



Institute of Particle Physics  
粒子物理研究所

# 味物理中新物理研究理论进展

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时间有限，无法涵盖很多优秀的工作😭😭😭

# Theoretical Tools

**SM-consistent  
measurements  
(precision measurements)**

**SM-inconsistent  
measurements  
(flavour anomalies)**

**new measurements  
and precision targets  
for the future**

# Theoretical Tools

**SM-consistent  
measurements  
(precision measurements)**

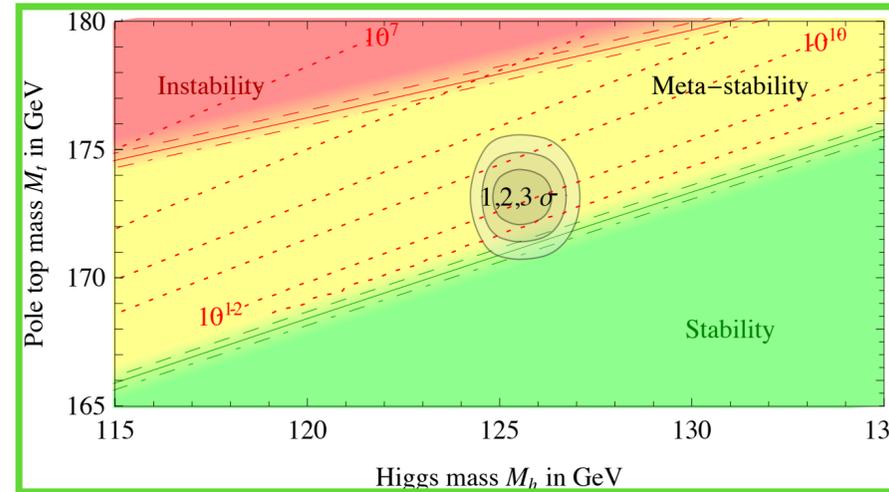
**SM-inconsistent  
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**new measurements  
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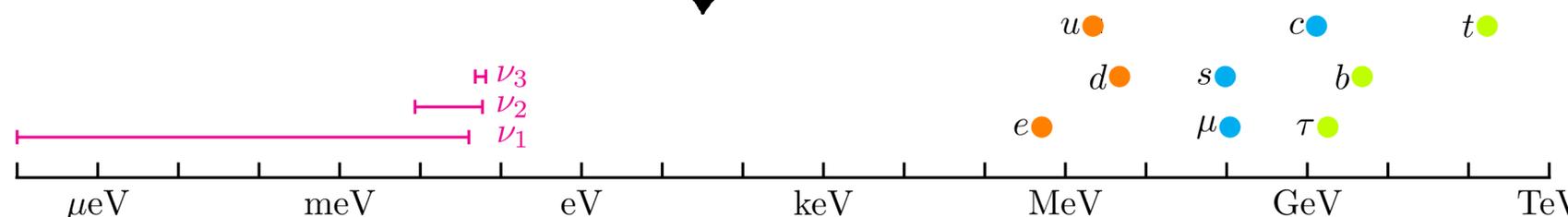
# Physics beyond the Standard Model

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

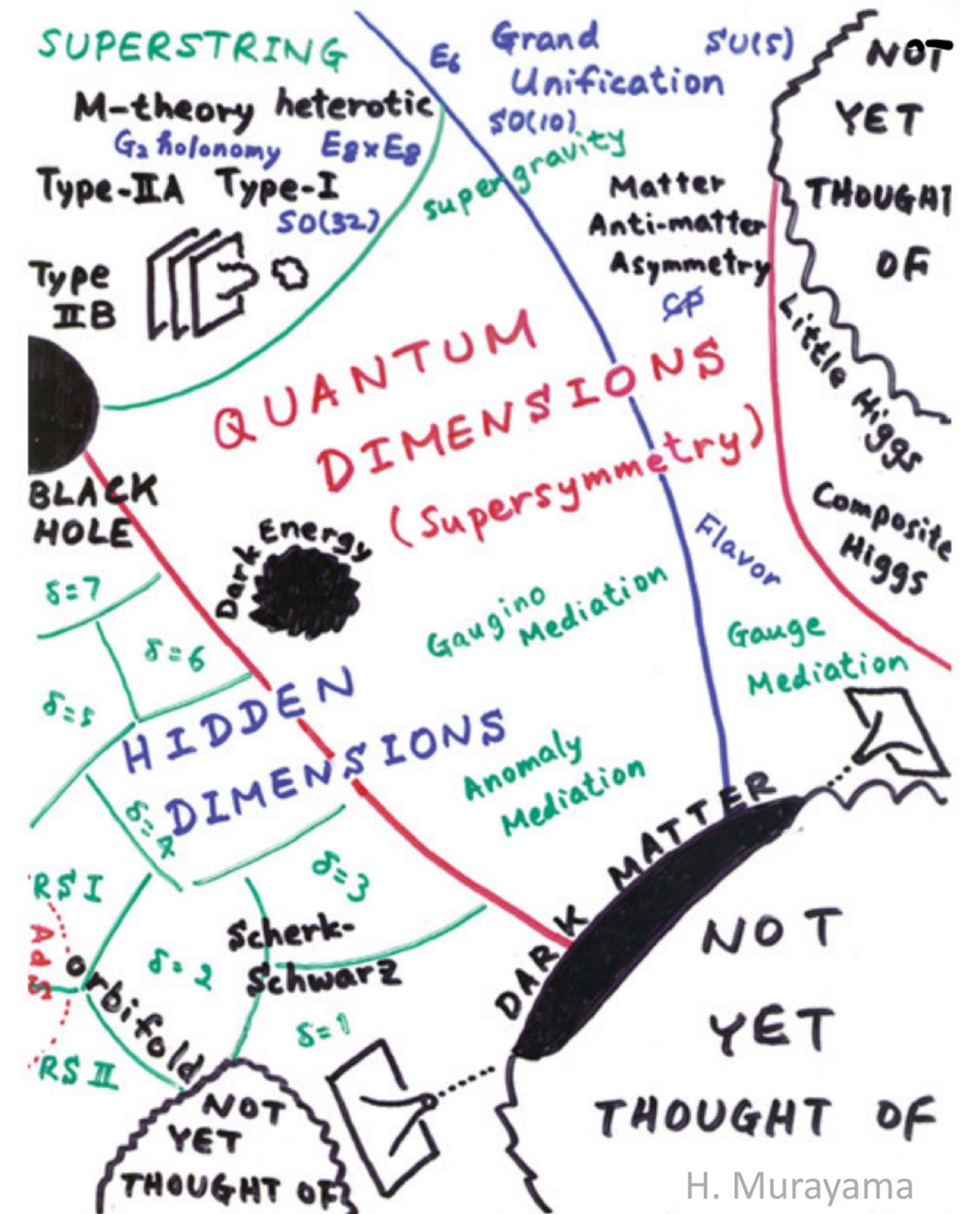
- experimental**
- Dark Matter (26%)
  - Dark Energy (69%)
  - Matter-antimatter asymmetry
  - Anomalies in experimental data
- conceptual**
- Neutrino masses
  - Strong CP problem
  - Vacuum metastability
  - NP flavour puzzle
  - Gravity
  - Hierarchy problem
  - SM flavour puzzle
  - Family replication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



$$\begin{aligned}
 & \text{---} \circlearrowleft \text{---} + \dots = \frac{c}{16\pi^2} \Lambda^2 \\
 & \text{fine-tuning} \\
 & m_{h,0}^2 + \frac{c}{16\pi^2} \Lambda^2 = 125 \text{ GeV}^2
 \end{aligned}$$



Theories beyond the SM

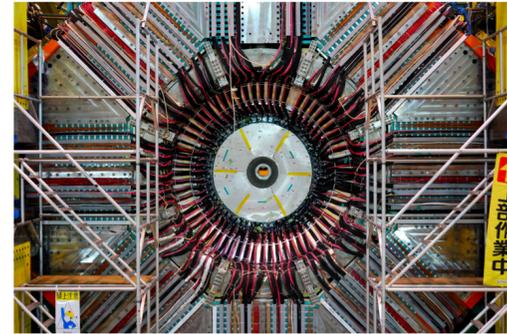


H. Murayama



# Experimental Searches

## 上一代对撞机

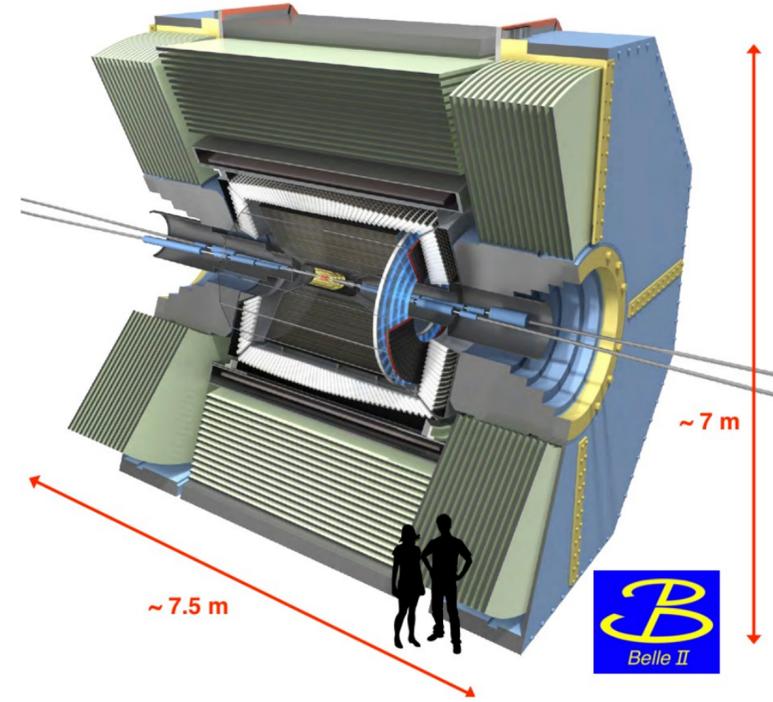


日本高能加速器上的Belle (1999-2010)

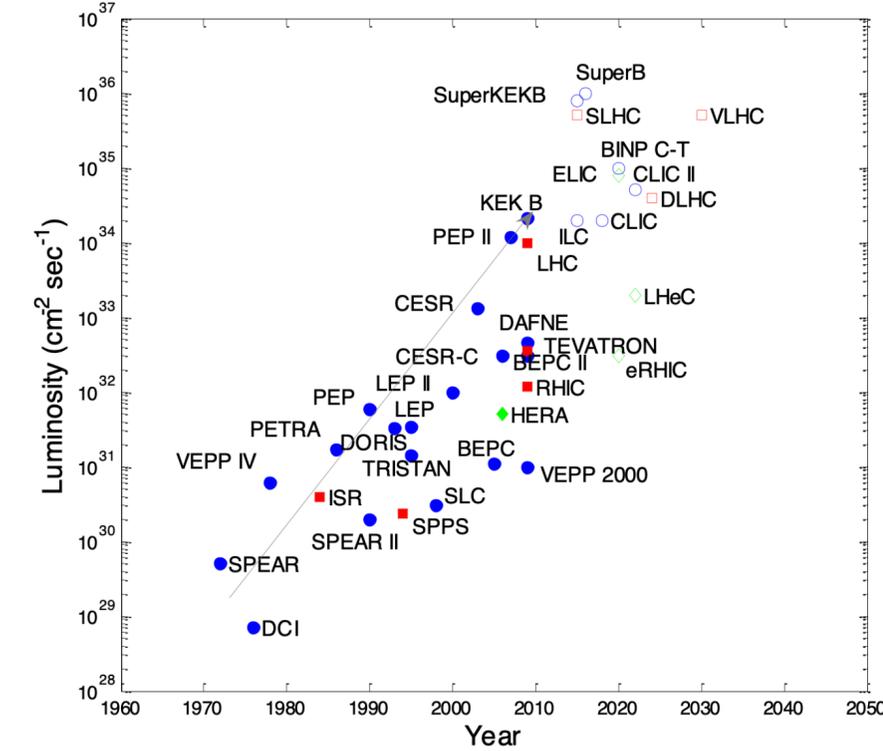


美国斯坦福直线加速器上的BaBar (1999-2008)

## 当前的对撞机

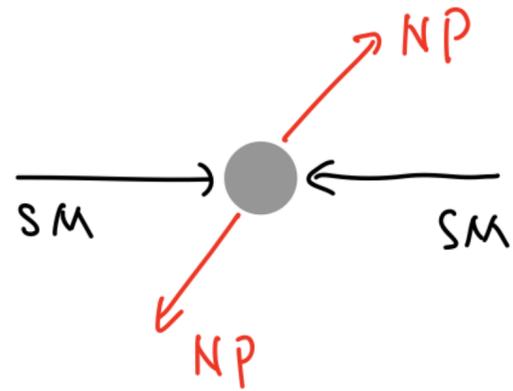


位于日本的超级B工厂



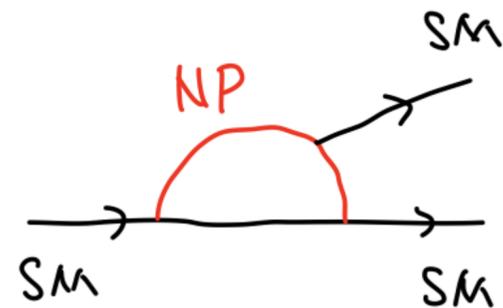
C.Biscari, EPS-HEP 2009

## Direct Searches



- ▶ energy frontier
- ▶ almost model independent
- ▶ probe  $m_{NP} < E_{collider}$

## Indirect Searches



- ▶ precision (intensity) frontier
- ▶ model dependent
- ▶ probe very large  $m_{NP}$
- ▶ flavour physics

- ▶ 共产生约 $10^9 B\bar{B}$  事例
- ▶ 证实了SM中CP破缺的KM机制

Nobel Prize 2008 for



Makoto Kobayashi



Toshihide Maskawa



LHC上的LHCb实验

# 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

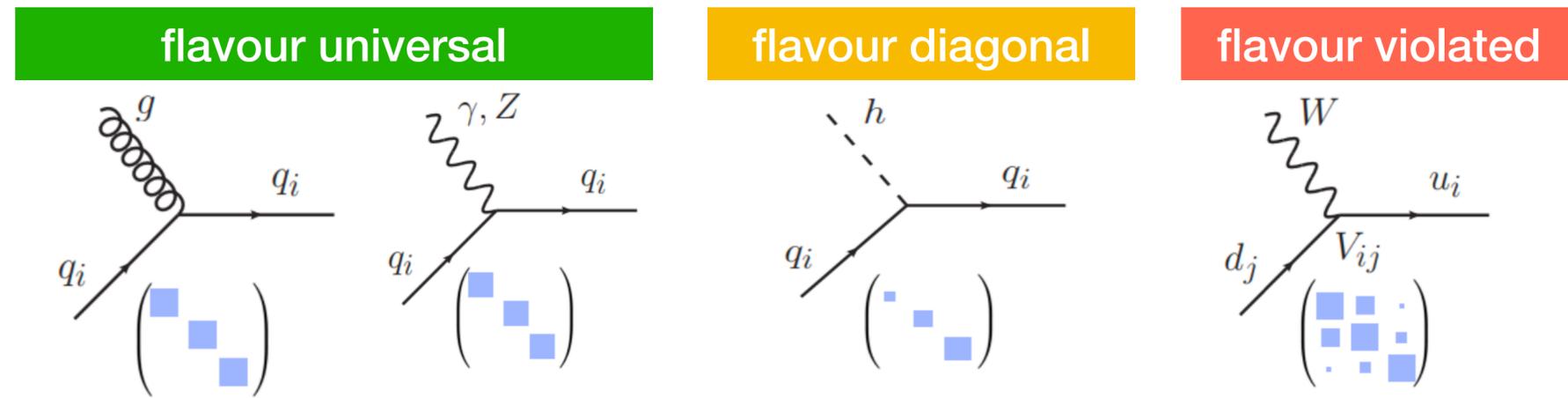
## ► Flavour Changing Neutral Current (FCNC)

- 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

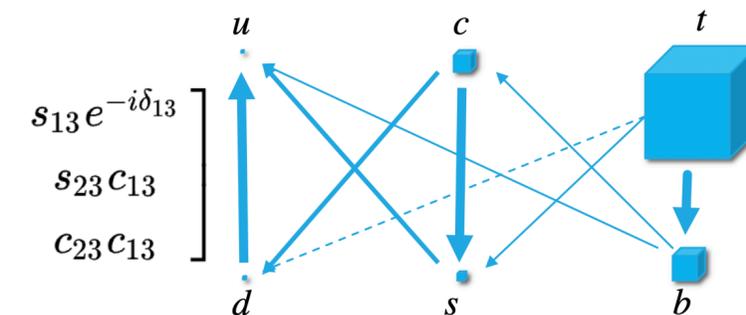
experimental status  
**no evidence of NP**  $> 5\sigma$   
**but, anomalies**  $2 \sim 4\sigma$



## CKM matrix

- Cabibbo–Kobayashi–Maskawa matrix

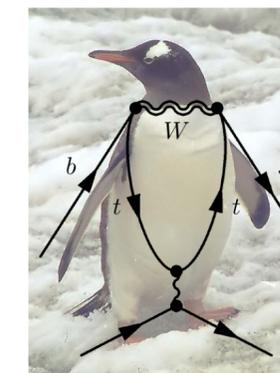
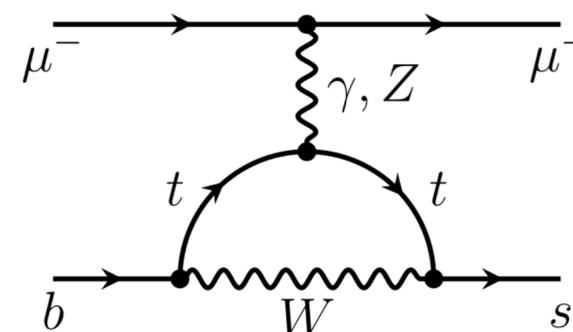
$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} \end{bmatrix}$$



- 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 Flavour-Physics Measurements

many measurements

Flavour Transition	Transition type					
	$\gamma$	quarks	$\mu$	$e$	$\tau$	$\nu$
$3_q \rightarrow 2_q$	$b \rightarrow s \gamma$ [*]	$B_s \leftrightarrow \bar{B}_s$ [*]	$b \rightarrow s \bar{\mu} \mu$ [*] $b \rightarrow c \mu \bar{\nu}$	$R_{bs}(e/\mu)$ [*] $R_{bc}(e/\mu)$ [•]	$b \rightarrow s \bar{\tau} \tau$ [•] $b \rightarrow c \tau \bar{\nu}$ [•]	$b \rightarrow s \nu \bar{\nu}$ [•]
$3_q \rightarrow 1_q$	$b \rightarrow d \gamma$ [*]	$B_d \leftrightarrow \bar{B}_d$ [*]	$b \rightarrow d \bar{\mu} \mu$ [*] $b \rightarrow u \mu \bar{\nu}$	$R_{bd}(e/\mu)$ [*] $R_{bu}(e/\mu)$ [•]	$b \rightarrow d \bar{\tau} \tau$ [•] $b \rightarrow u \tau \bar{\nu}$ [•]	$b \rightarrow d \nu \bar{\nu}$ [•]
$2_q \rightarrow \begin{matrix} 2_q \\ 1_q \end{matrix}$	$c \rightarrow u \gamma$	$D \leftrightarrow \bar{D}$ [*]	$c \rightarrow u \bar{\mu} \mu$ $c \rightarrow s \bar{\mu} \nu$ $c \rightarrow d \bar{\mu} \nu$	$R_{cu}(e/\mu)$ [*] $R_{cs}(e/\mu)$ [•] $R_{cd}(e/\mu)$ [•]		$c \rightarrow u \nu \bar{\nu}$ [•]
$3_\ell \rightarrow \begin{matrix} 2_\ell \\ 1_\ell \end{matrix}$	$\tau \rightarrow \mu \gamma$ [•] $\tau \rightarrow e \gamma$ [•]	$\tau \rightarrow \mu \bar{q} q$ [•] $\tau \rightarrow e \bar{q} q$ [•]	$\tau \rightarrow \mu \bar{\mu} \mu$ [•] $\tau \rightarrow e \bar{\mu} \mu$ [•]	$\tau \rightarrow \mu \bar{e} e$ [•] $\tau \rightarrow e \bar{e} e$ [•]		$\tau \rightarrow \mu \nu \bar{\nu}$ [•] $\tau \rightarrow e \nu \bar{\nu}$ [•]

[\*] = major progress @ HL-LHC, limited impact of  $e^+e^-$  colliders

[•] = major progress @ HL-LHC & Belle II + significant further progress @ FCC-ee

[•] = FCC-ee allows one order of magnitude precision improvement, or more, after HL-LHC & Belle II

$\begin{matrix} 2_q \\ 1_q \end{matrix} \rightarrow 1_q$	$s \rightarrow d \gamma$	$K^0 \leftrightarrow \bar{K}^0$	$s \rightarrow d \bar{\mu} \mu$ $s \rightarrow u \mu \bar{\nu}$ $d \rightarrow u \mu \bar{\nu}$	$R_{sd}(e/\mu)$ $R_{su}(e/\mu)$ $R_{du}(e/\mu)$		$s \rightarrow d \nu \bar{\nu}$
$2_\ell \rightarrow 1_\ell$	$\mu \rightarrow e \gamma$	$\mu N \rightarrow e N$		$\mu \rightarrow e \bar{e} e$		$\mu \rightarrow e \nu \bar{\nu}$

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$3_q \rightarrow 1_q$	$b \rightarrow s \gamma$ [●]	$B \leftrightarrow \bar{B}$ [●]	$b \rightarrow d \bar{\mu} \mu$ [*] $b \rightarrow d \nu \bar{\nu}$	$R_{bd}(e/\mu)$ [●] $R_{bu}(e/\mu)$ [●]	$b \rightarrow u \bar{\tau} \tau$ [●] $b \rightarrow u \tau \bar{\nu}$ [●]	$b \rightarrow d \nu \bar{\nu}$ [●]
$2_q \rightarrow 2_q$ $1_q$	$c \rightarrow u \gamma$	$D \leftrightarrow \bar{D}$ [*]	$c \rightarrow s \bar{\mu} \mu$ $c \rightarrow d \bar{\mu} \nu$	$R_{cu}(e/\mu)$ [*] $R_{cs}(e/\mu)$ [●] $R_{cd}(e/\mu)$ [●]		$c \rightarrow u \nu \bar{\nu}$ [●]
$3_\ell \rightarrow 2_\ell$ $1_\ell$	$\tau \rightarrow \mu \gamma$ [●] $\tau \rightarrow e \gamma$ [●]	$\tau \rightarrow \mu \bar{q} q$ [●] $\tau \rightarrow e \bar{q} q$ [●]	$\tau \rightarrow \mu \bar{\mu} \mu$ [●] $\tau \rightarrow e \bar{\mu} \mu$ [●]	$\tau \rightarrow \mu \bar{e} e$ [●] $\tau \rightarrow e \bar{e} e$ [●]		$\tau \rightarrow \mu \nu \bar{\nu}$ [●] $\tau \rightarrow e \nu \bar{\nu}$ [●]

$\Delta m_s = 17.765 \pm 0.006 \text{ ps}^{-1}$   
relative uncertainty = 0.03%

$Br(B \rightarrow K \mu^+ \mu^-)$  [●]  
 $A_{FB}(B \rightarrow K^* \mu^+ \mu^-)$  [●]

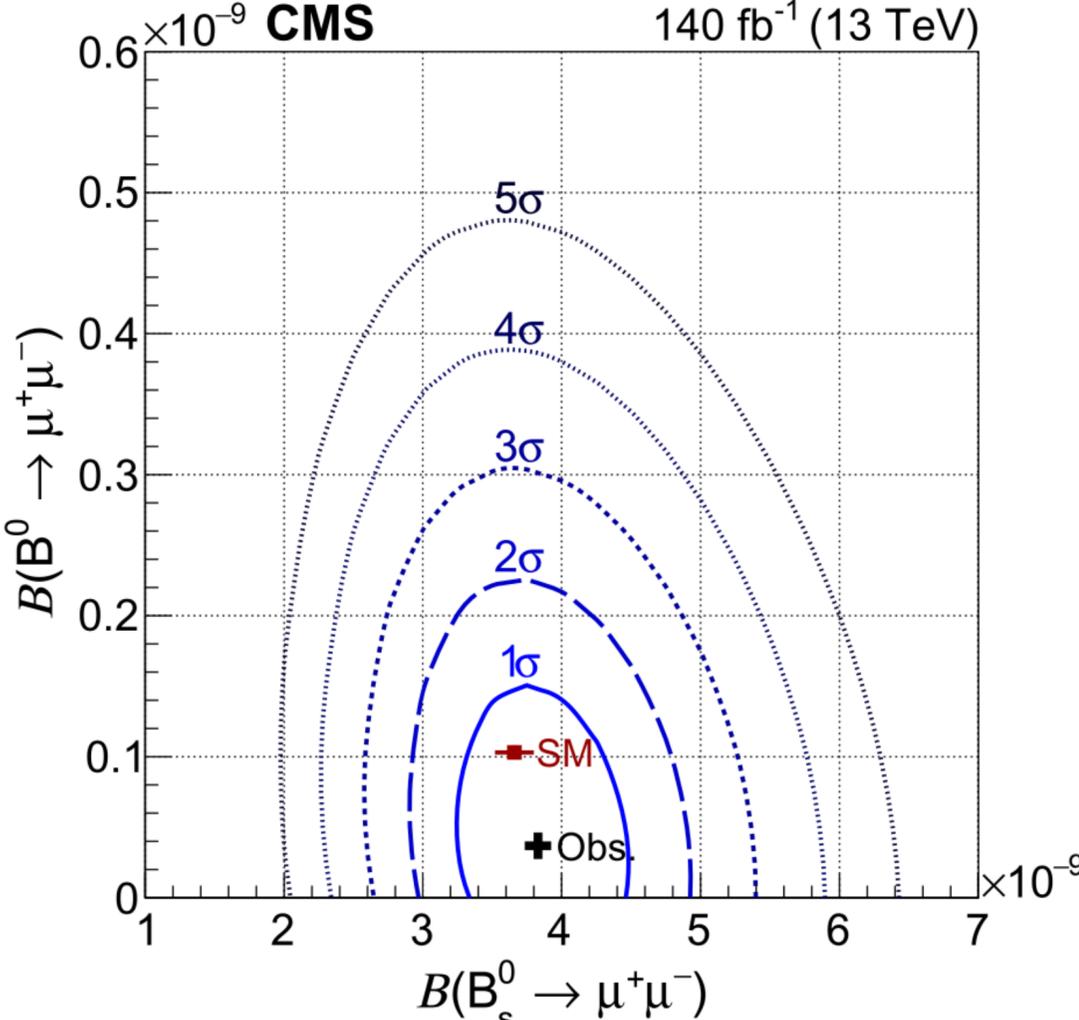
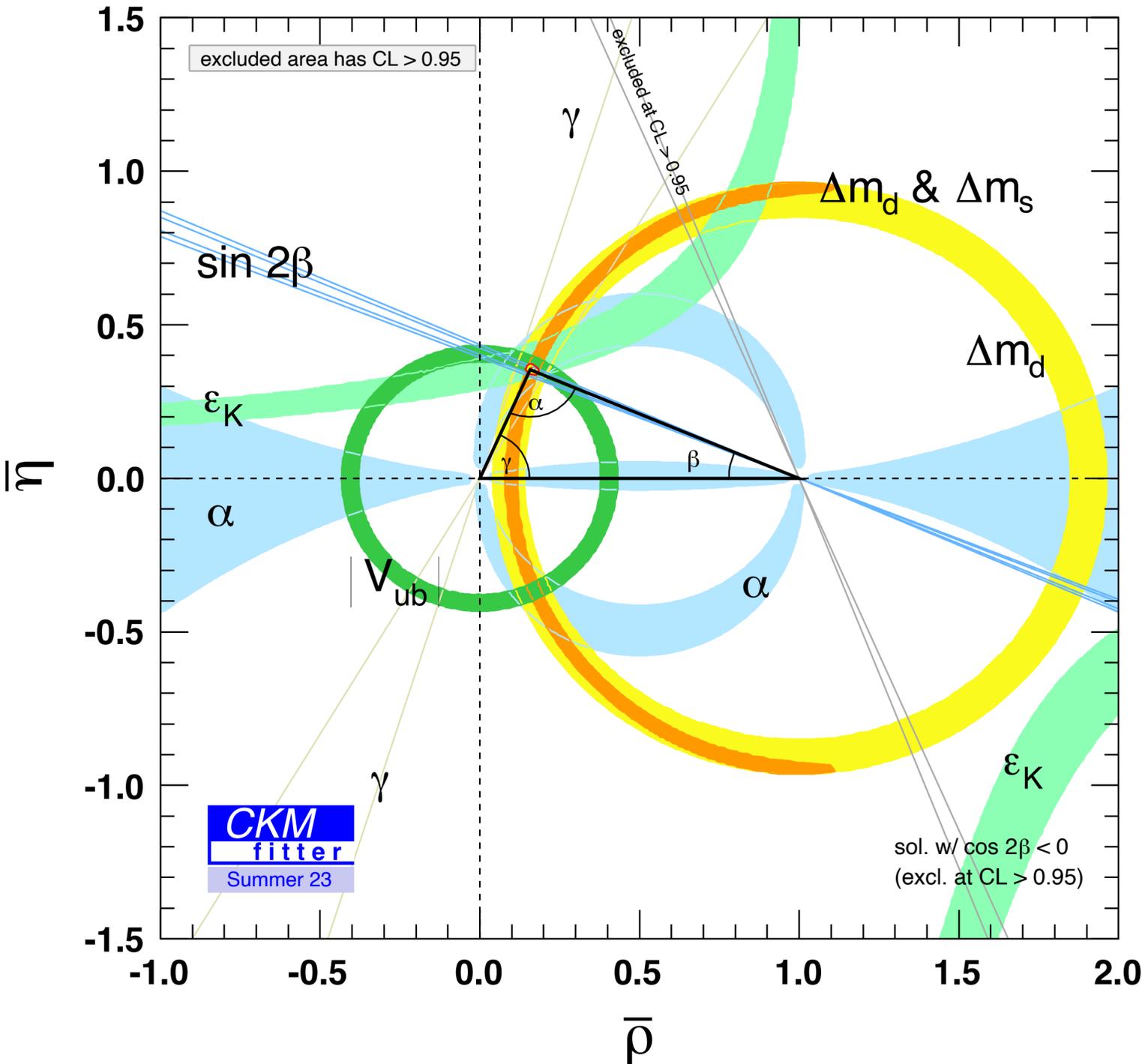
$Br(B \rightarrow K \nu \bar{\nu})$  [●]  
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$2_q \rightarrow 1_q$ $1_q$	$s \rightarrow d \gamma$	$K^0 \leftrightarrow \bar{K}^0$	$s \rightarrow d \bar{\mu} \mu$ $s \rightarrow u \mu \bar{\nu}$ $d \rightarrow u \mu \bar{\nu}$	$R_{sd}(e/\mu)$ $R_{su}(e/\mu)$ $R_{du}(e/\mu)$		$s \rightarrow d \nu \bar{\nu}$
$2_\ell \rightarrow 1_\ell$	$\mu \rightarrow e \gamma$	$\mu N \rightarrow e N$		$\mu \rightarrow e \bar{e} e$		$\mu \rightarrow e \nu \bar{\nu}$

# Current Flavour-Physics Measurements

most of them  
**consistent** with SM



$$\mathcal{B}(B_s \rightarrow \mu^+\mu^-)_{\text{ATLAS}} = (2.8^{+0.8}_{-0.7}) \times 10^{-9},$$

$$\mathcal{B}(B_s \rightarrow \mu^+\mu^-)_{\text{LHCb}} = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9},$$

$$\mathcal{B}(B_s \rightarrow \mu^+\mu^-)_{\text{CMS}} = (3.83^{+0.38+0.19+0.14}_{-0.36-0.16-0.13}) \times 10^{-9}.$$

$$\mathcal{B}(B_s \rightarrow \mu^+\mu^-)_{\text{avg}} = (3.52^{+0.32}_{-0.30}) \times 10^{-9}$$

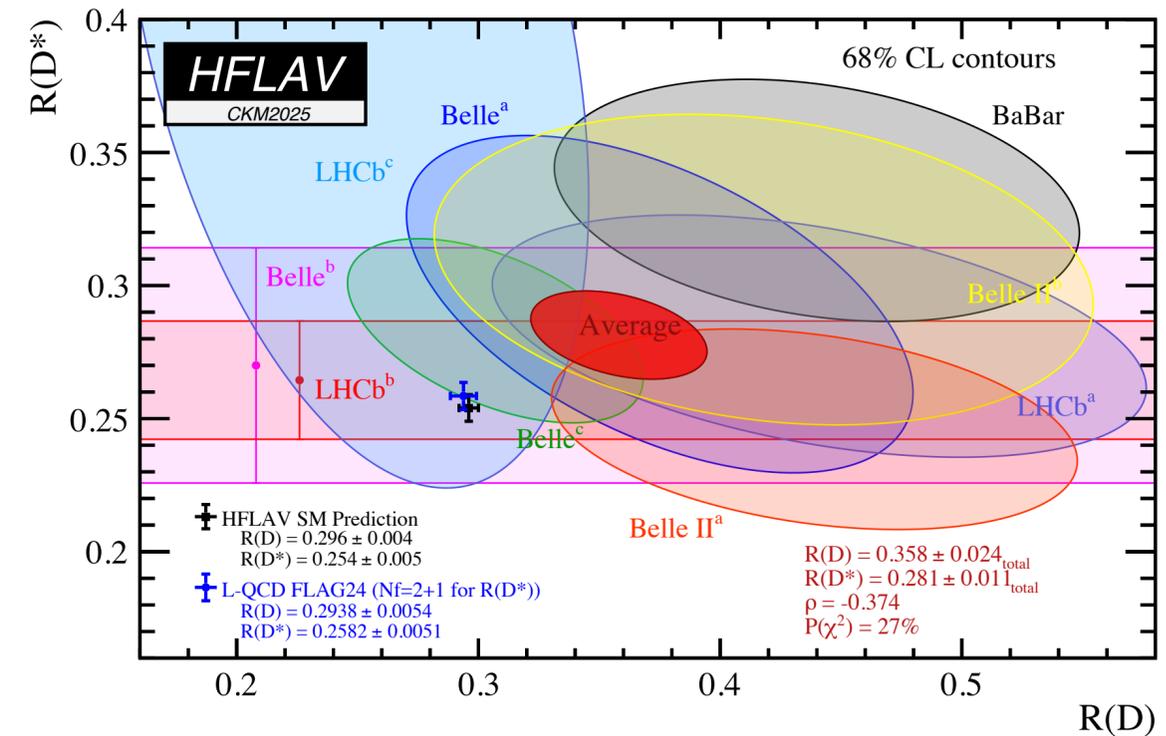
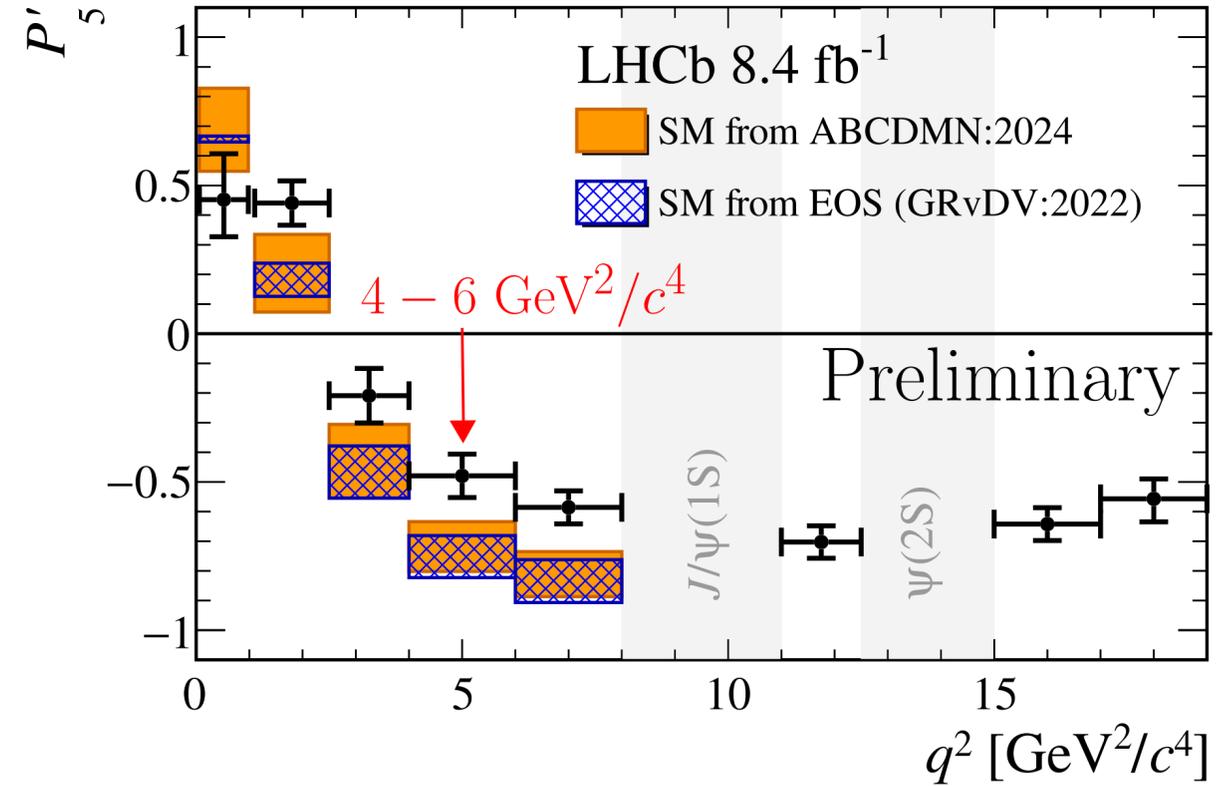
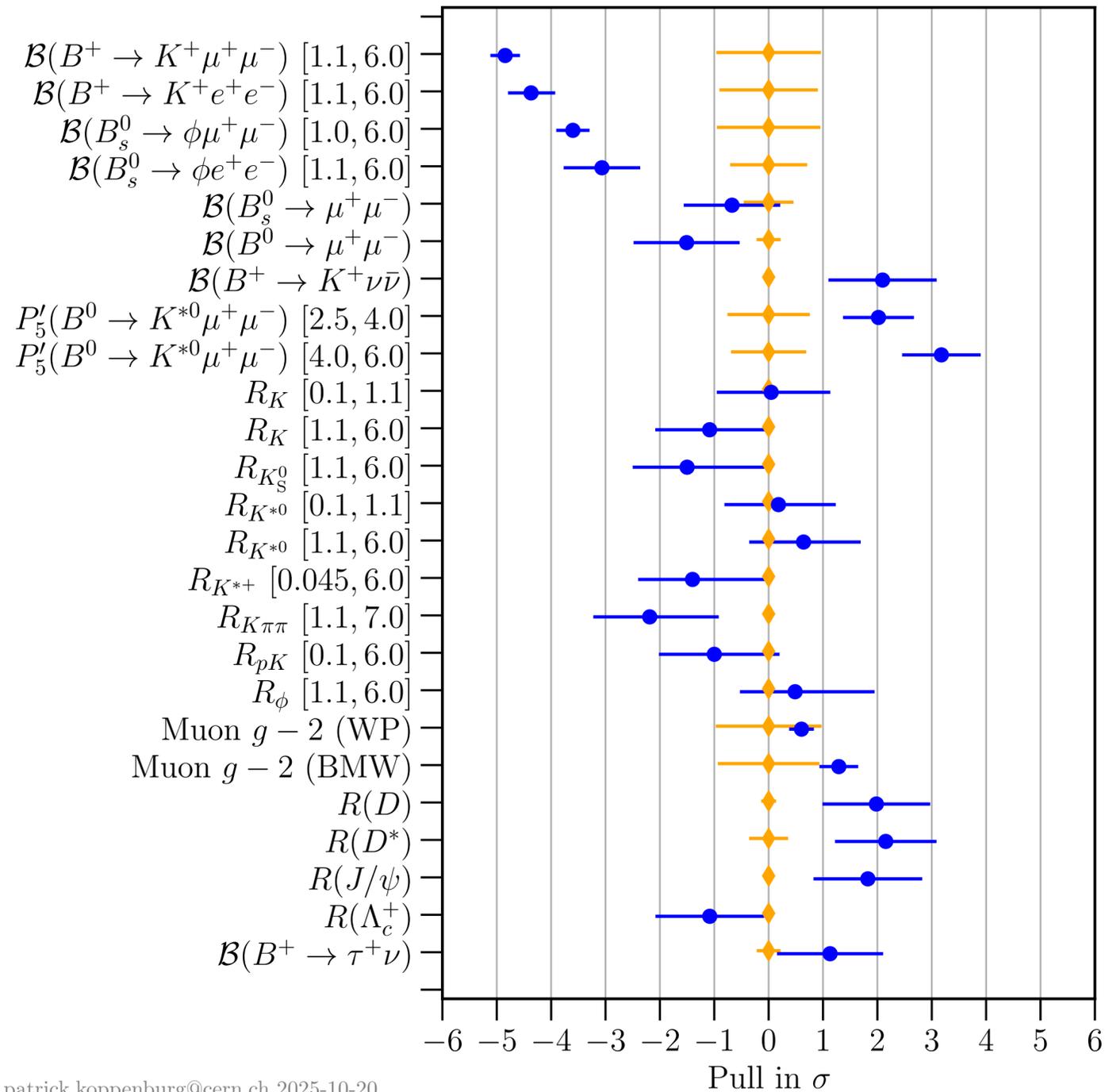
$$\mathcal{B}(B_s \rightarrow \mu^+\mu^-)_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

# Current Flavour-Physics Measurements

few anomalies

see also Liang Sun's talk

## Status of Flavour Anomaly

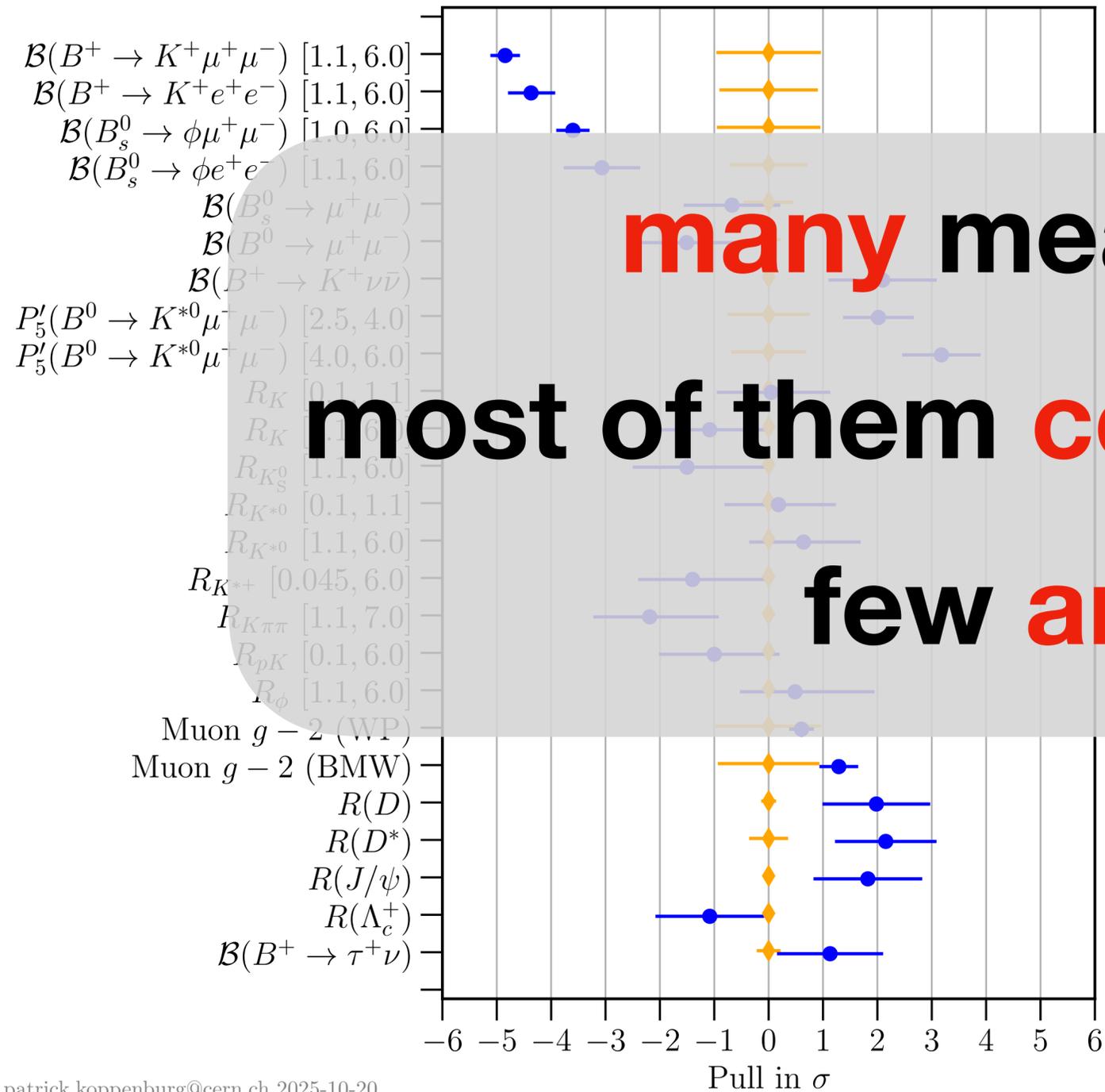


# Current Flavour-Physics Measurements

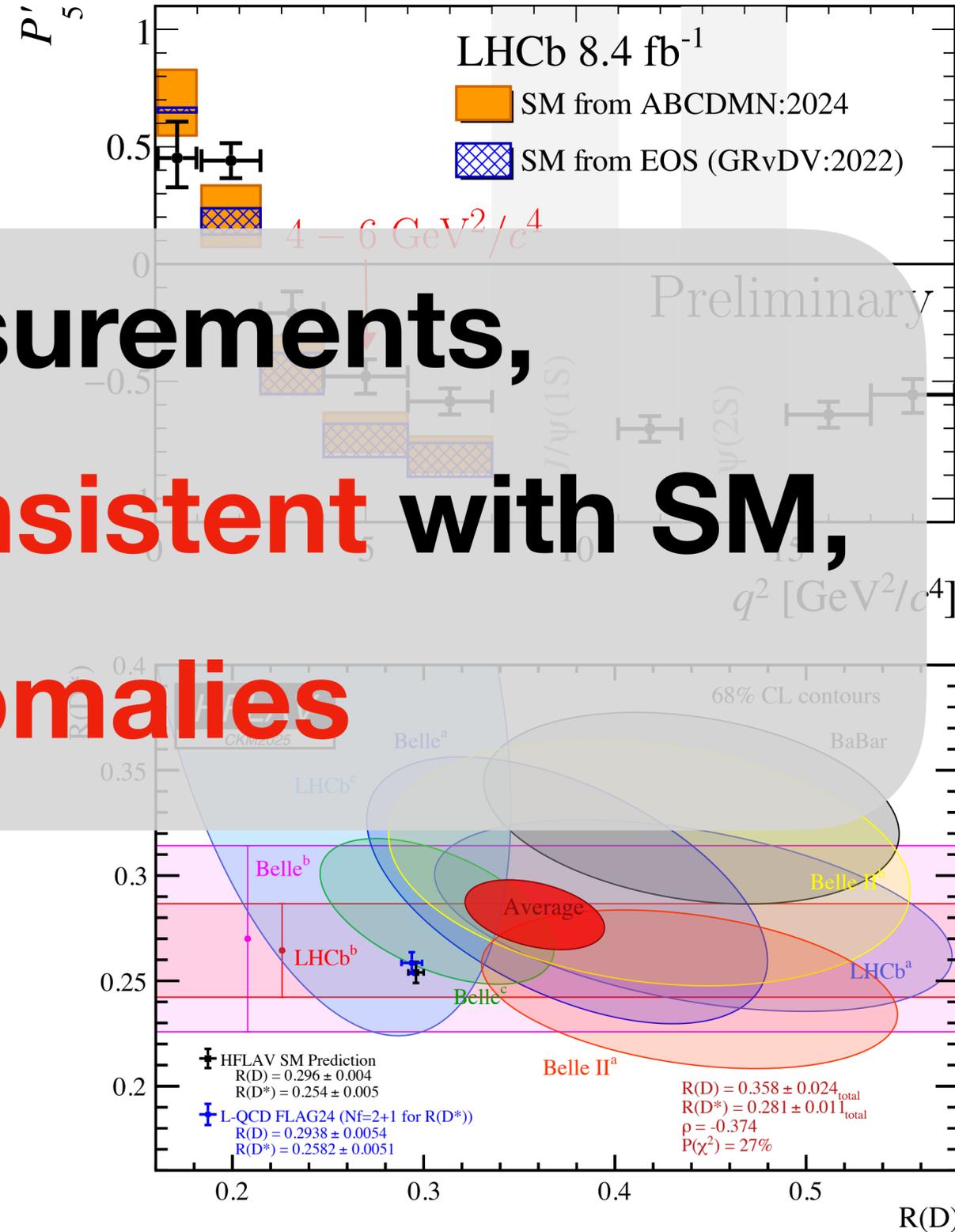
few **anomalies**

see also Liang Sun's talk

## Status of Flavour Anomaly



**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 $SU(3)_C \otimes U(1)_{em}$

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

## 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.

$(\bar{L}L)(\bar{L}L)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$\mathcal{O}_{\nu\nu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{\nu}_{Ls}\gamma_\mu\nu_{Lt})$	$\mathcal{O}_{\nu e}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$	$\mathcal{O}_{ee}^{S,RR}$	$(\bar{e}_{Lp}e_{Rr})(\bar{e}_{Ls}e_{Rt})$
$\mathcal{O}_{ee}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{e}_{Ls}\gamma_\mu e_{Lt})$	$\mathcal{O}_{ee}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$	$\mathcal{O}_{eu}^{S,RR}$	$(\bar{e}_{Lp}e_{Rr})(\bar{u}_{Ls}u_{Rt})$
$\mathcal{O}_{\nu e}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{e}_{Ls}\gamma_\mu e_{Lt})$	$\mathcal{O}_{\nu u}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$	$\mathcal{O}_{eu}^{T,RR}$	$(\bar{e}_{Lp}\sigma^{\mu\nu}e_{Rr})(\bar{u}_{Ls}\sigma_{\mu\nu}u_{Rt})$
$\mathcal{O}_{\nu u}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$	$\mathcal{O}_{\nu d}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$	$\mathcal{O}_{ed}^{S,RR}$	$(\bar{e}_{Lp}e_{Rr})(\bar{d}_{Ls}d_{Rt})$
$\mathcal{O}_{\nu d}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$	$\mathcal{O}_{eu}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$	$\mathcal{O}_{ed}^{T,RR}$	$(\bar{e}_{Lp}\sigma^{\mu\nu}e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu}d_{Rt})$
$\mathcal{O}_{eu}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$	$\mathcal{O}_{ed}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$	$\mathcal{O}_{vedu}^{S,RR}$	$(\bar{\nu}_{Lp}e_{Rr})(\bar{d}_{Ls}u_{Rt})$
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$\mathcal{O}_{vedu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Ls}\gamma_\mu u_{Lt}) + \text{h.c.}$	$\mathcal{O}_{de}^{V,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$	$\mathcal{O}_{uu}^{S1,RR}$	$(\bar{u}_{Lp}u_{Rr})(\bar{u}_{Ls}u_{Rt})$
$\mathcal{O}_{uu}^{V,LL}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$	$\mathcal{O}_{vedu}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt}) + \text{h.c.}$	$\mathcal{O}_{uu}^{S8,RR}$	$(\bar{u}_{Lp}T^A u_{Rr})(\bar{u}_{Ls}T^A u_{Rt})$
$\mathcal{O}_{dd}^{V,LL}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$	$\mathcal{O}_{uu}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$	$\mathcal{O}_{ud}^{S1,RR}$	$(\bar{u}_{Lp}u_{Rr})(\bar{d}_{Ls}d_{Rt})$
$\mathcal{O}_{ud}^{V1,LL}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$	$\mathcal{O}_{uu}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{u}_{Rs}\gamma_\mu T^A u_{Rt})$	$\mathcal{O}_{ud}^{S8,RR}$	$(\bar{u}_{Lp}T^A u_{Rr})(\bar{d}_{Ls}T^A d_{Rt})$
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$\mathcal{O}_{ed}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$			$\mathcal{O}_{vedu}^{S,RL}$	$(\bar{\nu}_{Lp}e_{Rr})(\bar{d}_{Rs}u_{Lt})$
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$\mathcal{O}_{ud}^{V1,RR}$	$(\bar{u}_{Rp}\gamma^\mu u_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$				
$\mathcal{O}_{ud}^{V8,RR}$	$(\bar{u}_{Rp}\gamma^\mu T^A u_{Rr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$				
$(\bar{R}R)(\bar{R}R)$		$(\bar{L}R)X + \text{h.c.}$		$X^3$	
		$\mathcal{O}_{e\gamma}$	$\bar{e}_{Lp}\sigma^{\mu\nu}e_{Rr}F_{\mu\nu}$	$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
		$\mathcal{O}_{u\gamma}$	$\bar{u}_{Lp}\sigma^{\mu\nu}u_{Rr}F_{\mu\nu}$	$\mathcal{O}_{\tilde{G}}$	$f^{ABC}\tilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
		$\mathcal{O}_{d\gamma}$	$\bar{d}_{Lp}\sigma^{\mu\nu}d_{Rr}F_{\mu\nu}$		
		$\mathcal{O}_{uG}$	$\bar{u}_{Lp}\sigma^{\mu\nu}T^A u_{Rr}G_{\mu\nu}^A$		
		$\mathcal{O}_{dG}$	$\bar{d}_{Lp}\sigma^{\mu\nu}T^A d_{Rr}G_{\mu\nu}^A$		



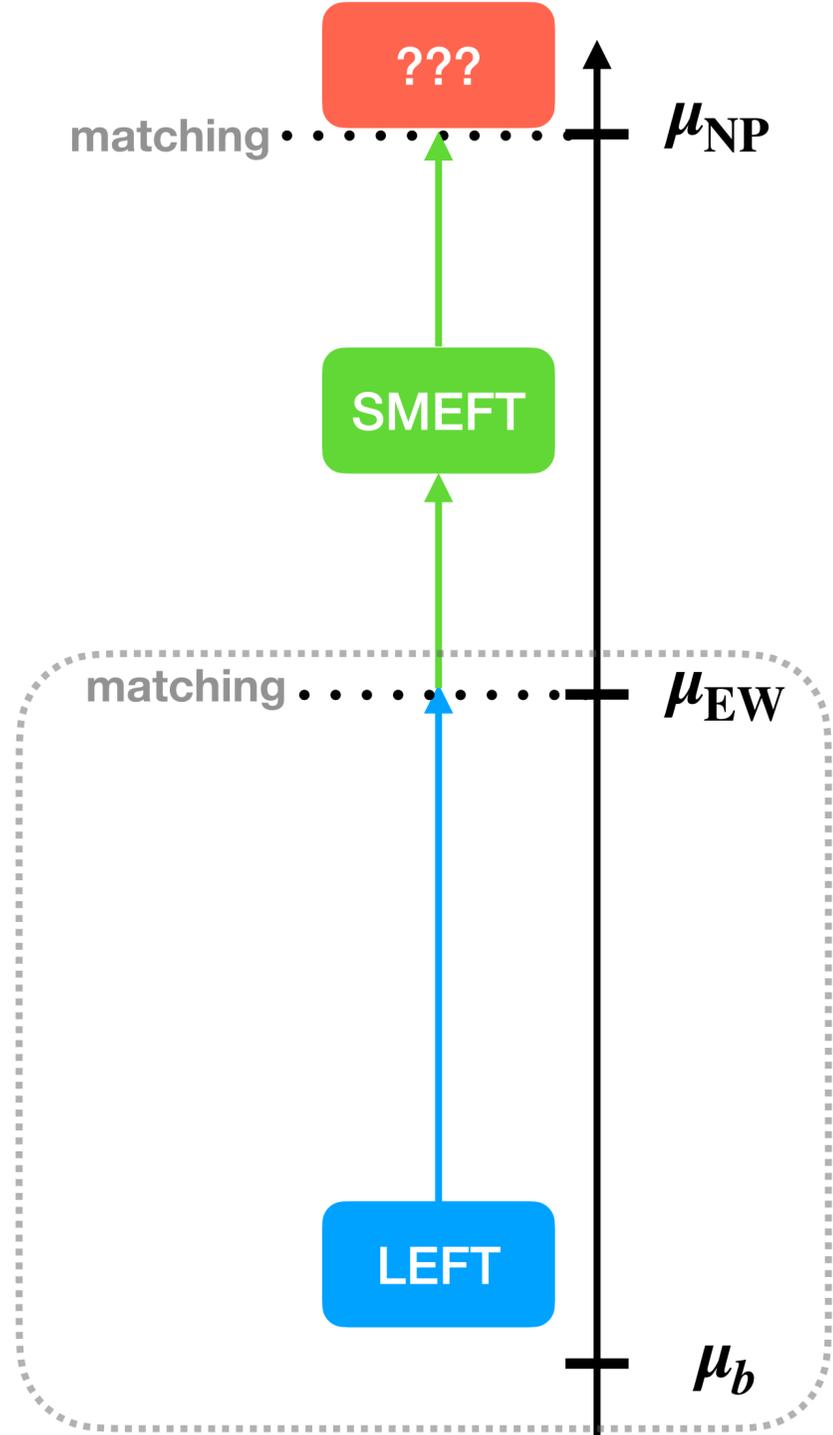
# Flavour anomalies: New Physics interpretation

## Matching between LEFT and SMEFT

- tree-level:** 1709.04486, Jenkins, Manohar, Stoffer
- one-level:** RMP 1996, Buchalla, Buras, Lautenbacher  
1908.05295, Dekens, Stoffer
- two-level:** 2410.13304, Haisch, Schnell, [four fermion]  
method: Feynman diagram(1, 2L), functional method(1L)

## RGE in LEFT

- one-level:** RMP 1996, Buchalla, Buras, Lautenbacher  
1711.05270, Jenkins, Manohar, Stoffer
- two-level:** 2501.08384, Aebischer, Morell, Pesut, Virto, [four-fermion]  
2505.03871, 2507.08926, Naterop, Stoffer, [full (without 2xdim-5 insertion) ]  
all by Feynman diagram



# Flavour anomalies: New Physics interpretation

## UV/IR dictionary

**tree-level:** 1711.10391, de Blas, Criado, Perez-Victoria, Santiago

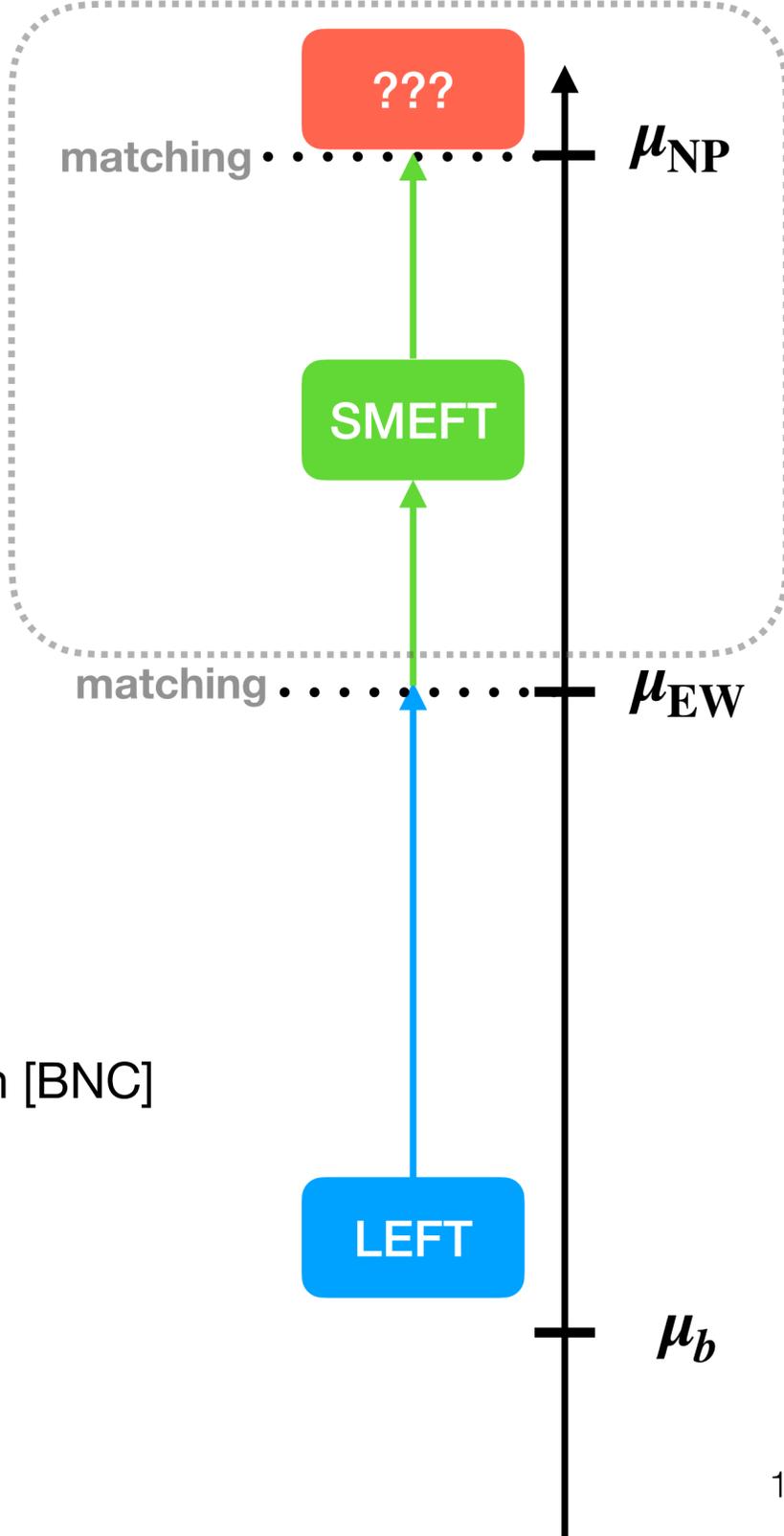
**one-level:** 2303.16965, Guedes, Olgoso, Santiago  
2412.14253, Guedes, Olgoso [one-loop (without vector)]

## RGE in SMEFT

**one-level:** 1308.2627, 1310.4838, 1312.2014, Jenkins, Manohar, Trott

**two-level:** 2308.06315, 2310.19883, Jenkins, Manohar, Naterop, Pagès [scalar]  
2410.07320, Born, Fuentes-Martín, Kvedaraite, Thomsen [boson]  
2510.08682, Banik, Crivellin, Naterop, Stoffer [BNV]  
2601.19974, ([LHC EFT Working Group meeting 2025](#)), Born, Fuentes-Martin, Thomsen [BNC]

method: Feynman diagram(1L), functional method(1, 2L)



# EFT technology

semi-automatic at one loop

## diagrammatic method RGE, matching

2410.13304, Haisch and L. Schnell, **two-loop LEFT-SMEFT matching, four fermion**

2501.08384, Aebischer, Morell, Pesut, Virto, **two-loop RGE in LEFT, four-fermion**

2411.12798, Chala, Miras, Santiago, Vilches, **on-shell matching**

**off-shell matching: 1LPI diagram  $\implies$  Green's basis  $\implies$  physical basis (e.g., Warsaw's basis) package: MatchMakerEFT**

**on-shell matching: all diagram (light-bridge diagram)  $\implies$  physical basis**

package: MOSCA

## functional method RGE, matching (2-loop still a problem)

Aitchison, Fraser, PLB 1984 1412.1837, B. Henning, X. Lu, Murayama,

Fraser, ZPC 1985 1512.03003, Drozd, Ellis, Quevillon and T. You,

Aitchison, Fraser, PRD 1985 1602.00126, del Aguila, Kunszt, Santiago,

Cheyette, PRL 1985 2410.07320, Born, Fuentes-Martín, Kvedaraite, Thomsen, **two-loop RGE in SMEFT, bosonic operator**

L. H. Chan, PRL 1985 2412.12270, Fuentes-Martin, Moreno-Sanchez, Palavric, Thomsen, **toward two-loop order**

L. H. Chan, PRL 1986

Gaillard, NPB 1986 **package: MatchETE**

## on-shell method RGE, matching, basis

2005.12917, Bern, Parra-Martinez, Sawyer, **part of two-loop RGE in SMEFT**

2005.00008, H.L. Li, Z. Ren, J. Shu, M.L. Xiao, J.H. Yu and Y.H. Zheng, **SMEFT basis@dim-8**

2308.00035, Angelis, Gauthier Durieux, **loop-level matching from dispersion relation**

2411.12798, Z.Y. Dong, C.H. Li, T. Ma, J.Shu, Z.Z. Zhou, **one-loop matching**

# Theoretical Tools

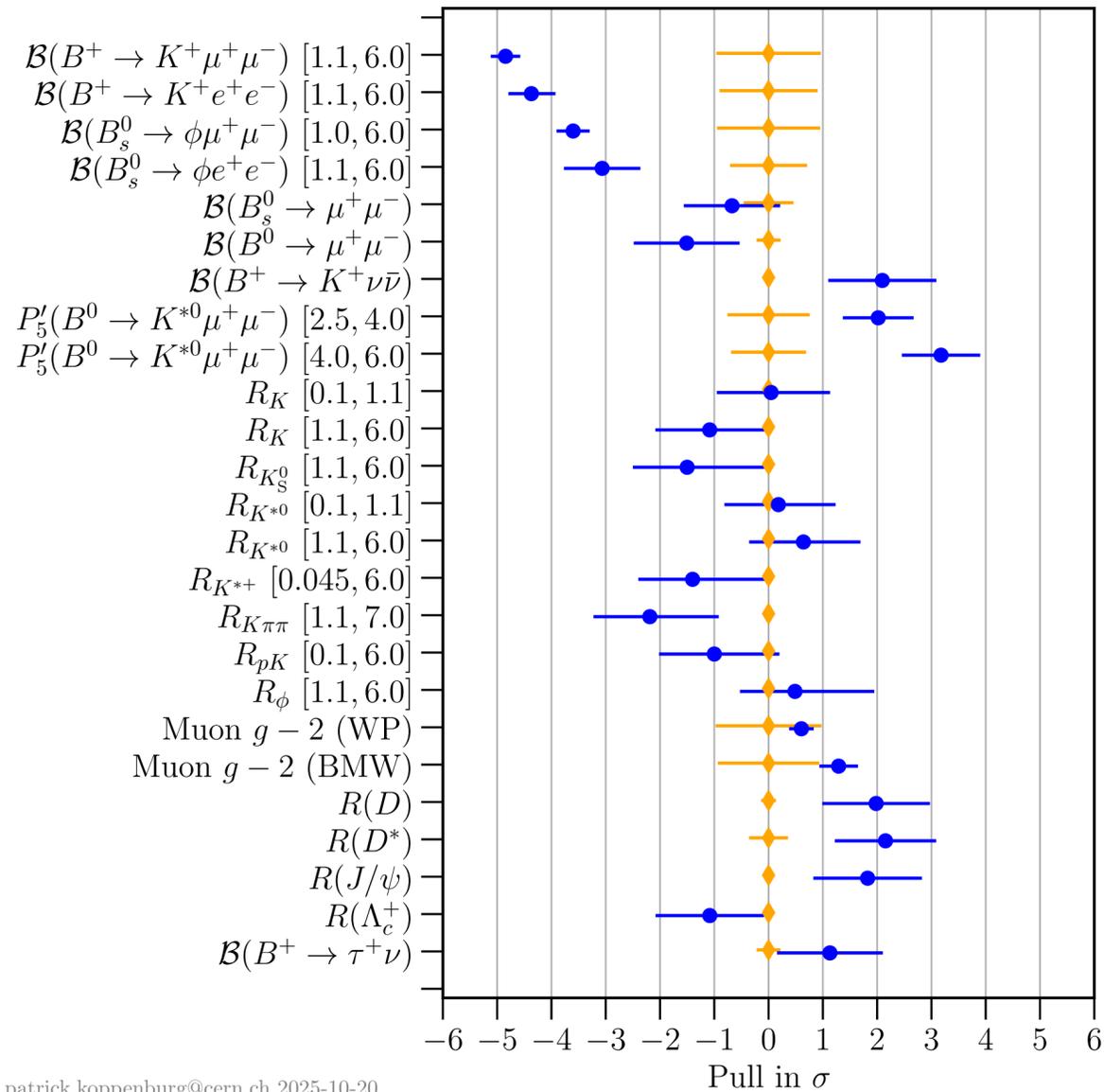
**SM-consistent  
measurements  
(precision measurements)**

**SM-inconsistent  
measurements  
(flavour anomalies)**

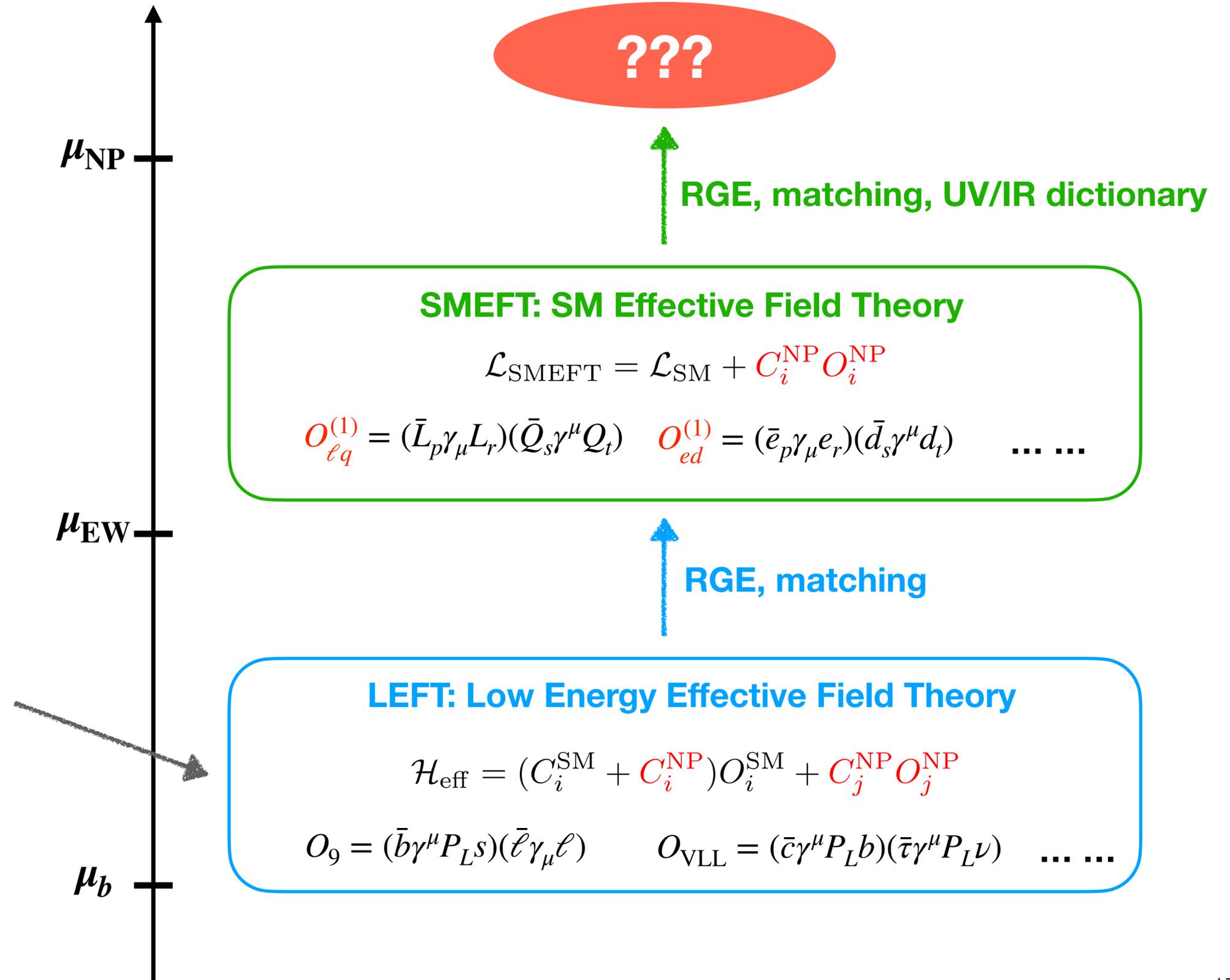
**new measurements  
and precision targets  
for the future**

# Flavour anomalies: New Physics interpretation

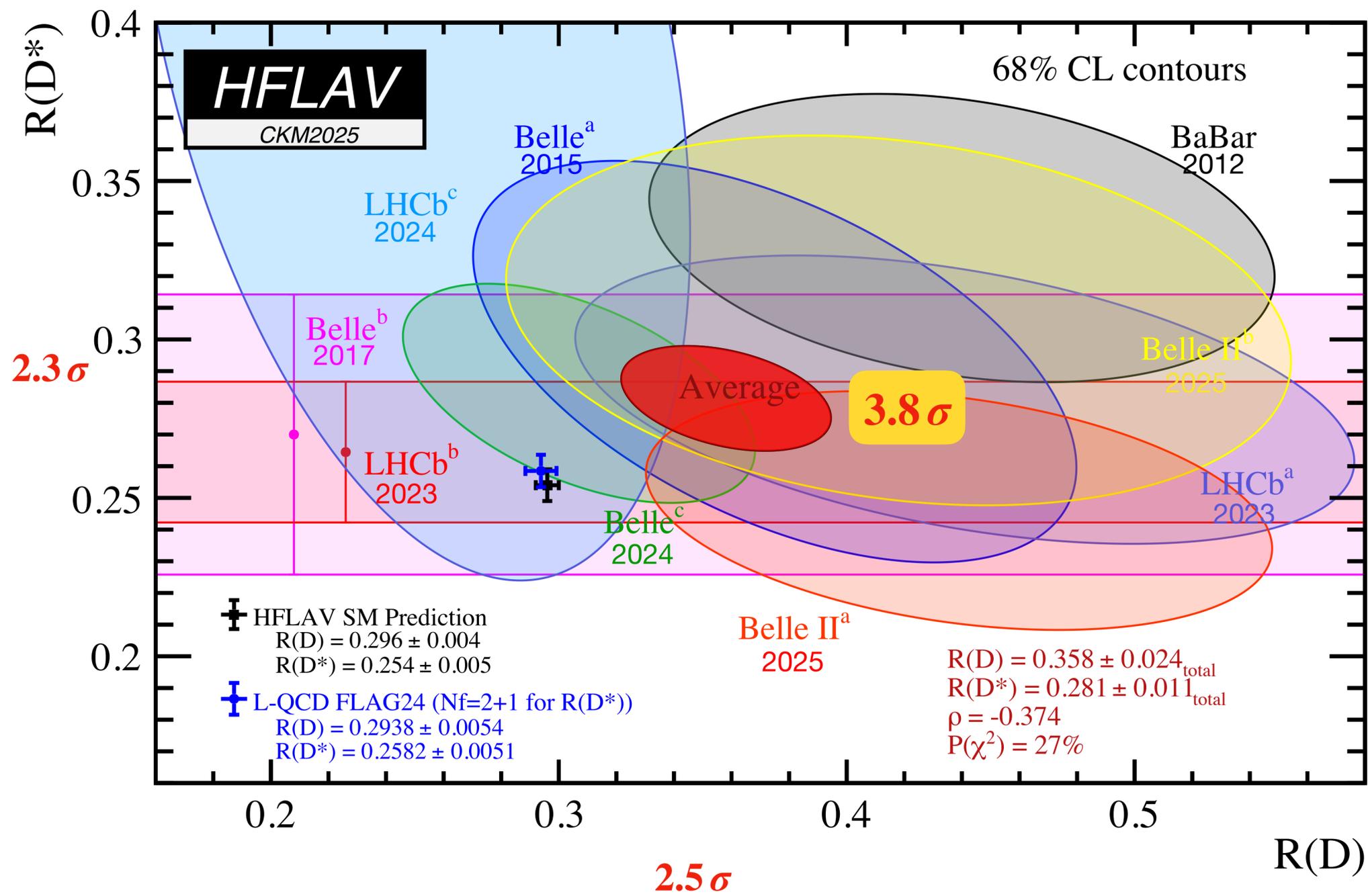
## Status of Flavour Anomaly



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



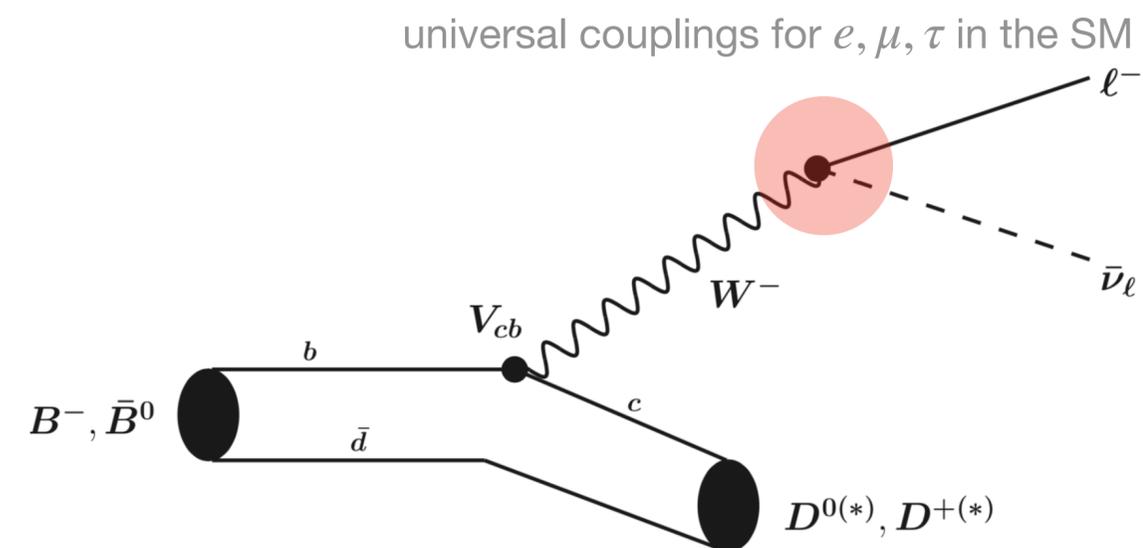
# $R_{D^{(*)}}$ anomalies: exp



## LFU Violation ratio $\tau$ v.s. $e, \mu$

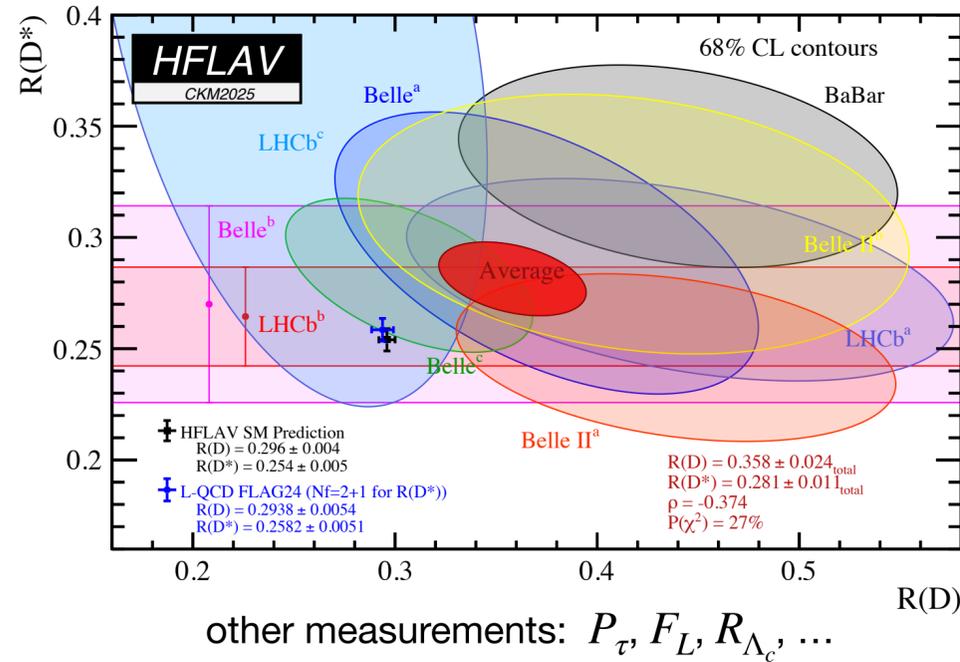
$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu)} \quad (\ell = e, \mu)$$

- ▶ QCD and EW contributions factorized
- ▶ hadronic and exp uncertainties cancelled
- ▶ tiny theoretical uncertainties



# $R_{D^{(*)}}$ anomalies: NP explanation

2405.06062, Iguro, Kitahara, Watanabe  
1811.07920, Greljo, Camalich, Ruiz-A'lvarez  
1810.04939, Q. Y. Hu, X. Q. Li, Y. D. Yang,



LEFT

$$\begin{aligned} \mathcal{O}_{V_L} &= (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu) \\ \mathcal{O}_{V_R} &= (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu) \\ \mathcal{O}_{S_L} &= (\bar{c}P_L b)(\bar{\ell}P_L \nu) \\ \mathcal{O}_{S_R} &= (\bar{c}P_R b)(\bar{\ell}P_L \nu) \\ \mathcal{O}_T &= (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu) \end{aligned}$$

highly constrained by  $B_c$  lifetime

best fit

$$\begin{aligned} C_{V_L} &= +0.08 & \text{Pull} &= 4.8 \\ C_{V_R} &= +0.01 \pm 0.41i & \text{Pull} &= 4.4 \\ C_{S_L} &= -0.79 \pm 0.86i & \text{Pull} &= 4.3 \\ C_{S_R} &= +0.18 & \text{Pull} &= 3.9 \\ C_T &= +0.02 \pm 0.13i & \text{Pull} &= 3.8 \end{aligned}$$

$\mathcal{B}(B_c \rightarrow \tau\nu) < 60\%$  assumed

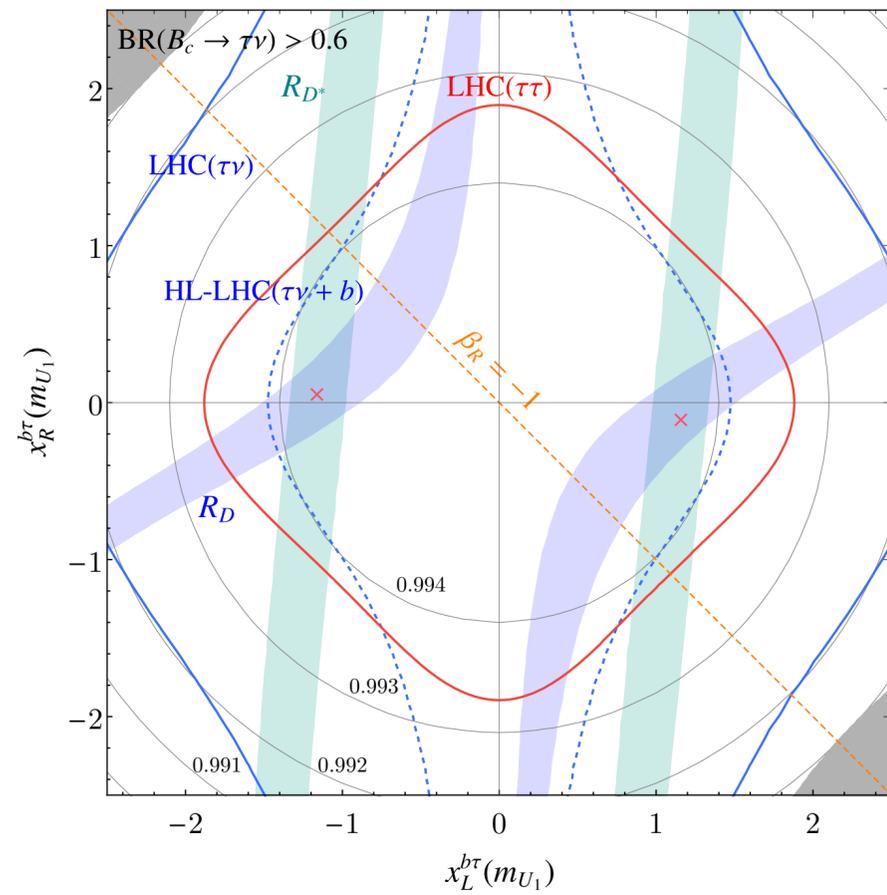
SMEFT

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

$$\mathcal{Q}_{ledq} = (\bar{l}_i e)(\bar{d}q_i)$$

$$\mathcal{Q}_{ledu}^{(1)} = (\bar{l}_i e)\epsilon_{ij}(\bar{q}_j u)$$

$$\mathcal{Q}_{ledu}^{(3)} = (\bar{l}_i \sigma_{\mu\nu} e)\epsilon_{ij}(\bar{q}_j \sigma^{\mu\nu} u)$$

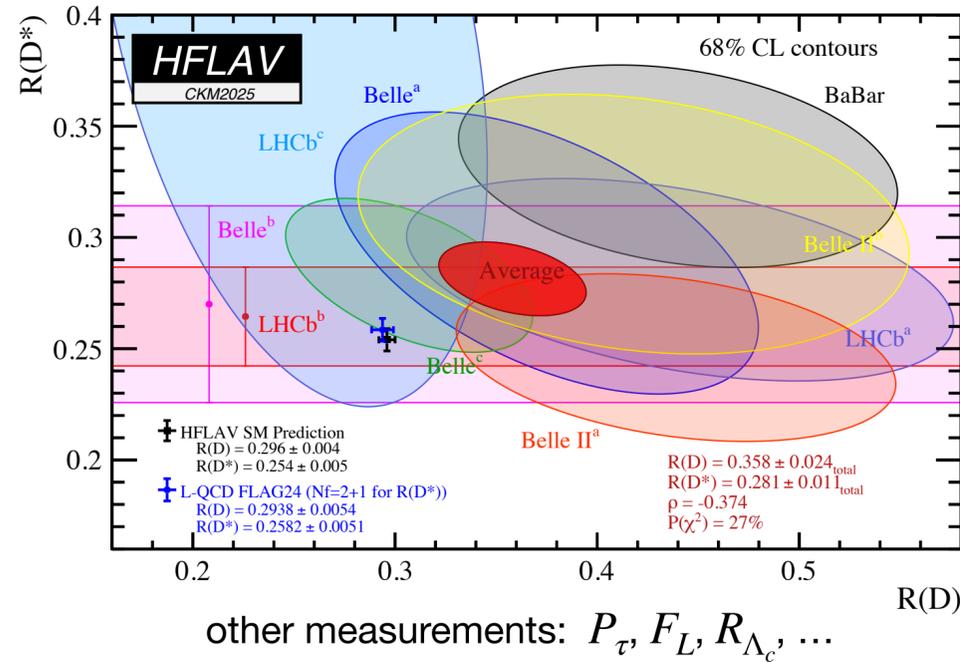


## Model

	Spin	Charge	Operators	$R_D$	$R_{D^*}$	LHC	Flavor
$H^\pm$	0	$(\mathbf{1}, \mathbf{2}, 1/2)$	$\mathcal{O}_{S_L}$	✓	✓	$b\tau\nu$	$B_c \rightarrow \tau\nu, F_L^{D^*}, P_\tau^{D^*}, M_W$
$S_1$	0	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$\mathcal{O}_{V_L}, \mathcal{O}_{S_L}, \mathcal{O}_T$	✓	✓	$\tau\tau$	$\Delta M_s, P_\tau^D, B \rightarrow K^{(*)}\nu\nu$
$R_2^{(2/3)}$	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	$\mathcal{O}_{S_L}, \mathcal{O}_T, (\mathcal{O}_{V_R})$	✓	✓	$b\tau\nu, \tau\tau$	$P_\tau^{D^*}, M_W, Z \rightarrow \tau\tau, d_N$
$U_1$	1	$(\mathbf{3}, \mathbf{1}, 2/3)$	$\mathcal{O}_{V_L}, \mathcal{O}_{S_R}$	✓	✓	$b\tau\nu, \tau\tau$	$\Delta M_s, R_{K^{(*)}}, B_s \rightarrow \tau\tau, d_N$
$V_2^{(1/3)}$	1	$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	$\mathcal{O}_{S_R}$	✓	$2\sigma$	$\tau\tau$	$B_s \rightarrow \tau\tau, B_u \rightarrow \tau\nu, M_W$

# $R_D^{(*)}$ anomalies: NP explanation

2405.06062, Iguro, Kitahara, Watanabe  
 1811.07920, Greljo, Camalich, Ruiz-A'lvarez  
 1810.04939, Q. Y. Hu, X. Q. Li, Y. D. Yang,



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$$\begin{aligned} \mathcal{O}_{V_L} &= (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu) \\ \mathcal{O}_{V_R} &= (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu) \\ \mathcal{O}_{S_L} &= (\bar{c}P_L b)(\bar{\ell}P_L \nu) \\ \mathcal{O}_{S_R} &= (\bar{c}P_R b)(\bar{\ell}P_L \nu) \\ \mathcal{O}_T &= (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu) \end{aligned}$$

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best fit

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$B(B_c \rightarrow \tau\nu) < 60\%$  assumed

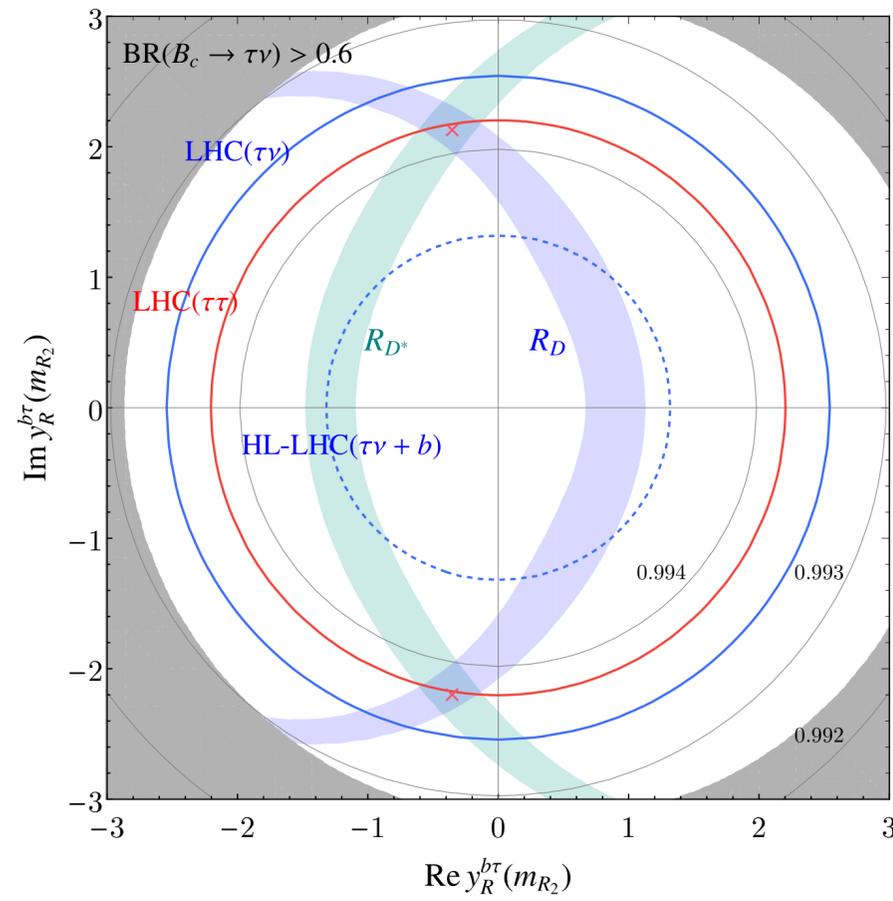
SMEFT

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

$$Q_{ledq} = (\bar{l}_i e)(\bar{d} q_i)$$

$$Q_{ledu}^{(1)} = (\bar{l}_i e)\epsilon_{ij}(\bar{q}_j u)$$

$$Q_{ledu}^{(3)} = (\bar{l}_i \sigma_{\mu\nu} e)\epsilon_{ij}(\bar{q}_j \sigma^{\mu\nu} u)$$



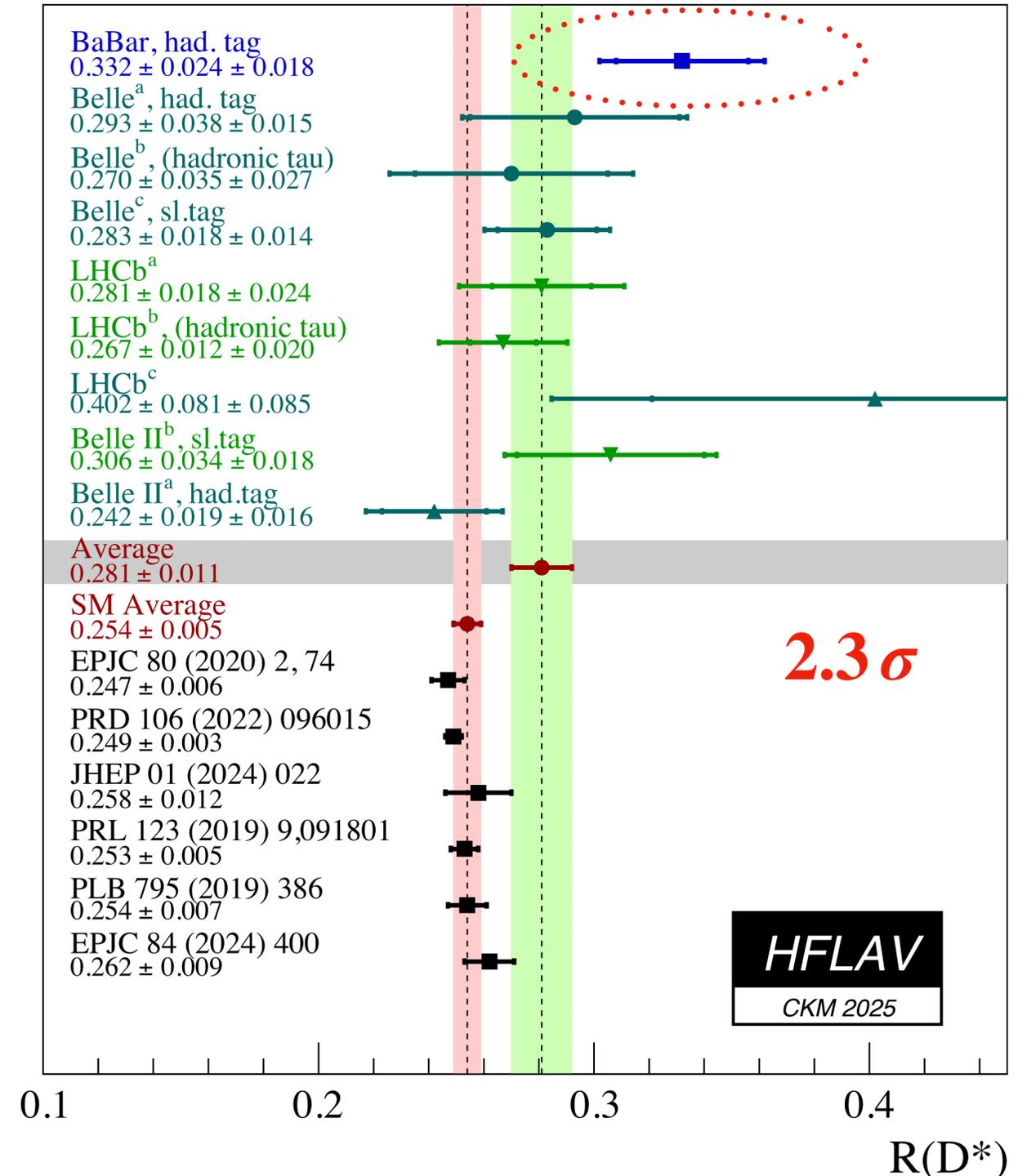
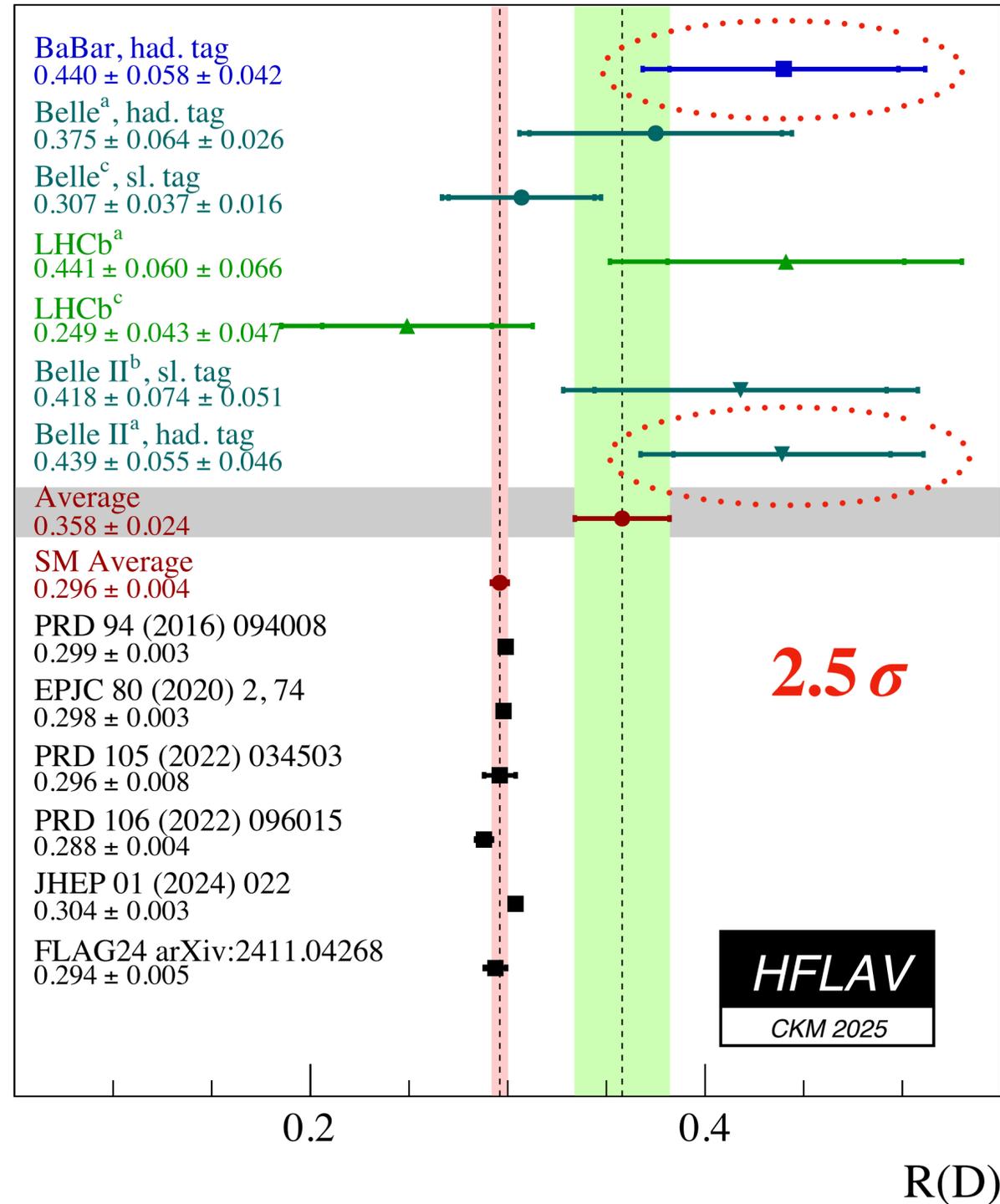
## Model

	Spin	Charge	Operators	$R_D$	$R_{D^*}$	LHC	Flavor
$H^\pm$	0	$(\mathbf{1}, \mathbf{2}, 1/2)$	$\mathcal{O}_{S_L}$	✓	✓	$b\tau\nu$	$B_c \rightarrow \tau\nu, F_L^{D^*}, P_\tau^{D^*}, M_W$
$S_1$	0	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$\mathcal{O}_{V_L}, \mathcal{O}_{S_L}, \mathcal{O}_T$	✓	✓	$\tau\tau$	$\Delta M_s, P_\tau^D, B \rightarrow K^{(*)}\nu\nu$
$R_2^{(2/3)}$	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	$\mathcal{O}_{S_L}, \mathcal{O}_T, (\mathcal{O}_{V_R})$	✓	✓	$b\tau\nu, \tau\tau$	$P_\tau^{D^*}, M_W, Z \rightarrow \tau\tau, d_N$
$U_1$	1	$(\mathbf{3}, \mathbf{1}, 2/3)$	$\mathcal{O}_{V_L}, \mathcal{O}_{S_R}$	✓	✓	$b\tau\nu, \tau\tau$	$\Delta M_s, R_{K^{(*)}}, B_s \rightarrow \tau\tau, d_N$
$V_2^{(1/3)}$	1	$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	$\mathcal{O}_{S_R}$	✓	$2\sigma$	$\tau\tau$	$B_s \rightarrow \tau\tau, B_u \rightarrow \tau\nu, M_W$

# $R_D^{(*)}$ anomalies: exp

## recent progresses on form factors

Jing Gao, Tobias Huber, Yao Ji, Chao Wang, Yu-Ming Wang, Yan-Bing Wei, 2112.12674  
 Bo-Yan Cui, Yong-Kang Huang, Yu-Ming Wang, Xue-Chen Zhao, 2301.12391  
 Shuang-Yi Li, Jie Xu, Rui-Xiang Shi, Li-Sheng Geng, Yi Zhang, 2412.05989



# $R_{D^{(*)}}$ anomalies: correlation

## sum rules for semi-leptonic decays

$$\frac{R_{\Lambda_c}}{R_{\Lambda_c}^{\text{SM}}} = (0.272 \pm 0.015) \frac{R_D}{R_D^{\text{SM}}} + (0.728 \mp 0.015) \frac{R_{D^*}}{R_{D^*}^{\text{SM}}} + \delta_{\Lambda_c} \quad \leftarrow \text{eliminate } |1 + C_{V_L}|^2, \text{Re}[(1 + C_{V_L})C_{S_L}^*]$$

$$\begin{aligned} \delta_{\Lambda_c} = & (-0.001 \pm 0.005) (|C_{S_L}^{c\tau}|^2 + |C_{S_R}^{c\tau}|^2) + (-0.007 \pm 0.005) \text{Re}(C_{S_L}^{c\tau} C_{S_R}^{c\tau*}) \\ & + (-2.681 \pm 6.907) |C_T^{c\tau}|^2 + (-0.561 \pm 1.439) \text{Re}(C_{V_R}^{c\tau} C_T^{c\tau*}) \\ & + \text{Re}[(1 + C_{V_L}^{c\tau}) \{(0.041 \pm 0.034)C_{V_R}^{c\tau*} + (0.594 \pm 1.274)C_T^{c\tau*}\}] \\ & + (-0.002 \pm 0.009) \text{Re}[(1 + C_{V_L}^{c\tau}) C_{S_R}^{c\tau*} + C_{S_L}^{c\tau} C_{V_R}^{c\tau*}] . \end{aligned} \quad (;$$

► based on LEFT, model-independent  $R_{\Lambda_c}^{\text{LHCb}} = 0.242 \pm 0.076$

► for any tau-philic NP  $R_{\Lambda_c}^{\text{SR}} = 0.372 \pm 0.017$

$$R_{\Lambda_c}^{\text{SM}} = 0.324 \pm 0.004$$

## other modes

►  $\frac{R_{X_c}}{R_{X_c}^{\text{SM}}} \simeq 0.288 \frac{R_D}{R_D^{\text{SM}}} + 0.712 \frac{R_{D^*}}{R_{D^*}^{\text{SM}}} + \delta_{X_c}$   $R_{X_c}^{\text{SR}} = 0.247 \pm 0.008$   $R_{X_c}^{\text{Belle II}} = 0.228 \pm 0.039$

►  $\frac{R_{J/\psi}}{R_{J/\psi}^{\text{SM}}} \simeq \frac{R_{D^*}}{R_{D^*}^{\text{SM}}}$   $\frac{R_{J/\psi}^{\text{exp}}}{R_{J/\psi}^{\text{SM}}} - \frac{R_{D^*}^{\text{exp}}}{R_{D^*}^{\text{SM}}} = 1.2 \pm 0.7$

►  $\frac{R_p}{R_p^{\text{SM}}} = (0.284 \pm 0.037) \frac{R_\pi}{R_\pi^{\text{SM}}} + (0.716 \mp 0.037) \frac{R_\rho}{R_\rho^{\text{SM}}} + \delta_p$

more precise measurements are needed !

$$\begin{aligned} \frac{R_P}{R_P^{\text{SM}}} = & |1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau}|^2 + a_P^{SS} |C_{S_L}^{q\tau} + C_{S_R}^{q\tau}|^2 + a_P^{TT} |C_T^{q\tau}|^2 \\ & + a_P^{VS} \text{Re}[(1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau})(C_{S_L}^{q\tau*} + C_{S_R}^{q\tau*})] + a_P^{VT} \text{Re}[(1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau})C_T^{q\tau*}] \end{aligned}$$

$$\begin{aligned} \frac{R_V}{R_V^{\text{SM}}} = & |1 + C_{V_L}^{q\tau}|^2 + |C_{V_R}^{q\tau}|^2 + a_V^{SS} |C_{S_L}^{q\tau} - C_{S_R}^{q\tau}|^2 + a_V^{TT} |C_T^{q\tau}|^2 \\ & + a_V^{V_L V_R} \text{Re}[(1 + C_{V_L}^{q\tau})C_{V_R}^{q\tau*}] + a_V^{VS} \text{Re}[(1 + C_{V_L}^{q\tau} - C_{V_R}^{q\tau})(C_{S_L}^{q\tau*} - C_{S_R}^{q\tau*})] \\ & + a_V^{V_L T} \text{Re}[(1 + C_{V_L}^{q\tau})C_T^{q\tau*}] + a_V^{V_R T} \text{Re}[C_{V_R}^{q\tau} C_T^{q\tau*}] , \end{aligned}$$

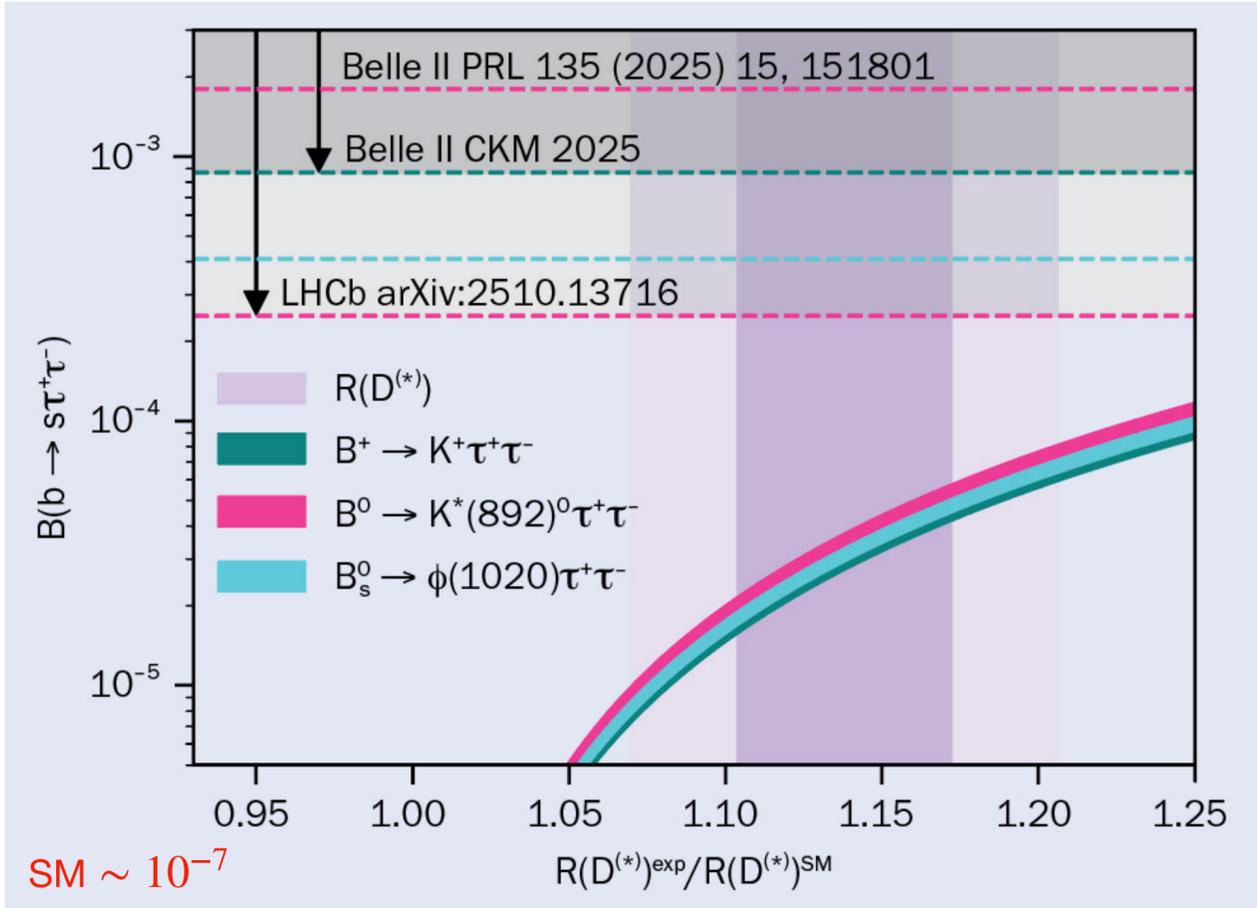
$$\begin{aligned} \frac{R_H}{R_H^{\text{SM}}} = & |1 + C_{V_L}^{q\tau}|^2 + |C_{V_R}^{q\tau}|^2 + a_H^{SS} [|C_{S_L}^{q\tau}|^2 + |C_{S_R}^{q\tau}|^2] + a_H^{TT} |C_T^{q\tau}|^2 \\ & + a_H^{V_L V_R} \text{Re}[(1 + C_{V_L}^{q\tau})C_{V_R}^{q\tau*}] + a_H^{VS_1} \text{Re}[(1 + C_{V_L}^{q\tau})C_{S_L}^{q\tau*} + C_{V_R}^{q\tau} C_{S_R}^{q\tau*}] \\ & + a_H^{VS_2} \text{Re}[(1 + C_{V_L}^{q\tau})C_{S_R}^{q\tau*} + C_{V_R}^{q\tau} C_{S_L}^{q\tau*}] + a_H^{S_L S_R} \text{Re}[C_{S_L}^{q\tau} C_{S_R}^{q\tau*}] \\ & + a_H^{V_L T} \text{Re}[(1 + C_{V_L}^{q\tau})C_T^{q\tau*}] + a_H^{V_R T} \text{Re}[C_{V_R}^{q\tau} C_T^{q\tau*}] , \end{aligned}$$

2  $\sigma$  deviation

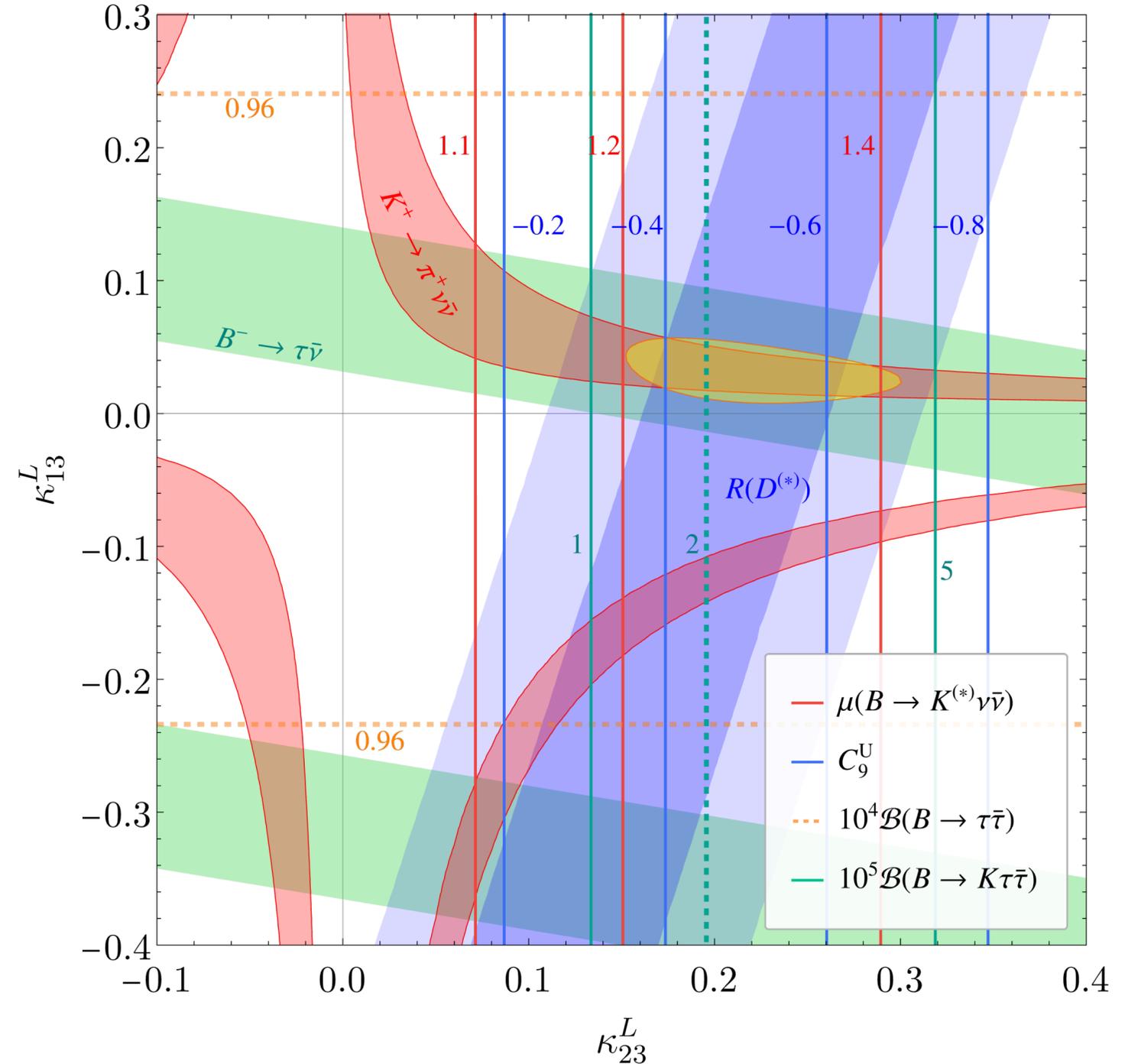
1811.09603, Blanke, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić  
 1905.08253, Blanke, Crivellin, Kitahara, Moscati, Nierste, Nišandžić  
 2211.14172, Fedele, Blanke, Crivellin, Iguro, Kitahara, Nierste, Watanabe  
**2410.21384, 段文烽, Iguro, 李新强, Watanabe, 杨亚东**  
 2501.09382, Endo, Iguro, Mishima, Watanabe, *heavy quark symmetry*  
 2506.16027, Endo, Iguro, Kretz, Mishima, Watanabe, *angular observable*  
 2508.06322, Endo, Iguro, Mishima, Watanabe,  
 2509.02006, Endo, Iguro, Mishima, Watanabe,

# $R_{D^{(*)}}$ anomalies: correlation

correlation with  $b \rightarrow s\tau^+\tau^-$  in SMEFT



correlations in  $U_1$  leptoquark



$$O_{ijkl}^{(1)} = [\bar{Q}_i \gamma_\mu Q_j] [\bar{L}_k \gamma^\mu L_l] \quad C^{(1)} \mathcal{O}^{(1)} \rightarrow C_{23}^{(1)} ([\bar{s}_L \gamma_\mu b_L] [\bar{\tau}_L \gamma^\mu \tau_L] + [\bar{s}_L \gamma_\mu b_L] [\bar{\nu}_\tau \gamma^\mu \nu_\tau]),$$

$$O_{ijkl}^{(3)} = [\bar{Q}_i \gamma_\mu \sigma^I Q_j] [\bar{L}_k \gamma^\mu \sigma^I L_l] \quad C^{(3)} \mathcal{O}^{(3)} \rightarrow C_{23}^{(3)} (2V_{cs} [\bar{c}_L \gamma_\mu b_L] [\bar{\tau}_L \gamma^\mu \nu_\tau] + [\bar{s}_L \gamma_\mu b_L] [\bar{\tau}_L \gamma^\mu \tau_L]$$

down basis with  $C^{(1)} = C^{(3)}$   $- [\bar{s}_L \gamma_\mu b_L] [\bar{\nu}_\tau \gamma^\mu \nu_\tau]) + C_{33}^{(3)} (2V_{cb} [\bar{c}_L \gamma_\mu b_L] [\bar{\tau}_L \gamma^\mu \nu_\tau]),$

LHCb, 2510.13716

Capdevila, Crivellin, Descotes-Genon, Hofer, Matias, 1712.01919

$m_{U_1} = 2 \text{ TeV}, \kappa_{33}^L = 1.5$

$\kappa_{23}^L$

Crivellin, Iguro, Kitahara, 2505.05552

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

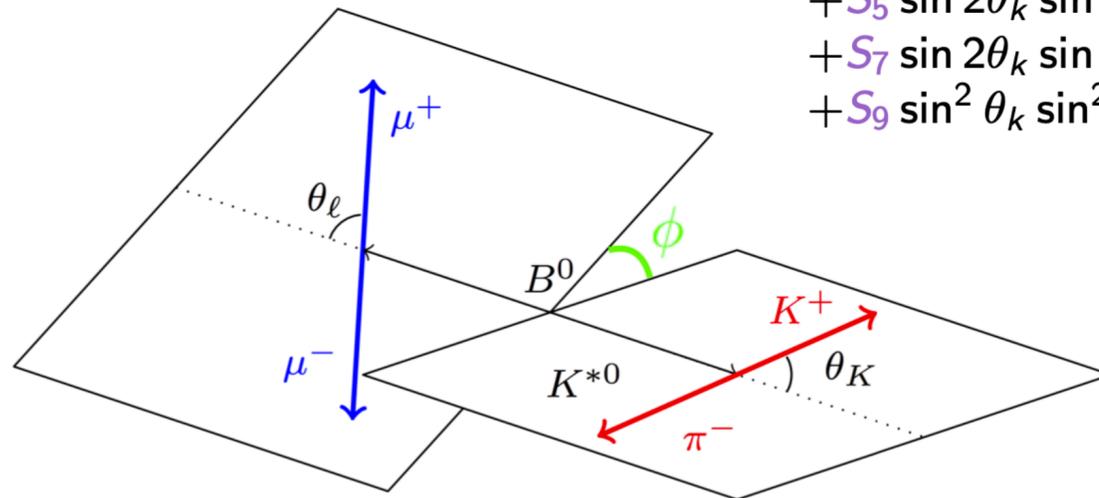
- ▶  $b \rightarrow s \ell^+ \ell^-$
- ▶  $B_s \rightarrow \ell^+ \ell^-$
- ▶  $B \rightarrow X_s \ell^+ \ell^-$
- ▶  $B \rightarrow K \ell^+ \ell^-$
- ▶  $B \rightarrow K^* \ell^+ \ell^-$
- ▶  $B_s \rightarrow \phi \ell^+ \ell^-$
- ▶  $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$

theoretical cleanliness

- ▶ Branching Ratio
- ▶ Angular Distribution
- ▶ Lepton Flavour Universality (LFU) ratio

function of  $(C_{7\gamma}, C_9, C_{10})$

angular distribution of  
 $B \rightarrow K^*( \rightarrow K\pi ) \mu^+ \mu^-$



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

angular observables

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

LFU ratio in  $B \rightarrow K \ell^+ \ell^-$

$$R_K = \frac{\mathcal{B}(B \rightarrow K \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K e^+ e^-)}$$

- ▶  $R_K^{\text{SM}} \approx 1$
- ▶ Hadronic uncertainties cancel
- ▶  $\mathcal{O}(10^{-2})$  QED correction

deviation from unity



Physics beyond the SM

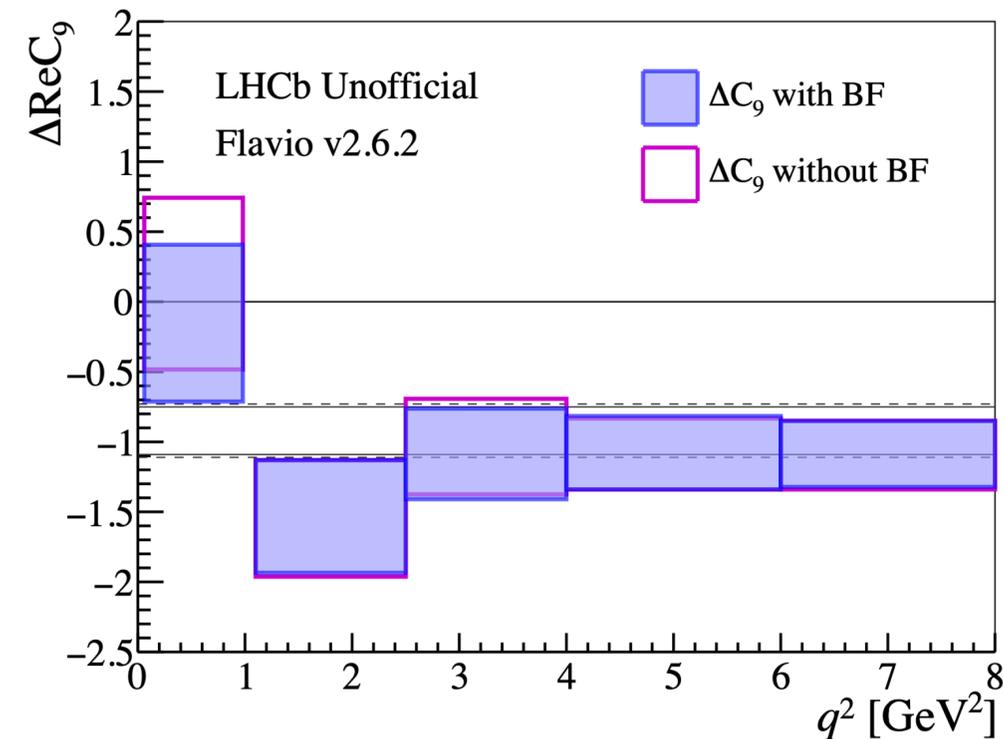
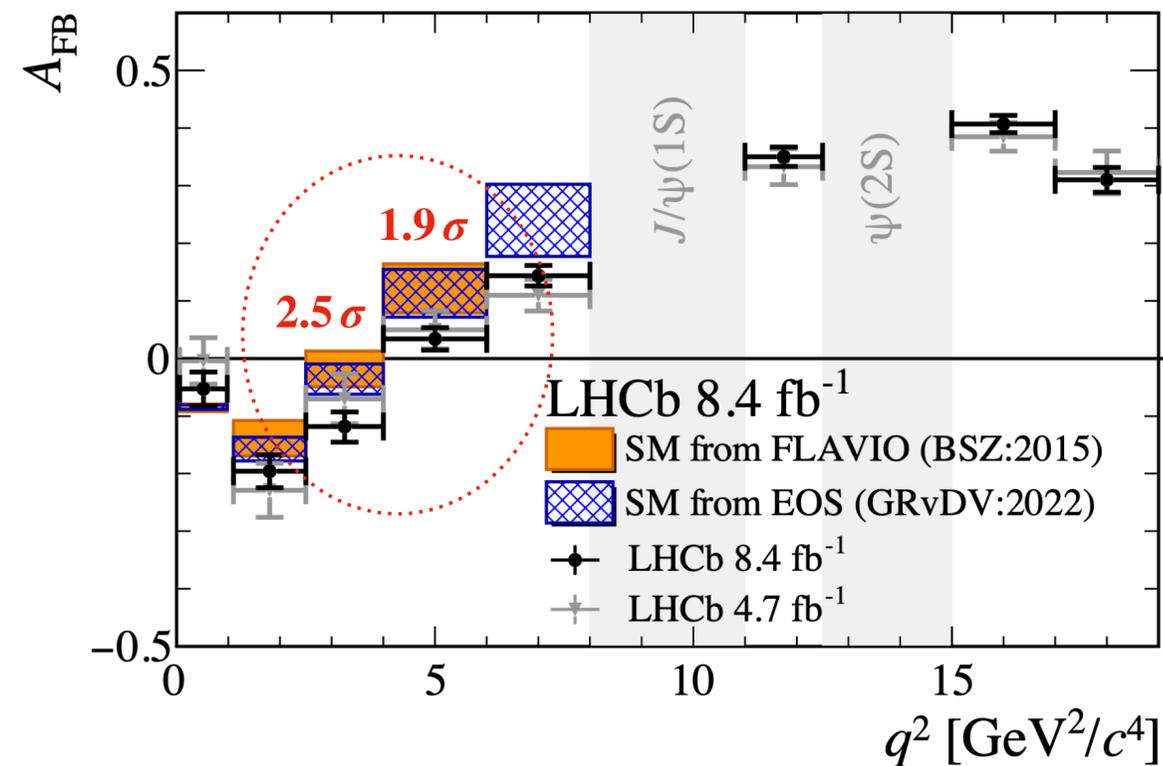
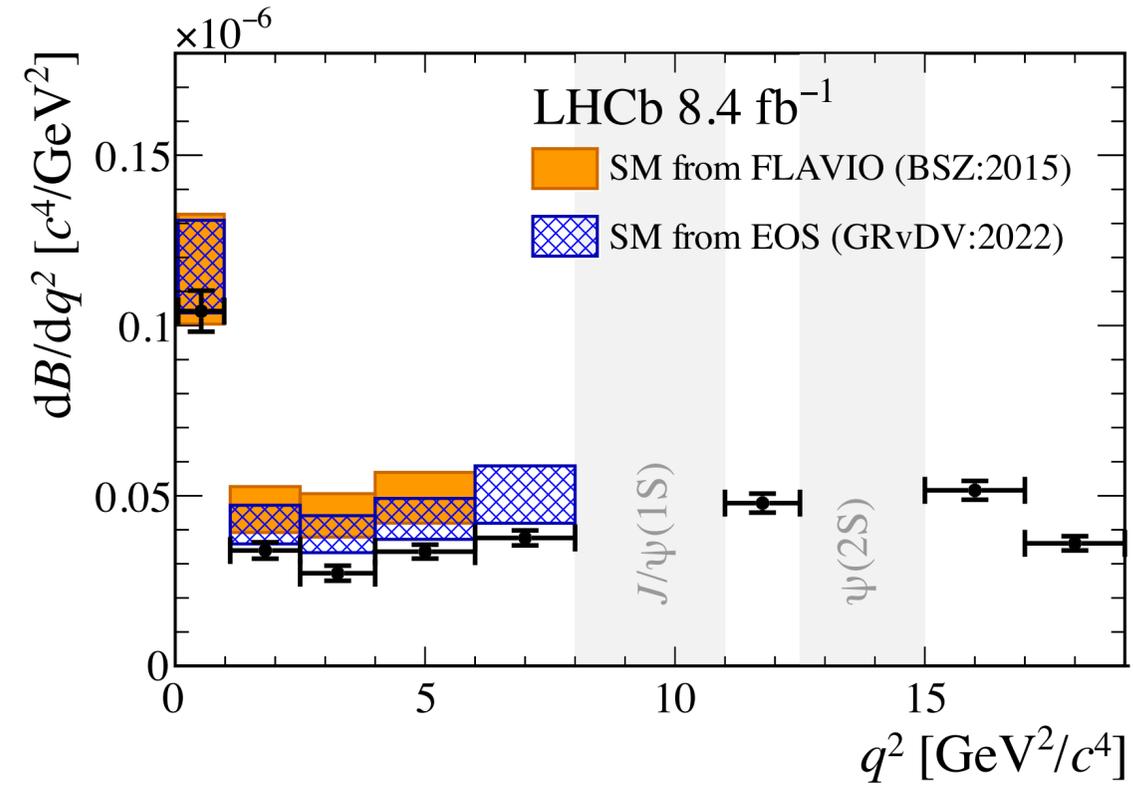
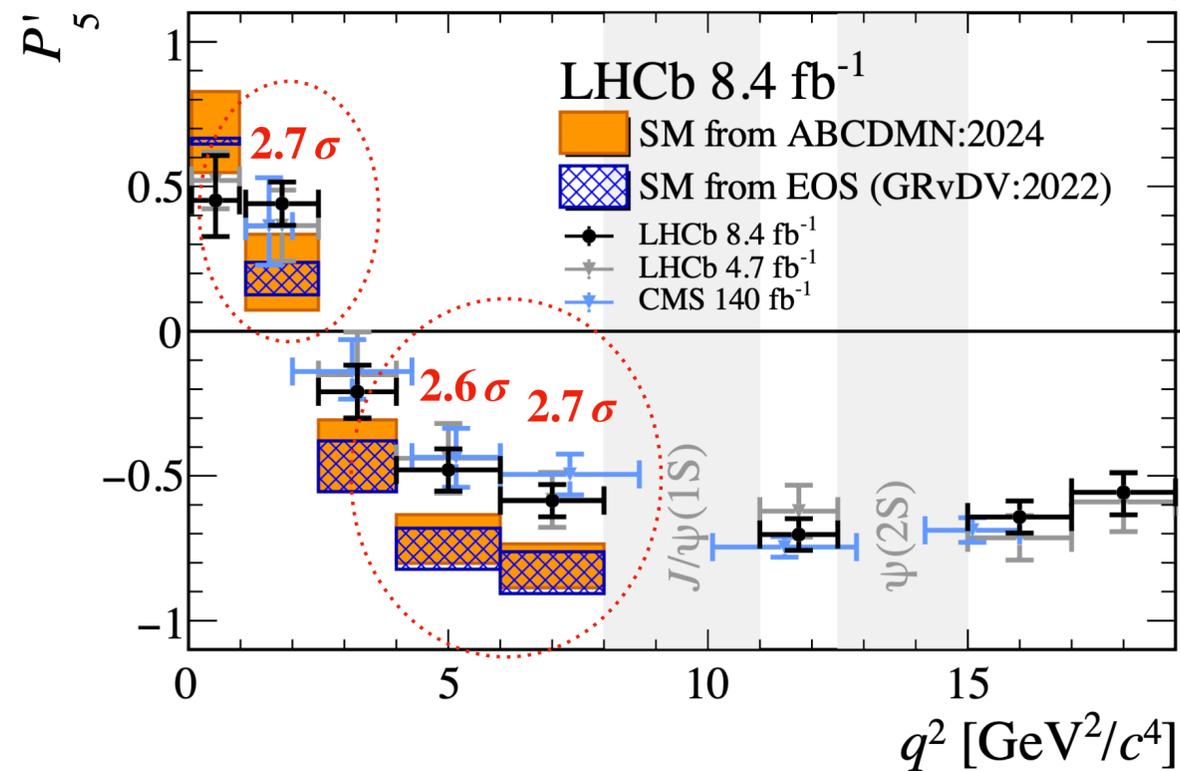
$$P_1 = \frac{2S_3}{1 - F_L}$$

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

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

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

# Experimental status



$q^2$ -dependent global fit  
to test charm-loop

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

## ▶ Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i$$

## ▶ Effective operator

~~$$O_7^{(\prime)} = \frac{m_b}{e} (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$~~

strongly constrained by  $b \rightarrow s\gamma$

$$O_9^\mu = (\bar{s} \gamma^\mu P_L b) (\bar{\mu} \gamma_\mu \mu) \quad O_9^{\mu'} = (\bar{s} \gamma^\mu P_R b) (\bar{\mu} \gamma_\mu \mu)$$

SM operator

~~$$O_{10}^\mu = (\bar{s} \gamma^\mu P_L b) (\bar{\mu} \gamma_\mu \gamma_5 \mu) \quad O_{10}^{\mu'} = (\bar{s} \gamma^\mu P_R b) (\bar{\mu} \gamma_\mu \gamma_5 \mu)$$~~

interference with SM

~~$$O_S^\mu = (\bar{s} P_R b) (\bar{\mu} \mu) \quad O_S^{\mu'} = (\bar{s} P_L b) (\bar{\mu} \mu)$$~~

~~$$O_P^\mu = (\bar{s} P_R b) (\bar{\mu} \gamma_5 \mu) \quad O_P^{\mu'} = (\bar{s} P_L b) (\bar{\mu} \gamma_5 \mu)$$~~

no helicity suppression

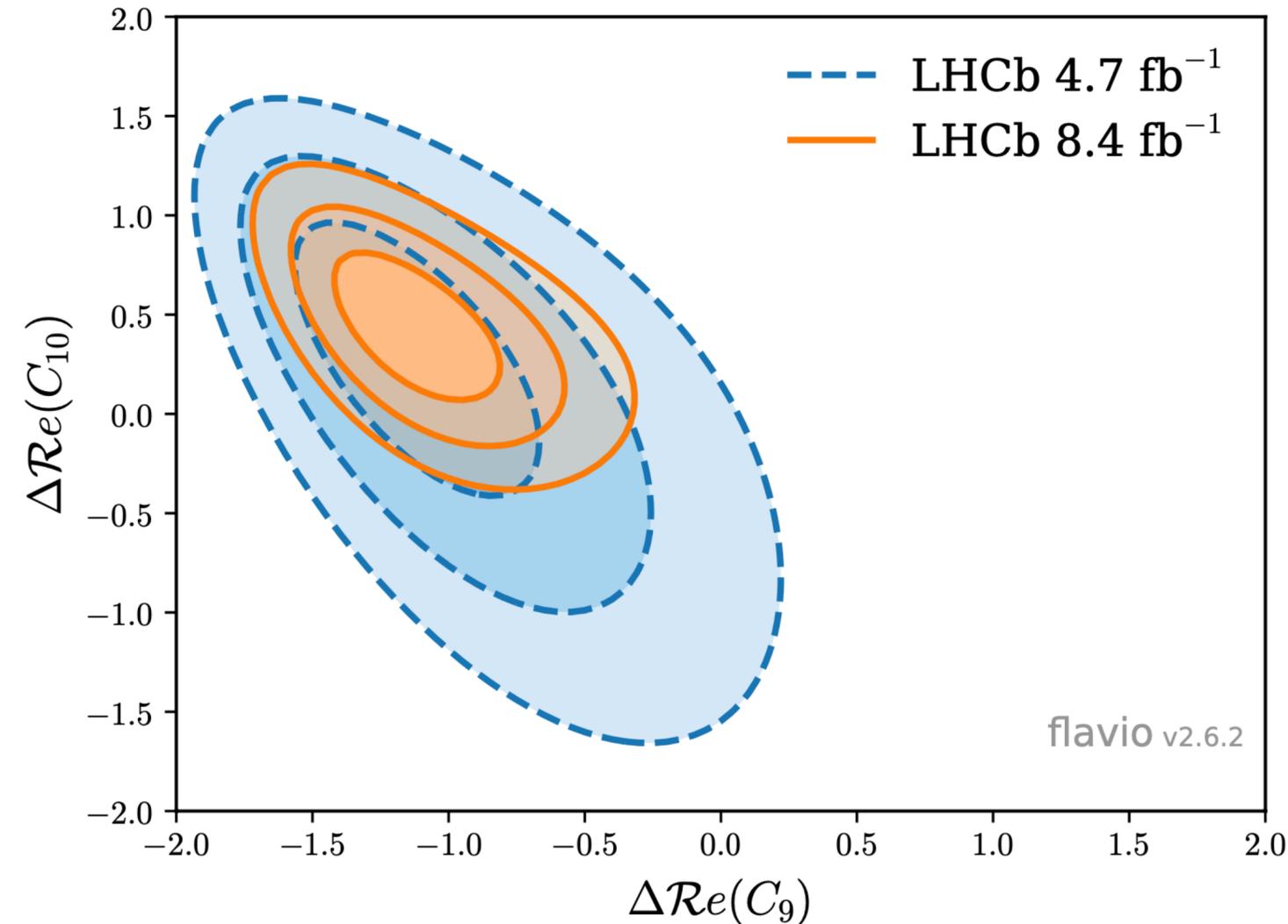
strongly constrained by  $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$

$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)_{\text{avg}} = (3.52_{-0.30}^{+0.32}) \times 10^{-9}$$

$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

global fit of branching ratios and angular observables in  $B \rightarrow K^* \mu^+ \mu^-$

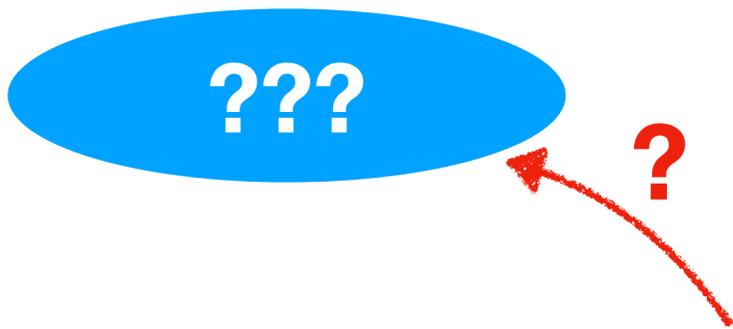
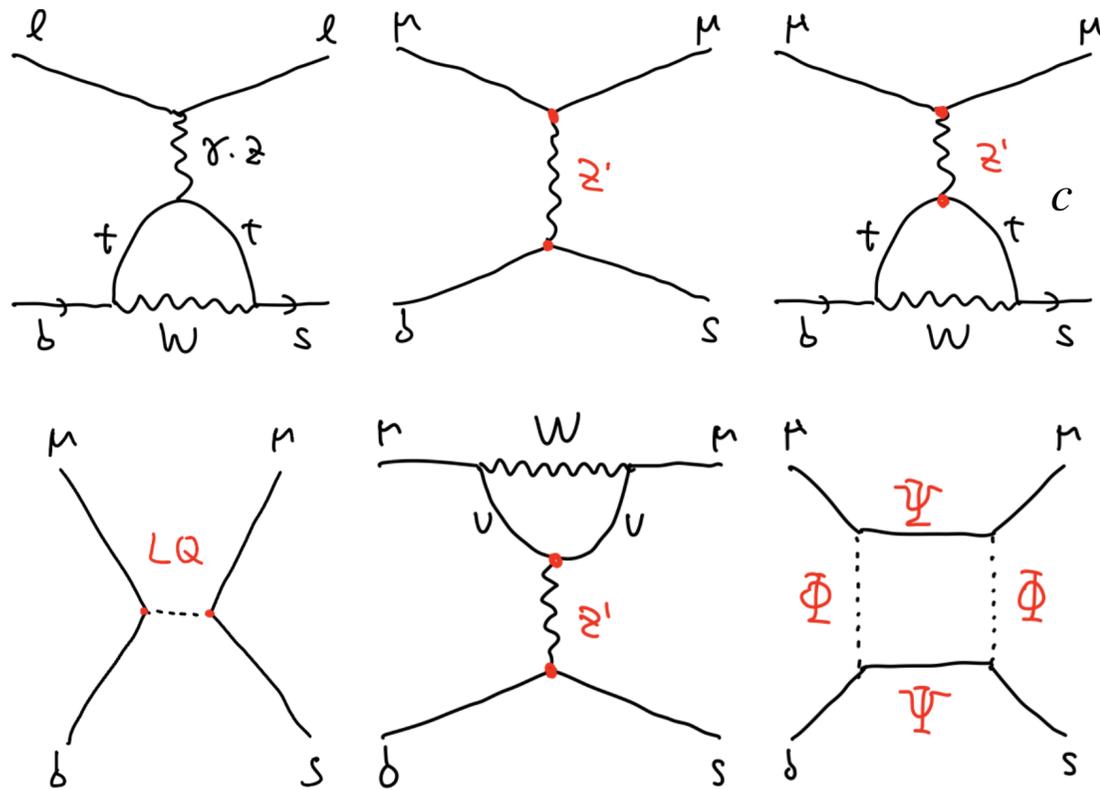
Langenbruch's talk@LHCb Implications workshop 2025



4.1  $\sigma$  tension with the SM

# Flavour anomalies: New Physics interpretation

## models for $b \rightarrow s \ell^+ \ell^-$ 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

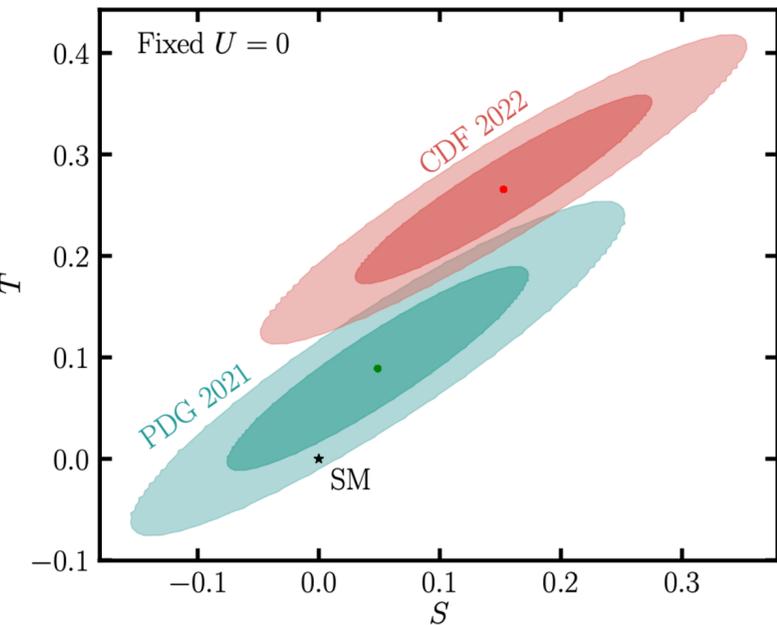
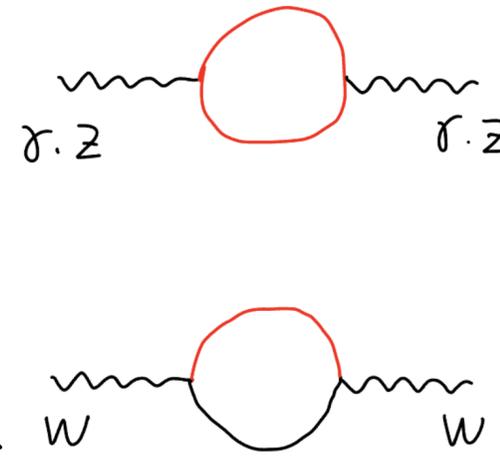
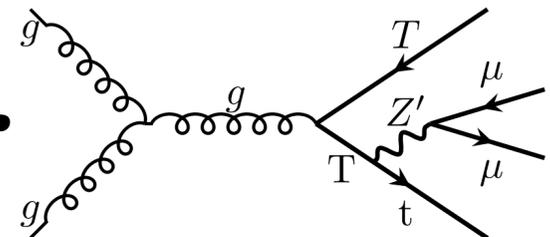
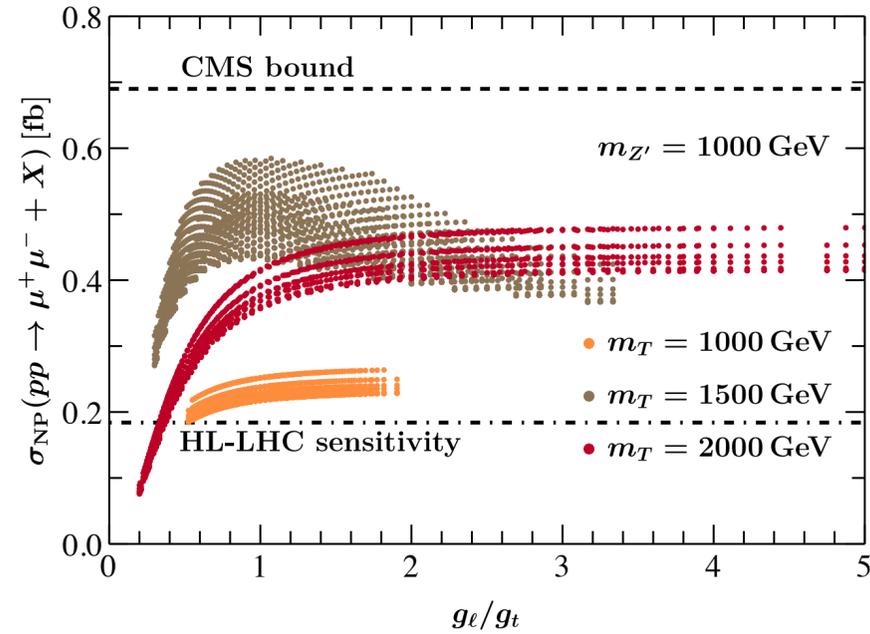
$$\mathcal{H}_{\text{eff}} = (C_i^{\text{SM}} + C_i^{\text{NP}}) O_i^{\text{SM}} + C_j^{\text{NP}} O_j^{\text{NP}} \quad SU(3)_C \otimes U(1)_{\text{em}}$$

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

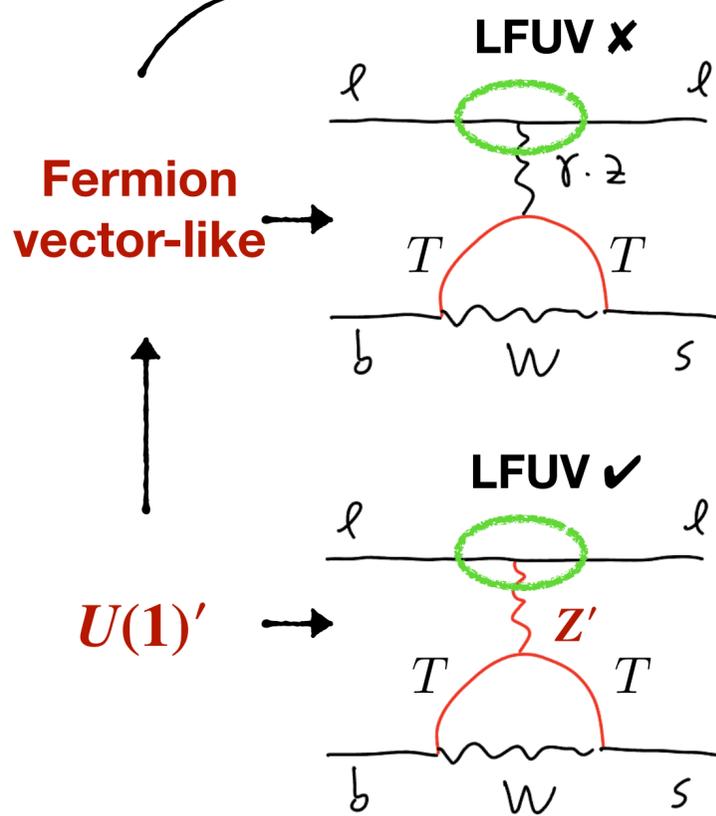
X.Q.Li, Y.D.Yang, **XBY**, et al, 2112.14215, 2205.02205, 2307.05290  
 Cheng-Wei Chiang, Xiao-Gang He, Jusak Tandean, **XBY**, 1706.02696  
 C. S. Kim, **XBY**, Ya-Juan Zheng, 1602.08107

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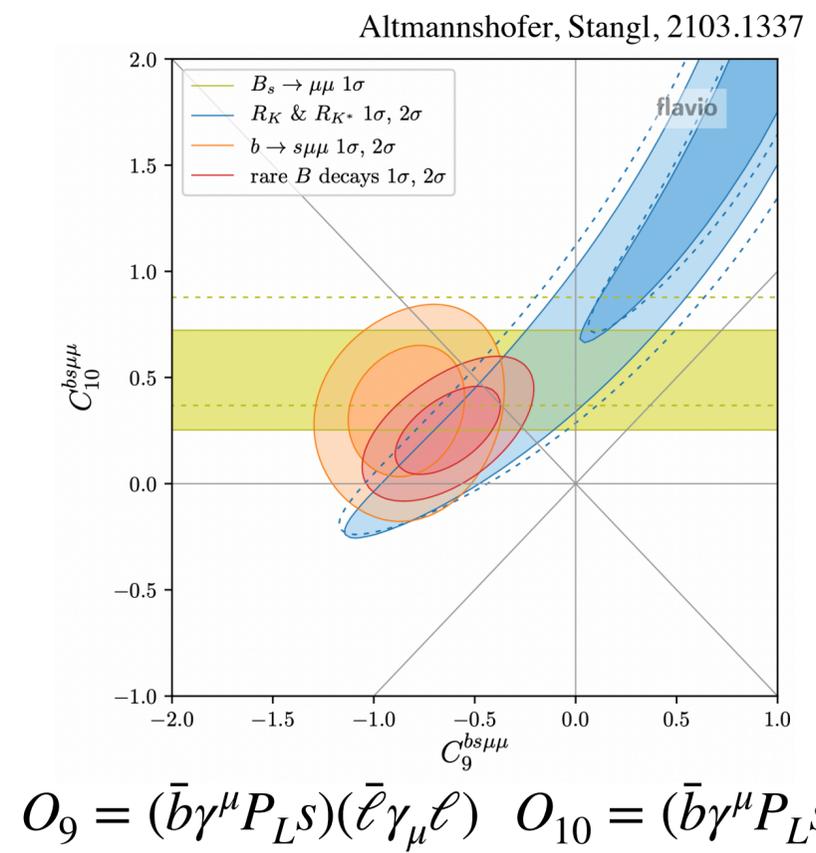


Chih-Ting Lu, Lei Wu, Yongcheng Wu, and Bin Zhu, 2204.03796

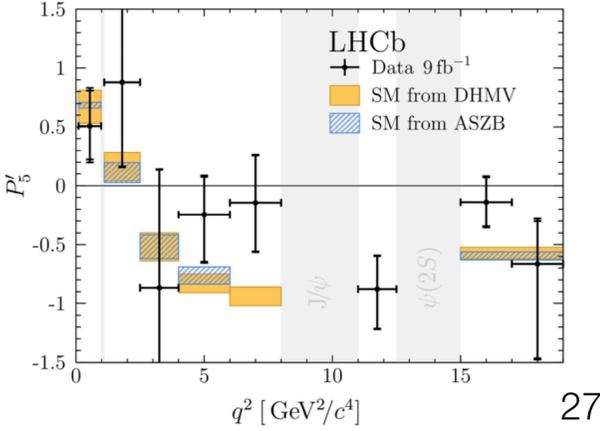
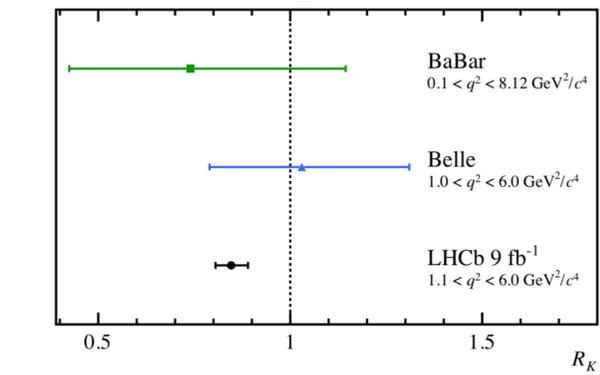
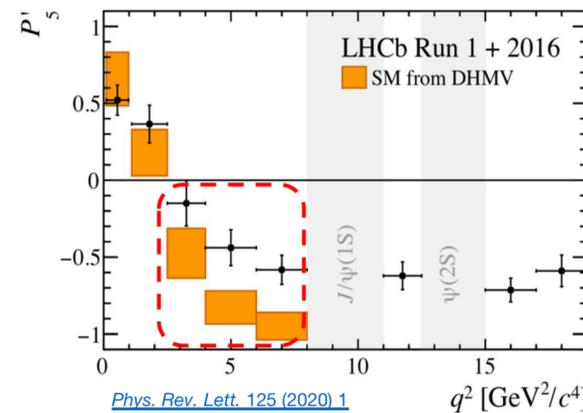
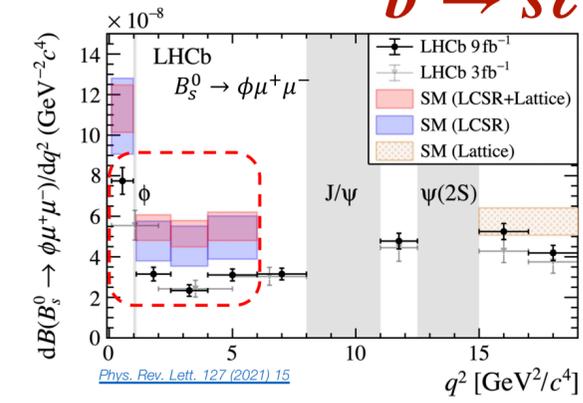


Fermion vector-like

$U(1)'$

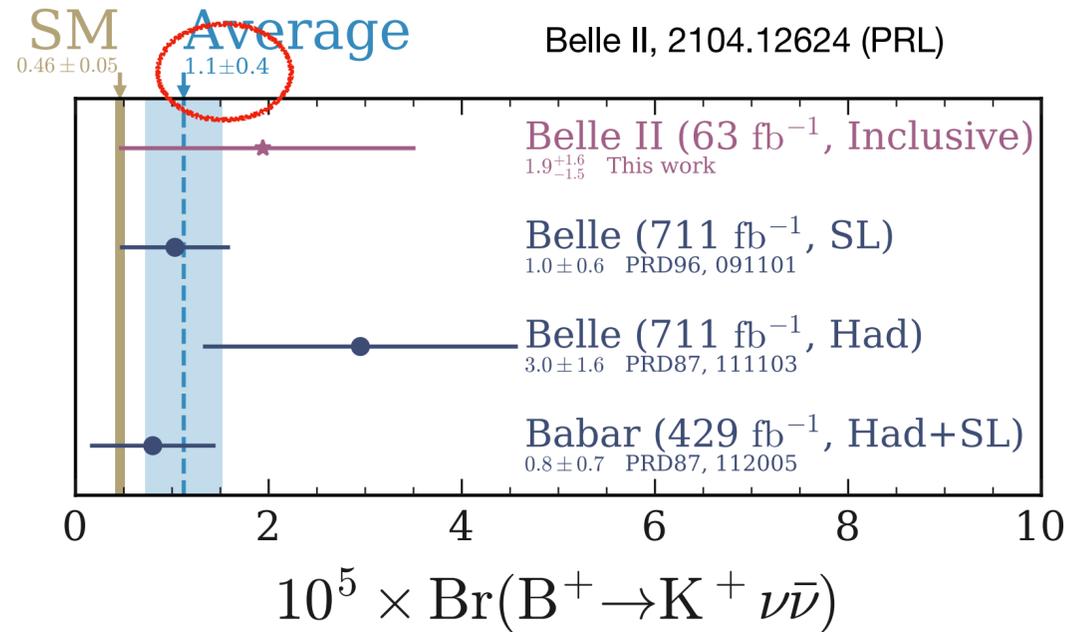


$b \rightarrow s \ell^+ \ell^-$  anomaly

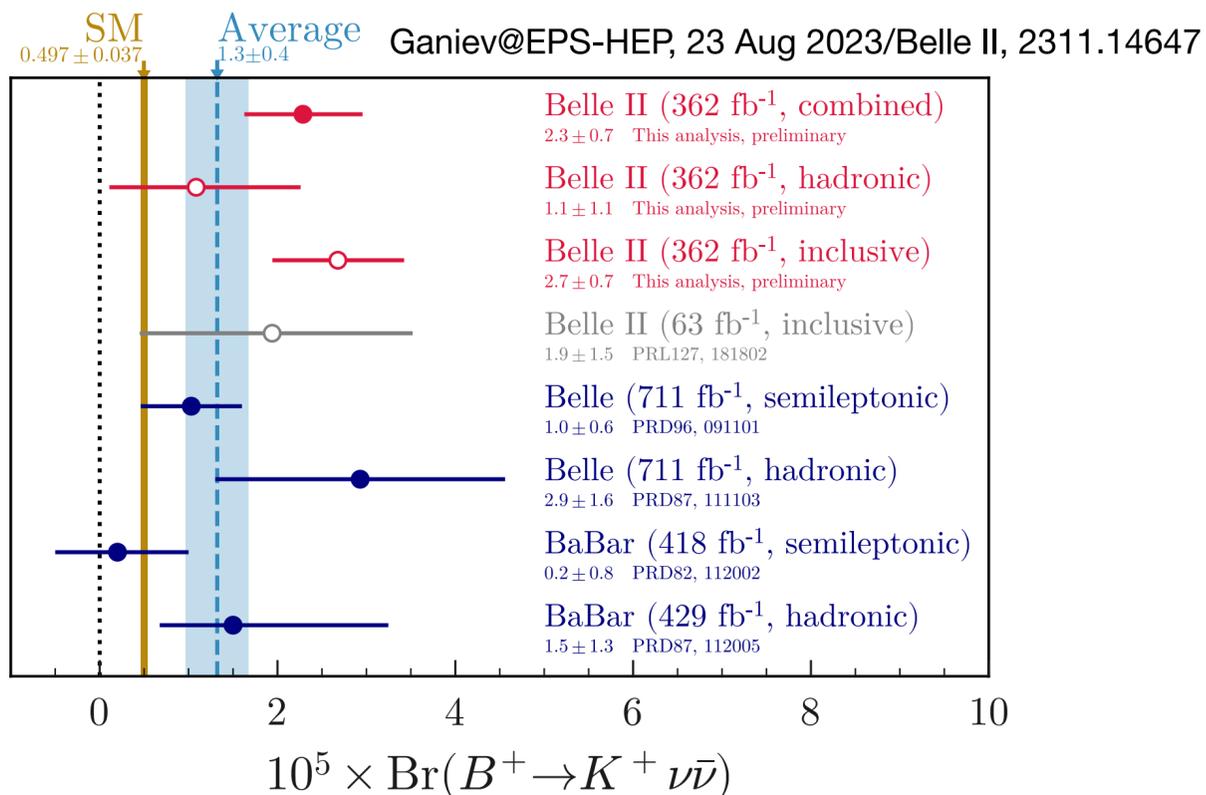


# $b \rightarrow s\nu\bar{\nu}$ : exp & theory

## 2021 Apr



## 2023 Aug



**Impact of  $B \rightarrow K\nu\bar{\nu}$  measurements on beyond the Standard Model theories** #69  
 Thomas E. Browder (Hawaii U.), Nilendra G. Deshpande (Oregon U.), Rusa Mandal (Siegen U.), Rahul Sinha (IMSC, Chennai and Bhubaneswar, Inst. Phys.) (Jul 2, 2021)  
 Published in: *Phys.Rev.D* 104 (2021) 5, 053007 · e-Print: 2107.01080 [hep-ph]  
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [34 citations](#)

150+ theory papers !

**Phenomenological study of a gauged  $L_\mu - L_\tau$  model with a scalar leptoquark** #42  
 Chuan-Hung Chen (Taiwan, Natl. Cheng Kung U. and NCTS, Taipei), Cheng-Wei Chiang (Taiwan, Natl. Taiwan U. and NCTS, Taipei), Chun-Wei Su (Taiwan, Natl. Taiwan U.) (May 16, 2023)  
 Published in: *Phys.Rev.D* 109 (2024) 5, 5 · e-Print: 2305.09256 [hep-ph]  
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [3 citations](#)

**Higgs portal interpretation of the Belle II  $B^+ \rightarrow K^+ \nu \bar{\nu}$  measurement** #29  
 David McKeen (TRIUMF), John N. Ng (TRIUMF), Douglas Tuckler (TRIUMF and Simon Fraser U.) (Dec 1, 2023)  
 Published in: *Phys.Rev.D* 109 (2024) 7, 075006 · e-Print: 2312.00982 [hep-ph]  
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [10 citations](#)

**Light new physics in  $B \rightarrow K^{(*)} \nu \bar{\nu}$ ?** #30  
 Wolfgang Altmannshofer (UC, Santa Cruz, Inst. Part. Phys.), Andreas Crivellin (Zurich U.), Huw Haigh (Vienna, OAW), Gianluca Inguglia (Vienna, OAW), Jorge Martin Camalich (IAC, La Laguna) (Nov 24, 2023)  
 Published in: *Phys.Rev.D* 109 (2024) 7, 075008 · e-Print: 2311.14629 [hep-ph]  
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [15 citations](#)

**$B \rightarrow K\nu\bar{\nu}$ , MiniBooNE and muon  $g - 2$  anomalies from a dark sector** #31  
 Alakabha Datta (Mississippi U. and SLAC and UC, Santa Cruz), Danny Marfatia (Hawaii U.), Lopamudra Mukherjee (Nankai U.) (Oct 23, 2023)  
 Published in: *Phys.Rev.D* 109 (2024) 3, L031701 · e-Print: 2310.15136 [hep-ph]  
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**$B \rightarrow K^* M_X$  vs  $B \rightarrow K M_X$  as a probe of a scalar-mediator dark matter scenario** #33  
 Alexander Berezhnoy (SINP, Moscow), Dmitri Melikhov (SINP, Moscow and Dubna, JINR and Vienna U.) (Sep 29, 2023)  
 Published in: *EPL* 145 (2024) 1, 14001 · e-Print: 2309.17191 [hep-ph]  
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [10 citations](#)

**Flavor anomalies in leptoquark model with gauged  $U(1)_{\nu_\mu - L_\tau}$**  #34  
 Chuan-Hung Chen (Taiwan, Natl. Cheng Kung U. and Unlisted, TW), Cheng-Wei Chiang (Taiwan, Natl. Taiwan U. and Unlisted, TW) (Sep 22, 2023)  
 Published in: *Phys.Rev.D* 109 (2024) 7, 075004 · e-Print: 2309.12904 [hep-ph]  
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [9 citations](#)

**Revisiting models that enhance  $B^+ \rightarrow K^+ \nu \bar{\nu}$  in light of the new Belle II measurement** #35  
 Belle-II Collaboration · Xiao-Gang He (Tsung-Dao Lee Inst., Shanghai and Taiwan, Natl. Taiwan U.) et al. (Sep 22, 2023)  
 Published in: *Phys.Rev.D* 109 (2024) 7, 075019 · e-Print: 2309.12741 [hep-ph]  
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [16 citations](#)

**A new look at  $\bar{b} \rightarrow s$  observables in 331 models** #18  
 Francesco Loporco (Jan 22, 2024)  
 e-Print: 2401.11999 [hep-ph]  
[pdf](#) [cite](#) [claim](#) [reference search](#) [1 citation](#)

**Correlating  $B \rightarrow K^{(*)} \nu \bar{\nu}$  and flavor anomalies in SMEFT** #19  
 Feng-Zhi Chen, Qiaoyi Wen, Fanrong Xu (Jan 21, 2024)  
 e-Print: 2401.11552 [hep-ph]  
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**Recent  $B^+ \rightarrow K^+ \nu \bar{\nu}$  Excess and Muon  $g - 2$  Illuminating Light Dark Sector with Higgs Portal** #20  
 Shu-Yu Ho, Jongkuk Kim, Pyungwon Ko (Jan 18, 2024)  
 e-Print: 2401.10112 [hep-ph]  
[pdf](#) [cite](#) [claim](#) [reference search](#) [4 citations](#)

**A tale of invisibility: constraints on new physics in  $b \rightarrow s\nu\bar{\nu}$**  #65  
 Tobias Felki (New South Wales U.), Sze Lok Li (New South Wales U.), Michael A. Schmidt (New South Wales U.) (Nov 8, 2021)  
 Published in: *JHEP* 12 (2021) 118 · e-Print: 2111.04327 [hep-ph]  
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**Explaining the  $B^+ \rightarrow K^+ \nu \bar{\nu}$  excess via a massless dark photon** #16  
 E. Gabrielli, L. Marzola, K. Mürsepp, M. Raidal (Feb 8, 2024)  
 e-Print: 2402.05901 [hep-ph]  
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**Decoding the  $B \rightarrow K \nu \bar{\nu}$  excess at Belle II: kinematics, operators, and masses** #27  
 Kåre Fridell, Mitrajyoti Ghosh, Takemichi Okui, Kohsaku Tobioka (Dec 19, 2023)  
 e-Print: 2312.12507 [hep-ph]  
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**Understanding the first measurement of  $B(B \rightarrow K \nu \bar{\nu})$**  #38  
 Lukas Allwicher (Zurich U.), Damir Becirevic (IJCLab, Orsay), Gioacchino Piazza (IJCLab, Orsay), Salvador Rosairo-Alcaraz (IJCLab, Orsay), Olcyr Sumensari (IJCLab, Orsay) (Sep 5, 2023)  
 Published in: *Phys.Lett.B* 848 (2024) 138411 · e-Print: 2309.02246 [hep-ph]  
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**Implications of an enhanced  $B \rightarrow K \nu \bar{\nu}$  branching ratio** #39  
 Rigo Bause (Tech. U., Dortmund (main)), Hector Gisbert (INFN, Padua and Padua U.), Gudrun Hiller (Tech. U., Dortmund (main) and Sussex U.) (Aug 31, 2023)  
 Published in: *Phys.Rev.D* 109 (2024) 1, 015006 · e-Print: 2309.00075 [hep-ph]  
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**B meson anomalies and large  $B^+ \rightarrow K^+ \nu \bar{\nu}$  in non-universal  $U(1)'$  models** #40  
 Peter Athron (Nanjing Normal U.), R. Martinez (Colombia, U. Natl.), Cristian Sierra (Nanjing Normal U.) (Aug 25, 2023)  
 Published in: *JHEP* 02 (2024) 121 · e-Print: 2308.13426 [hep-ph]  
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [22 citations](#)

**SMEFT predictions for semileptonic processes** #4  
 Siddhartha Karmakar, Amol Dighe, Rick S. Gupta (Apr 15, 2024)  
 e-Print: 2404.10061 [hep-ph]  
[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

**Implications of  $B \rightarrow K \nu \bar{\nu}$  under Rank-One Flavor Violation hypothesis** #5  
 David Marzocca, Marco Nardecchia, Alfredo Stanzione, Claudio Toni (Apr 9, 2024)  
 e-Print: 2404.06533 [hep-ph]  
[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

**The quark flavor-violating ALPs in light of B mesons and hadron colliders** #20  
 Tong Li (Nankai U.), Zhuoni Qian (Hangzhou Normal U.), Michael A. Schmidt (Sydney U. and New South Wales U.), Man Yuan (Nankai U.) (Feb 21, 2024)  
 Published in: *JHEP* 05 (2024) 232 · e-Print: 2402.14232 [hep-ph]  
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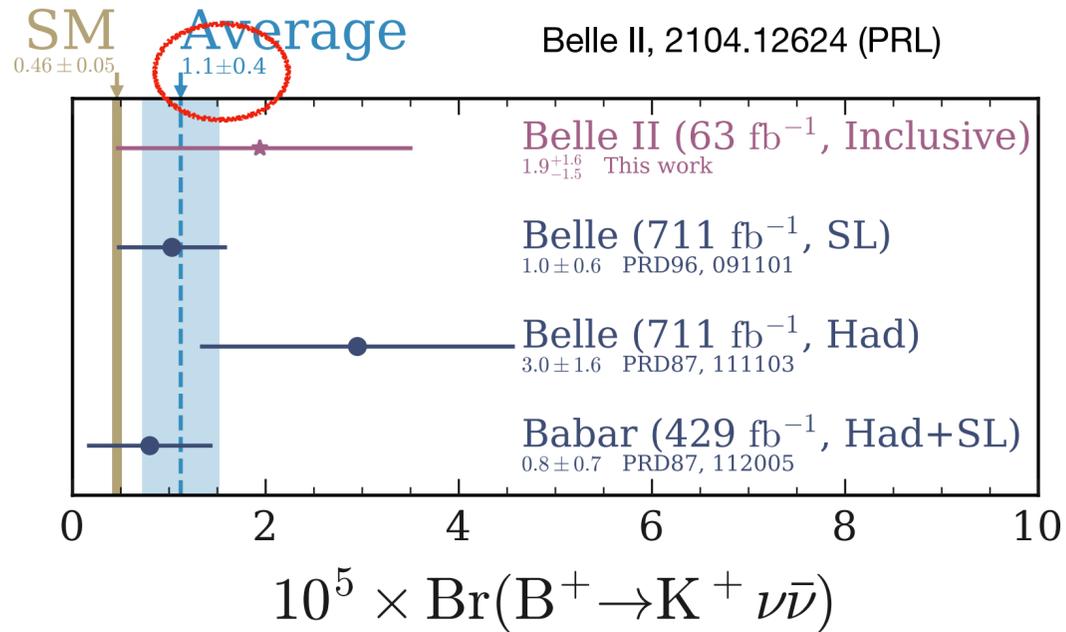
**Scalar dark matter explanation of the excess in the Belle II  $B^+ \rightarrow K^+ + \text{invisible}$  measurement** #9  
 Xiao-Gang He, Xiao-Dong Ma, Michael A. Schmidt, German Valencia, Raymond R. Volkas (Mar 19, 2024)  
 e-Print: 2403.12485 [hep-ph]  
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**Status and prospects of rare decays at Belle-II** #10  
 Elisa Manoni (Mar 12, 2024)  
 Published in: *PoS WFAI2023* (2024) 024 · Contribution to: *WFAI 2023*, 024  
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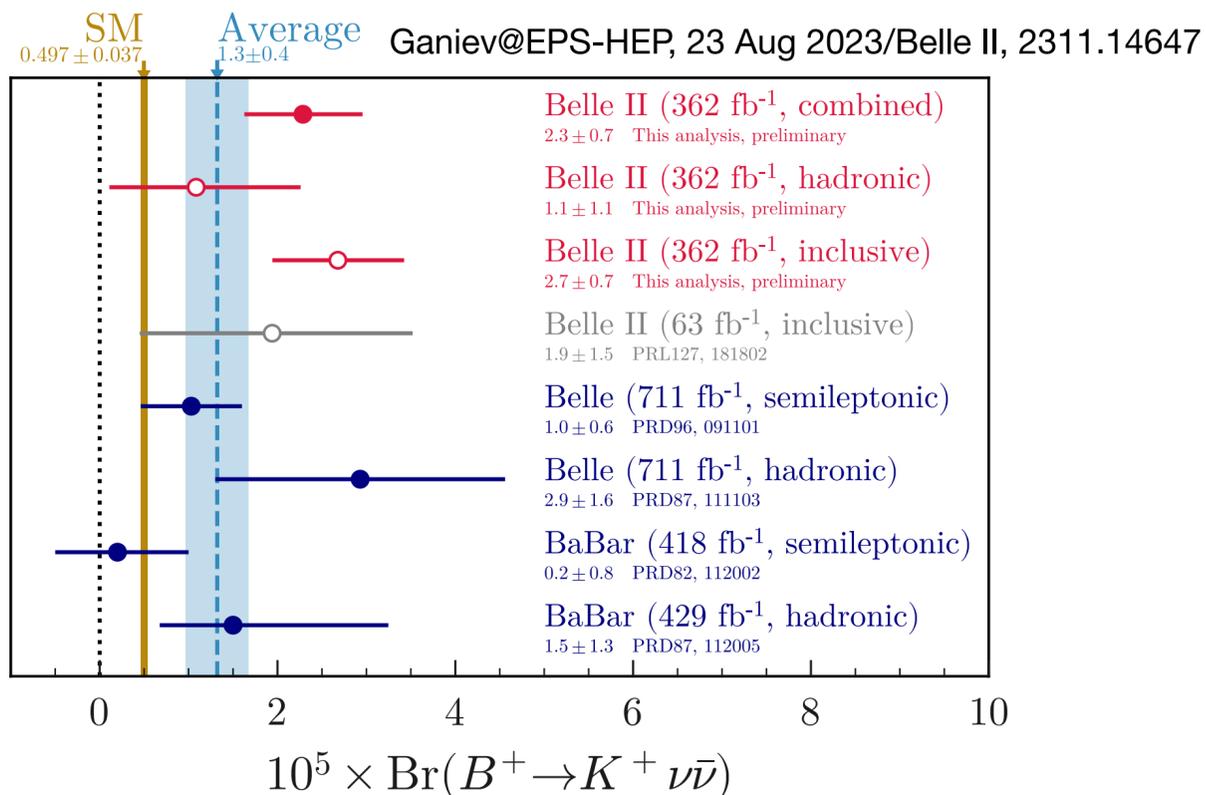
**Rare  $B$  and  $K$  decays in a scotogenic model** #11  
 Chuan-Hung Chen, Cheng-Wei Chiang (Mar 5, 2024)  
 e-Print: 2403.02897 [hep-ph]  
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# $b \rightarrow s\nu\bar{\nu}$ : exp & theory

► 2021 Apr



► 2023 Aug



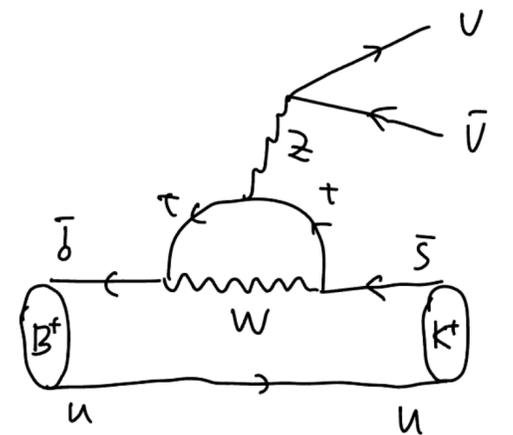
► Exp vs SM [10<sup>-6</sup>]

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}} = 4.16 \pm 0.57$$

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} = 23 \pm 7$$

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} \gtrsim 10 \text{ (} 2\sigma \text{ lower bound)}$$

**2.7 $\sigma$  difference**  
**NP/SM  $\gtrsim 2$**



► Theoretical prediction

**Factorization**

$$\mathcal{A} \propto C_L \cdot \langle K | \bar{s} \gamma^\mu b | \bar{B} \rangle \cdot \bar{\nu} \gamma_\mu \nu$$

Wilson coef    quark current    neutrino current

theoretically, simple and clean  
**one of the cleanest channels in flavour physics**

$$\mathcal{O}_L = (\bar{s} \gamma_\mu P_L b) (\bar{\nu} \gamma^\mu P_L \nu) \text{ in the SM}$$

$$\mathcal{O}_L = (\bar{s} P_L b) (\bar{\nu} P_L \nu) \times$$

$$\mathcal{O}_R = (\bar{s} \gamma_\mu P_R b) (\bar{\nu} \gamma^\mu P_L \nu) \text{ possible in BSM}$$

$$\mathcal{O}_R = (\bar{s} P_R b) (\bar{\nu} P_R \nu) \times$$

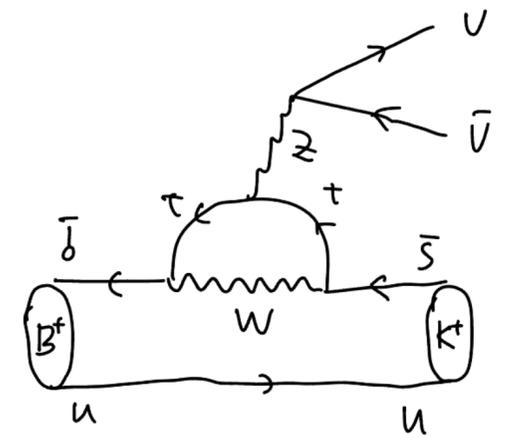
**simple interaction but complicated flavour**

$$\mathcal{O}_T = (\bar{s} \sigma_{\mu\nu} b) (\bar{\nu} \sigma^{\mu\nu} \nu) \times$$

operator structure highly  
constrained by LH neutrino

$$\mathcal{O}_{T5} = (\bar{s} \sigma_{\mu\nu} \gamma_5 b) (\bar{\nu} \sigma^{\mu\nu} \nu) \times$$

# $b \rightarrow s\nu\bar{\nu}$ : exp & theory



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

## ► Exp vs SM [10<sup>-6</sup>]

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}} = 4.16 \pm 0.57$$

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} = 23 \pm 7$$

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} \gtrsim 10 \text{ (} 2\sigma \text{ lower bound)}$$

**2.7 $\sigma$  difference**  
**NP/SM  $\gtrsim 2$**

## ► Theoretical prediction

### Factorization

$$\mathcal{A} \propto C_L \cdot \langle K | \bar{s} \gamma^\mu b | \bar{B} \rangle \cdot \bar{\nu} \gamma_\mu \nu$$

Wilson coef    quark current    neutrino current

**theoretically, simple and clean**  
**one of the cleanest channels in**  
**flavour physics**

$$\mathcal{O}_L = (\bar{s} \gamma_\mu P_L b)(\bar{\nu} \gamma^\mu P_L \nu) \text{ in the SM}$$

$$\mathcal{O}_L = (\bar{s} P_L b)(\bar{\nu} P_L \nu) \quad \times$$

$$\mathcal{O}_R = (\bar{s} \gamma_\mu P_R b)(\bar{\nu} \gamma^\mu P_L \nu) \text{ possible in BSM}$$

$$\mathcal{O}_R = (\bar{s} P_R b)(\bar{\nu} P_R \nu) \quad \times$$

**simple** interaction but **complicated** flavour

$$\mathcal{O}_T = (\bar{s} \sigma_{\mu\nu} b)(\bar{\nu} \sigma^{\mu\nu} \nu) \quad \times$$

operator structure highly  
constrained by LH neutrino

$$\mathcal{O}_{T5} = (\bar{s} \sigma_{\mu\nu} \gamma_5 b)(\bar{\nu} \sigma^{\mu\nu} \nu) \quad \times$$

**$B^0 \rightarrow K^{*0} \nu \bar{\nu}$  can put strong constraints on related BSM effects.**

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

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

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

## ► 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. (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

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

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

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

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

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

$\mu_{\text{EW}}$

LEFT

$\mu_b$

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

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

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

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

# $b \rightarrow s\nu\bar{\nu}$ : SMEFT with Minimal Flavor Violation

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

## ► Prediction

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

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

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

waiting for more precise measurements

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

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

SMEFT

$$C^{\text{MFV}} = \begin{cases} f(A, B) & \text{for } \bar{q}\gamma^\mu Cq, \\ f(A, B)Y_d & \text{for } \bar{q}Cd, \bar{q}\sigma^{\mu\nu}Cd, \\ \epsilon_0 \mathbb{1} + Y_d^\dagger g(A, B)Y_d & \text{for } \bar{d}\gamma^\mu Cd, \end{cases}$$

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

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

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

forbidden by MFV

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

$\mu_{\text{EW}}$

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

$\mu_b$

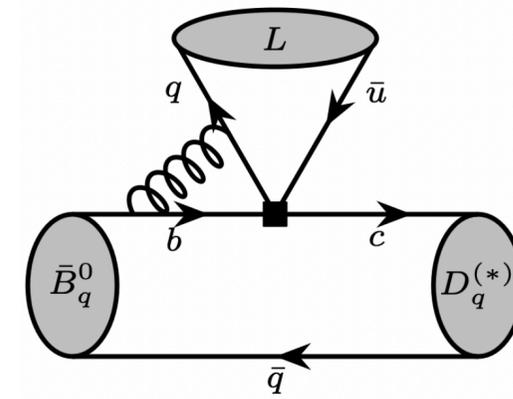
# $b \rightarrow c\bar{u}q$ puzzle

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衰变道	LO	NLO	NNLO	NNLO <sup>#</sup>	[45]	[46]	实验值 [18, 47]
$\bar{B}^0 \rightarrow D^+ \pi^-$	4.20	$4.45_{-0.40}^{+0.25}$	$4.58_{-0.38}^{+0.22}$	$4.74_{-0.69}^{+0.61}$	$3.93_{-0.42}^{+0.43}$		$2.53 \pm 0.08$
$\bar{B}^0 \rightarrow D^{*+} \pi^-$	3.77	$4.00_{-0.40}^{+0.29}$	$4.13_{-0.39}^{+0.27}$	$4.26_{-0.80}^{+0.75}$	$3.45_{-0.50}^{+0.53}$		$2.58 \pm 0.13$
$\bar{B}^0 \rightarrow D^+ \rho^-$	10.98	$11.64_{-1.18}^{+0.88}$	$11.96_{-1.15}^{+0.82}$	$12.28_{-1.63}^{+1.40}$	$10.42_{-1.20}^{+1.24}$		$7.6 \pm 1.2$
$\bar{B}^0 \rightarrow D^{*+} \rho^-$	10.32	$10.95_{-1.55}^{+1.40}$	$11.28_{-1.56}^{+1.40}$	$11.61_{-2.01}^{+1.88}$	$9.24_{-0.71}^{+0.72}$		$6.0 \pm 0.8$
$\bar{B}^0 \rightarrow D^+ K^-$	3.18	$3.37_{-0.29}^{+0.17}$	$3.48_{-0.28}^{+0.14}$		$3.01_{-0.31}^{+0.32}$	$3.26 \pm 0.15$	$2.08 \pm 0.08$
$\bar{B}^0 \rightarrow D^{*+} K^-$	2.82	$3.00_{-0.29}^{+0.20}$	$3.10_{-0.28}^{+0.19}$		$2.59_{-0.37}^{+0.39}$	$3.27_{-0.34}^{+0.39}$	$2.04 \pm 0.47$
$\bar{B}^0 \rightarrow D^+ K^{*-}$	5.48	$5.80_{-0.62}^{+0.48}$	$5.94_{-0.61}^{+0.46}$		$5.25_{-0.63}^{+0.65}$		$4.6 \pm 0.8$
$\bar{B}_s^0 \rightarrow D_s^+ \pi^-$	4.23	$4.49_{-0.41}^{+0.27}$	$4.61_{-0.39}^{+0.23}$		$4.39_{-1.19}^{+1.36}$	$4.42 \pm 0.21$	$3.23 \pm 0.18$
$\bar{B}_s^0 \rightarrow D_s^{*+} \pi^-$	3.51	$3.73_{-0.84}^{+0.88}$	$3.84_{-0.85}^{+0.90}$		$2.24_{-0.50}^{+0.56}$	$4.30_{-0.80}^{+0.90}$	$2.4_{-0.6}^{+0.7}$
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$\bar{B}_s^0 \rightarrow D_s^{*+} K^-$	2.62	$2.79_{-0.61}^{+0.65}$	$2.88_{-0.63}^{+0.66}$	$3.02_{-0.97}^{+0.99}$	$1.67_{-0.37}^{+0.42}$		$1.63 \pm 0.50$

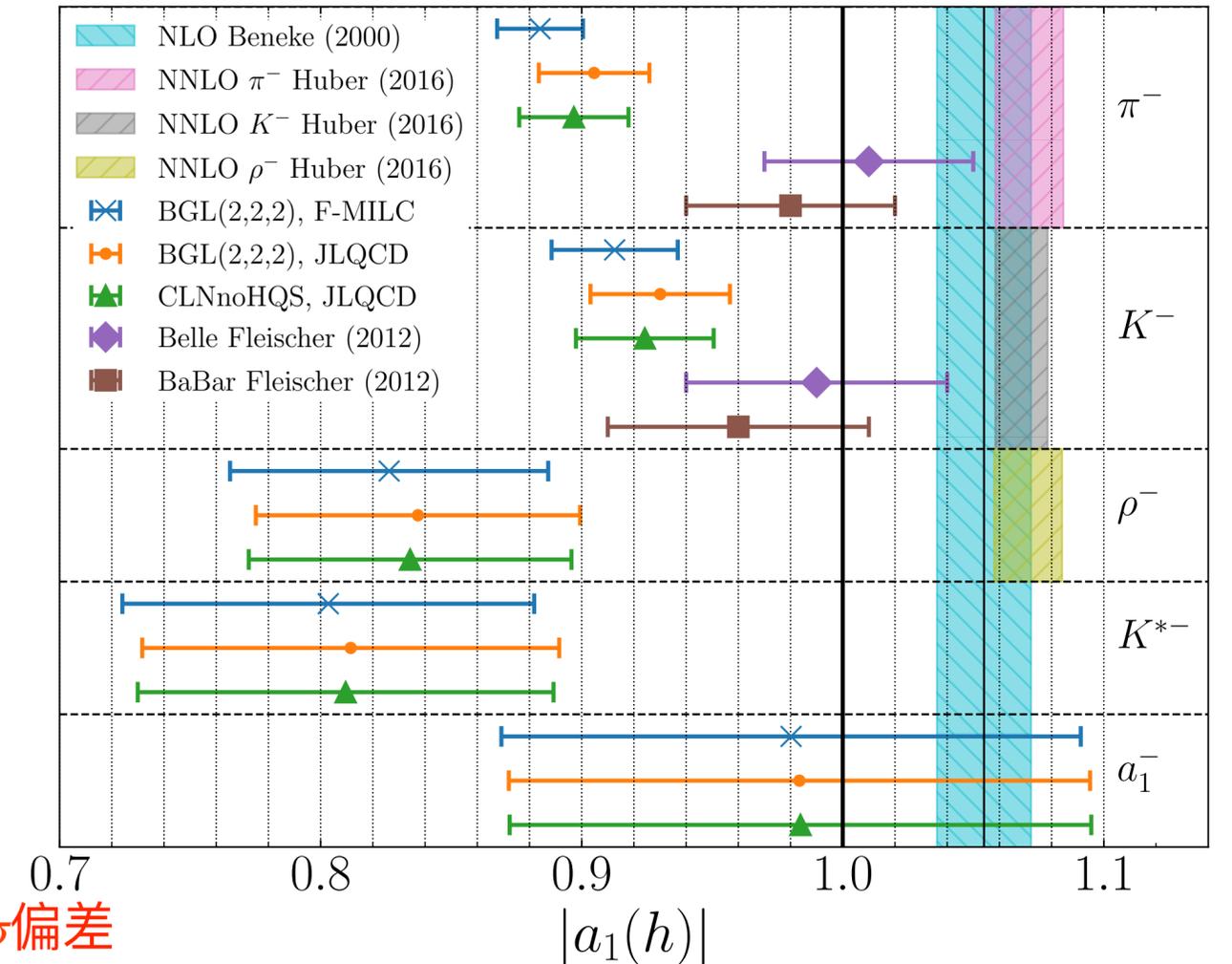
理论与实验间最大存在4-6 $\sigma$ 偏差



$$\frac{\Gamma(\bar{B}^0 \rightarrow D^{*+} L^-)}{d\Gamma(\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu})/dq^2|_{q^2=m_L^2}} = 6\pi^2 |V_{uq}|^2 f_L^2 X_L \cdot |a_1(L)|^2$$

form factor and  $V_{cb}$  cancelled

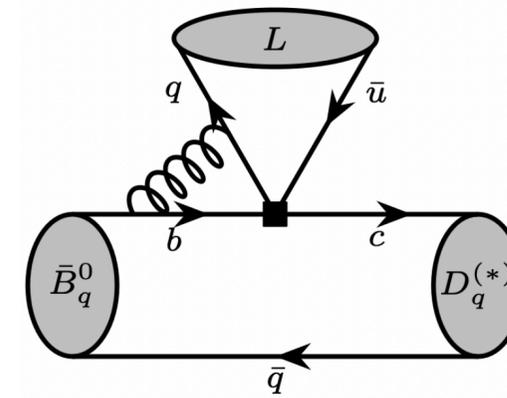
Belle, 2207.00134



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$\bar{B}_{(s)}^0 \rightarrow D_{(s)}^{(*)+} L^-$  ( $L = \pi, \rho, K^{(*)}$ ) decays

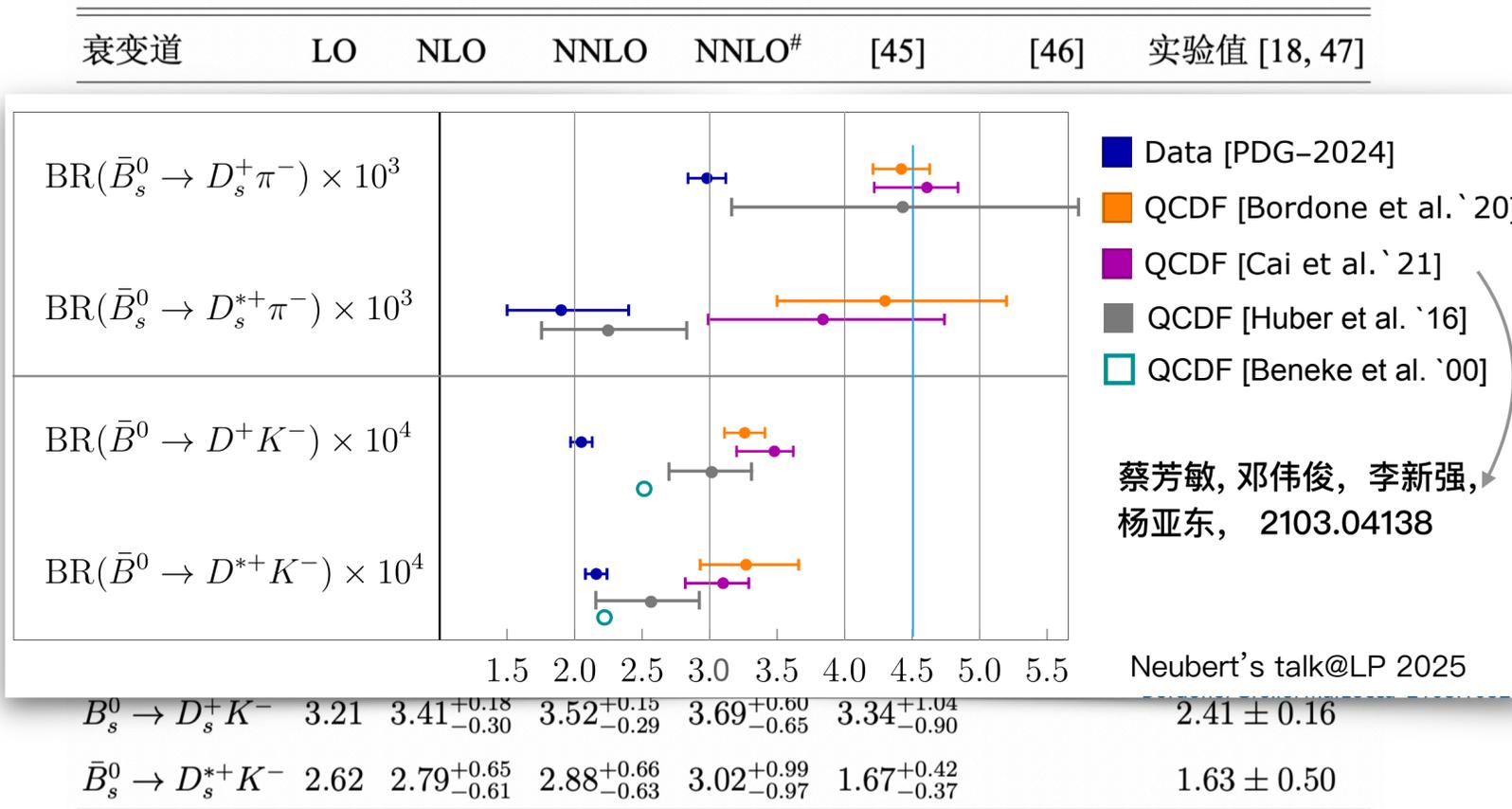
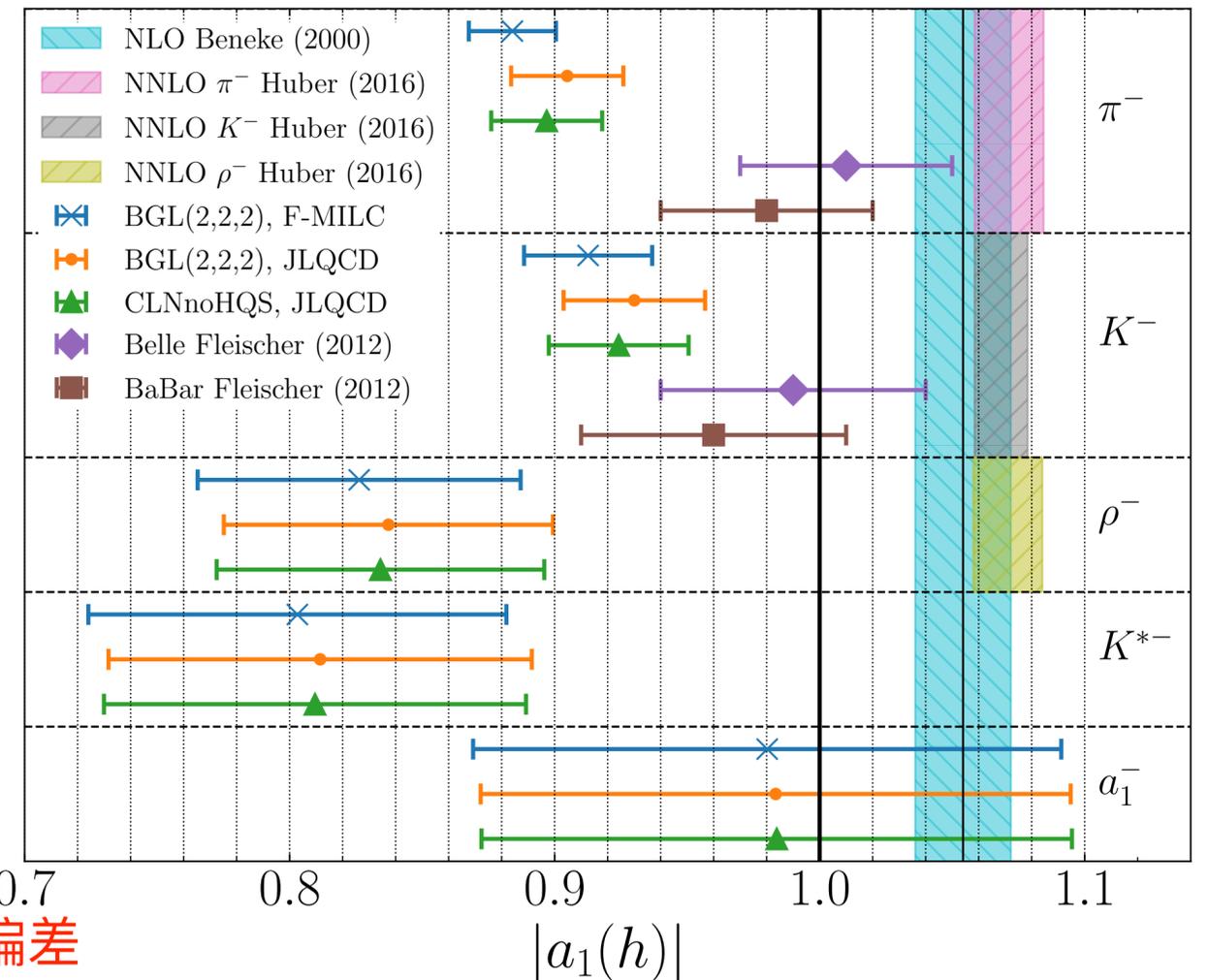
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Belle, 2207.00134



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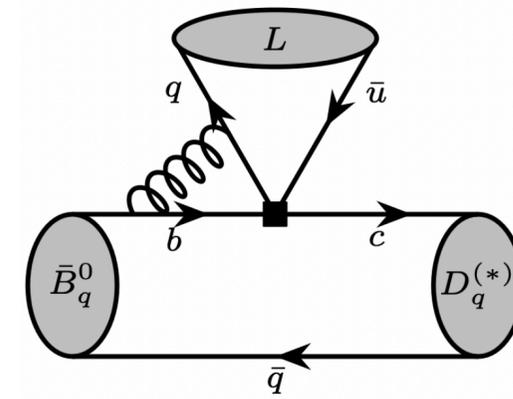
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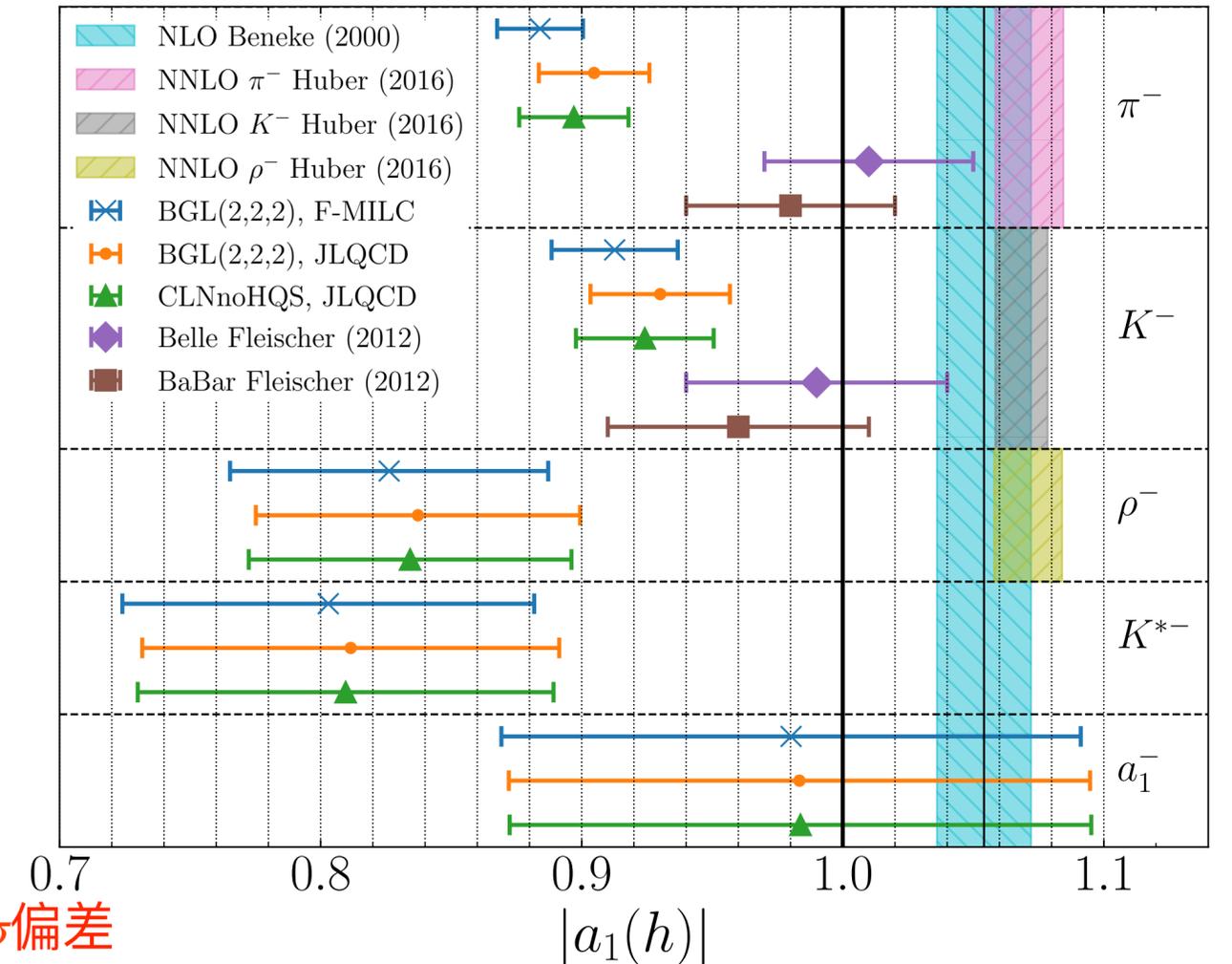
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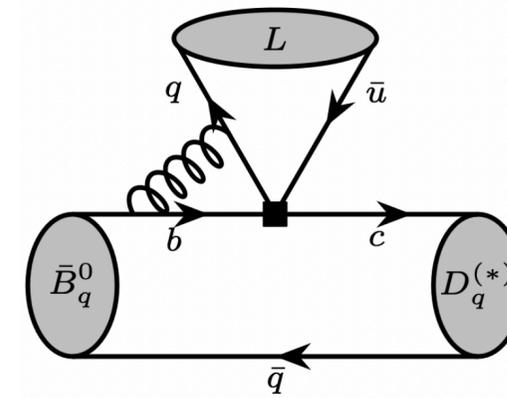
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## Explanation in the SM

- ▶ sub-leading power corrections Bordone, Gubernari, Huber, Jung, van Dyk, 2007.10338
- ▶ rescattering contributions Endo, Iguro, Mishima, 2109.10811
- ▶ non-factorizable soft-gluon contributions Piscopo, Rusov, 2307.07594
- ▶ three-particle contributions Meiser, van Dyk, Virto, 2411.09458

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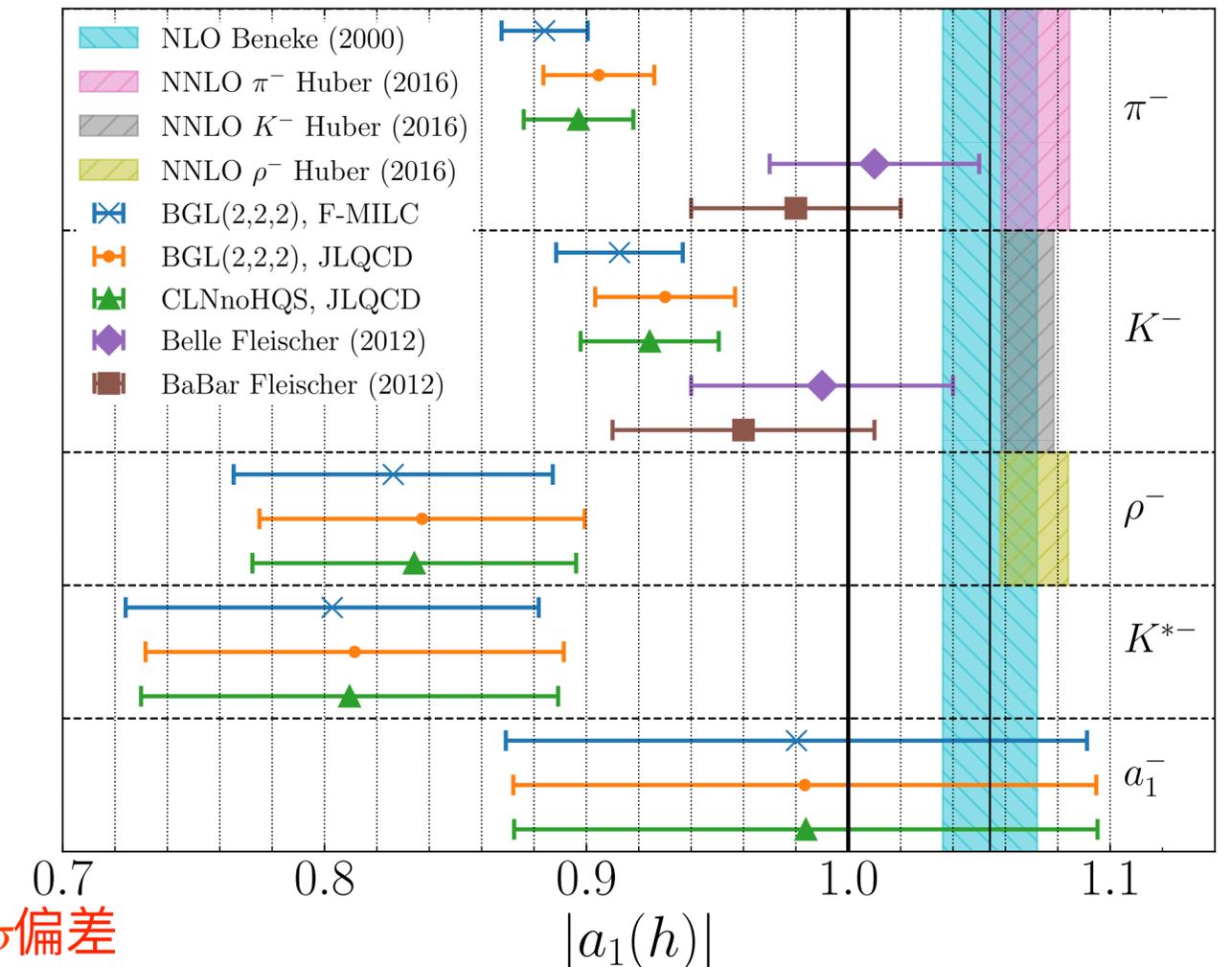
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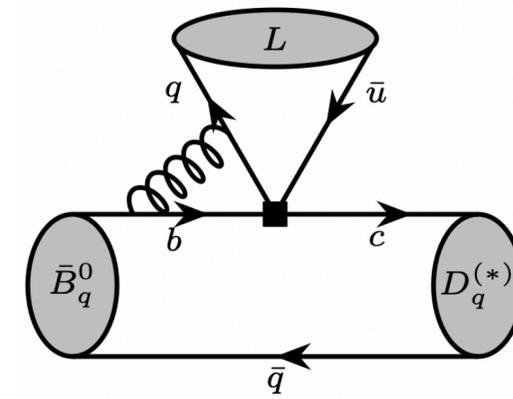
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## Explanation in the SM is not possible (more careful studies needed !)

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- ▶ three-particle contributions Meiser, van Dyk, Virto, 2411.09458

$\bar{B}_s^0 \rightarrow D_s^{*+} \pi^-$	3.51	$3.73^{+0.88}_{-0.84}$	$3.84^{+0.90}_{-0.85}$		$2.24^{+0.56}_{-0.50}$	$4.30^{+0.90}_{-0.80}$	$2.4^{+0.7}_{-0.6}$
$\bar{B}_s^0 \rightarrow D_s^+ K^-$	3.21	$3.41^{+0.18}_{-0.30}$	$3.52^{+0.15}_{-0.29}$	$3.69^{+0.60}_{-0.65}$	$3.34^{+1.04}_{-0.90}$		$2.41 \pm 0.16$
$\bar{B}_s^0 \rightarrow D_s^{*+} K^-$	2.62	$2.79^{+0.65}_{-0.61}$	$2.88^{+0.66}_{-0.63}$	$3.02^{+0.99}_{-0.97}$	$1.67^{+0.42}_{-0.37}$		$1.63 \pm 0.50$

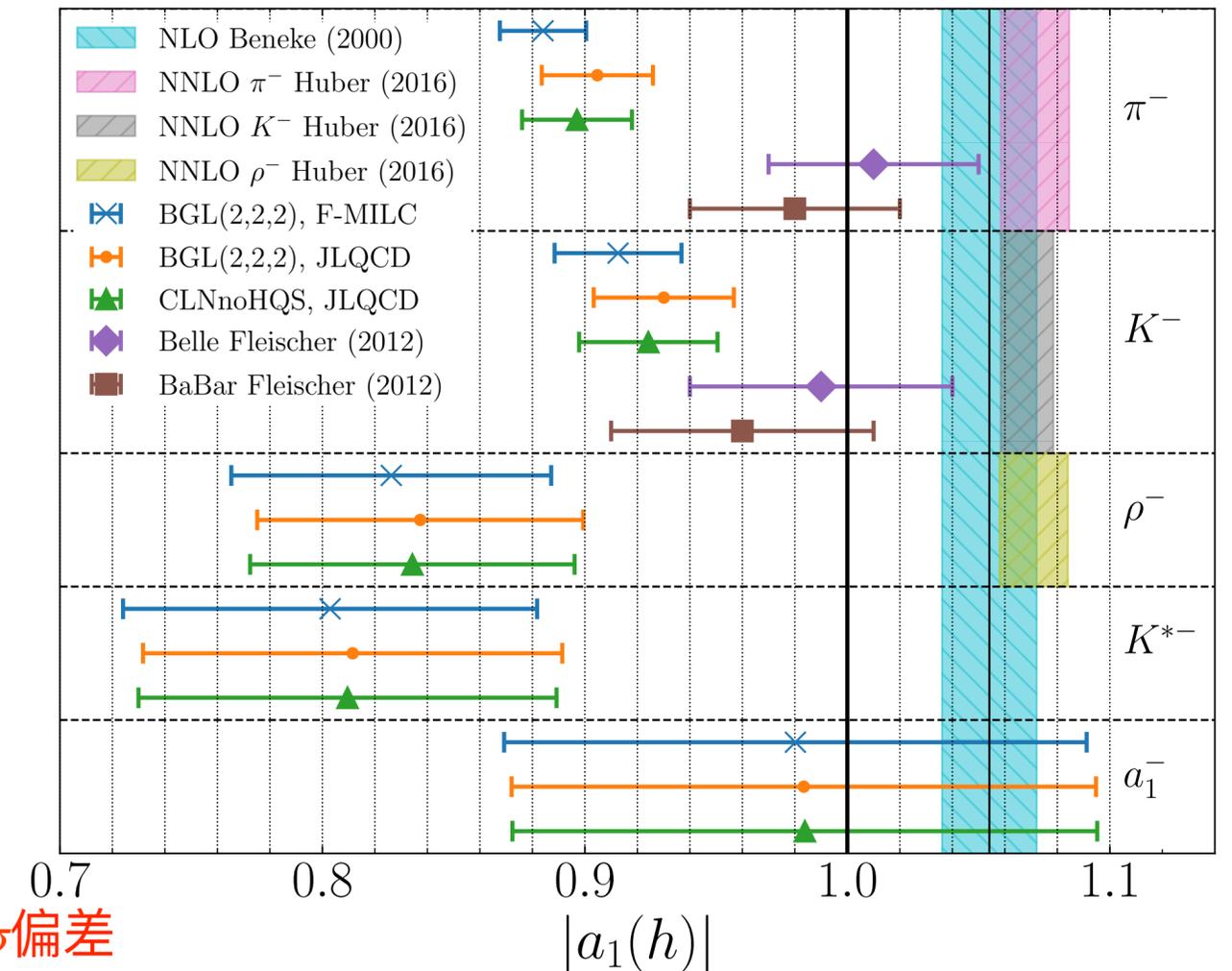
理论与实验间最大存在4-6 $\sigma$ 偏差



$$\frac{\Gamma(\bar{B}^0 \rightarrow D^{*+} L^-)}{d\Gamma(\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu})/dq^2|_{q^2=m_L^2}} = 6\pi^2 |V_{uq}|^2 f_L^2 X_L \cdot |a_1(L)|^2$$

form factor and  $V_{cb}$  cancelled

Belle, 2207.00134

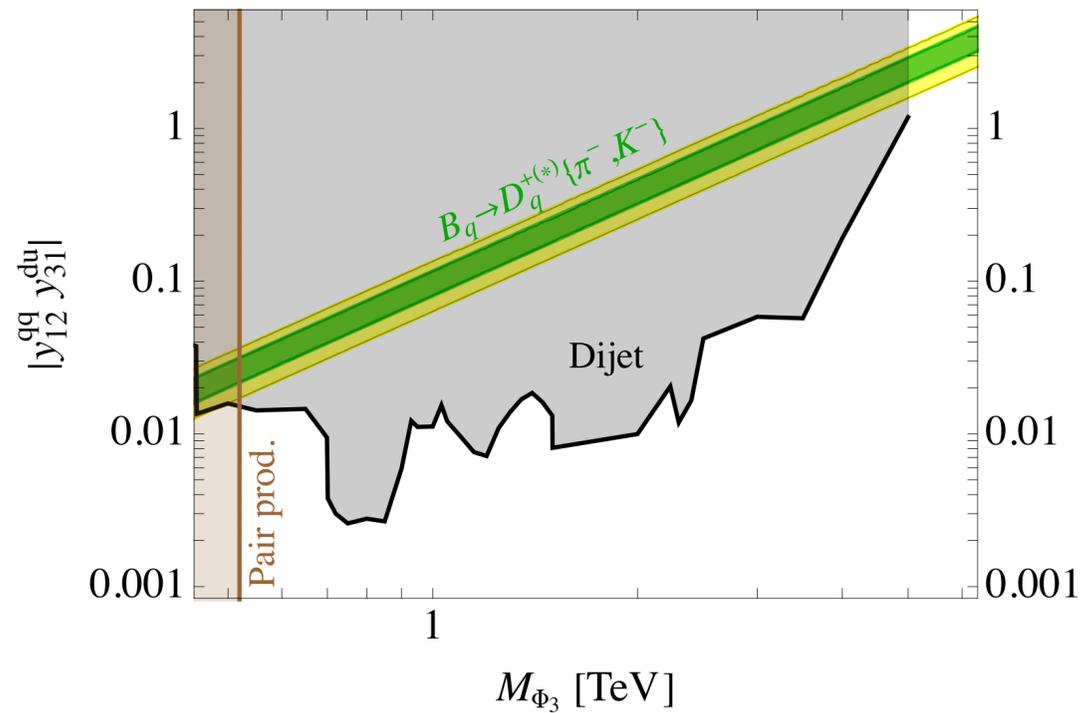


# $b \rightarrow c\bar{u}q$ puzzle

蔡芳敏, 邓伟俊, 李新强, 杨亚东, 2103.04138  
LEFT analysis shows only  $(V-A) \otimes (V-A)$  and  $(S+P) \otimes (S\pm P)$  can explain the puzzle

## New Physics Effects

dijet resonance searches@LHC provide strong bound



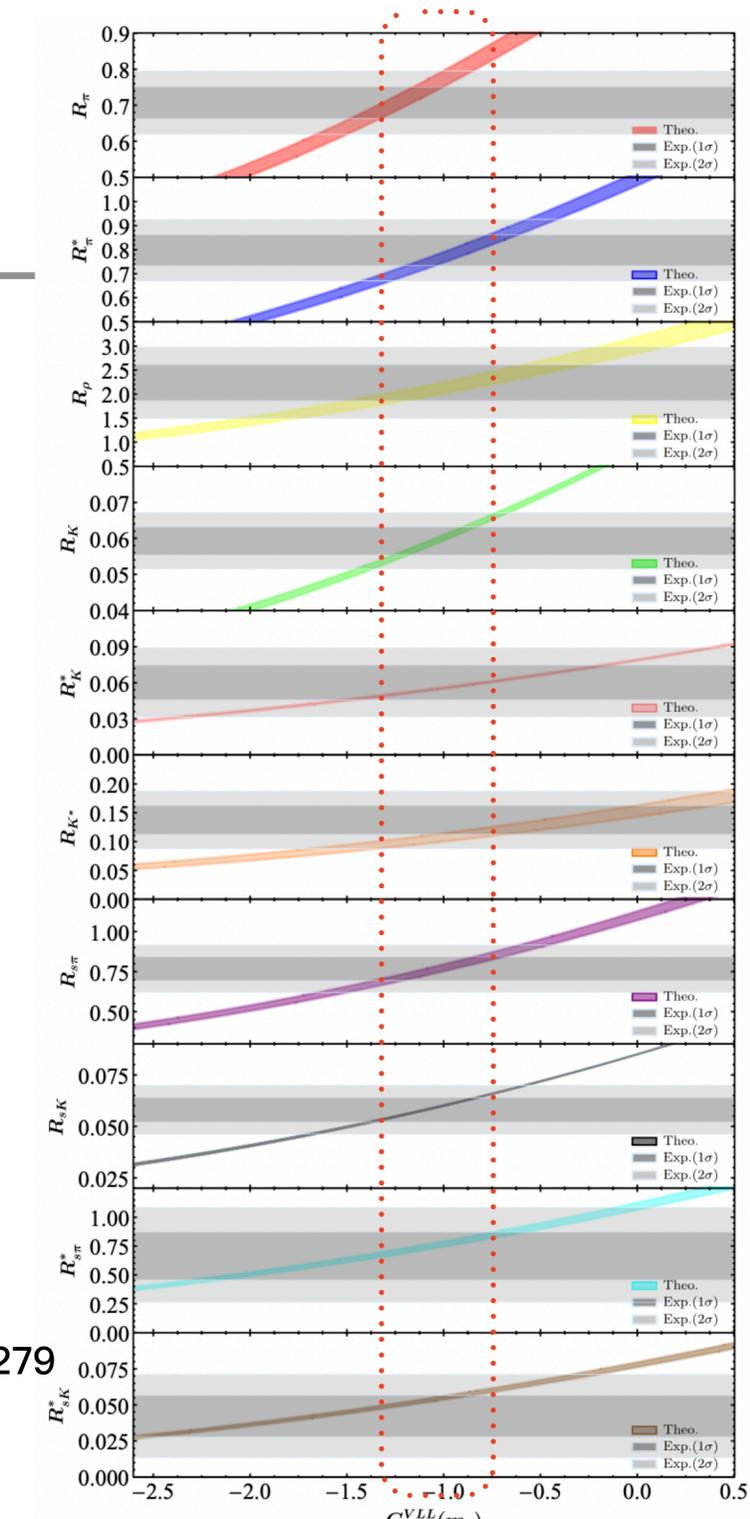
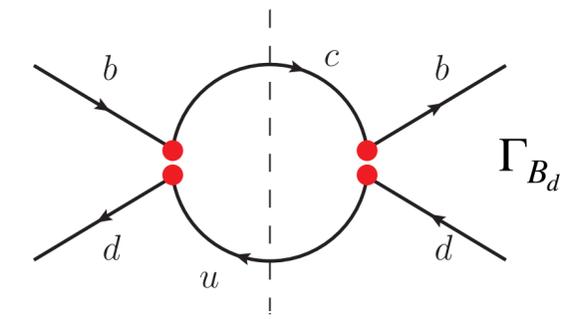
Bordone, Admir Greljo, David Marzocca, 2103.10332

relevant SMEFT operators

$[\mathcal{O}_{qq}^{(1)}]_{ijkl} = (\bar{q}_L^i \gamma_\mu q_L^j)(\bar{q}_L^k \gamma_\mu q_L^l)$	$[\mathcal{O}_{qq}^{(3)}]_{ijkl} = (\bar{q}_L^i \sigma^a \gamma_\mu q_L^j)(\bar{q}_L^k \sigma^a \gamma_\mu q_L^l)$
$[\mathcal{O}_{ud}^{(1)}]_{ijkl} = (\bar{u}_R^i \gamma_\mu u_R^j)(\bar{d}_R^k \gamma_\mu d_R^l)$	$[\mathcal{O}_{ud}^{(8)}]_{ijkl} = (\bar{u}_R^i T^A \gamma_\mu u_R^j)(\bar{d}_R^k T^A \gamma_\mu d_R^l)$
$[\mathcal{O}_{qd}^{(1)}]_{ijkl} = (\bar{q}_L^i \gamma_\mu q_L^j)(\bar{d}_R^k \gamma_\mu d_R^l)$	$[\mathcal{O}_{qd}^{(8)}]_{ijkl} = (\bar{q}_L^i T^A \gamma_\mu q_L^j)(\bar{d}_R^k T^A \gamma_\mu d_R^l)$
$[\mathcal{O}_{qu}^{(1)}]_{ijkl} = (\bar{q}_L^i \gamma_\mu q_L^j)(\bar{u}_R^k \gamma_\mu u_R^l)$	$[\mathcal{O}_{qu}^{(8)}]_{ijkl} = (\bar{q}_L^i T^A \gamma_\mu q_L^j)(\bar{u}_R^k T^A \gamma_\mu u_R^l)$
$[\mathcal{O}_{quqd}^{(1)}]_{ijkl} = (\bar{q}_L^i u_R^j)(i\sigma^2)(\bar{q}_L^k d_R^l)$	$[\mathcal{O}_{quqd}^{(8)}]_{ijkl} = (\bar{q}_L^i T^A u_R^j)(i\sigma^2)(\bar{q}_L^k d_R^l)$

simplified models

spin-0:	$\left\{ \begin{array}{ll} \Phi_1 = (\mathbf{1}, \mathbf{2}, 1/2), & \Phi_8 = (\mathbf{8}, \mathbf{2}, 1/2), \\ \Phi_3 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3), & \Psi_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3), \quad \Phi_6 = (\mathbf{6}, \mathbf{1}, 1/3) \end{array} \right.$
spin-1:	$\left\{ \begin{array}{ll} \mathcal{Q}_3 = (\mathbf{3}, \mathbf{2}, 1/6), & \mathcal{Q}_6 = (\bar{\mathbf{6}}, \mathbf{2}, 1/6) \end{array} \right.$



example:  $(V-A) \otimes (V-A)$

## Other Analysis

- ▶ constraints from B-meson lifetime Lenz, Müller, Piscopo, Rusov, 2211.02724
- ▶ global analysis in LEFT Meiser, van Dyk, Virto, 2411.09458
- ▶ further test by the  $B_c^- \rightarrow J/\psi(\eta_c)L^-$  decays: only  $(S+P) \otimes (S\pm P)$  works
- ▶ NP in top quark physics Atkinson, Englert, Kirk, Tetlalmatzi-Xolocotzi, 2411.00940

邓伟俊, 蔡芳敏, 李新强, 石岩, 杨亚东, 2503.11279

# Theoretical Tools

**SM-consistent  
measurements  
(precision measurements)**

**SM-inconsistent  
measurements  
(flavour anomalies)**

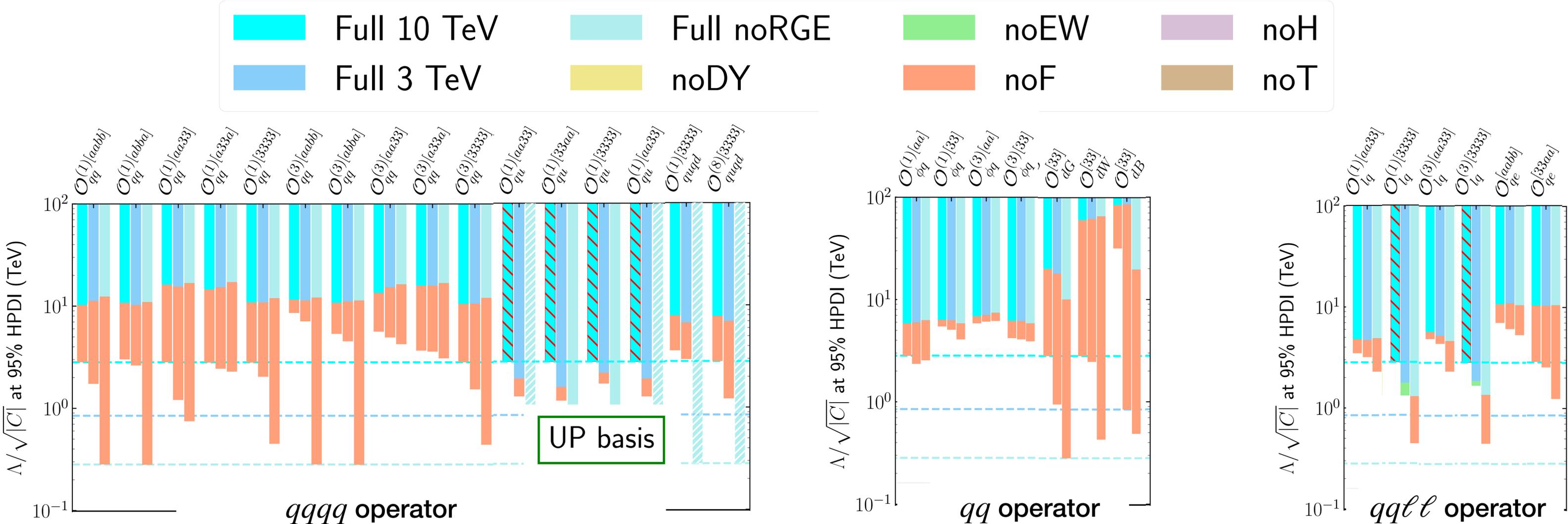
**new measurements  
and precision targets  
for the future**



# 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



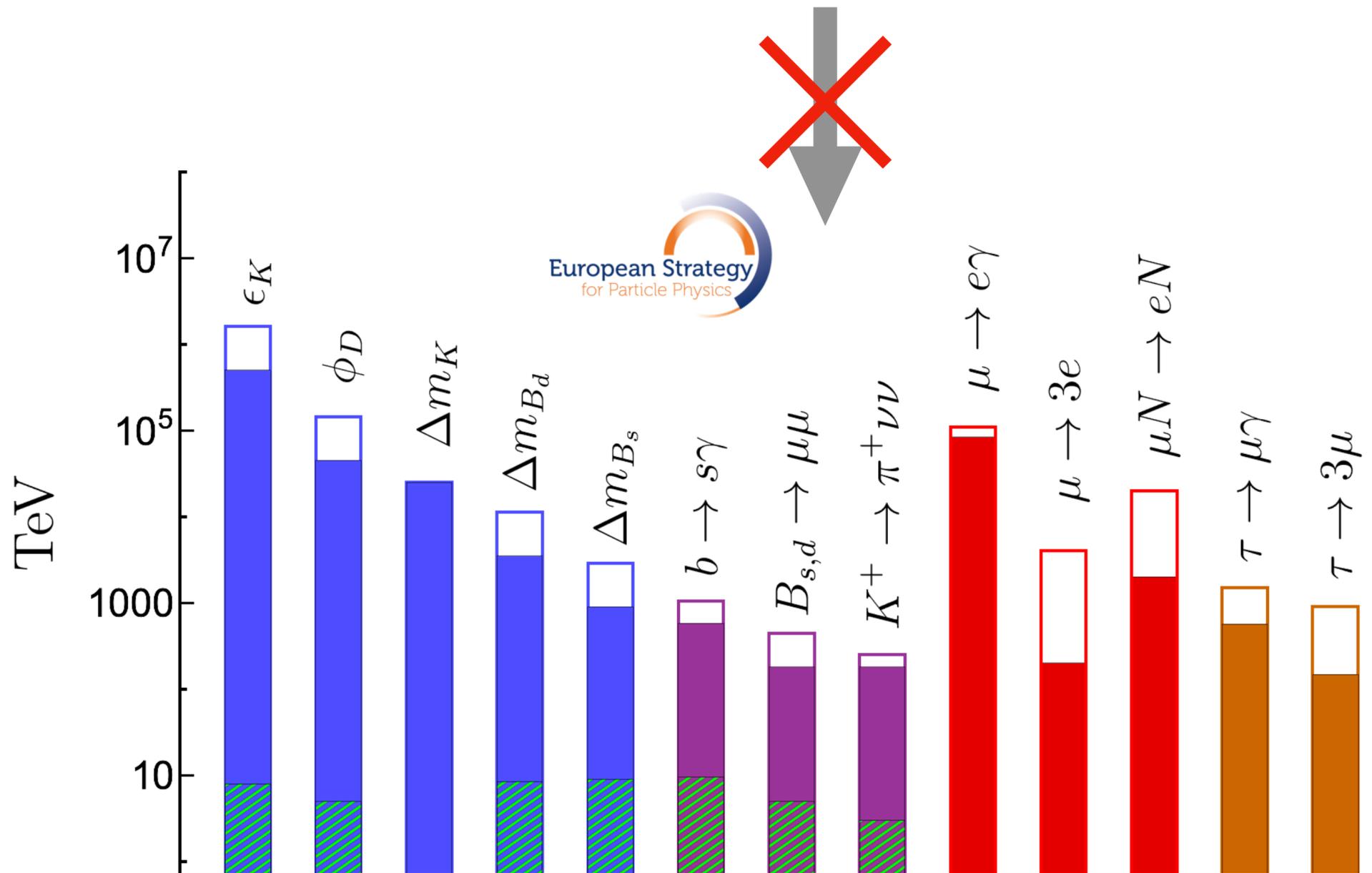
► Flavour structures  $U(2)^5$  and  $U(3)^5$  are assumed.

# NP Flavour Puzzle

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

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

NP Flavour  
Puzzle



Bounds on the scale  $\Lambda$  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  $\Lambda$  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

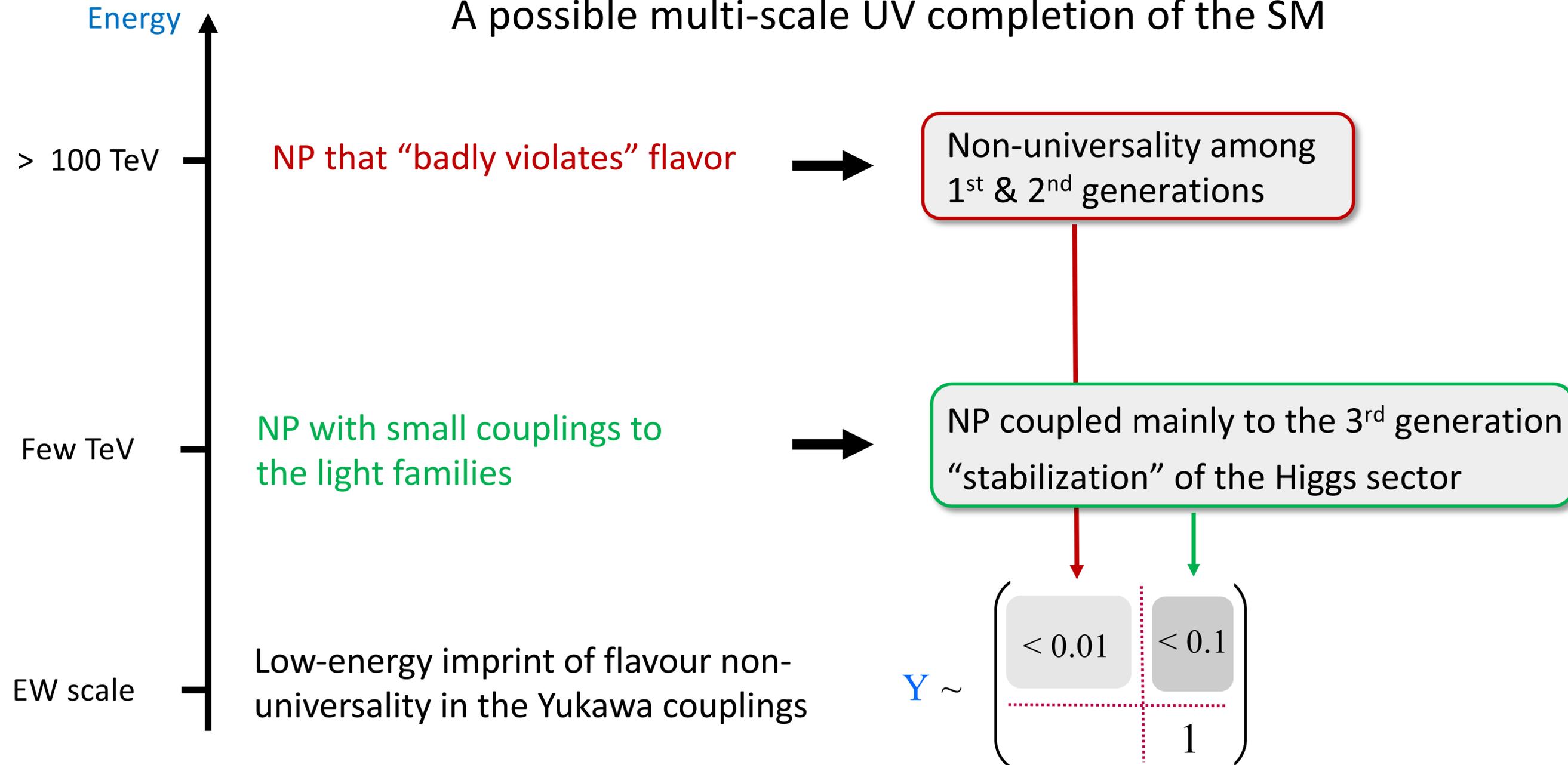
example: NP mainly couples to 3rd generation

😊 Higgs is still natural

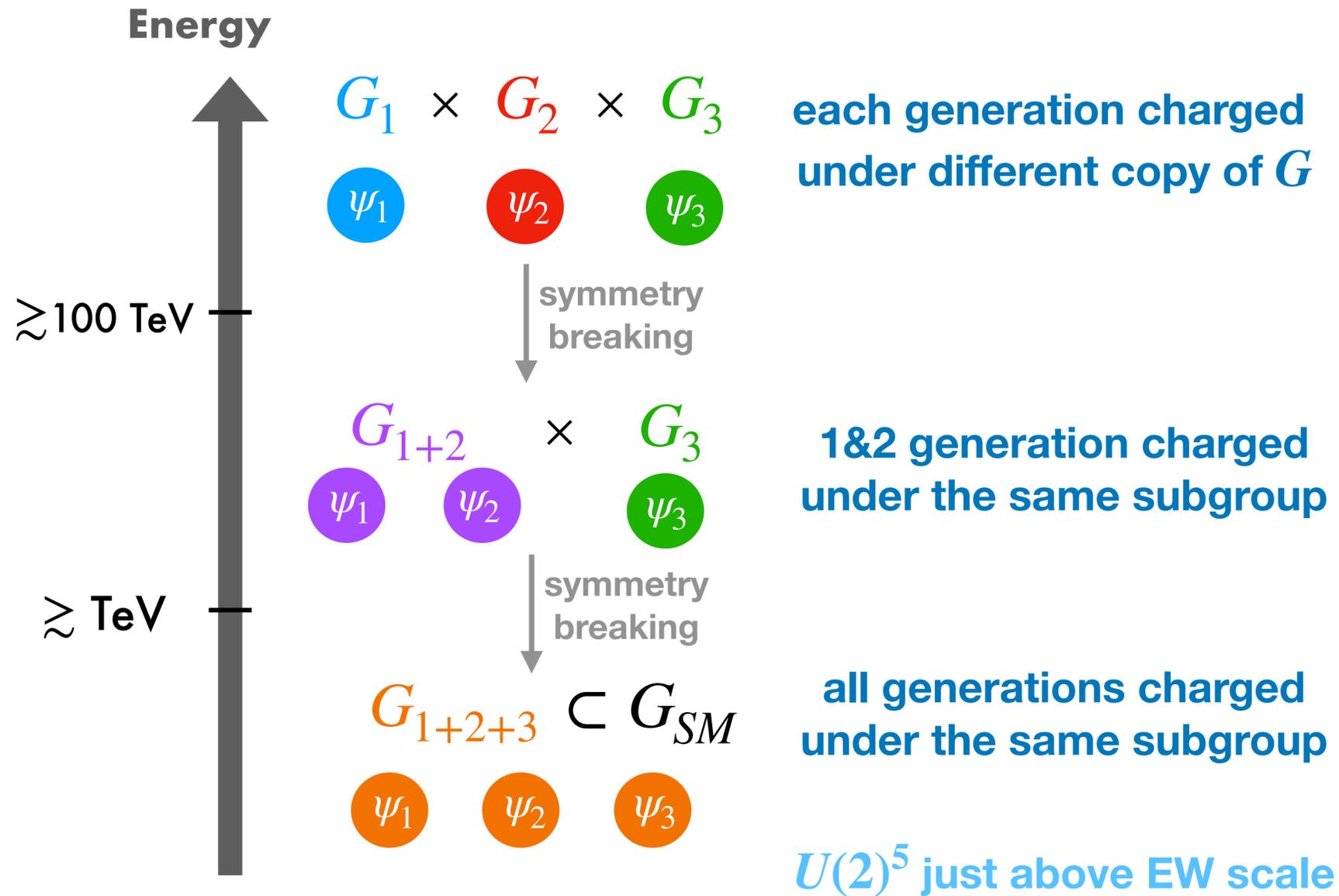
😊 NP could be found at the LHC, possibly answer the SM fermion mass hierarchy

# A Possible UV Picture from EFT Analysis

A possible multi-scale UV completion of the SM



# Flavour Deconstruction



Renner's talk@EPS 2025

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

## Gauge Model of Generation Nonuniversality

Xiao-yuan Li<sup>(a)</sup> 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  $\mu$ - $e$  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  $\tau$  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 structure constrained by analyticity, unitarity, ...

## Assumptions

- ▶ analyticity of the S-matrix, partial wave unitarity, and **high-energy behavior of forward scattering amplitudes**
- ▶ EFT interaction

$$\Lambda^2 \mathcal{L}_{\text{eff}}^{\text{LFC}} = C_{eett}^{\text{LR}} [(\bar{\nu}_e \gamma_\alpha P_L \nu_e) + (\bar{e} \gamma_\alpha P_L e)] (\bar{t} \gamma^\alpha P_R t) + C_{eett}^{\text{RR}} (\bar{e} \gamma_\alpha P_R e) (\bar{t} \gamma^\alpha P_R t) \\ + C_{eecc}^{\text{LR}} [(\bar{\nu}_e \gamma_\alpha P_L \nu_e) + (\bar{e} \gamma_\alpha P_L e)] (\bar{c} \gamma^\alpha P_R c) + C_{eecc}^{\text{RR}} (\bar{e} \gamma_\alpha P_R e) (\bar{c} \gamma^\alpha P_R c) \\ + \left( C_{eect}^{\text{LR}} [(\bar{\nu}_e \gamma_\alpha P_L \nu_e) + (\bar{e} \gamma_\alpha P_L e)] (\bar{c} \gamma^\alpha P_R t) + C_{eect}^{\text{RR}} (\bar{e} \gamma_\alpha P_R e) (\bar{c} \gamma^\alpha P_R t) + \text{H.c.} \right)$$

- ▶ EFT operator induced at tree level

## Constraints

$$C_{\ell\ell qq}^{\text{LR}} < 0 \quad \text{and} \quad C_{\ell\ell qq}^{\text{RR}} > 0 \quad \text{Scalar UV} \\ C_{\ell\ell qq}^{\text{LR}} > 0 \quad \text{and} \quad C_{\ell\ell qq}^{\text{RR}} < 0 \quad \text{Vector UV}$$

flavour conserving

$$|C_{eect}^{\text{LR}}|^2 < C_{eecc}^{\text{LR}} C_{eett}^{\text{LR}}, \quad |C_{\mu\mu ct}^{\text{LR}}|^2 < C_{\mu\mu cc}^{\text{LR}} C_{\mu\mu tt}^{\text{LR}}, \\ |C_{eect}^{\text{RR}}|^2 < C_{eecc}^{\text{RR}} C_{eett}^{\text{RR}}, \quad |C_{\mu\mu ct}^{\text{RR}}|^2 < C_{\mu\mu cc}^{\text{RR}} C_{\mu\mu tt}^{\text{RR}}.$$

flavour violating

### general analysis

0602178, Adams, Arkani-Hamed,  
Dubovsky, Nicolis, Rattazzi  
1605.06111, Bellazzini

### dim-8

2004.02885, Remmen, Rodd  
2112.11665, C. Zhang

### dim-6

2008.07551, J. Gu, L.T. Wang  
**2010.04723, Remmen, Rodd**  
2108.06334, Davighi, Melville, T. You  
2112.02302, Azatov, Ghosh, Singh  
2206.13524, Remmen, Rodd

# Flavour structure constrained by analyticity, unitarity, ...

## Assumptions

- ▶ analyticity of the S
- ▶ behavior of forward
- ▶ EFT interaction

$$\Lambda^2 \mathcal{L}_{\text{eff}}^{\text{LFC}} = C_{eett}^{\text{LR}} [(\bar{\nu}_e \gamma_\alpha P_L e) (\bar{t} \gamma_\alpha e)] + C_{eecc}^{\text{LR}} [(\bar{\nu}_e \gamma_\alpha P_L e) (\bar{c} \gamma_\alpha c)] + C_{eect}^{\text{LR}} [(\bar{\nu}_e \gamma_\alpha P_L e) (\bar{c} \gamma_\alpha e)]$$

- ▶ EFT operator indu

## Constraints

$$C_{\ell\ell qq}^{\text{LR}} < 0 \quad \text{and} \quad C_{\ell\ell qq}^{\text{RR}} > 0 \quad \text{Scalar UV}$$

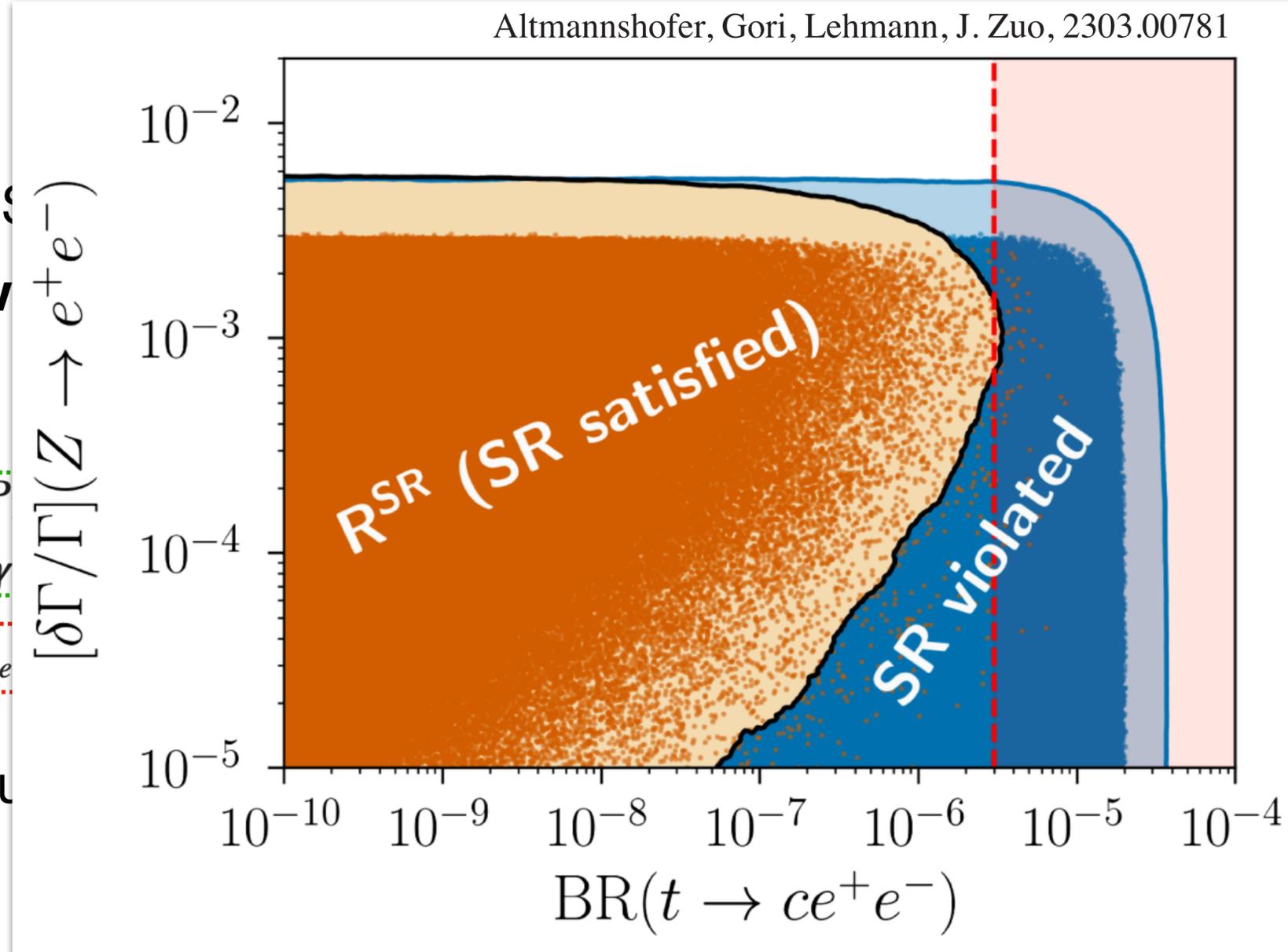
$$C_{\ell\ell qq}^{\text{LR}} > 0 \quad \text{and} \quad C_{\ell\ell qq}^{\text{RR}} < 0 \quad \text{Vector UV}$$

flavour conserving

$$|C_{eect}^{\text{LR}}|^2 < C_{eecc}^{\text{LR}} C_{eett}^{\text{LR}}, \quad |C_{\mu\mu ct}^{\text{LR}}|^2 < C_{\mu\mu cc}^{\text{LR}} C_{\mu\mu tt}^{\text{LR}},$$

$$|C_{eect}^{\text{RR}}|^2 < C_{eecc}^{\text{RR}} C_{eett}^{\text{RR}}, \quad |C_{\mu\mu ct}^{\text{RR}}|^2 < C_{\mu\mu cc}^{\text{RR}} C_{\mu\mu tt}^{\text{RR}}.$$

flavour violating



## general analysis

0602178, Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi  
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2112.02302, Azatov, Ghosh, Singh  
2206.13524, Remmen, Rodd

# Theoretical Tools

**SM-consistent  
measurements  
(precision measurements)**

**SM-inconsistent  
measurements  
(flavour anomalies)**

**new measurements  
and precision targets  
for the future**

# 味物理中新物理研究的一点思考 (个人观点)



# Precision Measurements

## Superstars of 2026-2046 (Flavour Physics)

$S_{\psi\phi}$   
 $\mathcal{CP}$  in  $B_s^0 - \bar{B}_s^0$   
 $(B_s \rightarrow \phi\phi)$

$B \rightarrow D(D^*)\tau\nu_\tau$

$\gamma, V_{cb}$   
 from Tree  
 Level  
 Decays

$B_s \rightarrow \mu^+\mu^-$   
 $(B_d \rightarrow \mu^+\mu^-)$

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

$\mu \rightarrow e\gamma$   
 $\tau \rightarrow \mu\gamma$   
 $\tau \rightarrow e\gamma$   
 $\mu \rightarrow 3e$   
 $\tau \rightarrow 3 \text{ leptons}$

$K^+ \rightarrow \pi^+\nu\bar{\nu}$   
 $(K_L \rightarrow \pi^0\nu\bar{\nu})$

$B \rightarrow K^*\nu\bar{\nu}$   
 $B \rightarrow K\nu\bar{\nu}$

$B^+ \rightarrow \tau^+\nu_\tau$

EDM's  
 $(g-2)_\mu$

$\epsilon'/\epsilon$

(Lattice)

## The Magnificent Seven Decays

Decay	SM Branching Ratio	Data
$B_s \rightarrow \mu^+\mu^-$	$(3.78_{-0.10}^{+0.15}) \cdot 10^{-9}$	$(3.45 \pm 0.29) \cdot 10^{-9}$ [463]
$B_d \rightarrow \mu^+\mu^-$	$(1.02_{-0.03}^{+0.05}) \cdot 10^{-10}$	$\leq 2.05 \cdot 10^{-10}$ [464]
$B^+ \rightarrow K^+\nu\bar{\nu}$	$(4.99 \pm 0.30) \cdot 10^{-6}$	$(13 \pm 4) \cdot 10^{-6}$ [248]
$B^0 \rightarrow K^{0*}\nu\bar{\nu}$	$(10.25 \pm 0.92) \cdot 10^{-6}$	$\leq 1.5 \cdot 10^{-5}$ [465]
$K^+ \rightarrow \pi^+\nu\bar{\nu}$	$(8.65 \pm 0.42) \cdot 10^{-11}$	$(13.0_{-3.0}^{+3.3}) \cdot 10^{-11}$ [466]
$K_L \rightarrow \pi^0\nu\bar{\nu}$	$(3.05 \pm 0.15) \cdot 10^{-11}$	$\leq 2.0 \cdot 10^{-9}$ [467]
$(K_S \rightarrow \mu\bar{\mu})_{SD}$	$(1.85 \pm 0.12) \cdot 10^{-13}$	$\leq 2.1 \cdot 10^{-10}$ [468]



豪勇七蛟龙

perturbative QCD effects, are indispensable. Equally important is the proper choice of observables that are best suited to revealing these new animalcula of particle physics. Moreover, in my view it is crucial to develop strategies for the search for New Physics (NP) that go beyond the global fits that are very popular today. While effective field theories such as WET and SMEFT are formulated in terms of Wilson coefficients of the relevant operators, with correlations characteristic of the SM and of specific NP scenarios, the most direct tests of the SM and its extensions are, in my opinion, correlations among different observables that are characteristic of particular new animalcula at work. Numerous colourful plots in this article illustrate this point. I hope that these ideas are clearly conveyed in my Flavour

**Example:** 
$$\frac{\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{exp}}}{[\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-)]_{\text{exp}}^{1.4}} = 91.4 \pm 22.8, \quad \text{SM} : 53.46 \pm 2.75$$

$V_{cb}$  independent see also Zhao-Feng Liu's talk

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}}}{\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-)_{\text{exp}}} = (3.8 \pm 1.2) \cdot 10^3, \quad \text{SM} : (1.32 \pm 0.07) \cdot 10^3$$

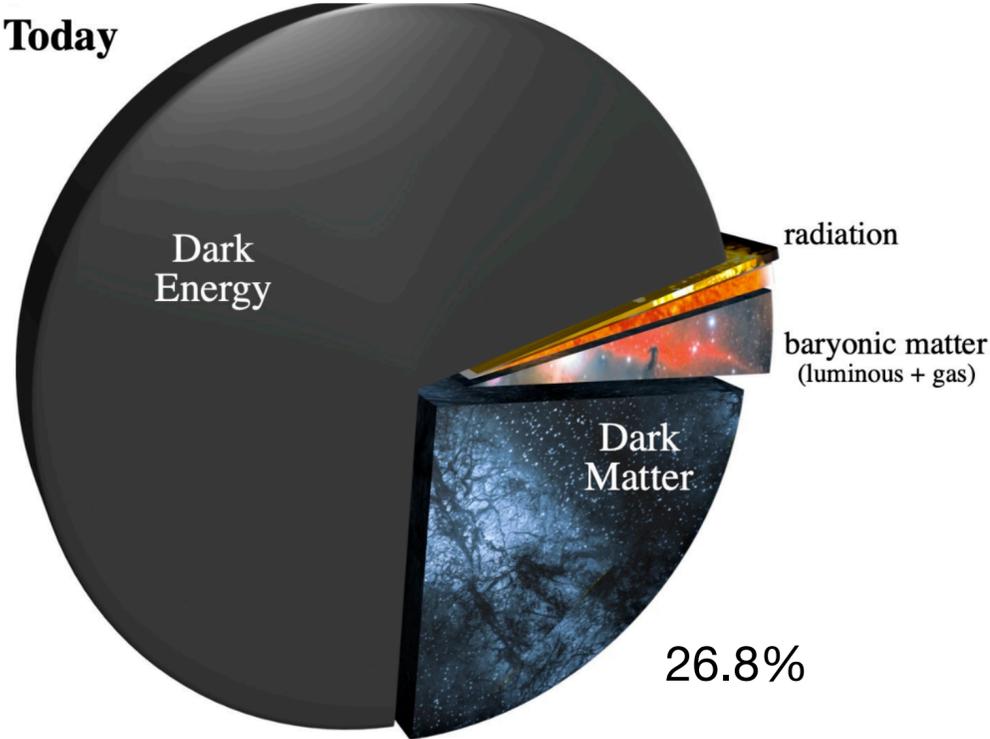
tensions with SM

# 味物理中新物理研究的一点思考 (个人观点)



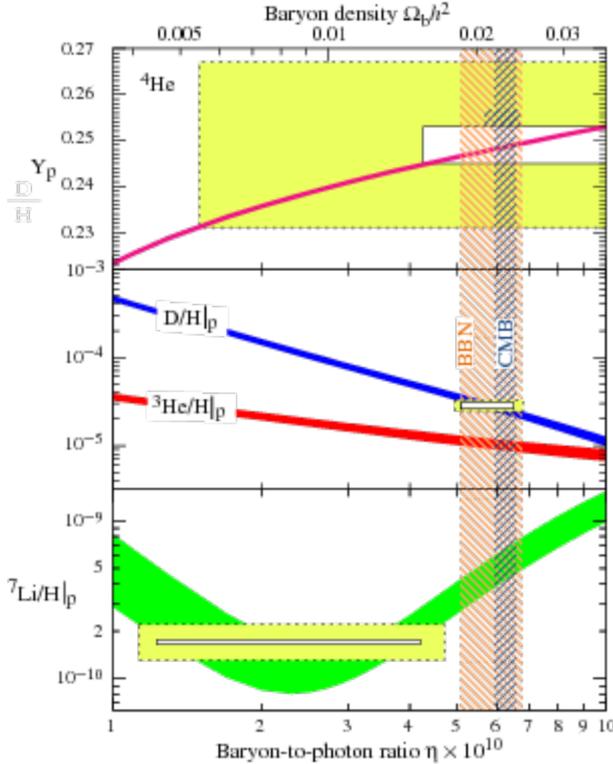
# Possible Flavour Path to New Physics

## Dark Matter

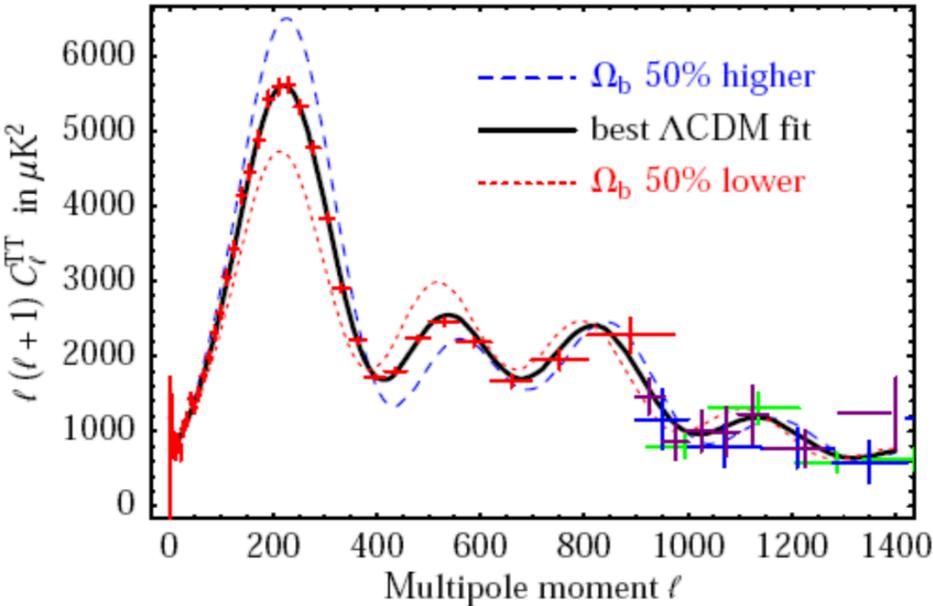


Cirelli, Strumia, Zupan/2406.01705

## Matter-antimatter Asymmetry



Rubakov/1804.11230



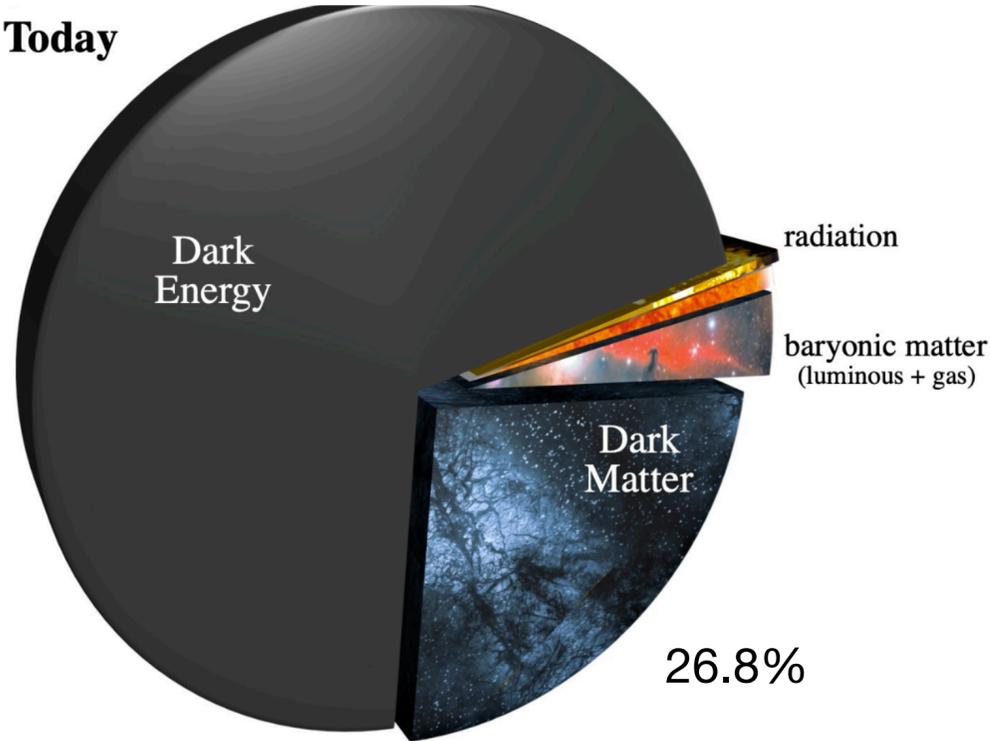
Blanchet/0807.1408

see also talks by Xiao-Gang He, Zuowei Liu, Lingfeng Li

see also talks by Xiao-Gang He, Wei Chao, ChengCheng Han, Fapeng Huang

# Possible Flavour Path to New Physics

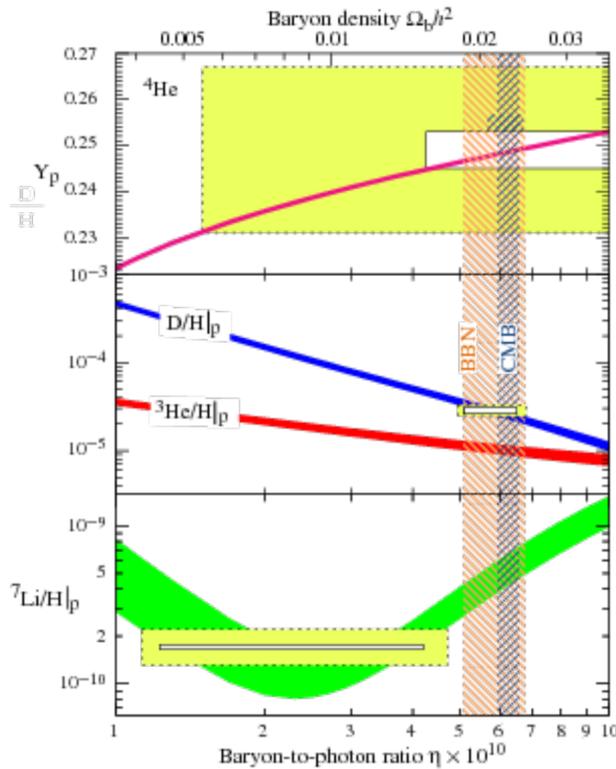
## Dark Matter



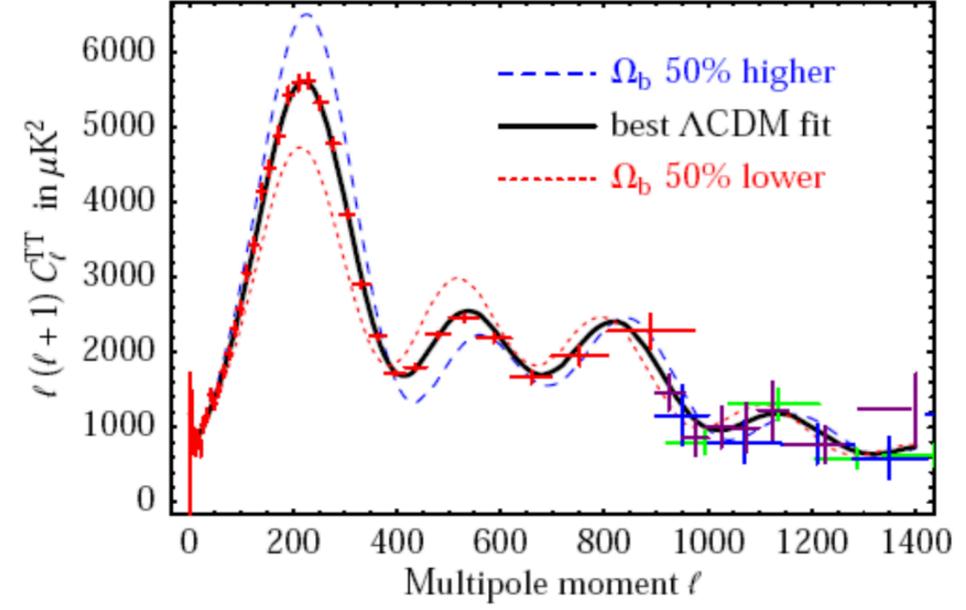
Cirelli, Strumia, Zupan/2406.01705

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## Matter-antimatter Asymmetry



Rubakov/1804.11230

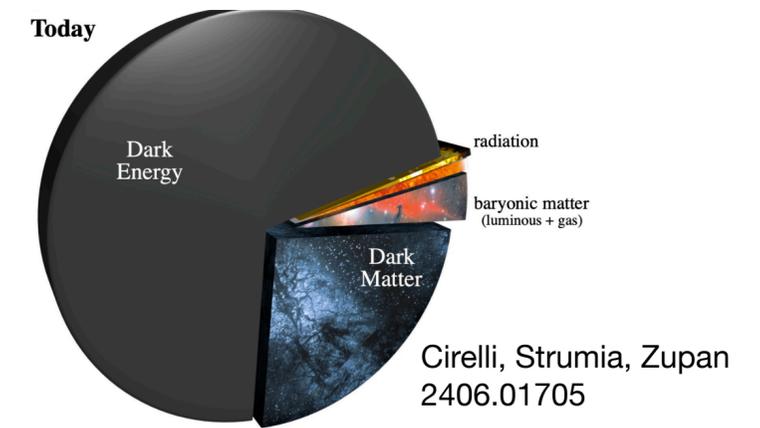


Blanchet/0807.1408

see also talks by Xiao-Gang He, Wei Chao, ChengCheng Han, Fapeng Huang

# Light DM: a bottom-up view

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

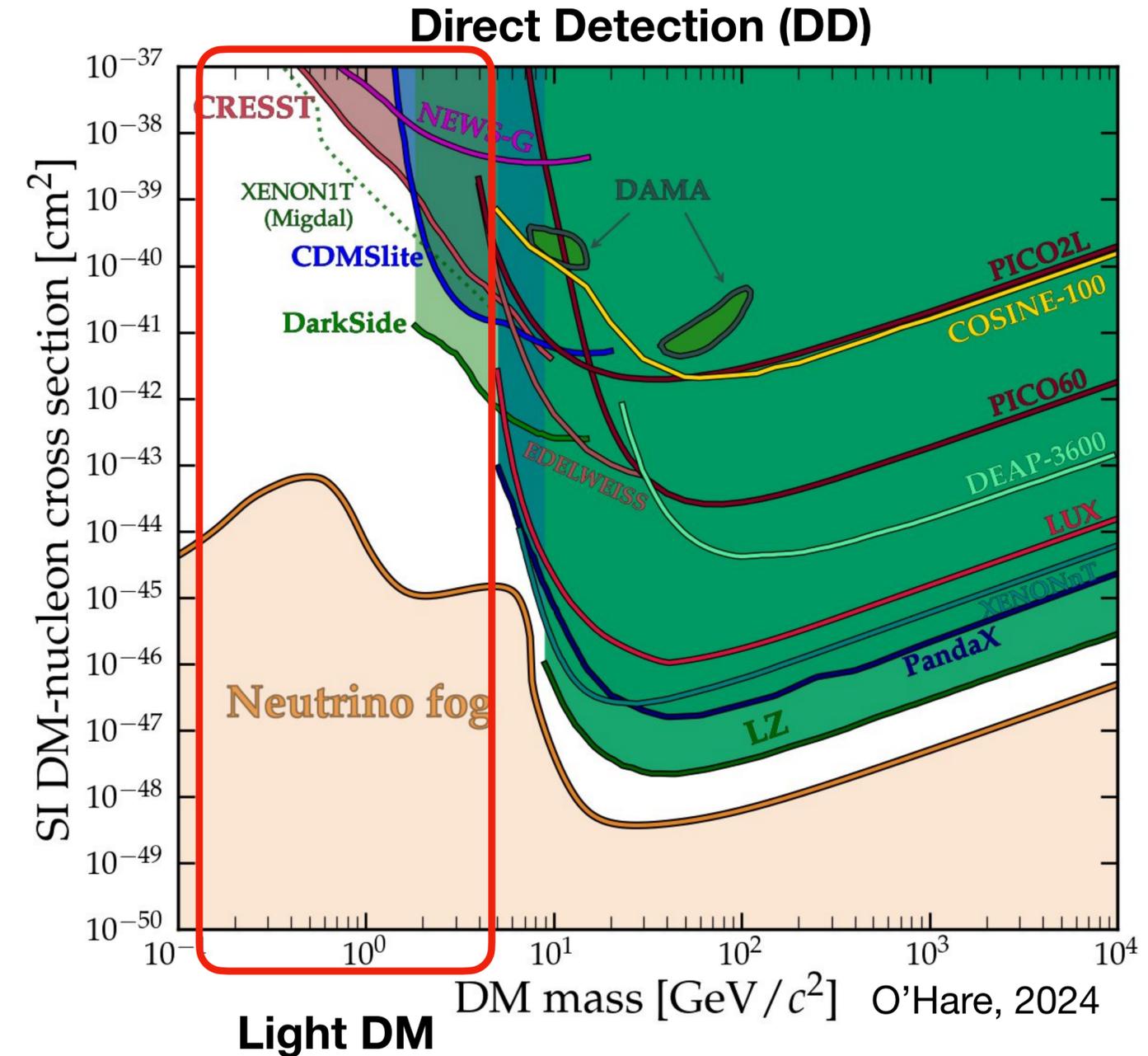


	<i>d</i>	<i>s</i>	<i>b</i>
<i>d</i>	DD	NA62/KOTO	Belle II
<i>s</i>		DD	Belle II
<i>b</i>			Belle II/LHC
	<i>u</i>	<i>c</i>	<i>t</i>
<i>u</i>	DD	BES/STCF	LHC/CEPC
<i>c</i>		BES/STCF	LHC/CEPC
<i>t</i>			LHC/CEPC

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



# 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 !

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

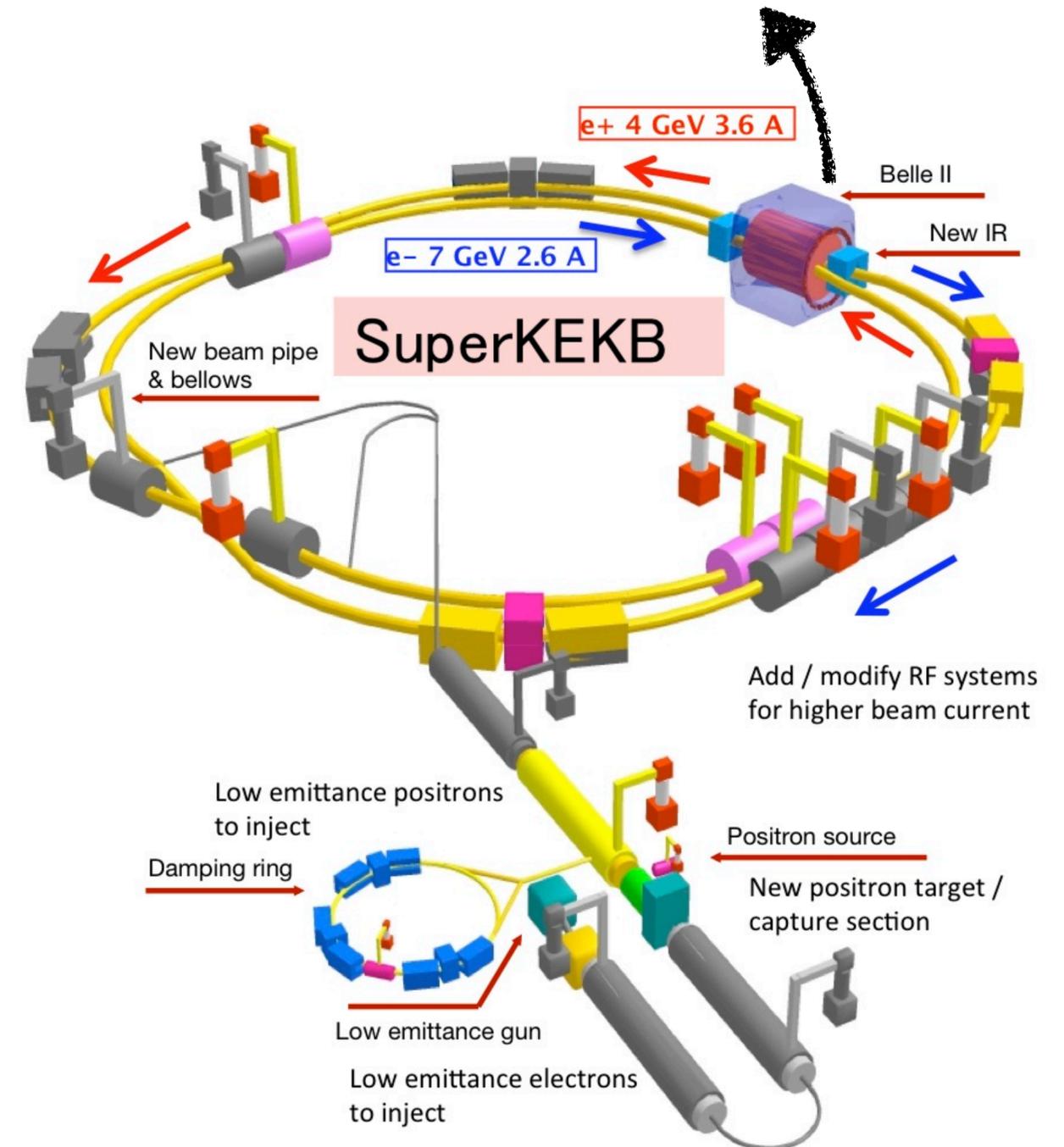
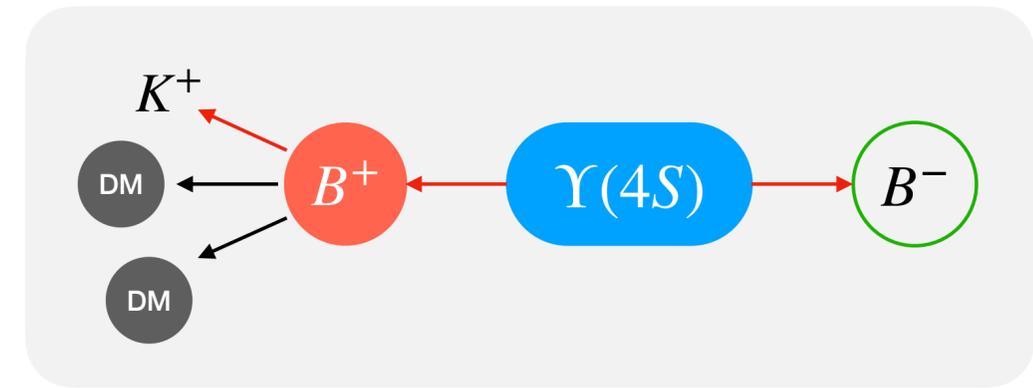
# Experimental Search

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

**Belle II**  
**CEPC**

**NA62**  
**KOTO**

**BESIII**  
**STCF**



# Experimental Search

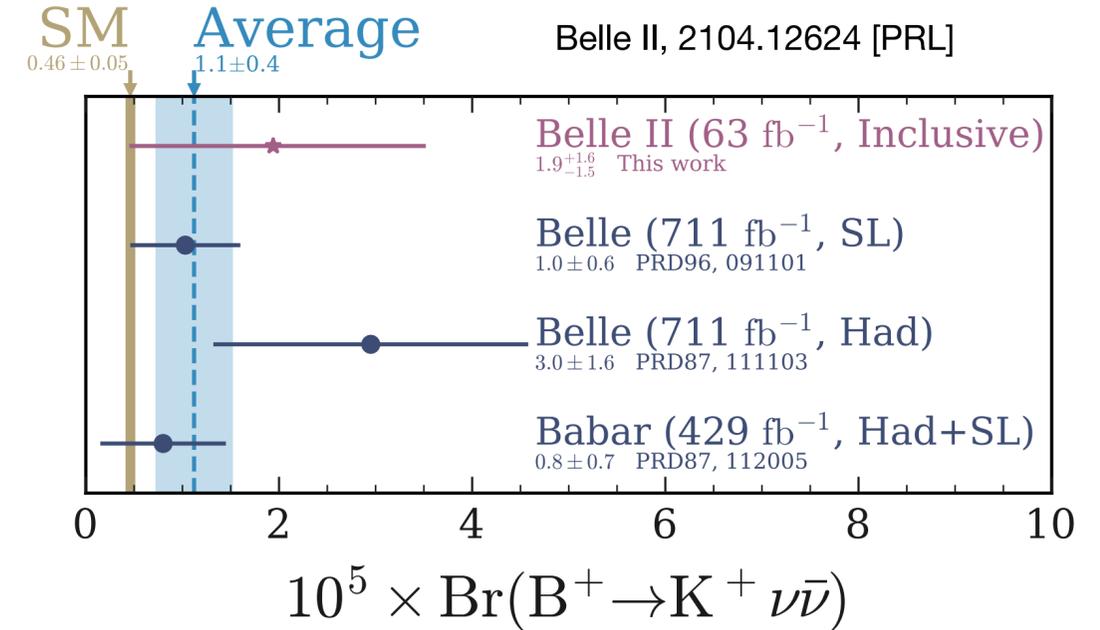
	Observable	SM	Exp	Unit
$b \rightarrow s$	$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$	$4.16 \pm 0.57$	$23 \pm 5_{-4}^{+5}$	$10^{-6}$
	$\mathcal{B}(B^0 \rightarrow K^0 \nu \bar{\nu})$	$3.85 \pm 0.52$	$< 26$	$10^{-6}$
	$\mathcal{B}(B^+ \rightarrow K^{*+} \nu \bar{\nu})$	$9.70 \pm 0.94$	$< 61$	$10^{-6}$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

**Belle II  
CEPC**

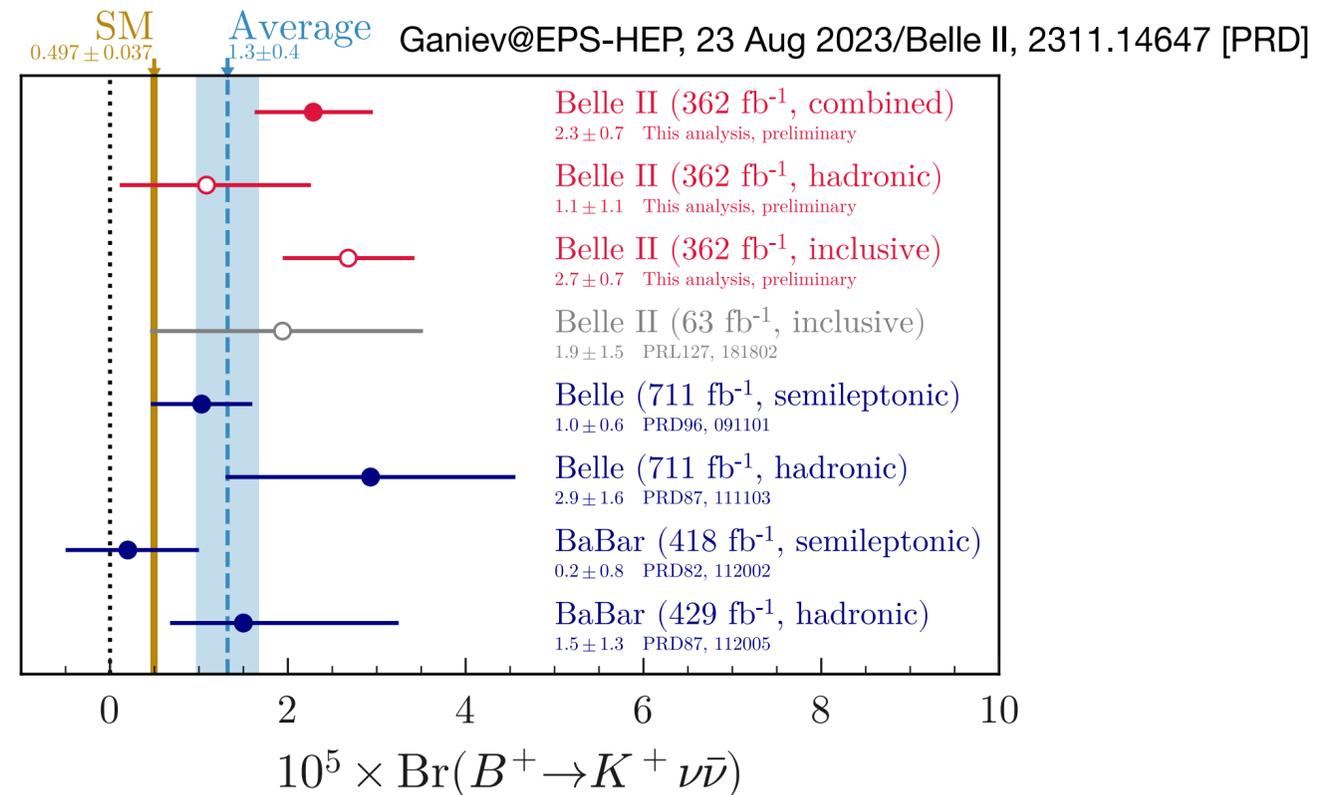
**NA62  
KOTO**

**BESIII  
STCF**

► **2021 Apr**

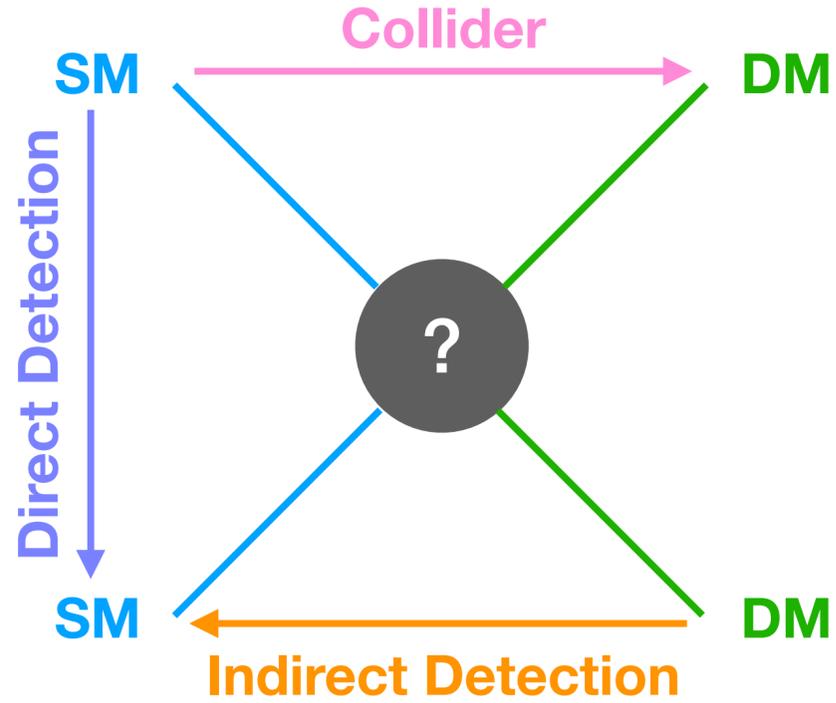
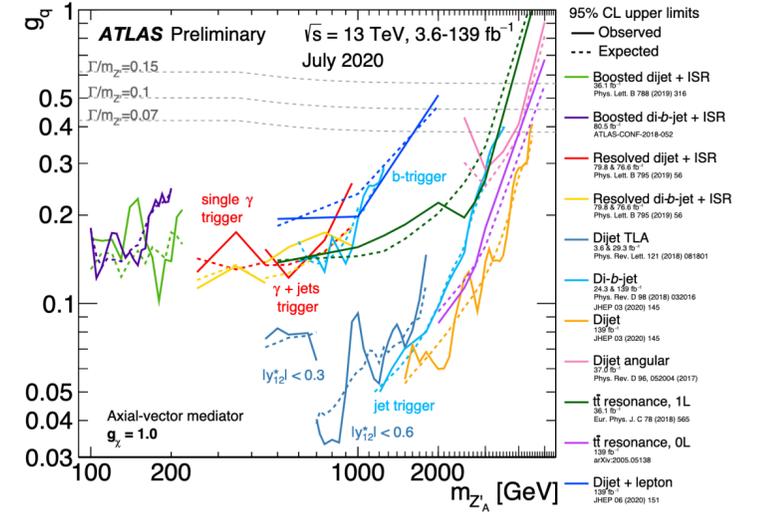
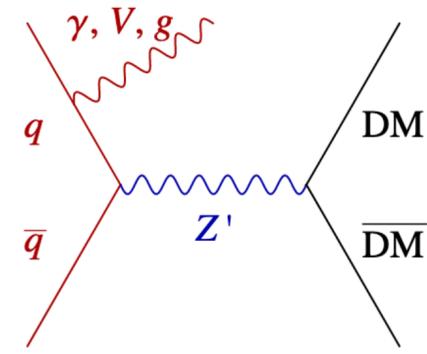


► **2023 Aug: first evidence**

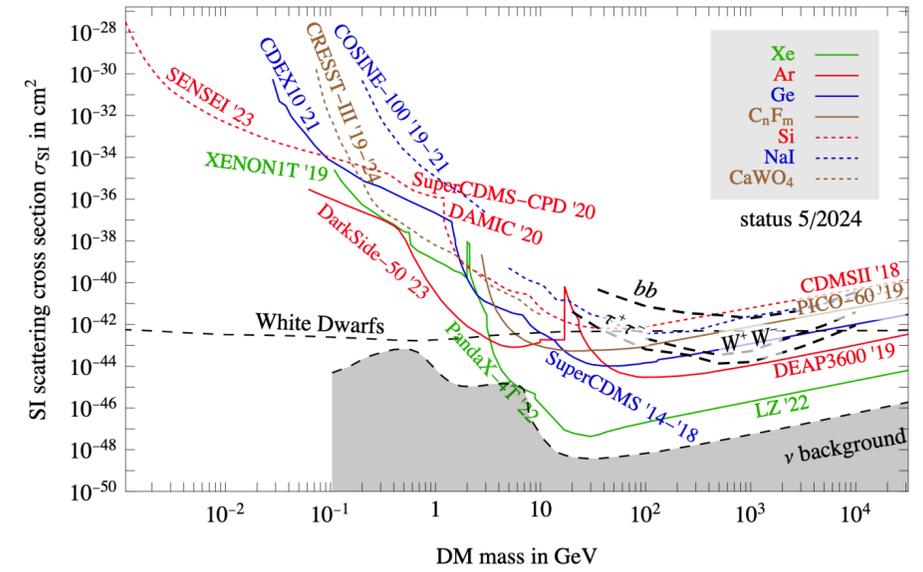
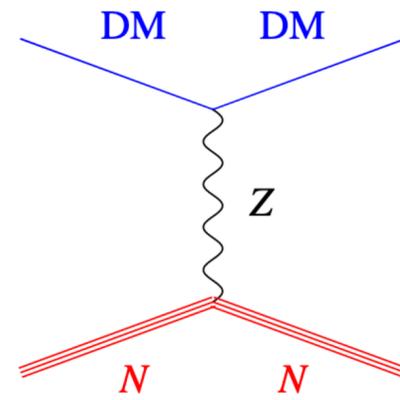


# Dark Matter Detection

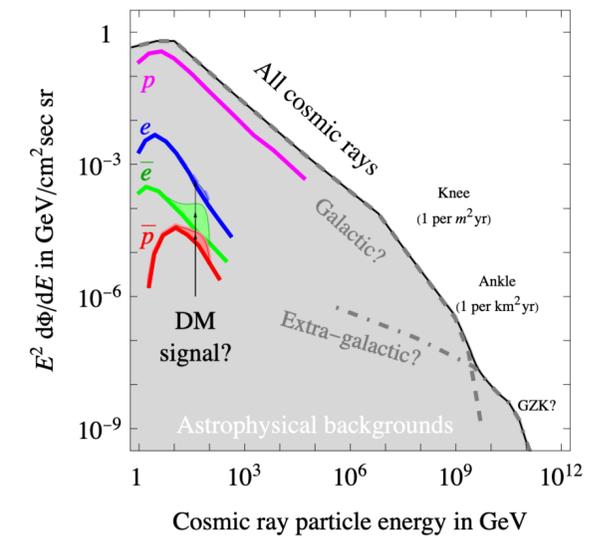
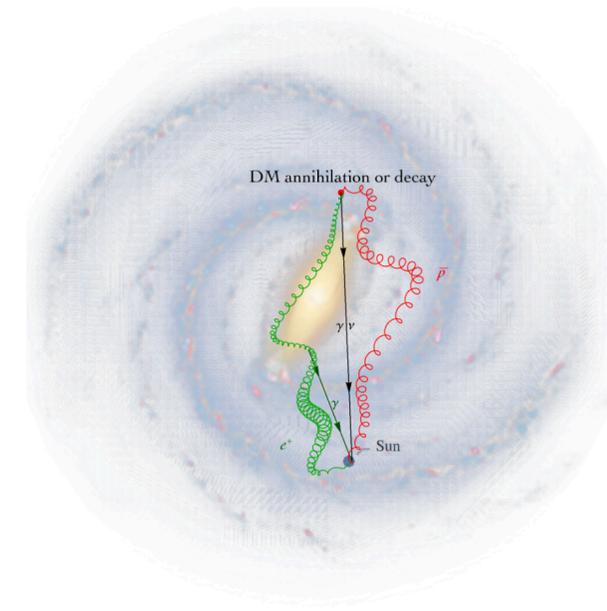
Collider



Direct Detection

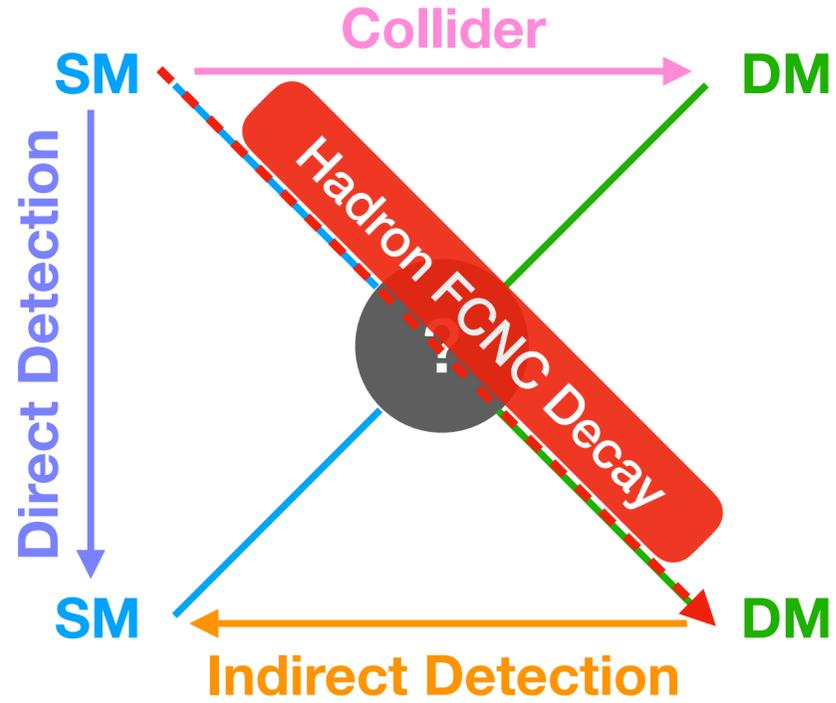
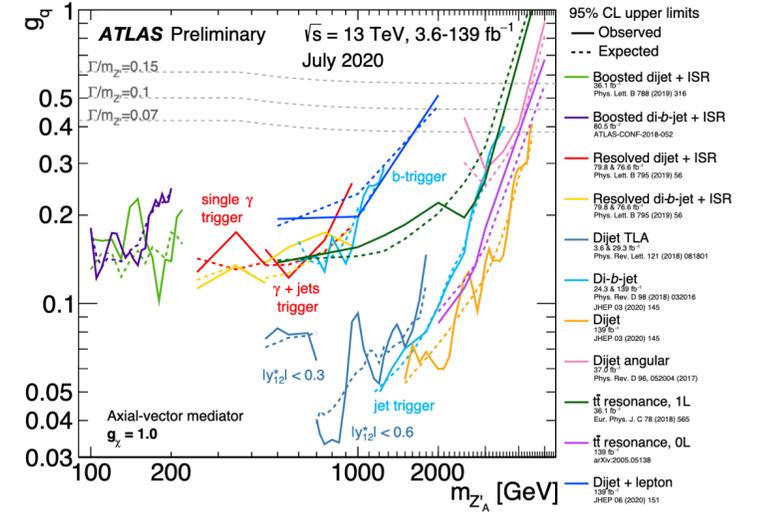
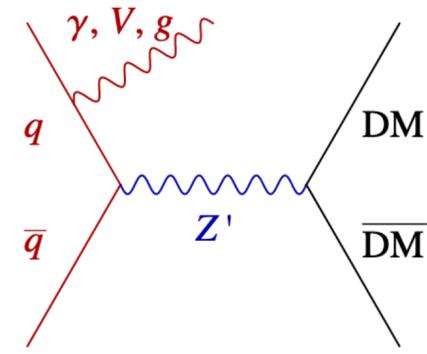


Indirect Detection

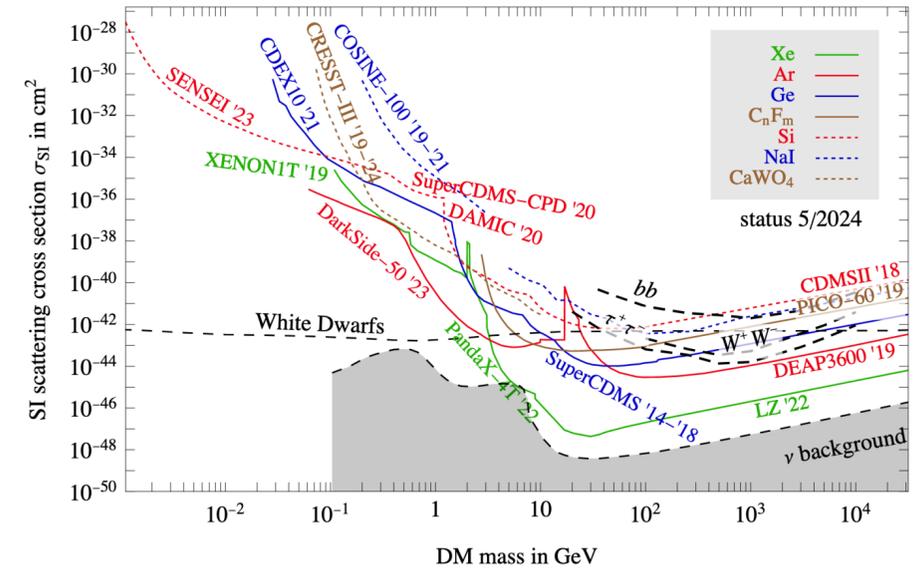
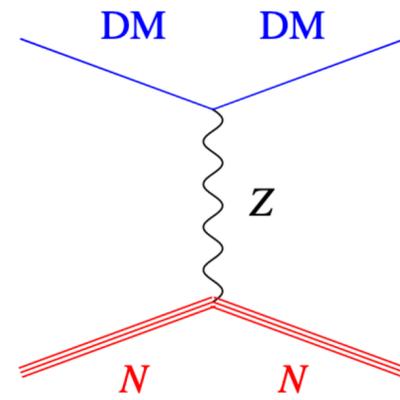


# Dark Matter Detection

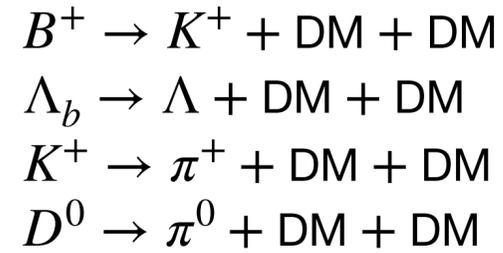
Collider



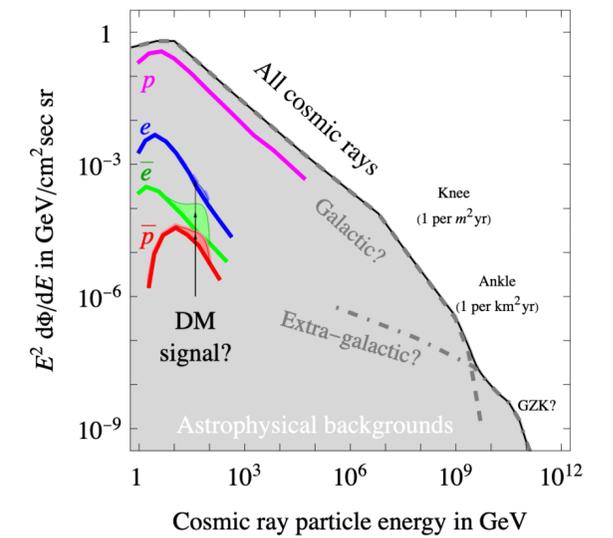
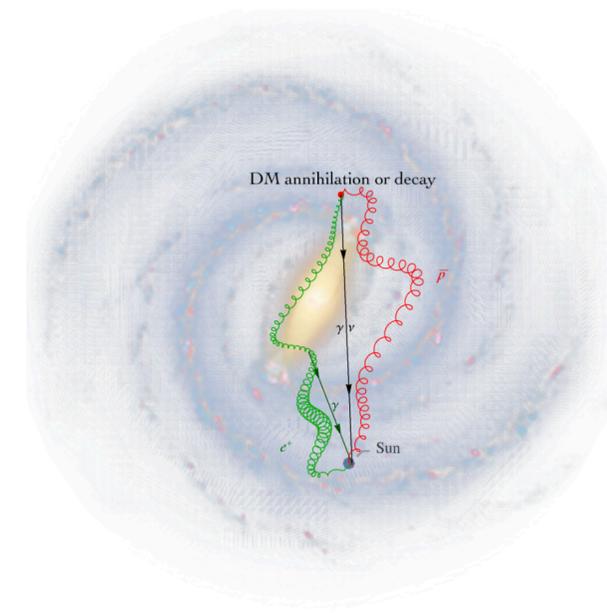
Direct Detection



Hadron FCNC Decay

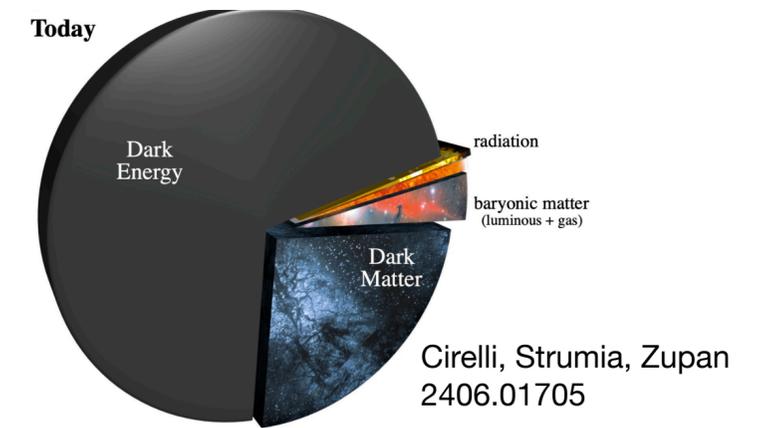


Indirect Detection



# 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

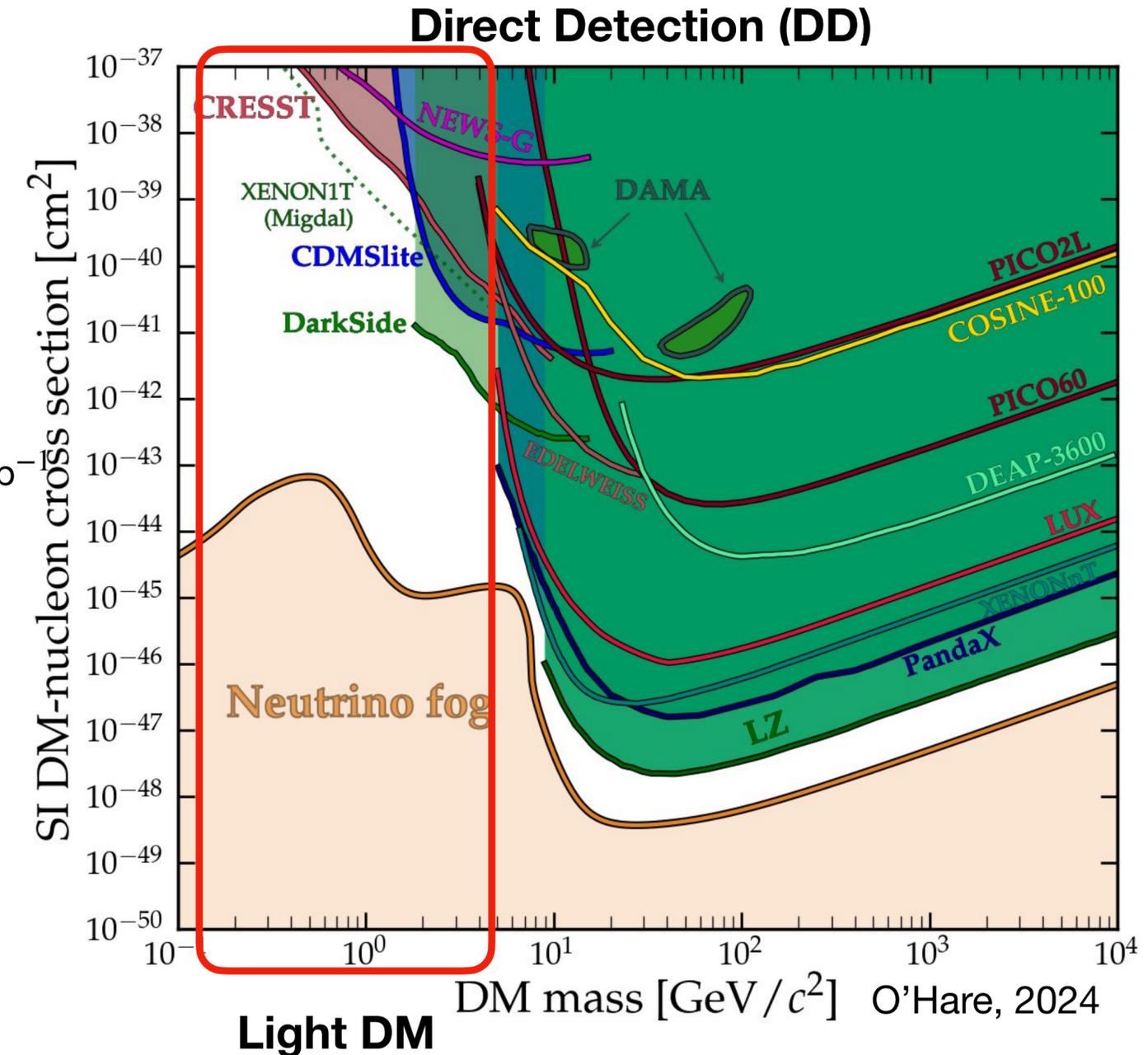
example:  
 $B^+ \rightarrow K^+ + \text{DM} + \text{DM}$   
 $K^+ \rightarrow \pi^+ + \text{DM} + \text{DM}$   
 $D^0 \rightarrow \pi^0 + \text{DM} + \text{DM}$

future exp uncertainties:  
 $\mathcal{O}(20 \sim 40\%)$ @Belle II with  $5\text{ab}^{-1}$   
 $\mathcal{O}(2\%)$ @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 !



	$d$	$s$	$b$
$d$	DD	NA62/KOTO	Belle II
$s$		DD	Belle II
$b$			Belle II/LHC

example:

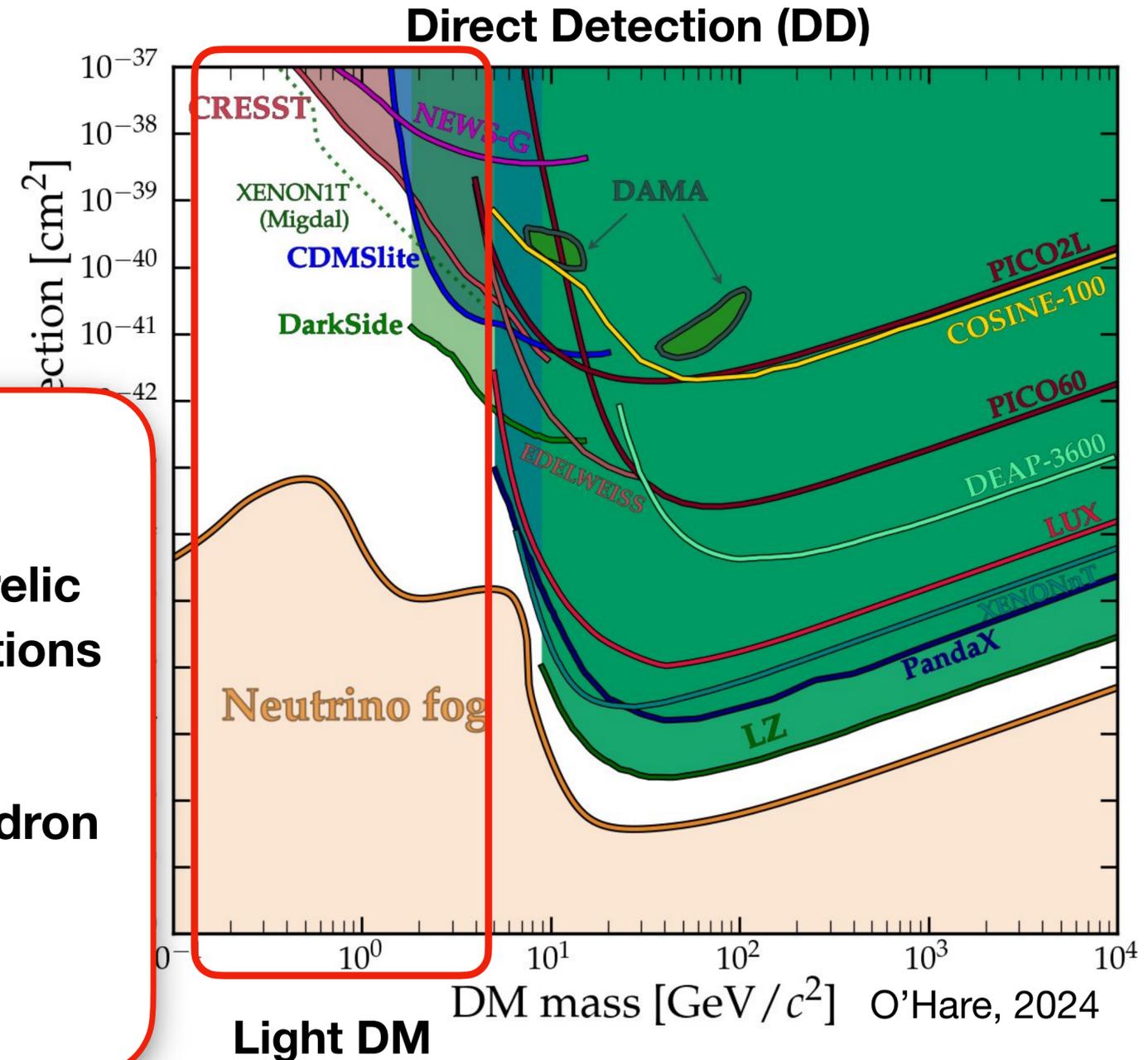
$$B^+ \rightarrow K^+ + \text{DM} + \text{DM}$$

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

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

It's natural to ask:

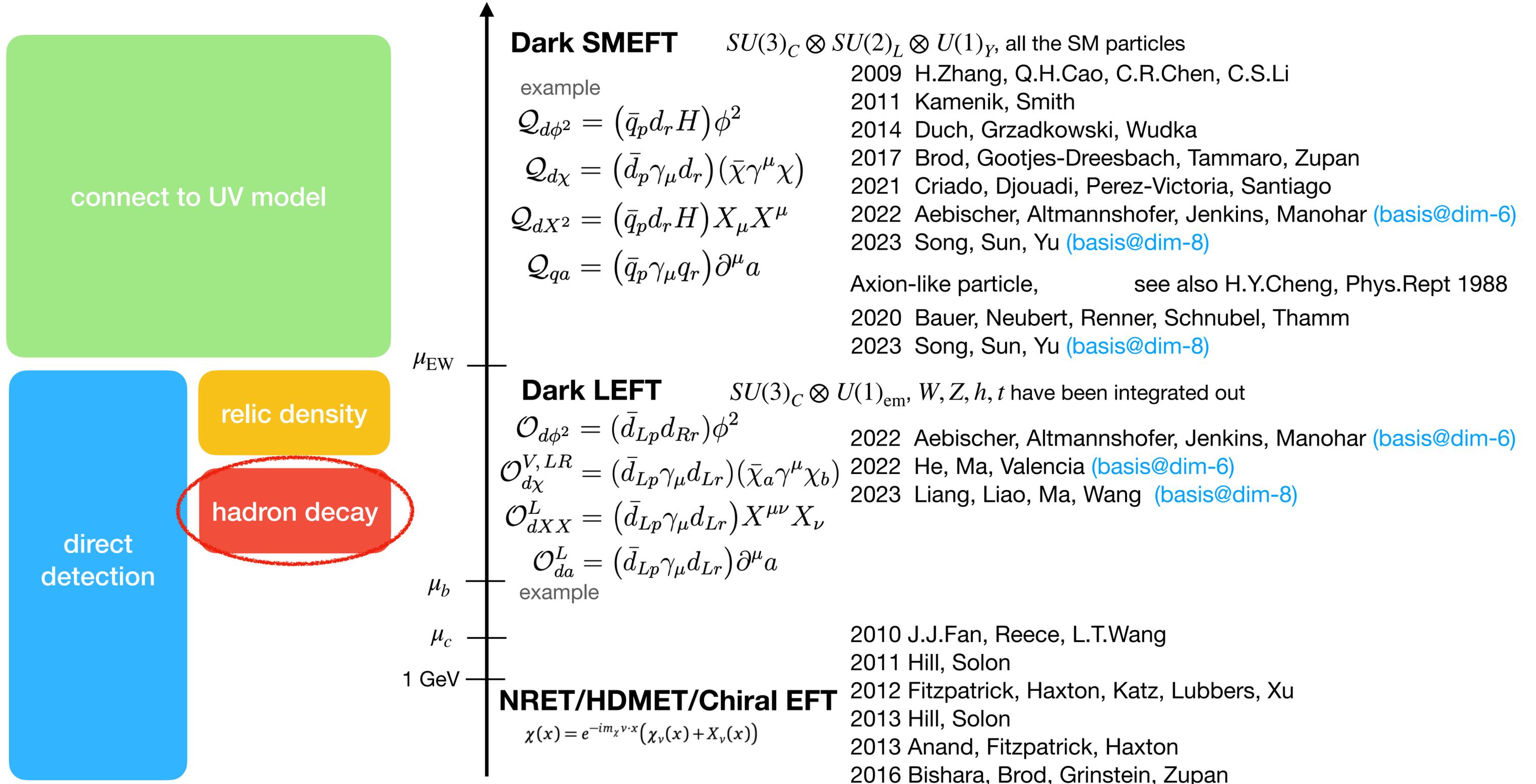
1. By combining the direct detection, flavour measurements, and relic density, is it possible to obtain the flavour structure of interactions between light DM and SM particles ?
2. Compared to DM direct detection, what's the advantage of hadron decays ? which DM scenario is more sensitive to ? Can they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

$$F_L$$

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

$\nu \rightarrow \mathbf{DM}$

**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, **XY** *to be finished*

## ▶ $c \rightarrow u + \mathbf{DM}$

2022 C.Q.Geng, G.Li

2023 G.Li, Tandean

$$D^0 \rightarrow s \bar{s}'$$

$$D^0 \rightarrow \gamma s \bar{s}'$$

$$D^0 \rightarrow \pi^0 s \bar{s}'$$

$$D^+ \rightarrow \pi^+ s \bar{s}'$$

$$D_s^+ \rightarrow K^+ s \bar{s}'$$

$$D^0 \rightarrow \rho^0 s \bar{s}'$$

$$D^+ \rightarrow \rho^+ s \bar{s}'$$

$$D_s^+ \rightarrow K^{*+} s \bar{s}'$$

$$\Lambda_c^+ \rightarrow p s \bar{s}'$$

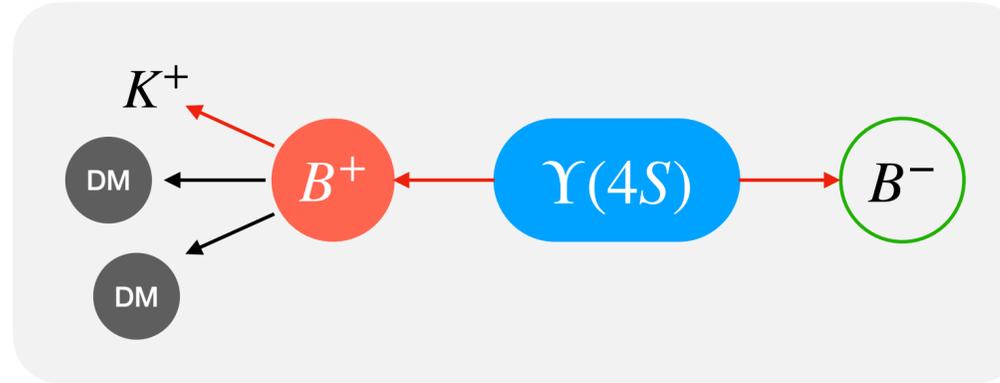
$$\Xi_c^+ \rightarrow \Sigma^+ s \bar{s}'$$

$$\Xi_c^0 \rightarrow \Sigma^0 s \bar{s}'$$

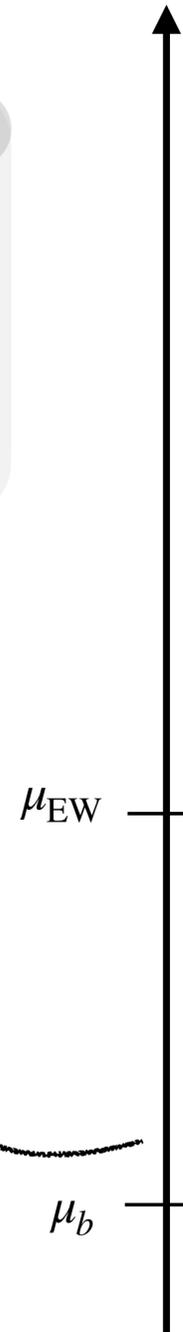
$$\Xi_c^0 \rightarrow \Lambda s \bar{s}'$$

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

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



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



## 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

$$\mathcal{O}_{d\phi} = (\bar{d}_{Lp} d_{Rr}) \phi + \text{h.c.}, \quad \mathcal{O}_{\phi d}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2),$$

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

$$\mathcal{O}_{dX}^T = (\bar{d}_{Lp} \sigma_{\mu\nu} d_{Rr}) X_a^{\mu\nu} \quad \mathcal{O}_{dXX}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) X^{\mu\nu} X_\nu$$

$$\mathcal{O}_{da}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) \partial^\mu a, \quad \mathcal{O}_{da}^R = (\bar{d}_{Rp} \gamma_\mu d_{Rr}) \partial^\mu a.$$

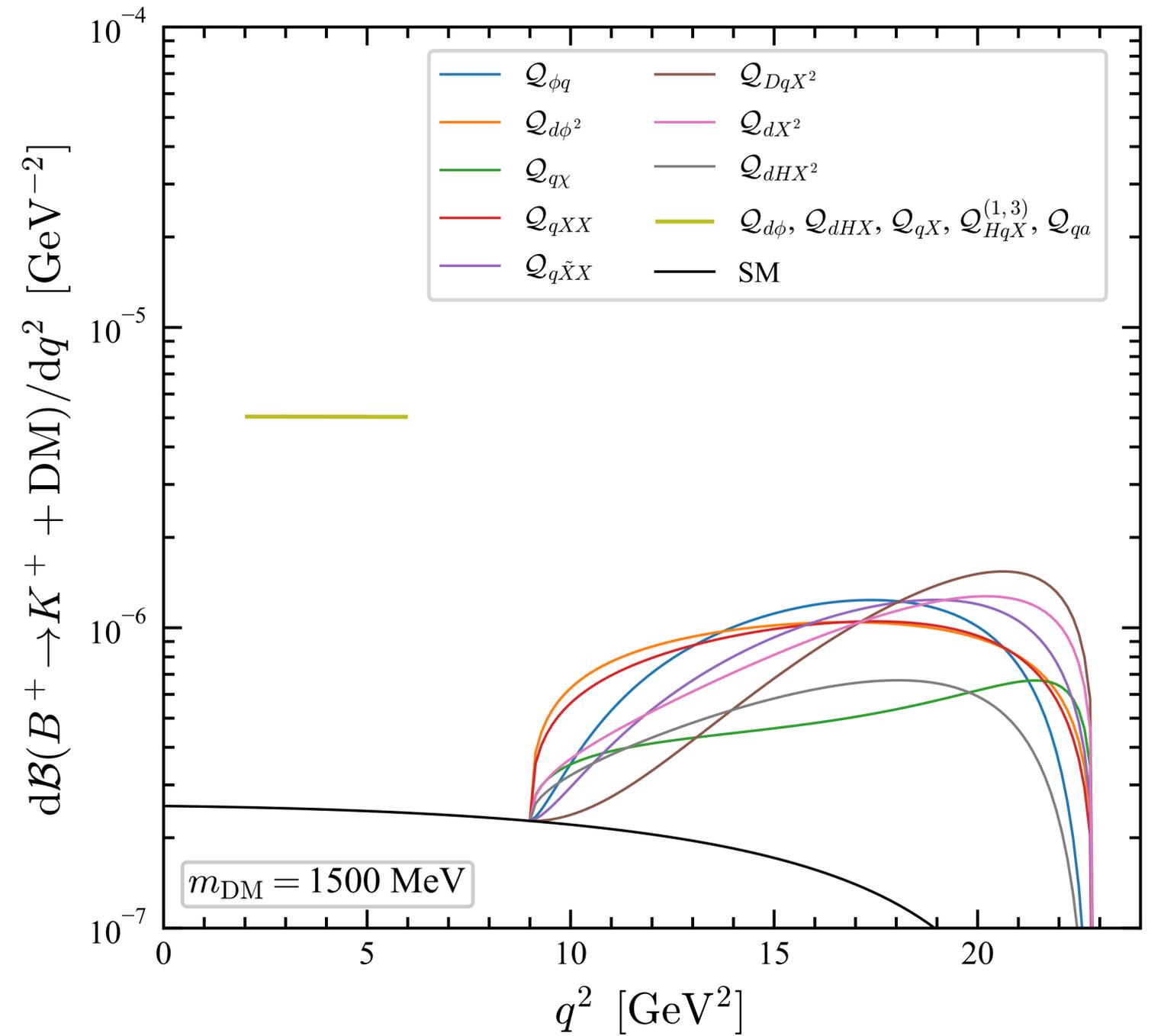
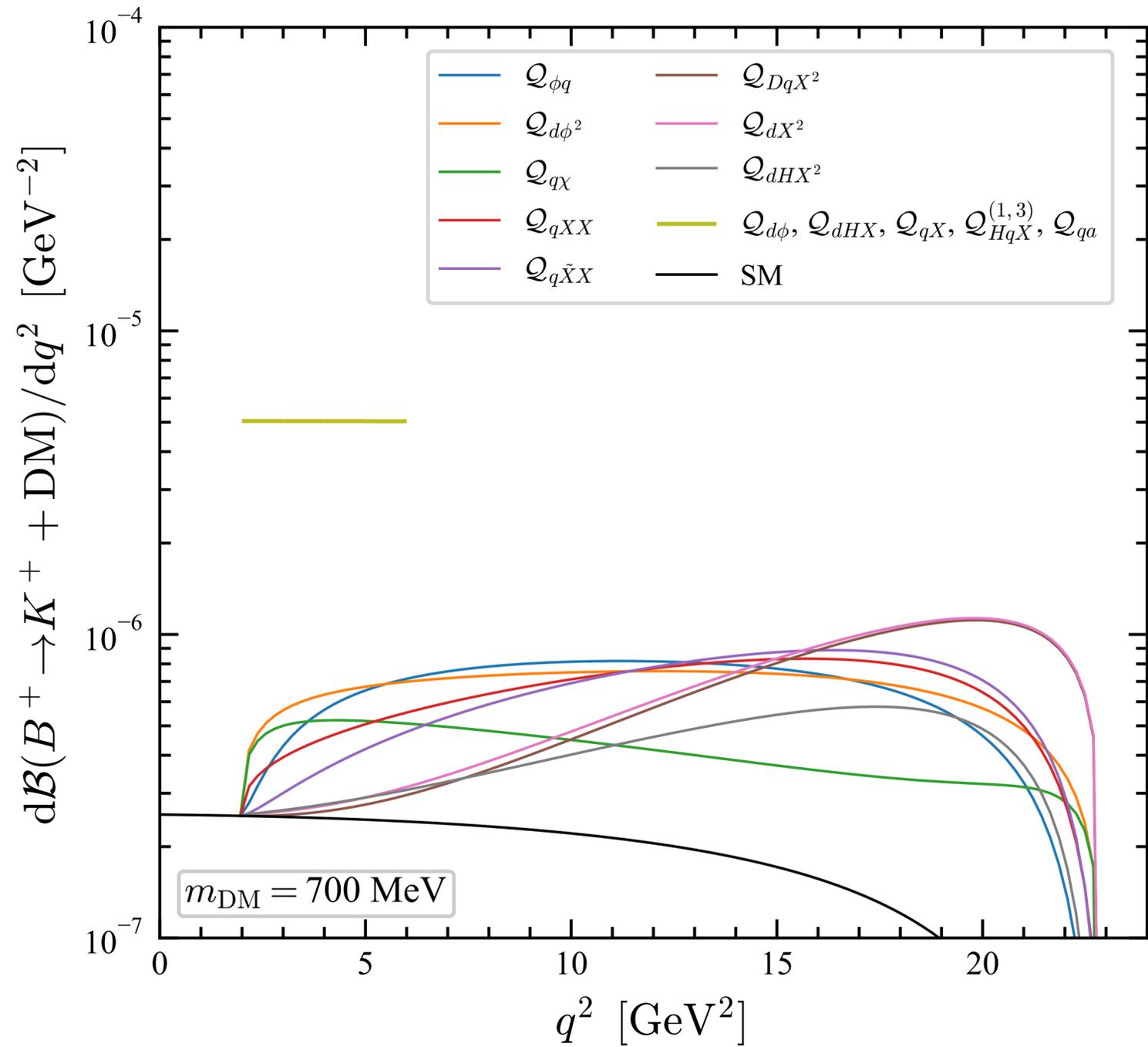
scalar: 4

fermion: 5

vector: 1+10

ALP: 2

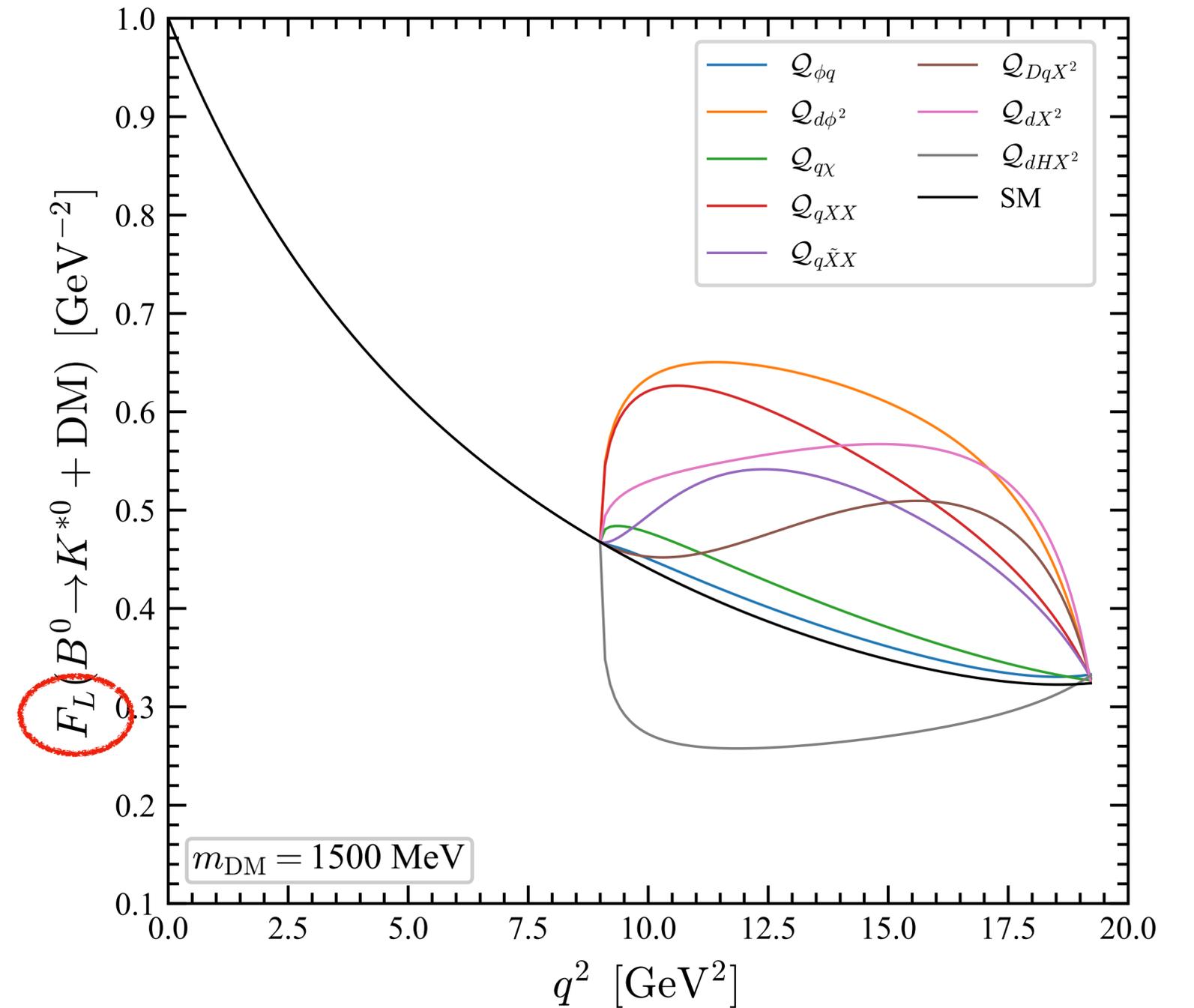
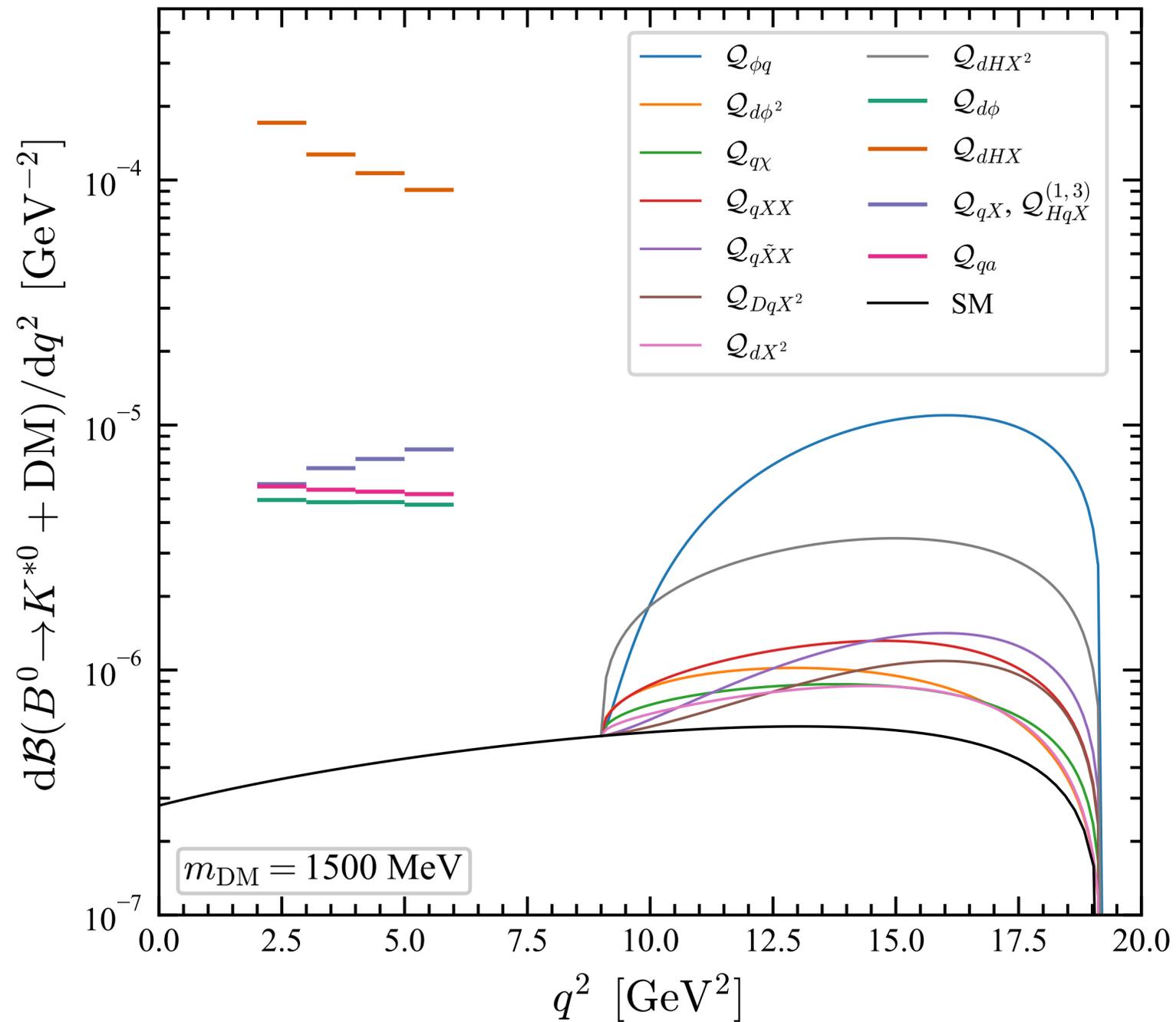
# Dark SMEFT: $dB/dq^2$



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

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

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

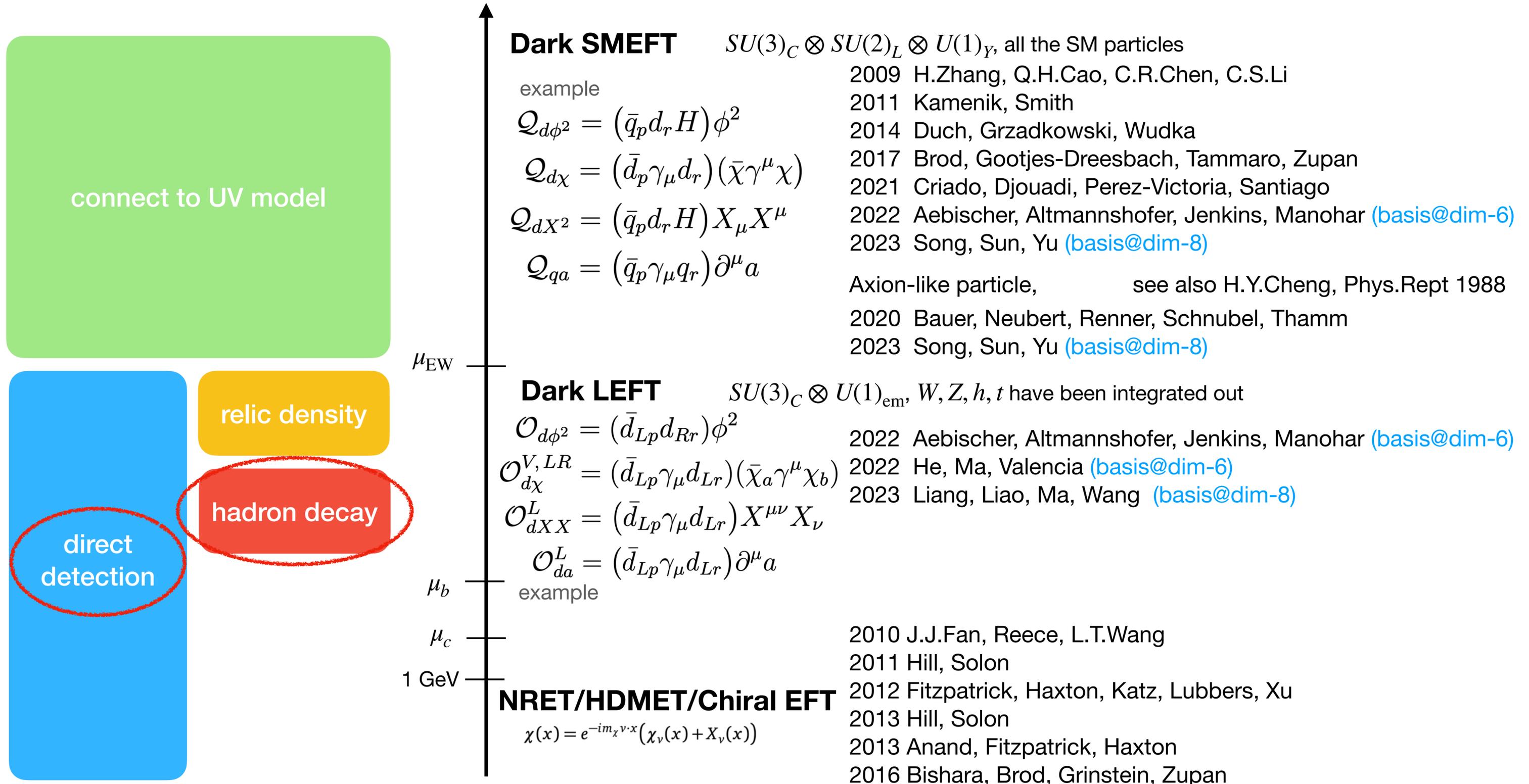


All the operators are **distinguishable** from each other by combing these observables

# 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 @  $\mu_{EW}$

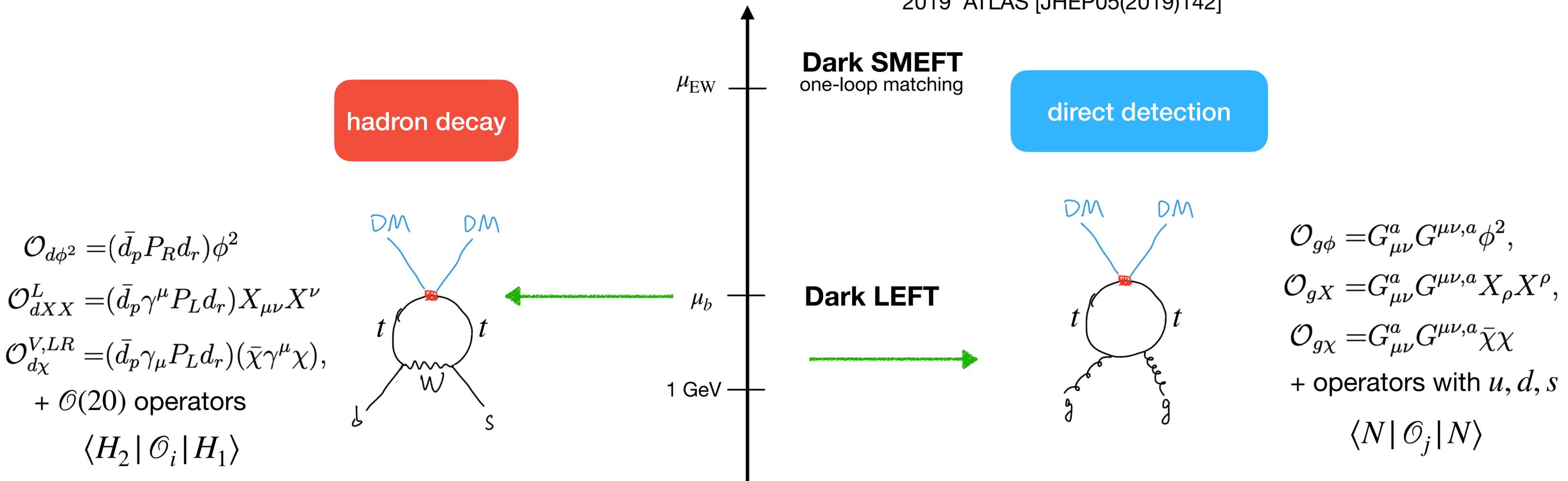
$$\mathcal{Q}_{u\chi} = (\bar{u}_p \gamma_\mu u_r)(\bar{\chi} \gamma^\mu \chi), \implies (\bar{t}_R \gamma_\mu t_R)(\bar{\chi} \gamma^\mu \chi)$$

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

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

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 Hermanna, Worek  
 2022 Yandong Liu, Bin Yan, Rui Zhang  
 ... ..

2019 ATLAS [JHEP05(2019)142]



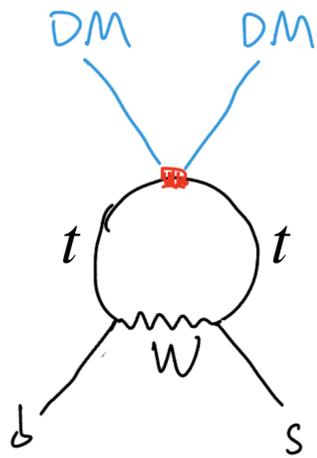
# One-Loop Matching between Dark SMEFT and Dark LEFT

## ► Dark SMEFT

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

$\mathcal{Q}_{u\phi^2} = (\bar{q}_p u_r \tilde{H}) \phi^2 + \text{h.c.}$	$\mathcal{Q}_{\phi u} = (\bar{u}_p \gamma_\mu u_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	$\mathcal{Q}_{\phi q} = (\bar{q}_p \gamma_\mu q_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	...	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: **hadron detection**

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

$\mathcal{O}_{\phi d}^R = (\bar{d}_p \gamma_\mu P_R d_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	$\mathcal{O}_{d\phi^2} = (\bar{d}_p P_R d_r) \phi^2$	...	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

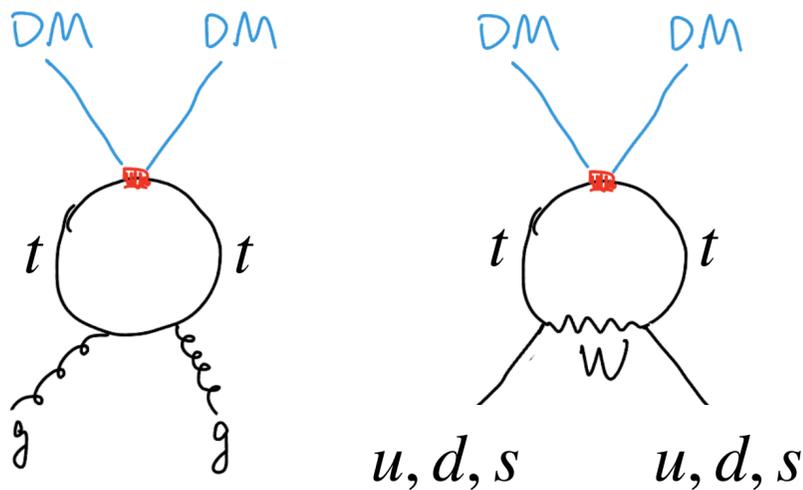
# One-Loop Matching between Dark SMEFT and Dark LEFT

## ► Dark SMEFT

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

$\mathcal{Q}_{u\phi^2} = (\bar{q}_p u_r \tilde{H}) \phi^2 + \text{h.c.}$	$\mathcal{Q}_{\phi u} = (\bar{u}_p \gamma_\mu u_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	$\mathcal{Q}_{\phi q} = (\bar{q}_p \gamma_\mu q_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	...	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

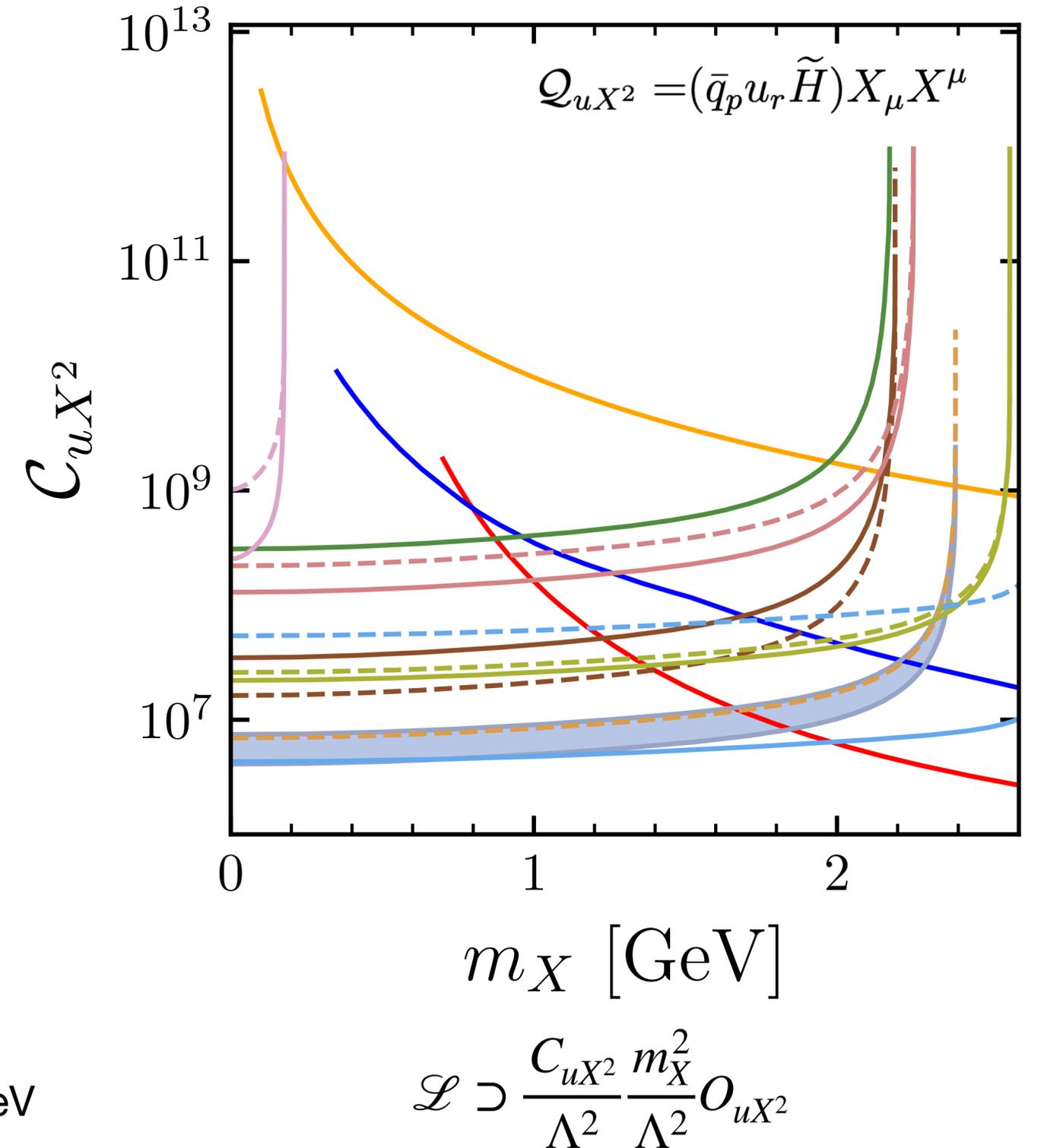
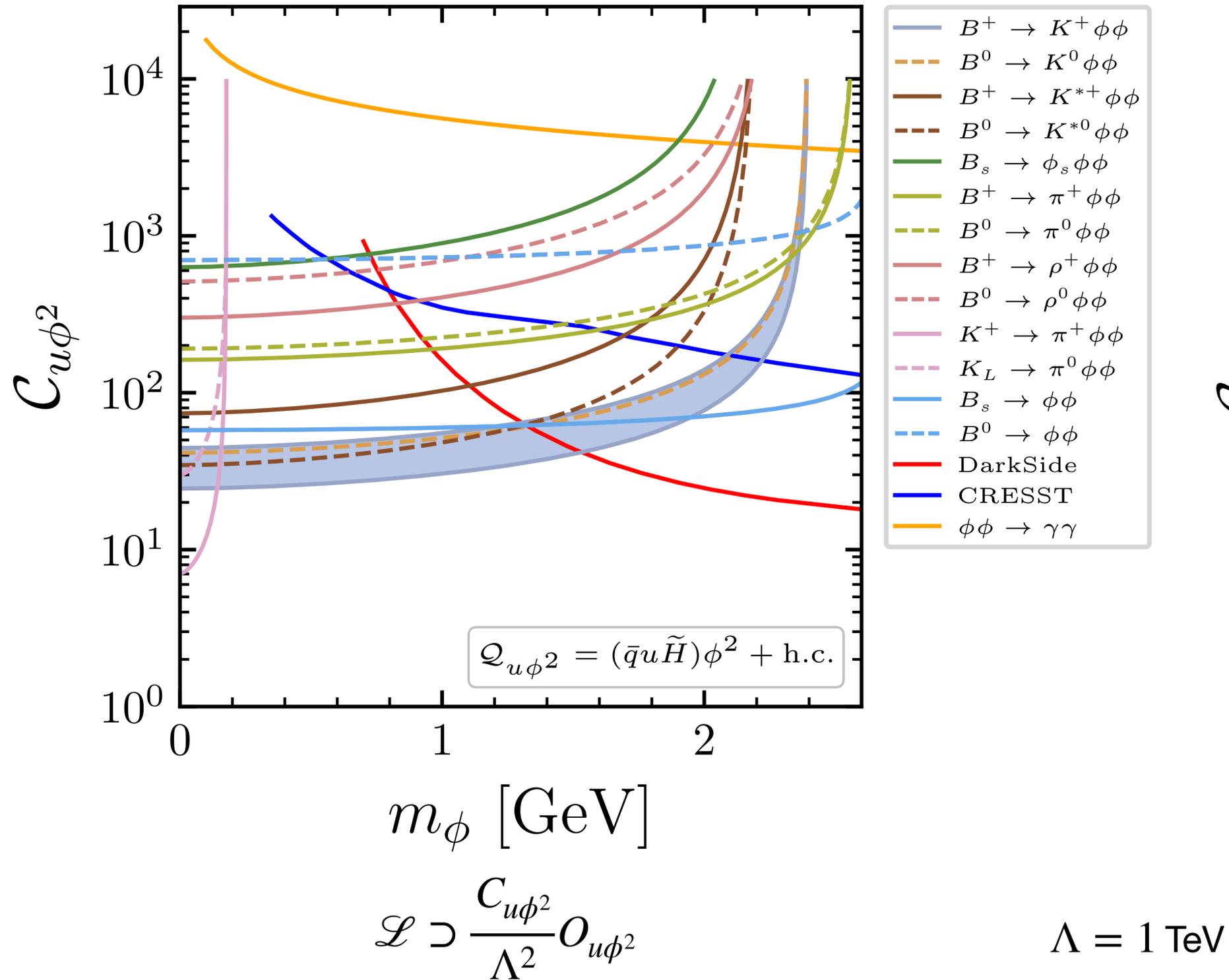


## ► Dark LEFT: **direct detection**

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

$\mathcal{O}_{g\phi} = G_{\mu\nu}^a G^{\mu\nu,a} \phi^2$	$\mathcal{O}_{d\phi^2} = (\bar{d}_p P_R d_r) \phi^2$	...	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



# Possible Flavour Path to Dark Matter

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**

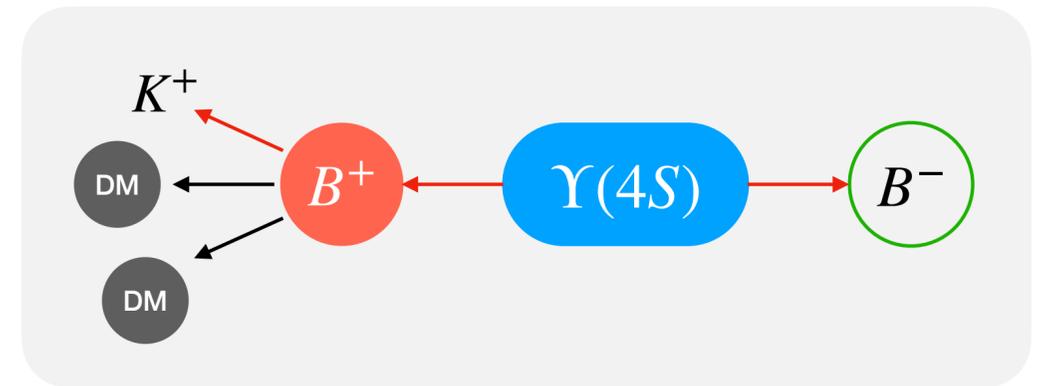
2. Compared to DM direct detection, what's the advantage of hadron decays? which DM scenario is more sensitive to ? Can they provide **other information** ?

**angular distribution ( $F_L$ ) ;**

**HadronToNP**: a package to calculate decay of hadron to new particles

$B \rightarrow K + \text{DM}, B \rightarrow \rho + \text{DM}, \Lambda_b \rightarrow \Lambda + \text{DM}, \Upsilon \rightarrow \text{DM}, \dots$  *to be finished*  
 $D \rightarrow \pi + \text{DM}, D \rightarrow \rho + \text{DM}, \Xi_c \rightarrow \Xi + \text{DM}, J/\psi \rightarrow \text{DM}, \dots$

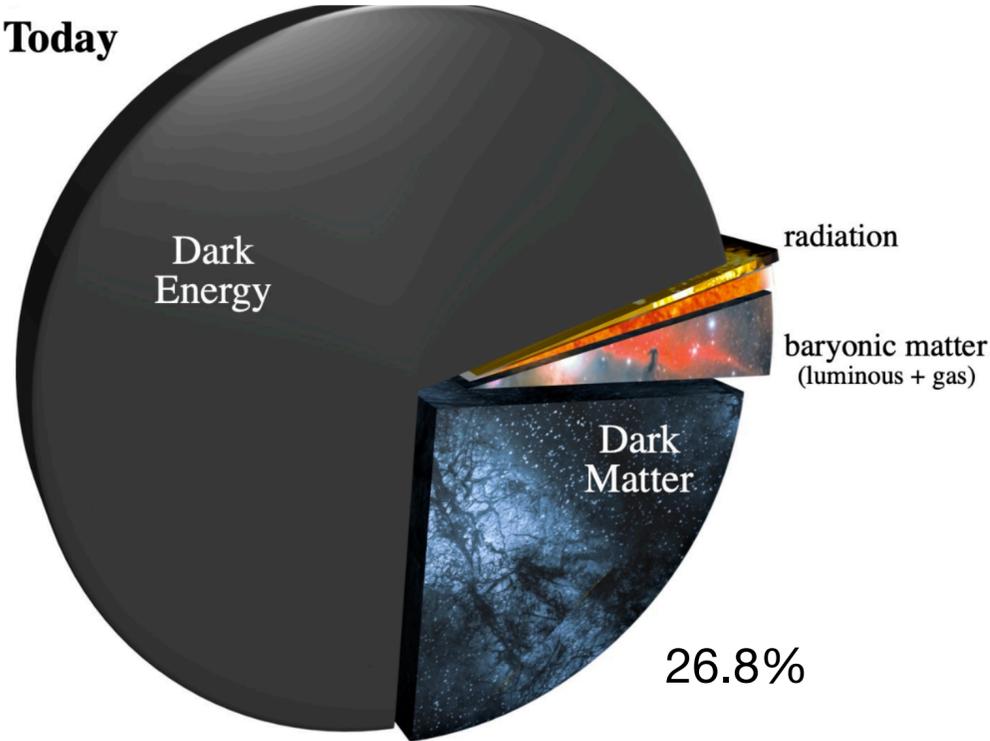
many things to do, e.g., other flavour structures (MFV,  $U(2)^5$ ), simplified model (light mediator), operator basis (SPVA), UV completion, full one-loop matching between DLEFT and DSMEFT, astro-constraints, ...



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

# Possible Flavour Path to New Physics

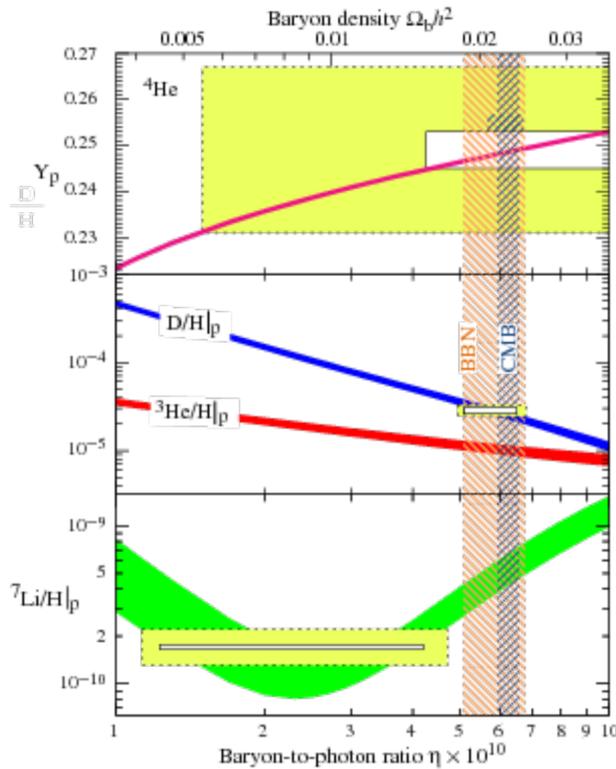
## Dark Matter



Cirelli, Strumia, Zupan/2406.01705

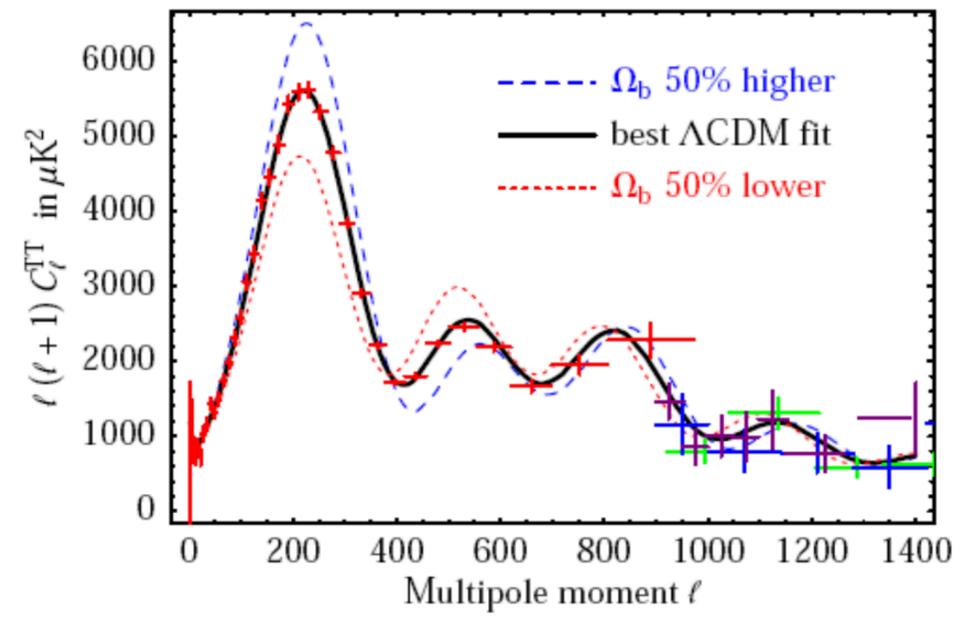
see also talks by Xiao-Gang He, Zuowei Liu, Lingfeng Li

## Matter-antimatter Asymmetry



Rubakov/1804.11230

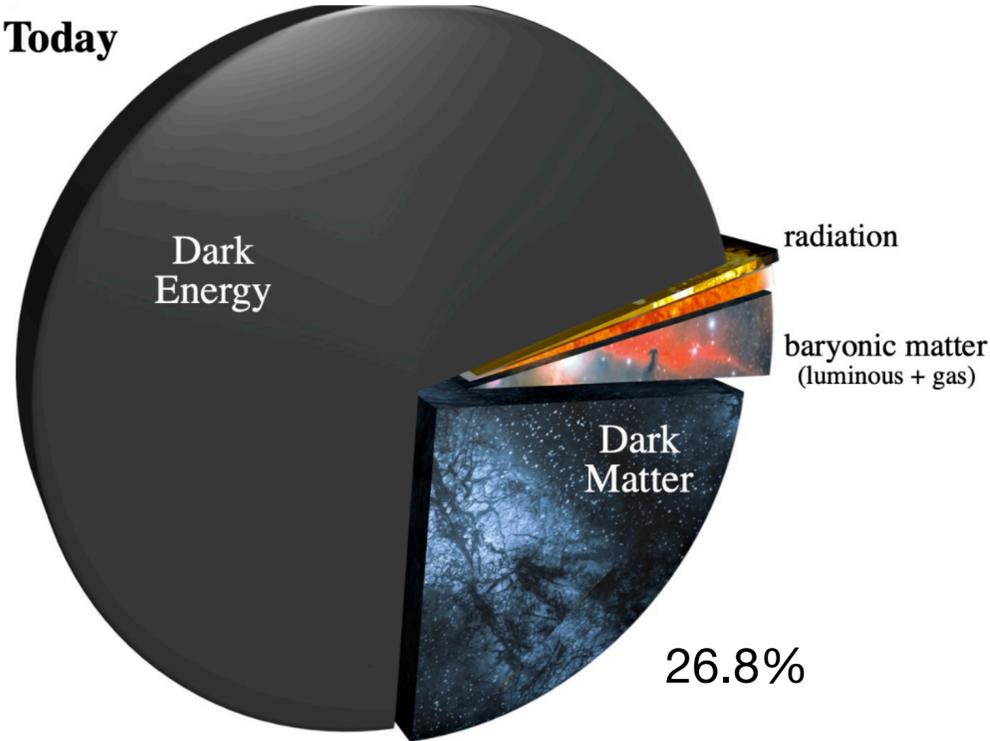
see also talks by Xiao-Gang He, Wei Chao, ChengCheng Han, Fapeng Huang



Blanchet/0807.1408

# Possible Flavour Path to New Physics

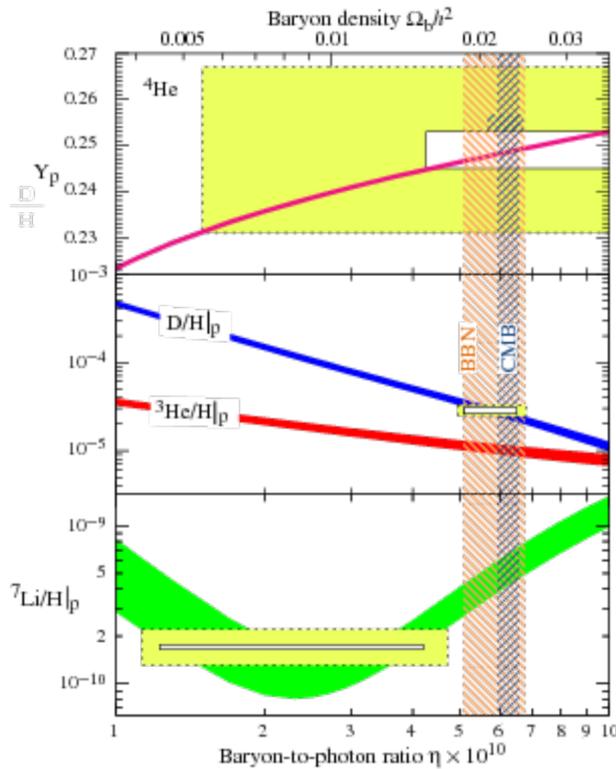
## Dark Matter



Cirelli, Strumia, Zupan/2406.01705

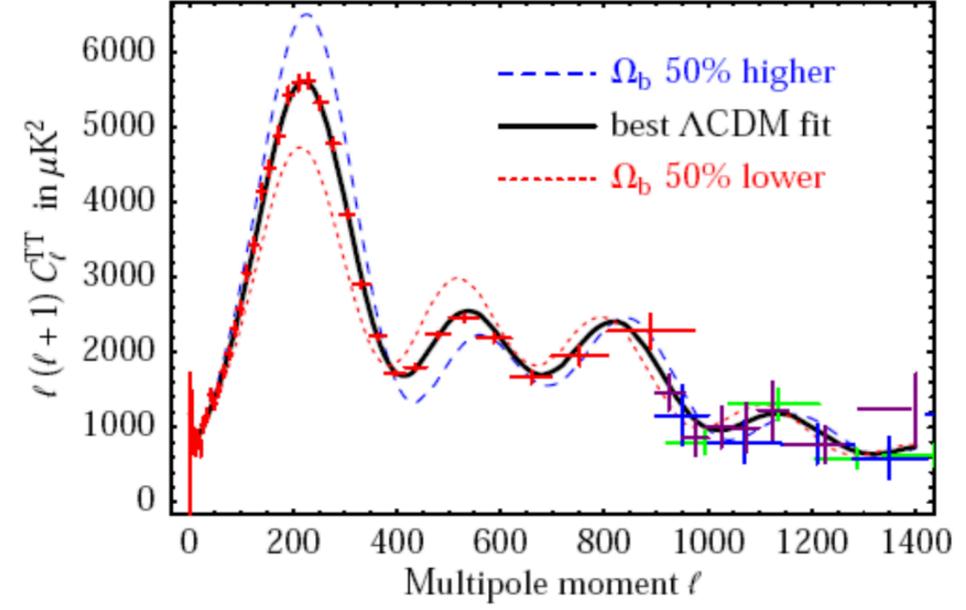
see also talks by Xiao-Gang He, Zuowei Liu, Lingfeng Li

## Matter-antimatter Asymmetry



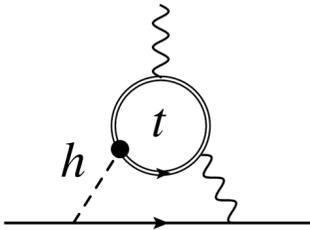
Rubakov/1804.11230

see also talks by Xiao-Gang He, Wei Chao, ChengCheng Han, Fapeng Huang

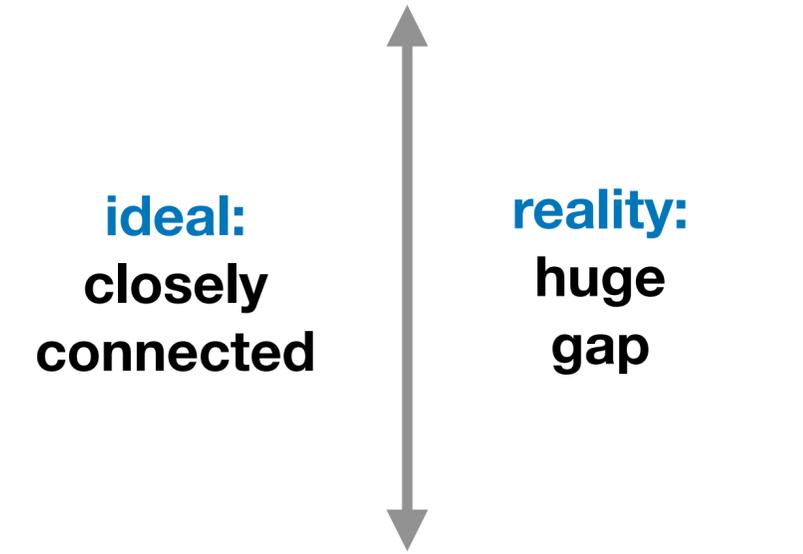


Blanchet/0807.1408

# BAU and flavour physics



**Baryon Asymmetry of the Universe**



**CP Violation in quark flavour physics**

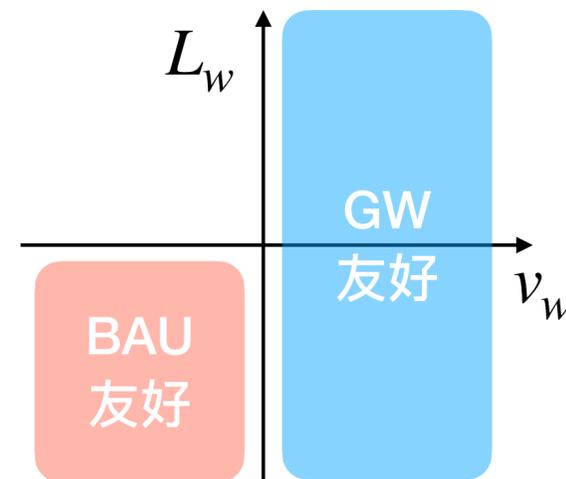
**ideal:**  
closely  
connected

**reality:**  
huge  
gap

## Question 1: why there is a huge gap ?

- ▶ **物理原因:** EWBG模型的CPV源通常是Higgs或new singlet与顶夸克的相互作用。这类相互作用容易影响edm, 但很难影响夸克味物理过程! 这也是为什么EWBG通常考虑edm而不是味物理CP限制的原因。
- ▶ **非物理原因:** 这类研究的性价比低! 研究要求的基础高 (味物理需要EFT、因子化等很多知识, EWBG需要有限温度场论, 相变动力学, 宇宙学等很多知识), 但产出低 (做GW相关研究的话, 话的时间更少, 且更容易出成果)。

## Question 2: any help from GW studies ?



### some related refs

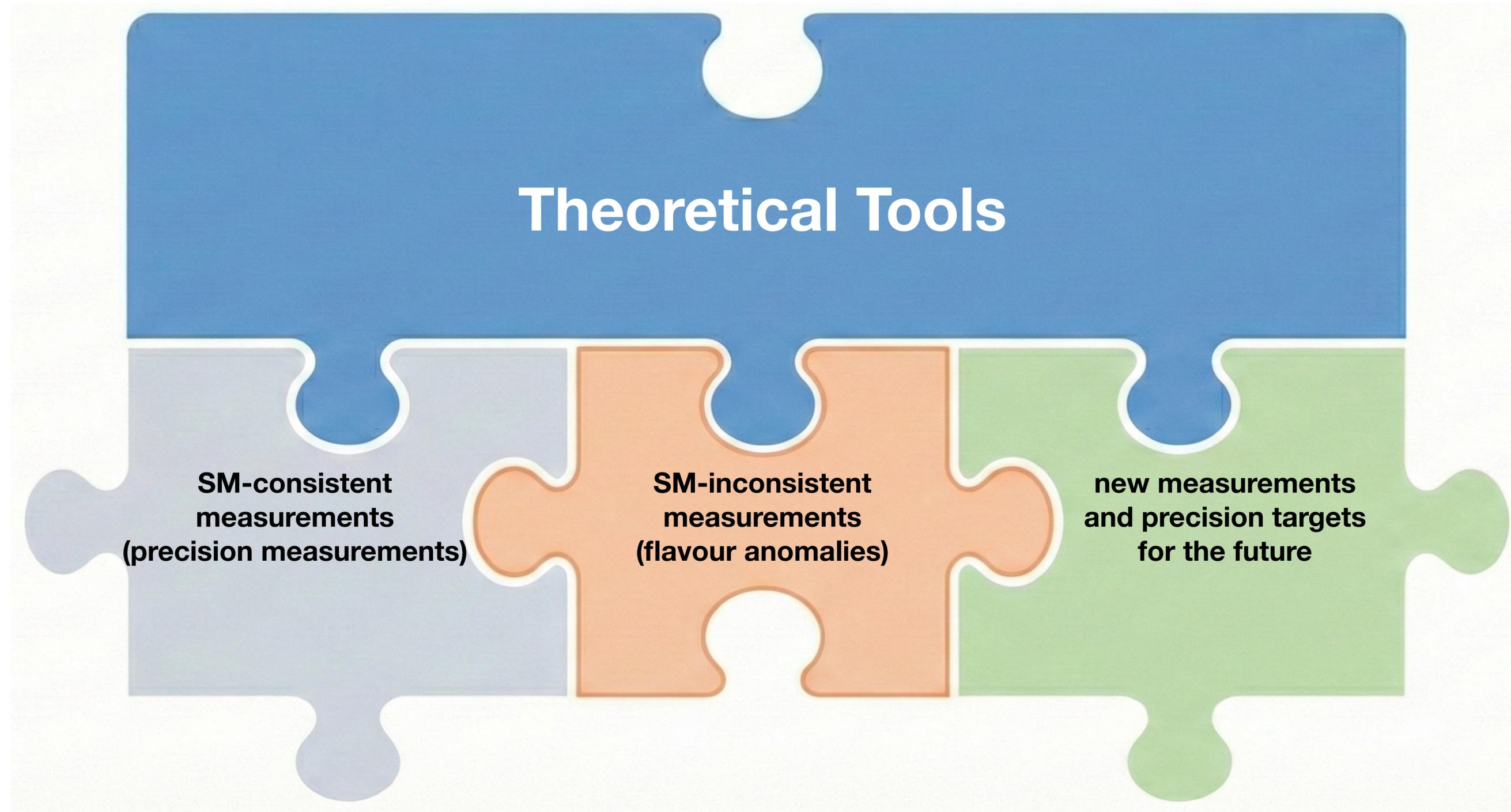
- 2502.00445, Athron, Ramsey-Musolf, Sierra, Wu,  $R_{D^{(*)}}$  in 2HDM
- 2303.11252, Kanemura, Mura
- 1705.05034, Fuyuto, Hou, Senaha
- 1109.4145, Liu, Ramsey-Musolf, Shu,  $B_s - \bar{B}_s$  mixing
- 1107.3559, Cline, Kainulainen, Trott, B anomalies

## Question 3: is this problem important ?

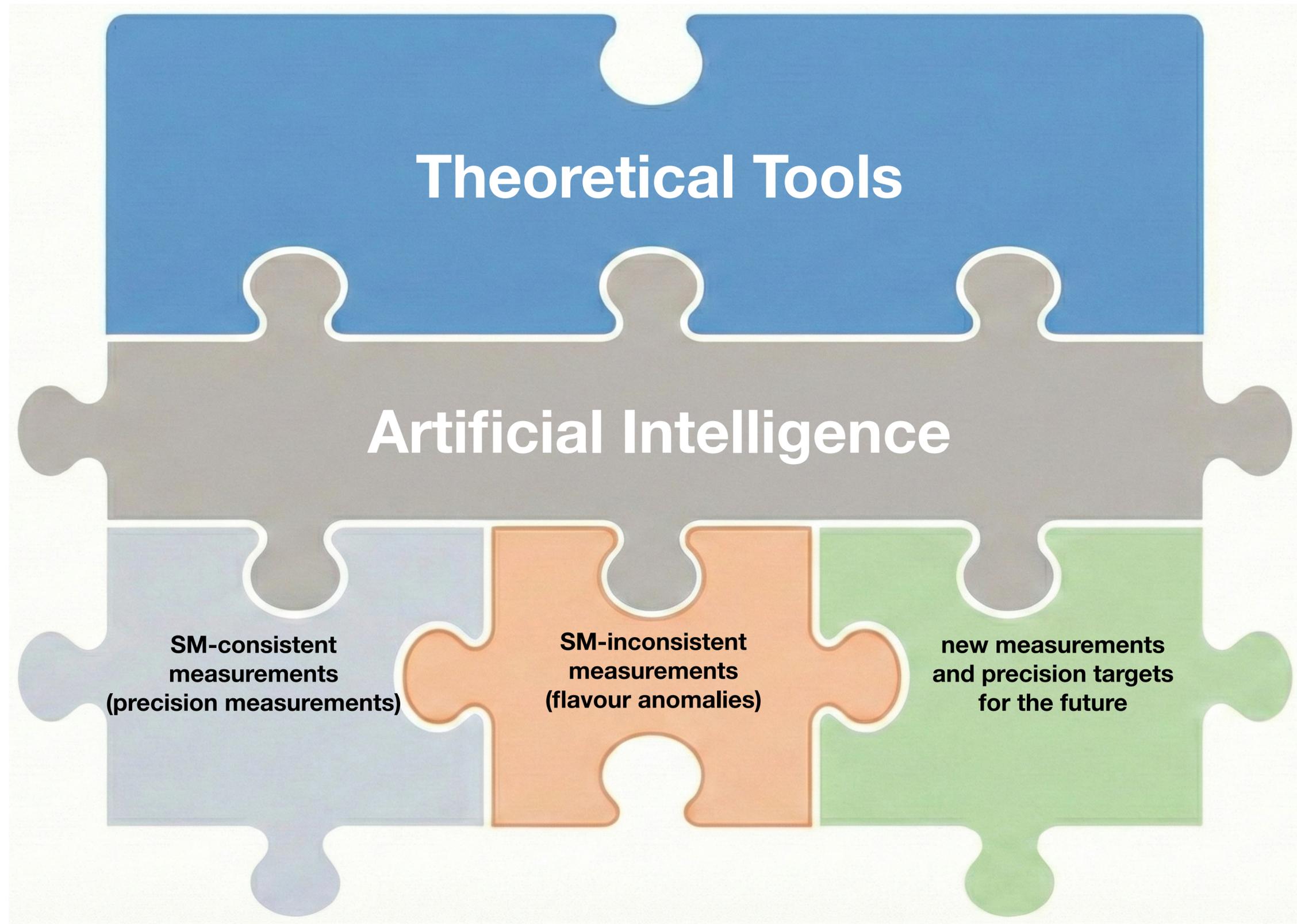
**Yes !**

example: **Hsiang-nan Li**, 2502.16099, 2601.21374

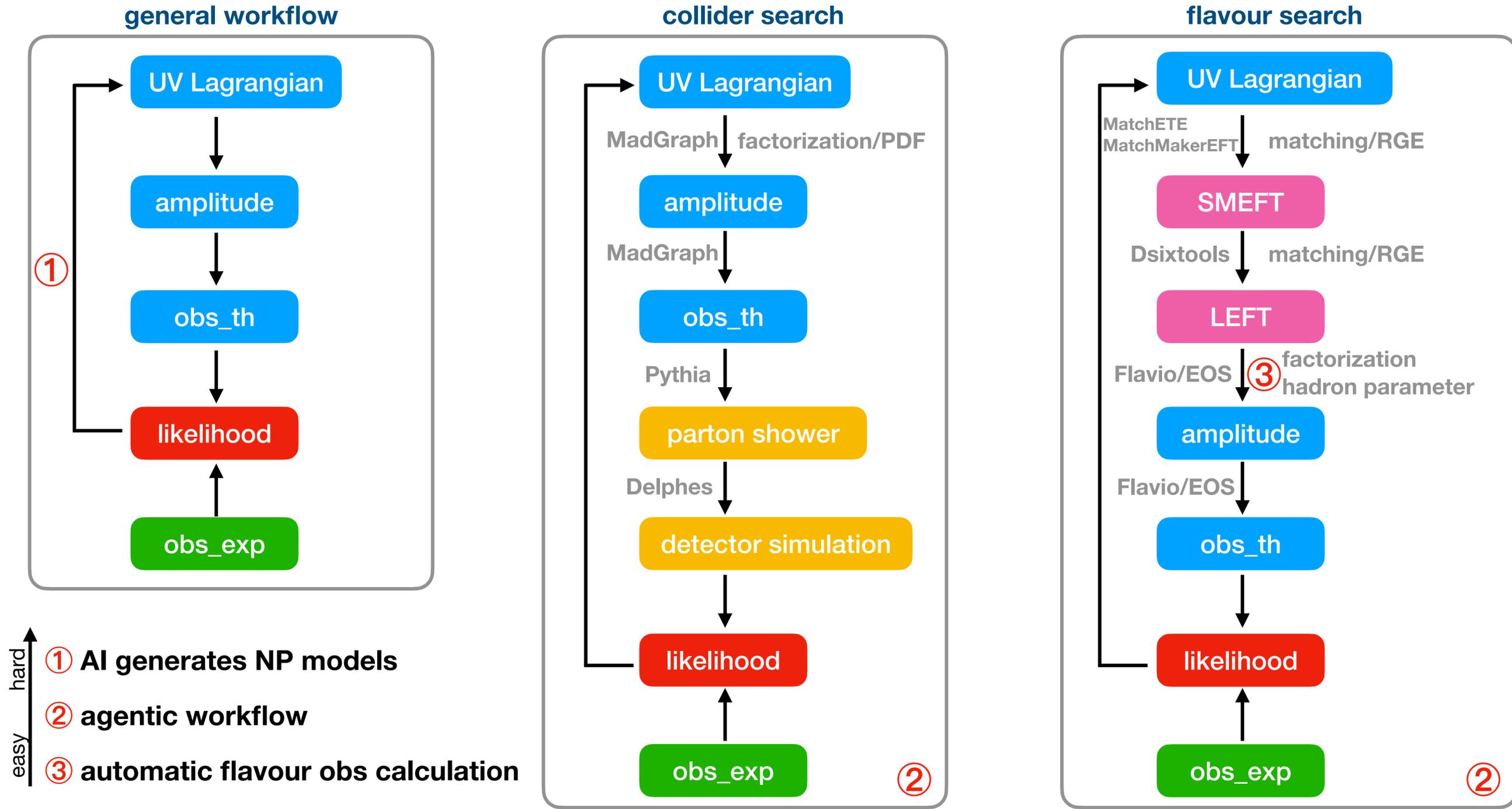
# One More Thing ...



# One More Thing ...



# Searches for NP in Flavour Measurements: AI Perspective



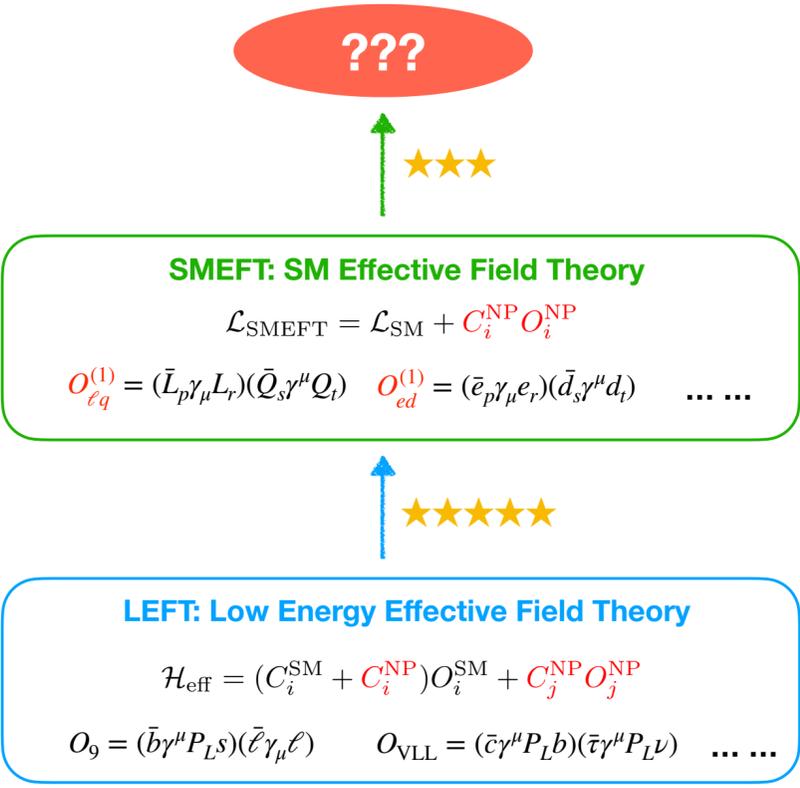
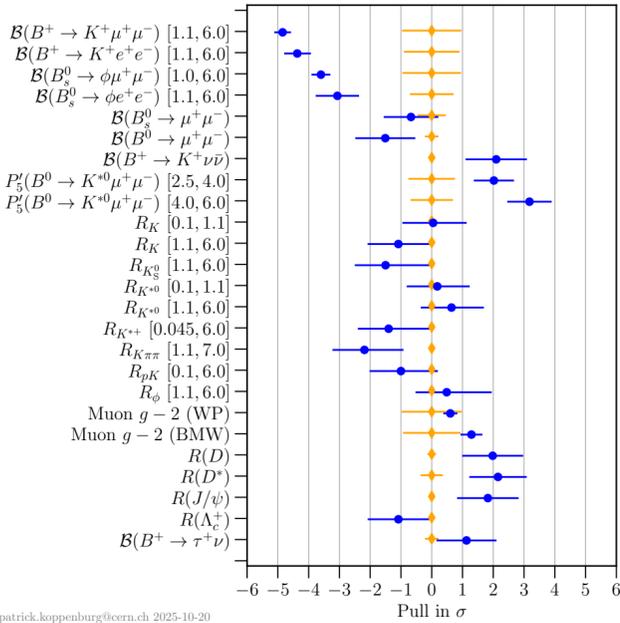
# Searches for NP in Flavour Measurements: AI Perspective

- ▶ discussions@高能理论与通用人工智能发展论坛, 北京大学, 2025.11.29-30
- ▶ Wei Wang's talk@重子物理与CP破坏研讨会, 高科大杭高院, 2025.12.13
- ▶ Tony Menzo, et al, 2512.15867
- ▶ Tilman Plehn, Daniel Schiller, Nikita Schmal, 2601.21015
- ▶ parallel developments for agent for experiments

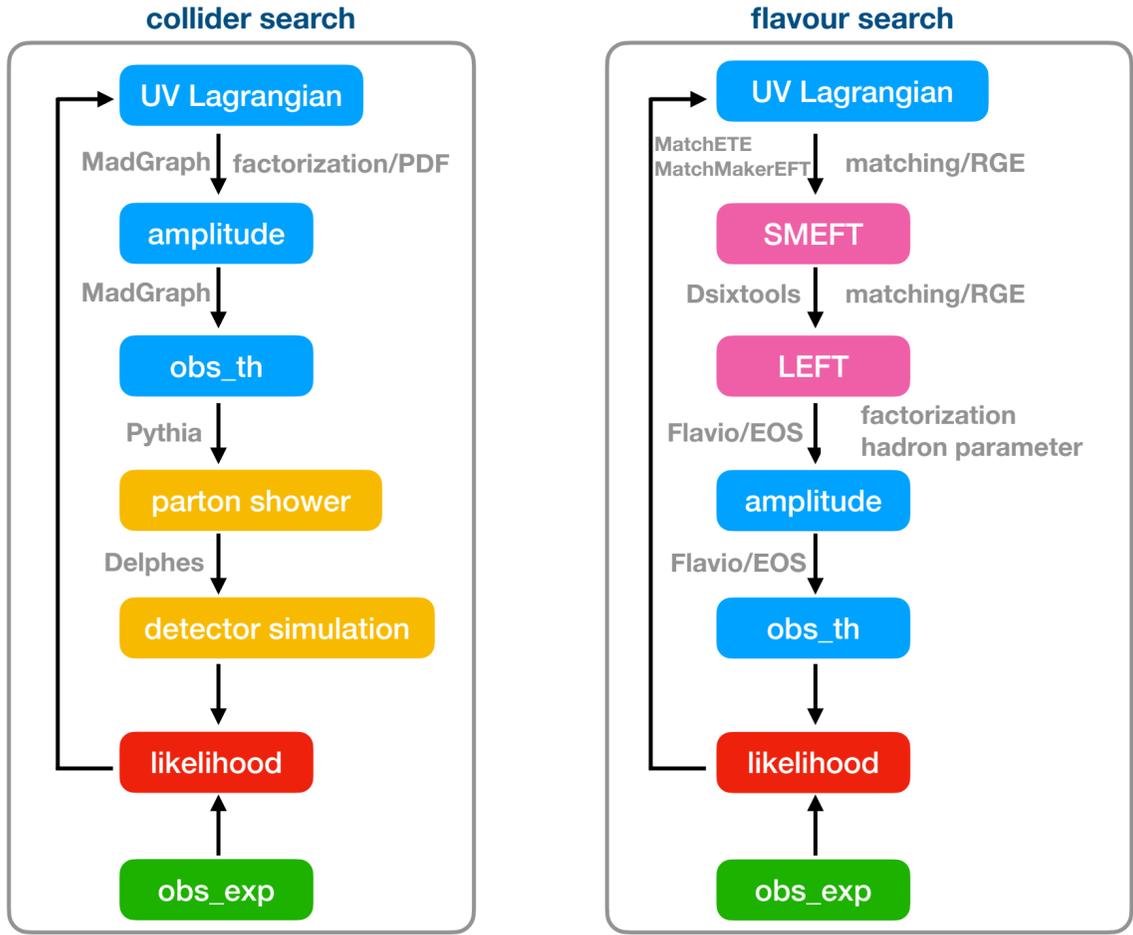
an active research field  
many open questions

## What can AI agent do ?

Status of Flavour Anomaly

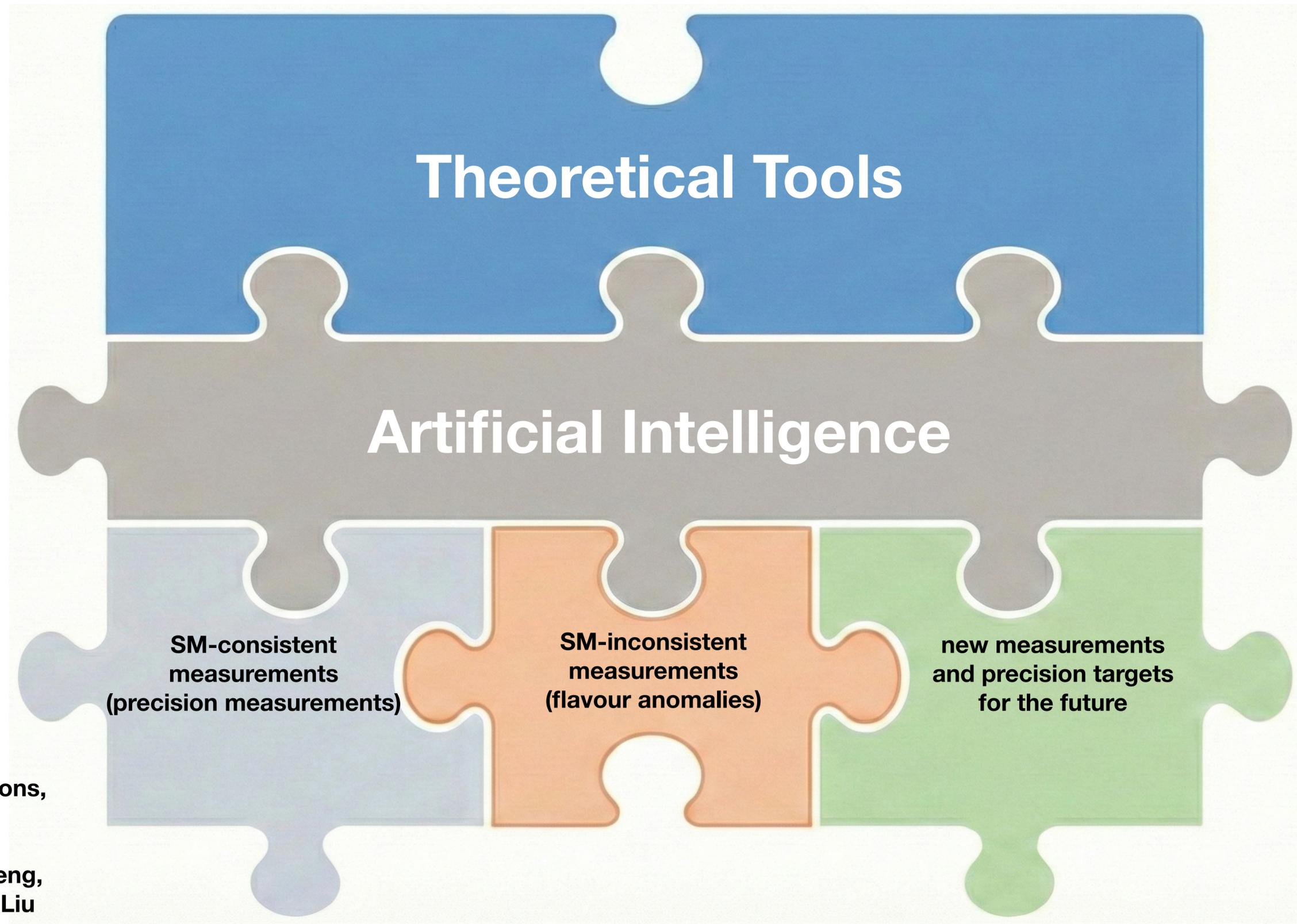


## AI Agent



global fit vs. global analysis (AI-assist)

# Conclusions



for theoretical calculations,  
see also talks by  
Wei Wang, Ying Li,  
Fu-Sheng Yu, Shan Cheng,  
Yi-Bo Yang, Zhaofeng Liu

谢谢!

# Backup