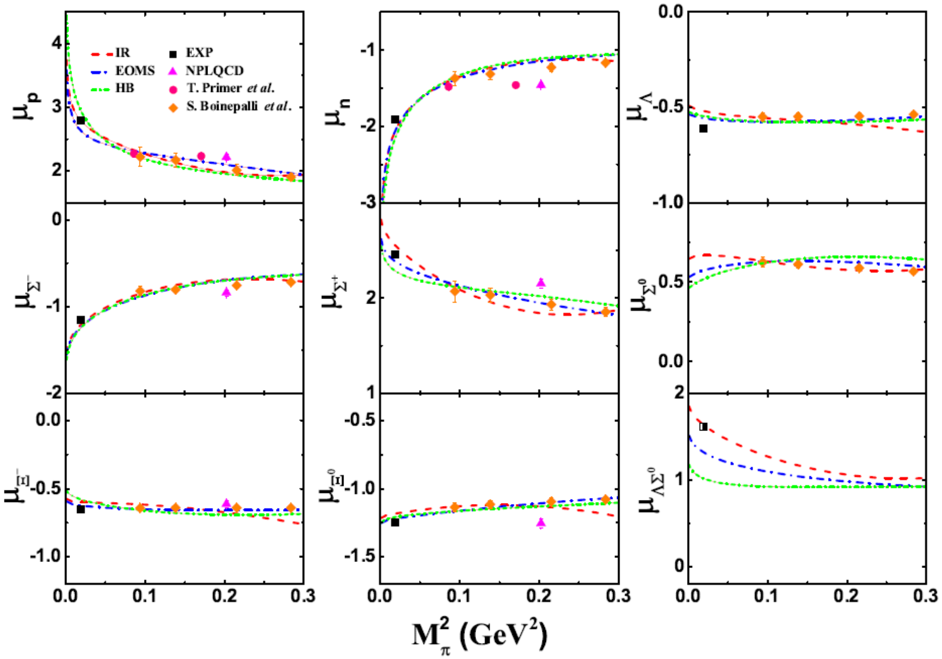
Pion mass dependence at NNLO

- Different **BChPT** results show **little discrepancy** when **fit to the LQCD data**



Fit to the exp data with constrained LECs

Fit to the LQCD data



Chi-square between BChPT and LQCD

Fit to the exp data with constrained LECs

OCTET BARYONS	CHIRAL SCHEME	$\tilde{\chi}^2$		
		T.Primer *et al.*	NPLQCD	S.Boinepalli *et al.*
Sum	IR	11.18	1.96	0.56
	HB	27.49	8.40	3.41
	EOMS	3.98	1.24	0.53

Fit to the LQCD data

	b_6^D	b_6^F	α_1	α_2	α_3	α_4	β_1	$b_6^{D'}$	$b_6^{F'}$	$\tilde{\chi}^2$
IR	4.02	2.08	-0.20	-0.83	0.06	0.20	-2.88	-3.66	-3.59	0.14
HB	2.16	1.08	-1.47	0.28	-1.47	1.53	-2.12	0.56	0.89	0.24
EOMS	3.03	1.40	0.17	0.30	0.15	0.60	-0.56	-0.69	-0.59	0.13

Contributions of different chiral orders

Fit to the exp data with constrained LECs

Baryons	EOMS		IR		HB	
	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$
P	-0.27	-0.38	-0.16	0.01	-0.44	-0.07
N	-0.19	0.02	-0.17	0.61	-0.18	0.74
Λ	-0.52	-0.08	-0.73	-0.27	-0.83	-0.32
Σ^-	0.18	-0.04	2.58	-0.73	-0.30	0.30
Σ^+	-0.31	-0.15	-0.05	4.20	-0.61	-0.22
Σ^0	-0.52	-0.13	-0.73	-0.31	-0.83	-0.35
Ξ^-	0.03	-12.88	3.10	1.02	-0.74	-0.12
Ξ^0	-0.54	-0.13	-0.77	-0.32	-0.87	-0.36
$\Lambda\Sigma^0$	-0.31	0.27	-0.38	-0.11	-0.43	0.46

Fit to the LQCD data

Baryons	EOMS		IR		HB	
	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$
P	-0.26	-0.12	-0.12	2.09	-0.73	-1.08
N	-0.22	-1.09	-0.17	0.38	-0.35	2.36
Λ	-0.61	-0.26	-0.72	-0.15	-1.62	-0.85
Σ^-	0.13	-1.85	1.02	-1.30	-0.41	-0.81
Σ^+	-0.31	-0.01	-0.04	10.21	-1.03	-0.82
Σ^0	-0.61	-0.29	-0.72	-0.31	-1.62	-0.82
Ξ^-	0.02	-28.25	1.22	-1.53	-1.03	-0.44
Ξ^0	-0.64	-0.38	-0.76	-0.27	-1.71	-0.91
$\Lambda\Sigma^0$	-0.37	-0.33	-0.38	-0.22	-0.84	-0.78

Contributions of different chiral orders

Fit to the exp data with constrained LECs

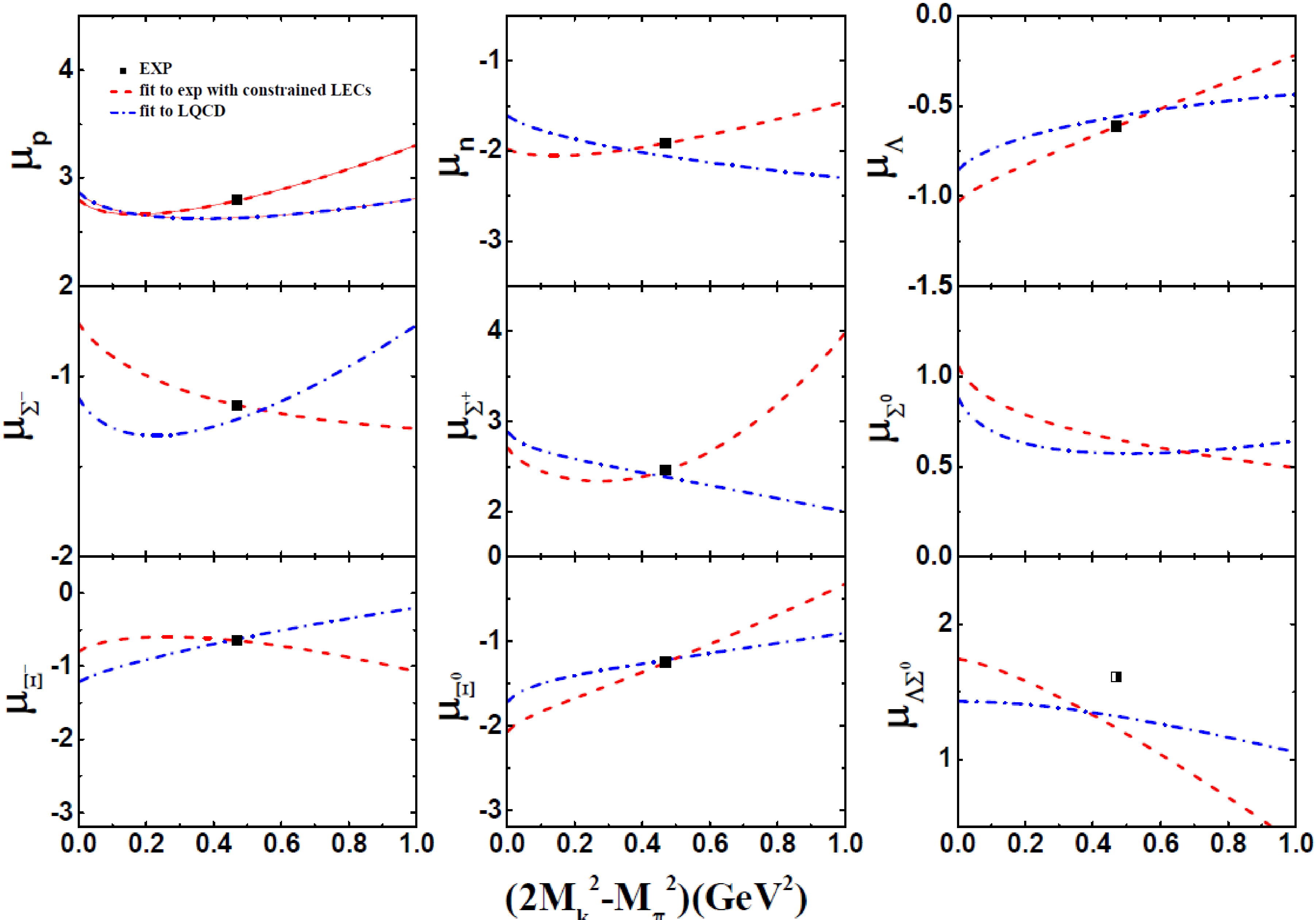
Baryons	EOMS		IR		HB	
	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$
P	-0.27	-0.38	-0.16	0.01	-0.44	-0.07
N	-0.19	[illegible]	[illegible]	[illegible]	[illegible]	0.74
Λ	-0.52	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Σ^-	0.18	-0.04	2.58	-0.73	-0.30	0.30
Σ^+	-0.31	-0.15	-0.05	4.20	-0.61	-0.22
Σ^0	-0.52	-0.13	-0.73	-0.31	[illegible]	[illegible]
Ξ^-	0.03	-12.88	3.10	1.02	-0.74	-0.12
Ξ^0	-0.54	-0.13	-0.77	-0.32	-0.87	-0.36
$\Lambda\Sigma^0$	-0.31	0.27	-0.38	-0.11	-0.43	0.46

Fit to the LQCD data

Baryons	EOMS		IR		HB	
	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$	$\mu_B^{(3)}/\mu_B^{(2)}$	$\mu_B^{(4)}/\mu_B^{(3)}$
P	-0.26	-0.12	-0.12	2.09	-0.73	-1.08
N	[illegible]	-1.09	[illegible]	[illegible]	-0.35	2.36
Λ	[illegible]	[illegible]	[illegible]	[illegible]	-1.62	-0.85
Σ^-	0.13	-1.85	1.02	-1.30	-0.41	-0.81
Σ^+	[illegible]	-0.01	-0.04	10.21	-1.03	-0.82
Σ^0	-0.61	-0.29	-0.72	-0.31	-1.62	-0.82
Ξ^-	0.02	-28.25	1.22	-1.53	-1.03	-0.44
Ξ^0	-0.64	-0.38	-0.76	-0.27	-1.71	-0.91
$\Lambda\Sigma^0$	-0.37	-0.33	-0.38	-0.22	-0.84	-0.78

Which method is better?

Strange quark mass dependence



4 CONCLUSION

Conclusion

- Calculated the baryon magnetic moments in EOMS ChPT up to next-to-next-to-leading order
- Determined low energy constants in two different ways
  - Fit to experiment data with LECs constrained by convergence properties
  - Fit to the lattice QCD data
- More lattice QCD simulations are needed to reach a firmer conclusion

Thanks !