『理論屋さん, 正直なところどうなんですか? その2』

Precision measurement で探る新物理

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updated:
Moriond 2021,
FNAL muon g-2

高エネルギー将来計画委員会: 第9回 勉強会

2021年4月22日, オンライン

本日のテーマ：

1, メジャーなアノマリーの紹介

2, 示唆される新物理の紹介

updated:
Moriond 2021,
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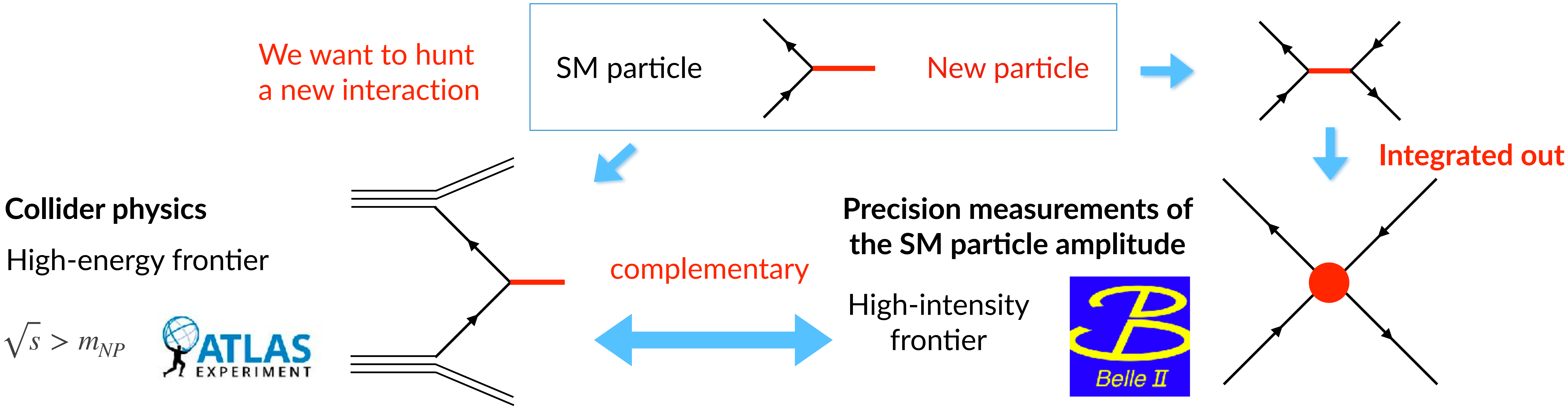
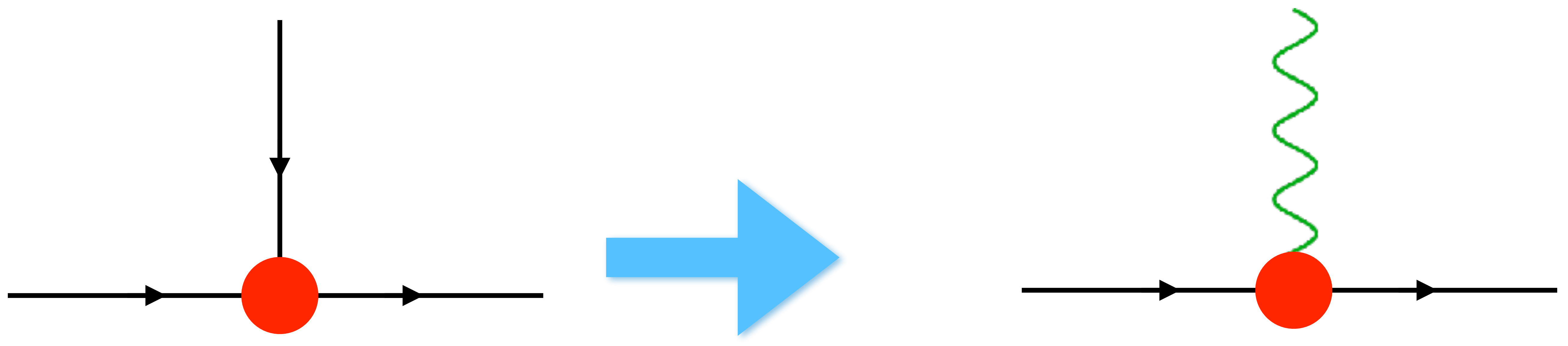
Introduction (1/3)

- The Standard Model (SM) is known to be an incomplete model that can not explain matter–antimatter asymmetry, dark matter, gauge hierarchy, quark mass hierarchy, neutrino mass, etc.
- Beyond the standard model (New Physics/NP) is, therefore, **required**

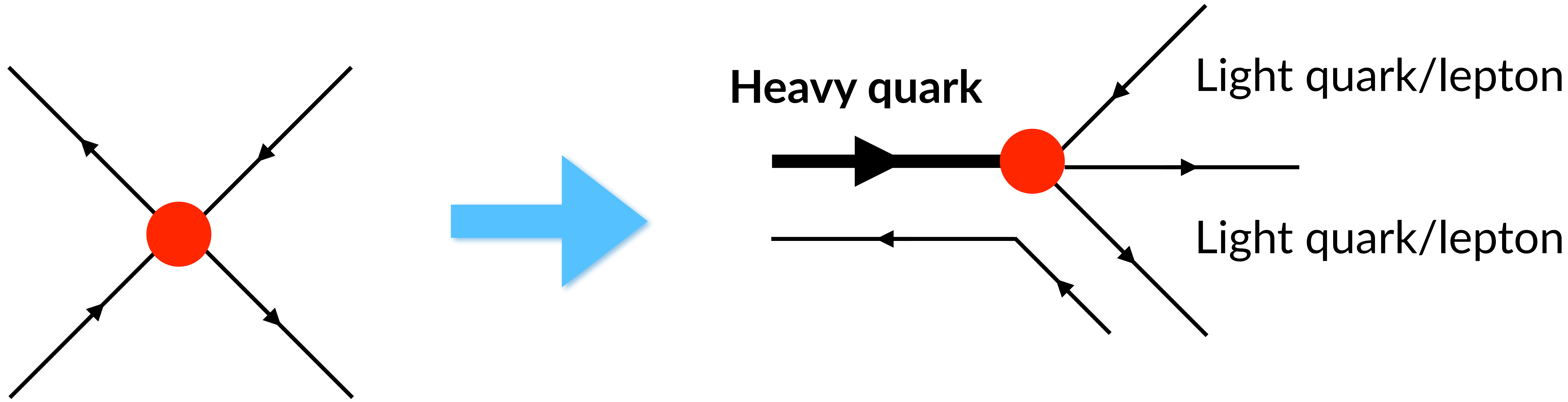


3-point amplitudes



Precision measurements of leptons

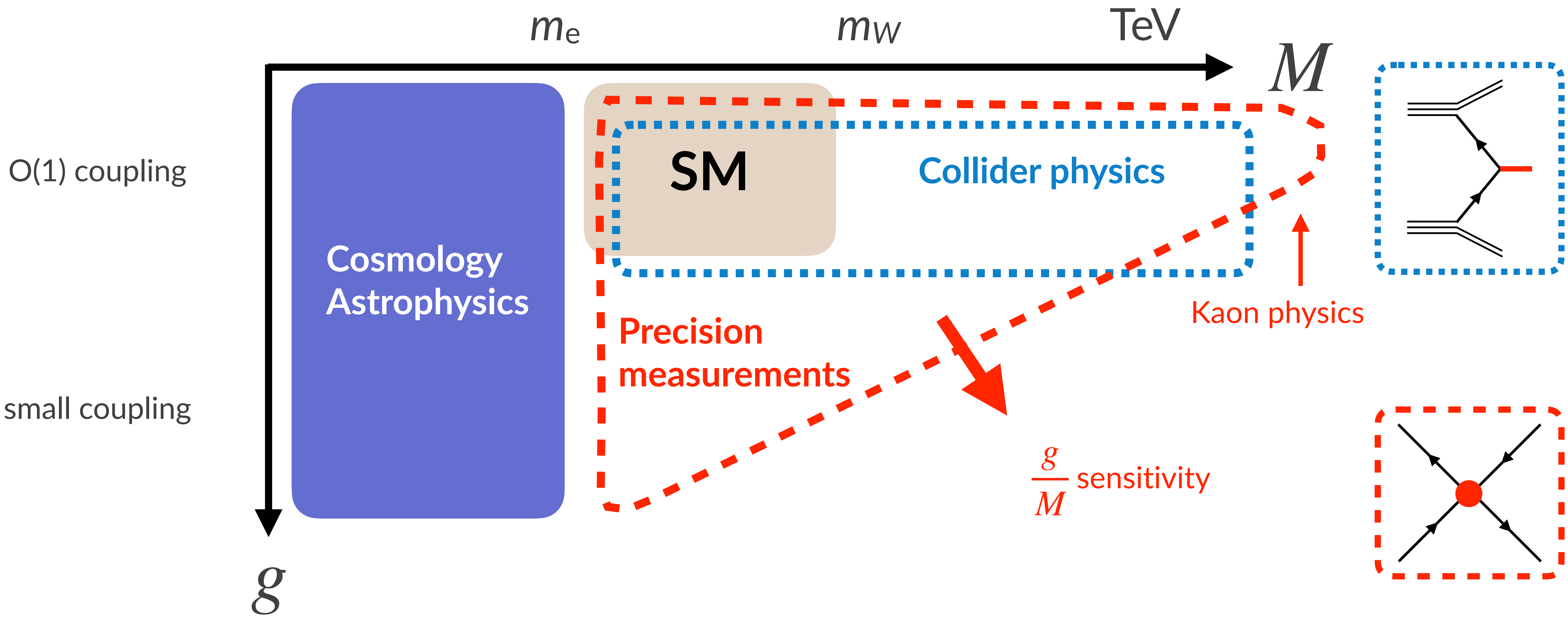
4-point amplitudes

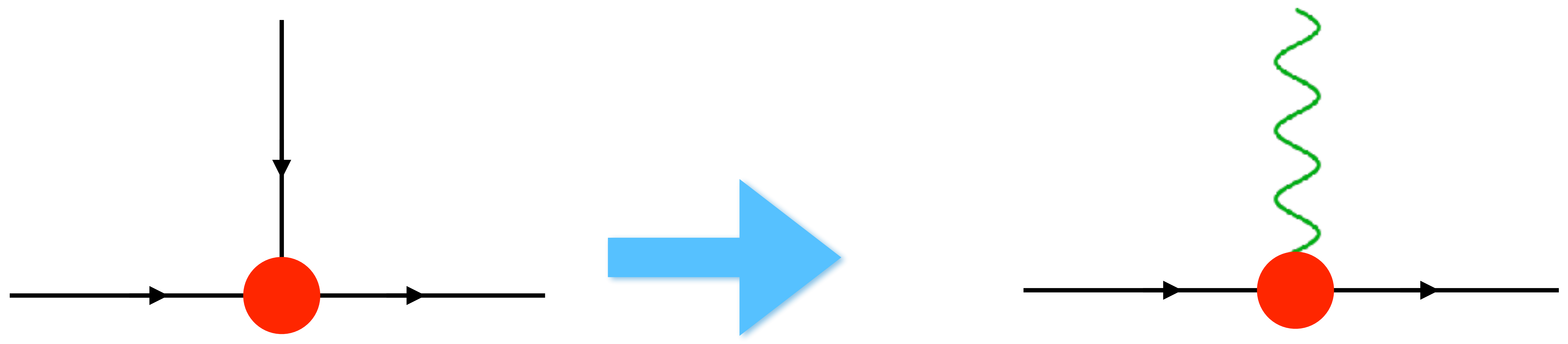


Precision measurements of flavor physics

Advantages:
Precise SM prediction (thanks to small QCD uncertainty, lattice QCD simulation, NN...LO calculations) provides great sensitivity to new physics

Introduction (3/3)



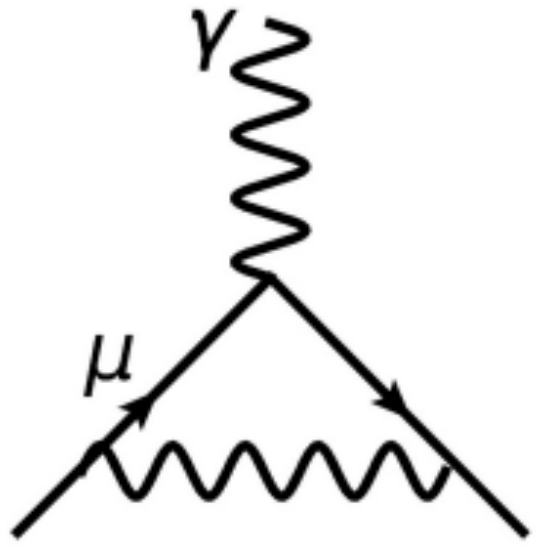


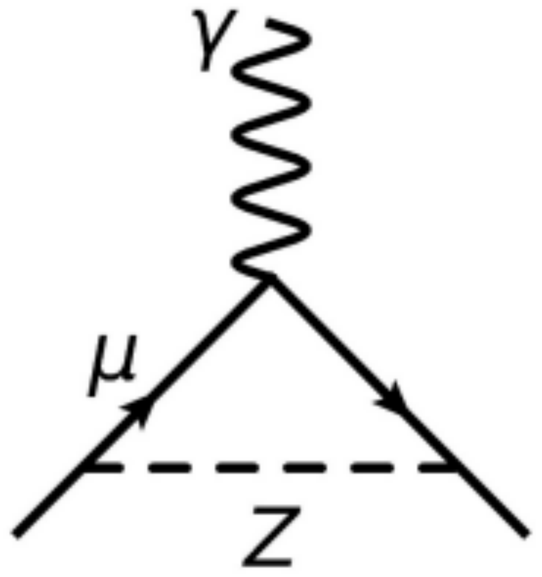
Precision measurements of leptons

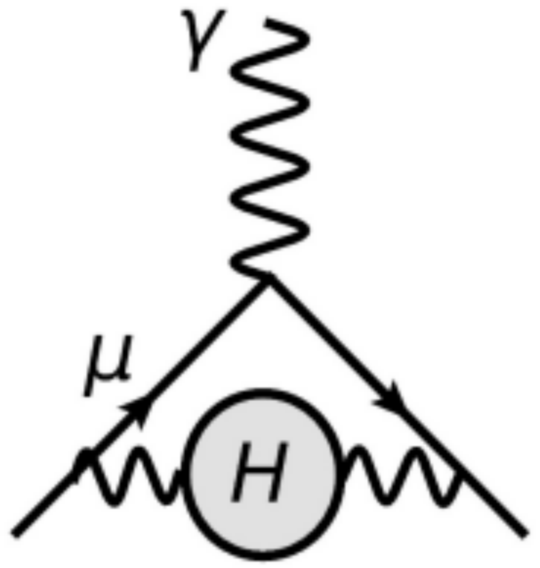
Muon g-2

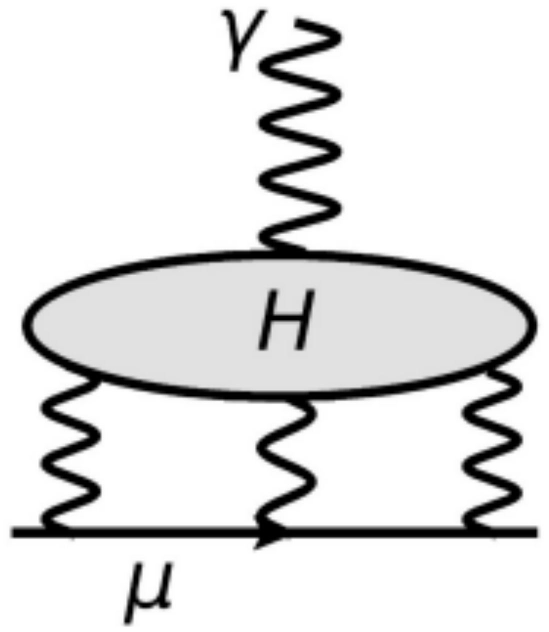
詳細は高エネ将来計画委員会: 第10回 勉強会
ミューオンで超える標準模型の壁 (三部さん)

Theory









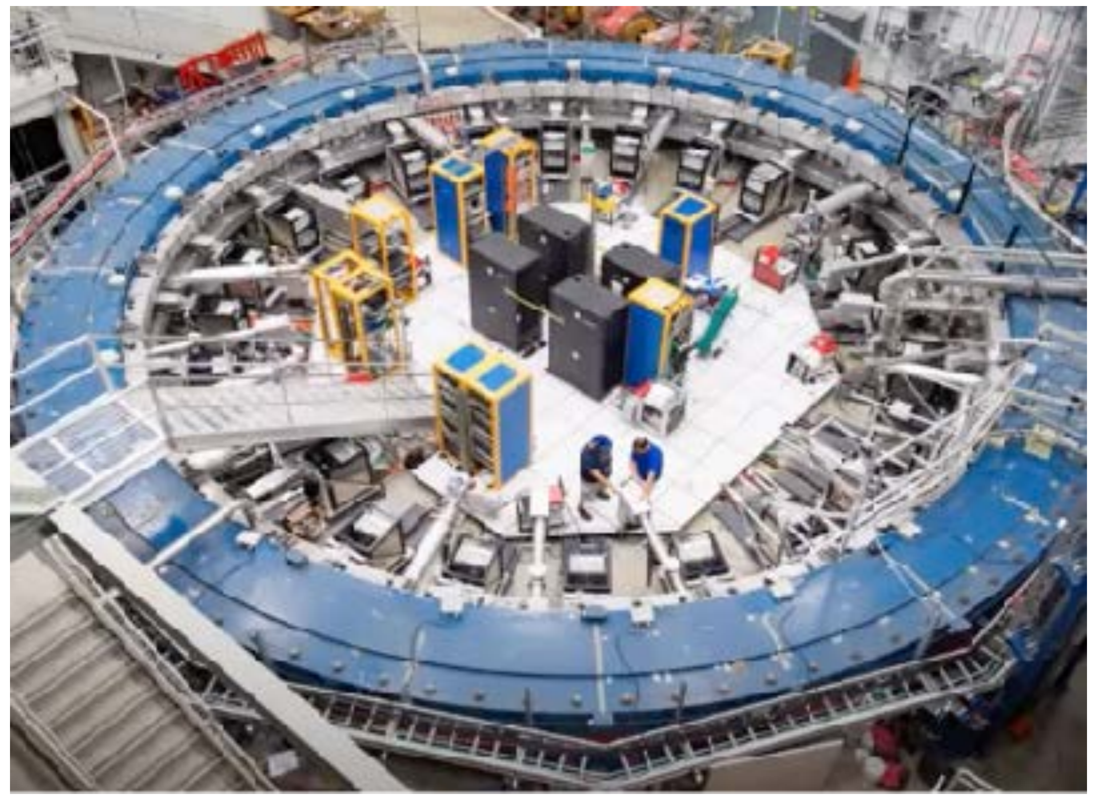
QED	EW	Hadronic vacuum polarization **(HVP)**	Hadronic light-by-light **(HLbL)**
		Phenomenological	Pheno.
Analytic	Analytic	Lattice	Lattice

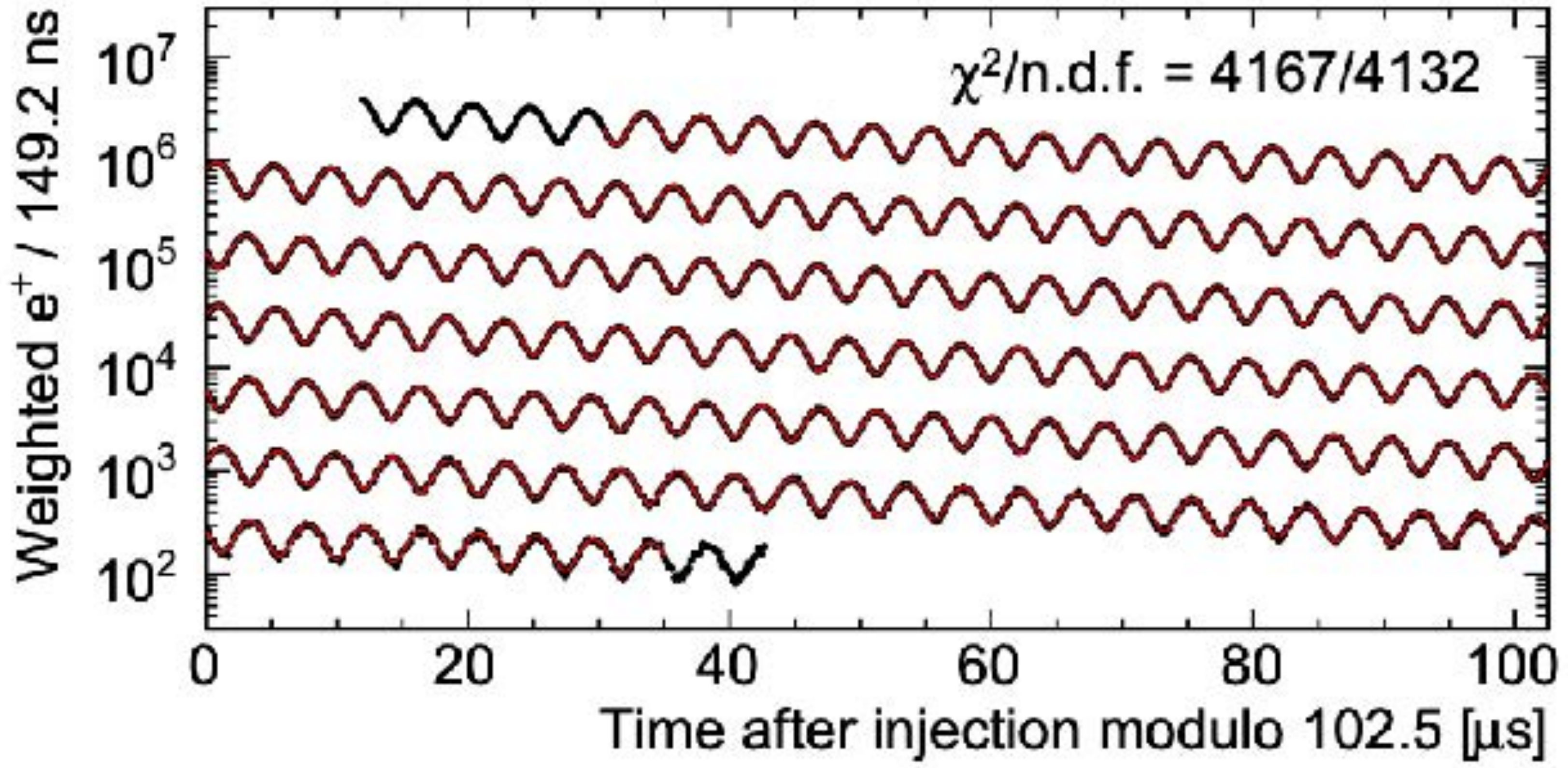
Exp.

BNL ’97-‘01

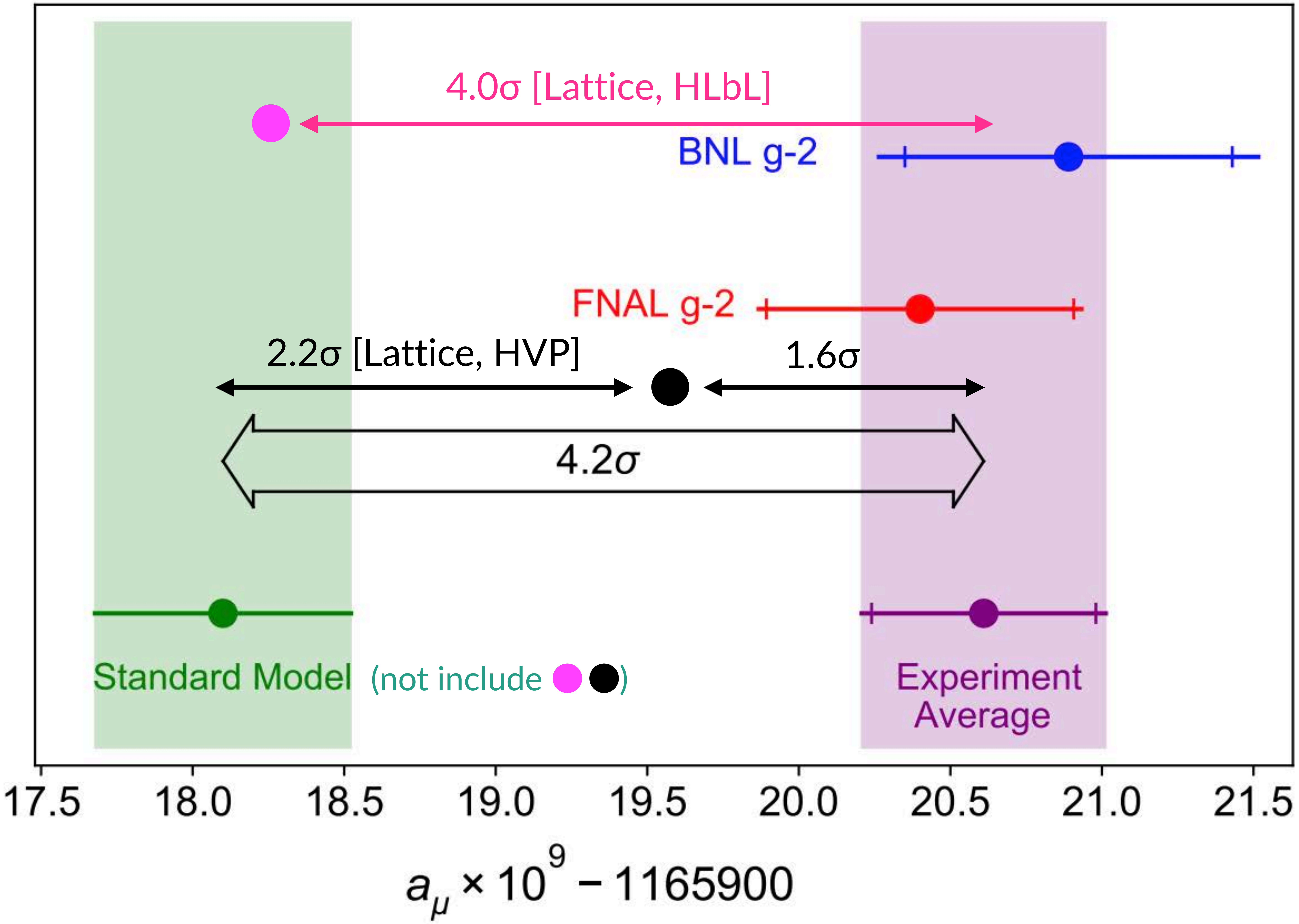
FNAL ongoing

J-PARC
near future





Based on [FNAL Muon g-2, PRL2021]



comments

Stat error dominated

Almost no correlation between BNL and FNAL syst errors

The latest lattice result for HLbL slightly reduces tension [Mainz group, 2104.02632]

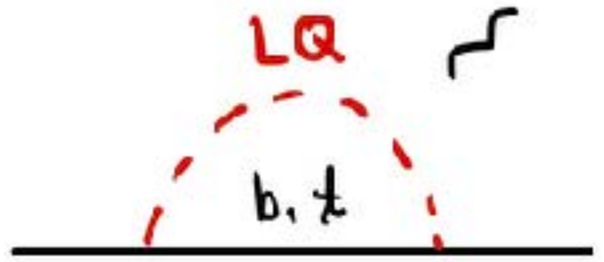
The latest lattice result for HVP significantly reduces tension [BMW, Nature '21]

Several analyses show that EW fit could be no problem, but there is additional tension in $e^+e^- \to 2\pi$ data, see e.g., [Colangelo et al, 2010.07943]

MUonE exp. will probe HVP [MUonE, 2004.13663]

New physics interpretations

[Refs: Athron et al, 2104.03691; Buen-Abad et al, 2104.03267; Krnjaic et al, 1902.07715; Dermisek et al, 2103.05645]

NP type	diagrams	mass range	probe
Supersymmtery		200〜500 GeV	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (h\tilde{\chi}_1^0)\,(W^\pm\tilde{\chi}_1^0)$ $pp \to \gamma\gamma \to \widetilde{\ell\ell^*}$
Scalar extensions		20〜100 GeV, 150〜250 GeV	$Z \to \tau^+\tau^-$ $h \to AA$
Axion-like particle		40 MeV〜6 GeV	$e^+e^- \to \gamma a, a \to \gamma\gamma$
Leptoquark		1.5〜2 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$
U(1) μ-τ		10〜200 MeV	$e^+e^- \to \mu^+\mu^- Z'$ $K^- \to \mu^-\bar{\nu}Z'$
Vector-like lepton		< 7 TeV	$h, Z \to \mu^+\mu^-$

SUSY example

[Endo, Hamaguchi, Iwamoto, TK, 2104.03217]

$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (h\tilde{\chi}_1^0)\,(W^\pm\tilde{\chi}_1^0)$

will be able to probe

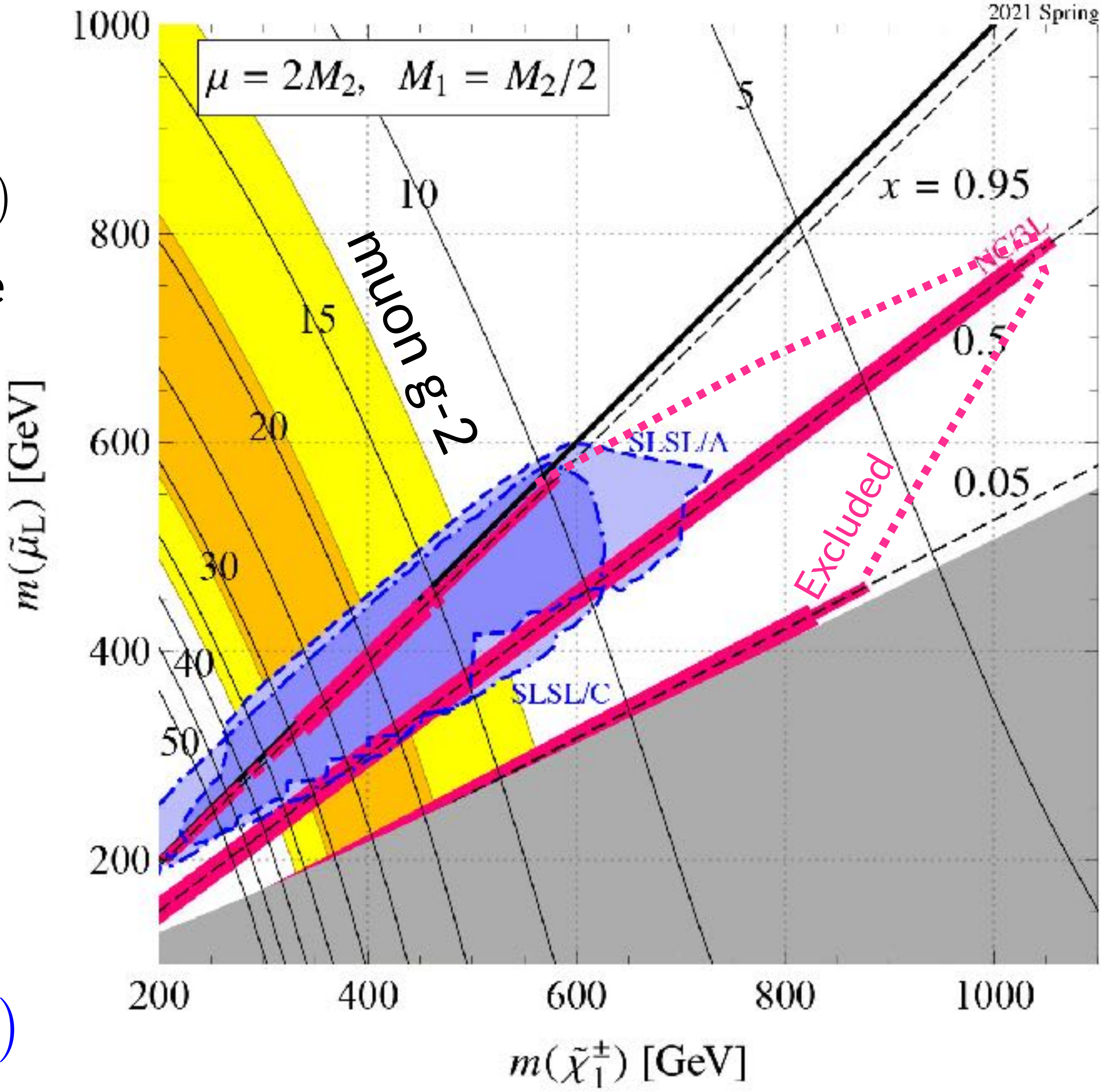
Point: $\tilde{W}^0$ decays into h not Z

strong bound from:

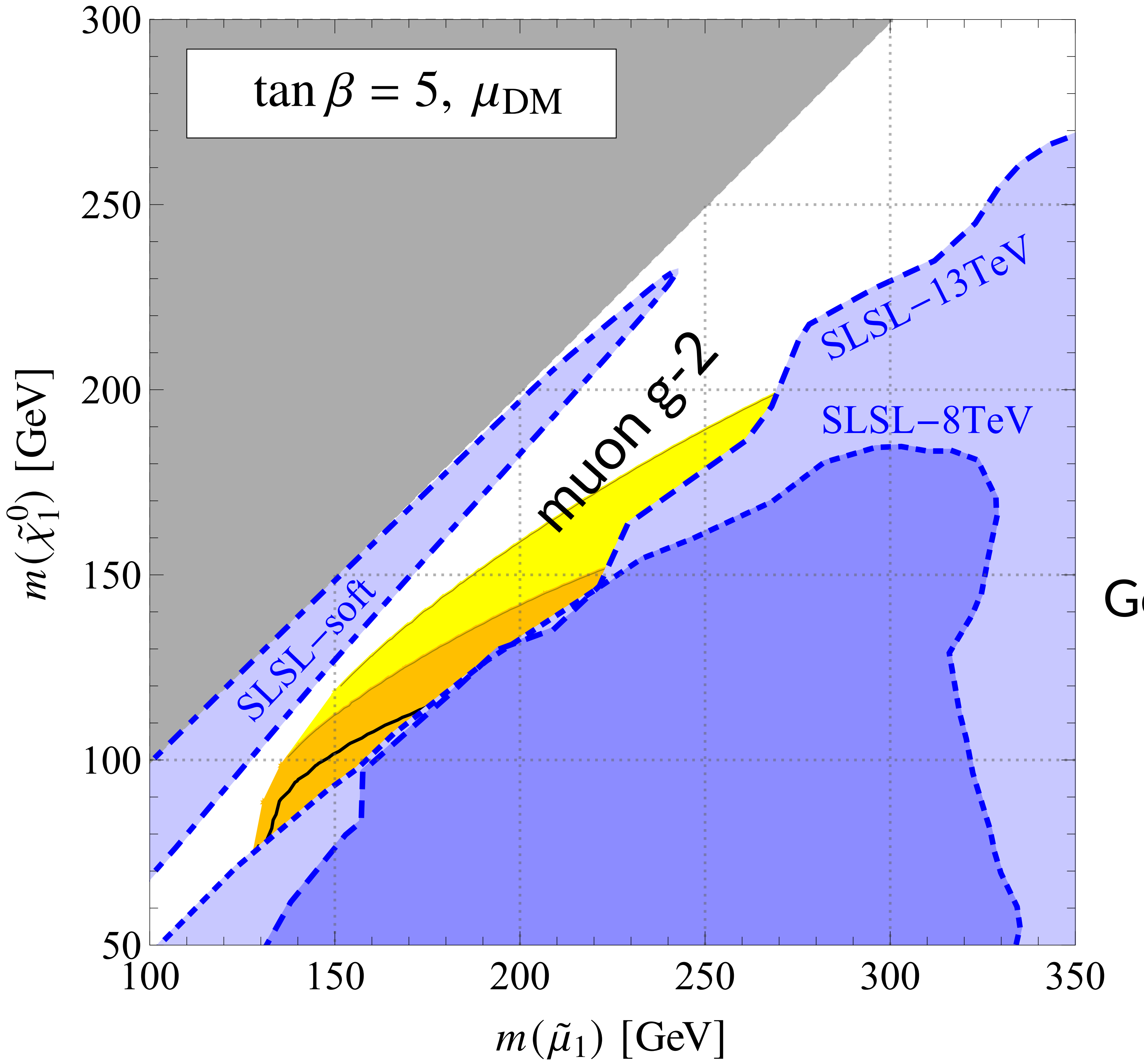
$\tilde{\ell}_L\tilde{\ell}_L^* \to (\ell\tilde{\chi}_1^0)\,(\bar{\ell}\tilde{\chi}_1^0)$

$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (\tilde{l}_L)\,(\nu\tilde{l}_L) \to (ll\tilde{\chi}_1^0)\,(\nu l\tilde{\chi}_1^0)$

chargino contribution



pure-bino contribution with correct Ω_{DM}

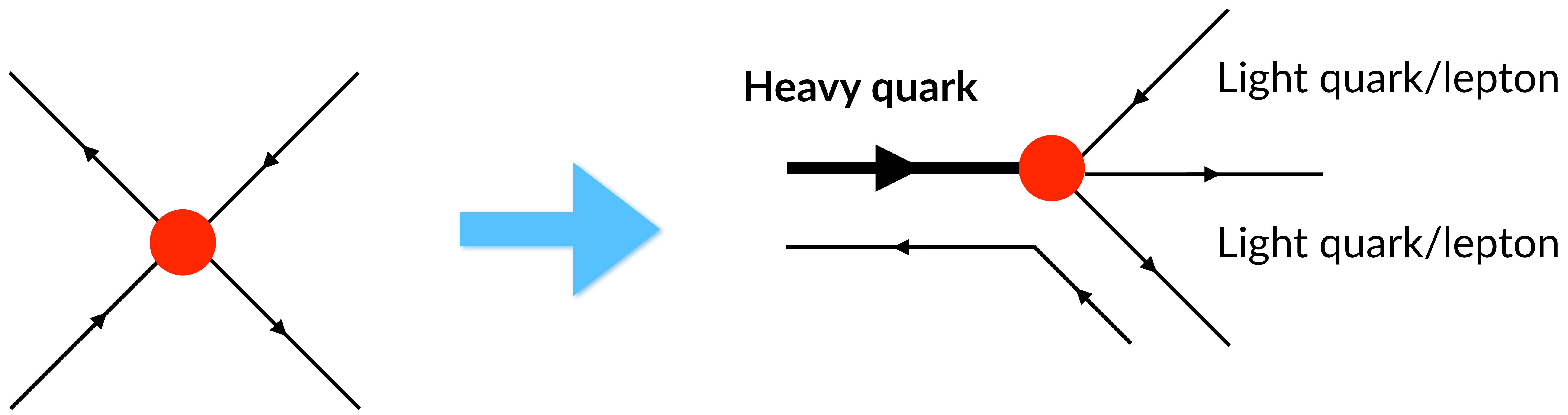


Low tanβ is preferred(!)

Good target for ILC

Photon collision $pp \to \gamma\gamma \to \tilde{\ell}\tilde{\ell}^* \to (\ell\tilde{\chi}_1^0)\,(\bar{\ell}\tilde{\chi}_1^0)$

will be able to probe [Beresford, Liu, PRL '19]

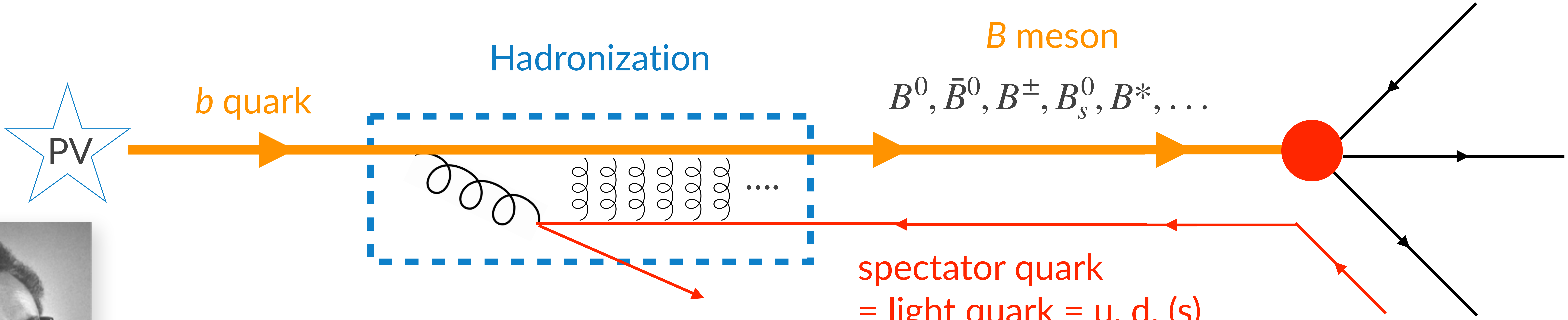


Precision measurements of flavor physics

What is flavor physics?

- Quarks can not become asymptotic field, but must be contained in hadron=meson or baryon

  b … *B* meson, *c* … *D* meson, *s* … *K* meson, or heavy baryons.



Gell-Mann named it "flavor" at an ice-cream store, just as ice-cream has both color and quark (cheese) flavor

Quark flavor physics means physics of meson/baryon transition;

$$B \to K + X(b \to s), D \to \pi + X(c \to u), K \to \pi + X(s \to d), \text{etc.}$$

http://www.wallcoo.net/

B physics

- **Main stream of the flavor physics.** There are three big experiments for B physics.
- Rich phenomenology; CKM, FCNC, CP violation, tau lepton, LFU, Hadron spectroscopy, dark sector

BaBar experiment @ **SLAC**, physics run was finished at 2008

$e^+e^- \to \Upsilon \to B\bar{B}$ $10^8 B\bar{B}$ per year

Belle and Belle II experiments @ **KEK**, Belle II started at 2019

$e^+e^- \to \Upsilon \to B\bar{B}$ $10^{10} B\bar{B}$ per year

LHCb experiment @ **CERN**, Run 1 and 2 were done, Run 3 will start at **2022**

$pp \to b\bar{b} \to B\bar{B}$ $10^{12} b\bar{b}$ per year

CKM matrix

- CKM matrix arises the relative misalignment between the Yukawa matrices and gauge interactions:

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\bar{u}^i_L \gamma^\mu d^i_L W^+_\mu \xrightarrow{\text{mass-eigenbasis}} -\frac{g}{\sqrt{2}}\bar{u}^i_L \gamma^\mu (U_u^\dagger U_d)^{ij} d^j_L W^+_\mu$$
$$= -\frac{g}{\sqrt{2}}\bar{u}^i_L \gamma^\mu V^{ij}_{\text{CKM}} d^j_L W^+_\mu$$

- Wolfenstein parametrization

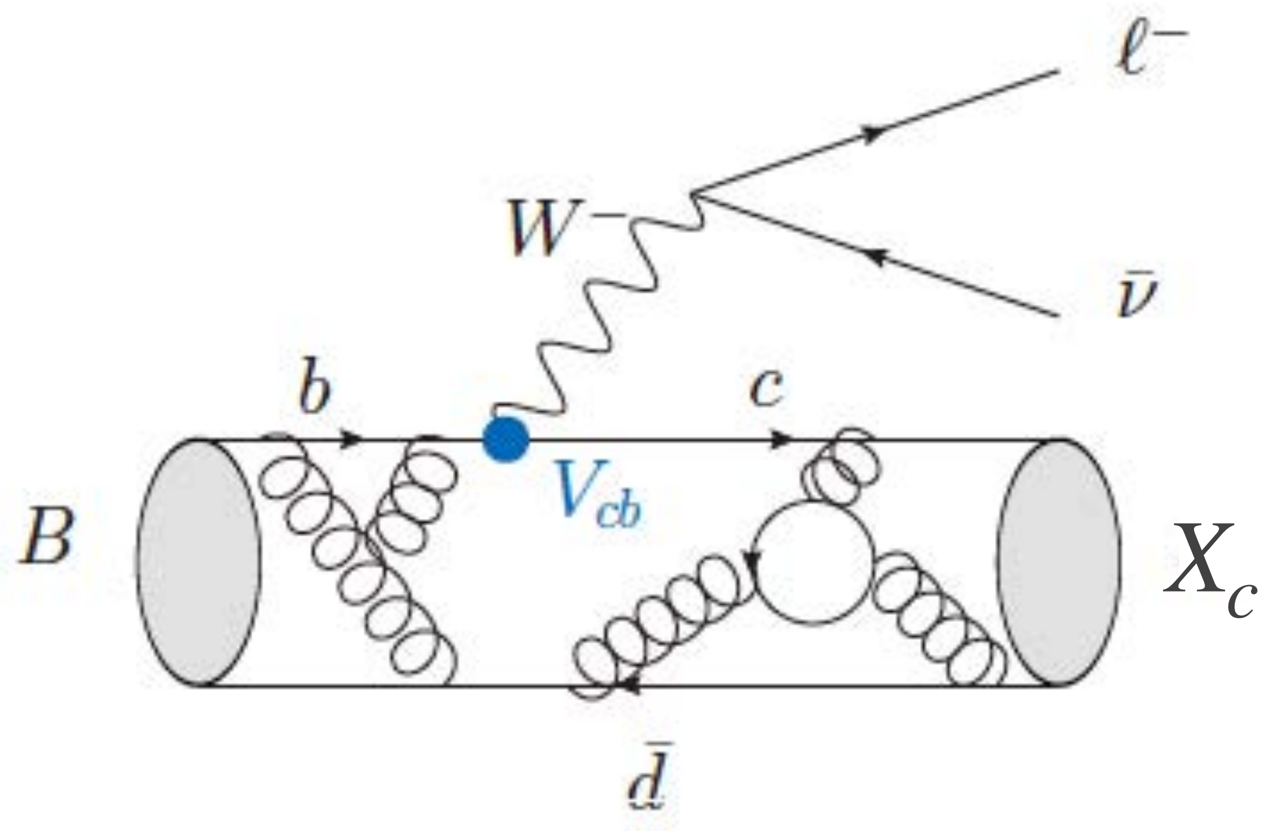
K physics B physics

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Parameter A is determined by B physics

Measurements of |V$_{cb}$|

- For determination of |V$_{cb}$|, one measures branching ratios of *B*-meson semileptonic decay modes, and compare TH



Semileptonic mode $\ell = e, \mu$

Hadron states X_c (=*D***, *D**, *D*, *Dπ*, *Dππ*...)

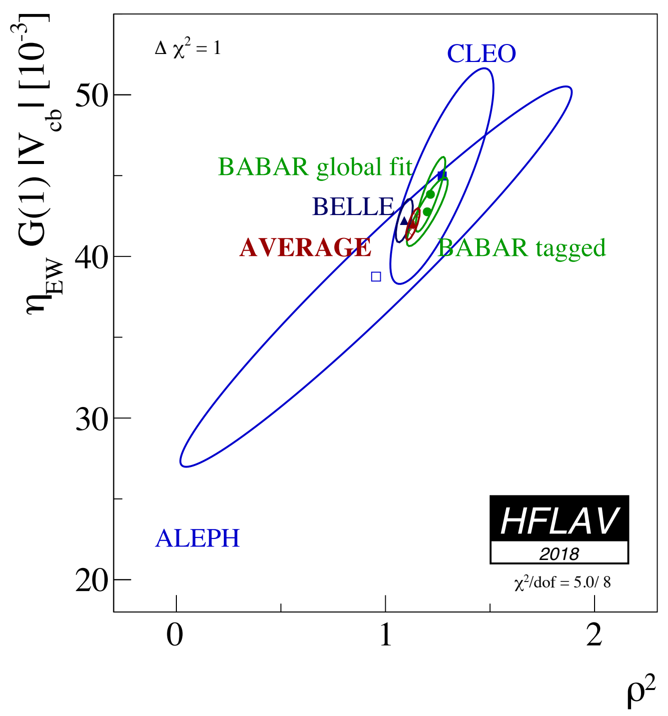
- Inclusive decays: $B \to X_c \ell \nu$
  - It corresponds to quark level decay rate ($b \to c\ell\nu$) + α_s, $\Lambda_{\rm QCD}/m_b$ corrections
  - Last data in 2010 → Belle II result coming soon; No lattice → the first lattice study [Gambino, Hashimoto, PRL '20]
- Exclusive decays: $B \to D\ell\nu, B \to D^*\ell\nu$
  - Many data with different schemes. One can use lattice simulations.

~3σ tension between inclusive vs. exclusive determinations of V_{cb} and V_{ub}

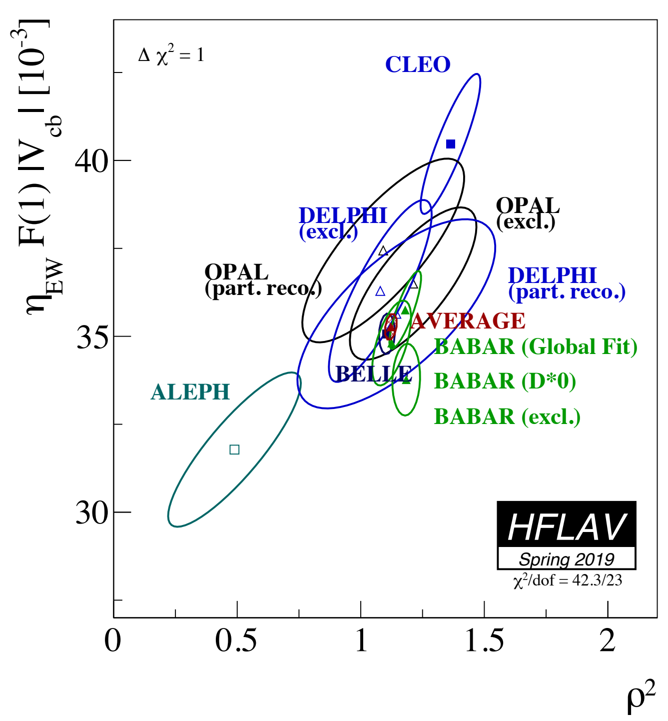
NP interpretation is difficult [Iguro, Watanabe, 2004.10208]

[HFLAV averages 2019, based on CLN]

$B \to D\ell\nu$



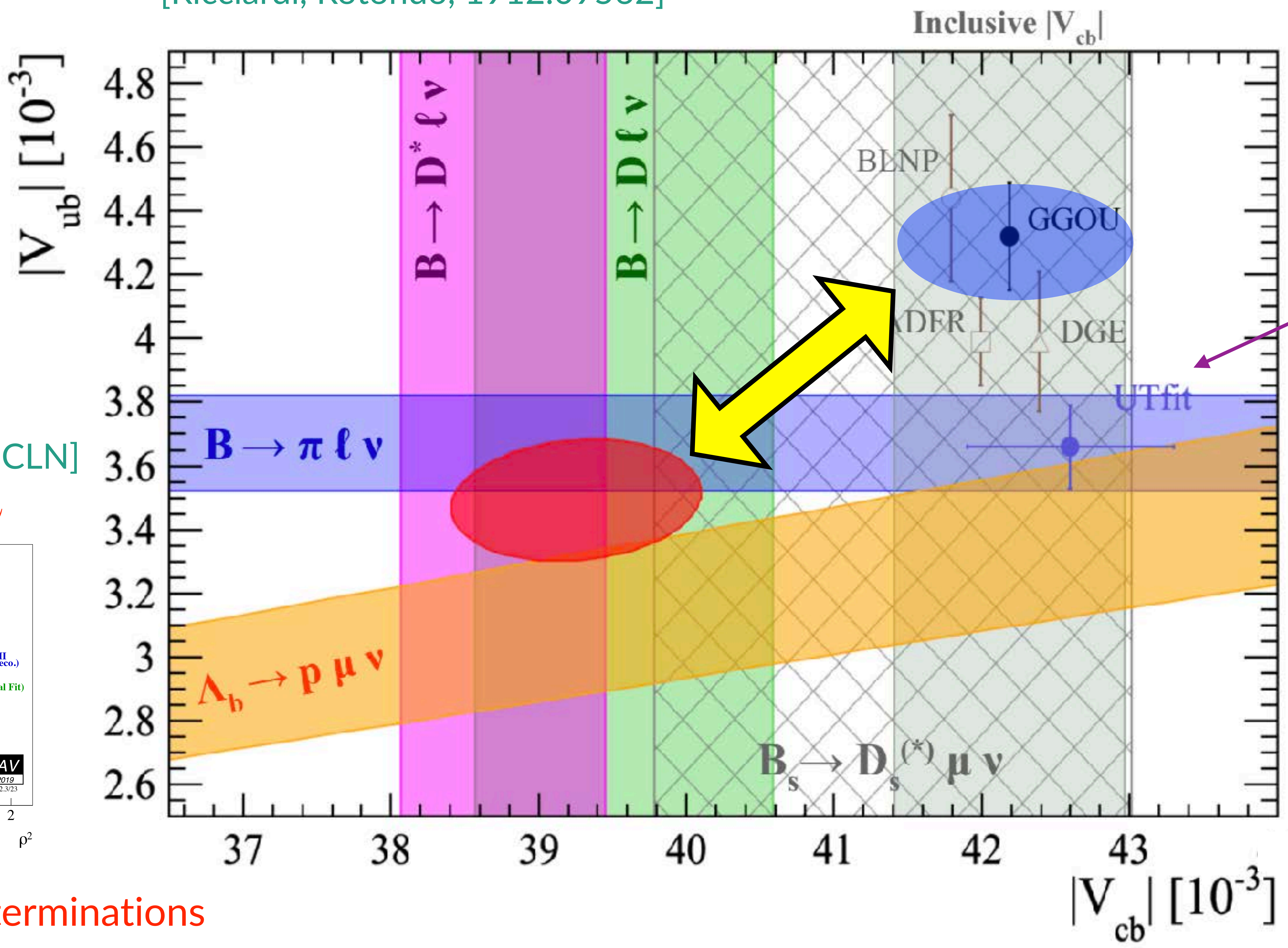
$B \to D^*\ell\nu$



Average of the exclusive determinations

Average of the inclusive determinations

[Ricciardi, Rotondo, 1912.09562]



CKM unitarity

Kaon physics prefers inclusive V_{cb}

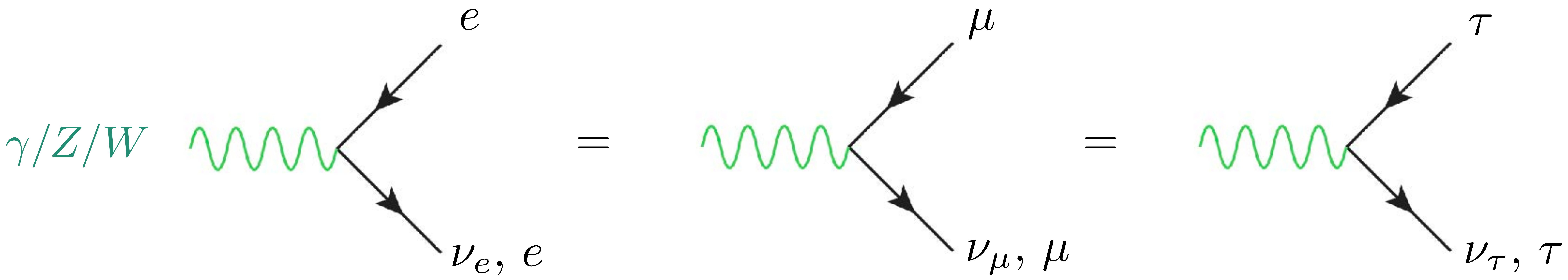
(→ page 36)

Belle II preliminary result [Moriond2021]

Inclusive Vcb = 41.7 (12) x 10^{-3}

Lepton flavor universality (LFU)

- Gauge symmetry predicts lepton flavor universal phenomena

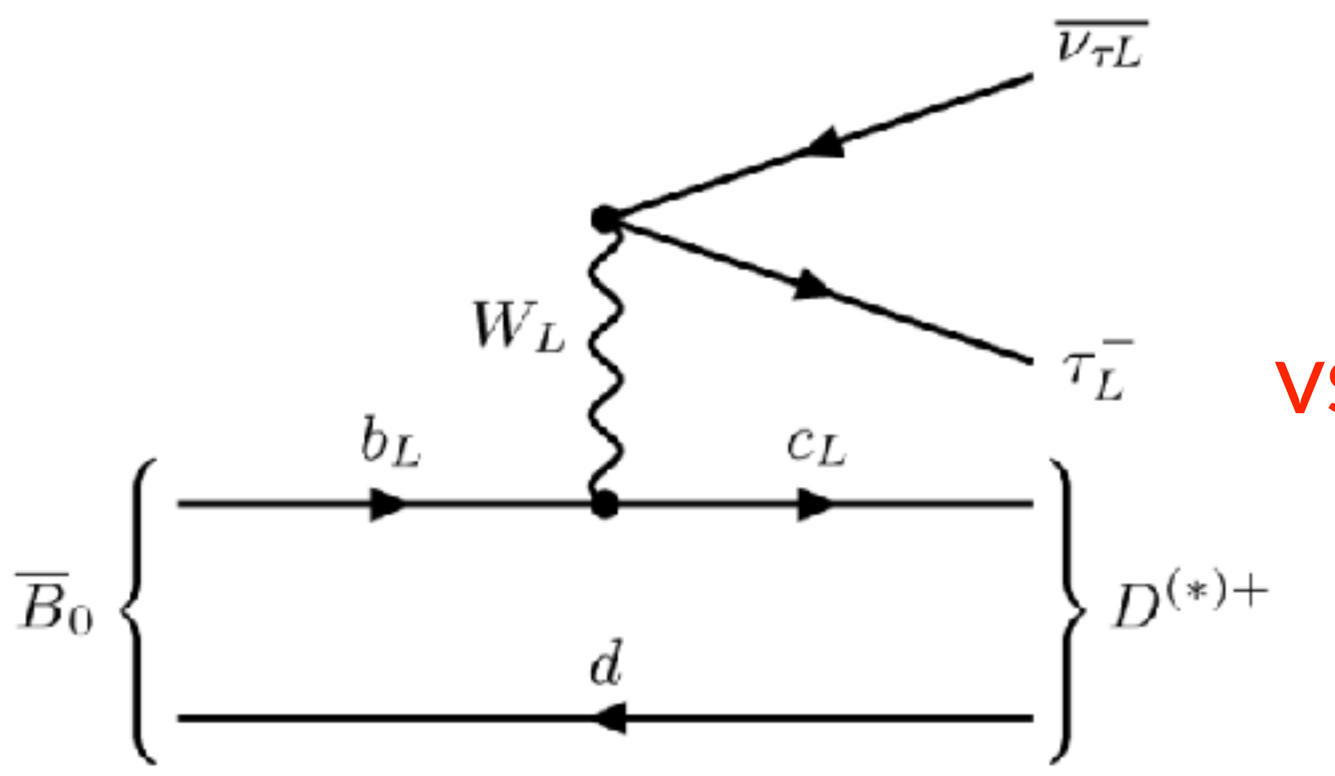


- **Charged lepton mass** changes **kinematics** and modifies **scalar form factors in the hadronization**, which eventually violates the lepton flavor universality
- Long-distance QED correction (beyond PHOTOS) could violate the lepton flavor universality [de Boer, TK, Nisandzic, PRL '18; Isidori, Nabeebaccus, Zwicky, '20]

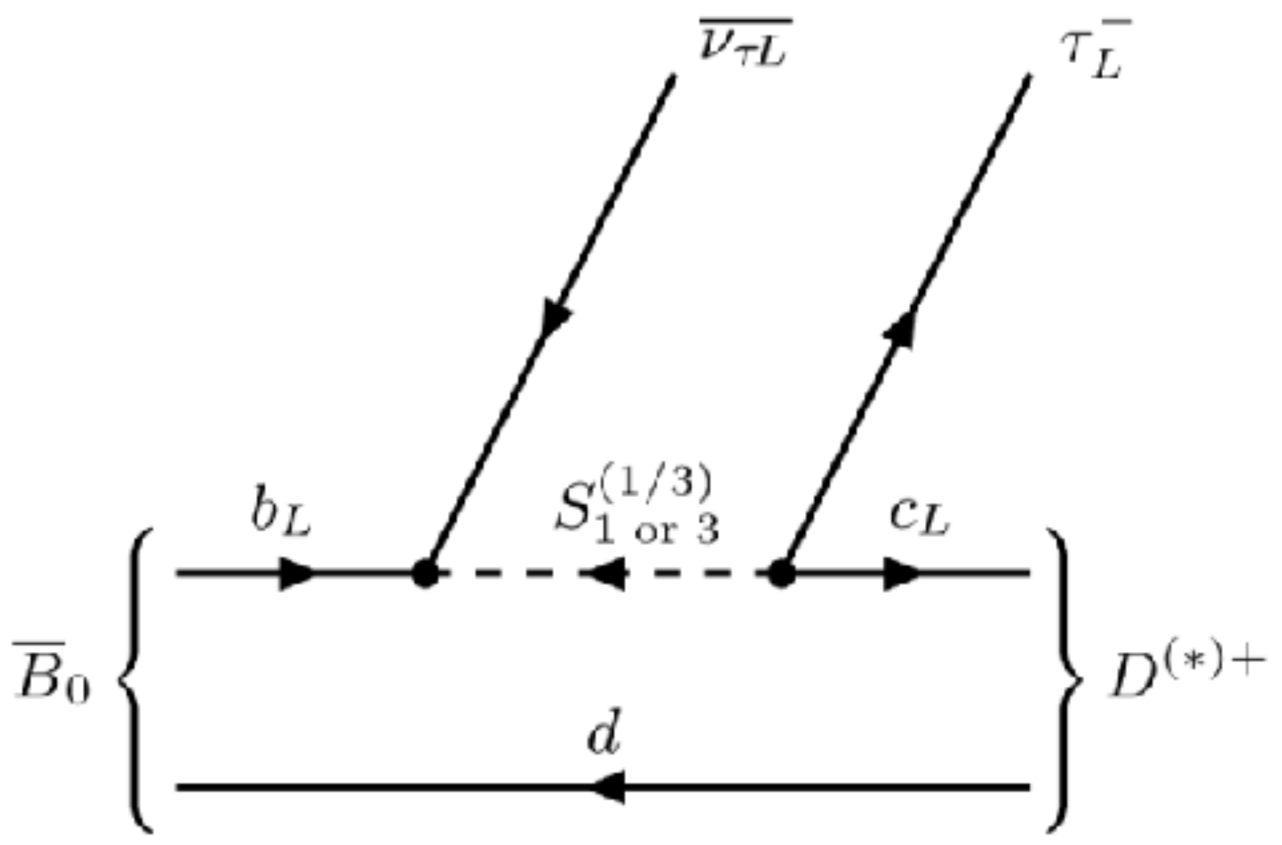
LFU observable *R*(*D*)

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\bar{\tau}\nu_\tau)}{\mathrm{BR}(B \to D^{(*)}\bar{\ell}\nu_\ell)}$$

V_{cb} dependence is dropped



vs.



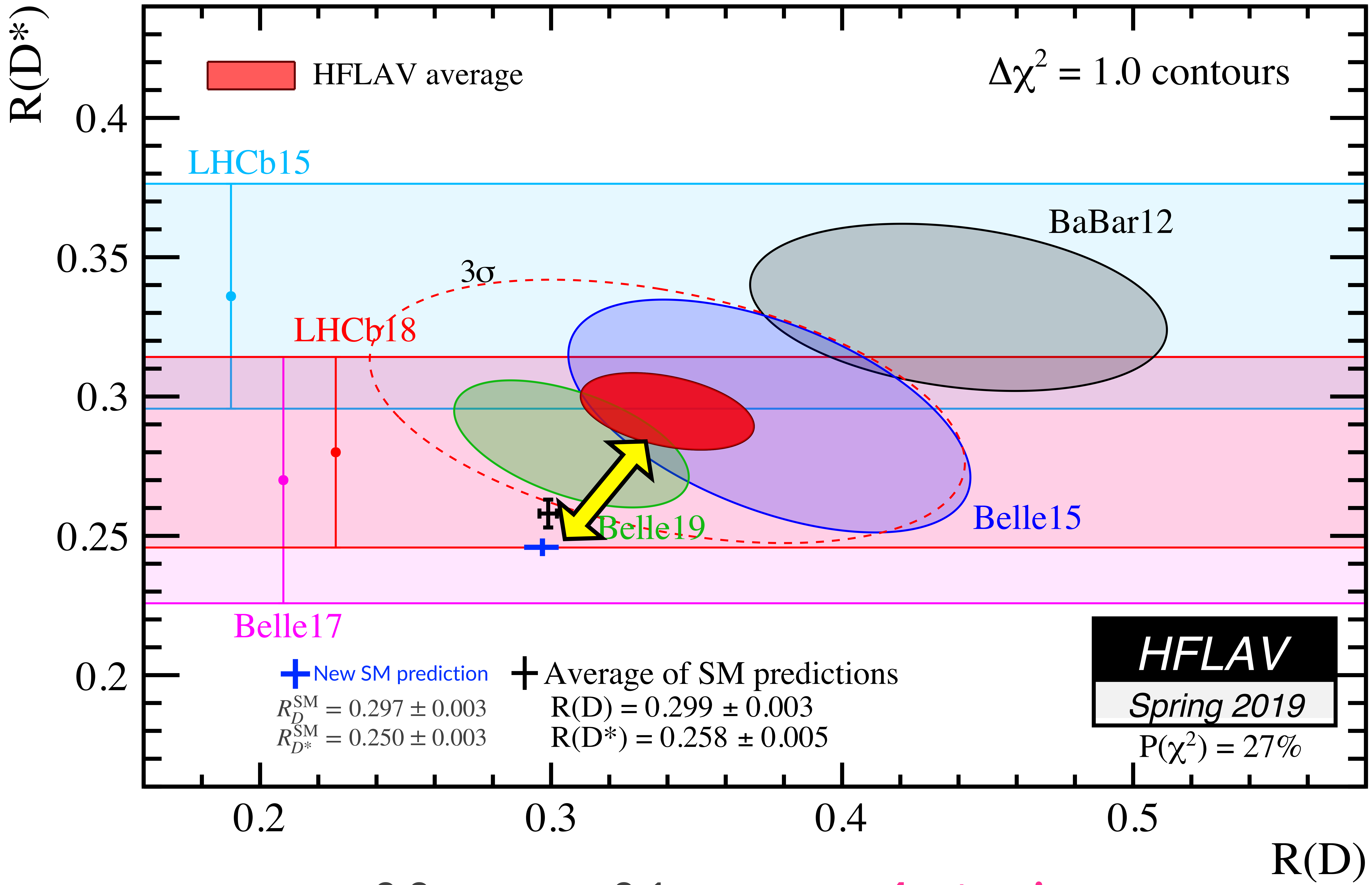
SM

NP, *e.g.*, Leptoquark

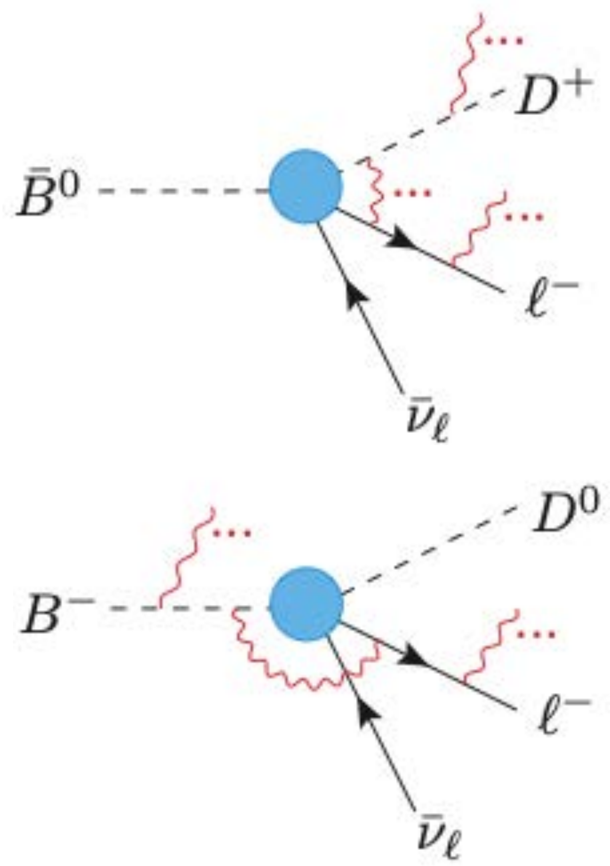
$\mathcal{B}(B \to D\ell\nu) = 2\%,\ \mathcal{B}(B \to D^*\ell\nu) = 5\%,$

[HFLAV averages 2019]

Average of the experimental data



Soft-photon QED corrections could change these tensions



It was shown that the QED correction violates LFU at a few % level

[de Boer, TK, Nisandzic, PRL ’18]

3.8 σ →→→ 3.1 σ →→→ **~ 4 σ tension**

New Belle data ‘19 New SM ‘20 [Bordone, Jung, van Dyk, ’20; Iguro Watanabe, ‘20]

EFT global fit [Blanke, Crivellin, TK, Moscati, Nierste, Nisandzic, '19]

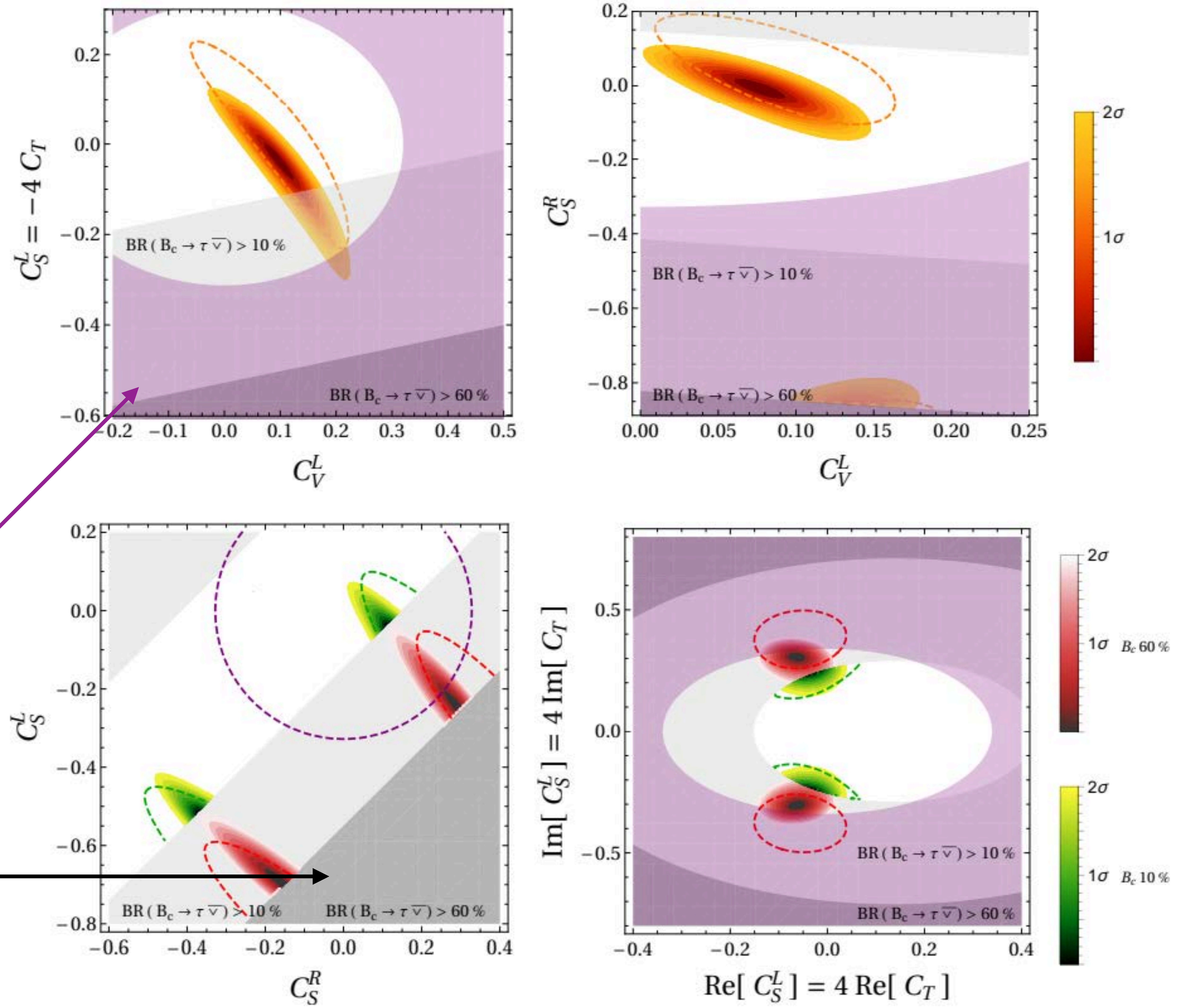
- Relevant effective Hamiltonian

$$\mathcal{H}_{\rm eff} = 2\sqrt{2}G_F V_{cb}\big[(1+C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\big]\,,$$

$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$
$$O_S^R = (\bar{c}P_R b)\,(\bar{\tau}P_L \nu_\tau)$$
$$O_S^L = (\bar{c}P_L b)\,(\bar{\tau}P_L \nu_\tau)$$
$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$

- Collider bound (→page 26)
- Bound from BR($B_c^+ \to \tau^+\nu$) < 60%

10% bound is too stringent



“Single particle” interpretations

- One WC scenarios

C_V^L	W', SU(2)$_L$-singlet vector LQ, SU(2)$_L$-triplet and/or -singlet scalar LQ
C_S^R	Charged Higgs, SU(2)$_L$-doublet vector LQ (V_2)
C_S^L	Charged Higgs with generic flavour structure
$C_S^L = 4C_T$	scalar SU(2)$_L$-doublet LQ (R_2) (“4” is modified by RG evolution)

- Two WCs scenarios

$(C_V^L, C_S^L = -4C_T)$	SU(2)$_L$-singlet scalar LQ (S_1)
(C_V^L, C_S^R)	SU(2)$_L$-singlet vector LQ (U_1)
(C_S^R, C_S^L)	Charged Higgs with generic flavour structure
(Re[$C_S^L = 4C_T$], Im[$C_S^L = 4C_T$])	scalar SU(2)$_L$-doublet LQ (R_2)

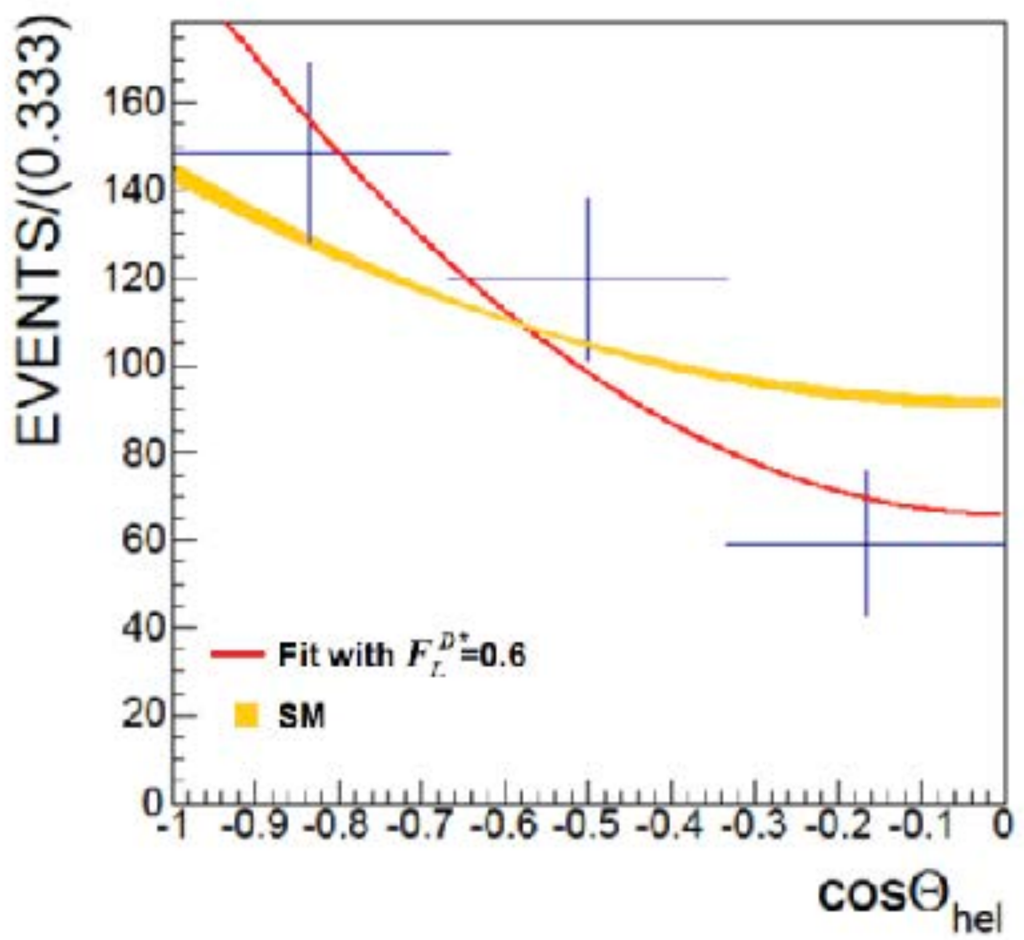
- There are so many detailed studies for **each** single particle scenarios
- There are also “two LQs” scenarios

Polarization observables in $b \to c\tau\nu$

- The following two polarization observables could be important to confirm/distinguish new physics
  - Longitudinal D^* polarization ($D^* \to D\pi$)

$$F_L(D^*) = \frac{\Gamma(B \to D_L^* \tau\nu)}{\Gamma(B \to D^* \tau\nu)}$$

θ_{hel} is the angle between D and B in the D^* rest frame



[Belle, 1903.03102]

1.4 σ consistent

  - τ polarization asymmetry along the longitudinal directions of τ ($\tau \to \pi\nu,\ \rho\nu$) [Tanaka, ZPC ’95]

$$P_\tau(D^{(*)}) = \frac{\Gamma\left(B \to D^{(*)}\tau^{\lambda=+1/2}\nu\right) - \Gamma\left(B \to D^{(*)}\tau^{\lambda=-1/2}\nu\right)}{\Gamma\left(B \to D^{(*)}\tau\nu\right)}$$

Fit of angle dependence: between π, ρ and $W^*(\tau\nu)$ in τ rest frame

Predicted ranges of polarization observables

- Full parameter searches of each LQ model, including LHC mono-τ bound and $\mathrm{BR}(B_c^+ \to \tau^+\nu) < 30\,\%$

  [Greljo, Martin Camalich, Ruiz-Alvarez, PRL '19; Alonso, Grinstein, Martin Camalich, PRL '17]

[Iguro, TK, Omura, Watanabe, Yamamoto, '19, **UPDATED**]

[Predicted ranges]

	$F_L^{D^*}$	P_τ^D	$P_\tau^{D^*}$	R_D	R_{D^*}
R_2 LQ	[0.442, 0.447]	[0.336, 0.456]	[−0.464, −0.424]	$1\,\sigma$ data	$1\,\sigma$ data
S_1 LQ	[0.436, 0.481]	[−0.006, 0.489]	[−0.512, −0.450]	$1\,\sigma$ data	$1\,\sigma$ data
U_1 LQ	[0.440, 0.459]	[0.156, 0.422]	[−0.542, −0.488]	$1\,\sigma$ data	$1\,\sigma$ data
SM	0.46(4)	0.325(9)	−0.497(13)	0.299(3)	0.258(5)
data	0.60(9)	-	−0.38(55)	**0.340(30)**	**0.295(14)**
(50 ab^{-1}) Belle II	0.04	3%	0.07	3%	2%

- $P_\tau(D)$ can discriminate the new physics

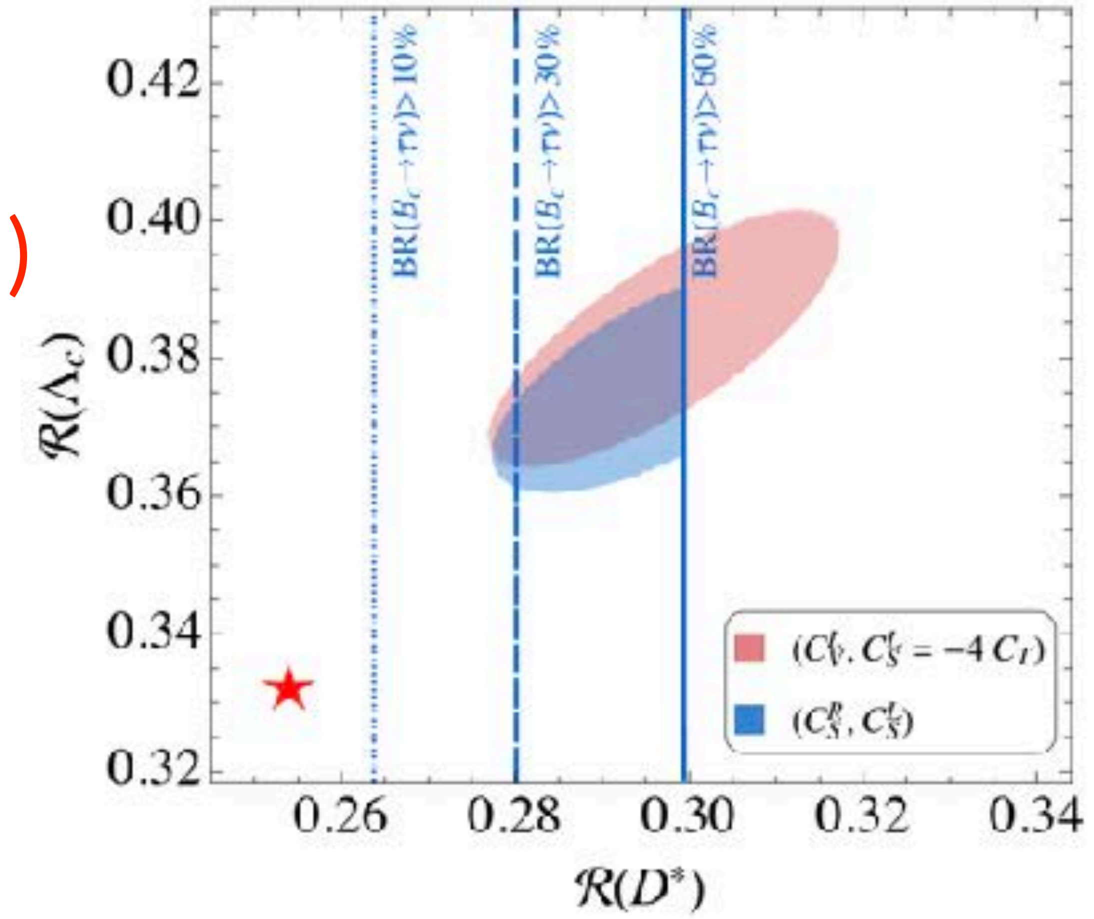
- LHC mono-τ search gives more severe bound than $\mathrm{BR}(B_c^+ \to \tau^+\nu) < 30\,\%$

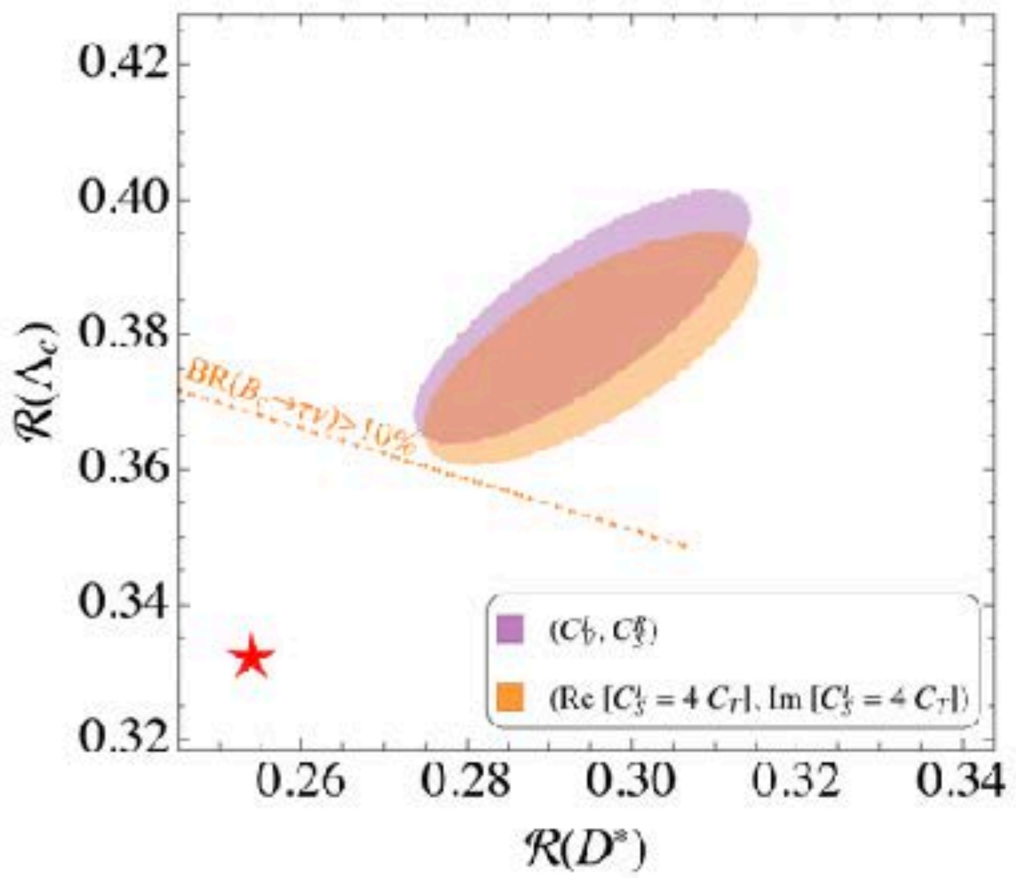
Model-independent prediction: $R(\Lambda_c)$

- Baryonic counterpart: $\mathcal{R}(\Lambda_c) = \dfrac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_\ell)}$ @ LHCb [Bernlochner, Liegt, Robinson, Sutcliffe, PRL '18]

SU(2)$_L$-singlet scalar LQ (S_1)

Charged Higgs





SU(2)$_L$-singlet vector LQ (U_1)

SU(2)$_L$-doublet scalar LQ (R_2)

Similar ellipses!

- Sum rule for $R(\Lambda_c)$ prediction from the form factor analysis

Model-independent sum rule
(also valid for RH neutrino scenarios)

$$\frac{R(\Lambda_c)}{R(\Lambda_c)_{\rm SM}} \simeq 0.26 \frac{R(D)}{R(D)_{\rm SM}} + 0.74 \frac{R(D^*)}{R(D^*)_{\rm SM}}$$

Crosscheck of $R(D^{(*)})$ anomaly is possible by $R(\Lambda_c)$

$$R(\Lambda_c) = 0.38 \pm 0.01_{R(D^{(*)})} \pm 0.01_{\rm FF}$$

$$R(\Lambda_c)_{\rm SM} = 0.324 \pm 0.004$$

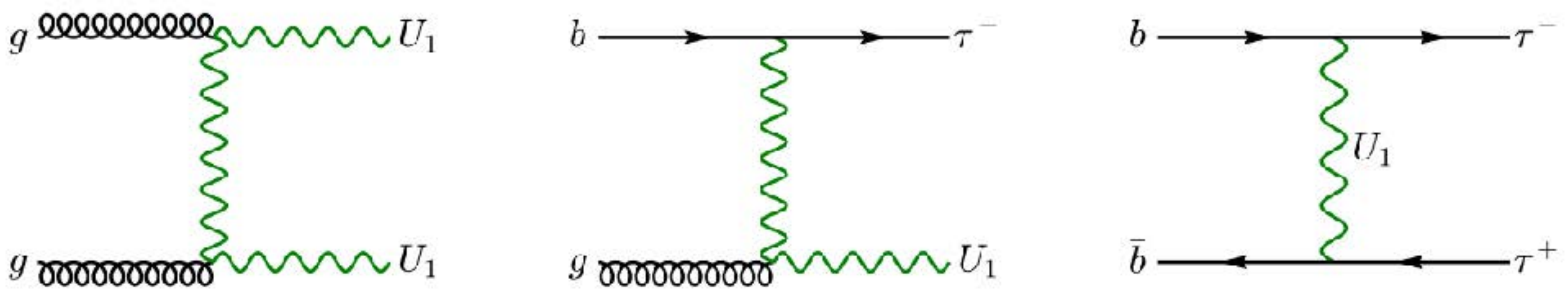
There is no data yet, but soon?

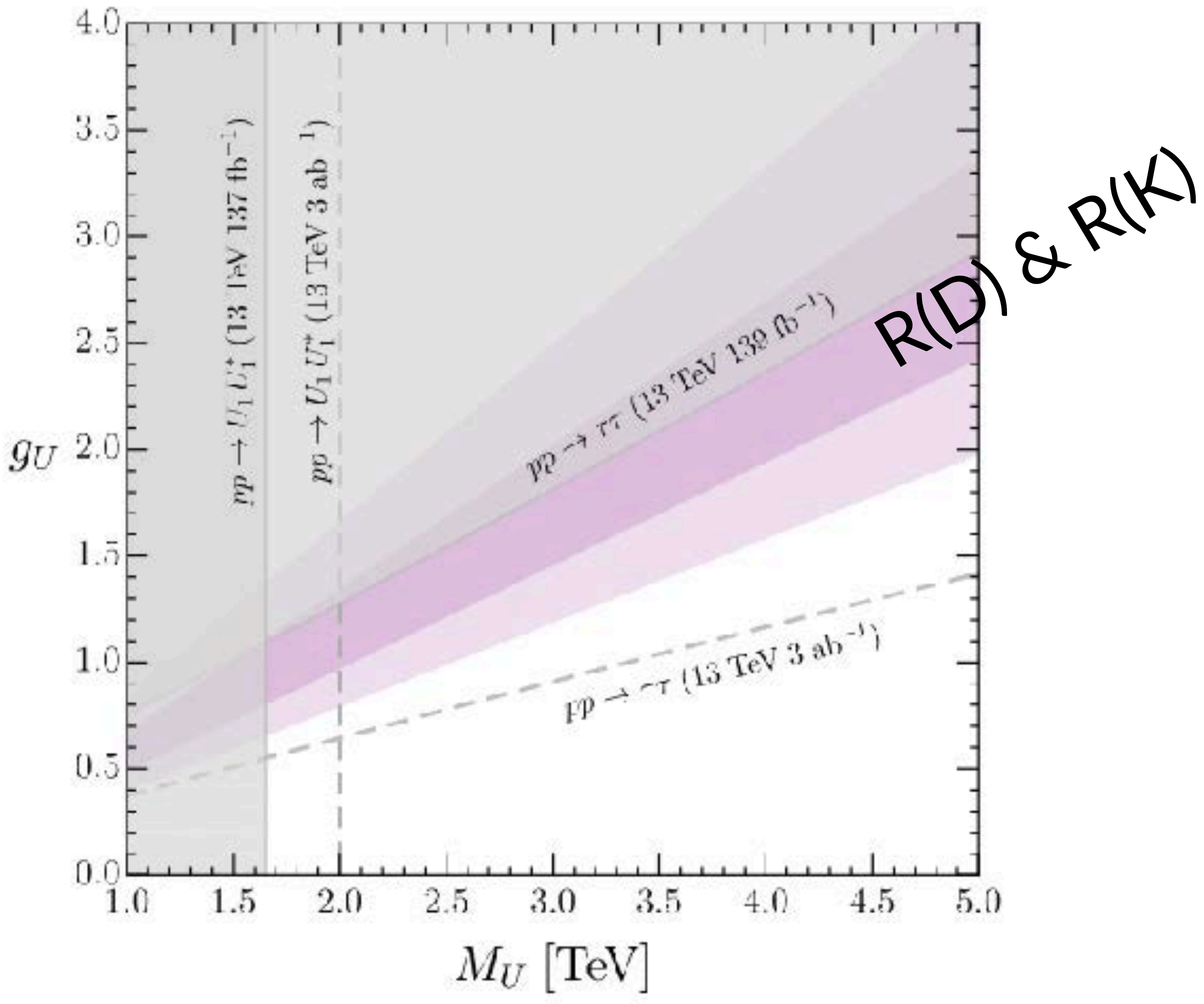
[Blanke, Crivellin, TK, Moscati, Nierste, Nisandzic, '19]

LQ vs LHC

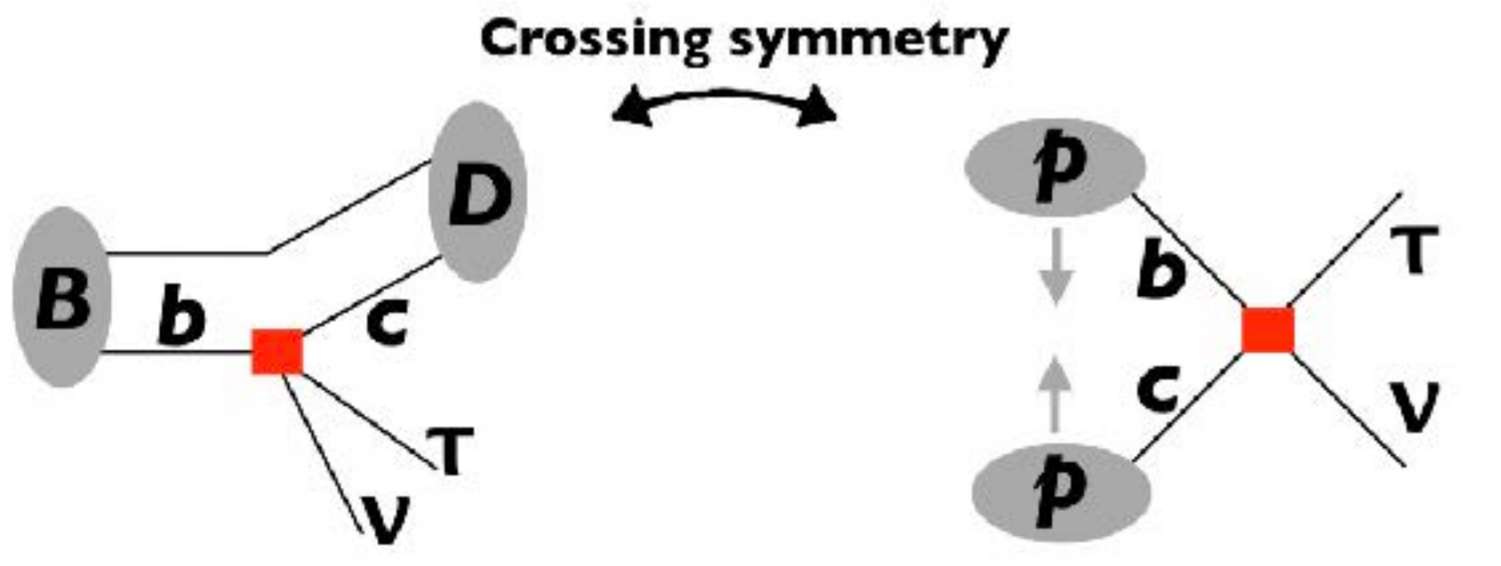
- LQ can be probed by LHC directly and indirectly

  Vector leptoquark scenario [Cornella et al, 2103.16558]





- The direct bound comes from high-p_T tails in mono-τ searches



[Greljo, Camalich, Ruiz-Alvarez PRL '19; Marzocca, Min, Son, '20; Iguro, Takeuchi, Watanabe 2011.02486]

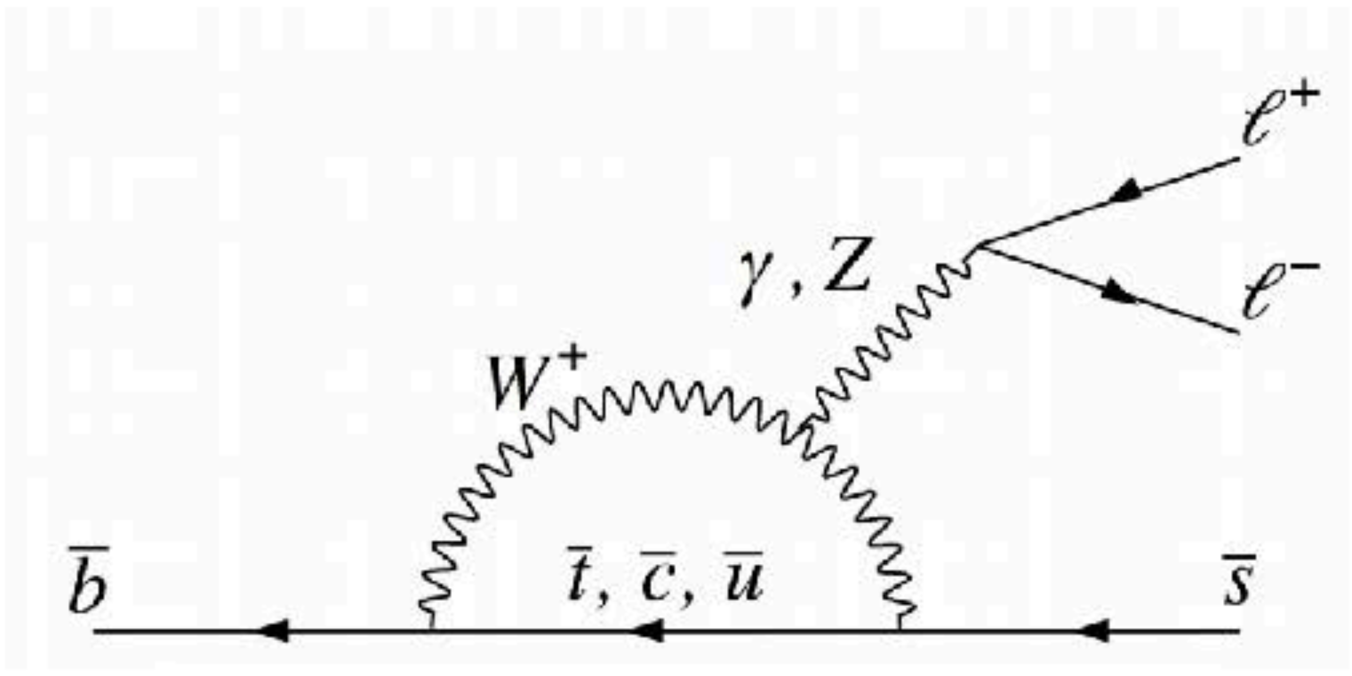
Current bounds:

EFT: $|C_V^L| < 0.32, \quad |C_S^{L(R)}| < 0.55, \quad |C_T| < 0.17$

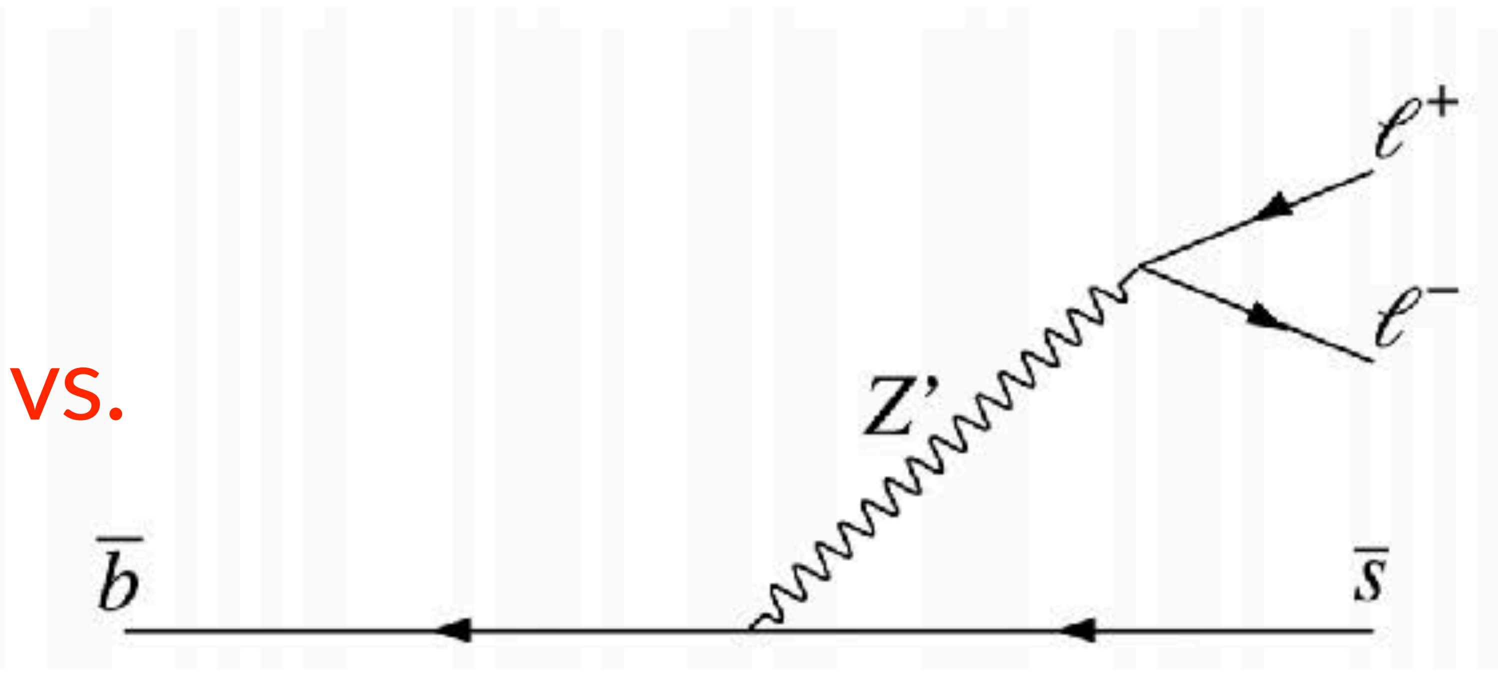
2TeV LQ: $|C_V^L| < 0.42, \quad |C_S^{L(R)}| < 0.8, \quad |C_T| < 0.35$

LFU observable *R*(*K*)

$$R(K^{(*)}) = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$



vs.



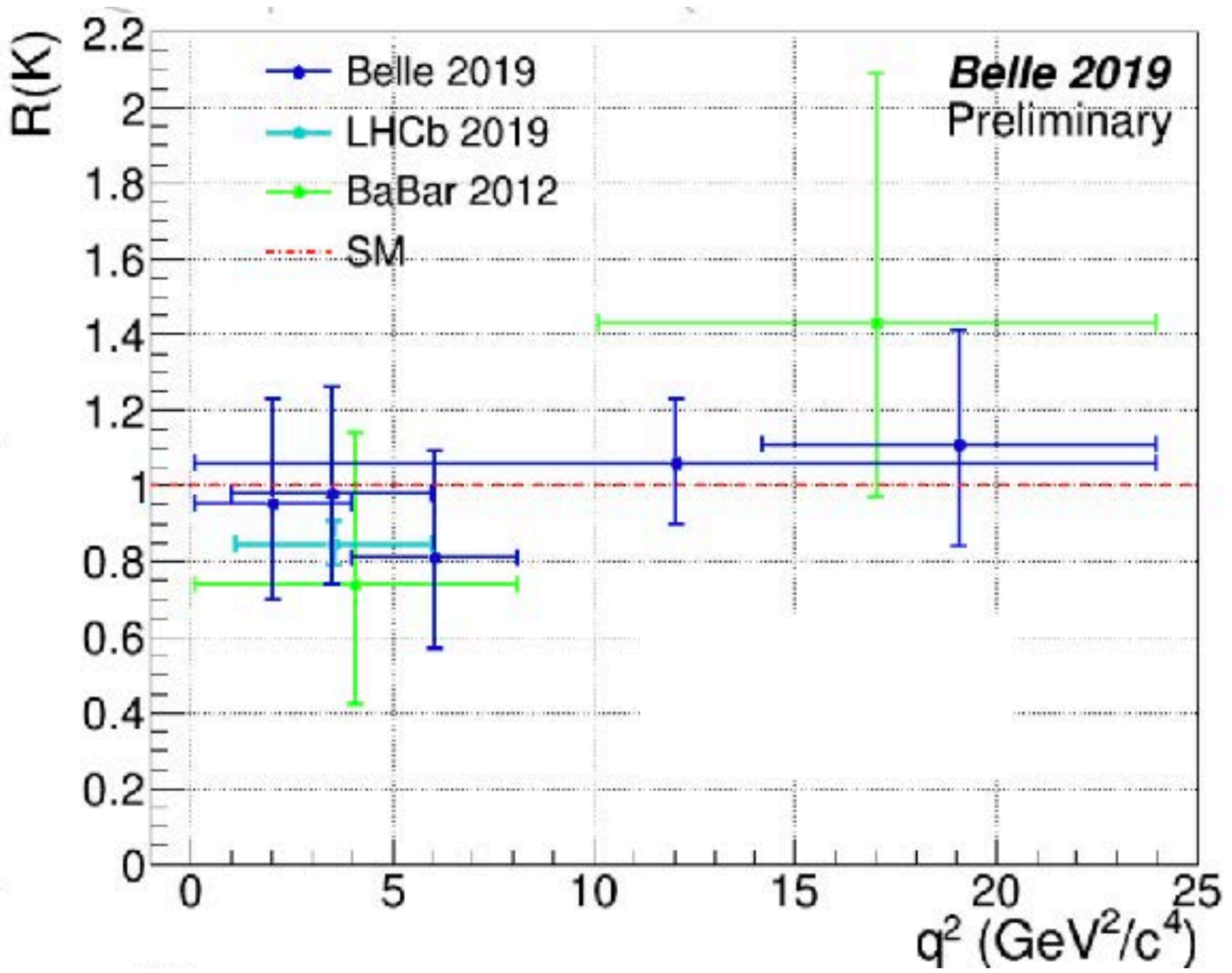
SM

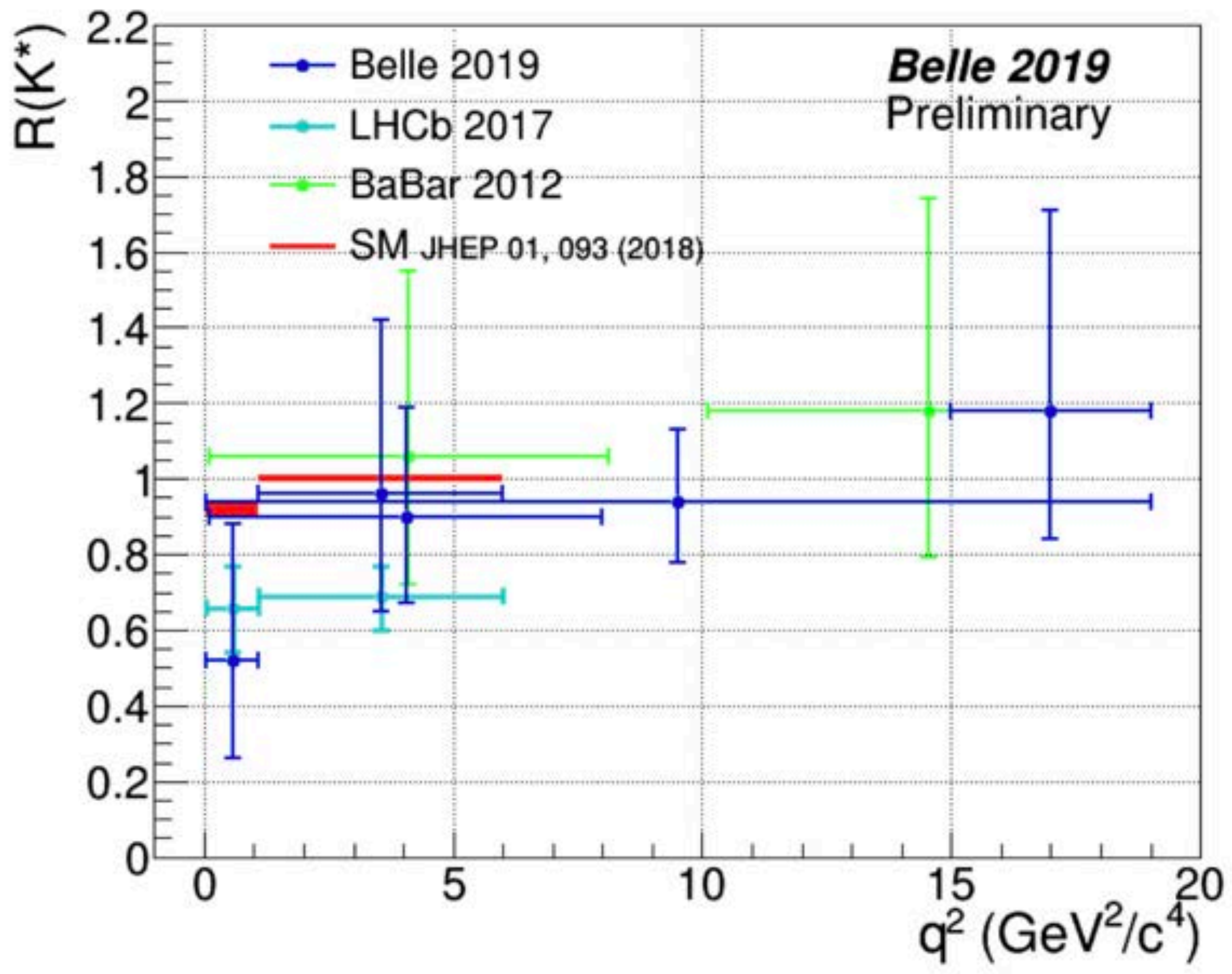
NP, *e.g.*, Z' boson

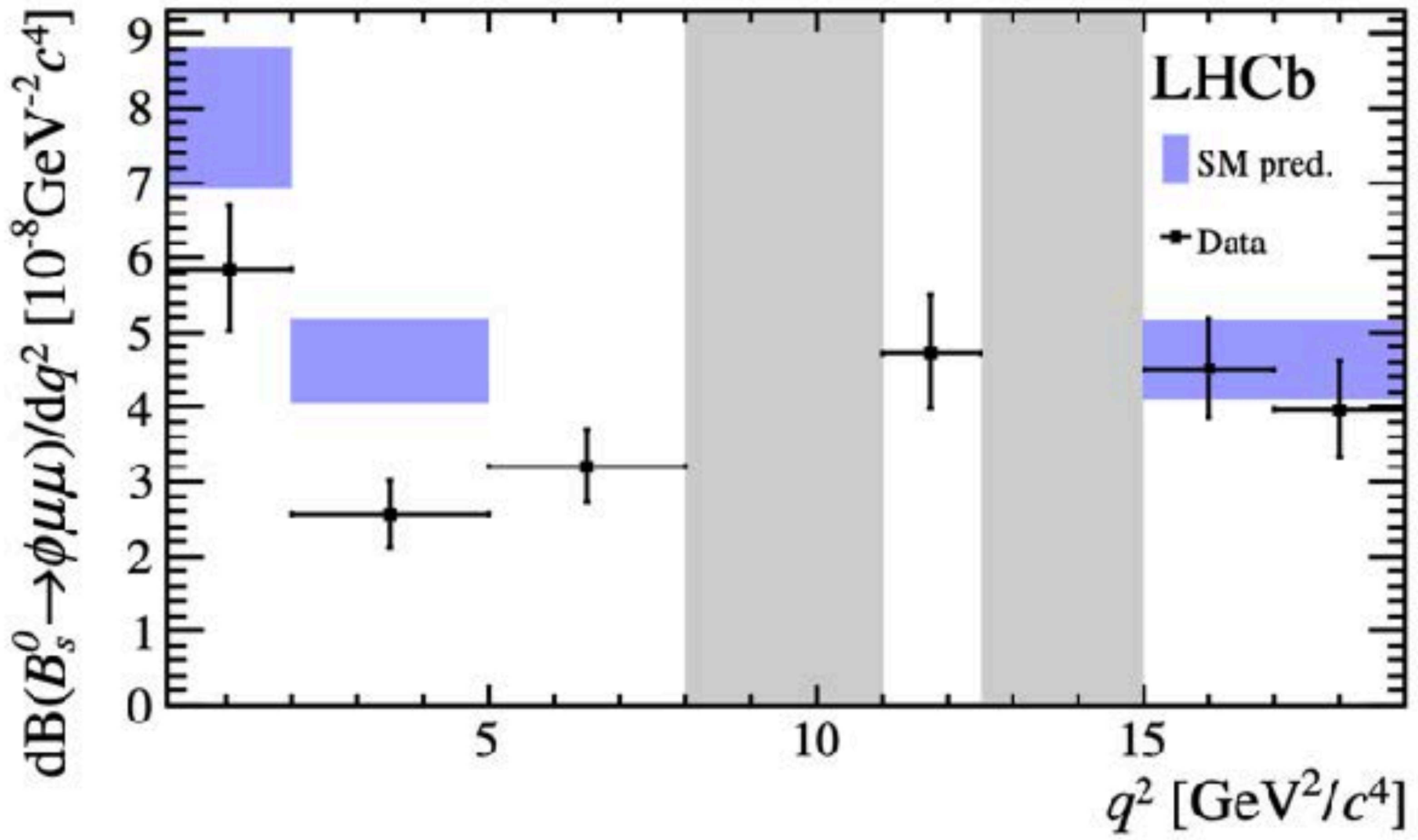
$\mathcal{B}(B \to K\ell^+\ell^-) = \mathcal{O}(10^{-7}),\ \mathcal{B}(B \to K^*\ell^+\ell^-) = \mathcal{O}(10^{-6})$

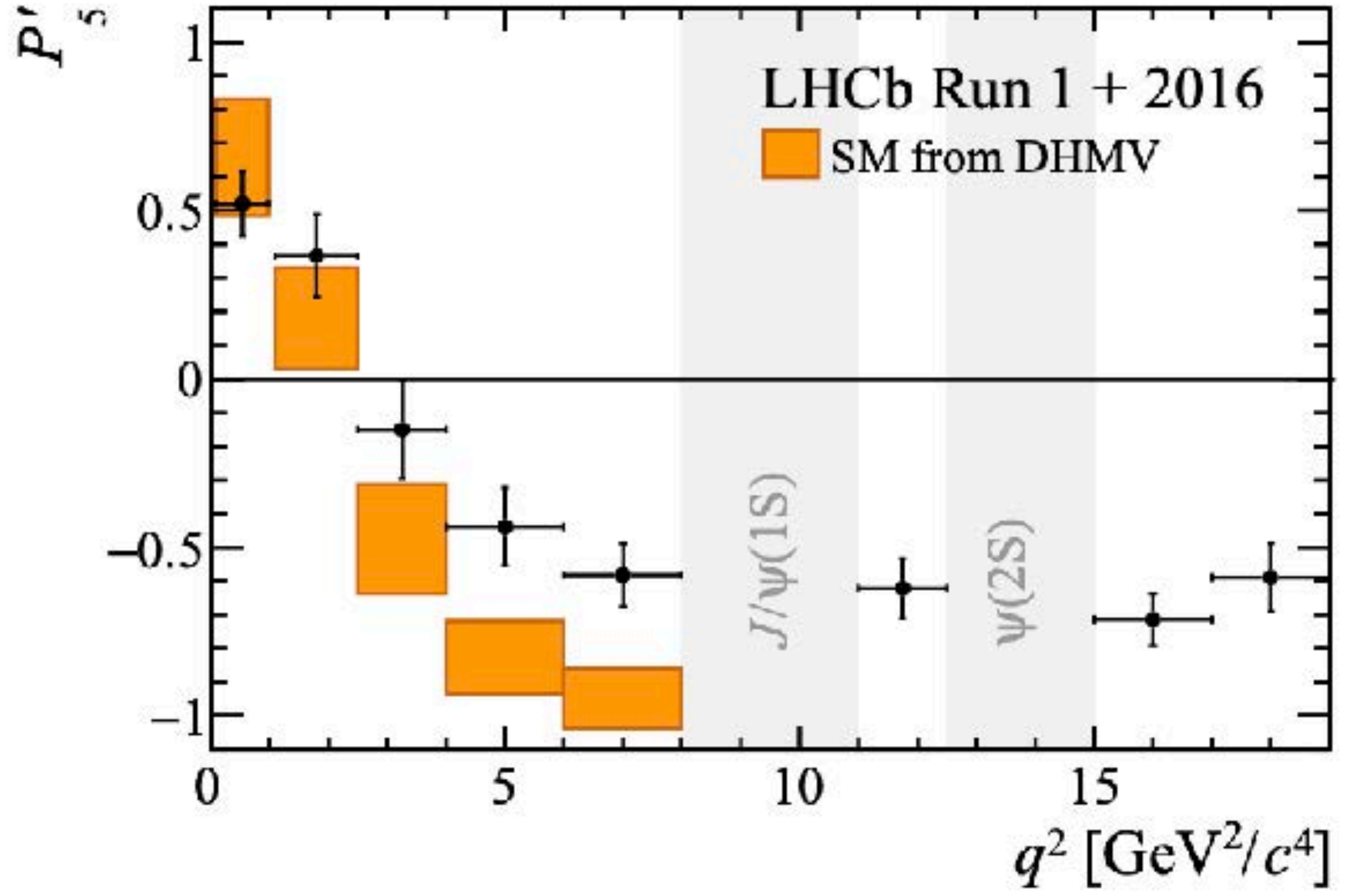
$b \to s\mu^+\mu^-$ anomalies

- In 2019 and 2020, LHCb and Belle presented new results





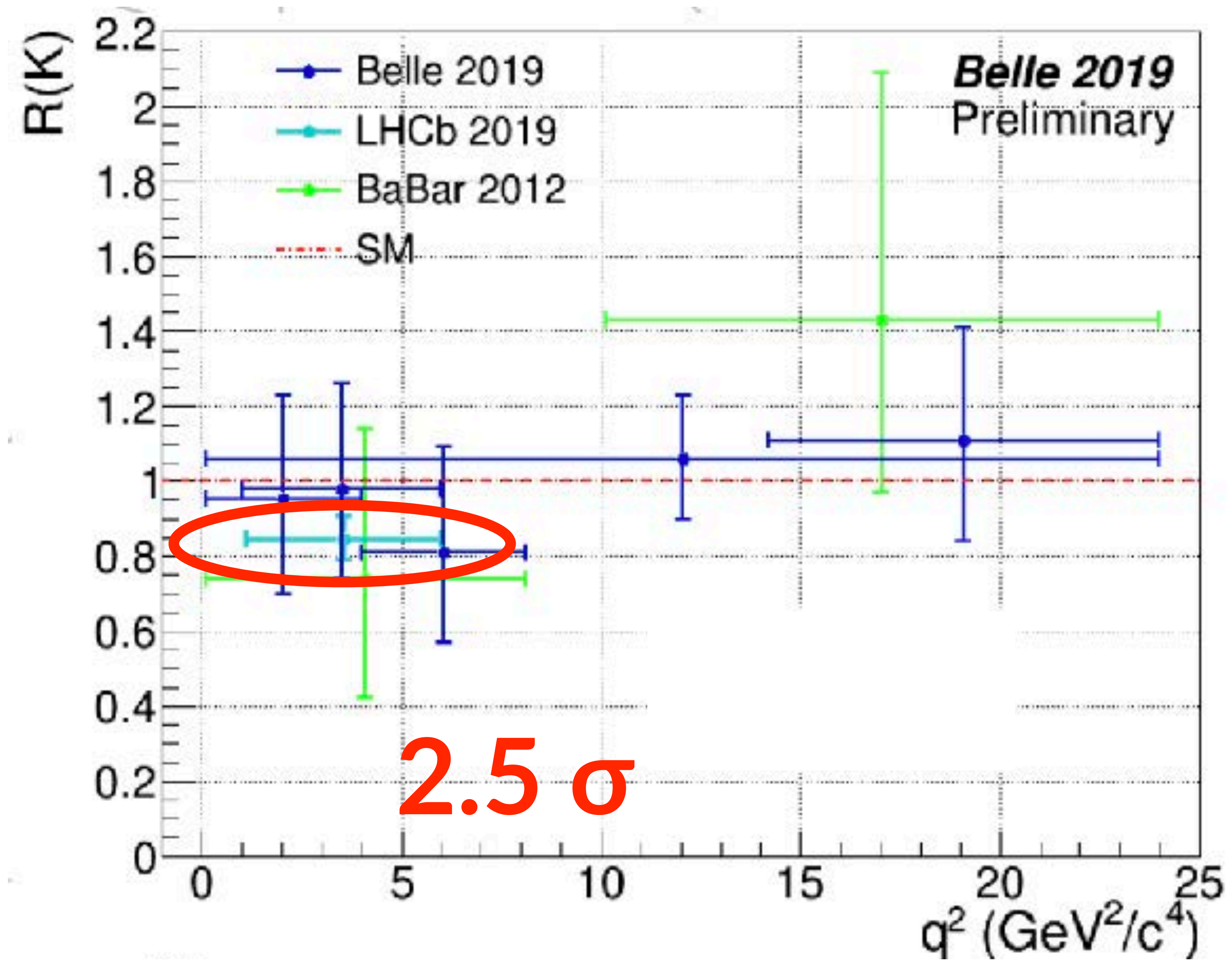


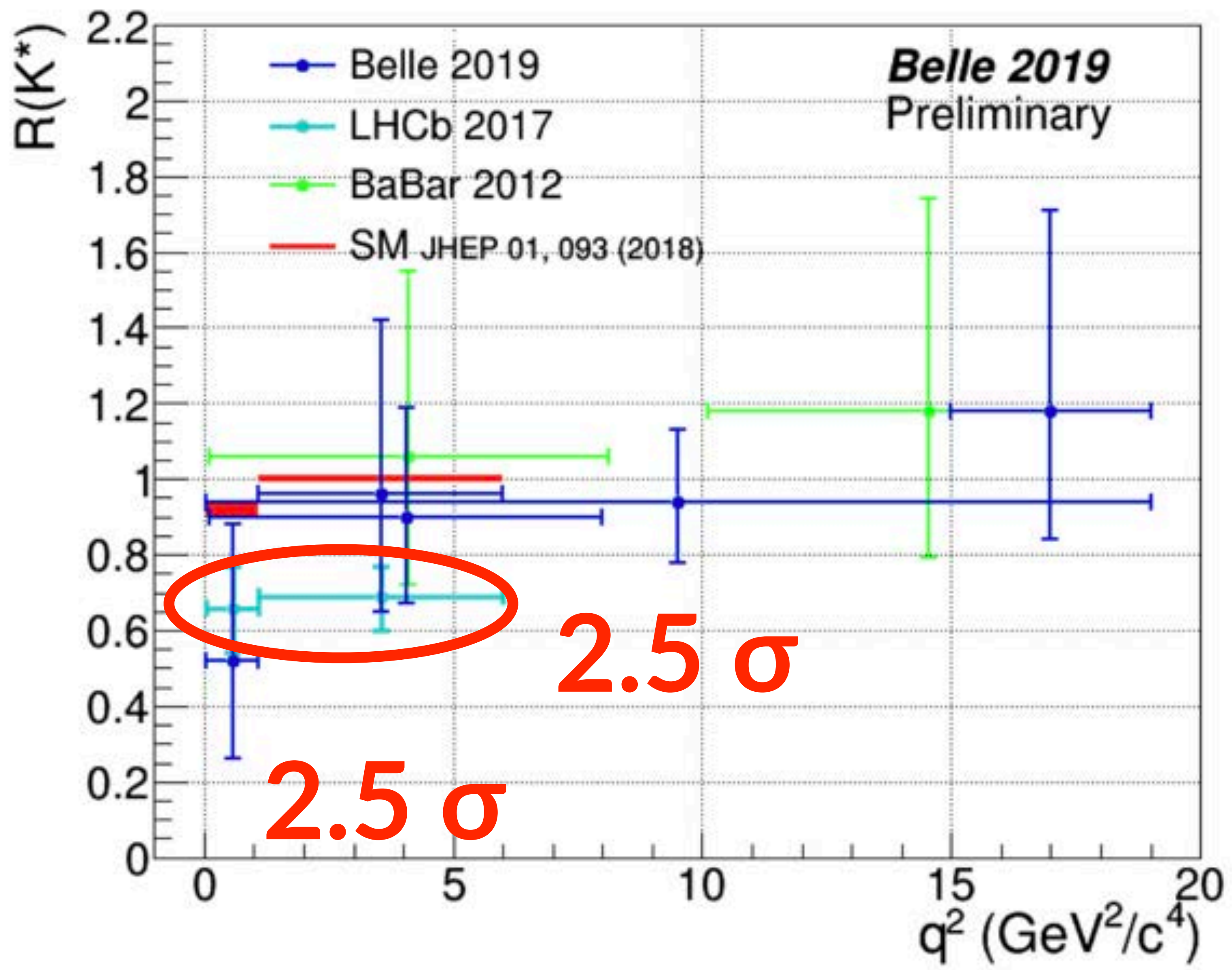


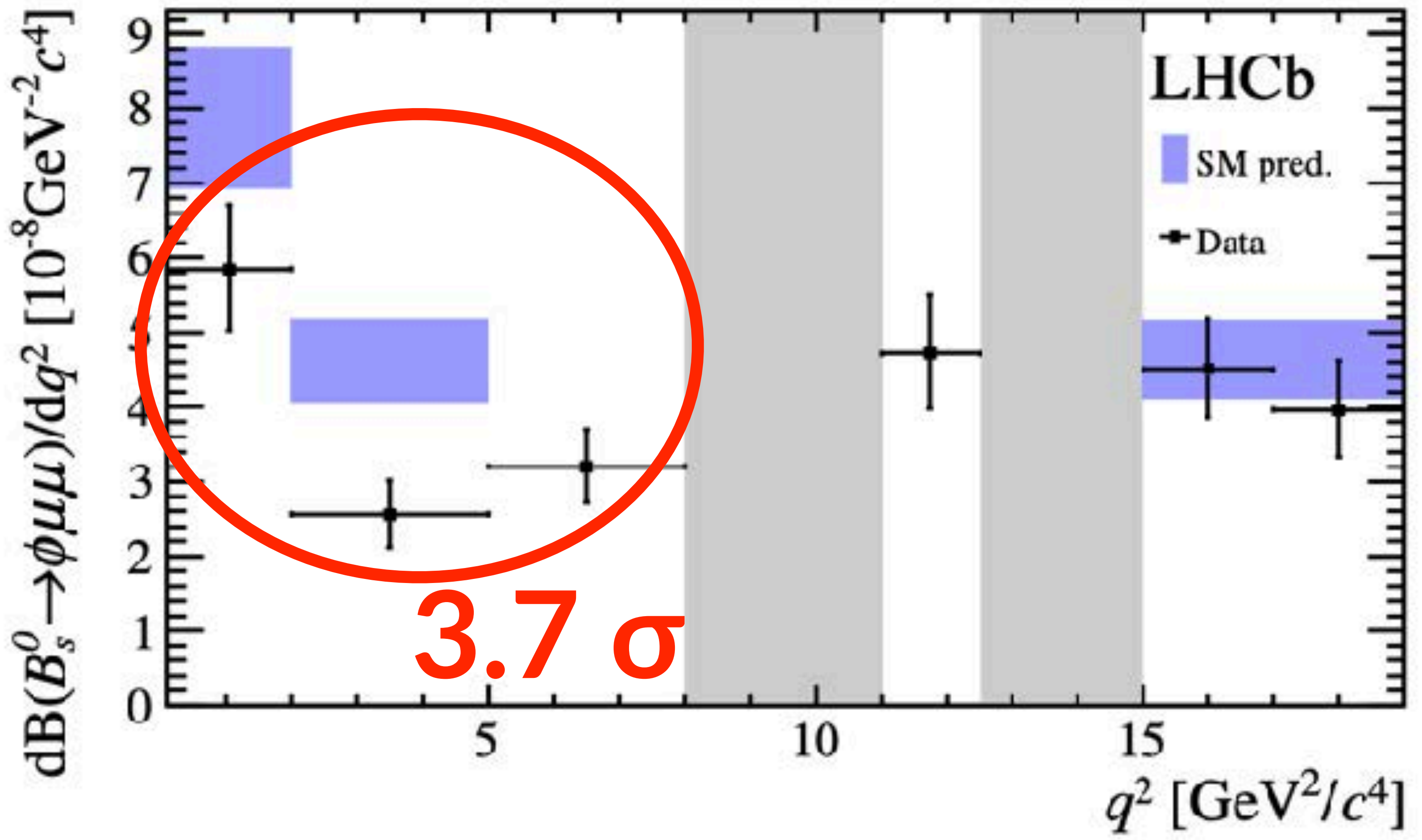
[LHCb, 2003.04831]

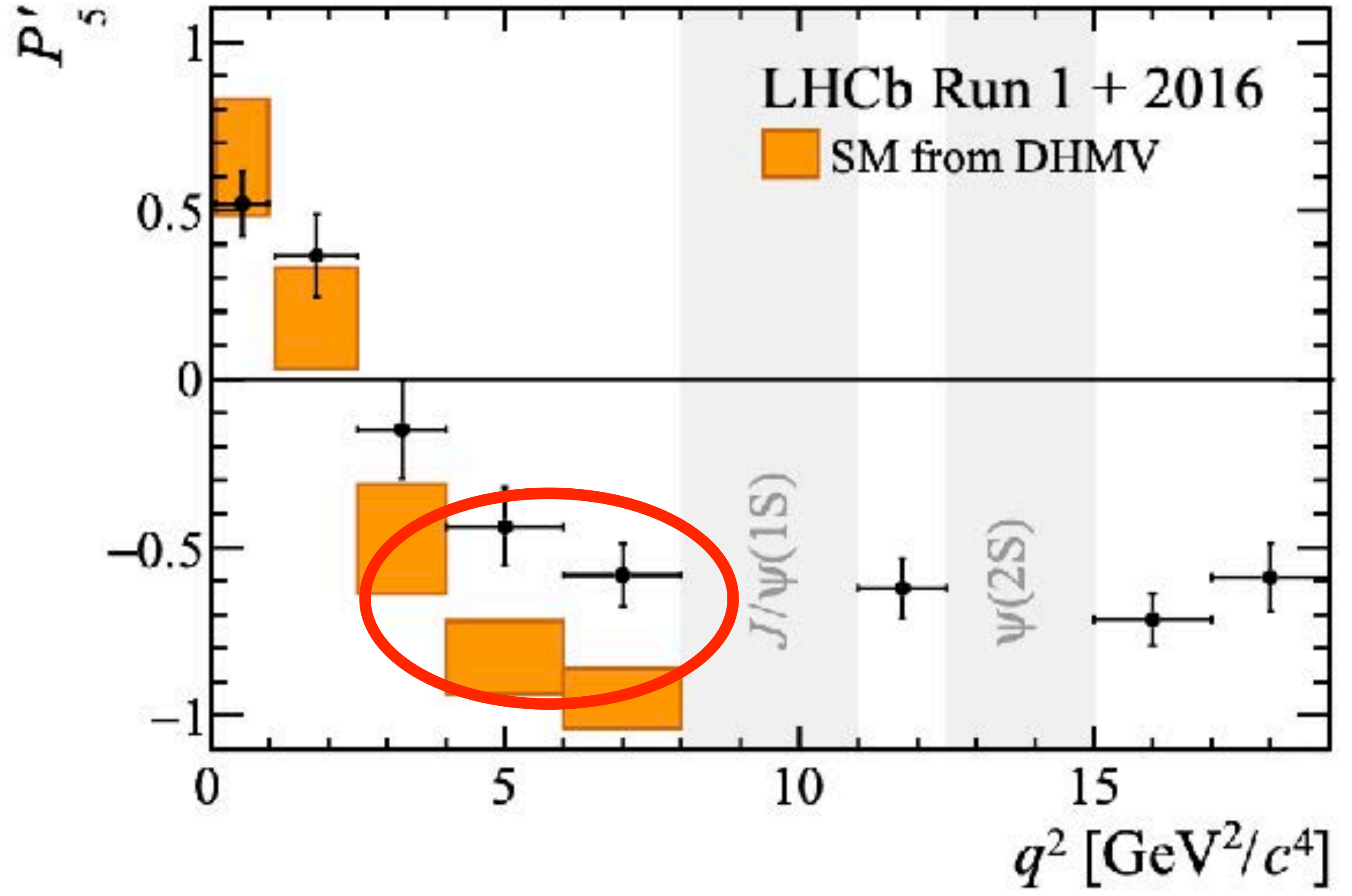
$b \to s\mu^+\mu^-$ anomalies

- In 2019 and 2020, LHCb and Belle presented new results









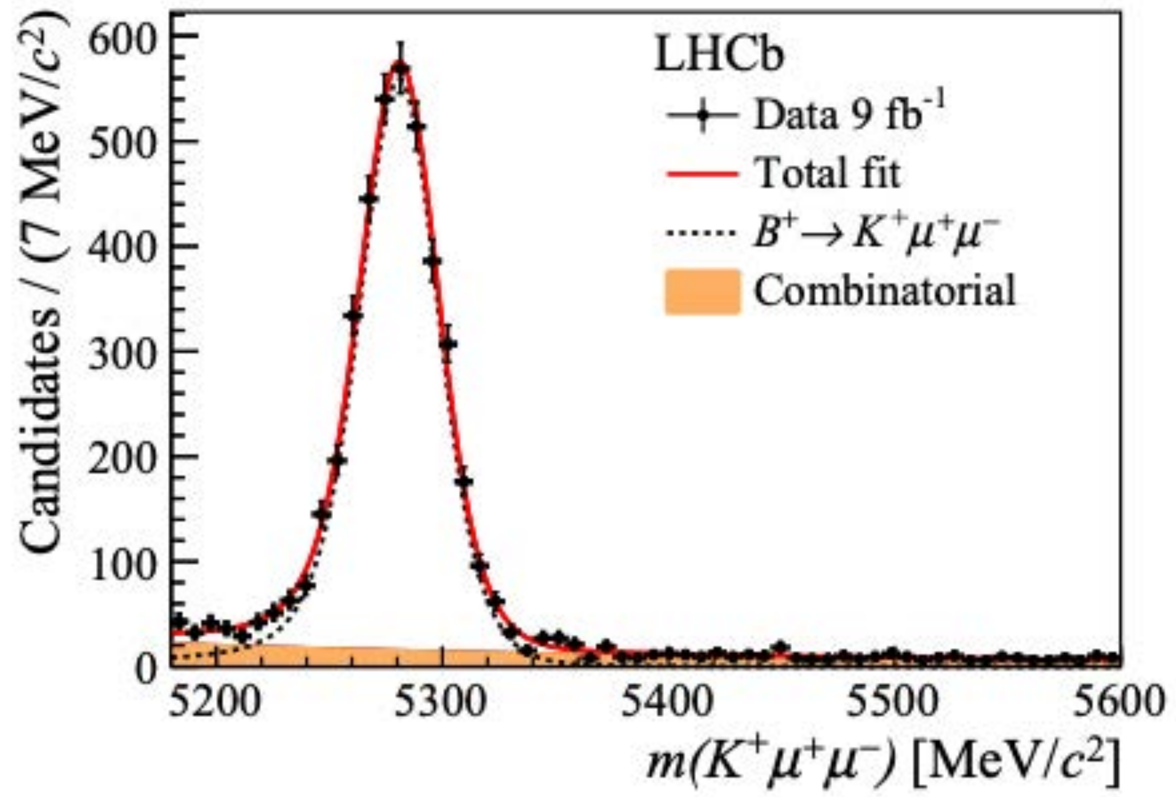
[LHCb, 2003.04831]

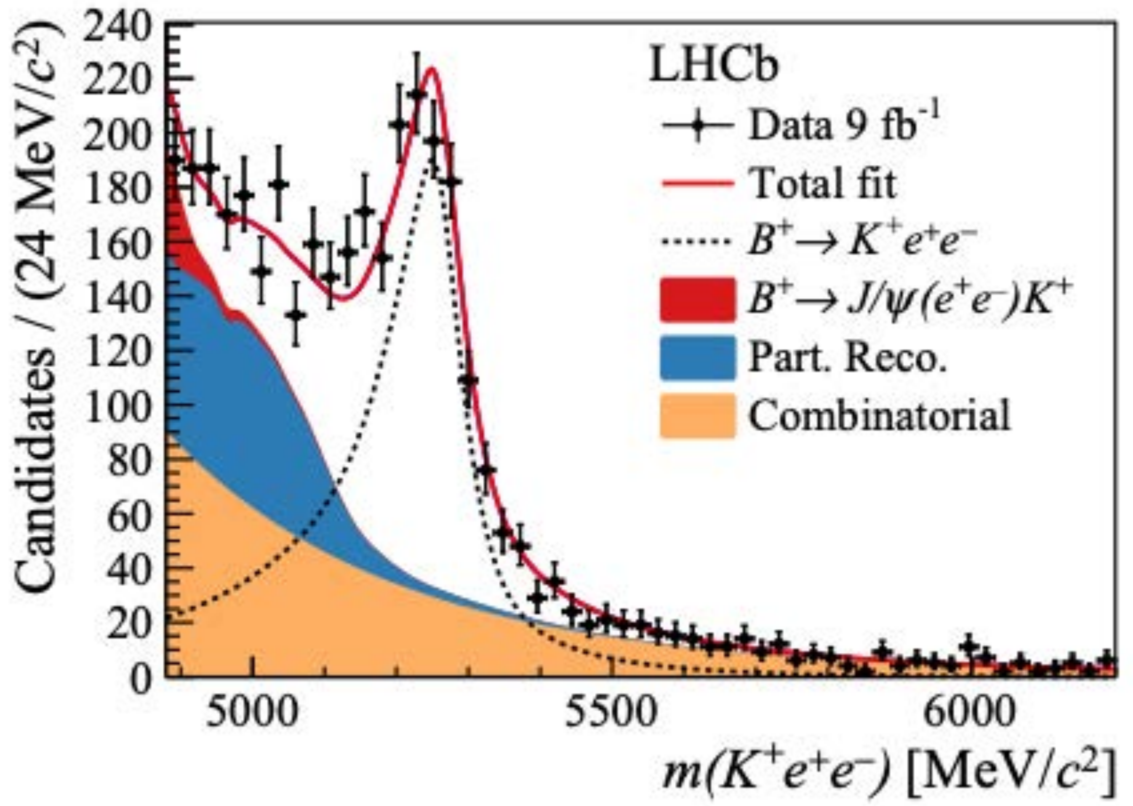
2.5 σ, 2.9 σ

- Angular distribution of $\Lambda_b \to \Lambda\mu^+\mu^-$ [K6] is also deviated at 2.6 σ [LHCb, 1808.00264]

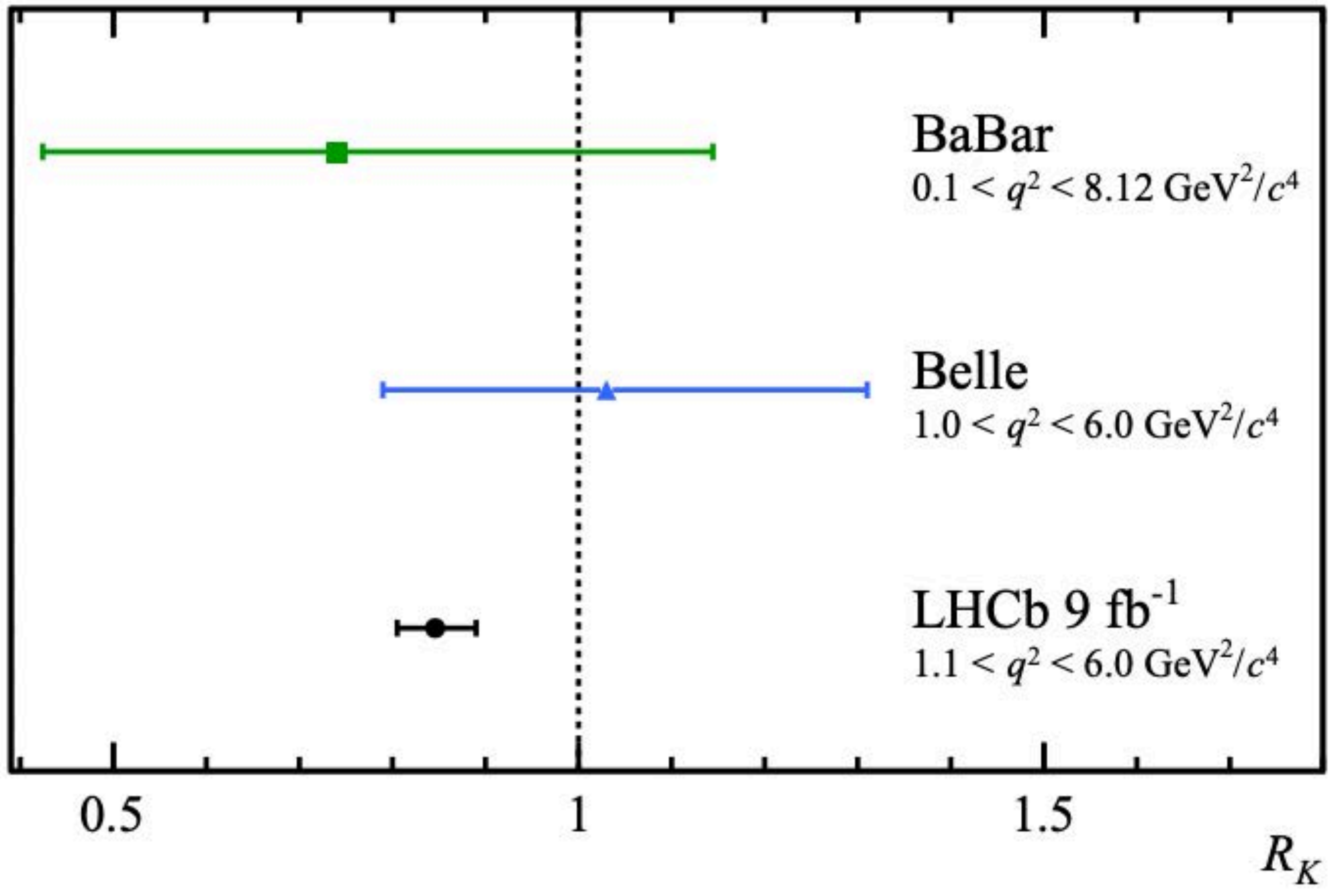
R(K) in Moriond2021

- Last month, R(K) was confirmed by using full Run 2 data [LHCb Moriond2021, 2103.11769]





$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\text{stat.})\ ^{+0.013}_{-0.012}\ (\text{syst.})$$



R(K) only

2.5 σ → **3.1σ**

Including the *look-elsewhere effect* and conservative theoretical error from charm loops, **the global significance of $b \to s\ell^+\ell^-$ is 3.9σ**

[Lancierini, Isidori, Owen, Serra, 2104.05631]

SMEFT global fit

[Geng et al, 2103.12738;
Altmannshofer et al, 2103.13370;
Cornella et al, 2103.16558;
Alguero et al, 2104.08921;
Hurth et al, 2104.10058]

- Relevant effective Hamiltonian

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

$$\mathcal{O}_7 = (\bar{s}\sigma_{\mu\nu}P_R b)\, F^{\mu\nu}$$

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\, (\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)\, (\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$C_9^{\rm SM} = 4.1 \quad C_{10}^{\rm SM} = -4.3$$

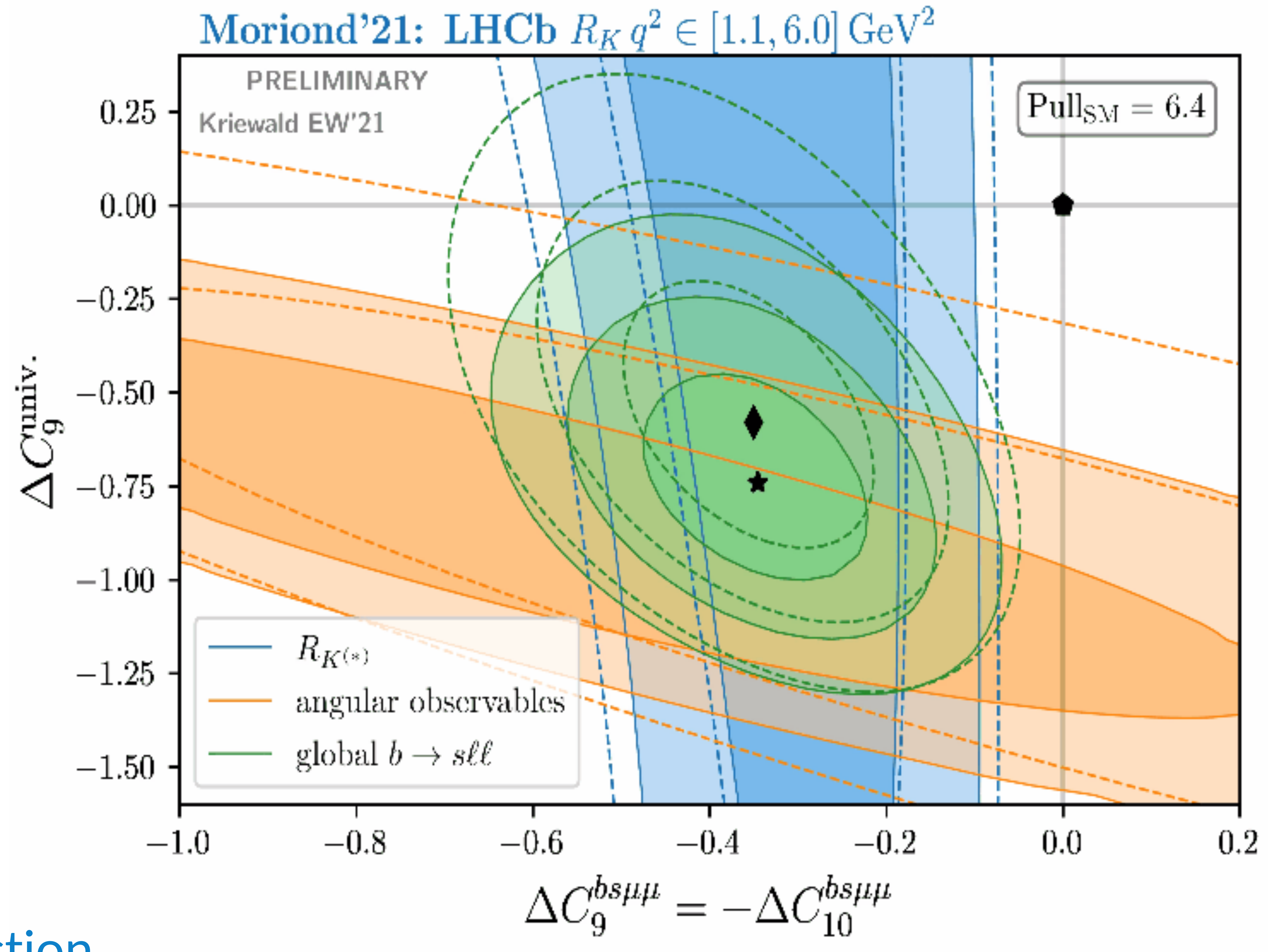
Current best fit: PullSM = **−6.4σ**

$$C_9 = -C_{10} = -0.34,\ C_9^{\rm univ.} = -0.74$$

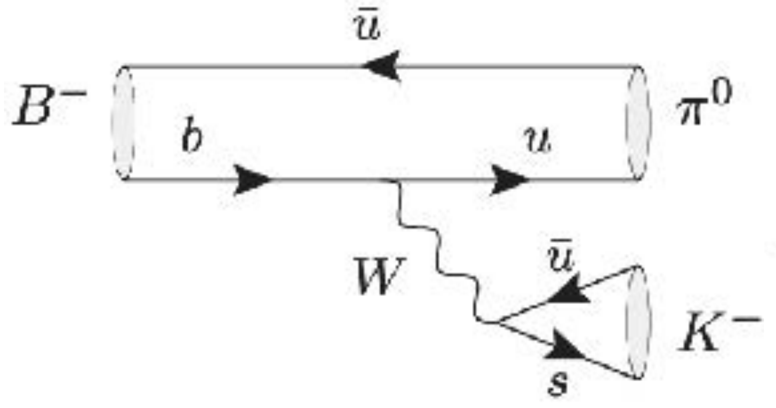
$$\Rightarrow \Lambda_{\rm NP} = \mathcal{O}(10)\mathrm{TeV}$$

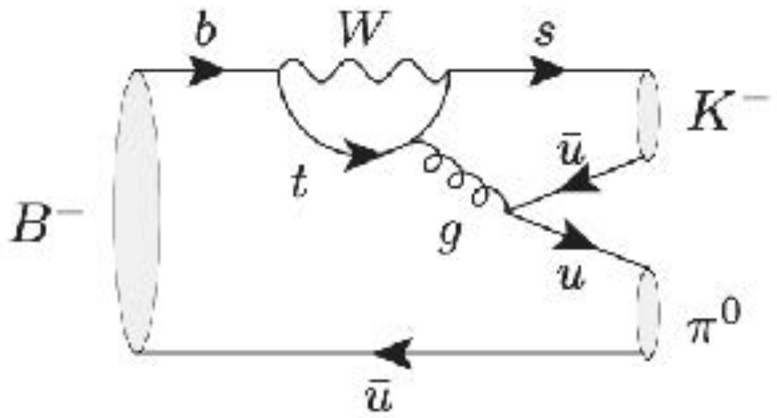
All deviations in $b \to s\mu^+\mu^-$ are the same direction

[Kriewald, Hat, Orloff, Teixeira, 2104.00015]



“$K\pi$ puzzle”: Direct CPV in $B \to K\pi$ modes





- Direct CP asymmetry is obtained by

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

- The difference between two direct CP asymmetries [note that $\mathcal{B}(B \to K\pi) = \mathcal{O}(10^{-5})$]

$$\Delta A_{CP}(K\pi) = A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+)$$ $= 0$ @ SM leading order

$\Delta A_{CP}|_{\rm SM}(K\pi) = (1.8^{+4.1}_{-3.2})\,\%$ [Hofer, Scherer, Vernazza, JHEP ’11; Crivellin, Gross, Pokorski, Vernazza, PRD '20]

All data are **in agreement with** each other

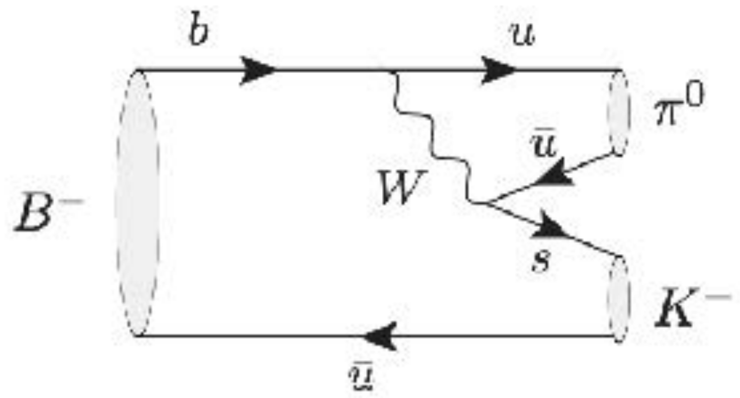
$A_{CP}|_{\rm BaBar}(B^+ \to \pi^0 K^+) = (3.0 \pm 3.9 \pm 1.0)\,\%$
$A_{CP}|_{\rm Belle}(B^+ \to \pi^0 K^+) = (4.3 \pm 2.4 \pm 0.2)\,\%$
New! $A_{CP}|_{\rm LHCb}(B^+ \to \pi^0 K^+) = (2.4 \pm 1.5 \pm 0.7)\,\%$

$A_{CP}|_{\rm BaBar}(B^0 \to \pi^- K^+) = (-10.7 \pm 1.6^{+0.6}_{-0.4})\,\%$
$A_{CP}|_{\rm Belle}(B^0 \to \pi^- K^+) = (-6.9 \pm 1.4 \pm 0.7)\,\%$
$A_{CP}|_{\rm CDF}(B^0 \to \pi^- K^+) = (-8.3 \pm 1.3 \pm 0.4)\,\%$
$A_{CP}|_{\rm LHCb}(B^0 \to \pi^- K^+) = (-8.4 \pm 0.4 \pm 0.3)\,\%$

2.2σ tension

$\Delta A_{CP}|_{\rm exp}(K\pi) = (11.5 \pm 1.4)\,\%$ [Moriond 2021 average]

SM explanation can be possible, if this HME is bigger than the NLO prediction by a factor of 2
[Li, Mishima, PRD '11; Beaudry, Datta, London, Rashed, Roux, JHEP '18]



http://www.wallcoo.net/

V_{us} vs unitarity

$K_L \to \pi^- \ell^+ \nu$

$K^+ \to \ell^+ \nu$

ε_K and ε'

RBC-UKQCD

$K_L \to \pi\pi$

CORRELATION

Belle II LHCb BABAR

B physics

FCNC and/or CPV

$K^0 \to \mu^+\mu^-$

LHCb

$K_S \to \pi^0\mu^+\mu^-$

$K_S \to \mu^+\mu^-\gamma$

$K_S \to 4\ell$

$K_S \to \pi^+\pi^- e^+ e^-$

Understanding of ChPT

Reduce th error

$K \to \pi\nu\bar{\nu}$

NA62 KOTO

$K_L \to \pi^0\ell^+\ell^-$

$K \to \pi X$

Direct CP violation in $K_L \to \pi\pi$

- Precise measurements of Kaon to two pions have discovered **the two type of CP violations**:

indirect CPV ε_K & direct CPV ε'

$$A(K_L \to \pi^+\pi^-) \propto \varepsilon_K + \varepsilon' \quad \text{with } \varepsilon_K = \mathcal{O}(10^{-3}) \neq 0$$

[Christenson, Cronin, Fitch, Turlay, PRL '64]

$$A(K_L \to \pi^0\pi^0) \propto \varepsilon_K - 2\varepsilon' \quad \varepsilon' = \mathcal{O}(10^{-6}) \neq 0$$

[NA48/CERN and KTeV/FNAL '99]

Isospin decomposition I=0 I=2

$$\mathrm{Re}\left[\frac{\epsilon'_K}{\epsilon_K}\right] \simeq \frac{1}{6}\frac{|\eta_{+-}|^2 - |\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{1}{6}\left(1 - \frac{\frac{\mathrm{Br}(K_L\to\pi^0\pi^0)}{\mathrm{Br}(K_S\to\pi^0\pi^0)}}{\frac{\mathrm{Br}(K_L\to\pi^+\pi^-)}{\mathrm{Br}(K_S\to\pi^+\pi^-)}}\right) \overset{\text{data}}{=} (16.6 \pm 2.3) \times 10^{-4}$$

PDG average

$\mathrm{Re}(\varepsilon'/\varepsilon_K)$ has been measured very precisely using the double ratio of branching ratios

$$\eta_{00} \equiv \frac{\mathcal{A}(K_L \to \pi^0\pi^0)}{\mathcal{A}(K_S \to \pi^0\pi^0)}$$

$$\eta_{+-} \equiv \frac{\mathcal{A}(K_L \to \pi^+\pi^-)}{\mathcal{A}(K_S \to \pi^+\pi^-)}$$

On the other hand, theoretical estimation is difficult due to non-perturbative QCD

ε_K discrepancy?

- SM prediction of the indirect *CP* violation ε_K is sensitive to $|V_{cb}|$

$$\varepsilon_K = \varepsilon_K(\mathrm{SD}) + \varepsilon_K(\mathrm{LD})$$

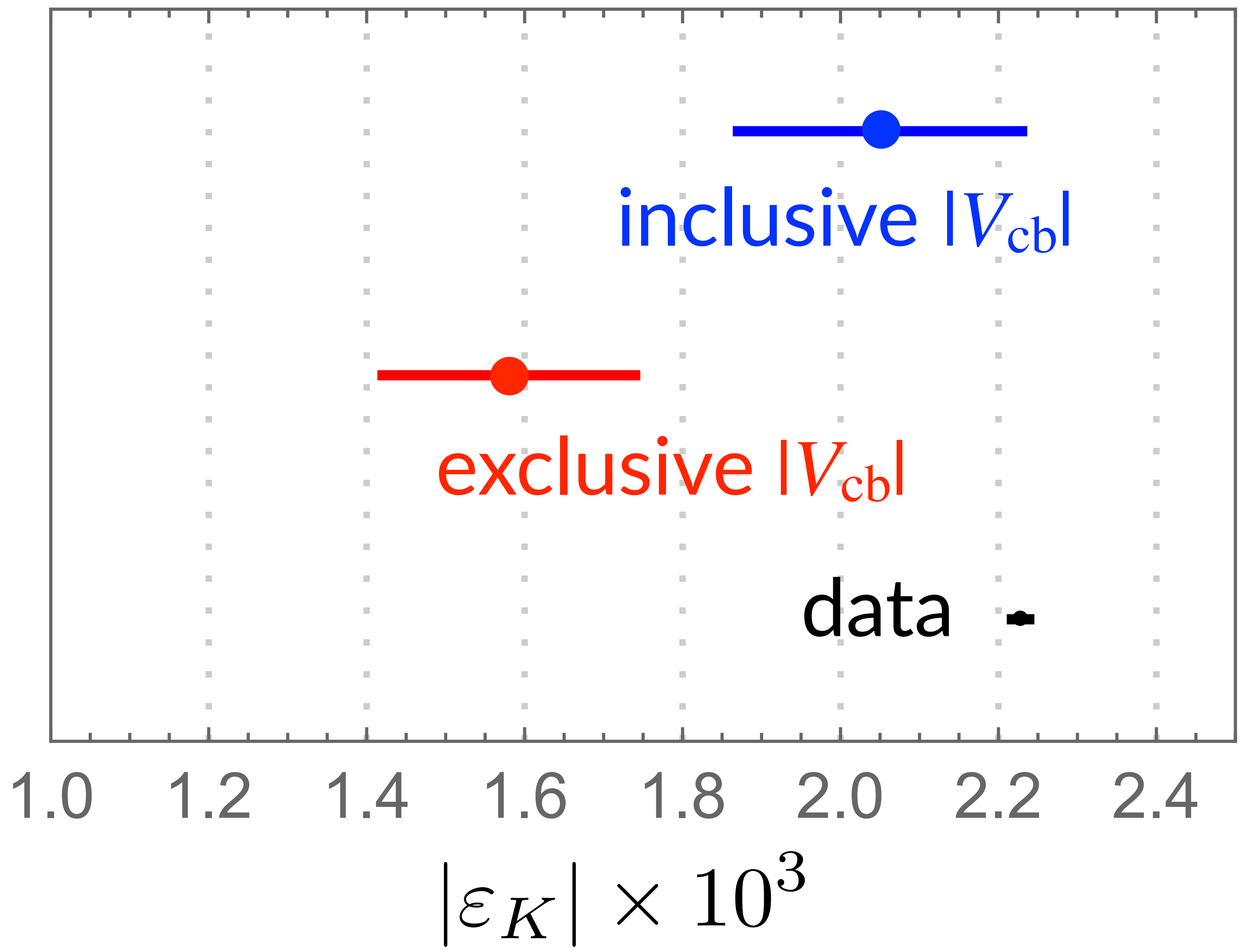
$\varepsilon_K(\mathrm{LD}) = -3.6(2.0)\% \times \varepsilon_K(\mathrm{SD})_{\mathrm{SM}}$

[Buras, Guadagnoli, Isidori, '10]
[Brod, Gorbahn, PRL '12]

$$\varepsilon_K(\mathrm{SD}) \propto \mathrm{Im}\lambda_t \left[-\mathrm{Re}\lambda_t \eta_{tt} S_0(x_t) + (\mathrm{Re}\lambda_t - \mathrm{Re}\lambda_c)\,\eta_{ct} S_0(x_c, x_t) + \mathrm{Re}\lambda_c \eta_{cc} S_0(x_c)\right]$$
$$\simeq \bar{\eta}\lambda^2 |V_{cb}|^2 \left[|V_{cb}|^2 (1-\bar{\rho})\eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} S_0(x_c)\right]$$

errors are dominated by V_{cb}, $\bar{\eta}$, η_{ct}, η_{cc}

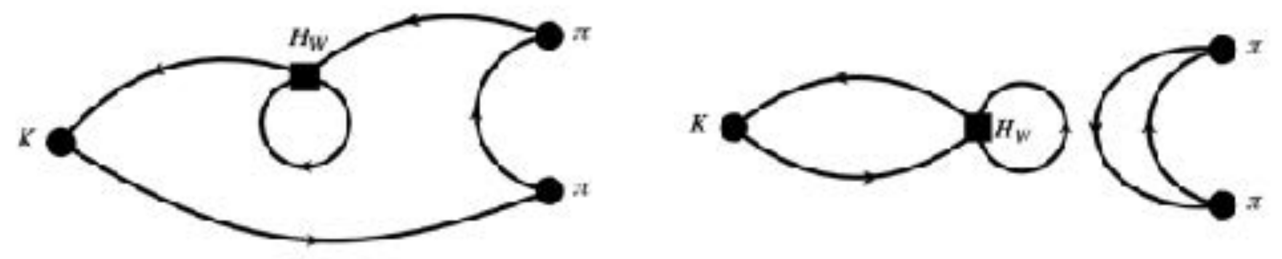
Leading contribution is proportional to $|V_{cb}|^4$



~4.2σ tension in exclusive $|V_{cb}|$ case

[LANL-SWME, 1912.03024, Wolfenstein parameters are determined by the angle-only fit]

Kaon physics prefers the inclusive V_{cb}



The latest situation of ε'/ε anomaly

RBC-UKQCD **(Lattice)** '15		RBC-UKQCD 2004.09440	Data
$(\epsilon'/\epsilon_K)_{\rm SM} = (1.4 \pm 5.2 \pm 4.6) \times 10^{-4}$ stat. sys.	→ 2.9σ shift	$(\epsilon'/\epsilon_K)_{\rm SM} = (21.7 \pm 2.6 \pm 6.2 \pm 5.0) \times 10^{-4}$ stat. sys. IB-sys.	$(\epsilon'/\epsilon_K)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$

Underestimated the sys. error

Buras, Gérard 2005.08976

$(\epsilon'/\epsilon_K)_{\rm SM} = (13.9 \pm 5.2) \times 10^{-4}$

+NNLO, η'

I=0 ππ phase shift

$\delta_0(m_K) = (23.8 \pm 4.9 \pm 1.2)^\circ$	→ 1.7σ shift	$\delta_0(E^{\rm lat}_{\pi\pi} = 479\,{\rm MeV}) = (32.3 \pm 1.0 \pm 1.8)^\circ$	$\delta_{0,{\rm disp.}} = 35.9^\circ$

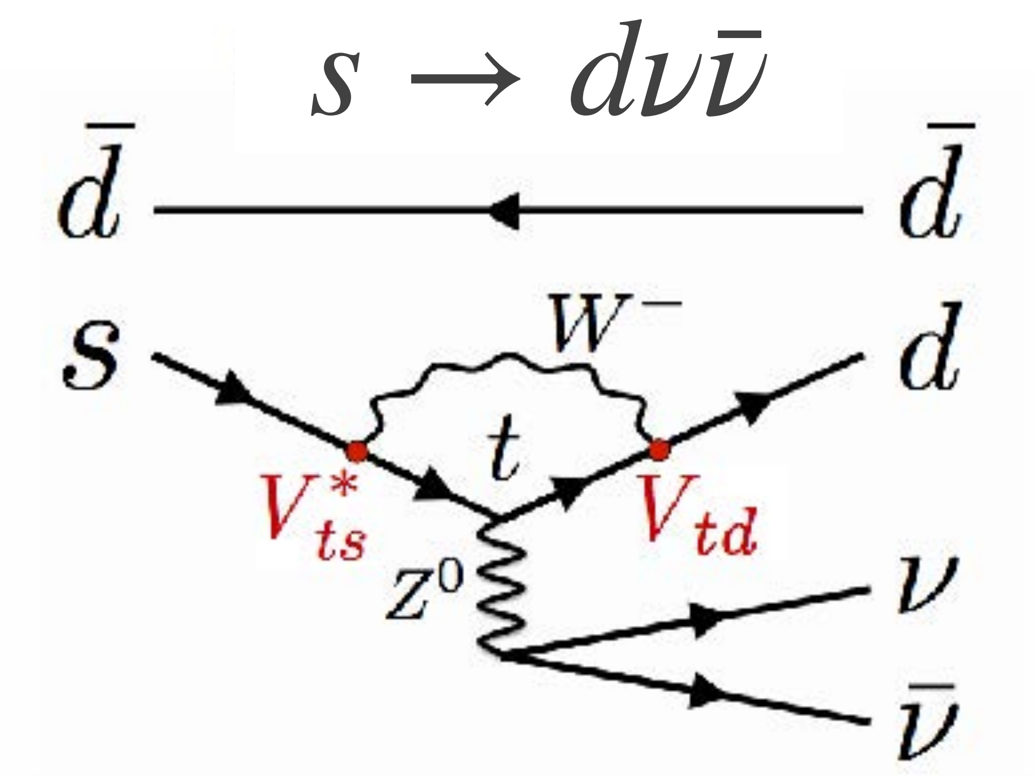
ΔI =1/2 rule

${\rm Re}(A_0)/{\rm Re}(A_2) = 31.0 \pm 11.1$	→ 1.0 σ shift	${\rm Re}(A_0)/{\rm Re}(A_2) = 19.9 \pm 2.3 \pm 4.4$	${\rm Re}(A_0)/{\rm Re}(A_2) = 22.45 \pm 0.06$

Now, all lattice results are consistent with data

$K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

- Both channels are theoretical clean and significantly sensitive to short-distance contributions, **especially $K_L \to \pi^0 \nu\bar{\nu}$ is purely CPV decay**
  (almost) CP-odd $\to$ CP-even in SM, see [Buchalla, Isidor, PLB '98]
  - **Sensitive to CPV in NP sector**



loop, GIM, and small CKM

- **SM predictions:** [Buras, Buttazzo, Girrbach-Noe, Knegjens, JHEP '15]

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = (8.4 \pm 1.0) \times 10^{-11},$$
$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm SM} = (3.4 \pm 0.6) \times 10^{-11}.$$

c.f.

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.06 \pm 0.09) \times 10^{-10}$$

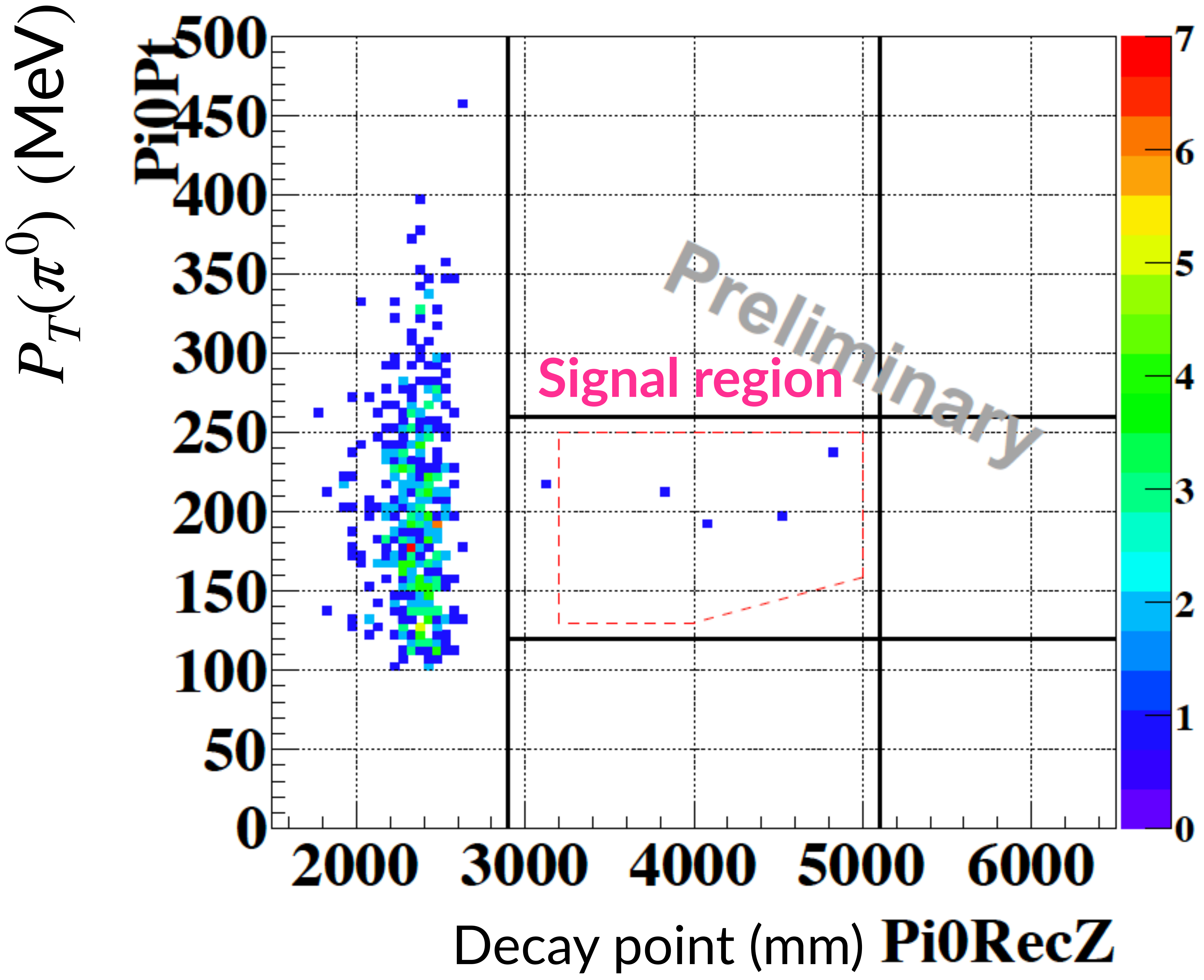
- On-going experiments:

KOTO K_L @J-PARC — SM event is expected in ~2024

NA62 K^+ @CERN — 20 SM events are expected in 2016-18 runs

KOTO@KAON2019

[KOTO, KAON2019; 2016-18 data]



[KOTO, 1810.09655; 2015 data]

$$\mathcal{B}\left(K_L \to \pi^0\nu\overline{\nu}\right) < 3.0 \times 10^{-9} \text{ at } 90\%\text{CL}$$

# of events	4 (3)
Single event sensitivity	6.9×10^{-10}
Expected BG	**0.05±0.02**
Expected SM	**0.05±0.01**

1 in 4 events is suspected that a peak selection was **mistaken** due to a wrong parameter

KOTO was planning to re-evaluate other BG sources, especially K^+ (special run for BG in May—Jun) **[done]**

KOTO@ICHEP2020 + JPS2020Fall + PRL '21

[KOTO, KAON2019]

# of events	4 (3)
Single event sensitivity	6.9×10-10
Expected BG	0.05±0.02
Expected SM	0.05±0.01

[KOTO, ICHEP2020]

3	
7.1×10-10	
0.39±0.10	**1.05**±0.28
0.05±0.01	

×8 [New K^+ BG]
Based on MC simulation of K^+ before the special run

×3 [calibrate K^+ flux]
Based on the special run for K^+

[KOTO, JPS2020Fall]

3
7.2×10-10
1.21±0.25
0.05±0.01

[New halo $K_L \to 2\gamma$ BG] added

[KOTO, PRL '21]

3
7.2×10-10
1.22±0.26
0.05±0.01

"observed events is statistically consistent with the background expectation"

CONGRATULATIONS!

Cabibbo angle anomaly

- Kaon measurements can determine the Cabbie angle: $|V_{us}| \equiv \lambda$

K physics B physics

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

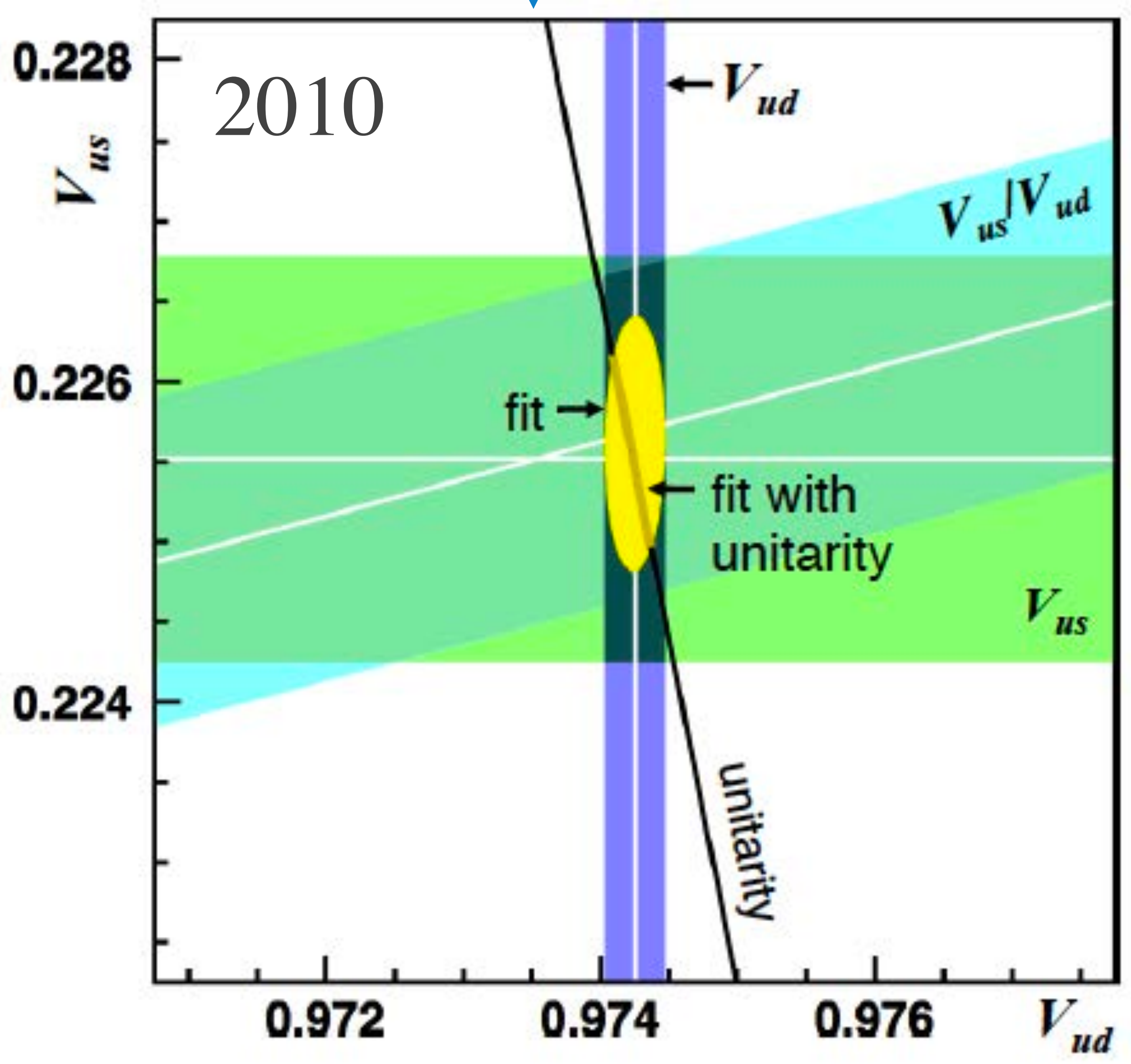
- CKM unitarity: $V^\dagger V = 1 \rightarrow |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \rightarrow |V_{ud}|^2 + |V_{us}|^2 = 1$

  $|V_{ub}|^2 \sim 1.4 \times 10^{-5}$

- Now, one can check this equality from precision data

Cabibbo angle anomaly: V_{ud}, V_{us} vs. CKM unitarity (1/2)

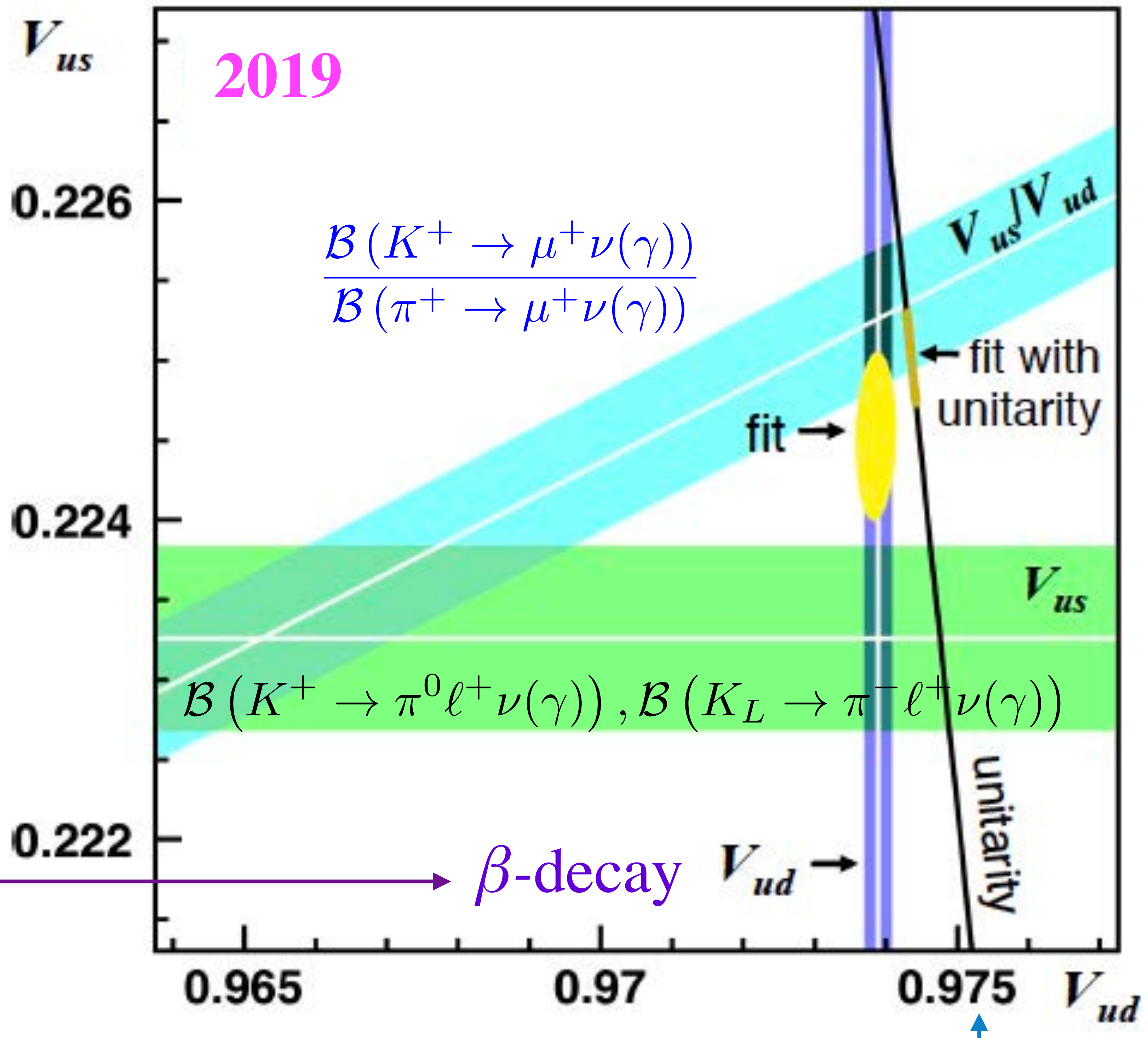
$|V_{ud}|^2 + |V_{us}|^2 = 1$



$\tau_n^{\text{trap}} = 879.4(6)\text{sec}$

[Czarnecki, Marciano, Sirlin, '19]

[E. Passemar, KAON2019]



$|V_{ud}|^2 + |V_{us}|^2 = 1$

[Grossman, Passemar, Schacht, JHEP '20] quantifies this situation:
CKM unitarity is **rejected at 3.0σ**, and new physics is favored over the SM **at 3.6σ level.**

New physics interpretations:

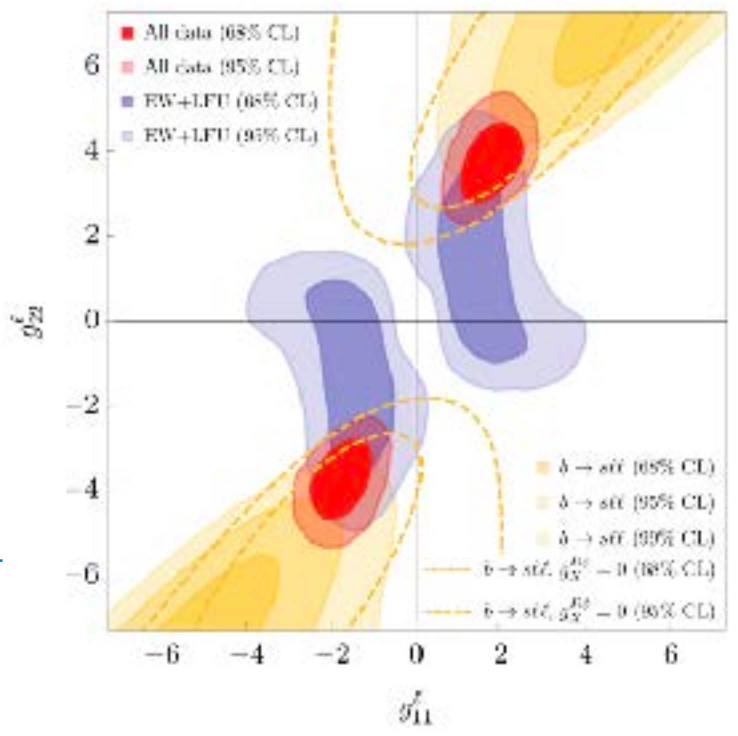
$(\bar{L}\gamma^\mu\tau^I L)(H^\dagger \overset{\leftrightarrow}{D}{}^I_\mu H)$ [Coutinho, Crivellin, Manzari, PRL '20]

Vector-like leptons (2TeV) [Endo, Mishima, '20]

Heavy SU(2)$_L$ (10TeV) [Capdevila et al, '20]

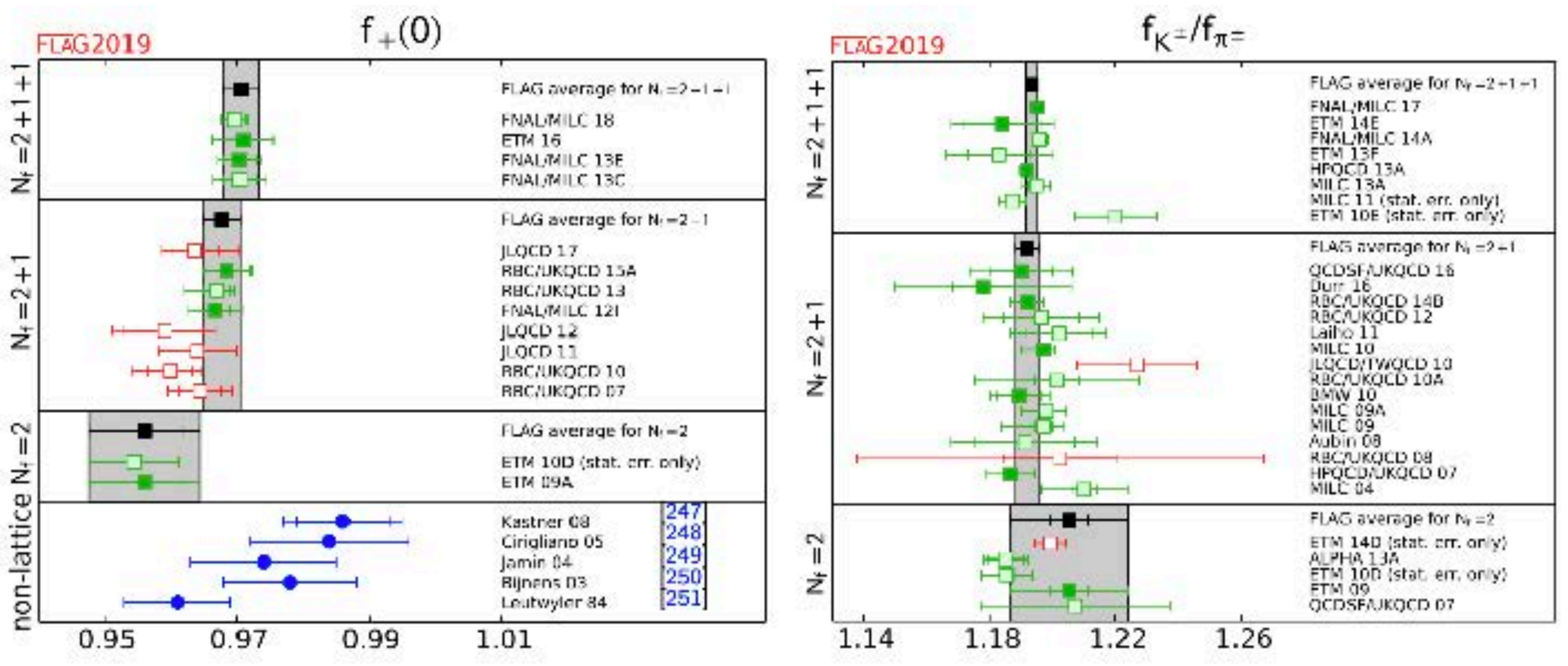
Cabbie angle anomaly

$b \to s\ell\ell$ anomaly



Cabibbo angle anomaly: V_{ud}, V_{us} vs. CKM unitarity (1/2)

- What's happened in the last ten years?
  - Lattice results [FLAG, 1902.08191]



  - New data [NA48/2, 1808.09041; OKA, 1708.09587]
  - Isospin breaking corrections are improved [Cirigliano, Neufeld, PLB '11; Bijnens, Ecker, ARNPS '14]
  - QED corrections to β decay are improved [Czarnecki, Marciano, Sirlin, PRD '19; Seng, Gorchtein, Ramsey-Musolf, PRD '19]
  - QCD+QED lattice [Sachrajda, et al, PRL '18; PRD '19]: the result is consistent with one which was obtained analytically and the error is reduced (chiral expansion error vs. lattice error)

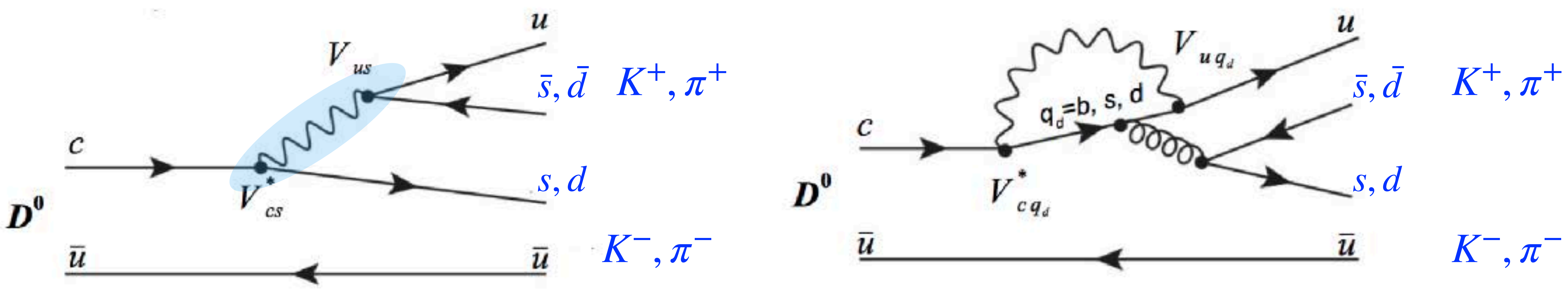
https://github.com/dlang/dlang.org

The first observation of CPV in *D*-meson

◆ Difference of Difference of $D^0 \to h^- h^+$ and $\bar{D}^0 \to h^- h^+$

Direct CPV $$A_{CP}(D^0 \to K^-K^+) \equiv \frac{\#(D^0(t=0) \to K^-K^+) - \#(\bar{D}^0(t=0) \to K^-K^+)}{\#(D^0(t=0) \to K^-K^+) + \#(\bar{D}^0(t=0) \to K^-K^+)}$$

Observable $$\Delta A_{CP} = A_{CP}(D^0 \to K^-K^+) - A_{CP}(D^0 \to \pi^-\pi^+)$$

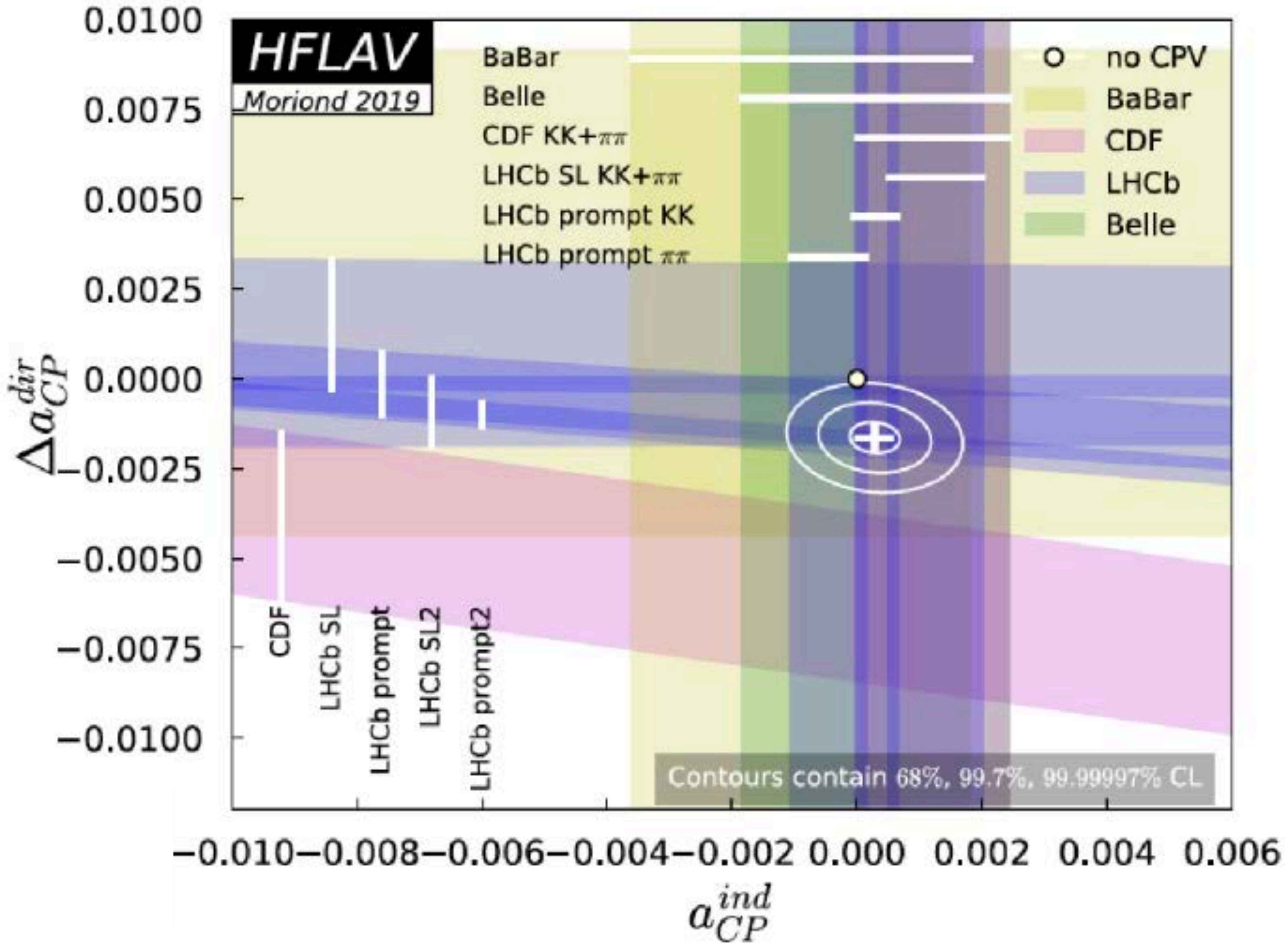


The Direct CPV is ***amplified*** in the difference! $V_{cd} : V_{us} \simeq -1 : 1$

Detection asymmetry and final-state independent uncertainty are completely dropped!

Direct *CP* violation in *D*

World average



Latest result [LHCb, 1903.08726]

$\Delta a_{CP}^{dir} = (-15.7 \pm 2.9) \times 10^{-4}$ 5.3σ discovery of CPV!

but, need confirmation by Belle II

A reliable SM prediction [QCD sum rule]

$\left|\Delta a_{CP}^{dir}\right| < (2.0 \pm 0.3) \times 10^{-4}$ [Khodjamirian, Petrov, '17]

Smaller than the data by a factor of 7; 4.7σ tension

(QCD sum rule works well in *B* physics)

SM explanation could be possible by QCD re scattering
$D^0 \to$ "$\pi\pi$" $\to K^-K^+$ [Grossman, FPCP2020]

New physics implications; 2HDM, MSSM, vector-like quark
[Dery, Nir, '19]

B anomaly + muon g-2 anomaly = ?

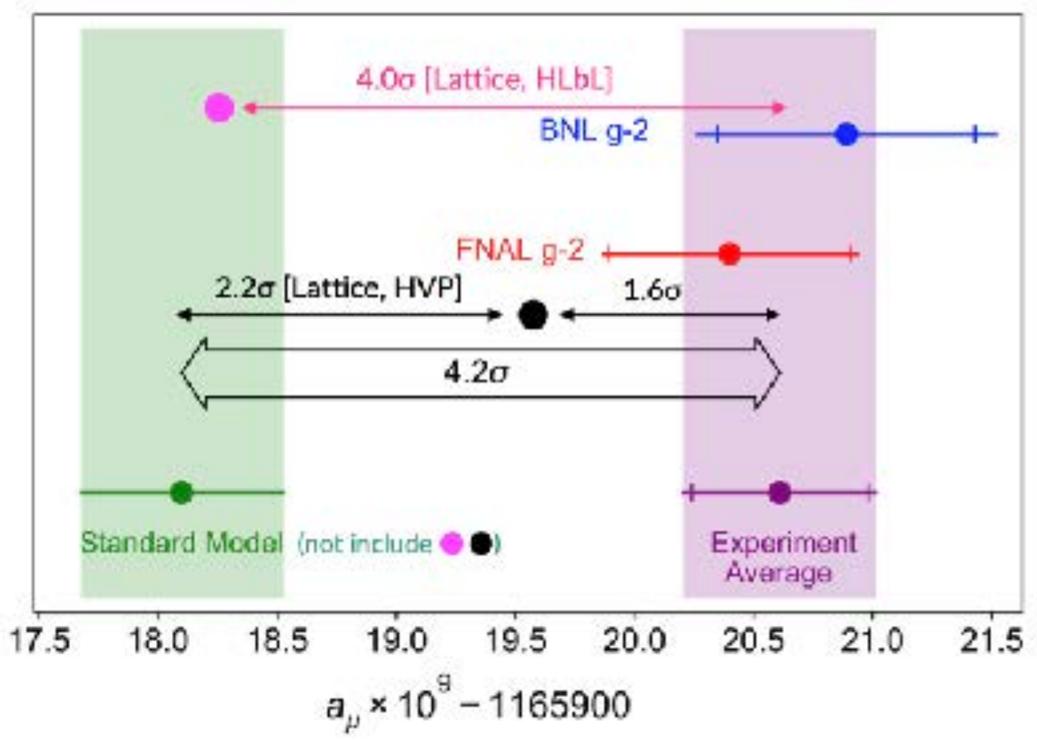
(B + muon g-2) anomaly =?

- I found 5 scenarios (6 papers)

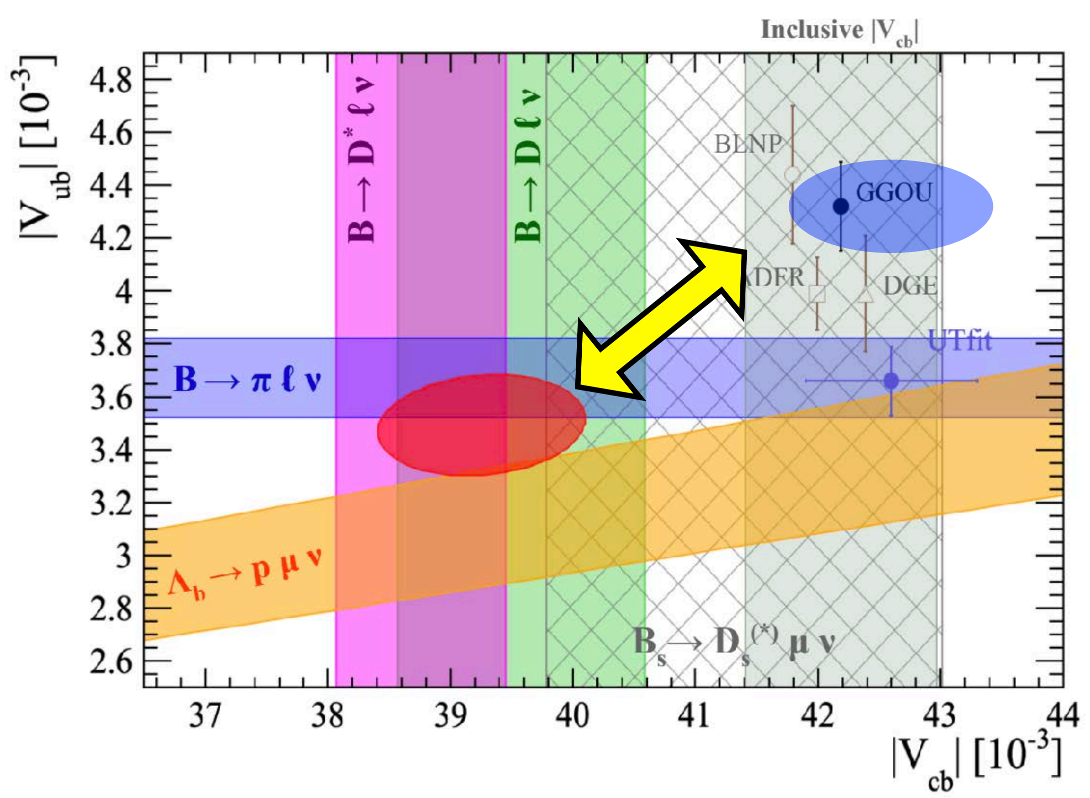
Refs	particles	solve	mass scale
Arcadi et al, 2104.03228	Vector-like fermion + scalars	muon g-2, R(K), DM	0.1〜1 TeV VL
Nomura, Okada 2104.03248	Scalar LQs	muon g-2, R(K), m_ν	〜5 TeV LQ
Bhattacharya et al, 2104.03947	ALP	muon g-2, $K\pi$ puzzle	〜140 MeV ALP
Marzocca, Trifinopoulos, 2104.05730	Scalar LQ + scalar	muon g-2, R(K), R(D), CAA	〜5 TeV LQ
Du et al, 2104.05685; Ban et al, 2104.06656	Vector LQ	muon g-2, R(K), R(D)	〜2 TeV LQ

Summary of anomalies —which is the truth?—

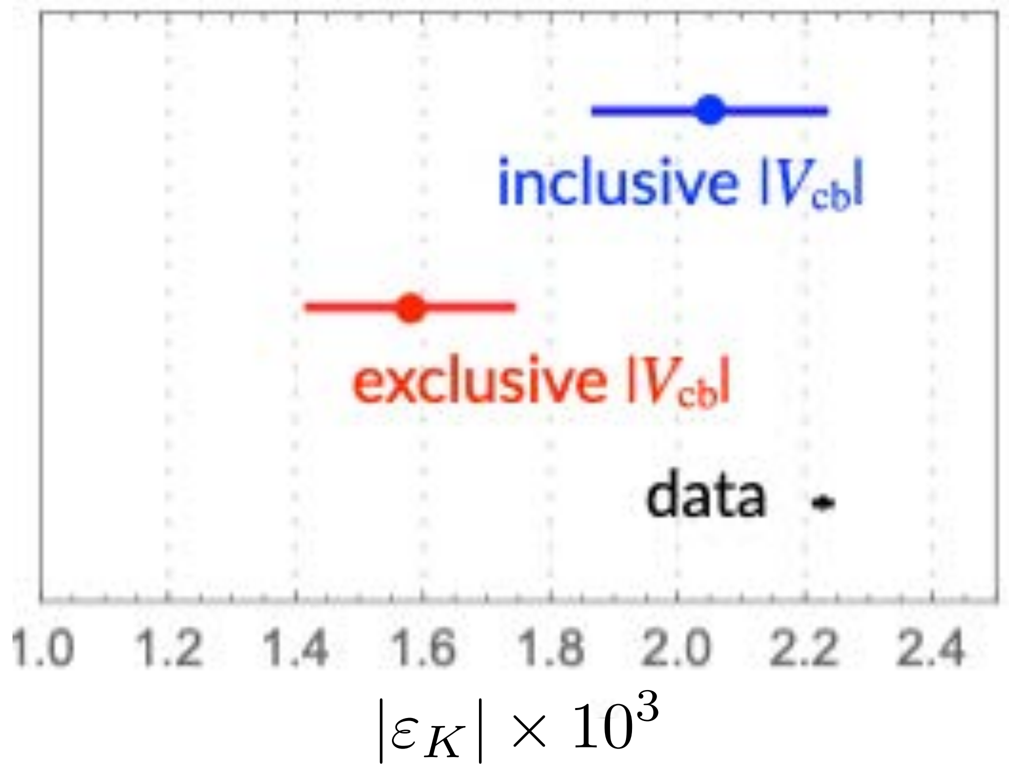
4.2σ?



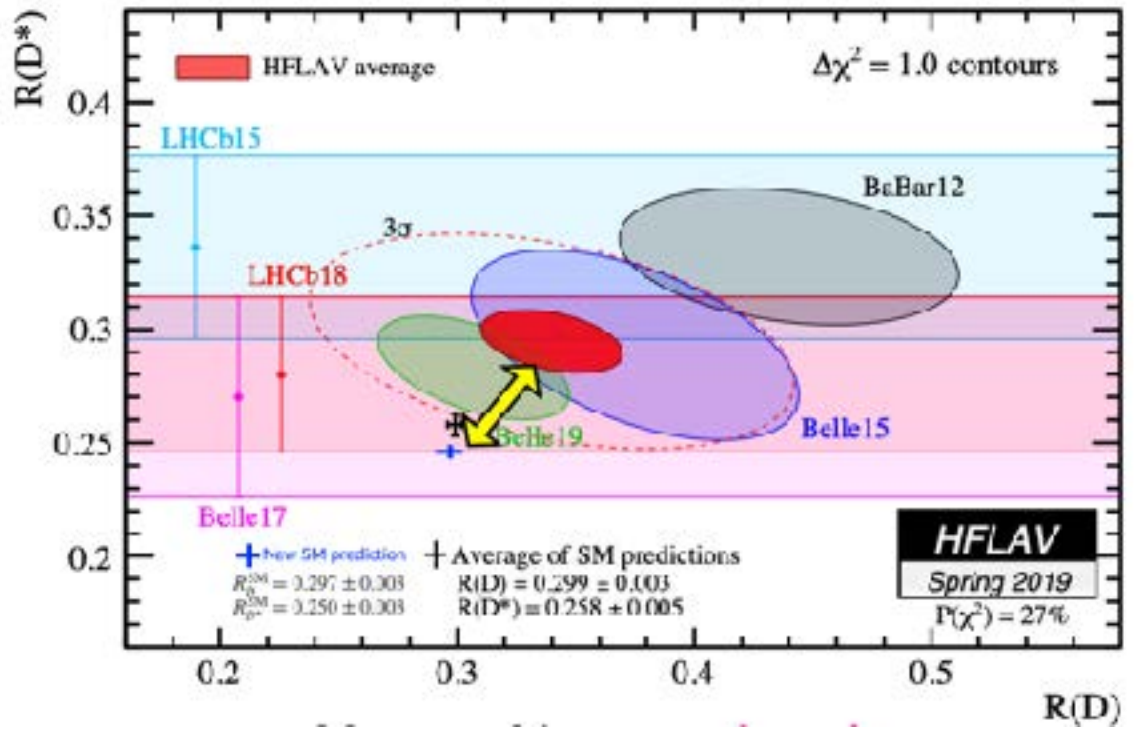
~3σ



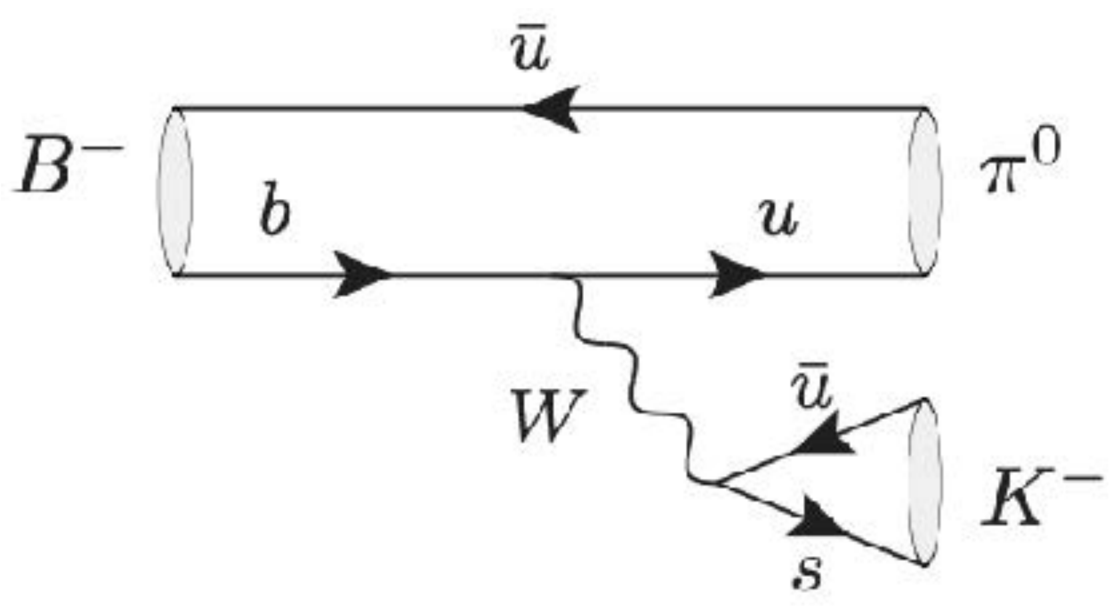
4.2σ?



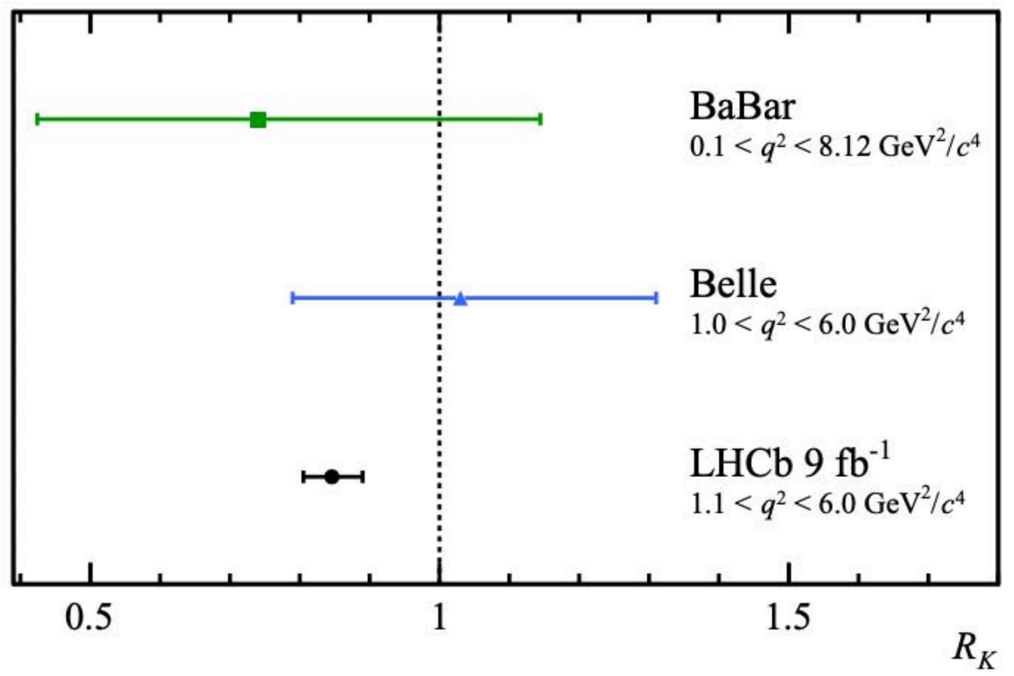
~4σ



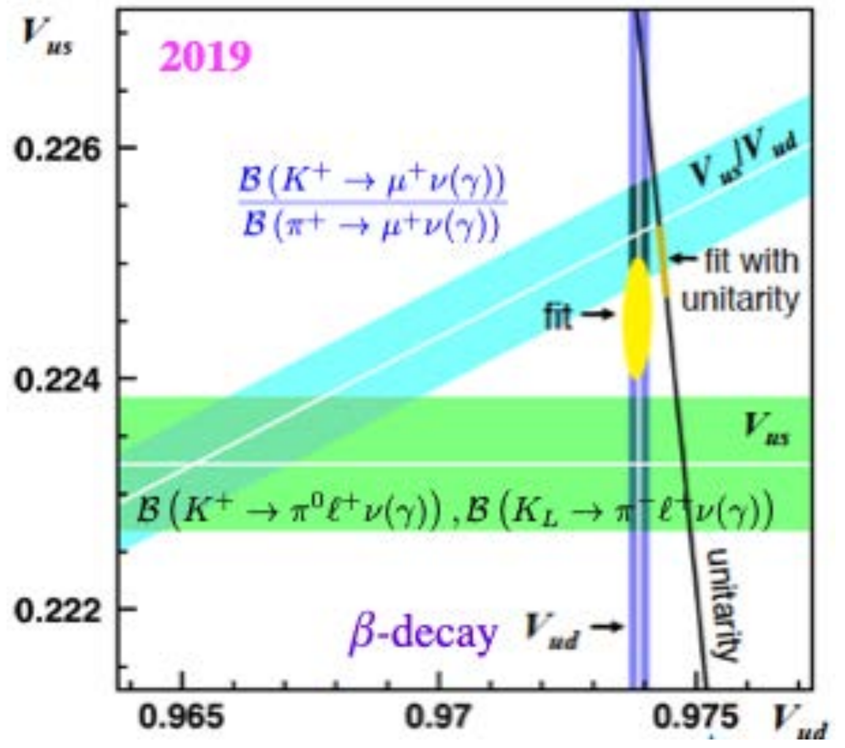
2.2σ?



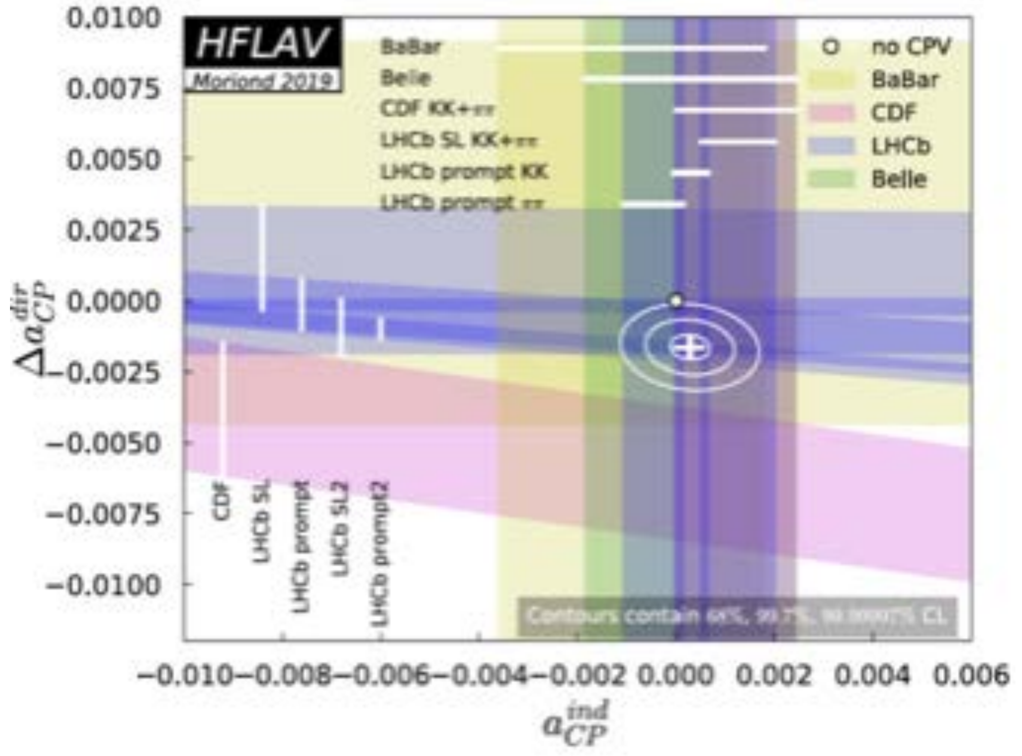
3.9σ



3-4σ



4.7σ?



SUSY? LQ? ALP? Z'? VL?

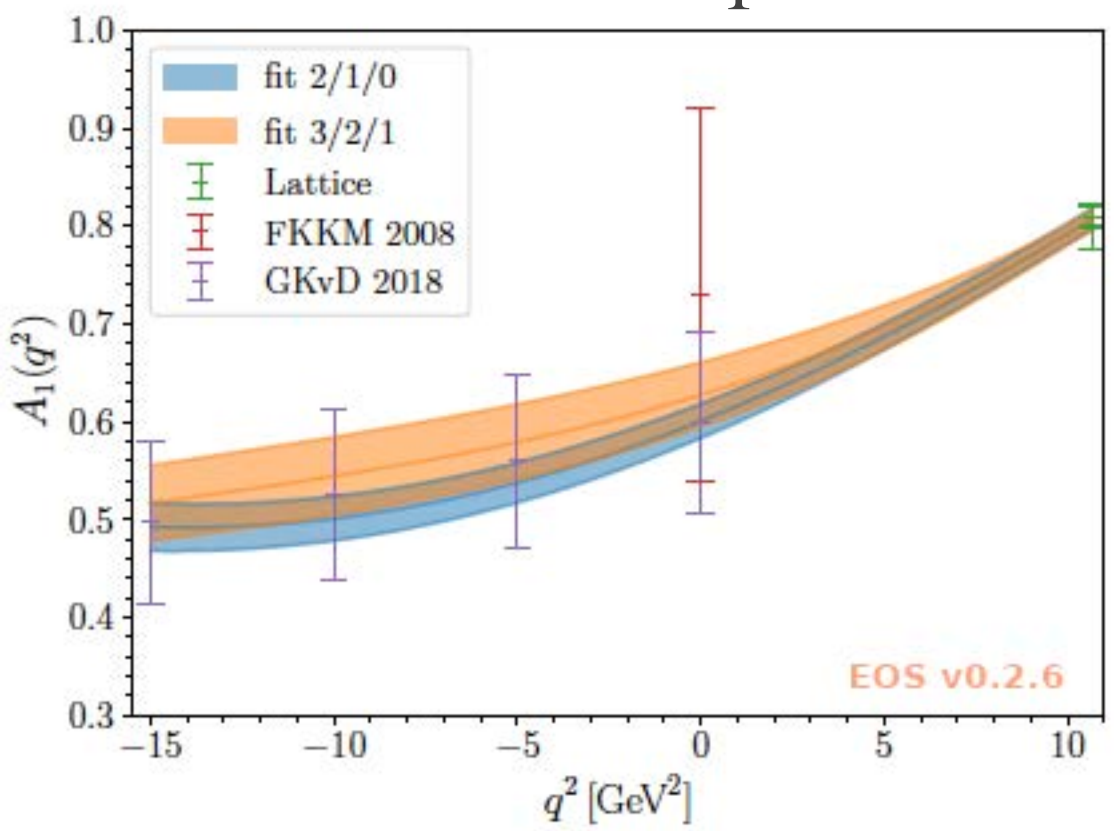
Backup

Latest SM predictions of $R(D)$ and $R(D^*)$

- All $\mathcal{O}(1/m_c^2)$ corrections in the heavy quark expansion are included and fit all form factors

[Bordone, Jung, van Dyk, EPJC '20; Iguro Watanabe, 2004.10208]

example: A_1 FF



2/1/0: $\mathcal{O}(1/m_c^2)$ corrections are just constants

3/2/1: ω dependence in $\mathcal{O}(1/m_c^2)$ is included

$$w = (m_B^2 + m_D^{(*)2} - q^2)/2m_B m_D^{(*)}$$

- All lattice data, QCDSR, and the latest LCSR result [Gubernari, Kokulu, van Dyk, JHEP '19]

$@q^2 = q^2_{\max}$ $\quad$ $@q^2 \leq 0$

$$R(D)_{\rm SM} = 0.298 \pm 0.003 \qquad R(D^*)_{\rm SM} = 0.247 \pm 0.006$$

- + Angular distributions from Belle data [Belle, 1510.03657; 1702.01521; 1809.03290]

$$R(D)_{\rm SM} = 0.297 \pm 0.003 \qquad R(D^*)_{\rm SM} = 0.250 \pm 0.003 \qquad \text{[BJD]}$$

$$R(D)_{\rm SM} = 0.297 \pm 0.006 \qquad R(D^*)_{\rm SM} = 0.245 \pm 0.004 \qquad \text{[IW]}$$

$R(D)$: 1.4 → 1.4, 1.4 σ

$R(D^*)$: 2.5 → 3.2, 3.5 σ

combine: 3.1 → 3.9, 4.1 σ (my personal analysis)

[Blanke, Crivellin, TK, Moscati, Nierste, Nisandzic, PRD '19]

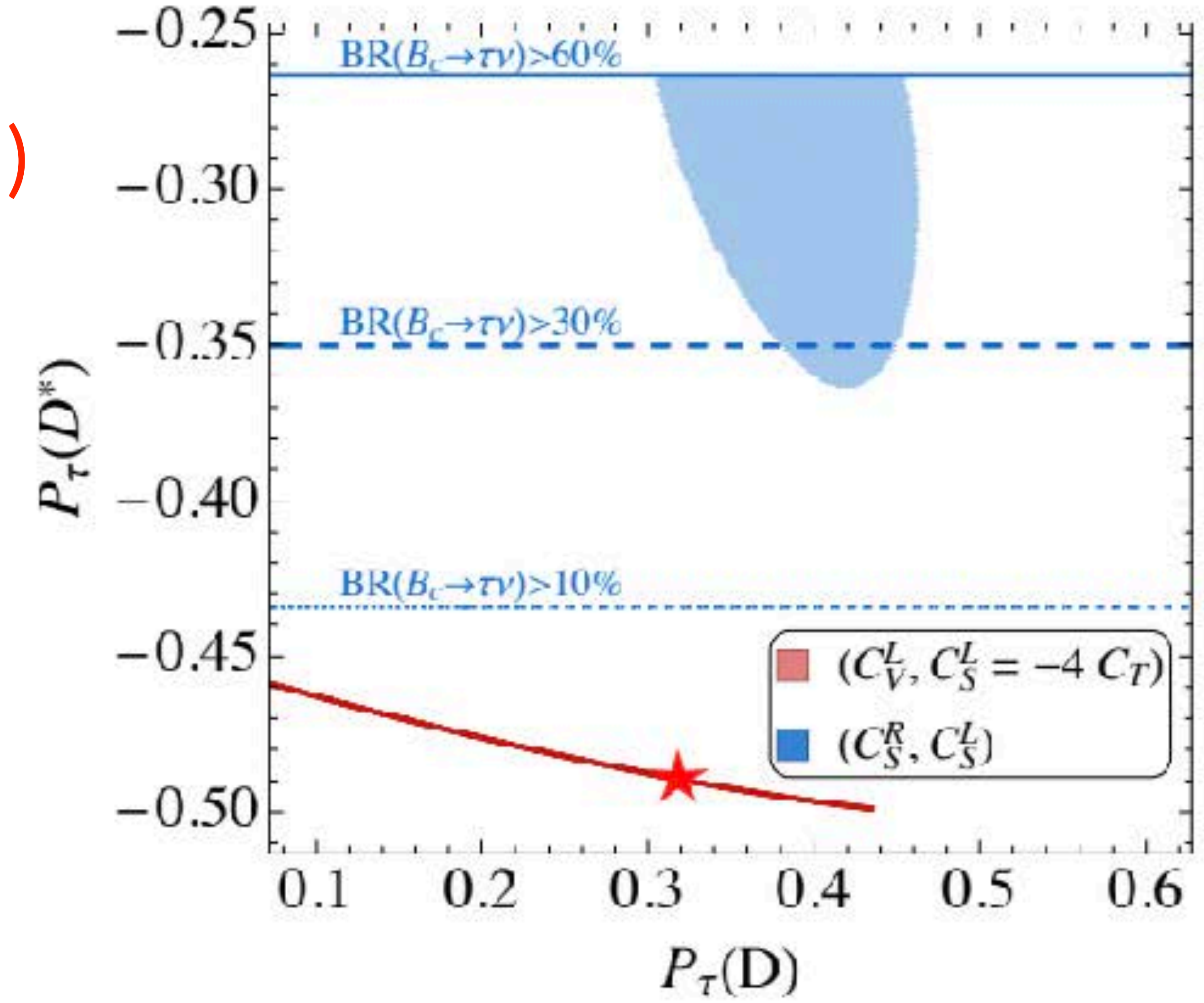
SU(2)$_L$-singlet scalar LQ (S_1)

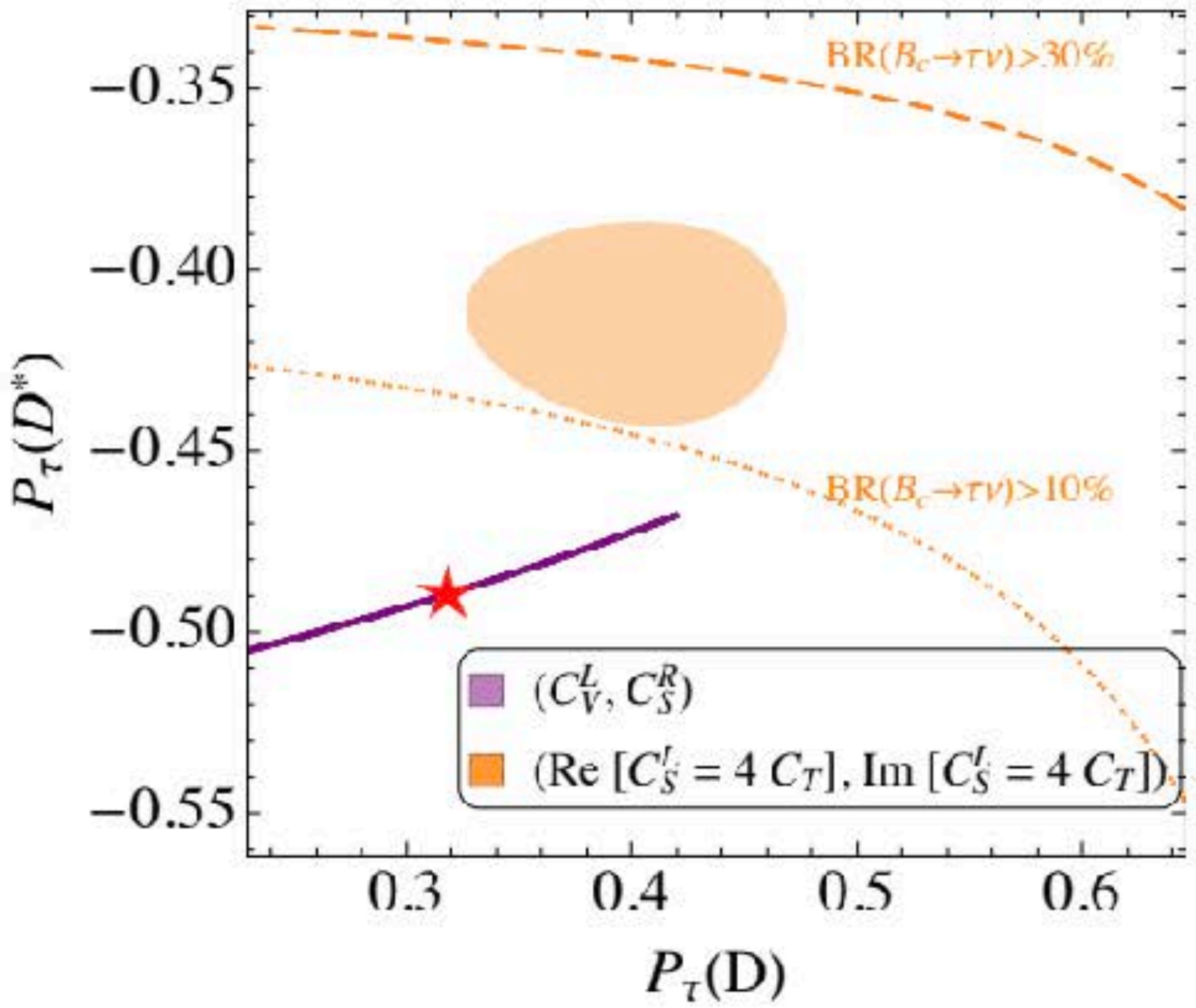
Charged Higgs

SU(2)$_L$-singlet vector LQ (U_1)

SU(2)$_L$-doublet scalar LQ (R_2)

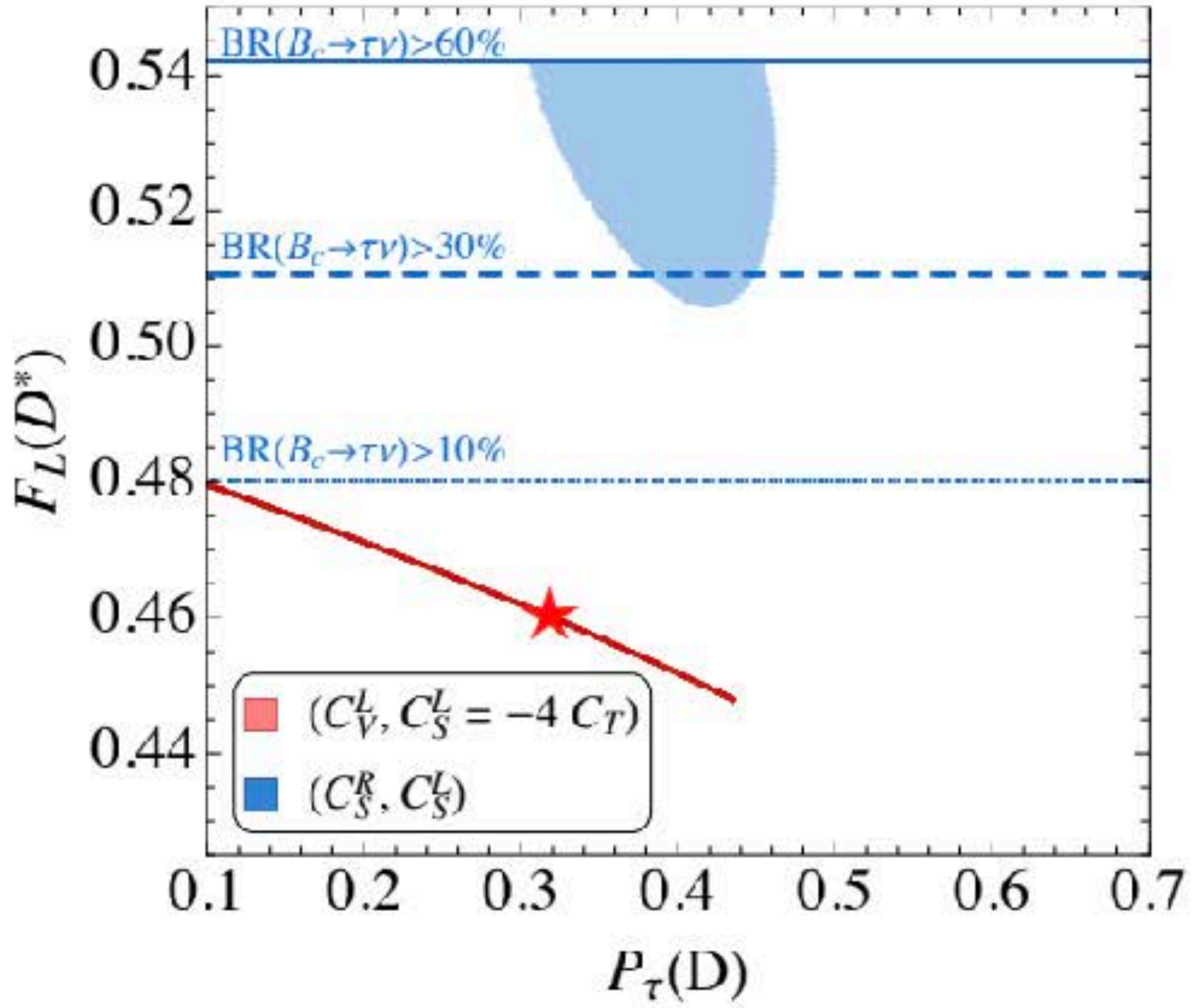
$\boldsymbol{P_\tau(D)}$ vs. $\boldsymbol{P_\tau(D^*)}$

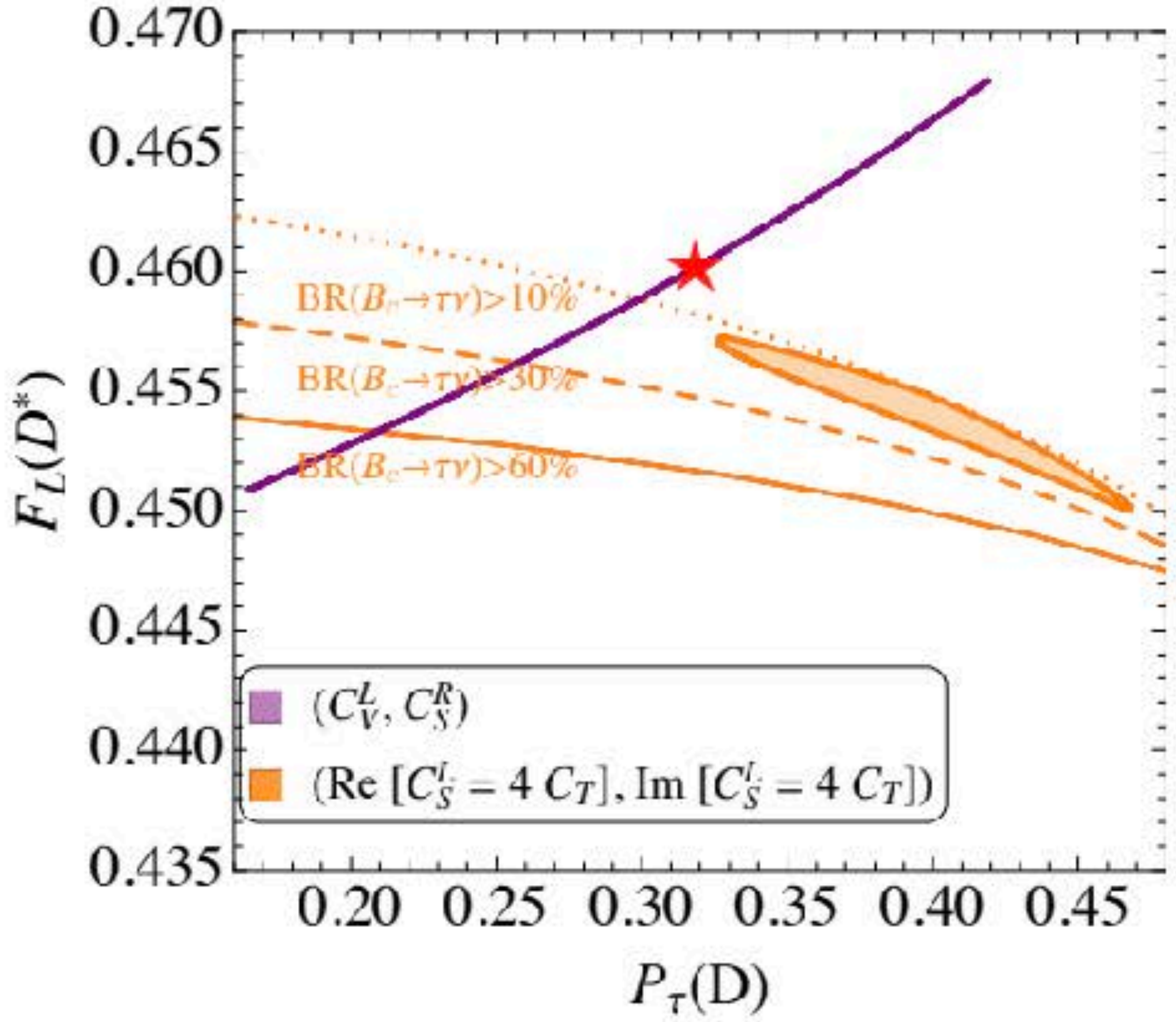




$P_\tau(D)$ can discriminate the new physics

$\boldsymbol{P_\tau(D)}$ vs. $\boldsymbol{F_L(D^*)}$





$P_\tau(D^*)$ could discriminate the new physics

$F_L(D^*)$ is difficult to discriminate them

Tensor operator vs. $F_L(D^*)$

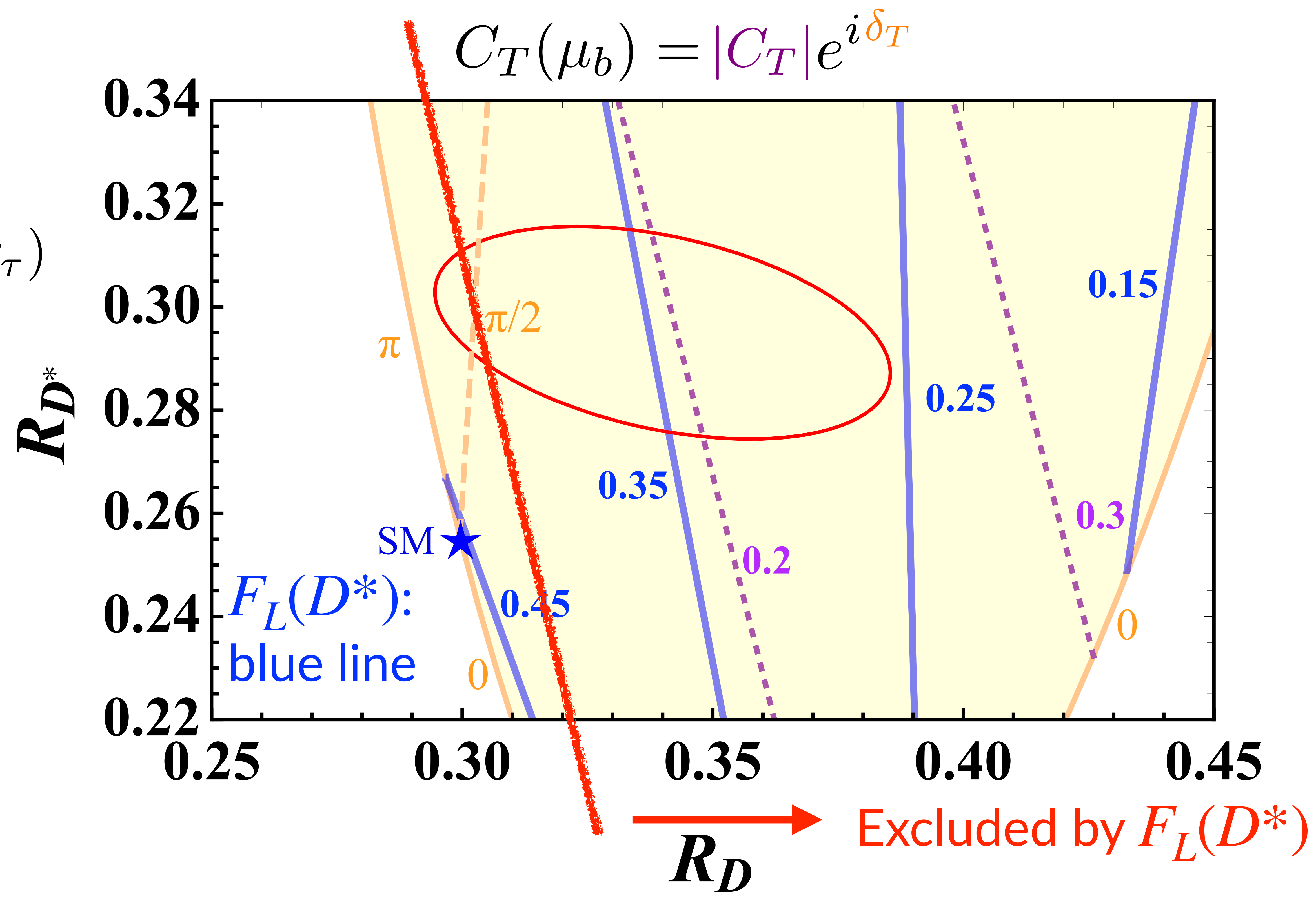
- Tensor operator in new physics scenario is significantly constrained by $F_L(D^*)$
  [Iguro, TK, Omura, Watanabe, Yamamoto, '19, UPDATED]

$$\mathcal{H}_{\rm eff} = 2\sqrt{2} G_F V_{cb} C_T(\mu)\,(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$

$$C_{T,\,\rm SM} = 0$$

$$F_L(D^*) = 0.60 \pm 0.08 \pm 0.04$$

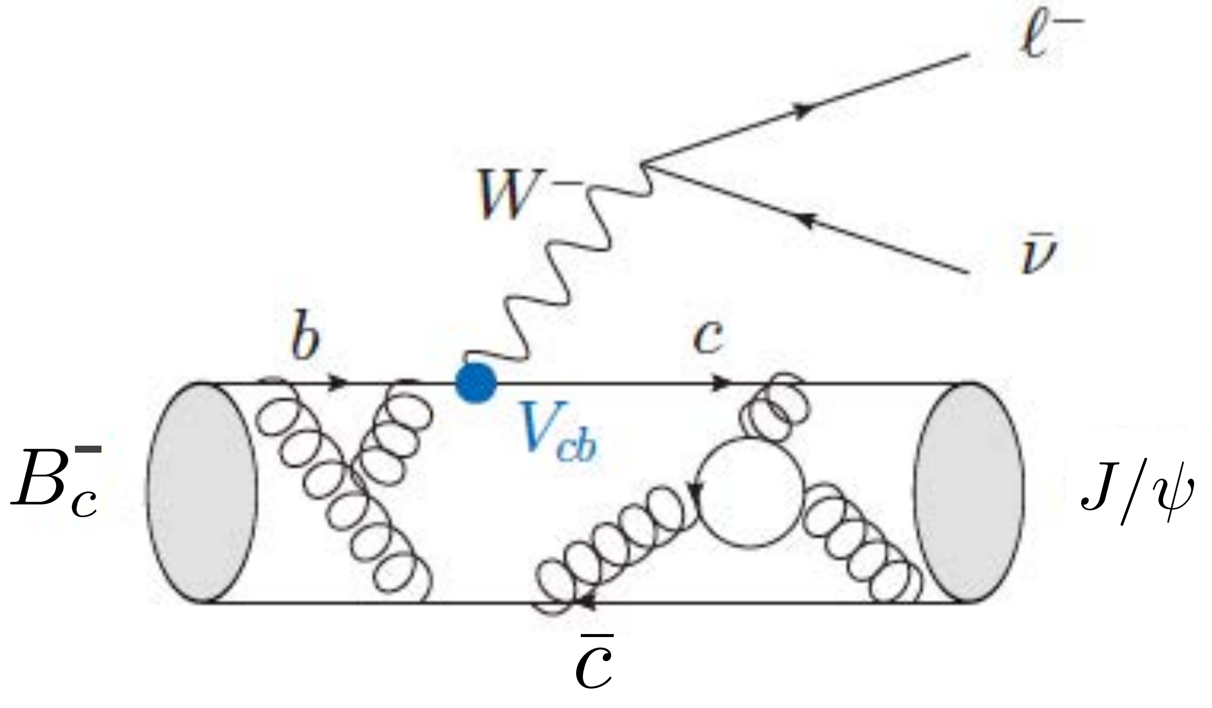
[Belle, 1903.03102]



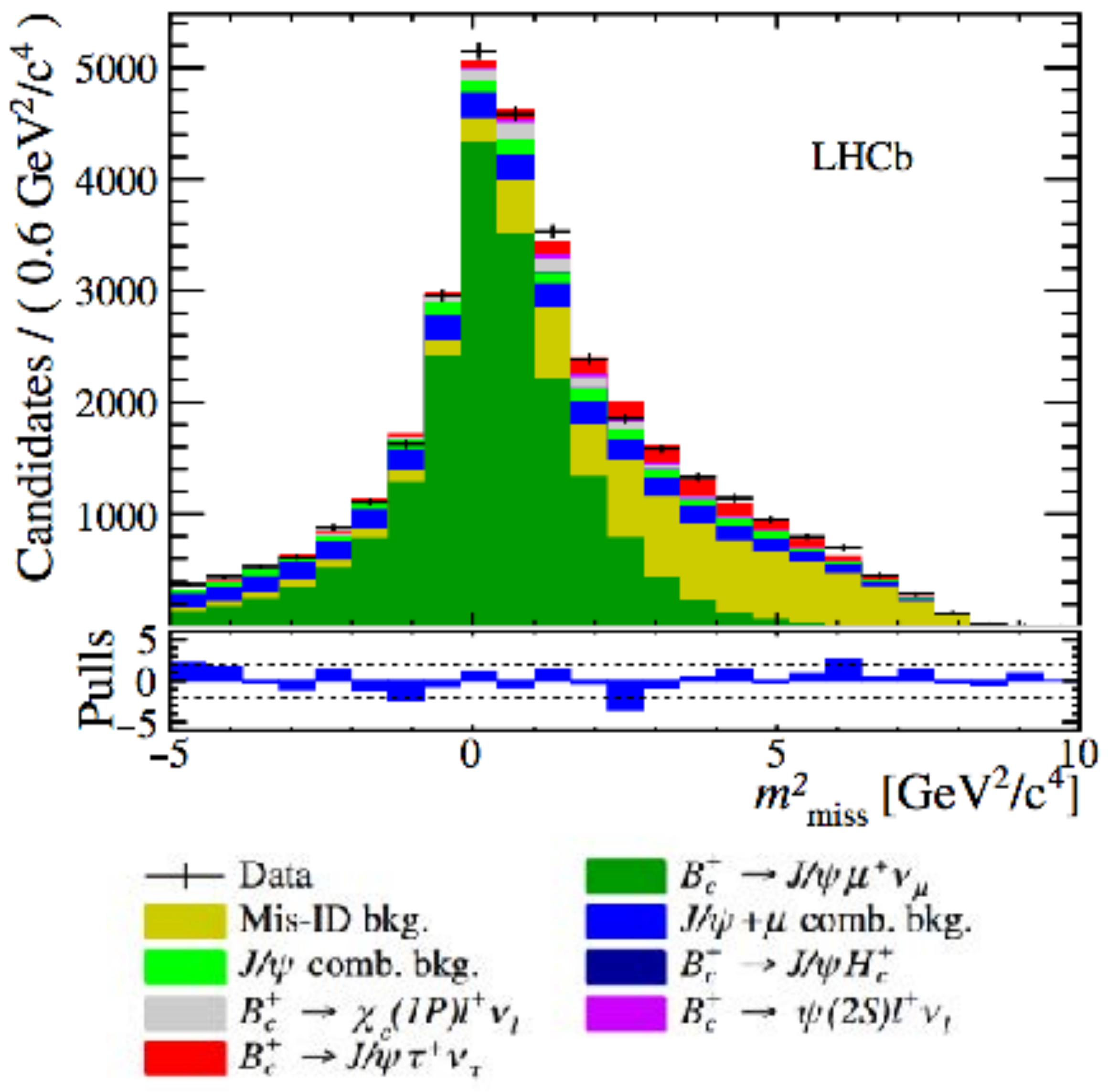
Another channel: $R(J/\psi)$

- The LFU violation was measured in $B_c^- \to J/\psi$ transitions

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^- \to J/\psi \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B_c^- \to J/\psi \ell^- \bar{\nu}_\ell)}$$



[LHCb, 1711.05623]



$$R(J/\psi)_{\rm exp} = 0.71 \pm 0.17_{\rm stat} \pm 0.18_{\rm syst}$$

$$R(J/\psi)_{\rm SM} \sim 0.25\text{-}0.28 \quad \to\to\to\to$$

Same-direction as R(D) and R(D*) tensions.

But, the form factors are poorly known

because heavy quark expansion is broken

by m_c (spectator quark here)

First lattice result [HPQCD, 2007.06956]

$$R(J/\psi)_{\rm SM} = 0.2601 \pm 0.0036$$

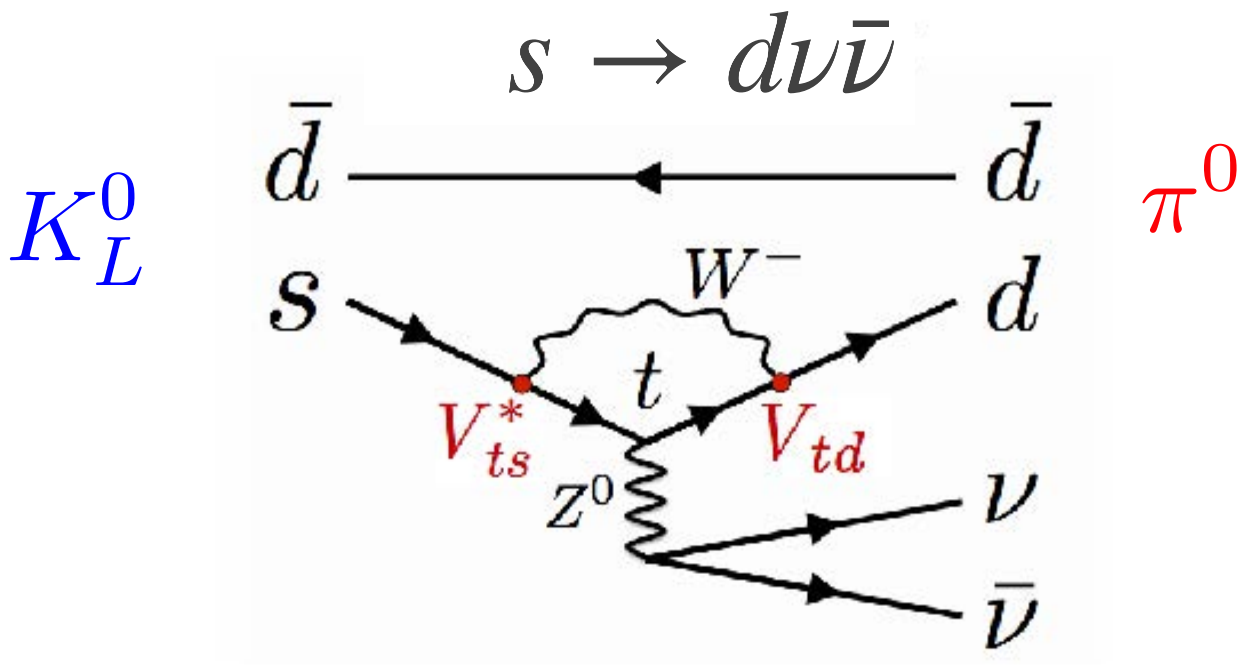
1.8σ consistent

using N_f=2+1+1, with "HISQ" *c* and heavy quark *b*

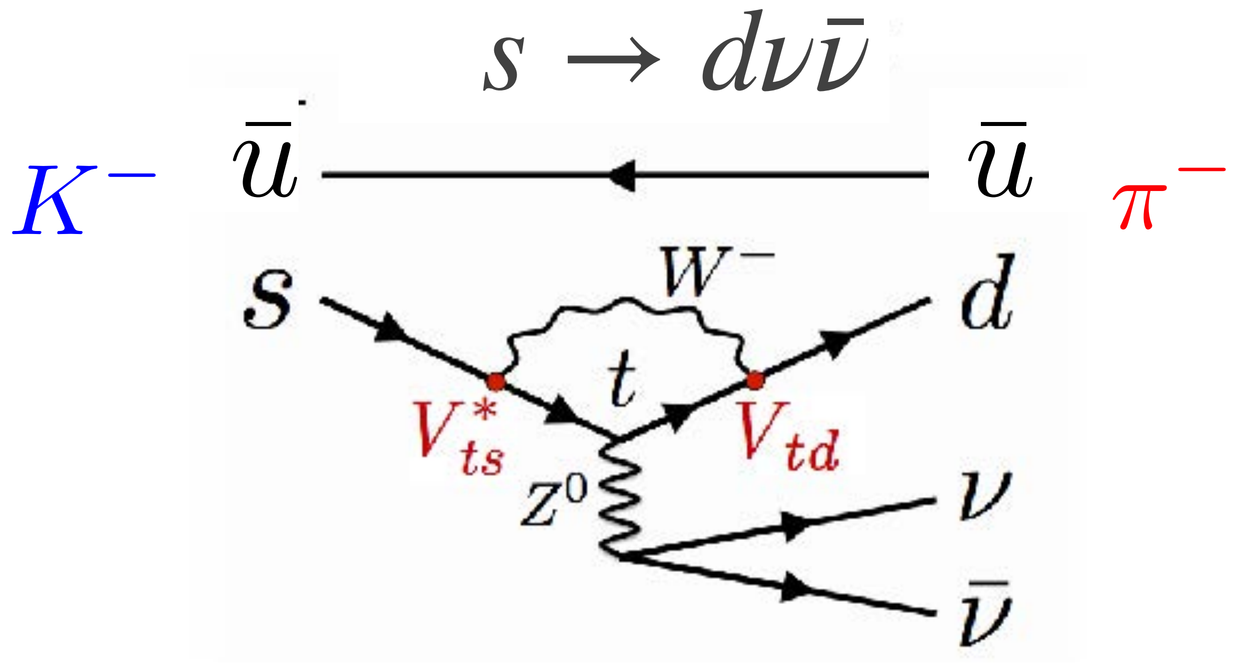
Early new physics study, *e.g.*, [Watanabe, PLB '18; Alok, Kumar, Kumar, Kumbhakar, Sankar, JHEP '18]

Signal reconstructed with tau leptonic decays and LHCb Run 1 data (3fb^{-1})

Grossman-Nir bound (theoretical relation)



Same diagram
in quark level



$$\left(\begin{aligned} \frac{\Gamma\left(K_L \to \pi^0\nu\bar{\nu}\right)}{\Gamma\left(K^+ \to \pi^+\nu\bar{\nu}\right)} &= \frac{\left|pA_{\pi^0\nu\bar{\nu}} - q\bar{A}_{\pi^0\nu\bar{\nu}}\right|^2}{\left|\sqrt{2}A_{\pi^0\nu\bar{\nu}}\right|^2} = \frac{1}{4}\left|1 - \lambda_{\pi\nu\bar{\nu}}\right|^2 \\ &= \frac{1}{4}\left(1 + |\lambda_{\pi\nu\bar{\nu}}|^2 - 2\mathrm{Re}\lambda_{\pi\nu\bar{\nu}}\right) \simeq \frac{1}{2}\left(1 - \mathrm{Re}\lambda_{\pi\nu\bar{\nu}}\right) = \sin^2\left[\frac{\mathrm{Arg}\left(\lambda_{\pi\nu\bar{\nu}}\right)}{2}\right] \end{aligned} \right)$$

$$K_L \propto pK^0 - q\bar{K}^0$$

$$A_{\pi^0\nu\bar{\nu}} = \langle \pi^0\nu\bar{\nu}|\mathcal{H}|K^0\rangle,$$

$$\bar{A}_{\pi^0\nu\bar{\nu}} = \langle \pi^0\nu\bar{\nu}|\mathcal{H}|\bar{K}^0\rangle,$$

$$\lambda_{\pi\nu\bar{\nu}} = \left(\frac{q}{p}\right)_K \frac{\bar{A}_{\pi^0\nu\bar{\nu}}}{A_{\pi^0\nu\bar{\nu}}}$$

- Grossman-Nir bound for general NP models (including $\nu_i\bar{\nu}_j$) [Grossman, Nir, PLB '97]

$$\mathcal{B}\left(K_L \to \pi^0\nu\bar{\nu}\right) = \left(\frac{\tau_L}{\tau^+} + \Delta_{\mathrm{IB,\,EM}}\right)\sin^2\theta\mathcal{B}\left(K^+ \to \pi^+\nu\bar{\nu}\right) \le 4.32\mathcal{B}\left(K^+ \to \pi^+\nu\bar{\nu}\right)$$