Anomalies in Flavour Physics

Marcin Chrząszcz
mchrzasz@cern.ch

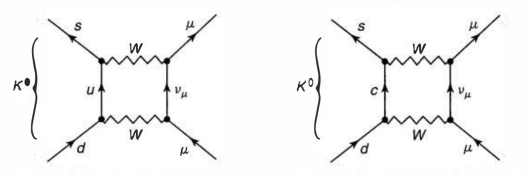
University of Zurich[UZH]

Imperial College
October 16, 2015

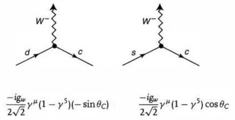
Outline

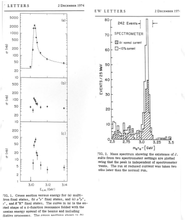
1. History of Flavour Physics discoveries.
2.
3.

A lesson from history - GIM mechanism

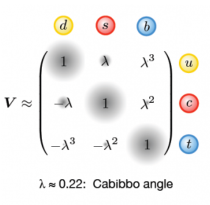


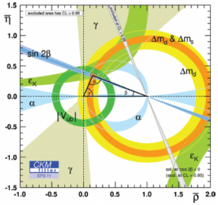
- Cabibbo angle was successful at explaining dozens of decay rates in the 1960s.
- There was one how ever that was not observed by experiments: $K^0 \to \mu^- \mu^+$.
- Glashow, Iliopoulos, Maiani (GIM) mechanism was proposed in the 1970 to fix this problem. The mechanism required the existence of the 4^{th} quark.
- At that point most of the people were skeptic about that. Fortunately in 1974 the discovery of the J/ψ meson silenced the skeptics.



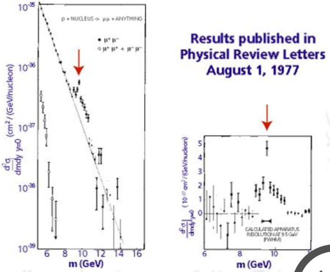


A lesson from history - CKM matrix

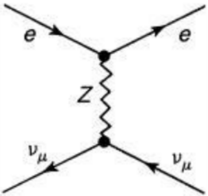


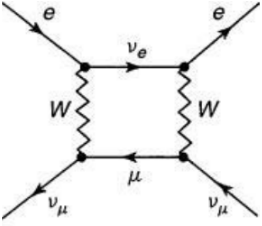


- Similarly CP violation was discovered in 1960s in the neutral kaons decays.
- 2×2 Cabbibo matrix could not allow for any CP violation.
- For the CP violation to be possible one needs atleast 3×3 unitary matrix $\looparrowright$ Cabibbo-Kobayashi-Maskawa matrix (1973).
- It predicts existence of b (1977) and t (1995) quarks.

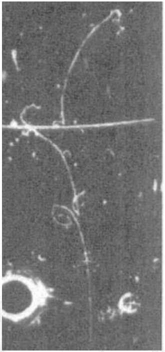


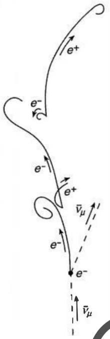
A lesson from history - Weak neutral current





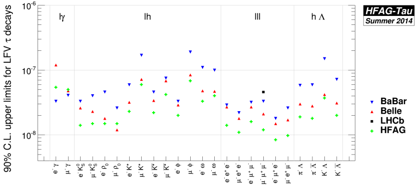
- First the weak neutral currents were introduced in 1958 by Buldman.
- Later on they were naturally build in unification of weak and electromagnetic interactions.
- ’t Hooft proved that the GWS models was renormalizable.
- Everything was there in theory side, only missing piece was the experiment, till 1973.

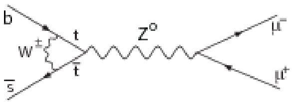


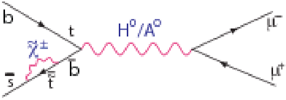


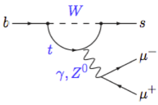
Modern challenges: loops come in to the game

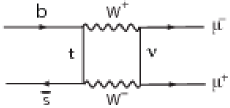
- Standard Model contributions suppressed or absent:
  - Flavour Changing Neutral Currents.
  - CP violation
  - Lepton Flavour/Number or Lepton Universality violation.
- In general can probe physics beyond GPD reach.

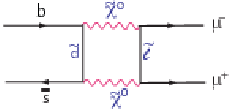


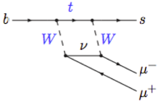












Recent measurements

⇛ Branching fractions:

$B^{0,\pm} \rightarrow K^{0,\pm}\mu^-\mu^+$	LHCb, Mar 14
$B^0 \rightarrow K^*\mu^-\mu^+$	CMS, Jul 15
$B_s^0 \rightarrow \phi\mu^-\mu^+$	LHCb, Jun 15
$B^\pm \rightarrow \pi^\pm\mu^-\mu^+$	LHCb, Sep 15
$\Lambda_b \rightarrow \Lambda\mu^-\mu^+$	LHCb, Mar 15
$B \rightarrow \mu^-\mu^+$	CMS+LHCb, Jun 15

⇛ CP asymmetry:

$B^\pm \rightarrow \pi^\pm\mu^-\mu^+$	LHCb, Sep 15

⇛ Isospin asymmetry:

$B \rightarrow K\mu^-\mu^+$	LHCb, Mar 14

⇛ Lepton Universality:

$B^\pm \rightarrow K^\pm\ell\bar{\ell}$	LHCb, Jun 14

⇛ Angular:

$B^0 \rightarrow K^*\ell\bar{\ell}$	LHCb, Jan 15
$B^\pm \rightarrow K^{*,\pm}\ell\bar{\ell}$	BaBar, Aug 15
$B_s^0 \rightarrow \phi\ell\bar{\ell}$	LHCb, Jun 15
$\Lambda_b \rightarrow \Lambda\mu^-\mu^+$	LHCb, Mar 15

Recent measurements

⇛ Branching fractions:

$B^{0,\pm} \to K^{0,\pm}\mu^-\mu^+$ LHCb, Mar 14

$B^0 \to K^*\mu^-\mu^+$ CMS, Jul 15

$B_s^0 \to \phi\mu^-\mu^+$ LHCb, Jun 15

$B^\pm \to \pi^\pm\mu^-\mu^+$ LHCb, Sep 15

$\Lambda_b \to \Lambda\mu^-\mu^+$ LHCb, Mar 15

$B \to \mu^-\mu^+$ CMS+LHCb, Jun 15

⇛ CP asymmetry:

$B^\pm \to \pi^\pm\mu^-\mu^+$ LHCb, Sep 15

⇛ Isospin asymmetry:

$B \to K\mu^-\mu^+$ LHCb, Mar 14

⇛ Lepton Universality:

$B^\pm \to K^\pm\ell\bar{\ell}$ LHCb, Jun 14

⇛ Angular:

$B^0 \to K^*\ell\bar{\ell}$ LHCb, Jan 15

$B^\pm \to K^{*,\pm}\ell\bar{\ell}$ BaBar, Aug 15

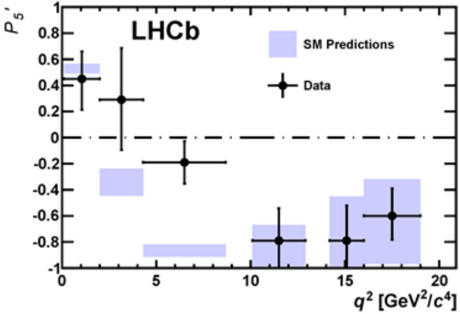
$B_s^0 \to \phi\ell\bar{\ell}$ LHCb, Jun 15

$\Lambda_b \to \Lambda\mu^-\mu^+$ LHCb, Mar 15

$> 2\ \sigma$ deviations from SM

$B^0 \to K^*\mu^-\mu^+$, where it all begun

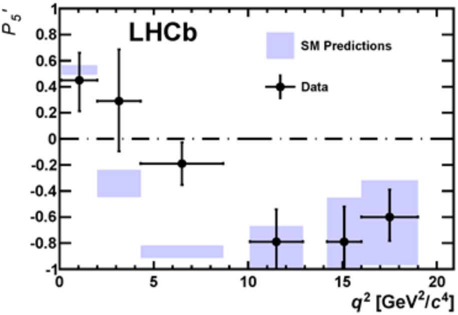
August 2013:



- LHCb observed a deviation in $4.3 - 8.68\ \mathrm{GeV}^2$ using $1\ \mathrm{fb}^{-1}$ of data.
- It turned out that the discrepancy occurred in an observable that was not constrained.

$B^0 \to K^* \mu^- \mu^+$, where it all begun

August 2013:



- LHCb observed a deviation in $4.3 - 8.68\ \mathrm{GeV}^2$ using $1\ \mathrm{fb}^{-1}$ of data.
- It turned out that the discrepancy occurred in an observable that was not constrained.

Now let's move back and see the theory behind the $B^0 \to K^* \mu^- \mu^+$ and P_5'.

Tools in rare B^0 decays

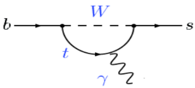
- **Operator Product Expansion and Effective Field Theory**

$$H_{eff} = -\frac{4G_f}{\sqrt{2}} VV'^{*} \sum_i \Bigg[\underbrace{C_i(\mu)O_i(\mu)}_{\text{left-handed}} + \underbrace{C'_i(\mu)O'_i(\mu)}_{\text{right-handed}} \Bigg],$$

i=1,2	Tree
i=3-6,8	Gluon penguin
i=7	Photon penguin
i=9.10	EW penguin
i=S	Scalar penguin
i=P	Pseudoscalar penguin

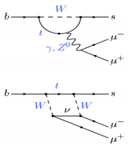
where C_i are the Wilson coefficients and O_i are the corresponding effective operators.

$b \to s\gamma$



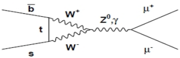
$C_7^{(\prime)}$

$b \to s\ell^+\ell^-$



$C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

$B^0_{(s)} \to \mu^+\mu^-$



$C_S^{(\prime)}, C_P^{(\prime)}, C_{10}^{(\prime)}$

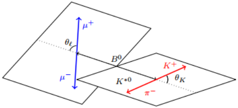
$B^0 \to K^{*}\mu^{-}\mu^{+}$ kinematics

⇛ The kinematics of $B^0 \to K^{*}\mu^{-}\mu^{+}$ decays is described in three angles θ_l, θ_k, ϕ and invariant mass of the dimuon system (q^2).

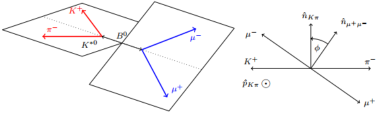
⇛ $\cos\theta_k$: the angle between the direction of the kaon in the K^{*} ($\overline{K^{*}}$) rest frame and the direction of the K^{*} ($\overline{K^{*}}$) in the B^0 ($\overline{B}^0$) rest frame.

⇛ $\cos\theta_l$: the angle between the direction of the μ^{-} (μ^{+}) in the dimuon rest frame and the direction of the dimuon in the B^0 ($\overline{B}^0$) rest frame.

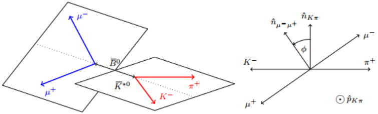
⇛ ϕ: the angle between the plane containing the μ^{-} and μ^{+} and the plane containing the kaon and pion from the K^{*}.



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



(c) ϕ definition for the $\overline{B}^0$ decay

$B^0 \to K^* \mu^- \mu^+$ kinematics

$\Rrightarrow$ The kinematics of $B^0 \to K^* \mu^- \mu^+$ decays is described in three angles θ_l, θ_k, ϕ and invariant mass of the dimuon system (q^2).

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$
$$+J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big], \tag{1}$$

$\Rrightarrow$ This is the most general expression of this kind of decays.

Transversity amplitudes

⇛ One can link the angular observables to transversity amplitudes

$$
\begin{aligned}
J_{1s} &= \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2+|A_\parallel^L|^2+|A_\perp^R|^2+|A_\parallel^R|^2\right]+\frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R*}+A_\parallel^L A_\parallel^{R*}\right),\\
J_{1c} &= |A_0^L|^2+|A_0^R|^2+\frac{4m_\ell^2}{q^2}\left[|A_t|^2+2\mathrm{Re}(A_0^L A_0^{R*})\right]+\beta_\ell^2\,|A_S|^2,\\
J_{2s} &= \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2+|A_\parallel^L|^2+|A_\perp^R|^2+|A_\parallel^R|^2\right], \qquad J_{2c}=-\beta_\ell^2\left[|A_0^L|^2+|A_0^R|^2\right],\\
J_3 &= \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2-|A_\parallel^L|^2+|A_\perp^R|^2-|A_\parallel^R|^2\right], \qquad J_4=\frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Re}(A_0^L A_\parallel^{L*}+A_0^R A_\parallel^{R*})\right],\\
J_5 &= \sqrt{2}\beta_\ell\left[\mathrm{Re}(A_0^L A_\perp^{L*}-A_0^R A_\perp^{R*})-\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^*+A_\parallel^{R*}A_S)\right],\\
J_{6s} &= 2\beta_\ell\left[\mathrm{Re}(A_\parallel^L A_\perp^{L*}-A_\parallel^R A_\perp^{R*})\right], \qquad J_{6c}=4\beta_\ell\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_0^L A_S^*+A_0^{R*}A_S),\\
J_7 &= \sqrt{2}\beta_\ell\left[\mathrm{Im}(\mathrm{A}_0^\mathrm{L}\mathrm{A}_\parallel^{\mathrm{L}*}-\mathrm{A}_0^\mathrm{R}\mathrm{A}_\parallel^{\mathrm{R}*})+\frac{\mathrm{m}_\ell}{\sqrt{\mathrm{q}^2}}\mathrm{Im}(\mathrm{A}_\perp^\mathrm{L}\mathrm{A}_\mathrm{S}^*-\mathrm{A}_\perp^{\mathrm{R}*}\mathrm{A}_\mathrm{S}))\right],\\
J_8 &= \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(\mathrm{A}_0^\mathrm{L}\mathrm{A}_\perp^{\mathrm{L}*}+\mathrm{A}_0^\mathrm{R}\mathrm{A}_\perp^{\mathrm{R}*})\right], \qquad J_9=\beta_\ell^2\left[\mathrm{Im}(\mathrm{A}_\parallel^{\mathrm{L}*}\mathrm{A}_\perp^\mathrm{L}+\mathrm{A}_\parallel^{\mathrm{R}*}\mathrm{A}_\perp^\mathrm{R})\right], \qquad (2)
\end{aligned}
$$

Link to effective operators

$\Rrightarrow$ So here is where the magic happens. At leading order the amplitudes can be written as:

$$\begin{aligned} A_{\perp}^{L,R} &= \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} + \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} + \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\perp}(E_{K^*}) \\ A_{\parallel}^{L,R} &= -\sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\perp}(E_{K^*}) \\ A_{0}^{L,R} &= -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + 2\hat{m}_b (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\parallel}(E_{K^*}), \qquad (3) \end{aligned}$$

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

Link to effective operators

⇛ So here is where the magic happens. At leading order the amplitudes can be written as:

$$
\begin{aligned}
A_{\perp}^{L,R} &= \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\rm eff} + \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\rm eff} + \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\perp}(E_{K^*}) \\
A_{\parallel}^{L,R} &= -\sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\perp}(E_{K^*}) \\
A_{0}^{L,R} &= -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + 2\hat{m}_b (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\parallel}(E_{K^*}), \qquad (3)
\end{aligned}
$$

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

⇛ Now we can construct observables that cancel the ξ form factors at leading order:

$$
P_5^{\prime} = \frac{J_5 + \bar{J}_5}{2\sqrt{-(J_2^c + \bar{J}_2^c)(J_2^s + \bar{J}_2^s)}} \qquad (4)
$$

LHCb update of the $B^0 \to K^* \mu^- \mu^+$

Backup