Recent Topics in Flavor Physics

三島 智 (KEK)

松江素粒子物理学研究会
Mar. 25, 2016

Outline

1. Introduction
2. Anomalies in flavor physics
3. Possible patterns of NP signals
4. Summary

Satoshi Mishima (KEK)

1. Introduction

NP search: direct vs. indirect

NP の探索方法

直接探索
high-energy frontier
ATLAS/CMS (LHC)

間接探索
high-intensity frontier

The NP scale might be higher than the TeV scale, against the naturalness argument.

⇩

Indirect searches for NP through the virtual effects of new particles can explore above TeV scale.

NP の間接測定 (Indirect search)

- Indirect searches are conducted at low-energy experiments based on high-statistics productions of the gauge bosons, kaon, D and B mesons, muon and tau, as well as with the precise measurements of the SM parameters at high-energy experiments.

Flavor physics, EW precision test, Higgs couplings, ….

- Historically, indirect hints to unobserved heavy particles were obtained from low-energy experiments:

e.g., the existence of charm quark from kaon decays,
the heavy top mass from B-Bbar oscillation,
the Higgs mass from the EW precision fit, …

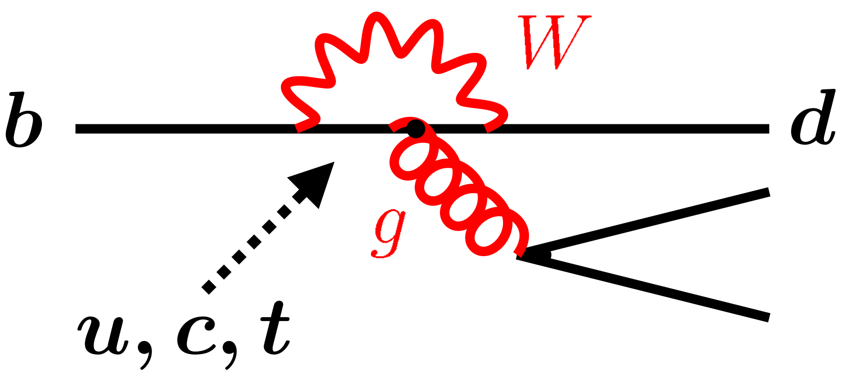
⇨ observed later directly at high-energy experiments.

- **Indirect searches are as relevant as ever after the LHC 7-8 TeV run.**

FCNC in the SM

Flavor Changing Neutral Current 過程は

SM では強く抑制されている：



One-loop level

GIM 機構

$$\mathcal{A} = V_{ub}^* V_{ud}\, f(m_u) + V_{cb}^* V_{cd}\, f(m_c) + V_{tb}^* V_{td}\, f(m_t)$$

CKM行列のユニタリティ

⇨ $\mathcal{A} = 0$ if $m_u = m_c = m_t$ but $m_t \gg m_{u,c}$

CKMの非対角成分 and/or Quark 質量が小さい

$$V_{ts}^* V_{td} \sim 5 \times 10^{-4} \ll V_{tb}^* V_{td} \sim 10^{-2} < V_{tb}^* V_{ts} \sim 4 \times 10^{-2}$$

K B B

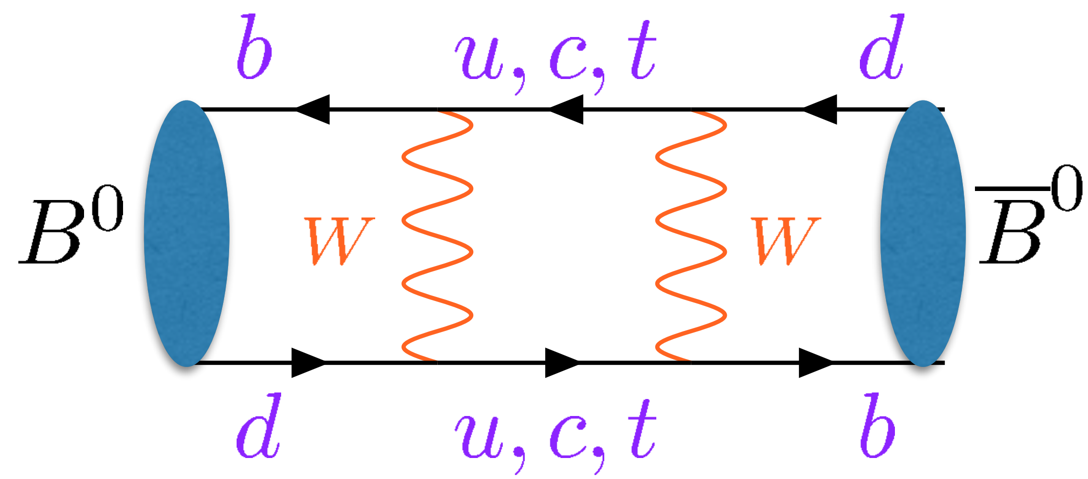
Why are FCNC processes interesting?

SM の寄与が小さいので、NP の効果が
相対的に大きくて観測出来るかも。

FCNC 過程の精密測定は、LHC での直接
探索では探ることの出来ない高エネルギー
の物理に対する感度がある

Bounds from mixings

$$\mathcal{L}_{\rm eff} = \sum \frac{c_{\rm NP}}{\Lambda^2} O_{\Delta F=2}$$



Operator	Λ in TeV $(c_{\rm NP}=1)$ Re	Λ in TeV $(c_{\rm NP}=1)$ Im	Bounds on $c_{\rm NP}$ $(\Lambda = 1$ TeV$)$ Re	Bounds on $c_{\rm NP}$ $(\Lambda = 1$ TeV$)$ Im	Observables	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K	$O(10^5$ TeV$)$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K	
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$	$O(10^4$ TeV$)$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$	
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$	$O(10^3$ TeV$)$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$	
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$	
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$	

Table 1: Bounds on representative dimension-six $\Delta F = 2$ operators with effective coupling $c_{\rm NP}/\Lambda^2$. The bounds are quoted on Λ, setting $|c_{\rm NP}| = 1$, or on $c_{\rm NP}$, setting $\Lambda = 1$ TeV. The right column denotes the main observables used to derive these bounds.[26]

Isidori, 1507.00867

Bounds from mixings

前のページでは Ci=1 を仮定

Note：

もし結合定数が loop-suppressed 等の理由で小さければ、NPスケールに対する感度は下がる。

Implication to NP

NP が特殊なフレーバー構造を持っている？

or

NP のスケールが very high？

TeV スケールの NP 模型は特殊なフレーバー構造を持っていなければならない

Model-independent and -dependent analyses

- Model-independent analysis with $\mathcal{L}_{\mathrm{eff}}$

  Correlations among observables

  ➡ Useful guide to look for NP effects

  Many operators

  ➡ Limited predictive power

  ➡ Additional assumption: e.g. MFV

- Model-dependent analysis with concrete models

  Stronger correlations among operators and observables, which cannot be captured in model-independent analysis

  どのNP模型を考える？

Example: MSSM

- General MSSM ではフレーバーを破る寄与が沢山出てくる：

  CKM-induced contributions from H^+, χ^+exchanges

  flavor mixings in the sfermion mass matrix

- Possible solutions:

  Decoupling, Alignment, Super-GIM

> フレーバー物理 ➡ SUSY breaking の機構の情報

- 他のNP模型でも一般にフレーバーを大きく破る寄与が出てしまう (NP flavor problem)

Satoshi Mishima (KEK)

Minimal Flavor Violation Hypothesis

G.D'Ambrosio, G.F.Giudice, G.Isidori & A.Strumia, hep-ph/0207036

- SMのゲージ相互作用はフレーバーに依らない
  - ⇨ フレーバー対称性： $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$
- SMでは、この対称性は Yukawa 結合で破れている

$$\mathcal{L} = Y^u_{ij}\,\overline{Q_{Li}}\,\tilde{\phi}\,U_{Rj} + Y^d_{ij}\,\overline{Q_{Li}}\,\phi\,D_{Rj} + \mathrm{h.c.}$$

$\overline{Q_L} : (\bar{3}, 1, 1)$
$U_R : (1, 3, 1)$
$D_R : (1, 1, 3)$

- NPの低エネルギー有効理論の(高次元)オペレーターが上記のフレーバー対称性に対して不変と仮定

ただし　$Y^u : (3, \bar{3}, 1)$　$Y^d : (3, 1, \bar{3})$　とする

e.g. $\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$

Minimal Flavor Violation Hypothesis

- MFVを仮定すると、FCNC過程の間に関係が付く

  e.g. $\mathcal{B}(B \to X_s \nu \bar{\nu}) \leftrightarrow \mathcal{B}(K \to \pi \nu \bar{\nu})$

- CP violation は CKM の位相を起源とする

- もし MFV の関係式からのズレが見つかれば

  ➡ 新しいフレーバー構造の存在

- MFV を実現するような具体的な模型の例：

  e.g. MSSM with gauge-mediated SUSY breaking

- Constrained MFV (CMFV)：

  SMと同じオペレーターのみを考える

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Sensitivity to NP scale with MFV

G.Isidori, 1302.0661

Operator	Bound on Λ	Observables
$\phi^\dagger \left(\overline{D}_R Y_d^\dagger Y_u Y_u^\dagger \sigma_{\mu\nu} Q_L\right) (eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$\phi^\dagger \left(\overline{D}_R Y_d^\dagger Y_u Y_u^\dagger \sigma_{\mu\nu} T^a Q_L\right) (g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right) (\overline{E}_R \gamma_\mu E_R)$	5.7 TeV	$B_s \to \mu^+\mu^-$, $B \to K^*\mu^+\mu^-$
$i\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right) \phi^\dagger D_\mu \phi$	4.1 TeV	$B_s \to \mu^+\mu^-$, $B \to K^*\mu^+\mu^-$
$\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right) (\overline{L}_L \gamma_\mu L_L)$	5.7 TeV	$B_s \to \mu^+\mu^-$, $B \to K^*\mu^+\mu^-$
$\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right) (eD_\mu F_{\mu\nu})$	1.7 TeV	$B \to K^*\mu^+\mu^-$

The bounds are in the TeV range.

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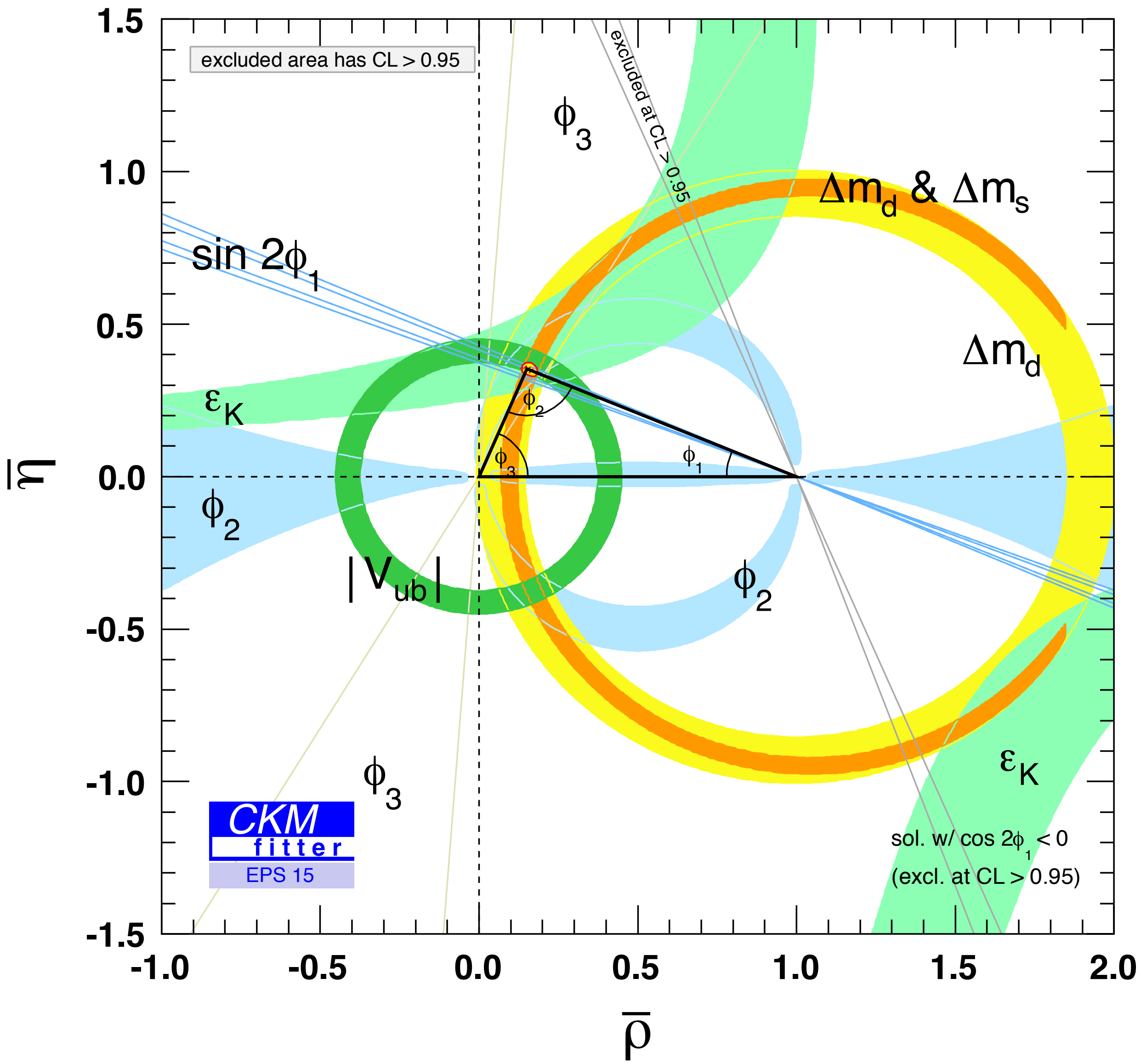
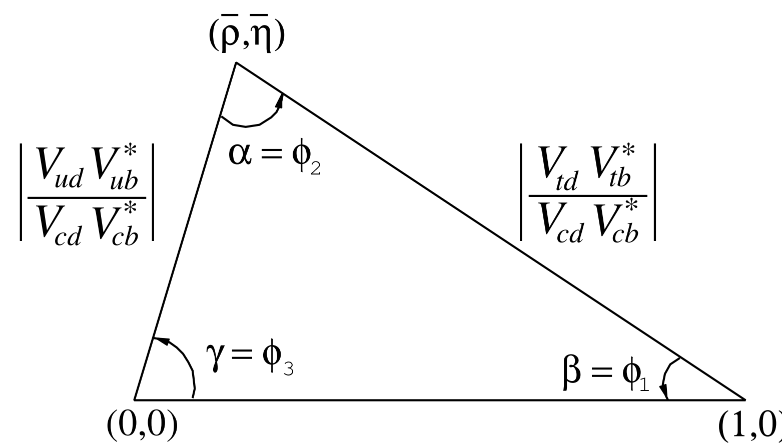
SM works very well.



$$\hat{V} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda + \mathcal{O}(\lambda^7) & A\lambda^3(\varrho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\varrho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 + \mathcal{O}(\lambda^8) \\ A\lambda^3(1 - \overline{\varrho} - i\overline{\eta}) & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\varrho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix}$$



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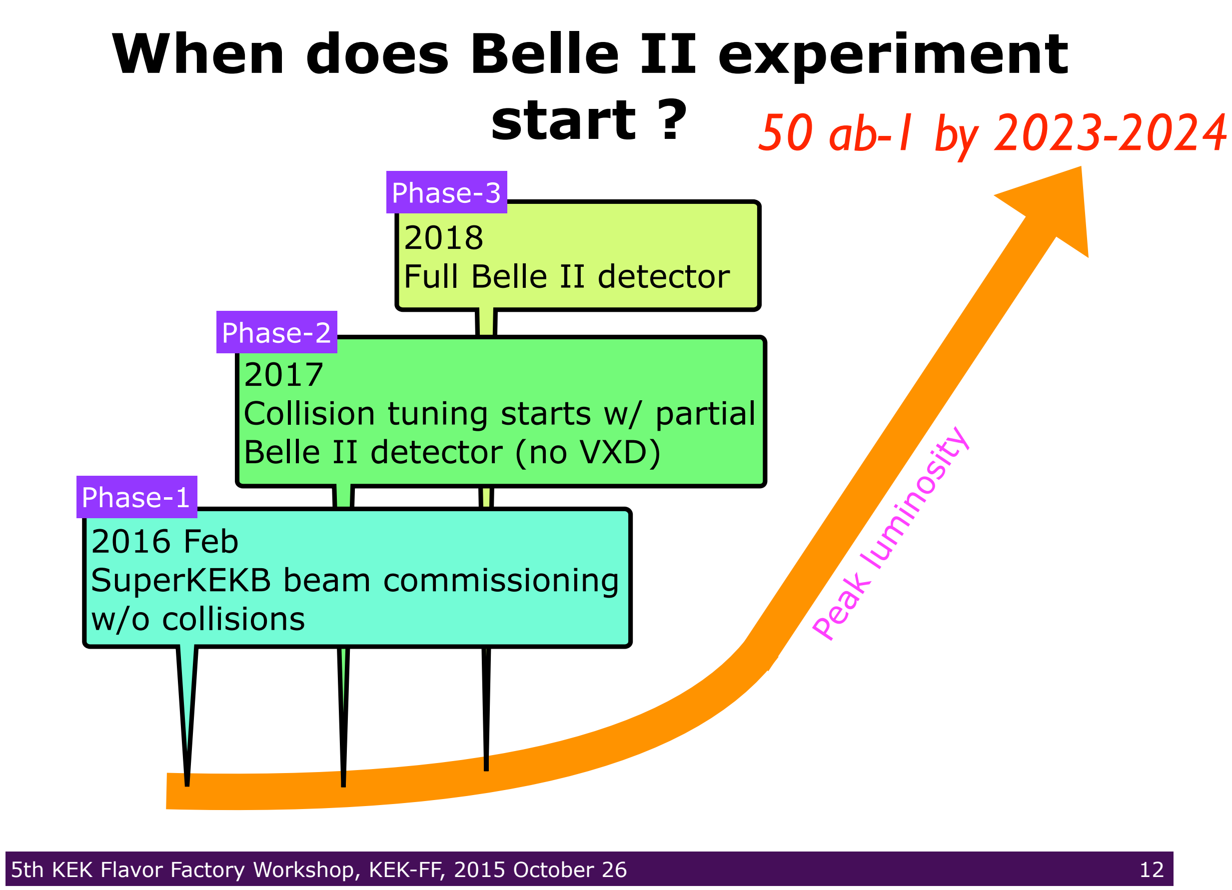
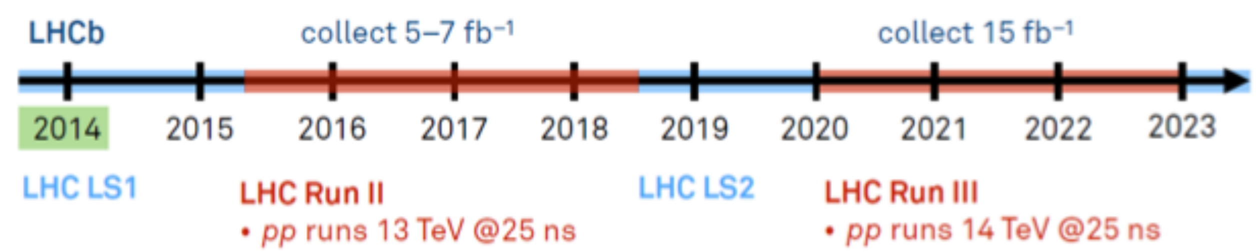
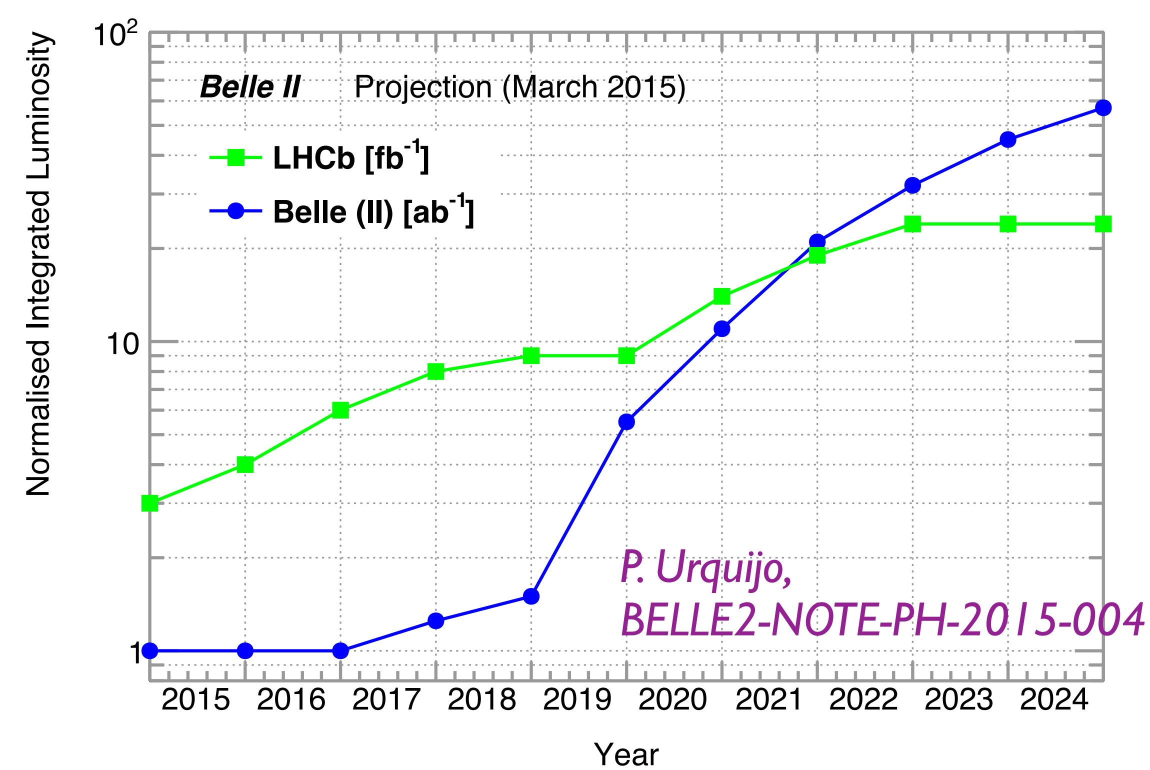
LHCb vs. Belle II

- LHCb: $\sigma(bb@14\mathrm{TeV})/\sigma(bb@8\mathrm{TeV}) \approx 3$
- SuperKEKB: $L = 8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ *higher statistics!*
- LHCb fb-1 / Belle II ab-1 ~ O(1) for various cases
- Complementary to direct searches for NP at the LHC.



I.Adachi, KEK-FF 2015





LHCb vs. Belle II

- LHCb:
  - huge statistics
  - (very) rare decays to clean final states

$$B_{d,s} \to \mu^+\mu^-,\ B \to K^*\mu^+\mu^-,\ \cdots$$

- Belle II: ⇨ Talk by 石川さん on 3/26
  - well-defined initial state (full reconstruction of B)
  - very clean environment
  - final states with neutrals

$$B \to \pi^0\pi^0,\ B \to K_S\pi^0,\ B \to K_S\pi^0\gamma,\ \cdots$$

  - final states with missing particles

$$B \to \tau\nu,\ B \to D^{(*)}\tau\nu,\ B \to K^{(*)}\nu\nu,\ \cdots$$

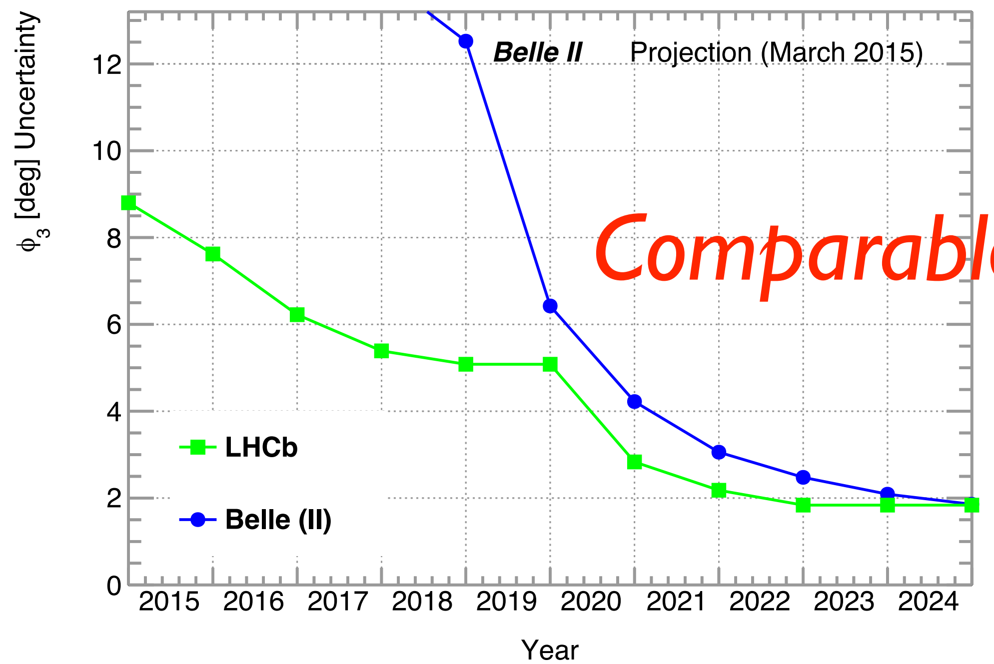
  - inclusive modes

$$B \to X_s\gamma,\ B \to X_s\ell^+\ell^-,\ \cdots$$

Competition and Complementarity

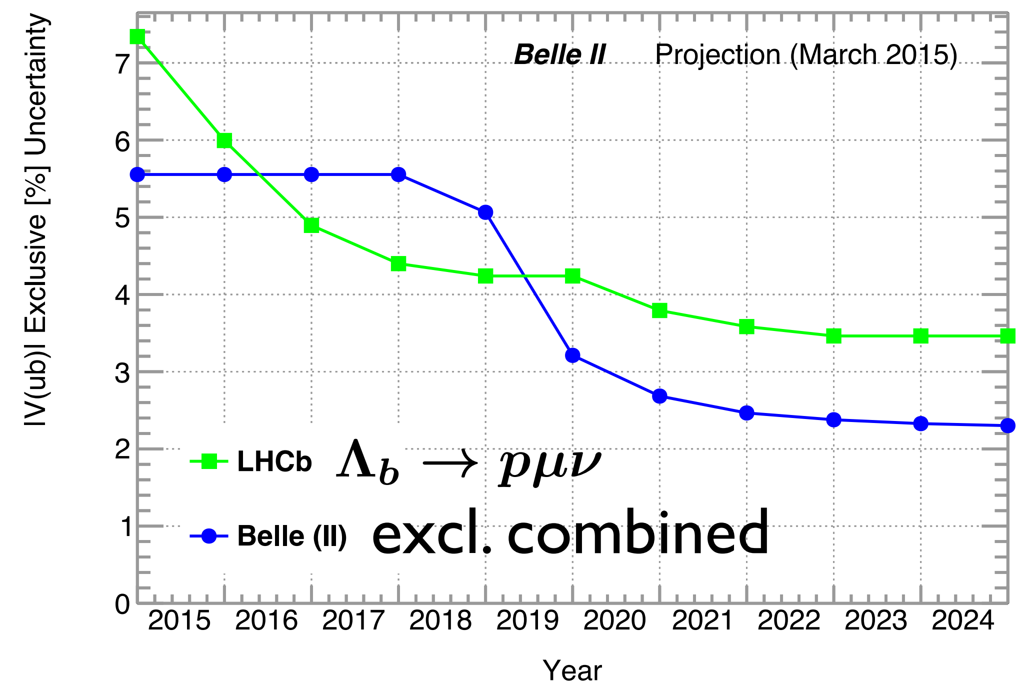
P. Urquijo, BELLE2-NOTE-PH-2015-004

ϕ_3

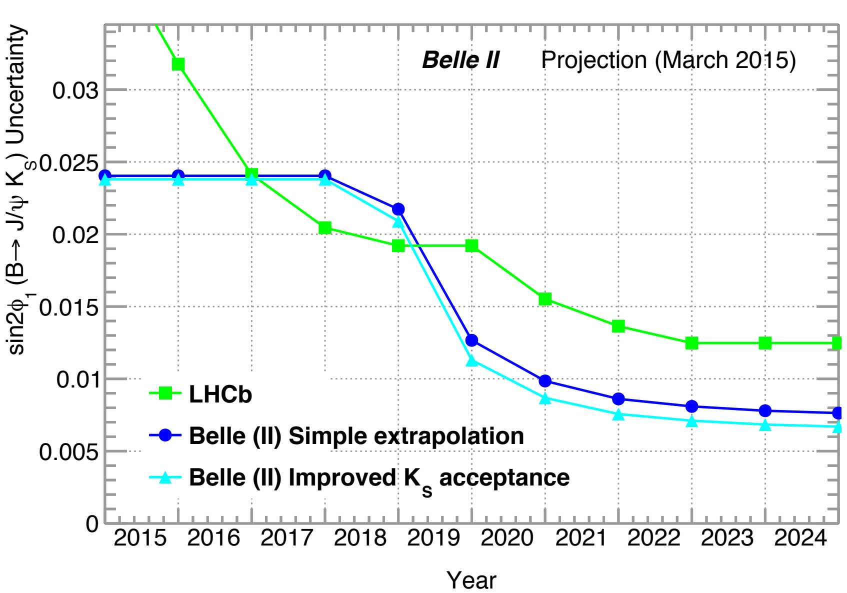


Comparable!

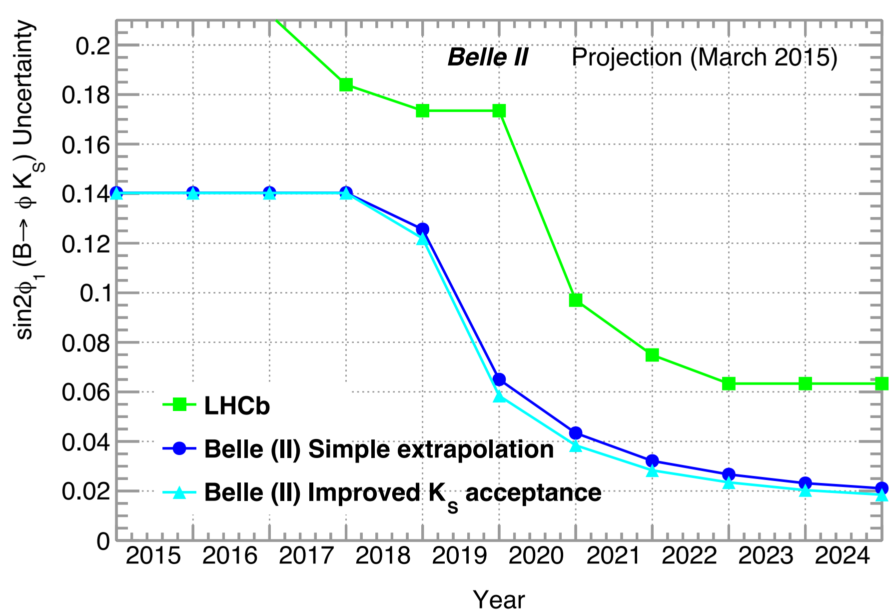
$|V_{ub}|$



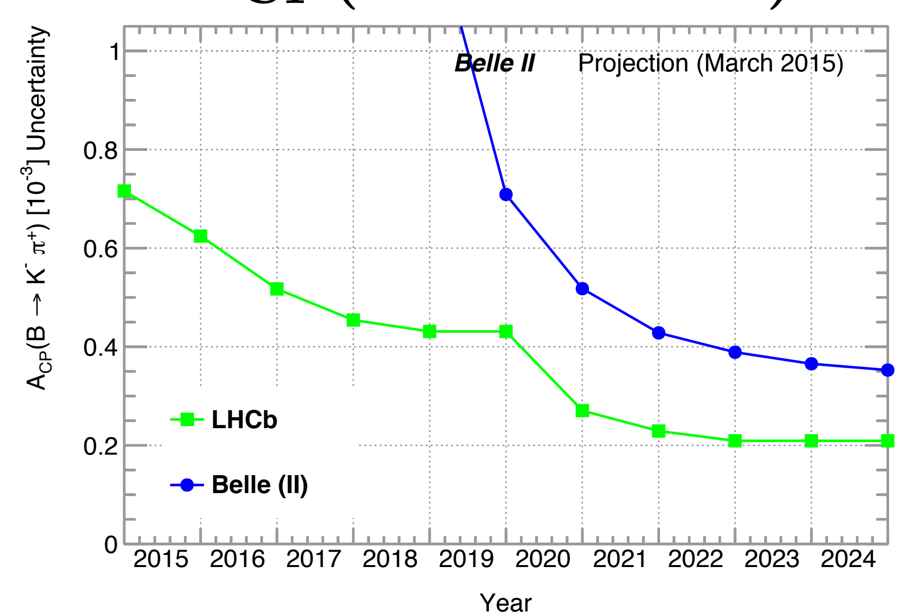
$\sin(2\phi_1)$



$S_{\phi K_S}$



$A_{CP}(B \to K^- \pi^+)$



Belle II Ks eff. wins!

LHCb wins!

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B2TiP

Belle II Theory Interface Platform (B2TiP)

- 理論と実験の共同プロジェクト (2014〜)
- Belle II の物理について、理論・実験の最近の発展及び LHC の結果を取り入れ、2017年初頭までに KEK report にまとめる。
- 現在、９つの WG で作業中。年に２回ペースでワークショップを開催。

https://belle2.cc.kek.jp/~twiki/bin/view/B2TiP

Committees

black = exp. *blue = th.*

- **Organizing committee:**

  Toru Goto (KEK)
  Emi Kou (LAL)
  Phillip Urquijo (Melbourne) *Belle2 physics coordinator*

- **Report editors:**

  Satoshi Mishima (KEK)

  Christoph Schwanda (HEPHY)

- **Advisory committee:**

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  Bostjan Golob (IJS Ljubljana)
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  Francois Le Diberder (LAL)
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- **Ex officio:**

  Hiroaki Aihara (Tokyo) *Belle2 EB chair*
  Thomas Browder (Hawaii) *Belle2 spokesperson*
  Marco Ciuchini (Rome3) *KEK-FF advisory*
  Thomas Mannel (Siegen) *KEK-FF advisory*

WGs and Coordinators

black = exp. *blue = th.*

43 coordinators!

- **WG1: Semileptonic & Leptonic B decays**
  G. De Nardo (Naples), A. Zupanc (IJS Slovenia),
  A. Kronfeld (Fermilab), F. Tackmann (DESY), M. Tanaka (Osaka), R. Watanabe (IBS)
- **WG2: Radiative & Electroweak Penguins**
  A. Ishikawa (Tohoku), J. Yamaoka (PNNL), T. Feldman (Siegen), U. Haisch (Oxford)
- **WG3: alpha = phi_2 & beta = phi_1**
  L. Li Gioi (MPI Munich), S. Mishima (KEK), J. Zupan (Cincinnati)
- **WG4: gamma = phi_3**
  J. Libby (Madras), M. Blanke (KIT), Y. Grossman (Cornell)
- **WG5: Charmless Hadronic B Decay**
  P. Goldenzweig (KIT), M. Beneke (TUM), C.-W. Chiang (NCU), S. Sharpe (Washington)
- **WG6: Charm**
  G. Casarosa (Pisa), A. Schwartz (Cincinnati), A. Kagan (Cincinnati), A. Petrov (Wayne)
- **WG7: Quarkonium(like)**
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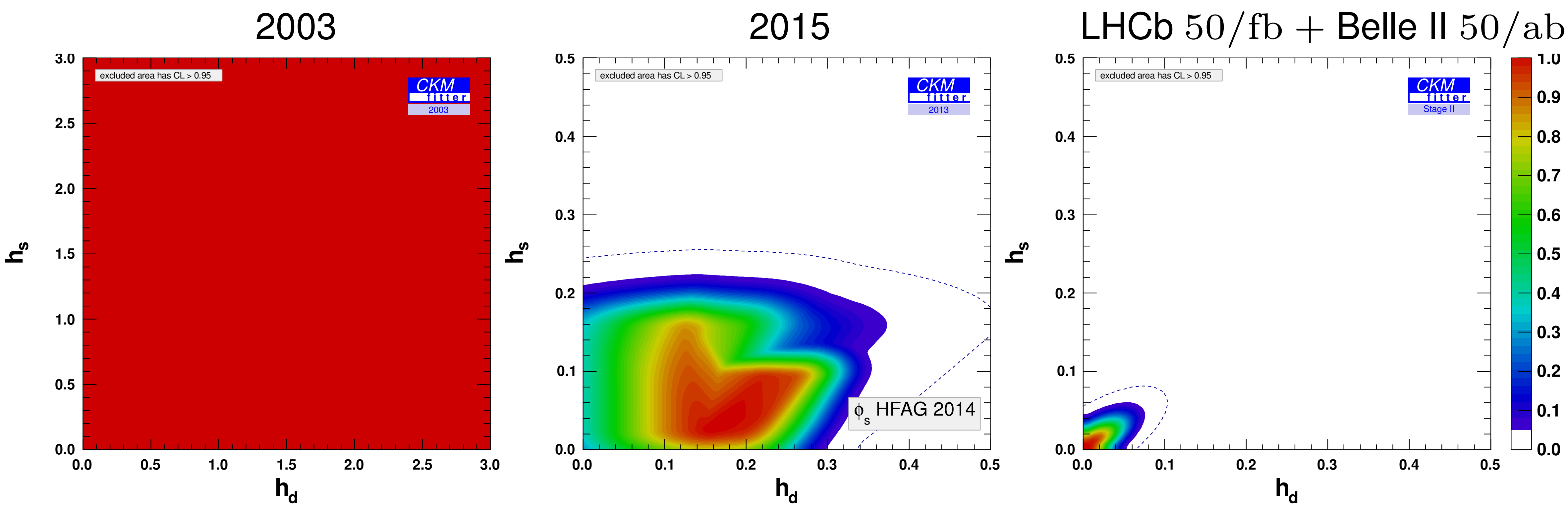
  C. Shen (Beihang), Y. Kiyo (Juntendo), A. Polosa (Rome), S. Prelovsek (Ljubljana)
- **WG8: Tau, low multiplicity & EW**
  K. Hayasaka (Niigata), T. Ferber (UBC), J. Hisano (Nagoya), E. Passemar (Indiana)
- **WG9: New Physics**
  F. Bernlochner (Bonn), R. Itoh (KEK), Y. Sato (Nagoya),
  J. Kamenik (IJS Ljubljana), U. Nierste (KIT), L. Silvestrini (Rome), S. Simula (Rome3)

Future sensitivity: e.g., NP in Bd & Bs mixings

- Magnitude of NP compared to SM contribution: $M_{12}^{(d,s)} = M_{12}^{\rm SM} \times (1 + h_{d,s}\, e^{2i\sigma_{d,s}})$



[color: 2σ, dotted: 3σ]

[ZL, Papucci, CKMfitter, 1309.2293]

Z. Ligeti, Talk at Moriond QCD 2016

$$\frac{C_{ij}^2}{\Lambda^2}\,(\bar q_{i,L}\gamma^\mu q_{j,L})^2$$

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

1309.2293

Satoshi Mishima (KEK)

2. Anomalies in Flavor Physics

Flavor anomalies

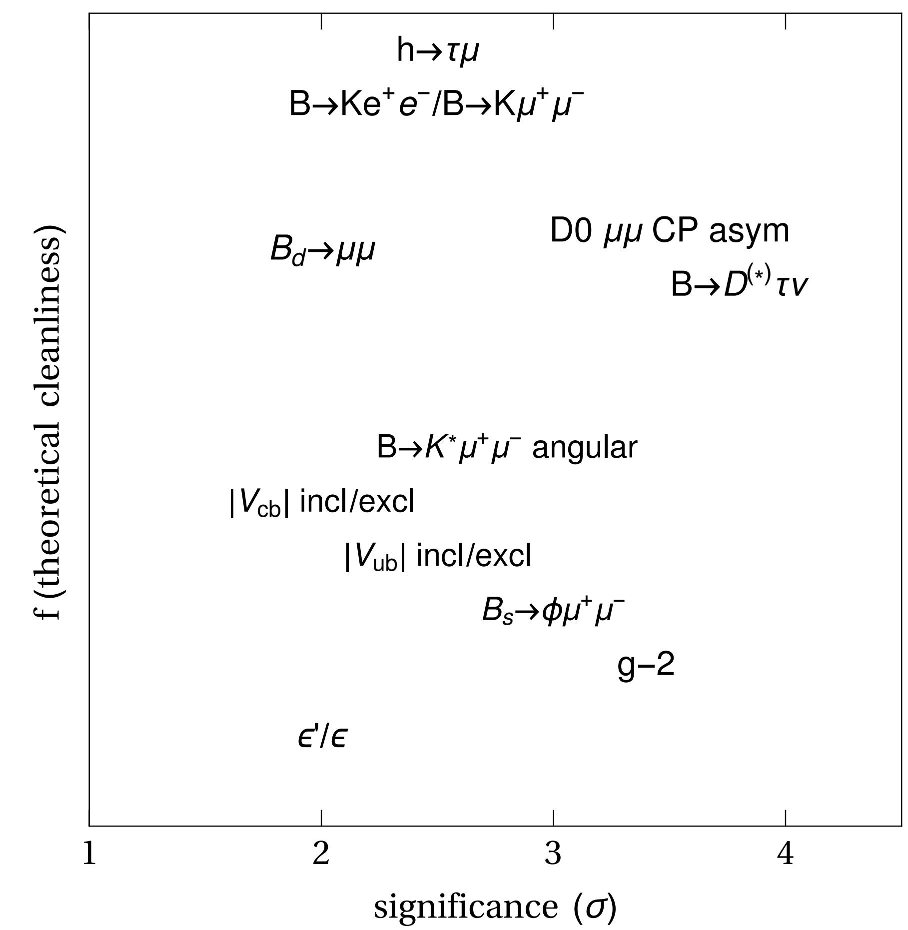
W. Almannshofer, Talk at Aspen, Jan. 2016

(Incomplete) List of Anomalies in Flavor Physics

- $\sim 3.5\sigma$ — $(g-2)_\mu$ anomaly
- $\sim 3.5\sigma$ — non-standard like-sign dimuon charge asymmetry
- $\sim 3.5\sigma$ — enhanced $B \to D^{(*)}\tau\nu$ rates
- $\sim 3.5\sigma$ — suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$
- $\sim 3\sigma$ — tension between inclusive and exclusive determination of $|V_{ub}|$
- $\sim 3\sigma$ — tension between inclusive and exclusive determination of $|V_{cb}|$
- $2-3\sigma$ — anomaly in $B \to K^*\mu^+\mu^-$ angular distributions
- $2-3\sigma$ — SM prediction for ϵ'/ϵ below experimental result
- $\sim 2.5\sigma$ — lepton flavor non-universality in $B \to K\mu^+\mu^-$ vs. $B \to Ke^+e^-$
- $\sim 2.5\sigma$ — non-zero $h \to \tau\mu$

Wolfgang Altmannshofer (UC) | Theoretical Advances in Flavor Physics | January 14, 2016 | 18 / 34

Z. Ligeti, Talk at Moriond QCD 2016



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Tension in Vub and Vcb measurements

- |Vub| :

  Exclusive ($B \to \pi \ell \nu$)

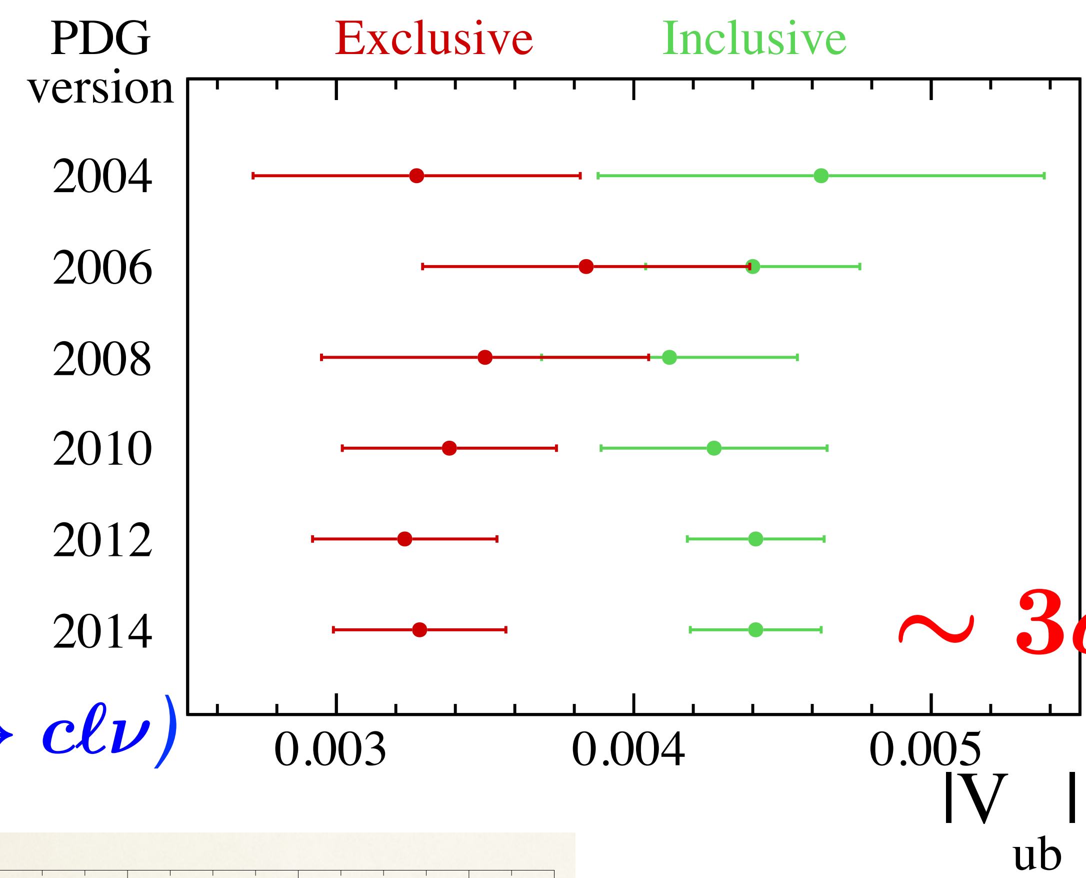
  Lattice QCD/Light-cone sum rules

  Inclusive ($B \to X_u \ell \nu$)

  OPE

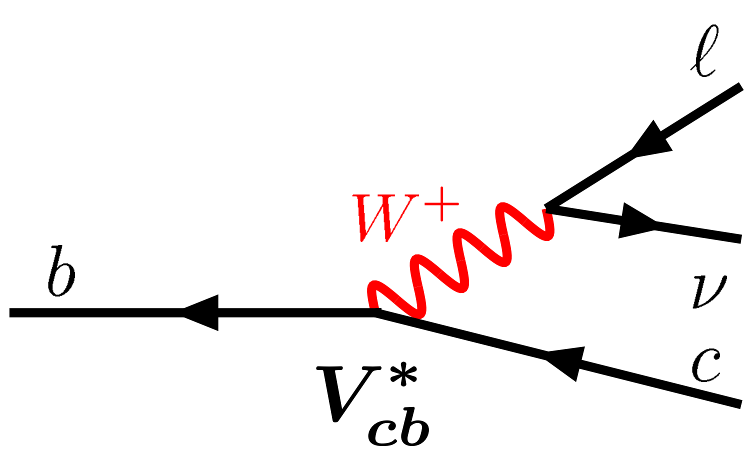
  Kinematical cut for background ($b \to c \ell \nu$)

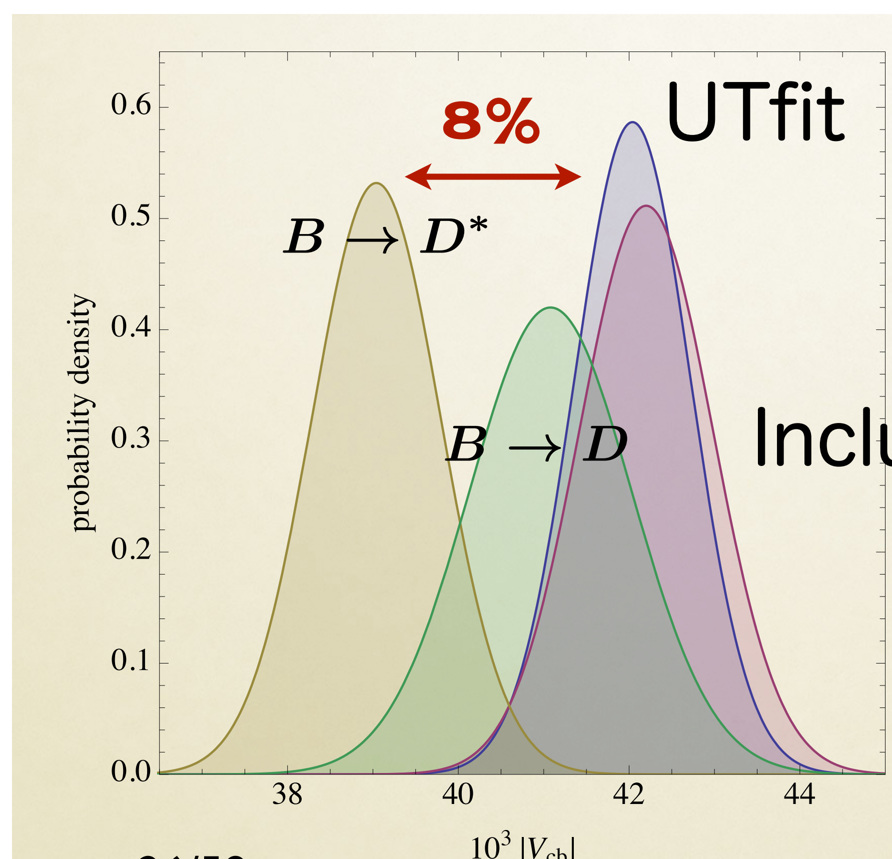
  Shape function



$\sim 3\sigma$

- |Vcb| :





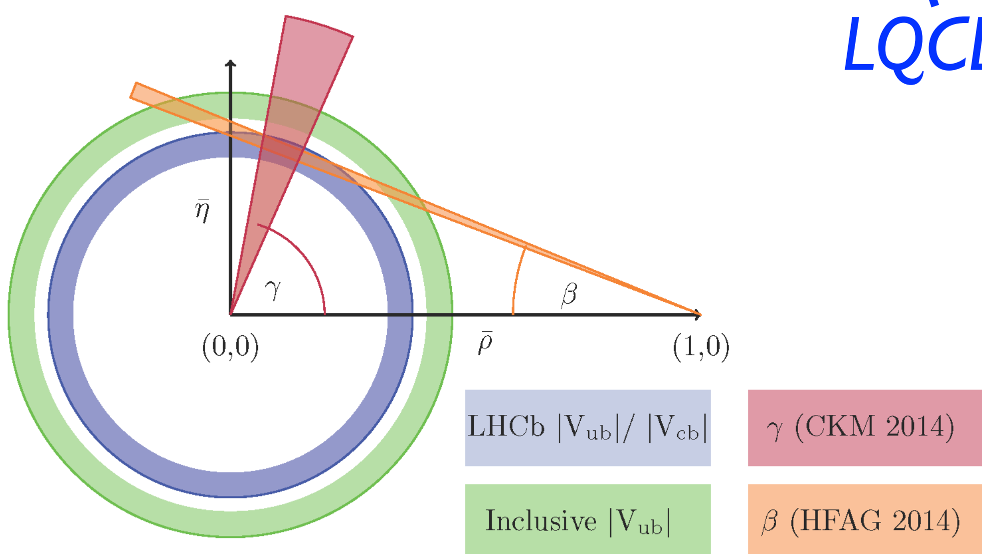
$\sim 3\sigma$

Recent LHCb measurement

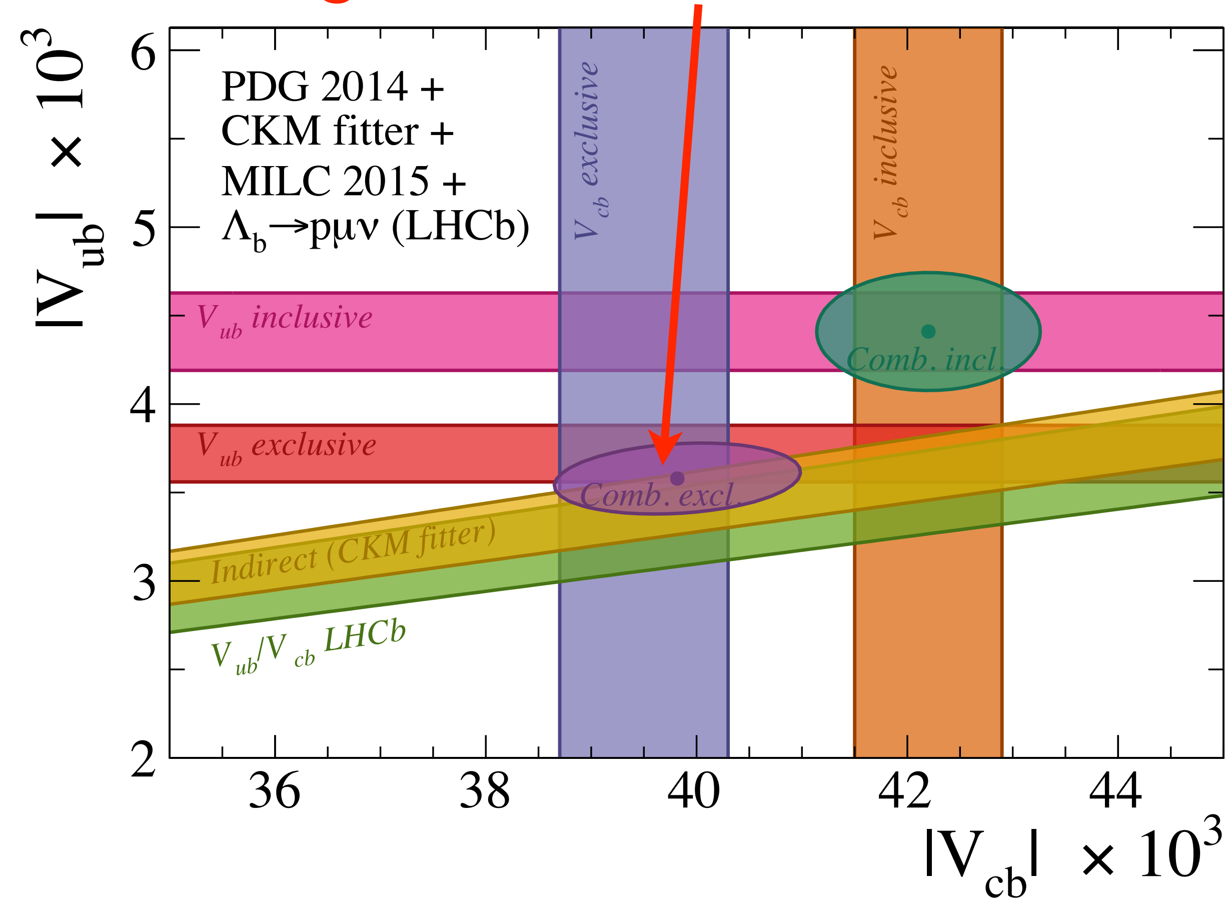
arXiv:1504.01568

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{\rm FF}$$

LQCD



in agreement with exclusive ones



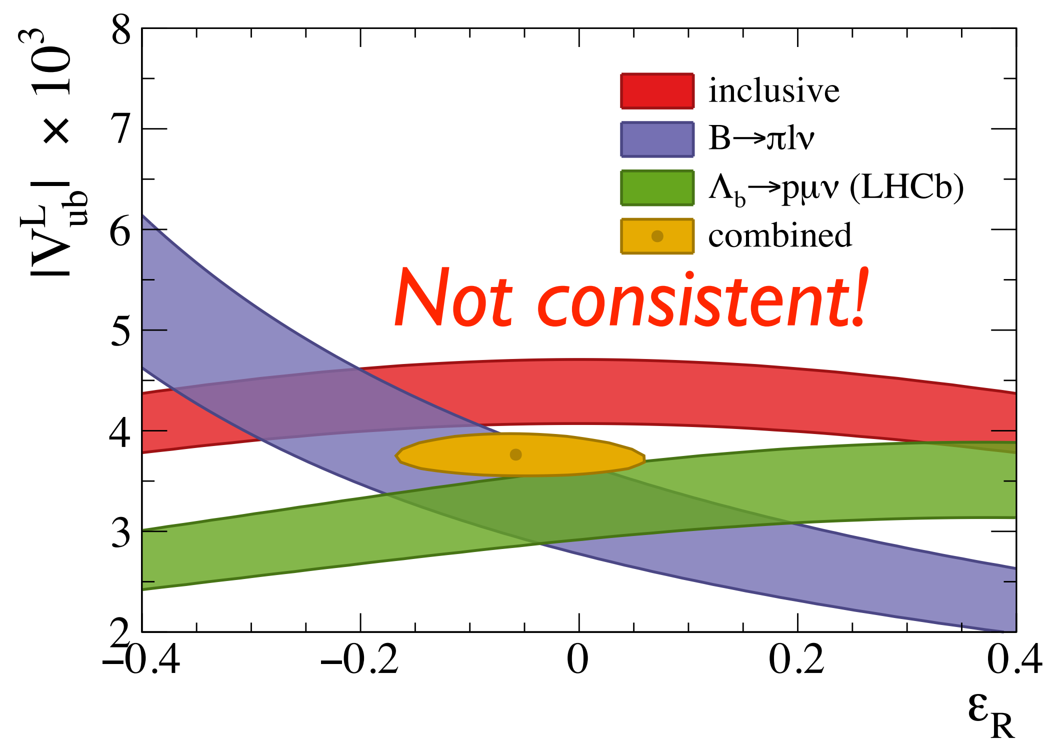
- RH current?

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L \left(\bar u\gamma_\mu P_L b + \epsilon_R\, \bar u\gamma_\mu P_R b\right)\left(\bar\nu\gamma^\mu P_L \ell\right) + {\rm h.c.},$$

$$|V_{ub}|_{\rm incl} \propto \sqrt{1+|\epsilon_R|^2}$$

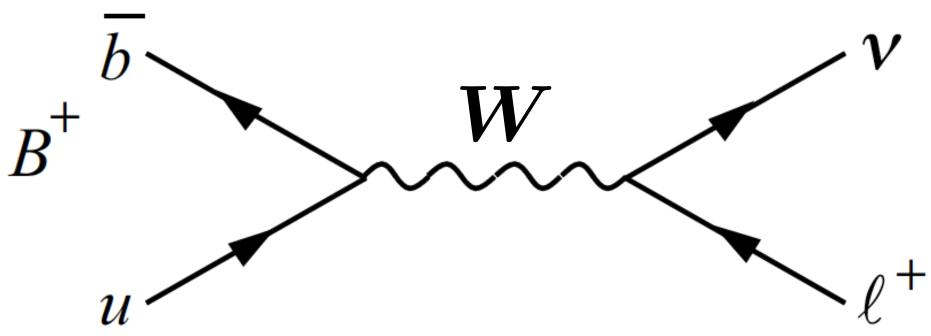
$$|V_{ub}|_{\pi\ell\nu} \propto |1+\epsilon_R|$$

$\Lambda_b \to p\mu\nu$: Axial-vector current is allowed.

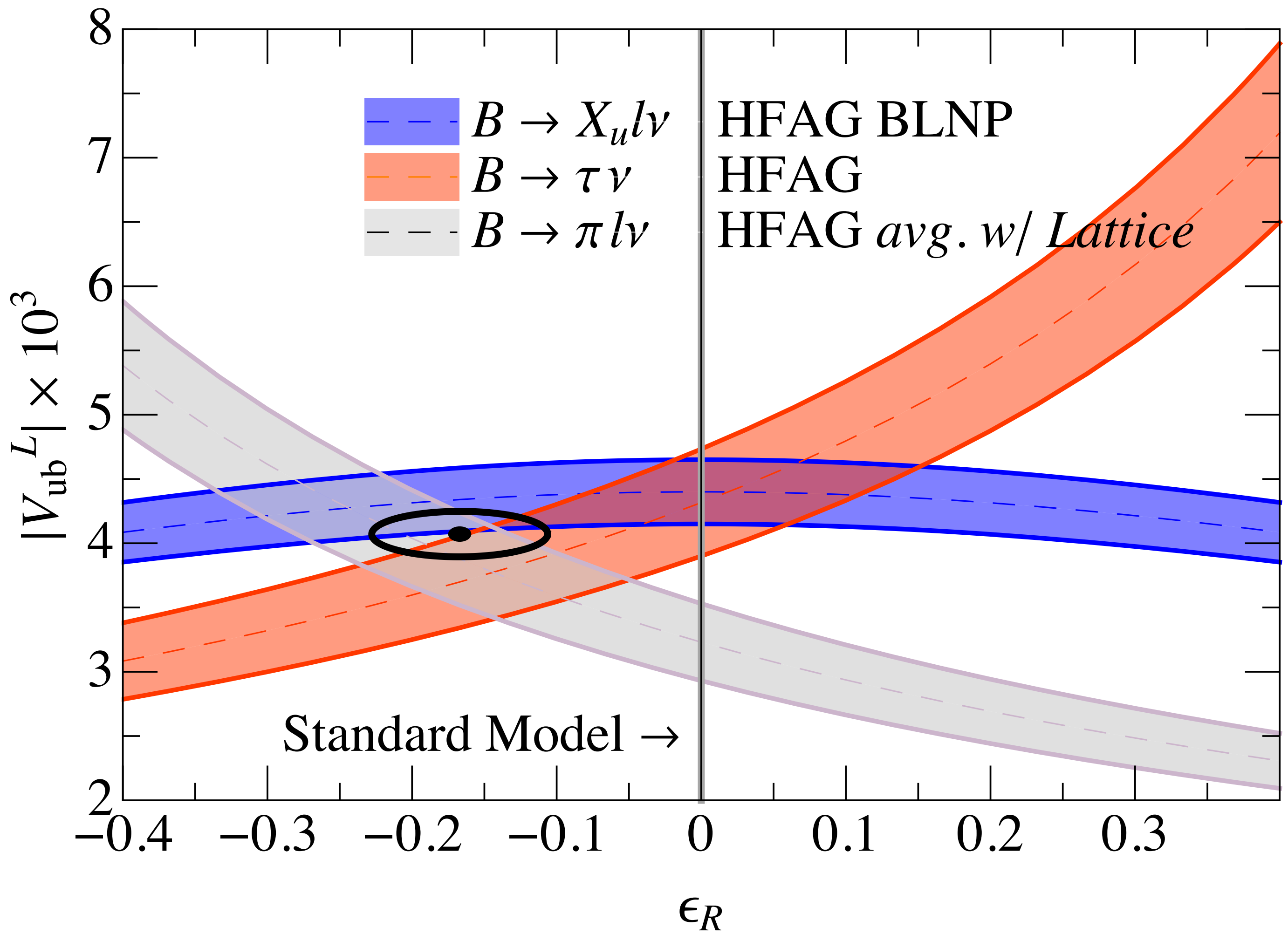


More on the RH current

Bernlochner, et al., arXiv:1408.2516



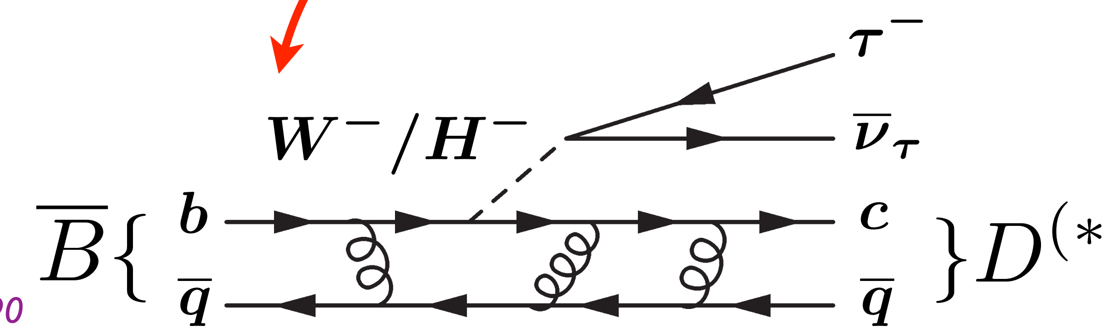
$$|V_{ub}|_{B\to\tau\nu} \propto |1 - \epsilon_R|$$



Satoshi Mishima (KEK)

Anomaly in $B \to D^{(*)} \tau \nu$

SM at tree level



$$R(X) = \frac{B(B \to X\tau\bar{\nu})}{B(B \to X\ell\bar{\nu})}$$

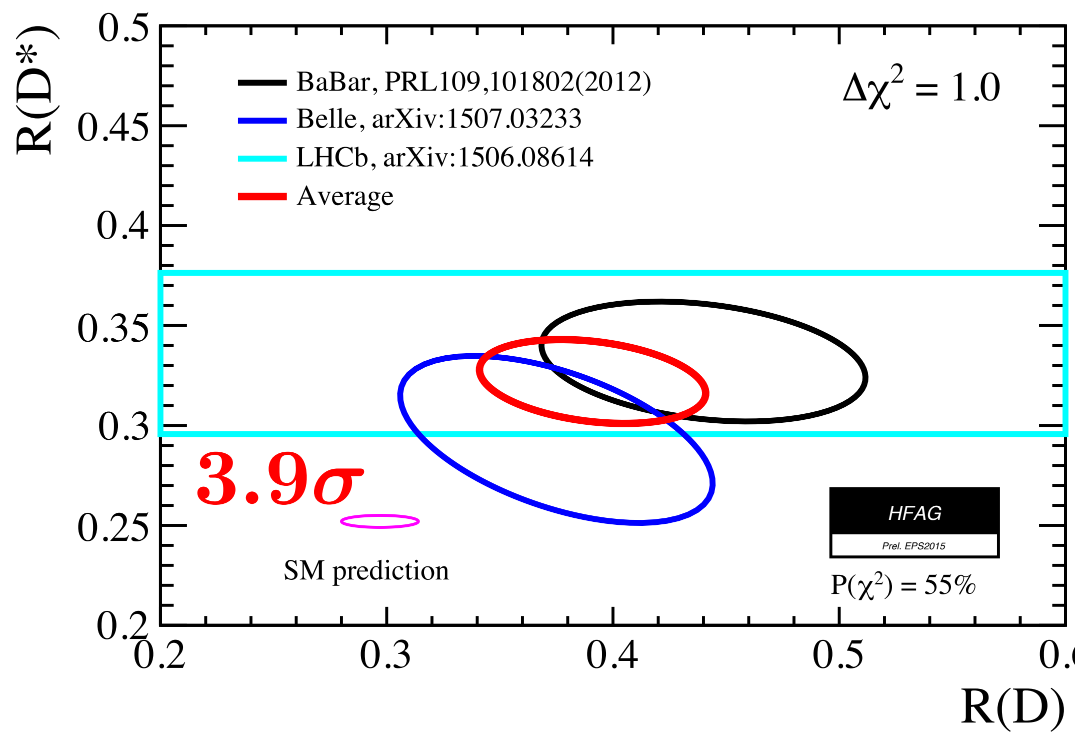
$\ell = e, \mu$ average

Vcb に依らない

Form factor の不定性がキャンセル

$R(D)_{\rm SM} = 0.297 \pm 0.017$ 0802.3790

$R(D^*)_{\rm SM} = 0.252 \pm 0.003$ 1203.2654



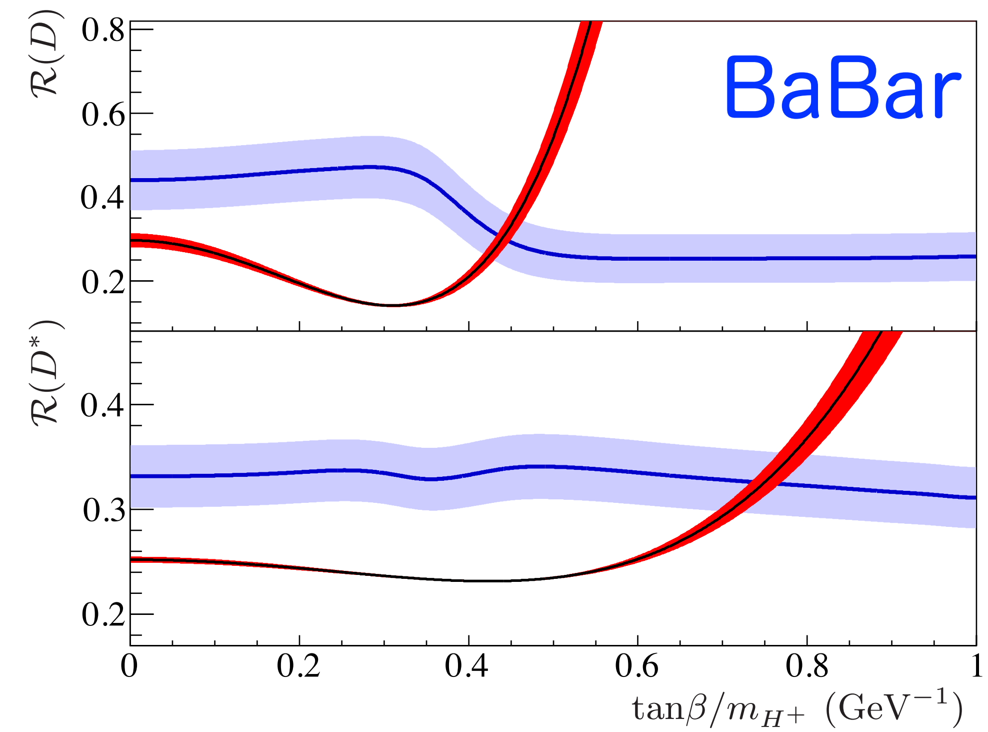


FIG. 2. (Color online) Comparison of the results of this analysis (light gray, blue) with predictions that include a charged Higgs boson of type II 2HDM (dark gray, red). The SM corresponds to $\tan\beta/m_{H^+} = 0$.

- BaBar: Type-II 2HDM and SM give nearly equally poor fits.
- NP (leptoquark, W', scalar, etc.) at fairly low scale?
  - ➡ visible at LHC ?

Operator analysis

Freytsis, et al., arXiv:1506.08896

	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\text{int}}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L) W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			
$\mathcal{O}_{S_R}$	$(\bar{c} P_R b)\,(\bar{\tau} P_L \nu)$		$\rangle (\mathbf{1},\mathbf{2})_{1/2}$	$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$
$\mathcal{O}_{S_L}$	$(\bar{c} P_L b)\,(\bar{\tau} P_L \nu)$			
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$			
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad \mathcal{O}_{V_L} \langle$	$(\mathbf{3},\mathbf{3})_{2/3}$	$\lambda\, \bar{q}_L \boldsymbol{\tau}\gamma_\mu \ell_L \boldsymbol{U}^\mu$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -2\mathcal{O}_{S_R}$	$\rangle (\mathbf{3},\mathbf{1})_{2/3}$	$(\lambda\, \bar{q}_L \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{d}_R \gamma_\mu e_R) U^\mu$
$\mathcal{O}'_{S_R}$	$(\bar{\tau} P_R b)\,(\bar{c} P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{V_R}$		
$\mathcal{O}'_{S_L}$	$(\bar{\tau} P_L b)\,(\bar{c} P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$	$(\mathbf{3},\mathbf{2})_{7/6}$	$(\lambda\, \bar{u}_R \ell_L + \tilde{\lambda}\, \bar{q}_L i\tau_2 e_R) R$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)\,(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow \quad -6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$		
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -\mathcal{O}_{V_R}$		
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -2\mathcal{O}_{S_R}$	$(\bar{\mathbf{3}},\mathbf{2})_{5/3}$	$(\lambda\, \bar{d}^c_R \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{q}^c_L \gamma_\mu e_R) V^\mu$
$\mathcal{O}''_{S_R}$	$(\bar{\tau} P_R c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow \quad \frac{1}{2}\mathcal{O}_{V_L} \langle$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$	$\lambda\, \bar{q}^c_L i\tau_2 \boldsymbol{\tau} \ell_L \boldsymbol{S}$
$\mathcal{O}''_{S_L}$	$(\bar{\tau} P_L c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$	$\rangle (\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$(\lambda\, \bar{q}^c_L i\tau_2 \ell_L + \tilde{\lambda}\, \bar{u}^c_R e_R) S$
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow \quad -6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$		

Coefficient(s)	Best fit value(s) ($\Lambda = 1$ TeV)	
C_{V_L}	0.18 ± 0.04,	-2.88 ± 0.04
C_T	0.52 ± 0.02,	-0.07 ± 0.02
C''_{S_L}	-0.46 ± 0.09	
$(C_R,\, C_L)$	$(1.25, -1.02)$,	$(-2.84, 3.08)$
$(C'_{V_R},\, C'_{V_L})$	$(-0.01, 0.18)$,	$(0.01, -2.88)$
$(C''_{S_R},\, C''_{S_L})$	$(0.35, -0.03)$,	$(0.96, 2.41)$,
	$(-5.74, 0.03)$,	$(-6.34, -2.39)$

e.g. leptoquarks

Lepton flavor non-universality?

- $B \to D^{(*)}\tau\nu$ **3.9σ**

  but no visible non-universality between e and mu.

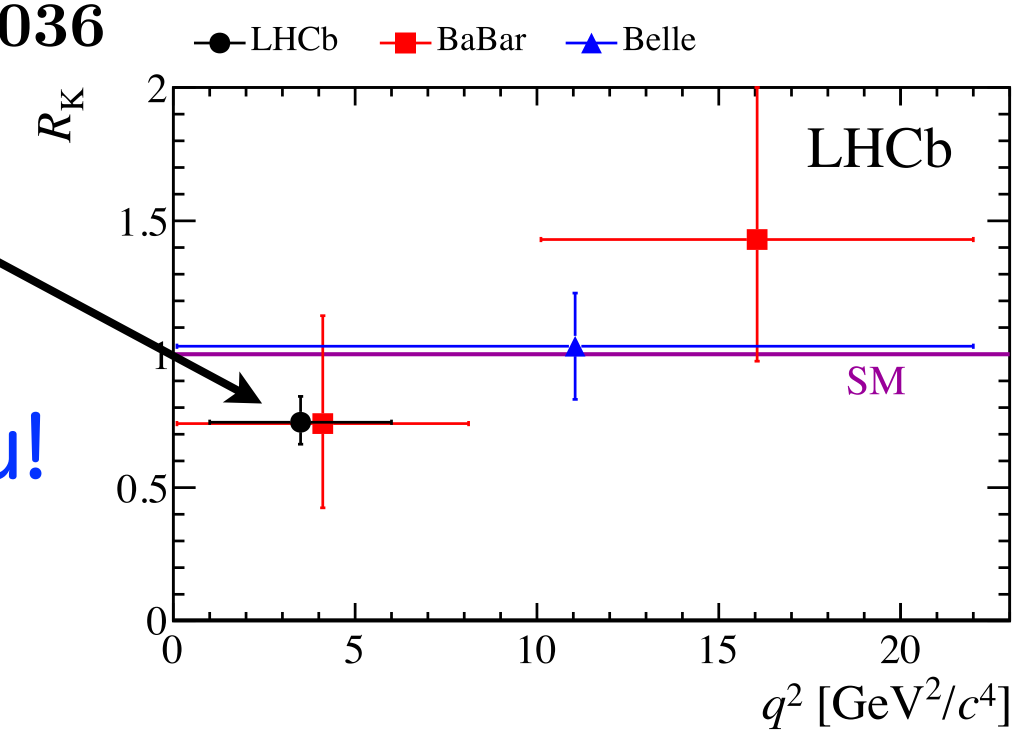
- Anomaly in LHCb data:

$$(R_K)_{\rm SM} = 1.0003 \pm 0.0001$$

0709.4174

$$R_K = \frac{B(B \to K\mu\mu)}{B(B \to Kee)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

2.6σ

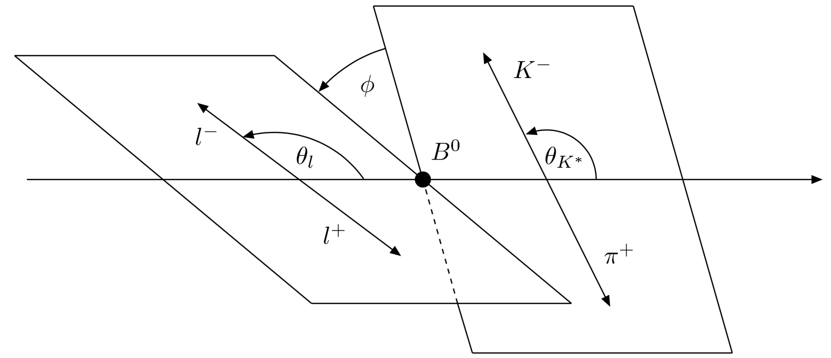


non-universality btw. e and mu!

⇨ **a bunch of NP studies (Z', leptoquarks, etc. with non-universal couplings)**

Optimized angular observables *Talk by A. Paul*

$$\frac{d^{(4)}\Gamma}{dq^2 d(cos\theta_l)d(cos\theta_K)d\phi} = \frac{9}{32\pi}\Big(I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K) cos2\theta_l$$
$$+ I_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_K \sin\theta_l \cos\phi + (I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K)\cos\theta_l$$
$$+ I_7 \sin 2\theta_K \sin\theta_l \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_l \sin\phi$$
$$+ I_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big).$$



$$I_1^c = F\left(\frac{1}{2}\left(|H_V^0|^2 + |H_A^0|^2\right) + |H_P^0|^2 + \frac{2m_l^2}{q^2}\left(|H_V^0|^2 - |H_A^0|^2\right)\right),$$
$$I_1^s = F\left(\frac{\beta^2+2}{8}\left(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2\right) + \frac{m_l^2}{q^2}\left(|H_V^+|^2 - |H_V^-|^2 - |H_A^+|^2 + |H_A^-|^2\right)\right),$$
$$I_2^c = -F\frac{\beta^2}{2}\left(|H_V^0|^2 + |H_A^0|^2\right),$$
$$I_2^s = F\frac{\beta^2}{8}\left(\left(|H_V^+|^2 + |H_V^-|^2\right) + \left(|H_A^+|^2 + |H_A^-|^2\right)\right),$$
$$I_3 = -\frac{F}{2}\Re\left[H_V^+(H_V^-)^* + H_A^+(H_A^-)^*\right],$$
$$I_4 = F\frac{\beta^2}{4}\Re\left[(H_V^+ + H_V^-)(H_V^0)^* + (H_A^+ + H_A^-)(H_A^0)^*\right],$$
$$I_5 = F\frac{\beta}{4}\Re\left[(H_V^- - H_V^+)(H_A^0)^* + (H_A^- - H_A^+)(H_V^0)^*\right],$$
$$I_6^s = F\beta\Re\left[H_V^-(H_A^-)^* - H_V^+(H_A^+)^*\right],$$
$$I_6^c = 0,$$
$$I_7 = F\frac{\beta}{2}\Im\left[(H_A^+ + H_A^-)(H_V^0)^* + (H_V^+ + H_V^-)(H_A^0)^*\right],$$
$$I_8 = F\frac{\beta}{4}\Im\left[(H_V^- - H_V^+)(H_V^0)^* + (H_A^- - H_A^+)(H_A^0)^*\right],$$
$$I_9 = F\frac{\beta^2}{4}\Im\left[H_V^+(H_V^-)^* + H_A^+(H_A^-)^*\right],$$

$$\Sigma_i = \frac{I_i + \bar{I}_i}{2}$$

$$\langle P_1\rangle = \frac{\langle\Sigma_3\rangle}{2\langle\Sigma_{2s}\rangle}, \qquad \langle P_2\rangle = \frac{\langle\Sigma_{6s}\rangle}{8\langle\Sigma_{2s}\rangle}, \qquad \langle P_3\rangle = -\frac{\langle\Sigma_9\rangle}{4\langle\Sigma_{2s}\rangle},$$
$$\langle P_4'\rangle = \frac{\langle\Sigma_4\rangle}{\sqrt{-\langle\Sigma_{2s}\Sigma_{2c}\rangle}}, \qquad \langle P_5'\rangle = \frac{\langle\Sigma_5\rangle}{2\sqrt{-\langle\Sigma_{2s}\Sigma_{2c}\rangle}},$$
$$\langle P_6'\rangle = -\frac{\langle\Sigma_7\rangle}{2\sqrt{-\langle\Sigma_{2s}\Sigma_{2c}\rangle}}, \qquad \langle P_8'\rangle = -\frac{\langle\Sigma_8\rangle}{2\sqrt{-\langle\Sigma_{2s}\Sigma_{2c}\rangle}},$$

Kruger, Matias (05); Egede et al. (08); Descotes-Genon et al. (13)

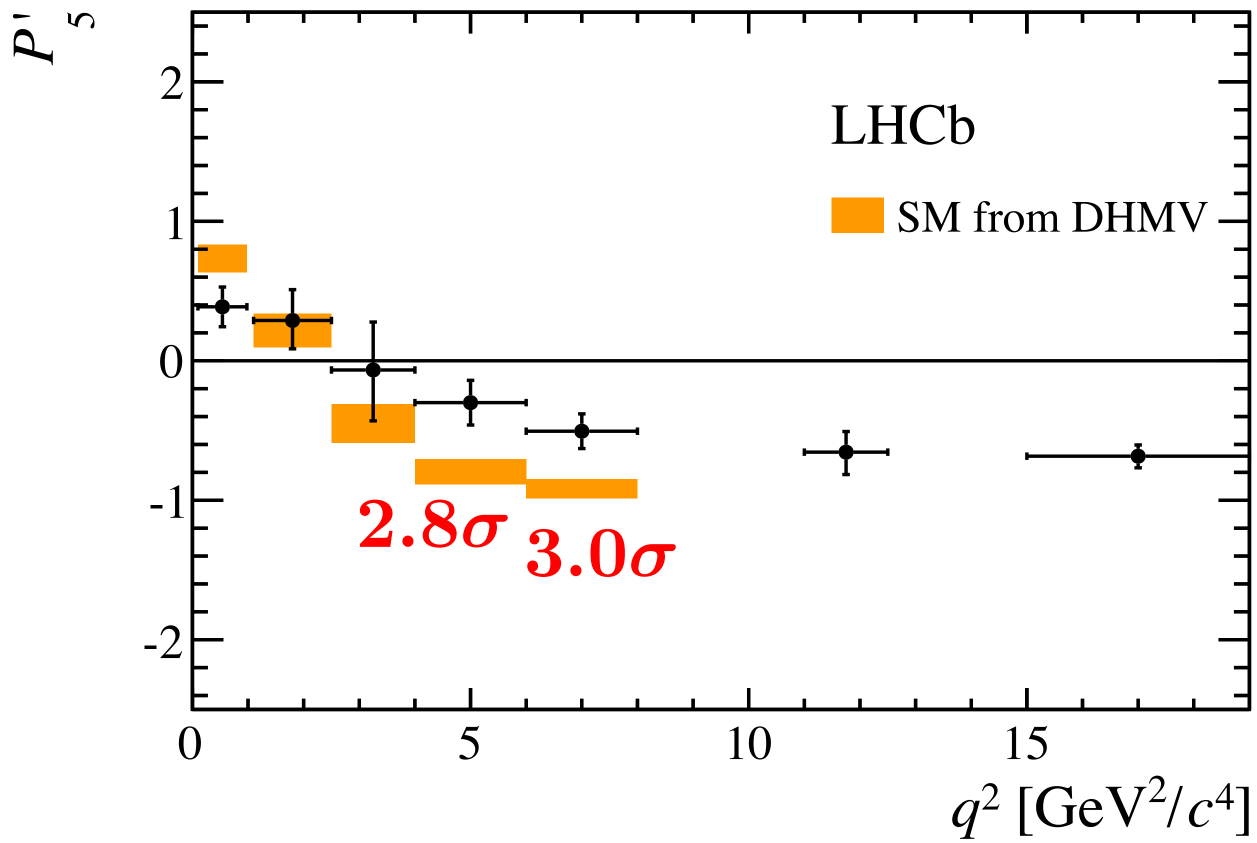
$$\langle\Gamma'\rangle = \langle\Sigma_{1c} + 4\Sigma_{2s}\rangle, \qquad \langle F_L\rangle = \frac{\langle 3\Sigma_{1c} - \Sigma_{2c}\rangle}{4\langle\Gamma'\rangle}, \qquad \langle A_{FB}\rangle = -\frac{3\langle\Sigma_{6s}\rangle}{4\langle\Gamma'\rangle}$$

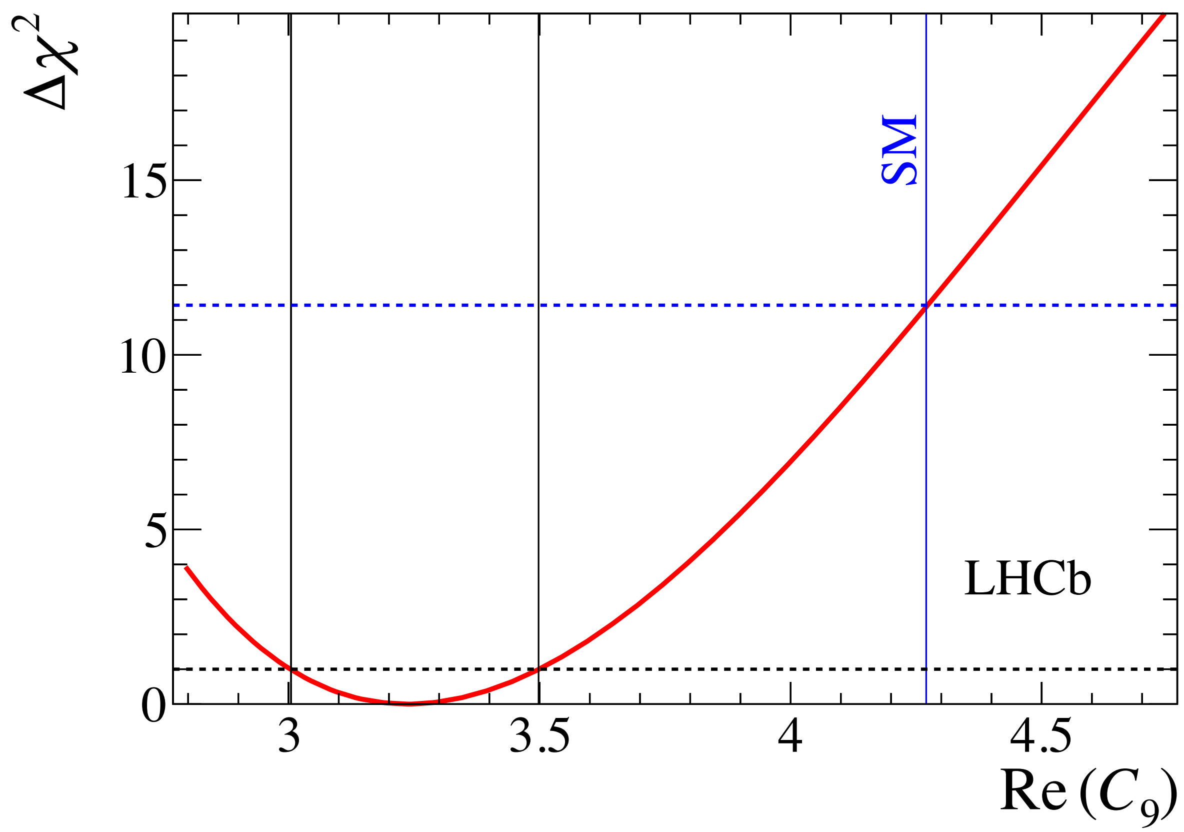
8

valid in the heavy quark limit ignoring α_s corrections and long-distance hadronic contribution.

Anomaly?

LHCb, 1512.04442





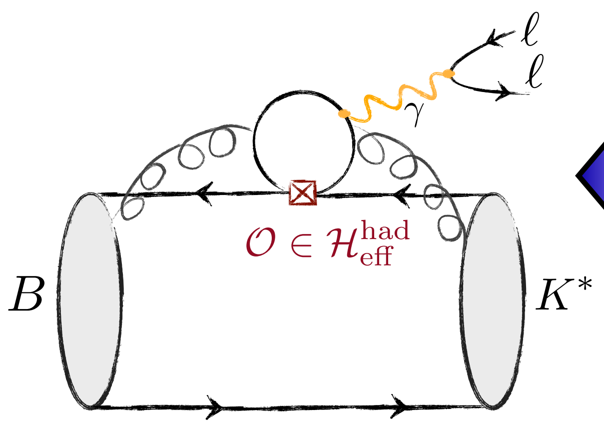
DHMV = Descotes-Genon, Hofer, Matias & Virto (2014)

$$C_9^{\rm NP} < 0$$

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

$$|C_9^{\rm NP}/C_9^{\rm SM}| \sim 25\,\%$$

Long-distance hadronic contribution:



LCSR estimate

Khodjamirian et al. (2010)

Global fit to various $b \to s$ data

$$B(B \to K\mu^+\mu^-),\ B(B \to X_s\mu^+\mu^-),\ B(B \to K^*\gamma),\ B(B \to X_s\gamma),$$
$$B(B_s \to \phi\mu^+\mu^-),\ B(B_s \to \mu^+\mu^-),$$
$$B(B \to K^*\mu^+\mu^-),\ A_{FB},\ F_L,\ P_4',\ P_5',\ P_6',\ P_8',\ \cdots$$

$$C_9^{\rm NP} < 0$$

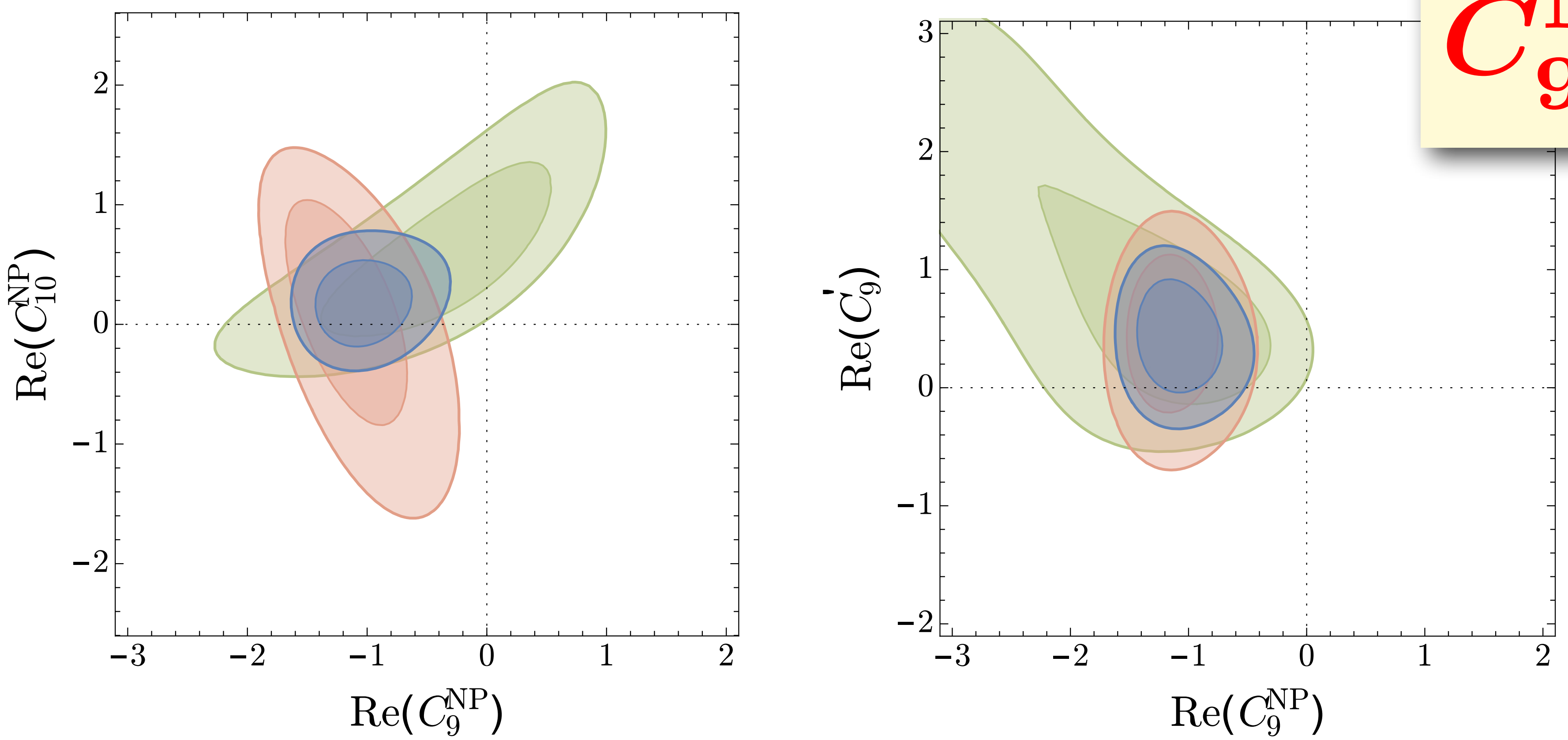


Figure 1 – Allowed regions in the Re($C_9^{\rm NP}$)-Re($C_{10}^{\rm NP}$) plane (left) and the Re($C_9^{\rm NP}$)-Re(C_9') plane (right). The blue contours correspond to the 1 and 2σ best fit regions from the global fit. The green and red contours correspond to the 1 and 2σ regions if only branching ratio data or only data on $B \to K^*\mu^+\mu^-$ angular observables is taken into account.

Altmannshofer & Straub, arXiv:1503.06199

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

Pulls

Altmannshofer & Straub, arXiv:1503.06199

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{d\mathrm{BR}}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{d\mathrm{BR}}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{d\mathrm{BR}}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{d\mathrm{BR}}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

Table 1: Observables where a single measurement deviates from the SM by 1.9σ or more (cf. [15] for the $B \to K^*\mu^+\mu^-$ predictions at low q^2).

$$P_5' = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$

Satoshi Mishima (KEK)

Implications to NP scale

W. Almannshofer, Talk at Aspen, Jan. 2016

generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35\ \mathrm{TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\ V_{tb}V_{ts}^*\ (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7\ \mathrm{TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3\ \mathrm{TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\ V_{tb}V_{ts}^*\ (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6\ \mathrm{TeV} \times (C_9^{\rm NP})^{-1/2}$

Signs of contributions to coefficients

Descotes-Genon, et al., arXiv:1510.04239

		R_K	$\langle P_5' \rangle_{[4,6],[6,8]}$	$\mathcal{B}_{B_s \to \phi\mu\mu}$
$\mathcal{C}_9^{\rm NP}$	$+$			
	$-$	✓	✓	✓
$\mathcal{C}_{10}^{\rm NP}$	$+$	✓		✓
	$-$		✓	
$\mathcal{C}_{9'}^{\rm NP}$	$+$			✓
	$-$	✓	✓	
$\mathcal{C}_{10'}^{\rm NP}$	$+$	✓	✓	
	$-$			✓

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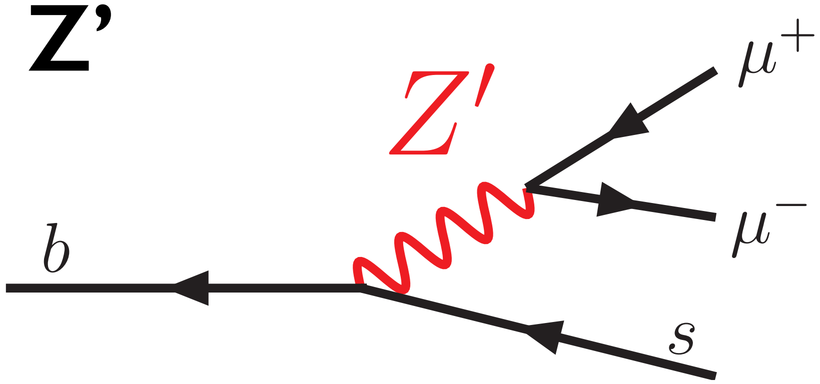
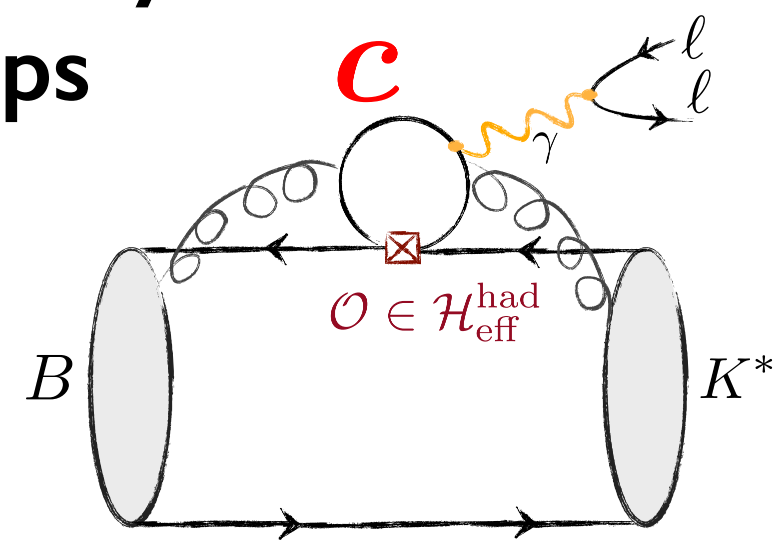
Possible interpretations

$$C_9^{\mathrm{NP}} < 0 \qquad O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

- **NP contribution, e.g., from Z'**



- **Underestimate of SM uncertainty from long-distance charm loops**



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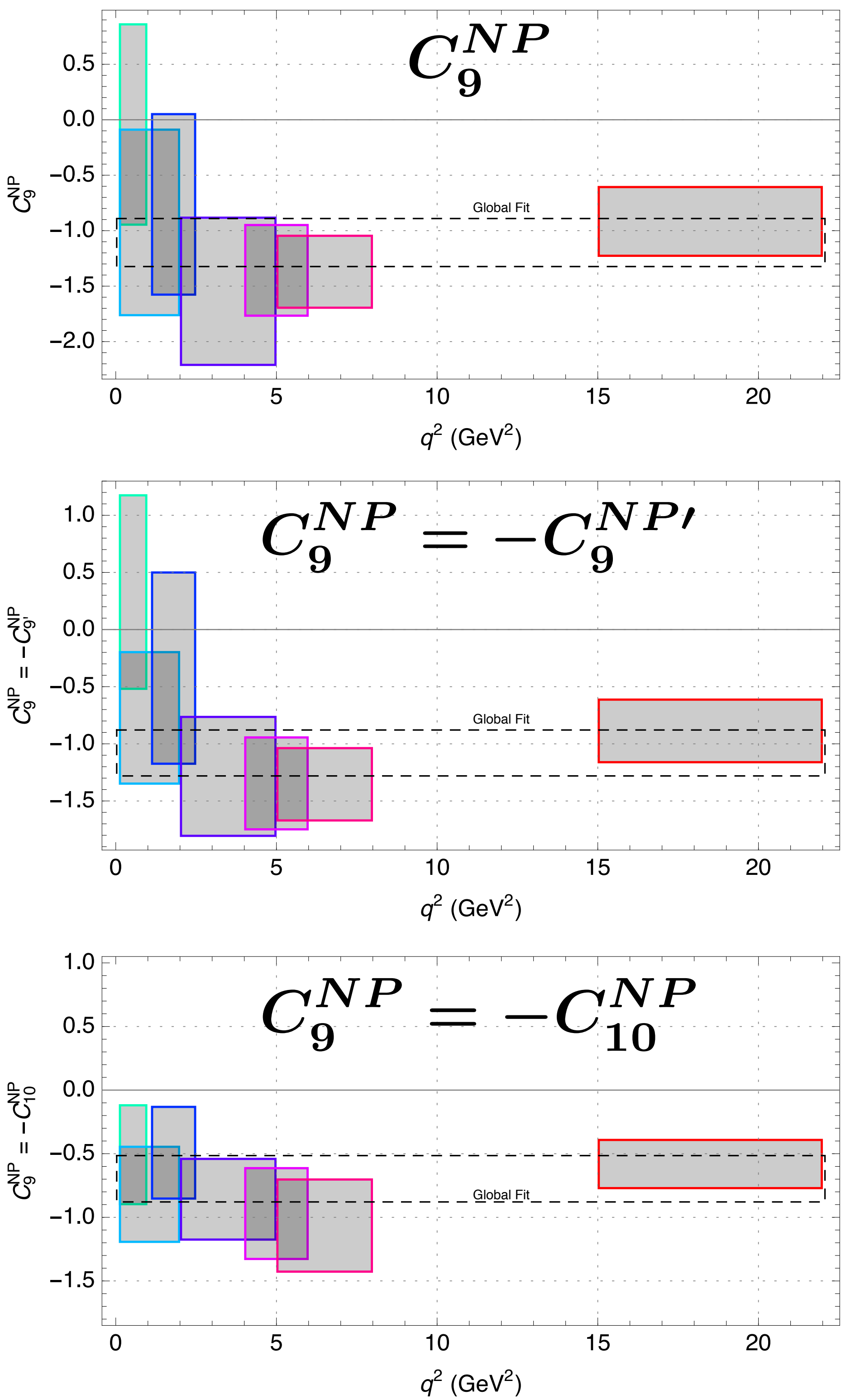
SM or NP?

Descotes-Genon, et al., arXiv:1510.04239



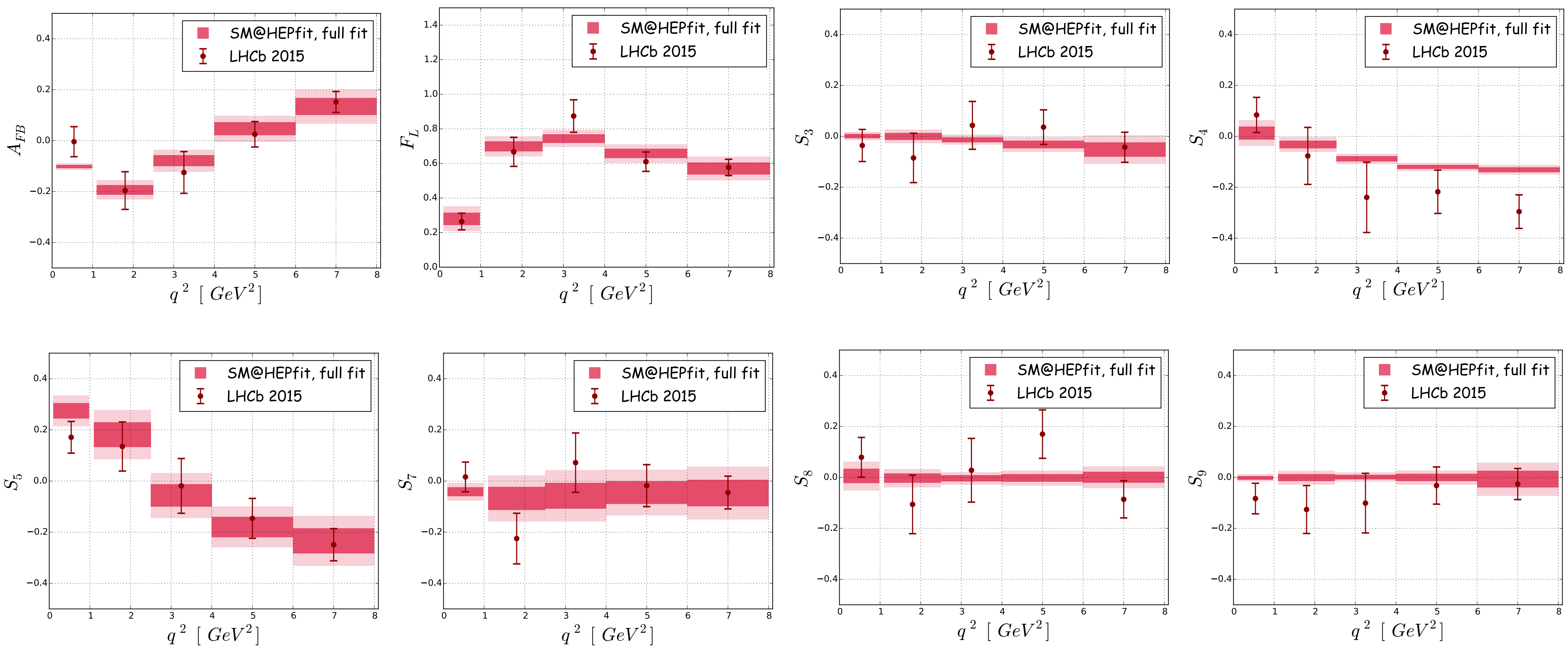
NP is independent of q2

No conclusive evidence for a q2 dependence!

Results from *HEPfit*

M. Ciuchini, M. Fedele, E. Franco, S.M., A. Paul, L. Silvestrini & M.Valli, arXiv:1512.07157

Non-factorizable charm loop has been fitted from the data.



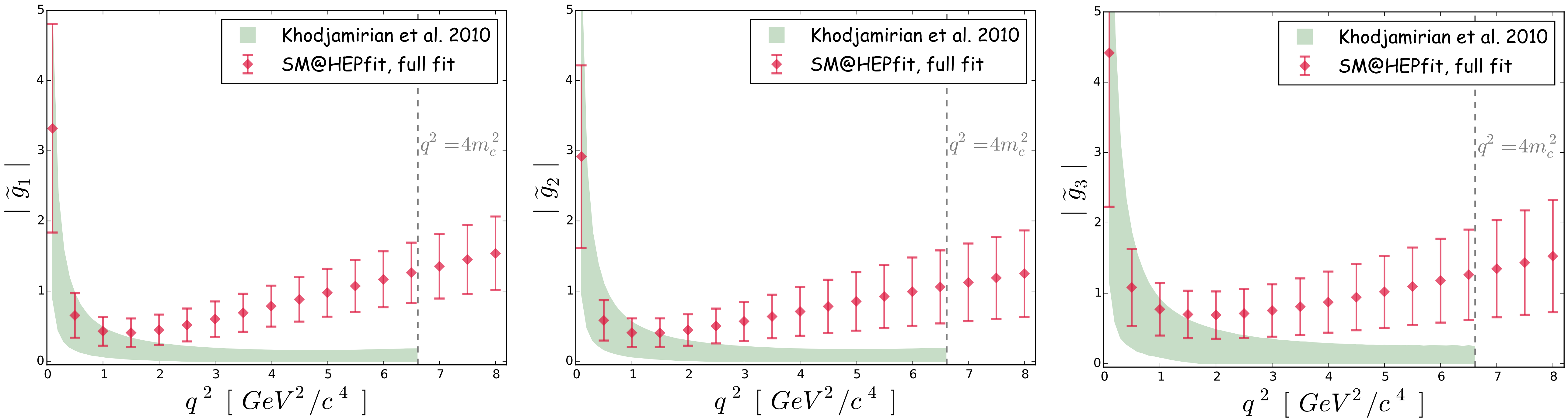
Observable	q^2 bin [GeV^2]	measurement	full fit	prediction
P_5'	$[0.1, 0.98]$	0.392 ± 0.146	0.781 ± 0.101	0.872 ± 0.087
	$[1.1, 2.5]$	0.297 ± 0.209	0.409 ± 0.104	0.485 ± 0.129
	$[2.5, 4]$	-0.076 ± 0.351	-0.133 ± 0.103	-0.153 ± 0.115
	$[4, 6]$	-0.301 ± 0.157	-0.383 ± 0.087	-0.430 ± 0.102
	$[6, 8]$	-0.505 ± 0.120	-0.477 ± 0.102	-0.314 ± 0.215

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

No significant discrepancy!

Fit result of the hadronic contributions

$$\tilde{g} \equiv \Delta C_9^{(\text{non pert.})}/(2C_1)$$



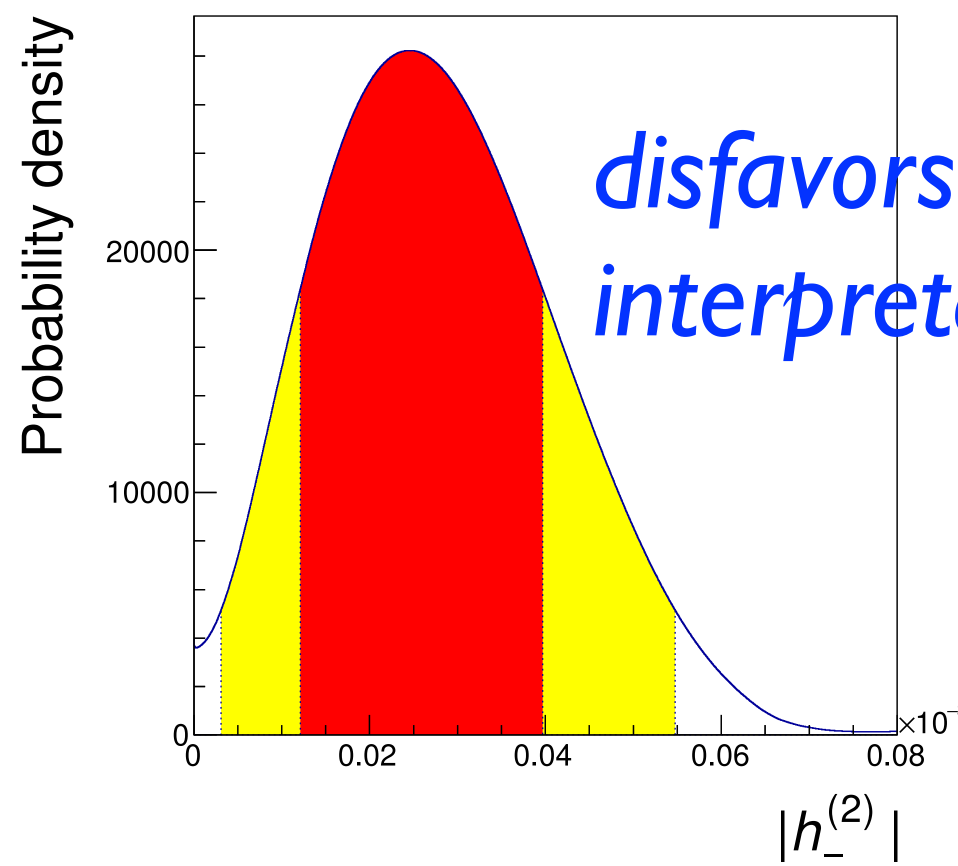
The hadronic cont's extracted from the data are compatible with the LCSR estimate for $q^2 \lesssim 1\ \mathrm{GeV}^2$ *and seem to grow towards charm resonances.*

Fit result of the hadronic contributions

$$h_\lambda(q^2) = \frac{\epsilon^*_\mu(\lambda)}{m_B^2} \int d^4x e^{iqx} \langle \bar{K}^* | T\{j^\mu_{\rm em}(x) \mathcal{H}^{\rm had}_{\rm eff}(0)\} | \bar{B} \rangle$$
$$= h_\lambda^{(0)} + \frac{q^2}{1\,{\rm GeV}^2} h_\lambda^{(1)} + \frac{q^4}{1\,{\rm GeV}^4} h_\lambda^{(2)} \,,$$

The first and second terms could be reinterpreted as a modification of C7 and C9, respectively.

Parameter	**Absolute value**	**Phase** (rad)
$h_0^{(0)}$	$(5.3 \pm 2.2) \cdot 10^{-4}$	3.41 ± 0.74
$h_0^{(1)}$	$(2.3 \pm 1.7) \cdot 10^{-4}$	-0.1 ± 1.2
$h_0^{(2)}$	$(2.7 \pm 2.1) \cdot 10^{-5}$	-0.1 ± 1.7
$h_+^{(0)}$	$(7.0 \pm 6.3) \cdot 10^{-6}$	0.0 ± 1.7
$h_+^{(1)}$	$(4.1 \pm 3.0) \cdot 10^{-5}$	-0.9 ± 1.6
$h_+^{(2)}$	$(1.6 \pm 1.1) \cdot 10^{-5}$	3.0 ± 1.6
$h_-^{(0)}$	$(4.7 \pm 2.0) \cdot 10^{-5}$	3.2 ± 1.5
$h_-^{(1)}$	$(4.9 \pm 3.6) \cdot 10^{-5}$	0.0 ± 1.8
$h_-^{(2)}$	$(2.7 \pm 1.1) \cdot 10^{-5}$	0.01 ± 0.76



Satoshi Mishima (KEK)

New lattice result for ε'/ε

RBC-UKQCD collaborations, 1505.07863

$$\sqrt{2}\, A_I e^{i\delta_I} = \langle (\pi\pi)_I | H_{\text{eff}} | K^0 \rangle$$

Amplitude	Lattice QCD	Exp. data
$\text{Re}A_0$ $[10^{-7}$ GeV$]$	$4.66 \pm 1.00 \pm 1.26$ [3]	3.322 ± 0.001 [1]
$\text{Im}A_0$ $[10^{-11}$ GeV$]$	$-1.90 \pm 1.23 \pm 1.08$ [3]	—
$\text{Re}A_2$ $[10^{-8}$ GeV$]$	$1.50 \pm 0.04 \pm 0.14$ [15]	1.479 ± 0.003 [1]
$\text{Im}A_2$ $[10^{-13}$ GeV$]$	$-6.99 \pm 0.20 \pm 0.84$ [15]	—

$$\mathbf{Re}\left(\frac{\epsilon'}{\epsilon}\right) \propto \frac{\mathbf{Re}A_2}{\mathbf{Re}A_0}\left(\frac{\mathbf{Im}A_0}{\mathbf{Re}A_0} - \frac{\mathbf{Im}A_2}{\mathbf{Re}A_2}\right)$$

[1] Buras, et al., 1507.06345
[3] RBC-UKQCD collaborations, 1505.07863
[15] RBC-UKQCD collaborations, 1502.00263

Observable	SM prediction(s)	Current data
ε'/ε $[10^{-4}]$	1.9 ± 4.5 [1]	$7.4 \pm 5.2 \pm 2.9$ (E731) [2]
	$1.38 \pm 5.15(\text{stat}) \pm 4.59(\text{sys})$ [3]	14.7 ± 2.2 (NA48) [4]
		19.2 ± 2.1 (KTeV) [5]
		16.6 ± 2.3 (PDG) [6]

2.9σ

New lattice results for Bd and Bs mixings

Fermilab Lattice and MILC collaborations, 1602.03560

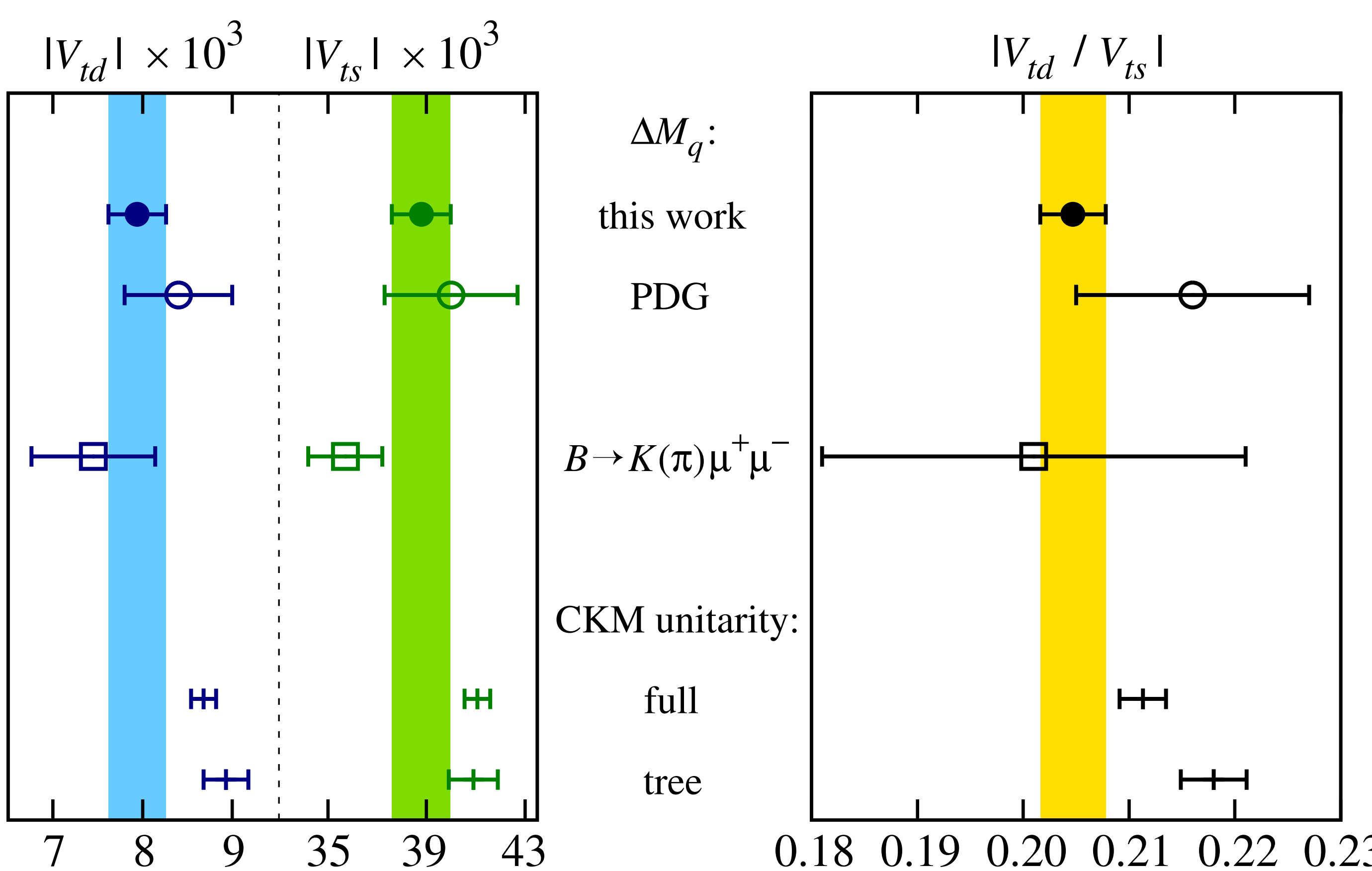
- First calculation with three flavors

$$\xi^2 = \frac{f_{B_s}^2 \hat{B}_{B_s}^{(1)}}{f_{B_d}^2 \hat{B}_{B_d}^{(1)}}, \qquad \xi = 1.203(17)(6)$$

1.268(63), previously

FLAG, 1310.8555

- Tension with the CKM fit:



3.0σ

3. Possible patterns of NP signals

NP 模型の識別

目標：SMからのずれの発見・NP模型の識別

様々な物理量を測定し、その間の相関を調べる

例として取り上げるもの：

B physics in MSSM (mSUGRA, SUSY SU(5)+ν_R)

Test of MFV with $B_d \to \mu^+\mu^-$, $B_s \to \mu^+\mu^-$

Modified Z couplings / new Z':

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

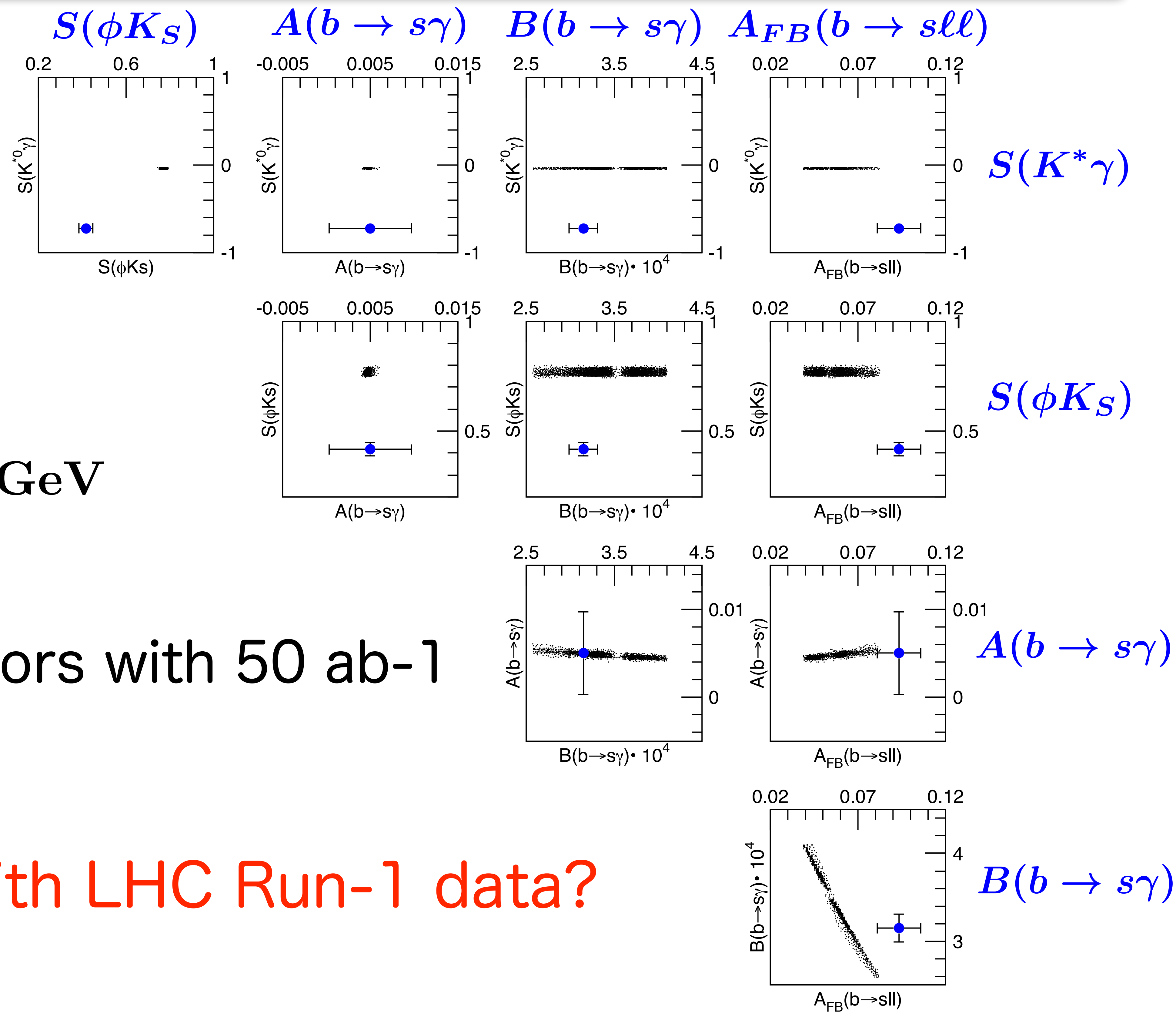
$$\varepsilon'/\varepsilon \quad \& \quad K_L \to \pi^0\nu\bar{\nu}$$

$$B \to K^*\nu\bar{\nu} \quad \& \quad K^+ \to \pi^+\nu\bar{\nu}$$

Satoshi Mishima (KEK)

Example: mSUGRA

SuperKEKB LOI (2004)



$M_{\rm gluino} = 600\,{\rm GeV}$

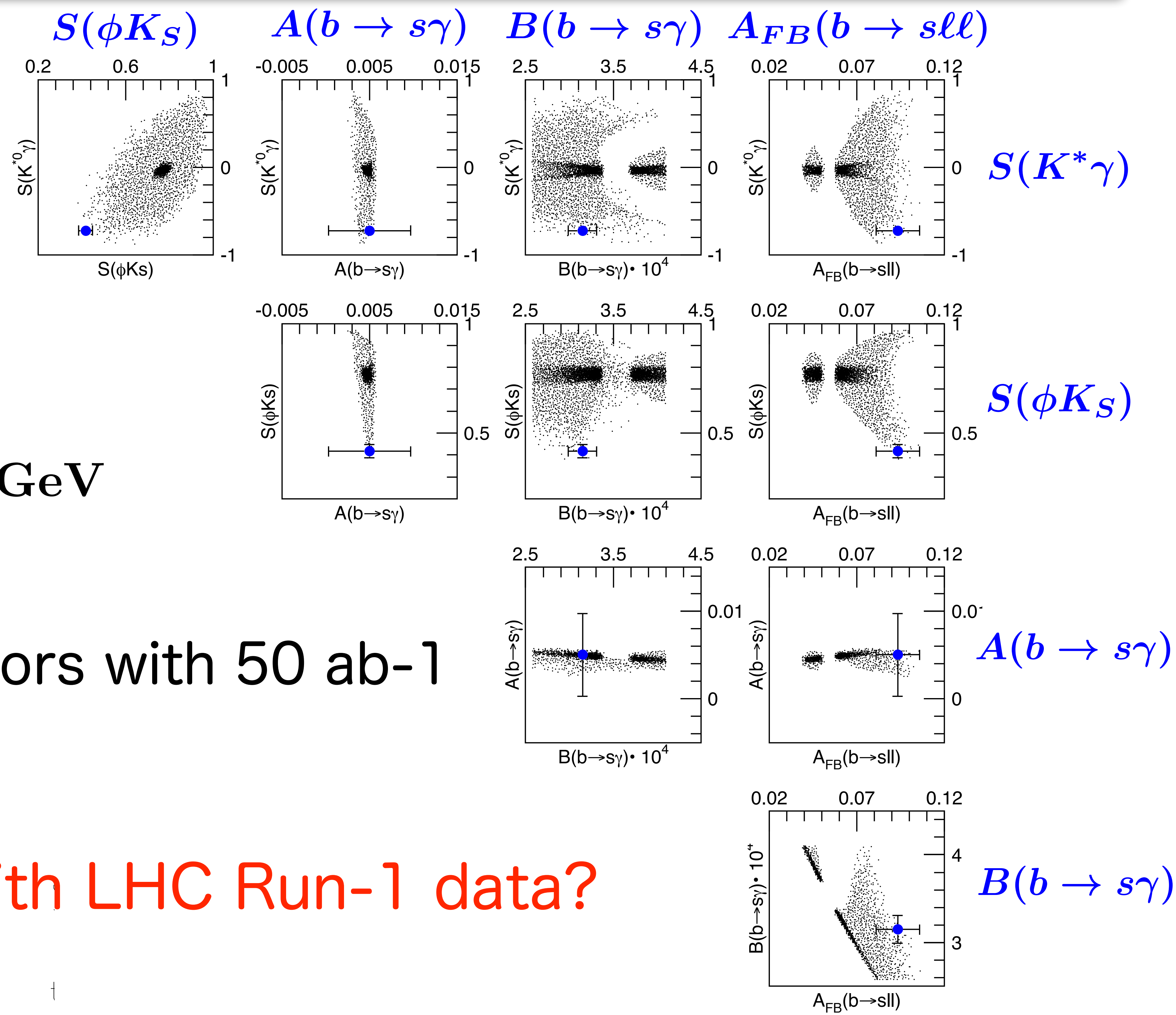
$\tan\beta = 30$

Expected errors with 50 ab-1

Update with LHC Run-1 data?

Satoshi Mishima (KEK)

Example: SUSY SU(5)+ν_R SuperKEKB LOI (2004)



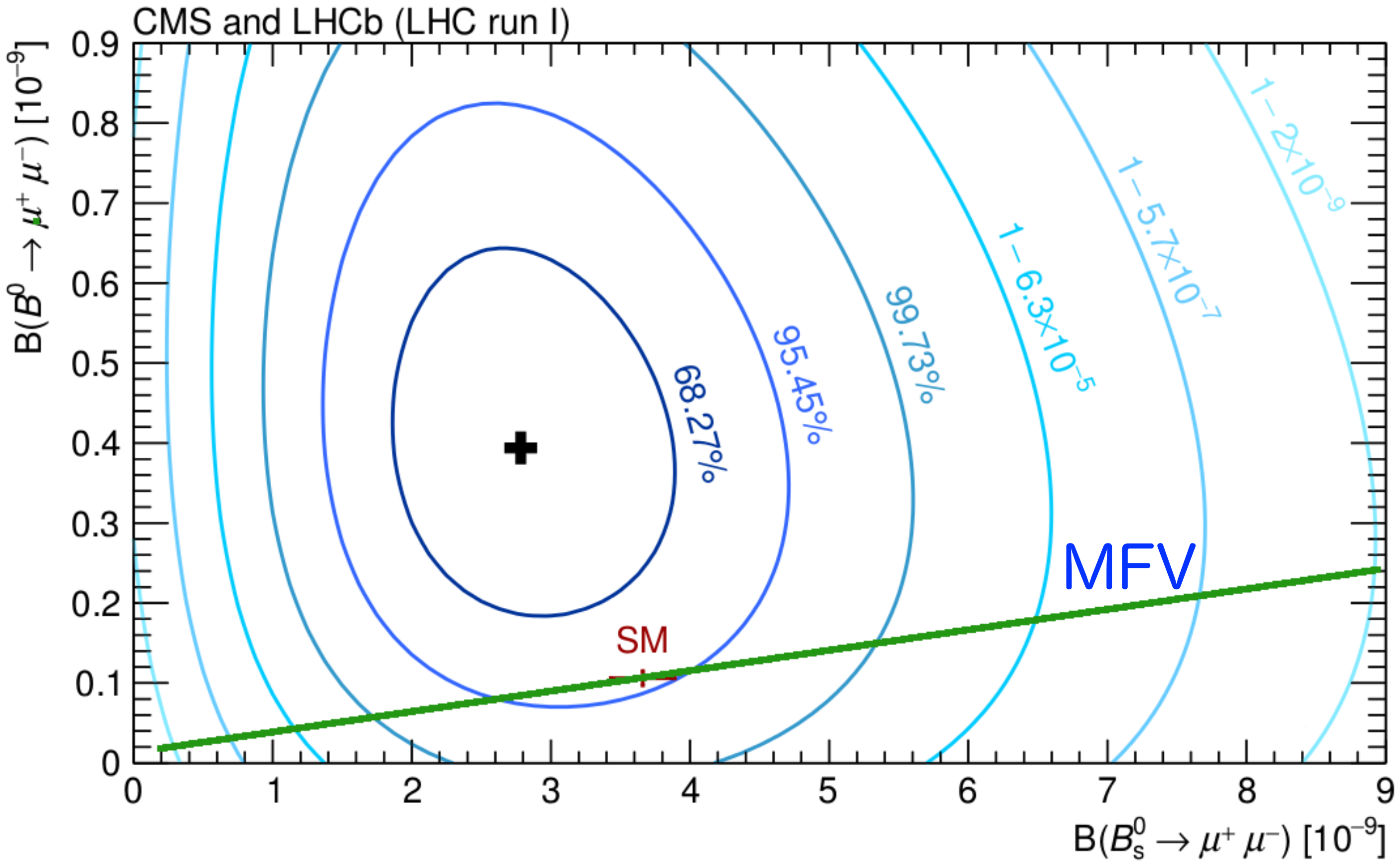
$M_{\text{gluino}} = 600\,\text{GeV}$

$\tan\beta = 30$

Expected errors with 50 ab-1

Update with LHC Run-1 data?

Example: Test of MFV with $B_{s,d} \to \mu^+\mu^-$

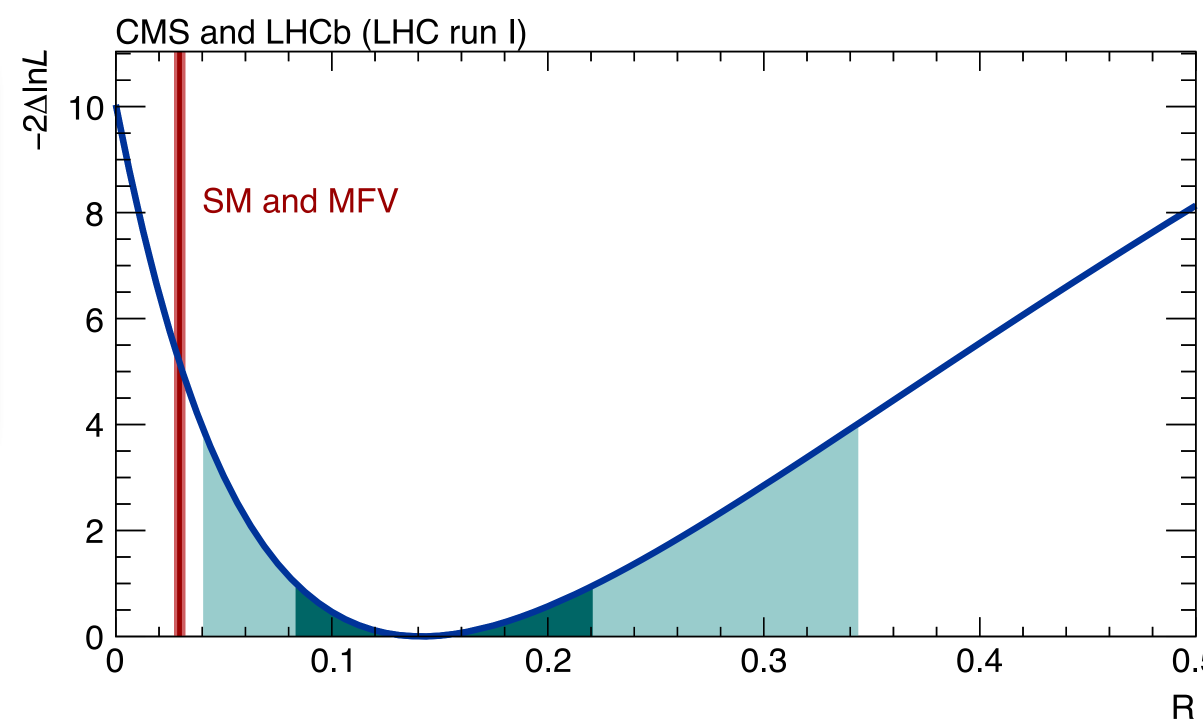


CMS & LHCb, 1411.4413

Figure from M. Blanke, 1412.1003

MFV:

$$R = \frac{B(B_d \to \mu\mu)}{B(B_s \to \mu\mu)} \propto \frac{|V_{td}|^2}{|V_{ts}|^2}\frac{f_{B_d}^2}{f_{B_s}^2}$$



Non-minimal FV?

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

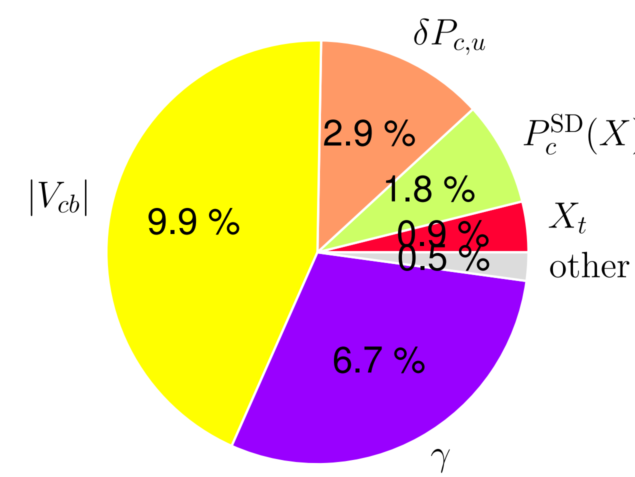
$$K^+ \to \pi^+\nu\bar{\nu} \qquad K_L \to \pi^0\nu\bar{\nu}$$

- In the SM, those decays are dominated by Z-penguin and box contributions.
- Theoretically very clean
- Large uncertainties due to CKM

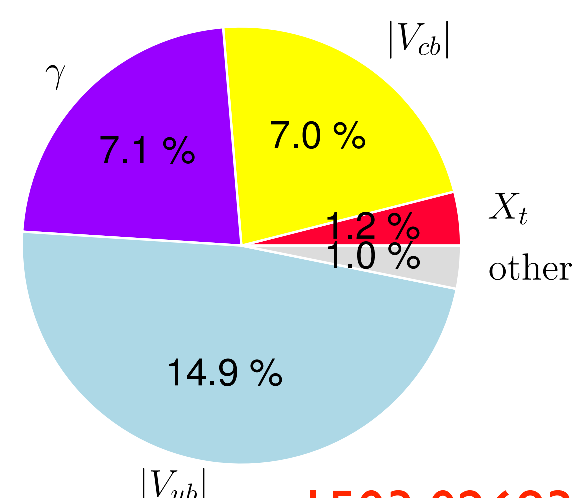
$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}X_{\mathrm{eff}}}{\lambda^5}\right)^2 + \left(\frac{\mathrm{Re}X_{\mathrm{eff}}}{\lambda^5} - \bar{P}_c(X)\right)^2\right],$$

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}X_{\mathrm{eff}}}{\lambda^5}\right)^2,$$

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$



$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$



1503.02693

- Grossman-Nir bound:

$$B(K_L \to \pi^0\nu\bar{\nu}) < 4.4\, B(K^+ \to \pi^+\nu\bar{\nu})$$

Satoshi Mishima (KEK)

Ongoing experiments for $K \to \pi\nu\bar{\nu}$

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\rm exp} = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$$ (BNL E949)

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\rm exp} \leq 2.6 \cdot 10^{-8}$$ (KEK E391a)

SM predictions:

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.00 \pm 0.31) \times 10^{-11}$$

- NA62 will resume data taking this April and collect about 100 $K^+ \to \pi^+\nu\bar{\nu}$ events at the SM value with S/B=10 in two years.

- KOTO is sensitive to the SM value for $K_L \to \pi^0\nu\bar{\nu}$ and will collect O(100) events at step 2 after 2018(?).

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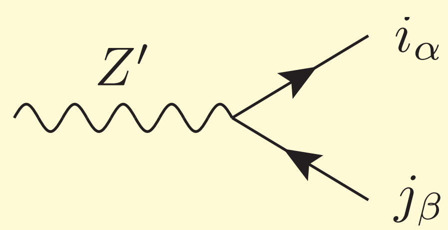
Modified Z couplings or new Z'

1211.1896, 1408.0728, 1507.08672, …



$$i\gamma_\mu \delta_{\alpha\beta} \left[\Delta_L^{ij}(Z') P_L + \Delta_R^{ij}(Z') P_R \right]$$

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |X + \cdots|^2$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) \propto (\mathrm{Im}\, X)^2$$

$$X = X(x_t)_{\mathrm{SM}} + \frac{\pi^2}{2M_W^2 G_F^2} \frac{\Delta_L^{\nu\nu}}{V_{ts}^* V_{td} M_{Z^{(\prime)}}^2} (\Delta_L^{sd} + \Delta_R^{sd})$$

$$|\epsilon_K| \propto \frac{1}{M_{Z^{(\prime)}}^2} \mathrm{Im}\left[(\Delta_L^{sd})^2 + (\Delta_R^{sd})^2 - 240 \Delta_L^{sd} \Delta_R^{sd} \right]$$

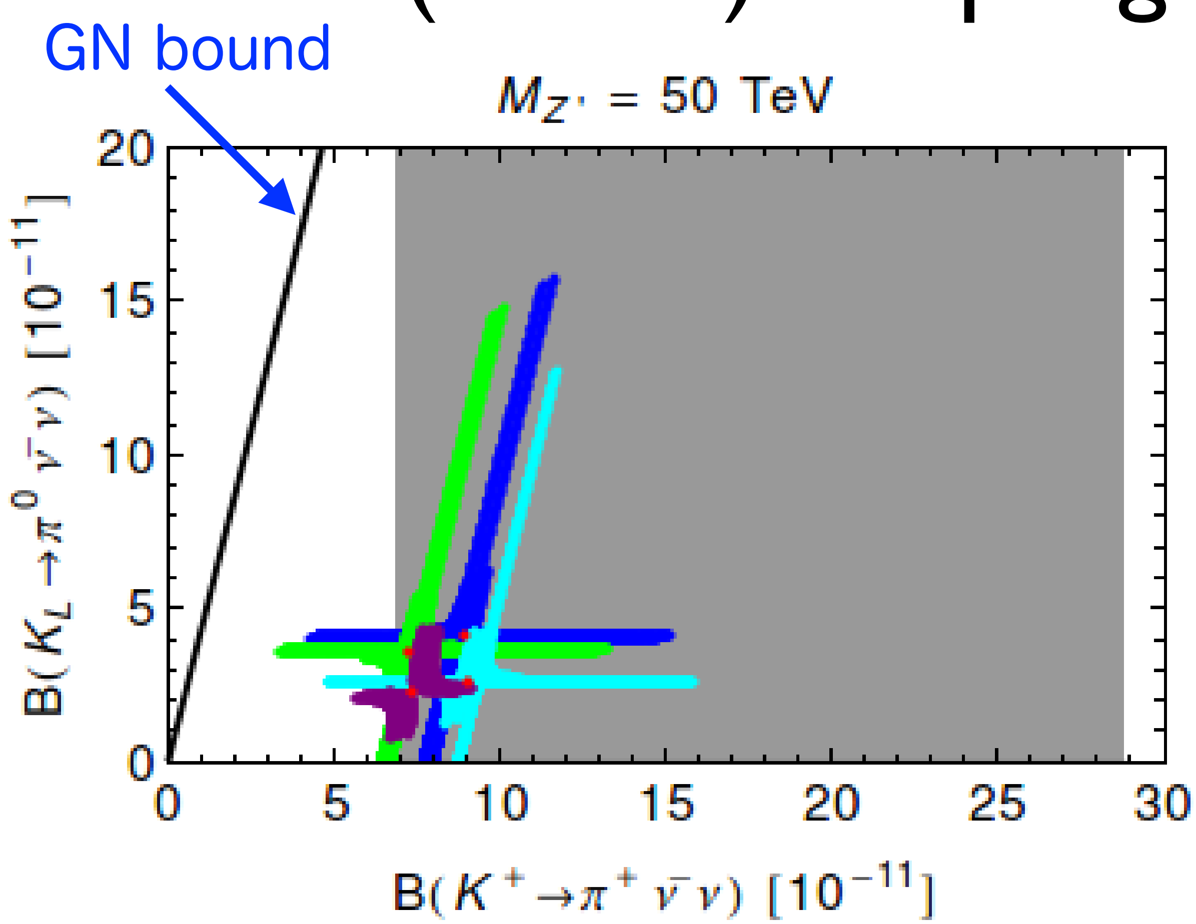
$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon} \right) \propto -\mathrm{Im}\, \Delta_L^{sd} - 3\, \mathrm{Im}\, \Delta_R^{sd} + \cdots$$

⇨ *See correlations!*

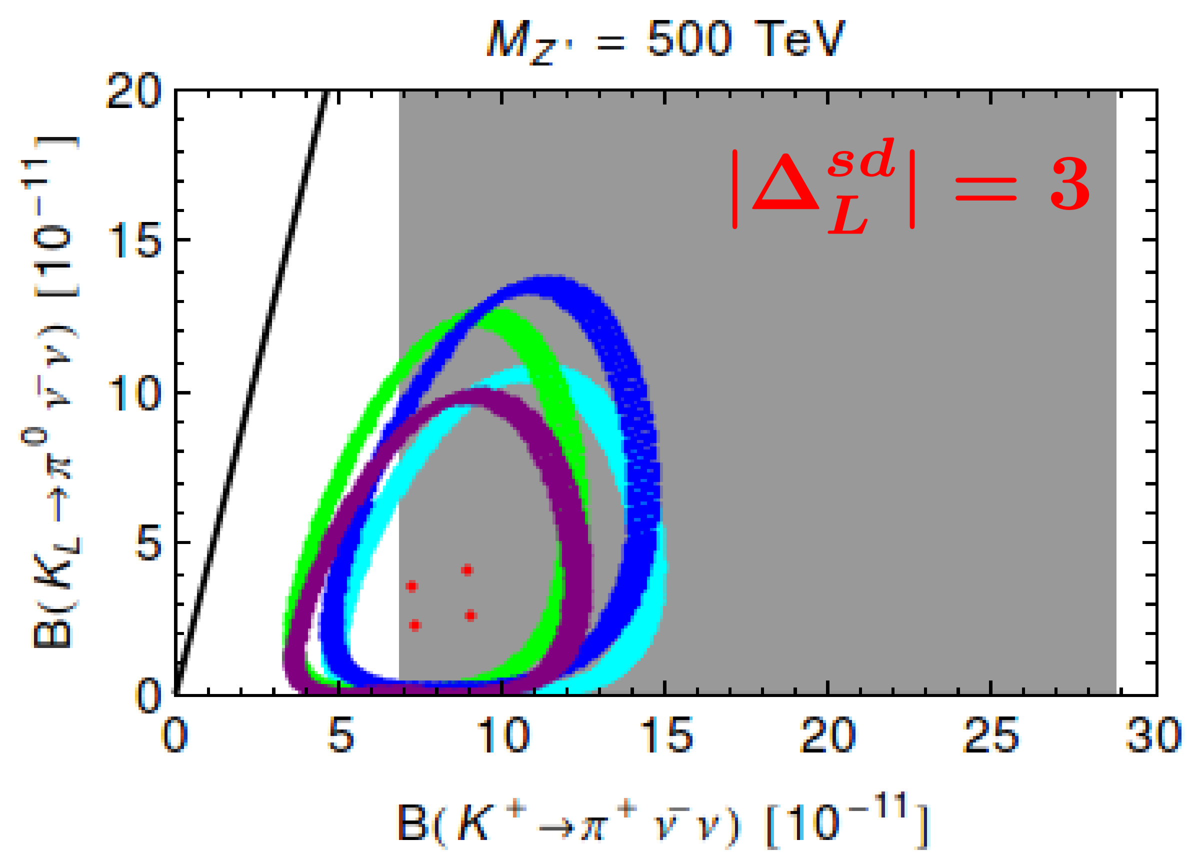
Example: Test of Z' with $K \to \pi\nu\bar{\nu}$

A.J.Buras, D.Buttazzo, J.Girrbach-Noe & R.Knegjens, 1408.0728

LH (or RH) coupling



LH+RH couplings



CKMの値の取り方で４つのシナリオ

LH: phase is constrained by ε_K.

LH+RH: possible cancellation in ε_K

➡ Heavier Z' can be probed.

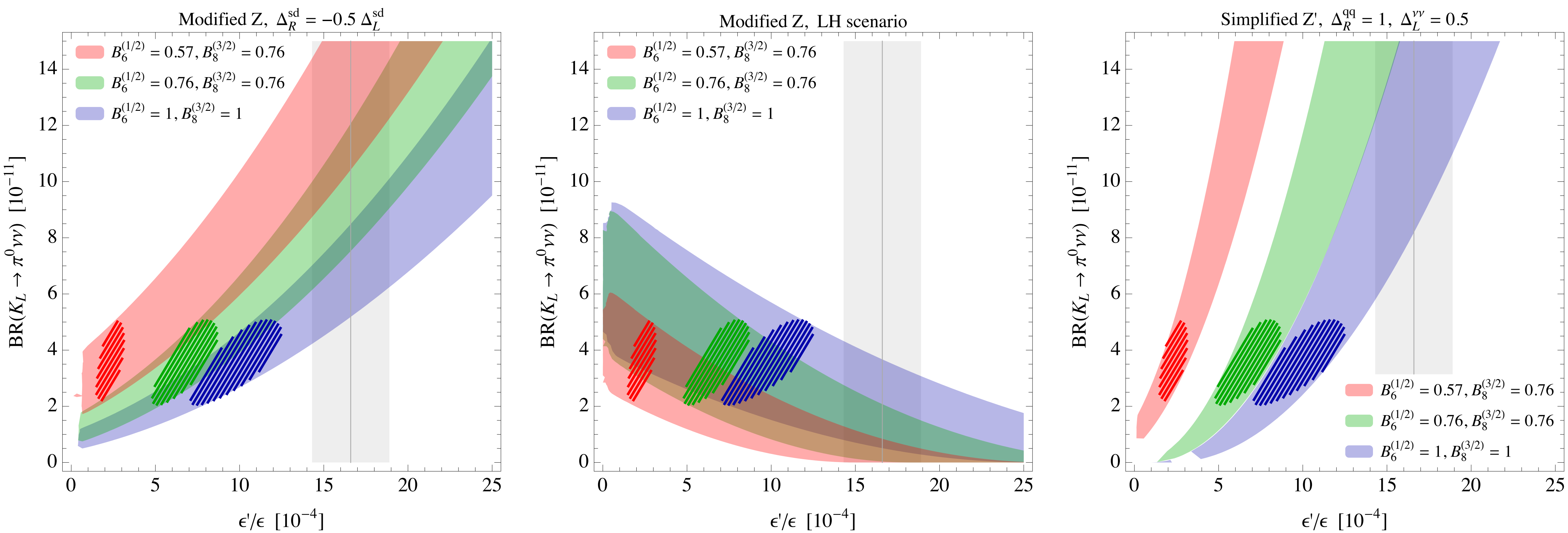
Current data:

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\rm exp} = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$ (E949)

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\rm exp} \le 2.6 \cdot 10^{-8}$ (E391a)

Example: $K \to \pi\nu\bar{\nu}$ and ε'/ε

A.J.Buras, D.Buttazzo & R.Knegjens, 1507.08672



$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) \propto (\mathrm{Im}\, X)^2$$

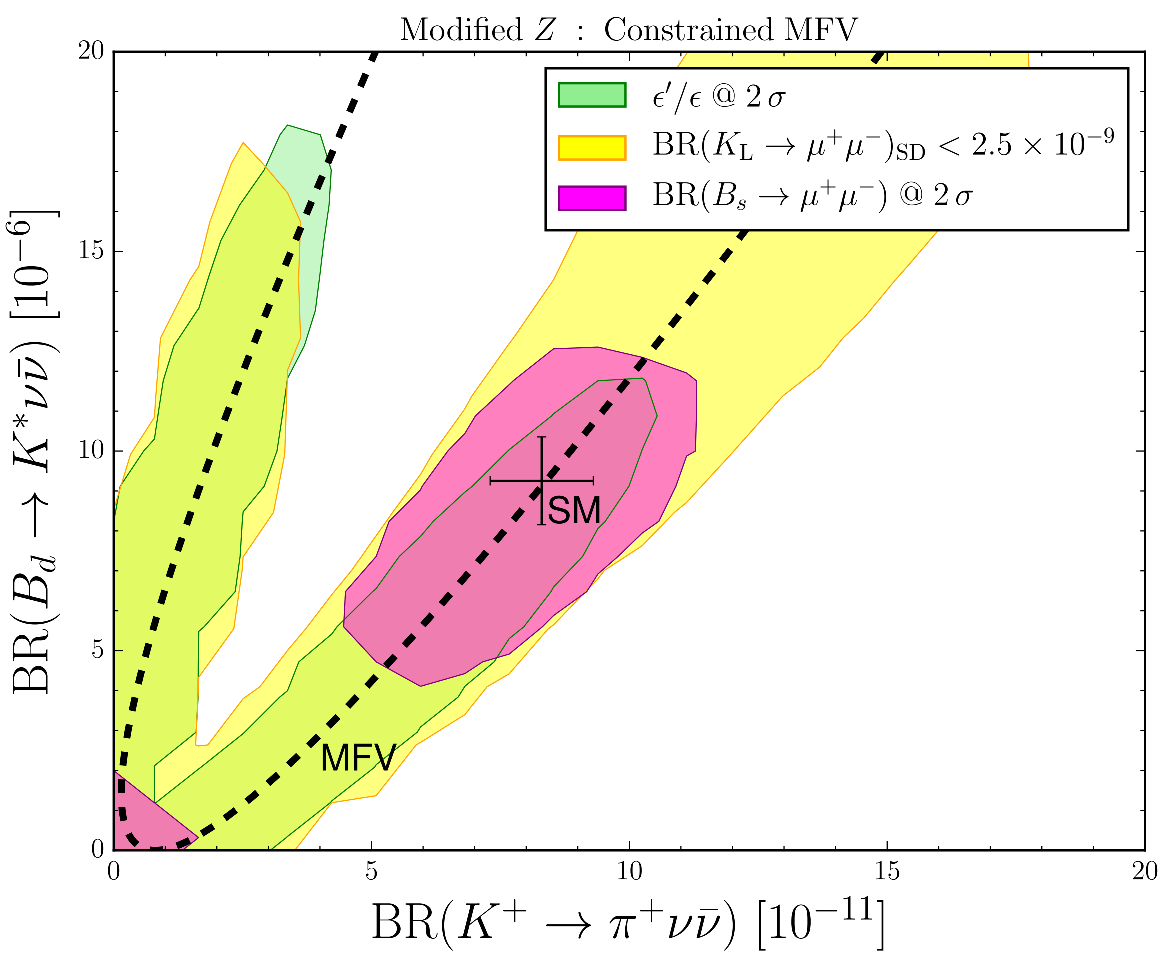
$$X = X(x_t)_{\mathrm{SM}} + \frac{\pi^2}{2M_W^2 G_F^2}\frac{\Delta_L^{\nu\nu}}{V_{ts}^* V_{td} M_{Z^{(\prime)}}^2}\left(\Delta_L^{sd} + \Delta_R^{sd}\right)$$

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) \propto -\mathrm{Im}\,\Delta_L^{sd} - 3\,\mathrm{Im}\,\Delta_R^{sd} + \cdots$$

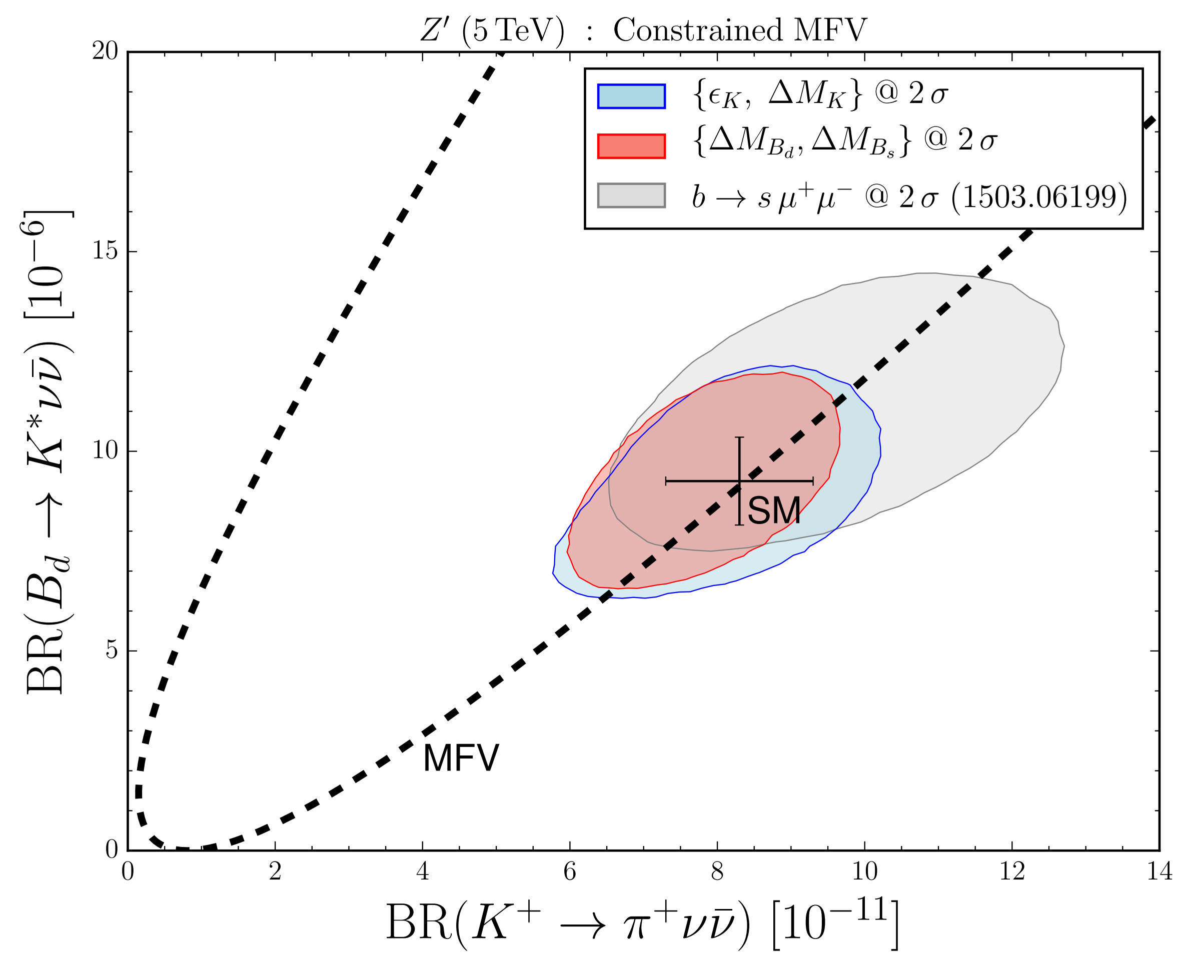
Example: $B \to K^* \nu\bar{\nu}$ vs. $K \to \pi\nu\bar{\nu}$

A.J.Buras, D.Buttazzo & R.Knegjens, 1507.08672

Modified Z couplings with CMFV



a new heavy Z' with CMFV



Strong correlations in models with CMFV

$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (3.98 \pm 0.43 \pm 0.19) \times 10^{-6}$$
$$\mathrm{BR}(B^0 \to K^{*0}\nu\bar{\nu})_{\mathrm{SM}} = (9.19 \pm 0.86 \pm 0.50) \times 10^{-6}$$

Belle (13)

$$\mathrm{BR}(B^0 \to K^{*0}\nu\bar{\nu}) < 5.5 \times 10^{-5}$$
$$\mathrm{BR}(B^+ \to K^{*+}\nu\bar{\nu}) < 4.0 \times 10^{-5}$$

Wait for Belle-II !

Example: DNA charts by Buras et al.

Figure from A.J.Buras, 1505.00618

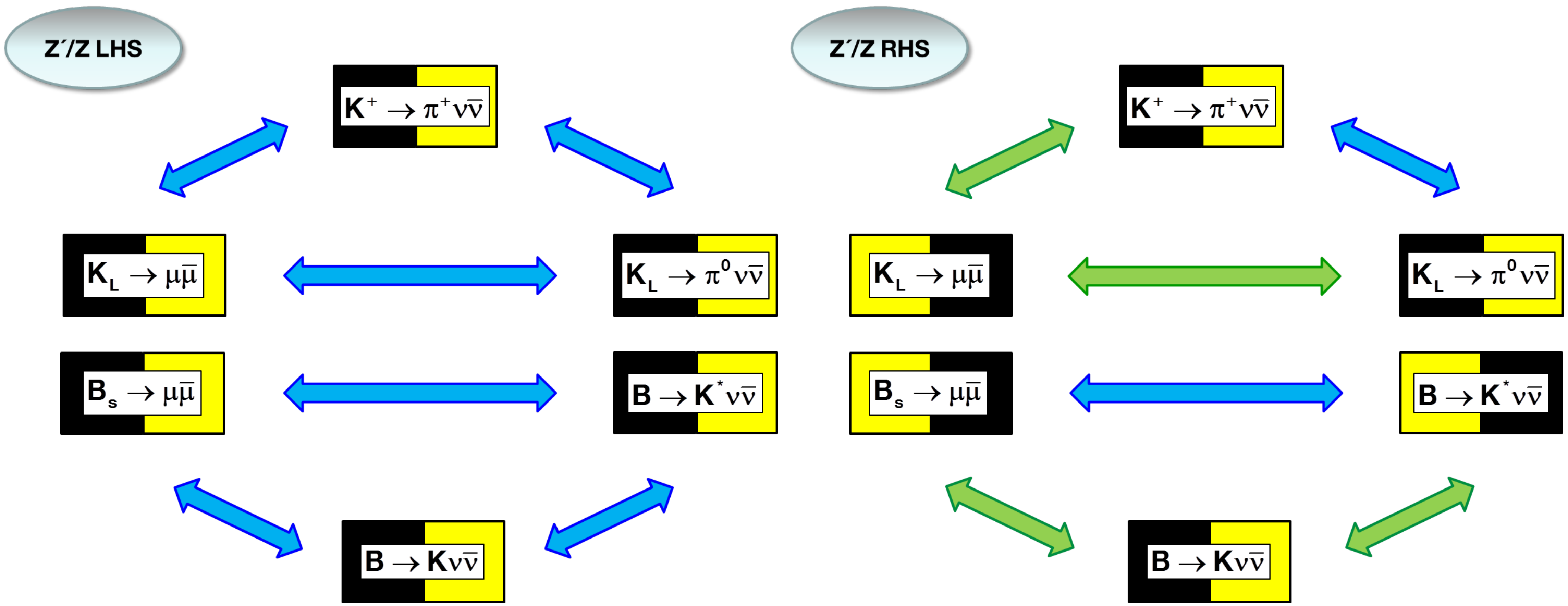


Figure 6: *DNA-charts of Z' models with LH and RH currents. Yellow means* *enhancement*, *black means* **suppression** *and white means* *no change*. *Blue arrows ⇔ indicate correlation and green arrows ⇔ indicate anti-correlation.*

Example: DNA charts by Buras et al.

Figure from A.J.Buras, 1505.00618

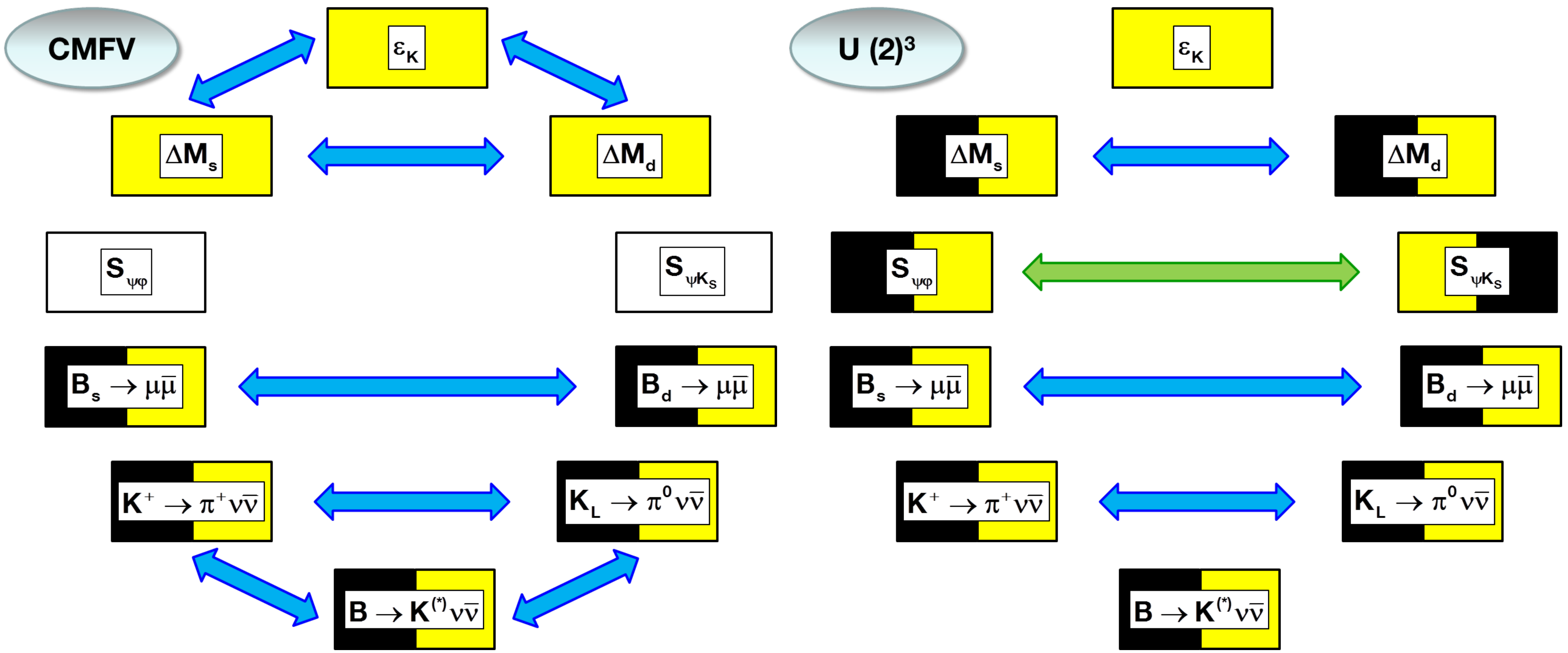


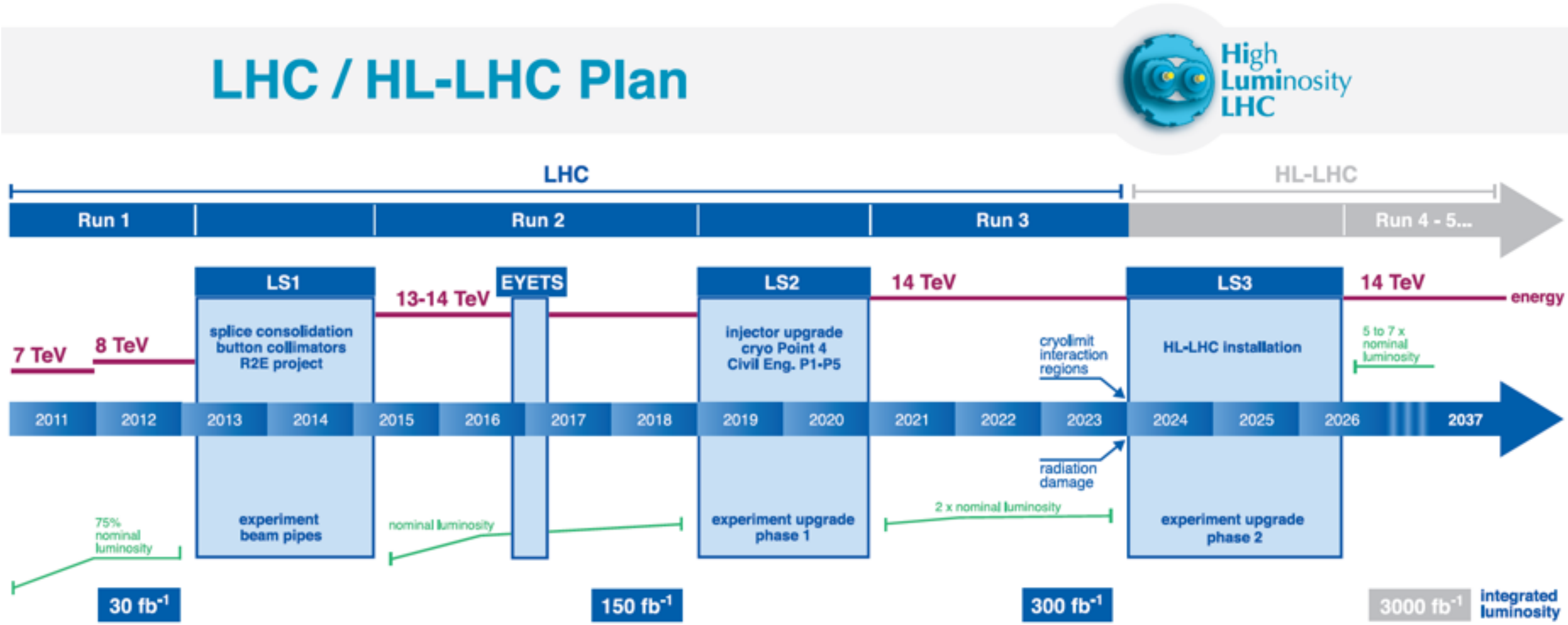
Figure 5: *DNA-chart of MFV models (left) and of $U(2)^3$ models (right). Yellow means* *enhancement*, *black means* **suppression** *and white means* *no change*. *Blue arrows* ⇔ *indicate correlation and green arrows* ⇔ *indicate anti-correlation.*

4. Summary

- フレーバー物理は TeV を超えるスケールの新物理に対して感度がある
- LHC Run 2 で新粒子が発見されない場合、フレーバー物理で新粒子の兆候を探る
- 新粒子が発見された場合、フレーバー物理で NP 模型の識別を行う
- 現在観測されている “anomalies” については理論・実験両面での更なる研究が必要

Backup

LHC / HL-LHC plan



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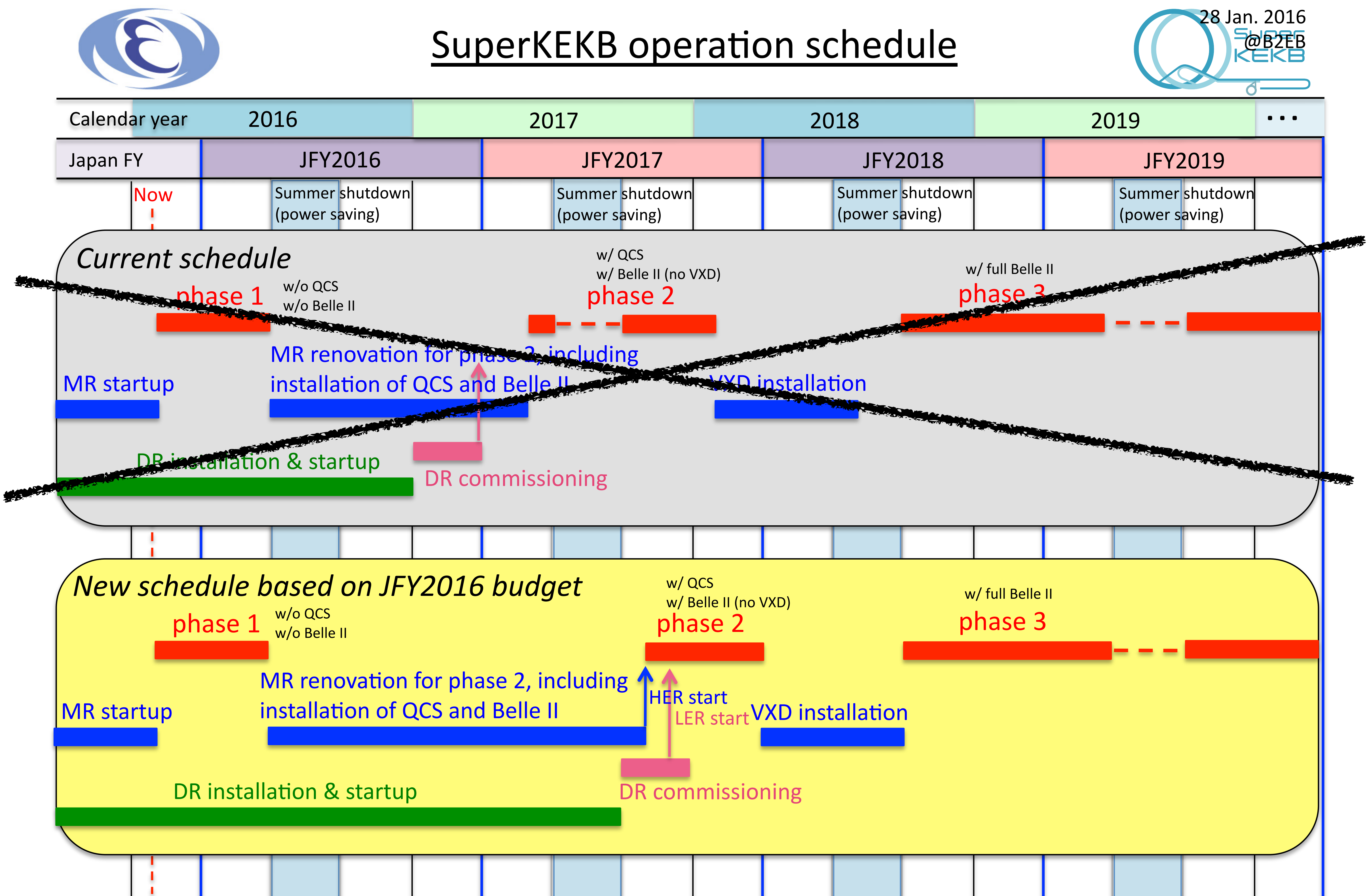
SuperKEKB / Belle II schedule



K. AKAI, SuperKEKB status, schedule and plans, Feb. 1, 2016 @B2GM

Satoshi Mishima (KEK)

Expected exp. precision

belle2-note-0021

TABLE XLI: Expected errors on several selected flavour observables with an integrated luminosity of 5 ab^{-1} and 50 ab^{-1} of Belle II data. The current results from Belle, or from BaBar where relevant (denoted with a †) are also given. Items marked with a ‡ are estimates based on similar measurements. Errors given in % represent relative errors.

	Observables	Belle or LHCb* (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 8 fb^{-1}(2018)	LHCb 50 fb^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012 (0.9^\circ)$	0.4°	0.3°	0.6°	0.3°
	α [°]	85 ± 4 (Belle+BaBar)	2	1		
	γ [°] $(B \to D^{(*)}K^{(*)})$	68 ± 14	6	1.5	4	1
	$2\beta_s(B_s \to J/\psi\phi)$ [rad]	$0.07 \pm 0.09 \pm 0.01^*$			0.025	0.009
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	0.053	0.018	0.2	0.04
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	0.028	0.011		
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	0.100	0.033		
	$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	$-0.17 \pm 0.15 \pm 0.03^*$			0.12	0.03
	$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	–			0.13	0.03
Direct CP in hadronic Decays	$\mathcal{A}(B \to K^0\pi^0)$	$-0.05 \pm 0.14 \pm 0.05$	0.07	0.04		
UT sides	$\|V_{cb}\|$ incl.	$41.6 \cdot 10^{-3}(1 \pm 2.4\%)$	1.2%			
	$\|V_{cb}\|$ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\rm ex.} \pm 2.7\%_{\rm th.})$	1.8%	1.4%		
	$\|V_{ub}\|$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\rm ex.} \pm 2.5\%_{\rm th.})$	3.4%	3.0%		
	$\|V_{ub}\|$ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 10.8\%)$	4.7%	2.4%		
Leptonic and Semi-tauonic	$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	$96(1 \pm 26\%)$	10%	5%		
	$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	20%	7%		
	$R(B \to D\tau\nu)$ [Had. tag]	$0.440(1 \pm 16.5\%)^\dagger$	5.6%	3.4%		
	$R(B \to D^*\tau\nu)^\dagger$ [Had. tag]	$0.332(1 \pm 9.0\%)^\dagger$	3.2%	2.1%	...	
Radiative	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%		
	$A_{CP}(B \to X_{s,d}\gamma)$ [10^{-2}]	$2.2 \pm 4.0 \pm 0.8$	1	0.5		
	$S(B \to K^0_S\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	0.11	0.035		
	$2\beta_s^{\rm eff}(B_s \to \phi\gamma)$	–			0.13	0.03
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	0.23	0.07		
	$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	0.3	–		
Electroweak penguins	$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$ [10^{-6}]	< 40	< 15	30%		
	$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$ [10^{-6}]	< 55	< 21	30%		
	C_7/C_9 $(B \to X_s\ell\ell)$	~20%	10%	5%		
	$\mathcal{B}(B_s \to \tau\tau)$ [10^{-3}]	–	< 2	–		
	$\mathcal{B}(B_s \to \mu\mu)$ [10^{-9}]	$2.9^{+1.1*}_{-1.0}$			0.5	0.2

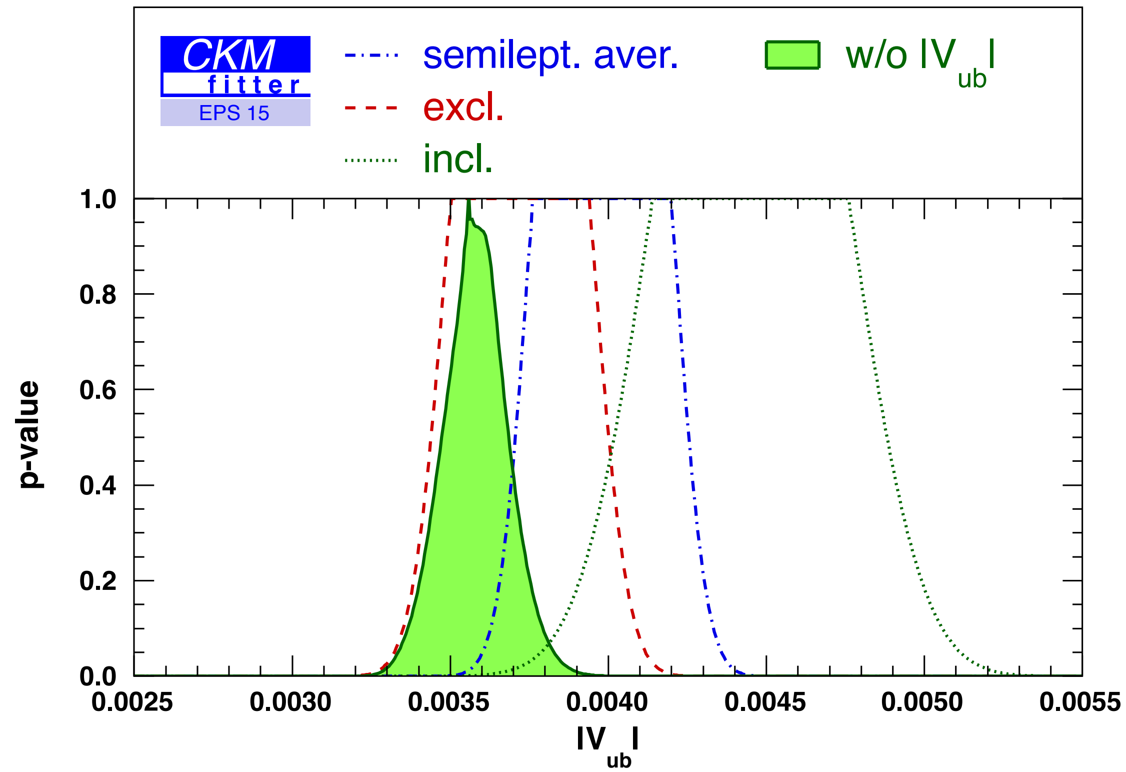
Future inputs from Lattice QCD

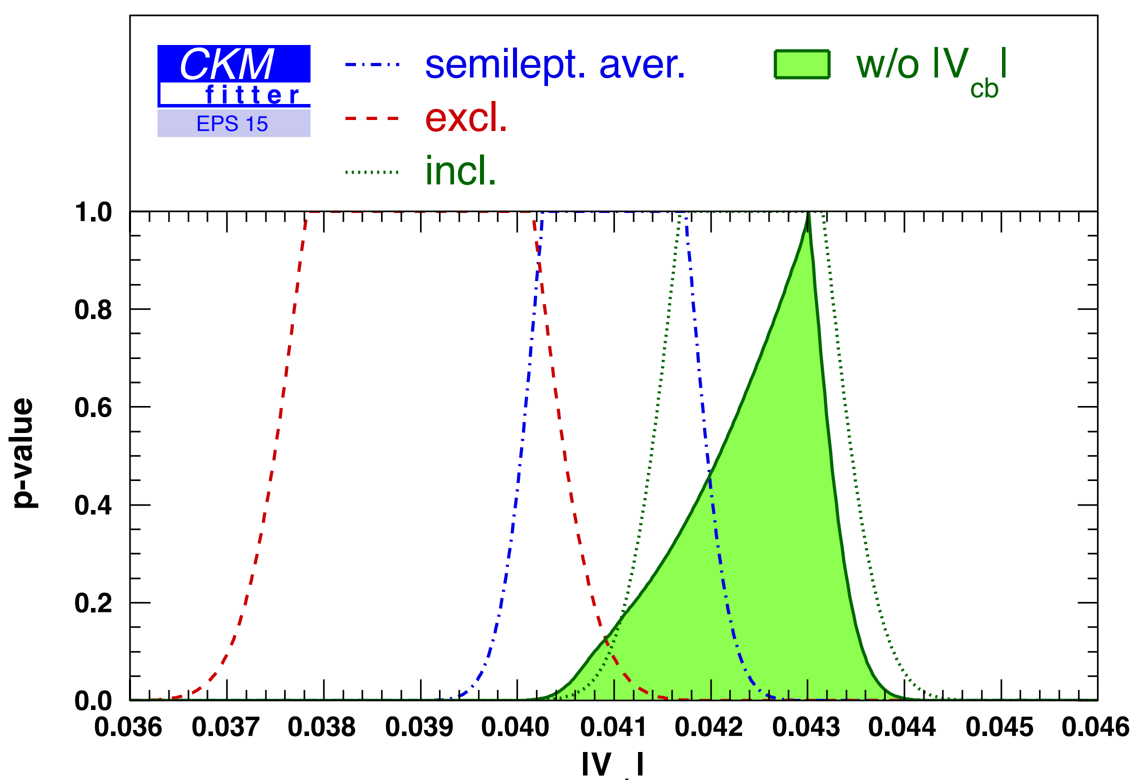
arXiv:1311.1076

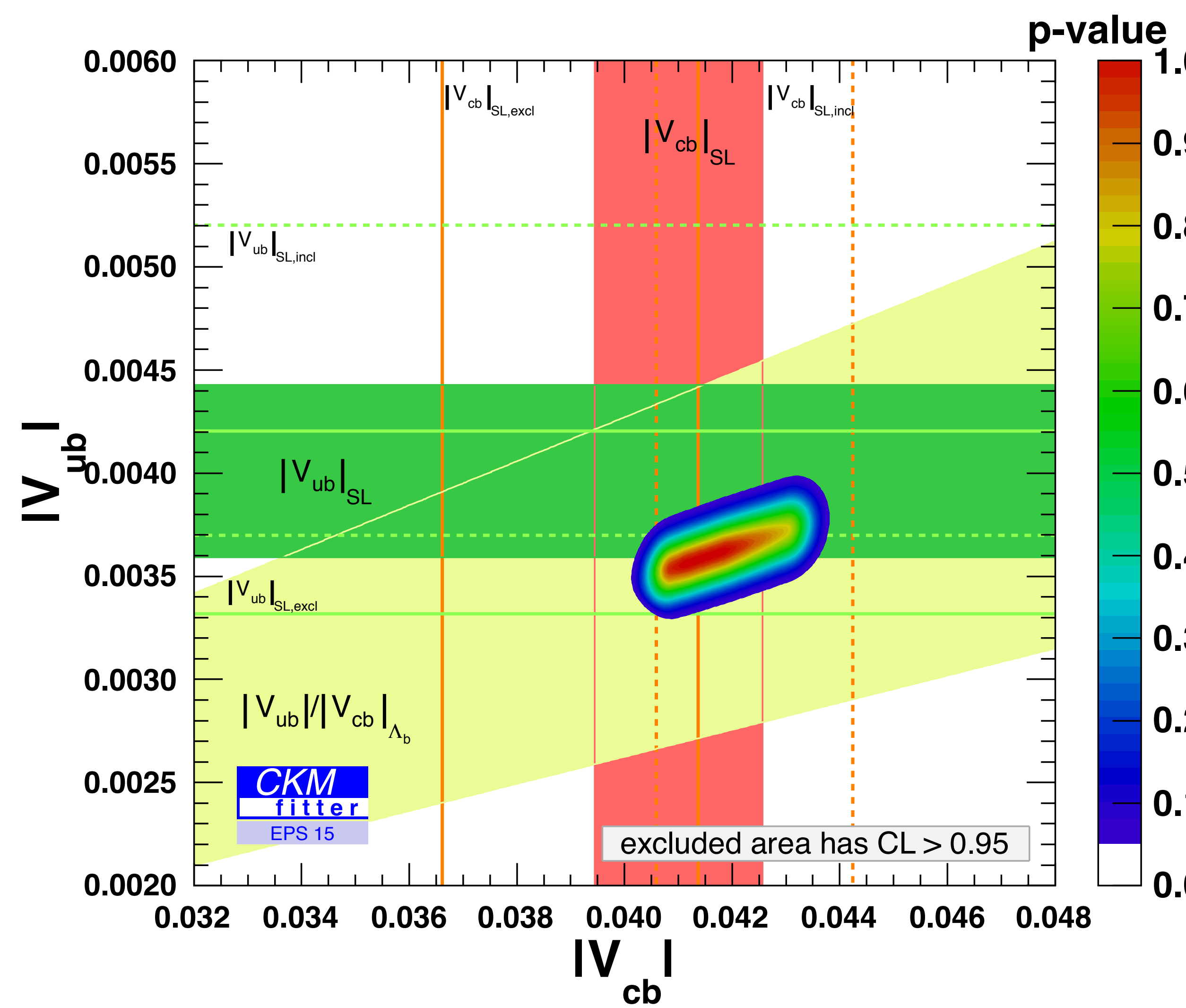
Quantity	CKM element	Present expt. error	2007 forecast lattice error	Present lattice error	2018 lattice error
f_K/f_π	$\lvert V_{us}\rvert$	0.2%	0.5%	0.4%	0.15%
$f_+^{K\pi}(0)$	$\lvert V_{us}\rvert$	0.2%	–	0.4%	0.2%
f_D	$\lvert V_{cd}\rvert$	4.3%	5%	2%	$< 1\%$
f_{D_s}	$\lvert V_{cs}\rvert$	2.1%	5%	2%	$< 1\%$
$D \to \pi\ell\nu$	$\lvert V_{cd}\rvert$	2.6%	–	4.4%	2%
$D \to K\ell\nu$	$\lvert V_{cs}\rvert$	1.1%	–	2.5%	1%
$B \to D^*\ell\nu$	$\lvert V_{cb}\rvert$	1.3%	–	1.8%	$< 1\%$
$B \to \pi\ell\nu$	$\lvert V_{ub}\rvert$	4.1%	–	8.7%	2%
f_B	$\lvert V_{ub}\rvert$	9%	–	2.5%	$< 1\%$
ξ	$\lvert V_{ts}/V_{td}\rvert$	0.4%	2–4%	4%	$< 1\%$
Δm_s	$\lvert V_{ts}V_{tb}\rvert^2$	0.24%	7–12%	11%	5%
B_K	$\mathrm{Im}(V_{td}^2)$	0.5%	3.5–6%	1.3%	$< 1\%$

Table 6. *History, status and future of selected lattice-QCD calculations needed for the determination of CKM matrix elements. 2007 forecasts are from Ref. [112]. Most present lattice results are taken from latticeaverages.org [113]. The quantity* ξ *is* $f_{B_s}\sqrt{B_{B_s}}/(f_B\sqrt{B_B})$.

Tension in Vub and Vcb measurements







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Belle R(D^(*))

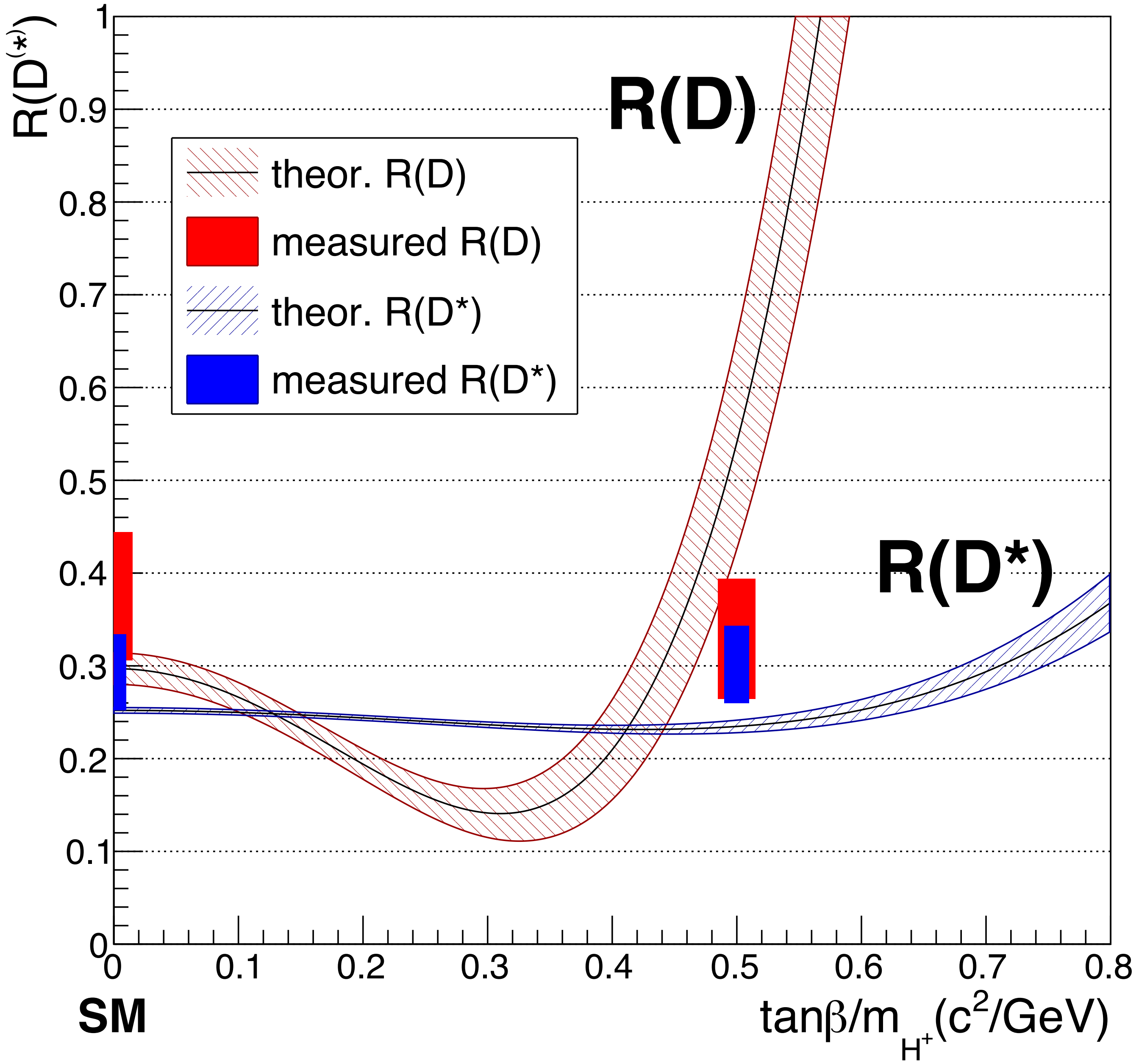


FIG. 7. Theoretical predictions with $1\,\sigma$ error ranges for $R(D)$ (red) and $R(D^*)$ (blue) for different values of $\tan\beta/m_{H^+}$ in the 2HDM of type II. The fit results for $\tan\beta/m_{H^+} = 0.5\,c^2/\mathrm{GeV}$ and SM are shown with their $1\,\sigma$ ranges as red and blue bars with arbitrary width for better visibility.

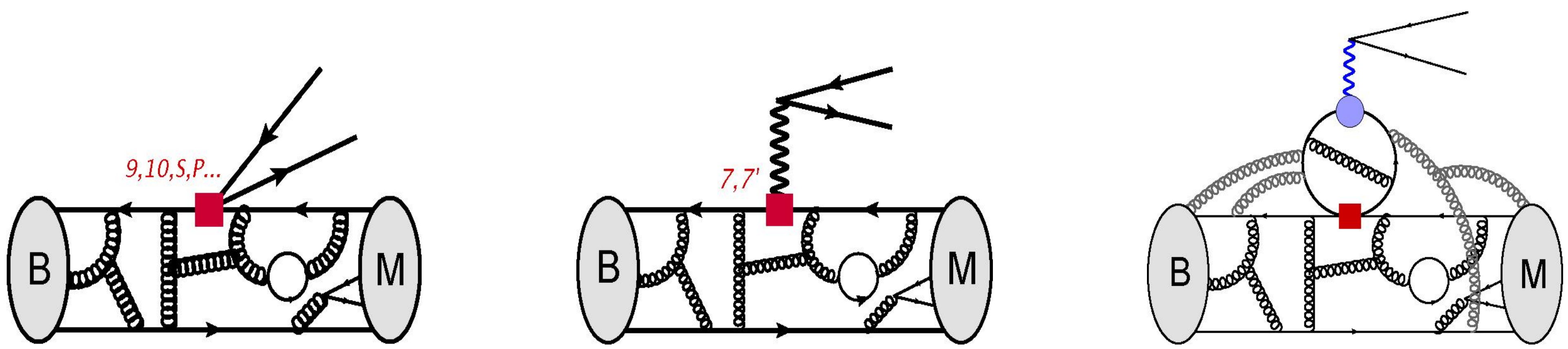
Satoshi Mishima (KEK)

Amplitudes

Talk by J.Virto

EFT Amplitudes

$$\mathcal{L} = \mathcal{L}_{QED+QCD} - \mathcal{C}_7\,[\bar{s}\sigma^{\mu\nu}P_R b]\,F_{\mu\nu} - \mathcal{C}_2\,[\bar{s}\gamma^{\nu}P_L c]\,[\bar{c}\gamma^{\mu}P_L b] + \cdots$$



$\mathcal{C}_9$ **contribution:** $\mathcal{A}_9 = \mathcal{C}_9\,\langle M_\lambda|\bar{s}\gamma_\mu P_L b|B\rangle L^\mu = \mathcal{C}_9\,F_\lambda(q^2)$

7 form factors!

$\mathcal{C}_7$ **contribution:** $\mathcal{A}_7 = \mathcal{C}_7\,\langle M_\lambda|\bar{s}\sigma_{\mu\nu}P_R b|B\rangle \frac{eq^\mu}{q^2} L^\nu = \mathcal{C}_7\,T_\lambda(q^2)$

$\mathcal{C}_2$ **contribution:** $\mathcal{A}_2 = \mathcal{C}_2 \cdot \frac{e^2}{q^2} L^\mu \int dx^4 e^{iq\cdot x}\langle M_\lambda|T\{\mathcal{J}^{em}_\mu(x)\mathcal{O}_2(0)\}|B\rangle$

Non-local!

2 main problems:

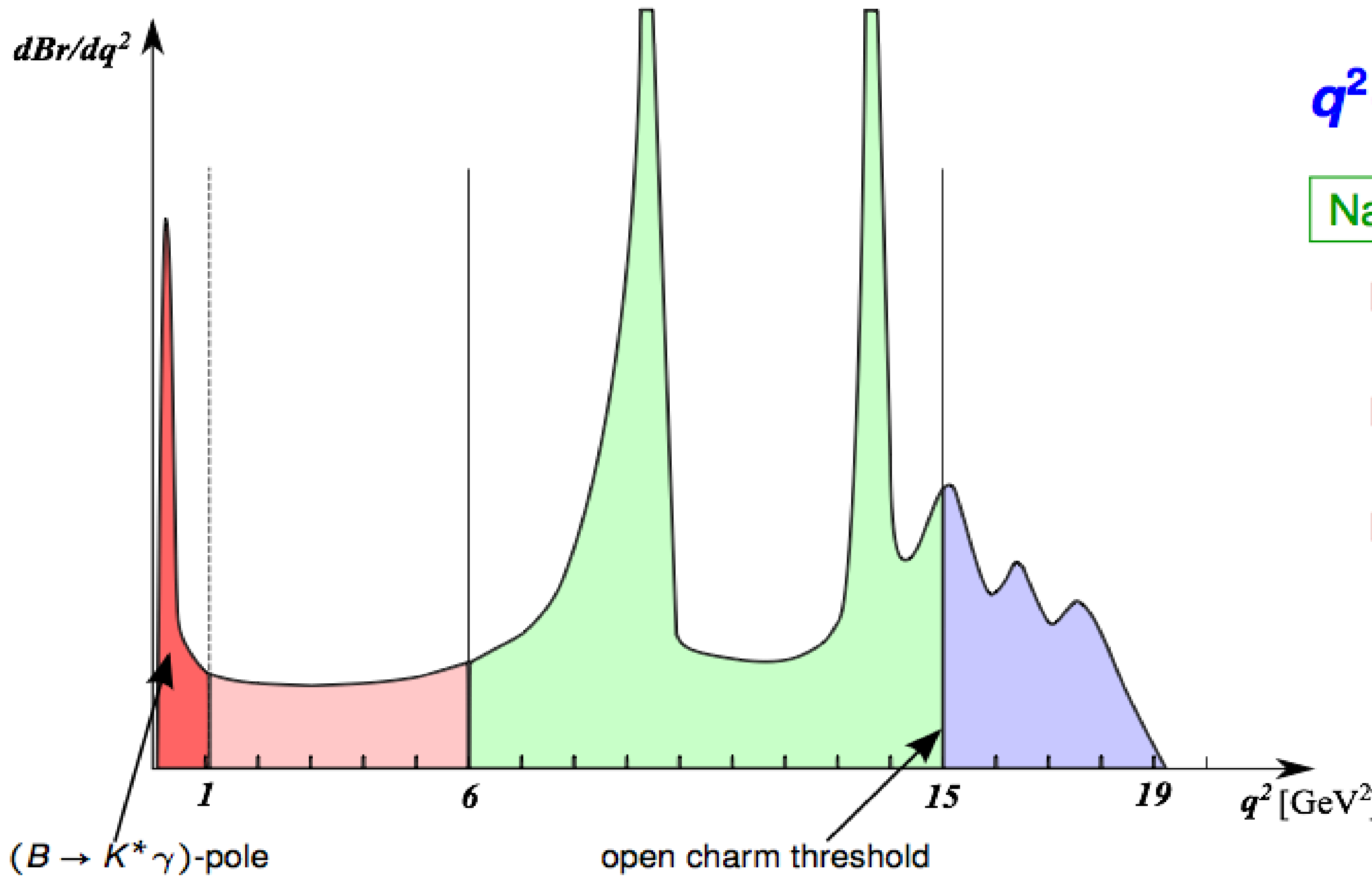
1. Determination of Form Factors (LCSRs, LQCD, . . .)
2. Computation of the hadronic contribution (SCET/QCDF, OPE, . . .)

Satoshi Mishima (KEK)

q^2 regions

Talk by J.Virto

$m^2_{\ell\ell}$ spectrum



q^2-Regions in $B \to K^*\bar{\ell}\ell$

Narrow resonances

- dominated by charged-cur. (tree-level) op's
- not sensitive to new physics in $b \to s\bar{\ell}\ell$
- nonperturbative predictions via: dispersion relations + $B \to K^*(\bar{c}c)$ data

Large Recoil (low-q^2)

- very low-q^2 ($\lesssim 1$ GeV^2) dominated by $\mathcal{O}_7$
- low-q^2 ($[1,6]$ GeV^2) dominated by $\mathcal{O}_{9,10}$
- 1) QCD factorization or SCET
  2) LCSR
  3) non-local OPE of $\bar{c}c$-tails

Low Recoil (high-q^2)

- dominated by $\mathcal{O}_{9,10}$
- local OPE (+ HQET) $\Rightarrow$ theory only for sufficiently large q^2-integrated obs's

(slide from C. Bobeth)

Form factors at low q^2

among them. In order to facilitate the use of the LCSR results, we perform fits of the full analytical result to a simplified series expansion (SSE), which is based on a rapidly converging series in the parameter

$$z(t) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}} \tag{14}$$

where $t_\pm = (m_B \pm m_V)^2$ and $t_0 = t_+(1 - \sqrt{1 - t_-/t_+})$. We write the form factors as

$$F_i(q^2) = P_i(q^2) \sum_k \alpha_k^i \left[z(q^2) - z(0)\right]^k , \tag{15}$$

where $P_i(q^2) = (1 - q^2/m_{R,i}^2)^{-1}$ is a simple pole corresponding to the first resonance in the spectrum. The appropriate resonance masses are given in table 3. We consider fits that are

	$B \to K^*$	$B \to \rho$	$B \to \omega$	$B_s \to \phi$	$B_s \to K^*$
$\alpha_0^{A_0}$	0.39 ± 0.04	0.37 ± 0.03	0.31 ± 0.04	0.43 ± 0.04	0.34 ± 0.03
$\alpha_1^{A_0}$	-1.15 ± 0.28	-0.99 ± 0.23	-0.90 ± 0.30	-1.06 ± 0.30	-0.93 ± 0.24
$\alpha_2^{A_0}$	2.08 ± 1.50	1.17 ± 1.21	1.19 ± 1.18	2.74 ± 1.52	2.22 ± 1.43
$\alpha_0^{A_1}$	0.29 ± 0.03	0.27 ± 0.02	0.24 ± 0.03	0.32 ± 0.03	0.25 ± 0.02
$\alpha_1^{A_1}$	0.31 ± 0.19	0.36 ± 0.13	0.34 ± 0.19	0.46 ± 0.22	0.26 ± 0.19
$\alpha_2^{A_1}$	0.72 ± 0.49	0.55 ± 0.35	0.55 ± 0.46	1.70 ± 0.83	0.86 ± 0.70
$\alpha_0^{A_{12}}$	0.28 ± 0.03	0.31 ± 0.03	0.26 ± 0.03	0.27 ± 0.02	0.25 ± 0.02
$\alpha_1^{A_{12}}$	0.57 ± 0.22	0.67 ± 0.20	0.51 ± 0.25	0.77 ± 0.18	0.55 ± 0.18
$\alpha_2^{A_{12}}$	0.14 ± 0.86	0.33 ± 0.75	0.15 ± 0.90	0.91 ± 1.00	0.68 ± 0.95
α_0^{V}	0.37 ± 0.04	0.33 ± 0.03	0.30 ± 0.04	0.41 ± 0.03	0.31 ± 0.03
α_1^{V}	-1.08 ± 0.24	-0.89 ± 0.18	-0.77 ± 0.24	-1.06 ± 0.30	-0.93 ± 0.33
α_2^{V}	2.47 ± 1.35	1.74 ± 1.13	1.49 ± 0.94	3.66 ± 1.54	2.89 ± 1.84
$\alpha_0^{T_1}$	0.31 ± 0.03	0.28 ± 0.03	0.25 ± 0.03	0.33 ± 0.03	0.25 ± 0.03
$\alpha_1^{T_1}$	-0.96 ± 0.20	-0.78 ± 0.14	-0.67 ± 0.19	-0.94 ± 0.23	-0.80 ± 0.30
$\alpha_2^{T_1}$	2.01 ± 1.09	1.51 ± 0.93	1.29 ± 0.74	3.20 ± 1.30	2.55 ± 1.42
$\alpha_0^{T_2}$	0.31 ± 0.03	0.28 ± 0.03	0.25 ± 0.03	0.33 ± 0.03	0.25 ± 0.03
$\alpha_1^{T_2}$	0.42 ± 0.20	0.47 ± 0.14	0.45 ± 0.19	0.58 ± 0.21	0.36 ± 0.24
$\alpha_2^{T_2}$	2.02 ± 0.72	1.58 ± 0.60	1.48 ± 0.57	3.69 ± 1.13	2.44 ± 1.05
$\alpha_0^{T_{23}}$	0.79 ± 0.06	0.81 ± 0.08	0.70 ± 0.08	0.76 ± 0.06	0.64 ± 0.06
$\alpha_1^{T_{23}}$	1.26 ± 0.61	1.45 ± 0.51	1.19 ± 0.63	1.55 ± 0.47	0.99 ± 0.49
$\alpha_2^{T_{23}}$	1.96 ± 2.38	2.50 ± 1.72	1.97 ± 2.11	4.59 ± 2.51	4.03 ± 2.45

Table 11: Fit results for the SSE expansion coefficients in the fit to the LCSR computation only. These numbers are provided (to higher accuracy) in electronic form along with the full correlation matrices as arXiv ancillary files.

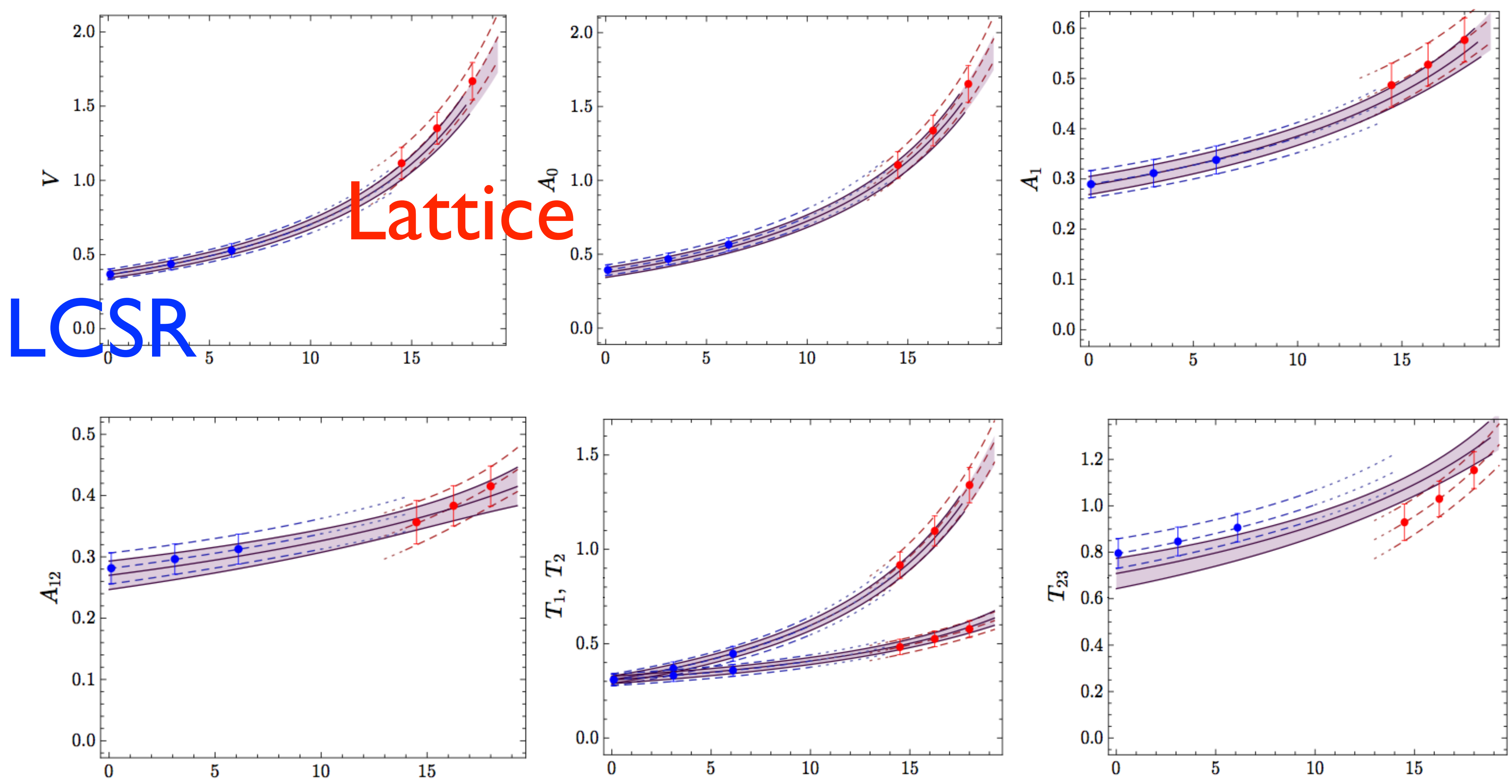
Bharucha, Straub & Zwicky, arXiv:1503.05534

up to k=2

Form factors

Talk by J.Virto

$B \to K^*\ell\bar{\ell}$: Form Factors

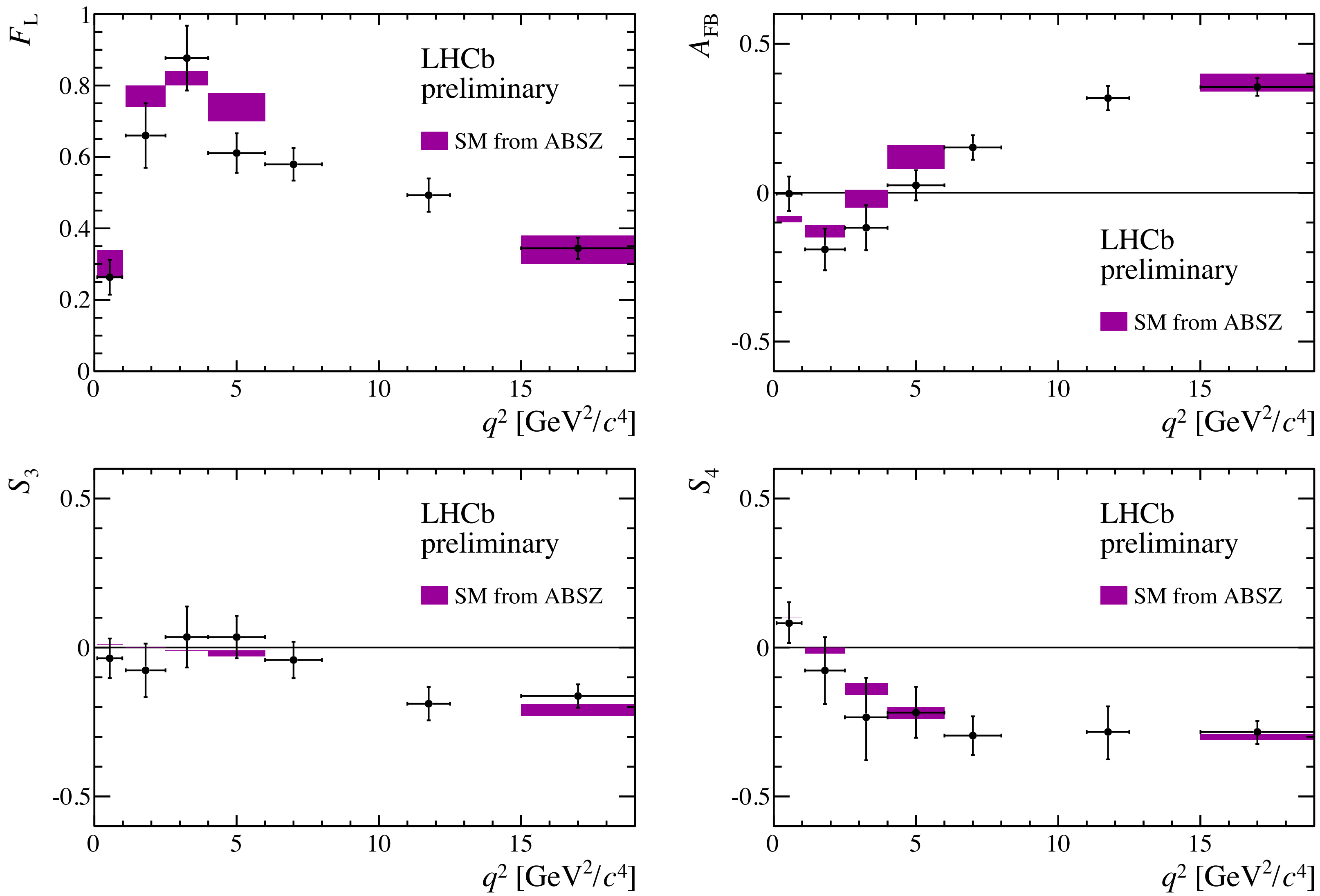


Bharucha, Straub, Zwicky'2015

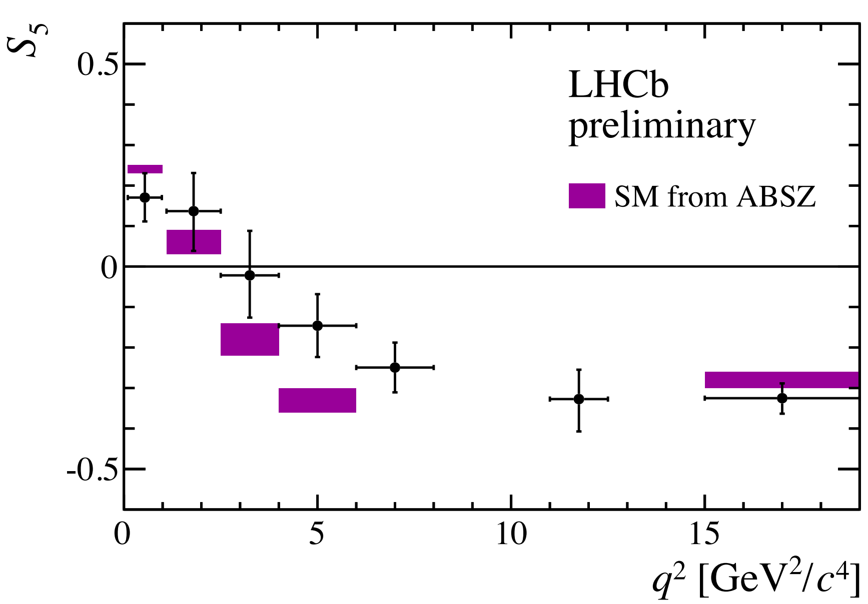
Satoshi Mishima (KEK)

More LHCb data (not all)

LHCb-CONF-2015-002



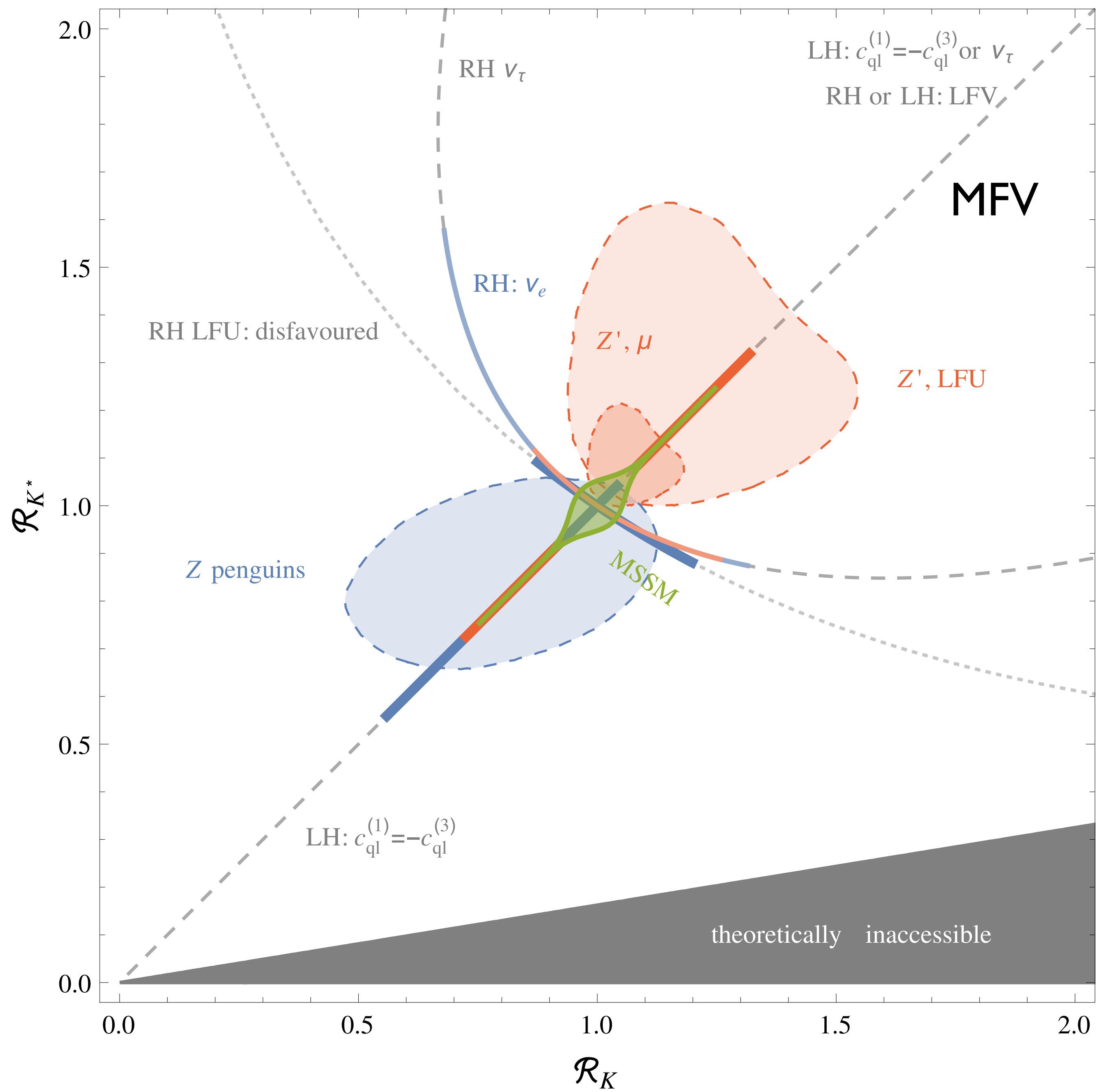
$$P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$



Example: Test of NP with $B \to K^{(*)}\nu\bar{\nu}$

A.J.Buras, J.Girrbach-Noe, C.Niehoff & D.M.Straub, 1409.4557

Allowed regions by the $b \to s$ data



$$R_{K^{(*)}} = \frac{B(B \to K^{(*)}\nu\bar{\nu})}{B(B \to K^{(*)}\nu\bar{\nu})_{\rm SM}}$$

$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\rm SM} = (3.98 \pm 0.43 \pm 0.19) \times 10^{-6}$$
$$\mathrm{BR}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM} = (9.19 \pm 0.86 \pm 0.50) \times 10^{-6}$$

Belle (13)

$$\mathrm{BR}(B^0 \to K^{*0}\nu\bar{\nu}) < 5.5 \times 10^{-5}$$
$$\mathrm{BR}(B^+ \to K^{*+}\nu\bar{\nu}) < 4.0 \times 10^{-5}$$

Wait for Belle-II