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Recent progress in covariant baryon chiral perturbation theory

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Xiu-Lei Ren, LSG, Jie Meng. Phys.Rev. D91 (2015) 051502
Xiu-Lei Ren, L. Alvarez-Ruso, LSG, T. Ledwig, Jie Meng, M. J. Vicente Vacas .Phys.Lett. B766 (2017) 325

Outline

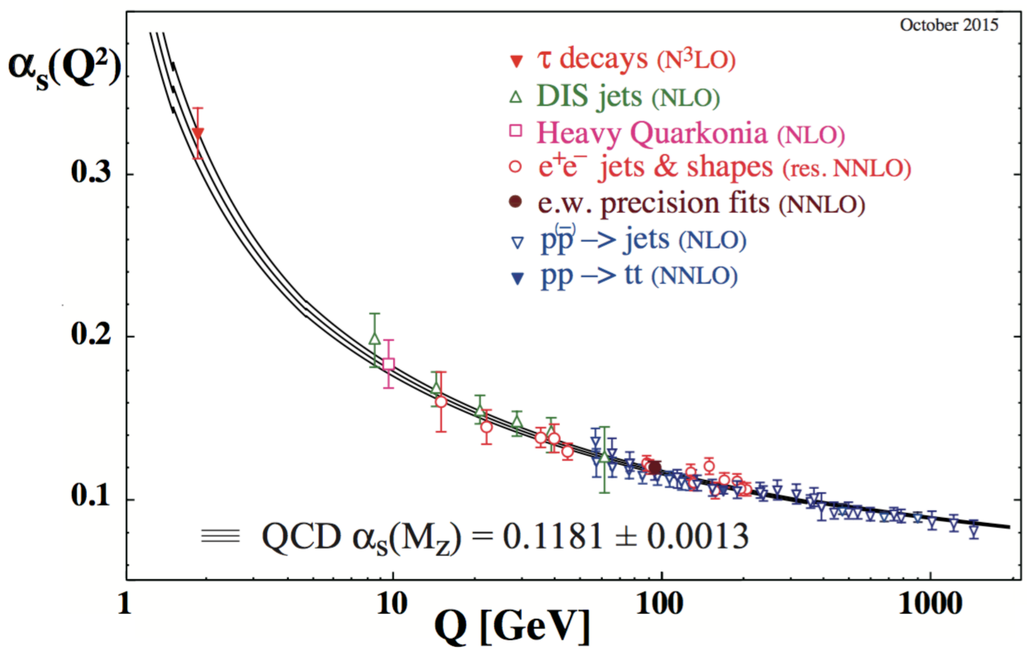
- **Introduction**
  - ***Essence of chiral perturbation theory***
  - ***Power counting breaking problem and solutions***
- **Recent progress**
  - **Determination of octet baryon sigma terms**
  - *Relativistic nucleon-nucleon interaction* Xiu-Lei Ren, Oral 5
  - *Baryon magnetic moments at NNLO* Yang Xiao, Oral 10
- **Summary**

QCD—theory of the strong interaction

- Simple: four parameters
- **Difficult to be applied to solve low-energy strong interaction physics**

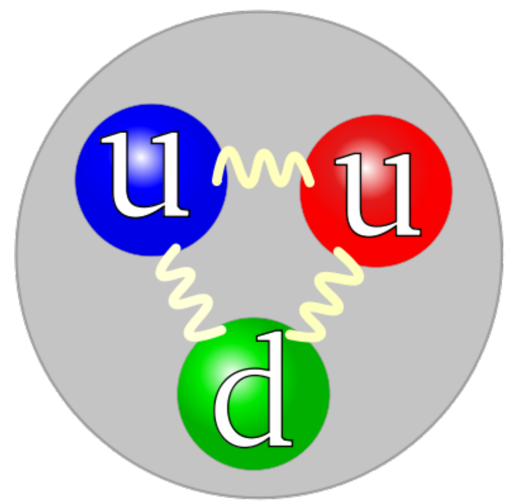
$$
\begin{aligned}
LQCD = &-\frac{1}{4}(\partial^{\mu} G_a^{\nu} - \partial^{\nu} G_a^{\mu})(\partial_{\mu} G_{\nu}^{a} - \partial_{\nu} G_{\mu}^{a}) + \sum_f \bar{q}_f^{\alpha} (i\gamma^{\mu}\partial_{\mu} - m_f) q_f^{\alpha} \\
&+ g_s G_a^{\mu} \sum_f \bar{q}_f^{\alpha} \gamma^{\mu} \left(\frac{\lambda^a}{2}\right)_{\alpha\beta} q_f^{\beta} \\
&- \frac{g_s}{2} f^{abc} (\partial^{\mu} G_a^{\nu} - \partial^{\nu} G_a^{\mu}) G_{\mu}^{b} G_{\nu}^{c} - \frac{g_s^2}{4} f^{abc} f_{ade} G_b^{\mu} G_c^{\nu} G_{\mu}^{d} G_{\nu}^{e}
\end{aligned}
$$

Asymptotic freedom



Nobel prize in physics 2004

Color confinement

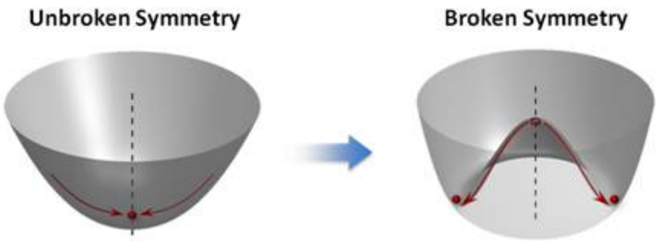


Clay Mathematics Institute seven million dollar problems, 2000

Chiral perturbation theory

Chiral symmetry : QCD Lagrangian invariant under **1979**

$$SU(3)_L \times SU(3)_R$$



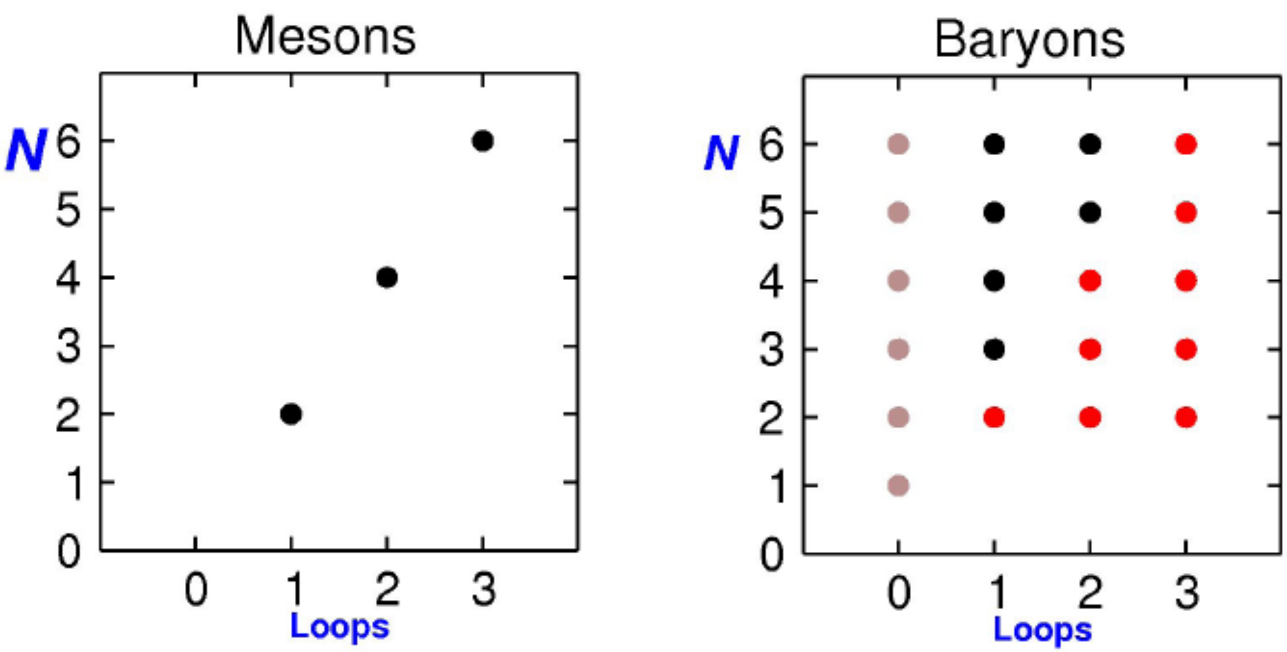
- **Spontaneously broken: pseudoscalar nonet**
- **Explicitly broken: small mass, perturbative**

In short

- Maps quark (u, d, s) dof's to those of the asymptotic states, hadrons
- Perturbative formulation of low energy QCD in powers of the external momenta and the light quark masses, instead of the running coupling constant

Power-counting-breaking (PCB) in the one-baryon sector

- **ChPT very successful in the study of Nanbu-Goldstone boson self-interactions.** (at least in SU(2))
- **In the one-baryon sector, things become problematic because of the nonzero (large) baryon mass in the chiral limit, which leads to the fact that high-order loops contribute to lower-order results, i.e., a systematic power counting is lost!**



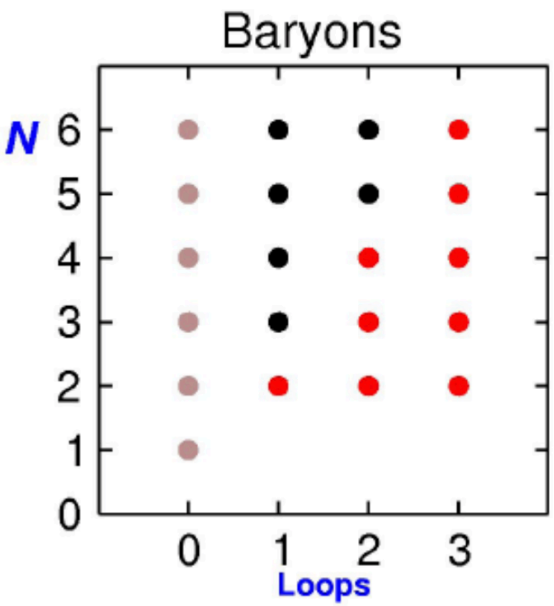
***red dots* denote possible PCB terms (pion-nucleon scattering)**

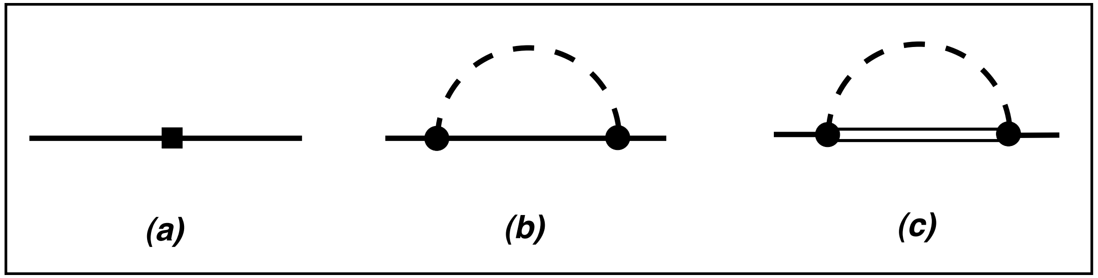
J. Gasser et al., NPB 307, 779(1988)

$$\boxed{\text{Chiral order} = 4L - 2N_M - N_B + \sum_k kV_k}$$

Chiral order = $4L - 2N_M - N_B + \sum_k kV_k$.

Nucleon mass up to O(p³)

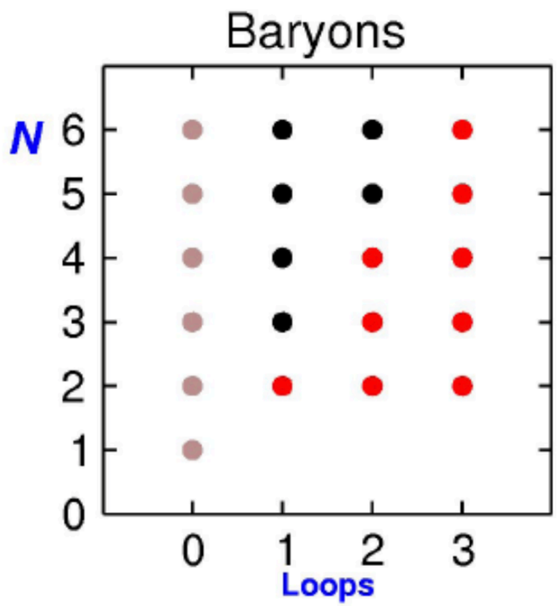


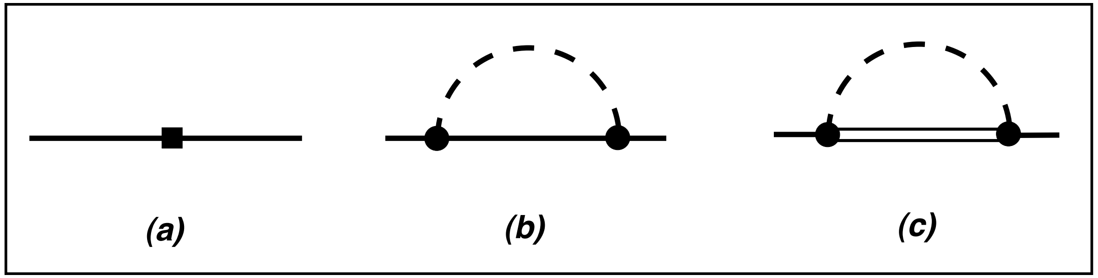


$$\text{order of the loop} = 1 + 1 + 4 - 1 - 2 = 3$$

$$\boxed{\text{Chiral order} = 4L - 2N_M - N_B + \sum_k kV_k.}$$

Nucleon mass up to $O(p^3)$





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Naively (no PCB)

$$M_N = M_0 + bm_\pi^2 + \text{loop}$$

$$\text{loop}(= cm_\pi^3 + \cdots)$$

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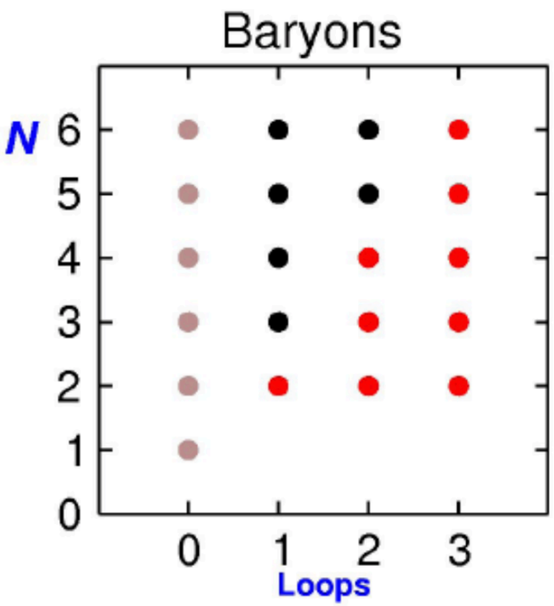

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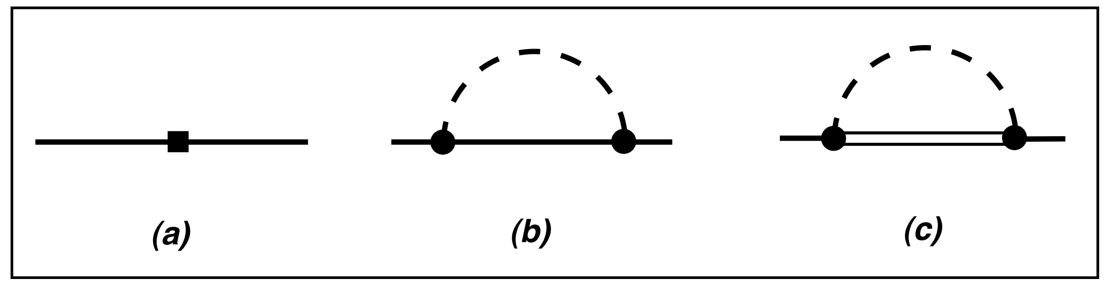

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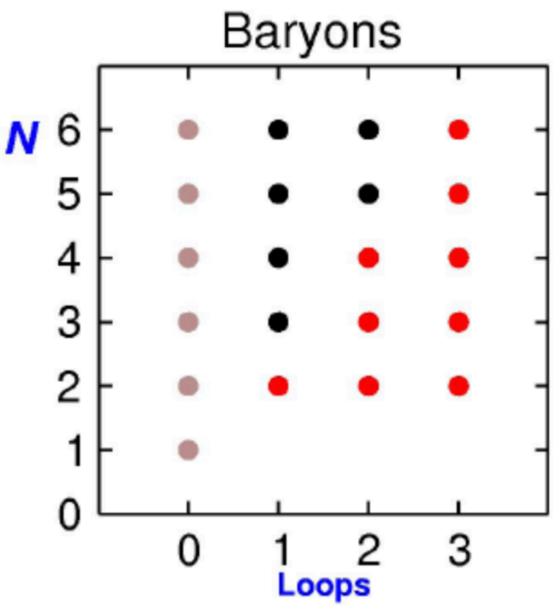
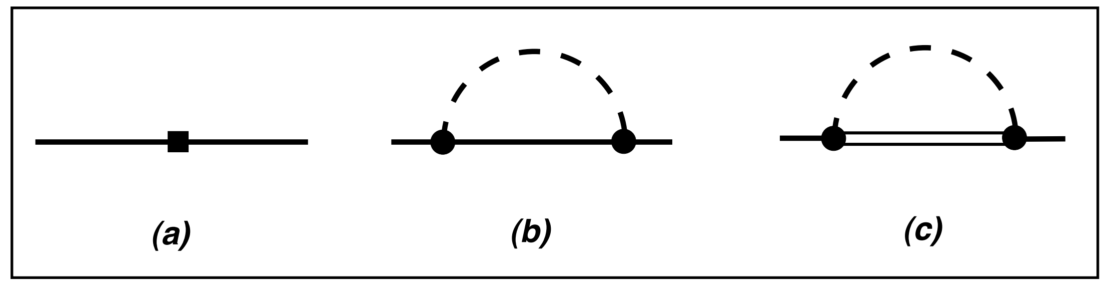
However $$\boxed{\text{loop} = aM_0^3 + b' M_0 m_\pi^2 + cm_\pi^3 + \cdots}$$

Chiral order = $4L - 2N_M - N_B + \sum_k kV_k$.

Nucleon mass up to O(p^3)





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$$\text{loop}(= cm_\pi^3 + \cdots)$$

However

$$\boxed{\text{loop} = aM_0^3 + b' M_0 m_\pi^2 + cm_\pi^3 + \cdots}$$

No need to calculate, simply recall that *$M_0 \sim O(p^0)$*

Power-counting-restoration methods

- **Heavy baryon ChPT**: baryons treated “semi-relativistically” (Jenkins et al., 1991, Bernard et al., 1992)
- **Relativistic baryon ChPT**: removing power counting breaking terms but retaining higher order corrections, thus keeping relativity
  - **Infrared baryon ChPT**: Becher & Leutwyler 1999
  - **Extended on mass shell (EOMS) scheme**: Gegelia 1999, Fuchs 2003

HB & Infrared

- **HB:** a simultaneous expansion in terms of external momenta and 1/mB
- **Infrared:** separating the full Feynman integral into a regular part and finite part

$$H = \frac{1}{ab} = \int_0^1 dz \frac{1}{[(1-z)a + zb]^2} \equiv I + R = \int_0^\infty \ldots dz - \int_1^\infty \ldots dz$$

HB & Infrared

- **HB:** a simultaneous expansion in terms of external momenta and 1/mB
- **Infrared:** separating the full Feynman integral into a regular part and finite part

$$H = \text{Infrared}$$

Extended-on-Mass-Shell (EOMS)

- **"Drop" the PCB terms**

$$\boxed{\mathrm{tree} = M_0 + b m_\pi^2} \quad + \quad \boxed{\mathrm{loop} = a M_0^3 + b' M_0 m_\pi^2 + c m_\pi^3 + \cdots}$$

$$\Big\Downarrow \; a = 0; b' = 0$$

$$\boxed{M_N = M_0 + b\ m_\pi^2 + c m_\pi^3 + \cdots \quad (\mathcal{O}(p^3))}$$

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- **Equivalent to redefinition of the LECs**

$$\boxed{\text{tree} = M_0 + b m_\pi^2} \quad + \quad \boxed{\text{loop} = a M_0^3 + b' M_0 m_\pi^2 + c m_\pi^3 + \cdots}$$

$$\Downarrow \; M_0^r = M_0(1 + a M_0^2); b^r = b^0 + b' M_0$$

$$\boxed{M_N = M_0^r + b^r m_\pi^2 + c m_\pi^3 + \cdots \quad (\mathcal{O}(p^3))}$$

Extended-on-Mass-Shell (EOMS)

- **"Drop" the PCB terms**

$$\boxed{\text{tree} = M_0 + b m_\pi^2} \quad + \quad \boxed{\text{loop} = a M_0^3 + b' M_0 m_\pi^2 + c m_\pi^3 + \cdots}$$

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- **Equivalent to redefinition of the LECs**

$$\boxed{\text{tree} = M_0 + b m_\pi^2} \quad + \quad \boxed{\text{loop} = a M_0^3 + b' M_0 m_\pi^2 + c m_\pi^3 + \cdots}$$

ChPT contains all possible terms allowed by symmetries, therefore whatever analytical terms come out from a loop amplitude, they must have a corresponding LEC

HB vs. Infrared vs. EOMS

- **Heavy baryon (HB) ChPT**
  - non-relativistic
  - breaks analyticity of loop amplitudes
  - converges slowly (particularly in three-flavor sector)
  - strict PC and simple non-analytical results
- **Infrared BChPT**
  - breaks analyticity of loop amplitudes
  - converges slowly (particularly in three-flavor sector)
  - analytical terms the same as HBChPT
- **Extended-on-mass-shell (EOMS) BChPT**
  - satisfies all symmetry and analyticity constraints
  - converges relatively faster--an appealing feature

Some successful applications of covariant BChPT (in the 3f sector)

- **Magnetic moments**

  PRL101:222002,2008; PLB676:63,2009; PRD80:034027,2009

- **Masses and sigma terms**

  PRD82:074504,2010; PRD84:074024,2011; JHEP12:073,2012; PRD 87:074001,2013; PRD89:054034,2014 ; EPJC74:2754,2014 ; PRD91:051502,2015; Phys.Lett. B766:325, (2017)

- **Vector form factors (couplings)**

  PRD79:094022,2009；PRD89:113007,2014

- **Axial form factors (couplings)**

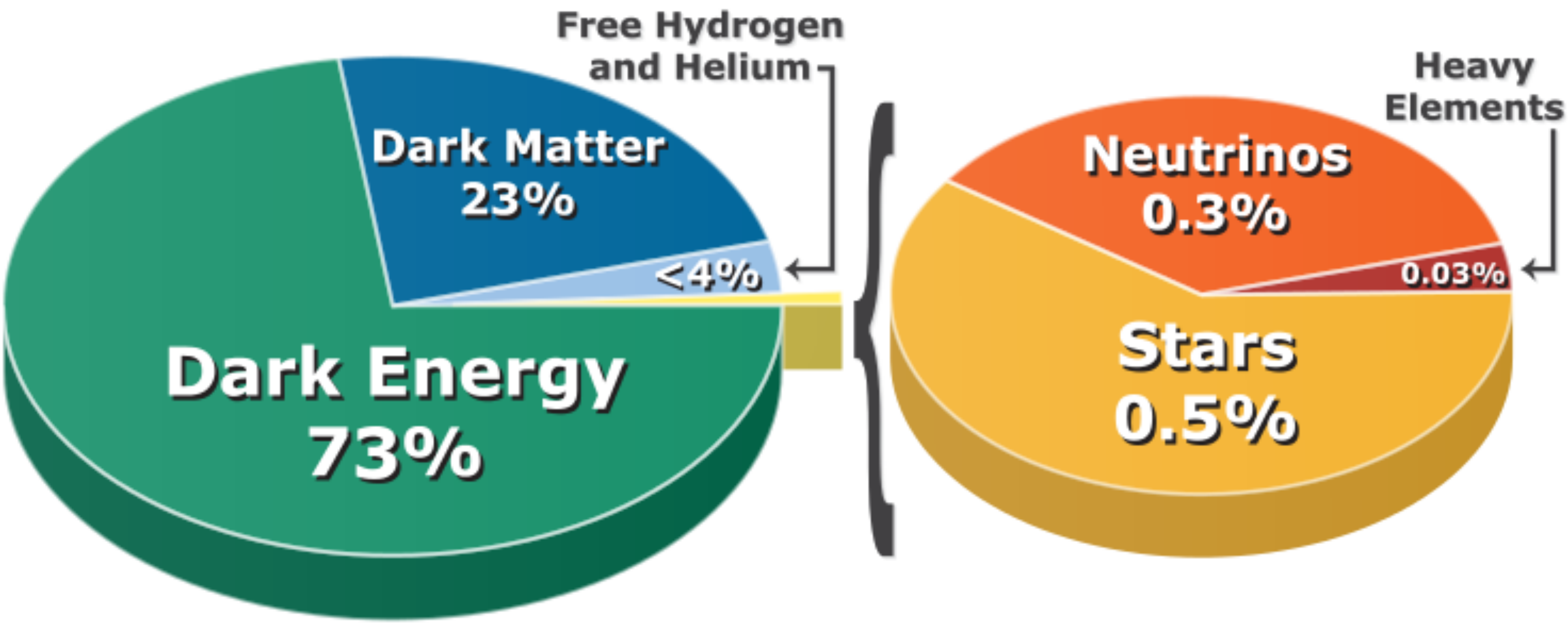
  PRD78:014011,2008；PRD90:054502,2014

Recent developments in SU(3) covariant baryon chiral perturbation theory
Li-sheng Geng, Front.Phys.(Beijing) 8 (2013) 328-348

Motivation: why sigma terms

Energy/matter composition of the universe

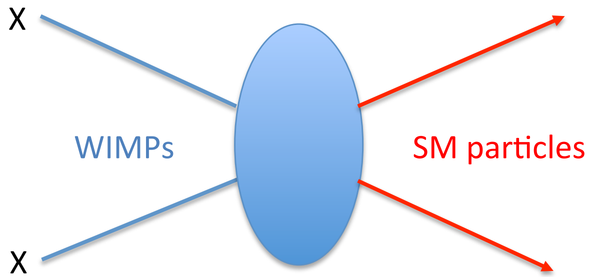
Plank: 1303.5062



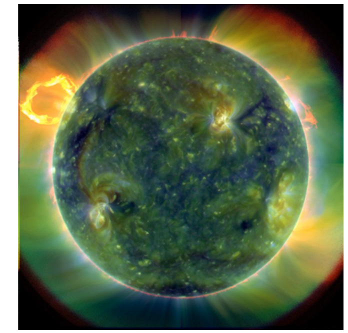
- **Weakly Interacting Massive Particles (WIMPS)**

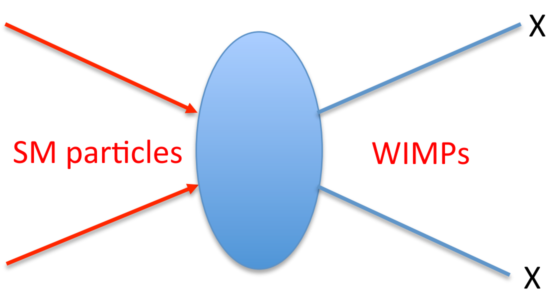
e.g., Neutralino in MSSM.

Particle searches for WIMPs

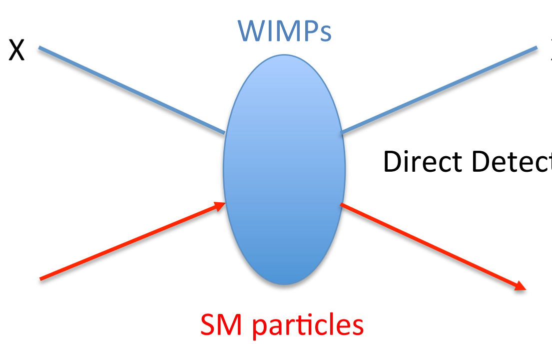


Indirect Detection



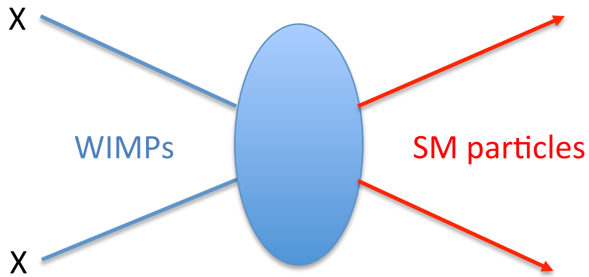


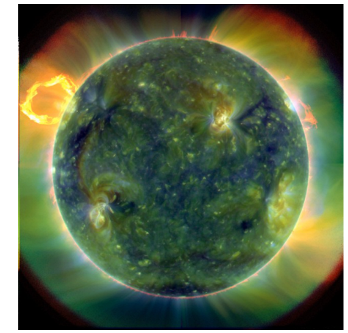
Collider Searches



Direct Detection

Particle searches for WIMPs





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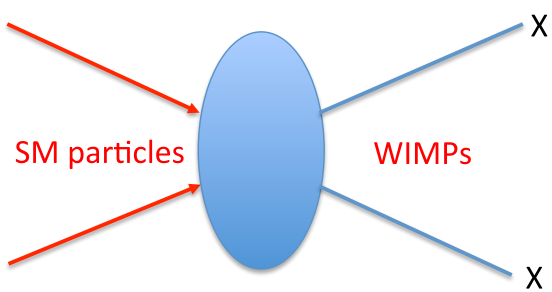
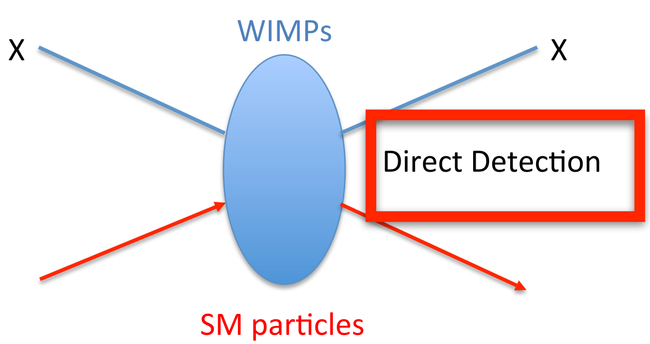
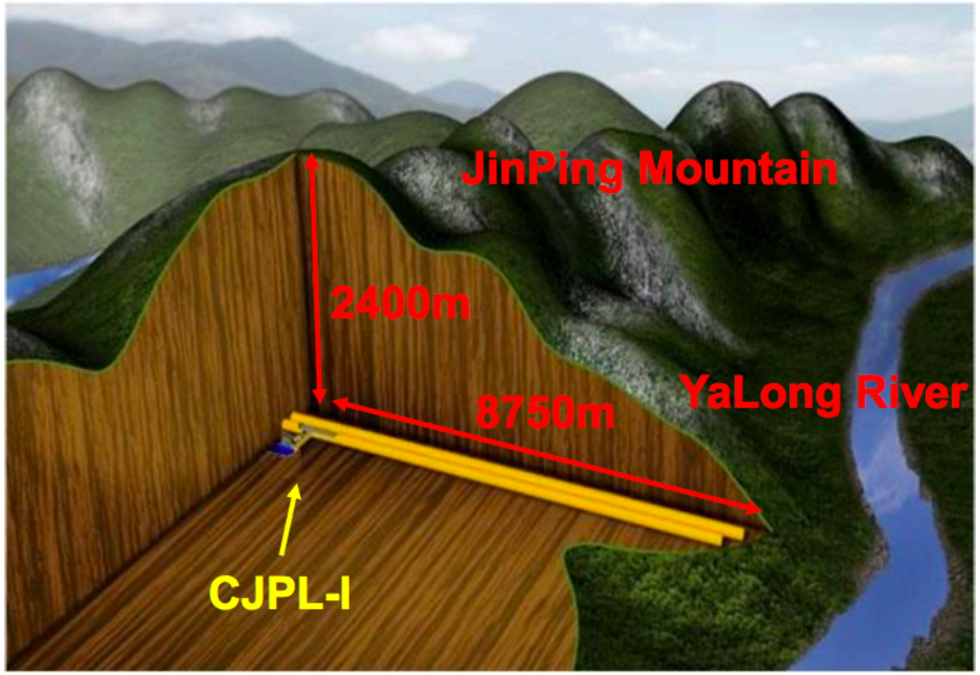
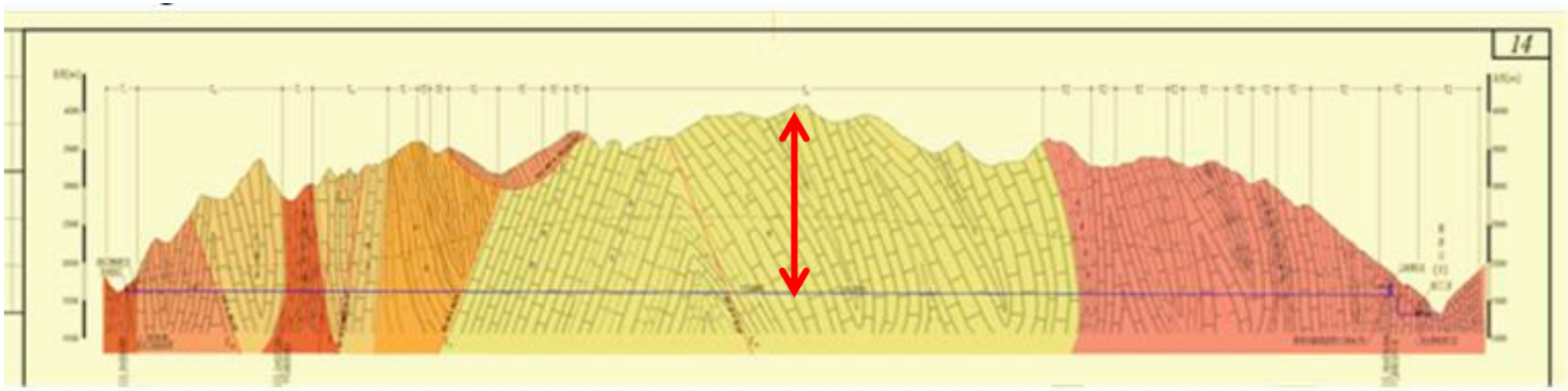


Collider Searches



Direct dark matter detection in China





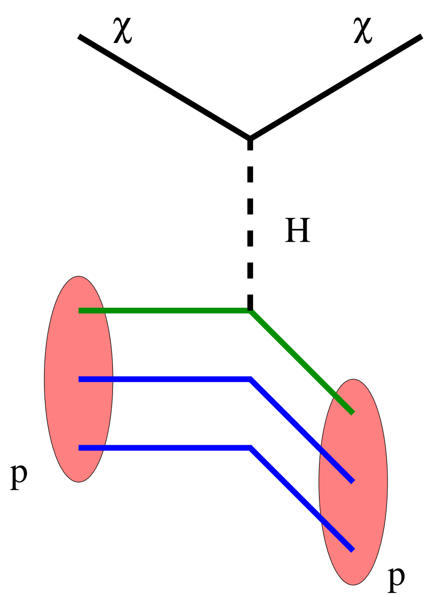
China JinPing Laboratory (CPJL): deepest and largest underground lab. in the world; PandaX and CDEX

Indirect dark matter detection in China

DAMPE (DArk Matter Particle Explore), Wukong（悟空）, launched on December 17, 2015

Spin-independent neutralino-nucleon scattering

MSSM



$$\mathcal{L}_{int} = \lambda_N \overline{n} n \overline{\chi} \chi \rightarrow \mathcal{L}_{int} = \lambda_q \overline{q} q \overline{\chi} \chi$$

$$\lambda_N \longrightarrow \sum_{q=1}^{6} f_q^N \lambda_q$$

Spin indep. WIMP-N X-section

$$\sigma_{SI} = \frac{4M^2}{\pi} \left[Z f_P + (A - Z) f_N \right]$$

with

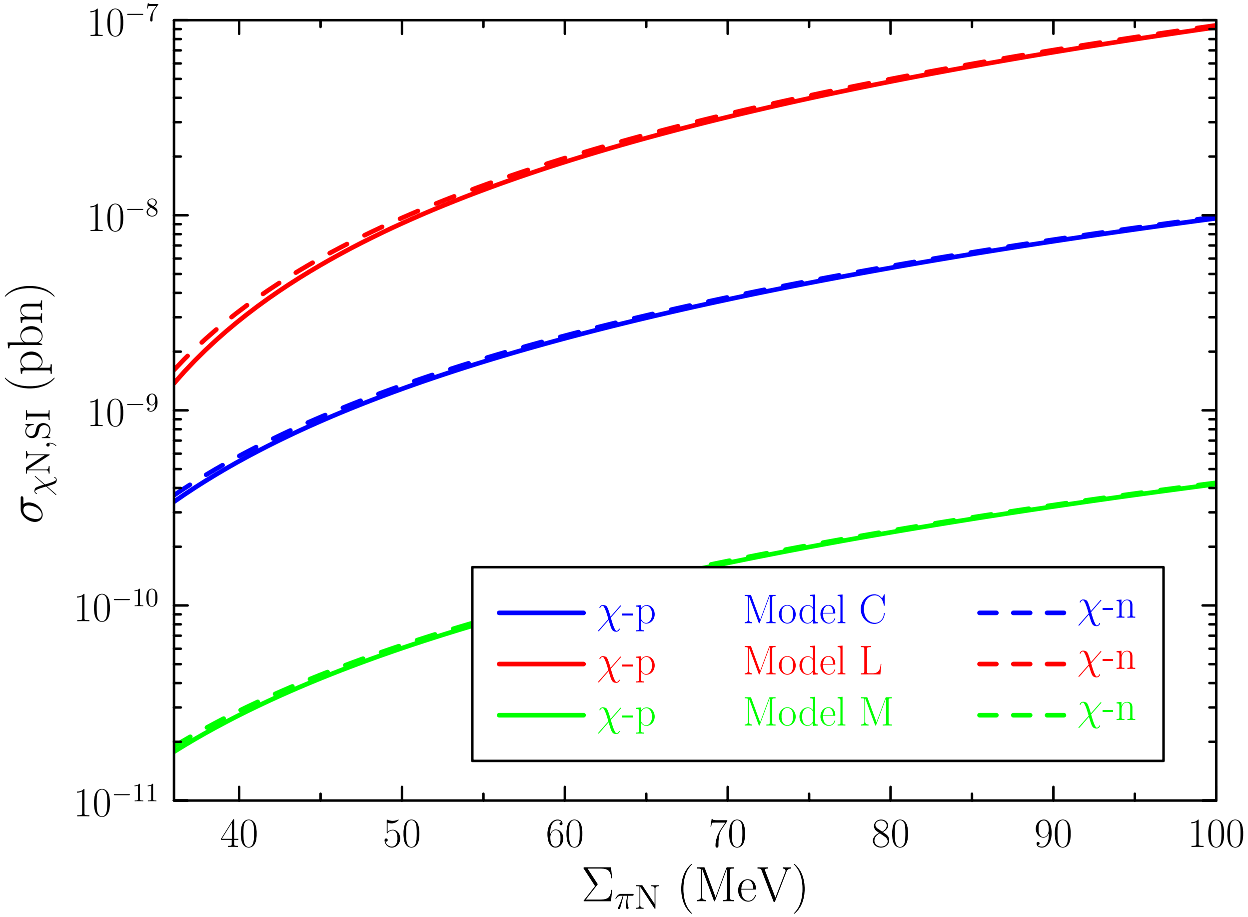
$$\frac{f_N}{M_N} = \sum_q f_q^N \frac{\lambda_q}{m_q}$$

pion- and strangeness sigma terms

$$\boxed{f_{ud}^N M_N = \sigma_{\pi N} = m_q \langle N | u\bar{u} + d\bar{d} | N \rangle}$$

$$\boxed{f_s^N M_N = \sigma_{sN}/2 = m_s \langle N | s\bar{u} | N \rangle}$$

Strong dependence on the strangeness sigma term



$$\sigma_{\chi p,SI} \sim (\Sigma_{\pi N} - \sigma_0)^2.$$

$$\boxed{\sigma_{sN} \propto \Sigma_{\pi N} - 36}$$

Ellis, Olive, Savage, PRD77(2008)065026

Quark-flavor structure of the proton

- Naive quark model—minimal quark contents

$$|p\rangle = |uud\rangle$$

- **In reality,** $|p\rangle = |uud\rangle(1 + |u\bar{u}\rangle + |d\bar{d}\rangle + |s\bar{s}\rangle)$
  - to the spin
    – deep-inelastic lepton scattering
  - to the electromagnetic formfactors
    - parity-violating electron-proton scattering
  - to the mass
    – scalar strangeness content, cannot be measured directly $\langle N|s\bar{s}|N\rangle$

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Determination of the scalar (strangeness) content of the nucleon (baryons) using ChPT

How to determine sigma terms

Pion-nucleon sigma term

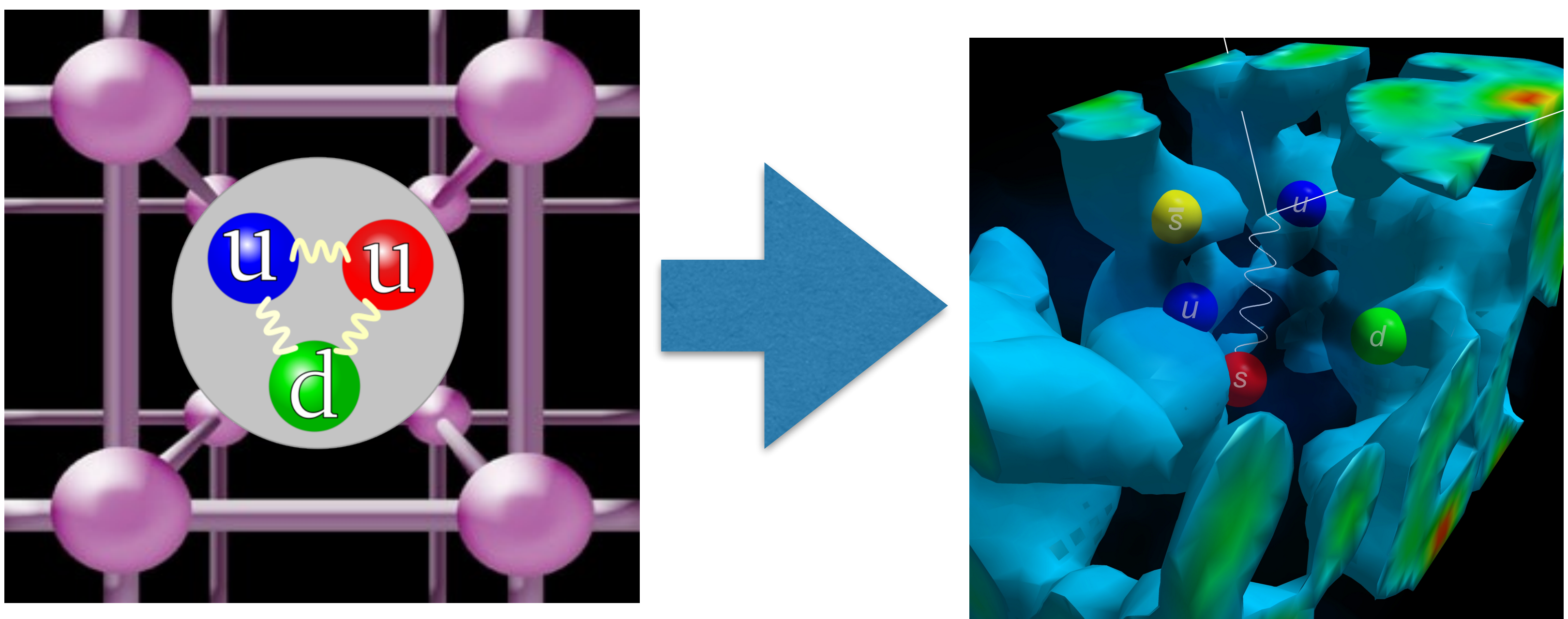
- Experimentally, the pion-nucleon sigma term can be inferred from pion-nucleon scattering data at Cheng-Dashen point

$$(s = u = m_N^2, t = 2M_\pi^2)$$

$\sigma_{\pi N} = 45 \pm 8 MeV$	**J. Gasser et al., PLB253,252**
$\sigma_{\pi N} = (59.1 \pm 1.9 \pm 3.0)\ \mathrm{MeV}$	**Hoferichter et al., PRL115, 092301**
$\sigma_{\pi N} = 59(7)\ \mathrm{MeV}$	**Alarcon et al., PRD 85, 051503(R)**
$\sigma_{\pi N} = 45 \pm 6\ \mathrm{MeV}$	**Chen et al., PRD 87, 054019**

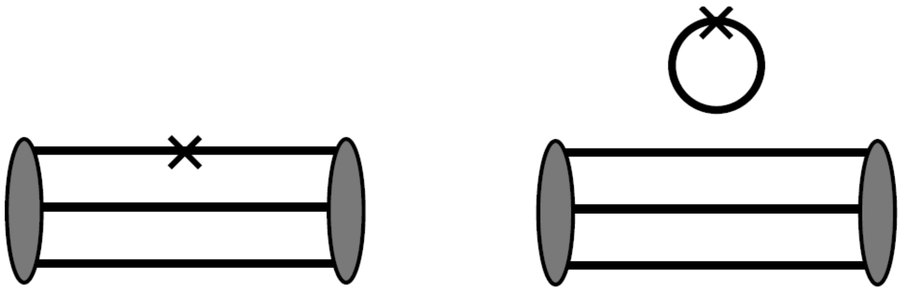
Strangeness sigma term

- Because of lack of kaon-nucleon scattering data, the strangeness-sigma term cannot be obtained this way
- **Lattice QCD** might be our hope to predict it from first principles



LQCD determination of sigma terms

- **Direct method**—calculates the 3-point connected and disconnect diagrams



– JLQCD, PRD83,114506 (2011)
– R. Babich *et al.*, PRD85,054510 (2012)
– QCDSF, PRD85, 054502 (2012)
– ETMC, JHEP 1208,037(2012)
– M. Engelhardt *et al.*, PRD86, 114510 (2012)
– JLQCD, PRD87, 034509 (2013)
– ETMC, PRL 116, 252001 (2016)
– RQCD, PRD 93, 094504 (2016)
– χ QCD, PRD94, 054503 (2016)

- **Spectrum method**-calculates the baryon masses, and relates the sigma terms to their quark mass dependence via the Feynman Hellmann theorem *R. Young, Plenary 01*

$$\sigma_{\pi B} = m_l \langle B(p)|\bar{u}u + \bar{d}d|B(p)\rangle = m_l \frac{\partial M_B}{\partial m_l}$$

$$\sigma_{sB} = m_s \langle B(p)|\bar{s}s|B(p)\rangle = m_s \frac{\partial M_B}{\partial m_s}.$$

– JLQCD, PRD83,114506 (2011)
– R. Babich *et al.*, PRD85,054510 (2012)
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– JLQCD, PRD87, 034509 (2013)
– BMW, PRL 116, 172001 (2016).

Our aim

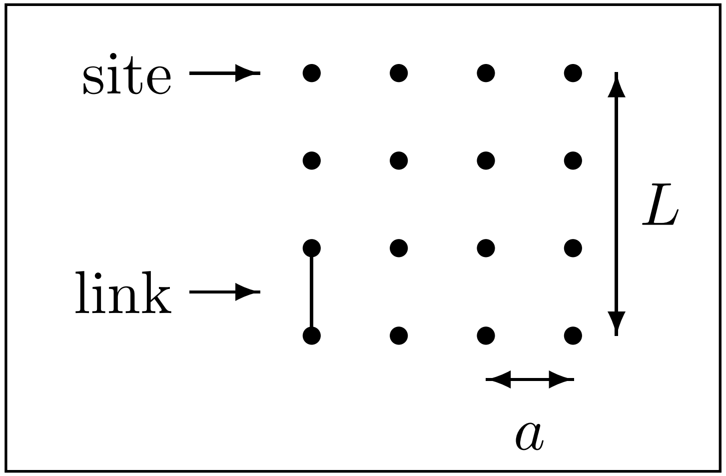
- To apply the **Feynman-Hellmann** theorem to predict the baryon sigma terms using the **covariant (EOMS) baryon chiral perturbation theory**

$$\boxed{\begin{aligned} \sigma_{\pi B} &= m_l \langle B(p)|\bar{u}u + \bar{d}d|B(p)\rangle = m_l \frac{\partial M_B}{\partial m_l} \\ \sigma_{sB} &= m_s \langle B(p)|\bar{s}s|B(p)\rangle = m_s \frac{\partial M_B}{\partial m_s}. \end{aligned}}$$

- To fix the unknown low-energy constants of BChPT, we rely on the lQCD simulations of baryon masses

LQCD parameters and simulation costs

- **light quark masses: m_u/m_d**
- **lattice spacing: a**
- **lattice volume: $V=L^4$**



$$\text{cost} \propto \left(\frac{L}{a}\right)^4 \frac{1}{a} \frac{1}{m_\pi^2 a}$$

- **To reduce cost: employ larger than physical light quark masses, finite lattice spacing and volume.**
- **To obtain physical quantities, multiple extrapolations are needed**

Multiple extrapolations

- **Chiral extrapolations:** **light quark masses to their physical values**

$$m_q \to m_q(\text{Phys.})$$

- **Finite volume corrections:** **infinite space-time**

$$L \to \infty$$

- **Continuum extrapolations:** **zero lattice spacing**

$$a \to 0$$

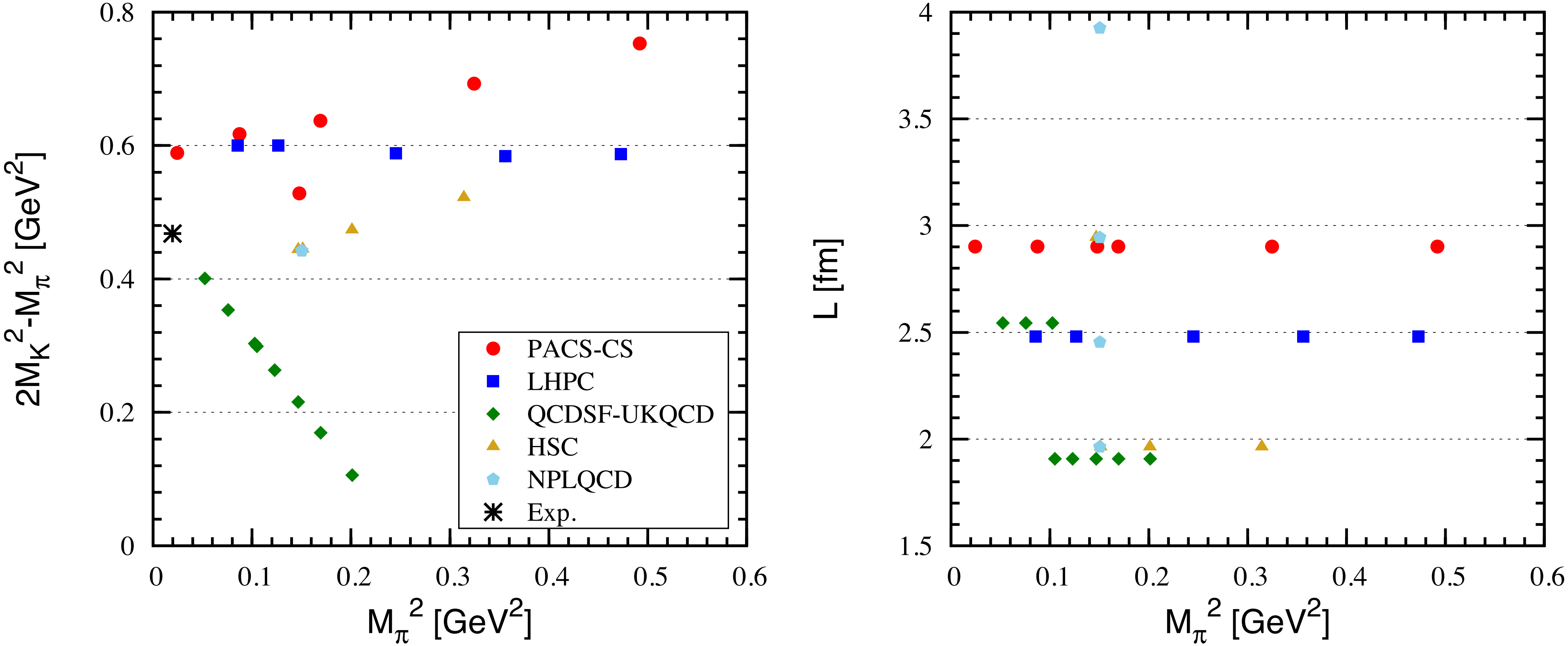
Two key factors for a reliable determination of sigma terms

- A reliable formulation of ChPT, which **not only** can well describe the LQCD data, **but also** needs to satisfy all symmetry and analyticity constrains

Our choice: the EOMS BChPT

- Lattice QCD simulations of baryon masses at **various** quark masses, volumes, and lattice spacings, and with various fermion/gauge actions

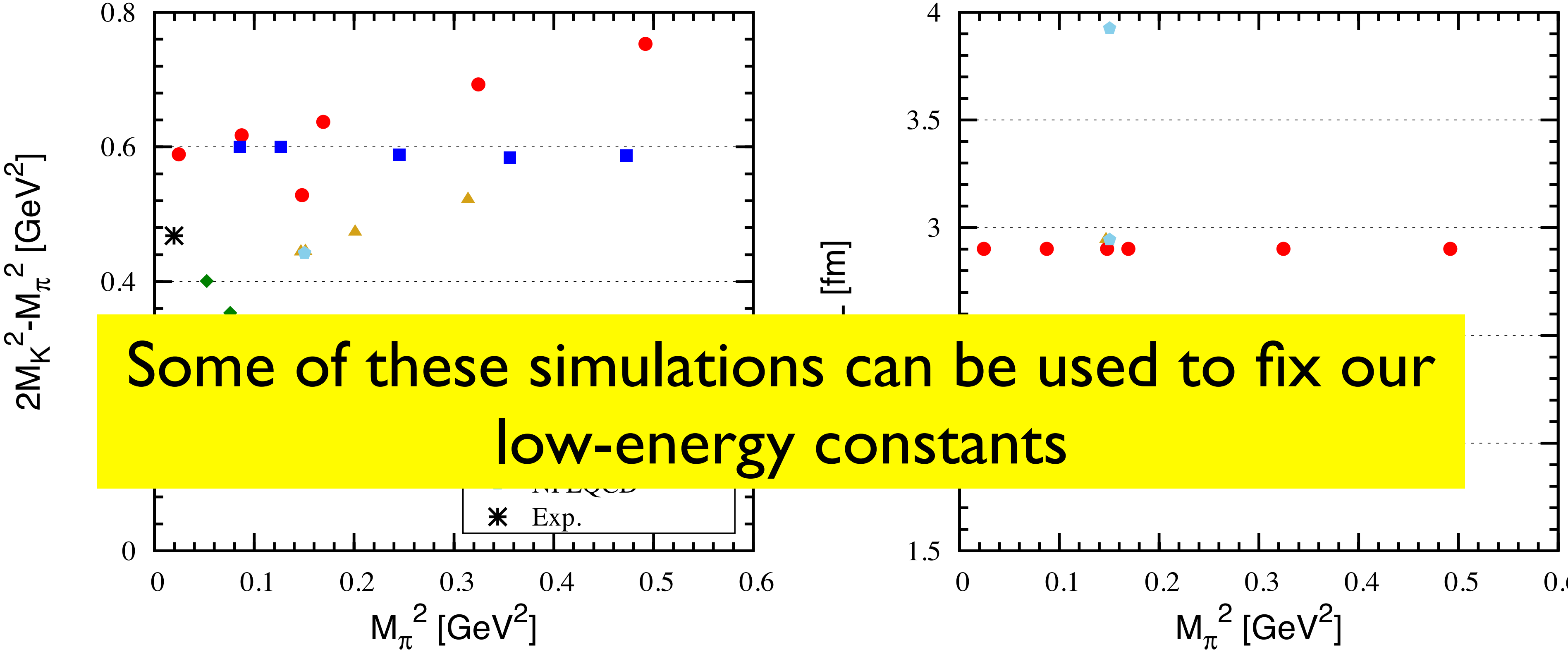
Landscape of latest (**before 2014**) 2+1f LQCD simulations of g.s. octet baryon



To obtain g.s. baryon masses in the physical world

- Extrapolate to the continuum: $a \to 0$
- Extrapolate to physical light quark masses: $m_q \to m_q(\mathrm{Phys.})$
- Extrapolate to infinite space-time: $L \to \infty$

Landscape of latest (before 2014) 2+1f LQCD simulations of g.s. octet baryon



Some of these simulations can be used to fix our low-energy constants

To obtain g.s. baryon masses in the physical world

- Extrapolate to the continuum: $a \to 0$
- Extrapolate to physical light quark masses: $m_q \to m_q(\text{Phys.})$
- Extrapolate to infinite space-time: $L \to \infty$

A careful selection of LQCD data

- All n_f=2+1 LQCD simulations
  - PACS-CS, LHPC, QCDSF-UKQCD, HSC, NPLQCD, BWM
  - BMW—not publicly available
  - HSC/NPLQCD—Low statistics/single combination of quark masses
- We take PACS-CS, LHPC, QCDSF-UKQCD

$$\boxed{\begin{array}{c} m_\pi<500\text{ MeV} \\ m_\Phi L>4 \end{array}}$$

An accurate determination of baryon sigma terms

- **Scale setting:** mass independent (given by the LQCD simulations or self-consistently determined) vs. mass dependent (r_0, r_1, X_π)
- **Isospin breaking effects:** better constrain the LQCD LECs—consistent with the latest BMW study [Science 347 (2015) 1452)]
- **Theoretical uncertainties caused by truncating chiral expansions:** NNLO vs. N3LO; EOMS vs. FRR

Systematic study of the LQCD data with the EOMS BChPT

- *NNLO EOMS BChPT study of the PACS-CS and LHPC data: Camalich, LSG, Vacas, PRD82(2010)074504*
- *Finite volume corrections: LSG, Ren, Camalich, Weise, PRD84(2011)074024;*
- *First systematic study of all publically available LQCD data: Ren, LSG, Camalich, Meng, Toki, JHEP12(2012)073;*
- *Effects of virtual decuplet baryons: Ren, LSG, Meng, Toki, PRD87(2013)074001*
- *Continuum extrapolations: Ren, LSG, Meng, Eur.Phys.J. C74:2754,2014*

Systematic study of the LQCD data with the EOMS BChPT

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- *Continuum extrapolations: Ren, LSG, Meng, Eur.Phys.J. C74:2754,2014*

The EOMS BChPT can be trusted to predict the baryon sigma terms

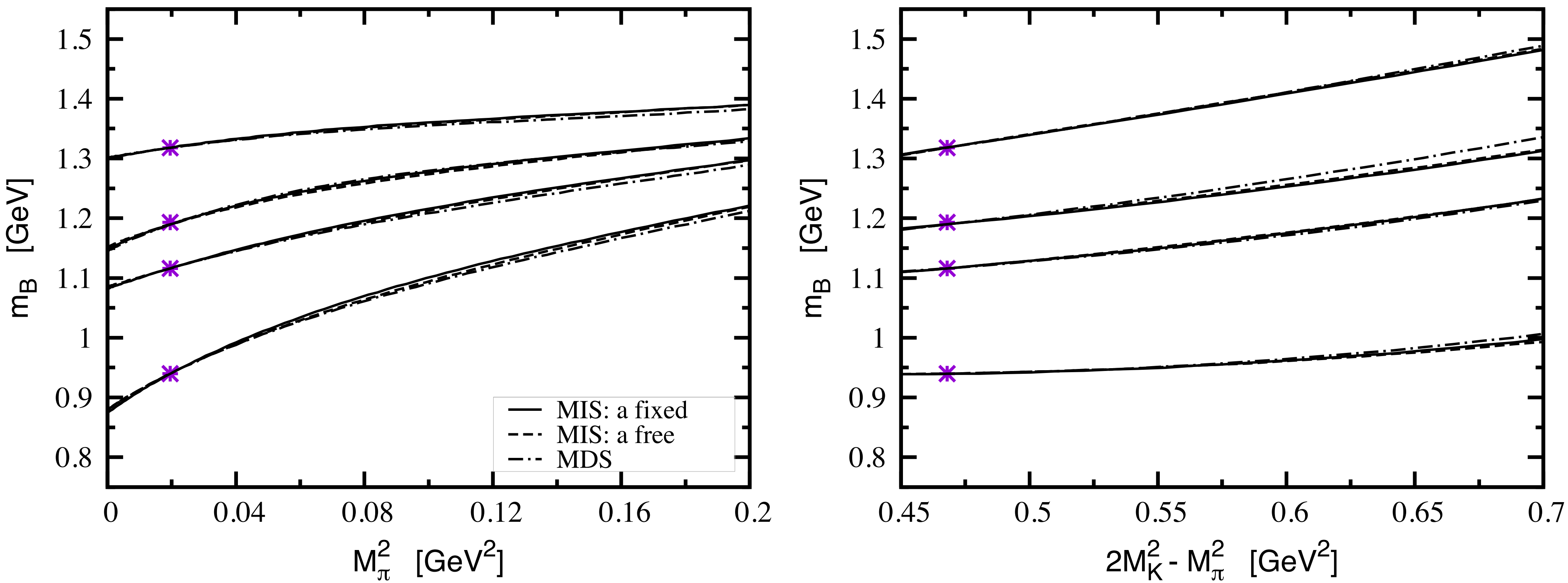
Three different fits at N^3LO

	MIS		MDS
	a fixed	a free	
m_0 [MeV]	884(11)	877(10)	887(10)
b_0 [GeV^{-1}]	$-0.998(2)$	$-0.967(6)$	$-0.911(10)$
b_D [GeV^{-1}]	0.179(5)	0.188(7)	0.039(15)
b_F [GeV^{-1}]	$-0.390(17)$	$-0.367(21)$	$-0.343(37)$
b_1 [GeV^{-1}]	0.351(9)	0.348(4)	$-0.070(23)$
b_2 [GeV^{-1}]	0.582(55)	0.486(11)	0.567(75)
b_3 [GeV^{-1}]	$-0.827(107)$	$-0.699(169)$	$-0.553(214)$
b_4 [GeV^{-1}]	$-0.732(27)$	$-0.966(8)$	$-1.30(4)$
b_5 [GeV^{-2}]	$-0.476(30)$	$-0.347(17)$	$-0.513(89)$
b_6 [GeV^{-2}]	0.165(158)	0.166(173)	$-0.0397(1574)$
b_7 [GeV^{-2}]	$-1.10(11)$	$-0.915(26)$	$-1.27(8)$
b_8 [GeV^{-2}]	$-1.84(4)$	$-1.13(7)$	0.192(30)
d_1 [GeV^{-3}]	0.0327(79)	0.0314(72)	0.0623(116)
d_2 [GeV^{-3}]	0.313(26)	0.269(42)	0.325(54)
d_3 [GeV^{-3}]	$-0.0346(87)$	$-0.0199(81)$	$-0.0879(136)$
d_4 [GeV^{-3}]	0.271(30)	0.230(24)	0.365(23)
d_5 [GeV^{-3}]	$-0.350(28)$	$-0.302(50)$	$-0.326(66)$
d_7 [GeV^{-3}]	$-0.435(10)$	$-0.352(8)$	$-0.322(7)$
d_8 [GeV^{-3}]	$-0.566(24)$	$-0.456(30)$	$-0.459(33)$
χ^2/d.o.f.	$\boxed{0.87}$	$\boxed{0.88}$	$\boxed{0.53}$

- **Mass independent**
  - Lattice spacing a fixed to the published value
  - Lattice spacing a determined self-consistently
- **Mass dependent**
  - r_0 for PACS-CS
  - r_1 for LHPC
  - X_π for QCDSF-UKQCD

Ren, LSG, Meng, PRD91 (2015) 051502

Evolution of baryon masses with u/d and s quark masses

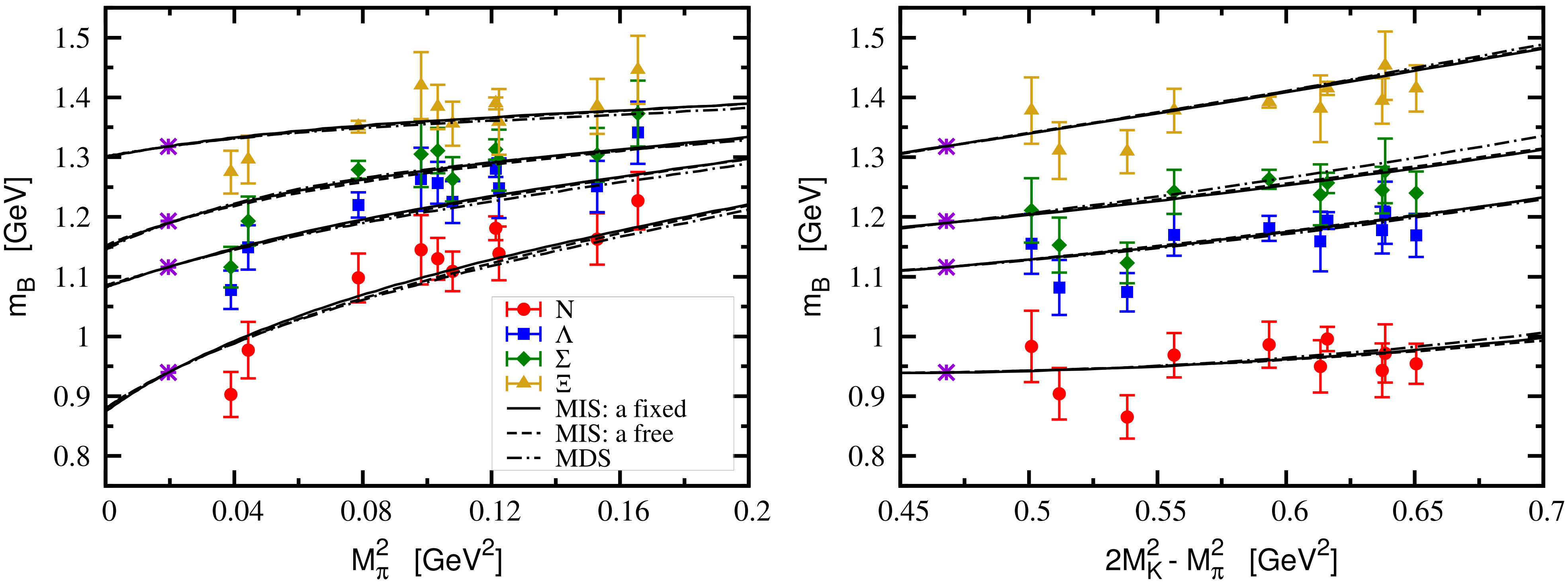


Only central values are shown!

Ren, LSG, PRD91 (2015) 051502

Ren, LSG, Meng, PRD91 (2015) 051502

In comparison with the BMW13 data



S. Durr et al., BMW collaboration, Phys.Rev. D85 (2012) 014509

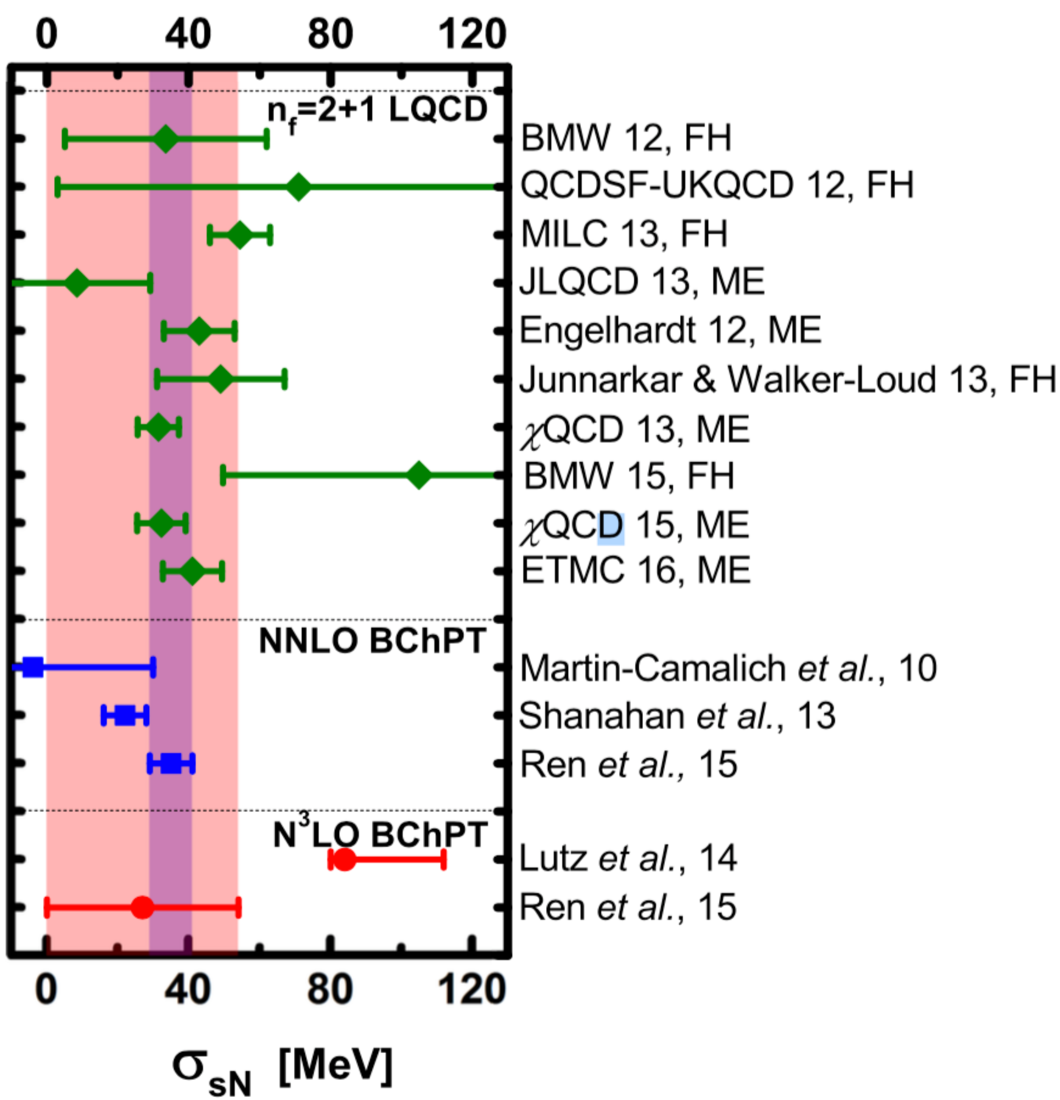
Baryon sigma terms from N^{3}LO BChPT

	MIS		MDS
	a fixed	a free	
$\sigma_{\pi N}$	55(1)(4)	54(1)	51(2)
$\sigma_{\pi\Lambda}$	32(1)(2)	32(1)	30(2)
$\sigma_{\pi\Sigma}$	34(1)(3)	33(1)	37(2)
$\sigma_{\pi\Xi}$	16(1)(2)	18(2)	15(3)
σ_{sN}	27(27)(4)	23(19)	26(21)
$\sigma_{s\Lambda}$	185(24)(17)	192(15)	168(14)
$\sigma_{s\Sigma}$	210(26)(42)	216(16)	252(15)
$\sigma_{s\Xi}$	333(25)(13)	346(15)	340(13)

- All three scale-setting methods yield similar baryon sigma terms

Ren, LSG, Meng, PRD91 (2015) 051502

Comparison with other studies

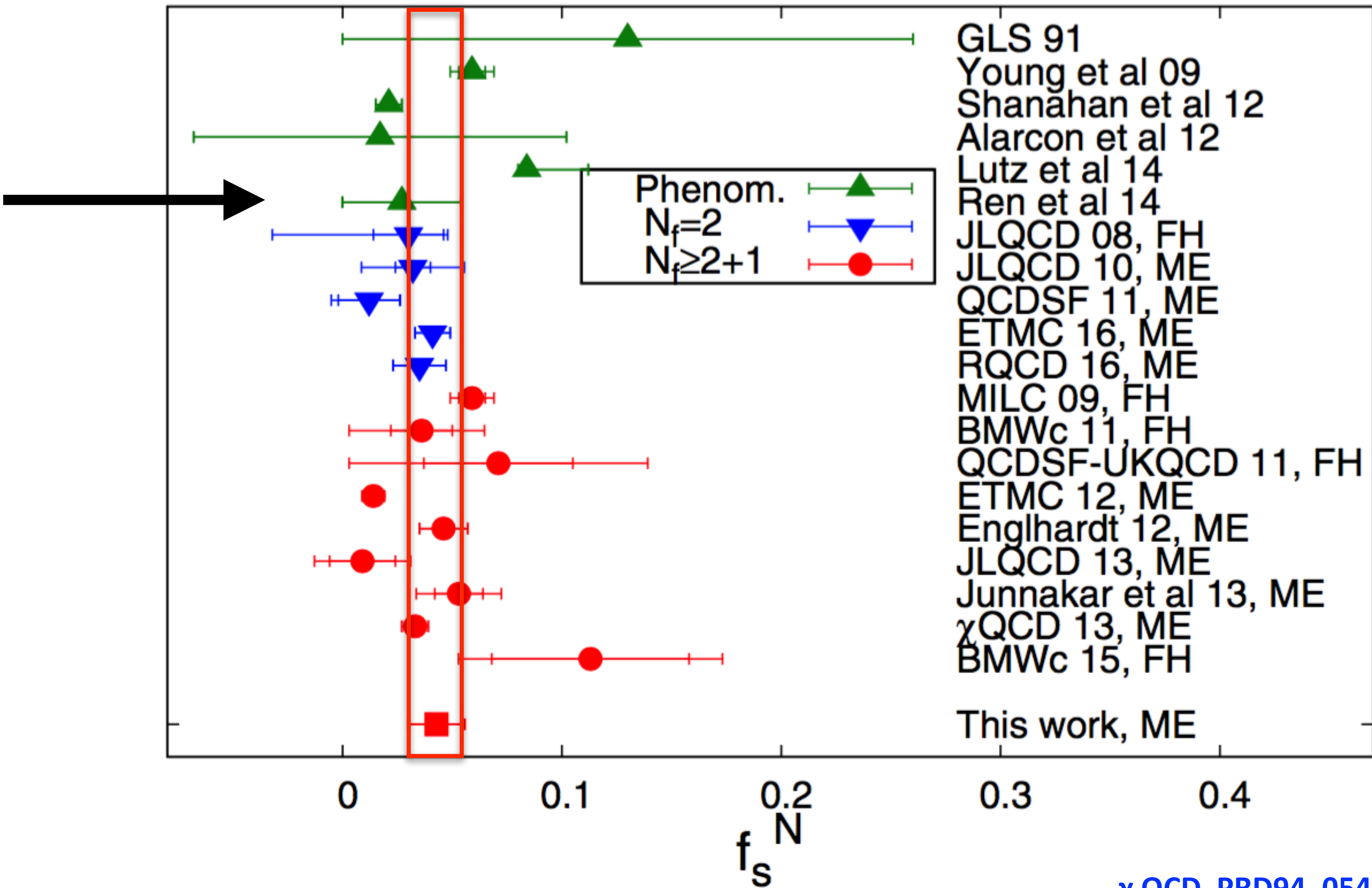


Nucleon Strangeness Sigma Term

- **Consistent with most recent LQCD studies and those of NNLO ChPT, e.g., that of Young and Shanahan**
- **Uncertainties at N^3LO substantially larger, because of the extra LECs**

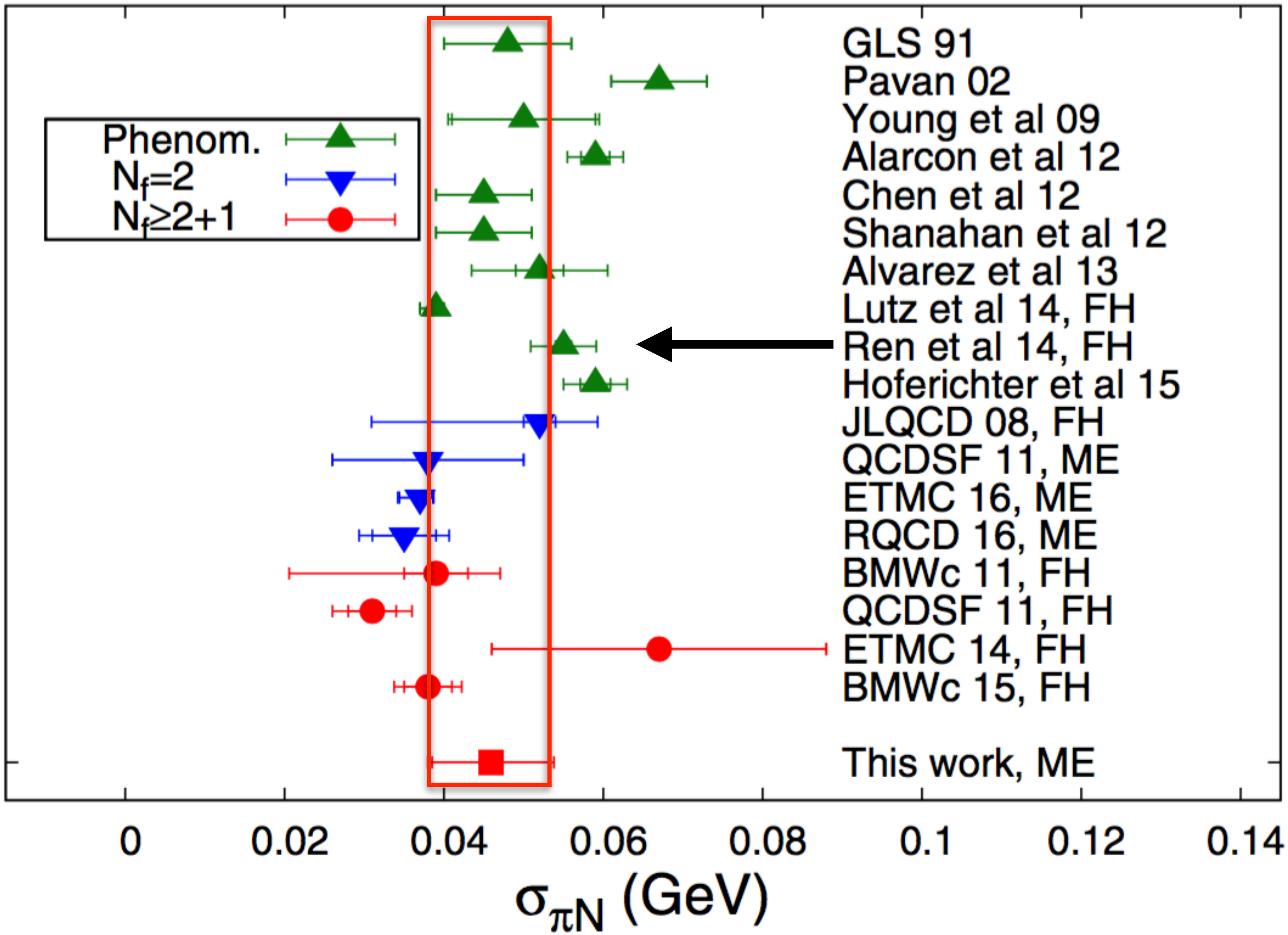
Ren, LSG, Meng, PRD91 (2015) 051502

Strangeness-nucleon sigma term



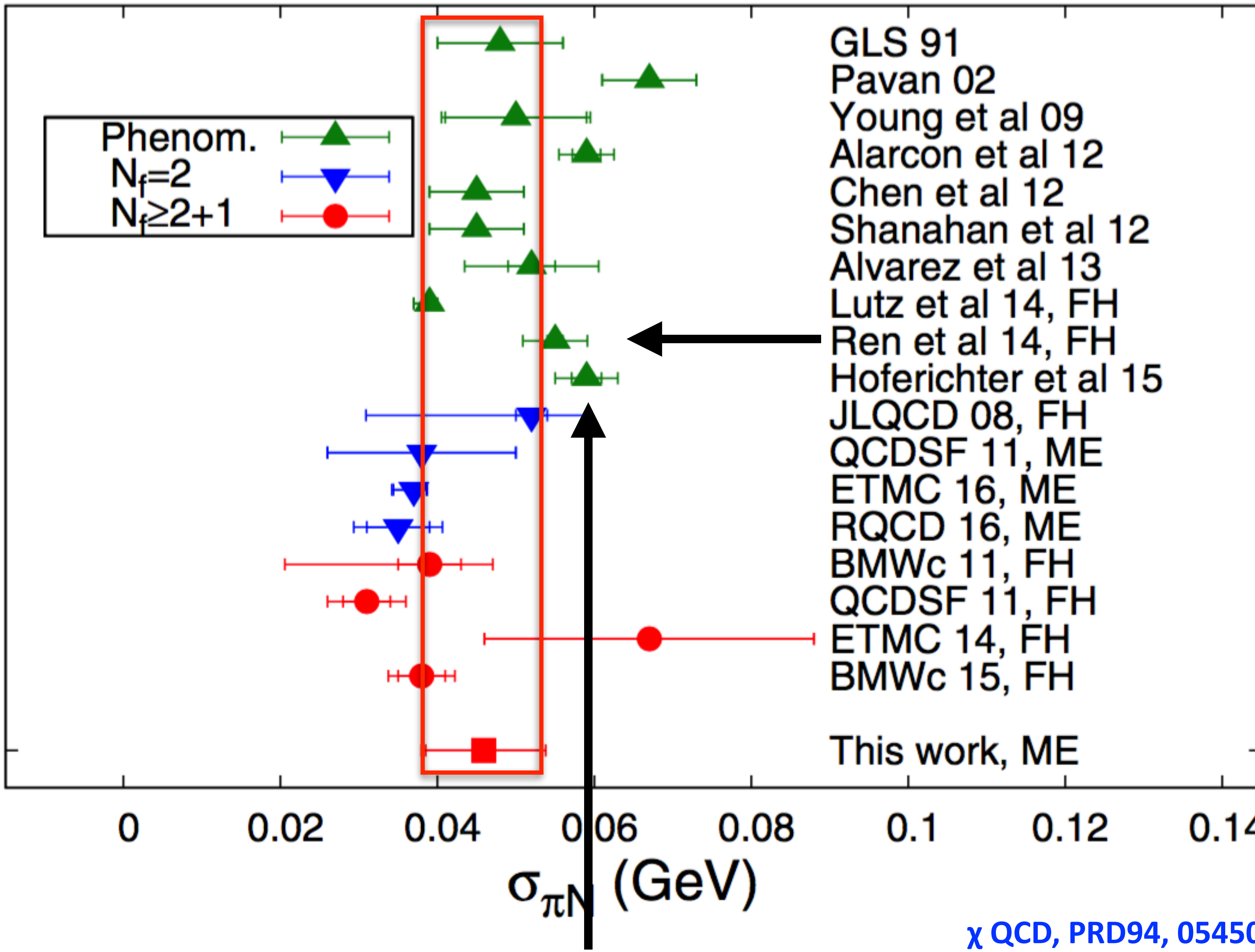
χ QCD, PRD94, 054503 (2016)

Pi-N sigma term still controversial



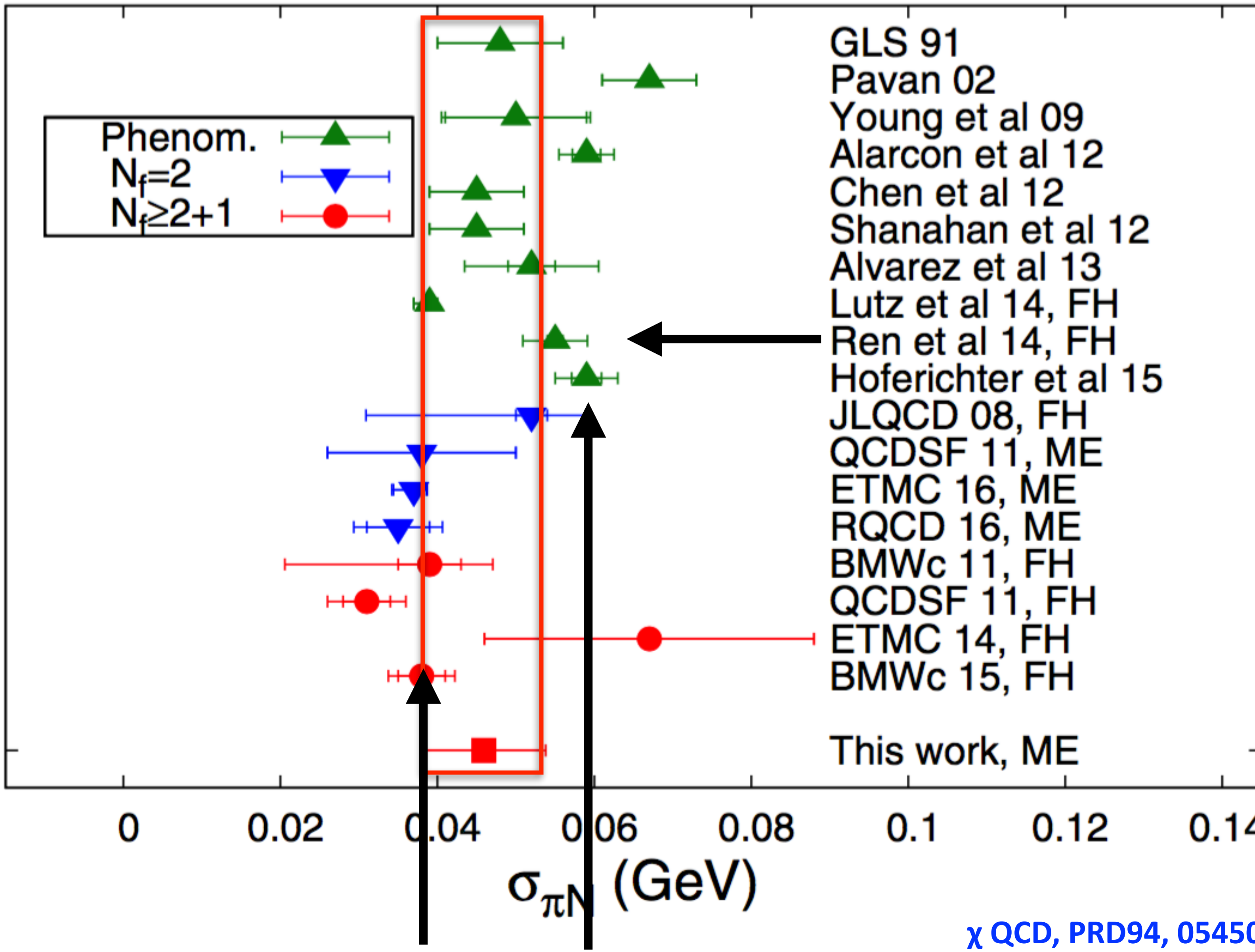
χ QCD, PRD94, 054503 (2016)

Pi-N sigma term still controversial



χ QCD, PRD94, 054503 (2016)

Pi-N sigma term still controversial



χ QCD, PRD94, 054503 (2016)

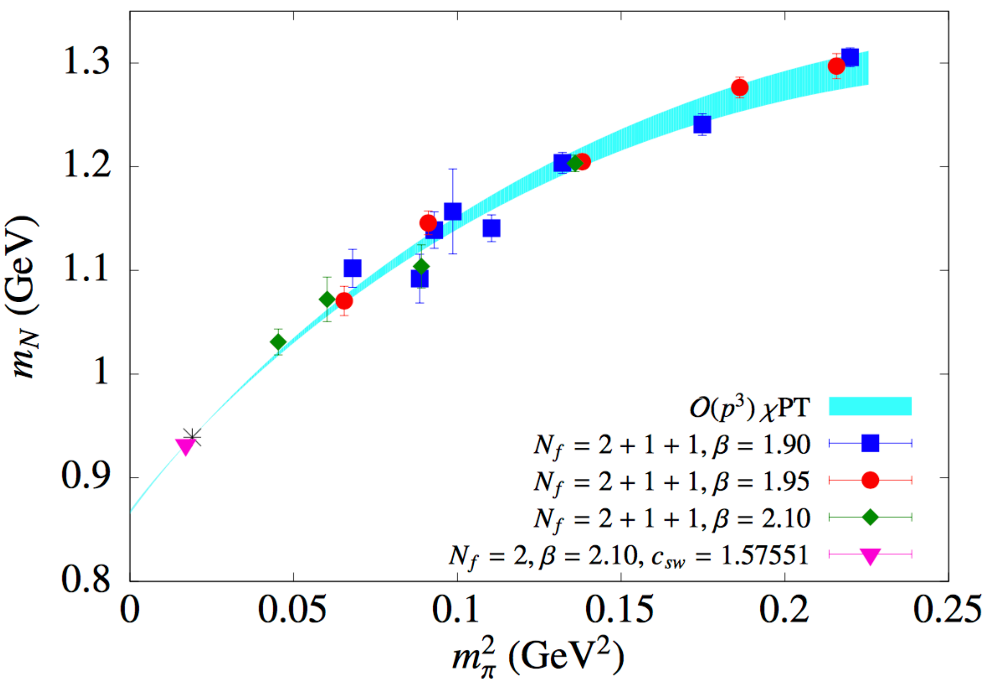
A latest determination of pi-N sigma term

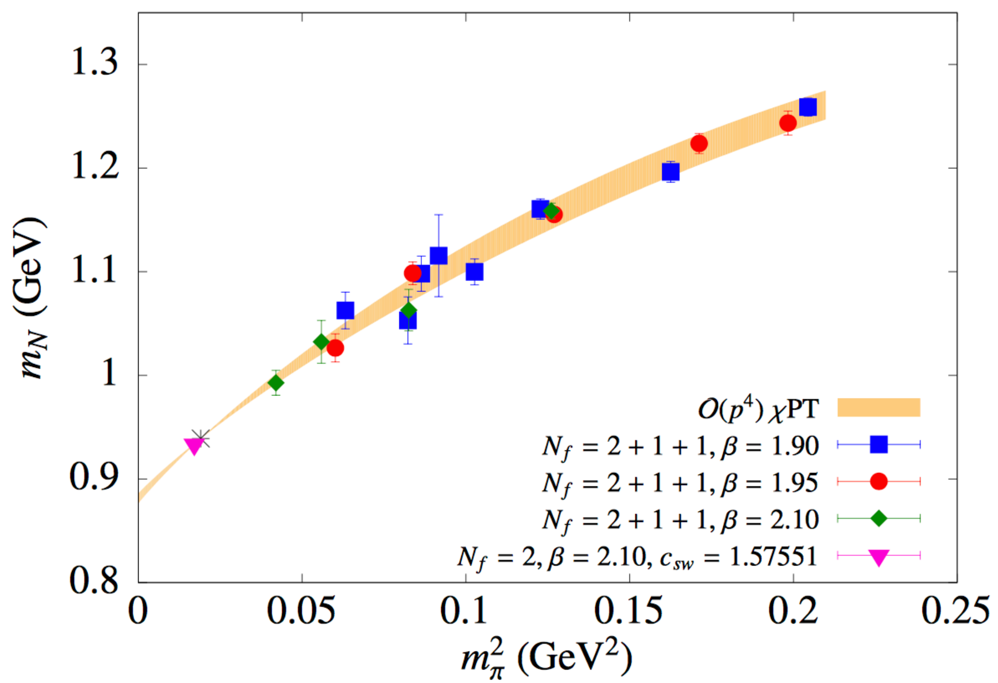
1704.02647

Low-lying baryon masses using $N_f = 2$ twisted mass clover-improved fermions directly at the physical point

C. Alexandrou[a,b], C. Kallidonis[b]

[a] Department of Physics, University of Cyprus, P.O. Box 20537, 1678 Nicosia, Cyprus
[b] Computation-based Science and Technology Research Center, The Cyprus Institute, 20 Kavafi Str., Nicosia 2121, Cyprus





$$\sigma_{\pi N} = 64.9 \pm 1.5 \pm 13.2 \text{ MeV}$$

Further checks

- We have studied **most relevant lattice artifacts**: chiral extrapolation, finite volume effects, finite lattice spacing effects , effects of heavier virtual states, and used all publicly available **LQCD data**

- What else is still **missing**?— an explicit check on the validity of SU(3) baryon chiral perturbation theory
  - large kaon mass leads to concerns about convergence of SU(3) BChPT, as seen in early failures of heavy-baryon BChPT and infrared BChPT

Prominent examples

- Octet baryon magnetic moments and chiral extrapolation of nucleon magnetic moments
  - V. Pascalutsa et al., Phys.Lett.B600:239-247,2004.
  - LSG, J. Martin Camalich , L. Alvarez-Ruso, M.J. Vicente Vacas, Phys.Rev.Lett.101:222002,2008
- lattice QCD baryon masses at leading one-loop order in HBChPT
  - LHPC (A. Walker-Loud et al.), Phys.Rev.D79:054502, 2009.
  - PACS-CS (K.-I. Ishikawa), Phys.Rev.D80:054502, 2009.
  - J. Martin Camalich, LSG, V. Vacas, PRD82(2010)074504

The application of the EOMS formulation seems to remove or at least alleviate the problem

Matching SU(3) to SU(2)

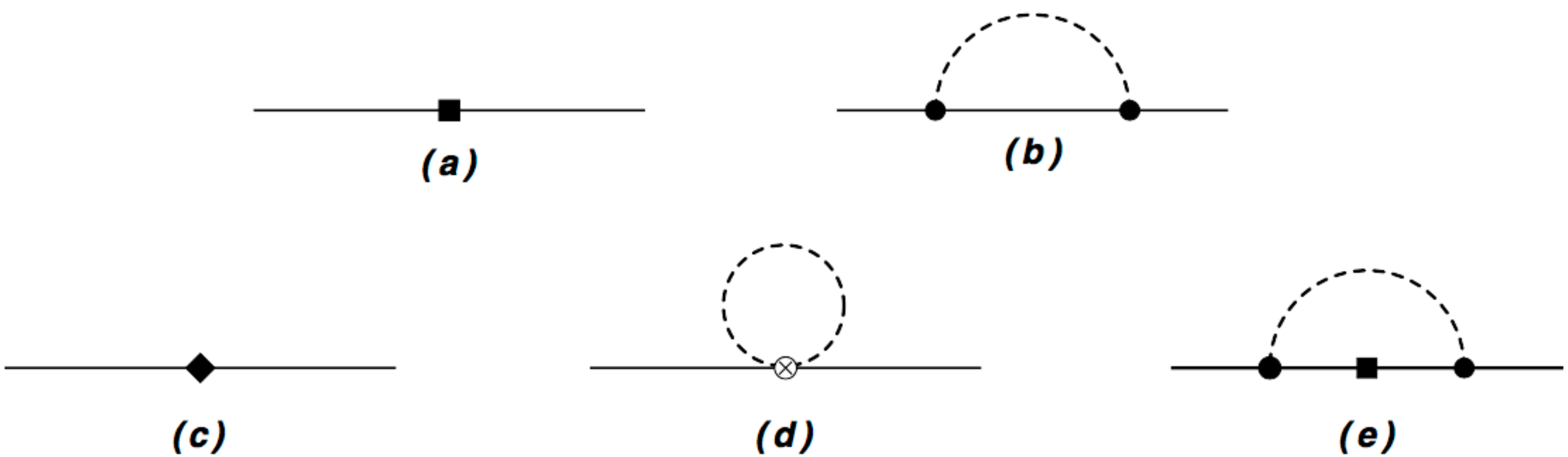
- Take the strange quark mass as a heavy scale and perform an expansion in terms of $m_{u/d}/m_s$ of the SU(3) results and compare them with the results of the SU(2) study
  - Alvarez-Ruso, Ledwig, Camalich, and Vicente-Vacas, PRD88, 054507 (2013)

- An earlier study similar in spirit, but with no quantitative analysis, tried to constrain the SU(3) LECs with SU(2) inputs
  - M. Frink and U.-G. Meissner, JHEP 0407, 028 (2004)

The procedure

- In SU(3) up to O(p^4)

$$
\begin{aligned}
M_N^{\mathrm{SU(3)}} &= m_0 + m_N^{(2)} + m_N^{(3)} + m_N^{(4)} \\
&= m_0 + \xi_{N\pi}^{(a)} m_\pi^2 + \xi_{NK}^{(a)} m_K^2 + \xi_{N\pi}^{(c)} m_\pi^4 + \xi_{NK}^{(c)} m_K^4 + \xi_{N\pi K}^{(c)} m_\pi^2 m_K^2 \\
&\quad + \frac{1}{(4\pi F_\phi)^2} \sum_{\phi=\pi,\, K,\, \eta} \left[\xi_{N\phi}^{(b)} H_N^{(b)} + \xi_{N\phi}^{(d)} H_N^{(d)} + \sum_{B=N,\, \Lambda,\, \Sigma} \xi_{NB\phi}^{(e)} H_{NB}^{(e)} \right]
\end{aligned}
$$



The procedure

- Isolate the strange quark contribution, introducing a fictitious meson

$$m_{s\bar{s}}^2 = 2B_0 m_s$$

- Leading-order ChPT

$$m_K^2 = \frac{1}{2}(m_\pi^2 + m_{s\bar{s}}^2), \quad m_\eta^2 = \frac{1}{3}(m_\pi^2 + 2m_{s\bar{s}}^2)$$

- Expand the kaon and eta contributions in terms of

$$m_\pi / m_{s\bar{s}}$$

$$\Sigma_{K,\,\eta}^{(i)} = A_{K,\,\eta}^{(i)} + B_{K,\,\eta}^{(i)} m_\pi^2 + C_{K,\,\eta}^{(i)} m_\pi^4 + \mathcal{O}\left(\frac{m_\pi}{m_{s\bar{s}}}\right)^5$$

- **SU(2) equivalent** nucleon mass

$$M_N = m_0^{\text{eff}} - 4c_1^{\text{eff}} m_\pi^2 + \alpha^{\text{eff}} m_\pi^4 + \beta^{\text{eff}} m_\pi^4 \log\frac{\mu^2}{m_\pi^2}$$
$$+ \frac{1}{(4\pi F_\phi)^2}\frac{3}{2}(D+F)^2\left[H_N^{(b)}(m_0, m_\pi) + \frac{1}{2}H_N^{(e)}(m_0, m_\pi, \Delta m_N, \mu)\right]$$

- To be compared with **the SU(2) result**

Alvarez-Ruso, Ledwig, Camalich, and Vicente-Vacas, PRD88, 054507 (2013)

$$M_N^{\mathrm{SU}(2)} = M_0 - 4c_1 m_\pi^2 + \frac{1}{2}\alpha m_\pi^4$$
$$+ \frac{1}{(4\pi f_\pi)^2}\frac{3}{8}\left[2(-8c_1 + c_2 + 4c_3) + c_2\right] m_\pi^4 - \frac{1}{(4\pi f_\pi)^2}\frac{3}{4}(8c_1 - c_2 - 4c_3) m_\pi^4 \log\frac{\mu^2}{m_\pi^2}$$
$$+ \frac{1}{(4\pi f_\pi)^2}\frac{3}{2}g_A^2\left[H_N^{(b)}(M_0, m_\pi) + \frac{1}{2}H_N^{(e)}(M_0, m_\pi, (-4c_1 m_\pi^2), \mu)\right],$$

*Ren, Alvarez-Ruso, **LSG**, Ledwig, Meng, Vicente Vacas, Phys.Lett. B766 (2017) 325*

- **SU(2) equivalent** nucleon mass

$$M_N = m_0^{\mathrm{eff}} - 4c_1^{\mathrm{eff}} m_\pi^2 + \alpha^{\mathrm{eff}} m_\pi^4 + \beta^{\mathrm{eff}} m_\pi^4 \log\frac{\mu^2}{m_\pi^2}$$
$$+ \frac{1}{(4\pi F_\phi)^2}\frac{3}{2}(D+F)^2 \left[H_N^{(b)}(m_0, m_\pi) + \frac{1}{2}H_N^{(e)}(m_0, m_\pi, \Delta m_N, \mu)\right]$$

- To be compared with **the rewritten SU(2) results**

$$M_N^{\mathrm{SU}(2)} = M_0 - 4c_1 m_\pi^2 + \alpha^{\mathrm{SU}(2)} m_\pi^4 + \beta^{\mathrm{SU}(2)} m_\pi^4 \log\frac{\mu^2}{m_\pi^2}$$
$$+ \frac{1}{(4\pi f_\pi)^2}\frac{3}{2}g_A^2 \left[H_N^{(b)}(M_0, m_\pi) + \frac{1}{2}H_N^{(e)}(M_0, m_\pi, (-4c_1 m_\pi^2), \mu)\right]$$

$$\alpha^{\mathrm{SU}(2)} = \frac{1}{2}\alpha - \frac{1}{(4\pi f_\pi)^2}\frac{3}{4}\left[(8c_1 - c_2 - 4c_3) - \frac{1}{2}c_2\right]$$
$$\beta^{\mathrm{SU}(2)} = -\frac{3}{4(4\pi f_\pi)^2}(8c_1 - c_2 - 4c_3).$$

*Ren, Alvarez-Ruso, **LSG**, Ledwig, Meng, Vicente Vacas, Phys.Lett. B766 (2017) 325*

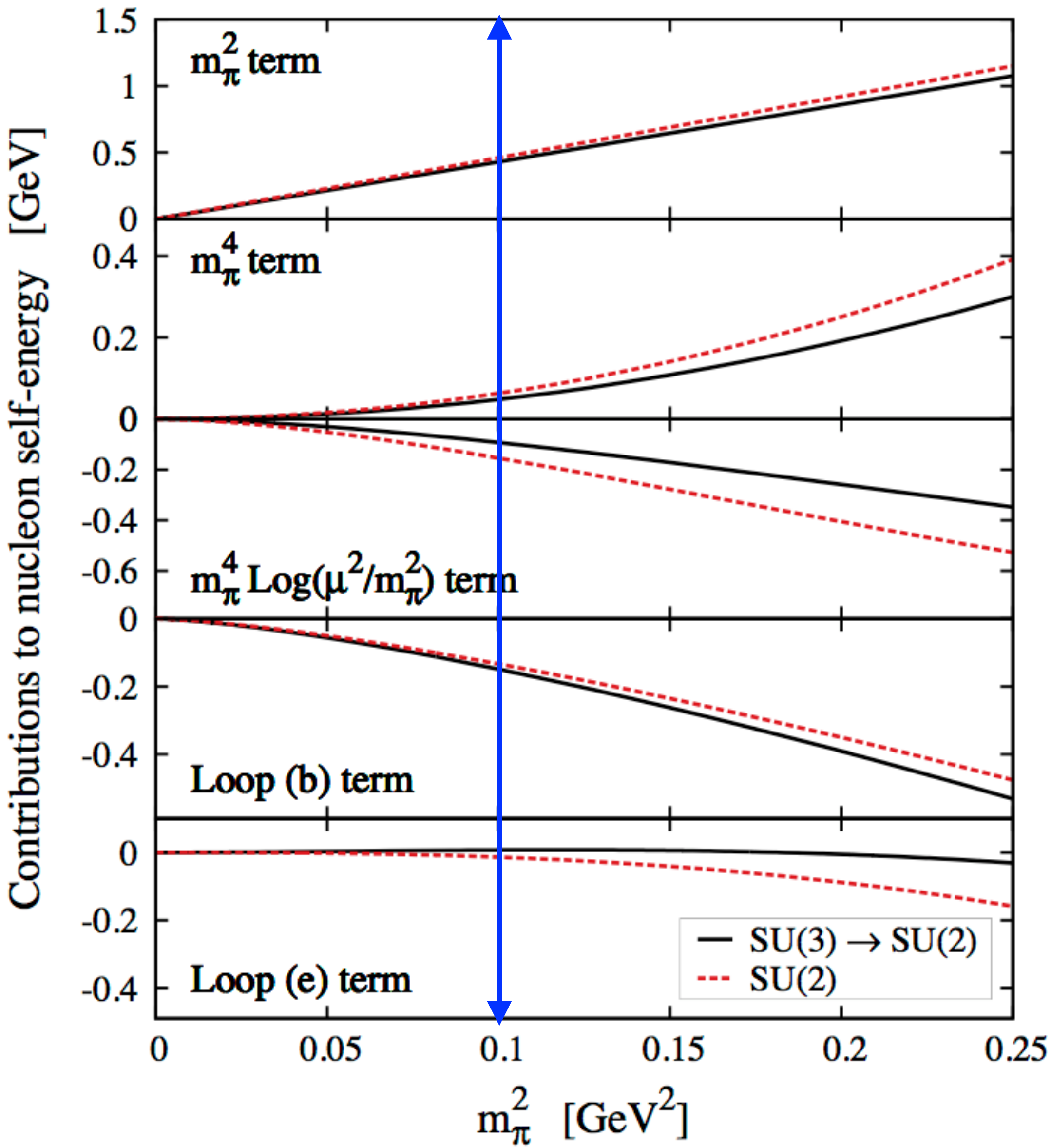
Comparison of effective parameters

SU(3)→SU(2)	SU(2)
$m_0^{\mathrm{eff}} = 875(10)\ \mathrm{MeV}$	$M_0 = 870(3)\ \mathrm{MeV}$
$c_1^{\mathrm{eff}} = -1.07(4)\ \mathrm{GeV}^{-1}$	$c_1 = -1.15(3)\ \mathrm{GeV}^{-1}$
$\alpha^{\mathrm{eff}} = 4.81(9)\ \mathrm{GeV}^{-3}$	$\alpha^{\mathrm{SU(2)}} = 6.27(1.98)\ \mathrm{GeV}^{-3}$
$\beta^{\mathrm{eff}} = -4.02(20)\ \mathrm{GeV}^{-3}$	$\beta^{\mathrm{SU(2)}} = -7.62(93)\ \mathrm{GeV}^{-3}$

- *SU(3): Ren, Geng, Meng, PRD91 (2015) 051502*
- *SU(2): Alvarez-Ruso, Ledwig, Camalich, and Vicente-Vacas, PRD88, 054507 (2013)*

*Ren, Alvarez-Ruso, **LSG**, Ledwig, Meng, Vicente Vacas, Phys.Lett. B766 (2017) 325*

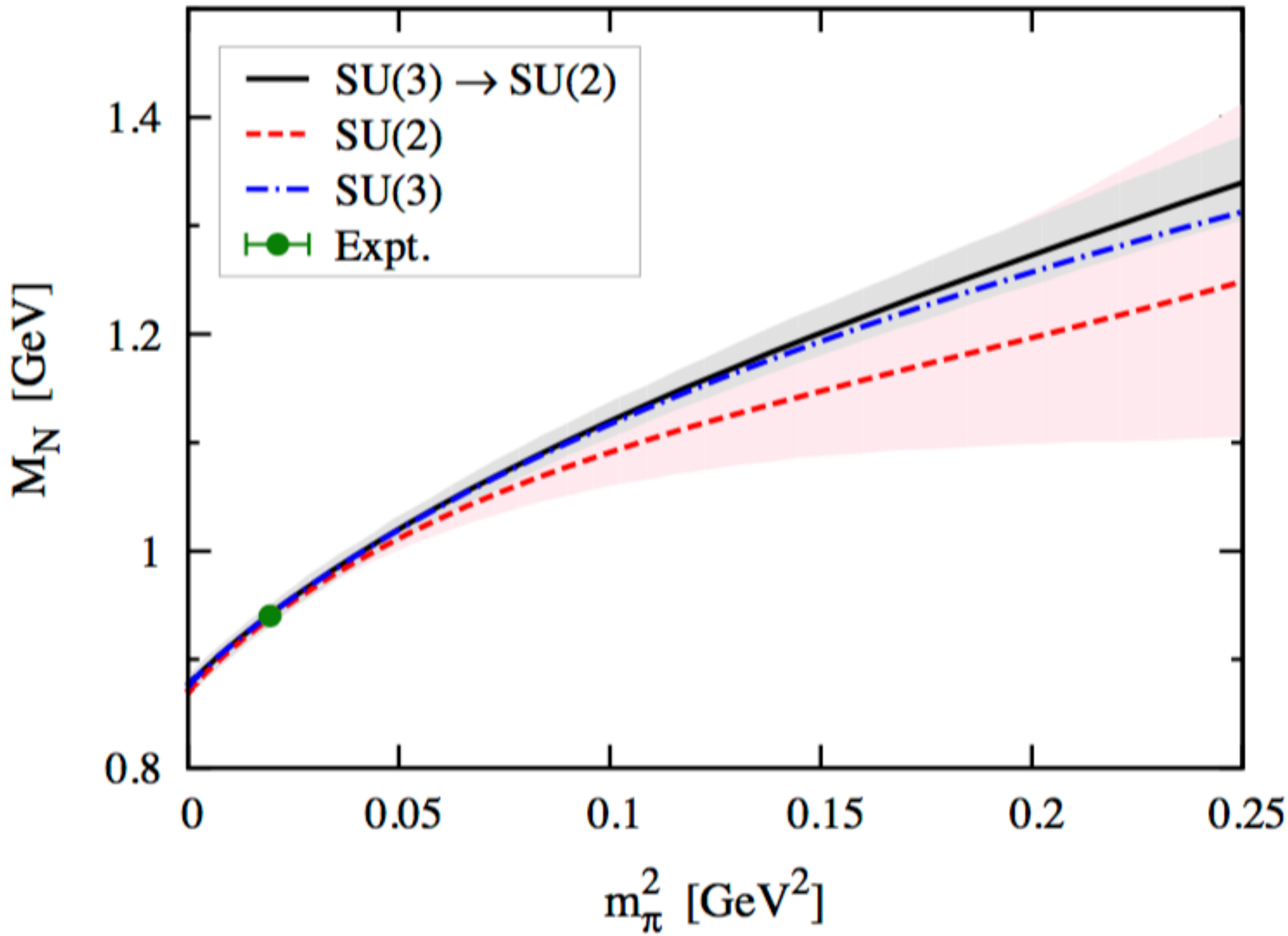
Decomposition of different contributions



agree at small m_π<300 MeV
differ at larger m_π

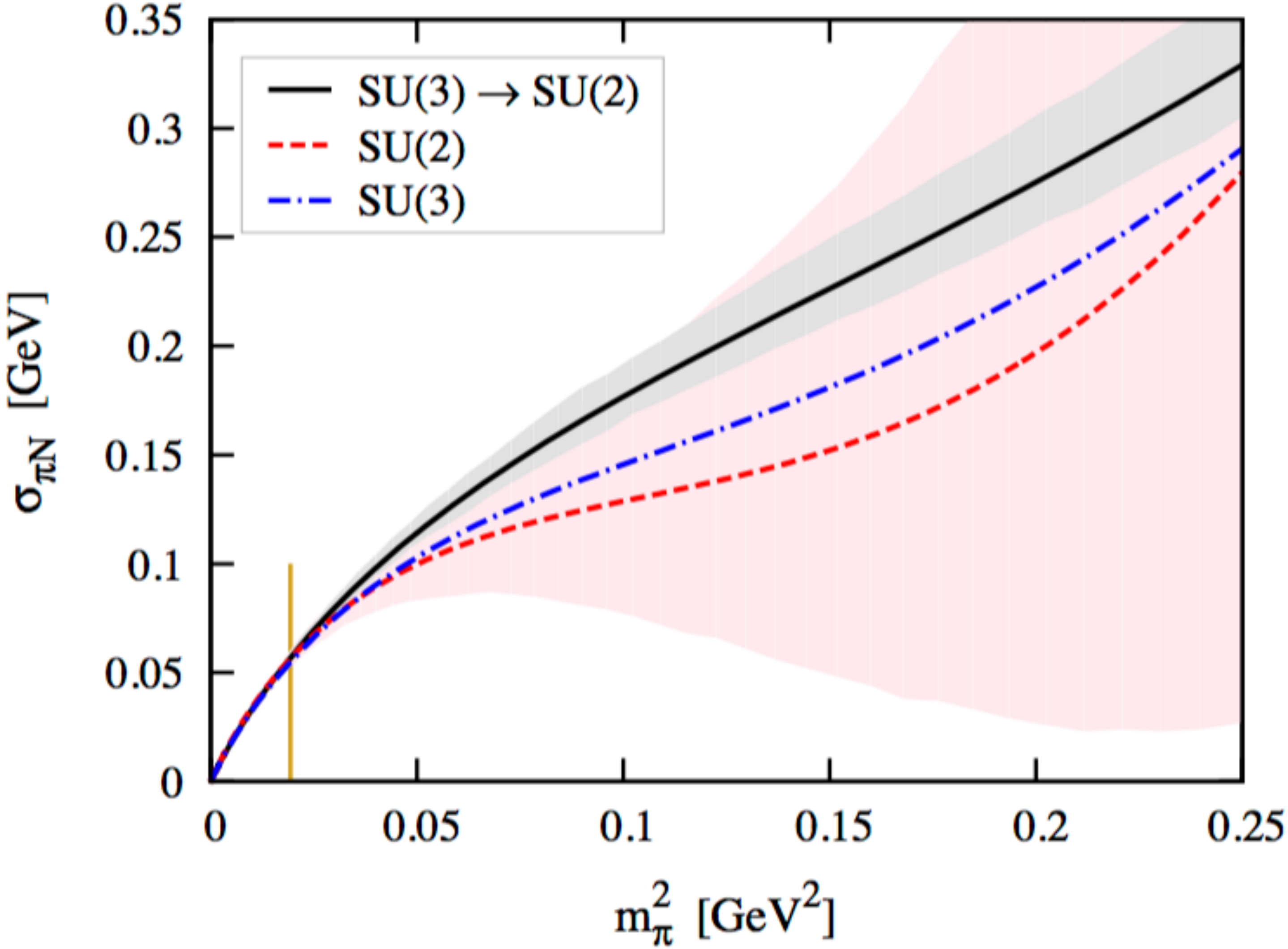
Ren, Alvarez-Ruso, ***LSG****, Ledwig, Meng, Vicente Vacas, Phys.Lett. B766 (2017) 325*

Chiral extrapolation of nucleon mass



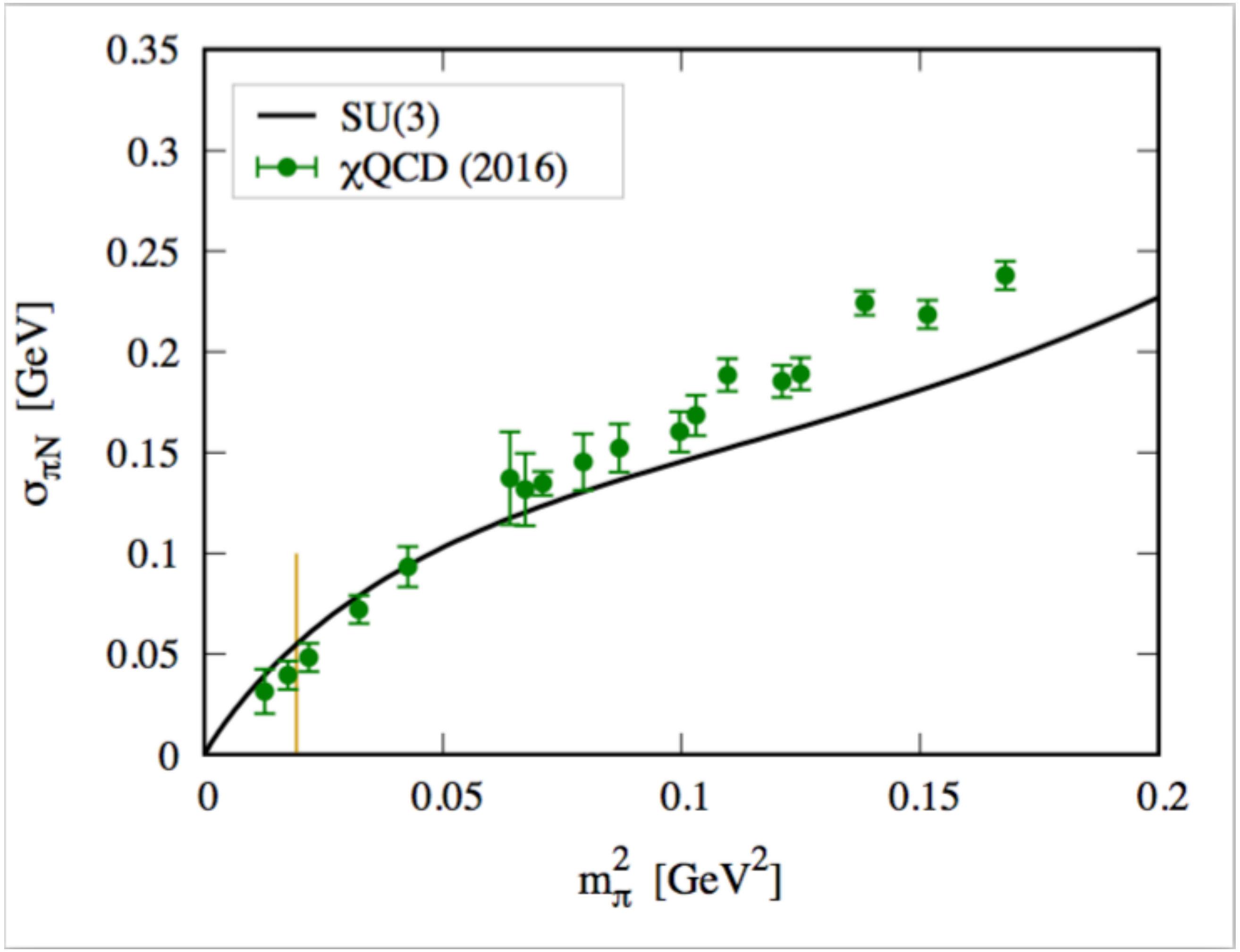
*Ren, Alvarez-Ruso, **LSG**, Ledwig, Meng, Vicente Vacas, Phys.Lett. B766 (2017) 325*

Light quark dependence of pion-nucleon sigma term



Ren, Alvarez-Ruso,LSG, Ledwig, Meng, Vicente Vacas, Phys.Lett. B766 (2017) 325

In comparison with χQCD16



χ QCD, PRD94, 054503 (2016)

Summary

- ✤ Explained how t**he baryon sigma terms** (particularly those of the nucleon) are **related** to dark matter direct searches and the quark-flavor structure of the nucleon.
- ✤ Shown how a combination of lattice QCD simulations and baryon chiral perturbation theory allows us to make a **reliable prediction** of these terms.
- ✤ It is to be stressed that we have taken into account **as much as possible lattice artifacts** and checked the validity of SU(3) BChP
- ✤ We should bear in mind, however, that our results **are tied to the reliability and accuracy** of the available lQCD simulations

Thank you very much for your attention!

Scale-setting effects on the determination of baryon sigma terms

arXiv:1301.3231

P.E. Shanahan, A.W. Thomas and R.D. Young*

- Lattice-scale setting
  - PACS-CS data with mass independent scale-setting:

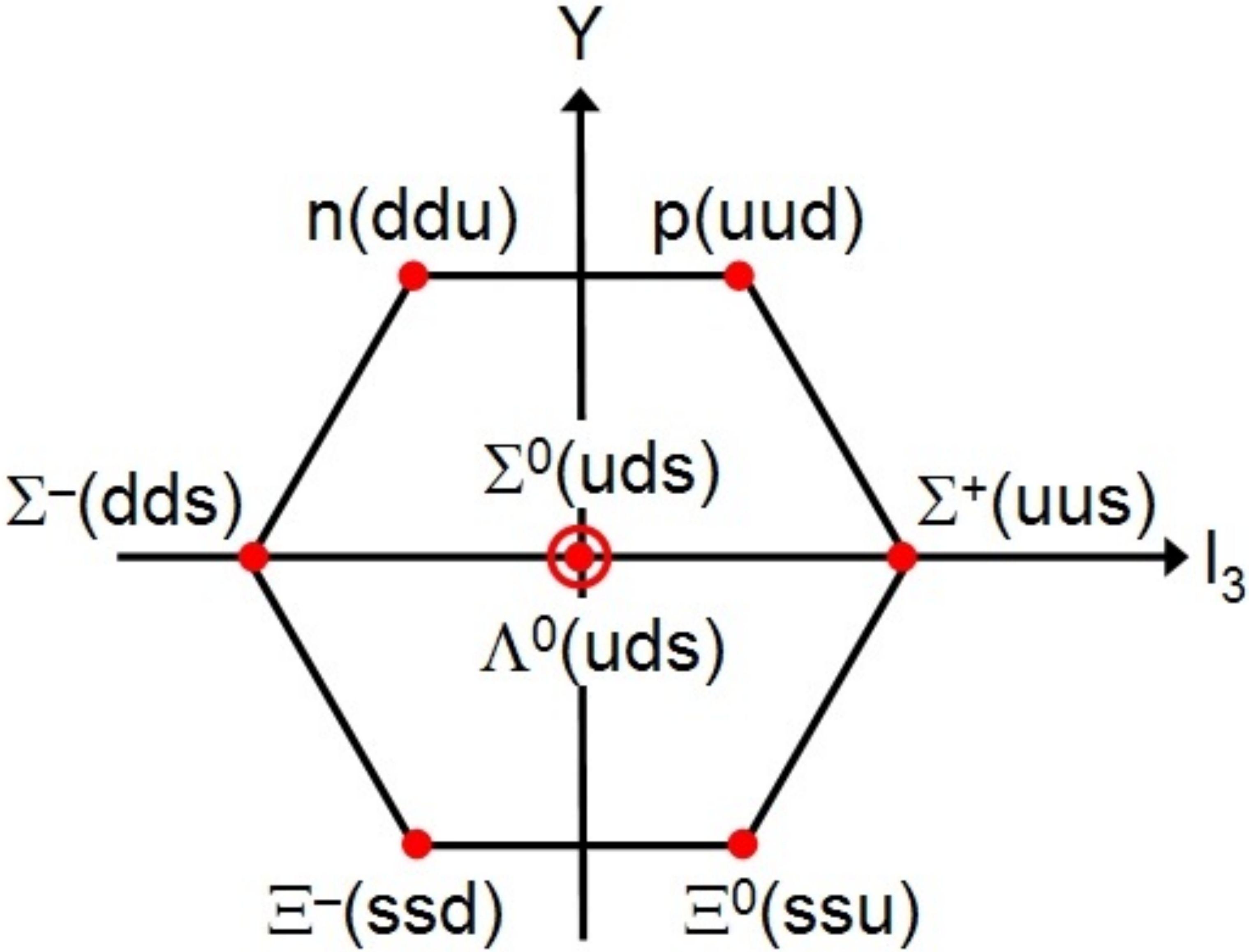
$$\sigma_{sN} = 59 \pm 7 \ (\mathrm{MeV})$$

  - PACS data with mass dependent (r_0) scale-setting:

$$\sigma_{sN} = 21 \pm 6 \ (\mathrm{MeV})$$

- Whether other LQCD data will show the same trend?

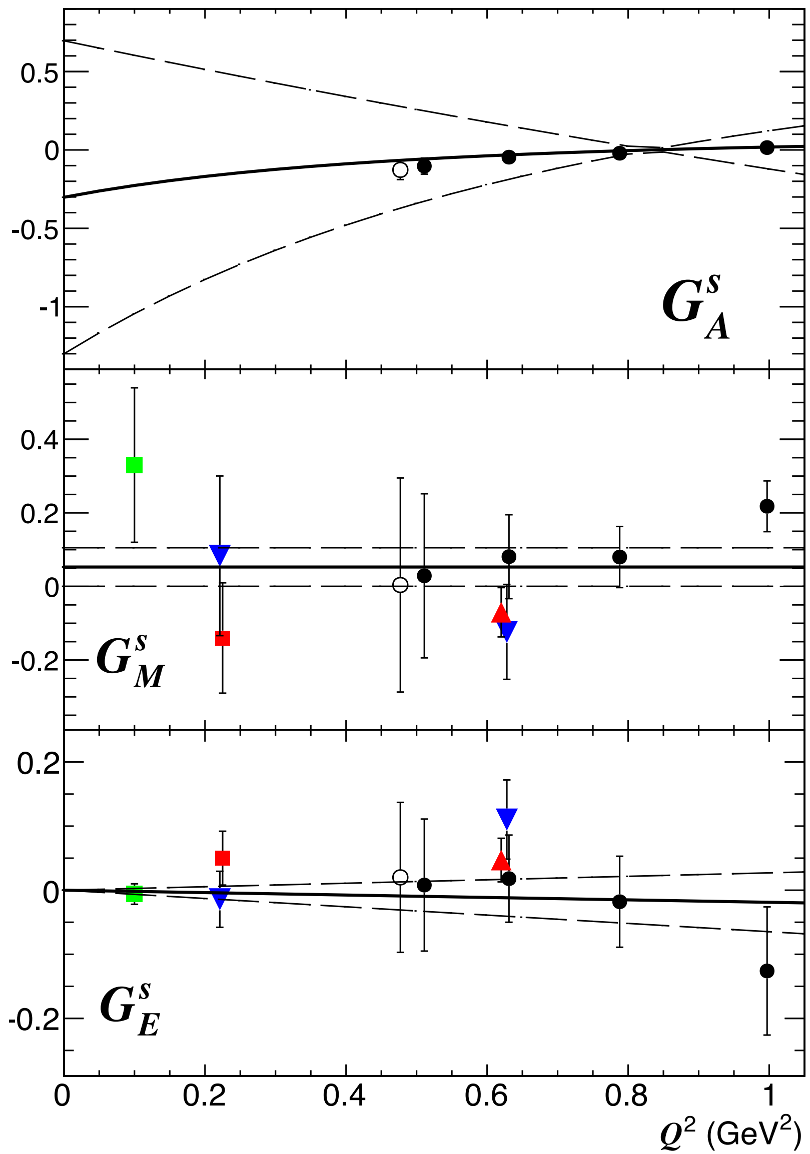
Quark-flavor structure of octet baryons



Naive quark model

Global fit of strangeness vector and axial vector form factors of nucleon

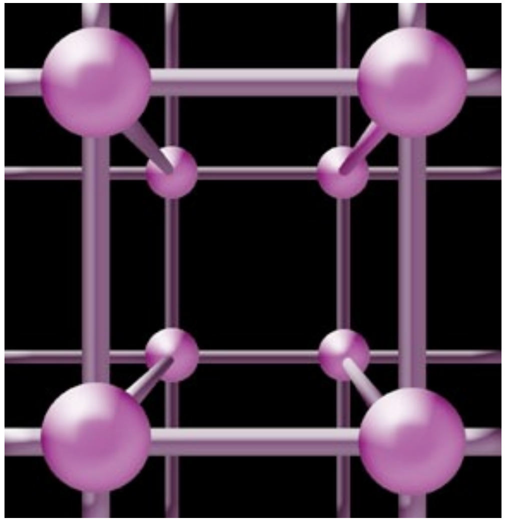
arXiv:1308.5694

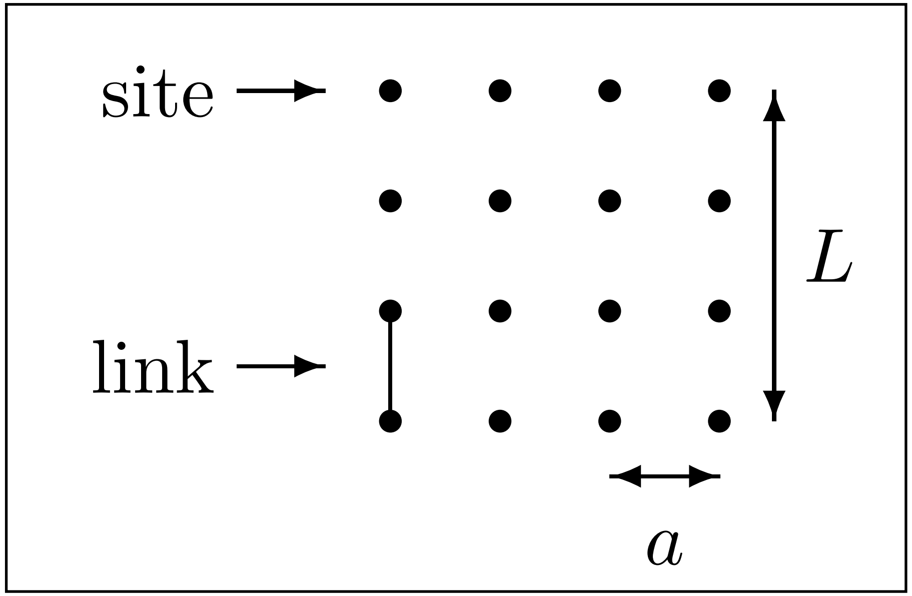


Parameter	Fit value
ρ_s	-0.071 ± 0.096
μ_s	0.053 ± 0.029
ΔS	-0.30 ± 0.42
Λ_A	1.1 ± 1.1
S_A	0.36 ± 0.50

The electric and magnetic form factors are consistent with **zero, but not** the axial-vector form factor

Lattice QCD





Basic idea： discretize space-time and solve non-perturbative strong interaction physics in a finite hypercube, utilizing monte carlo sampling techniques