



粒子物理理论研究简介

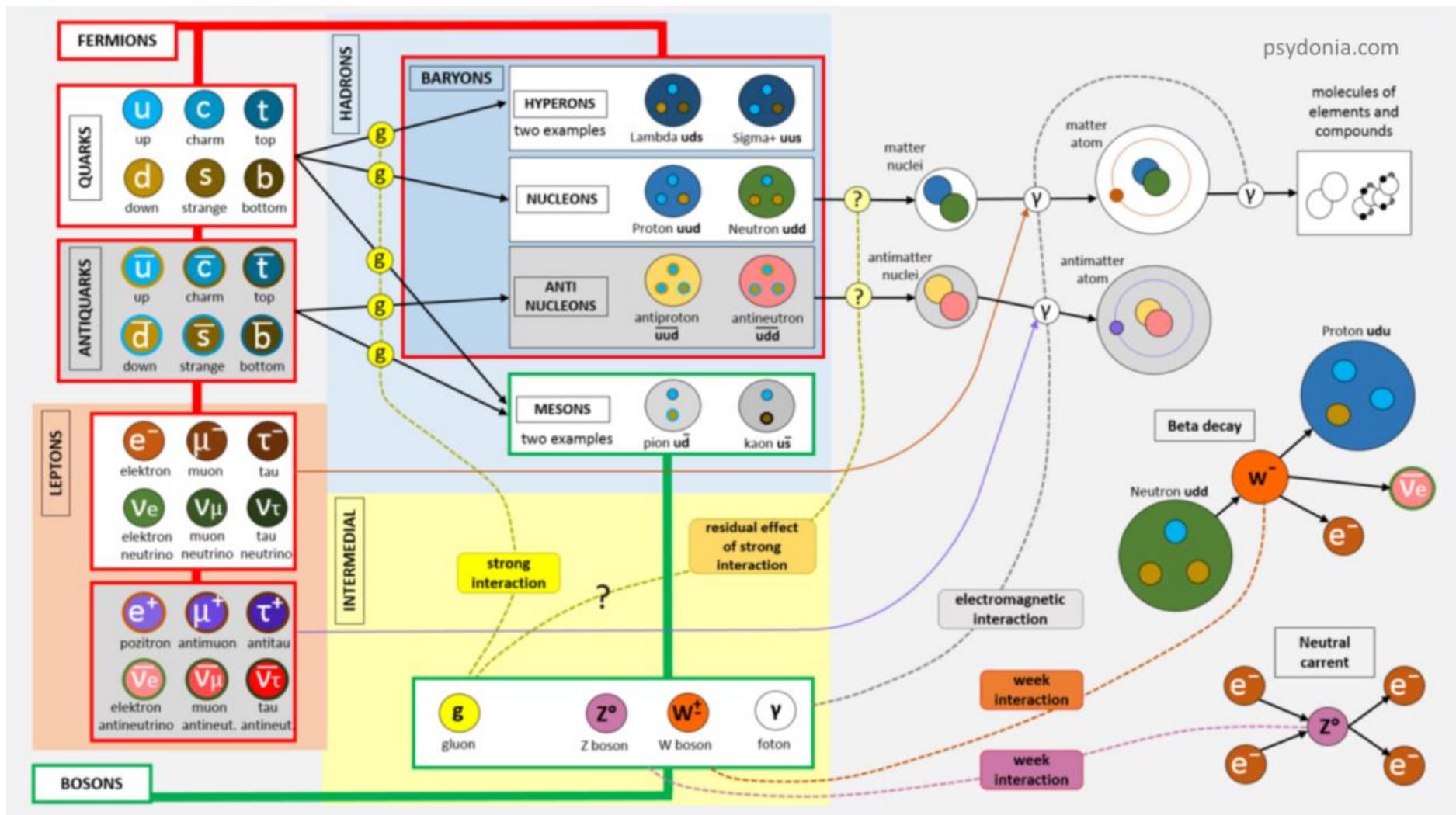
高孟超

导师：杨亚东，袁兴博

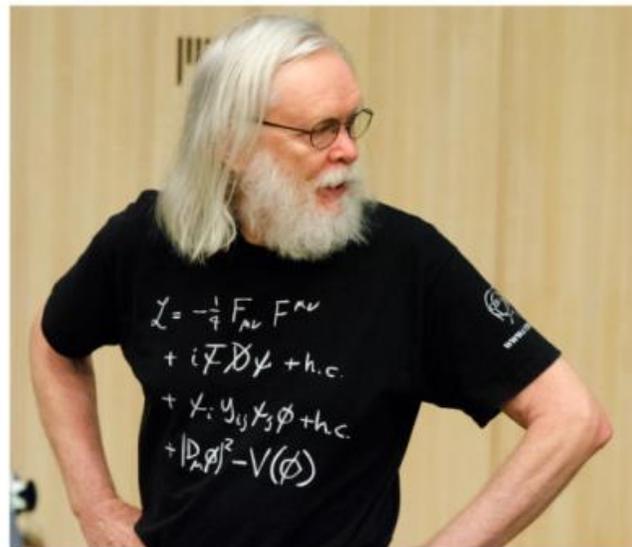
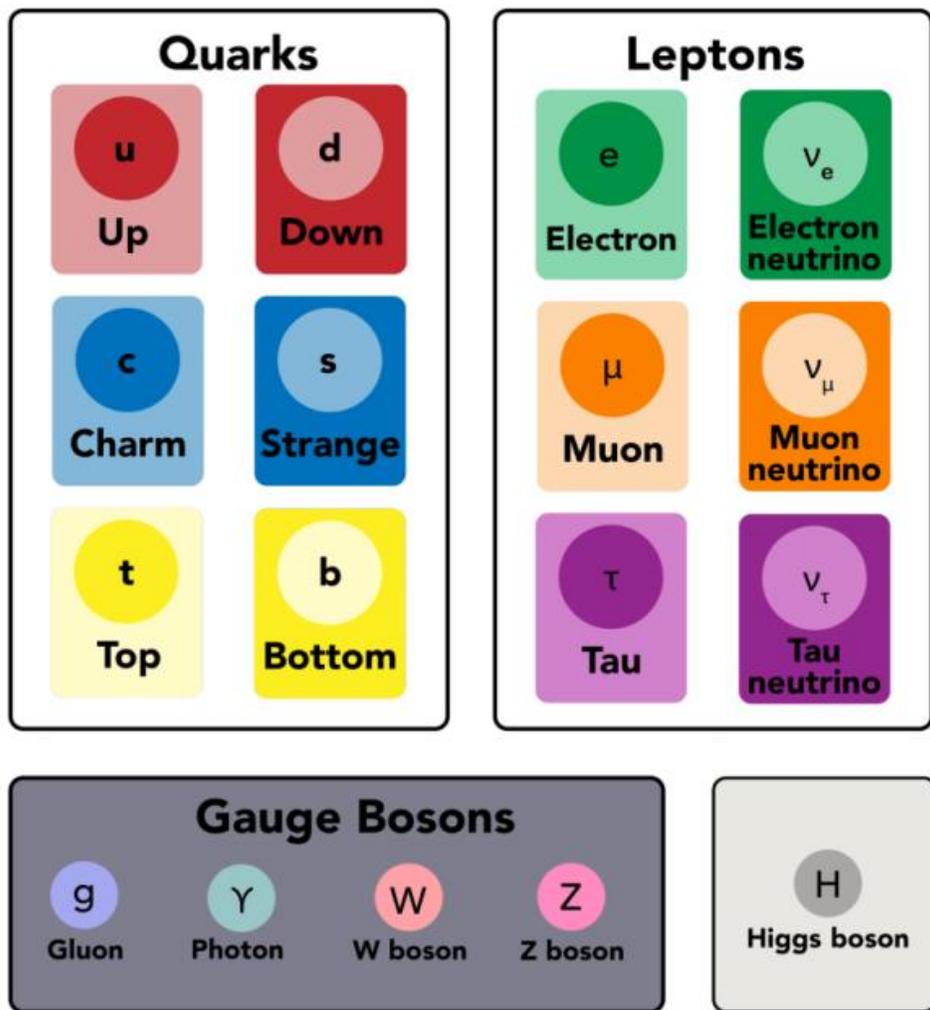
华中师范大学粒子物理理论组

第一期武汉高校“突破界限，前方高能”研究生论坛

粒子物理与标准模型



粒子物理与标准模型



John Ellis



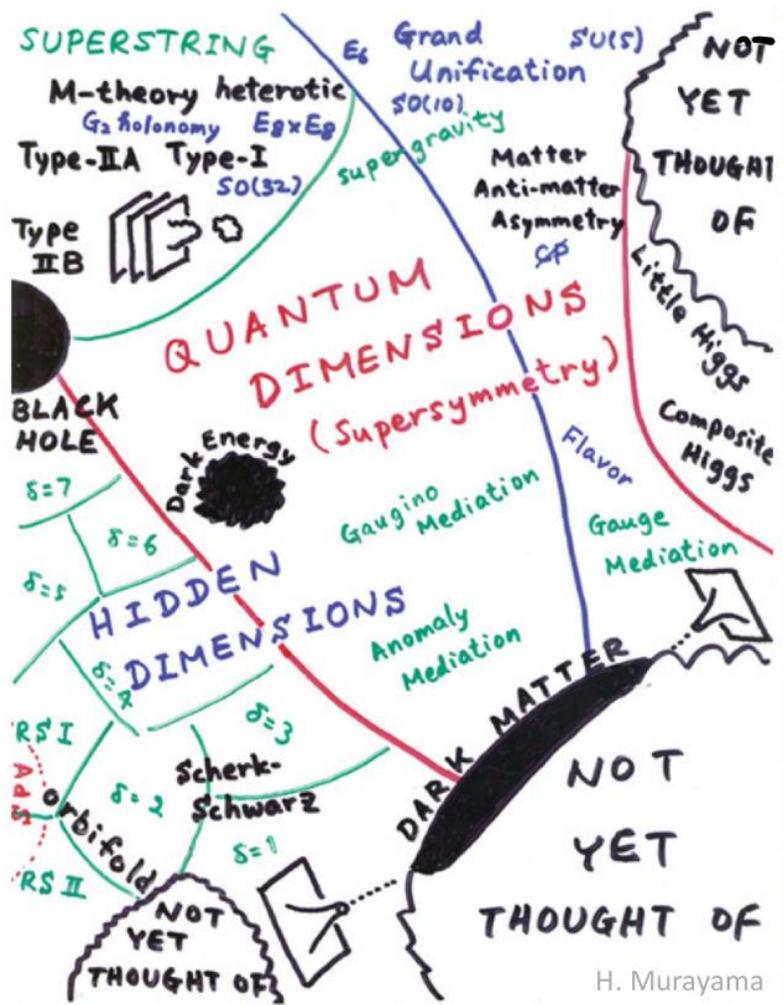
François Englert and Peter Higgs
2013 Nobel

新物理的迹象

Anomaly	Significance	Reference
Multileptons@LHC	2-5 σ	1901.05300
Dijet excess@LEP2	4-5 σ	1706.02255
Muon g-2	4.2 σ	2104.03281
LFUV in B-decays	3-5 σ	1909.12524
CKM unitarity	4 σ	2012.01580
LFUV in tau decay	$\sim 2 \sigma$	1909.12524
LSND/MiniBooNE	6.1 σ	2006.16883
NOvA vs T2K	$\sim 2 \sigma$	Neutrino 2020
IceCube HESE vs TG	$\sim 2 \sigma$	2011.03545
ANITA upgoing events	$\sim 2 \sigma$	2010.02869
Neutron lifetime	3.6 σ	2011.13272
^8Be transition	7.2 σ	1910.10459
Proton charge radius	5 σ	2105.00571

Anomaly	Significance	Reference
DAMA/LIBRA	12.9 σ	1907.06405
XENON1T e^- -recoil	2-3 σ	2006.09721
Fermi-LAT GC excess	2-3 σ	1704.03910
AMS e^+/\bar{p} excess	3-5 σ	Phys.Rep.894, 1
3.5 keV X-ray line	4 σ	2008.02283
511 keV gamma-ray line	58 σ	1512.00325
EDGES 21cm spectrum	3.8 σ	1810.05912
Primordial ^7Li problem	4-5 σ	1203.3551
Hubble tension	4.4 σ	2008.11284
σ_8 tension	3 σ	2005.03751
CMB anomalies	2-3 σ	1510.07929
NANOGrAV	$\gg 5 \sigma$	2009.04496
Fast Radio Bursts	$\gg 5 \sigma$	1906.05878

粒子物理的发展方向



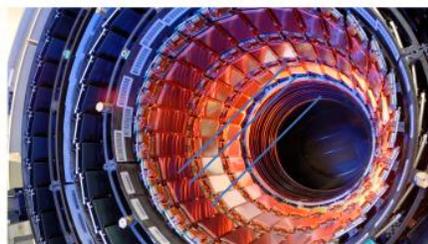
Dampe (暗物质)



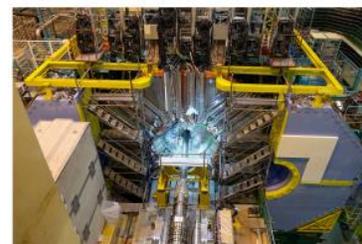
AMS-02 (暗物质)



LIGO (引力波)



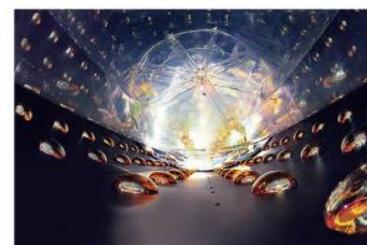
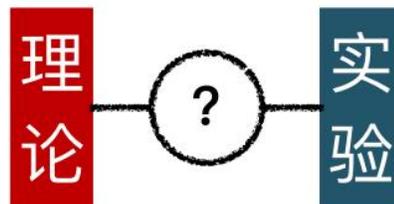
LHC (质子对撞机)



Belle II (电子对撞机)



BES III (电子对撞机)



DaYa Bay (中微子)



PandaX (暗物质)

重味物理

- B物理-B介子的非轻衰变

1. 味物理对检验SM和寻找新物理起着非常重要的作用，而B介子的非轻衰变一直是理论和实验研究的热点。

2. B介子的非轻衰变可以作为直接测量CKM矩阵元的有效途径，深入了解强相互作用动力学。

3. BaBar, Belle, Belle II, LHCb实验对这些衰变道进行了许多高精度的测量。

非轻衰变

- B介子两体衰变

$$\mathcal{A}(B \rightarrow M_1 M_2) = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu) \langle M_1 M_2 | Q_i | \bar{B} \rangle(\mu)$$

M_1, M_2 两个强子模态

CKM, Wilson系数(NLO)

强子矩阵元的计算



- 强子矩阵元

从QCD第一原理出发，没有找到一种完全自治的方法

QCD的色禁闭-强子化过程是非微扰的

- 简单因子化

强子矩阵元=形状因子×衰变常数

唯象上处理B介子两体衰变最简单的模型

依赖重整化标度的选择

D. Fakirov and B. Stech, *F and D Decays*, *Nucl. Phys. B* **133** (1978) 315–326.

M. Bauer and B. Stech, *Exclusive d Decays*, *Phys. Lett. B* **152** (1985) 380–384.

M. Bauer, B. Stech, and M. Wirbel, *Exclusive Nonleptonic Decays of D, D(s), and B Mesons*, *Z. Phys. C* **34** (1987) 103.

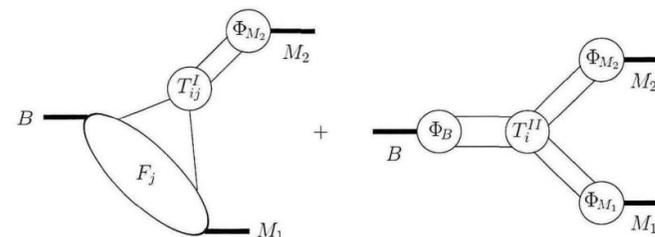
QCD因子化

M. Beneke, G. Buchalla, M. Neubert, and C. T. Sachrajda, *Phys. Rev. Lett.* **83** (1999) 1914–1917, [hep-ph/9905312].
 M. Beneke, G. Buchalla, M. Neubert, and C. T. Sachrajda, *Nucl. Phys.* **B591** (2000) 313–418, [hep-ph/0006124].

- QCD因子化

简洁，能够对非因子化贡献做系统的计算

$$\langle M_1 M_2 | Q_i | \bar{B} \rangle = \sum_j F_j^{B \rightarrow M_1}(m_2^2) \int_0^1 du T_{ij}^I(u) \Phi_{M_2}(u) + (M_1 \leftrightarrow M_2) \\ + \int_0^1 d\xi du dv T_i^{II}(\xi, u, v) \Phi_B(\xi) \Phi_{M_1}(v) \Phi_{M_2}(u).$$



- 硬散射核 T_{ij}^I 和 T_i^{II}

微扰可算

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* \left\{ \sum_i C_i(\mu) Q_i(\mu) + \sum_{i,j} \left[C_i^{VLL}(\mu) Q_i^{VLL}(\mu) + C_i^{VLR}(\mu) Q_i^{VLR}(\mu) \right. \right. \\ \left. \left. + C_j^{SLL}(\mu) Q_j^{SLL}(\mu) + C_i^{SLR}(\mu) Q_i^{SLR}(\mu) + (L \leftrightarrow R) \right] \right\} + \text{h.c.},$$

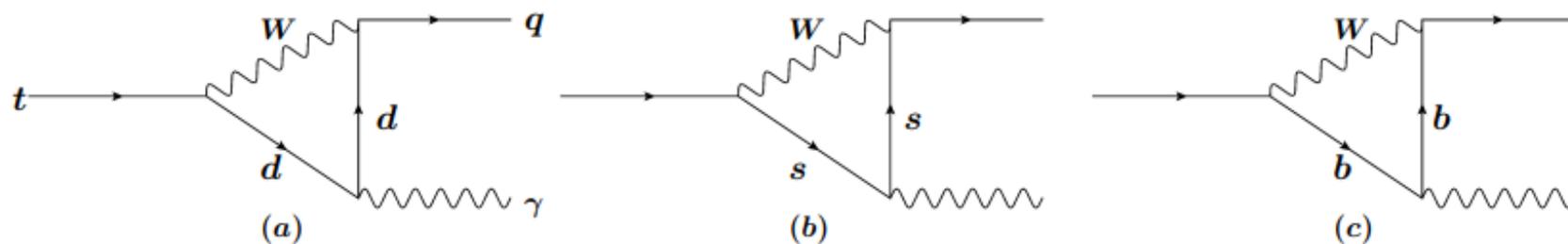
$B \rightarrow \pi\pi, B \rightarrow D\pi, B \rightarrow K\pi$



顶夸克物理

S. L. Glashow, J. Iliopoulos, and L. Maiani *Phys. Rev. D* **2** (1970) 1285–1292.

- 稀有衰变($t \rightarrow qg, t \rightarrow q\gamma, \dots$)—味改变中性流(FCNC)



$$\lambda_i = V_{ti}^* V_{qi}$$

$$\sum_i \lambda_i = 0$$

($i = d, s, b$)

$$\mathcal{M}(t \rightarrow q\gamma) \propto \lambda_d F(m_d) + \lambda_s F(m_s) + \lambda_b F(m_b) \xrightarrow{m_d=m_s=m_b} 0$$

GIM机制

- 顶夸克质量大，可以衰变道较重的粒子(例如: $t \rightarrow qZ$)
- 顶夸克寿命非常短，不会形成强子态，避免了理论计算的不确定性
- 新物理模型下(例如：2HDM等)研究这类过程的CP破坏

S. Balaji, 2009.03315

FCNC过程对新物理敏感，是寻找新物理的理想场所。

顶夸克物理

- 理论预言

J. A. Aguilar-Saavedra, *Acta Phys. Polon. B* **35** (2004) 2695–2710.

\mathcal{B}	SM	2HDM	A2HDM	MSSM
$t \rightarrow qg$	10^{-12}	10^{-4}	—	10^{-6}
$t \rightarrow q\gamma$	10^{-14}	10^{-6}	10^{-10}	10^{-6}
$t \rightarrow qZ$	10^{-14}	10^{-7}	10^{-11}	10^{-6}

- 实验测量

$$\text{CMS}^{2017} \begin{cases} \frac{\kappa_{tu}^g}{\Lambda} < 0.0041 \text{TeV}^{-1} \Rightarrow \mathcal{B}(t \rightarrow ug) < 2.0 \times 10^{-5} \\ \frac{\kappa_{tc}^g}{\Lambda} < 0.018 \text{TeV}^{-1} \Rightarrow \mathcal{B}(t \rightarrow cg) < 4.1 \times 10^{-4} \end{cases} \quad \text{ATLS}^{2018} \begin{cases} \mathcal{B}(t \rightarrow uZ) < 1.7 \times 10^{-4} \\ \mathcal{B}(t \rightarrow cZ) < 2.4 \times 10^{-4} \end{cases}$$

$$\text{ATLS}^{2020} \begin{cases} \mathcal{B}^L(t \rightarrow u\gamma) < 2.8 \times 10^{-5}, \quad \mathcal{B}^L(t \rightarrow c\gamma) < 2.2 \times 10^{-4} \\ \mathcal{B}^R(t \rightarrow u\gamma) < 6.1 \times 10^{-5}, \quad \mathcal{B}^R(t \rightarrow c\gamma) < 1.8 \times 10^{-4} \end{cases} \quad \text{HL-LHC} : 10^{-5} \sim 10^{-6}$$

未来只要探测到顶夸克味改变中性流衰变就确定是新物理信号。

新物理唯象

- Belle II 中心值:

Belle II Collaboration, A. Glazov, "News from Belle II," EPS conference 2023.

$$BR(B^+ \rightarrow K^+ + inv) = (2.3 \pm 0.7) \times 10^{-5}$$

- SM 预测值:

2.8 σ

D. Bečirević, G. Piazza and O. Sumensari, Eur. Phys. J. C **83** (2023) no.3, 252

$$BR(B^+ \rightarrow K^+ + \nu\bar{\nu}) = (5.06 \pm 0.14 \pm 0.28) \times 10^{-6}$$

- Belle, BaBar, Belle II 平均:

$$BR(B^+ \rightarrow K^+ + inv) = (1.4 \pm 0.4) \times 10^{-5}$$

- 解决方法:

Sterile Neutrinos

SMEFT

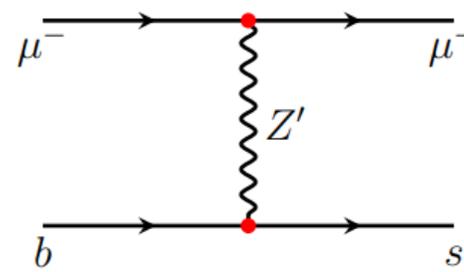
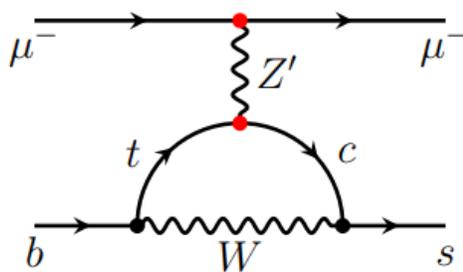
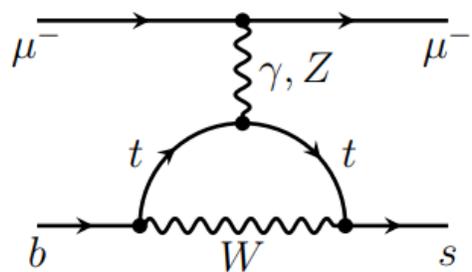
ν SMEFT

DM

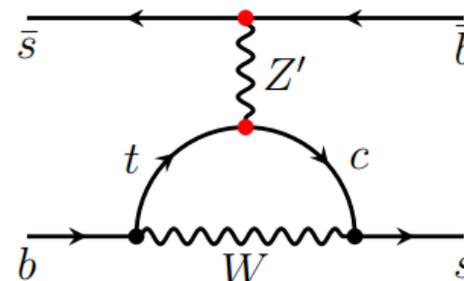
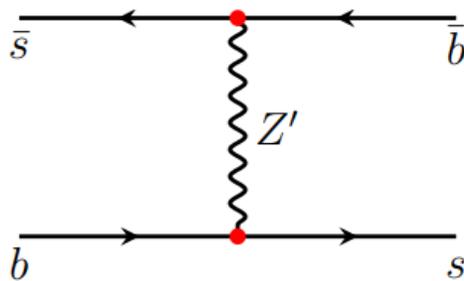
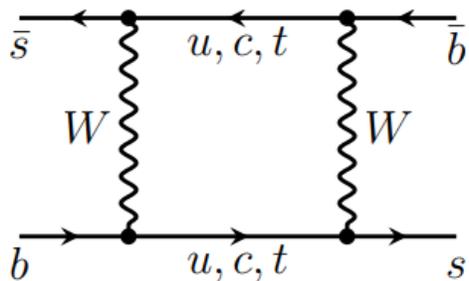
新物理唯象

- $b \rightarrow sll$ 反常

X.-Q. Li, M. Shen, D.-Y. Wang, Y.-D. Yang, and X.-B. Yuan, *Nucl. Phys. B* **980** (2022) 115828.



- $B_s - \bar{B}_s$ 混合



新物理唯象

G. Isidori, F. Wilsch and D. Wyler, **2303.16922**.

- 对称性 $U(2)^5 = U(2)_L \otimes U(2)_Q \otimes U(2)_E \otimes U(2)_U \otimes U(2)_D$

$$V_\ell \sim (2, 1, 1, 1, 1), \quad V_q \sim (1, 2, 1, 1, 1),$$

$$\Delta_e \sim (2, 1, \bar{2}, 1, 1), \quad \Delta_u \sim (1, 2, 1, \bar{2}, 1), \quad \Delta_d \sim (1, 2, 1, 1, \bar{2})$$

$$Y_e = y_\tau \begin{pmatrix} \Delta_e & x_\tau V_\ell \\ 0 & 1 \end{pmatrix}, \quad Y_u = y_t \begin{pmatrix} \Delta_u & x_t V_q \\ 0 & 1 \end{pmatrix}, \quad Y_d = y_b \begin{pmatrix} \Delta_d & x_b V_q \\ 0 & 1 \end{pmatrix} :$$

- 最小味破坏(MFV) $G_{\text{QF}} = SU(3)_{Q_L} \otimes SU(3)_{u_R} \otimes SU(3)_{d_R}$

$$-\mathcal{L}_Y = \bar{Q}_L H Y_d d_R + \bar{Q}_L \tilde{H} Y_u u_R + \text{h.c.}$$

Yukawa 耦合 \Rightarrow 假想场

$$Y_u \sim (3, \bar{3}, 1)$$

$$Y_d \sim (3, 1, \bar{3})$$

$$\bar{Q}_L H C_{LR} d_R \supset \frac{v}{\sqrt{2}} \bar{d}_L [\epsilon_0 + \epsilon_1 Y_u Y_u^\dagger] Y_d d_R$$

$$\rightarrow \frac{v}{\sqrt{2}} \bar{d}_L V^\dagger (\epsilon_0 + \epsilon_1 \lambda_u^2) V \lambda_d d_R.$$

$$\longrightarrow (\bar{d}_L \quad \bar{s}_L \quad \bar{b}_L) \begin{pmatrix} A_{11}, A_{12}, A_{13} \\ A_{21}, A_{22}, A_{23} \\ A_{31}, A_{32}, A_{33} \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix}$$

理论计算



Thanks!