北京航空航天大學
BEIHANG UNIVERSITY

超子弱辐射衰变：现状及展望

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Sci.Bull. 68 (2023) 779-782, Sci.Bull. 67 (2022) 2298-2304

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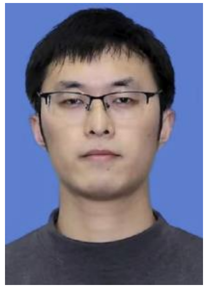

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Hadron Physics Online Forum (HAPOF)
https://indico.itp.ac.cn/category/5/

强子物理在线论坛

第二十二届论坛：自然界存在新的类原子核物质形

报告人：耿立升 教授　主持人：孟杰 教授

会议地址：https://meeting.tencent.com/p/673
腾讯会议室ID:　6733913824
会议时间：2021年4月16日 15:00– 16:30

摘要： 核力将不同数量的质子与中子束缚成原子核，其进而与电子组成原子，从而构成我们的可见宇宙。一个显然的问题是，自然界是否还存在由其它的色单态集团构成的类原子核物质形态？近年来，高能物理实验发现了很多的奇特强子态，其中的很大一部分[如Ds0*(2317)]可以解释为分子态。我们认为，这些分子态的存在意味着其组成成分间存在较强的相互吸引，从而可能形成新的物质形态。本报告将主要介绍近期关于D介子&K介子集团构成的新的物质形态的相关工作。

报告人介绍：耿立升

耿立升，兰州大学本科（2001），日本大阪大学（2005）和北京大学
北京航空航天大学物理学院长聘教授，研究生教学副院长。2010年
纪优秀人才支持计划”，2015年获国家自然科学基金委优秀青年科
年获中国核物理学会第六届胡济民教育科学奖，2017年入选教育部
“青年学者”项目。主要从事粒子物理与原子核物理理论研究。近
构建高精度相对论手征核力，理论解释和预言奇特强子态，寻找超
理，医学物理等。发表SCI论文150余篇（包括2篇PRL,100余篇PRD
被引5000余次(inspirehep)。主持国家自然科学基金重点、面上等省

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强子物理在线论坛

第六十三届论坛　新一代高精度核力--相对论手征核力

报告人：耿立升　教授　主持人：许甫荣

会议地址：https://meeting.tencent.com/dm/RgyVds
腾讯会议室 ID: 241-457-120　　时间：2023 年 02 月

摘 要： 理解自由和介质中的核子-核子相互作用一直是核物理研究的重要课
置如 HIAF 和 FRIB 的重要科学目标。第一性原理计算已经成为现代核结构与
由诺奖得主温伯格于上个世纪90年代初首次提出，经过全球众多科学家共同
手征核力是这些研究的最重要理论输入。然而，与原子物理和化学等学科不
法在核物理中的应用才刚刚起步。制约其发展的一个重要因素是缺少现代的
为了推动相对论第一性原理核物理研究，更好地理解非微扰强相互作用，弥
固有缺陷，我们构建了第一个高精度相对论手征核力。本报告将对其进行介
和进一步发展。

报告人介绍：耿立升，北京航空航天大学物理学院长聘教授、博导、副院长，北航-理论所彭桓武科教合作中心执行主任，教育部青年长江学者，国家自然科学基金委优秀青年科学基金获得者。2001年毕业于兰州大学物理科学与技术学院；2005年和2007年分别获日本大阪大学和北京大学理学博士学位；2007-2009年在西班牙瓦伦西亚大学做博士后；2009-2011年在德国慕尼黑工业大学做洪堡学者。主要研究兴趣包括有效场论方法在强子物理及核物理中的应用、超出标准模型的新物理、机器学习方法在核物理及医学物理中的应用等。发表SCI论文200余篇，引 用 7000 余次，H因子46。主持国家自然科学基金以及省部级项目 10 余项。

特别鸣谢：本届论坛由国家自然科学基金委创新群体“强子物理研究”

Hadron Physics Online Forum (HAPOF)
https://indico.itp.ac.cn/category/5/

强子物理在线论坛

第九十五期论坛　超子弱辐射衰变：现状及展望

报告人：耿立升 教授　主持人：彭海平 教授

会议地址: https://meeting.tencent.com/dm/bpkAwuvpJ3NY
腾讯会议室：　270-631-727　时间：2024 年 5 月 10 日 15:00– 17:00

摘要： 超子弱辐射衰变是少有的同时涉及强, 弱和电磁三种相互作用的独特物理过程. 这个看似简单的两体衰变, 由于长久以来实验测量和理论预言存在较大差异, 一直是粒子物理研究的难点问题之一, 被称为超子弱辐射衰变疑难. 近期, 北京正负电子对撞机上的 BESIII 合作组首次测量了$\Lambda \to n\gamma$衰变的不对称参数, 更新了其衰变分支比, 发现已有的理论预言均无法解释新的实验数据, 这进一步加剧了超子弱辐射衰变疑难问题. 本报告主要介绍基于协变手征微扰理论研究超子弱辐射衰变的最新进展及对其他相关过程（如超子非轻衰变和稀有衰变）的影响及启示.

报告人介绍： 耿立升，北京航空航天大学二级教授、博士生导师、教育部长江学者特聘教授。主要从事理论物理和医学物理研究，发表 SCI 文章200余篇，近年来主要研究兴趣包括：相对论第一性原理核物理计算；解释和预言奇特强子态，揭示非微扰强相互作用本质；质子重离子放疗中的关键科学与技术问题等。担任中国核学会核物理分会、医学物理分会，中国物理学会高能物理分会，中国生物医学工程学会医学物理分会等学会（常务）理事；担任 Science Bulletin、Chinese Physics C、Frontiers of Physics、Chinese Physics Letters、Frontiers in Physics、Symmetry、International Journal of Modern Physics E等学术期刊编委。主持国家自然科学基金重点项目、优秀青年科学基金等省部级项目 10 余项。

特别鸣谢：本届论坛由国家自然科学基金委重点项目资金支持

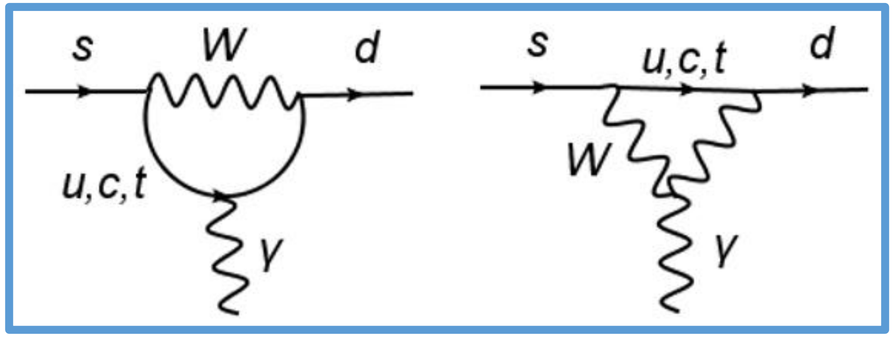
Contents

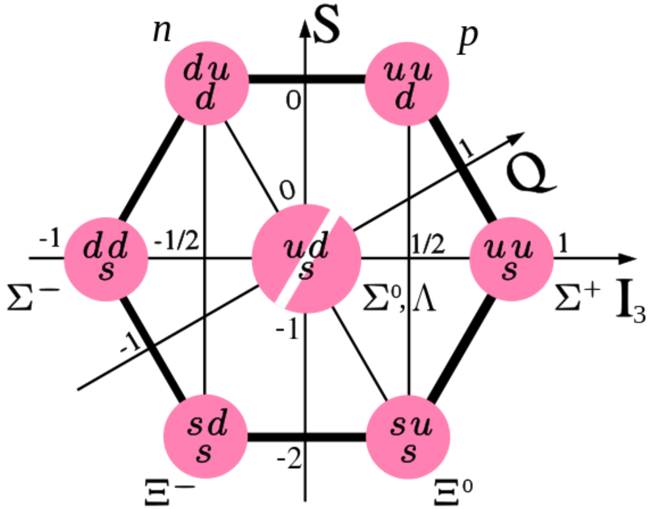
Contents

- ☞ Brief introduction: motivation and purpose
- ☞ Theoretical framework: covariant ChPT
- ☞ Results & discussions
  - ➢ Conventional ChPT results
  - ➢ Contribution of negative parity heavy resonances (preliminary)
- ☞ Summary and outlook

What are weak radiative hyperon decays

- **Weak radiative hyperon decays (WRHDs)** are interesting physical processes **involving the electromagnetic, weak, and strong interactions**
- $s \to d\gamma$ transitions at the quark level





- **Six** WRHDs channels of the ground-state octet baryons

$\Lambda \to n\gamma$	$\Sigma^0 \to n\gamma$	$\Xi^0 \to \Sigma^0\gamma$
$\Sigma^+ \to p\gamma$	$\Xi^0 \to \Lambda\gamma$	$\Xi^- \to \Sigma^-\gamma$

Weak decays of hyperons: related to various processes

Weak radiative hyperon decays (WRHDs): $(B_i \to B_f\,\gamma)$

- ✓ WRHDs puzzle

Inputs

Rare semi-leptonic decays of hyperons:

- $B_i \to B_f \gamma^* \to B_f l\, l$ and $B_i \to B_f \nu\bar{\nu}$
  New physics (NP)
- $B_i \to B_f l \nu$
  NP and V_{us}

Inputs

Non-leptonic decays of hyperons: $(B_i \to B_f\,\pi)$

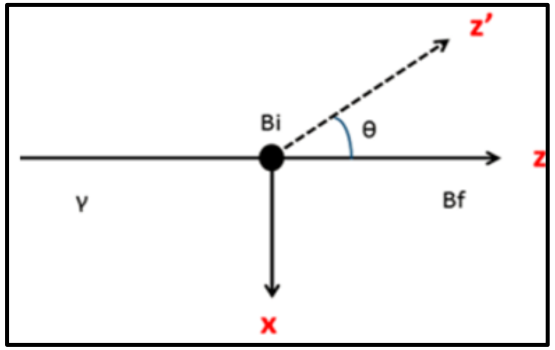
- ✓ S/P puzzle
- ✓ CP violation

What are weak radiative hyperon decays

- The effective Lagrangian describing the $B_i \to B_f\,\gamma$ WRHDs

$$\mathcal{L} = \frac{eG_F}{2}\bar{B}_f(a + b\gamma_5)\sigma^{\mu\nu}B_iF_{\mu\nu},$$

a: partity-conserving amplitude **b: partity-violating amplitude**



- **Only two observables** for the WRHDs

$$\frac{d\Gamma}{d\cos\theta} = \frac{e^2G_F^2}{\pi}(|a|^2 + |b|^2)[1 + \frac{2\mathrm{Re}(ab^*)}{|a|^2 + |b|^2}\cos\theta]\cdot|\vec{k}|^3,$$

$$\alpha_\gamma = \frac{2\mathrm{Re}(ab^*)}{|a|^2 + |b|^2}, \qquad \Gamma = \frac{e^2G_F^2}{\pi}(|a|^2 + |b|^2)\cdot|\vec{k}|^3, \qquad |\vec{k}| = \frac{m_i^2 - m_f^2}{2m_i}$$

α_γ: **asymmetry parameter**

θ: **angle between spin of the initial baryon B_i and 3-momentum $\vec{k}$ of the final baryon B_f**

Why study WRHDs: the WRHDs puzzle

Hara's theorem *Y. Hara, PRL12, 378 (1964)*

- Based on gauge invariance, CP conservation, and U-spin symmetry

- Hara' s theorem dictates that the WRHDs $B \to B'\gamma$ and $B' \to B\gamma$ must be identical under the U-spin transformation $s \Leftrightarrow d$

$$\mathcal{L}_{\text{p.c.}} = a\left(\bar{p}\sigma^{\mu\nu}\Sigma^{+}F_{\mu\nu} + \bar{\Sigma}^{+}\sigma^{\mu\nu}pF_{\mu\nu}\right)\frac{eG_F}{2},$$

$$\mathcal{L}_{\text{p.v.}} = b\left(\bar{p}\sigma^{\mu\nu}\gamma_5\Sigma^{+}F_{\mu\nu} - \bar{\Sigma}^{+}\sigma^{\mu\nu}\gamma_5 pF_{\mu\nu}\right)\frac{eG_F}{2},$$

leads to

$$b = -b, \;\; \text{i.e.,} \;\; b = 0$$

$$\alpha_\gamma = \frac{2\,\mathrm{Re}(ab^*)}{|a|^2 + |b|^2} = 0$$

Why study WRHDs: the WRHDs puzzle

PHYSICAL REVIEW VOLUME 188, NUMBER 5 25 DECEMBER 1969

Asymmetry Parameter and Branching Ratio of $\Sigma^+ \to p\gamma$*

LAWRENCE K. GERSHWIN,† MARGARET ALSTON-GARNJOST, ROGER O. BANGERTER, ANGELA BARBARO-GALTIERI, TERRY S. MAST, FRANK T. SOLMITZ, AND ROBERT D. TRIPP

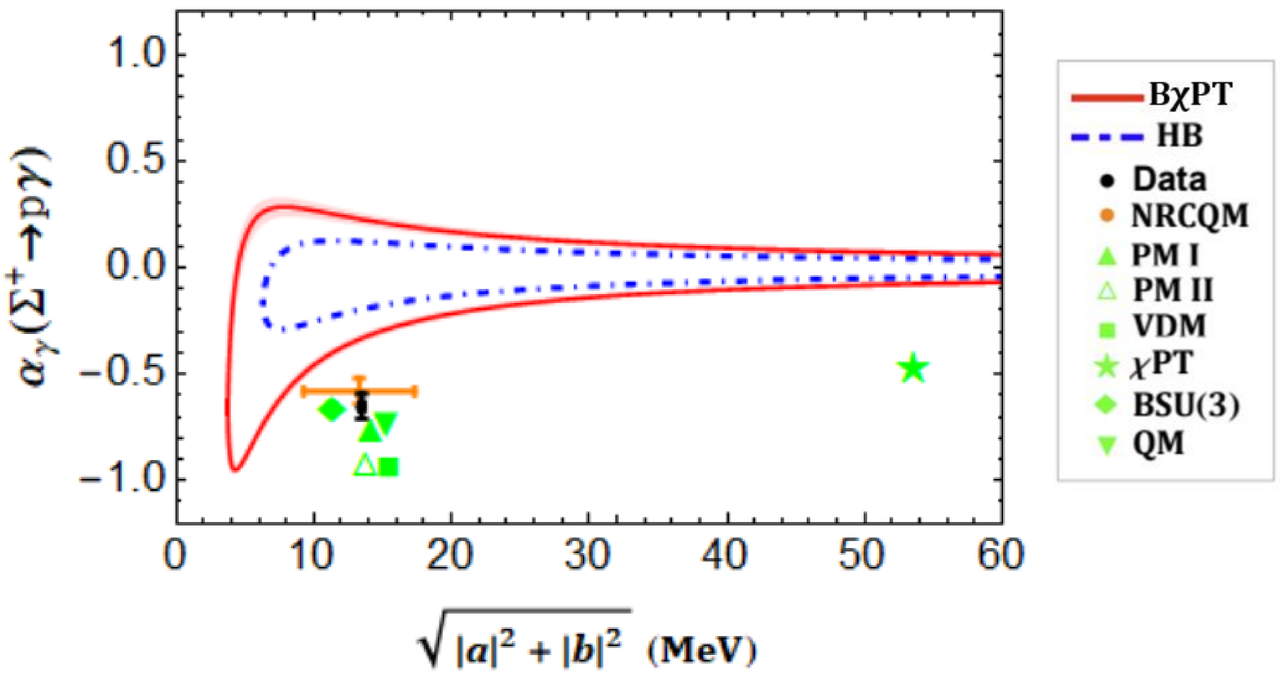
Lawrence Radiation Laboratory, University of California, Berkeley, California 94720

(Received 25 August 1969)

An experiment to study the decay $\Sigma^+ \to p\gamma$ was performed in the Berkeley 25-in. hydrogen bubble chamber. An analysis was made of 48 000 events of the type $K^- p \to \Sigma^+ \pi^-$, $\Sigma^+ \to p$+neutral with K^- momenta near 400 MeV/c. The Σ's produced in this momentum region are polarized because of the interference of the Y_0^* (1520) amplitude with the background amplitudes. We have measured the proton asymmetry parameter α for 61 $\Sigma^+ \to p\gamma$ events with an average polarization of 0.4. We found $\alpha = -1.03_{-0.42}^{+0.52}$. $SU(3)$ predicts a value $\alpha = 0$. A more restricted sample of events was used to determine the $\Sigma^+ \to p\gamma$ branching ratio. From 31 $\Sigma^+ \to p\gamma$ events and 11 670 $\Sigma^+ \to p\pi^0$ events, we found $(\Sigma^+ \to p\gamma)/(\Sigma^+ \to p\pi^0) = (2.76 \pm 0.51) \times 10^{-3}$. The result is in agreement with the previous measurements.

Why study WRHDs: the WRHDs puzzle

- The $\Sigma^+ \to p\,\gamma$ asymmetry parameter remains **large and negative**:
  −0.652±0.056stat±0.020syst.



Data: BESIII, PRL130 (2023) 21, 211901

HB χPT: E. E. Jenkins et al, NPB 397, 84 (1993)

$B\chi PT$: H. Neufeld, Nucl. Phys. B 402, 166 (1993)

NRCQM: Qiang Zhao et al, CPC45, 013101 (2021)

PM1: M. B. Gavela et al, PLB 101, 417 (1981)

PM2: G. Nardulli, PLB 190, 187 (1987)

VDM: P. Zenczykowski, PRD 44, 1485 (1991)

χPT: B. Borasoy et al, PRD 59, 054019 (1999)

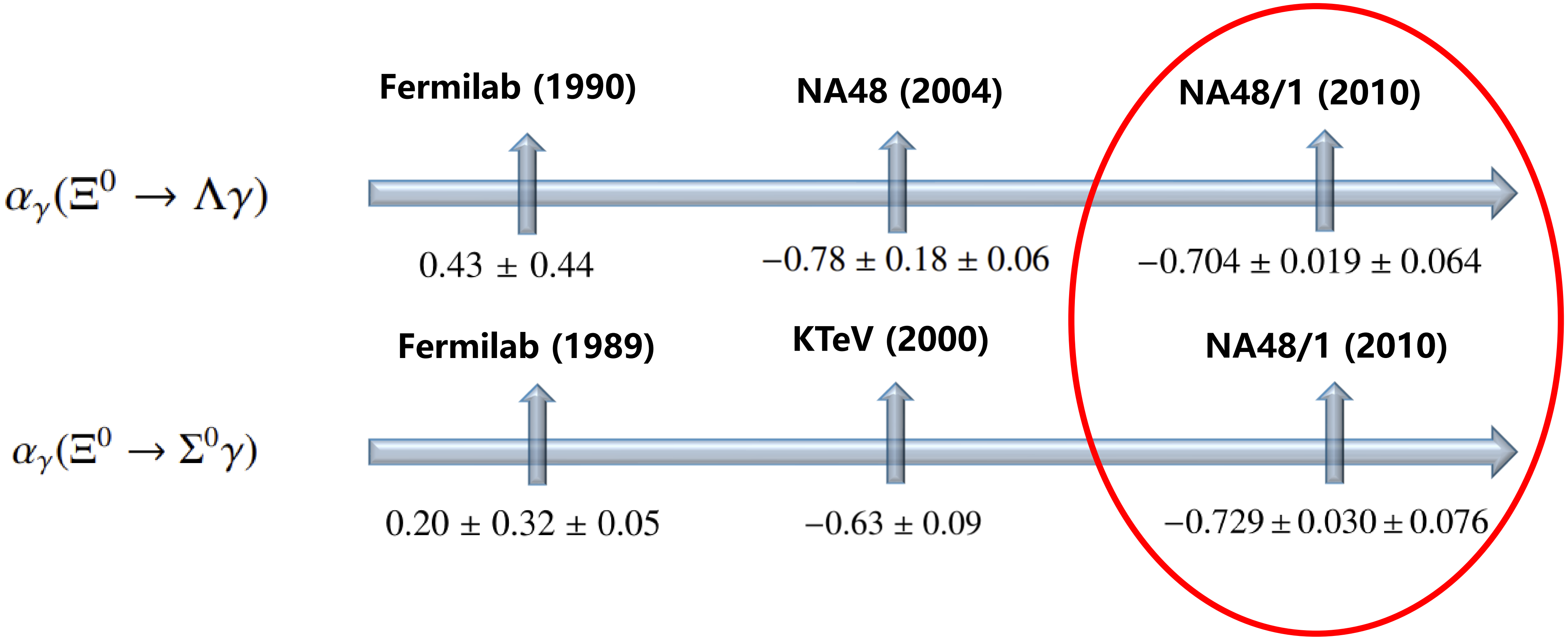
BSU(3): P. Zenczykowski, PRD 73, 076005 (2006)

QM: E. N. Dubovik et al, Phys. Atom. Nucl. 71, 136 (2008)

- Although some predictions agree with the measured large asymmetry of the $\Sigma^+ \to p\,\gamma$ decay, **they explain poorly the data of other WRHDs (as shown later)**

Why study WRHDs： experimentally challenging

- **Significant changes** in the asymmetry parameters of $\Xi^0 \to \Sigma^0 \gamma$ and $\Xi^0 \to \Lambda \gamma$



Why study WRHDs--$\Lambda \to n\gamma$

- **New BESIII** measurement for the $\Lambda \to n\,\gamma$ decay (PRL129(2022)21,212002)

Decay Mode	$\Lambda \to n\gamma$	$\bar{\Lambda} \to \bar{n}\gamma$
$N_{\rm ST}$ $(\times 10^3)$	6853.2 ± 2.6	7036.2 ± 2.7
$\varepsilon_{\rm ST}$ (%)	51.13 ± 0.01	52.53 ± 0.01
$N_{\rm DT}$	723 ± 40	498 ± 41
$\varepsilon_{\rm DT}$ (%)	6.58 ± 0.04	4.32 ± 0.03
BF $(\times 10^{-3})$	$0.820 \pm 0.045 \pm 0.066$	$0.862 \pm 0.071 \pm 0.084$
	$0.832 \pm 0.038 \pm 0.054$	
α_γ	$-0.13 \pm 0.13 \pm 0.03$	$0.21 \pm 0.15 \pm 0.06$
	$-0.16 \pm 0.10 \pm 0.05$	

PDG2022

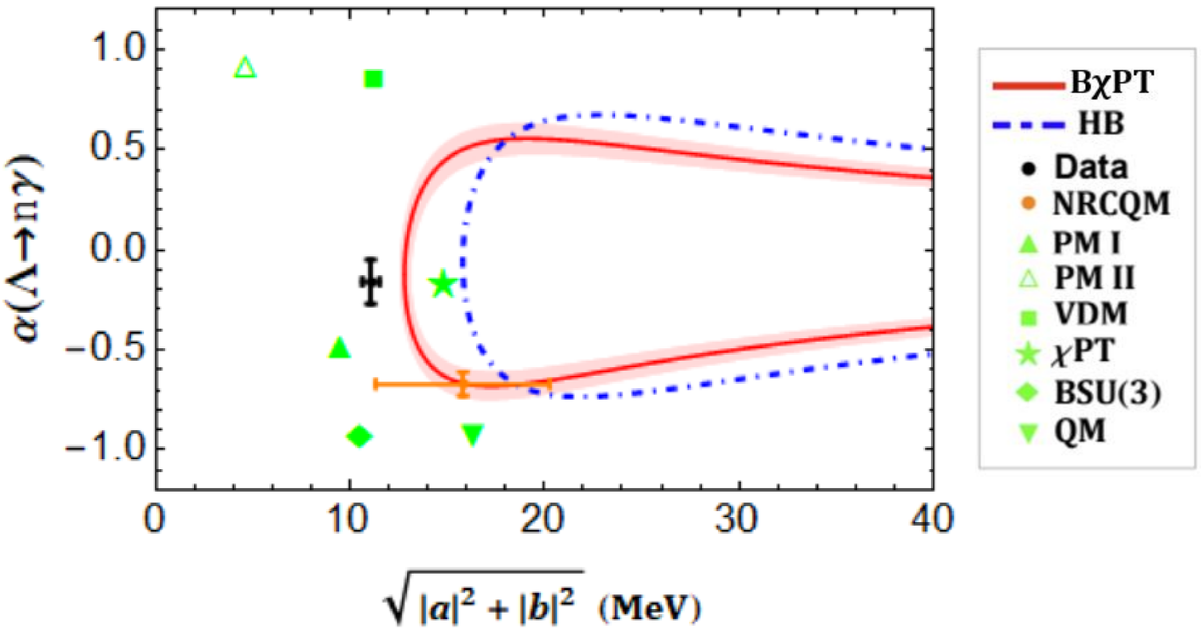
$\Gamma(n\gamma)/\Gamma_{\rm total}$ Γ_3/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.75±0.15 OUR FIT					
1.75±0.15	1816	LARSON	93	SPEC	$K^- p$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.78 \pm 0.24^{+0.14}_{-0.16}$	287	NOBLE	92	SPEC	See LARSON 93

- The branching fraction is only **about one half** of the current PDG average
- The asymmetry parameter α_γ **is determined for the first time**

Why study WRHDs—$\Lambda \to n\gamma$

- **None of the existing predictions can describe** the new BESIII measurement for the $\Lambda \to n\,\gamma$ decay



Data: BESIII, PRL129(2022)21,212002

HB χPT: E. E. Jenkins et al, NPB 397, 84 (1993)

$B\chi PT$: H. Neufeld, Nucl. Phys. B 402, 166 (1993)

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χPT: B. Borasoy et al, PRD 59, 054019 (1999)

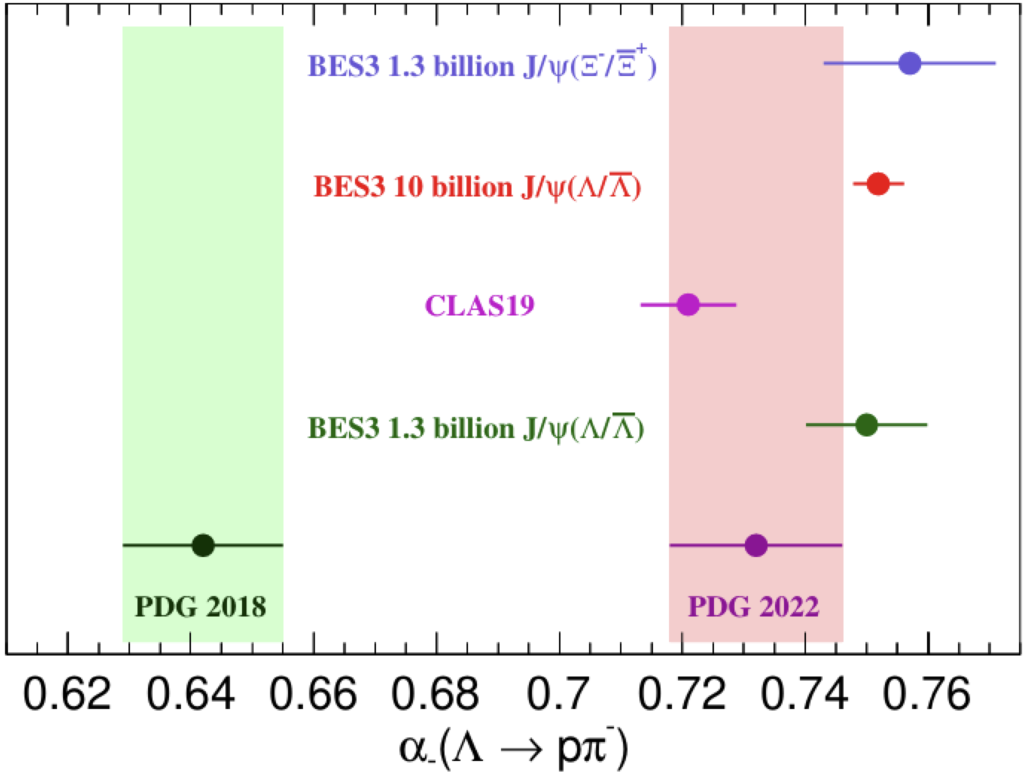
BSU(3): P. Zenczykowski, PRD 73, 076005 (2006)

QM: E. N. Dubovik et al, Phys. Atom. Nucl. 71, 136 (2008)

Why study WRHDs

☐ New BESIII and CLAS data for hyperon non-leptonic decays

BESIII: Nature Phys. 15, 631 (2019)	CLAS: PRL123,182301 (2019)
BESIII: Nature 606, 64 (2022)	BESIII: PRL129,131801 (2022)



- Definition of decay parameter for the $\Lambda \to p\,\pi^-$ decay

$$\mathcal{M}(B_i \to B_f \pi) = iG_F m_\pi^2 \bar{B}_f (A_S - A_P \gamma_5) B_i$$

$$\alpha_\pi = \frac{2\mathrm{Re}\,(s \cdot p)}{|s|^2 + |p|^2} \qquad s = A_S \qquad p = A_P|\vec{q}|/(E_f + m_f)$$

- Featured by a **larger statistics** and a **small uncertainty** and very different from previous PDG average

- A significant change for the baryon decay parameter of $\Lambda \to p\,\pi^-$ may **greatly affect the values of LECs hD, hF and hyperon non-leptonic decay amplitudes as inputs to WRHDs**

Why study WRHDs—theoretical tools

- Theoretically, **two phenomenological models** are able to explain the current experimental data of WRHDs at least qualitatively **except for the $\Lambda \to n\,\gamma$ decay**

  - *E. N. Dubovik et al, Phys. Atom. Nucl. 71, 136 (2008)—QM*
  - *P. Zenczykowski, PRD 73, 076005 (2006)—BSU(3)*

- **Chiral perturbation theory (χPT)** studies on the WRHDs

  - *B. Borasoy et al, PRD 59, 054019 (1999)*
  - *E. E. Jenkins et al, NPB397, 84 (1993)*
  - *J. W. Bos et al, PRD 51, 6308 (1995)*
  - *J. W. Bos et al, PRD 54, 3321 (1996)*
  - *J. W. Bos, et al, PRD 57, 4101 (1998)*

  (Tree or loop level in the heavy baryon formulation)

  - *H. Neufeld, NPB 402, 166 (1993)* *(Loop level in the covariant formulation)*

Our purpose

Our goal is to study the WRHDs in covariant baryon chiral perturbation theory (BχPT) with the extended-on-mass-shell (EOMS) renormalization scheme

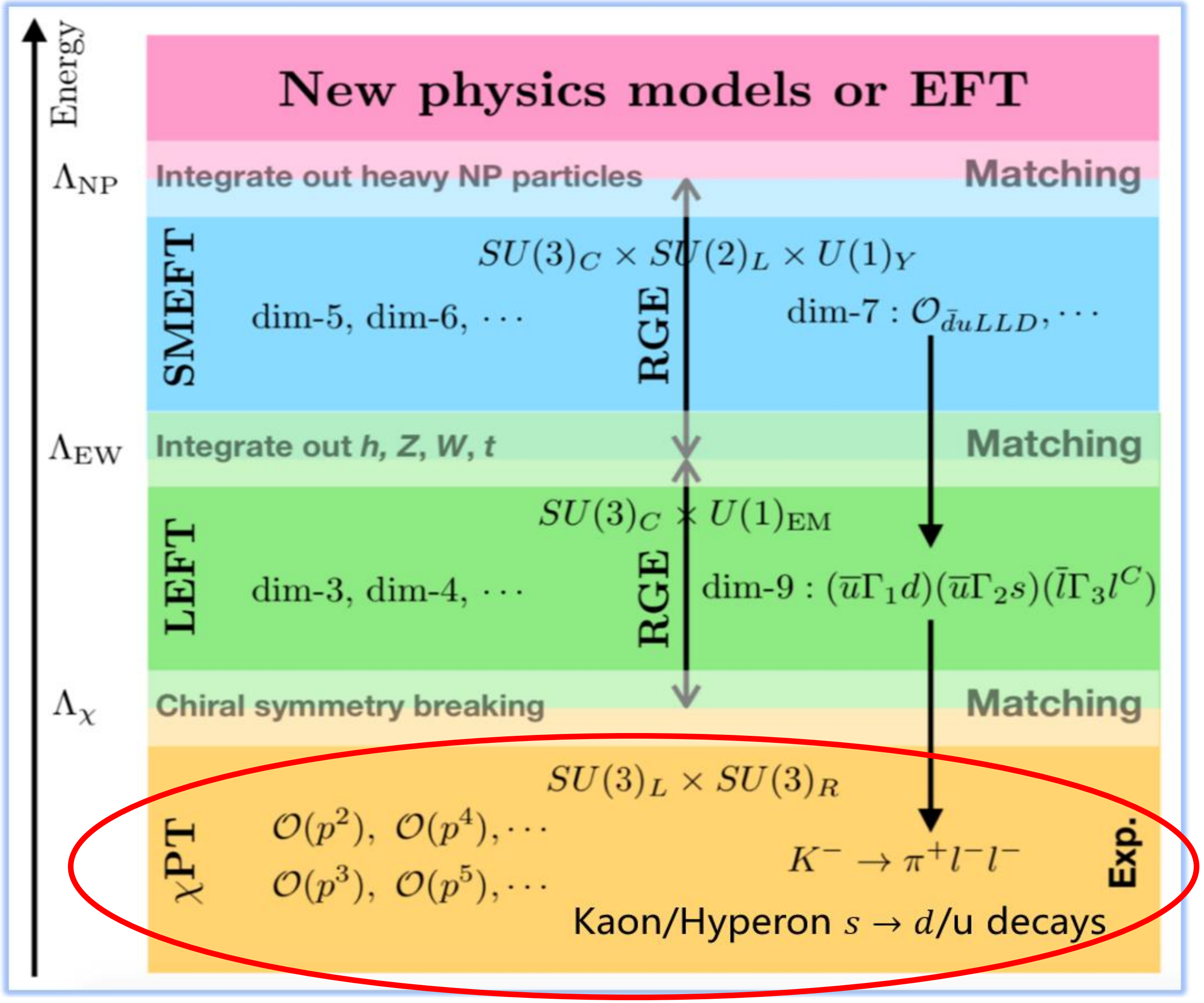
- **The work in the BχPT** *H. Neufeld, NPB 402, 166 (1993)*

  - ✓ The used low energy constants (LECs) and hyperon non-leptonic decay amplitudes are **out of date**
  - ✓ No efforts were taken to ensure a **consistent power counting**

Updating the relevant LECs and hyperon non-leptonic decay amplitudes → Calculating the branching fractions and asymmetry parameters, i.e., **amplitudes a and b**, of the WRHDs order by order → Comparing our predictions with those from other approaches/experimental data

Contents

Chiral perturbation theory : a bottom-up EFT approach

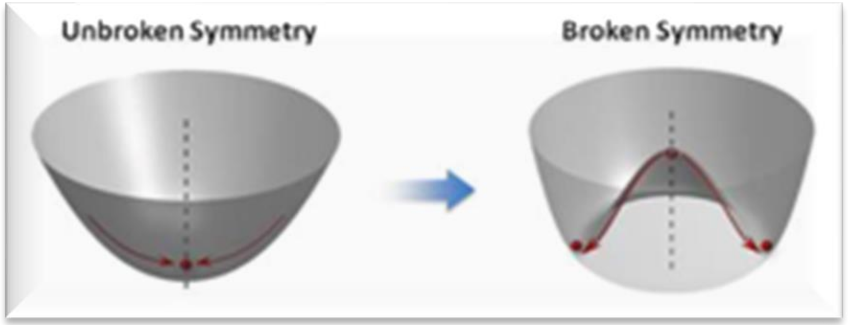


- **Effective theory:** the physics in low energy regions does not depend on the details of the higher energy physics, which has been integrated out

- **Chiral perturbation theory is a powerful tool to study the WRHDs**

Chiral perturbation theory – the essence

Because of quark confinement and asymptotic freedom, low energy QCD can not be solved perturbatively



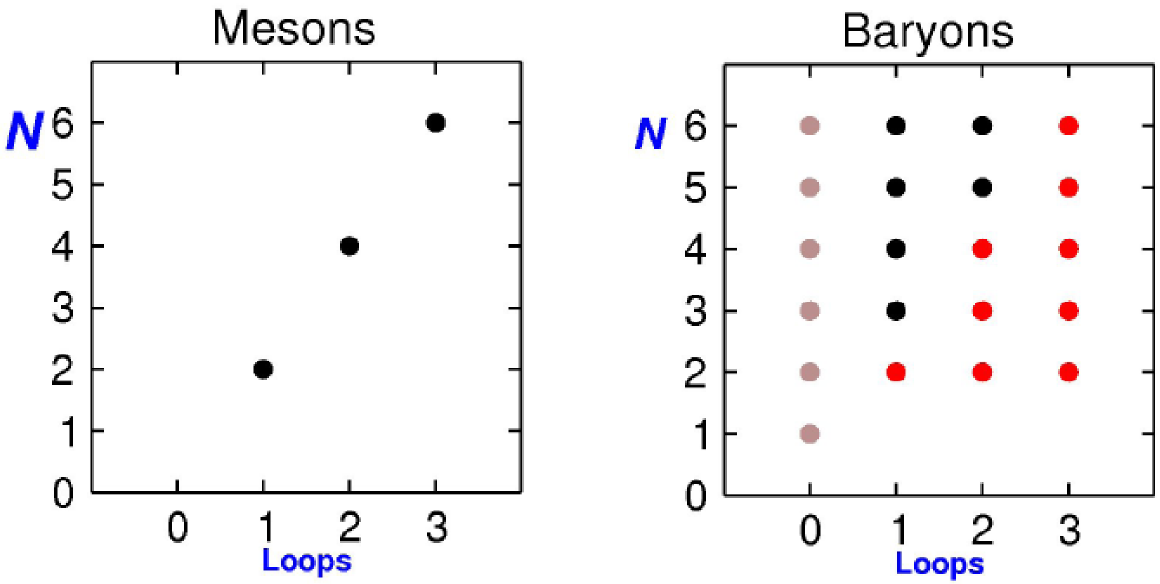
- **Chiral perturbation theory—low energy EFT of QCD**
  - ✓ **Maps quark (u, d, s) dof's to those of the asymptotic states, hadrons**
  - ✓ **Allows a perturbative formulation of low energy QCD in powers of external momenta and light quark masses, by utilizing chiral symmetry and its breaking pattern (the third feature of QCD)**
- **Development—Trilogy**
  - ✓ **1979, pion-pion, Weinberg—relativistic**
  - ✓ **1989, to the one-baryon sector, Gasser, Sainio, Svarc--nonrelativistic**
  - ✓ **1990/91/92, to NN/NNN, Weinberg—nonrelativistic**

Steven Weinberg
Nobel Prize in Physics in 1979

Rev. Mod. Phys. 81(2009)1773; Phys. Rept. 503(2011)1; Rev. Mod. Phys. 92 (2020) 025004

Power-Counting-Breaking in the baryon sector

- ChPT very successful in the study of Nanbu-Goldstone boson self-interactions, at least in SU(2)
- In the 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!

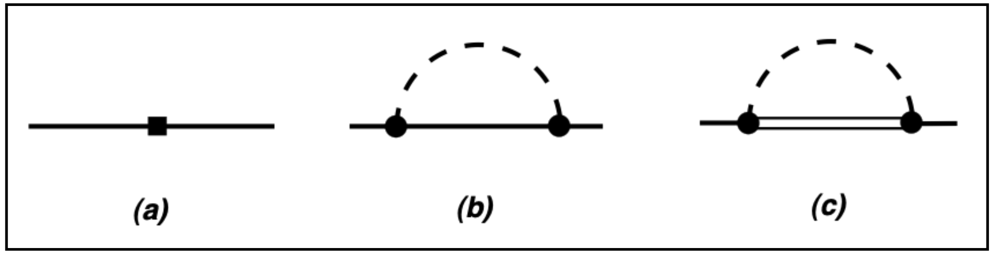


red dots denote possible PCB terms (pion-nucleon scattering)

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

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

Example: nucleon mass up to $O(p^3)$



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

order of the loop $= 1 + 1 + 4 - 1 - 2 = 3$

Naively (no PCB)

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

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

However

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

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

Power-Counting-Restoration methods

- **Heavy Baryon ChPT**: baryons are treated "semi-relativistically" by a simultaneous expansion in terms of external momenta and $1/M_N$ (Jenkins & Manohar, 1991, 1121 citations). It converges slowly for certain observables!

- **Relativistic baryon ChPT**: removing power counting breaking terms but retaining higher-order relativistic corrections, thus, keeping relativity.

  - **Infrared baryon ChPT** (T. Becher and H. Leutwyler, 1999, 608 citations)

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

  - **Fully relativistic baryon ChPT-Extended On-Mass-Shell (EOMS) scheme**

    One-Baryon: J. Gegelia et al., 1999; T. Fuchs et al.,2003

    Two-Baryon: LSG et al., PRC99(2019)024004, PRC102(2020)054001

Extended-on-Mass-Shell (EOMS)

- **"Drop" the PCB terms**

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

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

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

- **Equivalent to redefinition of the LECs**

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

$$\Downarrow \quad M_0^r = M_0(1 + aM_0^2); b^r = b^0 + b' M_0$$

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

Extended-on-Mass-Shell (EOMS)

- "Drop" the PCB terms

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

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

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

- Equivalent to redefinition of the LECs

$$\text{tree} = M_0 + bm_\pi^2 \quad +$$

$$\Downarrow$$

$$M_N = M_0^r + b^r$$

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

LSG,
Front.Phys.(Beijing) 8 (2013) 328

Extended-on-mass-shell (EOMS) BChPT

- satisfies all symmetry and analyticity constraints
- converges relatively faster--an appealing feature

Heavy baryon (HB) ChPT

- non-relativistic
- breaks analyticity of loop amplitudes
- converges slowly (particularly in three-flavor sector)
- strict PC and simple nonanalytical results

Infrared BChPT

- relativistic
- breaks analyticity of loop amplitudes
- converges slowly (particularly in three-flavor sector)
- analytical terms the same as HB ChPT

Three applications of covariant ChPT

LSG, Front.Phys.(Beijing) 8 (2013) 328

PRL **101,** 222002 (2008) PHYSICAL REVIEW LETTERS week ending 28 NOVEMBER 2008

Leading SU(3)-Breaking Corrections to the Baryon Magnetic Moments in Chiral Perturbation Theory

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(Received 9 May 2008; published 26 November 2008)

We calculate the baryon magnetic moments using covariant chiral perturbation theory (χPT) within the extended-on-mass-shell renormalization scheme. By fitting the two available low-energy constants, we improve the Coleman-Glashow description of the data when we include the leading SU(3)-breaking effects coming from the lowest-order loops. This success is in dramatic contrast with previous attempts at the same order using heavy-baryon χPT and covariant infrared χPT. We also analyze the source of this improvement with particular attention to the comparison between the covariant results.

PHYSICAL REVIEW LETTERS **130,** 071902 (2023)

Cross-Channel Constraints on Resonant Antikaon-Nucleon Scattering

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(Received 9 September 2022; revised 22 December 2022; accepted 24 January 2023; published 17 February 2023)

Chiral perturbation theory and its unitarized versions have played an important role in our understanding of the low-energy strong interaction. Yet, so far, such studies typically deal exclusively with perturbative or nonperturbative channels. In this Letter, we report on the first global study of meson-baryon scattering up to one-loop order. It is shown that covariant baryon chiral perturbation theory, including its unitarization for the negative strangeness sector, can describe meson-baryon scattering data remarkably well. This provides a highly nontrivial check on the validity of this important low-energy effective field theory of QCD. We show that the $\bar{K}N$ related quantities can be better described in comparison with those of lower-order studies, and with reduced uncertainties due to the stringent constraints from the πN and KN phase shifts. In particular, we find that the two-pole structure of $\Lambda(1405)$ persists up to one-loop order reinforcing the existence of two-pole structures in dynamically generated states.

PHYSICAL REVIEW LETTERS **128,** 142002 (2022)

Accurate Relativistic Chiral Nucleon-Nucleon Interaction up to Next-to-Next-to-Leading Order

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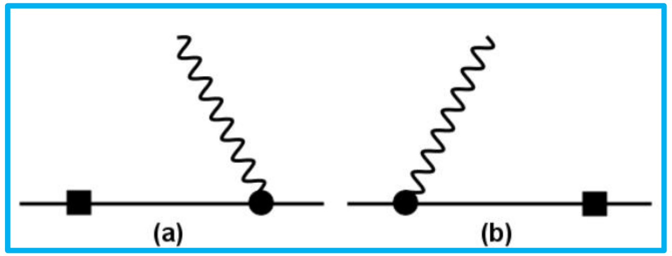
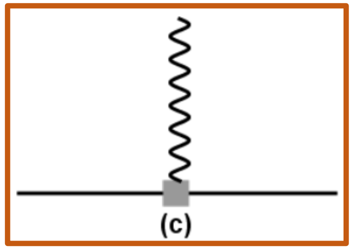
We construct a relativistic chiral nucleon-nucleon interaction up to the next-to-next-to-leading order in covariant baryon chiral perturbation theory. We show that a good description of the np phase shifts up to $T_{\rm lab} = 200$ MeV and even higher can be achieved with a $\tilde{\chi}^2$/d.o.f. less than 1. Both the next-to-leading-order results and the next-to-next-to-leading-order results describe the phase shifts equally well up to $T_{\rm lab} = 200$ MeV, but for higher energies, the latter behaves better, showing satisfactory convergence. The relativistic chiral potential provides the most essential inputs for relativistic *ab initio* studies of nuclear structure and reactions, which has been in need for almost two decades.

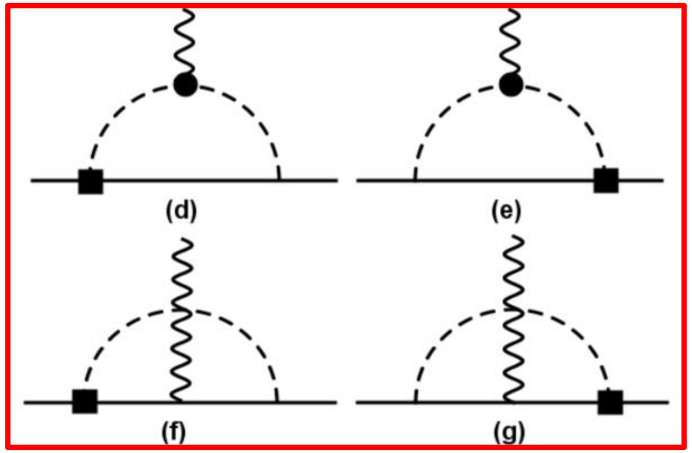
WRHDs in the EOMS BχPT

$$a_{B_iB_f} = a_{B_iB_f}^{(1,\text{tree})} + a_{B_iB_f}^{(2,\text{tree})} + a_{B_iB_f}^{(2,\text{loop})}$$
$$b_{B_iB_f} = b_{B_iB_f}^{(2,\text{tree})} + b_{B_iB_f}^{(2,\text{loop})}$$

Feynman diagrams







Lagrangians

$$\mathcal{L}_{\Delta S=1}^{(0)} = \sqrt{2}G_F m_\pi^2 F_\phi \langle h_D \bar{B}\{u^\dagger \lambda u, B\} + h_F \bar{B}[u^\dagger \lambda u, B]\rangle,$$
$$\mathcal{L}_{MB}^{(2)} = \frac{b_6^D}{8m_B}\langle \bar{B}\sigma^{\mu\nu}\{F_{\mu\nu}^+, B\}\rangle + \frac{b_6^F}{8m_B}\langle \bar{B}\sigma^{\mu\nu}[F_{\mu\nu}^+, B]\rangle,$$

$$\mathcal{L}_\alpha^{(2)} = C_\alpha \langle \bar{B}\sigma^{\mu\nu}F_{\mu\nu}\lambda Q B\rangle,$$
$$\mathcal{L}_\beta^{(2)} = C_\beta \langle \sigma^{\mu\nu}F_{\mu\nu}\bar{B}QB\lambda\rangle,$$
$$\mathcal{L}_\gamma^{(2)} = C_\gamma \langle \bar{B}\sigma^{\mu\nu}F_{\mu\nu}B\lambda Q\rangle,$$
$$\mathcal{L}_\sigma^{(2)} = C_\sigma \langle \bar{B}\sigma^{\mu\nu}F_{\mu\nu}\lambda B Q\rangle,$$
$$\mathcal{L}_\rho^{(2)} = C_\rho \left(\langle \bar{B}\sigma^{\mu\nu}\gamma_5 F_{\mu\nu}Q\rangle\langle B\lambda\rangle - \langle \bar{B}\sigma^{\mu\nu}\gamma_5 F_{\mu\nu}\lambda\rangle\langle BQ\rangle\right)$$

$$\mathcal{L}_{\Delta S=1}^{(0)} = \sqrt{2}G_F m_\pi^2 F_\phi \langle h_D \bar{B}\{u^\dagger \lambda u, B\} + h_F \bar{B}[u^\dagger \lambda u, B]\rangle$$
$$\mathcal{L}_B^{(1)} = \langle \bar{B}i\gamma^\mu D_\mu B - m_0 \bar{B}B\rangle,$$
$$\mathcal{L}_M^{(2)} = \frac{F_\phi^2}{4}\langle u_\mu u^\mu + \chi^+\rangle,$$
$$\mathcal{L}_{MB}^{(1)} = \frac{D}{2}\langle \bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}\rangle + \frac{F}{2}\langle \bar{B}\gamma^\mu\gamma_5[u_\mu, B]\rangle,$$

Order contributions

$$a_{B_iB_f}^{(1,\text{tree})}$$

LECs b_6^D and b_6^F : the experimental data of Octet baryon magnetic moment

$$a_{B_iB_f}^{(2,\text{tree})} \quad b_{B_iB_f}^{(2,\text{tree})}$$

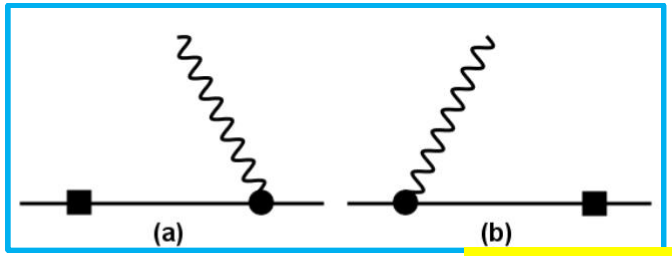
LECs D and F have been determined in Ref. LSG et al, PRD 90, 054502 (2014)

$$a_{B_iB_f}^{(2,\text{loop})} \quad b_{B_iB_f}^{(2,\text{loop})}$$

WRHDs in the EOMS BχPT

$$a_{B_iB_f} = a^{(1,\text{tree})}_{B_iB_f} + a^{(2,\text{tree})}_{B_iB_f} + a^{(2,\text{loop})}_{B_iB_f}$$
$$b_{B_iB_f} = b^{(2,\text{tree})}_{B_iB_f} + b^{(2,\text{loop})}_{B_iB_f}$$

Feynman diagrams | **Lagrangians** | **Order contributions**

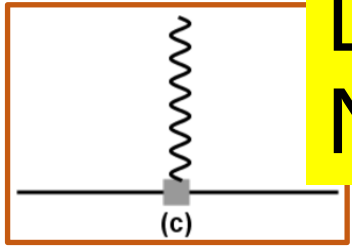


$$\mathcal{L}^{(0)}_{\Delta S=1} = \sqrt{2}G_F m_\pi^2 F_\phi \langle h_D \bar{B}\{u^\dagger \lambda u, B\} + h_F \bar{B}[u^\dagger \lambda u, B]\rangle,$$
$$\mathcal{L}^{(2)}_{MB} = \frac{b_6^D}{8m_B}\langle \bar{B}\sigma^{\mu\nu}\{F^+_{\mu\nu}, B\}\rangle + \frac{b_6^F}{8m_B}\langle \bar{B}\sigma^{\mu\nu}[F^+_{\mu\nu}, B]\rangle,$$

$a^{(1,\text{tree})}_{B_iB_f}$

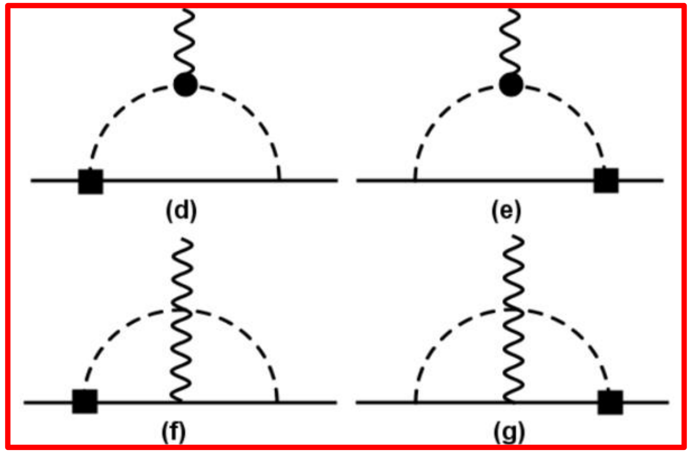
LECs b_6^D and b_6^F : the experimental data of Octet baryon magnetic moment

Leading order LECs hD & hF
NLO LECs: five C’ s



$$\mathcal{L}^{(2)}_{\sigma} = C_\sigma \langle \bar{B}\sigma^{\mu\nu} F_{\mu\nu} \lambda B Q\rangle,$$
$$\mathcal{L}^{(2)}_{\rho} = C_\rho \left(\langle \bar{B}\sigma^{\mu\nu}\gamma_5 F_{\mu\nu} Q\rangle\langle B\lambda\rangle - \langle \bar{B}\sigma^{\mu\nu}\gamma_5 F_{\mu\nu}\lambda\rangle\langle BQ\rangle\right)$$

$a^{(2,\text{tree})}_{B_iB_f}$ $b^{(2,\text{tree})}_{B_iB_f}$



$$\mathcal{L}^{(0)}_{\Delta S=1} = \sqrt{2}G_F m_\pi^2 F_\phi \langle h_D \bar{B}\{u^\dagger \lambda u, B\} + h_F \bar{B}[u^\dagger \lambda u, B]\rangle$$
$$\mathcal{L}^{(1)}_{B} = \langle \bar{B} i\gamma^\mu D_\mu B - m_0 \bar{B}B\rangle,$$
$$\mathcal{L}^{(2)}_{M} = \frac{F_\phi^2}{4}\langle u_\mu u^\mu + \chi^+\rangle,$$
$$\mathcal{L}^{(1)}_{MB} = \frac{D}{2}\langle \bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}\rangle + \frac{F}{2}\langle \bar{B}\gamma^\mu\gamma_5[u_\mu, B]\rangle,$$

LECs D and F have been determined in Ref. LSG et al, PRD 90, 054502 (2014)

$a^{(2,\text{loop})}_{B_iB_f}$ $b^{(2,\text{loop})}_{B_iB_f}$

Contents

LECs hD, hF and hyperon non-leptonic decay amplitudes

- The hyperon non-leptonic decay amplitudes for the octet-to-octet transitions have the following form

$$\mathcal{M}(B_i \to B_f\pi) = iG_F m_\pi^2 \bar{B}_f\,(A_S - A_P\gamma_5)\,B_i$$

Hyperon non-leptonic decay amplitudes: S-wave amplitude A_S and P-wave amplitude A_P

- **Decay width and baryon decay parameters α_π, β_π and γ_π** for $B_i \to B_f\,\pi$ decays

$$\Gamma(B_i \to B_f\pi) = \frac{\left(G_F m_\pi^2\right)^2}{8\pi m_i^2}|\vec{q}|\left\{\left[(m_i+m_f)^2 - m_\pi^2\right]|s|^2 + \left[(m_i-m_f)^2 - m_\pi^2\right]\left|p\cdot\frac{(E_f+m_f)}{|\vec{q}|}\right|^2\right\}$$

$$\alpha_\pi = \frac{2\,\mathrm{Re}(s\cdot p)}{|s|^2+|p|^2},\ \beta_\pi = \frac{2\,\mathrm{Im}(s\cdot p)}{|s|^2+|p|^2},\ \gamma_\pi = \frac{|s|^2-|p|^2}{|s|^2+|p|^2},$$

with

$$s = A_S \qquad p = A_P|\vec{q}|/(E_f + m_f) \qquad \alpha^2+\beta^2+\gamma^2 = 1$$

where E_f and $\vec{q}$ are the energy and 3-momentum of the final baryon

LECs hD, hF and hyperon non-leptonic decay amplitudes

Table: By means of isospin symmetry, the Lee-Sugawara relations and the criterion that $A_S(\Lambda \to p\pi^-)$ is conventionally positive, **S - and P-wave hyperon non-leptonic decay amplitudes are uniquely determined by fitting to the recent data** [3,51-53] of branching fraction $\mathcal{B}$, baryon decay parameters α_π and γ_π

Decay modes	$\mathcal{B}$ [3]	α_π [3, 51–53]	ϕ_π (°) [3, 52]	$s = A_S^{(\text{Expt})}$		$p = A_P^{(\text{Expt})}\lvert\vec{q}\rvert/(E_f + m_f)$	
				This work	[49]	This work	[49]
$\Sigma^+ \to n\pi^+$	0.4831(30)	0.068(13)	167(20)	0.06(1)	0.06(1)	1.81(1)	1.81(1)
$\Sigma^- \to n\pi^-$	0.99848(5)	−0.068(8)	10(15)	1.88(1)	1.88(1)	−0.06(1)	−0.06(1)
$\Lambda \to p\pi^-$	0.639(5)	0.7462(88)	−6.5(35)	1.38(1)	1.42(1)	0.62(1)	0.52(2)
$\Xi^- \to \Lambda\pi^-$	0.99887(35)	−0.376(8)	0.6(12)	−1.99(1)	−1.98(1)	0.39(1)	0.48(2)
$\Sigma^+ \to p\pi^0$	0.5157(30)	−0.982(14)	36(34)	−1.50(3)	−1.43(5)	1.29(4)	1.17(7)
$\Lambda \to n\pi^0$	0.358(5)	0.74(5)	···	−1.09(2)	−1.04(1)	−0.48(4)	−0.39(4)
$\Xi^0 \to \Lambda\pi^0$	0.99524(12)	−0.356(11)	21(12)	1.62(10)	1.52(2)	−0.30(10)	−0.33(2)

- Comparing our results with those of Ref. [49]:

$$\gamma_\pi = \sqrt{1-\alpha_\pi^2}\cos(\phi_\pi)$$

  - ✓ P-wave amplitudes, especially for $A_P(\Lambda \to p\pi^-)$ **and** $A_P(\Xi^- \to \Lambda\pi^-)$, differ a lot, which would **affect the imaginary parts of the parity-conserving amplitude a**
  - ✓ Experimental S -wave amplitudes remain almost unchanged

[3] P. A. Zyla et al. PDG, PTEP 2020, 083C01(2020) [49] E. E. Jenkins, NPB 375, 561 (1992) [51] M. Ablikim et al., BESIII, 2204.11058 (2022) [52] M. Ablikim et al. (BESIII), Nature 606, 64, 2105.11155 (2022) [53] D. G. Ireland et al, PRL 123,182301 (2019)

Non-leptonic decay amplitudes—S/P puzzle

- **Amplitudes of hyperon non-leptonic decays**

$$\mathcal{M}(B_i \to B_f \pi) = i G_F m_\pi^2 \bar{B}_f \left(A_S - A_P \gamma_5\right) B_i$$

Here, both S-wave amplitude A_S and P-wave amplitude A_P are functions of LECs hD and hF

- **The so-called S/P puzzle: if the two LECs hD and hF can describe well the experimental S-wave amplitudes, they reproduce very poorly the P-wave amplitudes**

As a result, we only updated the values of hD and hF by fitting to the experimental S -wave amplitudes for hyperon non-leptonic decays

LECs hD, hF and hyperon non-leptonic decay amplitudes

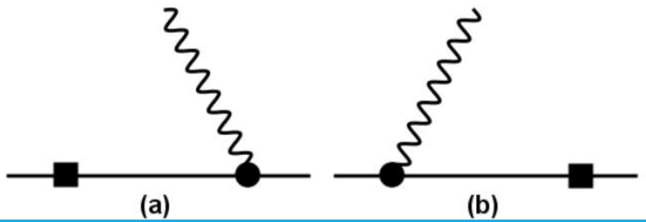
Table: LECs hD and hF determined by fitting to the S –wave hyperon non-leptonic decay amplitudes.

Decay modes	A_S^{th}	A_S^{Expt}
$\Sigma^+ \to n\pi^+$	0	0.06(1)
$\Sigma^- \to n\pi^-$	$-h_D + h_F$	1.88(1)
$\Lambda \to p\pi^-$	$\frac{1}{\sqrt{6}}(h_D + 3h_F)$	1.38(1)
$\Xi^- \to \Lambda\pi^-$	$\frac{1}{\sqrt{6}}(h_D - 3h_F)$	−1.99(1)
$\Sigma^+ \to p\pi^0$	$\frac{1}{\sqrt{2}}(h_D - h_F)$	−1.50(3)
$\Lambda \to n\pi^0$	$-\frac{1}{2\sqrt{3}}(h_D + 3h_F)$	−1.09(2)
$\Xi^0 \to \Lambda\pi^0$	$-\frac{1}{2\sqrt{3}}(h_D - 3h_F)$	1.62(10)
$\chi^2/\text{d.o.f.} = 0.24$	$h_D = -0.61(24)$	$h_F = 1.42(14)$

- In our least-squares fit, an absolute uncertainty of 0.3 is added to each S -wave amplitude in order to match the theoretical predictions with the experimental data at 1σ confidence level
- The tree-level formulae for the S -wave amplitudes derived from the following Lagrangian

$$\mathcal{L}^{(0)}_{\Delta S=1} = \sqrt{2} G_F m_\pi^2 F_\phi \langle h_D \bar{B}\{u^\dagger \lambda u, B\} + h_F \bar{B}[u^\dagger \lambda u, B]\rangle$$

Real part of amplitude a at $O(p^1)$—tree



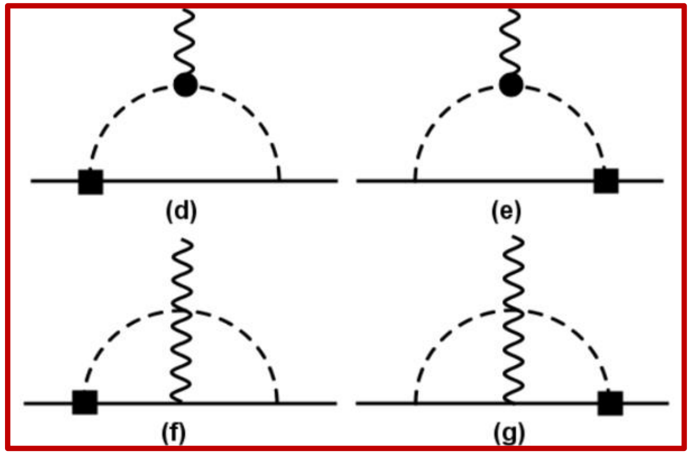
$$\mathcal{L}^{(0)}_{\Delta S=1} = \sqrt{2}G_F m_\pi^2 F_\phi \langle h_D \bar{B}\{u^\dagger \lambda u, B\} + h_F \bar{B}[u^\dagger \lambda u, B]\rangle,$$
$$\mathcal{L}^{(2)}_{MB} = \frac{b_6^D}{8m_B}\langle \bar{B}\sigma^{\mu\nu}\{F^+_{\mu\nu}, B\}\rangle + \frac{b_6^F}{8m_B}\langle \bar{B}\sigma^{\mu\nu}[F^+_{\mu\nu}, B]\rangle,$$

$$a^{(1,\mathrm{tree})}_{\Lambda n} = \frac{m_\pi^2 F_\phi}{2m_B}\left[\frac{1}{\sqrt{3}}(h_D+3h_F)\frac{\mu_n^{(2)}-\mu_\Lambda^{(2)}}{m_\Lambda - m_n} - (h_D - h_F)\frac{\mu^{(2)}_{\Lambda\Sigma^0}}{m_{\Sigma^0}-m_n}\right],$$
$$a^{(1,\mathrm{tree})}_{\Sigma^+ p} = \frac{m_\pi^2 F_\phi}{2m_B}\left[-\sqrt{2}(h_D-h_F)\frac{\mu_p^{(2)}-\mu_{\Sigma^+}^{(2)}}{m_{\Sigma^+}-m_p}\right],$$
$$a^{(1,\mathrm{tree})}_{\Sigma^0 n} = \frac{m_\pi^2 F_\phi}{2m_B}\left[(h_D-h_F)\frac{\mu_n^{(2)}-\mu_{\Sigma^0}^{(2)}}{m_{\Sigma^0}-m_n} - \frac{1}{\sqrt{3}}(h_D+3h_F)\frac{\mu^{(2)}_{\Sigma^0\Lambda}}{m_\Lambda - m_n}\right],$$
$$a^{(1,\mathrm{tree})}_{\Xi^0 \Lambda} = \frac{m_\pi^2 F_\phi}{2m_B}\left[\frac{1}{\sqrt{3}}(h_D-3h_F)\frac{\mu_\Lambda^{(2)}-\mu_{\Xi^0}^{(2)}}{m_{\Xi^0}-m_\Lambda} + (h_D+h_F)\frac{\mu^{(2)}_{\Sigma^0\Lambda}}{m_{\Xi^0}-m_{\Sigma^0}}\right],$$
$$a^{(1,\mathrm{tree})}_{\Xi^0 \Sigma^0} = \frac{m_\pi^2 F_\phi}{2m_B}\left[(h_D+h_F)\frac{\mu_{\Sigma^0}^{(2)}-\mu_{\Xi^0}^{(2)}}{m_{\Xi^0}-m_{\Sigma^0}} + \frac{1}{\sqrt{3}}(h_D-3h_F)\frac{\mu^{(2)}_{\Lambda\Sigma^0}}{m_{\Xi^0}-m_\Lambda}\right],$$
$$a^{(1,\mathrm{tree})}_{\Xi^- \Sigma^-} = \frac{m_\pi^2 F_\phi}{2m_B}\left[\sqrt{2}(h_D+h_F)\frac{\mu_{\Xi^-}^{(2)}-\mu_{\Sigma^-}^{(2)}}{m_{\Xi^-}-m_{\Sigma^-}}\right],$$

- **hD and hF are LECs**
- **$\mu_B^{(2)}$ are the experimental baryon magnetic moments**

$$a_{B_iB_f} = a^{(1,\mathrm{tree})}_{B_iB_f} + a^{(2,\mathrm{tree})}_{B_iB_f} + a^{(2,\mathrm{loop})}_{B_iB_f}$$
$$b_{B_iB_f} = b^{(2,\mathrm{tree})}_{B_iB_f} + b^{(2,\mathrm{loop})}_{B_iB_f}$$

Amplitude b and imaginary part of amplitude a at $\mathcal{O}(p^2)$—loop



$$\mathcal{L}^{(0)}_{\Delta S=1} = \sqrt{2}G_F m_\pi^2 F_\phi \langle h_D \bar{B}\{u^\dagger \lambda u, B\} + h_F \bar{B}[u^\dagger \lambda u, B]\rangle$$

$$\mathcal{L}^{(1)}_{B} = \langle \bar{B} i \gamma^\mu D_\mu B - m_0 \bar{B} B\rangle,$$

$$\mathcal{L}^{(2)}_{M} = \frac{F_\phi^2}{4}\langle u_\mu u^\mu + \chi^+\rangle,$$

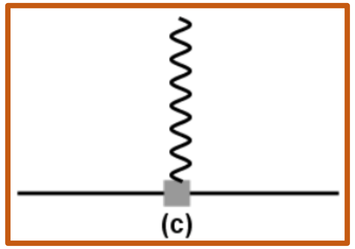
$$\mathcal{L}^{(1)}_{MB} = \frac{D}{2}\langle \bar{B}\gamma^\mu \gamma_5 \{u_\mu, B\}\rangle + \frac{F}{2}\langle \bar{B}\gamma^\mu \gamma_5 [u_\mu, B]\rangle,$$

Real part of amplitude a in the loop level cannot be reliably determined due to S/P puzzle in hyperon non-leptonic decays.

$$a_{B_iB_f} = a^{(1,\text{tree})}_{B_iB_f} + a^{(2,\text{tree})}_{B_iB_f} + a^{(2,\text{loop})}_{B_iB_f}$$

$$b_{B_iB_f} = b^{(2,\text{tree})}_{B_iB_f} + b^{(2,\text{loop})}_{B_iB_f}$$

Real part of amplitude a and b at $O(p^2)$—tree



$$\mathcal{L}_\alpha^{(2)} = C_\alpha\langle\bar{B}\sigma^{\mu\nu}F_{\mu\nu}\lambda QB\rangle,$$
$$\mathcal{L}_\beta^{(2)} = C_\beta\langle\sigma^{\mu\nu}F_{\mu\nu}\bar{B}QB\lambda\rangle,$$
$$\mathcal{L}_\gamma^{(2)} = C_\gamma\langle\bar{B}\sigma^{\mu\nu}F_{\mu\nu}B\lambda Q\rangle,$$
$$\mathcal{L}_\sigma^{(2)} = C_\sigma\langle\bar{B}\sigma^{\mu\nu}F_{\mu\nu}\lambda BQ\rangle,$$
$$\mathcal{L}_\rho^{(2)} = C_\rho\left(\langle\bar{B}\sigma^{\mu\nu}\gamma_5F_{\mu\nu}Q\rangle\langle B\lambda\rangle - \langle\bar{B}\sigma^{\mu\nu}\gamma_5F_{\mu\nu}\lambda\rangle\langle BQ\rangle\right)$$

counter-terms

- CPS is CP followed by the SU(3) transformation of $u \to -u$, $d \to s$ and $s \to d$ which exchanges s and d quarks.
- CPS symmetry dictates the existence of five unknown LECs

Table: Contributions to the real parts of amplitudes a and b at tree-level $O(p)^2$. The normalization $2(eG_F)^{-1}$ has been factored out.

	$\Lambda \to n\gamma$	$\Sigma^+ \to p\gamma$	$\Sigma^0 \to n\gamma$	$\Xi^0 \to \Lambda\gamma$	$\Xi^0 \to \Sigma^0\gamma$	$\Xi^- \to \Sigma^-\gamma$
$a^{(2,\text{tree})}$	$\frac{2C_\alpha-C_\beta-C_\gamma+2C_\sigma}{3\sqrt{6}}$	$\frac{2C_\beta-C_\gamma}{3}$	$\frac{C_\beta+C_\gamma}{3\sqrt{2}}$	$-\frac{C_\alpha-2C_\beta-2C_\gamma+C_\sigma}{3\sqrt{6}}$	$\frac{C_\alpha+C_\sigma}{3\sqrt{2}}$	$\frac{2C_\sigma-C_\alpha}{3}$
$b^{(2,\text{tree})}$	$-\frac{C_\rho}{\sqrt{6}}$	0	$-\frac{C_\rho}{\sqrt{2}}$	$\frac{C_\rho}{\sqrt{6}}$	$\frac{C_\rho}{\sqrt{2}}$	0

$$b_{\Xi^0\Sigma^0}^{(2,\text{tree})} = \sqrt{3}b_{\Xi^0\Lambda}^{(2,\text{tree})}, \quad b_{\Lambda n}^{(2,\text{tree})} = -b_{\Xi^0\Lambda}^{(2,\text{tree})},$$
$$b_{\Sigma^0 n}^{(2,\text{tree})} = -\sqrt{3}b_{\Xi^0\Lambda}^{(2,\text{tree})}, \quad b_{\Sigma^+ p}^{(2,\text{tree})} = 0, \quad b_{\Xi^-\Sigma^-}^{(2,\text{tree})} = 0.$$

Determining the contributions of counter-terms

- **Total amplitudes a and b are a sum of the tree and loop contributions and read:**

$$a_{B_iB_f} = a^{(1,\text{tree})}_{B_iB_f} + a^{(2,\text{tree})}_{B_iB_f} + a^{(2,\text{loop})}_{B_iB_f} = \text{Re}\, a_{B_iB_f} + \text{Im}\, a^{(2,\text{loop})}_{B_iB_f}$$
$$b_{B_iB_f} = b^{(2,\text{tree})}_{B_iB_f} + b^{(2,\text{loop})}_{B_iB_f}$$

- **Using $b^{(2,\text{tree})}_{\Xi^0\Sigma^0} = \sqrt{3}b^{(2,\text{tree})}_{\Xi^0\Lambda}$ and fitting to $\mathcal{B}$ and α_γ for $\Xi^0 \to \Sigma^0\gamma$ and $\Xi^0 \to \Lambda\gamma$ decays, we determine for the first time the contributions of counter-terms**

	Solution I	Solution II
$b^{(2,\text{tree})}_{\Xi^0\Lambda}$	5.62(53)	−8.34(48)
Re $a_{\Xi^0\Lambda}$	−9.56(34)	3.89(45)
Re $a_{\Xi^0\Sigma^0}$	−32.22(64)	32.50(61)
χ^2/d.o.f.	0.04	1.22

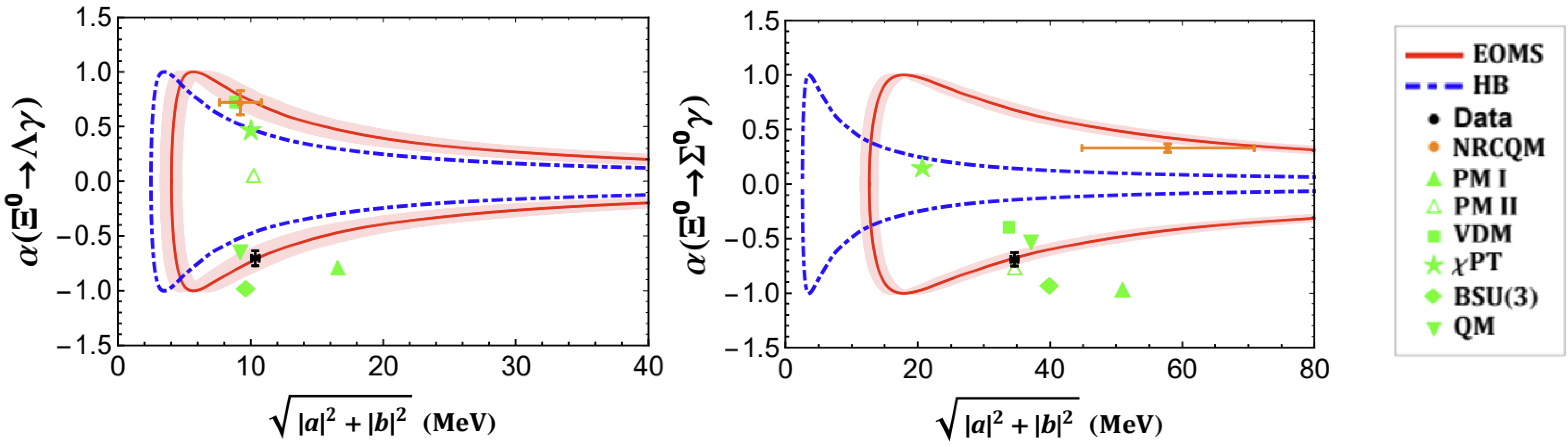
- The $\chi^2/d.o.f.$ of Solution I much smaller than that of Solution II.
- Contributions of counter-terms for other WRHDs obtained by the following relations

$$b^{(2,\text{tree})}_{\Lambda n} = -b^{(2,\text{tree})}_{\Xi^0\Lambda}\quad b^{(2,\text{tree})}_{\Sigma^0 n} = -\sqrt{3}b^{(2,\text{tree})}_{\Xi^0\Lambda},\quad b^{(2,\text{tree})}_{\Sigma^+ p} = 0,\quad b^{(2,\text{tree})}_{\Xi^-\Sigma^-} = 0$$

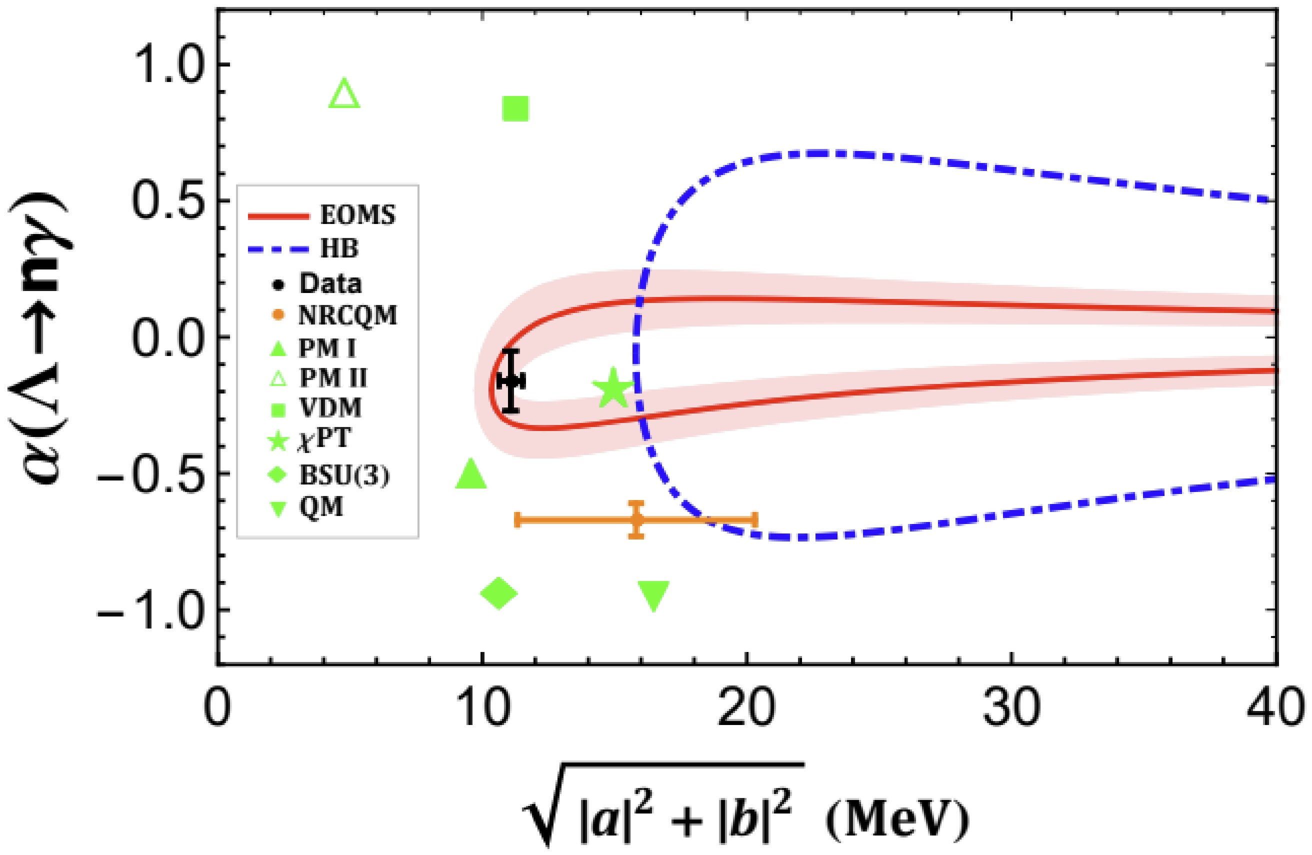
$$a_{B_iB_f} = a^{(1,\text{tree})}_{B_iB_f} + a^{(2,\text{tree})}_{B_iB_f} + a^{(2,\text{loop})}_{B_iB_f} = \text{Re}\, a_{B_iB_f} + \text{Im}\, a^{(2,\text{loop})}_{B_iB_f}$$
$$b_{B_iB_f} = b^{(2,\text{tree})}_{B_iB_f} + b^{(2,\text{loop})}_{B_iB_f}$$

Therefore, we take the Re a for each WRHD as a free parameter due to the unknown real parts of amplitudes a at $O(p^2)$ order

α_γ of $\Xi^0 \to \Sigma^0 \gamma$ and $\Xi^0 \to \Lambda \gamma$ as a function of $\sqrt{|a|^2 + |b|^2}$



α_γ of the $\Lambda \to n\,\gamma$ decay as a function of $\sqrt{|a|^2 + |b|^2}$



Data: *BESIII, PRL129(2022)21,212002*

HB χPT : *E. E. Jenkins et al, NPB 397, 84 (1993)*

NRCQM: *Qiang Zhao et al, CPC45, 013101 (2021)*

PM1: *M. B. Gavela et al, PLB 101, 417 (1981)*

PM2: *G. Nardulli, PLB 190, 187 (1987)*

VDM: *P. Zenczykowski, PRD 44, 1485 (1991)*

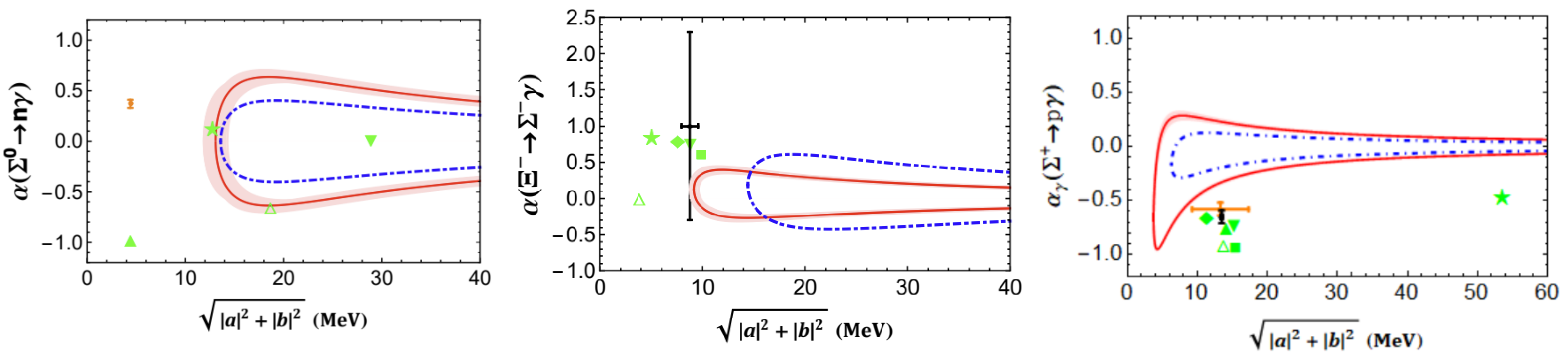
χPT: *B. Borasoy et al, PRD 59, 054019 (1999)*

BSU(3): *P. Zenczykowski, PRD 73, 076005 (2006)*

QM: *E. N. Dubovik et al, Phys. Atom. Nucl. 71, 136 (2008)*

- Interestingly, only **EOMS BχPT agrees with** the latest BESIII measurement
- The prediction in the HB χPT **with counter-term contributions** is very close to the BESIII data
- The vector dominance model (VDM) and the pole model (PM II) **are disfavored** by the BESIII data

α_γ of the other WRHDs as a function of $\sqrt{|a|^2+|b|^2}$



- For the $\Sigma^0 \to n\,\gamma$ decay, not yet measured, **our result contradicts** the predictions of PM I and NRCQM
- For the $\Xi^- \to \Sigma^-\gamma$ decay, **our prediction agrees better** with the experimental measurement, and the current PDG data disfavor the results of PM II and tree-level χPT
- **For the $\Sigma^+ \to p\,\gamma$ decay, the results predicted in all the χPT deviate from the PDG average but our prediction is closer**

Hara's theorem: α_γ for $\Xi^- \to \Sigma^-\gamma$ and $\Sigma^+ \to p\,\gamma$ should not be too large.

What happed to $\Sigma^+ \to p\,\gamma$? What is still missing?

- **For the $\Sigma^+ \to p\,\gamma$ decay, the results predicted in all the χPT deviate from the PDG average but our prediction is closer**
- **Could this be somehow rescued?**
  - How about contributions of heavier resonances? Have been tried previously, but the results do not look good, e.g., B. Borasoy et al, PRD 59, 054019(1999)

$$\alpha^{p\Sigma^+} = -0.49 \qquad \alpha^{\Sigma^-\Xi^-} = 0.84$$

$$\alpha^{n\Sigma^0} = 0.12 \qquad \alpha^{n\Lambda} = -0.19$$

$$\alpha^{\Sigma^0\Xi^0} = 0.15 \qquad \alpha^{\Lambda\Xi^0} = 0.46.$$

Uncertainties of the relevant LECs are important but remain unstudied

N(1535) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	32–52 %
Γ_2	$N\eta$	30–55 %
Γ_3	$N\pi\pi$	4–31 %
Γ_4	$\Delta(1232)\pi$, D-wave	1–4 %
Γ_5	$N\rho$	2–17 %
Γ_6	$N\rho$, S=1/2, S-wave	2–16 %
Γ_7	$N\rho$, S=3/2, D-wave	<1 %
Γ_8	$N\sigma$	2–10 %
Γ_9	$N(1440)\pi$	5–12 %
Γ_{10}	$p\gamma$, helicity=1/2	0.15–0.30 %
Γ_{11}	$n\gamma$, helicity=1/2	0.01–0.25 %

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- Brief introduction: motivation and purpose
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- Results & discussions
  - Conventional ChPT results
  - Contribution of negative parity heavy resonances (preliminary)
- Summary and outlook

Contributions of heavier resonances

- **Consider only additional contributions of heavier resonances at tree-level**

$$\mathcal{L}_{RB}^{W} = i w_d \Big[\mathrm{tr}\big(\bar{R}\{h_+, B\}\big) - \mathrm{tr}\big(\bar{B}\{h_+, R\}\big) \Big] + i w_f \Big[\mathrm{tr}\big(\bar{R}[h_+, B]\big) - \mathrm{tr}\big(\bar{B}[h_+, R]\big) \Big]$$

$$\mathcal{L}_{RB}^{s} = i r_d \Big[\mathrm{tr}\big(\bar{R}\sigma_{\mu\nu}\gamma_5\{f_+^{\mu\nu}, B\}\big) + \mathrm{tr}\big(\bar{B}\sigma_{\mu\nu}\gamma_5\{f_+^{\mu\nu}, R\}\big)\Big] + i r_f \Big[\mathrm{tr}\big(\bar{R}\sigma_{\mu\nu}\gamma_5[f_+^{\mu\nu}, B]\big) + \mathrm{tr}\big(\bar{B}\sigma_{\mu\nu}\gamma_5[f_+^{\mu\nu}, R]\big)\Big]$$

Following B. Borasoy et al, PRD 59, 054019(1999)

$$a_{B_iB_f} = a_{B_iB_f}^{(1,\mathrm{tree})} + a_{B_iB_f}^{(2,\mathrm{tree})} + a_{B_iB_f}^{(2,\mathrm{loop})} = \mathrm{Re}\, a_{B_iB_f} + \mathrm{Im}\, a_{B_iB_f}^{(2,\mathrm{loop})}$$

$$b_{B_iB_f} = b_{B_iB_f}^{(1,\mathrm{tree})} + b_{B_iB_f}^{(2,\mathrm{tree})} + b_{B_iB_f}^{(2,\mathrm{loop})}.$$

- At tree level, only $\frac{1}{2}^-$ **states** contributing to $\mathrm{Re}\, b$ can affect the EOMS results because $\frac{1}{2}^+$ states contribute to $\mathrm{Re}\, a$ which are taken as free parameters
- Due to charge conservation, contributions of $b_{B_iB_f}^{(1,\mathrm{tree})}$ to $\Sigma^+ \to p\gamma$ and $\Xi^- \to \Sigma^-\gamma$ are dominated by $N(1535)$. For other channels, $b_{B_iB_f}^{(1,\mathrm{tree})}$ are mainly from $\Lambda(1405)$.

Contributions of heavier resonances

- $b^{(1,\text{tree})}_{B_iB_f}$ at leading order

$$B^{p\Sigma^+} = e\frac{4(M_\Sigma - M_N)}{(M_\Sigma - M_R)(M_N - M_R)}(\frac{1}{3}r_d + r_f)(w_d - w_f)$$

$$B^{\Sigma^-\Xi^-} = e\frac{4(M_\Xi - M_\Sigma)}{(M_\Sigma - M_R)(M_\Xi - M_R)}(\frac{1}{3}r_d - r_f)(w_d + w_f)$$

$$B^{n\Sigma^0} = e\frac{4}{(M_R - M_\Sigma)}\frac{\sqrt{2}}{3}r_d(w_d - w_f) + e\frac{4}{(M_R - M_N)}\frac{\sqrt{2}}{3}r_d(w_d + w_f)$$

$$B^{n\Lambda} = e\frac{4}{(M_R - M_\Lambda)}\frac{\sqrt{2}}{3\sqrt{3}}r_d(w_d + 3w_f) + e\frac{4}{(M_R - M_N)}\frac{\sqrt{2}}{3\sqrt{3}}r_d(w_d - 3w_f)$$

$$B^{\Sigma^0\Xi^0} = e\frac{4}{(M_\Xi - M_R)}\frac{\sqrt{2}}{3}r_d(w_d - w_f) + e\frac{4}{(M_\Sigma - M_R)}\frac{\sqrt{2}}{3}r_d(w_d + w_f)$$

$$B^{\Lambda\Xi^0} = e\frac{4}{(M_\Xi - M_R)}\frac{\sqrt{2}}{3\sqrt{3}}r_d(w_d + 3w_f) + e\frac{4}{(M_\Lambda - M_R)}\frac{\sqrt{2}}{3\sqrt{3}}r_d(w_d - 3w_f)$$

$N(1535)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
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Γ_{11}	$n\gamma$, helicity=1/2	0.01–0.25 %

- r_d and r_f can be determined by fitting to **electromagnetic decays** of the resonances
- ω_d and ω_f can be determined by fitting to **the nonleptonic hyperon** decays

B. Borasoy et al, PRD 59, 054019(1999), PRD 59, 094025(1999)

Contributions of heavier resonances

- $b^{(1,\mathrm{tree})}_{B_iB_f}$ **at leading order**

$$a_{B_iB_f} = a^{(1,\mathrm{tree})}_{B_iB_f} + a^{(2,\mathrm{tree})}_{B_iB_f} + a^{(2,\mathrm{loop})}_{B_iB_f} = \mathrm{Re}\, a_{B_iB_f} + \mathrm{Im}\, a^{(2,\mathrm{loop})}_{B_iB_f}$$

$$b_{B_iB_f} = b^{(1,\mathrm{tree})}_{B_iB_f} + b^{(2,\mathrm{tree})}_{B_iB_f} + b^{(2,\mathrm{loop})}_{B_iB_f}.$$

Results in B. Borasoy et al, PRD 59, 054019(1999)

$$B^{p\Sigma^+} = 0.47 \quad B^{\Sigma^-\Xi^-} = 0.15$$

$$B^{n\Sigma^0} = -0.45 \quad B^{n\Lambda} = -0.05$$

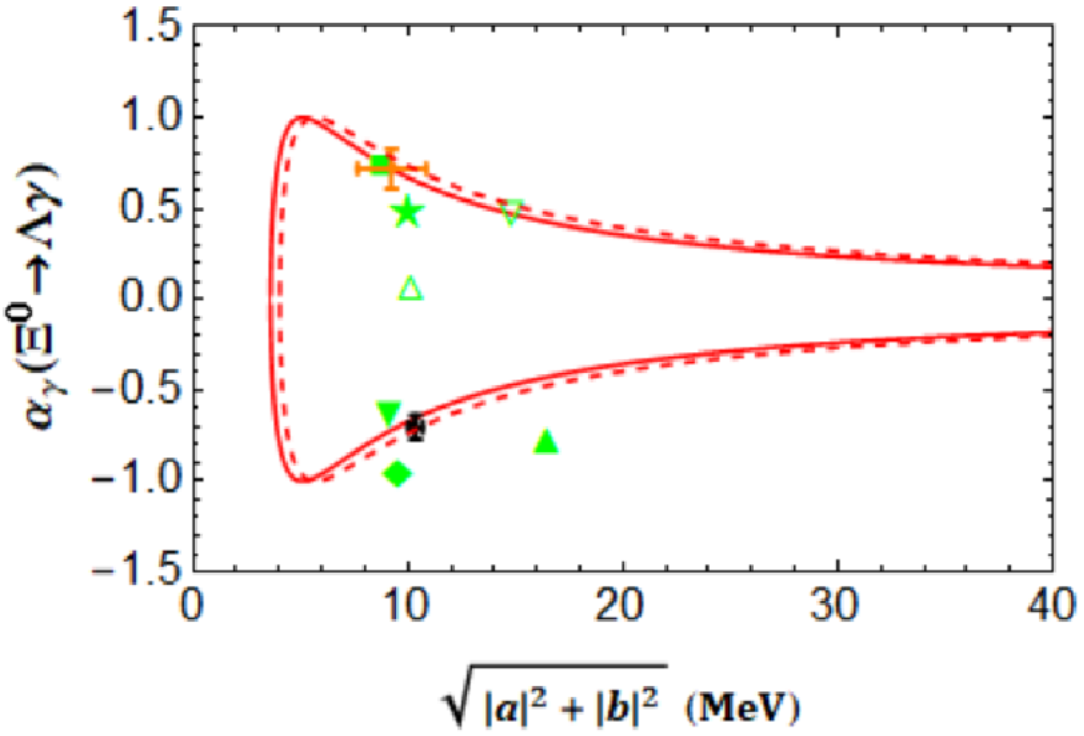
$$B^{\Sigma^0\Xi^0} = 0.70 \quad B^{\Lambda\Xi^0} = -0.08.$$

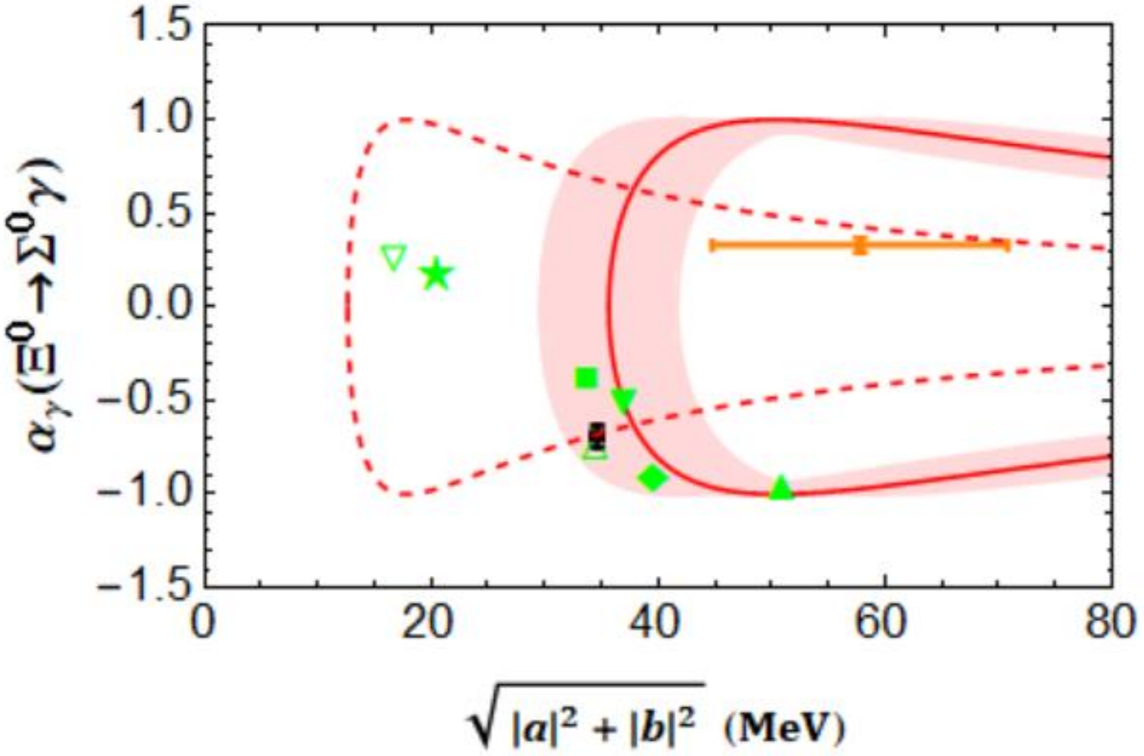
$$B^{B_iB_f} = \sqrt{4\pi\alpha}G_F \times b^{(1,\mathrm{tree})}_{B_iB_f}$$

We consider 50% uncertainties in these numbers

- **Using** $b^{(2,\mathrm{tree})}_{\Xi^0\Sigma^0} = \sqrt{3}b^{(2,\mathrm{tree})}_{\Xi^0\Lambda}$**, considering the uncertainties of** $b^{(1,\mathrm{tree})}_{B_iB_f}$ **and fitting to** $\mathcal{B}$ **and** α_γ **for** $\Xi^0 \to \Sigma^0\gamma$ **and** $\Xi^0 \to \Lambda\gamma$ **decays, we re-determine the contributions of counter-terms**

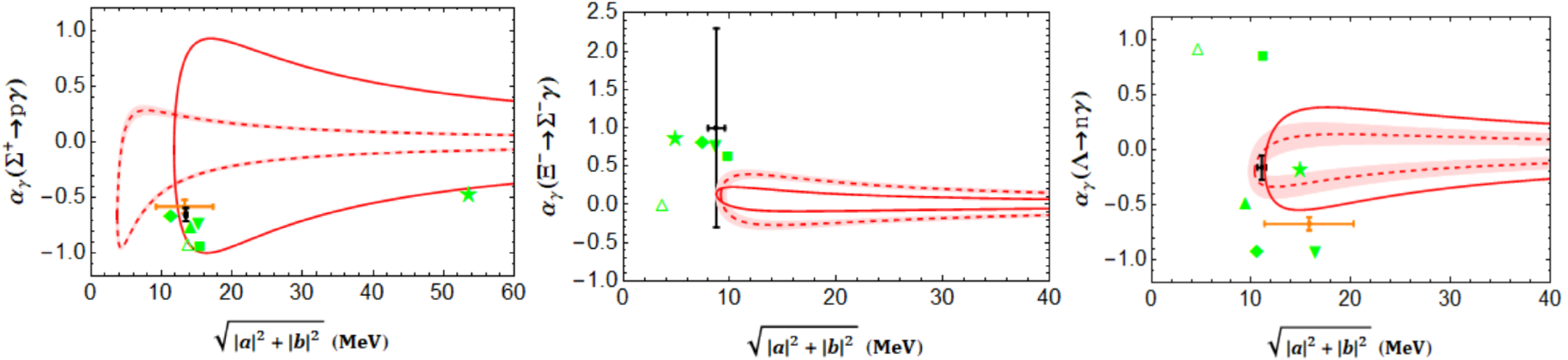
Contributions of heavier resonances





- Solid and dashed lines in red represent the EOMS results **with/without** heavier resonances, respectively.
- In the figure on the right, we show that after considering the uncertainties of input quantities (LECs), the experimental data can also be well described.

Contributions of heavier resonances



- Contributions of $\frac{1}{2}^-$ states can improve the present EOMS results **(solid lines in red)**
- Uncertainties of resonance contributions are not fully taken into account

Contents

- ☞ **Brief introduction: motivation and purpose**
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  - ➢ **Conventional ChPT results**
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- ☞ **Summary and outlook**

Summary and outlook

- Motivated by the latest BESIII results and the success of the covariant baryon chiral perturbation theory, we revisited the long-standing WRHDs.
  - LECs hD, hF and hyperon non-leptonic decay amplitudes are determined by fitting to the latest experimental data on the $B_i \to B_f\, \pi$ decays
  - $O(p^2)$ counter-term contributions are determined by fitting to $\Xi^0 \to \Sigma^0\, \gamma$ and $\Xi^0 \to \Lambda\, \gamma$ for the first time
- We showed that the latest measurement of $\Lambda \to n\, \gamma$ by the BESIII Collaboration can be well explained. The contributions of heavier $\frac{1}{2}^-$ states are important to explain the $\Sigma^+ \to p\, \gamma$ asymetry, and finally bring an overall solution to the WRHDs puzzle.
- This work provides essential SM inputs for studying new physics in the rare hyperon semi-leptonic decay $B_i \to B_f \gamma^* \to B_f l\, l$

LHCb: JHEP 05 (2019) 048 and CERN Yellow Rep.Monogr. 7 (2019) 867-1158

Summary and **outlook**

- A more precise measurement of $\boldsymbol{\alpha_\gamma(\Xi^- \to \Sigma^-\gamma)}$ is highly desirable in order to test Hara' s theorem and confirm the present experimental result.

Super tau-charm factory: Zhou XR, PoSCHARM2020(2021)007
A.Y.Barnyakov, JPhysConfSer1561(1)(2020)012004

- A more careful and systematic study of the contribution of heavier resonances, especially for $\frac{1}{2}^-$ states ($\Lambda(1405), N(1535)$) contributing to amplitude b.

B. Borasoy et al, PRD 59, 054019(1999) & Qiang Zhao et al, CPC45, 013101 (2021)

Summary and **outlook**

◻ Revisiting the S/P puzzle of hyperon non-leptonic decays $(B_i \to B_f\,\pi)$

✓ Latest BESIII study shows that $\Delta I = 1/2$ rule may be violated

$$\langle\alpha_{\Lambda 0}\rangle/\langle\alpha_{\Lambda -}\rangle = 0.870 \pm 0.012^{+0.011}_{-0.010}$$

BESIII: PRL 132 (2024) 10, 101801

✓ **Previous theoretical studies in HBχPT neglected the contributions of either the counterterms or intermediate decuplet-baryons**

HB χPT: Borasoy B et al, EPJC 6 (1999) 85-107
Abd El-Hady A, PRD 61 (2000) 114014

Inputs

◻ Revisiting CP violation (CPV) of hyperon non-leptonic decays $(B_i \to B_f\,\pi)$

CPV observables	SM predictions	BESIII data
A_{CP}^{Λ}	$(-3\sim 3)\times 10^{-5}$	$(-2.5\pm 4.6\pm 1.2)\times 10^{-3}$
A_{CP}^{Ξ}	$(0.5\sim 6)\times 10^{-5}$	$(6\pm 13.4\pm 5.6)\times 10^{-3}$
B_{CP}^{Ξ}	$(-3.8\sim -0.3)\times 10^{-4}$	$(1.2\pm 3.4\pm 0.8)\times 10^{-2}$

- Jusak Tandean et al , PRD 67 (2003) 056001
- Salone N et al , PRD 105 (2022) 11, 116022
- Xiao-Gang He et al, Sci.Bull. 67 (2022) 1840-1843
- Wang XF,arXiv:2312.17486

✓ The large uncertainties predicted in SM are related to the S/P puzzle

$$\alpha = \frac{2\mathrm{Re}(S^*P)}{|S|^2+|P|^2},\quad \beta = \frac{2\mathrm{Im}(S^*P)}{|S|^2+|P|^2}$$
$$\gamma = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}$$

$$A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} \qquad B_{CP} = \frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}}$$

Thanks for your attention!