Status and Prospects of LFUV Measurements in B physics

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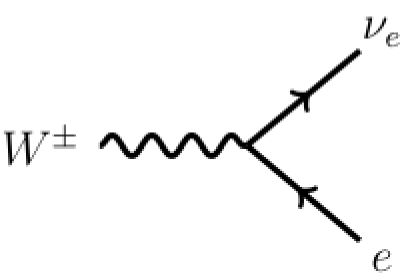
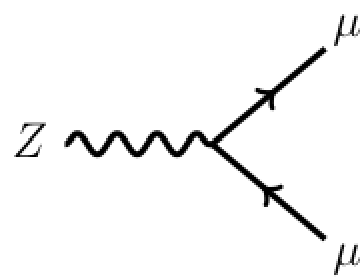
Lepton Flavor Universality Violation

- In the Standard Model (SM) of the elementary particle physics, Lepton Flavor Universality (LFU) holds (except for Higgs) and is well tested in many decays.
  - Charged current : ~2% precision in W decay BF (~2.7sigma deviation for τ/μ?)
  - Neutral current : ~0.3% precision in Z decay BF
- If LFU Violation (LFUV) is observed, it is a clear sign of new physics (NP).



$$\frac{\mathcal{B}(W^+ \to \mu^+ \nu_\mu)}{\mathcal{B}(W^+ \to e^+ \nu_e)}$$



$$\frac{\mathcal{B}(Z \to \mu^+ \mu^-)}{\mathcal{B}(Z \to e^+ e^-)}$$

PDG2018

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)
Γ_1	$\ell^+ \nu$	[a]	(10.86 ± 0.09) %
Γ_2	$e^+ \nu$		(10.71 ± 0.16) %
Γ_3	$\mu^+ \nu$		(10.63 ± 0.15) %
Γ_4	$\tau^+ \nu$		(11.38 ± 0.21) %

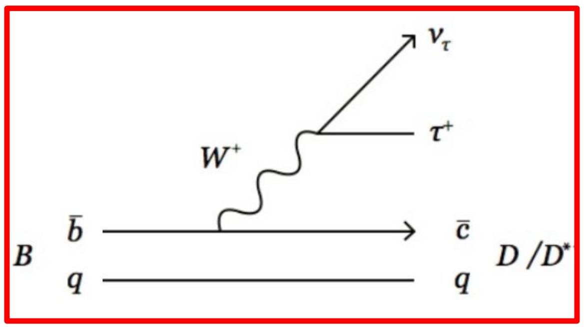
Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)
Γ_1	$e^+ e^-$	[a]	(3.3632 ± 0.0042) %
Γ_2	$\mu^+ \mu^-$	[a]	(3.3662 ± 0.0066) %
Γ_3	$\tau^+ \tau^-$	[a]	(3.3696 ± 0.0083) %
Γ_4	$\ell^+ \ell^-$	[a,b]	(3.3658 ± 0.0023) %

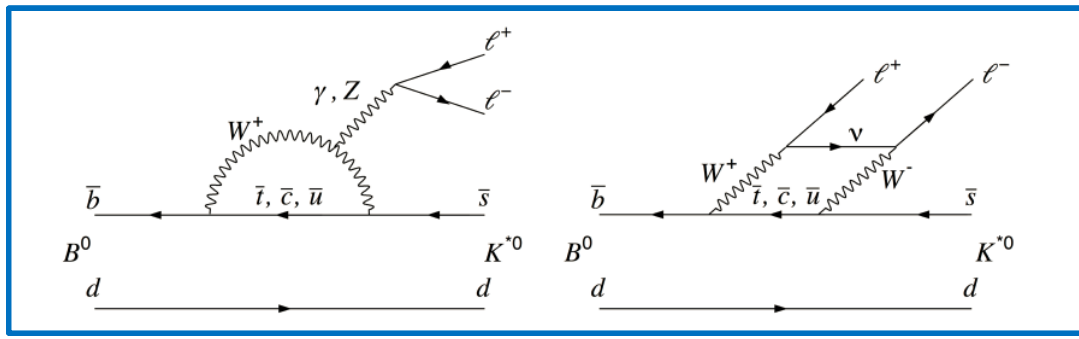
LFUV in B decays

- Recently, two hints of LFUV are found in b→cτν and b→sl⁺l⁻
  - Anomaly in b→cτν driven by LHCb, Babar and Belle.
  - Anomaly in b→sl⁺l⁻ Driven by LHCb

b→cτν



b→sl⁺l⁻



Tree
BF~O(10^{-2})

Loop
BF~O(10^{-6})

LFUV in B decays

- Recently, two hints of LFUV are found in $b \to c\tau\nu$ and $b \to s l^+ l^-$
  - Anomaly in $b \to c\tau\nu$ driven by LHCb, Babar and Belle. ~3.8σ
  - Anomaly in $b \to s l^+ l^-$ Driven by LHCb   Naïve combination of R_K and R_{K^*} ~4σ

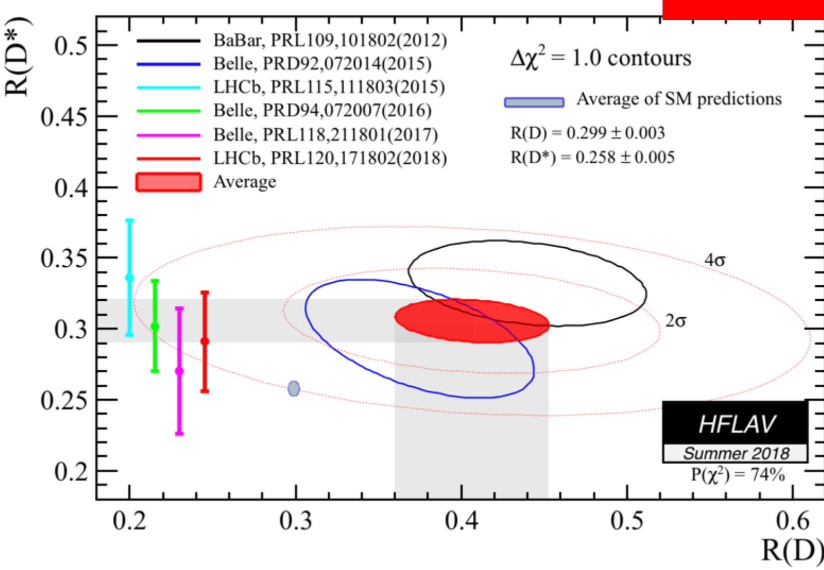
$$R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$

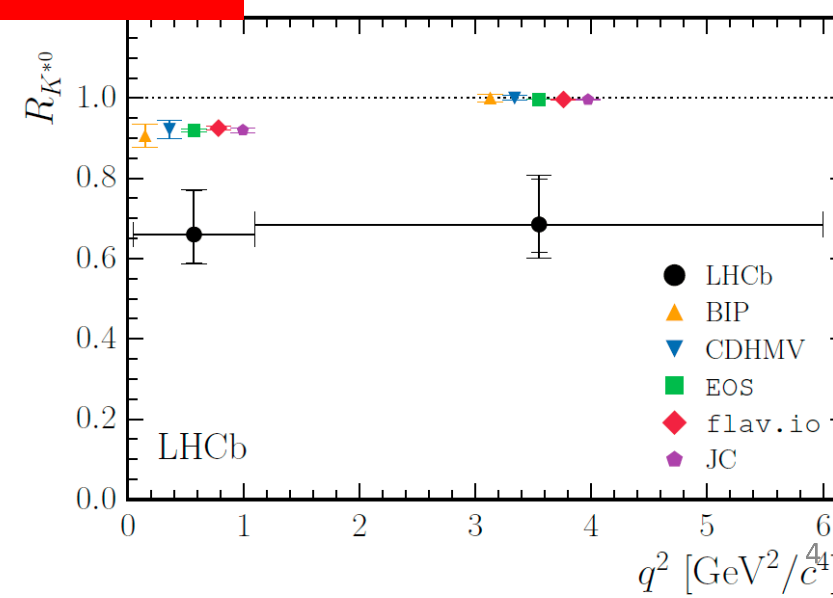
l=e,μ

$$R_H = \frac{\mathcal{B}(B \to H\mu^+\mu^-)}{B(B \to He^+e^-)}$$

$$H = K, K^*, X_s, \ldots$$

30% deviation!

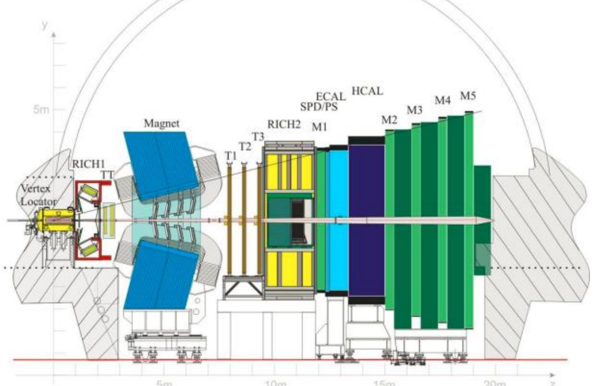


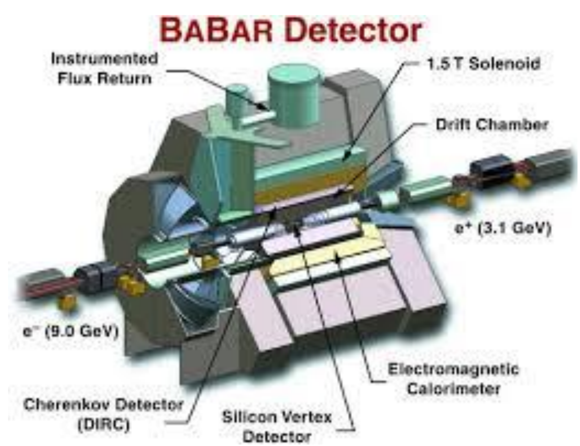


Comparison of Experiments
“LHCb” and “Babar and Belle”

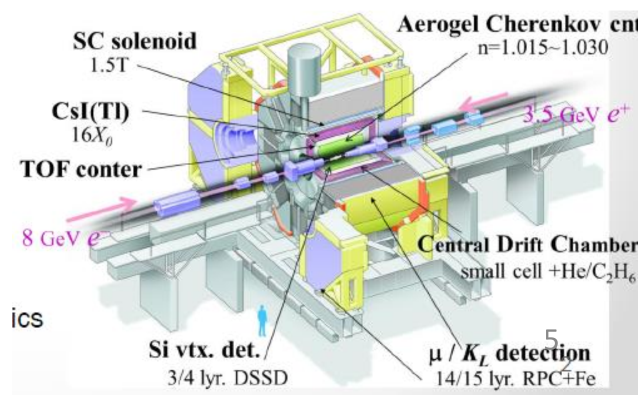
exp@accel	LHCb@LHC	Babar@PEP-II and Belle@KEKB
collision	Proton-proton collisions at 7~13TeV	Electron-positron collisions at 10.58GeV on Y(4S) resonance
b pair cross section	σ=71~144pb	σ=1.08 nb
b motion in CMS	Boosted to forward, p/M>>1	Almost at rest, p/M<<1
Background in b events	Many particles from primary vertex	No physics background Only pair of B mesons produced
Detector coverage	2<η<5, forward spectrometer	~94% of 4π

LHCb detector





Belle detector



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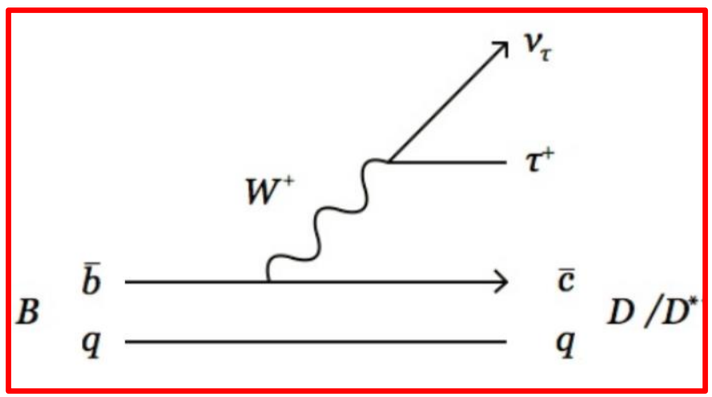
b→cτν

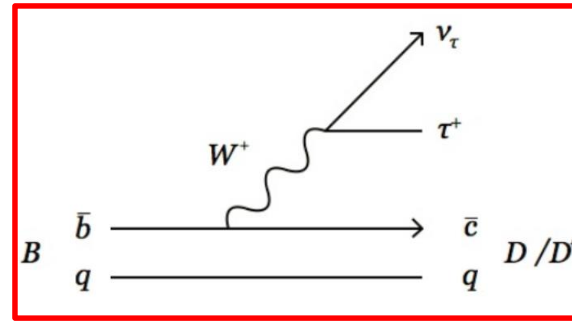


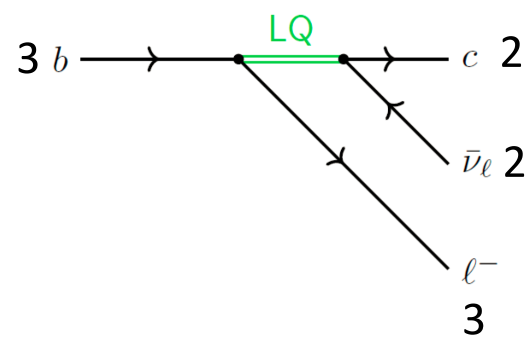
LFUV in b→cτν

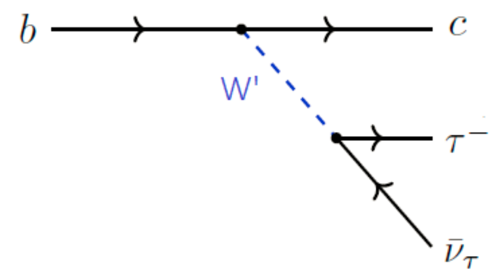
- b→cτν decay
  - At least two neutrinos in the final states
  - Decay from 3rd generation b quark to 3rd generation τ lepton
    - Sensitive to NP coupling to heavy particles : charged Higgs
    - Sensitive to NP strongly coupling to 3rd generation : Leptoquark (LQ), flavored W’
- The ratio of BF to electron or muon modes is good observable
  - Form factor uncertainties (mostly) cancel out
  - Experimental systematics also cancel out

$$R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$

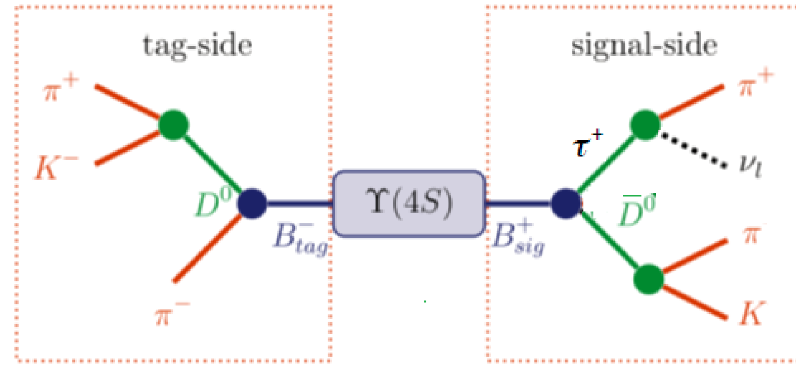
- Kinematic distributions can be used to discriminate new physics models
  - q^2 distribution : mass squared of τ-ν system
  - Polarizations of τ and D*







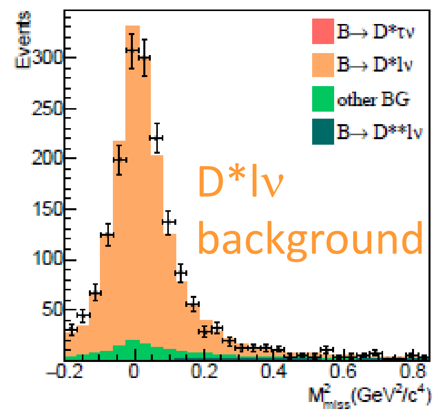
Reconstruction of $B \to D^{(*)}\tau\nu$ at Babar/Belle



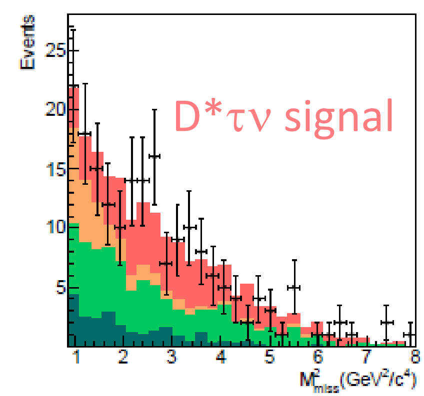
- Reconstruct the other B meson (tag side)
  - Hadronic B decays : $B \to D\pi$ etc
  - Semi-leptonic B decay : $B \to D^*l\nu$ $_{l=e,\mu}$
  - Tagging efficiencies are about 0.3%
- Reconstruct decay products of $D^{(*)}$ and τ from signal side
  - leptonic τ decays : $e\nu\nu$, $\mu\nu\nu$
  - hadronic τ decays : $\pi^+\nu$, $\rho^+\nu$
- Missing mass squared is a powerful discriminator of main backgrounds $B \to D^{(*)}l\nu$
  - Zero missing mass for normalization $B \to D^{(*)}l\nu$
    - One neutrino
  - Large missing mass for $B \to D^{(*)}\tau\nu$ signal
    - At least two neutrinos
- Extra energy in Calorimeter is the final discriminator
  - Should be consistent with zero

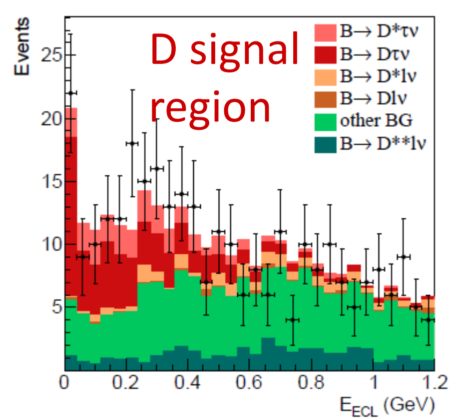
Vertical scale different

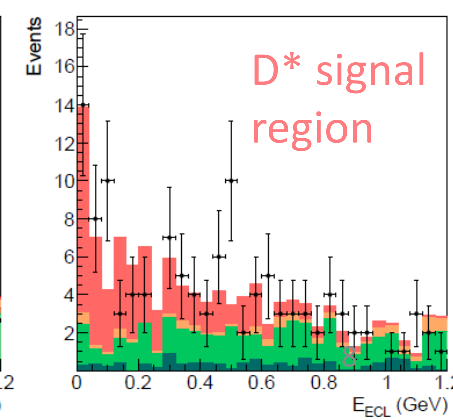
M^2_{miss}<0.85 GeV^2



0.85GeV^2<M^2_{miss}

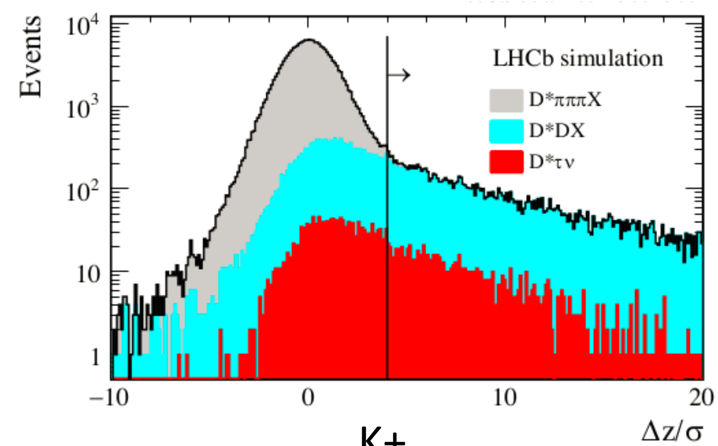


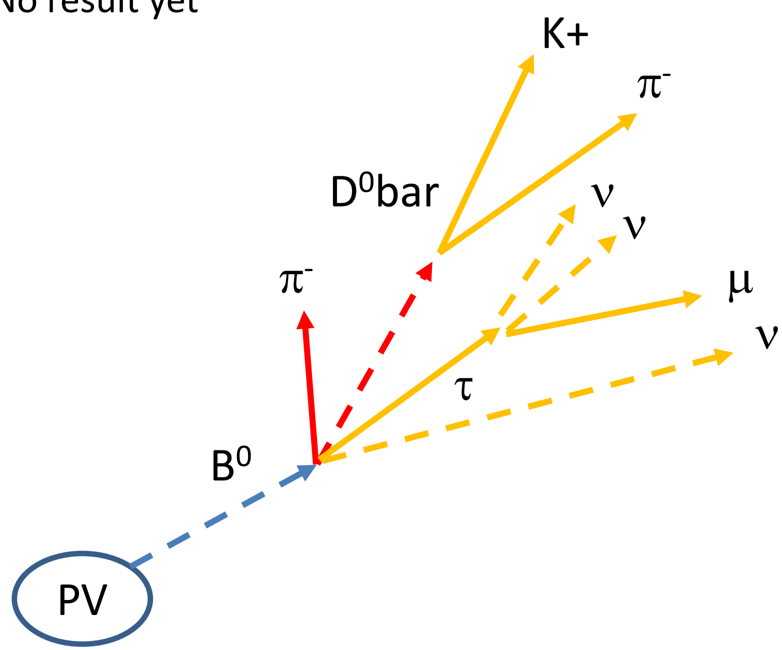




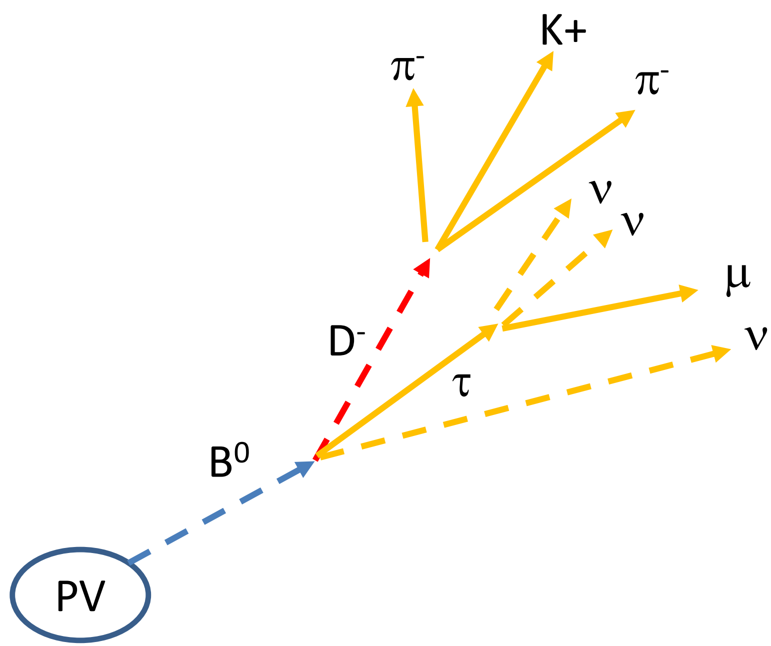
Reconstruction of $B^0 \rightarrow D^{*+}\tau\nu$ @ LHCb

- Identification of B meson decay vertex is crucial
  - At least 2 (pseudo-)tracks needed
    - D and τ fly since both have finite lifetime of O(1)ps
  - Displacement of the vertex position from primary vertex is powerful tool to eliminate backgrounds
- $B \rightarrow D\tau\nu$ is more difficult than $B^0 \rightarrow D^{*+}\tau\nu$
  - No result yet





$B^0 \rightarrow D^{*-}\tau\nu$: 2(pseudo-)tracks → OK

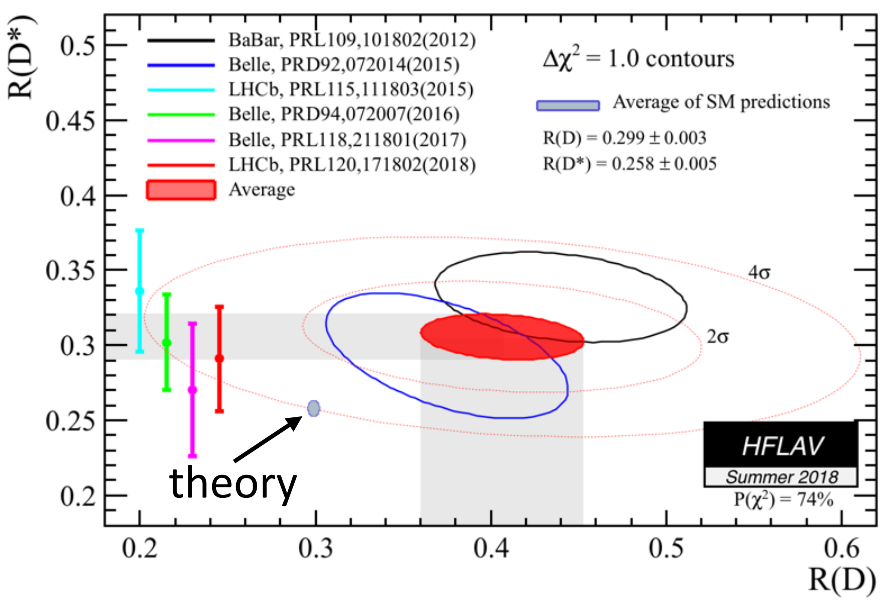


$B^0 \rightarrow D^{-}\tau\nu$: 1 track → difficult

Summary on $R(D^{(*)})$

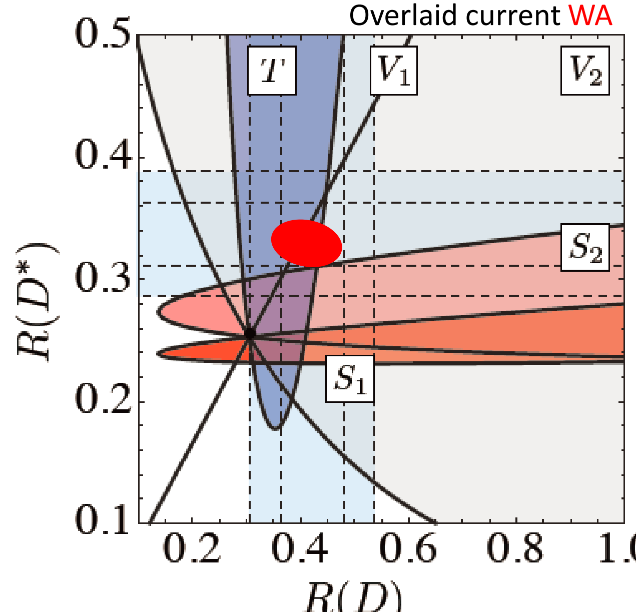
	tagging	τ Decays	R(D*)	R(D)
Babar2012	Hadronic	e,μ	$0.332 \pm 0.024 \pm 0.018$	$0.440 \pm 0.058 \pm 0.042$
Belle2015	Hadronic	e,μ	$0.293 \pm 0.038 \pm 0.015$	$0.375 \pm 0.064 \pm 0.026$
LHCb2015	--	μ	$0.336 \pm 0.027 \pm 0.030$	--
Belle2016	Semileptonic	e,μ	$0.302 \pm 0.030 \pm 0.011$	--
Belle2016	hadronic	π, ρ	$0.270 \pm 0.035 ^{+0.028}_{-0.025}$	--
LHCb2018	--	a_1	$0.291 \pm 0.019 \pm 0.029$	--
theory			0.258 ± 0.005	0.299 ± 0.003

3.8σ deviation



Some sensitivity to NP model

Tanaka and Watanabe 1212.1878
Overlaid current WA



Polarizations

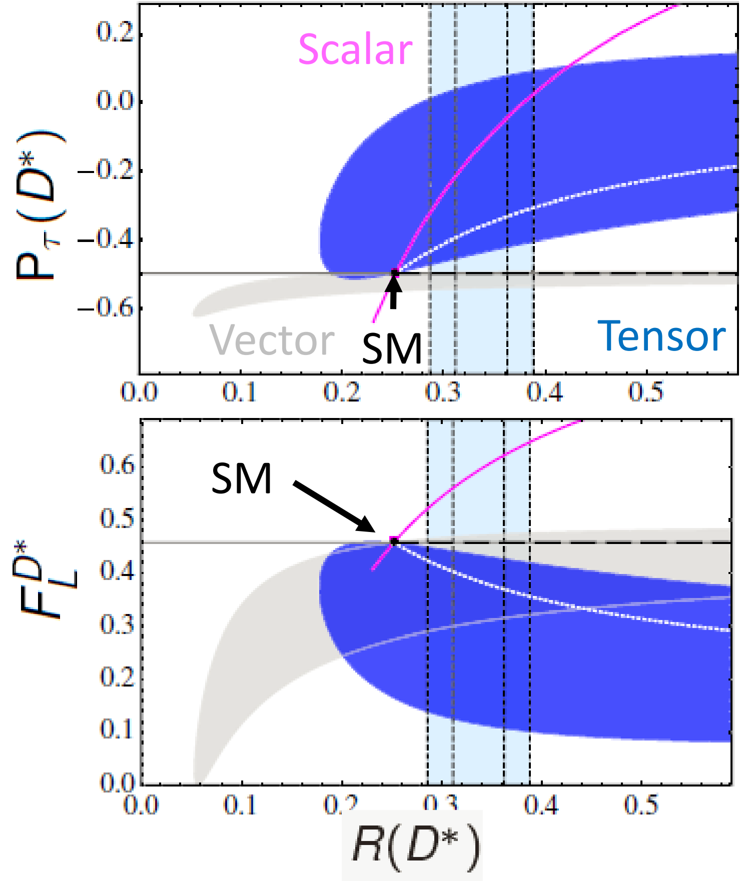
- Measurements of Polarizations of τ and D* can discriminate NP models
  - τ polarization

$$\frac{d\Gamma}{d\cos\theta_{hel}(\tau)} = \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{hel}(\tau))$$

$\alpha = 1.0$ for $\tau \to \pi\nu$; $\alpha = 0.45$ for $\tau \to \rho\nu$

$$P_\tau(D^*)_{SM} = -0.497 \pm 0.013$$

M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)



  - D* longitudinal polarization

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}(D^*)} = \frac{3}{4}[2F_L^{D^*}\cos^2(\theta_{\rm hel}(D^*)) + (1 - F_L^{D^*})\sin^2(\theta_{\rm hel}(D^*))]$$

$$\text{SM: } F_L^{D^*} = 0.4\bar{6} \pm 0.03$$

(Phys. Rev. D **95**, 115038 (2017), A.K. Alok, et al)

The first polarization measurements are performed by Belle

Measurements of Polarizations at Belle

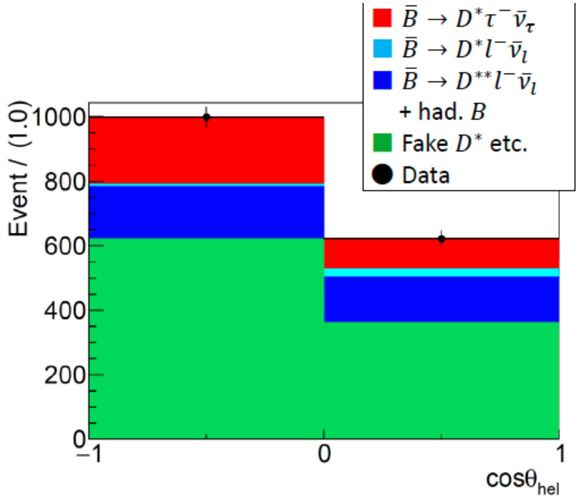
Phys. Rev. Lett. **118**, 211801 (2017)

- τ polarization
  - Hadronic tagging
  - $\tau \to \pi\nu$ and $\rho\nu$ are used as polarimeter

$$P_\tau(D^*) = -0.38 \pm 0.51(stat.)^{+0.21}_{-0.16}(syst.)$$

$$P_\tau(D^*)_{SM} = -0.497 \pm 0.013$$

M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)



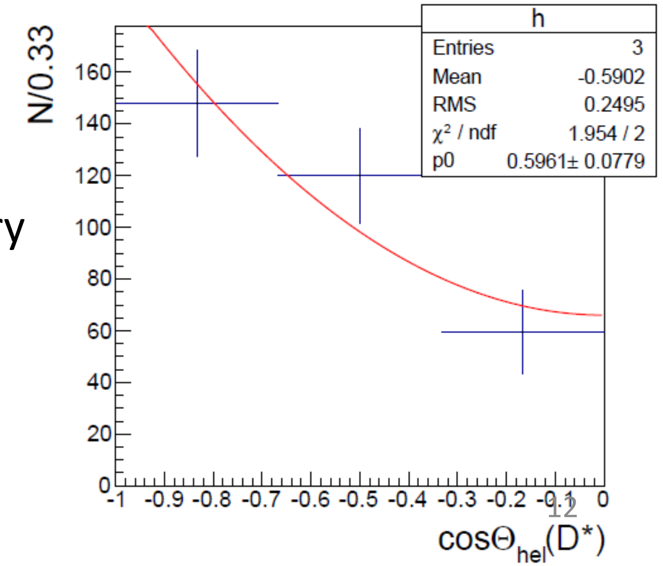
- D* longitudinal polarization
  - Inclusive hadronic tagging to increase signal
  - $D^{*+} \to D^0\pi+$
    - Only cosθ_{hel}<0 is used where slow pion efficiency is reliable
  - $\tau \to \pi\nu$, $e\nu\nu$, $\mu\nu\nu$

New at CKM2018

Preliminary

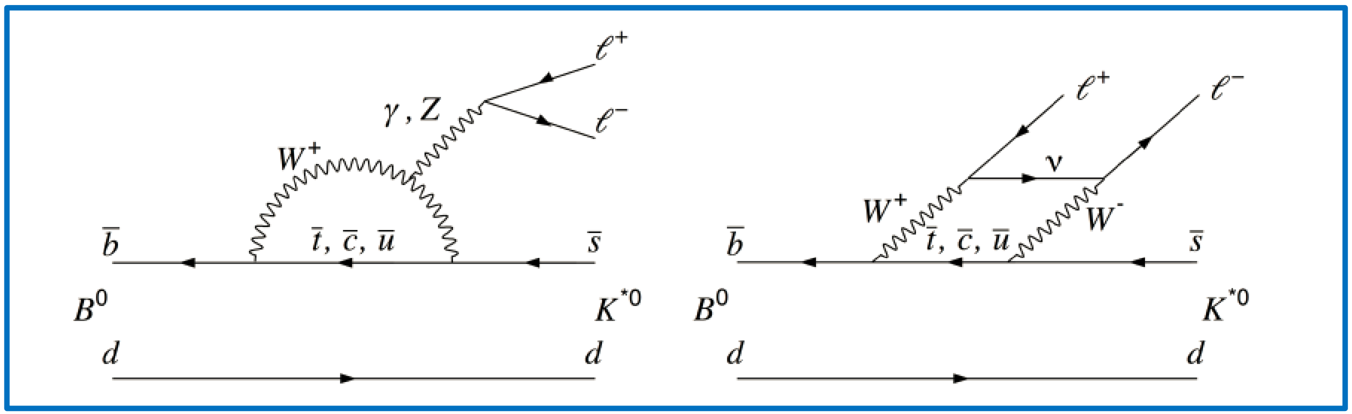
$$F_L^{D^*} = 0.60 \pm 0.08(stat.) \pm 0.035(syst.)$$

$$\text{SM: } F_L^{D^*} = 0.46 \pm 0.03$$

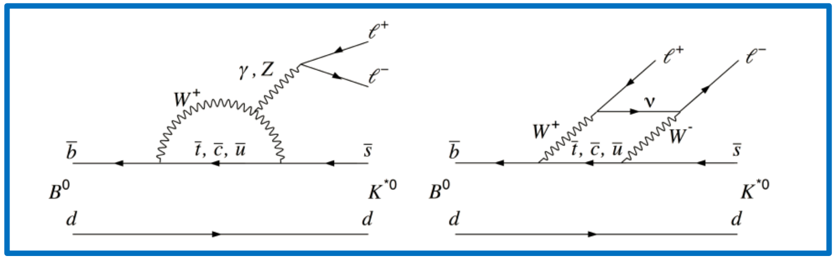


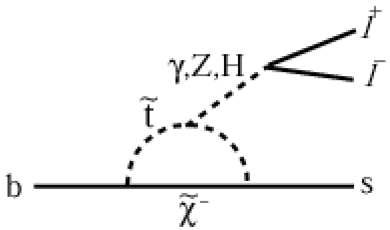
- Both are consistent with the SM prediction

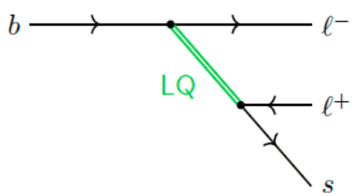
$b \rightarrow s l^+ l^-$

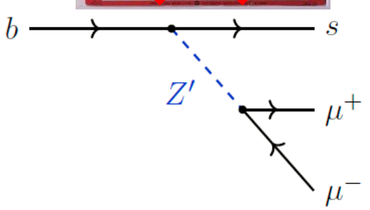


LFUV in b→sl$^+$l$^-$









- b→sl+l- decay
  - Sensitive to
    - NP in loop : SUSY (but not generate large LFUV)
    - NP in tree : Leptoquark (LQ), flavored Z'
- The ratio of BF for electron to muon modes clean observable
  - Form factor uncertainties cancel out
  - No uncertainty due to charm loop
  - Consistent with unity except for very low q^2

$$R_H = \frac{\mathcal{B}(B \to H\mu^+\mu^-)}{B(B \to He^+e^-)}$$

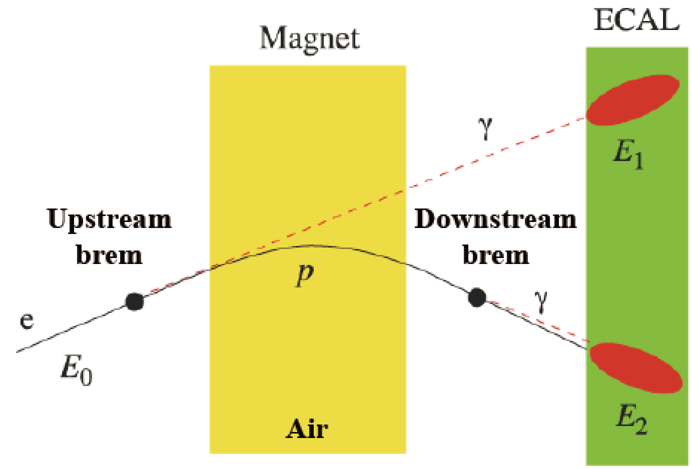
	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
SM prediction	1.00 ± 0.01	0.92 ± 0.02	1.00 ± 0.01

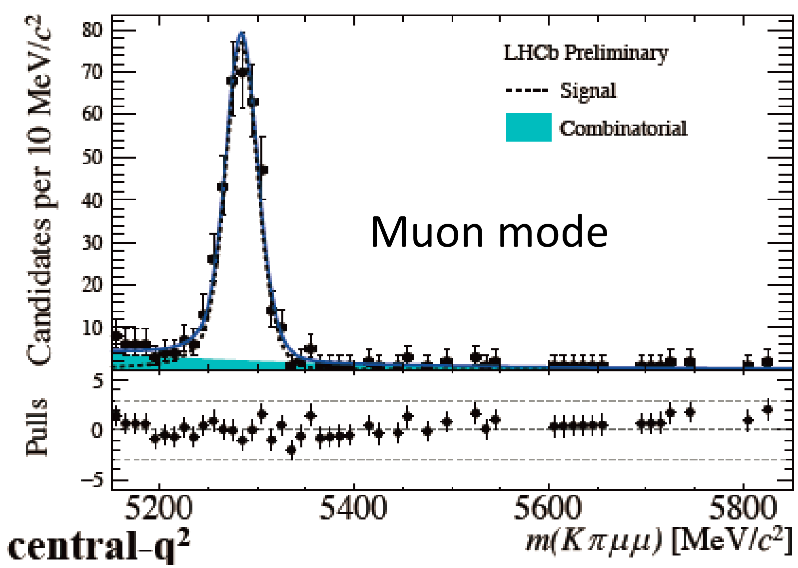
Capdevila, Crivellin, Descotes-Genon, Matias, Virto 1704.05340

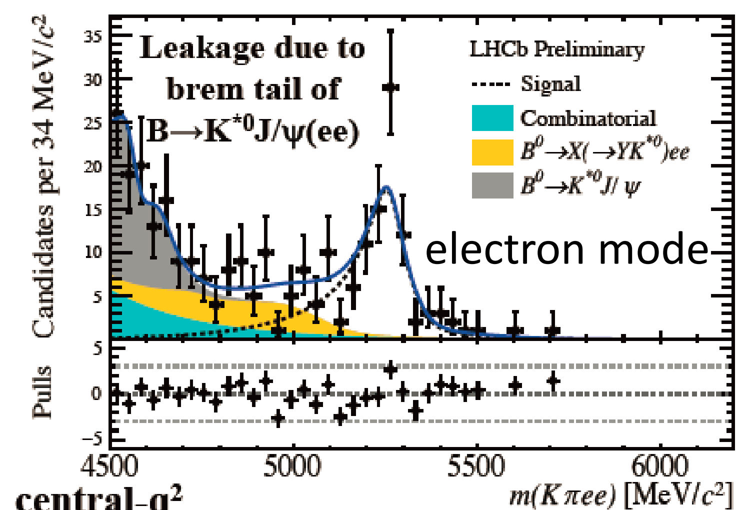
- LFUV in kinematic distributions are also sensitive to NP
  - Angular distribution such as $Q_5 = P_5'^{\mu} - P_5'^{e}$

Measurement of R_{K*} at LHCb

- Muon mode is easy and very clean
- Electron mode is hard due to bremsstrahlung
  - Tail in B mass distribution
  - Background from J/psi and partcial reconstruction of similar decay modes







Results on R_K and R_{K*} by LHCb

- All results are about 30% smaller than the SM predictions.
- Naïve combination gives ~4σ effects

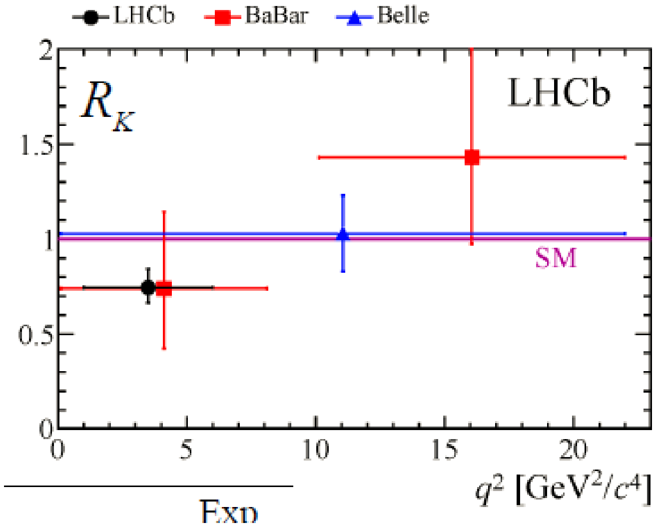
[1.1, 6]GeV^2

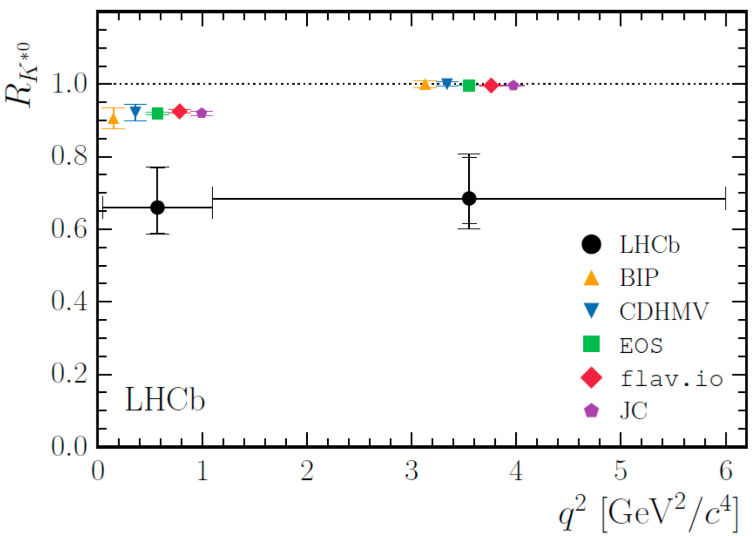
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

2.6σ

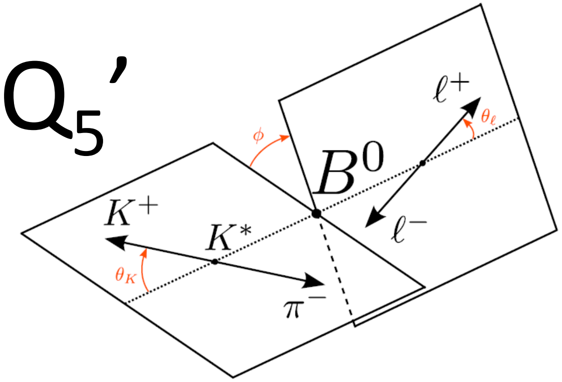
[0.045, 1.1]GeV^2 [1.1, 6]GeV^2

	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
	~2.2σ	~2.5σ

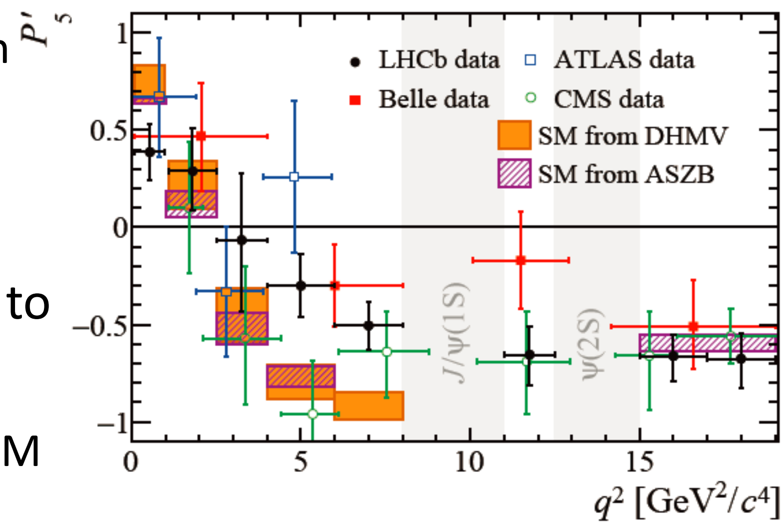




LFUV in Angular Distribution : Q_5'



- LHCb first observed deviation in one of the angular observables P_5' for muon mode in 2013
  - LHCb updated in 2015. Still 3.9σ deviation seen
  - Then Belle and ATLAS confirmed.
  - Suggest new physics in vector current in muon mode (or charm loop??)
    - $C_{9\mu}^{NP} \sim -1.1$ ($C_{9\mu}^{SM} \sim 4$)
    - About 30% deficit from the SM
- Belle then, measure both electron and muon to test LFUV in the angular observables
  - $Q_5 = P_5'^{\mu} - P_5'^{e}$ Difference should be zero in SM



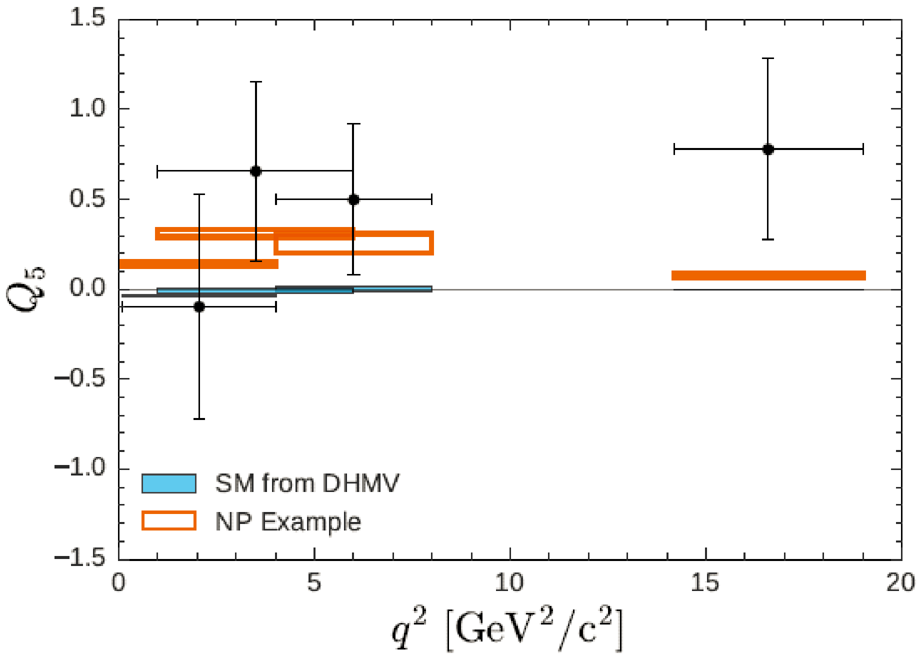
q² and three angles

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

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

Results on Q_5 at Belle

- Consistent with both SM and NP with $C_9^{\mu}{}_{NP} = -1$
  - Uncertainty is still large to discriminate

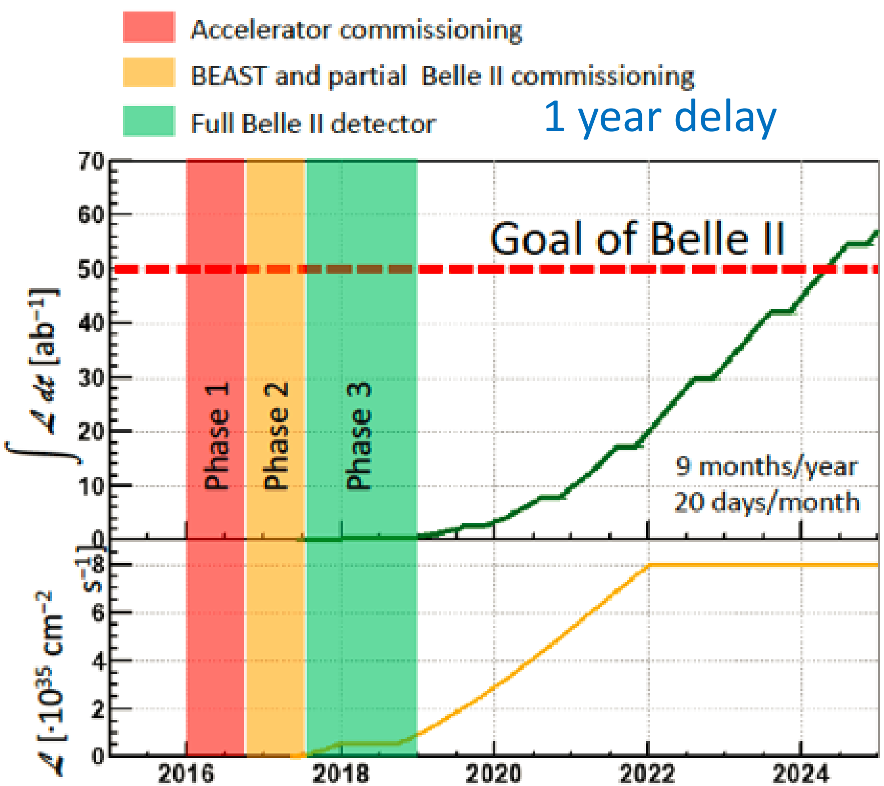


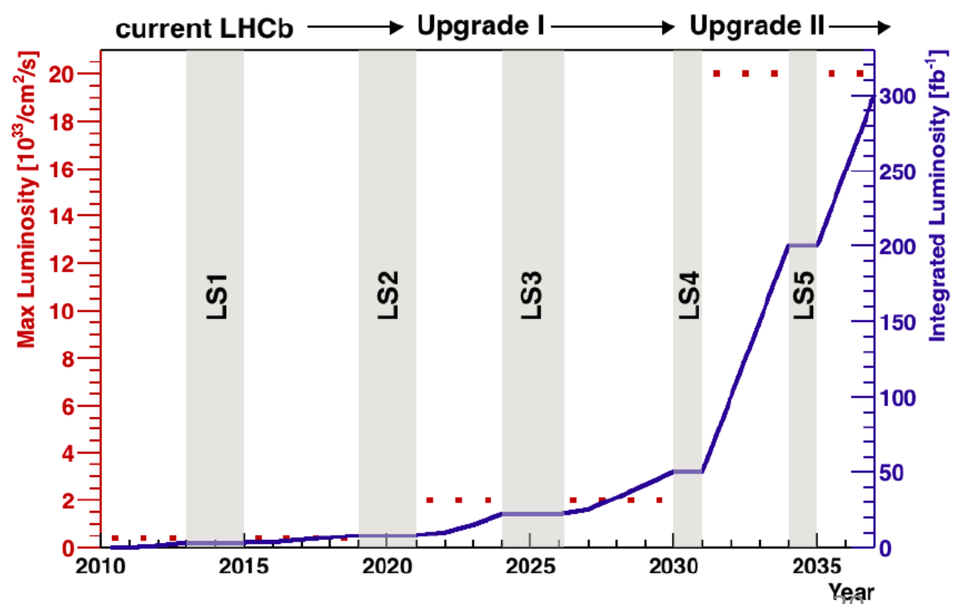
q^2 in GeV$^2/c^2$	Q_5
[1.00, 6.00]	$0.656 \pm 0.485 \pm 0.103$
[0.10, 4.00]	$-0.097 \pm 0.601 \pm 0.164$
[4.00, 8.00]	$0.498 \pm 0.410 \pm 0.095$
[14.18, 19.00]	$0.778 \pm 0.502 \pm 0.065$

Future Prospects on LFUV

Belle II and Upgraded LHCb

- Belle II will accumulate 50ab^{-1} in 2025
  - 50times larger than Belle
- Upgraded LHCb will accumulate 50(300)fb^{-1} in 2030(2037)

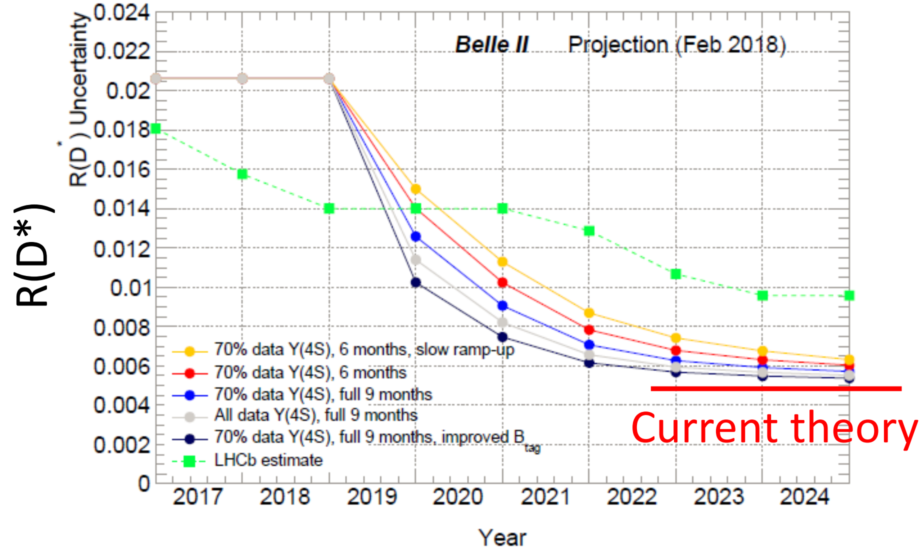




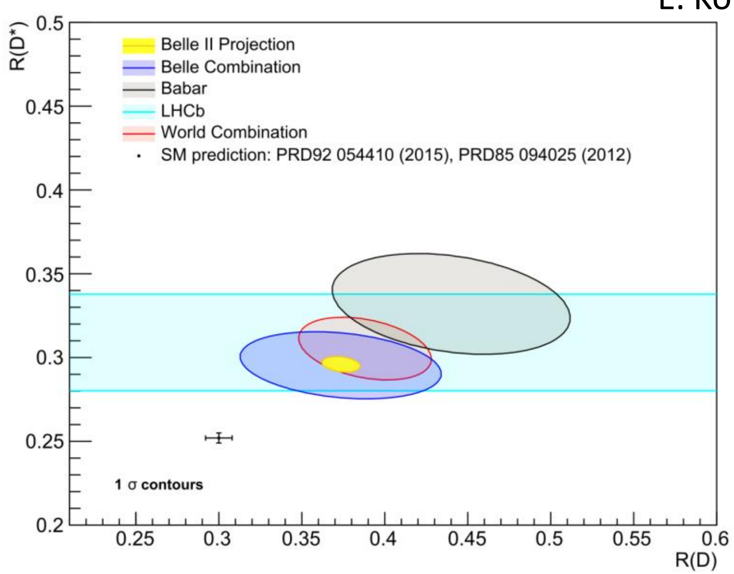
Future Prospects on $R(D^{(*)})$ at Belle II

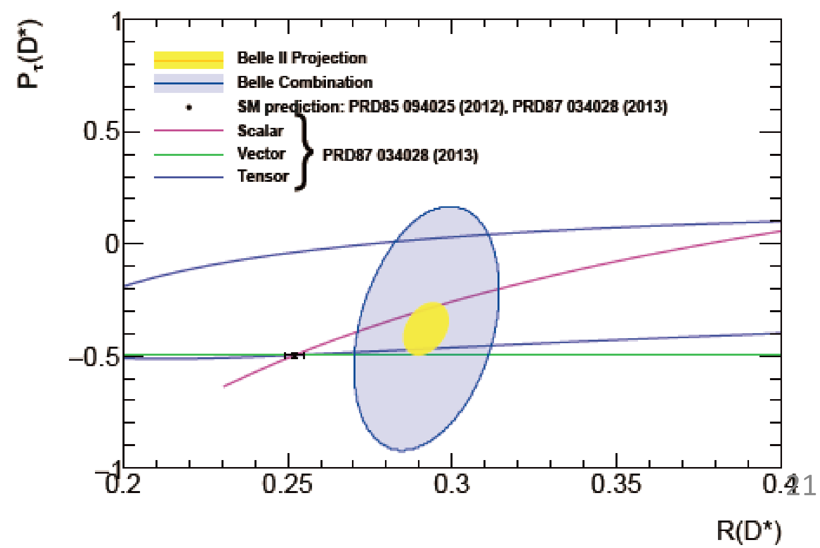
1year delay, Blue one is nominal scenario

- Tagging effciency improved about factor 2
- We could observe 5σ deviation of R(D) VS R(D*) in 2021 if central value unchanged
  - Sensitivity of R(D*) is 0.006 in 2025.
- Then, model descrimination with Polarization measurments



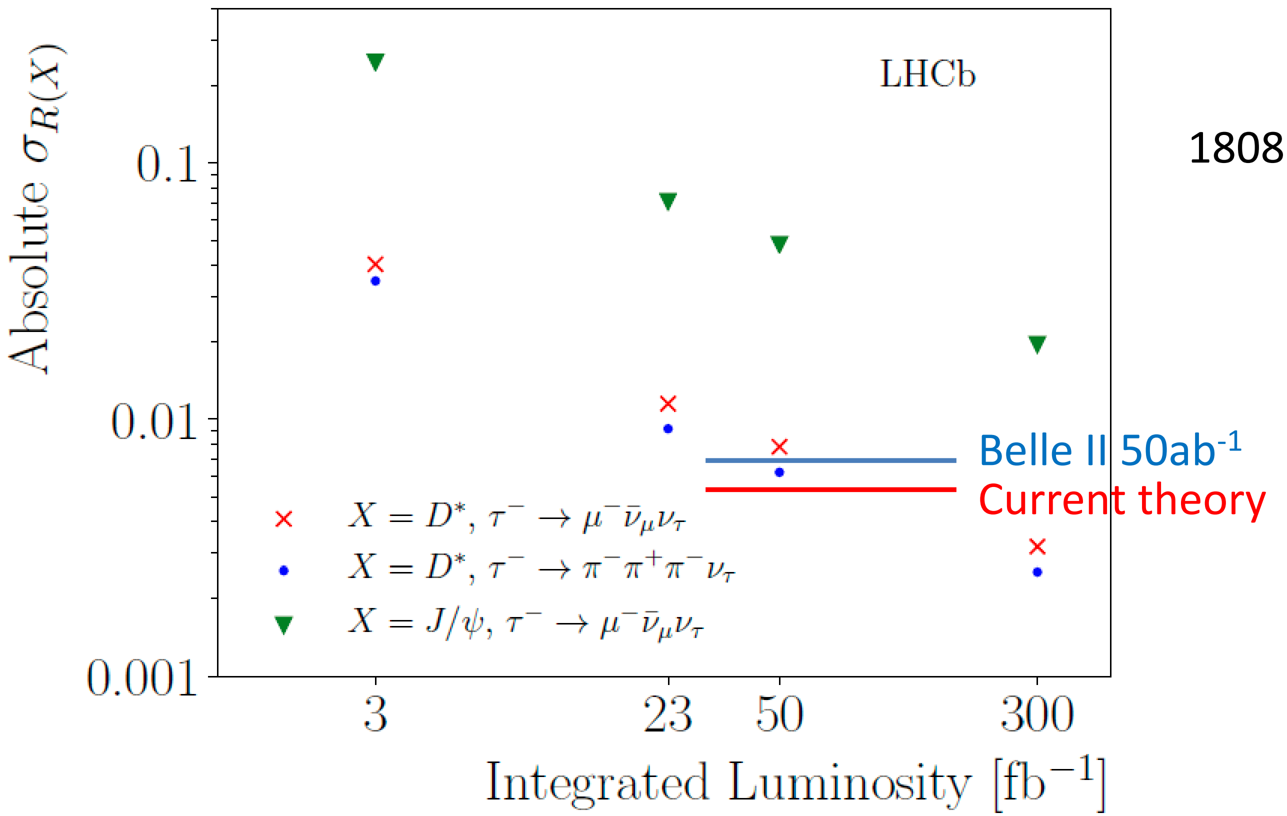
E. Kou et al. 1808.10567





Future Prospects on R(D*) at LHCb

- LHCb could observe 5σ deviation of R(D*) in 2022 if central value unchanged
- With 300fb^{-1}, the sensitivity is better than Belle II with 50ab^{-1} and current theory
  - Systematic uncertainty is assumed to scale as inverse of square root of luminosity : L$^{-1/2}$

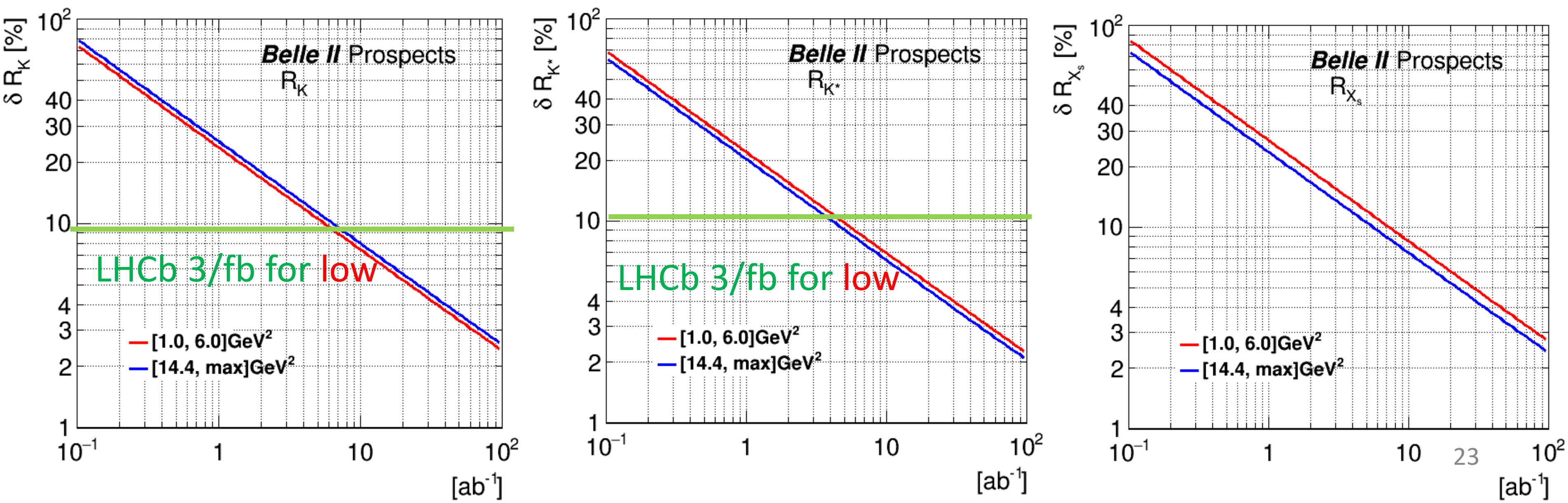


1808.08865

Prospects on R_K, R_{K*} and R_{Xs} at Belle II

- Ideal place to measure R_H
  - bremsstrahlung photon can be recovered easily
  - Both high and low q^2 accessible
  - Dominant systematics due to lepton ID ~0.4% is smaller than stat one even with 50ab^{-1}
- We can observe NP using R_K and R_{K*} with ~10/ab data in 2022
  - if central values unchanged
  - Using R_{Xs} with 20/ab correlation
- About 3% uncertainty for both high and low q^2 with 50/ab
  - Assuming SM predictions for R_X

Low $1<q^2<6GeV^2$
High $q^2>14.4GeV^2$



Prospects on R_K, R_{K*} and R_{Xs} at LHCb

- With 23fb^{-1}, sensitivity for low q^2 [1.1, 6]GeV^2 is comparable to Belle II with 50ab^{-1} (~3%).
- With 300fb^{-1} , sensitivity for low q^2 is better than current theory uncertainty (~1%).

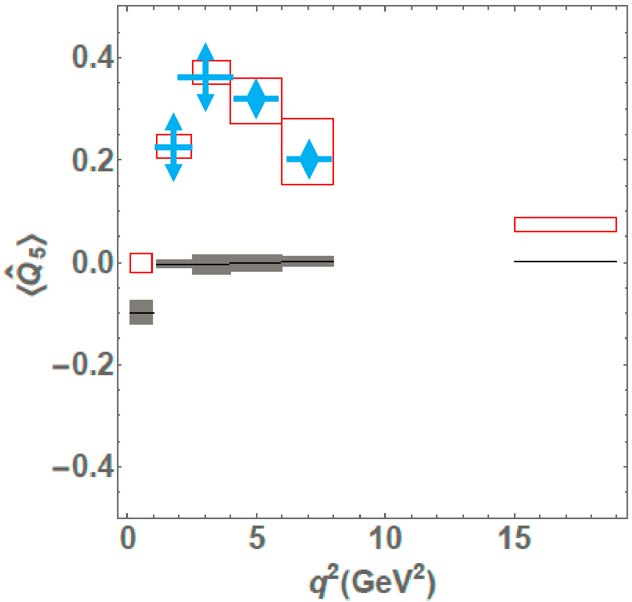
[1.1, 6]GeV^2

R_X precision	Run 1 result	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

1808.08865

Prospects on Q_5 at Belle II

- Q_5
  - Uncertainty is 0.04 for [4,6]GeV^2 with 50/ab
  - Can discriminate NP scenario. Confirm or deny NP in $C_{9\mu}^{NP}$



Belle II 50ab^{-1}

SM : gray

NP : red

$$C_{9\mu}^{\rm NP} = -1.11$$

Capdevila, Crivellin, Descotes-Genon, Matias, Virto 1704.05340

Overlaid Belle II sensitivity

E. Kou et al. 1808.10567

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
Q_5 ($1 < q^2 < 2.5$ GeV^2)	0.47	0.17	0.054
Q_5 ($2.5 < q^2 < 4$ GeV^2)	0.42	0.15	0.049
Q_5 ($4 < q^2 < 6$ GeV^2)	0.34	0.12	0.040
Q_5 ($6 < q^2 < 8$ GeV^2)	0.27	0.094	0.030
Q_5 ($q^2 > 14.2$ GeV^2)	0.23	0.088	0.027

Summary

- Two hints of Lepton Flavor Universality Violation are found in B decays
  - $b \rightarrow c\tau\nu$
  - $b \rightarrow s l^+ l^-$
- Both are about 4σ effects.
- If this is true, we could observe new physics in early 2020's at both Belle II and upgraded LHCb.

- Exiting time will be stated soon.
  - Belle II phase 3 with VTX detector will start in Jan. 2019
  - Upgraded LHC will start in 2021
- Stay tuned.

backup

Correlation among R's

- Understanding of correlation among R_K, R_{K^*} and R_{X_s} is important to identify NP

$$R_K \simeq 1 + \Delta_+$$

$$R_{K^*} \simeq 1 + p\,(\Delta_- - \Delta_+) + \Delta_+ \,,$$

$$R_{X_s} \simeq 1 + (\Delta_+ + \Delta_-)/2 \,,$$

Prediction

$$R_{X_s} \sim 0.73 \pm 0.07$$

$$p = \frac{g_0 + g_\parallel}{g_0 + g_\parallel + g_\perp} \,.$$

$$\Delta_\pm = \frac{2}{|C_9^{\rm SM}|^2 + |C_{10}^{\rm SM}|^2} \left[{\rm Re}\left(C_9^{\rm SM} (C_9^{{\rm NP}\mu} \pm C_9'^{\mu})^* \right) + {\rm Re}\left(C_{10}^{\rm SM} (C_{10}^{{\rm NP}\mu} \pm C_{10}'^{\mu})^* \right) - (\mu \to e) \right] .$$

Hiller, Schmartz 1411.4773
Hiller, Nisandzic 1704.05444

Prospects of LFUV in b→sll at Belle II

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ($1 < q^2 < 6$ GeV^2)	0.28	0.11	0.036
R_K ($q^2 > 14.4$ GeV^2)	0.30	0.12	0.036
R_{K^*} ($4m_\mu^2 < q^2 < 1$ GeV^2)	0.26	0.10	0.032
R_{K^*} ($1 < q^2 < 6$ GeV^2)	0.26	0.10	0.032
R_{K^*} ($q^2 > 14.4$ GeV^2)	0.24	0.92	0.028
R_{X_s} ($4m_\mu^2 < q^2 < 1$ GeV^2)	0.26	0.10	0.032
R_{X_s} ($1 < q^2 < 6$ GeV^2)	0.32	0.12	0.040
R_{X_s} ($q^2 > 14.4$ GeV^2)	0.28	0.11	0.034