Recent highlights on CPV and rare decays from the LHCb experiment

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2020/11/08

Outline

- **Introduction**

- **Recent highlights on SM candle measurements**

  CKM angle γ， $|V_{ub}|$， $|V_{cb}|$ etc.

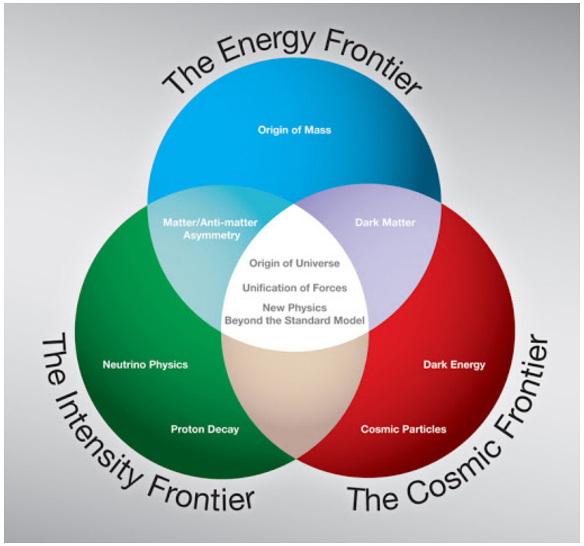
- **Recent highlights on New Physics probe**

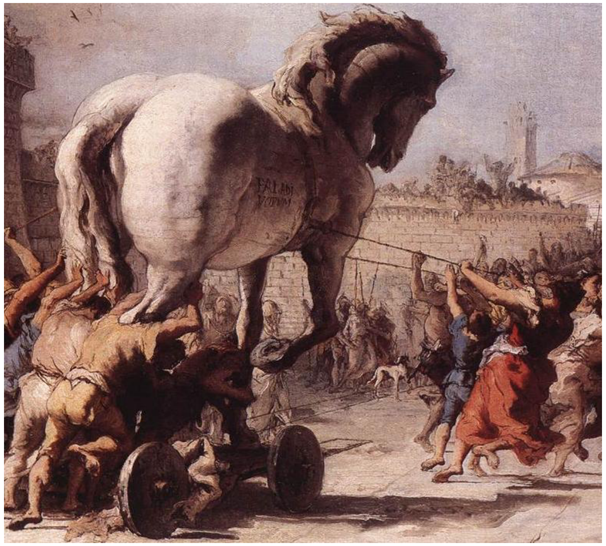
  ϕ_s， charmless b decays, FCNC, LFU etc.

- **Conclusion**

New Physics search

- All SM particles, including Higgs, have been found;
- However new mechanism needed for DM, matter-antimatter asymmetry, hierarchy problems etc.;
- Two ways to search for New Physics: direct search and indirect search through precision measurements;
- Examples in history: many beyond "current" model New Physics first found through indirect search



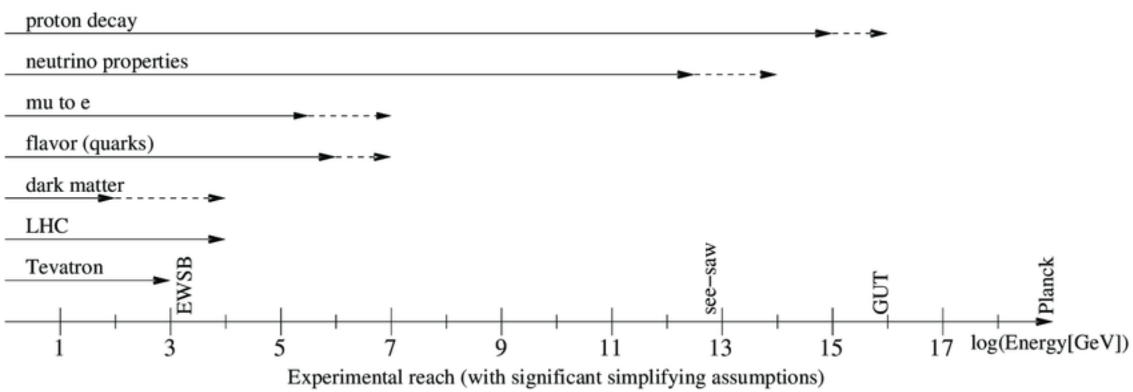


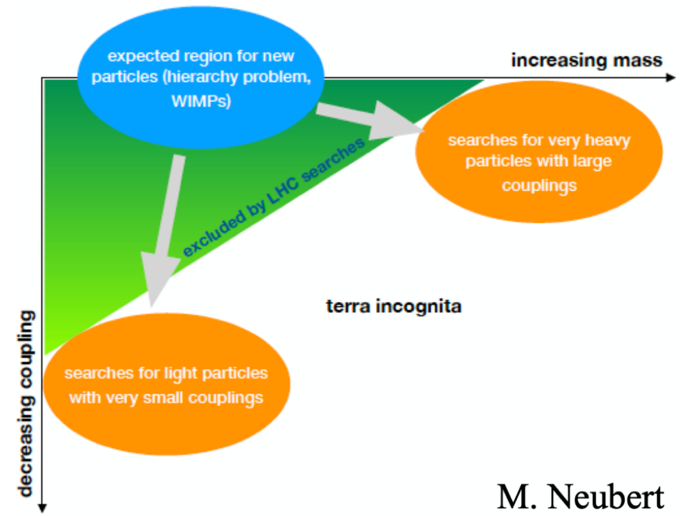
New Physics search at flavor sector

- Sensitive to New Physics scale much higher than direct search: 1-10^4 TeV

Couplings $\mathcal{O}(1)$ to avoid fine tuning

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}).$$



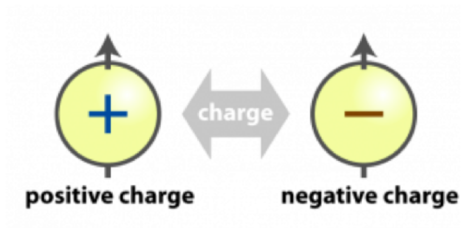


- Also "tasteful", not only can tell there is New Physics, but also tell properties of New Physics based on flavor it couples to
- Statistics or precision is key for flavor program: New Physics scale, i.e. Dim = 6, proportional to $\sqrt[4]{\text{statistics}}$ or $1/\sqrt{\text{Uncertainty}}$,

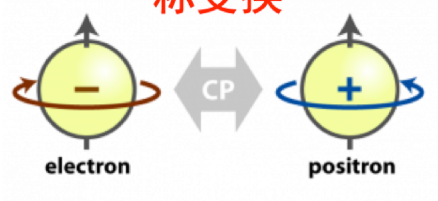
Fundamental questions

- If there are new CPV mechanism needed to explain the large matter-antimatter asymmetry observed in Universe; and what are they?

C:物质－反物质变换



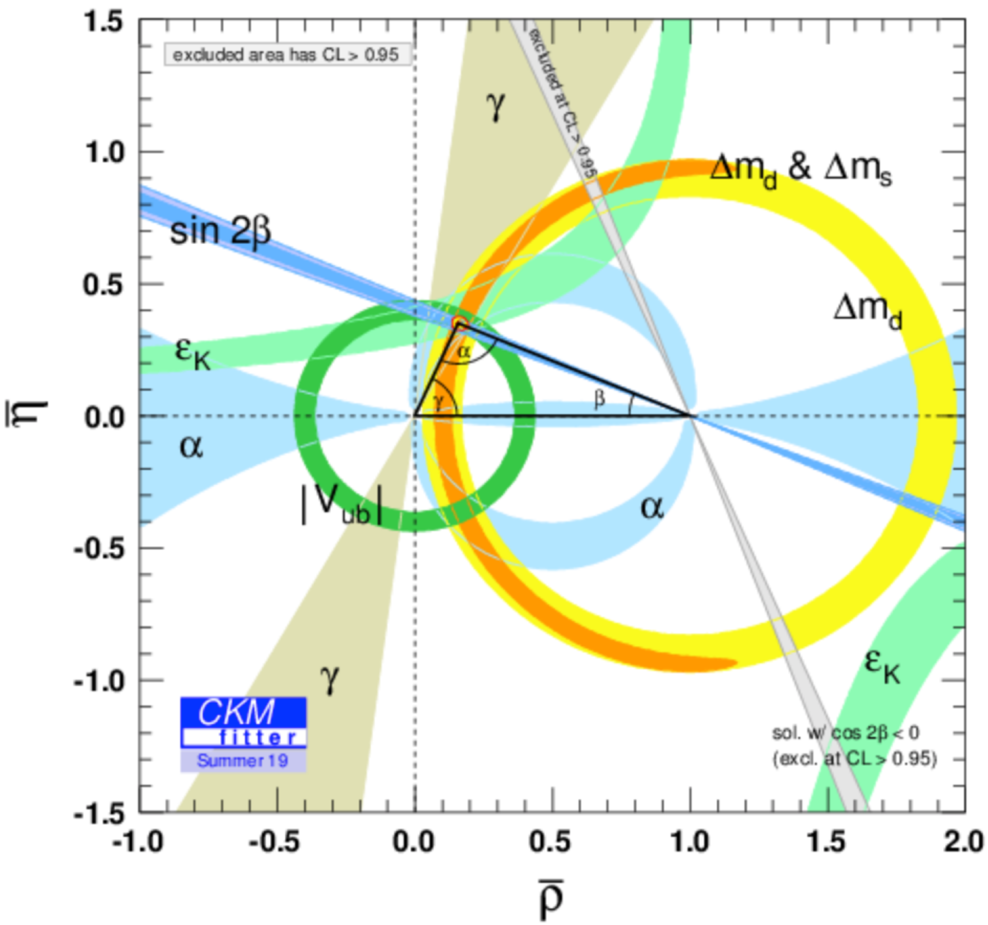
CP：电荷共轭和宇称变换



- If there are New Physics coupling to flavor sector? Their energy scale and properties?
- Two main streams: CPV + rare decay, core physics programs at LHCb

CKM Physics

- SM CPV offered by CKM mechanism; however, orders of magnitude smaller than matter-antimatter asymmetry observed in Universe

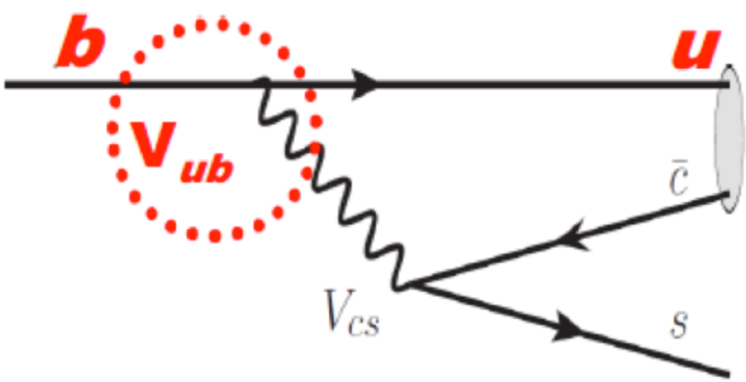


- CKM mechanism can explain what has been observed in current experiments, though still ~20% space for New Physics; More precision needed
- Strategy:
  - SM candle: tree level measurements such as γ, $|V_{ub}|$, $|V_{cb}|$ etc.
  - New Physics search: finding deviations in loop level processes w.r.t SM predictions

Key parameter: angle γ

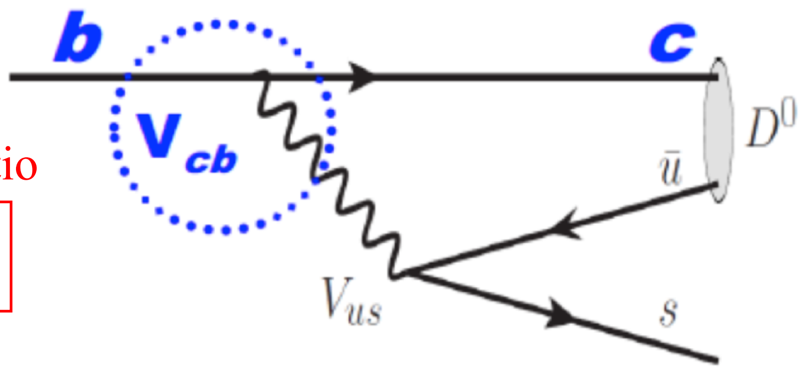
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

- Angle γ is the phase response for CPV in SM, directly related to the triangle of b quarks
- Measured through $b \to u$ and $b \to c$ interference with $B \to D^{(*)} K^{(*)}$ etc., theoretically clean



Amplitude ratio

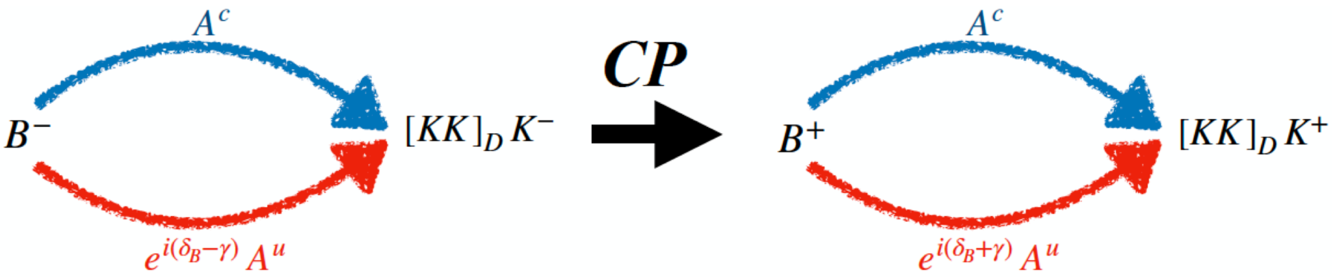
$$r_B e^{i\delta_B}$$

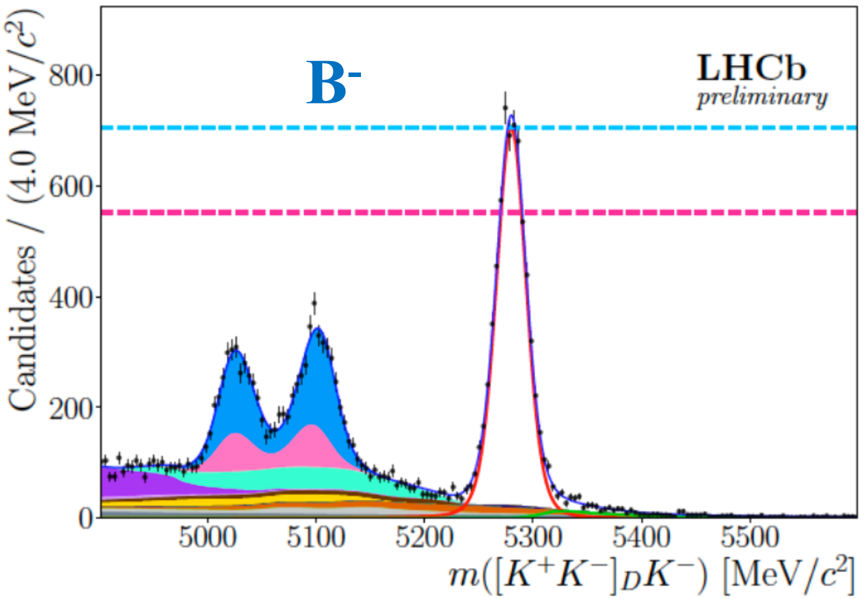


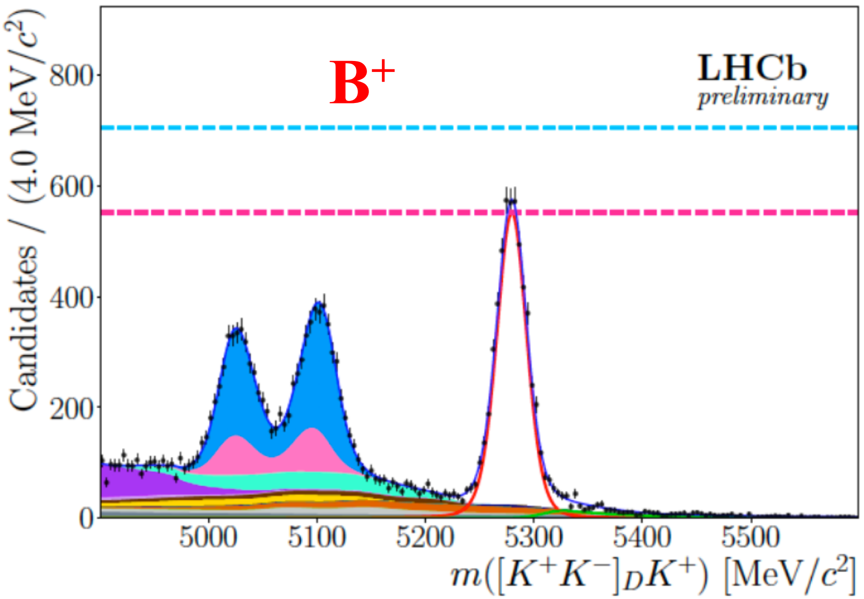
- Indirect measurements give: $\gamma = (65.7^{+1.0}_{-2.5})^\circ$ [CKMFitter19]
- Before LHCb, precision from B-factories around 14°

Two-body D decays

- GLW/ADS measurements now performed with full Run1+Run2 data, for $B \to DK, D\pi$ and partially reconstructed $B \to D^*K, D^*\pi$ [LHCB-PAPER-2020-036 (in preparation)]

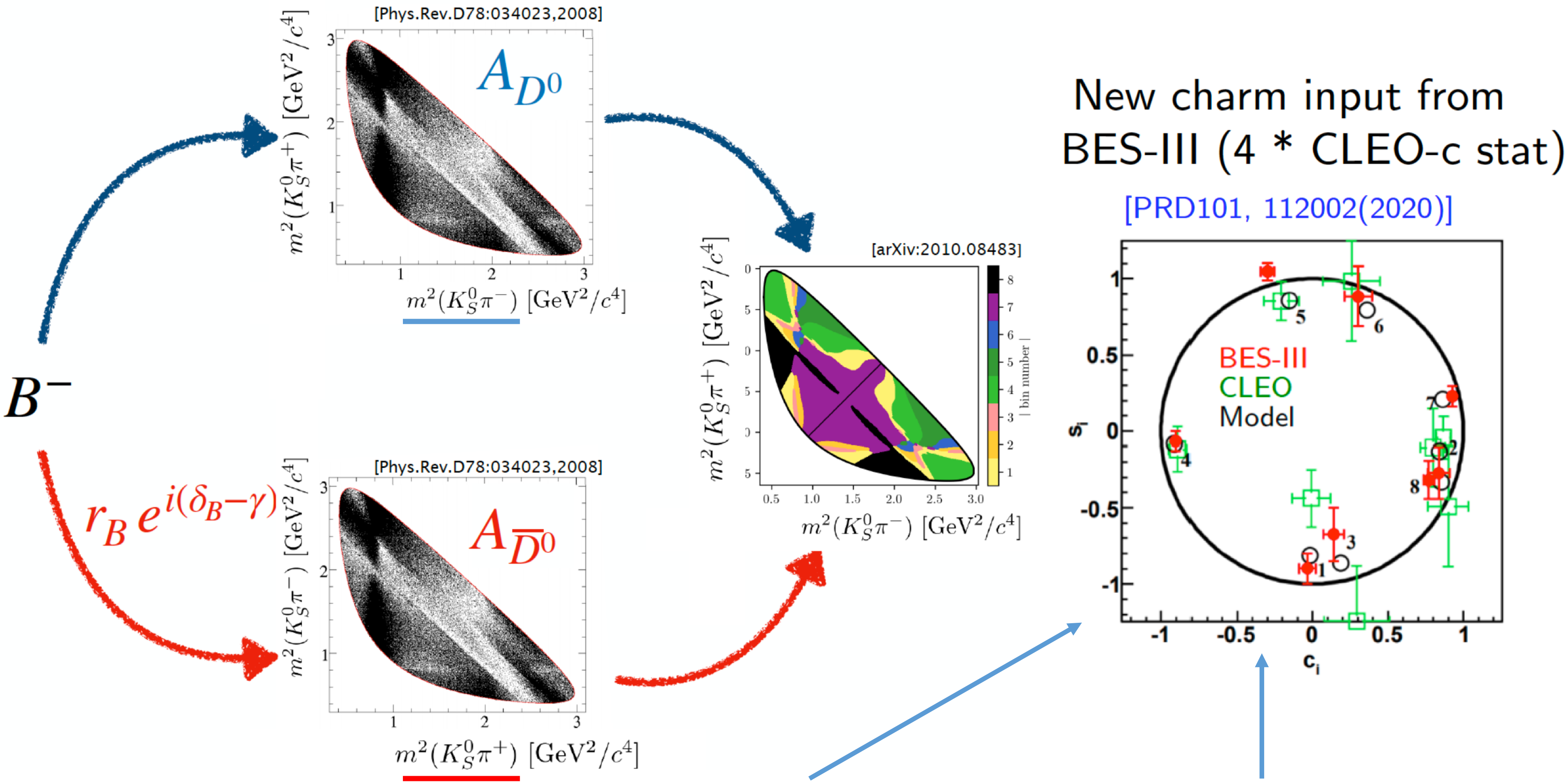






Three-body D decays

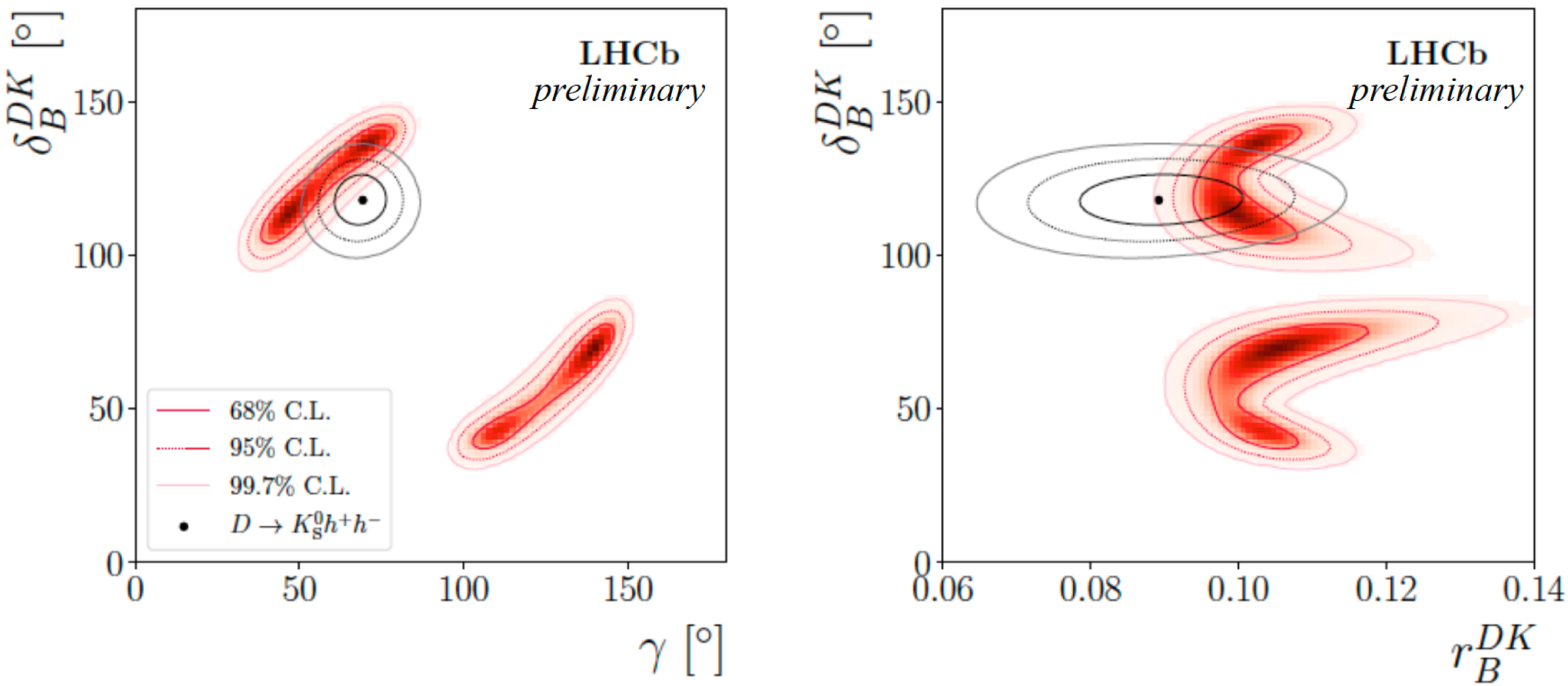
- BPGGSZ (GLW/ADS over Dalitz plot) measurements now performed with full Run1+Run2 data, for $B \rightarrow DK, D \rightarrow Ks\pi\pi, KsKK$ [arXiv:2010.08483]



$$A_{B\mp}(m^2_{K_s\pi^+}, m^2_{K_s\pi^-}) = A_{D^0}(m^2_{K_s\pi^+}, m^2_{K_s\pi^-}) + r_B\, e^{i(\delta_B\mp\gamma)}\, A_{D^0}(m^2_{K_s\pi^-}, m^2_{K_s\pi^+})$$

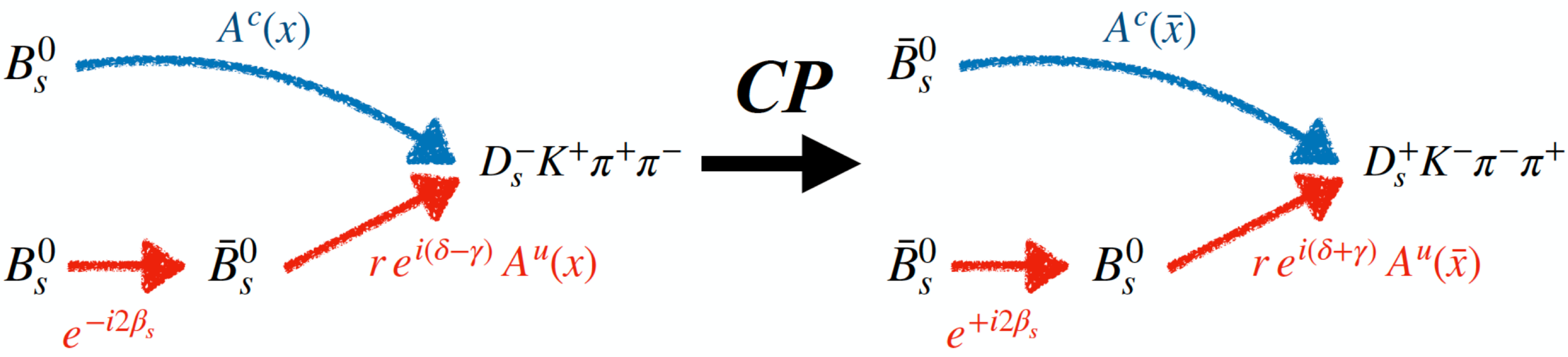
Combination between the two

[LHCB-PAPER-2020-036 (in preparation), arXiv:2010.08483]

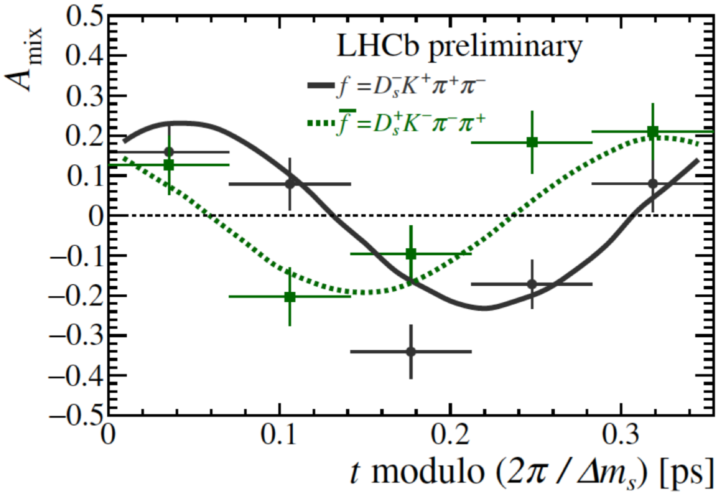


- Good agreement between the two modes (expected)
- Much better sensitivity when combined ➔ key feature for γ measurements
- Important to add more channels and compare between them

New story from B_s decays



- $b \to u$ and $b \to c$ interference can also came with B_s mixing



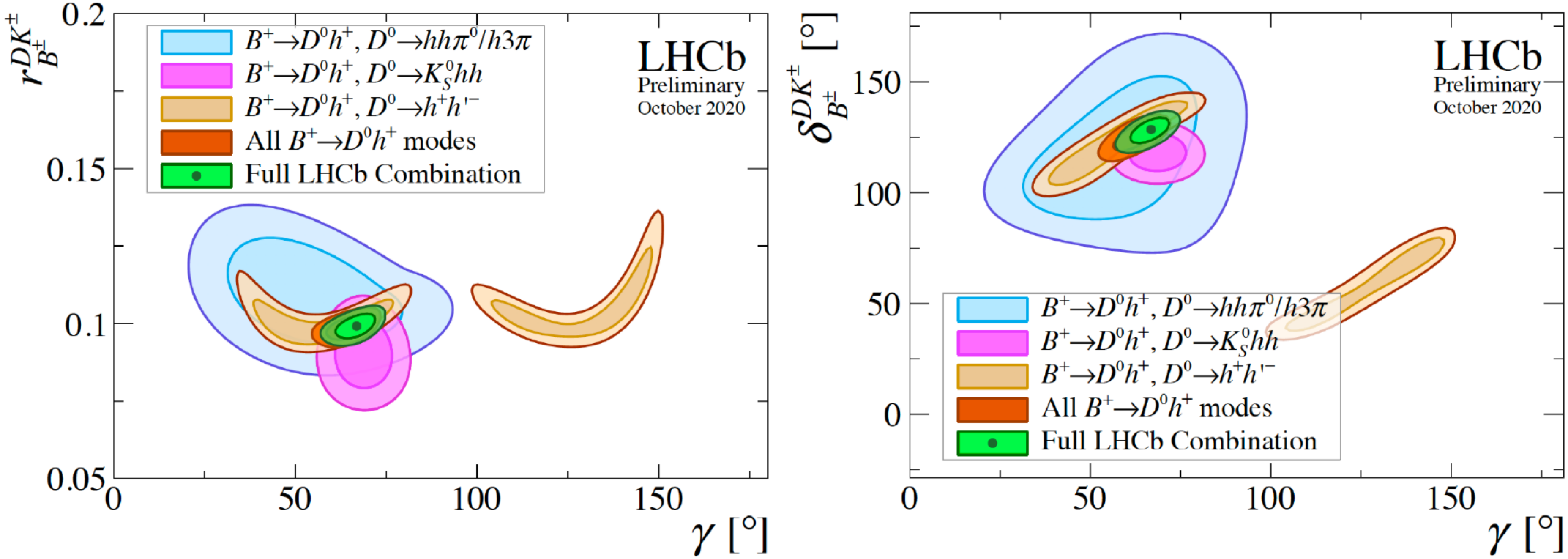
	value	stat	sys	model
r	0.56	± 0.05	± 0.04	± 0.07
κ	0.72	± 0.04	± 0.06	± 0.04
δ [°]	-14	± 10	± 4	± 5
$\gamma - 2\beta_s$ [°]	42	± 10	± 4	± 5

[LHCB-PAPER-2020-030 (in preparation)]

- Other stories in B_s decays to $D^{(*)}\phi$ can be found in X. Zhou's talk in parallel session

New γ combination

LHCb-CONF-2020-003 (in preparation)



- Now precision mainly from B^+ decays, large potential from other b hadrons
- New average on γ from LHCb: $\gamma = (67 \pm 4)°$, compared to 14° in B-factories
- Also now much closer to indirect determination: $\gamma = (65.7^{+1.0}_{-2.5})°$

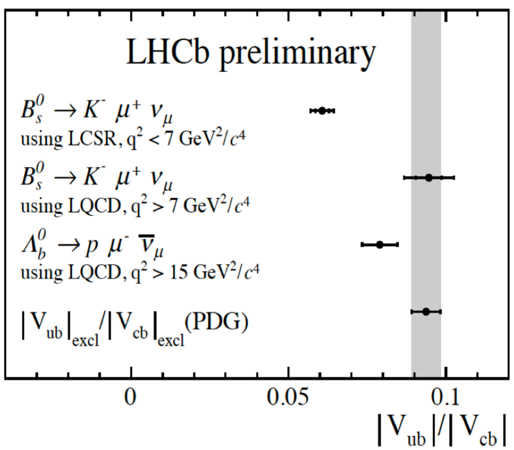
Unforeseen measurements on V_{ub}, V_{cb}

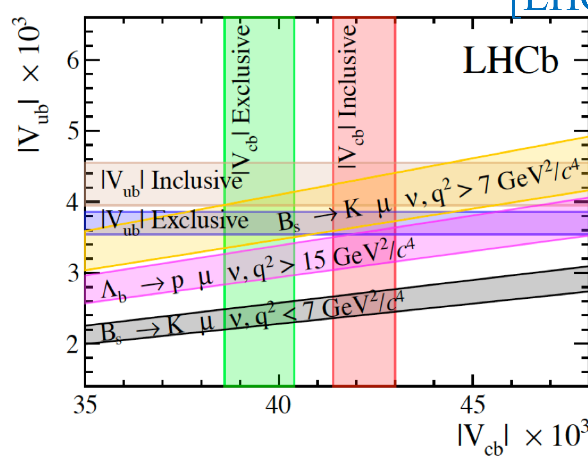
- $|V_{ub}|$ and $|V_{cb}|$ are key elements for CKM triangle global fit； Tensions observed in exclusive and inclusive measurements of $|V_{ub}|$ and $|V_{cb}|$ from B-factories;
- Suppose to be impossible at LHCb, now we have two new measurements, one $|V_{ub}|/|V_{cb}|$ from $B_s \to K\mu\nu_\mu$, and the other $|V_{cb}|$ from $B_s \to D_s^{(*)-}\mu\nu_\mu$

$$|V_{\rm ub}|/|V_{\rm cb}|({\rm low}) = 0.0607 \pm 0.0015({\rm stat}) \pm 0.0013({\rm syst}) \pm 0.0008({\rm D_s}) \pm 0.0030(FF)$$

$$|V_{\rm ub}|/|V_{\rm cb}|({\rm high}) = 0.0946 \pm 0.0030({\rm stat})^{+0.0024}_{-0.0025}({\rm syst}) \pm 0.0013({\rm D_s}) \pm 0.0068(FF)$$

[LHCb-PAPER-2020-038]

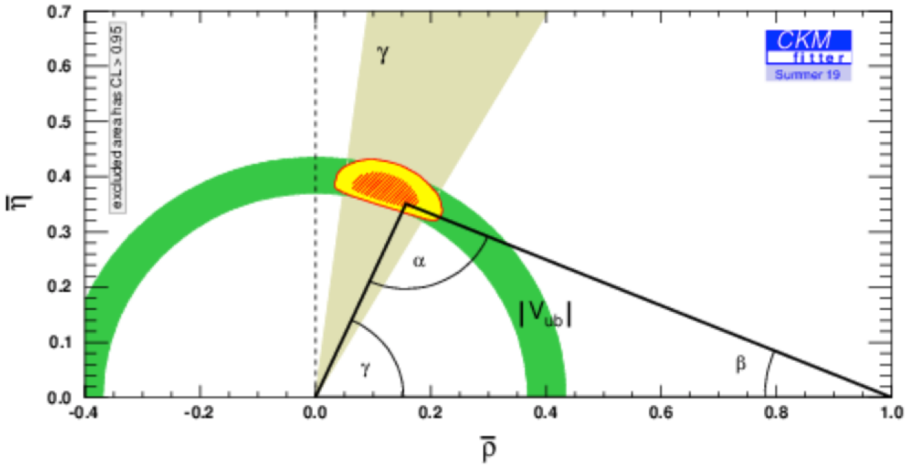




- Discrepancy found in high and low q^2 region with different form factors, further investigation from both experimental and theoretical parts needed

Tree-level determination and new physics probe

- Using γ and $|V_{ub}|/|V_{cb}|$, CKM triangle can already be determined; though real story is more complicated

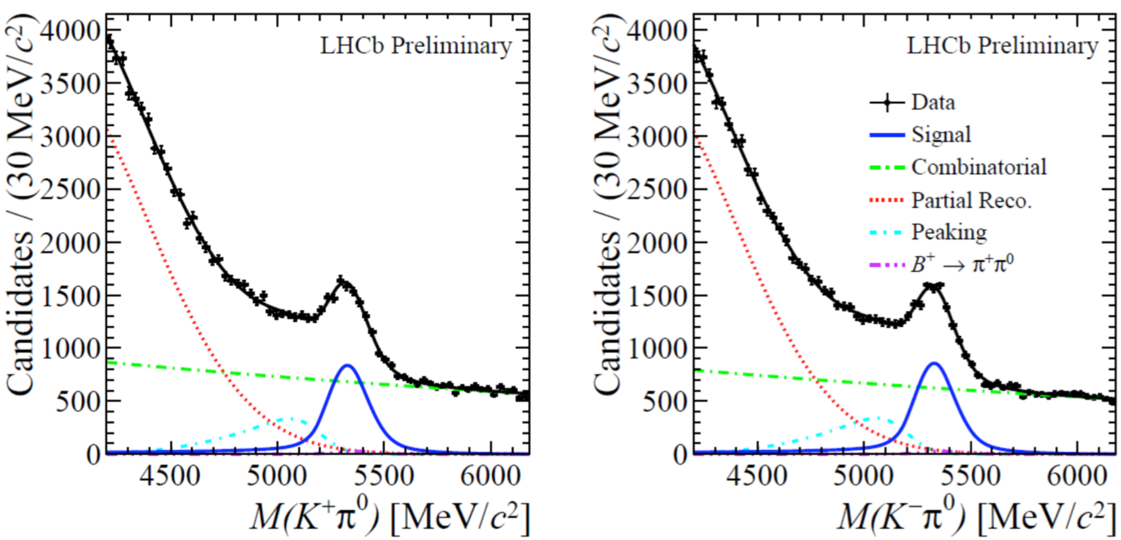


- Based on CKM global determination, predictions can be made for various New Physics sensitive parameters, like ϕ_s, $B_s \to \mu\mu$ etc.
- Can also help understanding CPV from tree-level and loop-level interference, see talk from Y. Yang on $B \to \pi\pi\pi$

$K\pi$ puzzle

- CPV from interference between suppressed tree-level process and QCD/EW penguin is sensitive for New Physics, $K\pi$ puzzle as an example [LHCb-PAPER-2020-040]
- Simple version of $K\pi$ puzzle: Isopin violated as $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.122 \pm 0.022$ (HFLAV); More complicated version involves full analysis of $K\pi$ system and tension also found inside.

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{\mathrm{B}(K^0\pi^+)}{\mathrm{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\mathrm{B}(K^+\pi^0)}{\mathrm{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2\mathrm{B}(K^0\pi^0)}{\mathrm{B}(K^+\pi^-)}$$



- Very difficult measurements in hadron colliders

$\mathrm{A_{CP}}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015(\mathrm{stat.}) \pm 0.006(\mathrm{syst.}) \pm 0.003(\mathrm{ext.})$

- Strengthen the $K\pi$ puzzling and motivate further investigation in $B^0 \to K^0\pi^0$

$B_s \to \mu\mu$ updates

- $B_s \to \mu\mu$ has been measured by all the three experiments at LHC with Run1 + part of Run2 data； sensitive to New Physics as very suppressed in SM
- Now combination made with the three experiments on branching fractions and on lifetime

$$\mathcal{B}(B_q^0 \to \mu^+\mu^-)_{\rm exp}^{\rm SM} = \frac{\tau_{B_q} G_F^4 M_W^4 \sin^4\theta_W}{8\pi^5} |C_{10}^{\rm SM} V_{tb} V_{tq}^*|^2 \times f_{B_q}^2 m_{B_q} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_q}^2}} \frac{1+y_q}{1-y_q^2},$$

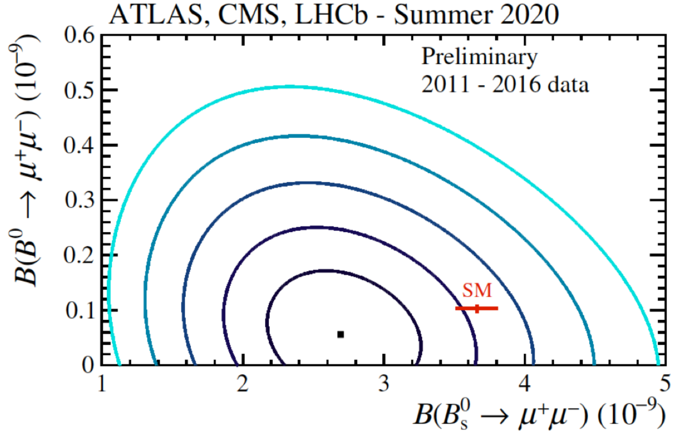
Single Wilson coefficient & Single hadronic constant

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

[JHEP 10 (2019) 232]

$$\mathcal{R}_{\mu^+\mu^-} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = 0.0281 \pm 0.0016$$

Around 2.1σ deviation from SM predictions



- Combined results

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.69^{+0.37}_{-0.35}\right) \times 10^{-9}$$
$$\tau(B_s^0 \to \mu^+\mu^-) = 1.91^{+0.37}_{-0.35}\ \text{ps}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.6(1.9) \times 10^{-10} (*)$$

- Ratio also matters, smaller uncertainties, only NP violates MFV can change

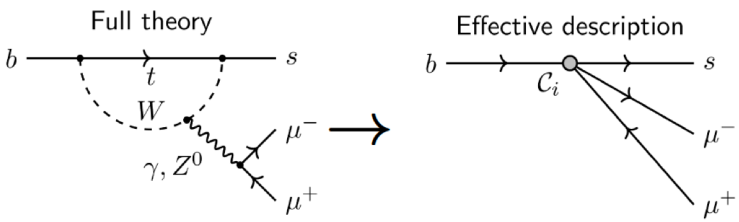
$$\mathcal{R} = 0.0206^{+0.0302}_{-0.0246}$$

New physics probe in FCNC processes

- Similar to $B_s \to \mu\mu$, $b \to sll$ processes can relate to more Wilson coefficients, and anomalies have been found previously in FCNC processes and in LFU test;

$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e}\left(\bar{s}\sigma^{\mu\nu}P_{\mathrm{R(L)}}b\right)F_{\mu\nu}\ ,$$
$$\mathcal{O}_9^{(\prime)} = \left(\bar{s}P_{\mathrm{L(R)}}b\right)\left(\bar{\ell}\gamma^{\mu}\ell\right)\ ,$$
$$\mathcal{O}_{10}^{(\prime)} = \left(\bar{s}P_{\mathrm{L(R)}}b\right)\left(\bar{\ell}\gamma^{\mu}\gamma^5\ell\right)\ ,$$

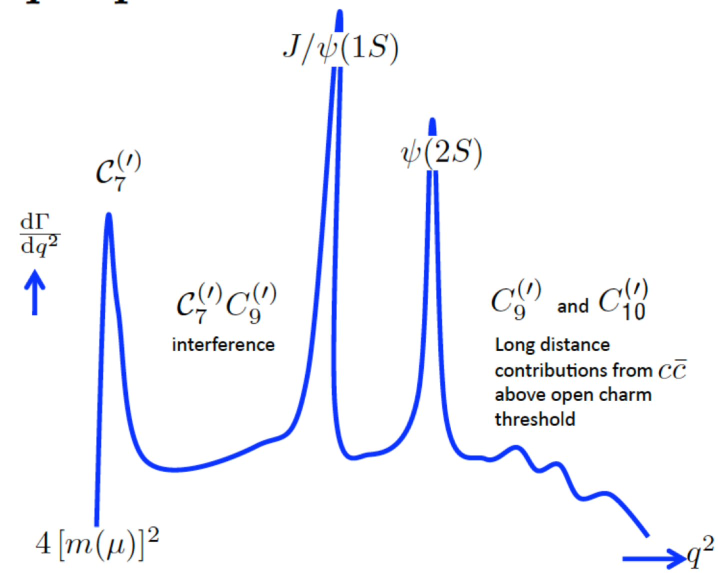
Effective field theories:



$$\mathcal{H}_{\mathrm{eff}} = -\frac{G_F}{\sqrt{2}}V_{\mathrm{CKM}}\sum_i \mathcal{C}_i\mathcal{O}_i$$

- Use Wilson coefficients c_i to effectively describing the processes
- New Physics effects can either modify Wilson coefficients c_i or adding new operators
- Different q^2 region sensitive to different Wilson coefficients c_i

q^2 spectrum:



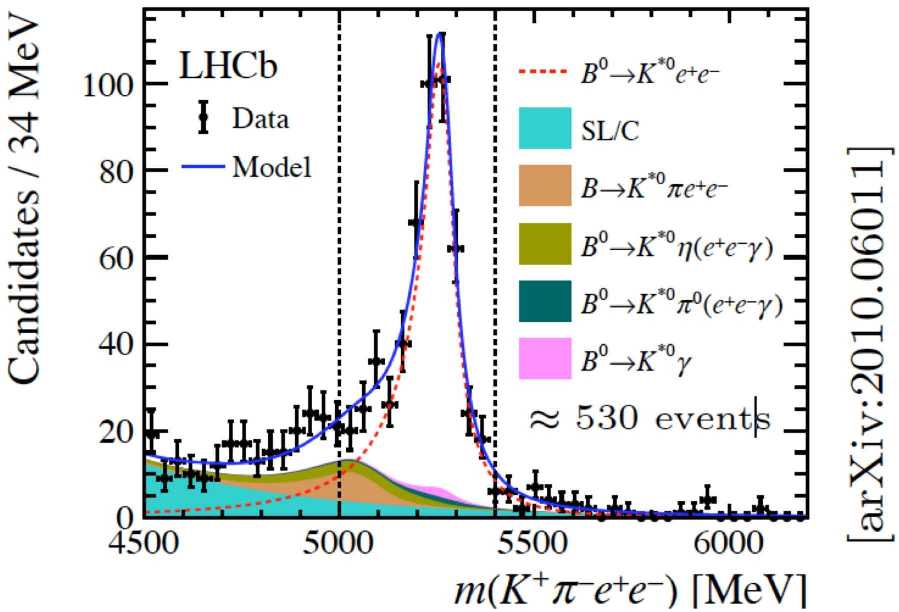
left-handed: $\mathcal{C}_i$
right-handed: $\mathcal{C}_i'$
photon: $\mathcal{C}_7$
(axial) vector: $(\mathcal{C}_{10})$ $\mathcal{C}_9$

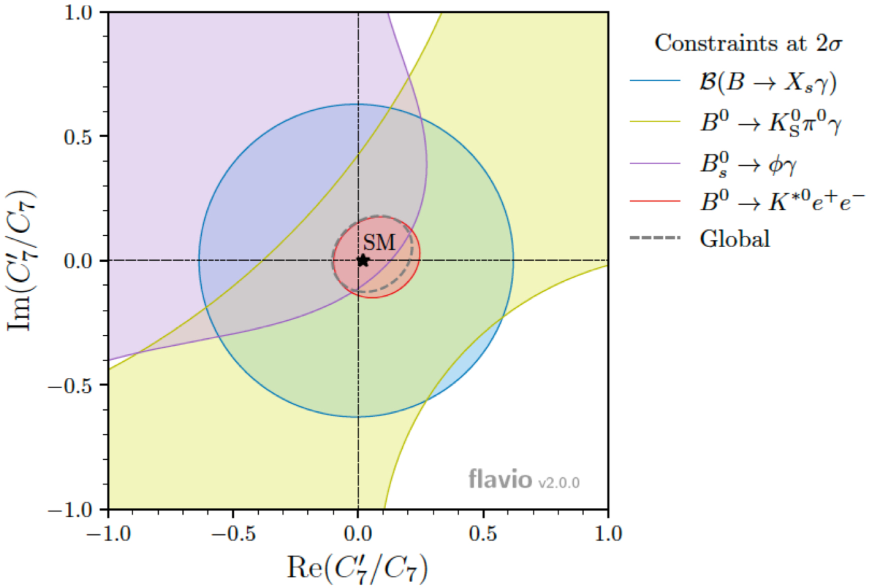
Low-q² region: $K^{*0}e^+e^-$

- New angular analysis performed at low-q² region [0.0008, 0.257] GeV²/c² for $B^0 \to K^{*0}e^+e^-$ with full Run1 + Run2 data, constraining photon polarization, predominately left-handed in SM, while NP can alter

$$\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_L - F_L\cos^2\theta_K\cos 2\theta_L$$
$$+\frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_L\cos 2\tilde{\phi}$$
$$+(1-F_L)A_T^{Re}\sin^2\theta_K\cos\theta_L$$
$$+\frac{1}{2}(1-F_L)A_T^{Im}\sin^2\theta_K\sin^2\theta_L\sin 2\tilde{\phi}$$

$$F_L = 0.044 \pm 0.026 \pm 0.014$$
$$A_T^{Re} = -0.06 \pm 0.08 \pm 0.02$$
$$A_T^{(2)} = +0.11 \pm 0.10 \pm 0.02$$
$$A_T^{Im} = +0.02 \pm 0.10 \pm 0.01$$





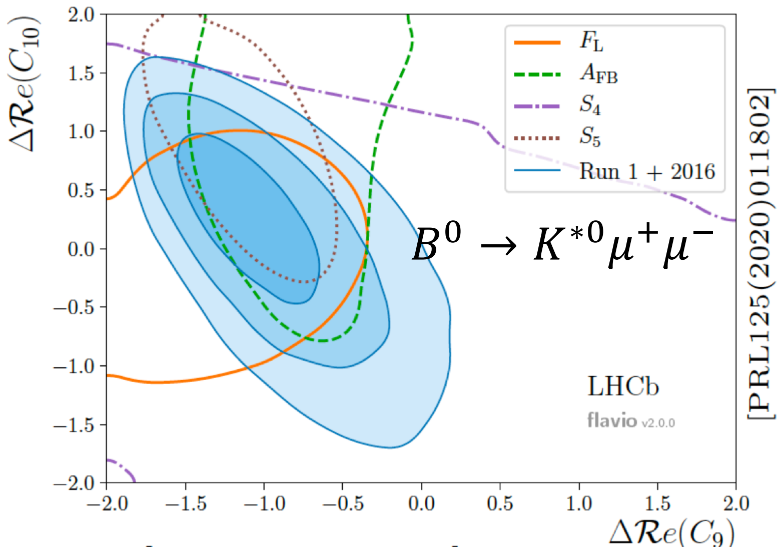
generated with FLAVIO [arXiv:1810.08132]

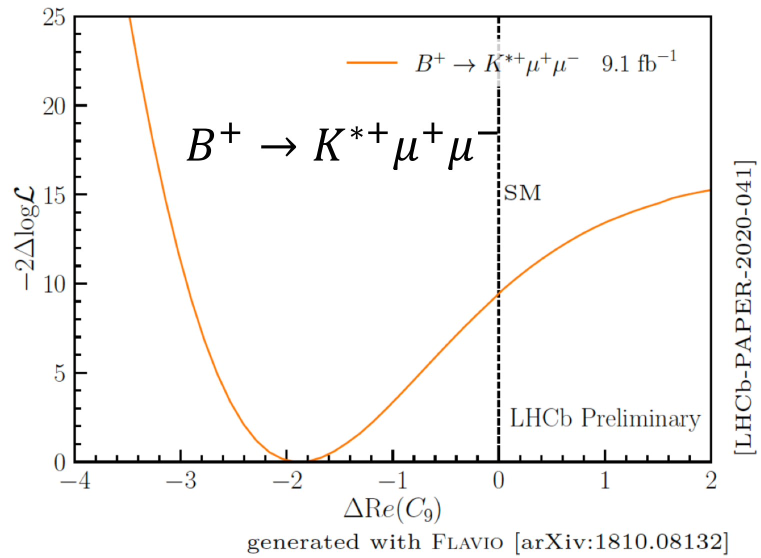
High-q² region: $K^{*0(+)}\mu^+\mu^-$

- Two new results $B^0 \to K^{*0}\mu^+\mu^-$ with Run1 + 2016 data and $B^+ \to K^{*+}\mu^+\mu^-$ with full Run1+Run2 data and deepen the anomalies

PRL125 (2020) 011802
[LHCb-PAPER-2020-041]

- $B^0 \to K^{*0}\mu^+\mu^-$: global discrepancy to SM remains, $\sim 3.3\sigma$, fit favors $\Delta Re(C_9) \sim -1.0$ scenario
- $B^+ \to K^{*+}\mu^+\mu^-$: use large q² bin [15,19] GeV²/c², deviation from SM by $3.1\ \sigma$, fit favors $\Delta Re(C_9) \sim -1.9$
- Constant deviation from SM in Dim-6 FCNC processes may indicate NP inside





Conclusion

- We are entering an era of flavor, an era of precision measurements
- Great New Physics discovery potential in Flavor physics, access to energy scale much higher than collision energy
- Precision measurements ongoing both in SM candle channels and in New Physics sensitive channels
- Some anomalies already found, need more data/measurements to clear the situation

Thank you for your attention