5. Phenomenology of FCNC (ΔF=1) decays

In the Standard Modell flavor changing neutral current (FCNC) decays, e.g. $K^0 \to \mu\mu$ or $B^0 \to K^* \mu\mu$ are not possible at tree-level but only at loop-level. They are therefore strongly suppressed (typ. BR ~ O(10^{-6} ….10^{-12})) – there is often also an additional helicity suppression.

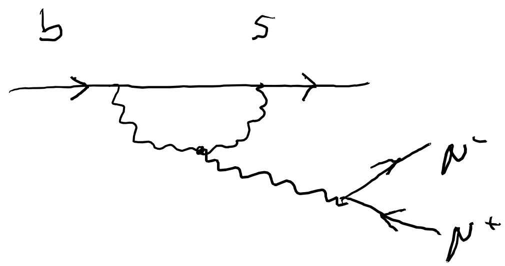
Due to this strong suppression these decays are excellent probes to search for physics beyond the Standard Model: SM contributions are small $\to$ any additional contribution – even if it is very small – is easily visible.

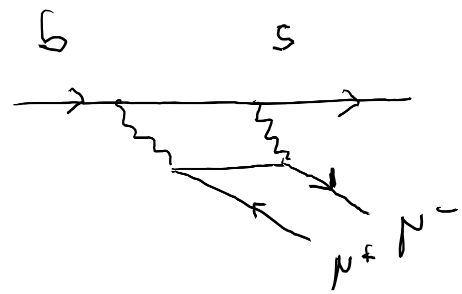
Observables are:

- BR: allow searches for New Effects (often called New Physics, NP) only if the Standard Model BR can be calculated with small errors (difficult).
- Angular distributions, polarizations, etc.: probe the Lorentz structure of the effective coupling (“Wu experiment”), very often calculable with small errors (hadronic uncertainties mostly cancel because measurements are often “ratios”).

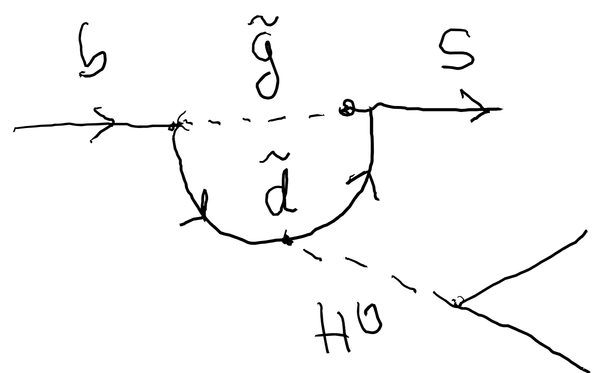
Example: $B^0 \to K^* \mu\mu$

Standard Model:





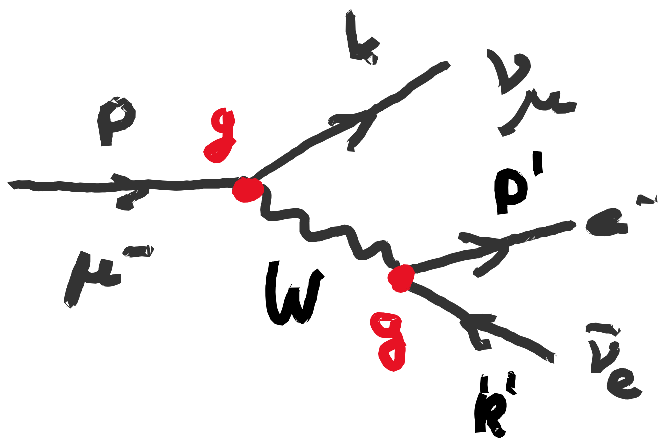
New Physics e.g.: extended Higgs-sector in SUSY theories



$\rightarrow$ Enhancement of effective S (scalar) and P (pseudo scalar) coupling components (see later) which even overcomes the helicity suppression

5.1 Effective Theories “for pedestrians”

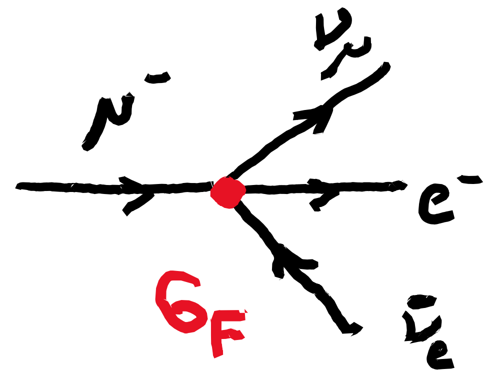
a) Reminder: Muon decay



$m_\mu \ll M_W$

$\Longrightarrow$

effective local interaction



$$\mathcal{M} \sim g \cdot J^{\alpha}_{muon} \cdot \left(\frac{g_{\alpha\beta}}{M_W^2 - q^2} \right) \cdot g \cdot J^{\beta}_{electron} \quad \longrightarrow \quad \mathcal{M} \sim \frac{G_F}{\sqrt{2}} \cdot J^{+\alpha} \cdot J^{-}_{\beta}$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

expansion of propagator

Effective Lagrangian: $$\mathcal{L}^{eff}_{weak} = -\frac{4G_F}{\sqrt{2}} \underbrace{J^{-}_{\alpha} J^{+,\alpha}}_{Q} + O\left(\frac{q^2}{M_W^2} \right); \quad J^{-}_{\alpha} = \left(J^{+,\alpha} \right)^{\dagger}$$

$$Q = \left(\bar{u}_{iL} \gamma_\mu d_{jL} \right) \left(\bar{\nu}_{iL} \gamma_\mu \ell_{iL} \right)$$

For a realistic description of quark flavor processes one needs to take into account effects of the strong interaction.

To account for the perturbative QCD effects one introduces Wilson-coefficients C_i into the effective Lagrangian. Replacing the 4-fermion currents by a corresponding operator O_i one obtains:

$$\mathcal{L}_{weak}^{eff} = -\frac{4G_F}{\sqrt{2}} \sum_i C_i O_i$$

The Wilson-coefficients are process independent (specific for the operator – here: the 4 quark current). They are obtained by matching amplitudes of the full theory onto the effective theory:

$$\langle f \,|\, \mathcal{L}_{SM} \,|\, i \rangle = -\frac{4G_F}{\sqrt{2}} \sum_i C_i(\mu) \langle f \,|\, O_i(\mu) \,|\, i \rangle + \ldots$$

The Wilson-coefficients depend on a cutoff-scale $\mu \sim \Lambda$ for the perturbative treatment of the QCD corrections.

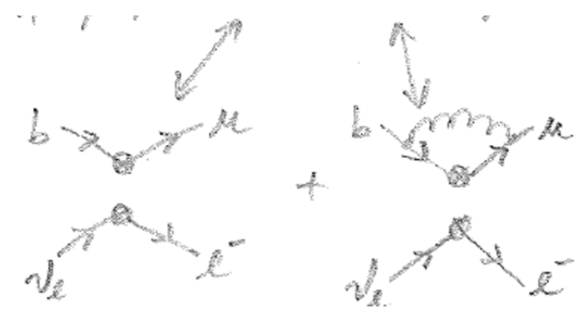
<u>Example:</u>

Semileptonic decay $\bar{B}^0 \to \pi^+ e^- \bar{\nu}_e$ involves only one 4-fermion operator:

$$O_1 = \left(\bar{u}_L^\alpha \gamma^\mu b_L^\alpha\right)\left(\bar{e}_L \gamma_\mu \nu_L\right) \qquad (\alpha = \text{color index})$$

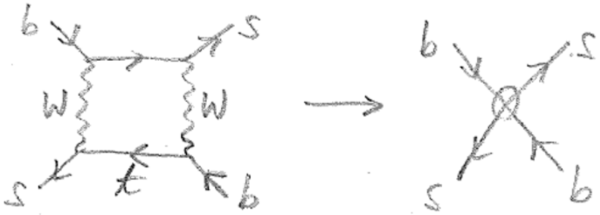
Matching yields

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ub} C_1(\mu) O_1; \quad C_1(\mu) = 1 + O(\alpha_s)$$



Relevant operators for FCNC processes: (full list: M. Neubert hep-ph/0512222)

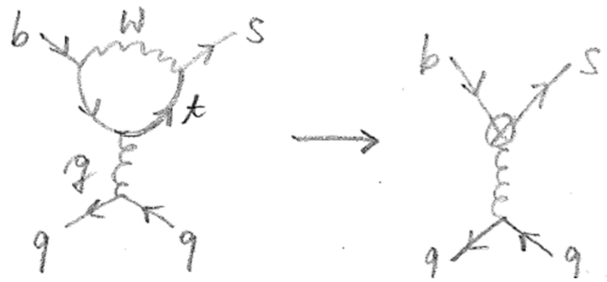
- Current-current operators:



$$O_{4q} = \left(\bar{s}_L \gamma_\mu b_L\right)\left(\bar{s}_L \gamma^\mu b_L\right)$$

($B_s \bar{B}_s$ mixing)

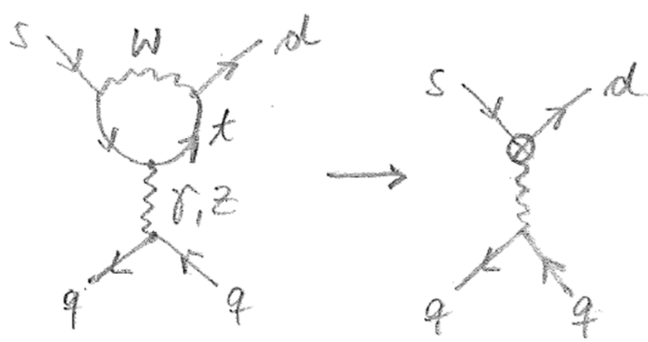
- QCD penguin operators:



$$Q_{QCD} = \left(\bar{s}_L \gamma_\mu b_L\right) \sum_{q=u,d,\ldots,b} \left(\bar{q}_L \gamma^\mu q_L\right)$$

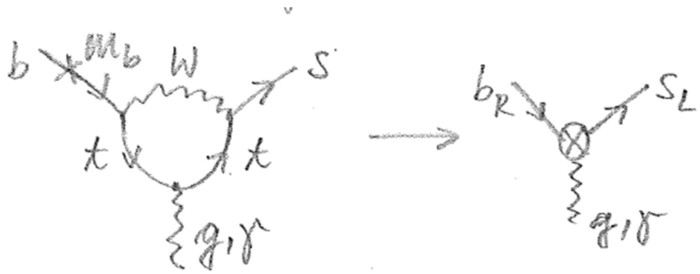
$$\left(B^- \to K^- X\right)$$

- Electroweak penguin operators



$$Q_{EW} = \left(\bar{d}_L \gamma_\mu s_L\right) \sum_{q=u,d\ldots b} \frac{2}{3} e_q \left(\bar{q}_R \gamma^\mu q_R\right)$$

- Electromagnetics and chromo-magnetic dipole operator

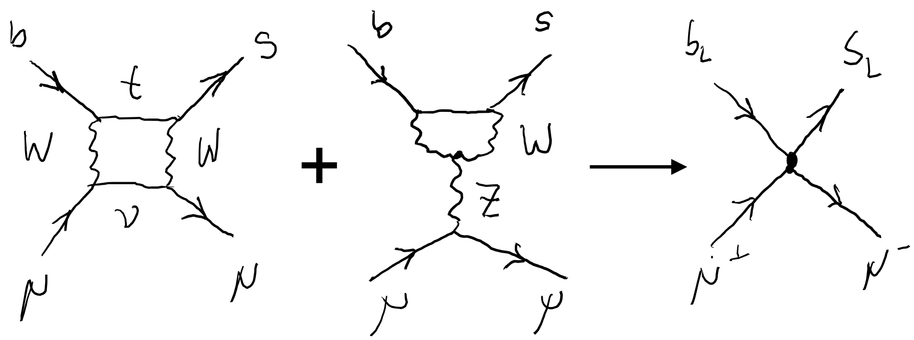


$$Q_\gamma, Q_7 = -\frac{e m_b}{8\pi^2} \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R$$

$$\left(B_s \to K^* \gamma\right)$$

$$Q_g, Q_8 = -\frac{g_s m_b}{8\pi^2} \bar{s}_L \sigma_{\mu\nu} G_a^{\mu\nu} T_a b_R$$

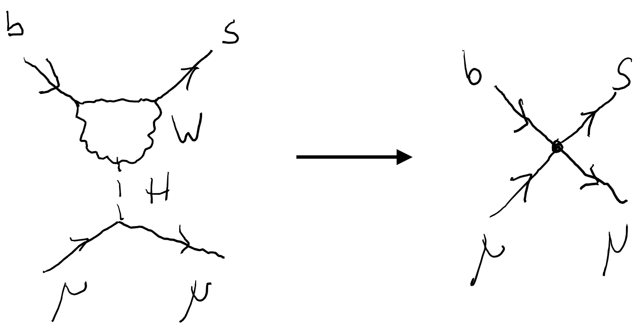
- Vector and axial vector operators



$$Q_9 = \left(\bar{s}_L \gamma_\mu b_L\right)\left(\bar{\ell} \gamma^\mu \ell\right)$$

$$Q_{10} = \left(\bar{s}_L \gamma_\mu b_L\right)\left(\bar{\ell} \gamma^5 \gamma^\mu \ell\right)$$

- Scalar and pseudo-scalar operators



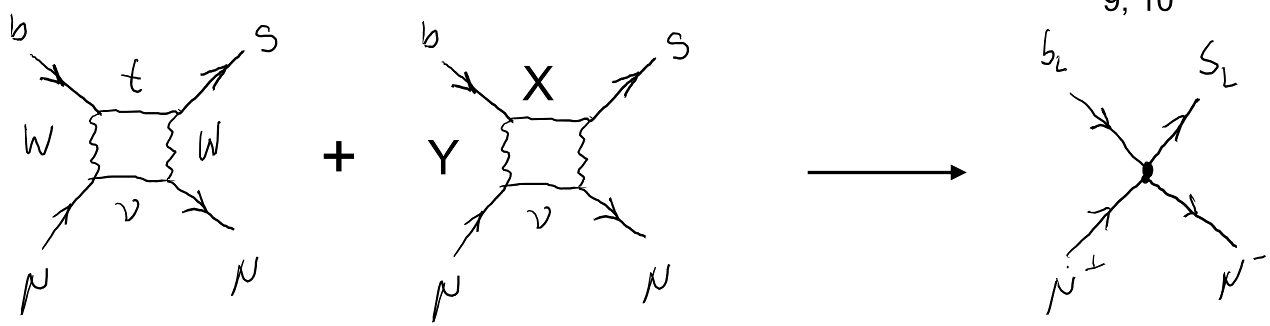
$$Q_S = \left(\bar{s} b\right)\left(\bar{\ell} \ell\right)$$

$$Q_P = \left(\bar{s} b\right)\left(\bar{\ell} \gamma^5 \ell\right)$$

- In addition to $O_{7,8,9,10,S,P}$ there are $O'_{7,8,9,10,S,P}$ for which $P_R \Leftrightarrow P_L$ (quarks)

Sensitivity to New Effects:

$O_{9,\,10}$

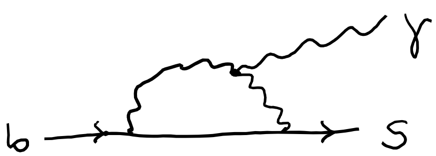


New physics effects lead to different Wilson coefficients or even to new operators w/r to SM

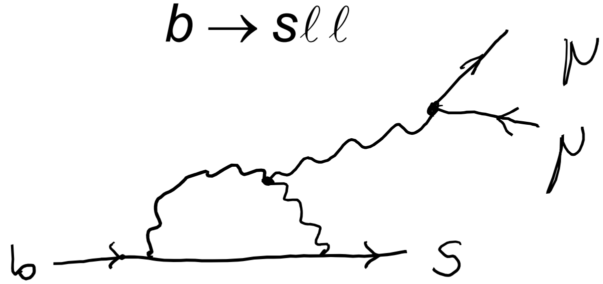
$$C'_{9,10} = C^{SM}_{9,10} + C^{NP}_{9,10}$$

Particular interesting are processes which are strongly suppressed:

$b \to s\gamma$



$b \to s\ell\bar{\ell}$



$B^0_s \to \ell\bar{\ell}$

additional suppression ~α

Helicity suppression $\sim \dfrac{m_\ell^2}{m_B^2}$

What did we learn?

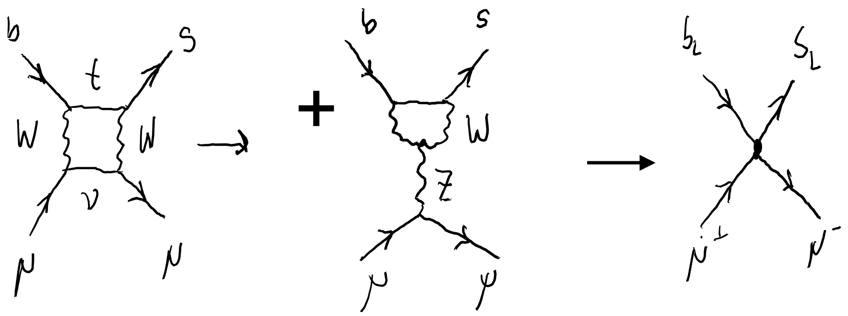
We can expand the Standard Model Langrangian into a sum of effective operators (point interactions)

$$\langle f | \mathcal{L}_{SM} | i \rangle = -\frac{4G_F}{\sqrt{2}} \sum_i C_i(\mu) \langle f | O_i(\mu) | i \rangle + \ldots$$

Wilson-coefficients, depend on cut-off scale $\mu \sim \Lambda$ for perturbative treatment of QCD

effective operators

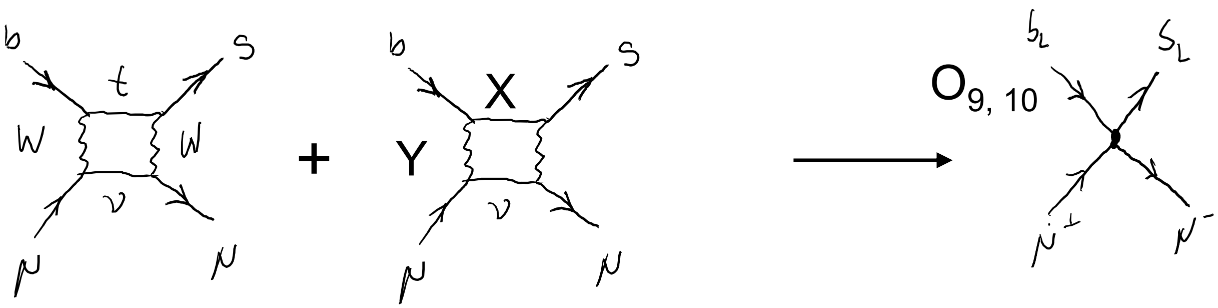
e.g.: effective operator for an effective qqll coupling:



$$Q_9 = \left(\bar{s}_L \gamma_\mu b_L\right)\left(\bar{\ell} \gamma^\mu \ell\right)$$

$$Q_{10} = \left(\bar{s}_L \gamma_\mu b_L\right)\left(\bar{\ell} \gamma^5 \gamma^\mu \ell\right)$$

Parametrization of New Effects

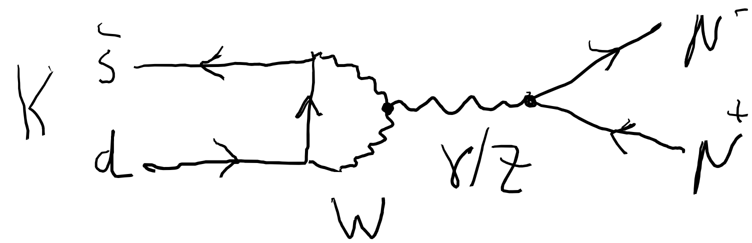


$$C'_{9,10} = C^{SM}_{9,10} + C^{NP}_{9,10}$$

5.2 Helicity suppressed decays: K^0, $B^0 \rightarrow \mu\mu$

Pure leptonic decays of mesons (K, D, B) are particularly interesting FCNC decays: Helicity suppression of vector and axial-vector terms (O_9 and O_{10}) makes these decays very sensitive to new (pseudo)-scalar interactions which would enhance the observed branching fractions significantly.

E.g.: Higgs-penguins diagrams

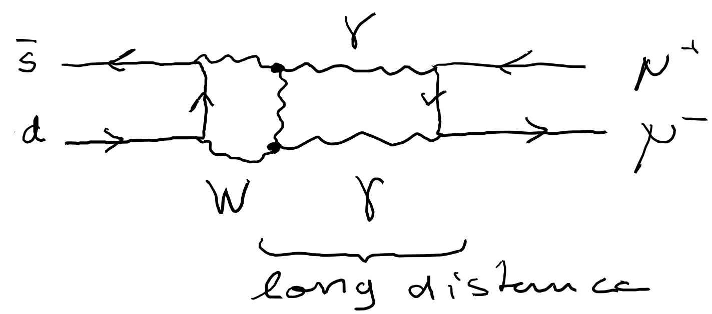


K_S, $K_L \rightarrow \mu\mu$ decays:

$K_L \rightarrow \mu\mu$

The most recent measurement BR($K_L \rightarrow \mu\mu$) = $(6.86 \pm 0.11) \times 10^{-9}$ (BNL E781 2000) is in agreement with the theoretical prediction, which however is dominated by long distance contributions from photon rescattering (difficult to calculate):

K_L



Remark:
Different long-distance amplitudes with different C and P behavior contribute differently to K_L and K_S.

New Physics tests limited by theory prediction

$K_S \rightarrow \mu\mu$

For K_s the absorptive (long-distance) part is only ~5×10^{-12}, i.e. very small. New physics contribution of $O(10^{-11})$ can be probed sensitively. However measurements have not reached this sensitivity yet:

$$BR(K_S \rightarrow \mu\mu) < 3.2 \cdot 10^{-7} \text{ (1973)}$$

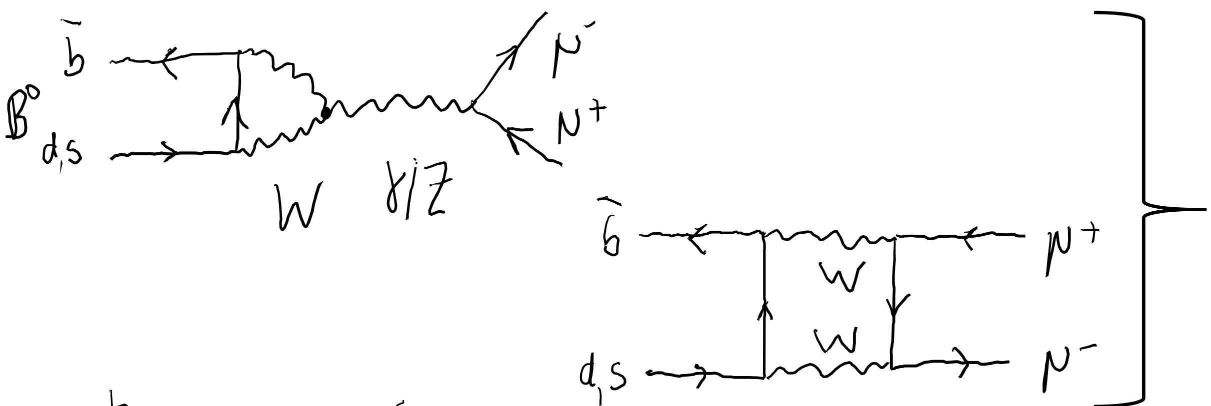
$$BR(K_S \rightarrow \mu\mu) < 11 \cdot 10^{-9} \text{ (LHCb, 2012)}$$

In future, LHCb will be able to probe new physics contributions down to 10^{-11} .

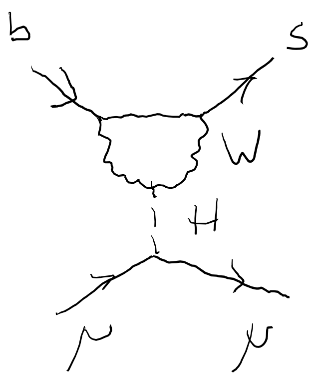
New Physics tests are limited by experimental sensitivity.

$B_{s,d} \rightarrow \mu\mu$

B-mesons (as K^0 mesons) are pseudo-scalars. The $\mu\mu$ final-state with spin ½ of the two muons and axial-vector / vector couplings prefers $\bar{\mu}_R \mu_L$ or $\bar{\mu}_L \mu_R$ configurations, i.e. final-states with J=1 $\rightarrow$ strong helicity suppression as we have discussed for the $\pi^+ \rightarrow \mu^+ \nu$ decay.



Vector and axial-vector coupling: strong helicity suppression



Scalar- or pseudo-scalar coupling: no helicity suppression, but strongly suppressed in SM!

$\rightarrow$ Sensitive to new (pseudo)-scalar contributions

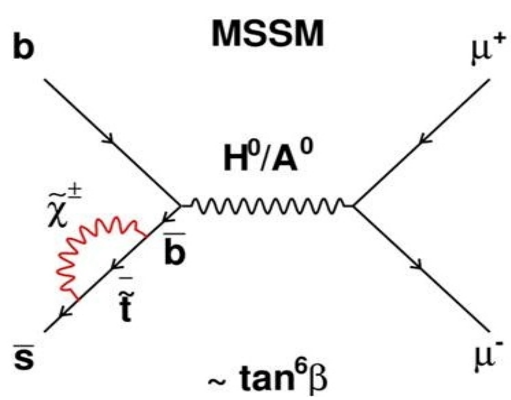
$$BR\left(B_q^0 \to \mu\mu\right) = \frac{G_F^2 \alpha^2}{64\pi^3 \sin^4\theta_w} \cdot \left|V_{tb}^* V_{tq}\right|^2 \tau_{B_q} m_{B_q}^3 f_{B_q}^2 \sqrt{1-\frac{4m_\mu^2}{m_{B_q}^2}} \cdot$$

$$\left\{ m_{B_q}^2 \left(1-\frac{4m_\mu^2}{m_{B_q}^2}\right)\left(\frac{C_s-\mu_q C_S'}{1+\mu_q}\right)^2 + m_{B_q}^2 \left(\left(\frac{C_P-\mu_q C_p'}{1+\mu_q}\right) + \underbrace{\frac{2m_\mu}{m_{B_q}}}_{\text{Helicity suppression}}\left(C_{10}-C_{10}'\right)\right)^2 \right\}$$

$$\mu_q = m_q / M_W$$

In the Standard Modell the contributions from C_S and C_P are very small.
SM contribution from C_{10} is helicity suppressed: BR ~ 3×10^{-9} (1×10^{-10}) for B_s (B_d)

$\Rightarrow$ Superb possibility to test additional new (pseudo)scalar contributions:
Very sensitive to SUSY with an extended Higgs-sector (2 Higgs Doublets)

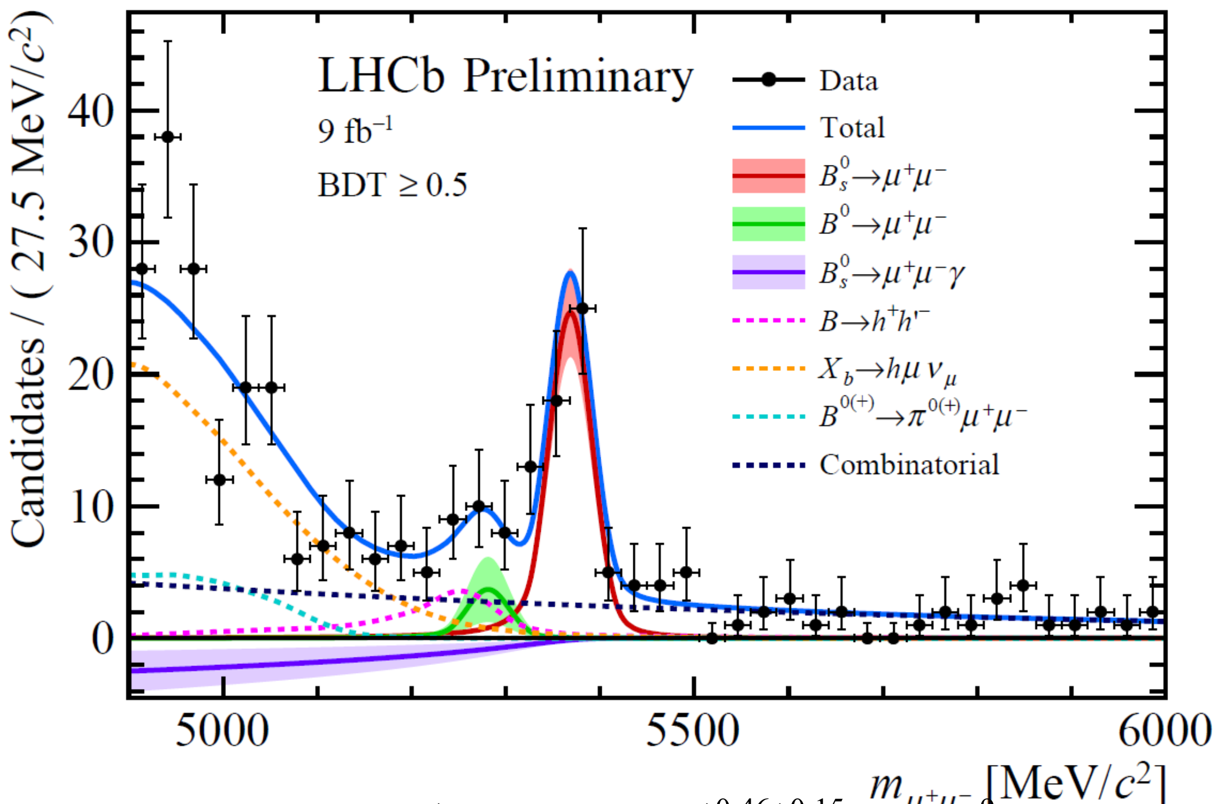


$$\tan\beta = \frac{\upsilon_u}{\upsilon_d}$$ (ratio of the VEV of the 2 doublets)

$$\longrightarrow \quad BR\left(B_s^0 \to \mu\mu\right) \propto \frac{\tan^6\beta}{m_A^4}$$

Observation of $B_s \to \mu\mu$:

LHCb, March 2021, to be published.



$$BR(B_s \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10} \ @ 90\% \ C.L.$$

Standard Model $BR(B_s \to \mu\mu)$ $(3.66 \pm 0.14) \times 10^{-9}$

$BR(B_d \to \mu\mu) = (1.03 \pm 0.05) \times 10^{-10}$

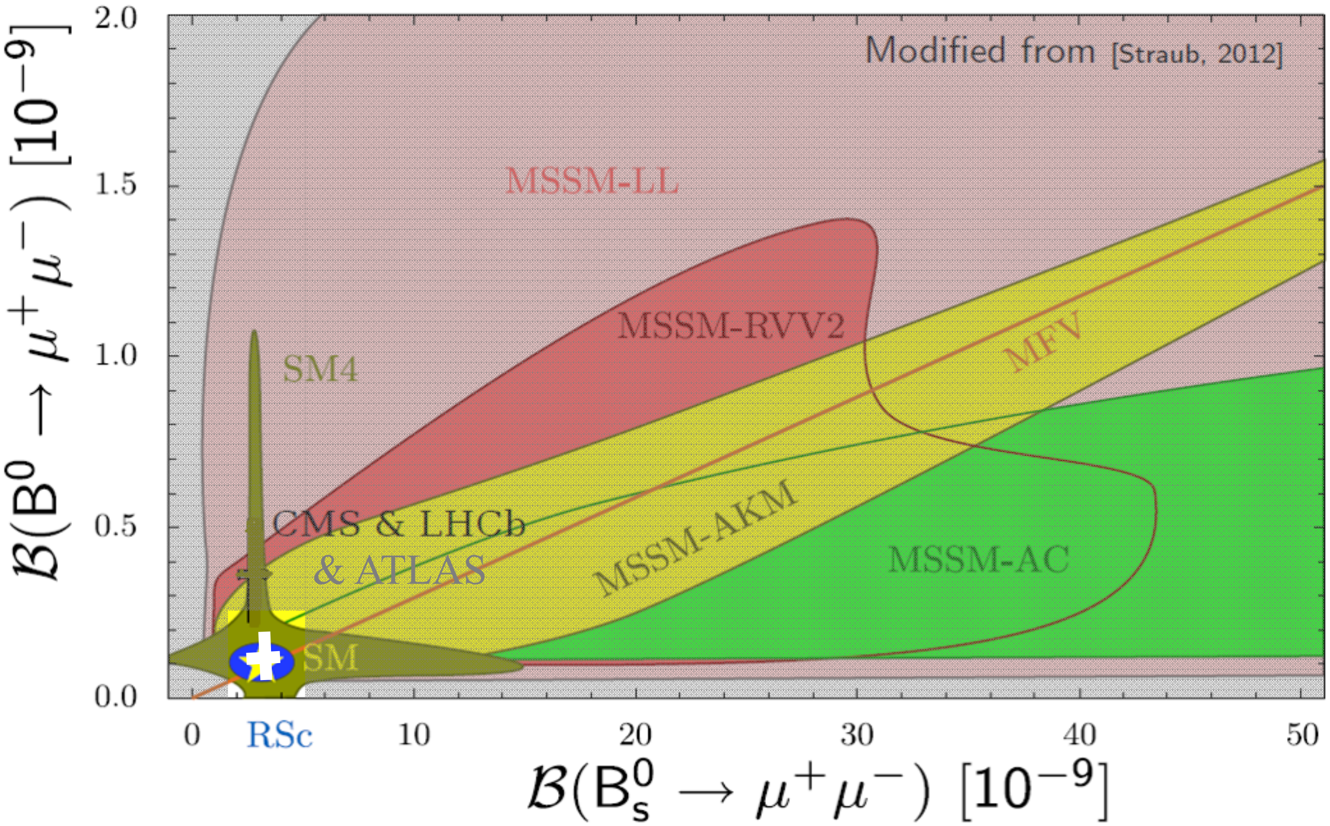
M.Beneke et al. JHEP10(2019)232

Interpretation of results in view of New Physics models

Combination;
ATLAS, CMS, LHCb

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) = (2.67^{+0.45}_{-0.35}) \times 10^{-9}$$
$$\mathrm{BR}(B^0 \to \mu^+\mu^-) = (1.00^{+0.86}_{-0.57}) \times 10^{-10}$$

ATLAS: 1812.03017
CMS: PRL111(2013)101804
LHCb: PRL118(2017)191801



Decay channel B → μμ was often called “SUSY Killer”

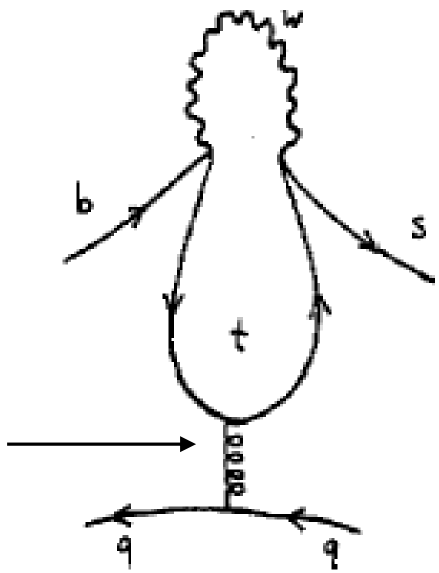
Remarks:

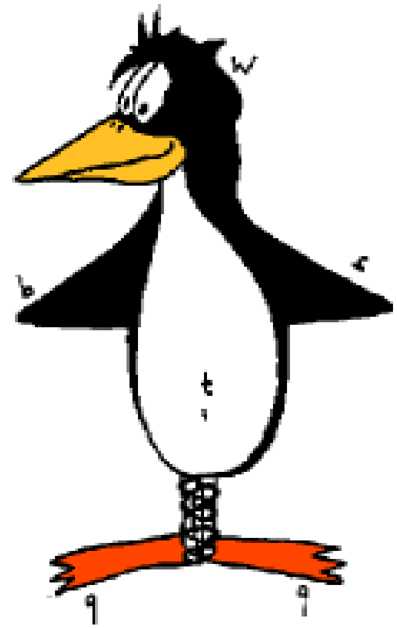
- BR ($B \to \tau\tau$) is much less helicity suppressed – however difficult to measure because of the experimental problem to reconstruct the τ: τ decay and produce a undetectable neutrino (no mass constraint)

- Question: What happens with BR ($B \to \mu\mu$) if all u-type quarks would have the same mass? Unitarity of CKM matrix $\to$ BR=0.

5.3 Penguin decays

Depending on the boson g, γ or Z one calls the diagram “gluonic” or electro-weak penguin.





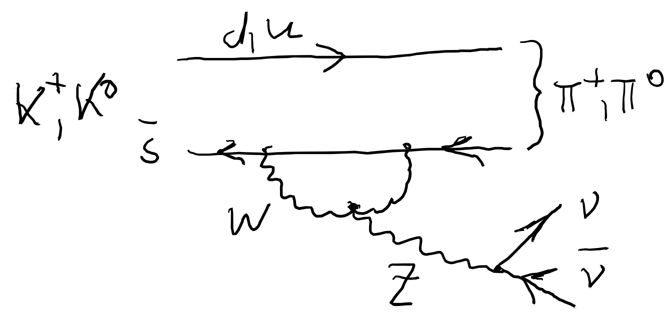
by A. Lenz

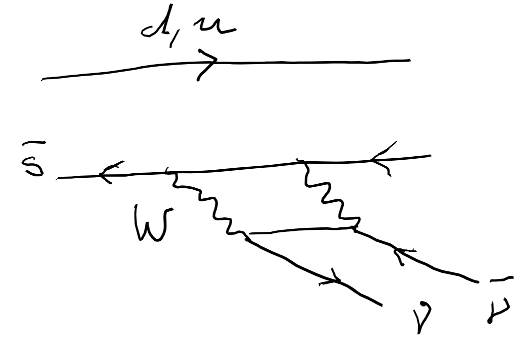
The expression “penguin decays” was introduced by J. Ellis.

5.3 Penguin decays

<u>Rare Kaon Decays:</u>

$$K^{0,\pm} \to \pi^{0,\pm} \nu \bar{\nu}$$

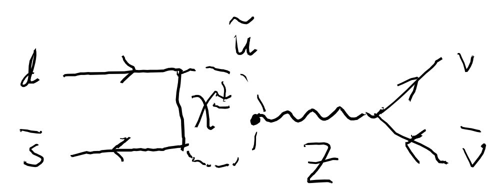




Theory prediction: $BR\left(K^{+} \to \pi^{+} \nu \bar{\nu}\right) = \left(7.8 \pm 0.8\right) \cdot 10^{-11}$

$BR\left(K^{0} \to \pi^{0} \nu \bar{\nu}\right) = \left(2.4 \pm 0.4\right) \cdot 10^{-11}$

Theoretical uncertainties are expected to be <10%
$\rightarrow$ The two decays are very sensitive probes for new effects, e.g. SUSY:



Experimental efforts:

- KOTO (KEK, JP): $K_L \to \pi^0 \nu \bar{\nu}$ with $\pi^0 \to \gamma\gamma$

  Signature: 2γ + nothing: difficult!

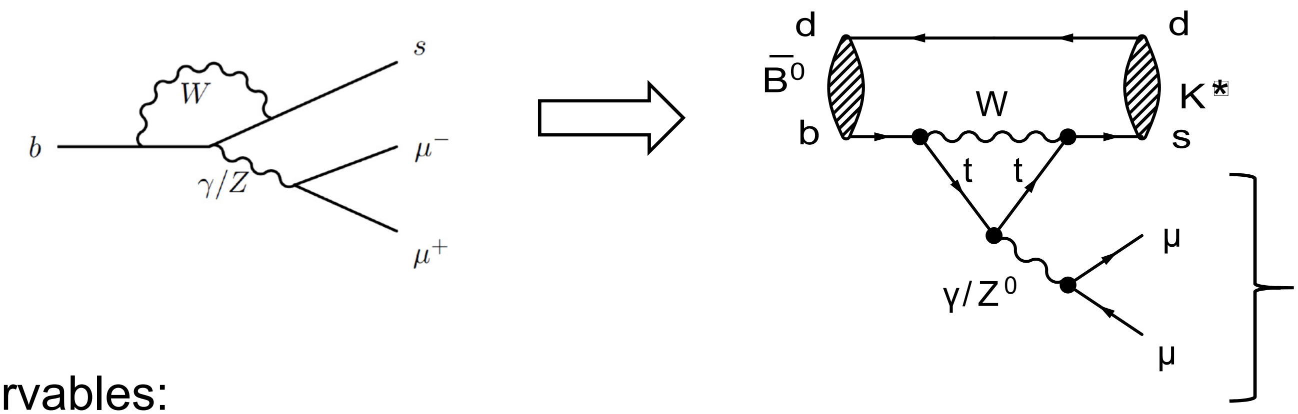
- BNL 787: $K^{\pm} \to \pi^{\pm} \nu \bar{\nu}$: 7 events observed – $(17 \pm 11) \times 10^{-11}$
- NA62 (CERN) - first measurement w/ 17 events (2020).

  BR=(11.0+4.0−3.5±0.3)×10−11

Aim for a 10% measurement

B decays: $B^0 \to K^* \mu\mu$

$B^0 \to K^* \mu\mu$ is the “golden mode” to test the (axial)vector couplings C_9 and C_{10} in b$\to$sll transitions

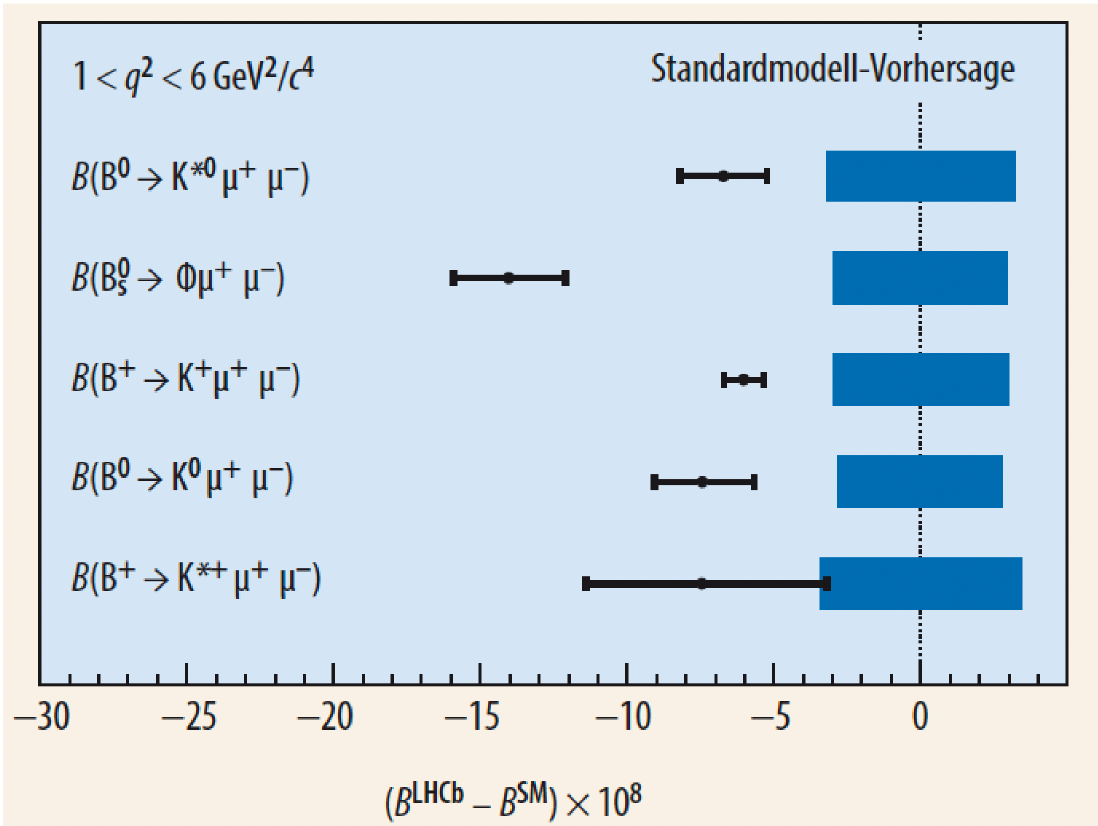


$$q^2 = m^2_{\mu\mu}$$

Observables:

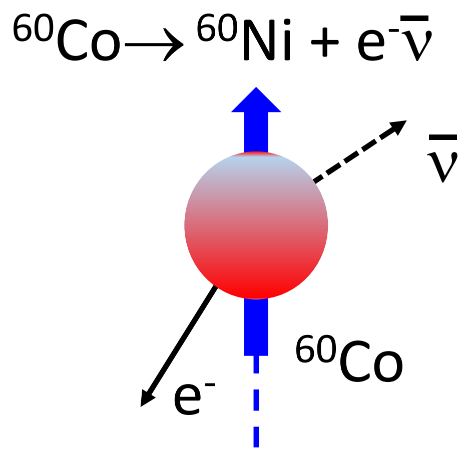
- absolute rate / differential decay rates (as function of q^2 : theoretical uncertainties are large compared to $B_s \to \mu\mu$
- Angular distributions of the final state particles: provide information on the Lorentz-structure of the effective couplings. ”Wu experiment” for B mesons.

Branching fractions for b → s ll modes: $1 < q^2 < 6\ \mathrm{GeV}^2$

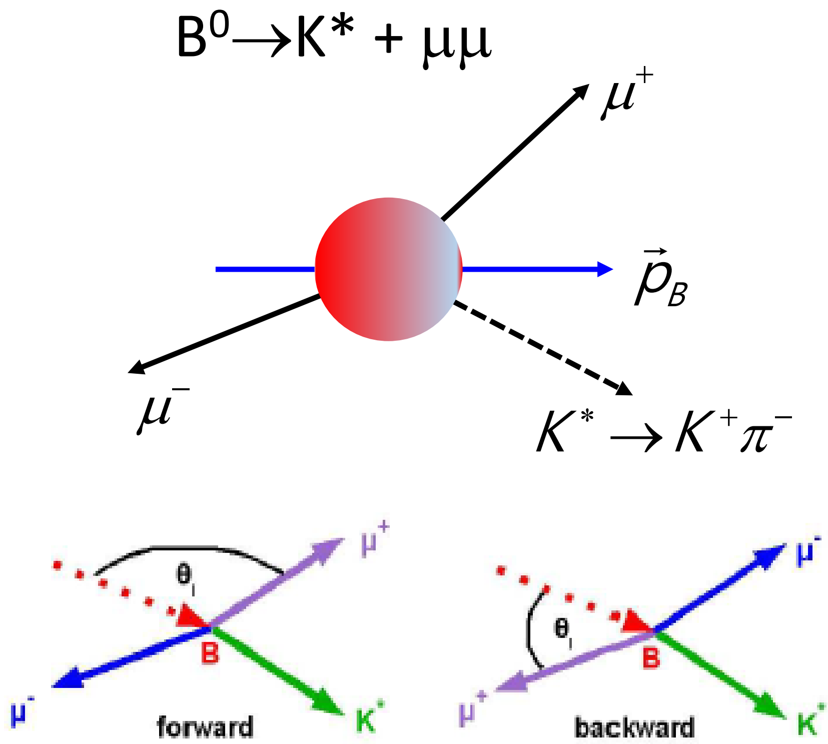


For all tested modes the measured branching fractions are above the Standard Model prediction: problems in the theoretical description or new physics?

Wu-Experiment with B-mesons: angular distribution of $B^0 \to K^* \mu\mu$, $K^* \to K^+\pi^-$



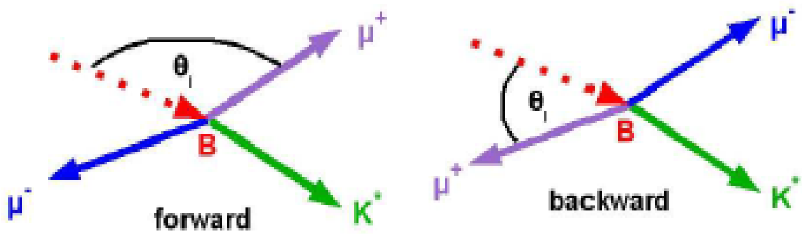
"Wu-experiment" to test
Lorentz structure of β-decay:
V-A



For B-meson (pseudo-scalar, no spin):
reference axis is the flight direction of the B.

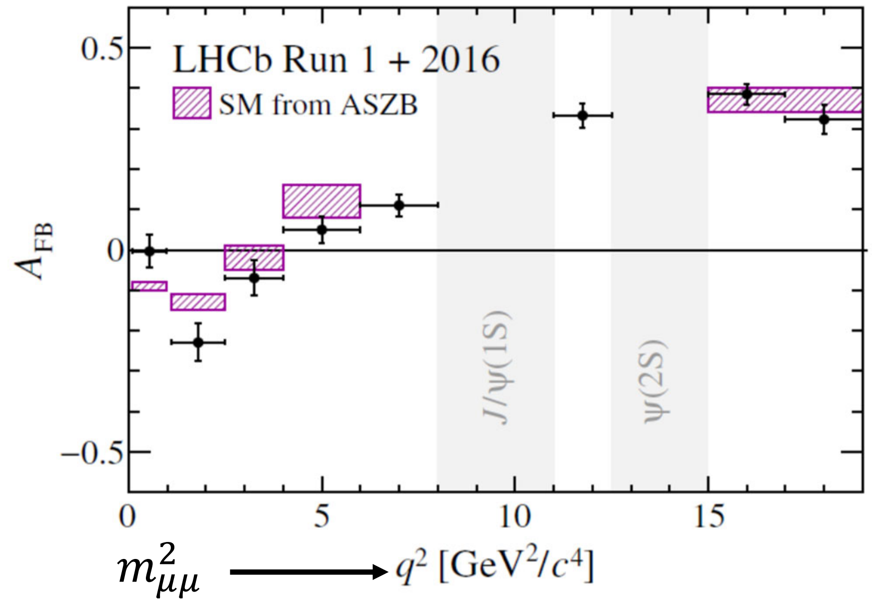
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

Forward-backward asymmetry:



$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

Phys. Rev. Lett. 125, 011802 (2020)

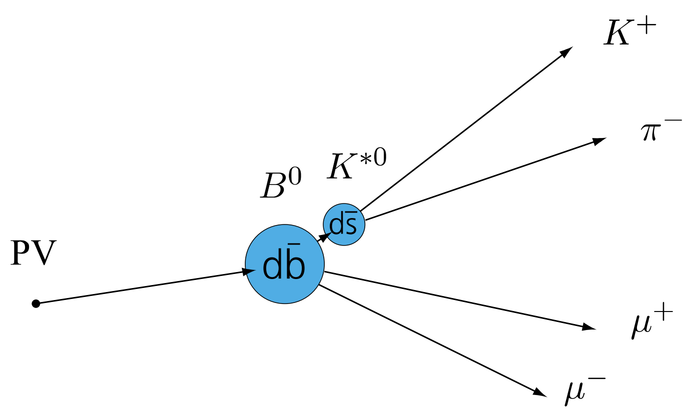


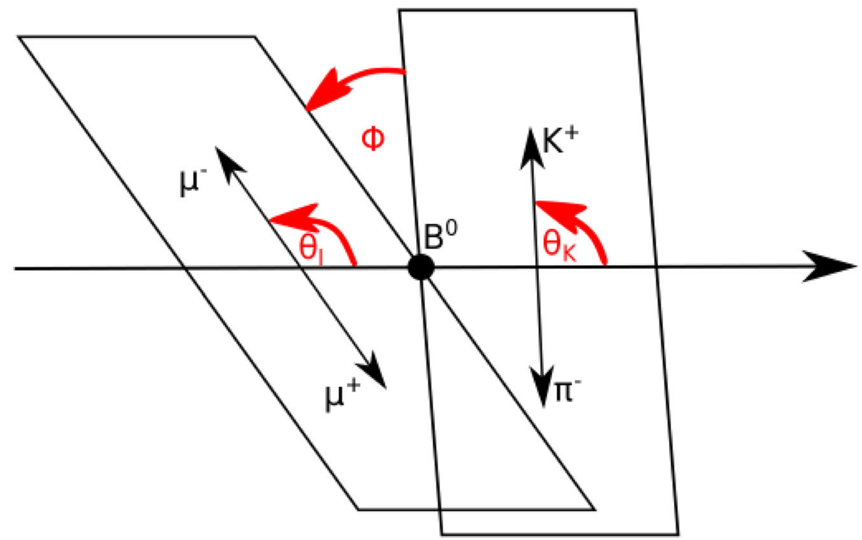
Some tension with theory prediction

More angular observables for $B^0 \to K^* \mu\mu$:

The forward backward asymmetry is only one possible angular variable. The decay topology allows to study more observables.

Topology





Decay can be fully described by 3 angles: θ_l, θ_K, Φ

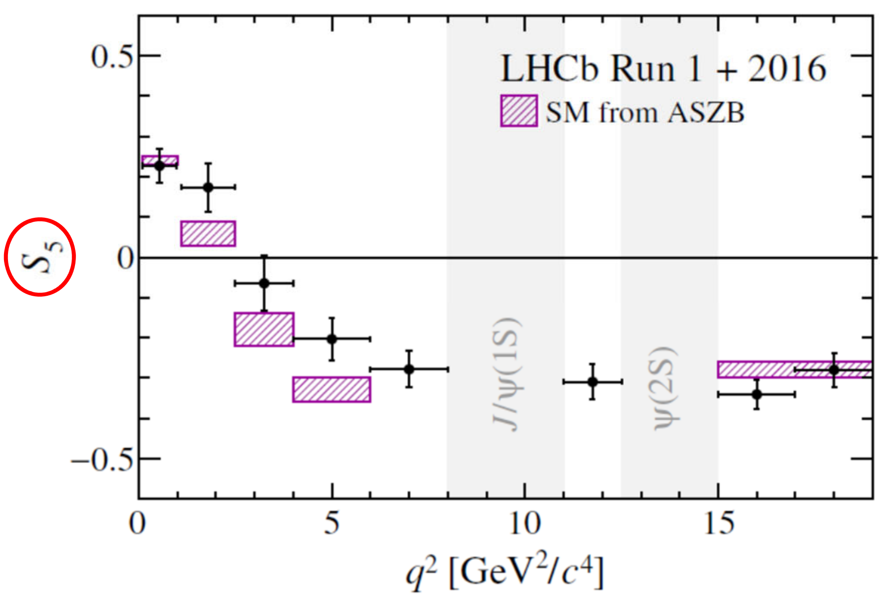
Differential decay rate (expressed in the 3 angles): *Phys. Rev. Lett. 125, 011802 (2020)*

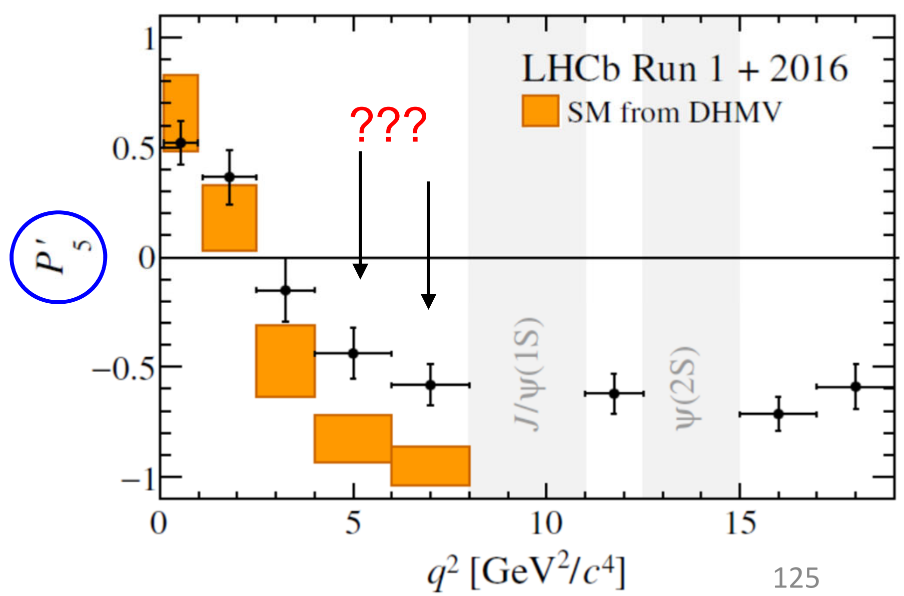
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

F_L is the longuitudinal polarization of the K*

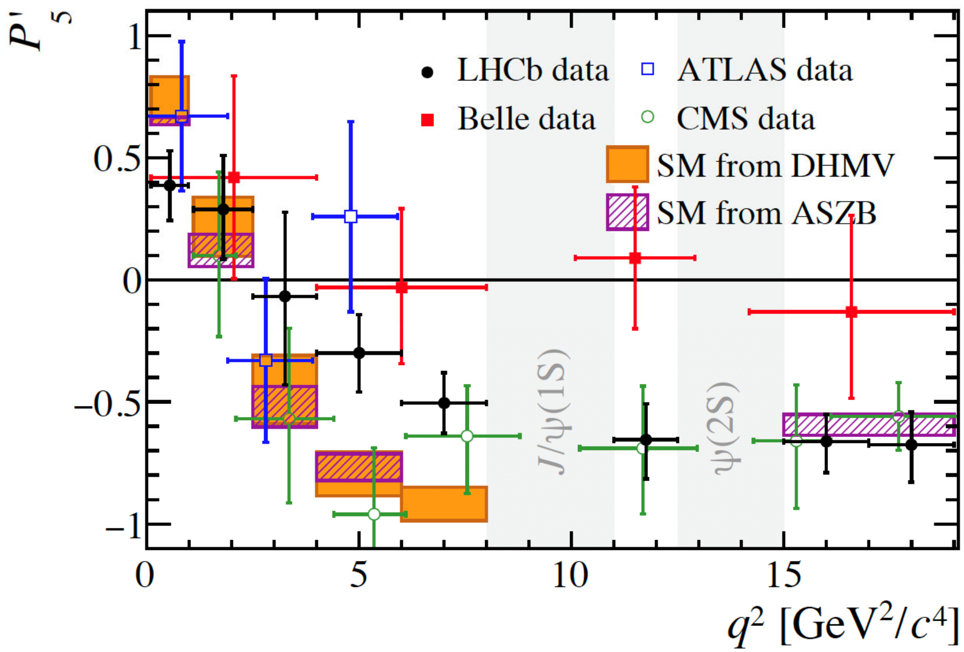
$$\boxed{P_5' = S_5/\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$$

is theoretically more robust





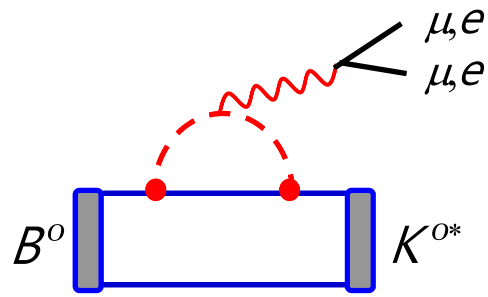
There is an interesting tension which even stays if data from other experiments are added:



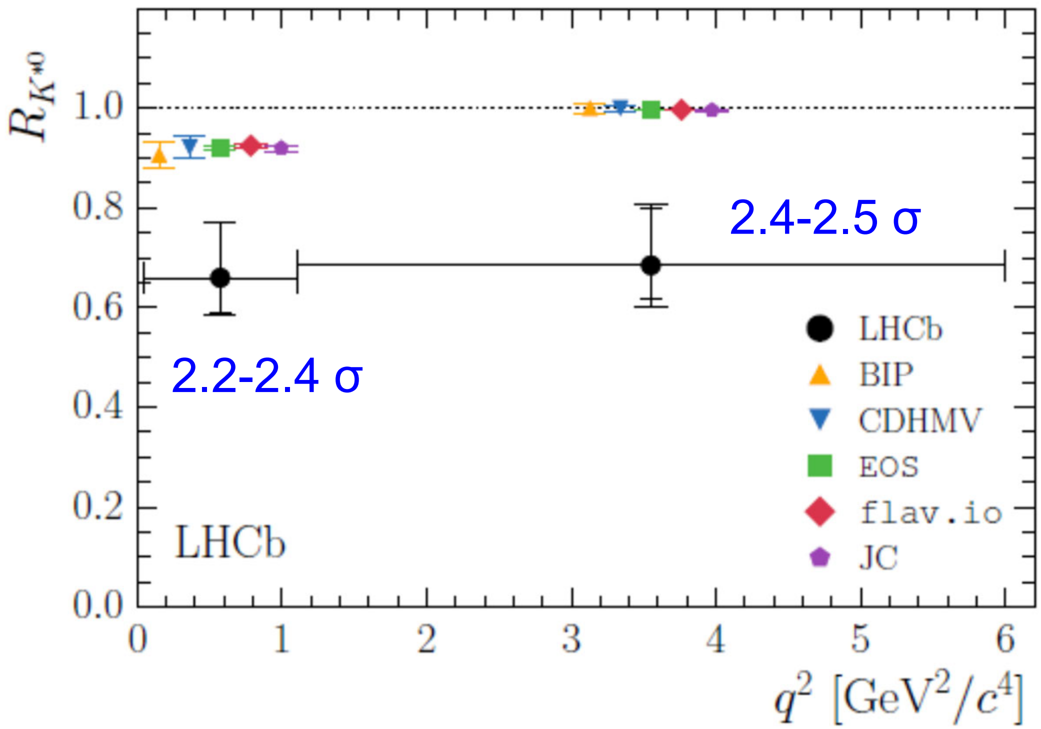
The P'_5 tension has caused a lot of scientific discussions: additional untreated QCD corrections (cc-loop) or really New Physics?

Another interesting tension in $B^0 \to K^* \ell\ell$ events: *JHEP 08 (2017) 055]*

$$R_{K*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu\mu)}{\mathcal{B}(B^0 \to K^{*0}ee)}$$



lepton-universality: $R_{K*} \approx 1$



Unexpected!

Lepton universality violated in b→sll transitions?

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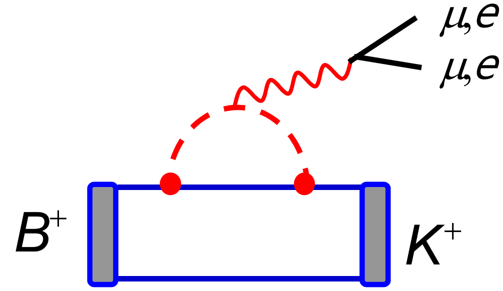
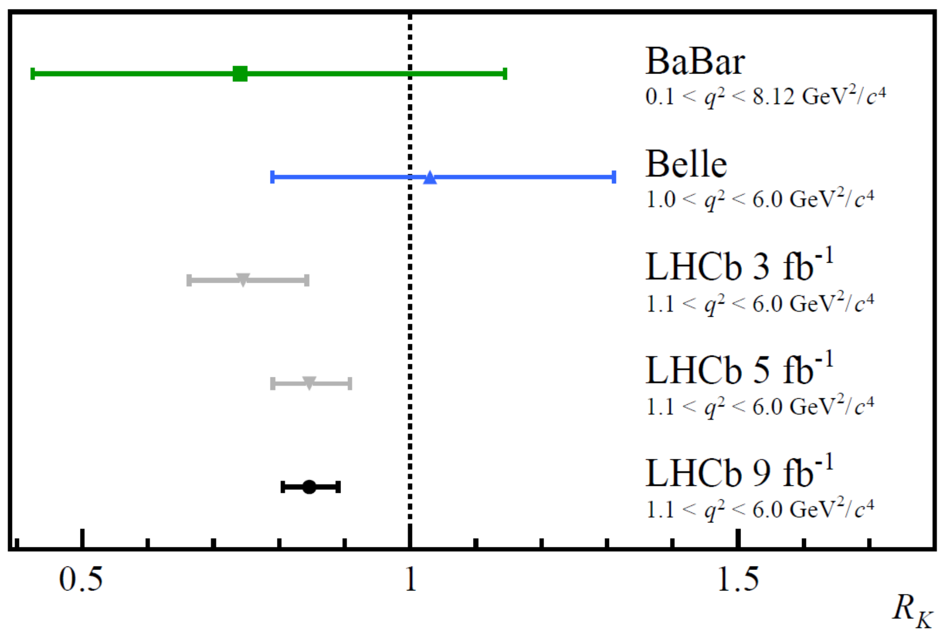
What about the charged counter part: $B^+ \to K^+ \ell\ell$

$$R_K = \frac{\mathrm{B}(B^+ \to K^+ \mu\mu)}{\mathrm{B}(B^+ \to K^+ ee)}$$



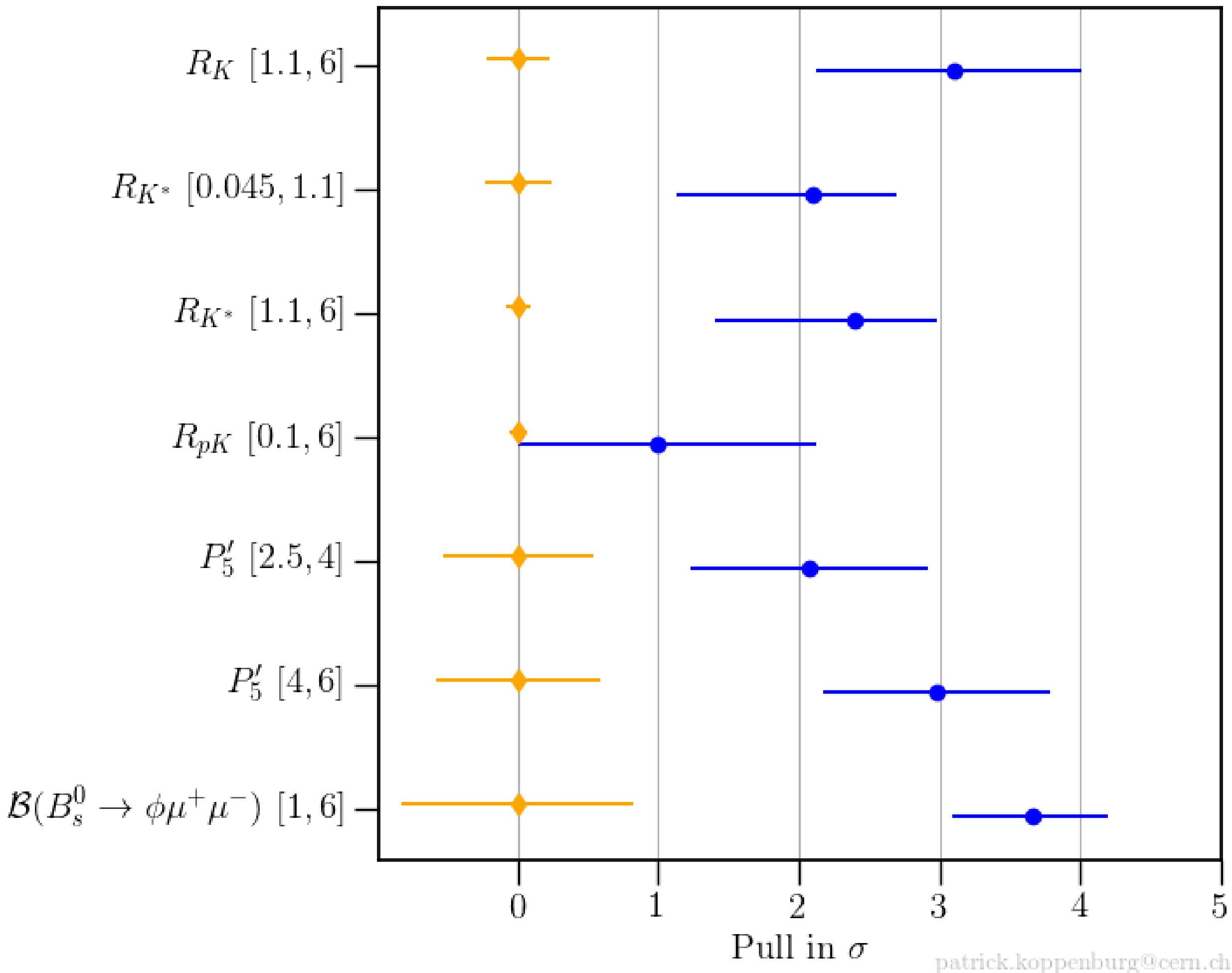
lepton-universality: $R_{K*} \approx 1$



arXiv:2103.11769

Is the lepton (muon/electron) universality violated in b→sll transition?

Summary of the deviations from Standard Modell in b→s ll transitions:



Statistical fluctuation seems an unlikely explaination! New Physics??

The recent measurements of b→sll transitions deviate from the theoretical predictions: b→sμμ transitions show larger deviations from theory, of b→see are consistent with theory.

A global fit to the data has been performed to determine the Wilson coefficients for the muons and to compare them with the Standard Modell.

Reminder:

$$\mathcal{L} \sim \sum_i \left(C_i^{SM} + C_i^{NP} \right) O_i$$

i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

⇩

Global fit: Wilson coefficient C_9 for μμ is not consistent with the SM but needs a sizeable correction C^{NP}_9.

An exciting Standard Model tension!

arxiv:1709.10308