Electroweak penguin decays to leptons and Radiative decays at LHCb

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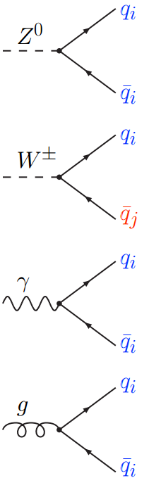
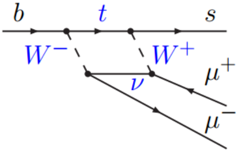
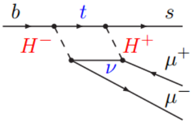
1. Rare B decays:
   - $B^+ \to K^+\pi^-\pi^+\gamma$
   - $B_s^0/B^0 \to \mu^-\mu^+$.
   - $B^0 \to K^*\mu^-\mu^+$.

Why rare decays?

- In SM allows only the charged interactions to change flavour.
  - Other interactions are flavour conserving.
- One can escape this constrain and produce $b \to s$ and $b \to d$ at loop level.
  - This kind of processes are suppressed in SM $\to$ Rare decays.
  - New Physics can enter in the loops.







Tools

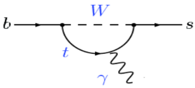
- **Operator Product Expansion and Effective Field Theory**

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

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 pen

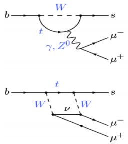
where C_i are the Wilson coefficients and O_i are the corresponding effective operators.

$b \to s\gamma$



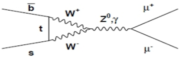
$C_7^{(\prime)}$

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



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

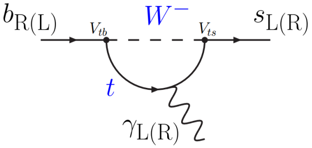
$B^0_{(s)} \to \mu^+\mu^-$



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

Radiative decays

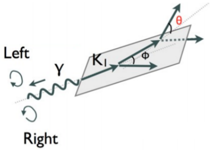
- $B^0 \to K^*\gamma$ - first observed penguin!
  - CLEO, [PRL, 71 (1993) 674]
- B-factories probed NP measuring, inclusively/ semi-inclusively $\mathcal{B}(b \to s\gamma)$
- Is there any way LHCb can contribute?
  - Measurements of $\mathcal{B}(b \to s\gamma)$ very difficult.
  - Can probe the photon polarization!

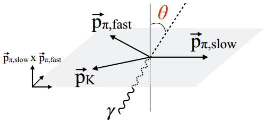


- In SM, photons form $b \to s\gamma$ decays are left handed.
  - Charged current interactions: $C_7/C_7' \sim m_b/m_s$
- Can test C_7/C_7' using:
  - Mixing induced CP violation: Atwood et. al. PRL 79 (1997) 185-188
  - Λ_b baryons: Hiller & kagan PRD 65 (2002) 074038

Photon polarization from $B^+ \to K^+\pi^-\pi^+\gamma$

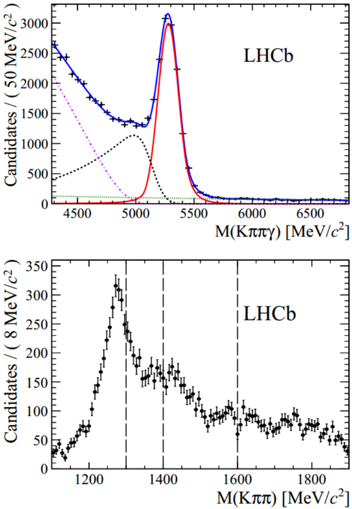
- OR: Study $B \to K^{**}\gamma$ decays like $B^+ \to K_1(1270)\gamma$
  - Gronau & Pirjol PRD 66 (2002) 054008
- The trick is to get the photon polarization from the up-down asymmetry of photon direction in the $K\pi\pi$ rest frame.
  - No asymmetry $\to$ Unpolarised photons.
- Conceptionally this measurement is similar to the Wu experiment, which first observed parity violation.



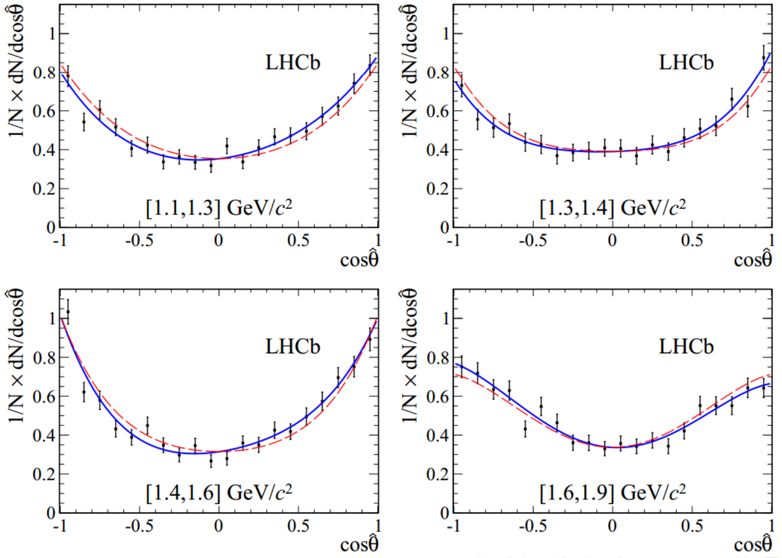


$B^+ \to K^+\pi^-\pi^+\gamma$ at LHCb

- LHCb looked at $B^+ \to K^+\pi^-\pi^+\gamma$, using un-converted photons.
- Got over 13.000 candidates in $3\ fb^{-1}$!
- Phys. Rev. Lett. 112, 161801
- $K^+\pi^-\pi^+$ system has variety of resonances.
  - $K\pi\pi$ system studied inclusively.
  - Bin the $m_{K\pi\pi}$ mass and look for polarization there.

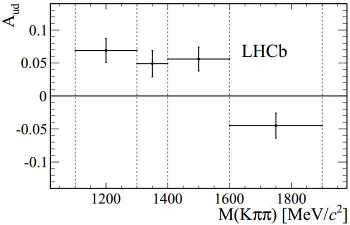


Fit with $(C_7' - C_7)/(C_7' + C_7) = 0$, Best fit



Up-down asymmetry

- Combining the 4 bins, the hypothesis of non photon polarisation can be excluded with $5.2\ \sigma$ significance.
- Unfortunately without understanding the hadron system it is impossible to tell if the photon is left or right -handed.

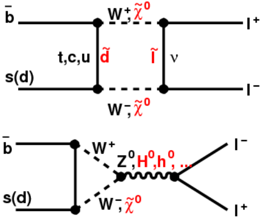


$\longrightarrow$ First observation of photon polarization in $b \rightarrow s\gamma$!

- Ideal solution would be to leave photon polarization free in the fit.
- No general description exist $\rightarrow$ input from theory community needed.

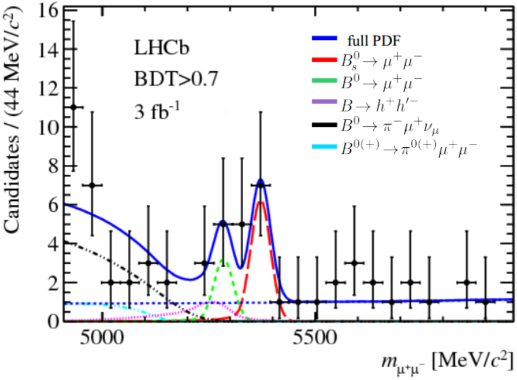
$B_{(s)} \to \mu^+\mu^-$

- Clean theoretical prediction, GIM and helicity suppressed in the SM:
  - $\mathcal{B}(B_s^0 \to \mu^-\mu^+) = (3.66 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu^-\mu^+) = (1.06 \pm 0.09) \times 10^{-10}$
- 50% of the error comes from lattice.
- SM predictions from Phys. Rev. Lett. 112, 101801 (2014).
- Sensitive to contributions from scalar and pesudoscalar couplings.
- Probing: MSSM, higgs sector, etc.
- In MSSM: $\mathcal{B}(B_s^0 \to \mu^-\mu^+) \sim \mathrm{tg}^6\,\beta/m_A^4$



$B_{(s)} \to \mu^+\mu^-$ Results

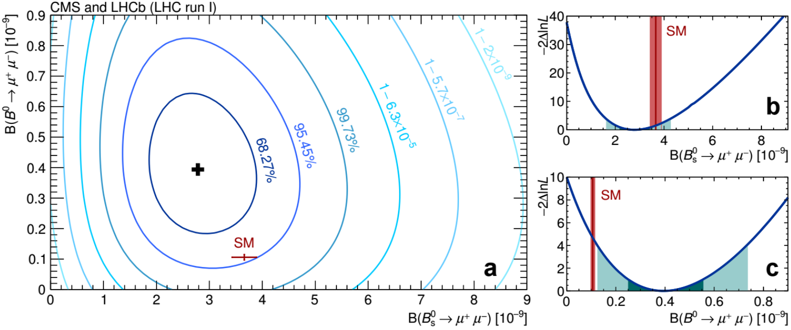
- Nov. 2012:
  - First evidence 3.5σ for $B_s \to \mu^+\mu^-$. with $2.1\ fb^{-1}$.
- Summer 2013:
  - Full data sample: $3\ fb^{-1}$.



- Measured BF:
  $\mathcal{B}(B_s^0 \to \mu^-\mu^+) = (2.9^{+1.1}_{-1.0}(stat.)^{+0.3}_{-0.1}(syst.)) \times 10^{-9}$
- 4.0σ significance!
- $\mathcal{B}(B^0 \to \mu^-\mu^+) < 7 \times 10^{-10}$ at 95% CL
- PRL 110 (2013) 021801
- CMS result: PRL 111 (2013) 101805

LHCb+CMS combined analysis

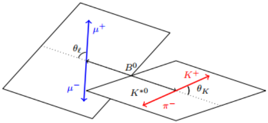
$$\mathcal{B}(B_s^0 \to \mu^-\mu^+) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^-\mu^+) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$



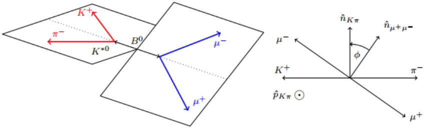
- Nature 522, 7554

$B^0 \to K^*\mu\mu$ angular distributions

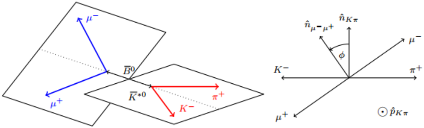
- $b \to s\ell\ell$ decays poses large spectrum of observables.
- LHCb favourite: $B^0 \to K^*\mu^-\mu^+$.
- Sensitive to lot of new physics models.
- Decay described by three angles θ_l, θ_K, ϕ and dimuon invariant mass q^2.
- Analysis is performed in bins of q^2.



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

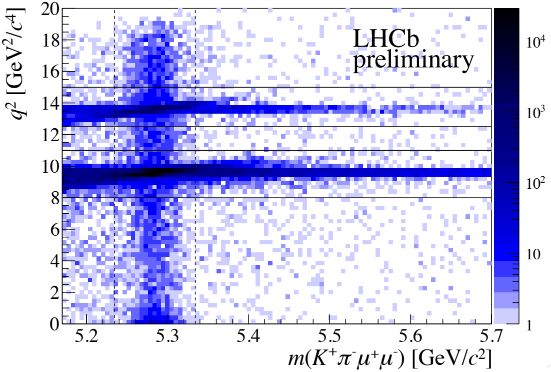


(b) ϕ definition for the B^0 decay



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

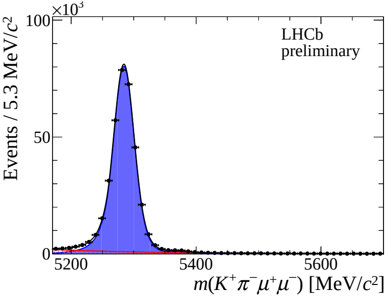
$B^0 \to K^*\mu\mu$ selection



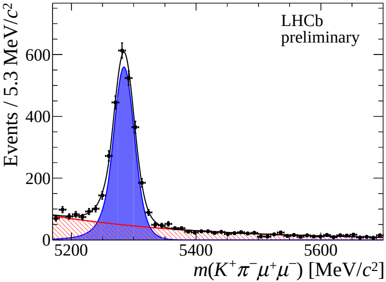
- BDT to suppress combinatorial background.
  Input variables: PID, kinematics and geometric quantities, isolations.
- Veto the J/ψ and $\Psi(2S)$ resonances.
- CONF-2015-002

$B^0 \to K^*\mu\mu$ mass modeling

Control Channel: $B^0 \to J/\psi K^*$



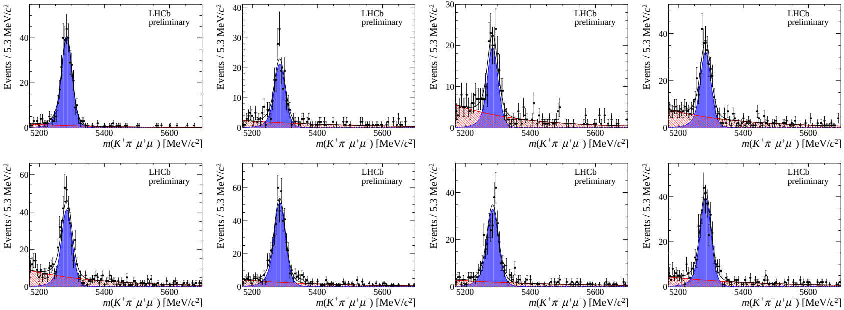
Signal Channel: $B^0 \to \mu^-\mu^+K^*$



- Signal mass model from high statistics $B^0 \to J/\psi K^*$.
- Correction factor from simulation to account for q^2 dep. resolution.

- Finer q^2 binning allow more flexible usage for theoriets.
- Significant signal yield in all bins!
- Integrated over all bins we have 2398 ± 57 candidates.

$B^0 \to K^*\mu\mu$ mass modeling



- Finer q^2 binning allow more flexible usage for theoriets.
- Significant signal yield in all bins!
- Integrated over all bins we have 2398 ± 57 candidates.

$B^0 \to K^*\mu\mu$ angular distributions

- Angular distributions depends on 11 angular terms:

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

where the S_i are bilinear combinations of helicity amplitudes.

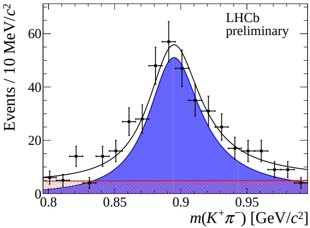
- We assume no scalar and tensor contribution and massless leptons.

S-wave pollution

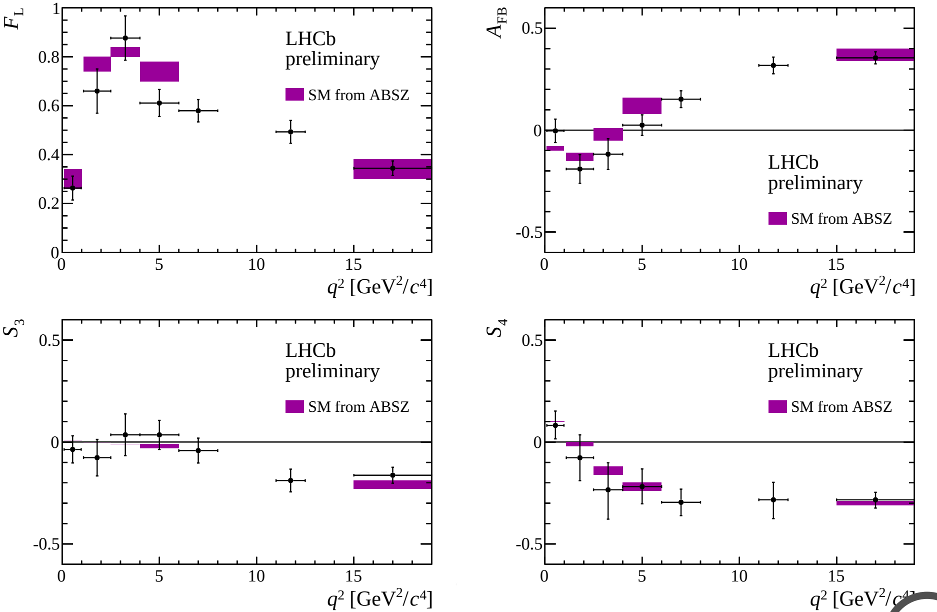
- S-wave: $K^+\pi^-$ in spin 0 configuration
- Introduced by additional two decay amplitudes → six observables.

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_k\,\mathrm{d}\phi}\Bigg|_{\mathrm{S+P}} = (1-F_S)\,\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_k\,\mathrm{d}\phi}\Bigg|_{\mathrm{P}} + \tfrac{3}{16\pi}\left[F_S\sin^2\theta_l + S-P\ \text{interefence}\right].$$

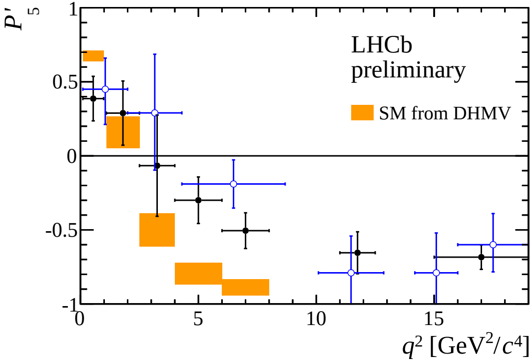
- F_S dilutes the P-wave observables by a factor $1-F_S$.
- Needs to be taken into account → fit the $m_{K\pi}$.
- Rel. BW for P-wave.
- LASS model for S-wave



$B^0 \to K^*\mu\mu$ results



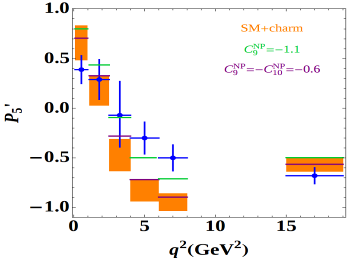
$B^0 \to K^* \mu\mu$ results



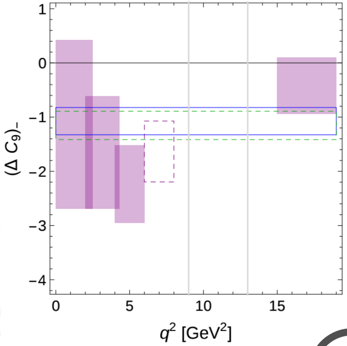
- Tension in P_5' confirmed!
- $[4.0, 6.0]$ and $[6.0, 8.0]$ $\mathrm{GeV^2/c^4}$ show 2.9σ deviation each.
- Naive combination shows 3.7σ discrepancy.
- Result compatible with previous result.

Understanding the $B^0 \to K^* \mu\mu$ anomaly

- Matias, Decotes-Genon & Virto performed a fit to our preliminary result.s
- Found $\sim 4\sigma$ discrepancy from SM.
- Fit favours $C_9^{NP} = -1.1$
- Moriond 2015 slides



- Straub performed the same analysis as Matias et. al.
- Found the same solution: $\to C_9$ modification.
- Data can be explained by introducing a flavour changing Z' boson, with mass $\mathcal{O}(10\ TeV)$
- Moriond 2015 slides

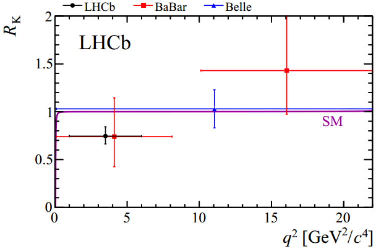


Lepton universality

- If Z' is responsible for the P_5' anomaly, does it couple equally to all flavours?

$$R_{\mathrm{K}} = \frac{\int_{q^2=1\,\mathrm{GeV}^2/c^4}^{q^2=6\,\mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2)\mathrm{d}q^2}{\int_{q^2=1\,\mathrm{GeV}^2/c^4}^{q^2=6\,\mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+e^+e^-]/\mathrm{d}q^2)\mathrm{d}q^2} = 1 \pm \mathcal{O}(10^{-3}) \,.$$

- Challenging analysis due to bremsstrahlung.
- Migration of events modeled by MC.
- Correct bremsstrahlung.
- Take double ratio with $B^+ \to J/\psi K^+$ to cancel systematics.
- In $3 fb^{-1}$, LHCb measures $R_K = 0.745^{+0.090}_{-0.074}(stat.)^{+0.036}_{-0.036}(syst.)$
- Consistent with SM at 2.6σ.

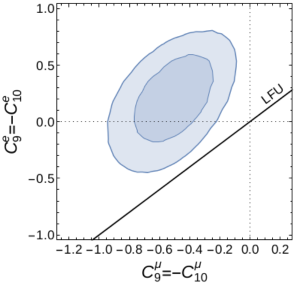


- Phys. Rev. Lett. 113, 151601 (2014)

Lepton universality with $B^0 \to K^* \mu\mu$ anomaly

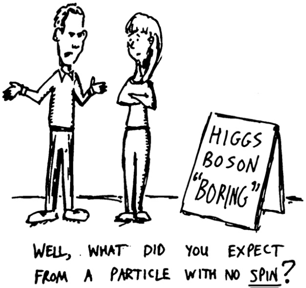
- Lepton flavour universality cannot be explained by any QCD effect!
- This effect is consistent with anomaly (non universal Z')
- Global fit to $b \to s\mu^-\mu^+$ and $b \to se^-e^+$ seems to favour Z' with non lepton universal couplings.

  JHEP (2014) 131



Conclusions

- Rare decays play important role in hutting NP.
- Can access NP scales beyond reach of GPD.
- Tension in $b \to s\ell\ell$, theory correct?
- List of decays presented in this talk is just a tip of iceberg:
  - Please look at ours: isospin, A_{CP}.
  - More results are on their way.
- Many results really on SM prediction, QCD improved calculations would be highly appreciated.



Backup