Latest results on rare decays at LHCb

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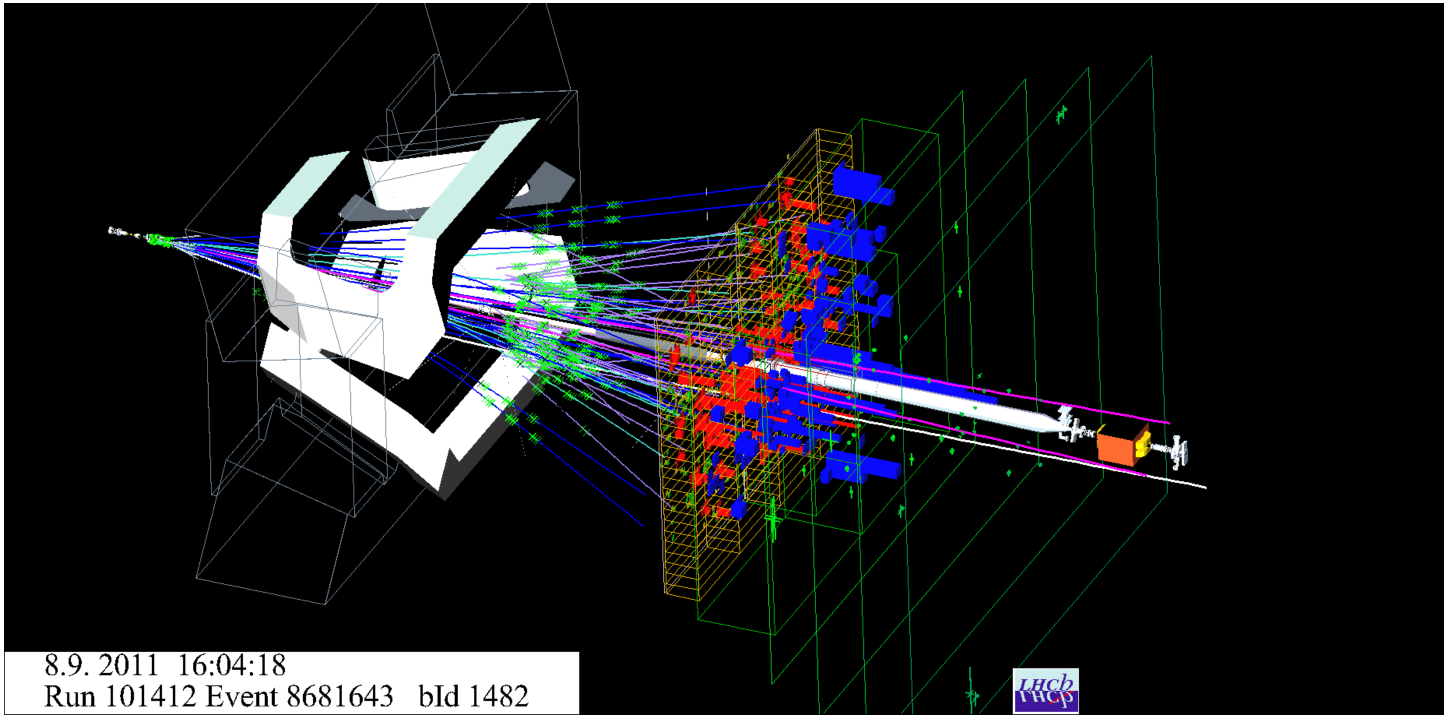


Rencontres de Physique de la vallée d'Aoste, LaThuile 2014

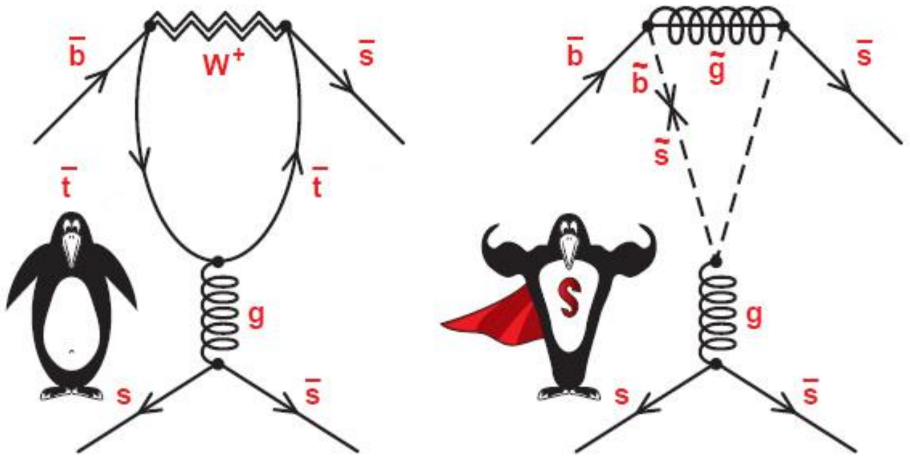
Outline

- Radiative decay:
  - Photon polarization in $B^+ \to K^+\pi^-\pi^+ \gamma$
- Lepton number violationg decay:
  - Search for Majorana neutrinos with $B^- \to \pi^+\mu^-\mu^-$
- B semileptonic decay:
  - Measurement of angular observables in $B_d \to K^{*0}\mu^+\mu^-$
- Rare charm decay:
  - $BR(D^0 \to \pi^+\pi^-\mu^+\mu^-)$
- $BR(B_{s/d} \to \mu^+\mu^-)$
- Conclusion

Why rare decays ?

- Up to now, no sign of New Physics (NP) from direct searches... but indirect NP effects can also appear in heavy flavour rare decays.

- Flavour changing neutral currents are forbidden at the tree level in the SM, they can only proceed through loop diagrams.

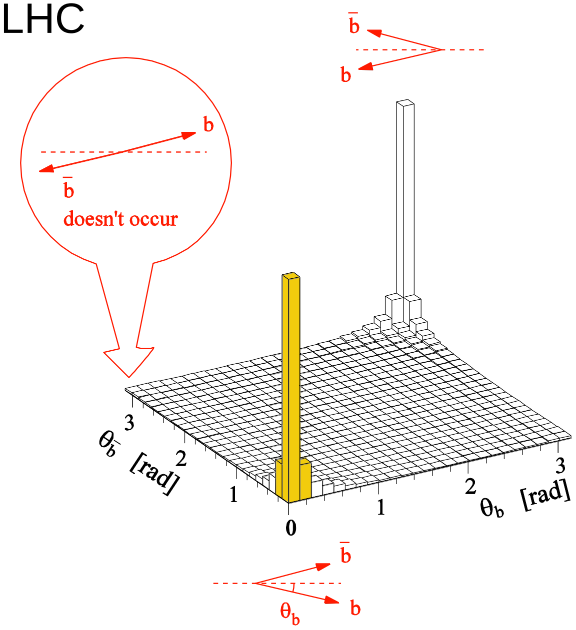


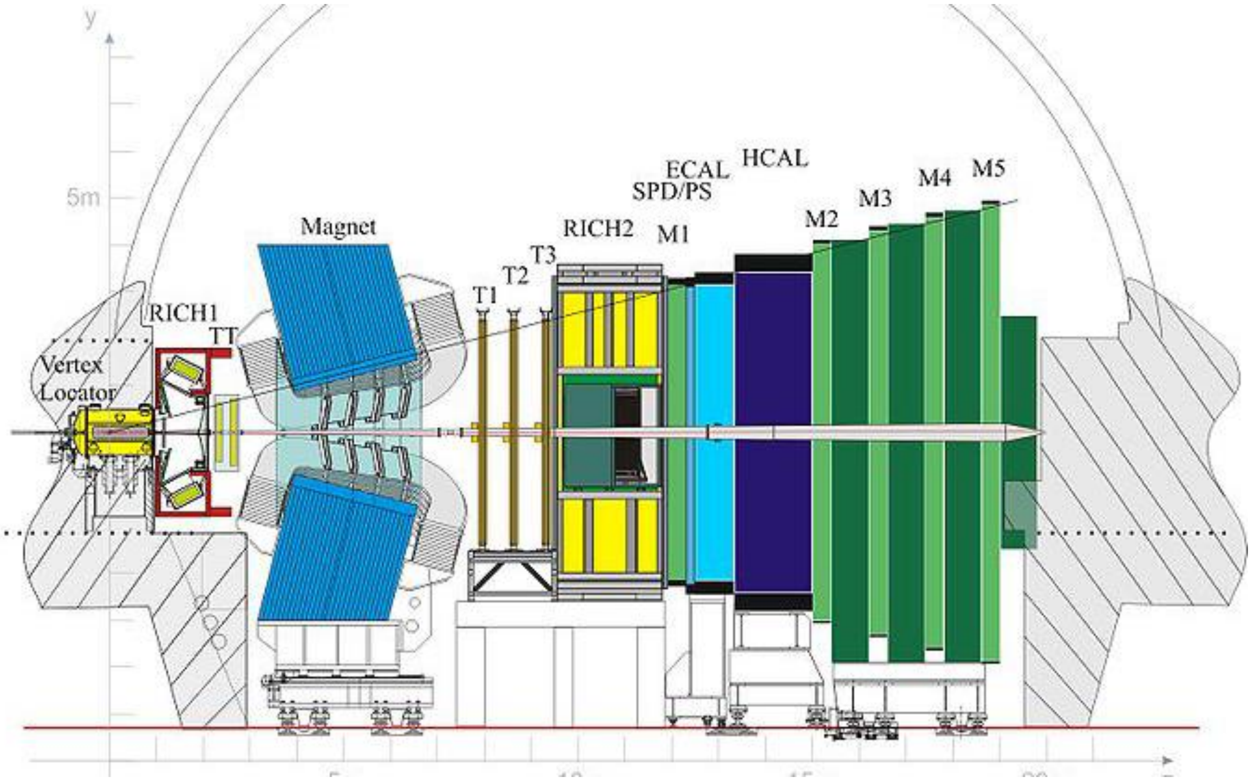
- NP virtual particles can enter the loop and modify observables such as branching ratios, CP asymmetries, angular distributions,…

- Complementary to ATLAS/CMS searches, flavour can probe a very high scale!

LHCb

- Forward spectrometer optimised for heavy flavour physics at the LHC
  - Large acceptance 2<η<5
  - Low trigger thresholds
  - Precise vertexing
  - Efficient particle identification
  - Large boost (B mesons flight ~1cm)



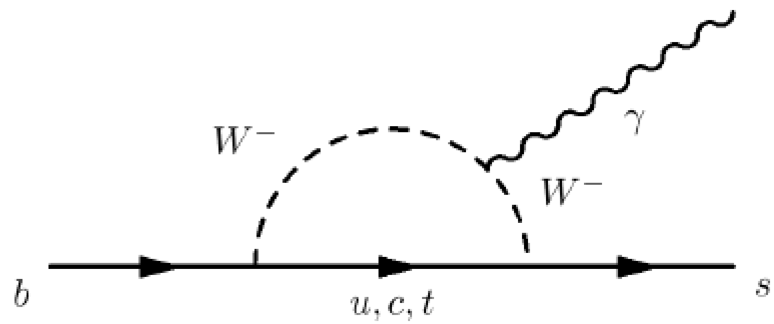


Integrated luminosity:
1 fb^{-1} @ 7TeV (2011)
2 fb^{-1} @ 8TeV (2012)

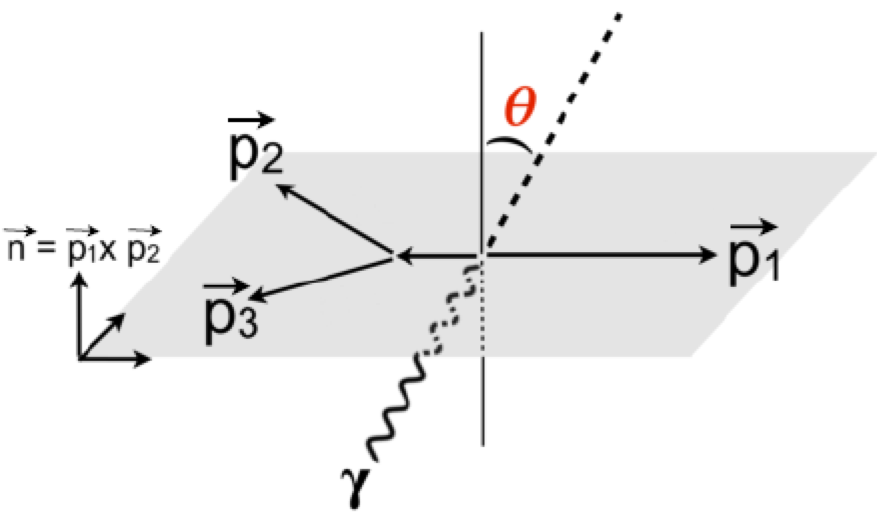
Photon polarization in $B^+ \to K^+\pi^-\pi^+\gamma$

LHCb-PAPER-2014-001

- $b \to s\gamma$ FCNC are sensitive to NP through the presence of new physics particle that can enter the electroweak penguin diagram



- Photons are predominantly left handed in SM
- Significant right handed component possible in many NP models



- The up-down asymmetry is proportional to the photon polarization $A_{ud} \propto \lambda_\gamma$
- We present an update of LHCb-CONF-2013-009 based on 3 fb $^{-1}$

Theory

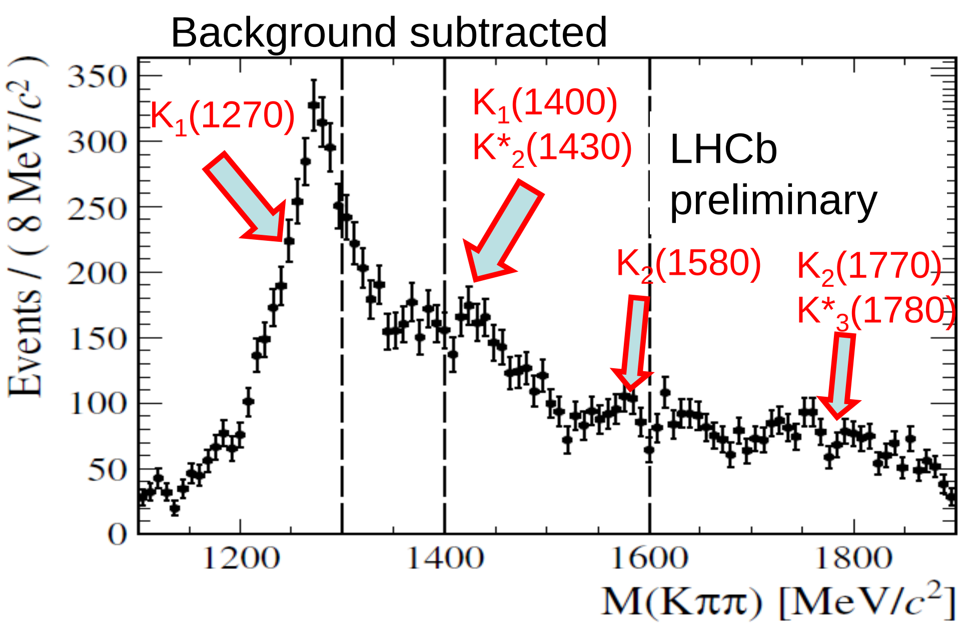
LHCb-PAPER-2014-001

- Differential decay rate of $B^+ \to K^+\pi^-\pi^+\gamma$ (*Gronau, et al. PRD66 (2002) 054008*):

$$\frac{d\Gamma}{ds\, ds_{13}\, ds_{23}\, d\cos\theta} \propto \sum_{i=0,2,4} a_i(s, s_{13}, s_{23}) \cos^i\theta + \lambda_\gamma \sum_{j=1,3} a_j(s, s_{13}, s_{23}) \cos^j\theta \,,$$

$$s_{ij} = (p_i + p_j)^2$$

Depends on the resonances in the Kππ spectrum and their interferences



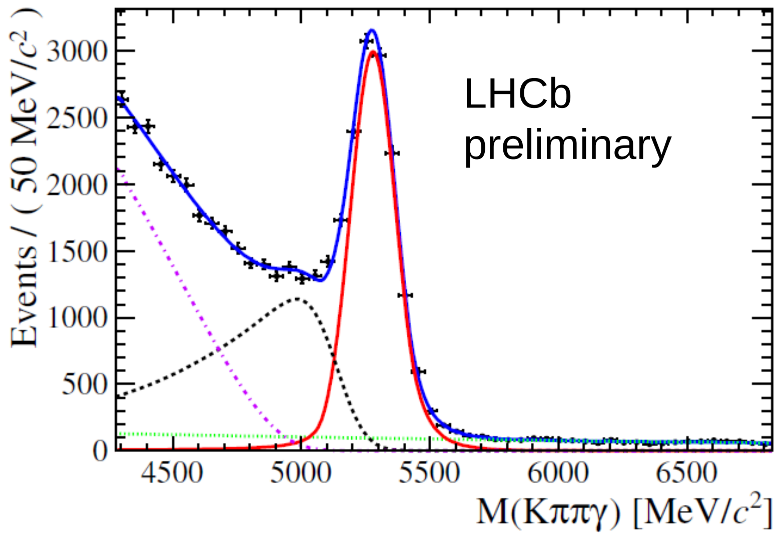
We measure the up-down asymmetry in four bins of the Kππ mass spectrum

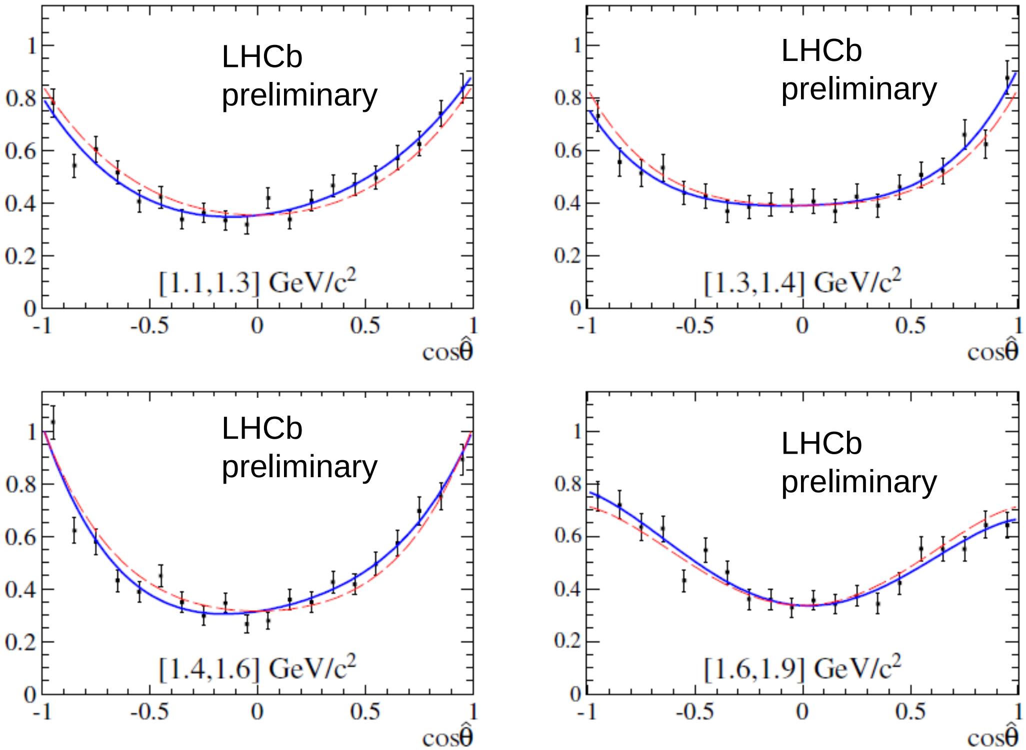
Asymmetry measurement

LHCb-PAPER-2014-001

- Fit to the B mass distribution gives ~14000 signal events

- Angular distributions obtained in the 4 M(Kππ) bins using a fit to the B mass spectrum in bins of cosθ





- Angular distributions are then fitted with :

$$f(\cos\hat{\theta}; c_0 = 0.5, c_1, c_2, c_3, c_4) = \sum_{i=0}^{4} c_i L_i(\cos\hat{\theta}) ,$$

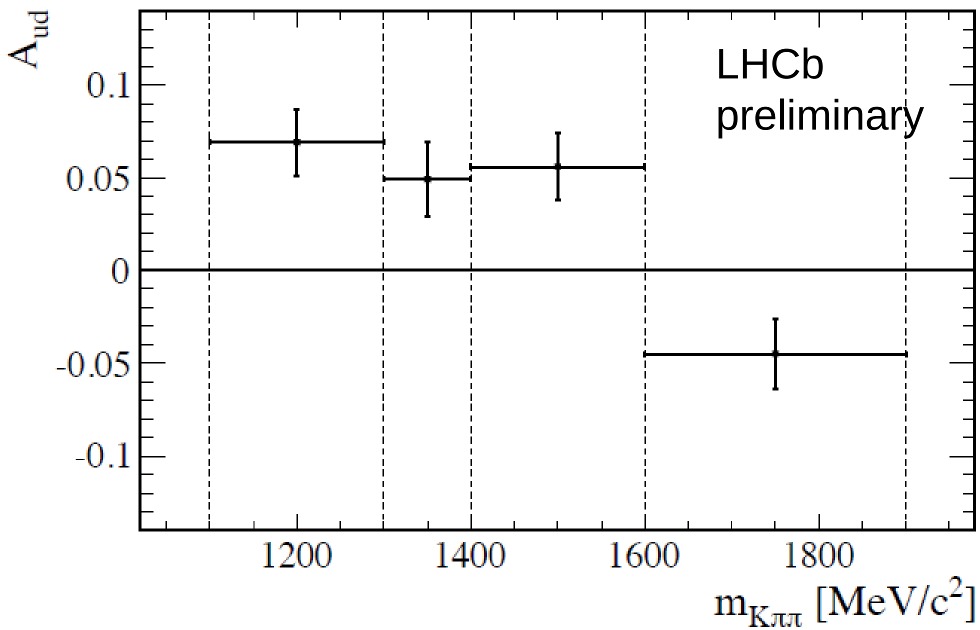
$$\mathcal{A}_{\rm ud} = c_1 - \frac{c_3}{4} .$$

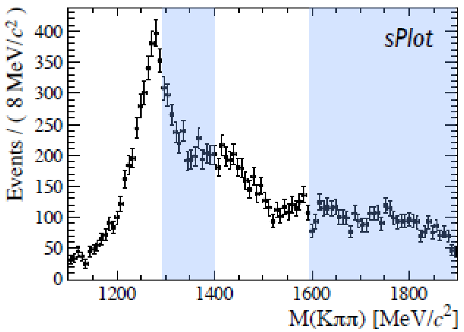
$$\cos\hat{\theta} \stackrel{\text{def}}{=} charge(B)cos\theta$$

Results

LHCb-PAPER-2014-001

- We obtain 4 independent measurements of the asymmetry:





- This translates into a 5.2 σ significance for a non zero up-down asymmetry

  ⇒ first observation of photon polarization in $b \rightarrow s\gamma$ transition

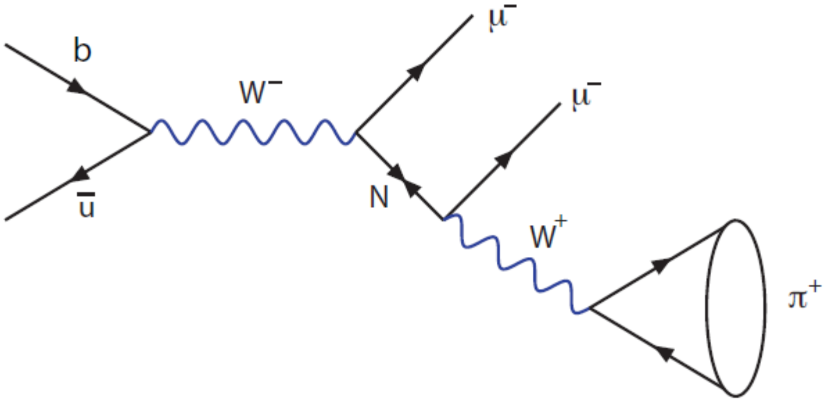
Search for Majorana neutrinos in $B^- \to \pi^+ \mu^- \mu^-$

- Lepton number violating decay forbidden in the SM

- Can probe Majorana neutrino with any mass in $m(\pi)+m(\mu) < m(N) < 5$ GeV

- The lifetime of N is unknown, we search for N with a lifetime up to 1000 ps

- Experimental status:



CLEO	$BR(B^- \to \pi^+ \mu^- \mu^-) < 1.4 \times 10^{-6}$ at 90%, PRD65:111102 (2002)
Babar	$BR(B^- \to \pi^+ \mu^- \mu^-) < 10.7 \times 10^{-8}$ at 90%, PRD85:071103 (2012)
LHCb ($0.41 fb^{-1}$)	$BR(B^- \to \pi^+ \mu^- \mu^-) < 1.3 \times 10^{-8}$ at 95%, PRD 85:112004 (2012)

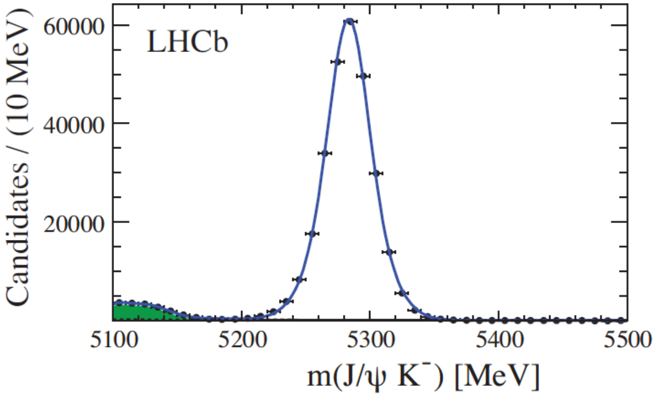
Here we present an update based on the $3 fb^{-1}$ recorded

arXiv:1401.5361, submitted to PRL

Analysis strategy

arXiv:1401.5361

- 2 selections :
  - Assuming N has zero lifetime, B vertex formed by $\pi^+\mu^-\mu^-$
  - Detached neutrino: first vertex for $\pi^+\mu^-$, attached to the second μ^- to form the B candidate



- Normalization to $B^+ \to J/\Psi K^+$
  - Find ~280 000 events

- Ratio of efficiencies taken from MC or data driven methods

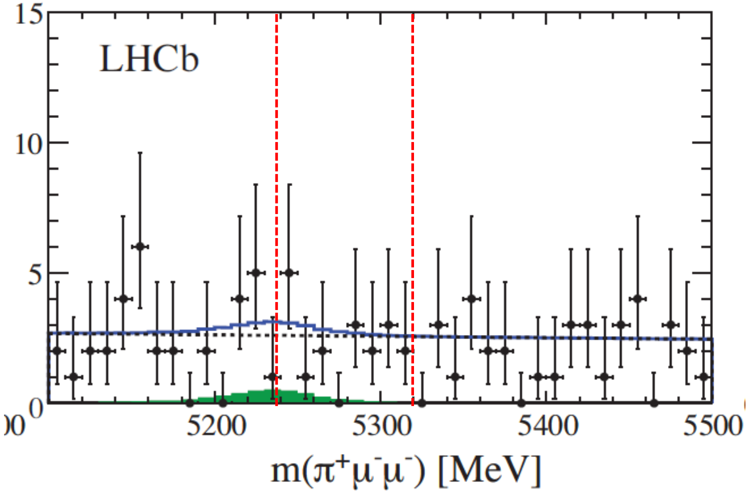
- Extended maximum likelihood fit to the $\pi^+\mu^-\mu^-$ sidebands to determine the combinatorial background

- Peaking background shape taken from MC, yields constrained to $B^+ \to J/\Psi K^+$

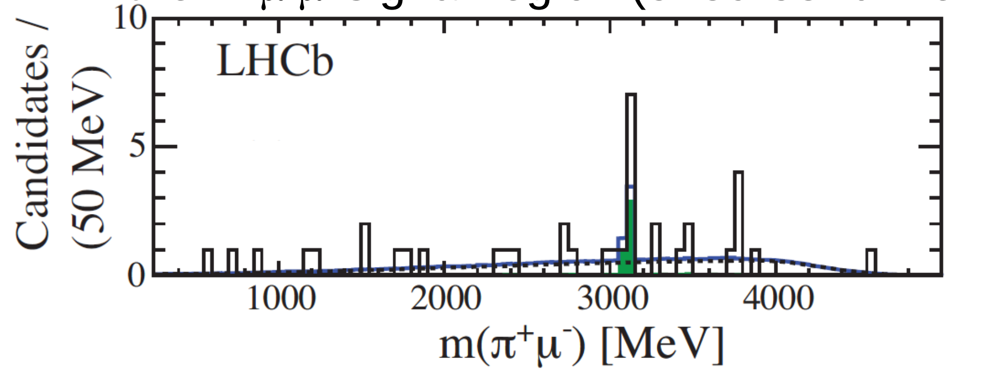
- Limits obtained with the CLs method

$B^- \rightarrow \pi^+\mu^-\mu^-$, short neutrino lifetime

arXiv:1401.5361

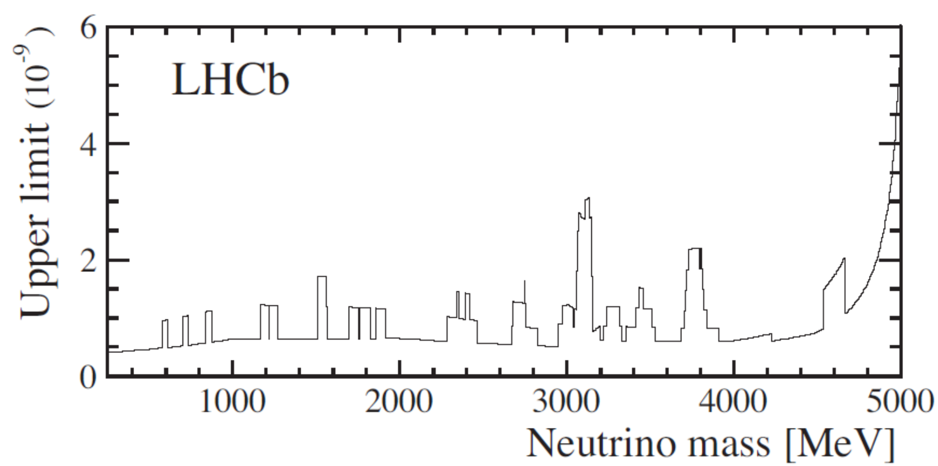


in the $\pi^+\mu^-\mu^-$ signal region (5239-5320 MeV)



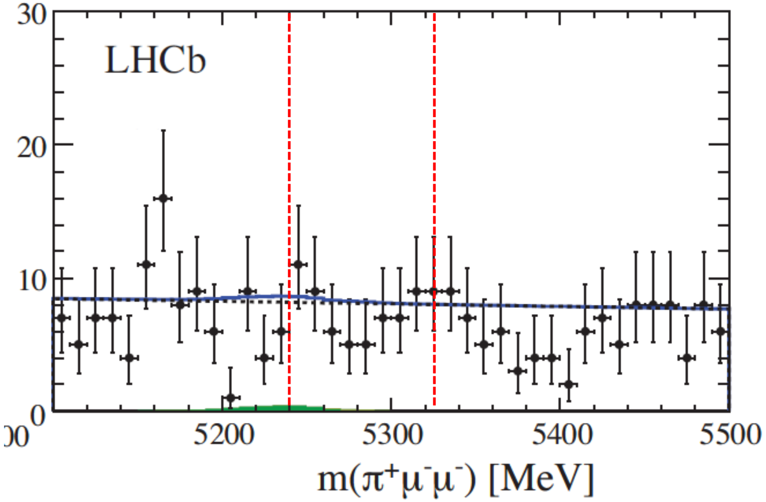
- Peaking background : $B^+ \rightarrow J/\Psi\ K^+(\pi^+)$, $B^+ \rightarrow \Psi(2S)\ K^+$
- No signal found, $BR(B^- \rightarrow \pi^+\mu^-\mu^-) < 4.0 \times 10^{-9}$ at 95% CL

- Limit as function of neutrino mass:
  - Scan over neutrino mass with 5 MeV step up to 5000 MeV
  - At each point, fit $m(\pi^+\mu^-)$ in a 3σ window, σ being the neutrino mass resolution evaluated from MC

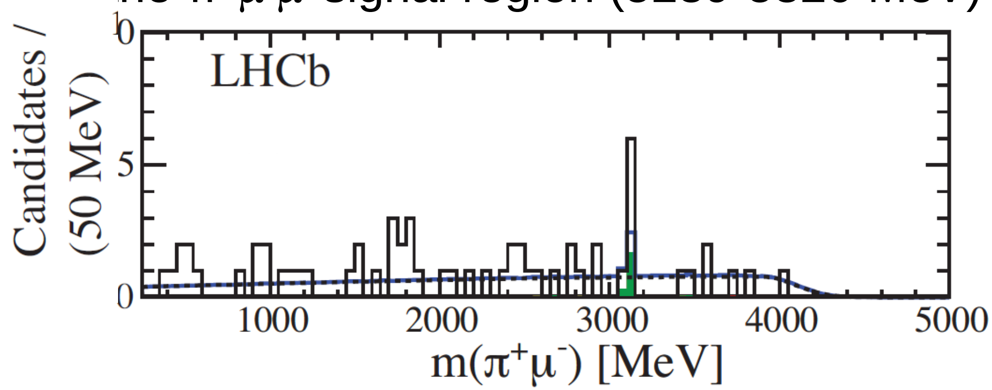


$B^- \to \pi^+\mu^-\mu^-$, long neutrino lifetime

arXiv:1401.5361

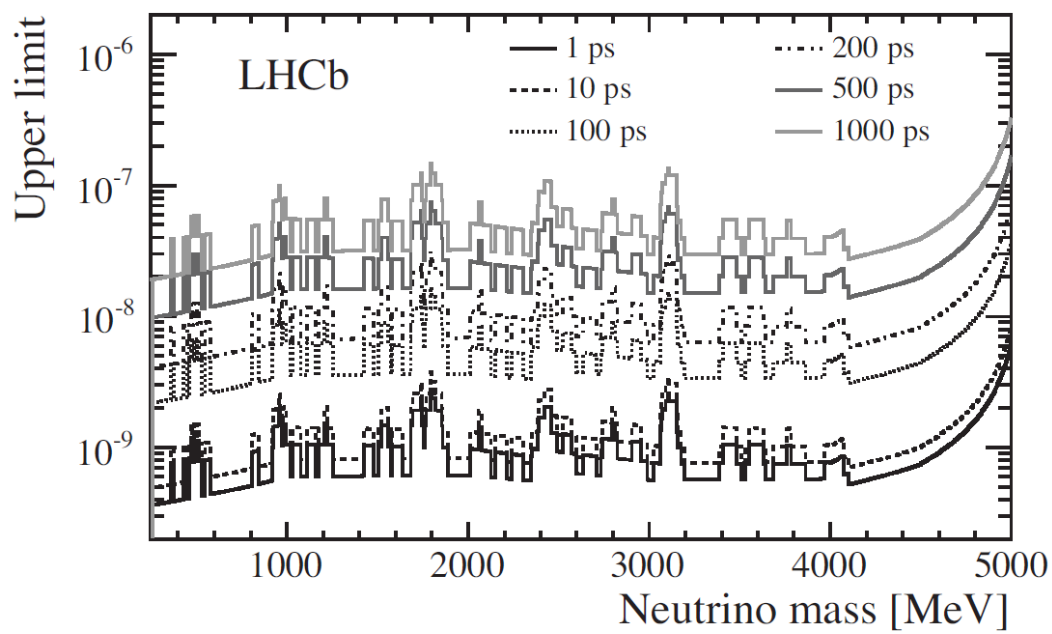


in the $\pi^+\mu^-\mu^-$ signal region (5239-5320 MeV)

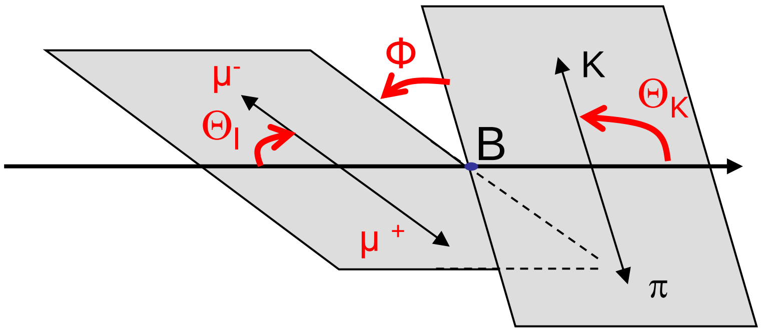


- Peaking background : $B^+ \to J/\Psi K^+(\pi^+)$, $B^+ \to \Psi(2S) K^+$

- No signal found, limit as function of neutrino mass and lifetime



- Decay described by 3 angles and di-muon invariant mass squared q^2
- Folding the ϕ angle (if $\phi<0$, $\phi=\phi+\pi$), we can reduce the number of free parameters:



$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{16\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \frac{1}{2}(1-F_L)A_T^{Re}\sin^2\theta_K\cos\theta_\ell + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$A_{FB} = \frac{3}{4}(1-F_L)A_T^{\mathrm{Re}}$$

A_{FB} : forward-backward asymmetry
F_L : fraction of K^{*0} longitudinally polarized

A_{FB} zero crossing point precisely predicted in SM:

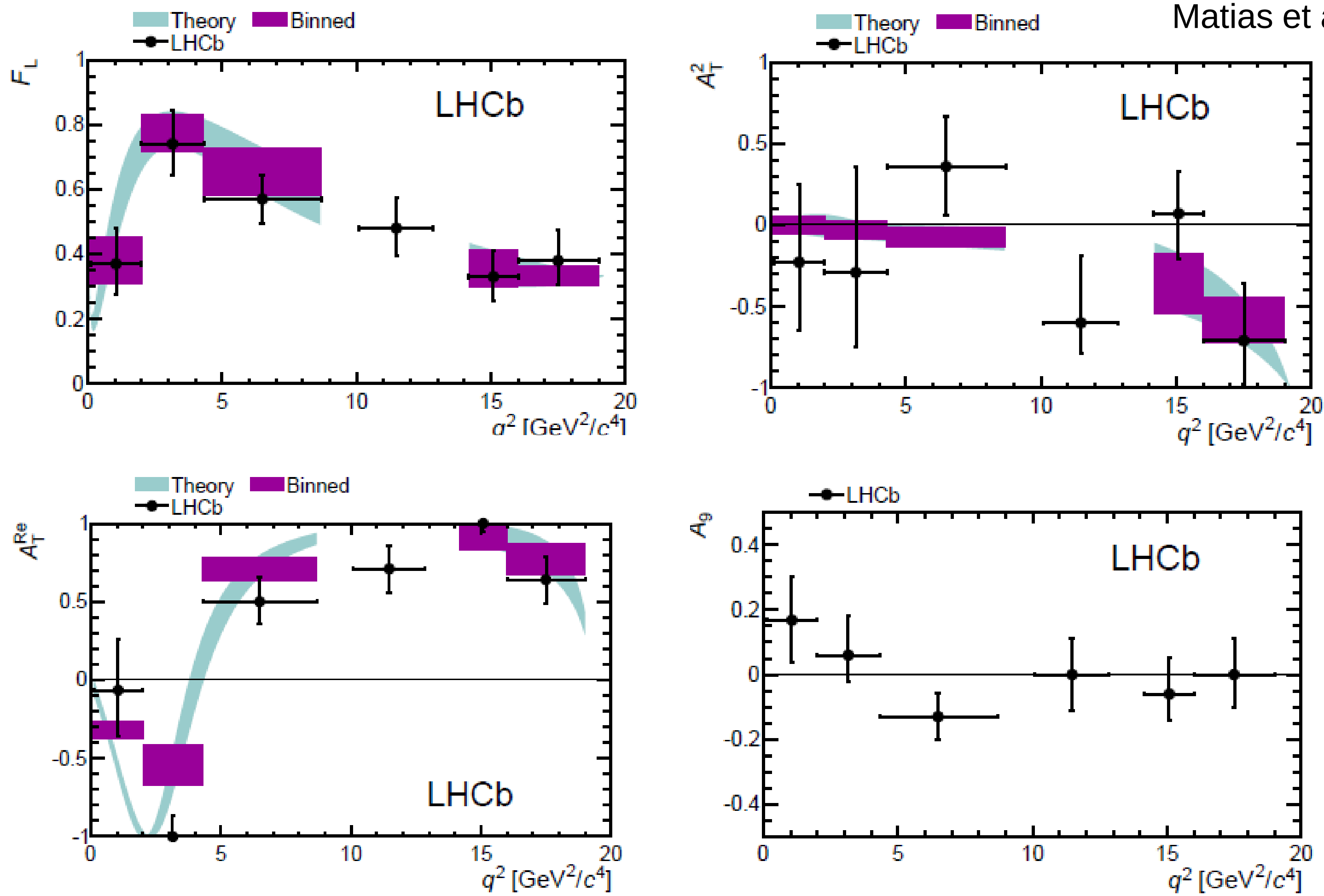
$$q_0^2 = 4.36^{+0.33}_{-0.31}\, GeV^2/c^4$$

Beneke et al, EPJ C41 (2005) 173

JHEP 08 (2013) 131

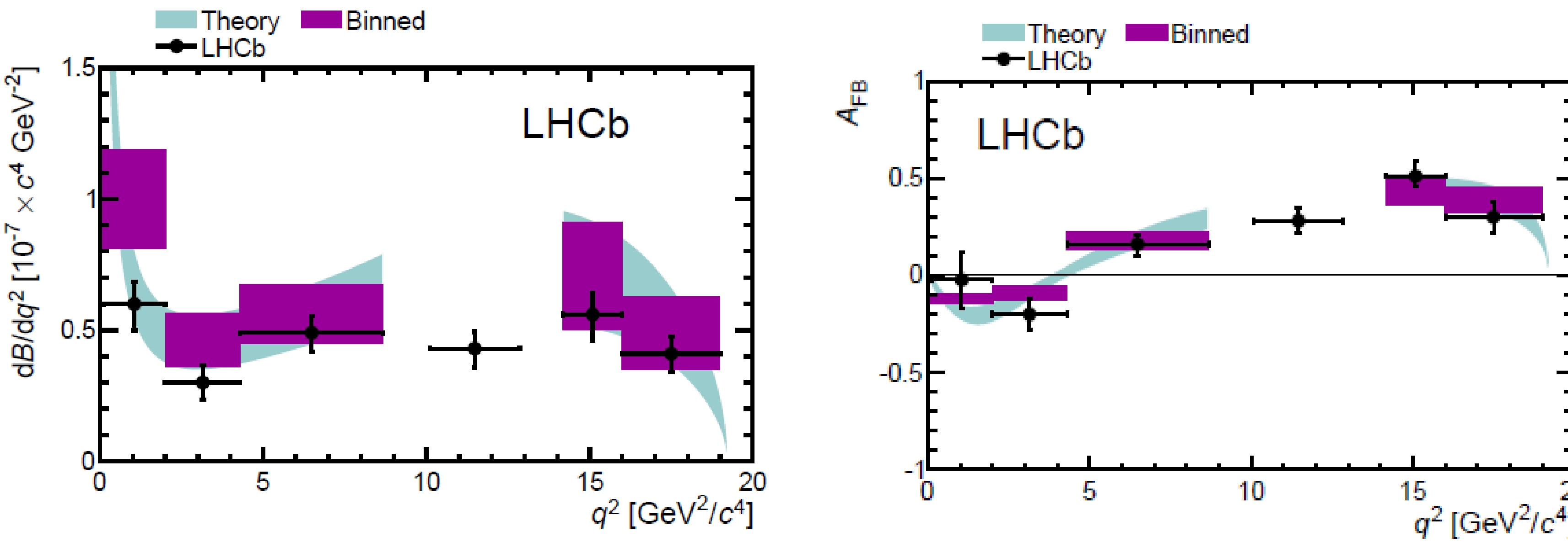
- Analysis based on 1 fb^{-1}, ~900 events
- Observables measured in 6 q^2 bins

Theory from bobeth-Hiller-Van Dyk (2011), consistent with Matias et al (2013)



Results

JHEP 08 (2013) 131



Theory from bobeth-Hiller-Van Dyk (2011), consistent with Matias et al (2013)

- Good agreement with SM predictions
- First measurement of zero crossing point: $q_0^2 = 4.9 \pm 0.9 \;\; GeV^2/c^4$

New observables

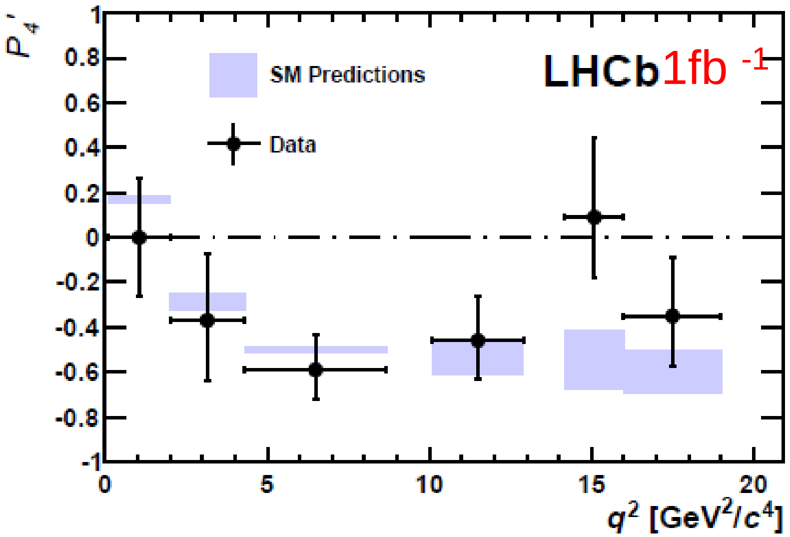
- Observables with limited dependence on form-factors uncertainty have been proposed by several theorists
- Different set of observables give different constraints $\Rightarrow$ complementarity!
- Use different folding to measure each P'_i

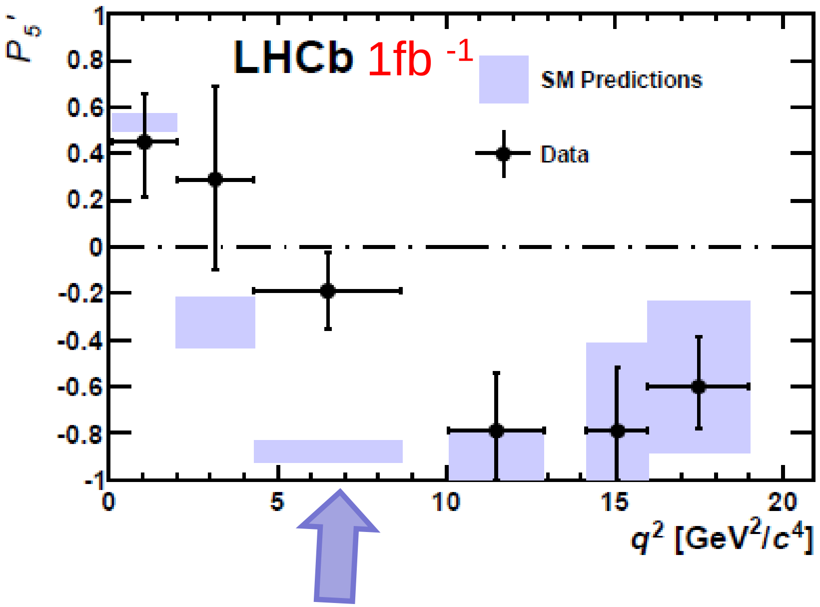
$$
\begin{aligned}
\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \\
&- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \\
&\sqrt{F_L(1-F_\mathrm{L})}P'_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P'_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \\
&(1-F_\mathrm{L})A_{Re}^\mathrm{T}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P'_6\sin 2\theta_K\sin\theta_\ell\sin\phi + \\
&\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P'_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\ \Big]
\end{aligned}
$$

Results for new observables

PRL 111 (2013) 191801

P_4', P_6' and P_8' are in good agreement with theoretical predictions (Descotes-Genon et al, JHEP 05 (2013) 137), but large deviation in P_5'





3.7 σ discrepancy in the bin $4.3<q^2<8.68$ GeV^2

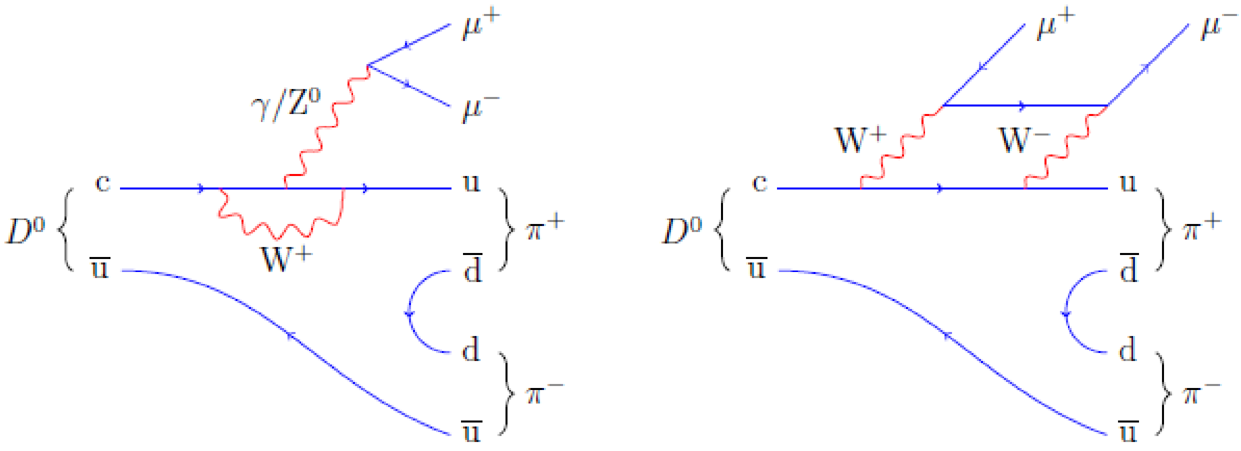
2.5 σ discrepancy in the bin $1<q^2<6$ GeV^2

Could be interpreted as NP contribution in Wilson coefficient C_9

Rare charm decay: $D^0 \to \pi^+\pi^-\mu^+\mu^-$

PLB 728 (2014) 234-243

- SM prediction for the BR ~10^{-9}
- Never seen yet, latest result by E791 BR($D^0 \to \pi^+\pi^-\mu^+\mu^-$) < 3.0 x$10^{-5}$ @ 90% CL

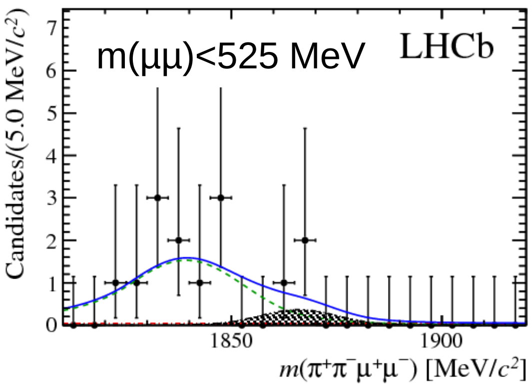


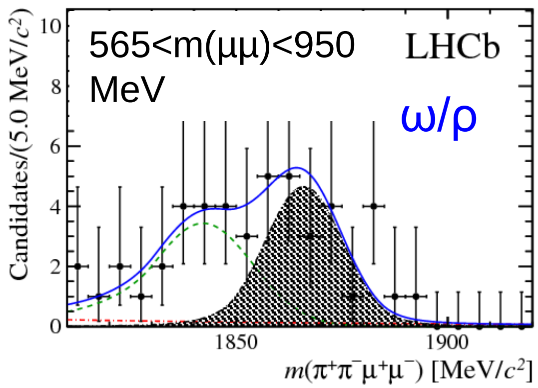
- 1 fb^{-1} analysed, using $D^{*+} \to D^0(\to \mu^+\mu^-)\pi^+_{slow}$
- Yields from 2D fit: $m(D^0)$ vs $\Delta m(D^{*+}-D^0)$
- $D^0 \to \pi^+\pi^-\phi(\to \mu^+\mu^-)$ is used as normalization channel

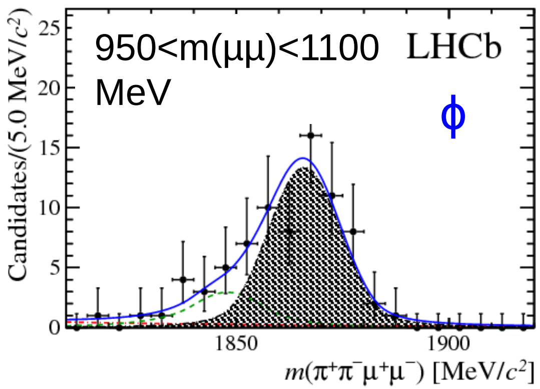
Results

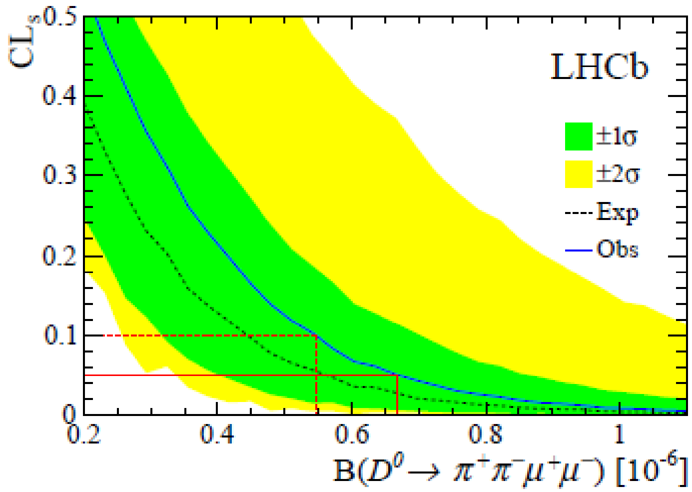
PLB 728 (2014) 234-243

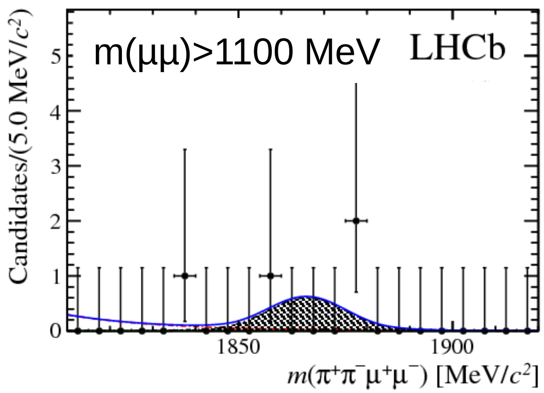
- Fit performed in 4 bins of the μμ mass:











Limit in the high+low bin:
$BR(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 6.7 \times 10^{-7}$ @ 95%CL

50 times better than previous result!

$B_{s/d} \to \mu^+\mu^-$

CMS PAS BPH-13-007, LHCb-CONF-2013-012

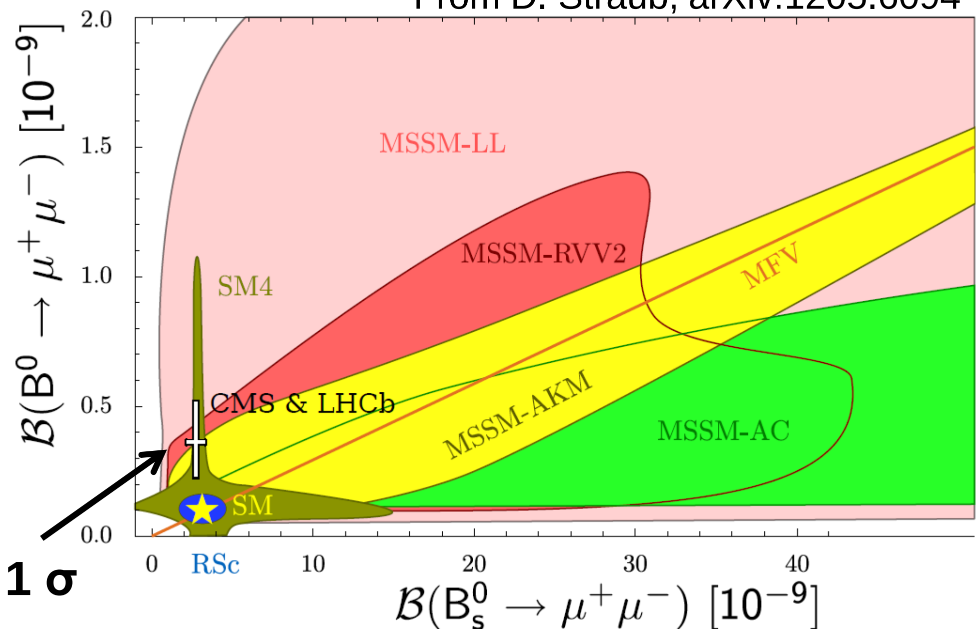
- CMS (25 fb^{-1}) and LHCb (3 fb^{-1}) both found evidence for the very rare decay $B_s \to \mu^+\mu^-$, in agreement with SM
- Combining CMS and LHCb: first observation of $B_s \to \mu^+\mu^-$

$$BR(B^0_S \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

- We are entering the precision era
- The current SM BR($B_s \to \mu^+\mu^-$) has a 10% uncertainty $\Rightarrow$ crucial to improve theoretical errors

From D. Straub, arXiv:1205.6094



See A. Morda talk for more details!

Conclusion

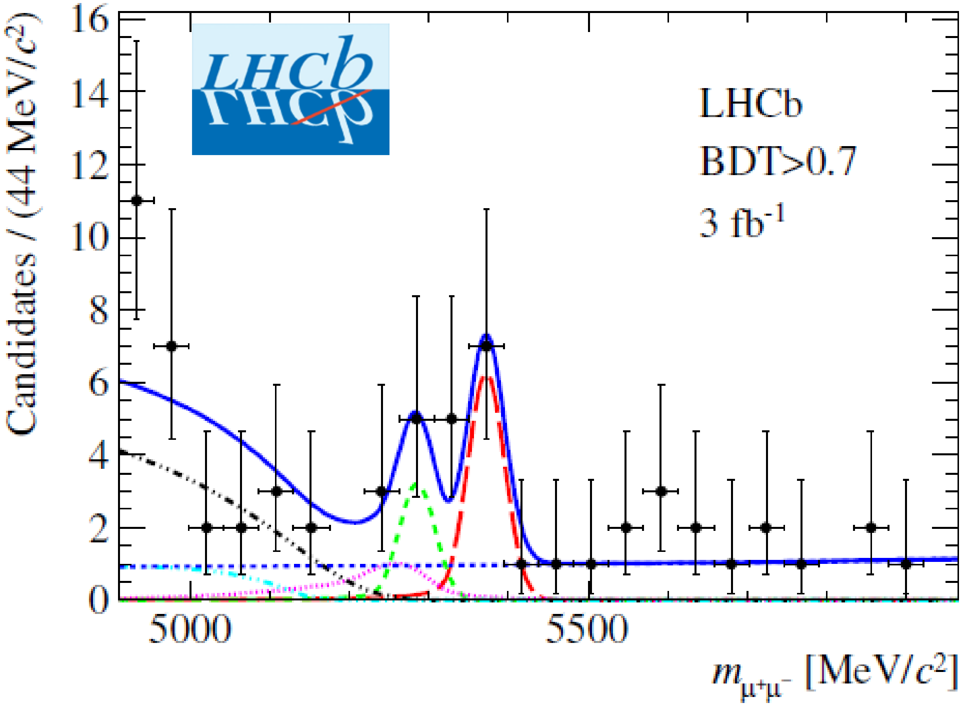
- LHCb is providing a lot of interesting new results on rare decays:
  - First observation of the photon polarization in $B^+ \to K^+ \pi^- \pi^+ \gamma$
  - Improved limit BR($B^+ \to K^+ \mu^+ \mu^-$) sensitive to Majorana neutrino
  - Measurement of form factor independent observables in $B_d \to K^{*0} \mu^+ \mu^-$
  - World best upper limit on BR($D^0 \to \pi^+ \pi^- \mu^+ \mu^-$)
  - BR measurement for $B_s \to \mu^+ \mu^-$ with 4 σ significance

- Overall good agreement with SM, except for a local discrepancy in the low q^2 region for P_5' in $B_d \to K^{*0} \mu^+ \mu^-$. This analysis uses 1 fb^{-1}, stay tuned!

Penguins can still be hiding new physics!

backup

Results: $B_{s/d} \to \mu^+\mu^-$



arXiv:1307.5024
Phys.Rev. Lett.111(2013) 101805

$B^0 \to \pi^-\mu^+\nu$
$B_s \to K^-\mu^+\nu$
$B^{0/+} \to \pi^{0/+}\mu\mu$
$B_{d/s} \to h^+h'^-$
$B_s \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
Total

$$BR(B_S^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$

Significance: 4.0 σ
(5 σ expected)

$$BR(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)) \times 10^{-10}$$

Significance: 2.0 σ

$B(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95% CL

Experimental observable

- Experimental observable is the time integrated B:

$$B(B_s^0 \to f)_{\text{exp}} \equiv \frac{1}{2}\int_0^\infty \langle \Gamma(B_s^0(t) \to f)\rangle dt$$

- Theoretical definition for the prediction:

$$B(B_s^0 \to f)_{\text{theo}} \equiv \frac{\tau_{B_s^0}}{2}\langle \Gamma(B_s^0(t) \to f)\rangle\Big|_{t=0}$$

- Time integrated prediction:

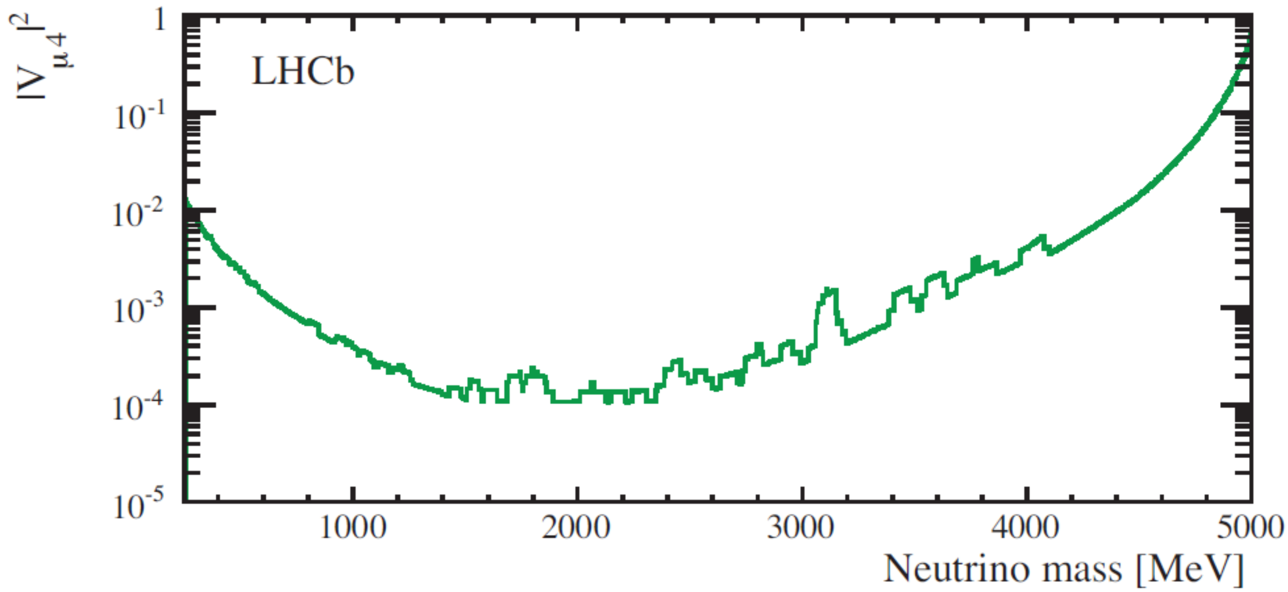
$$BF(B_s^0 \to \mu^+\mu^-)_{exp} = BF(B_s^0(t) \to \mu^+\mu^-)_{t=0} \times \frac{1 + A_{\Delta\Gamma} y_s}{1 - y_s^2}$$

$$\mathcal{A}^f_{\Delta\Gamma} = \frac{\Gamma(B_{s,\mathrm{H}} \to f) - \Gamma(B_{s,\mathrm{L}} \to f)}{\Gamma(B_{s,\mathrm{H}} \to f) + \Gamma(B_{s,\mathrm{L}} \to f)} \qquad y_s = \frac{\Gamma_L - \Gamma_H}{\Gamma_L + \Gamma_H} = 0.0615 \pm 0.0085$$

$$\textit{in the SM}:\ A_{\Delta\Gamma} = 1 \quad B(B_s^0 \to \mu^+\mu^-)^{SM}_{exp} = (3.56 \pm 0.30) \times 10^{-9}$$

De Bruyn et al., PRL 109, 041801(2012), uses ys from HFAG

Limit on $|V_{\mu 4}|^2$



Atre et al. JHEP 05 (2009) 030 :

$$\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-) = \frac{G_F^4 f_B^2 f_\pi^2 m_B^5}{128\pi^2 \hbar} |V_{ub} V_{ud}|^2 \tau_B \left(1 - \frac{m_N^2}{m_B^2}\right) \frac{m_N}{\Gamma_N} |V_{\mu 4}|^4$$

We use for the total width of the neutrino decay:

$$\Gamma_N = \left[3.95 m_N^3 + 2.00 m_N^5 (1.44 m_N^3 + 1.14)\right] 10^{-13} |V_{\mu 4}|^2$$

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

- Full angular distribution:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + I_2^s \sin^2\theta_K \cos 2\theta_\ell + I_2^c \cos^2\theta_K \cos 2\theta_\ell + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + I_6 \sin^2\theta_K \cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big] ,$$

$$S_j = \left(I_j + \bar{I}_j\right) \Big/ \frac{d\Gamma}{dq^2} \quad \text{or} \quad A_j = \left(I_j - \bar{I}_j\right) \Big/ \frac{d\Gamma}{dq^2}$$

- To few events to fit for the 11 angular terms: Folding the ϕ angle cancels terms with sin ϕ or cos ϕ dependence.

New observables in $B_d \to K^{*0}\mu^+\mu^-$

- Folding technique:

Measurement of the other observables with other folding techniques for P_5' (or equivalently S_5) $\phi \to -\phi$ (if $\phi<0$) and $\vartheta_l \to \pi-\vartheta_l$ (if $\vartheta_l<\pi/2$)

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{8\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi\Big]$$

$$Pdf = \frac{9}{8\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi\Big]$$

$$P_4', S_4: \begin{cases}\phi\to-\phi & \text{for } \phi<0\\ \phi\to\pi-\phi & \text{for } \theta_\ell>\pi/2\\ \theta_\ell\to\pi-\theta_\ell & \text{for } \theta_\ell>\pi/2,\end{cases}$$

$$Pdf = \frac{9}{8\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi\Big]$$

$$P_6', S_7: \begin{cases}\phi\to\pi-\phi & \text{for } \phi>\pi/2\\ \phi\to-\pi-\phi & \text{for } \phi<-\pi/2\\ \theta_\ell\to\pi-\theta_\ell & \text{for } \theta_\ell>\pi/2,\end{cases}$$

$$Pdf = \frac{9}{8\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi\Big]$$

$$P_8', S_8: \begin{cases}\phi\to\pi-\phi & \text{for } \phi>\pi/2\\ \phi\to-\pi-\phi & \text{for } \phi<-\pi/2\\ \theta_K\to\pi-\theta_K & \text{for } \theta_\ell>\pi/2\\ \theta_\ell\to\pi-\theta_\ell & \text{for } \theta_\ell>\pi/2.\end{cases}$$

$D^0 \to \pi^+\pi^-\mu^+\mu^-$