

# Searches for long-lived particles at LHCb



Marcin Chrzaszcz  
mchrzasz@cern.ch



University of  
Zurich <sup>UZH</sup>

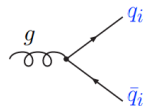
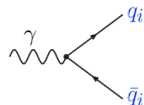
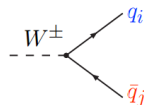
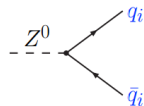
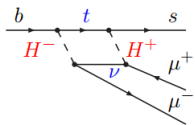
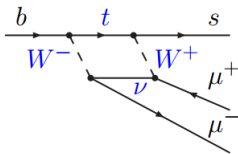
Zurich meeting, CERN  
September 24, 2014

## 1. Rare $B$ decays:

- $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$
- $B_s^0/B^0 \rightarrow \mu^- \mu^+$ .
- $B^0 \rightarrow K^* \mu^- \mu^+$ .

# 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  $b \rightarrow s$  and  $b \rightarrow d$  at loop level.
  - This kind of processes are suppressed in SM  $\rightarrow$  Rare decays.
  - New Physics can enter in the loops.

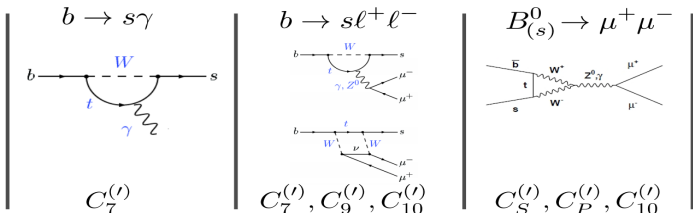


## • Operator Product Expansion and Effective Field Theory

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

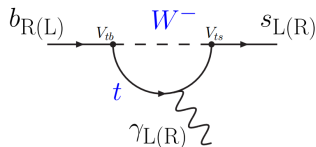
- i=1,2 Tree
- i=3-6,8 Gluon penguin
- i=7 Photon penguin
- i=9,10 EW penguin
- i=S Scalar penguin
- i=P Pseudoscalar pen

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



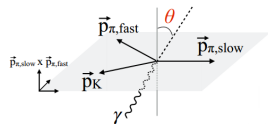
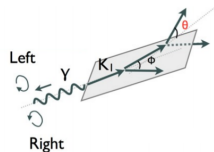
# Radiative decays

- $B^0 \rightarrow K^* \gamma$  - first observed penguin!
  - CLEO, [PRL, 71 (1993) 674]
- B-factories probed NP measuring, inclusively/ semi-inclusively  $\mathcal{B}(b \rightarrow s \gamma)$
- Is there any way LHCb can contribute?
  - Measurements of  $\mathcal{B}(b \rightarrow s \gamma)$  very difficult.
  - Can probe the photon polarization!
- In SM, photons from  $b \rightarrow s \gamma$  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
  - $\Lambda_b$  baryons: Hiller & Kagan PRD 65 (2002) 074038



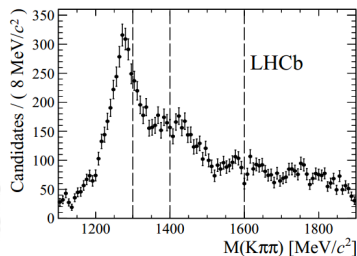
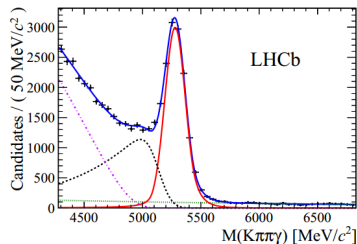
# Photon polarization from $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

- OR: Study  $B \rightarrow K^{**} \gamma$  decays like  $B^+ \rightarrow K_1(1270) \gamma$ 
  - [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  $\rightarrow$  Unpolarised photons.
- Conceptionally this measurement is similar to the Wu experiment, which first observed parity violation.

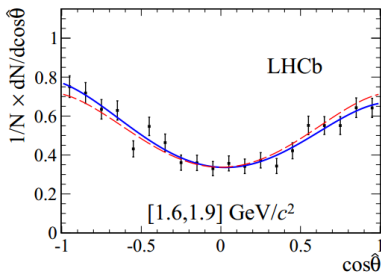
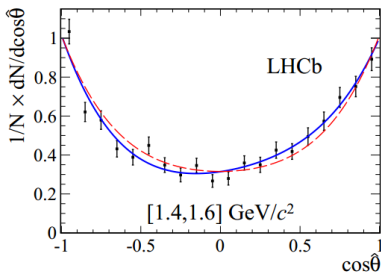
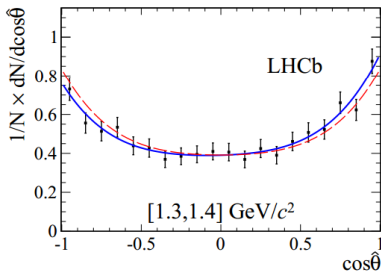
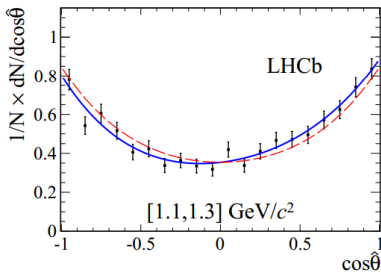


# $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ at LHCb

- LHCb looked at  $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ , using un-converted photons.
- Got over 13.000 candidates in  $3 \text{ fb}^{-1}$ !
- [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.



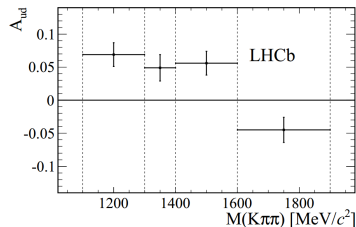
Fit with  $(C_7' - C_7)/(C_7' + C_7) = 0$ , Best fit





# 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.

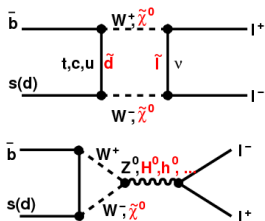


→ First observation of photon polarization in  $b \rightarrow s\gamma$ !

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

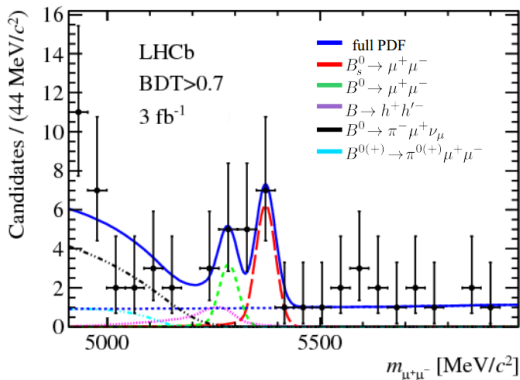
$$B_{(s)} \rightarrow \mu^+ \mu^-$$

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



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

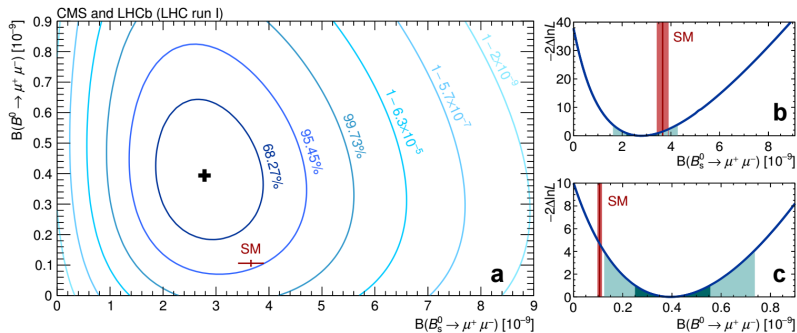
- Nov. 2012:
  - First evidence  $3.5\sigma$  for  $B_s \rightarrow \mu^+ \mu^-$  with  $2.1 fb^{-1}$ .
- Summer 2013:
  - Full data sample:  $3 fb^{-1}$ .



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

# LHCb+CMS combined analysis

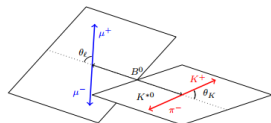
$$\mathcal{B}(B_s^0 \rightarrow \mu^- \mu^+) = (2.8_{-0.6}^{+0.7}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \rightarrow \mu^- \mu^+) = (3.9_{-1.4}^{+1.6}) \times 10^{-10}$$



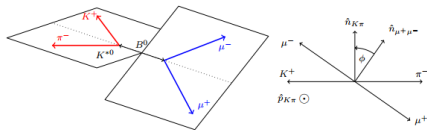
- Nature 522, 7554

# $B^0 \rightarrow K^* \mu \mu$ angular distributions

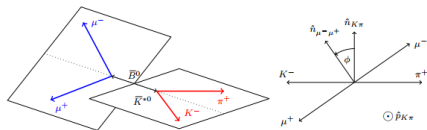
- $b \rightarrow sll$  decays poses large spectrum of observables.
- LHCb favourite:  $B^0 \rightarrow K^* \mu^- \mu^+$ .
- Sensitive to lot of new physics models.
- Decay described by three angles  $\theta_l, \theta_K, \phi$  and dimuon invariant mass  $q^2$ .
- Analysis is performed in bins of  $q^2$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



(a)  $\theta_K$  and  $\theta_l$  definitions for the  $B^0$  decay

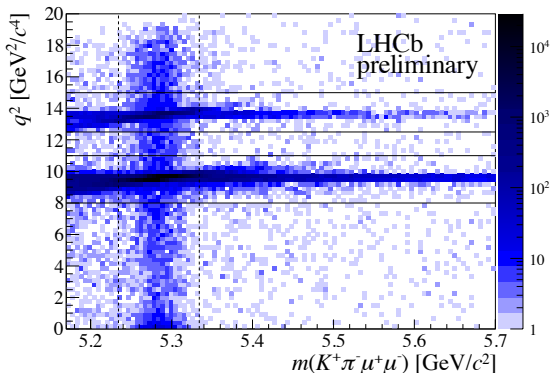


(b)  $\phi$  definition for the  $B^0$  decay



(c)  $\phi$  definition for the  $\bar{B}^0$  decay

# $B^0 \rightarrow K^* \mu\mu$ selection

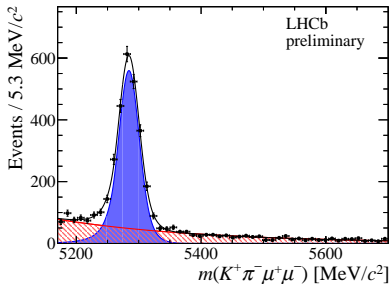
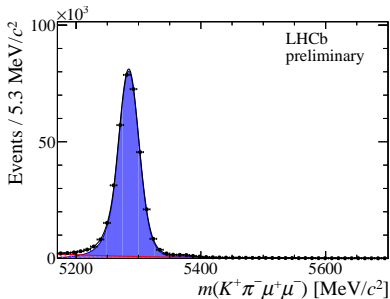


- BDT to suppress combinatorial background.  
Input variables: PID, kinematics and geometric quantities, isolations.
- Veto the  $J/\psi$  and  $\Psi(2S)$  resonances.
- [CONF-2015-002](#)

# $B^0 \rightarrow K^* \mu \mu$ mass modeling

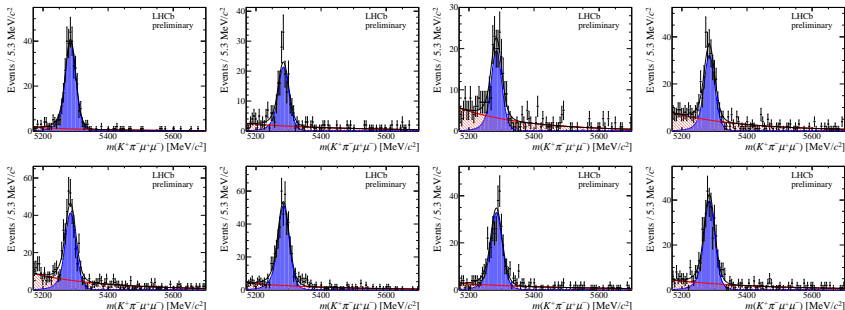
Control Channel:  $B^0 \rightarrow J/\psi K^*$

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



- Signal mass model from high statistics  $B^0 \rightarrow J/\psi K^*$ .
- Correction factor from simulation to account for  $q^2$  dep. resolution.
- Finer  $q^2$  binning allow more flexible usage for theorists.
- Significant signal yield in all bins!
- Integrated over all bins we have  $2398 \pm 57$  candidates.

# $B^0 \rightarrow K^* \mu \mu$ mass modeling



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



# $B^0 \rightarrow K^* \mu \mu$ angular distributions

- Angular distributions depends on 11 angular terms:

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d(\Gamma + \bar{\Gamma})}{d\cos\theta_l d\cos\theta_k d\phi} \Big|_{\mathbf{P}} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_k \right. \\ + F_L \cos^2 \theta_k + \frac{1}{4}(1 - F_L) \sin^2 \theta_k \cos 2\theta_l \\ - F_L \cos^2 \theta_k \cos 2\theta_l + S_3 \sin^2 \theta_k \sin^2 \theta_l \cos 2\phi \\ + S_4 \sin 2\theta_k \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_k \sin \theta_l \cos \phi \\ + \frac{4}{3} A_{FB} \sin^2 \theta_k \cos \theta_l + S_7 \sin 2\theta_k \sin \theta_l \sin \phi \\ \left. + S_8 \sin 2\theta_k \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_k \sin^2 \theta_l \sin 2\phi \right].$$

where the  $S_i$  are bilinear combinations of helicity amplitudes.

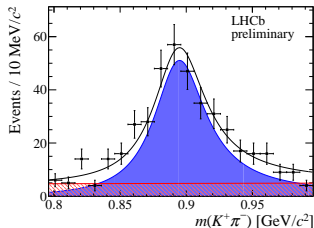
- We assume no scalar and tensor contribution and massless leptons.

# S-wave pollution

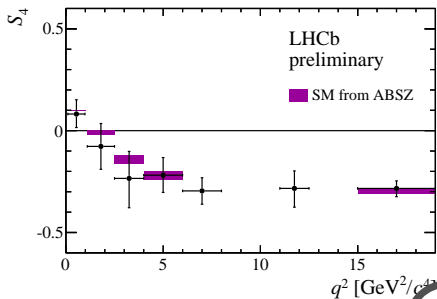
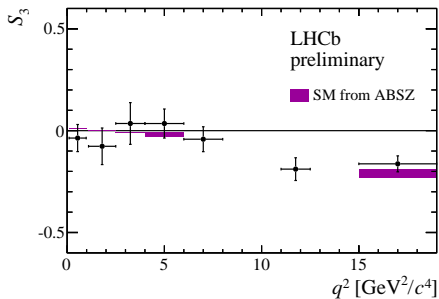
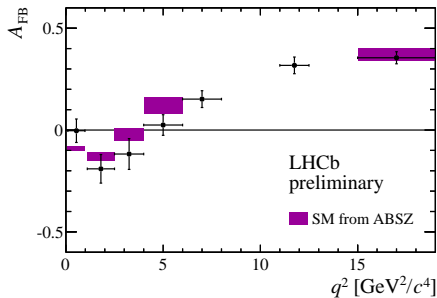
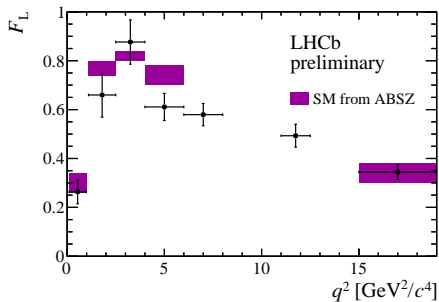
- S-wave:  $K^+\pi^-$  in spin 0 configuration
- Introduced by additional two decay amplitudes  $\rightarrow$  six observables.

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

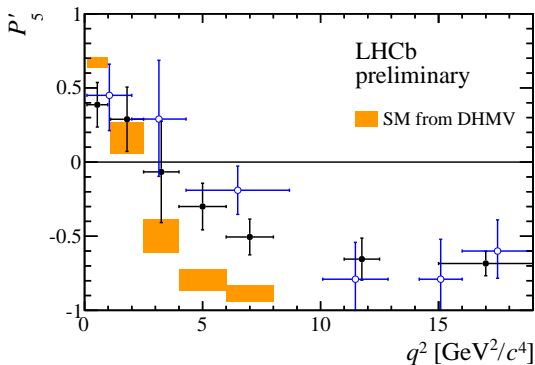
- $F_S$  dilutes the P-wave observables by a factor  $1 - F_S$ .
- Needs to be taken into account  $\rightarrow$  fit the  $m_{K\pi}$ .
- Rel. BW for P-wave.
- LASS model for S-wave



# $B^0 \rightarrow K^* \mu \mu$ results



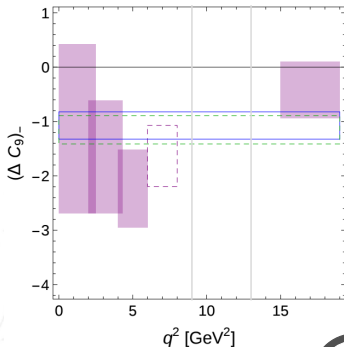
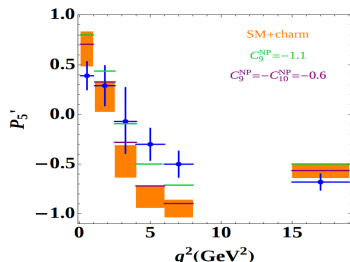
# $B^0 \rightarrow K^* \mu \mu$ results



- Tension in  $P'_5$  confirmed!
- [4.0, 6.0] and [6.0, 8.0] GeV<sup>2</sup>/c<sup>4</sup> show 2.9 $\sigma$  deviation each.
- Naive combination shows 3.7 $\sigma$  discrepancy.
- Result compatible with previous result.

# Understanding the $B^0 \rightarrow K^* \mu\mu$ anomaly

- Matias, Decotes-Genon & Virto performed a fit to our preliminary results
- 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:  
 $\rightarrow C_9$  modification.
- Data can be explained by introducing a flavour changing  $Z'$  boson, with mass  $\mathcal{O}(10 \text{ TeV})$
- [Moriond 2015 slides](#)



# Lepton universality

- If  $Z'$  is responsible for the  $P'_5$  anomaly, does it couple equally to all flavours?

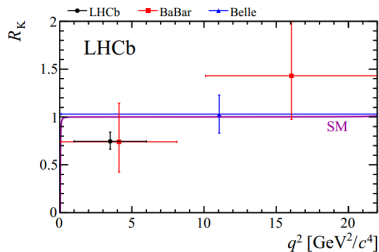
$$R_K = \frac{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \rightarrow K^+ \mu^+ \mu^-]/dq^2) dq^2}{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \rightarrow K^+ e^+ e^-]/dq^2) dq^2} = 1 \pm \mathcal{O}(10^{-3}) .$$

- Challenging analysis due to bremsstrahlung.
- Migration of events modeled by MC.
- Correct bremsstrahlung.
- Take double ratio with  $B^+ \rightarrow J/\psi K^+$  to cancel systematics.

• In  $3fb^{-1}$ , LHCb measures

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

- Consistent with SM at  $2.6\sigma$ .

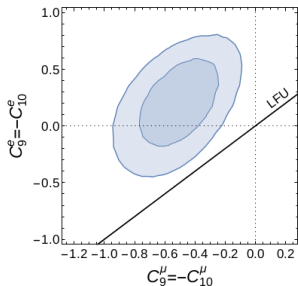


- Phys. Rev. Lett. 113, 151601 (2014)

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

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

JHEP (2014) 131



# Conclusions

- Rare decays play important role in hitting NP.
- Can access NP scales beyond reach of GPD.
- Tension in  $b \rightarrow sll$ , 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.



WELL, WHAT DID YOU EXPECT FROM A PARTICLE WITH NO SPIN?



