赵忠尧博士后奖学金答辩

上海交通大学
李政道研究所
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合作导师：葛韶锋

2021.6.5

Outline

- 个人简介

- 工作成绩介绍
  - 有效场论和超出标准模型的新物理
  - 重子数和轻子数破坏过程, 中微子非标准相互作用
  - Muon $g-2$

- 当前和未来研究规划

个人简历

SHANGHAI JIAO TONG UNIVERSITY

教育和科研工作经历

- 2010.9 - 2014. 6 天津理工大学 理学院 理学学士
- 2014.9 - 2019. 6 南开大学 物理科学学院 理学博士
  导师： 廖益 教授
- 2019.7 - 2021. 3 国立台湾大学 物理系 博士后
  导师： 何小刚 教授
- 2021. 3 - 至今 上海交通大学 李政道研究所 博士后
  导师： 葛韶锋

主要研究方向

- 有效场论和新物理
- 暗物质物理, 中微子物理

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  - 重子数和轻子数破坏过程, 中微子非标准相互作用
  - Muon $g-2$
- 当前和未来研究规划

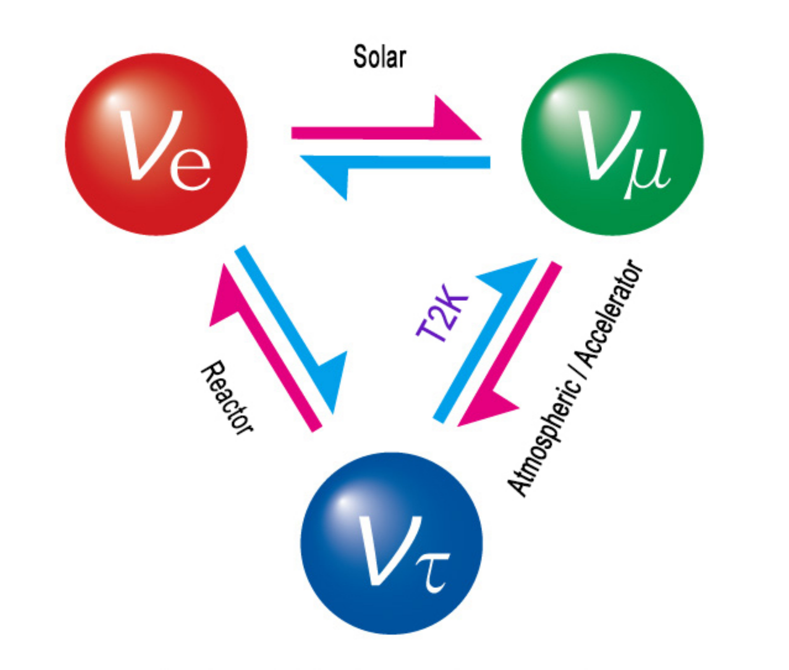
超出标准模型的新物理

实验观测层面：

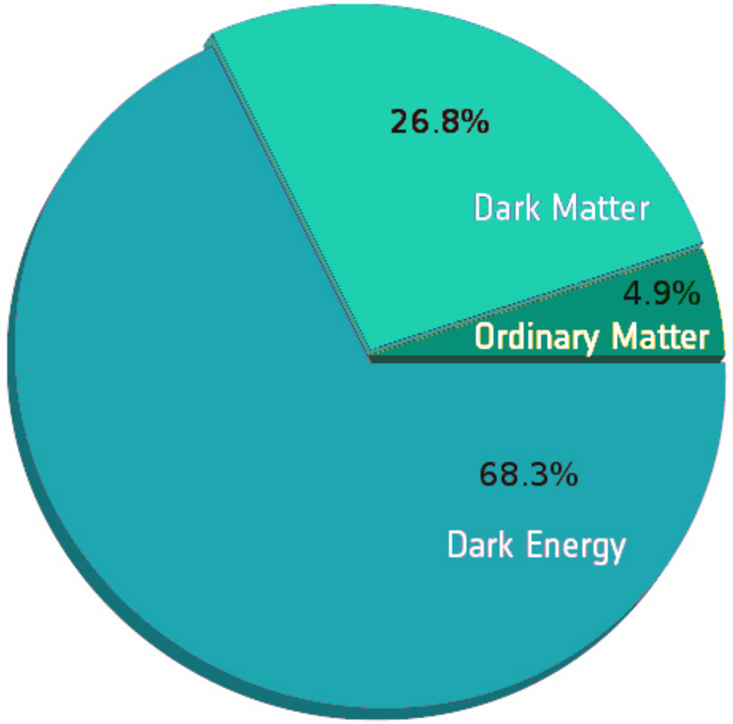
- 中微子振荡 $\Longrightarrow$ 中微子质量，产生机制是什么？
- 天文观测 $\Longrightarrow$ 暗物质， 暗物质是什么？
- 宇宙正反物质不对称的起源；
- 暗能量；
- 地面实验发现的反常信号：muon $g-2$, R_K, R_K^*, LFUV, etc.

理论层面：

- 强CP问题；
- Higgs质量等级问题；
- ......



Neutrino oscillation between three generations (Credit: J-PART)



如何寻找新物理

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模型构造/top-down

- **基于具体问题构造新的物理理论/模型**
- **流行的模型**：跷跷板机制 (seesaw), 超对称, 大统一模型, …
- **优点**：UV 完备, 针对性解决具体问题
- **缺点**：各类不同的模型

本人研究相关

模型无关的有效场论/bottom-up

- **假定**：存在高能标的新物理
- **根据低能物理的自由度和相关对称性写下最一般的相互作用**
- **主要的有效场论**：标准模型有效场论 (SMEFT)，低能有效场论 (LEFT), νSMEFT, DMEFT, χPT, etc.
- **优点**：模型无关性

标准模型有效场论 (SMEFT)

1. 适用能区： $\ll \Lambda$
2. 量子场: $Q,\ u,\ d;\ \ L,\ e$
3. 对称性: $SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)_{\rm Y}$
4. 拉氏量:

其中本人和博士导师首次得到了完备的量纲为7 (dim 7)和 dim 9 的 SMEFT 算符基底，并且计算了 dim 7 算符的单圈重整化效应。

JHEP11(2016)043
JHEP03(2019)179
JHEP11(2020)152
Commun. Theor. Phys. 69 (2018) 285–290

*Liao, **XDMA**, 2016* *Liao, **XDMA**, 2020*

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{\dim 5,i} \frac{\hat{C}_{5,i}}{\Lambda}\mathscr{O}^i_{\dim-5} + \sum_{\dim 6,i} \frac{\hat{C}_{6,i}}{\Lambda^2}\mathscr{O}^i_{\dim-6} + \sum_{\dim 7,i} \frac{\hat{C}_{7,i}}{\Lambda^3}\mathscr{O}^i_{\dim-7} + \sum_{\dim 8,i} \frac{\hat{C}_{8,i}}{\Lambda^4}\mathscr{O}^i_{\dim-8} + \sum_{\dim 9,i} \frac{\hat{C}_{9,i}}{\Lambda^5}\mathscr{O}^i_{\dim-9} + \cdots$$

Weinberg, 1979 *Buchmuller, Wyler 1986* *Lehman 2014* *Murphy, 2020* *Li, Ren, Shu, Xiao, Yu, Zheng, 2020*
Grzadkowski, Iskrzynski, Misiak Rosiek 2010 *Li, Ren, Xiao, Yu, Zheng, 2020*

SMEFT dim 9 算符

我们通过考虑以下算符约化技术：

本人主导完成

- **Integration by parts(IBP)**: the total derivative term has no contribution to the action $D(\mathcal{Q}_1\mathcal{O}_2) = D(\mathcal{Q}_1)\mathcal{O}_2(\checkmark) + \mathcal{Q}_1 D(\mathcal{O}_2)(\times), \cdots$
- **Fierz identity(FI)**: rearrangement of the fermion bilinears

$$(\overline{\Psi_{1L}}\Psi_{2R})(\overline{\Psi^{C}_{3R}}\Psi_{4R}) = -(\overline{\Psi_{1L}}\Psi_{3R})(\overline{\Psi^{C}_{4R}}\Psi_{2R}) - (\overline{\Psi_{1L}}\Psi_{4R})(\overline{\Psi^{C}_{2R}}\Psi_{3R}), \cdots$$

- **Equation of motion(EoM) & Field redefinition**: $i\not{D}Q = Y_u u\tilde{H} + Y_d dH, \cdots$
- **Group identity (GI)**: $(T^A)_{ab}(T^A)_{cd} = \frac{1}{2}\delta_{ad}\delta_{bc} - \frac{1}{2N}\delta_{ab}\delta_{cd}[SU(N)], \cdots$
- **Schouten identity (SI)**: $\epsilon_{ij}\epsilon_{kl} = \epsilon_{il}\epsilon_{kj} - \epsilon_{ik}\epsilon_{lj}, \cdots$
- **Dirac gamma matrix(DG)**: $\sigma_{\mu\nu}P_{\pm} = \mp\frac{1}{2}i\epsilon_{\mu\nu\rho\sigma}\sigma^{\rho\sigma}P_{\pm}, \cdots$
- **Bianchi identity (BI)**: $D_\nu\tilde{X}^{\mu\nu} = 0$.

* Jiang-Hao Yu et al: arXiv:2007.07899 .

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An explicit construction of the dimension-9 operator basis in the standard model effective field theory

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Abstract: We investigate systematically dimension-9 operators in the standard model effective field theory which contains only standard model fields and respects its gauge symmetry. With the help of the Hilbert series approach to classifying operators according to their lepton and baryon numbers and their field contents, we construct the basis of operators explicitly. We remove redundant operators by employing various kinematic and algebraic relations including integration by parts, equations of motion, Schouten identities, Dirac matrix and Fierz identities, and Bianchi identities. We confirm counting of independent operators by analyzing their flavor symmetry relations. All operators violate lepton or baryon number or both, and are thus non-Hermitian. Including Hermitian conjugated operators there are $384|^{\Delta L=\pm 2}_{\Delta B=0} + 10|^{\Delta L=0}_{\Delta B=\pm 2} + 4|^{\Delta L=\pm 3}_{\Delta B=\pm 1} + 236|^{\Delta L=\mp 1}_{\Delta B=\pm 1}$ operators without referring to fermion generations, and $44874|^{\Delta L=\pm 2}_{\Delta B=0} + 2862|^{\Delta L=0}_{\Delta B=\pm 2} + 486|^{\Delta L=\pm 3}_{\Delta B=\pm 1} + 42234|^{\Delta L=\pm 1}_{\Delta B=\mp 1}$ operators when three generations of fermions are referred to, where ΔL, ΔB denote the net lepton and baryon numbers of the operators. Our result provides a starting point for consistent phenomenological studies associated with dimension-9 operators.

JHEP11(2020)152

低能有效场论 (LEFT)

电弱对称性破缺: $SU(2)_{\rm L} \times U(1)_{\rm Y} \to U(1)_{\rm EM}$

其中本人和博士导师首次得到了完备的 LEFT dim 7 算符基底以及破坏两个单位轻子数的 dim 9 算符。

JHEP01(2020)127

JHEP08(2020)162

*Liao, **XDMA**, Wang, 2020*　　*Liao, **XDMA**, Wang, 2020*

$$\mathscr{L}_{\rm LEFT} = \mathscr{L}_{\rm dim\leq 4} + \sum_{\rm dim\,5,\it i} \frac{\hat{C}_{5,i}}{\Lambda}\mathscr{Q}^i_{\rm dim-5} + \sum_{\rm dim\,6,\it i} \frac{\hat{C}_{6,i}}{\Lambda^2}\mathscr{Q}^i_{\rm dim-6} + \sum_{\rm dim\,7,\it i} \frac{\hat{C}_{7,i}}{\Lambda^3}\mathscr{Q}^i_{\rm dim-7} + \sum_{\rm dim\,8,\it i} \frac{\hat{C}_{8,i}}{\Lambda^4}\mathscr{Q}^i_{\rm dim-8} + \sum_{\rm dim\,9,\it i} \frac{\hat{C}_{9,i}}{\Lambda^5}\mathscr{Q}^i_{\rm dim-9} + \cdots$$

Jenkins, Manohar, Stoffer, 2018

Murphy, 2020

Li, Ren, Xiao, Yu, Zheng, 2020

νSMEFT

SHANGHAI JIAO TONG UNIVERSITY 上海交通大學

νSMEFT=SMEFT+ N ← 惰性中微子 →

中微子质量；暗物质

首次得到完备且独立的 dim 6 & dim 7 算符

$\psi^2 H^3$		$\psi^2 H^2 D$		$\psi^2 HX(+\text{h.c.})$	
$\mathcal{O}_{LNH}(+\text{h.c.})$	$(\bar{L}N)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{HN}$ $\mathcal{O}_{HNe}(+\text{h.c.})$	$(\bar{N}\gamma^\mu N)(H^\dagger i\overleftrightarrow{D}_\mu H)$ $(\bar{N}\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{NB}$ $\mathcal{O}_{NW}$	$(\bar{L}\sigma_{\mu\nu}N)\tilde{H}B^{\mu\nu}$ $(\bar{L}\sigma_{\mu\nu}N)\tau^I\tilde{H}W^{I\mu\nu}$
$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R)(+\text{h.c.})$	
$\mathcal{O}_{NN}$ $\mathcal{O}_{eN}$ $\mathcal{O}_{uN}$ $\mathcal{O}_{dN}$ $\mathcal{O}_{duNe}(+\text{h.c.})$	$(\bar{N}\gamma^\mu N)(\bar{N}\gamma_\mu N)$ $(\bar{e}\gamma^\mu e)(\bar{N}\gamma_\mu N)$ $(\bar{u}\gamma^\mu u)(\bar{N}\gamma_\mu N)$ $(\bar{d}\gamma^\mu d)(\bar{N}\gamma_\mu N)$ $(\bar{d}\gamma^\mu u)(\bar{N}\gamma_\mu e)$	$\mathcal{O}_{LN}$ $\mathcal{O}_{QN}$	$(\bar{L}\gamma^\mu L)(\bar{N}\gamma_\mu N)$ $(\bar{Q}\gamma^\mu Q)(\bar{N}\gamma_\mu N)$	$\mathcal{O}_{LNLe}$ $\mathcal{O}_{LNQd}$ $\mathcal{O}_{LdQN}$	$(\bar{L}N)\epsilon(\bar{L}e)$ $(\bar{L}N)\epsilon(\bar{Q}d))$ $(\bar{L}d)\epsilon(\bar{Q}N)$
$(\bar{L}R)(\bar{R}L)$		$(\not{L}\cap B)(+\text{h.c.})$		$(\not{L}\cap \not{B})(+\text{h.c.})$	
$\mathcal{O}_{QuNL}(+\text{h.c.})$	$(\bar{Q}u)(\bar{N}L)$	$\mathcal{O}_{NNNN}$	$(NCN)(NCN)$	$\mathcal{O}_{QQdN}$ $\mathcal{O}_{uddN}$	$\epsilon_{ij}(Q^i CQ^j)(dCN)$ $(uCd)(dCN)$

PHYSICAL REVIEW D **96,** 015012 (2017)

Operators up to dimension seven in standard model effective field theory extended with sterile neutrinos

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We revisit the effective field theory of the standard model that is extended with sterile neutrinos, N. We examine the basis of complete and independent effective operators involving N up to mass dimension seven (dim-7). By employing equations of motion, integration by parts, and Fierz and group identities, we construct relations among operators that were considered independent in the previous literature, and we find 7 redundant operators at dim-6, as well as 16 redundant operators and two new operators at dim-7. The correct numbers of operators involving N are, without counting Hermitian conjugates, $16(L\cap B)+1(\not{L}\cap B)+2(\not{L}\cap\not{B})$ at dim-6 and $47(\not{L}\cap B)+5(\not{L}\cap\not{B})$ at dim-7. Here $L/B(\not{L}/\not{B})$ stands for lepton/baryon number conservation (violation). We verify our counting by the Hilbert series approach for n_f generations of the standard model fermions and sterile neutrinos. When operators involving different flavors of fermions are counted separately and their Hermitian conjugates are included, we find there are 29 (1614) and 80 (4206) operators involving sterile neutrinos at dim-6 and dim-7, respectively, for $n_f = 1$ (3).

DOI: 10.1103/PhysRevD.96.015012

引用60+

本人主导完成

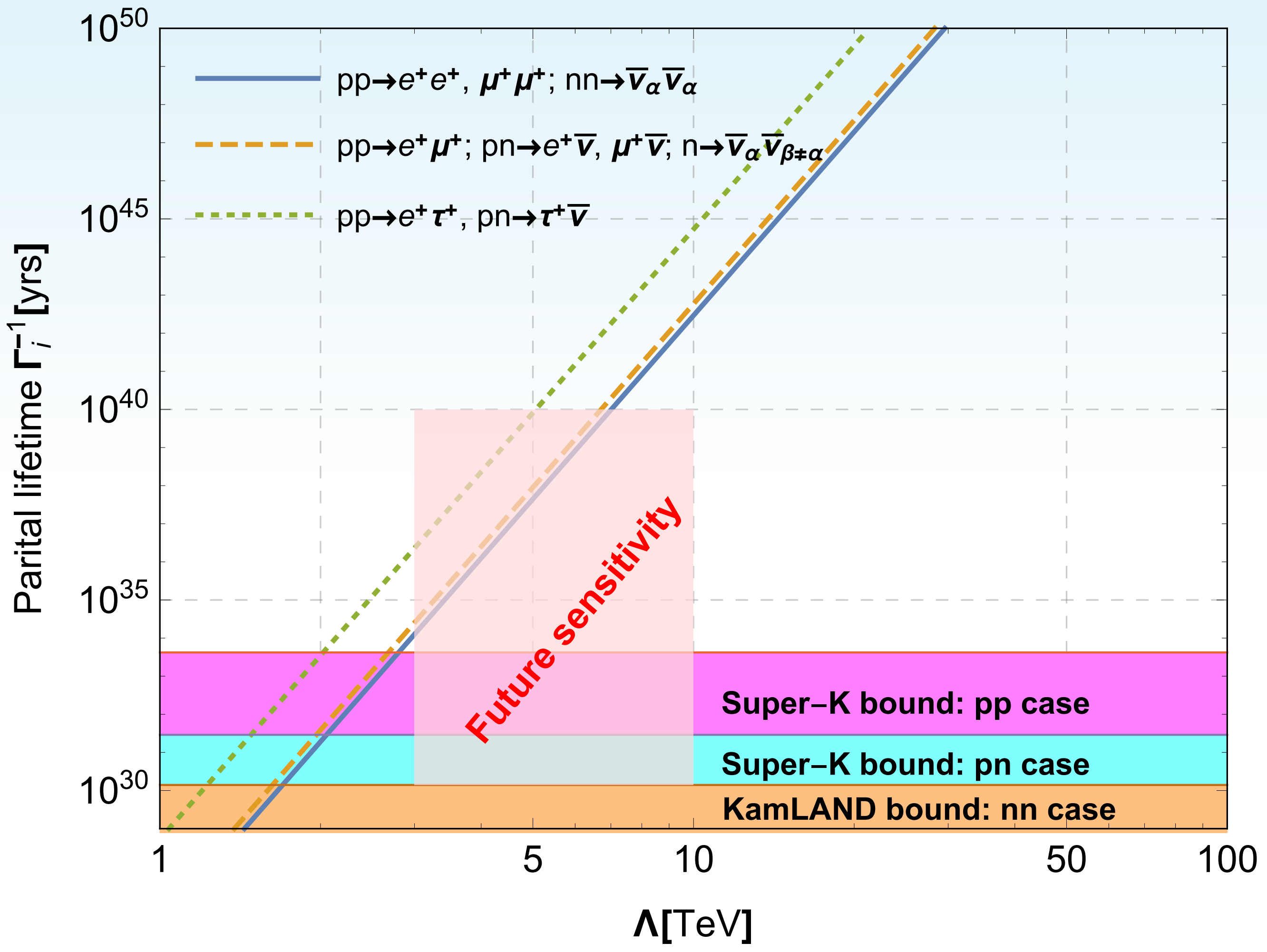
F. del Aguila, S. Bar-Shalom, A. Soni, and J. Wudka, Phys. Lett. B 670, 399 (2009)

重子数/轻子数破坏(BNV/LNV)过程

- $n \to \bar{p} e^+ \nu(\bar{\nu}) \Longrightarrow \Gamma^{-1}_{n\to\bar{p}e^+\chi} > 5.7 \times 10^{39}$ yr
- $pp \to \ell^+ \ell'^+, pn \to \ell^+ \bar{\nu}', nn \to \bar{\nu}\bar{\nu}'$
- $K^- \to \pi^+ \ell^-_\alpha \ell^-_\beta \Longrightarrow \mathscr{B}_{\text{SMEFT}} \leq 10^{-16}$

dim 12 算符: $pp \to \ell^+ \ell'^+$

$$\mathcal{Q}^{(pp)S,\pm}_{1LLL,a} = (u_L^{i\mathrm{T}} C u_L^j)(u_L^{k\mathrm{T}} C d_L^l)(u_L^{m\mathrm{T}} C d_L^n) j^{\ell\ell'}_{S,\pm} T^{SSS}_{\{ij\}\{kl\}\{mn\}} ,$$
$$\mathcal{Q}^{(pp)S,\pm}_{1LLL,b} = (u_L^{i\mathrm{T}} C u_L^j)(u_L^{k\mathrm{T}} C d_L^l)(u_L^{m\mathrm{T}} C d_L^n) j^{\ell\ell'}_{S,\pm} T^{SAA}_{\{ij\}[kl][mn]} ,$$
$$\mathcal{Q}^{(pp)S,\pm}_{2LLR,a} = (u_L^{i\mathrm{T}} C u_L^j)(u_L^{k\mathrm{T}} C d_L^l)(u_R^{m\mathrm{T}} C d_R^n) j^{\ell\ell'}_{S,\pm} T^{SSS}_{\{ij\}\{kl\}\{mn\}} ,$$
$$\mathcal{Q}^{(pp)S,\pm}_{2LLR,b} = (u_L^{i\mathrm{T}} C u_L^j)(u_L^{k\mathrm{T}} C d_L^l)(u_R^{m\mathrm{T}} C d_R^n) j^{\ell\ell'}_{S,\pm} T^{SAA}_{\{ij\}[kl][mn]} ,$$
$$\mathcal{Q}^{(pp)S,\pm}_{3LLR,a} = (u_L^{i\mathrm{T}} C d_L^j)(u_L^{k\mathrm{T}} C d_L^l)(u_R^{m\mathrm{T}} C u_R^n) j^{\ell\ell'}_{S,\pm} T^{SSS}_{\{ij\}\{kl\}\{mn\}} ,$$
$$\mathcal{Q}^{(pp)S,\pm}_{3LLR,b} = (u_L^{i\mathrm{T}} C d_L^j)(u_L^{k\mathrm{T}} C d_L^l)(u_R^{m\mathrm{T}} C u_R^n) j^{\ell\ell'}_{S,\pm} T^{SAA}_{\{mn\}[ij][kl]} ,$$
$$\mathcal{Q}^{(pp)S,\pm}_{4LLR} = (u_L^{i\mathrm{T}} C u_L^j)(u_L^{k\mathrm{T}} C u_L^l)(d_R^{m\mathrm{T}} C d_R^n) j^{\ell\ell'}_{S,\pm} T^{SSS}_{\{ij\}\{kl\}\{mn\}} ,$$



这些工作由本人主导完成

Phys. Lett. B **817** (2021), 136298
2102.02562 (accepted by JHEP)
JHEP **01**, 127 (2020)
JHEP **03**, 120 (2020)

中微子非标准相互作用

在 ν**SMEFT** & ν**LEFT** 框架下，系统研究了几类不同观测量对中微子非标准相互作用的限制

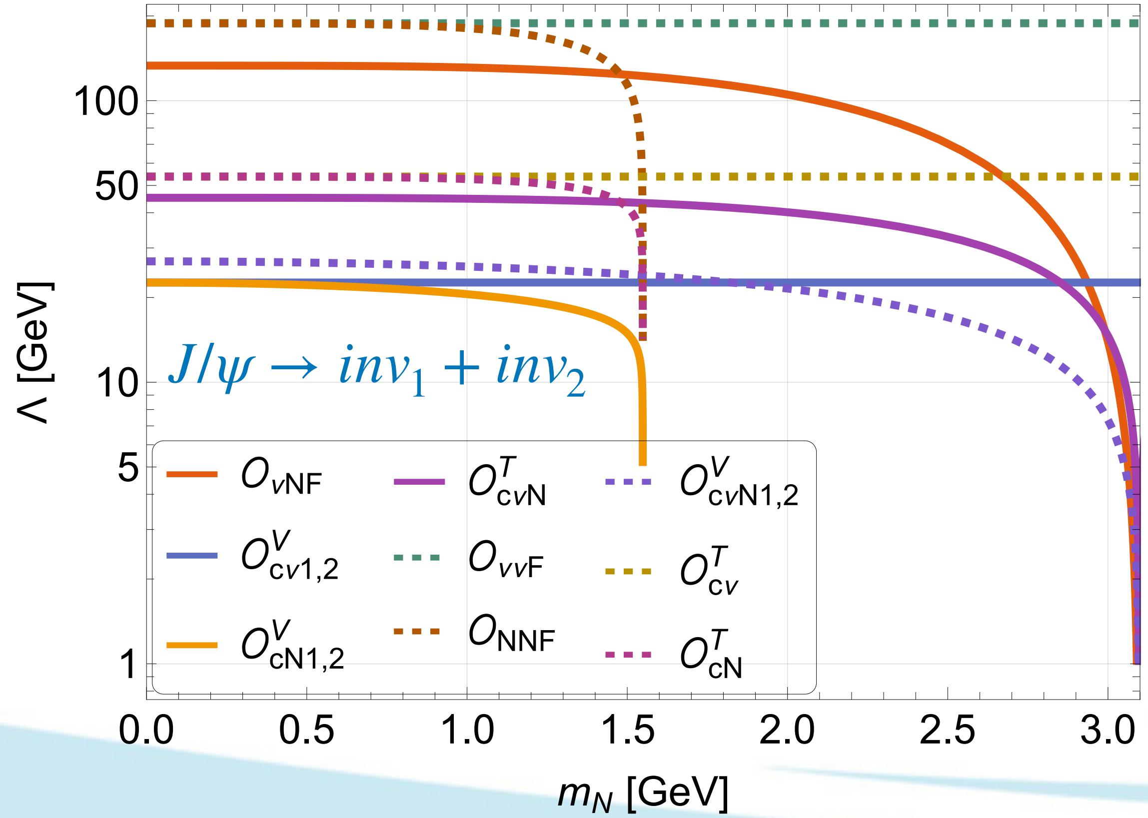
- 中微子-核子的相干散射 (CEνNS)
- 介子的invisible 衰变, 核子的 beta 衰变
- 轻子味道普适性(LFU)
- CKM 幺正性

与南开大学李佟教授和悉尼大学 Micheal Schmidt教授合作完成

JHEP07(2020)152

JHEP10(2020)115

2104.01780 (under review)



LNEFT WC [GeV^{4-d}]	CEνNS $\alpha = e$ or μ	$\pi^0 \to$ inv. 2.7×10^{-7}	$\eta \to$ inv. 1.0×10^{-4}	$\eta' \to$ inv. 5.0×10^{-4}	$\omega \to$ inv. 7.0×10^{-5}	$\phi \to$ inv. 1.7×10^{-4}	$\Lambda_{\rm LNEFT} = \lvert C_i \rvert^{\frac{1}{4-d}}$ [GeV]
$C^{V,ee}_{u\nu 1(2),\rm NP}$	1.5×10^{-5}	-	-	-	1.5×10^{-1}	-	260
$C^{V,e\mu}_{u\nu 1(2),\rm NP}$	4.3×10^{-6}	-	-	-	1.5×10^{-1}	-	480
$C^{V,e\tau}_{u\nu 1(2),\rm NP}$	5.9×10^{-6}	-	-	-	1.5×10^{-1}	-	410
$C^{V,\mu\mu}_{u\nu 1(2),\rm NP}$	1.5×10^{-5}	-	-	-	1.5×10^{-1}	-	260
$C^{V,\mu\tau}_{u\nu 1(2),\rm NP}$	5.3×10^{-6}	-	-	-	1.5×10^{-1}	-	440

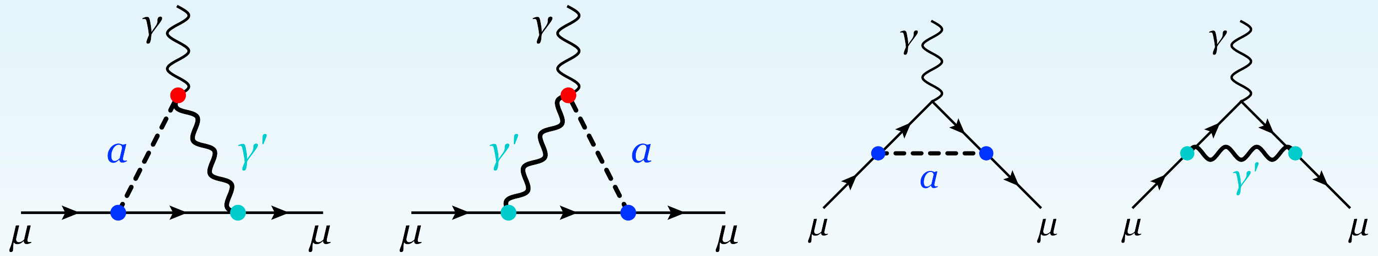
Muon g-2

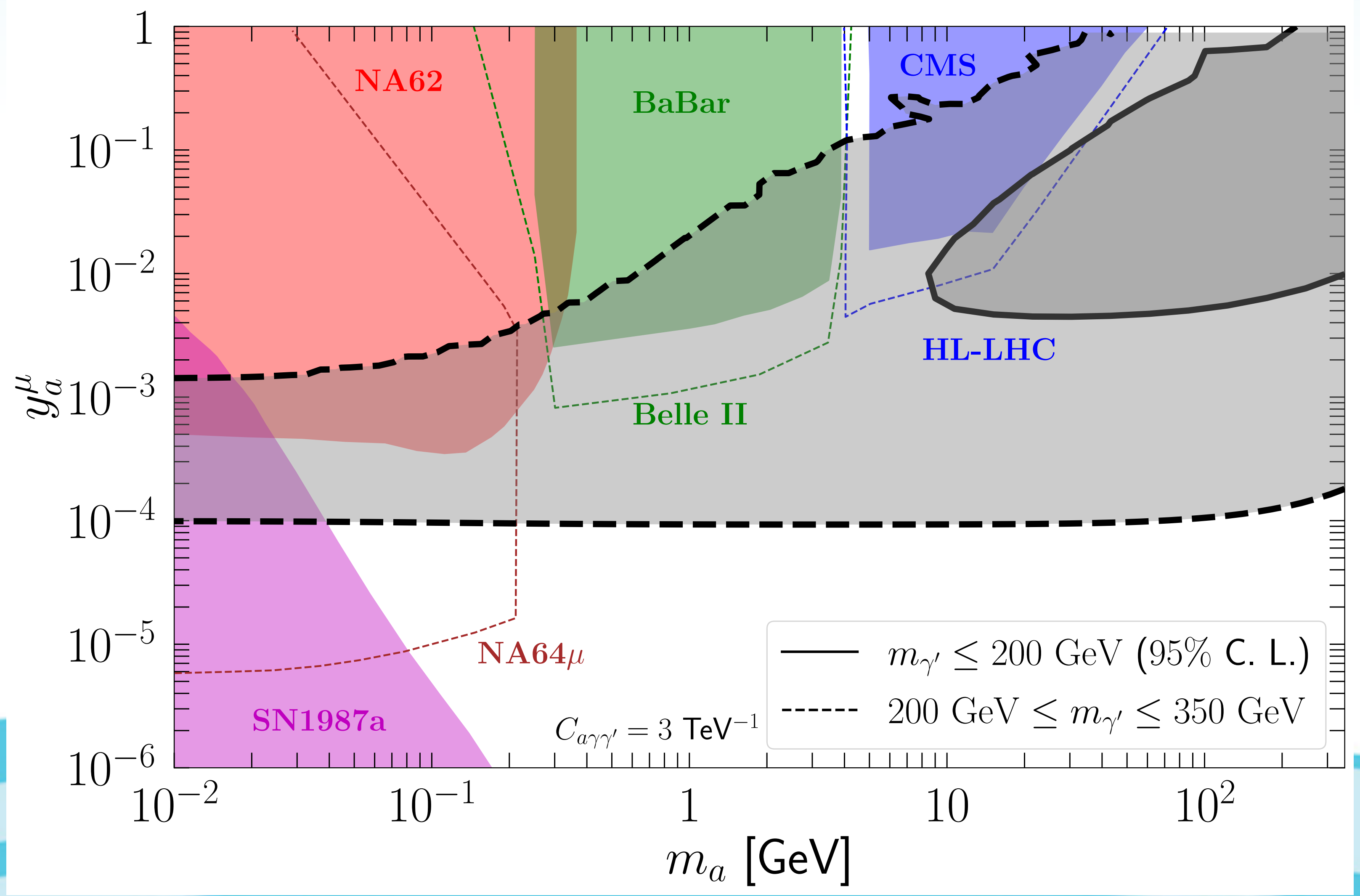
$$\mathscr{L} \ni \frac{1}{2} C_{a\gamma\gamma'} a F^{\mu\nu} \widetilde{X}_{\mu\nu}$$

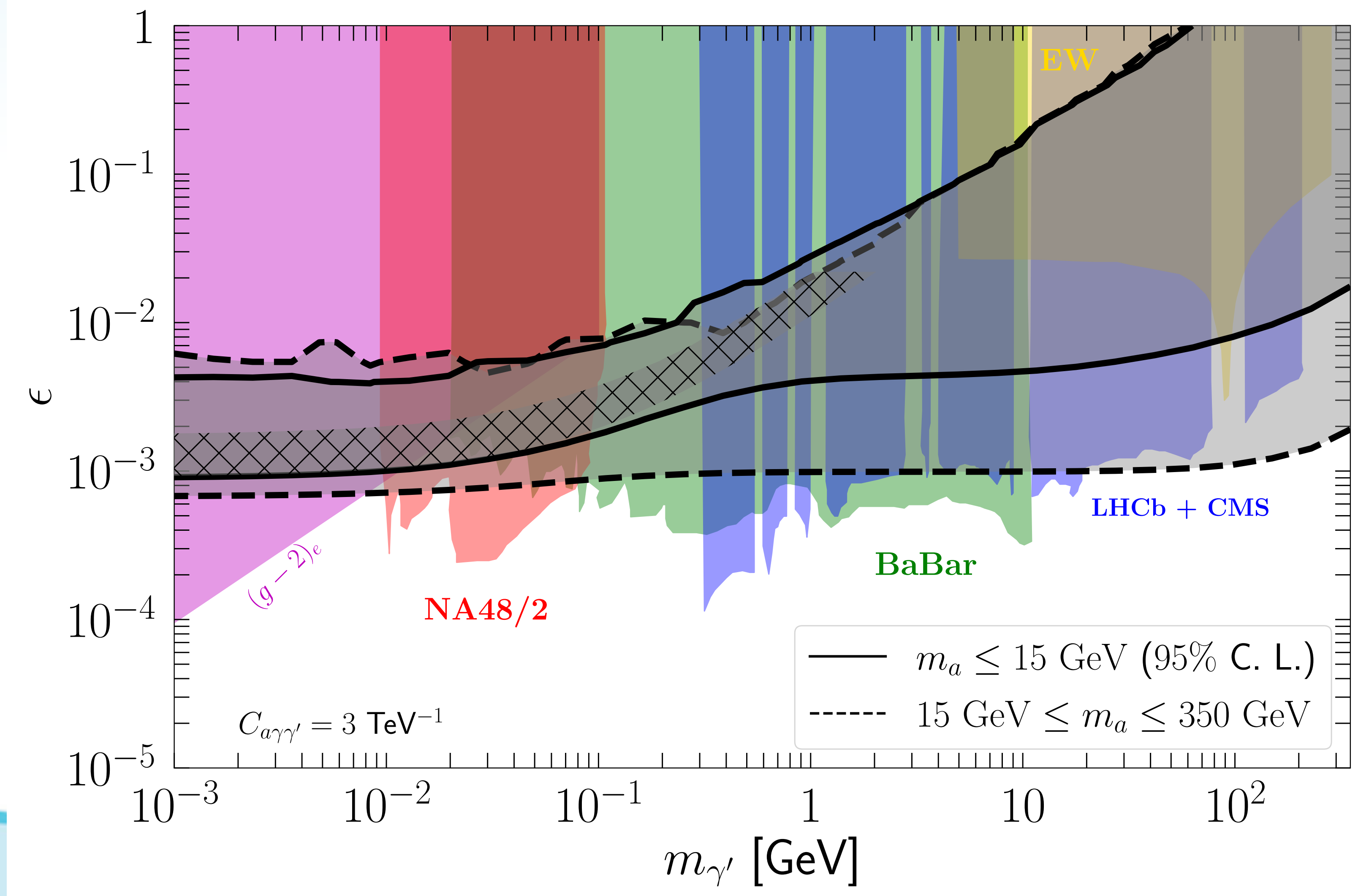
a: ALP

$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$: photon

$X^{\mu\nu} = \partial^\mu X^\nu - \partial^\nu X^\mu$: dark photon







葛韶锋, Pedro Pasquini, arXiv: 2104.03276 (under review)

主要研究成果

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

- 首次确定了完备且独立的:
  1. SMEFT dim 7 和 dim 9 的算符基底，并且计算了dim 7 算符的单圈重整化效应；
  2. LEFT dim 7 的算符基底；
  3. νSMEFT dim 6 和 dim 7的算符基底；
- 首次用有效场论系统研究了 BNV/LNV 过程： $pp \to \ell^+\ell'^+, pn \to \ell^+\bar{\nu}', nn \to \bar{\nu}\bar{\nu}'$, $n \to \bar{p}e^+\nu$, $K^- \to \pi^+\ell_\alpha^-\ell_\beta^-$, 给出了比当前实验结果更严格的限制；
- 在 νSMEFT & νLEFT 中，通过不同过程对某些中微子非标准相互作用首次给出了严格的限制；
- 提出用 dark axion portal 解释 muon $g-2$ 反常，同时拯救了ALP 和 Dark photon 单独解释 muon $g-2$ 的可能性.

代表性文章

上海交通大学 SHANGHAI JIAO TONG UNIVERSITY

有效场论中算符的构造

- Y. Liao and **XDM**, An explicit construction of the dimension-9 operator basis in the standard model effective field theory, JHEP **11**, 152 (2020)
- Y. Liao and **XDM**, Operators up to Dimension Seven in Standard Model Effective Field Theory Extended with Sterile Neutrinos, Phys. Rev. D **96**, no. 1, 015012 (2017)
- Y. Liao and **XDM**, Renormalization Group Evolution of Dimension-seven Baryon- and Lepton-number-violating Operators, JHEP **1611**, 043 (2016)
- Y. Liao, **XDM** and Q. Y. Wang, Extending low energy effective field theory with a complete set of dimension-7 operators, JHEP **08**, 162 (2020)

重子数破坏过程

- X. G. He and **XDM**, $\Delta B = 2$ neutron decay into antiproton mode $n \to \bar{p}e^+\nu(\bar{\nu})$, Phys. Lett. B **817** (2021), 136298
- X. G. He and **XDM**, An EFT toolbox for baryon and lepton number violating dinucleon to dilepton decays, (accepted by JHEP)

轻子数破坏过程

- Y. Liao and **XDM**, Perturbative Power Counting, Lowest-Index Operators and Their Renormalization in Standard Model Effective Field Theory, Commun. Theor. Phys. **69**, no. 3, 285 (2018)
- Y. Liao and **XDM**, Renormalization Group Evolution of Dimension-seven Operators in Standard Model Effective Field Theory and Relevant Phenomenology, JHEP **03**, 179 (2019)
- Y. Liao, **XDM** and H. L. Wang, Effective field theory approach to lepton number violating decays $K^\pm \to \pi^\mp l^\pm l^\pm$: short-distance contribution, JHEP **01**, 127 (2020)
- Y. Liao, **XDM** and H. L. Wang, Effective field theory approach to lepton number violating decays $K^\pm \to \pi^\mp l^\pm_\alpha l^\pm_\beta$: long-distance contribution, JHEP **03**, 120 (2020)
- Y. Liao, **XDM** and H. L. Wang, Effective field theory approach to lepton number violating τ decays, [arXiv:2102.03491 [hep-ph]]. (accepted by CPC)

中微子非标准相互作用

- T. Li, **XDM** and M. A. Schmidt, Implication of $K \to \pi\nu\bar{\nu}$ for generic neutrino interactions in effective field theories, Phys. Rev. D 101, no.5, 055019 (2020)
- T. Li, **XDM** and M. A. Schmidt, General neutrino interactions with sterile neutrinos in light of coherent neutrino-nucleus scattering and meson invisible decays, JHEP **07**, 152 (2020)
- T. Li, **XDM** and M. A. Schmidt, Constraints on the charged currents in general neutrino interactions with sterile neutrinos, JHEP **10**, 115 (2020)
- T. Li, **XDM**, M. A. Schmidt, and R. J. Zhang, The implication of $J/\psi \to \gamma + \mathrm{invisible}$ for the effective field theories of neutrino and dark matter, (under review)

Kaon衰变中的GN bound 破坏机制

- X. G. He, **XDM**, J. Tandean and G. Valencia, Breaking the Grossman-Nir Bound in Kaon Decays, JHEP **04**, 057 (2020)
- X. G. He, **XDM**, J. Tandean and G. Valencia, Evading the Grossman-Nir bound with $\Delta I = 3/2$ new physics, JHEP **08**, 034 (2020)

*所以文章根据国际惯例按姓氏字母顺序；
*其中6篇文章本人为通讯作者

Outline

- 个人简介
- 工作成绩介绍
  - 有效场论和超出标准模型的新物理
  - 重子数和轻子数破坏过程, 中微子非标准相互作用
  - Muon $g-2$
- 当前和未来研究规划

研究规划

上海交通大学 SHANGHAI JIAO TONG UNIVERSITY

● 结合国内暗物质，无中微子衰变以及正在规划的muon等实验，理论与实验结合的方式去探寻相关的新物理信号；

●暗物质唯象研究：当前利用DMEFT研究不同类型暗物质粒子在直接探测实验(例如国内的PandaX-4T)中的信号。目前正在与交大的理论及PandaX等实验团队做费米型轻暗物质在原子核中吸收信号的研究；

● 中微子唯象研究：同时也在做与中微子磁偶极矩探测相关的工作；

●未来继续深入研究中微子与暗物质物理，探讨它们可能在各种环境中产生的独特物理信号，并结合各种中微子和暗物质实验数据从理论上进行解读。

谢谢各位老师!