



Institute of Particle Physics
粒子物理研究所

New Physics beyond the SM from B decays: Status and Prospect

Xing-Bo Yuan (袁兴博)

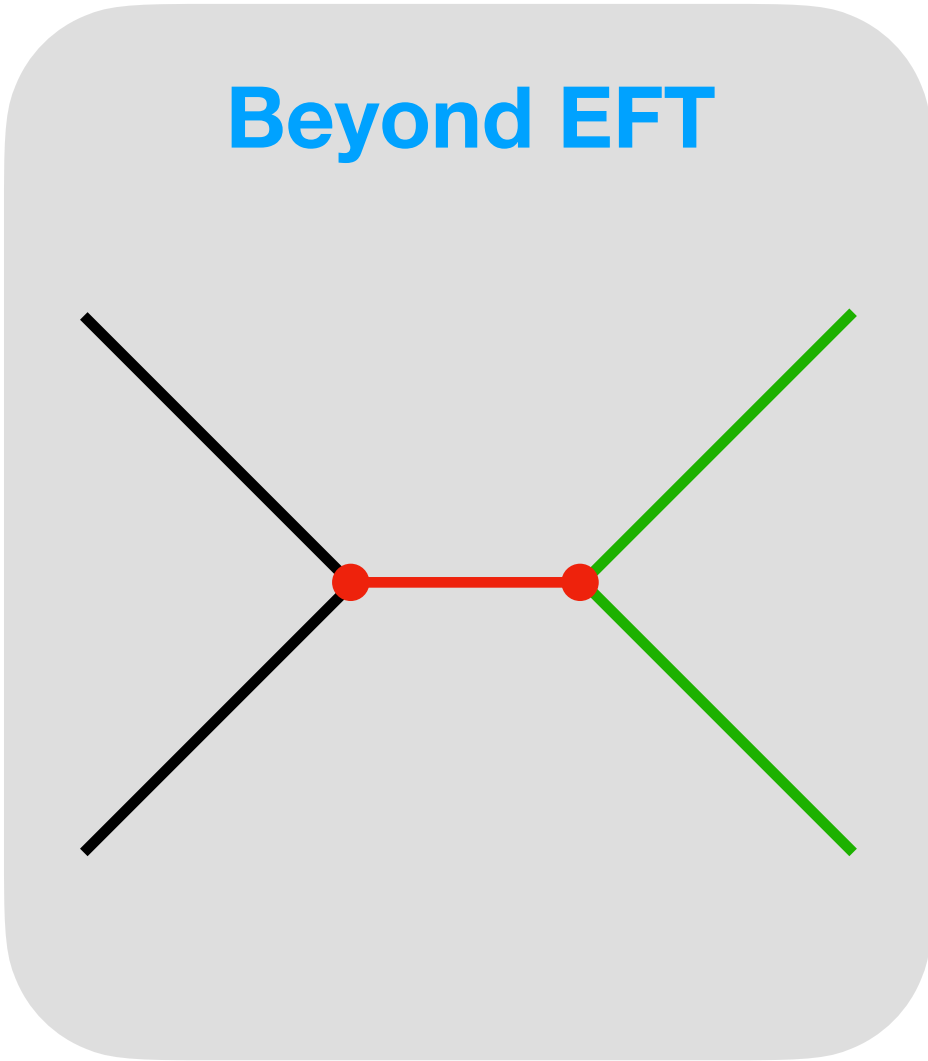
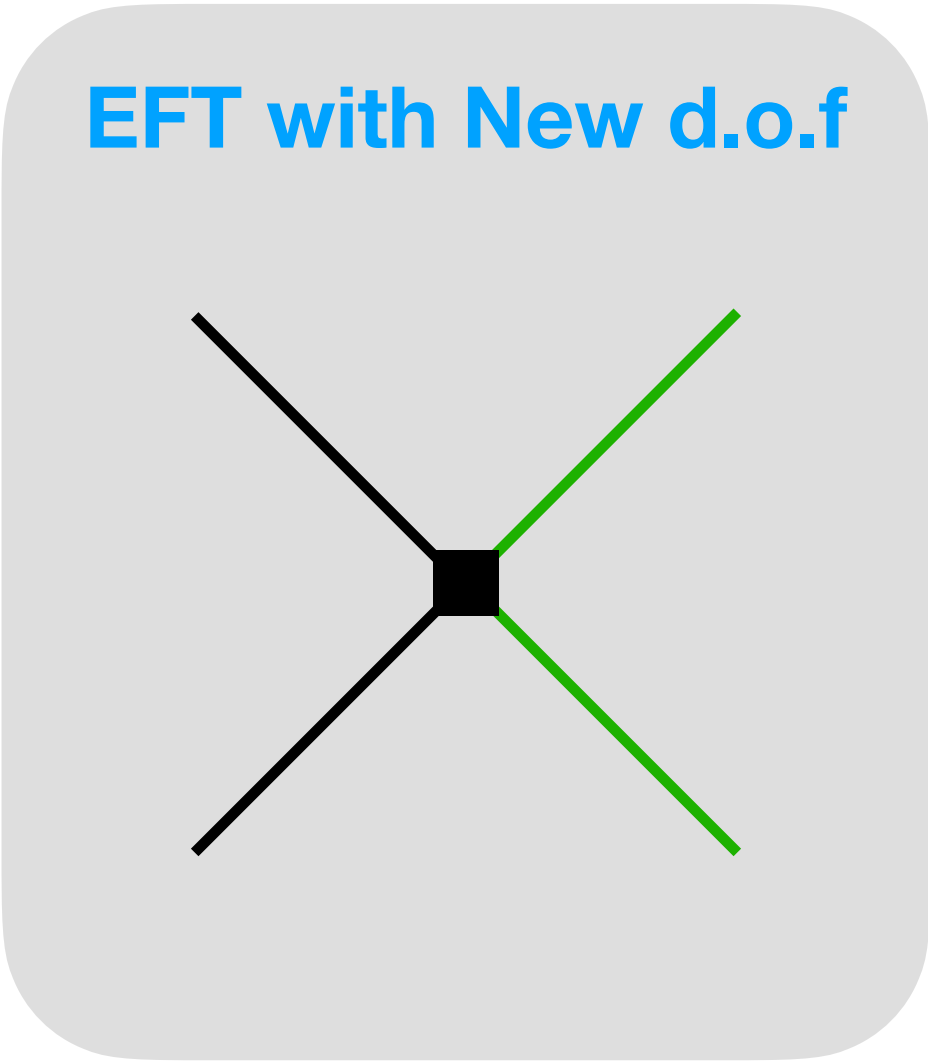
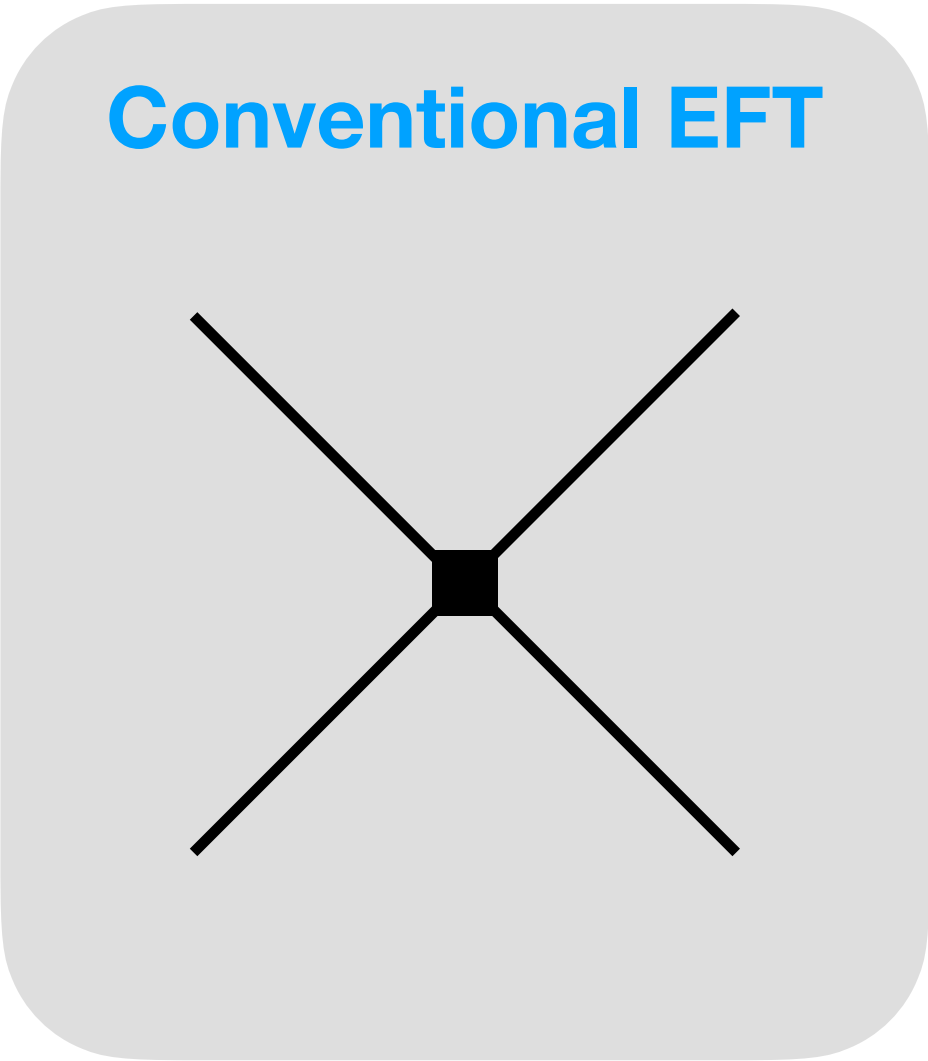
Central China Normal University (华中师范大学)

报告时间有限，无法涵盖国内很多优秀的工作😭😭😭

Outline

EFT Perspective

AI Perspective



SM Flavour Puzzle

NP Flavour Puzzle

Flavour Anomaly

Dark Matter

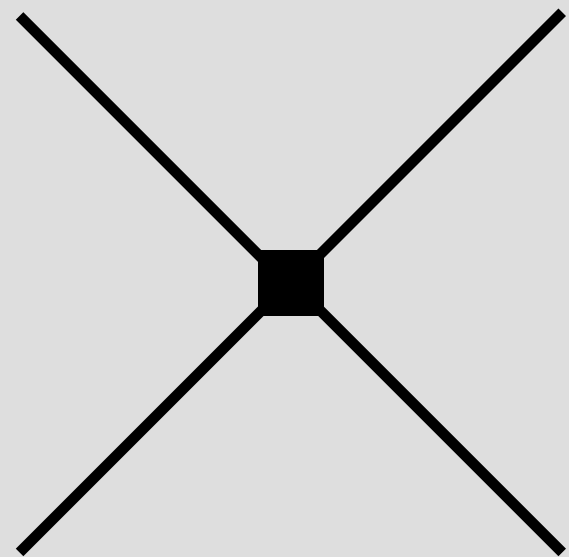
Matter-antimatter Asymmetry

CKM Unitarity Violation

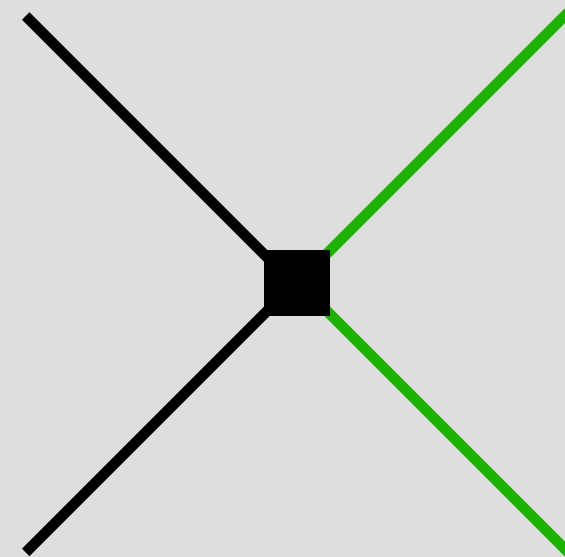
Outline

EFT Perspective

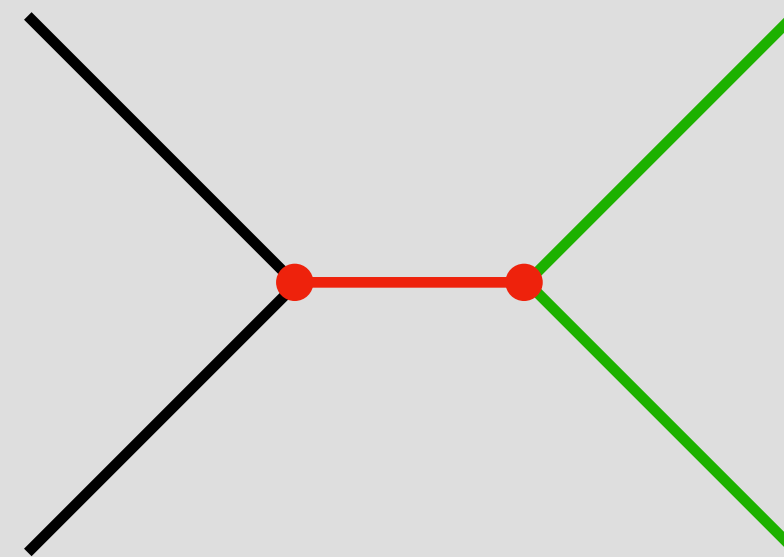
Conventional EFT



EFT with New d.o.f



Beyond EFT



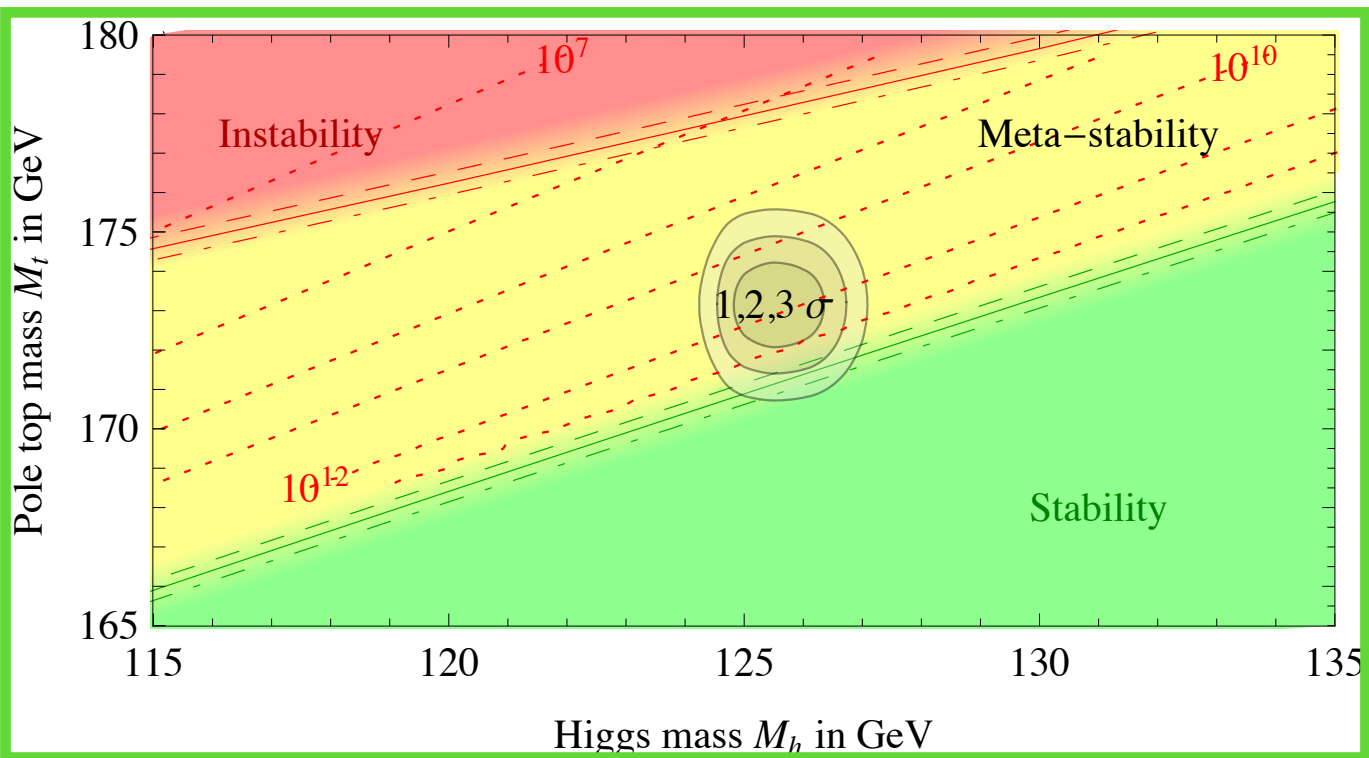
AI Perspective



Physics beyond the Standard Model

Problems of the SM $\implies$ Physics beyond the SM

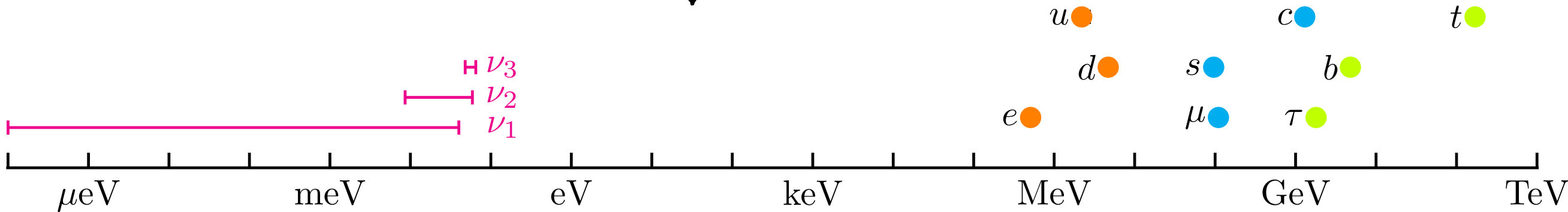
- experimental
- Dark Matter (26%)
 - Dark Energy (69%)
 - Matter-antimatter asymmetry
 - Anomalies in experimental data
- conceptual
- Neutrino masses
 - Strong CP problem
 - Vacuum metastability
 - NP flavour puzzle
 - Gravity
 - Hierarchy problem
 - SM flavour puzzle
 - Family replication ...



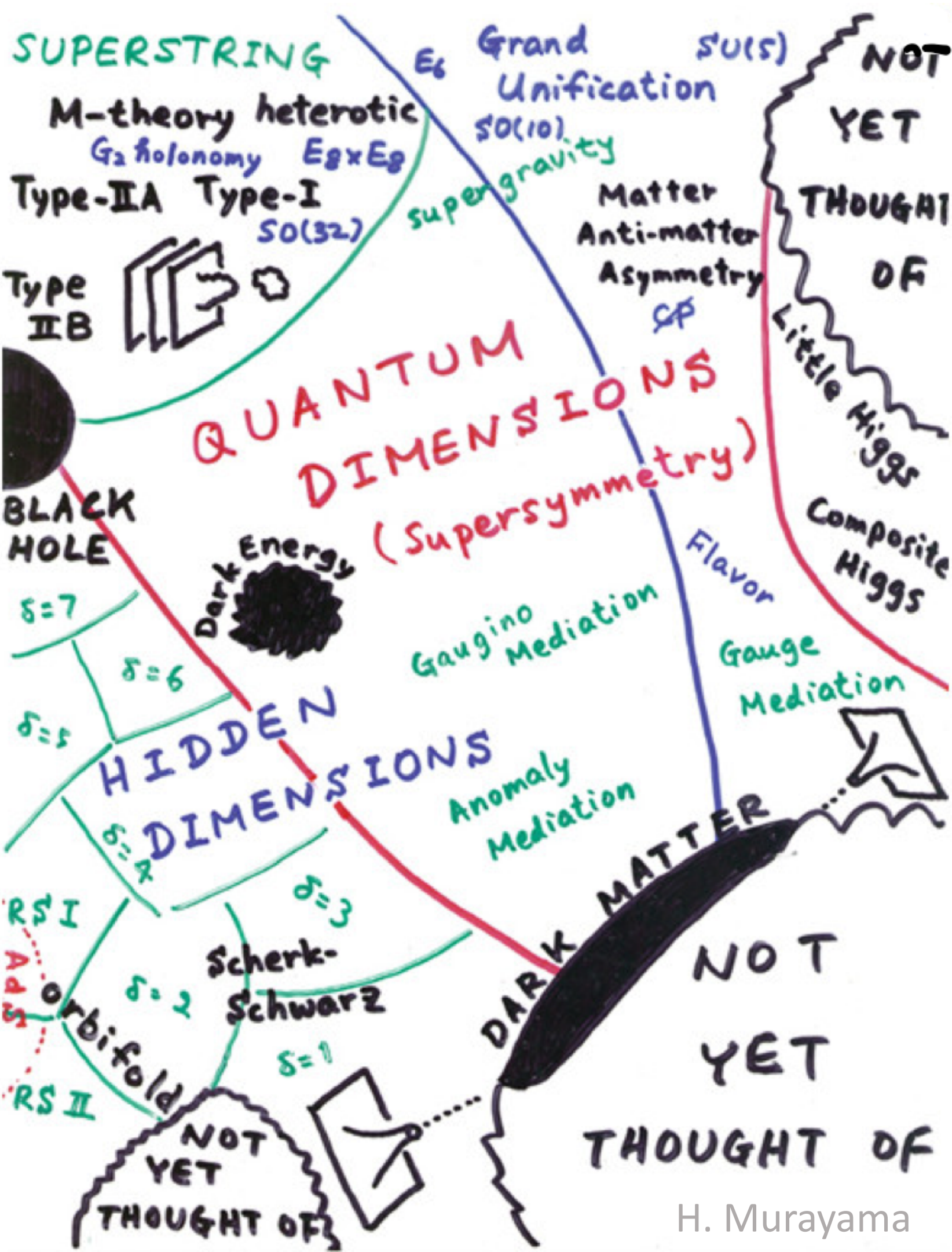
$$-\cdots - \text{t} \text{ loop} - \cdots + \dots = \frac{c}{16\pi^2} \Lambda^2$$

fine-tuning

$$m_{h,0}^2 + \frac{c}{16\pi^2} \Lambda^2 = 125 \text{ GeV}^2$$



Theories beyond the SM



Flavour Physics as a Probe of New Physics

► **Flavour universal**

- couplings $\propto \delta_{ij}$ in flavour space
- example: strong and electromagnetic interactions
- consequence of gauge invariance

► **Flavour diagonal**

- couplings $\propto \lambda_i \delta_{ij}$ (diagonal, but not necessarily universal)
- example: Yukawa interactions

► **Flavour violation (changing)**

- couplings involve different quarks
- no flavour violation in lepton sector ($m_\nu = 0$)
- example: $W^\pm$ interactions in quark sector

► **Flavour Changing Neutral Current (FCNC)**

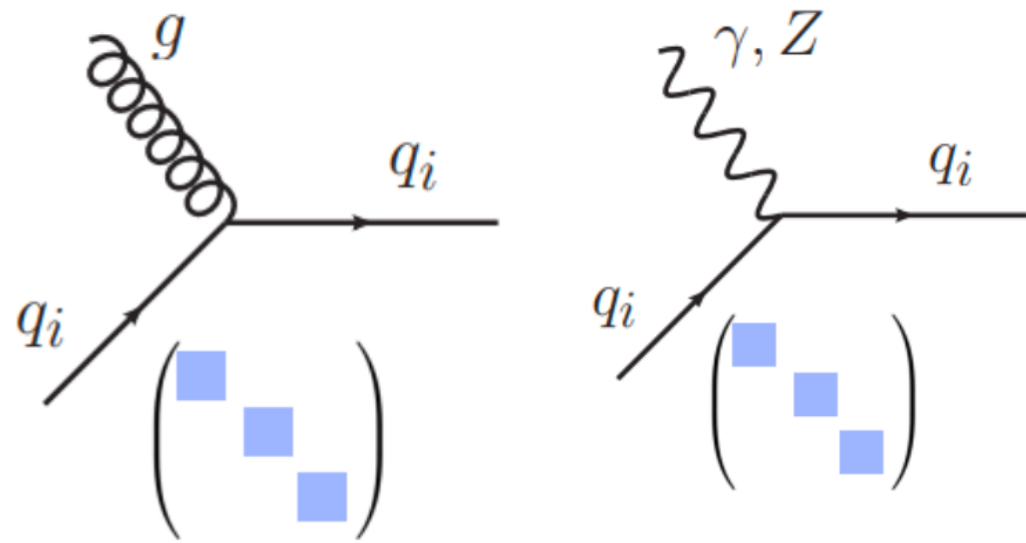
- absent at the tree-level
- arise at the one-loop, but suppressed by GIM mechanism

► **Why flavour physics**

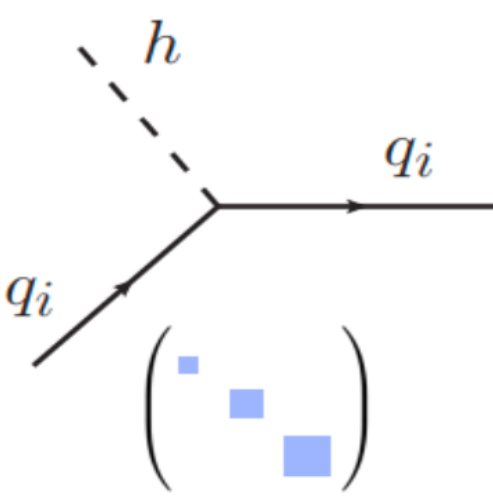
- New physics $\iff \mathcal{O}(10^9)$ $B\bar{B}$ events at BaBar and Belle
- structure of CKM and mass
- CP violation
- strong interaction

experimental status
no evidence of NP $> 5\sigma$
but, anomalies $2 \sim 4\sigma$

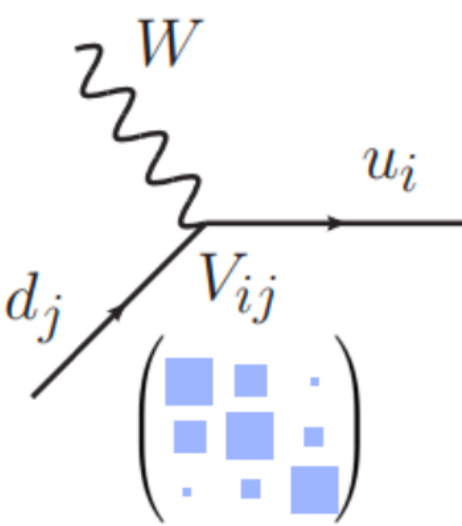
flavour universal



flavour diagonal



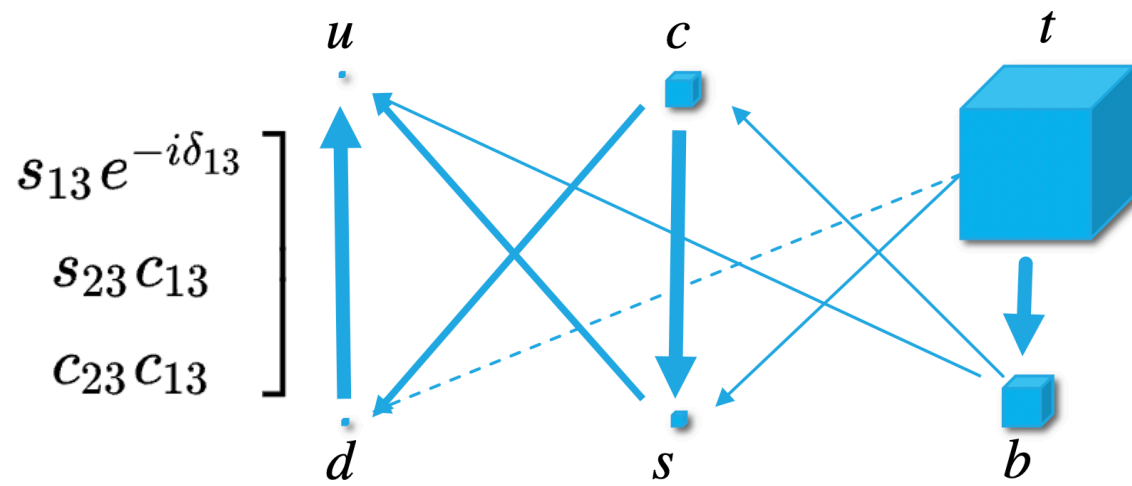
flavour violation



CKM matrix

► Cabibbo–Kobayashi–Maskawa matrix

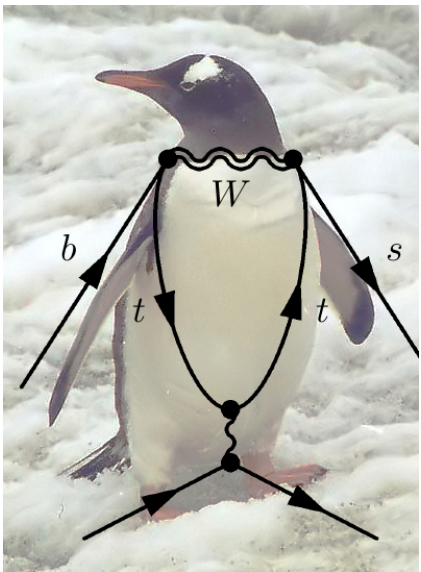
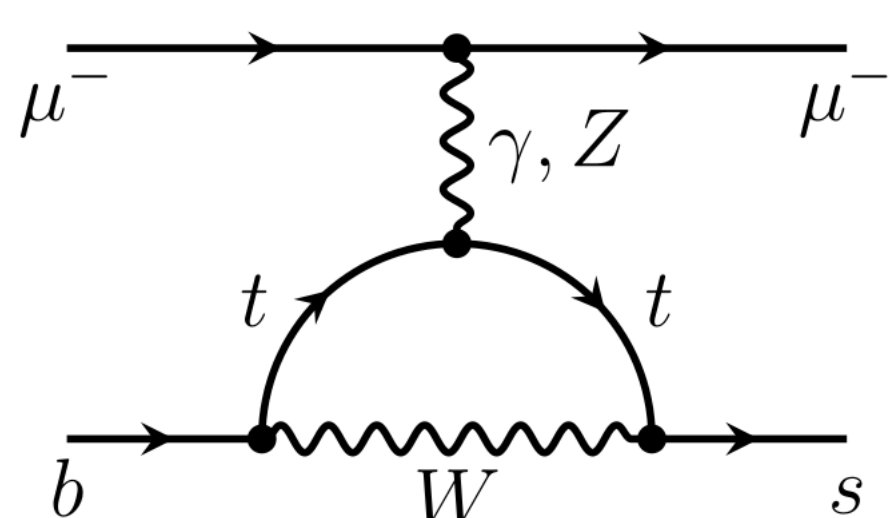
$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} \end{bmatrix}$$



- 3 mixing angles and 1 CP phase
- CP violation in the Standard Model

not enough to explain the baryon asymmetry in our universe

new CP violation sources



penguin diagram

Current Status of Flavour Measurements



Highlights of Recent LHCb Results

Liang Sun
Wuhan University
2025/10/25

HFCPV 2025, Beijing



Overview of the Belle II experiment

贾森 (jjasen@seu.edu.cn)
东南大学

第二十二届全国重味物理与CP破坏研讨会 (HFCPV2025)
2025年10月24-28日 北京



BESIII Experiment Overview
Pei-Rong Li (李培荣)
Lanzhou University
On behalf of the BESIII Collaboration

2025.10.25 @ Beijing



Recent HF and CPV results
from the CMS experiment



Zhen Hu
on behalf of the CMS collaboration

Oct 25, 2025



many measurements,
most of them consistent with SM,
few **anomalies**

Low-energy Effective Field Theory

Buchalla, Buras, Lautenbacher, RMP 1996
Jenkins, Manohar, Stoffer, JHEP 2018

► LEFT/WET/Effective Hamiltonian $SU(3)_C \otimes U(1)_{\text{em}}$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD+QED}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}$$

► New Physics scale $\Lambda \gg m_b$ is assumed

Almost all the flavour experimental measurements
(consistent with SM, or not) can be described by
these operators model-independently.

$(\overline{LL})(\overline{LL})$	
$\mathcal{O}_{\nu\nu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{\nu}_{Ls}\gamma_\mu\nu_{Lt})$
$\mathcal{O}_{ee}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{e}_{Ls}\gamma_\mu e_{Lt})$
$\mathcal{O}_{\nu e}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{e}_{Ls}\gamma_\mu e_{Lt})$
$\mathcal{O}_{\nu u}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{\nu d}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{eu}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{ed}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{vedu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Ls}\gamma_\mu u_{Lt}) + \text{h.c.}$
$\mathcal{O}_{uu}^{V,LL}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{dd}^{V,LL}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{ud}^{V1,LL}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{ud}^{V8,LL}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{d}_{Ls}\gamma_\mu T^A d_{Lt})$

$(\overline{RR})(\overline{RR})$	
$\mathcal{O}_{ee}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{eu}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{ed}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{eu}^{V,RR}$	$(\bar{u}_{Rp}\gamma^\mu u_{Rr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{dd}^{V,RR}$	$(\bar{d}_{Rp}\gamma^\mu d_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ud}^{V1,RR}$	$(\bar{u}_{Rp}\gamma^\mu u_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ud}^{V8,RR}$	$(\bar{u}_{Rp}\gamma^\mu T^A u_{Rr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$

$(\overline{LL})(\overline{RR})$	
$\mathcal{O}_{\nu e}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{ee}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{\nu u}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{\nu d}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{eu}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{ed}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ue}^{V,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{de}^{V,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{vedu}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt}) + \text{h.c.}$
$\mathcal{O}_{uu}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{uu}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{u}_{Rs}\gamma_\mu T^A u_{Rt})$
$\mathcal{O}_{ud}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ud}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$
$\mathcal{O}_{du}^{V1,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{du}^{V8,LR}$	$(\bar{d}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{u}_{Rs}\gamma_\mu T^A u_{Rt})$
$\mathcal{O}_{dd}^{V1,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{dd}^{V8,LR}$	$(\bar{d}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$
$\mathcal{O}_{uddu}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt}) + \text{h.c.}$
$\mathcal{O}_{uddu}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A u_{Rt}) + \text{h.c.}$

$(\overline{LR})(\overline{LR}) + \text{h.c.}$	
$\mathcal{O}_{ee}^{S,RR}$	$(\bar{e}_{Lp}e_{Rr})(\bar{e}_{Ls}e_{Rt})$
$\mathcal{O}_{eu}^{S,RR}$	$(\bar{e}_{Lp}e_{Rr})(\bar{u}_{Ls}u_{Rt})$
$\mathcal{O}_{eu}^{T,RR}$	$(\bar{e}_{Lp}\sigma^{\mu\nu}e_{Rr})(\bar{u}_{Ls}\sigma_{\mu\nu}u_{Rt})$
$\mathcal{O}_{ed}^{S,RR}$	$(\bar{e}_{Lp}e_{Rr})(\bar{d}_{Ls}d_{Rt})$
$\mathcal{O}_{ed}^{T,RR}$	$(\bar{e}_{Lp}\sigma^{\mu\nu}e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu}d_{Rt})$
$\mathcal{O}_{vedu}^{S,RR}$	$(\bar{\nu}_{Lp}e_{Rr})(\bar{d}_{Ls}u_{Rt})$
$\mathcal{O}_{vedu}^{T,RR}$	$(\bar{\nu}_{Lp}\sigma^{\mu\nu}e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu}u_{Rt})$
$\mathcal{O}_{uu}^{S1,RR}$	$(\bar{u}_{Lp}u_{Rr})(\bar{u}_{Ls}u_{Rt})$
$\mathcal{O}_{uu}^{S8,RR}$	$(\bar{u}_{Lp}T^A u_{Rr})(\bar{u}_{Ls}T^A u_{Rt})$
$\mathcal{O}_{ud}^{S1,RR}$	$(\bar{u}_{Lp}u_{Rr})(\bar{d}_{Ls}d_{Rt})$
$\mathcal{O}_{ud}^{S8,RR}$	$(\bar{u}_{Lp}T^A u_{Rr})(\bar{d}_{Ls}T^A d_{Rt})$
$\mathcal{O}_{dd}^{S1,RR}$	$(\bar{d}_{Lp}d_{Rr})(\bar{d}_{Ls}d_{Rt})$
$\mathcal{O}_{dd}^{S8,RR}$	$(\bar{d}_{Lp}T^A d_{Rr})(\bar{d}_{Ls}T^A d_{Rt})$
$\mathcal{O}_{uddu}^{S1,RR}$	$(\bar{u}_{Lp}d_{Rr})(\bar{d}_{Ls}u_{Rt})$
$\mathcal{O}_{uddu}^{S8,RR}$	$(\bar{u}_{Lp}T^A d_{Rr})(\bar{d}_{Ls}T^A u_{Rt})$

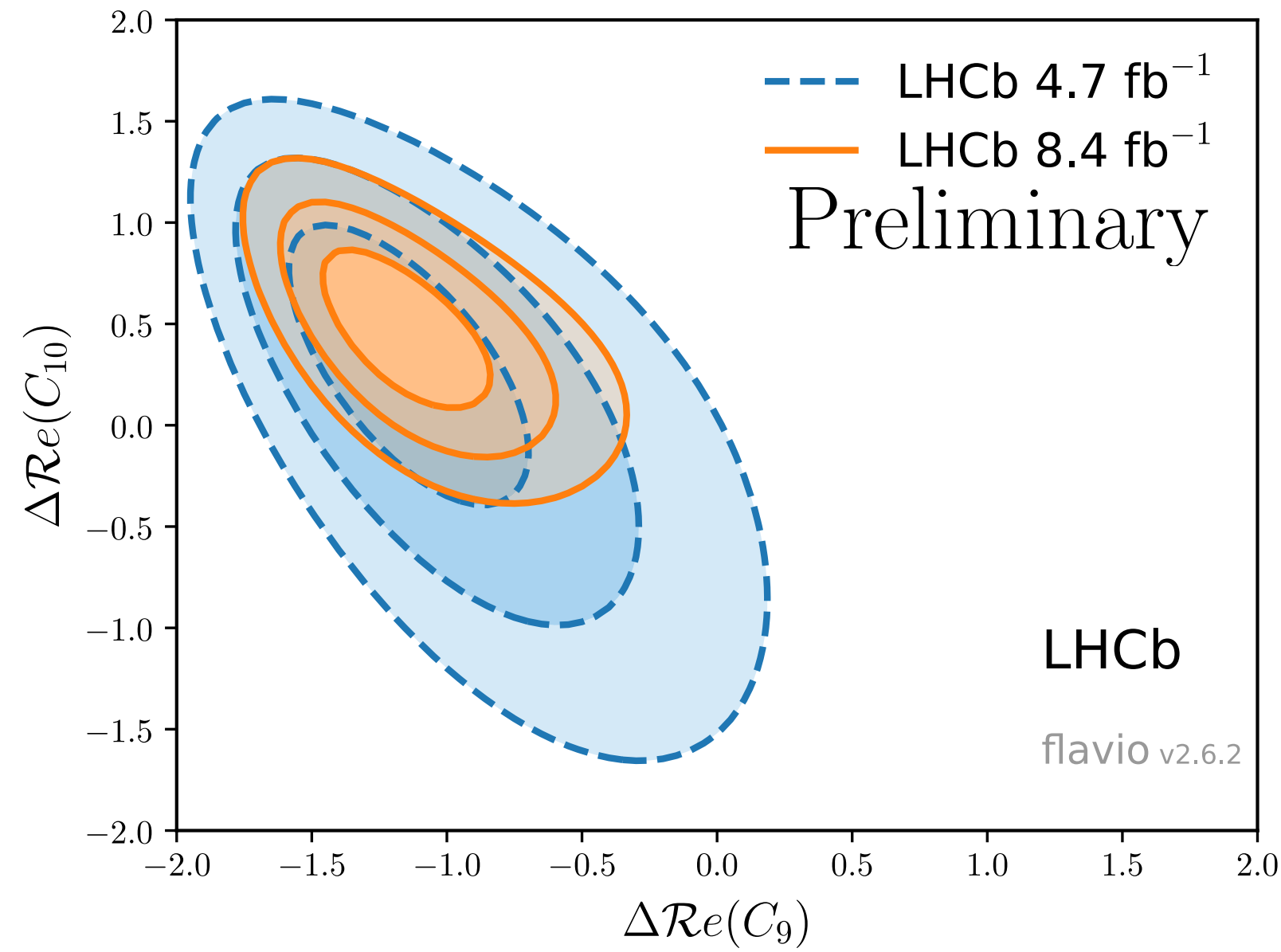
$(\overline{LR})(\overline{RL}) + \text{h.c.}$	
$\mathcal{O}_{eu}^{S,RL}$	$(\bar{e}_{Lp}e_{Rr})(\bar{u}_{Rs}u_{Lt})$
$\mathcal{O}_{ed}^{S,RL}$	$(\bar{e}_{Lp}e_{Rr})(\bar{d}_{Rs}d_{Lt})$
$\mathcal{O}_{vedu}^{S,RL}$	$(\bar{\nu}_{Lp}e_{Rr})(\bar{d}_{Rs}u_{Lt})$

$(\overline{LR})X + \text{h.c.}$	
$\mathcal{O}_{e\gamma}$	$\bar{e}_{Lp}\sigma^{\mu\nu}e_{Rr}F_{\mu\nu}$
$\mathcal{O}_{u\gamma}$	$\bar{u}_{Lp}\sigma^{\mu\nu}u_{Rr}F_{\mu\nu}$
$\mathcal{O}_{d\gamma}$	$\bar{d}_{Lp}\sigma^{\mu\nu}d_{Rr}F_{\mu\nu}$
$\mathcal{O}_{uG}$	$\bar{u}_{Lp}\sigma^{\mu\nu}T^A u_{Rr}G_{\mu\nu}^A$
$\mathcal{O}_{dG}$	$\bar{d}_{Lp}\sigma^{\mu\nu}T^A d_{Rr}G_{\mu\nu}^A$

X^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\tilde{G}}$	$f^{ABC}\tilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$

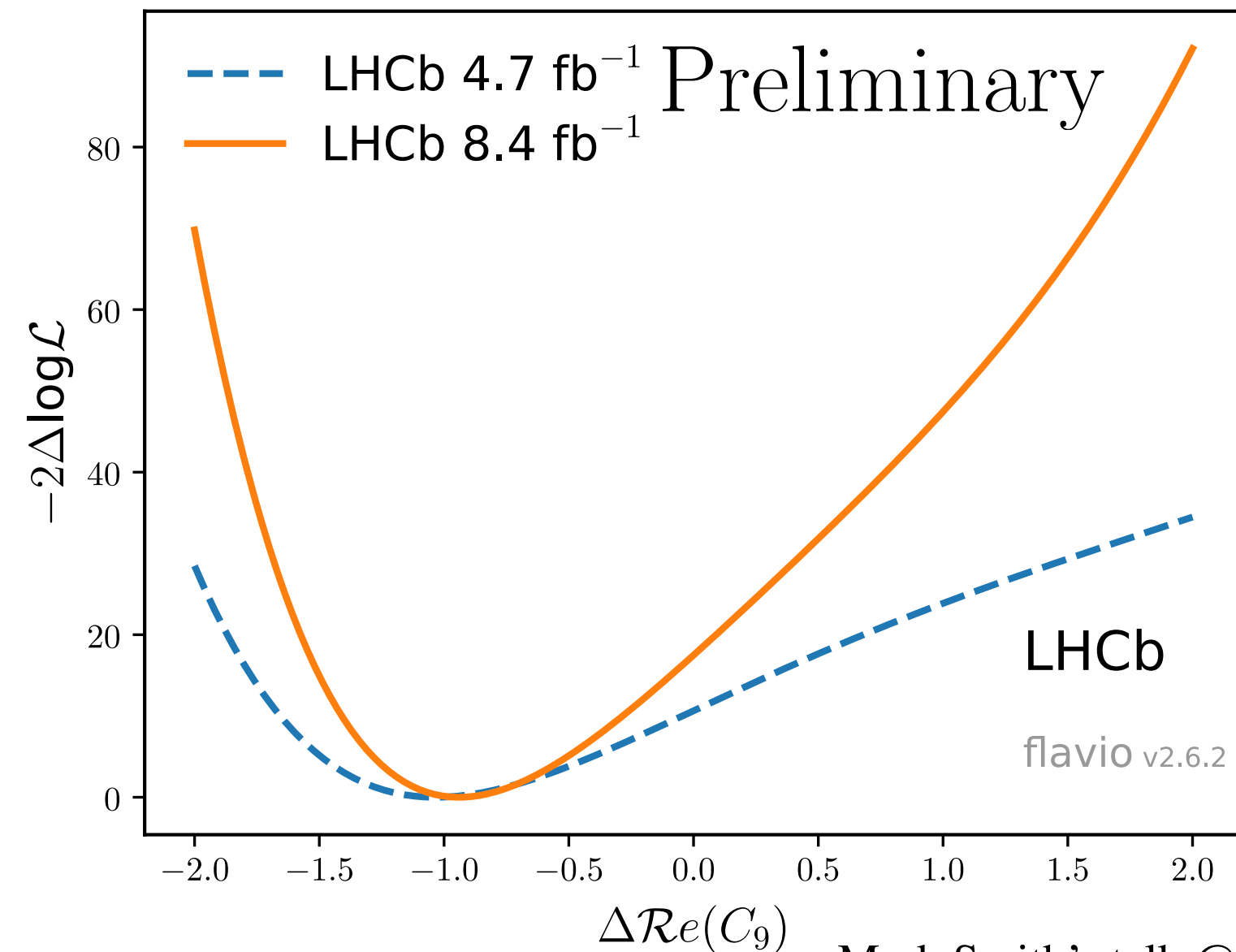
$B \rightarrow K^* \mu^+ \mu^-$ in LEFT

see also, Qiaoyi Wen, Fanrong Xu 2305.19038
Hurth, Mahmoudi, Monceaux, Neshatpour, 2508.09986



$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2} \frac{d^4(\Gamma+\bar{\Gamma})}{d\Omega d q^2} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_k + F_L \cos^2 \theta_k \right. \\ \left. + \frac{1}{4}(1 - F_L) \sin^2 \theta_k \cos 2\theta_\ell - F_L \cos^2 \theta_k \cos 2\theta_\ell \right. \\ \left. + S_3 \sin^2 \theta_k \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_k \sin 2\theta_\ell \cos \phi \right. \\ \left. + S_5 \sin 2\theta_k \sin \theta_\ell \cos \phi + \frac{4}{3} A_{FB} \sin^2 \theta_k \cos \theta_\ell \right. \\ \left. + S_7 \sin 2\theta_k \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_k \sin 2\theta_\ell \sin \phi \right. \\ \left. + S_9 \sin^2 \theta_k \sin^2 \theta_\ell \sin 2\phi \right],$$

angular observables
 $F_L, A_{FB}, S_i = f(C_7, C_9, C_{10})$,
combinations of K^{*0} decay amplitudes



4.1 σ tension with the SM

$$P_1 = \frac{2S_3}{1 - F_L}$$

$$P_2 = \frac{2}{3} \frac{A_{FB}}{1 - F_L}$$

$$P_3 = -\frac{S_9}{1 - F_L}$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}.$$

Standard Model Effective Field Theory

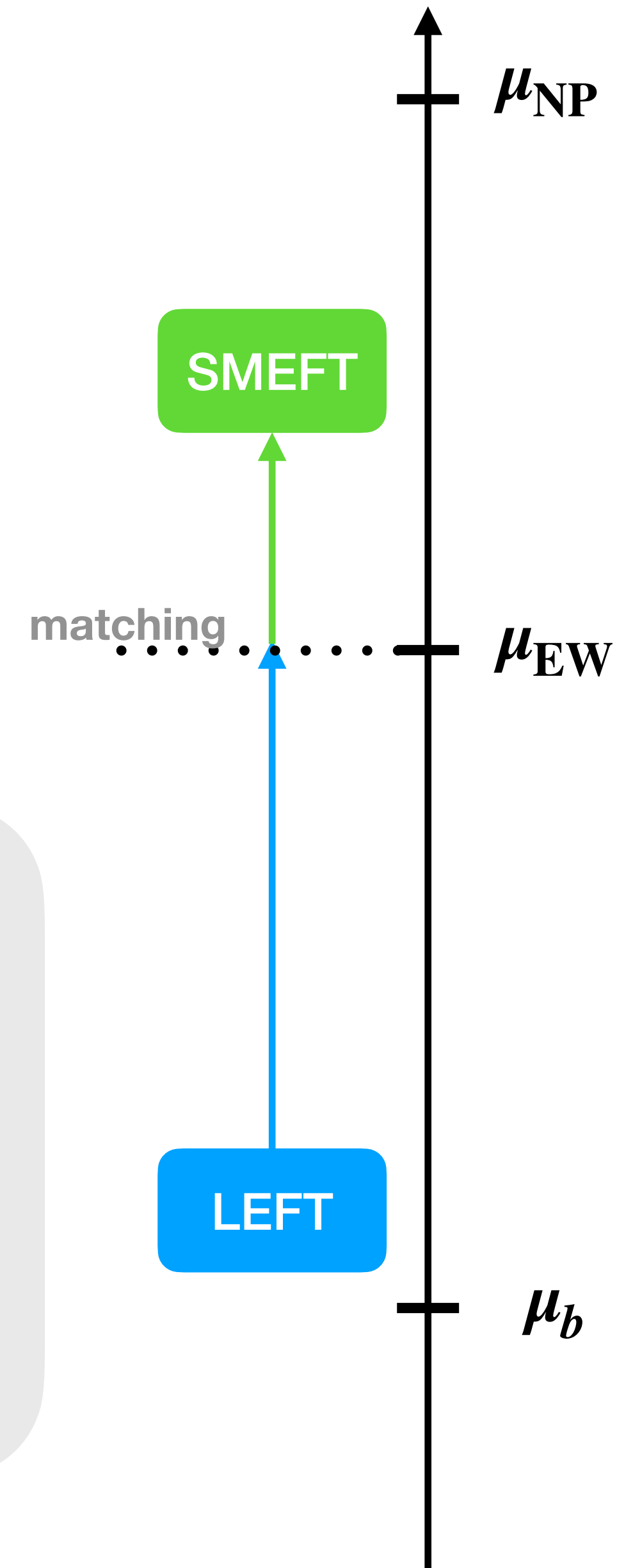
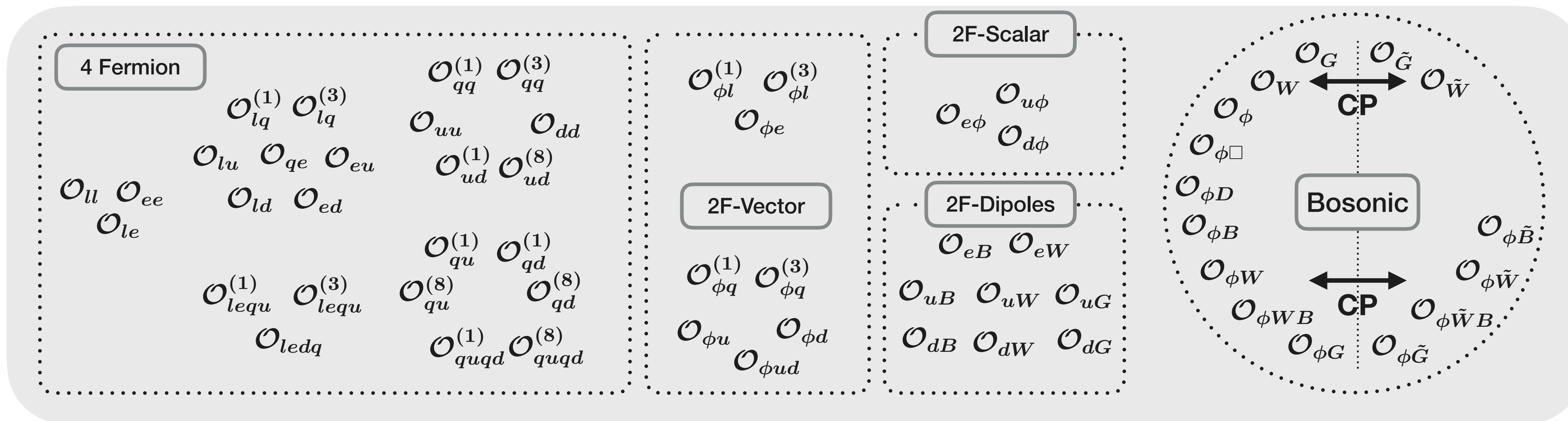
► SMEFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \sum_i \mathcal{C}_i^{(d)} \mathcal{O}_i^{(d)}$$

Buchmuller, Wyler NPB 1986

Grzadkowski, Iskrzynski, Misiak, Rosiek, JHEP 2010

- ▶ **New Physics scale $\Lambda \gg \mu_{EW}$ is assumed**
- ▶ **At dim=6: 59 operators (without flavour)**



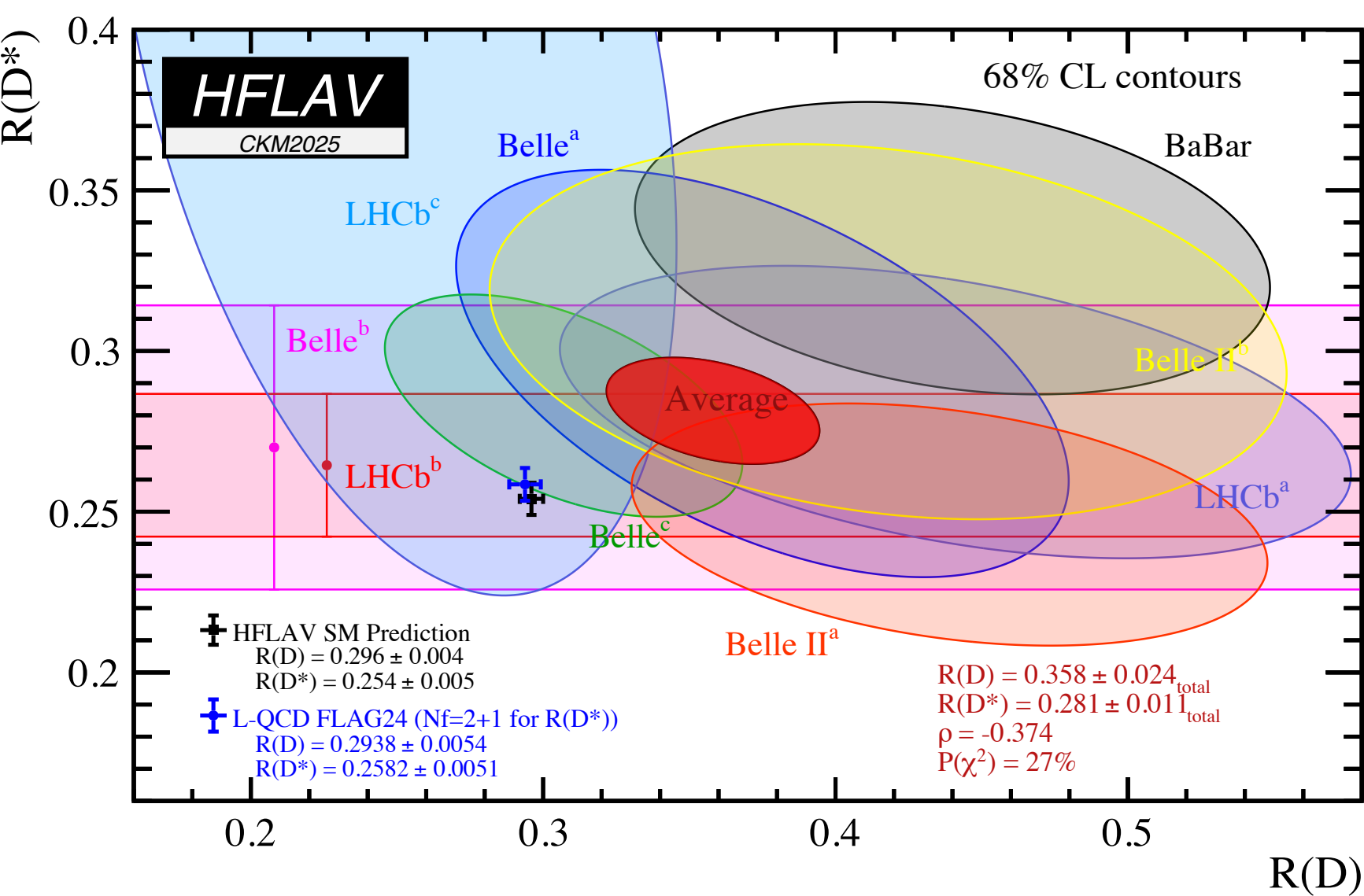
- **Largely model-independent parameterization of NP**

Standard Model Effective Field Theory

General Feature

- ▶ NP effects in neutral and charged currents could be correlated
- ▶ NP effects in different scales (e.g., flavour and collider) could be correlated

Example: semi-leptonic operator

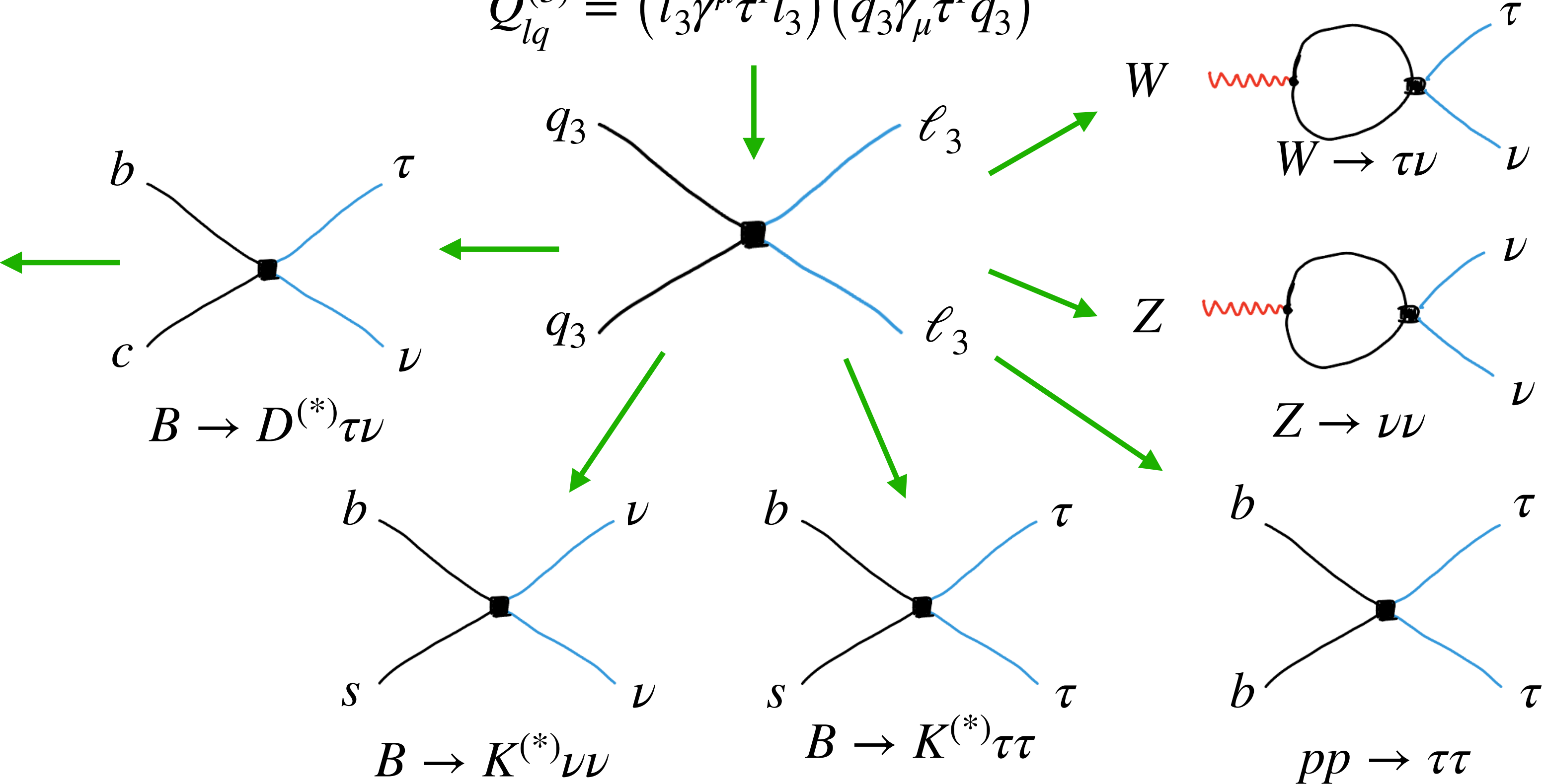


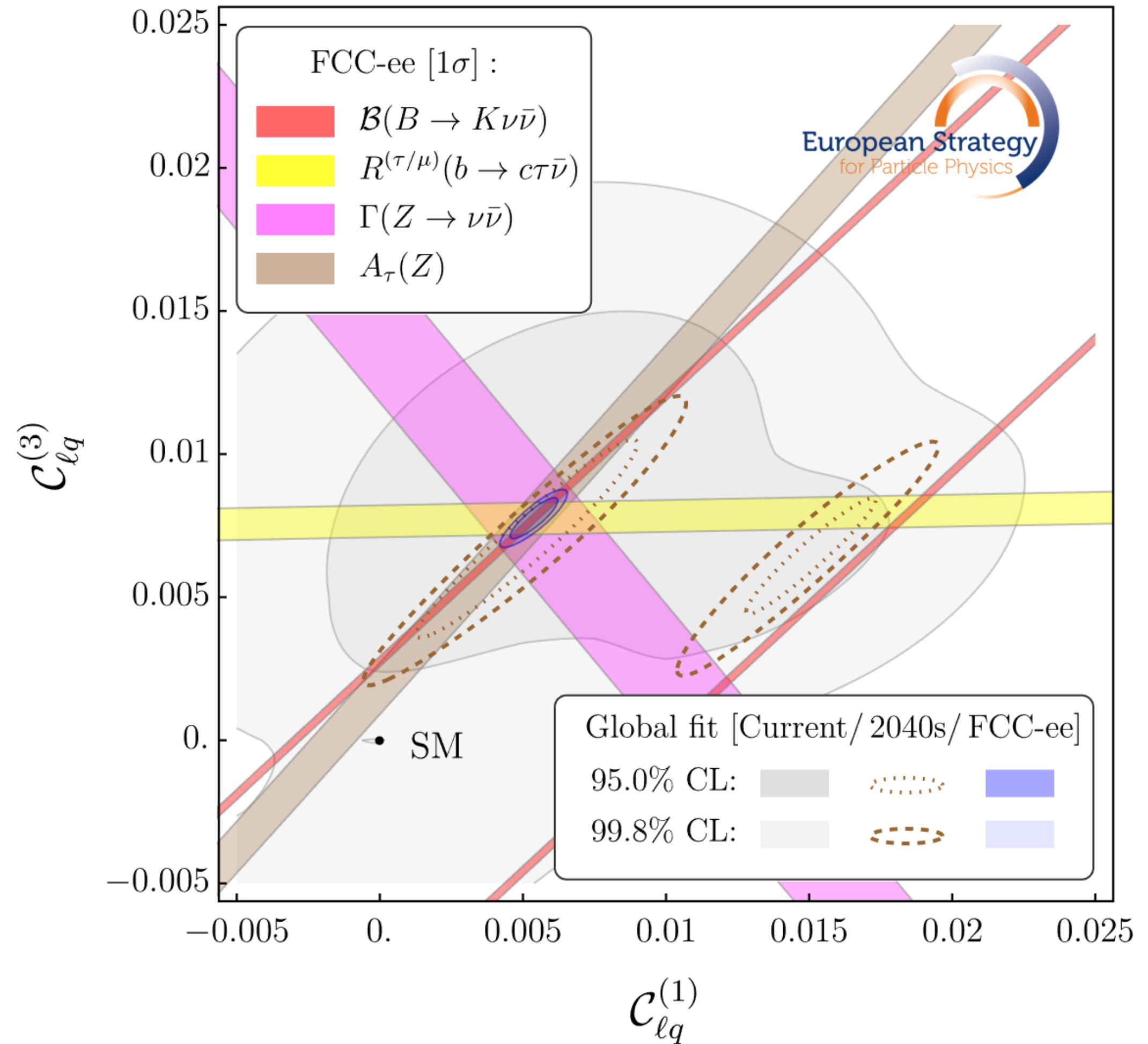
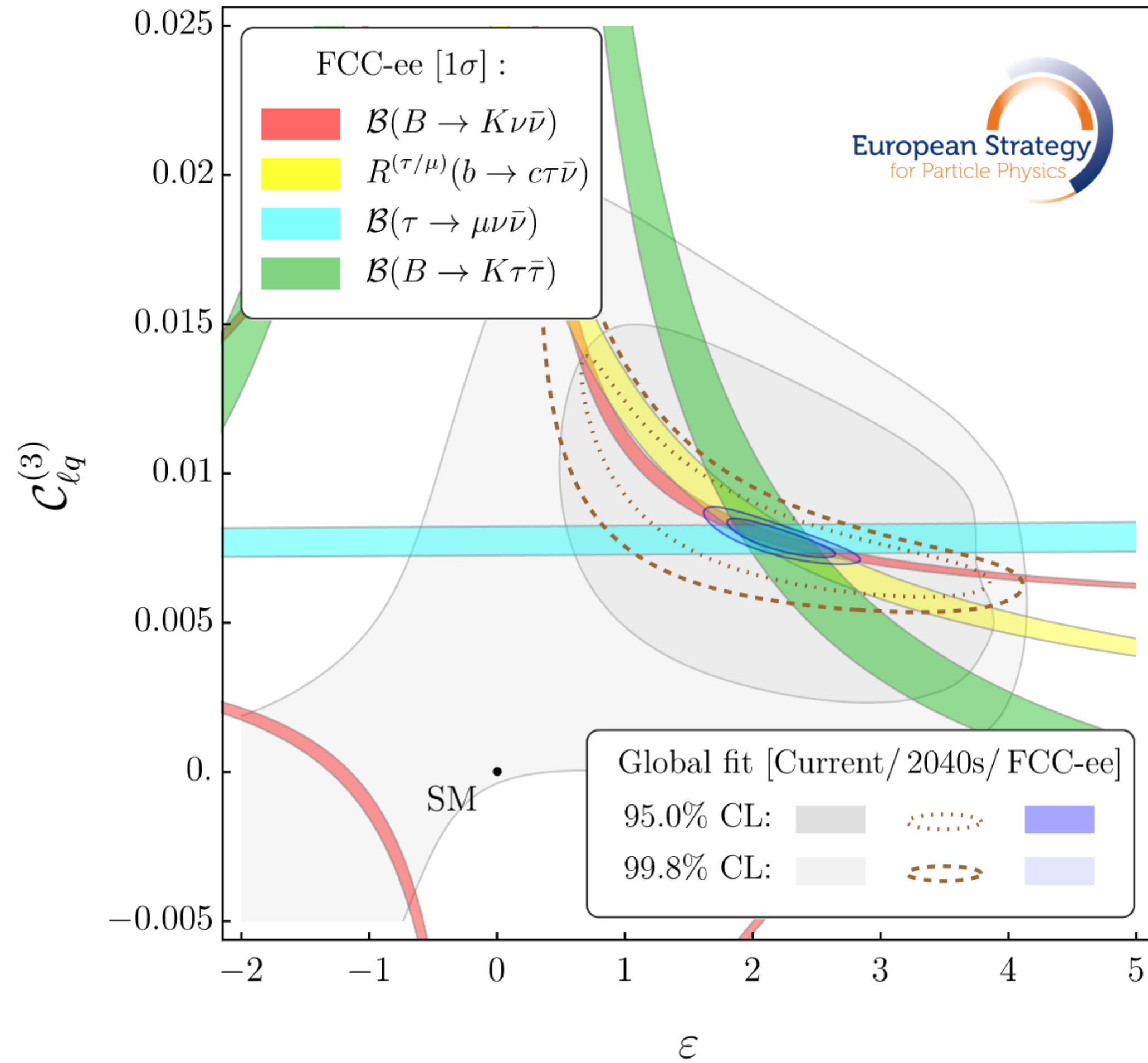
$$q_3 = b_L + \varepsilon V_{ts} s_L$$

$$Q_{lq}^{(1)} = (\bar{l}_3 \gamma^\mu l_3) (\bar{q}_3 \gamma_\mu q_3)$$

$$Q_{lq}^{(3)} = (\bar{l}_3 \gamma^\mu \tau^I l_3) (\bar{q}_3 \gamma_\mu \tau^I q_3)$$

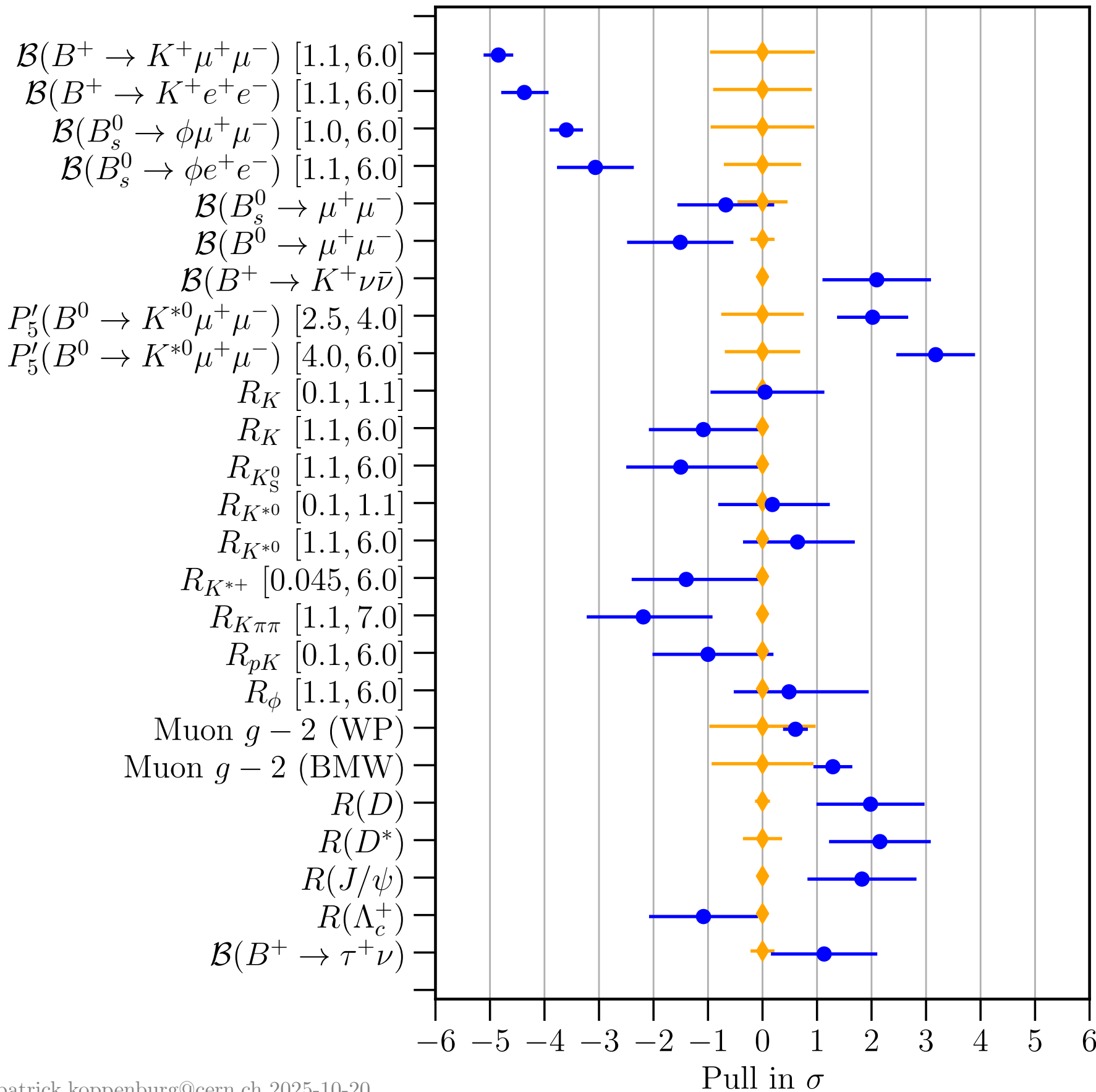
CERN-ESU-2025-001 (Input for ESPP 2026)



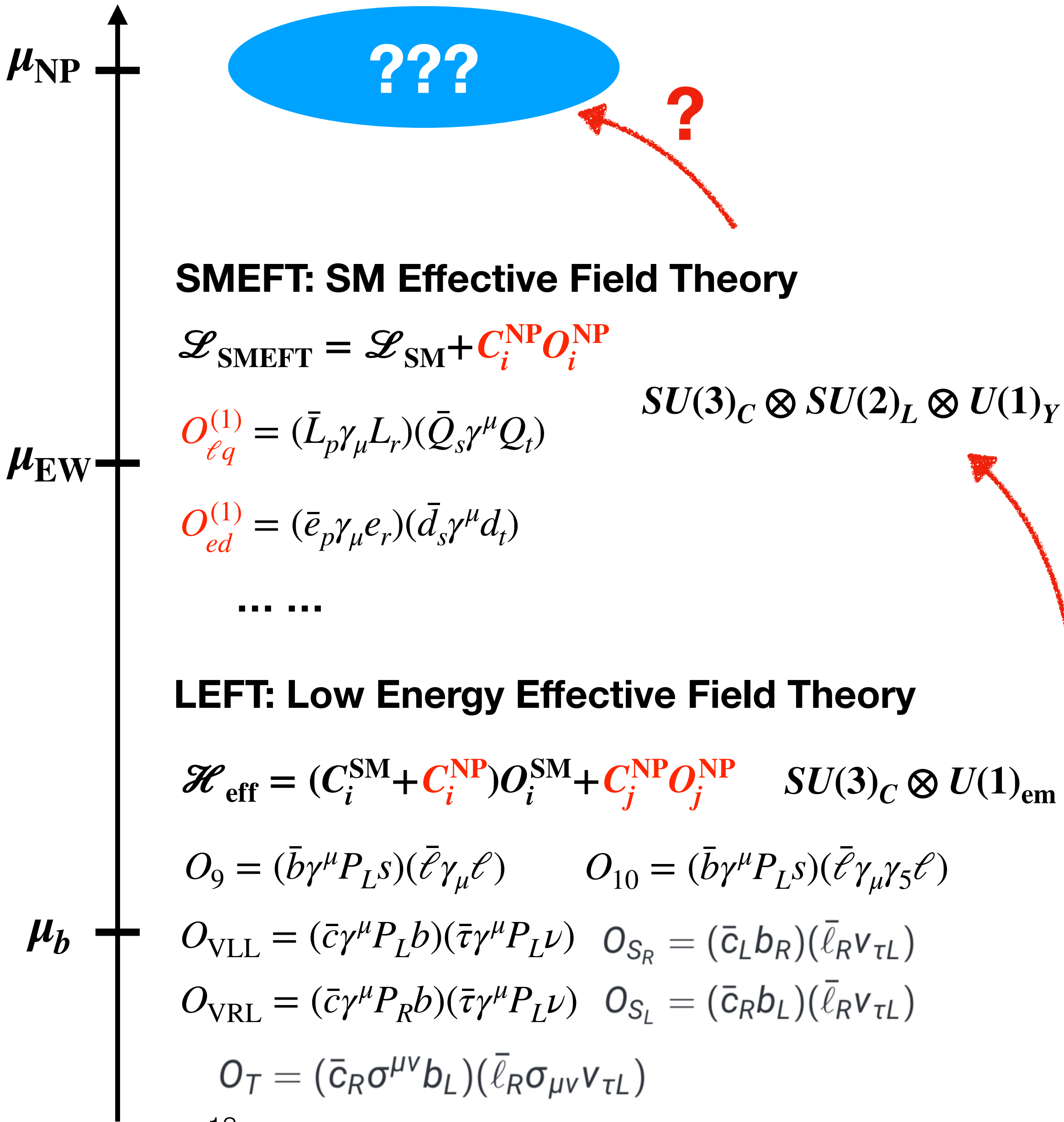


Flavour anomalies: New Physics interpretation

Status of Flavour Anomaly



patrick.koppenburg@cern.ch 2025-10-20

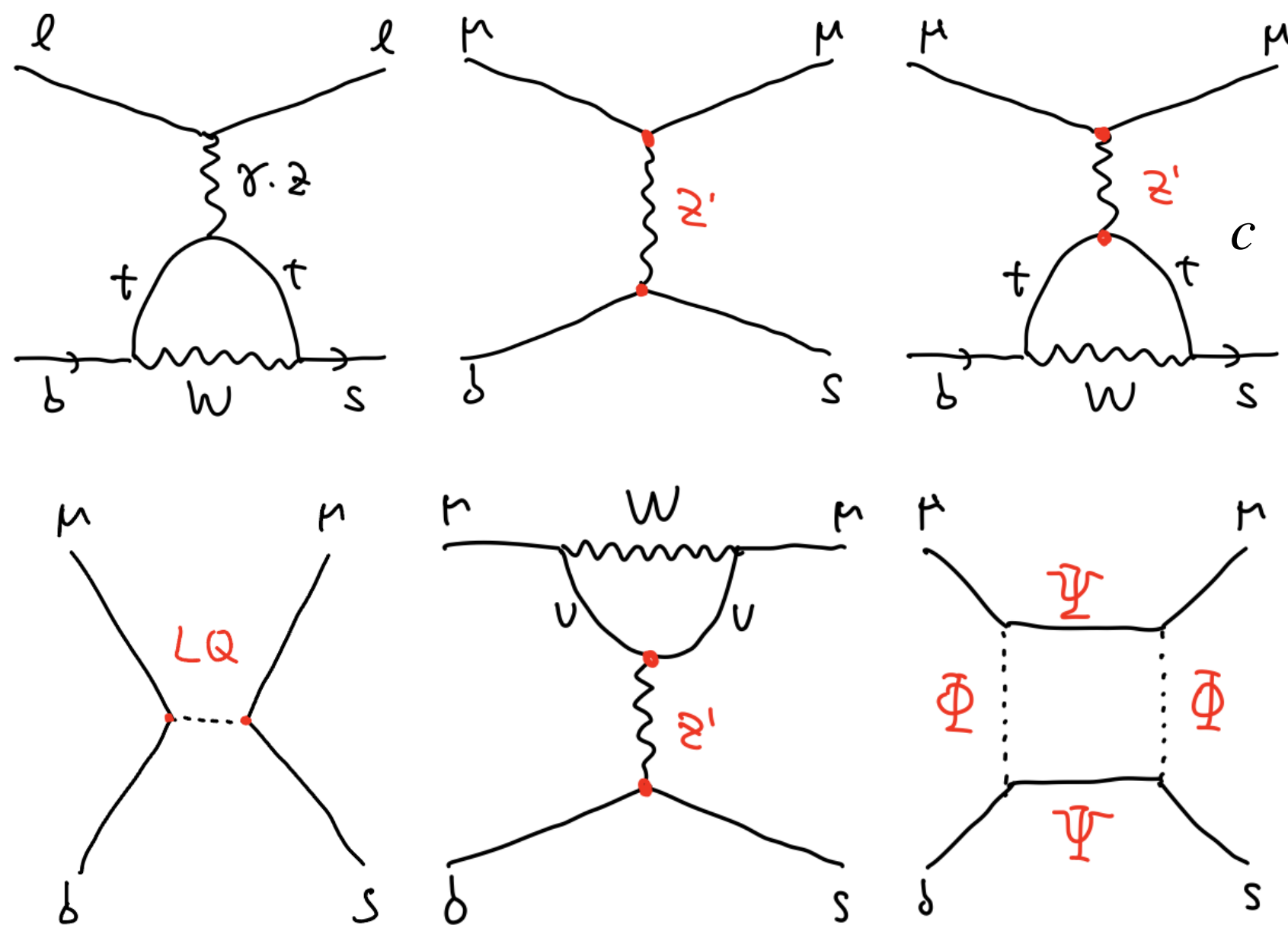


Flavour anomalies: New Physics interpretation

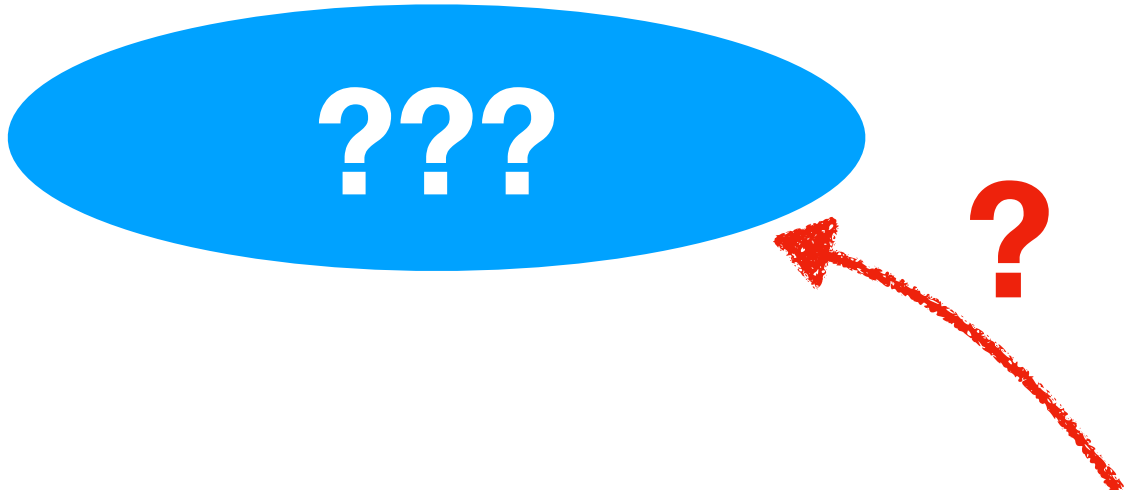
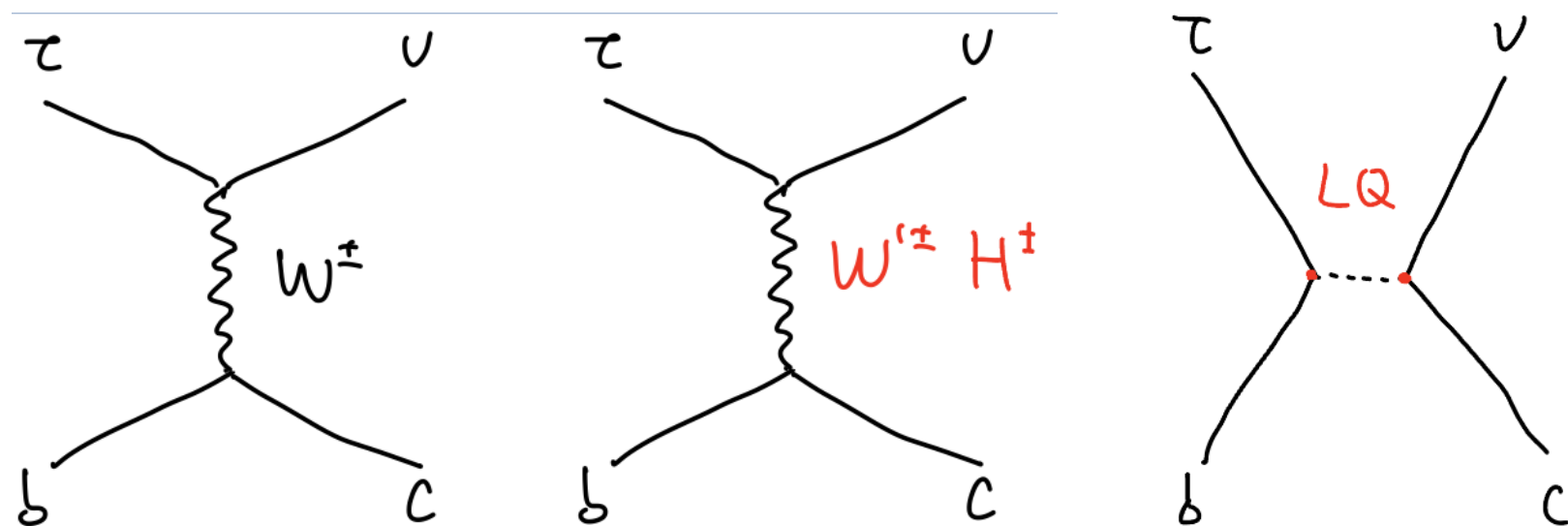
Ying Li, Cai-Dian Lu, 1808.02990

$b \rightarrow s \ell^+ \ell^-$ anomalies

X.Q.Li, Y.D.Yang, **XY**, et al, 2112.14215, 2205.02205, 2307.05290



$b \rightarrow c \tau \nu$ anomalies



SMEFT: SM Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + C_i^{\text{NP}} O_i^{\text{NP}}$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$$O_{\ell q}^{(1)} = (\bar{L}_p \gamma_\mu L_r)(\bar{Q}_s \gamma^\mu Q_t)$$

$$O_{ed}^{(1)} = (\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$$

... ..

LEFT: Low Energy Effective Field Theory

$$\mathcal{H}_{\text{eff}} = (C_i^{\text{SM}} + C_i^{\text{NP}}) O_i^{\text{SM}} + C_j^{\text{NP}} O_j^{\text{NP}} \quad SU(3)_C \otimes U(1)_{\text{em}}$$

$$O_9 = (\bar{b} \gamma^\mu P_L s)(\bar{\ell} \gamma_\mu \ell) \quad O_{10} = (\bar{b} \gamma^\mu P_L s)(\bar{\ell} \gamma_\mu \gamma_5 \ell)$$

$$O_{\text{VLL}} = (\bar{c} \gamma^\mu P_L b)(\bar{\tau} \gamma^\mu P_L \nu) \quad O_{\text{SR}} = (\bar{c}_L b_R)(\bar{\ell}_R \nu_{\text{TL}})$$

$$O_{\text{VRL}} = (\bar{c} \gamma^\mu P_R b)(\bar{\tau} \gamma^\mu P_L \nu) \quad O_{\text{SL}} = (\bar{c}_R b_L)(\bar{\ell}_R \nu_{\text{TL}})$$

$$O_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu_{\text{TL}})$$

Standard Model Effective Field Theory

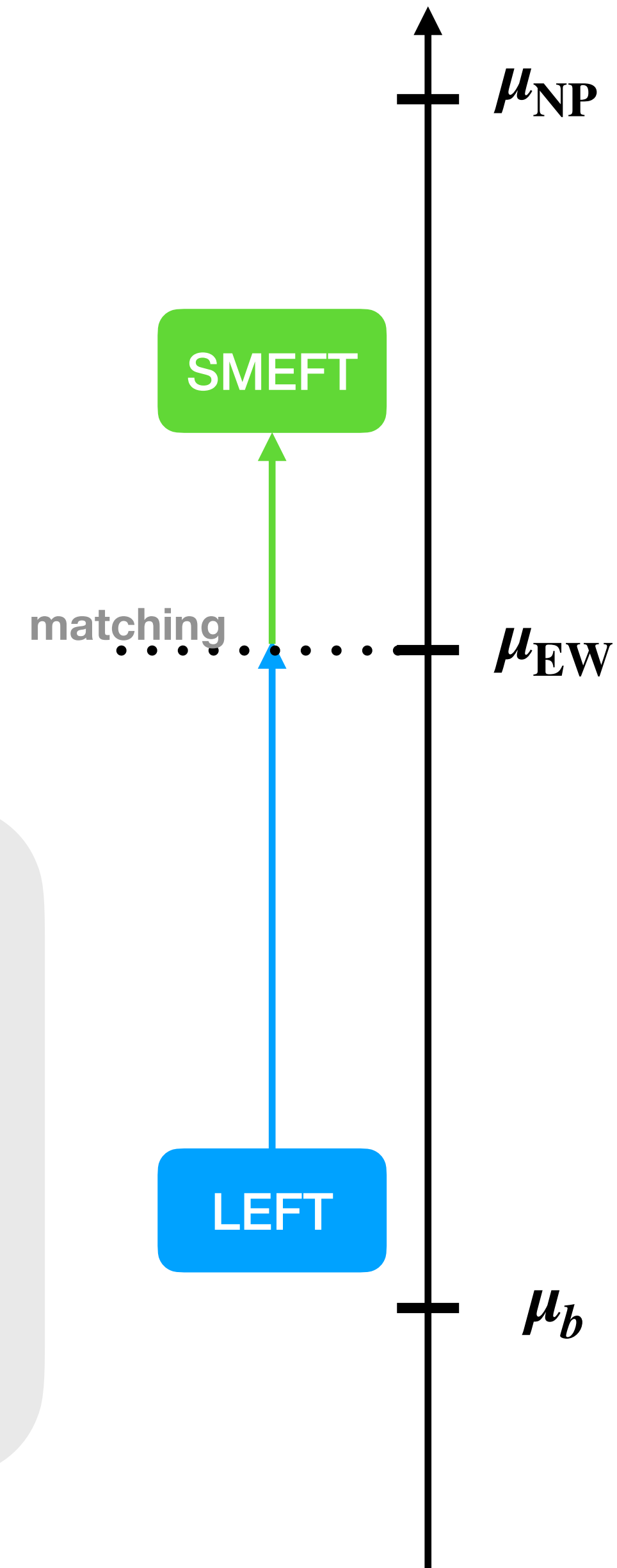
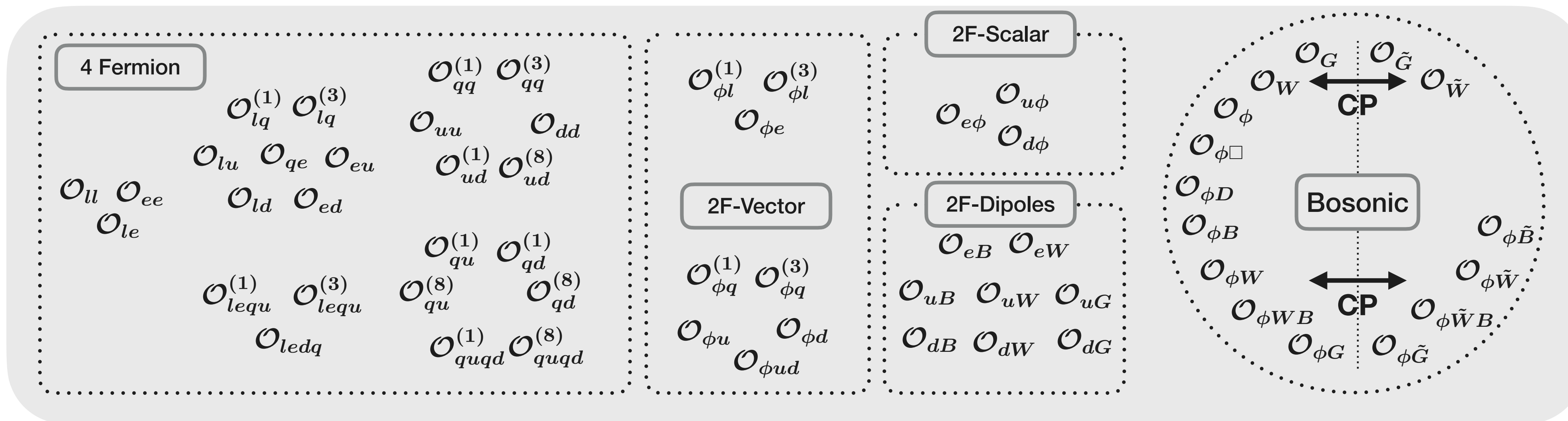
► SMEFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \sum_i \mathcal{C}_i^{(d)} \mathcal{O}_i^{(d)}$$

Buchmuller, Wyler NPB 1986

Grzadkowski, Iskrzynski, Misiak, Rosiek, JHEP 2010

- ▶ **New Physics scale $\Lambda \gg \mu_{EW}$ is assumed**
- ▶ **At dim=6: 59 $\implies$ 2499 operator after considering flavour**

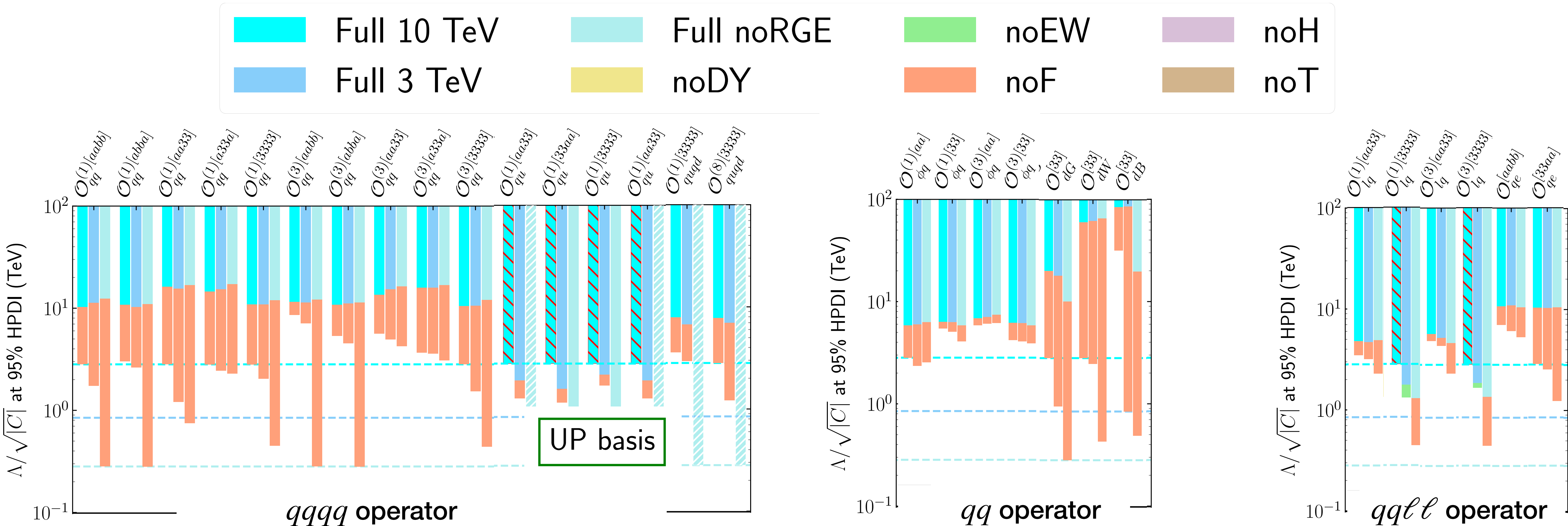


- **Largely model-independent parameterization of NP**

Standard Model Effective Field Theory

SMEFT global fit of EW, Drell-Yan, Higgs, top, and flavour observables

de Blas, Goncalves, Miralles, Reina, Silvestrini, Valli, 2507.06191



► Flavour structures $U(2)^5$ and $U(3)^5$ are assumed.

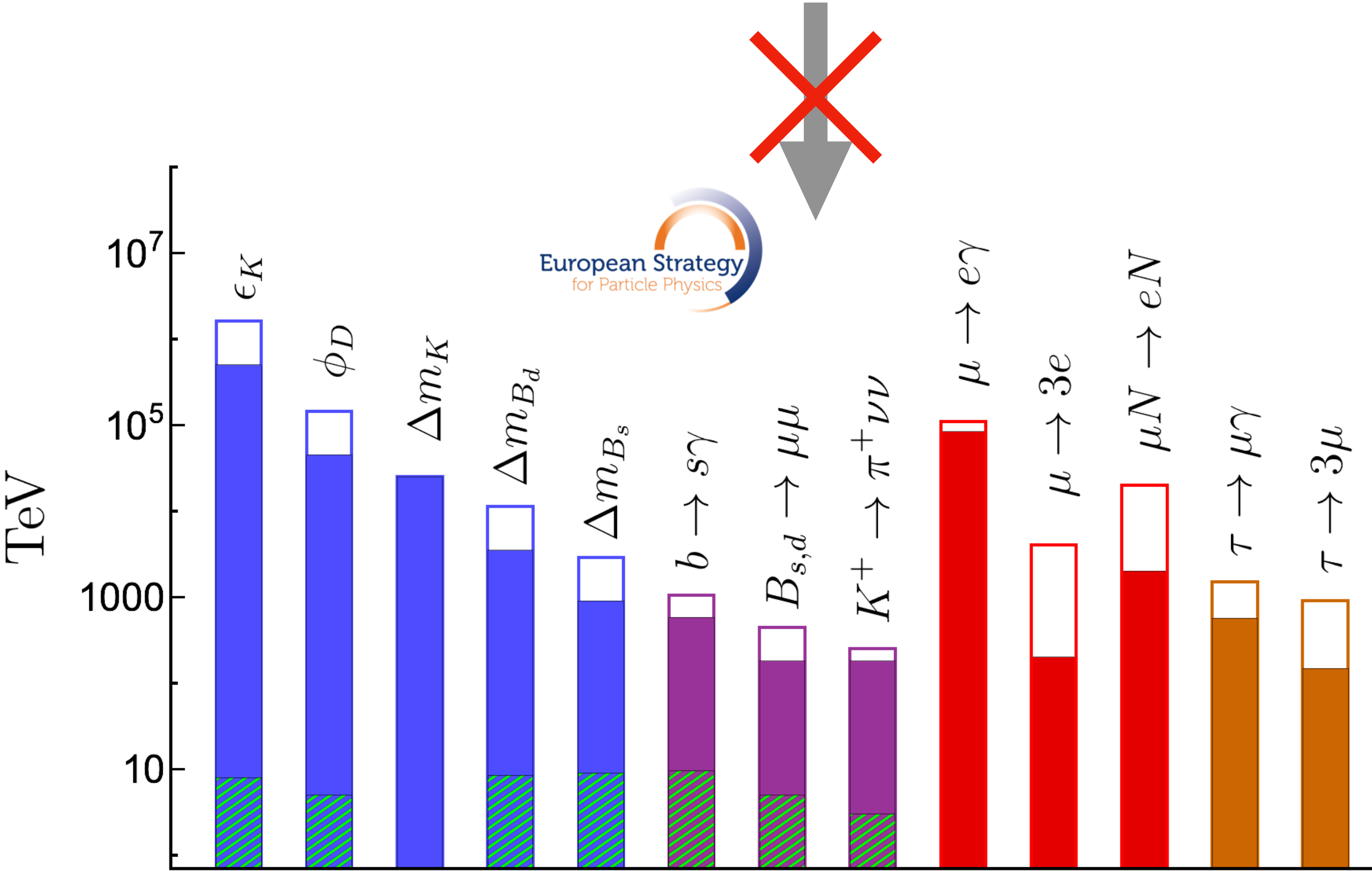
flavour observables correlated
B.F. Hou, X.Q.Li, M.Shen, Y.D.Yang, **XBY**, JHEP 2024
W.F.Duan, S. Iguro, X.Q.Li, R. Watanabe, Y.D.Yang, JHEP 2025

NP Flavour Puzzle

Higgs hierarchy problem $\implies$ NP scale Λ should be few TeV

UV theory is natural $\implies C_{ij} = \mathcal{O}(1)$

NP Flavour
Puzzle



Bounds on the scale Λ from various processes,
by assuming unit couplings for Wilson coefficients

$$\frac{C_{ij}}{\Lambda^2} = \frac{1}{\Lambda^2}$$

NP Flavour Puzzle

Higgs hierarchy problem $\implies$ NP scale Λ should be few TeV

UV theory is natural $\implies C_{ij} = \mathcal{O}(1)$

NP Flavour
Puzzle

Solution 1: $C_{ij} = \mathcal{O}(1)$, but NP scale is very high.

😓 induce large fine-tuning in Higgs mass

😓 How to understand the hierarchy of the SM fermion masses.

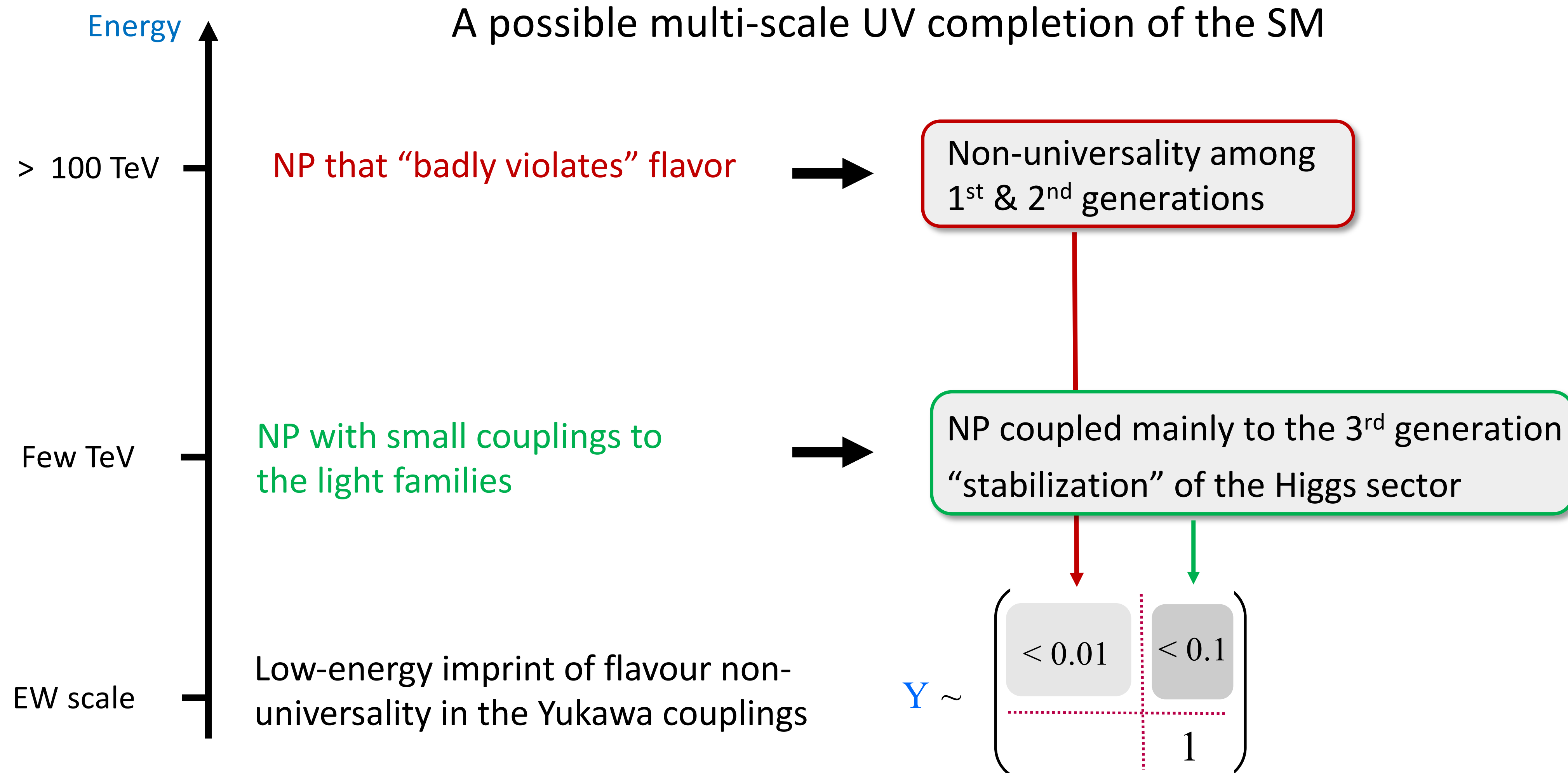
Solution 2: NP@TeV, but flavour structure is highly non-trivial

example: NP mainly couples to 3rd generation

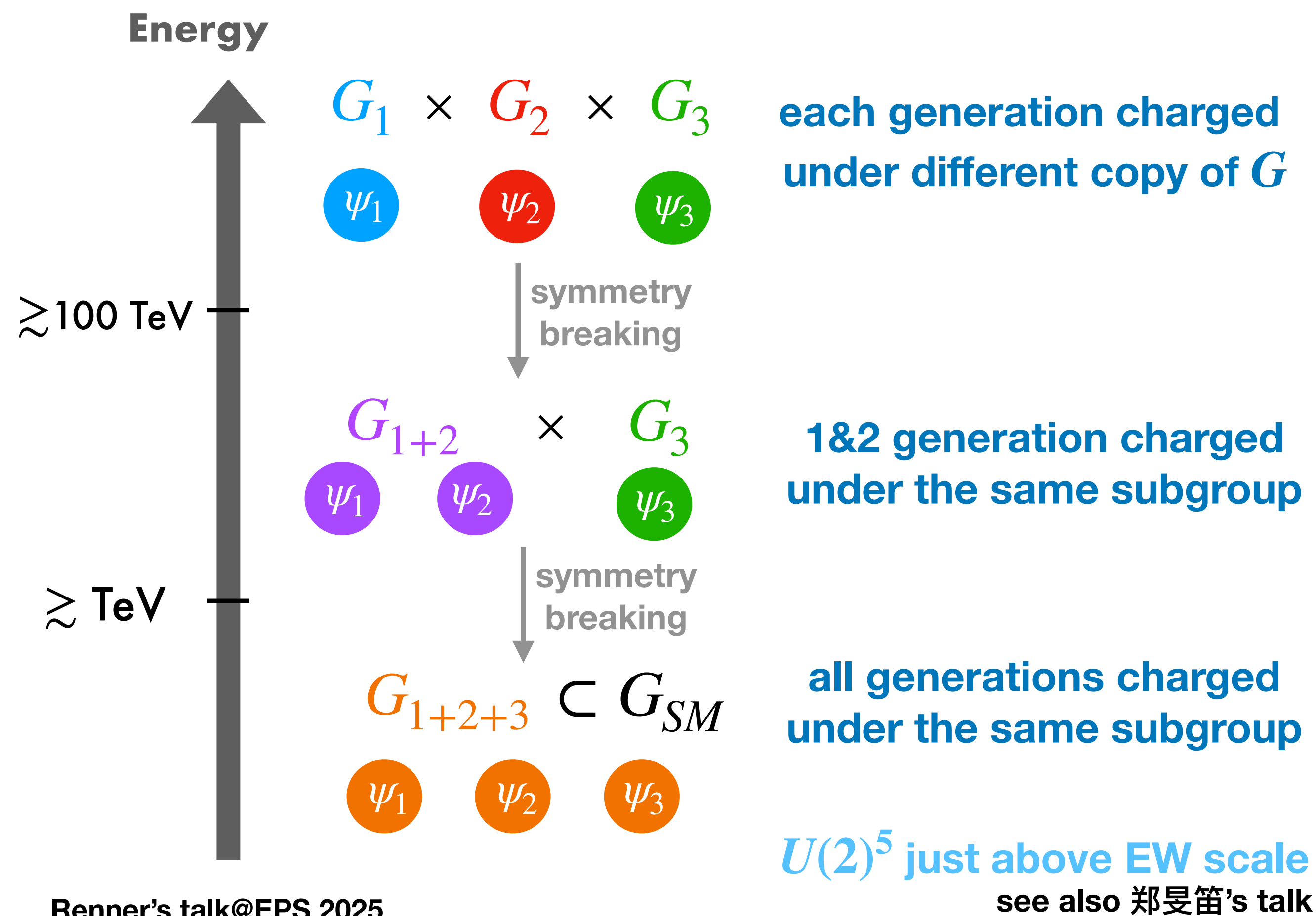
😊 Higgs is still natural

😊 NP could be found at the LHC, possibly answer the SM fermion mass hierarchy

A Possible UV Picture from EFT Analysis



Flavour Deconstruction



Gauge Model of Generation Nonuniversality

Xiao-yuan Li^(a) and Ernest Ma

Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822

(Received 13 October 1981)

An electroweak gauge model is discussed, where generations are associated with separate gauge groups with different couplings. The observed μ - e universality is the result of a mass-scale inequality, $\nu_{03} \ll \nu_{12}$, in much the same way as strong isospin is the result of $m_u, m_d \ll 1 \text{ GeV}$. However, in contrast to the standard model, it is now possible to have (1) a longer τ lifetime, (2) an observable B^0 - $\bar{B}^0$ mixing, and (3) many gauge bosons W_i, Z_i in place of W, Z with $M_{W_i} > M_W$ and $M_{Z_i} > M_Z$.

Arkani-Hamed, Cohen, Georgi, hep-th/0104005

Craig, Green, Katz, 1103.3708

Covone, Davighi, Isidori, Pesut/2407.10950

Fuentes-Martín, Lizana/2402.09507

Davighi, Gosnay, Miller, Renner/2312.13346

Barbieri, Isidori/2312.14004

Isidori/2308.11612

Navarro, King/2305.07690

Davighi, Stefanek/2305.16280

Davighi, Isidori/2303.01520

active research field

- ▶ Flavour non-universal interactions already at the TeV scale.
- ▶ NP flavour problem and Higgs hierarchy problem is connected.

Theoretically cleanest processes in heavy flavour physics

$B_{s,d} - \bar{B}_{s,d}$ mixing

$b \rightarrow u(c)\ell\bar{\nu}$: $B \rightarrow D\ell\bar{\nu}$, $B \rightarrow D^*\ell\bar{\nu}$,

$b \rightarrow s(d)\gamma$: $B \rightarrow X_s\gamma$, $B \rightarrow K^*\gamma$,

$b \rightarrow s(d)\ell^+\ell^-$: $B_s \rightarrow \ell^+\ell^-$, $B \rightarrow K^*\ell^+\ell^-$,

$b \rightarrow s(d)\nu\bar{\nu}$: $B \rightarrow K\nu\bar{\nu}$, $K \rightarrow \pi\nu\bar{\nu}$, ...

NP Effects $< \mathcal{O}(20\%)$

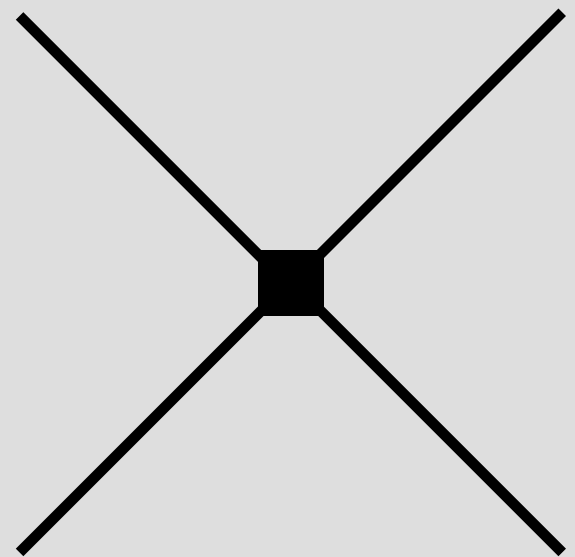
Signal: $B \rightarrow K + \text{inv}$ NOT measured yet !

$B \rightarrow K + \nu + \bar{\nu}$
 $B \rightarrow K + \text{DM} + \text{DM}$

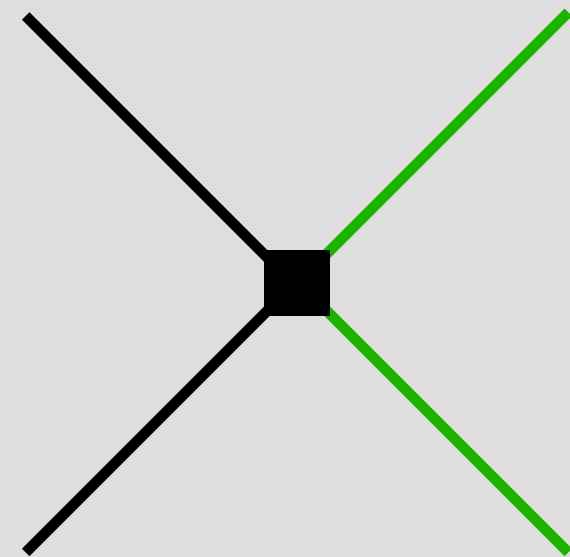
Outline

EFT Perspective

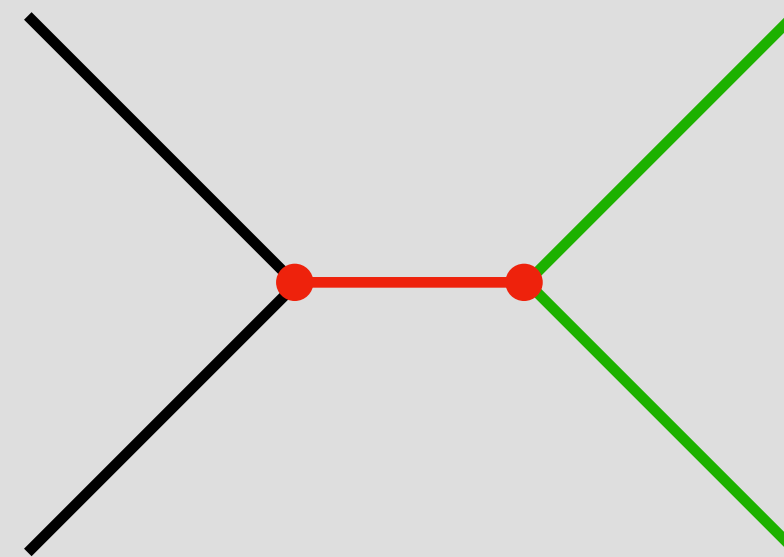
Conventional EFT



EFT with New d.o.f



Beyond EFT

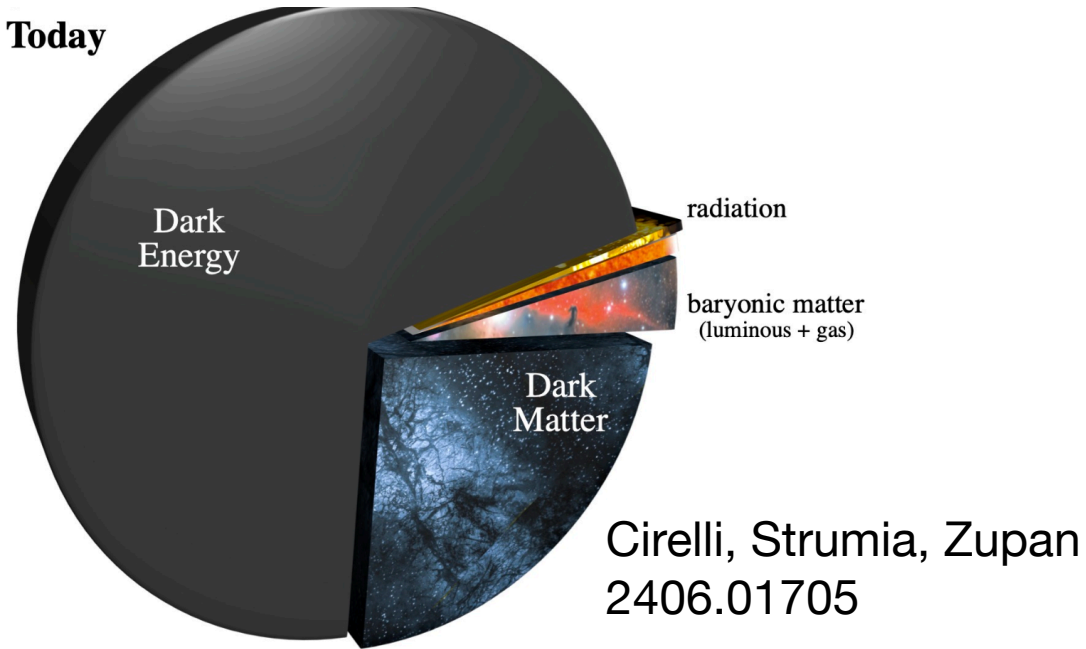


AI Perspective



Light DM: a bottom-up view

DM is electrically neutral ! $\implies$ DM only have FC or FCNC couplings to fermions !

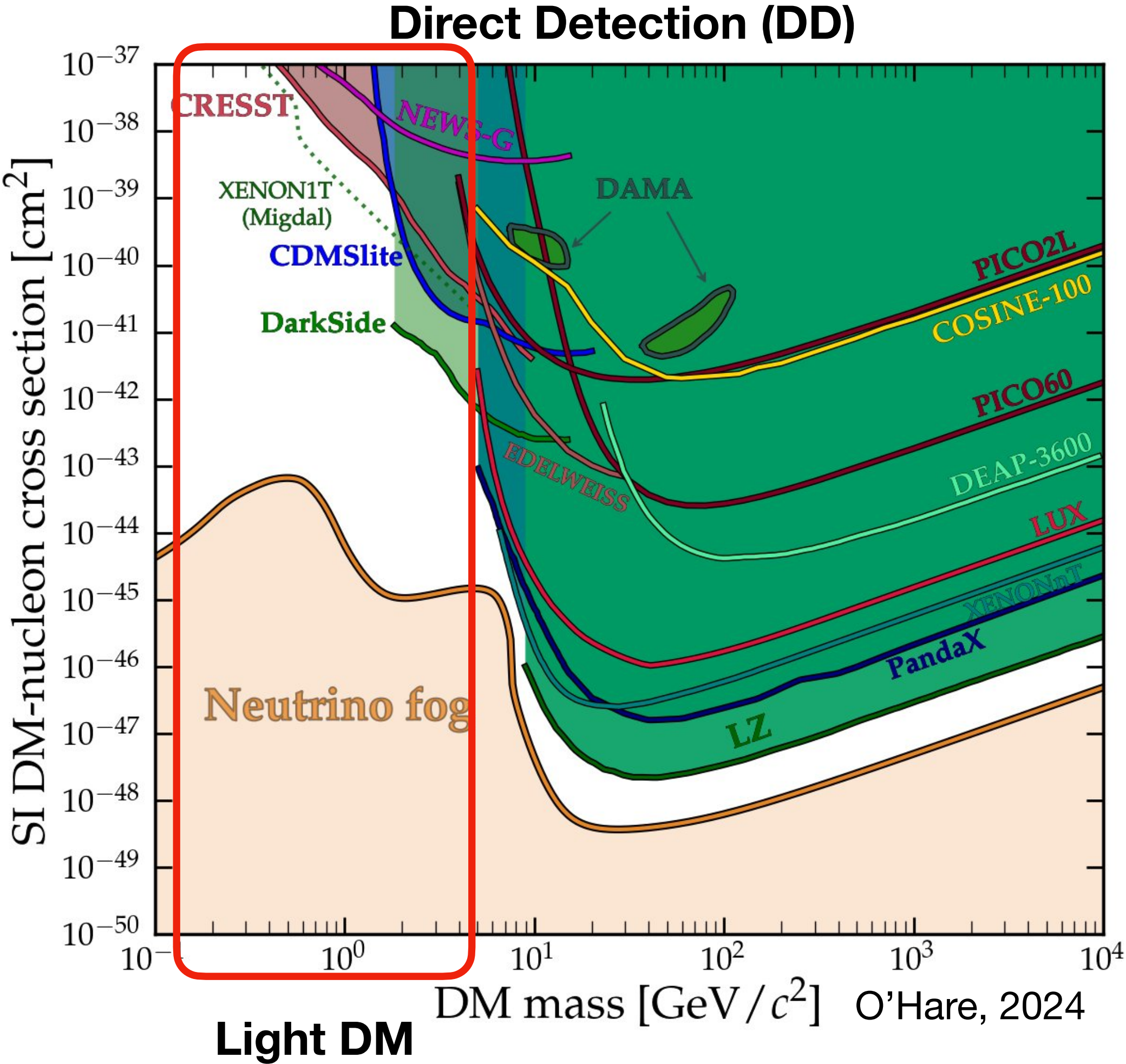


	<i>d</i>	<i>s</i>	<i>b</i>
<i>d</i>	DD	NA62/KOTO	Belle II
<i>s</i>		DD	Belle II
<i>b</i>			Belle II/LHC
	<i>u</i>	<i>c</i>	<i>t</i>
<i>u</i>	DD	BES/STCF	LHC/CEPC
<i>c</i>		BES/STCF	LHC/CEPC
<i>t</i>			LHC/CEPC

example:
 $B^+ \rightarrow K^+ + \text{DM} + \text{DM}$
 $K^+ \rightarrow \pi^+ + \text{DM} + \text{DM}$
 $D^0 \rightarrow \pi^0 + \text{DM} + \text{DM}$

DD = Direct Detection

 means related to the DM relic density



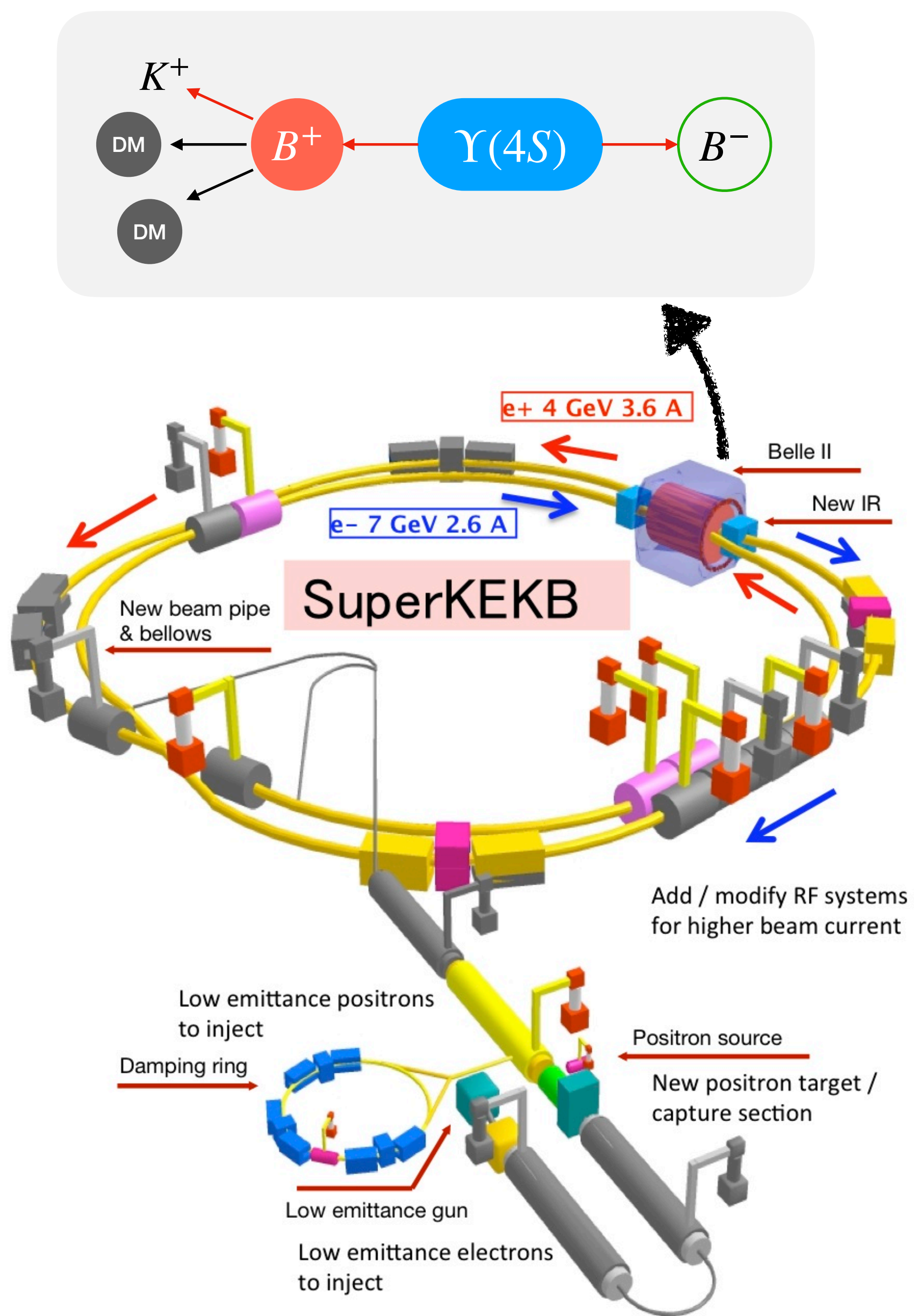
Experimental Search

	Observable	SM	Exp	Unit
$b \rightarrow s$	$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}
	$\mathcal{B}(B^0 \rightarrow K^0 \nu \bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
	$\mathcal{B}(B^+ \rightarrow K^{*+} \nu \bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
	$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})$	9.00 ± 0.87	< 18	10^{-6}
	$\mathcal{B}(B_s \rightarrow \phi \nu \bar{\nu})$	9.93 ± 0.72	< 5400	10^{-6}
	$\mathcal{B}(B_s \rightarrow \nu \bar{\nu})$	≈ 0	< 5.9	10^{-4}
$b \rightarrow d$	$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})$	1.40 ± 0.18	< 140	10^{-7}
	$\mathcal{B}(B^0 \rightarrow \pi^0 \nu \bar{\nu})$	6.52 ± 0.85	< 900	10^{-8}
	$\mathcal{B}(B^+ \rightarrow \rho^+ \nu \bar{\nu})$	4.06 ± 0.79	< 300	10^{-7}
	$\mathcal{B}(B^0 \rightarrow \rho^0 \nu \bar{\nu})$	1.89 ± 0.36	< 400	10^{-7}
	$\mathcal{B}(B^0 \rightarrow \nu \bar{\nu})$	≈ 0	< 1.4	10^{-4}
$s \rightarrow d$	$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	8.42 ± 0.61	$10.6^{+4.0}_{-3.4} \pm 0.9$	10^{-11}
	$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}
$c \rightarrow u$	$D^+ \rightarrow \pi^+ + \text{inv}, D^0 \rightarrow \rho^0 + \text{inv}, \dots$			

Belle II
CEPC

NA62
KOTO

BESIII
STCF



Experimental Search

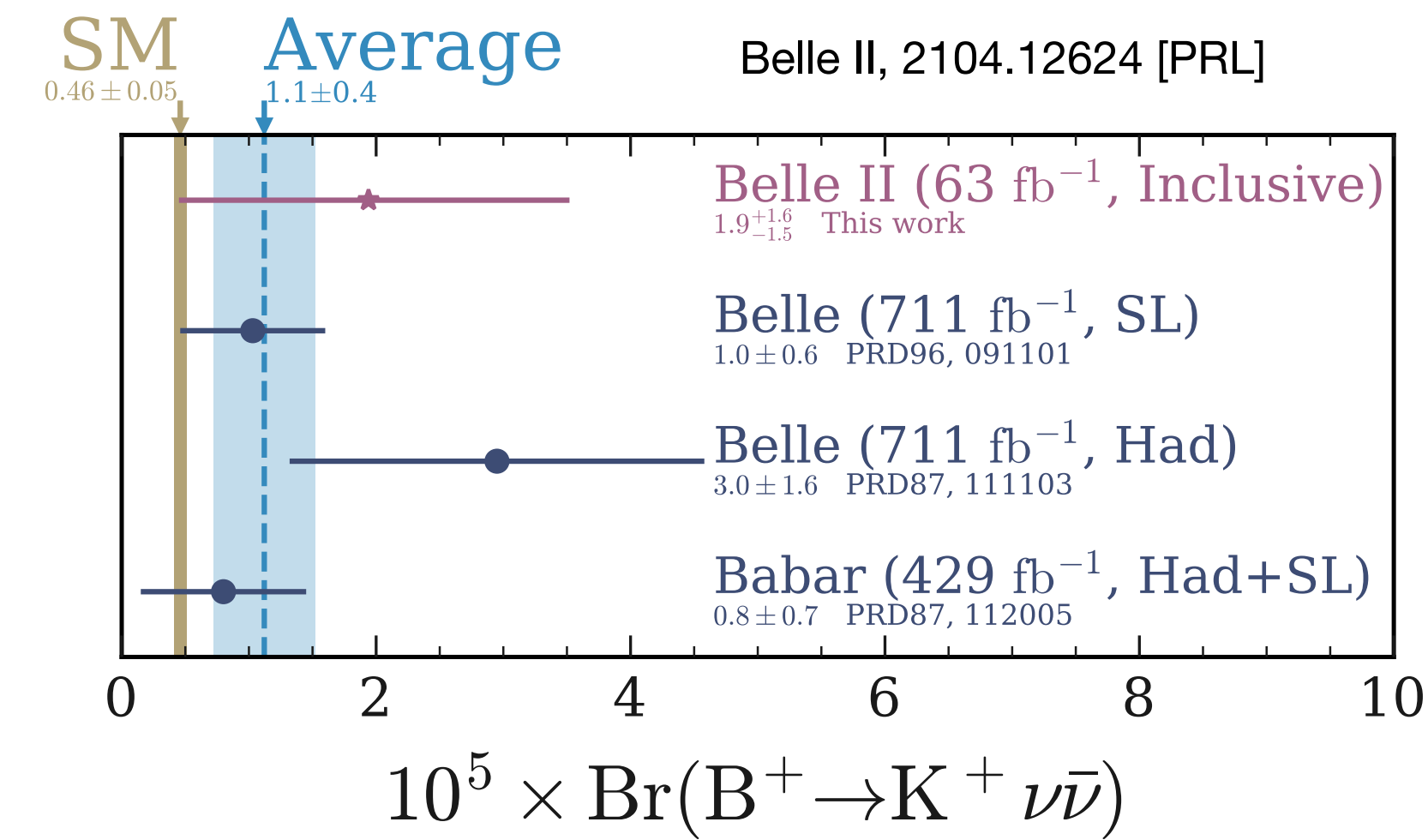
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	$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}
$c \rightarrow u$ $D^+ \rightarrow \pi^+ + \text{inv}, D^0 \rightarrow \rho^0 + \text{inv}, \dots$				

Belle II
CEPC

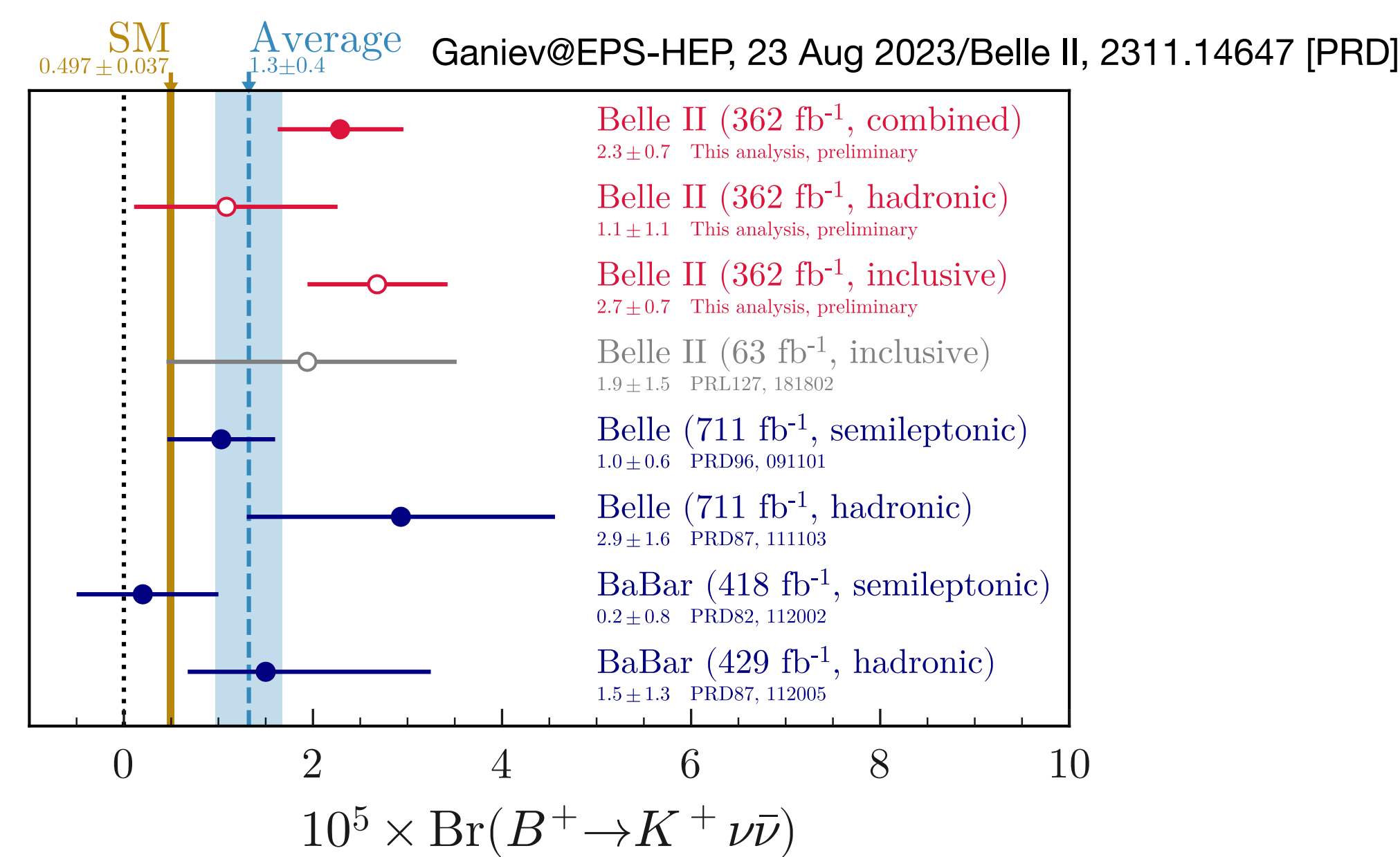
NA62
KOTO

BESIII
STCF

► 2021 Apr

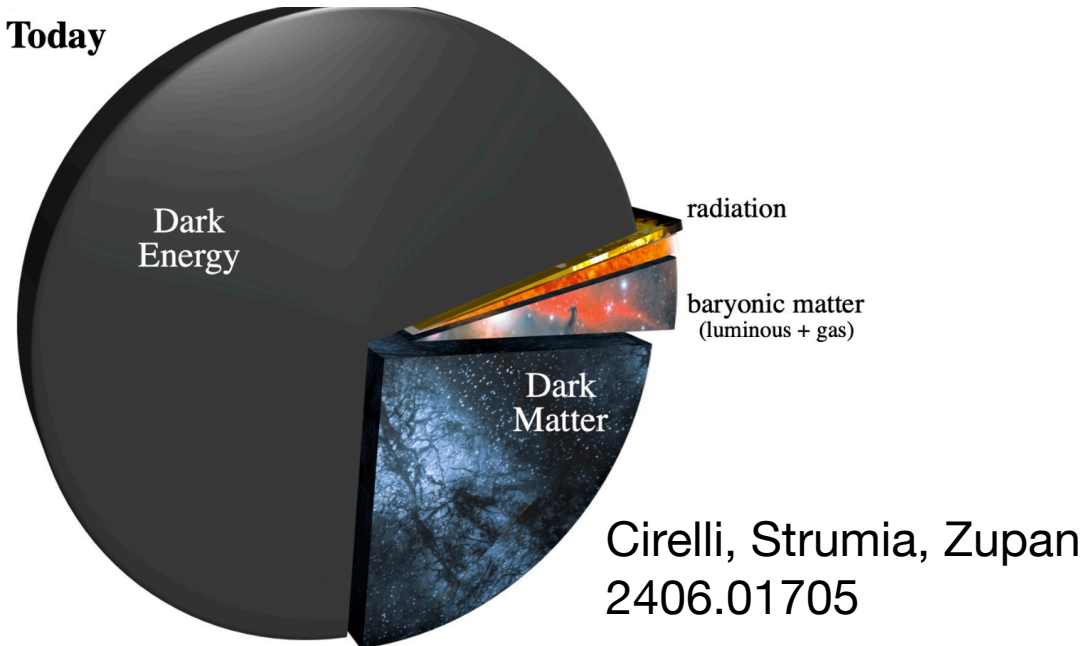


► 2023 Aug: first evidence



Light DM: a bottom-up view

DM is electrically neutral ! $\implies$ DM only have FC or FCNC couplings to fermions !



	<i>d</i>	<i>s</i>	<i>b</i>
<i>d</i>	DD	NA62/KOTO	Belle II
<i>s</i>		DD	Belle II
<i>b</i>			Belle II/LHC
	<i>u</i>	<i>c</i>	<i>t</i>
<i>u</i>	DD	BES/STCF	LHC/CEPC
<i>c</i>		BES/STCF	LHC/CEPC
<i>t</i>			LHC/CEPC

example:

$B^+ \rightarrow K^+ + \text{DM} + \text{DM}$

$K^+ \rightarrow \pi^+ + \text{DM} + \text{DM}$

$D^0 \rightarrow \pi^0 + \text{DM} + \text{DM}$

future exp uncertainties:

$\mathcal{O}(20 \sim 40\%)$ @Belle II with 5ab⁻¹

$\mathcal{O}(2\%)$ @CEPC Tera-Z

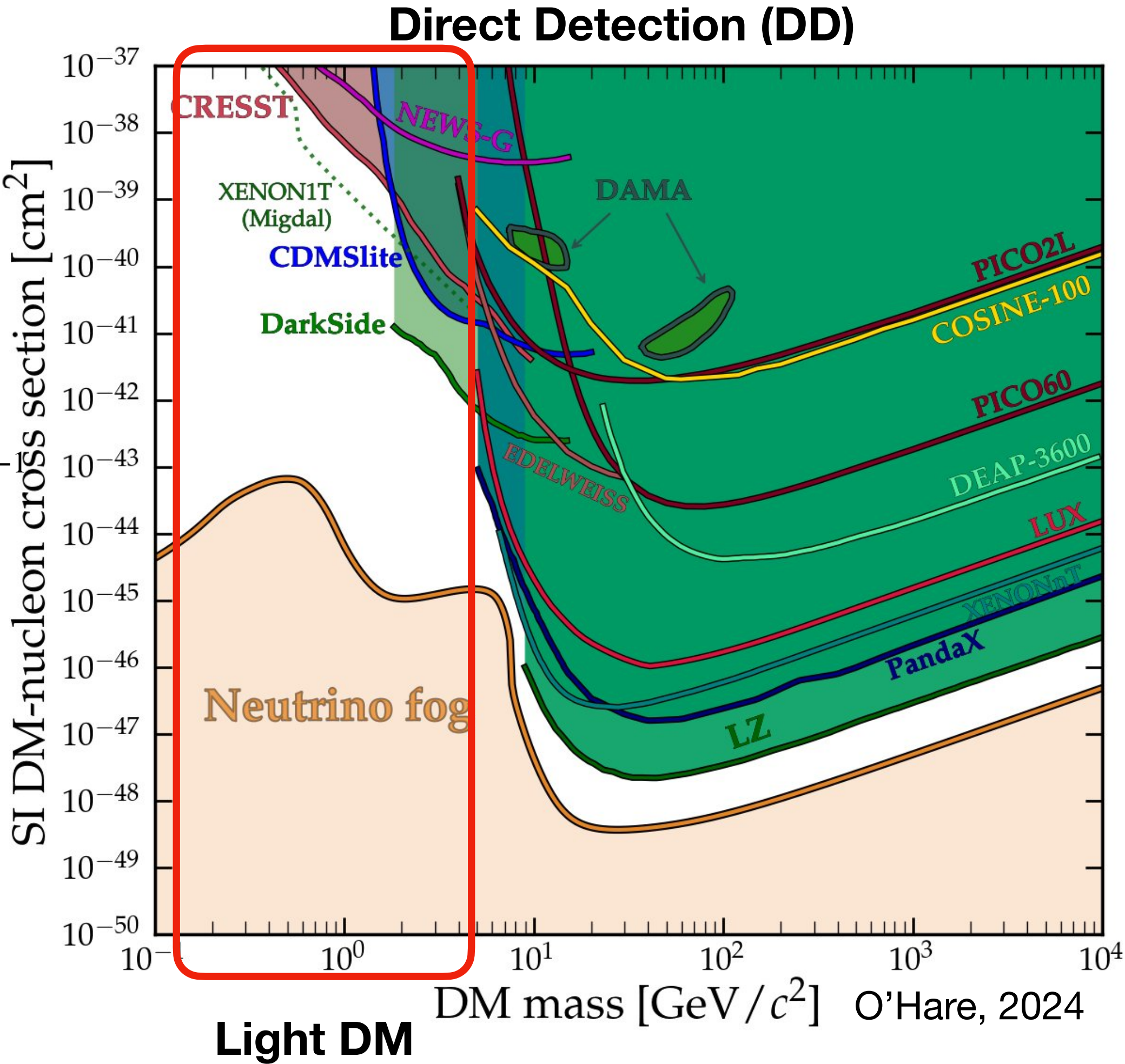
CEPC Flavour WP

future theo uncertainties:

less than 10 %

DD = Direct Detection

 means related to the DM relic density



Light DM: a bottom-up view

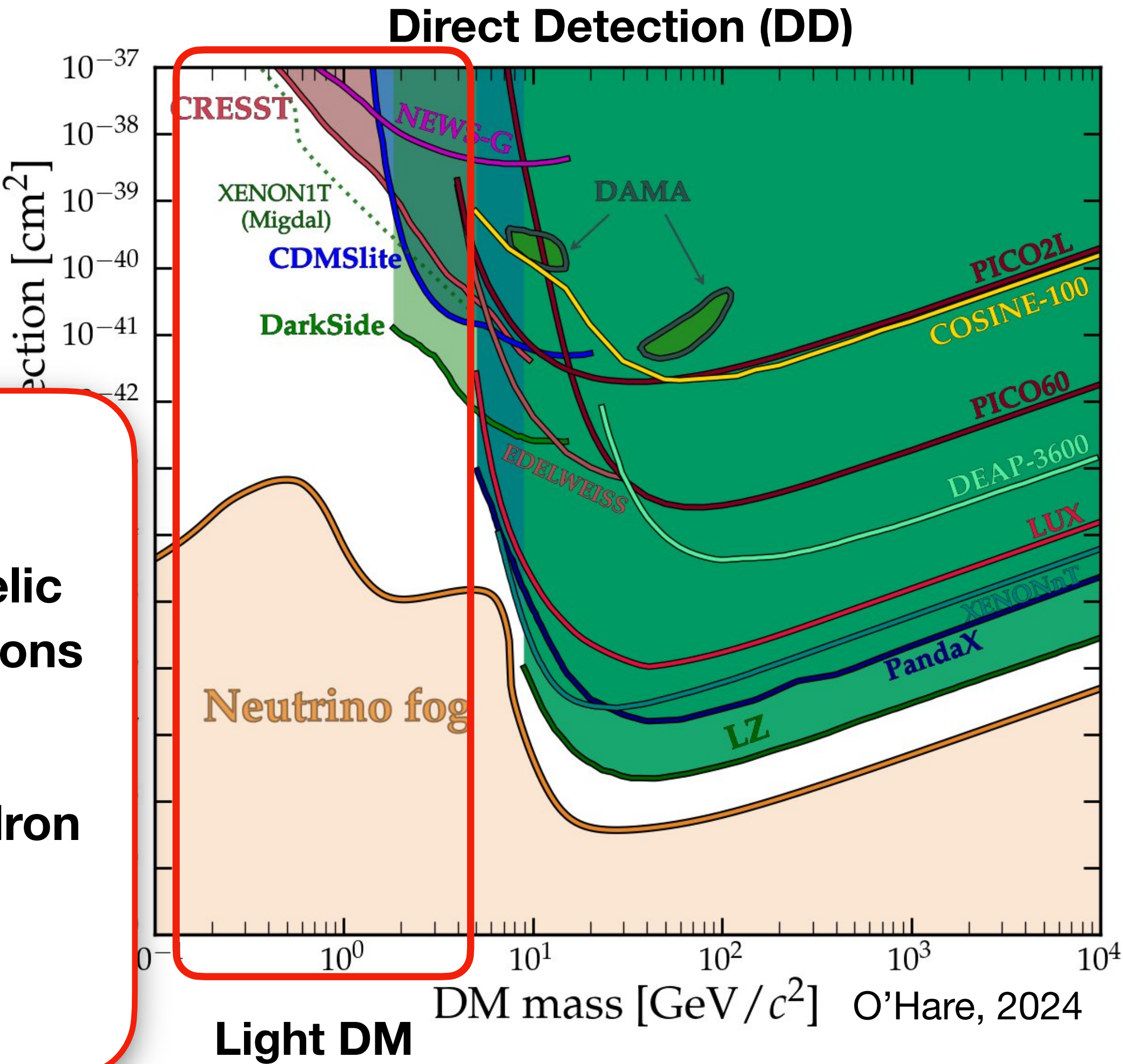
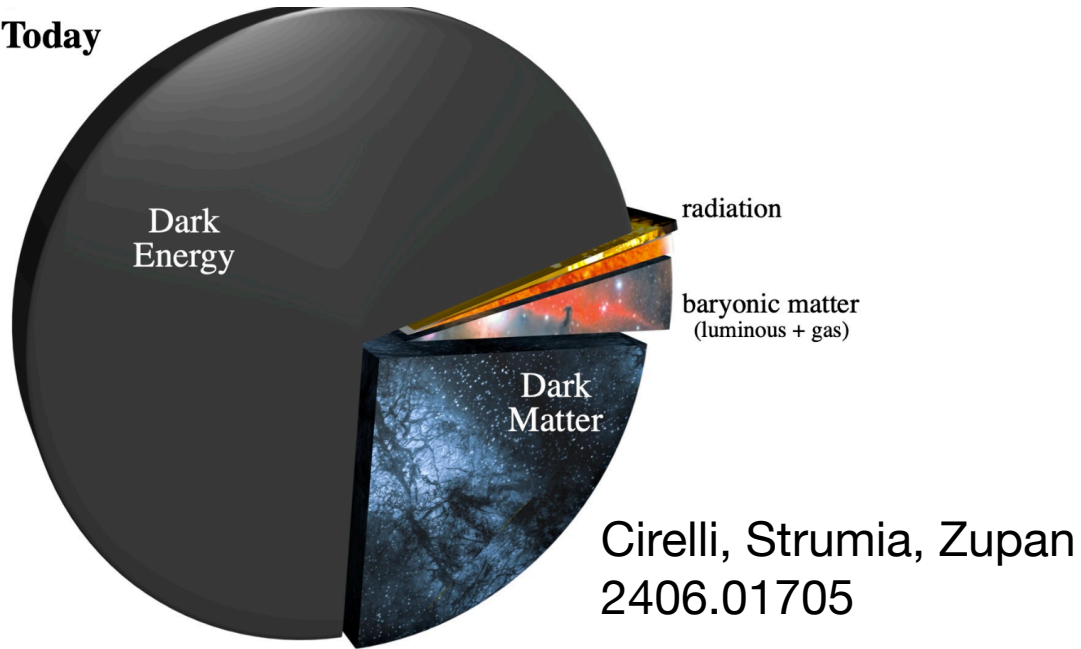
DM is electrically neutral ! $\implies$ DM only have FC or FCNC couplings to fermions !

	<i>d</i>	<i>s</i>	<i>b</i>
<i>d</i>	DD	NA62/KOTO	Belle II
<i>s</i>		DD	Belle II
<i>b</i>			Belle II/LHC

example:
 $B^+ \rightarrow K^+ + \text{DM} + \text{DM}$
 $K^+ \rightarrow \pi^+ + \text{DM} + \text{DM}$
 $D^0 \rightarrow \pi^0 + \text{DM} + \text{DM}$

It's natural to ask:

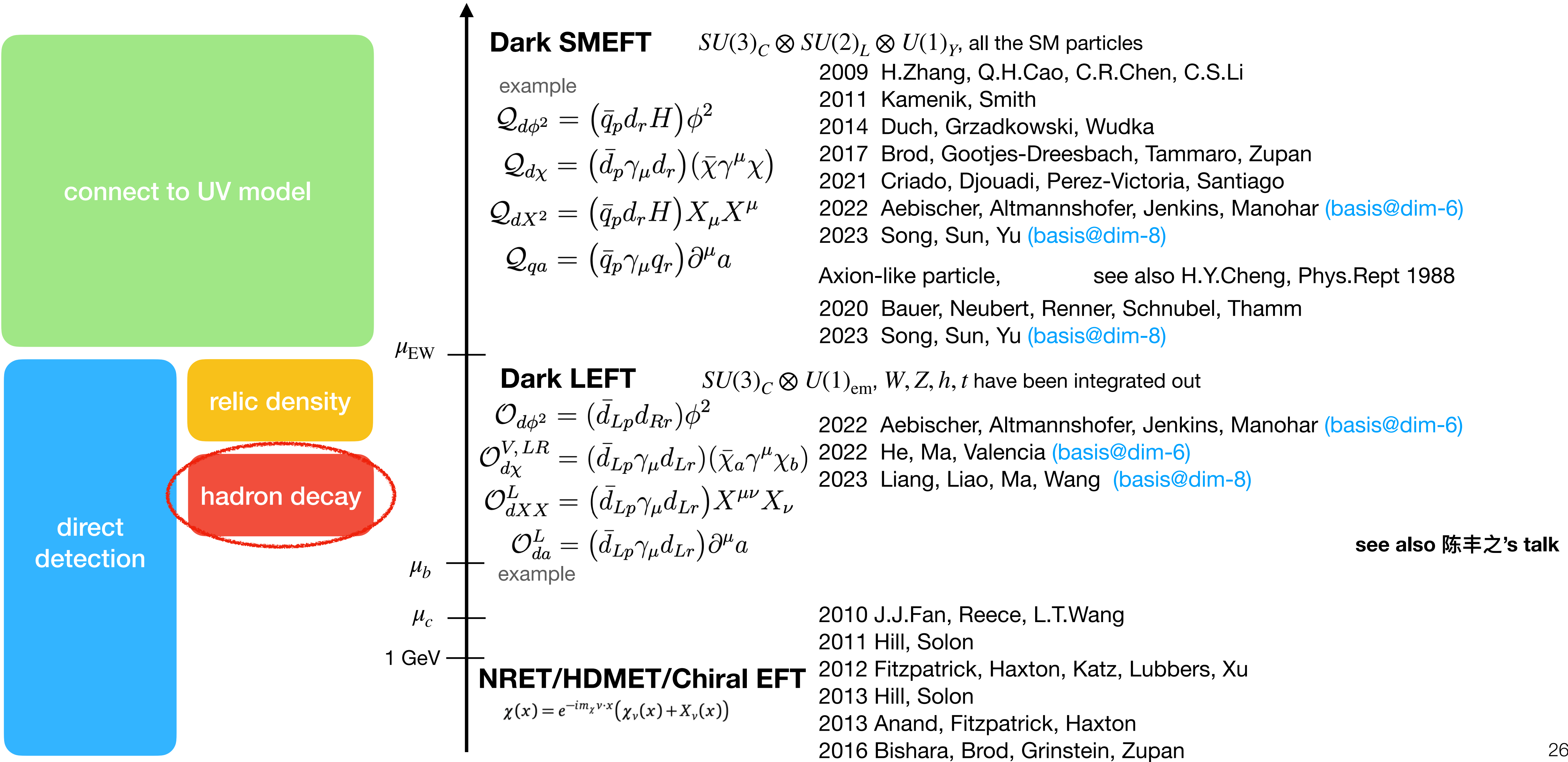
1. By combing the direct detection, flavour measurements, and relic density, is it possible to obtain the flavour structure of interactions between light DM and SM particles ?
2. Compared to DM direct detection, what's the advantage of hadron decays ? which DM scenario is more sensitive to ? Can they provide other information ?



Effective Field Theory approach to combine the various experimental searches

In EFT, DM is just a singlet under the SM gauge group.

for light DM



$H_1 \rightarrow H_2 + \mathbf{DM}$ theoretical calculation and experimental searches

► $d_i \rightarrow d_j + \phi + \phi$

- 2011 Kamenik, Smith
- 2014 Bird, Jackson, Kowalewski, Pospelov
- 2019 G.Li, J.Y. Su, Tandean
- $\Lambda \rightarrow n + \phi\phi, \Sigma^+ \rightarrow p + \phi\phi, \Xi^0 \rightarrow \Lambda + \phi\phi,$
 $\Xi^- \rightarrow \Sigma^- \phi\phi, \Omega^- \rightarrow \Sigma^- + \phi\phi$
- 2020 X.G. He, X.D. Ma, Tandean, Valencia
- 2020 C.Q.Geng, Tandean, $K \rightarrow \pi\pi + \phi\phi$
- 2021 G. Li, T. Wang, J.B. Zhang, G.L. Wang
- 2022 Kling, S. Li, H. Song, S. Su, W. Su

► $d_i \rightarrow d_j + \chi + \chi$

- 2011 Kamenik, Smith
- 2019 J.Y. Su, Tandean
- 2020 G. Li, T. Wang, Y. Jiang, J.B. Zhang, G.L. Wang
- 2021 Felkl, S. L. Li, Schmidt

► $d_i \rightarrow d_j + X + X$

- 2011 Kamenik, Smith
- 2021 G. Li, T. Wang, J.B. Zhang, G.L. Wang
- 2022 X.G. He, X.D. Ma, Valencia

► $d_i \rightarrow d_j + a$

- 2020 Camalich, Pospelov, Vuong, Ziegler, Zupan,
- 2021 Bauer, Neubert, Renner, Schnubel, Thamm
- 2022 Guerrero and S. Rigolin

- theoretically clean: $A \propto C \cdot \langle H_2 | O | H_1 \rangle \cdot \text{DM current}$ ^{form factor}
 - no GIM suppression
 - possibly two-body decay
- } **enhancement**

Observable
$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$
$\mathcal{B}(B^0 \rightarrow K^0 \nu \bar{\nu})$
$\mathcal{B}(B^+ \rightarrow K^{*+} \nu \bar{\nu})$
$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})$
$\mathcal{B}(B_s \rightarrow \phi \nu \bar{\nu})$
$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})$
$\mathcal{B}(B^0 \rightarrow \pi^0 \nu \bar{\nu})$
$\mathcal{B}(B^+ \rightarrow \rho^+ \nu \bar{\nu})$
$\mathcal{B}(B^0 \rightarrow \rho^0 \nu \bar{\nu})$
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$
$\mathcal{B}(B_s \rightarrow \nu \bar{\nu})$
$\mathcal{B}(B^0 \rightarrow \nu \bar{\nu})$

longitudinal polarization
 F_L

$\Lambda_b \rightarrow \Lambda + \mathbf{DM} + \mathbf{DM}$

► $c \rightarrow u + \mathbf{DM}$

- 2022 C.Q.Geng, G.Li
- 2023 G.Li, Tandean

- $D^0 \rightarrow S \bar{S}'$
- $D^0 \rightarrow \gamma S \bar{S}'$
- $D^0 \rightarrow \pi^0 S \bar{S}'$
- $D^+ \rightarrow \pi^+ S \bar{S}'$
- $D_s^+ \rightarrow K^+ S \bar{S}'$
- $D^0 \rightarrow \rho^0 S \bar{S}'$
- $D^+ \rightarrow \rho^+ S \bar{S}'$
- $D_s^+ \rightarrow K^{*+} S \bar{S}'$
- $\Lambda_c^+ \rightarrow p S \bar{S}'$
- $\Xi_c^+ \rightarrow \Sigma^+ S \bar{S}'$
- $\Xi_c^0 \rightarrow \Sigma^0 S \bar{S}'$
- $\Xi_c^0 \rightarrow \Lambda S \bar{S}'$

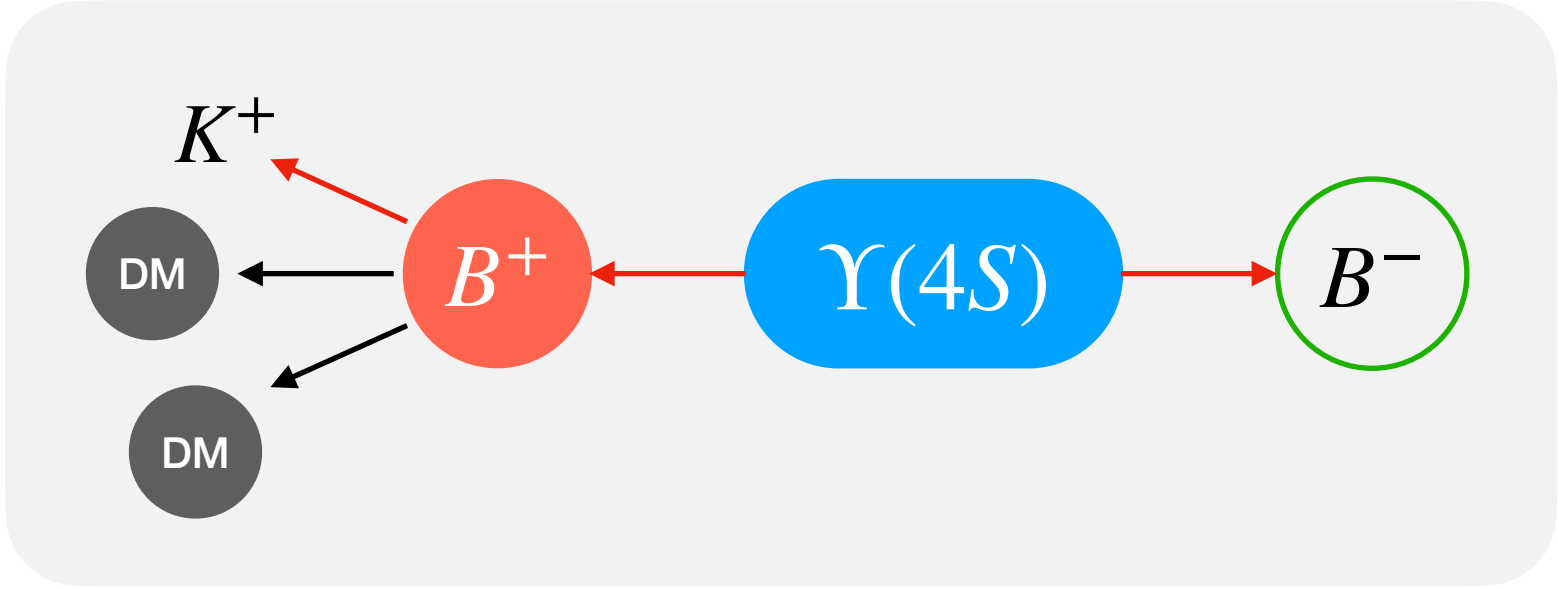
$\nu \rightarrow \mathbf{DM}$ **based on complete EFT basis (Dark LEFT)**

HadronToNP: a package to calculate decay of hadron to new particles
B.F. Hou, X.Q.Li, H.Yan, Y.D.Yang, **XBY** *to be finished*

$b \rightarrow s\nu\bar{\nu}$: DSMEFT

Can DSMEFT operators explain the Belle II excess, while satisfy other $b \rightarrow s$ bounds ?

Observable	SM	Exp	Unit
$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}
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Dark SMEFT

$$\mathcal{Q}_{d\phi} = (\bar{q}_p d_r H) \phi + \text{h.c.}, \quad \mathcal{Q}_{d\phi^2} = (\bar{q}_p d_r H) \phi^2 + \text{h.c.},$$
$$\mathcal{Q}_{\phi q} = (\bar{q}_p \gamma_\mu q_r) (i \phi_1 \overleftrightarrow{\partial}^\mu \phi_2), \quad \mathcal{Q}_{\phi d} = (\bar{d}_p \gamma_\mu d_r) (i \phi_1 \overleftrightarrow{\partial}^\mu \phi_2),$$
$$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r) (\bar{\chi} \gamma^\mu \chi), \quad \mathcal{Q}_{d\chi} = (\bar{d}_p \gamma_\mu d_r) (\bar{\chi} \gamma^\mu \chi),$$
$$\mathcal{Q}_{dHX} = (\bar{q}_p \sigma_{\mu\nu} d_r) H X^{\mu\nu} \quad \mathcal{Q}_{dX^2} = (\bar{q}_p d_r H) X_\mu X^\mu$$
$$\mathcal{Q}_{qa} = (\bar{q}_p \gamma_\mu q_r) \partial^\mu a \quad \mathcal{Q}_{da} = (\bar{d}_p \gamma_\mu d_r) \partial^\mu a$$

scalar: 4

fermion: 2

vector: 1+13

ALP: 2

Dark LEFT

$$\mathcal{O}_{d\phi} = (\bar{d}_{Lp} d_{Rr}) \phi + \text{h.c.}, \quad \mathcal{O}_{\phi d}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) (i \phi_1 \overleftrightarrow{\partial}^\mu \phi_2),$$
$$\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) (\bar{\chi}_a \gamma^\mu \chi_b), \quad \mathcal{O}_{d\chi}^{V,RR} = (\bar{d}_{Rp} \gamma_\mu d_{Rr}) (\bar{\chi}_a \gamma^\mu \chi_b),$$
$$\mathcal{O}_{dX}^T = (\bar{d}_{Lp} \sigma_{\mu\nu} d_{Rr}) X_a^{\mu\nu} \quad \mathcal{O}_{dXX}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) X^{\mu\nu} X_\nu$$
$$\mathcal{O}_{da}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) \partial^\mu a, \quad \mathcal{O}_{da}^R = (\bar{d}_{Rp} \gamma_\mu d_{Rr}) \partial^\mu a.$$

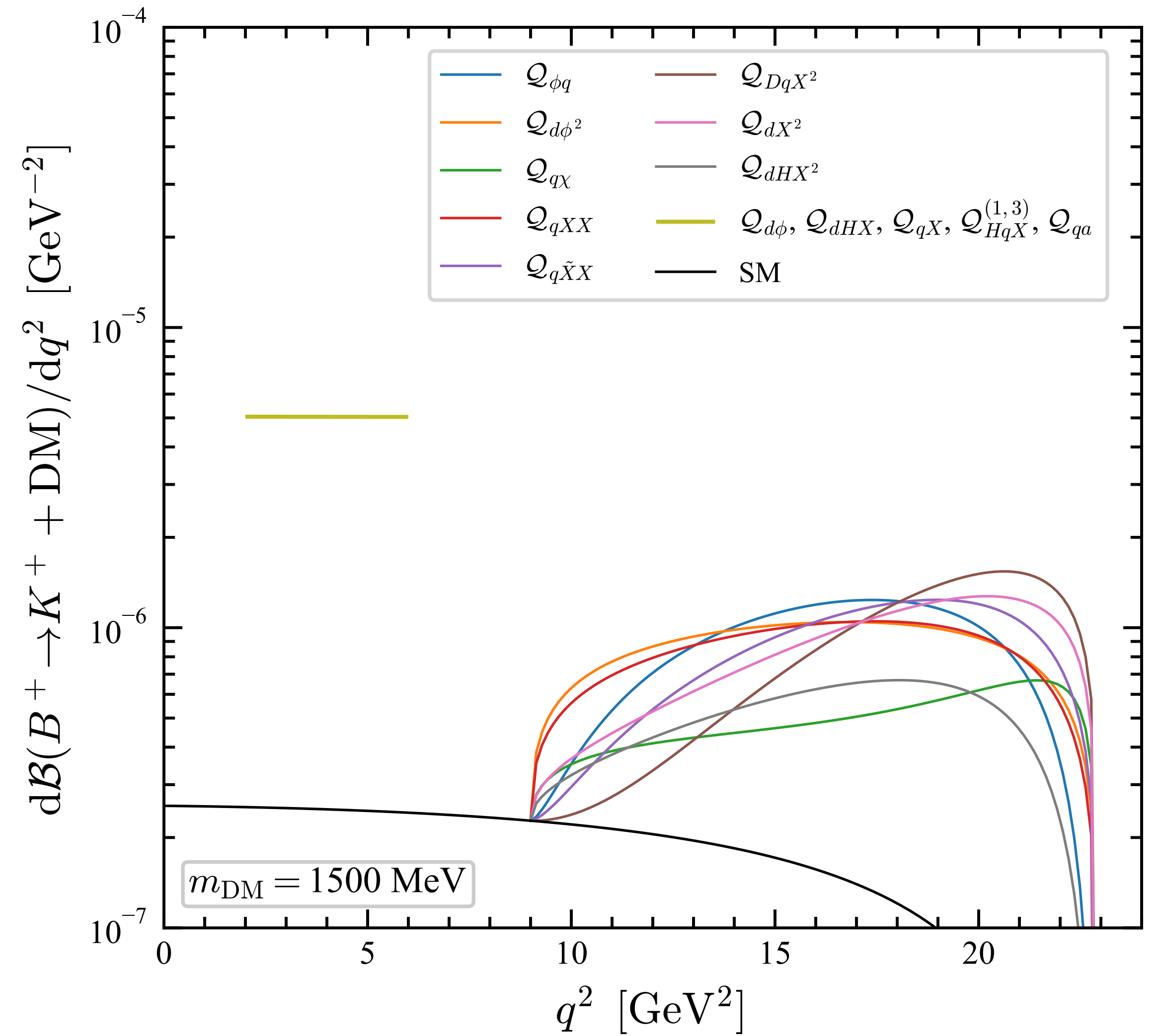
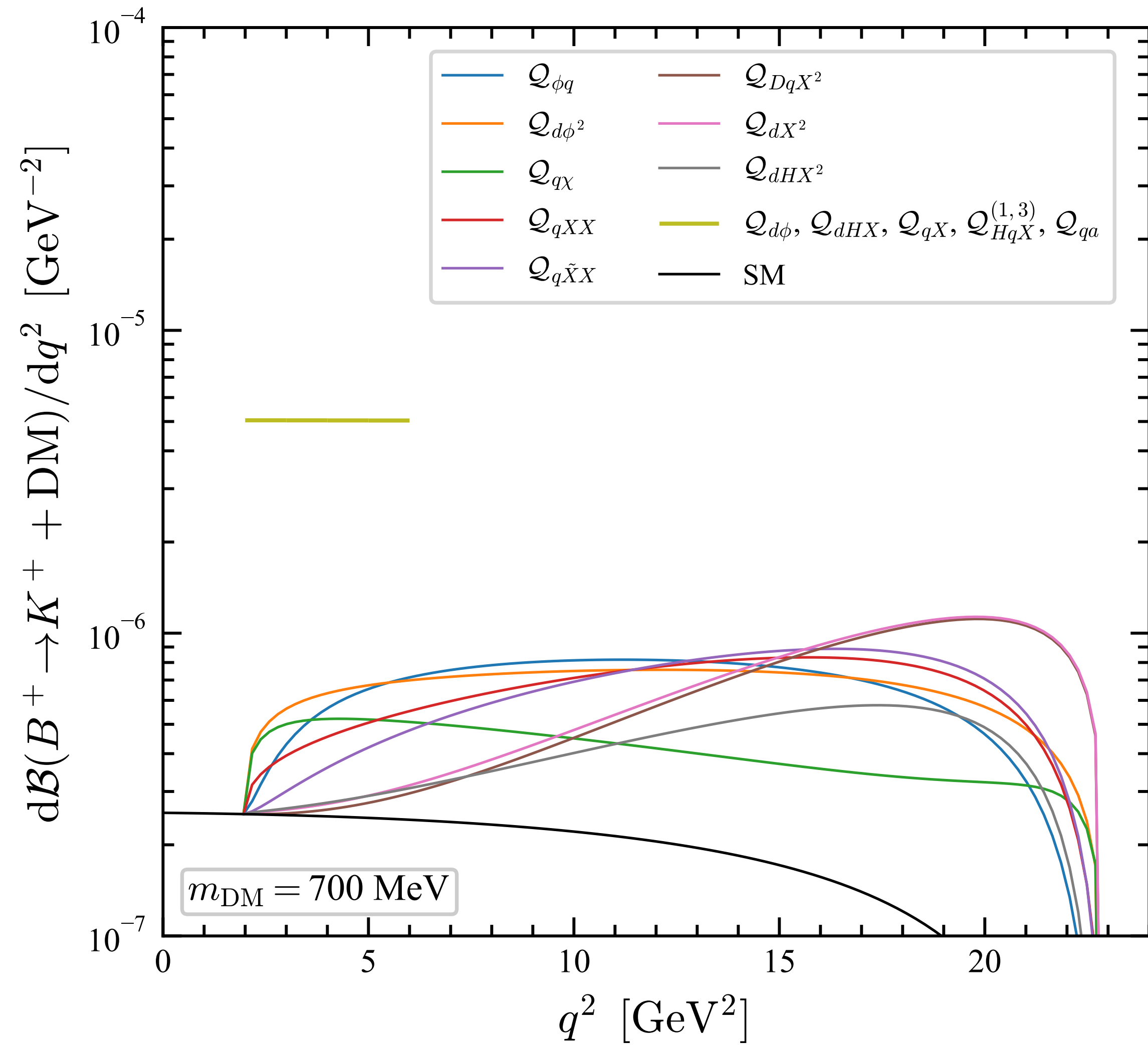
scalar: 4

fermion: 5

vector: 1+10

ALP: 2

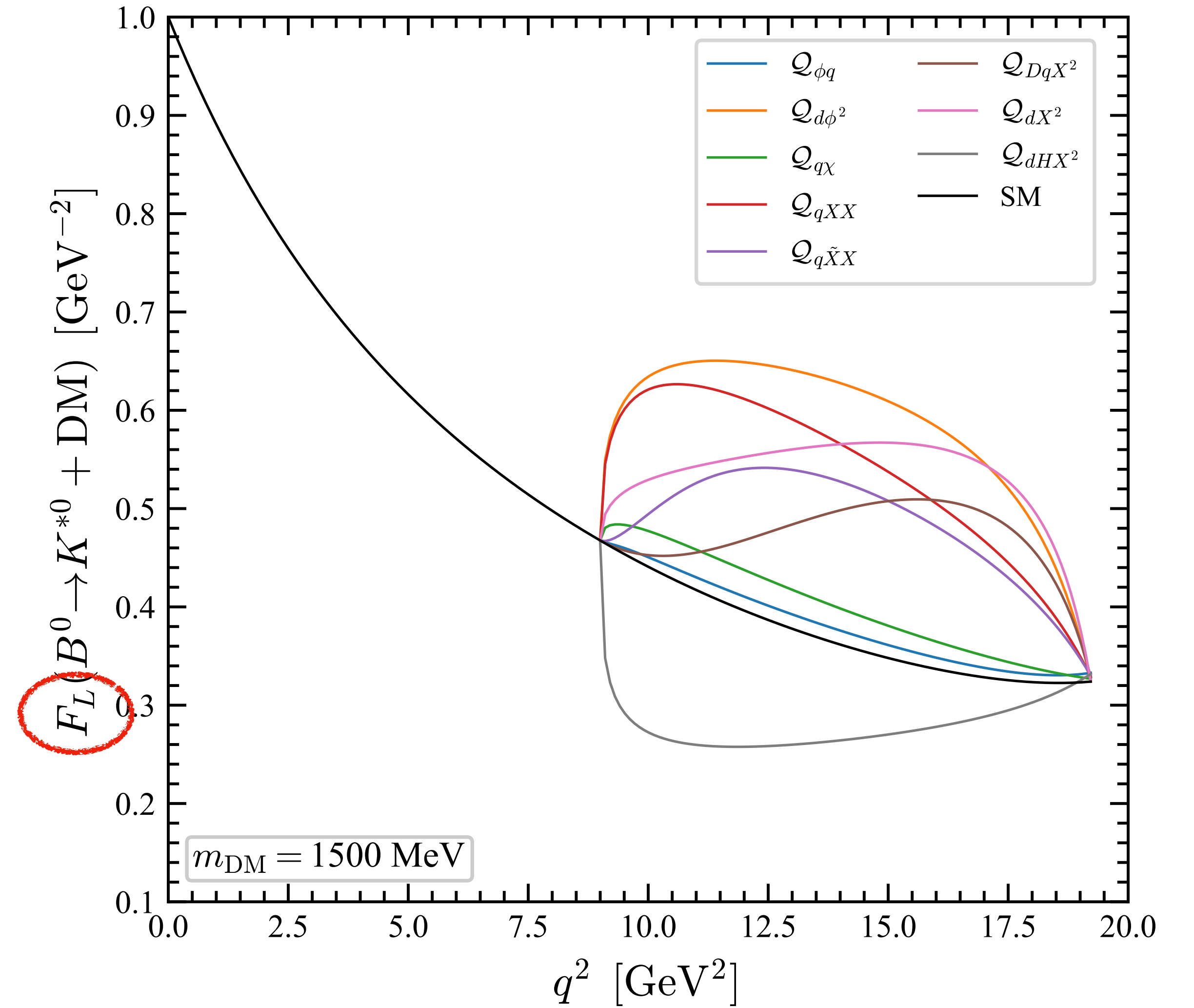
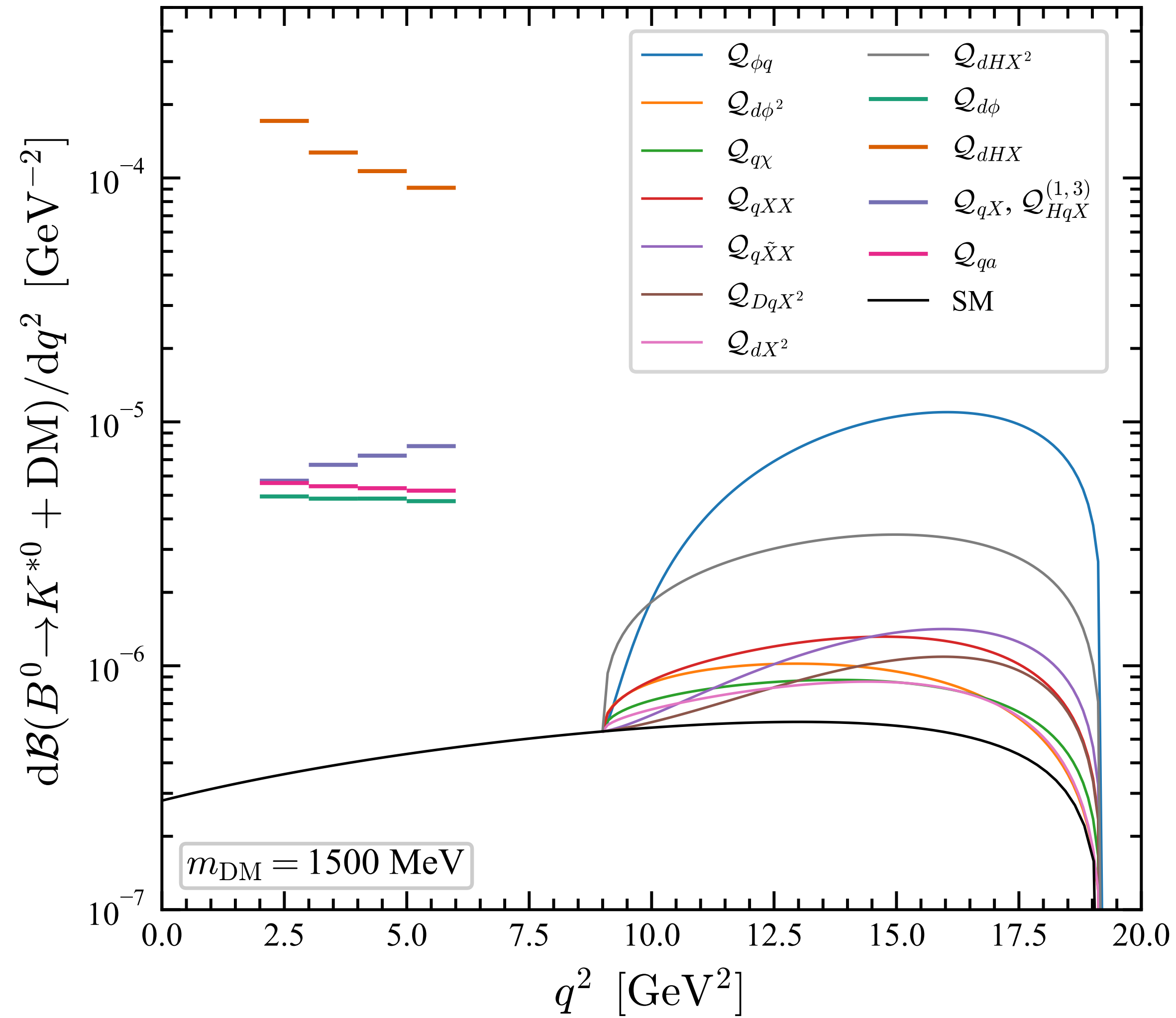
Dark SMEFT: $\mathrm{d}B/\mathrm{d}q^2$



Difficult to distinguish the DSMEFT operators by considering only the $B^+ \rightarrow K^+ \nu \bar{\nu}$ decay. However,

Dark SMEFT: $dB/dq^2, F_L$

$$m_{\text{DM}} = 1500 \text{ MeV}$$

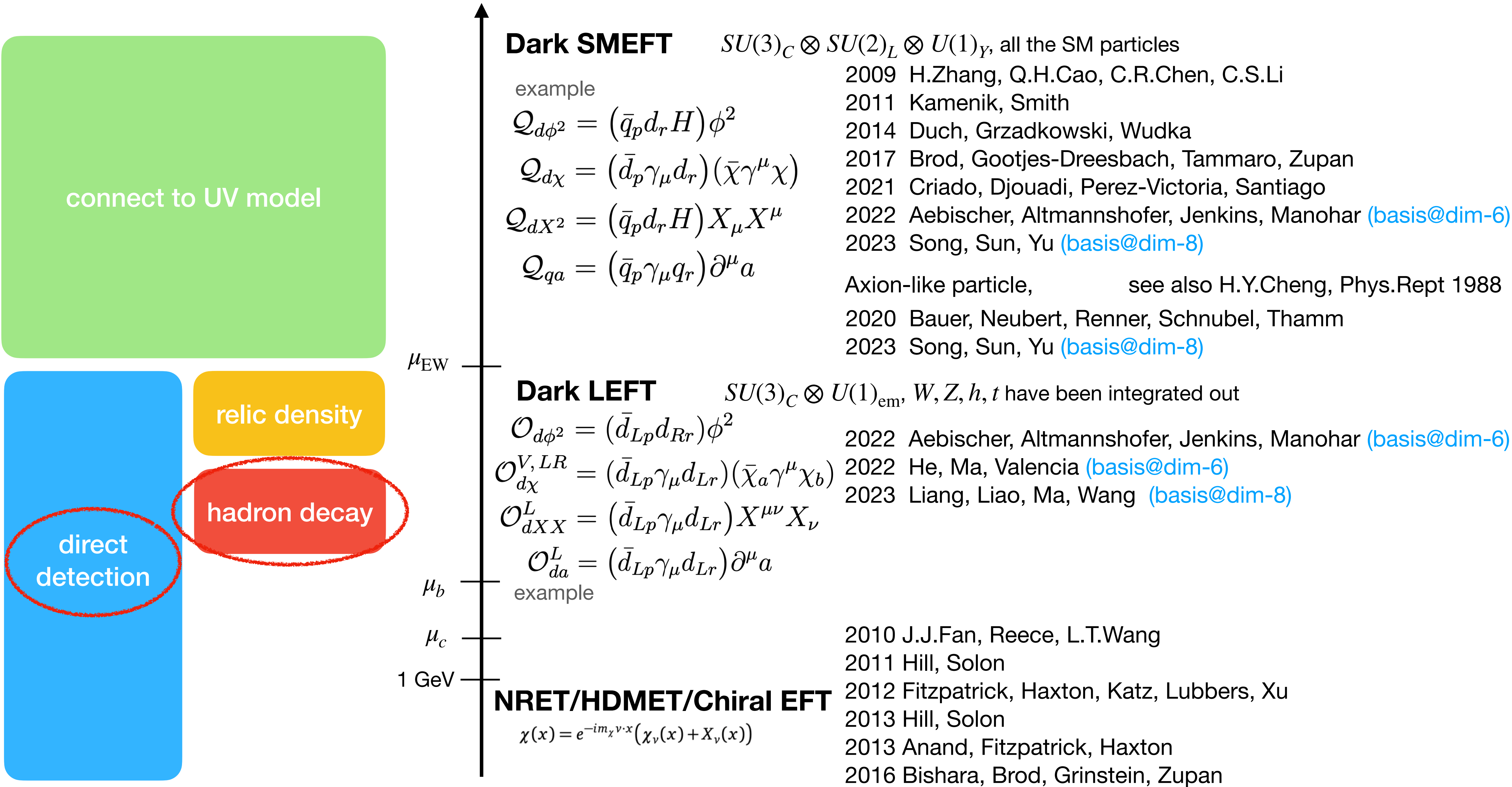


All the operators are **distinguishable** from each other by combining these observables

Effective Field Theory approach to combine the various experimental searches

In EFT, DM is just a singlet under the SM gauge group.

for light DM



Top-flavored DM

► Dark SMEFT with 3rd generation@ μ_{EW}

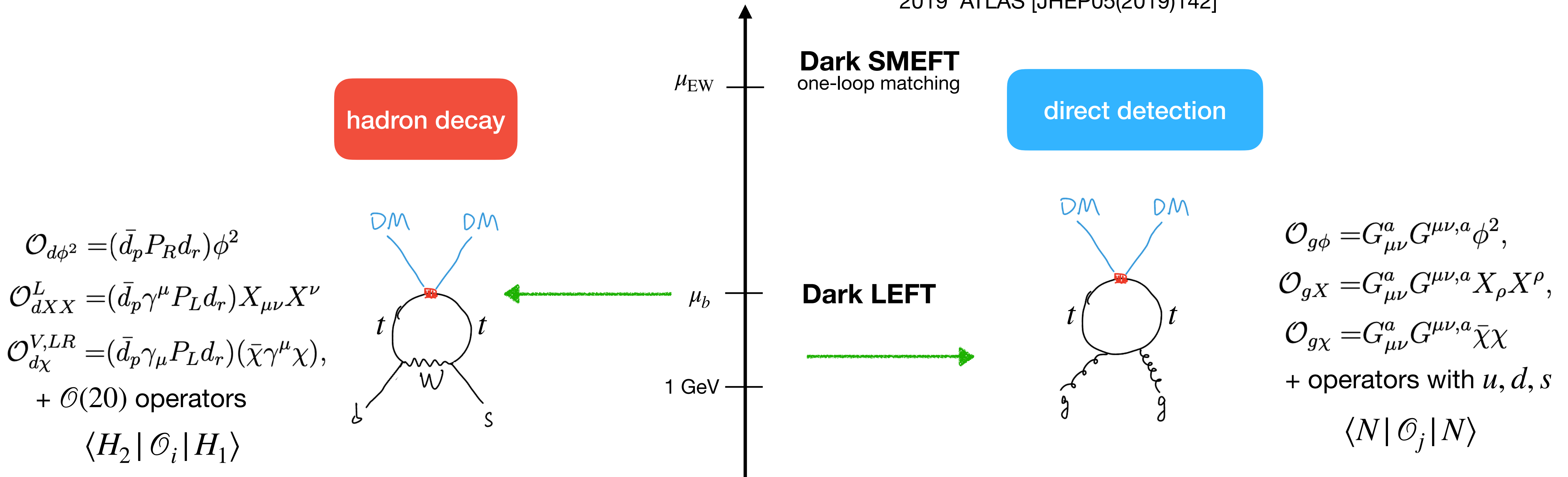
$$\mathcal{Q}_{u\chi} = (\bar{u}_p \gamma_\mu u_r)(\bar{\chi} \gamma^\mu \chi), \implies (\bar{t}_R \gamma_\mu t_R)(\bar{\chi} \gamma^\mu \chi)$$

$$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r)(\bar{\chi} \gamma^\mu \chi),$$

$$\mathcal{Q}_{u\chi^2} = (\bar{q}_p u_r \tilde{H})(\bar{\chi} \chi), \quad \mathcal{C} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathcal{C}_{33}$$

2013 Tongyan Lin, Kolb, Lian-Tao Wang
 2015 Kilic, Klimek, Jiang-Hao Yu
 2015 Haisch, Re
 2015 Boucheneb, Cacciapaglia, Deandrea, Fuks
 2017 Blanke, Kast
 2021 Blanke, Pani, Polesello, Rovelli
 2021 Haisch, Polesello, Schulte
 2021 Hermann, Worek
 2022 Yandong Liu, Bin Yan, Rui Zhang

2019 ATLAS [JHEP05(2019)142]



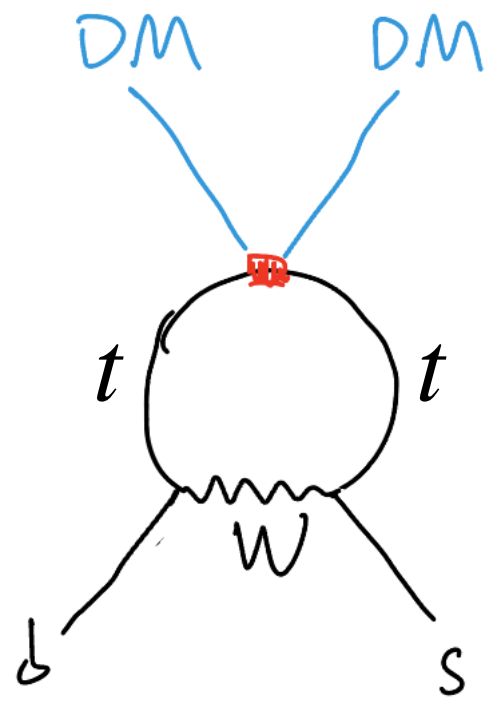
One-Loop Matching between Dark SMEFT and Dark LEFT

► Dark SMEFT

$$\mathcal{L}_{\text{DSMEFT}} \supset \sum_i \mathcal{C}_i \mathcal{Q}_i^{(4)} + \boxed{\frac{1}{\Lambda} \sum_j \mathcal{C}_j \mathcal{Q}_j^{(5)}} + \boxed{\frac{1}{\Lambda^2} \sum_k \mathcal{C}_k \mathcal{Q}_k^{(6)}} + \boxed{\frac{1}{\Lambda^3} \sum_l \mathcal{C}_l \mathcal{Q}_l^{(7)}}$$

$\mathcal{Q}_{u\phi^2} = (\bar{q}_p u_r \tilde{H}) \phi^2 + \text{h.c.}$	$\mathcal{Q}_{\phi u} = (\bar{u}_p \gamma_\mu u_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	$\mathcal{Q}_{\phi q} = (\bar{q}_p \gamma_\mu q_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	...	scalar
$\mathcal{Q}_{u\chi^2} = (\bar{q}_p u_r \tilde{H}) (\chi^T C \chi)$	$\mathcal{Q}_{u\chi} = (\bar{u}_p \gamma_\mu u_r) (\bar{\chi} \gamma^\mu \chi)$	$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r) (\bar{\chi} \gamma^\mu \chi)$	...	fermion
$\mathcal{Q}_{qXX} = (\bar{q}_p \gamma_\mu q_r) X^{\mu\nu} X_\nu$	$\mathcal{Q}_{u\tilde{X}X} = (\bar{u}_p \gamma_\mu u_r) \tilde{X}^{\mu\nu} X_\nu$	$\mathcal{Q}_{uX^2} = (\bar{q}_p u_r \tilde{H}) X_\mu X^\mu + \text{h.c.}$	...	vector

► Matching



► Dark LEFT: **hadron detection**

$$\mathcal{L}_{\text{DLEFT}} \supset \sum_k L_k \mathcal{O}_k^{(4)} + \boxed{\frac{1}{v} \sum_i L_i \mathcal{O}_i^{(5)}} + \boxed{\frac{1}{v^2} \sum_j L_j \mathcal{O}_j^{(6)}} + \boxed{\frac{1}{v^3} \sum_l L_l \mathcal{O}_l^{(7)}}$$

$\mathcal{O}_{\phi d}^R = (\bar{d}_p \gamma_\mu P_R d_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	$\mathcal{O}_{d\phi^2} = (\bar{d}_p P_R d_r) \phi^2$	...	scalar
$\mathcal{O}_{d\chi}^{V,RR} = (\bar{d}_p \gamma_\mu P_R d_r) (\bar{\chi} \gamma^\mu \chi)$	$\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_p \gamma_\mu P_L d_r) (\bar{\chi} \gamma^\mu \chi)$	...	fermion
$\mathcal{O}_{dXX}^R = (\bar{d}_p \gamma^\mu P_R d_r) X_{\mu\nu} X^\nu$	$\mathcal{O}_{dXX}^L = (\bar{d}_p \gamma^\mu P_L d_r) X_{\mu\nu} X^\nu$	...	vector

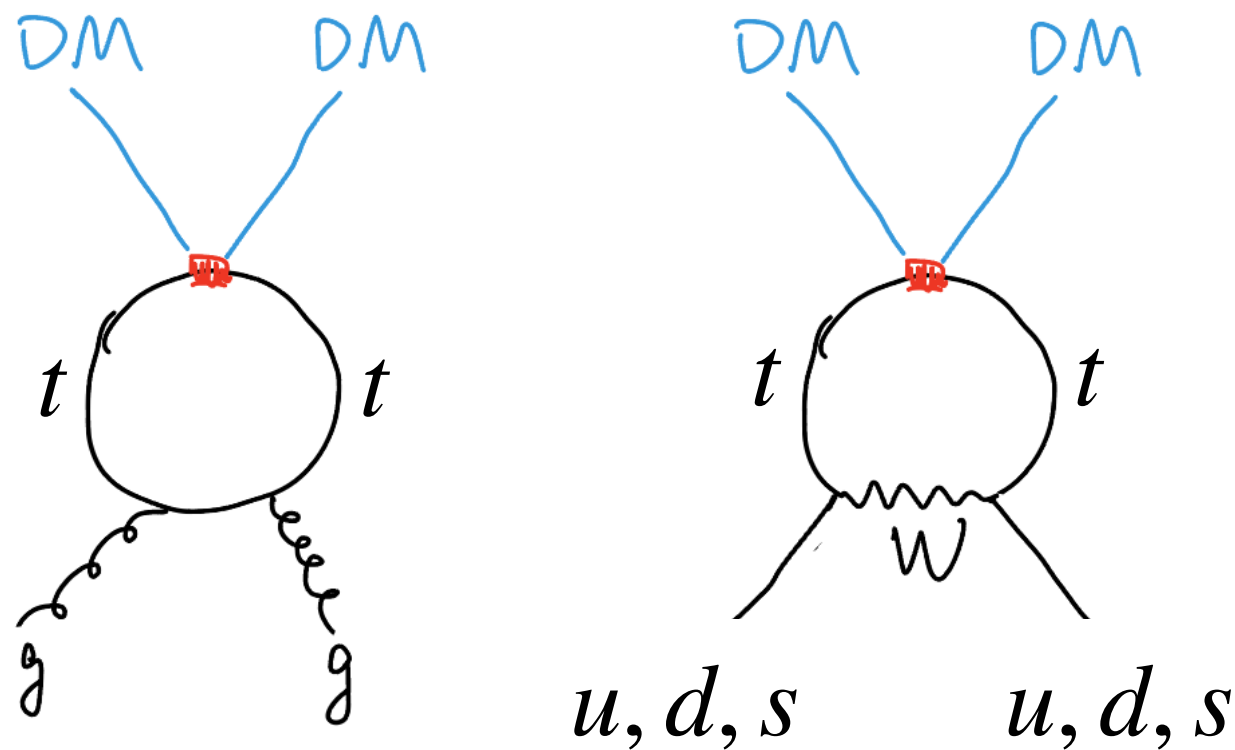
One-Loop Matching between Dark SMEFT and Dark LEFT

► Dark SMEFT

$$\mathcal{L}_{\text{DSMEFT}} \supset \sum_i c_i \mathcal{Q}_i^{(4)} + \boxed{\frac{1}{\Lambda} \sum_j c_j \mathcal{Q}_j^{(5)}} + \boxed{\frac{1}{\Lambda^2} \sum_k c_k \mathcal{Q}_k^{(6)}} + \boxed{\frac{1}{\Lambda^3} \sum_l c_l \mathcal{Q}_l^{(7)}}$$

$\mathcal{Q}_{u\phi^2} = (\bar{q}_p u_r \tilde{H}) \phi^2 + \text{h.c.}$	$\mathcal{Q}_{\phi u} = (\bar{u}_p \gamma_\mu u_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	$\mathcal{Q}_{\phi q} = (\bar{q}_p \gamma_\mu q_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	...	scalar
$\mathcal{Q}_{u\chi^2} = (\bar{q}_p u_r \tilde{H}) (\chi^T C \chi)$	$\mathcal{Q}_{u\chi} = (\bar{u}_p \gamma_\mu u_r) (\bar{\chi} \gamma^\mu \chi)$	$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r) (\bar{\chi} \gamma^\mu \chi)$	...	fermion
$\mathcal{Q}_{qXX} = (\bar{q}_p \gamma_\mu q_r) X^{\mu\nu} X_\nu$	$\mathcal{Q}_{u\tilde{X}X} = (\bar{u}_p \gamma_\mu u_r) \tilde{X}^{\mu\nu} X_\nu$	$\mathcal{Q}_{uX^2} = (\bar{q}_p u_r \tilde{H}) X_\mu X^\mu + \text{h.c.}$	...	vector

► Matching

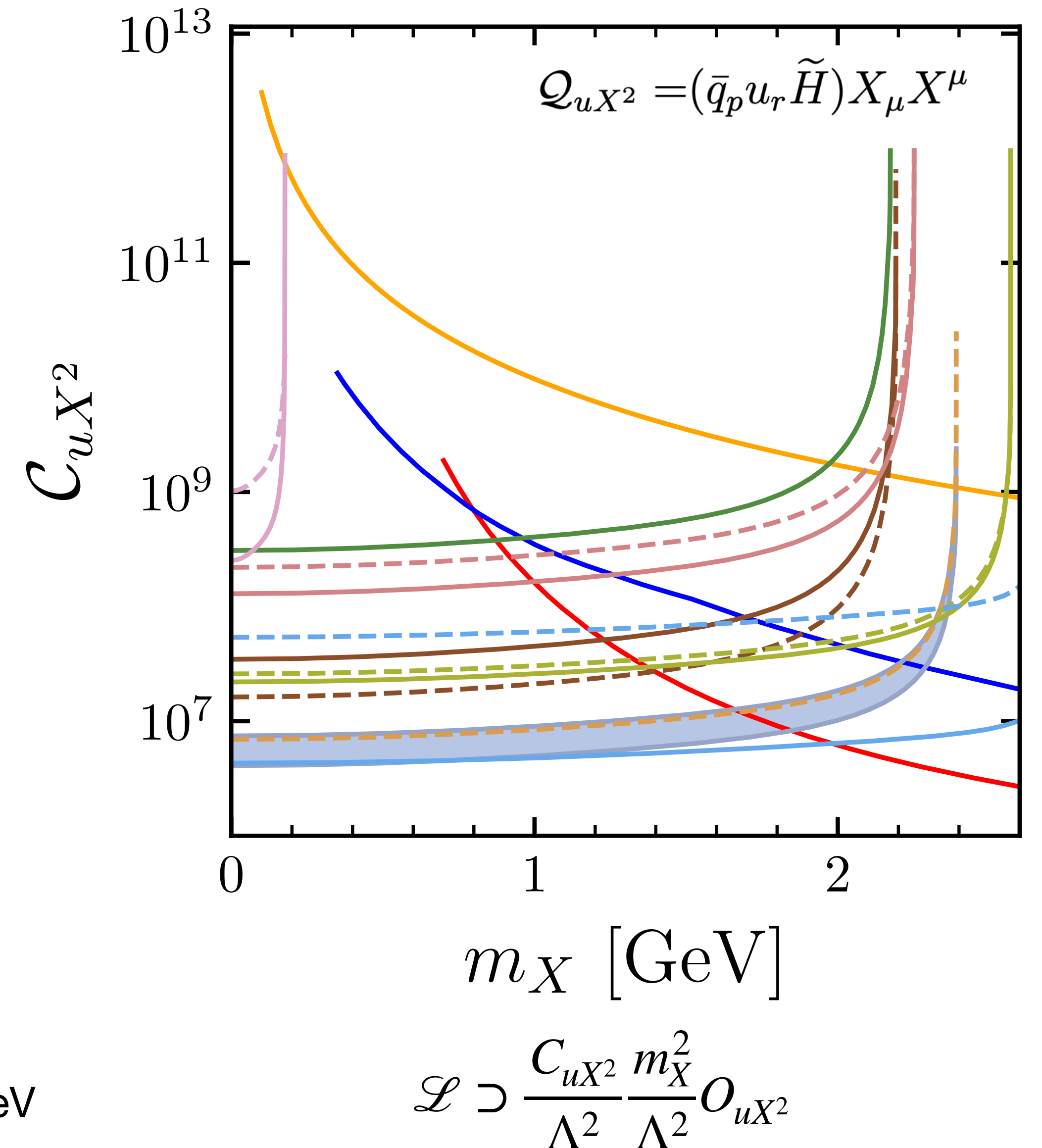
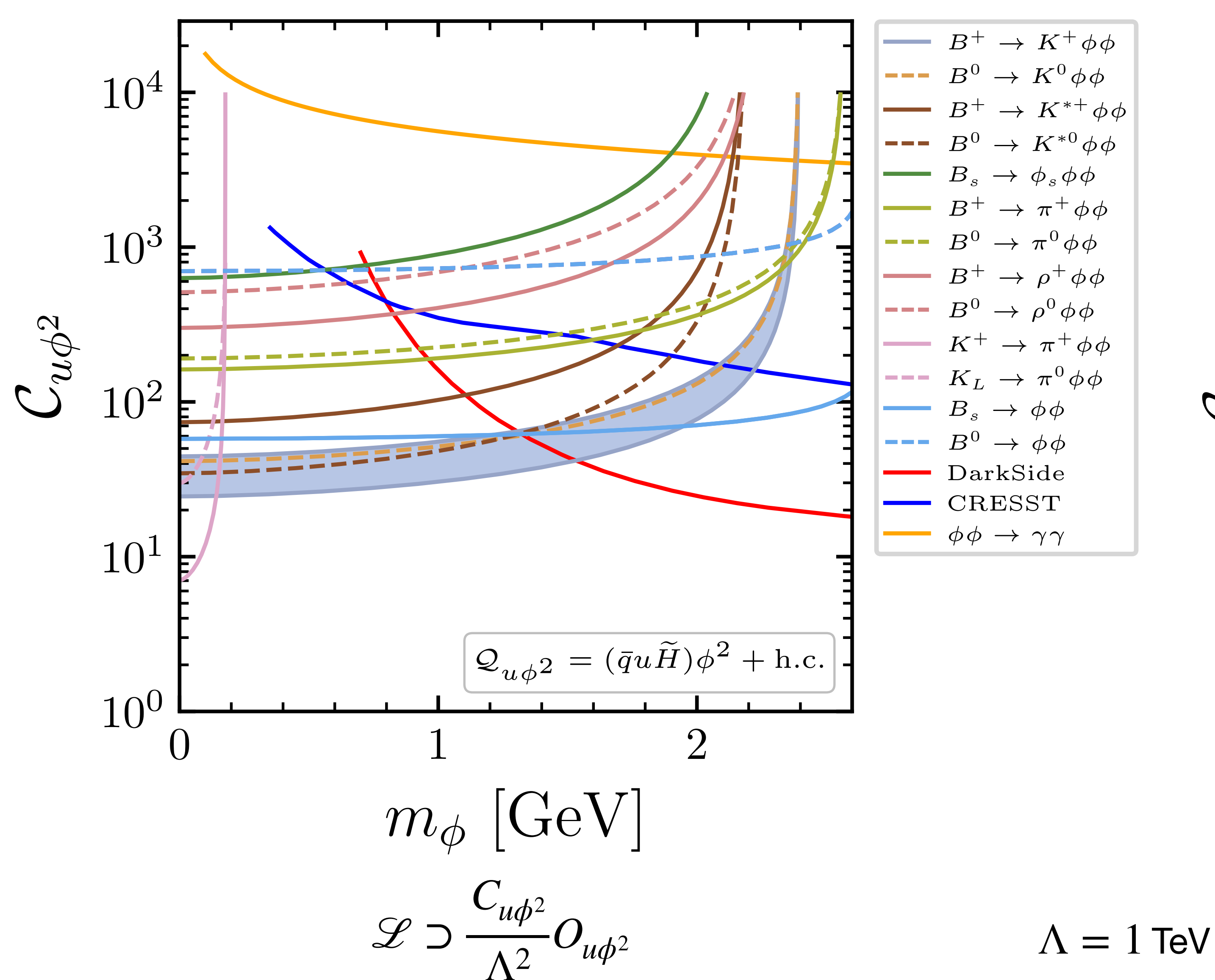


► Dark LEFT: **direct detection**

$$\mathcal{L}_{\text{DLEFT}} \supset \sum_k L_k \mathcal{O}_k^{(4)} + \boxed{\frac{1}{v} \sum_i L_i \mathcal{O}_i^{(5)}} + \boxed{\frac{1}{v^2} \sum_j L_j \mathcal{O}_j^{(6)}} + \boxed{\frac{1}{v^3} \sum_l L_l \mathcal{O}_l^{(7)}}$$

$\mathcal{O}_{g\phi} = G_{\mu\nu}^a G^{\mu\nu,a} \phi^2$	$\mathcal{O}_{d\phi^2} = (\bar{d}_p P_R d_r) \phi^2$	...	scalar
$\mathcal{O}_{g\chi} = G_{\mu\nu}^a G^{\mu\nu,a} \bar{\chi} \chi$	$\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_p \gamma_\mu P_L d_r) (\bar{\chi} \gamma^\mu \chi)$	...	fermion
$\mathcal{O}_{gX} = G_{\mu\nu}^a G^{\mu\nu,a} X_\rho X^\rho$	$\mathcal{O}_{dXX}^L = (\bar{d}_p \gamma^\mu P_L d_r) X_{\mu\nu} X^\nu$	...	vector

Hadron decay vs Direct detection



Dark SMEFT

It's natural to ask:

- 1. By combining the direct detection, flavour measurements, and relic density, is it possible to obtain the **flavour structure** of interactions between light DM and SM particles ?

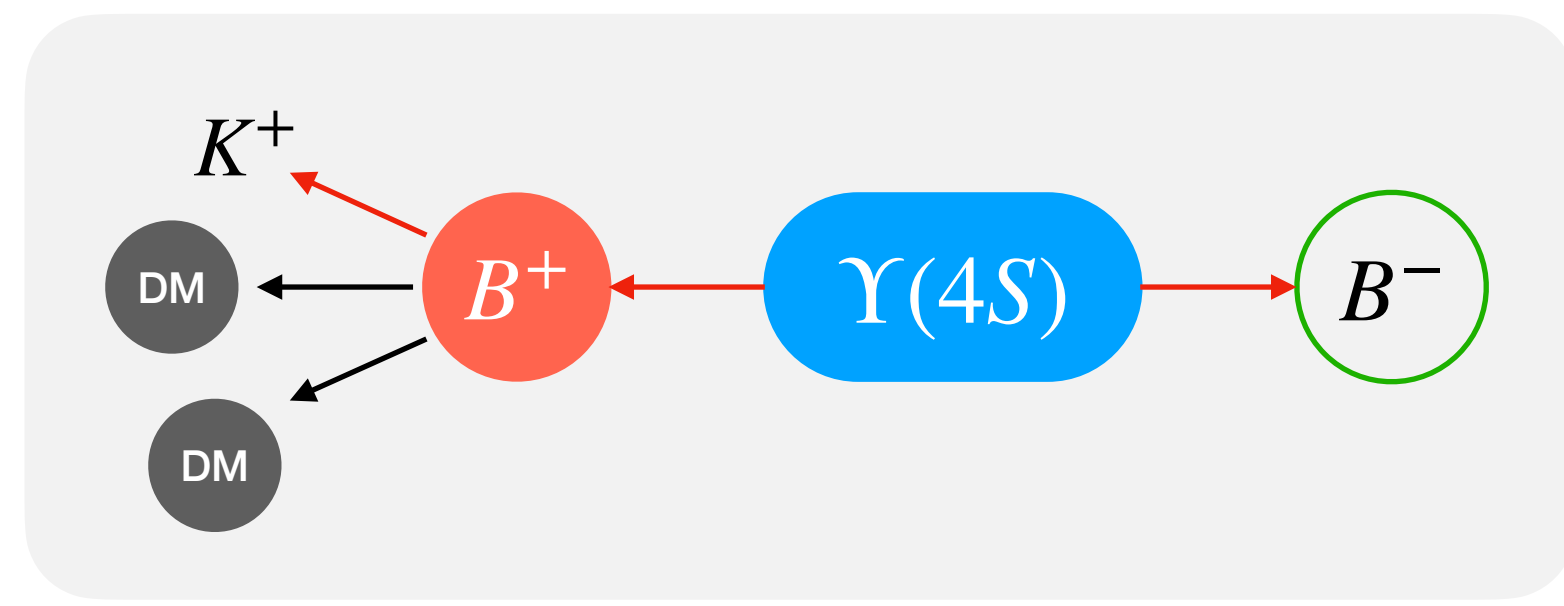
top-flavoured DM

- 2. Compared to DM direct detection, what's the advantage of hadron decays? which DM scenario is more sensitive to ? Can they provide **other information** ?

angular distribution (F_L) ;

HadronToNP: a package to calculate decay of hadron to new particles
 $B \rightarrow K + \text{DM}, B \rightarrow \rho + \text{DM}, \Lambda_b \rightarrow \Lambda + \text{DM}, \Upsilon \rightarrow \text{DM}, \dots$
 $D \rightarrow \pi + \text{DM}, D \rightarrow \rho + \text{DM}, \Xi_c \rightarrow \Xi + \text{DM}, J/\psi \rightarrow \text{DM}, \dots$ *to be finished*

many things to do, e.g., other flavour structures (MFV, $U(2)^5$), simplified model (light mediator), operator basis (SPVA), UV completion, full one-loop matching between DLEFT and DSMEFT, astro-constraints, ...



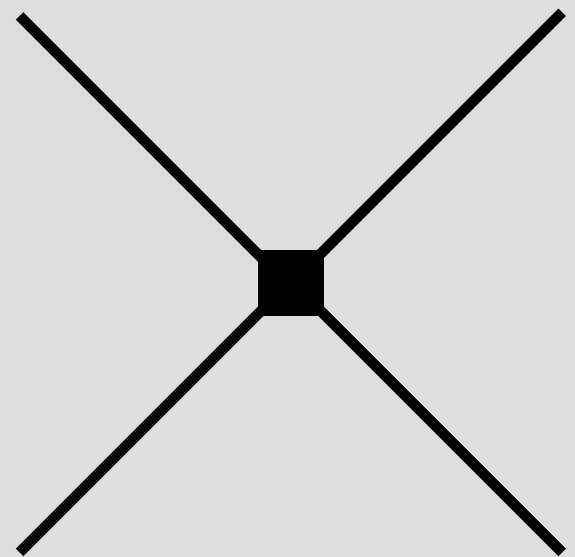
A Possible Flavour Path to Dark Matter

	<i>d</i>	<i>s</i>	<i>b</i>
<i>d</i>	DD	NA62/KOTO	Belle II
<i>s</i>		DD	Belle II
<i>b</i>			Belle II/LHC
	<i>u</i>	<i>c</i>	<i>t</i>
<i>u</i>	DD	BES/STCF	LHC/CEPC
<i>c</i>		BES/STCF	LHC/CEPC
<i>t</i>			LHC/CEPC

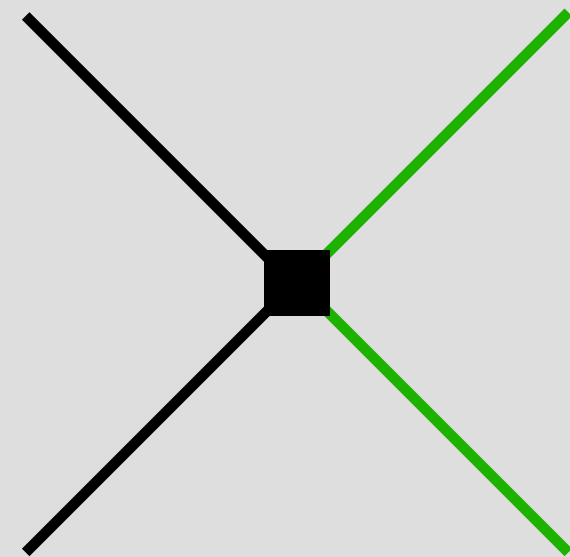
Outline

EFT Perspective

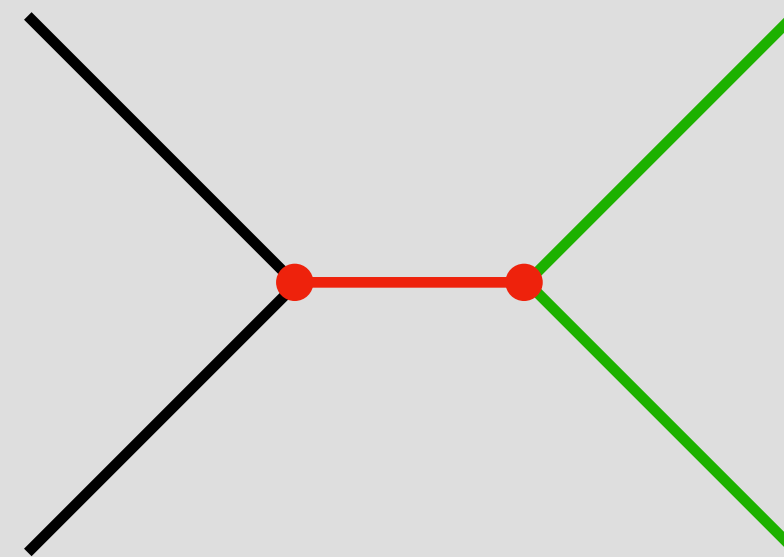
Conventional EFT



EFT with New d.o.f



Beyond EFT



AI Perspective



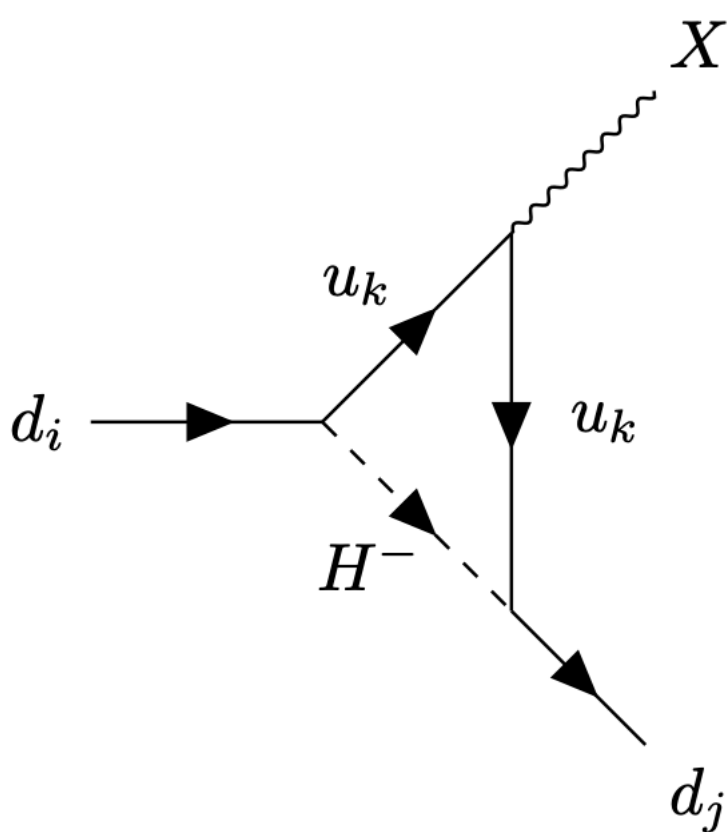
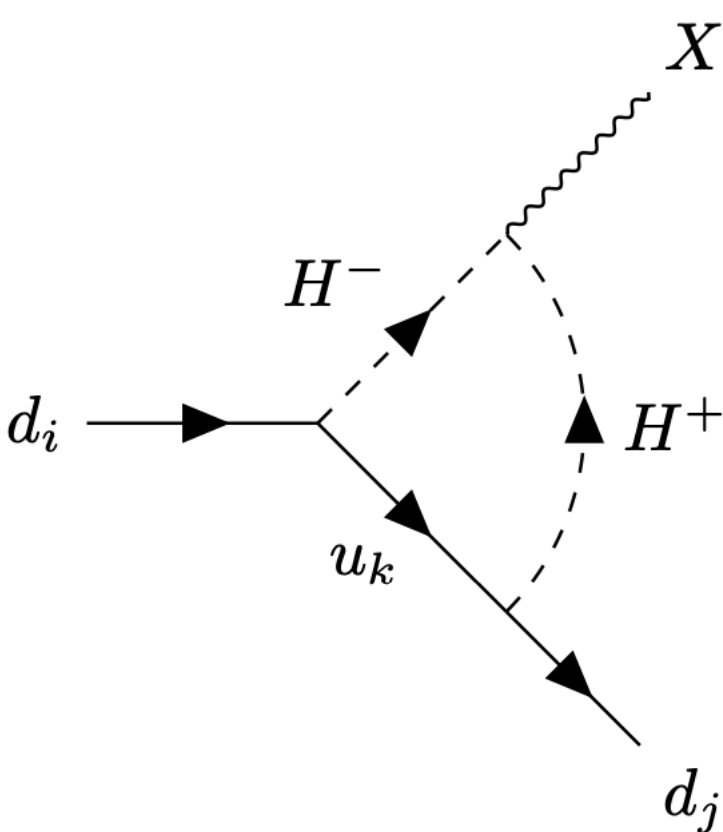
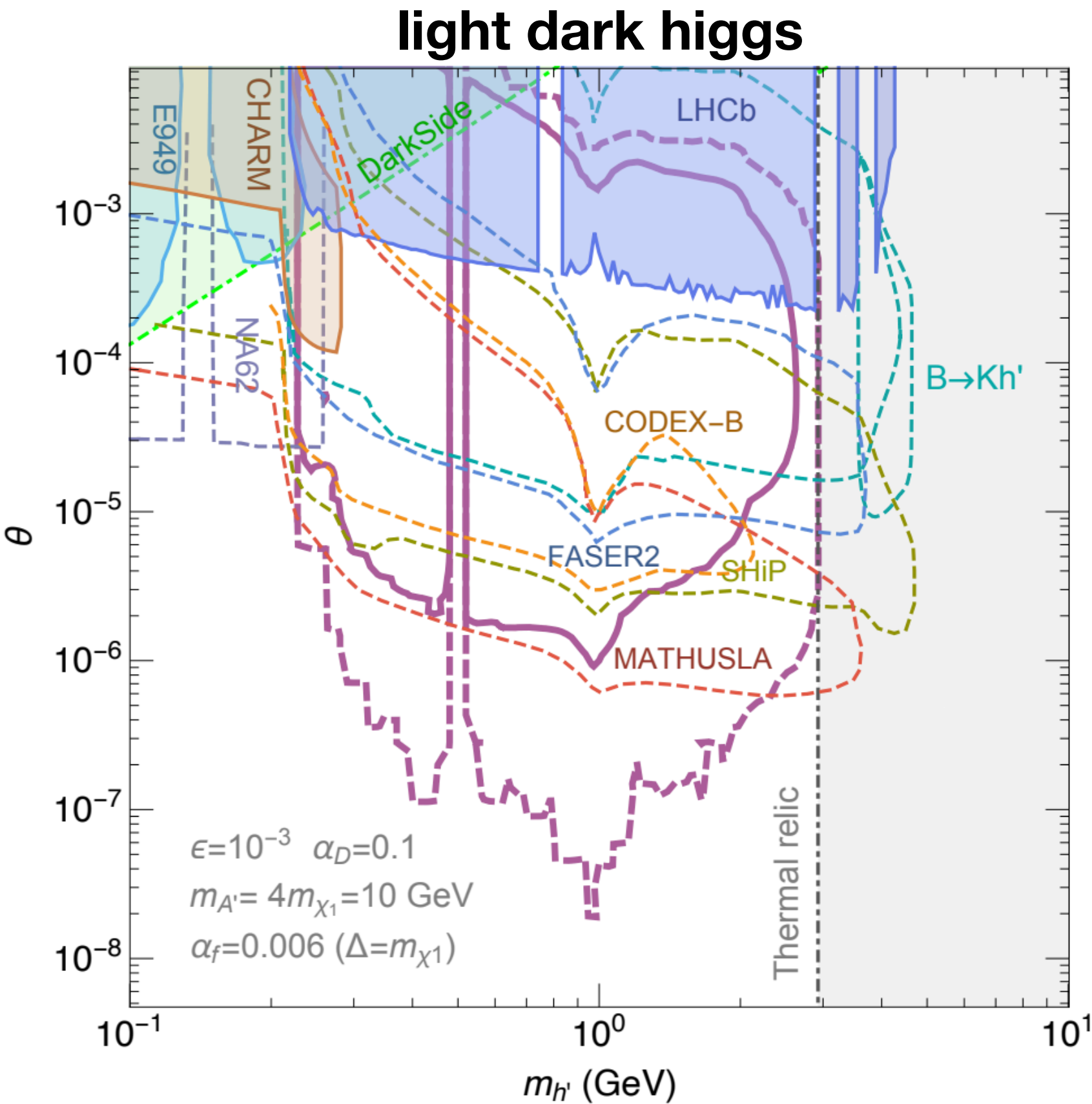
Beyond EFT/Simplified Model

Seto, Shimomura, Yoshida, 2504.15896
Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg, 2012.08595
Izaguirre, Krnjaic, Shuve, 1508.03050

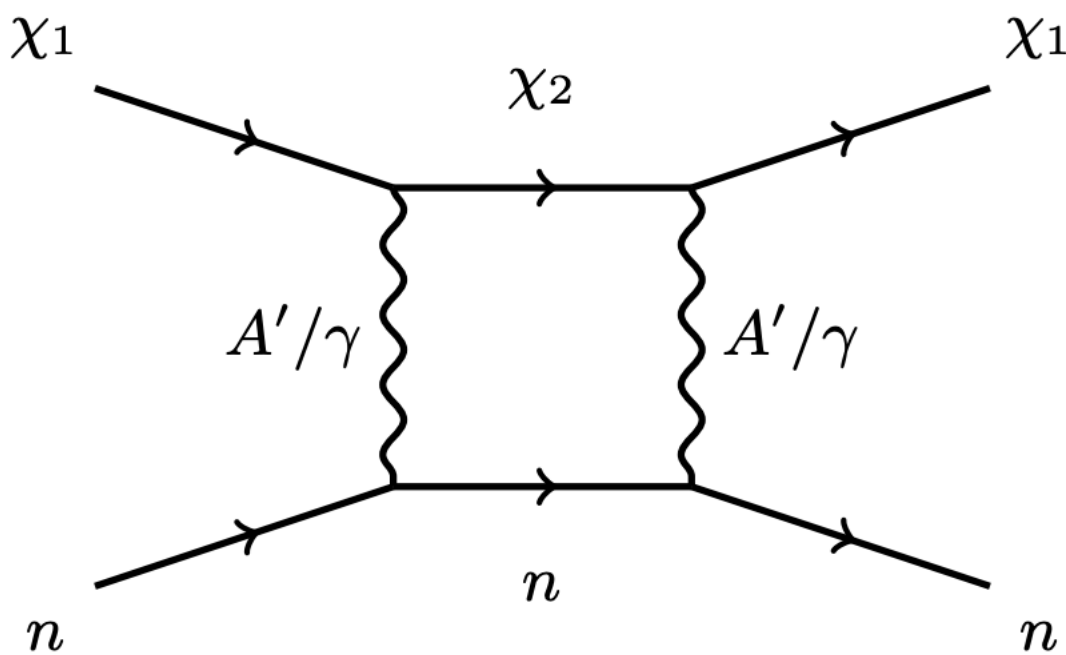
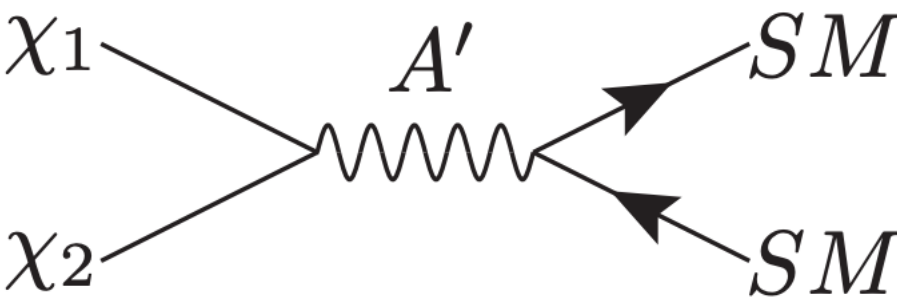
- ▶ Light new particle could mediate the interactions between SM particles.
- ▶ Light new particle could also mediate the interactions between SM particles and dark matter.
- ▶ **Light mediator** is naturally consistent with **light dark matter**.

$$\text{Br} \left(B^- \rightarrow K^- (X \rightarrow \ell^+ \ell^-) \right) = \text{Br}(B^- \rightarrow K^- X) \text{Br}(X \rightarrow \ell^+ \ell^-),$$

$$\text{Br} \left(K^- \rightarrow \pi^- (X \rightarrow \nu \bar{\nu}) \right) = \text{Br}(K^- \rightarrow \pi^- X) \text{Br}(X \rightarrow \nu \bar{\nu}),$$



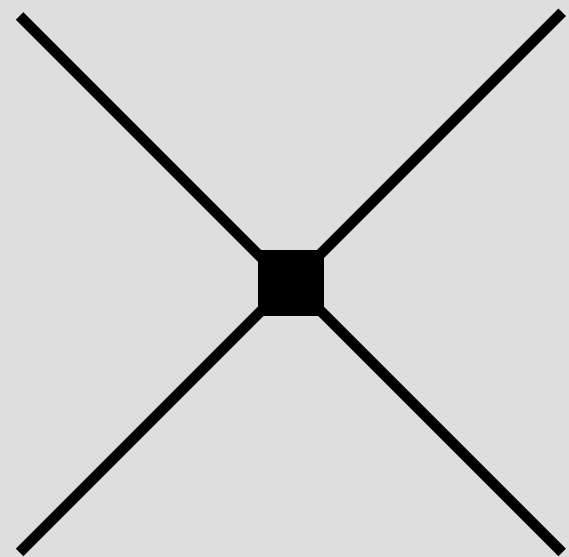
inelastic dark matter



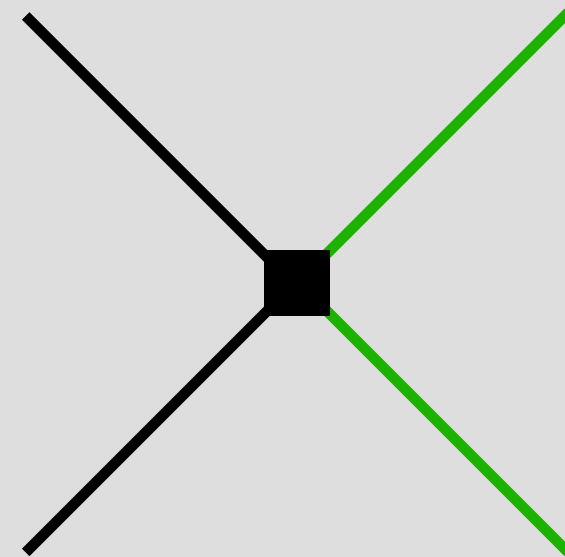
Outline

EFT Perspective

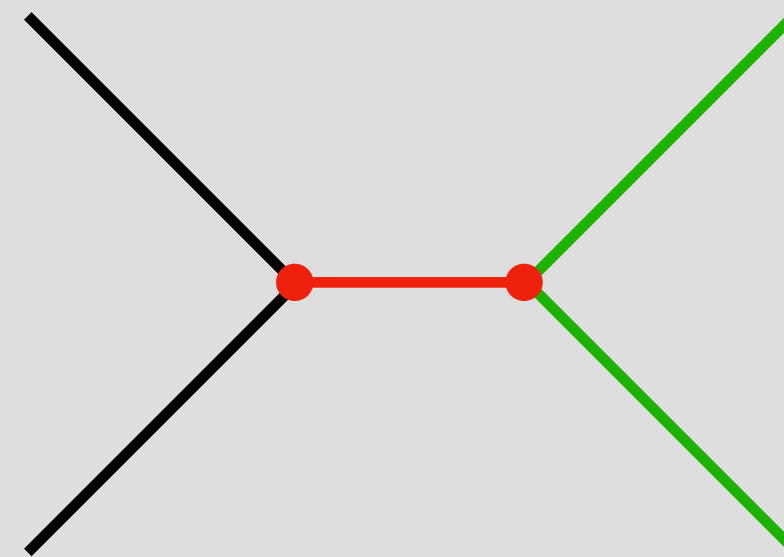
Conventional EFT



EFT with New d.o.f



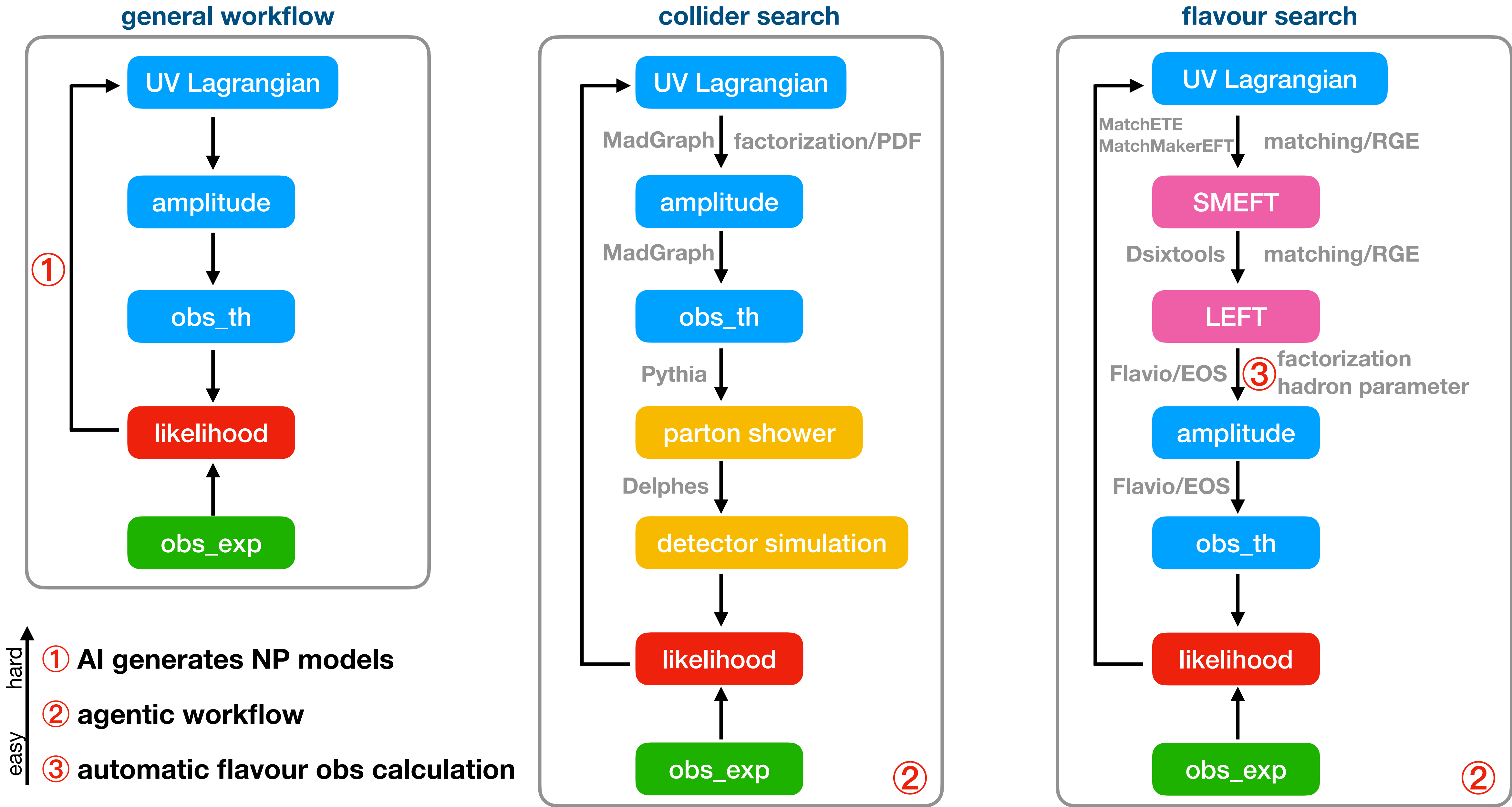
Beyond EFT



AI Perspective

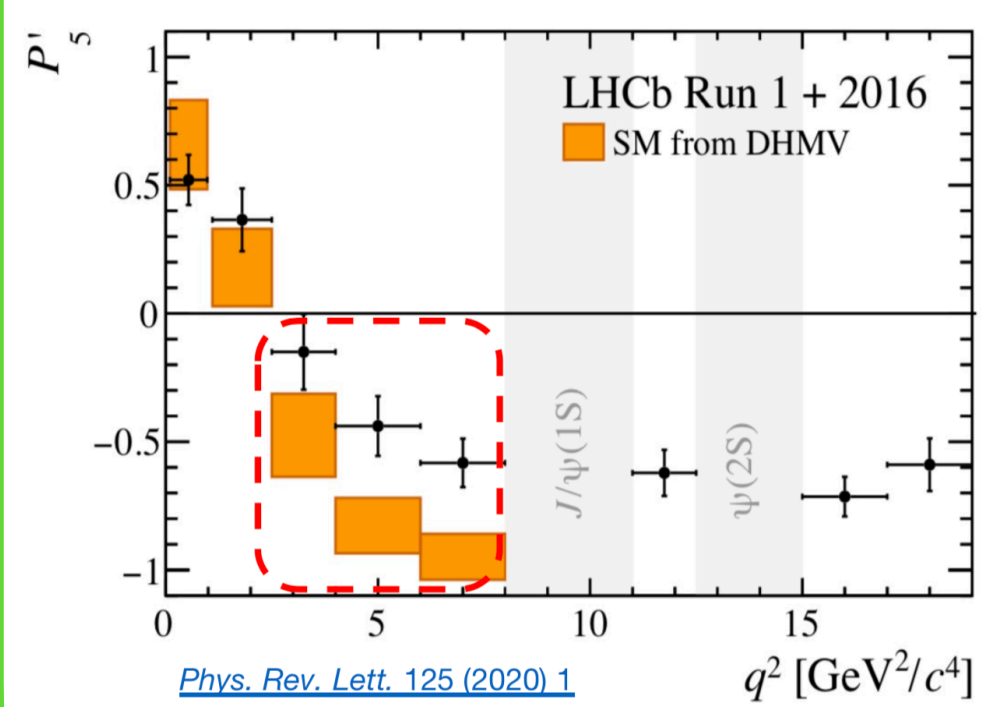
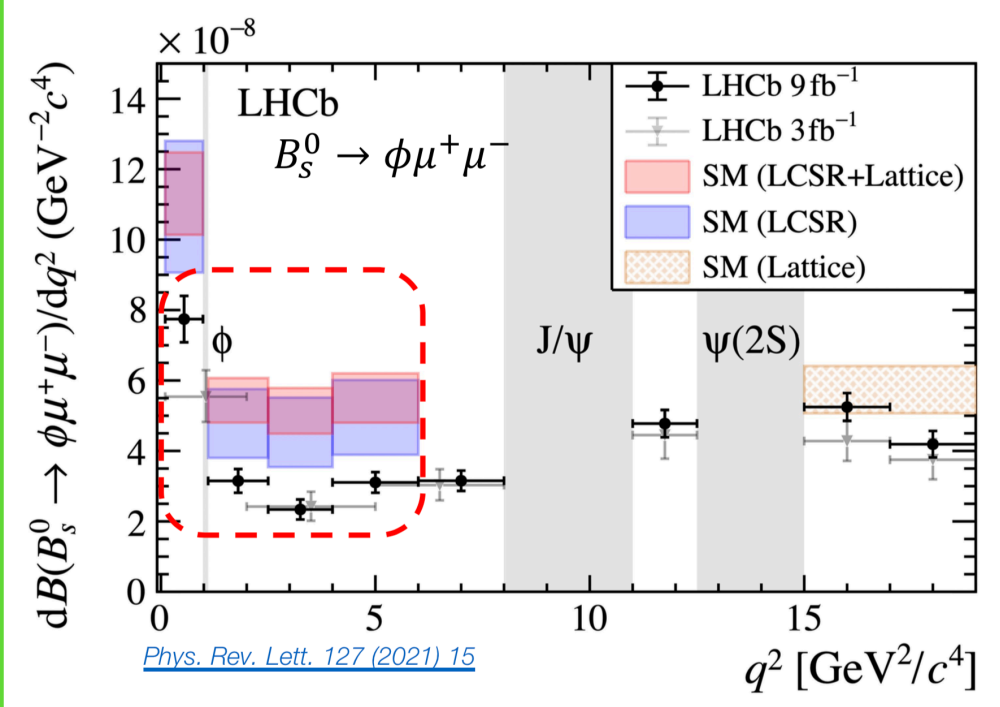
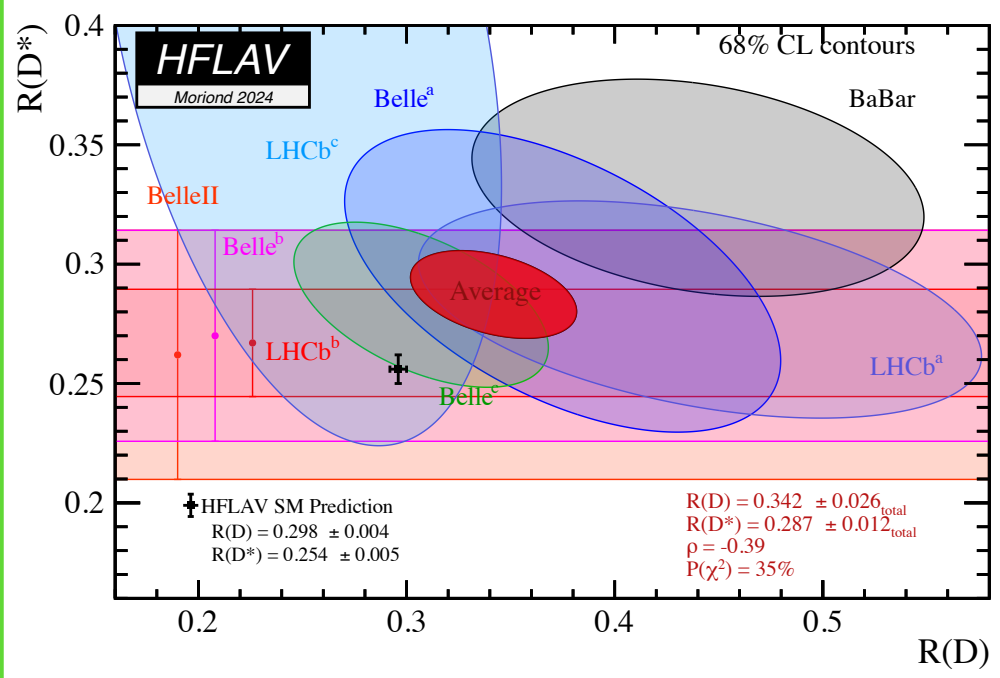


Searches for NP in Flavour Measurements: AI Perspective



Summary

exp measurement



more precise data needed !

SMEFT

inverse problem
(e.g., Fermi theory to SM)

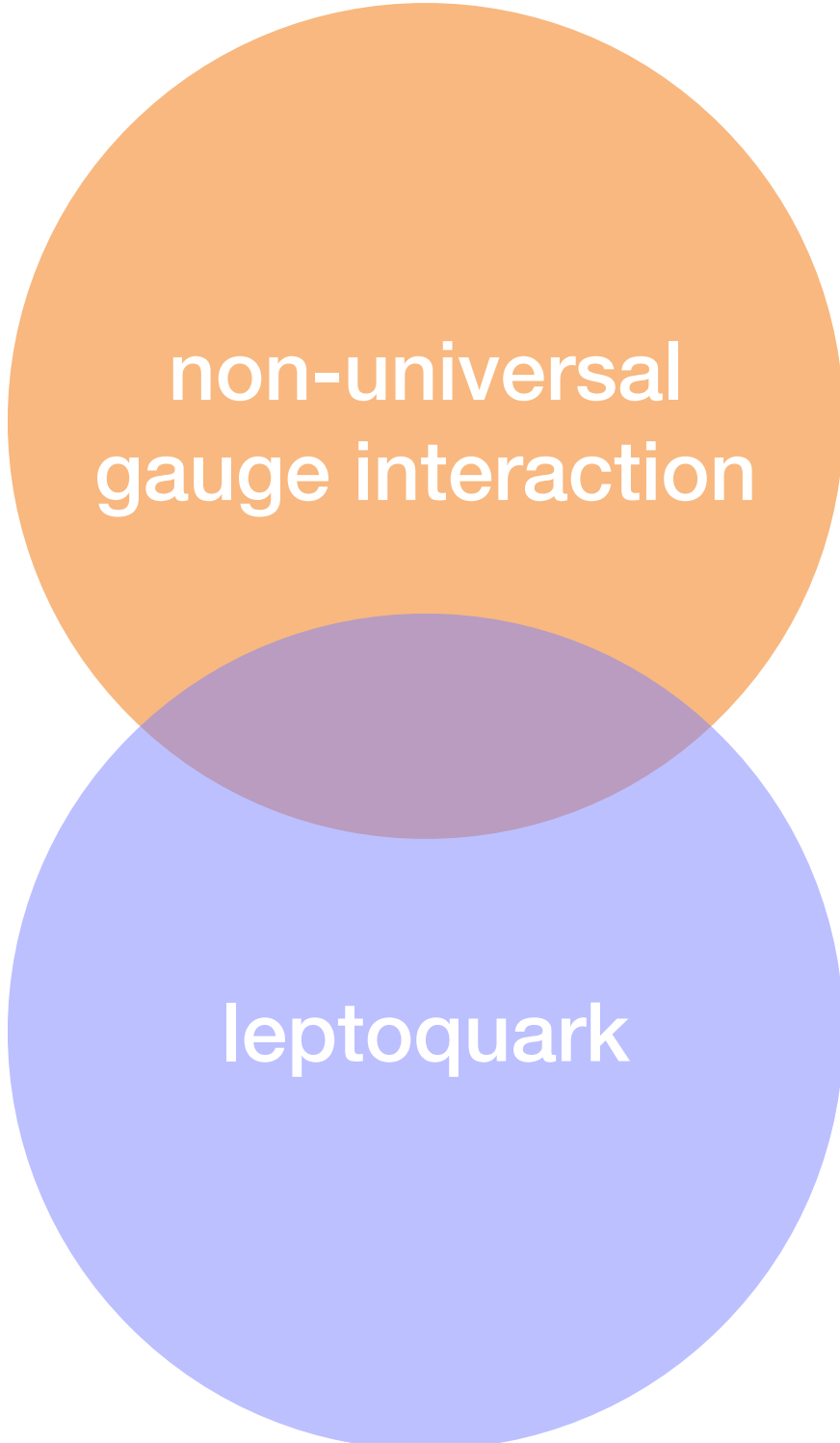
RGE
(well understood !)

LEFT/WET

QCD corrections
form factor/LCDA
non-local matrix element

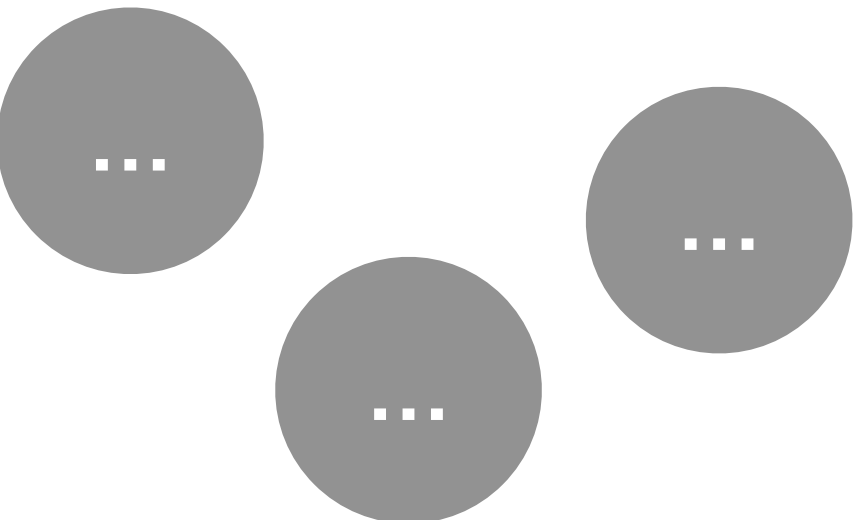
agentic workflow

NP model



question

- SM flavour puzzle
- NP flavour puzzle
- EW hierarchy problem
- Dark matter
- Matter-antimatter asymmetry
- CKM unitary violation



Thank You !

Backup

Dark SMEFT Operator

operator	definition	tree	loop	eq
$\mathcal{Q}_{u\phi}$	$(\bar{q}_p u_r \tilde{H})\phi + \text{h.c.}$			
$\mathcal{Q}_{u\phi^2}$	$(\bar{q}_p u_r \tilde{H})\phi^2 + \text{h.c.}$			
$\mathcal{Q}_{\phi q}$	$(\bar{q}_p \gamma_\mu q_r)(i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$			
$\mathcal{Q}_{\phi u}$	$(\bar{u}_p \gamma_\mu u_r)(i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$			
$\mathcal{Q}_{q\chi}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{\chi} \gamma^\mu \chi)$			
$\mathcal{Q}_{u\chi}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{\chi} \gamma^\mu \chi)$			
$\mathcal{Q}_{u\chi^2}$	$(\bar{q}_p u_r \tilde{H})(\chi^T C \chi)$			

$\mathcal{Q}_{qX}$	$(\bar{q}_p \gamma^\mu q_r) X_\mu$			
$\mathcal{Q}_{uX}$	$(\bar{u}_p \gamma^\mu u_r) X_\mu$			
$\mathcal{Q}_{HqX}^{(1)}$	$(H^\dagger H)(\bar{q}_p \gamma^\mu q_r) X_\mu$			
$\mathcal{Q}_{HqX}^{(3)}$	$(H^\dagger \tau^I H)(\bar{q}_p \tau^I \gamma^\mu q_r) X_\mu$			
$\mathcal{Q}_{uX^2}$	$(\bar{q}_p u_r \tilde{H}) X_\mu X^\mu + \text{h.c.}$			
$\mathcal{Q}_{HuX}$	$(H^\dagger H)(\bar{u}_p \gamma^\mu u_r) X_\mu$			
$\mathcal{Q}_{qXX}$	$(\bar{q}_p \gamma_\mu q_r) X^{\mu\nu} X_\nu$			
$\mathcal{Q}_{q\tilde{X}X}$	$(\bar{q}_p \gamma_\mu q_r) \tilde{X}^{\mu\nu} X_\nu$			
$\mathcal{Q}_{uXX}$	$(\bar{u}_p \gamma_\mu u_r) X^{\mu\nu} X_\nu$			
$\mathcal{Q}_{u\tilde{X}X}$	$(\bar{u}_p \gamma_\mu u_r) \tilde{X}^{\mu\nu} X_\nu$			
$\mathcal{Q}_{DqX^2}$	$(\bar{q}_p \gamma^\nu i D^\mu q_r) X_\mu X_\nu + \text{h.c.}$			
$\mathcal{Q}_{DuX^2}$	$(\bar{u}_p \gamma^\nu i D^\mu u_r) X_\mu X_\nu + \text{h.c.}$			
$\mathcal{Q}_{uHX^2}$	$(\bar{q}_p \sigma_{\mu\nu} u_r \tilde{H}) X_1^\mu X_2^\nu + \text{h.c.}$			
$\mathcal{Q}_{uHX}$	$(\bar{q}_p \sigma_{\mu\nu} u_r) \tilde{H} X^{\mu\nu} + \text{h.c.}$			

Dark LEFT Operator

operator	definition	tree	loop
$\mathcal{O}_{d\phi}$	$(\bar{d}_{Lp}d_{Rr})\phi + \text{h.c.}$	—	$\mathcal{Q}_{u\phi}$
$\mathcal{O}_{d\phi^2}$	$(\bar{d}_{Lp}d_{Rr})\phi^2 + \text{h.c.}$	—	$\mathcal{Q}_{u\phi^2}$
$\mathcal{O}_{\phi d}^L$	$(\bar{d}_{Lp}\gamma_\mu d_{Lr})(i\phi_1\overleftrightarrow{\partial}^\mu\phi_2)$	$\mathcal{Q}_{\phi q}$	$\mathcal{Q}_{\phi u}$
$\mathcal{O}_{\phi d}^R$	$(\bar{d}_{Rp}\gamma_\mu d_{Rr})(i\phi_1\overleftrightarrow{\partial}^\mu\phi_2)$	—	—
$\mathcal{O}_{d\chi}^{S,LR}$	$(\bar{d}_{Rp}d_{Lr})(\chi^TC\chi) + \text{h.c.}$	—	$\mathcal{Q}_{u\chi^2}$
$\mathcal{O}_{d\chi}^{S,RR}$	$(\bar{d}_{Lp}d_{Rr})(\chi^TC\chi) + \text{h.c.}$	—	$\mathcal{Q}_{u\chi^2}$
$\mathcal{O}_{d\chi}^{V,LR}$	$(\bar{d}_{Lp}\gamma_\mu d_{Lr})(\bar{\chi}\gamma^\mu\chi)$	$\mathcal{Q}_{q\chi}$	$\mathcal{Q}_{u\chi}$
$\mathcal{O}_{d\chi}^{V,RR}$	$(\bar{d}_{Rp}\gamma_\mu d_{Rr})(\bar{\chi}\gamma^\mu\chi)$	—	—
$\mathcal{O}_{d\chi}^{T,RR}$	$(\bar{d}_{Lp}\sigma^{\mu\nu}d_{Rr})(\chi^TC\sigma_{\mu\nu}\chi) + \text{h.c.}$	—	—
$\mathcal{O}_{dX}^T$	$(\bar{d}_{Lp}\sigma^{\mu\nu}d_{Rr})X_{\mu\nu} + \text{h.c.}$	—	$\mathcal{Q}_{uX}, \mathcal{Q}_{qX}, \mathcal{Q}_{uHX}, \mathcal{Q}_{HuX}, \mathcal{Q}_{HqX}$
$\mathcal{O}_{dX}^L$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})X_\mu$	$\mathcal{Q}_{qX}, \mathcal{Q}_{HqX}$	$\mathcal{Q}_{uX}, \mathcal{Q}_{HuX}$
$\mathcal{O}_{dX}^R$	$(\bar{d}_{Rp}\gamma^\mu d_{Rr})X_\mu$	—	—
$\mathcal{O}_{dX^2}$	$(\bar{d}_{Lp}d_{Rr})X_\mu X^\mu + \text{h.c.}$	—	$\mathcal{Q}_{uX^2}, \mathcal{Q}_{DuX^2}, \mathcal{Q}_{DqX^2}$
$\mathcal{O}_{dX^2}^T$	$(\bar{d}_{Lp}\sigma_{\mu\nu}d_{Rr})X_1^\mu X_2^\nu + \text{h.c.}$	—	$\mathcal{Q}_{uHX^2}$
$\mathcal{O}_{dXX}^L$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})X_{\mu\nu}X^\nu$	$\mathcal{Q}_{qXX}$	$\mathcal{Q}_{uXX}$
$\mathcal{O}_{dXX}^R$	$(\bar{d}_{Rp}\gamma^\mu d_{Rr})X_{\mu\nu}X^\nu$	—	—
$\mathcal{O}_{d\tilde{X}X}^L$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})\tilde{X}_{\mu\nu}X^\nu$		
$\mathcal{O}_{d\tilde{X}X}^R$	$(\bar{d}_{Rp}\gamma^\mu d_{Rr})\tilde{X}_{\mu\nu}X^\nu$		
$\mathcal{O}_{DdX^2}^L$	$(\bar{d}_{Lp}\gamma^\mu iD^\nu d_{Lr})X_\mu X_\nu + \text{h.c.}$	$\mathcal{Q}_{DqX^2}$	$\mathcal{Q}_{DuX^2}$
$\mathcal{O}_{DdX^2}^R$	$(\bar{d}_{Rp}\gamma^\mu iD^\nu d_{Rr})X_\mu X_\nu + \text{h.c.}$	—	—

$\mathcal{O}_{da}^L$	$(\bar{d}_{Lp}\gamma_\mu d_{Lr})\partial^\mu a$	$\mathcal{Q}_{qa}$	$\mathcal{Q}_{ua}$
$\mathcal{O}_{da}^R$	$(\bar{d}_{Rp}\gamma_\mu d_{Rr})\partial^\mu a$	—	—
$\mathcal{O}_{GG\phi^2}$	$G_{\mu\nu}^a G^{\mu\nu,a}\phi^2 (\mathcal{O}_{g\phi})$	—	$\mathcal{Q}_{u\phi^2}$
$\mathcal{O}_{G\tilde{G}\phi^2}$	$G_{\mu\nu}^a \tilde{G}^{\mu\nu,a}\phi^2 (\mathcal{O}_{g\phi})$	—	$\mathcal{Q}_{u\phi^2}$
$\mathcal{O}_{GG\chi}$	$G_{\mu\nu}^a G^{\mu\nu,a}\chi^TC\chi (\mathcal{O}_{g\chi})$	—	$\mathcal{Q}_{u\chi^2}$
$\mathcal{O}_{G\tilde{G}\chi}$	$G_{\mu\nu}^a \tilde{G}^{\mu\nu,a}\chi^TC\chi (\mathcal{O}_{g\chi})$	—	$\mathcal{Q}_{u\chi^2}$
$\mathcal{O}_{GGXX}$	$G_{\mu\nu}^a G^{\mu\nu,a}X_\rho X^\rho (\mathcal{O}_{gX})$	—	$\mathcal{Q}_{uX^2}$
$\mathcal{O}_{G\tilde{G}XX}$	$G_{\mu\nu}^a \tilde{G}^{\mu\nu,a}X_\rho X^\rho (\mathcal{O}_{gX})$	—	$\mathcal{Q}_{uX^2}$
$\mathcal{O}_{GXXGX}$	$G_{\lambda\mu}^a G_{\nu}^{\lambda,a}X^\mu X^\nu (\mathcal{O}_{gXX})$	—	$\mathcal{Q}_{DqX^2}, \mathcal{Q}_{DuX^2}$
$\mathcal{O}_{GX\tilde{G}X}$	$G_{\lambda\mu}^a \tilde{G}_{\nu}^{\lambda,a}X^\mu X^\nu (\mathcal{O}_{gXX})$		
$\mathcal{O}_{FF\phi^2}$	$F_{\mu\nu}F^{\mu\nu}\phi^2 (\mathcal{O}_{\phi\gamma})$	—	$\mathcal{Q}_{u\phi^2}$
$\mathcal{O}_{F\tilde{F}\phi^2}$	$F_{\mu\nu}\tilde{F}^{\mu\nu}\phi^2 (\mathcal{O}_{\phi\gamma})$		
$\mathcal{O}_{FF\chi}$	$F_{\mu\nu}F^{\mu\nu}\chi^TC\chi (\mathcal{O}_{\chi\gamma})$	—	$\mathcal{Q}_{u\chi}$
$\mathcal{O}_{F\tilde{F}\chi}$	$F_{\mu\nu}\tilde{F}^{\mu\nu}\chi^TC\chi (\mathcal{O}_{\chi\gamma})$		
$\mathcal{O}_{FFXX}$	$F_{\mu\nu}F^{\mu\nu}X_\rho X^\rho (\mathcal{O}_{X\gamma})$	—	$\mathcal{Q}_{uX^2}$
$\mathcal{O}_{F\tilde{F}XX}$	$F_{\mu\nu}\tilde{F}^{\mu\nu}X_\rho X^\rho (\mathcal{O}_{X\gamma})$		
$\mathcal{O}_{FXFX}$	$F_{\lambda\mu}F_{\nu}^{\lambda}X^\mu X^\nu (\mathcal{O}_{XX\gamma})$	—	$\mathcal{Q}_{DqX^2}, \mathcal{Q}_{DuX^2}$
$\mathcal{O}_{FX\tilde{F}X}$	$F_{\lambda\mu}\tilde{F}_{\nu}^{\lambda}X^\mu X^\nu (\mathcal{O}_{XX\gamma})$		

$$\mathcal{C} = \begin{cases} \mathcal{C}_t & \text{for } \bar{u}_L \gamma^\mu \mathcal{C} u_L, u_R \gamma^\mu \mathcal{C} u_R, \bar{u}_L \mathcal{C} u_R, \bar{u}_L \sigma^{\mu\nu} \mathcal{C} u_R, \\ V^\dagger \mathcal{C}_t V & \text{for } \bar{d}_L \gamma^\mu \mathcal{C} d_L, \\ V^\dagger \mathcal{C}_t & \text{for } \bar{d}_L \mathcal{C} u_R, \bar{d}_L \sigma^{\mu\nu} \mathcal{C} u_R, \end{cases}$$

$$V^\dagger \mathcal{C}_t V = \mathcal{C}_{33} \begin{pmatrix} V_{td}^* V_{td} & V_{td}^* V_{ts} & V_{td}^* V_{tb} \\ V_{ts}^* V_{td} & V_{ts}^* V_{ts} & V_{ts}^* V_{tb} \\ V_{tb}^* V_{td} & V_{tb}^* V_{ts} & V_{tb}^* V_{tb} \end{pmatrix} \quad \mathcal{C}_t \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \mathcal{C}_{33} \end{pmatrix}$$

$$= \mathcal{C}_{33} \begin{pmatrix} 0.71 & -3.09 - 1.45i & 76.81 + 34.29i \\ -3.09 + 1.45i & 16.43 & -404.93 + 7.87i \\ 76.81 - 34.29i & -404.93 - 7.87i & 9982.86 \end{pmatrix} \times 10^{-4}$$

$$V^\dagger \mathcal{C}_t = \mathcal{C}_{33} \begin{pmatrix} 0 & 0 & V_{td}^* \\ 0 & 0 & V_{ts}^* \\ 0 & 0 & V_{tb}^* \end{pmatrix} = \mathcal{C}_{33} \begin{pmatrix} 0 & 0 & 0.77 + 0.34i \\ 0 & 0 & -4.05 + 0.08i \\ 0 & 0 & 99.91 \end{pmatrix} \times 10^{-2}$$

$$\mathcal{C}_i = \begin{cases} \mathcal{C}_t^i & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi u}, \mathcal{Q}_{u\chi}, \mathcal{Q}_{uX}, \mathcal{Q}_{HuX}, \mathcal{Q}_{uXX}, \mathcal{Q}_{u\tilde{X}X}, \mathcal{Q}_{DuX^2}, \mathcal{Q}_{ua}, \\ (\mathcal{C}_t^i, V^\dagger \mathcal{C}_t^i) & \text{for } \mathcal{Q}_i = \mathcal{Q}_{u\phi}, \mathcal{Q}_{u\phi^2}, \mathcal{Q}_{u\chi^2}, \mathcal{Q}_{qu\chi l}, \mathcal{Q}_{uHX}, \mathcal{Q}_{uX^2}, \mathcal{Q}_{uHX^2}, \\ (\mathcal{C}_t^i, V^\dagger \mathcal{C}_t^i V) & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi q}, \mathcal{Q}_{q\chi}, \mathcal{Q}_{qX}, \mathcal{Q}_{HqX}^{(1,3)}, \mathcal{Q}_{qXX}, \mathcal{Q}_{q\tilde{X}X}, \mathcal{Q}_{DqX^2}, \mathcal{Q}_{qa}, \end{cases}$$

$b \rightarrow s\nu\bar{\nu}$: SMEFT with MFV

► Prediction

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})}{\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})} = \frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}}}{\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SM}}} = 0.46 \pm 0.07$$

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})}{\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})} = \frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}}}{\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}}} = 29.7 \pm 5.6$$

► prediction

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SM}} = (9.00 \pm 0.87) \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{MFV}} = (50_{-16}^{+17}) \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{exp}} < 18 \times 10^{-6}$$

$$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} = (1.40 \pm 0.18) \times 10^{-7}$$

$$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{MFV}} = (7.8_{-2.6}^{+2.8}) \times 10^{-7}$$

$$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{exp}} < 140 \times 10^{-7}$$

SMEFT

$$\mathcal{Q}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{q}_p \gamma^\mu q_r),$$

$$\mathcal{Q}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^I H) (\bar{q}_p \tau^I \gamma^\mu q_r),$$

$$\mathcal{Q}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{d}_p \gamma^\mu d_r),$$

induce $\bar{s}bZ$ interaction,
Thus, universally affect
 $b \rightarrow s e^+ e^-, \mu^+ \mu^-, \tau^+ \tau^-$

$$\mathcal{Q}_{ld} = (\bar{l}_p \gamma^\mu l_r) (\bar{d}_s \gamma_\mu d_t),$$

forbidden by MFV

$$\mathcal{Q}_{lq}^{(1)} = (\bar{l}_p \gamma^\mu l_r) (\bar{q}_s \gamma_\mu q_t),$$

$$\mathcal{Q}_{lq}^{(3)} = (\bar{l}_p \gamma^\mu \tau^I l_r) (\bar{q}_s \tau^I \gamma_\mu q_t),$$

μ_{EW}

LEFT

$$\mathcal{O}_L^{\nu_i \nu_j} = (\bar{s} \gamma_\mu P_L b) (\bar{\nu}_i \gamma^\mu P_L \nu_j)$$

$$\mathcal{O}_R^{\nu_i \nu_j} = (\bar{s} \gamma_\mu P_R b) (\bar{\nu}_i \gamma^\mu P_L \nu_j)$$

one LEFT operator !
just the SM operator

μ_b

$b \rightarrow s\nu\bar{\nu}$: SMEFT with MFV

► Prediction

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})}{\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})} = \frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}}}{\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SM}}} = 0.46 \pm 0.07$$

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})}{\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})} = \frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}}}{\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}}} = 29.7 \pm 5.6$$

► prediction

$$\left. \begin{aligned} \mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SM}} &= (9.00 \pm 0.87) \times 10^{-6} \\ \mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{MFV}} &= (50^{+17}_{-16}) \times 10^{-6} \\ \mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{exp}} &< 18 \times 10^{-6} \end{aligned} \right\} \text{Inconsistent} \longrightarrow$$

$$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} = (1.40 \pm 0.18) \times 10^{-7}$$

$$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{MFV}} = (7.8^{+2.8}_{-2.6}) \times 10^{-7}$$

$$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{exp}} < 140 \times 10^{-7}$$

Belle II excess (if confirmed in the future) implies:

- impossible to explain in SMEFT with MFV
- NP flavour structure is highly non-trivial
- **NP structure in quark sector is beyond MFV**
- **flavour violation is beyond Yukawa coupling**

This conclusion only assumes the quark MFV.
No lepton flavour structure is assumed.

$b \rightarrow s\nu\bar{\nu}$: SMEFT

SMEFT

$$\mathcal{Q}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{q}_p \gamma^\mu q_r),$$

$$\mathcal{Q}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^I H) (\bar{q}_p \tau^I \gamma^\mu q_r),$$

$$\mathcal{Q}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{d}_p \gamma^\mu d_r),$$

$$\mathcal{Q}_{ld} = (\bar{l}_p \gamma^\mu l_r) (\bar{d}_s \gamma_\mu d_t),$$

$$\mathcal{Q}_{lq}^{(1)} = (\bar{l}_p \gamma^\mu l_r) (\bar{q}_s \gamma_\mu q_t),$$

$$\mathcal{Q}_{lq}^{(3)} = (\bar{l}_p \gamma^\mu \tau^I l_r) (\bar{q}_s \tau^I \gamma_\mu q_t),$$

μ_{EW}

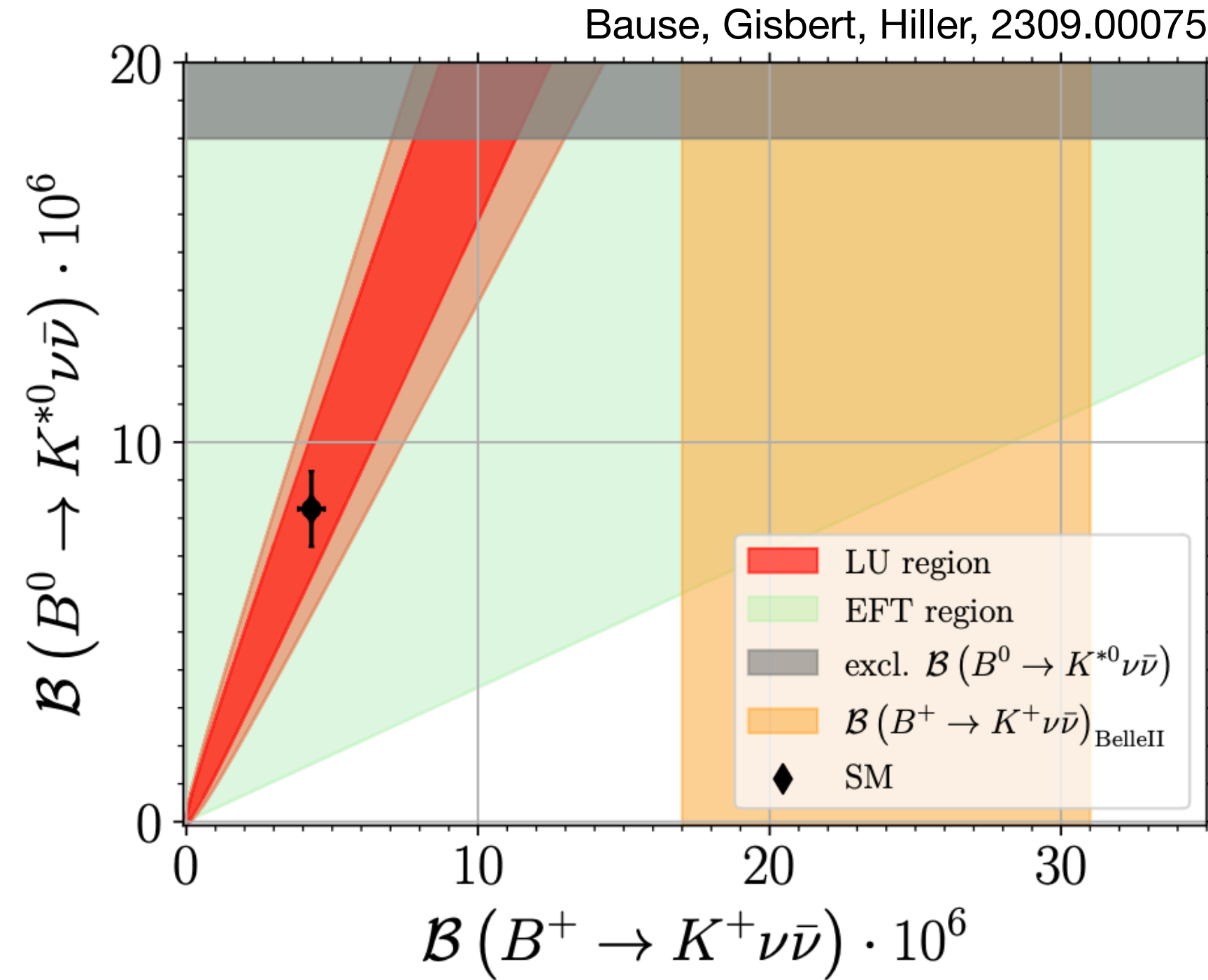
LEFT

$$\mathcal{O}_L^{\nu_i \nu_j} = (\bar{s} \gamma_\mu P_L b) (\bar{\nu}_i \gamma^\mu P_L \nu_j)$$

$$\mathcal{O}_R^{\nu_i \nu_j} = (\bar{s} \gamma_\mu P_R b) (\bar{\nu}_i \gamma^\mu P_L \nu_j)$$

μ_b

operator structure highly
constrained by Left-handed neutrino



$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) = A_+^{BK} x^+,$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu}) = A_+^{BK^*} x^+ + A_-^{BK^*} x^-,$$

$$x^\pm = \sum_{\nu, \nu'} |C_L^{\nu \nu'} \pm C_R^{\nu \nu'}|^2,$$

Bause, Gisbert, Hiller, 2309.00075

Allwicher, Becirevic, Piazza, Rosauero-Alcaraz, Sumensari, 2309.02246

Chen, Wen, Xu, 2401.11552

$b \rightarrow s\nu\bar{\nu}$: SMEFT

SMEFT	$\mathcal{Q}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{q}_p \gamma^\mu q_r),$
	$\mathcal{Q}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^I H) (\bar{q}_p \tau^I \gamma^\mu q_r),$
	$\mathcal{Q}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{d}_p \gamma^\mu d_r),$
	$\mathcal{Q}_{ld} = (\bar{l}_p \gamma^\mu l_r) (\bar{d}_s \gamma_\mu d_t),$
	$\mathcal{Q}_{lq}^{(1)} = (\bar{l}_p \gamma^\mu l_r) (\bar{q}_s \gamma_\mu q_t),$
μ_{EW}	$\mathcal{Q}_{lq}^{(3)} = (\bar{l}_p \gamma^\mu \tau^I l_r) (\bar{q}_s \tau^I \gamma_\mu q_t),$
	$\mathcal{O}_L^{\nu_i \nu_j} = (\bar{s} \gamma_\mu P_L b) (\bar{\nu}_i \gamma^\mu P_L \nu_j)$
	$\mathcal{O}_R^{\nu_i \nu_j} = (\bar{s} \gamma_\mu P_R b) (\bar{\nu}_i \gamma^\mu P_L \nu_j)$
LEFT	
μ_b	operator structure highly constrained by Left-handed neutrino

$b \rightarrow s$

Observable	SM	Exp	Unit
$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$	4.16 ± 0.57	$23 \pm 5_{-4}^{+5}$	10^{-6}
$\mathcal{B}(B^0 \rightarrow K^0 \nu \bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
$\mathcal{B}(B^+ \rightarrow K^{*+} \nu \bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})$	9.00 ± 0.87	< 18	10^{-6}
$\mathcal{B}(B_s \rightarrow \phi \nu \bar{\nu})$	9.93 ± 0.72	< 5400	10^{-6}
$\mathcal{B}(B_s \rightarrow \nu \bar{\nu})$	≈ 0	< 5.9	10^{-4}
$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})$	1.40 ± 0.18	< 140	10^{-7}
$\mathcal{B}(B^0 \rightarrow \pi^0 \nu \bar{\nu})$	6.52 ± 0.85	< 900	10^{-8}
$\mathcal{B}(B^+ \rightarrow \rho^+ \nu \bar{\nu})$	4.06 ± 0.79	< 300	10^{-7}
$\mathcal{B}(B^0 \rightarrow \rho^0 \nu \bar{\nu})$	1.89 ± 0.36	< 400	10^{-7}
$\mathcal{B}(B^0 \rightarrow \nu \bar{\nu})$	≈ 0	< 1.4	10^{-4}
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	8.42 ± 0.61	$10.6_{-3.4}^{+4.0} \pm 0.9$	10^{-11}
$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}

$b \rightarrow d$

$s \rightarrow d$

Why such a large NP effect has not shown up in other $b \rightarrow s$ decays ?
in $b \rightarrow d, s \rightarrow d$ decays ? **NP flavour structure**

$b \rightarrow s\nu\bar{\nu}$ and $b \rightarrow s\ell\ell$

SMEFT notation: $l = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$, $q = \begin{pmatrix} u \\ d \end{pmatrix}_L$, $d = d_R$

B.F.Hou, X.Q.Li, M.Shen, Y.D.Yang, **XB**Y, 2402.19208

► Prediction

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})}{\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})} = \frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}}}{\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SM}}} = 0.46 \pm 0.07$$

► prediction

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SM}} = (9.00 \pm 0.87) \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SMEFT}} = (50^{+17}_{-16}) \times 10^{-6} \quad \text{conflict}$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{exp}} < 18 \times 10^{-6}$$

► Only $\mathcal{O}_{lq}^{(3)}$ is relevant with $R_{D^{(*)}}$

► $\mathcal{O}_{ld}$ can explain the $B^+ \rightarrow K^+ \nu \bar{\nu}$ data

► $\mathcal{O}_{ld}$ also induce $O'_{9,ij}$ and $O'_{10,ij}$

► They can't improve the $b \rightarrow s\ell\ell$ fit

► O'_{9e} and $O'_{10\mu}$ worsen the fit. **weird** (LFV, $\tau\tau \gg ee, \mu\mu$)

► $O'_{9,ij}$ and $O'_{10,ij}$ with $i = j = \tau$ has no effect.

► $O'_{9,ij}$ and $O'_{10,ij}$ with $i \neq j$ (i.e. LFV) has no effect.

SMEFT

$$\begin{aligned} \mathcal{Q}_{Hq}^{(1)} &= (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{q}_p \gamma^\mu q_r), \\ \mathcal{Q}_{Hq}^{(3)} &= (H^\dagger i \overleftrightarrow{D}_\mu^I H) (\bar{q}_p \tau^I \gamma^\mu q_r), \\ \mathcal{Q}_{Hd} &= (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{d}_p \gamma^\mu d_r), \end{aligned}$$

$$\mathcal{Q}_{ld} = (\bar{l}_p \gamma^\mu l_r) (\bar{d}_s \gamma_\mu d_t),$$

$$\begin{aligned} \mathcal{Q}_{lq}^{(1)} &= (\bar{l}_p \gamma^\mu l_r) (\bar{q}_s \gamma_\mu q_t), \\ \mathcal{Q}_{lq}^{(3)} &= (\bar{l}_p \gamma^\mu \tau^I l_r) (\bar{q}_s \tau^I \gamma_\mu q_t), \end{aligned}$$

induce $\bar{s}bZ$ interaction,
Thus, universally affect
 $b \rightarrow se^+e^-, \mu^+\mu^-, \tau^+\tau^-$

μ_{EW}

LEFT

$$\begin{aligned} \mathcal{O}_L^{\nu_i \nu_j} &= (\bar{s} \gamma_\mu P_L b) (\bar{\nu}_i \gamma^\mu P_L \nu_j) \\ \mathcal{O}_R^{\nu_i \nu_j} &= (\bar{s} \gamma_\mu P_R b) (\bar{\nu}_i \gamma^\mu P_L \nu_j) \end{aligned}$$

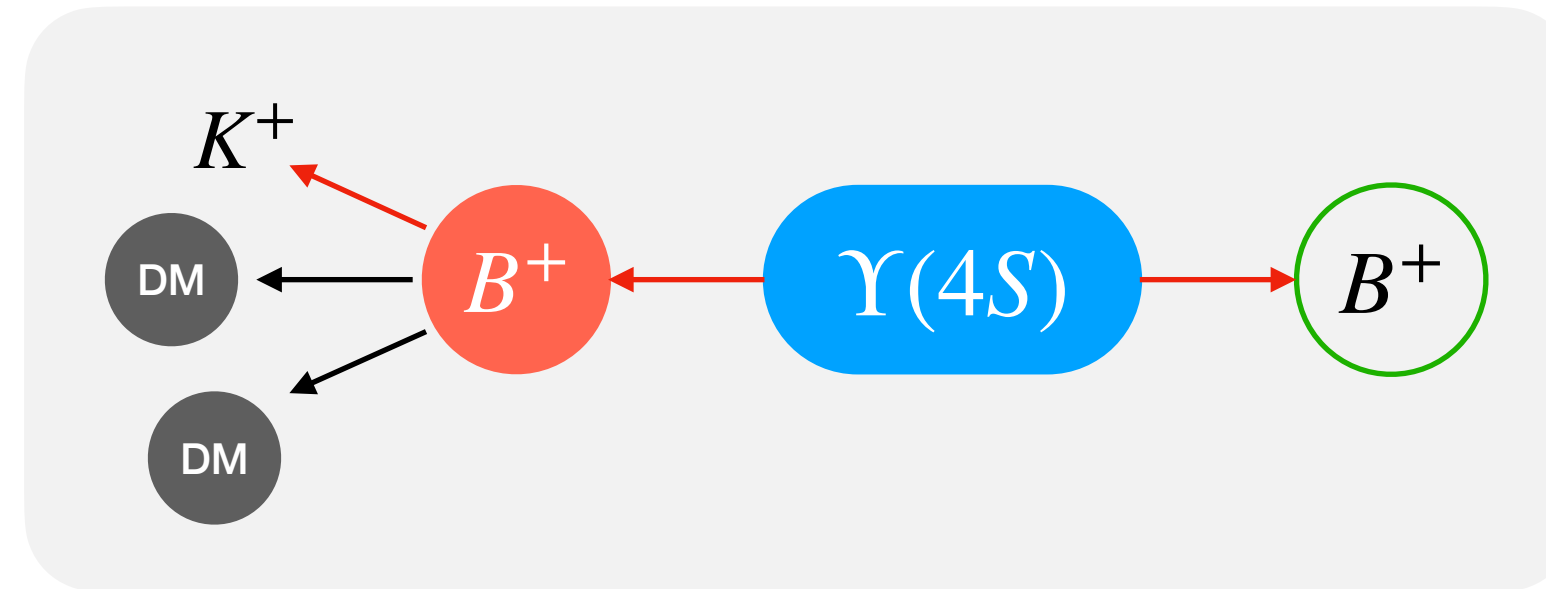
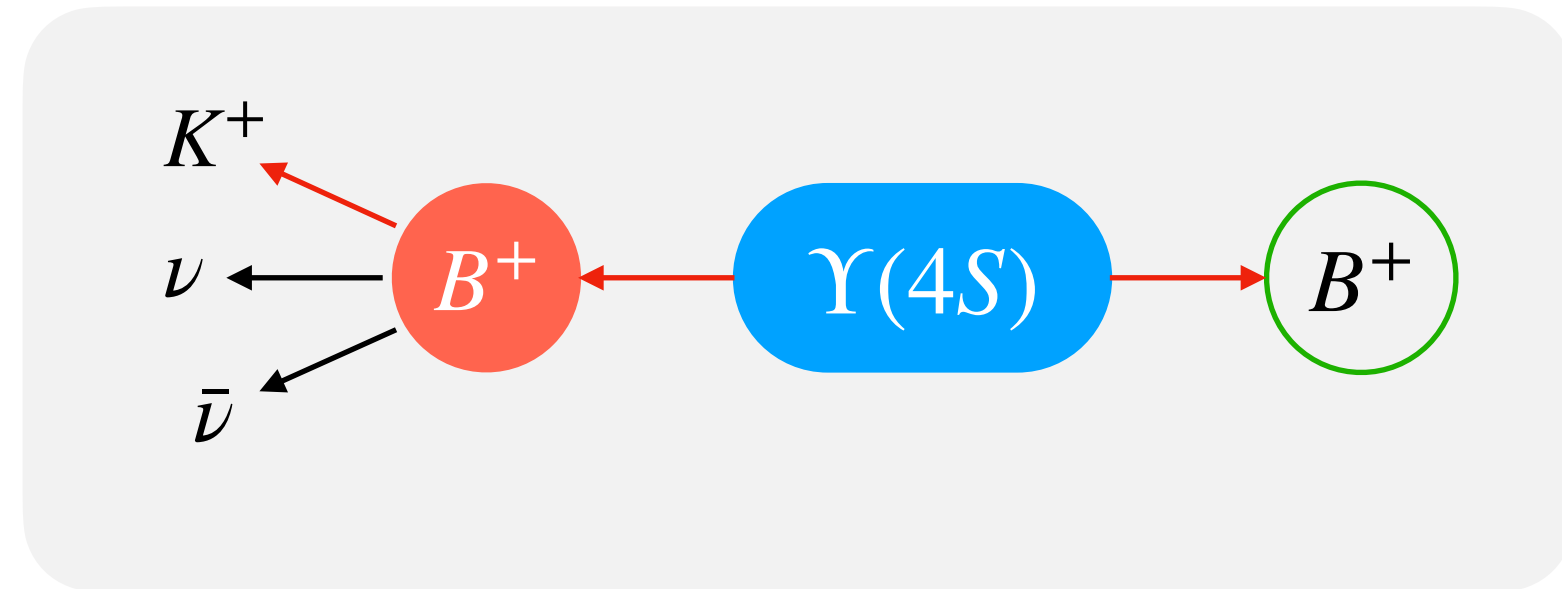
one LEFT operator !
just the SM operator

μ_b

$$O'_{9,ij} = (\bar{b} \gamma^\mu P_R s) (\bar{\ell}_i \gamma_\mu \ell_j)$$

$$O'_{10,ij} = (\bar{b} \gamma^\mu P_R s) (\bar{\ell}_i \gamma_\mu \gamma_5 \ell_j)$$

$b \rightarrow s\nu\bar{\nu}$: exp picture



$$\begin{aligned} \mathcal{Q}_{Hq}^{(1)} &= (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{q}_p \gamma^\mu q_r), \\ \mathcal{Q}_{Hq}^{(3)} &= (H^\dagger i \overleftrightarrow{D}_\mu^I H) (\bar{q}_p \tau^I \gamma^\mu q_r), \\ \mathcal{Q}_{Hd} &= (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{d}_p \gamma^\mu d_r), \end{aligned}$$

$$\mathcal{Q}_{ld} = (\bar{l}_p \gamma^\mu l_r) (\bar{d}_s \gamma_\mu d_t),$$

$$\begin{aligned} \mathcal{Q}_{lq}^{(1)} &= (\bar{l}_p \gamma^\mu l_r) (\bar{q}_s \gamma_\mu q_t), \\ \mathcal{Q}_{lq}^{(3)} &= (\bar{l}_p \gamma^\mu \tau^I l_r) (\bar{q}_s \tau^I \gamma_\mu q_t), \end{aligned}$$

$$\begin{aligned} \mathcal{O}_L^{\nu_i \nu_j} &= (\bar{s} \gamma_\mu P_L b) (\bar{\nu}_i \gamma^\mu P_L \nu_j) \\ \mathcal{O}_R^{\nu_i \nu_j} &= (\bar{s} \gamma_\mu P_R b) (\bar{\nu}_i \gamma^\mu P_L \nu_j) \end{aligned}$$

SMEFT

Dark SMEFT

example

$$\mathcal{Q}_{d\phi^2} = (\bar{q}_p d_r H) \phi^2$$

$$\mathcal{Q}_{d\chi} = (\bar{d}_p \gamma_\mu d_r) (\bar{\chi} \gamma^\mu \chi)$$

$$\mathcal{Q}_{dX^2} = (\bar{q}_p d_r H) X_\mu X^\mu$$

$$\mathcal{Q}_{qa} = (\bar{q}_p \gamma_\mu q_r) \partial^\mu a$$

2011 Kamenik, Smith

2014 Duch, Grzadkowski, Wudka

2017 Brod, Gootjes-Dreesbach, Tamaro, Zupan

2021 Criado, Djouadi, Perez-Victoria, Santiago

2022 Aebischer, Altmannshofer, Jenkins, Manohar ([basis@dim-6](#))

2023 Song, Sun, Yu ([basis@dim-8](#))

Axion-like particle,

see also H.Y.Cheng, Phys.Rept 1988

2020 Bauer, Neubert, Renner, Schnubel, Thamm

2023 Song, Sun, Yu ([basis@dim-8](#))

μ_{EW}
LEFT

Dark LEFT

$$\mathcal{O}_{d\phi^2} = (\bar{d}_{Lp} d_{Rr}) \phi^2$$

$$\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) (\bar{\chi}_a \gamma^\mu \chi_b)$$

$$\mathcal{O}_{dXX}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) X^{\mu\nu} X_\nu$$

$$\mathcal{O}_{da}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) \partial^\mu a$$

example

2022 Aebischer, Altmannshofer, Jenkins, Manohar ([basis@dim-6](#))

2022 He, Ma, Valencia ([basis@dim-6](#))

2023 Liang, Liao, Ma, Wang ([basis@dim-8](#))

μ_b

Dark SMEFT with MFV

- ▶ MFV coupling $b \rightarrow s, b \rightarrow d, s \rightarrow d$ are connected with each other.

$$c_i^{\text{MFV}} = \begin{cases} \epsilon_0^i \hat{\lambda}_d + \epsilon_1^i \Delta_q \hat{\lambda}_d & \text{for } \mathcal{Q}_i = \mathcal{Q}_{d\phi}, \mathcal{Q}_{d\phi^2}, \mathcal{Q}_{dHX}, \mathcal{Q}_{dHX^2}, \mathcal{Q}_{dX^2}, \\ \epsilon_0^i \mathbb{1} + \epsilon_1^i \Delta_q & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi q}, \mathcal{Q}_{q\chi}, \mathcal{Q}_{qXX}, \mathcal{Q}_{q\tilde{X}X}, \mathcal{Q}_{DqX^2}, \mathcal{Q}_{qX}, \mathcal{Q}_{HqX}^{(1,3)}, \mathcal{Q}_{qa}, \\ \epsilon_0^i \mathbb{1} & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi d}, \mathcal{Q}_{d\chi}, \mathcal{Q}_{dXX}, \mathcal{Q}_{d\tilde{X}X}, \mathcal{Q}_{DdX^2}, \mathcal{Q}_{dX}, \mathcal{Q}_{HdX}, \mathcal{Q}_{da}, \end{cases}$$

8 operators are eliminated

- ▶ Numerics

$$\Delta_q = \begin{pmatrix} 0.8 & -3.3 - 1.5i & 79.3 + 35.4i \\ -3.3 + 1.5i & 16.6 & -397.5 + 8.1i \\ 79.3 - 35.4i & -397.5 - 8.1i & 9839.0 \end{pmatrix} \times 10^{-4}$$

$$\Delta_q \hat{\lambda}_d = \begin{pmatrix} 0.0021 & -0.18 - 0.08i & 191.3 + 85.4i \\ -0.009 + 0.004i & 0.88 & -958.7 + 19.6i \\ 0.21 - 0.10i & -21.1 - 0.4i & 23728.1 \end{pmatrix} \times 10^{-6}$$

Backup

$$\begin{aligned}\mathcal{Q}_{d\phi} &= (\bar{q}_p d_r H) \phi + \text{h.c.}, & \mathcal{Q}_{d\phi^2} &= (\bar{q}_p d_r H) \phi^2 + \text{h.c.}, \\ \mathcal{Q}_{\phi q} &= (\bar{q}_p \gamma_\mu q_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2), & \mathcal{Q}_{\phi d} &= (\bar{d}_p \gamma_\mu d_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2),\end{aligned}\quad (4.2)$$

$$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r) (\bar{\chi} \gamma^\mu \chi), \quad \mathcal{Q}_{d\chi} = (\bar{d}_p \gamma_\mu d_r) (\bar{\chi} \gamma^\mu \chi), \quad (4.3)$$

$$\mathcal{Q}_{dHX} = (\bar{q}_p \sigma_{\mu\nu} d_r) H X^{\mu\nu} + \text{h.c.}, \quad (4.4)$$

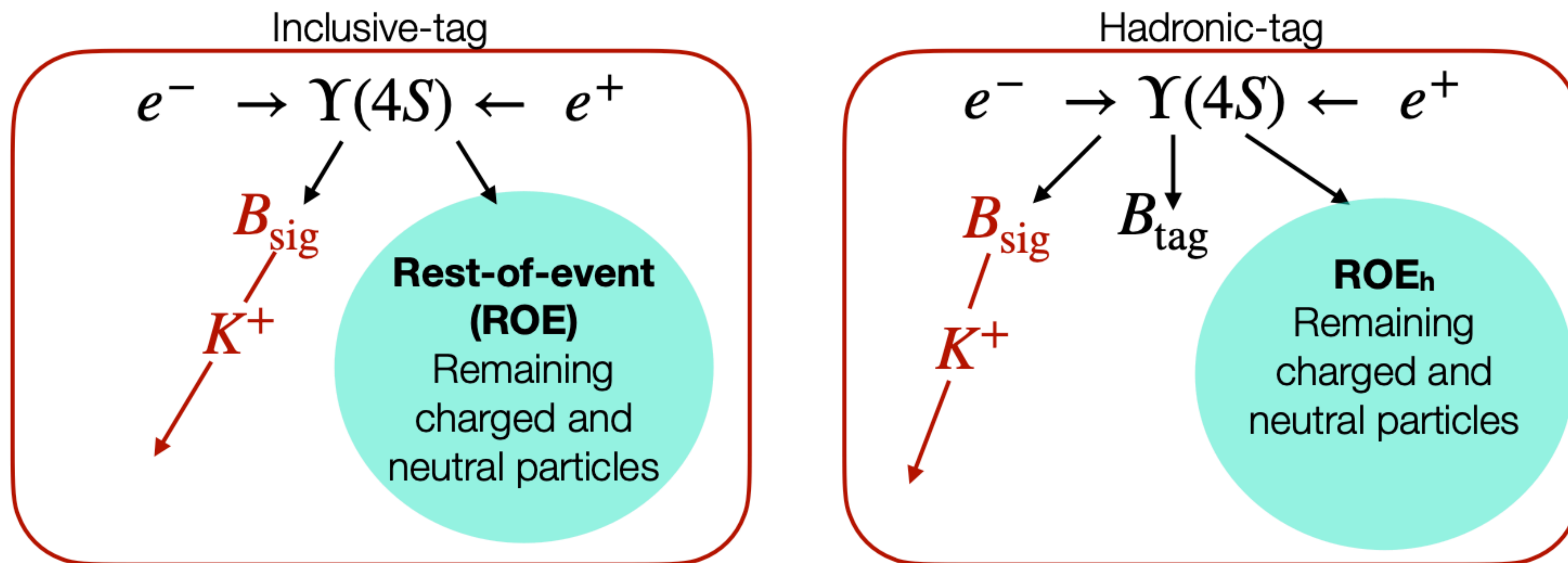
$$\begin{aligned}\mathcal{Q}_{dX} &= (\bar{d}_p \gamma_\mu d_r) X^\mu, & \mathcal{Q}_{HdX} &= (H^\dagger H) (\bar{d}_p \gamma^\mu d_r) X_\mu, \\ \mathcal{Q}_{qX} &= (\bar{q}_p \gamma_\mu q_r) X^\mu, & \mathcal{Q}_{HqX}^{(1)} &= (H^\dagger H) (\bar{q}_p \gamma^\mu q_r) X_\mu, \\ \mathcal{Q}_{dX^2} &= (\bar{q}_p d_r H) X_\mu X^\mu + \text{h.c.}, & \mathcal{Q}_{HqX}^{(3)} &= (H^\dagger \tau^I H) (\bar{q}_p \tau^I \gamma^\mu q_r) X_\mu, \\ \mathcal{Q}_{qXX} &= (\bar{q}_p \gamma_\mu q_r) X^{\mu\nu} X_\nu, & \mathcal{Q}_{dXX} &= (\bar{d}_p \gamma_\mu d_r) X^{\mu\nu} X_\nu, \\ \mathcal{Q}_{q\tilde{X}X} &= (\bar{q}_p \gamma_\mu q_r) \tilde{X}^{\mu\nu} X_\nu, & \mathcal{Q}_{d\tilde{X}X} &= (\bar{d}_p \gamma_\mu d_r) \tilde{X}^{\mu\nu} X_\nu, \\ \mathcal{Q}_{DqX^2} &= i(\bar{q}_p \gamma^\mu D^\nu q_r) X_\mu X_\nu + \text{h.c.}, & \mathcal{Q}_{DdX^2} &= i(\bar{d}_p \gamma^\mu D^\nu d_r) X_\mu X_\nu + \text{h.c.}, \\ \mathcal{Q}_{dHX^2} &= (\bar{q}_p \sigma_{\mu\nu} d_r H) X_1^\mu X_2^\nu + \text{h.c.}, & & \end{aligned}\quad (4.5)$$

$$\mathcal{C}_i = \tilde{\mathcal{C}}_i \cdot \begin{cases} (m_X/\Lambda)^2 & \text{for } \mathcal{Q}_i = \mathcal{Q}_{dX^2}, \mathcal{Q}_{DdX^2}, \mathcal{Q}_{DqX^2}, \mathcal{Q}_{dHX^2}, \\ (m_X/\Lambda) & \text{for } \mathcal{Q}_i = \text{others.} \end{cases}$$

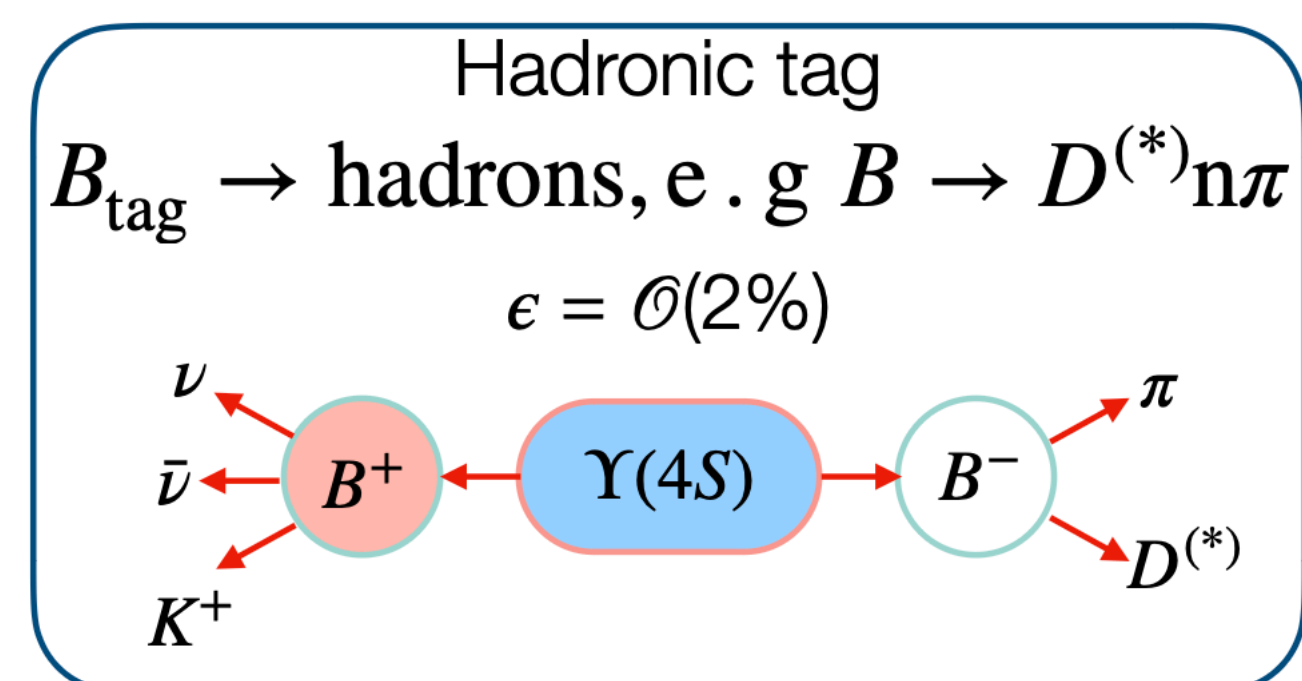
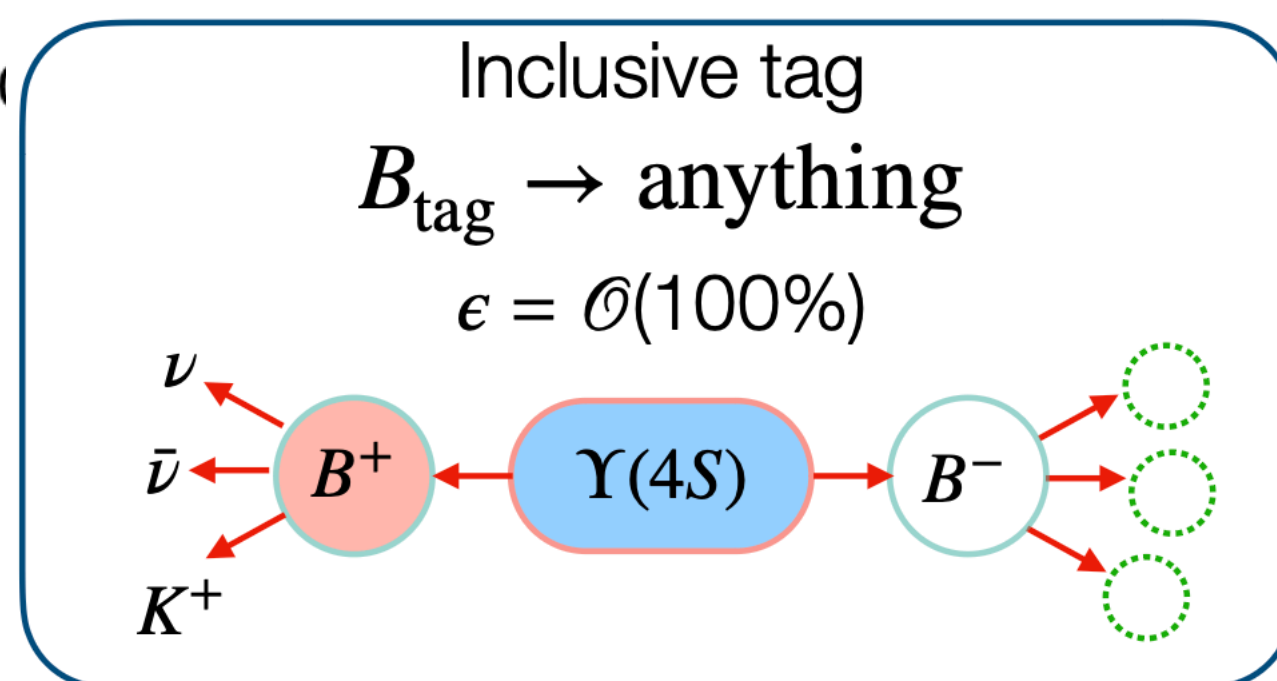
$$\mathcal{Q}_{qa} = (\bar{q}_p \gamma_\mu q_r) \partial^\mu a, \quad \mathcal{Q}_{da} = (\bar{d}_p \gamma_\mu d_r) \partial^\mu a, \quad (4.7)$$

RECONSTRUCTION AND SELECTION

- Charged particles: $p_T > 100$ MeV/c, close to collision point, in the central part of the detector
- Neutral particles: $E > 100$ MeV, in the central part of the detector
- Signal kaon candidates reconstructed applying kaon-enriching selection



In following, for



LHCb-PAPER-2025-041 (in preparation)

- New study of the FCNC decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ with the LHCb Run 1 and Run 2 data sets
- **Several innovations and new approaches in this analysis**
 - $\frac{d\mathcal{B}}{dq^2}$ extracted with the angular observables
 - Full set of CP -asymmetries
 - First consideration of the effect of the muon mass on the angular distribution
 - New binning scheme for finer q^2 determination of the observables
 - Full set of P- and S-wave interference observables presented for the first time
- **Unprecedented precision**
- **The discrepancies with theory predictions remain and the significances have increased**